Science of the Nuclear Energy (and not the technology)

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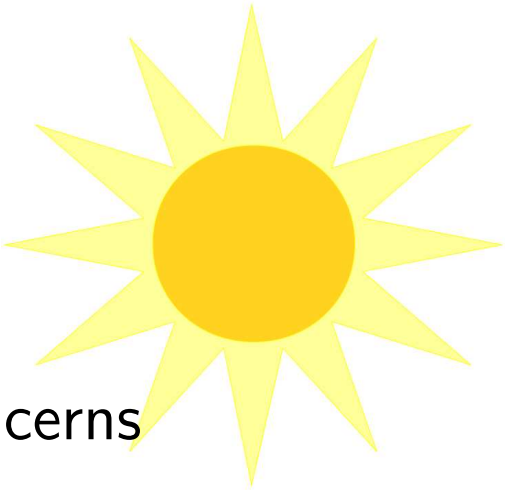
29 July 2013

JHU QuarkNet meeting

Energy Sources



- Fossil fuel (current $\sim 86\%$)

  petroleum, coal, natural gas

  – energy from the Sun stored in the past
  – limited supply 40–400 years, environmental concerns

- Renewable energy (current $\sim 7\%$)

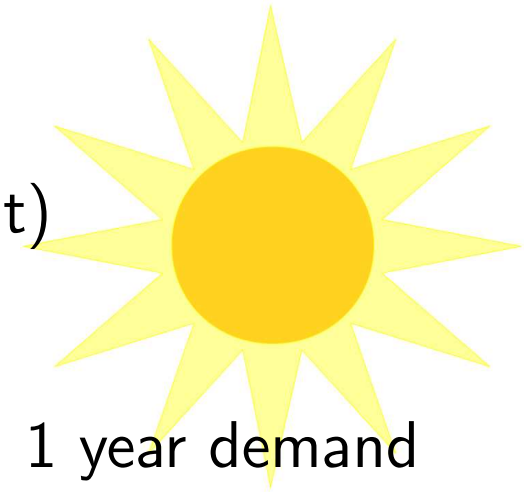
  sunlight, wind, hydro, biomass (&wood, waste),..

  – one way or another, mostly convert present Sun energy

- Nuclear energy (current $\sim 7\%$)

  – uranium-235, plutonium-239 (fission)
  – supply 100's years (fission), safety concerns
  – there is also fusion, but need technology

Energy Source: Sun as a "Nuclear Reactor"



- Both fossil fuel and renewable energy

  mostly pass energy from the Sun (past or present)

  Sun – huge nuclear fusion reactor

  supply: billions of years, 1 hour flux on Earth = 1 year demand

- Challenge with renewable energy technological:

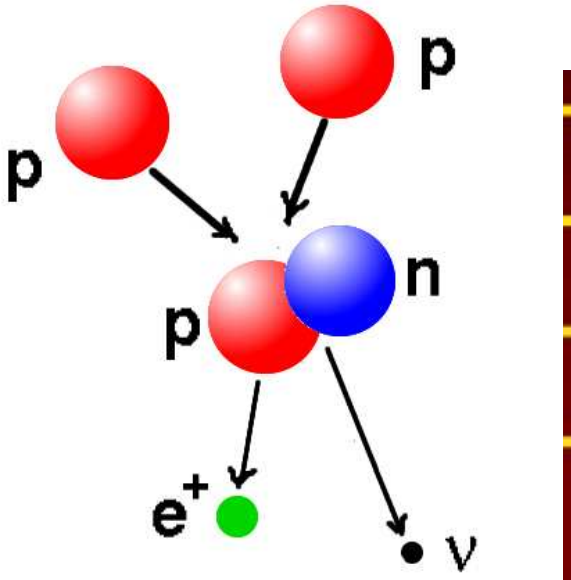
  collect enough Sun light

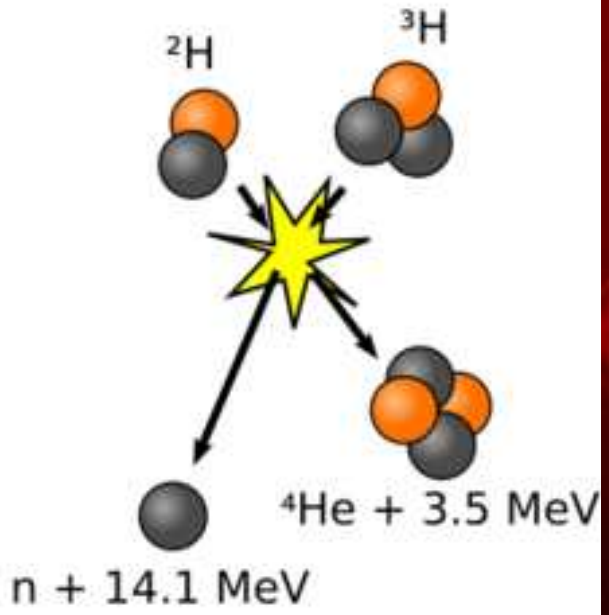
  effectively convert and store collected energy

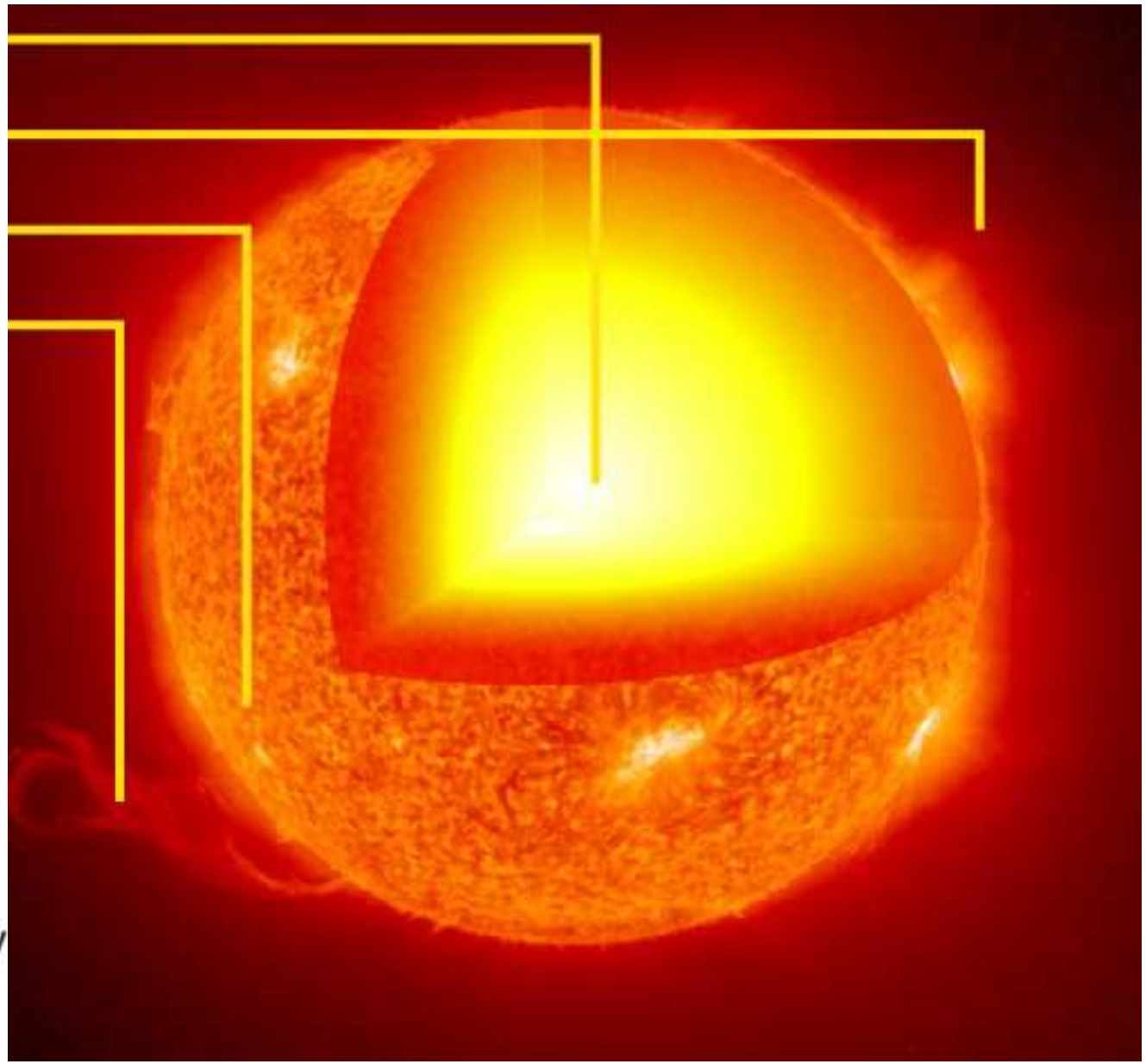
  examples: photosynthesis by green plants;
  solar power panels

  beyond the scope of this discussion

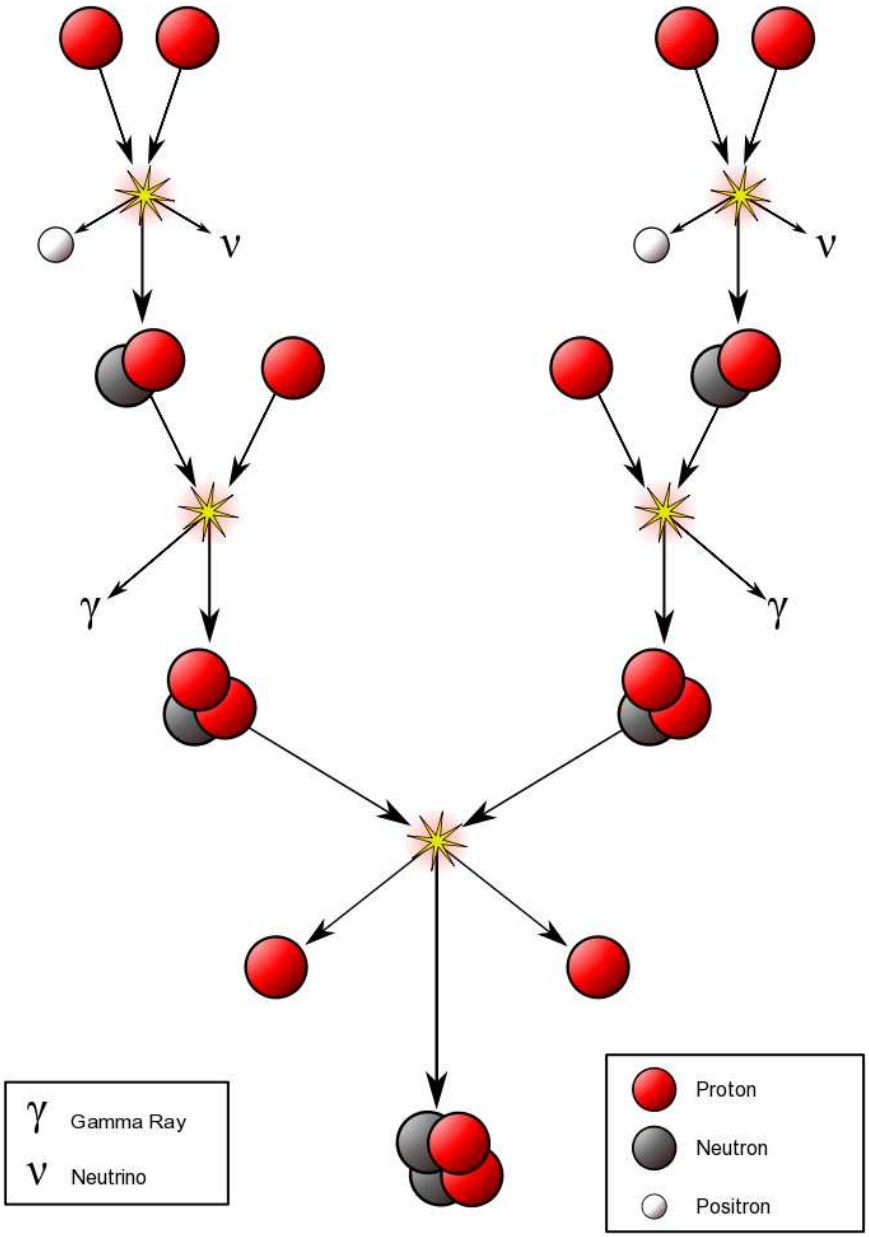
Sun as a "Nuclear Reactor"

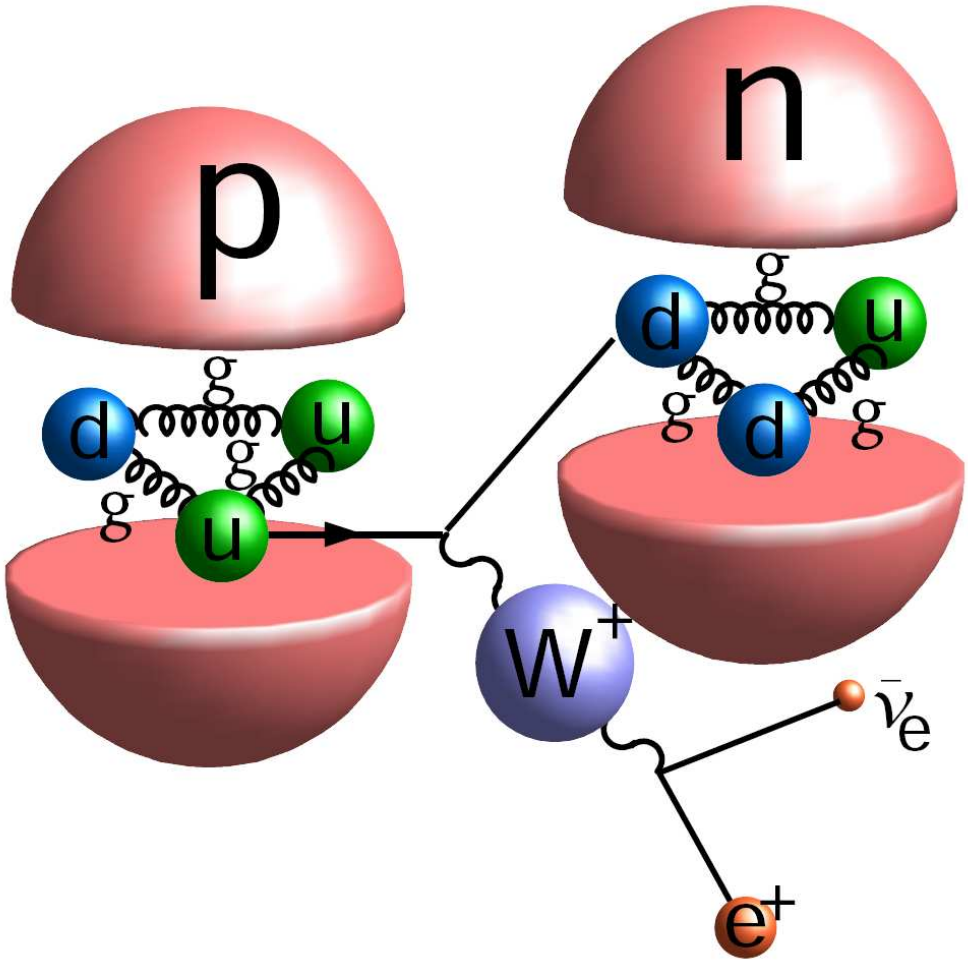






Sun as a "Nuclear Reactor"





Energy Source: Physics

- Convert Mass (matter) into Energy

$$E = mc^2$$

mass of initial matter $>$ mass of produced matter

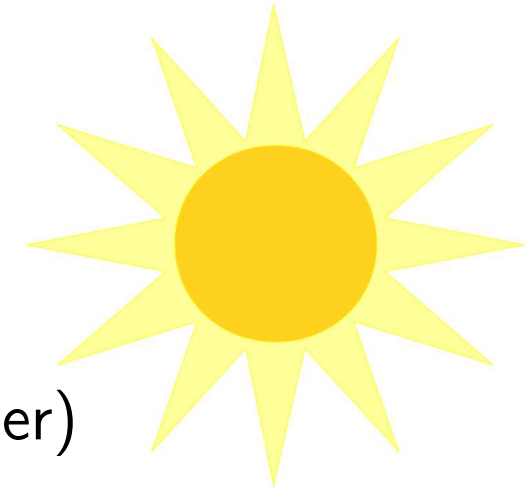
$\Rightarrow$ release of energy

- Matter (mass) was created from Energy in Big Bang

$$mc^2 = E$$

Nuclear Energy: $E = mc^2$

Energy Source: Fuel



- combustion

  burn fuel (carbon)

  $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O +$ energy

(methane) + (oxygen) $\rightarrow$ (carbon dioxide) + (water)

- nuclear fission

  $n + {}^{235}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3\ n +$ energy

- nuclear fusion

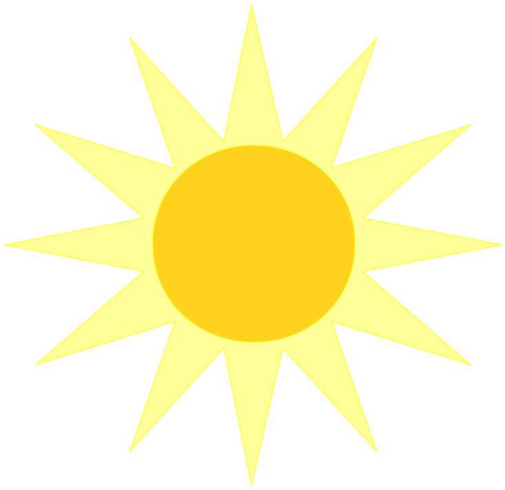
  ${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n +$ energy

- antimatter annihilation

  ${}^{1}H^{+}$ (matter) + ${}^{1}H^{-}$ (antimatter) $\rightarrow$ energy

  science fiction (e.g. see Angels and Demons with Tom Hanks)

Energy Source: Fuel "Efficiency"



- combustion

  $CH_4 + 2\ O_2 \rightarrow CO_2 + 2\ H_2O +$ energy

  energy $\sim$ few 0.000001 MeV / 12 a.units (^{12}C)

- nuclear fission

  $n + {}^{235}U \rightarrow {}^{92}Kr + {}^{141}Ba + 3\ n +$ energy

  energy = 0.8 MeV / a.unit

- nuclear fusion

  ${}^{2}H + {}^{3}H \rightarrow {}^{4}He + n +$ energy

  energy = 3.5 MeV / a.unit

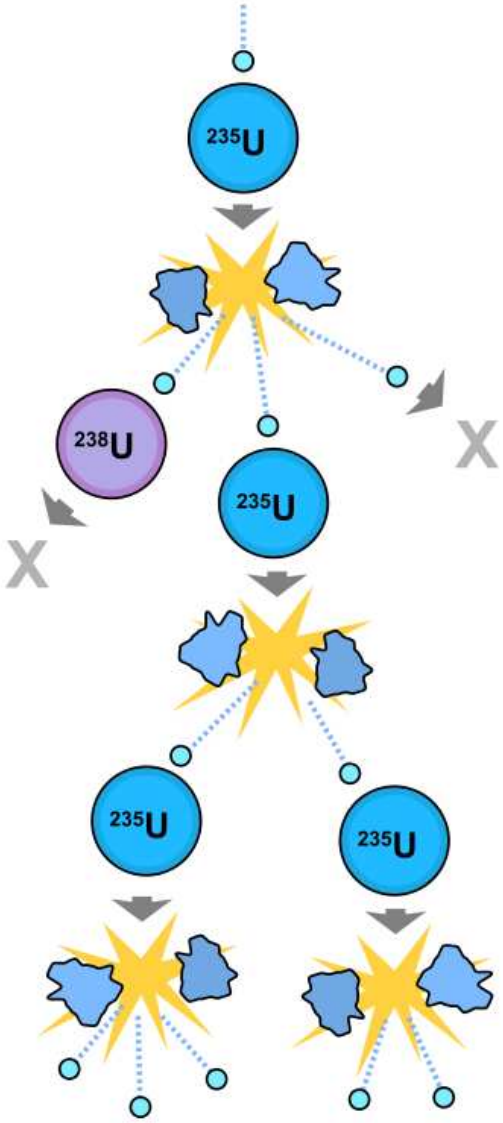
- annihilation

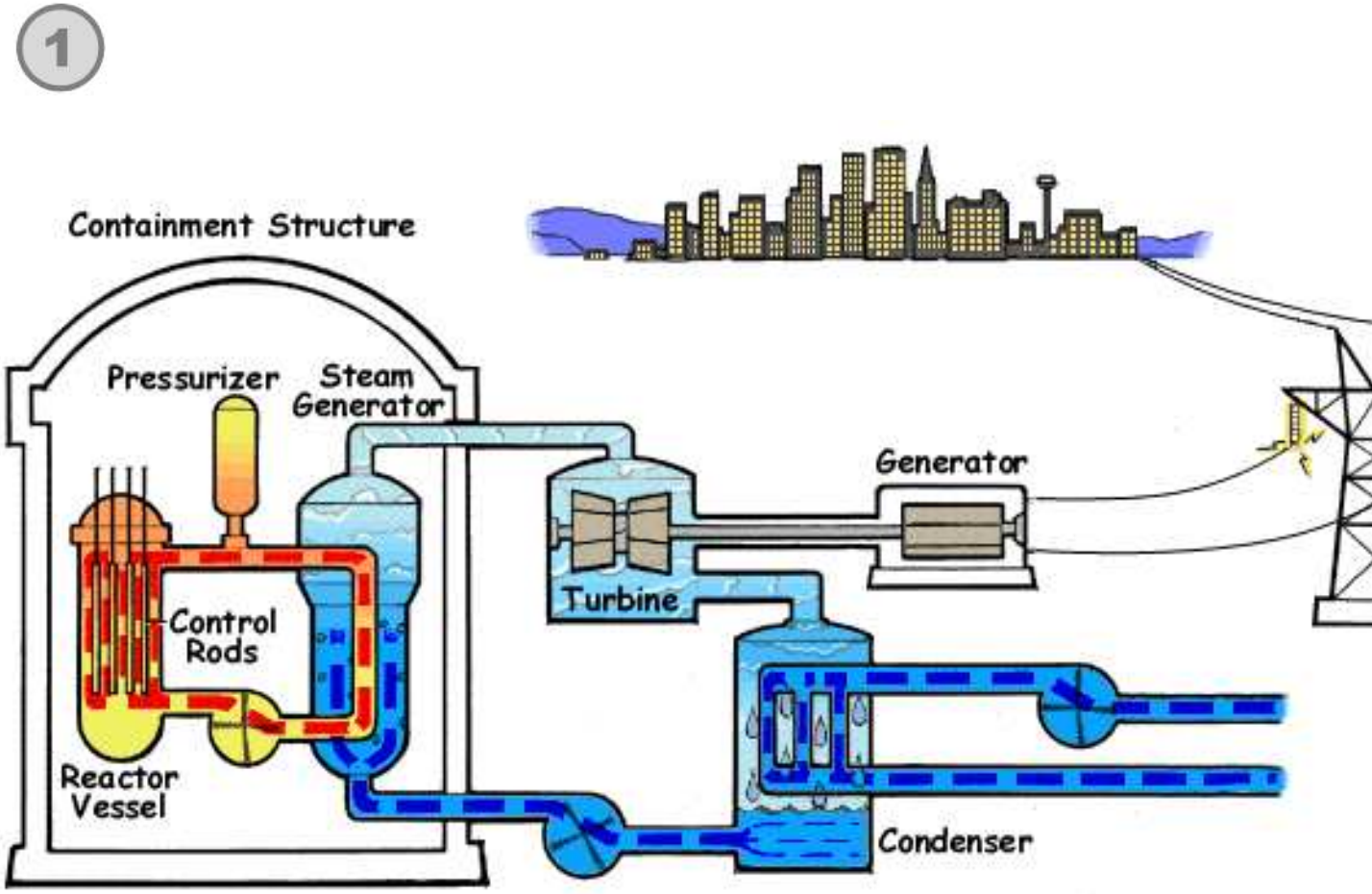
  ${}^{1}H^{+} + {}^{1}H^{-} \rightarrow$ energy

  energy = 938 MeV / a.unit

Nuclear Energy: Present

- Nuclear fission reactor

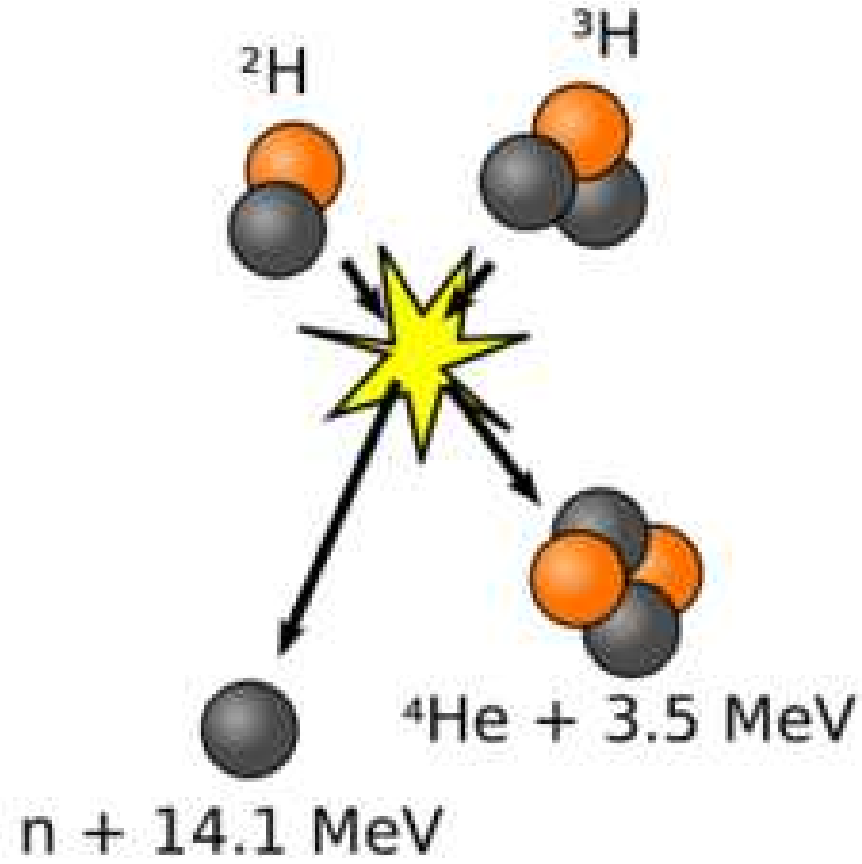


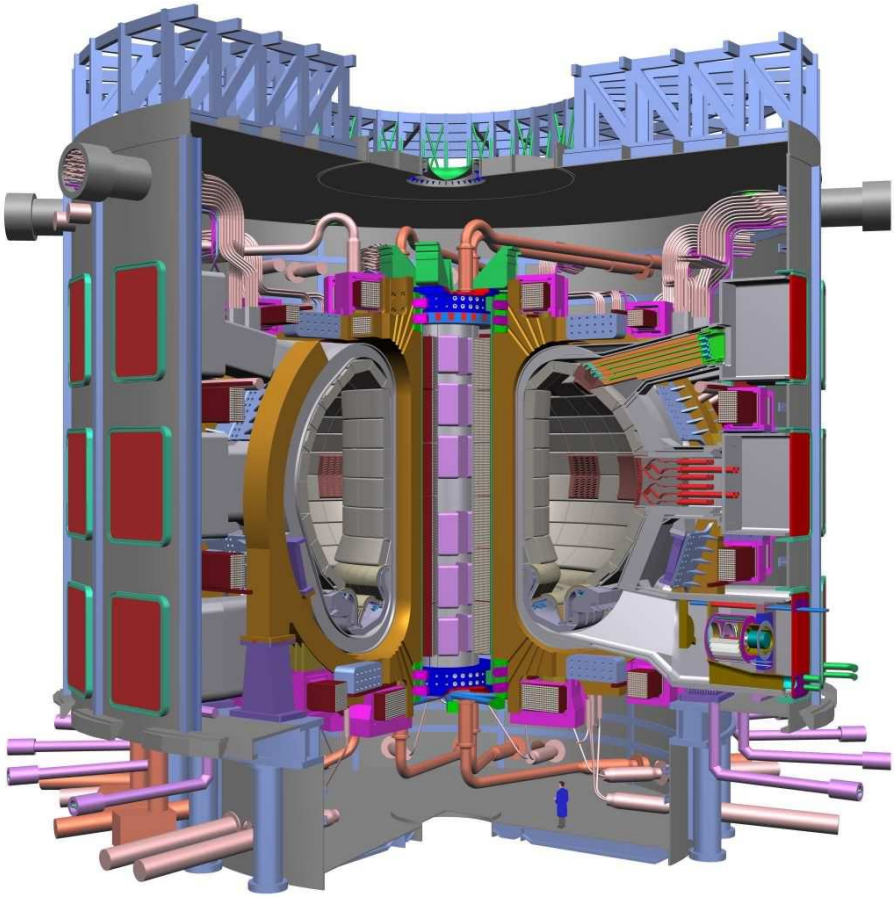


Nuclear Energy: Perhaps the Future (?)

- Nuclear fusion: challenging technology, goal $Q > 10$ (output/input)
- Example: ITER Tokamak

  2011 construction, 2015 assembly, 2019 plasma, 2026 operation





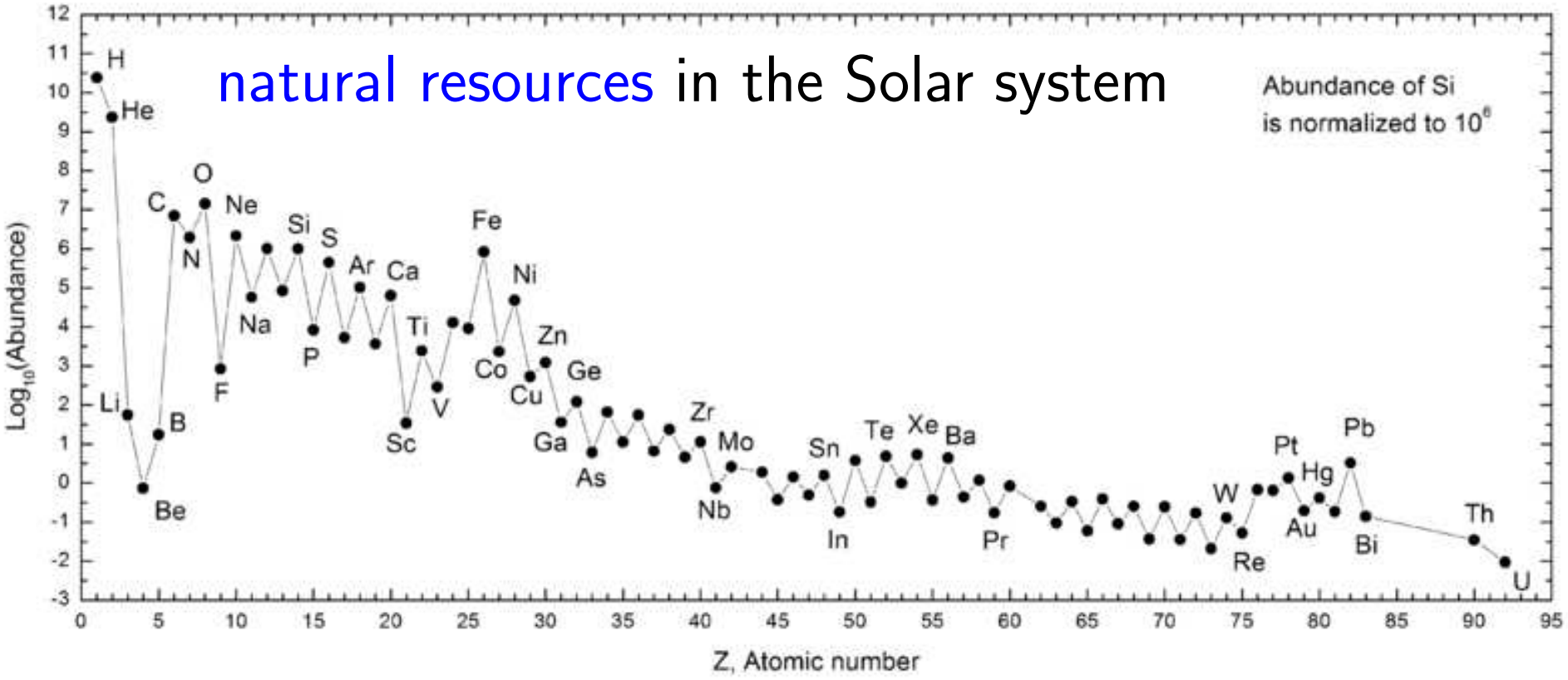
Sub-Nuclear Energy: Antimatter (?)

- Antimatter is real but not practical for energy technology
  - plenty of Antimatter produced in Big Bang
  - almost none survived to present day
  - very expensive to create (per unit energy)

    antimatter particles in colliders, cosmic rays
    antihydrogen at CERN (ALPHA) for 1000 seconds
  - essentially impossible to store
  - even if found outside of Earth (none seen), better stay away...

Natural Resources in the Solar System

- 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



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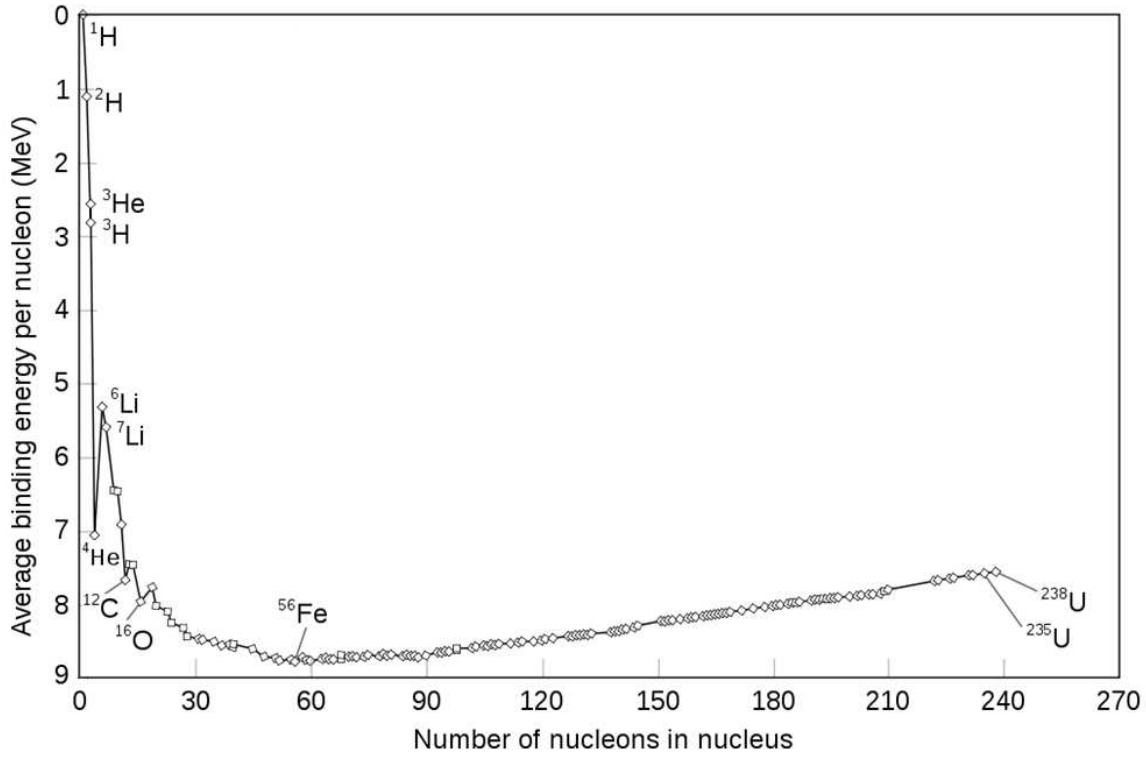


Nuclear Energy: Conclusion

- Nuclear Energy is our main source
  - indirectly: from the Sun (e.g. stored in fossil fuel)
  - directly: power plants (nuclear fission)

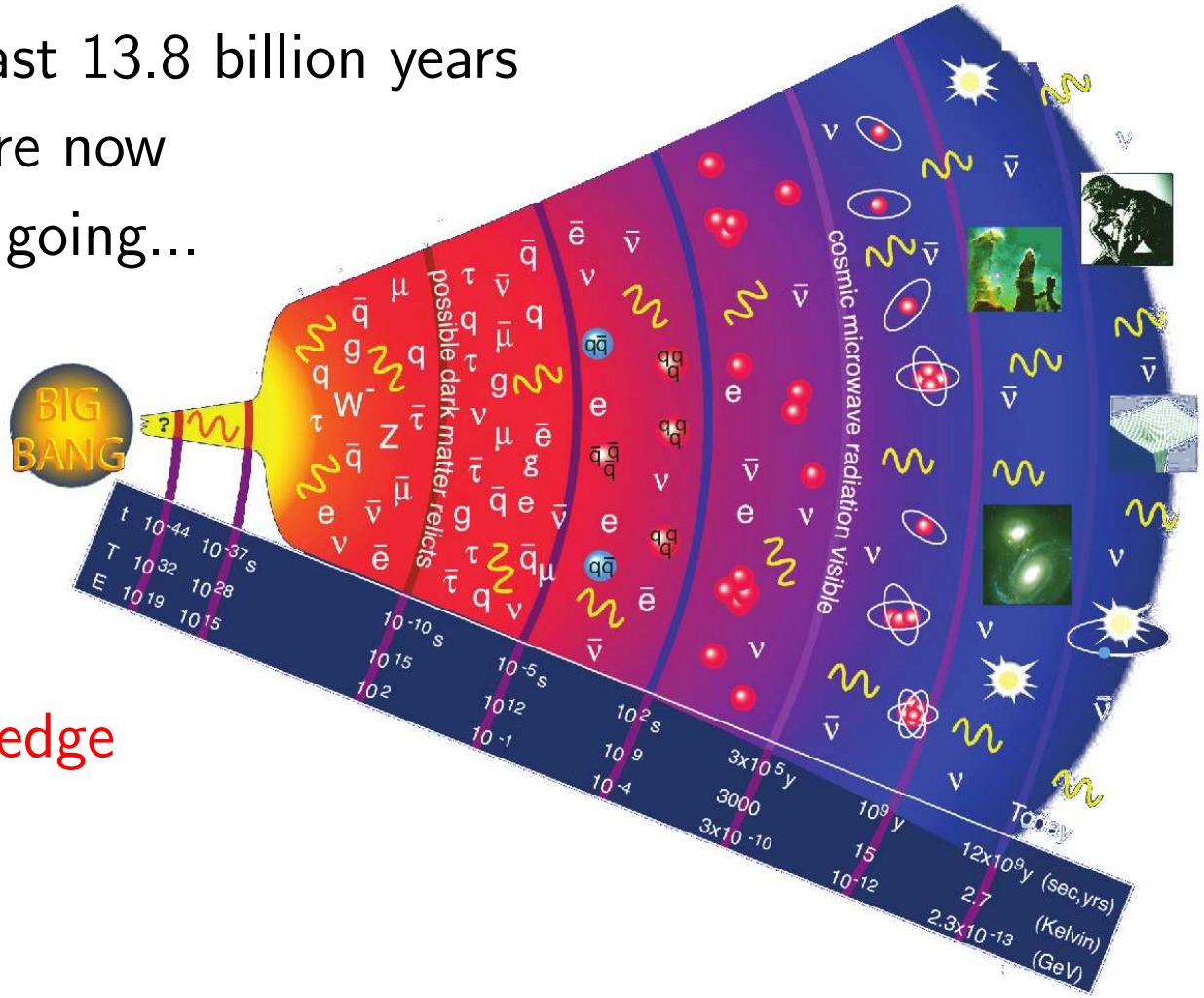
- Future use depends on technology, potential long-term sources:
  - solar energy (artificial "photosynthesis", wind,...)
  - fusion energy (artificial "Sun" with nuclear fusion)

- Should be responsible with energy

Part 2: Physics Case for the Energy Frontier

Why Pursue Energy Frontier

- First of all it is a cultural reason:
  - learn about the past 13.8 billion years
  - about where we are now
  - and where we are going...



- Stay on the cutting edge
  - of education
  - of technology
  - of fundamental scientific knowledge

Discovery of a Higgs Boson

- Discovery of a Higgs Boson

– absolutely new form of matter-energy
– consistent with fundamental $J^P = 0^+$
scalar excitation of a vacuum field

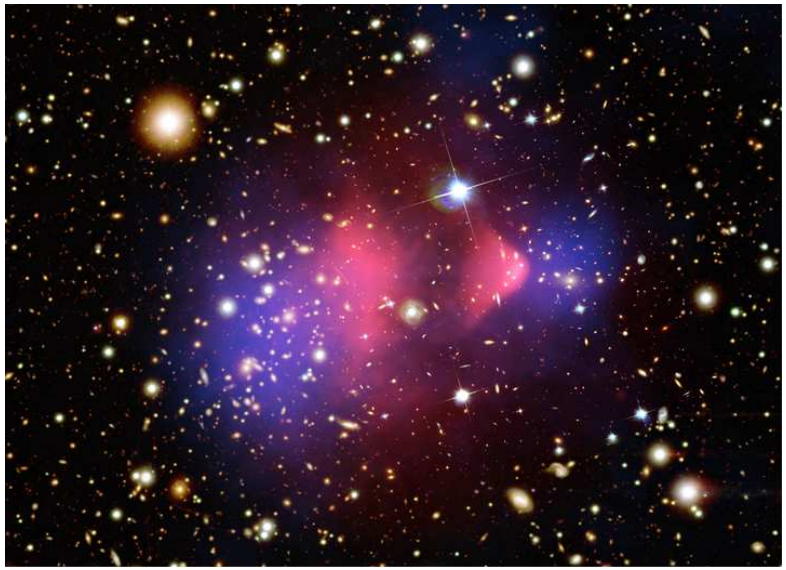
- It would be foolish to stop here

– is it the only such a state?
– what does it tell us?
– where does it lead us?

- It is also a triumph of predictive power of scientific knowledge

– we knew where to look
– but a discovery was not guaranteed, also true for the next steps

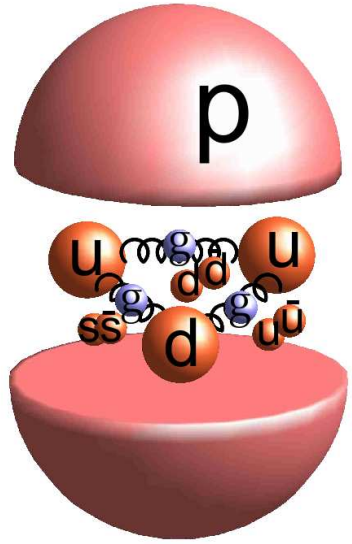
The dark questions: What we do not see



- What is in the vacuum?
  - dark energy, 10^{120} too small ?
  - $\sim$70% of matter-energy balance
  - Higgs field, related to dark energy?
  - is vacuum (Higgs field) unstable?
- What is dark matter?
  - $\sim$25% of matter-energy
  - is it a WIMP? does it interact with the Higgs field/boson?
- Where did antimatter go?
  - $\sim$0%
  - CP violation in the Higgs sector? anywhere else?
  - why is proton so stable?

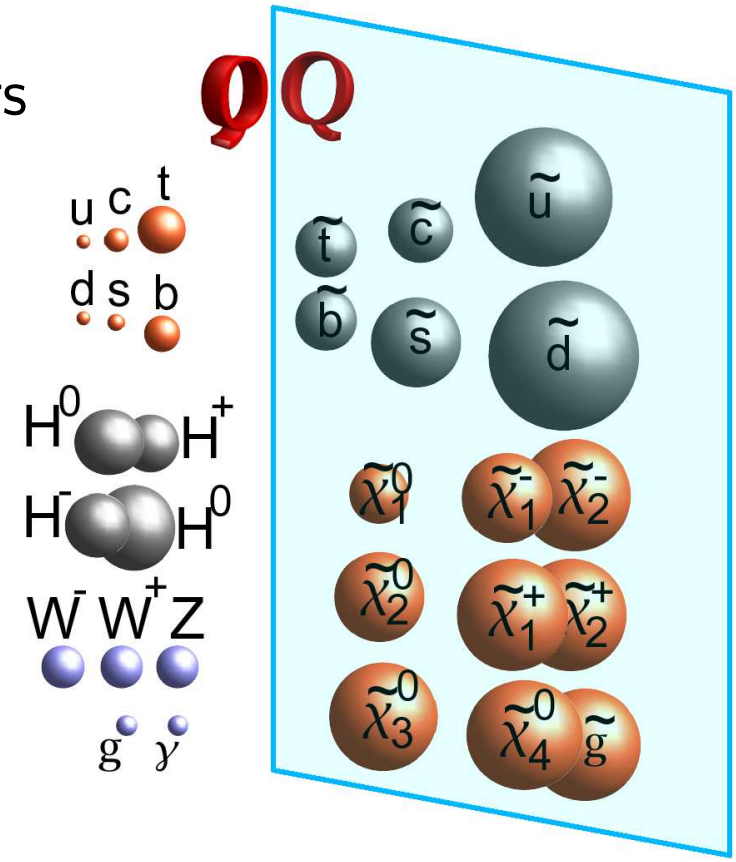
The light questions: What we do see

- We do not understand (see) 95% of the Universe
- But even what we do see:
  - why is light (γ) so light?
    and does not see the Higgs field?
  - masses of fermions from <1 eV to $>10^{11}$ eV
    are the Higgs field couplings random?
  - how do we keep the Higgs boson stable
    against large radiative corrections?
  - why is gravity so weak? $\sim 10^{32}$ weaker than the weak force
    do we understand the space-time? extra dimensions?
    how do we approach quantum gravity? are there gravitons?



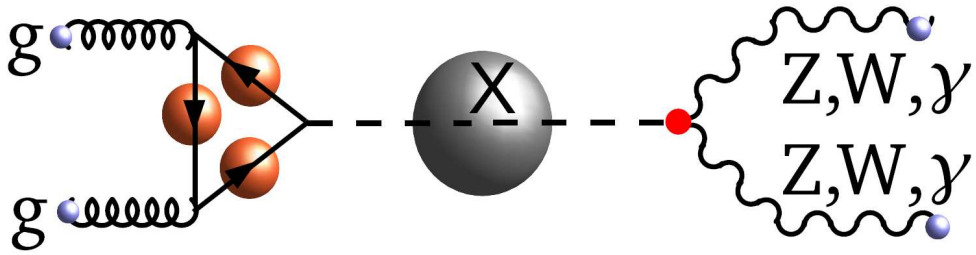
Looking for answers

- With so many questions, we need answers
- Motivated models exist
  - but must confirm experimentally
- Implications for the Energy Frontier
  - Higgs boson is not alone
  - its properties affected
  - CP violation observable
  - dark matter candidate
  - many partner particles may be within reach (direct or indirect)
- The reach depends on the dial of Nature
  - the whole new view on the Universe may open up
  - we are very close to find out...

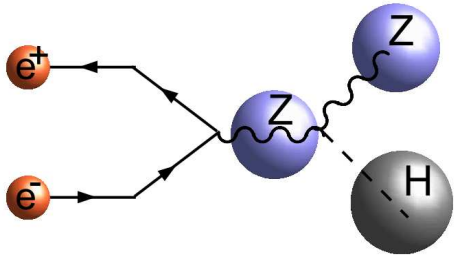


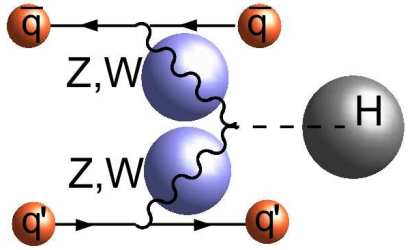
Two paths to reach

- We have seen this



- We are now guaranteed to have these





- Two paths to proceed

(1) precision measurements of new state of matter-energy (H)

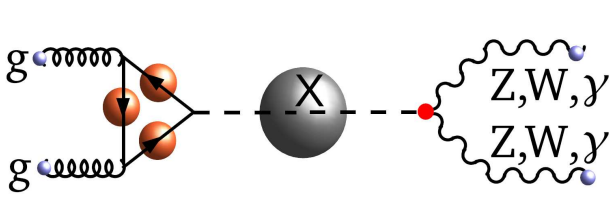
(2) reaching higher in mass+sensitivity for other states (X)

5-10% precision on (1) $\Leftrightarrow$ few TeV mass reach (2)

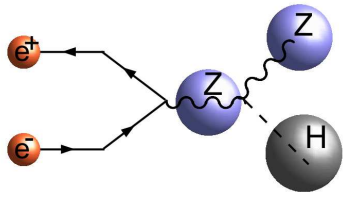
We have the knowledge and technology

- LHC pp
- H-factory $\sim$250 GeV
- ILC $\sim$1 TeV

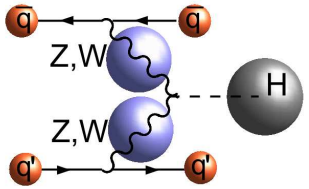
$gg \to H$

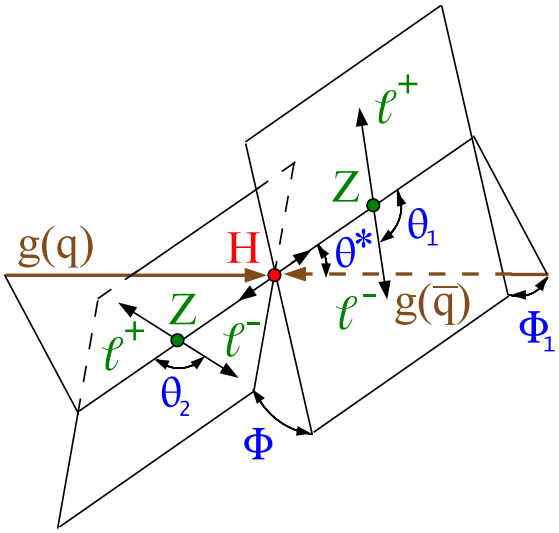


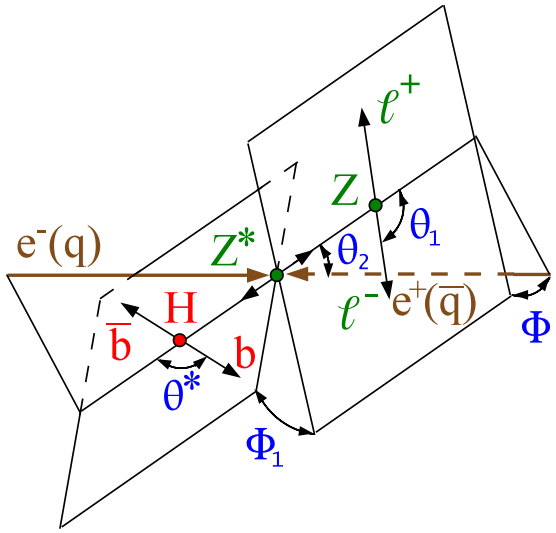
$e^+e^- \to Z^* \to ZH$

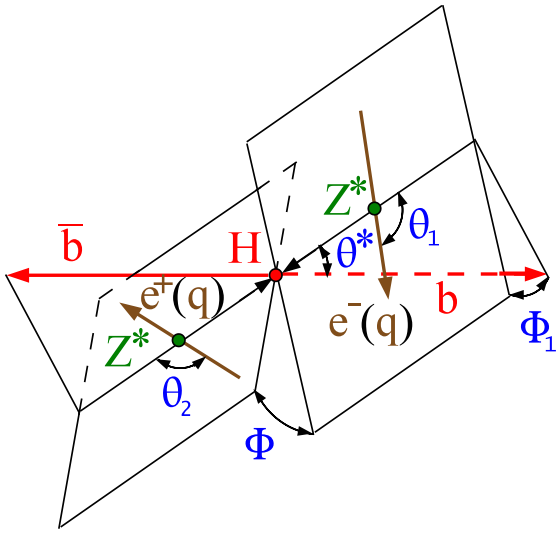


$e^+e^-VV \to \ell\ell H$









- With complementary approaches
  - guaranteed precision understanding of the Higgs boson
  - when new discoveries happen, use facilities for deep understanding

Frontier facilities

5-10% precision on (H) $\Leftrightarrow$ few TeV mass reach (X)

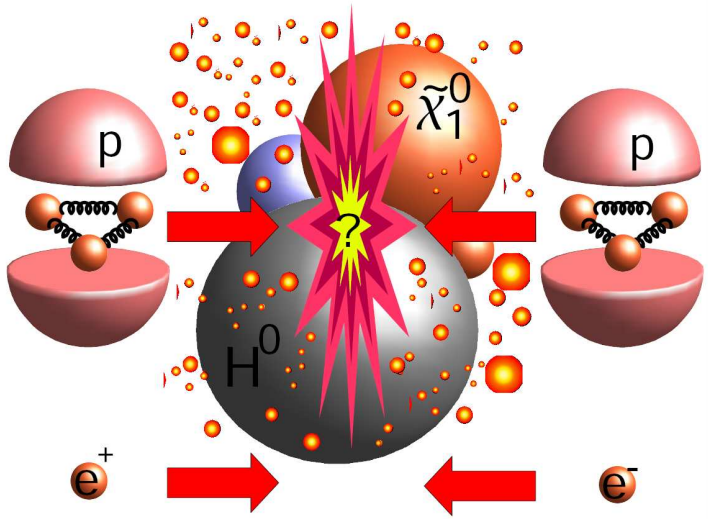
- This is a model-dependent statement, we need BOTH
- Exciting opportunities:

  (1) LHC pp at 14 TeV
  with further upgrade of lumi and possibly energy

  (2) Linear e^+e^-
  with further upgrade of energy

  (3) Circular e^+e^-
  with further upgrade to pp ~100 TeV

  (4, 5) Muon and photon colliders



- Discoveries may be at reach but not guaranteed
  we can guarantee (a) not to miss & (b) stay on the cutting edge

The other questions we face

- It all looks excellent, but
  - with limited support, where can we focus
- Questions to US community
  - join CERN for LHC lumi/energy upgrade (1)
  - join overseas e^+e^- machine (2)
  - have the next Energy Frontier facility in the US (3)
  - more than one (all) of the above
  - substitute Energy Frontier with "smaller alternatives"
- We have the Physics Case
  - make it sharp (Snowmass effort) and do the best we can...

Physics Case

- We have a very strong Physics Case for the Energy Frontier

- We also have to face the question:
  - Why did not we discover the Higgs boson at the SSC?

Part 3

Two Events in the Last Two Years

- December 10, 2011

  Award Ceremony, 2011 Nobel Prize in Physics:

  "for the discovery of the accelerating expansion of the Universe through observations of distant supernovae"

  http://www.nobelprize.org/nobel_prizes/physics/laureates/2011/

- July 4, 2012 CERN – European Organization for Nuclear Research

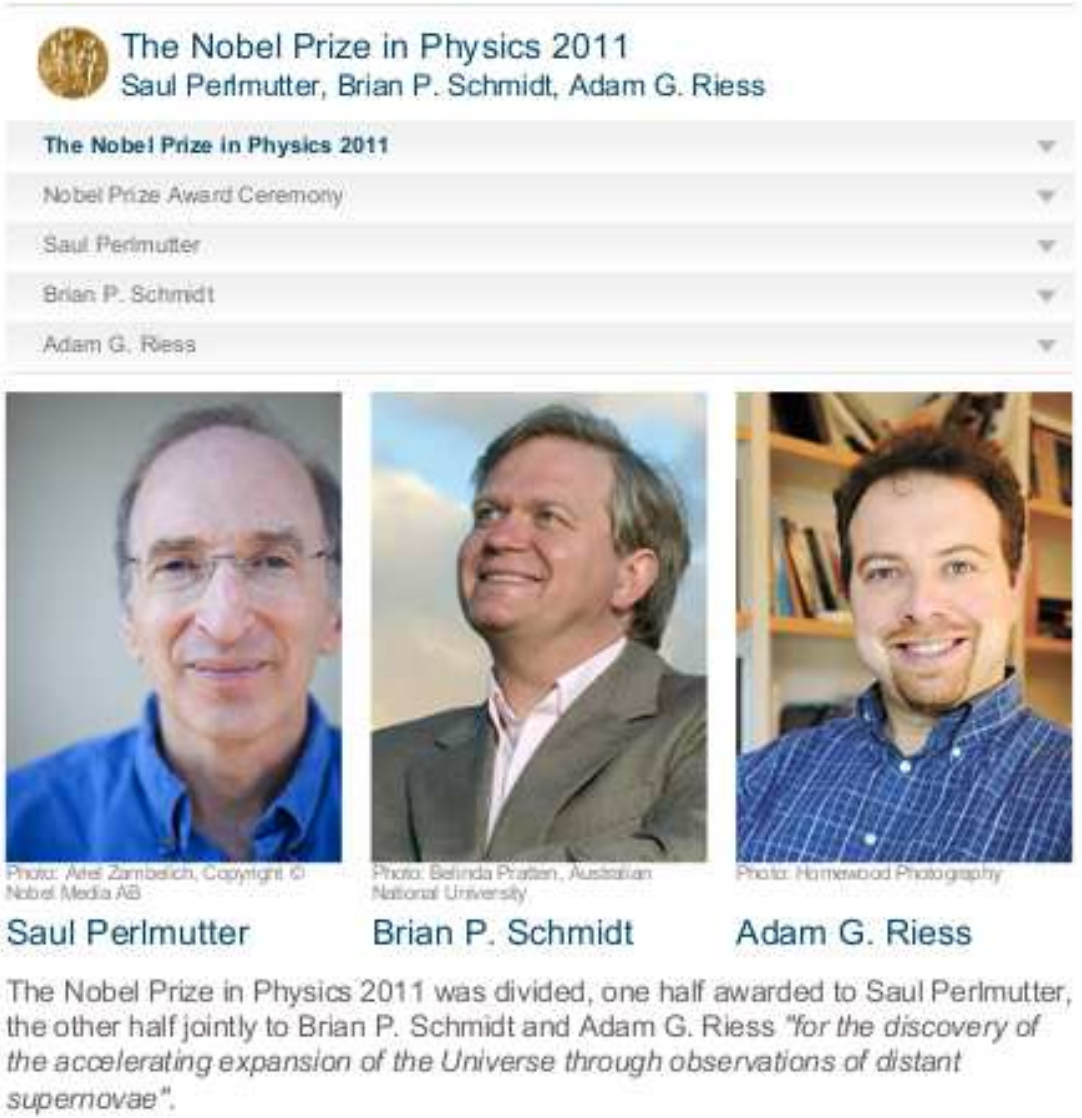
  CMS and ATLAS experiments discovered a Higgs-like boson

  "The discovery of a particle consistent with the Higgs boson opens the way to more detailed studies, requiring larger statistics, which will pin down the new particles properties, and is likely to shed light on other mysteries of our universe"

2011 Nobel Prize in Physics

- Accelerating expansion of the Universe

  requires some kind of "dark energy" through empty space



Higgs Field

- The property of mass requires some kind of invisible force the "Higgs field" filling the empty space

Vacuum

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

  is not exactly empty

- like a bank account balance:

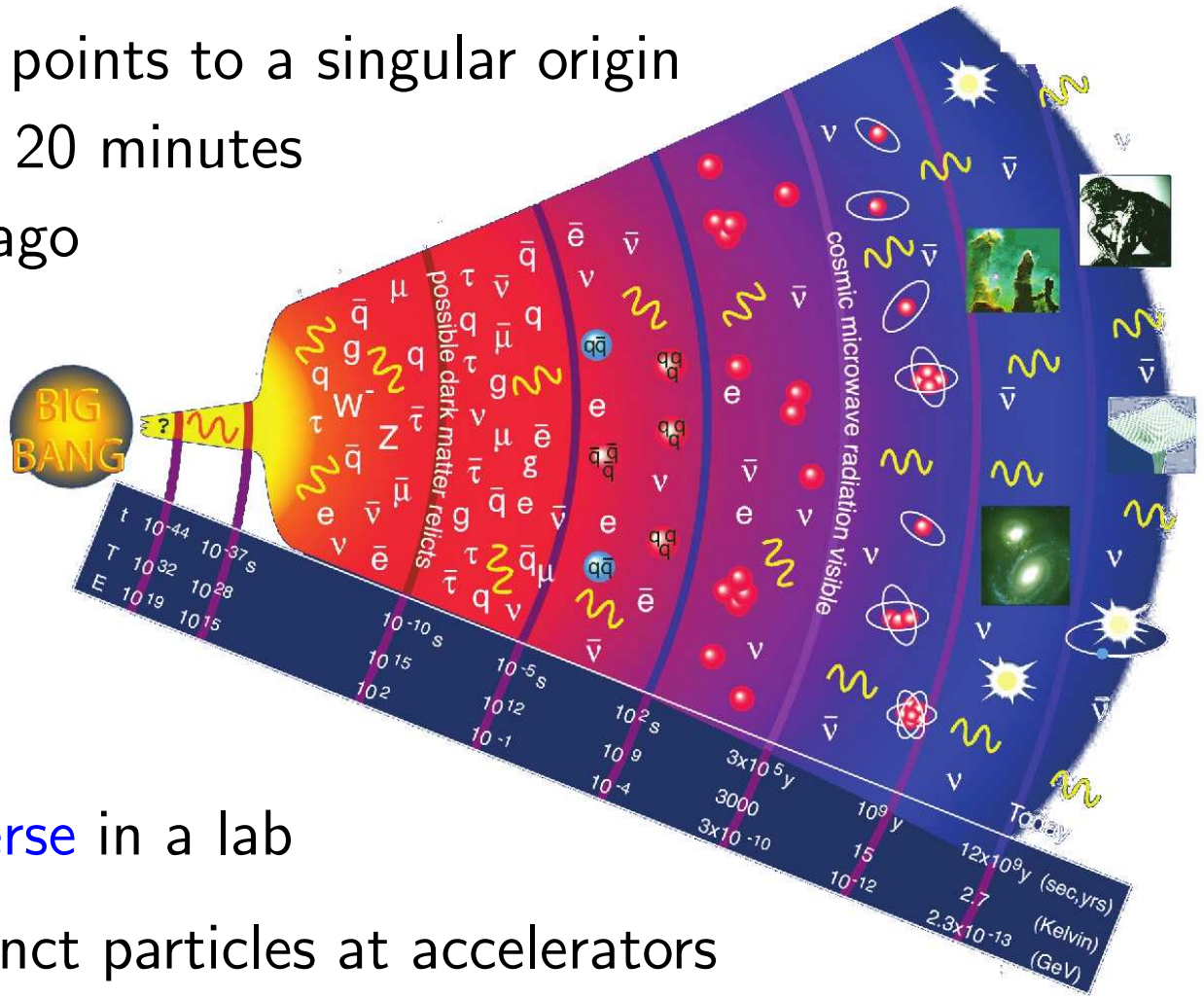
when you take all your money out

there is a minimum balance left

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

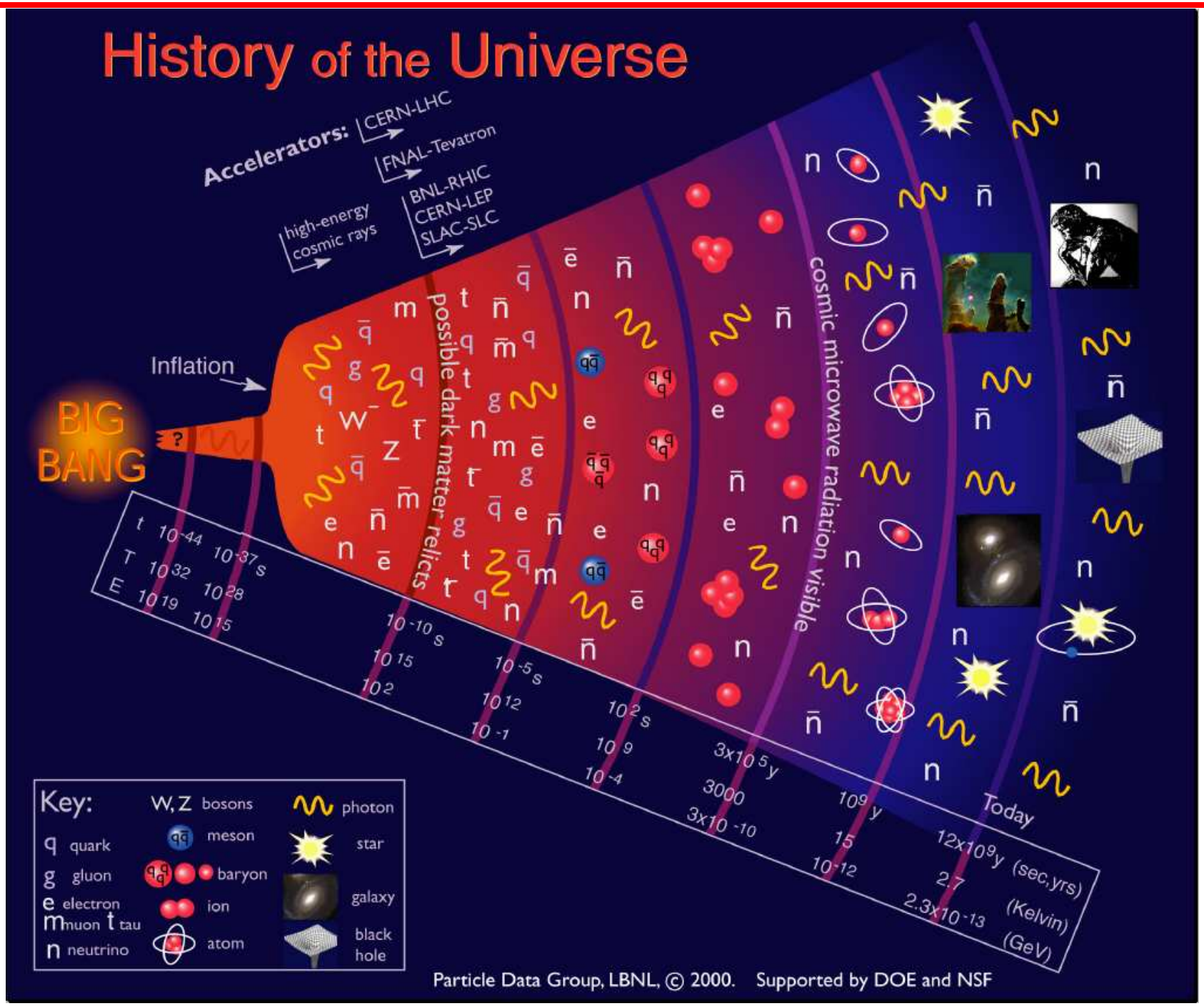
Start from the Beginning: The Big Bang

- 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


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
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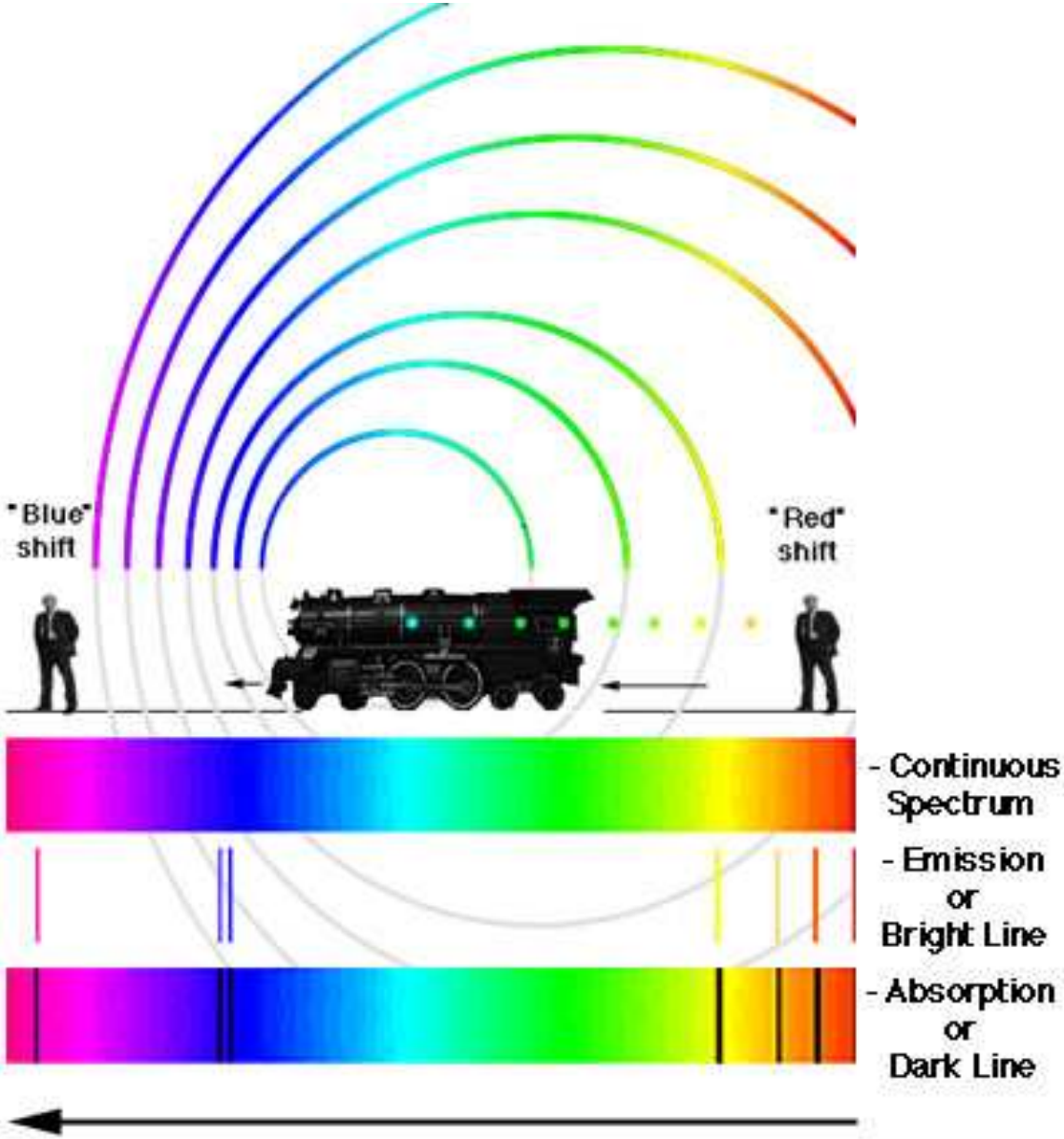
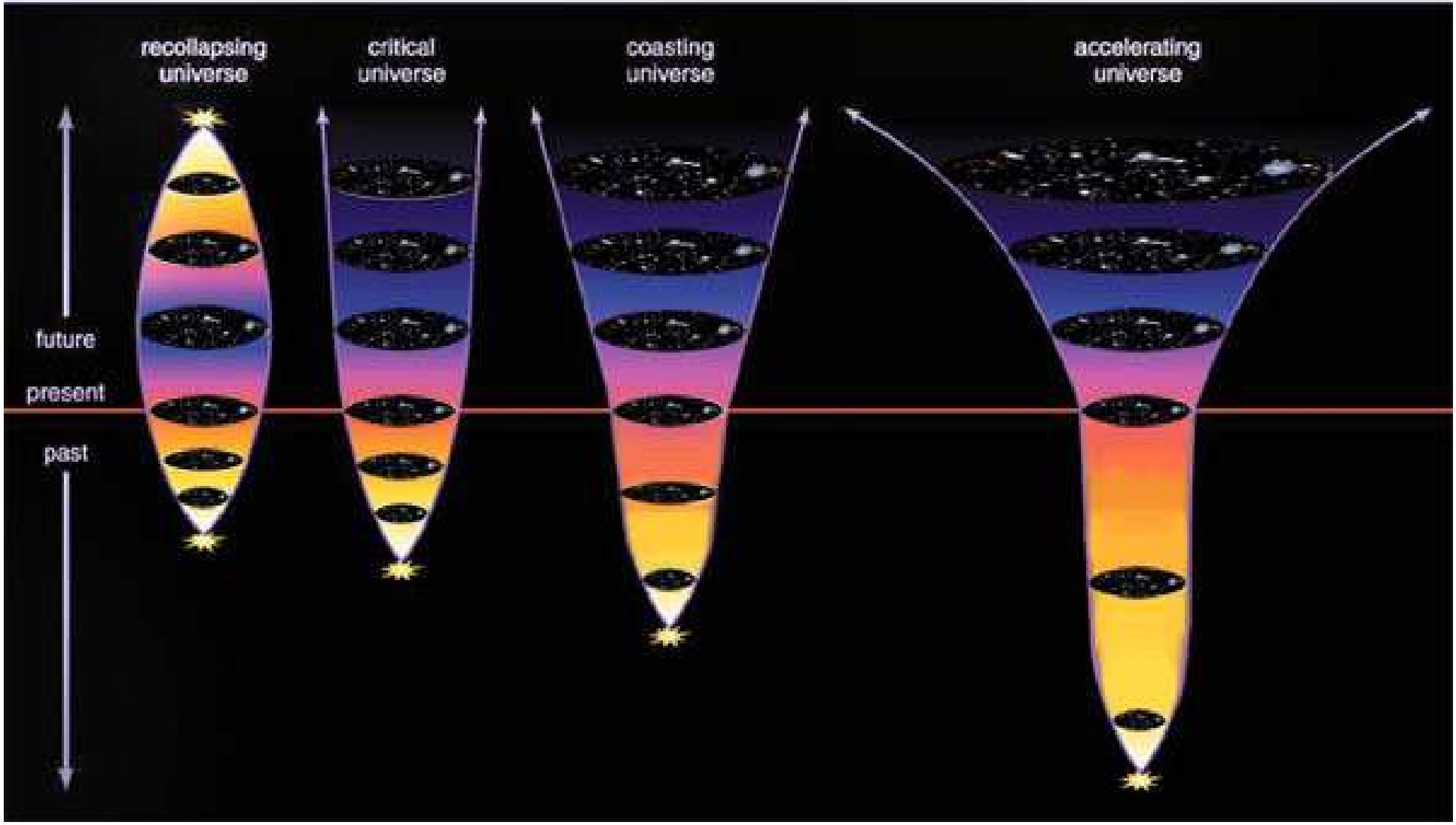
Expanding Universe

- Observe stars as trains moving AWAY from us



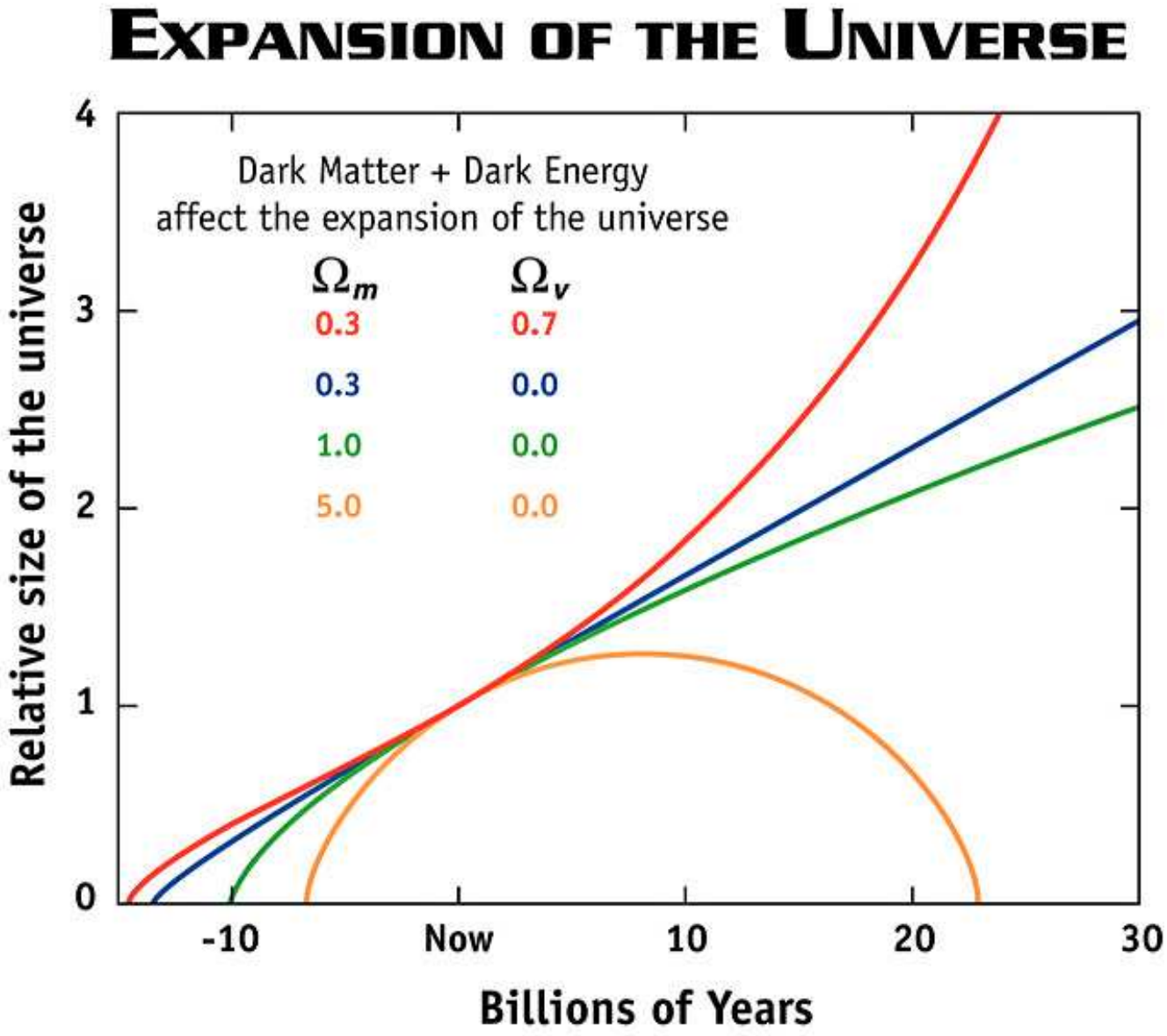
Will Universe Expand Forever?

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

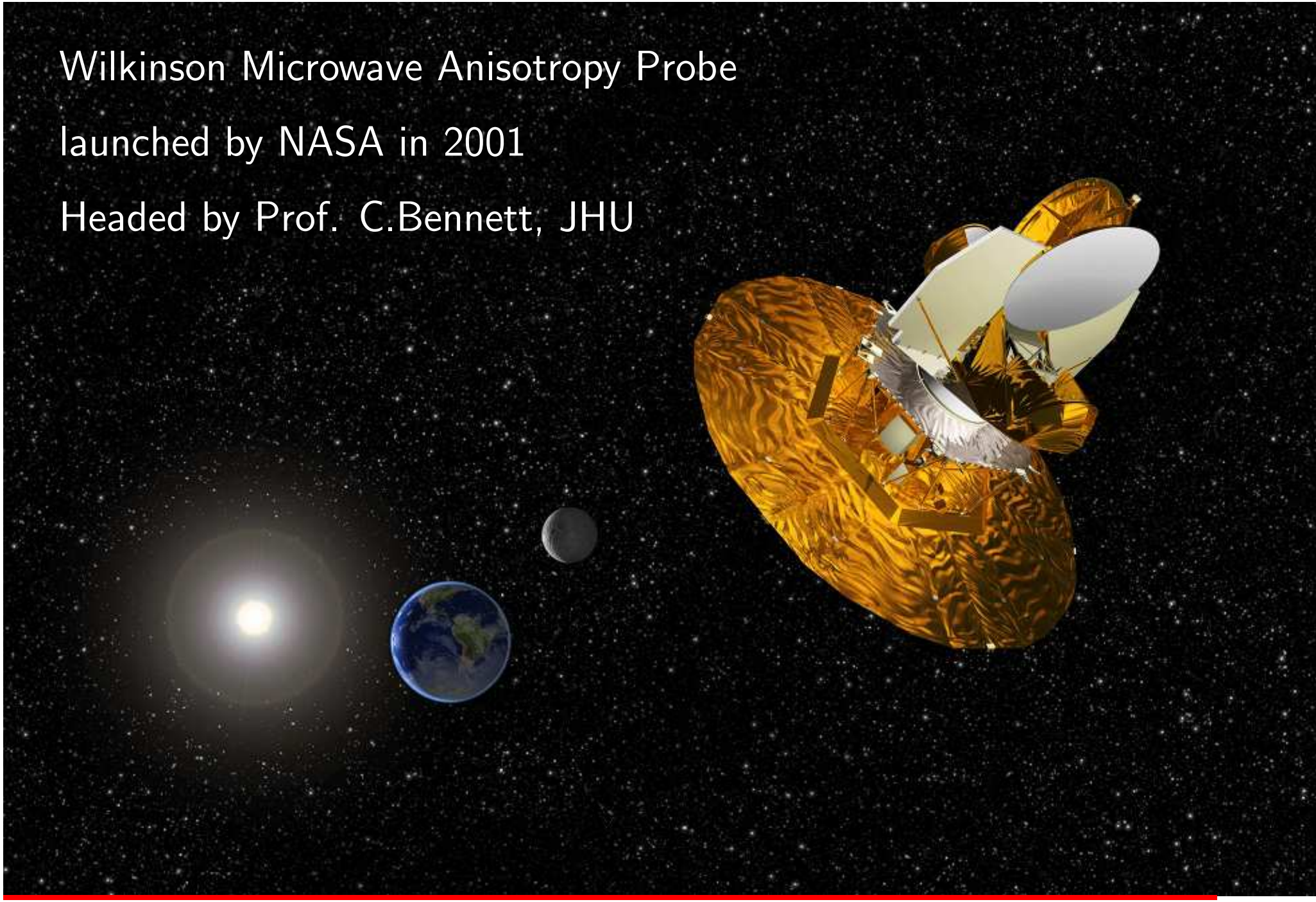


Expansion of the Universe

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



Example: WMAP Explorer Mission



Example: Hubble Space Telescope

launched by NASA in 1990

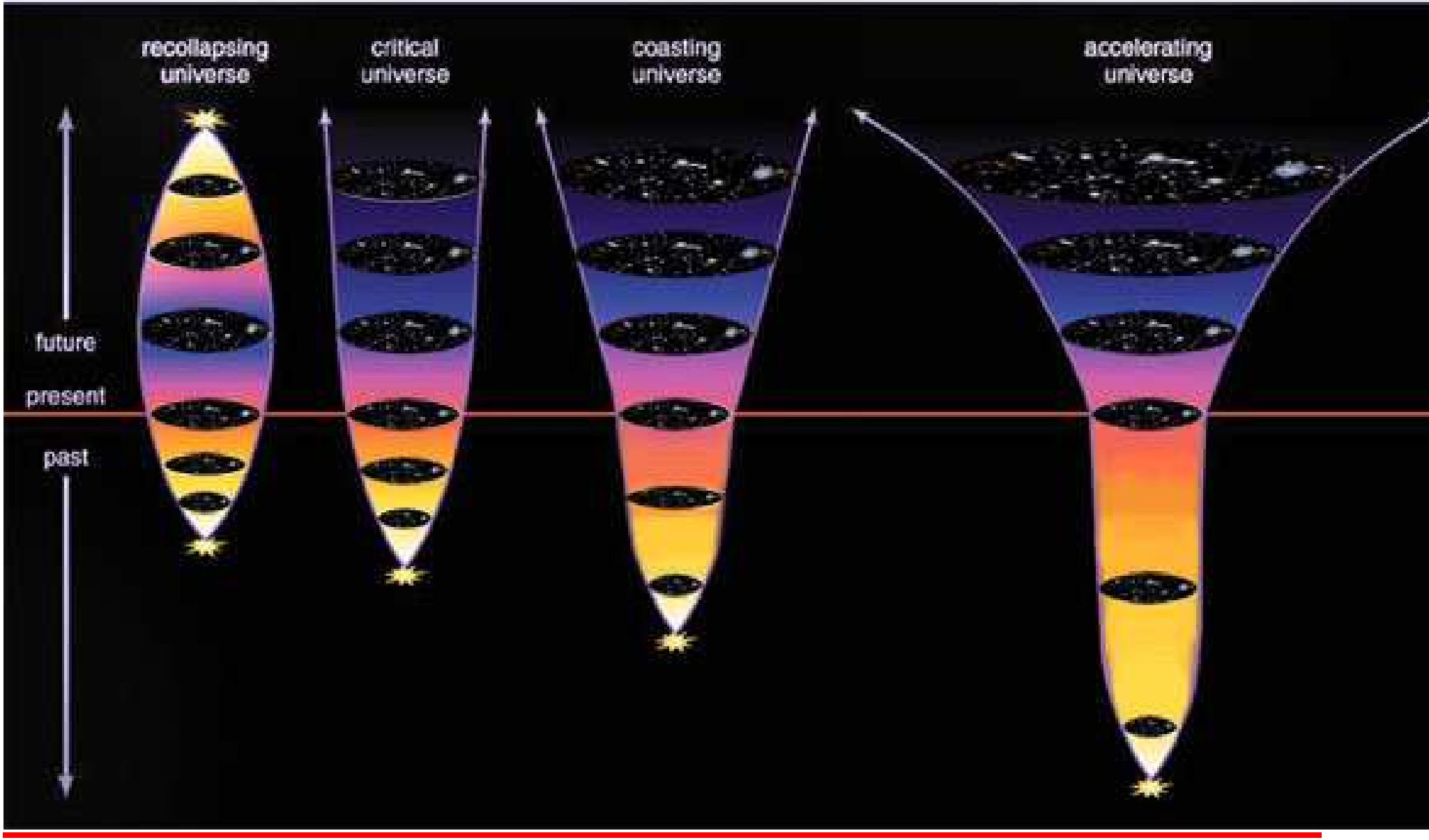
operated by Space Telescope Science Institute

replace by James Webb Space Telescope in 2018

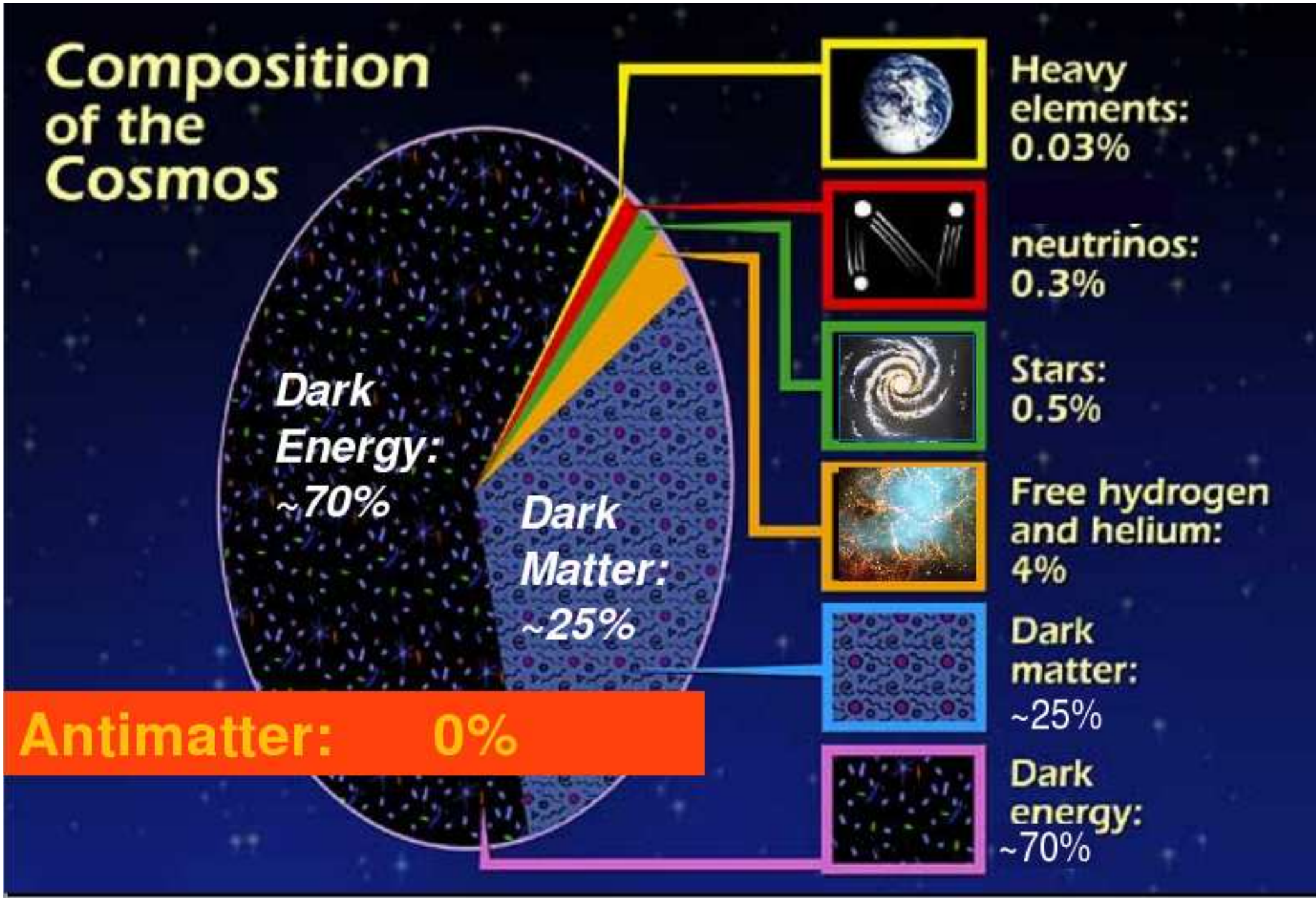
Gravity Should Slow Expansion

Expansion is Accelerating

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



Puzzles of the Universe

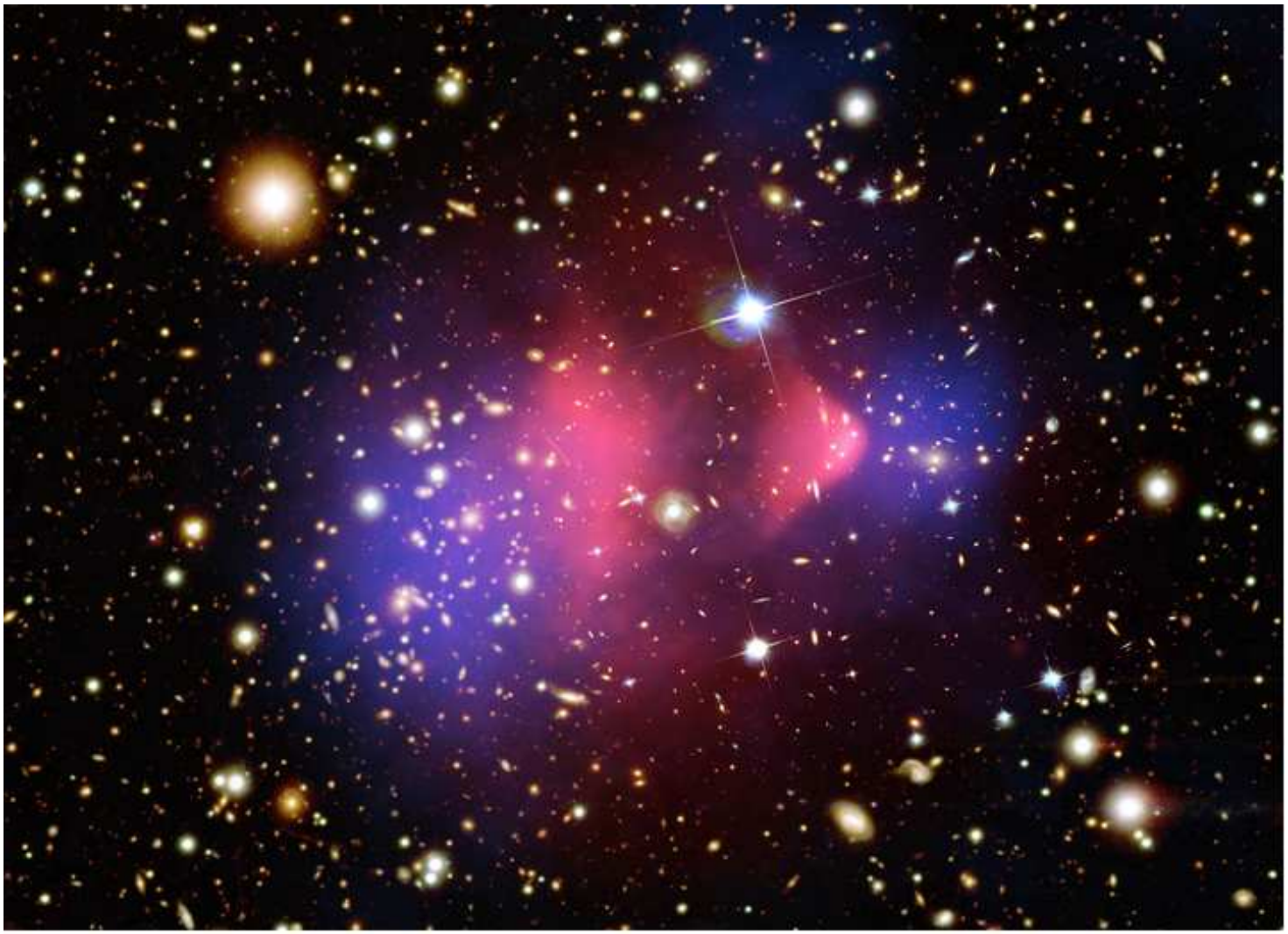


Puzzles of the Universe

- 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

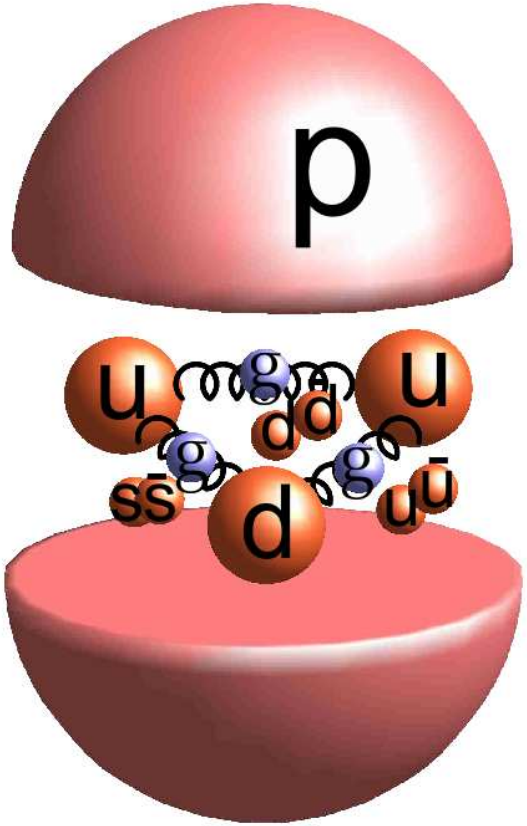
- Dark matter (25%) – "dark" does not emit light, unknown
  - left over from Big Bang, may create in accelerators...



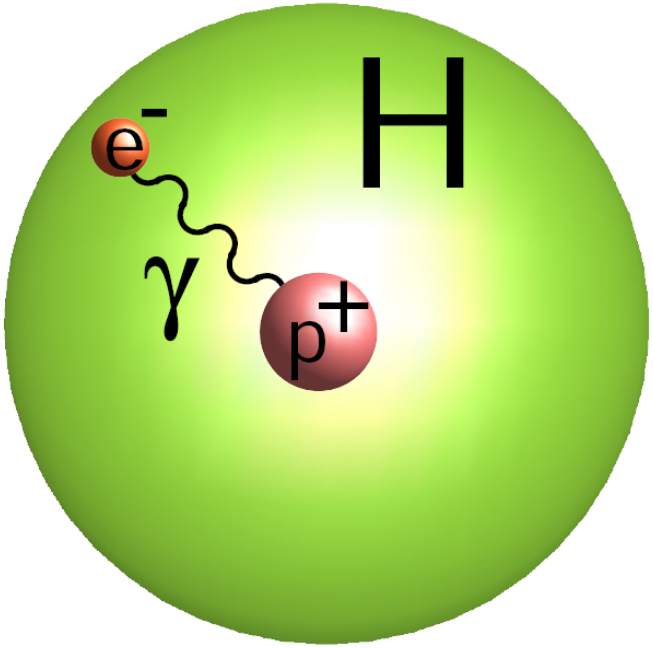
(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

Ordinary Matter in Big Bang

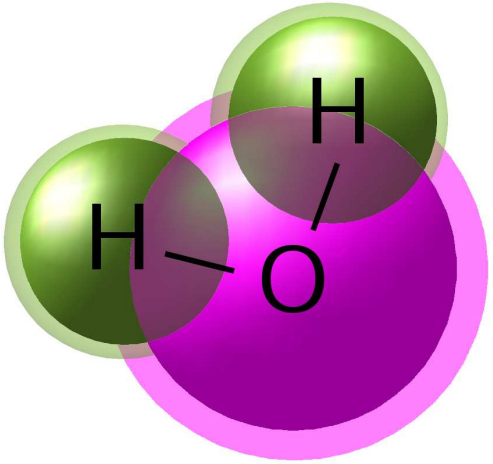
- Quark-gluon soup fraction of a second after Big Bang
  - within minutes protons and neutrons formed
  - billions of years to create all known elements



proton/neutron

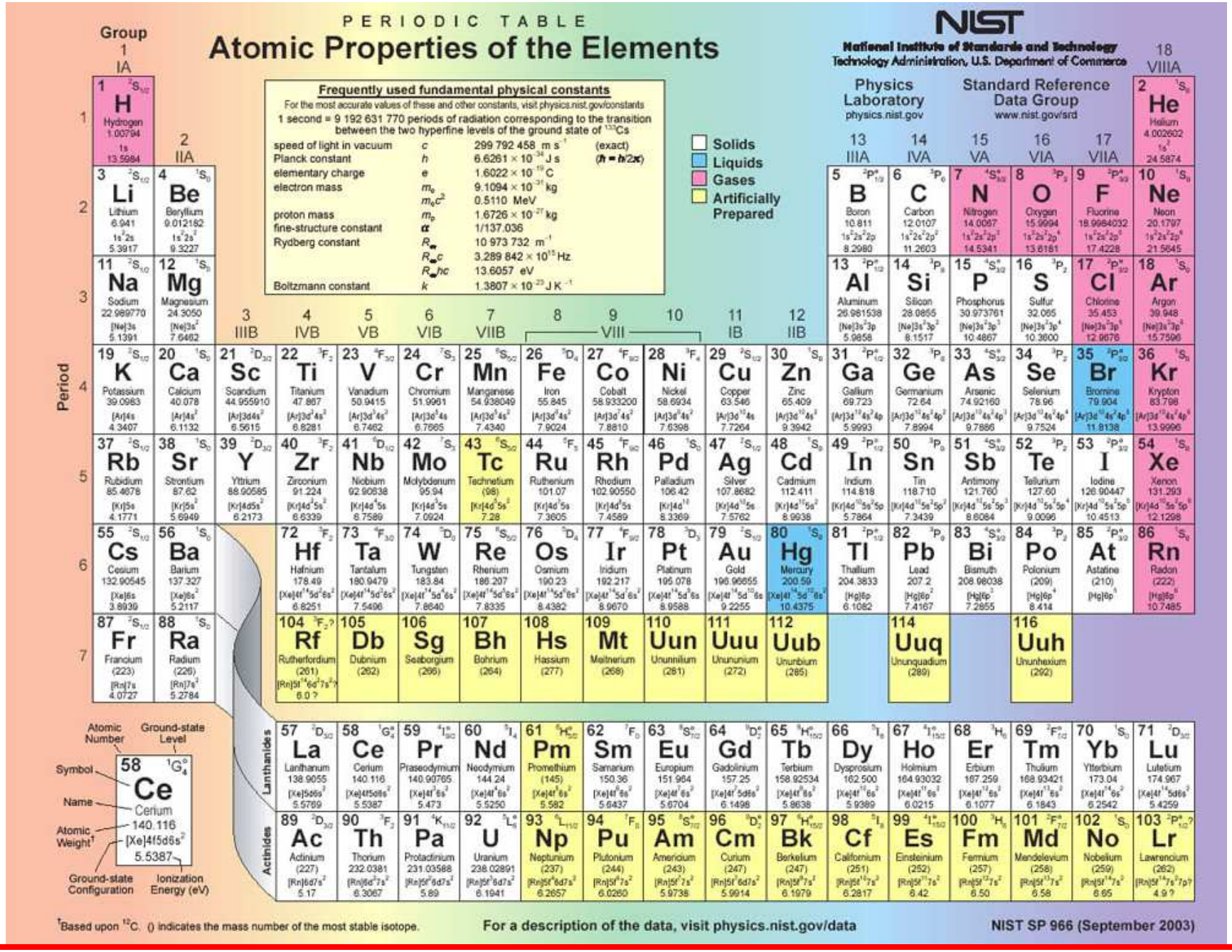


atom



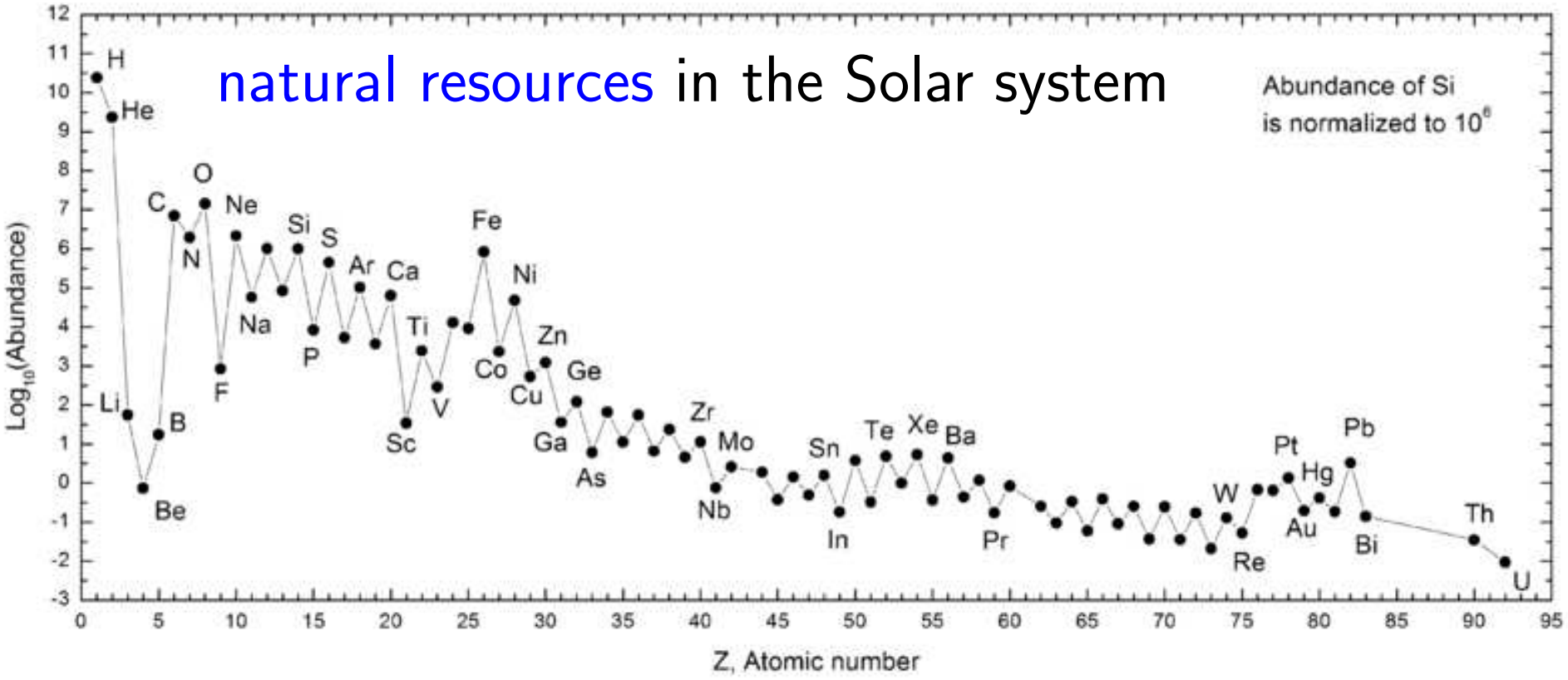
molecule

Periodic Table of Matter

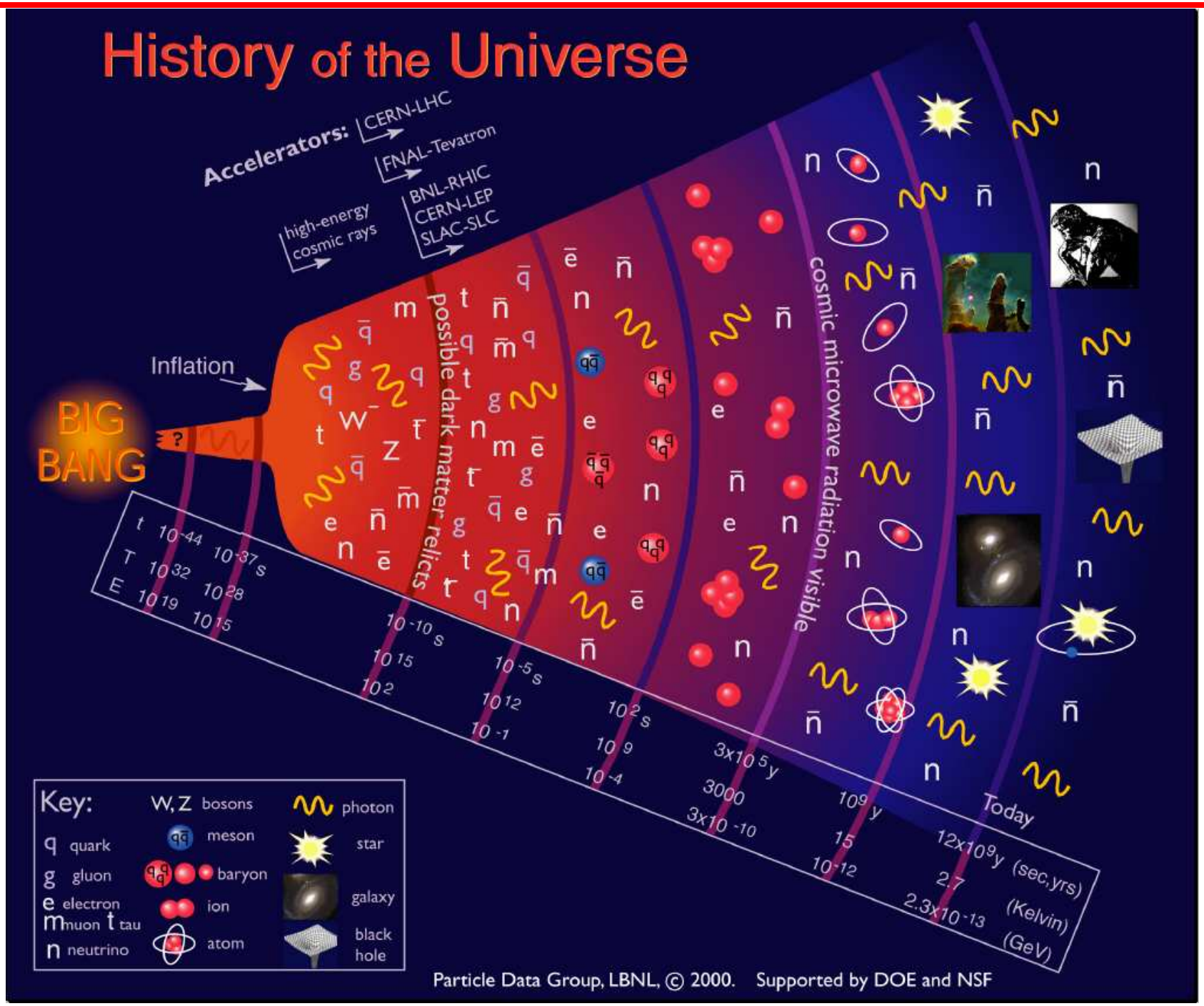


Formation of All Elements

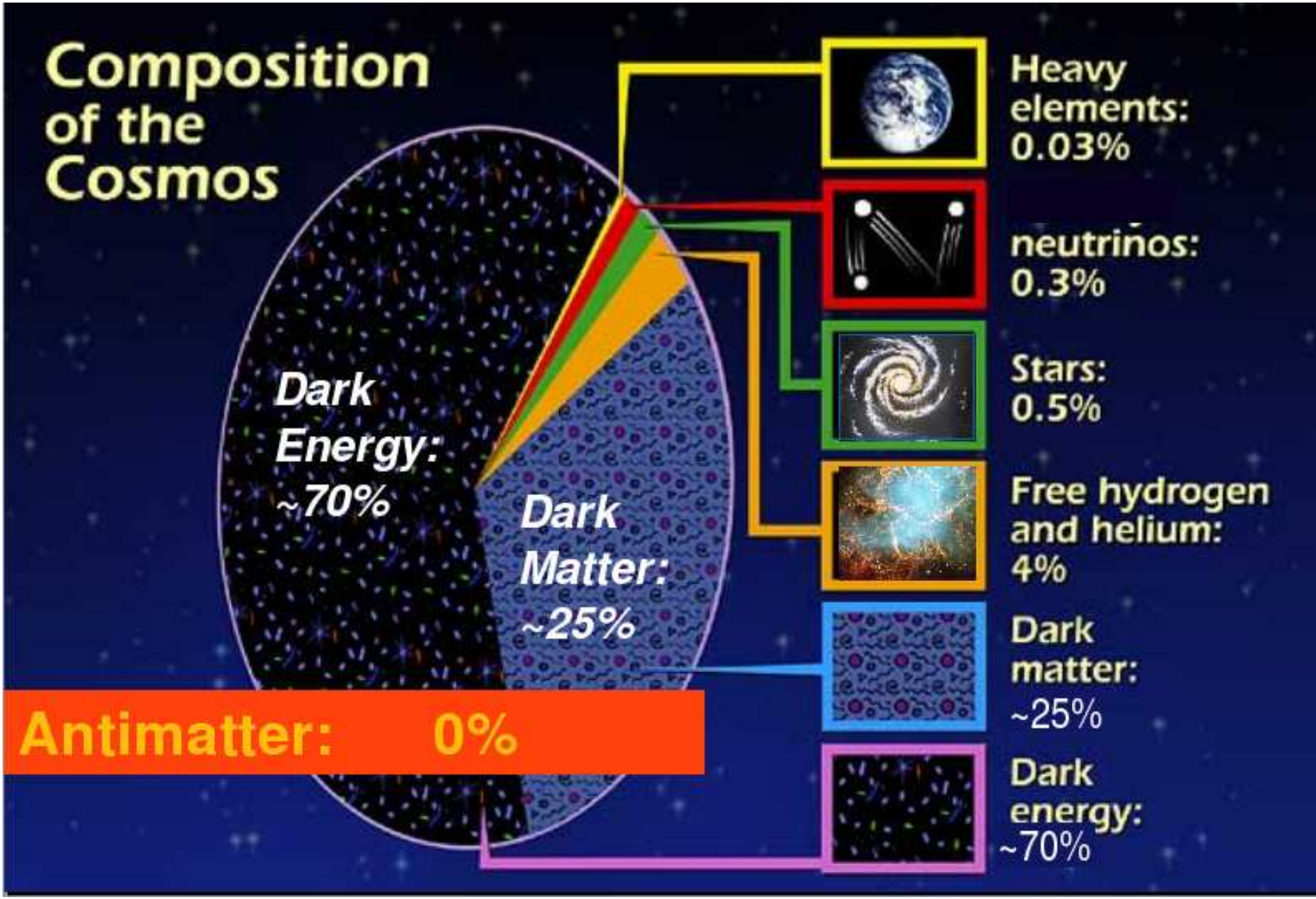
- Success of Big Bang theory – predict formation of elements
  - light elements (H, He) in early moments
  - heavy elements (C – U) in fusion within stars
- Nuclear energy – in the gluon soup binding the quarks



The Big Bang


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

Puzzles of the Universe



Puzzles of the Universe

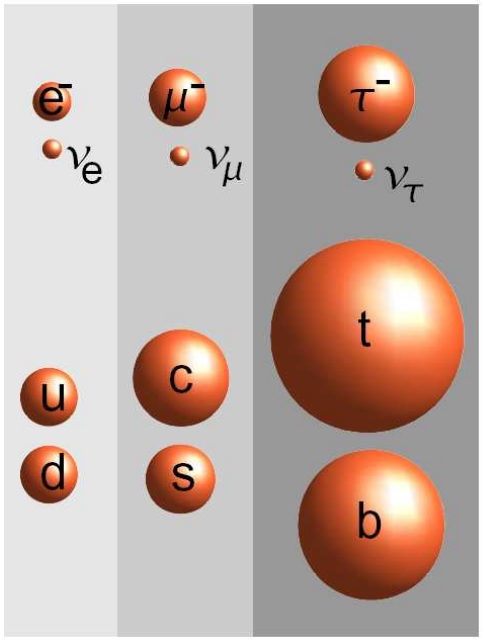
- Dark energy (∼70%)
  - do not know what it is; explain accelerated expansion
- Dark matter (∼25%)
  - does not emit light, but seen with gravity
- Ordinary matter (∼5%)
  - the only thing we knew until recently: from Hydrogen to Uranium
- Ordinary antimatter (∼0%)
  - equal amount of matter and antimatter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

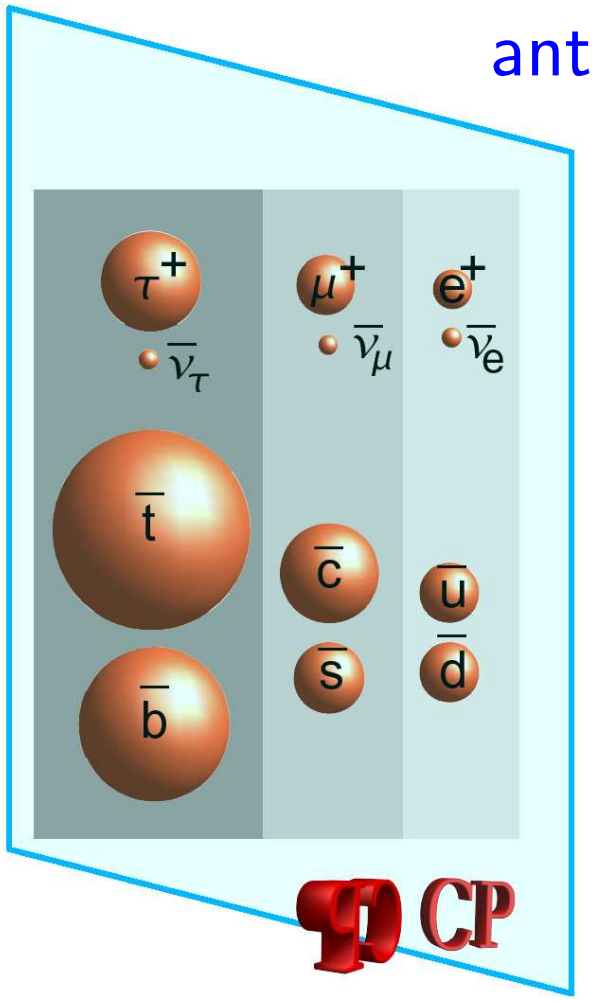
Anti-Matter: Mirror Object of Matter

- 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

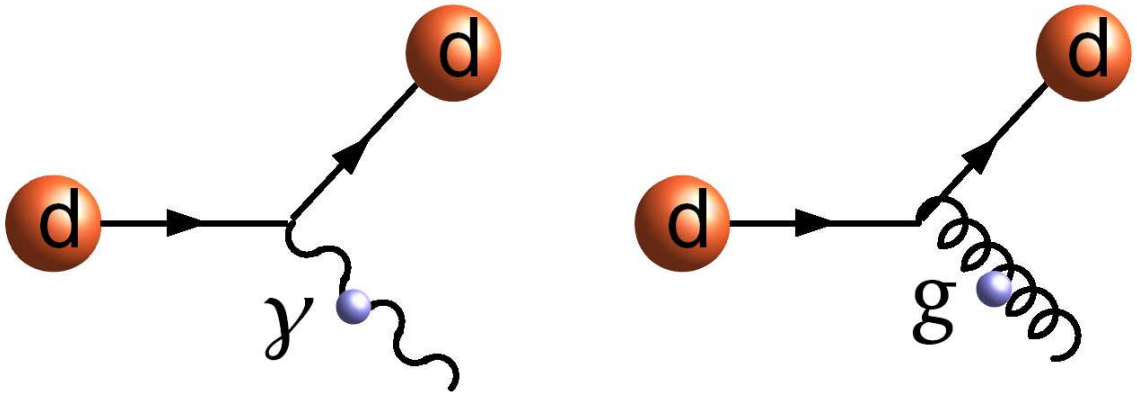

© The Nobel Foundation Photo: U. Montan

Toshihide Maskawa

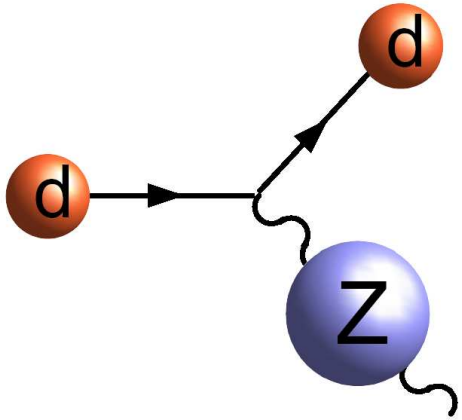
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu *"for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics"*, the other half jointly to Makoto Kobayashi and Toshihide Maskawa *"for the discovery of the origin of the broken symmetry which predicts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



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

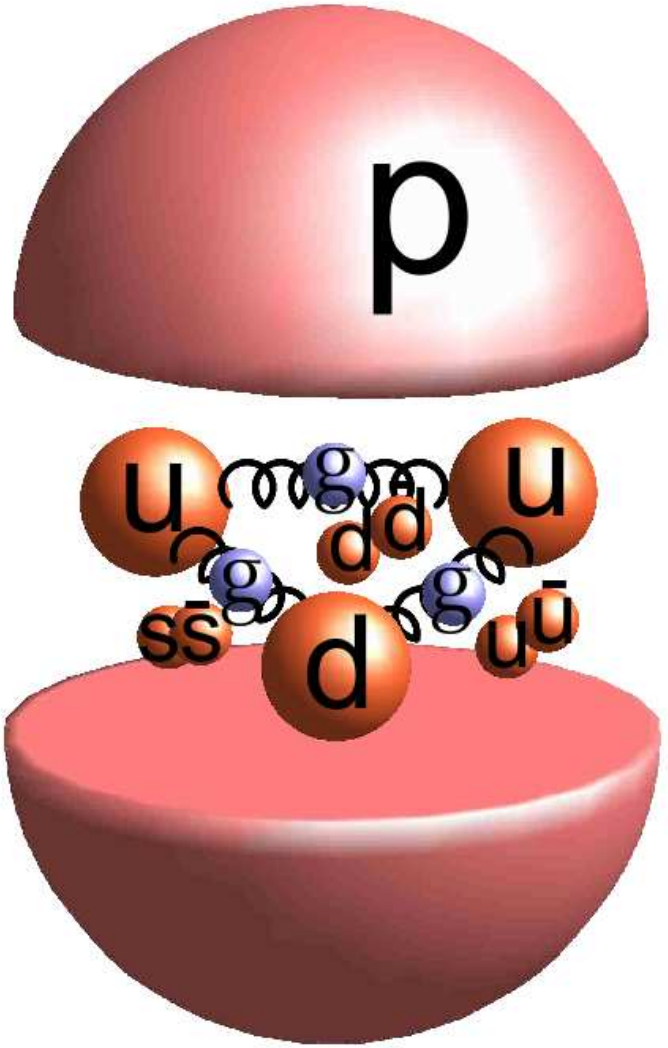
- Pass energy into the Higgs field (no particle)

Idea - the Higgs Field

- The Higgs particle cluster created from the Higgs field

Mass of Matter

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



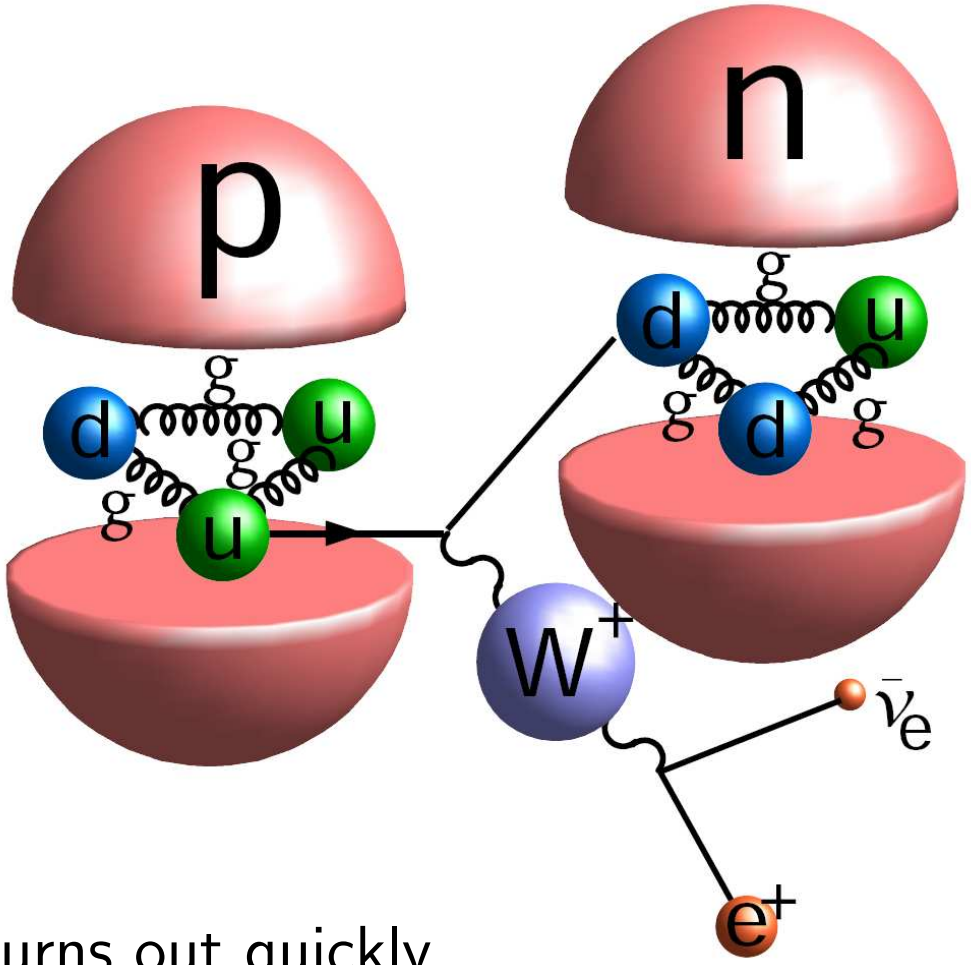
Mass from quark-glue soup energy:
$m_p c^2 = 938$ MeV

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

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

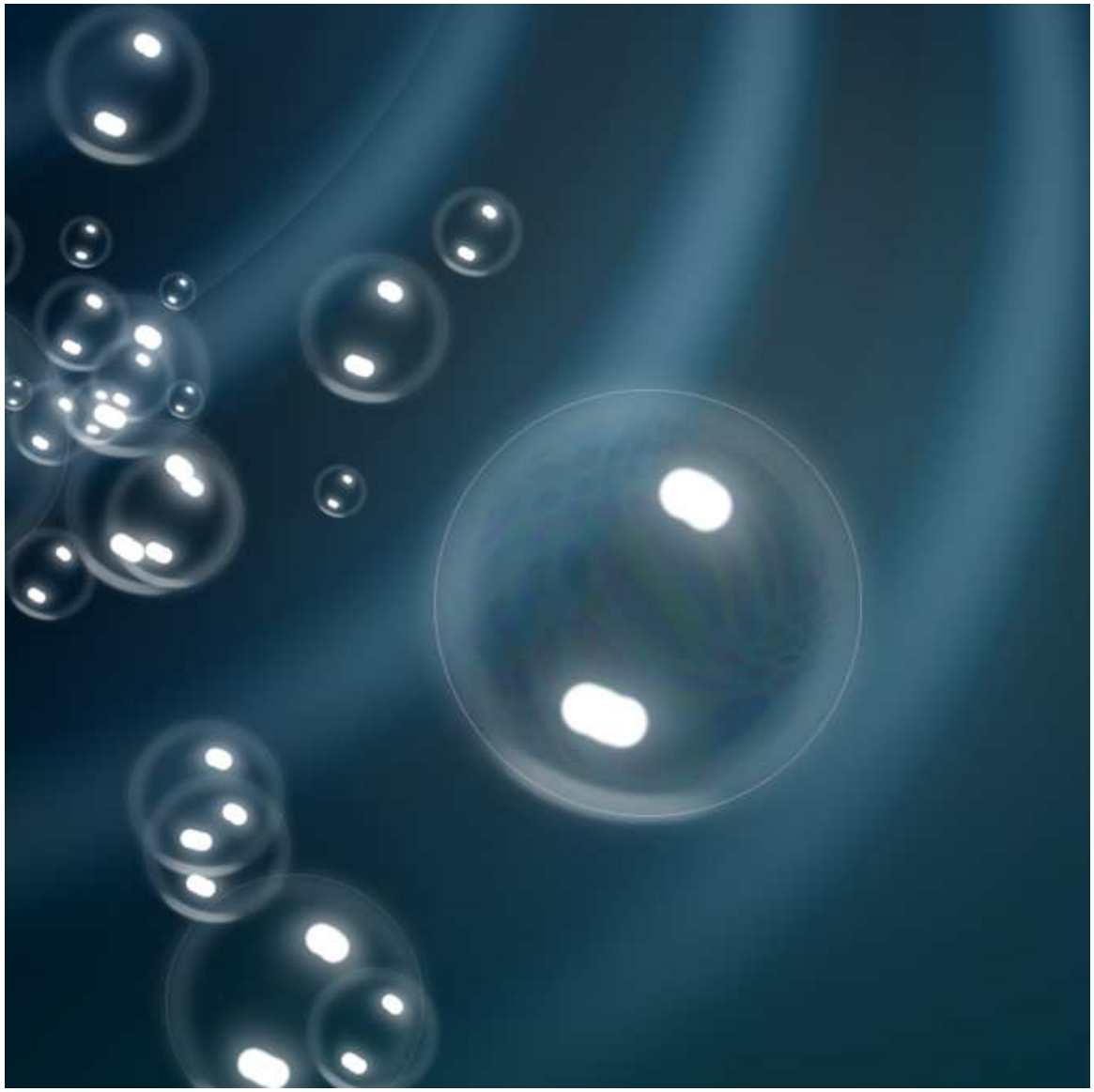
  $p + p \longrightarrow d(pn) + e^+ + \nu_e$

  slow burning due to heavy W^+

  Remove the Higgs field – Sun burns out quickly

News from the Large Hadron Collider

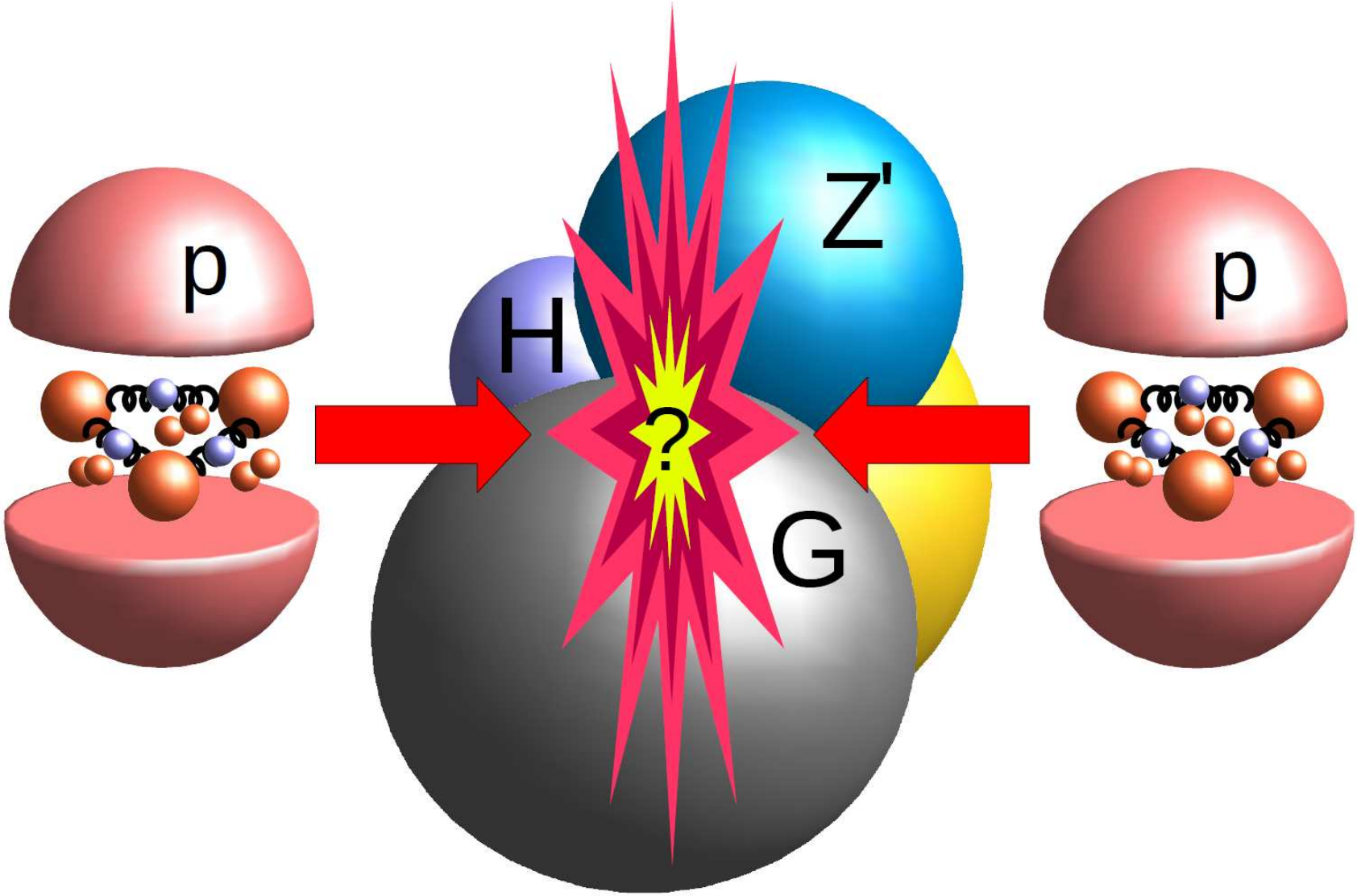
- Idea: if the Higgs field exists, like soap:
  - blow into the soap, create a bubble (Higgs boson)



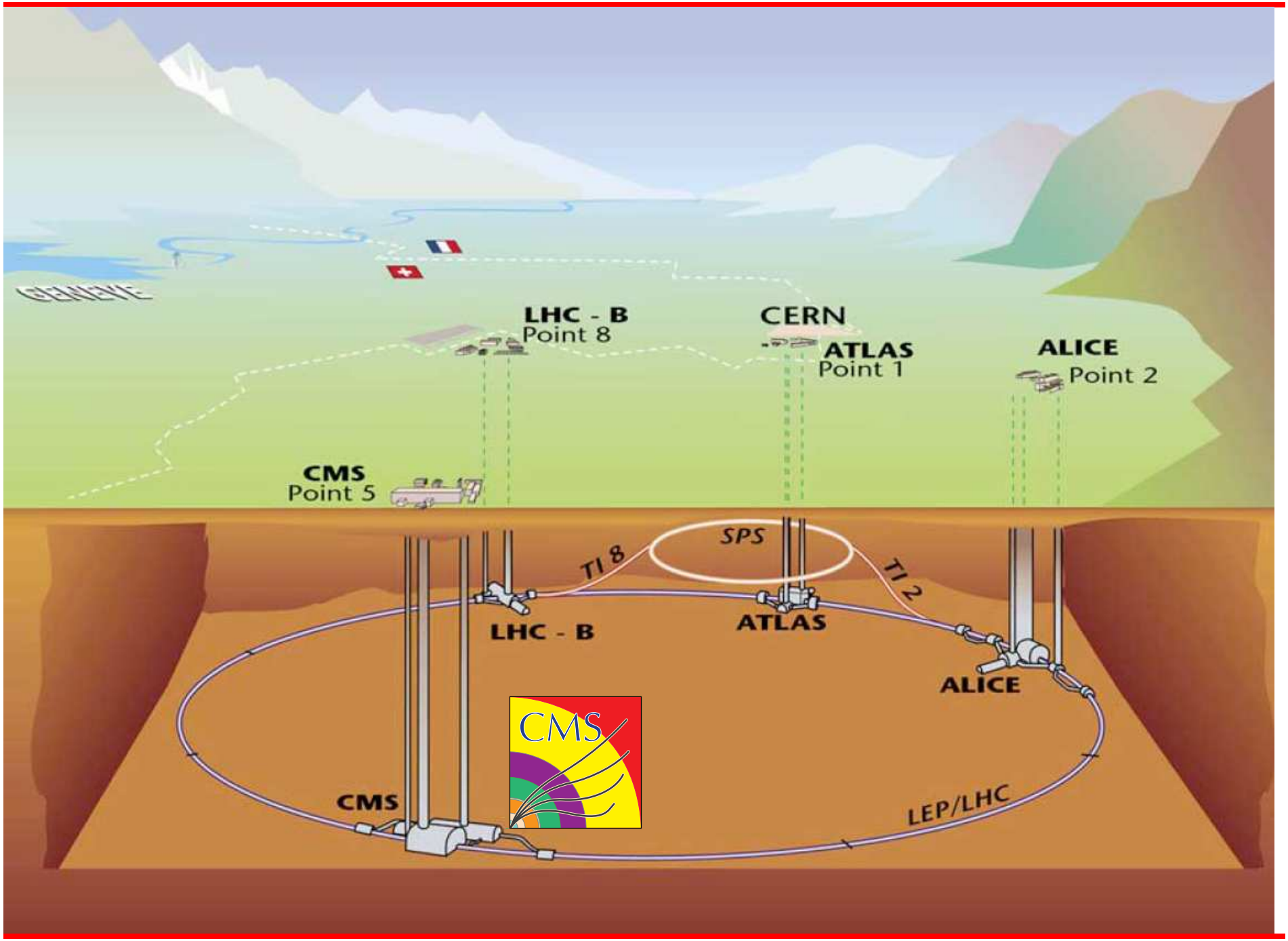
The Large Hadron Collider

The Large Hadron Collider

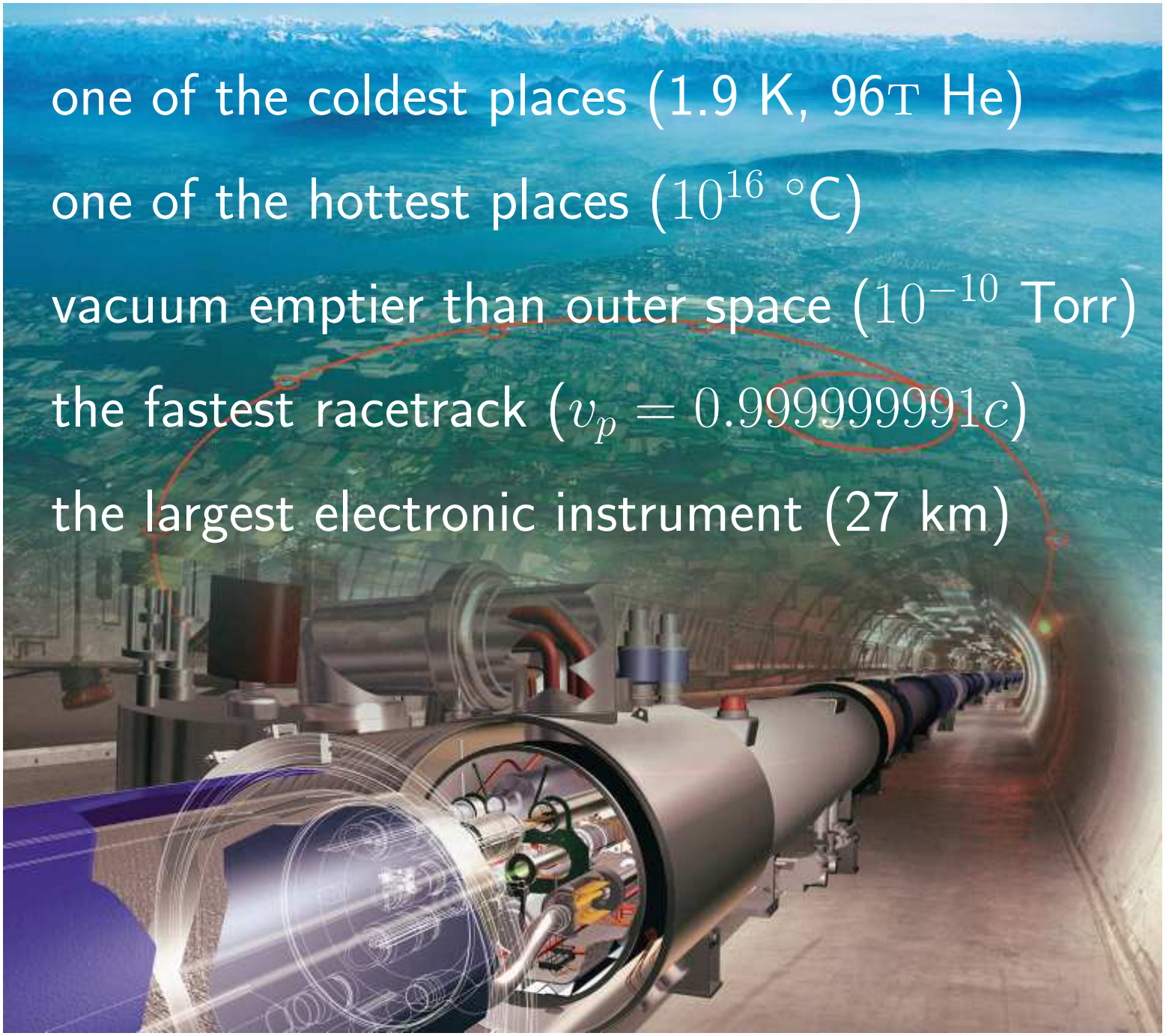
- Creating "bubbles" in the Large Hadron Collider: $E = mc^2$



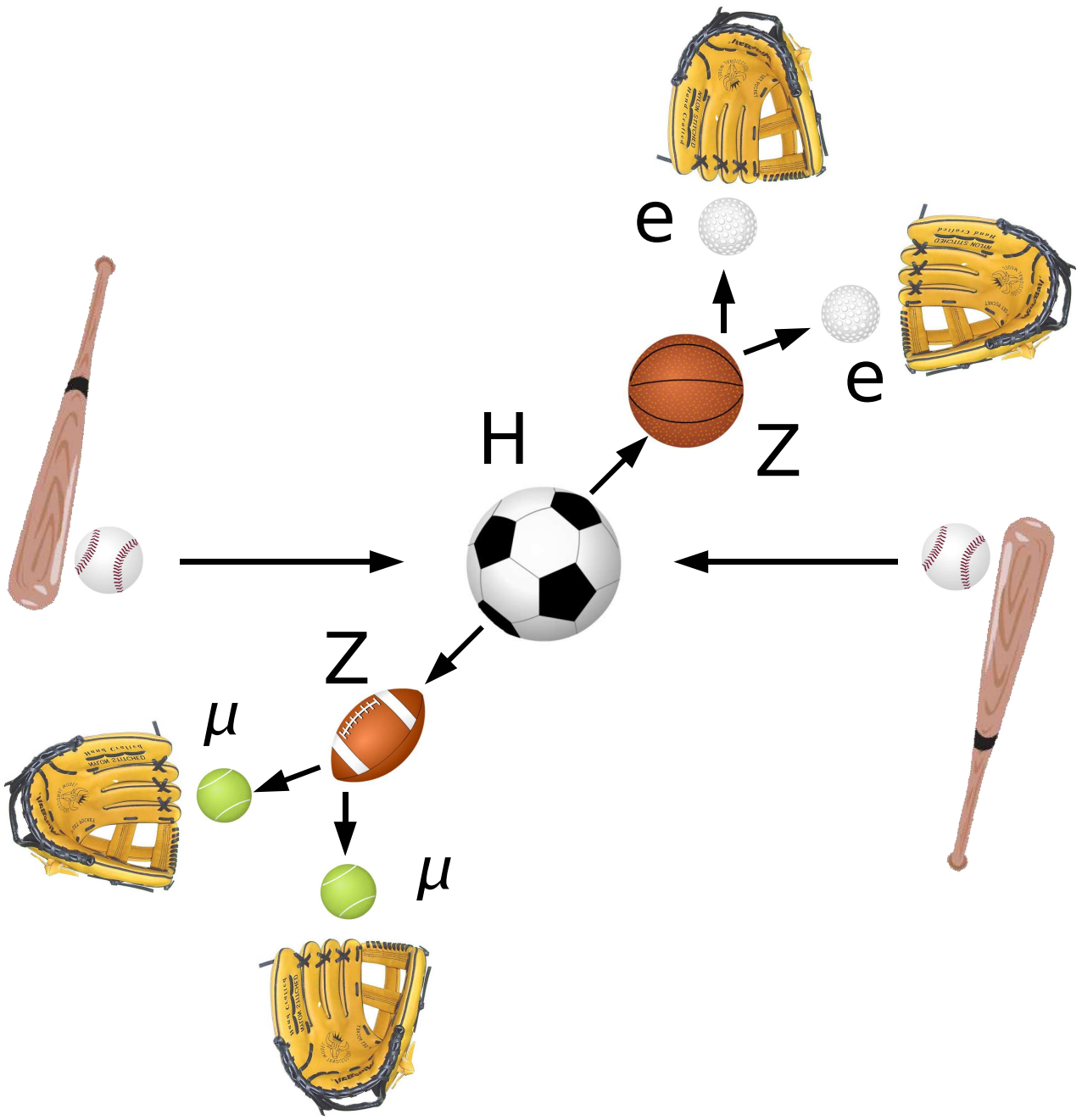
The Large Hadron Collider



The Large Hadron Collider



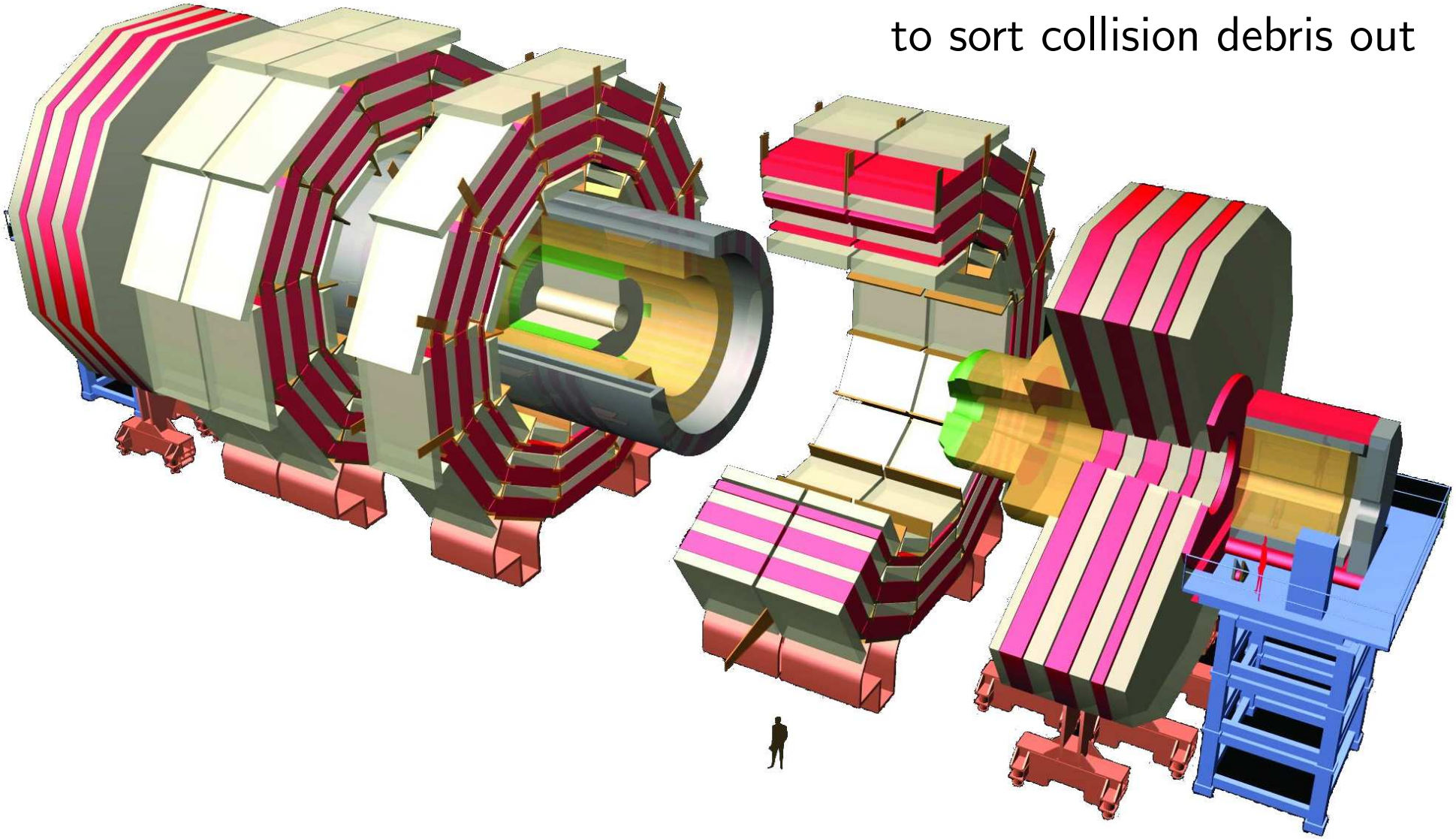
The Large Hadron Collider



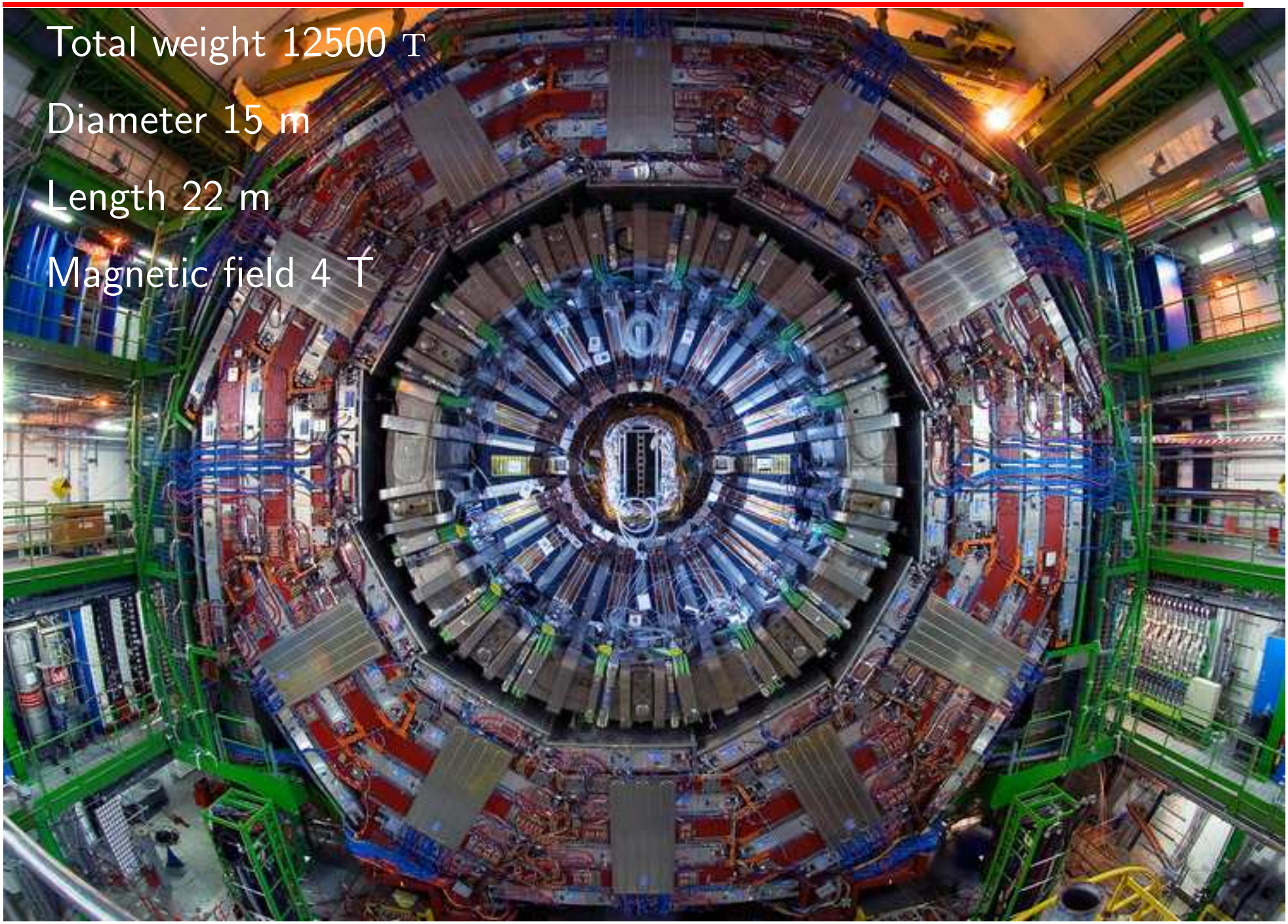
Example: the CMS Detector

- Complex detector

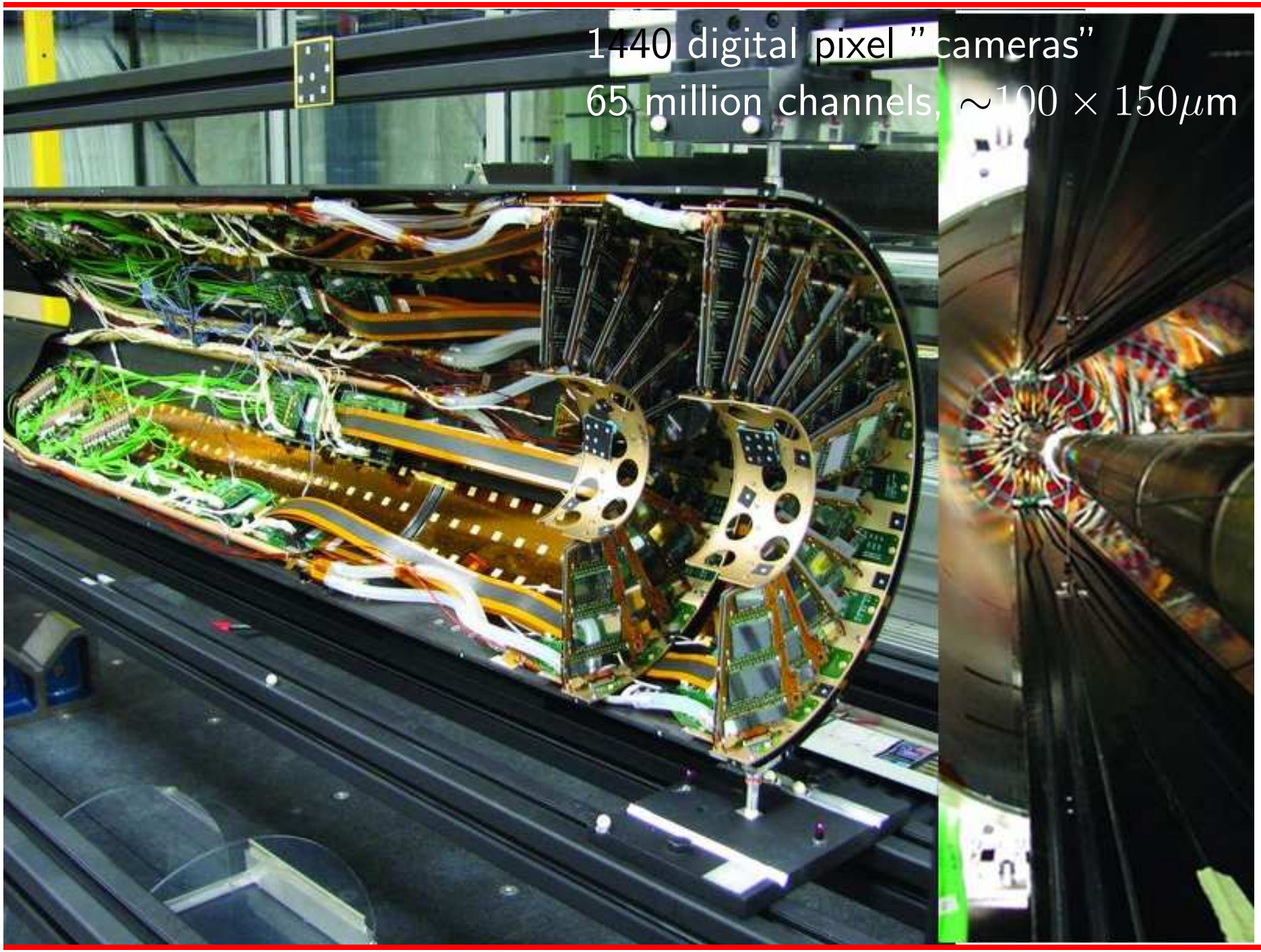
  to sort collision debris out



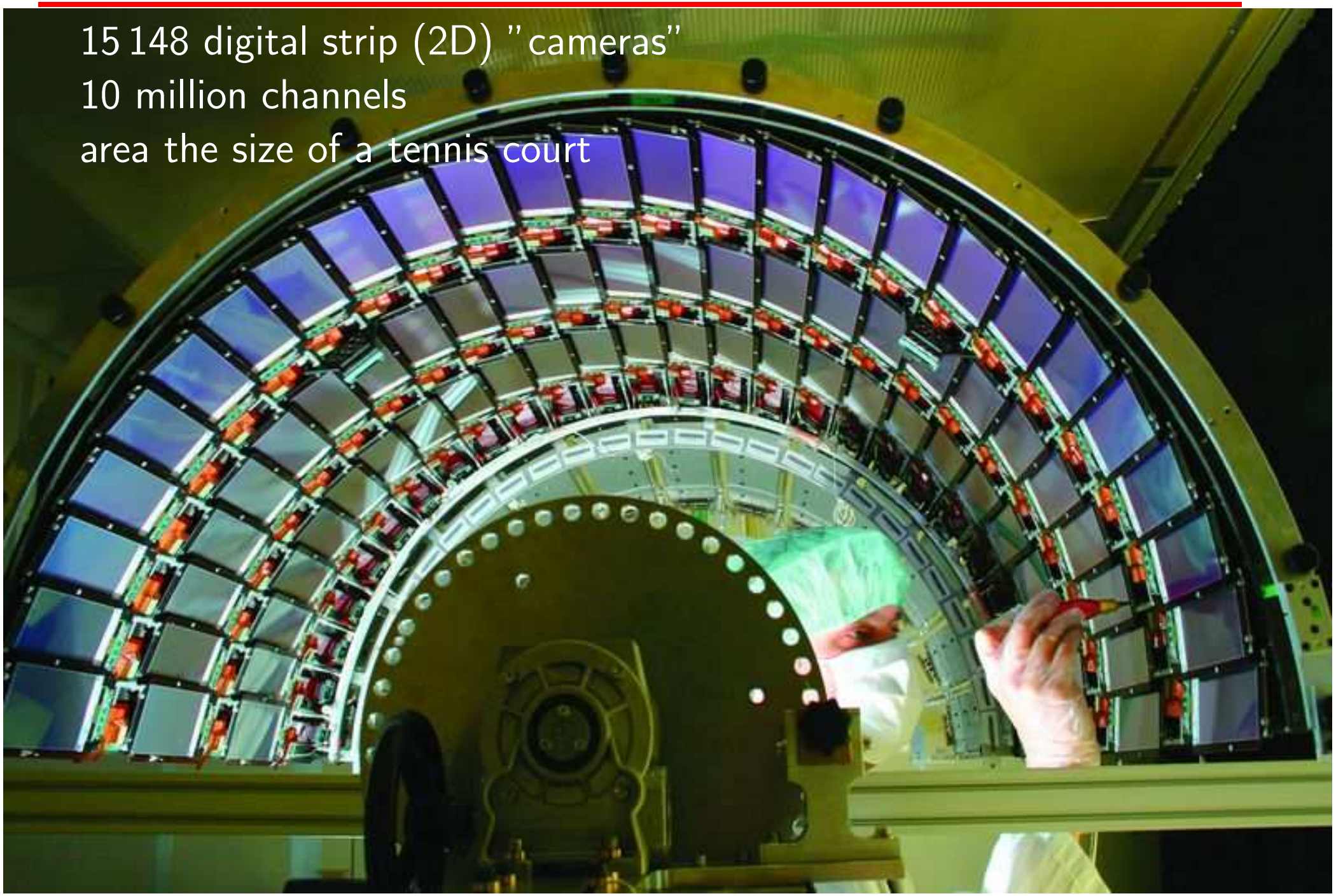
The CMS Detector



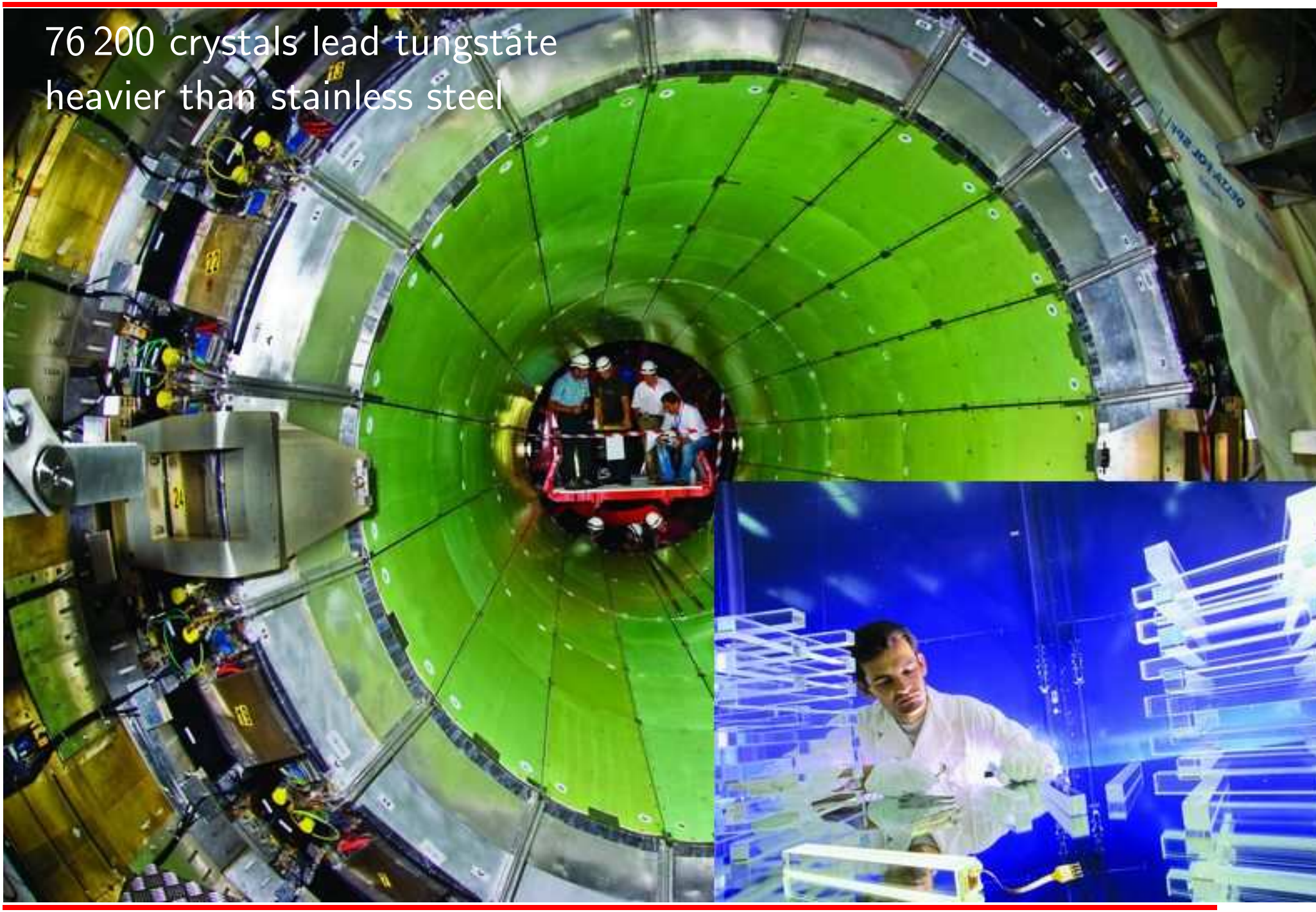
The Silicon Pixel Detector



The Silicon Strip Detector

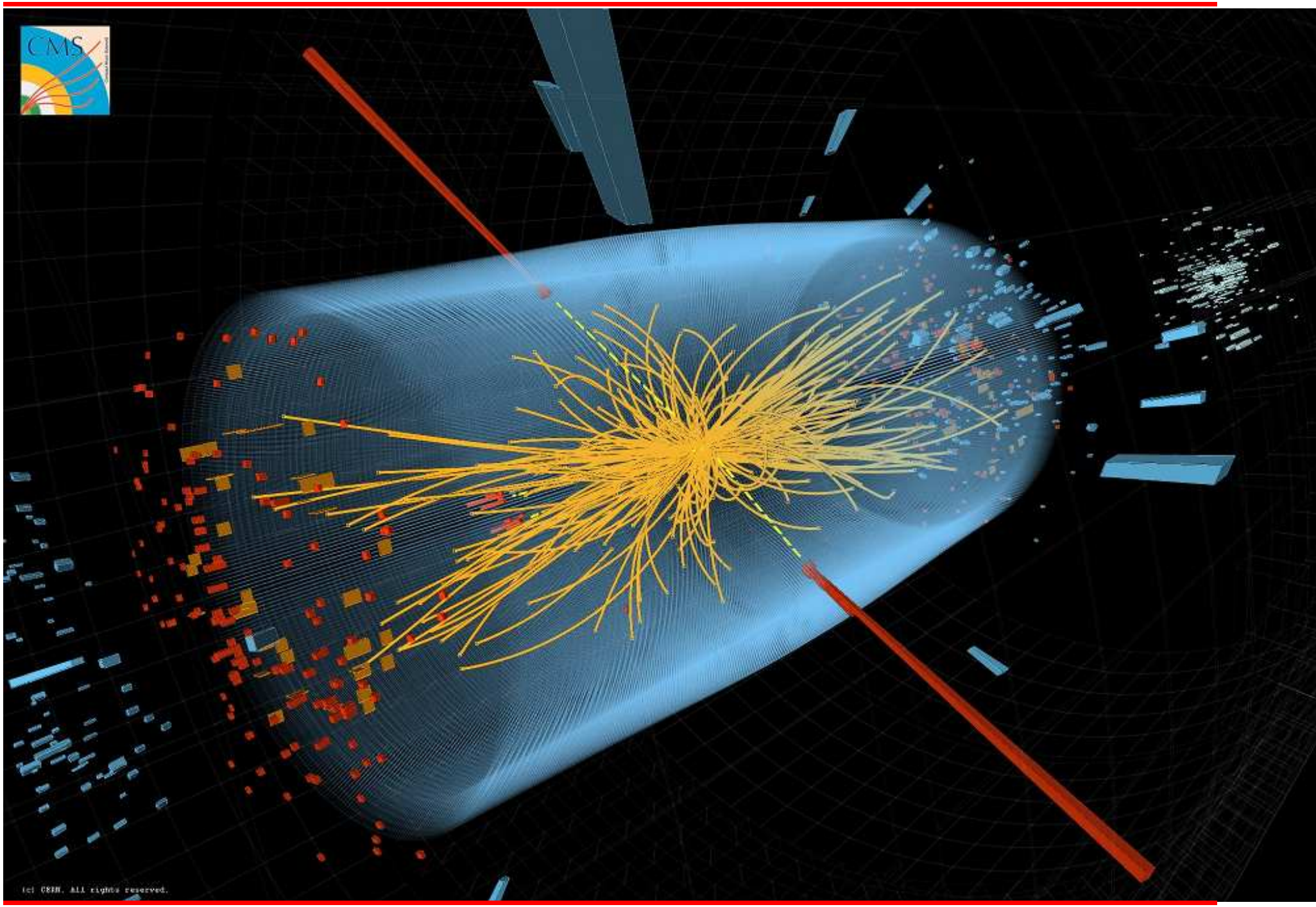


Electromagnetic Calorimeter



Hadronic Calorimeter and Muon System

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 >34 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):

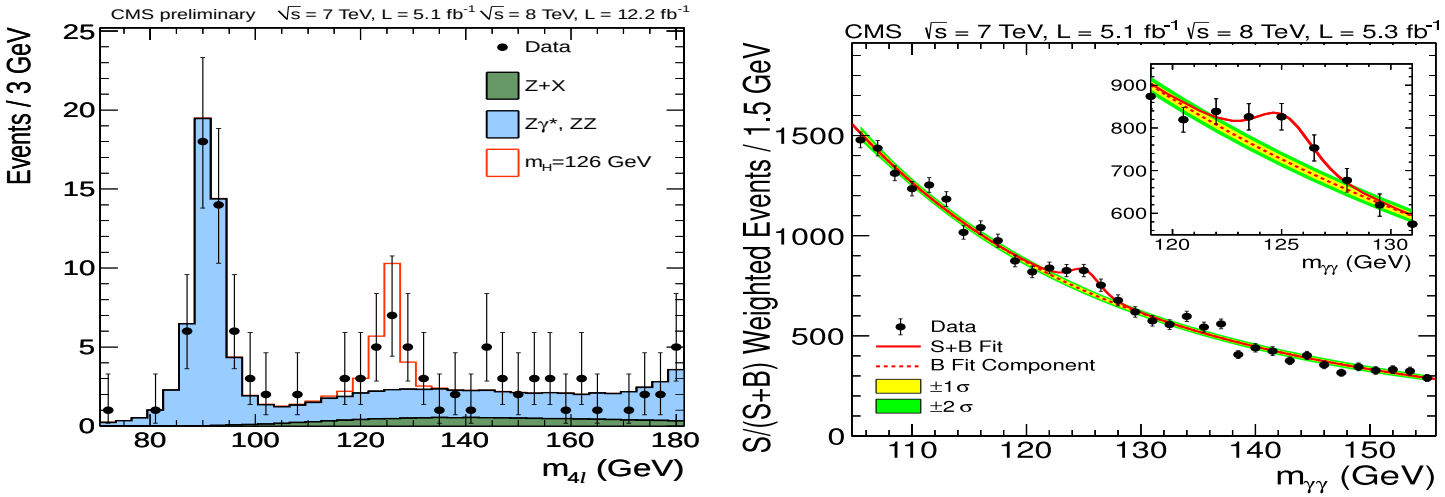
  > 300 trillion proton-proton collisions in 2011

  > 3 billion "events" recorded on disk in 2011

Discovery of a Higgs-like Boson

- Major Discovery of the decade(s), CMS example here:

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



  - it is a boson, spin$\neq$1 $\Rightarrow$ spin $= 0$ or 2... nothing like this before (!) even if composite, not from known objects (!)
  - quantum numbers: $J^P = 0^-$ excluded ($> 95\%$ CL),..
  - couples to fermions (matter) and bosons similar to SM Higgs boson

- Need to go deeper and broader to answer
  - if it is the Higgs boson, associated with the Higgs field
  - if it is a tip of an Iceberg of new states of matter / energy

LHC – The Big Bang Machine

- LHC program:

– test of the Higgs field

– may connect to dark energy

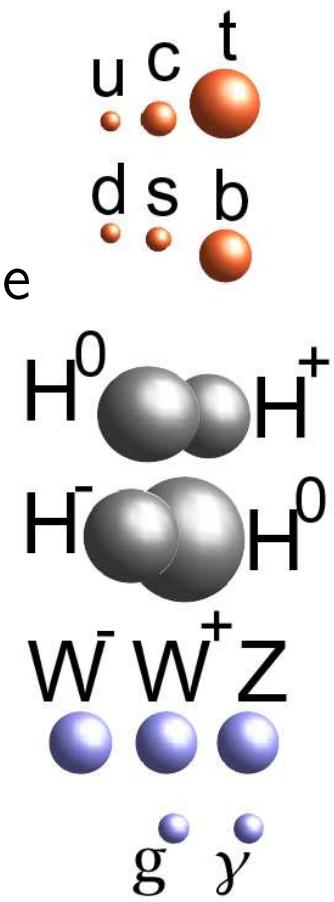
– may explain antimatter puzzle

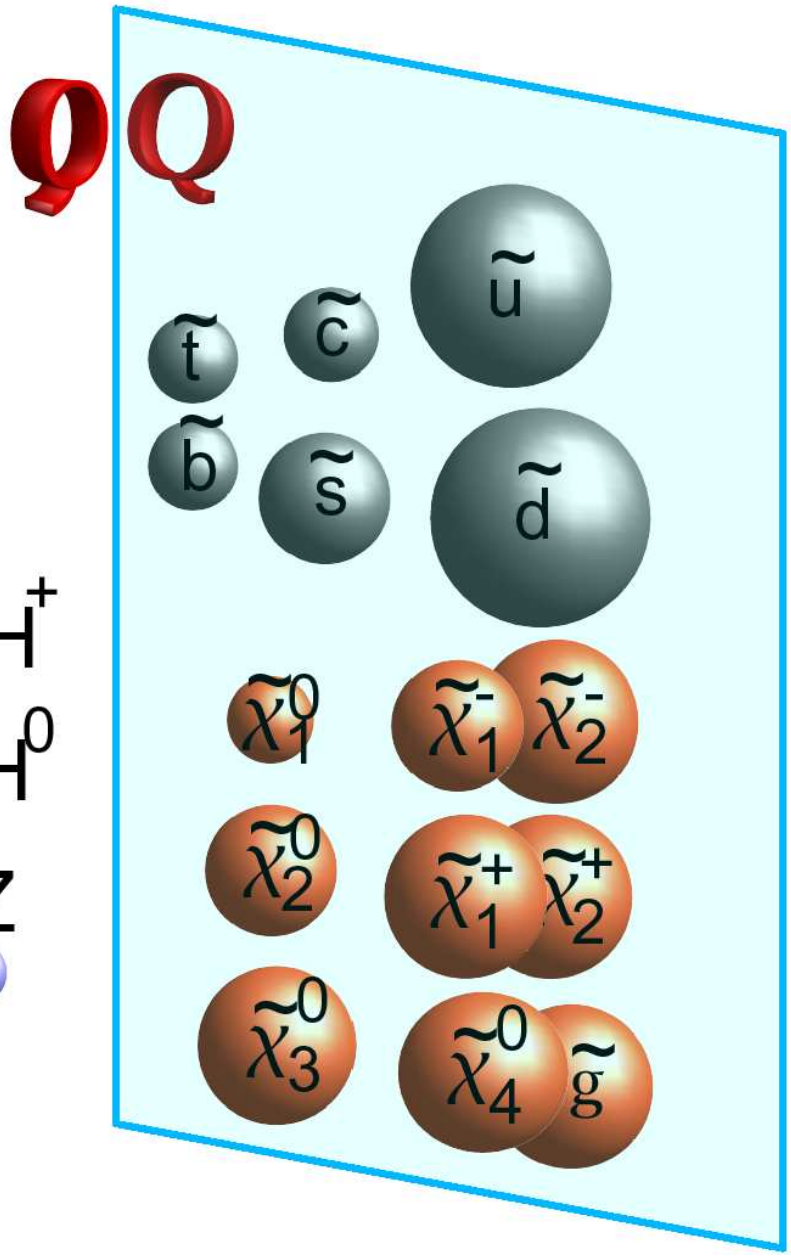
– may produce dark matter

– re-create quark-gluon plasma

– extra dimensions of space ?

– prepare for unexpected ...





The Big Bang Theory: Puzzles of the Universe

- Dark energy (∼70%)
  - leads to accelerated expansion of the Universe (what is it?)
- Dark matter (∼25%)
  - behaves differently from ordinary matter (what is it?)
- Ordinary matter (∼5%)
  - from Hydrogen to Uranium – our natural resources
- Antimatter (∼0%)
  - disappeared after the Big Bang (why?)
- Higgs field or something alike
  - origin of mass (how?)