IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE
東京大学 THE UNIVERSITY OF TOKYO

Standard Model I
Introductory Lecture

CERN Summer Student Programme
July 20, 2009

Hitoshi Murayama (IPMU Tokyo & Berkeley)

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT
BERKELEY CENTER FOR THEORETICAL PHYSICS
BERKELEY LAB

Plan

- Today is mostly a review of things you already know with a few extra
- Quantum ElectroDynamics (QED)
- Strong interaction
(QCD = Quantum ChromoDynamics)
- Weak interaction (Electrowork Theory)
- Flavor physics

Hierarchy of scales

• distance scales in Nature

Hierarchy of scales

0.1m

- distance scales in Nature

Hierarchy of scales

10^3m

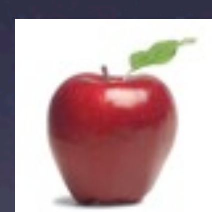
0.1m

- distance scales in Nature

Hierarchy of scales

10^7m

10^3m



0.1m

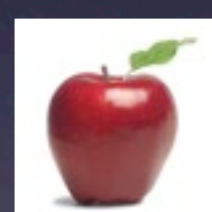
- distance scales in Nature

Hierarchy of scales

10^{11}m

10^{7}m

10^{3}m



0.1m

- distance scales in Nature

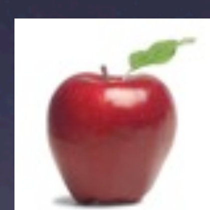
Hierarchy of scales

10^{20}m

10^{11}m

10^{7}m

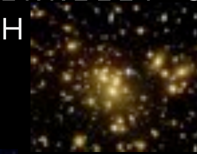
10^{3}m



0.1m

- distance scales in Nature

Hierarchy of scales

10^{23}m



10^{20}m


10^{11}m


10^{7}m


10^{3}m


0.1m

- distance scales in Nature

Hierarchy of scales

10^{27}m

10^{23}m

10^{20}m

10^{11}m

10^{7}m

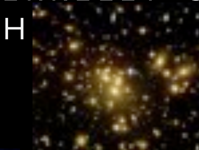
10^{3}m

0.1m

- distance scales in Nature

Hierarchy of scales

10^{27}m



10^{23}m

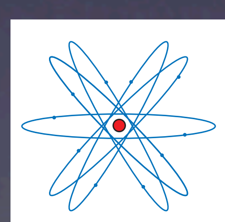
10^{20}m

10^{11}m

10^{7}m

10^{3}m

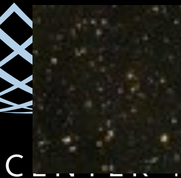
0.1m

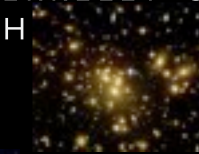


10^{-10}m

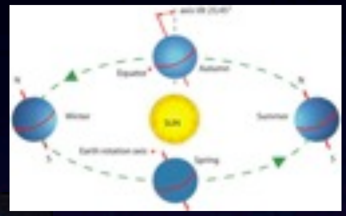
- distance scales in Nature

Hierarchy of scales


10^{27}m


10^{23}m

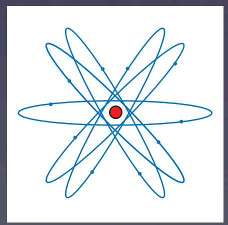

10^{20}m

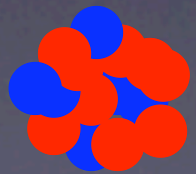

10^{11}m


10^{7}m


10^{3}m

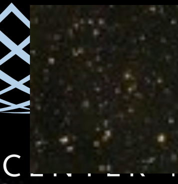

0.1m


10^{-10}m

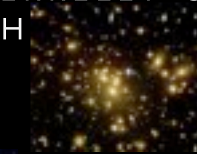

10^{-15}m

- distance scales in Nature

Hierarchy of scales



10^{27}m



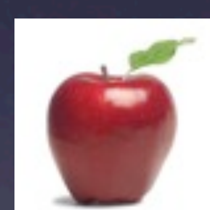
10^{23}m

10^{20}m

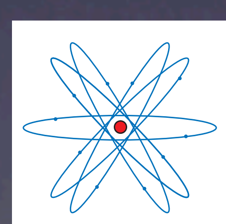
10^{11}m

10^{7}m

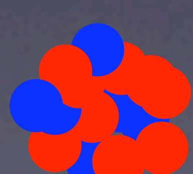
10^{3}m



0.1m



10^{-10}m

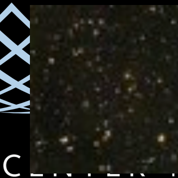
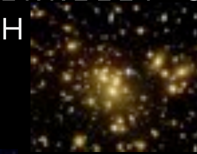


10^{-15}m

10^{-19}m

- distance scales in Nature

Hierarchy of scales

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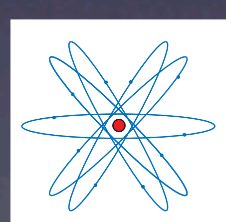
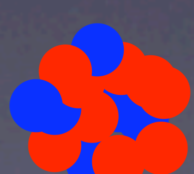


10^{-10}m



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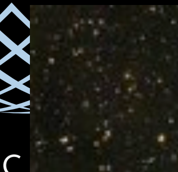

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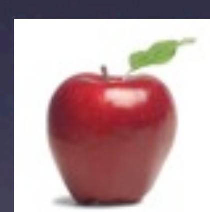

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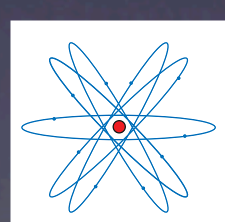
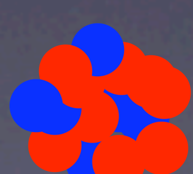


10^{-10}m



10^{-15}m

10^{-19}m

- distance scales in Nature

Particle Physics

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Particle Physics

- What are things made of?

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Particle Physics

- What are things made of?
- Why do they stick together to build things around us?

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Particle Physics

CERN

- What are things made of?
- Why do they stick together to build things around us?
- discipline to study the constituents and forces among them

Particle Physics

- What are things made of?
- Why do they stick together to build things around us?
- discipline to study the constituents and forces among them
- tear things down, see what make them up

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Particle Physics

CERN

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- See how they interact with each other

Particle Physics

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- everything should be understood based on their fundamental constituents and forces

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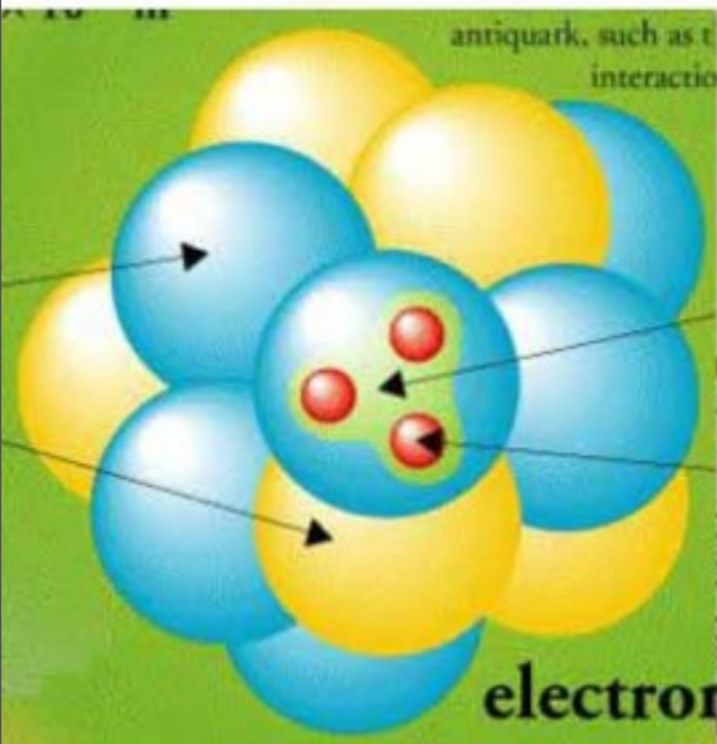
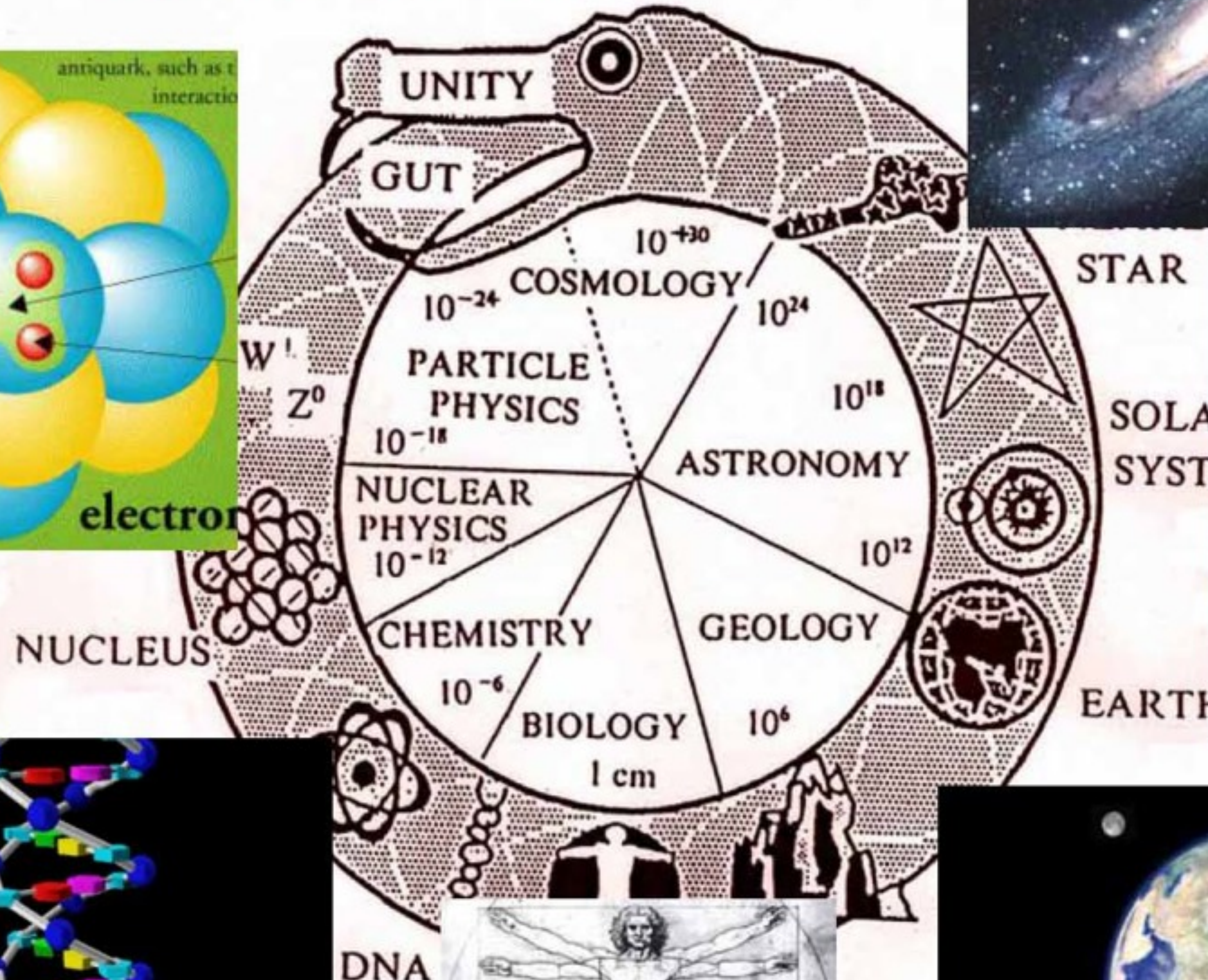
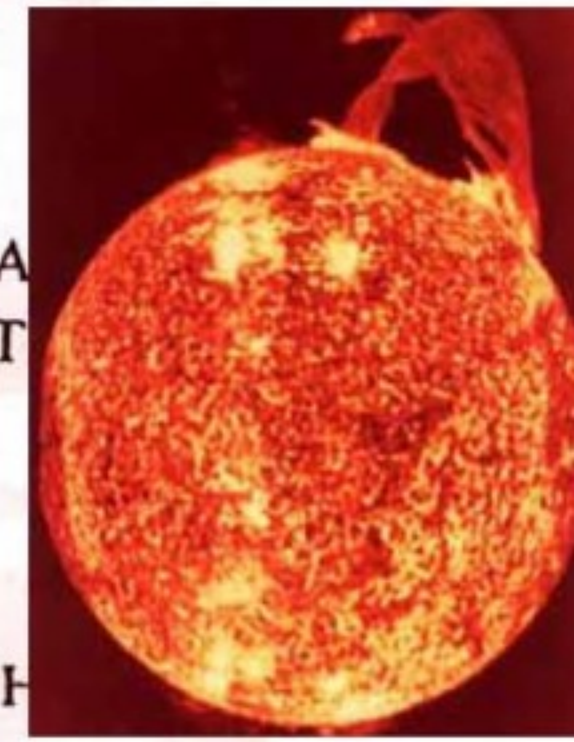
Particle Physics

- What are things made of?
- Why do they stick together to build things around us?
- discipline to study the constituents and forces among them
- tear things down, see what make them up
- See how they interact with each other
- everything should be understood based on their fundamental constituents and forces
- *We need it to understand the Universe*

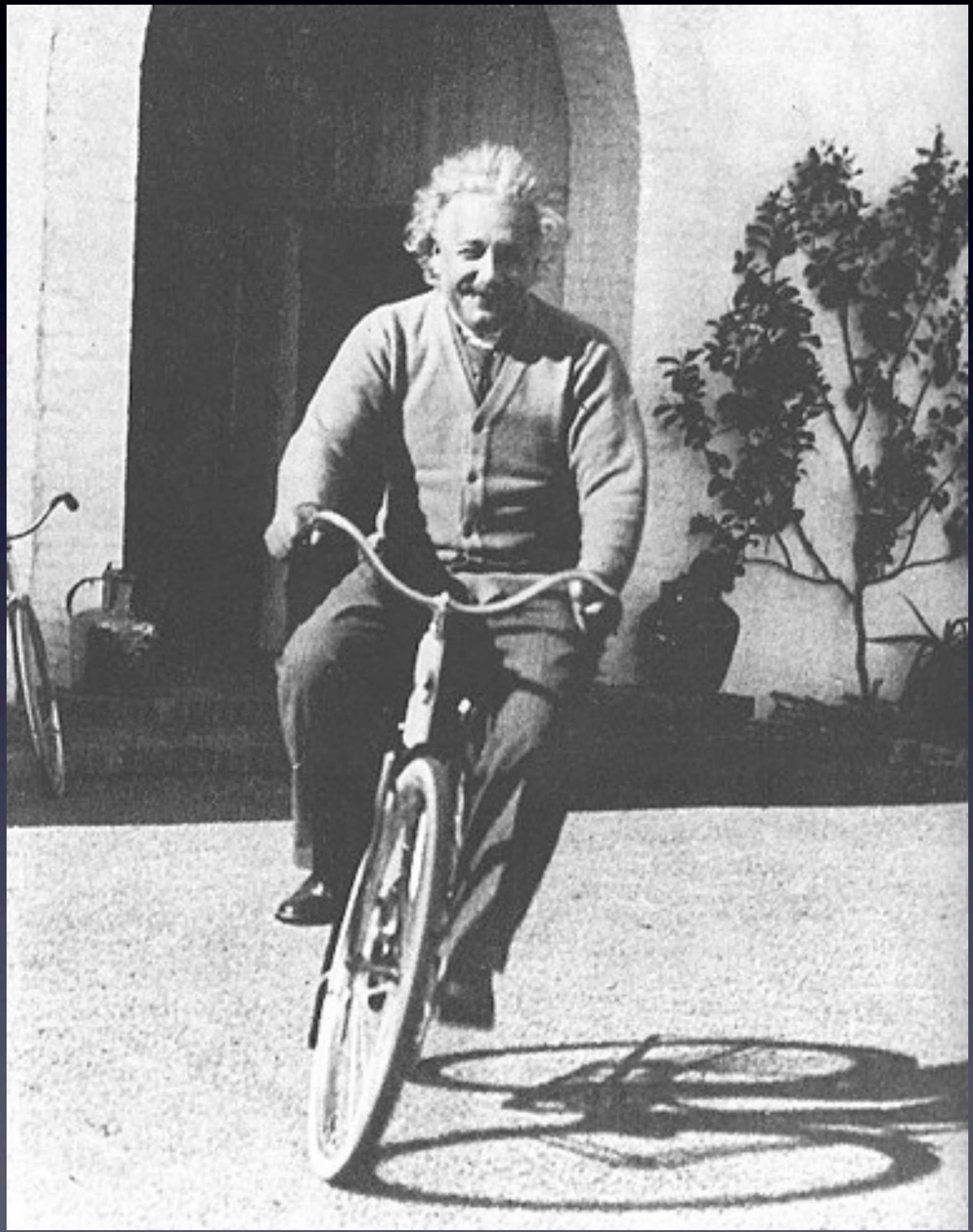
Uroborus' snake





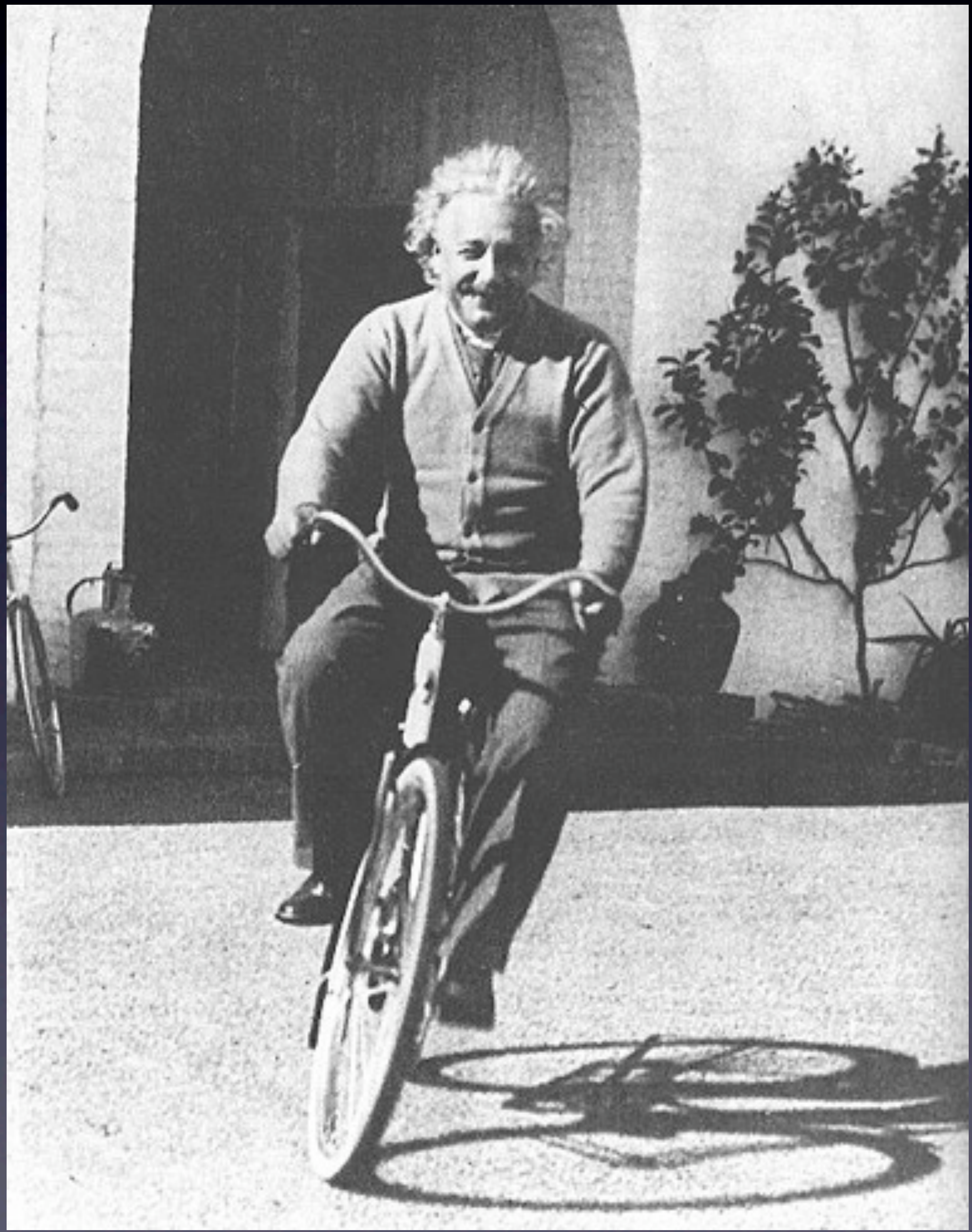


Einstein's Dream



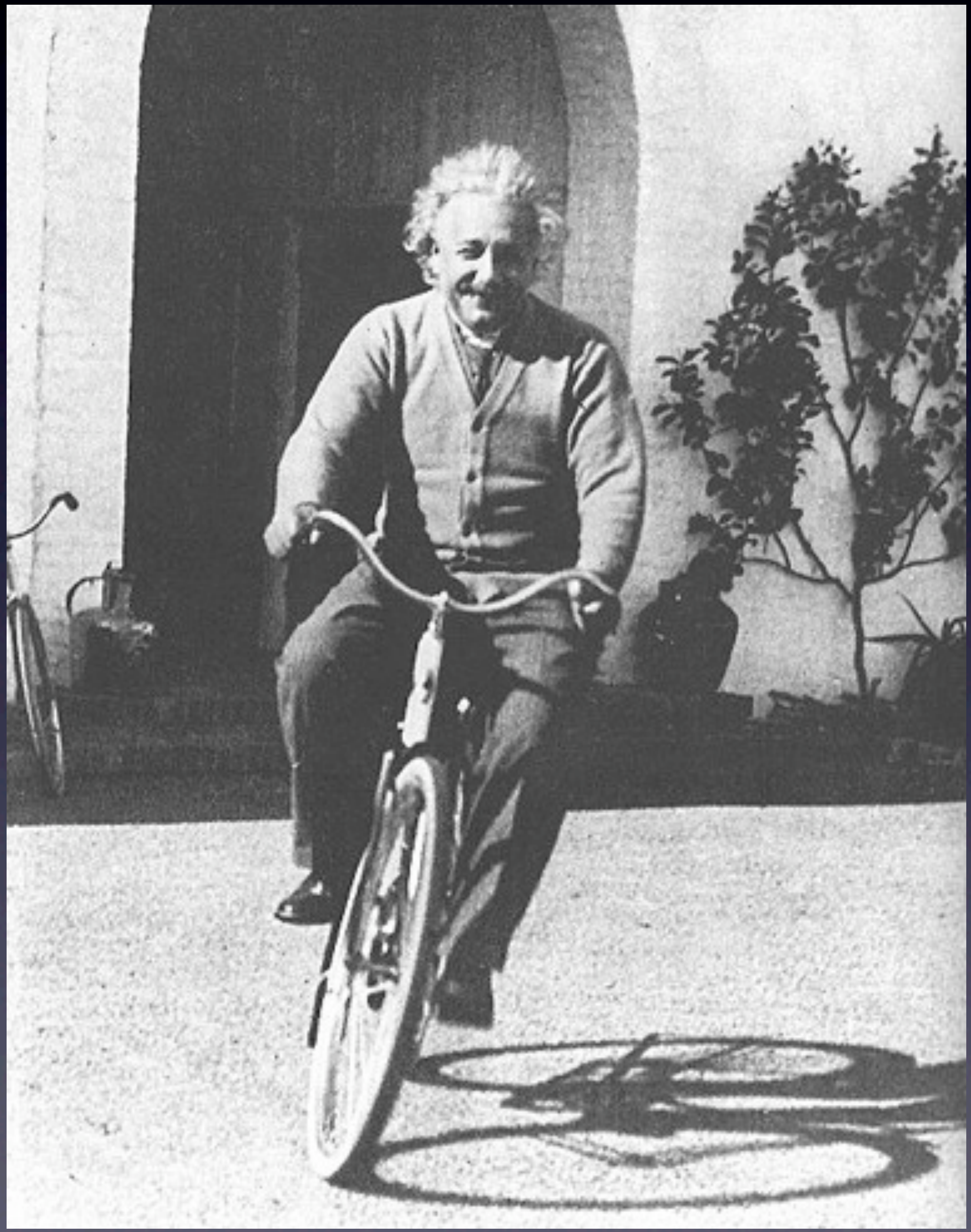
Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?



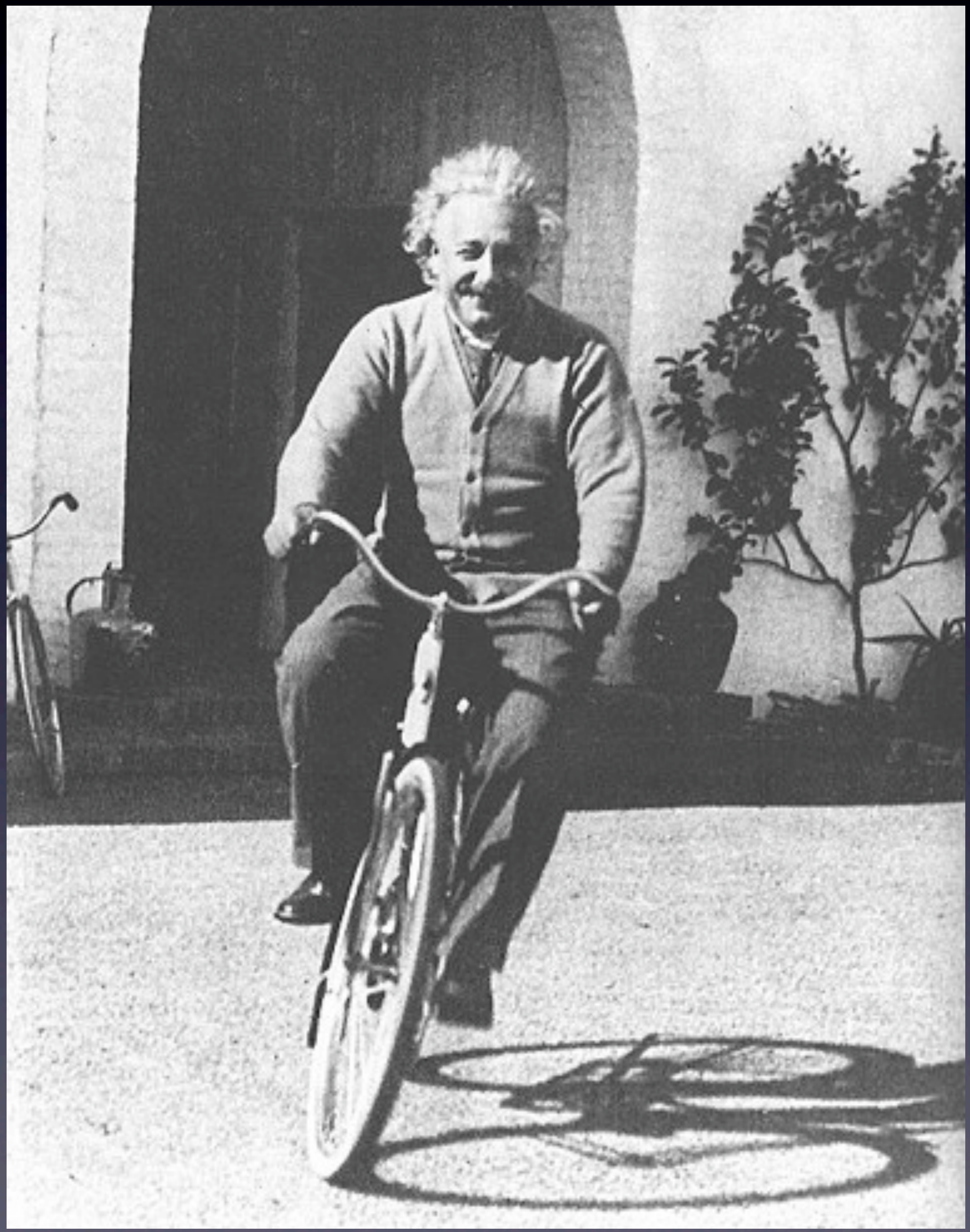
Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description

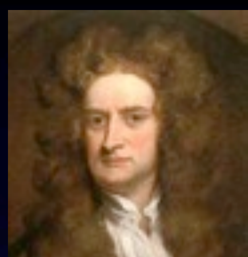


Einstein's Dream

- Is there an underlying simplicity behind vast phenomena in Nature?
- Einstein dreamed to come up with a unified description
- But he failed to unify electromagnetism and gravity (GR)



History of Unification



planets *apple*

→ *gravity* *mechanics*

electric *magnetic*

→ *electromagnetism*

atoms

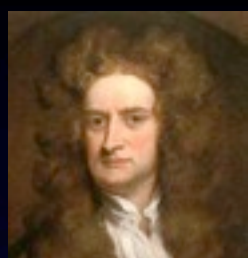
→ *Quantum mechanics*

γ-*decay*

β-*decay*

α-*decay*

History of Unification



planets *apple*

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Special relativity

atoms

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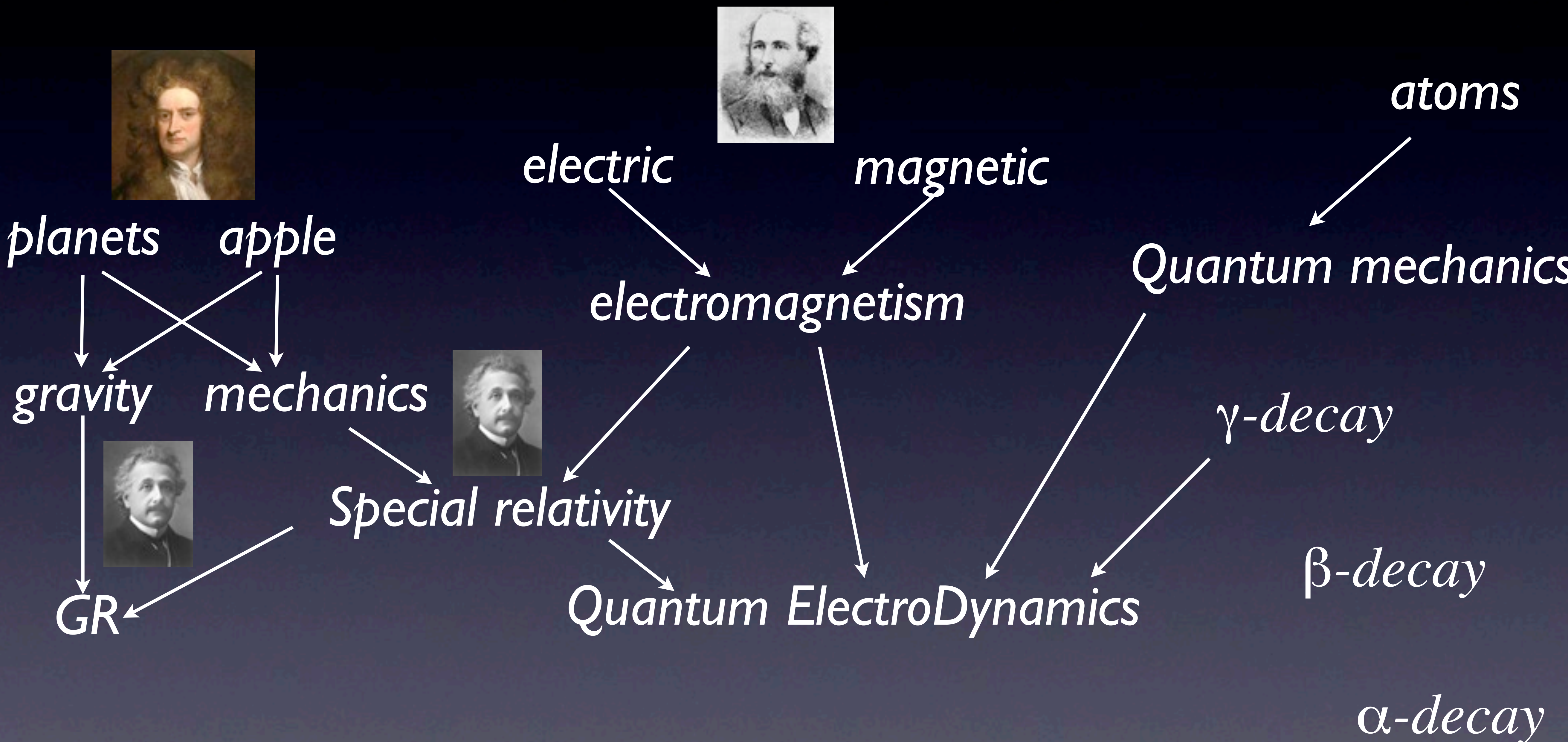
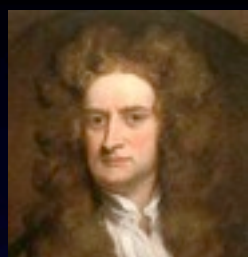


History of Unification

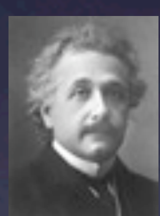


planets *apple*

gravity *mechanics*

electric *magnetic*

electromagnetism



Special relativity

GR

atoms

Quantum mechanics

Quantum ElectroDynamics

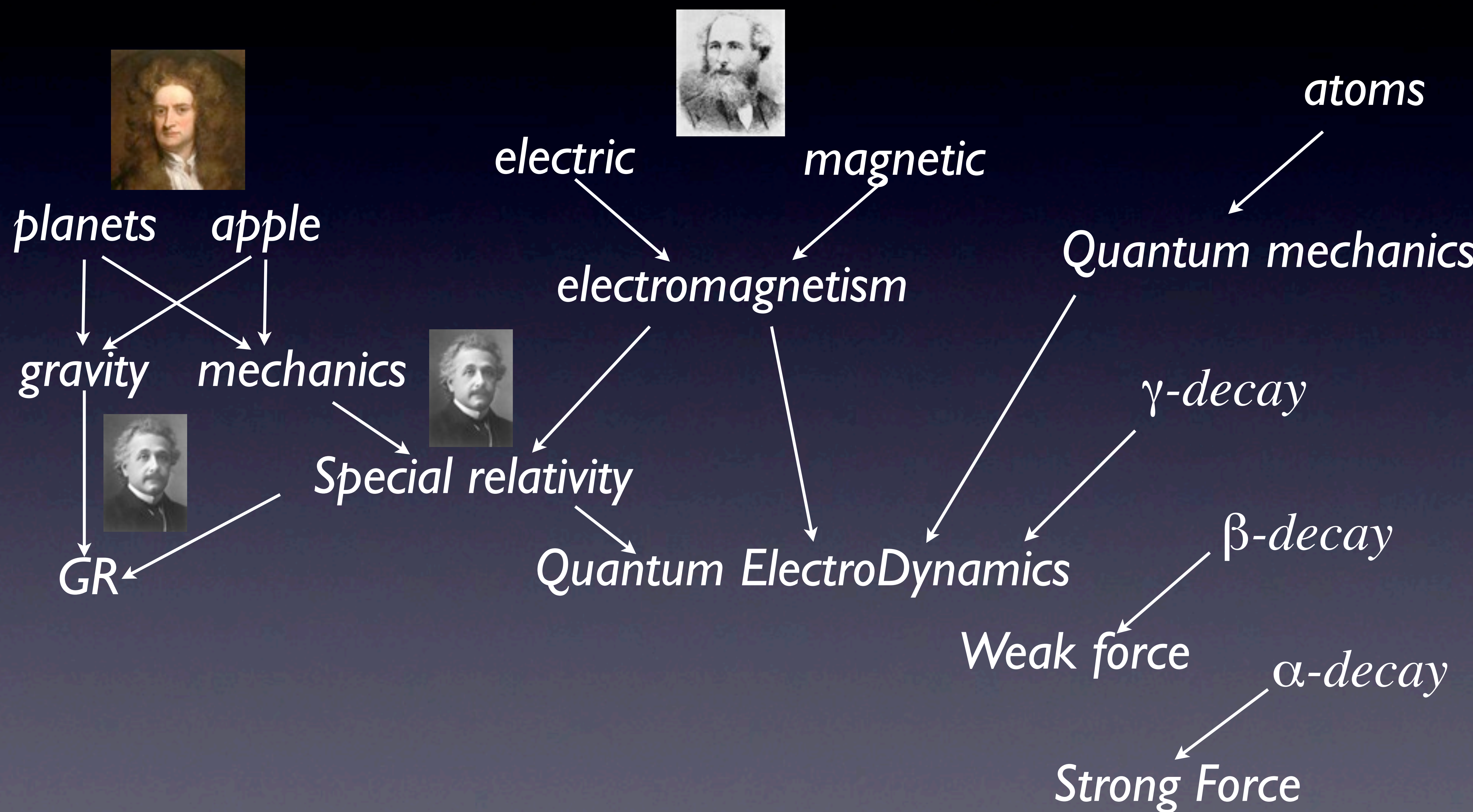
γ-decay

β-decay

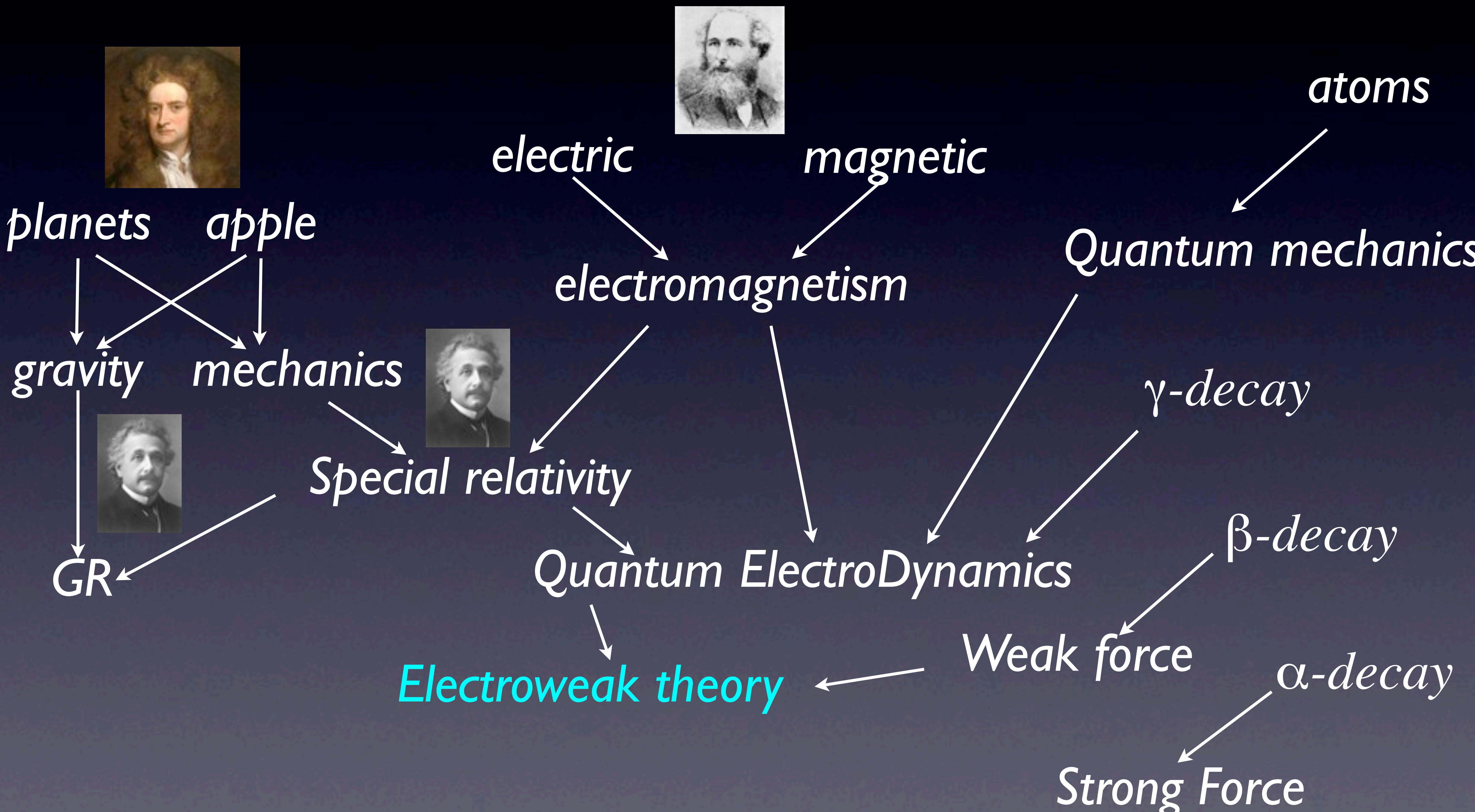
Weak force

α-decay

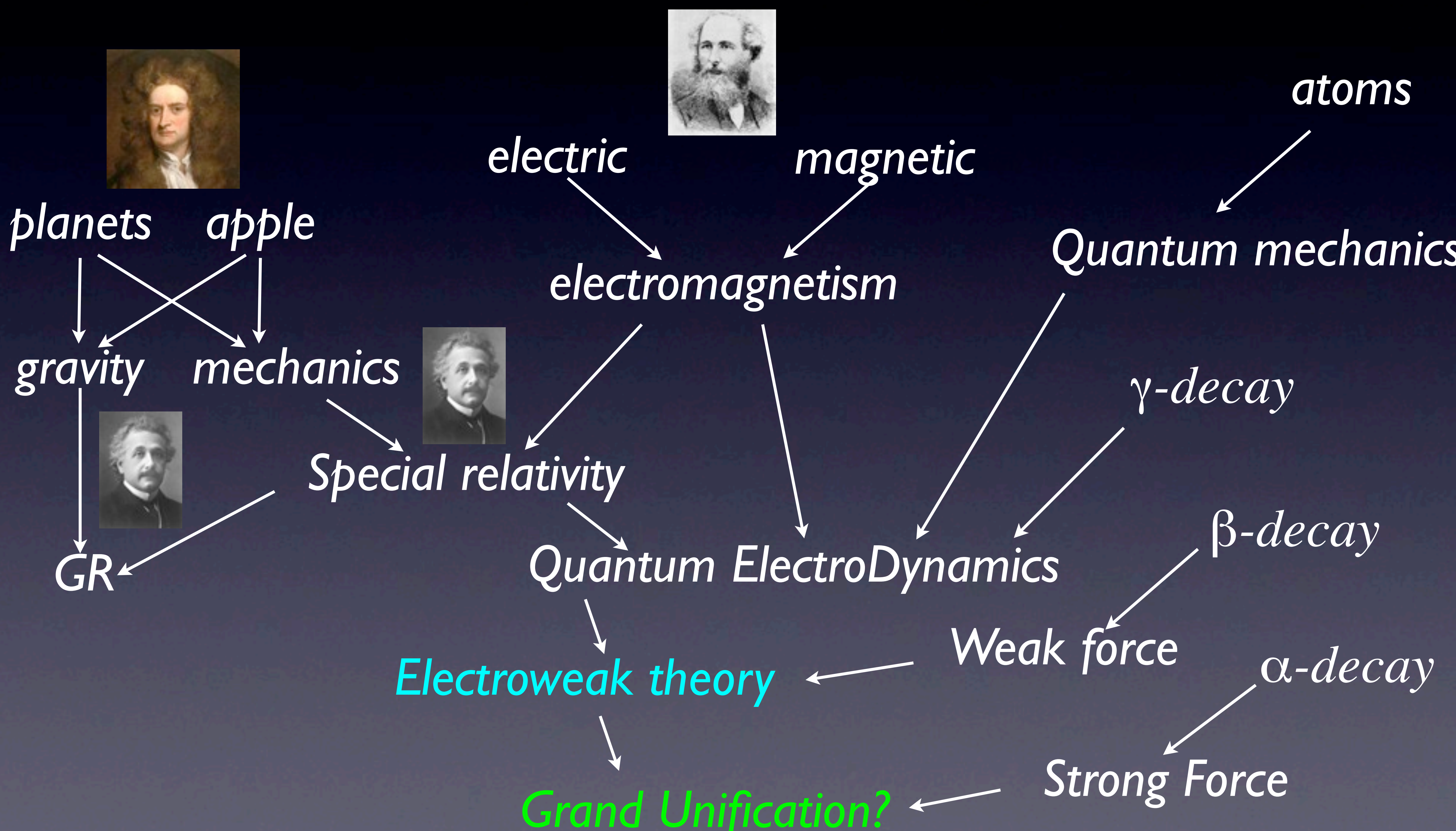
History of Unification



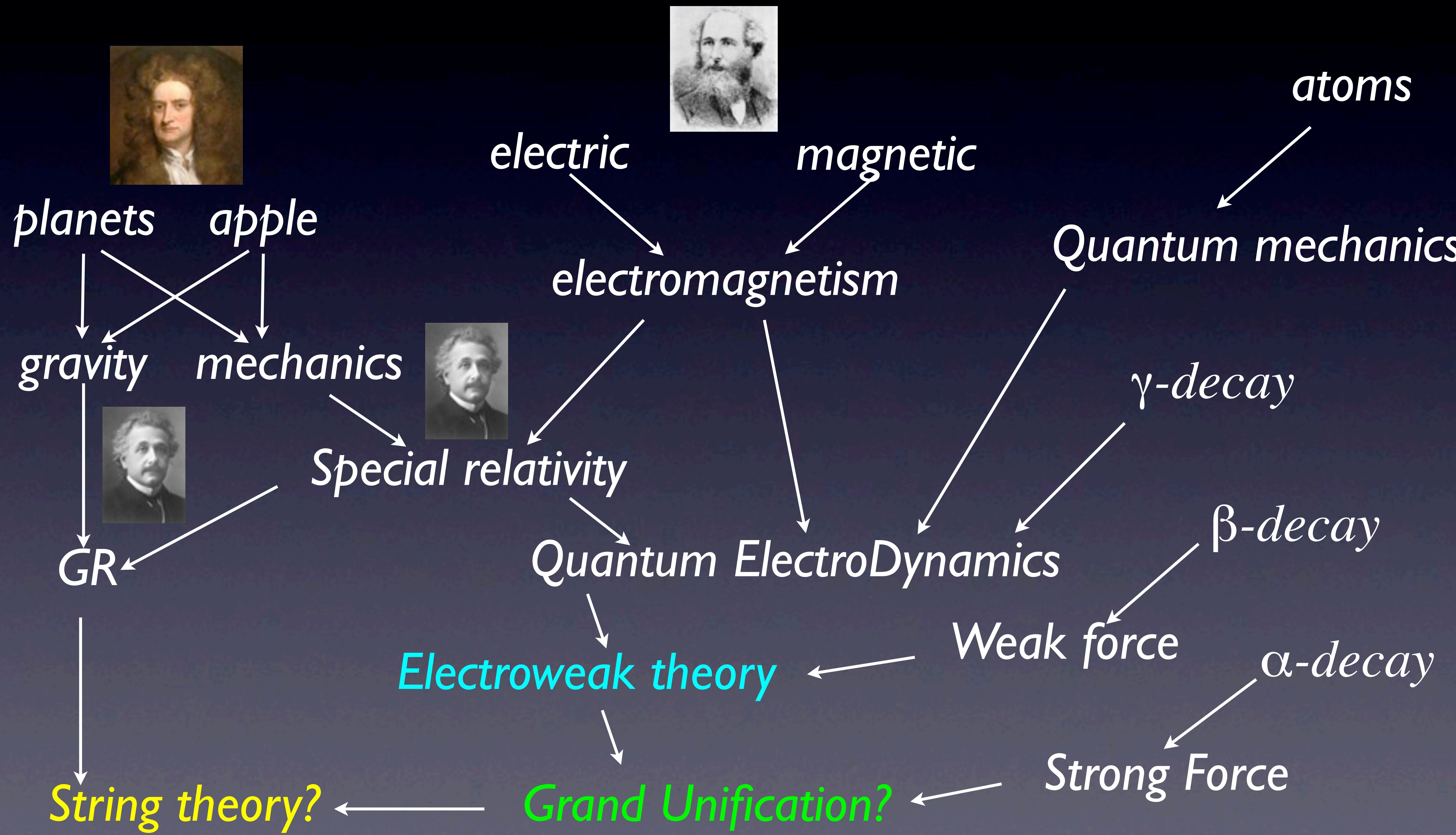
History of Unification



History of Unification



History of Unification



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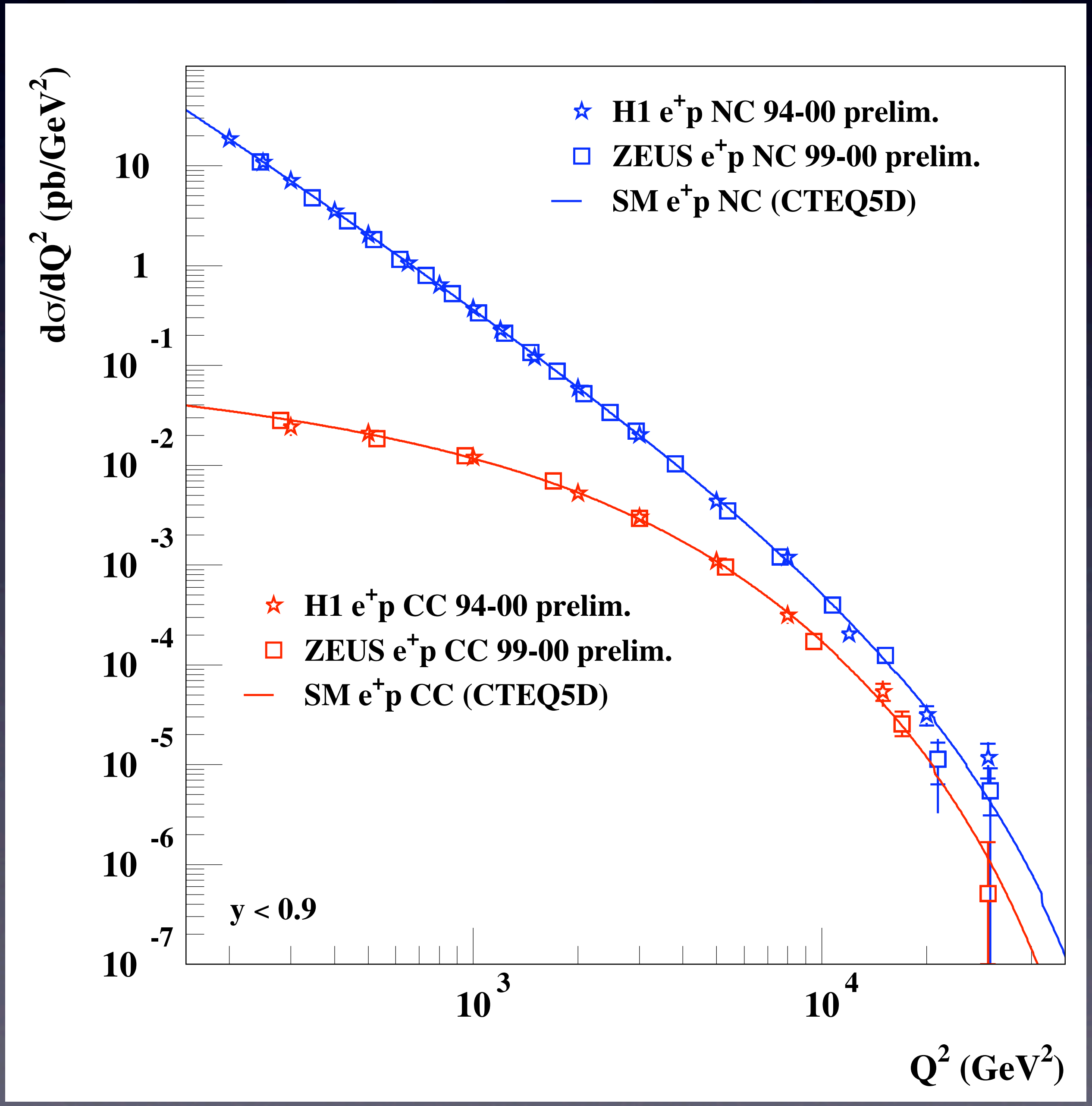
We are just about to achieve another layer of unification

HERA ep collider



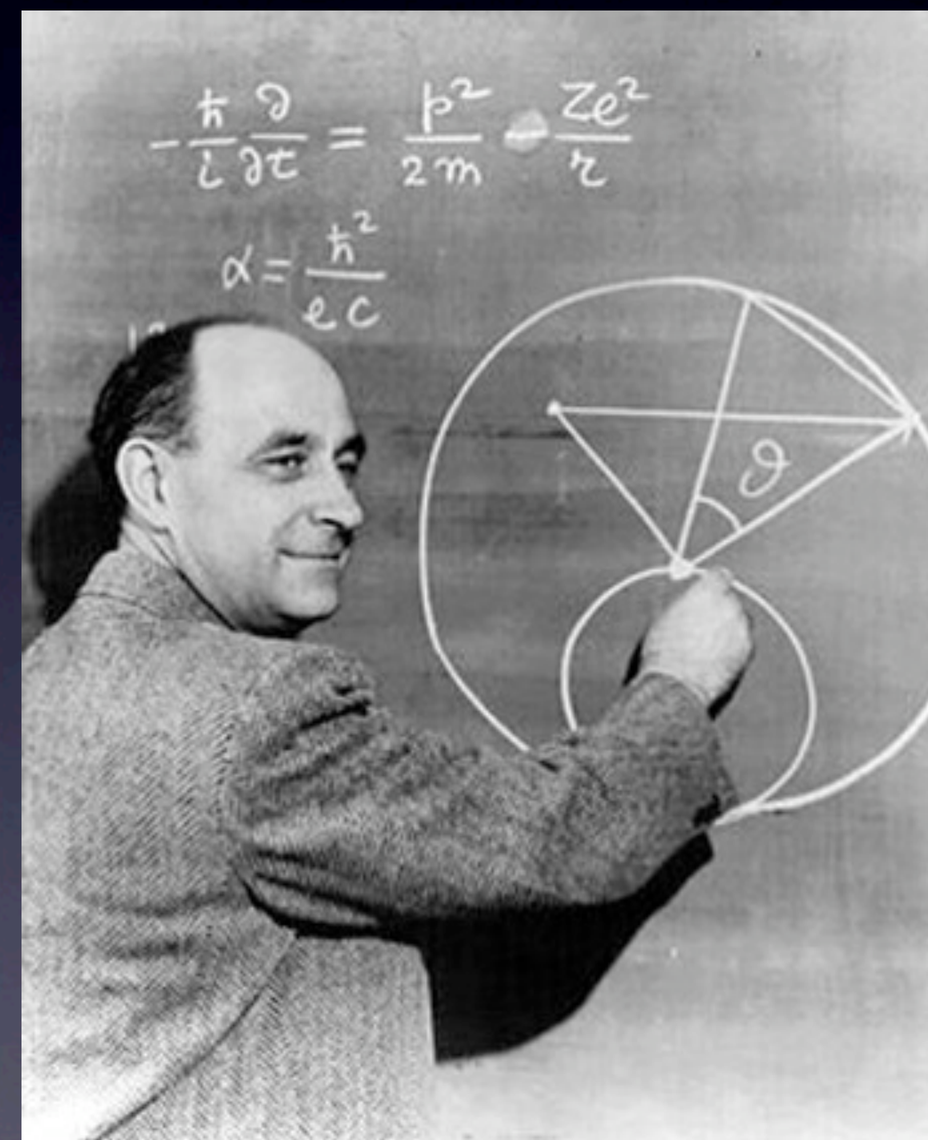
- Unification of electromagnetic and weak forces

$\Longrightarrow$ electroweak theory

- Long-term goal since '60s
- We are getting there!
- The main missing link: Dark Field=Higgs

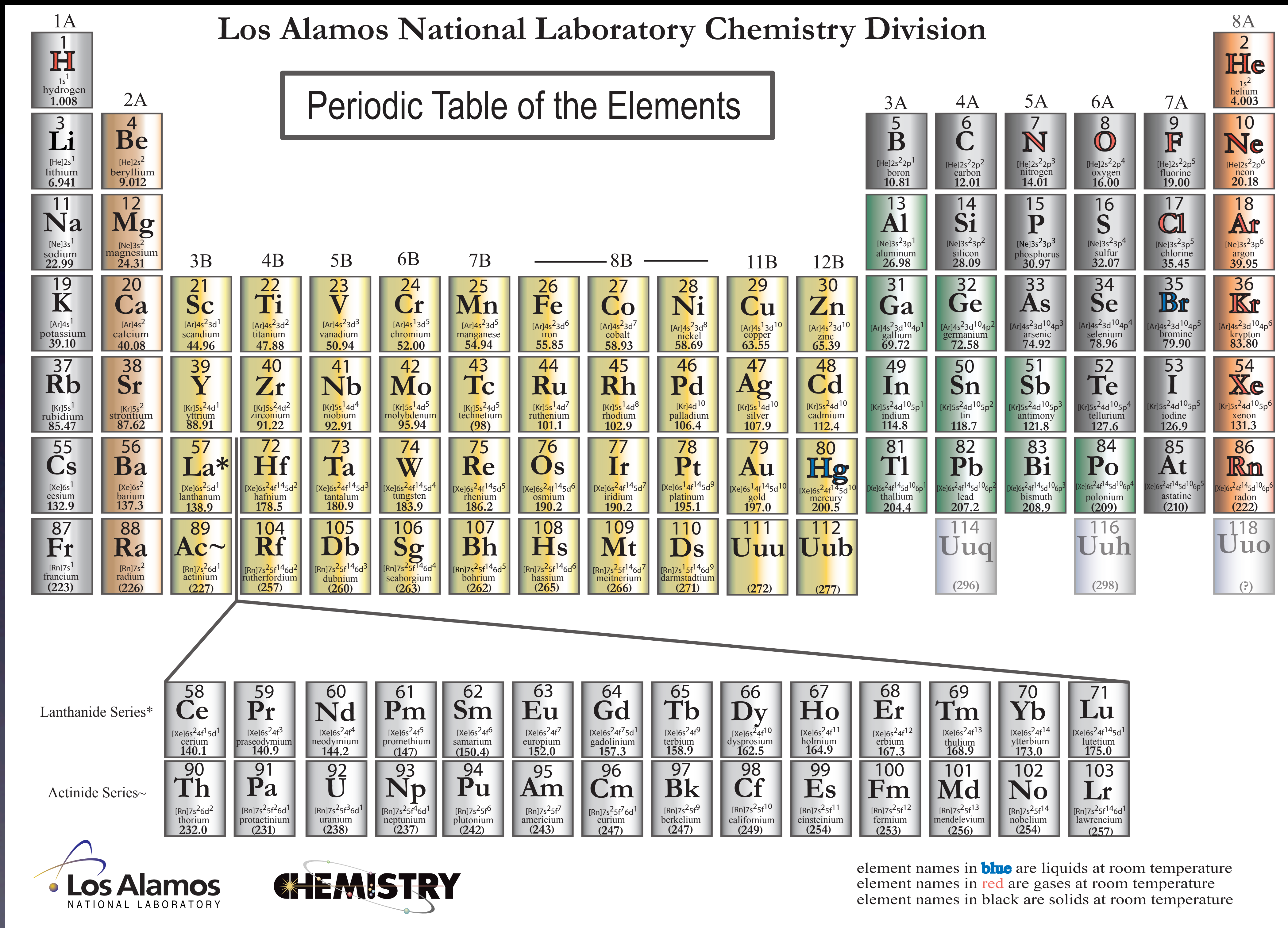
Fermi's dream era

- Fermi formulated the first theory of the weak force (1932)
- *The required energy scale to study the problem known since then:* ~TeV
- We are finally getting there with LHC!



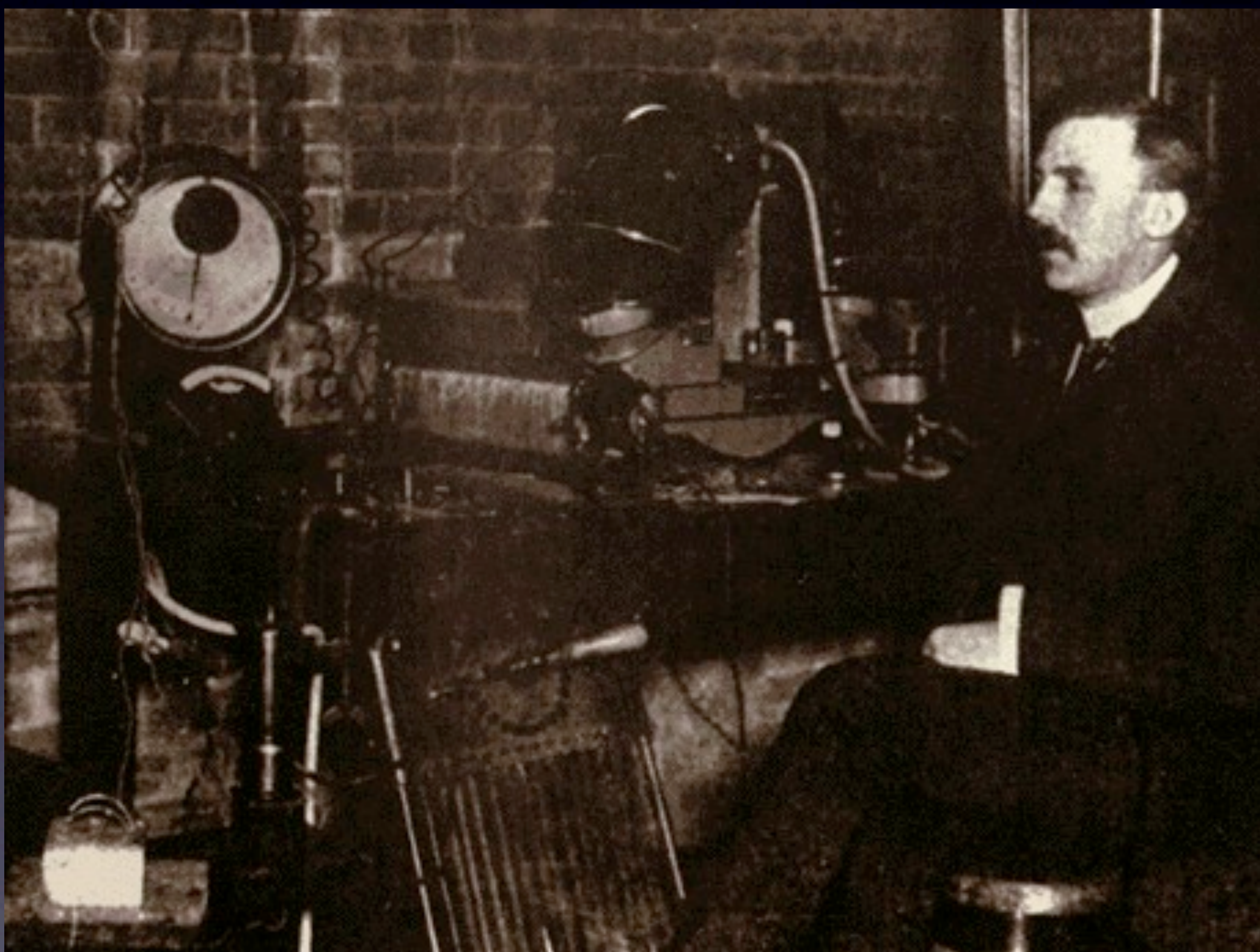
Ancient Greeks: Elements

Periodic Table

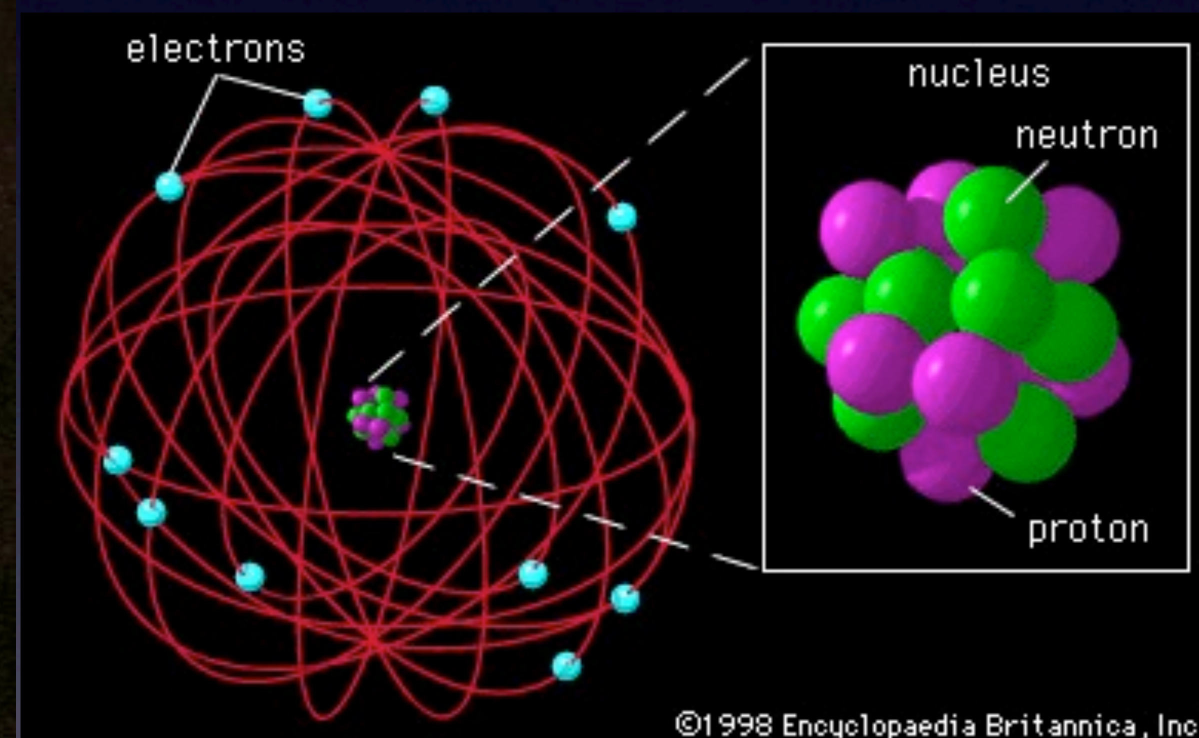


So many *flavors* of atoms?

Rutherford (New Zealand)



all chemical elements



deeper into the heart of the matter (literally)

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increase resolution

deeper into the heart of the matter (literally)

increase resolution

Einstein?

deeper into the heart of the matter (literally)

increase resolution

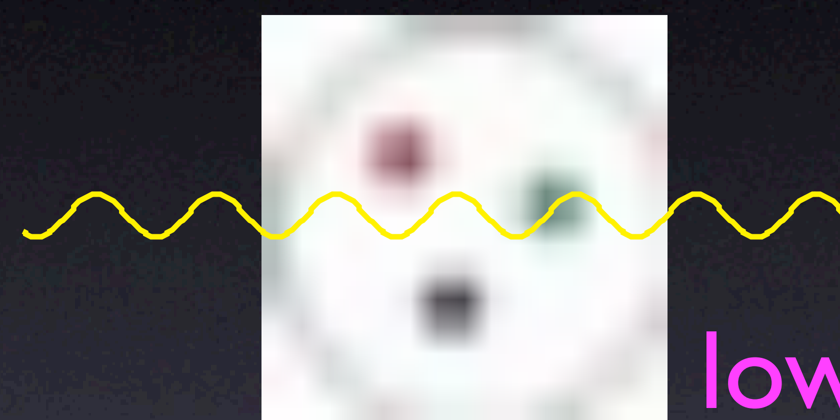
Einstein?

My son on Halloween!

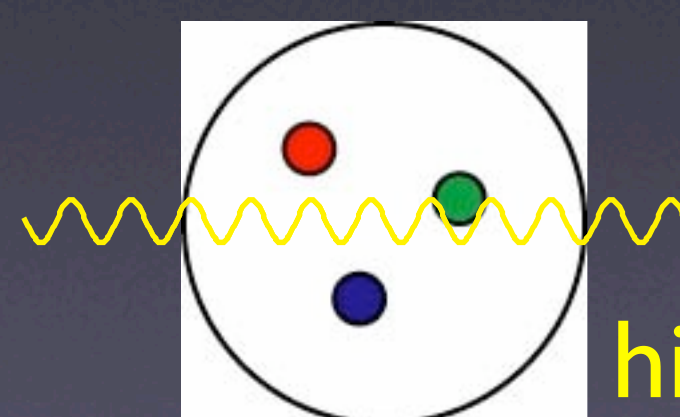
resolution=energy

- Quantum Mechanics: particle=wave

- higher energy
= shorter wavelength
= better resolution



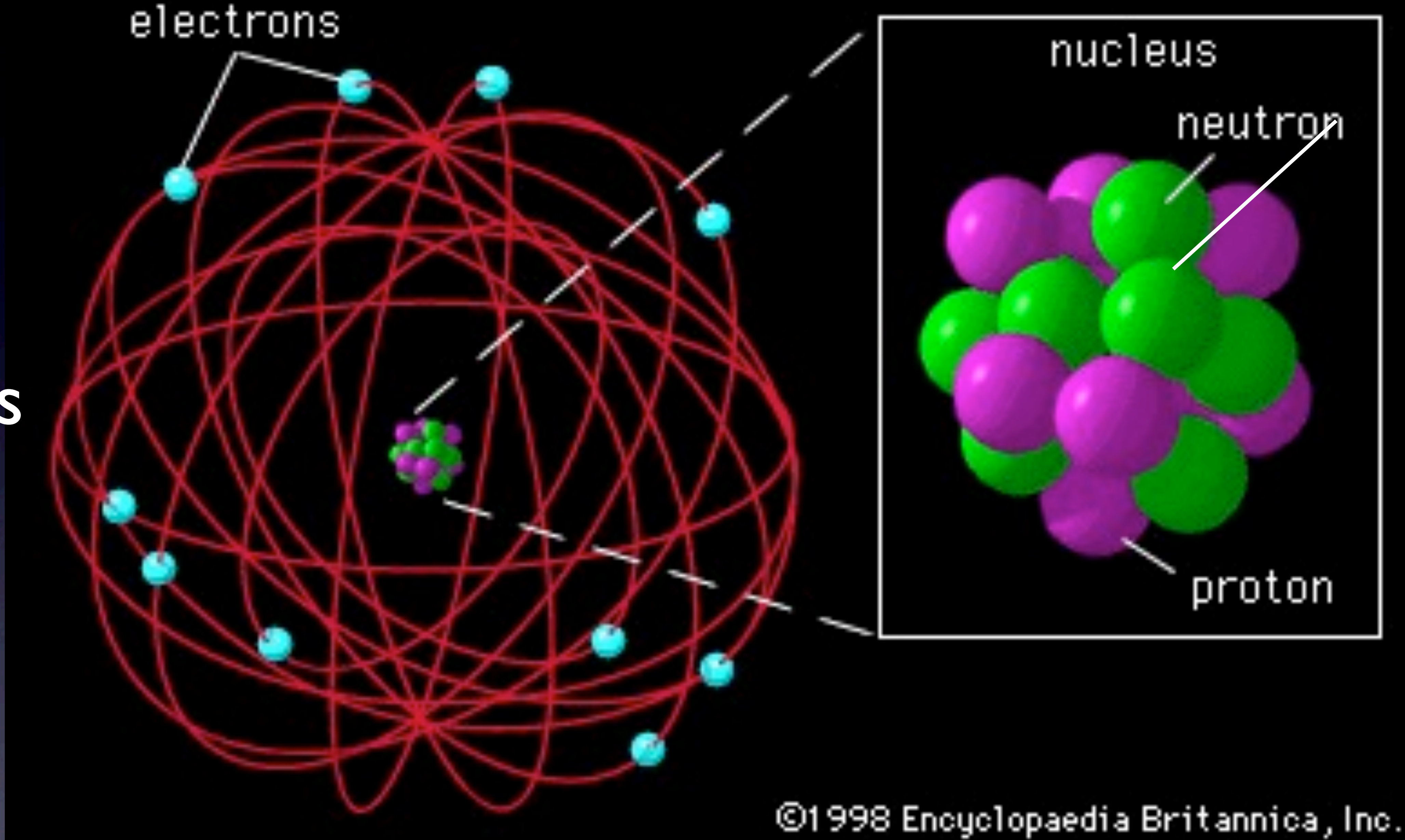
low energy



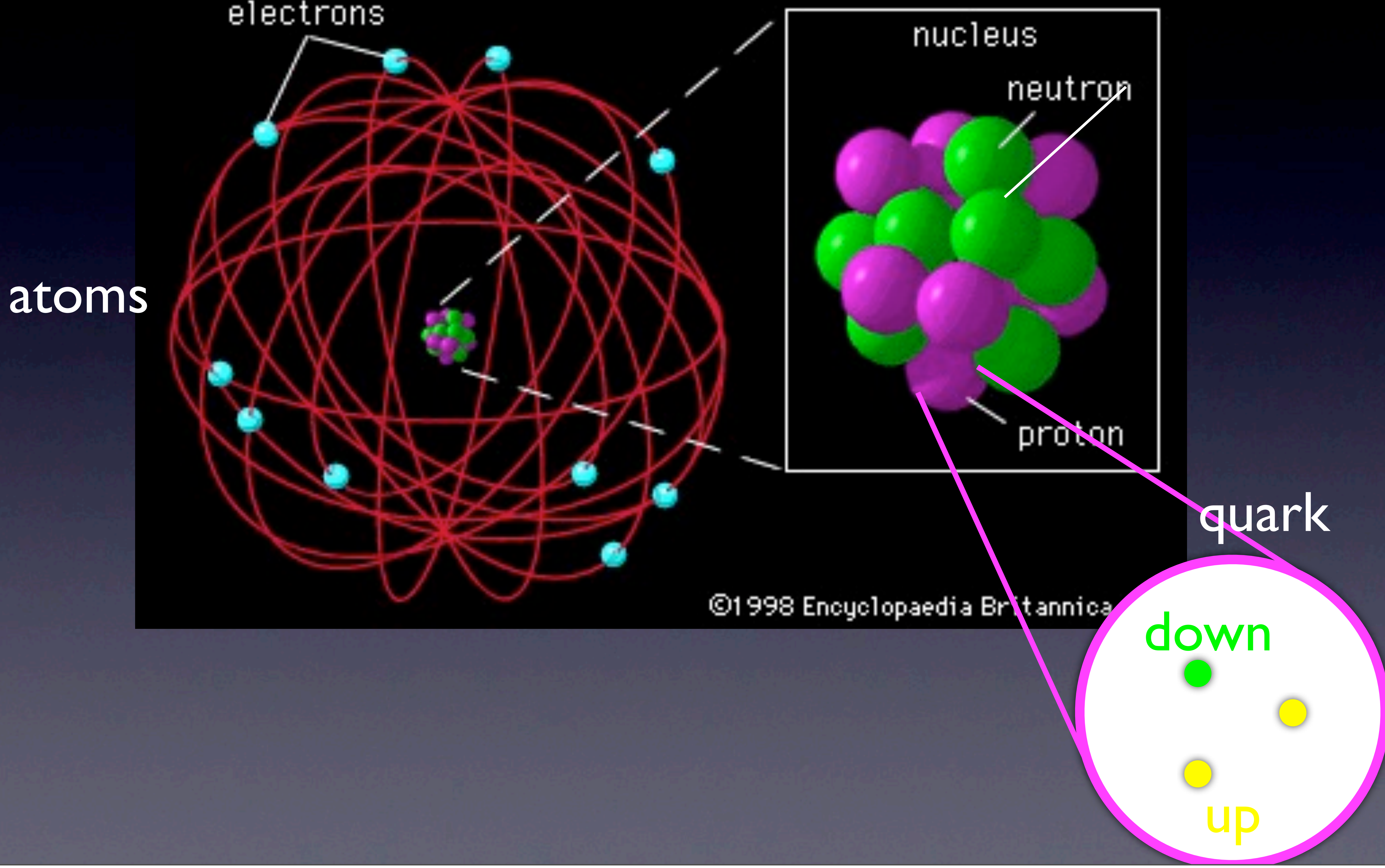
high energy

Things around us

atoms



Things around us



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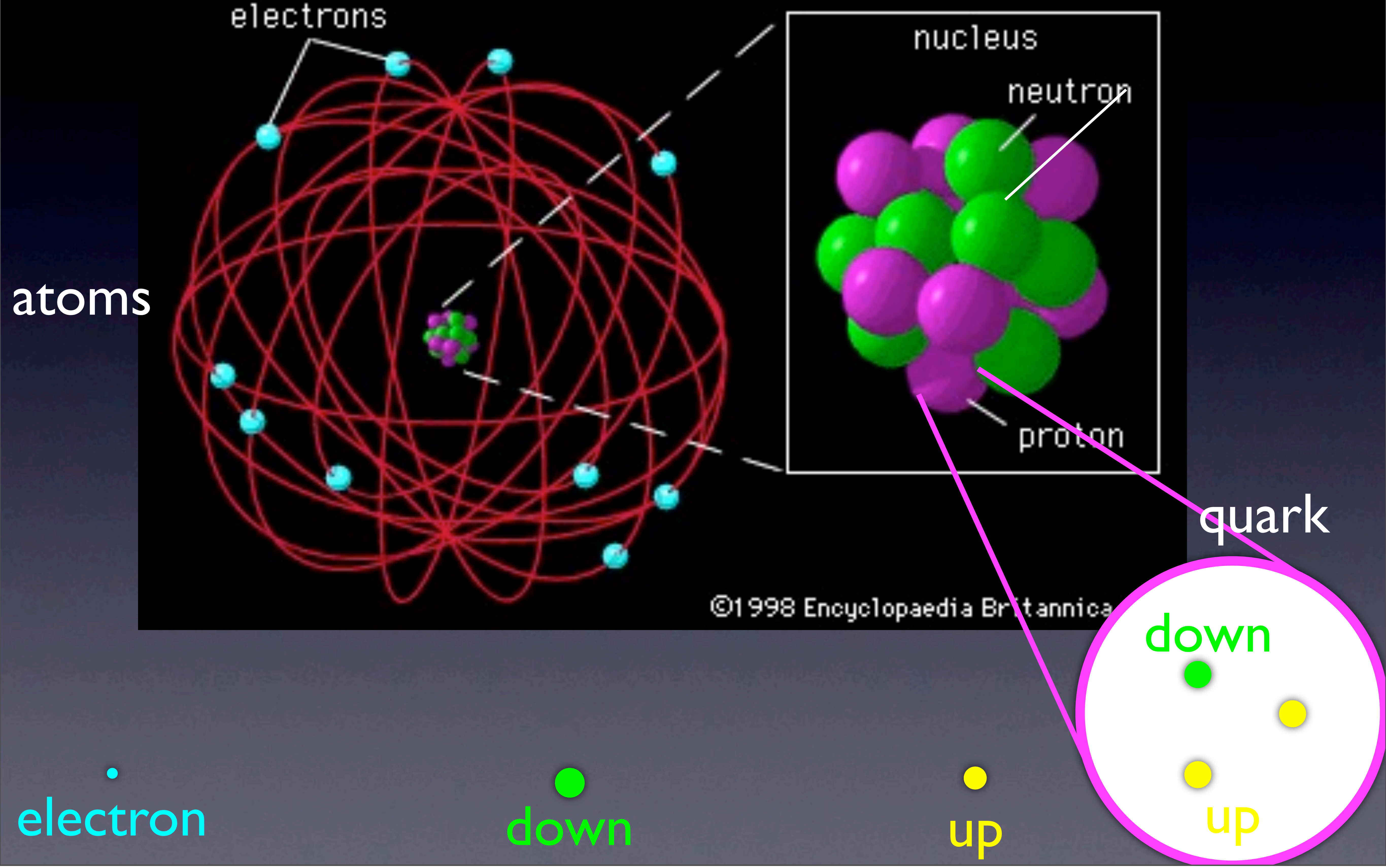

Things around us

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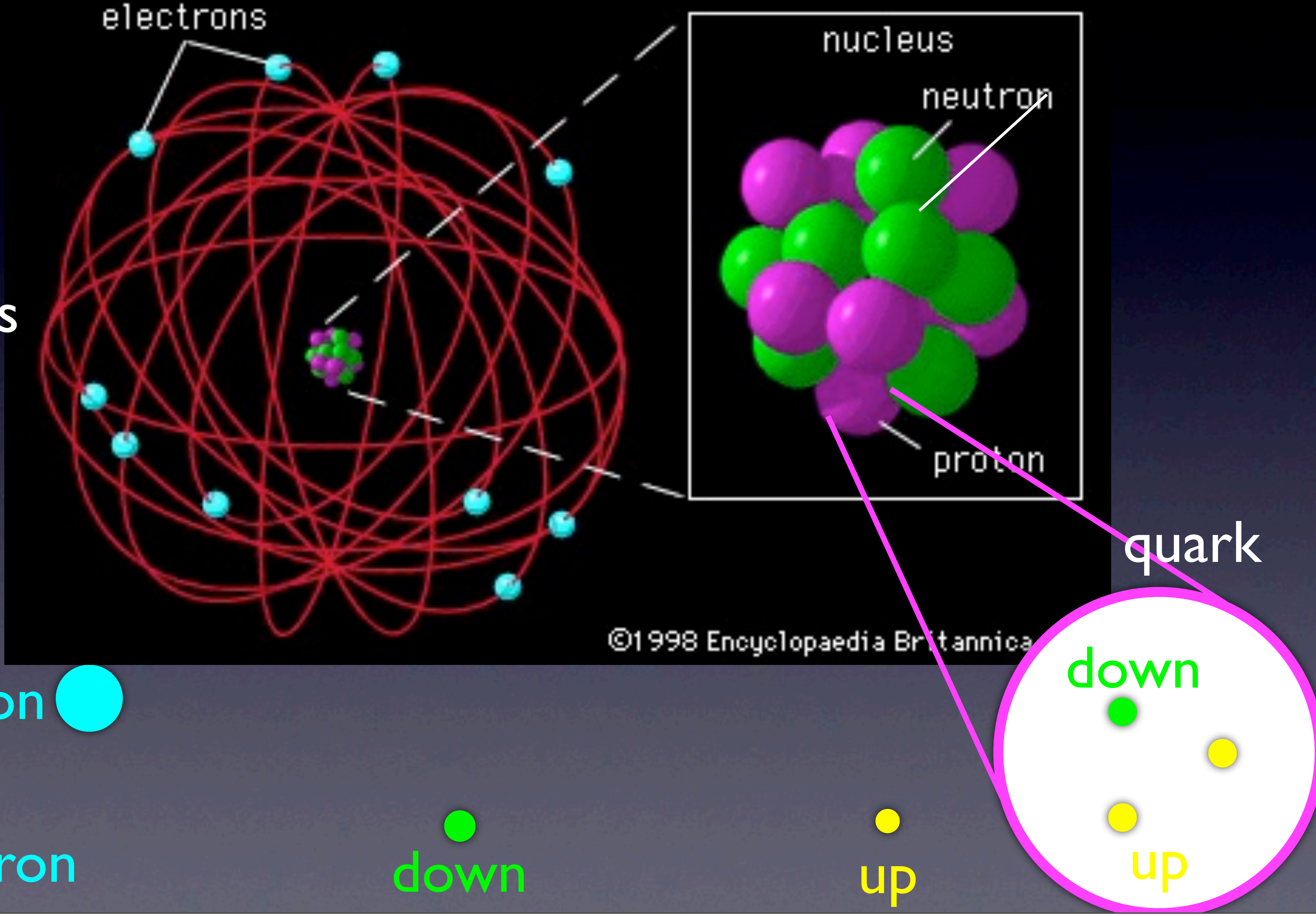
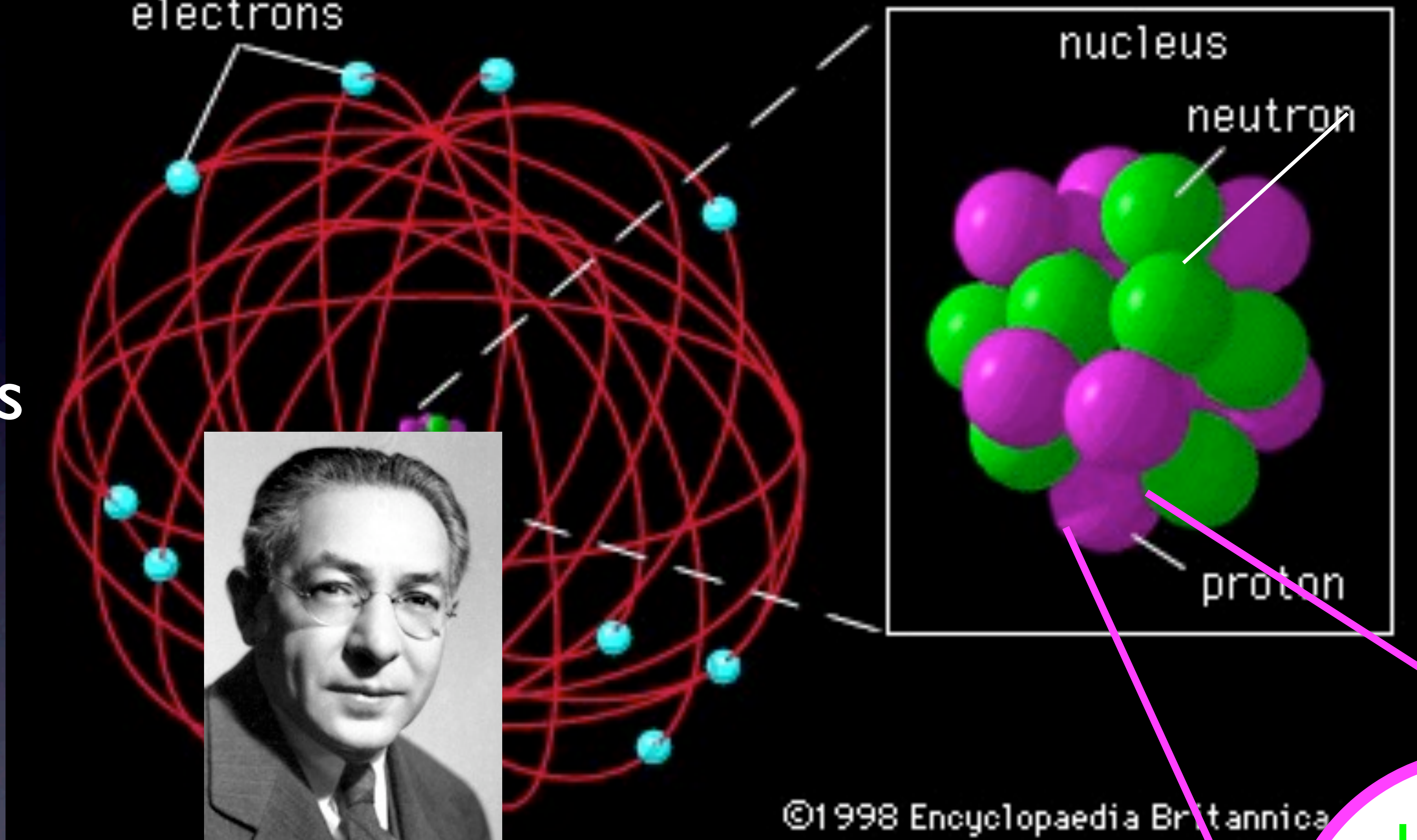


Things around us

atoms



quark

muon

Who ordered that?

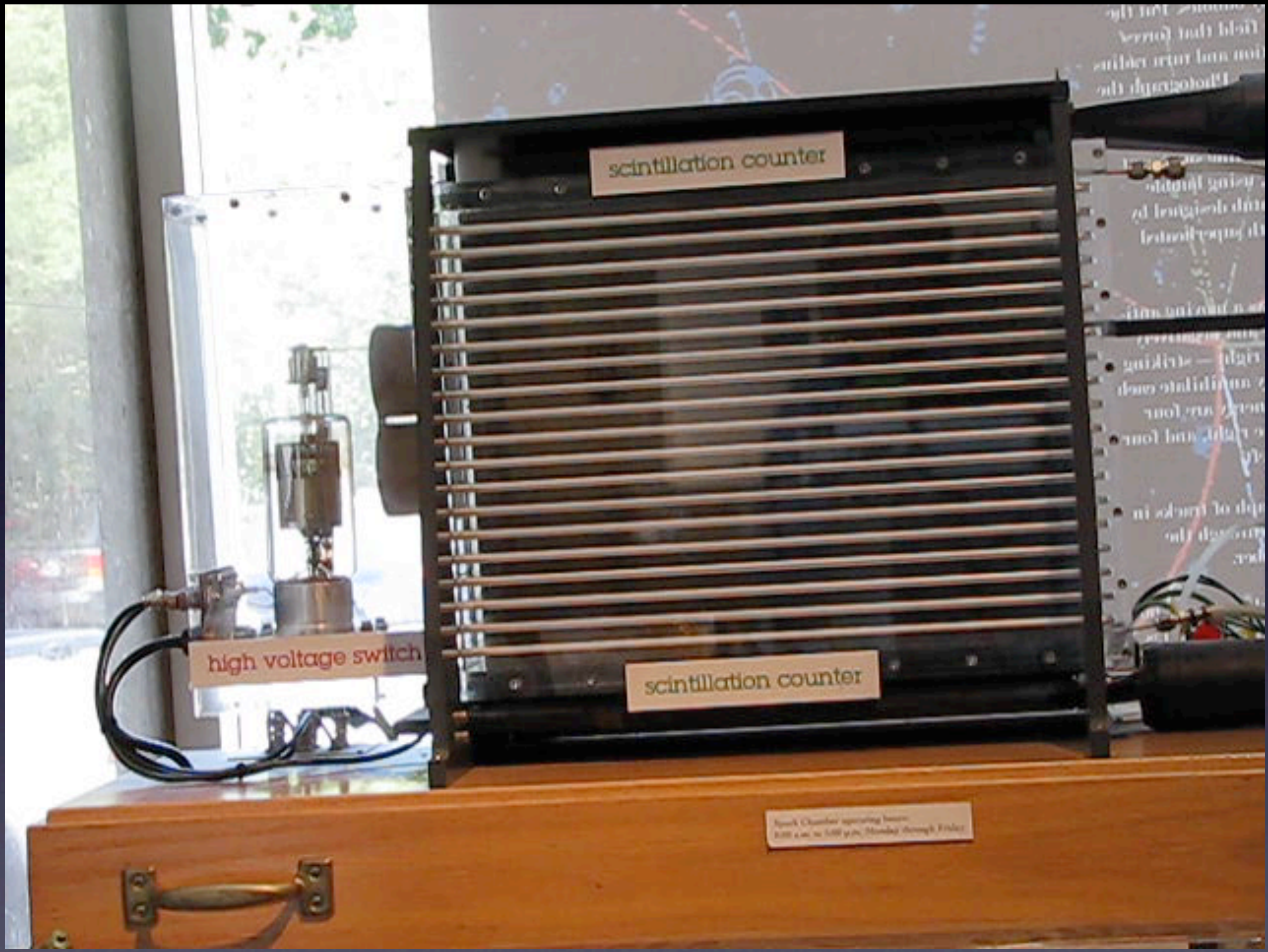
I.I. Rabi

electron

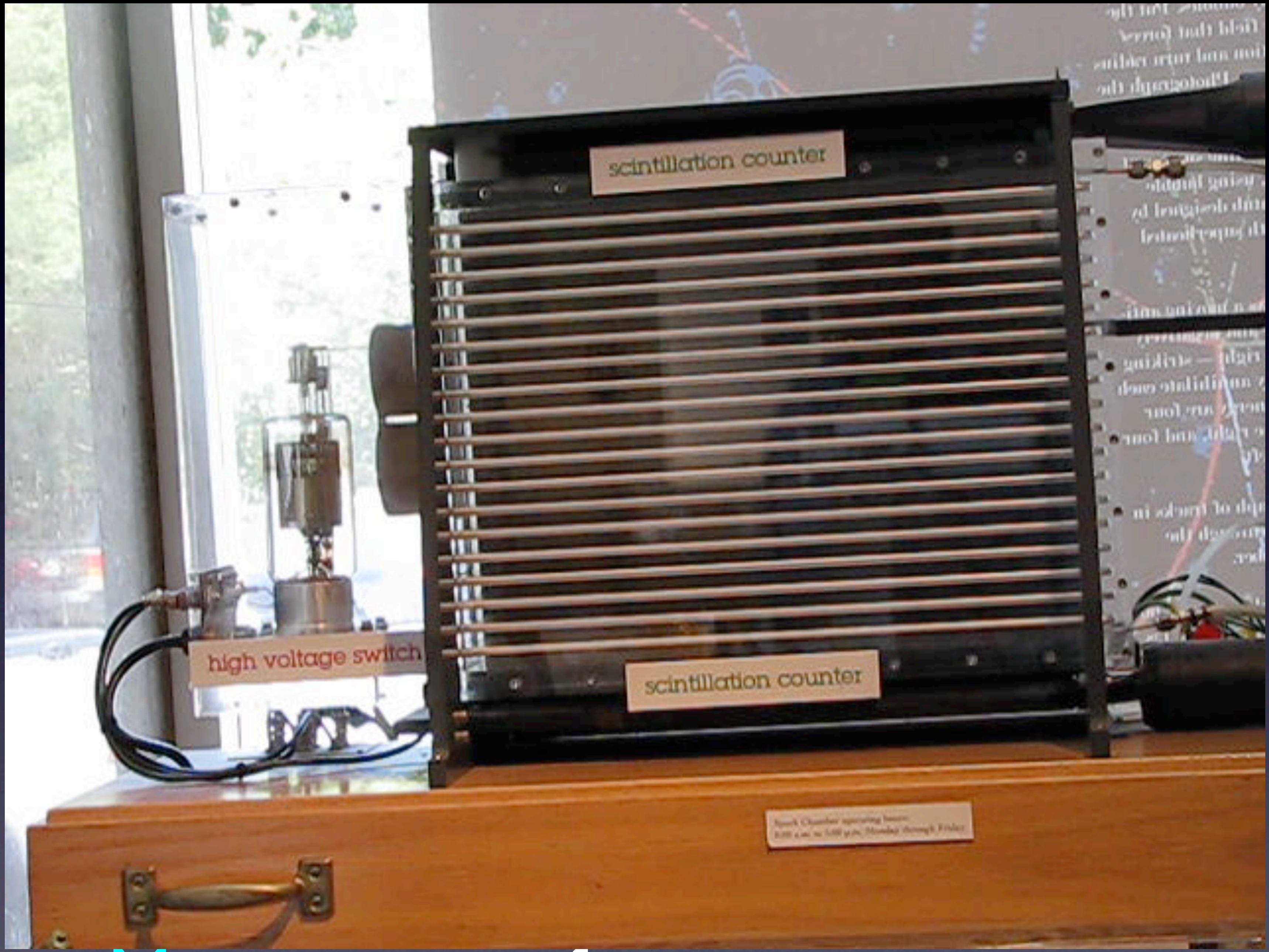
down

up

Muons


scintillation counter
high voltage switch
scintillation counter

Muons



Muons come from outer space.
About a *thousand* of them go through our body every minute like X-ray.

Science 167, 832 (1970)

Search for Hidden Chambers in the Pyramids

The structure of the Second Pyramid of Giza is determined by cosmic-ray absorption.

Luis W. Alvarez, Jared A. Anderson, F. El Bedwei, James Burkhard, Ahmed Fakhry, Adib Girgis, Amr Goneid, Fikhry Hassan, Dennis Iverson, Gerald Lynch, Zenab Miligy, Ali Hilmy Moussa, Mohammed-Sharkawi, Lauren Yazolino

The three pyramids of Giza are situ-

mun in the 9th century A.D., almost

of th
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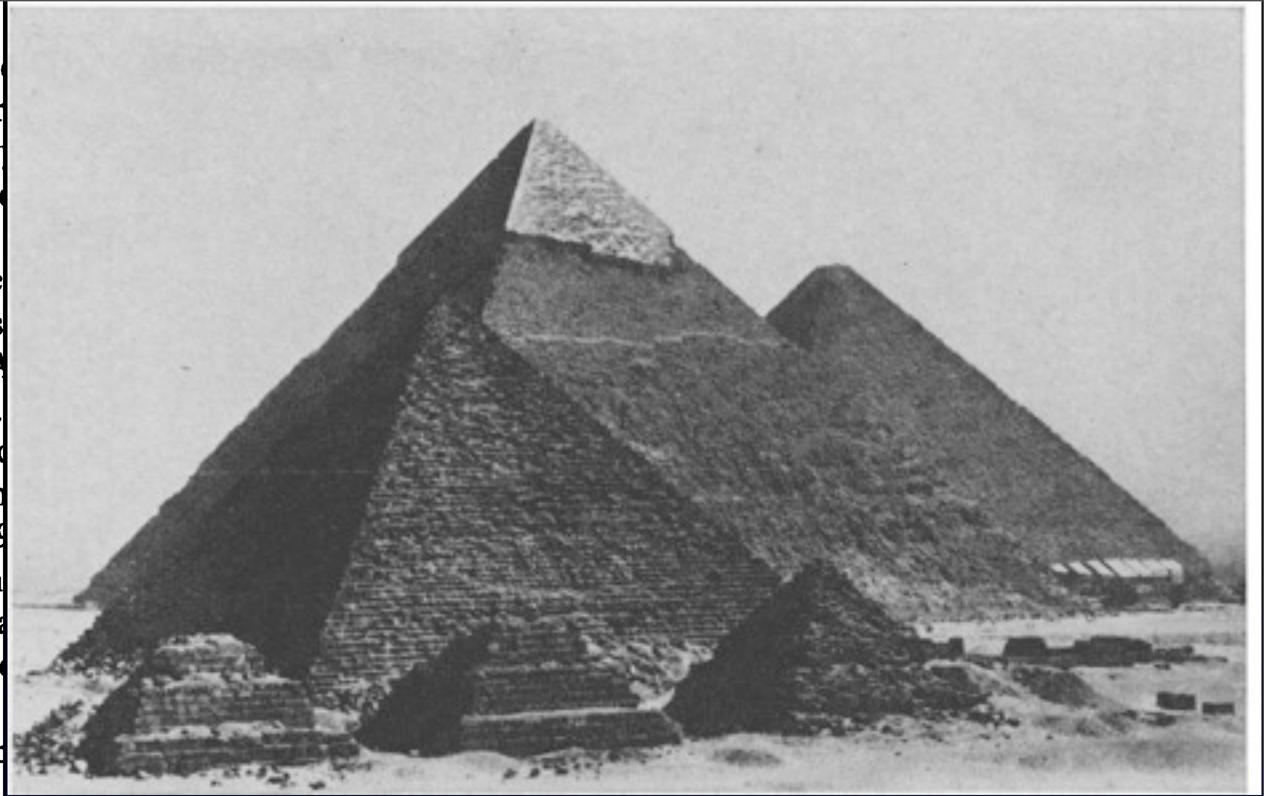

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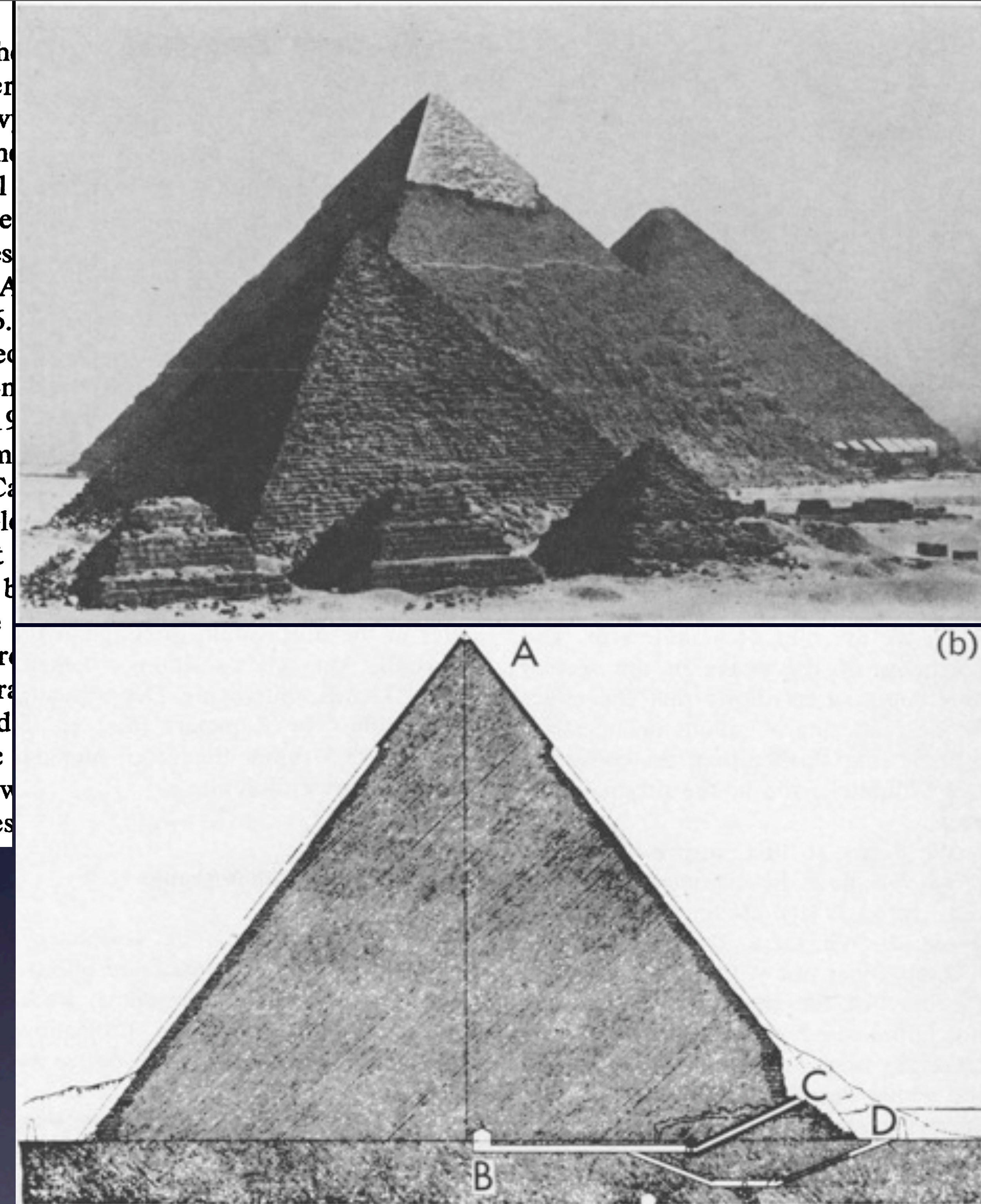

Science 167, 832 (1970)

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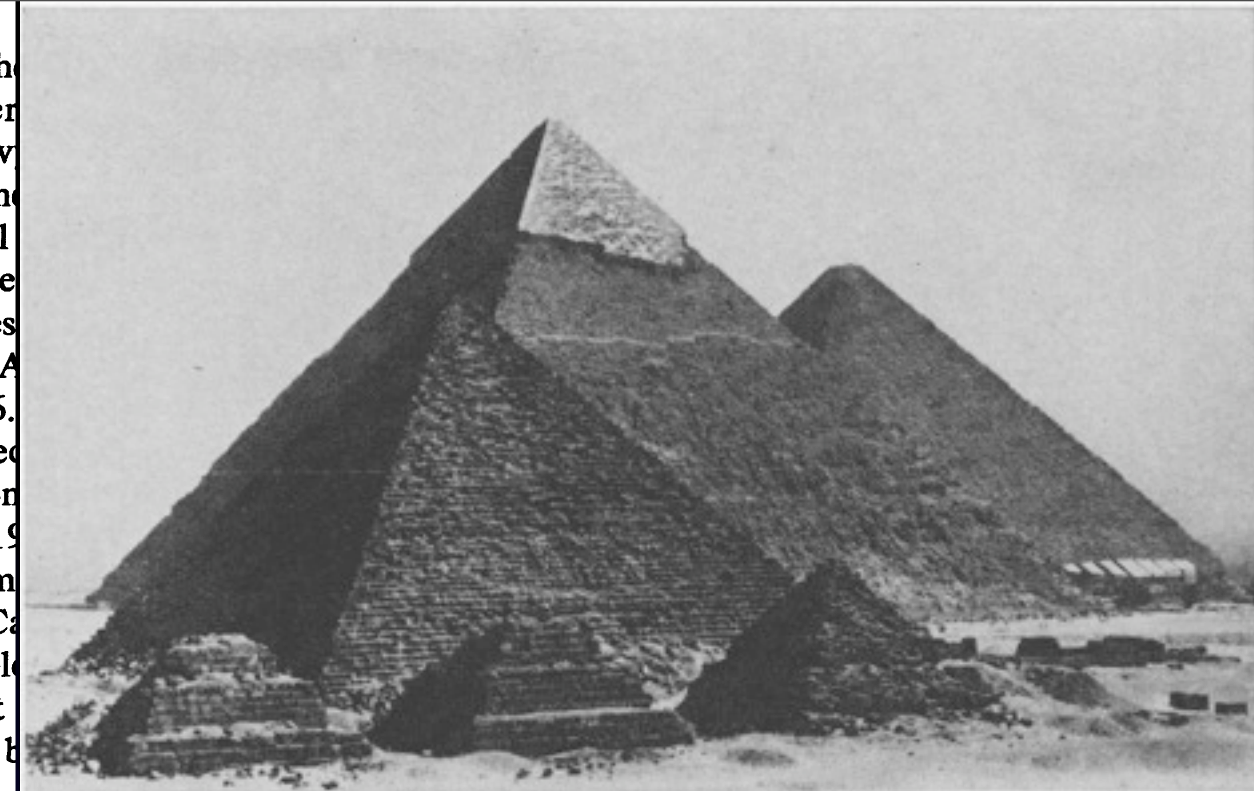

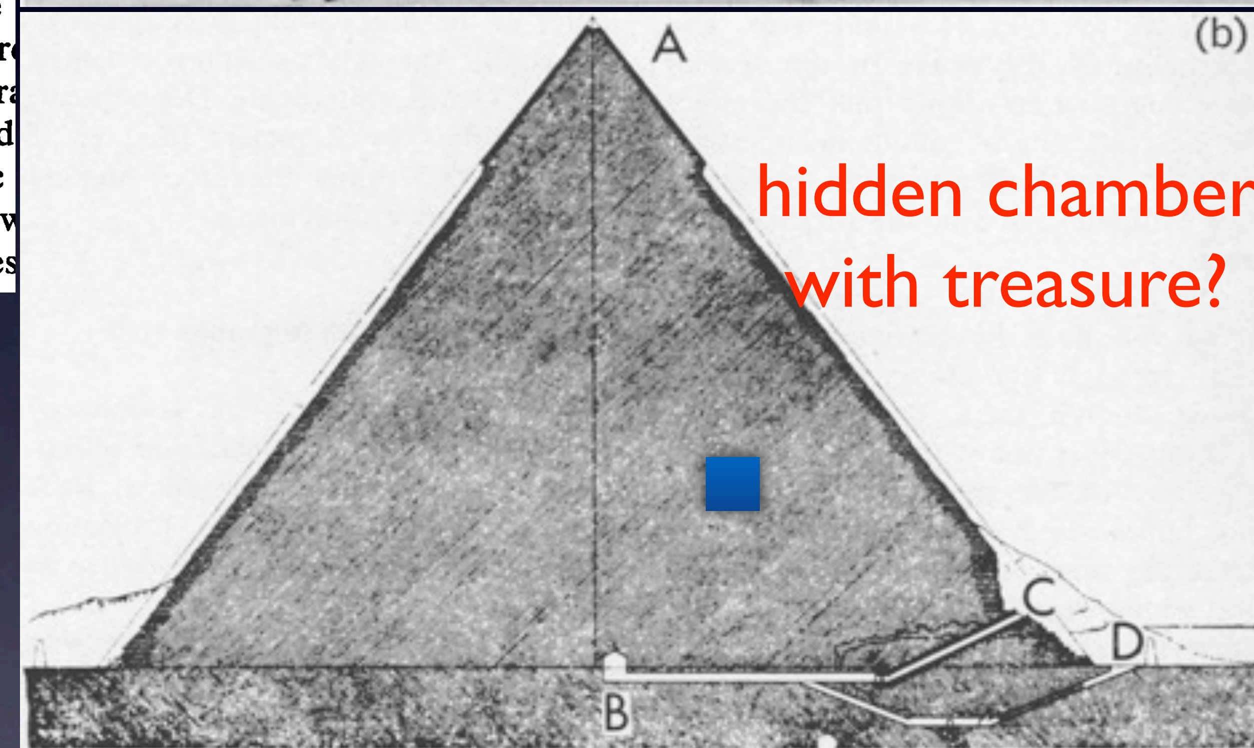

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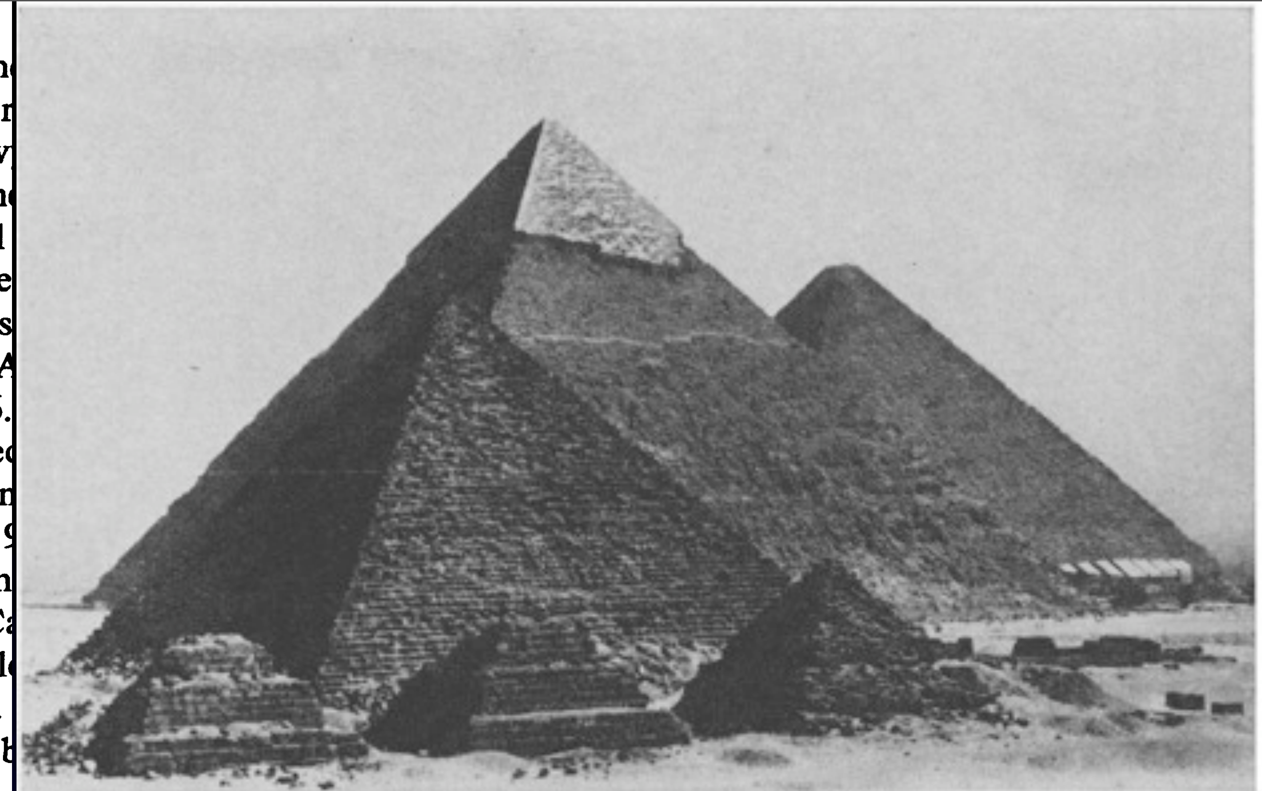

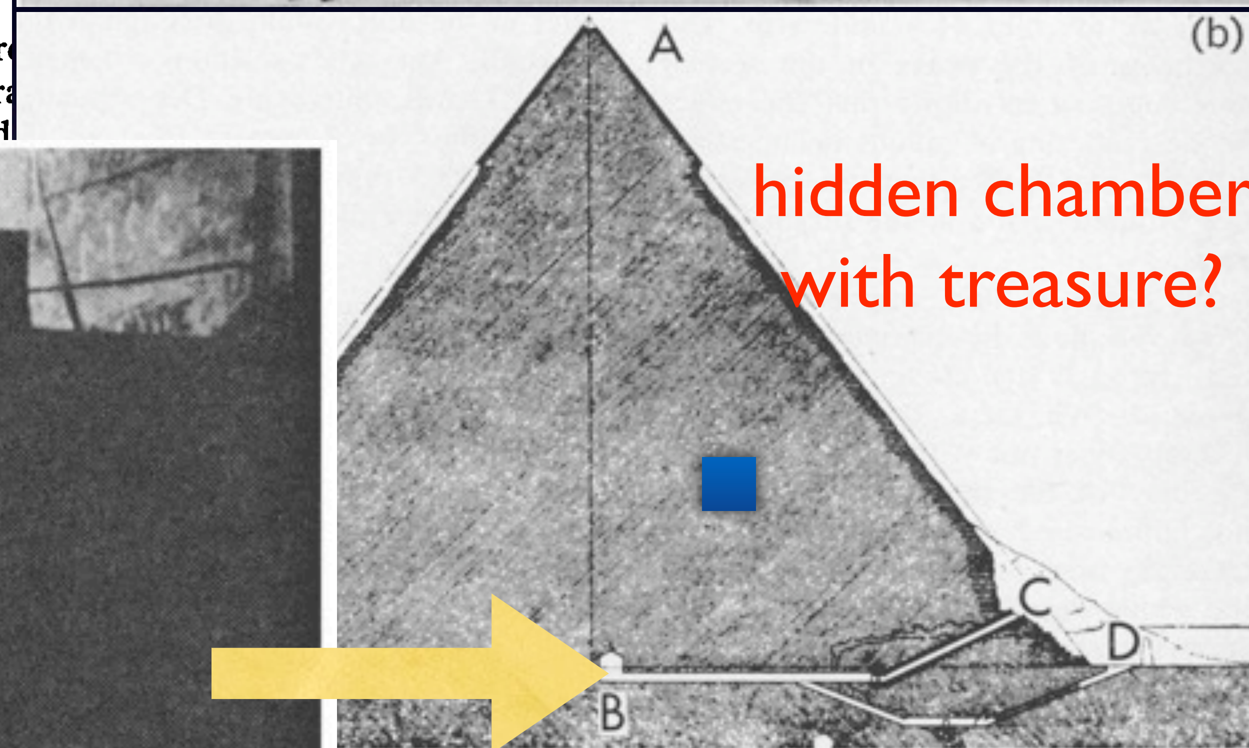

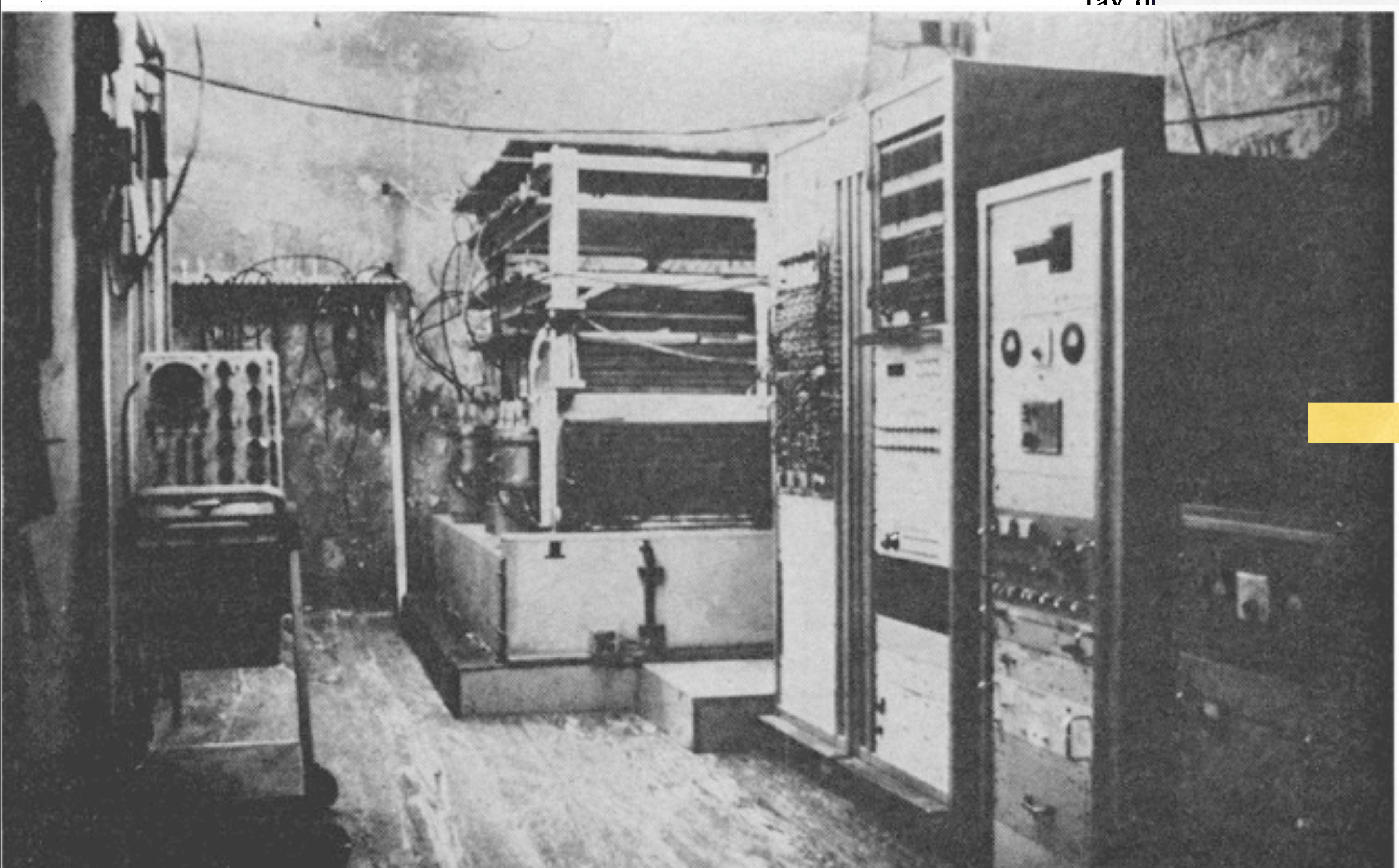

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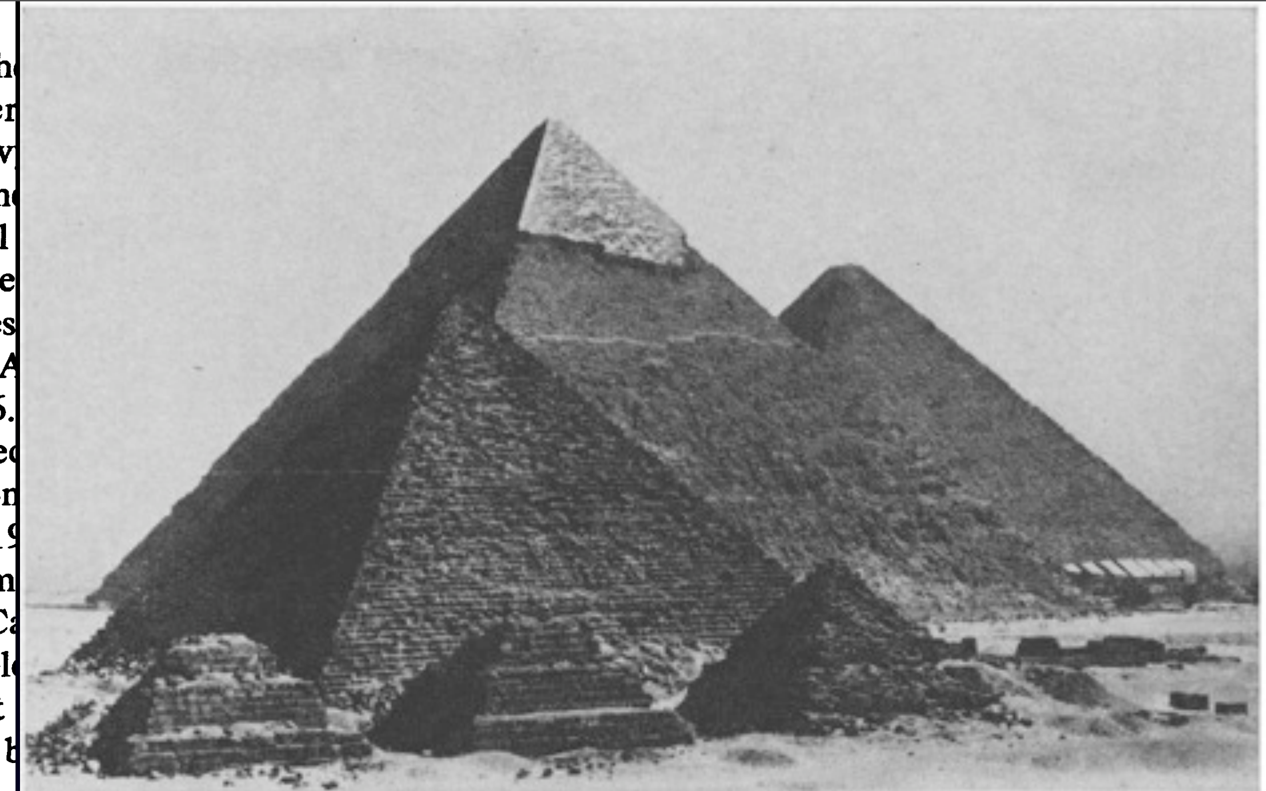

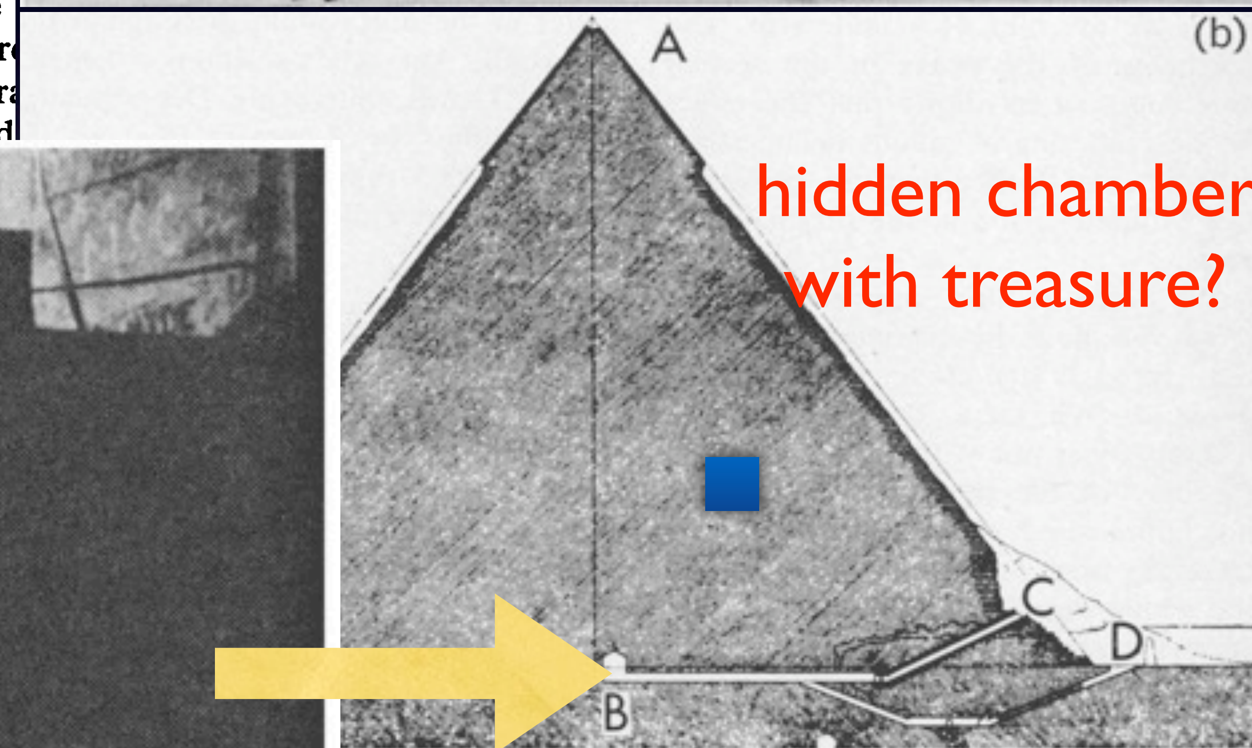

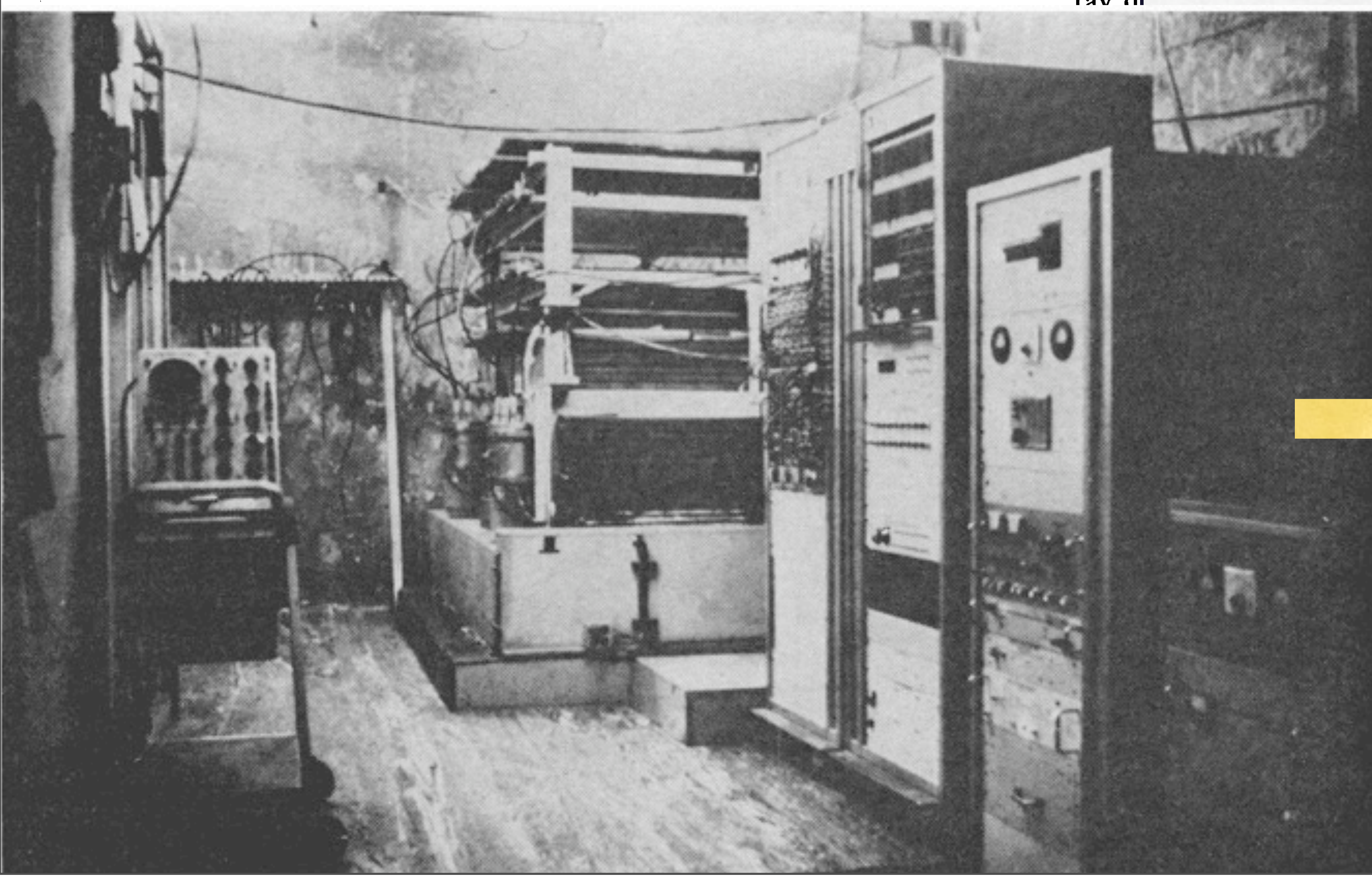

No Hidden Chamber!


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THE CRYSTAL SKULL
IN THEATERS MAY 22
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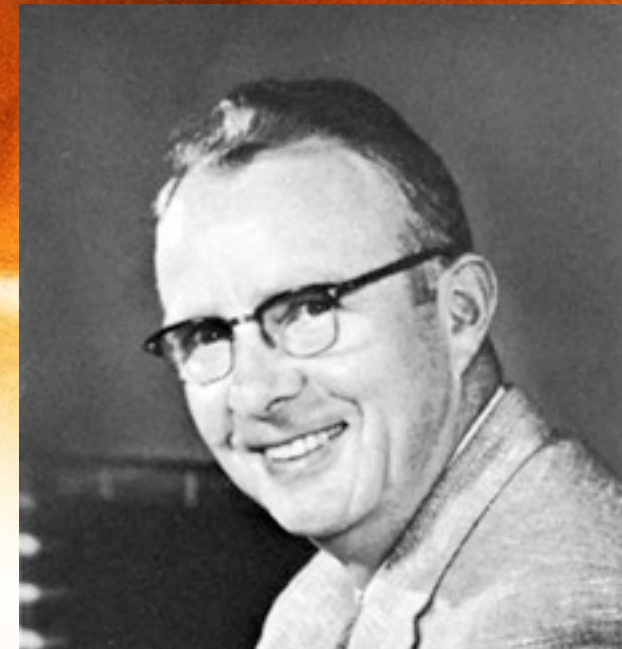
Luis Walter Alvarez

Luis Walter Alvarez



Luis Walter Alvarez

Monitor a volcano

- See through a volcano using muons
- University of Tokyo group demonstrated that one can monitor movement of magma insider a volcano in a southern island
- can predict eruption!

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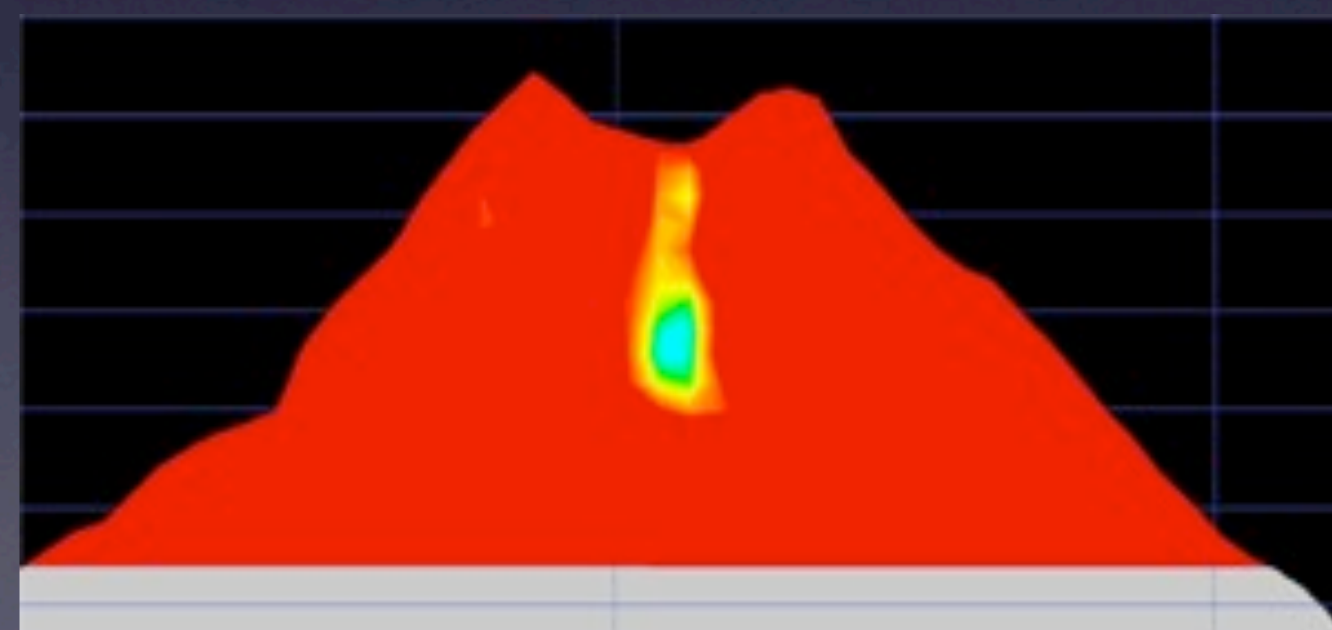

It's A Small World?

muon

electron

down

up

All you need to build atoms

It's A ~~Small~~ Messy World?

muon

electron

down

up

All you need
to build atoms

It's A ~~Small~~ Messy World?

muon

strange

electron

down

up

All you need
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muon

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charm

1974

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All you need to build atoms

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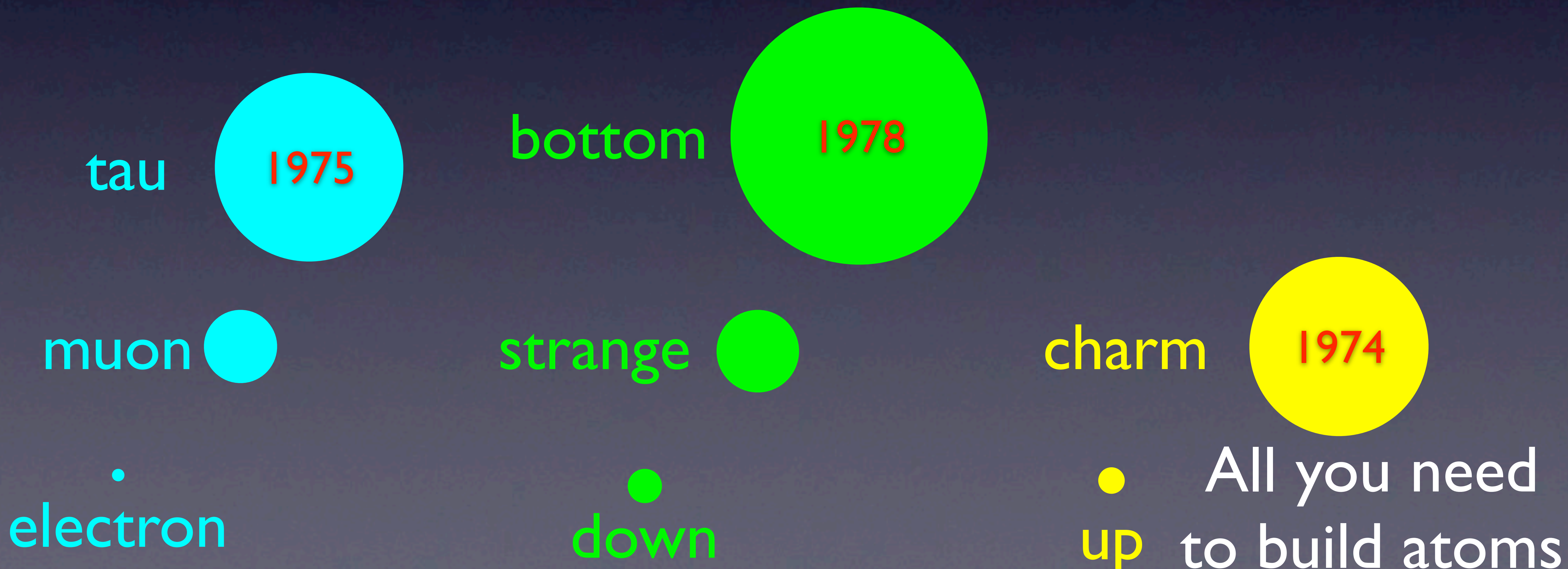
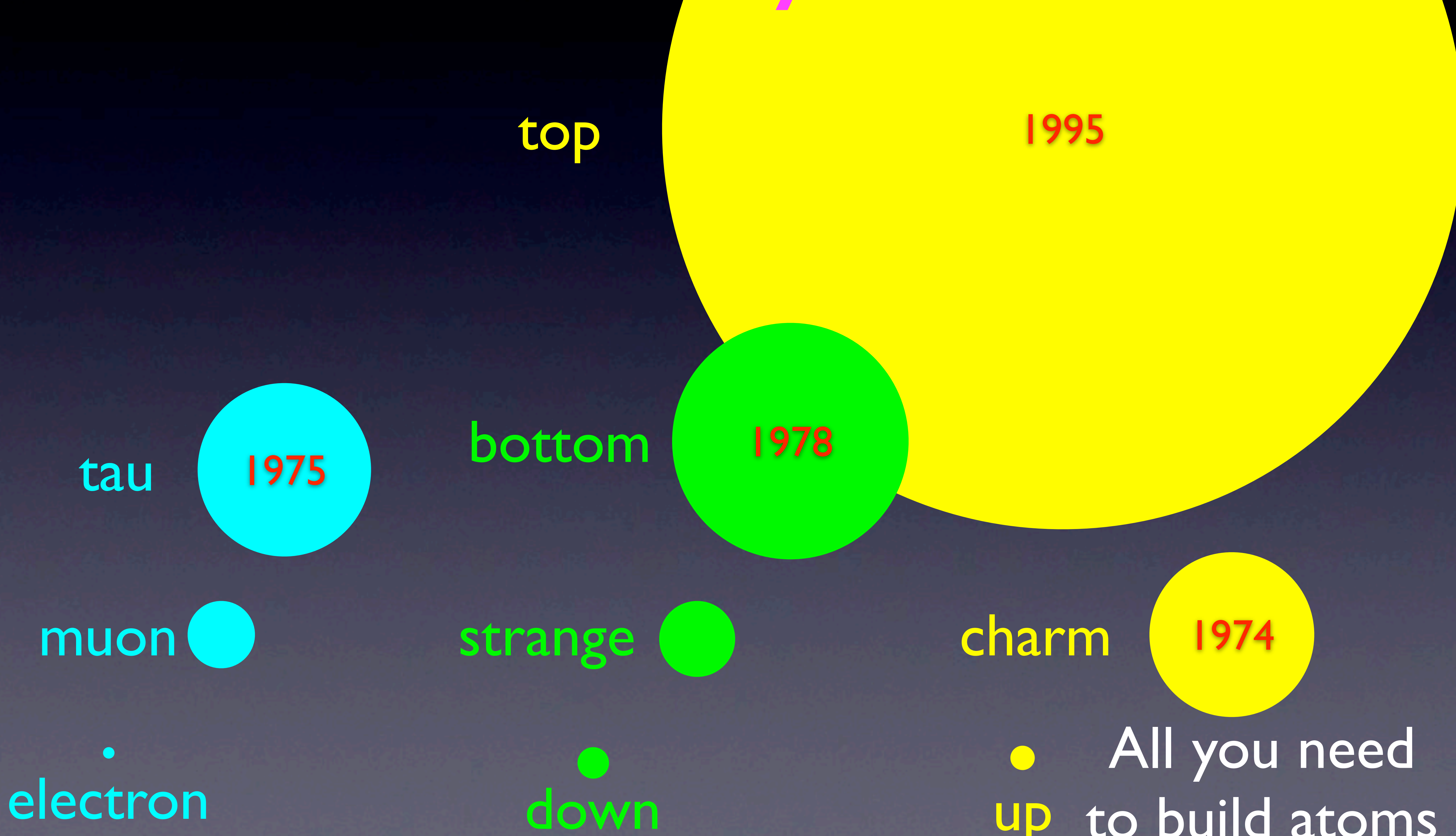


It’s A ~~Small~~ Messy



had predicted
three for each type

top 1995

tau 1975

bottom 1978

muon

strange

charm 1974

electron

down

up

All you need
to build atoms

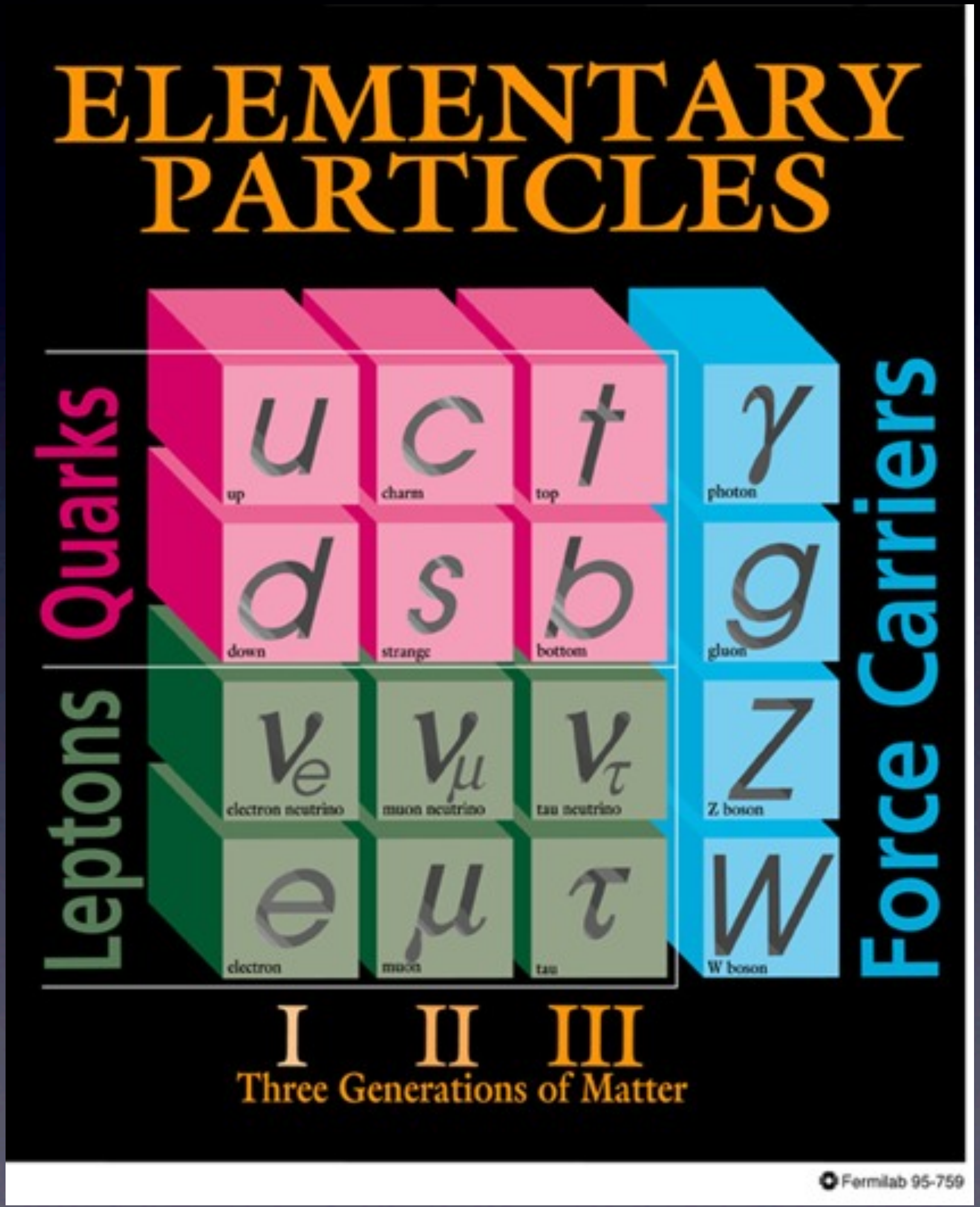

baskin robbins


flavors

BERKELEY CENTER FOR THEORETICAL PHYSICS

Standard Model

- *triumph of 20th century physics*
- most successful physical theory ever
- describes three forces:
  - electromagnetism
  - strong
  - weak
- Particle Data Group complies more than 24,000 measurements from more than 7,000 papers, all agree with the SM except for a few
- but we see problems in the 21st century



Some Basic Concepts

two pillars

- Two pillars in 20th century physics
  - relativity (Einstein)
  - quantum mechanics (Bohr, Heisenberg, Schrödinger, Pauli, Dirac, ...)
- Only way to combine them together is *Quantum Field Theory*
- very different way to describe nature from most people are used to

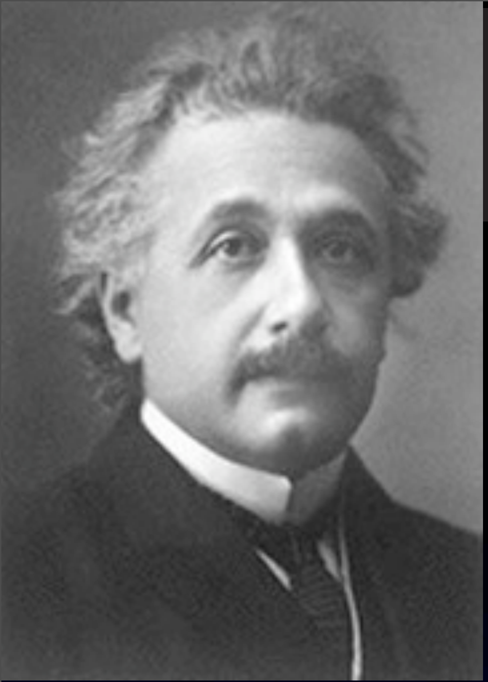
Conservation of Energy

- kinetic energy
- potential energy
- thermal energy
- chemical energy
- nuclear energy
- they can all transform from one to another
- but the grand total does not change

Conservation of Energy

Conservation of Energy

chemical energy in the body ⇒ *potential energy of the train*



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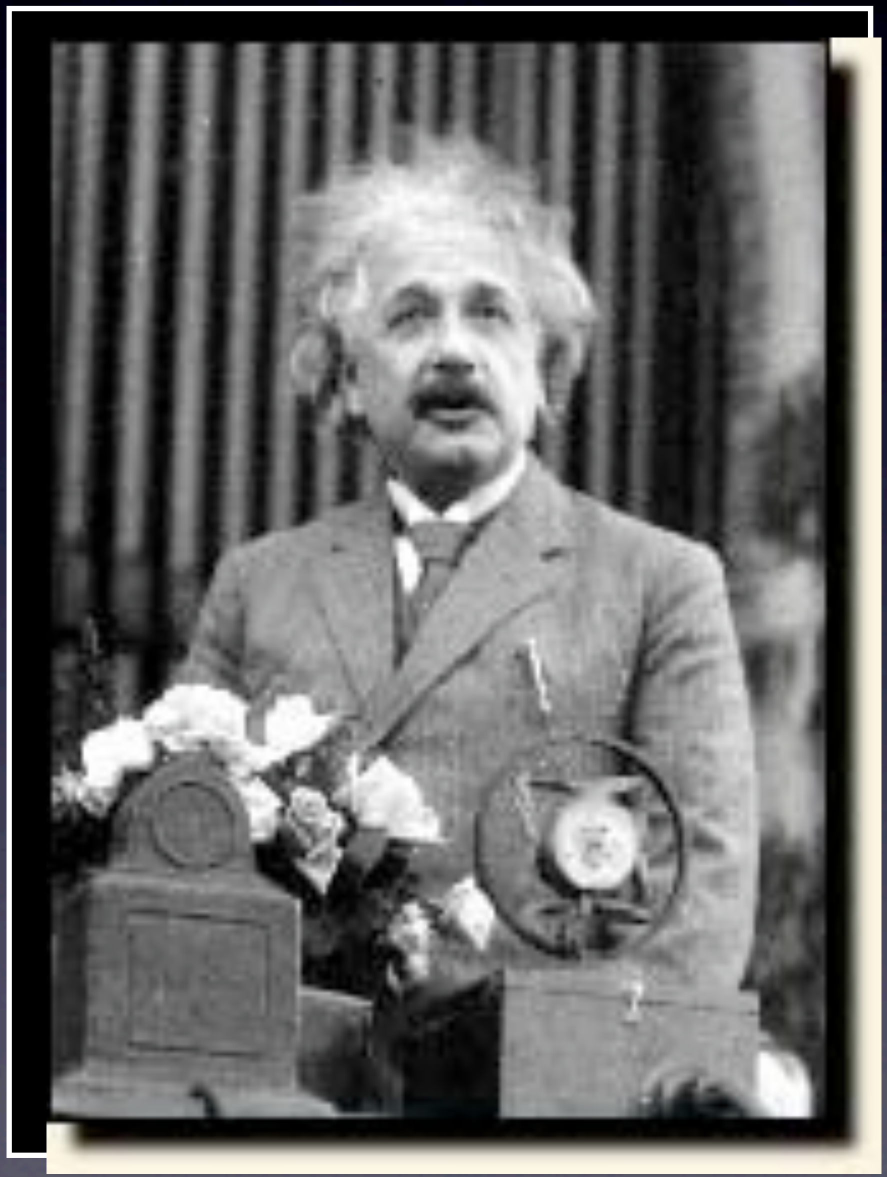
Special Relativity

- light speed is the speed limit
- the faster you move, time goes more slowly, things look shorter, and you feel heavier
- $c=3.00\times10^8$ m/s is a natural constant, the same no matter how you move
- we can measure distance with time
  - 1m=3.3nsec
  - light year$\approx10^{16}$m

$E=mc^2$

"It followed from the special theory of relativity that mass and energy are both but different manifestations of the same thing -- a somewhat unfamiliar conception for the average mind. Furthermore, the equation *E* is equal to *m* *c*-squared, in which energy is put equal to mass, multiplied by the square of the velocity of light, showed that very small amounts of mass may be converted into a very large amount of energy and vice versa. The mass and energy were in fact equivalent, according to the formula mentioned before. This was demonstrated by Cockcroft and Walton in 1932, experimentally."



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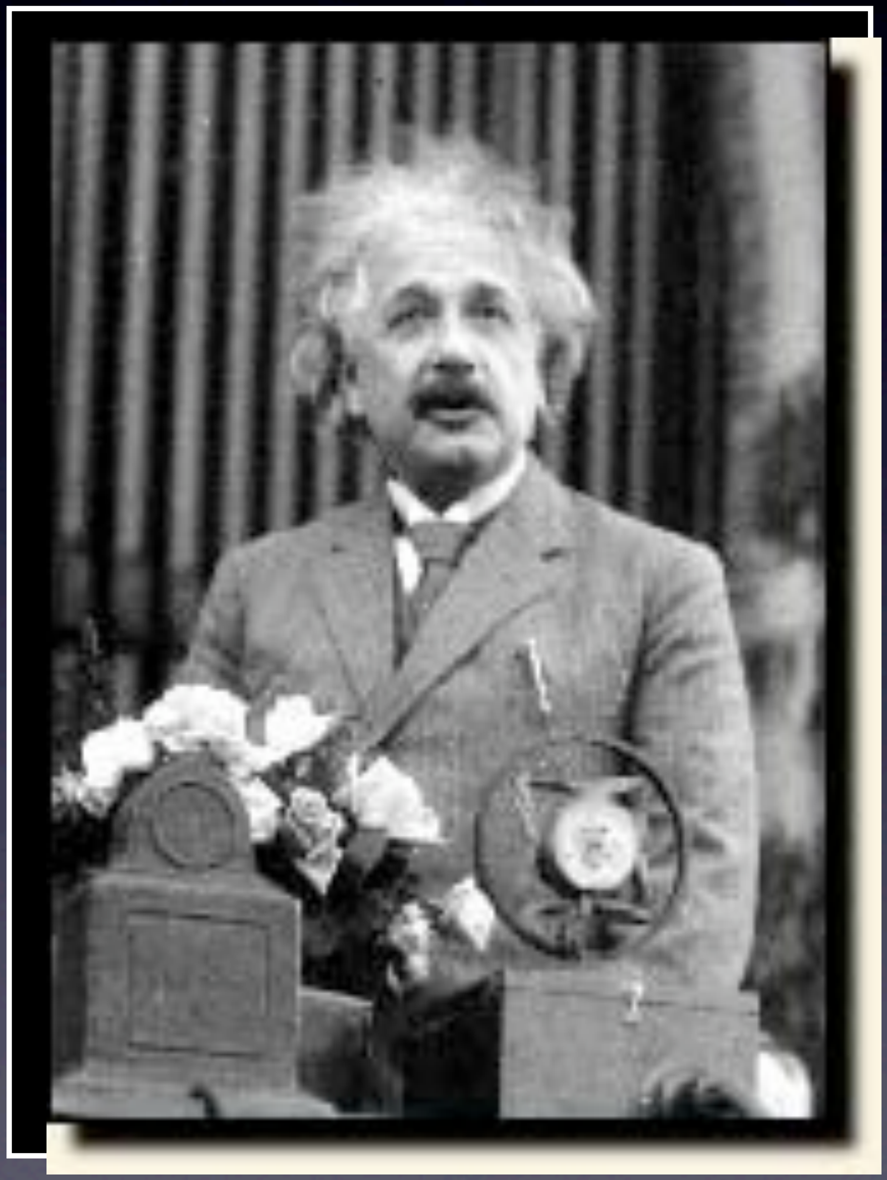


First Accelerator

- Cockroft and Walton *split the atoms* for the first time (1932)

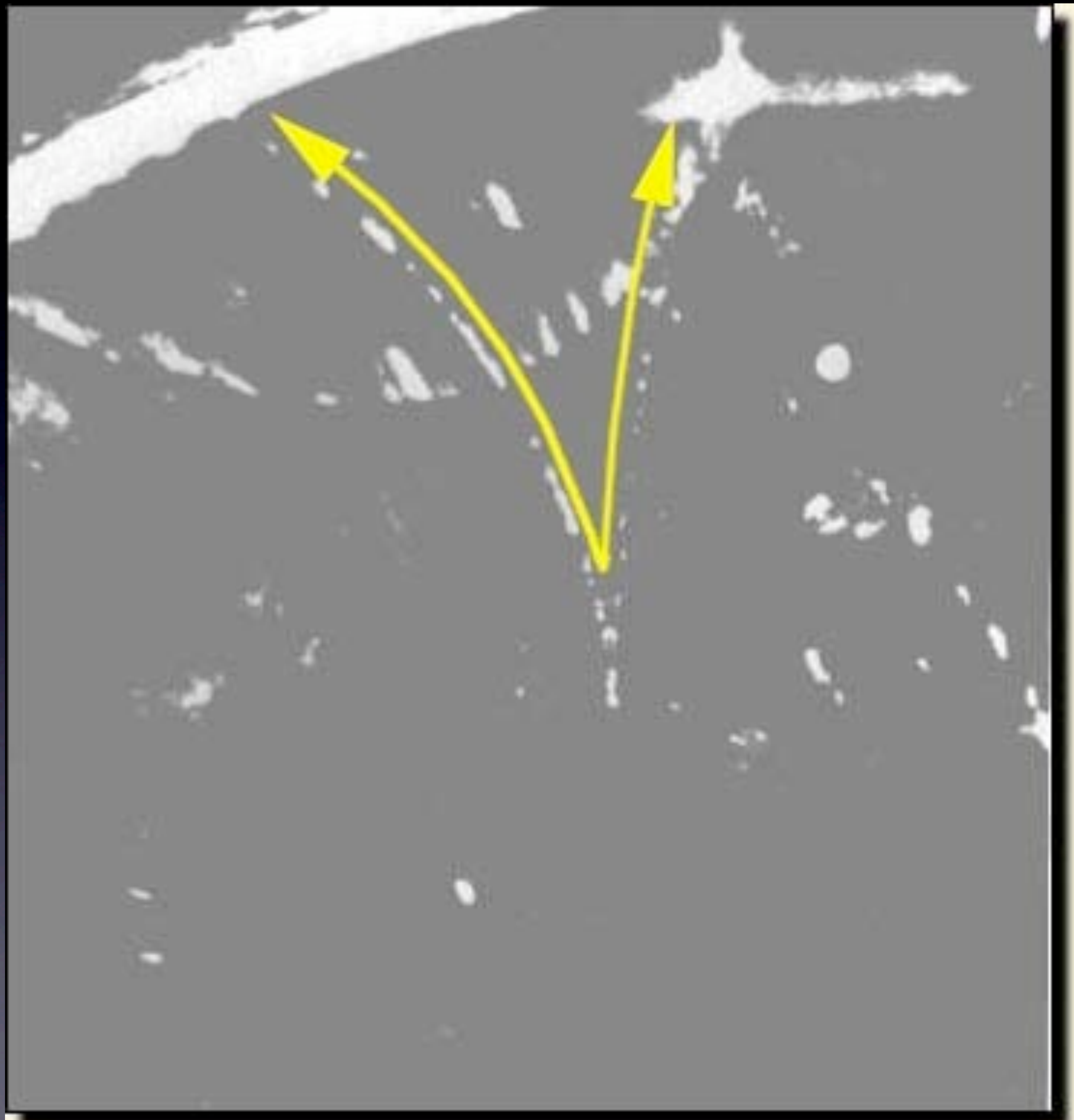
  $p + {}^{7}\mathrm{Li} \rightarrow {}^{4}\mathrm{He} + {}^{4}\mathrm{He}$

  Modern alchemy!
- p weighs 1.0078u
- ^{7}Li weighs 7.0160u
- ^{4}He weighs 4.0026u

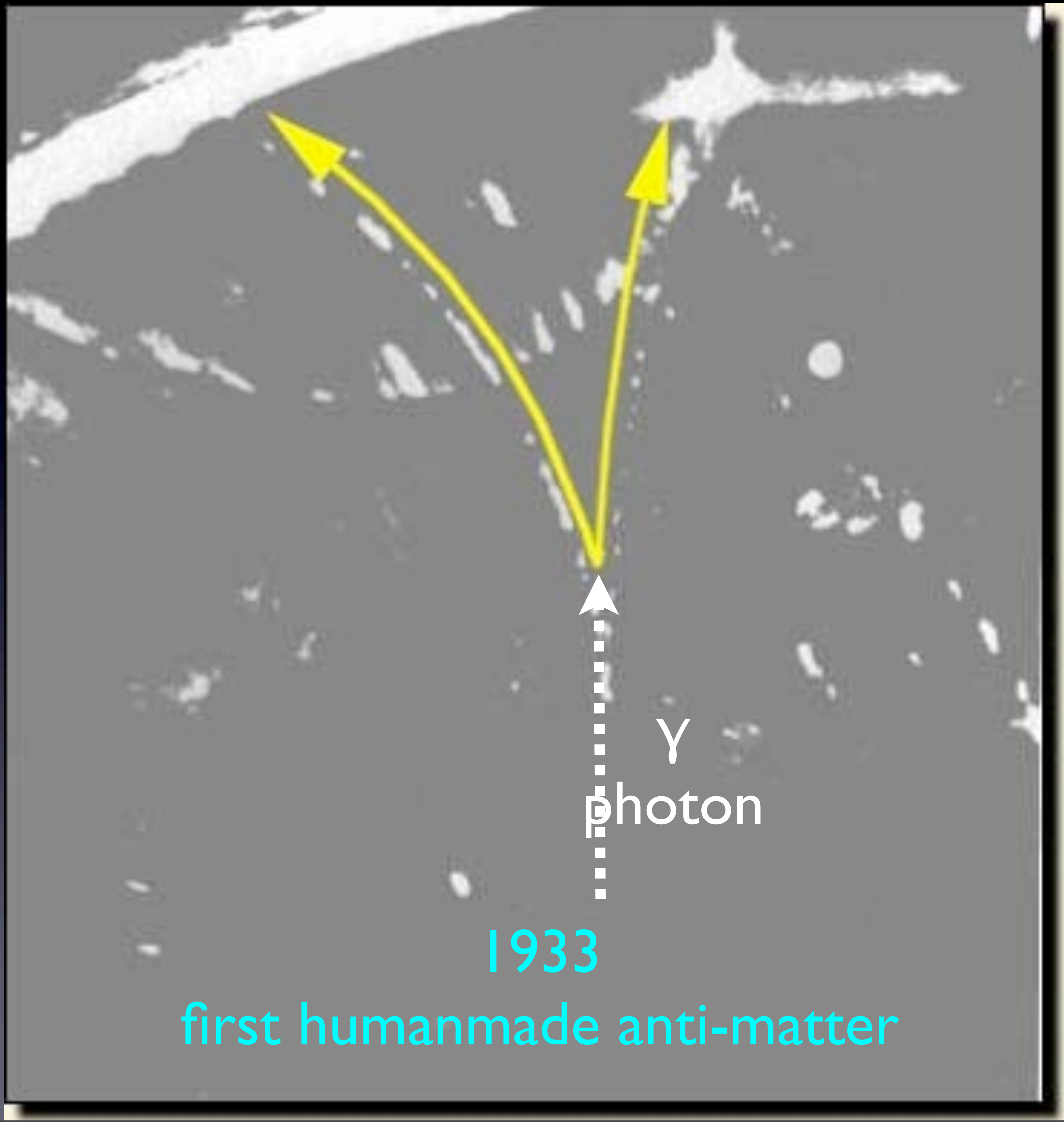
  $1.0078u + 7.0160u$

  $-2 \times 4.0026u = 0.0186u$
- two helium atoms flew apart with lots of kinetic energy
- mass turns into energy!

1951 Nobel Prize in Physics




1933
first humanmade anti-matter


γ
photon
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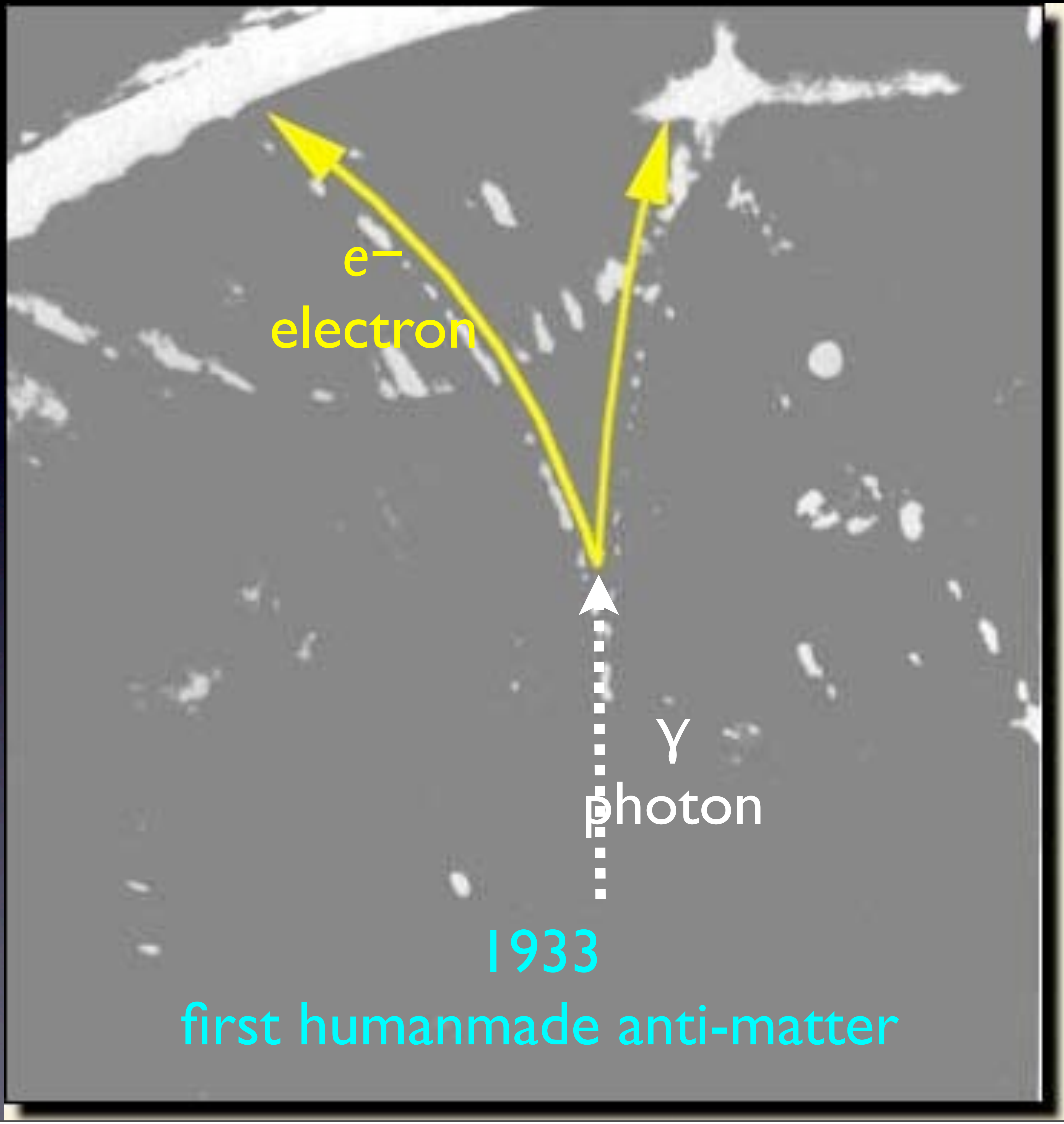
first humanmade anti-matter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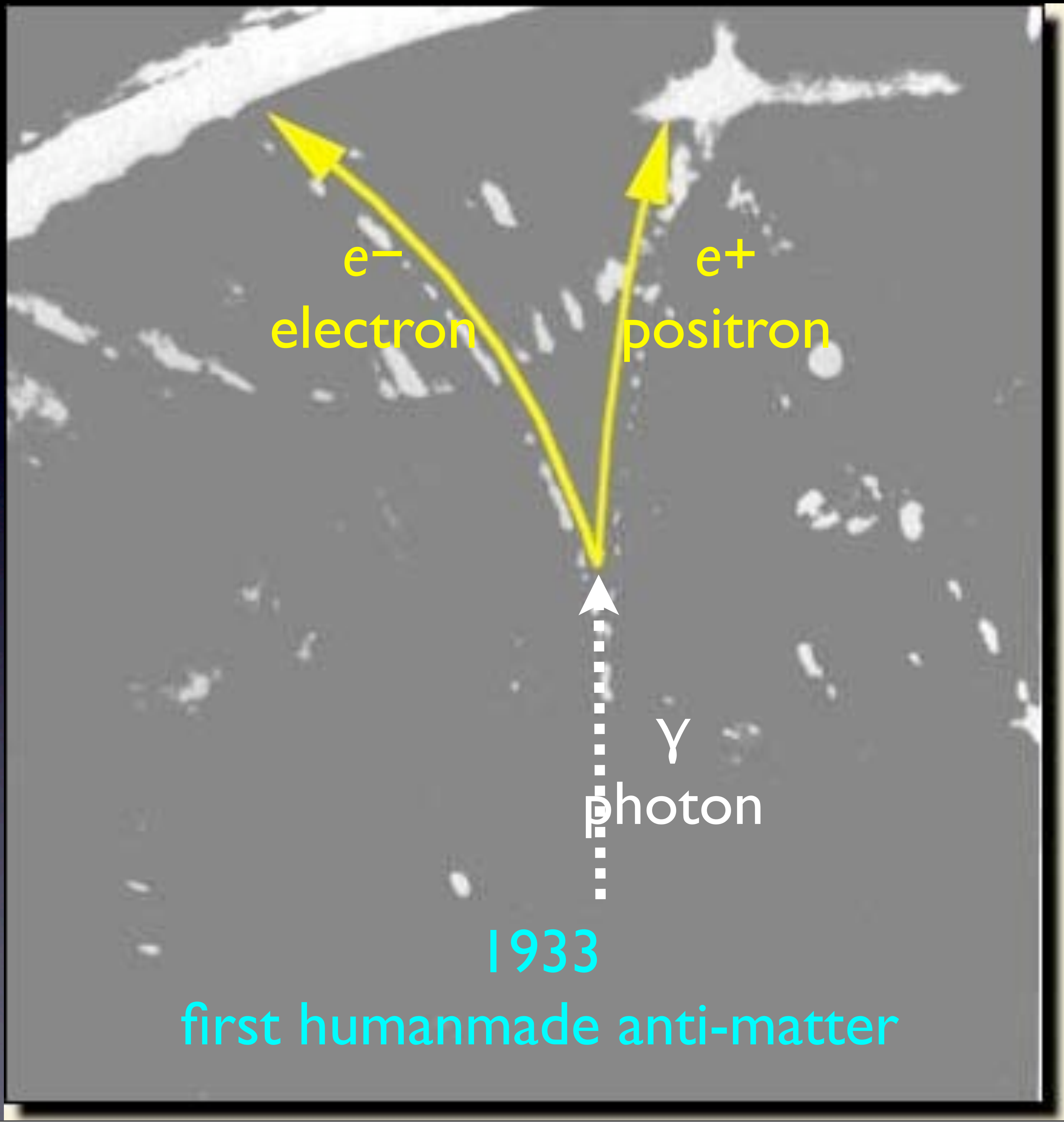
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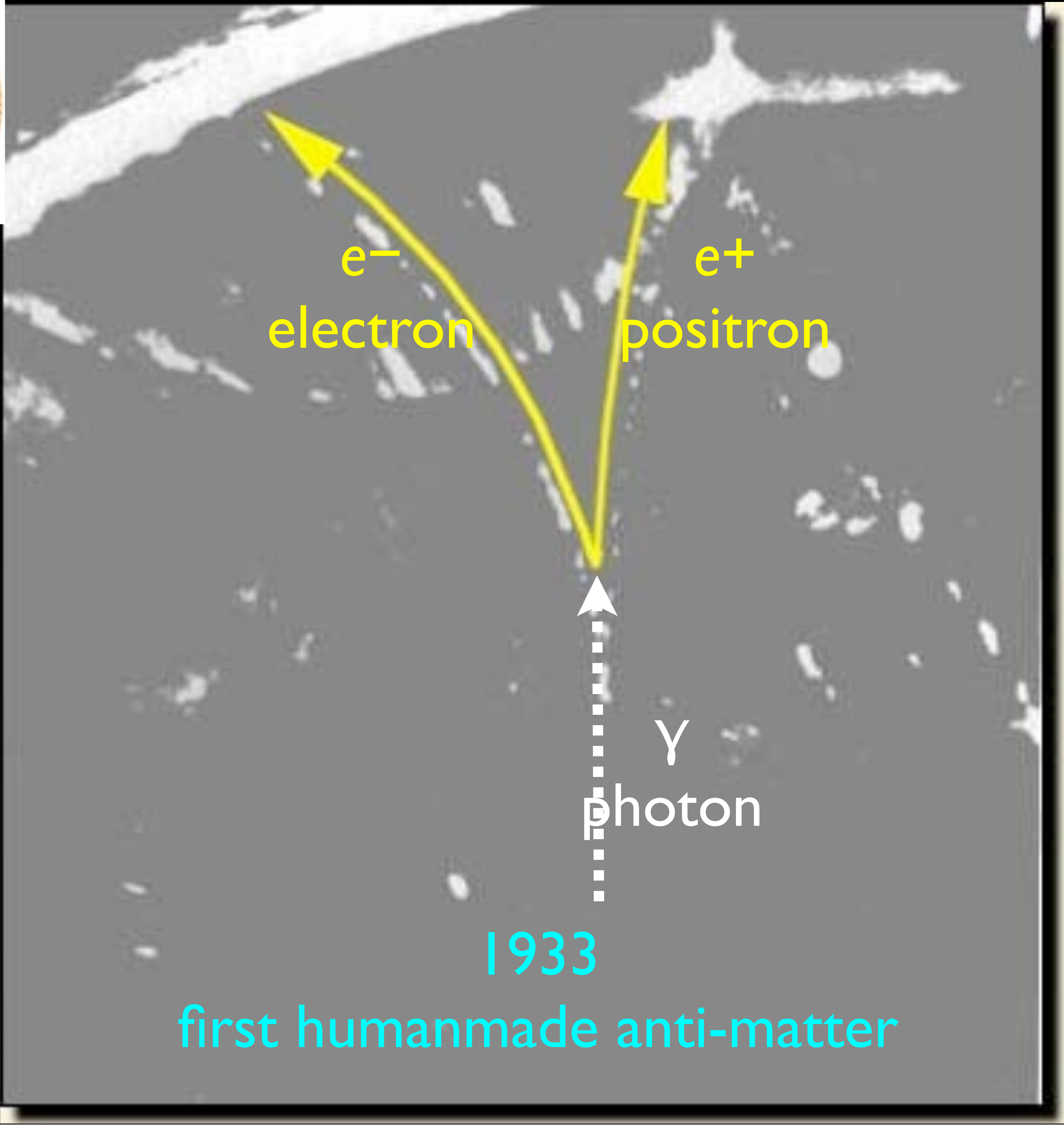
Frédéric Joliot-Curie

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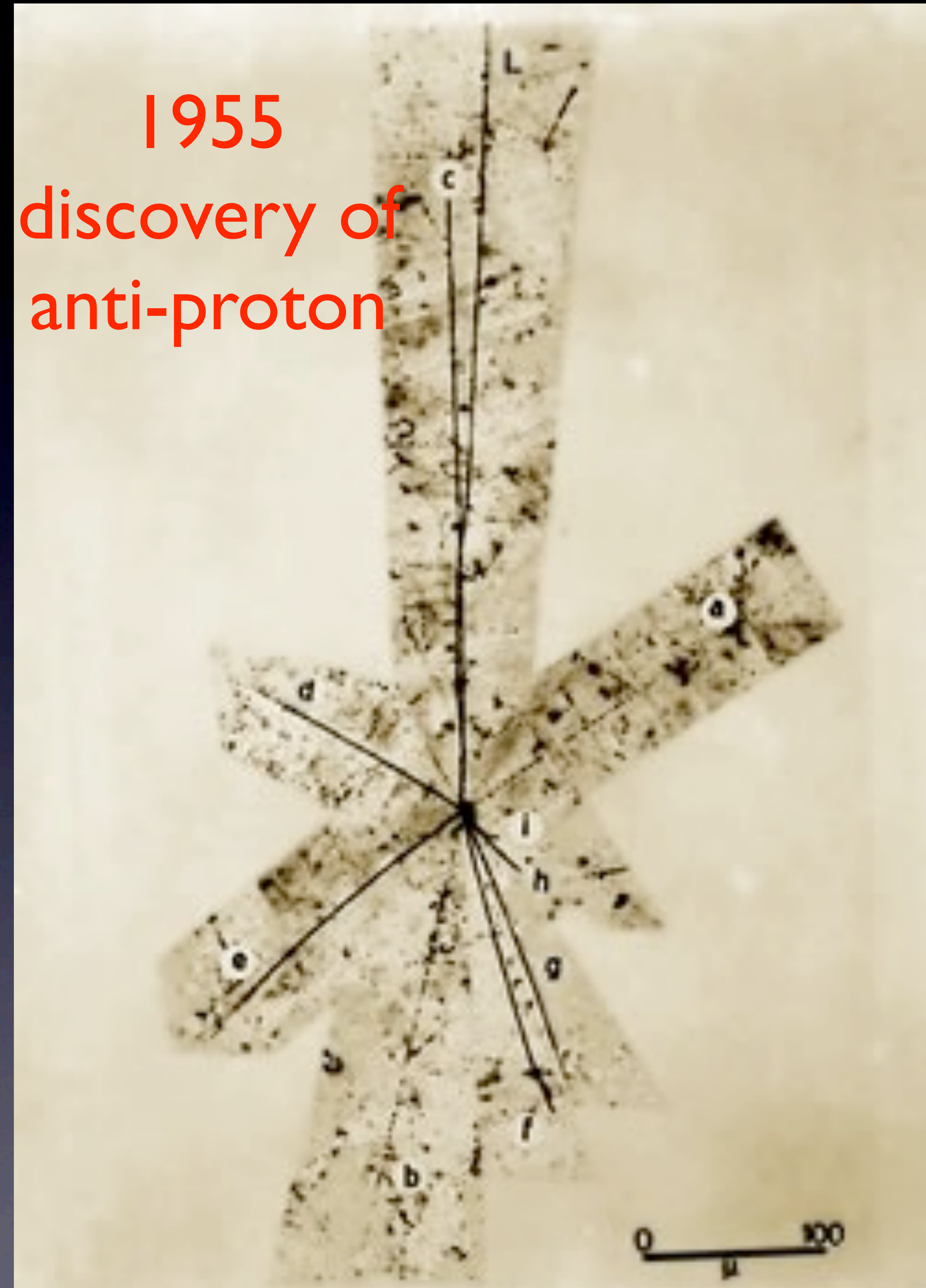
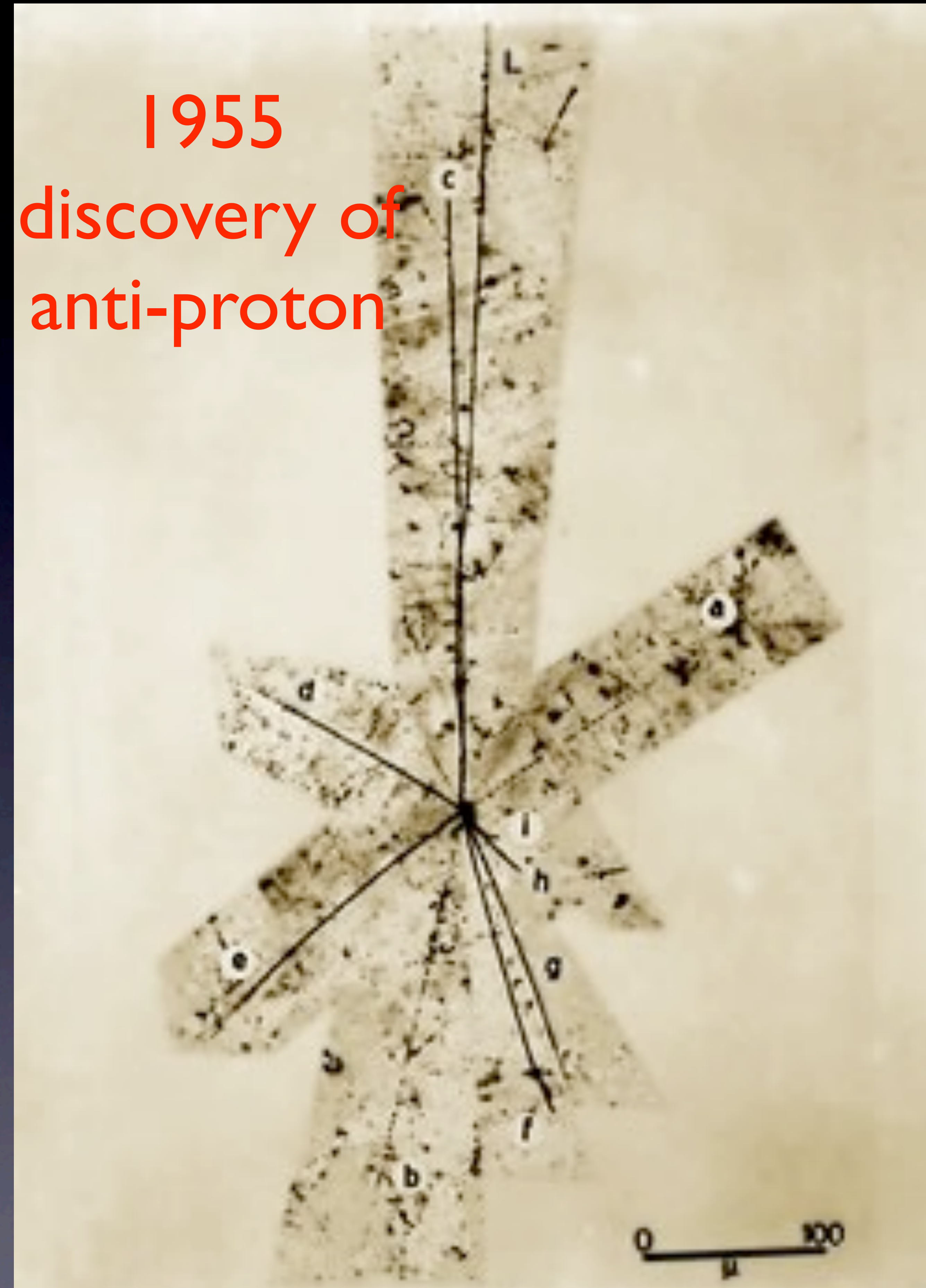

1955
discovery of
anti-proton


Berkeley
Emilio Segrè
Owen Chamberlain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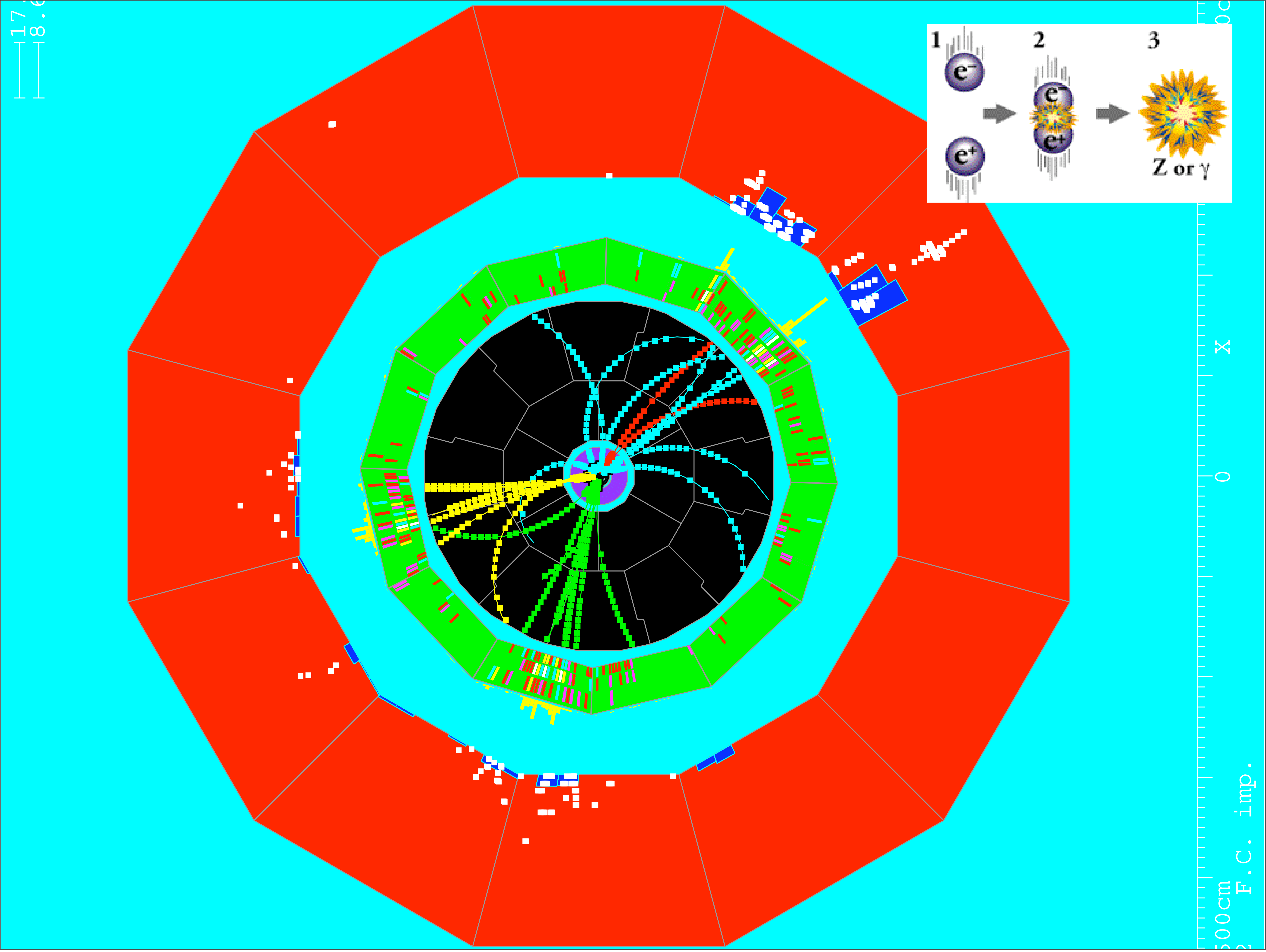
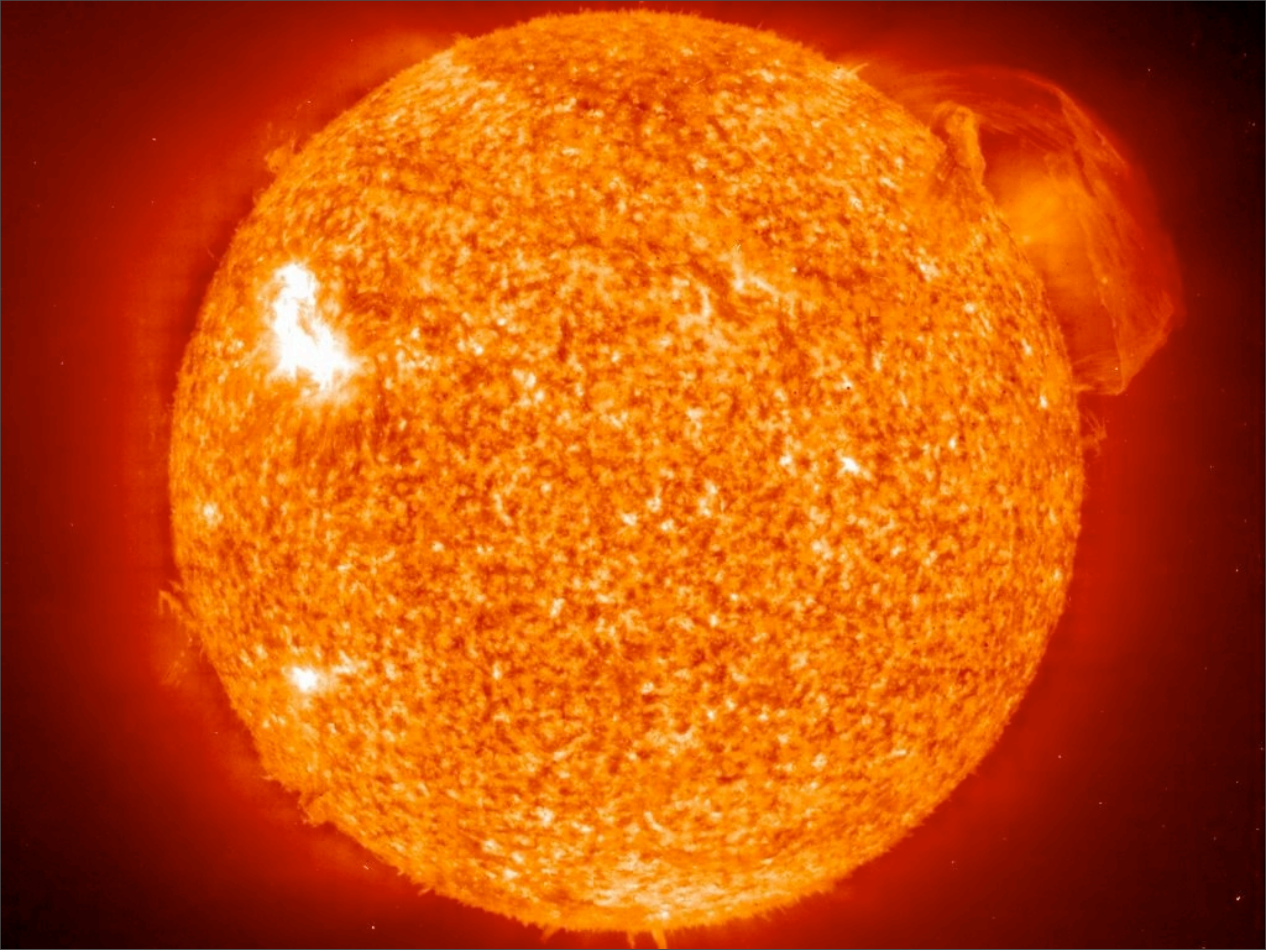
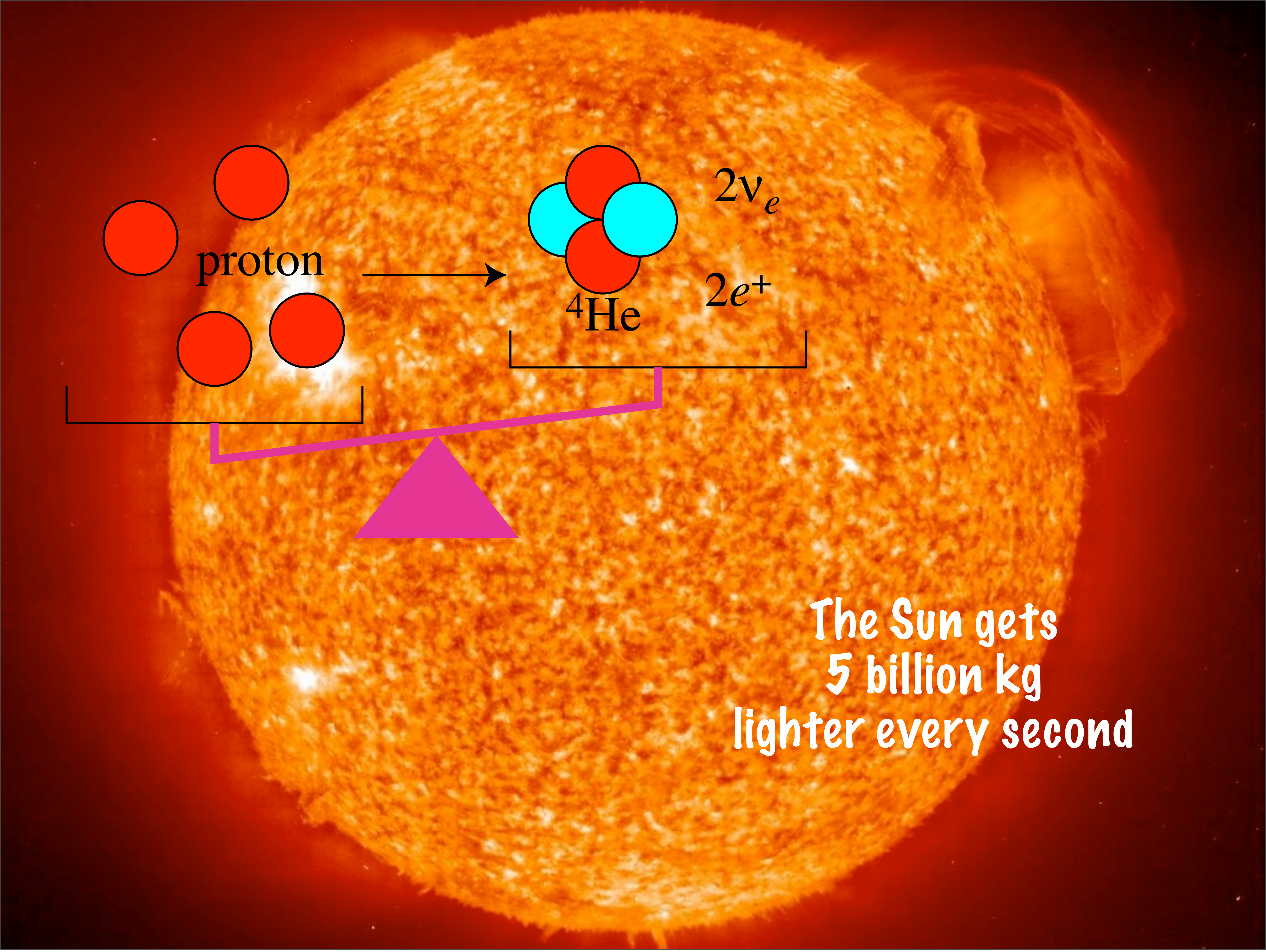


Thursday, July 23, 2009




The Sun gets
5 billion kg
lighter every second


proton
$2\nu_e$
$2e^+$
^{4}He
The Sun gets
5 billion kg
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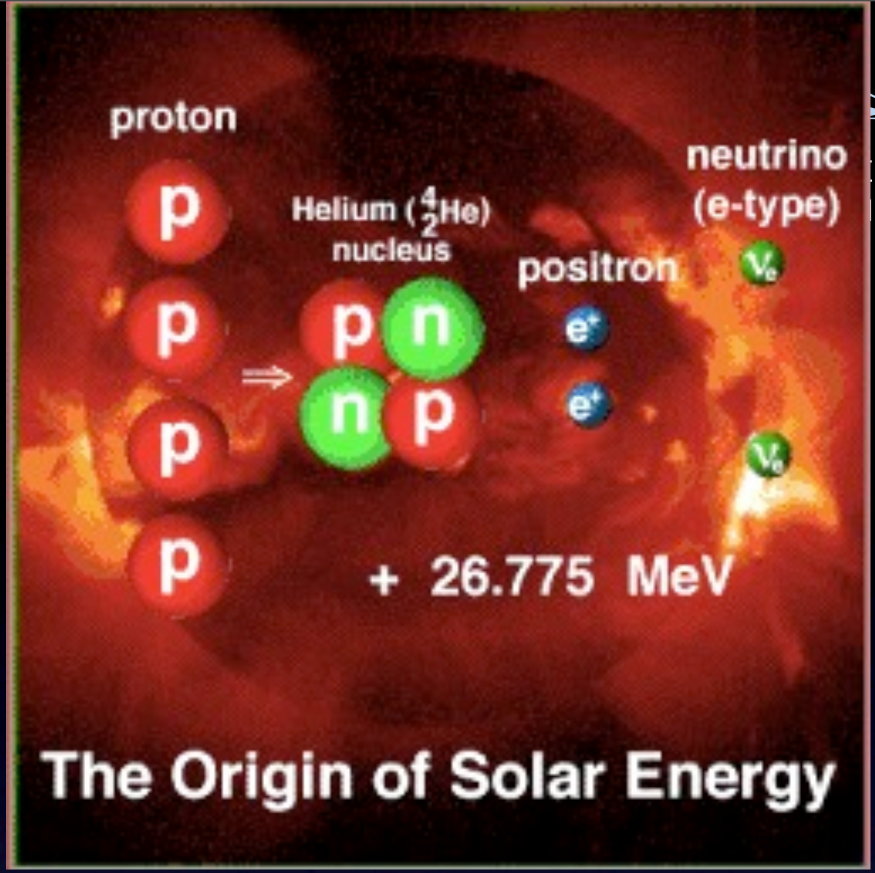
- trillions of neutrinos go through our body every second



Final proof

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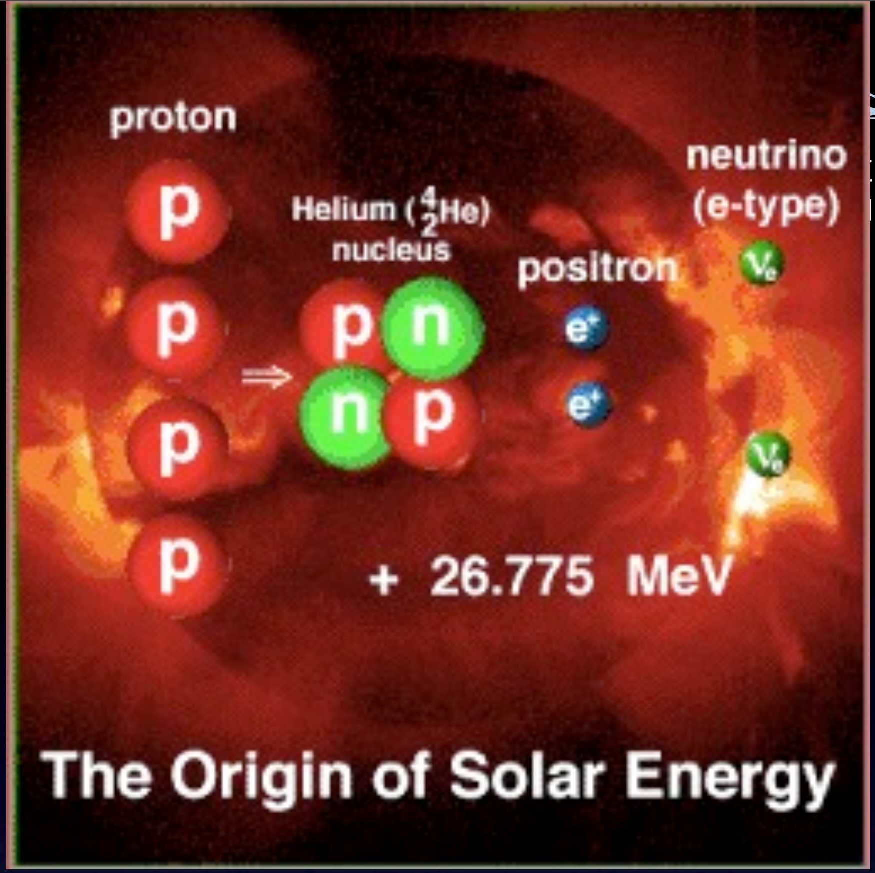

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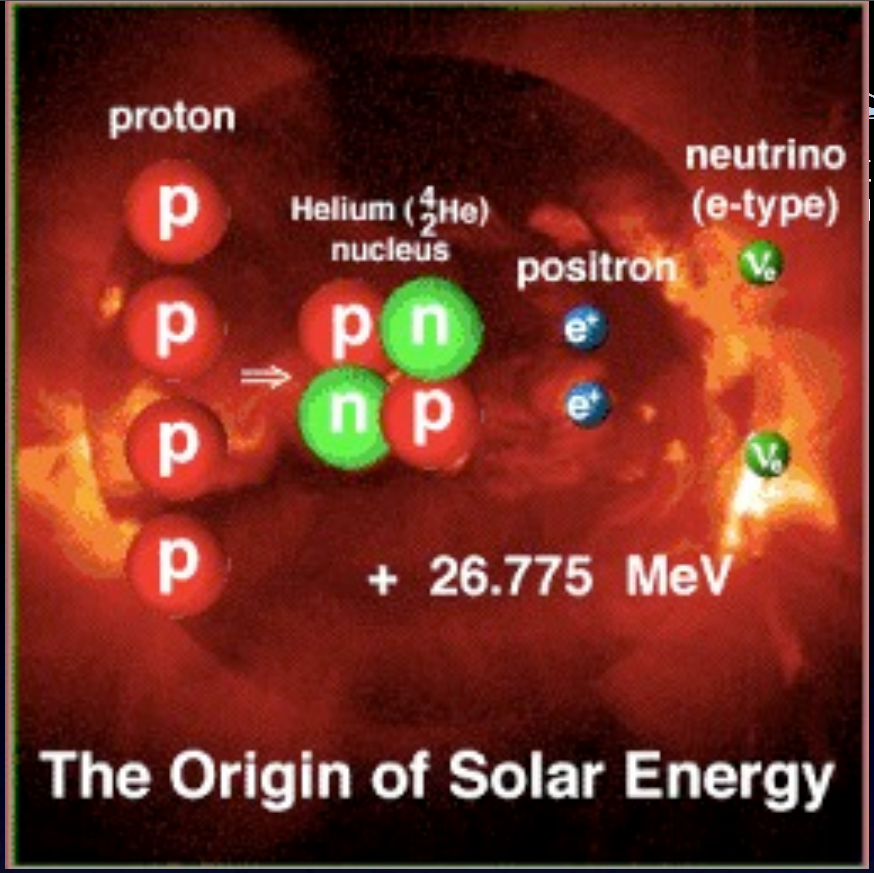

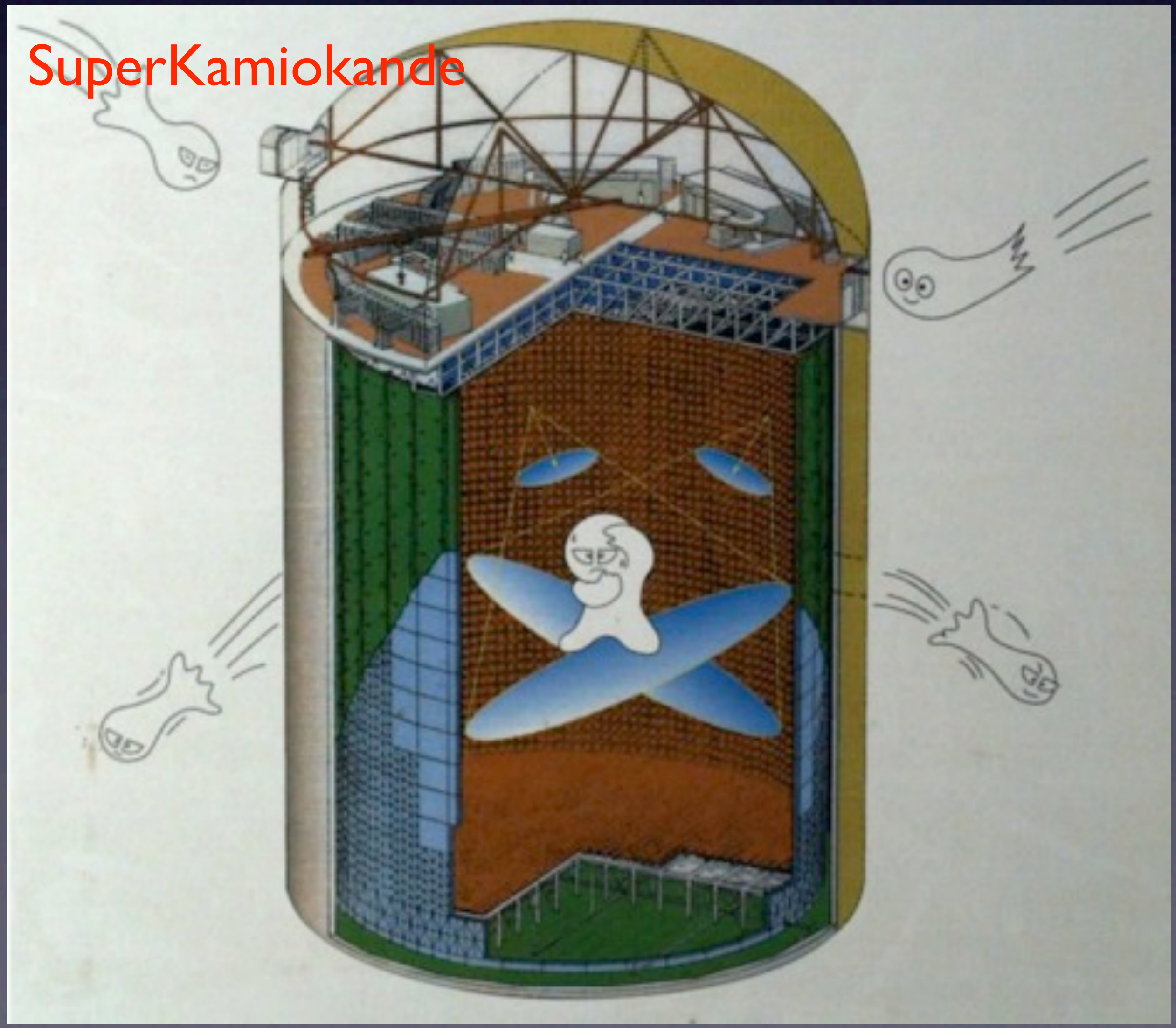

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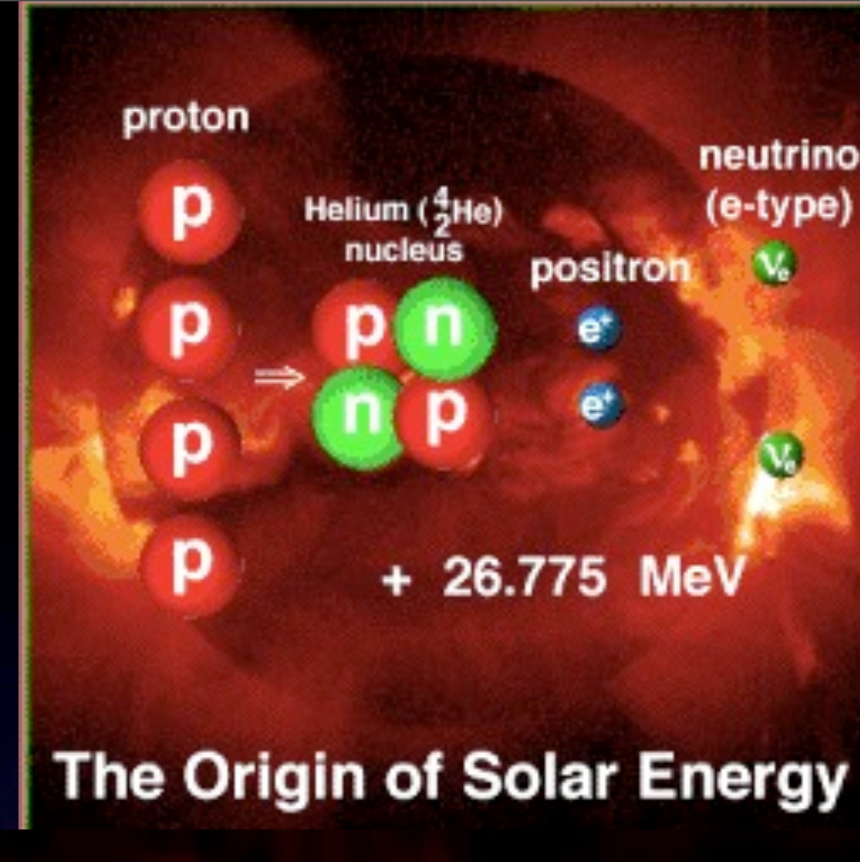

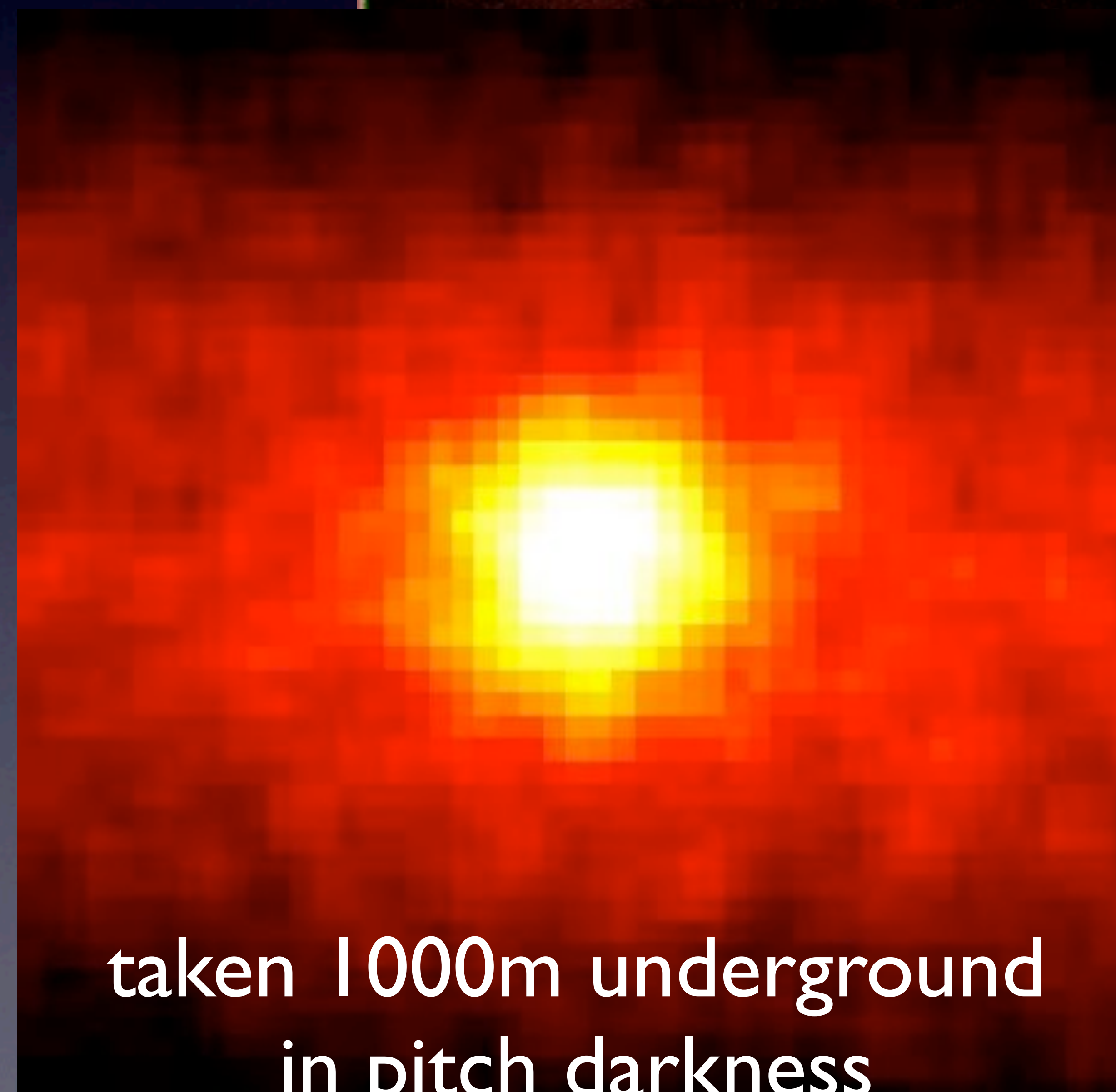

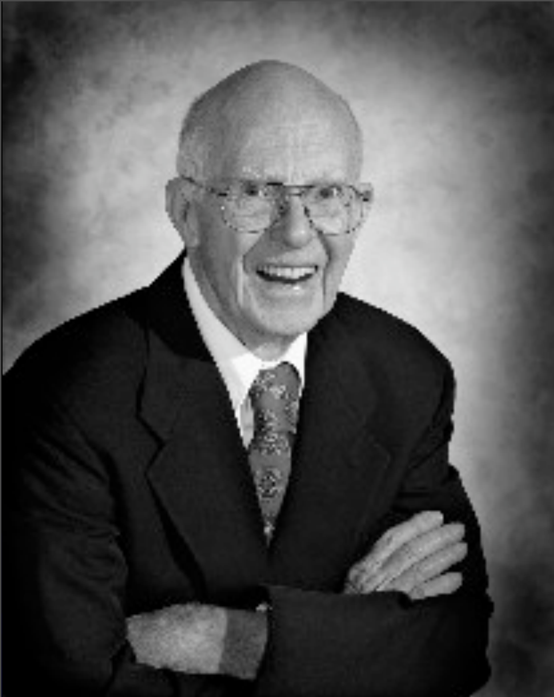

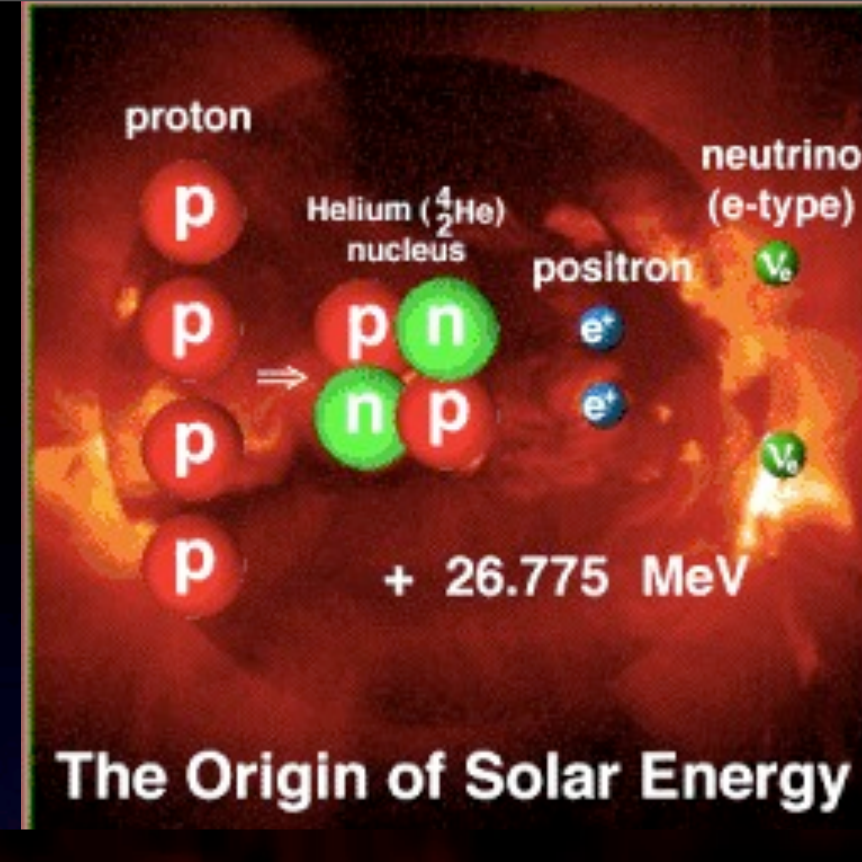

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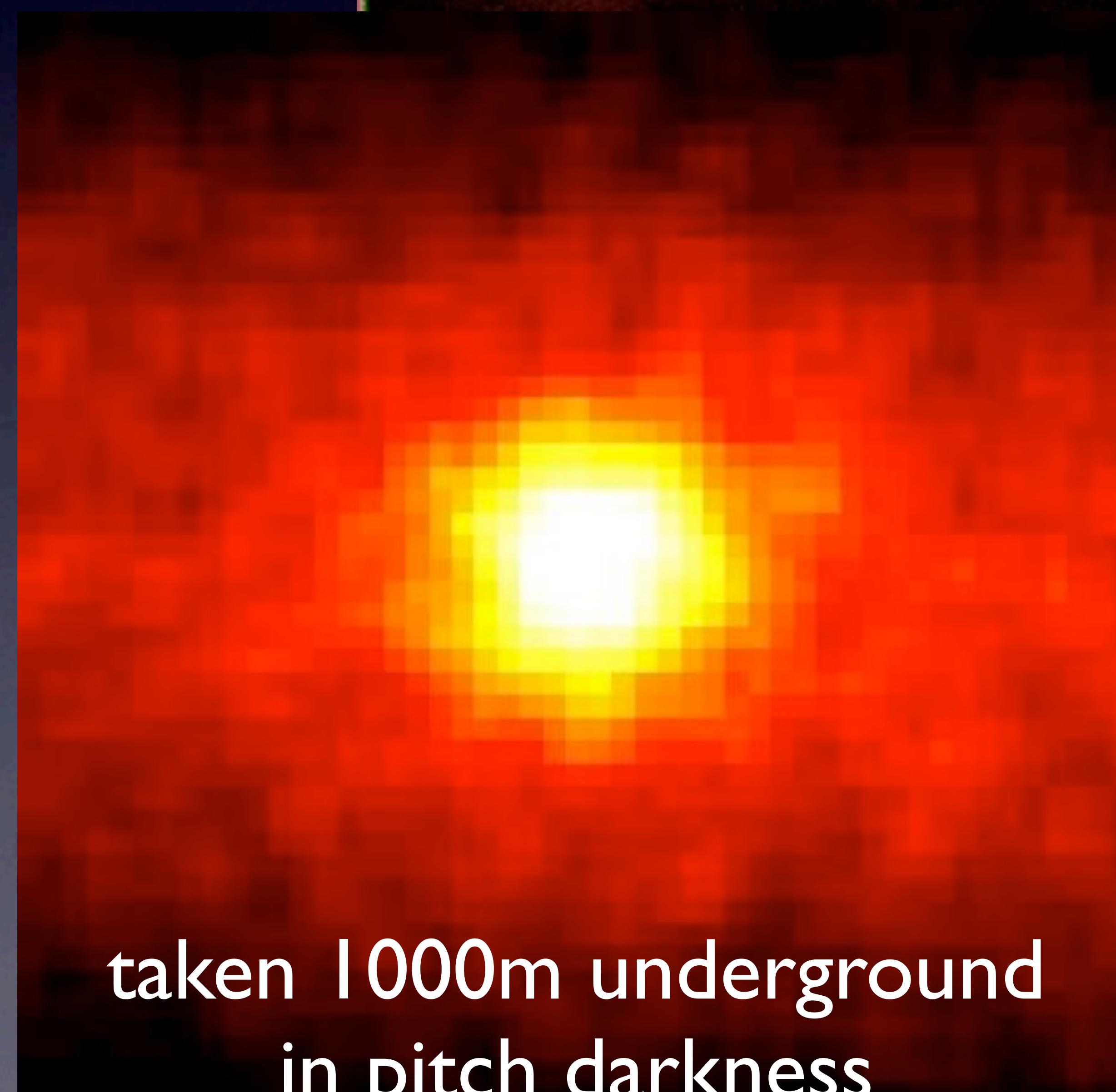

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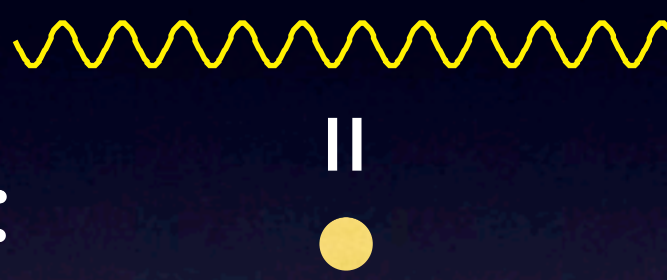
Quantum Mechanics

- particle is wave, wave is particle
- Heisenberg uncertainty principle: $\Delta x \Delta p \geq \hbar/2$
- $\hbar = 6.63\times10^{-34}$ J s is a natural constant
- $\hbar c = 0.197$ GeV fm is a useful combination
- can measure distance with energy
  - $1\text{fm} = 10^{-13}\text{cm} = 5.0\text{GeV}^{-1}$



Copenhagen interpretation

- In quantum mechanics, one can only talk about *probability*
- We cannot predict with certainty what should happen
- Only after repeating the same experiment many times, we can test the prediction
- Einstein: *God doesn't play dice.*
- Apparently He does.

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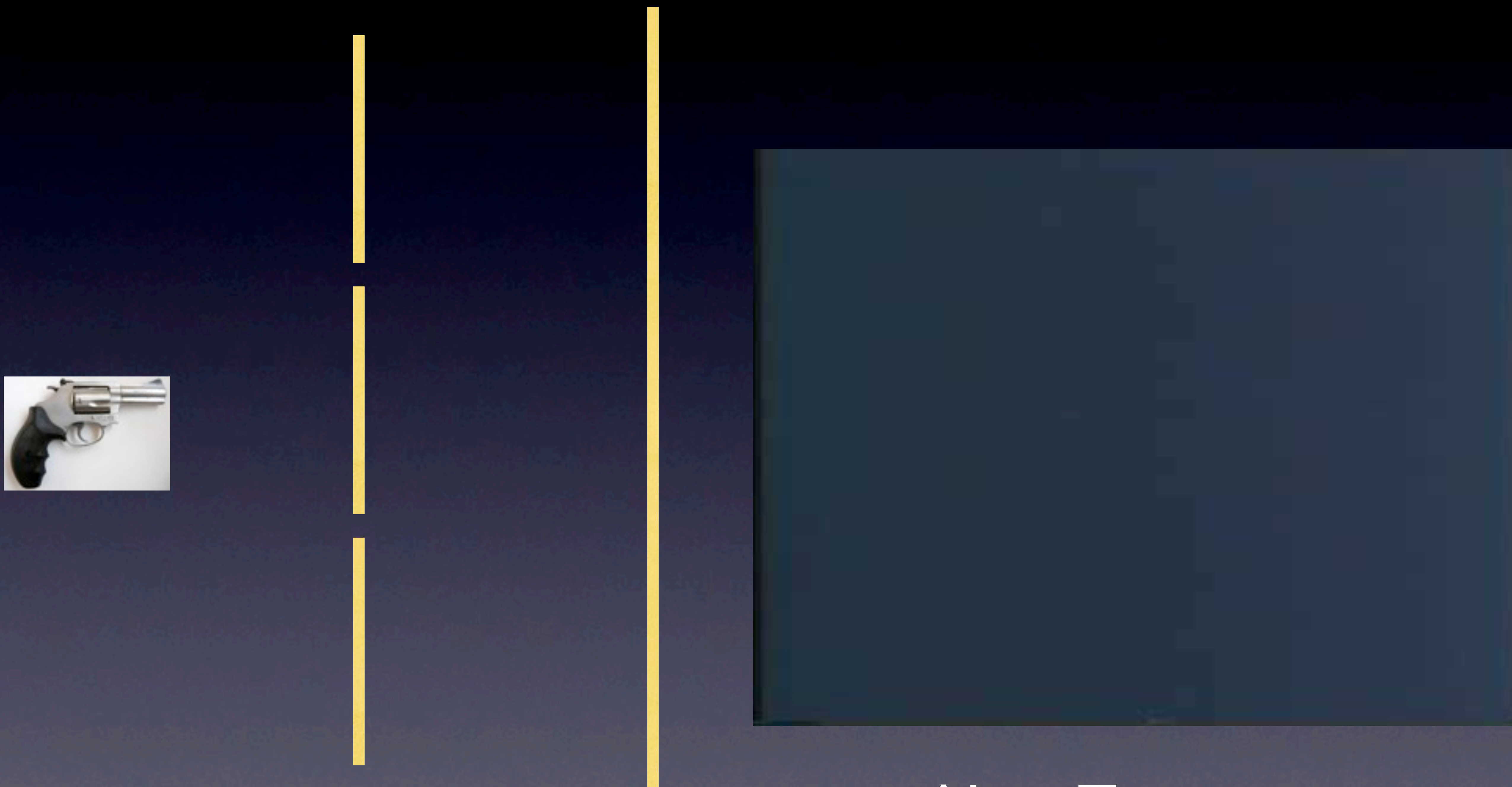
electron is a wave

Akira Tonomura

electron is a wave



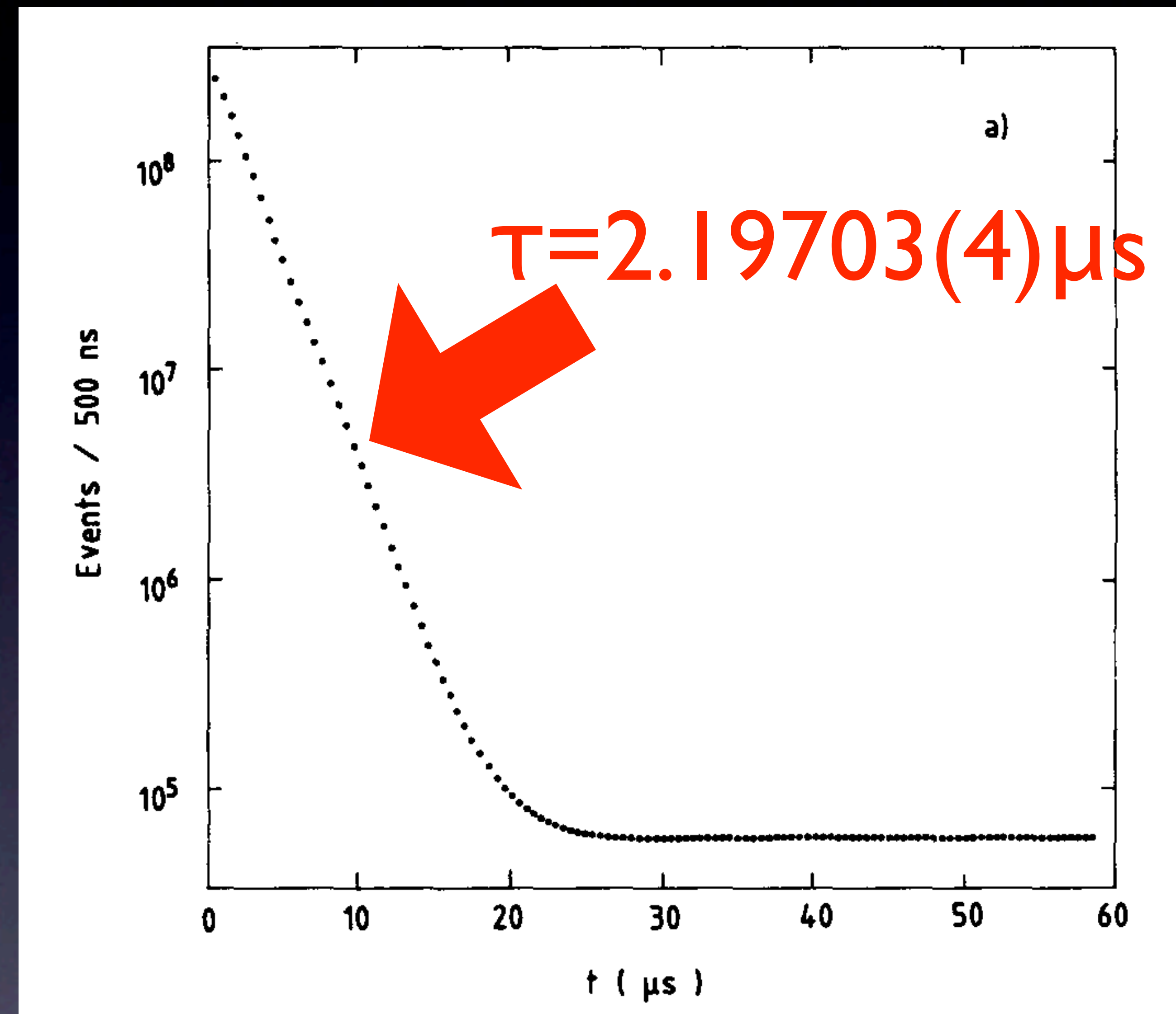
Akira Tonomura

spin and statistics

- particles spin eternally like a top
- spin angular momentum s=(half-integer)×$\hbar$
- s=1/2 for electrons, follows Fermi statistics (exclusion principle)
- s=1 for photons, follows Bose statistics
- Quantum Field Theory predicts that all particles with integer spins are bosons, those with half-odd spins are fermions

Lifetime

- Most particles have a finite lifetime, decay into other ligher particles
- $1/\tau$ is the probability of decay in unit time
- $dn/dt = -n/\tau$
- $n(t)=n(0)e^{-t/\tau}$
- time-energy uncertainty principle $\Delta E\ \Delta t \approx \hbar$
- $\Gamma=\hbar/\tau$ is the *width* of *energy* (mass)
- stronger the force, shorter the lifetime



$$\int_0^\infty dt\ e^{-2t/\tau} e^{-i(\omega-\omega_0)t} = \frac{i\tau/2}{i+\tau(\omega-\omega_0)/2}$$

$$\left|\frac{i\tau/2}{i+\tau(\omega-\omega_0)/2}\right|^2 = \frac{1}{(E-E_0)^2+\Gamma^2/4}$$

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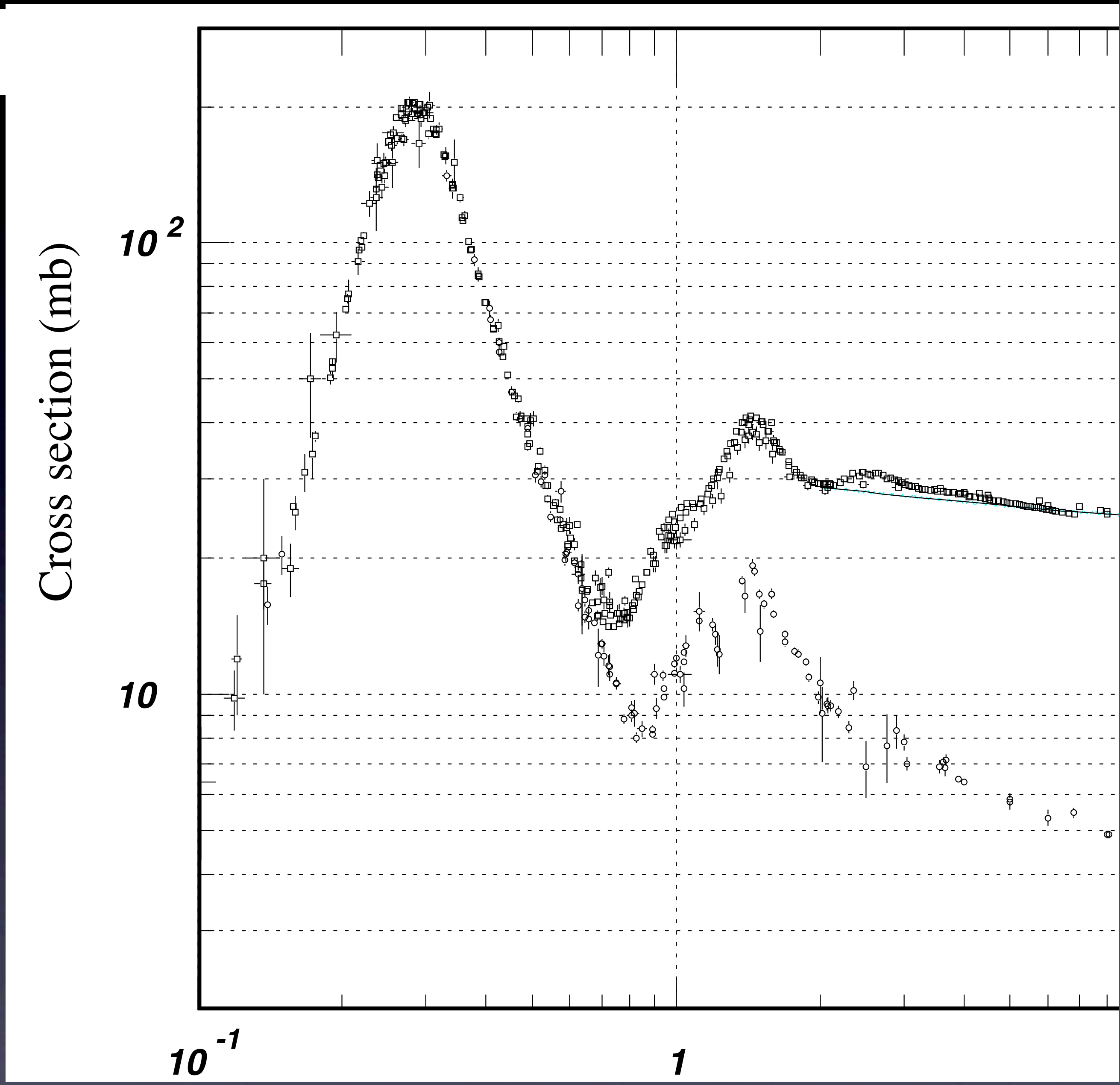
Lifeti



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$$\left|\frac{i\tau/2}{i+\tau(\omega-\omega_0)/2}\right|^2 = \frac{1}{(E-E_0)^2+\Gamma^2/4}$$

conservation of matter particle number

- As far as we know, particle number is conserved
- particle number = #matter - #anti-matter
- photon→electron+positron: $\gamma \to e^+ e^-$
- neutron→proton+electron+anti-neutrino $n \to p\ e^-\ \bar{\nu}_e$
- nuclear reaction in the Sun $p\ p \to d\ e^+\ \nu_e$ (d=[pn])
- Many believe it should be violated, so that we could survive the Big Bang!

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Standard Model 2

CERN Summer Student Programme

July 21, 2009

Hitoshi Murayama (IPMU Tokyo & Berkeley)

THE UNIVERSITY OF CALIFORNIA BERKELEY 1868 LET THERE BE LIGHT

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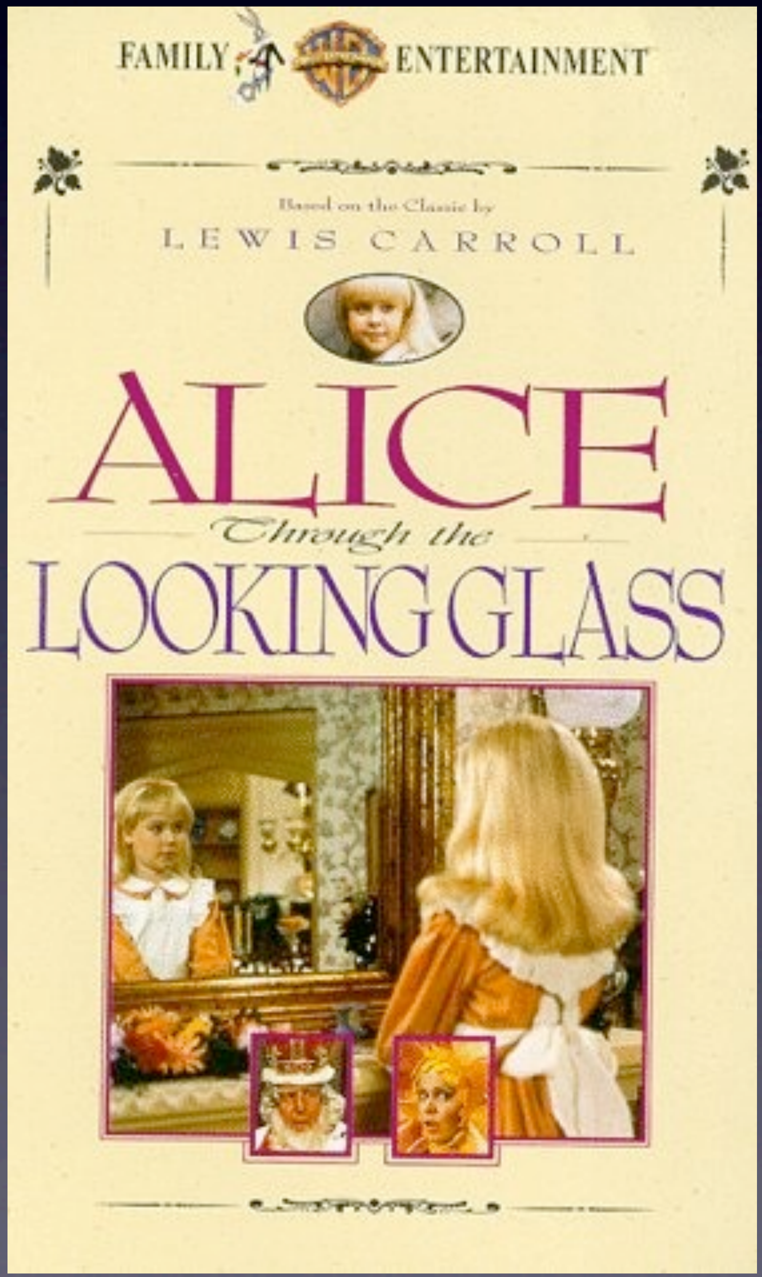
CPT

- Another important prediction of *Quantum Field Theory*
- Doing all three operations should leave physics unchanged:
  - charge conjugation *C*
  - parity *P*
  - time reversal *T*
- predicts that particle and anti-particle have
  - same mass
  - same lifetime
- weak force violates all *C, T, P, but not CPT*

parity: *P*

- space inversion $x \to -x$, $p \to -p$, $J \to +J$, $t \to +t$, $E \to -E$, $B \to +B$
- inverts force: $F \to -F$
- mirror=same law of physics
  - $F=ma \to -F=m(-a)$
- quantum state: $\psi \to \pm\psi$
  - *classify even and odd states*
  - photon (electric field) is odd
  - matter particles are even
  - anti-matter particles are odd



charge conjugation: *C*

- particles and anti-particles are mirrors
- both of them *fall* the same way
- interchange particles and anti-particles, and flip the sign of *E* & *B* fields: nothing changes with electromagnetism
- photon is *odd* under *C*
- It looks like the distinction between matter and anti-matter is just a convention

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charge conjugation: *C*

- particles and anti-particles are mirrors
- both of them *fall* the same way
- interchange particles and anti-particles, and flip the sign of *E* & *B* fields: nothing changes with electromagnetism
- photon is *odd* under *C*
- It looks like the distinction between matter and anti-matter is just a convention

time reversal: *T*

- can't reverse time, but we can discuss if we can reverse the motion exactly
- basically play the video backwards
- $t \to -t$、$p \to -p$、$J \to -J$、$x \to +x$、$F \to +F$
- $F=ma \to F=ma$
- It is an *anti-unitarity transformation* in quantum mechanics

possible in principle

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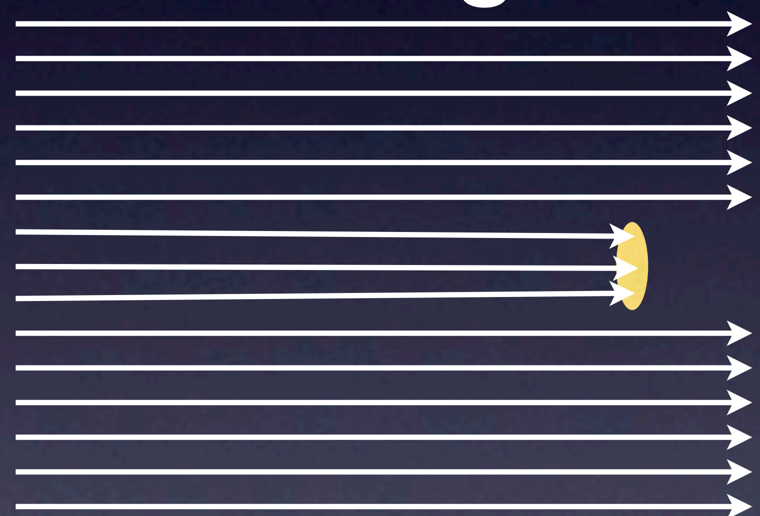
possible in principle

scattering experiments

- How do we probe microscopic world we can't see even with the best microscope?
- Uncertainty principle: $\Delta x \Delta p \geq \hbar/2$
- If we shoot a particle with a big momentum, and if gets bounced, Δp is big, and we can see small distances Δx

cross section

- scattering experiment
- You can't control your projectile precisely enough to make sure it hits the target



- probability is

  (size of the target) / (size of the beam)
- (size of the target) is called *cross section*

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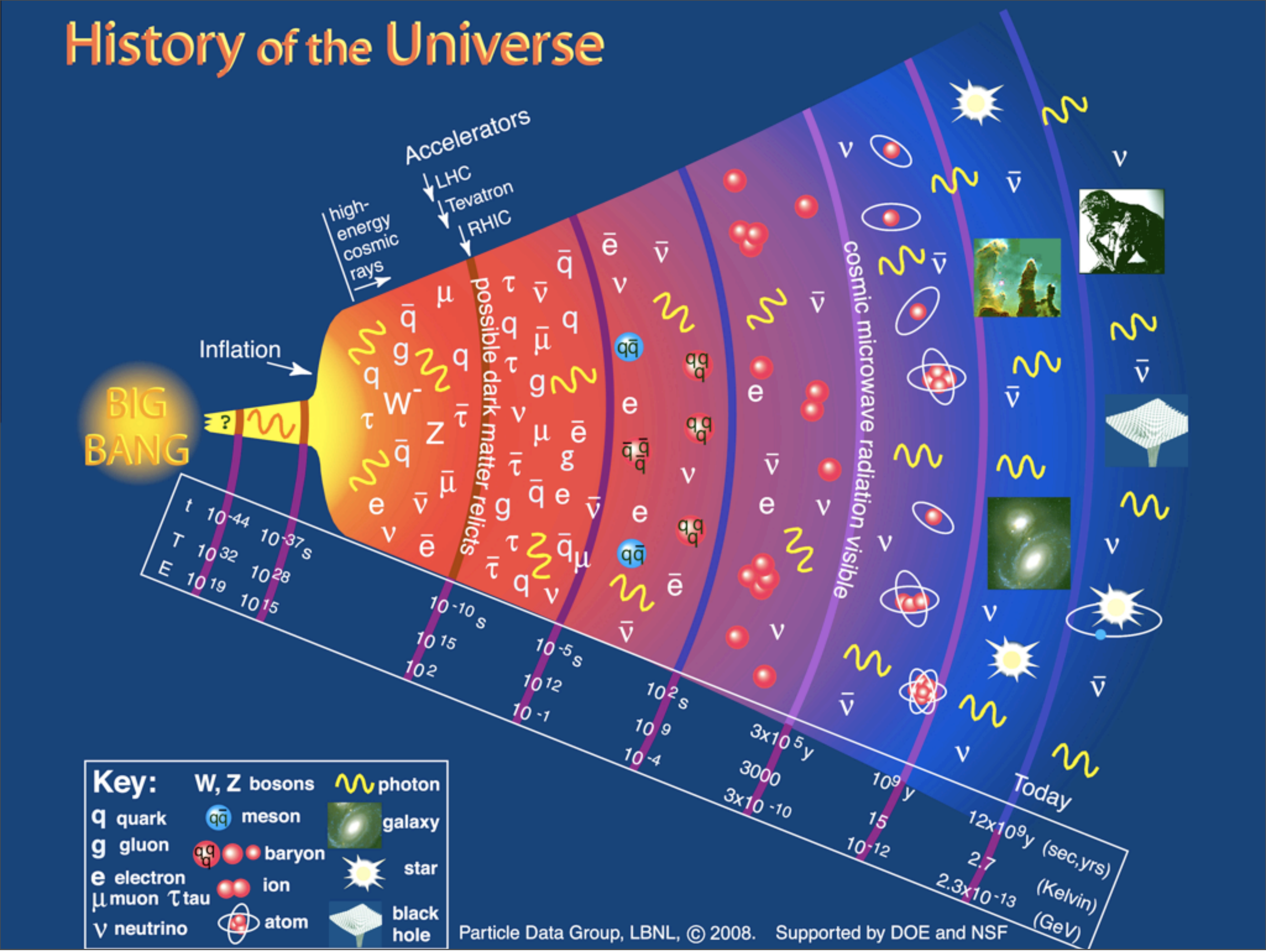
Early Universe and elementary particle

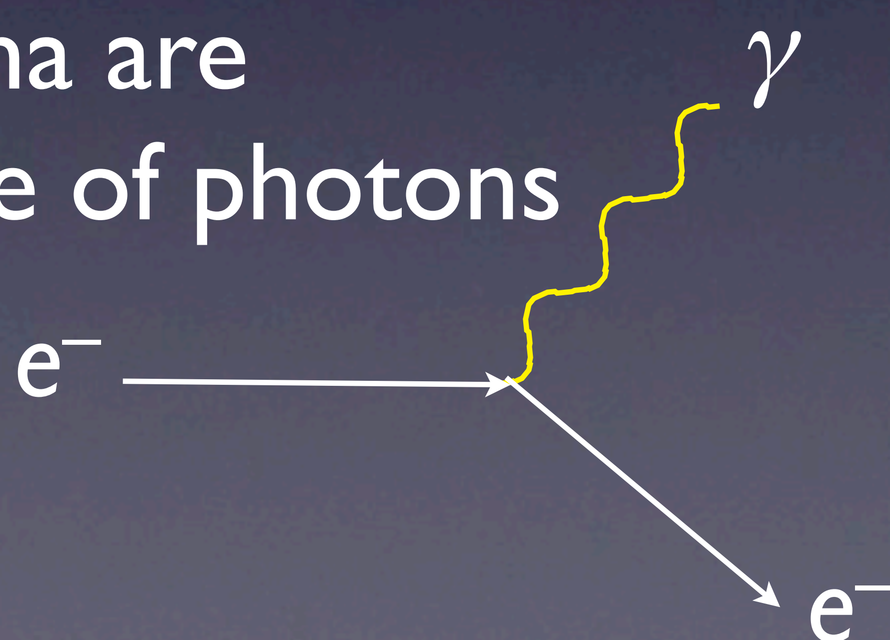
- Early Universe: high temperature T
- high energy: $E=kT$
- large momentum: $p=E/c=kT/c$
- small distance: $x=\hbar/p=\hbar c/kT$
- elementary particles or physics at short distances are very important in the early Universe!


History of the Universe
BIG BANG
Inflation
high-energy cosmic rays
Accelerators
LHC
Tevatron
RHIC
possible dark matter relicts
cosmic microwave radiation visible
Today
t
T
E
10-44
10-37 s
10 32
10 28
10 19
10 15
10 -10 s
10 15
10 2
10 -5 s
10 12
10 -1
10 2 s
10 9
10 -4
3x10 5 y
3000
3x10 -10
10 9 y
15
10 -12
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10 -13 (GeV)
Key:
W, Z bosons
photon
q quark
meson
galaxy
g gluon
baryon
e electron
ion
star
μ muon τ tau
ν neutrino
atom
black hole
Particle Data Group, LBNL, © 2008. Supported by DOE and NSF

Quantum Electro Dynamics (QED)

Maxwell

- electricity and magnetism unified
- predicts electromagnetic wave=light
- it is *photon* in QED
- all electromagnetic phenomena are described in term of exchange of photons



Rutherford experiment

- bombard gold foil with alphas
- *When I fired a bullet at a Kleenex tissue, the bullet came back!*
- shows electric charge is concentrated at the center of a gold atom
- but when alpha gets too close, it shows deviation from theory
- nucleus ~ 10^{-12}cm

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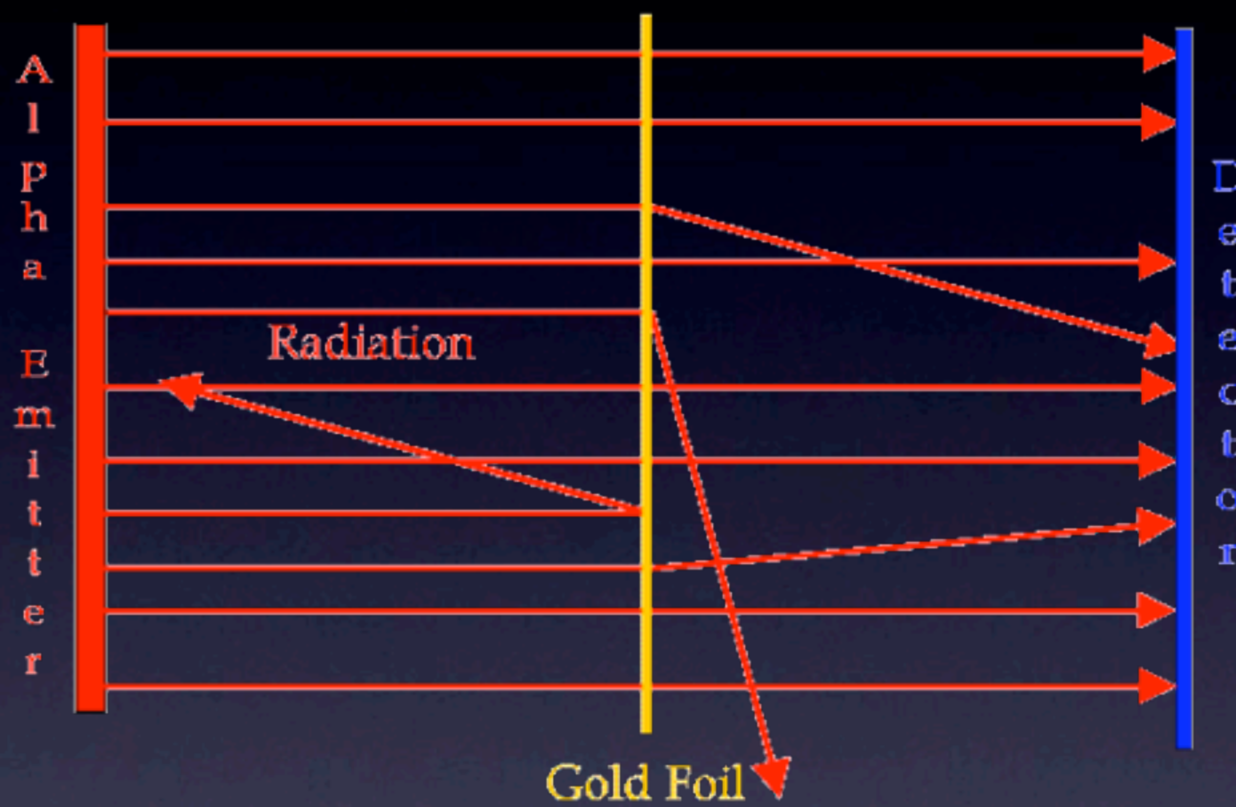

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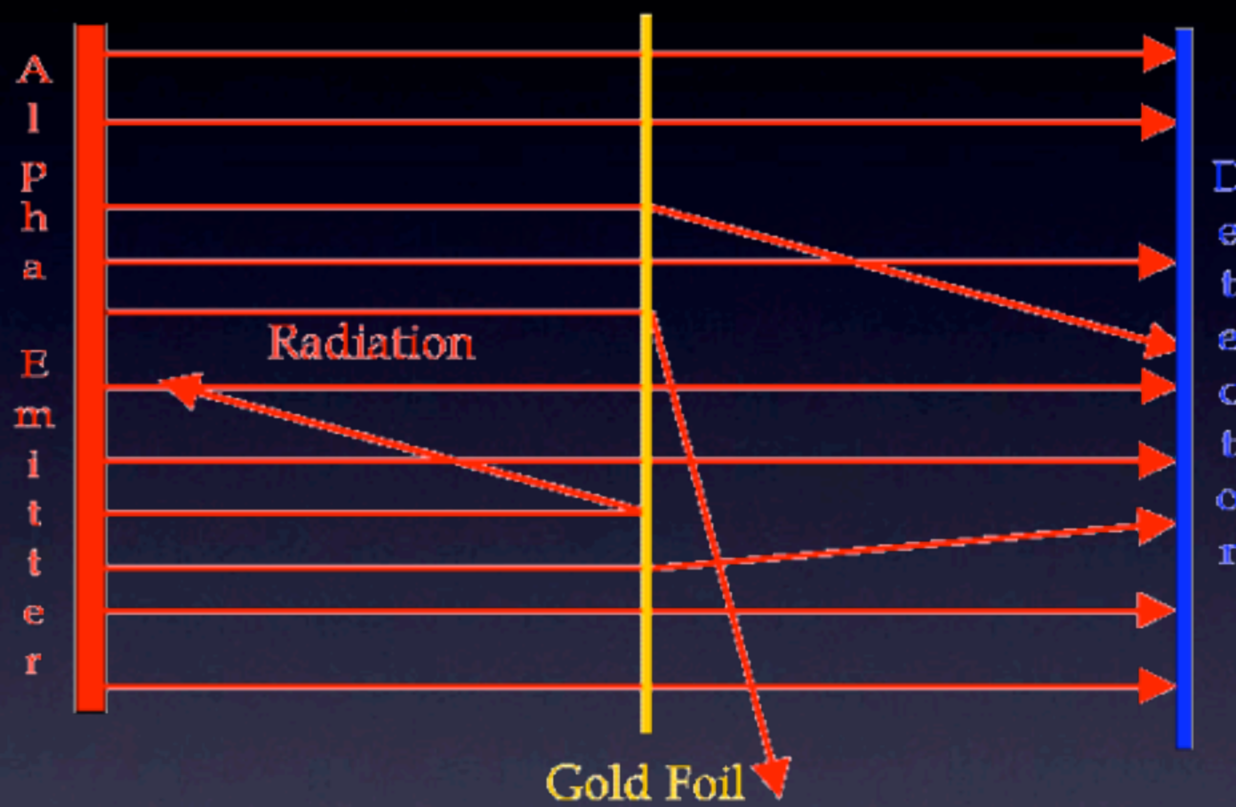
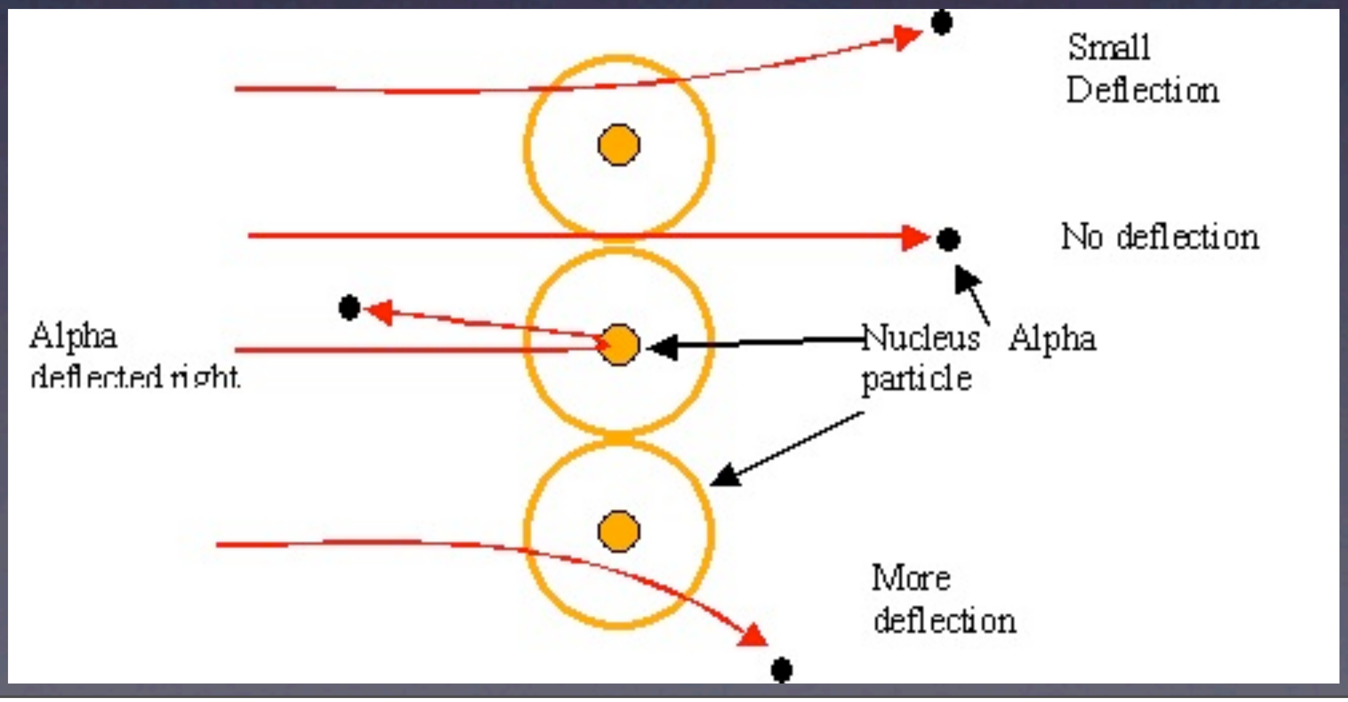
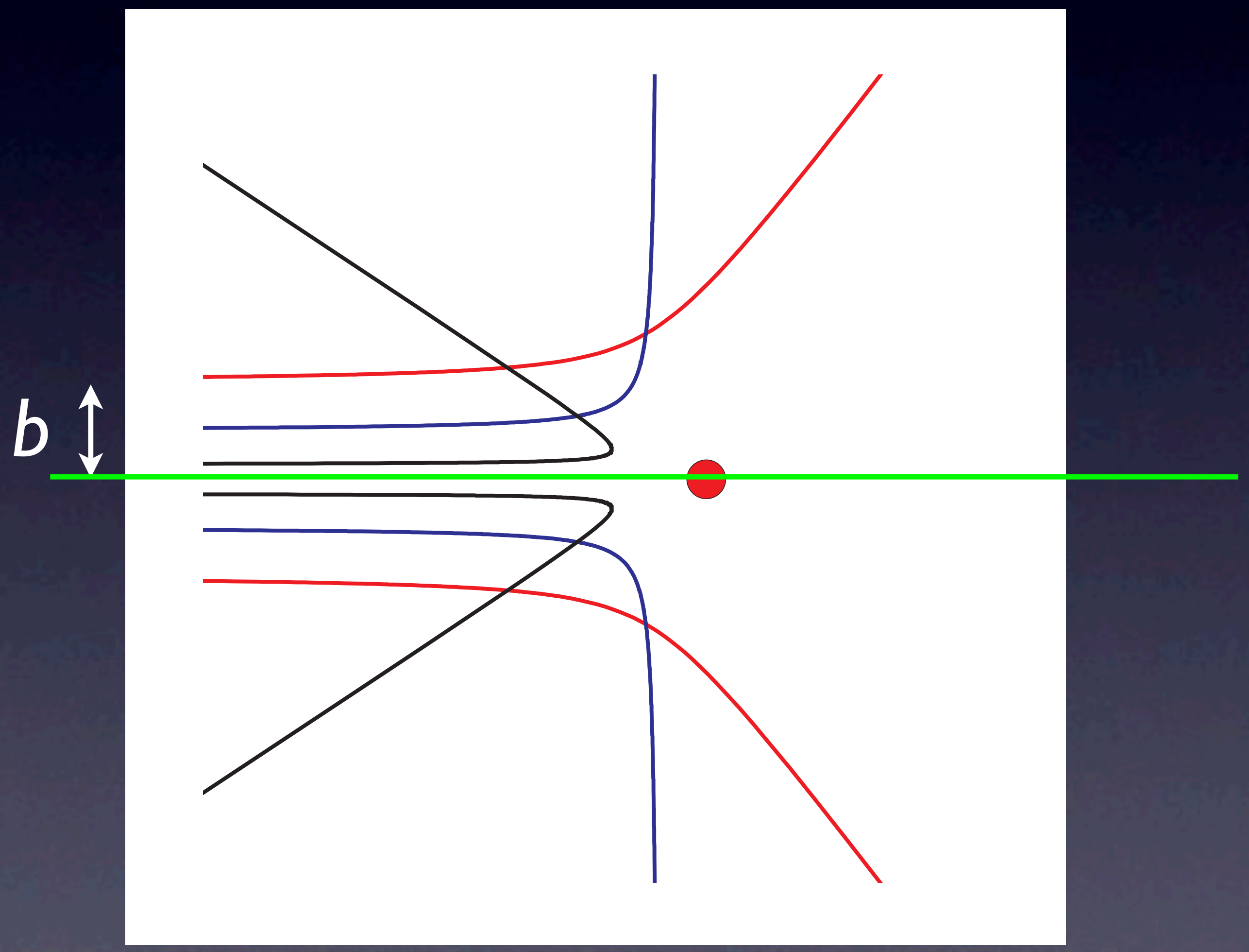




Rutherford scattering

- Classically, you solve the equation of motion of the alpha particle for a fixed *p*, with varying impact parameter *b*
- The differential cross section is

$$\frac{d\sigma}{d\cos\theta} \propto \frac{1}{\sin^4\theta/2}$$



Virtual photon

- Coulomb potential around a charged particle is a cloud of *virtual photons*
- the charge is emitting a virtual photon all the time, costing the energy of $\Delta E = c\,p$
- the smaller the momentum, it costs less energy and can survive longer $\Delta t \approx \hbar / c\,p$, and can go further $\Delta x \approx c\Delta t \approx \hbar / p$, basically one wavelength away from the source

Quantum Description

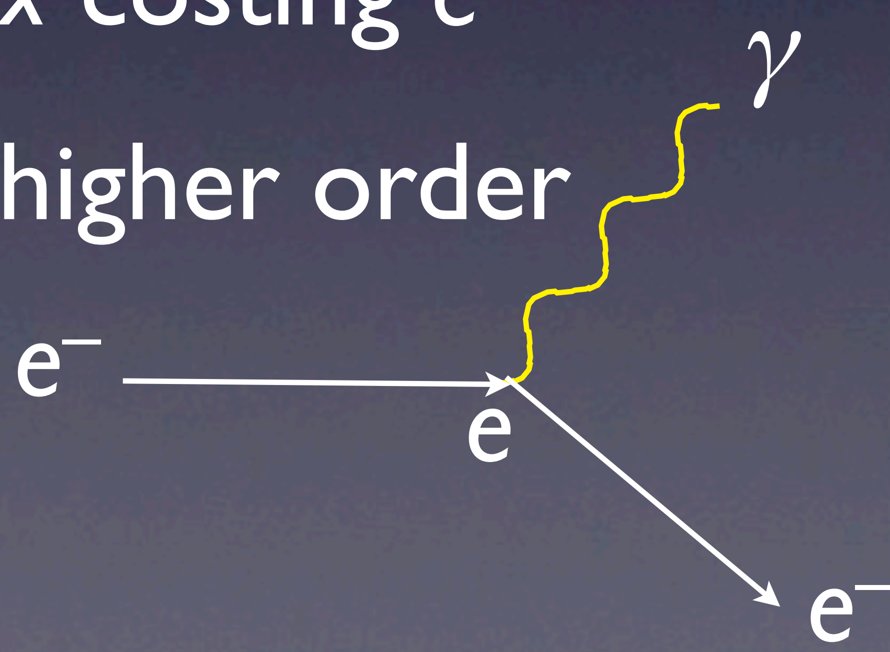
- The nucleus is emitting a virtual photon all the time
- One with large λ (small $q=h/\lambda$) does not cost much ΔE and goes far
- One with small λ (large $q=h/\lambda$) costs much ΔE and does not go far
- photon momentum *kicks* the alpha

$$\begin{aligned} q^2 &= -\vec{q}^2 = -|\vec{p}-\vec{p}'|^2 \\ &= -2|\vec{p}|^2(1-\cos\theta) \end{aligned}$$

- photon propagator goes as $1/q^2 \propto 1/(1-\cos\theta)$
- The cross section goes as $1/(1-\cos\theta)^2 = 1/\sin^4(\theta/2)$!

Feynman diagram

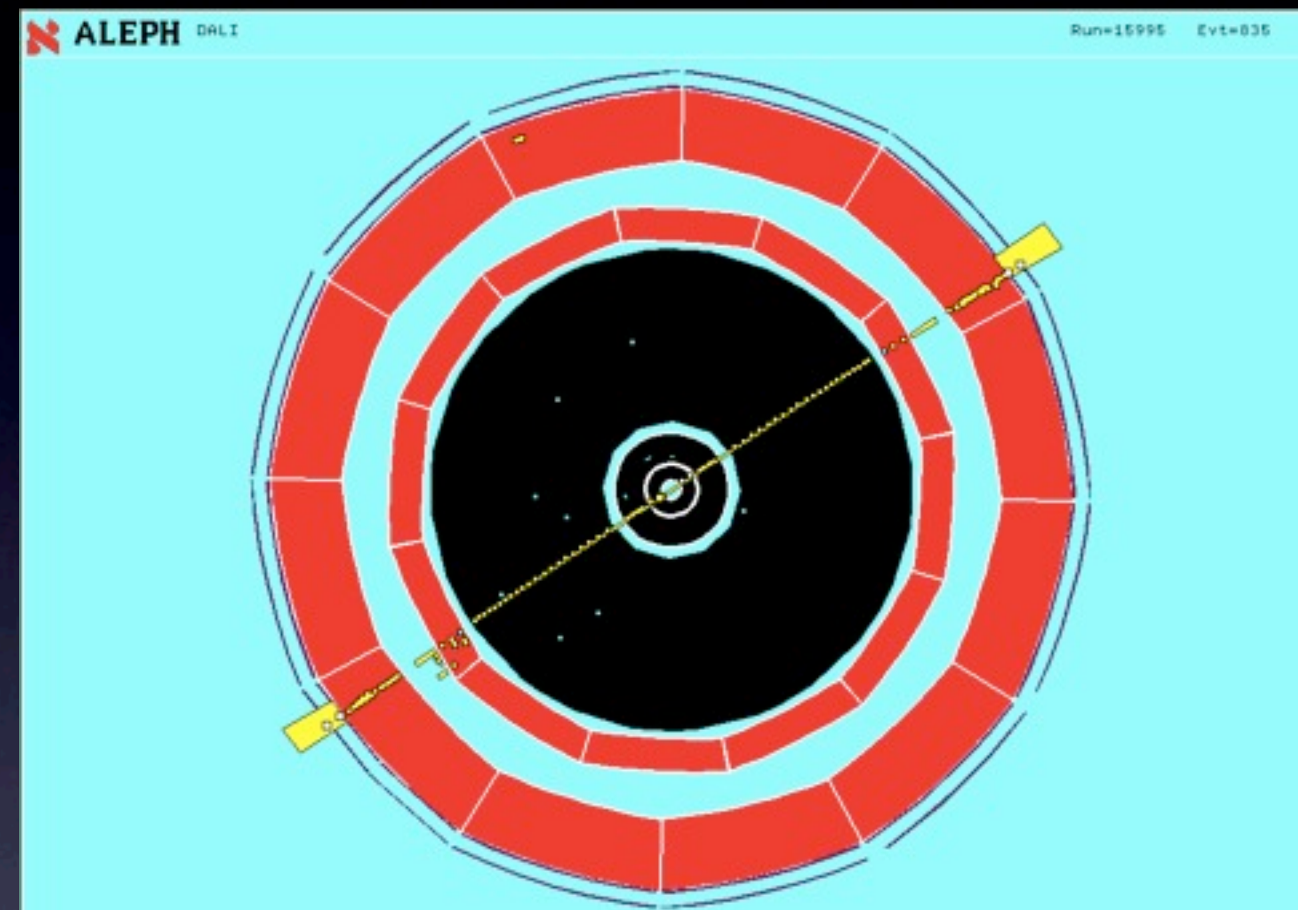
- exchange virtual particles for scattering
- anti-particles are particles going backward in time
- all you need to know about the electromagnetism is this *vertex* costing e
- diagrams with more vertices: higher order in $\alpha = e^2/4\pi = 1/137$

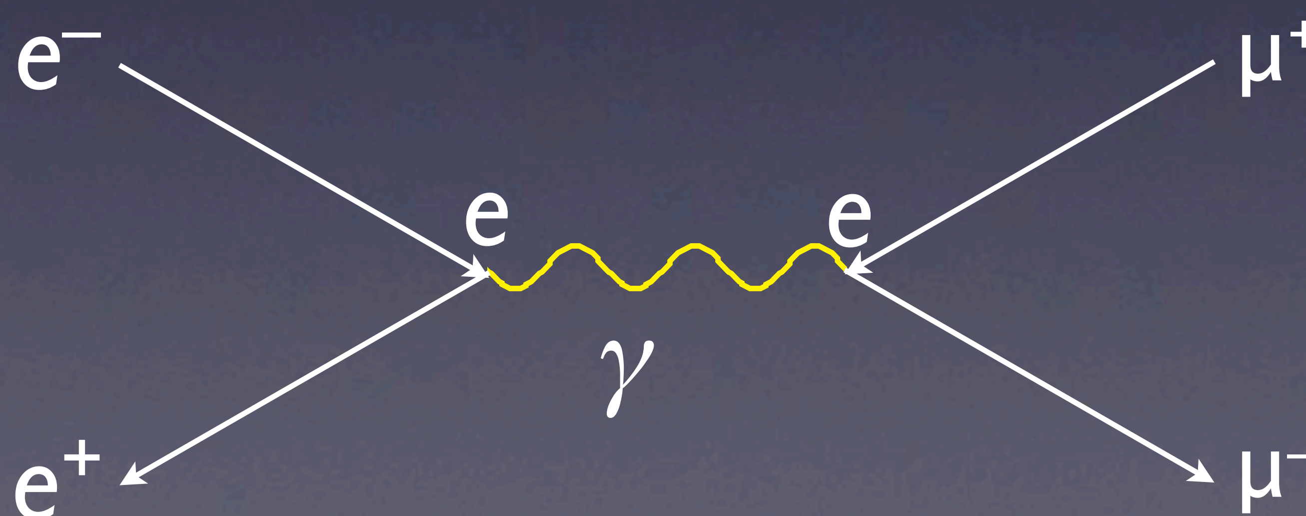


Useful formula

- $e^+e^- \to \mu^+\mu^-$
- cross section is

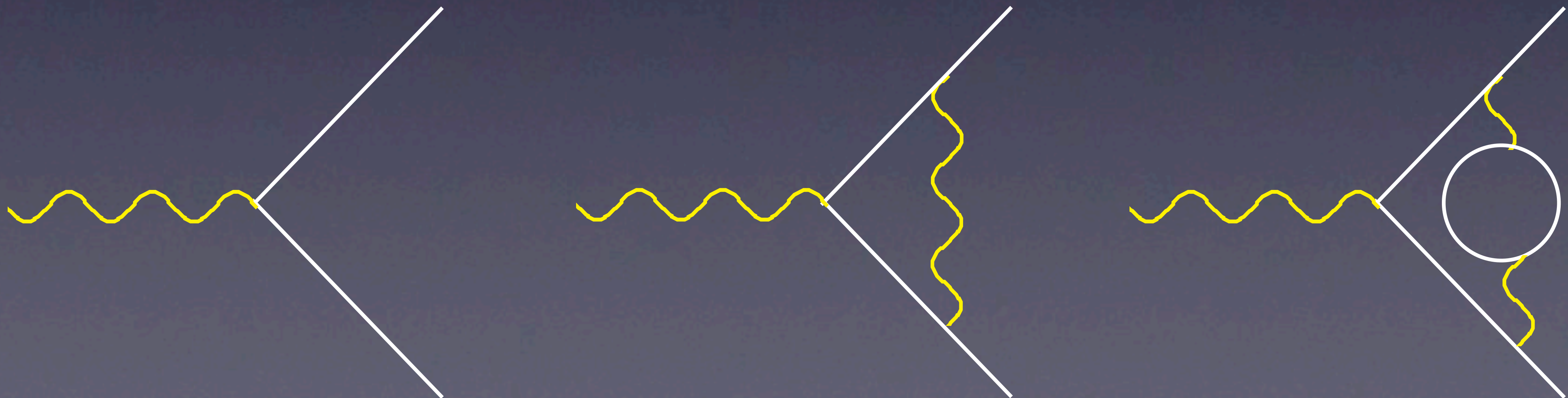
$$\sigma = \frac{4\pi\alpha^2}{3s} = \frac{86.8\ \text{fb}}{s/\text{TeV}^2}$$





electron magnetic moment

- g=2 is the prediction by Dirac
- in QED, there are higher order corrections
- $O(\alpha)$: 1 diagram
- $O(\alpha^2)$: 7 diagrams
- $O(\alpha^3)$: 72 diagrams
- $O(\alpha^4)$: 891 diagrams



8th order $O(\alpha^4)$

- 891 diagrams computed numerically using a supercomputer

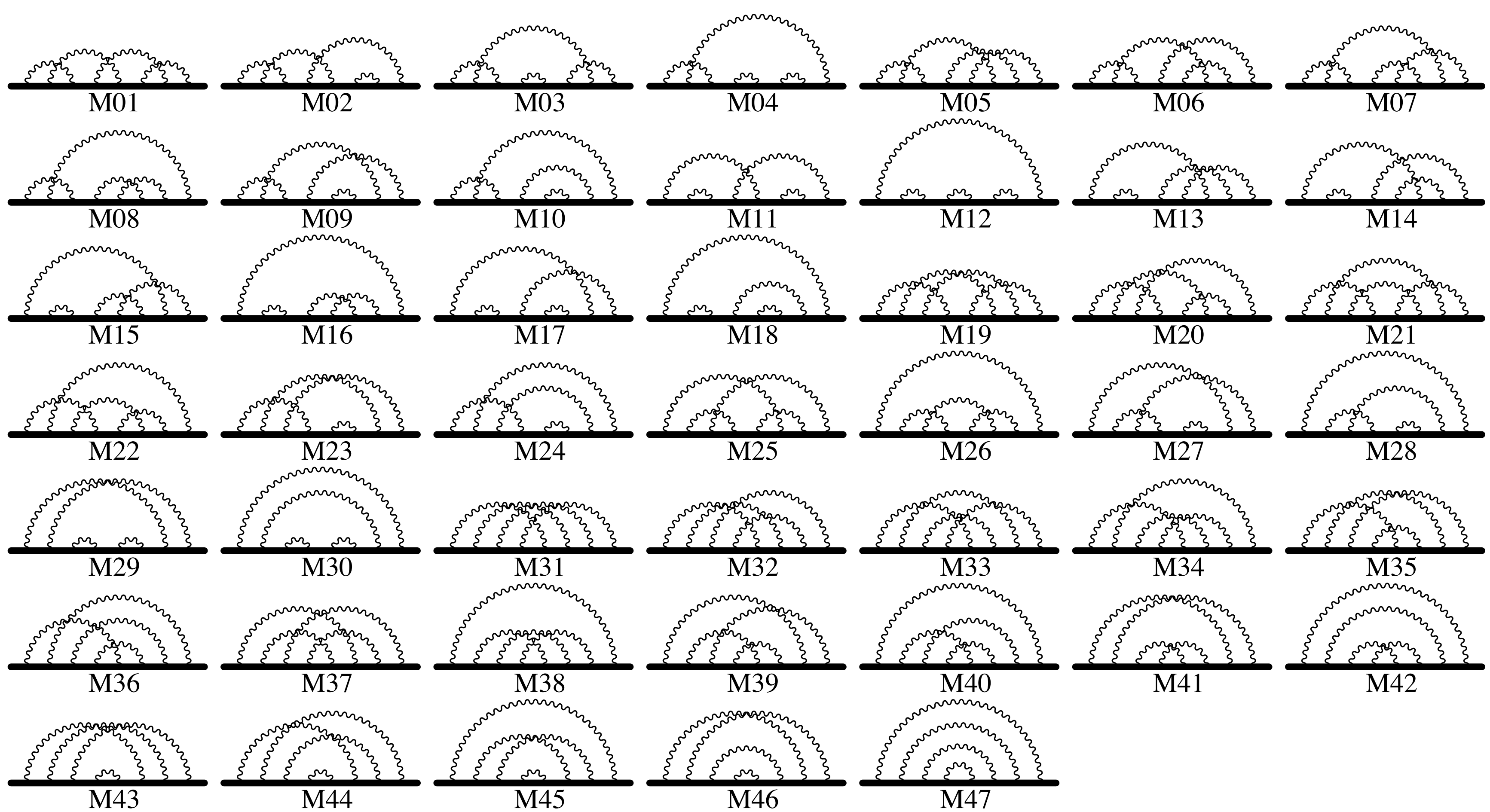


FIG. 1: Eighth-order Group V diagrams represented by 47 self-energy-like diagrams M_{01}–M_{47}.

The answer

$$\frac{1}{2}g = 1 + A_2\frac{\alpha}{\pi} + A_4\left(\frac{\alpha}{\pi}\right)^2 + A_6\left(\frac{\alpha}{\pi}\right)^3 + A_8\left(\frac{\alpha}{\pi}\right)^4 + \cdots$$

$$A_2 = \frac{1}{2}$$

$$A_4 = \frac{197}{144} + \left(\frac{1}{2} - 3\ln 2\right)\zeta(2) + \frac{3}{4}\zeta(3) = -0.328\ 478\ 965\ 579$$

$$A_6 = \frac{83}{72}\pi^2\zeta(3) - \frac{215}{24}\zeta(5) - \frac{239}{2160}\pi^4 + \frac{139}{18}\zeta(3) - \frac{298}{9}\pi^2\ln 2$$
$$+\frac{17101}{810}\pi^2 + \frac{28259}{5184} + \frac{100}{3}\left[\left(\mathrm{Li}_4\left(\frac{1}{2}\right) + \frac{1}{24}\ln^4 2\right) - \frac{1}{24}\pi^2\ln^2 2\right]$$
$$= 1.181\ 241\ 456\ 587\ldots$$

$$A_8 = -1.914\ 4\ (35)$$

The data

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- 2008 measurement by Harvard group

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- the theoretical value is
  $g_e/2$ = 1.001 159 652 182.79 (0.10)(0.31) (7.71)
- The biggest error is that we don't know α well enough

comparison

PHYSICAL REVIEW A **74**, 052109 (2006)

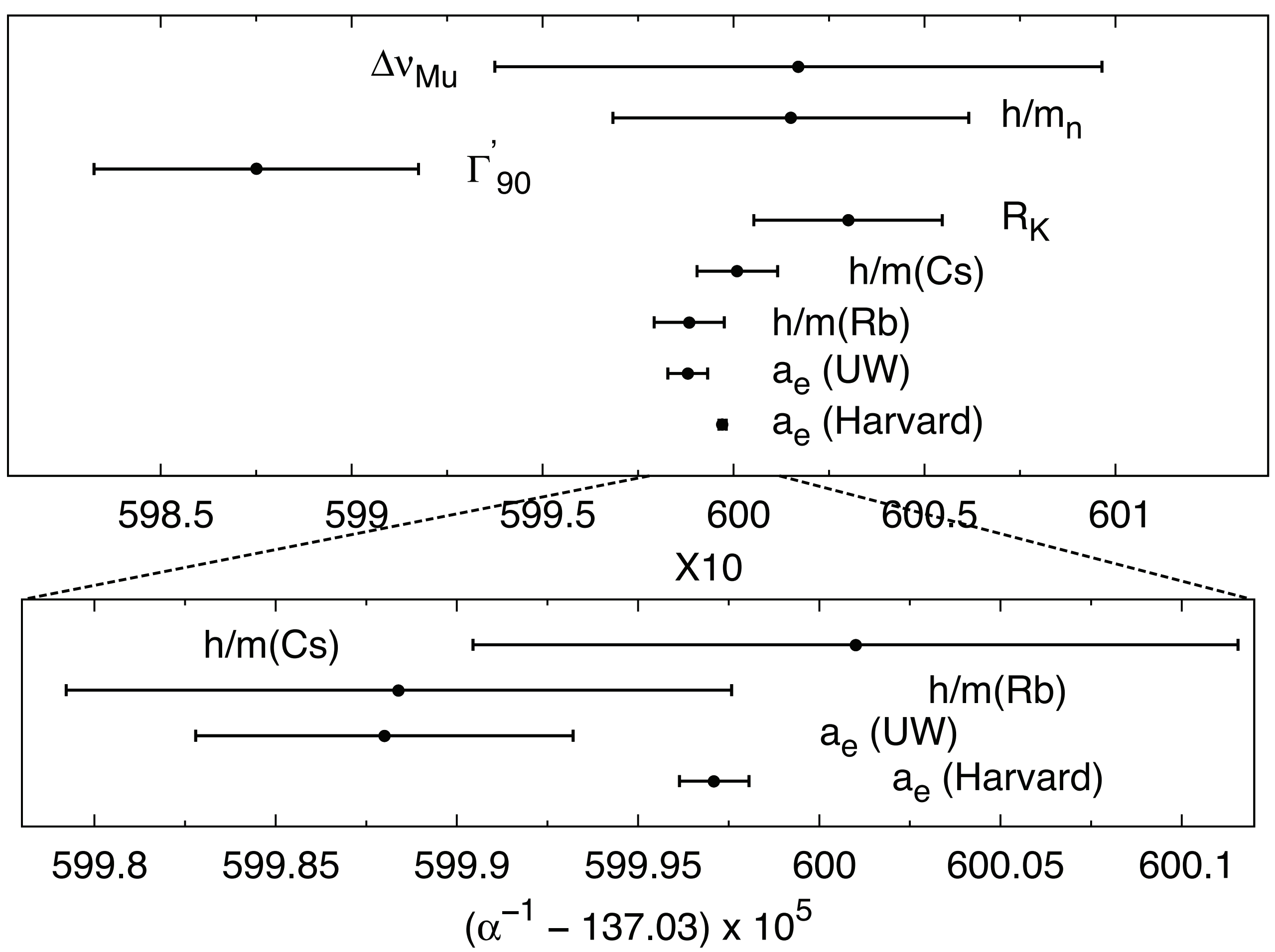
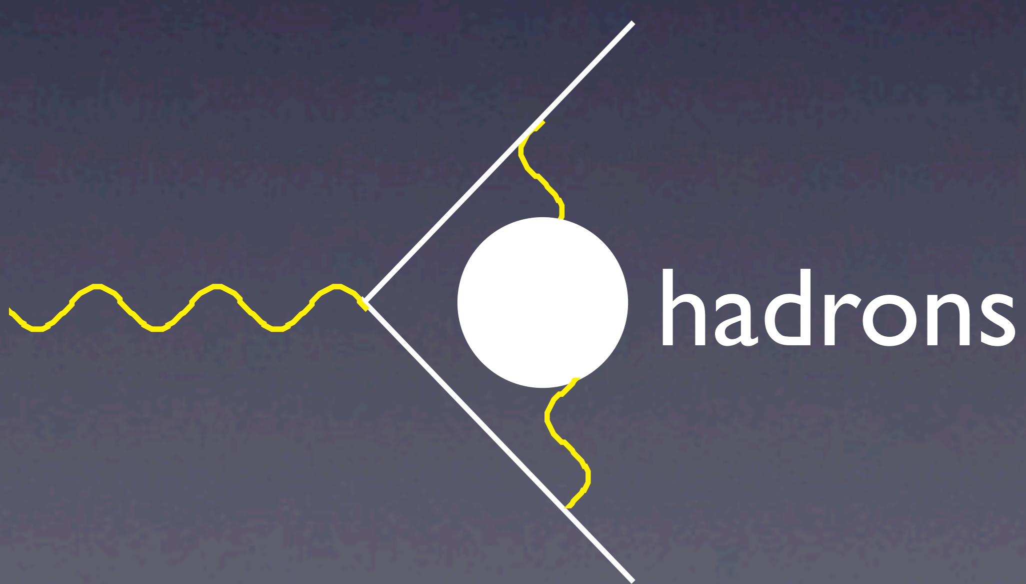
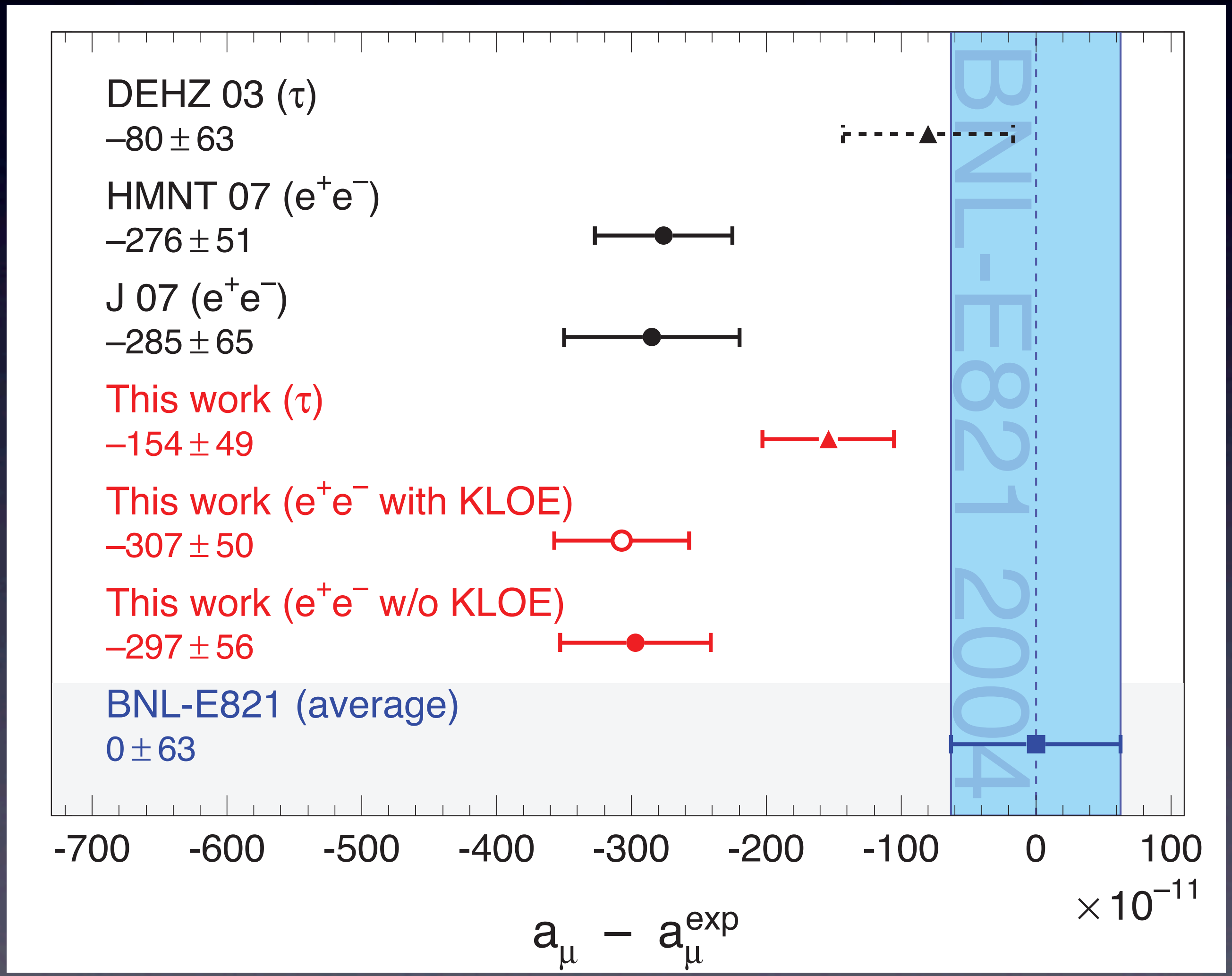


FIG. 18. Comparison of our measurement [h/m(Rb)] with the measurements used for the 2002 CODATA adjustment [1] and the measurement of Ref. [5] (Harvard).

hot topic: muon g–2

- muon is basically the same as electron, but heavier
- important contribution from hadrons
- Calculated based on data in e+e- colliders



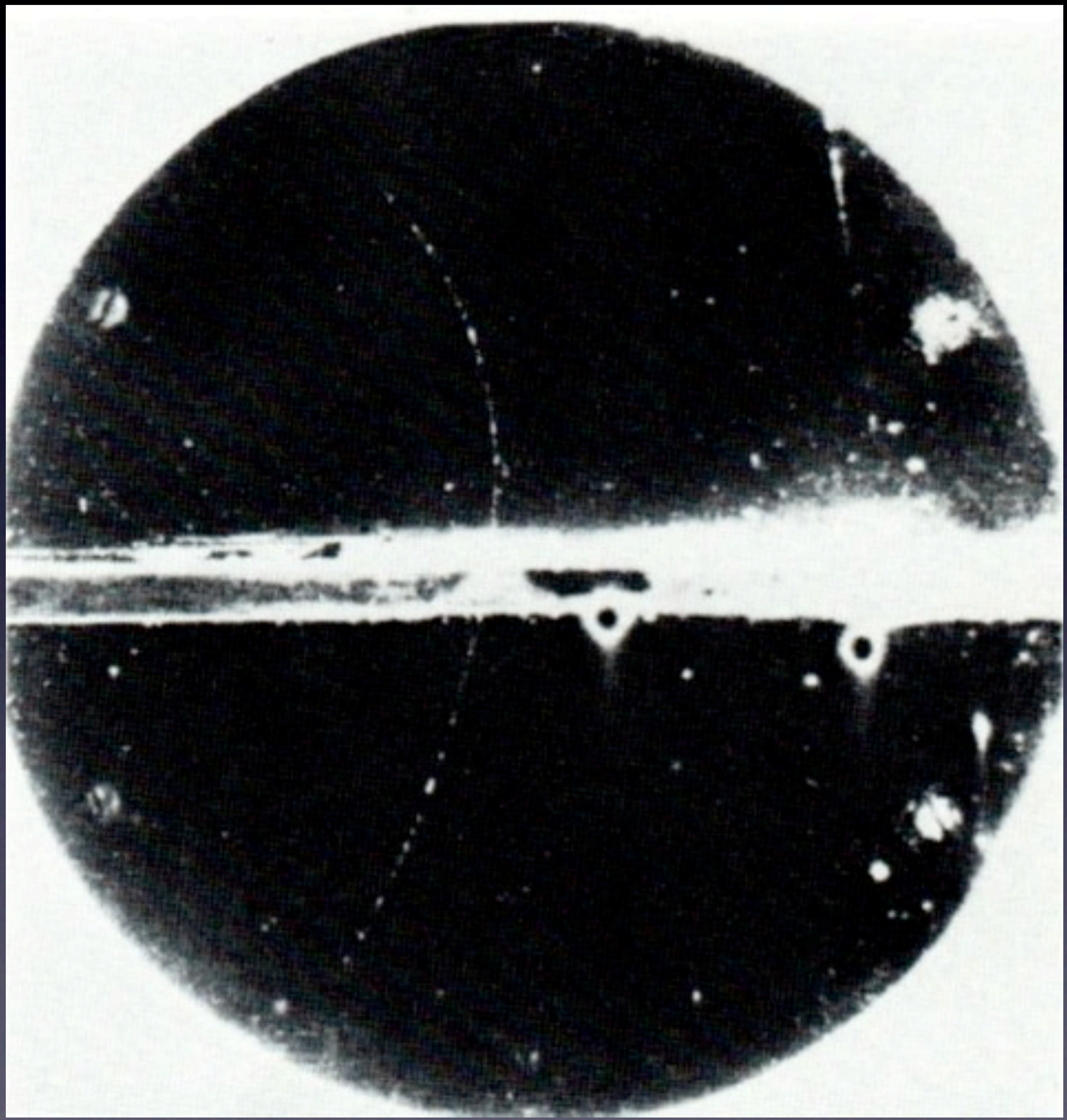


arXiv:0906.5443

Strong Interaction
Quantum
ChromoDynamics

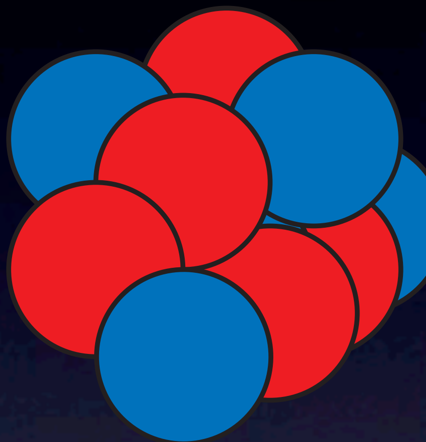
Baryon Number

- In 1932 Anderson discovered positron using cloud chamber exposed to cosmic rays
- Why don't we see $p \rightarrow e^+ + \gamma$?
- Stückelberg made up a new conservation law: #baryon=#p+#n
- "baryon" means heavy, at that stage p and n
- "lepton" means light, at that stage e^+ and e^-



Now, best limit is $\tau(p \rightarrow e^+ + \pi^0) > 8.2 \times 10^{33}$ years (SuperK)

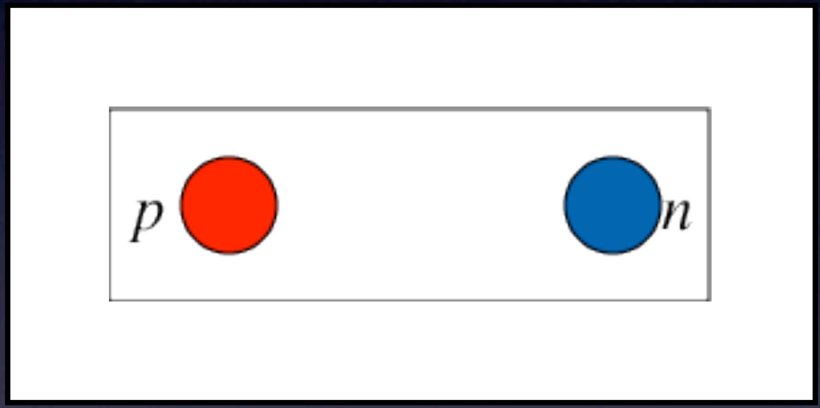
Basic properties of nuclei



- Z protons and $(A\text{–}Z)$ neutrons
- $B \approx 16\text{MeV} \times A$
- $R \approx 1.12\text{fm} \times A^{1/3}$
- *cf.* Coulomb energy $\approx 0.7\text{MeV} \times Z^2/A^{1/3}$
- something is keeping the nuclei from falling apart due to Coulomb repulsion among p's
- 1fm is the range of the force, not much beyond the size of nucleons. Basically nucleons shoulder-to-shoulder

Yukawa theory

- assume the force carrier particle has a finite mass m
- It costs a minimum energy $\Delta E > mc^2$ to emit the virtual massive particle
- We need to give it back within $\Delta t \approx \hbar / \Delta E$
- It cannot go beyond $c\Delta t \approx \hbar c / \Delta E < \hbar c / mc^2$
- the range of the force is then $\hbar / mc$
- assuming this is 2fm, we need $m \approx 100\text{MeV}/c^2$
- the mass is somewhere between "lepton" (electron) and "baryon" (nucleon) and was called "meson"



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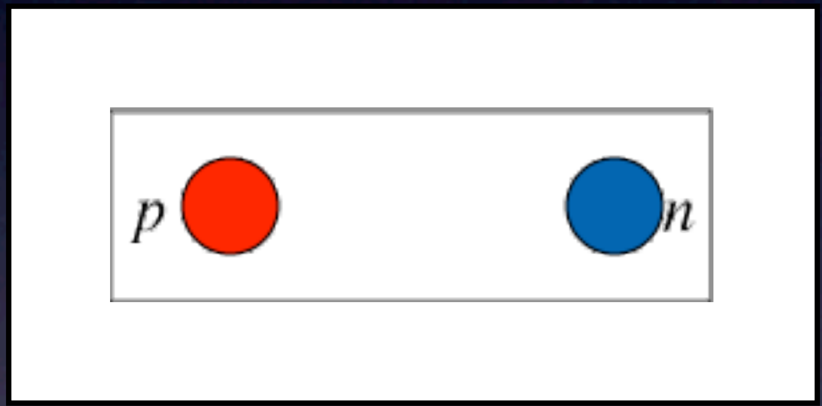

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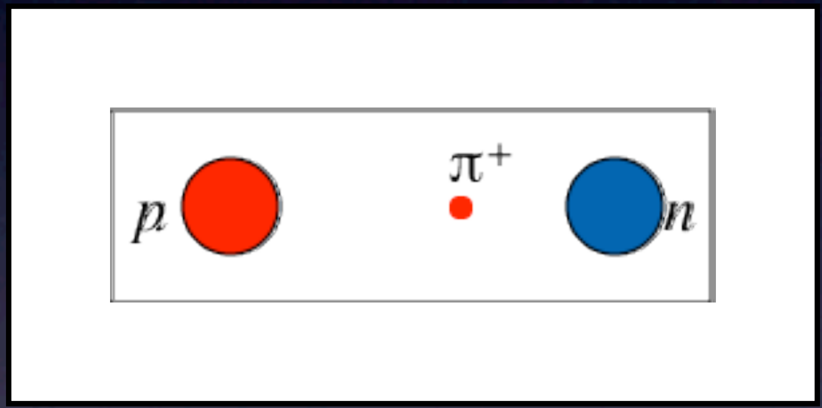

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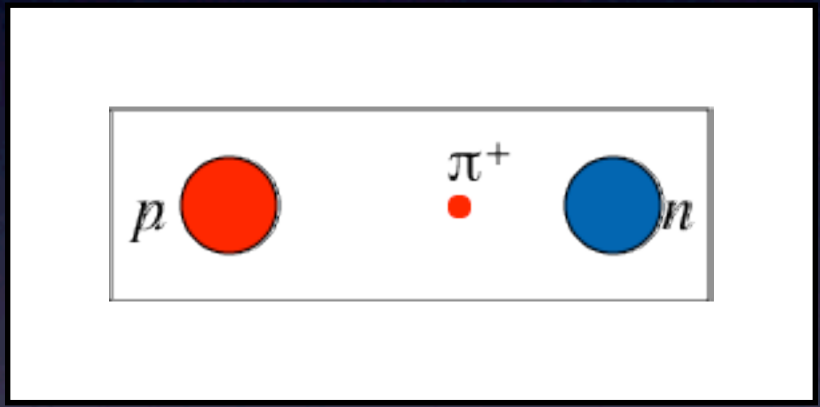

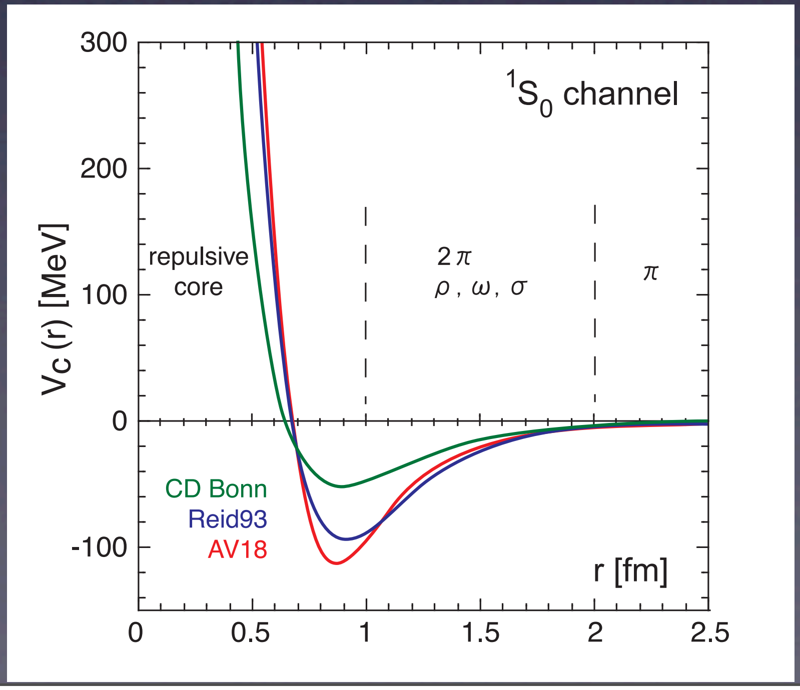

The Andes

- It was confusing when muon was discovered at the mass range, but does not do strong interaction
- Maybe there is one more?
- look for more *mesons* on top of the Andes
- there was!
- cosmic rays interact at15-20km alititude
- $p+A \rightarrow \pi^+ + X$, $\pi^+ \rightarrow \mu^+ X$
- $\tau(\pi^+)=0.026\mu sec$
- $\tau(\mu^+)=2.2\mu sec$
- then muons reach the surface thanks to time dilation
- but on high mountains pions are still "alive"

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$c\,\tau(\mu^+)$=660m << 10km!

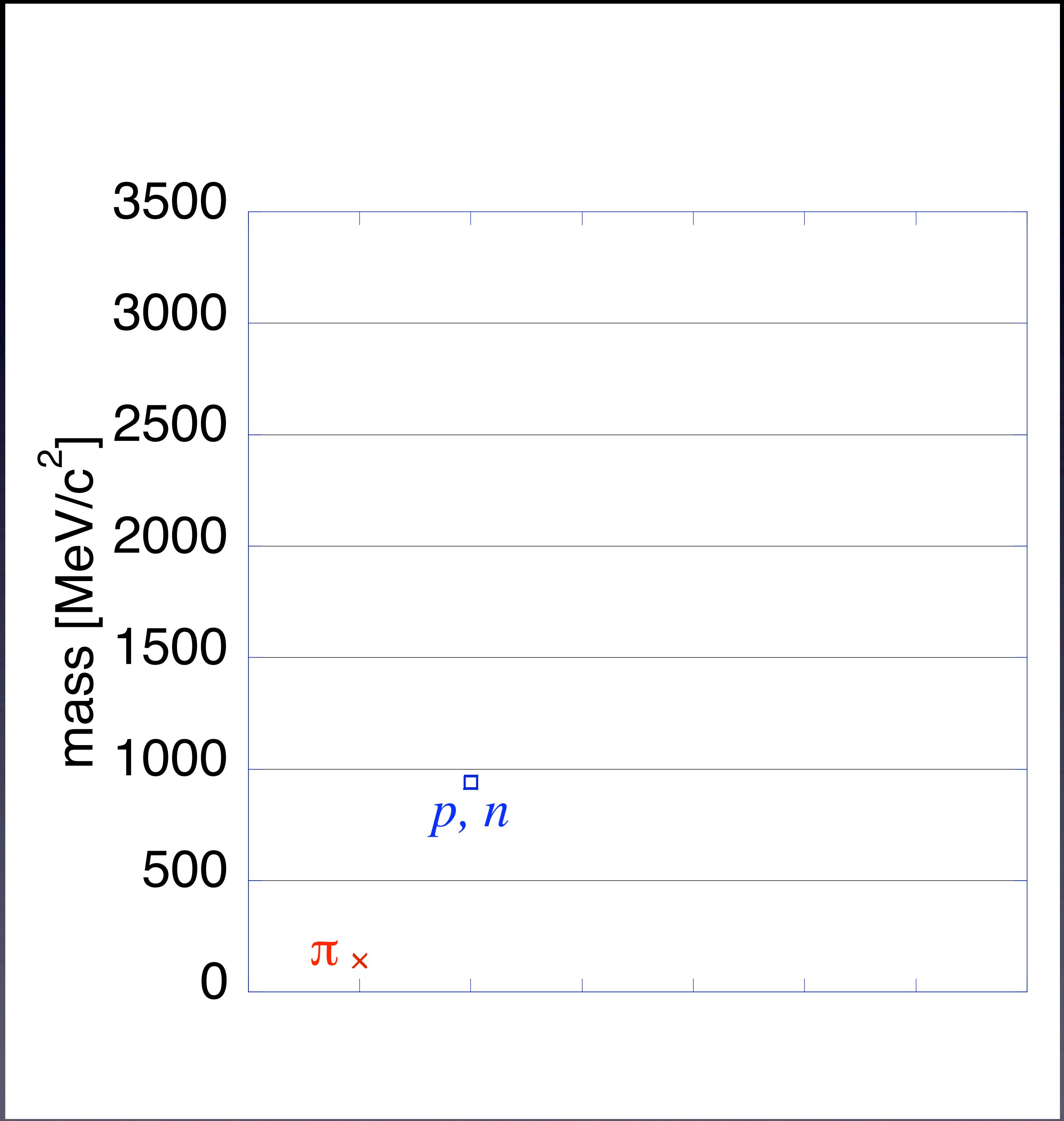
$c\,\tau(\pi^+)$=7.8m

$\gamma\beta > 1000$

$E\,(\pi^+) = \gamma\, m\,(\pi^+) > 100$ GeV!

hadrons

- But this was just the beginning
- soon many many particles discovered that participate in the strong interaction
- *baryons* and *mesons*
- A big mess!
- collectively called *hadrons* (thick particles)



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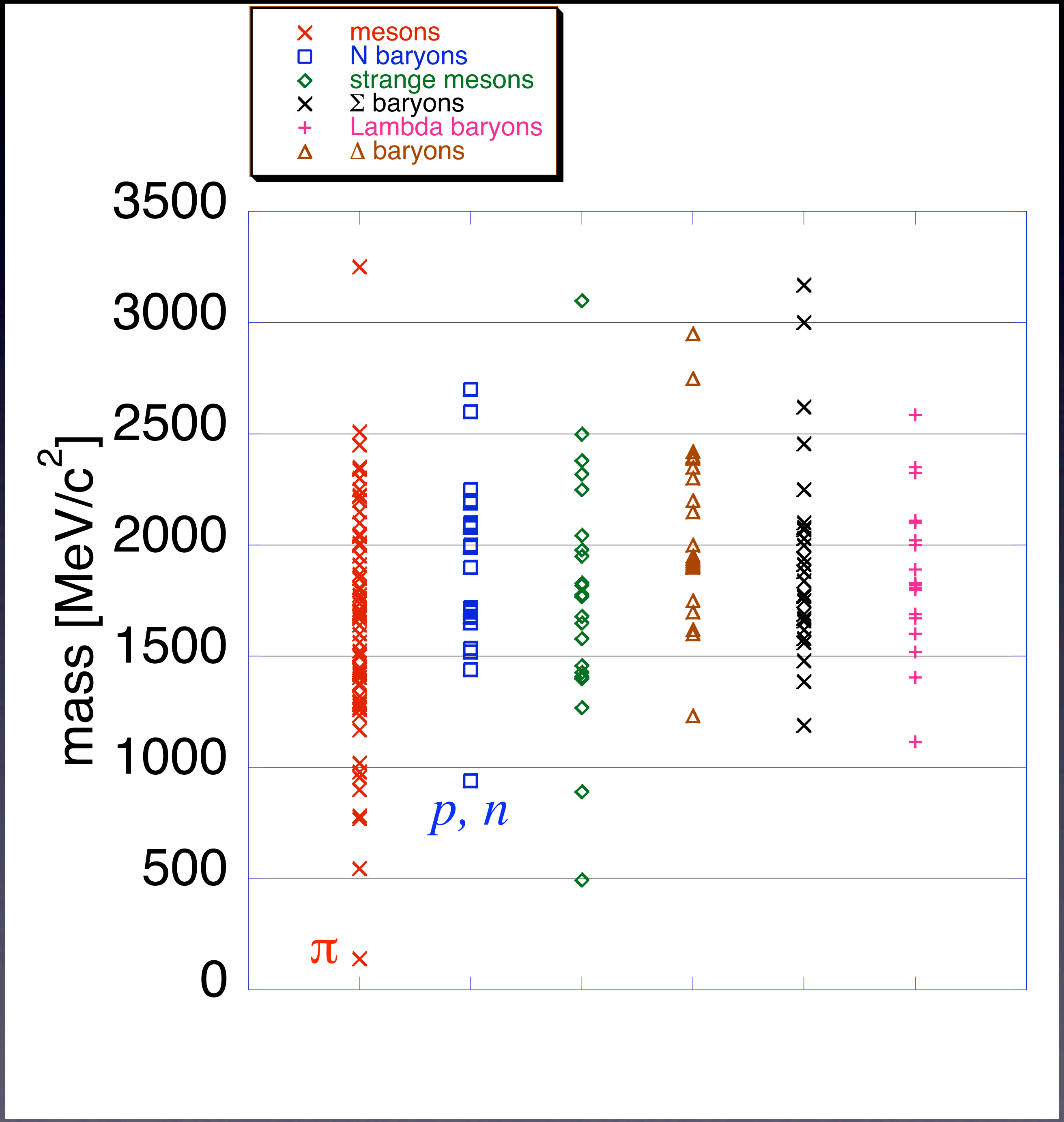

resonance

πp scattering

- πp scattering expt
- cross section goes *very* big at a particular energy
- resonance: new particle $\pi p \to \Delta \to \pi p$
- the width of the resonance ΔE is $\hbar/\tau$
- VERY short-lived $\tau \sim 10^{-23}$sec!

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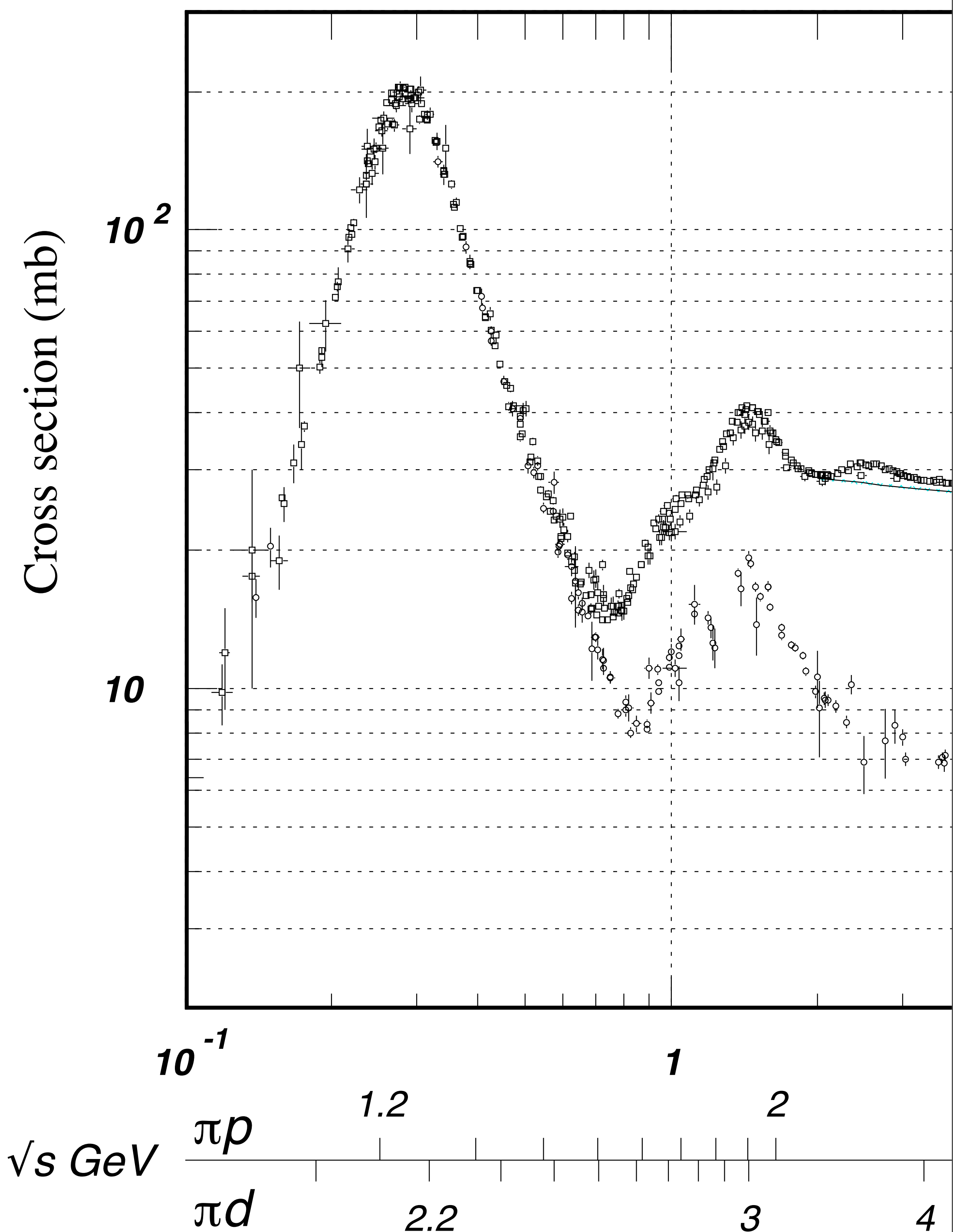
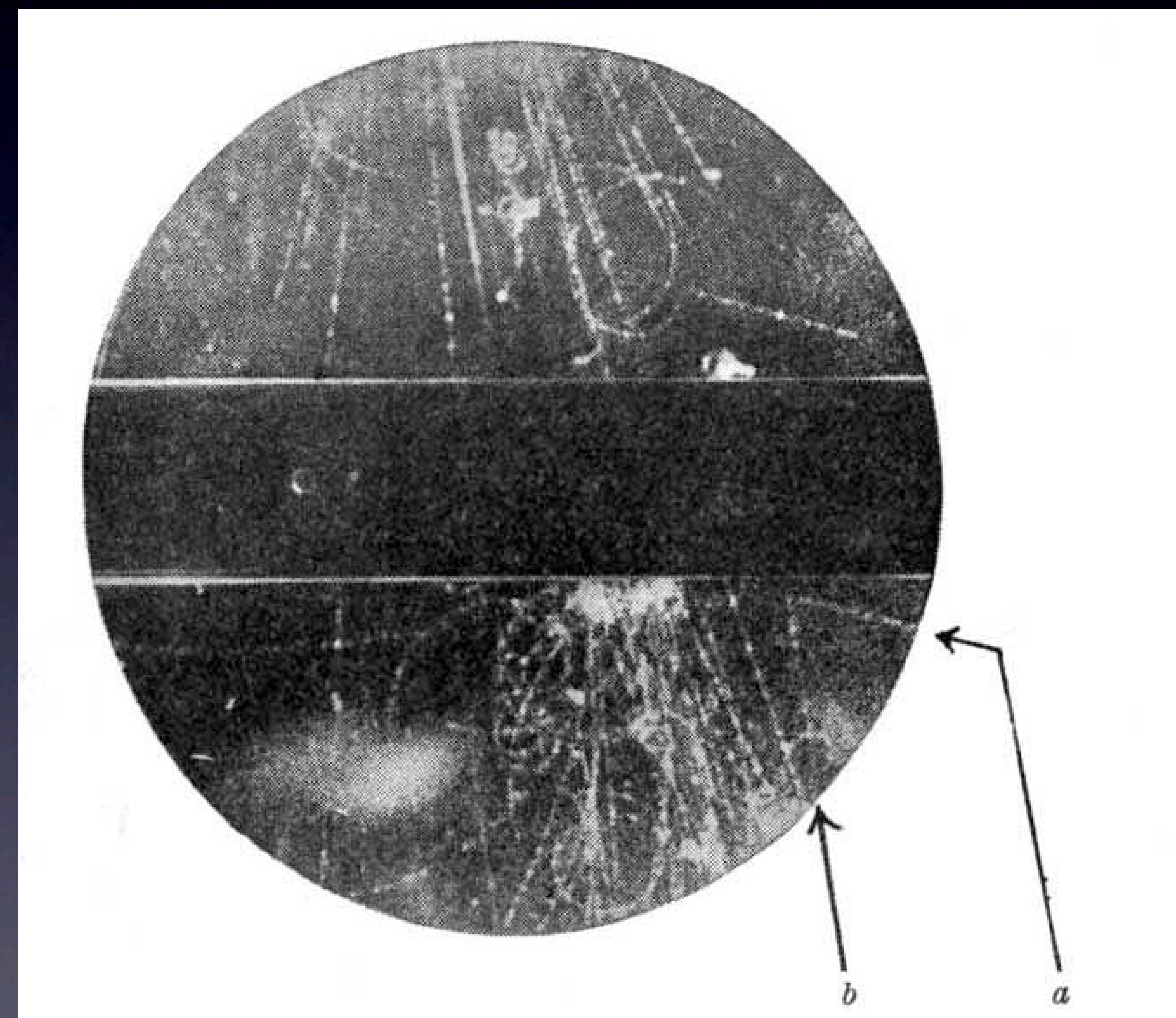


V-particles

- produced in pairs K^+ or Σ^+
- somehow "long-lived" $\tau \sim 10^{-10}$sec
- Nishijima, Gell-Mann
- produced in pairs by strong interaction because they carry a new quantum number +1 and –1
- hence can't decay by strong interaction
- *"strangeness"*



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Standard Model 3

CERN Summer Student Programme
July 22, 2009

Hitoshi Murayama (IPMU Tokyo & Berkeley)

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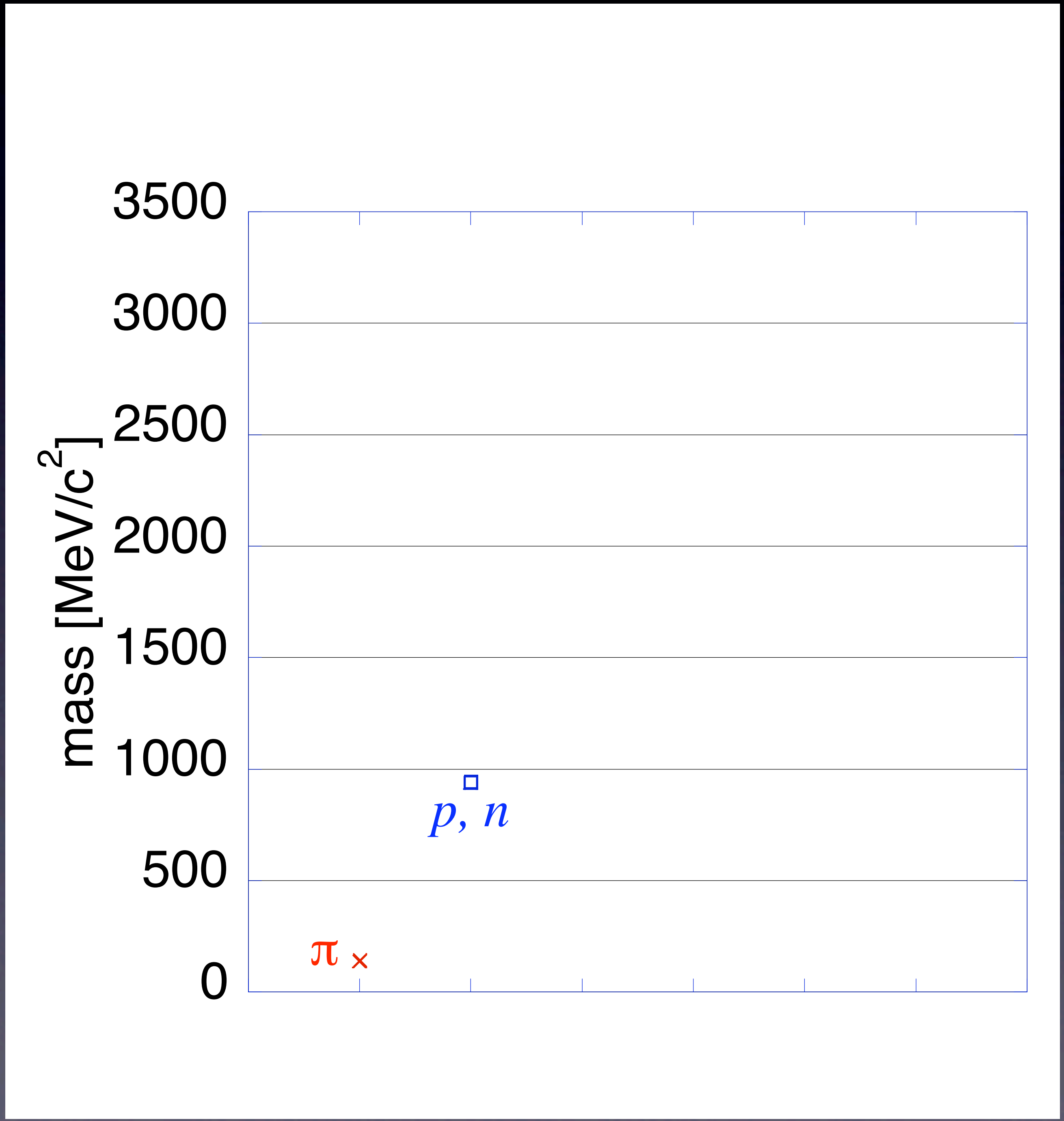

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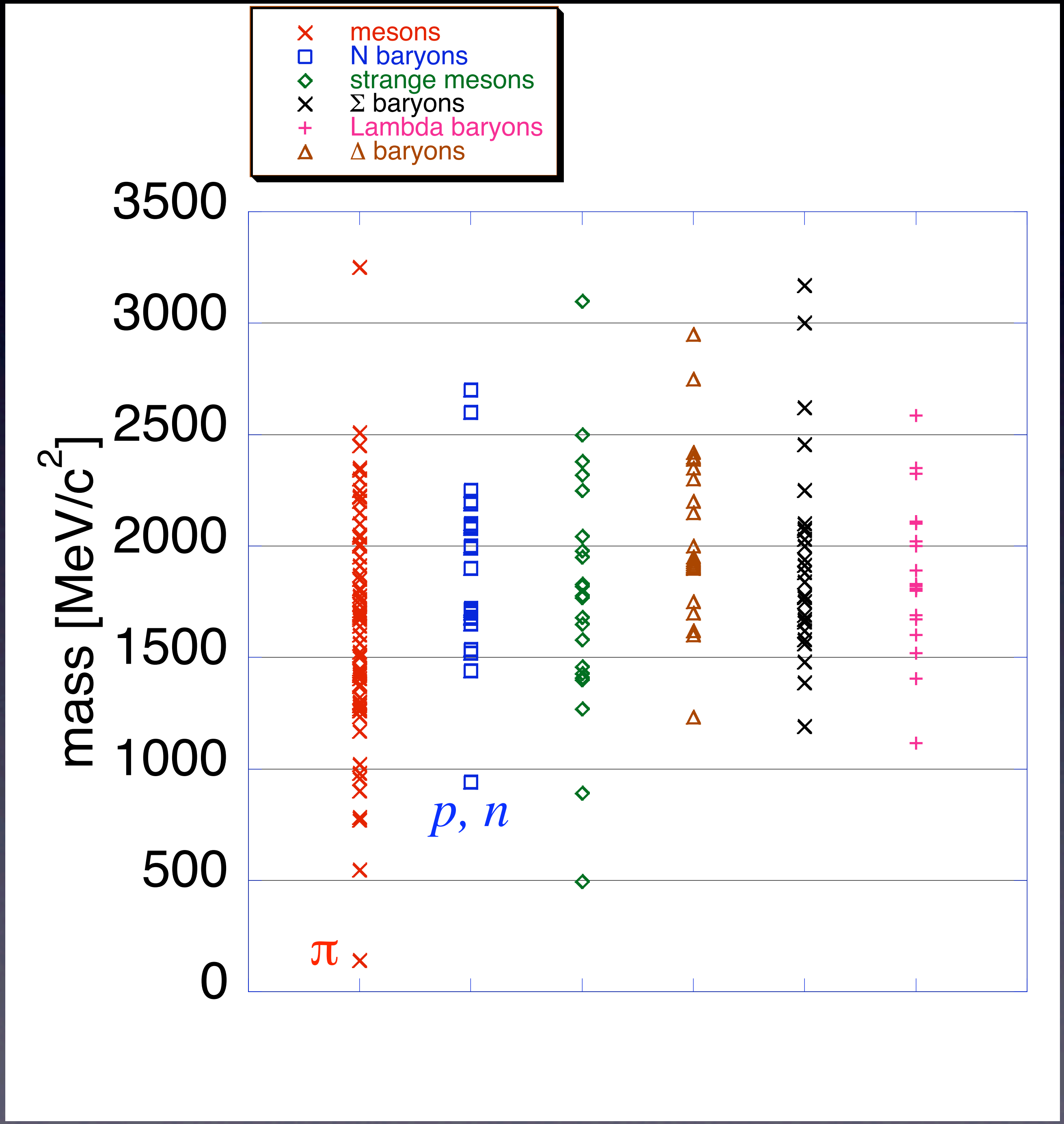

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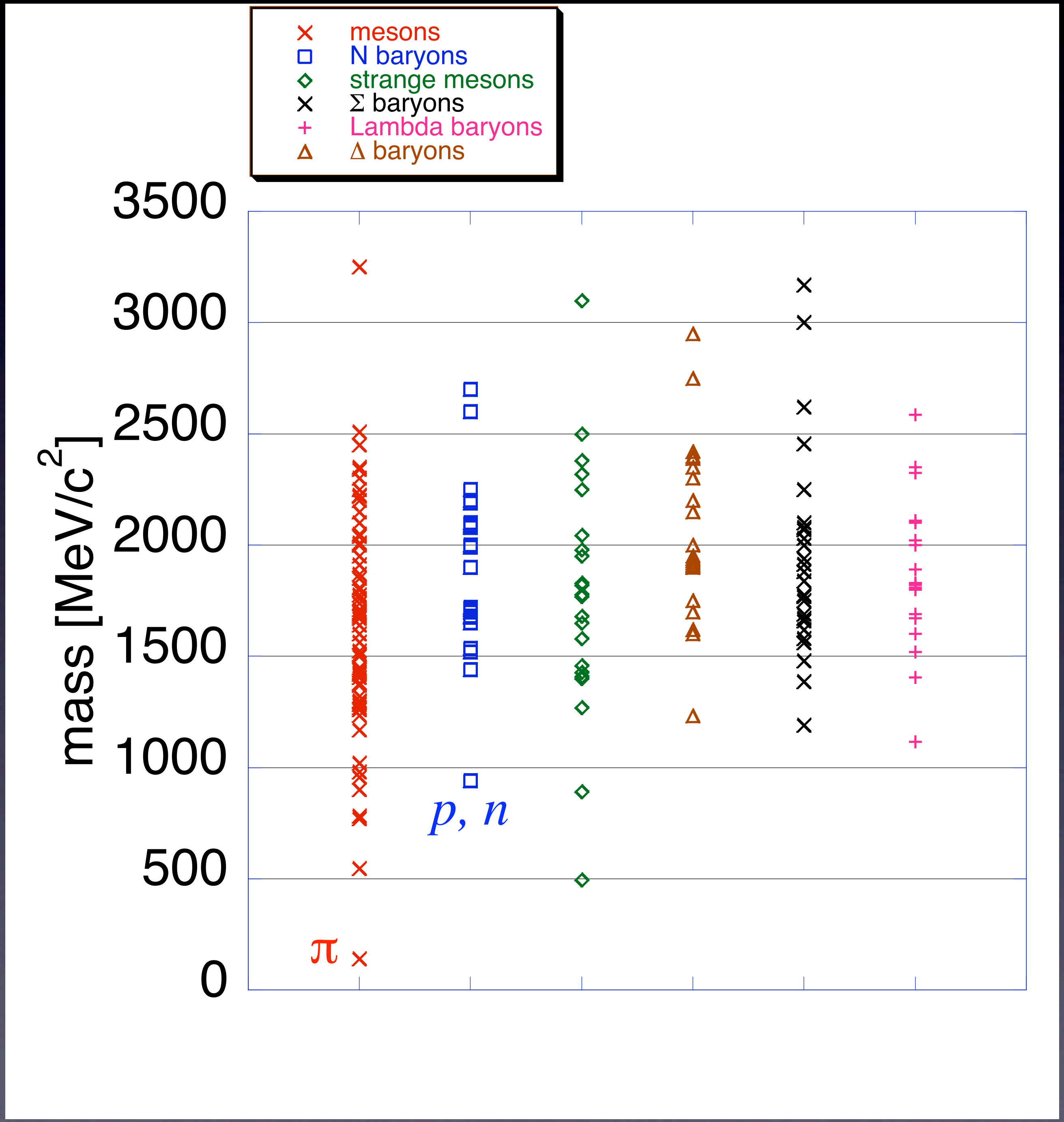

fundamental constitutents? like 100 atmos with e, *p*, *n*

Deep Inelastic Scattering (DIS)

Murray Gell-Mann
1969 Nobel

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- e *p* scattering
- scoffed at because electron does not do strong interaction
- turned out *brilliant* because of well-defined roles
  e=probe
  p=probed
- found *partons* inside proton, quarks?
- 1990 Nobel Prize:
Friedman, Kendall, Taylor

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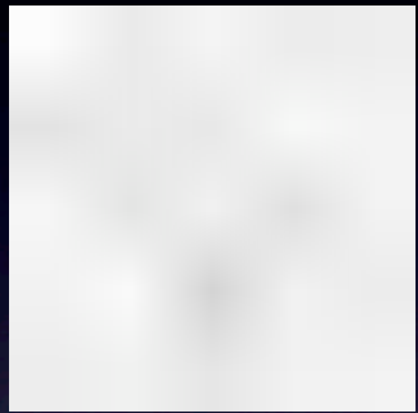

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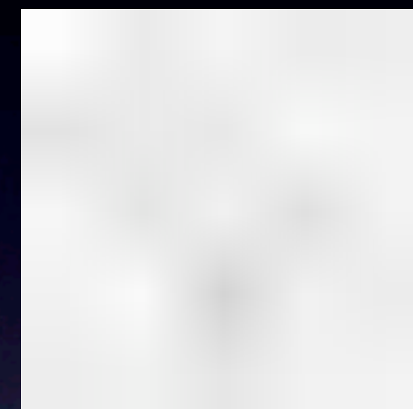

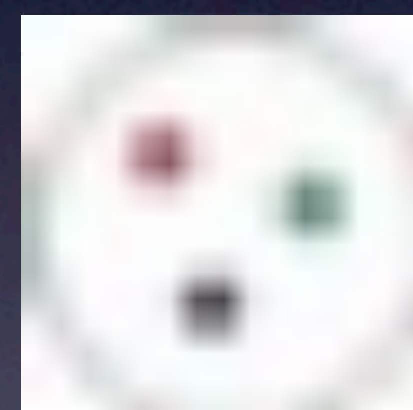

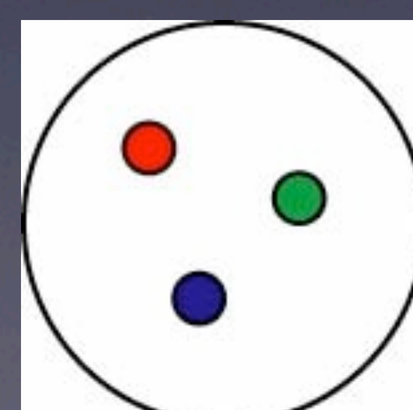

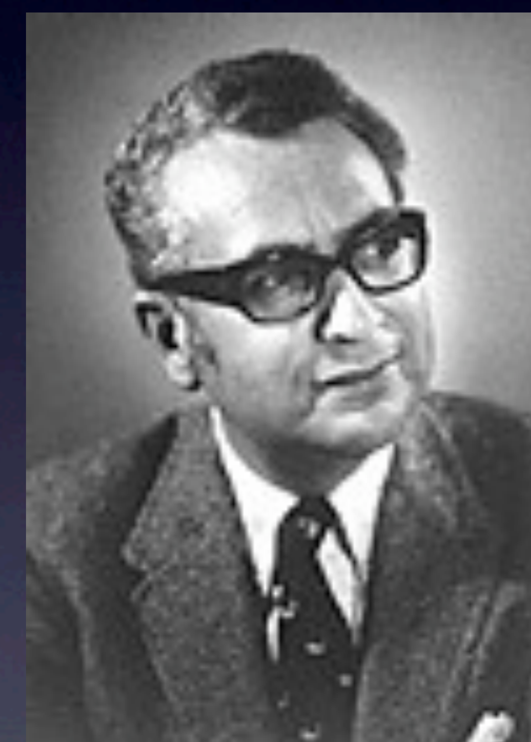

Murray Gell-Mann
1969 Nobel

puzzles about quarks

- We need
- up u(+2/3 e)
- down d(-1/3 e)
- strange s(-1/3 e)
- proton is (uud)
- neutron is n(udd)
- pion is $\pi^+(u\bar{d})$
- kaon is $K^+(u\bar{s})$
- baryons have three quarks
- mesons have a quark and an anti-quark
- but quarks have not been seen
- must be *confined*
- and fractionally charged
- do they *really* exist?

puzzles about quarks

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- quarks must have s=1/2
- therefore fermions
- obey exclusion principle
- but there is $\Delta^{++}(uuu)$
- three up-quarks in the same state?
- introduce *color*
- $\Delta^{++}(uuu)$
- sounds *ad hoc*

puzzles about quarks

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- confined
- but they were *seen* in DIS experiments
- they behave as if they are free
- why do they appear free when struck at high energies?

November revolution

- Brookhaven: proton on a target, look for e^+e^- pairs
- SLAC: e^+e^- collider, look for hadrons

Experimental Observation of a Heavy Particle J†

J

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Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
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Y. Y. Lee
Brookhaven National Laboratory, Upton, New York 11973
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We report the observation of a heavy particle J, with mass $m = 3.1$ GeV and width approximately zero. The observation was made from the reaction $p + \text{Be} \rightarrow e^+ + e^- + x$ by measuring the e^+e^- mass spectrum with a precise pair spectrometer at the Brookhaven National Laboratory's 30-GeV alternating-gradient synchrotron.

This experiment is part of a large program to study the behavior of timelike photons in $p + p \rightarrow e^+ + e^- + x$ reactions[1] and to search for new particles which decay into e^+e^- and $\mu^+\mu^-$ pairs.

We use a slow extracted beam from the Brookhaven National Laboratory's alternating-gradient synchrotron. The beam intensity varies from 10^{10} to 2×10^{12} p/pulse. The beam is guided onto an extended target, normally nine pieces of 70-mil Be, to enable us to reject the pair accidentals by requiring the two tracks to come from the same origin. The beam intensity is monitored with a secondary emission counter, calibrated daily with a thin Al foil. The beam spot si
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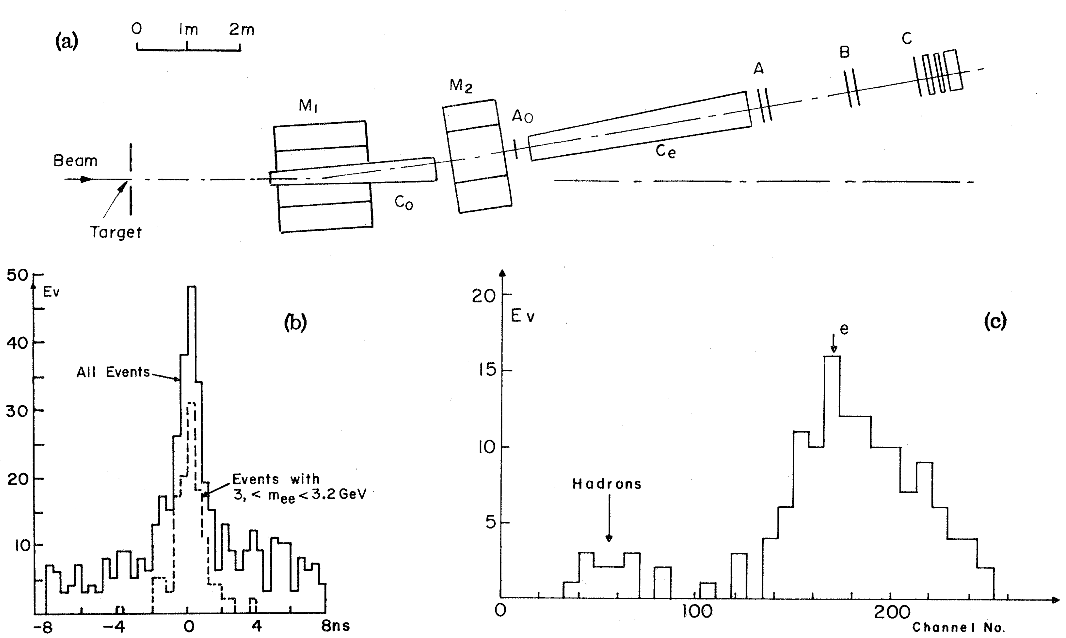

FIG. 1. (a) Simplified side view of one of the spectrometer arms. (b) Time-of-flight spectrum of e^+e^- pa
of those events with $3.0 < m < 3.2$ GeV. (c) Pulse-height spectrum of e^- (same for e^+) of the e^+e^- pair.

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The magnets were measured with a three-dimensional Hall probe. A total of 10^5 points were mapped at various current settings. The acceptance of the spectrometer is $\Delta\theta = \pm 1°$, $\Delta\varphi = \pm 2°$, $\Delta m = 2$ GeV. Thus the spectrometer enables us to map the e^+e^- mass region from 1 to 5 GeV in three overlapping settings.

Figure 1(b) shows the time-of-flight spectrum between the e^+ and e^- arms in the mass region $2.5 < m < 3.5$ GeV. A clear peak of 1.5-nsec width is observed. This enables us to reject the accidentals easily. Track reconstruction between the two arms was made and again we have a clear-cut distinction between real pairs and accidentals. Figure 1(c) shows the shower and lead-glass pulse height spectrum for the events in the mass region $3.0 < m < 3.2$ GeV. They are again in agreement with the calibration made by the e beam.

Typical data are shown in Fig. 2. There is a clear sharp enhancement at $m = 3.1$ GeV. Without folding in the 10^5 mapped magnetic points and the radiative corrections, we estimate a mass resolution of 20 MeV. As seen from Fig. 2 the width of the particle is consistent with zero.

To ensure that the observed peak is indeed a real particle ($J \rightarrow e^+e^-$) many experimental checks were made. We list seven examples:

(1) When we decreased the magnet currents by 10%, the peak remained fixed at 3.1 GeV (see Fig. 2).

(2) To check second-order effects on the target, we increased the target thickness by a factor of 2. The yield increased by a factor of 2, not by 4.

(3) To check the pileup in the lead glass and shower counters, different runs with different voltage settings on the counters were made. No effect was observed on the yield of J.

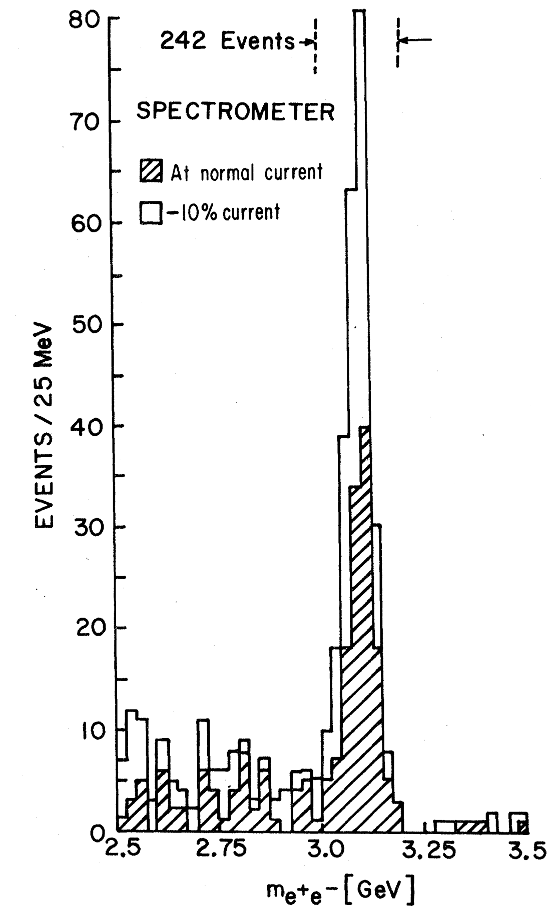

FIG. 2. Mass spectrum showing the existence of J. Results from two spectrometer settings are plotted showing that the peak is independent of spectrometer currents. The run at reduced current was taken two months later than the normal run.

(4) To ensure that the peak is not due to scattering from the sides of magnets, cuts were made in the data to reduce the effective aperture. No significant reduction in the J yield was found.

(5) To check the read-out system of the chambers and the triggering system of the hodoscopes, runs were made with a few planes of chambers deleted and with sections of the hodoscopes omitted from the trigger. No effect was observed on the J yield.

(6) Runs with different beam intensity were made and the yield did not change.

(7) To avoid systematic errors, half of the data were taken at each spectrometer polarity.

These and many other checks convinced us that we have observed a real massive particle $J \rightarrow ee$.

If we assume a production mechanism for J to be $d\sigma/dp_\perp \propto \exp(-6p_\perp)$ we obtain a yield of J of ap-

Thursday, July 23, 2009

J

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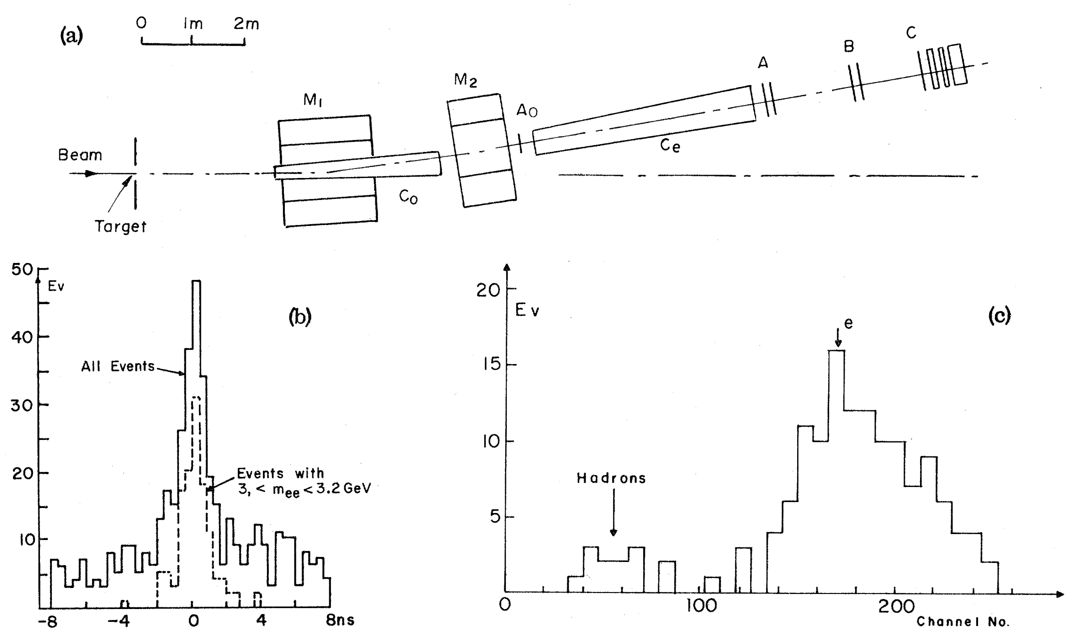

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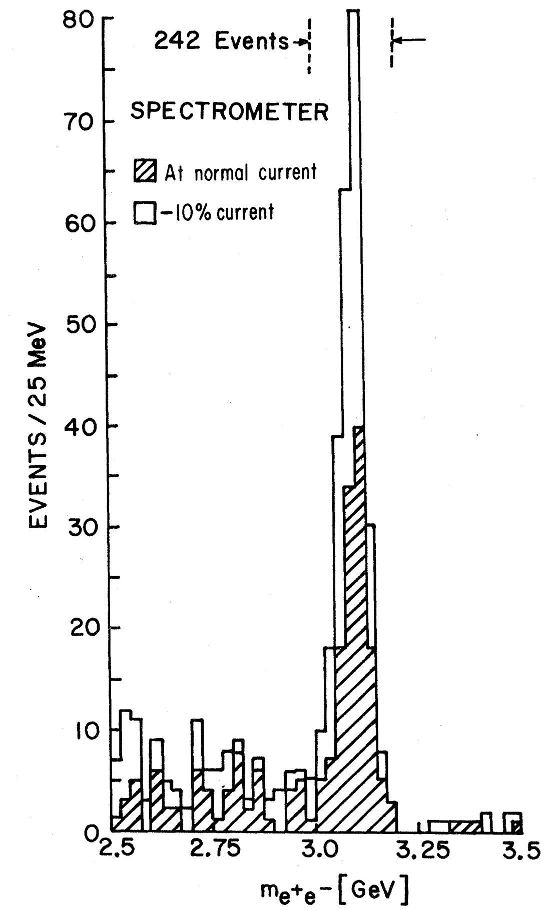

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Sam Ting: 丁 1976 Nobel

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Discovery of a Narrow Resonance in e^+e^- Annihilation*

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and

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Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720

(Received 13 November 1974)

We have observed a very sharp peak in the cross section for $e^+e^-\to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ at a center-of-mass energy of 3.105 ± 0.003 GeV. The upper limit to the full width at half-maximum is 1.3 MeV.

We have observed a very sharp peak in the cross section for $e^+e^-\to$ hadrons, e^+e^-, and possibly $\mu^+\mu^-$ in the Stanford Linear Accelerator Center (SLAC)–Lawrence Berkeley Laboratory magnetic detector[1] at the SLAC electron-positron storage ring SPEAR. The resonance has the parameters

$$E=3.105\pm0.003\ \text{GeV},$$

$$\Gamma\leqslant1.3\ \text{MeV}$$

(full width at half-maximum), where the uncertainty in the energy of the resonance reflects the uncertainty in the absolute energy calibration of the storage ring. [We suggest naming this structure $\psi(3105)$.] The cross section for hadron production at the peak of the resonance is $\geqslant2300$ nb, an enhancement of about 100 times the cross section outside the resonance. The large mass, large cross section, and narrow width of this structure are entirely unexpected.

Our attention was first drawn to the possibility of structure in the $e^+e^-\to$ hadron cross section during a scan of the cross section carried out in 200-MeV steps. A 30% (6 nb) enhancement was observed at a c.m. energy of 3.2 GeV. Subsequently, we repeated the measurement at 3.2 GeV and also made measurements at 3.1 and 3.3 GeV. The 3.2-GeV results reproduced, the 3.3-GeV measurement showed no enhancement, but the 3.1-GeV measurements were internally inconsistent—six out of eight runs giving a low cross section and two runs giving a factor of 3 to 5 higher cross section. This pattern could have been caused by a very narrow resonance at an energy slightly larger than the nominal 3.1-GeV setting of the storage ring, the inconsistent 3.1-GeV cross sections then being caused by setting errors in the ring energy. The 3.2-GeV enhancement would arise from radiative corrections which give a high-energy tail to the structure.

We have now repeated the measurements using much finer energy steps and using a nuclear magnetic resonance magnetometer to monitor the ring energy. The magnetometer, coupled with measurements of the circulating beam position in the storage ring made at sixteen points around the orbit, allowed the relative energy to be determined to 1 part in 10^4. The determination of the absolute energy setting of the ring requires the knowledge of $\int B\,dl$ around the orbit and is accurate to ±0.1%.

The data are shown in Fig. 1. All cross sections are normalized to Bhabha scattering at 20 mrad. The cross section for the production of hadrons is shown in Fig. 1(a). Hadronic events are required to have in the final state either $\geqslant3$ detected charged particles or 2 charged particles noncoplanar by $>20°$.[2] The observed cross section rises sharply from a level of about 25 nb to a value of 2300 ± 200 nb at the peak[3] and then exhibits the long high-energy tail characteristic of radiative corrections in e^+e^- reactions. The detection efficiency for hadronic events is 45% over the region shown. The error quoted above includes both the statistical error and a 7% contribution from uncertainty in the detection efficiency.

Our mass resolution is determined by the energy spread in the colliding beams which arises from quantum fluctuations in the synchrotron radiation emitted by the beams. The expected Gaussian c.m. energy distribution ($\sigma=0.56$ MeV), folded with the radiative processes,[4] is shown as the dashed curve in Fig. 1(a). The width of the resonance must be smaller than this spread; thus an upper limit to the full width at half-maximum is 1.3 MeV.

Figure 1(b) shows the cross section for e^+e^- final states. Outside the peak this cross section is equal to the Bhabha cross section integrated over the acceptance of the apparatus.[1]

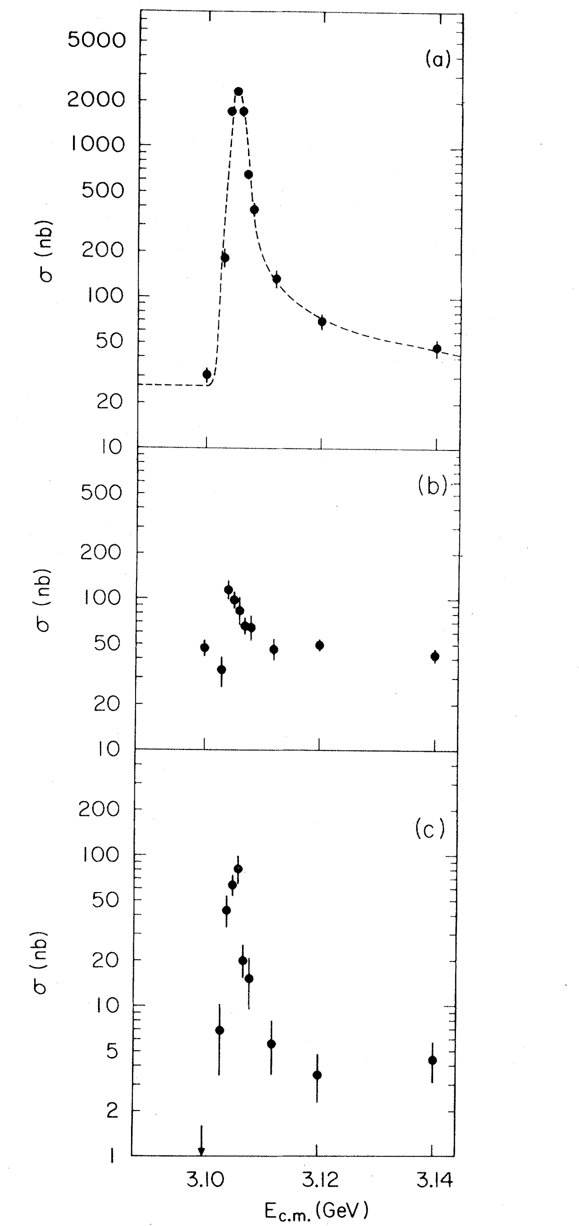

FIG. 1. Cross section versus energy for (a) multi-hadron final states, (b) e^+e^- final states, and (c) $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- final states. The curve in (a) is the expected shape of a δ-function resonance folded with the Gaussian energy spread of the beams and including radiative processes. The cross sections shown in (b) and (c) are integrated over the detector acceptance. The total hadron cross section, (a), has been corrected for detection efficiency.

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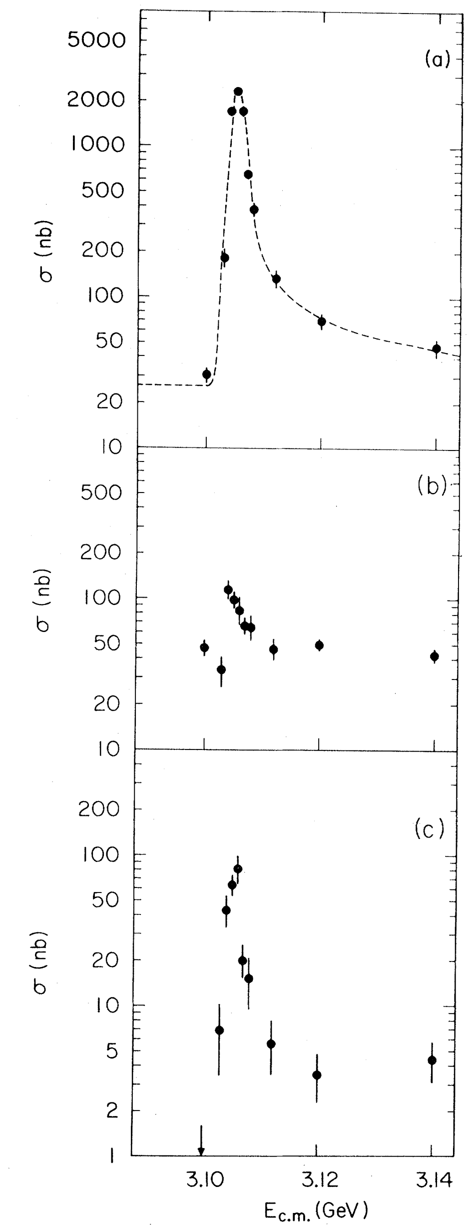

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Burton Richter 1976 Nobel

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We report on the results at ADONE to study the properties of the newly found 3.1-BeV particle.

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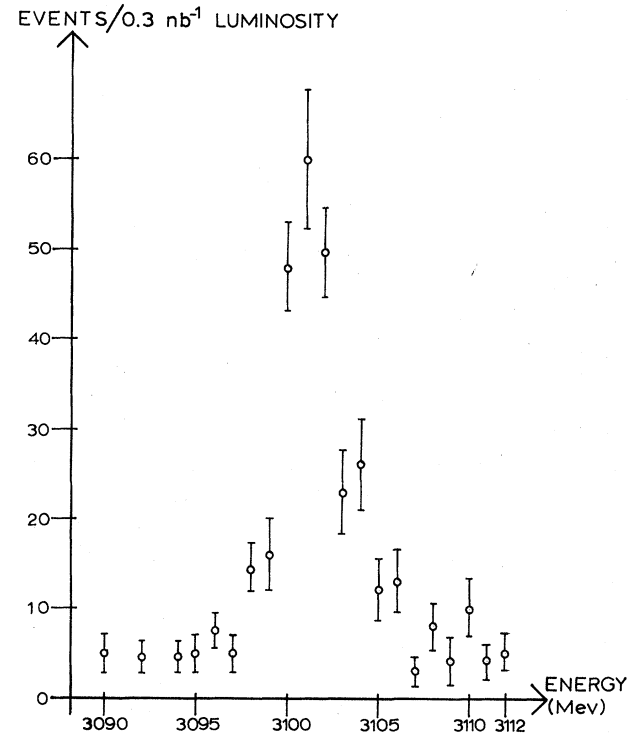

FIG. 1. Result from the Gamma-Gamma Group, total of 446 events. The number of events per 0.3 nb^{-1} luminosity is plotted versus the total c.m. energy of the machine.

(MEA), and the Baryon-Antibaryon Group], already prepared to analyze systematically the 1.5- to 3.0-GeV c.m. energy region, started to analyze the energy interval between 3.08 and 3.12 GeV in 0.5-MeV steps. A striking increase in the total counting rate was observed soon afterwards in all three experiments, and the film analysis was immediately started. We report in the following the preliminary results that have been obtained.

Results of the Gamma-Gamma Group.—The apparatus, which covers a solid angle of approximately $0.75 \times 4\pi$, consists of optical spark chambers and wire chambers and is particularly suited to analyze the neutral and electromagnetic components (γ rays and electrons). The number of events in this reaction, $e^+e^- \to >3$ bodies (tracks or showers), is plotted in Fig. 1 in the region 3.090 to 3.112 GeV. The analysis of the events indicates an average charged multiplicity of 3.4 ± 0.5, with a maximum of 8. The presence of K and a rather abundant photon component (average number of observed photons per event is 1.6 ± 0.1 with a maximum of 7) have been established.
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peak is found to be approximately 800 nb. The energy resolution of ADONE is approximately ± 1.5 MeV; this has so far prevented a direct measurement of the cross section at the peak.

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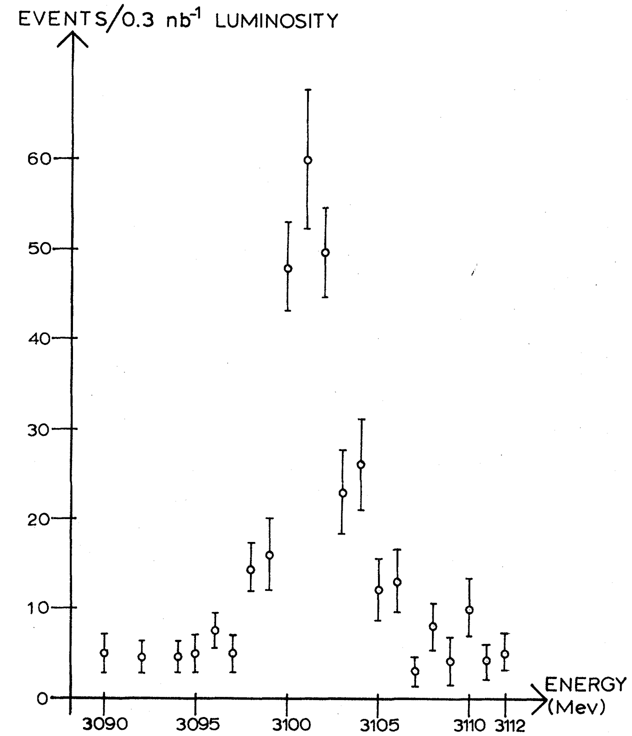

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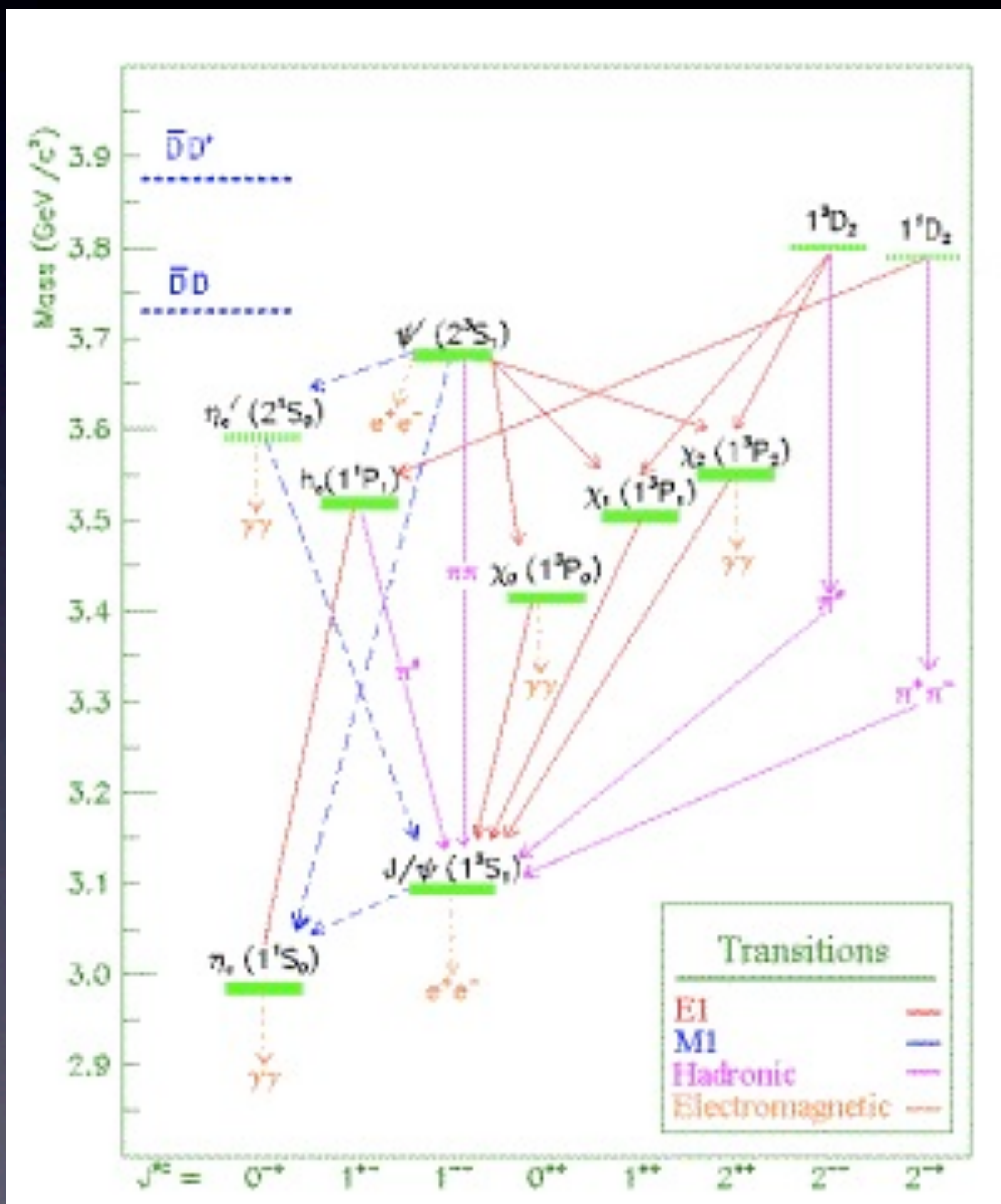
No Nobel

New Quark

- *Very* narrow resonance
- meson made of charm (c) & anti-charm ($\bar{c}$)
- later, more mesons with "naked charm" with *u*, *d*, *s* quarks (D^+, D^0, D_s, ...)
- all made sense using quarks
- people were forced to accept the idea of quarks

New Quark



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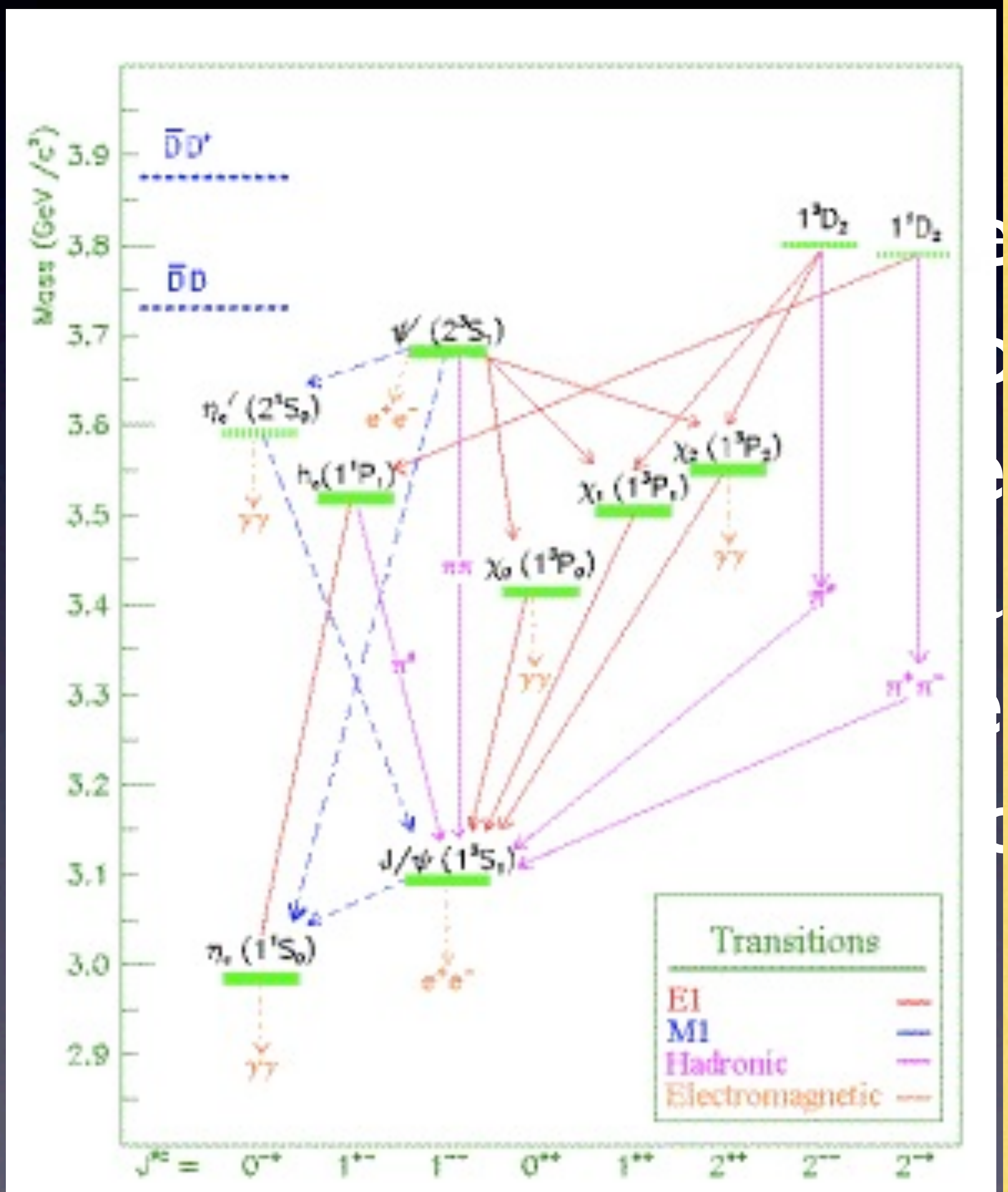
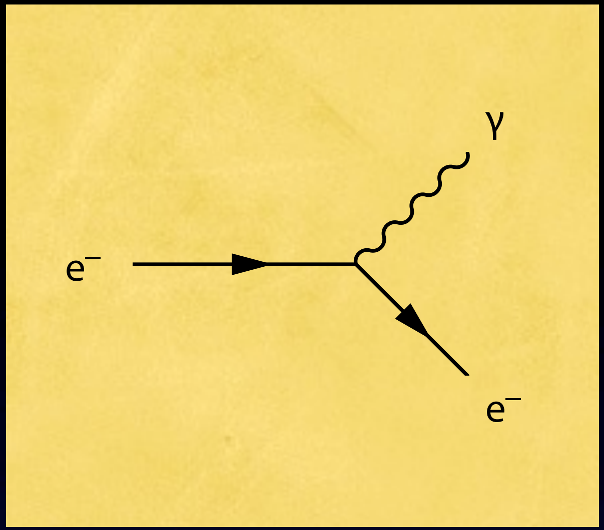


Table 14.3: $q\overline{q}$ quark-model assignments for the observed heavy mesons. Mesons in bold face are in

$n\ ^{2s+1}\ell_J$	J^{PC}	I = 0 $c\overline{c}$	I = 0 $b\overline{b}$	I = $\frac{1}{2}$ $c\overline{u}$, $c\overline{d}$; $\overline{c}u$, $\overline{c}d$	I = 0 $c\overline{s}$; $\overline{c}s$
$1\ ^1S_0$	0^{-+}	$\boldsymbol{\eta_c(1S)}$	$\eta_b(1S)$	$\boldsymbol{D}$	$\boldsymbol{D_s^{\pm}}$
$1\ ^3S_1$	1^{--}	$\boldsymbol{J/\psi(1S)}$	$\boldsymbol{\Upsilon(1S)}$	$\boldsymbol{D^*}$	$\boldsymbol{D_s^{*\pm}}$
$1\ ^1P_1$	1^{+-}	$h_c(1P)$		$\boldsymbol{D_1(2420)}$	$\boldsymbol{D_{s1}(2536)^{\pm}}$
$1\ ^3P_0$	0^{++}	$\boldsymbol{\chi_{c0}(1P)}$	$\boldsymbol{\chi_{b0}(1P)}$		$\boldsymbol{D_{s0}^*(2317)^{\pm\dagger}}$
$1\ ^3P_1$	1^{++}	$\boldsymbol{\chi_{c1}(1P)}$	$\boldsymbol{\chi_{b1}(1P)}$		$\boldsymbol{D_{s1}(2460)^{\pm\dagger}}$
$1\ ^3P_2$	2^{++}	$\boldsymbol{\chi_{c2}(1P)}$	$\boldsymbol{\chi_{b2}(1P)}$	$\boldsymbol{D_2^*(2460)}$	$\boldsymbol{D_{s2}(2573)^{\pm}}$
$1\ ^3D_1$	1^{--}	$\boldsymbol{\psi(3770)}$			
$2\ ^1S_0$	0^{-+}	$\boldsymbol{\eta_c(2S)}$			
$2\ ^3S_1$	1^{--}	$\boldsymbol{\psi(2S)}$	$\boldsymbol{\Upsilon(2S)}$		
$2\ ^3P_{0,1,2}$	$0^{++}, 1^{++}, 2^{++}$		$\boldsymbol{\chi_{b\,0,1,2}(2P)}$		

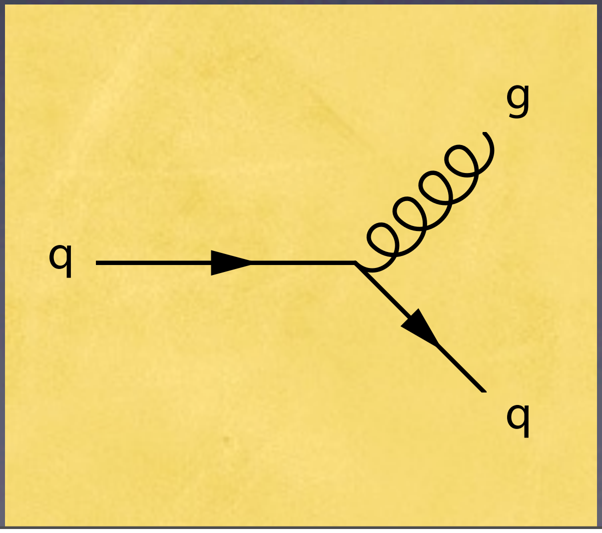
† The masses of these states are considerably smaller than most theoretical predictions. They have a (See the "Note on Non-$q\overline{q}$ Mesons" at the end of the Meson Listings). The $D_{s1}(2460)^{\pm}$ and $D_{s1}(25$

color



- actually, color was not just a *fix*
- only "white" combination was not confined
- baryon=R+G+B=white
- meson = R+anti-R=white

- maybe color is the source for force?
- color creates *gluon* just like the electric charge creates *photon*?



gluon's color

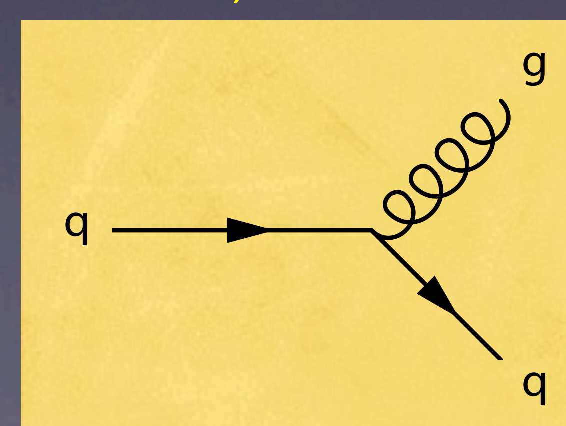
- quark has three colors
- gluon *acts* on the three colors: 3x3 matrices!
- but cares only about the difference between colors, not on the overall baryon number=1/3
- keep the matrices traceless
- $3^2-1=8$ gluons
  - $T^a = \lambda^a/2$
- SU(3) gauge theory

$$\lambda^1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \lambda^2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$\lambda^3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix}, \qquad \lambda^4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix},$$

$$\lambda^5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, \qquad \lambda^6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$\lambda^7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, \qquad \lambda^8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}$$



$g_s\ T^a$

Gauge Theory

- Physics shouldn't change not matter which color you call red, blue, or green
- arbitrary change of basis in three colors: 3x3 *U*
- also arbitrarily on where you are: *U*(x)
- but want to keep the Dirac equation unchanged
- need *gauge field* A_μ

$$\psi = \begin{pmatrix} \psi_R \\ \psi_G \\ \psi_B \end{pmatrix}$$

$$\psi(x) \to \psi'(x) = U(x)\psi(x)$$

$$A_\mu = A^a_\mu T^a \to A'_\mu = U A_\mu U^\dagger - \frac{i}{g_s} U \partial_\mu U^\dagger$$

$$[i\gamma^\mu(\partial_\mu - i g_s A_\mu) - m]\psi = 0$$

$$[i\gamma^\mu(\partial_\mu - i g_s A'_\mu) - m]\psi' = 0$$

SU(*N*)

- SU(*N*) is a group of *N* x *N* matrices
  - S: special (det=1)
  - U: unitary
- N^2-1 generators: *N* x *N* hermitian matrices with zero trace
- generators satisfy commutation relations (Lie algebra)

$$U = e^{-i\omega^a T^a}$$

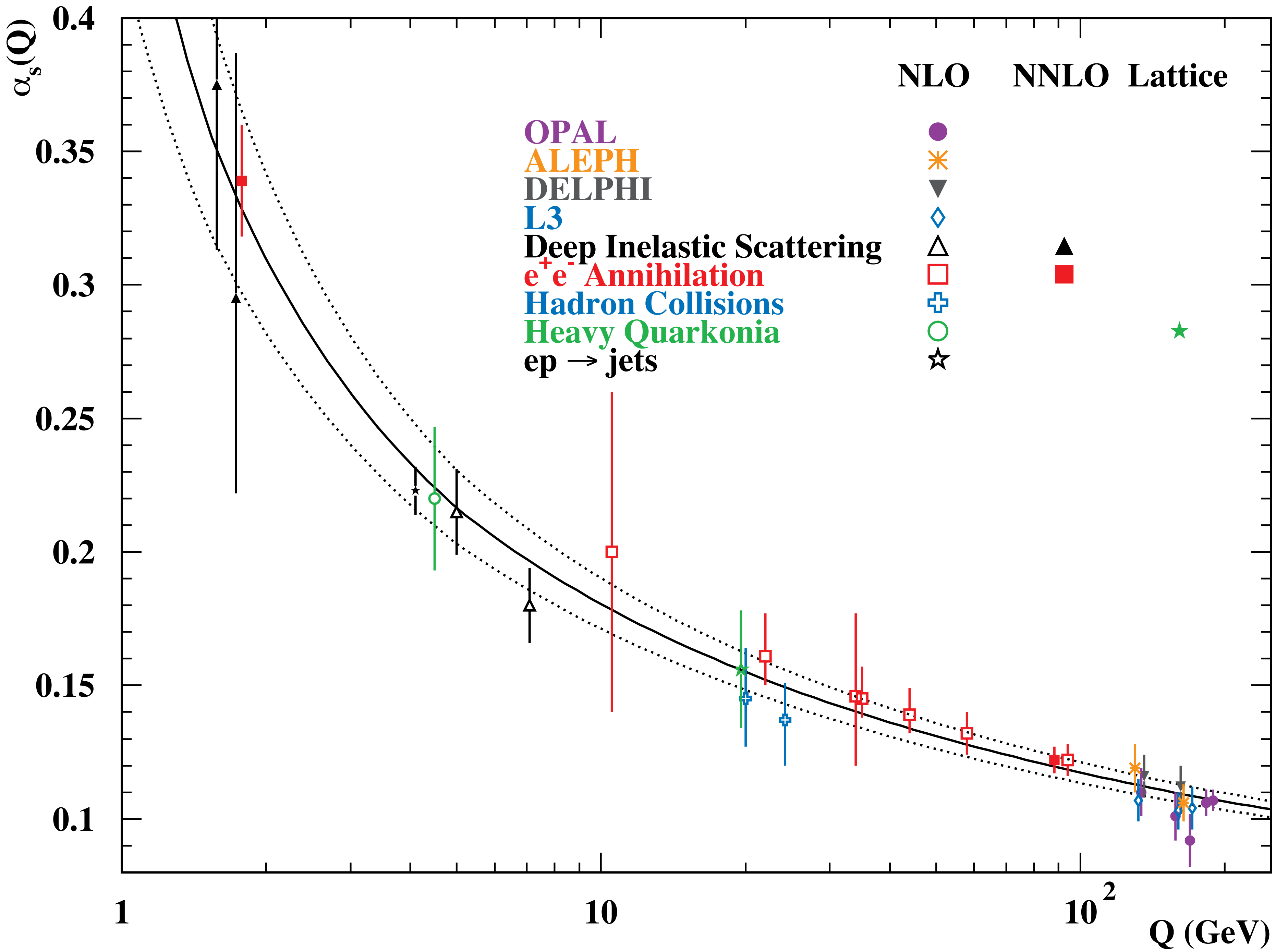
$$UU^\dagger = 1 \leftrightarrow T^{a\dagger} = T^a$$

$$\det U = e^{-i\omega^a \mathrm{Tr} T^a} = 1$$

$$[T^a, T^b] = i f^{abc} T^c$$

Lie groups are completely classified
SU(*N*), SO(*N*), Sp(*N*), G_2, F_4, E_6, E_7, E_8

asymptotic freedom



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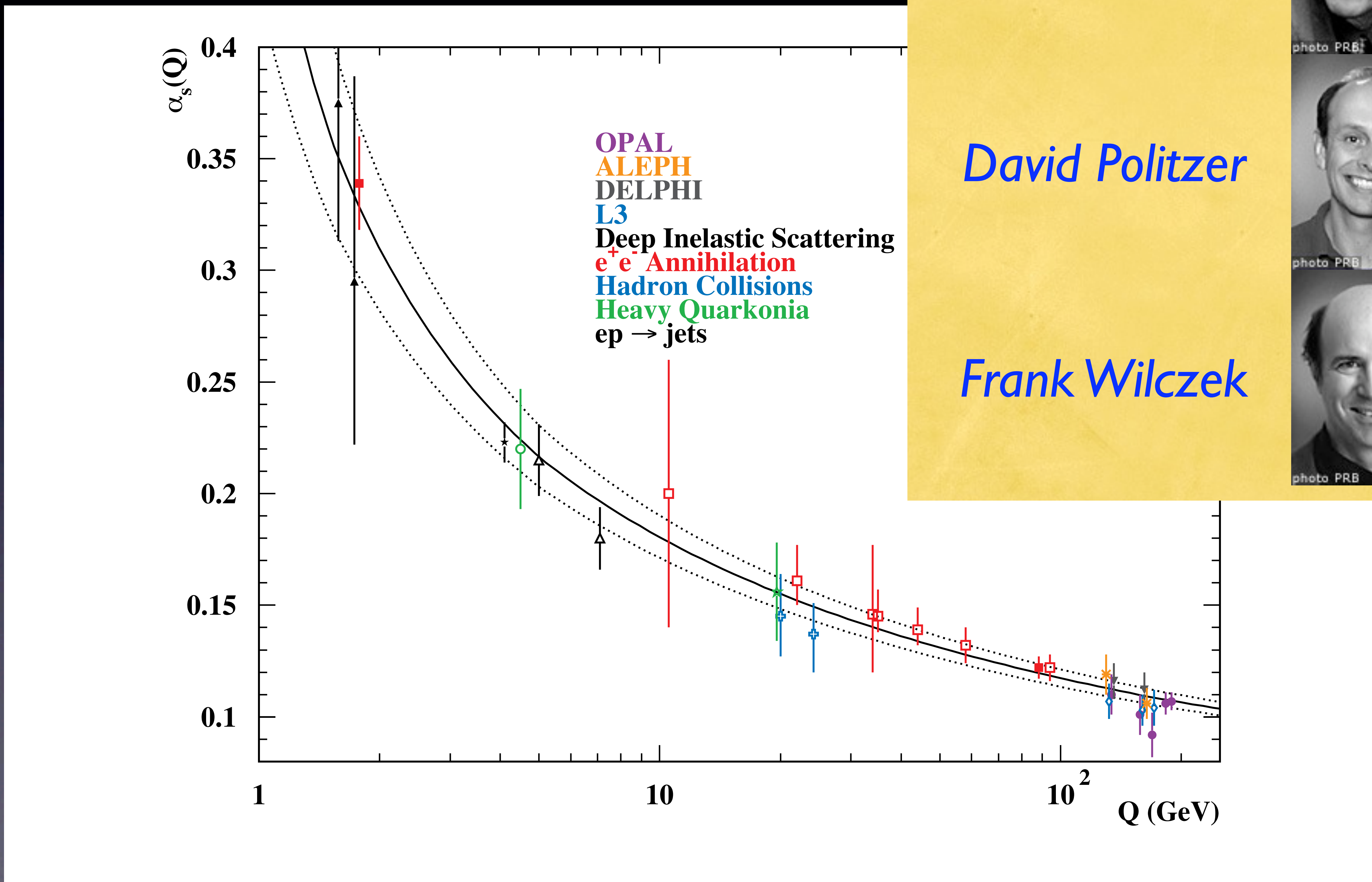
asymptotic freedom

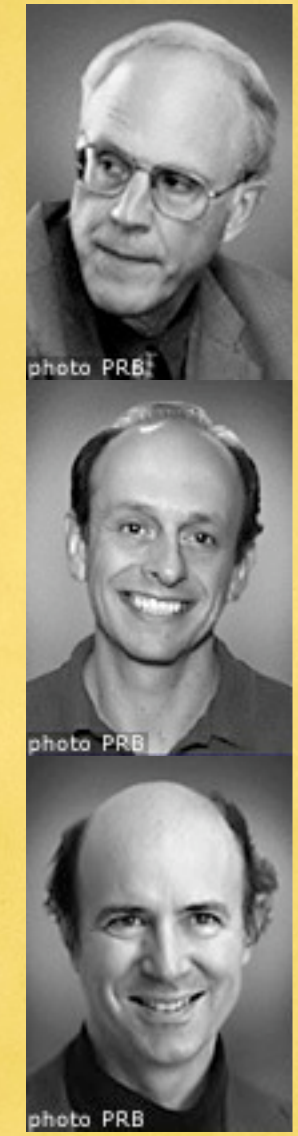


2004 Nobel

David Gross

David Politzer

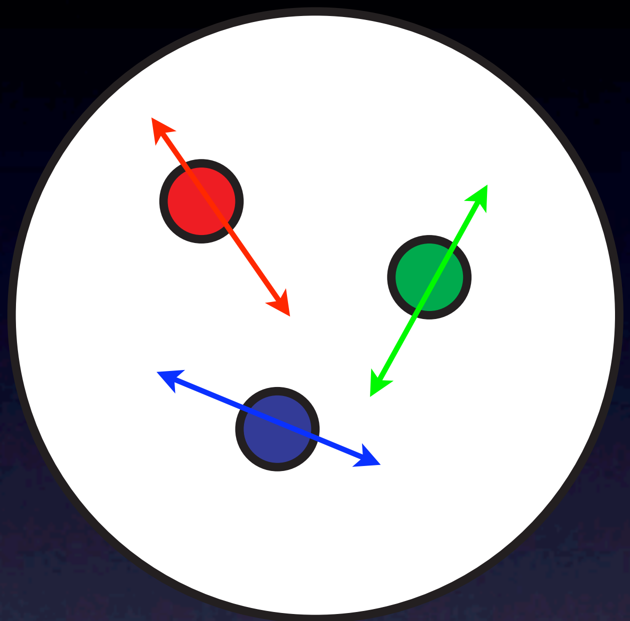
Frank Wilczek



source of our weight

- up, down quarks are very light (2-10MeV)
- quarks move around in a proton of size ≈0.7fm
- this kinetic energy is much of the source of proton mass
- $E_q \approx c\, p \approx \hbar c/\Delta x$
  ≈ 0.2 GeV fm/0.7fm
  ≈ 0.3 GeV
- $3E_q \approx 1$ GeV $\approx m_p$

p



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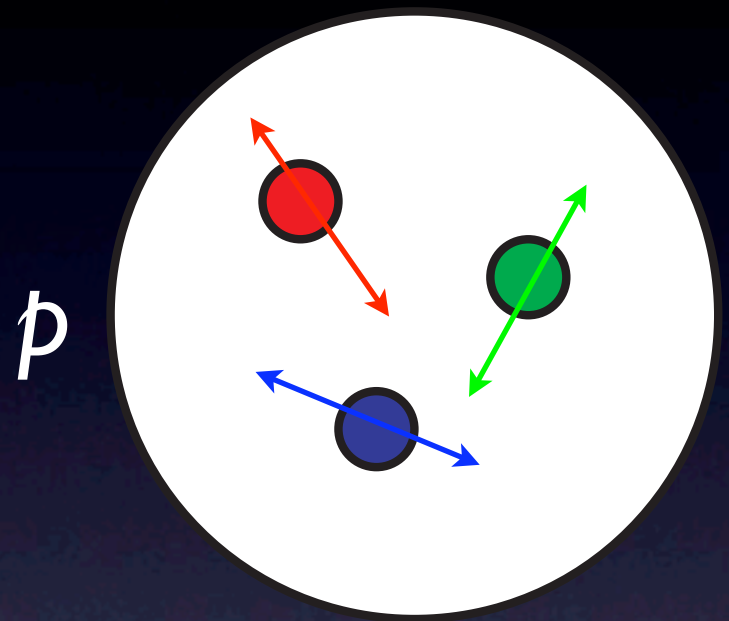
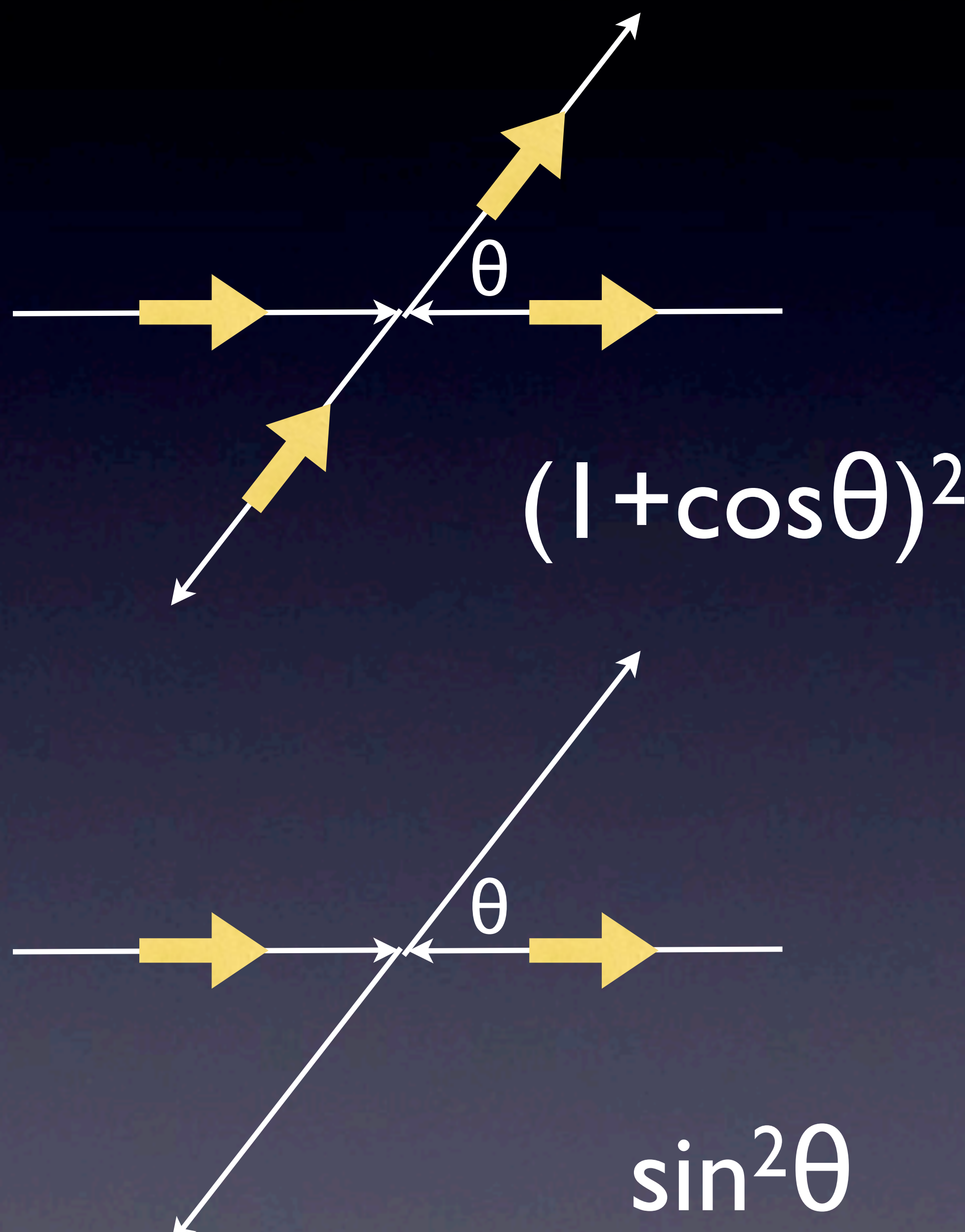
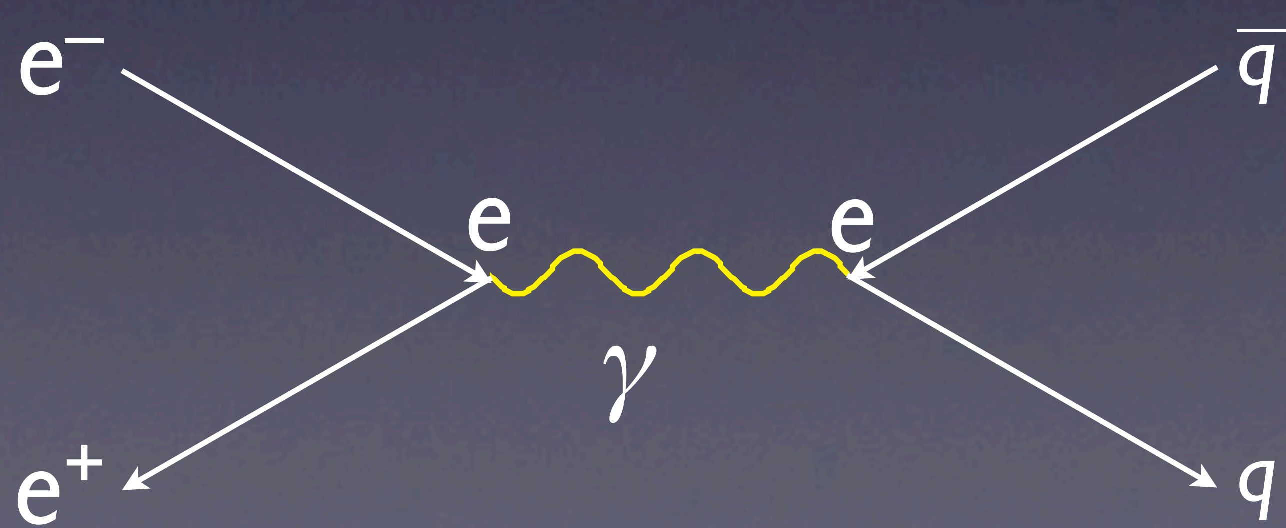
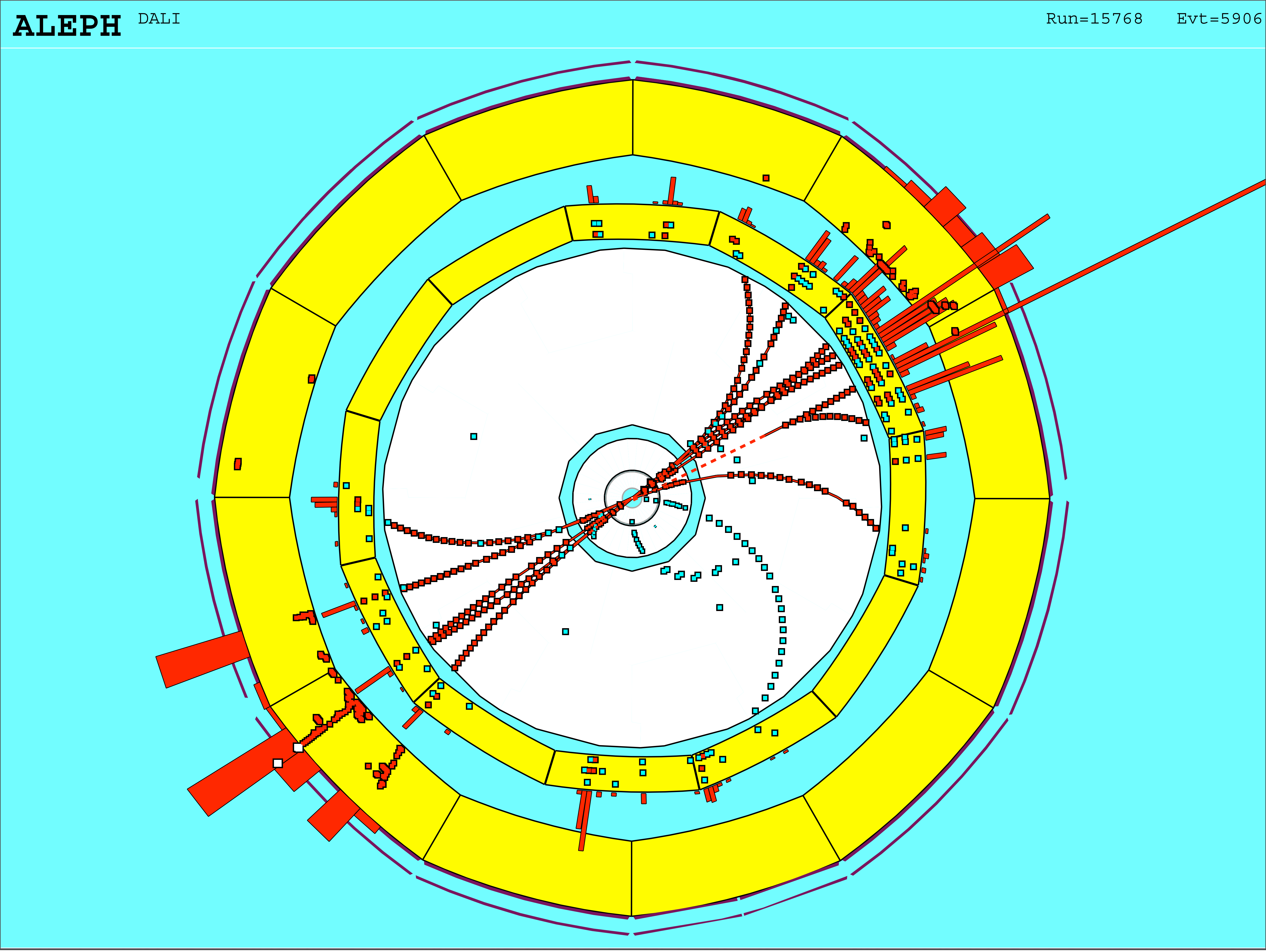


Spin

- production angle distribution well above the threshold:
- spin 1/2
- spin 0







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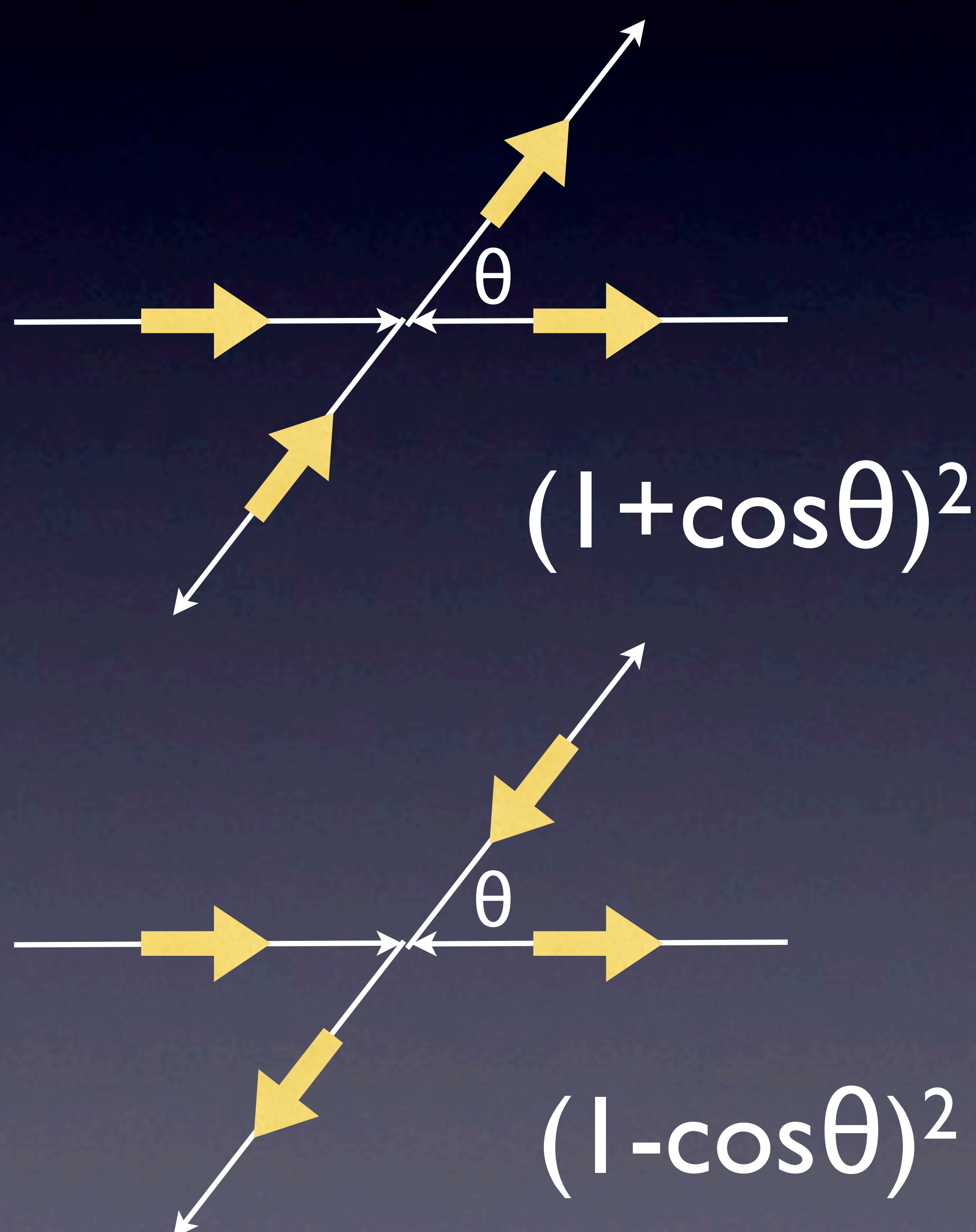
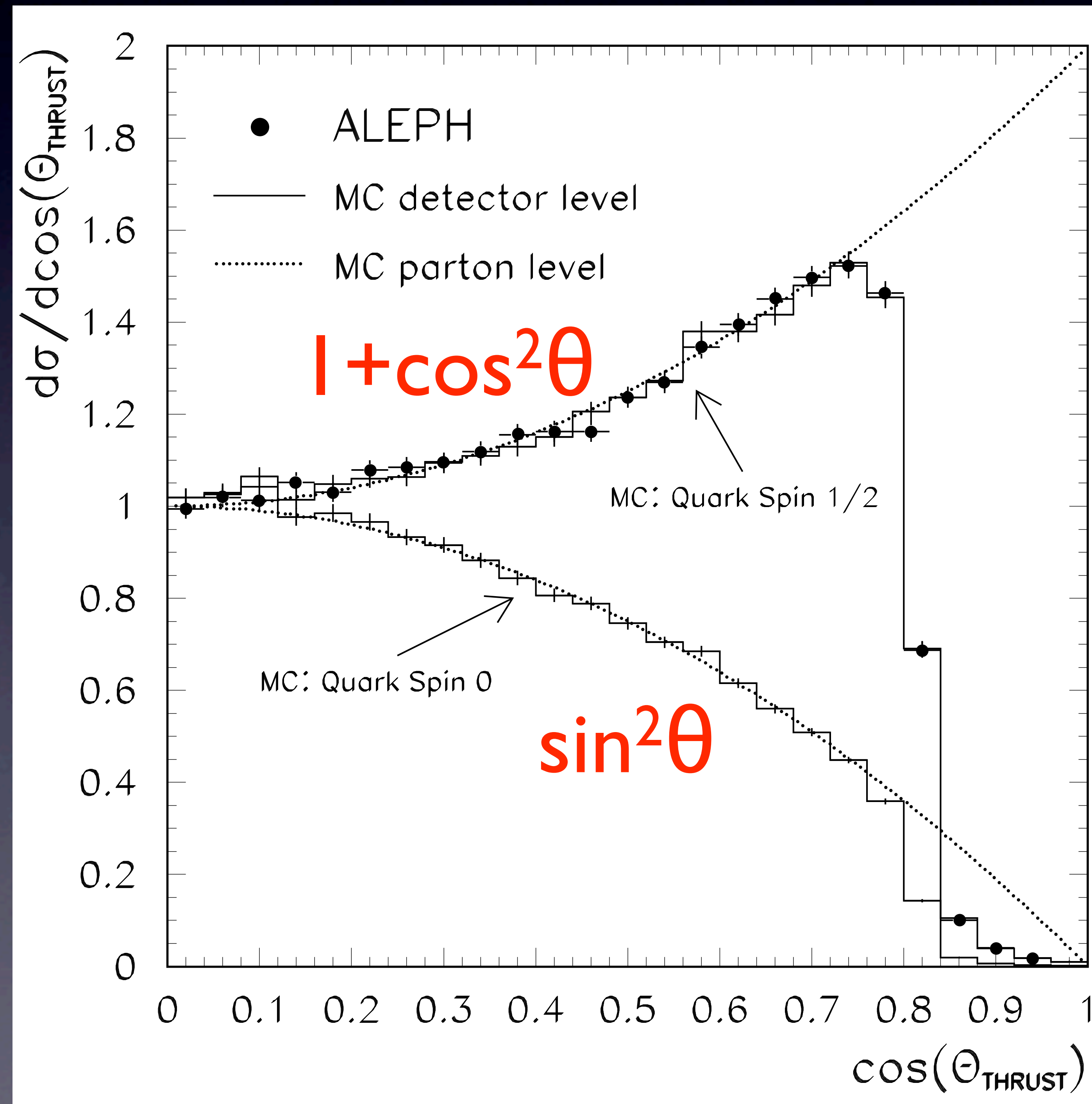
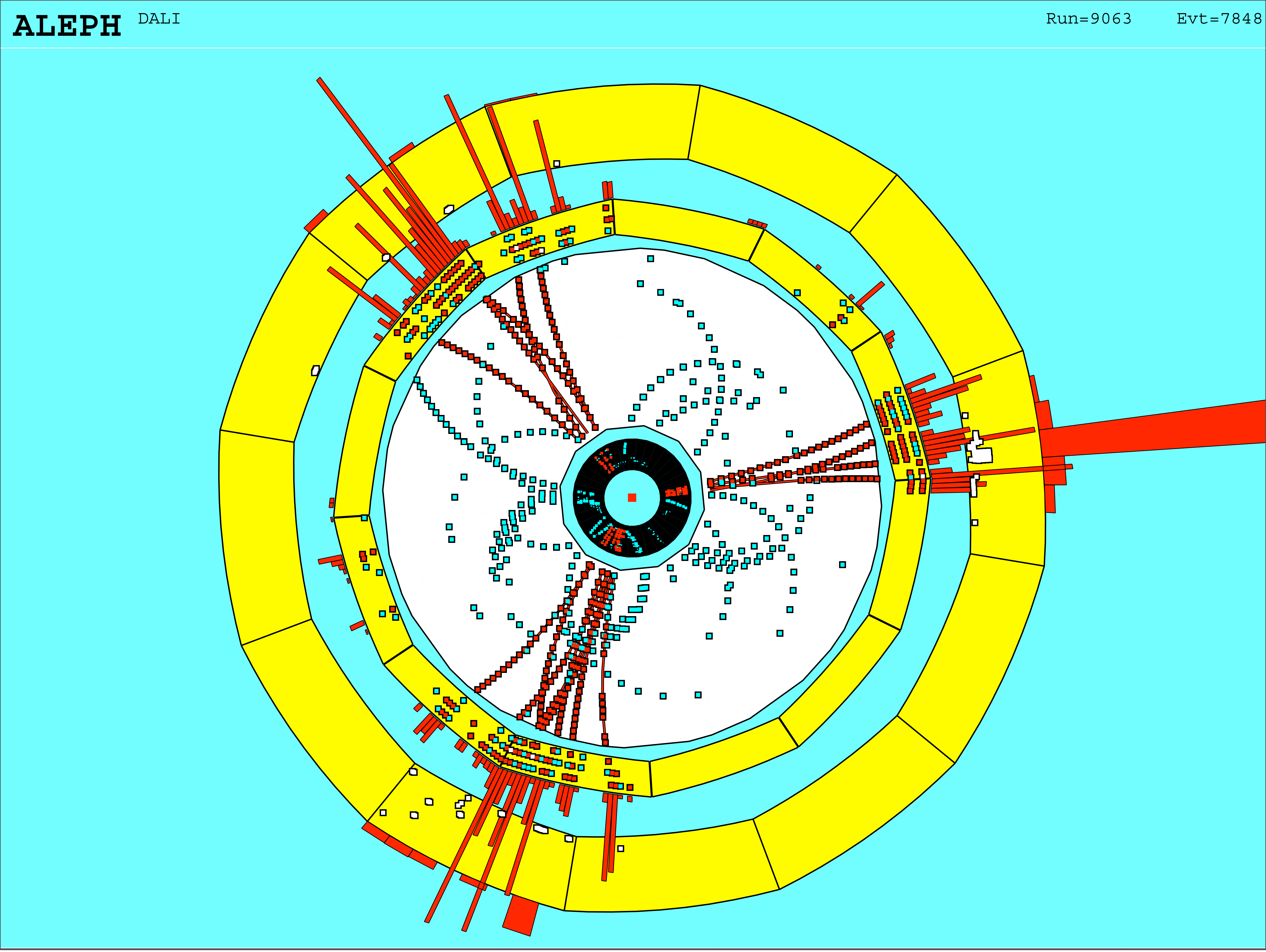
“New particle” has spin 1/2







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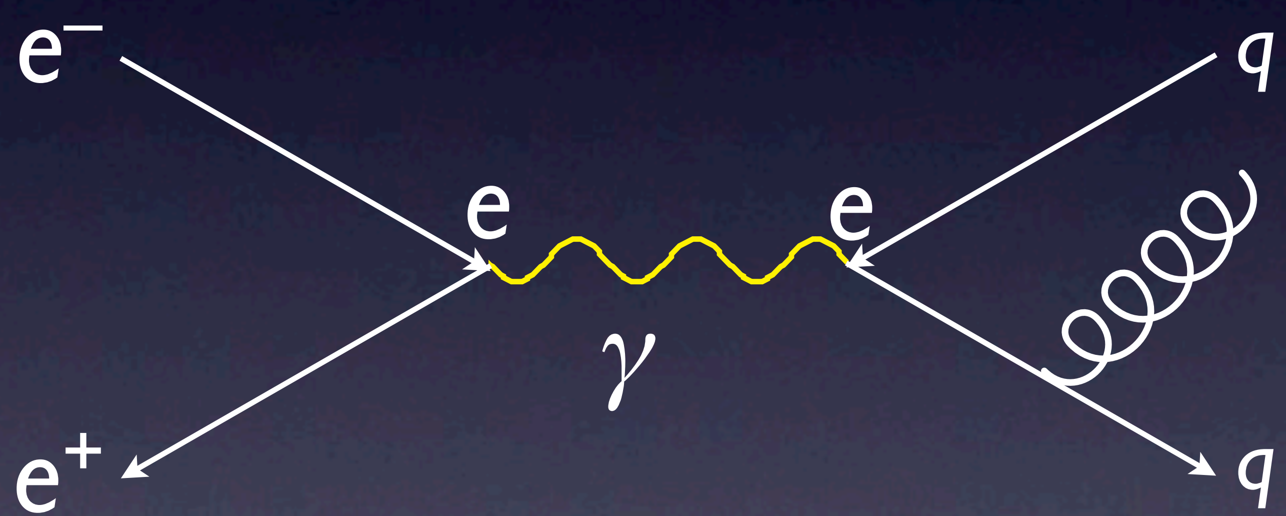
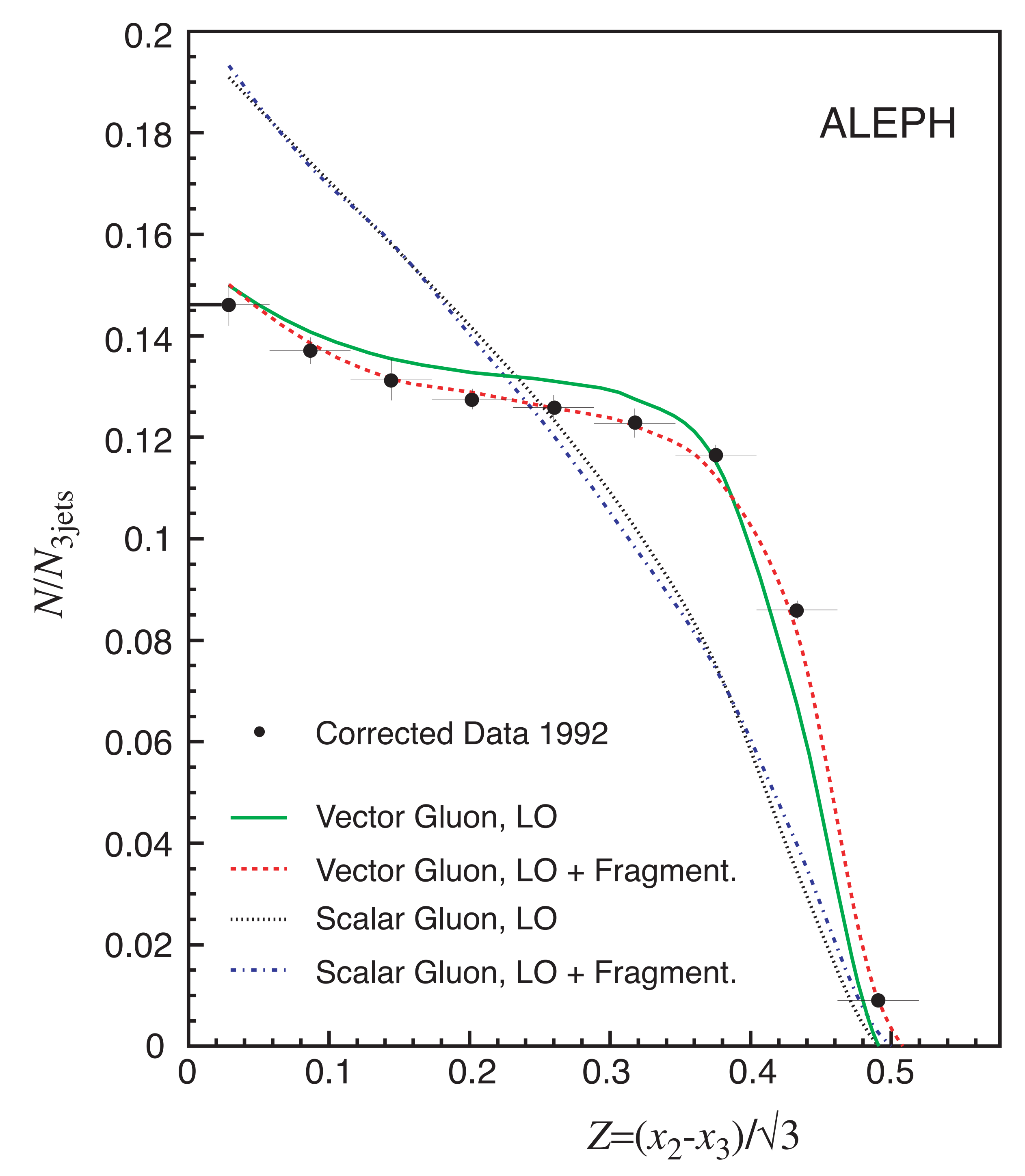
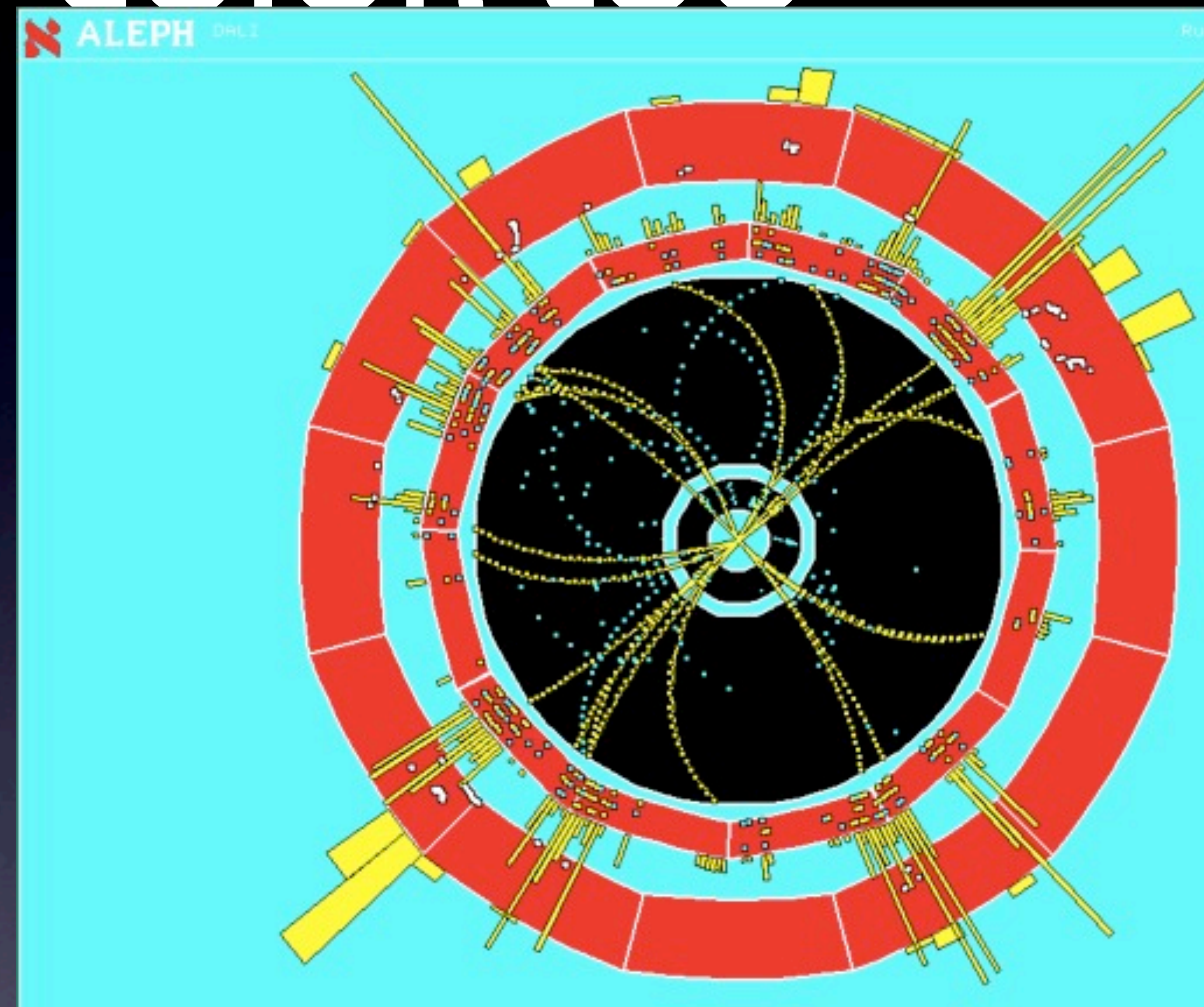
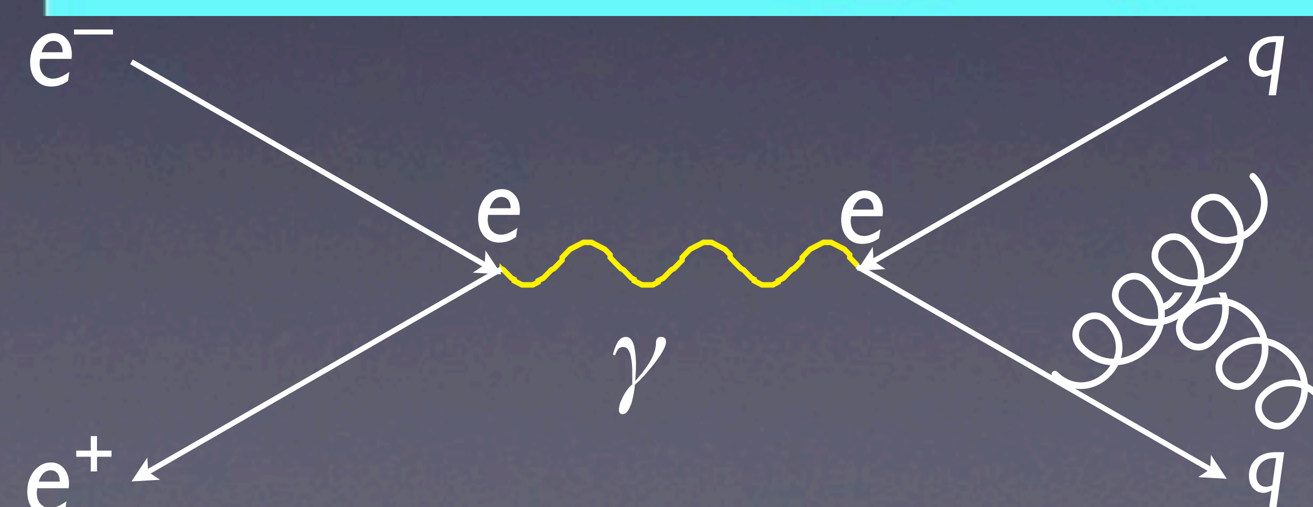




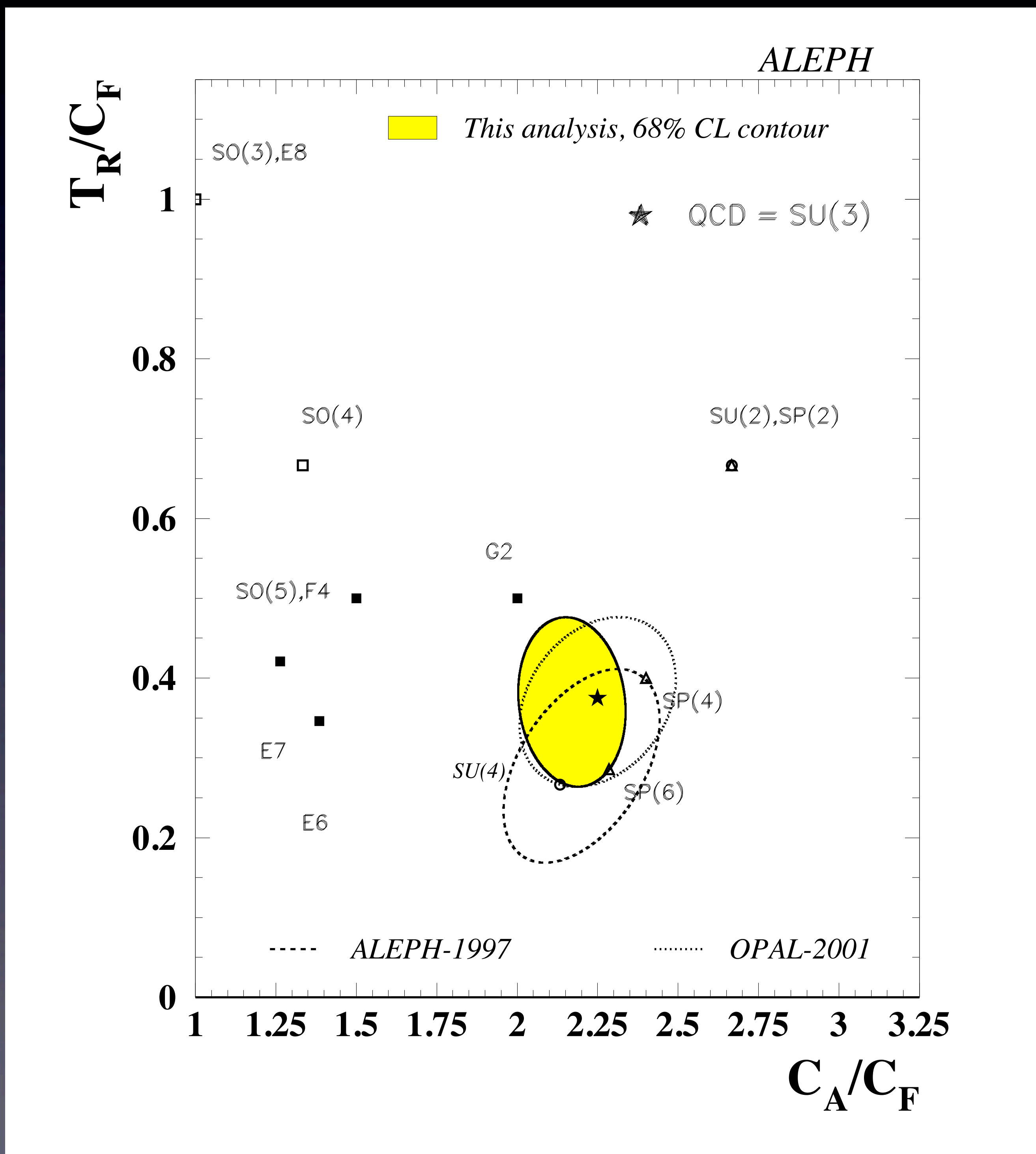
gluon has color, too

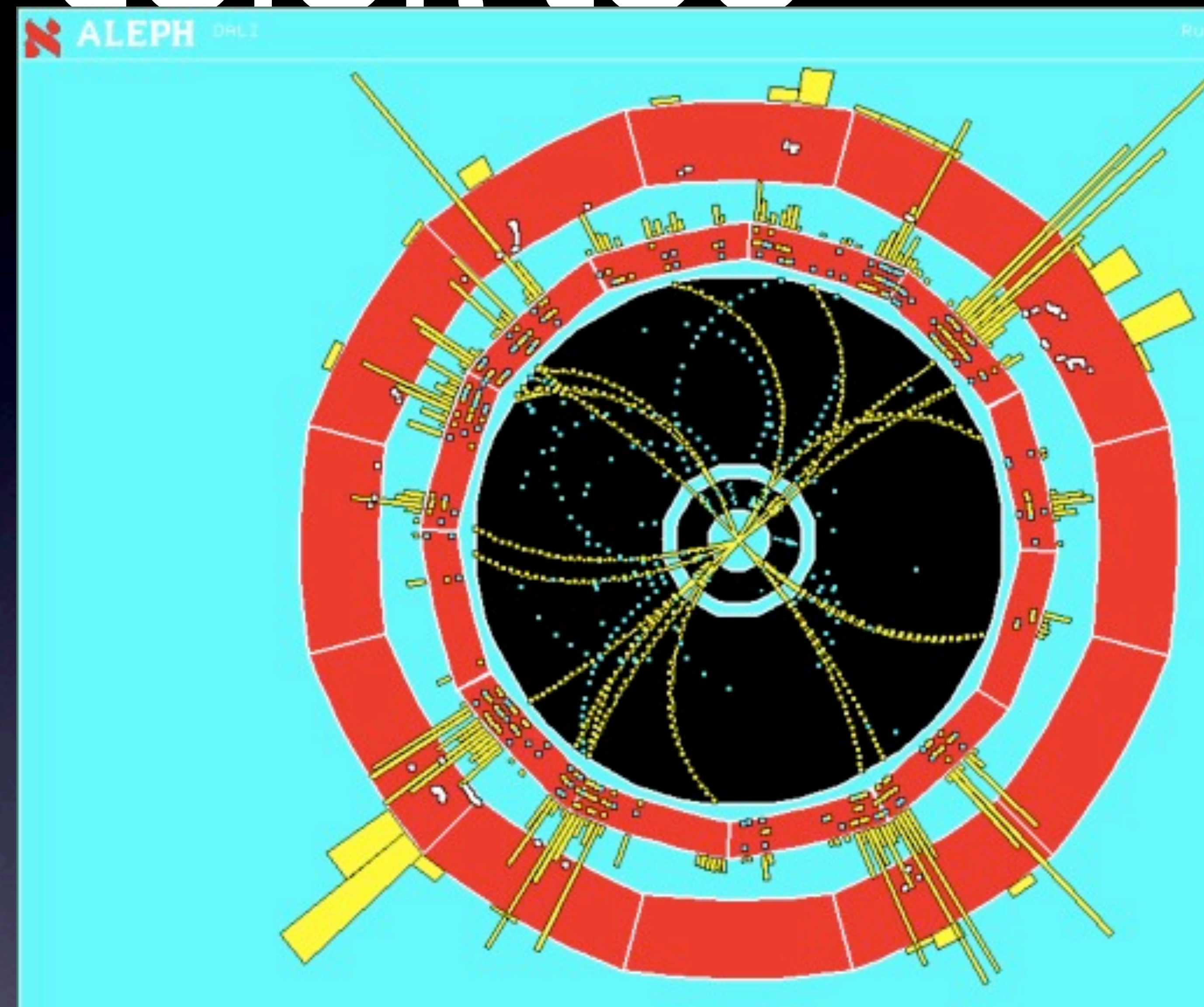
- gluon discovered and its spin determined at PETRA, DESY, Germany
- gluon can emit a gluon, too, because it also has color
- gluon self-coupling was discovered at TRISTAN experiment in Japan
- LEP determined that it really has to be SU(3)

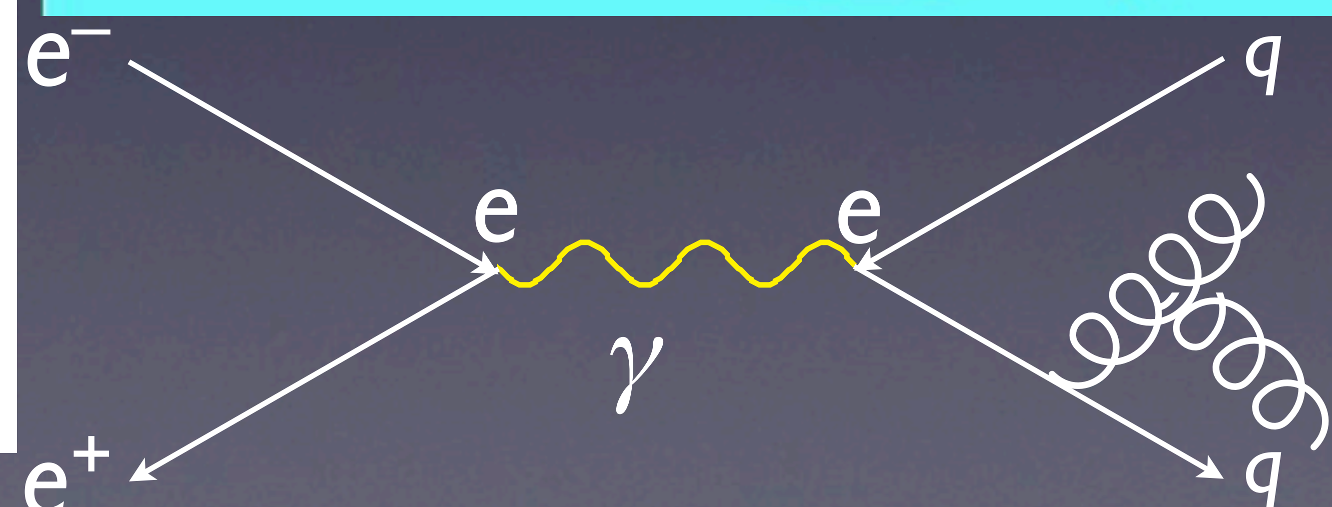




gluon has color, too







strong force

- now we believe it is understood theoretically
- but in order to compute bound state quantities, we need to face *strong* coupling
- no good approximation method
- put the QFT on a computer and do calculations by brute force
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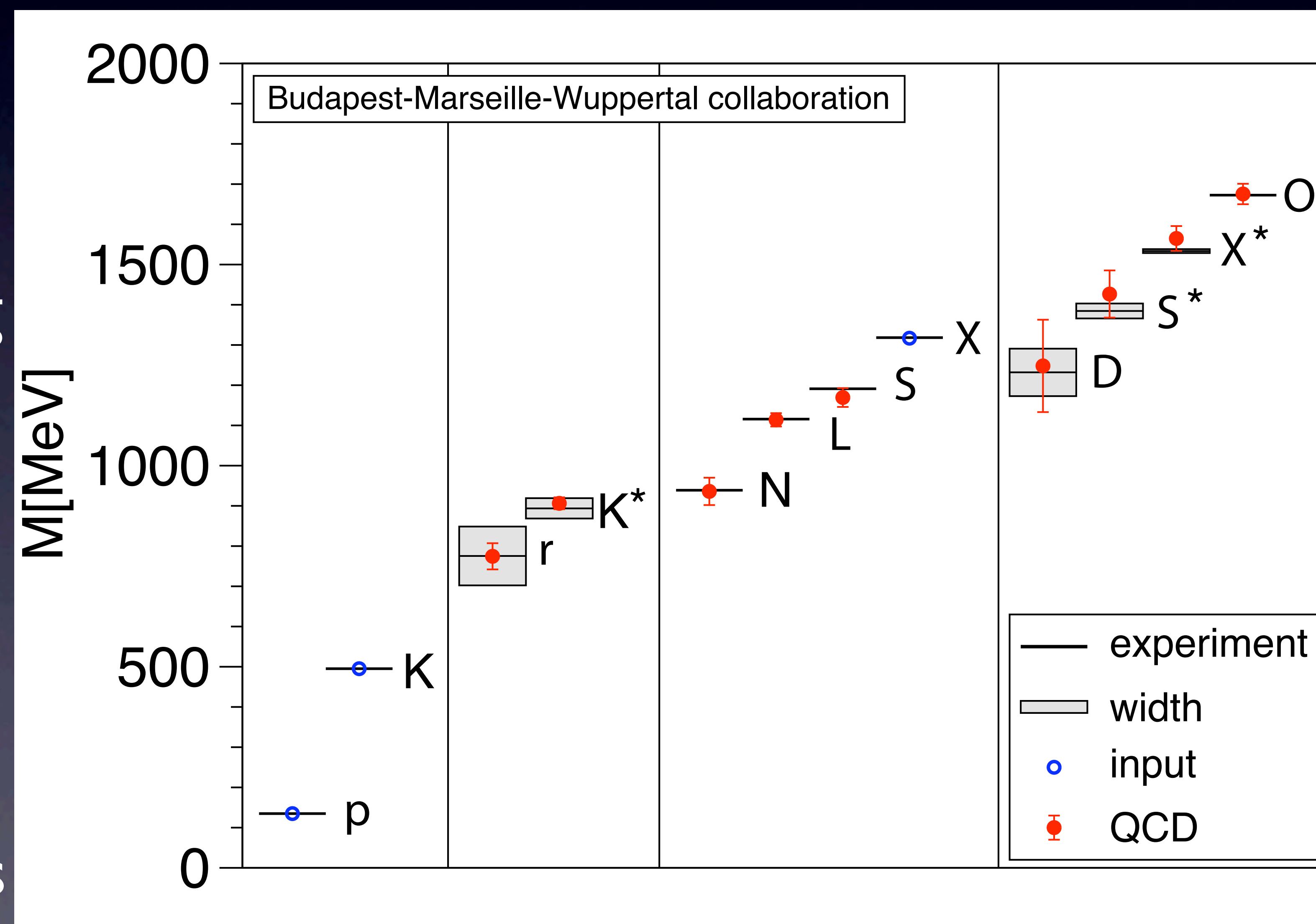

Our “particle accelerators”

IBM Blue Gene/L (JUBL), FZ Jülich
45.8 Tflop/s peak

IBM Blue Gene/P (JUGENE), FZ Jülich
223 Tflop/s peak

IBM Blue Gene/P (Babel), IDRIS Paris
139 Tflop/s peak

And computer clusters at Uni. Wuppertal and CPT Marseille

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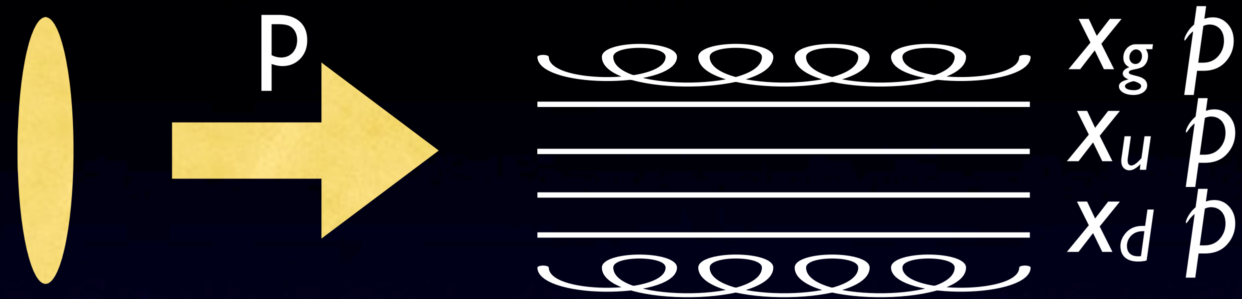
PDF



$0<x<1$

probability to find a "parton" *i* of momentum $x\,p$

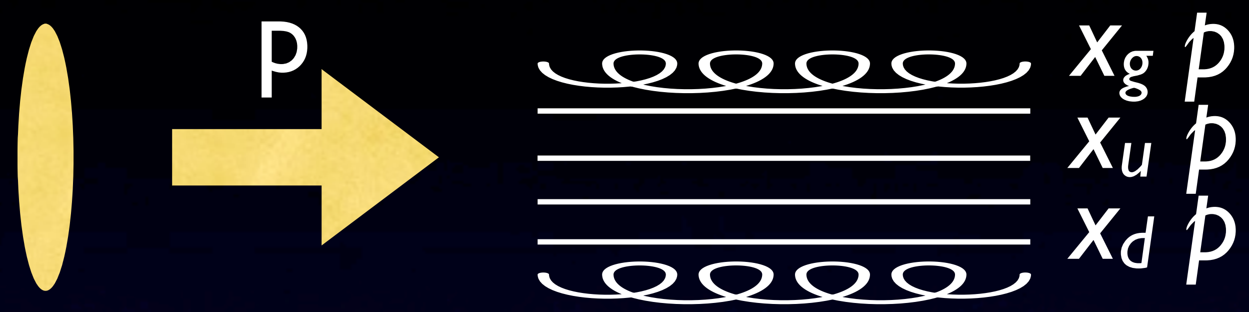
parton distribution function $f_i(x_i)$

p p collision = sum of parton-parton collision

$$\sigma = \int_0^a dx_1 \int_0^1 dx_2 f_i(x_1) f_i(x_2) \sigma(ij \to X)$$

but if you look closely (high Q^2), partons split further

PDF



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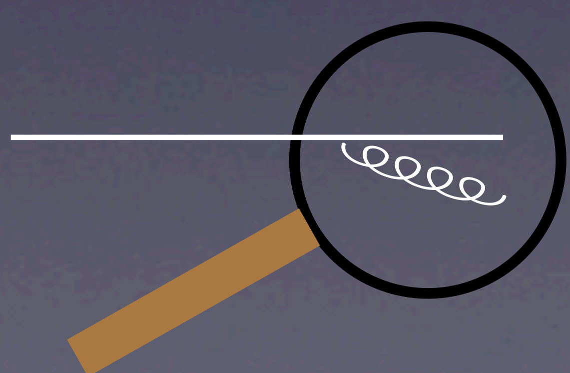

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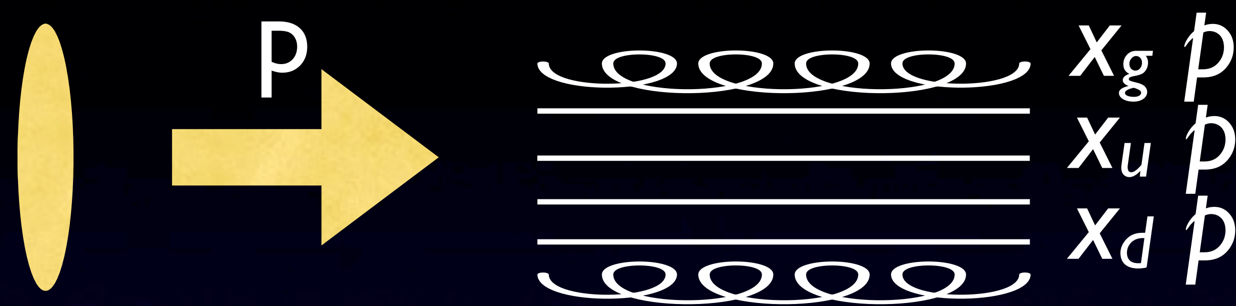

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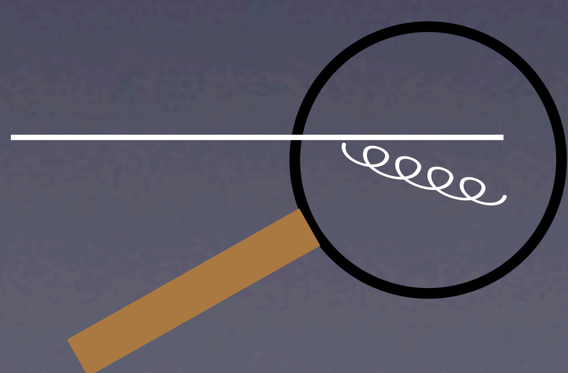
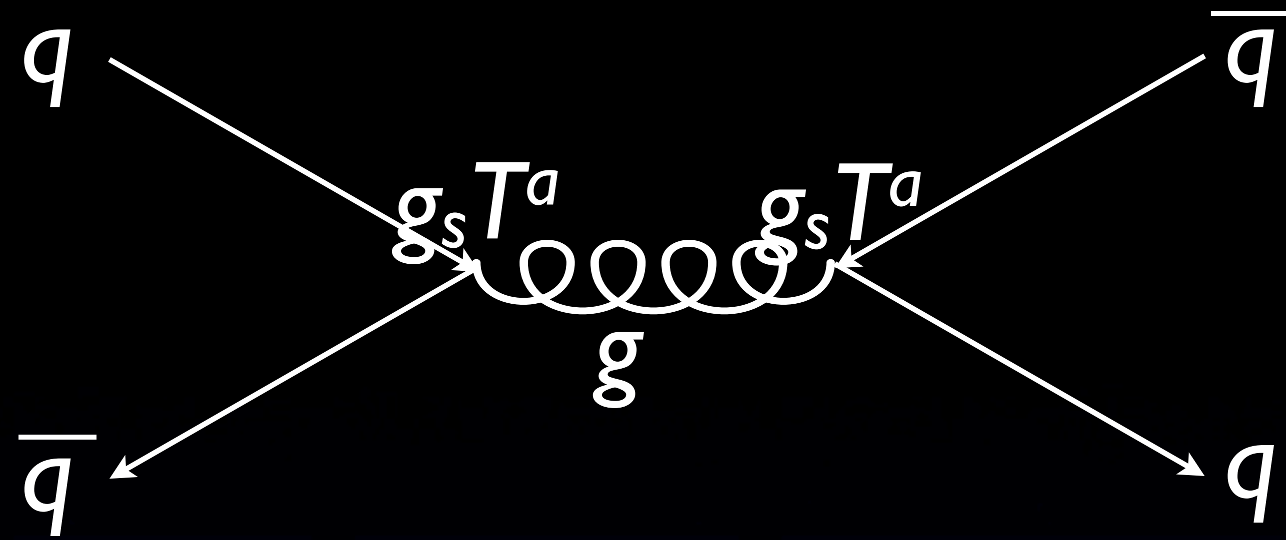


DGLAP equation

$$\frac{df_i(x)}{dQ^2} = \int_x^1 dx' f_j(x') P(j \to i + X)$$

example of parton-level cross section



pretend this is the only diagram

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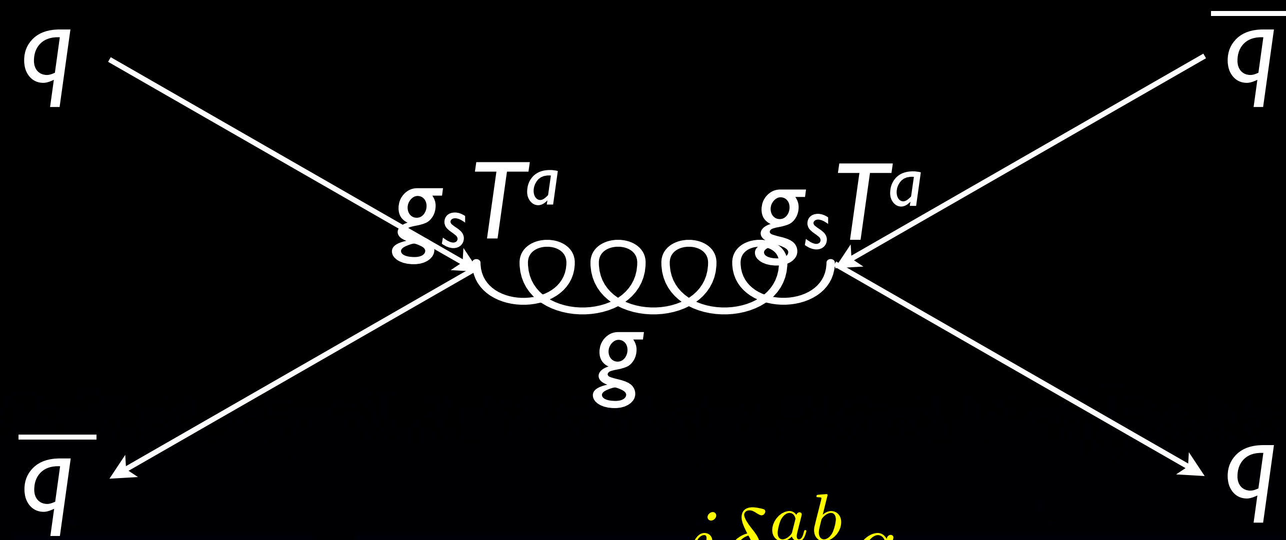

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$$i\mathcal{M} = \bar{u}(k')(-ig_s T^a)\gamma^\mu v(k) \frac{-i\delta^{ab} g_{\mu\nu}}{q^2} \bar{v}(p')(-ig_s T^a)\gamma^\nu u(p)$$

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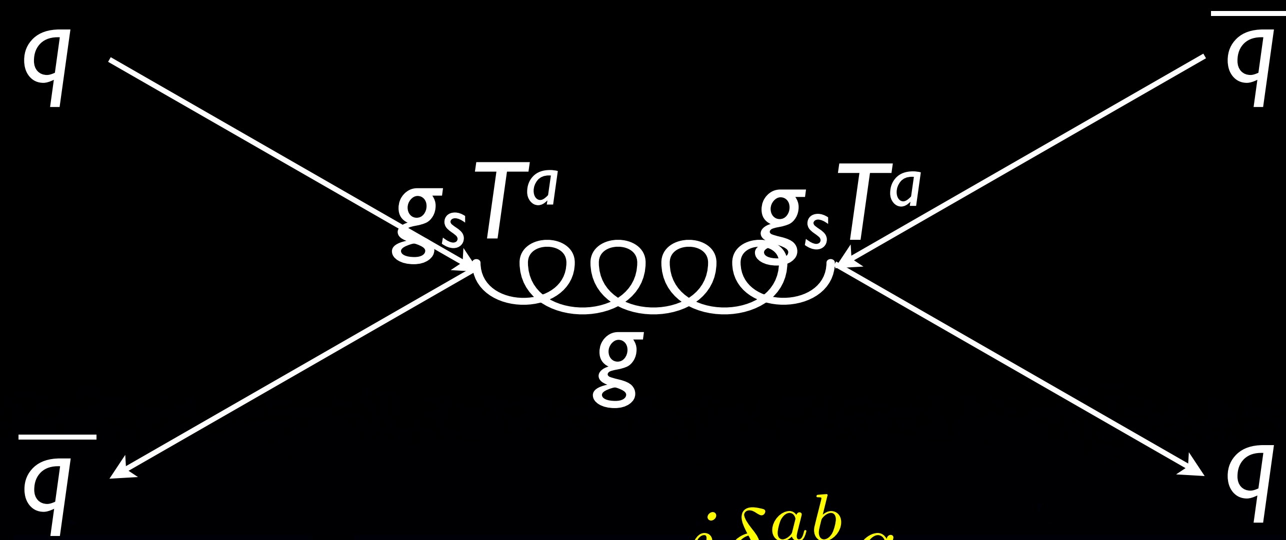

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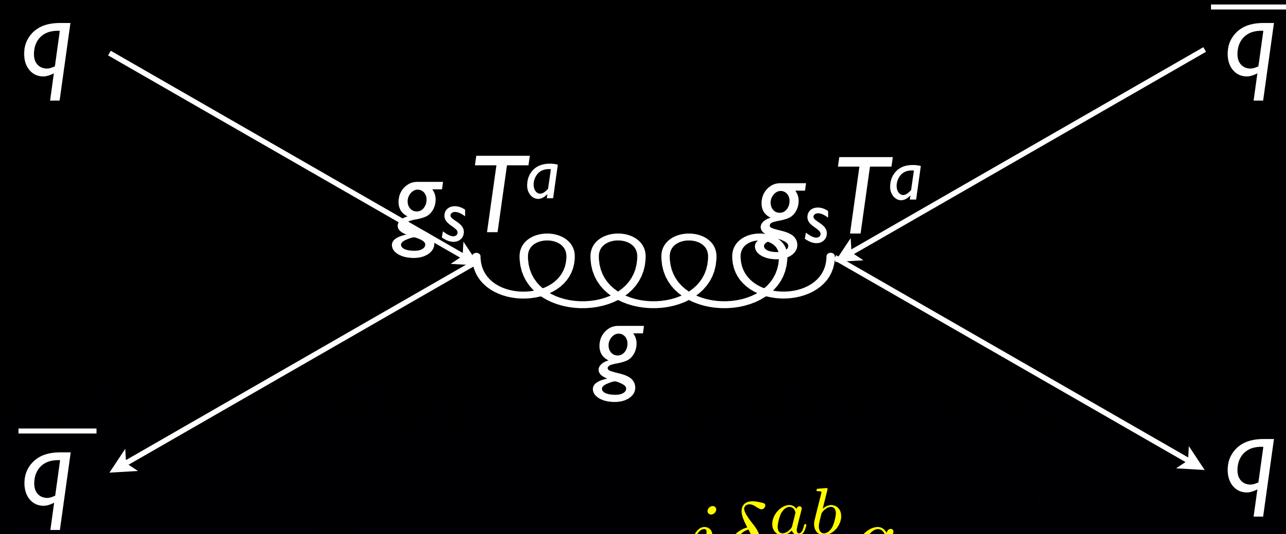

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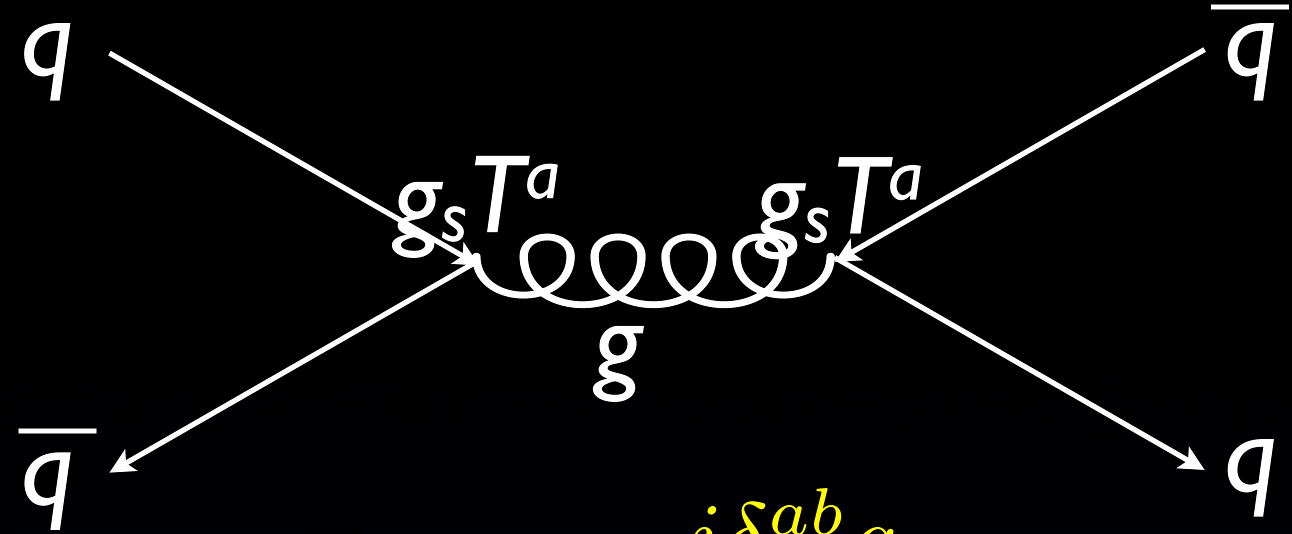

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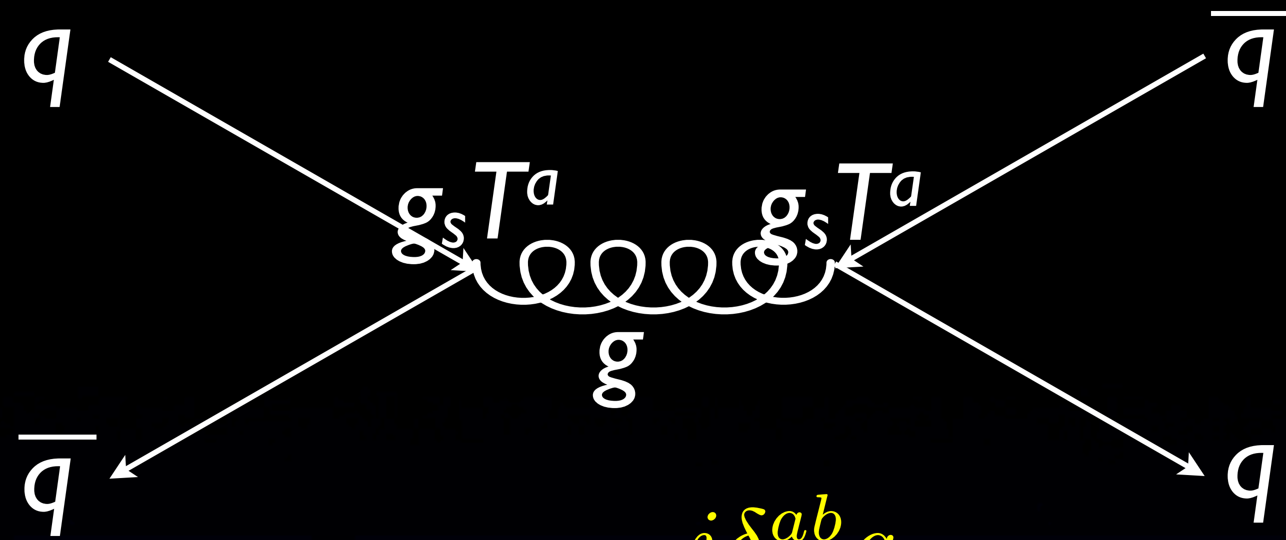

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helicity	$+$	$-$
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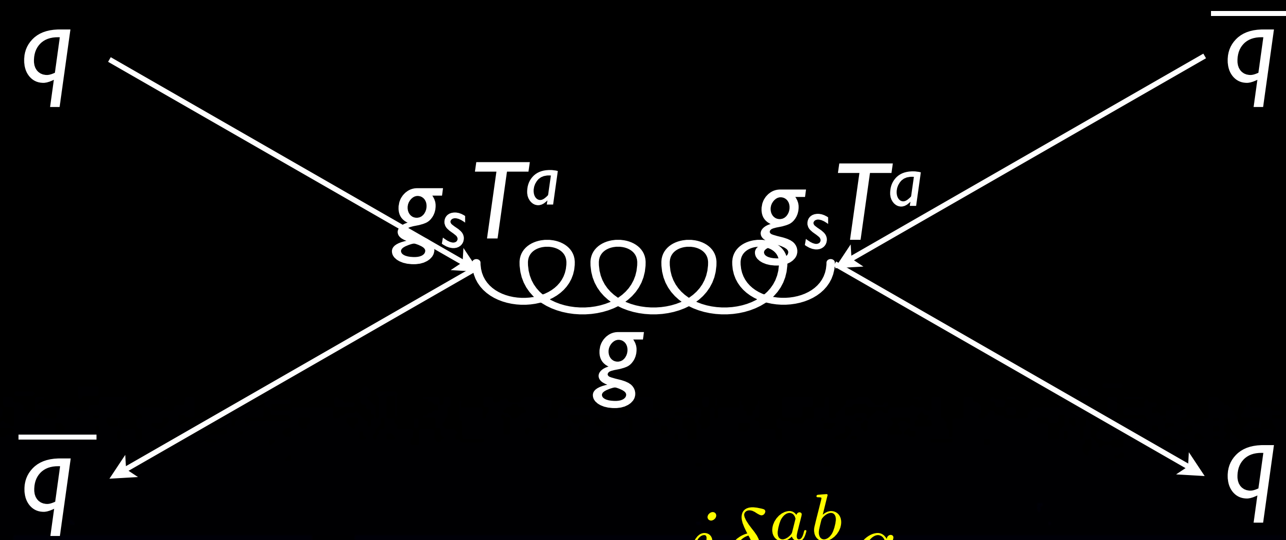

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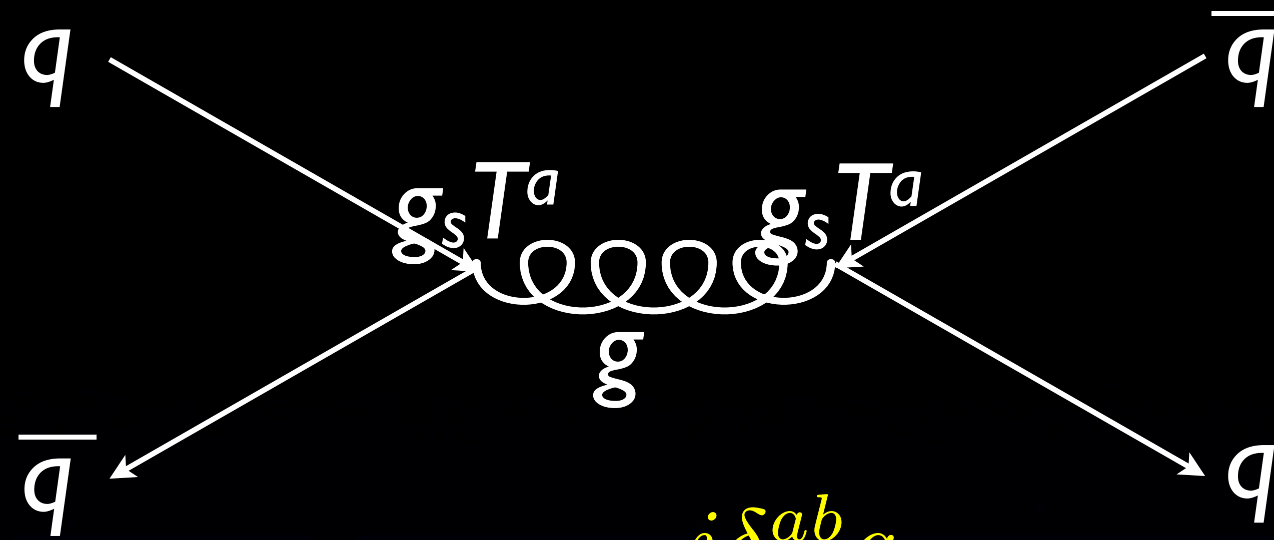

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phase space

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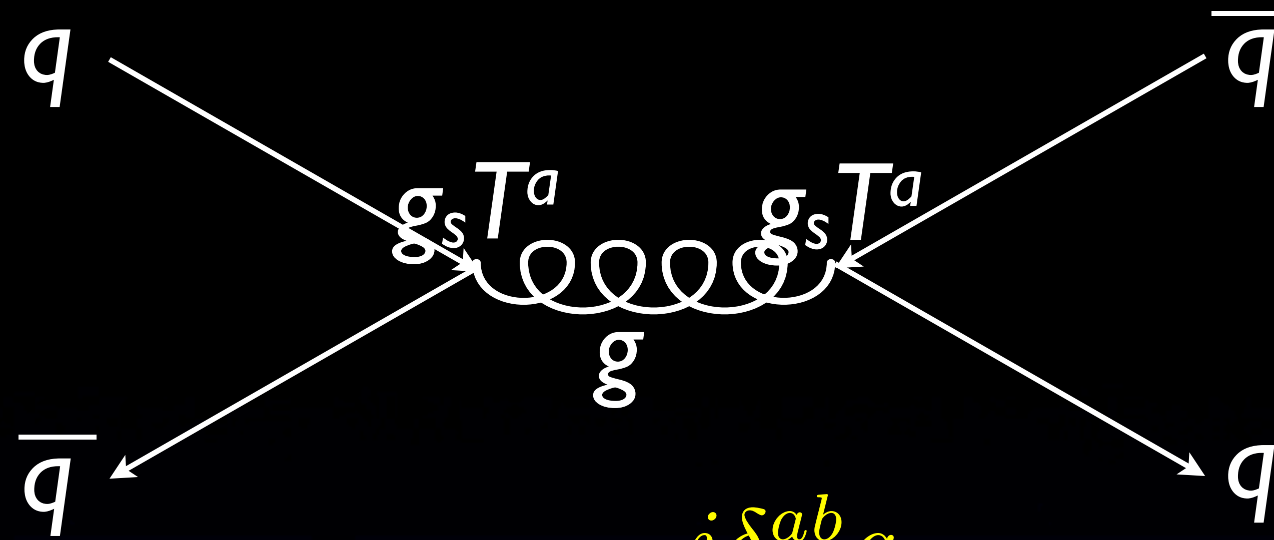
example of parton-level cross section



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phase space

flux factor

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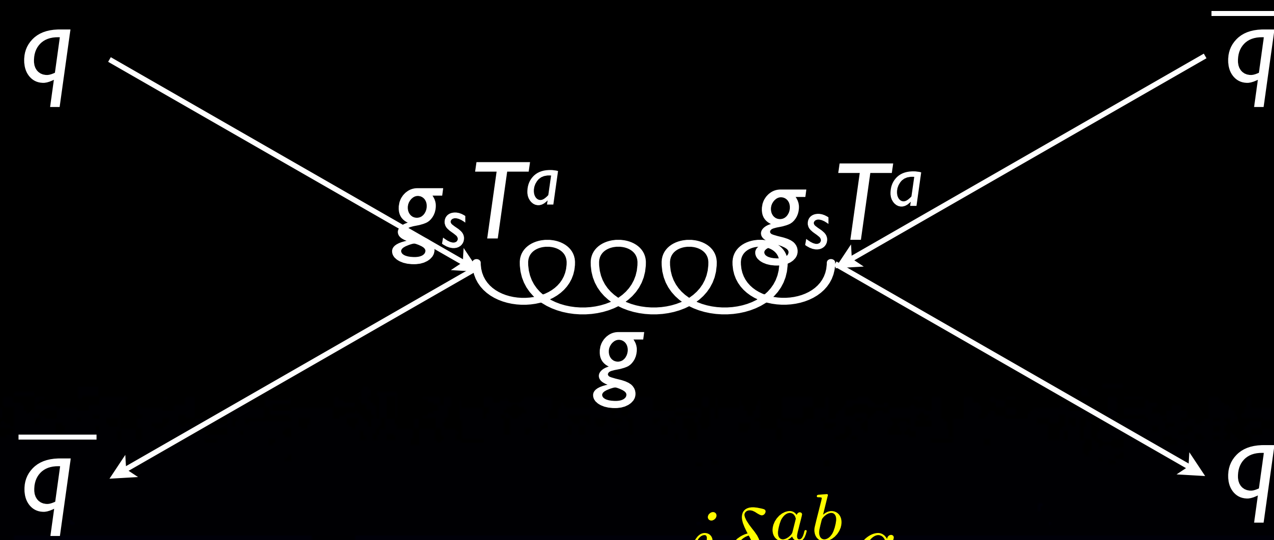
example of parton-level cross section



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phase space — flux factor — color average

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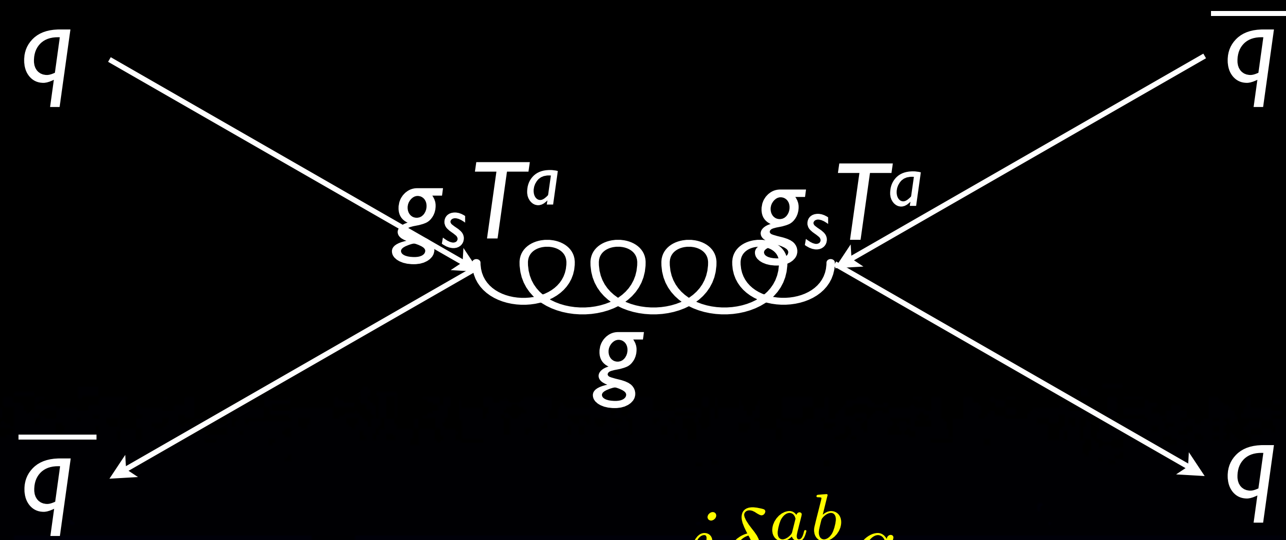

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phase space | flux factor | color average | helicity average

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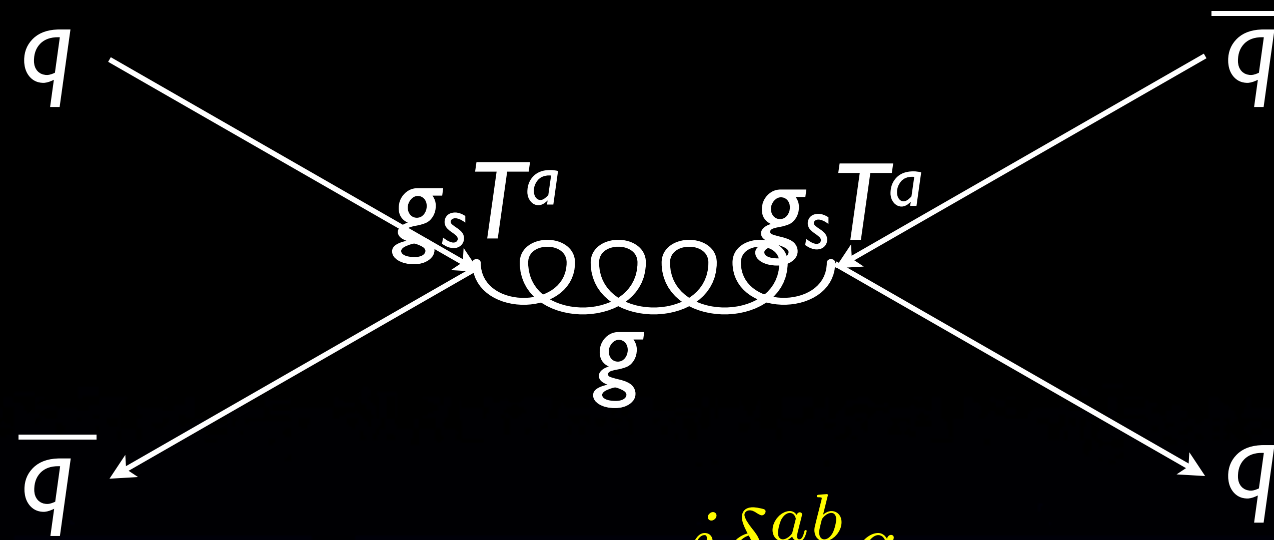

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phase space ($\frac{1}{8\pi}$) — flux factor ($\frac{1}{2s}$) — color average ($\frac{1}{N_c}\frac{1}{N_c}$) — helicity average ($\frac{1}{2}\frac{1}{2}$) — final state solid angle ($\frac{d\Omega}{4\pi}$)

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IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Standard Model 4

CERN Summer Student Programme

July 23, 2009

Hitoshi Murayama (IPMU Tokyo & Berkeley)

BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

Weak Interaction
Electroweak Theory

Weak Interaction
Electroweak Theory

Beware: too many matrices!

Fermi theory

- beta decay=decay of neutrons inside nuclei
- $n \rightarrow p\ e^- \bar{\nu}_e$
- coupling strength is G_V=1.136 10^{-5} GeV^{-2}
- vast range of nuclear lifetimes can be given by just a single constant!
- dimensional estimate: $\Gamma \propto G_F^2\, Q^5$、 $Q = E_f - E_i$

E. Fermi, Z. Physik, 88, 161 (1934)
English translation by F. Wilson

that the product

$$\tau F(\eta_0), \tag{51}$$

has the same order of magnitude for all allowed transitions. If, however, the transition in question is forbidden, the lifetime is about 100 times greater than in the normal case and, therefore, the product (51) will be correspondingly larger.

TABLE II. The values of $\tau F(\eta_0)$ for the radioactive elements for which there are sufficient data on the continuous β spectra.

Element	τ(hours)	η_0	$F(\eta_0)$	$\tau F(\eta_0)$
UX_2	0.026	5.4	115	3.0
RaB	0.64	2.04	1.34	0.9
ThB	15.3	1.37	0.176	2.7
ThC″	0.076	4.4	44	3.3
AcC″	0.115	3.6	17.6	2.0
RaC	0.47	7.07	398	190
RaE	173	3.23	10.5	1800
ThC	2.4	5.2	95	230
$MsTh_2$	8.8	6.13	73	640

In Table II, the product (51) is tabulated for the radioactive elements for which one has sufficient data concerning the continuous β spectrum. From Table II the two anticipated groups are immediately recognizable. Indeed, such a classification has already been established empirically by Sargent,[13] from whose work the values of η_0

[13] B. W. Sargent, Proc. Roy. Soc. (London) **A139**, 659 (1933).

If one assumes, say, that $\tau F(\eta_0)=1$ (i.e. measured in seconds, $=3600$) in the cases where the integral (50) equals unity, one obtains from Eq. (45)

$$g=4(10^{-50})\text{ cm}^3\text{ erg.}$$

This value naturally will be only an order of magnitude of g.

To summarize, one can say that this comparison of theory and experiment gives as good an agreement as one could expect. The discrepancies found for the hard-to-pin-down data for elements, RaD and AcB, probably could be explained in part through inaccuracy of the measurements, partly, also, by the abnormally large, although not at all implausible, variations of the matrix elements in Eq. (50). Note further that one can

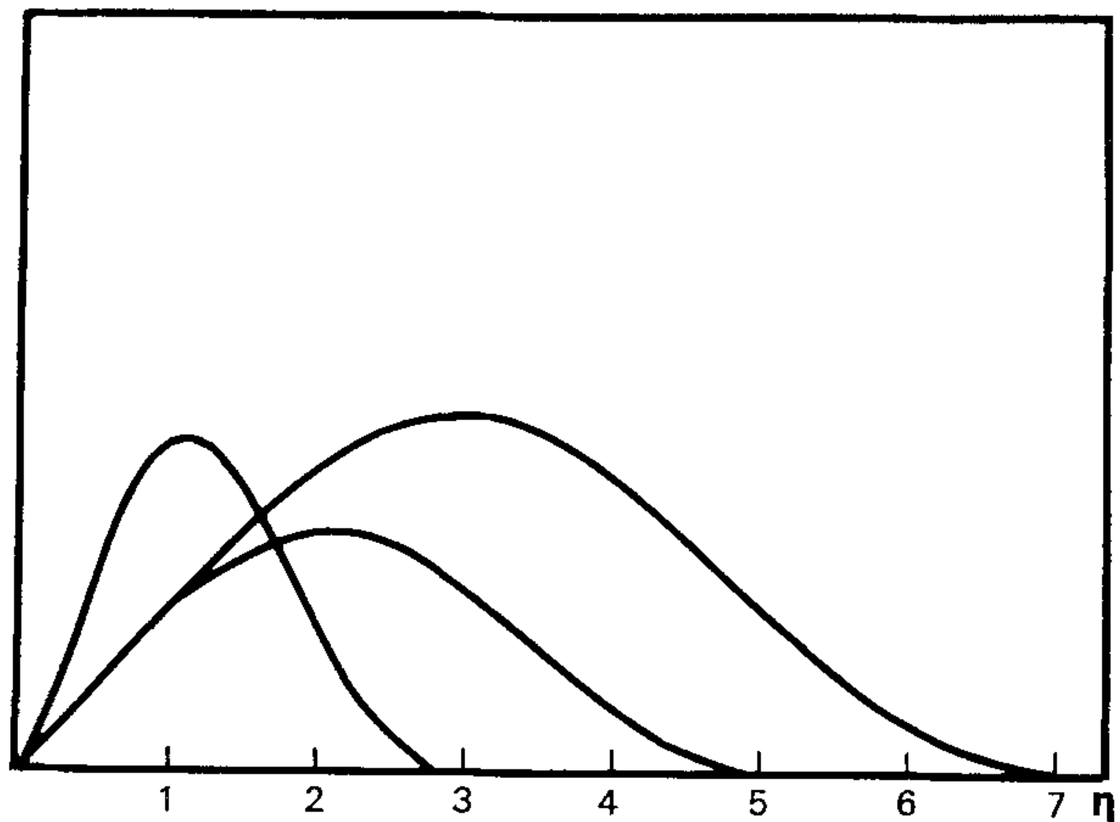

FIG. 2. Velocity distribution curves for different values of η_0.

E. Fermi, Z. Physik, 88, 161 (1934)
English translation by F. Wilson

Thursday, July 23, 2009

Universality

	$t_{1/2}$ (s)	G_V (GeV^{-2})
^{14}O	70603	1.156
$^{26}Al^m$	6344.9	1.157
^{34}Cl	1525.8	1.154
$^{38}K^m$	923.95	1.154
^{42}Sc	679.90	1.155
^{46}V	422.37	1.155
^{50}Mn	283.07	1.156
^{54}Co	193.23	1.155

J. C. Hardy and I. S. Towner, Phys. Rev. Lett. 94, 092502 (2005)

Fermi Scale

- $G_F^{-1/2}$=300 GeV
- $G_F^{1/2}$=6.7×10^{-17} cm
- We will be there soon!

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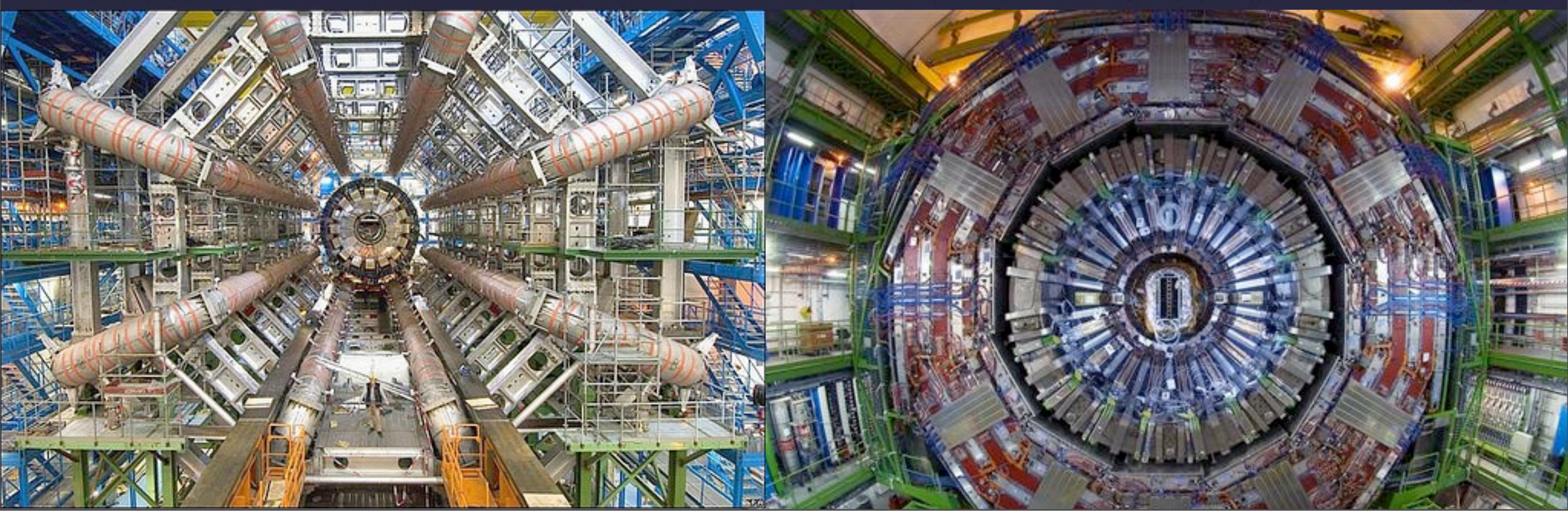
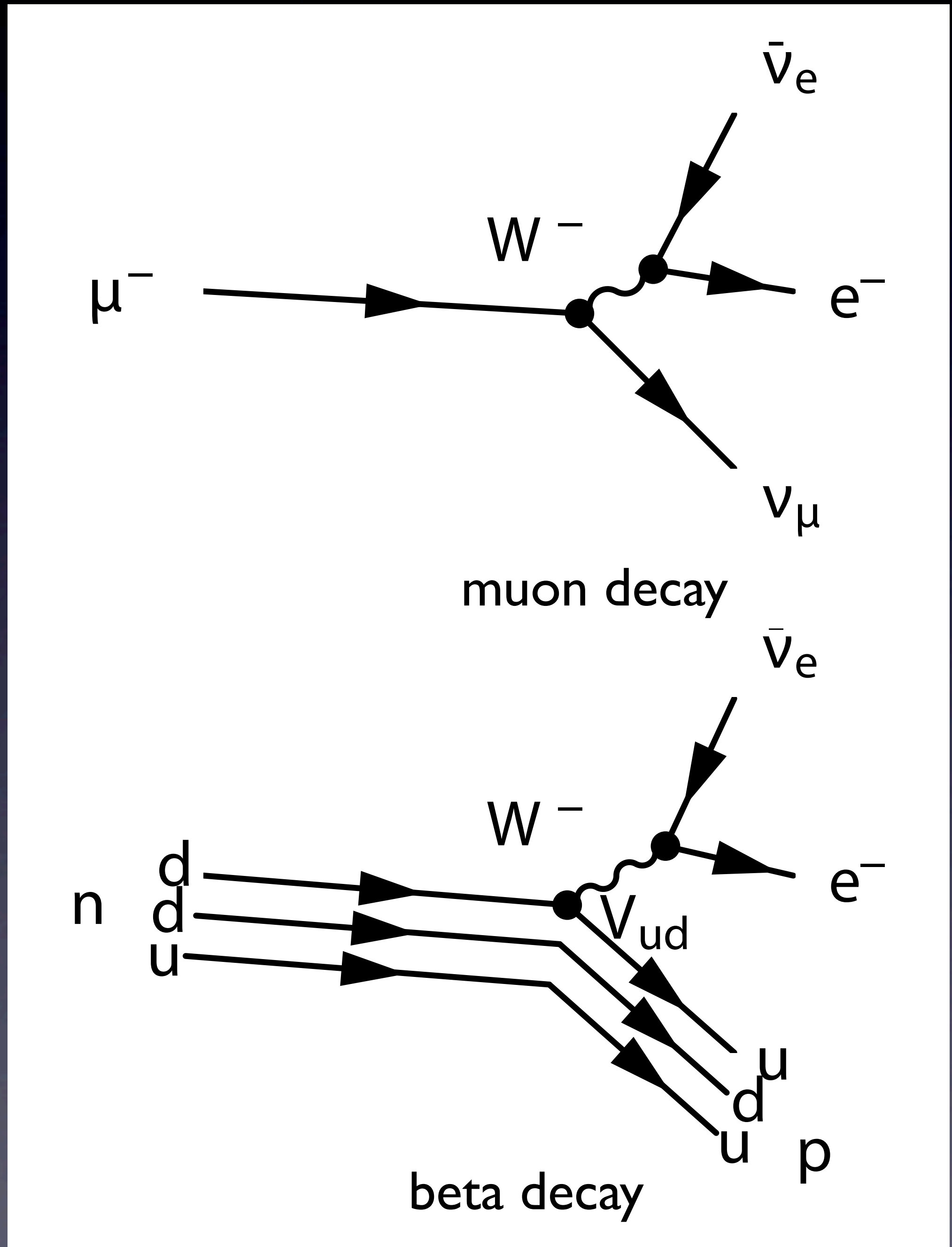


Universality

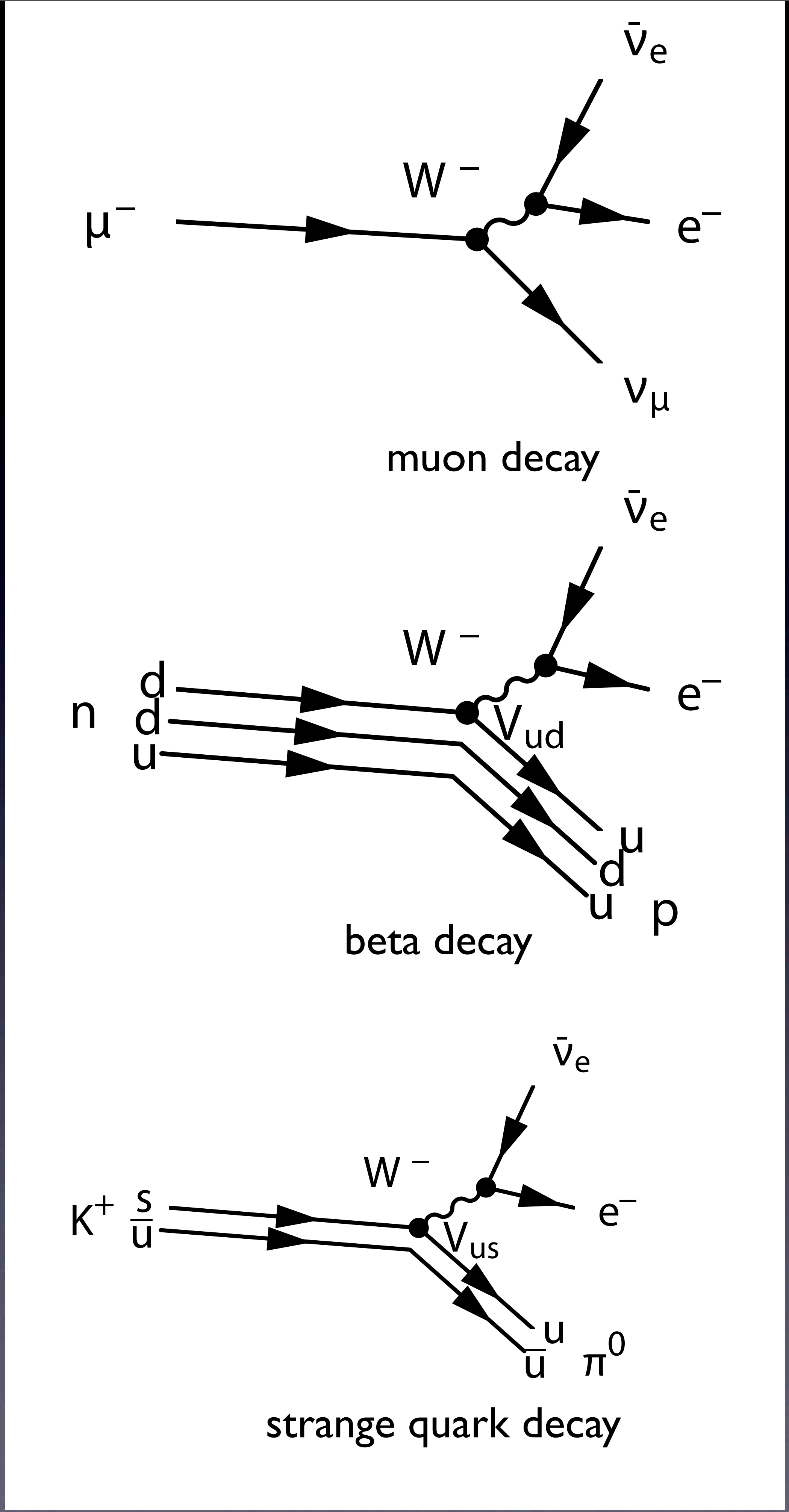
- Fermi tried something analogous to QED, but the force is short-ranged
- a new massive spin 1 boson? (W boson)
- G_F=1.16637(1) 10^{-5} GeV^{-2}
- G_V=1.136(3) 10^{-5} GeV^{-2}
- agreed with past accuracies
- but don't agree with current accuracies



Cabibbo angle

- strange quark decays into up quark, too
- *generalized* universality
- the *total strength* of weak interaction into the up quark
- $|V_{ud}|^2+|V_{us}|^2=1$
- $V_{ud}=\cos\theta_C$, $V_{us}=\sin\theta_C$
- Idea is that up quark is *paired* with a linear combination
  $d' = d\,V_{ud} + s\,V_{us}$
- Now very well tested:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 0.9992 \pm 0.0011$$



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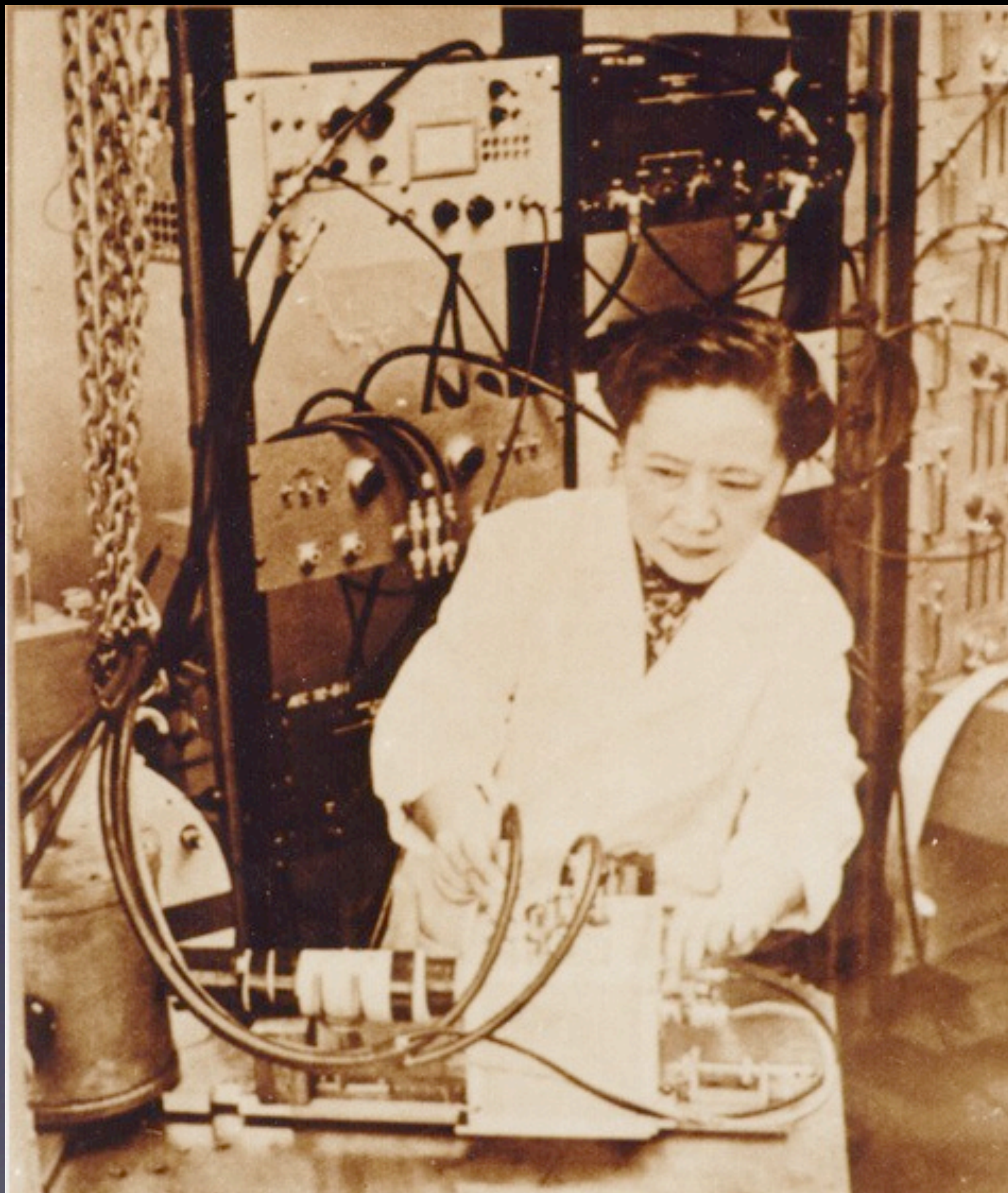
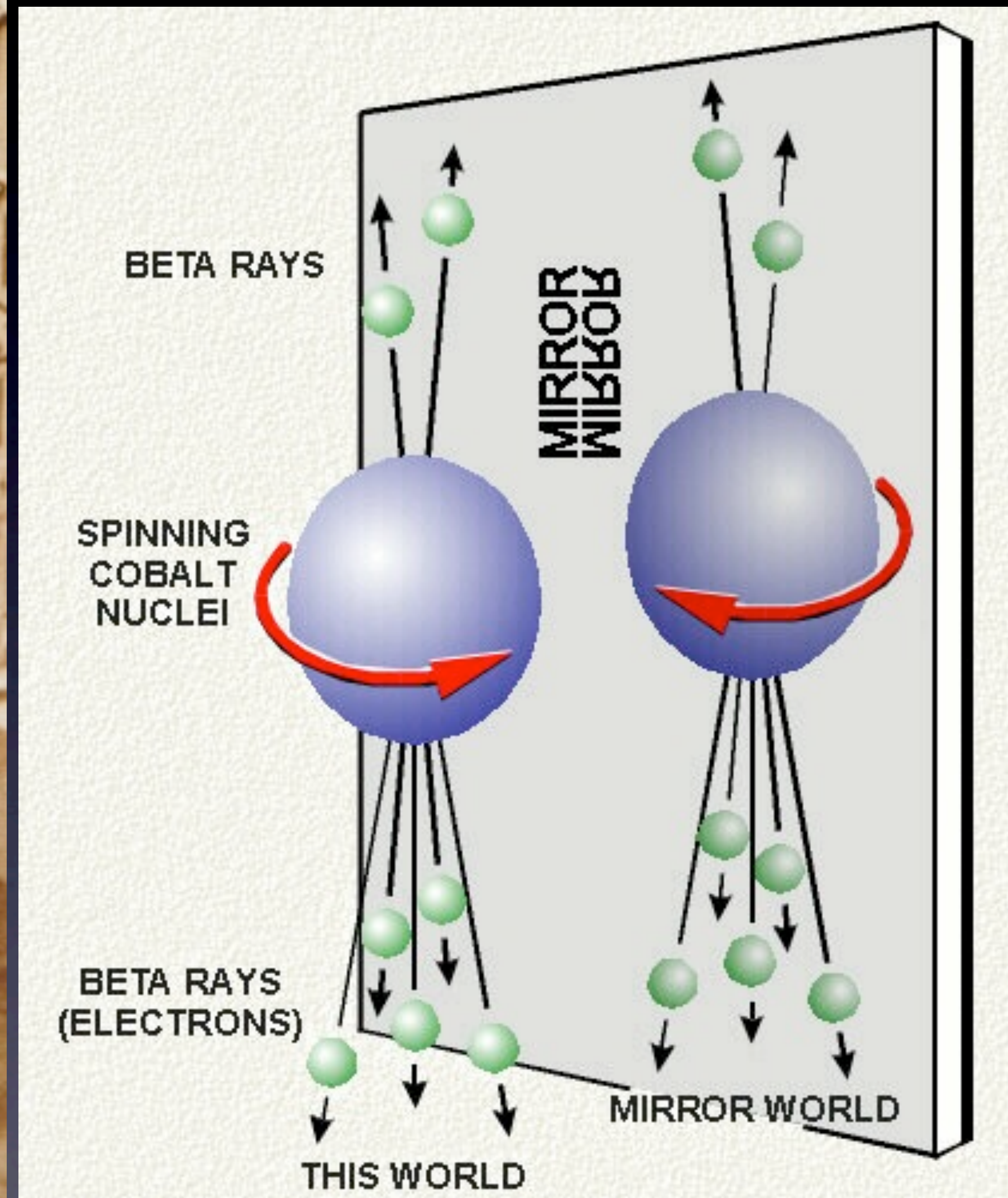
- weak interaction is *left-handed*, namely it acts only of left-handed quarks and leptons

C.S. Wu's experiment





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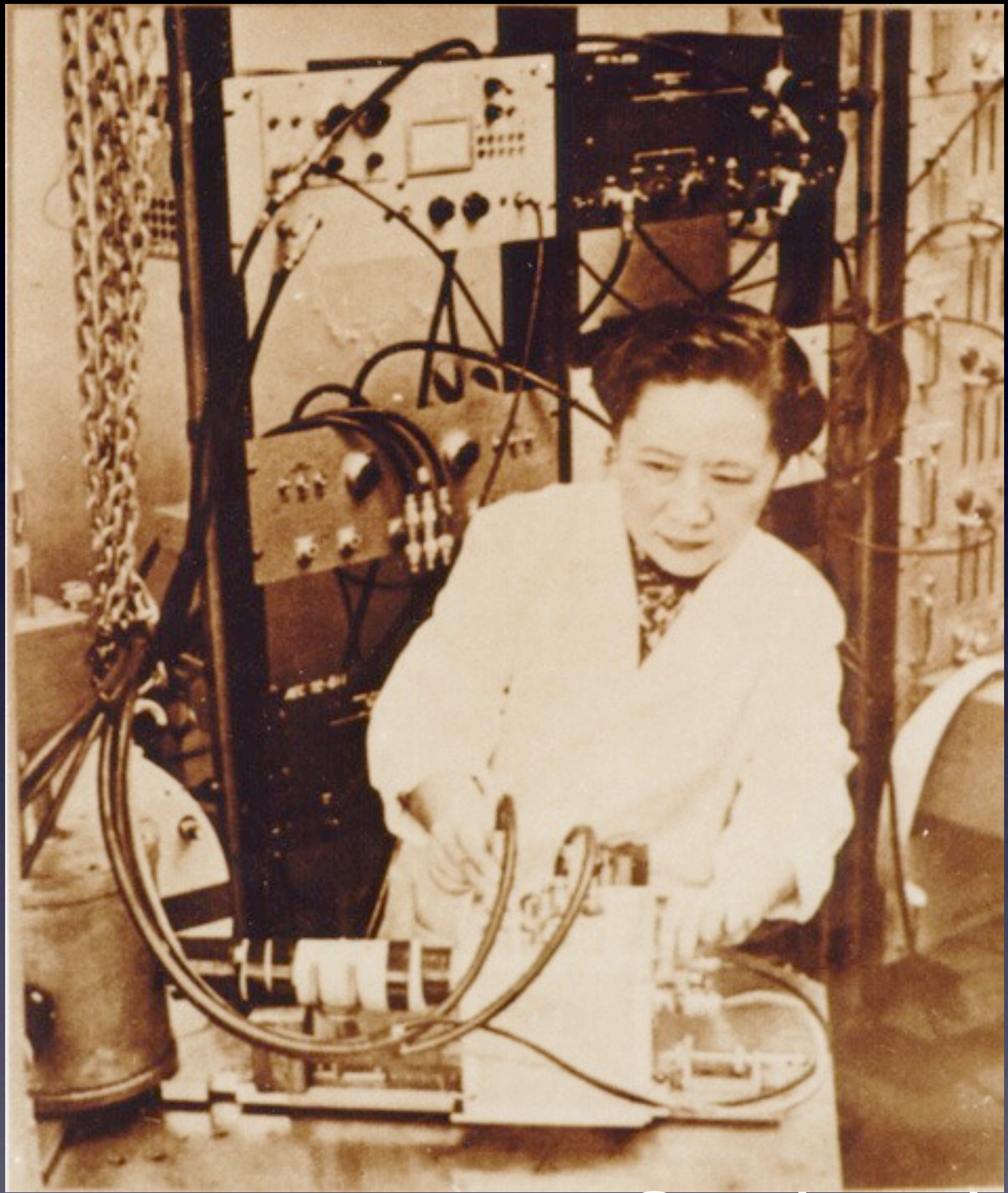

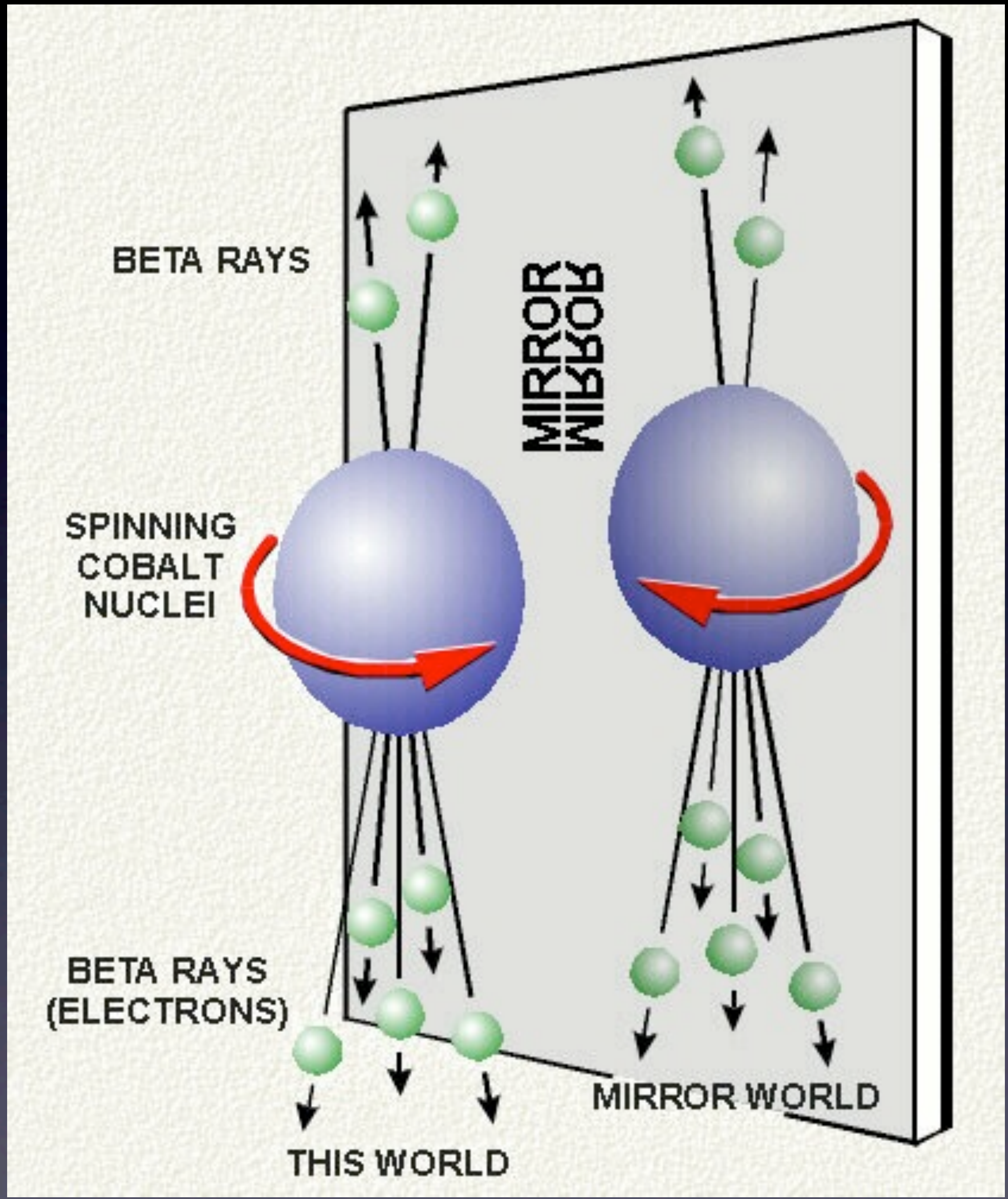

Quickest Nobel prize

1956 paper and 1957 prize to Lee & Yang!

Big shock!

Big shock!

- Right and Left are fundamentally different

Big shock!

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- Right and Left are fundamentally different
- You can tell aliens on a distant planet which is right, which is left

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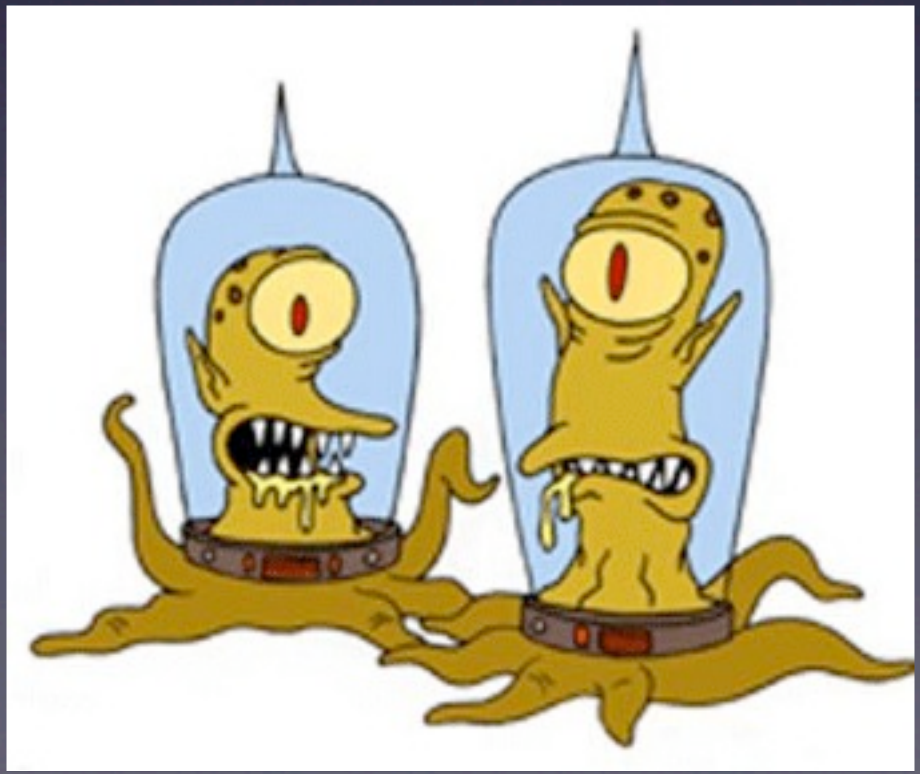
Big shock!

- Right and Left are fundamentally different
- You can tell aliens on a distant planet which is right, which is left
- should *not* be related to why most humans are right-handed




CP

Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).

CP

- Famous experiment by Goldhaber, Grodzins, Sunyar
- Neutrinos are all left-handed
- This of course violates parity
- What about CP?
- All anti-neutrinos are right-handed
- CP still appears still good!

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IPMU

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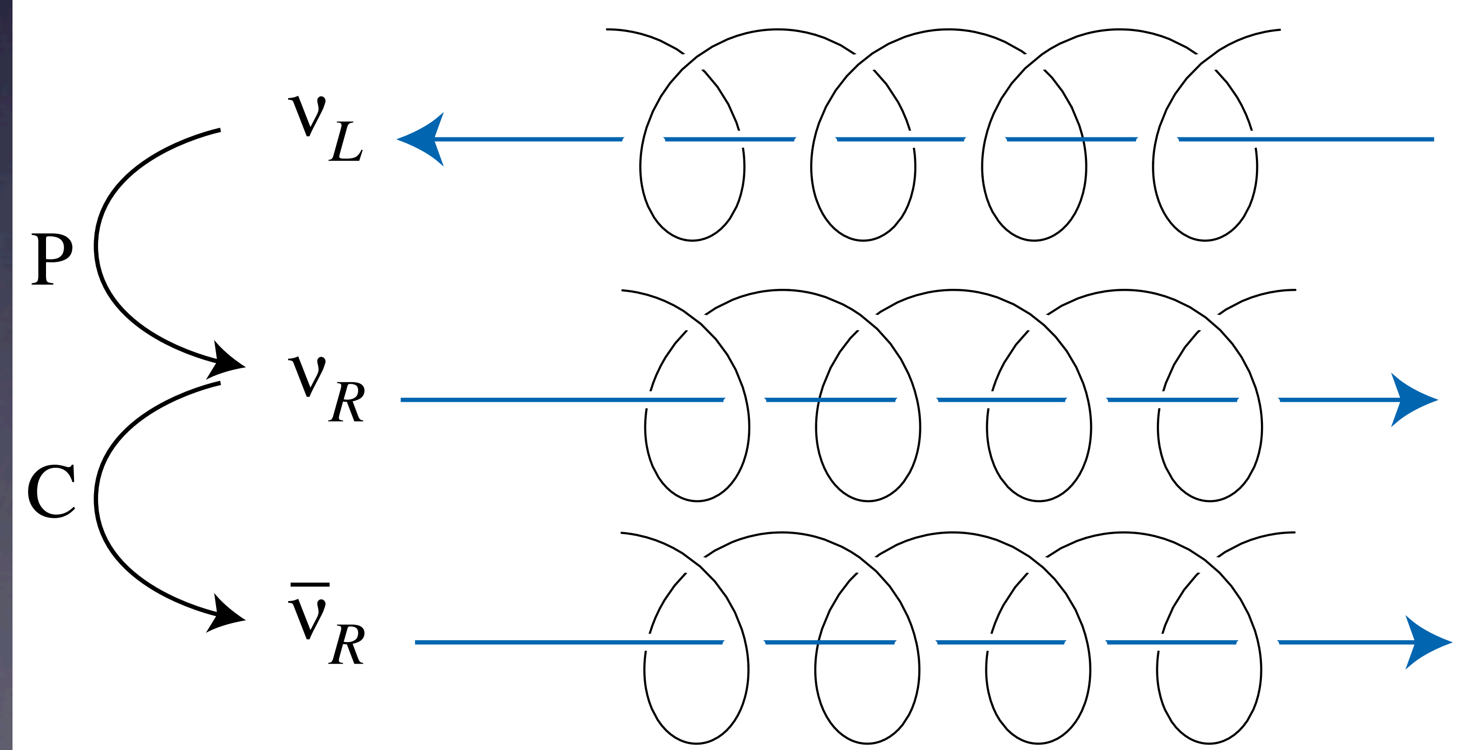


Glashow-Weinberg-Salam Model

- We need many left-handed doublets

$$\begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}, \begin{pmatrix} u \\ d' = dV_{ud} + sV_{us} \end{pmatrix}, \begin{pmatrix} c \\ s' = dV_{cd} + sV_{cs} \end{pmatrix}$$

- *W*-boson raises or lowers within doublets
- needs generators of the types

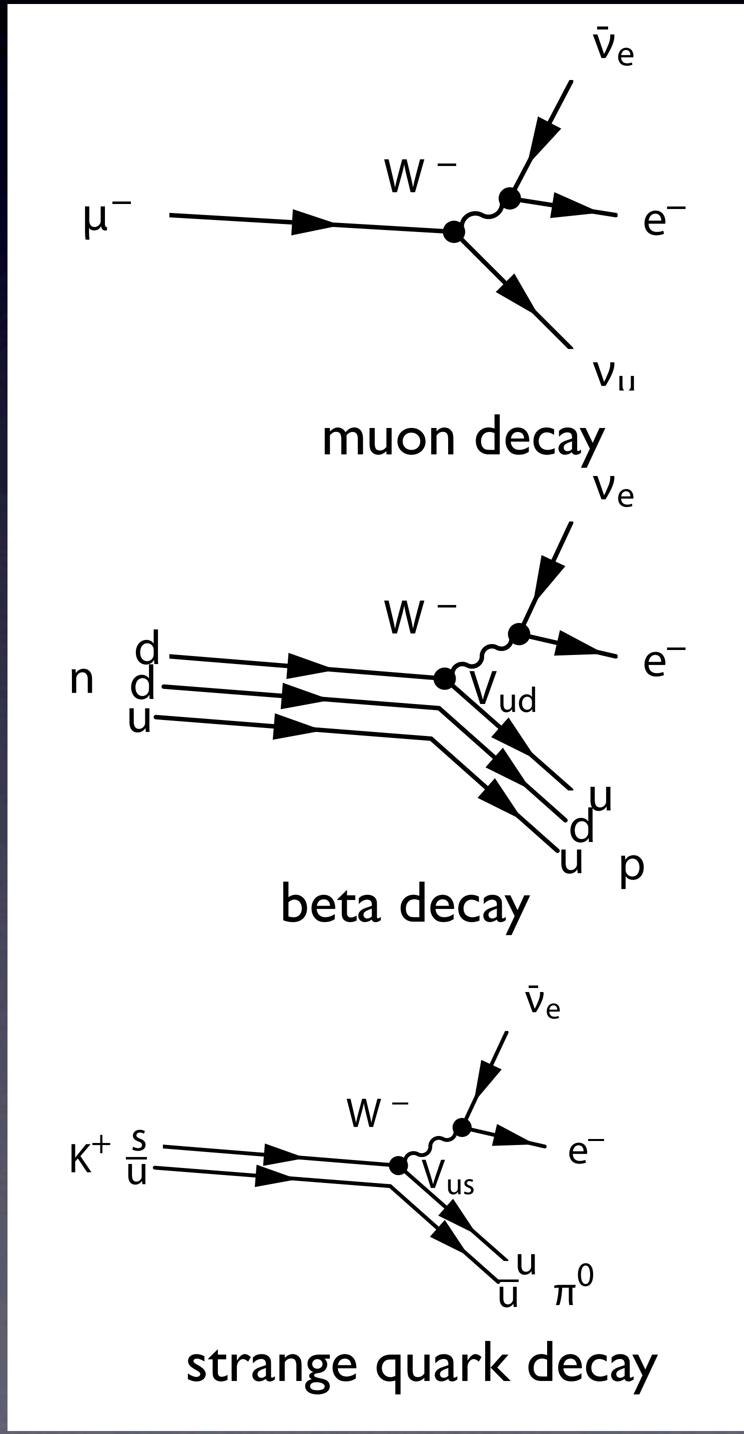
$$\frac{1}{2}\tau_1 = \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

$$\frac{1}{2}\tau_2 = \frac{1}{2}\begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}$$

- Looks like SU(2)!
- But then what about the third one

$$\frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

- not quite electric charges....



Glashow-Weinberg-Salam Model

- Need something weird
- need both SU(2) & U(1)
- *four* generators
- τ_1, τ_2: $W^\pm$ bosons for "*charged-current* weak interaction"
- use one combination $\frac{1}{2}\tau_3+Y$ for photon
- then remaining combination is a new force "*neutral-current* weak interaction"

$$\frac{1}{2}\tau_1 = \frac{1}{2}\begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}$$

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$$\frac{1}{2}\tau_3 = \frac{1}{2}\begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$

$$Y$$

$$Q = \frac{1}{2}\tau_3 + Y = \begin{pmatrix} \frac{1}{2}+Y & 0 \\ 0 & -\frac{1}{2}+Y \end{pmatrix}$$

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- For lepton doublets, we need $Y=-1/2$, so that electric charges are $Q=I_3+Y=0$ and -1
- For quark doublets, we need $Y=1/6$, so that the charges are $Q=+2/3$ and $-1/3$

photon and Z

- Interaction with quarks & leptons

$$g\frac{1}{2}\begin{pmatrix} W_\mu^3 & W_\mu^1 - iW_\mu^2 \\ W_\mu^1 + iW_\mu^2 & -W_\mu^3 \end{pmatrix} + g'YB_\mu$$

$$= \frac{1}{2}g\begin{pmatrix} 0 & \sqrt{2}\,W_\mu^+ \\ \sqrt{2}\,W_\mu^- & 0 \end{pmatrix} + \begin{pmatrix} \frac{1}{2}gW_\mu^3 + g'YB_\mu & 0 \\ 0 & -\frac{1}{2}gW_\mu^3 + g'YB_\mu \end{pmatrix}$$

- introduce the weak mixing angle θ_W and write $\begin{pmatrix} B_\mu \\ W_\mu^3 \end{pmatrix} = \begin{pmatrix} \cos\theta_W & -\sin\theta_W \\ \sin\theta_W & \cos\theta_W \end{pmatrix}\begin{pmatrix} A_\mu \\ Z_\mu \end{pmatrix}$
- Now make sure photon couples correctly

$$g'Y\cos\theta_W + gI_3\sin\theta_W = e(I_3 + Y) = eQ$$

$$g'\cos\theta_W = g\sin\theta_W = e$$

photon and Z

- Now we know how Z couples

$$
\begin{aligned}
& g I_3 \cos\theta_W - g' Y \sin\theta_W \\
&\quad = \frac{e}{\sin\theta_W \cos\theta_W}\left(I_3 \cos^2\theta_W - Y \sin^2\theta_W\right) \\
&\quad = g_Z\left(I_3 - Q\sin^2\theta_W\right)
\end{aligned}
$$

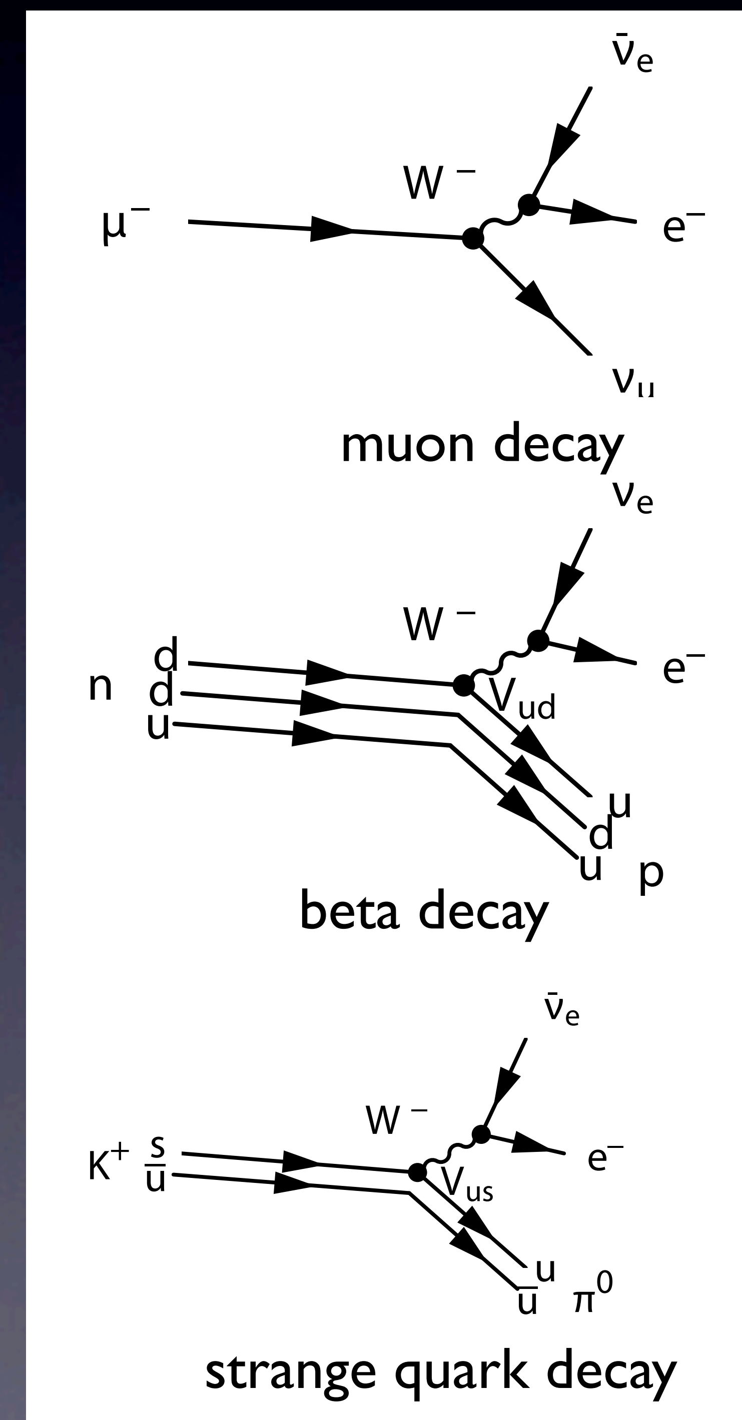
- a new force that does not change the charge, but couples to neutrinos!
- Gargamelle found it in 1973 in the reaction $\nu_\mu e^- \to \nu_\mu e^-$, see François' lectures

Back to Fermi

- Fermi constant comes from exchange of *W* boson

$$G_F = 1.16637(1) \times 10^{-5}\mathrm{GeV}^{-2} = \frac{g^2}{4\sqrt{2}m_W^2}$$

- Can't predict m_W unless you know $g = e/\sin\theta_W$
- Thankfully, NC weak interaction strengths depend on θ_W $\frac{e}{s_W c_W}(I_3 - Q s_W^2)$
- neutrino experiments and an e *d* scattering experiment measured θ_W, and predicted $m_W \approx 80$ GeV, $m_Z \approx 90$ GeV



Discovery of *W* and *Z*

- SppS at CERN produced *W* and *Z* (1983)
- 1984 Nobel to Rubbia and van der Meer
- LEP mass-produced $e^+e^- \to Z$, $e^+e^- \to W^+W^-$
- very precise measurements

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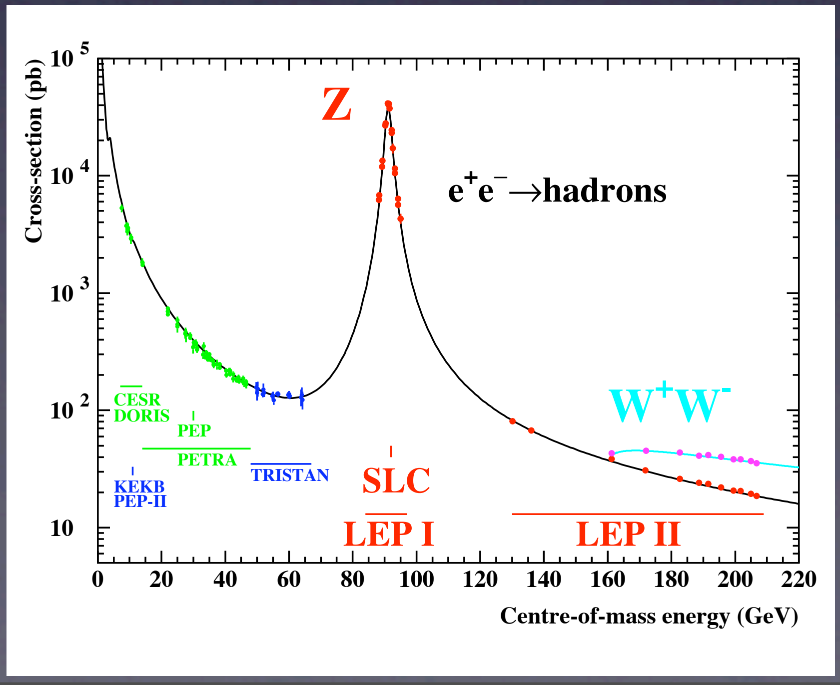

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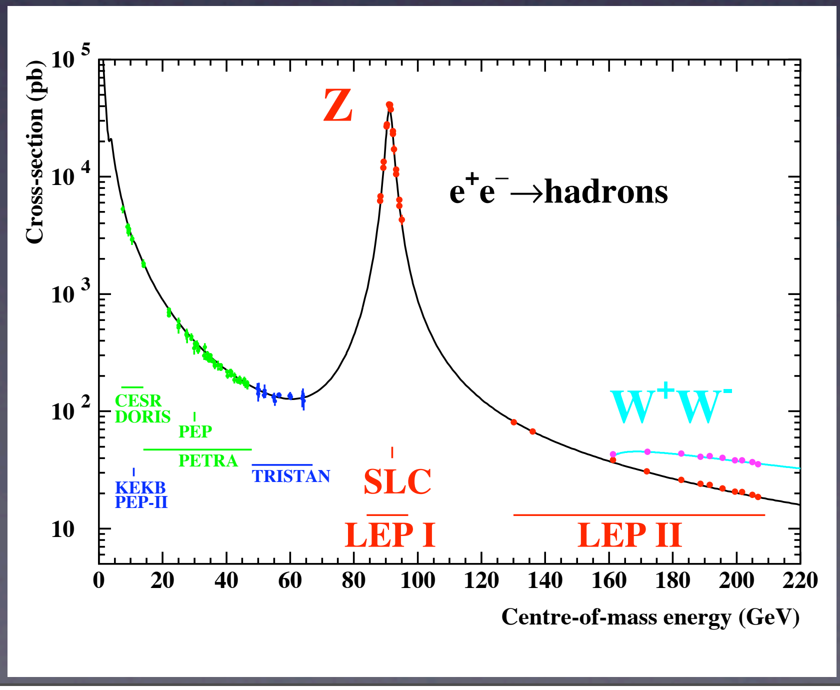

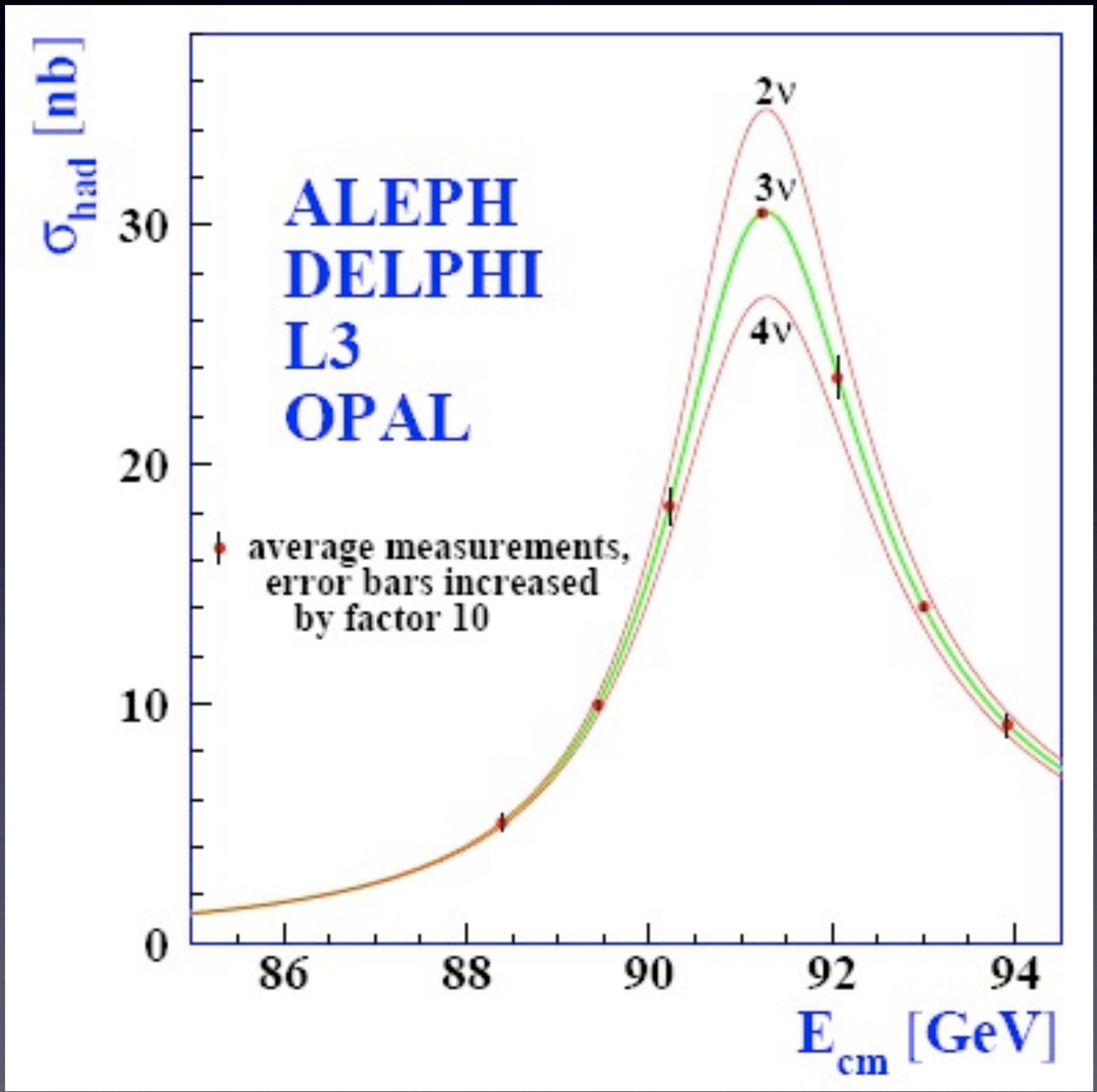

LEP discovered the moon and TGV

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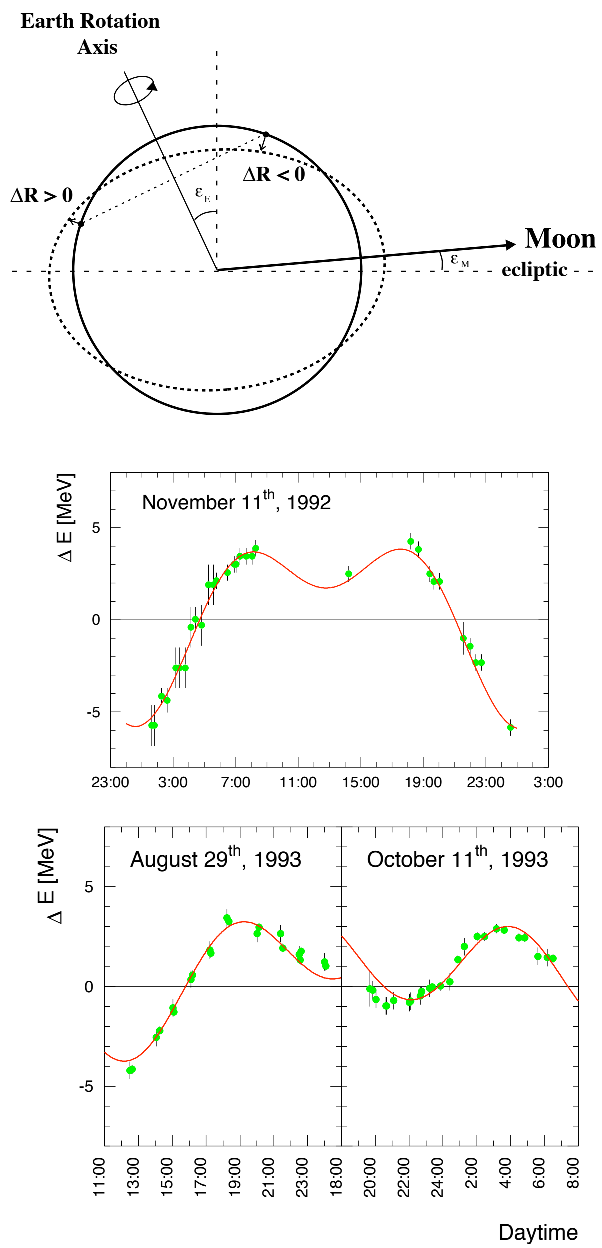

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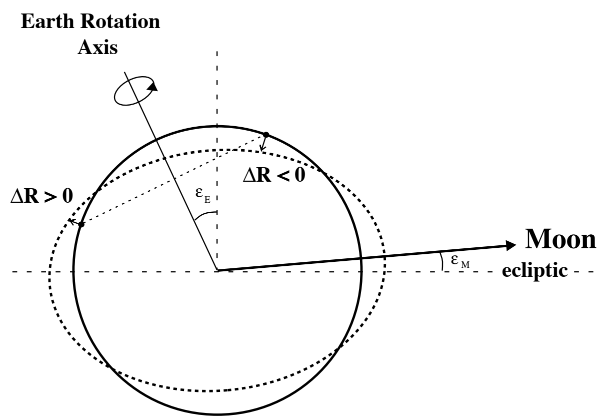
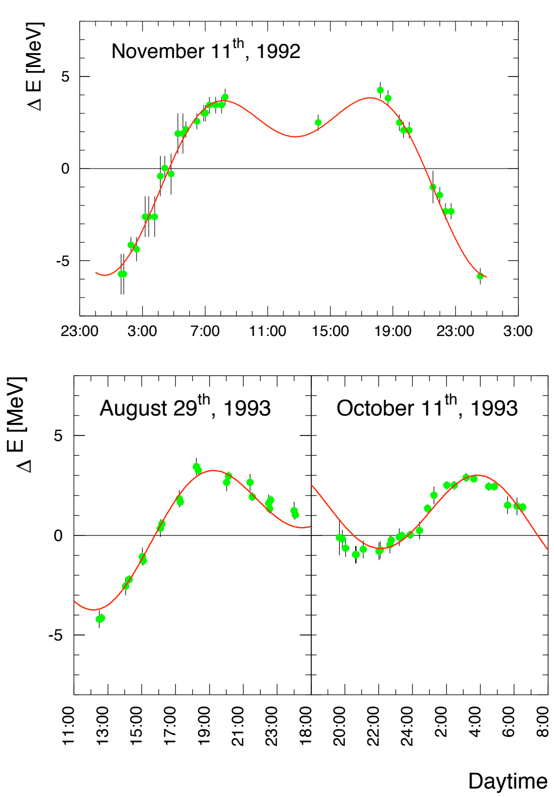
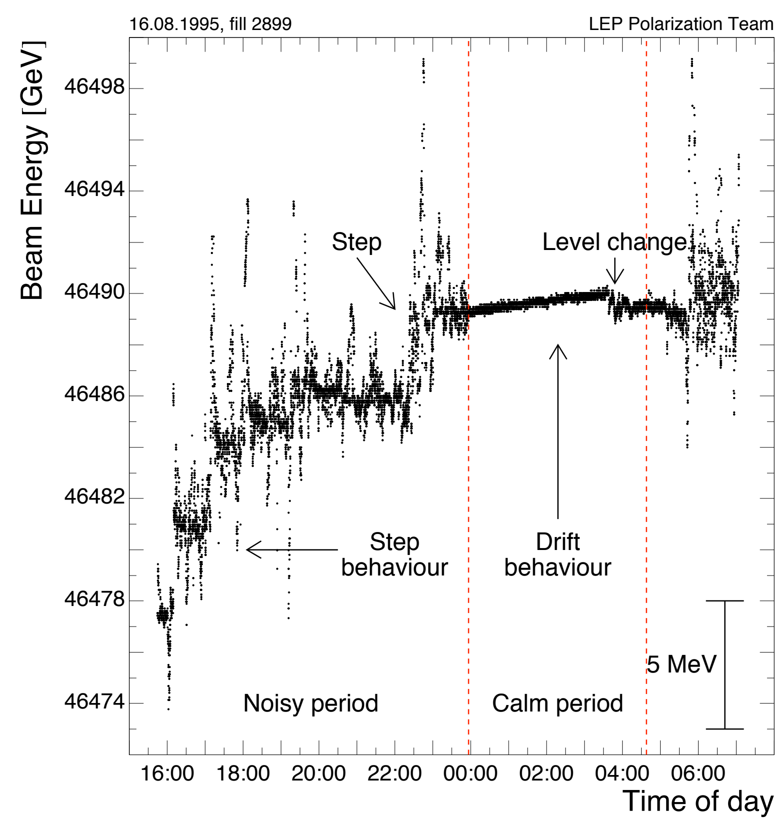
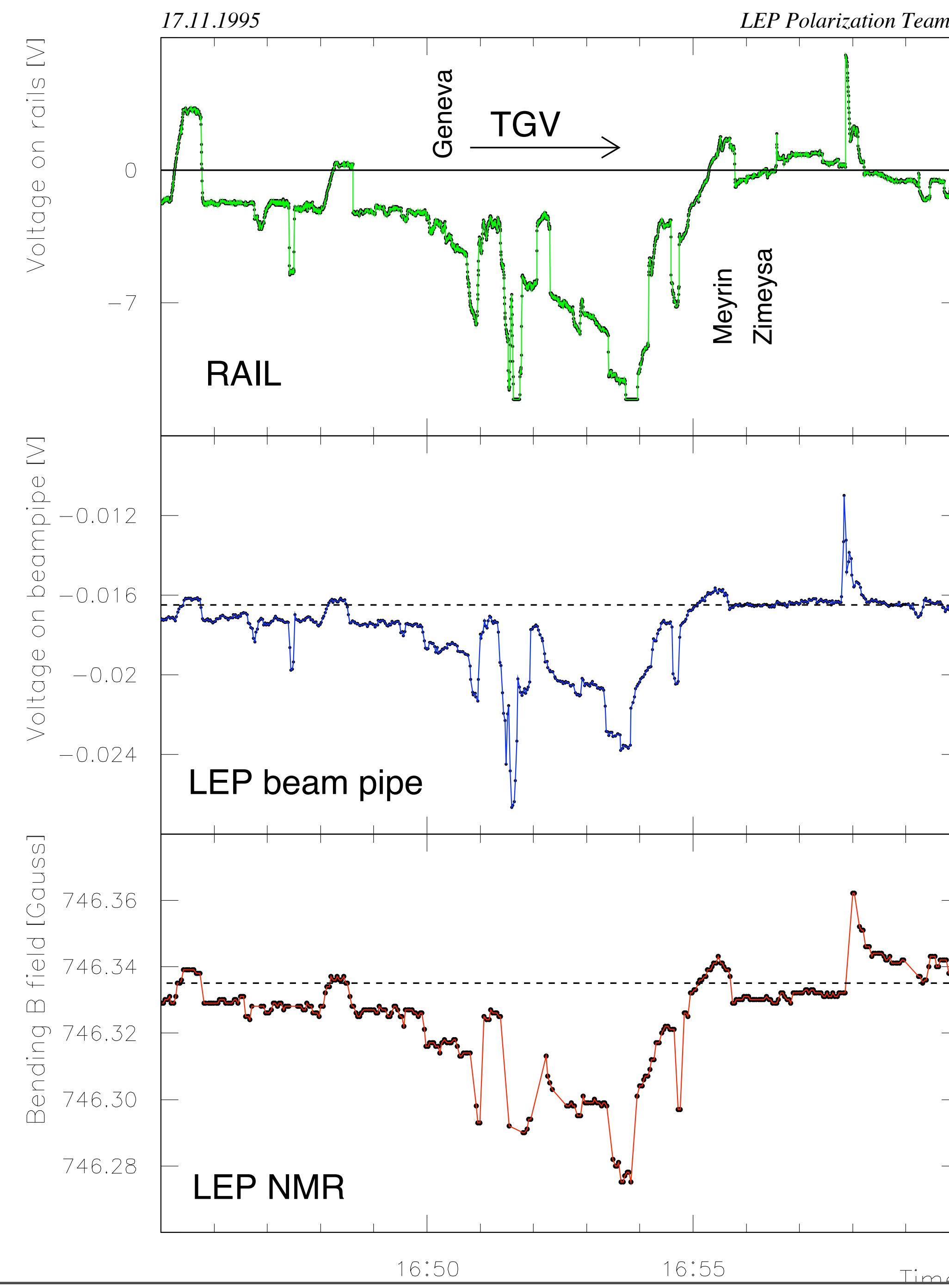
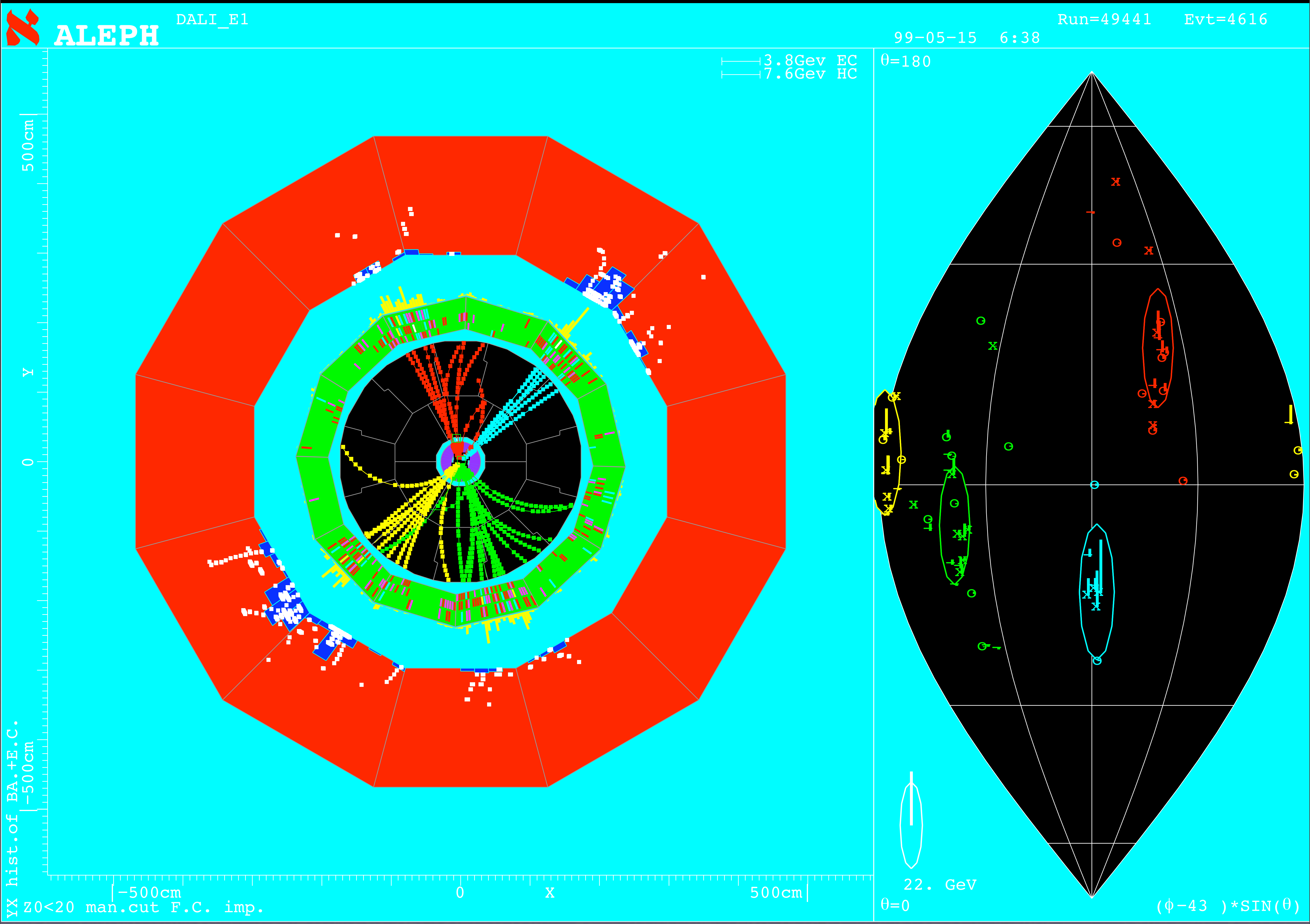
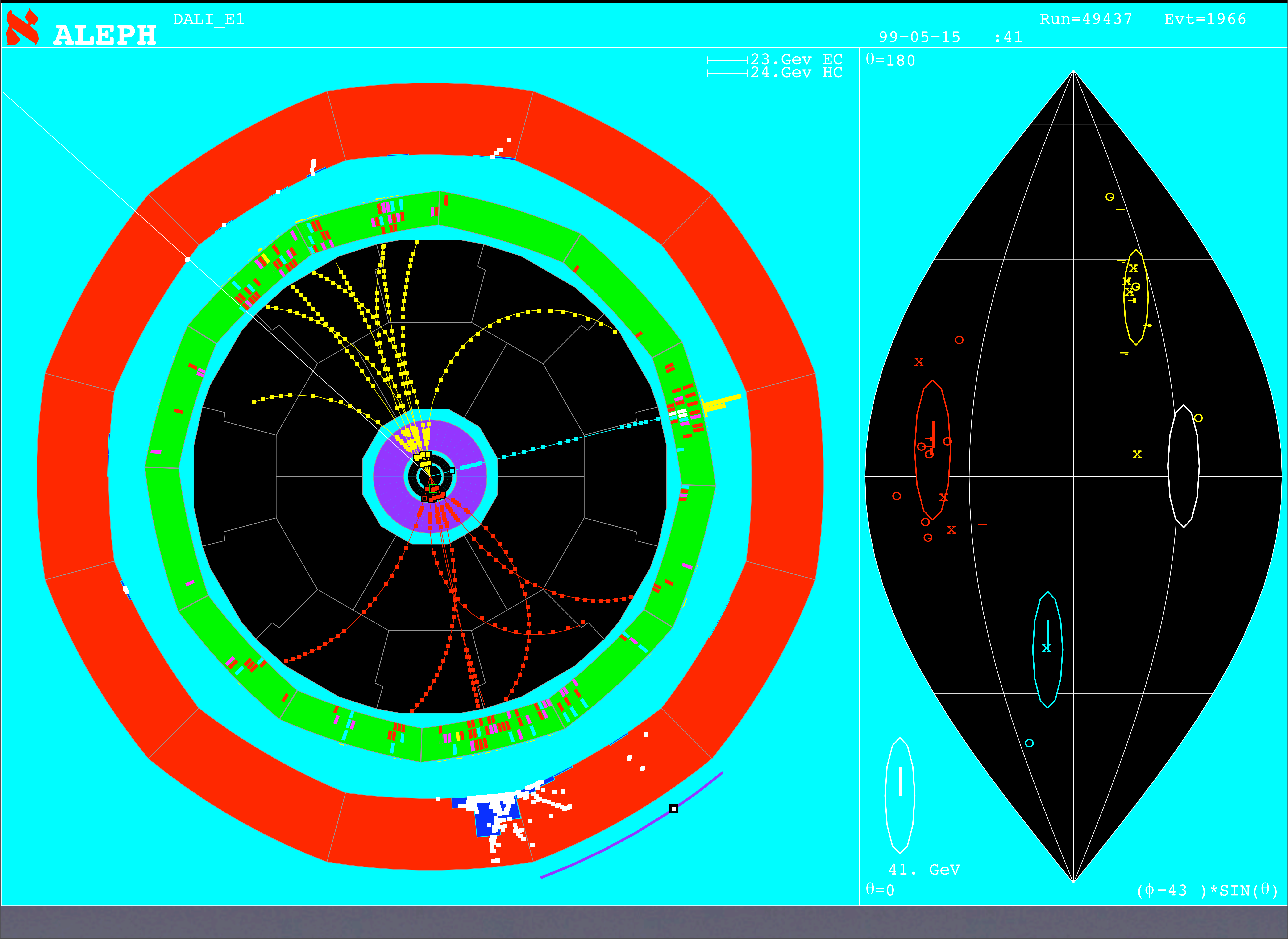




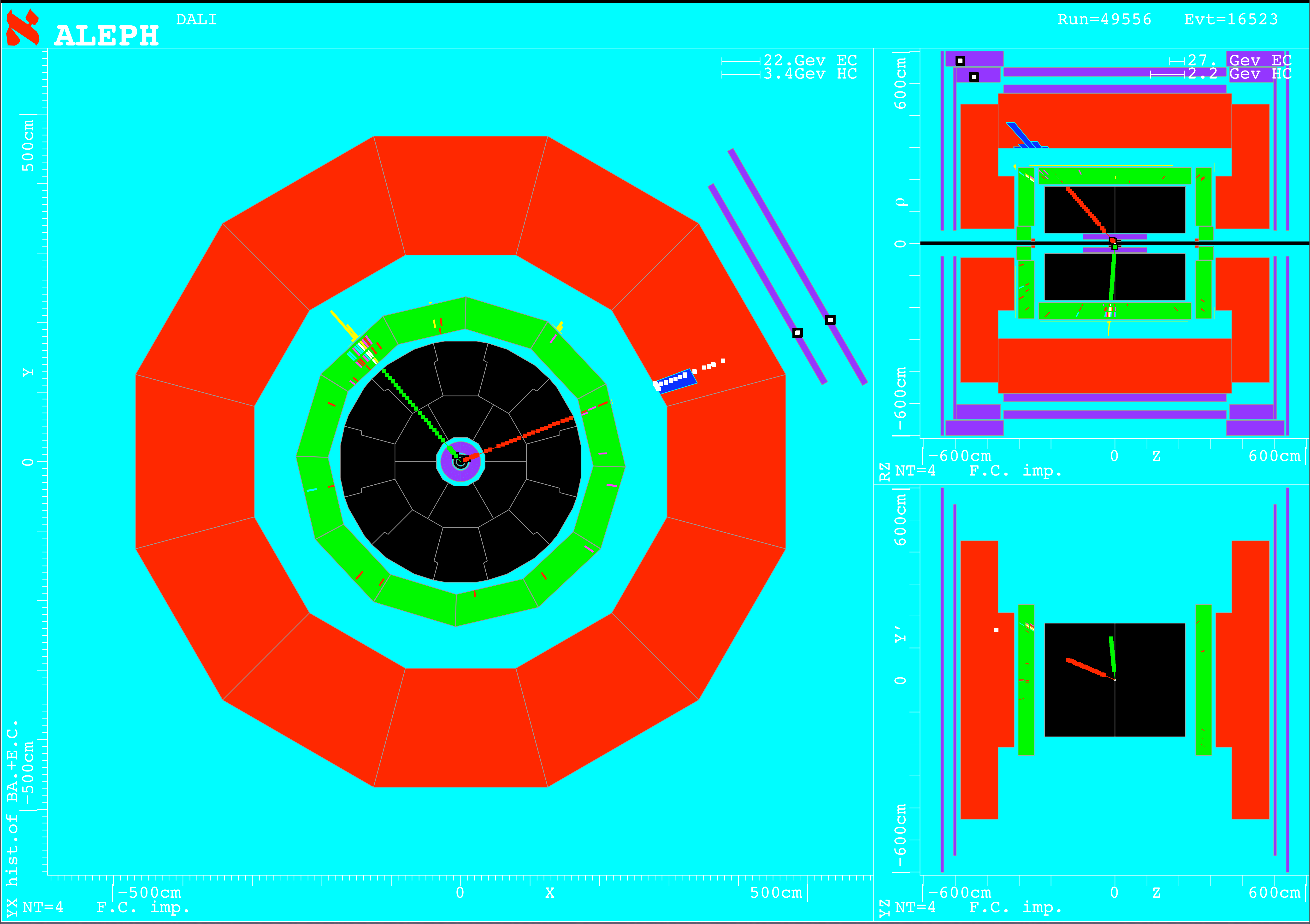





ALEPH
DALI_E1
Run=49441 Evt=4616
99-05-15 6:38
3.8Gev EC
7.6Gev HC
θ=180
500cm
Y
0
-500cm
YX hist.of BA.+E.C.
Z0<20 man.cut F.C. imp.
-500cm
0
X
500cm
22. GeV
θ=0
(ϕ-43)*SIN(θ)



Thursday, July 23, 2009


ALEPH
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500cm
Y
0
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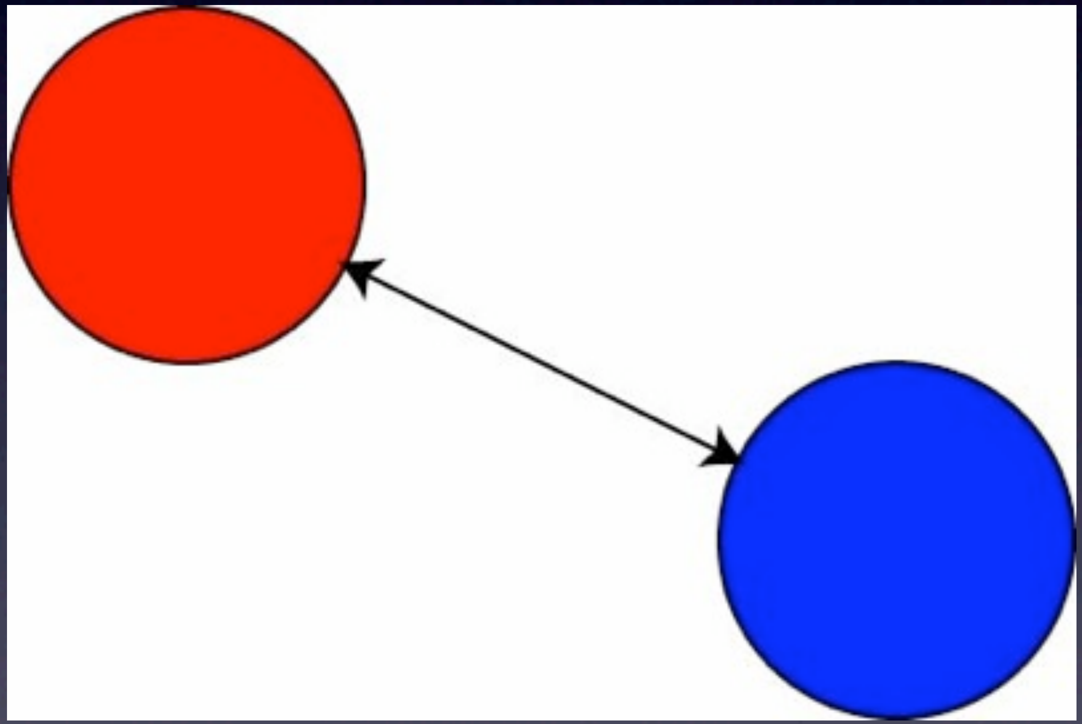
YX hist.of BA.+E.C.
-500cm
0
X
500cm
YX NT=4 F.C. imp.
600cm
ρ
0
-600cm
-600cm
0
Z
600cm
RZ NT=4 F.C. imp.
600cm
Y'
0
-600cm
-600cm
0
Z
600cm
YZ NT=4 F.C. imp.

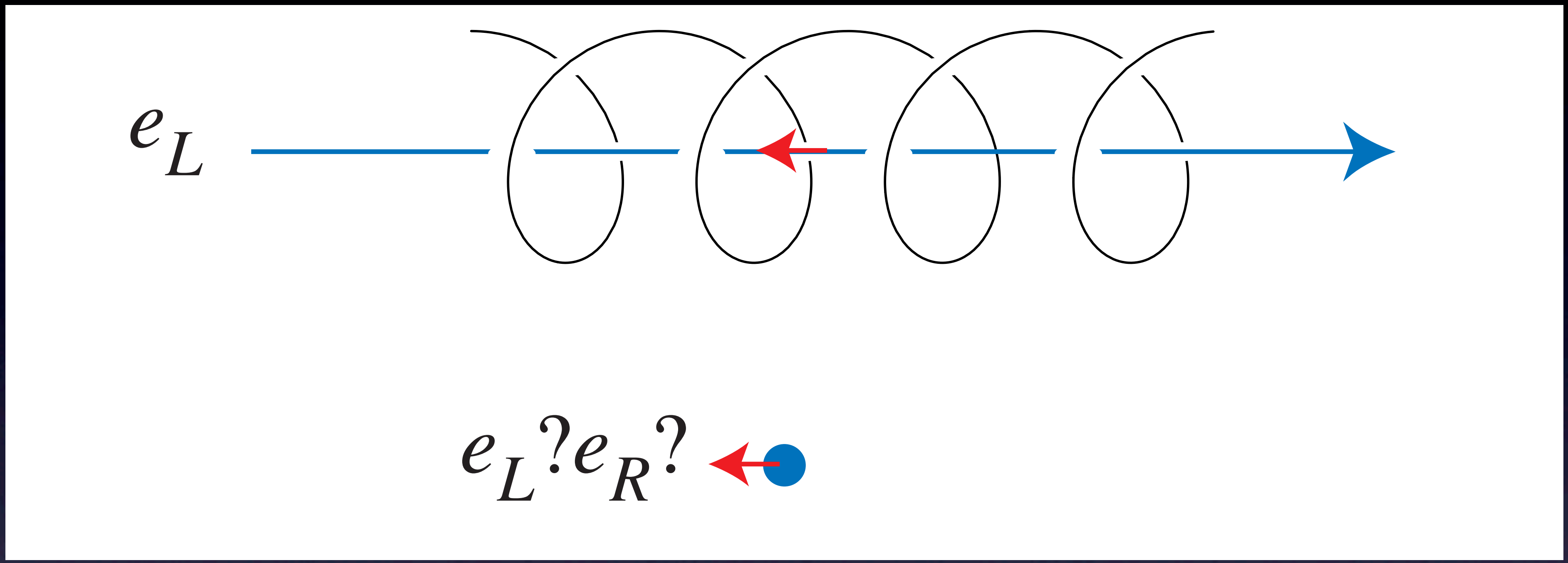
A big hole
Higgs

Why short-ranged?

- gravity pull masses (long-ranged)
- electromagnetism repels like charges (long-ranged)
- weak force pulls protons and electrons (short-ranged) acts only over a *billionth of a nanometer*
- We know the energy scale: ~0.3 TeV



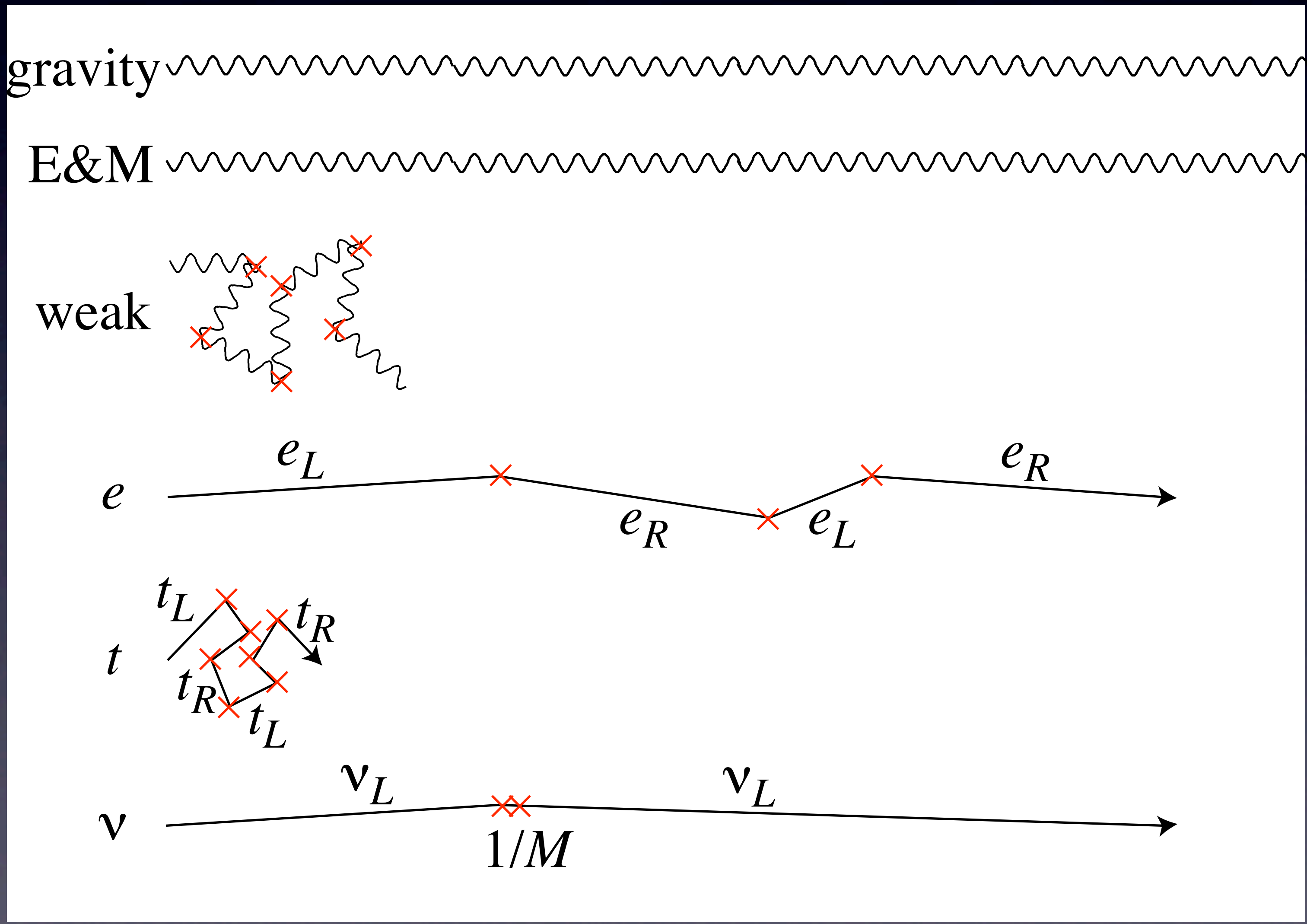
Mystery deepens



- Strangely, only left-handed particles participate in the weak force
- That sounds OK as long as they are moving
- but when they stop???

We are swimming in Dark Field

- There is quantum liquid filling our Universe
- It doesn't disturb gravity or electric force
- It does disturb weak force and make it short-ranged
- It slows down all elementary particles from speed of light
- otherwise no atoms!
- What is it??



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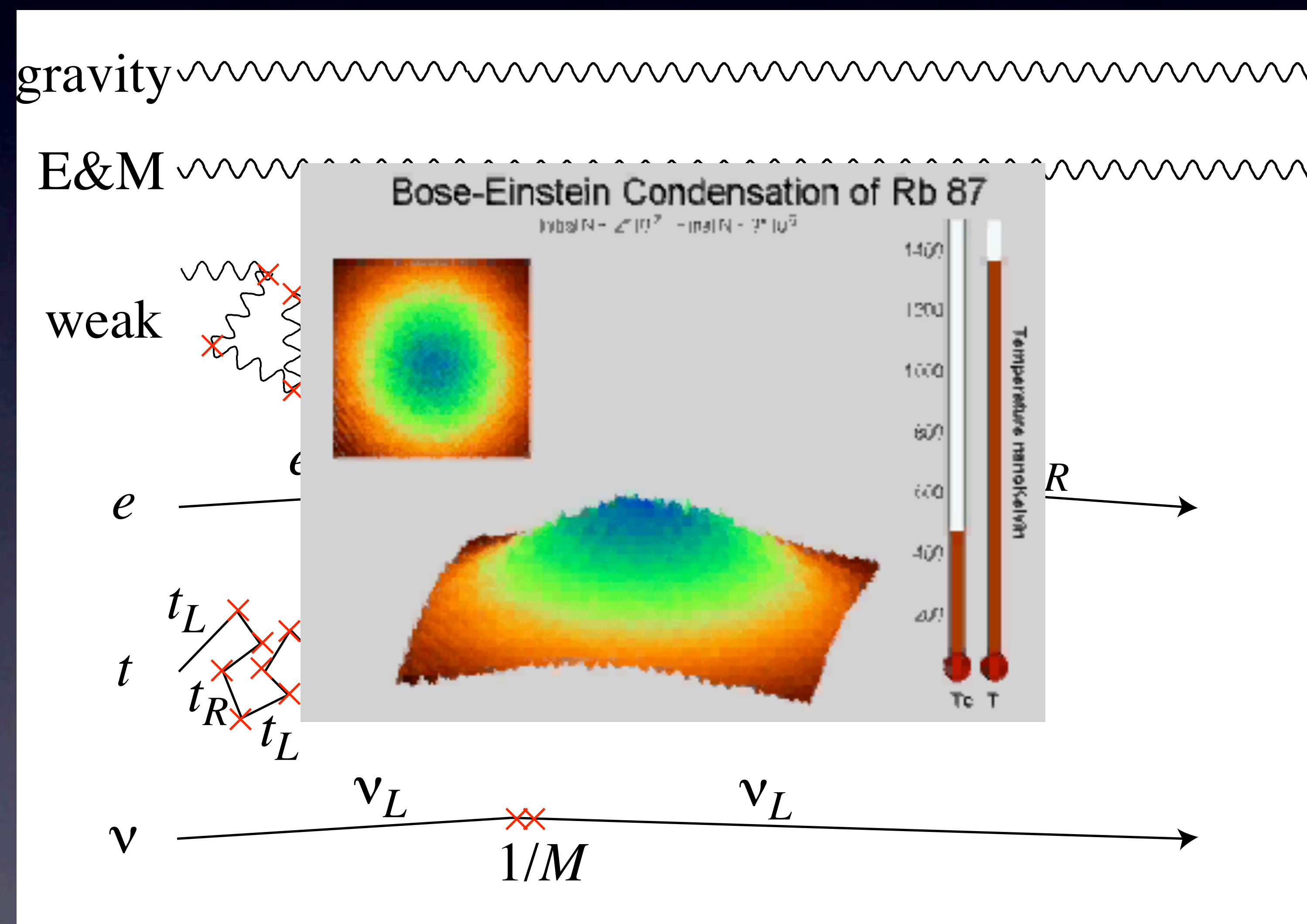


Cosmic Superconductor

- In a superconductor, magnetic field gets repelled (Meißner effect), and penetrates only over the “penetration length”

  ⇒ Magnetic field is short-ranged!

- Imagine a physicist living in a superconductor
- She finally figured:
  - magnetic field must be long-ranged
  - there must be a mysterious charge-two condensate in her “Universe”
  - But doesn’t know what the condensate is, nor why it condenses
  - Doesn’t have enough energy (gap) to break up Cooper pairs

That’s the stage where we are!

INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

東京大学 THE UNIVERSITY OF TOKYO

Standard Model 5

CERN Summer Student Programme
July 23, 2009

Hitoshi Murayama (IPMU Tokyo & Berkeley)

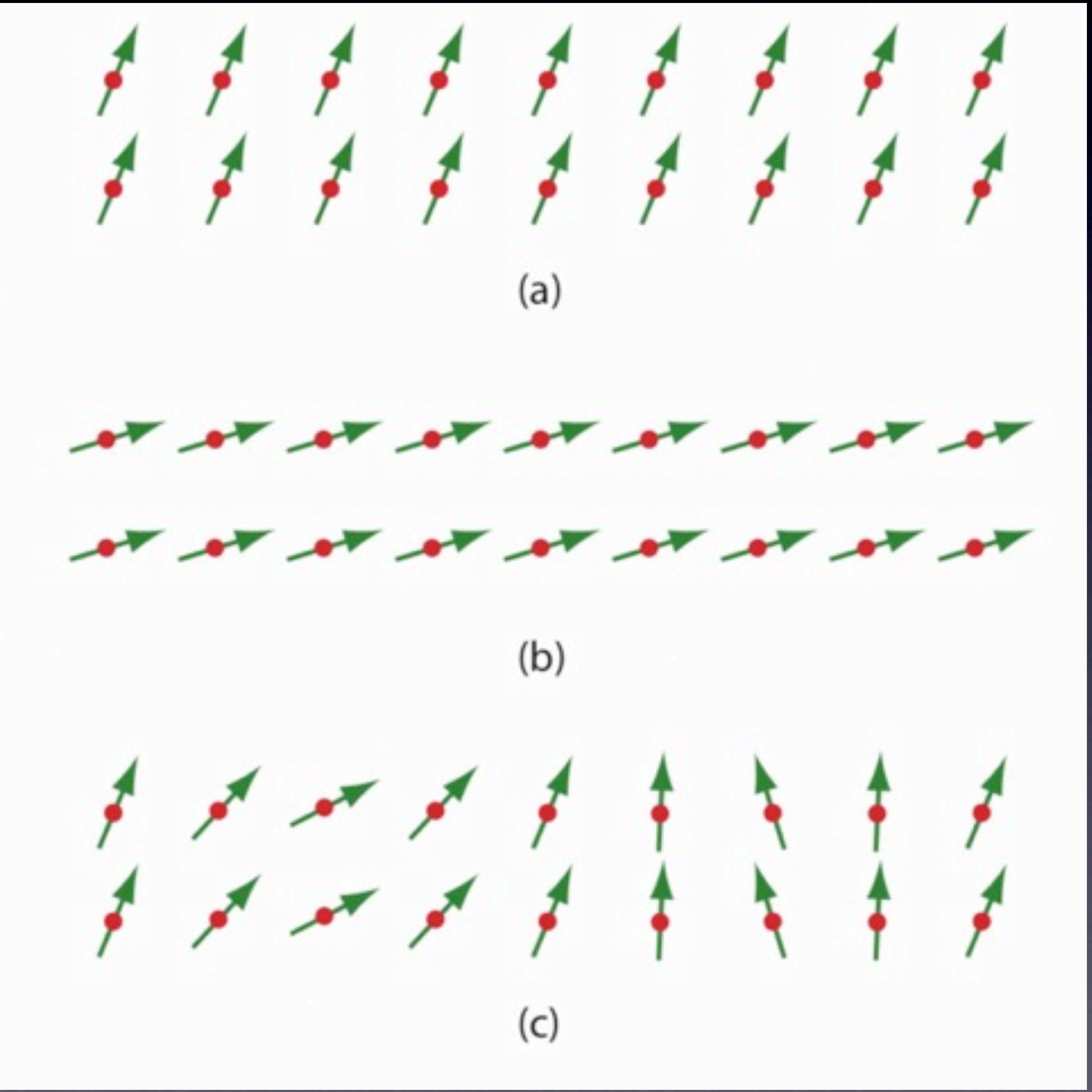
BERKELEY CENTER FOR THEORETICAL PHYSICS

BERKELEY LAB

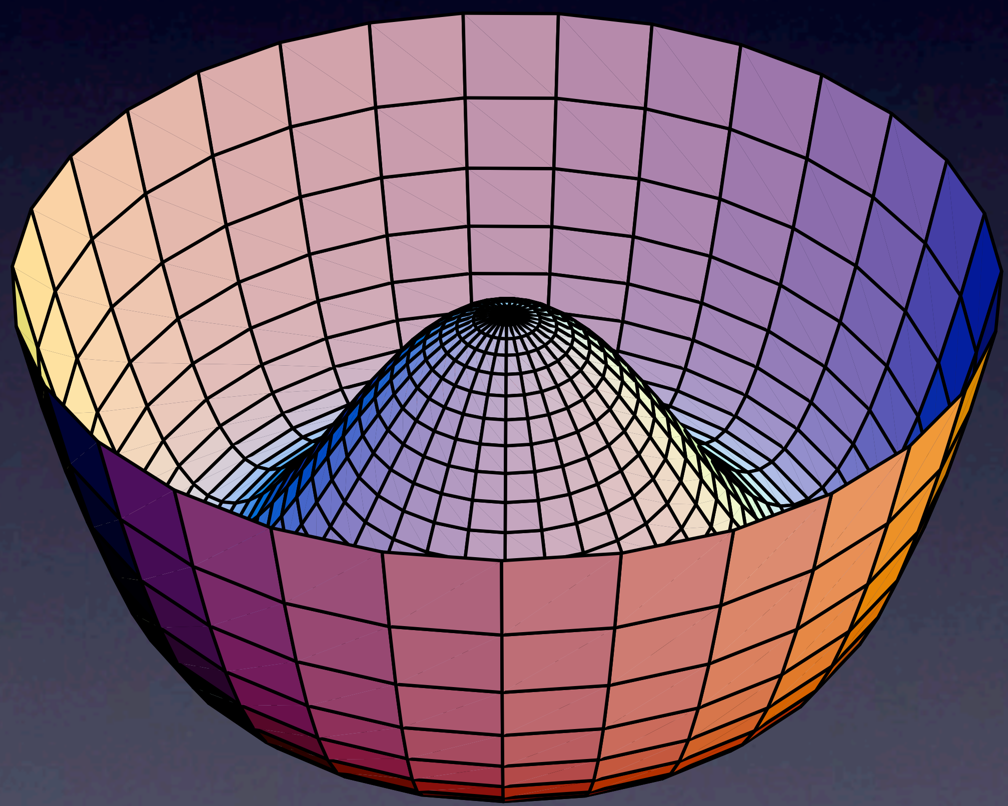
spontaneous symmetry breaking

2008 Nobel
Nambu

- electron spins are magnets
- in many solids, they'd like to line up
- but once they line up, they have to pick one particular direction
- rotational invariance of the system is lost by picking one particular ground state
- symmetry is broken!

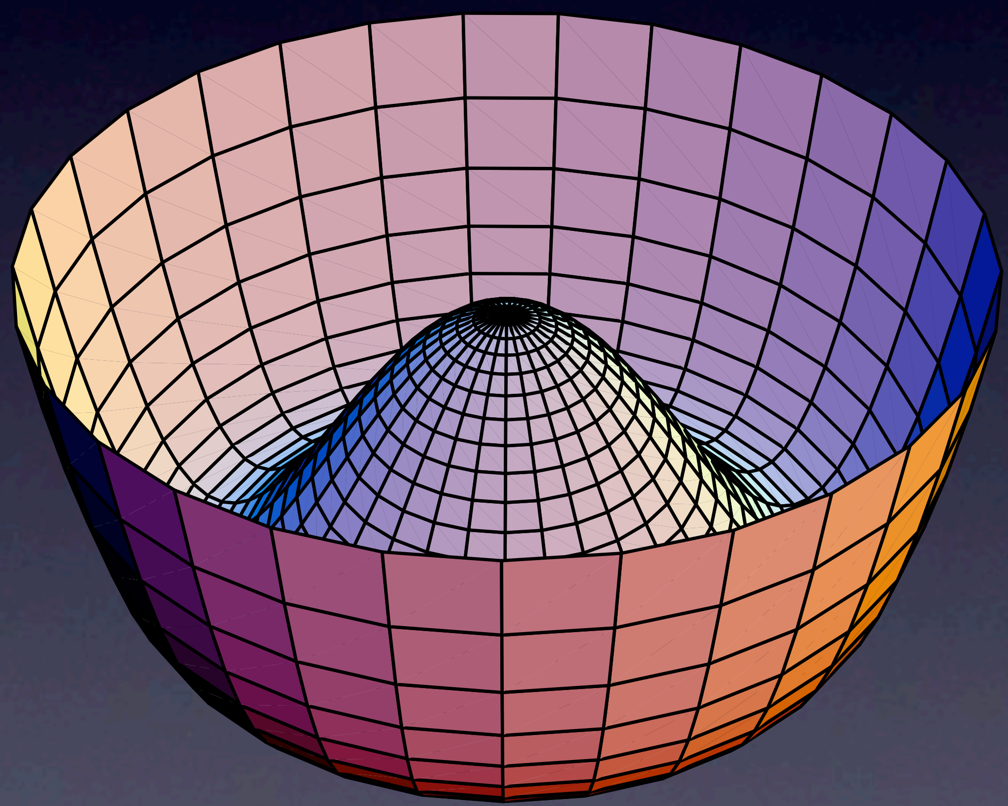


spontaneous symmetry breaking



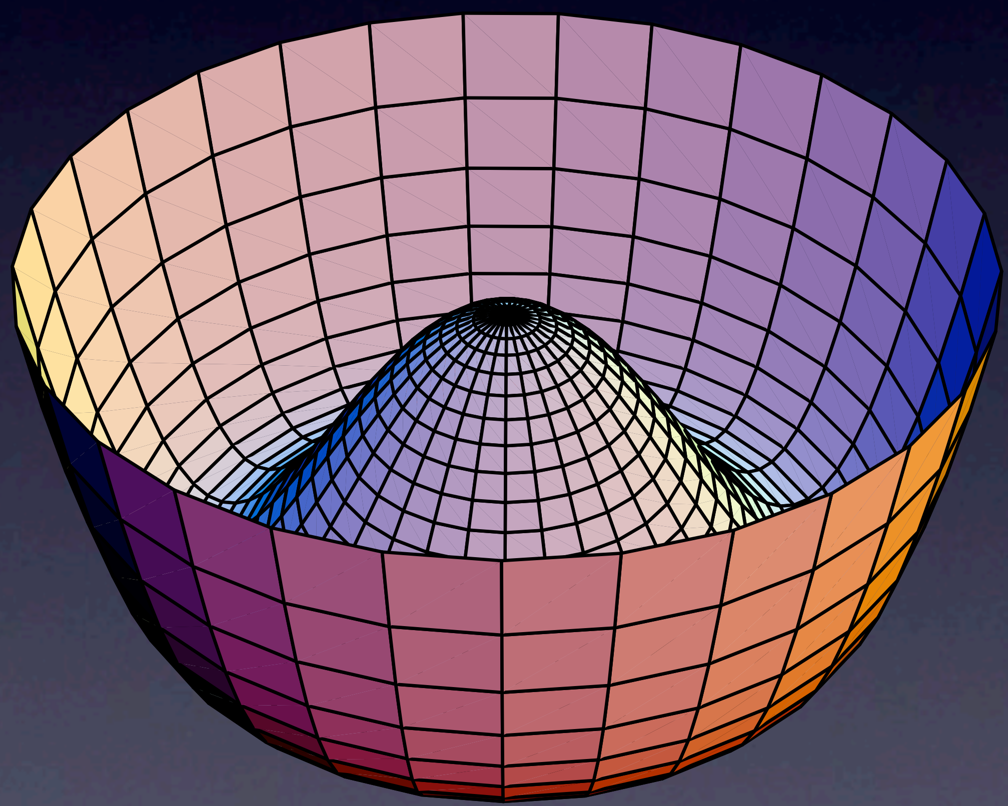
spontaneous symmetry breaking

- introduce spin zero doublet with *Y*=1/2 $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$



spontaneous symmetry breaking

- introduce spin zero doublet with Y=1/2 $H = \begin{pmatrix} H^+ \\ H^0 \end{pmatrix}$
- $V = \lambda|H|^4 - \mu^2|H|^2$



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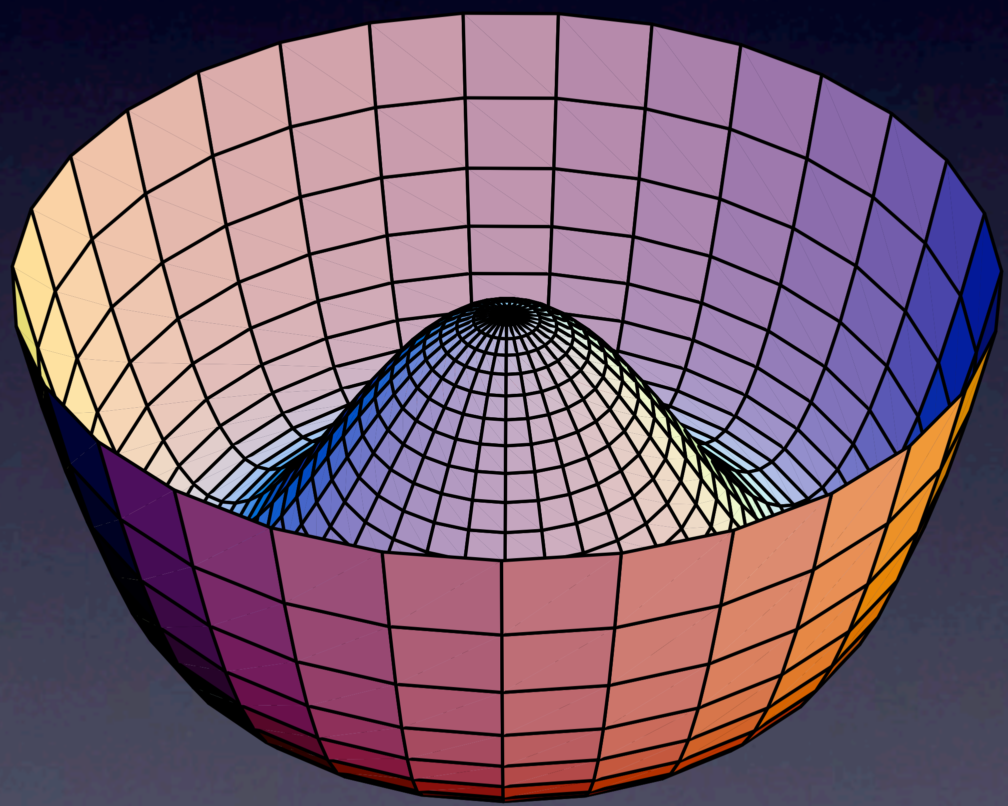
- ground state: $\langle H \rangle$



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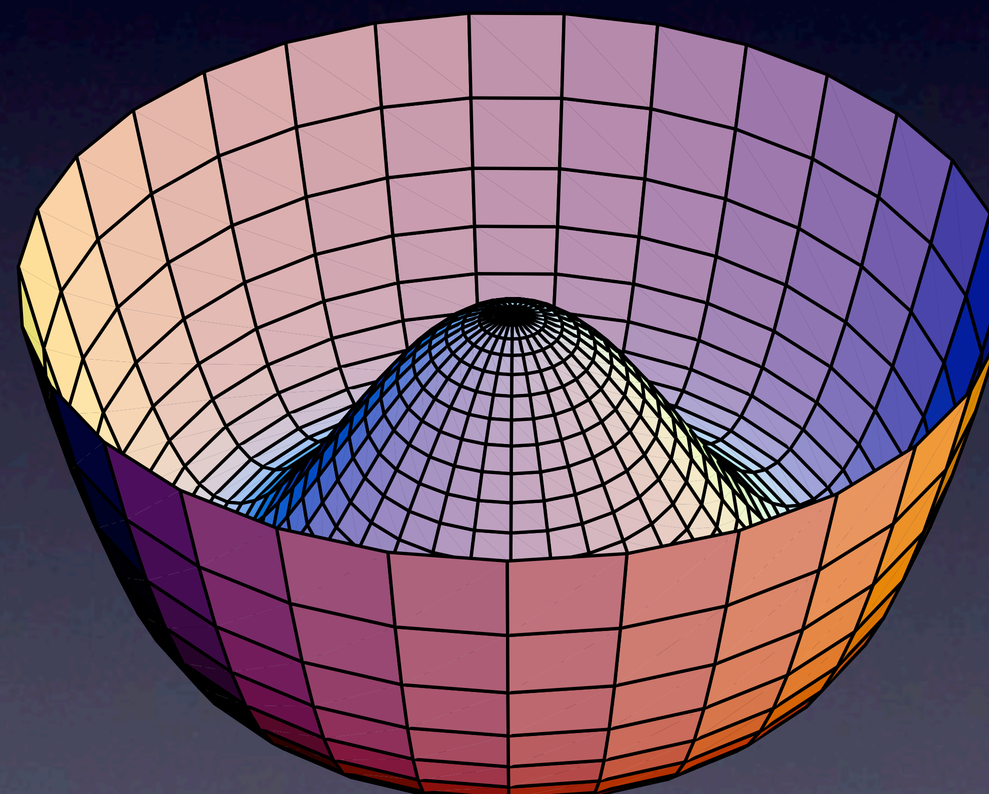
- picks one particular orientation in SU(2), one particular phase in U(1)



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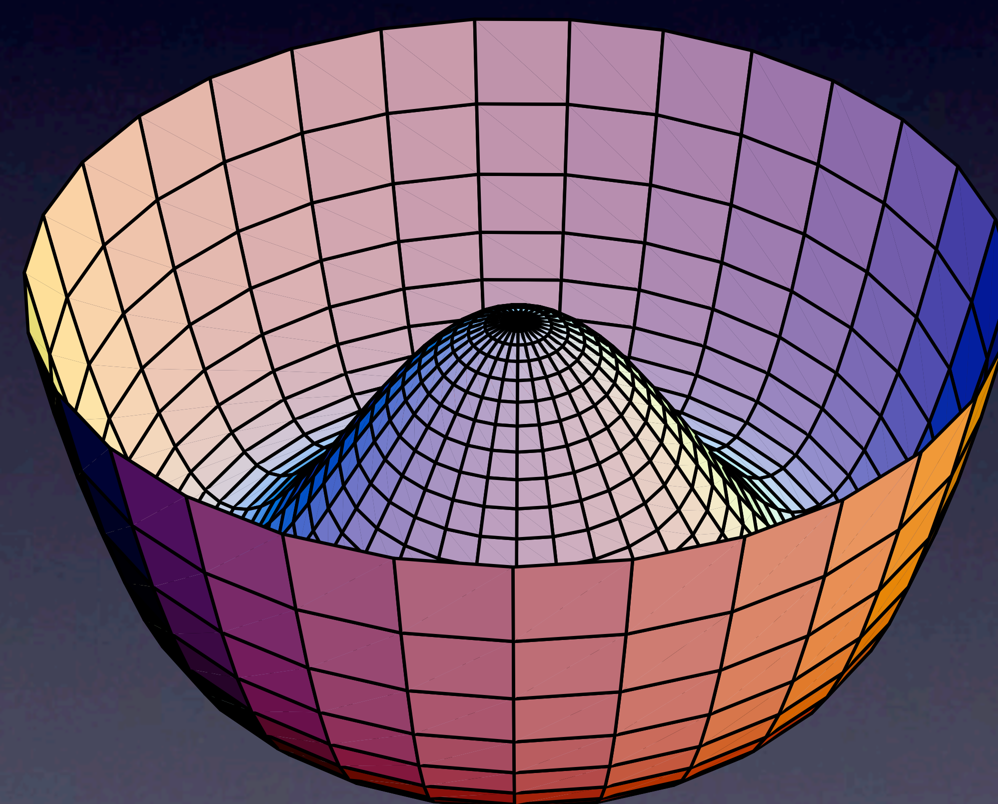
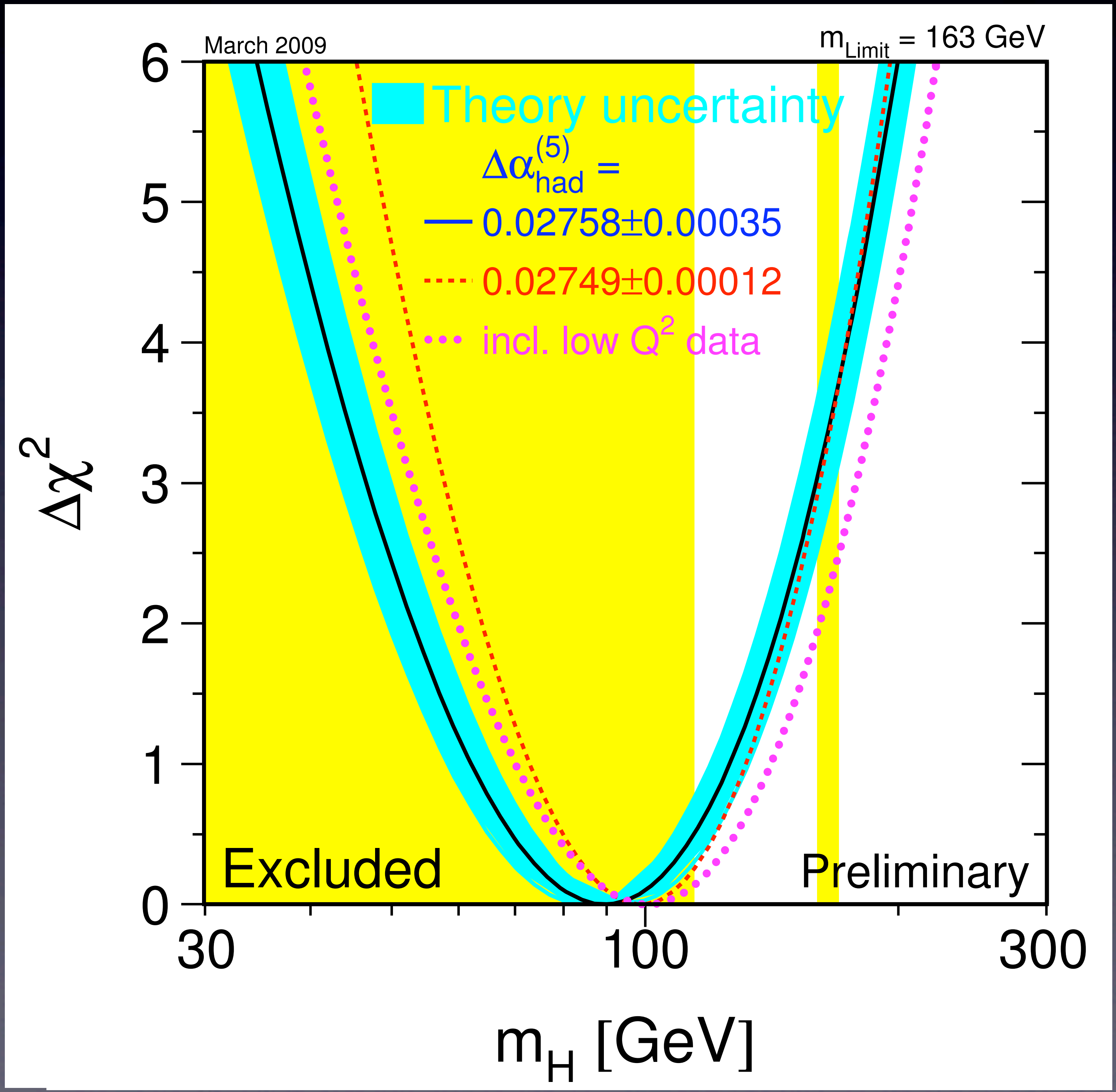
- ground state: $\langle H \rangle$
- picks one particular orientation in SU(2), one particular phase in U(1)
- but is symmetric under $I_3+Y=Q$, electromagnetism is *unbroken!*



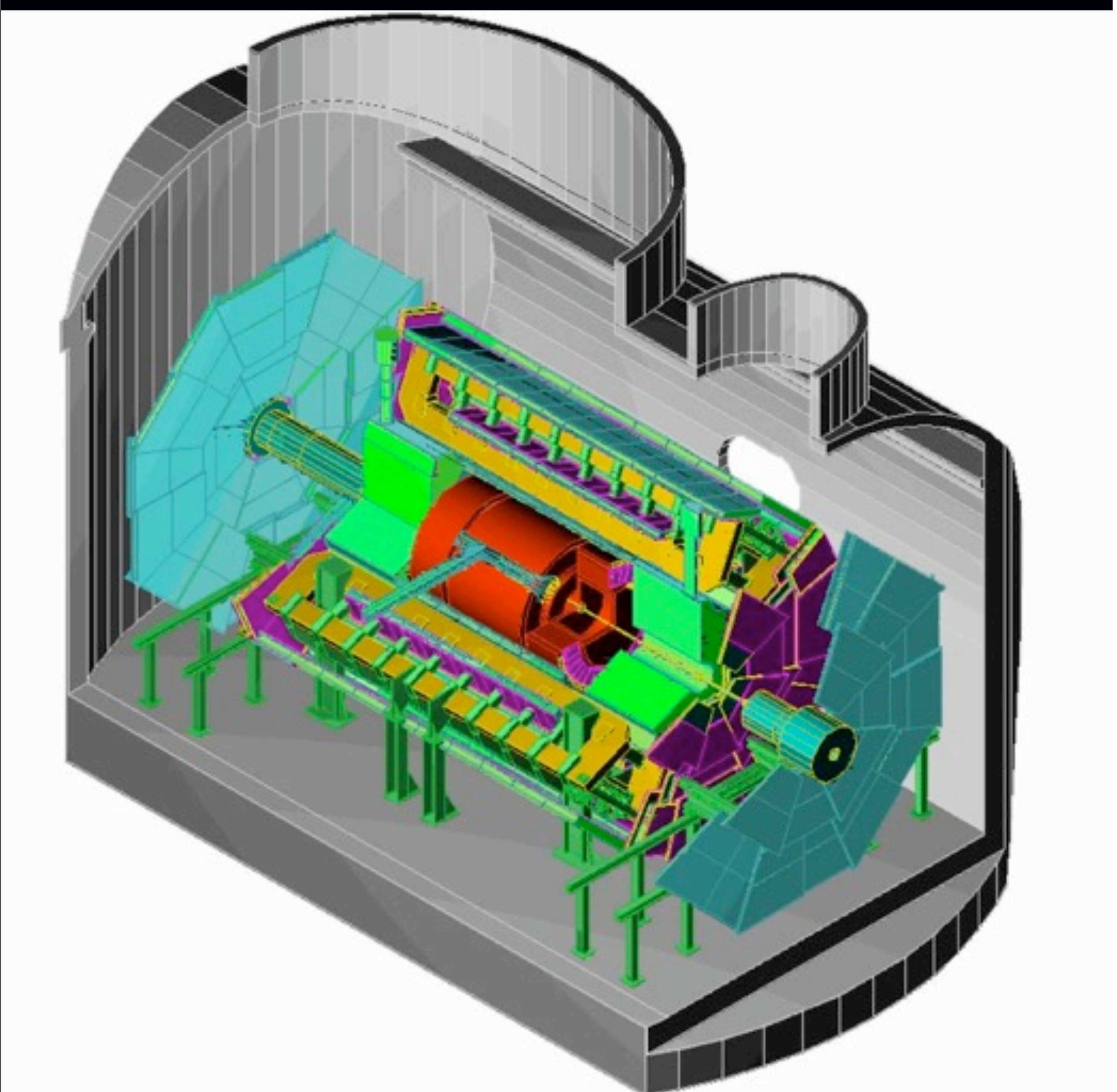
Gap Excitation

- We know the energy scale of the problem: $G_F \approx (300\ \text{GeV})^{-2}$
- the gap excitation is called "Higgs boson"
- Current data combined with the Standard Model theory predict

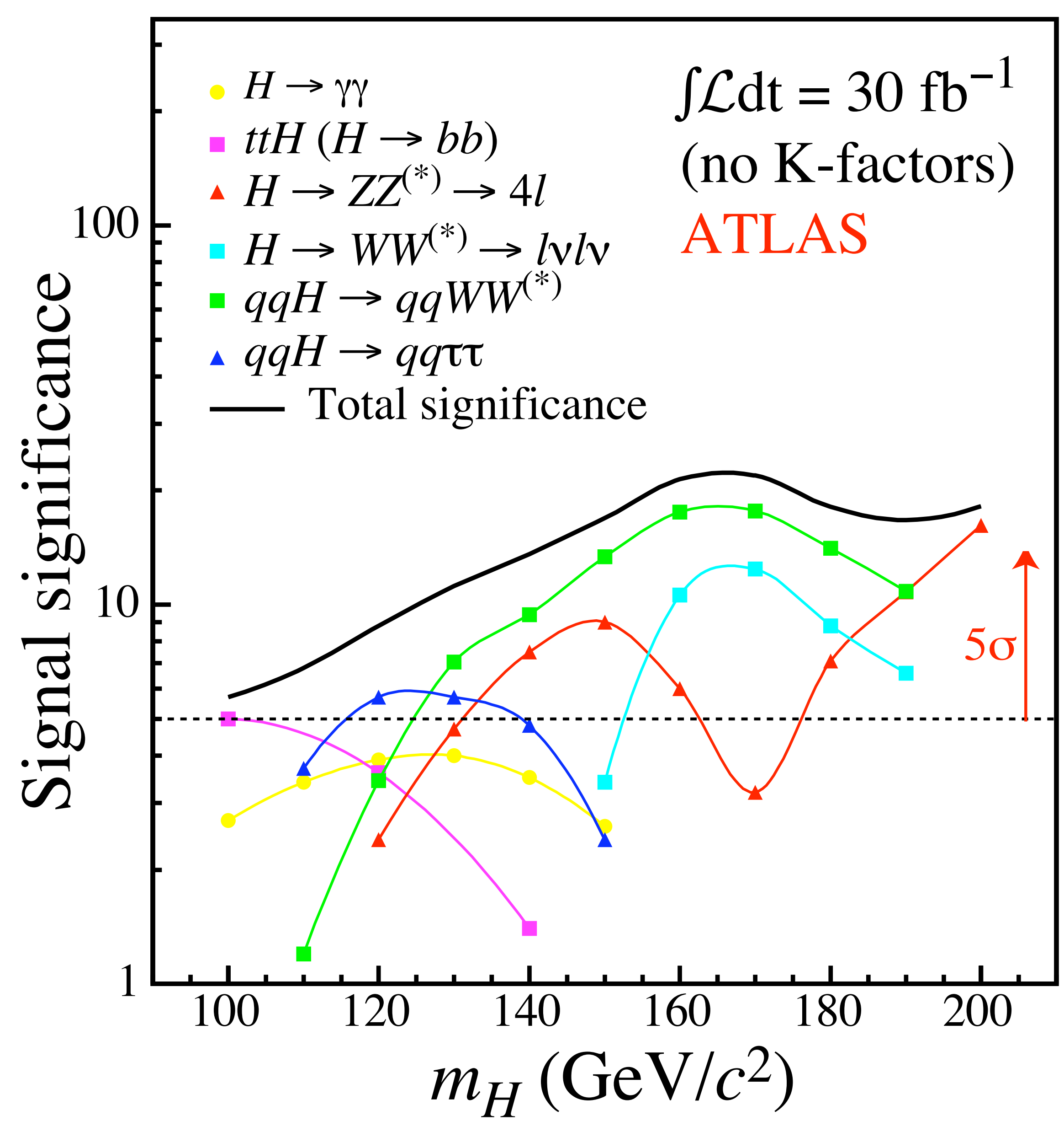
$m_H < 163\text{GeV}$ (95%CL)



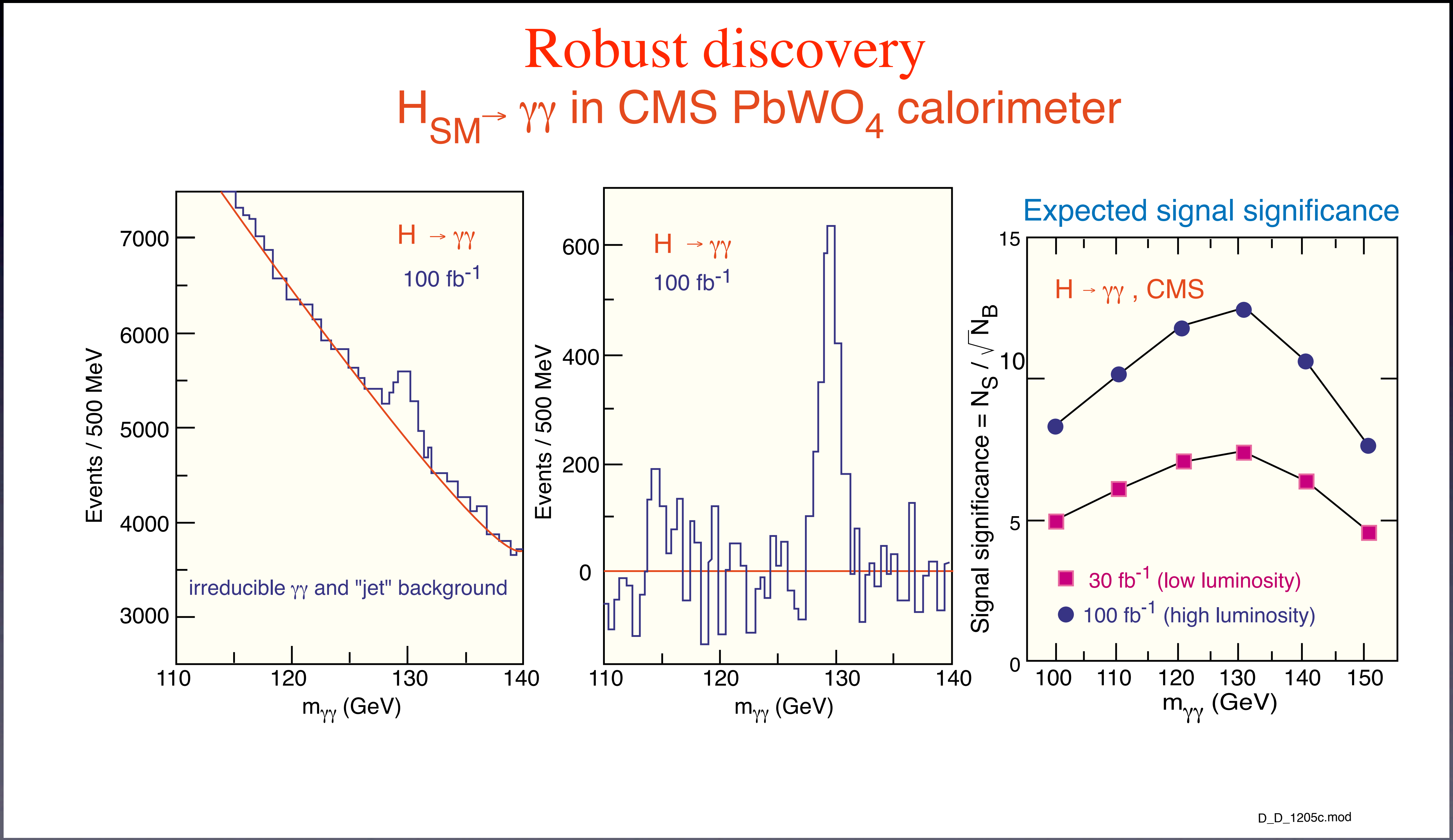
Higgs at ATLAS



Robust discovery

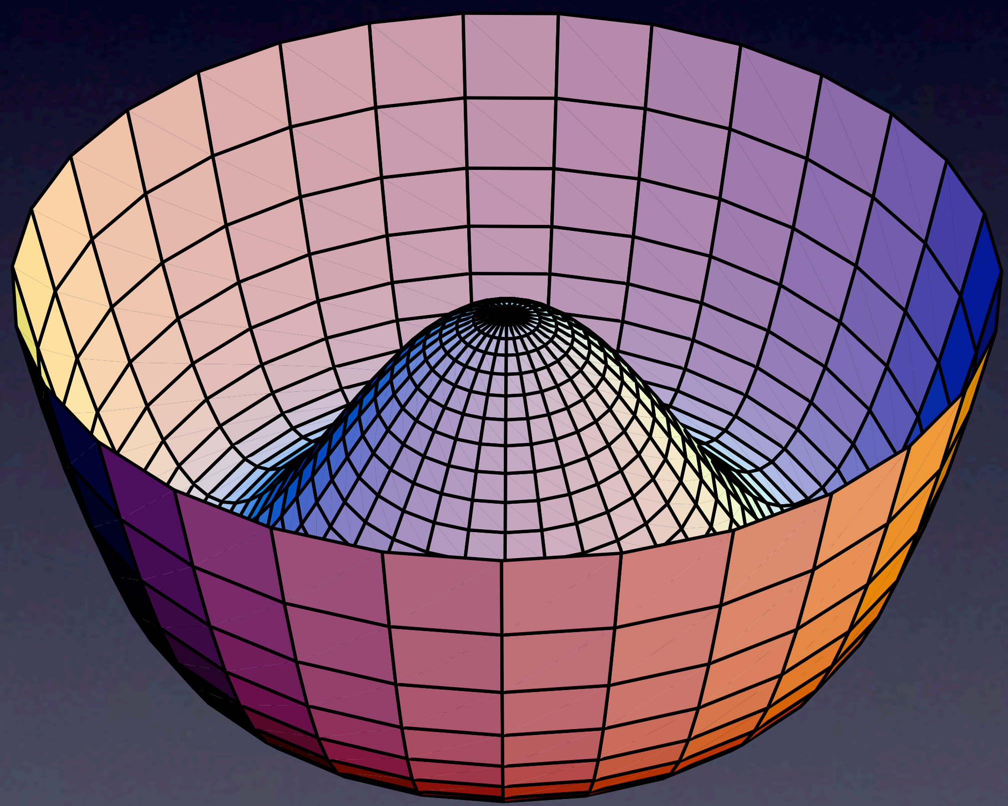


Higgs at CMS



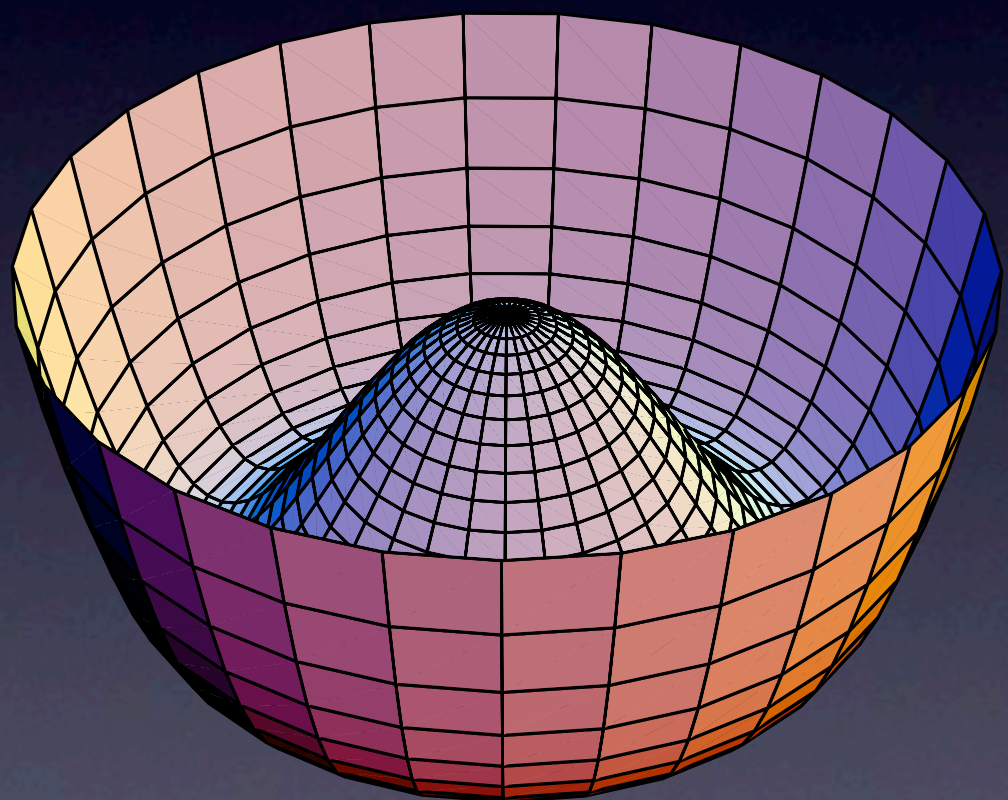
Robust discovery
H_SM→ γγ in CMS PbWO_4 calorimeter
H → γγ
100 fb^-1
Events / 500 MeV
irreducible γγ and "jet" background
m_γγ (GeV)
H → γγ
100 fb^-1
Events / 500 MeV
m_γγ (GeV)
Expected signal significance
H → γγ , CMS
Signal significance = N_S / √N_B
30 fb^-1 (low luminosity)
100 fb^-1 (high luminosity)
m_γγ (GeV)
D_D_1205c.mod

ugly



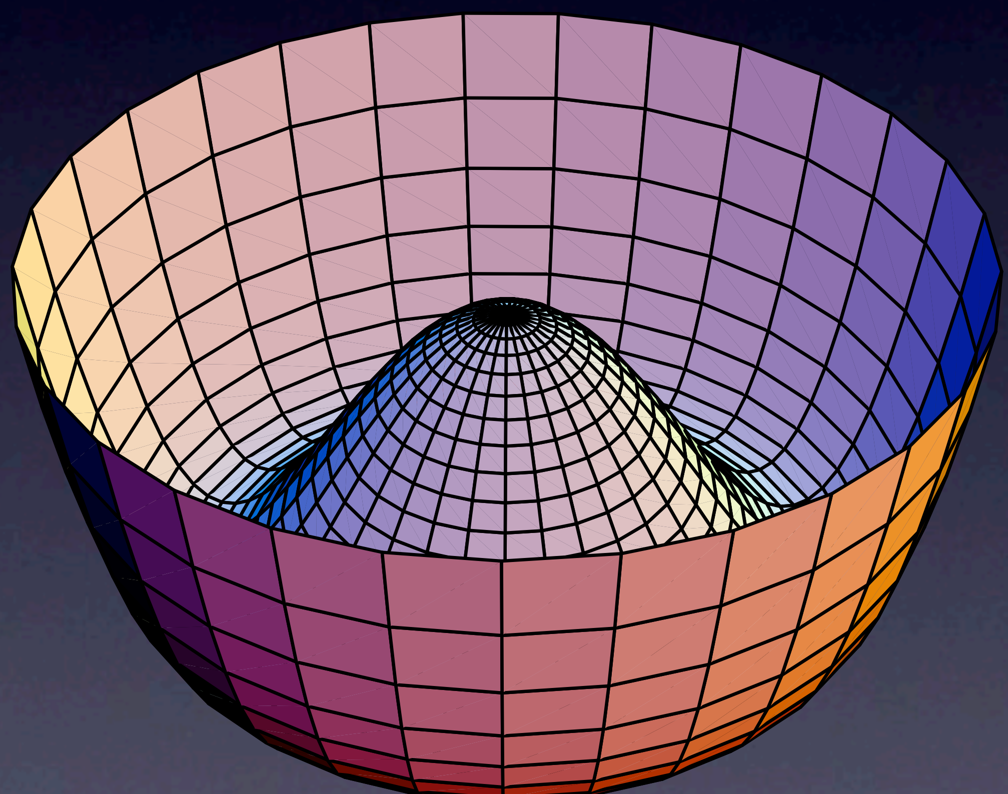
ugly

- $V = \lambda|H|^4 - \mu^2|H|^2$



ugly

- $V = \lambda |H|^4 - \mu^2 |H|^2$
- Why negative mass-squred?



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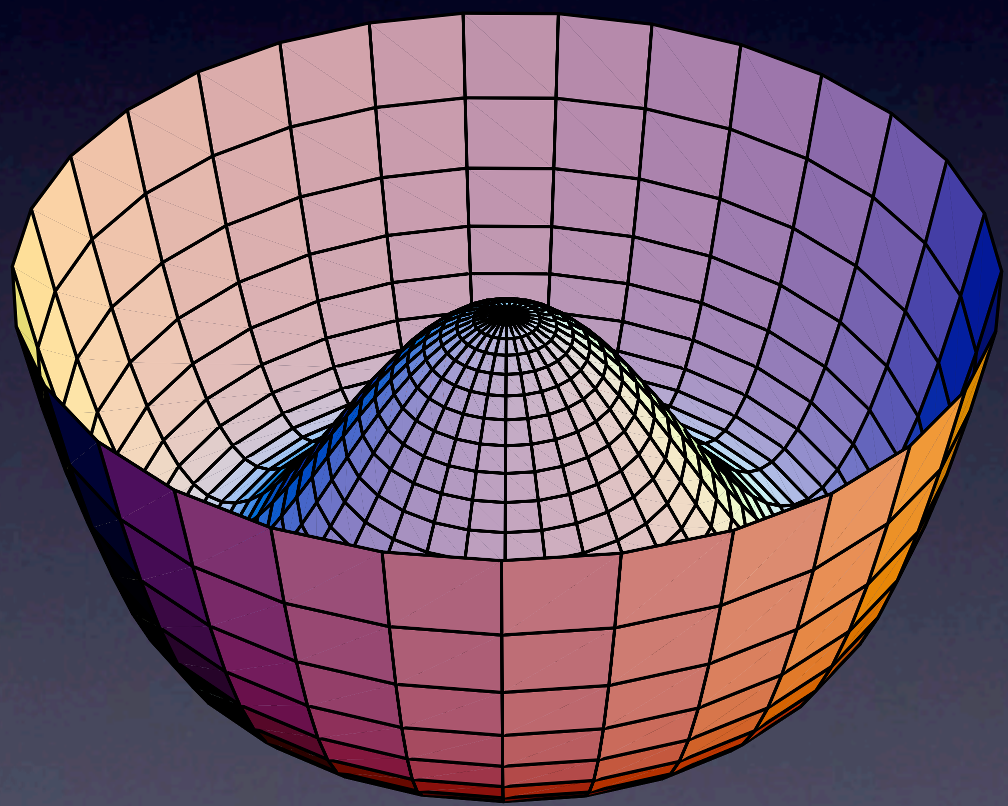

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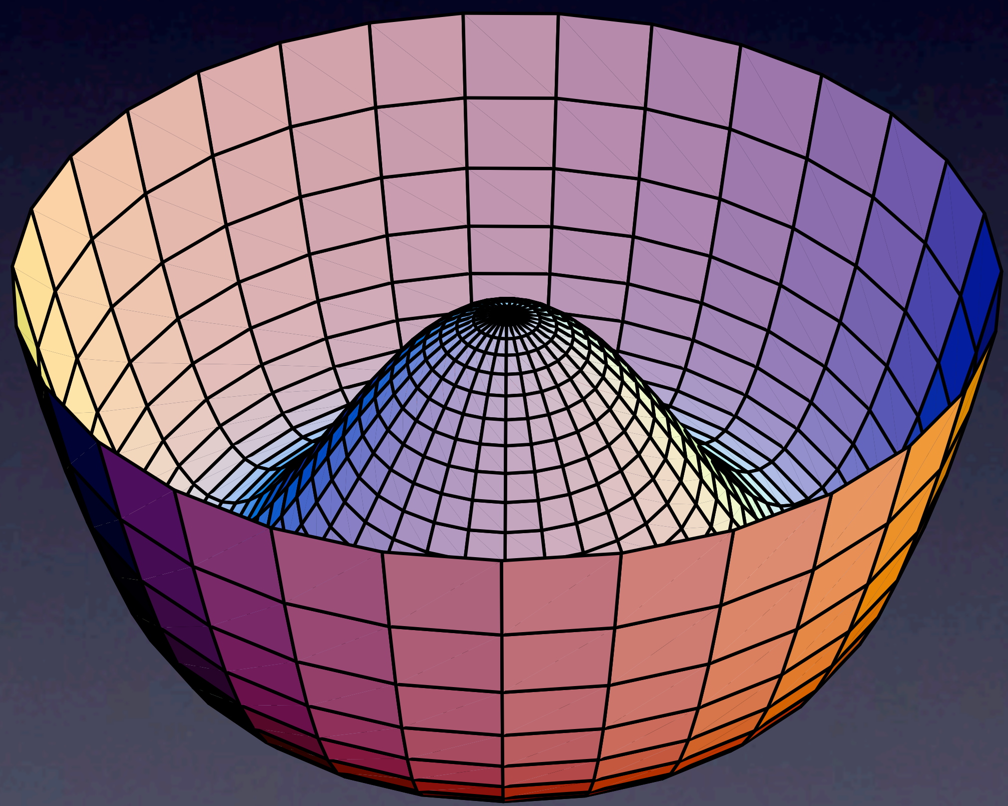
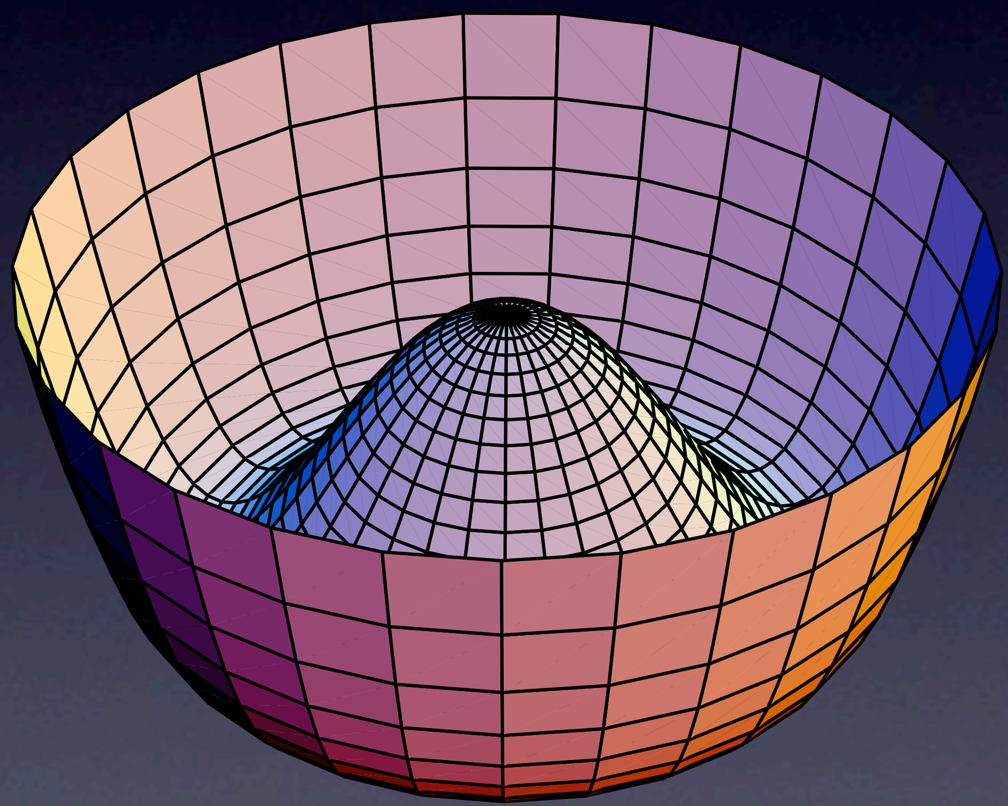


ugly

- $V = \lambda|H|^4 - \mu^2|H|^2$
- Why negative mass-squred?
- Why only one scalar in the SM?
- Hierarchy problem because of its quadratic divergence
- does not appear fundamental, i.e. Ginzburg-Landau vs BCS



Once upon a time, there was a hierarchy problem...

- At the end of 19th century: a "crisis" about electron
  - Like charges repel: hard to keep electric charge in a small pack
  - Electron is point-like
  - At least smaller than 10^{-17}cm
- Need a lot of energy to keep it small!

$$\Delta m_e c^2 \sim \frac{e^2}{r_e} \sim \text{GeV}\frac{10^{-17}\text{cm}}{r_e}$$

- Correction $\Delta m_e c^2 > m_e c^2$ for $r_e < 10^{-13}\text{cm}$
- Breakdown of theory of electromagnetism

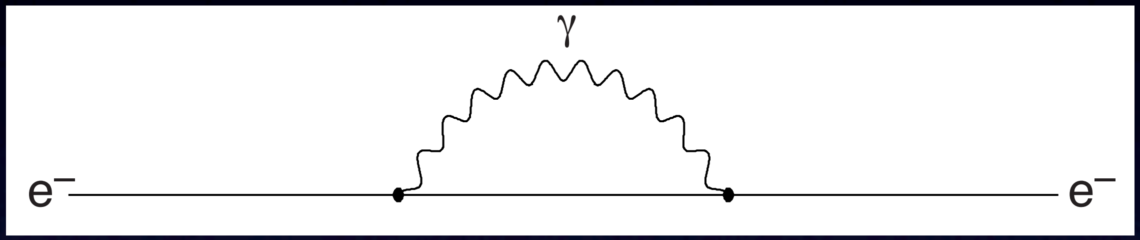
  $\Rightarrow$ Can't discuss physics below 10^{-13}cm

Anti-Matter Comes to Rescue by Doubling of #Particles

- Electron creates a force to repel itself
- Vacuum bubble of matter anti-matter creation/annihilation
- Electron annihilates the positron in the bubble

⇒ only 10% of mass even

for Planck-size r_e~10^{-33}cm



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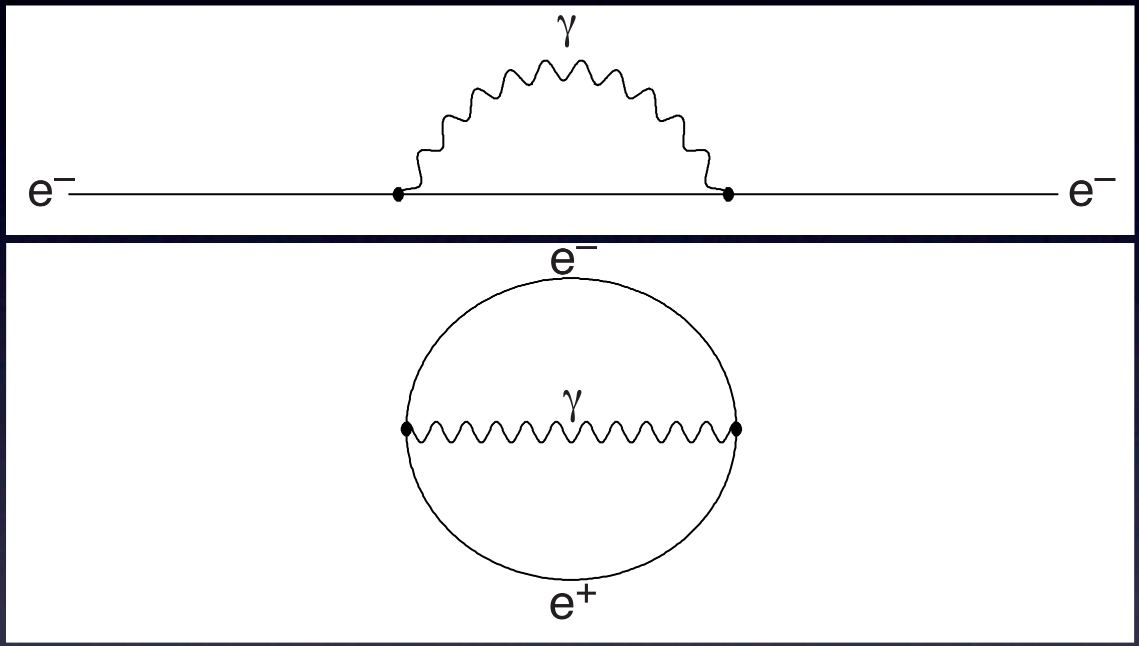

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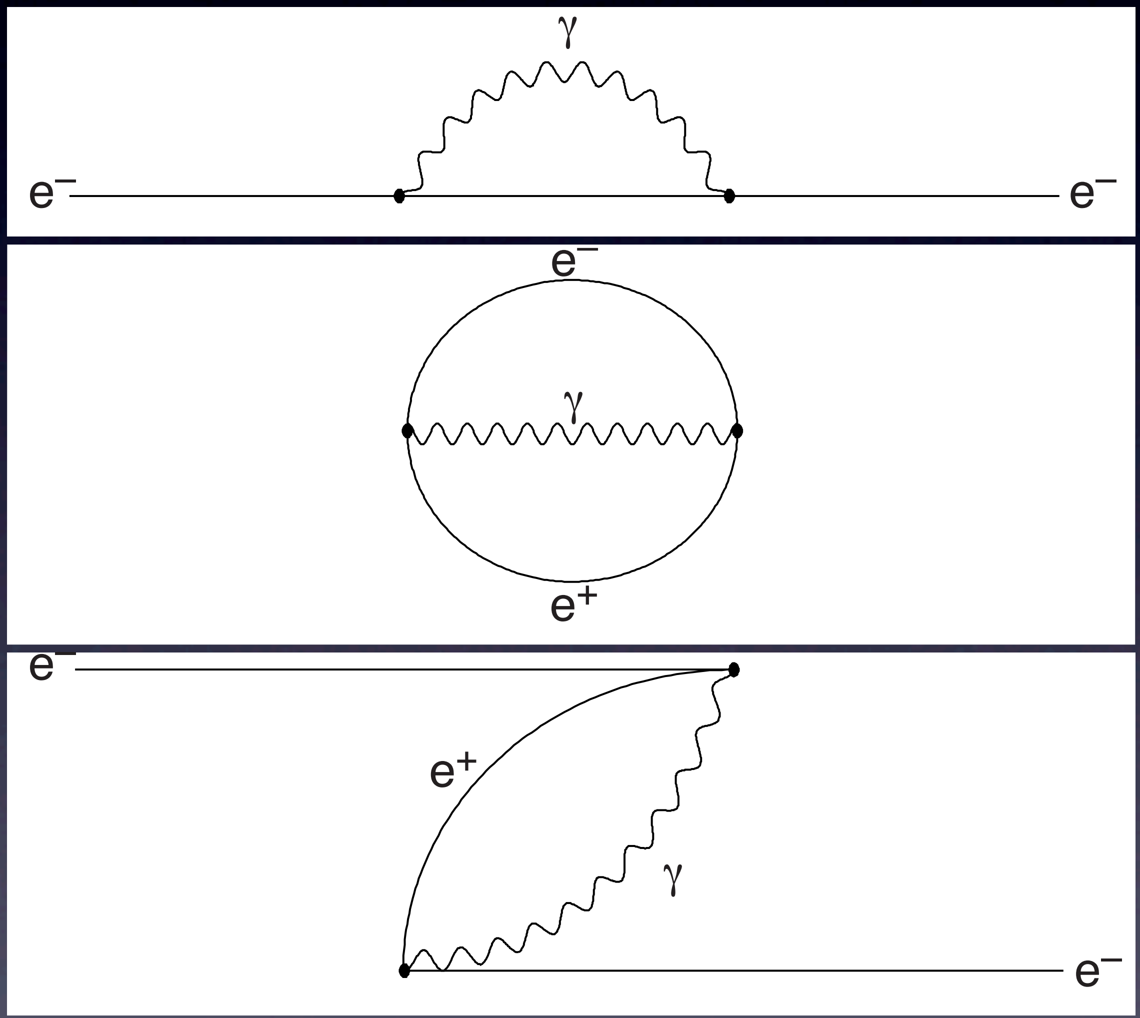

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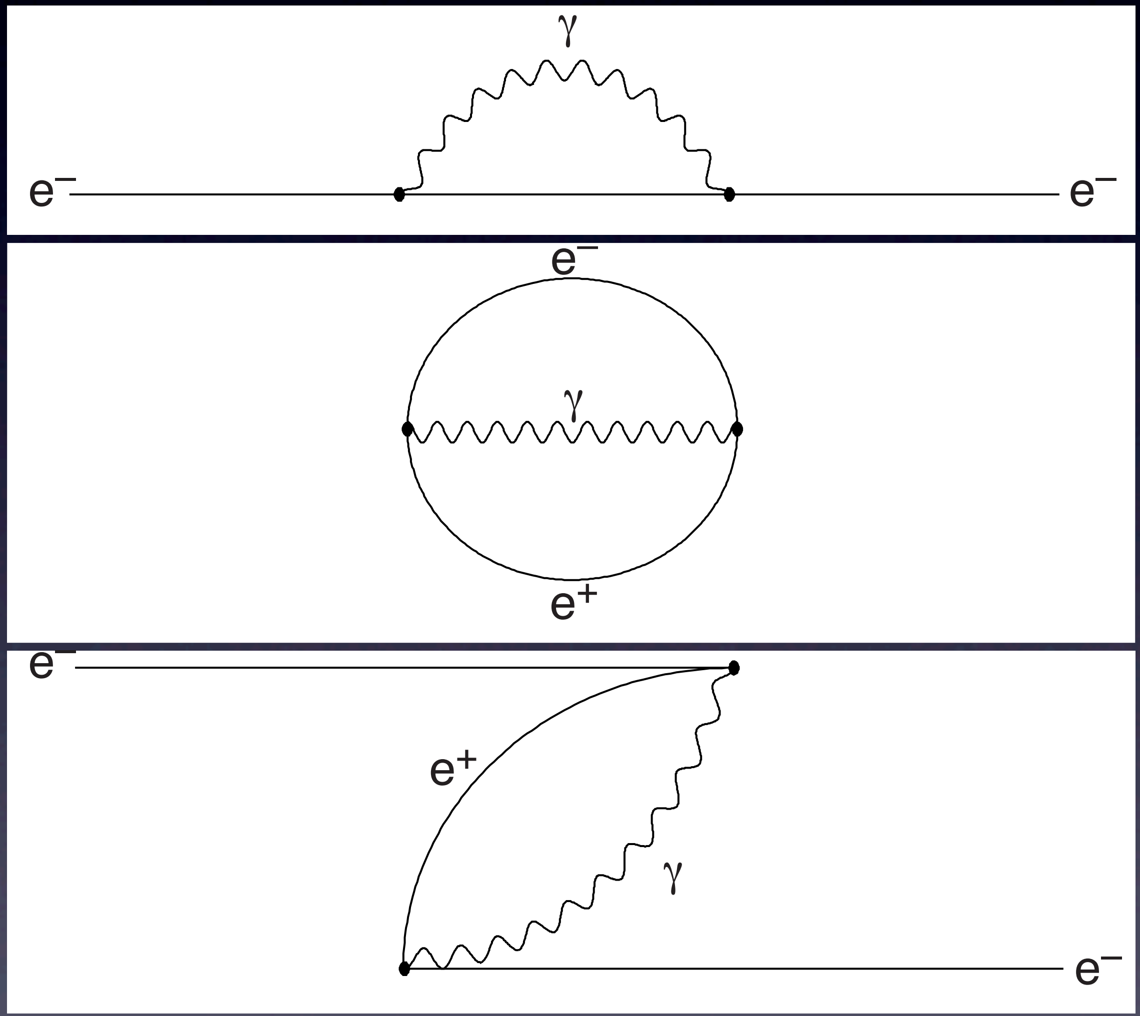
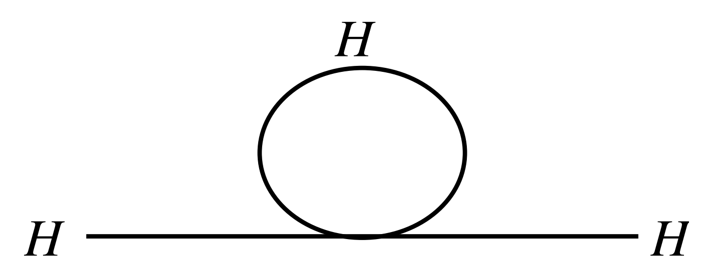


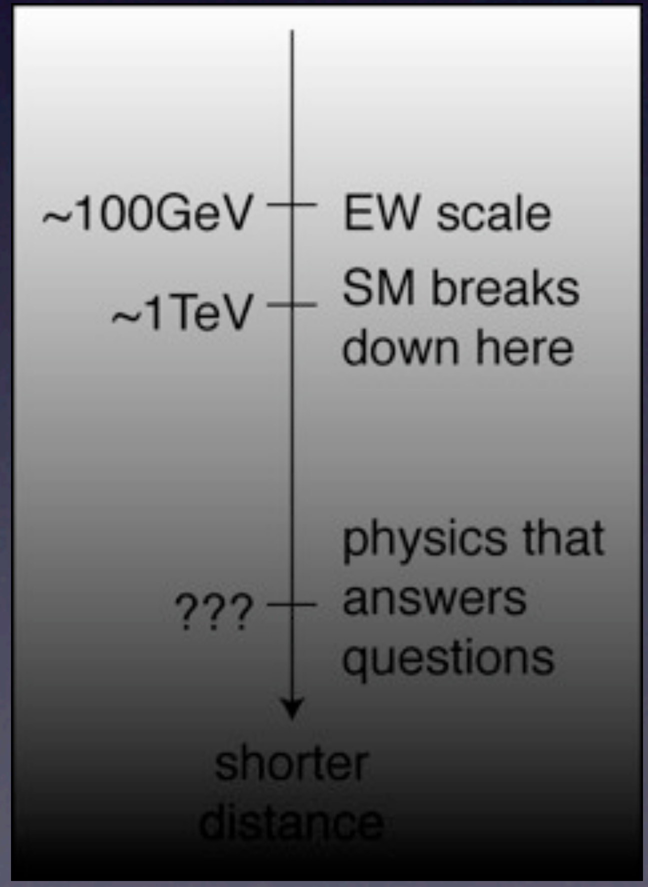
$$\Delta m_e \sim m_e \frac{\alpha}{4\pi} \log(m_e r_e)$$

Higgs repels itself, too

- Just like electron repelling itself because of its charge, Higgs boson also repels itself
- Requires a lot of energy to contain itself in its point-like size!
- Breakdown of theory of weak force
- Can't get started!

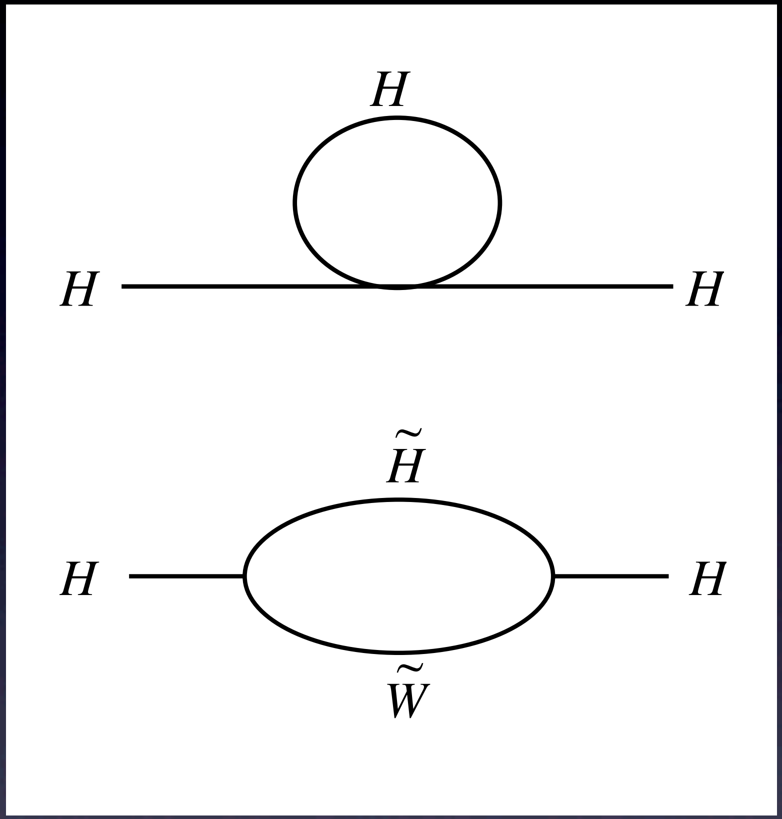


$$\Delta m_H^2 c^4 \sim \left(\frac{\hbar c}{r_H}\right)^2$$



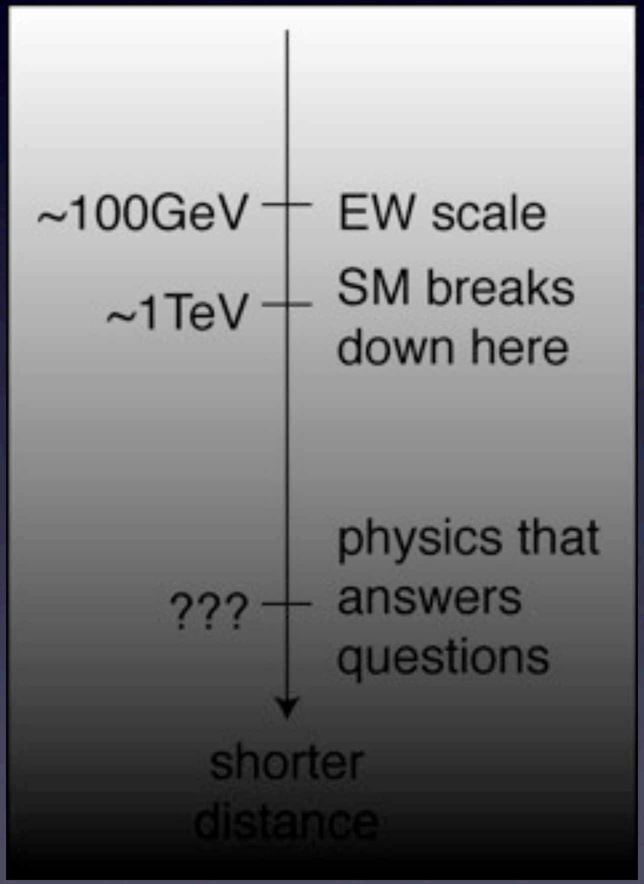
History repeats itself?

- Double #particles again ⇒ superpartners
- "Vacuum bubbles" of superpartners cancel the energy required to contain Higgs boson in itself
- Standard Model made consistent with whatever physics at shorter distances



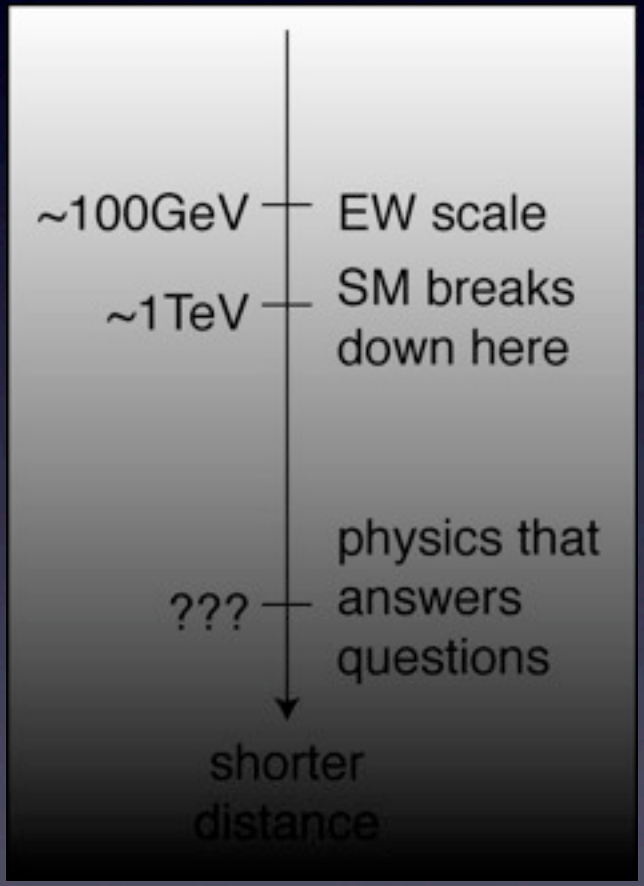
$$\Delta m_H^2 \sim \frac{\alpha}{4\pi} m_{SUSY}^2 \log(m_H r_H)$$

Opening the door



Opening the door

- Once the hierarchy problem solved, we can get started to discuss physics at shorter distances and earlier universe.
- It opens the door to the next level:
  Hope to answer big questions
- The solution to the hierarchy problem itself, e.g., SUSY, provides additional probe to physics at short distances



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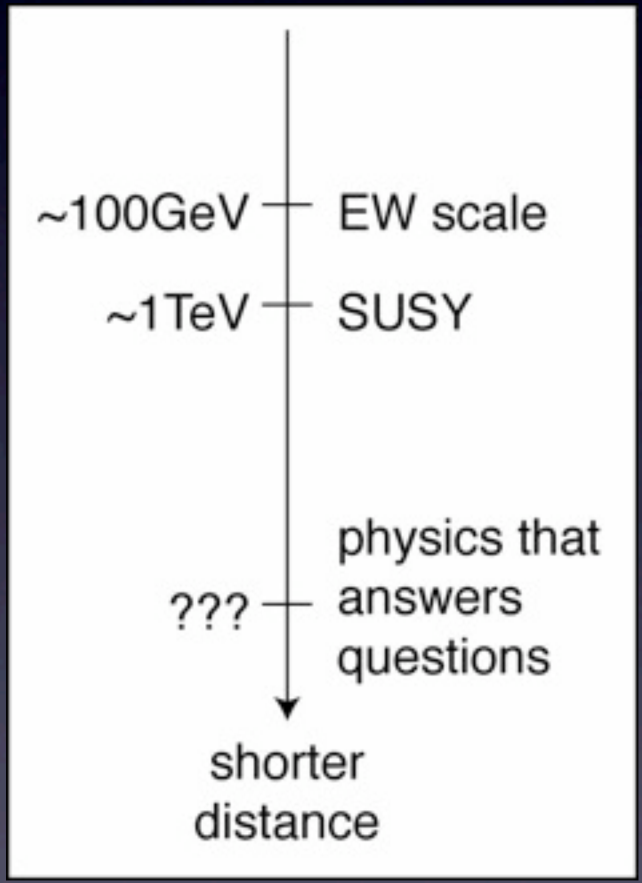


Lesson

- In general, we'd like to see physics that *stabilizes* the hierarchy between Fermi scale (0.3 TeV) and whatever the next high-energy scale is
- supersymmetry, large extra dimensions, warped extra dimensions, little Higgs, composite Higgs, etc etc

Flavor Physics

CP

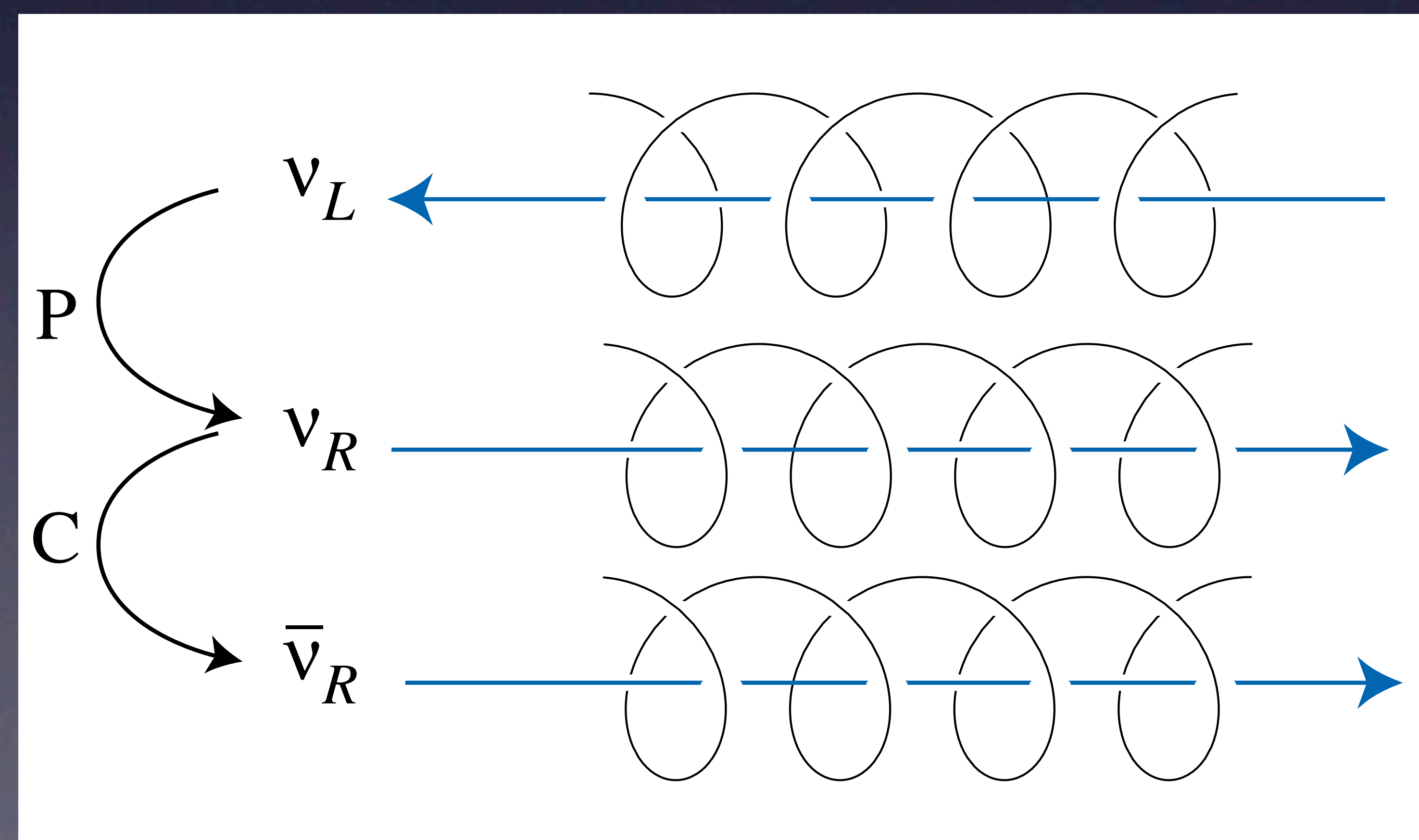
Helicity of Neutrinos*

M. Goldhaber, L. Grodzins, and A. W. Sunyar

Brookhaven National Laboratory, Upton, New York

(Received December 11, 1957)

A COMBINED analysis of circular polarization and resonant scattering of γ rays following orbital electron capture measures the helicity of the neutrino. We have carried out such a measurement with Eu^{152m}, which decays by orbital electron capture. If we assume the most plausible spin-parity assignment for this isomer compatible with its decay scheme,[1] 0−, we find that the neutrino is "left-handed," i.e., $\boldsymbol{\sigma}_\nu \cdot \hat{p}_\nu = -1$ (negative helicity).



CP

- Famous experiment by Goldhaber, Grodzins, Sunyar
- Neutrinos are all left-handed
- This of course violates parity
- What about CP?
- All anti-neutrinos are right-handed
- CP still appears still good!

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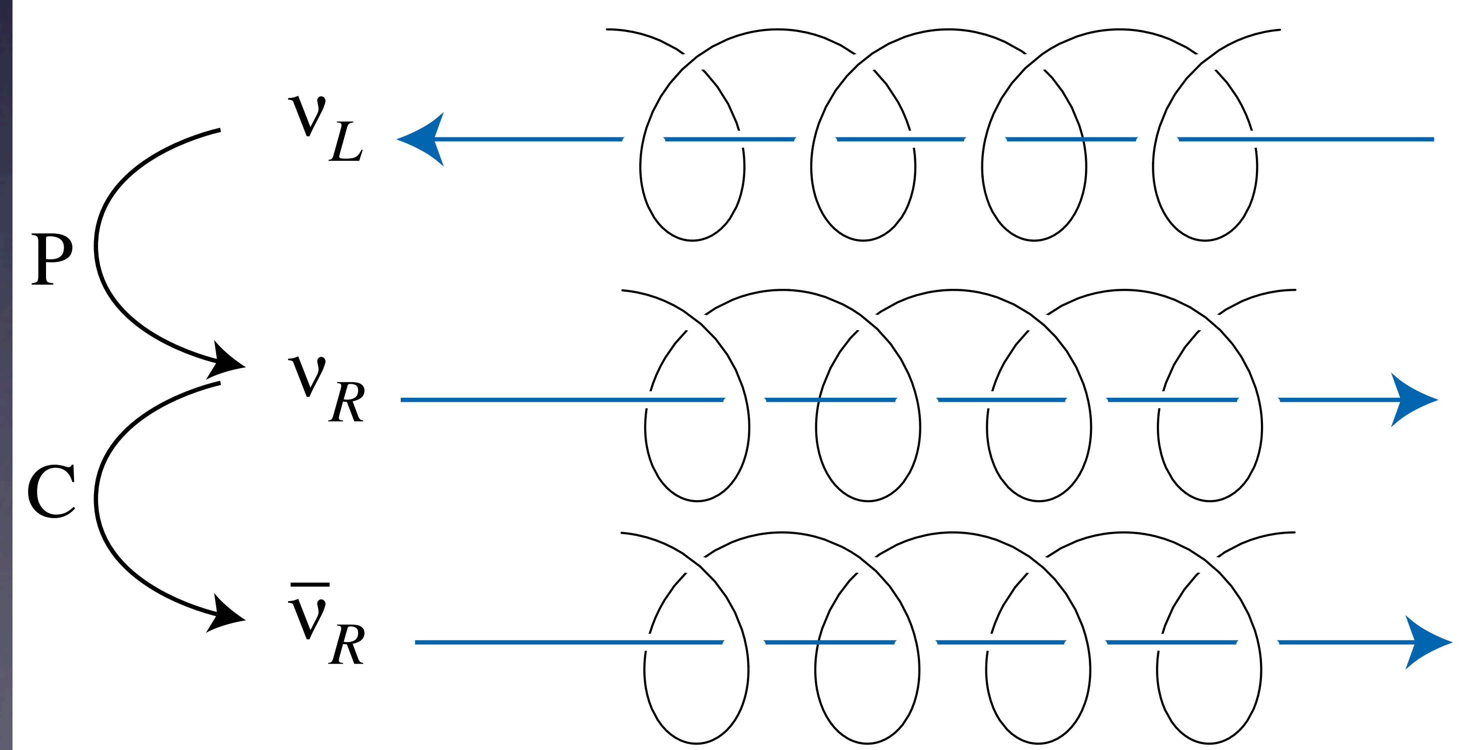
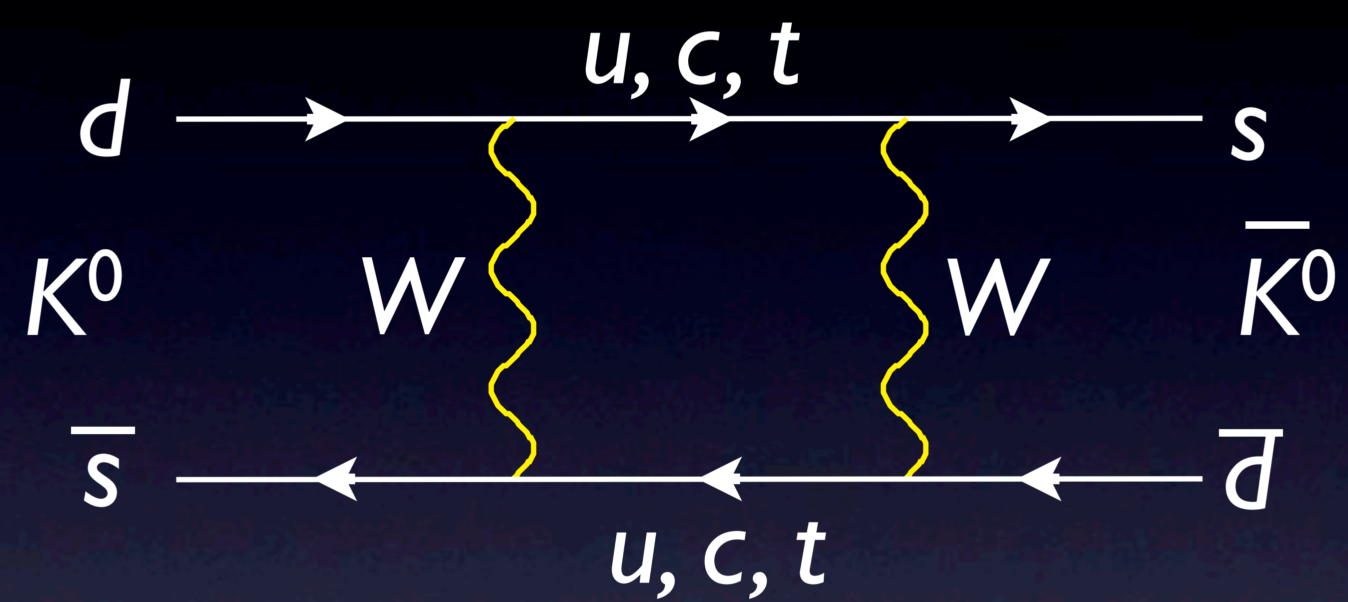


neutral kaons

- K^0 and its anti-particle actually mix!
- What is produced as K^0 *oscillates* to its anti-particle and come back
- define CP eigenstates

$$K_S = \frac{1}{\sqrt{2}}(K^0 + \overline{K}^0)$$

$$K_L = \frac{1}{\sqrt{2}}(K^0 - \overline{K}^0)$$



- Assuming CP invariance, K_S decays into ππ, K_L decays into πππ

CP fell, too

- Cronin, Fitch
- $K^0_S \rightarrow \pi\pi$ (CP=+1)
- $K^0_L \rightarrow \pi\pi\pi$ (CP=–1)
- But, $K^0_L \rightarrow \pi\pi$ occurs with about once in thousand times! (Cronin, Fitch, 1980 Nobel)
- With only one system, we couldn't figure this out

CP fell, too

Brutus, you too?

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T fell also in the end

- If CP is violated, CPT theorem says T must also be violated in such a way that CPT is conserved
- Can we see time-reversal violation?
- CPLEAR@CERN showed

$$\frac{\Gamma(\overline{K}^0 \to K^0) - \Gamma(K^0 \to \overline{K}^0)}{\Gamma(\overline{K}^0 \to K^0) + \Gamma(K^0 \to \overline{K}^0)} = (6.6 \pm 1.3 \pm 1.0) \times 10^{-3}$$

- microscopic arrow of time!

Kobayashi-Maskawa

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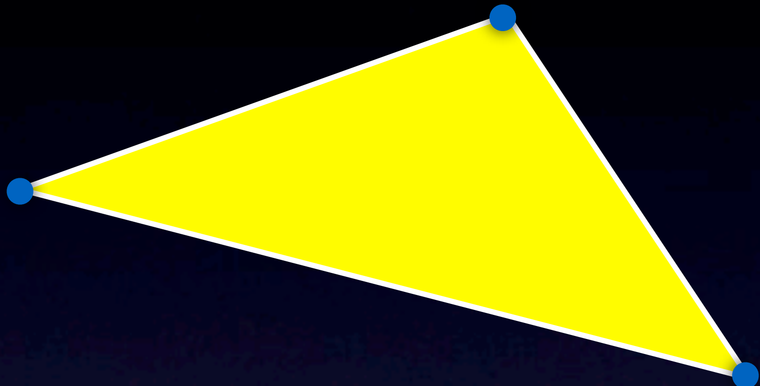

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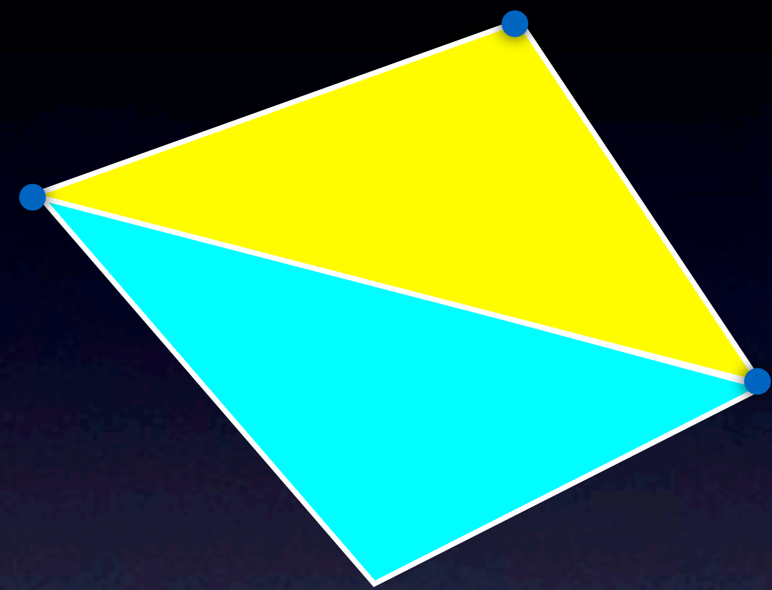

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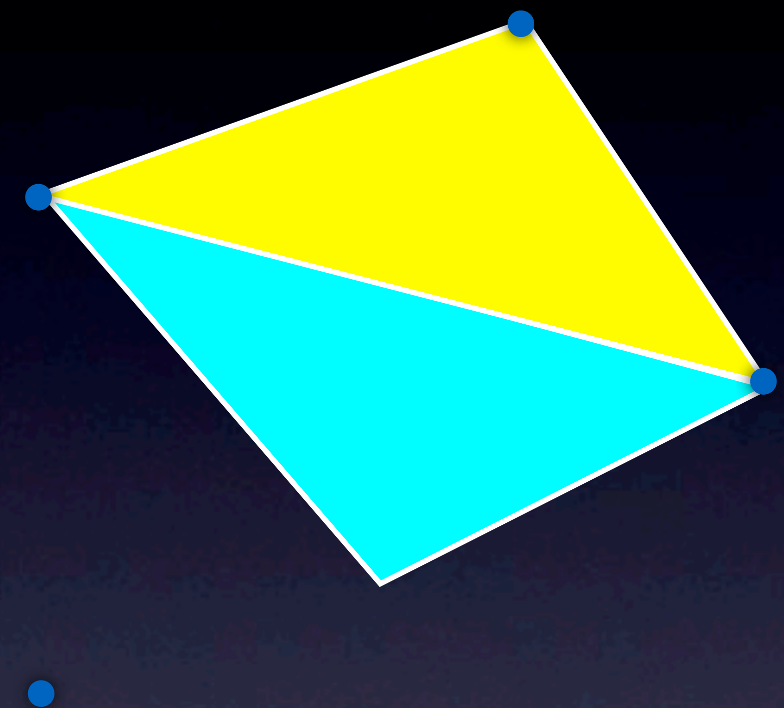

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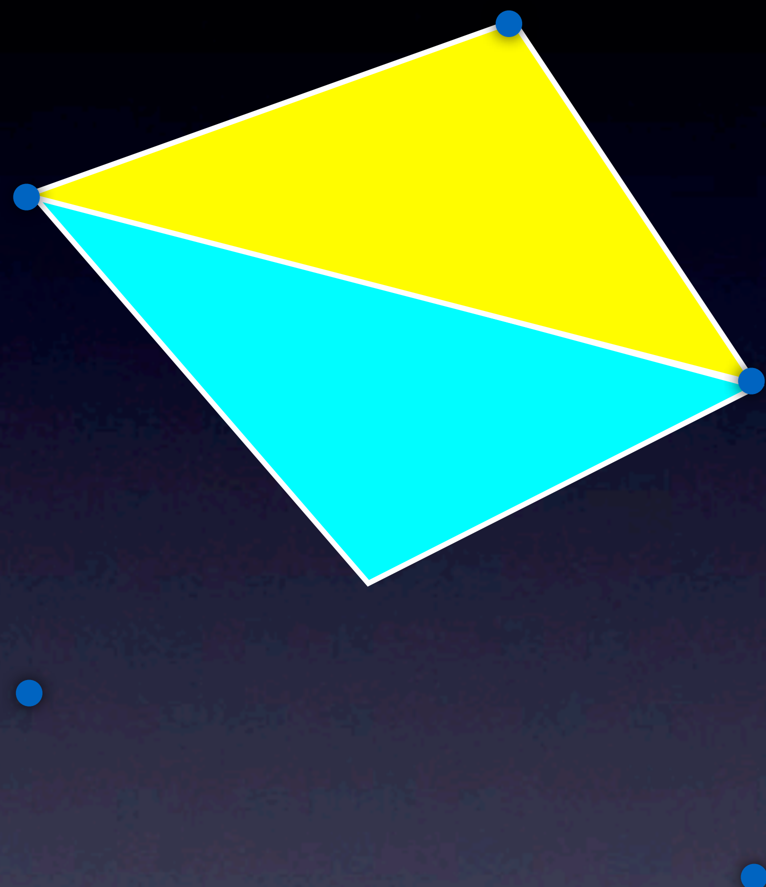

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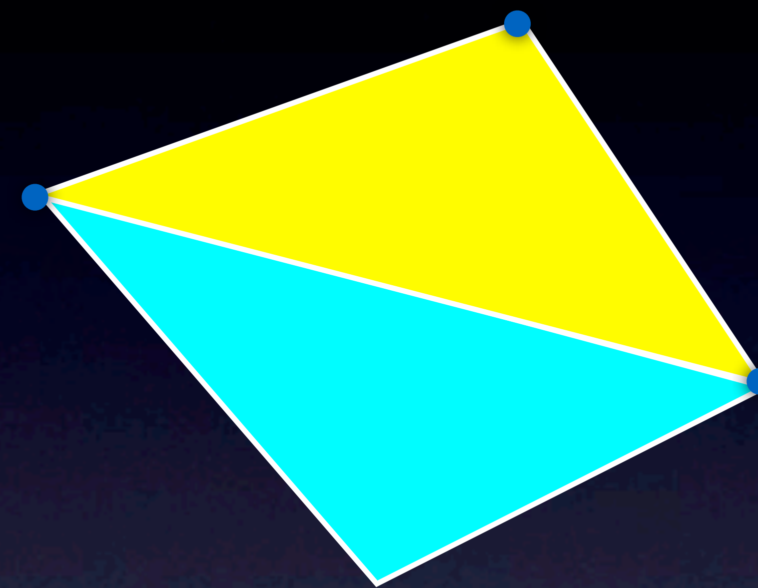
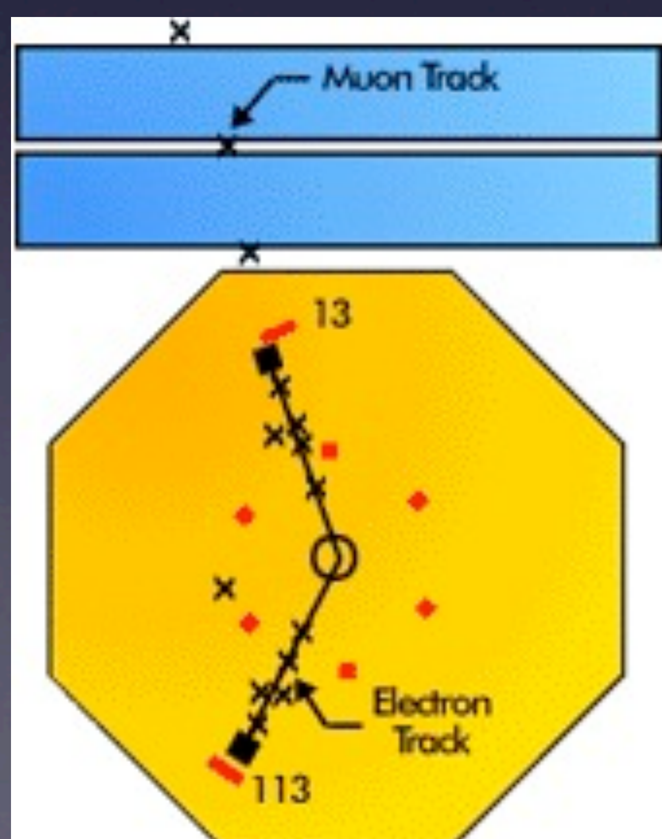
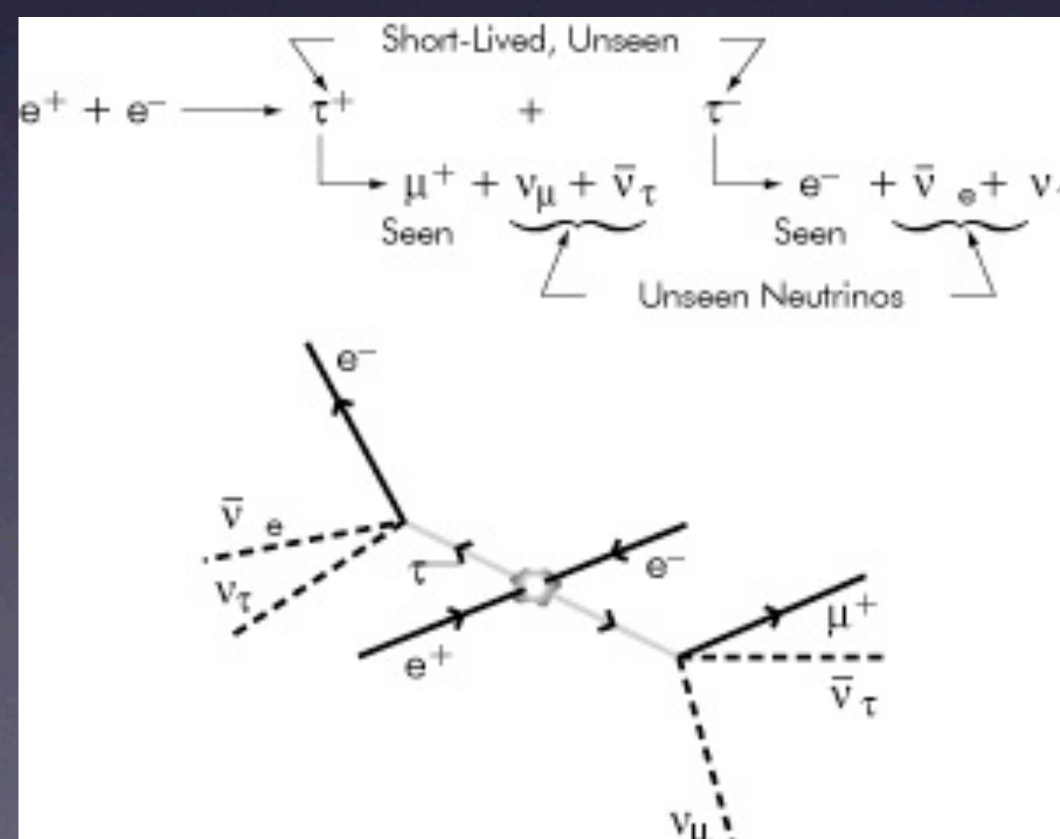


the third generation!

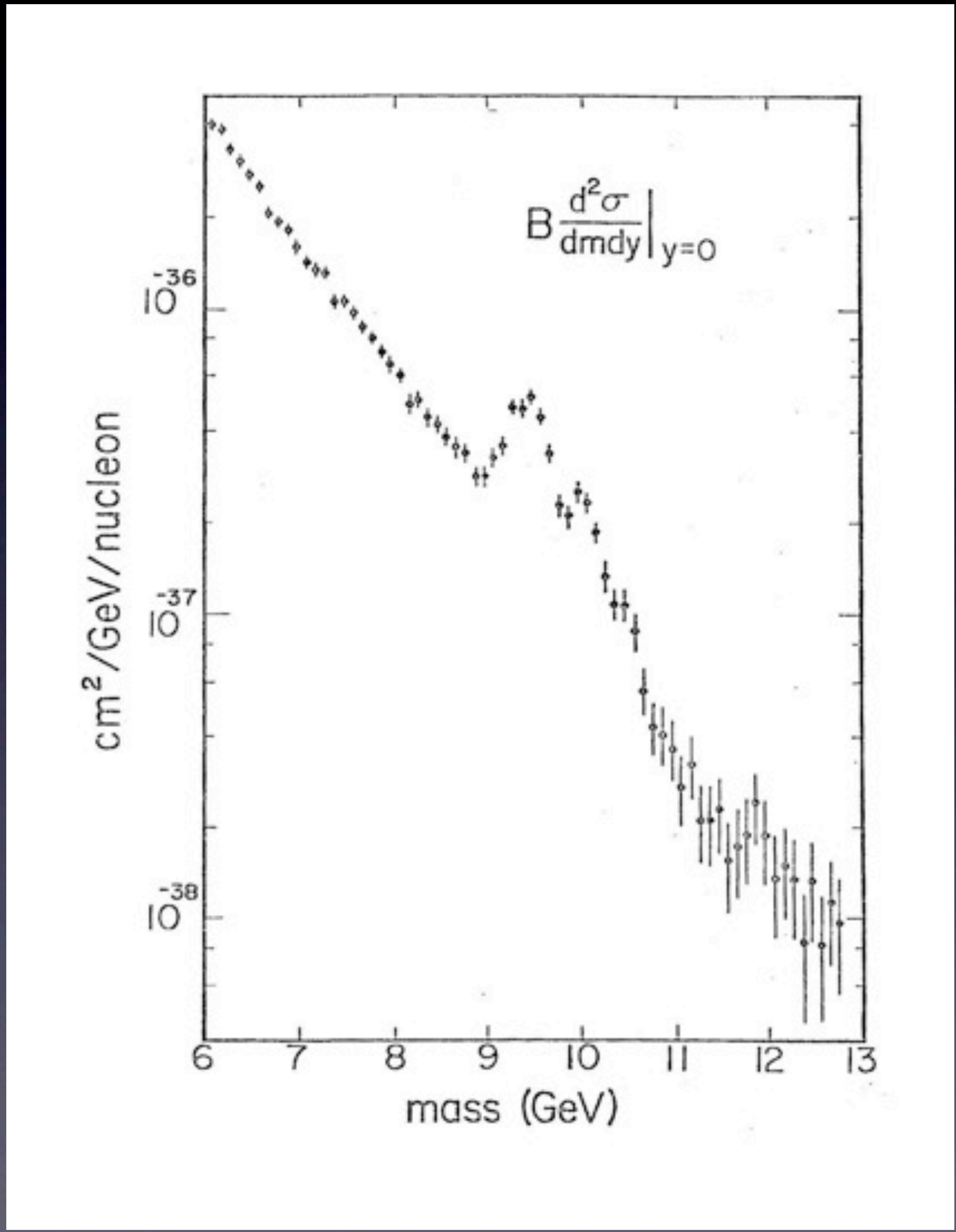
- SLAC e^+e^- experiment has seen "anomalous e mu events" (1975)
- Martin Perl: 1995 Nobel





bottom quark

- Leon Lederman led an experiment at Fermilab
- looked for $\mu^+\mu^-$ in hadron collisions
- a resonance *mis*covered in 1976
- finally real Upsilon $\Upsilon \to \mu^+\mu^-$ discovered as narrow as J/ψ (1978)
- bound states of bottom and anti-bottom



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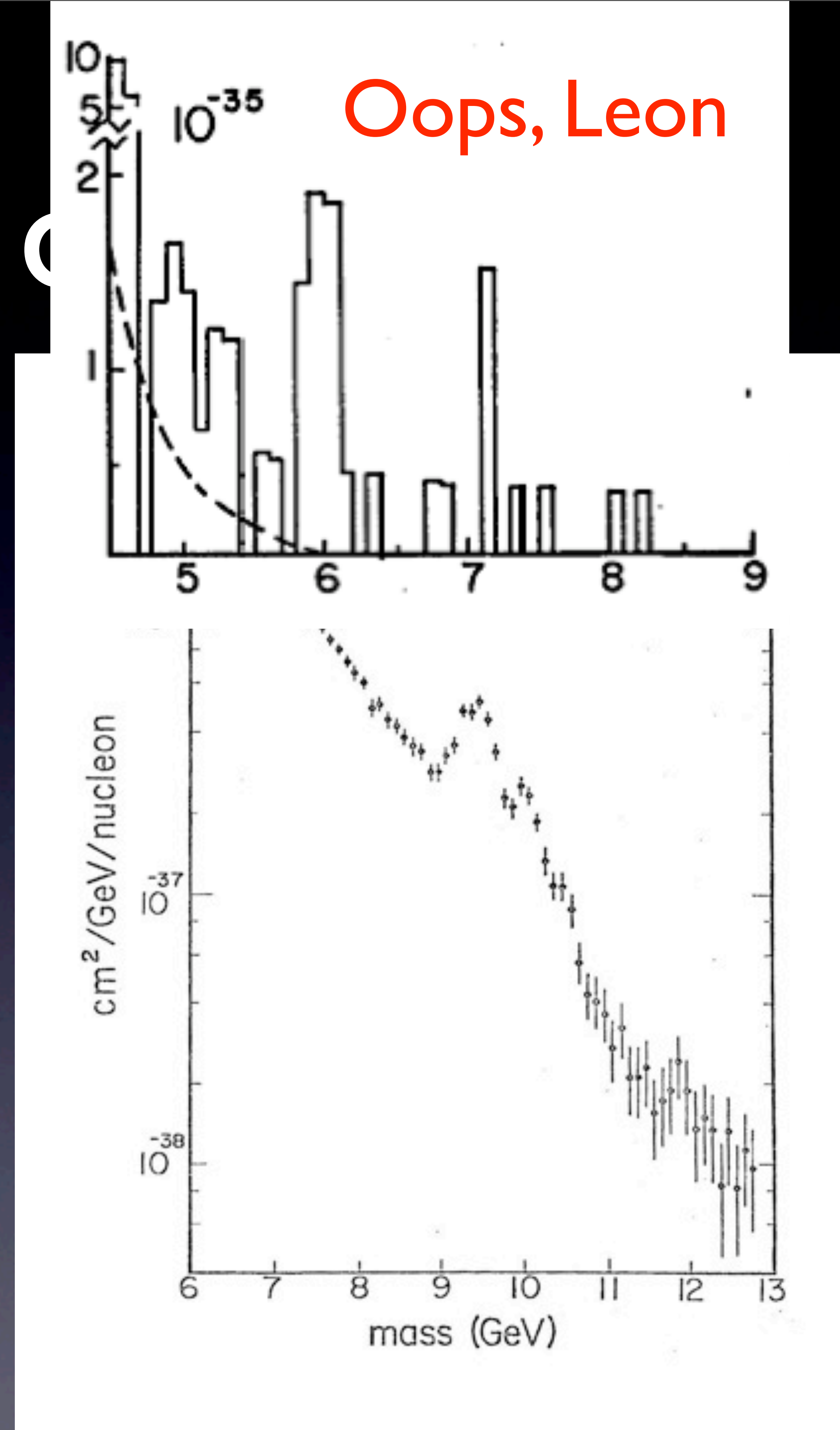
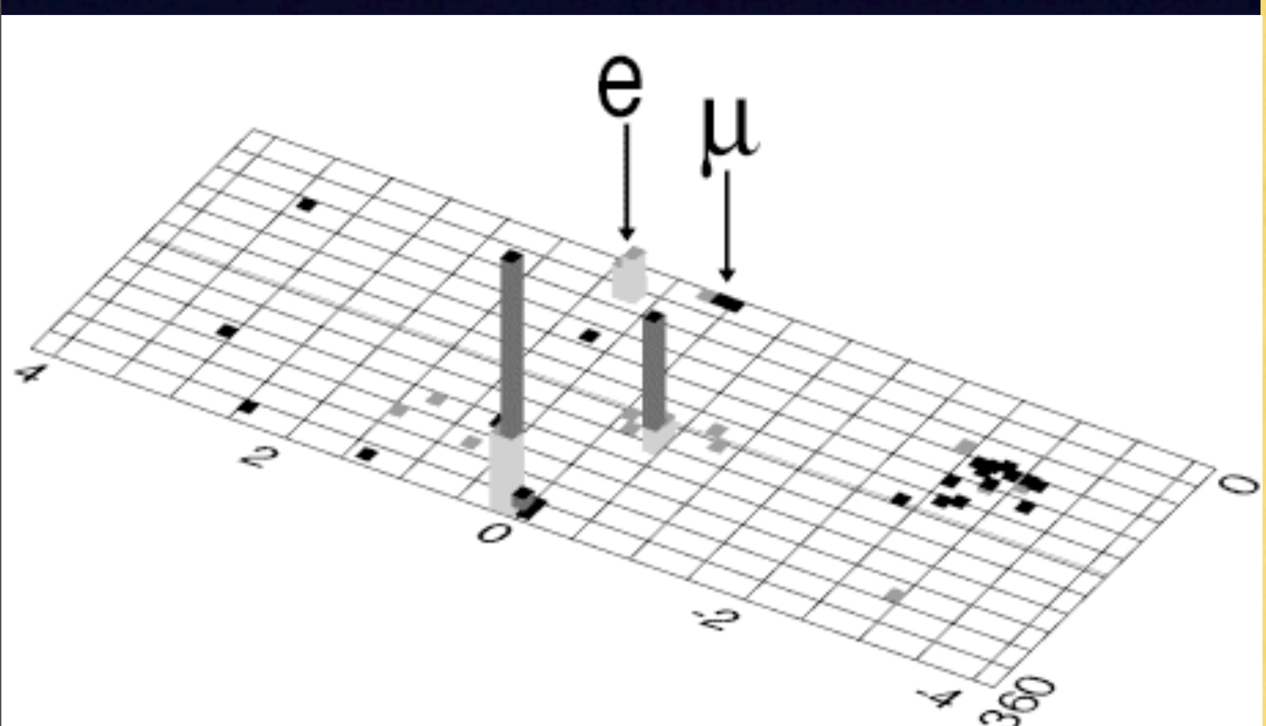
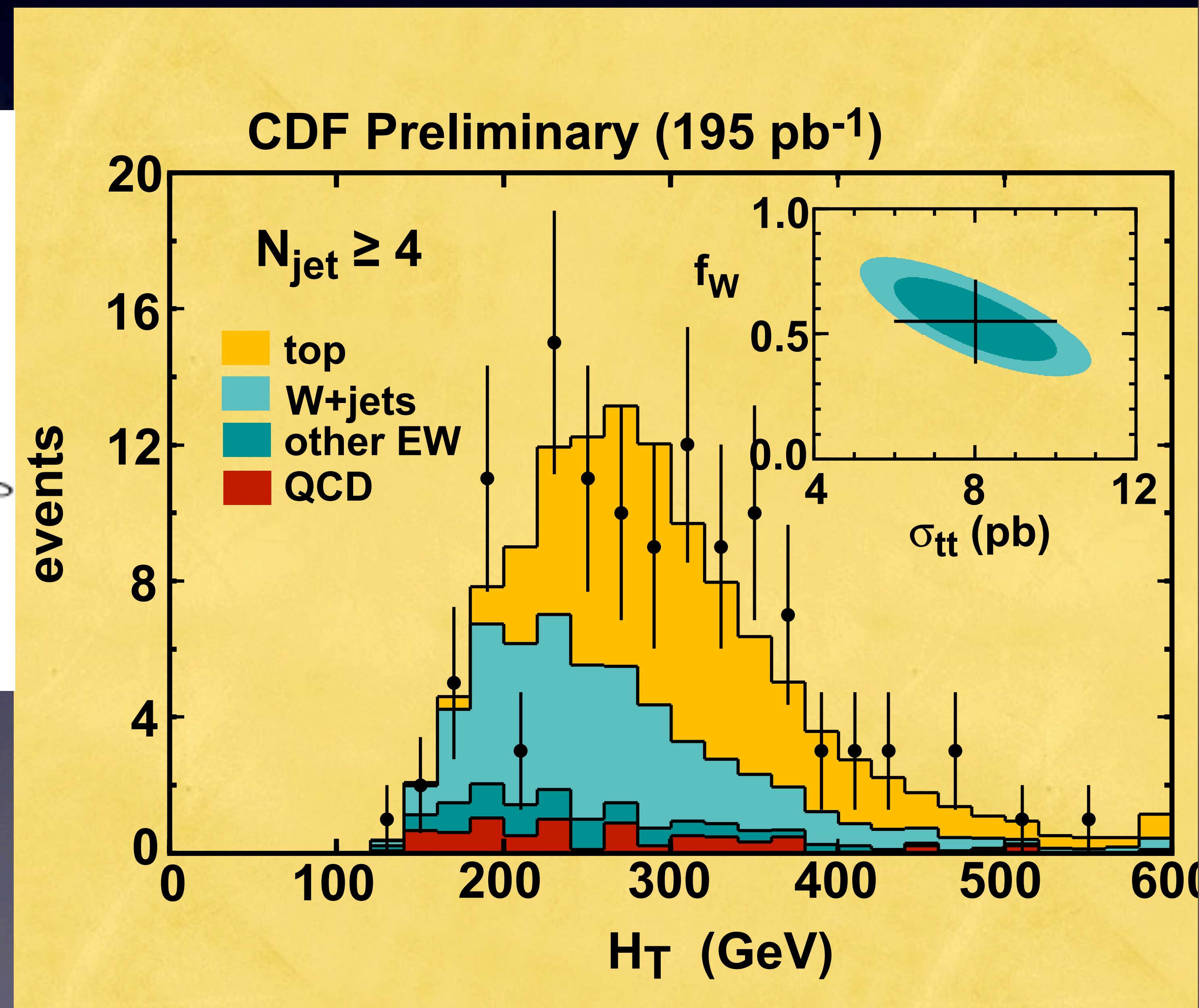


And (the drum roll) the top quark!

- proton anti-proton collider Tevatron 1995





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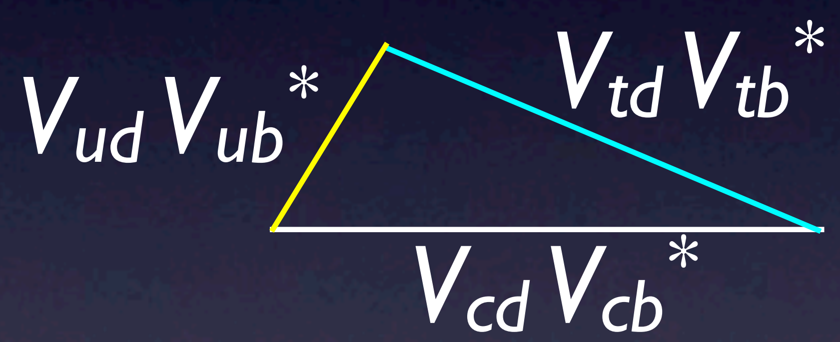
$$V_{CKM} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

Unitarity triangle

- Unitarity of the CKM matrix says

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

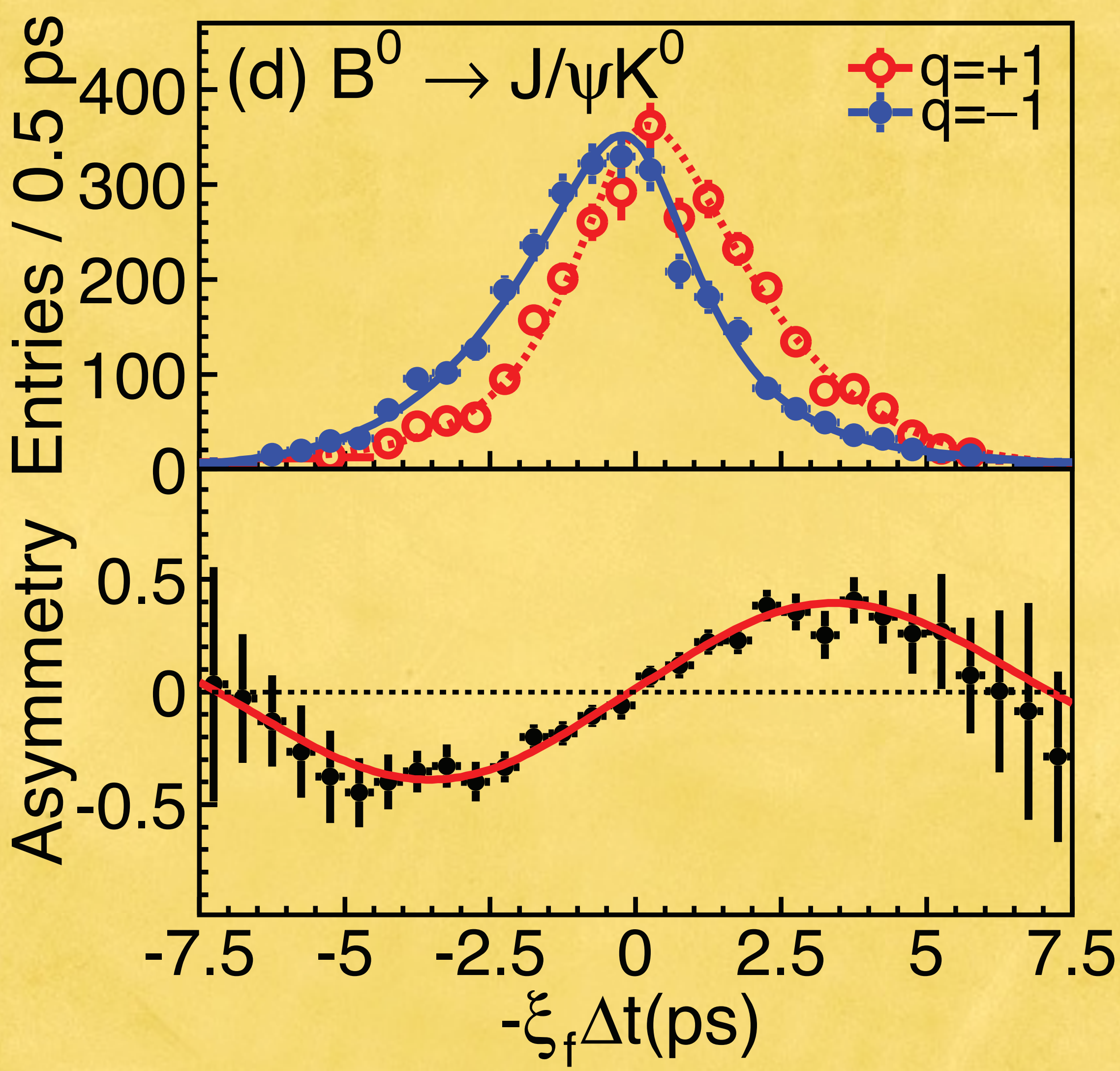


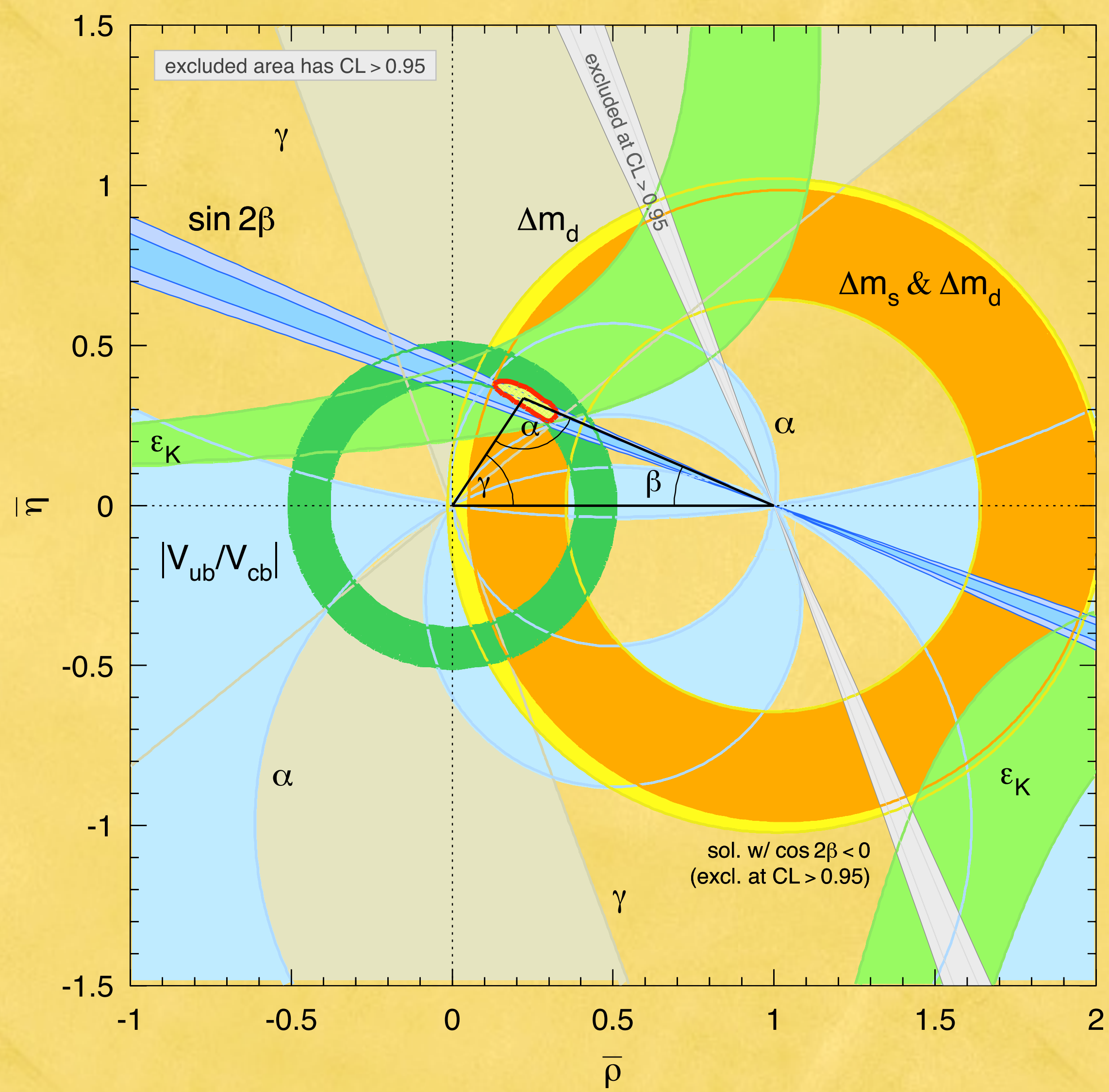
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$\approx \begin{pmatrix} 0.97 & 0.22 & 0.004e^{i\gamma} \\ -0.22 & 0.97 & 0.04 \\ 0.008 & -0.04 & 1 \end{pmatrix}, \quad \gamma \approx 60^\circ$$

Exactly!

- BaBar and Belle 2002

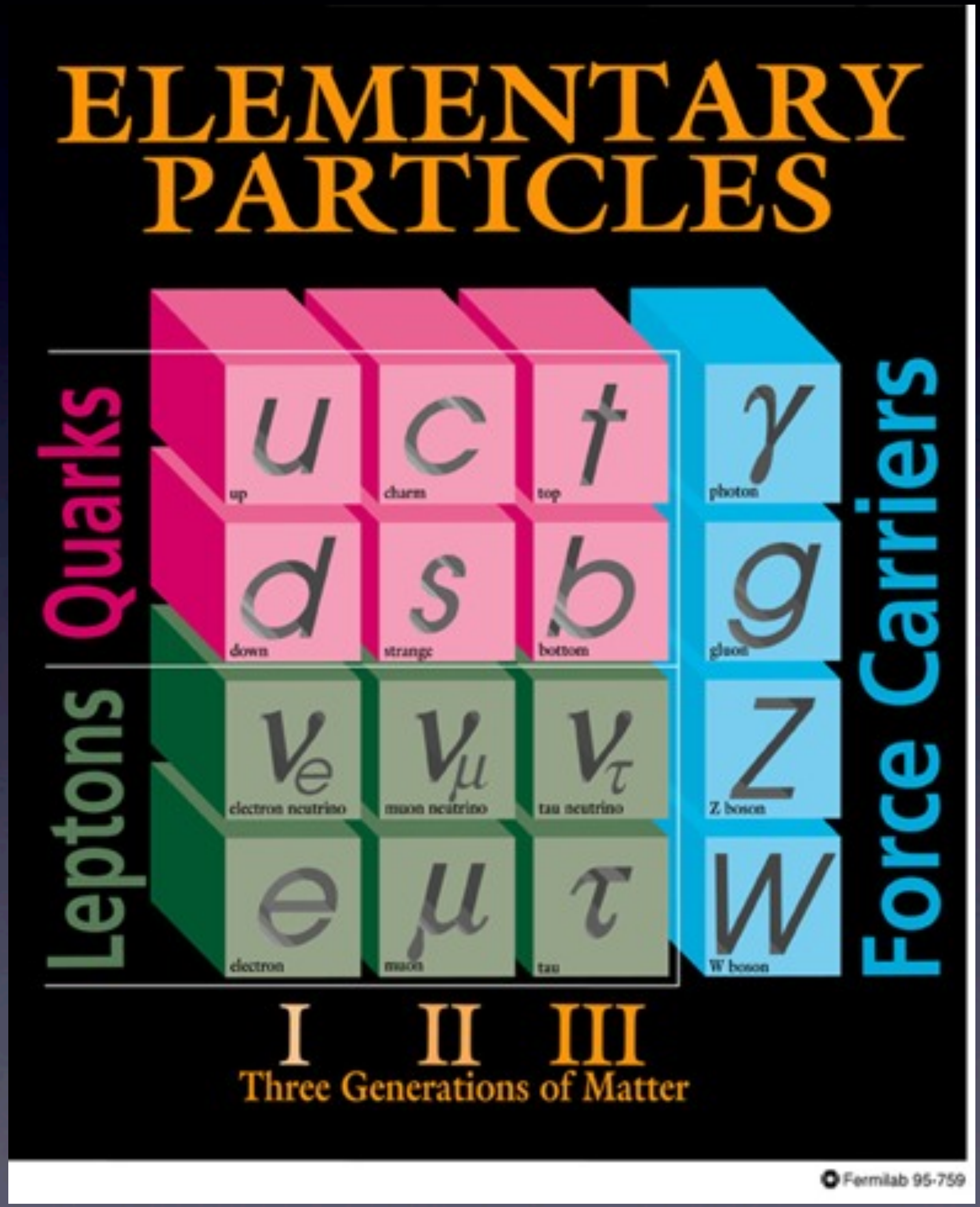




The Standard Model

Three generations
Three forces

- Standard Model
- three generations of quarks and leptons
- electromagnetism, weak, and strong
- $SU(3)_C \times SU(2)_L \times U(1)_Y$



Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

$SU(3)_C$
$SU(2)_L$
$U(1)_Y$
spin
flavor
seen?

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q
$SU(3)_C$	3
$SU(2)_L$	2
$U(1)_Y$	+1/6
spin	-1/2
flavor	3
seen?	Y

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*
$SU(3)_C$	3	3
$SU(2)_L$	2	1
$U(1)_Y$	+1/6	-1/3
spin	-1/2	+1/2
flavor	3	3
seen?	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C x SU(2)_L x U(1)_Y$ gauge theory

	Q	*d*	*u*
$SU(3)_C$	3	3	3
$SU(2)_L$	2	1	1
$U(1)_Y$	+1/6	-1/3	+2/3
spin	-1/2	+1/2	+1/2
flavor	3	3	3
seen?	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*
$SU(3)_C$	3	3	3	1
$SU(2)_L$	2	1	1	2
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2
spin	-1/2	+1/2	+1/2	-1/2
flavor	3	3	3	3
seen?	Y	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	d	u	L	e
$SU(3)_C$	3	3	3	1	1
$SU(2)_L$	2	1	1	2	1
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1
spin	-1/2	+1/2	+1/2	-1/2	+1/2
flavor	3	3	3	3	3
seen?	Y	Y	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C x SU(2)_L x U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	e	*B*
$SU(3)_C$	3	3	3	1	1	1
$SU(2)_L$	2	1	1	2	1	1
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1	0
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1
flavor	3	3	3	3	3	1
seen?	Y	Y	Y	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	*e*	*B*	*W*
$SU(3)_C$	3	3	3	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	3
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1	0	0
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1	1
flavor	3	3	3	3	3	1	1
seen?	Y	Y	Y	Y	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C x SU(2)_L x U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	*e*	*B*	*W*	*g*
$SU(3)_C$	3	3	3	1	1	1	1	8
$SU(2)_L$	2	1	1	2	1	1	3	1
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1	0	0	0
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1	1	1
flavor	3	3	3	3	3	1	1	1
seen?	Y	Y	Y	Y	Y	Y	Y	Y

Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	e	*B*	*W*	*g*	*H*
$SU(3)_C$	3	3	3	1	1	1	1	8	1
$SU(2)_L$	2	1	1	2	1	1	3	1	2
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1	0	0	0	-1/2
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1	1	1	0
flavor	3	3	3	3	3	1	1	1	1
seen?	Y	Y	Y	Y	Y	Y	Y	Y	N

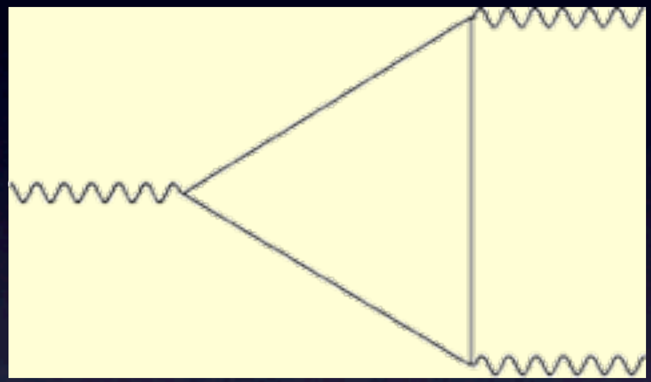
Renormalizable Quantum Field Theory

- $SU(3)_C \times SU(2)_L \times U(1)_Y$ gauge theory

	Q	*d*	*u*	*L*	*e*	*B*	*W*	*g*	*H*	*G*
$SU(3)_C$	3	3	3	1	1	1	1	8	1	1
$SU(2)_L$	2	1	1	2	1	1	3	1	2	1
$U(1)_Y$	+1/6	-1/3	+2/3	-1/2	+1	0	0	0	-1/2	0
spin	-1/2	+1/2	+1/2	-1/2	+1/2	1	1	1	0	2
flavor	3	3	3	3	3	1	1	1	1	1
seen?	Y	Y	Y	Y	Y	Y	Y	Y	N	N

Gauge Anomaly

- Gauge symmetry crucial to keep quantum field theories (including the SM) under control
- Triangle diagrams:



may spoil the gauge invariance at quantum level $\Rightarrow$ *disaster*

- Anomalies must all vanish for three gauge vertices (not for global currents, e.g. B, L)
- Sum up all standard model fermions and see if they indeed vanish

Anomaly Cancellation

- $U(1)^3$ $3\cdot 2\left(\frac{1}{6}\right)^3 + 3\left(-\frac{2}{3}\right)^3 + 3\left(\frac{1}{3}\right)^3 + 2\left(-\frac{1}{2}\right)^3 + (1)^3 = 0$
- $U(1)(\text{gravity})^2$ $3\cdot 2\left(\frac{1}{6}\right) + 3\left(-\frac{2}{3}\right) + 3\left(\frac{1}{3}\right) + 2\left(-\frac{1}{2}\right) + (1) = 0$
- $U(1)(SU(2))^2$ $3\cdot 2\left(\frac{1}{6}\right) + 2\left(-\frac{1}{2}\right) = 0$
- $U(1)(SU(3))^2$ $3\cdot 2\left(\frac{1}{6}\right) + 3\left(-\frac{2}{3}\right) + 3\left(\frac{1}{3}\right) = 0$
- $(SU(3))^3$ $\#\underline{3} - \#\underline{3}^* = 2 - 1 - 1 = 0$
- $(SU(2))^3$, $(SU(3))^2 SU(2)$, $SU(3)(SU(2))^2$ 0
- $SU(2)$ $\#\underline{2} = 3 + 1 = 4 = \text{even}$

Non-trivial connection between q & l

General

- The most general renormalizable Lagrangian with the given particle content

$$
\begin{aligned}
\mathcal{L} \quad = \quad & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{a\mu\nu} \\
& +\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{e}_i i\not{D}e_i \\
& +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + |D_\mu H|^2 \\
& -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}
\end{aligned}
$$

Parameters

- 3 gauge coupling constants + θ_{QCD}
- 2 parameters in the Higgs potential (G_F, m_H)

$$\begin{aligned}\mathcal{L} \;=\; & -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{a\mu\nu} \\ & +\bar{Q}_i i\not{D} Q_i + \bar{u}_i i\not{D} u_i + \bar{d}_i i\not{D} d_i + \bar{L}_i i\not{D} L_i + \bar{e}_i i\not{D} e_i \\ & +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + |D_\mu H|^2 \\ & -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}\end{aligned}$$

g'~0.36, g~0.65, gs~1.2

G_F~(300 GeV)$^{-2}$, m_H unknown, $\theta_{QCD} < 10^{-10}$

Parameters

- 3x3 complex $Y_u^{ij}, Y_d^{ij}, Y_l^{ij}$: 54 real params
- reparameterization $SU(3)^5 \times U(1) = 41$

$$\begin{aligned}\mathcal{L} \;=\;& -\frac{1}{4g'^2}B_{\mu\nu}B^{\mu\nu} - \frac{1}{4g^2}W^a_{\mu\nu}W^{a\mu\nu} - \frac{1}{4g_s^2}G^a_{\mu\nu}G^{a\mu\nu} \\ & +\bar{Q}_i i\not{D}Q_i + \bar{u}_i i\not{D}u_i + \bar{d}_i i\not{D}d_i + \bar{L}_i i\not{D}L_i + \bar{e}_i i\not{D}e_i \\ & +Y_u^{ij}\bar{Q}_i u_j \tilde{H} + Y_d^{ij}\bar{Q}_i d_j H + Y_l^{ij}\bar{L}_i e_j H + |D_\mu H|^2 \\ & -\lambda(H^\dagger H)^2 + \lambda v^2 H^\dagger H + \frac{\theta}{64\pi^2}\epsilon^{\mu\nu\rho\sigma}G^a_{\mu\nu}G^a_{\rho\sigma}\end{aligned}$$

$54-41=13=3_u+3_d+3_l+(3+1)_{CKM}$

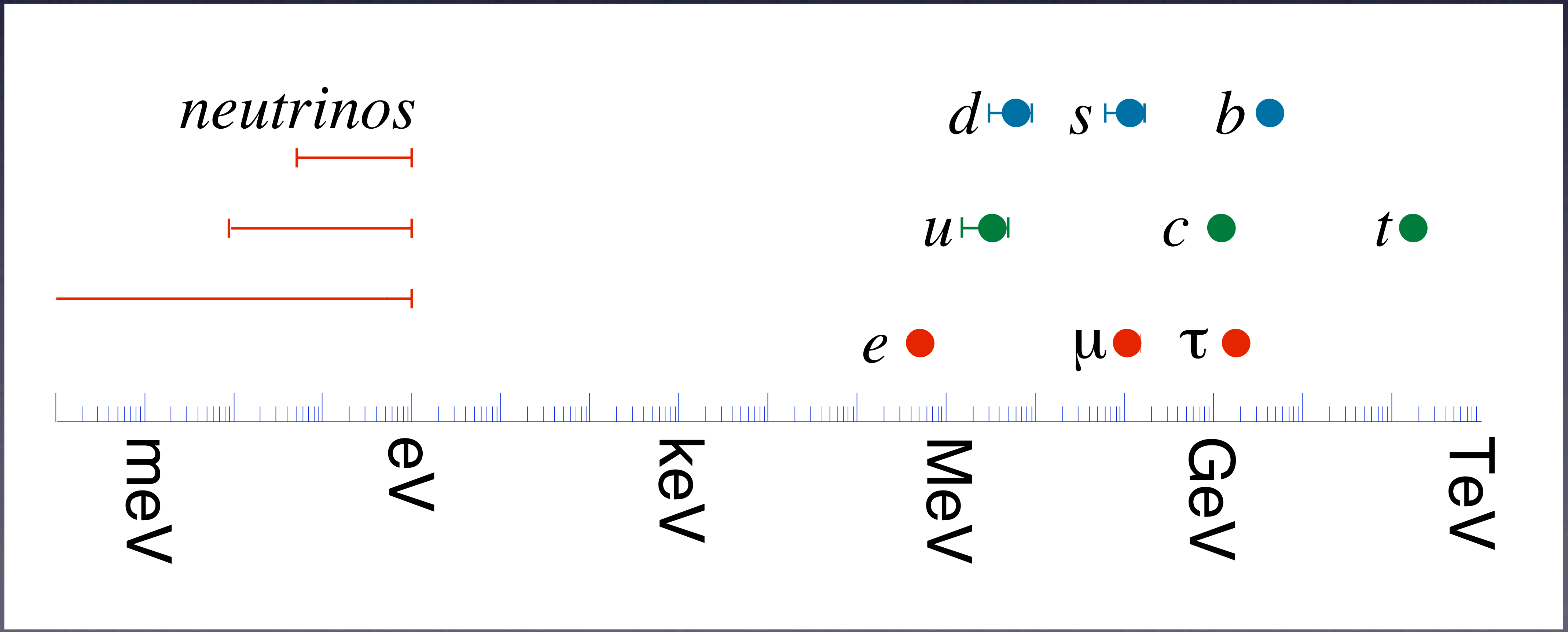
Masses and Mixings

- Choose masses and mixings as observed

$$V_{CKM} \simeq \begin{pmatrix} 1 & \lambda & A\lambda^3(\rho + i\eta) \\ -\lambda & 1 & A\lambda^2 \\ -\lambda^3(1+\rho-i\eta) & -A\lambda^2 & 1 \end{pmatrix}$$

$\lambda \approx 0.22$

$A, \rho, \eta \approx O(1)$

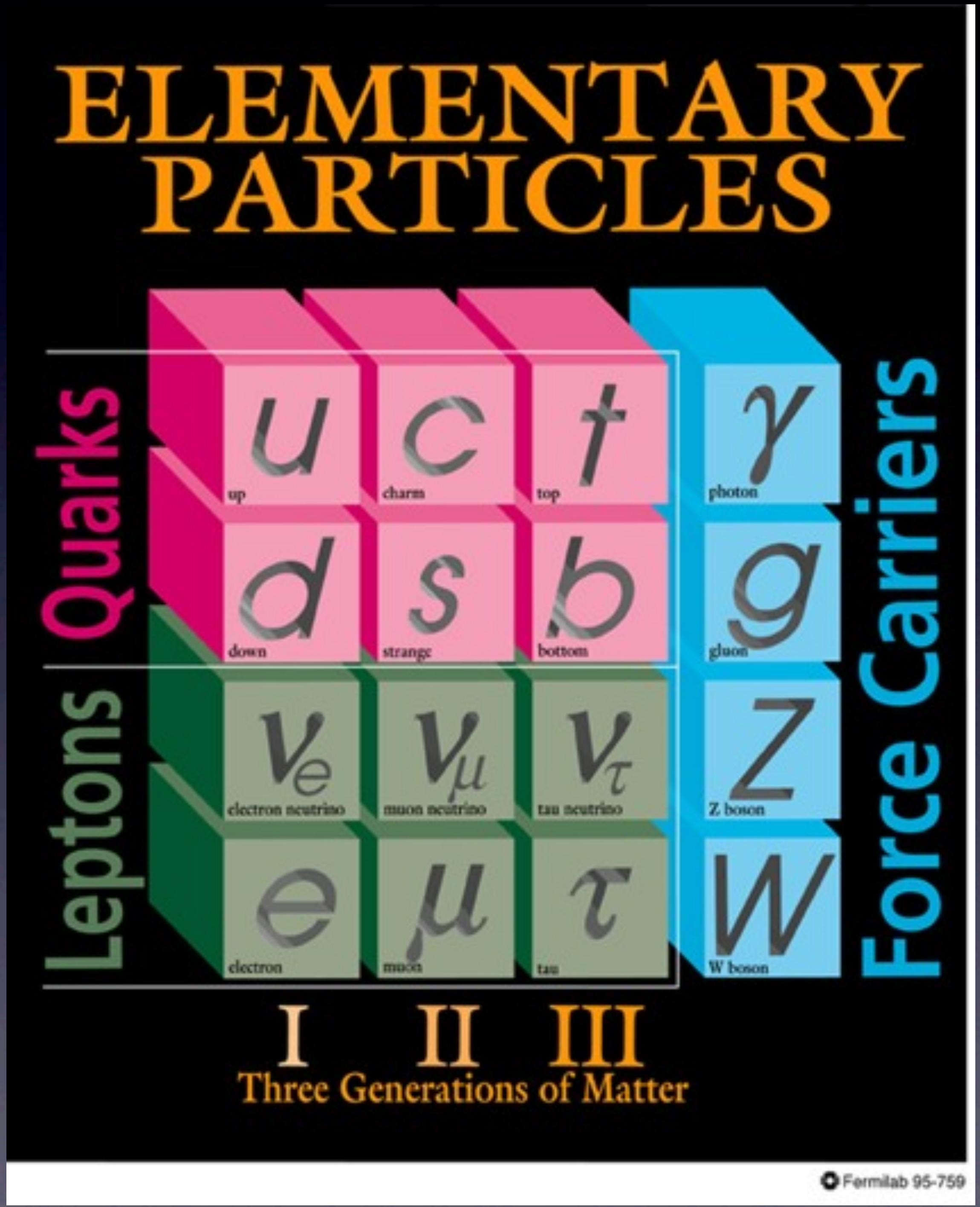


Incomplete

- Now we have experimental data that say the Standard Model is incomplete
  - neutrino mass
  - dark matter
  - dark energy
  - absence of anti-matter in the Universe
  - apparently acausal density perturbation

Standard Model

- *triumph of 20th century physics*
- most successful physical theory ever
- describes three forces:
  - electromagnetism
  - strong
  - weak
- but we see problems in the 21st century
- *and it's weird!*
- There must be something *beyond the Standard Model*
- *Expect big discoveries!*



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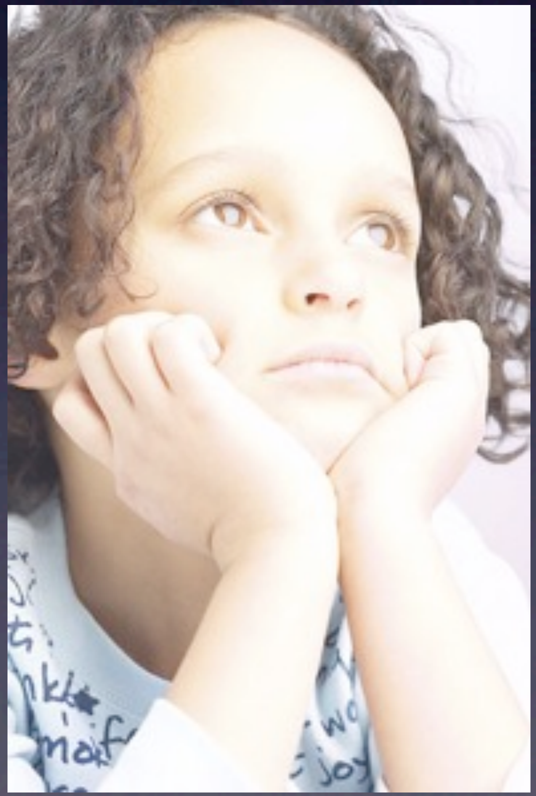
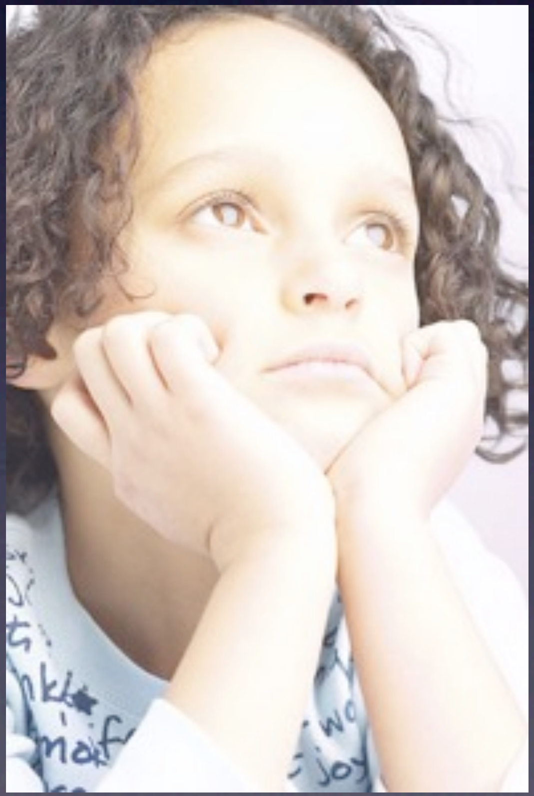
Science



INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Science

- What is the Universe made of?



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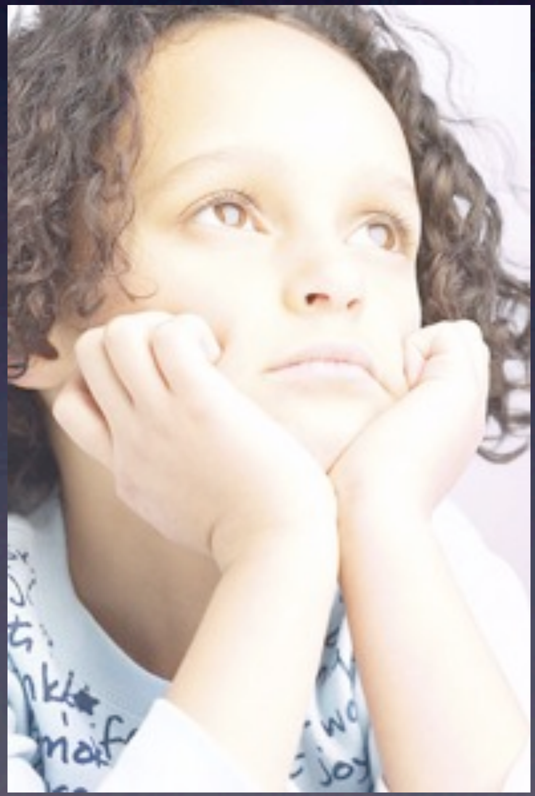
Science

- What is the Universe made of?
- How did it start?



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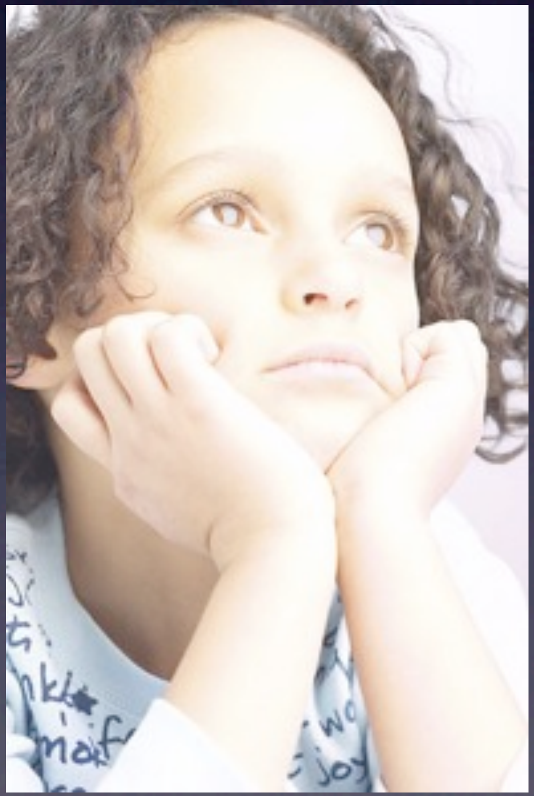

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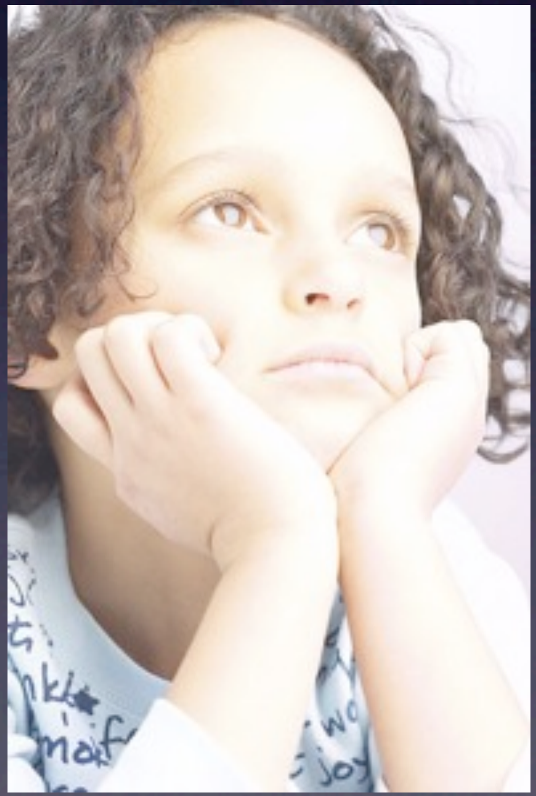

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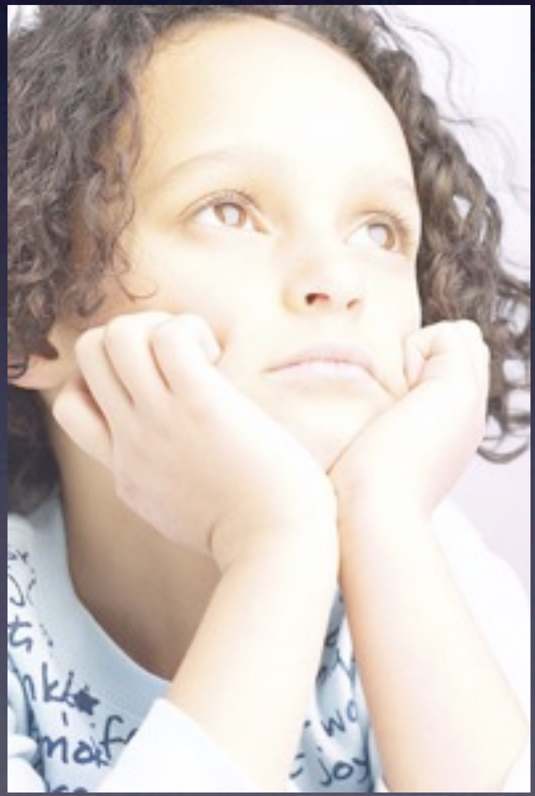

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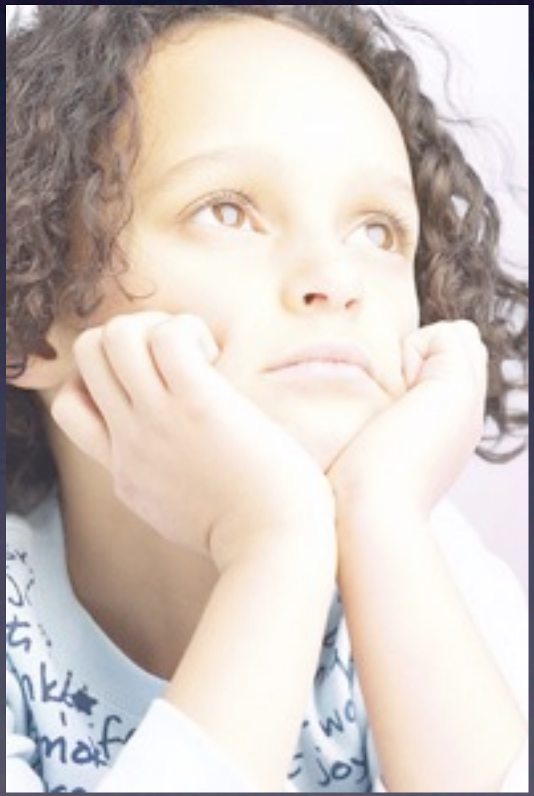

- New intl research institute in Japan
  - astrophysics
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- intl guest house in 2009
- workshops roughly every other month

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How we look like

東京大学
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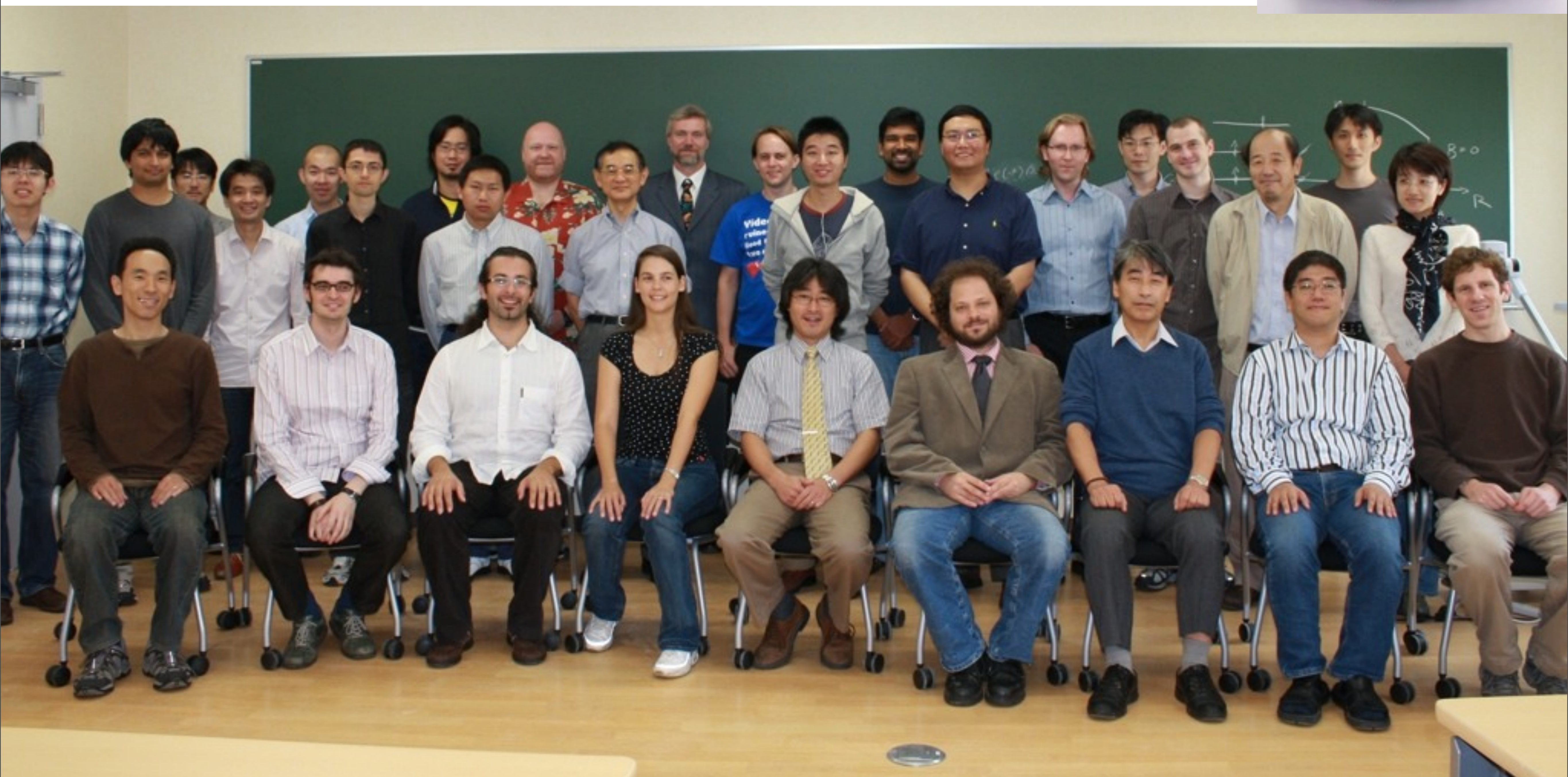
How we look like



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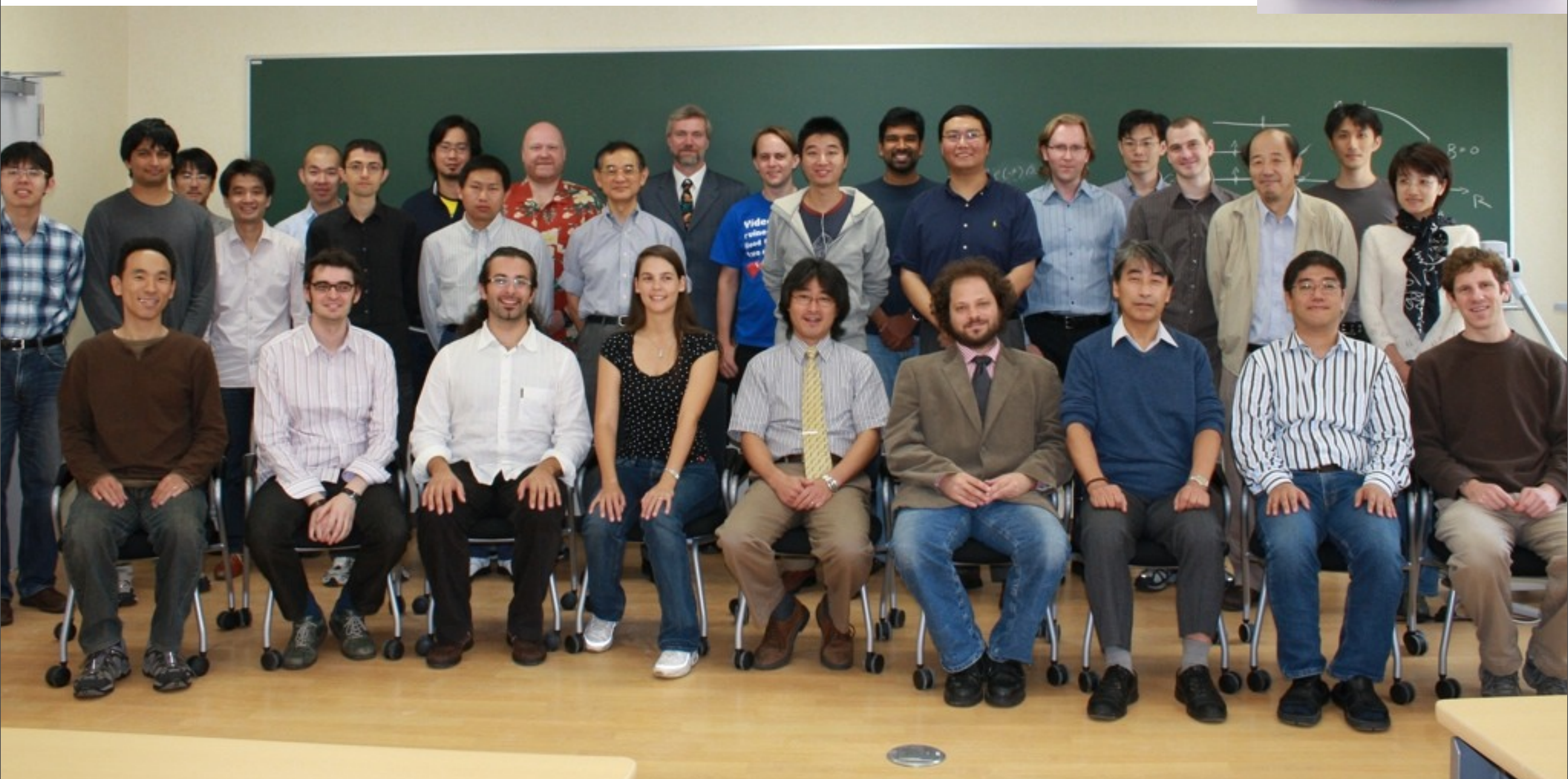
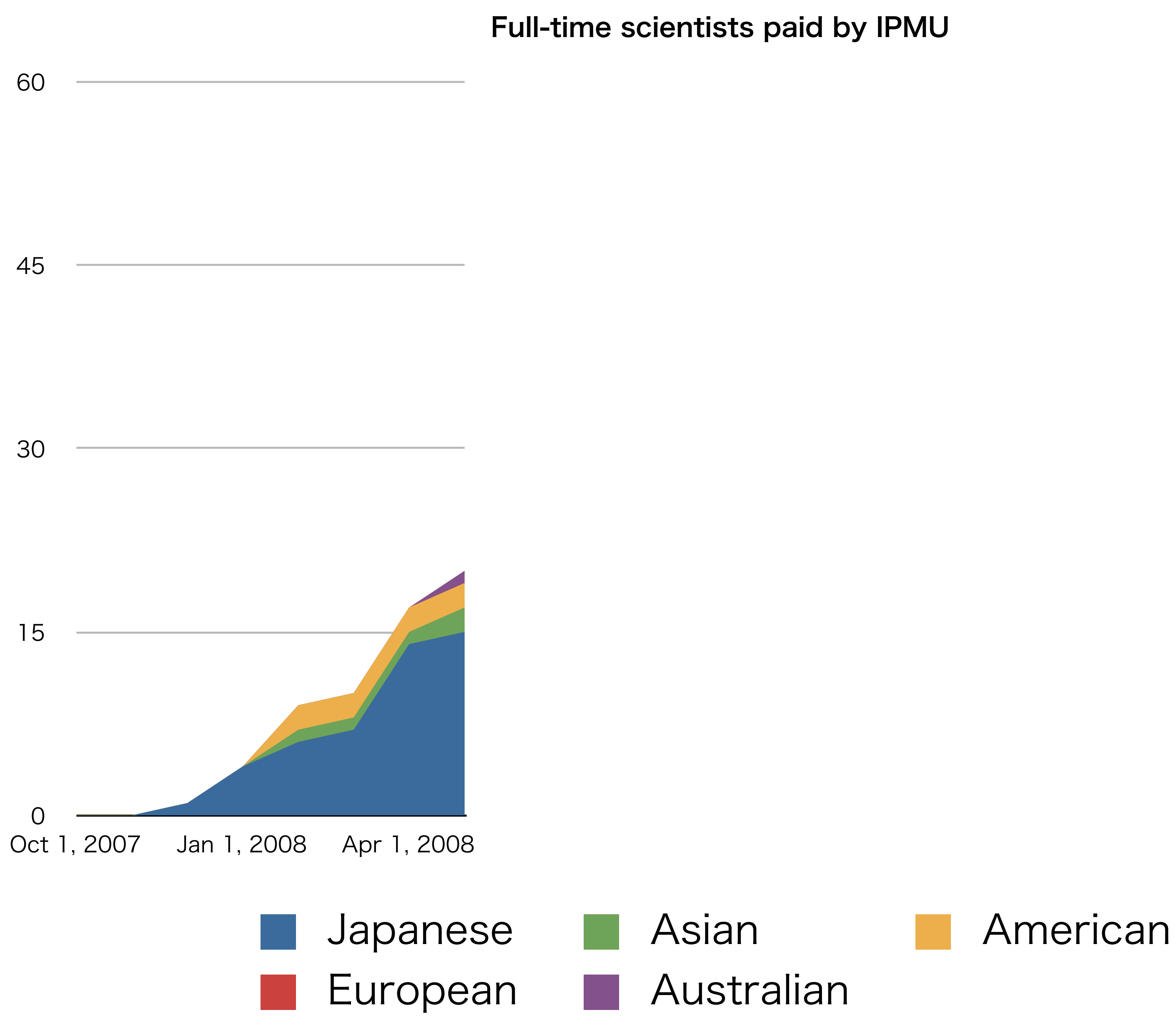


received $1.25M extra

Full-time Scientists



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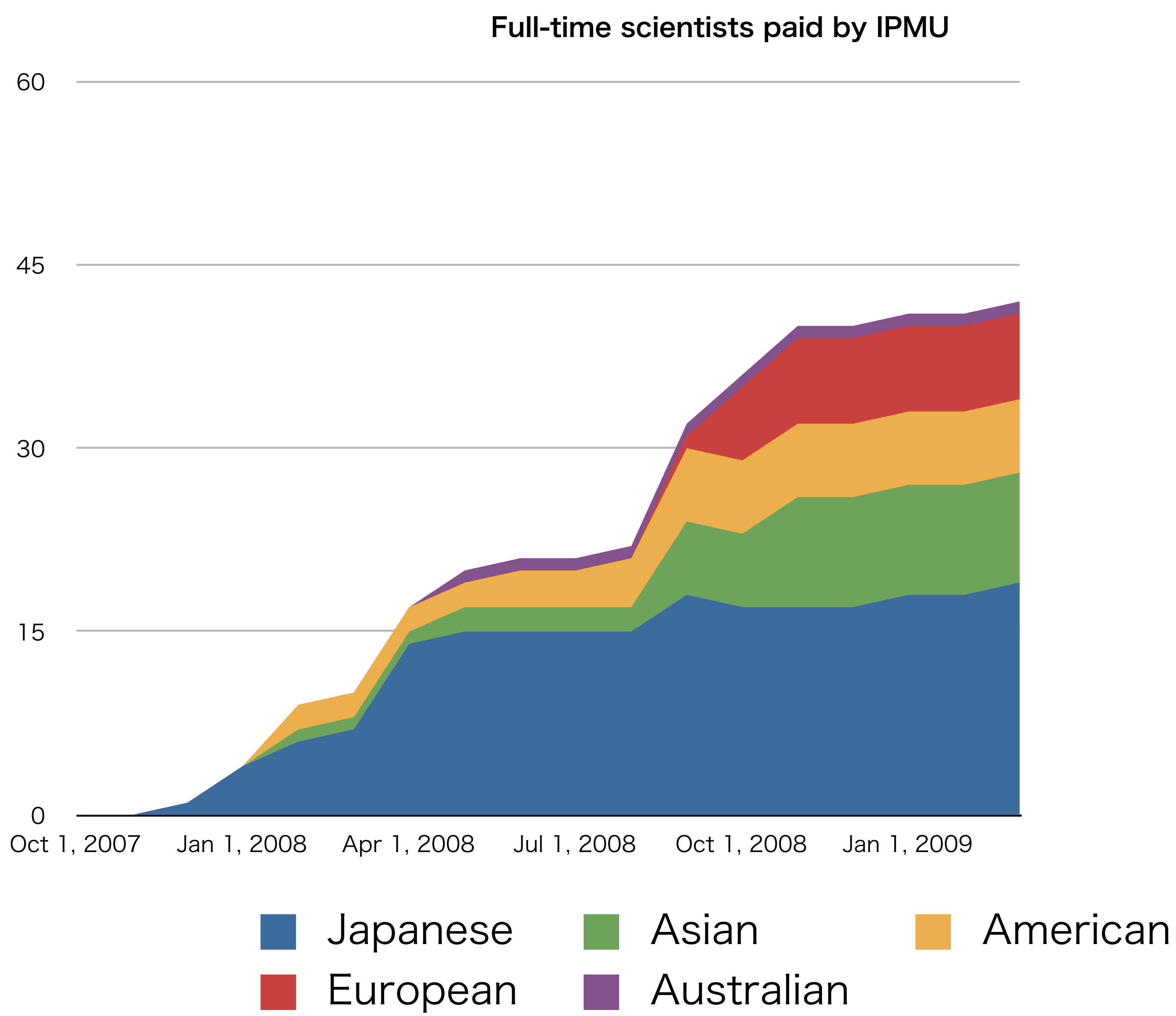

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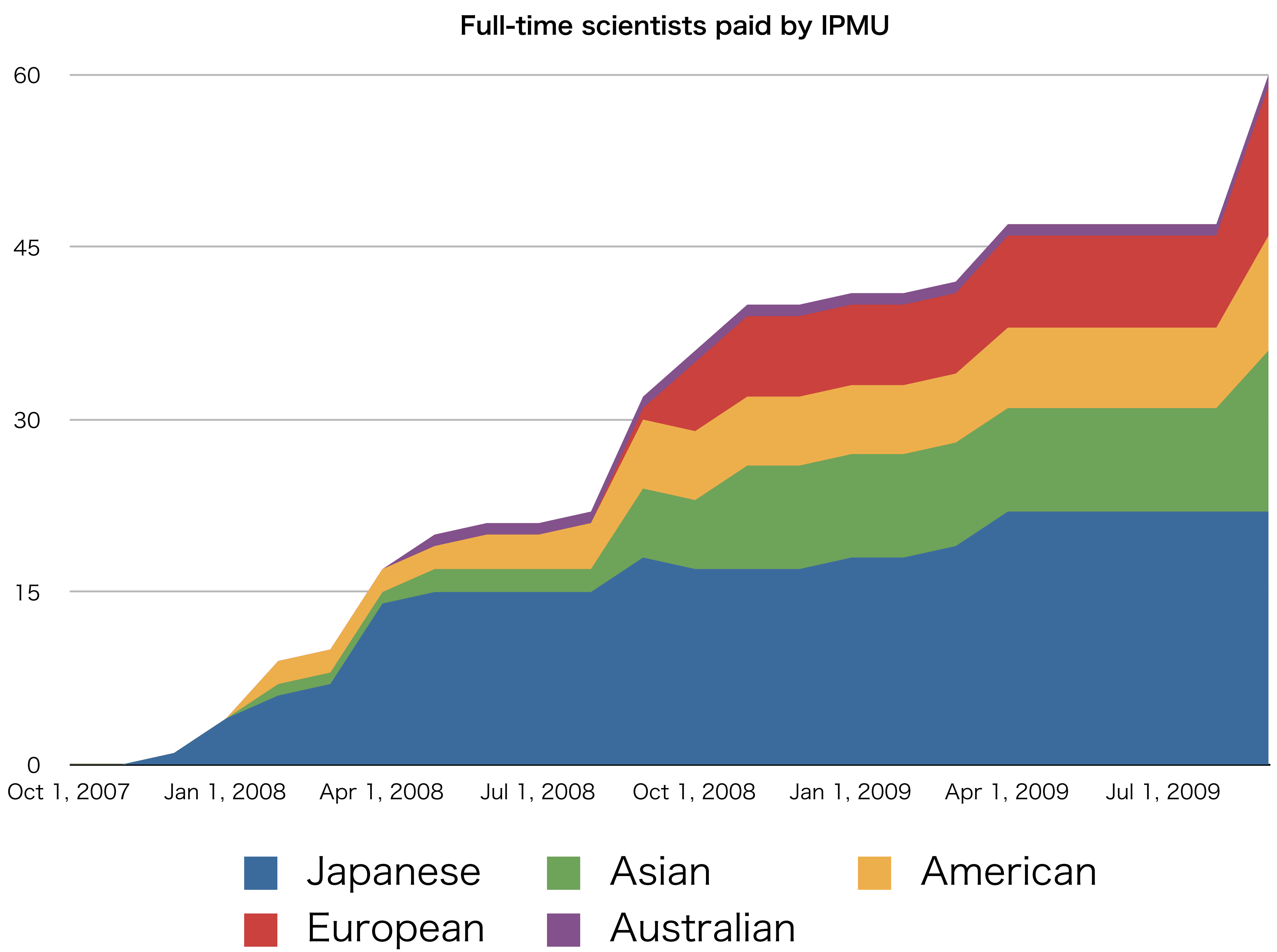

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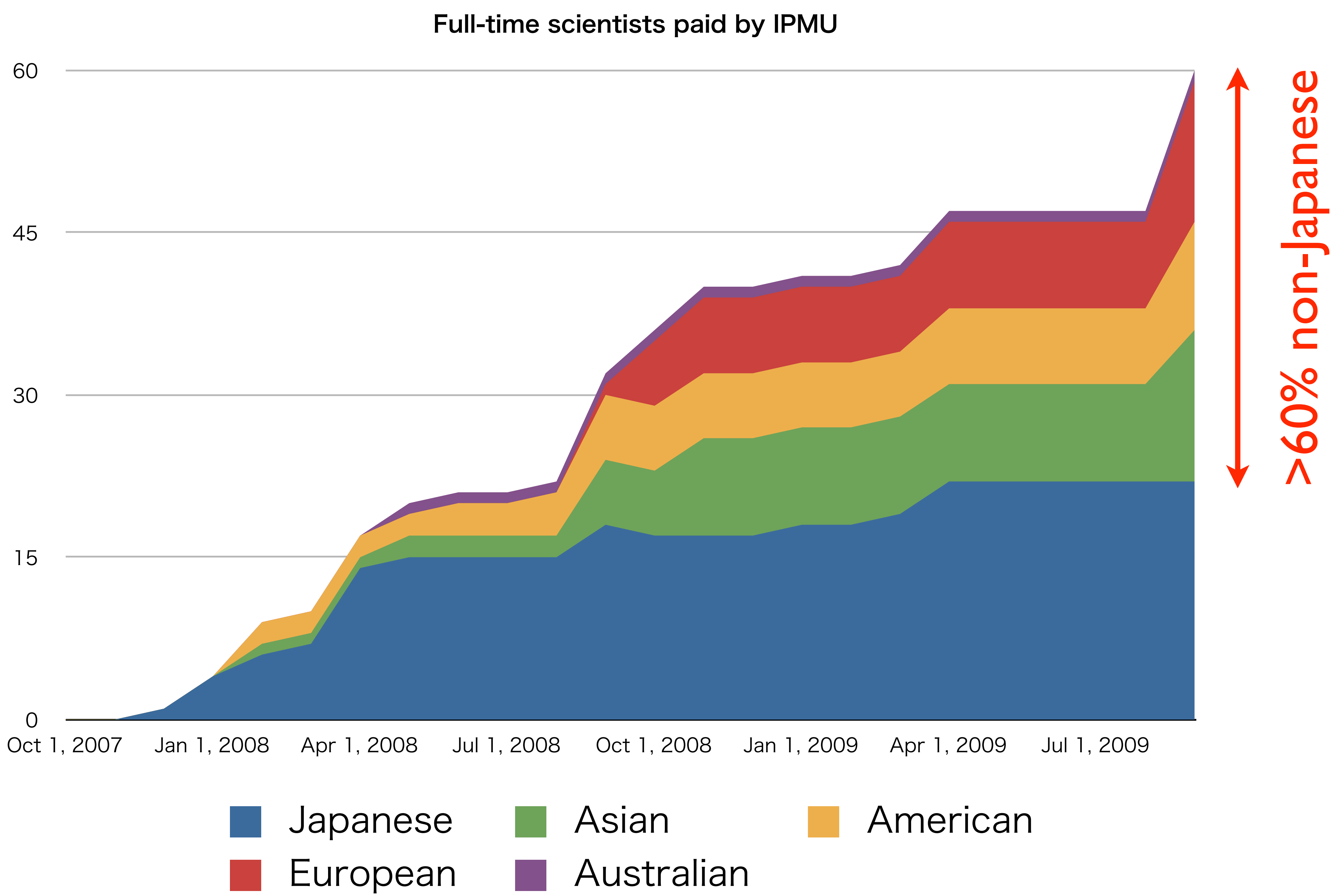

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translation for you:

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translation for you:

- nature of dark matter

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translation for you:

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- resolving space-like singularity
- w of dark energy

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translation for you:

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- w of dark energy
- string theory, unification, proton decay

IPMU INSTITUTE FOR THE PHYSICS AND MATHEMATICS OF THE UNIVERSE

Science

For the agency/public:

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IPMU initiatives in expts/observations

- Vagins: let SuperK detect neutrinos from long past supernovae
- Kozlov: use KamLAND to see if $\nu=\bar{\nu}$?
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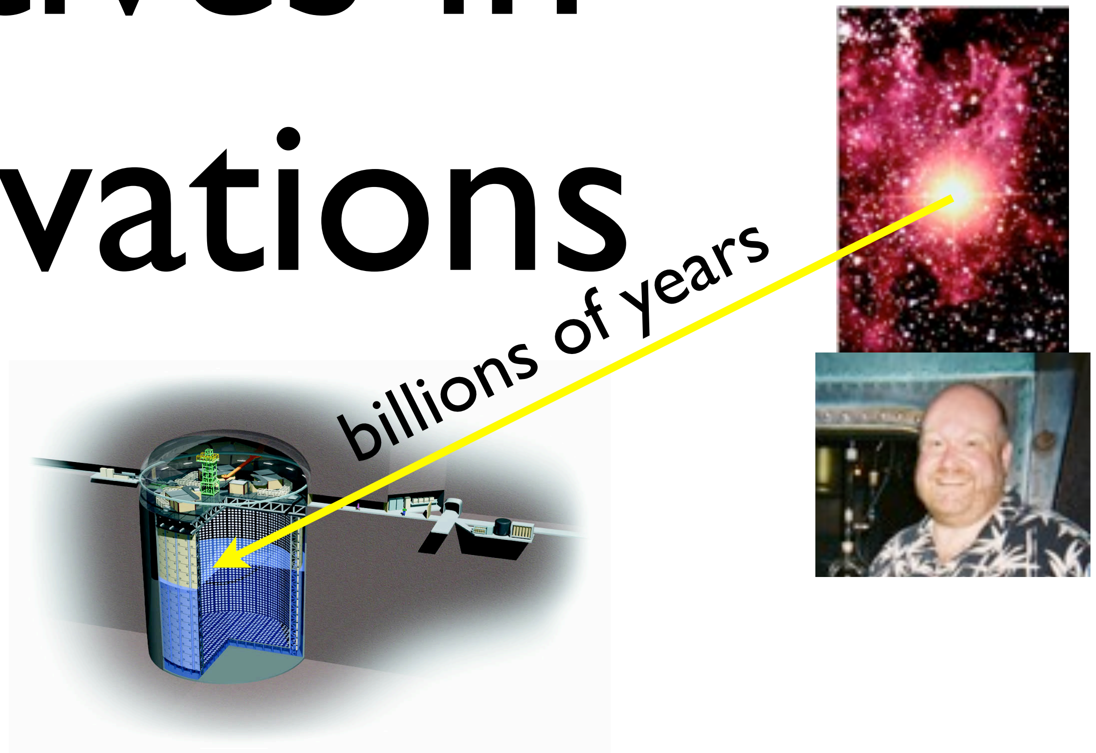

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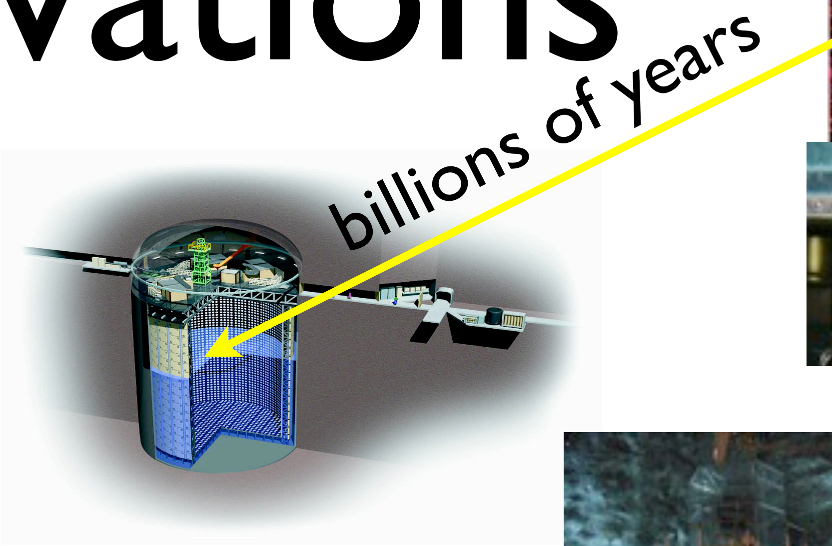

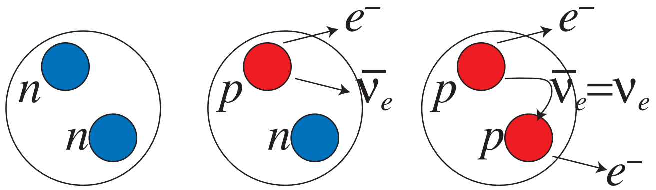

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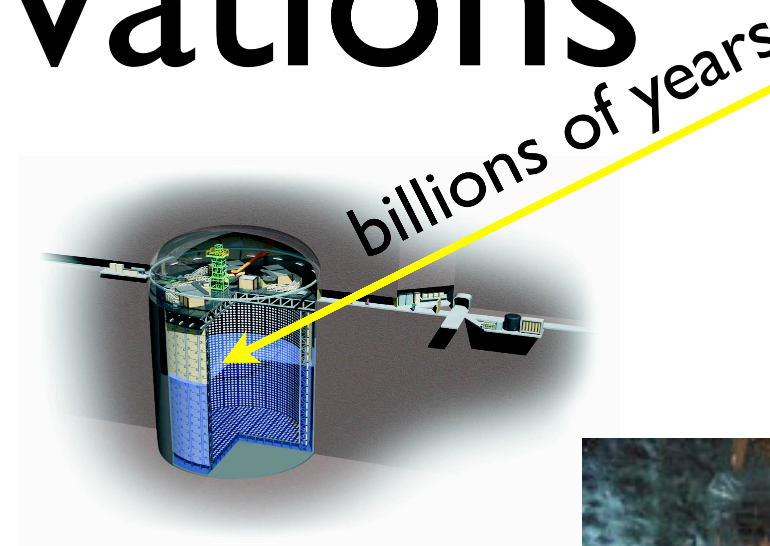

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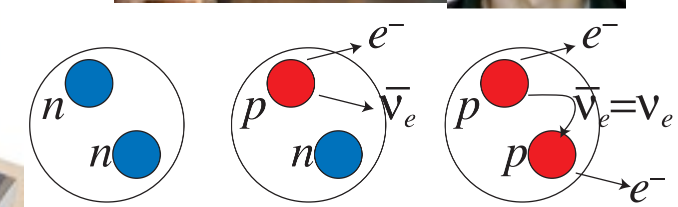

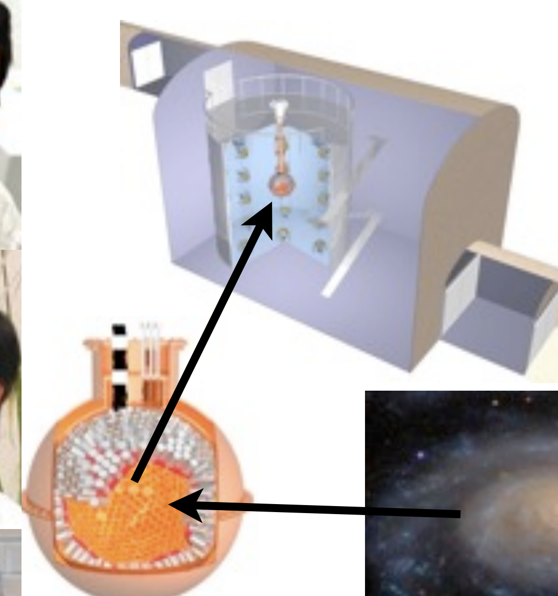

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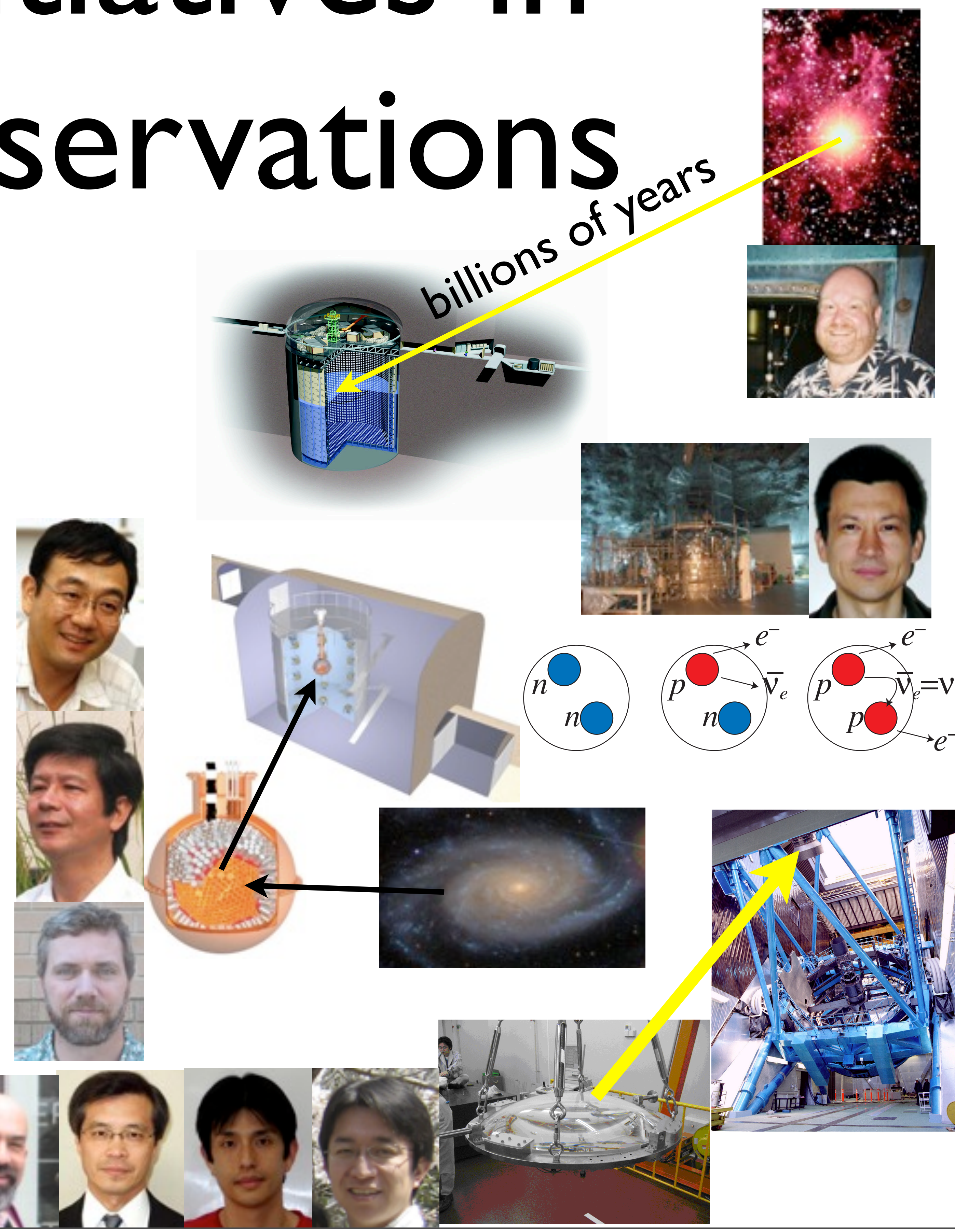

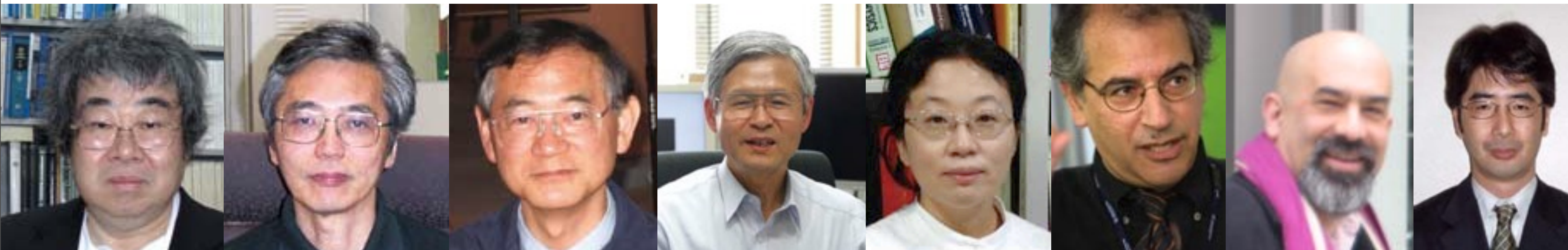

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		Suzuki (Tokyo)
		. Nakahata (Tokyo)

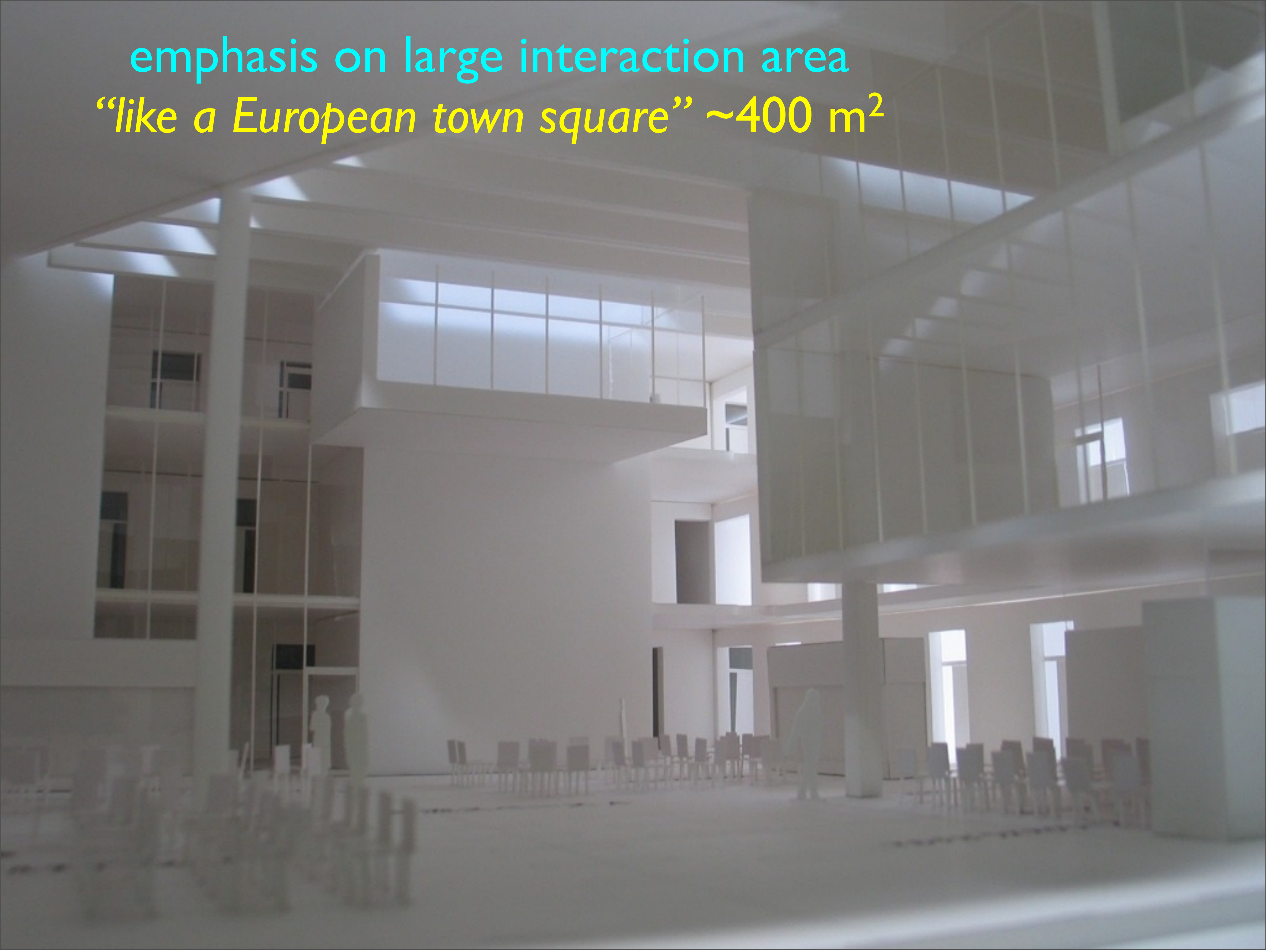
ist, Astronomer

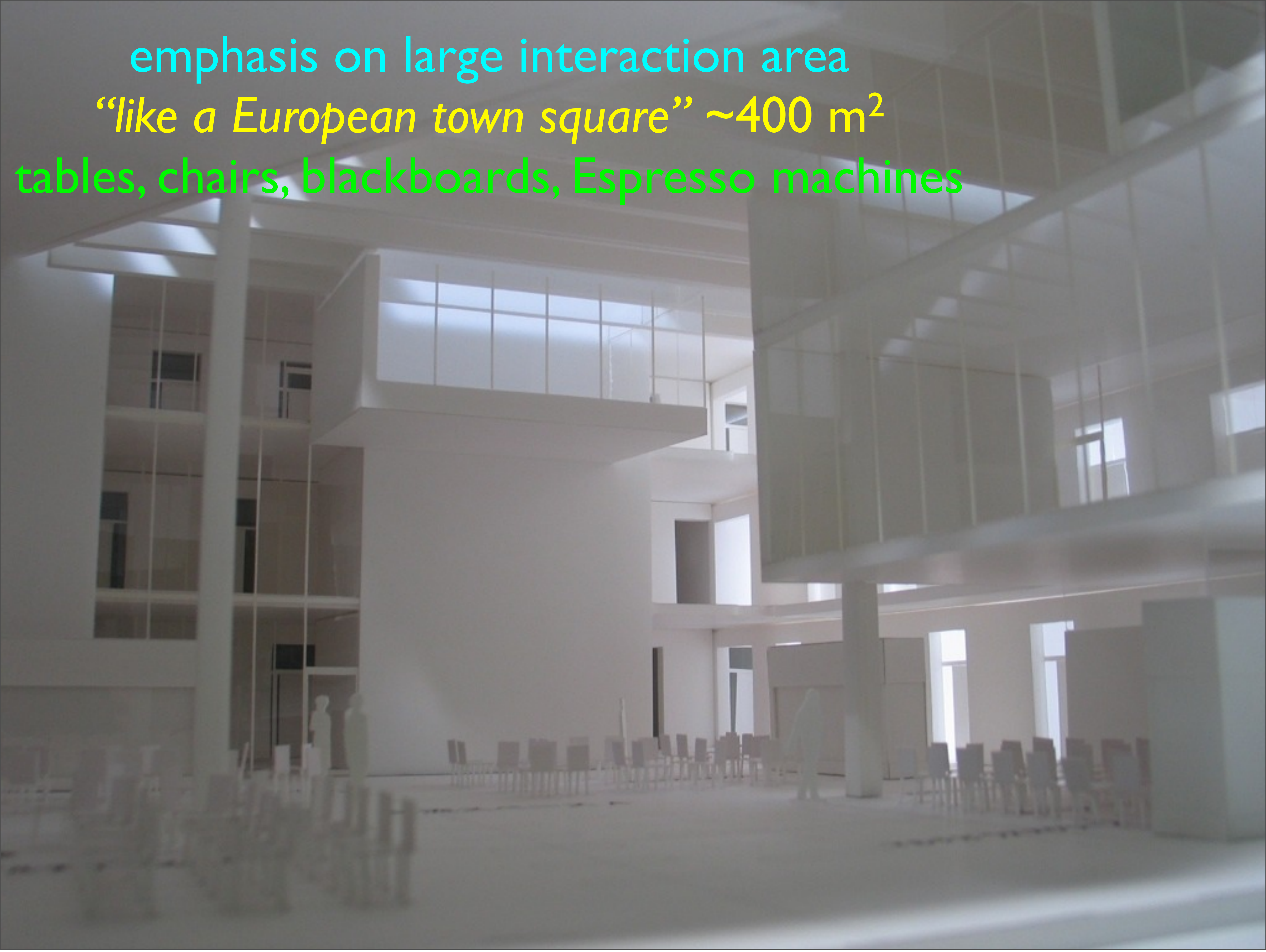
Winter 2009 occupancy
~5900m^2

emphasis on large interaction area

emphasis on large interaction area

"like a European town square" ~400 m^2




emphasis on large interaction area
"like a European town square" ~400 m^2
tables, chairs, blackboards, Espresso machines

http://ipmu.jp

practical info