Mass

Chris Quigg
Fermi National Accelerator Laboratory

Wu-Ki Tung Symposium · Michigan State University · 12 May 2007

I. Newton (1687)

Mass: *the quantity of matter …*
arising from its density and bulk conjointly

$$\mathbf{F} = m\mathbf{a}$$

+

Universal Gravitation

Measure of Inertia
Gravitational Source

Mass is conserved.

Mass of an object: summed masses of parts

Law of Conservation of Mass

Lavoisier, Lomonosov, … Dalton

↪ Atomic Theory

Classically, mass does not arise, it simply is.

(1881 · J. J. Thomson)

ca. 1900 · M. Abraham & H. A. Lorentz:
electron mass as EM self-energy?

1905 · A. Einstein:
Does the inertia of a body depend on its energy content?

The mass of a body is a measure of its energy content;
Mass is rest energy

$$m = E_0/c^2; \qquad m = (1/c^2)\sqrt{E^2 - p^2c^2}$$

Invitation to consider the origins of mass

sum of parts

rest energy

Atoms & molecules: nuclear masses, electron mass, binding energy (QED) H atom: BE ≈ 10^{-8} Mass

$2H_2 + O_2 \rightarrow 2H_2O$: $\Delta M \approx 10^{-10}$

fossil-fuel economy feeds on such tiny deviations

sum of parts

rest energy

Nuclei: nucleon masses + nuclear forces

Mass defect of ^{4}He: ¾%

proxy for a prodigious store of energy

sum of parts

rest energy

Nucleon mass: exemplar of $m = E_0/c^2$

up and down quarks contribute 1%

$$3\frac{m_u + m_d}{2} = 10 \pm 2 \text{ MeV}$$

Lattice QCD: quark confinement origin of nucleon mass has explained nearly all visible mass in the Universe

up and down quark masses are crucial

$$\boxed{M_n - M_p = 1.29 \text{ MeV}}$$

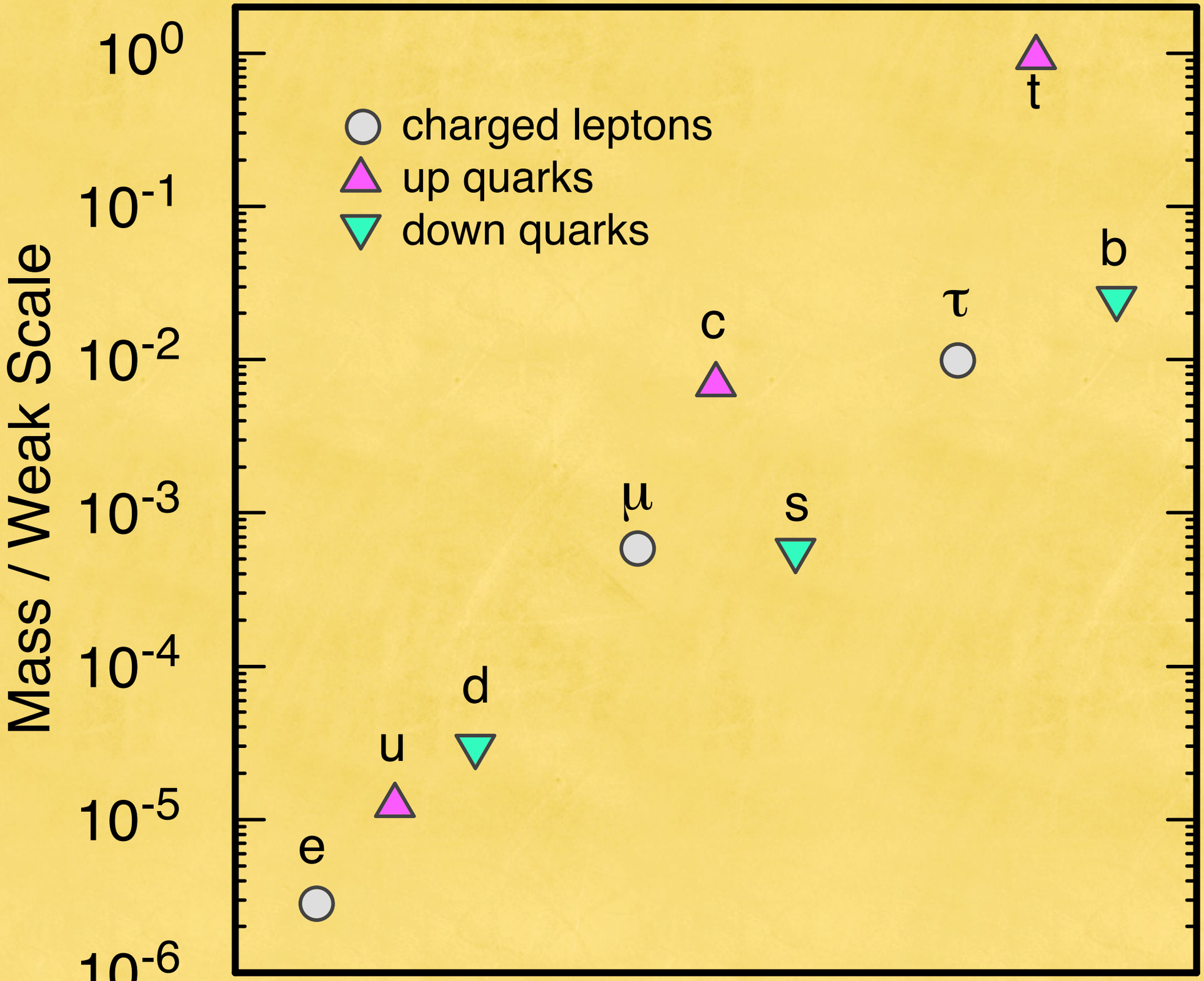
$m_d > m_u$ overcomes electrostatic energy, so proton is lightest nucleus

$p = uud, n = udd$

The Higgs boson is *not*
the source of all mass
in the Universe

The Higgs boson & EWSB are of capital importance:

- Masses of weak force particles:
  gauge couplings x *vev*
- Quark & lepton masses?
  Yukawa couplings x *vev*


charged leptons
up quarks
down quarks
Mass / Weak Scale
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
t
b
τ
c
μ
s
d
u
e

The Higgs boson is *not*
the source of all mass
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The Higgs boson & EWSB are of capital importance:

- Masses of weak force particles:
  gauge couplings x *vev*
- Quark & lepton masses?
  Yukawa couplings x *vev*
- Shaping the everyday world
  Why atoms? chemical bonds? stable structures?

Imagine a world without a Higgs mechanism

If electroweak symmetry were not hidden …

- Massless quarks and leptons
- QCD confines quarks into color-singlet hadrons
- *Nucleon mass little changed*
- QCD breaks EW symmetry, gives tiny W, Z masses; weak-isospin force doesn't confine
- *p outweighs n:* rapid β-decay
  ⇒ lightest nucleus is *n* … no hydrogen atom
- Some light elements from BBN, but ∞ Bohr radius
- No atoms means no chemistry, no stable composite structures like liquids, solids, …

… character of the physical world would be profoundly changed

Searching for the mechanism of electroweak symmetry breaking, we seek to understand

why the world is the way it is.

This is one of the deepest questions humans have ever pursued, and

it is coming within the reach of particle physics.

Kepler 1596

Prodromus

DISSERTATIONVM COSMOGRAPHICARVM, CONTINENS MYSTERIVM COSMOGRAPHICVM,

DE ADMIRABILI PROPORTIONE ORBIVM COELESTIVM, DEQVE CAVSIS

cœlorum numeri, magnitudinis, motuumque periodicorum genuinis & proprijs,

DEMONSTRATVM, PER QVINQVE regularia corpora Geometrica,

A

M. IOANNE KEPLERO, VVIRTEMbergico, Illustrium Styriæ prouincialium Mathematico.

Quotidiè morior, fateorque: sed inter Olympi
Dum tenet assiduas me mea cura vias:
Non pedibus terram contingo: sed ante Tonantem
Nectare, diuina pascor & ambrosiâ.

Addita est erudita NARRATIO M. GEORGII IOACHIMI RHETICI, de Libris Reuolutionum, atq; admirandis de numero, ordine, & distantijs Sphærarum Mundi hypothesibus, excellentissimi Mathematici, totiusq; Astronomiæ Restauratoris D. NICOLAI COPERNICI.

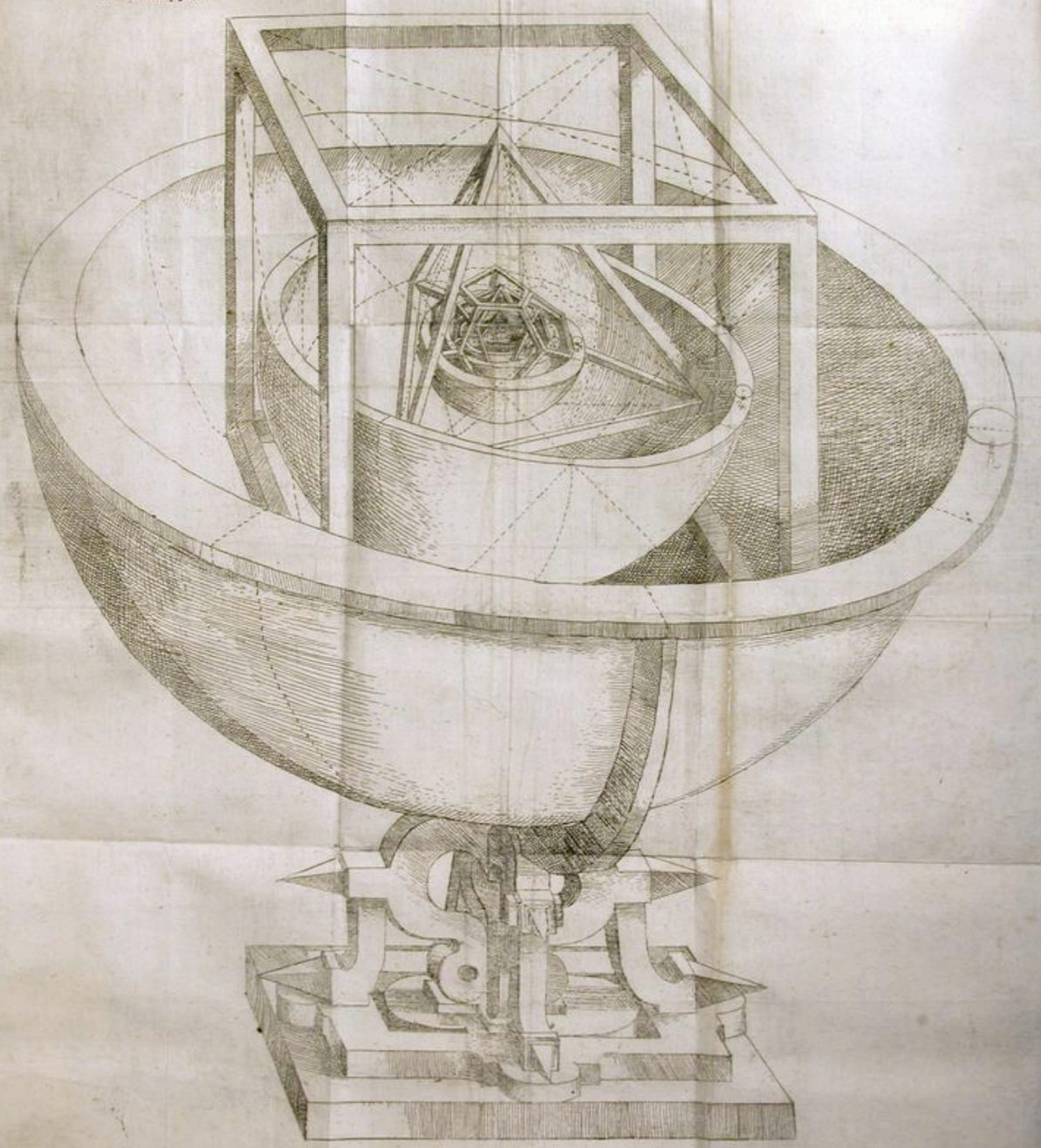
TVBINGÆ
Excudebat Georgius Gruppenbachius,
ANNO M. D. XCVI.

Congregationis S. Carli
Ludovici Viviani in Urbe Cardi.

TABVLA III. ORBIVM PLANETARVM DIMENSIONES, ET DISTANTIAS PER QVINQVE REGVLARIA CORPORA Geometrica exhibens.

ILLVSTRISSIMO PRINCIPI, AC DOMINO DOMINO FRIDERICO, DVCI VVIRTENBERGICO, ET TECCIO, COMITI MONTIS Belgarum, &c, consecrata.

Tertiæ Tabulæ pag. 24.



New Physics on the Fermi Scale

Thought experiment (1977): *WW* scattering

Electroweak theory makes sense if

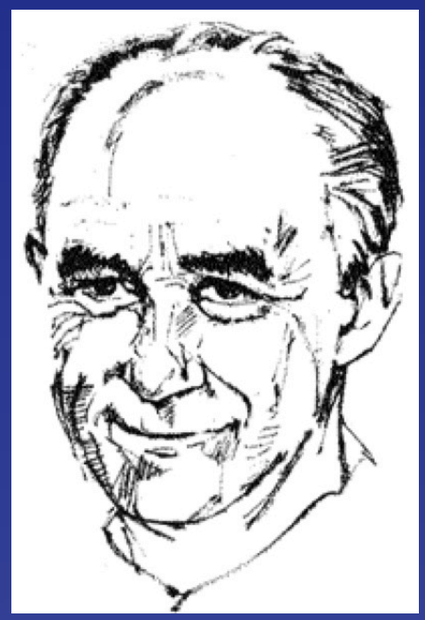
something happens

at energies around 1 TeV

Either the Higgs boson

Or strong *WW* scattering

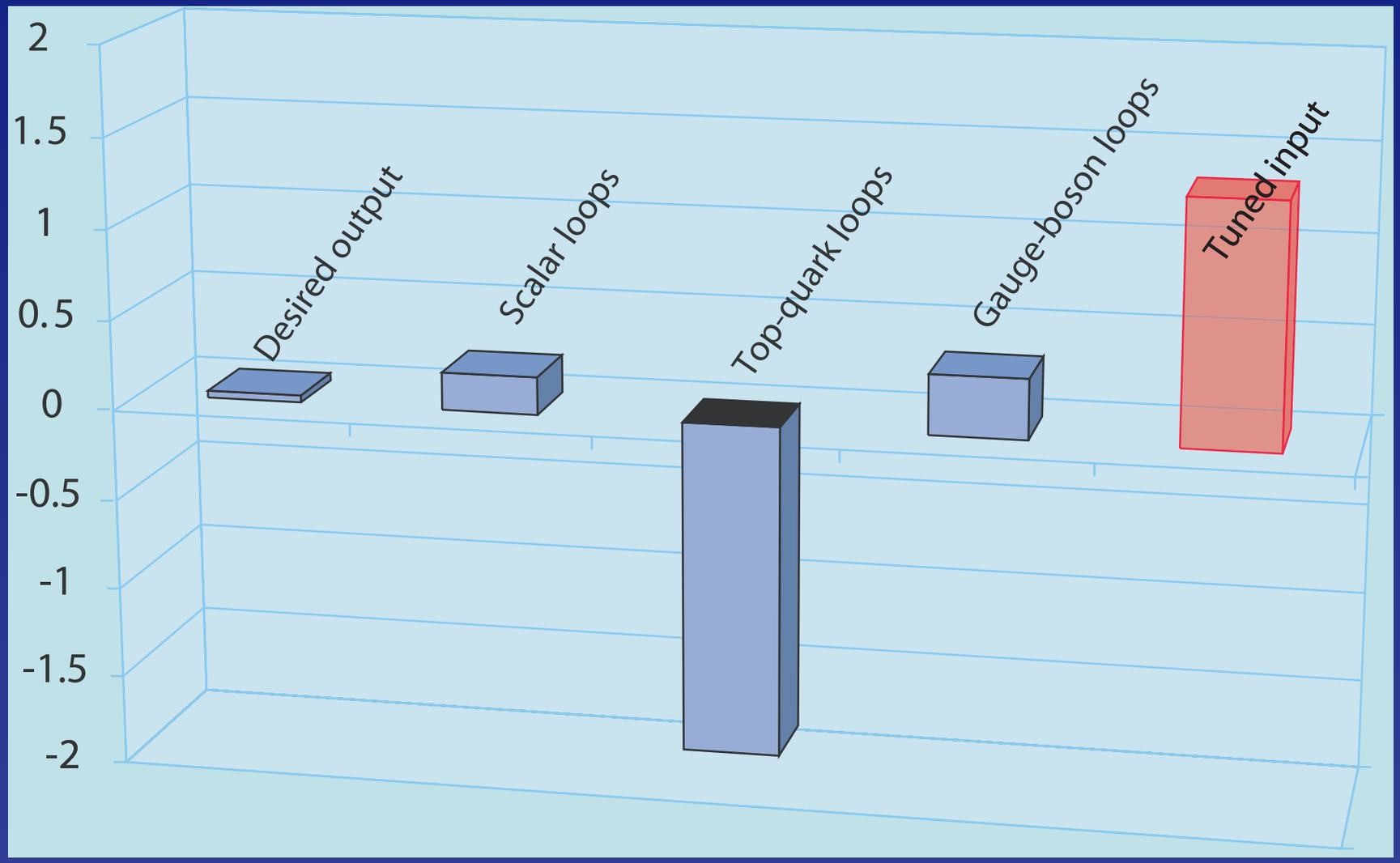
Tipping point: $M_{Higgs} < \left(\frac{8\pi\sqrt{2}}{3G_F}\right)^{1/2}$



More New Physics on the Fermi Scale?

Does M_H < 1 TeV make sense?

The peril of quantum corrections – hierarchy problem



5 TeV

More New Physics on the Fermi Scale?

Does $M_H < 1$ TeV make sense?

The peril of quantum corrections – hierarchy problem

Responses: extend electroweak theory

Supersymmetry

Technicolor

Extra spacetime dimensions

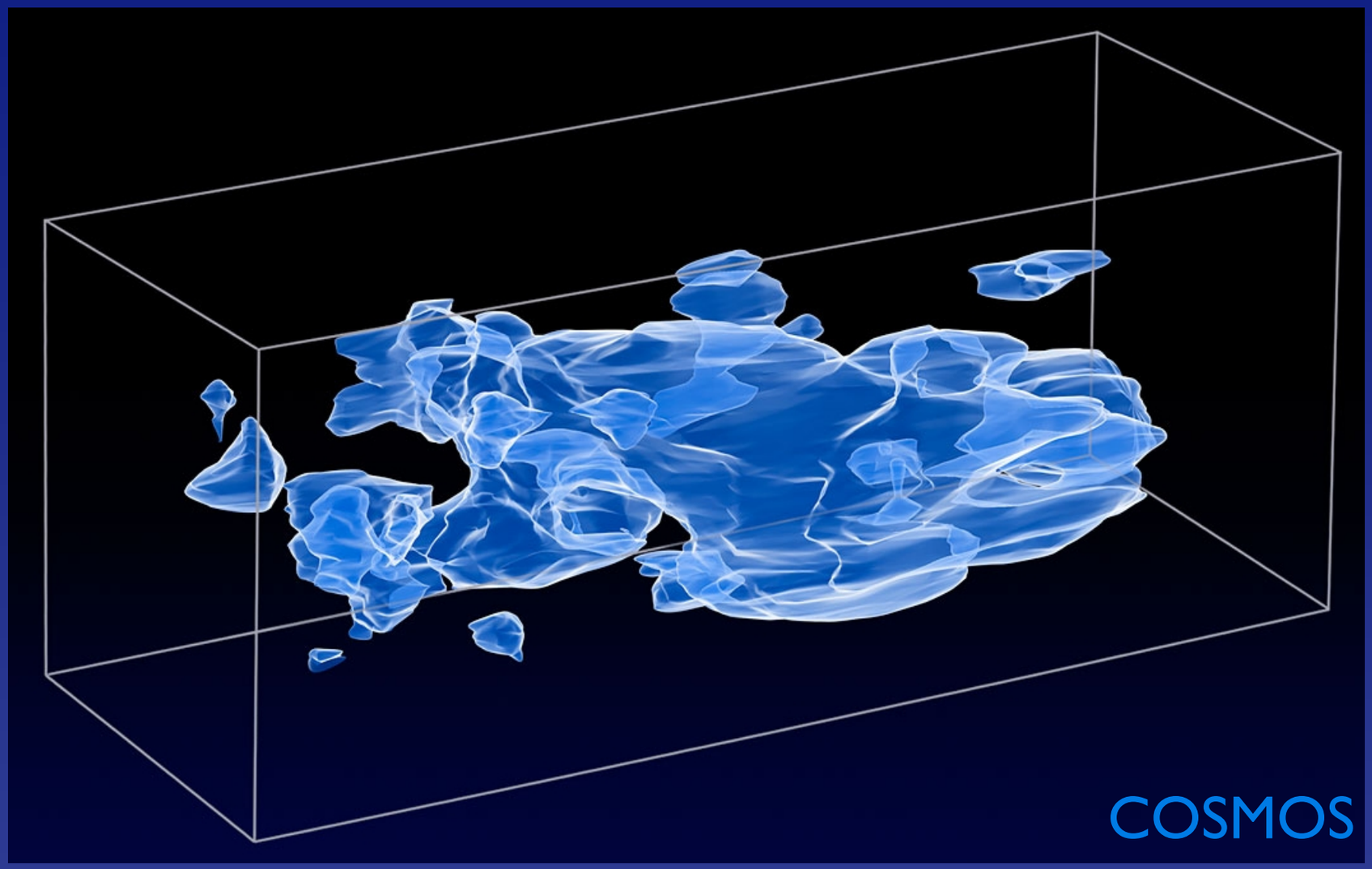
"Little Higgs" models

Bring new physics down to 1 TeV

Opinion: Fermi scale holds Higgs boson + other new physics

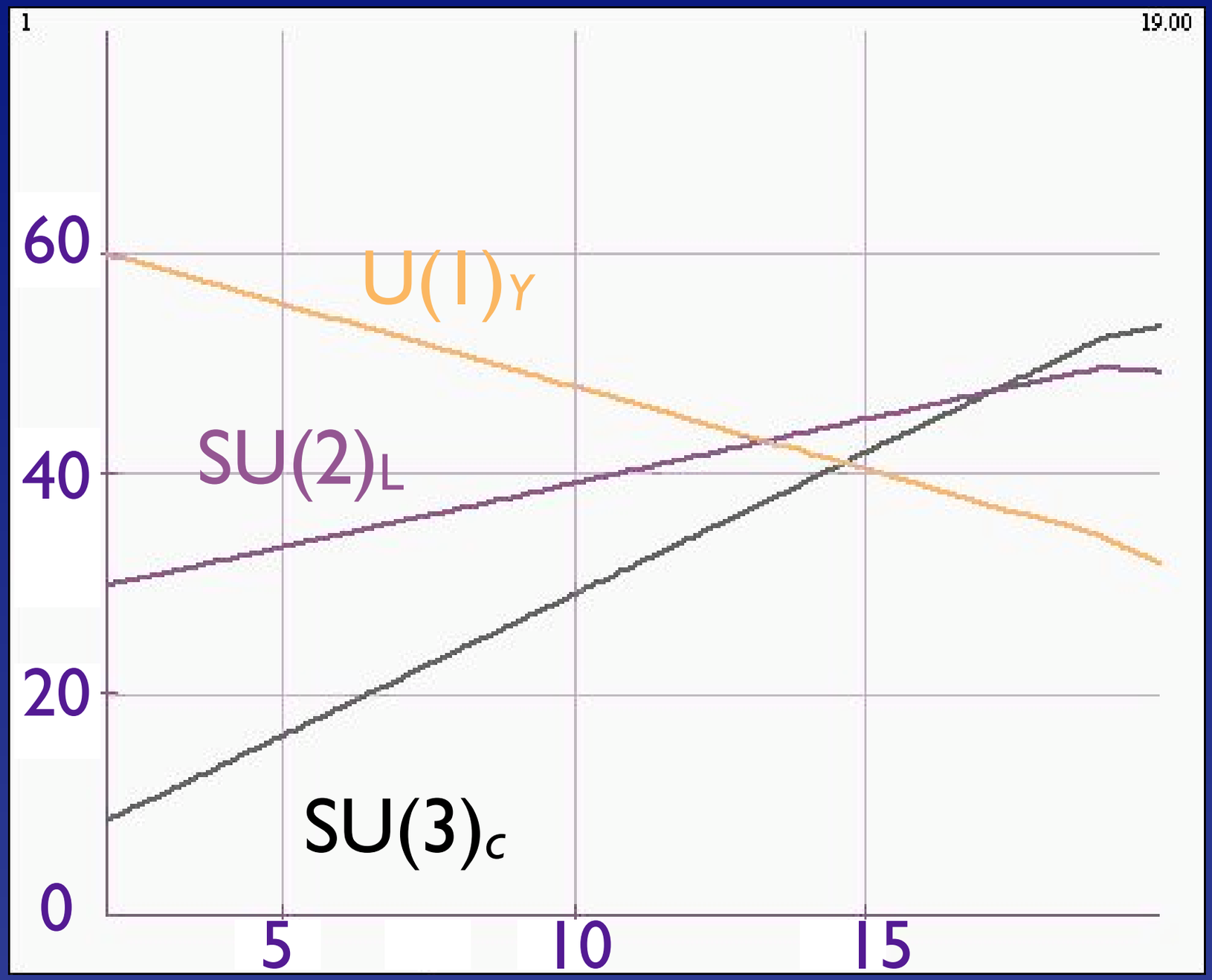
More New Physics on the Fermi Scale?

If dark matter interacts weakly …

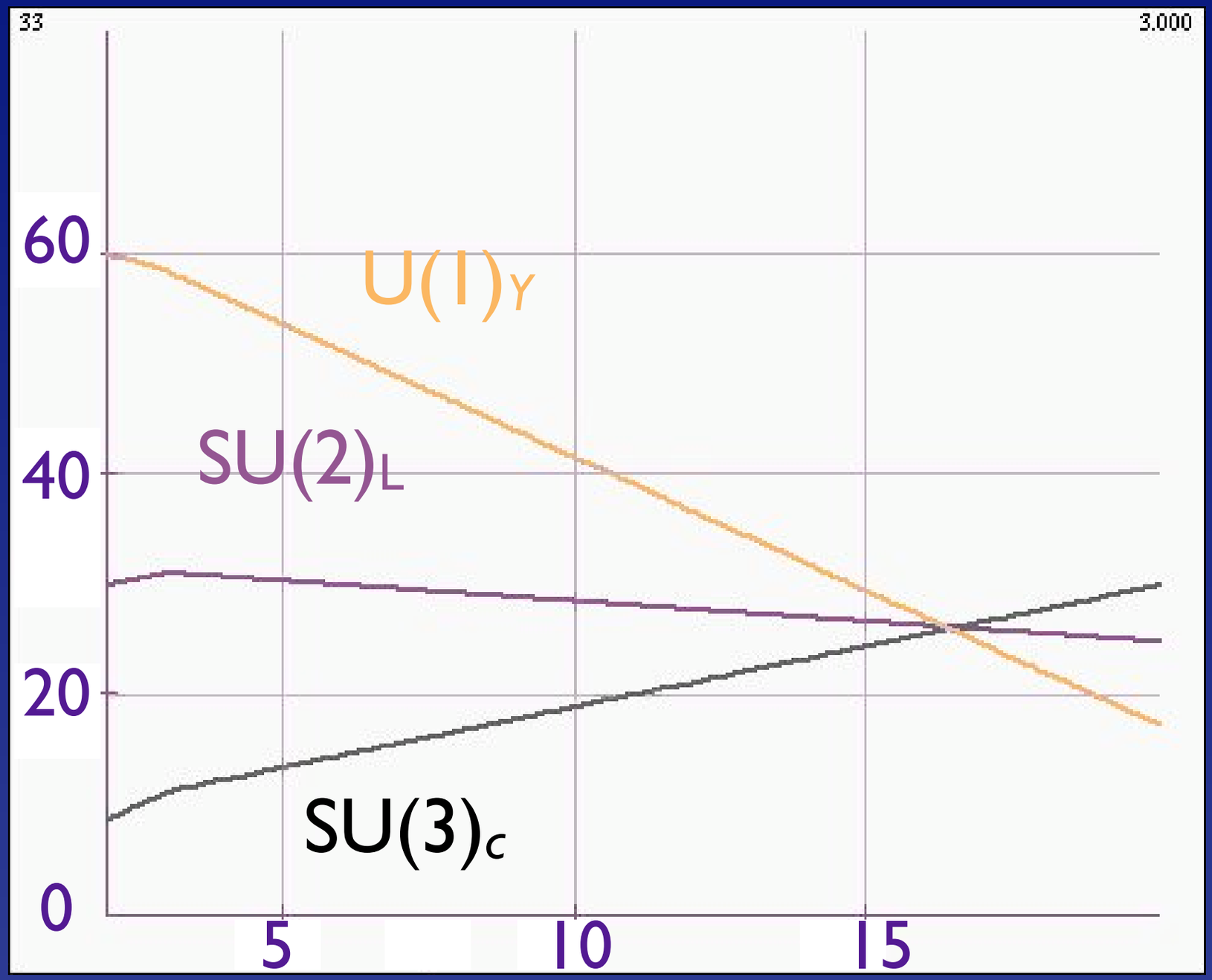


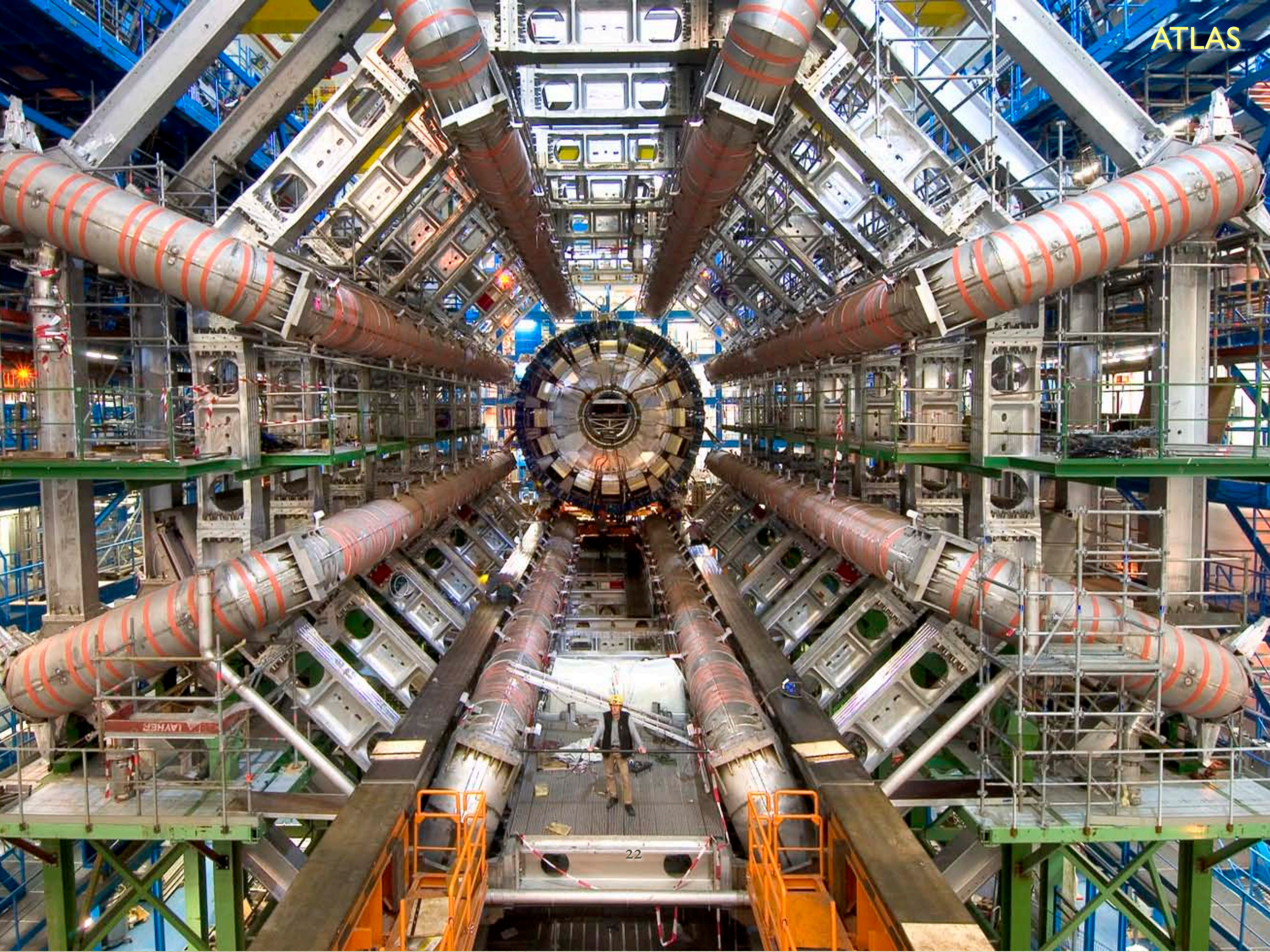
… its likely mass is 0.1 to 1 TeV: *Fermi scale*

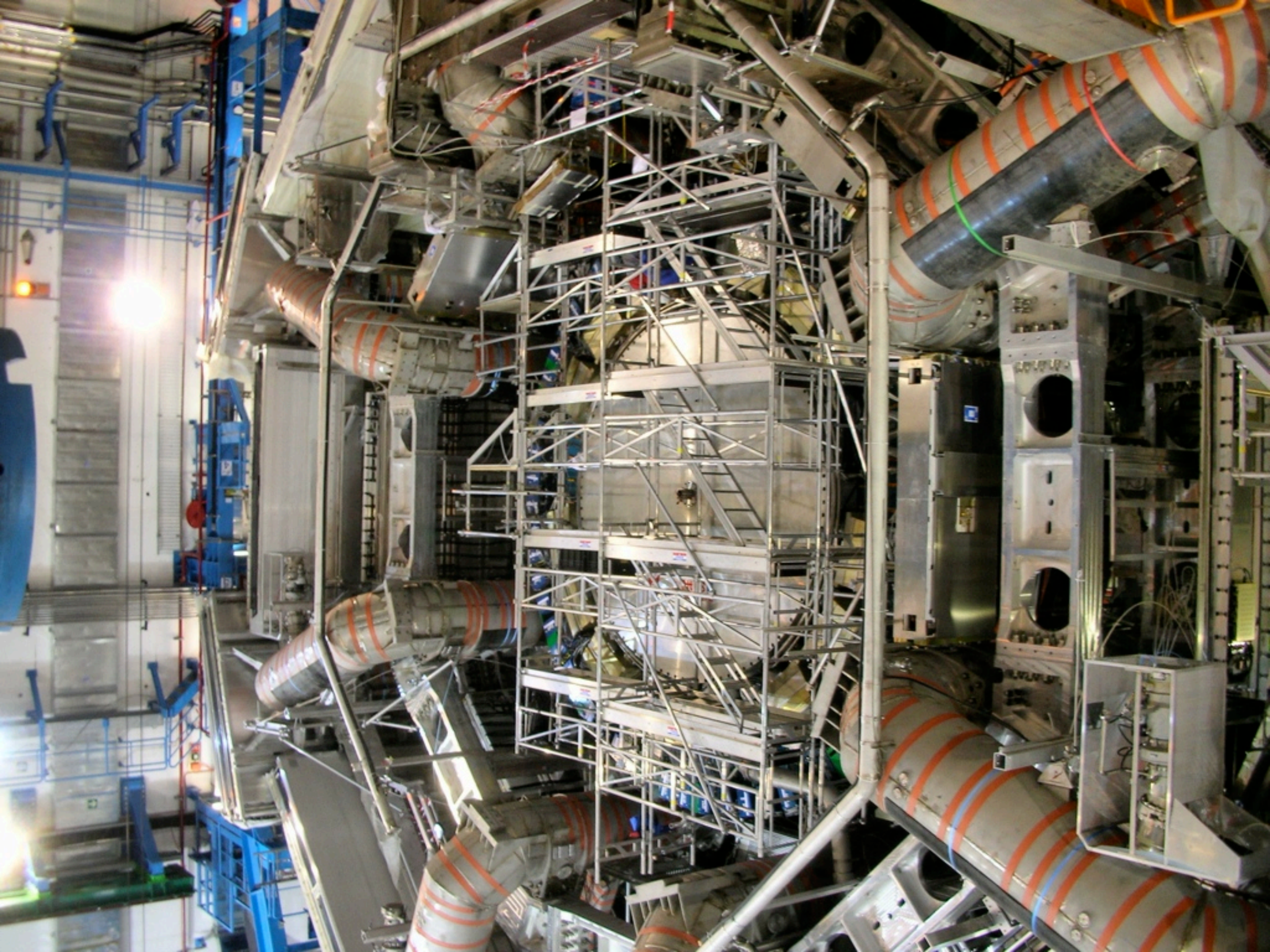
Fermi scale + supersymmetry : unification?

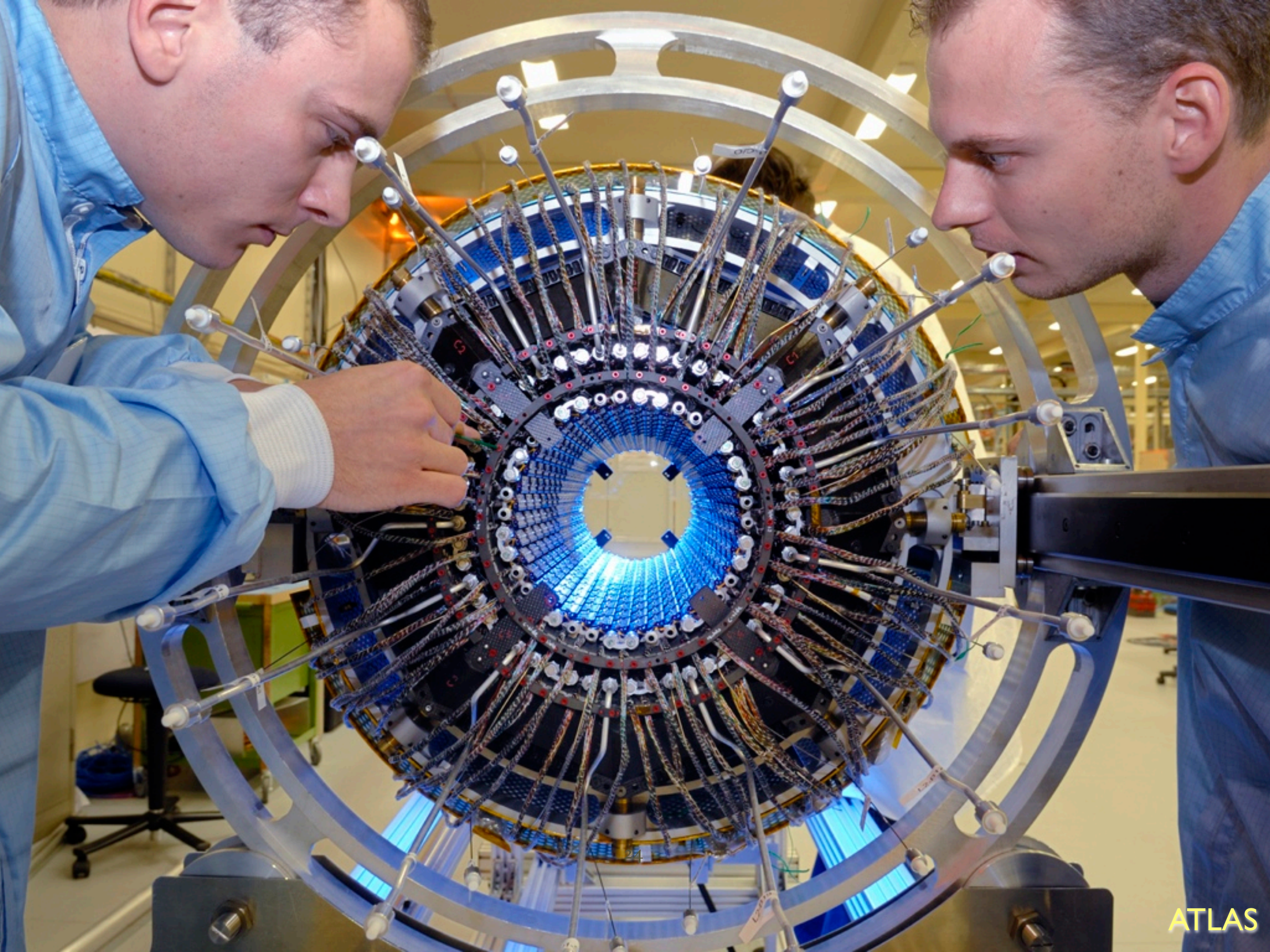


Fermi scale + supersymmetry : unification?




ATLAS

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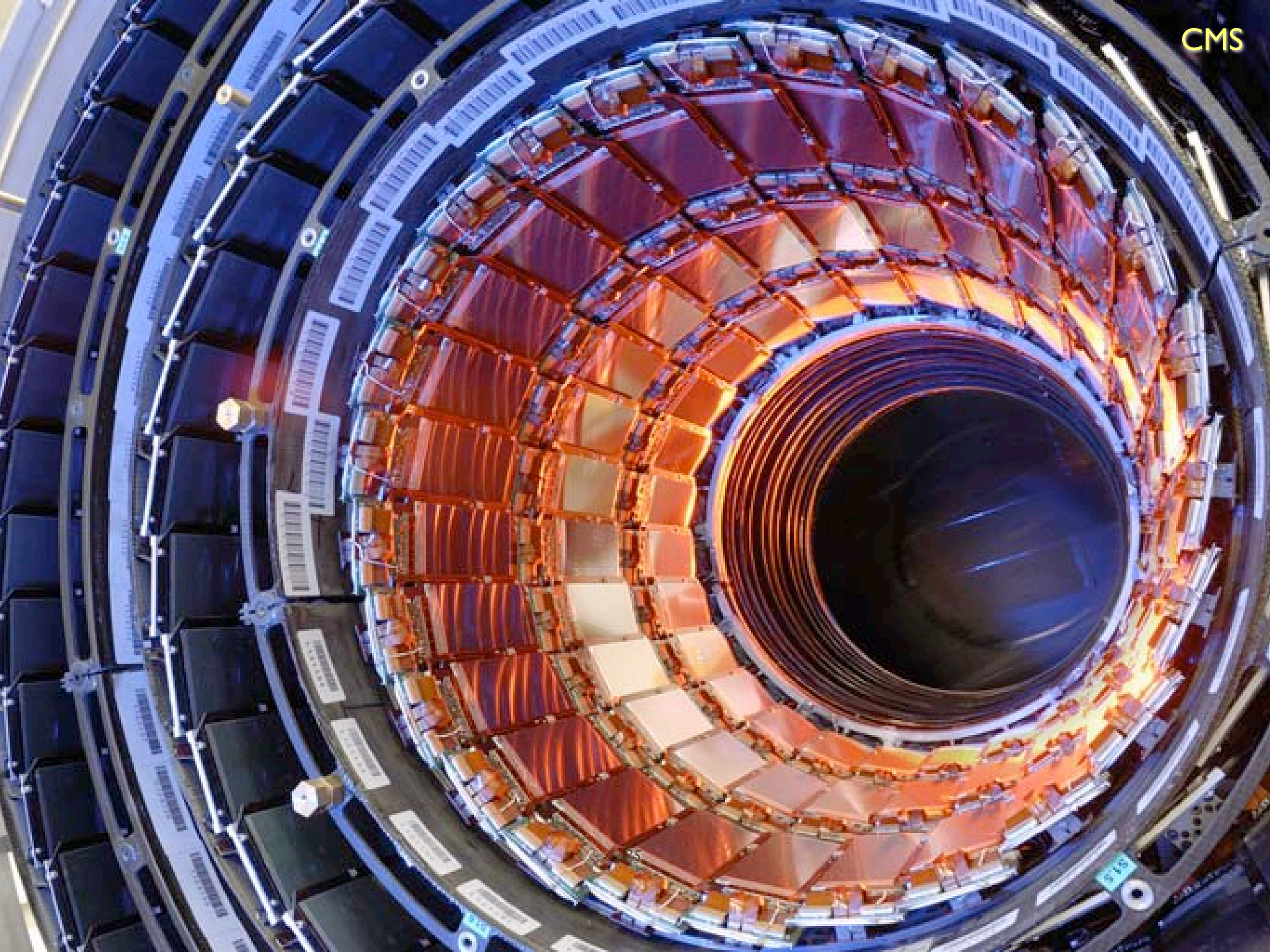
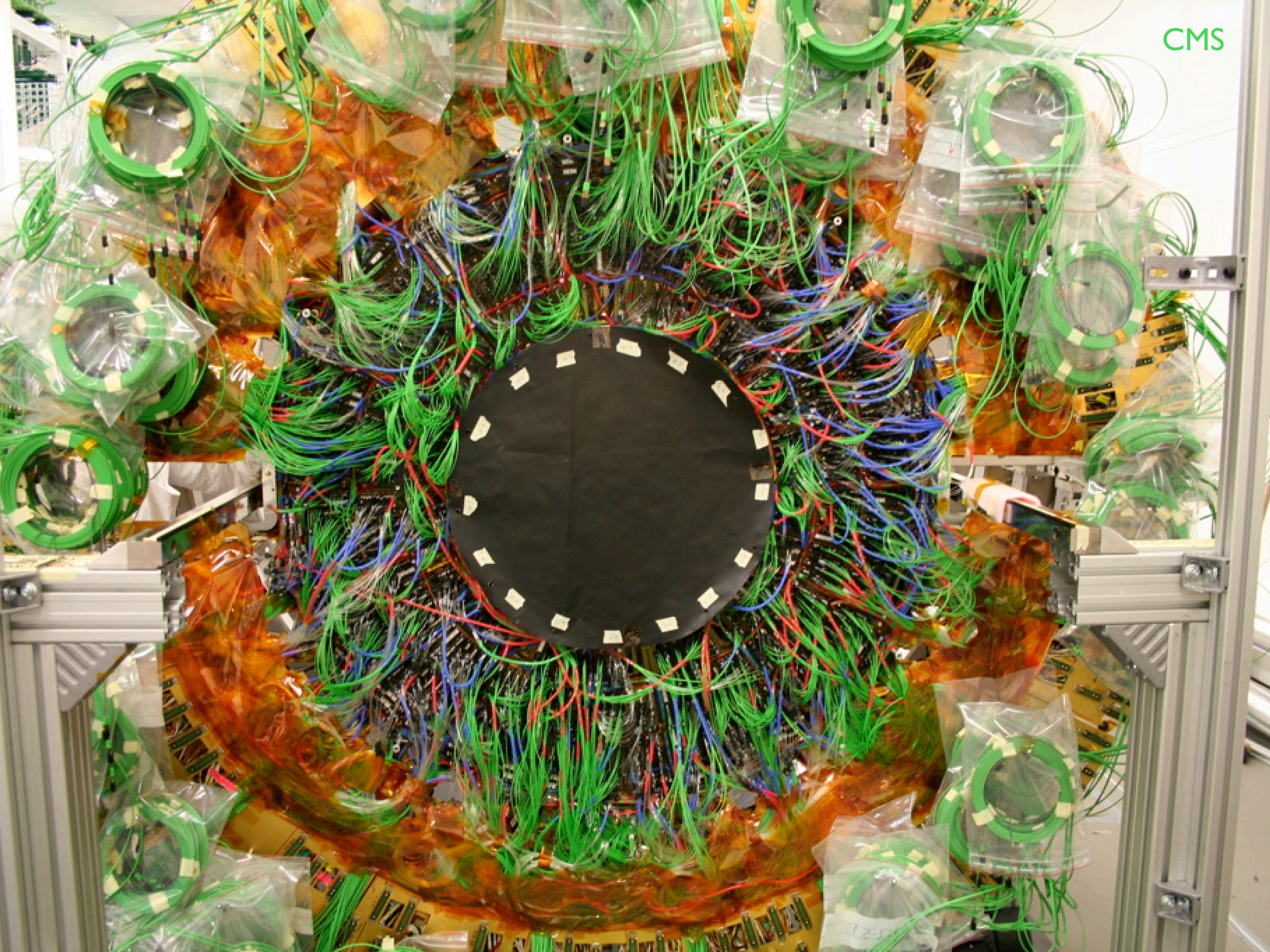

CMS


CMS

What hides electroweak symmetry?
Is there a Higgs boson? Several?
Does *H* give mass to fermions, or only to *W*, *Z*?
How does *H* interact with itself?
Do we live in a metastable vacuum?
Is *H* elementary or composite?
New physics in *H* decays? New kinds of matter?
What stabilizes M_H < 1 TeV?
Is nature supersymmetric?
New strong dynamics? Extra dimensions?
What resolves vacuum energy problem?

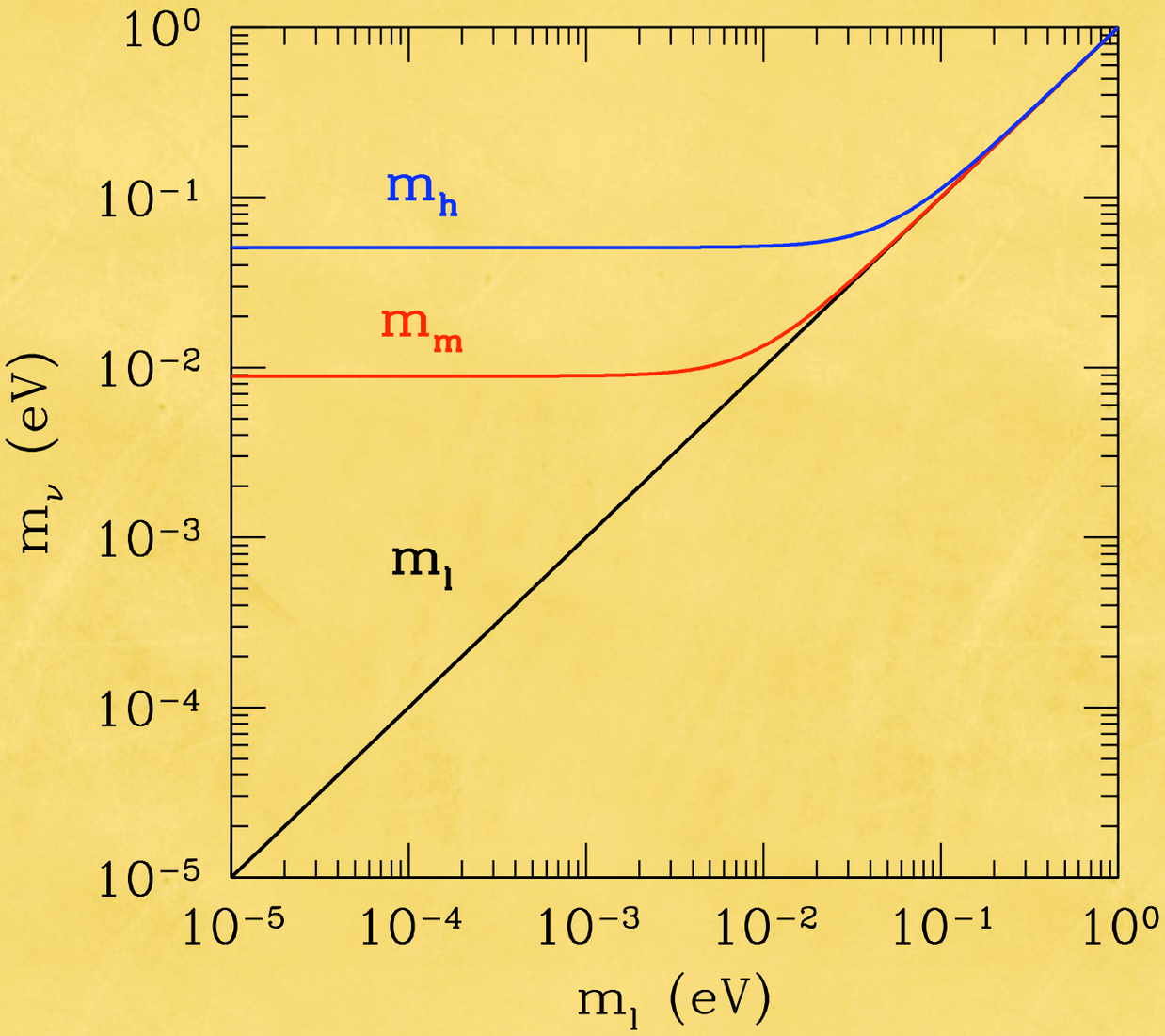
What lessons for unified theories?
for inflationary U? for dark energy?

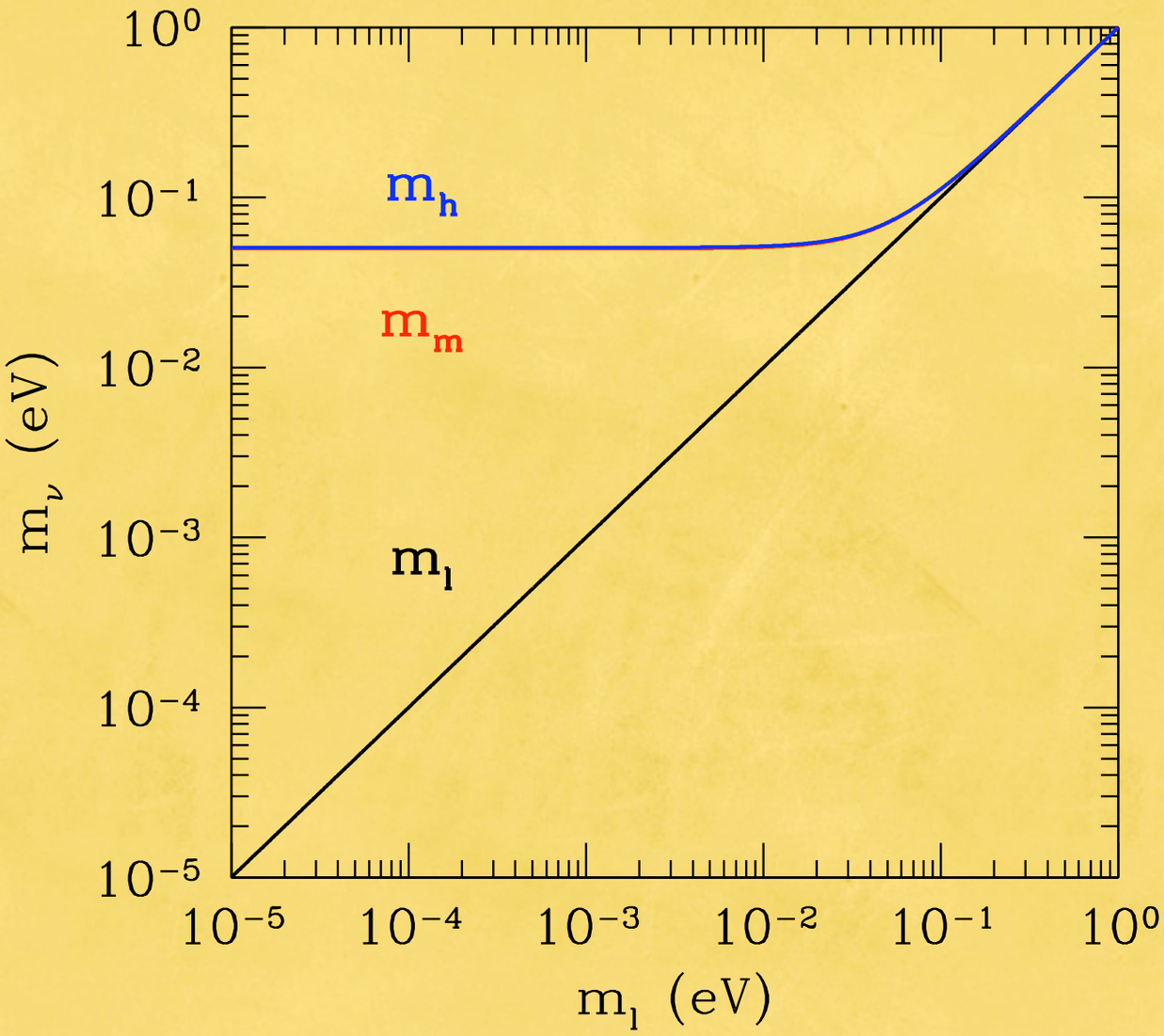
?

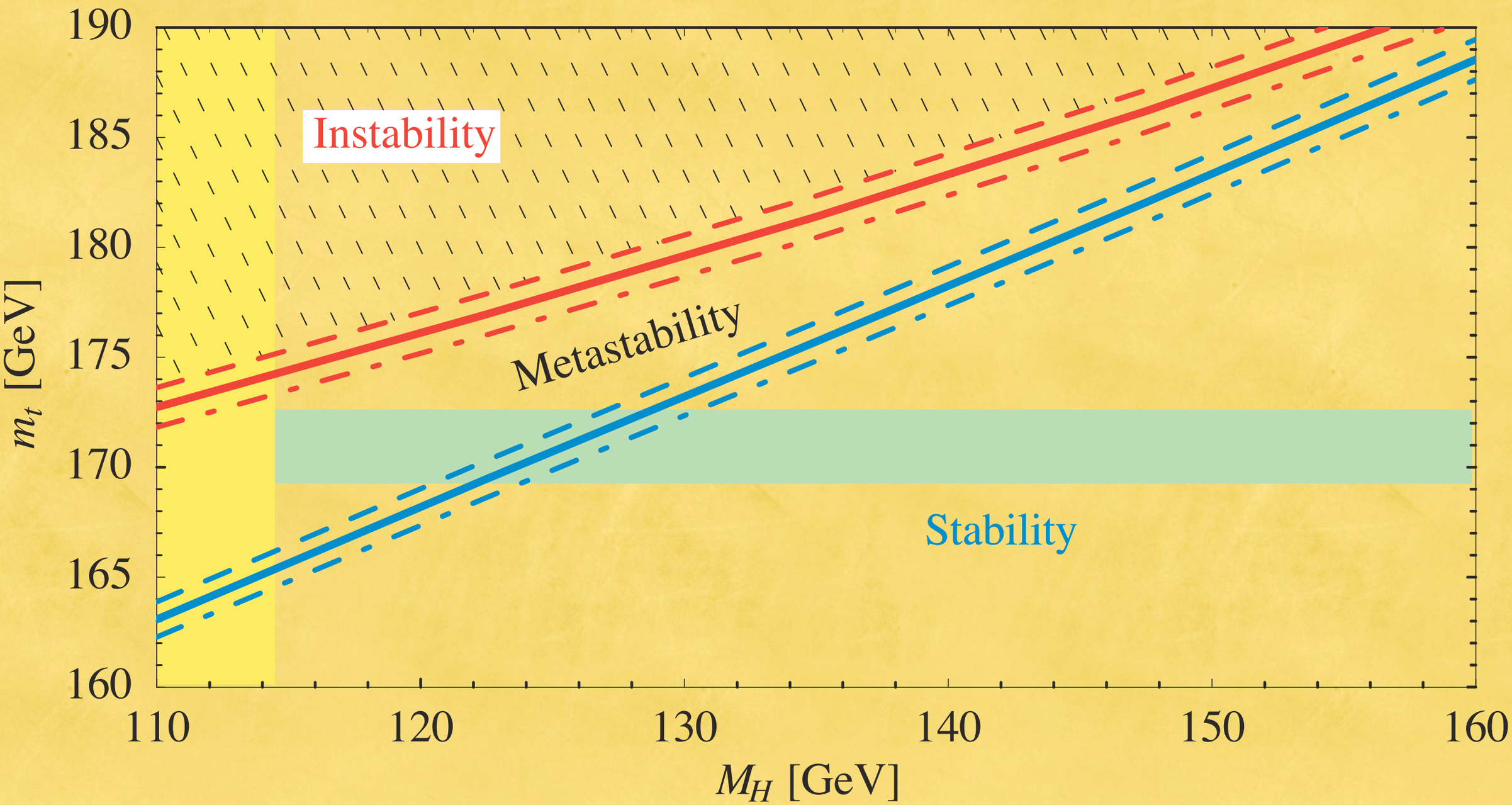
arXiv:0704.2232

Supplement

Neutrino Masses






Instability
Metastability
Stability
190
185
180
175
170
165
160
110
120
130
140
150
160
m_t [GeV]
M_H [GeV]