The background of the slide is Salvador Dalí's painting 'The Persistence of Memory'. It depicts a desolate, rocky coastline with a sea and cliffs in the distance. In the foreground, a pocket watch is draped over a branch, another is on a table, and a third is on a surface. A melting pocket watch is on a table in the lower left, and a melting pocket watch is on a surface in the lower right. A melting pocket watch is also on a surface in the lower right.

**Michelangelo Mangano,
Department of Theoretical Physics
CERN, Geneva**

michelangelo.mangano@cern.ch

**Visible and
invisible in
modern physics**

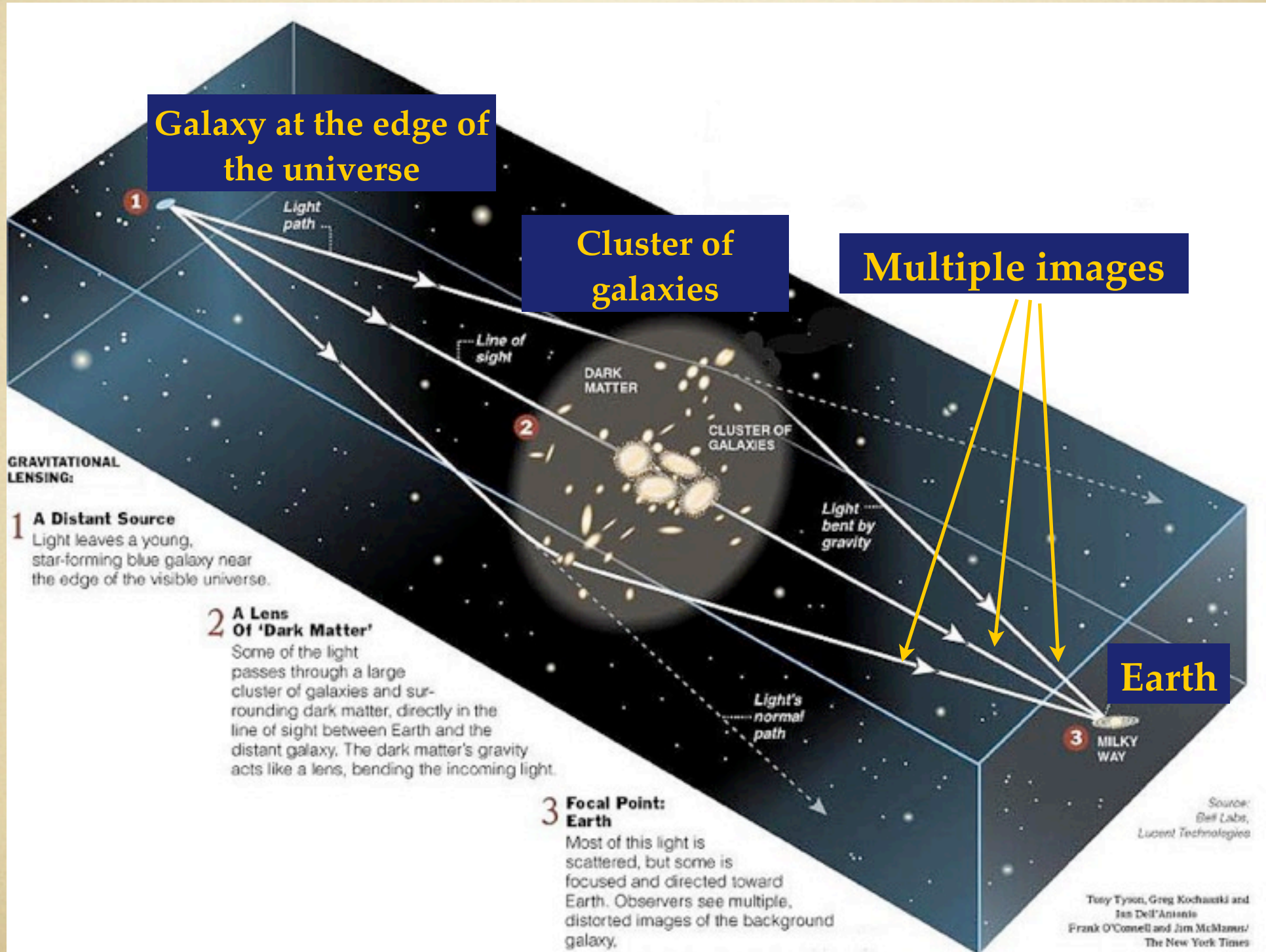


Hubble Ultra Deep Field
Hubble Space Telescope • Advanced Camera for Surveys

NASA, ESA, S. Beckwith (STScI) and the HUDF Team

STScI-PRC04-07a

Gravitational lensing



GRAVITATIONAL LENSING:

1 A Distant Source
Light leaves a young, star-forming blue galaxy near the edge of the visible universe.

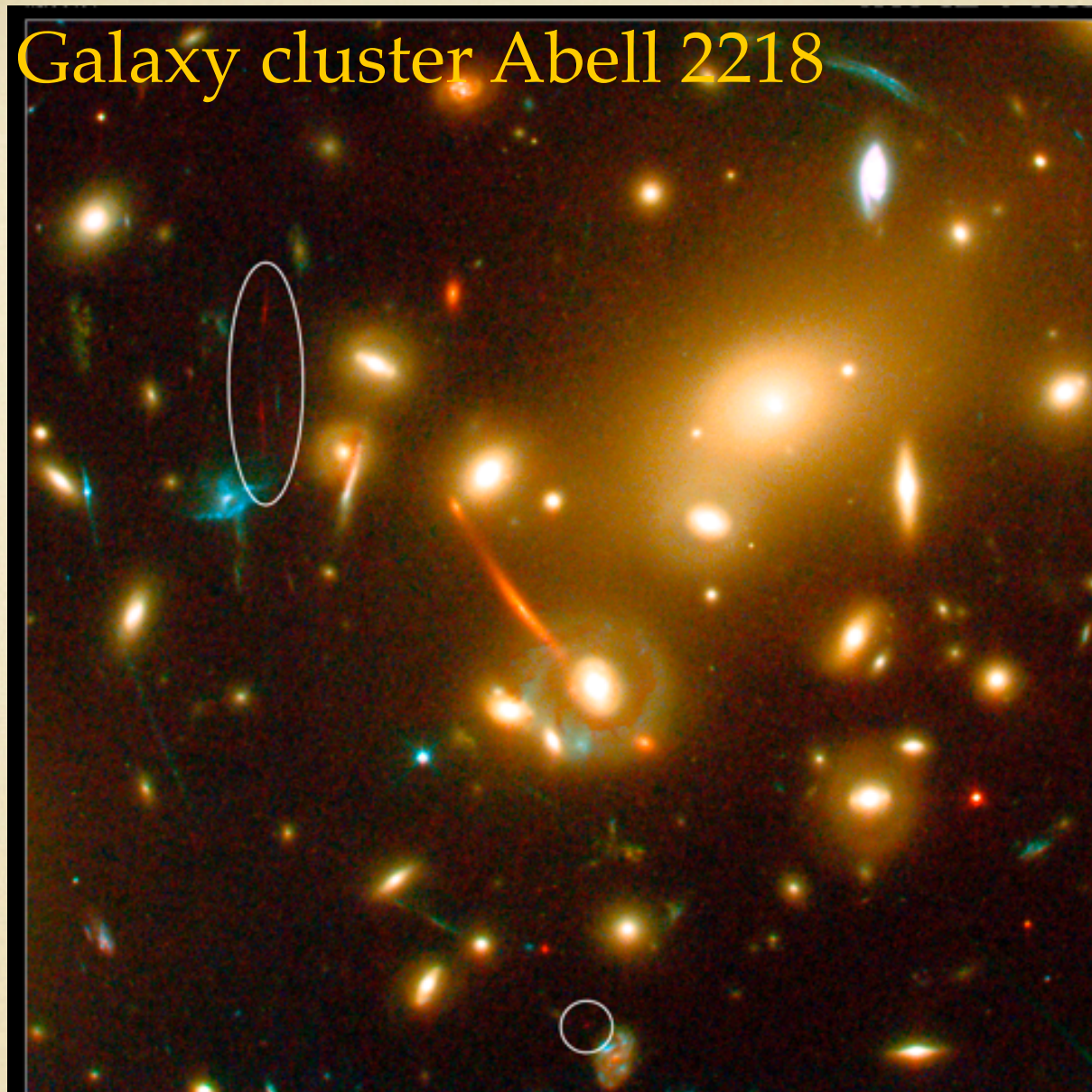
2 A Lens Of 'Dark Matter'
Some of the light passes through a large cluster of galaxies and surrounding dark matter, directly in the line of sight between Earth and the distant galaxy. The dark matter's gravity acts like a lens, bending the incoming light.

3 Focal Point: Earth
Most of this light is scattered, but some is focused and directed toward Earth. Observers see multiple, distorted images of the background galaxy.

Source:
Bell Labs,
Lucent Technologies

Tony Tyson, Greg Kochanski and
Ian Dell'Annisio
Frank O'Connell and Jim McCluskey/
The New York Times

Galaxy cluster Abell 2218



Credits: *European Space Agency, NASA, J.-P. Kneib (Observatoire Midi-Pyrénées) and R. Ellis (Caltech)*

The shape and intensity of lensed images requires the presence of 5 times more mass than contained in the **visible** galaxies !



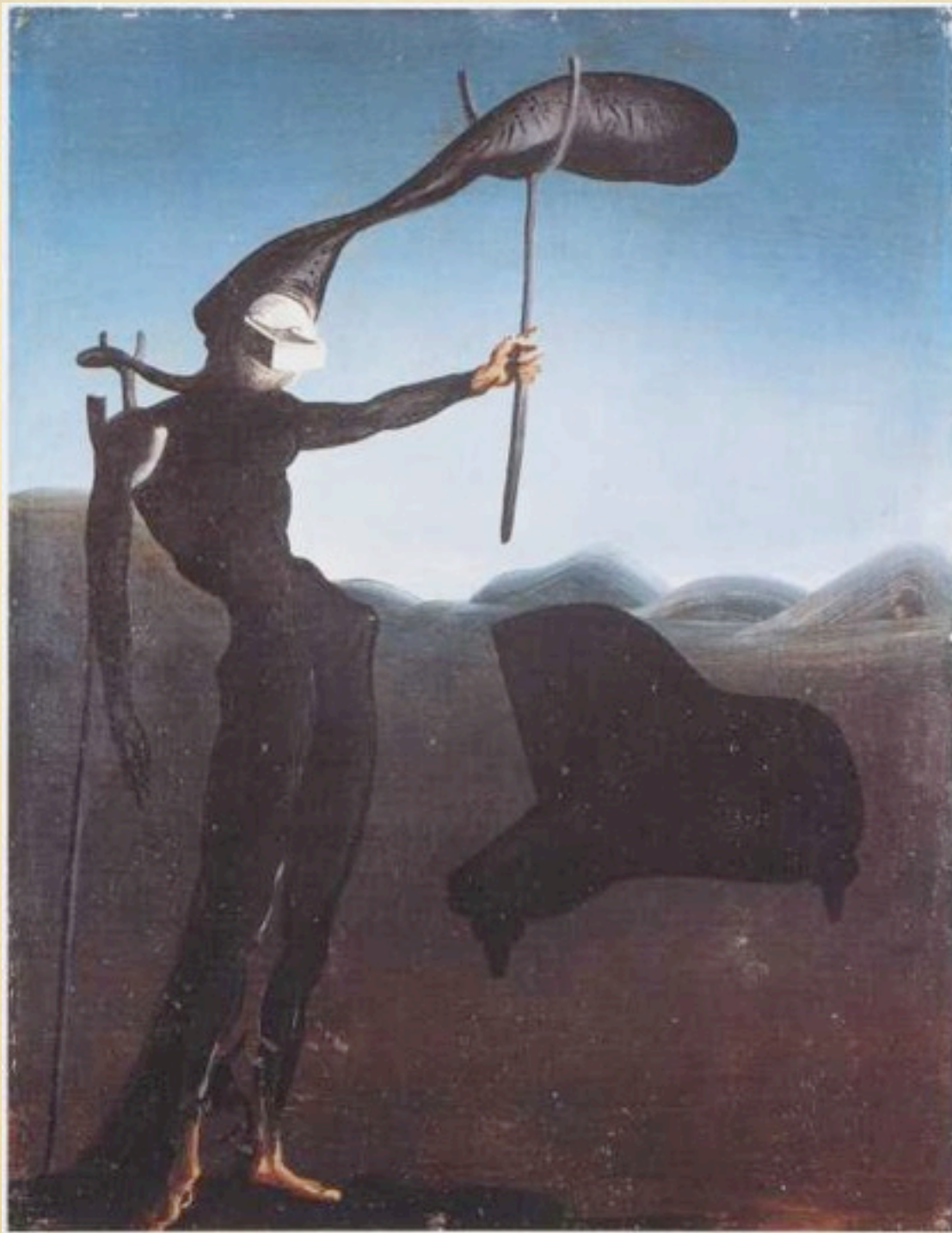
Invisible dark matter

For something to be
declared invisible, we
must know it's there, and
if we know it's there, it's
not *truly* invisible any
longer



Surrealist Composition with Invisible Figures, 1936

Proving the **existence** of the invisible
is a common theme of enquiry in
science, which distinguishes science
from magic and superstition



Invisible Harp, 1934

Establishing the **nature** of the
invisible is the really crucial step

What are the invisible forces that tie things together?
How many, how do they work?



What's hidden inside *things*?

What are *things* ultimately made of?

Goal of modern physics: to unveil the
invisible, give it substance, and
explore its consequences for the life of
the universe

what? how?

- Are there fundamental building blocks?
- If so, what are they?
- How do they interact?
- How do they determine the properties of the Universe?

A few anecdotes ...

Late 20's, a puzzle of the invisible



If this were all that happens, energy conservation would demand that the energy of the emitted electron be the same for each decay

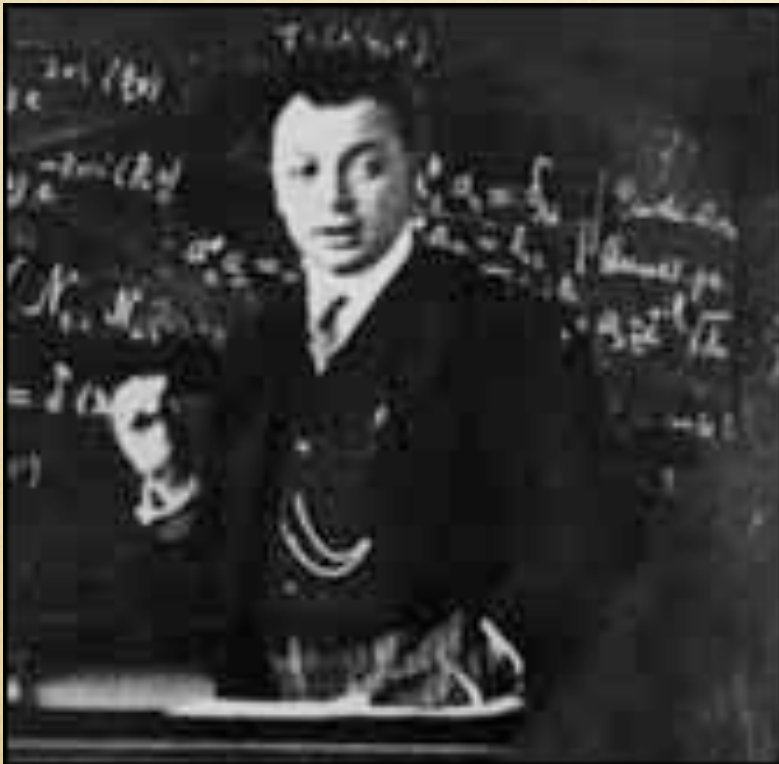
$$\text{Energy}[e^{-}] = \text{Mass}[{}^6\text{He}] - \text{Mass}[{}^6\text{Li}]$$



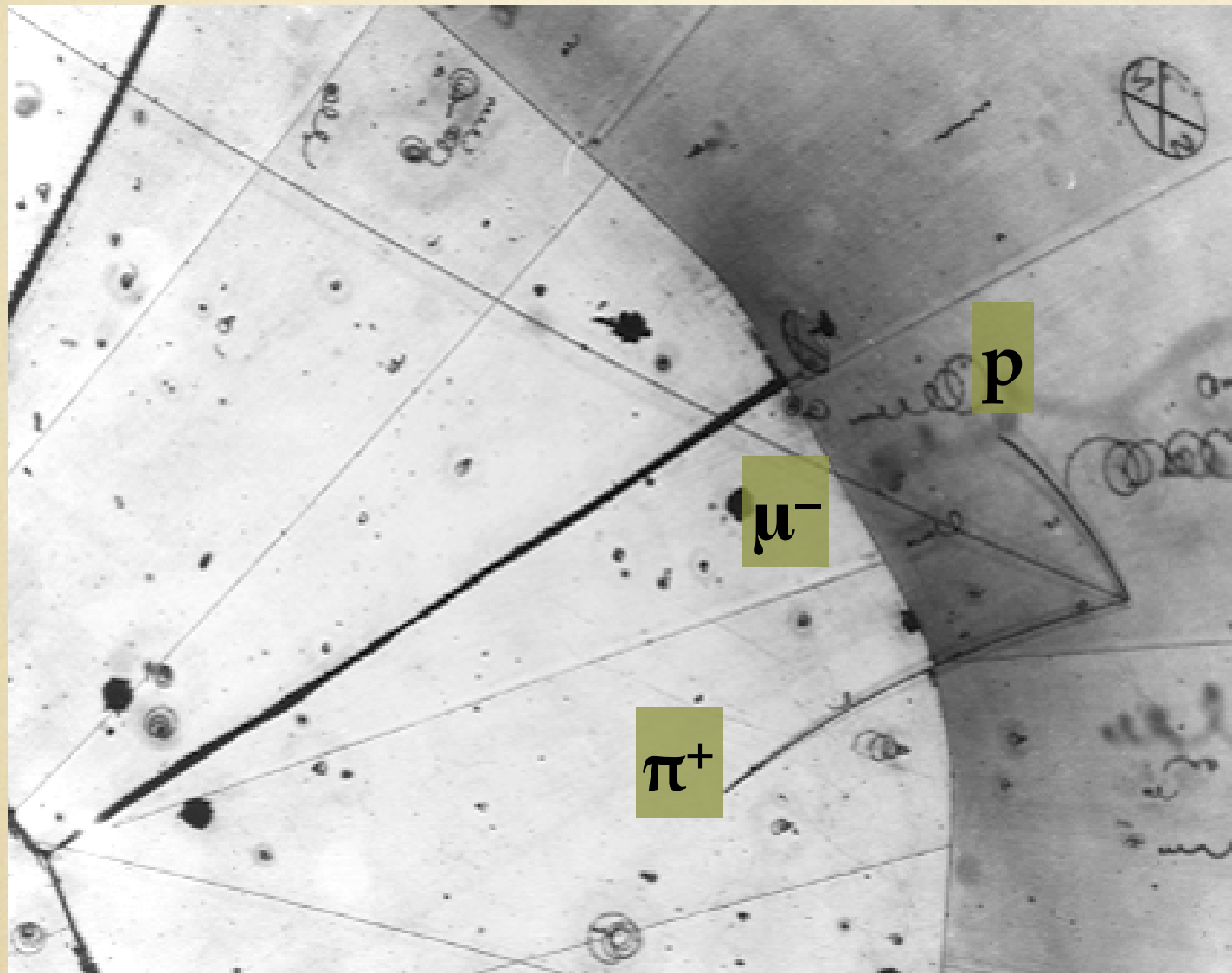
But in some decays the electron is very slow.....

Enter neutrinos ...

After months of speculations, including the possibility that the principle of energy conservation be violated in microscopic quantum phenomena, Wolfgang Pauli proposes the existence of the **invisible neutrino**



It took more than 20 years for a neutrino to be directly observed!

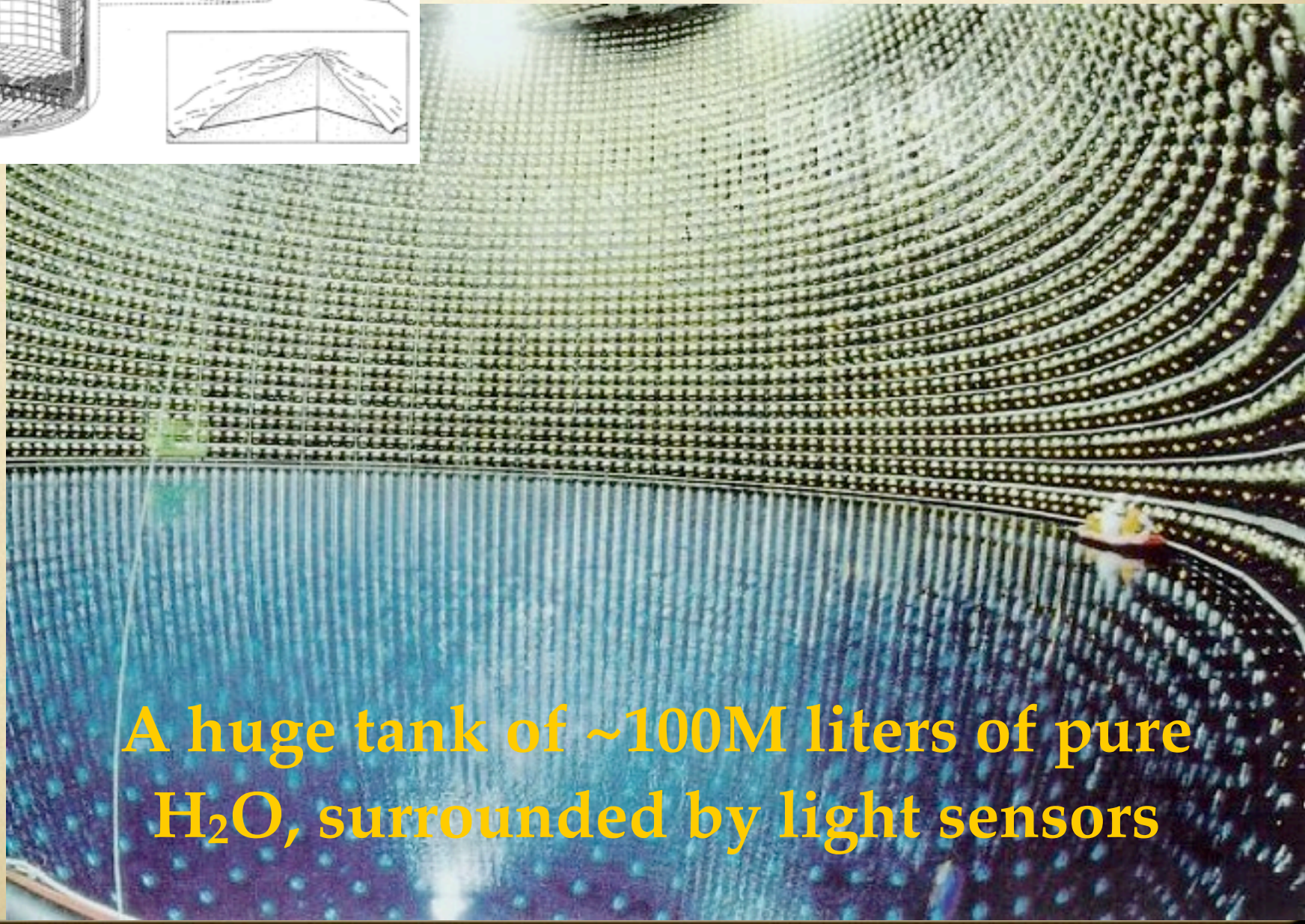
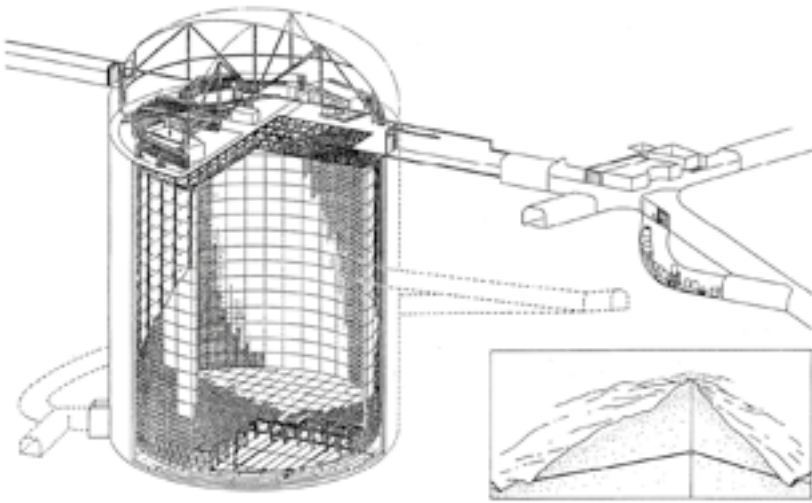


ν from a beam
of π mesons

The world's first neutrino observation in a hydrogen bubble chamber. It was found Nov. 13, 1970, in this photograph from the Zero Gradient Synchrotron's 12-foot bubble chamber. The invisible neutrino strikes a proton where three particle tracks originate (lower right). The neutrino turns into a mu-meson, the long center track (extending up and left). The short track is the proton. The third track (extending down and left) is a pi-meson created by the collision.

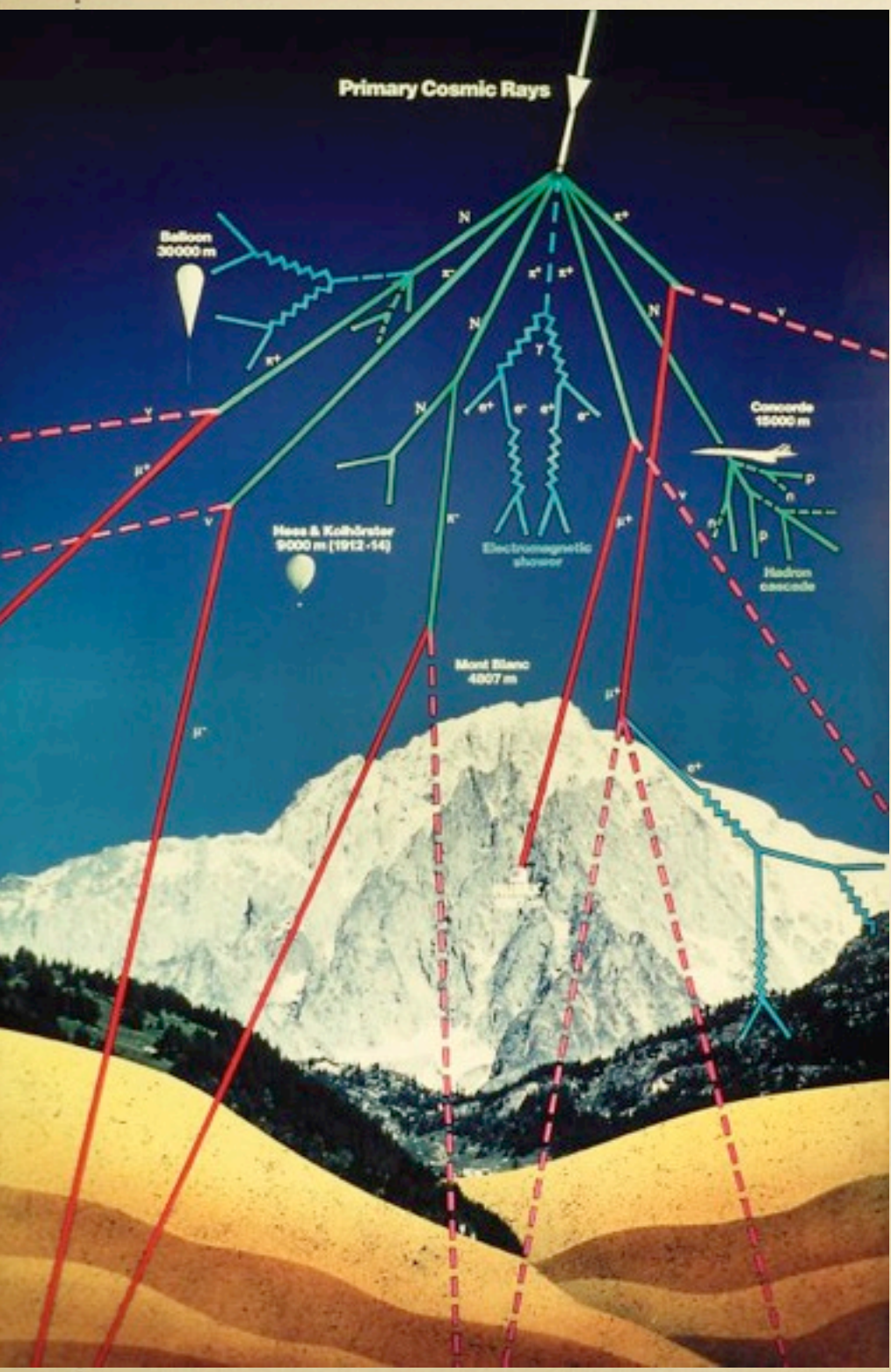
Argonne National Laboratory

Today:
Superkamiokande (Japan)

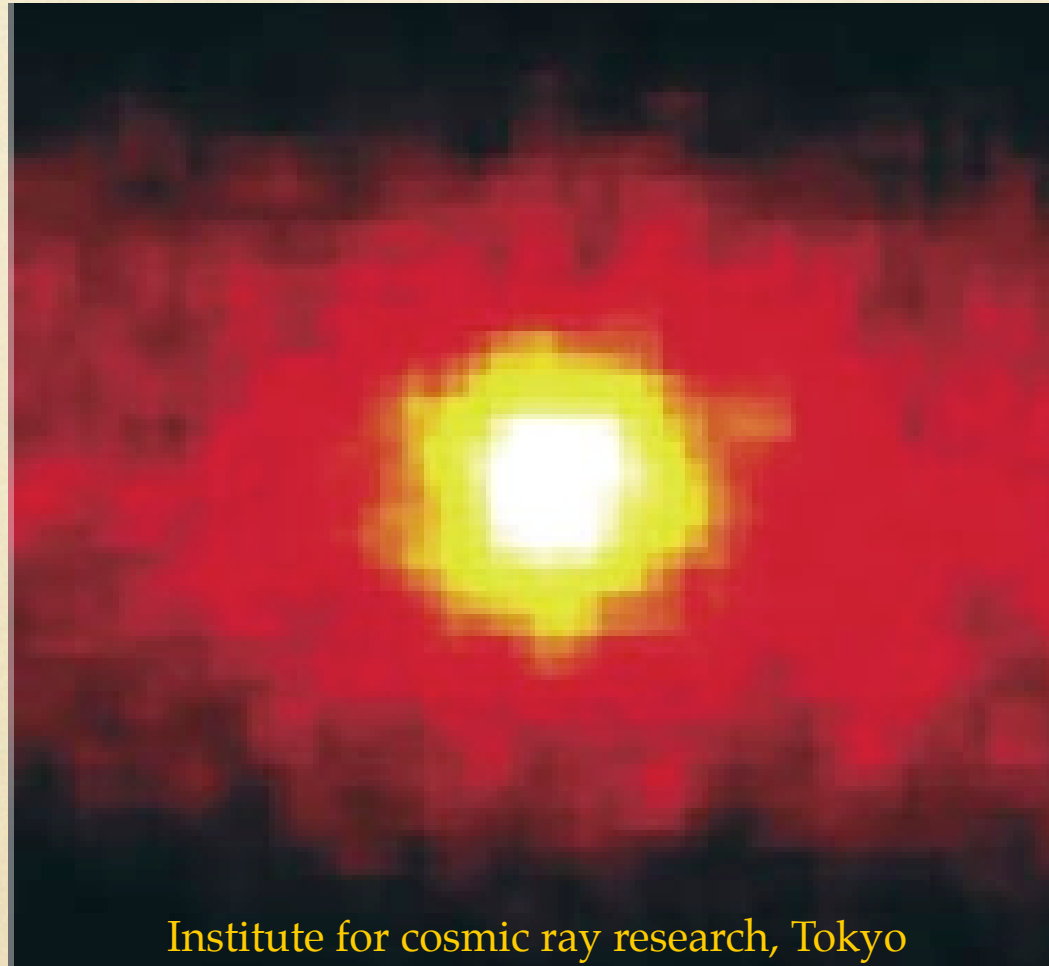


A huge tank of ~100M liters of pure
 H_2O , surrounded by light sensors

Primary Cosmic Rays

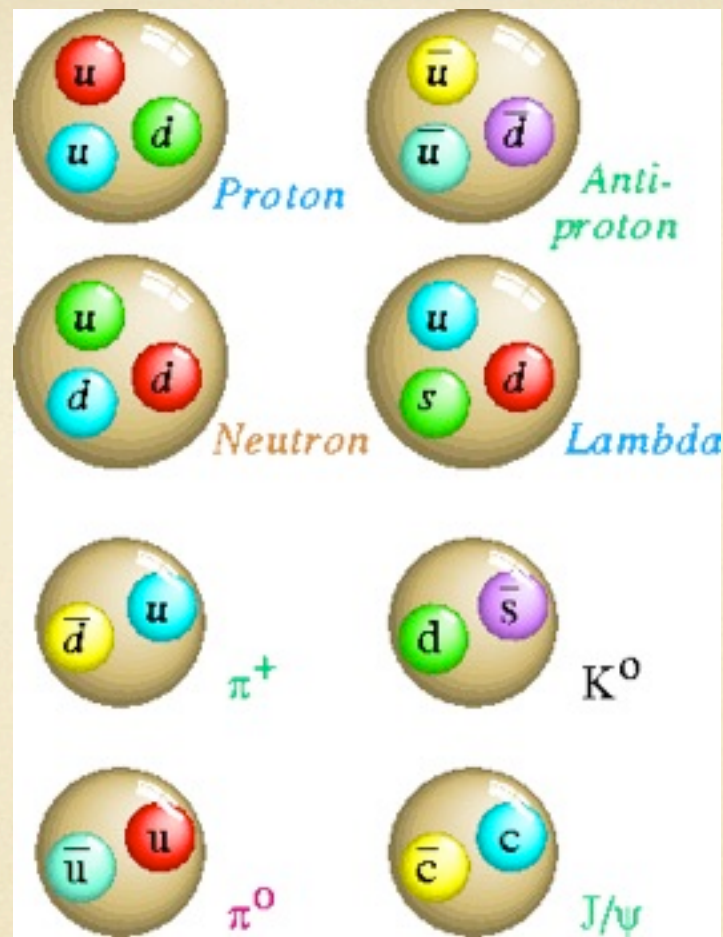


Reconstructing the neutrino direction, and mapping on the sky the position of their origin, allows to use neutrino detectors as “telescopes”: neutrino eyes!

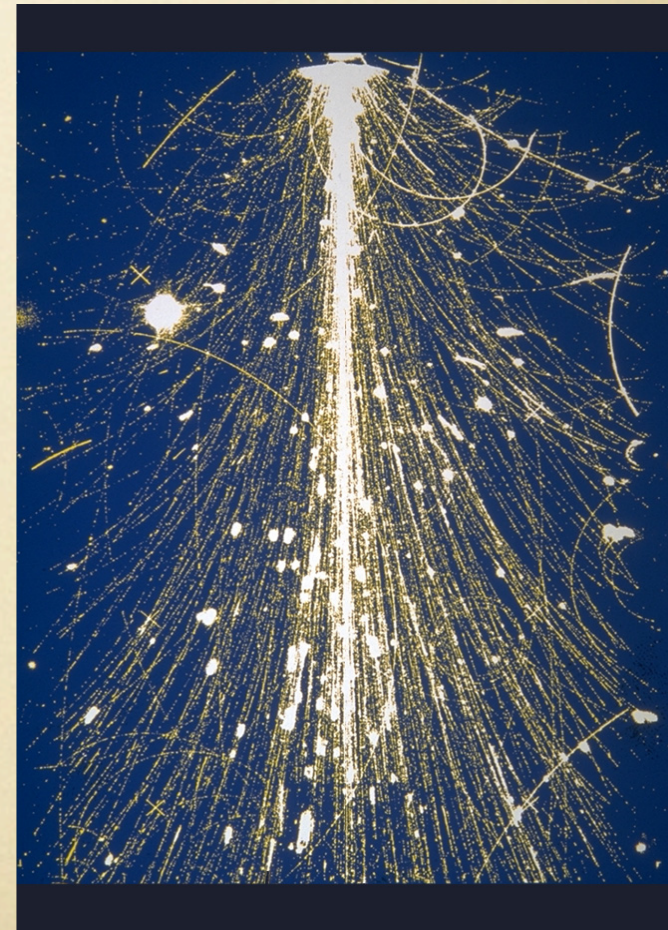


Institute for cosmic ray research, Tokyo

A picture of the invisible part of the Sun, namely its innermost core, where nuclear reactions take place!

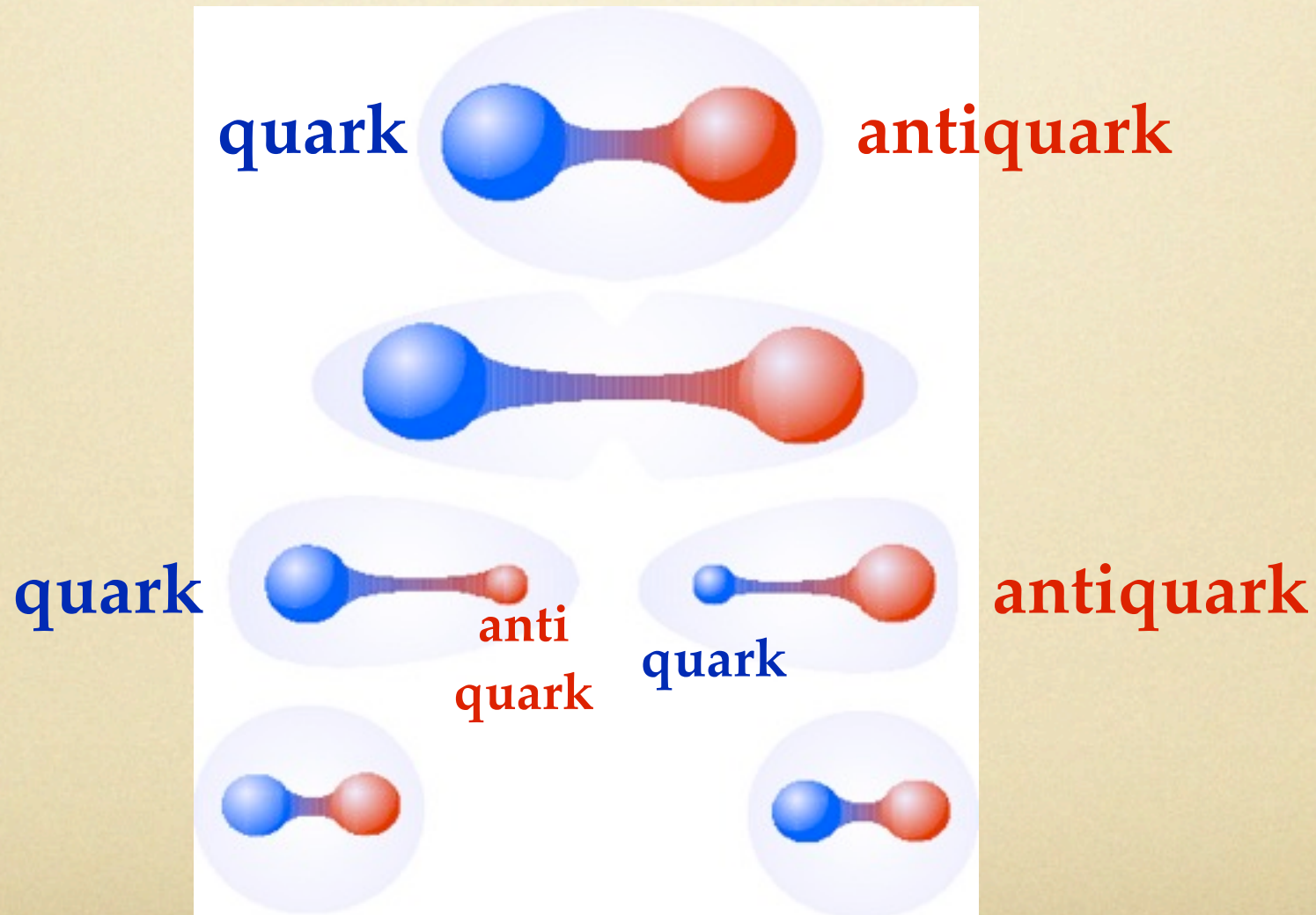


Saint surrounded by three π mesons, 1956



... just π mesons ...

The ultimate invisible: quarks inside the proton
like a nut, we see the shell and not the fruit.
If we try to crack it open it splits into two new nuts ...
we know quarks are there, but can't get them out!



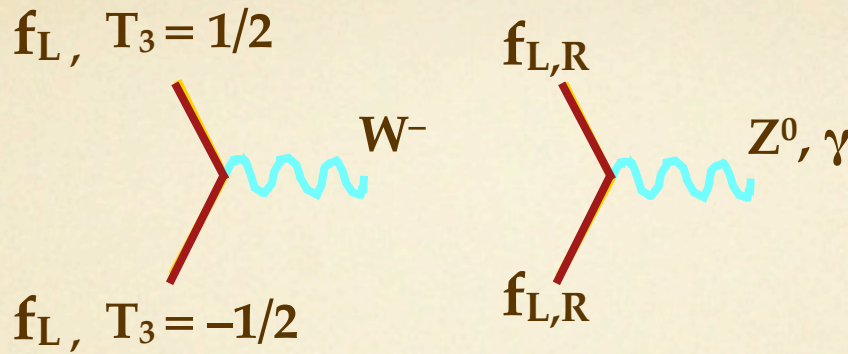
The vacuum: invisible nothingness, or seed of mass and structure?

Why do particles have a mass?

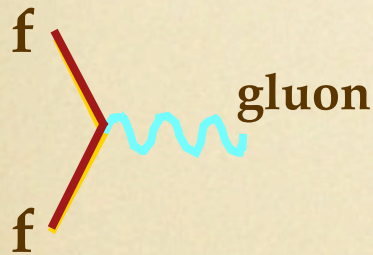


The echo of void, 1935

$SU(2)_L \otimes U(1)$



$SU(3)$



$\begin{pmatrix} \mathbf{u}_{2/3} \\ \mathbf{d}_{-1/3} \end{pmatrix}_L \quad i=1,2,3$	$\mathbf{u}^i_R, \mathbf{d}^i_R$
$\begin{pmatrix} \nu \\ \mathbf{e}^- \end{pmatrix}_L$	\mathbf{e}^-_R

Spin ←

Spin →

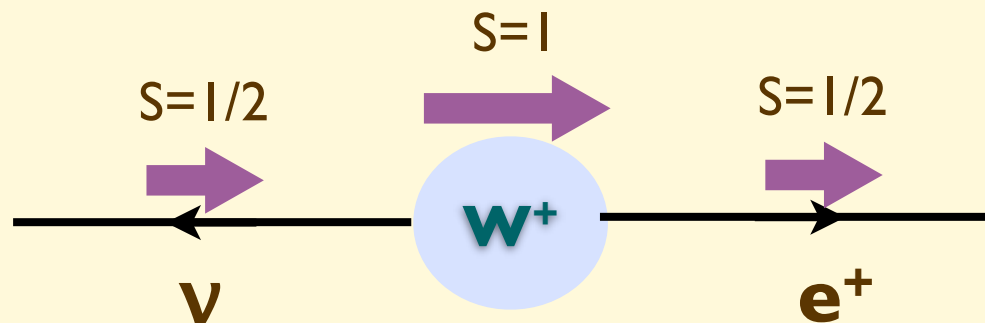
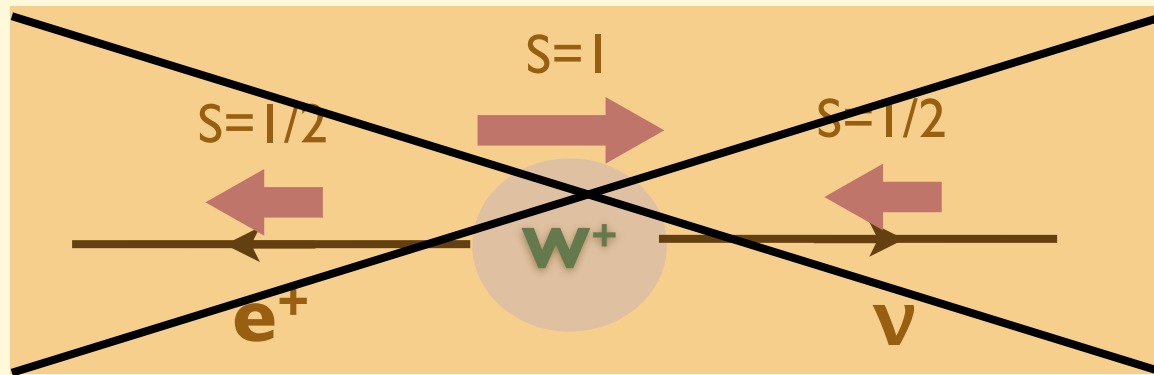
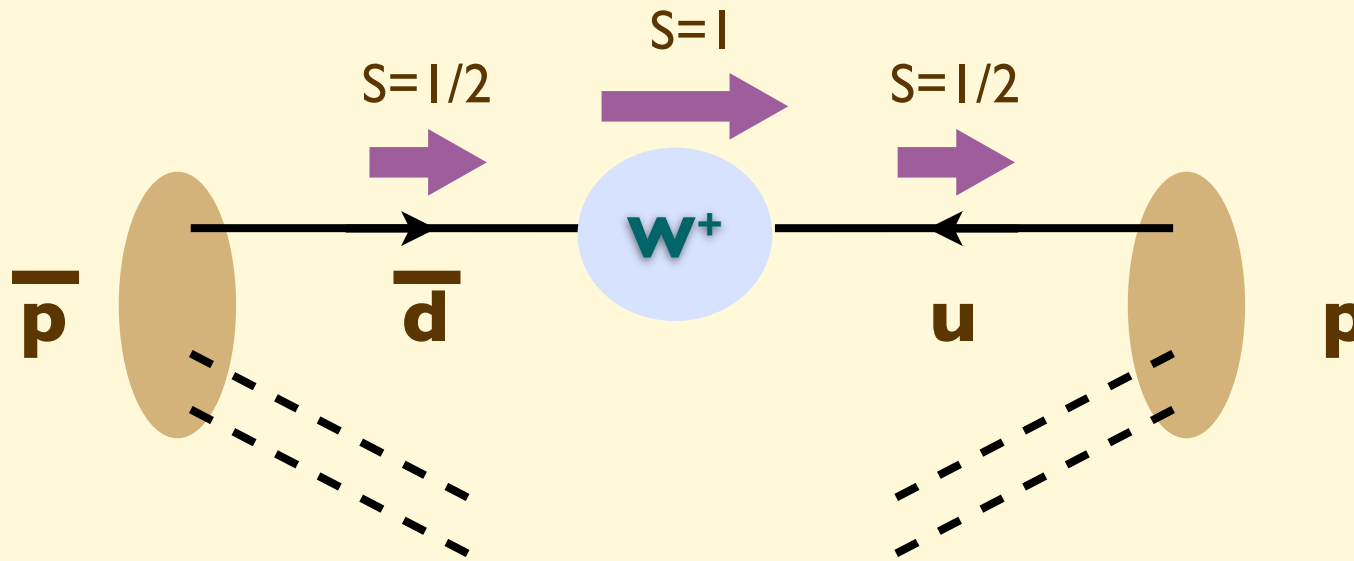
L-handed helicity

R-handed helicity

+ 2 more "families" differing from the 1st one only in the mass of their elements

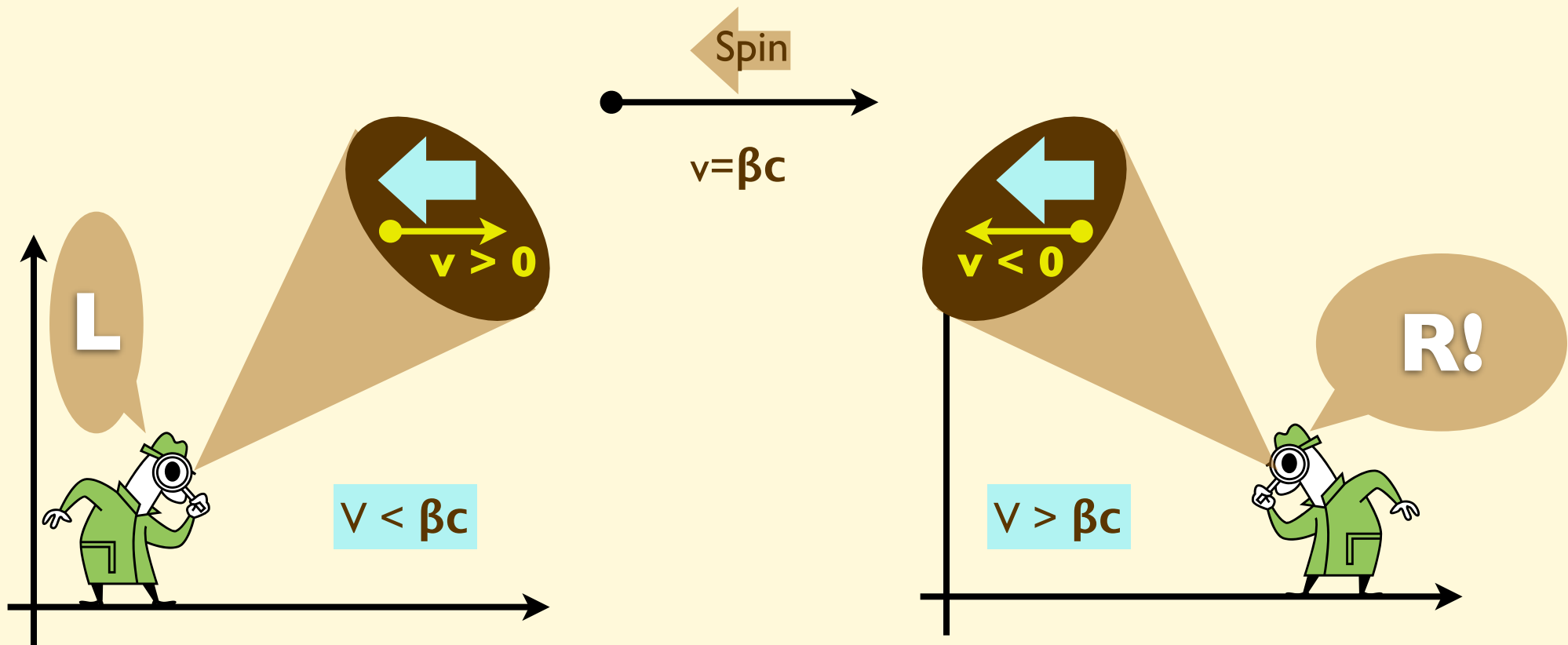
Parity violation in W interactions

Mme Wu et al, ^{60}Co β -decay,
1956-57



Explicitly tested with
ever increasing
accuracy at SpS,
LEP, Tevatron, PSI, 24

Parity asymmetry and mass



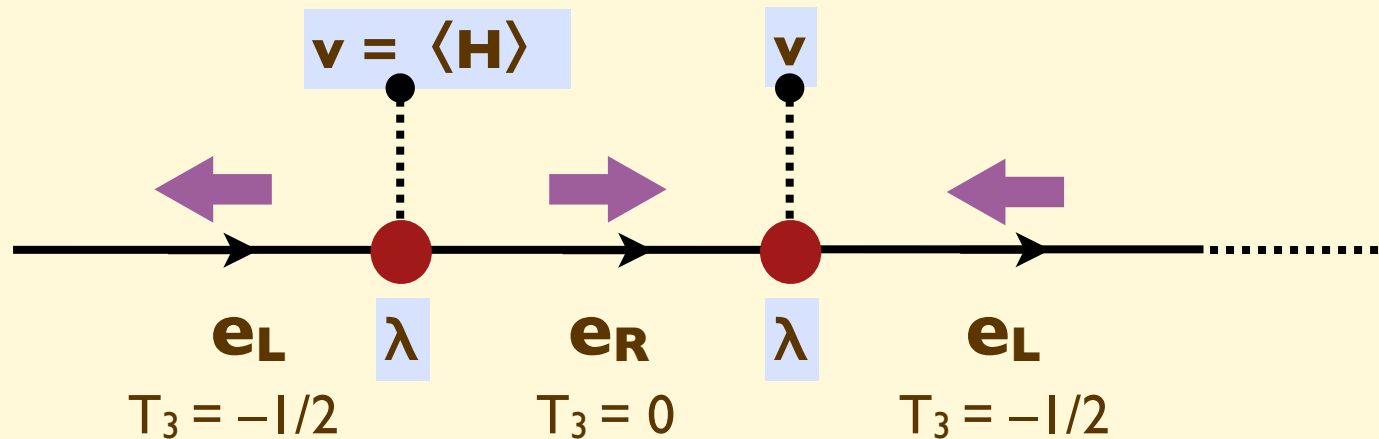
Helicity does not commute with Hamiltonian, so it cannot be conserved for a massive particle

Since helicity is directly connected with the weak charge, the weak charge of a massive particle is not observable, and cannot be conserved.

The symmetry associated with the conservation of the weak charge must therefore be broken for weakly-interacting massive particles to exist

Higgs mechanism

Time evolution of a massive particle:



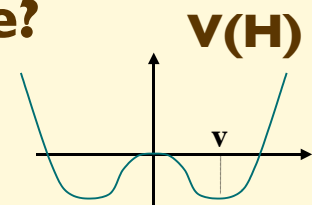
The transition between L and R states, and the absorption of the changes in weak charge, are ensured by the interaction with a background scalar field, **H**. Its “vacuum density” provides an infinite reservoir of weak charge.

The number “**v**” is the expectation value of the so-called **Higgs field**.

The quantity “**λ**” is characteristic of the particle interacting with the Higgs field.

It can easily be shown that **this interaction leads to a mass $m \propto \lambda v$**

Why should the field H develop a non-zero background value?



What assigns to the various fermions the value of λ corresponding to their mass? Why $\lambda[\text{muon}] \neq \lambda[\text{electron}]$?

Detecting the Higgs boson

Like any other medium, the Higgs continuum background can be perturbed. Similarly to what happens if we bang on a table, creating sound waves, if we “bang” on the Higgs background (something achieved by concentrating a lot of energy in a small volume) we can stimulate “Higgs waves”. These waves manifest themselves as particles, the so-called Higgs bosons



The echo of void, 1935

What is required is that the energy available be sufficient \Rightarrow LHC !!!

Particle masses play a crucial role in determining the nature of the universe as we know it:

$m[\text{electron}]$ determines the “size of things”

$m[\text{electron}]$ vs $m[\text{down}] - m[\text{up}]$ determines the rates of both fission and fusion processes, defining the lifetime of stars, as well as abundance of primordial elements in the early universe

So does the family structure

only with 3 generations can the SM accommodate CP violation, and possibly induce a baryon asymmetry during the evolution of the universe

Intriguing questions arise from the spectrum of and mixings among different flavours

Since $m[\text{top}] = 170 \text{ GeV}$, $\lambda[\text{top}] = 1$: **coincidence?**

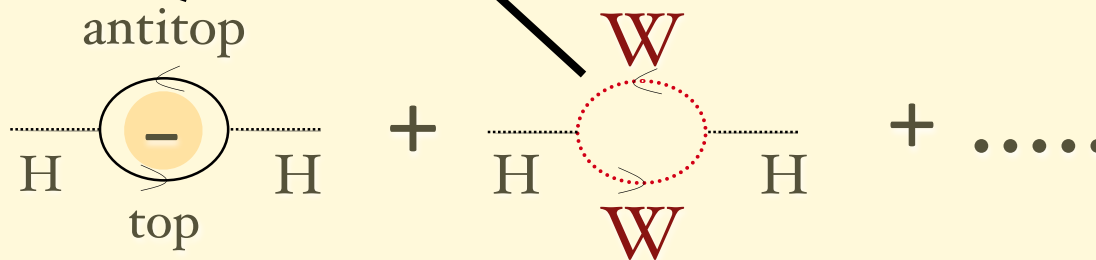
In several theories beyond the SM, $m[\text{top}] \approx 170 \text{ GeV}$ is required for a dynamical breaking of the EW symmetry: **message?**

The precise identification of the cause of electroweak symmetry breaking phenomenon, of its dynamics and of the origin of the flavour structure, are therefore crucial goals for the progress of our understanding of Nature

Seen the Higgs, what's next?

Calculating the radiative corrections to the Higgs mass in the SM poses an intriguing puzzle:

$$m_H^2 = m_0^2 - \frac{6G_F}{\sqrt{2}\pi^2} \left(m_t^2 - \frac{1}{2}m_W^2 - \frac{1}{4}m_Z^2 - \frac{1}{4}m_H^2 \right) \Lambda^2 \sim m_0^2 - (115\text{GeV})^2 \left(\frac{\Lambda}{400\text{GeV}} \right)^2$$



$\Lambda =$ scale up to which the SM is valid

renormalizability =>

$$m_H^2(v) \sim m_H^2(\Lambda) - (\Lambda^2 - v^2) \quad , \quad v = \langle H \rangle \sim 250\text{GeV}$$

Assuming Λ can extend up to the highest energy beyond which quantum gravity will enter the game, 10^{19} GeV, keeping m_H below 1 TeV requires a fine tuning among the different terms at a level of 10^{-34} :

$$\frac{m_H^2(\Lambda) - \Lambda^2}{\Lambda^2} \sim \frac{v^2}{\Lambda^2} = O(10^{-34}) \text{ if } \Lambda \sim M_{Planck}$$

extremely **unnatural** if it is to be an accident !!

hierarchy, or fine tuning, problem

The issue can be rephrased with the following example:

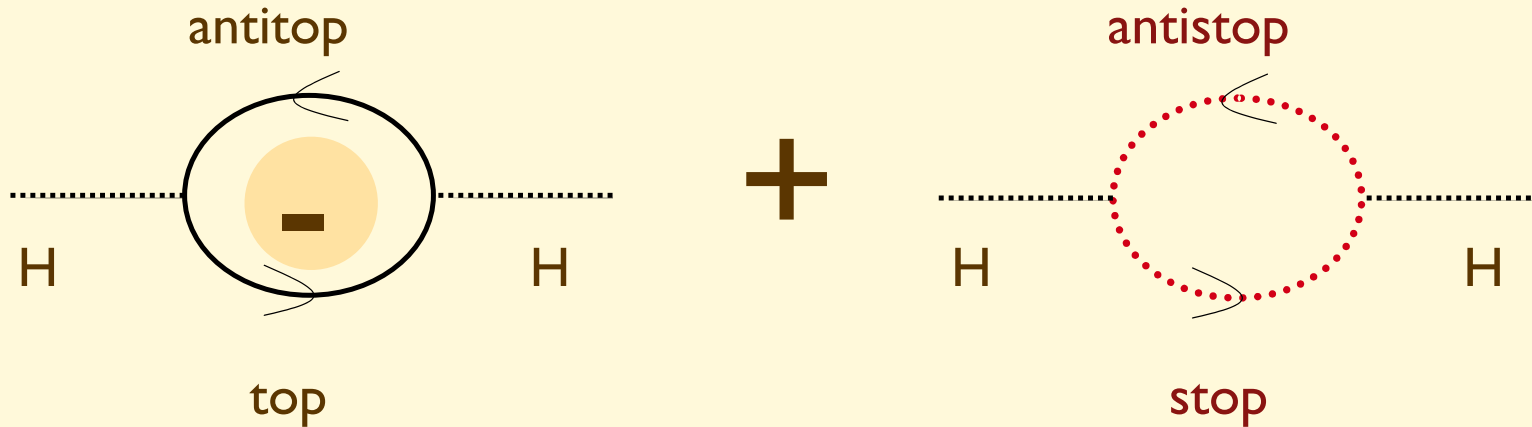
- Ask 10 of your friends to each give you an **irrational number, randomly** distributed between -1 and 1 .
- **Sum the 10 numbers**
- **How would you feel** if the sum were smaller than 10^{-32} ?

Nothing wrong with it, it can happen, but **most likely** your friends agreed in advance on the numbers to give you, and forced the cancellation with a judicious choice.

**Theorists feel the same about the Higgs mass
the accurate cancellation between bare mass
and rad corr's can't be an accident!**

We are therefore led to speculate the existence of **new phenomena at a scale of the order of the TeV**, to introduce new contributions to the Higgs self-energy equation, which cancel the quadratic growth with Λ in a natural **way**

Higgs self-energy, Susy fix



(I)

$$\Delta m_H^2 \propto G_F m_t^4 \log(m_t/m_{stop})$$



stability of the natural scale of the Higgs mass restored!

(II)

SUSY+ gauge invariance



$$\lambda \leftrightarrow g_w$$



$$m_H \leq M_Z + \text{radiative corrections } (\propto \log(m_t/m_{stop})) \leq 135 \text{ GeV}$$

More in general

Tie the Higgs mass to some symmetry which protects it against quadratic divergencies

Supersymmetry

H (scalar) \leftrightarrow fermion

$$\delta m_e = \frac{\alpha_{em}}{3\pi} m_e \log \frac{\Lambda}{m_e}$$

Gauge symmetry

H (scalar) \leftrightarrow 5th component of a gauge bosons in 5 dimensions or more

\Rightarrow extra dimensional theories

Global symmetry

H \rightarrow H + a \Rightarrow L(H)=L(∂ H)

**\Rightarrow Little Higgs theories, Technicolor
H=pseudo-goldstone boson**

What's the origin of invisible dark matter ?



L'homme invisible, 1929

Whatever happened to the antimatter in the Universe?



Antiprotonic assumption, '56

Why do we live in 4 dimensions?

Are there extra *invisible* dimensions?



In the search of the 4th dimension

The Four Fundamental Forces of Nature

Electro-
magnetism



Weak
Interaction



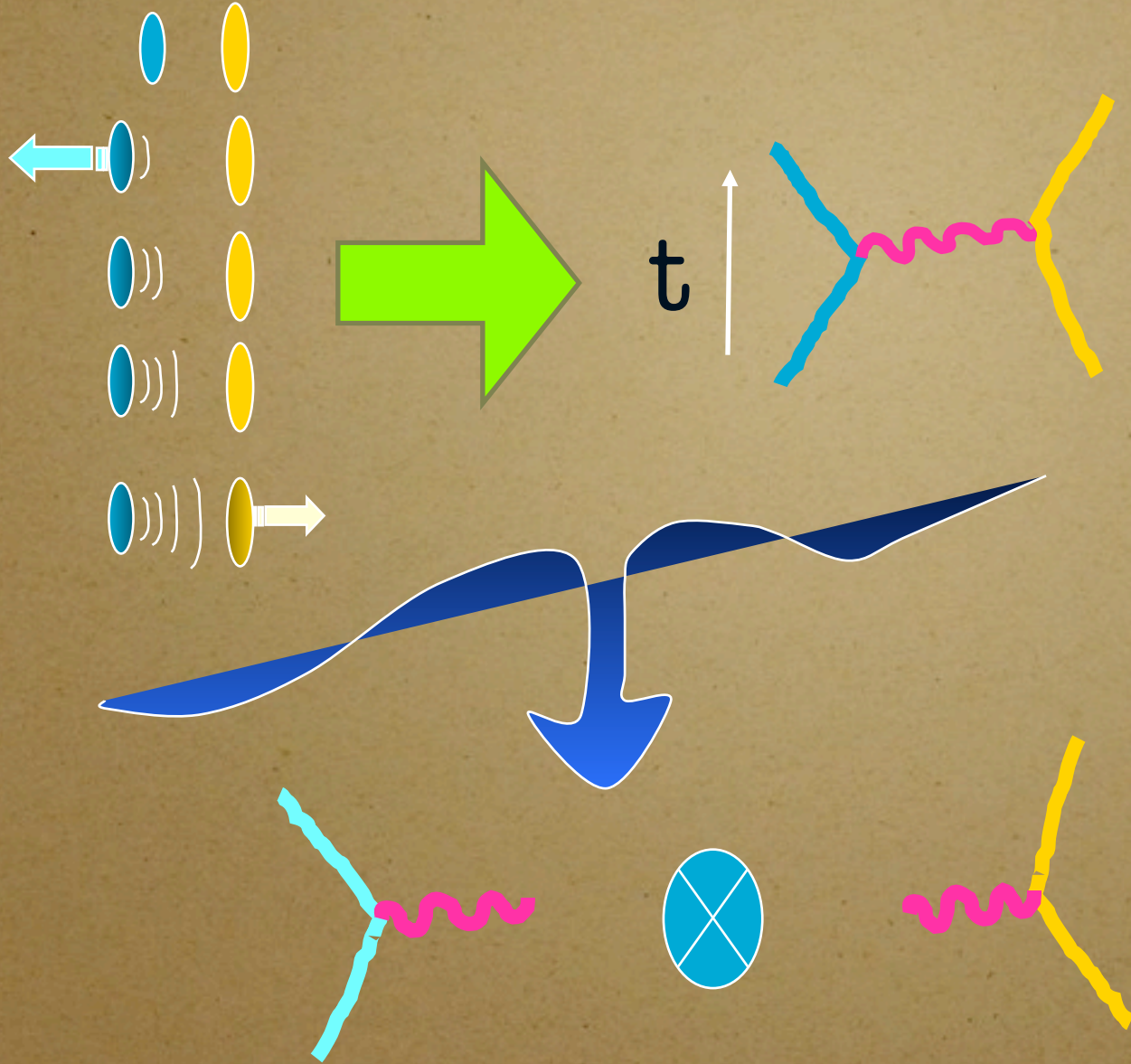
Strong
Interaction



Gravitation

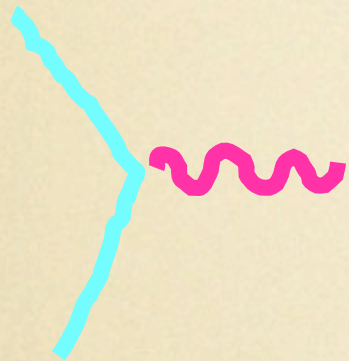



Representation of interactions



**locality,
factorization**

Simple ... but subtle!



before: 

after:  + 

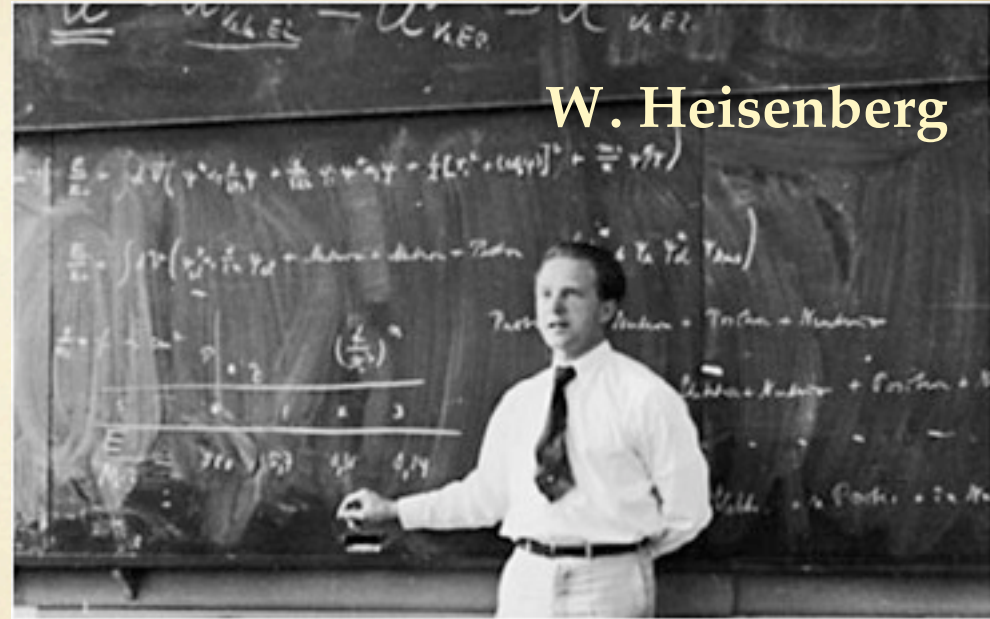


Energy(after) \neq Energy(before)

Quantum mechanics

Heisenberg uncertainty principle:

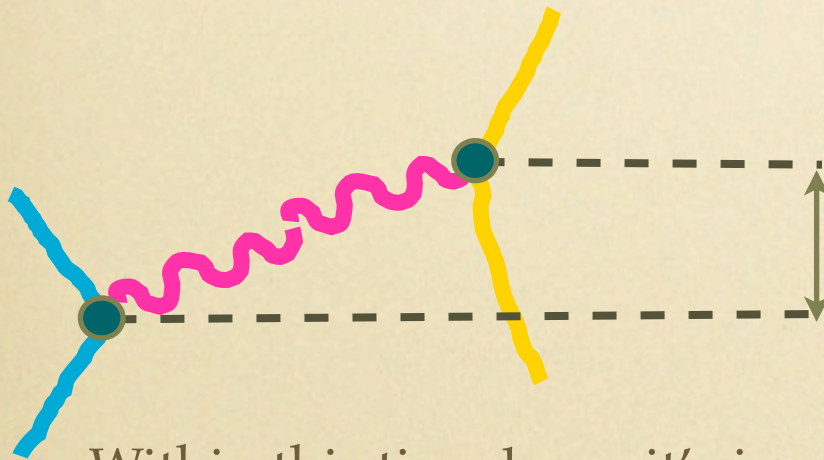
an energy measurement performed within a short time Δt can at best reach a precision $\Delta E \geq \hbar/\Delta t$



W. Heisenberg

"I am studying; I want to find the way to transport my works into anti-matter. That would involve the application of a new equation formulated by Doctor Werner Heisenberg (...) That is why I, who previously only admired Dalí, will now start to admire that Heisenberg who resembles me".

S.Dali, Antimatter manifesto

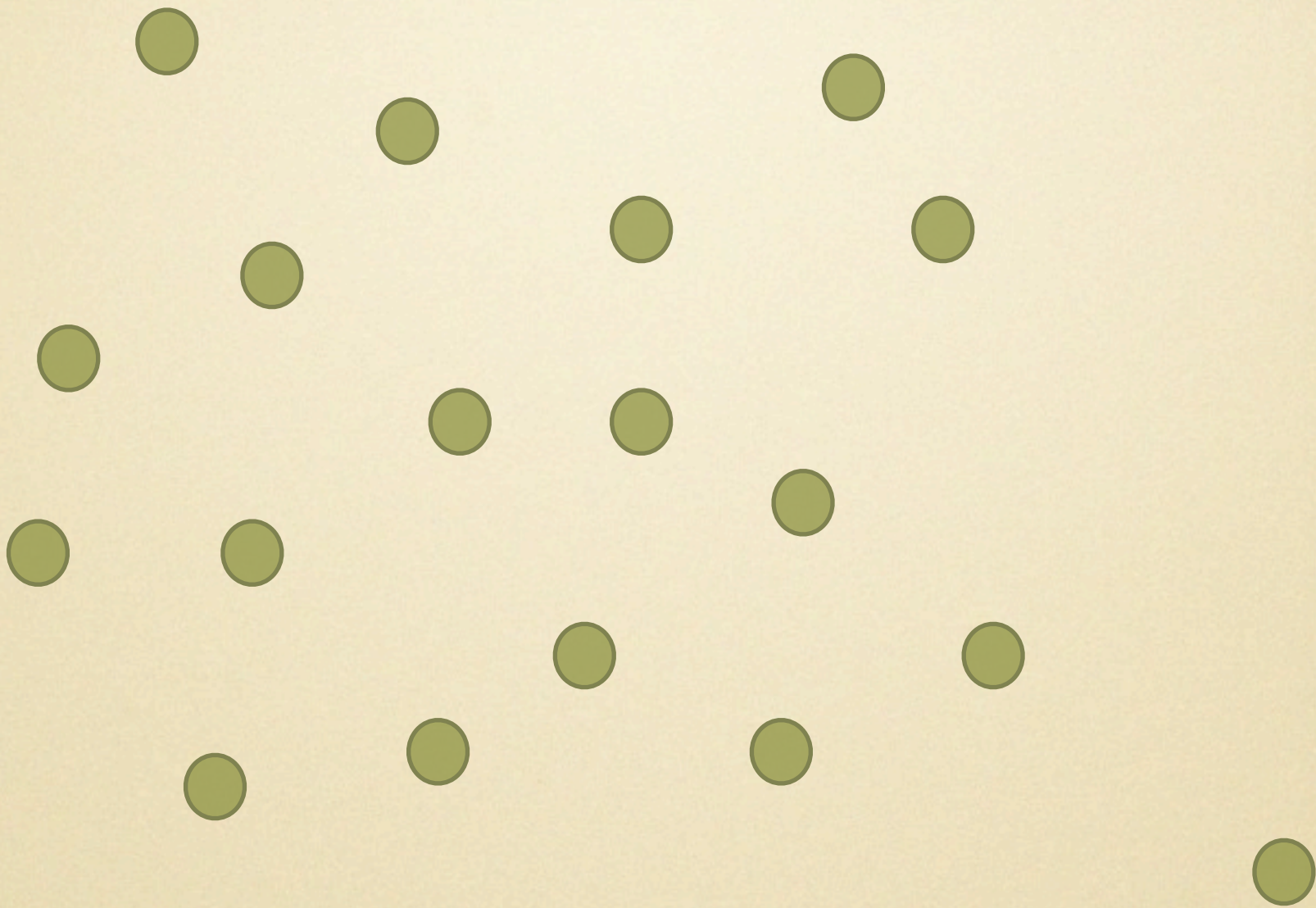


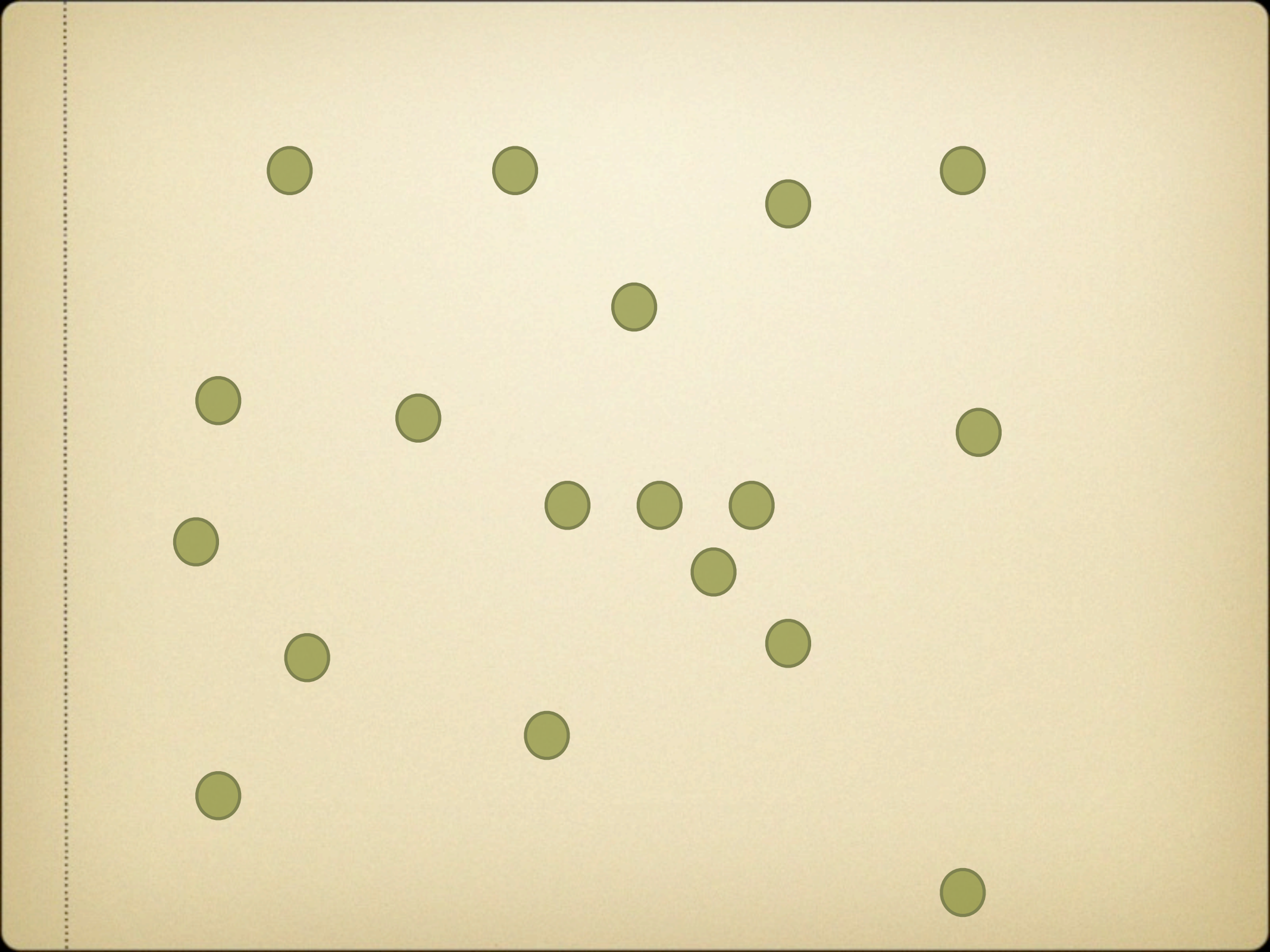
$$\Delta t < \hbar/\Delta E$$

Within this time lapse it's impossible to determine whether energy is conserved or not, since we can't measure it accurately enough. Therefore it's possible to "cheat" nature, and allow the exchange of energy between the two particles

Count fast !







The future: the Large Hadron Collider (LHC)

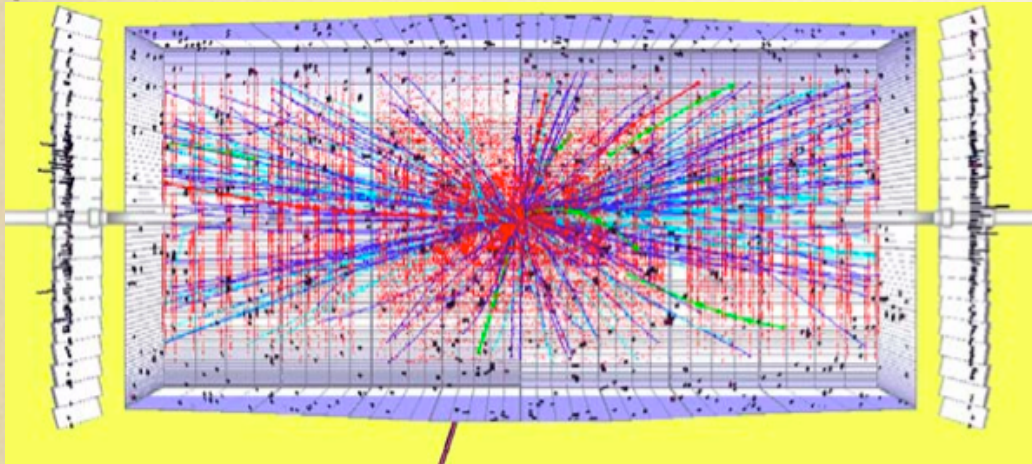


The goals of the LHC

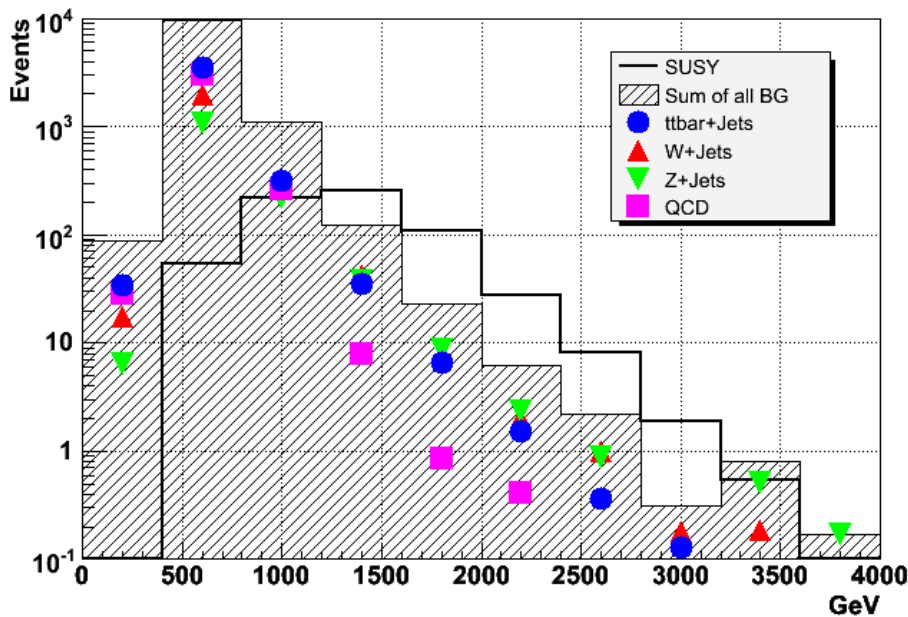
- To firmly establish the “**what**”:
 - discover the crucial missing element of the Standard Model, namely the **Higgs boson**, responsible for particles’ masses
 - search for possible **new fundamental interactions**, too weak to have been observed so far
 - search for possible **new generations** of quarks or leptons
 - confirm/ disprove the **elementary nature** of quarks/ leptons
 - discover direct evidence for the particle responsible for the **Dark Matter** in the Universe
- To firmly establish the “**how**”: the observation of the Higgs boson, and the determination of its properties, will complete the dynamical picture of the Standard Model, confirming (hopefully!) our presumed understanding of “**how**” **particles acquire a mass**.
- To seek new elements which can help us shedding light on the most difficult question, namely **WHY?**

The LHC inverse problem

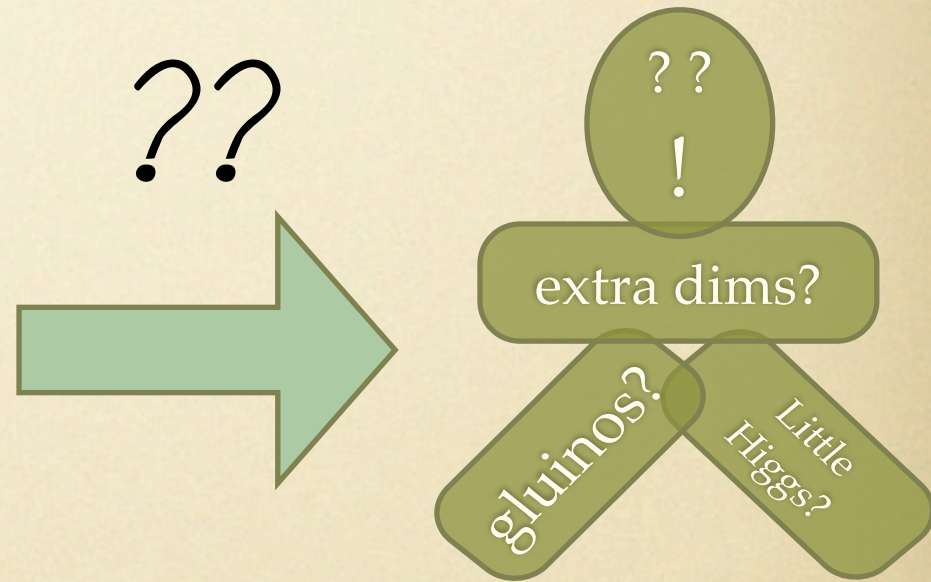
Reconstruct the Lagrangian of new physics from the LHC data



Effective Mass Oepton SUSY



$$M_{\text{eff}} (\text{GeV}) = \sum_{i=1,4} E_T (i) + E_T^{\text{miss}}$$



\mathcal{L}

● < 1973: theoretical foundations of the SM

- renormalizability of $SU(2)\times U(1)$ with Higgs mechanism for EWSB
- asymptotic freedom, QCD as gauge theory of strong interactions
- KM description of CP violation

● Followed by 30 years of consolidation:

- **technical theoretical advances** (higher-order calculations, lattice QCD, ...)
- **experimental** verification, via **discovery** of
 - **Fermions**: charm, 3rd family (USA)
 - **Bosons**: gluon, W and Z (Europe; waiting to add the Higgs)
- **experimental** consolidation, via **measurement** of
 - EW radiative corrections
 - running of α_s
 - CKM parameters

It's unlikely it will take less than 30 yrs to clarify and consolidate the understanding of new phenomena to be unveiled by the LHC!

What will be the main driving theme of the exploration of the new physics revealed by the LHC?

the gauge sector
(Higgs, EWSB)



The High Energy Frontier

LHC
SLHC
VLHC
ILC
CLIC
....

the flavour sector
(ν mixings, CPV, FCNC,
EDM, LFV)



The High Intensity Frontier

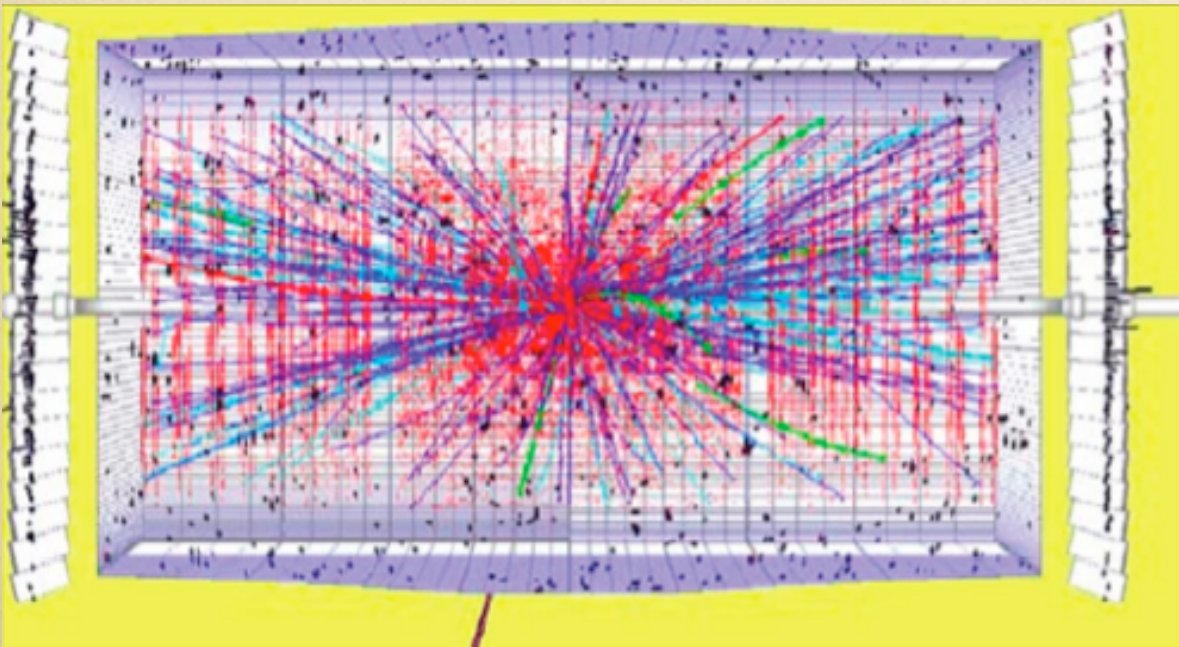
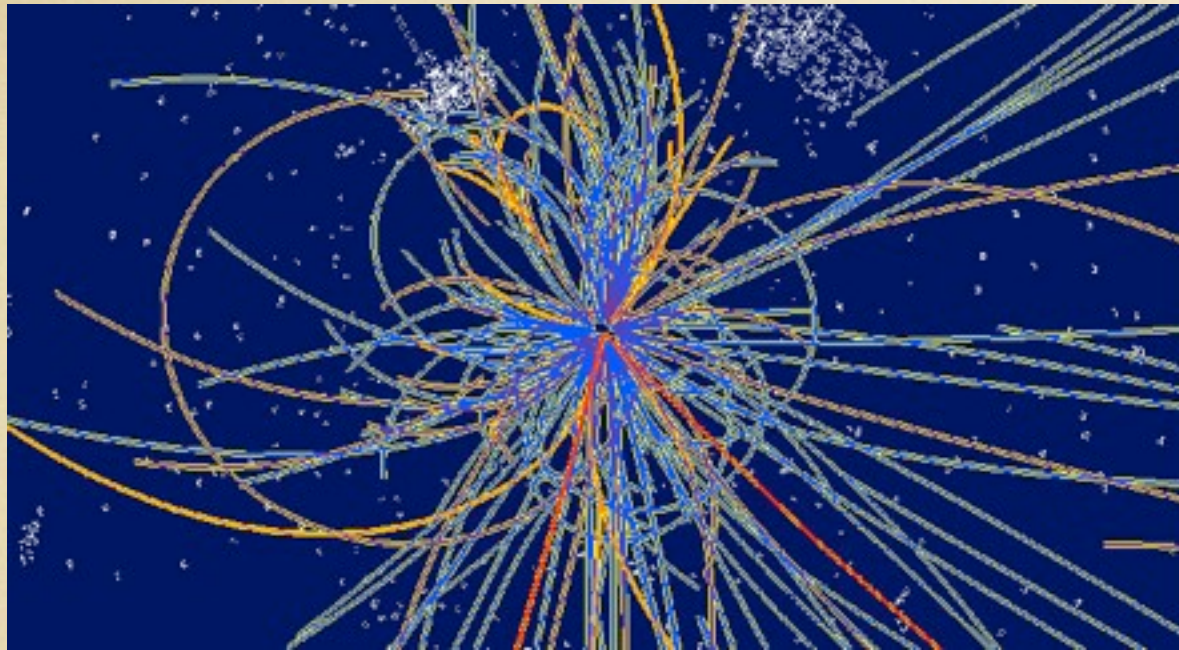
Neutrinos:	Quarks:	Charged leptons:
super beams	B factories	stopped μ
beta-beams	K factories	$l \rightarrow l'$ conversion
ν factory	n EDM	e/ μ EDM

+ Astrophysics and cosmology

2015, a dream scenario

- SUSY is seen at LHC, with squarks/gluinos at ~ 1 TeV, weak sparticles at ~ 0.1 TeV
- Observe in parallel:
 - LHCb: $B_s \rightarrow \mu^+ \mu^-$ at rates $> SM$, and NA62: $K^+ \rightarrow \pi^+ \nu \nu$ at rates $> SM$
 - MEG: $\mu \rightarrow e \gamma$
 - ILL/PSI: neutron EDM
 - large $\theta_{13} \rightarrow$ measurable CP violation in nu mixing
- Z' at 2–2.5 TeV seen at LHC:
 - open decays to all SUSY sparticles \Rightarrow very accurate studies
 - the LHC turns into a Z' factory
 - CLIC is above threshold to further study it in the future
- Direct DM detection underground fits with neutralino properties
-

It's a dream, but not an impossible one !



Conclusions

- Great process has taken place in our understanding of the universe
- The depth of our understanding has reached new levels, uncovering the nature and meaning of many *invisibles*
- but the most exciting part is still to come, and it's for you to discover and explore it !

**BEST WISHES TO ALL
OF YOU FOR A MOST
SUCCESSFUL CAREER
IN PHYSICS !!**