Au dela de boson de Higgs

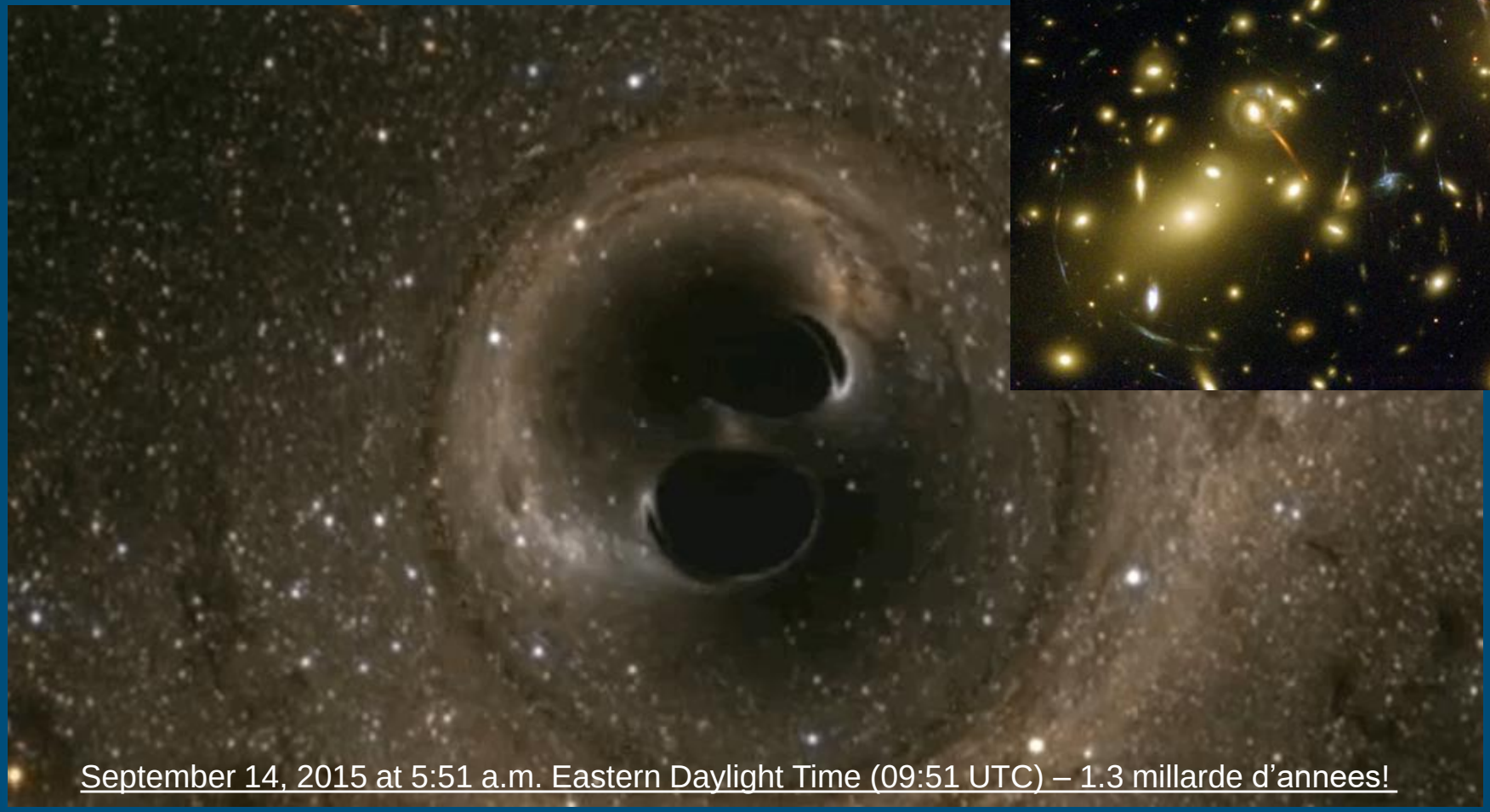
- Le Passé est le plus facile a prédire?-

R. Jacobsson
CERN

La decouverte de l'annee! (jusqu'a maintenant...)

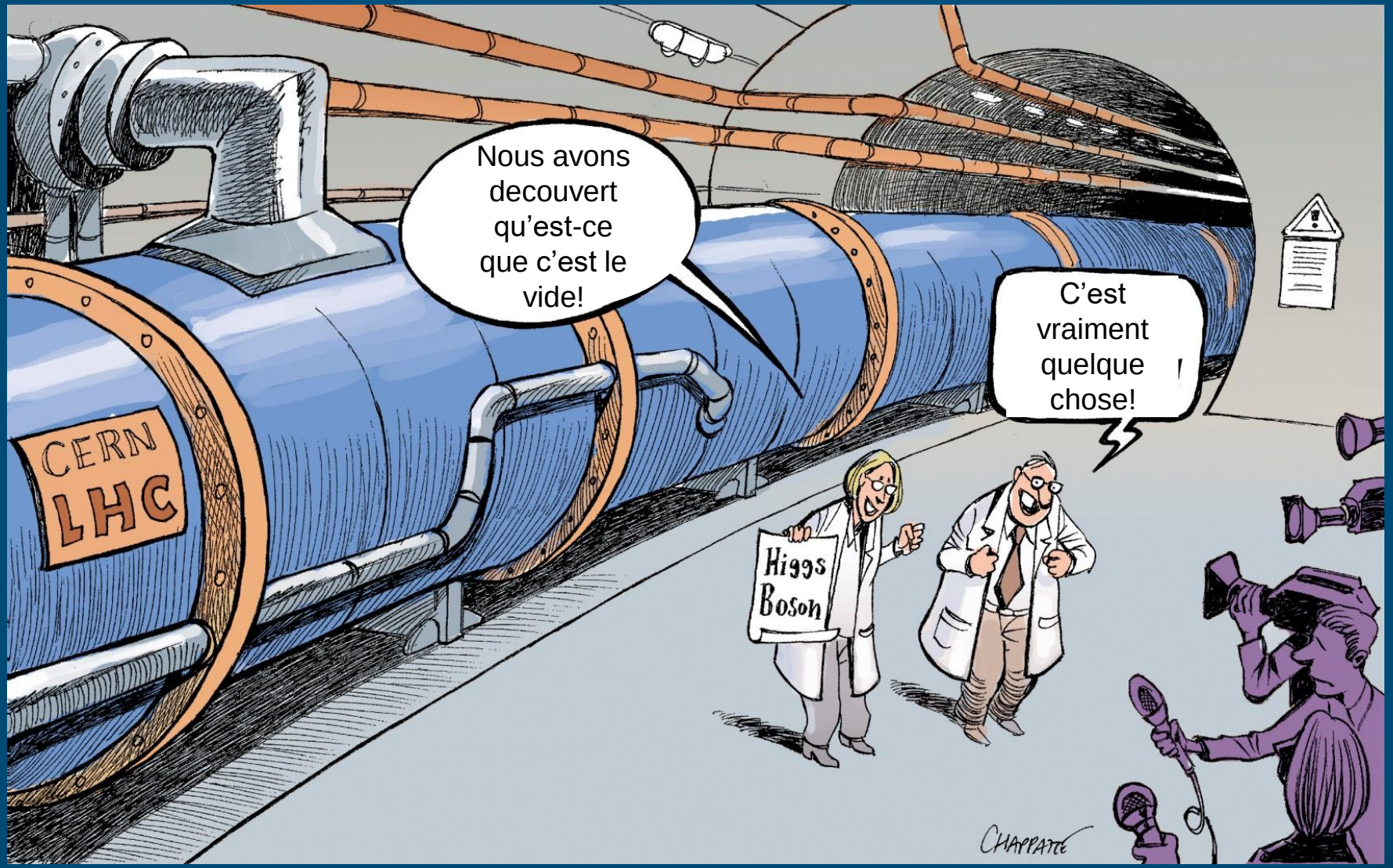
- We know there are some really cool things going on around us!

➔ For instance, the remarkable discovery of gravitational waves!



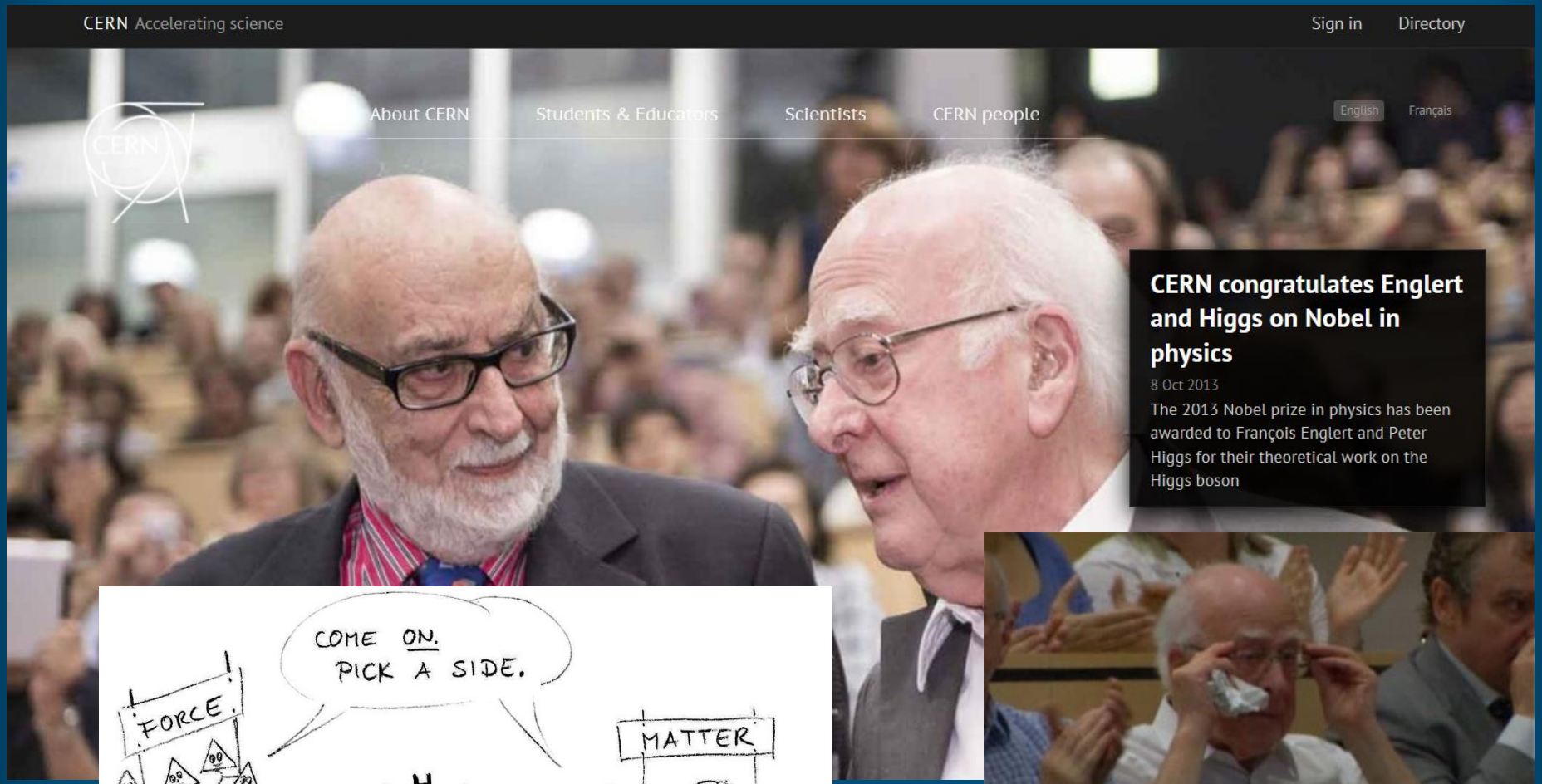
September 14, 2015 at 5:51 a.m. Eastern Daylight Time (09:51 UTC) – 1.3 millarde d'annees!

La decouverte de l'Annee 2012!



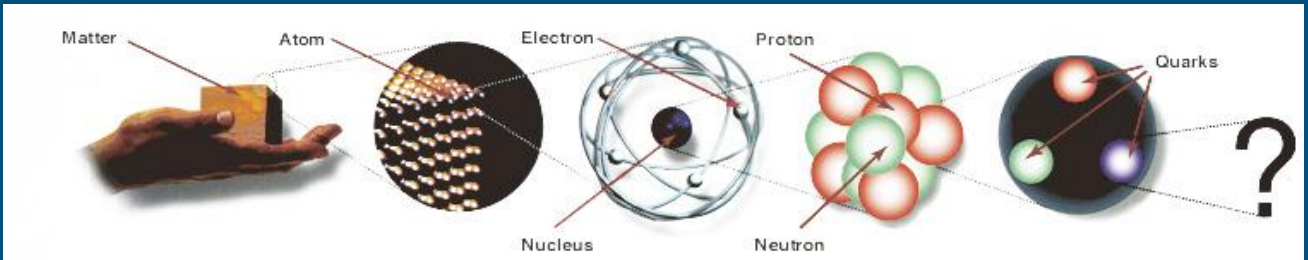
Prix Nobel 2013 !

- Rien de ce que nous avons vu jusqu'à aujourd'hui ressemble au boson de Higgs!



Qu'est-ce que la physique de particule?

- Une quête pour comprendre:
  - Les constituants fondamentaux de la matière- les particules de matière
  - Les interactions avec lesquelles les particules interagissent- Les interactions
  - Les particules qui propagent les interactions – les particules messagères



- But ultime:
  - La naissance de l'Univers, le Big Bang
  - Les Evolutions passées et futures

Limite de l'Univers qui peut être observé

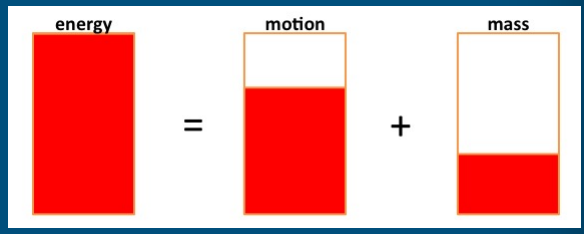
L'ingredient manquant - La "masse fondamentale"

"Masse fondamentale" = "Masse au repos"

- Pourquoi la "masse au repos" des particules matières est tellement importante?

$$Energie = masse * c^2$$

$$E^2 = masse^2 * c^4 + impulsion^2 * c^2 * c^2$$



➔ Sans la masse au repos, une particule se deplace toujours à la vitesse de la lumière!

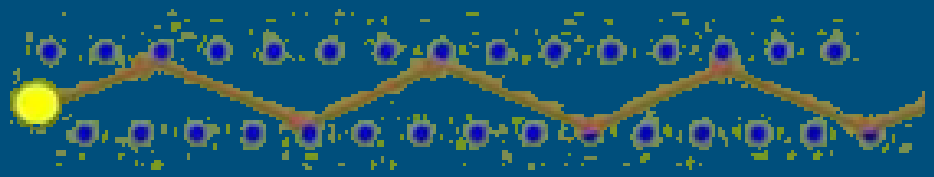
➔ Difficile de construire un Univers avec des objets complexes….

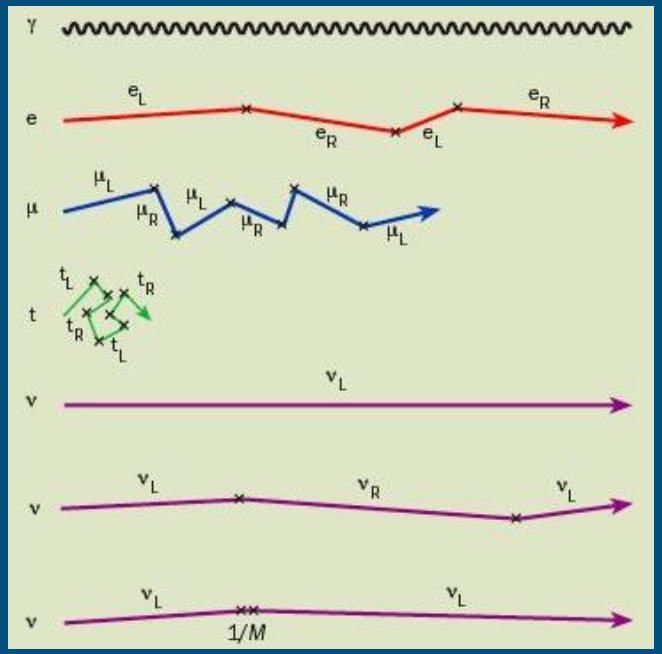
➔ Acquisition d'une propriété appelée "masse au repos" *est nécessaire* pour l'Univers

➔ Masse au repos n'a rien avoir avec une forme de solidité!

L'acquisition de masse

- La propriété perçue comme une masse au repos est acquise par un "champ" qui remplit l'espace vide comme un medium.
  - Le champ est present dans le vide, au contraire de toutes les autres interactions!
- L'interaction entre le champ et les particules, consiste en un échange d'un "boson"



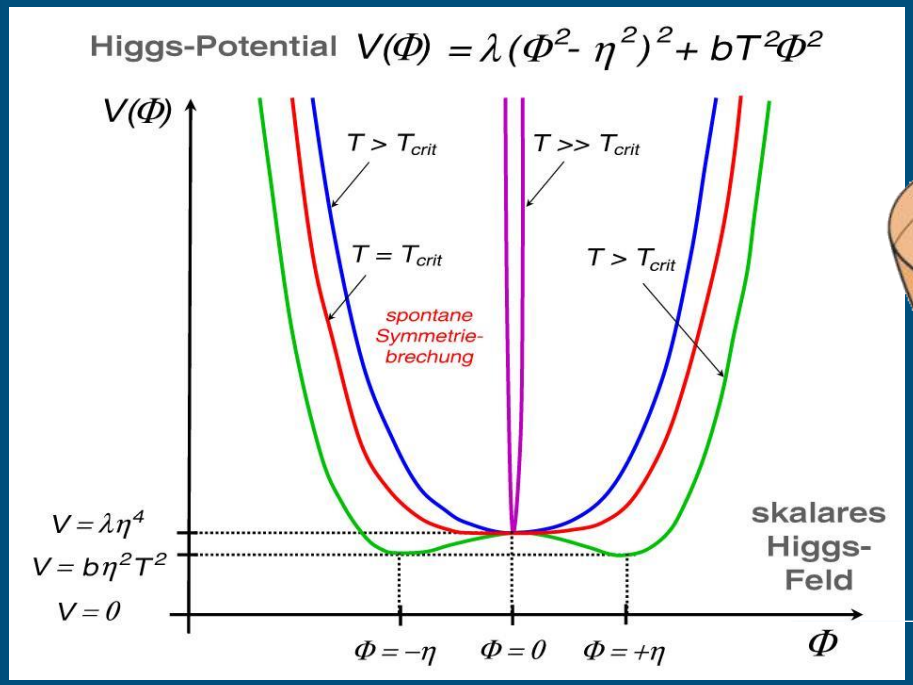


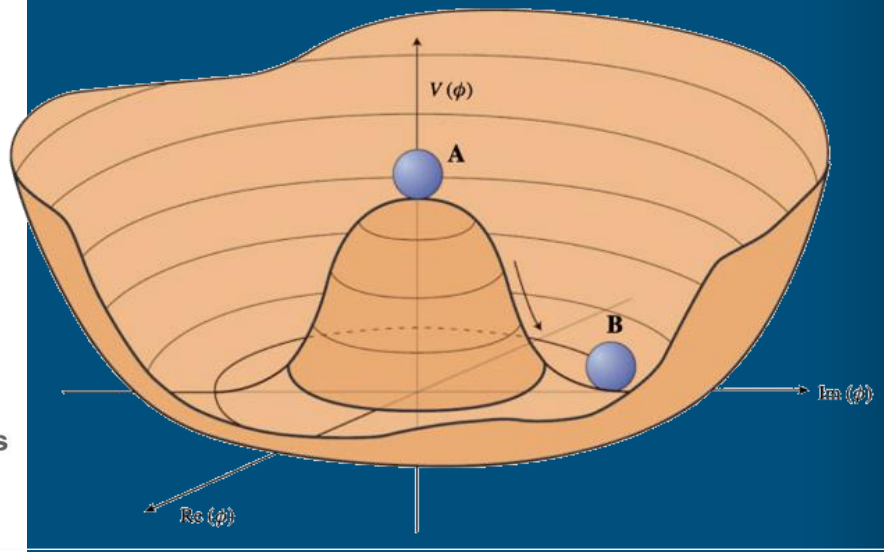
- Plus forte est l'interaction avec la particule, plus lourde est la masse
- Il faut que le champ produise une interaction "scalaire"
  - Les interaction sont invariables par rapport aux rotations
  - Le champ n'indique pas une direction préférée

Le champ

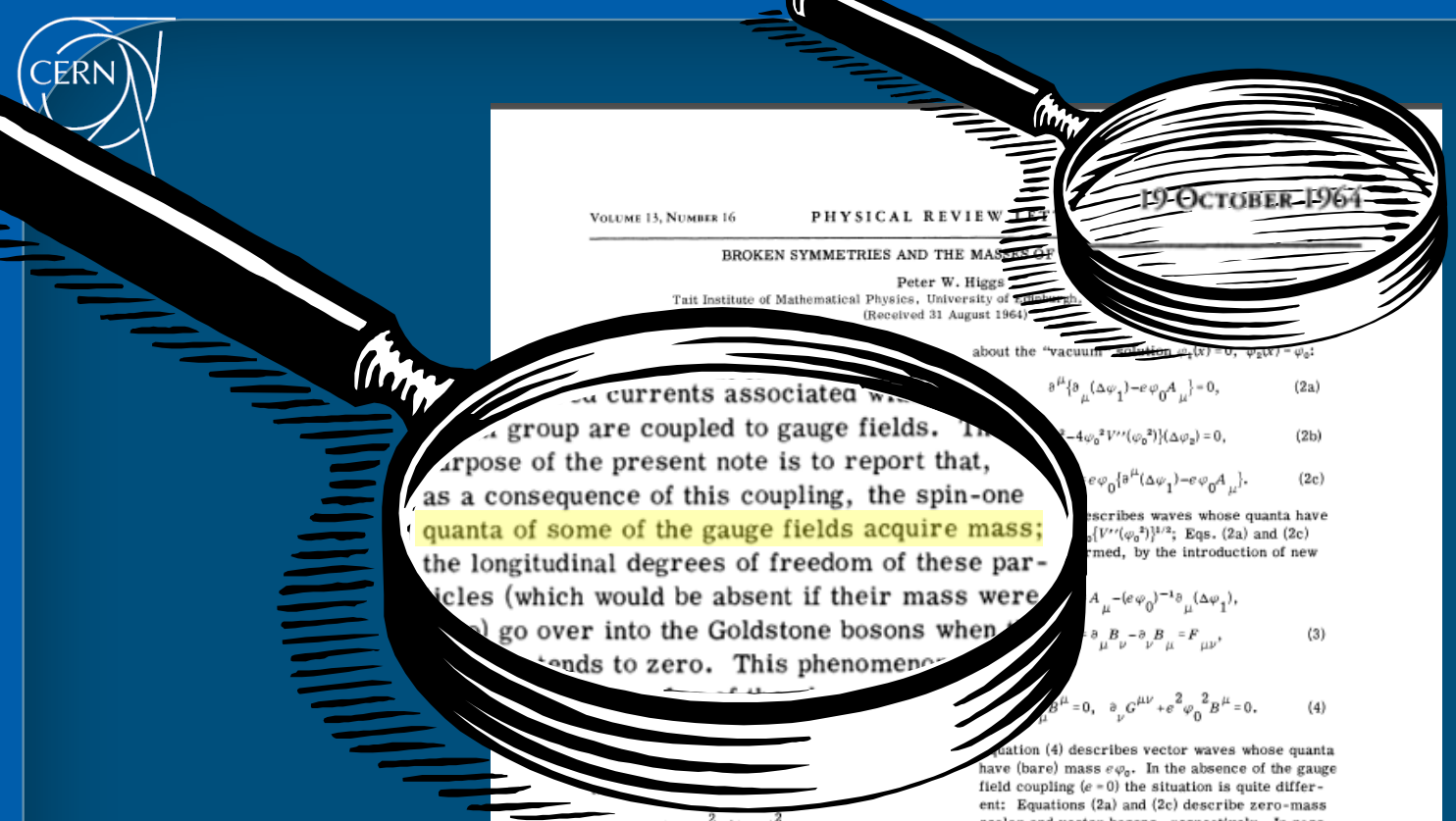
- Le champ d'interaction est née spontanément tout au debut de l'Univers avec le refroidissement du a l'expansion

➔ Tout d'abord, toutes les particules sont sans masse
➔ Avec l'apparition du champ certaines obtiennent la propriété, d'autres non





➔ Voilà, la proposition de Brout-Englert-Higgs en 1964 !



VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh
(Received 31 August 1964)

currents associated w
group are coupled to gauge fields. T
rpose of the present note is to report that,
as a consequence of this coupling, the spin-one
quanta of some of the gauge fields acquire mass;
the longitudinal degrees of freedom of these par-
icles (which would be absent if their mass were
) go over into the Goldstone bosons when
ends to zero. This phenomen

about the "vacuum" solution $\varphi_1(x)=0$, $\varphi_2(x)=\varphi_0$:

$$\partial^\mu\{\partial_\mu(\Delta\varphi_1)-e\varphi_0 A_\mu\}=0, \quad (2a)$$

$$\{\partial^2-4\varphi_0^2V''(\varphi_0^2)\}(\Delta\varphi_2)=0, \quad (2b)$$

$$e\varphi_0\{\partial^\mu(\Delta\varphi_1)-e\varphi_0 A_\mu\}. \quad (2c)$$

escribes waves whose quanta have
$\{V''(\varphi_0^2)\}^{1/2}$; Eqs. (2a) and (2c)
rmed, by the introduction of new

$$A_\mu-(e\varphi_0)^{-1}\partial_\mu(\Delta\varphi_1),$$

$$\partial_\mu B_\nu-\partial_\nu B_\mu=F_{\mu\nu}, \quad (3)$$

$$\partial_\mu B^\mu=0, \quad \partial_\nu G^{\mu\nu}+e^2\varphi_0^2 B^\mu=0. \quad (4)$$

gation (4) describes vector waves whose quanta have (bare) mass $e\varphi_0$. In the absence of the gauge field coupling ($e=0$) the situation is quite different: Equations (2a) and (2c) describe zero-mass scalar and vector bosons, respectively. In passing, we note that the right-hand side of (2c) is just the linear approximation to the conserved current: It is linear in the vector potential, gauge invariance being maintained by the presence of the gradient term.[5]

When one considers theoretical models in which spontaneous breakdown of symmetry under a semisimple group occurs, one encounters a variety of possible situations corresponding to the various distinct irreducible representations to which the scalar fields may belong; the gauge field always belongs to the adjoint representation.[6] The model of the most immediate interest is that in which the scalar fields form an octet under SU(3): Here one finds the possibility of two nonvanishing vacuum expectation values, which may be chosen to be the two $Y=0$, $I_3=0$ members of the octet.[7] There are two massive scalar bosons with just these quantum numbers; the remaining six components of the scalar octet combine with the corresponding components of the gauge-field octet to describe

$$L=-\tfrac{1}{2}(\nabla\varphi_1)^2-\tfrac{1}{2}(\nabla\varphi_2)^2$$
$$-V(\varphi_1^2+\varphi_2^2)-\tfrac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (1)$$

where

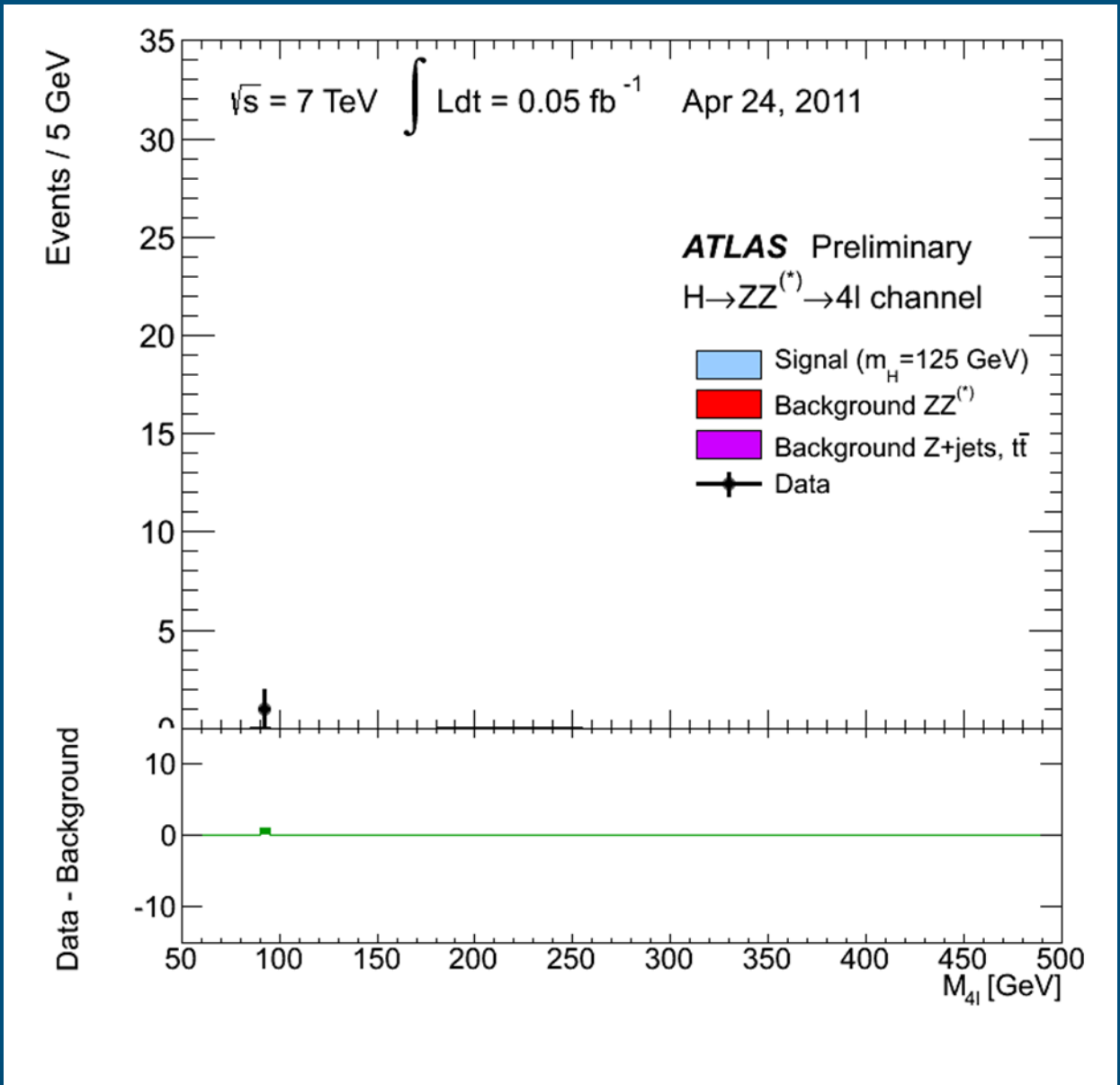
$$\nabla_\mu\varphi_1=\partial_\mu\varphi_1-eA_\mu\varphi_2,$$

$$\nabla_\mu\varphi_2=\partial_\mu\varphi_2+eA_\mu\varphi_1,$$

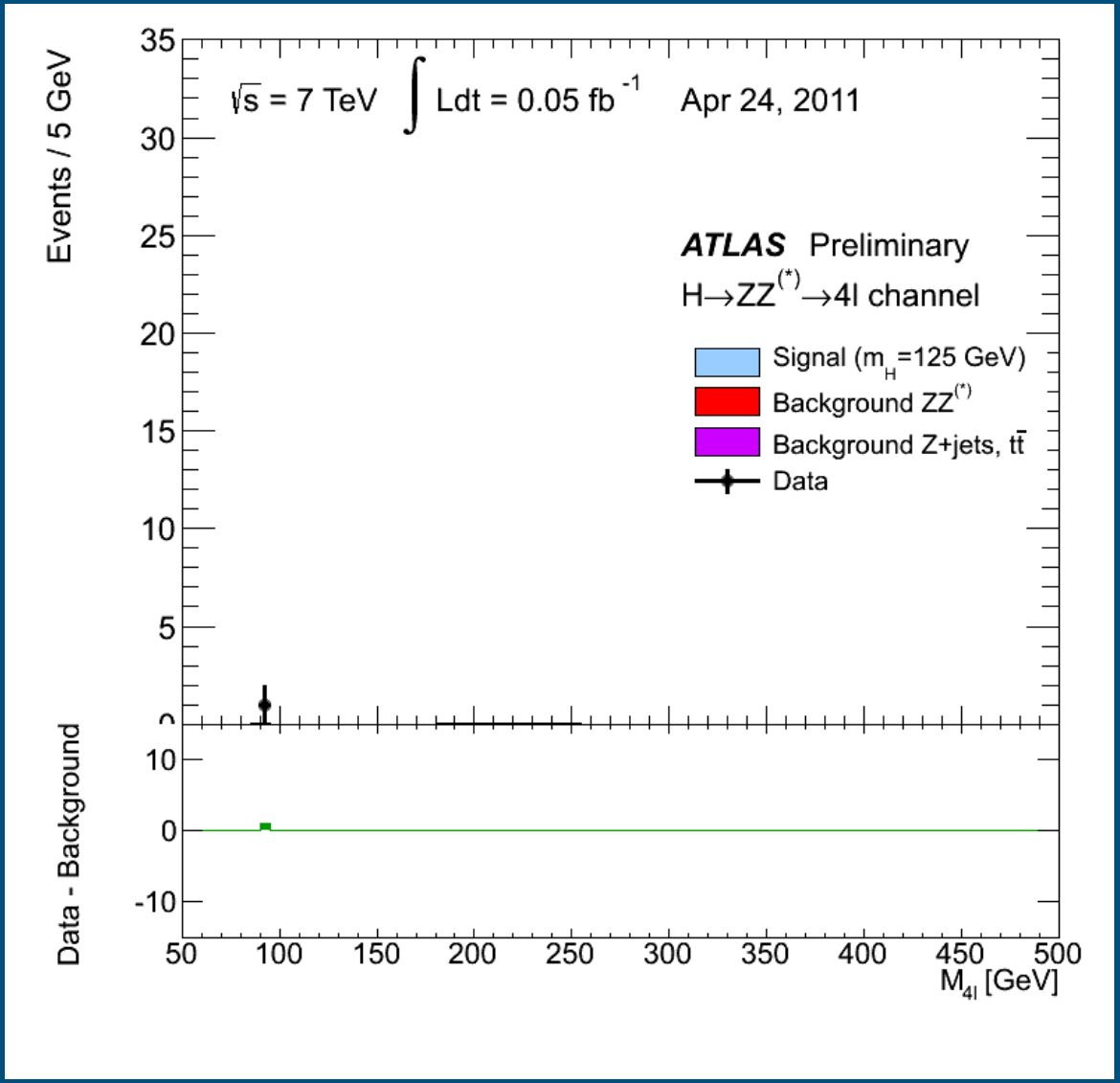
$$F_{\mu\nu}=\partial_\mu A_\nu-\partial_\nu A_\mu,$$

e is a dimensionless coupling constant, and the metric is taken as $-+++$. L is invariant under simultaneous gauge transformations of the first kind on $\varphi_1\pm i\varphi_2$ and of the second kind on A_μ. Let us suppose that $V'(\varphi_0^2)=0$, $V''(\varphi_0^2)>0$; then spontaneous breakdown of U(1) symmetry occurs. Consider the equations [derived from (1) by treating $\Delta\varphi_1$, $\Delta\varphi_2$, and A_μ as small quantities] governing the propagation of small oscillations

2011 - 2012


√s = 7 TeV ∫ Ldt = 0.05 fb-1 Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Events / 5 GeV
Data - Background
M4l [GeV]

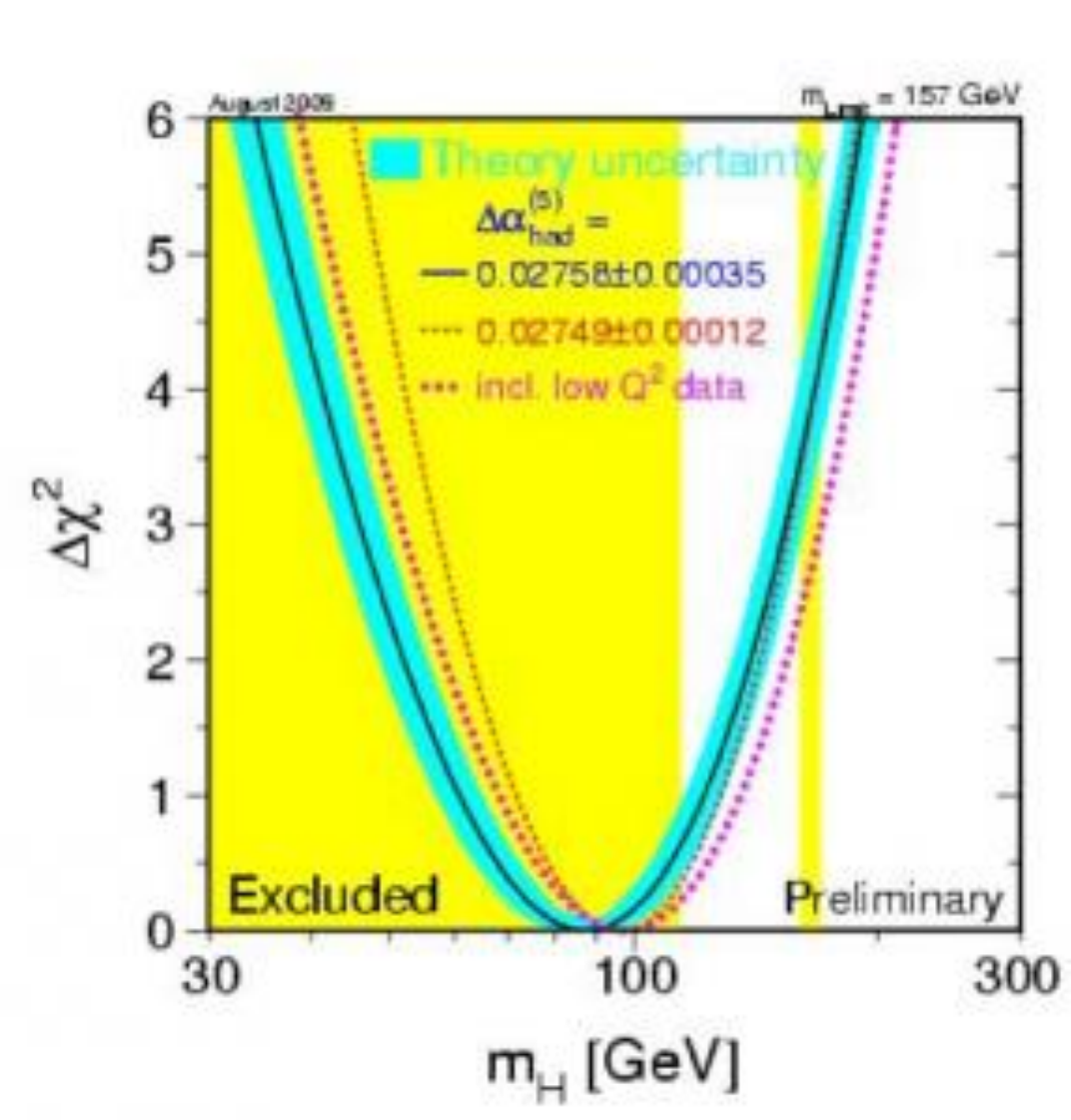
2011 – 2012 !



- La masse de Higgs egale a la masse de l'ensemble de 130 proton!

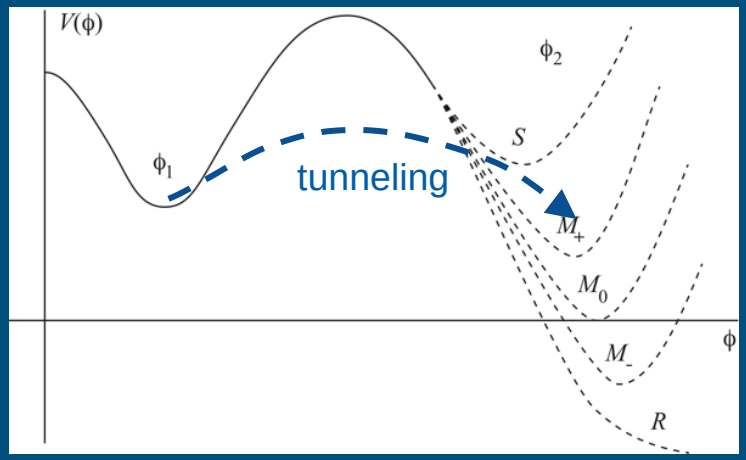
Mais on “savait” un peu pres...!

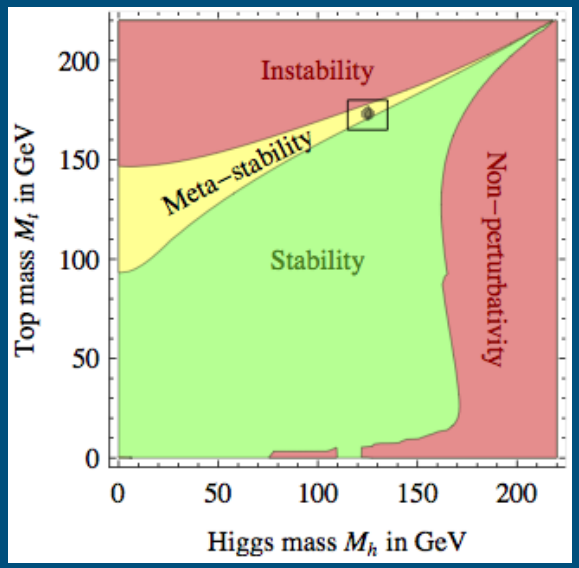
- August 2009!



(Est-ce que le vide (de l'Univers) est stable?)

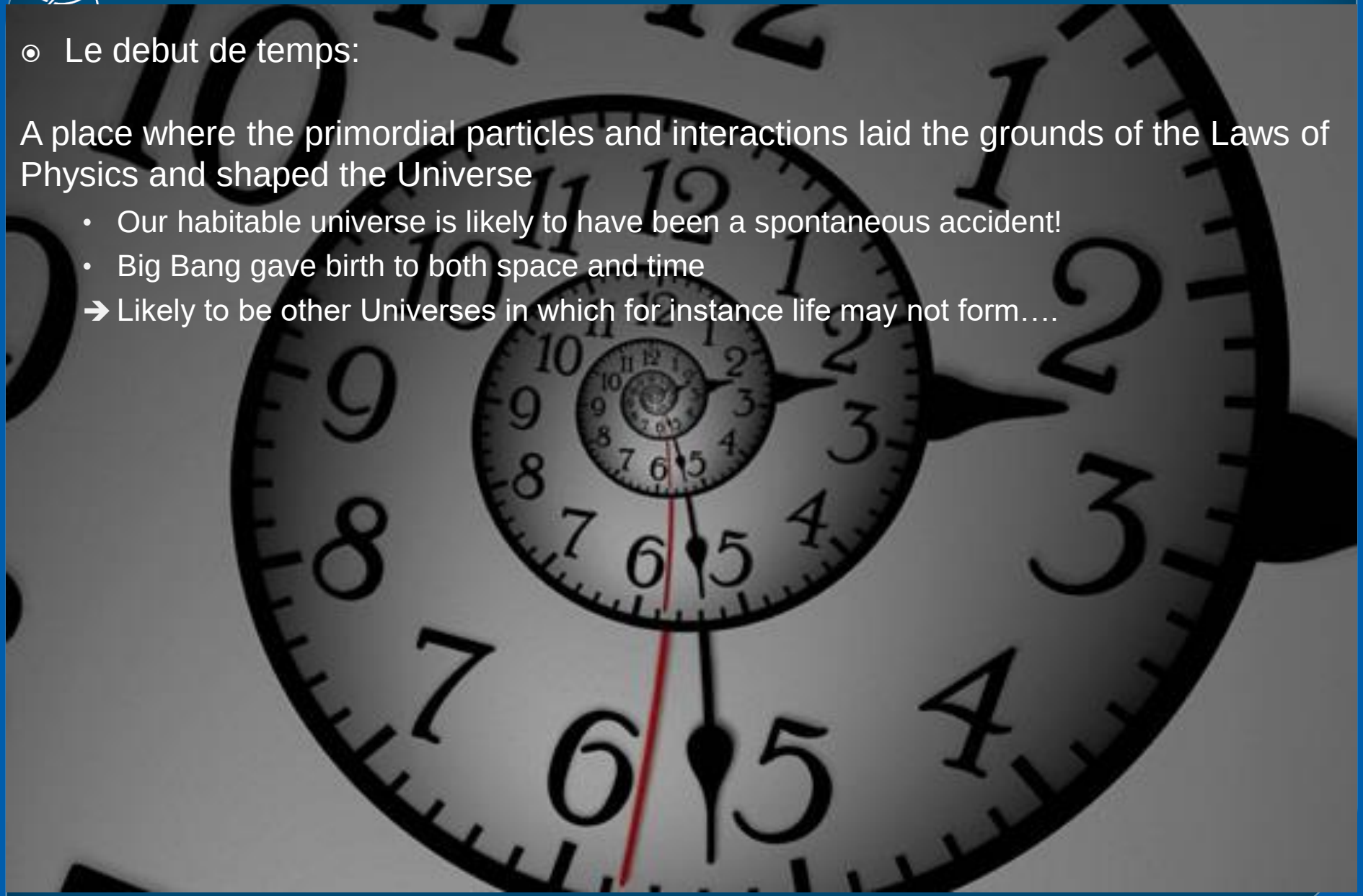
- L'incroyable hazard!
  - Probablement, juste, juste, juste avec une marge d'un cheveu
  - Et forcement…. ça s'est passé, vu que nous sommes ici pour en parler!





- Sinon:
  - Une bulle de vrai vide pourrait etre semée quelquepart et s'étendre ….
  - L'effet d'une bulle grandissant du point de l'espace-temps où il a commencé, prend plutôt du temps vu la taille actuelle de l'Univers
  - Les structures, les particules et les forces actuelles seraient perdues et remplacées par une version différente des mêmes champs de quantum.

Qu'est-ce que nous avons appris?



- Le debut de temps:

A place where the primordial particles and interactions laid the grounds of the Laws of Physics and shaped the Universe

- Our habitable universe is likely to have been a spontaneous accident!
- Big Bang gave birth to both space and time

➔ Likely to be other Universes in which for instance life may not form….

Qu'est-ce que nous savons sur l'Univers?

L'echelle TeV

10^{27} K — L'Unives a commence comme une soupe tres chaude et tres dense d'energie et des particules.

Les particules obtiennent leurs masses

10^{15} K — L'Univers qui est en expansion rapide a deja un exces de la matiere par rapport a l'antimetieree, et des petites variation de densite.

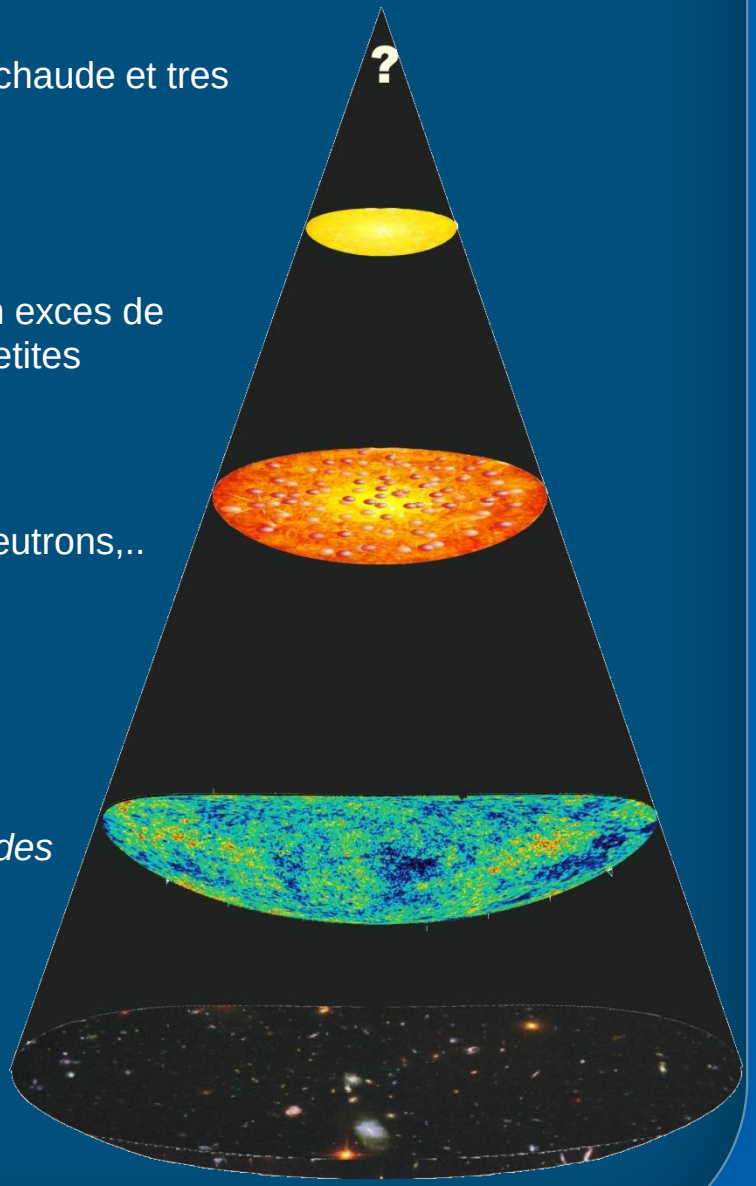
10^{12} K — 0.000000000001 sec

10^{9} K — La soupe des quark se condense en protons, neutrons,.. — 0.00001 sec

10^{6} K — Les premiers nouyeux legers sont formes — 1 min

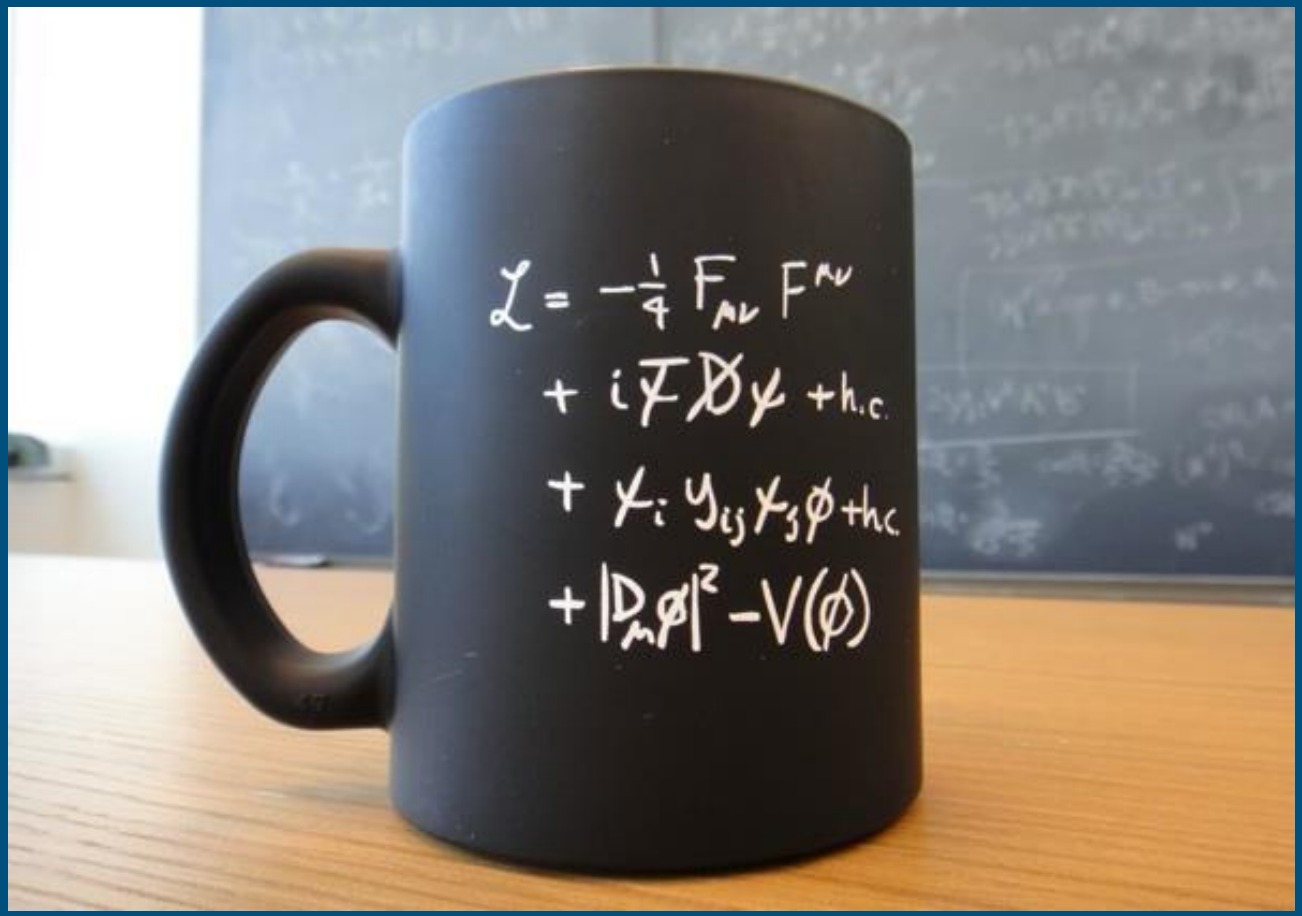
10^{3} K — Les atoms sont formes
Cet etape marque la frontiere entre l'utilisation des telescope et des accelerateurs — 380 000 yrs

2.7 K — Les resultats recents nous montre que nous connaisson seulement 4% da la composition de l'Univers, et que son expansion est en acceleration — 13.7 billion yrs



L'Univers à 0 K – 10^{15}K en une seule formule?

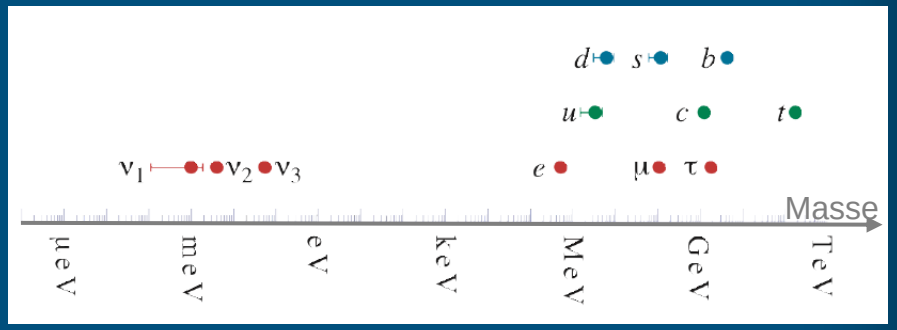
- Pas mal! C'est si simple que ça, ou…?



Les questions fondamentales 1

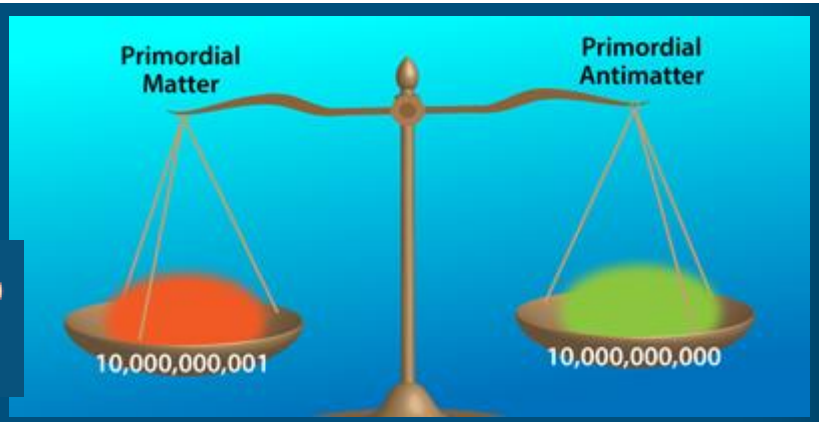
"Evidences" experimentals:

- Les masses et oscillations des neutrinos

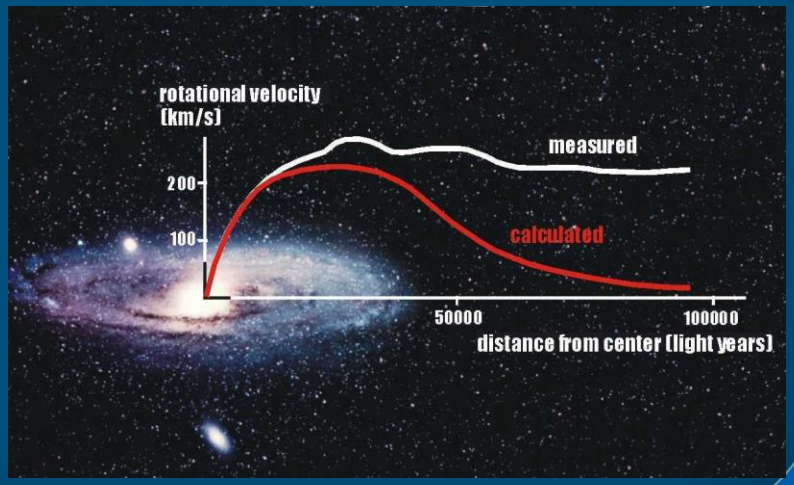


- Absence de l'antimatiere
  - → BBN and CMB

$$\eta = \left\langle \frac{n_B}{n_\gamma} \right\rangle_{T=3K} \sim 6 \times 10^{-10}$$



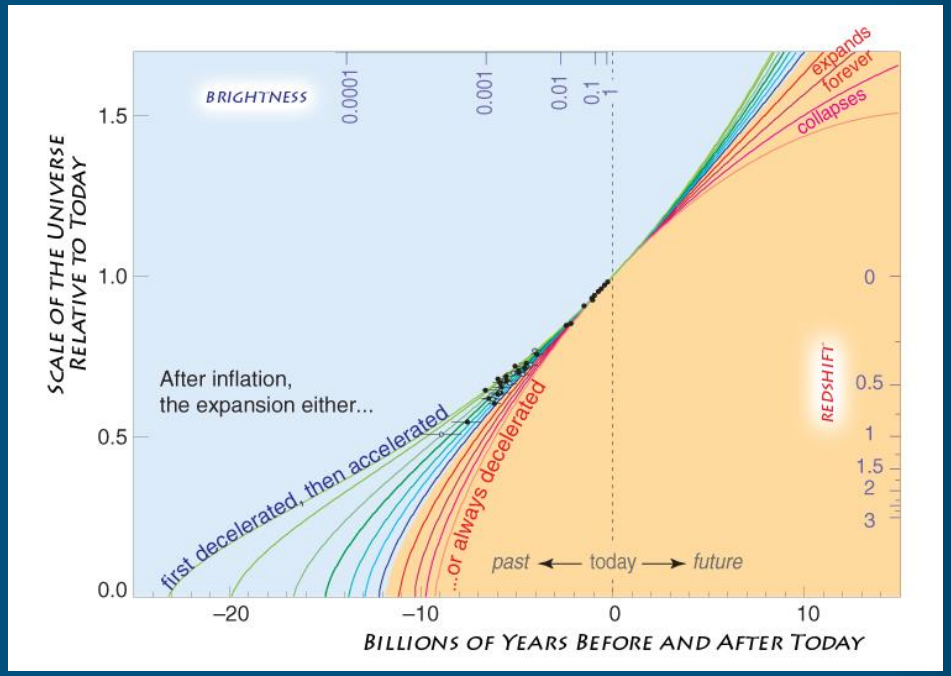
- Matiere noire

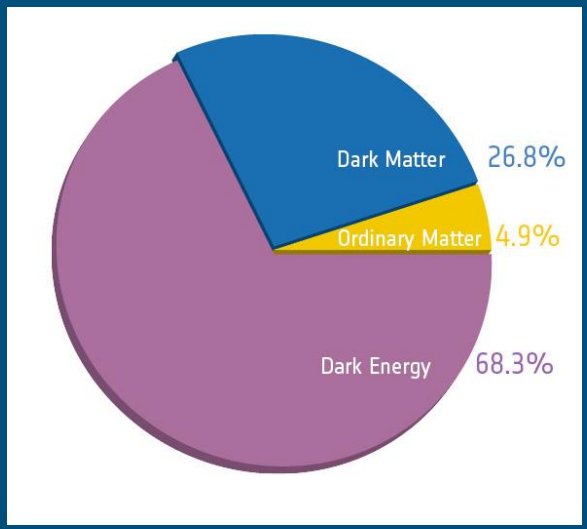


Les questions fondamentales 2

"Evidences" experimentals:

- Energie noire
  - → From apparent luminosity-distance observations of supernovae



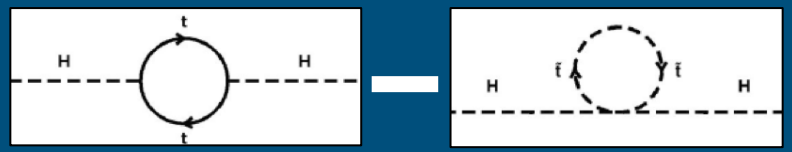


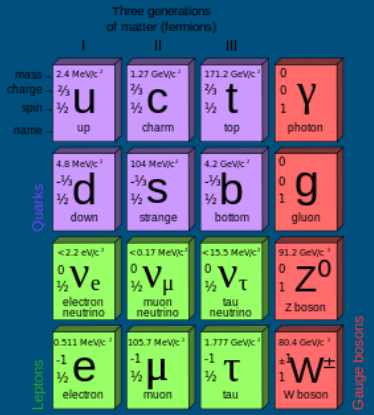
➔ Le budget matiere-energie dans l'univers!

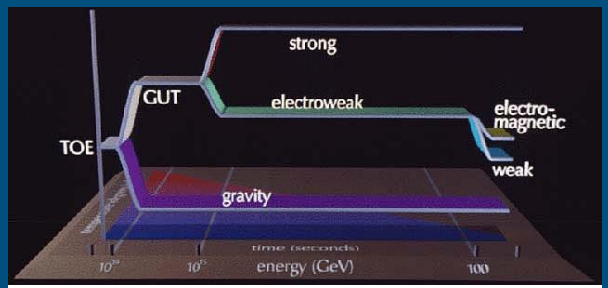
Les questions fondamentales 3

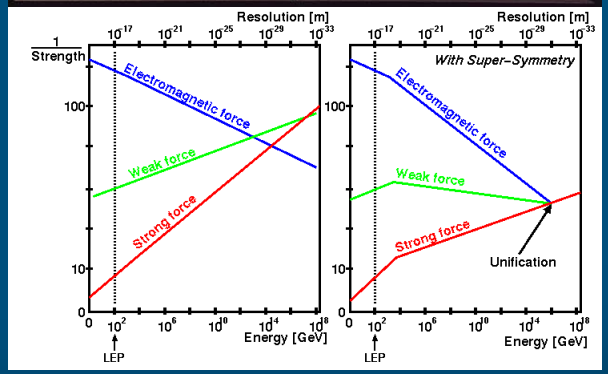
"Evidences" theoriques:

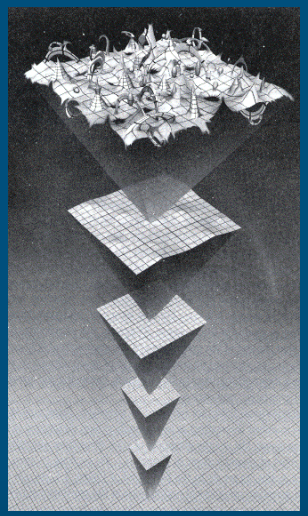
- Stabilite de la masse de Higgs
- Les generations de quarks et leptons
- Unification des interactions
- Gravitation
- Etc…





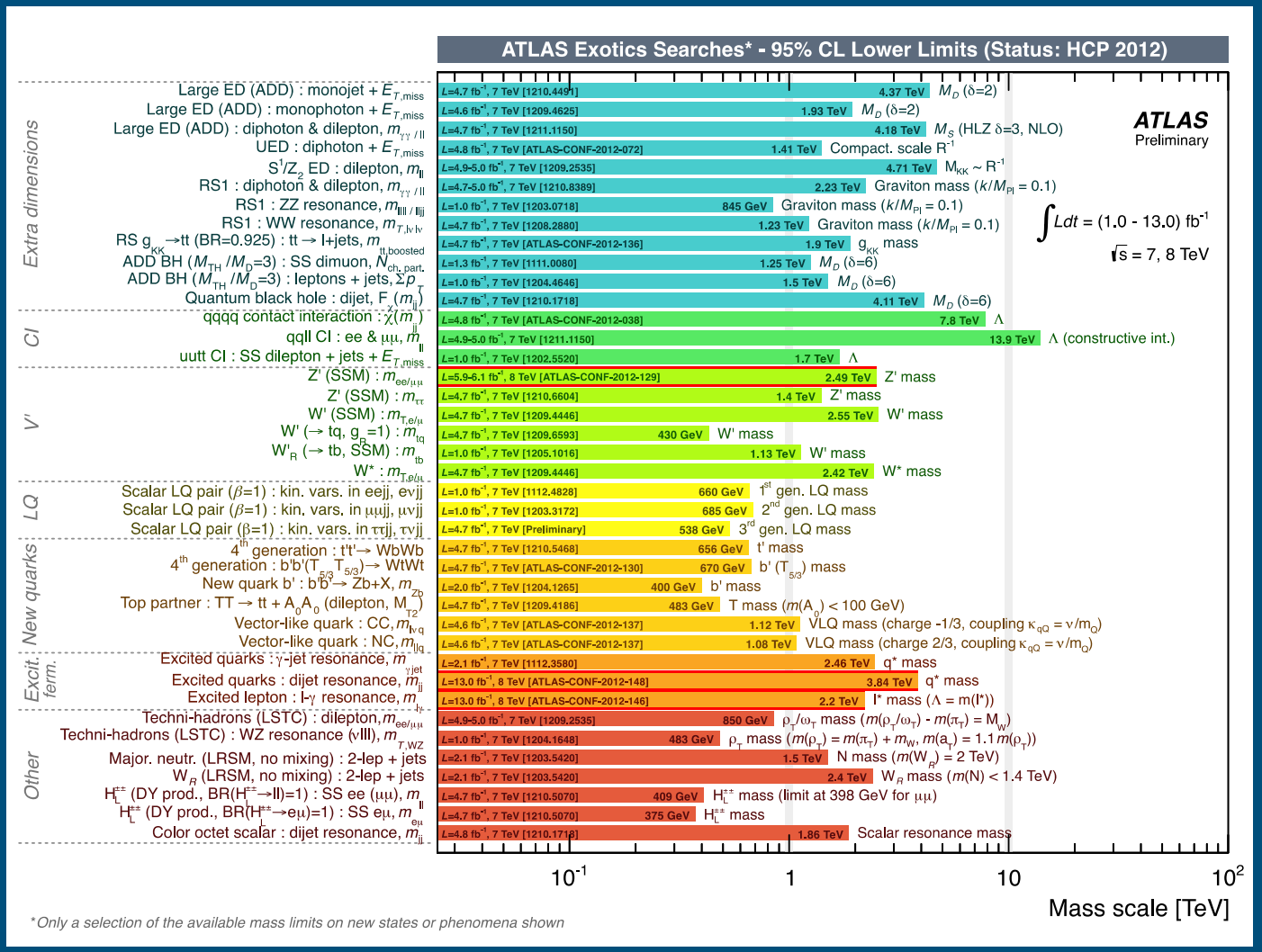






La situation actuelle!

“where is everybody?”



Heisenberg Uncertainty Principle

- A tiny little complication though…. with astronomic consequences:

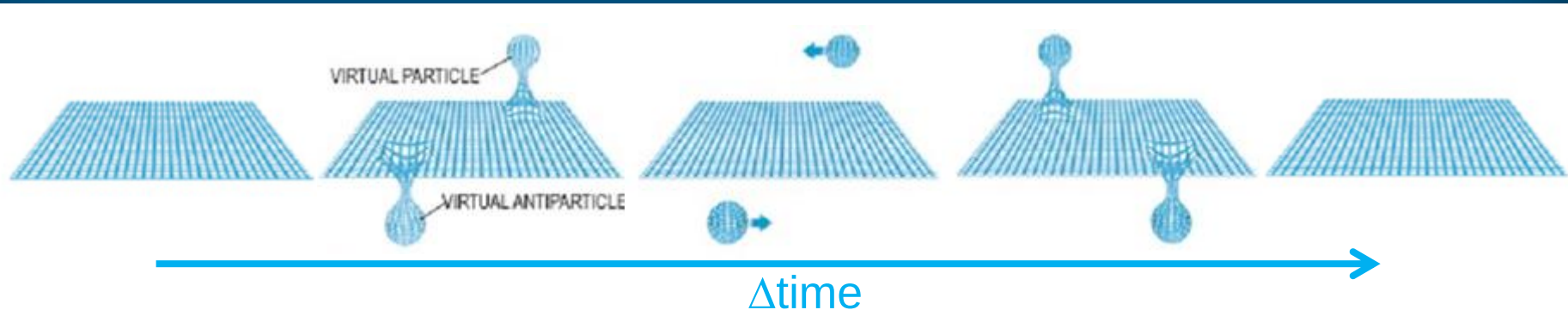
➔ Nature has built in an unavoidable intrinsic randomness:

$$\Delta p \Delta x \leq \frac{h}{2\pi} \qquad \Delta E \Delta t \leq \frac{h}{2\pi} \; ; \; \frac{h}{2\pi}$$

➔

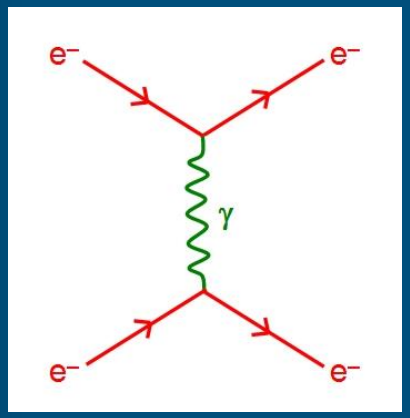
$$\Delta E \leq \frac{h}{2\pi \Delta t}$$

- Vacuum fluctuation = vacuum polarization = virtual particle creation (many names..)

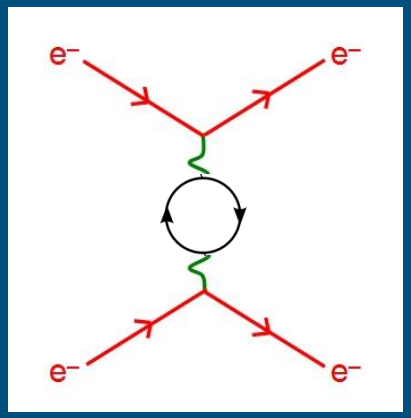


Heisenberg and virtual particles

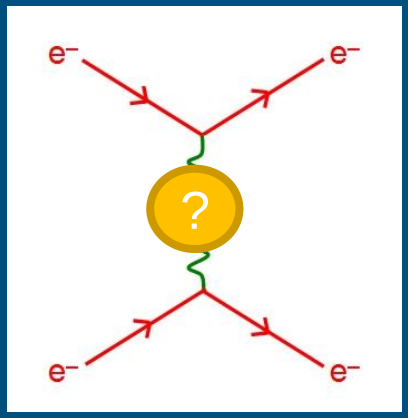
- In an example: electron – electron scattering (electromagnetic "repulsion" simply:



but also



but also…



➔ Gives nature several ways to do the same thing!

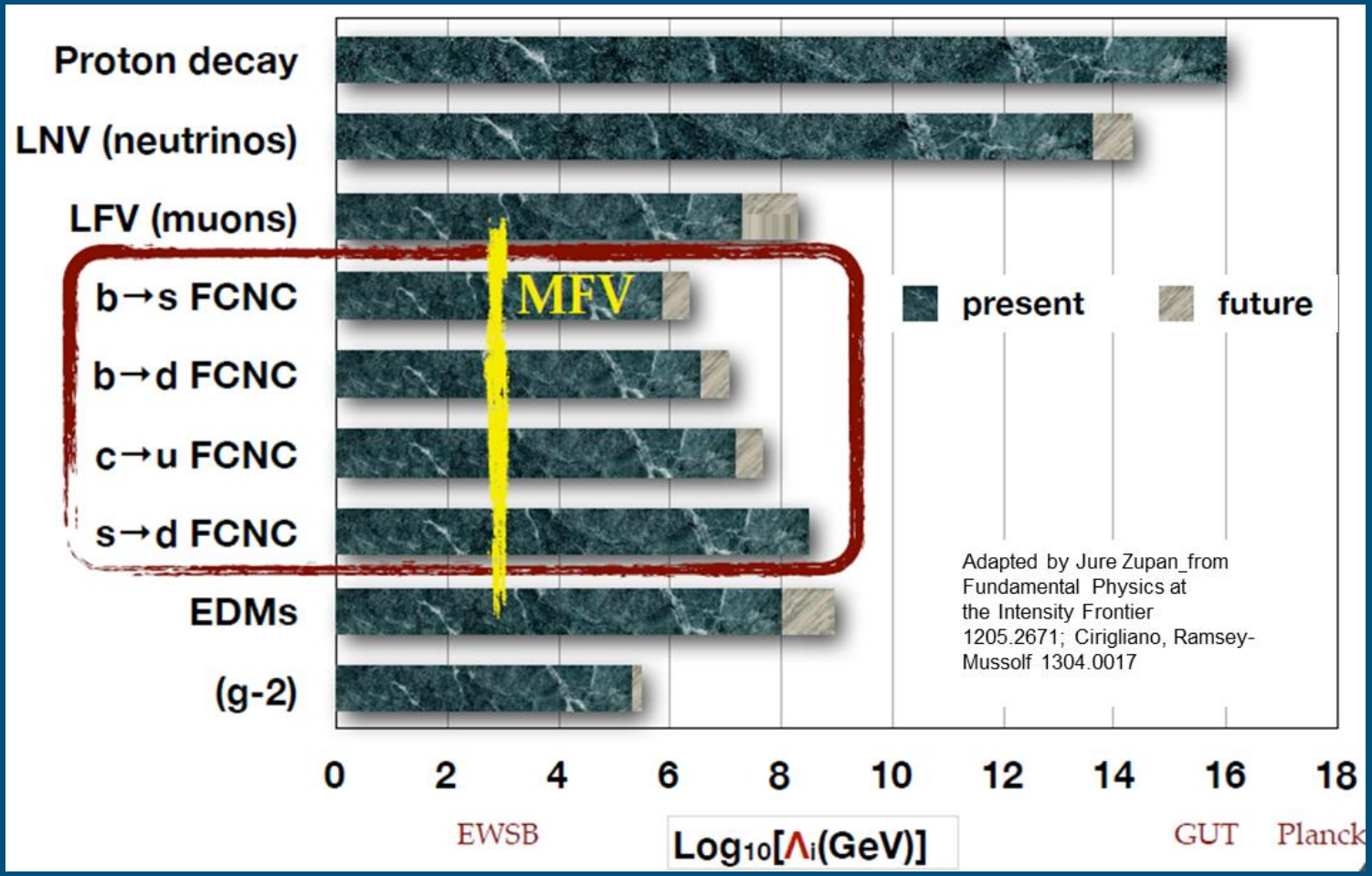
- Probability (strength) of interaction is sum of both possibilities
  - But any of the known particles can be in the loop.
  - Actually any of UNKNOWN particles can appear in there and modify the strength

➔ Allows measure precisely effect of new physics beyond the current knowledge and beyond reachable energy!!!

➔ It's a tool to search for the physics beyond current knowledge

$$\Phi_s^{exp} = \Phi_s^{SM} + \Phi_s^{NP}$$

La situation actuelle!

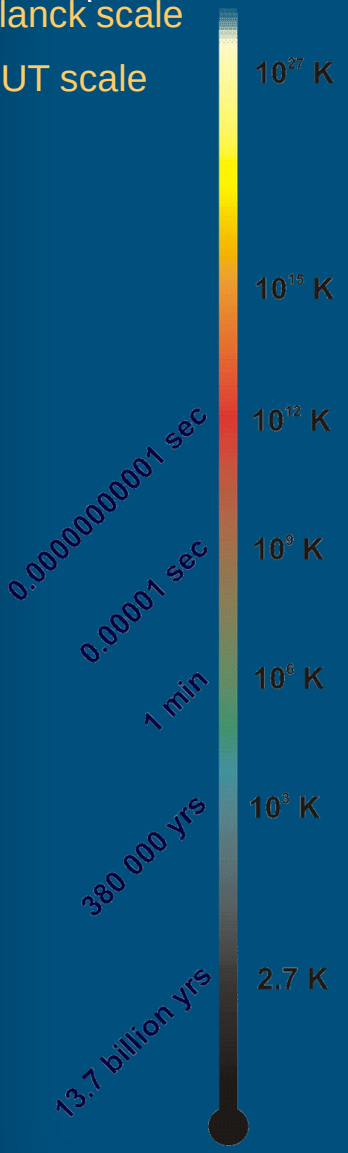


Pour la première fois,
nous ne disposons pas
d'une indication non ambigu
où trouver les réponses!...

Validity of Standard Model

Planck scale

GUT scale



New Physics
(SUSY, extra dimensions, GUT, …)

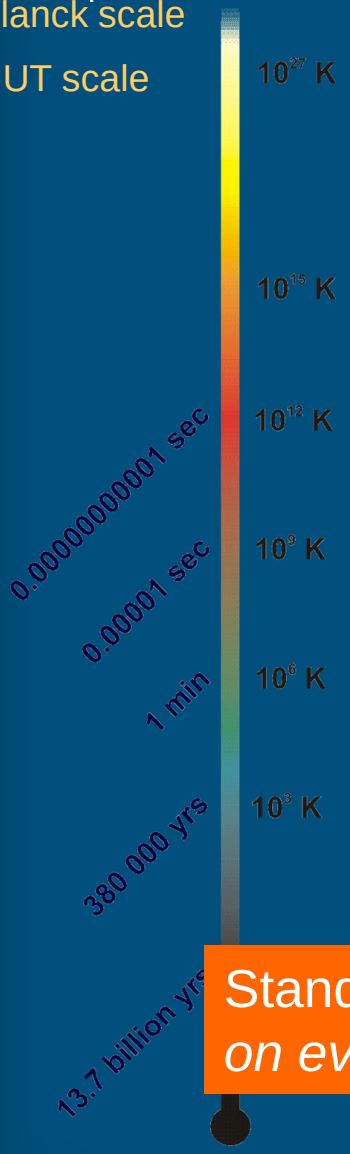
Standard Model

What we thought, or *hoped….*
And still do…

Validity of Standard Model

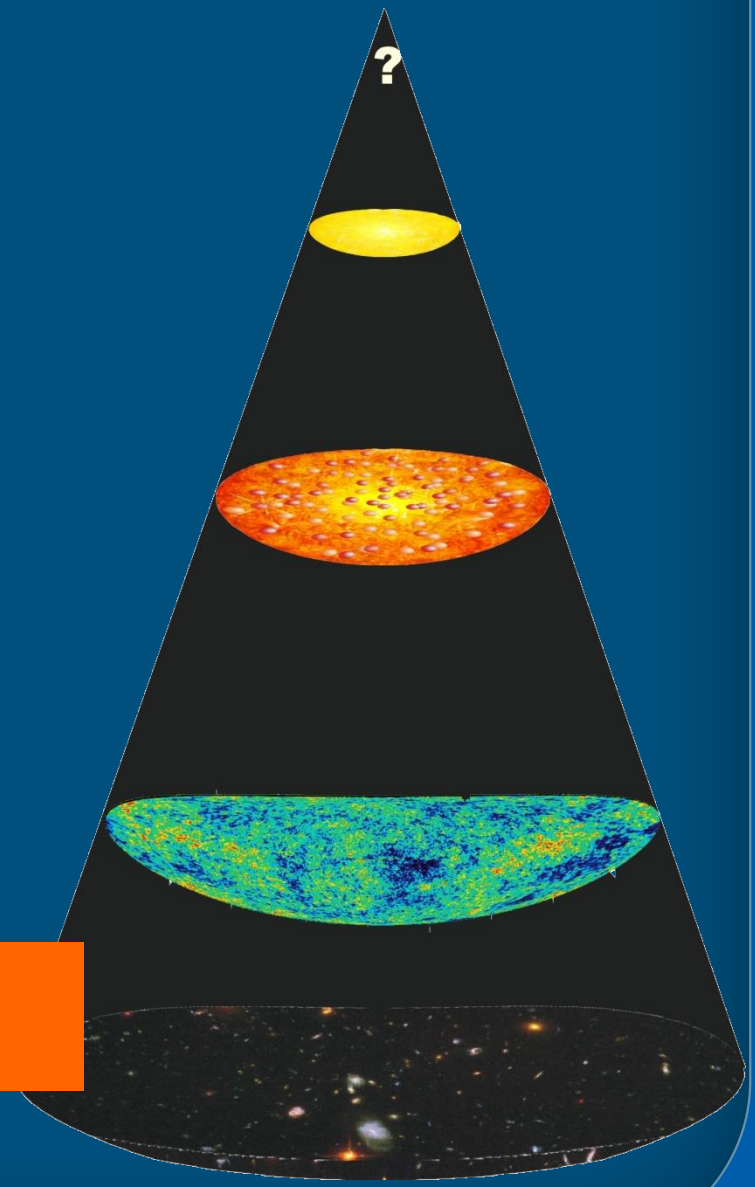
Planck scale

GUT scale



New Physics

Standard Model



Standard Model works perfectly well
on everything it attempts to explain

Validity of Standard Model

Planck scale

GUT scale

10^{27} K

10^{15} K

10^{12} K

10^{9} K

10^{6} K

10^{3} K

2.7 K

0.0000000001 sec

0.00001 sec

1 min

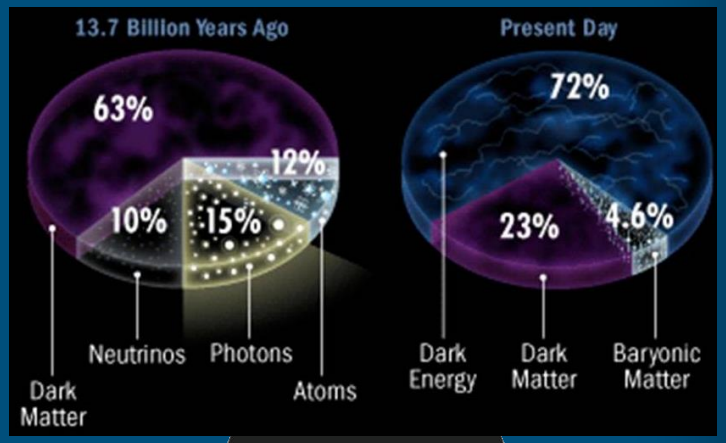
380 000 yrs

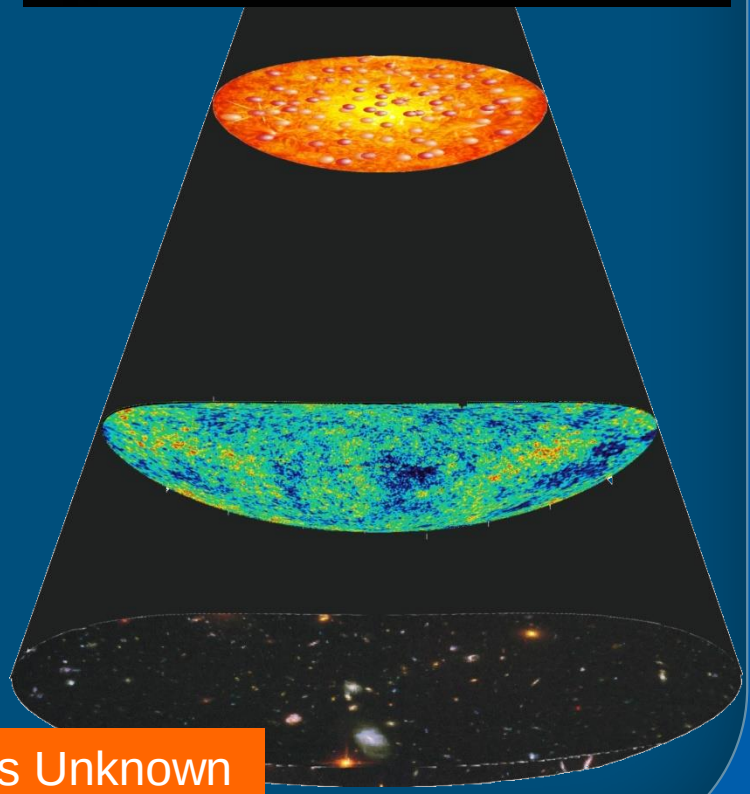
13.7 billion yrs

GUT - SUT

Standard Model

Hidden Sector





96% of energy content in Universe today is Unknown

Direct searches on Energy Frontier

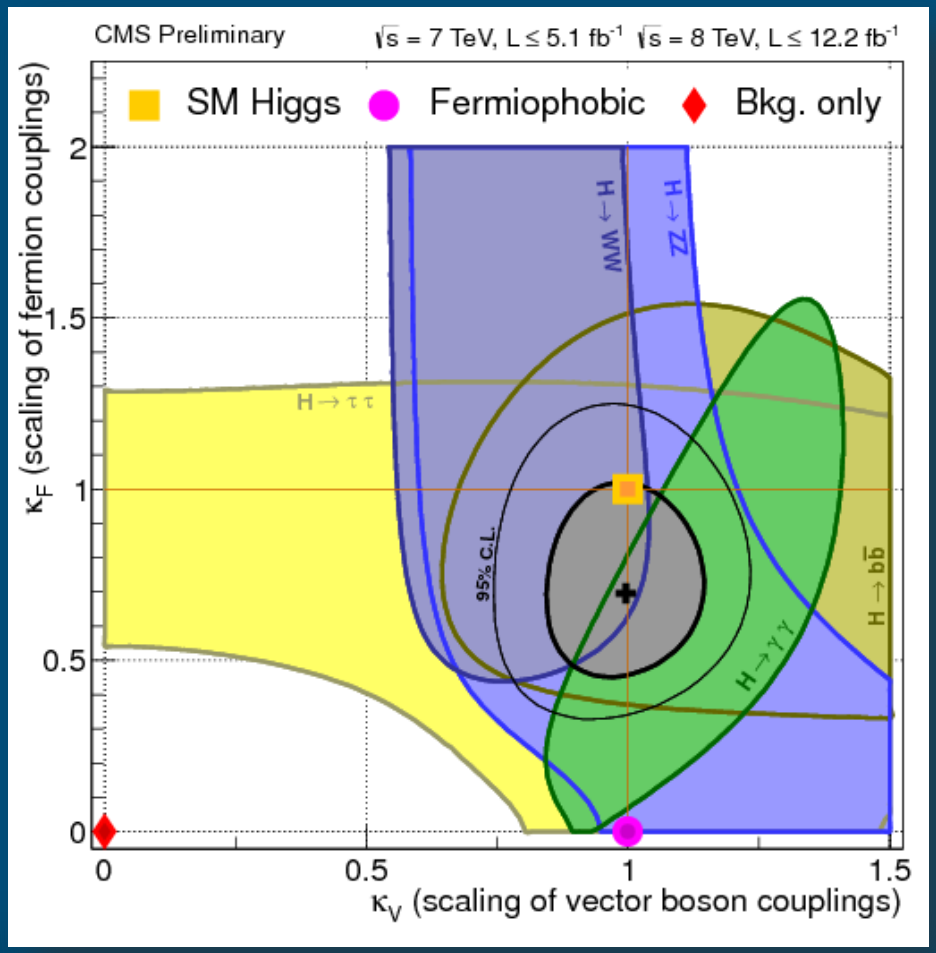
Precision measurements on rare processes at Intensity Frontier/Energy Frontier

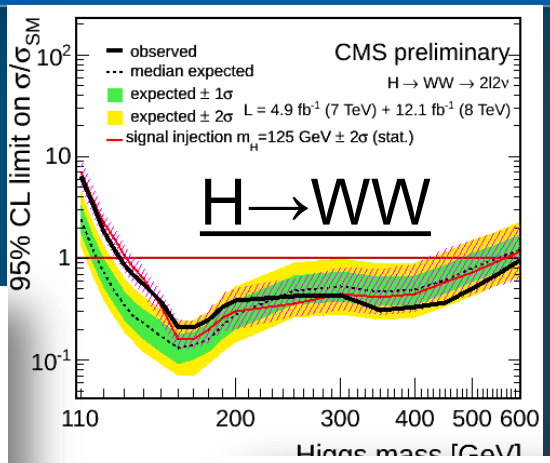
Search hidden sector at Intensity Frontier

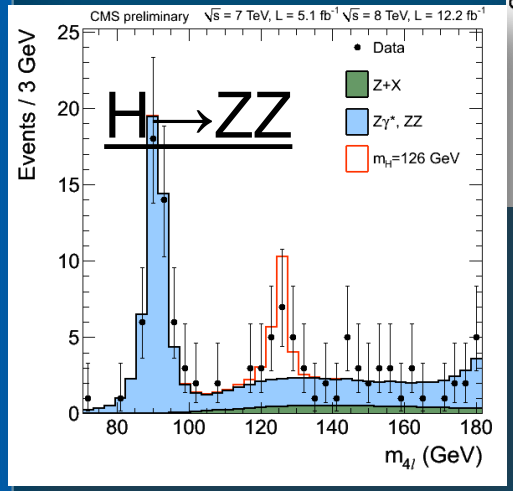
Explore Cosmic Frontier!

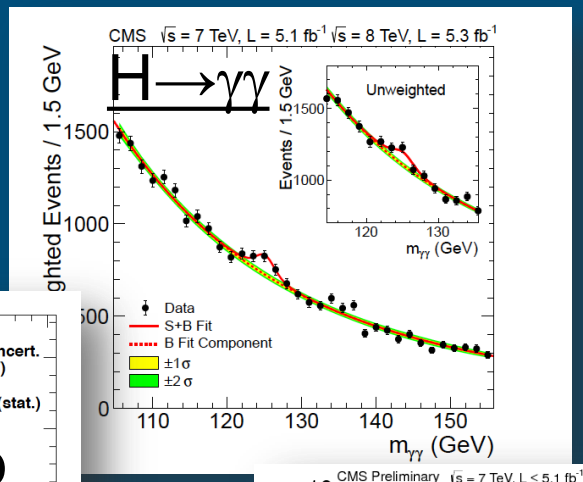
Future – mesure de precision

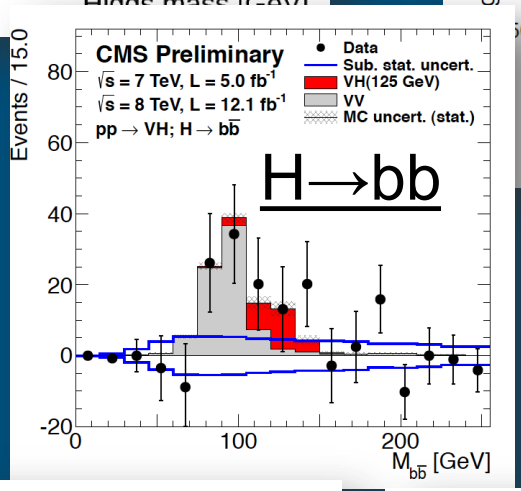
- Characteriser le boson avec une grand precision!
  - ➔ C'est un boson de Higgs, mais est-ce que c'est LE boson de Higgs?
  - ➔ Est-ce qu'il peut nous montrer le chemin vers la "Nouvelle Physique" toujours necessaire pour expliquer le grandes mysteres dans l'Univere?

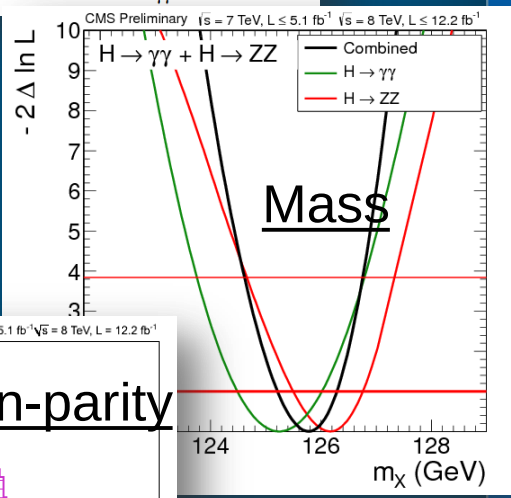


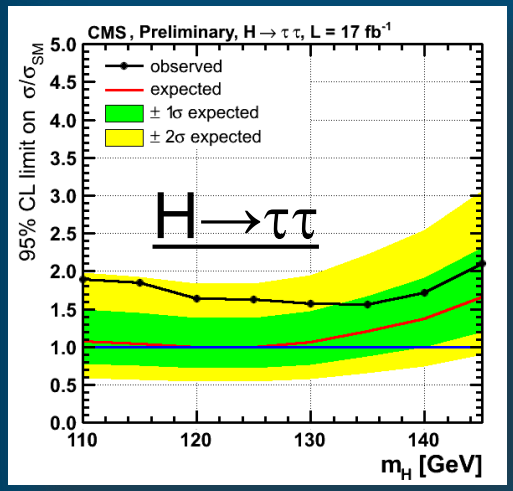

observed
median expected
expected ± 1σ
expected ± 2σ
signal injection m_H=125 GeV ± 2σ (stat.)
CMS preliminary
H → WW → 2l2ν
L = 4.9 fb-1 (7 TeV) + 12.1 fb-1 (8 TeV)
95% CL limit on σ/σSM
H→WW
Higgs mass [GeV]

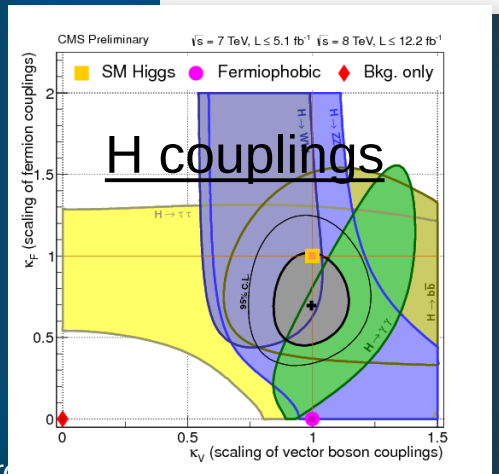

CMS preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 12.2 fb-1
Data
Z+X
Zγ*, ZZ
m_H=126 GeV
H→ZZ
Events / 3 GeV
m4l (GeV)

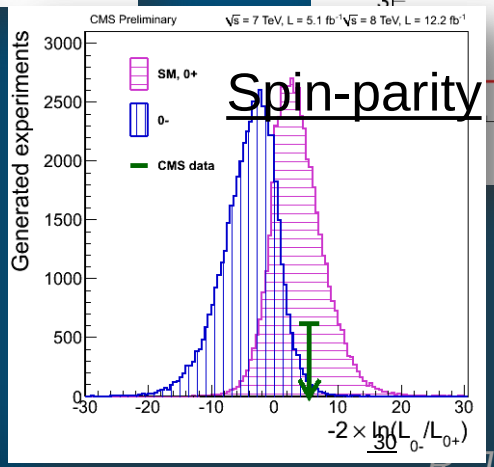

CMS √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 5.3 fb-1
H→γγ
Unweighted
Data
S+B Fit
B Fit Component
±1σ
±2σ
mγγ (GeV)


CMS Preliminary
√s = 7 TeV, L = 5.0 fb-1
√s = 8 TeV, L = 12.1 fb-1
pp → VH; H → bb̄
Data
Sub. stat. uncert.
VH(125 GeV)
VV
MC uncert. (stat.)
H→bb
Events / 15.0
Mbb̄ [GeV]


CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
H → γγ + H → ZZ
Combined
H → γγ
H → ZZ
- 2 Δ ln L
Mass
mX (GeV)

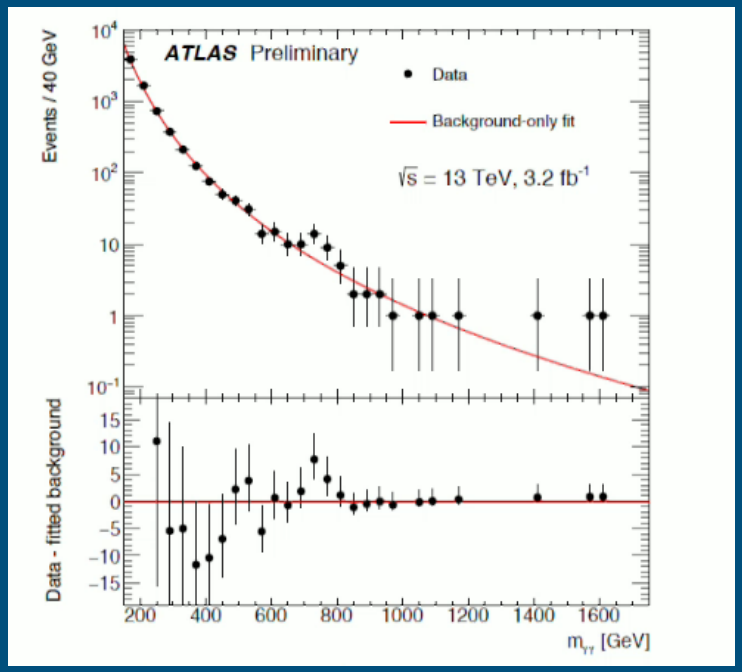

CMS, Preliminary, H → τ τ, L = 17 fb-1
observed
expected
± 1σ expected
± 2σ expected
95% CL limit on σ/σSM
H→ττ
mH [GeV]

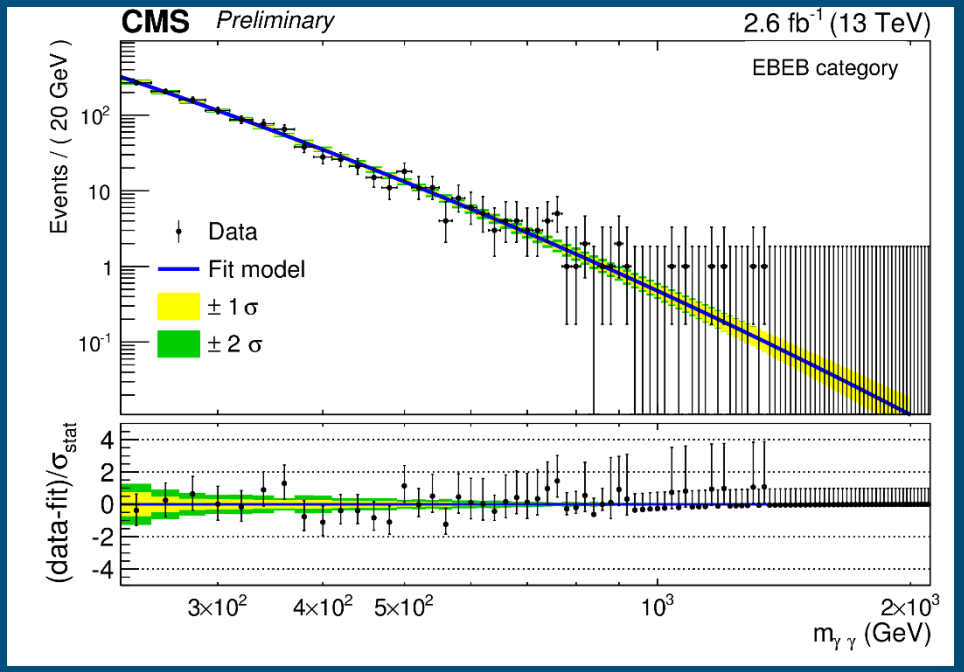

CMS Preliminary √s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 12.2 fb-1
SM Higgs
Fermiophobic
Bkg. only
H couplings
κF (scaling of fermion couplings)
κV (scaling of vector boson couplings)

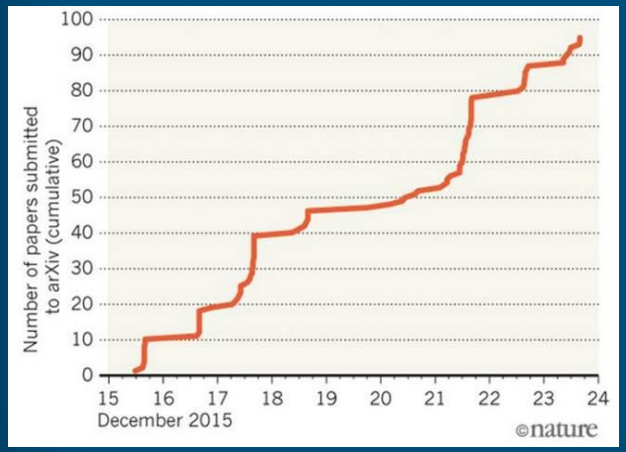

CMS Preliminary √s = 7 TeV, L = 5.1 fb-1 √s = 8 TeV, L = 12.2 fb-1
SM, 0+
0-
CMS data
Spin-parity
Generated experiments
-2 × ln(L0- /L0+)

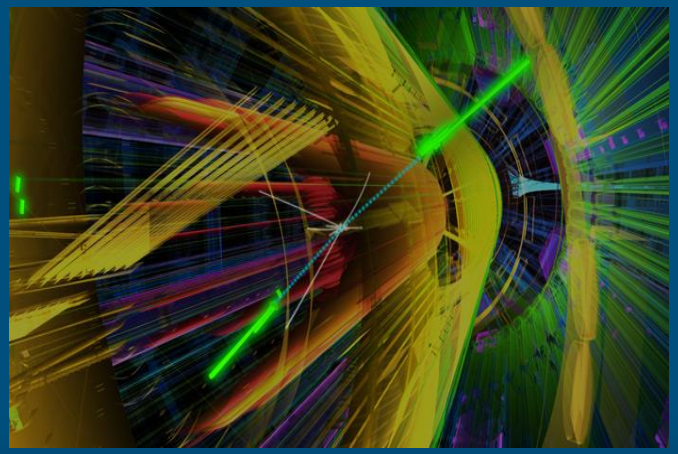
X(750) - un phantom?

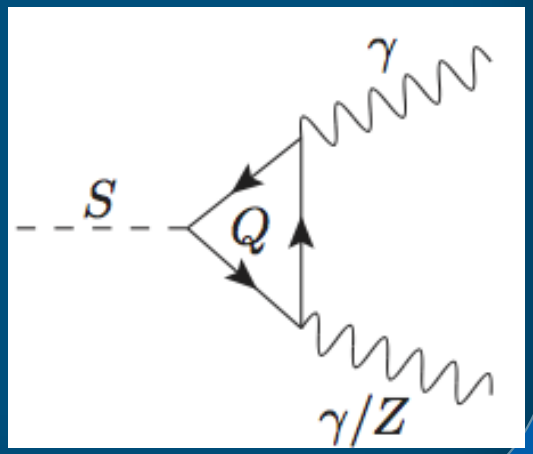
- 15 Decembre 2015:



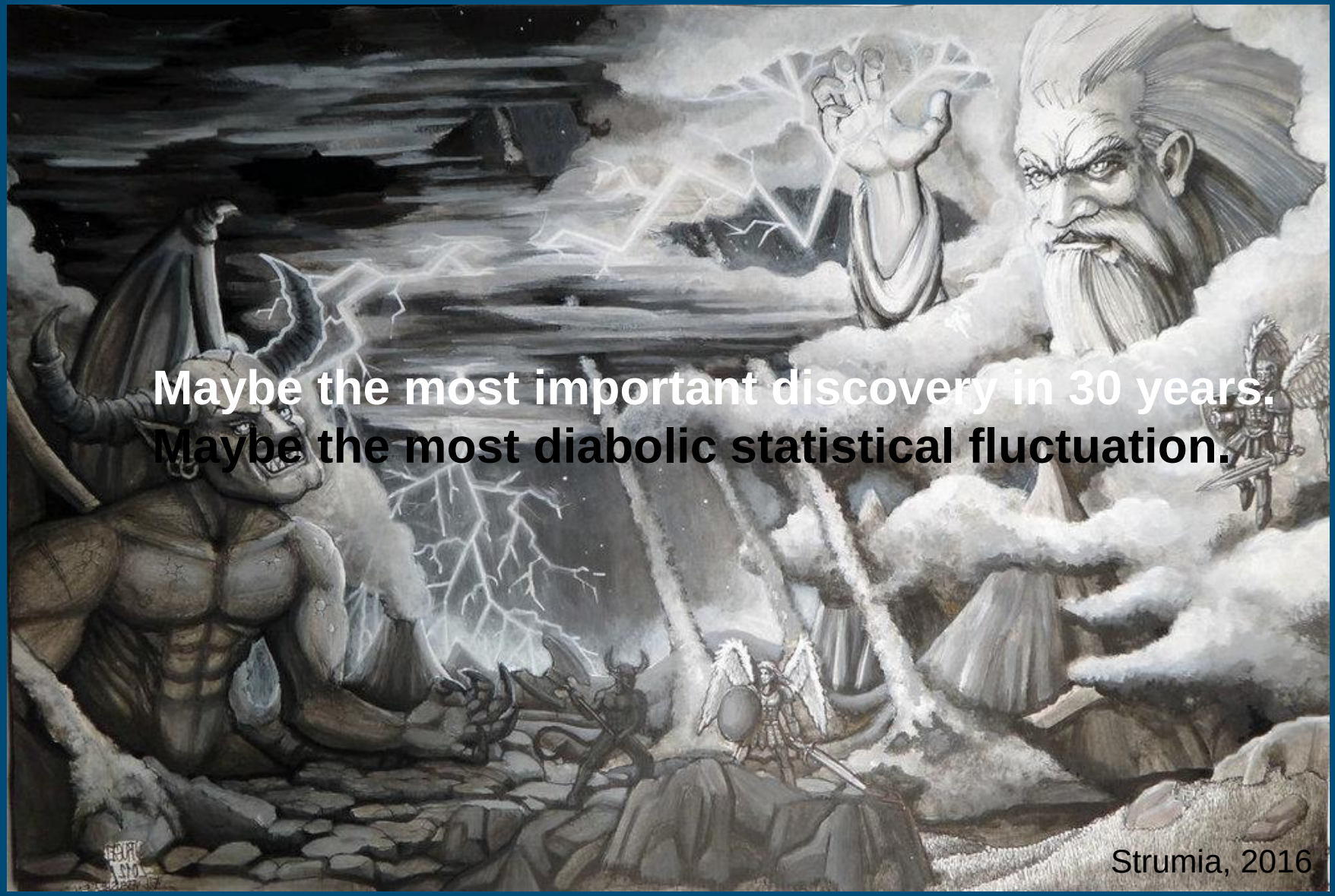








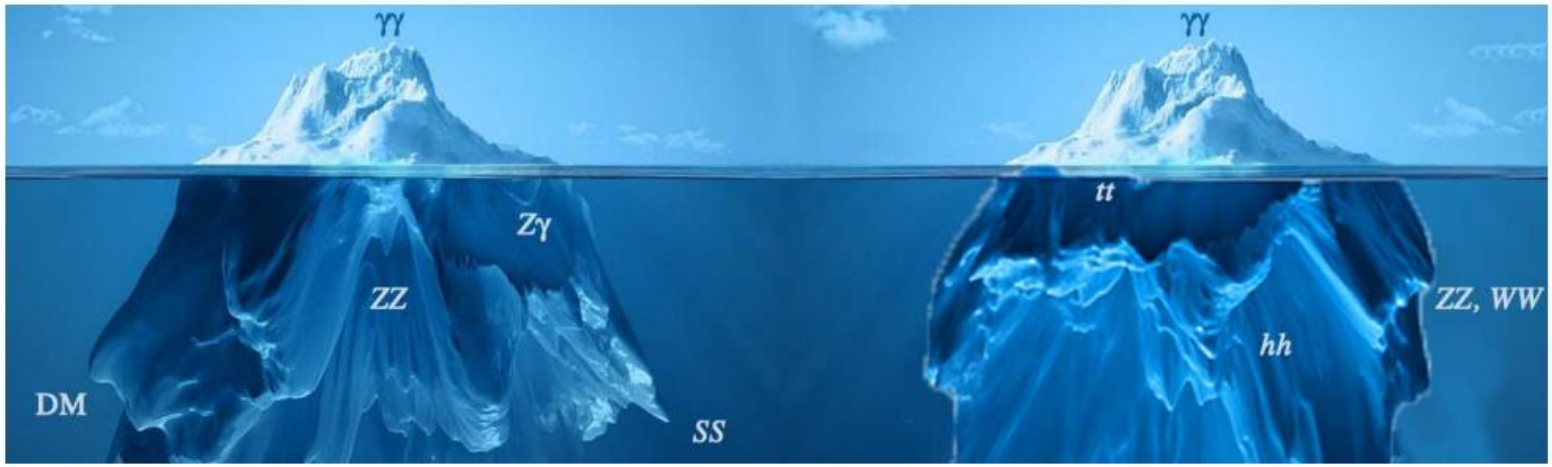
Donc...


Maybe the most important discovery in 30 years.
Maybe the most diabolic statistical fluctuation.
Strumia, 2016

Conclusions

Strumia, 2016

- $\gamma\gamma$@750 should be accompanied by $\gamma Z, ZZ$@750 and by new particles.
- A large $\Gamma/M \sim 0.06$ would point to new strong interactions.
- Finding simple reasonable models is (too) easy. A jungle of options:



Narrow or broad? Spin 0 or 2 or...? Singlet or doublet or...? Scalar or pseudo or $\not{C}\not{P}$? Elementary or composite? A cousin of H or not? [...] Real or not?

Today it could be everything, including nothing. In july we will know.

If real, new data (width, $pp \to jS$, $S \to ZZ, \gamma Z$, ...) will kill models, after the massacre the right theory and its fundamental meaning will emerge.

Search for Hidden Particles

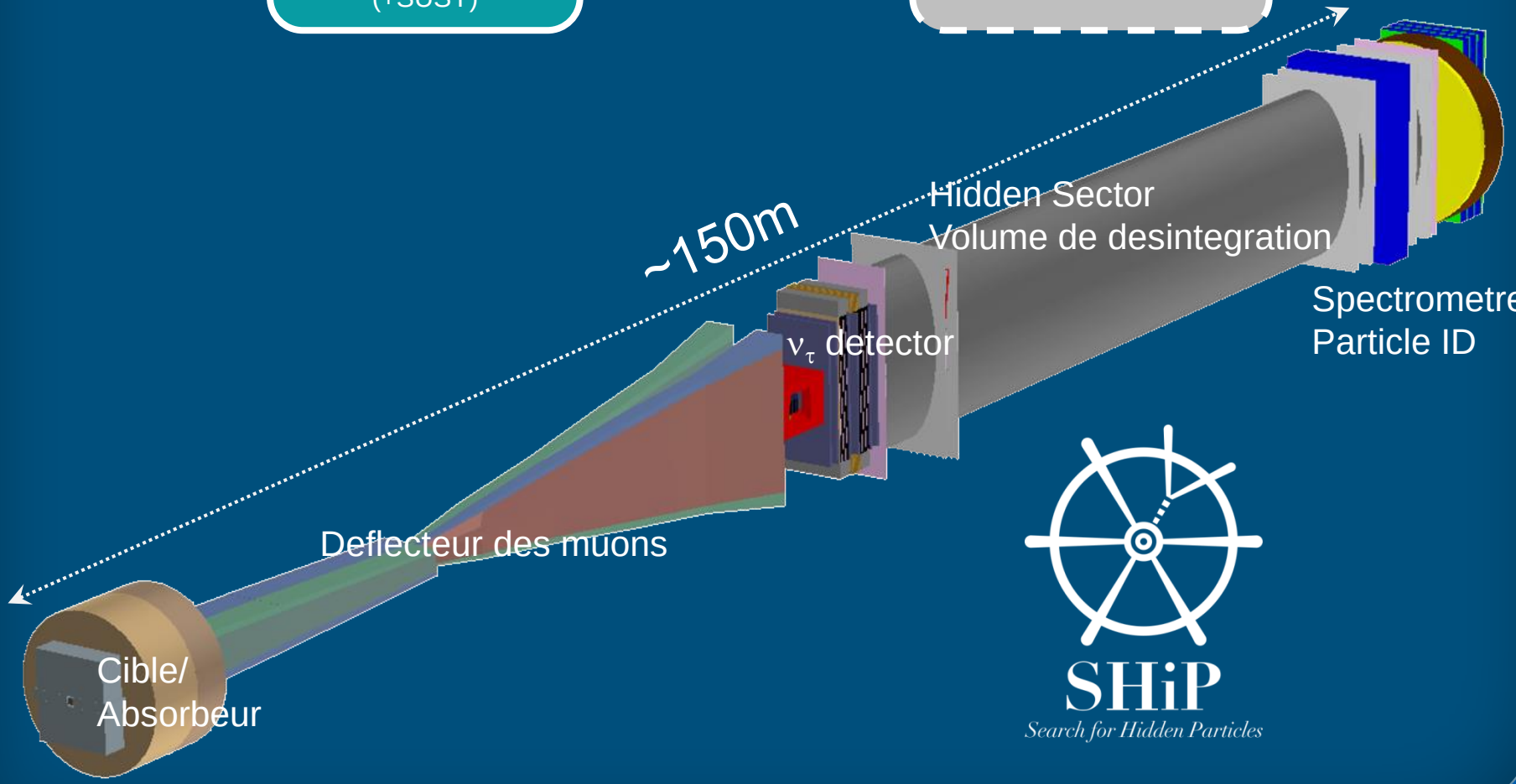
"The particle physicist and the cosmologist…"

La recherche du monde cache!

Visible Sector
$G_{SM} = SU(3)_c \times SU(2)_L \times U(1)_Y$ (+SUSY)

Messenger interaction
"Portals"

Hidden Sector
SM singlets - Non-minimal with G_{HS}



SHiP
Search for Hidden Particles

Vos questions sont aussi nos questions!

Merci!

“Wet dreams”


LINEAR COLLIDER
CIRCULAR COLLIDER
MUON COLLIDER
GAMMA COLLIDER