What is the Higgs Boson
Why do some call it the "God Particle"?

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JHU QuarkNet meeting

What is the Higgs Boson

- From the Big Bang to present
- What is the Higgs boson?
- What is mass and energy?
- Why is it important to us? Is it the God particle?
- How did we find the the Higgs particle?
- Puzzles of the Universe: beyond the Higgs boson
- Optional topics:
  - Science of the Nuclear Energy
  - Space-Time
  - Higgs boson in motion pictures

The Nobel Prize in Physics 2013

Photo: A. Mahmoud

François Englert

Prize share: 1/2

Photo: A. Mahmoud

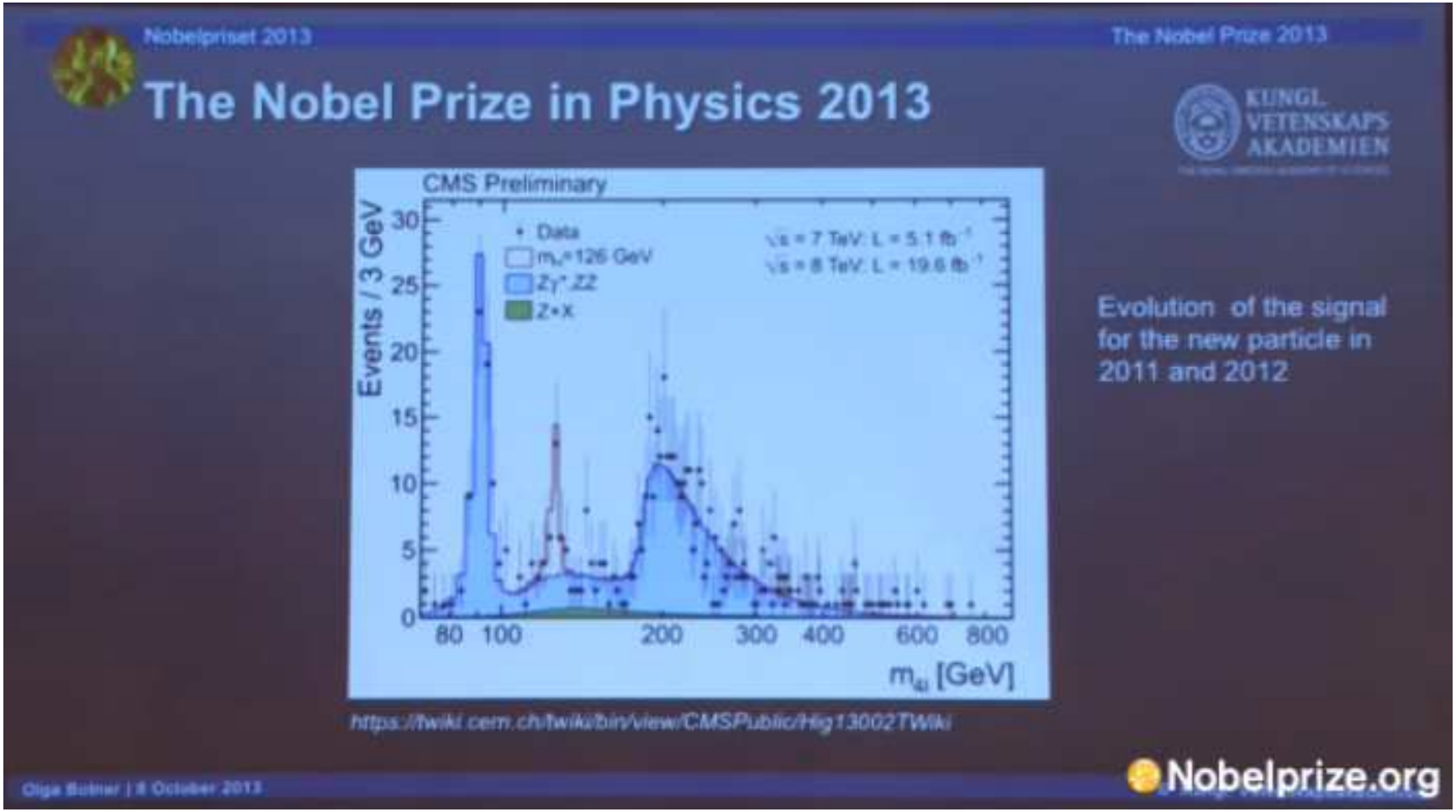
Peter W. Higgs

Prize share: 1/2

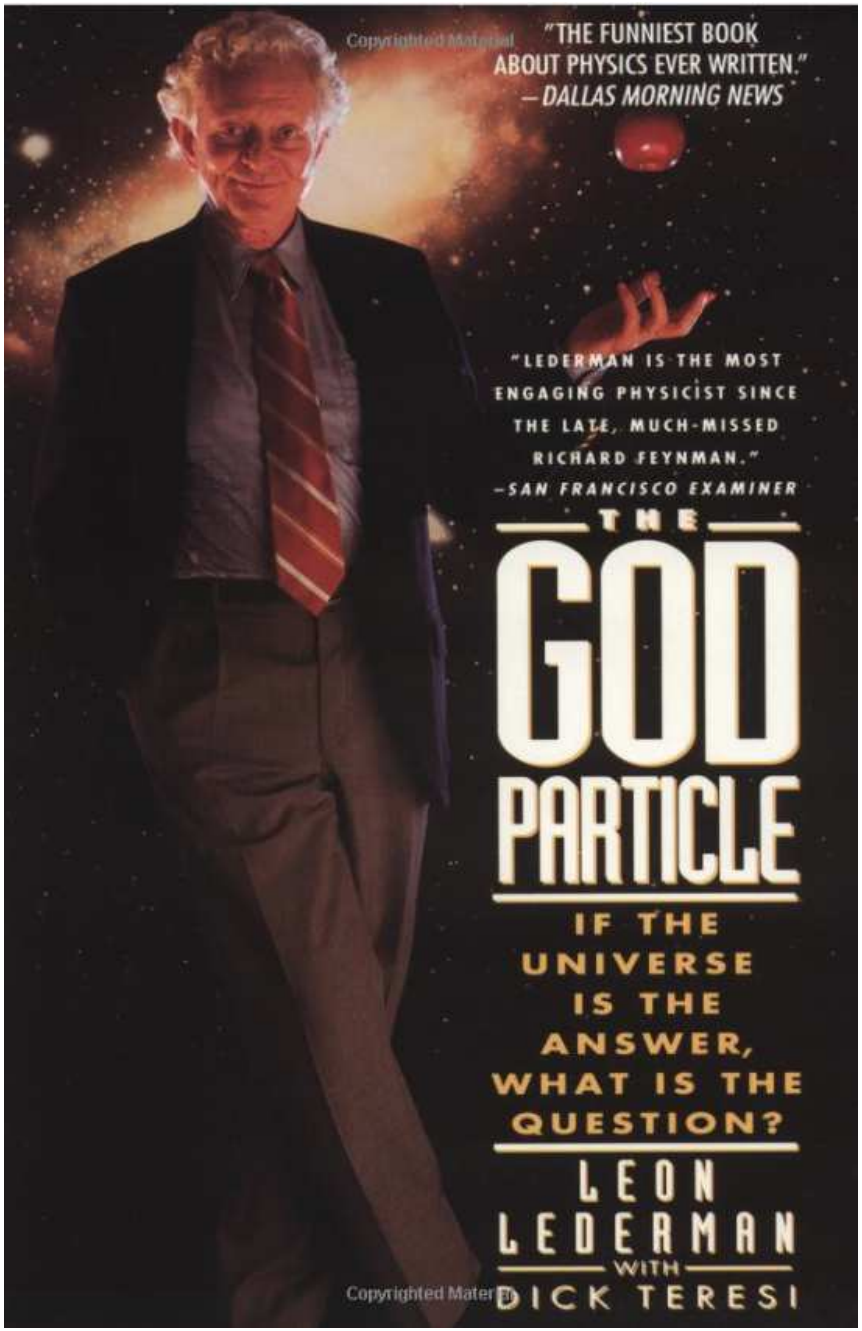
The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter W. Higgs *"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"*

The Higgs Particle

- The Nobel prize for the Higgs mechanism
  - theoretical idea $\sim$50 years ago
- This idea became the reality with the Higgs particle
  - experimental discovery $<$2 years ago



Why do some call it the "God Particle"?



Lets Start from "Nothing": Vacuum

- As far as we can tell vacuum (empty space)

  is not exactly empty

- like a bank account balance:

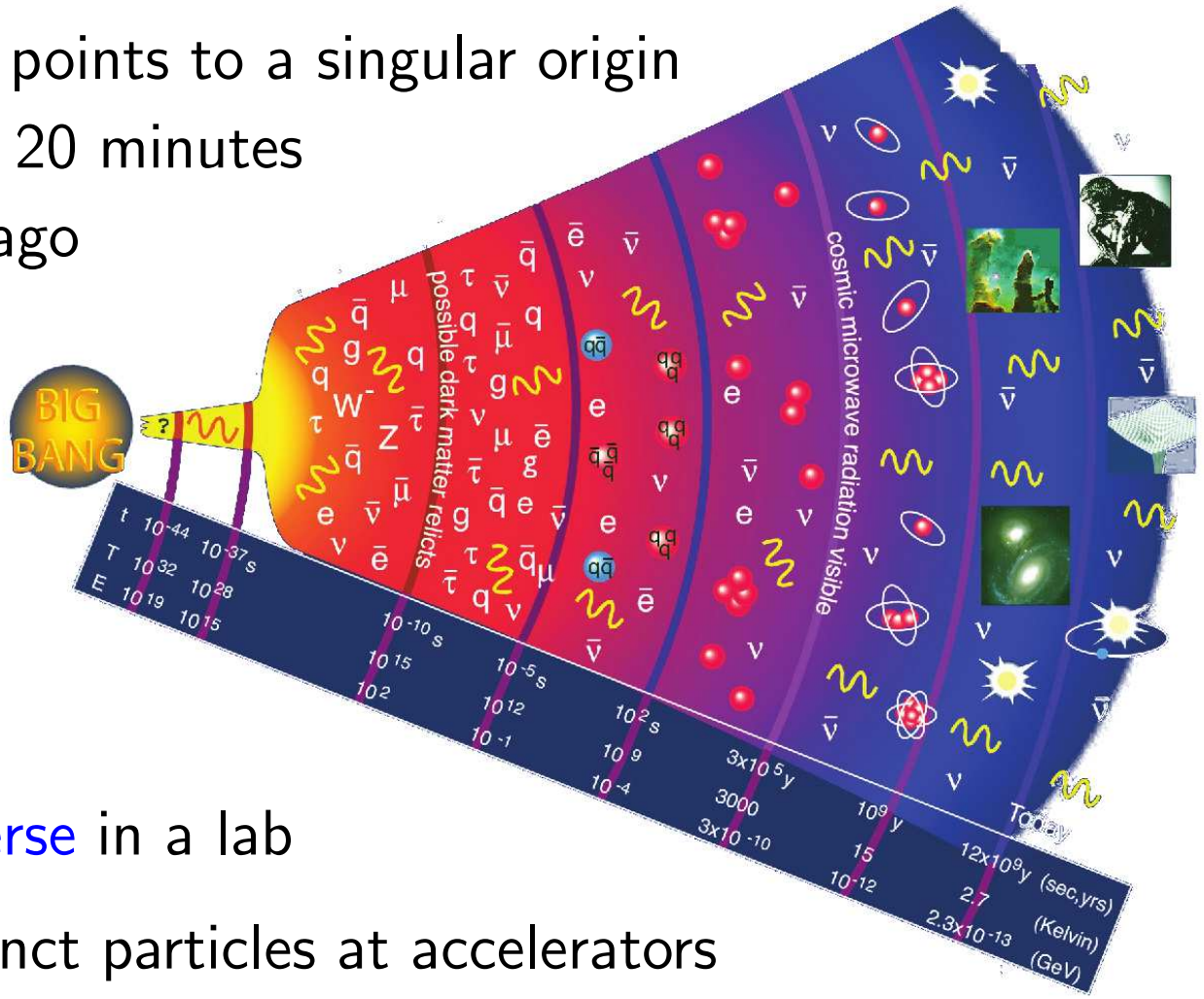
when you take all your money out

there is a minimum balance left

- Invisible "force" present
  - dark energy
  - Higgs field

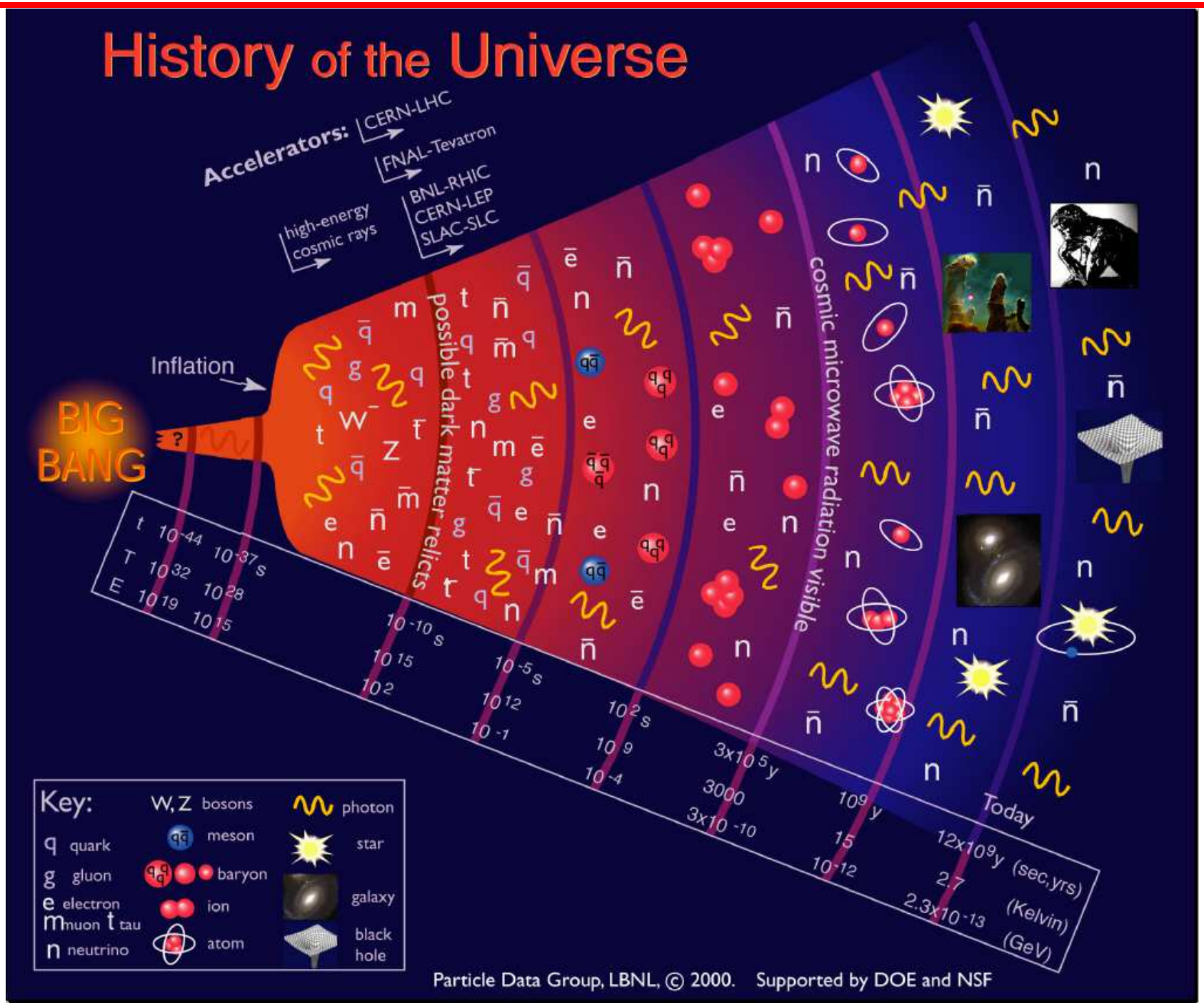
And also Look at the Beginning: The Big Bang

- Early moments of the Universe (astronomical observations):
  - current expansion points to a singular origin
  - nucleosynthesis in 20 minutes
  - 13.8 billion years ago



- Recreate early Universe in a lab
  - re-create now extinct particles at accelerators
  - re-create conditions and understand laws

The Big Bang


History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

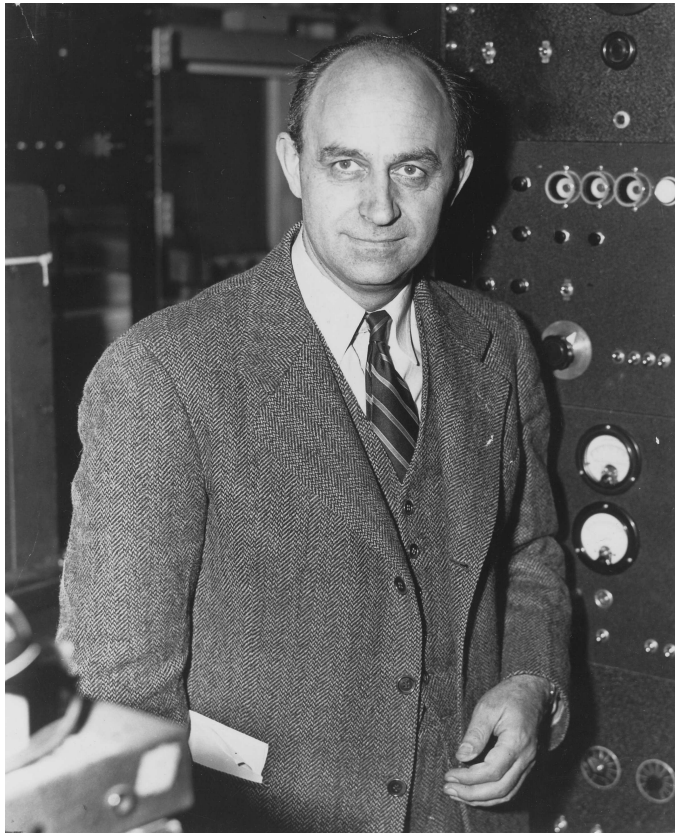
What is the Higgs Boson ?

What is a Boson?

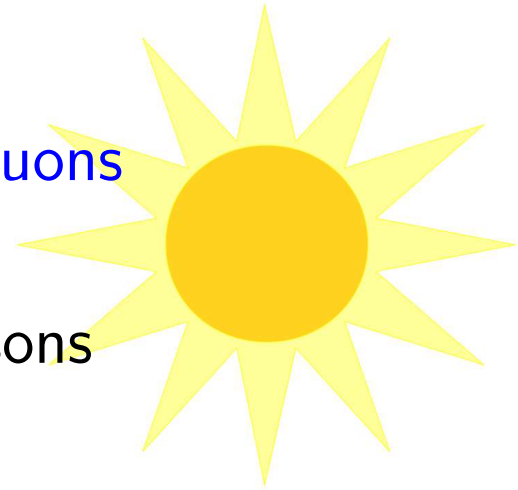
- Named after Satyendra Nath Bose
  - foundation of Bose - Einstein statistics
  - describing particles of integer spin $S = 0,\ 1\hbar,\ 2\hbar, ..$ ("force")

What is a Fermion?

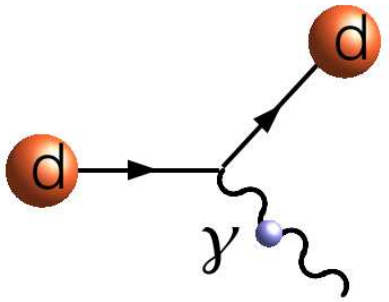
- Named after Enrico Fermi
  - foundation of Fermi - Dirac statistics
  - describing particles of half-integer spin $S = \frac{1}{2}\hbar, \frac{3}{2}\hbar, ..$ ("matter")
  - one of the fathers of the atomic bomb (Italy $\rightarrow$ USA in 1938)



How many Bosons did we know in 2012?

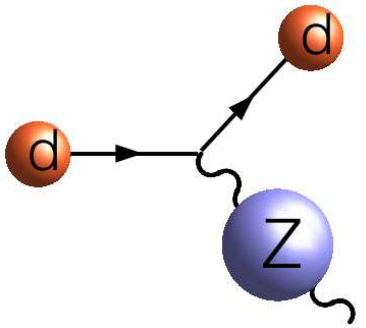


- We knew 12 bosons: photon, Z^0, W^+, W^-, 8 gluons
- Photons (γ) are massless vector (spin=$\hbar$=1) bosons
- Z^0 and $W^{\pm}$ are heavy $\rightarrow$ weak force



- Gauge bosons in unified electro-weak theory after spontaneous symmetry breaking

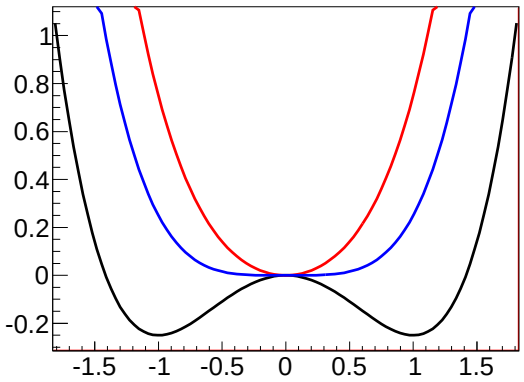
$$|\gamma\rangle = \cos\theta_W|B^0\rangle + \sin\theta_W|W^0\rangle \quad \text{light (massless)}$$
$$|Z^0\rangle = \sin\theta_W|B^0\rangle + \cos\theta_W|W^0\rangle \quad \text{heavy}$$

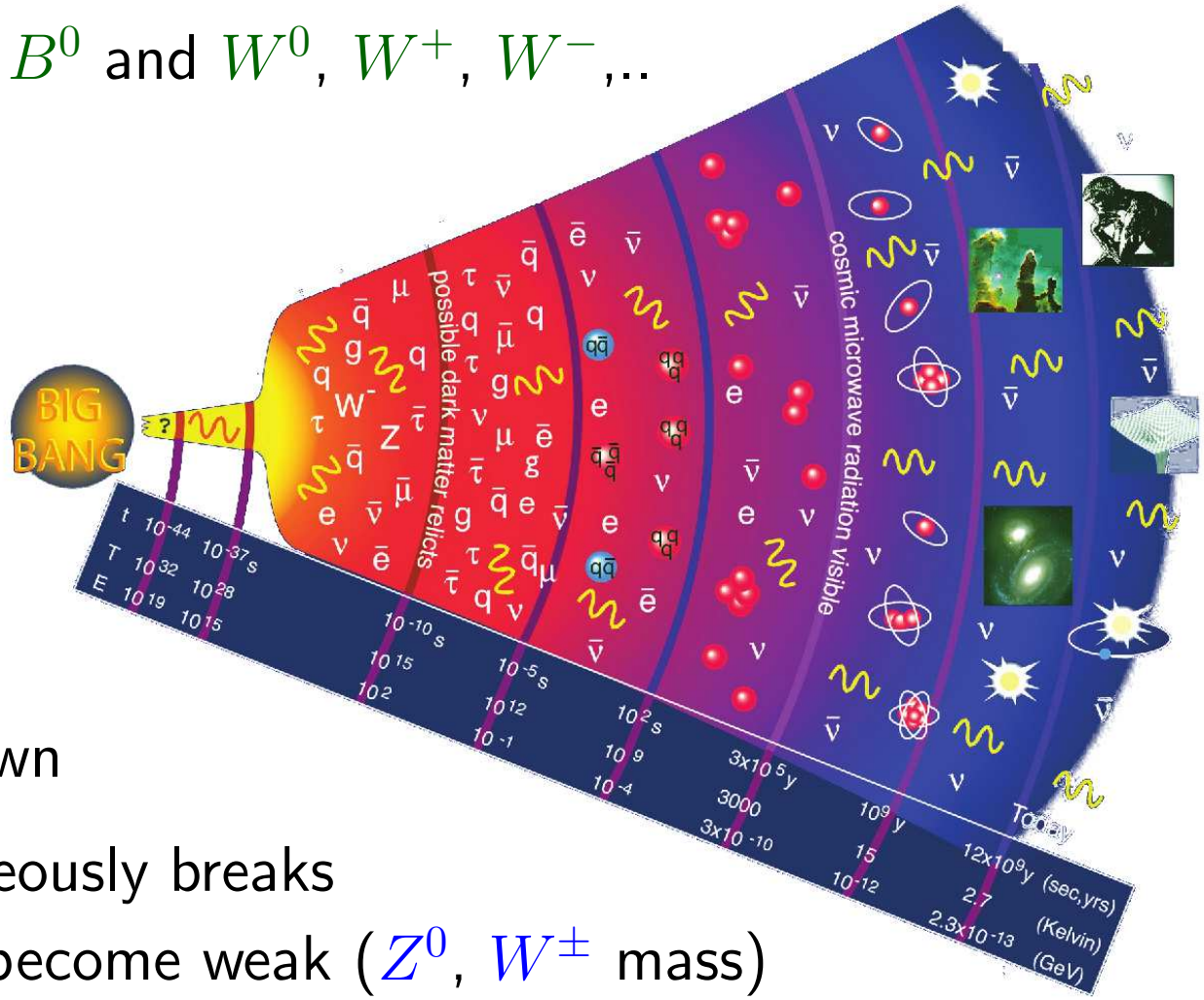


θ_W - Weak mixing (Weinberg) angle

Path from Light to Heavy

- Early moments of the Universe
  - massless particles: B^0 and W^0, W^+, W^-,..
  - all forces unify



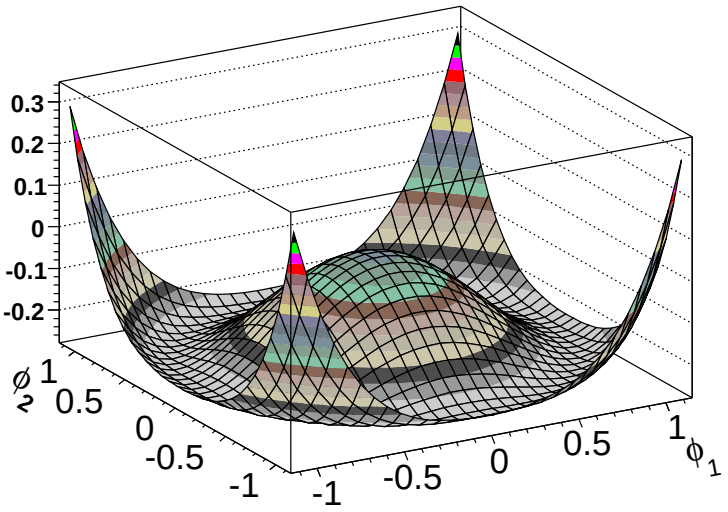


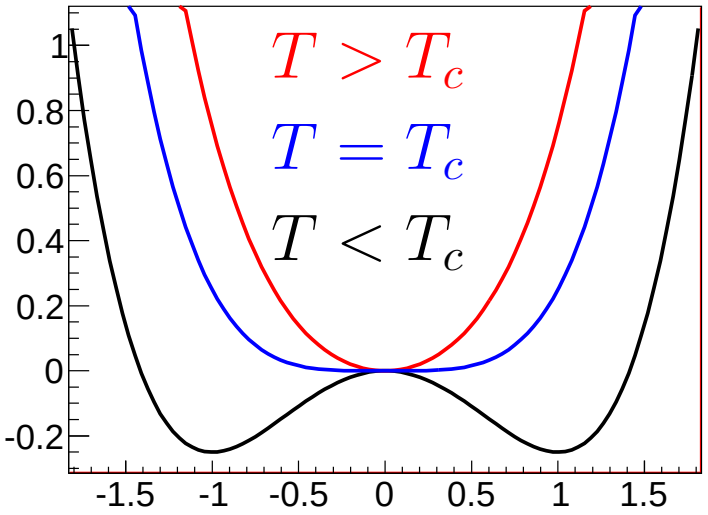
- As Universe cools down
  - symmetry spontaneously breaks
  - weak interactions become weak (Z^0, $W^\pm$ mass)
  - Higgs field – possible mechanism

The Englert-Brout-Higgs Mechanism

- Symmetry spontaneously breaks near minimum (vacuum) energy of Higgs field $(\phi_1, \phi_2, \phi_3, \phi_4)$

$$V = \frac{1}{4}\lambda\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]^2 + \frac{1}{2}\mu^2\left[\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\right]$$





- Higgs particle described by one component of the Higgs field

$$h = \phi_1 - v$$

- The other Higgs field components ϕ_2, ϕ_3, ϕ_4 couple to Weak bosons Z^0, W^-, W^+ and generate mass, longitudinal polarization (not γ)

Idea - the Higgs Field

- Empty space filled with invisible "force" – the Higgs field

Idea - the Higgs Field

- The Higgs field clusters around the particle – gives mass

Idea - the Higgs Field

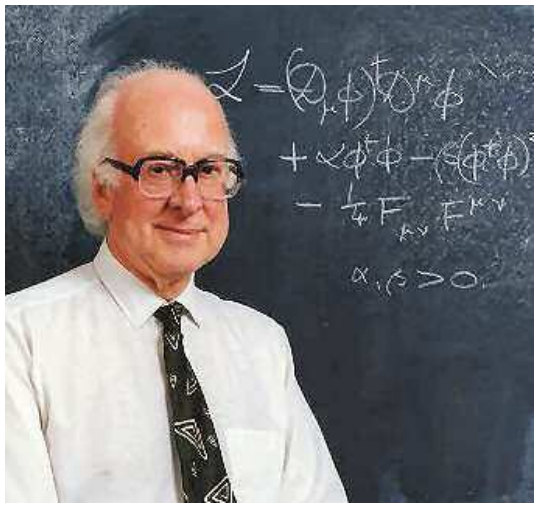
- Pass energy into the Higgs field (no particle)

Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field

What is Higgs?

- There are several phenomena:
  - Peter Higgs
  - Higgs mechanism
  - Higgs field
  - Higgs particle (boson)



- People sometimes confuse these phenomena
  - especially the last two
- We have hard evidence for two:
  - 1964 article by Peter Higgs in *Physics Review Letters*
  - 2012 discovery of a new Boson by CMS and ATLAS

More on the History of the Higgs Mechanism

- In fact, there are several names of the Higgs mechanism:
  - Brout-Englert-Higgs mechanism
  - Higgs-Brout-Englert-Guralnik-Hagen-Kibble mechanism
  - Anderson-Higgs mechanism
  - Higgs mechanism is just simpler
  - all for authors of independent papers on the topic

- Partly due to ironic history with the paper by Higgs:
  - rejected from European *Physics Letters*
    "of no obvious relevance to physics"
  - added a reference to predicting a new particle

More on the History of the Higgs Mechanism

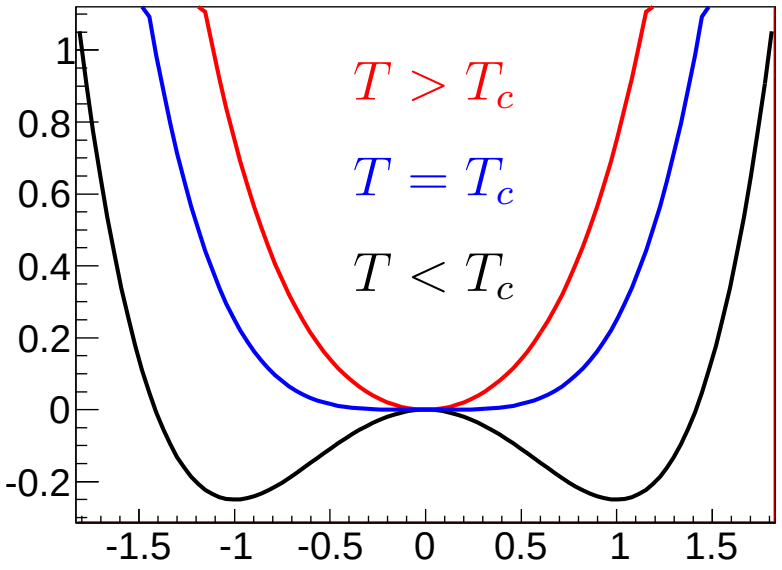
1950: Ginzburg- Landau model of superconductivity

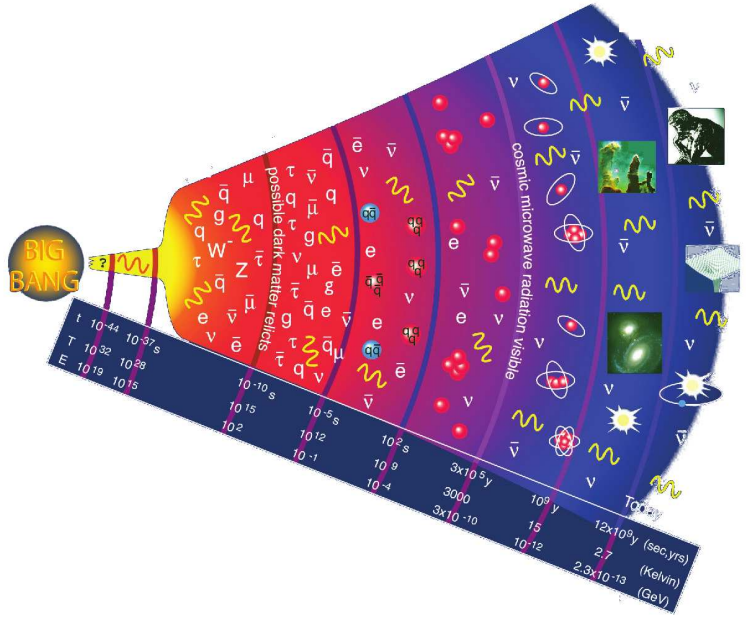
1959-60: Nambu- Goldstone bosons in spontaneous symmetry breaking

1962: P. Anderson - nonrelativistic example

1964: R. Brout & F. Englert; P. Higgs; G. Guralnik & C. R. Hagen & T. Kibble

1967: Incorporated into Standard Model by S. Weinberg and A. Salam





What is Mass?

What is Mass?

- We are all familiar with either inertial mass or gravitational mass

$$\vec{F} = m\vec{a} \text{ or } \vec{F} = m\vec{g}$$

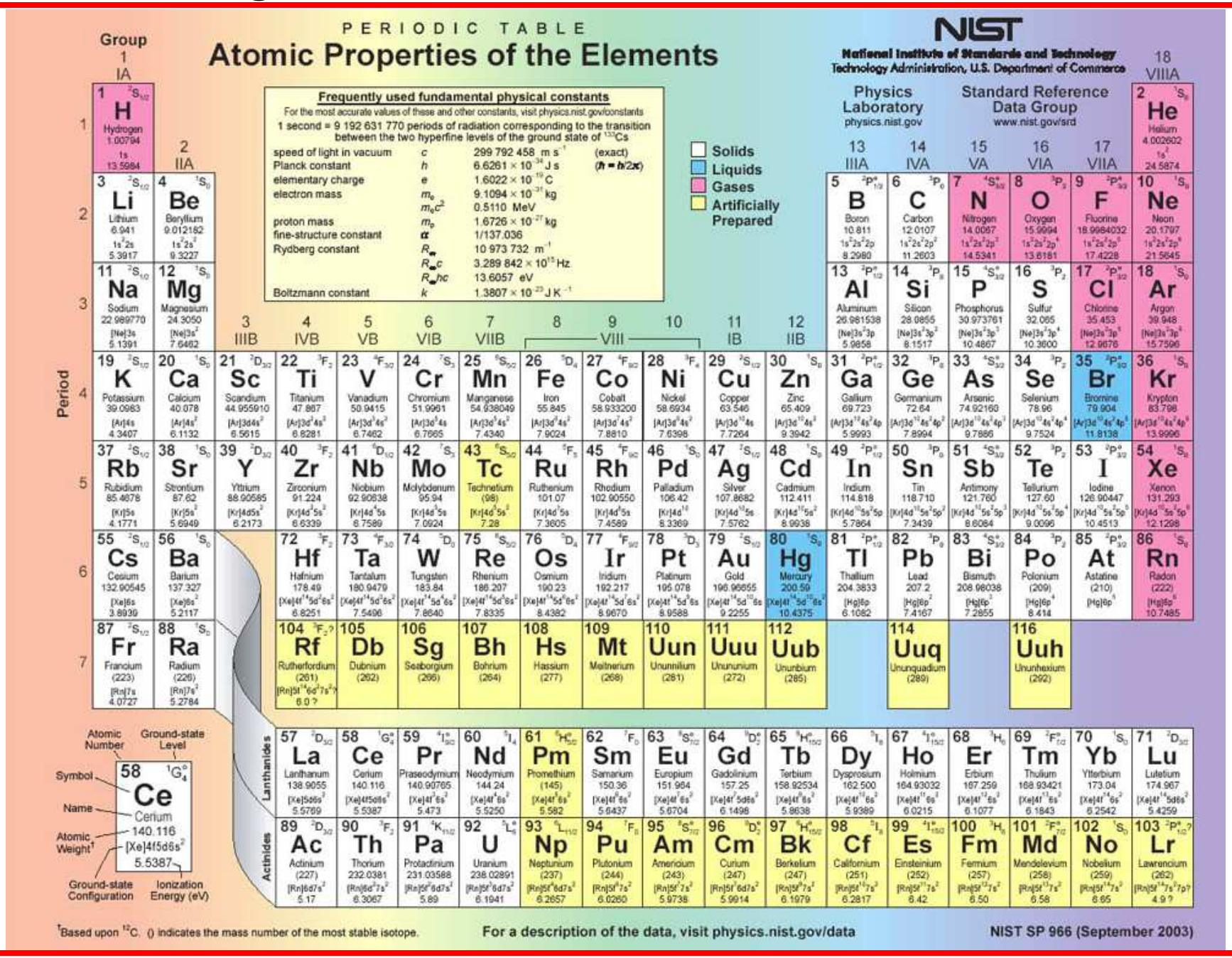
they are equivalent in General Relativity

- Mass and Energy are equivalent

$$E = mc^2$$ in Special Relativity

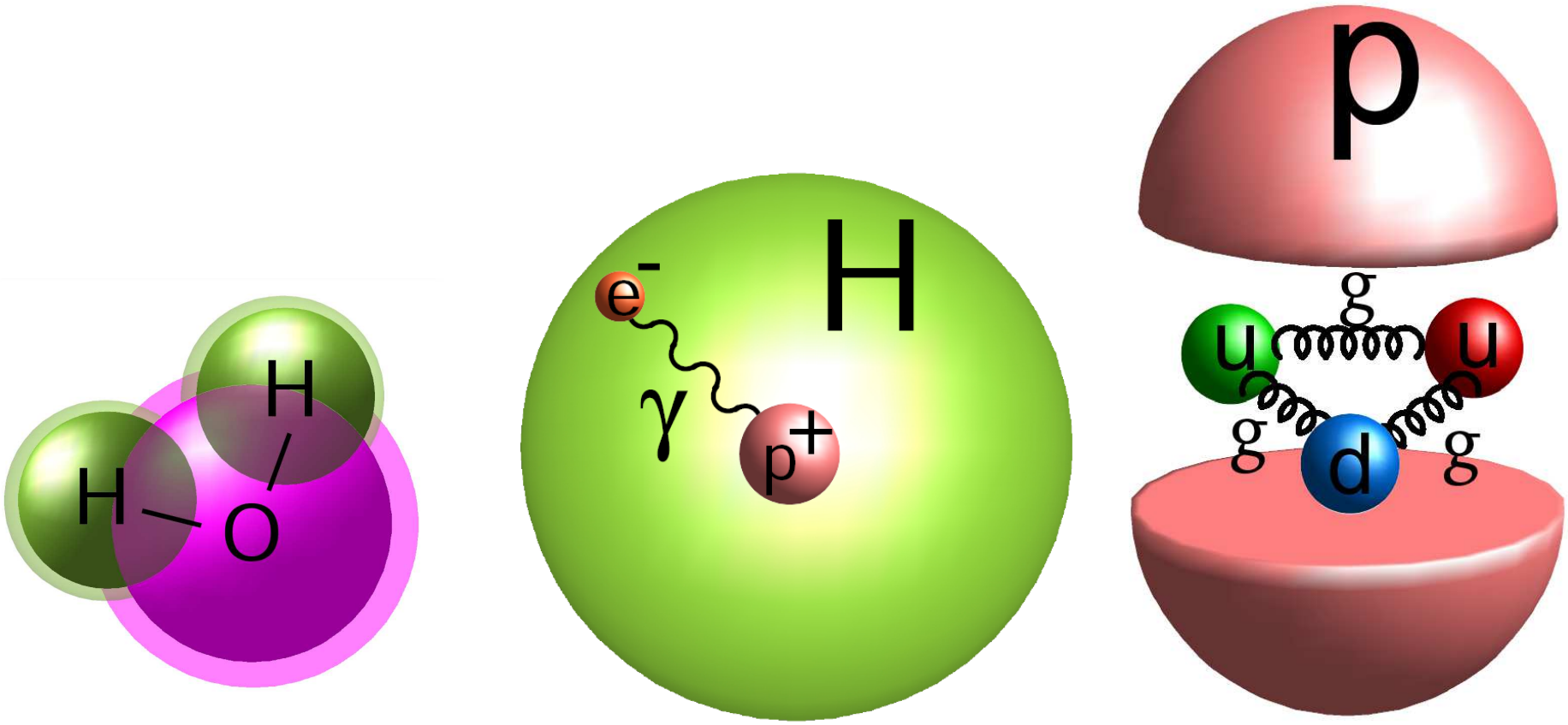
- Mass is important even without Gravity (e.g. in vacuum)
- The Higgs Mechanism provides mass to elementary particles
- Is our MASS due to the Higgs Mechanism ???

What gives us mass? Molecules? Atoms?



What makes mass?

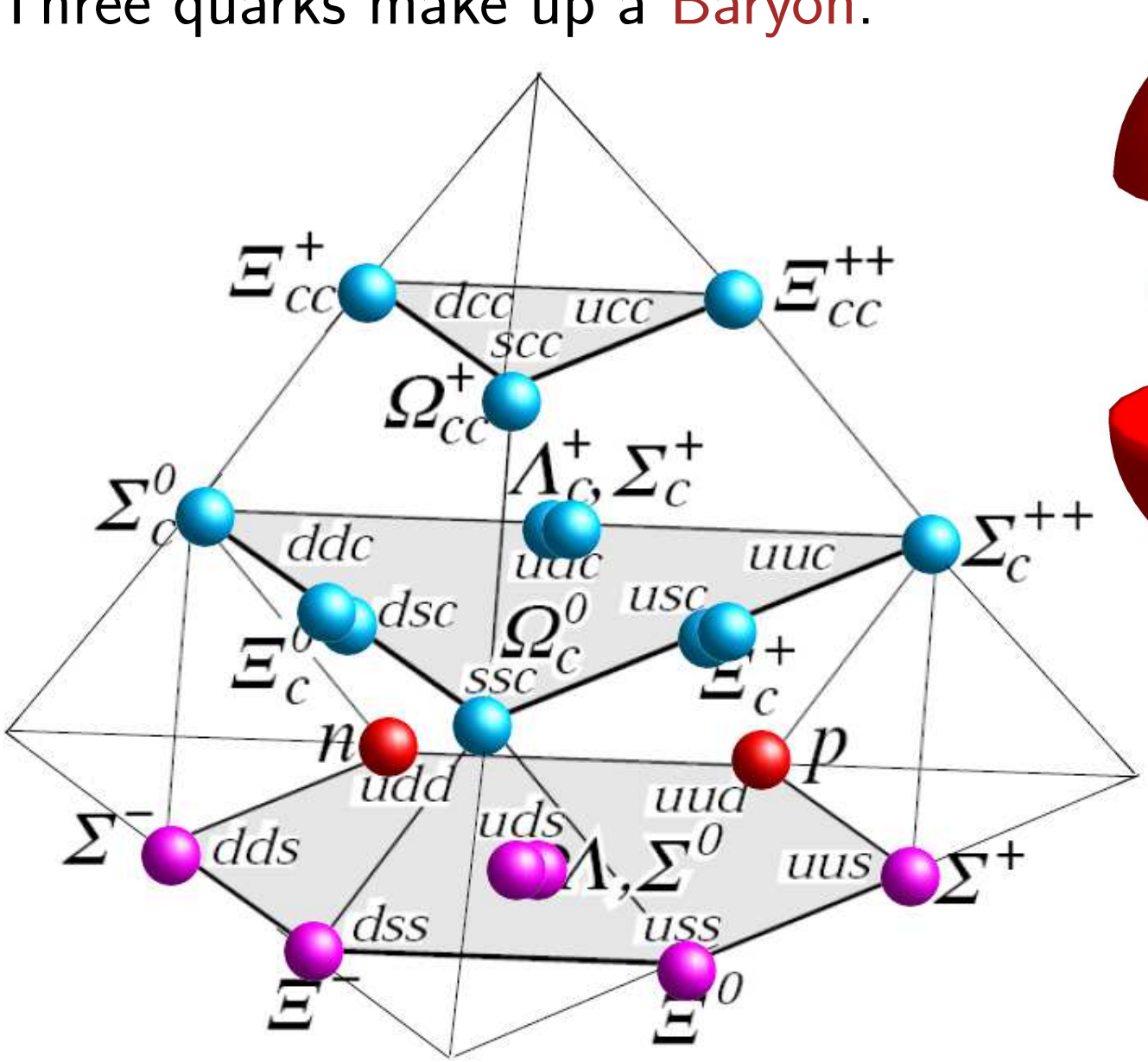
- What gives us mass?

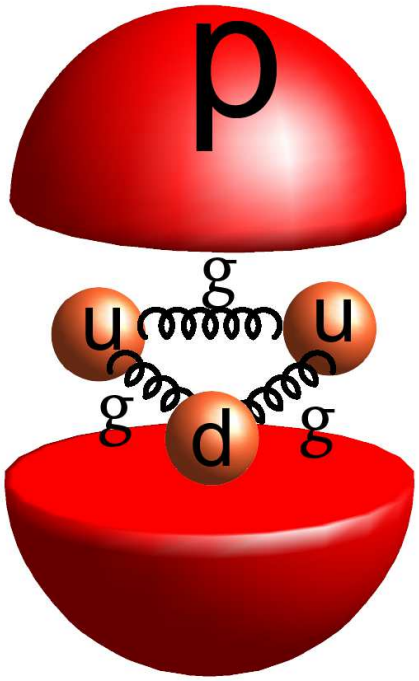


Molecules Atoms Nucleus

"Periodic Table" of Baryons: Proton, Neutron,...

- Three quarks make up a Baryon:



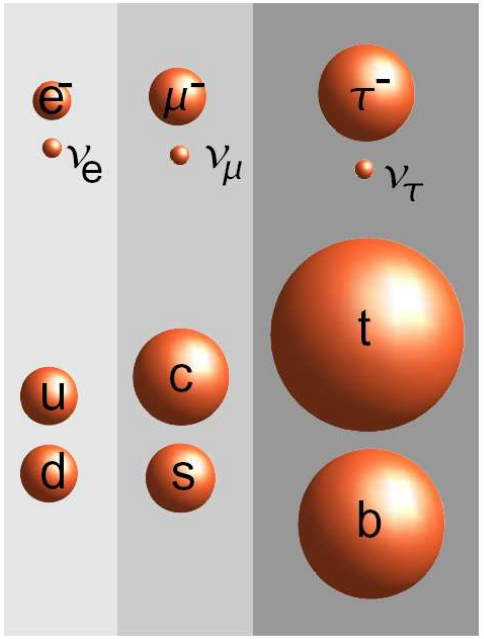


All Elementary Particles get Mass from Higgs Field

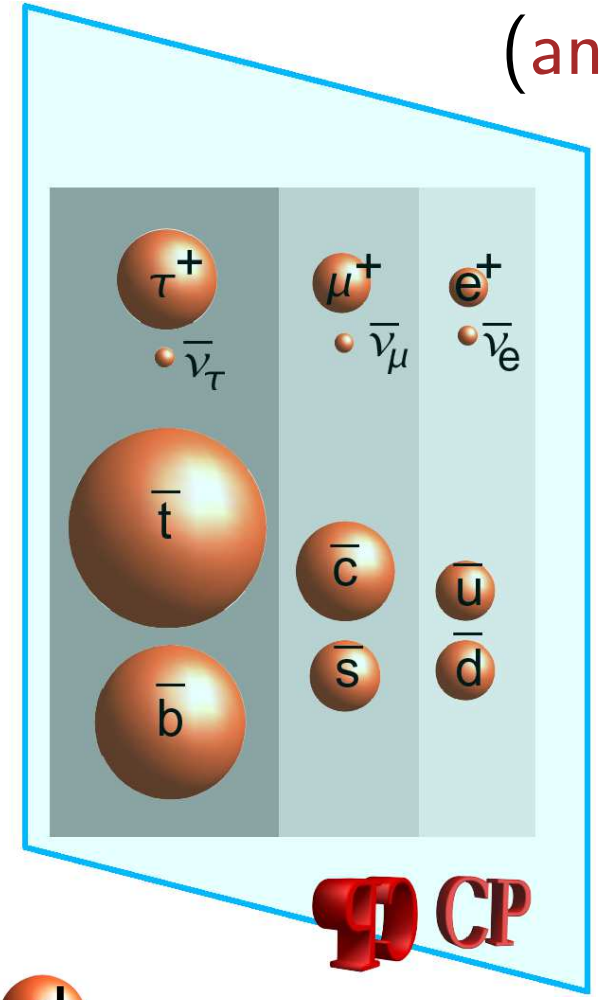
- Fermions $S = \frac{\hbar}{2}$ (matter)

leptons

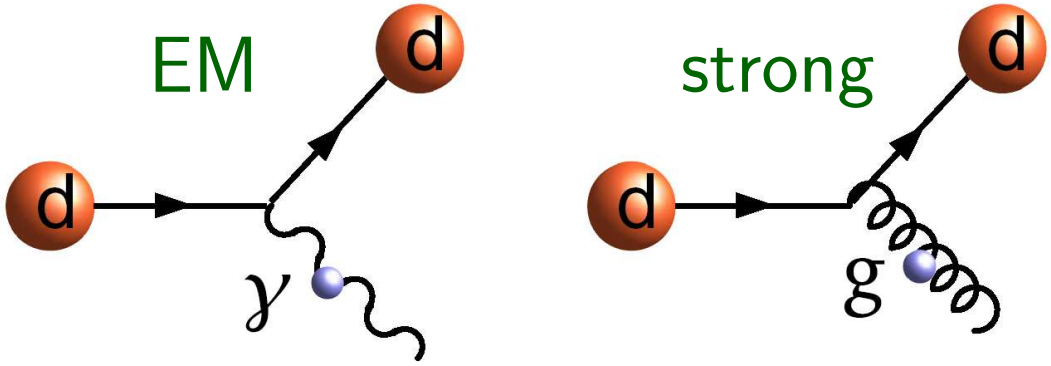
quarks



(anti-matter)



- Bosons $S = \hbar$ (force carries):

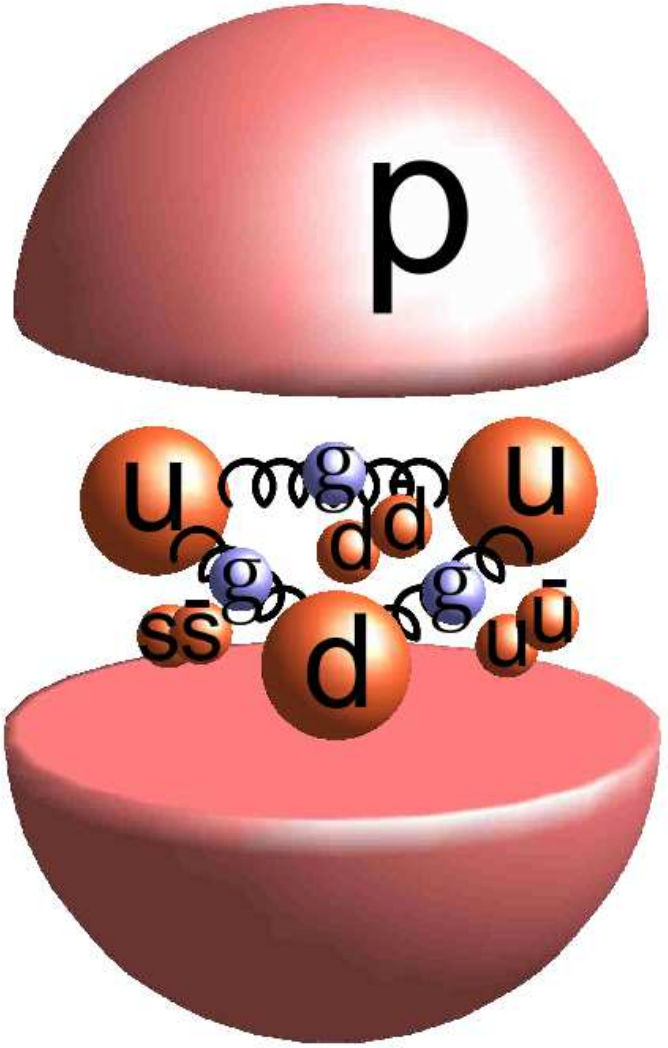


← massless

(weak force bosons mass)

Mass of Matter

- Most of our mass is protons and neutrons
  - most mass is energy of quark-gluon soup: $m_p c^2 = E$



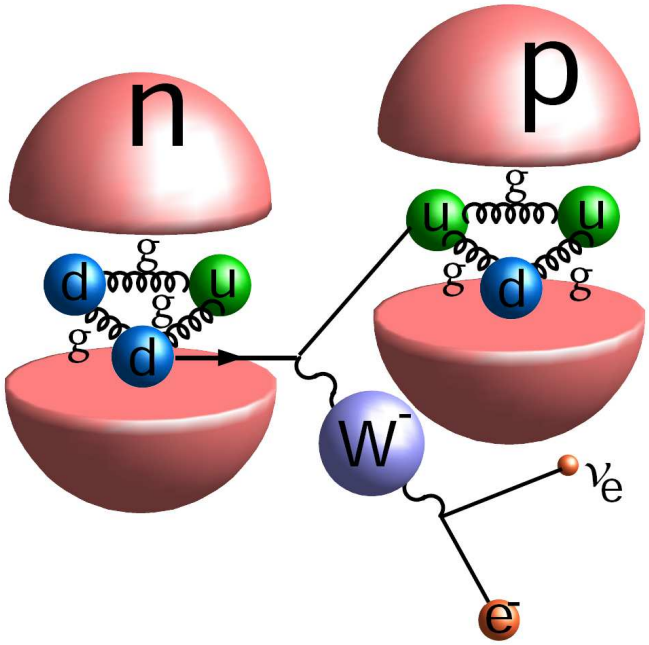
Mass from quark-glue soup energy:
$m_p c^2 = 938$ MeV $\simeq 1.7 \times 10^{-27}$ kg

Mass from the Higgs field:
$m_u c^2 \sim 3$ MeV, $m_d c^2 \sim 5$ MeV

but Higgs field is very important

But Higgs Mechanism is Very Important

- Makes Weak Interactions weak: mass of Z, W^-, W^+



similarly first step in sun fusion

$$p + p \to d + e^+ + \nu_e$$

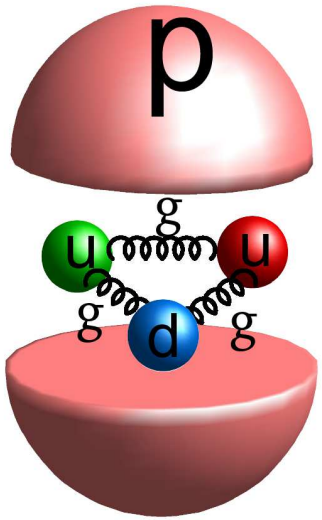
- Recall: mass is very important without gravity (energy)
- Higgs Mechanism makes certain hierarchy of masses essential for our existence

Hypothetical Scenario: Different Quark Mass

- Again, normally proton is stable and neutron decays:

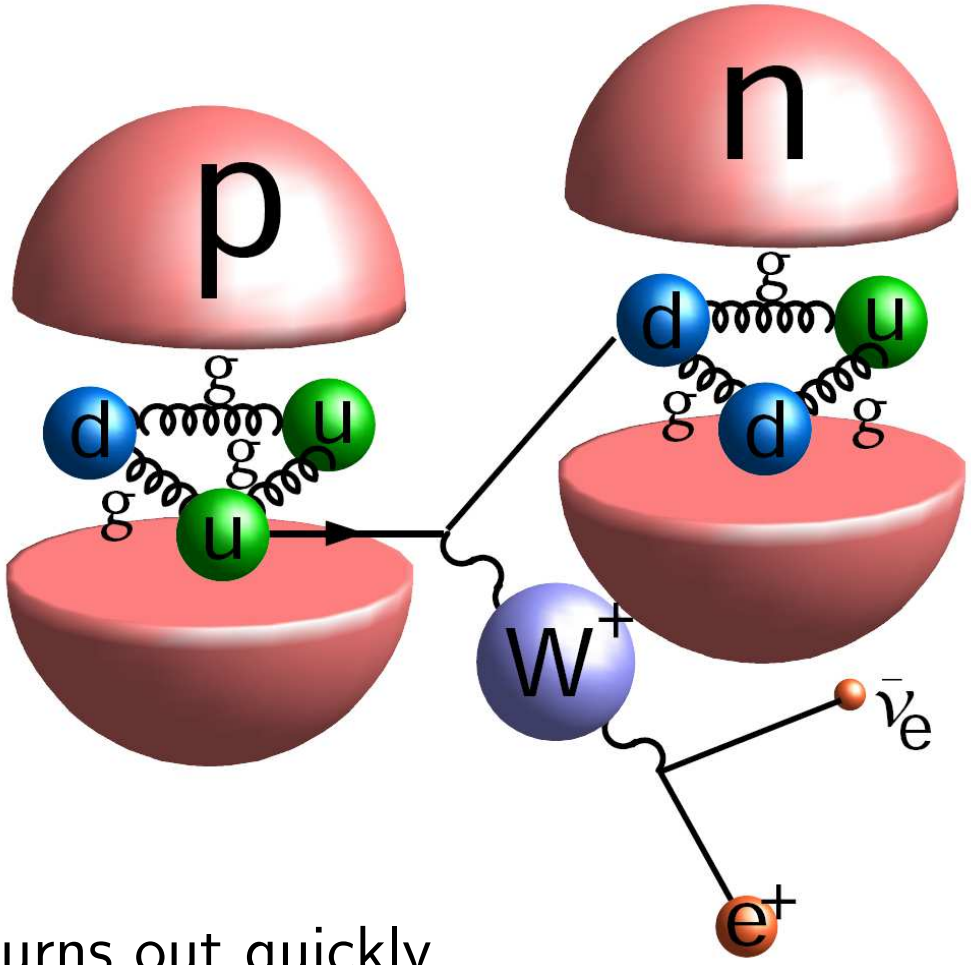
$$\mathrm{m}(n) > \mathrm{m}(p) + \mathrm{m}(e) + \mathrm{m}(\nu_e)$$

- Why is $\mathrm{m}(n) > \mathrm{m}(p)$
  - $\mathrm{m}(p) = 938$ MeV, $\mathrm{m}(n) - \mathrm{m}(p) = 1.3$ MeV
  - tiny difference makes a big difference!
  - naively expect $\mathrm{m}(p) > \mathrm{m}(n)$ if u and d were the same
  - but $\mathrm{m}(d) > \mathrm{m}(u)$
- New scenario:
  - what if $\mathrm{m}(d) \leq \mathrm{m}(u)$



Higgs Field in our Life

- Remove the Higgs field:
  - catastrophic decay of a proton
  - no H_2O (water), no life



- Origin of Sun light

  starts from Weak fusion

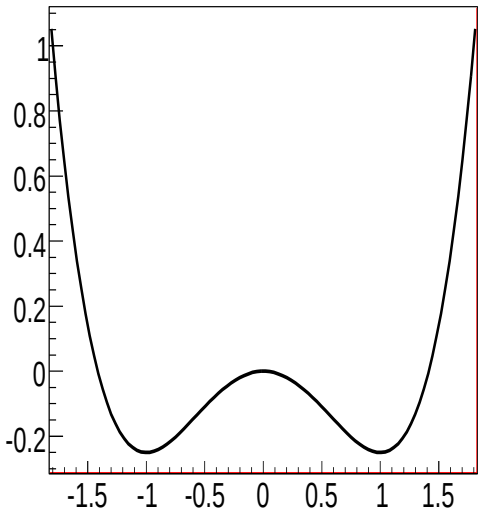
  $p + p \to d(pn) + e^+ + \nu_e$

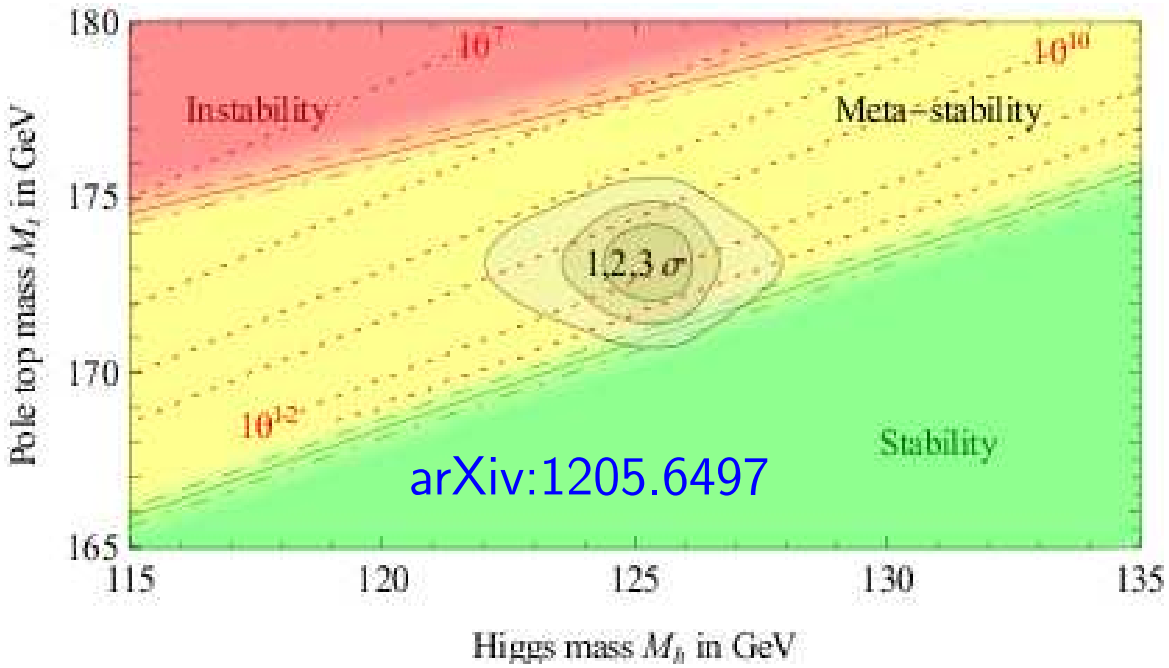
  slow burning due to heavy W^+

  Remove the Higgs field – Sun burns out quickly

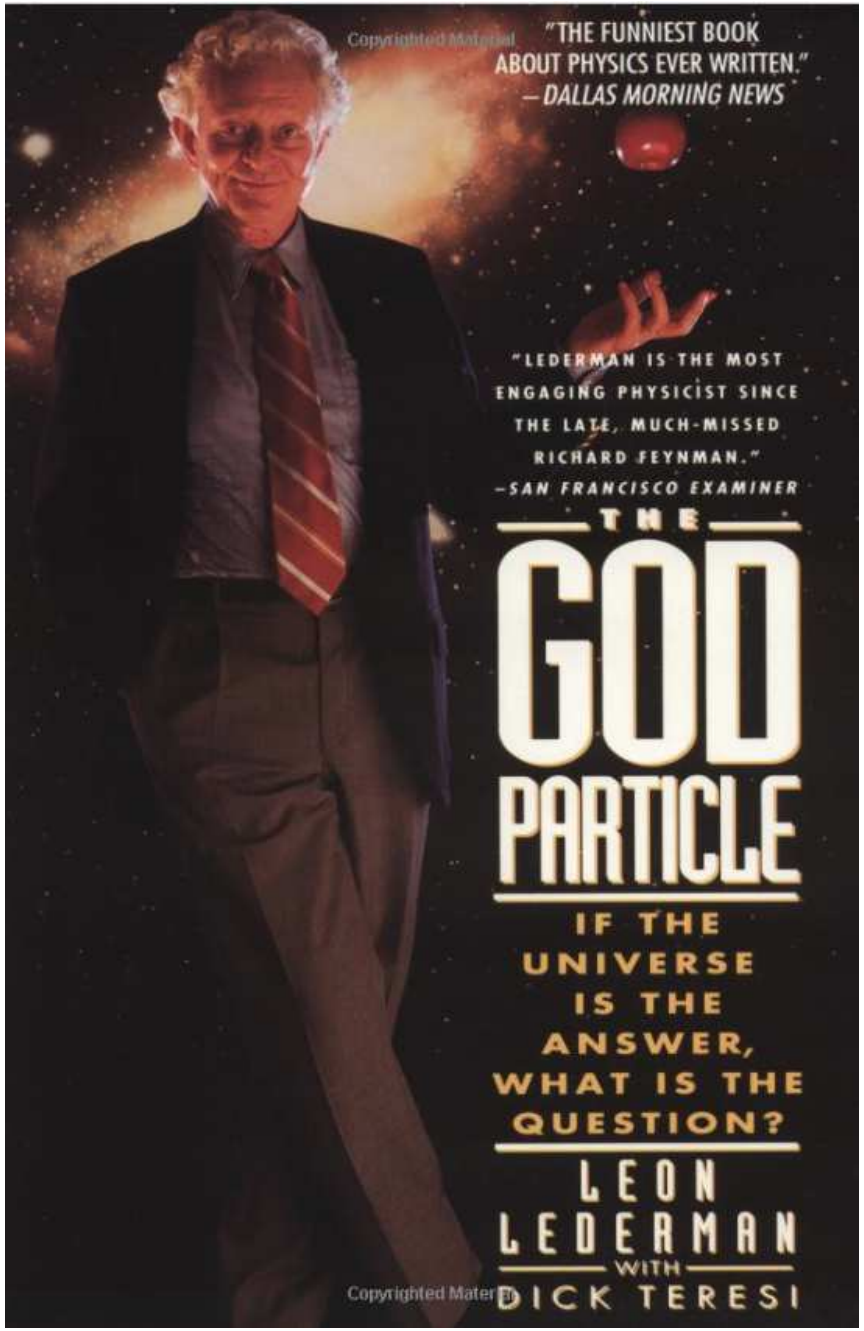
Stability of the Vacuum

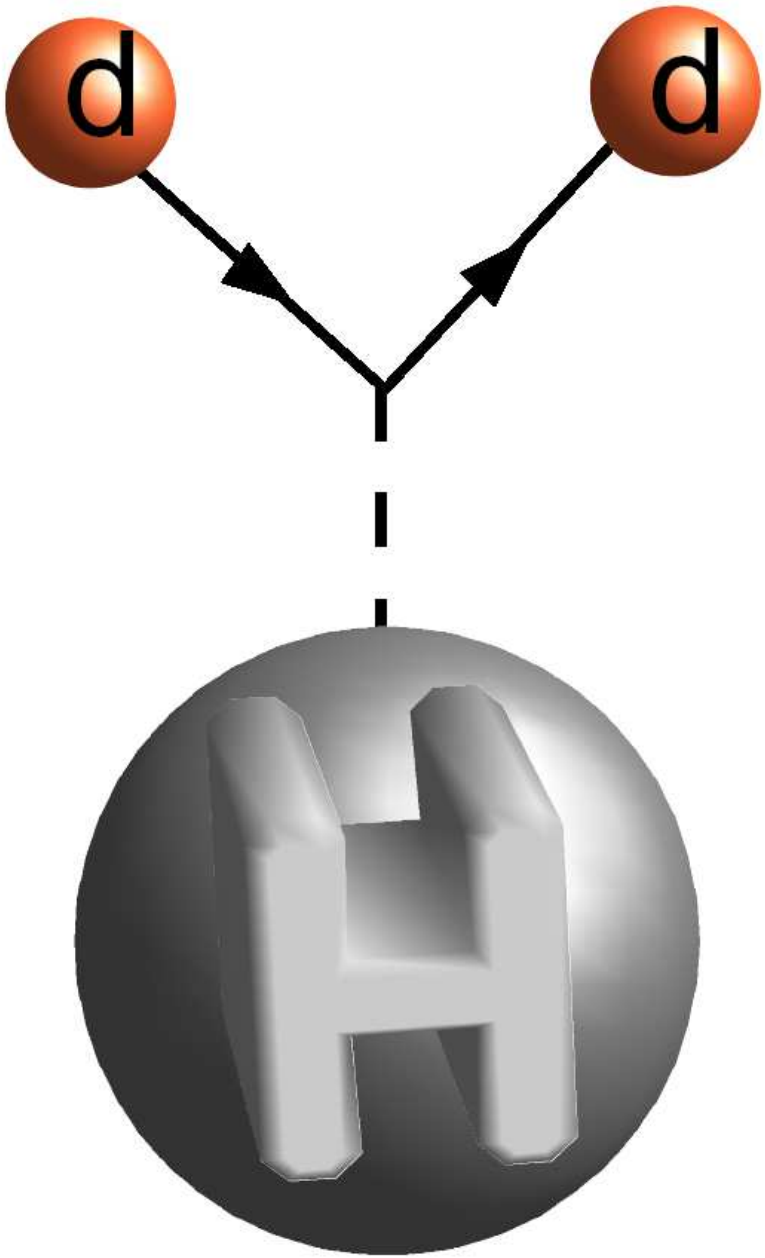
- Higgs self-coupling $\lambda < 0$ at higher scale
  - may tunnel thru "potential barrier" $\Rightarrow$ unstable Universe
  - tunneling time $>$ Universe lifetime $\Rightarrow$ metastable Universe
  - for $m_H \sim$ 126 GeV/c^2 and SM Higgs field $\Rightarrow$ metastable





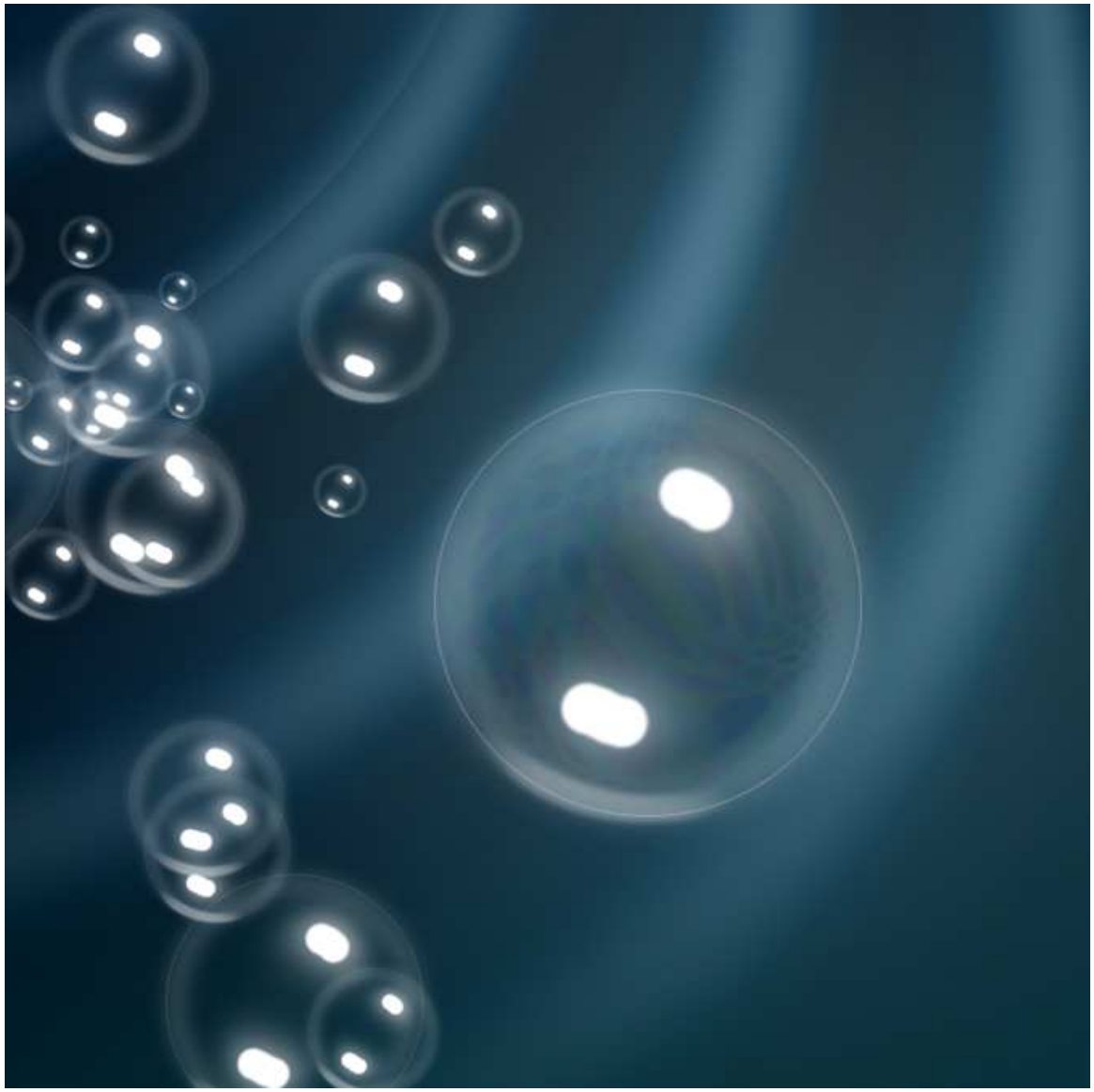
The Higgs Boson





Create Higgs Boson from the Higgs Field

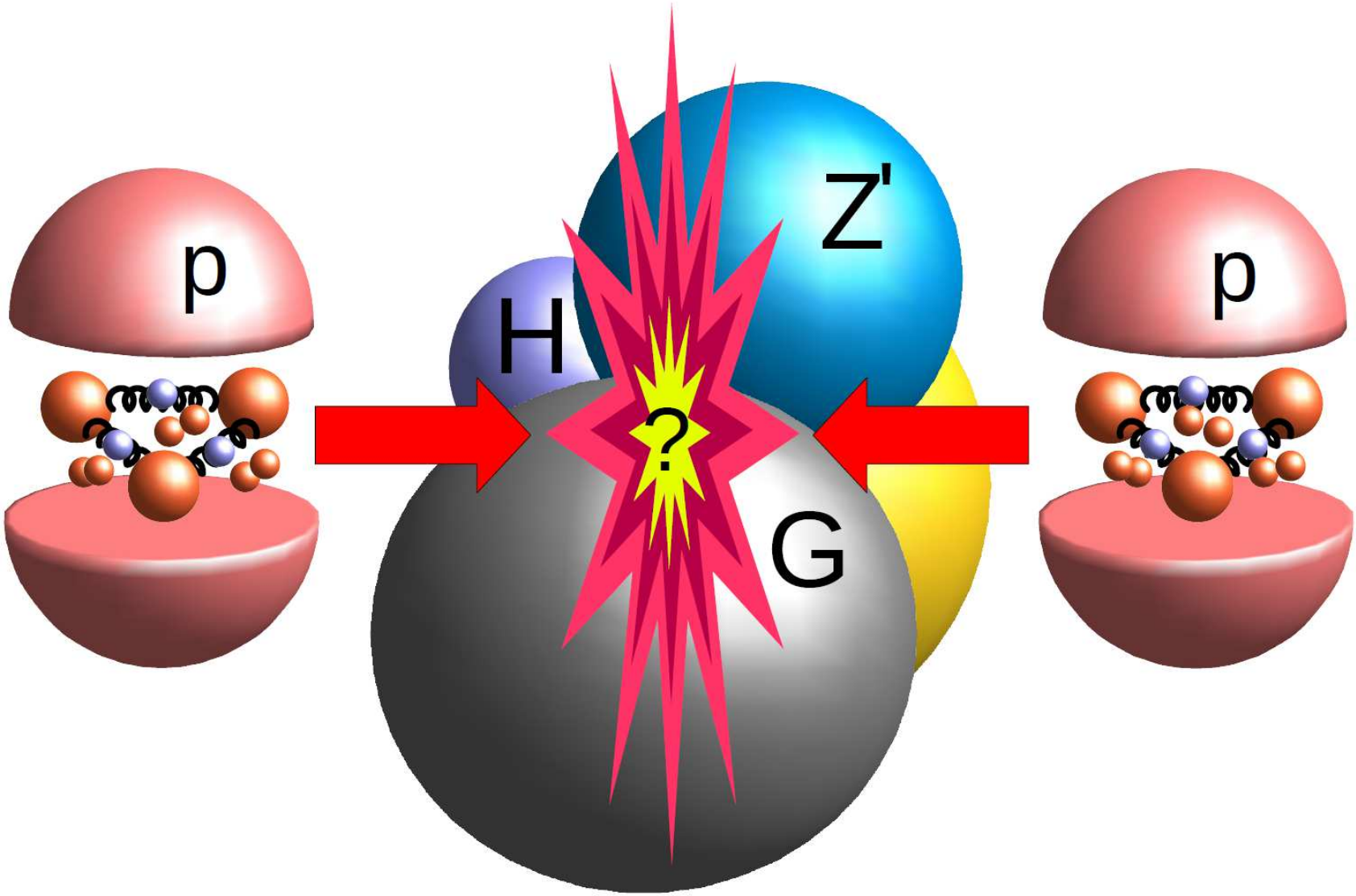
- Idea: if the Higgs field exists, like soap:
  - blow into the soap, create a bubble (Higgs boson)



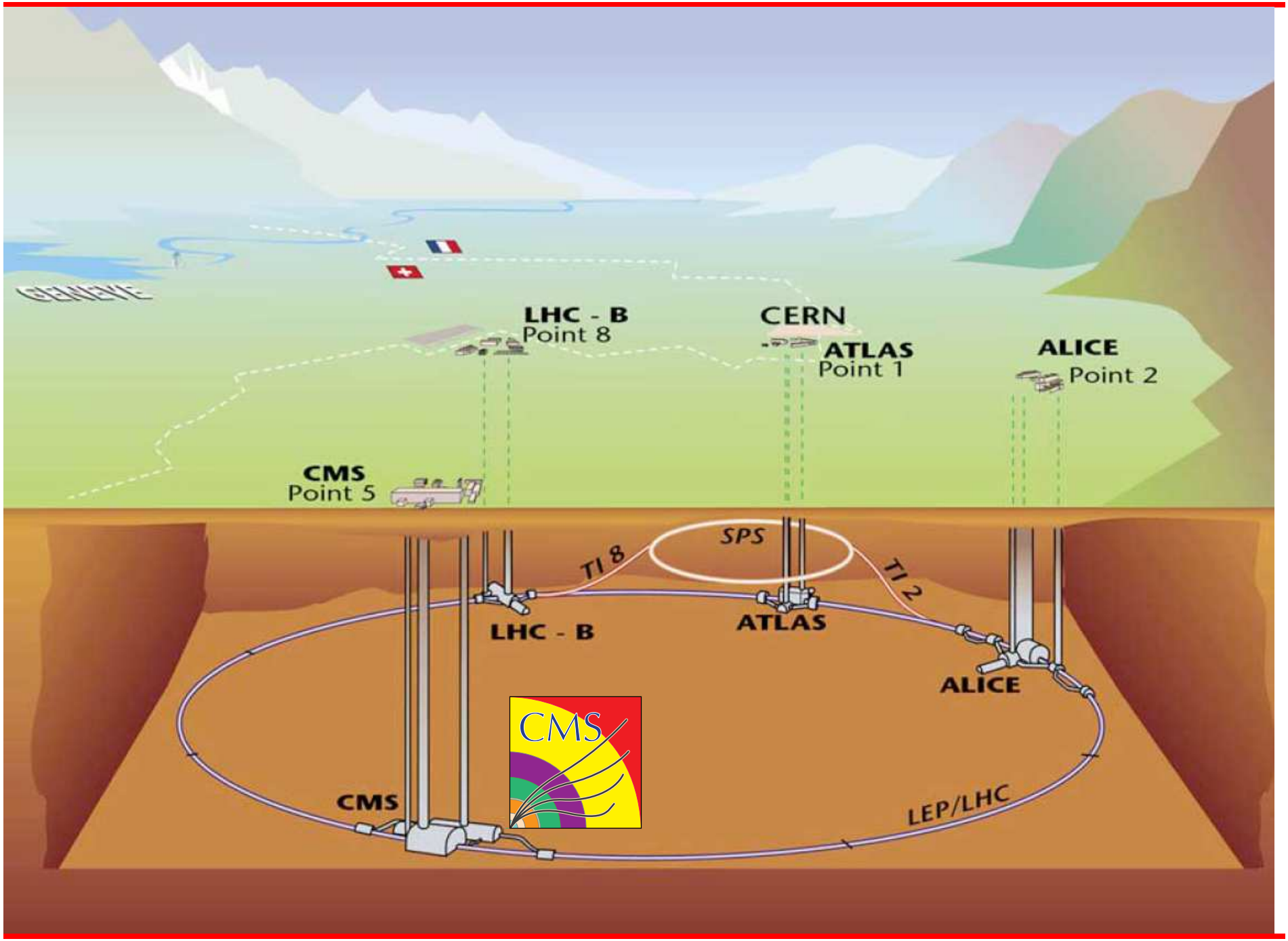
How Do We Know This ?

We Smash Matter

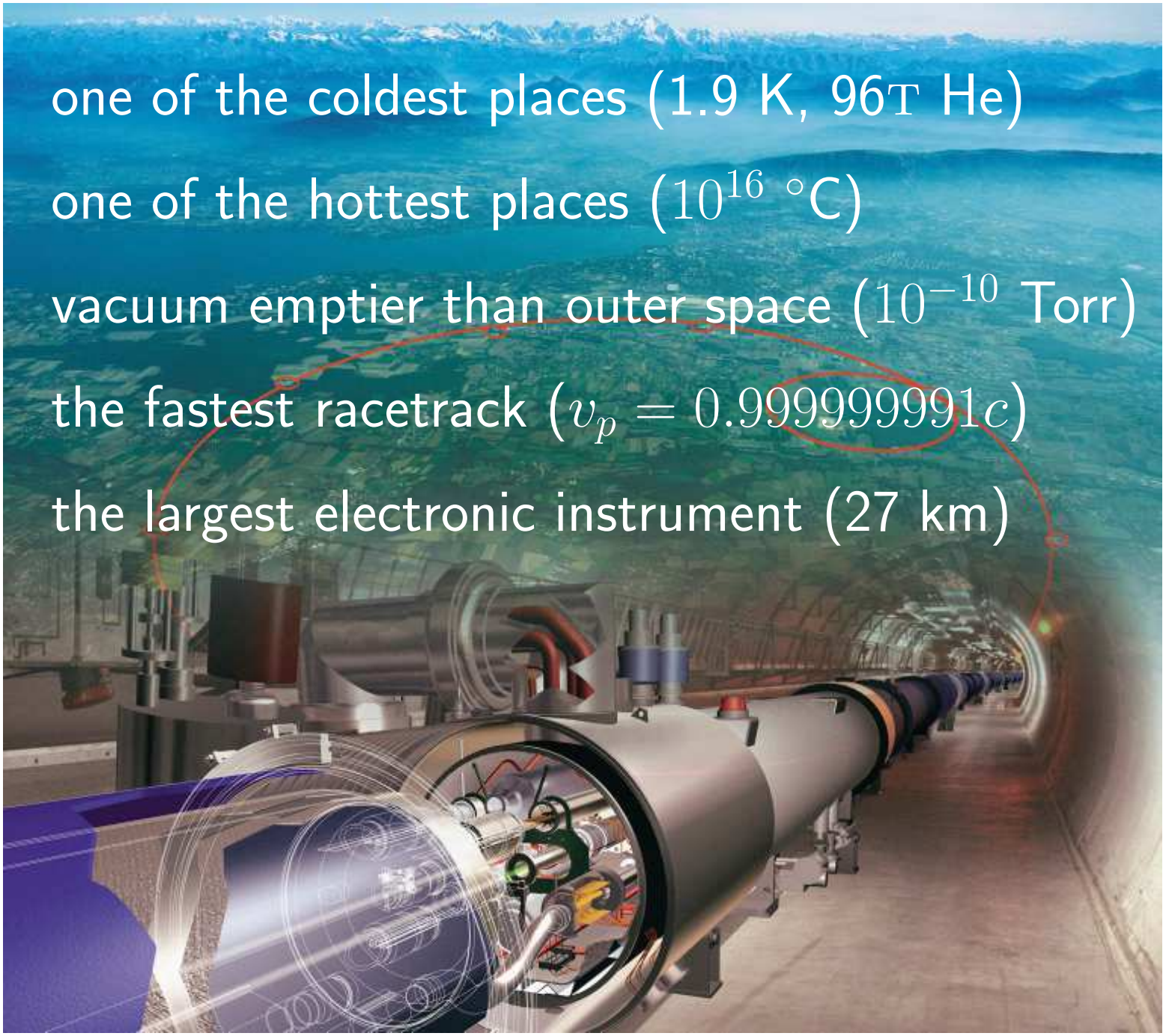
- Supply Energy into tiny spot: produce new matter / energy $E = mc^2$



The Large Hadron Collider



The Large Hadron Collider



The Large Hadron Collider

- Enormous amount of data from LHC

  > 2000 trillion proton-proton collisions in 2011-2012

  > 20 billion events recorded, $\sim$0.6 Mbyte each (Petabytes)

  > 200 million Z^0 bosons

  > 200 thousand Higgs bosons produced – assuming we see it

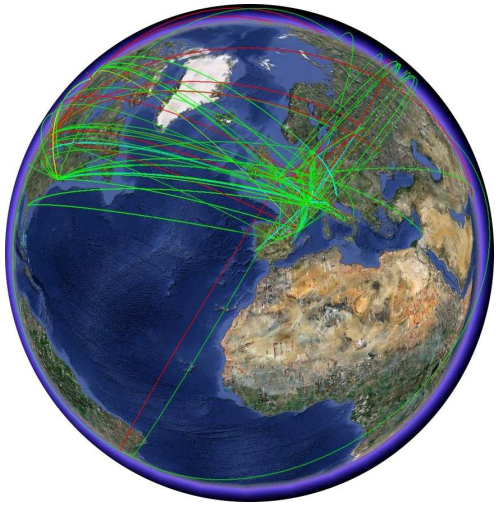
- LHC Computing Grid

  world's largest computing grid

  over 170 computing centers in 36 countries

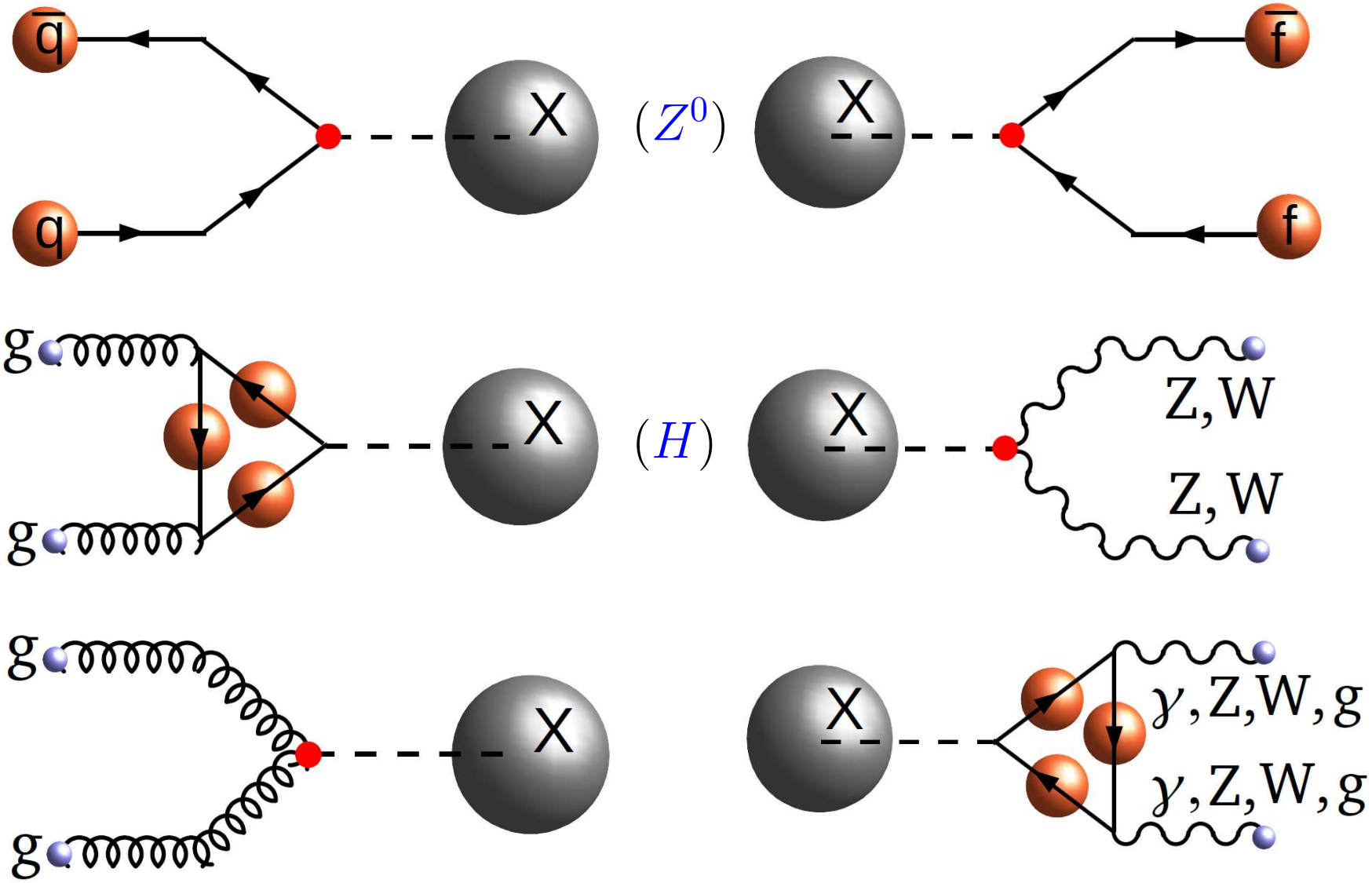
  $\sim$ 25 Petabytes / year (25×10^{15} bytes)

  ($>$ 5 million DVDs, comparable to Facebook storage)



Production of New Particles at LHC

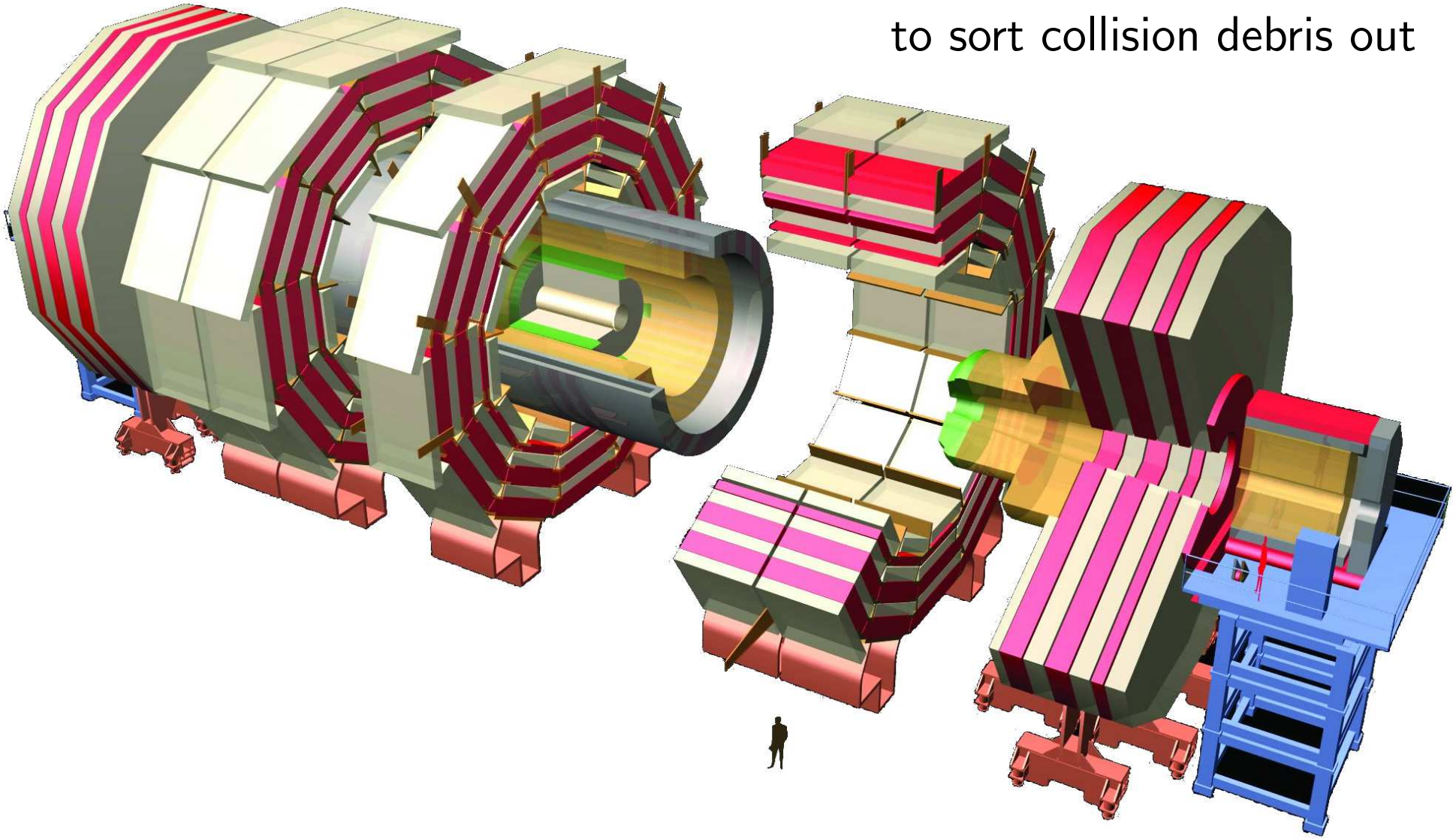
- Particles are produced and decay: $X = Z^0$, Higgs, RS Graviton, ...



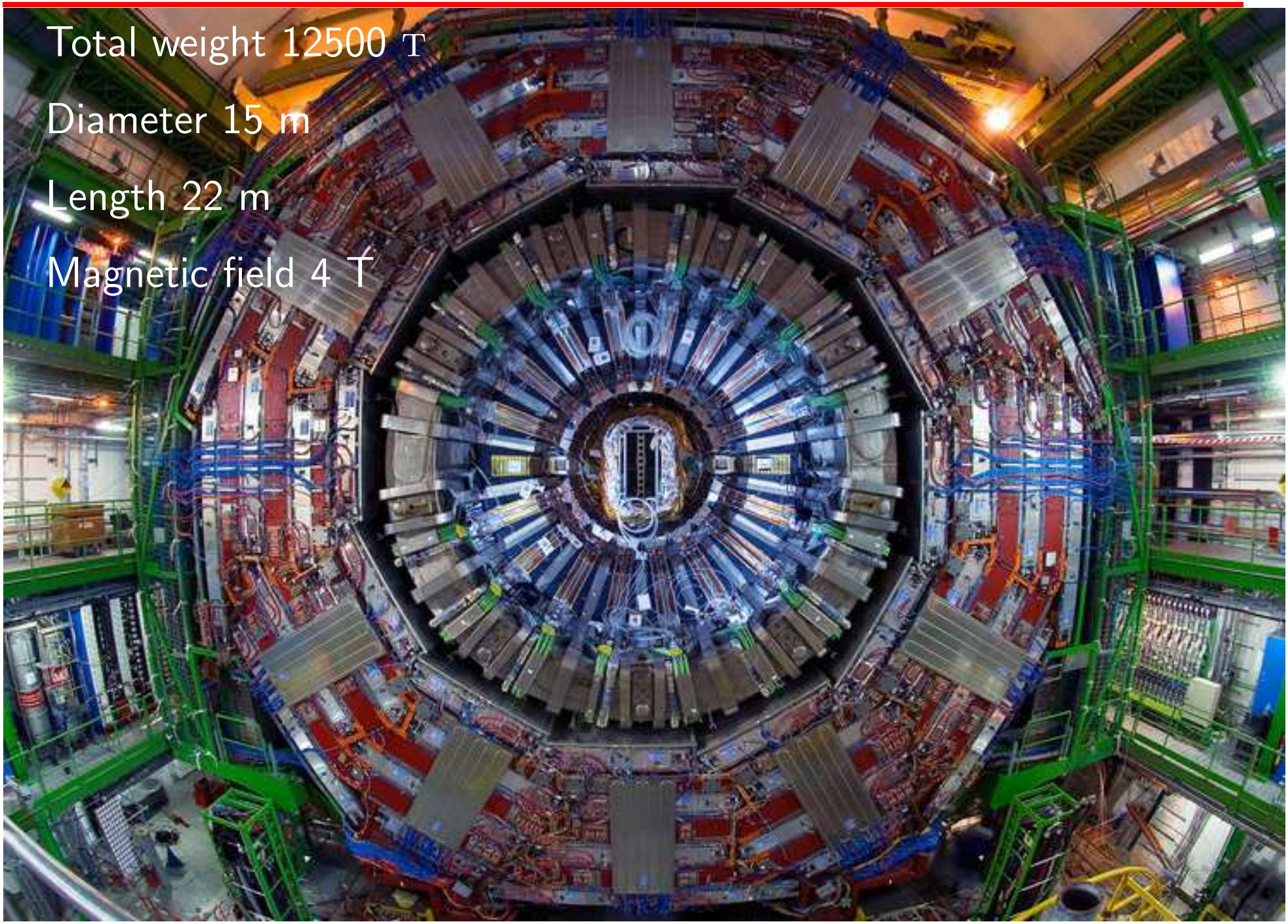
The CMS Detector

- Complex detector

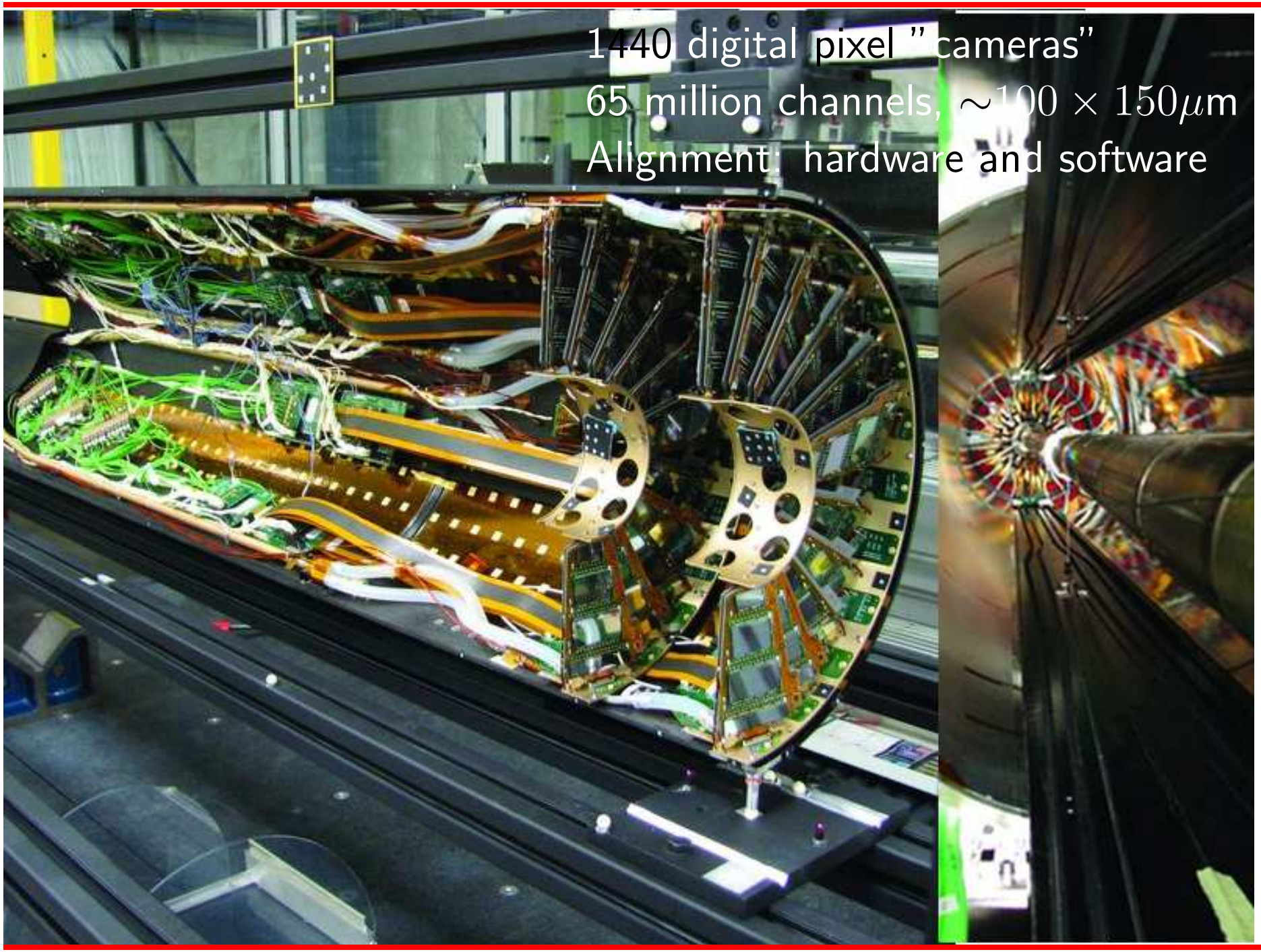
  to sort collision debris out



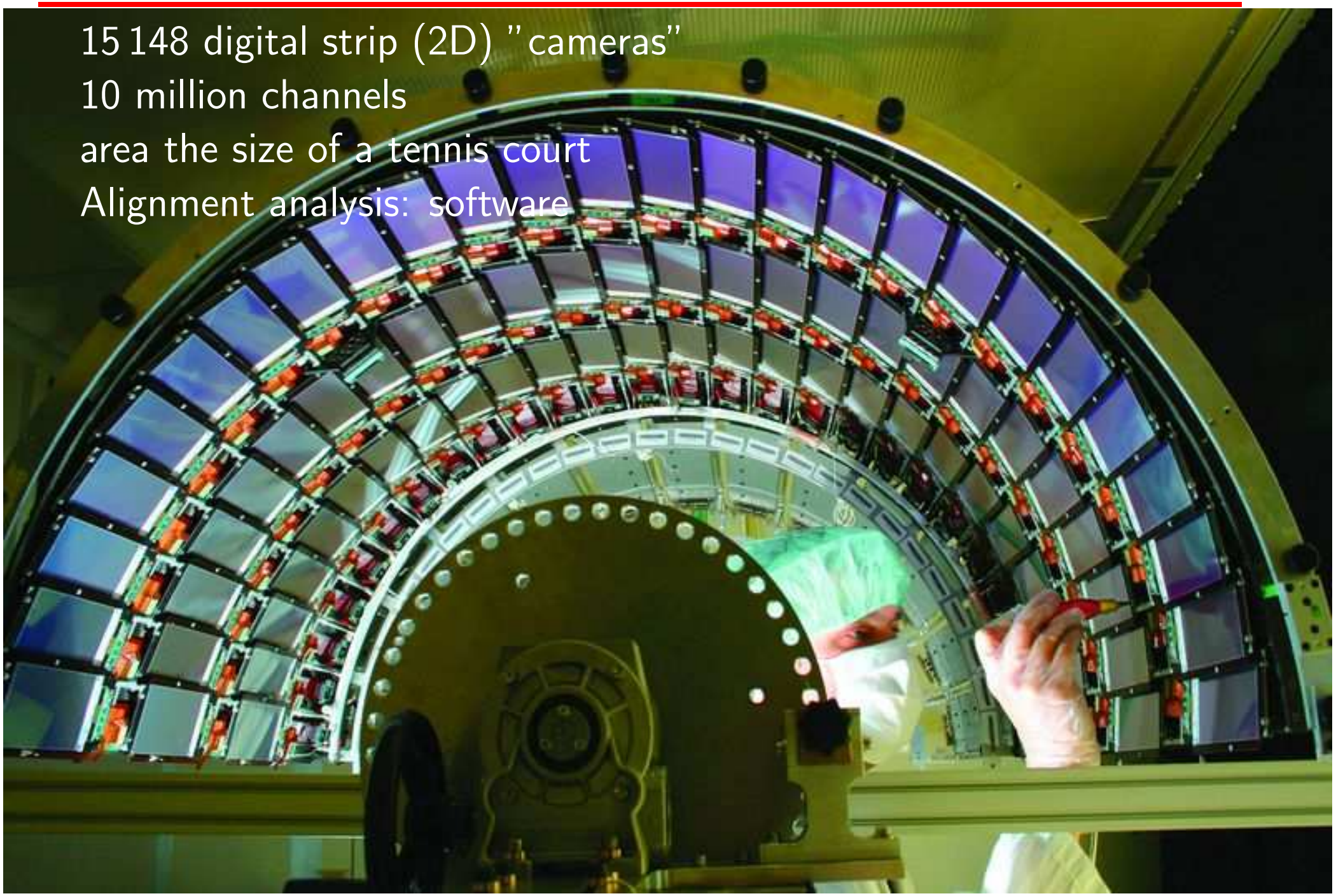
The CMS Detector



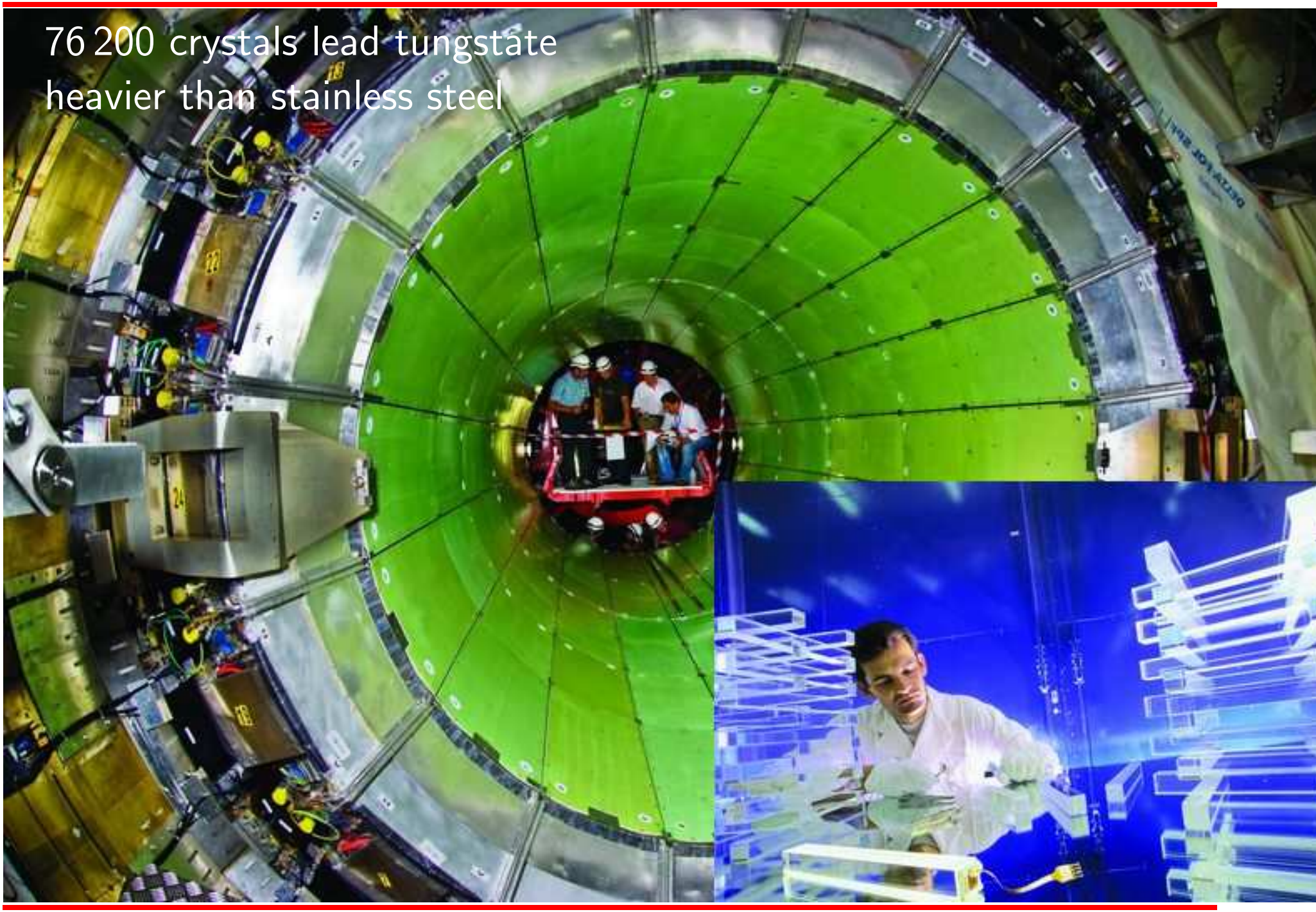
The Silicon Pixel Detector



The Silicon Strip Detector



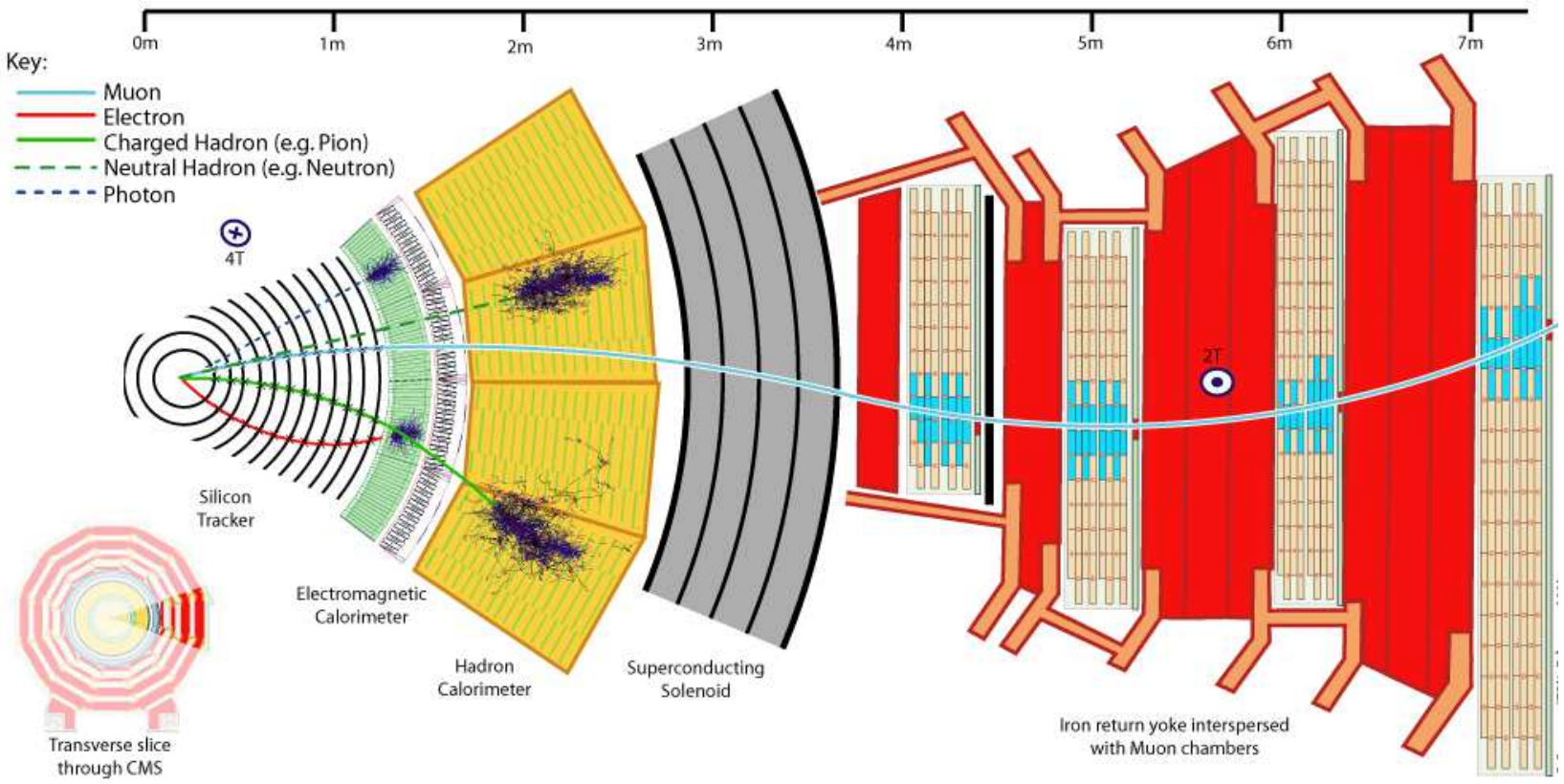
Electromagnetic Calorimeter



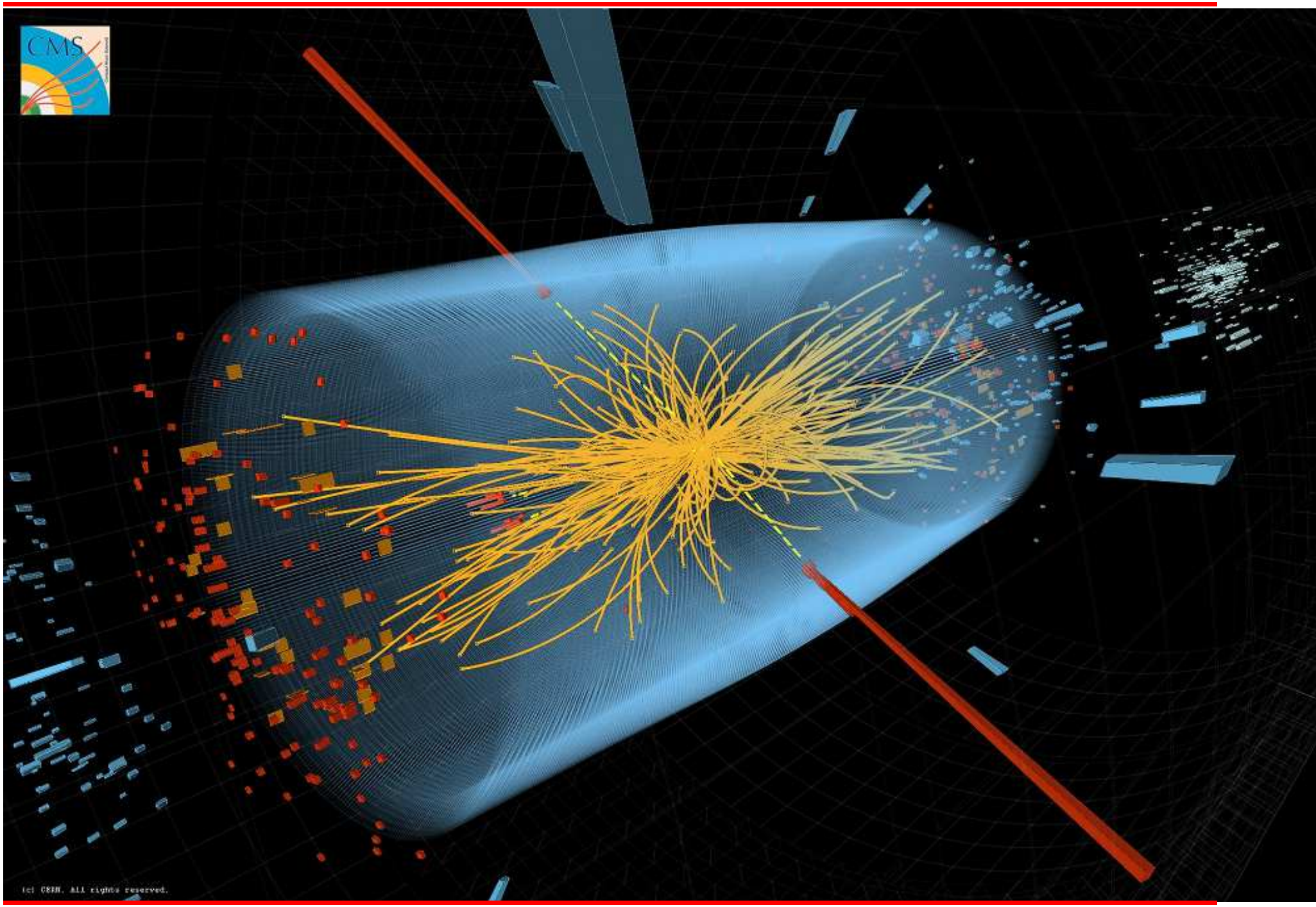
Hadronic Calorimeter and Muon System

How the Detector Works

- Tracking: electrons $e^{\pm}$ (EM Calorimeter), muons $\mu^{\pm}$ (Muon System)
- Photons γ (EM Calorimeter)
- Quark q & gluon g jets $\rightarrow$ flow of partciles thru Hadronic Calorimer
- Neutrinos $\nu \Rightarrow$ missing energy

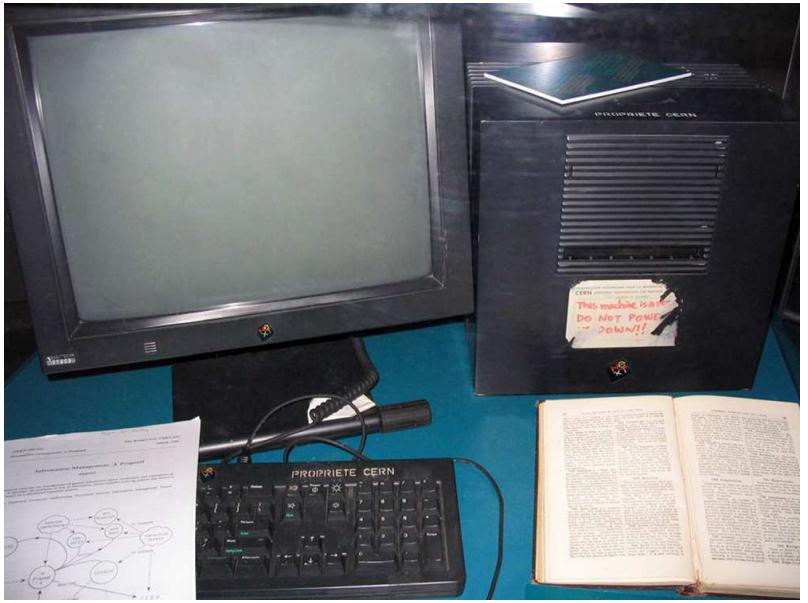


Computer Reconstruction of a "Bubble"



Global Effort at the Large Hadron Collider

- 1991: first World Wide Web (http://www...) server at CERN



- 20 years later: LHC Computing Grid
  - distributed across 36 countries
  - 200,000 computer cores
  - 150 Petabytes of disk space

  Petabyte = Million Gigabytes

  1 Gigabyte $\simeq$ 1 CD

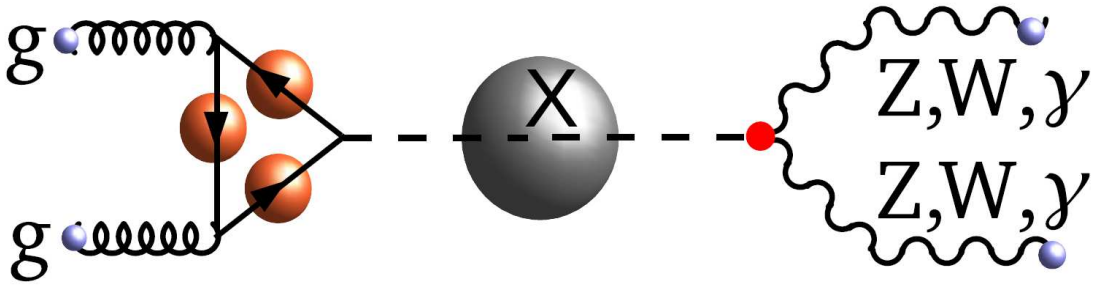
- Flow of data from one experiment alone (CMS):

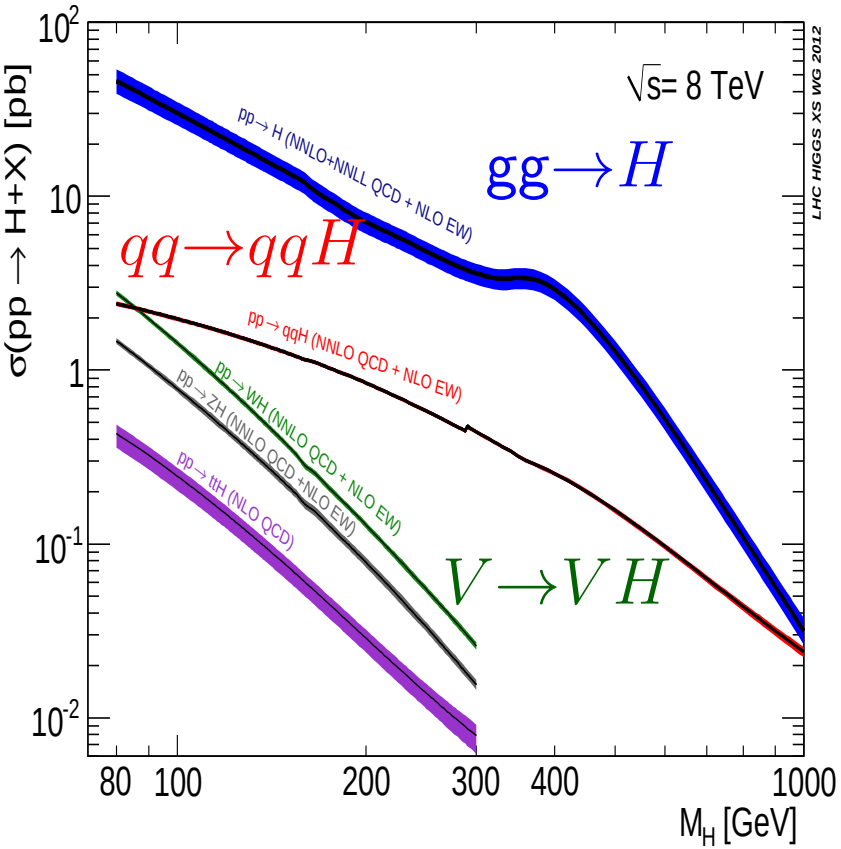
  > 300 trillion proton-proton collisions in 2011

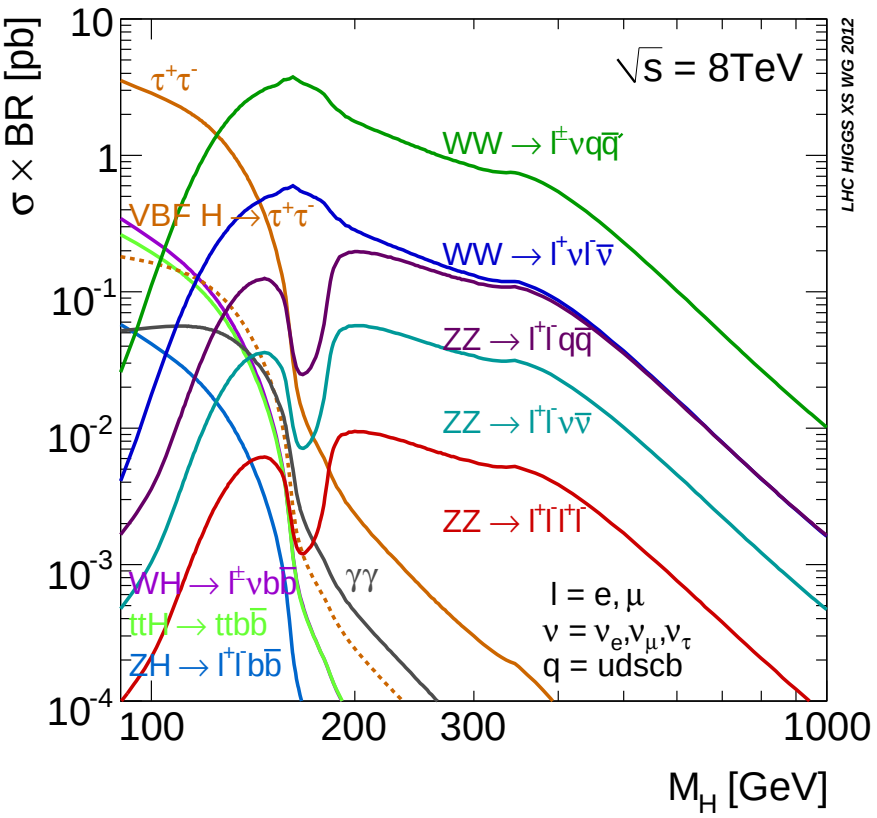
  > 3 billion "events" recorded on disk in 2011

Production and Decay of a Higgs Boson

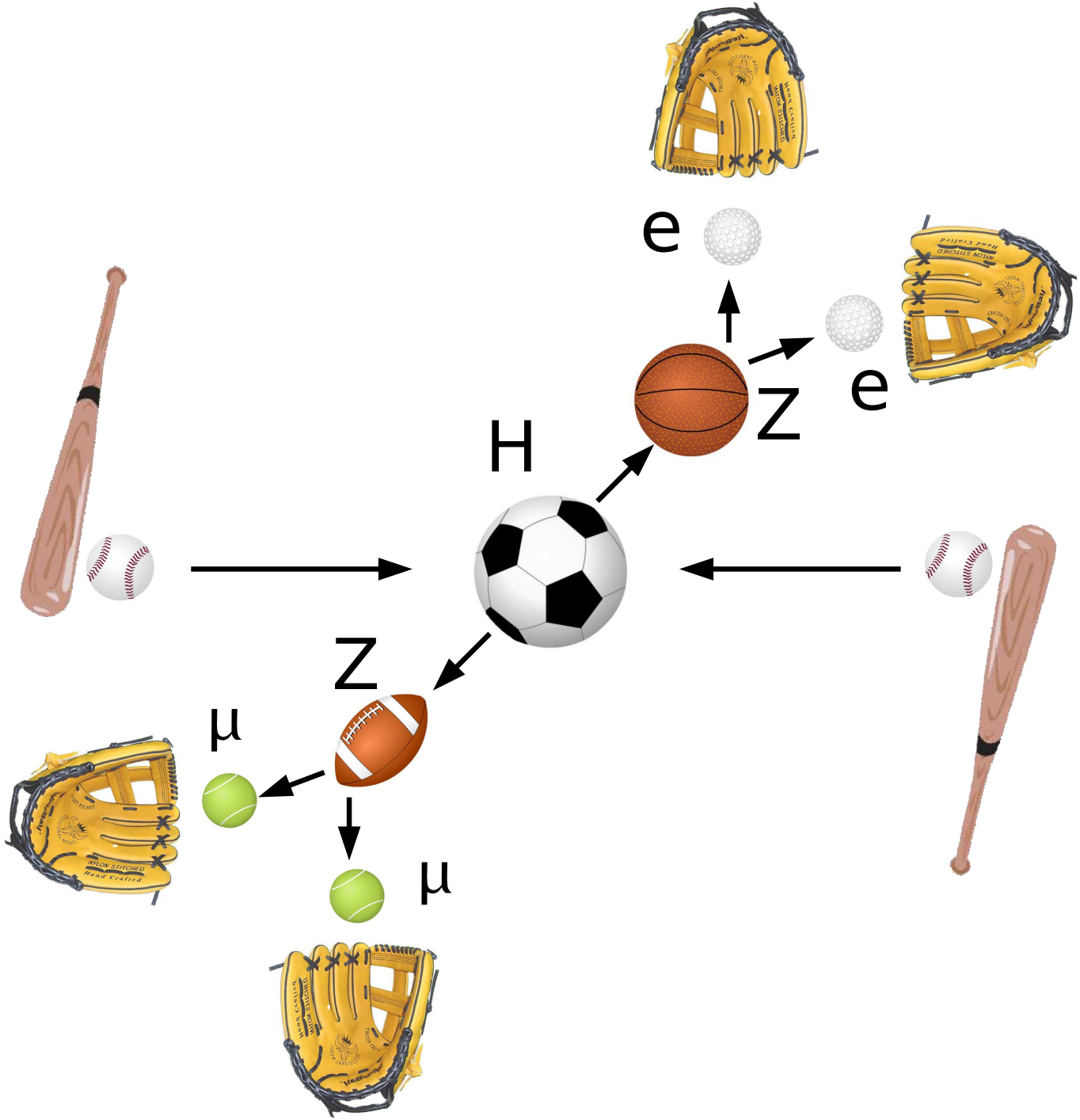
$$gg \to H \to \gamma\gamma,\ ZZ^{(*)},\ W^+W^-,\ b\bar{b},\ \tau^+\tau^-,..$$







Data Analysis



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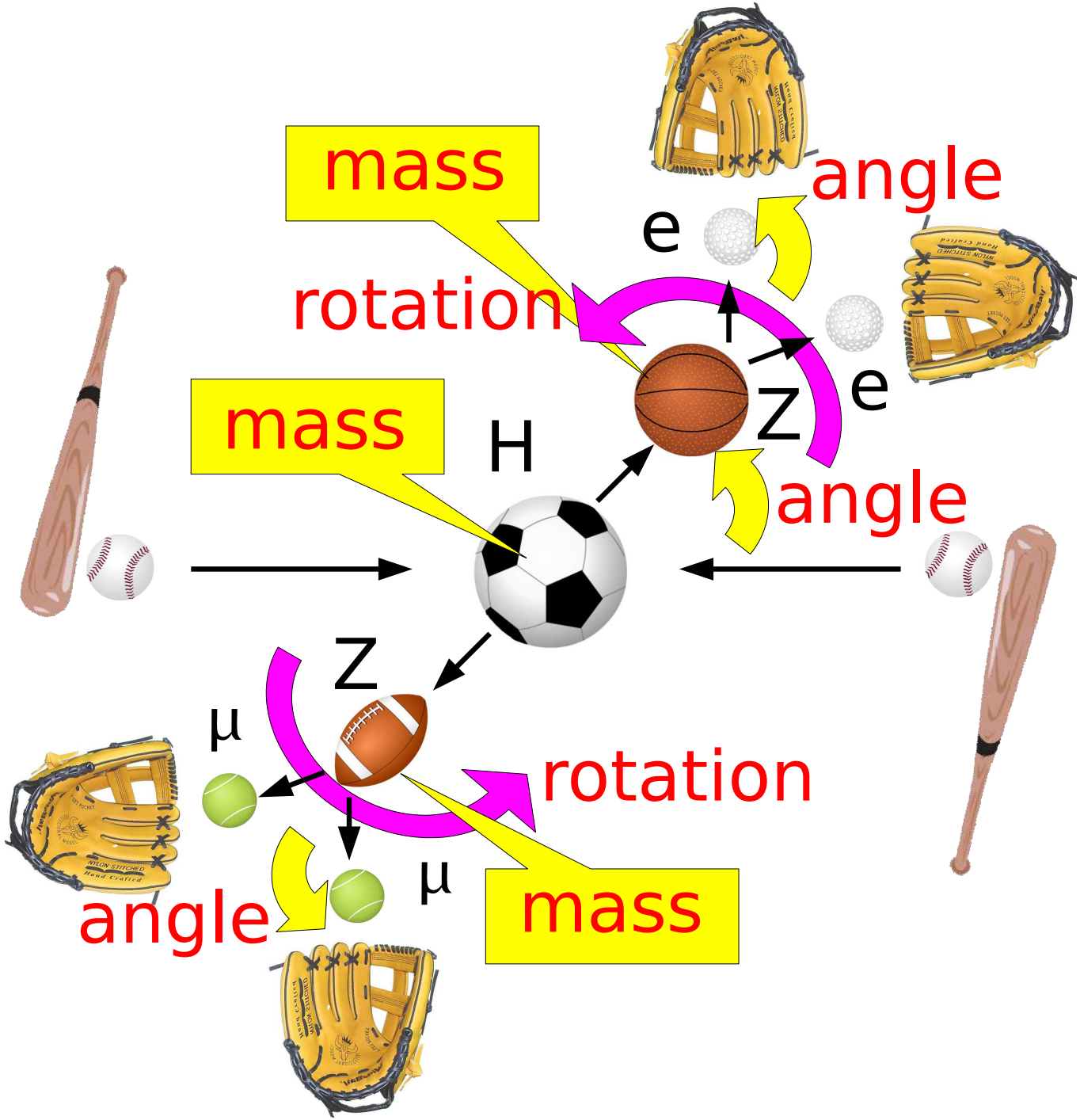
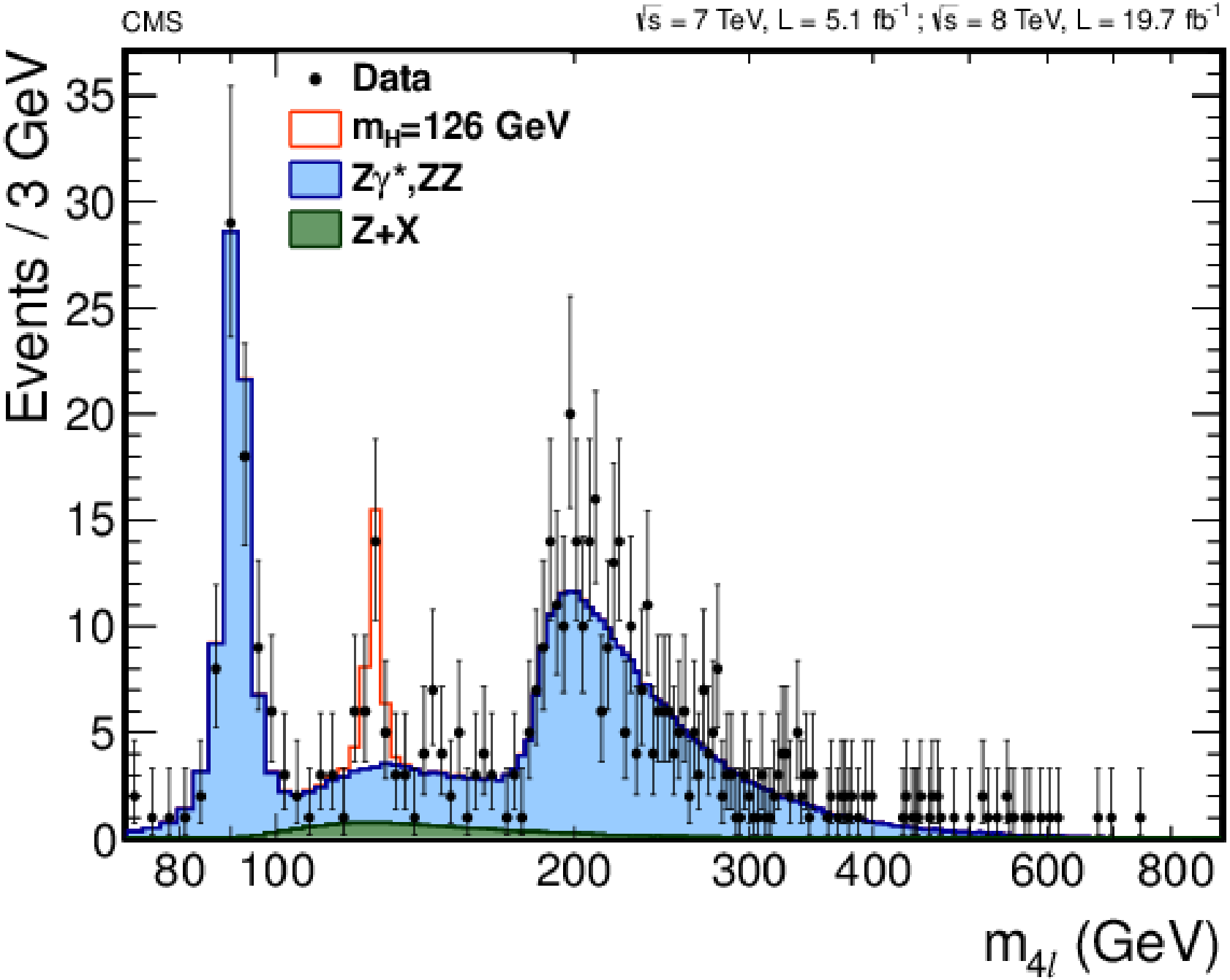


$H \to ZZ \to 4\ell$



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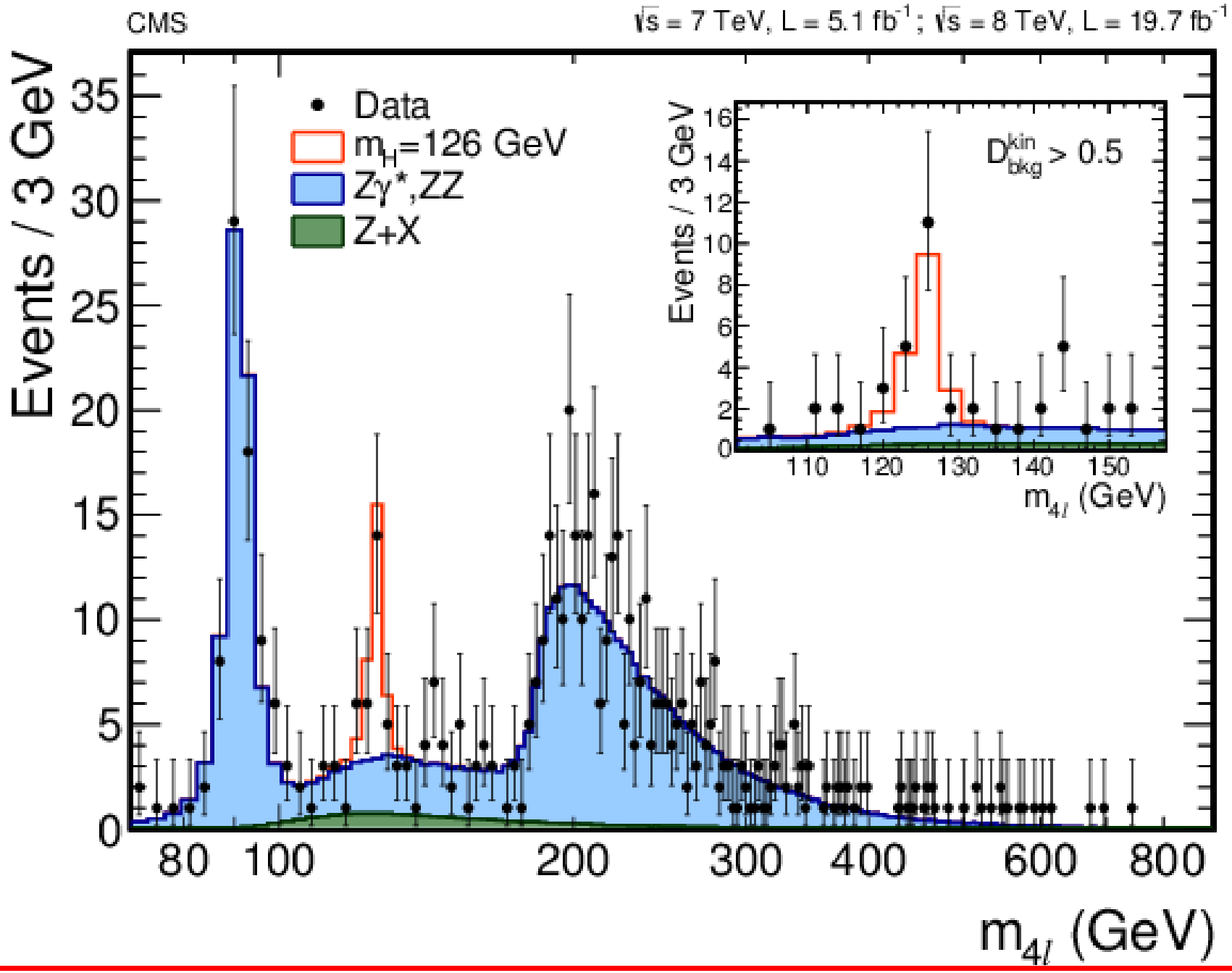
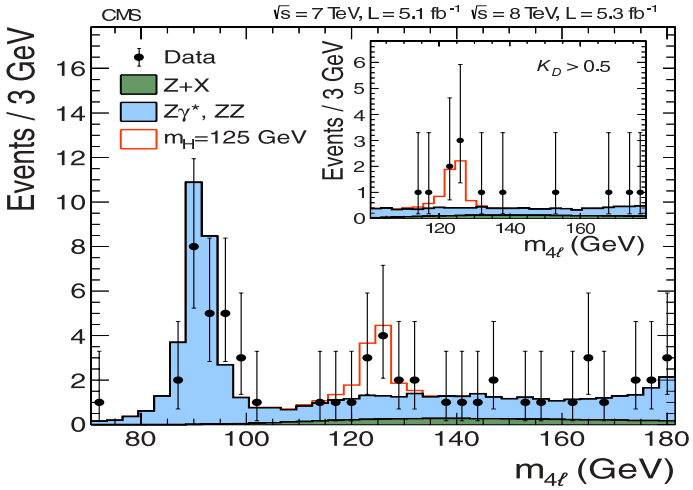


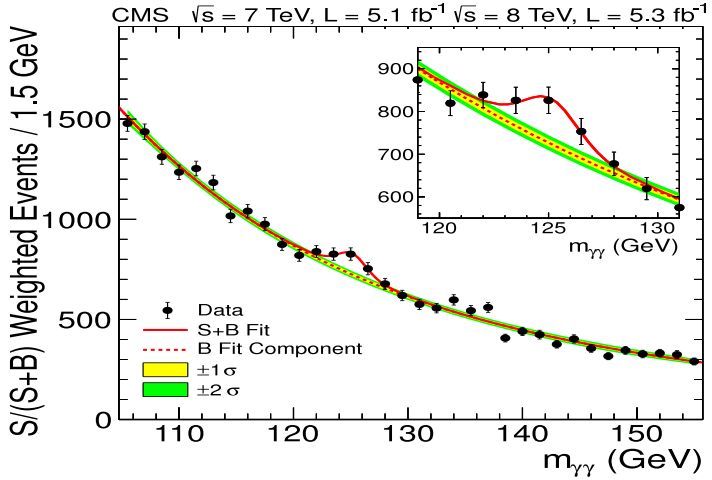
July 2012: Observation of a New Boson

- Observation of a New Boson on CMS: 5σ excess

$X \to Z^{(*)}Z^{(*)}$

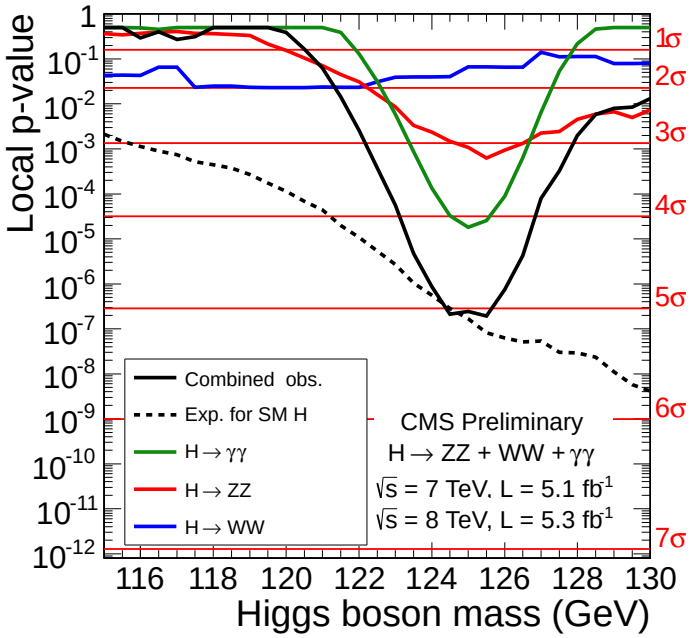


$X \to \gamma\gamma$



- Probability of background

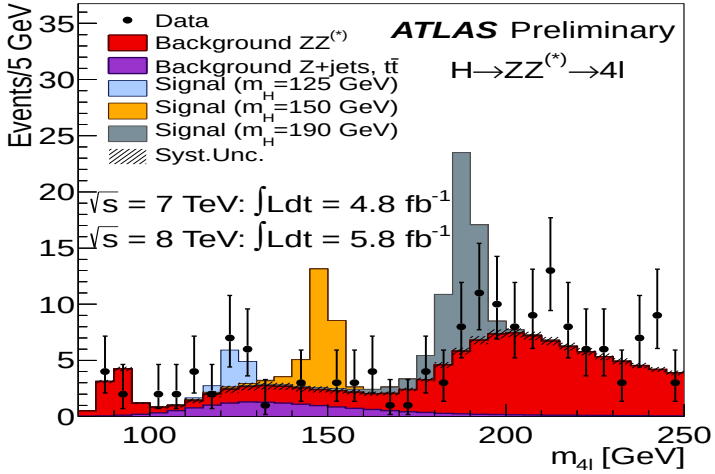
$$\sim 0.2 \times 10^{-6}$$



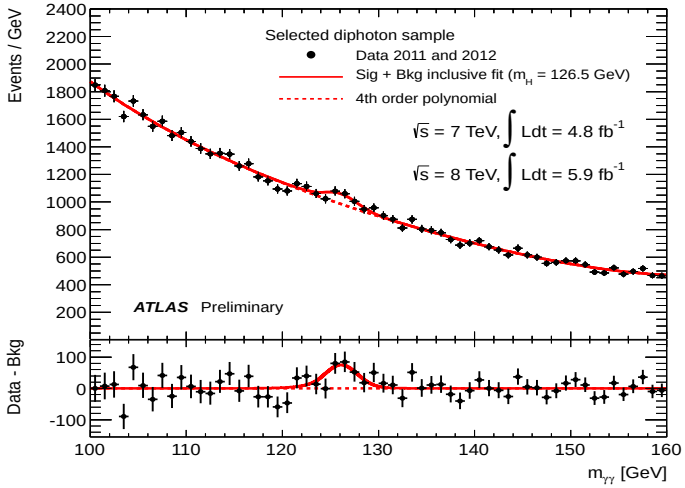
July 2012: Observation of a New Boson

- Observation of a New Boson on ATLAS: 5σ excess

$X \to Z^{(*)}Z^{(*)}$



$X \to \gamma\gamma$



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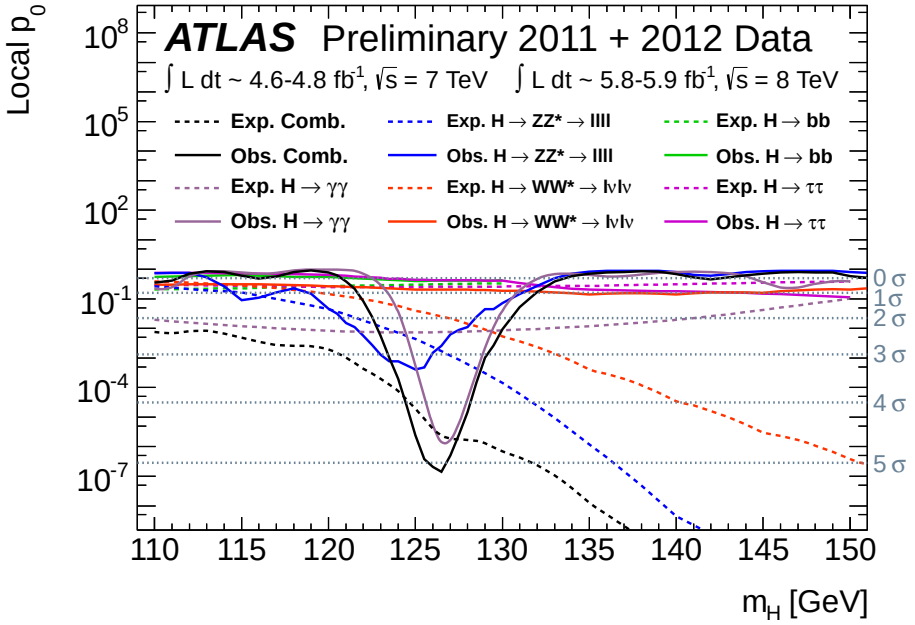
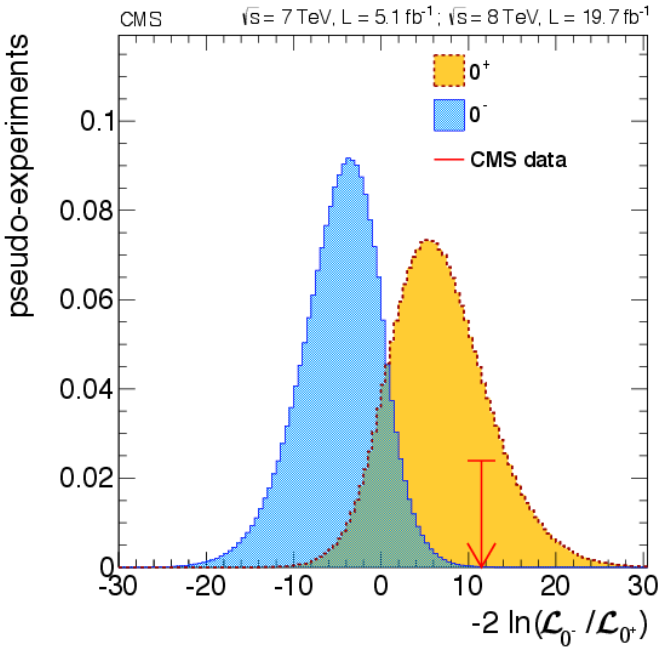
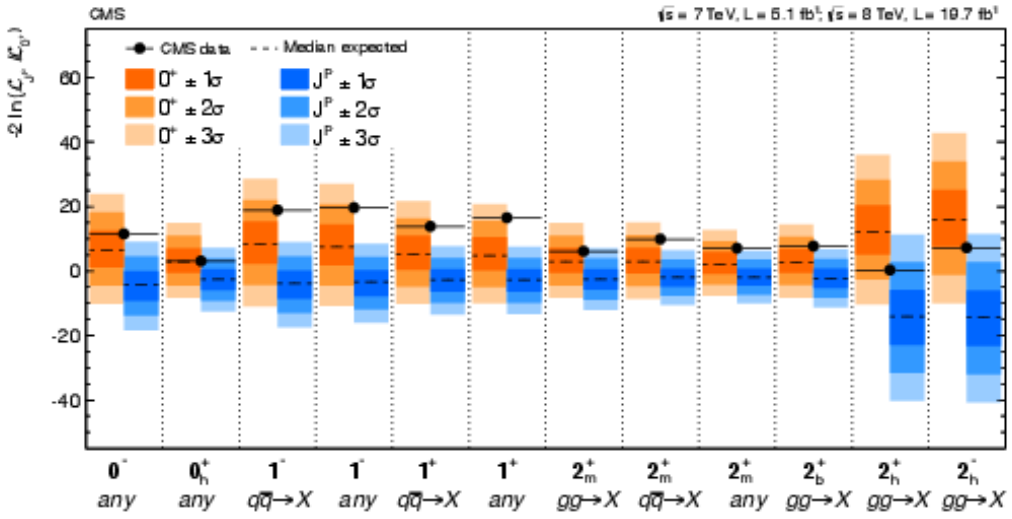


Is it the Higgs Boson?

- We found the new boson, but is the Higgs boson?
  - all indications: it is consistent
  - its spin is 0
  - its symmetry (mirror image) is $+$





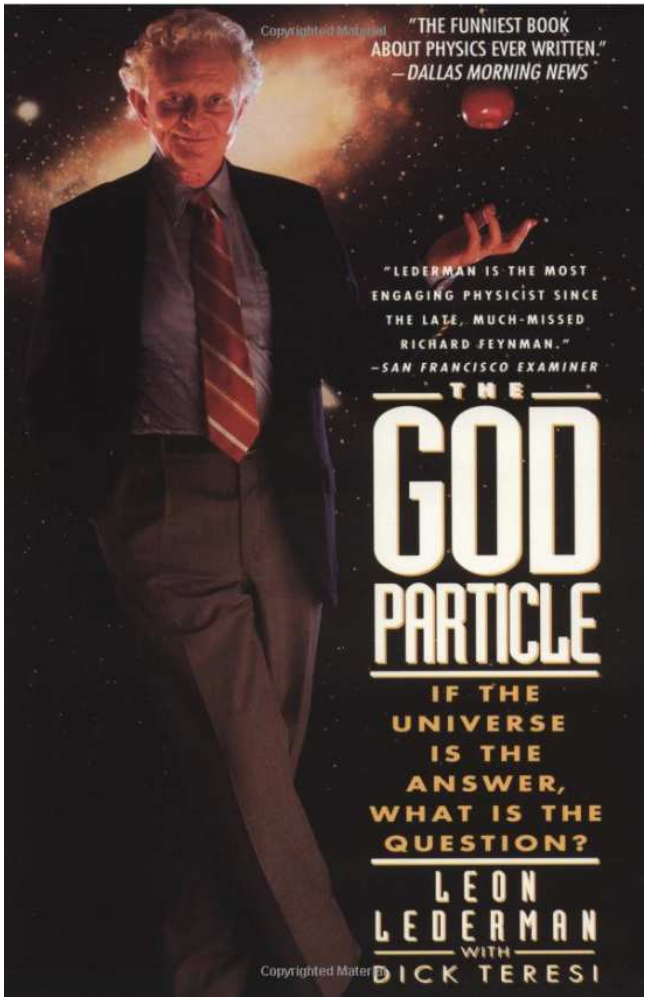
- New state of matter-energy never seen before (like vacuum 0^+)

Could have we seen this earlier?

- Superconducting Super Collider (in Texas) cancelled in 1993

  3 times longer, 3 times stronger than LHC

  almost 1/3 tunnel done, $2 billion spent

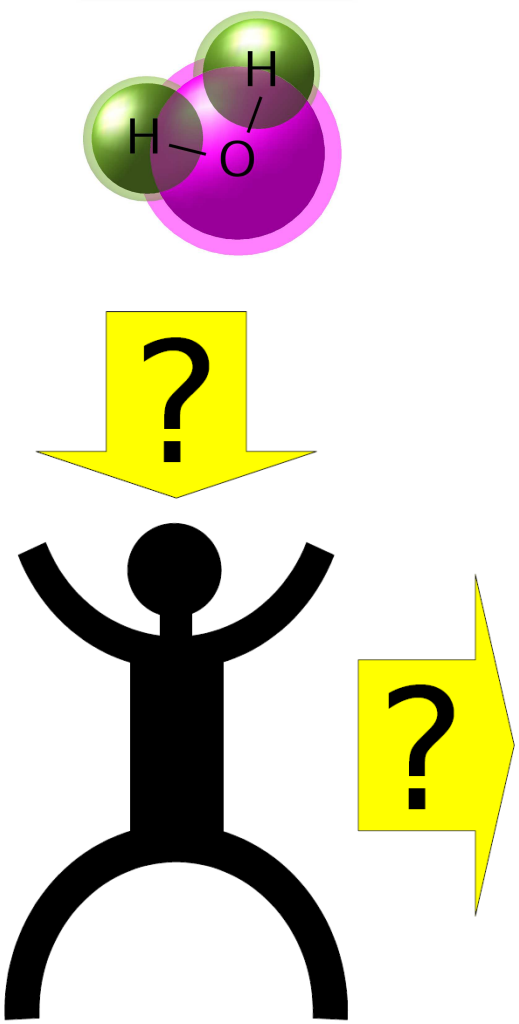


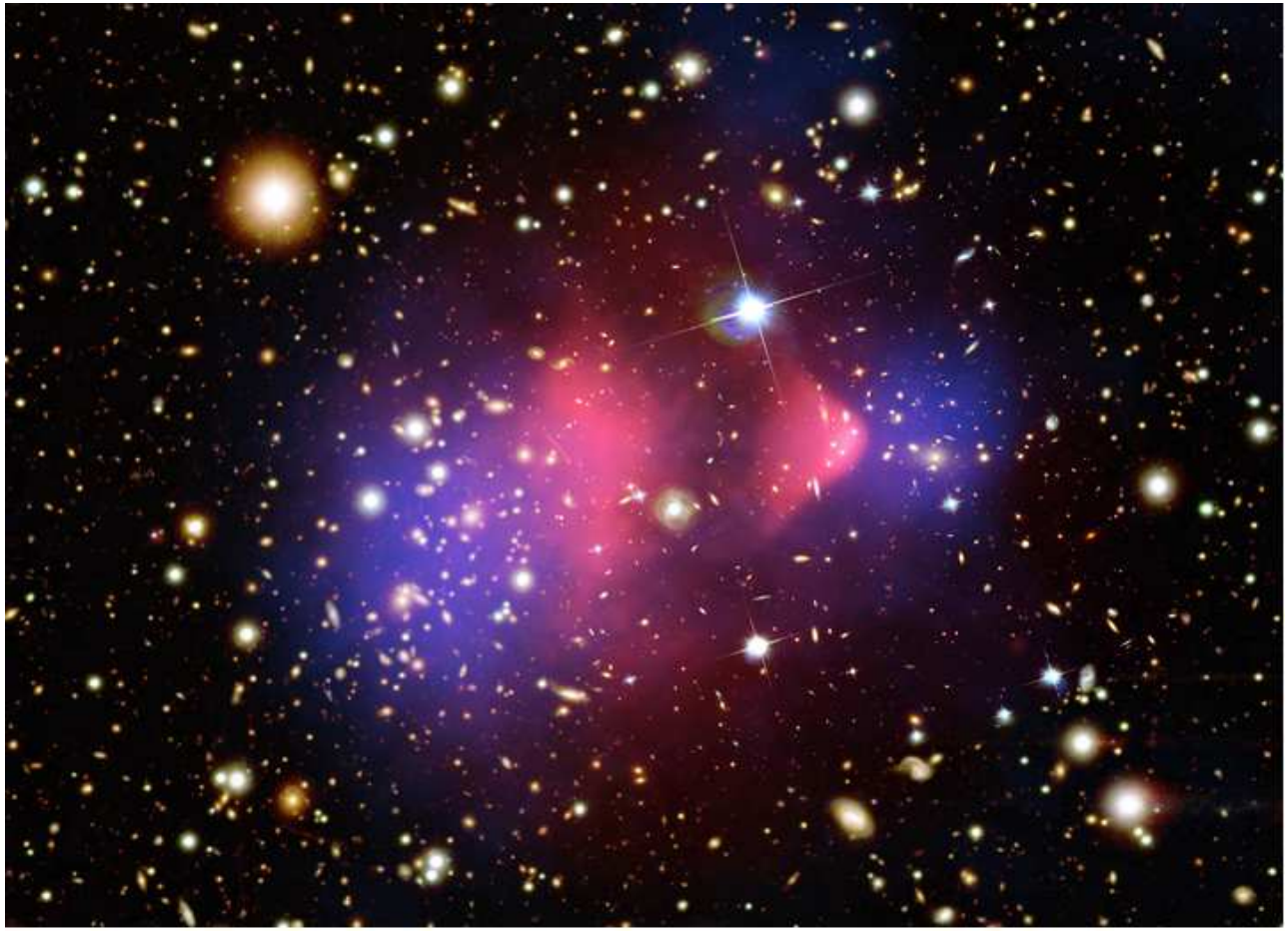
Puzzles of the Universe

The Particle World: the Smallest to the Largest

- On the smallest and largest scale:

  what are we made of and why





(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

Nobel Prize Prize in Physics

- Accelerating expansion of the Universe

  requires some kind of "dark energy" through empty space

The Nobel Prize in Physics 2011
Saul Perlmutter, Brian P. Schmidt, Adam G. Riess

The Nobel Prize in Physics 2011

Nobel Prize Award Ceremony

Saul Perlmutter

Brian P. Schmidt

Adam G. Riess

Photo: Alexi Zambelich, Copyright © Nobel Media AB

Saul Perlmutter

Photo: Belinda Pratten, Australian National University

Brian P. Schmidt

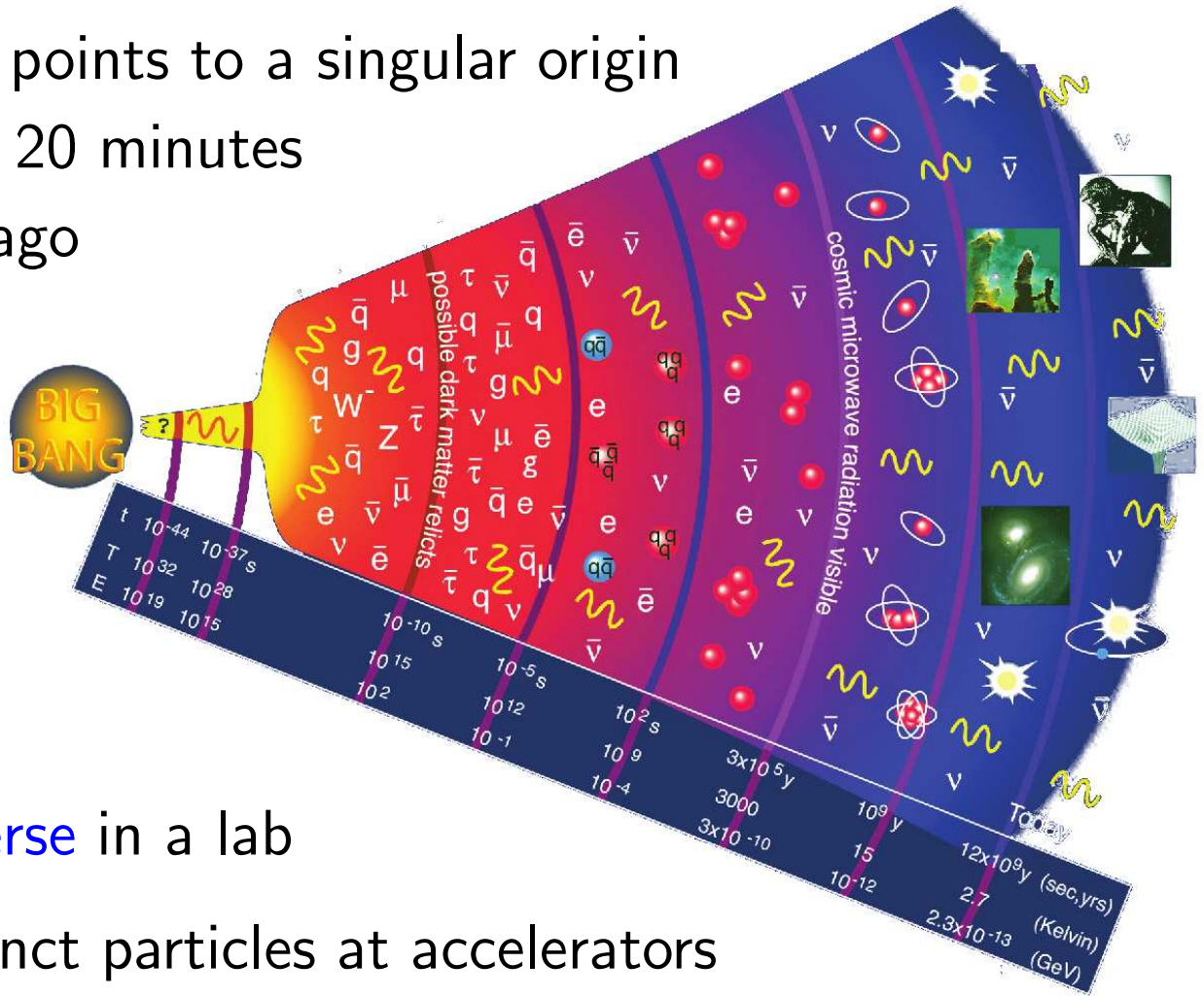
Photo: Homewood Photography

Adam G. Riess

The Nobel Prize in Physics 2011 was divided, one half awarded to Saul Perlmutter, the other half jointly to Brian P. Schmidt and Adam G. Riess *"for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"*.

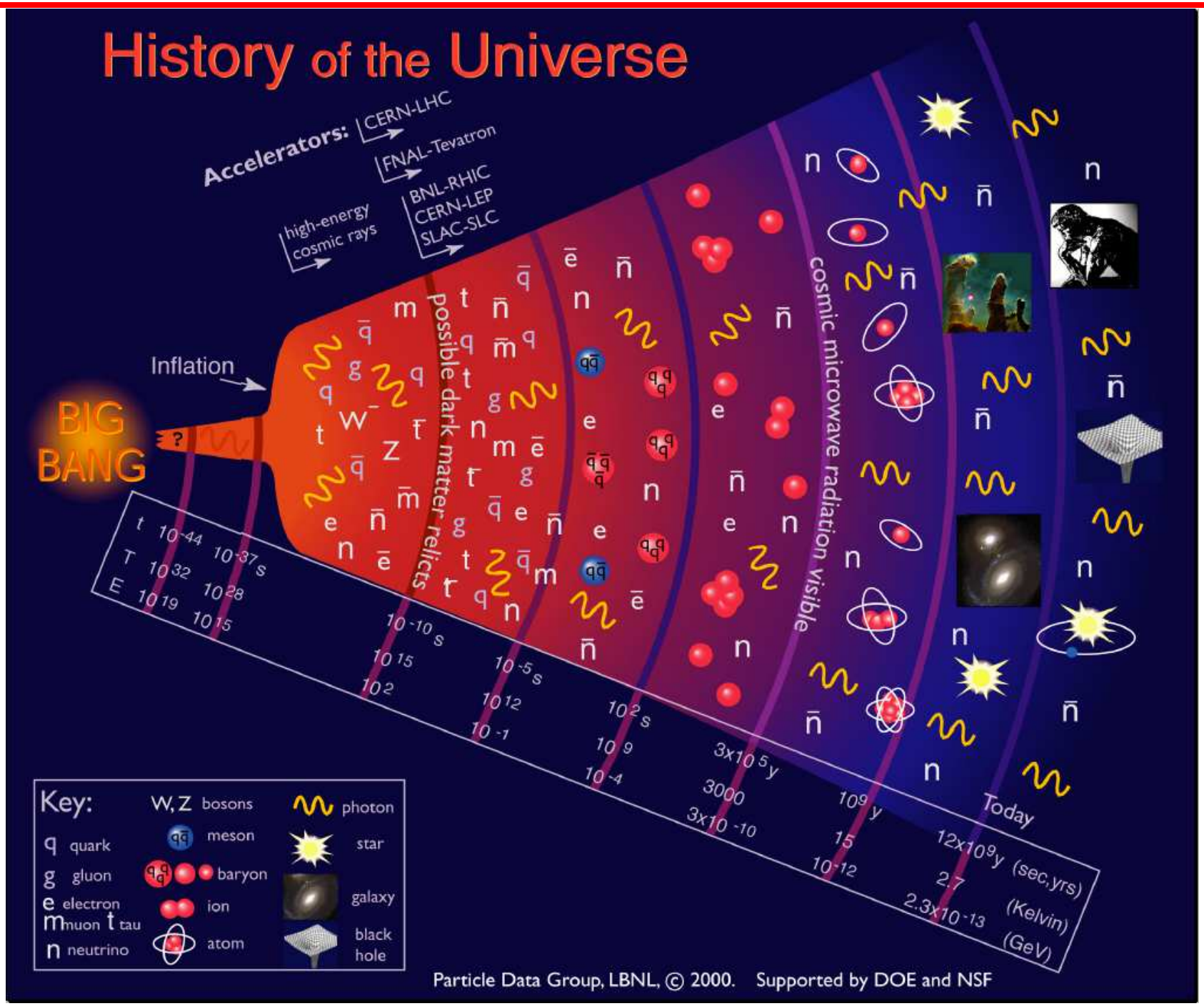
Start from the Beginning: The Big Bang

- Early moments of the Universe (astronomical observations):
  - current expansion points to a singular origin
  - nucleosynthesis in 20 minutes
  - 13.8 billion years ago



- Recreate early Universe in a lab
  - re-create now extinct particles at accelerators
  - re-create conditions and understand laws

The Big Bang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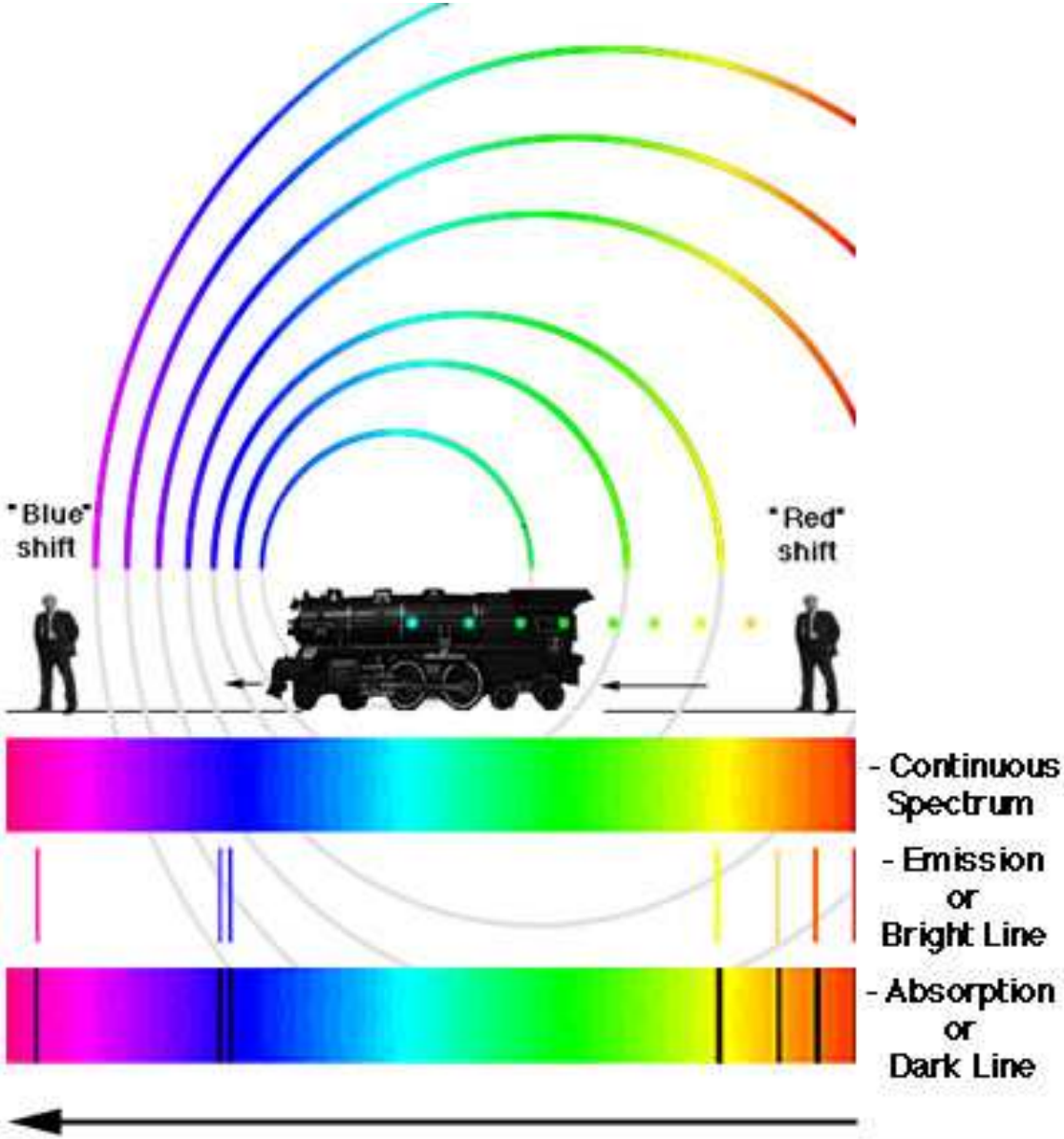
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
Today
Key:
q quark
g gluon
e electron
m muon
t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

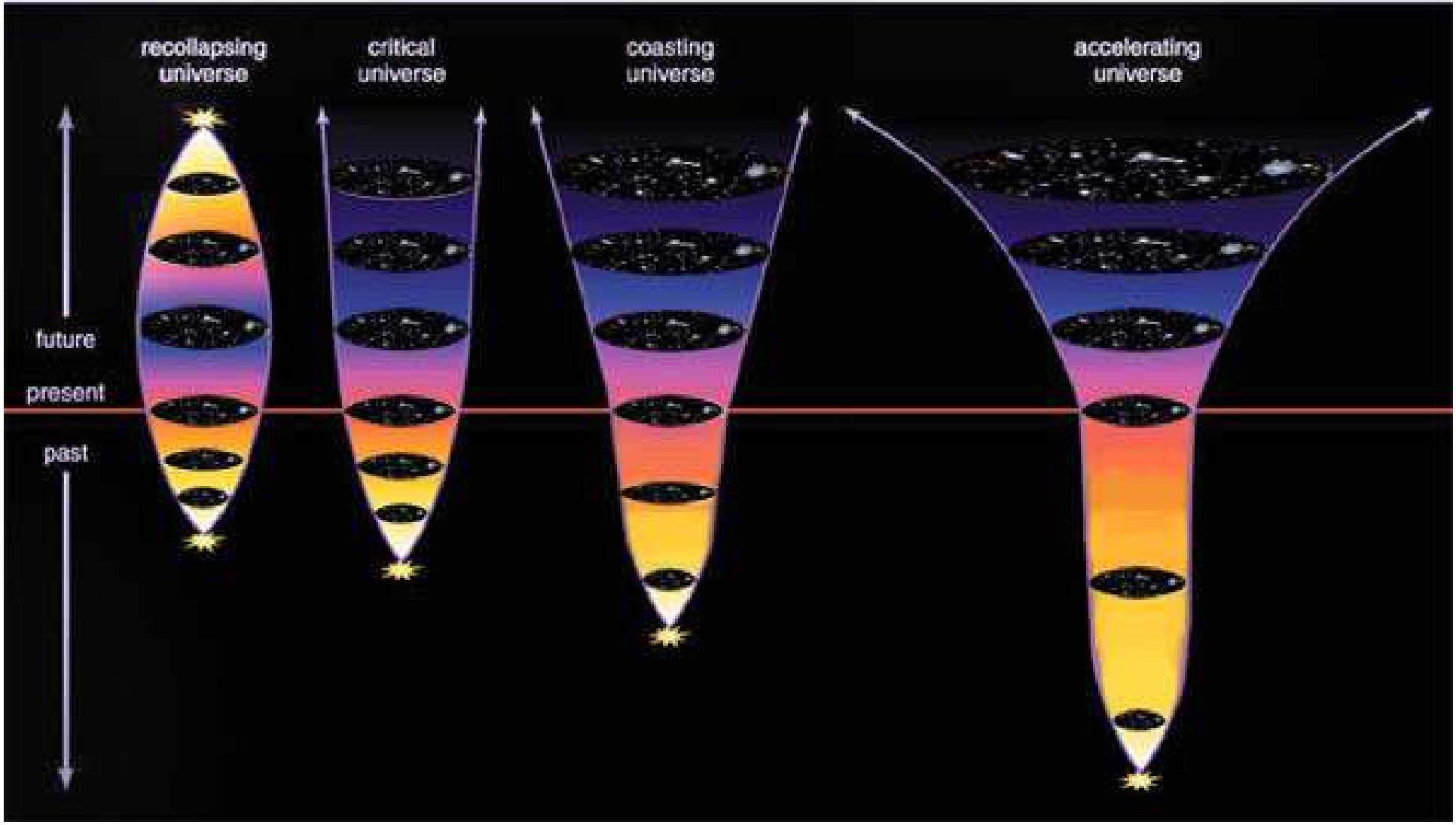
Expanding Universe

- Observe stars as trains moving AWAY from us



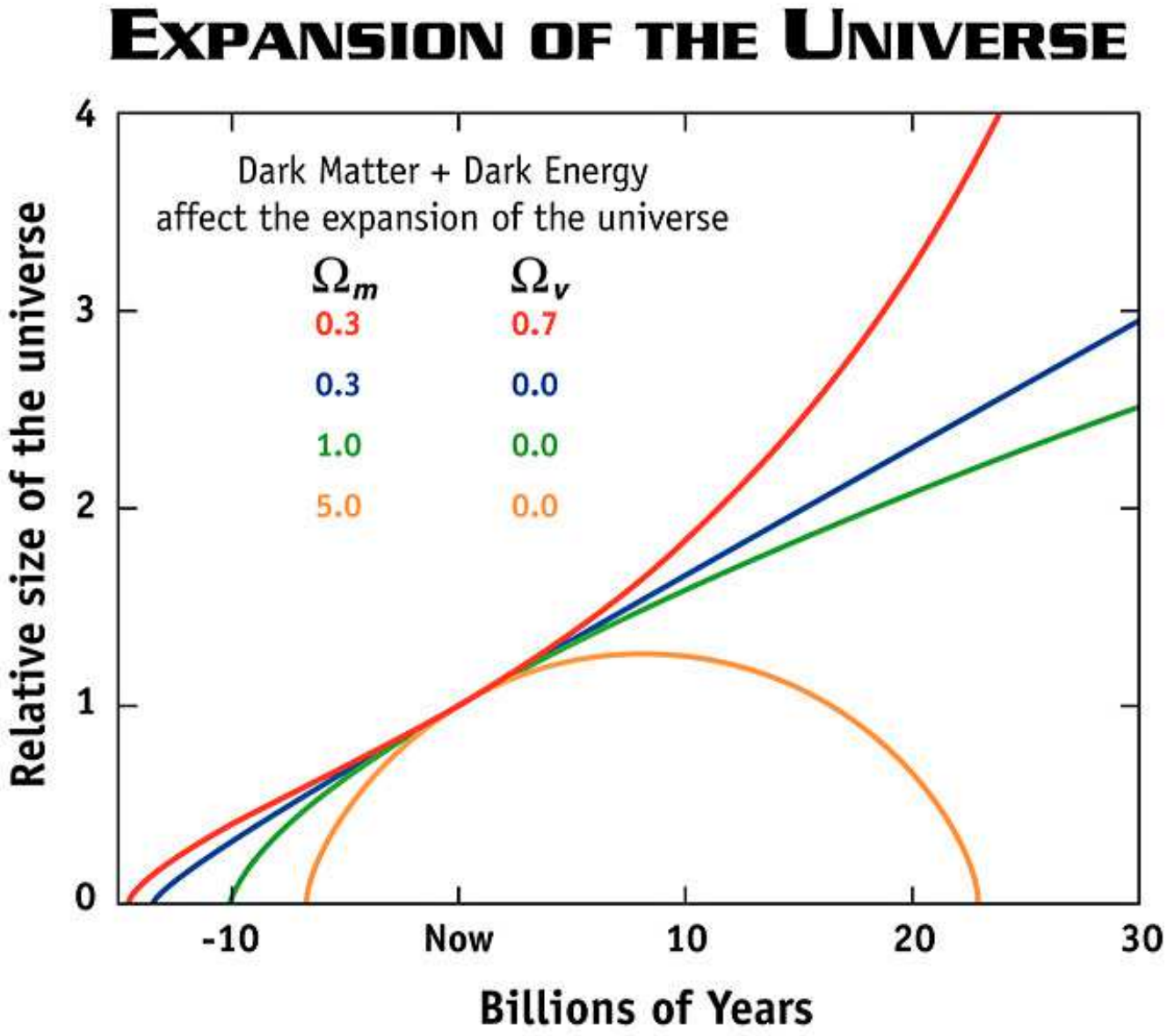
Will Universe Expand Forever?

- Several scenarios
  - Big Bang followed by a "Big Crunch" or not ?

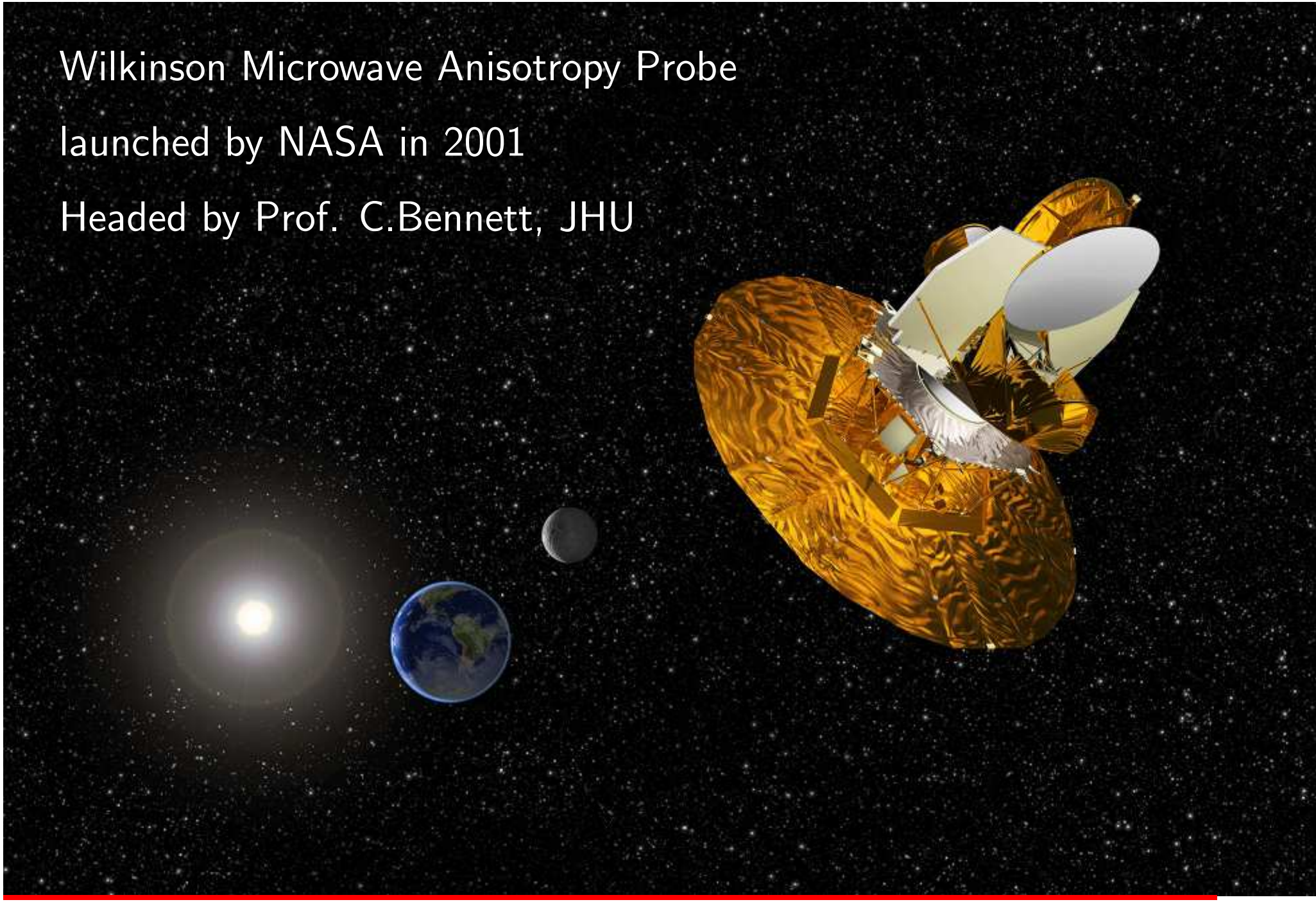


Expansion of the Universe

- Future depends on density of matter and energy in the Universe



Example: WMAP Explorer Mission



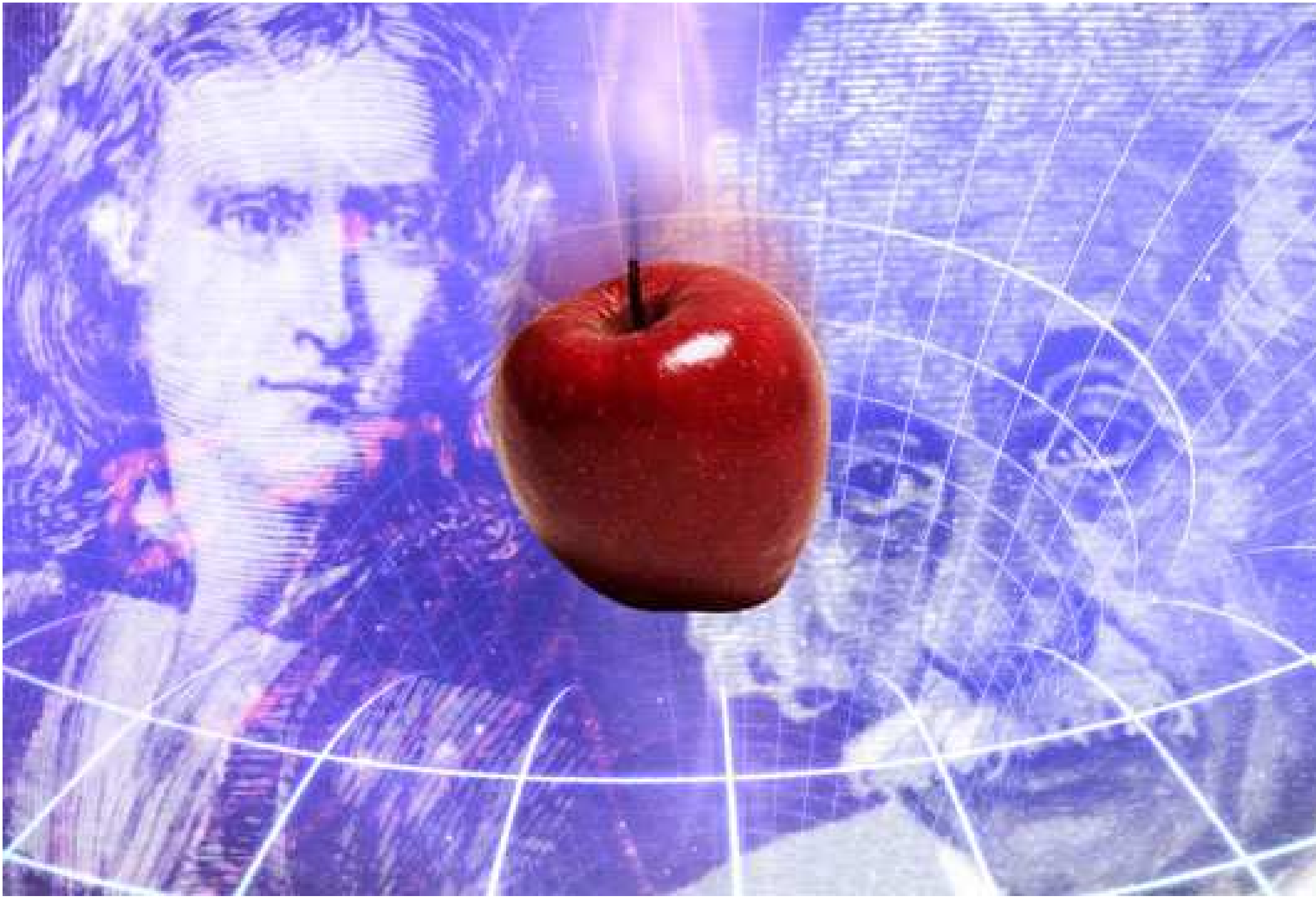
Example: Hubble Space Telescope

launched by NASA in 1990

operated by Space Telescope Science Institute

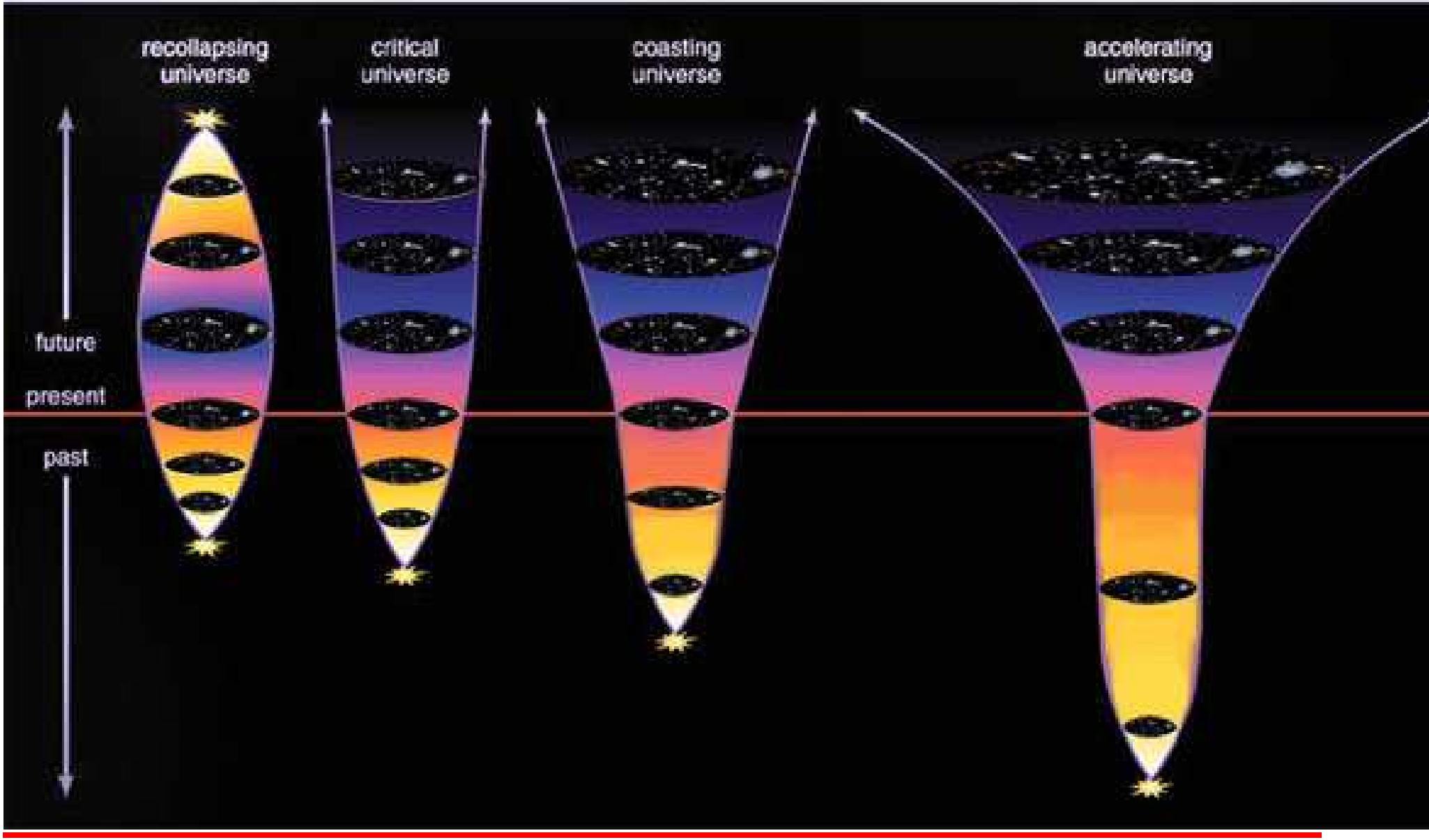
replace by James Webb Space Telescope in 2018

Gravity Should Slow Expansion

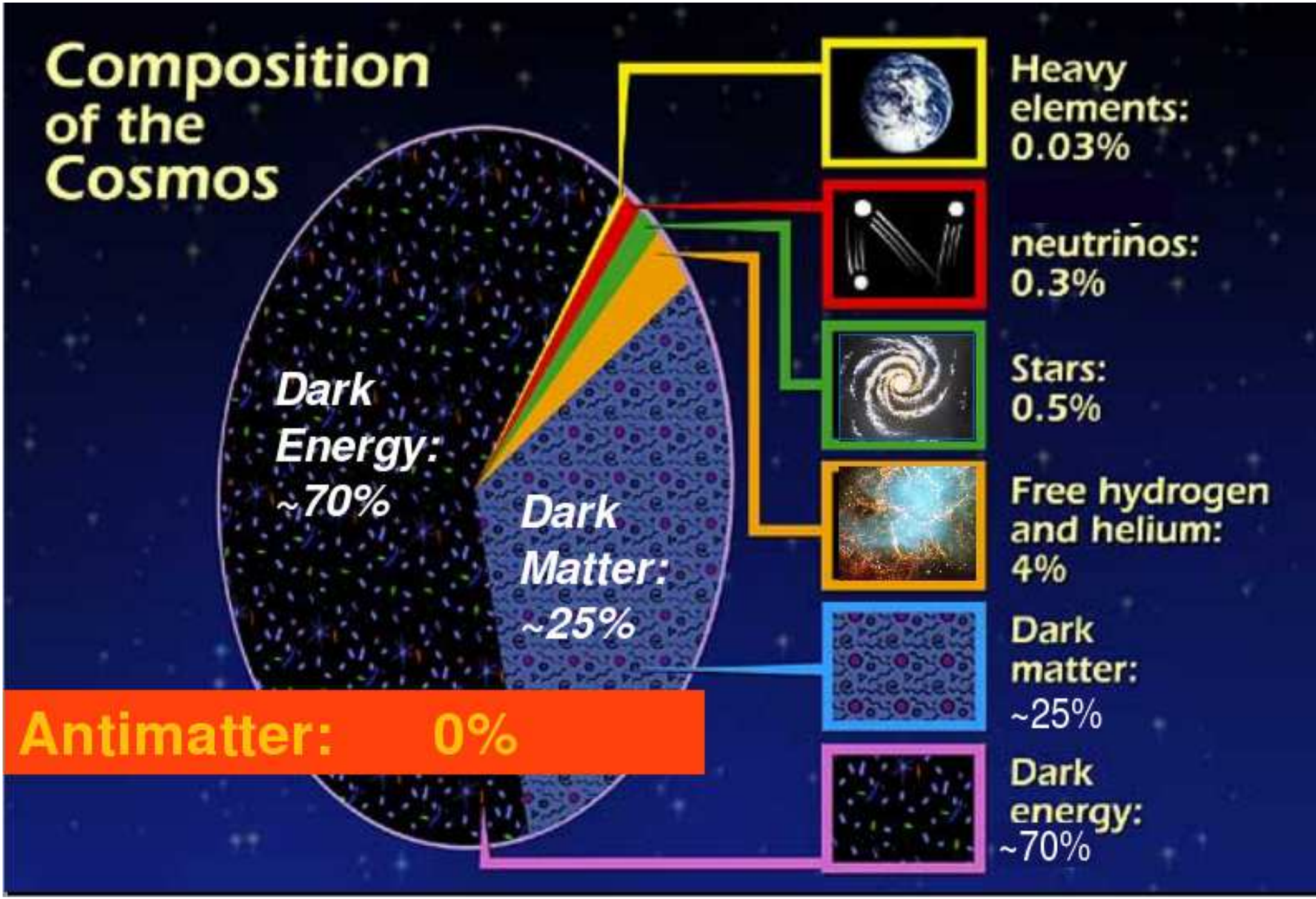


Expansion is Accelerating

- Accelerating Universe: requires some kind of Dark Energy
  - Nobel Prize in Physics 2011



Puzzles of the Universe

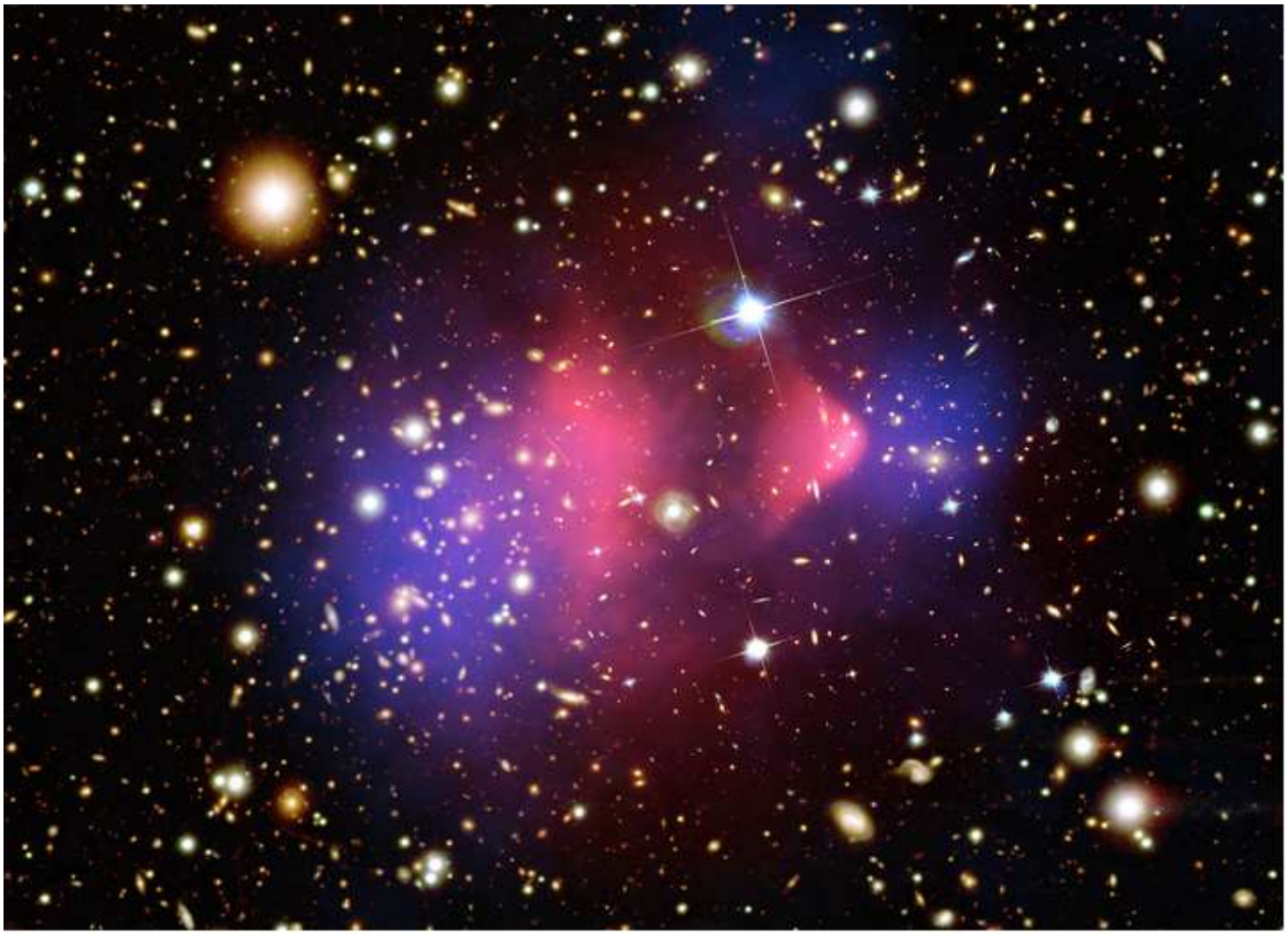


Puzzles of the Universe

- Dark energy (∼70%)
  - do not know what it is; explain accelerated expansion
- Dark matter (∼25%)
  - does not emit light, but seen with gravity
- Ordinary matter (∼5%)
  - the only thing we knew until recently: from Hydrogen to Uranium
- Ordinary antimatter (∼0%)
  - equal amount of matter and antimatter in the Big Bang
- Origin of mass
  - everything created equal and massless in the Big Bang

Dark Matter

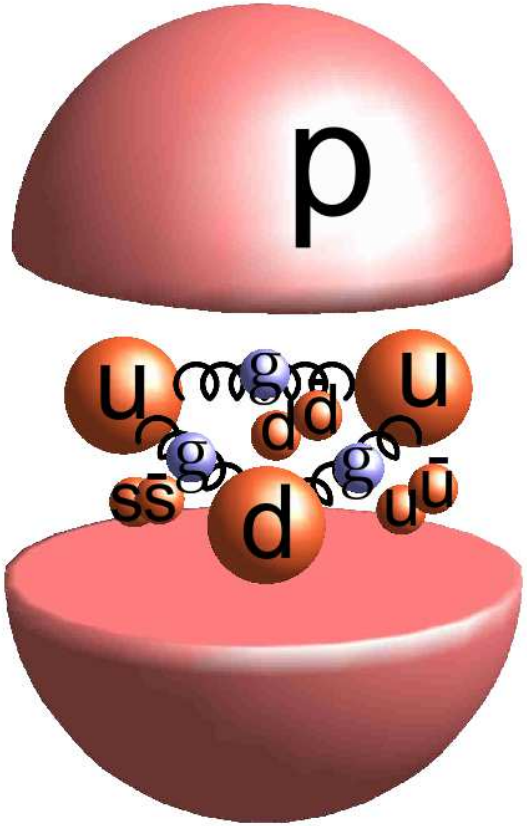
- Dark matter (25%) – "dark" does not emit light, unknown
  - left over from Big Bang, may create in accelerators...



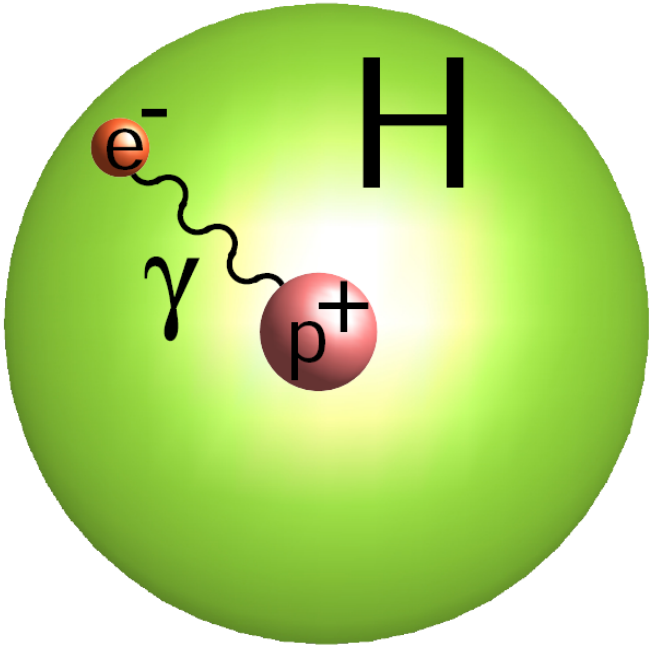
(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

Ordinary Matter in Big Bang

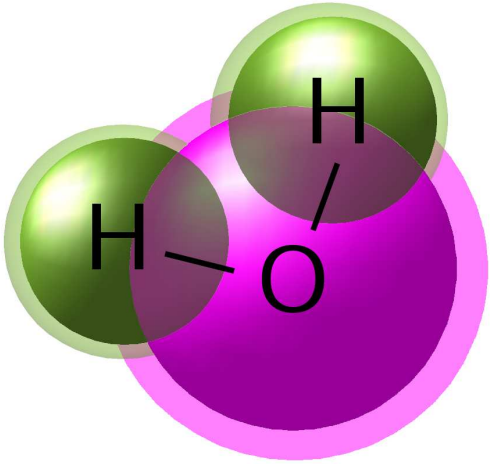
- Quark-gluon soup fraction of a second after Big Bang
  - within minutes protons and neutrons formed
  - billions of years to create all known elements



proton/neutron

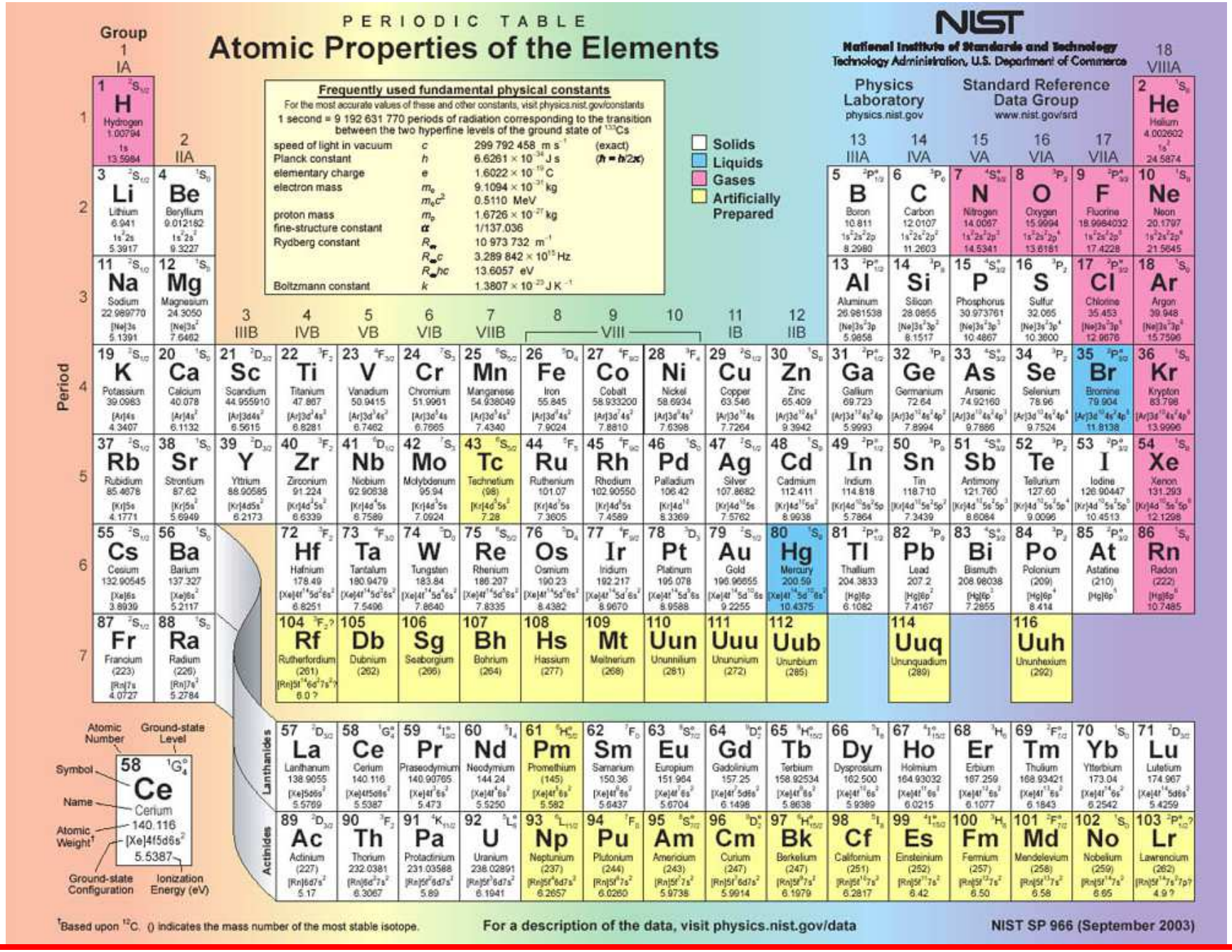


atom



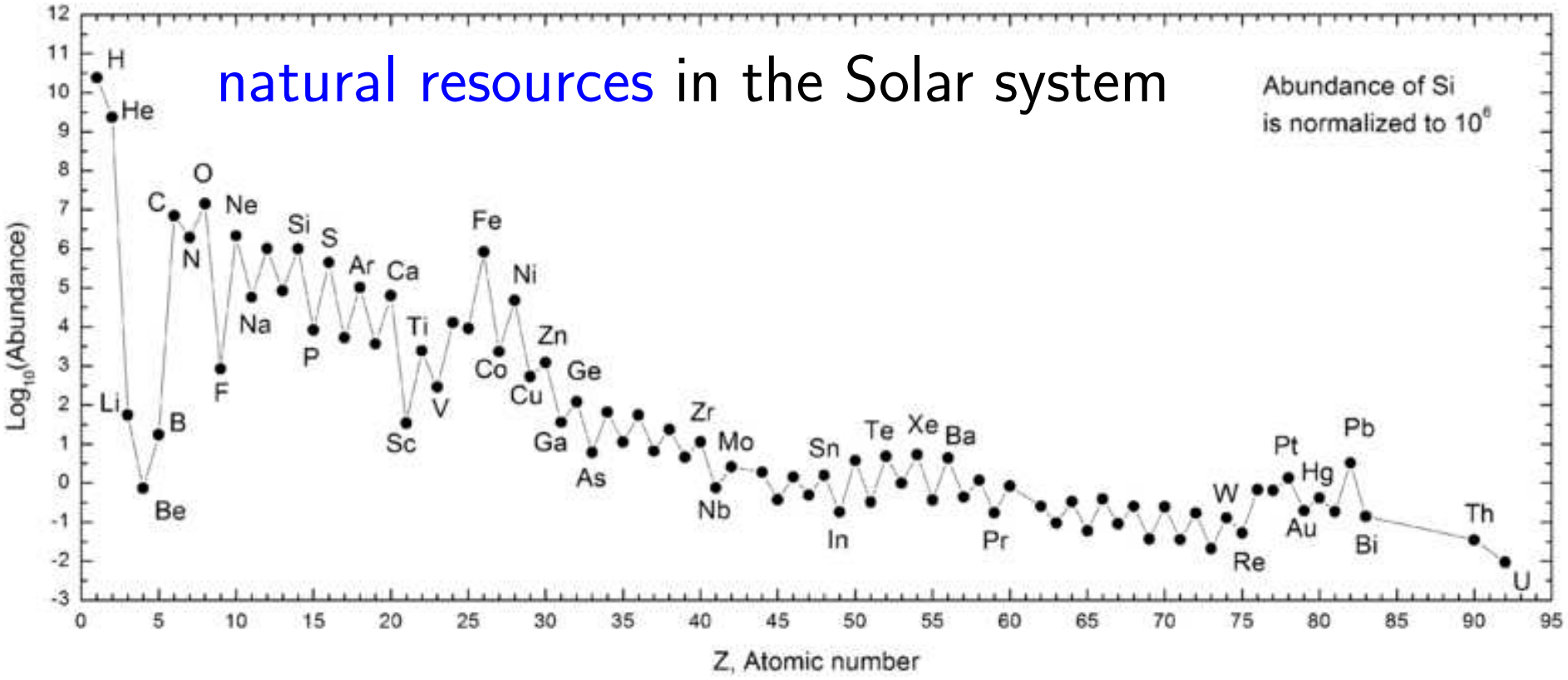
molecule

Periodic Table of Matter

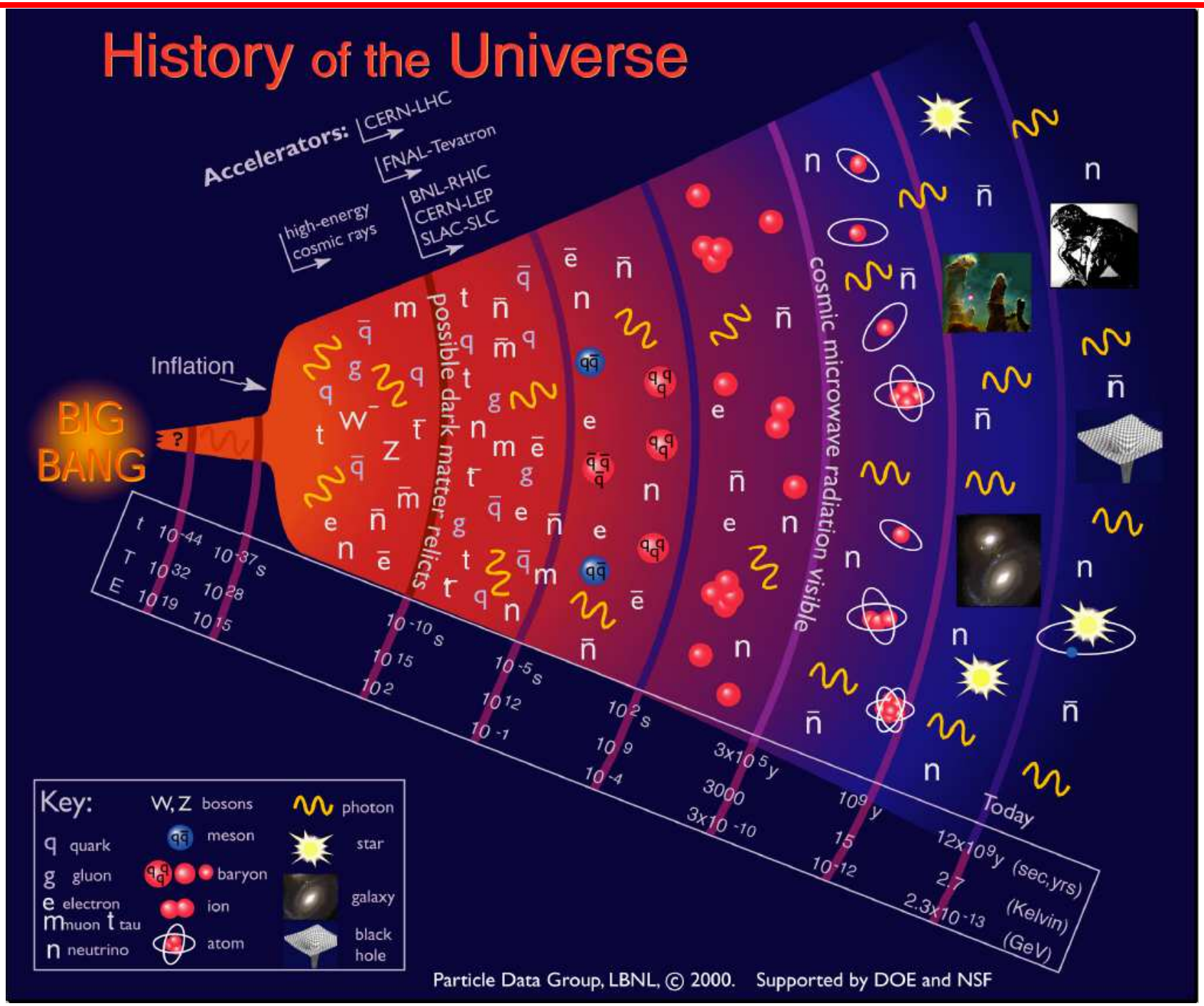


Formation of All Elements

- Success of Big Bang theory – predict formation of elements
  - light elements (H, He) in early moments
  - heavy elements (C – U) in fusion within stars
- Nuclear energy – in the gluon soup binding the quarks



The Big Bang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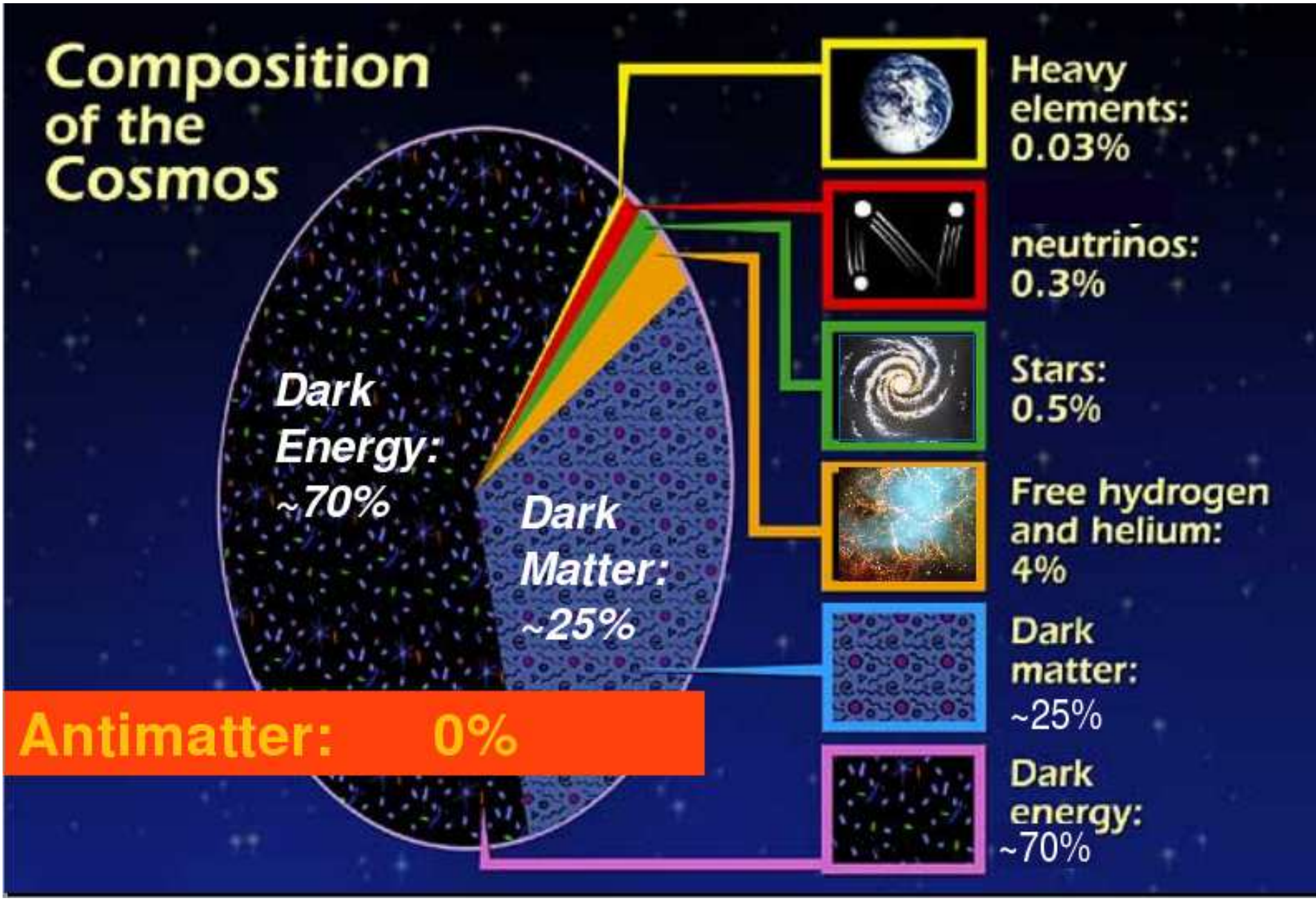
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Puzzles of the Universe



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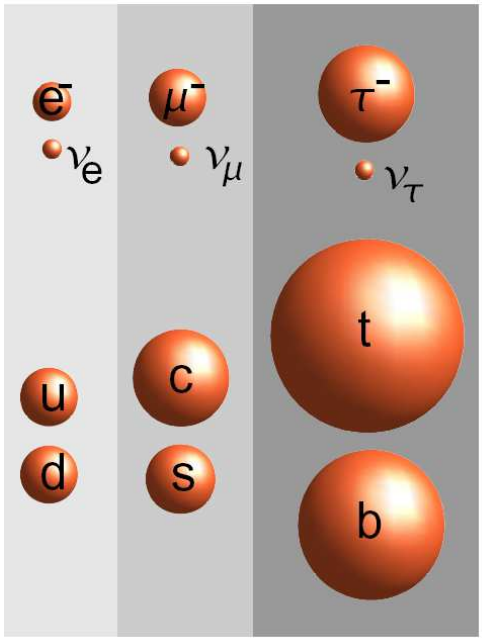
  - everything created equal and massless in the Big Bang

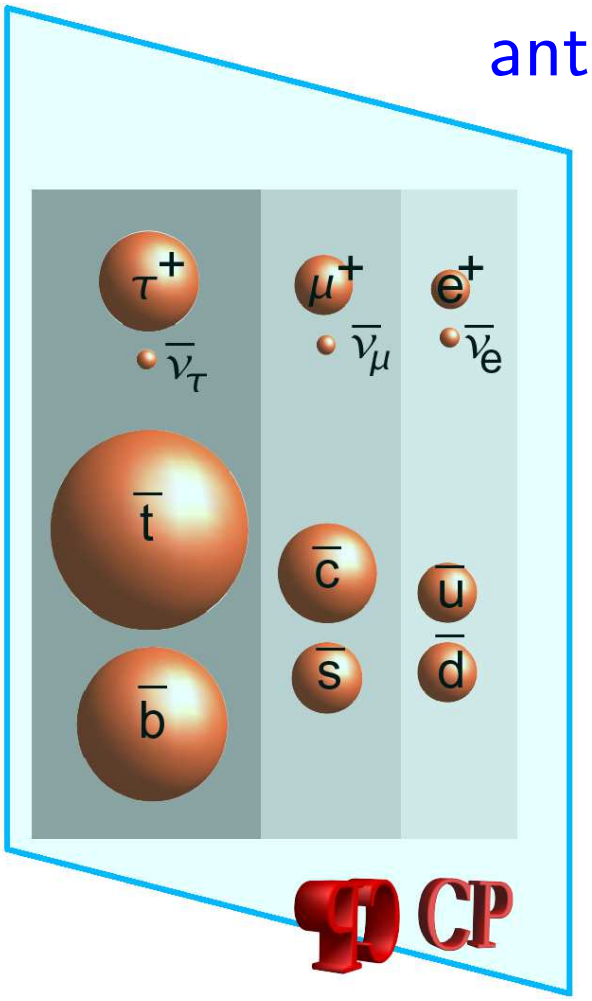
Anti-Matter: Mirror Object of Matter

- matter

leptons

quarks





- Produced equal in Big Bang

energy $\longrightarrow$ matter + antimatter

anti-matter should behave differently than matter

Nobel Prize in Physics 2008

- $\frac{1}{2}$ Prize – Mechanism leading to matter-antimatter asymmetry
  – still not sufficient on cosmological scale
- $\frac{1}{2}$ Prize – related to the next topic

The Nobel Prize in Physics 2008
Yoichiro Nambu, Makoto Kobayashi, Toshihide Maskawa

The Nobel Prize in Physics 2008
Nobel Prize Award Ceremony
Yoichiro Nambu
Makoto Kobayashi
Toshihide Maskawa


Photo: University of Chicago

Yoichiro Nambu


© The Nobel Foundation Photo: U. Montan

Makoto Kobayashi

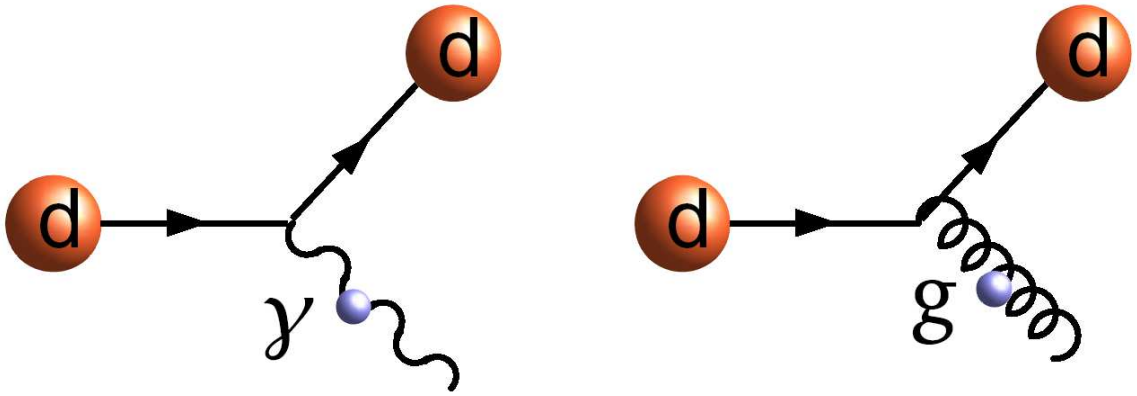

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

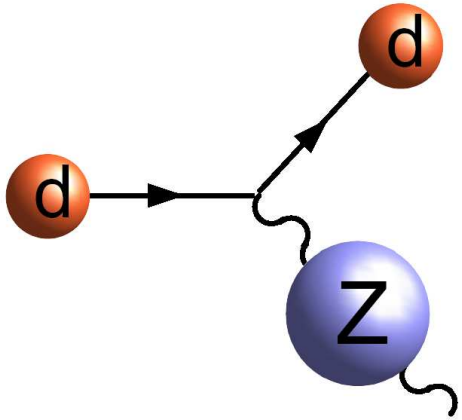
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts the existence of at least three families of quarks in nature"*.

Origin of Mass

- Created equal and massless in the Big Bang
  - light and glue carried by massless "bosons"



- As Universe cooled
  - sister "bosons" to light got mass (spontaneous symmetry breaking)



Need something else to explain these puzzles

- One idea: (super)symmetry

$Q|\text{fermion}\rangle = |\text{boson}\rangle$

$Q|\text{boson}\rangle = |\text{fermion}\rangle$

- Solve:

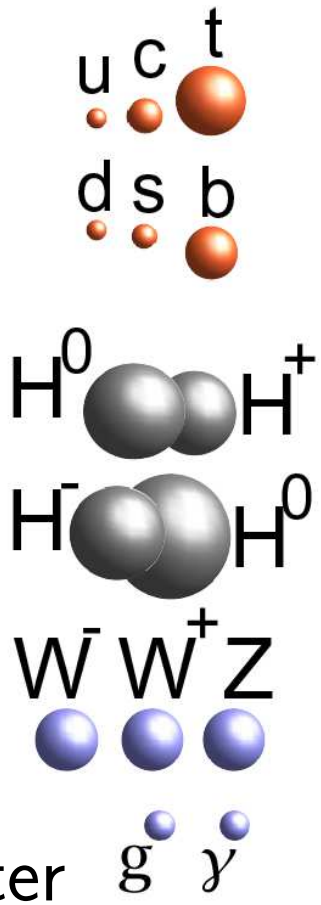
(1) natural light

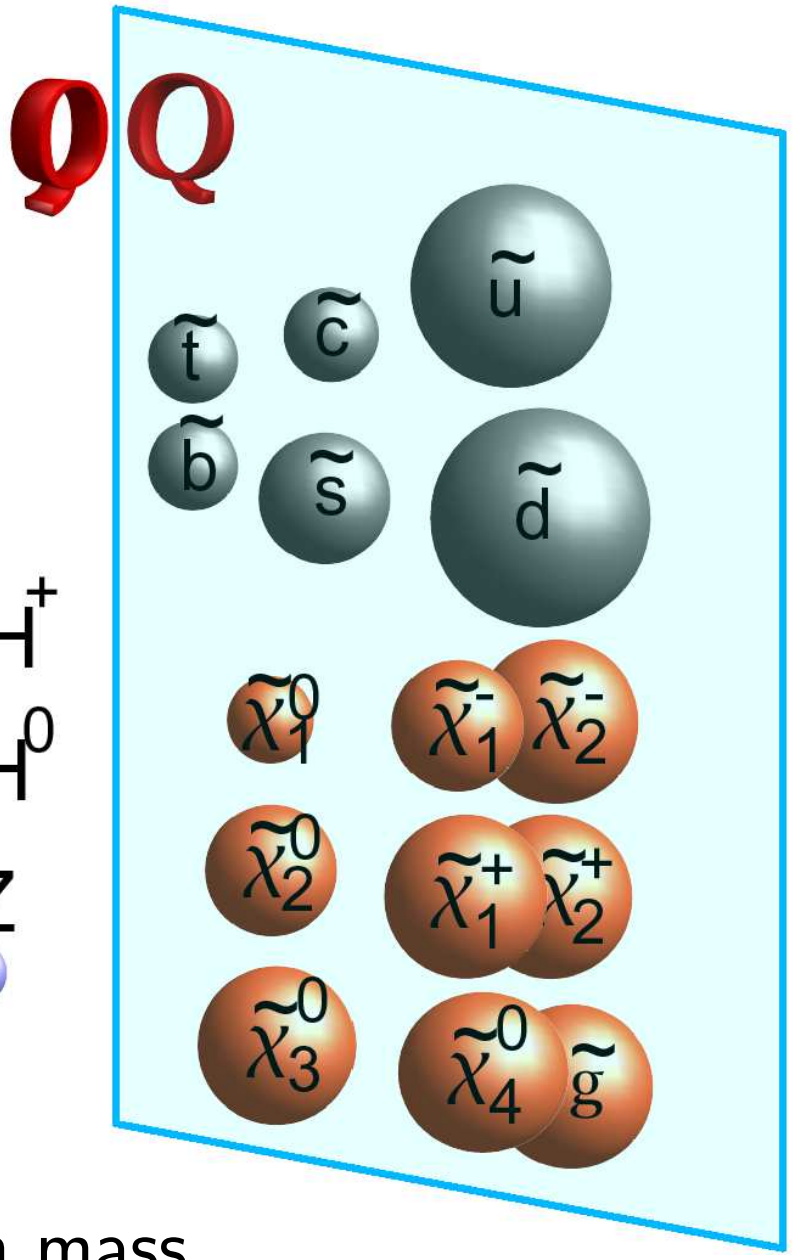
*H*iggs

(2) dark matter

lightest $\tilde{\chi}_1^0$

(3) large matter/antimatter





- May be just around the corner in mass...

LHC – The Big Bang Machine

- LHC program:

– test of the Higgs field

– may connect to dark energy

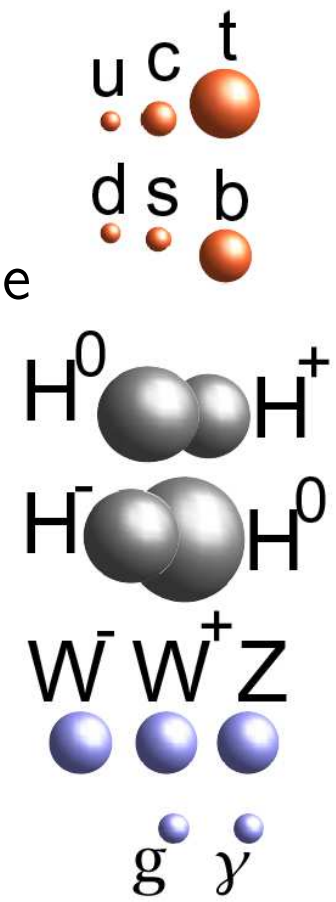
– may explain antimatter puzzle

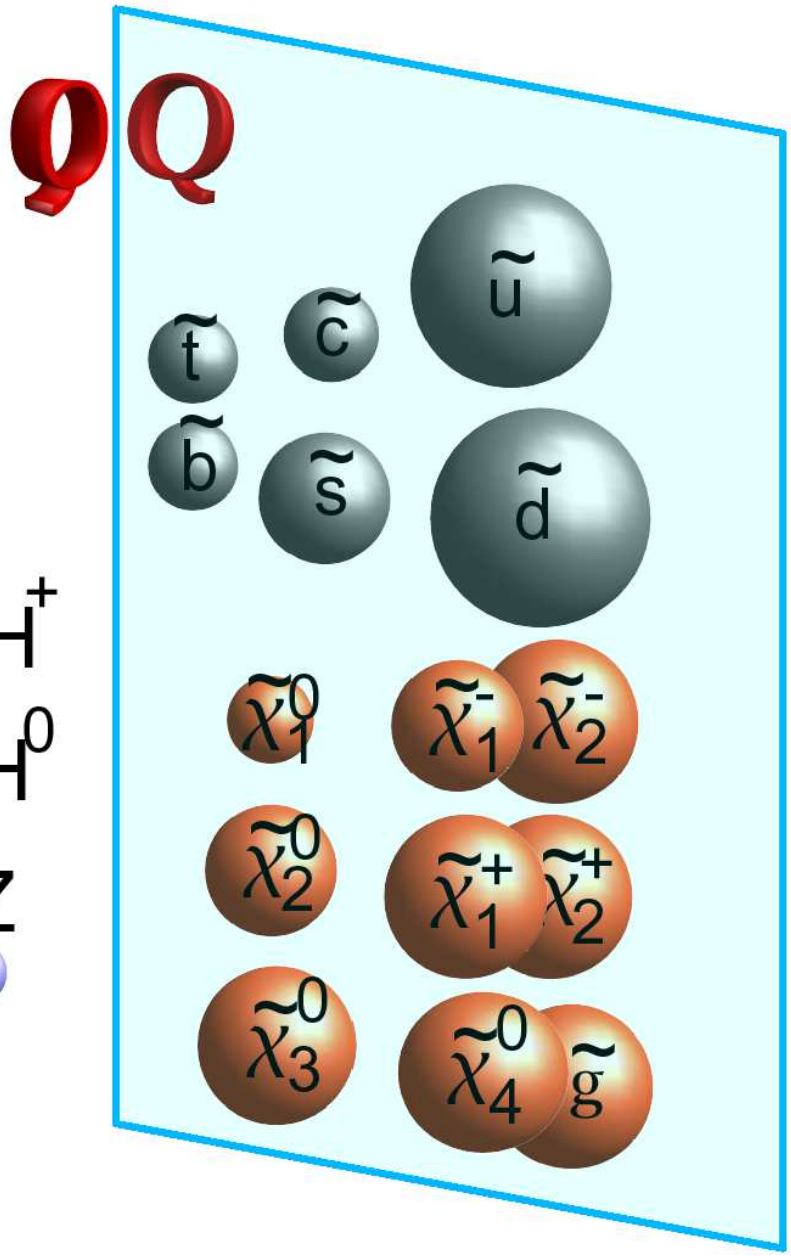
– may produce dark matter

– re-create quark-gluon plasma

– extra dimensions of space ?

– prepare for unexpected ...





Reaching Highest Energy

- $mc^2 = E$