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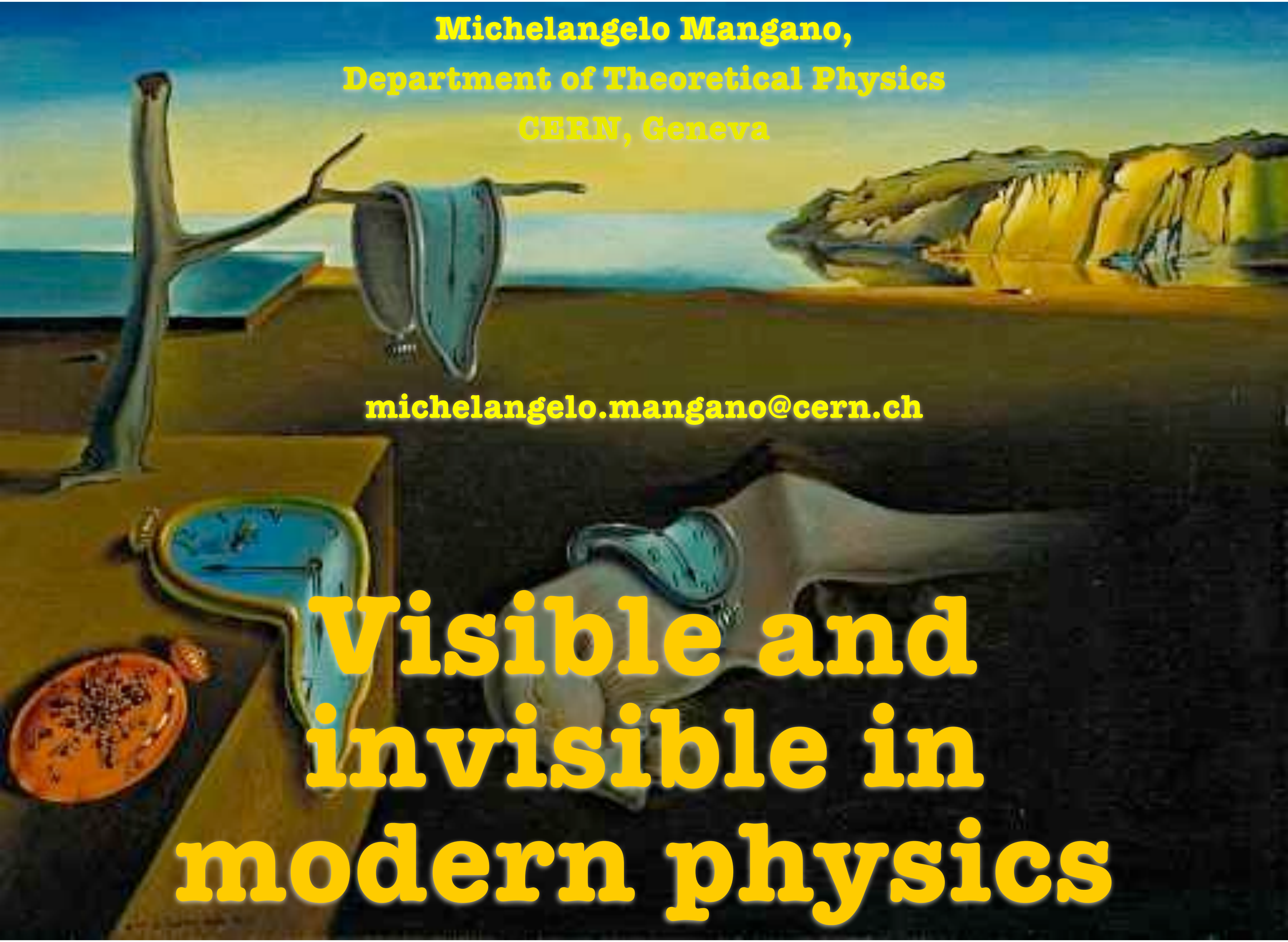


Visible and invisible in modern physics

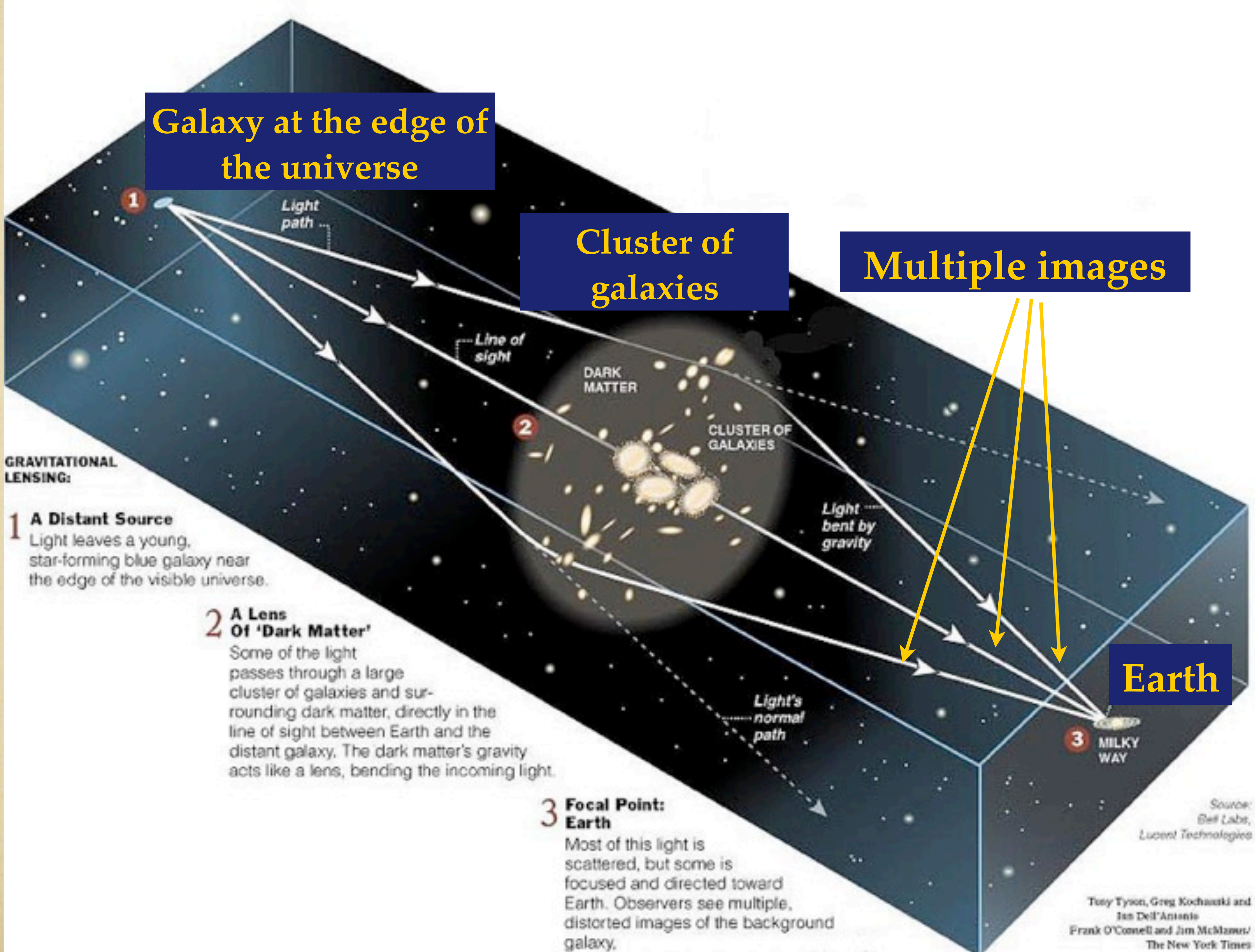
Hubble Ultra Deep Field

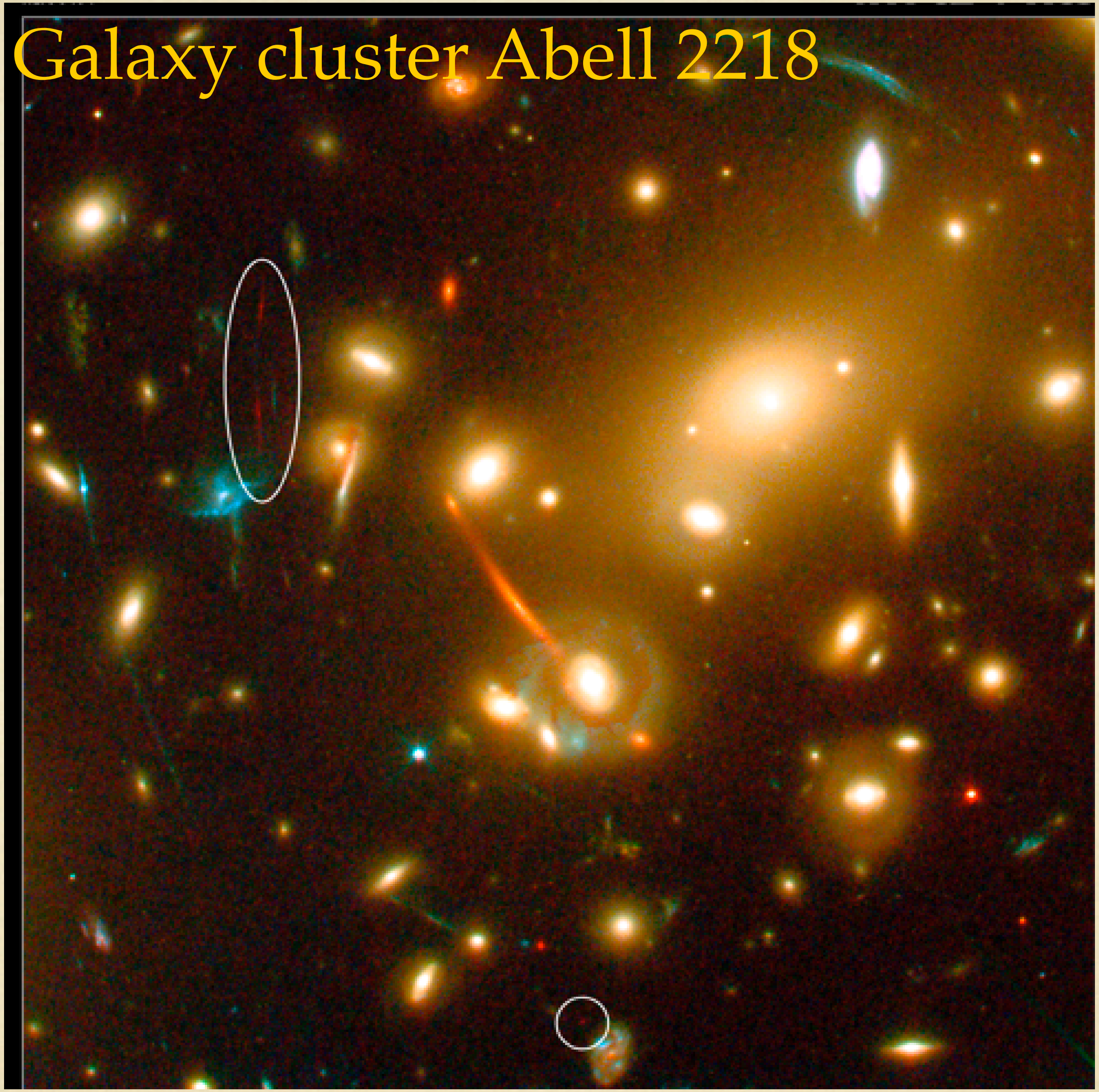
Hubble Space Telescope • Advanced Camera for Surveys

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

STScI-PRC04-07a

Gravitational lensing





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

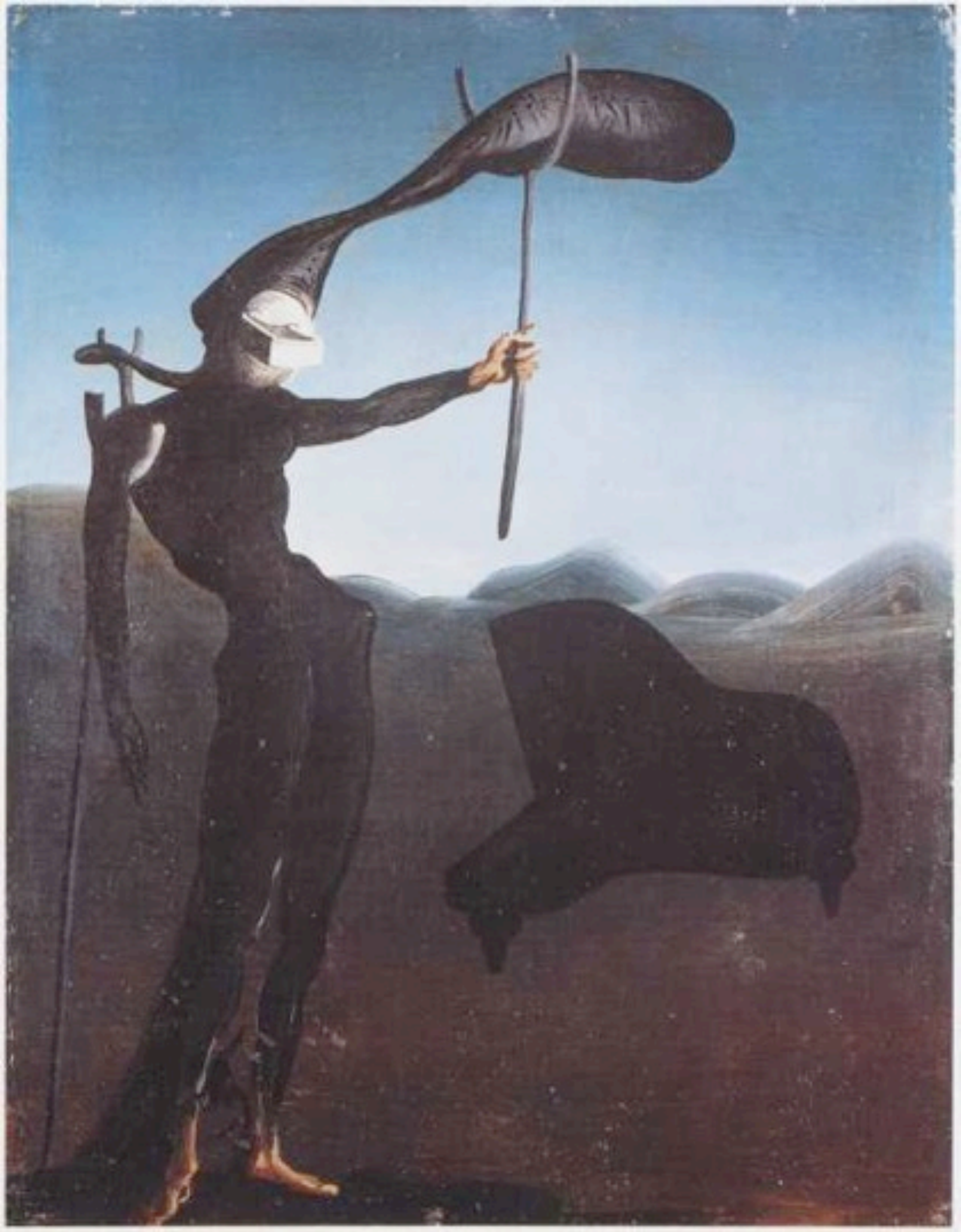
The shape and intensity of lensed images requires the presence of 5 times more mass than contained in the **visible** galaxies !

→ 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 to 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

$^6He \rightarrow {}^6Li + e^-$

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

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

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

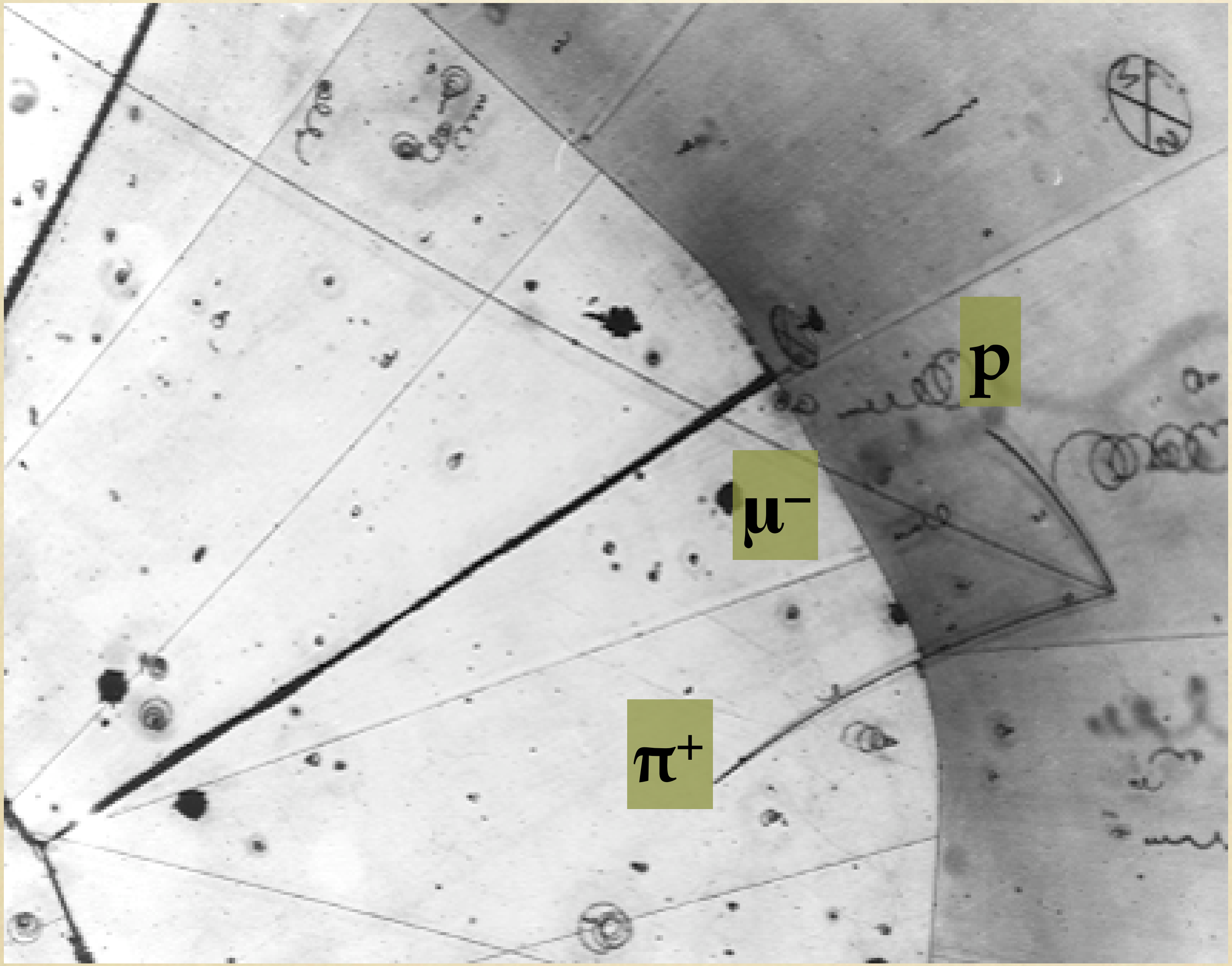
... while in others it is very fast

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**

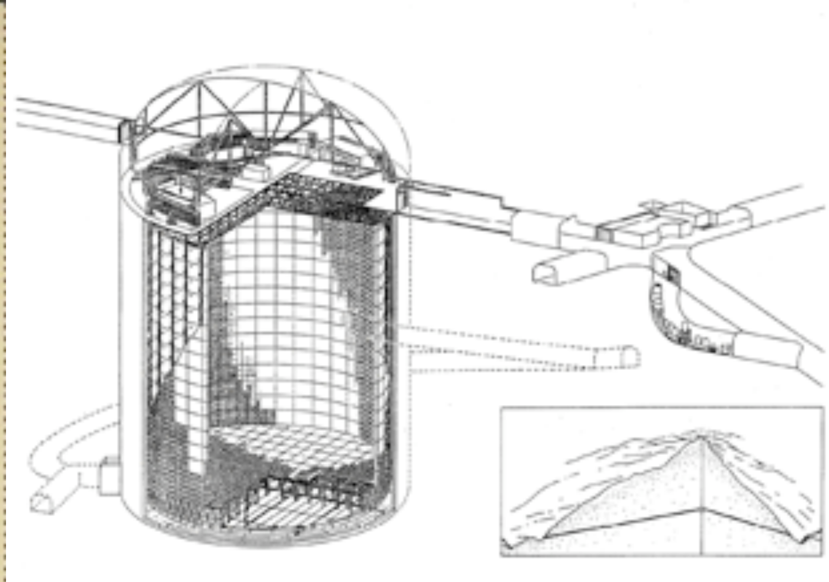
$$^{6}He \rightarrow {}^{6}Li + e^{-} + \nu$$

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

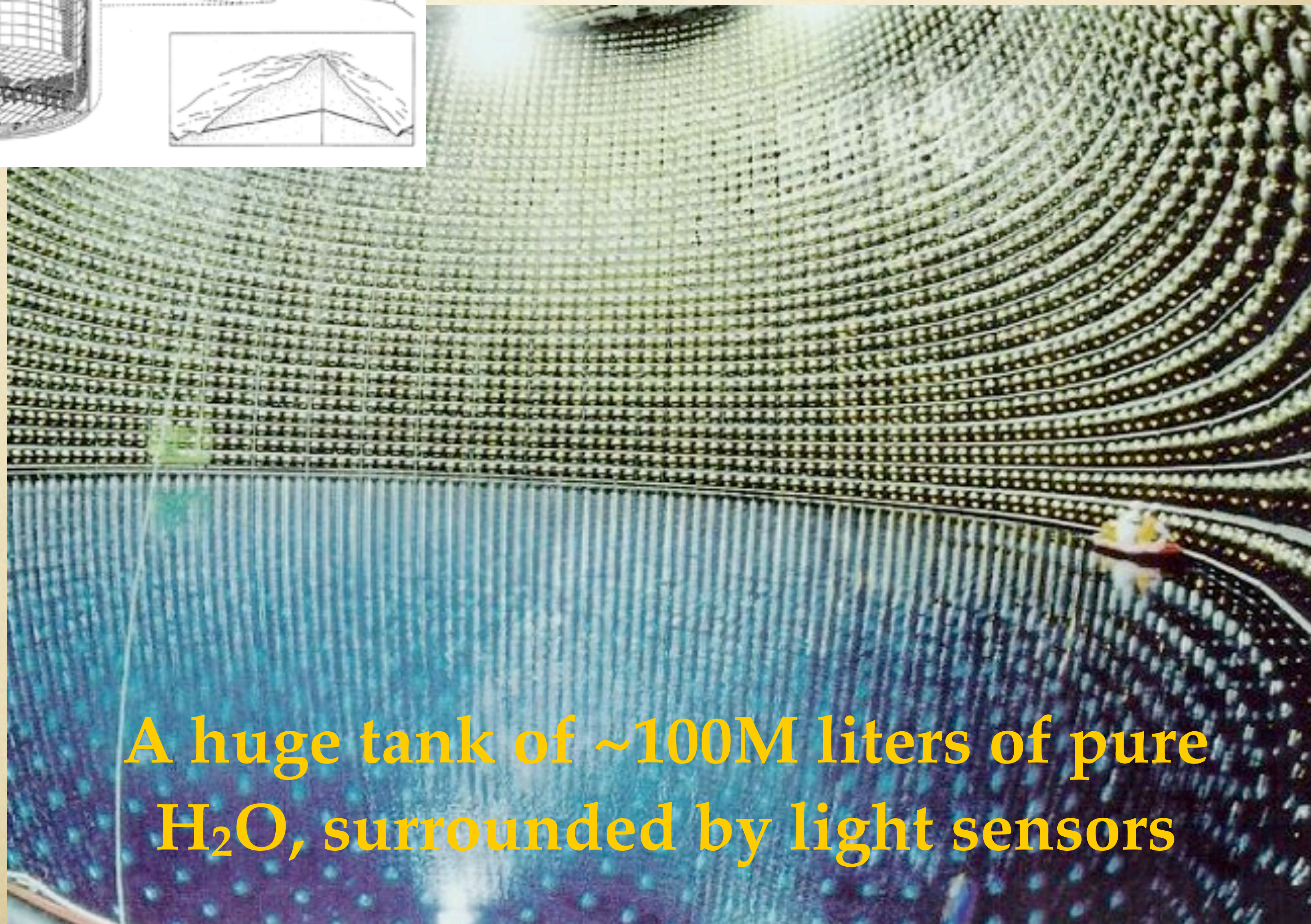


ν from a beam of π mesons

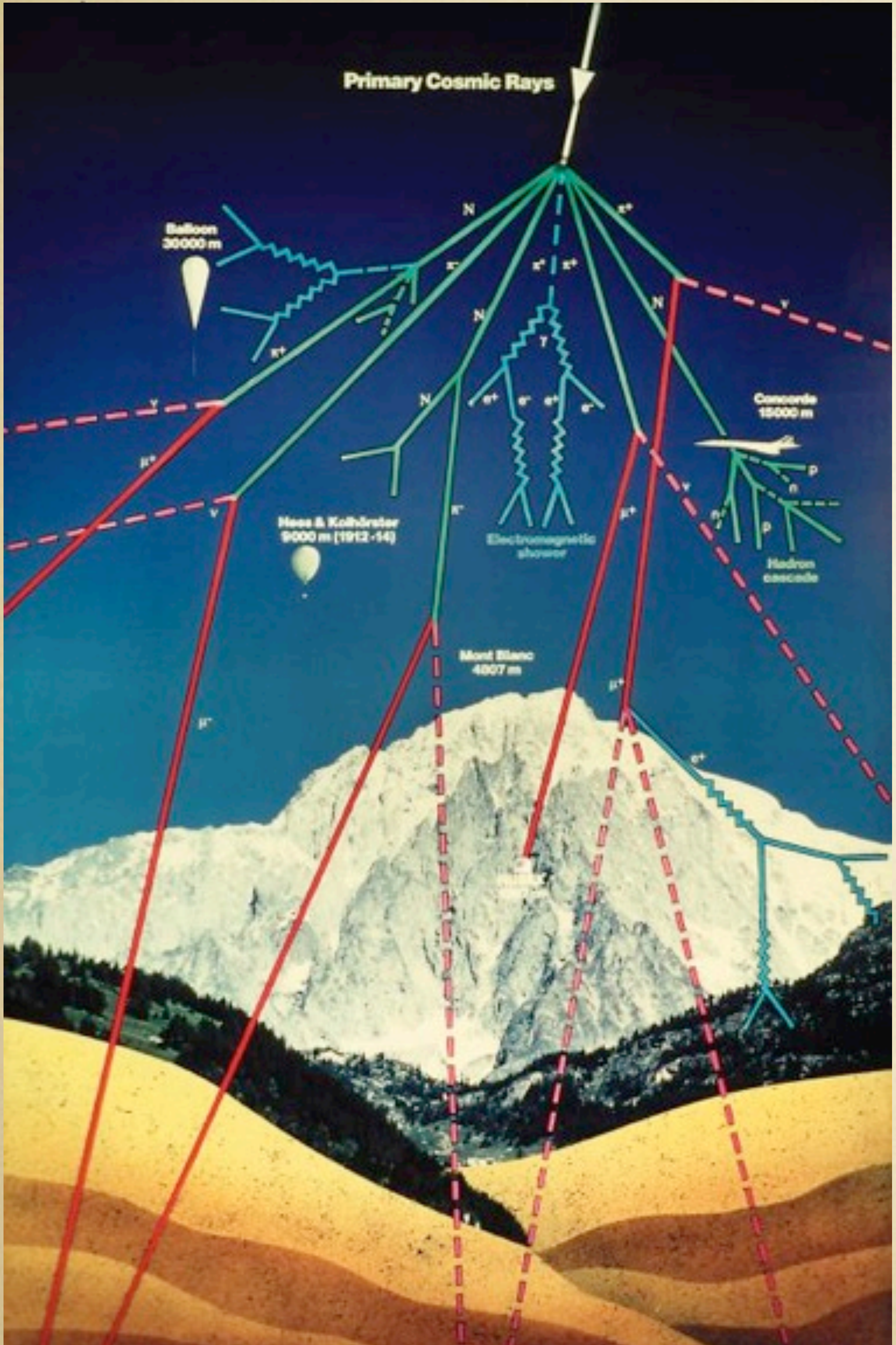
The world's first neutrino observation in a hydrogen bubble chamber. It was found Nov. 13, 1970, in this photograph from the Zero Gradient Synchrotron's 12-foot bubble chamber. The invisible neutrino strikes a proton where three particle tracks originate (lower right). The neutrino turns into a mu-meson, 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)

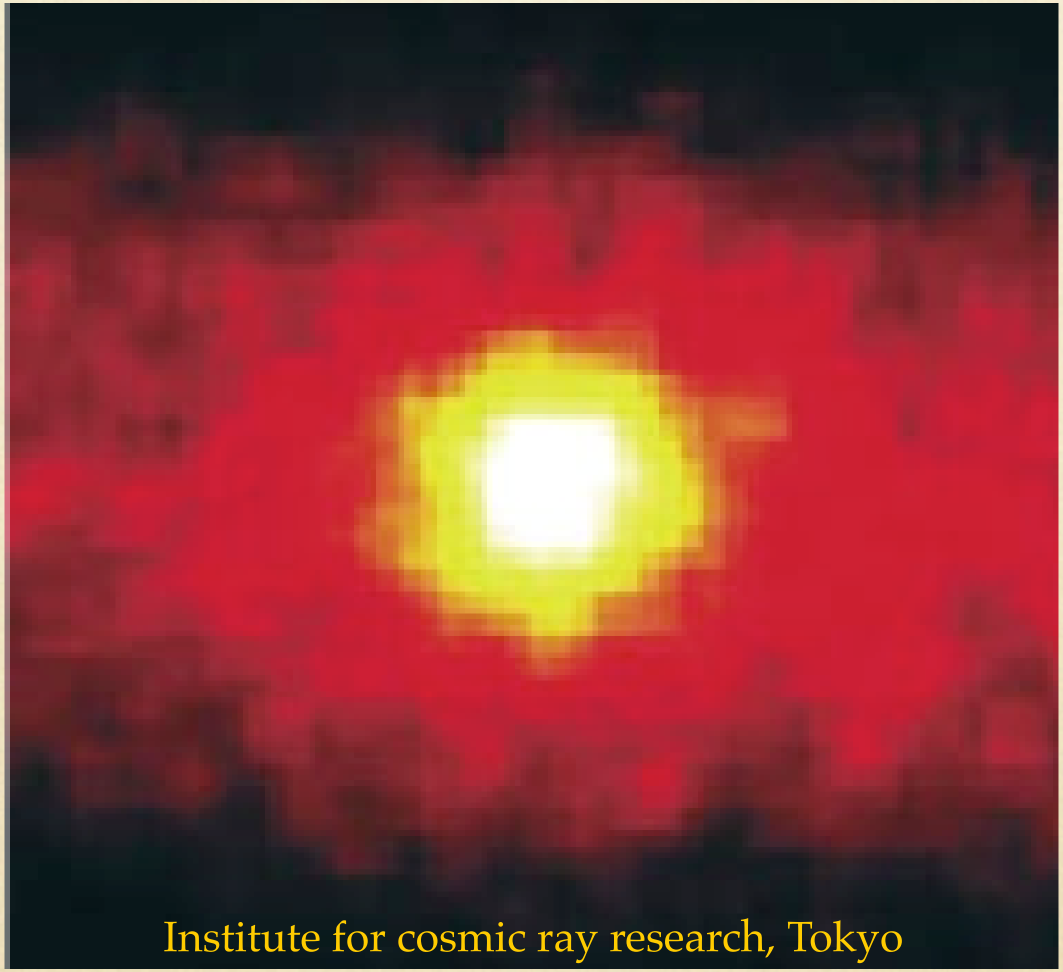


A huge tank of ~100M liters of pure H_2O, surrounded by light sensors

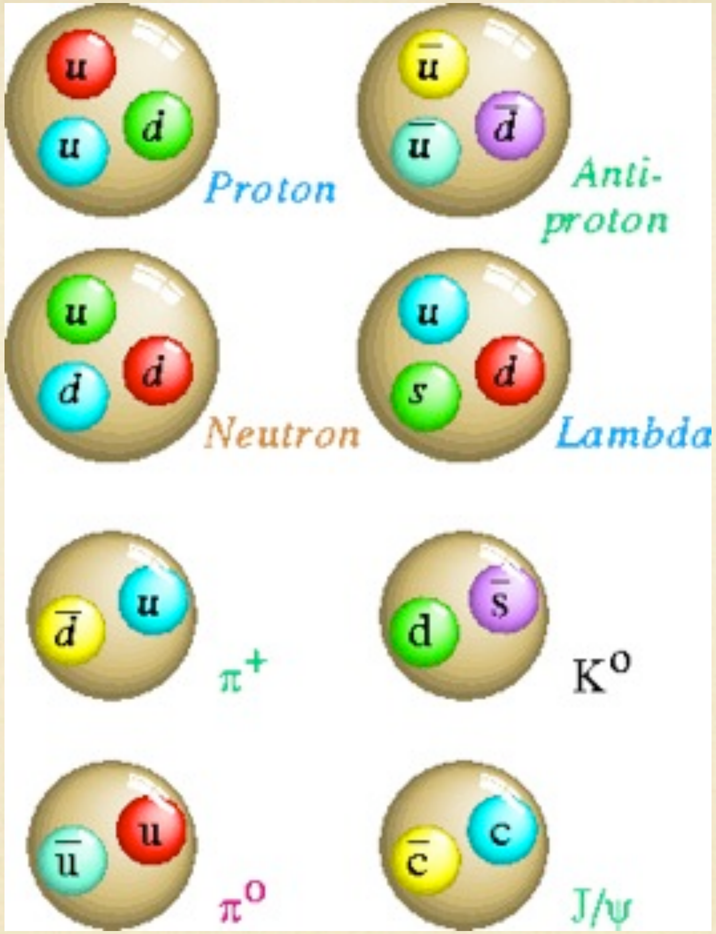


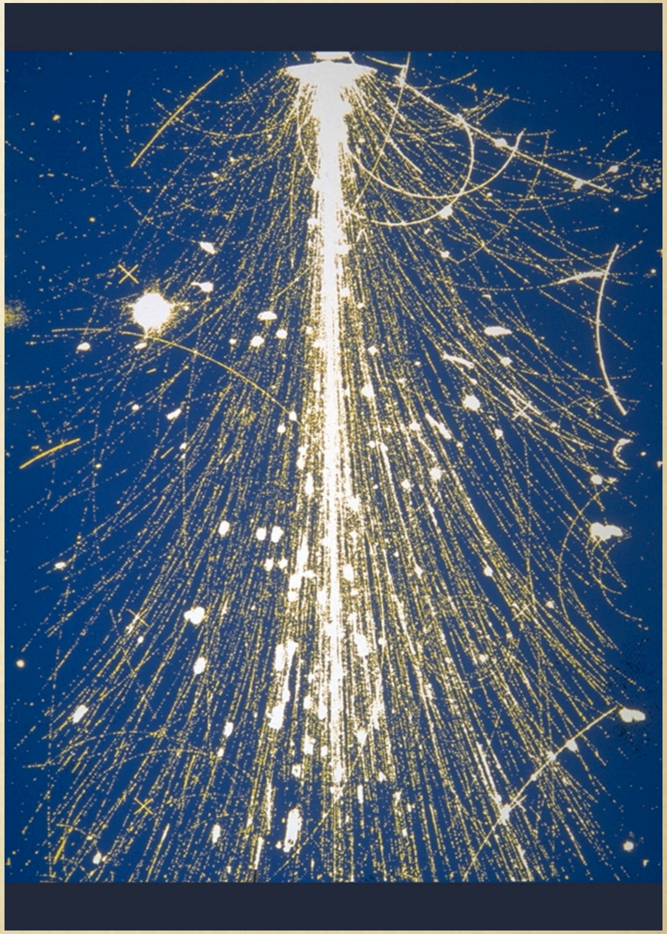
Primary Cosmic Rays
Balloon
30000 m
Concorde
15000 m
Hess & Kolhörster
9000 m (1912-14)
Electromagnetic
shower
Hadron
cascade
Mont Blanc
4807 m

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



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

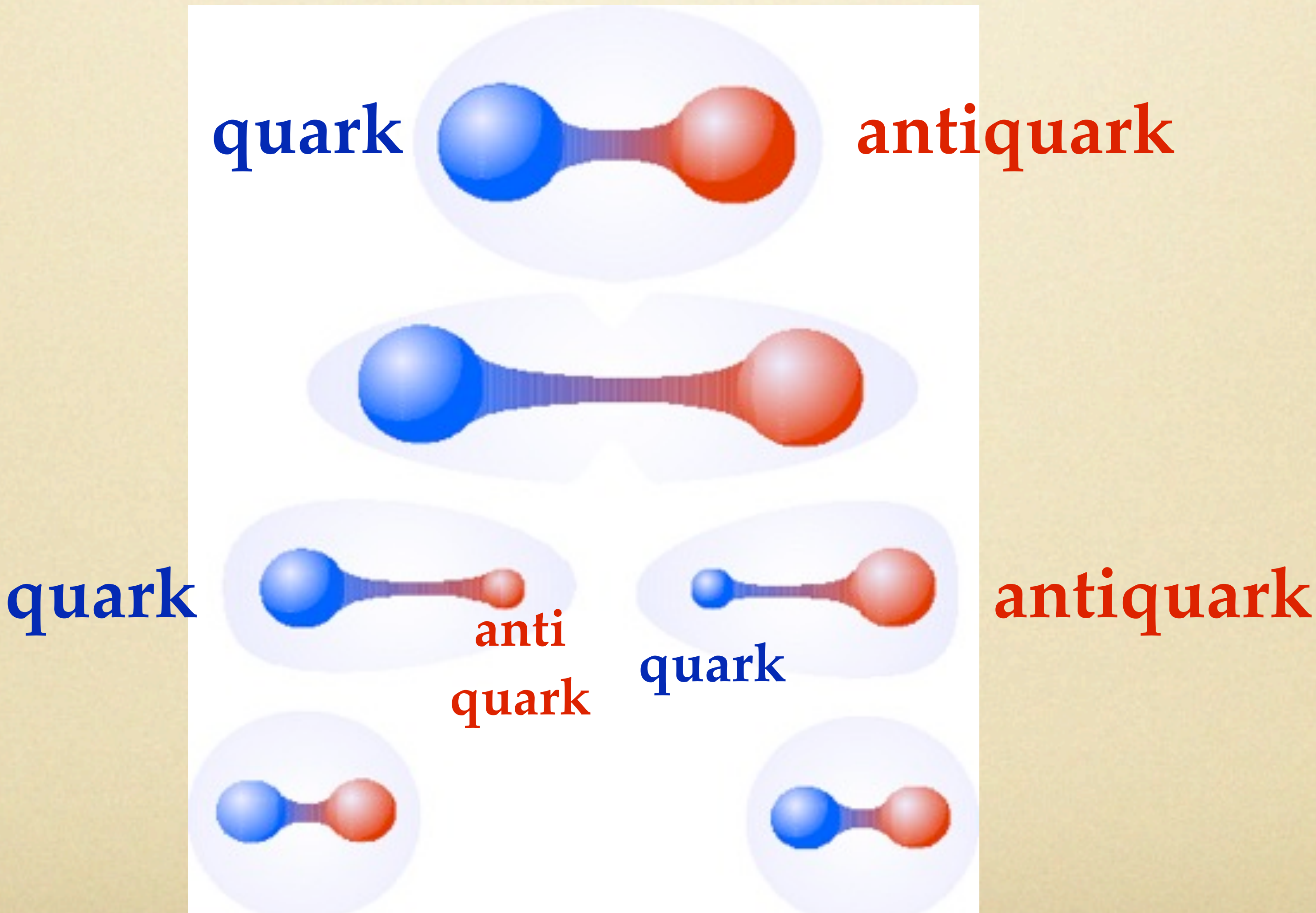




Saint surrounded by three π mesons, 1956

... 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!



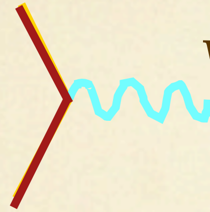
The vacuum: invisible nothingness, or seed of mass and structure?

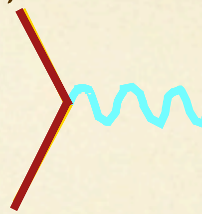
Why do particles have a mass?

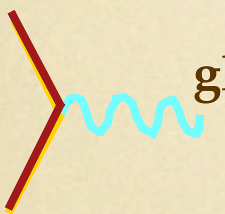
The echo of void, 1935

SU(3)

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







$\begin{pmatrix} u_{2/3} \\ d_{-1/3} \end{pmatrix}_L^{i=1,2,3}$	$u^i{}_R\,,\ d^i{}_R$
$\begin{pmatrix} \nu \\ e^- \end{pmatrix}_L$	$e^-{}_R$

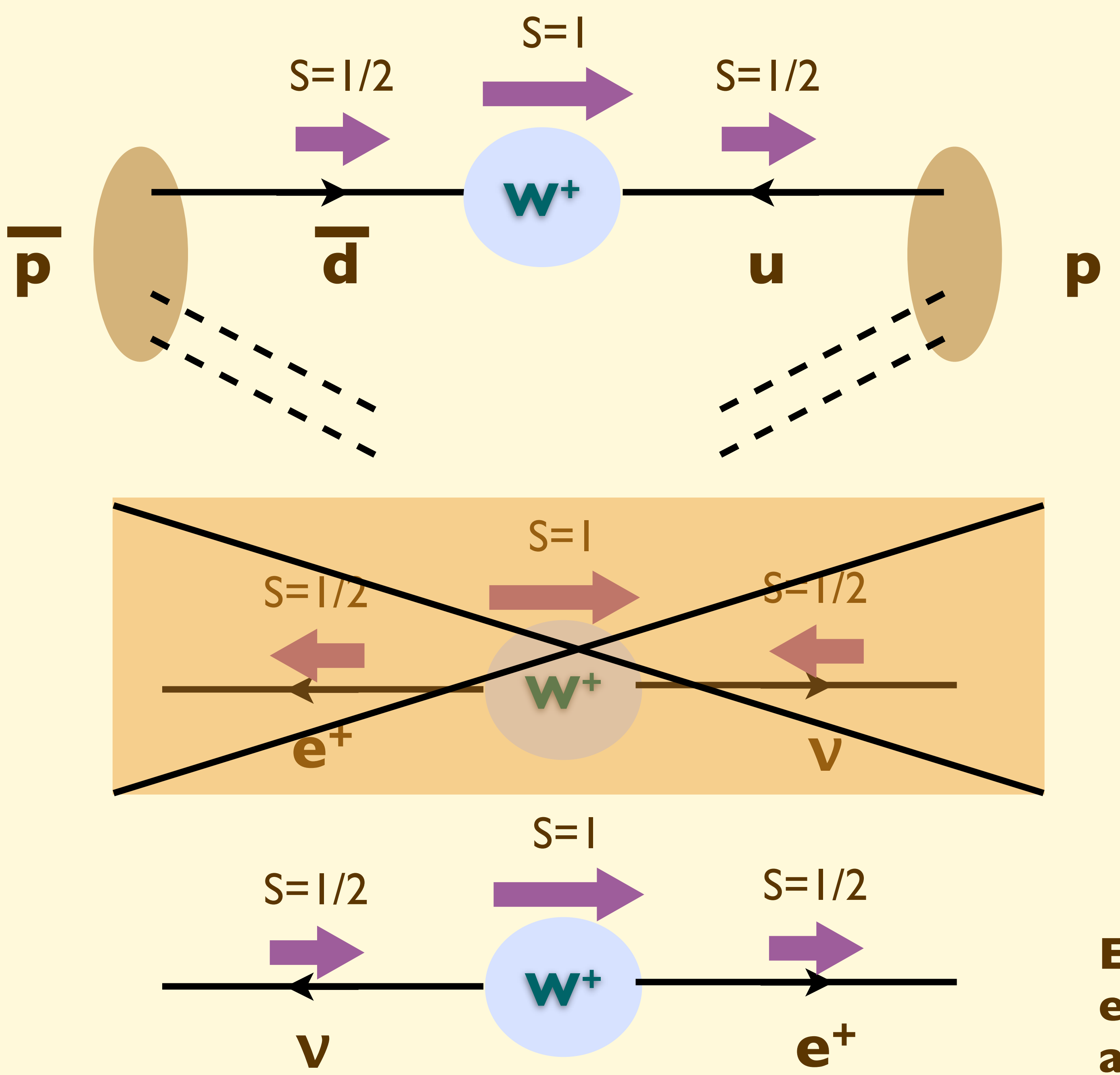
Spin — **L-handed helicity**

Spin — **R-handed helicity**

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

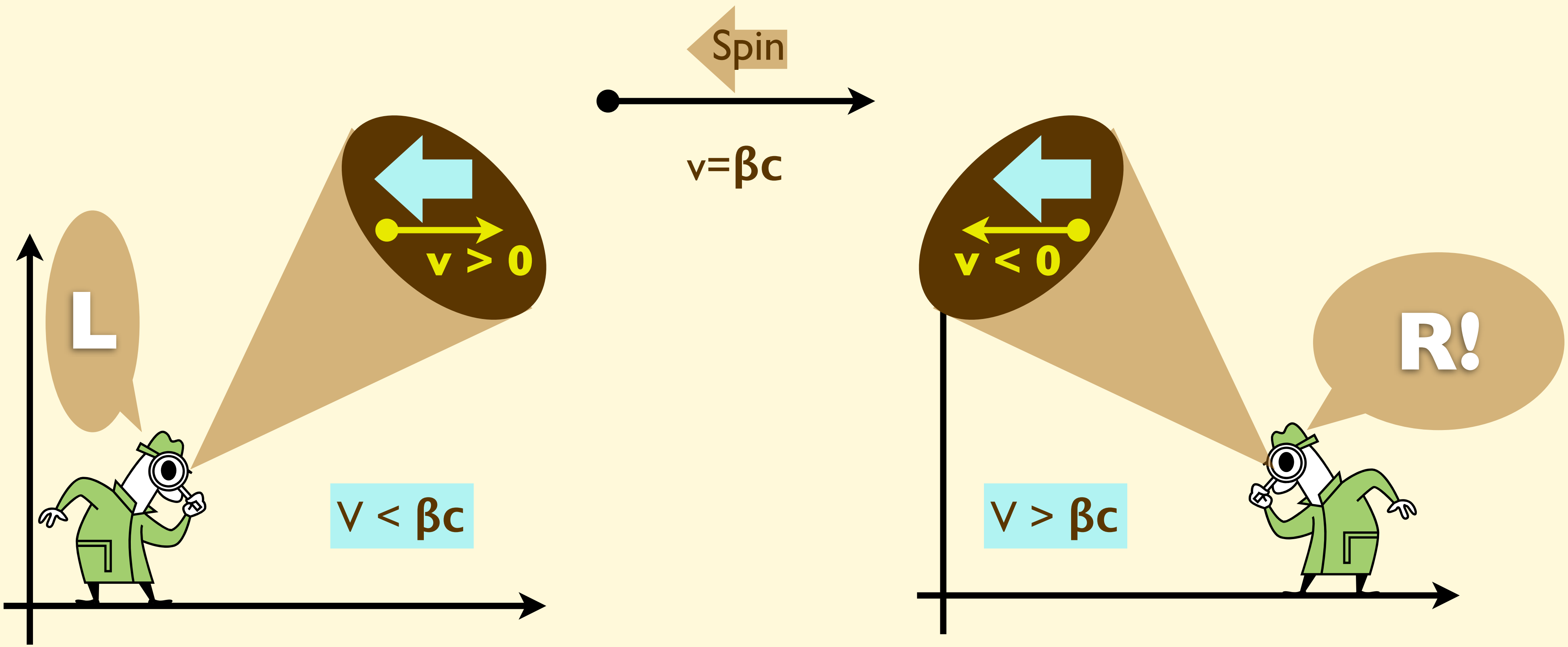
Parity violation in W interactions

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



Explicitly tested with ever increasing accuracy at SppS, LEP, Tevatron, PSI, ..

Parity asymmetry and mass



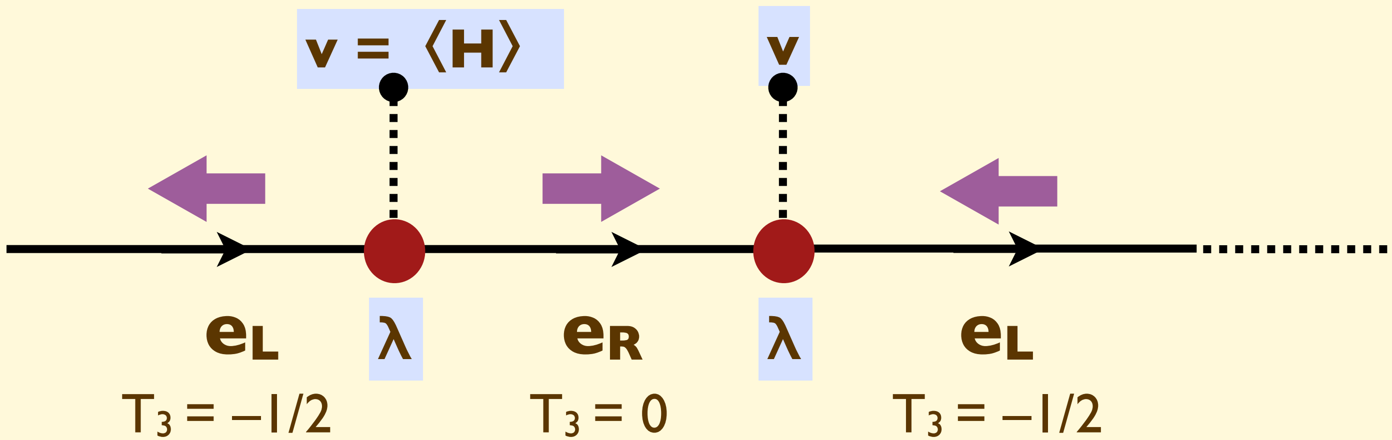
Helicity does not commute with Hamiltonian, so it cannot be conserved for a massive particle

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

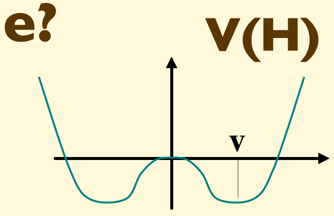
Time evolution of a massive particle:



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** $\mathbf{m \propto \lambda\, v}$

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 λ[muon]≠ λ[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 ⇒ LHC !!!

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

m[electron] determines the "size of things"

m[electron] vs m[down]–m[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 accomodate 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[top]=170 GeV, λ[top]=1: **coincidence**?

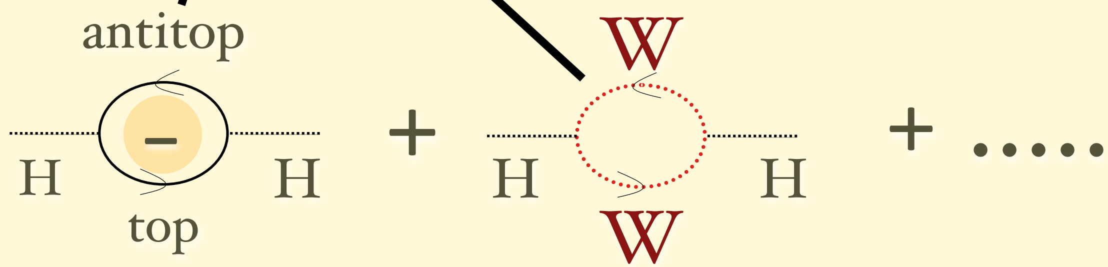
In several theories beyond the SM, m[top]$\approx$170 GeV is required for a dynamical breaking ofthe EW symmetry: **message**?

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:

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



Λ= scale up to which the SM is valid

renormalizability =>

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

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**

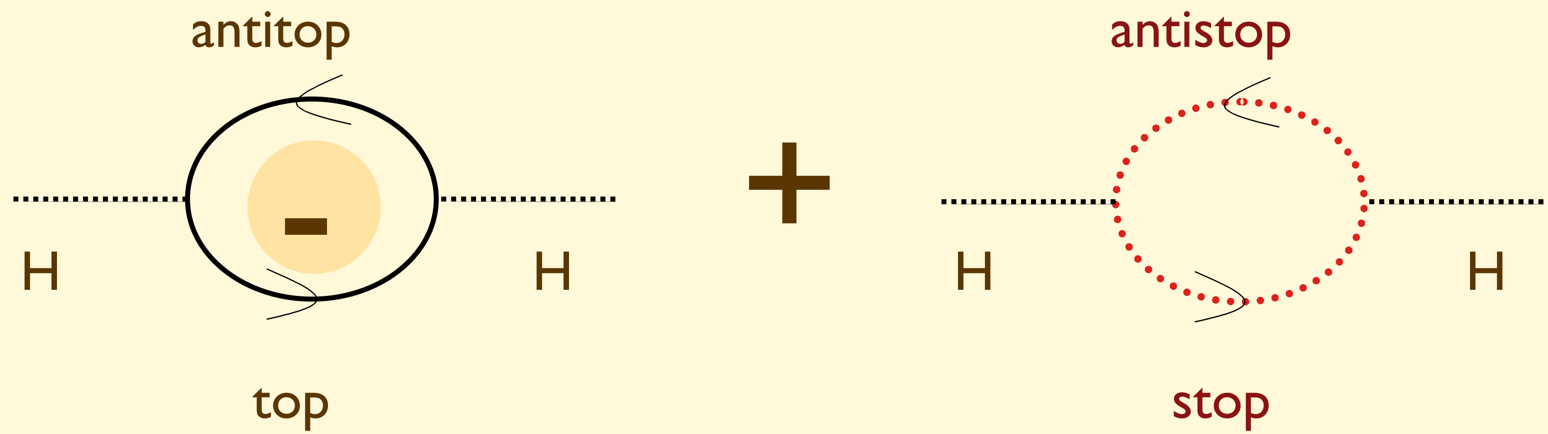
- **How would you feel** if the sum were smaller than 10^{-32} ?

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) ↔ fermion

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

Gauge symmetry

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

=> extra dimensional theories

Global symmetry

$H \rightarrow H + a \Rightarrow L(H)=L(\partial H)$

=> 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

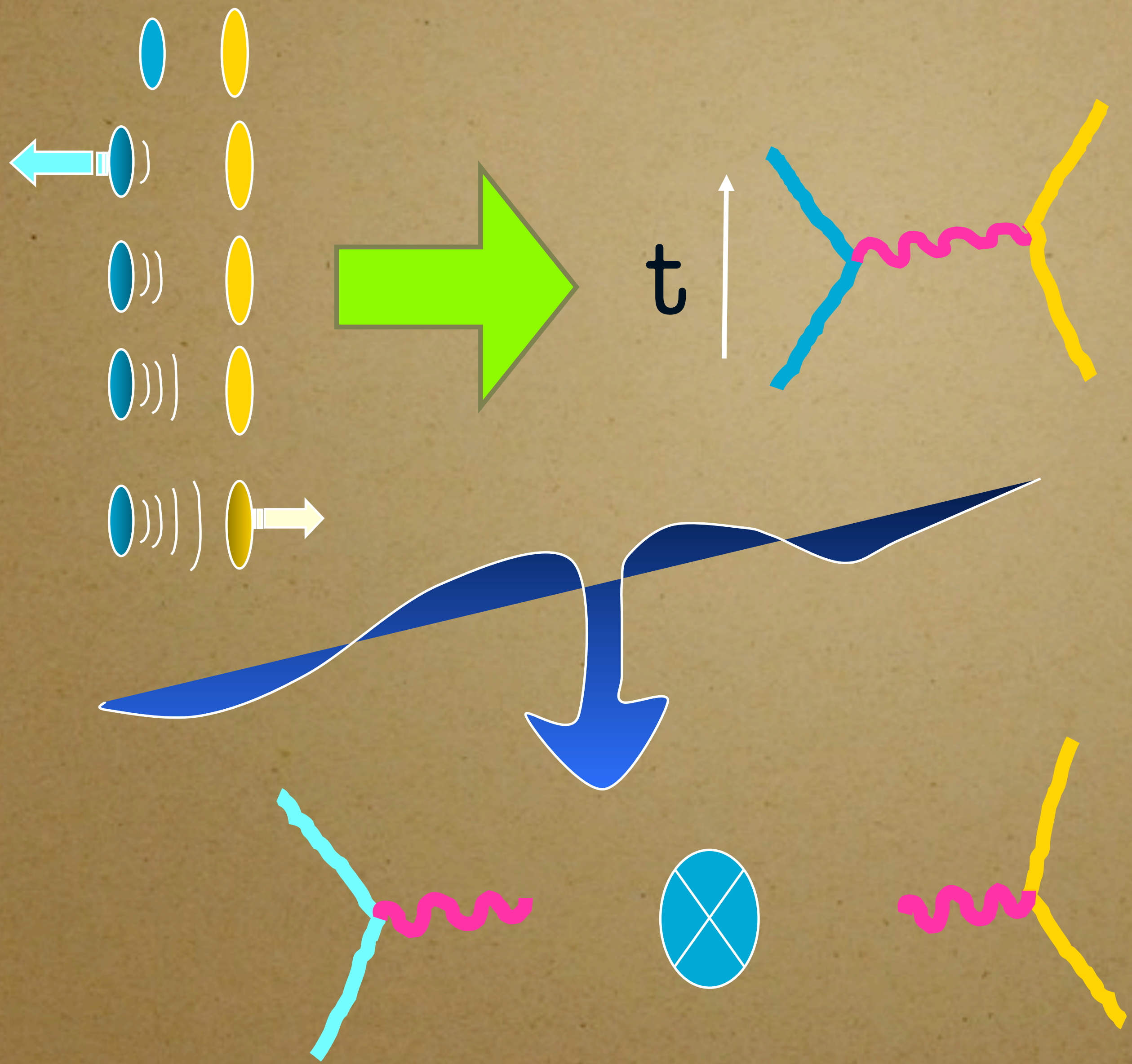
Why do we live in 4 dimensions?

Are there extra *invisible* dimensions?

In the search of the 4th dimension

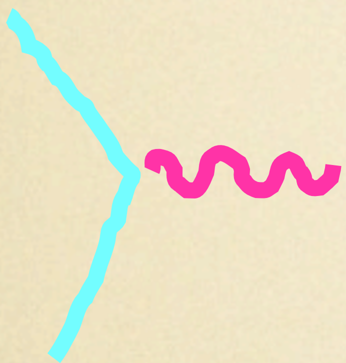
The Four Fundamental Forces of Nature
Electro-magnetism
Weak Interaction
Strong Interaction
Gravitation

Representation of interactions



locality,
factorization

Simple ... but subtle!

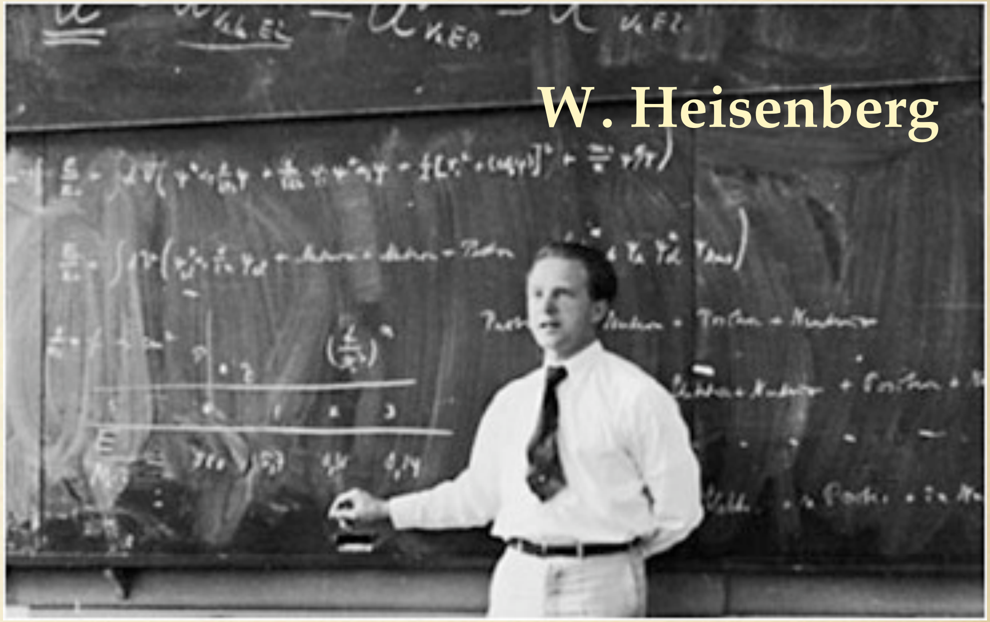


before: 

after:  + 

Energy(after) ≠ Energy(before)

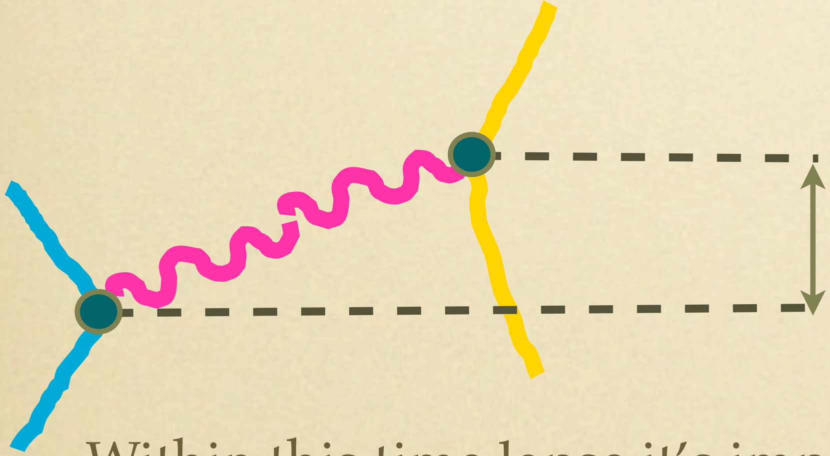
Quantum mechanics



"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

Heisenberg uncertainty principle:

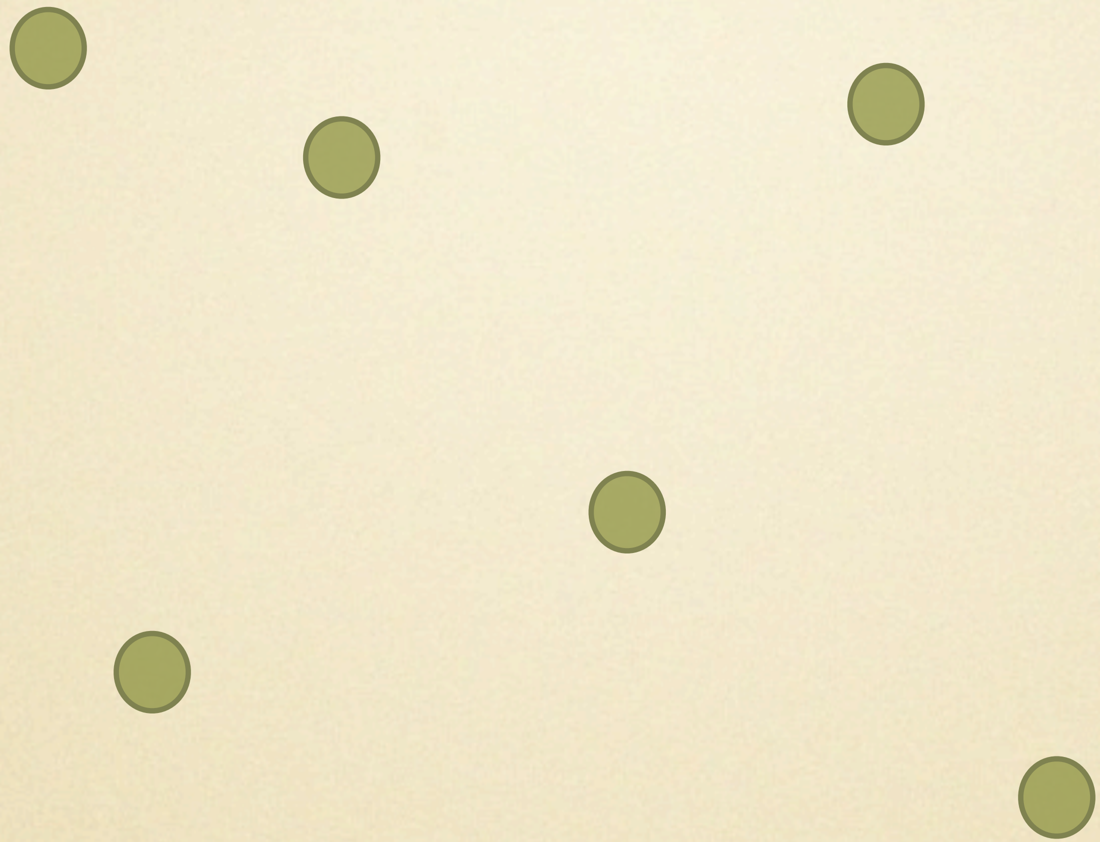
an energy measurement performed within a short time **Δt** can at best reach a precision **$\Delta E \geq 1/\Delta t$**

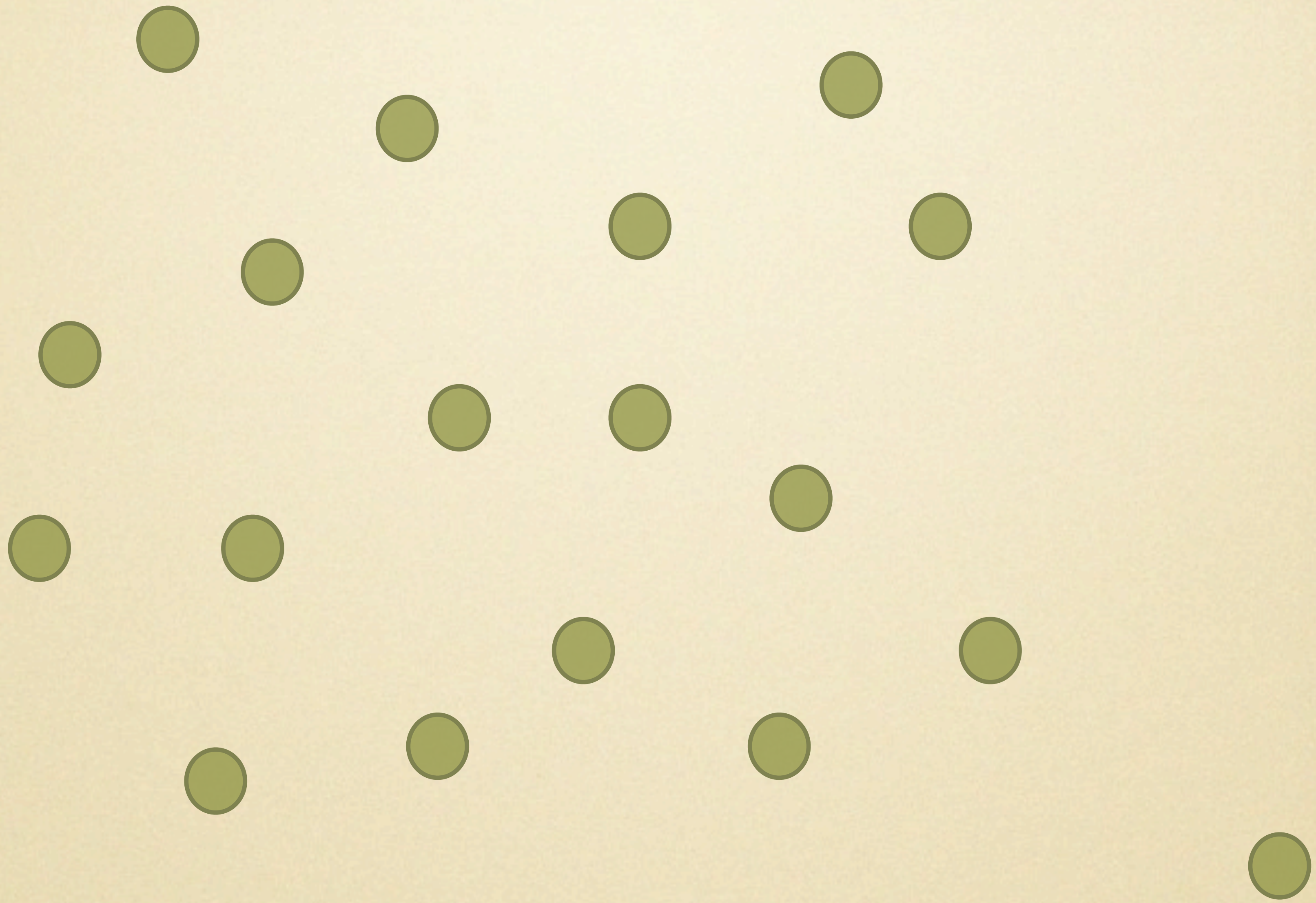


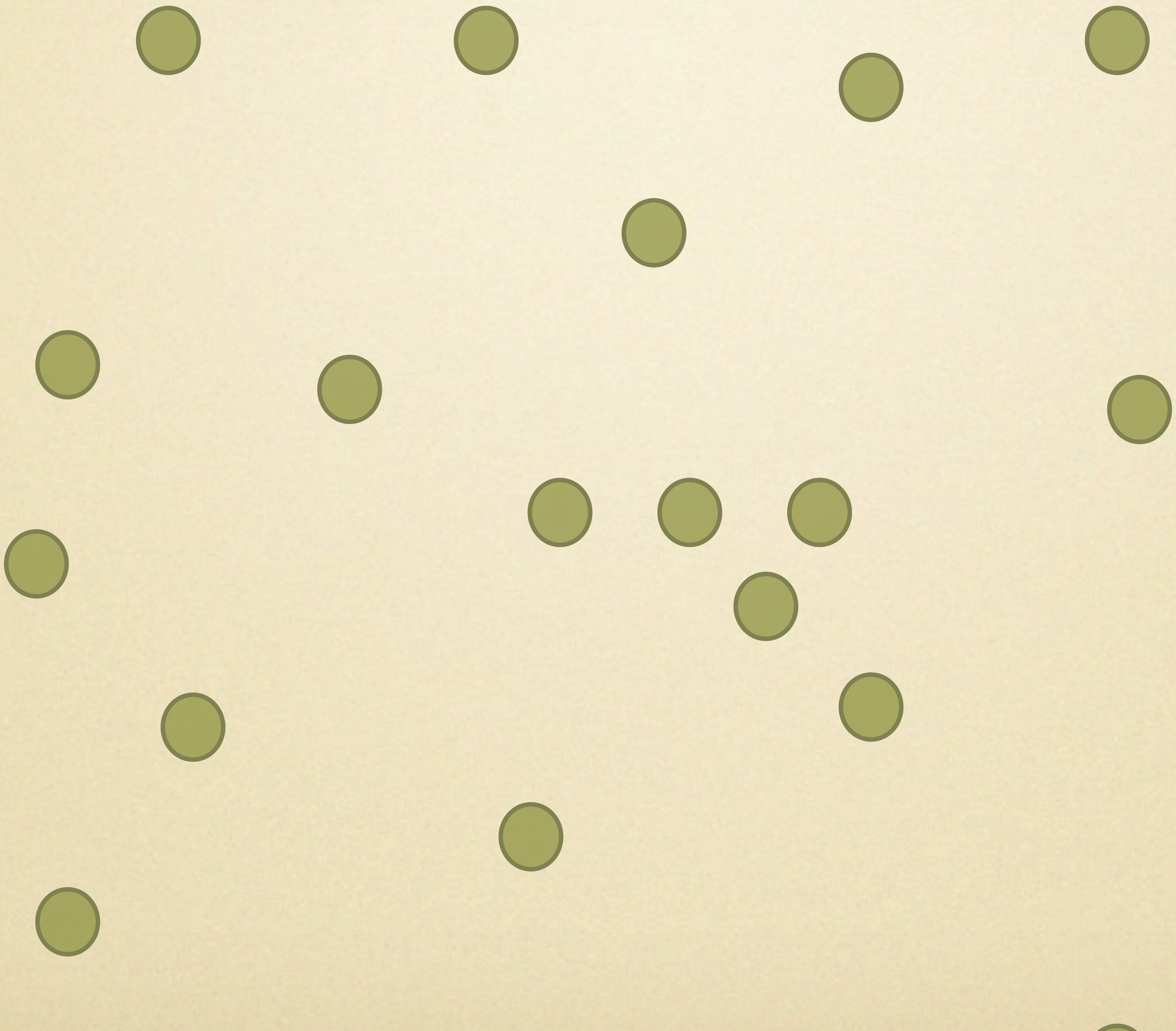
$\Delta t < 1/\Delta E$

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 !







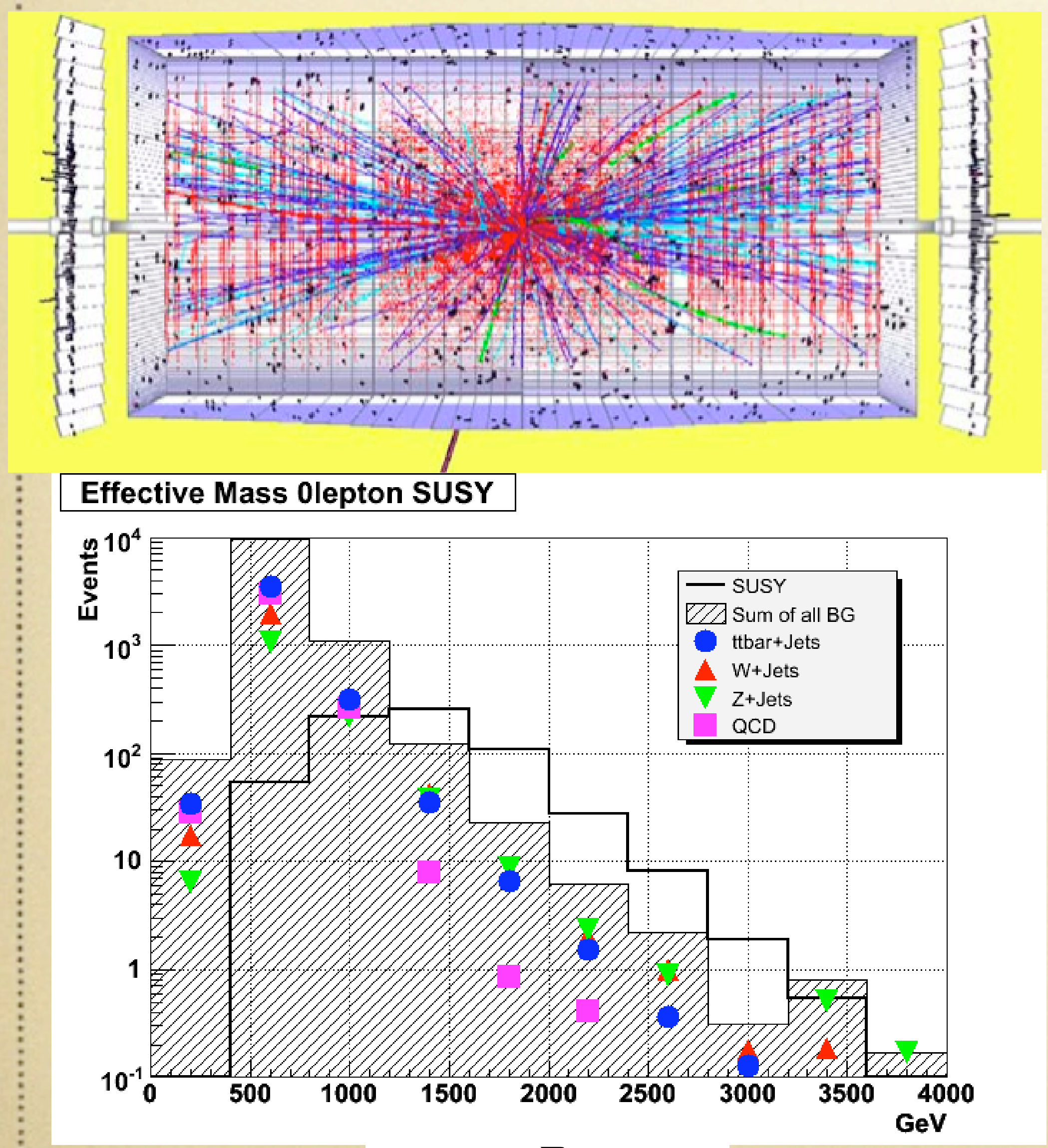
The future: the Large Hadron Collider (LHC)

The goals of the LHC

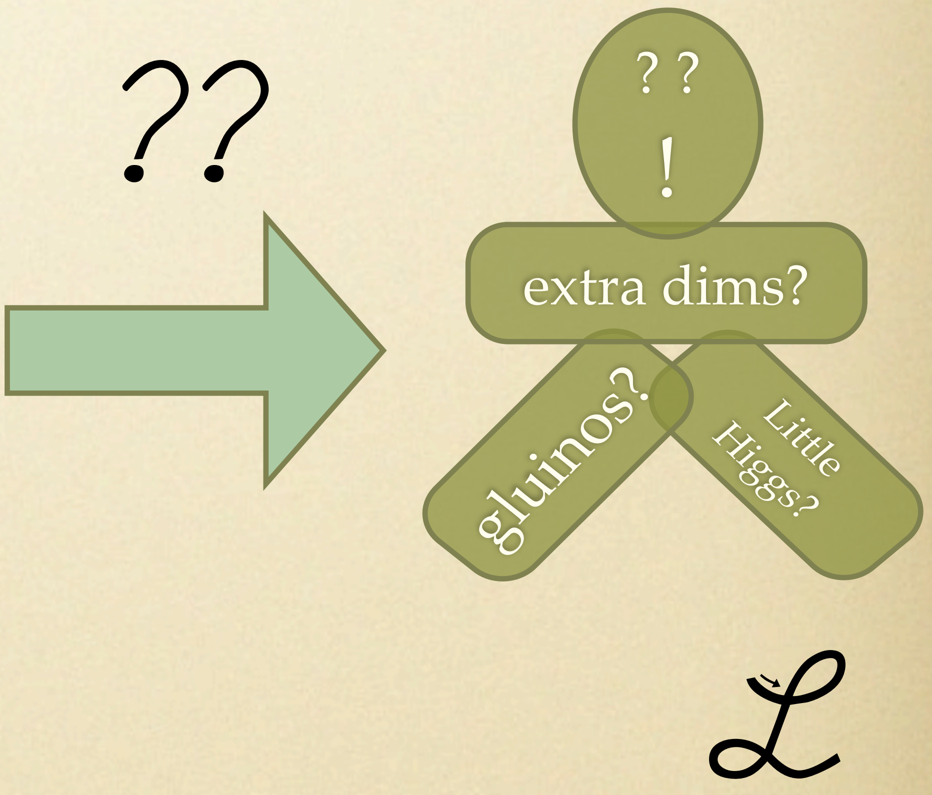
- To firmly establish the **"what"**:
  - discover the crucial missing element of the Standard Model, namely the **Higgs boson,** responsible for particles' masses
  - search for possible new fundamental interactions, too weak to have been observed so far
  - search for possible new generations of quarks 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



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



- **< 1973: theoretical foundations of the SM**
  - renormalizability of SU(2)xU(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

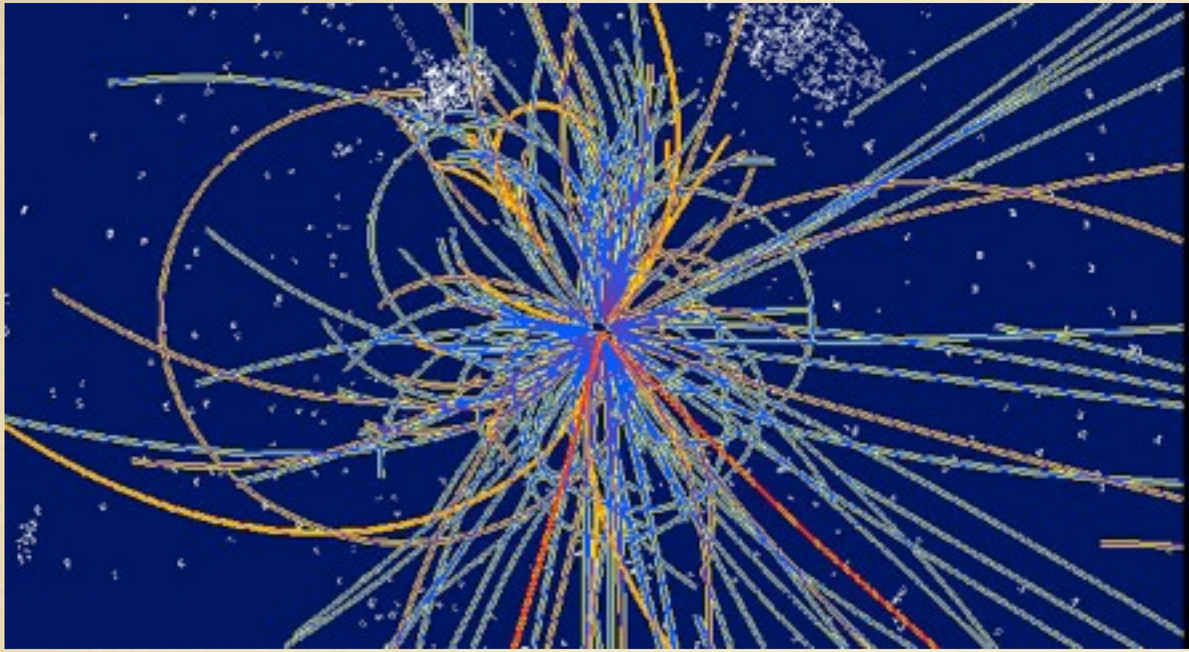
Neutrinos:	**Quarks:**	**Charged leptons:**
super beams	B factories	stopped μ
beta-beams	K factories	$\ell \rightarrow \ell'$ conversion
ν factory	n EDM	e/μ EDM

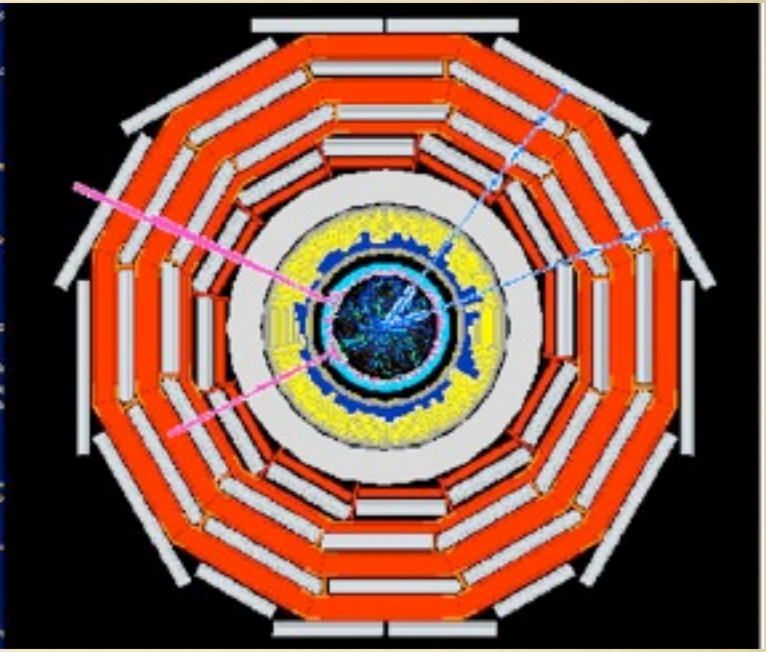
+ Astrophysics and cosmology

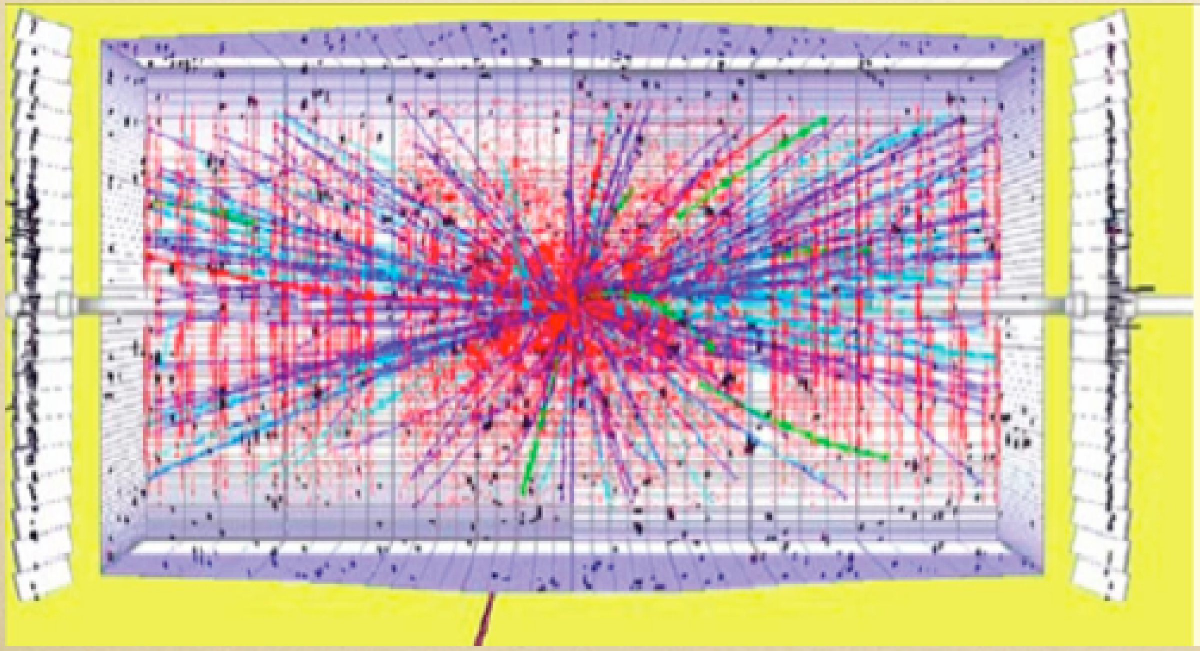
2015, a dream scenario

- SUSY is seen at LHC, with squarks/gluinos at ~ 1 TeV, weak sparticles at ~0.1 TeV
- Observe in parallel:
  - LHCb: $B_S \to \mu^+\mu^-$ at rates > SM, and NA62: $K^+ \to \pi^+ \nu\nu$ at rates > SM
  - MEG: $\mu \to e\gamma$
  - ILL/PSI: neutron EDM
  - large θ_{13} → measurable CP violation in nu mixing
- Z' at 2–2.5 TeV seen at LHC:
  - open decays to all SUSY sparticles => 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 !







Els focs artificials, 1922

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 SUCCESSFULL CAREER IN PHYSICS !!