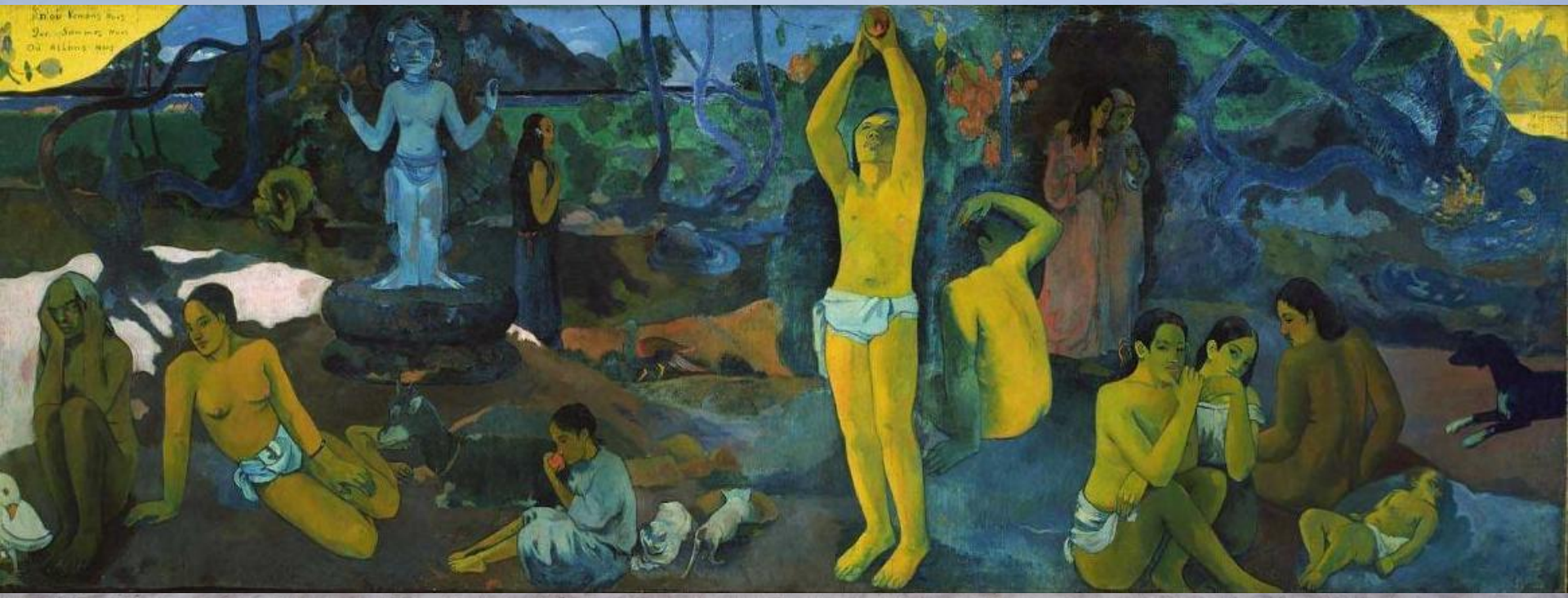
What are we?

Where do we come from?

Where are we going?

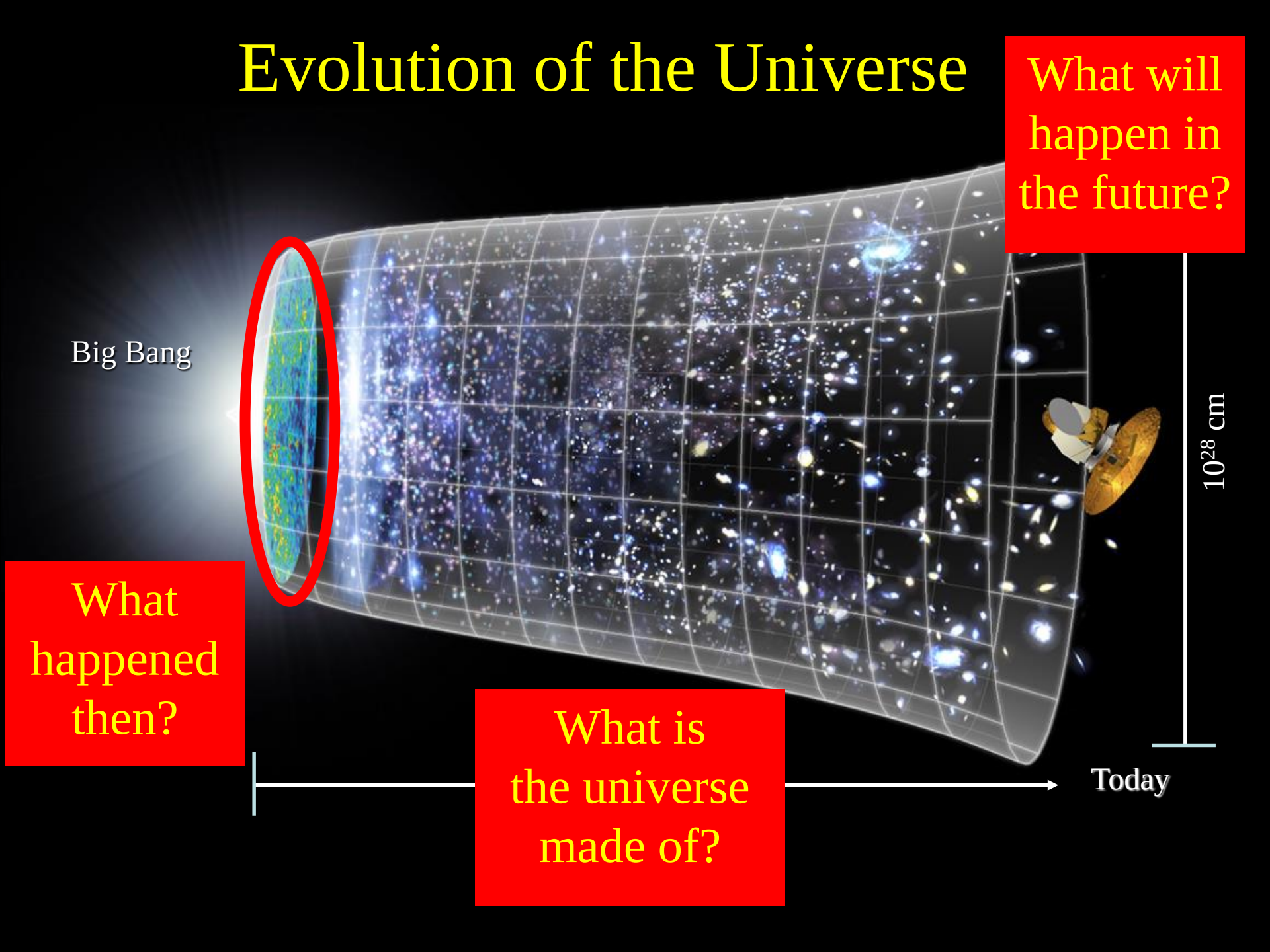


The aim of particle physics:
What is matter in the Universe made of?

John Ellis

KING'S College LONDON

Evolution of the Universe



Gauguin's Questions in the Language of Particle Physics

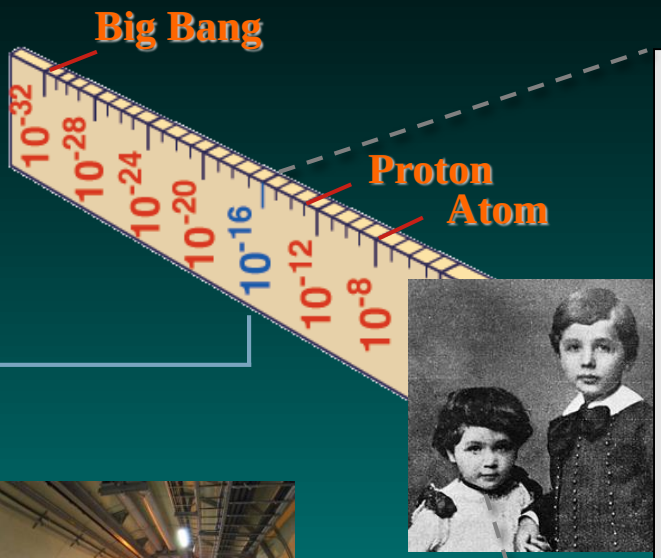
- What is matter made of?
  - Why do things weigh?

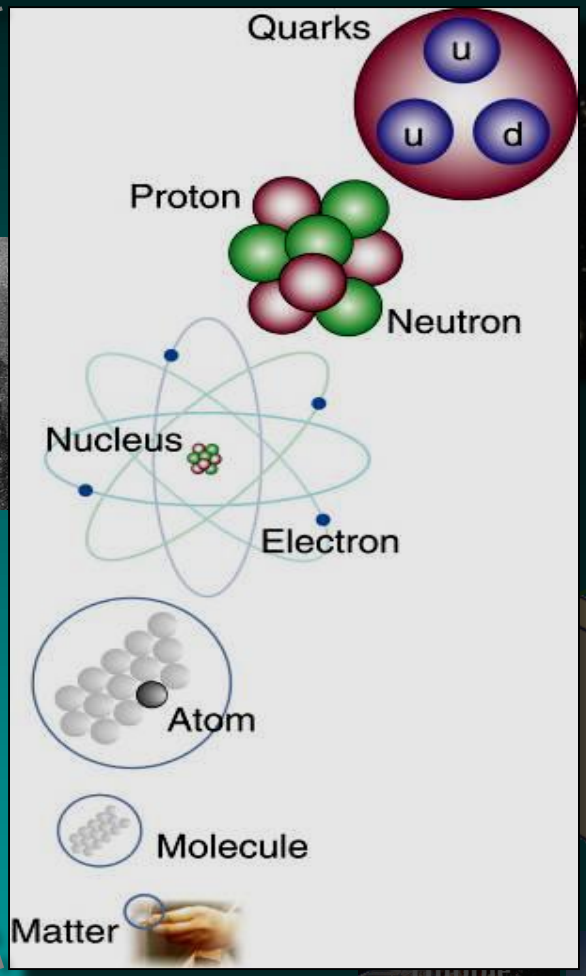
- What is the origin of matter? LHC
- What is the dark matter that fills the Univ LHC
- How does the Universe evolve?
- Why is the Universe so big and old? LHC
- What is the future of the Universe? LHC

Our job is to ask - and answer - these questions

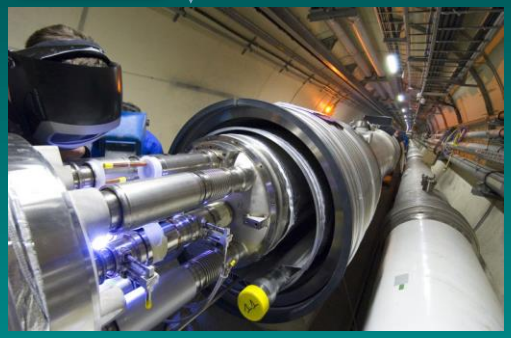
Need physics beyond the Standard Model

/Users/johne/Desktop/YoungEinsteins.png



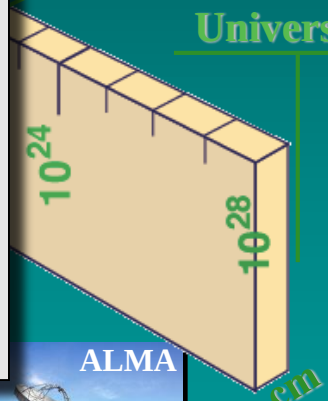


CERN



LHC

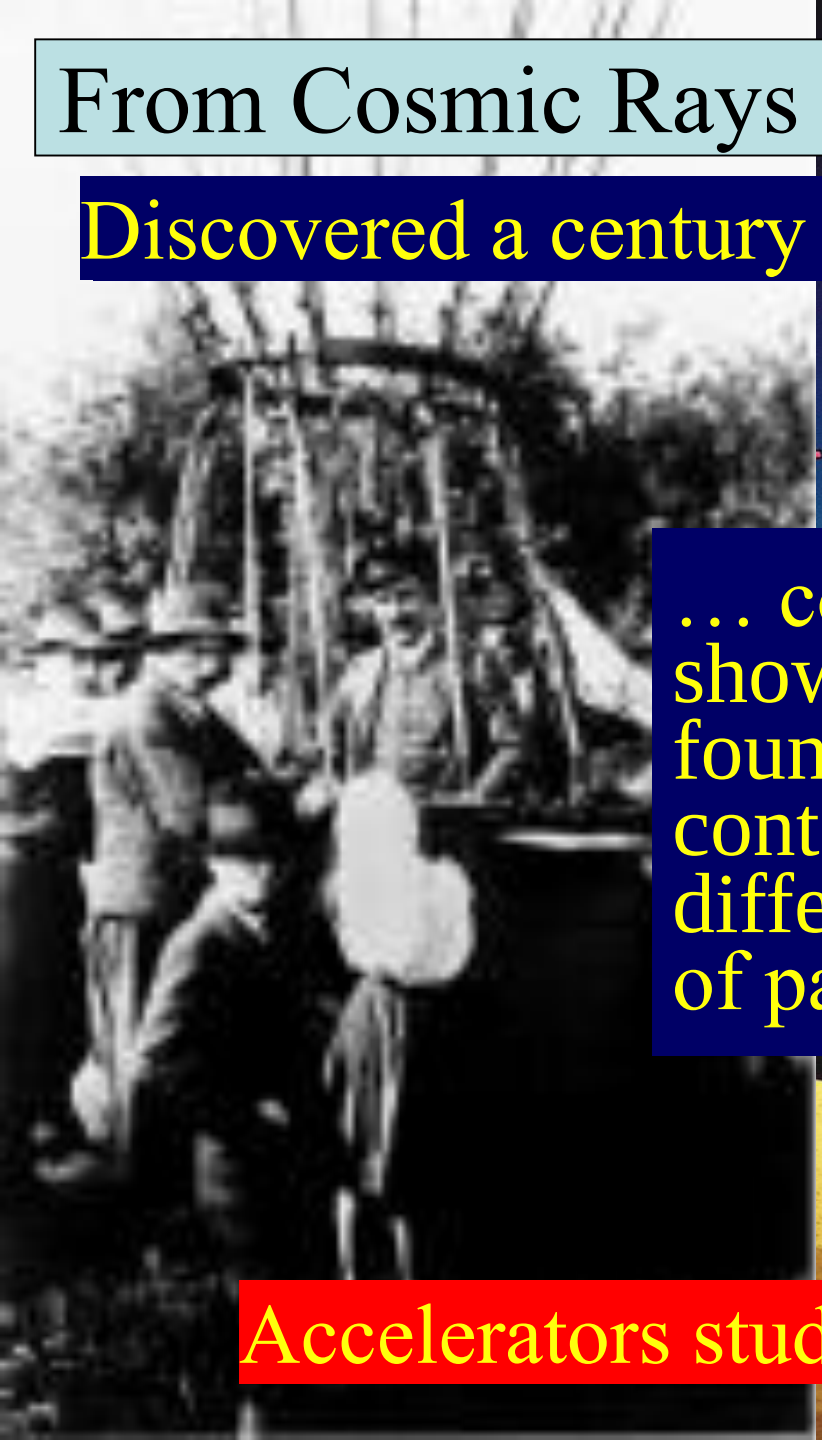
Super-Microscope

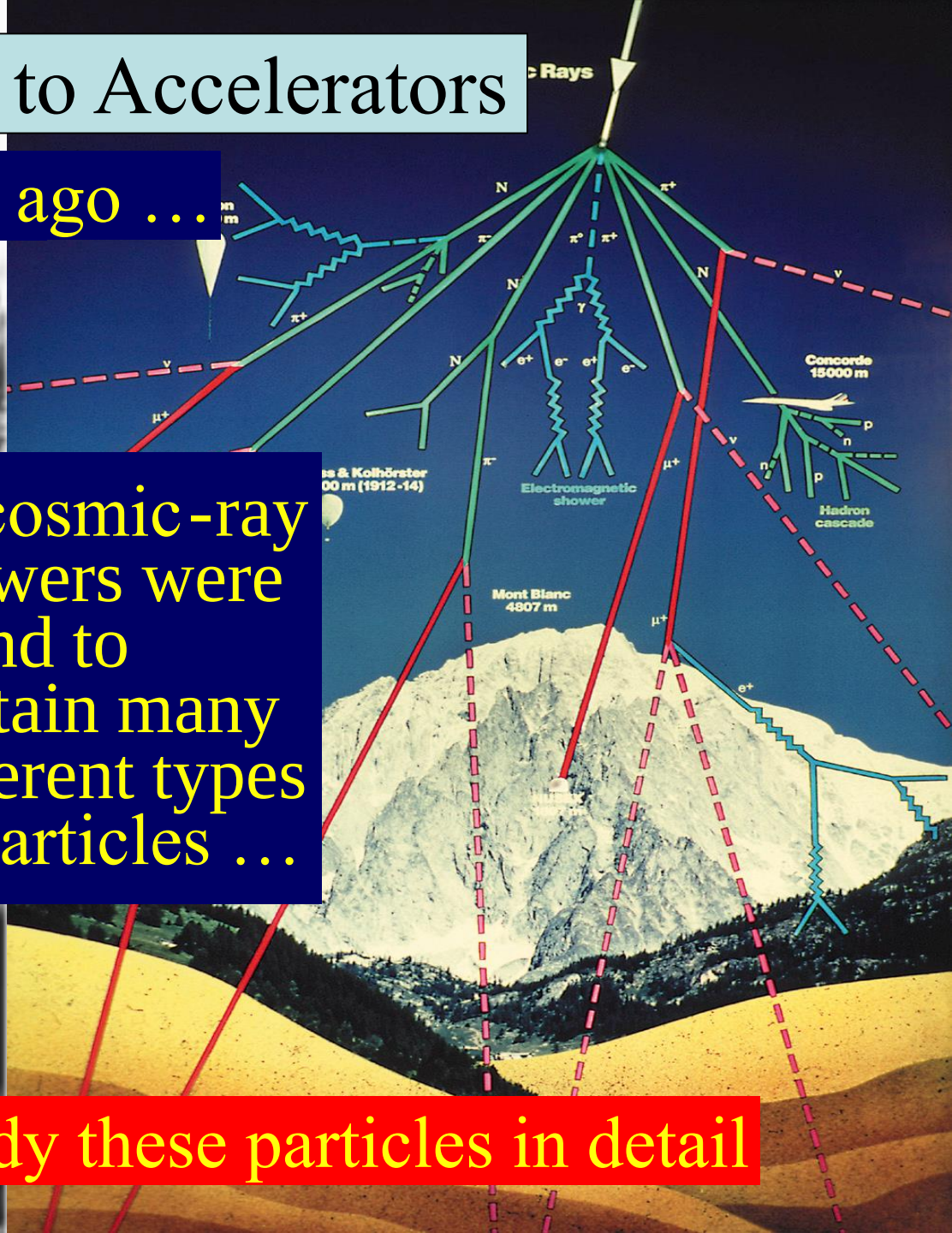


Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

From Cosmic Rays to Accelerators

Discovered a century ago …





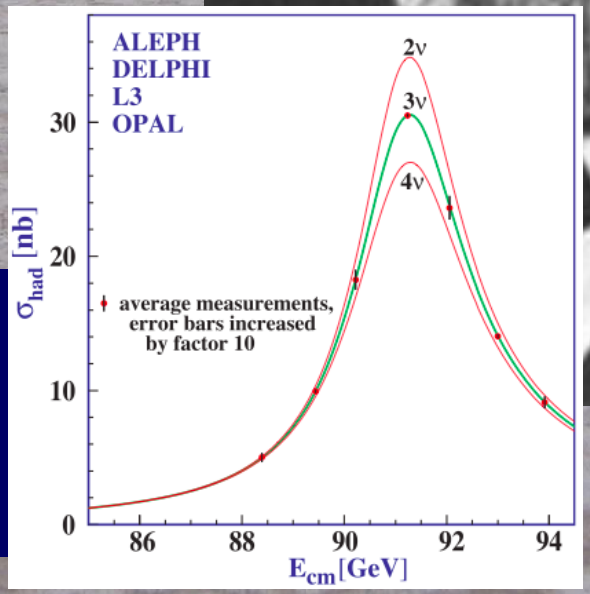
… cosmic-ray showers were found to contain many different types of particles …

Accelerators study these particles in detail

The ‘Standard Model’ of Particle Physics

Proposed by Abdus Salam, Glashow and Weinberg

Tested by experiments at CERN

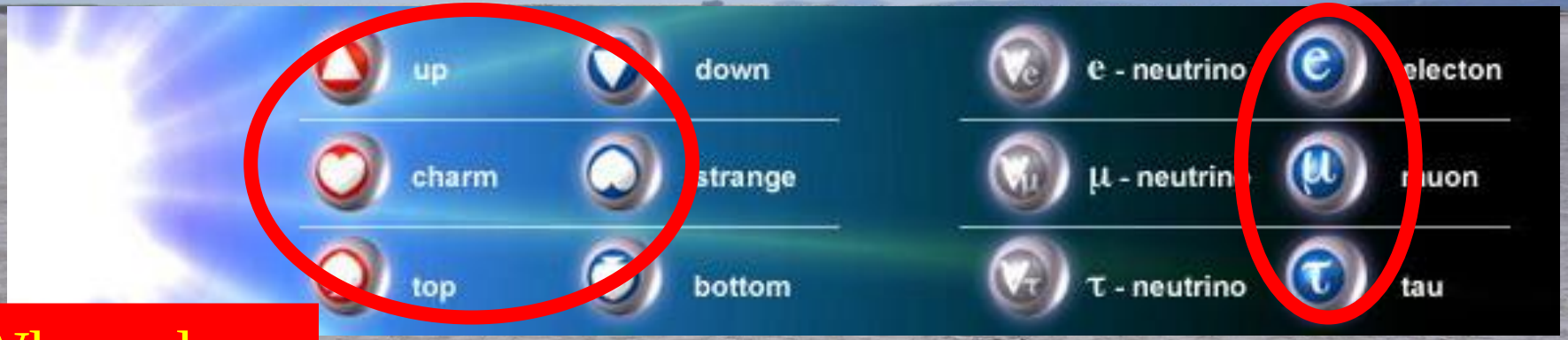


Perfect agreement between theory and experiments in all laboratories

The ‘Standard Model’

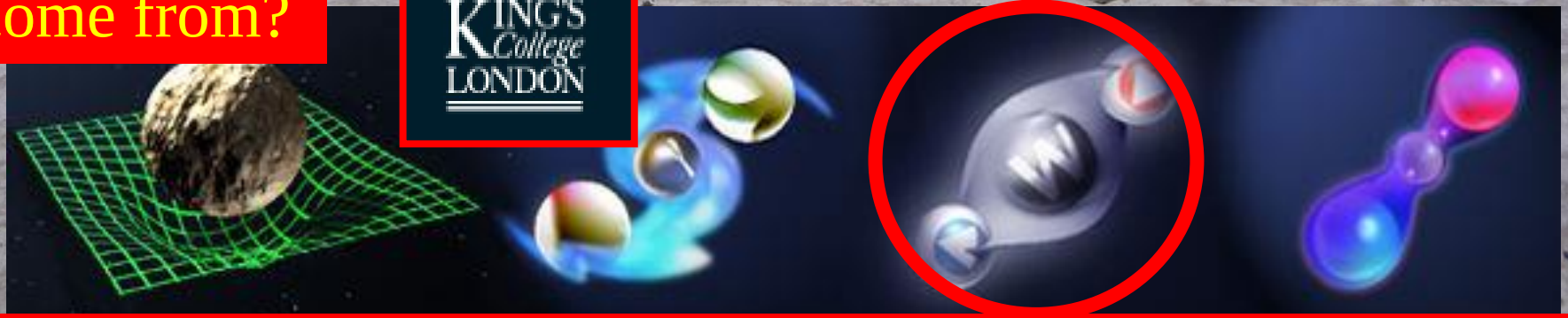
= Cosmic DNA

The matter particles



Where does mass come from?

The fundamental interactions



Gravitation electromagnetism weak nuclear force strong nuclear force

Why do Things Weigh?

Newton:

Weight proportional to Mass

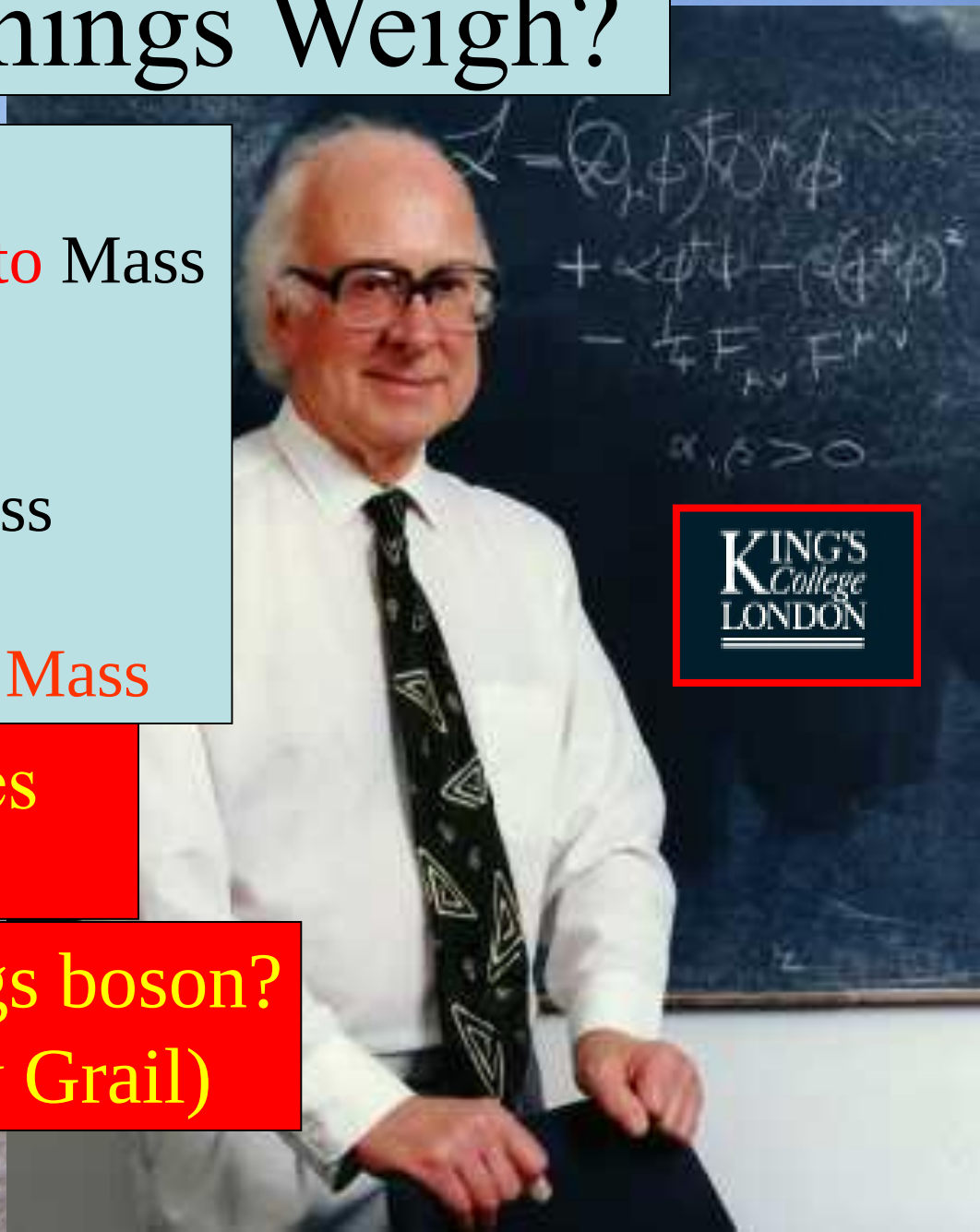
Einstein:

Energy related to Mass

Neither explained origin of Mass

Where do the masses come from?

Are masses due to Higgs boson? (the physicists' Holy Grail)



Think of a Snowfield

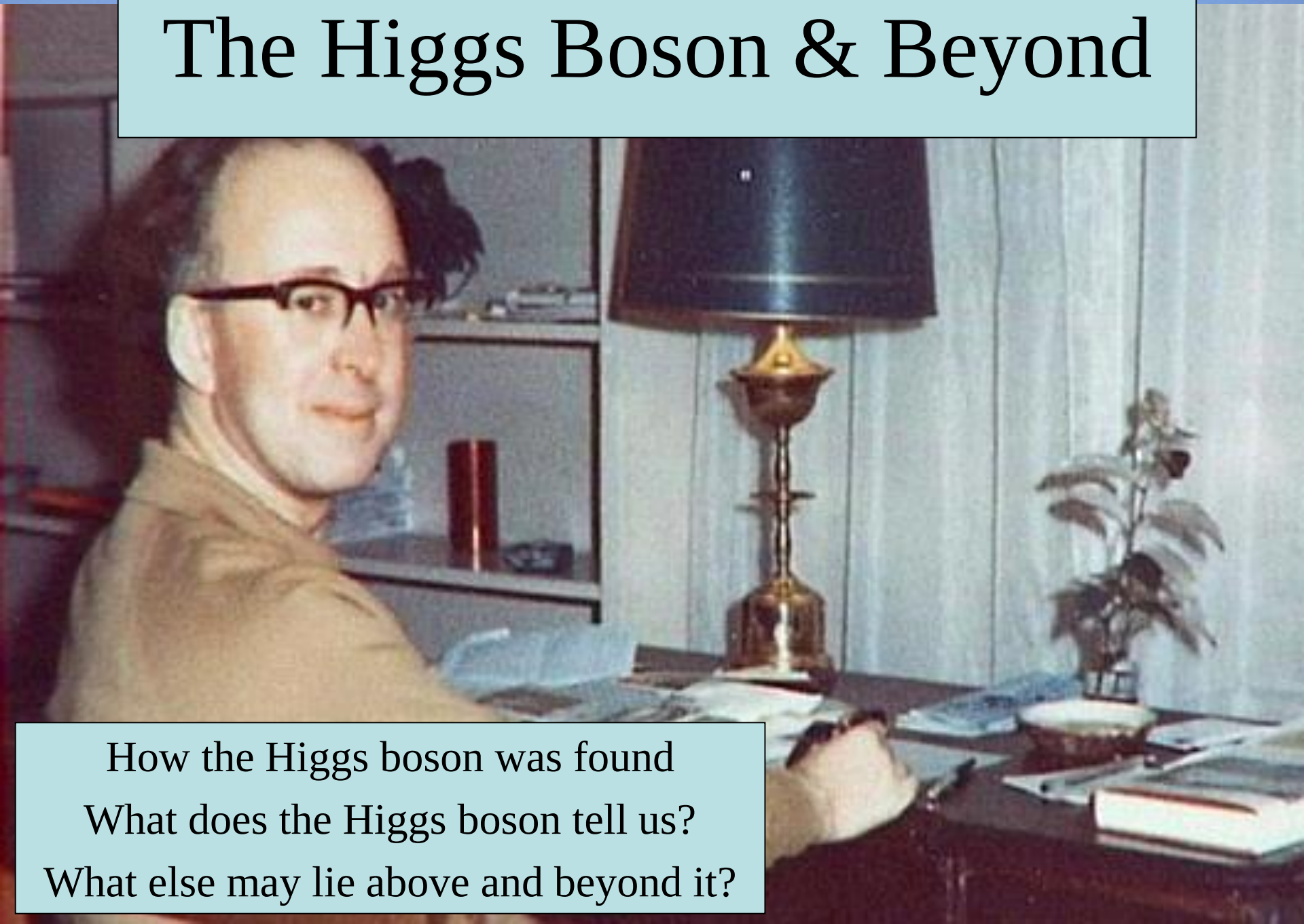
The LHC discovered the snowflake: The Higgs Boson

Skier moves fast:
Like particle without mass
e.g., photon = particle of light

Snowshoer sinks into snow, moves slower:
Like particle with mass
e.g., electron

Hiker sinks deep, moves very slowly:
Particle with large mass

The Higgs Boson & Beyond



How the Higgs boson was found

What does the Higgs boson tell us?

What else may lie above and beyond it?

Summary of the Standard Model

- Particles and SU(3) × SU(2) × U(1) quantum numbers:

L_L	$\begin{pmatrix} \nu_e \\ e^- \end{pmatrix}_L , \begin{pmatrix} \nu_\mu \\ \mu^- \end{pmatrix}_L , \begin{pmatrix} \nu_\tau \\ \tau^- \end{pmatrix}_L$	$(\mathbf{1},\mathbf{2},-1)$
E_R	$e_R^- , \mu_R^- , \tau_R^-$	$(\mathbf{1},\mathbf{1},-2)$
Q_L	$\begin{pmatrix} u \\ d \end{pmatrix}_L , \begin{pmatrix} c \\ s \end{pmatrix}_L , \begin{pmatrix} t \\ b \end{pmatrix}_L$	$(\mathbf{3},\mathbf{2},+1/3)$
U_R	u_R , c_R , t_R	$(\mathbf{3},\mathbf{1},+4/3)$
D_R	d_R , s_R , b_R	$(\mathbf{3},\mathbf{1},-2/3)$

- Lagrangian:

$$\begin{aligned} \mathcal{L} &= -\frac{1}{4} F^a_{\mu\nu} F^{a\ \mu\nu} \\ &+ i\bar{\psi}\ \not{D}\psi + h.c. \\ &+ \psi_i y_{ij} \psi_j \phi + h.c. \\ &+ |D_\mu \phi|^2 - V(\phi) \end{aligned}$$

gauge interactions

matter fermions

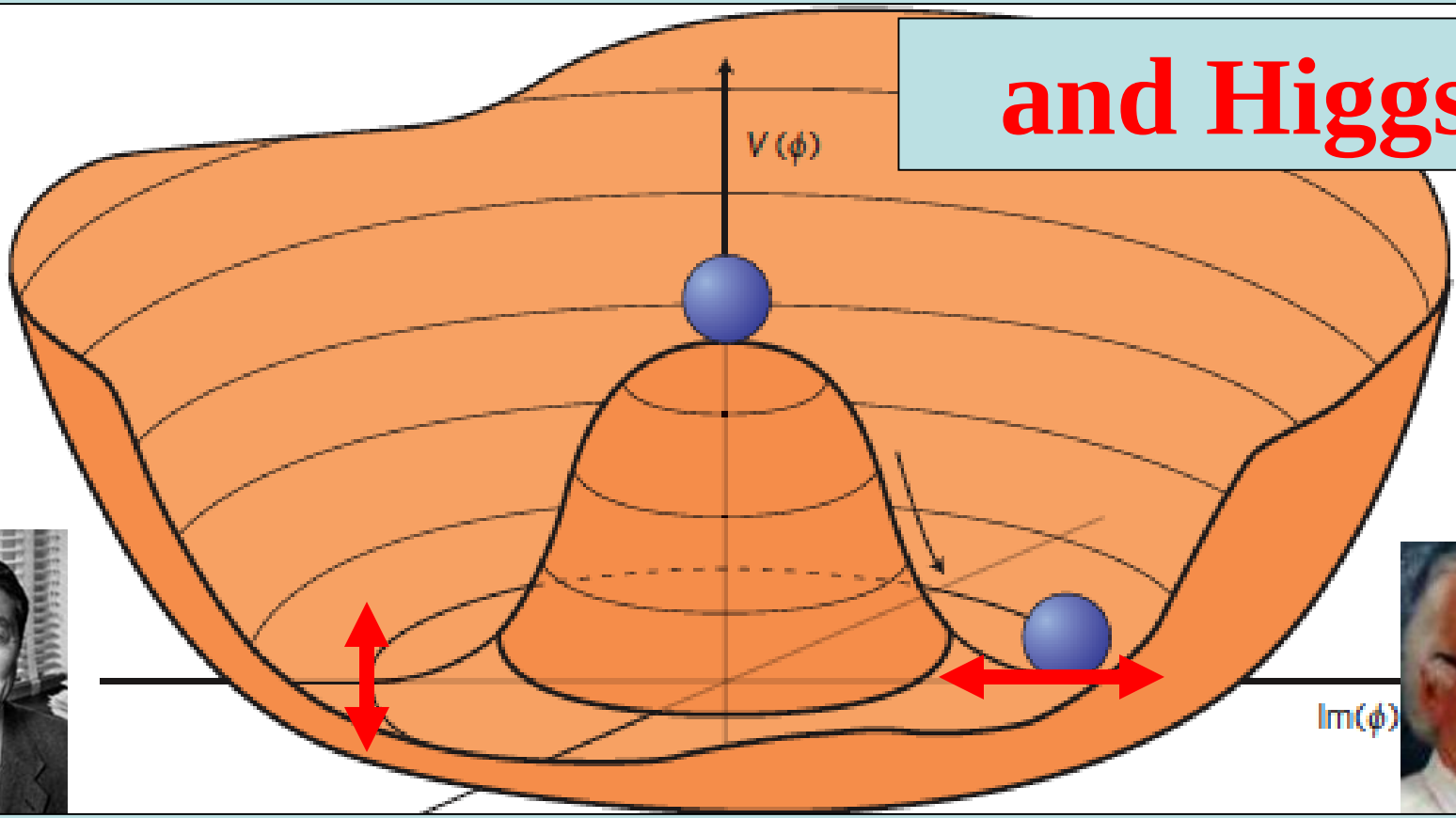
Yukawa interactions

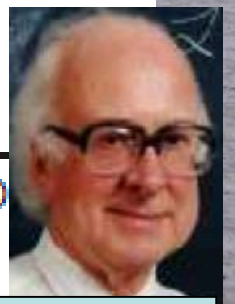
Higgs potential

Untested before 2012

Spontaneous Symmetry Breaking

and Higgs





Around bottom : massless Nambu-Goldstone boson

'Eaten' by massless gauge boson : massive vector boson

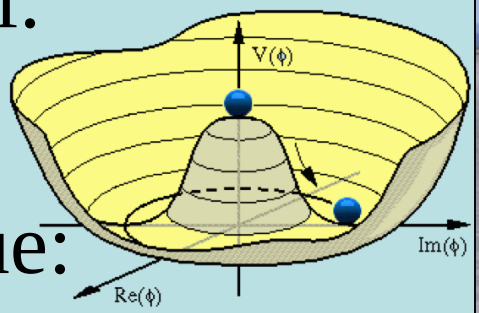
Accompanied by massive scalar particle

1964

The Higgs Mechanism

- Postulate effective Higgs potential:

$$V[\phi] = -\mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2$$



- Minimum energy at non-zero value:

$$\phi_0 =< 0|\phi|0 >= \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ +v \end{pmatrix} \quad v = \sqrt{\frac{-\mu^2}{\lambda}}$$

- Components of Higgs field: $\phi(x) = \frac{1}{\sqrt{2}}(v + \sigma(x))e^{i\pi(x)}$
- π massless, σ massive: $m_H^2 = 2\mu^2 = 2\lambda v$
- Couple to fermions: on-zero masses: $M_f = y_f \frac{v}{\sqrt{2}}$
- After gauging: $M_W = \frac{g\,v}{2}$

1967

Masses for SM Gauge Bosons

- Kinetic terms for SU(2) and U(1) gauge bosons:

$$\mathcal{L} = -\frac{1}{4}\, G^i_{\mu\nu} G^{i\mu\nu} - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

  where $G^i_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu + i g \epsilon_{ijk} W^j_\mu W^k_\nu$ $F_{\mu\nu} \equiv \partial_\mu W^i_\nu - \partial_\nu W^i_\mu$

- Kinetic term for Higgs field:

$$\mathcal{L}_\phi = -|D_\mu \phi|^2 \quad D_\mu \equiv \partial_\mu - i\, g\, \sigma_i\, W^i_\mu - i\, g'\, Y\, B_\mu$$

- Expanding around vacuum: $\phi = < 0|\phi|0 > + \hat{\phi}$

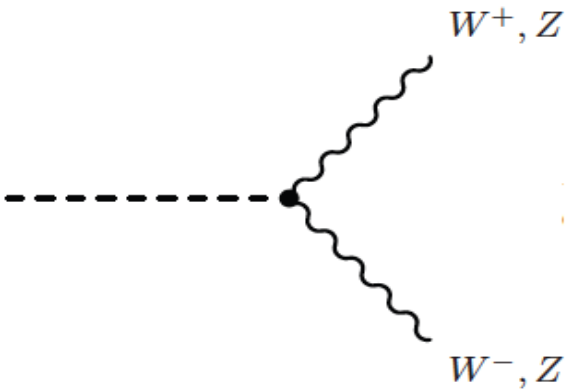
$$\mathcal{L}_\phi \ni -\frac{g^2 v^2}{2}\, W^+_\mu\, W^{\mu -} + g'^2\, \frac{v^2}{2}\, B_\mu\, B^\mu + g\, g' v^2\, B_\mu\, W^{\mu 3} - g^2\, \frac{v^2}{2}\, W^3_\mu\, W^{\mu}$$

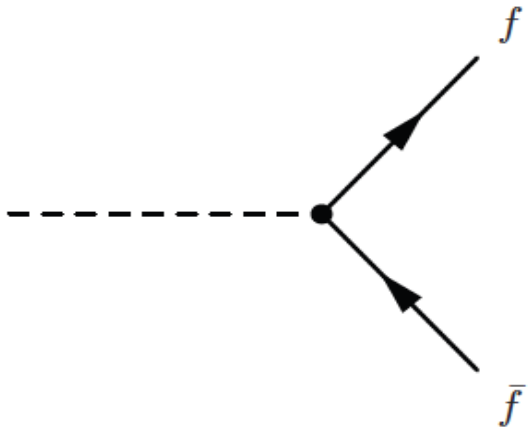
- Boson masses:

$$m_{W^\pm} = \frac{g v}{2} \qquad Z_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_Z = \frac{1}{2}\sqrt{g^2 + g'^2}\, v \;; \quad A_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}} \;:\; m_A = 0$$

1966, 1967

Higgs Boson Couplings





$$g_2 M_W \ , \quad g_2 \frac{M_Z}{c_W} \qquad \frac{m_f}{v} = \frac{g_2 \, m_f}{2 M_W}$$

$$\Gamma(H \to f\bar{f}) = N_c \frac{G_F M_H}{4\pi\sqrt{2}} m_f^2, \quad N_C = 3\,(1) \text{ for quarks (leptons)}$$

$$\Gamma(H \to VV) = \frac{G_F M_H^3}{8\pi\sqrt{2}} F(r) \left(\frac{1}{2}\right)_Z, \quad r = \frac{M_V}{M_H}$$

1975

A Phenomenological Profile of the Higgs Boson

- First attempt at systematic survey

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

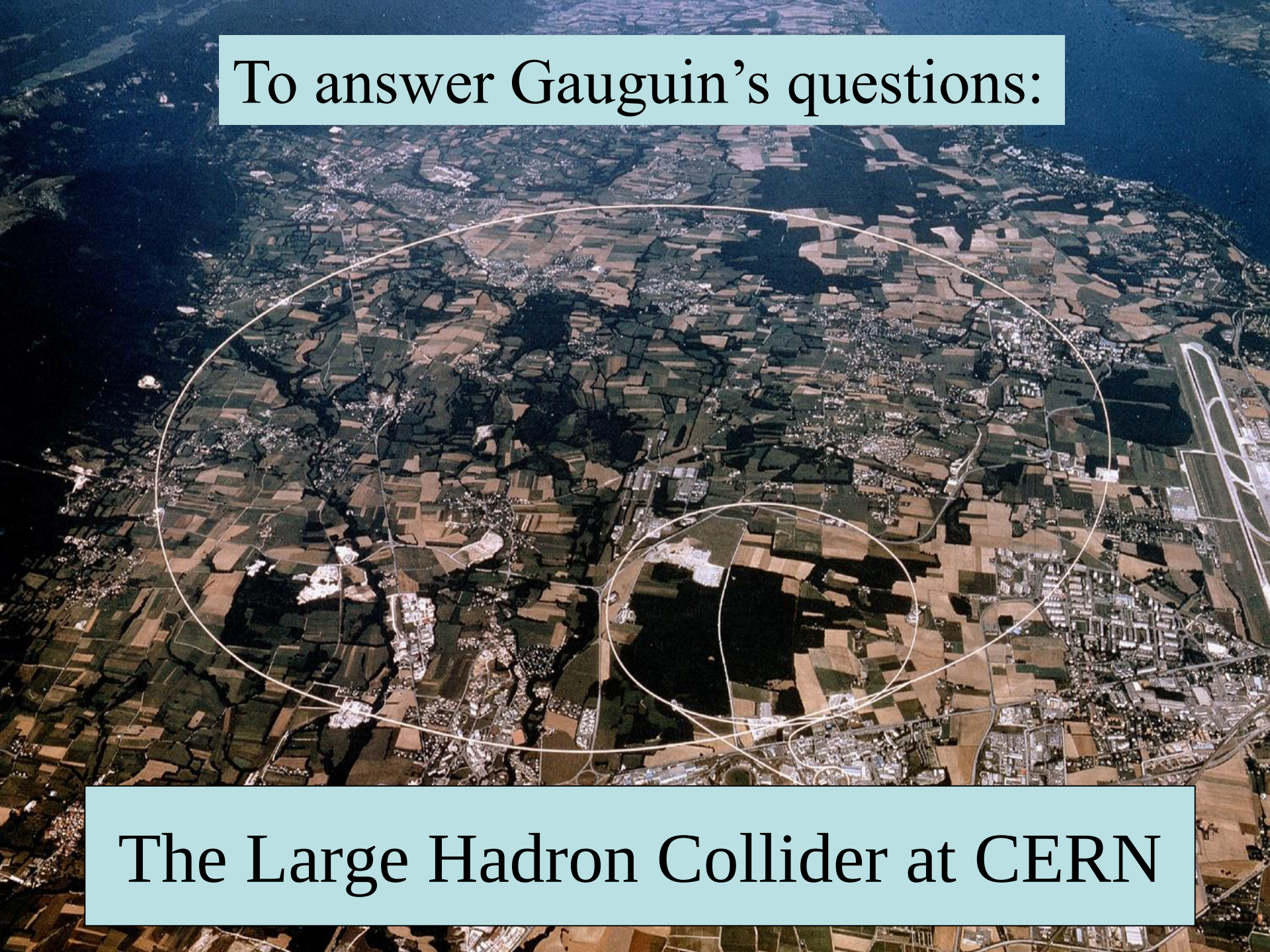
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

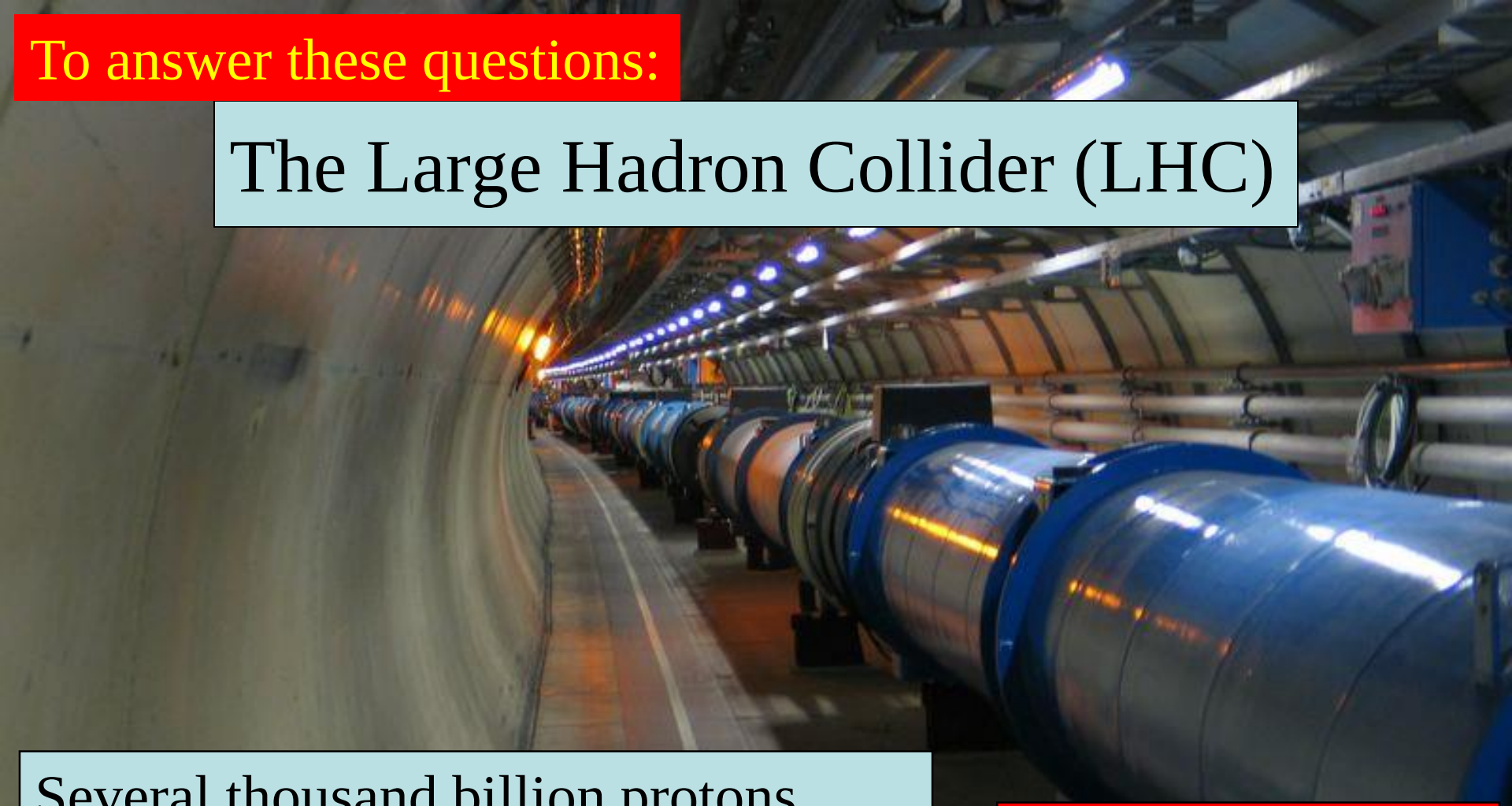
To answer Gauguin's questions:



The Large Hadron Collider at CERN

To answer these questions:

The Large Hadron Collider (LHC)



Several thousand billion protons
Each with the energy of a fly
99.9999991% of light speed
Orbit 27km ring 11 000 times/second
A billion collisions a second

Primary targets:
- Origin of mass
- Nature of Dark Matter
- Primordial Plasma
- Matter vs Antimatter

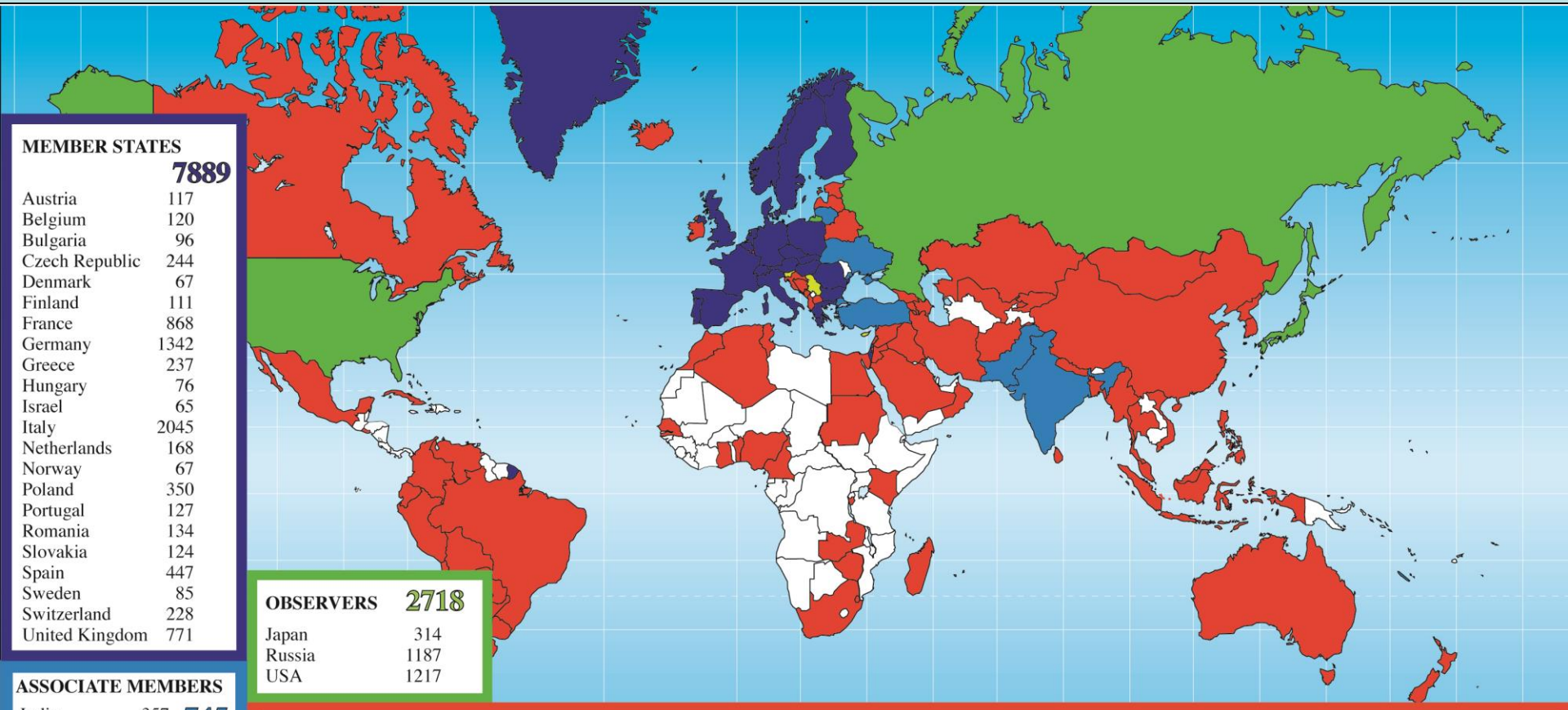
ALICE: Primordial cosmic plasma

ATLAS: Higgs and dark matter

CMS: Higgs and dark matter

LHCb: Matter-antimatter difference

Scientists from around the World



MEMBER STATES **7889**

Austria	117
Belgium	120
Bulgaria	96
Czech Republic	244
Denmark	67
Finland	111
France	868
Germany	1342
Greece	237
Hungary	76
Israel	65
Italy	2045
Netherlands	168
Norway	67
Poland	350
Portugal	127
Romania	134
Slovakia	124
Spain	447
Sweden	85
Switzerland	228
United Kingdom	771

OBSERVERS **2718**

Japan	314
Russia	1187
USA	1217

ASSOCIATE MEMBERS **745**

India	357
Lithuania	35
Pakistan	65
Turkey	173
Ukraine	115

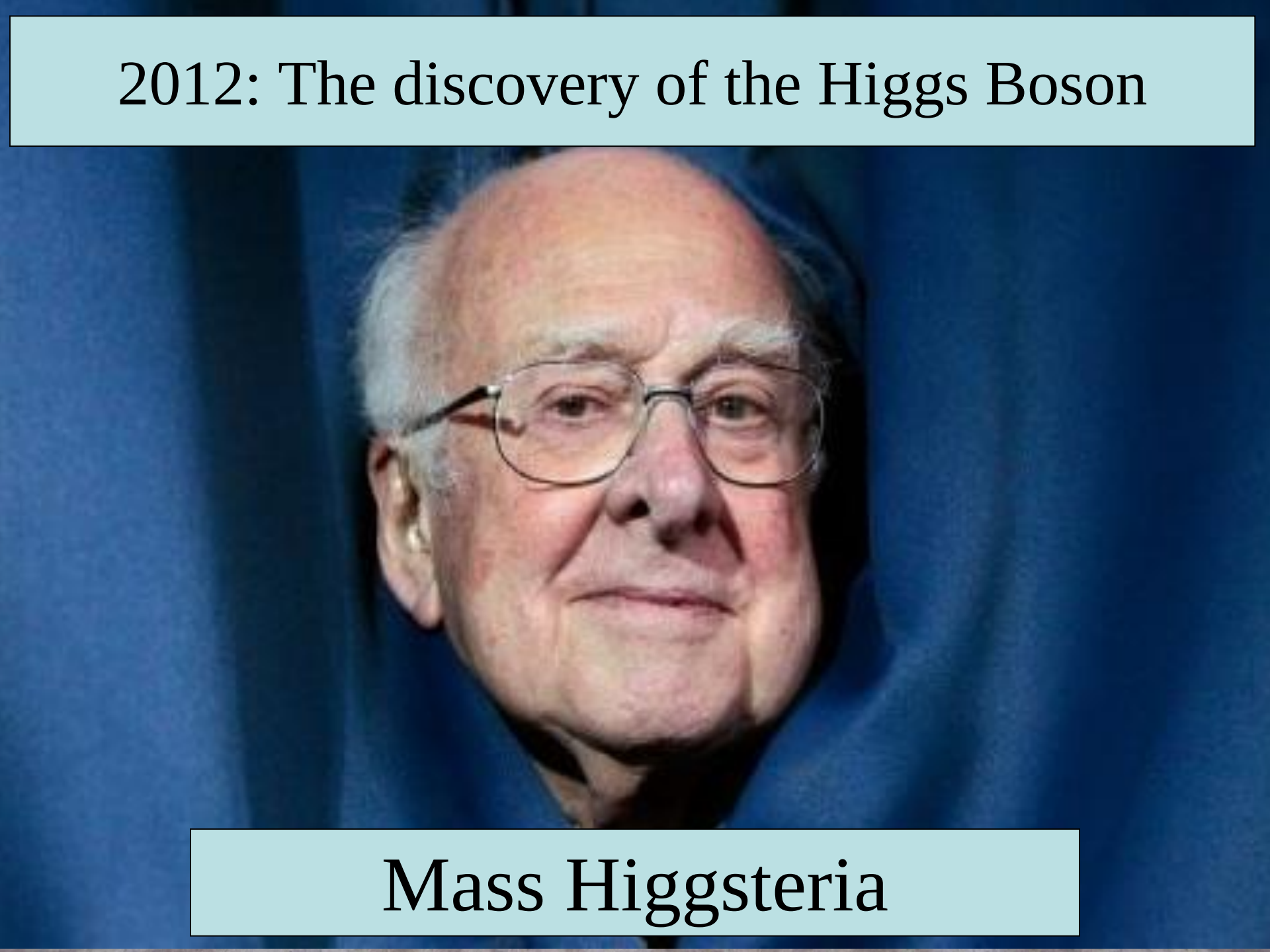
ASSOCIATE MEMBERS IN THE PRE-STAGE TO MEMBERSHIP **118**

Cyprus	26
Serbia	57
Slovenia	35

OTHERS **1872**

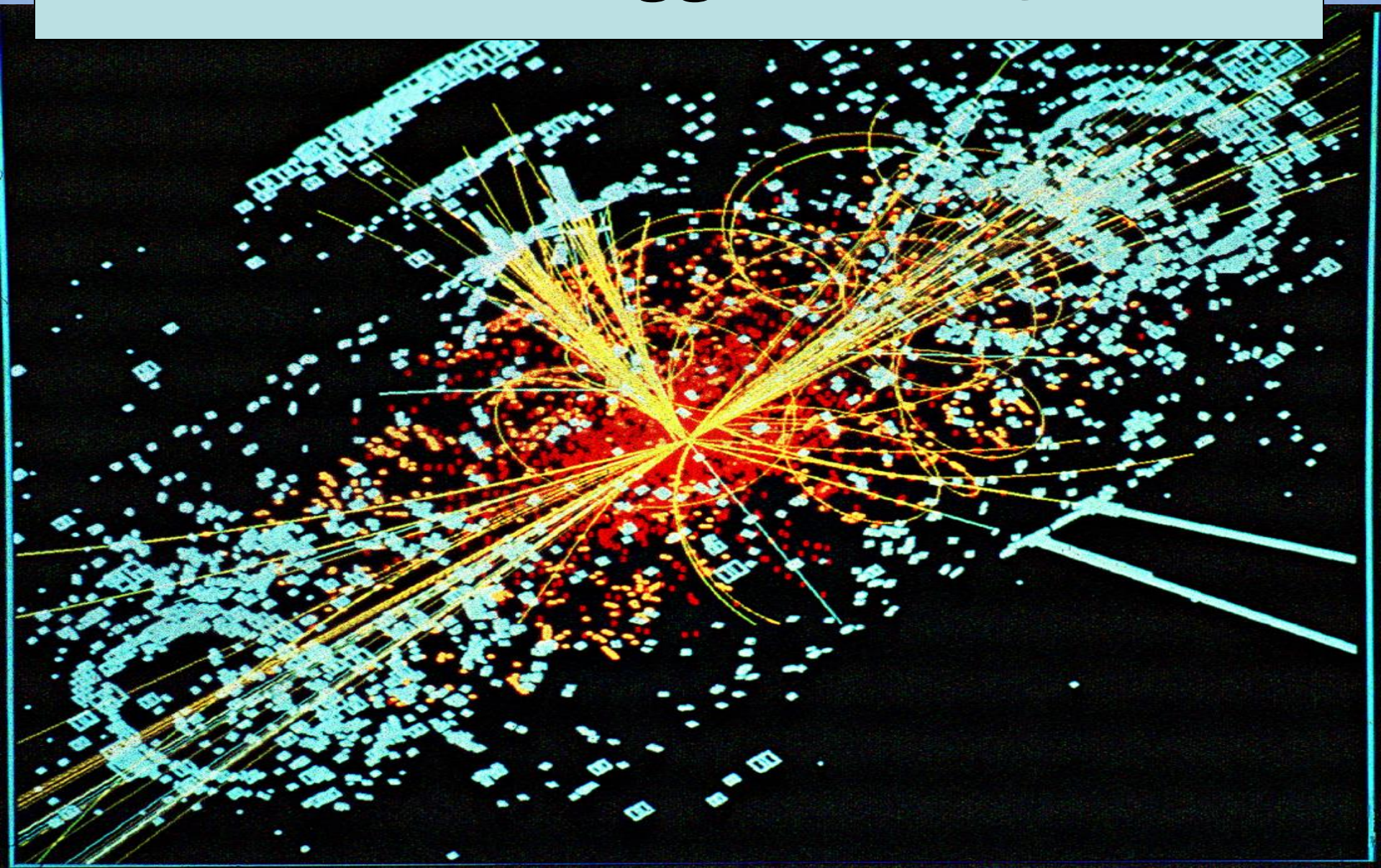
Afghanistan	1	Bolivia	4	Egypt	31	Kazakhstan	5	Mongolia	2	Philippines	3
Albania	3	Bosnia & Herzegovina	2	El Salvador	1	Kenya	3	Montenegro	11	Saint Kitts and Nevis	1
Algeria	14	Brazil	135	Estonia	15	Korea Rep.	185	Morocco	20	Saudi Arabia	2
Argentina	27	Burundi	1	Georgia	46	Kyrgyzstan	1	Myanmar	1	Senegal	1
Armenia	19	Cameroon	1	Ghana	1	Latvia	2	Nepal	10	Singapore	4
Australia	31	Canada	161	Hong Kong	1	Lebanon	23	New Zealand	5	South Africa	56
Azerbaijan	10	Chile	20	Iceland	3	Luxembourg	2	Nigeria	3	Sri Lanka	6
Bangladesh	11	China	510	Indonesia	11	Madagascar	4	North Korea	1	Sudan	1
Belarus	48	Colombia	45	Iran	51	Malaysia	15	Oman	3	Swaziland	1
Benin	1	Croatia	41	Iraq	1	Malta	9	Palestine (O.T.).	7	Syria	1
		Cuba	12	Ireland	16	Mauritius	1	Paraguay	2	Taiwan	51
		Ecuador	6	Jordan	1	Mexico	82	Peru	7	Thailand	22
										T.F.Y.R.O.M.	2
										Tunisia	5
										Uruguay	1
										Uzbekistan	4
										Venezuela	10
										Viet Nam	13
										Zambia	1
										Zimbabwe	2

2012: The discovery of the Higgs Boson

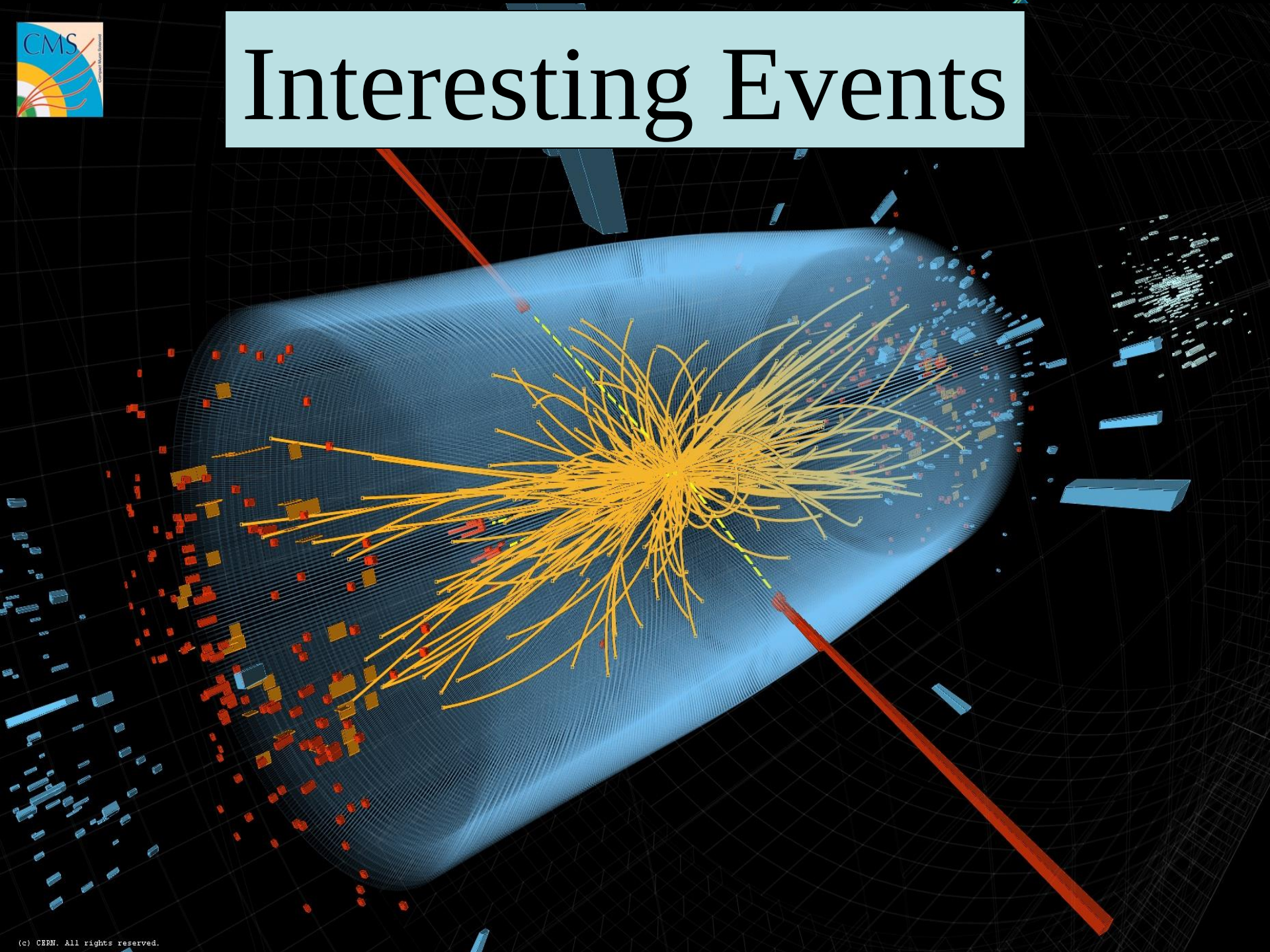


Mass Higgsteria

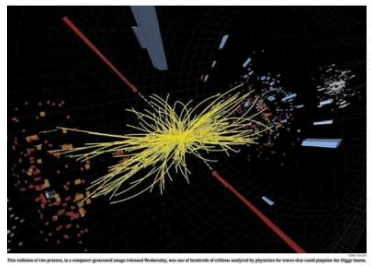
A Simulated Higgs Event @ LHC



Interesting Events

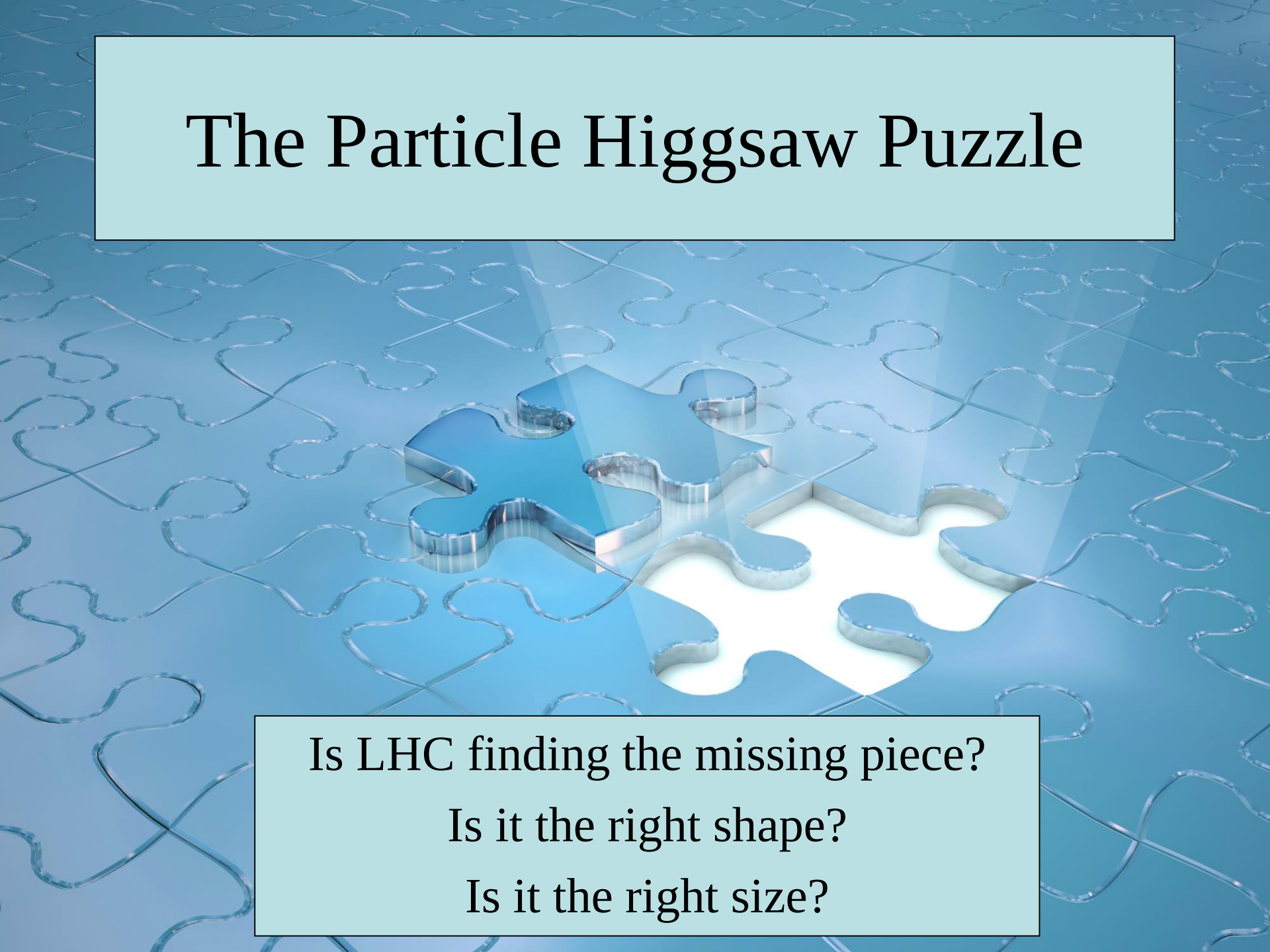


July 4th 2012
The discovery of a new particle



Higgsdependence Day!

The Particle Higgsaw Puzzle



Is LHC finding the missing piece?

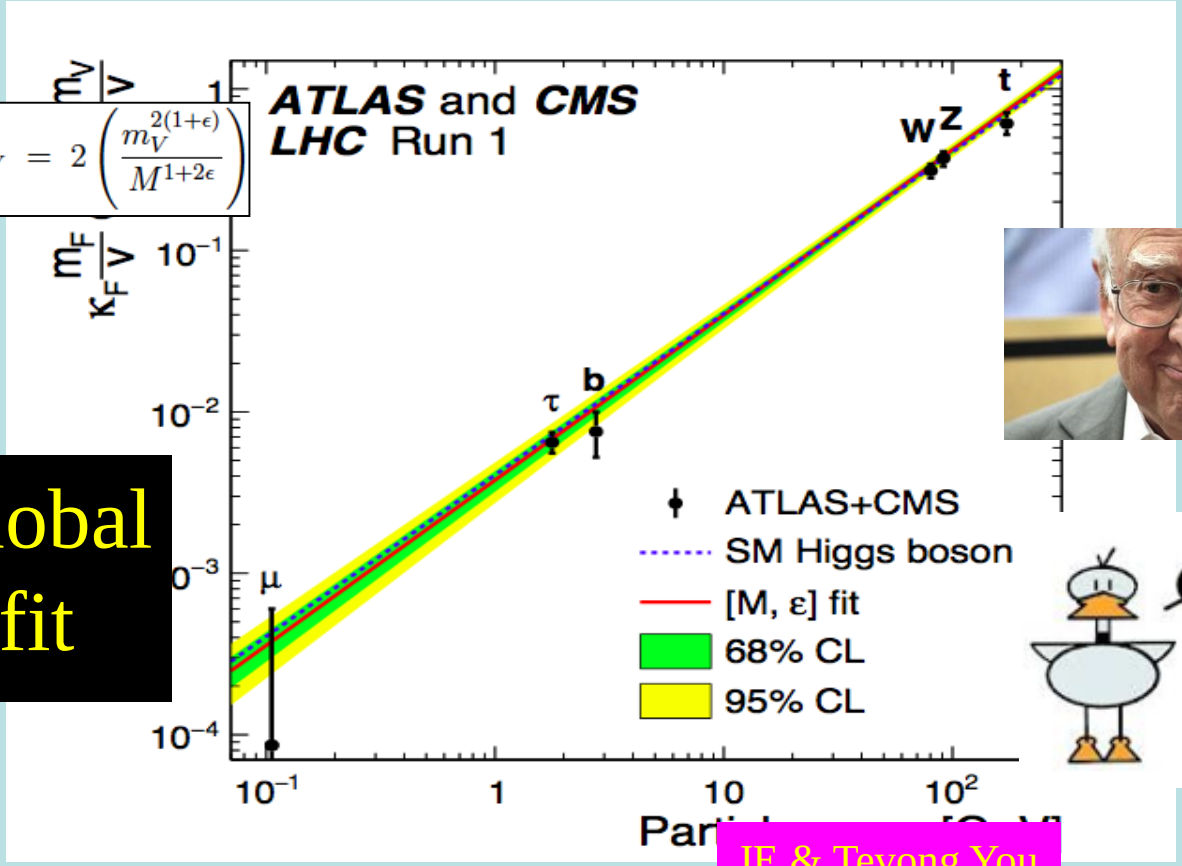
Is it the right shape?

Is it the right size?

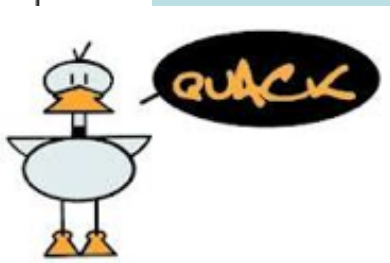
It Walks and Quacks like a Higgs

- Do couplings scale ~ mass? With scale = v?

$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$



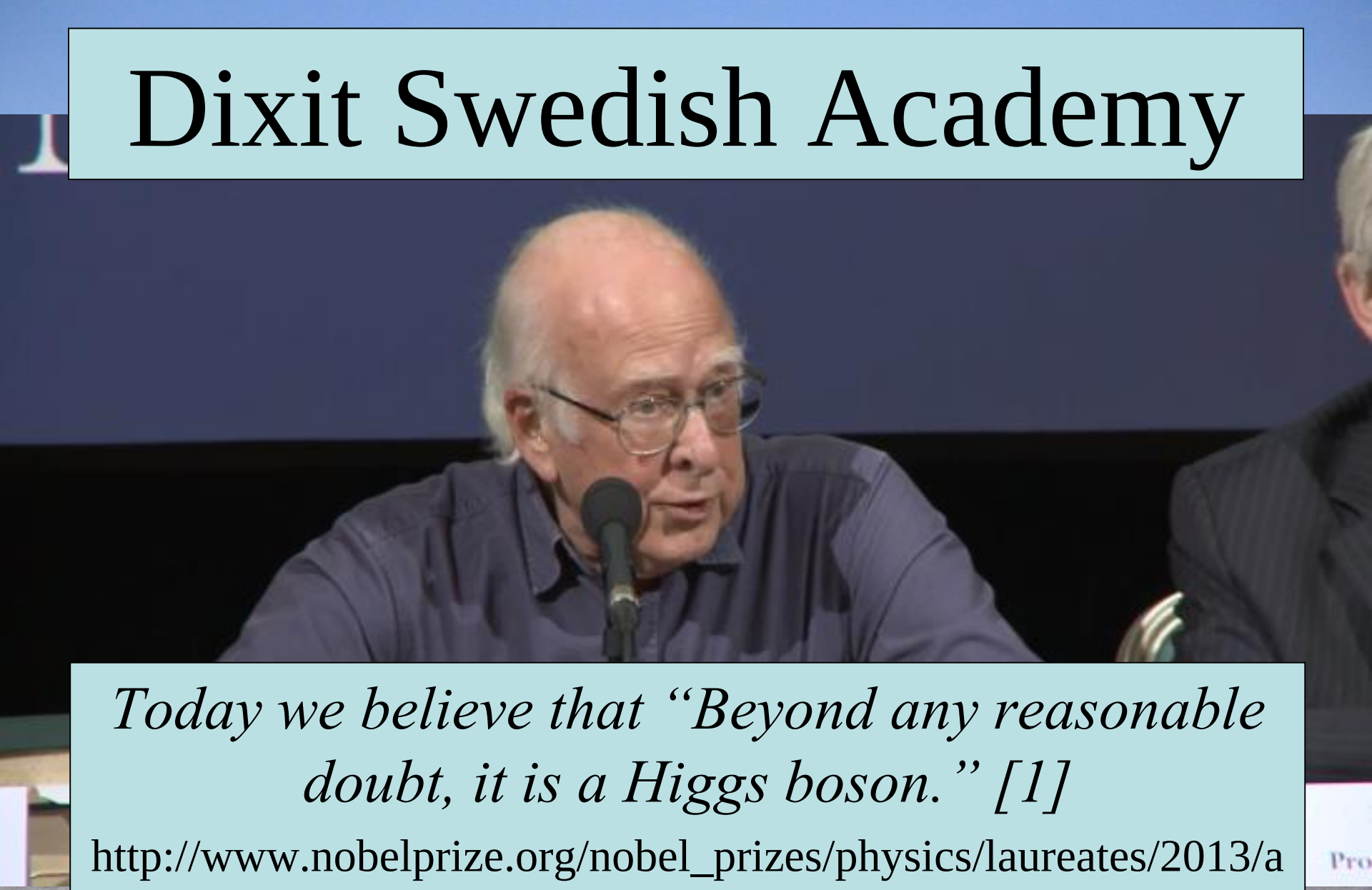
Global fit



JE & Tevong You

- **Blue** dashed line = Standard Model

Dixit Swedish Academy



Today we believe that "Beyond any reasonable doubt, it is a Higgs boson." [1]

http://www.nobelprize.org/nobel_prizes/physics/laureates/2013/advanced-physicsprize2013.pdf

[1] = JE & Tevong You, arXiv:1303.3879

Without Higgs …

… there would be no atoms

- massless electrons would escape at the speed of light

… there would be no heavy nuclei

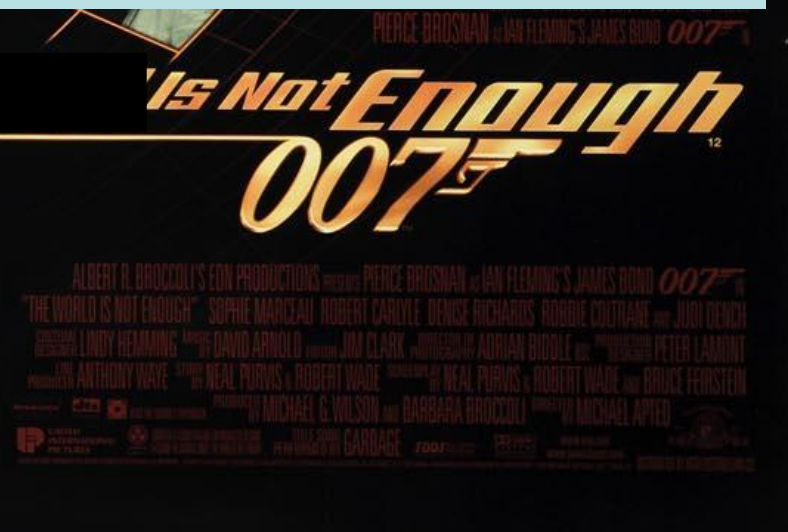
… weak interactions would not be weak

- Life would be impossible: everything would be radioactive

Its existence is a big deal!

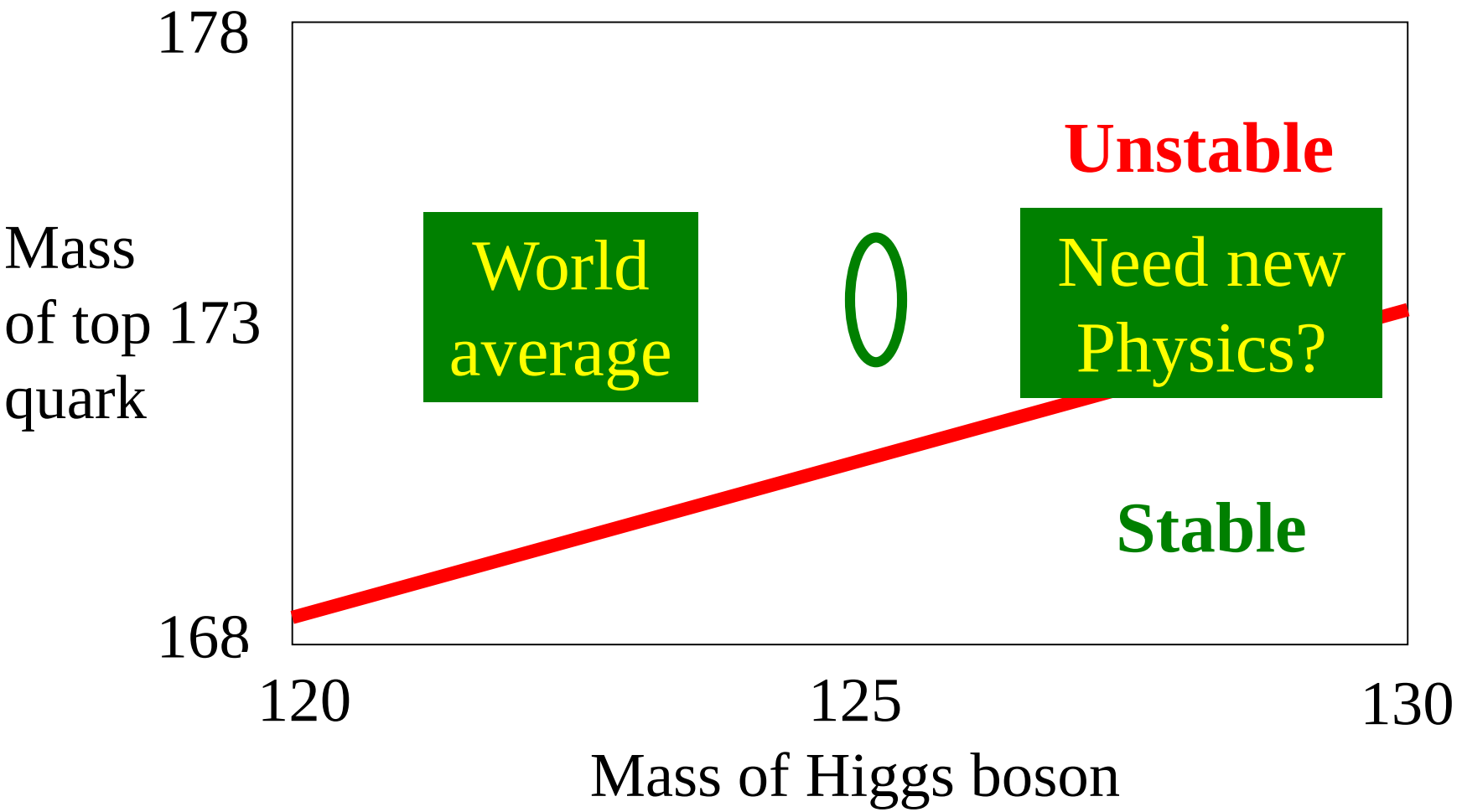
- « Empty » space is unstab LHC
- Dark matter LHC
- Origin of matter LHC
- Sizes of masses LHC
- Properties of neutrinos
- Cosmological inflation LHC
- Quantum gravity
- …

The Standard Model

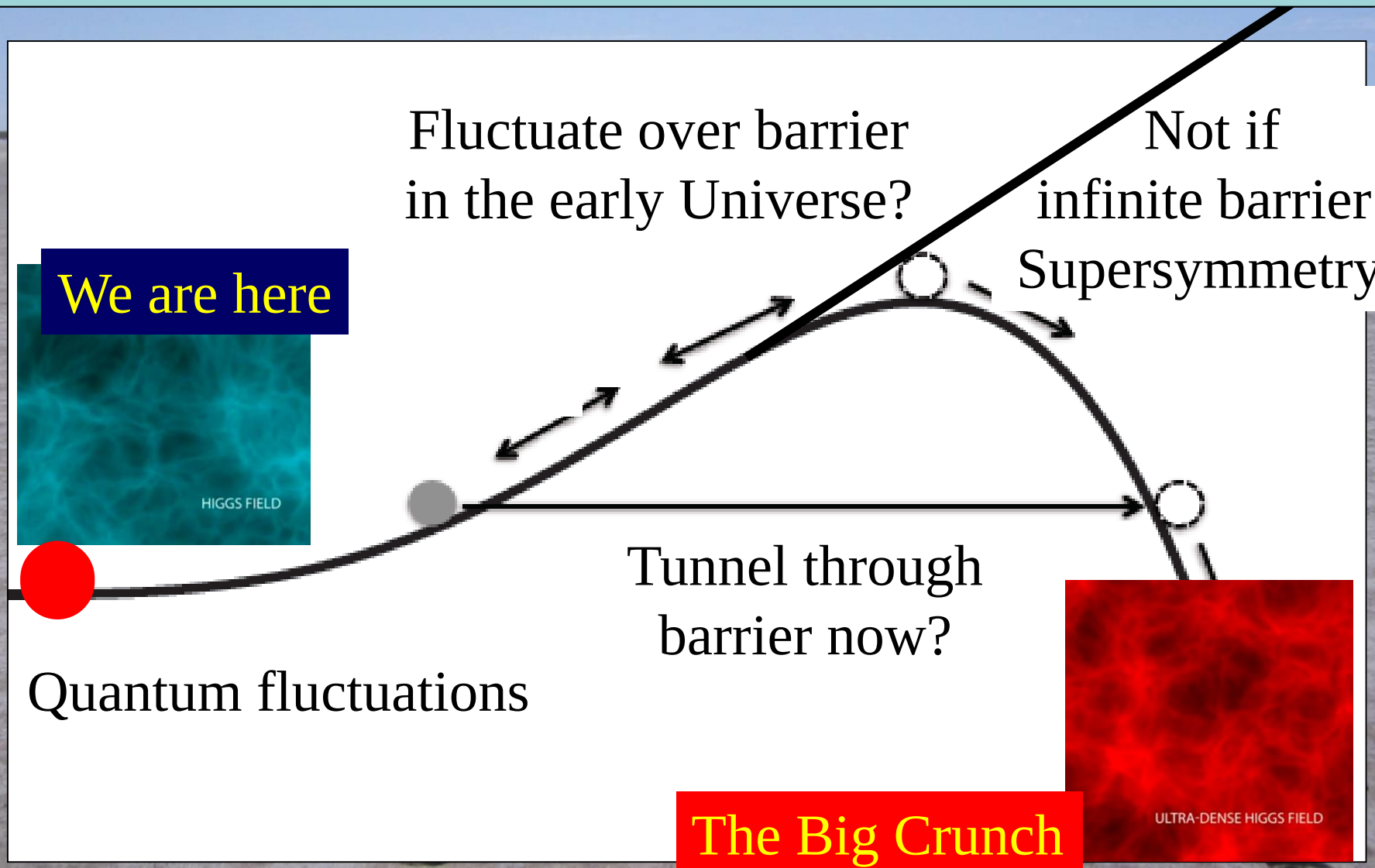


Is “Empty Space” Unstable?

- Depends on masses of Higgs boson and top quark



Should it have Collapsed already?

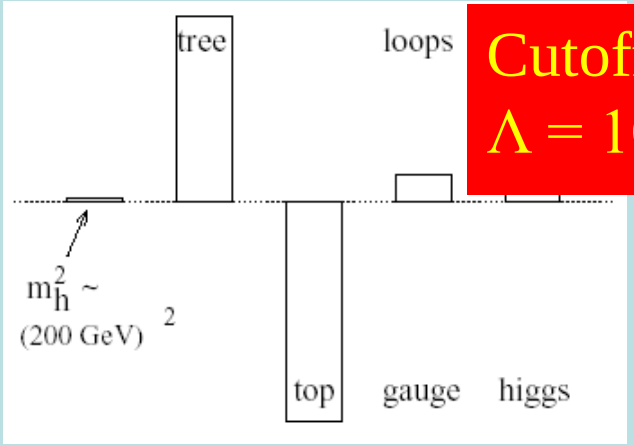


Elementary Higgs or Composite?

- Higgs field:

  $\langle 0|H|0\rangle \neq 0$

- Quantum loop problems



Cutoff
Λ = 10 TeV

Cut-off $\Lambda \sim 1$ TeV with **Supersymmetry?**

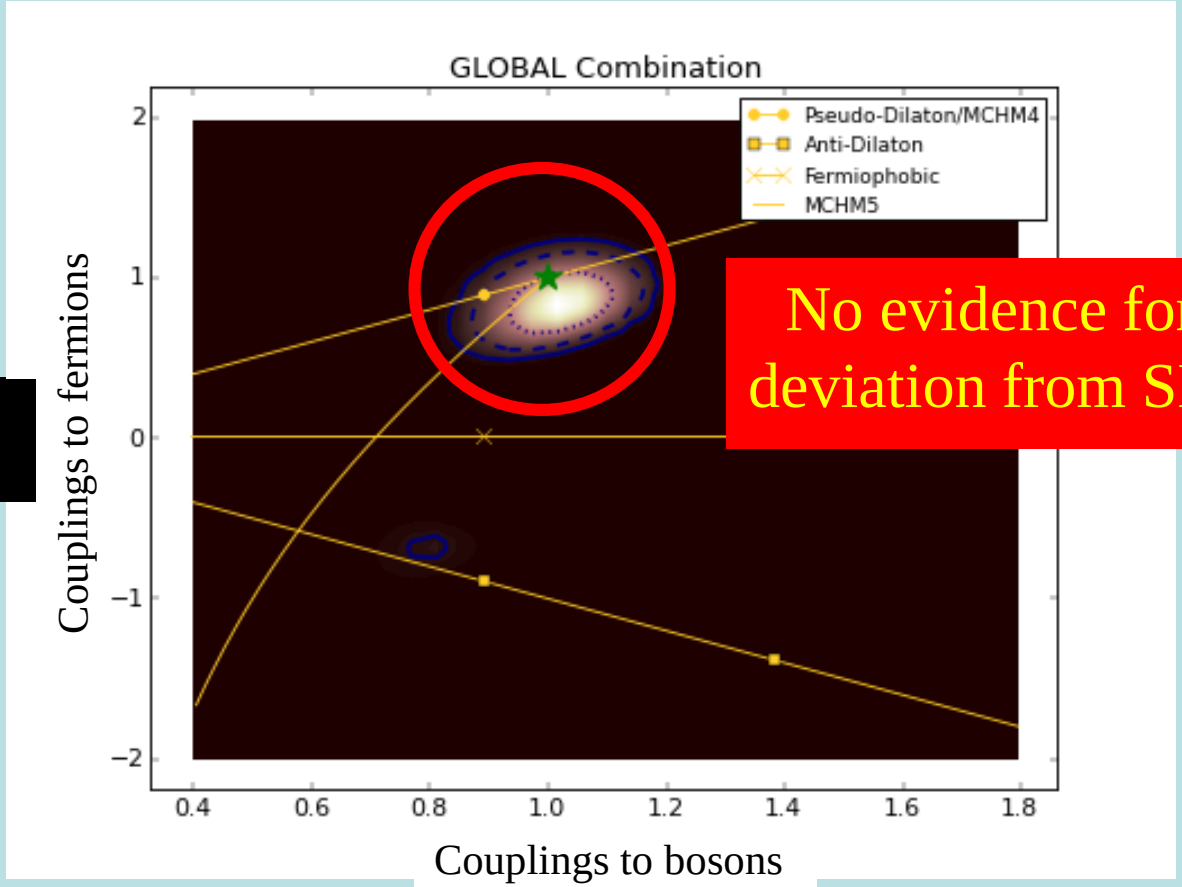
- Fermion-antifermion condensate
- Just like QCD, BCS superconductivity
- New ‘technicolour’ force?

- Heavy scalar resonance?
- **Problems with precision electroweak data**
- Pseudo-Nambu-Goldstone boson?

Global Analysis of Higgs-like Models

- Rescale couplings: to bosons by a, to fermions by c

Global



No evidence for deviation from SM

- Standard Model: $a = c = 1$

JE & Tevong You, arXiv:1303.3879

How to Explain Sizes of Masses?

- **Hierarchy problem: why is $m_W << m_P$?**
  ($m_W \sim 80$ GeV vs $m_P \sim 10^{19}$ GeV, scale of gravity)
- Alternatively, why is
  $$G_F = 1/ m_W^2 >> G_N = 1/m_P^2 \text{ ?}$$
- Or, why is
  $$V_{Coulomb} >> V_{Newton} \text{ ? } e^2 >> G\, m^2 = m^2 / m_P^2$$
- Set by hand? Beware loop corrections?
  $$\delta m_{H,W}^2 = O(\alpha/\pi)\, \Lambda^2$$
- **Naturalness problem!**
- **Cancel boson loops ⇔ fermions**
- Need $|\, m_B^2 - m_F^2| < 1$ TeV^2

What lies beyond the Standard Model?

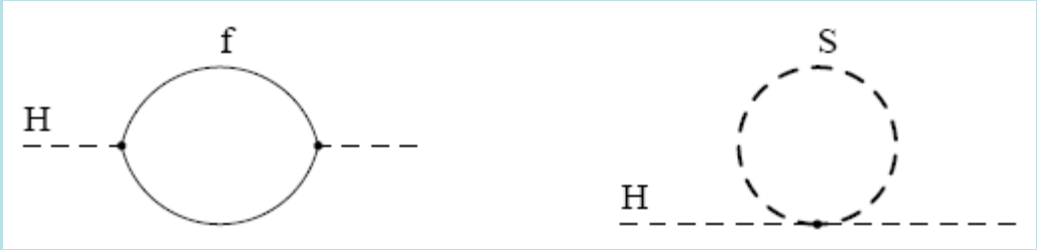
Supersymmetry

New motivations
From LHC Run 1

- **Stabilize electroweak vacuum**
- **Successful prediction for Higgs mass**
  - **Should be < 130 GeV in simple models**
- **Successful predictions for couplings**
  - **Should be within few % of SM values**
- Naturalness, GUTs, string, …, **dark matter**

Loop Corrections to Higgs Mass^2

- Consider generic fermion and boson loops:



- Each is quadratically divergent: $\int^{\Lambda} d^4k/k^2$

$$\Delta m_H^2 = -\frac{y_f^2}{16\pi^2}[2\Lambda^2 + 6m_f^2 \ln(\Lambda/m_f) + ...]$$

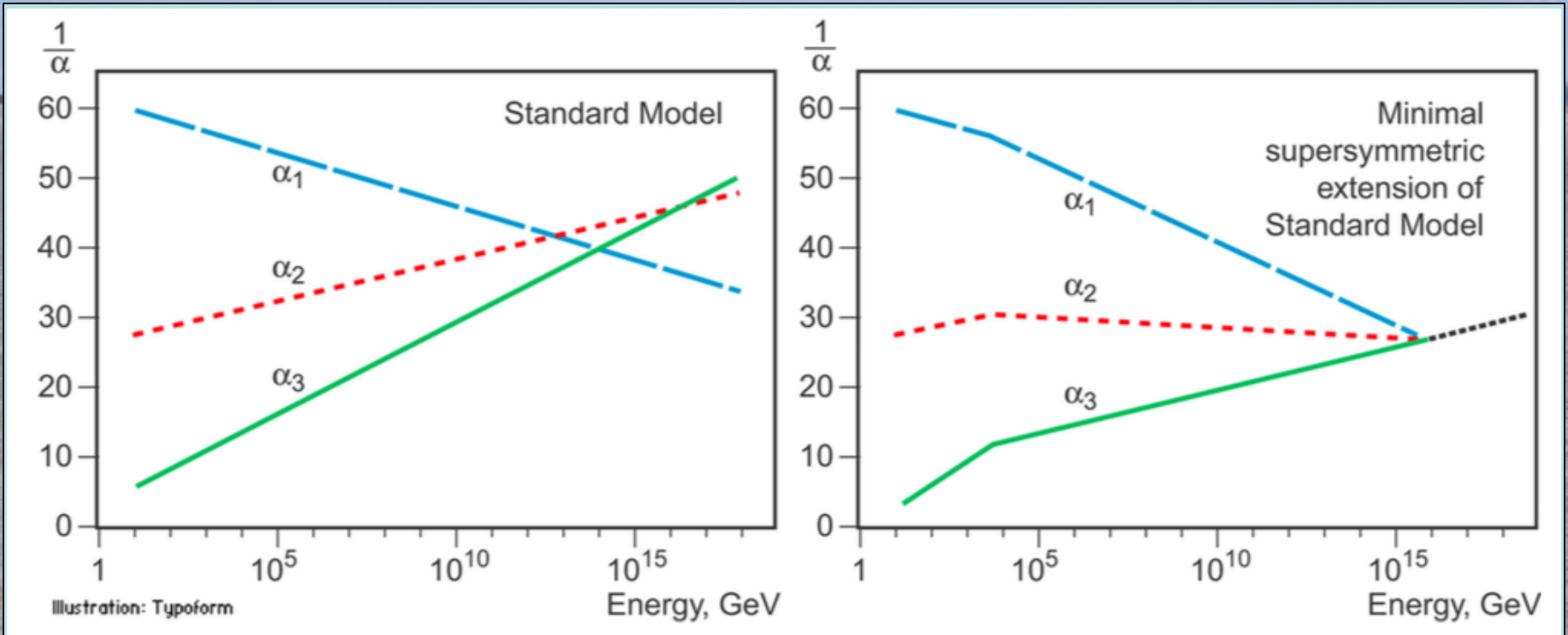
$$\Delta m_H^2 = \frac{\lambda_S}{16\pi^2}[\Lambda^2 - 2m_S^2 \ln(\Lambda/m_S) + ...]$$

- Leading divergence cancelled if

$$\lambda_S = y_f^2 \quad \text{x 2}$$

Supersymmetry!

Unification of Gauge Couplings



- **Impressive!**
- **Over-ambitious? Hubristic?**

Supersymmetry?

- Would unify matter particles and force particles
- Related particles spinning at different rates

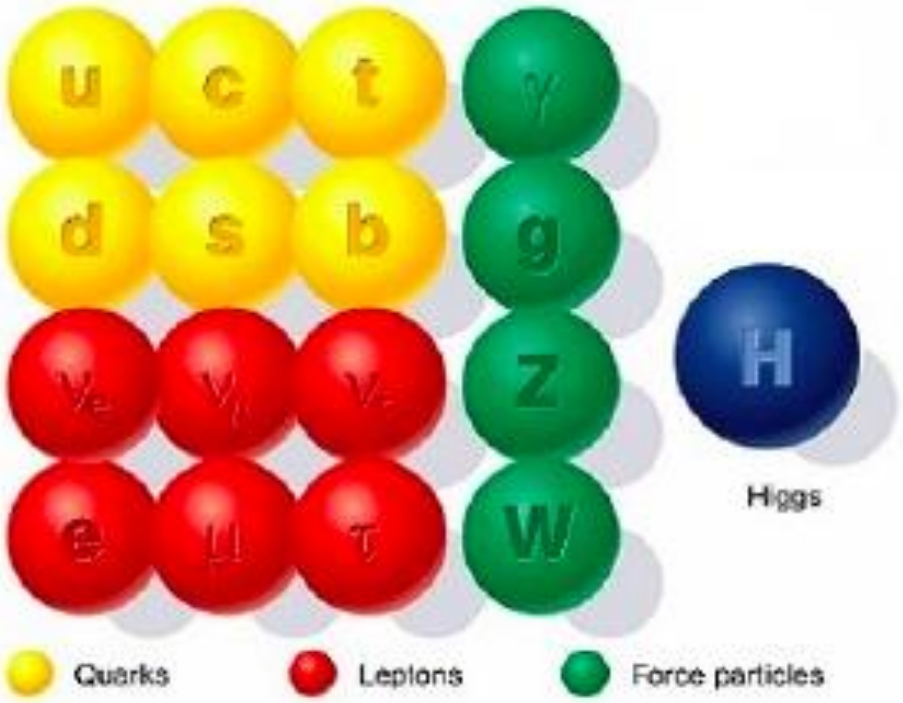
  0 - ½ - 1 - 3/2 - 2

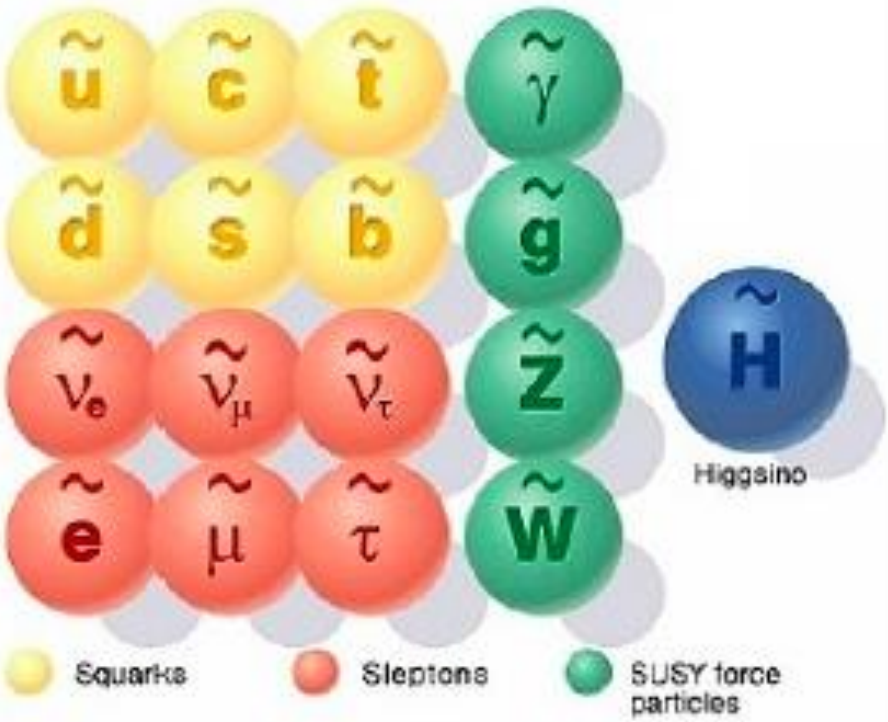
  Higgs - Electron - Photon - Gravitino - Graviton

  (Every particle is a 'ballet dancer')

  (pirouette at different speeds)
- Would help fix particle masses
- Would help unify forces
- Predicted light Higgs boson
- **Could provide dark matter for the astrophysicists and cosmologists**

Minimal Supersymmetric Extension of the Standard Model





Standard particles **SUSY particles**

The Dark Matter Hypothesis

- Proposed by Fritz Zwicky, based on observations of the Coma galaxy cluster
- The galaxies move too quickly
- The observations require a stronger gravitational field than provided by the visible matter
- **Dark matter?**

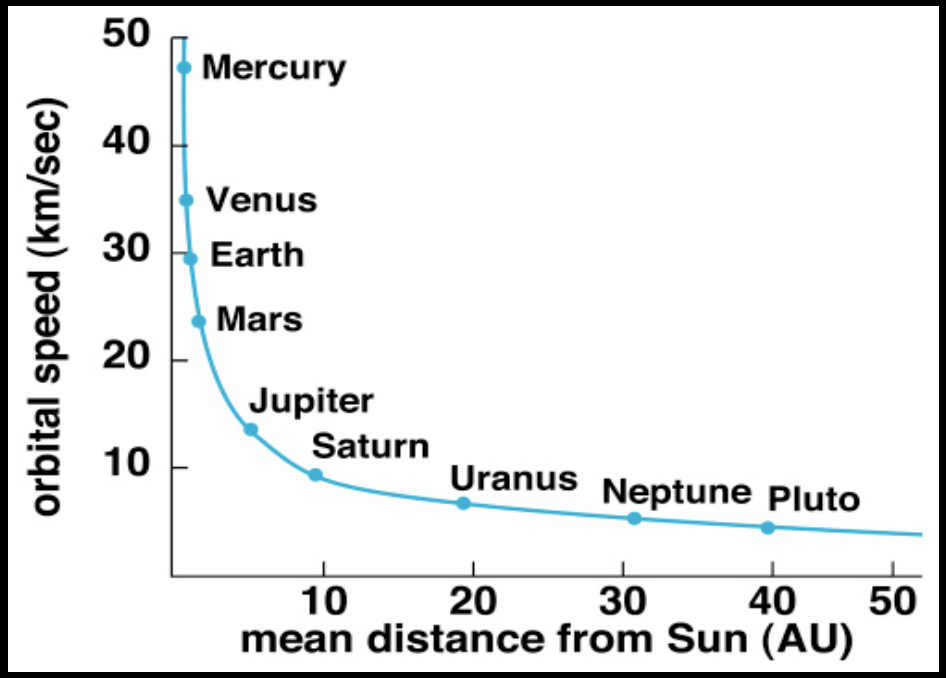
The Rotation Curves of Galaxies

- Measured by Vera Rubin
- The stars also orbit ‘too quickly’
- Her observations also required a stronger gravitational field than provided by the visible matter
- **Further strong evidence for dark matter**


Scanned at the American Institute of Physics

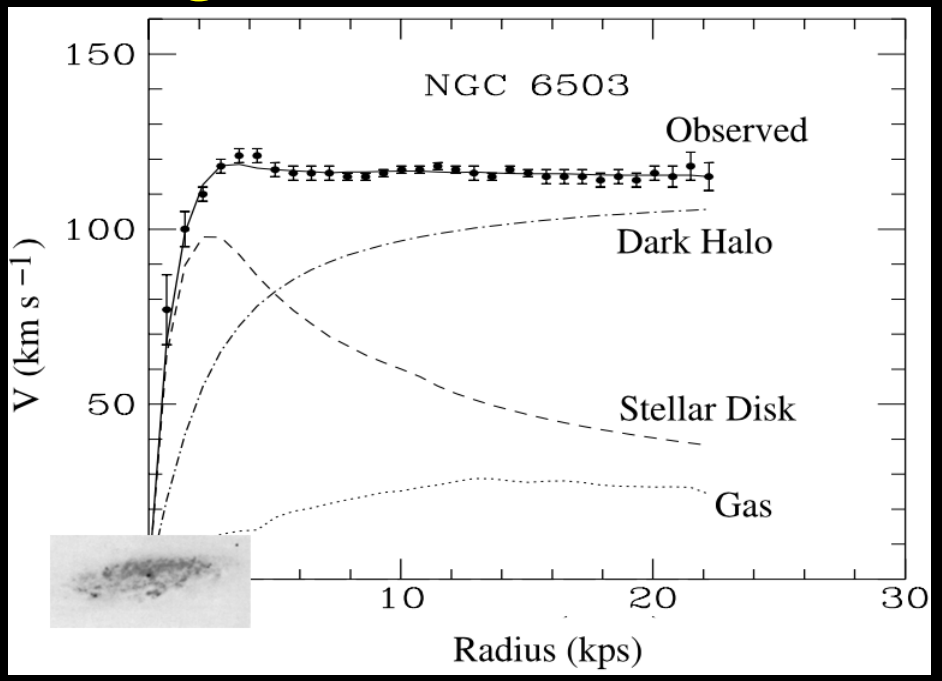
Rotation Curves

- In the Solar System



- The velocities decrease with distance from Sun
- Mass lumped at centre

- In galaxies

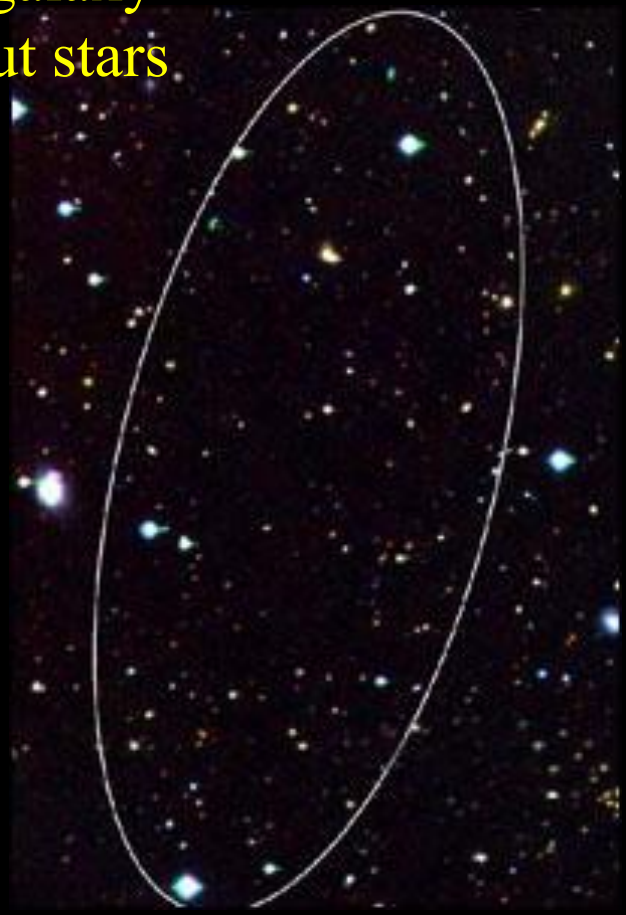


- The velocities do not decrease with distance
- Dark matter spread out

More Evidence for Dark Matter

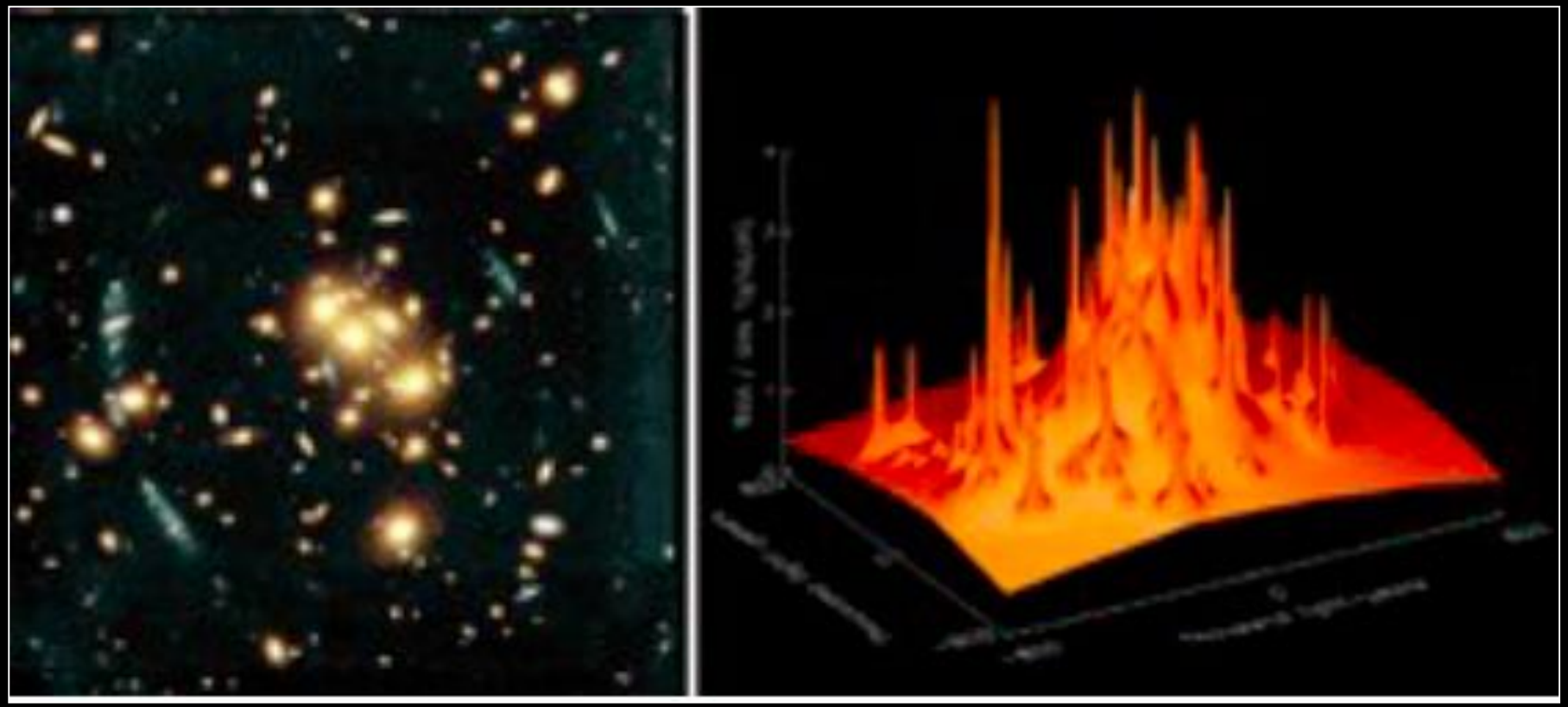
X-ray emitting gas held in place by extra dark matter

Even a 'dark galaxy' without stars



Gravitational Lensing

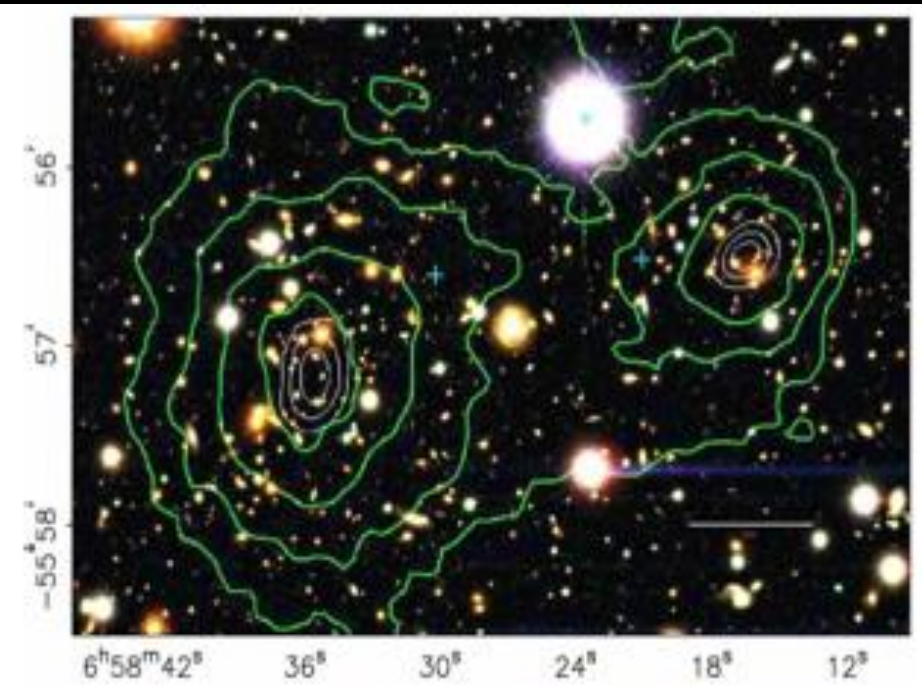
- Reveals all the matter



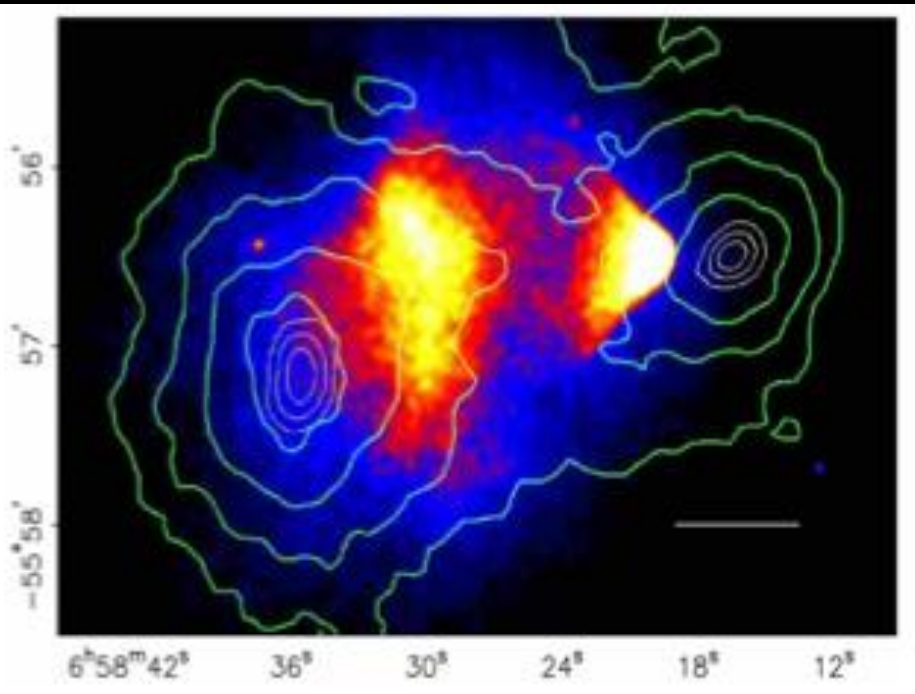
- Galaxies = peaks on a background of dark matter

More Evidence for Dark Matter

Collision between
2 clusters of galaxies:
Dark matter passes through



Collision between
2 clusters of galaxies:
Gas interacts, heats and stops

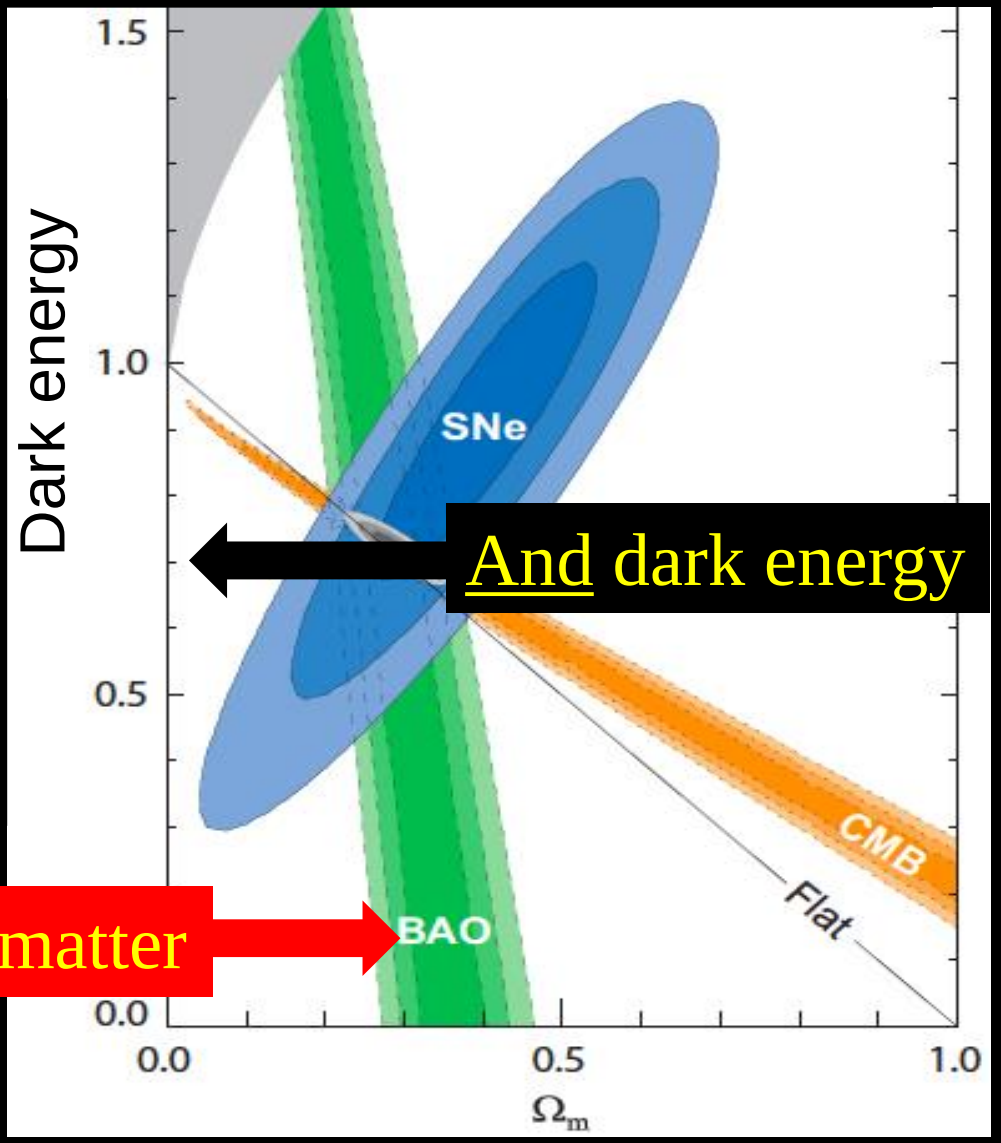


Dark Energy

- Energy density spread throughout space
- Not clustered like matter in galaxies, etc.
- Apparently ~ constant for billions of years
- Expect in many theories of fundamental physics, e.g., Higgs
- Mystery is why it is so small

The Content of the Universe

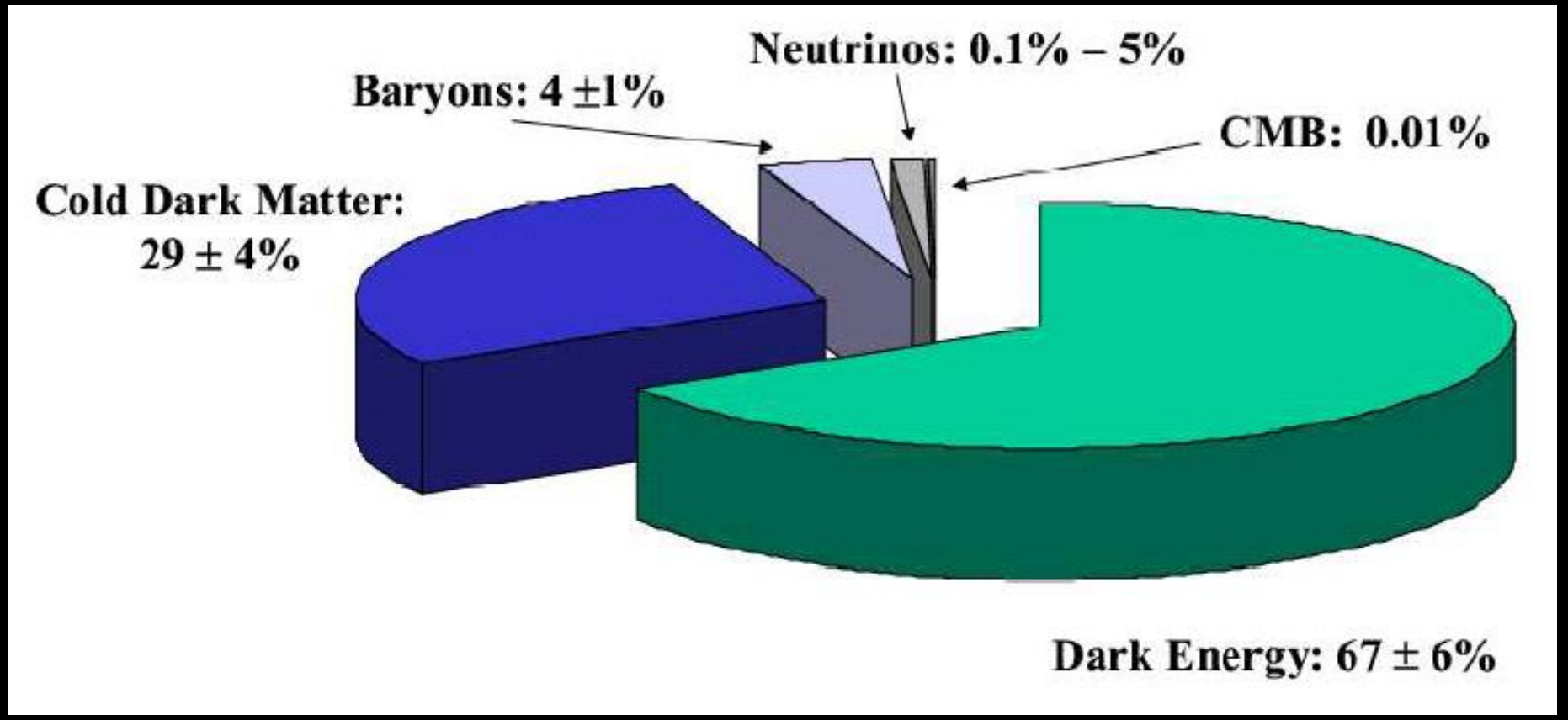
- According to
  - Microwave background
  - Supernovae
  - Structures (galaxies, clusters, …) in the Universe



And dark energy

There is dark matter

Strange Recipe for a Universe



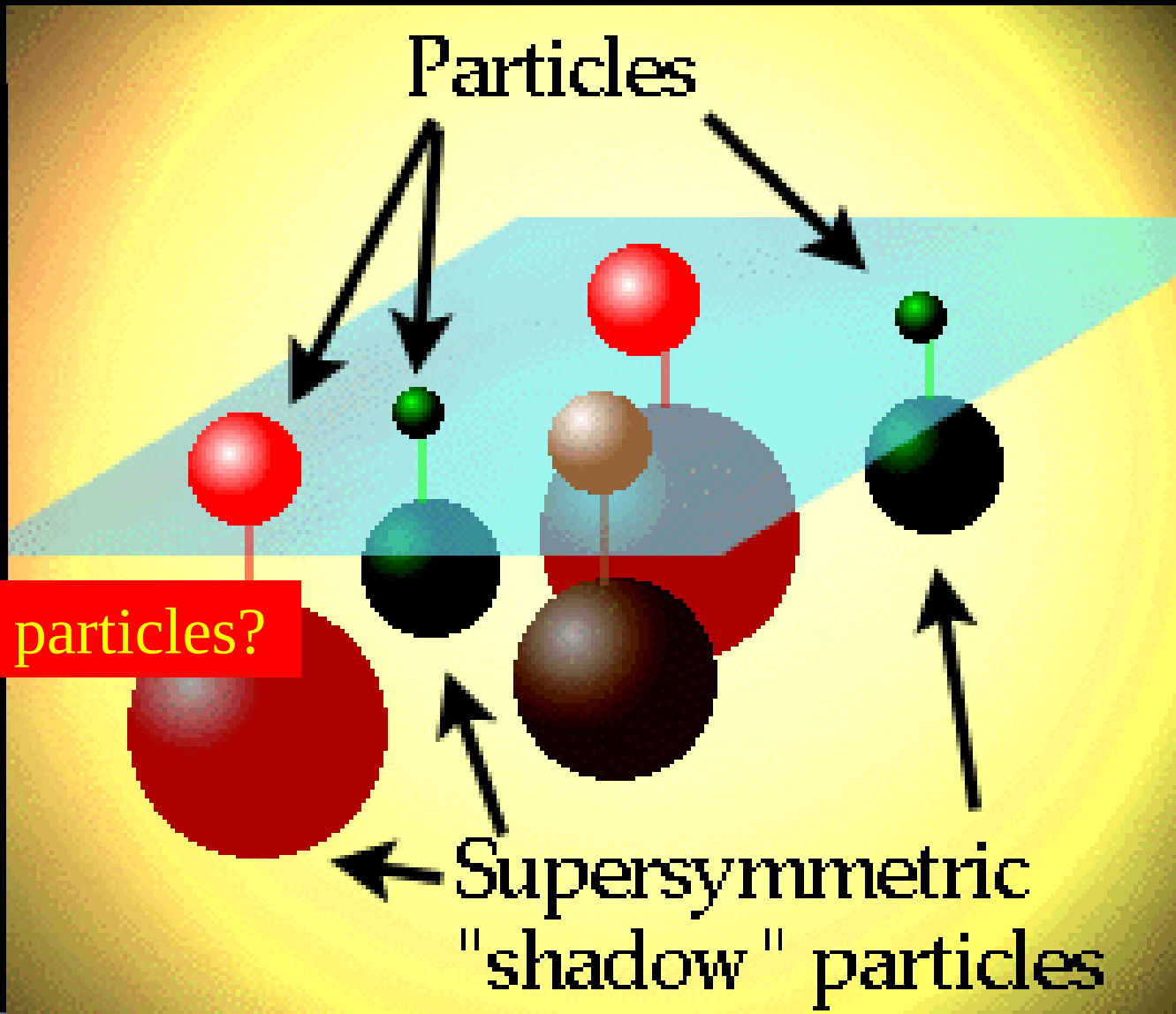
The ‘Standard Model’ of the Universe
indicated by astrophysics and cosmology

What is the Dark Matter in the Universe?

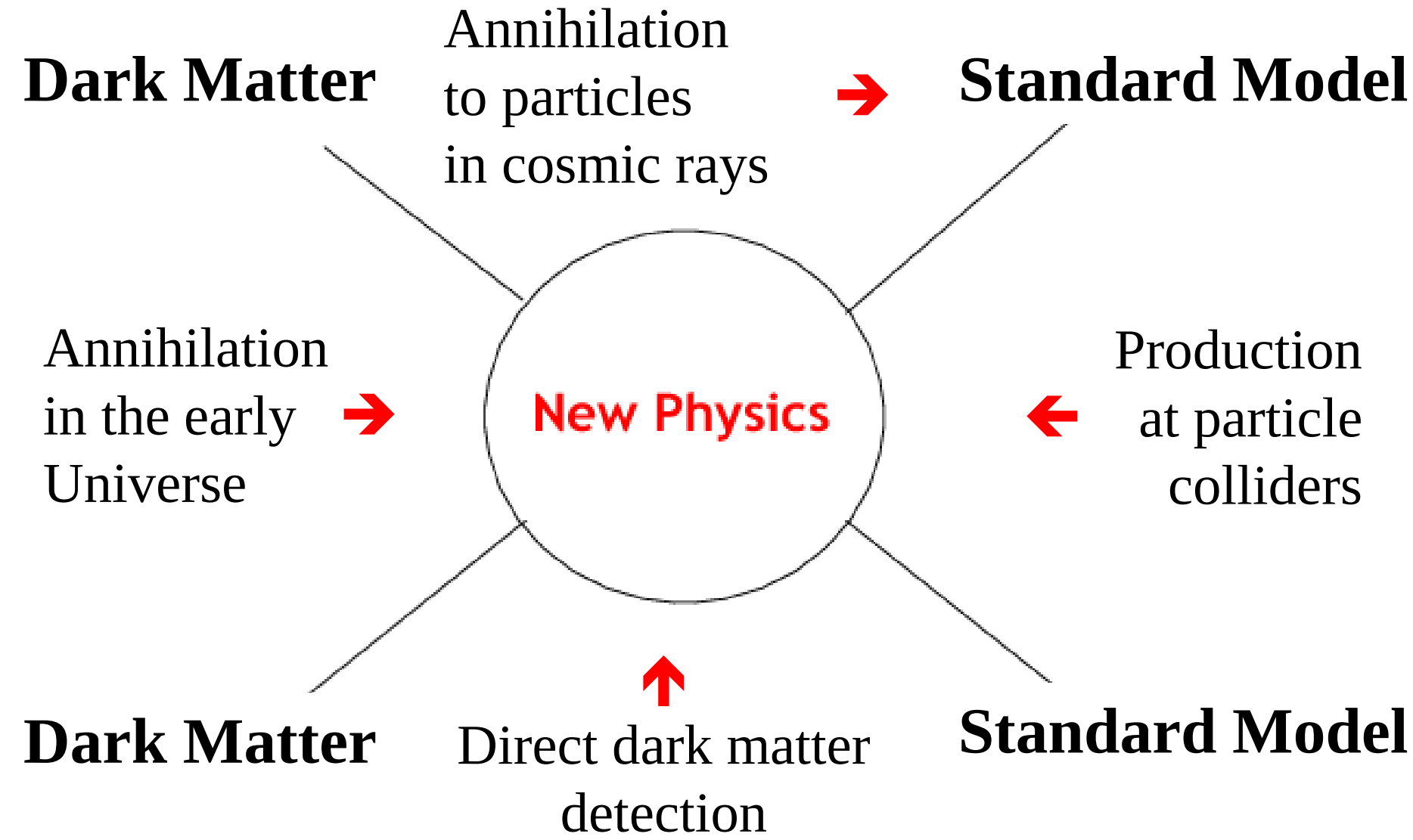
Astronomers say that most of the matter in the Universe is invisible Dark Matter

Made of unknown particles?

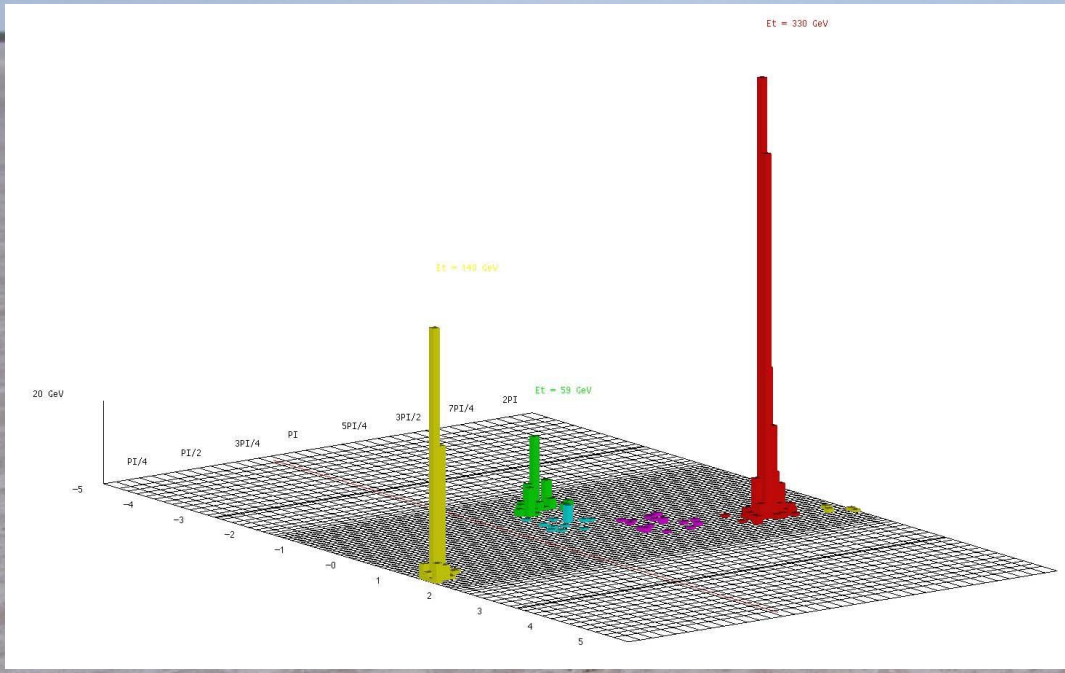
We are searching for them at the LHC

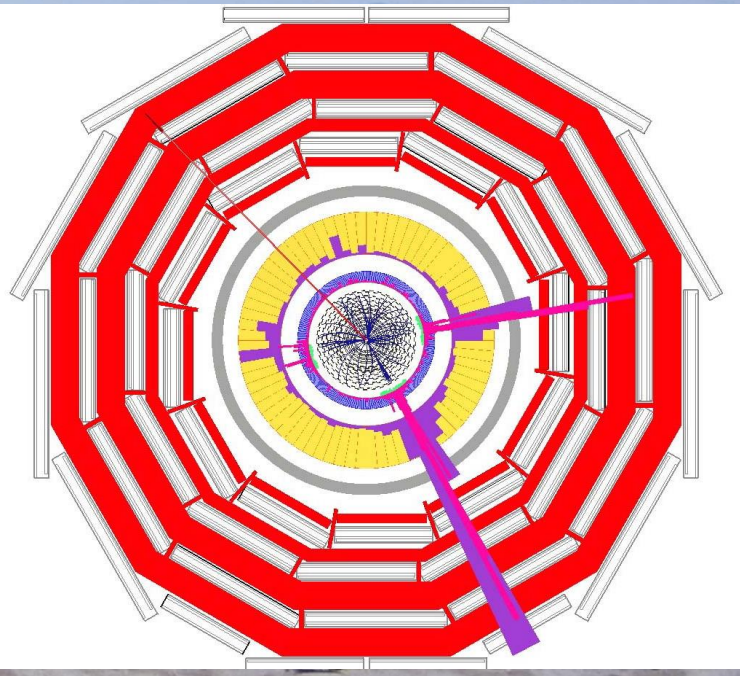


Searches for Dark Matter



Classic Dark Matter Signature



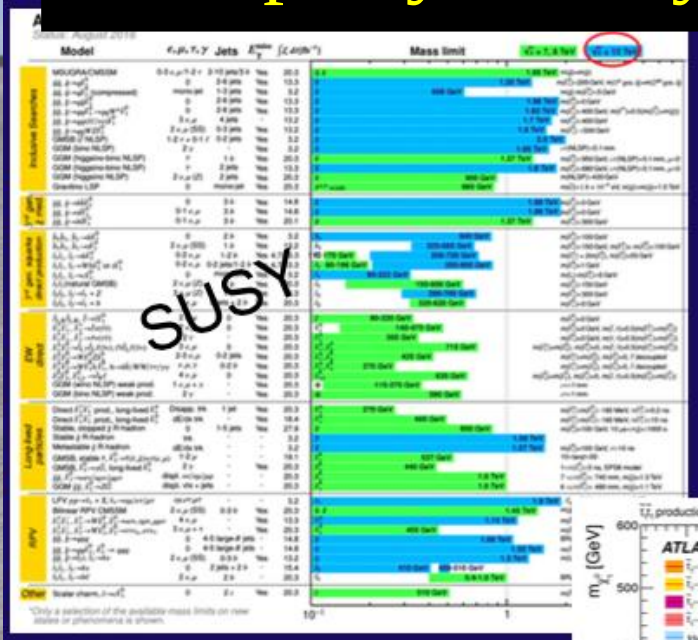


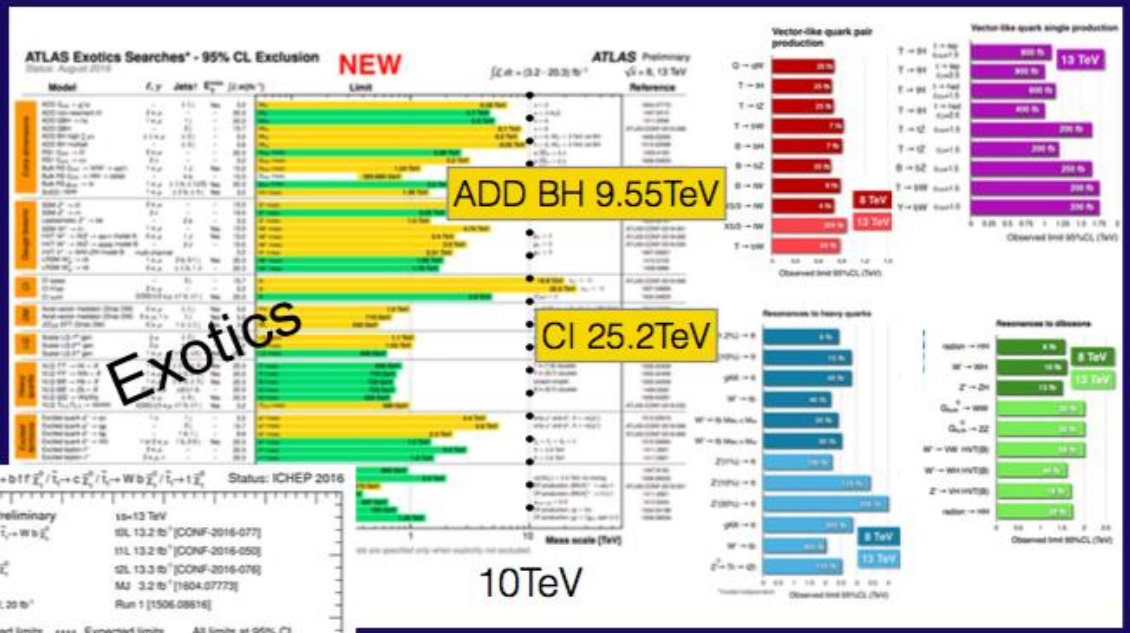
Missing transverse energy
carried away by dark matter particles

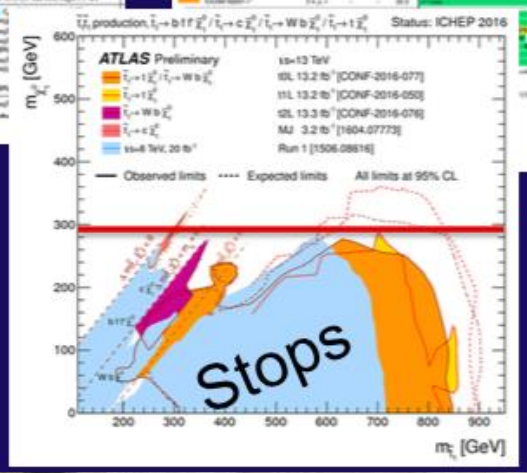
Nothing (yet) at the LHC

No supersymmetry

Nothing else, either



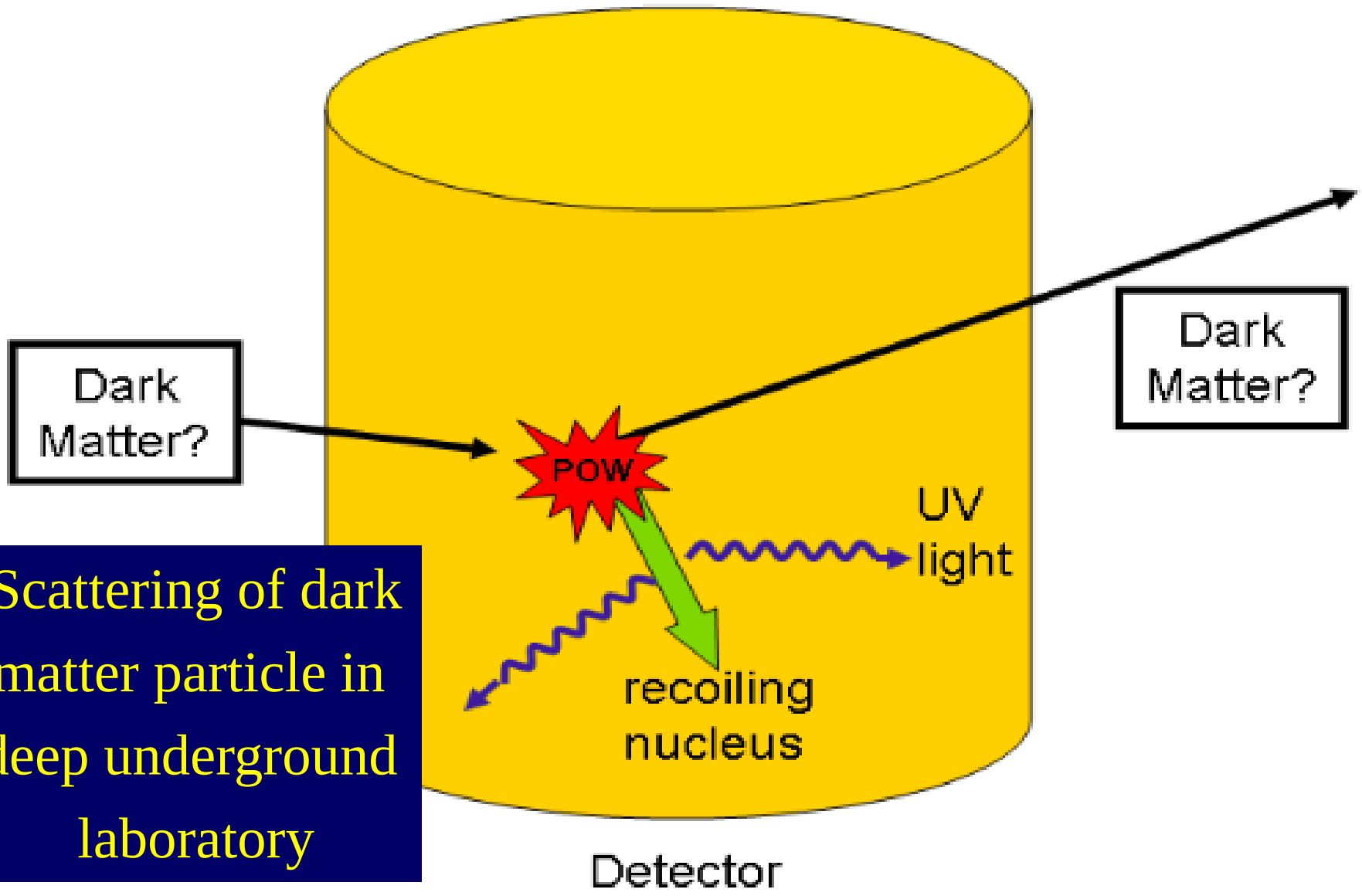




SJTU

More of same?
Unexplored nooks?
Novel signatures?

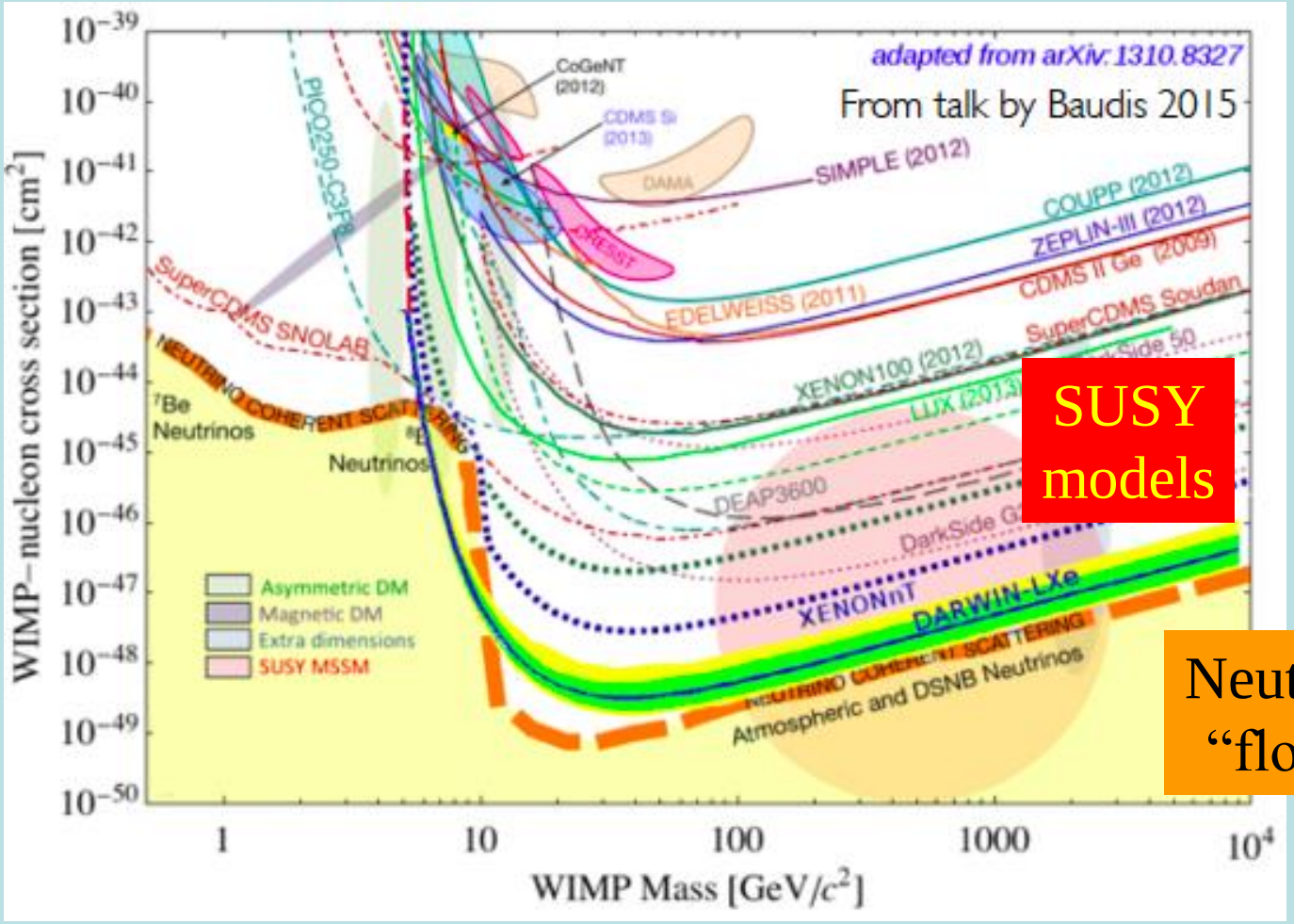
Direct Dark Matter Detection



Scattering of dark matter particle in deep underground laboratory

Direct Dark Matter Searches

- Compilation of present and future sensitivities



General Interest in Antimatter Physics

Physicists cannot make enough for
Star Trek or Dan Brown!

How do Matter and Antimatter Differ?

Dirac predicted the existence of antimatter:
- same mass
- opposite internal properties:
  - electric charge, …

Discovered in cosmic rays

Studied using accelerators

Used in PET scanners

Matter and antimatter not quite equal and opposite: WHY?

Why does the Universe mainly contain matter, not antimatter?

Experiments at LHC and elsewhere looking for answers

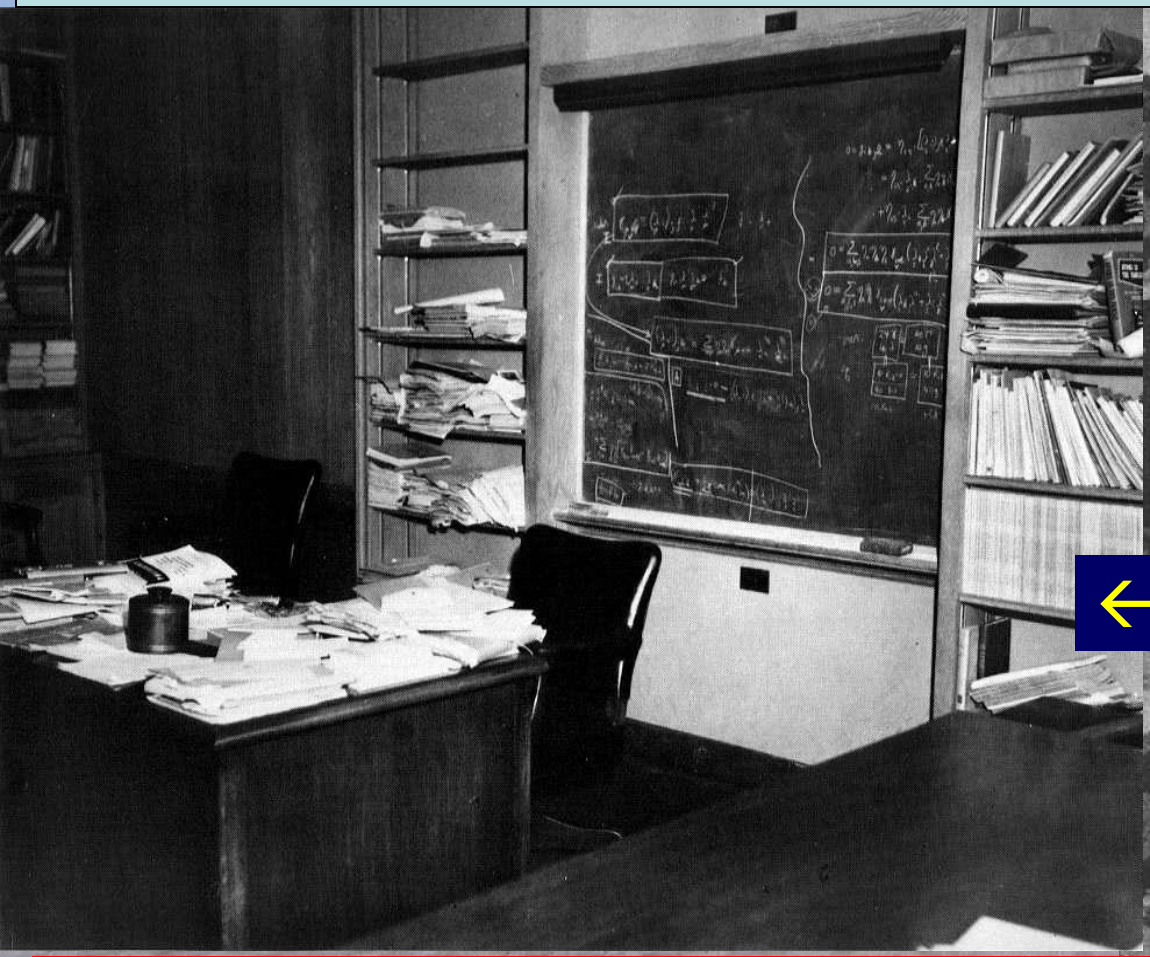
How to Create the Matter in the Universe?

Sakharov

- Need a difference between matter and antimatter
  observed in the laboratory
- Need interactions able to create matter
  predicted by theories
  not yet seen by experiment
- Need the expansion of the Universe
  a role for the Higgs boson?

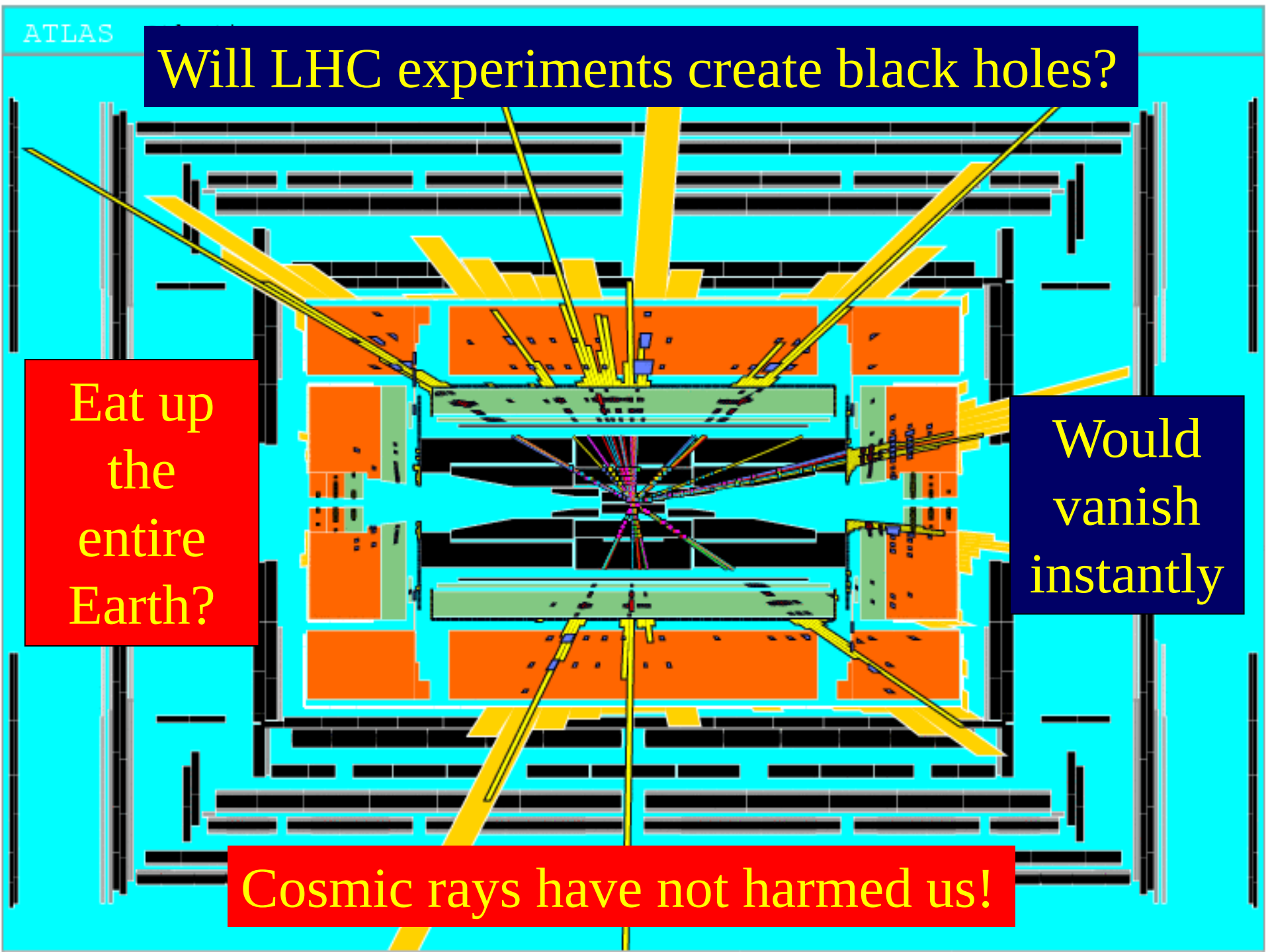
Will we be able to calculate using laboratory data?

Unify the Fundamental Interactions: Einstein's Dream …



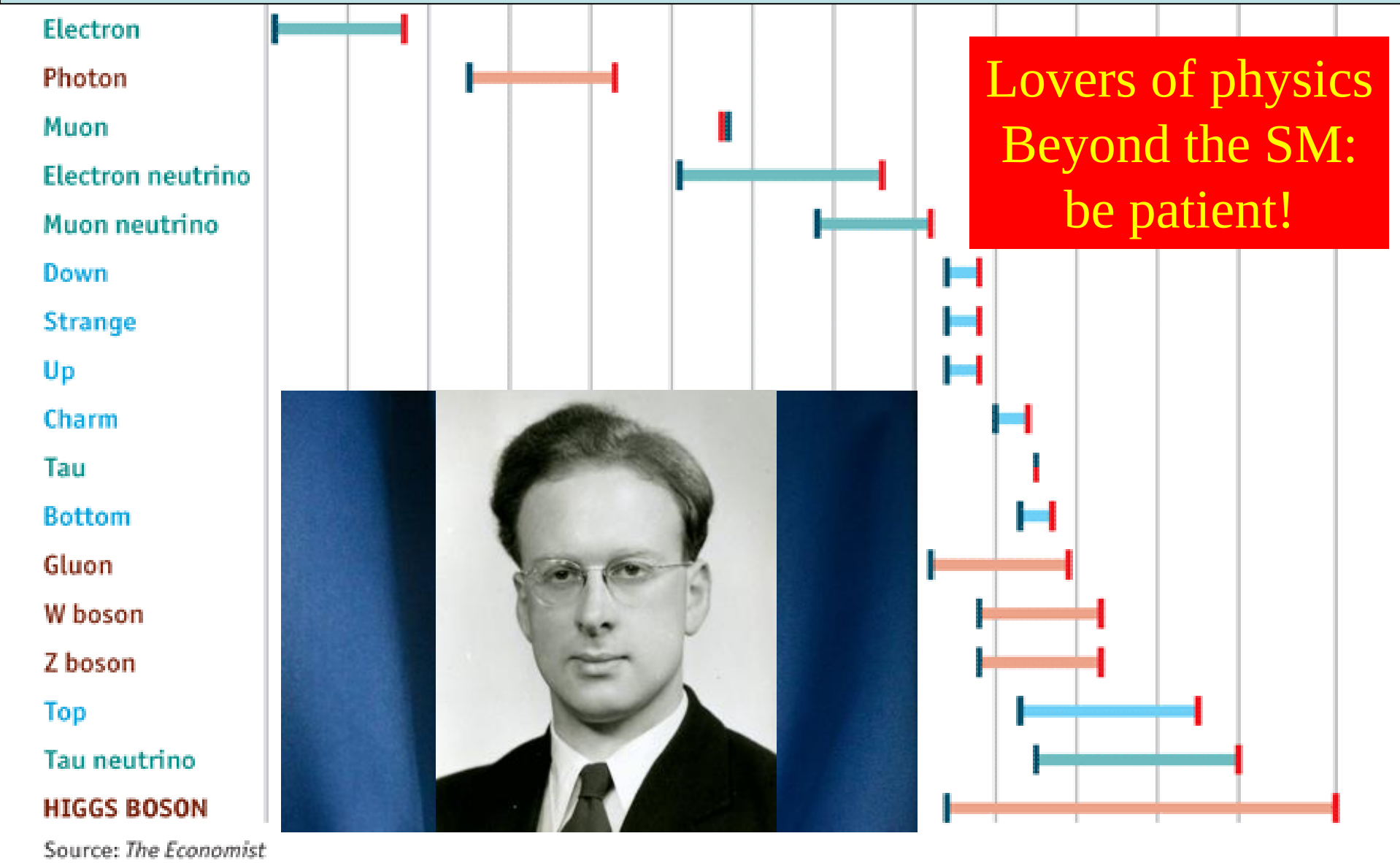
← … but he never succeeded

Unification via extra dimensions of space?


ATLAS
Will LHC experiments create black holes?
Eat up the entire Earth?
Would vanish instantly
Cosmic rays have not harmed us!


The LHC is the world's most powerful microscope …
… and also a telescope addressing Gauguin's questions

Standard Model Particles:
Years from Proposal to Discovery



Summary