

Science of the Nuclear Energy (and not the technology)

Andrei Gritsan

Johns Hopkins University



29 July 2013

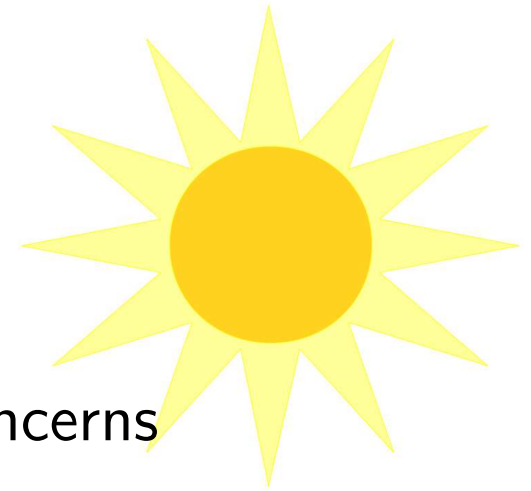
JHU QuarkNet meeting

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

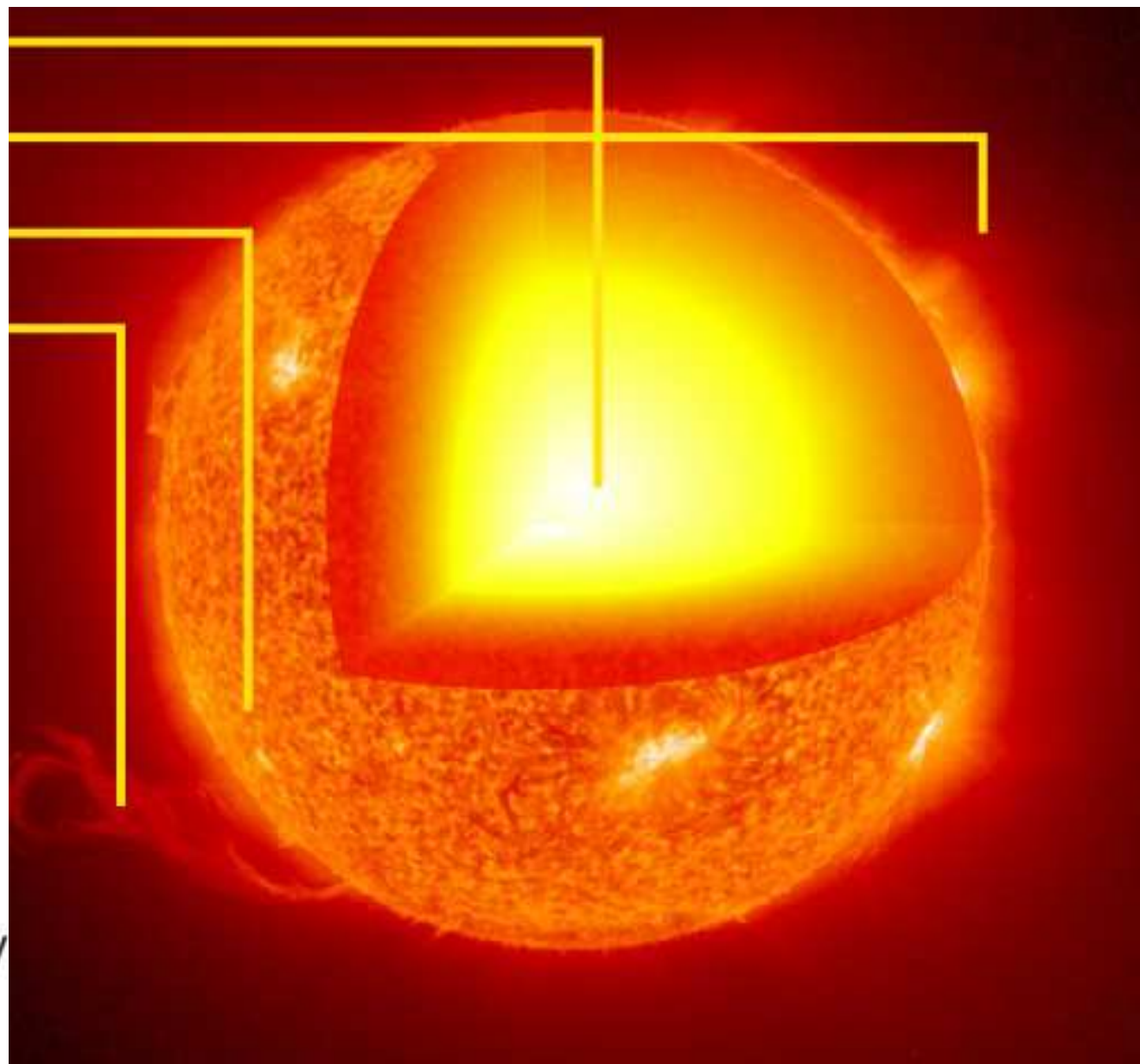
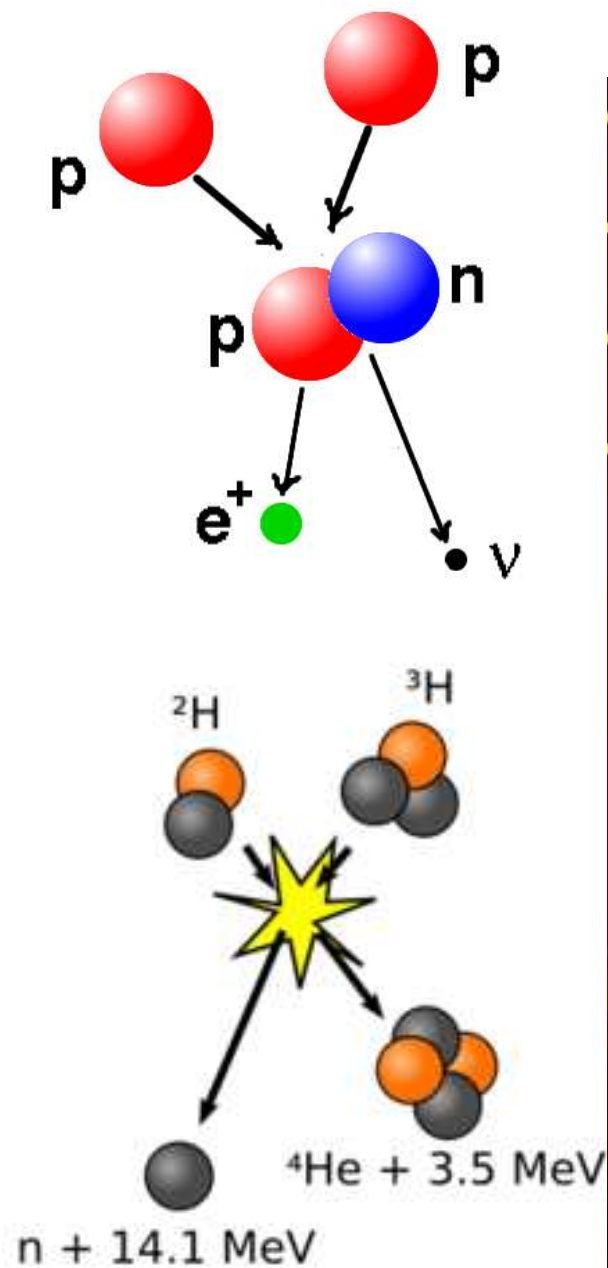
effectively convert and store collected energy

examples: photosynthesis by green plants;

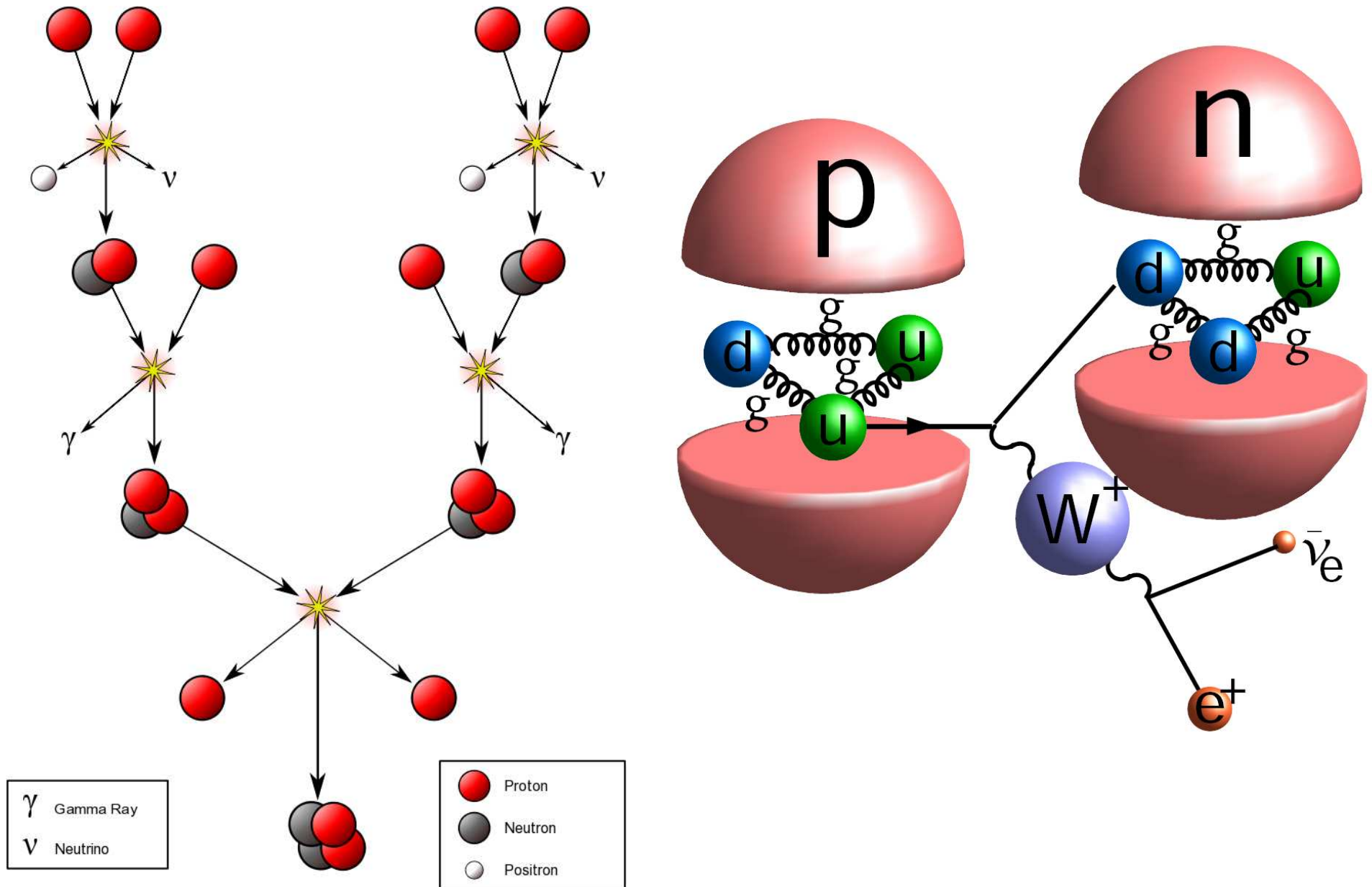
solar power panels

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

$$mc^2 = E$$

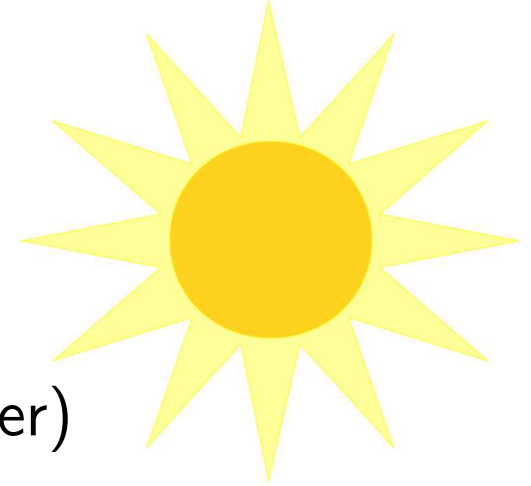
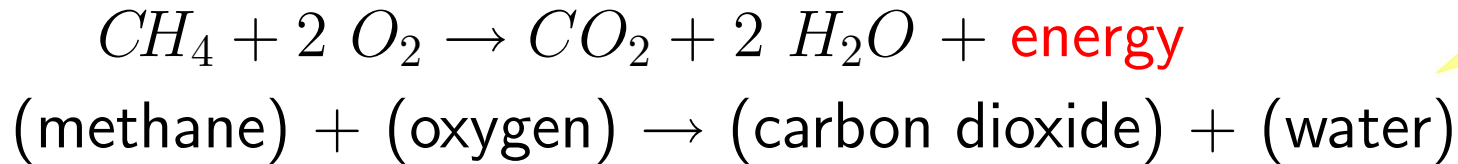
Nuclear Energy: $E = mc^2$



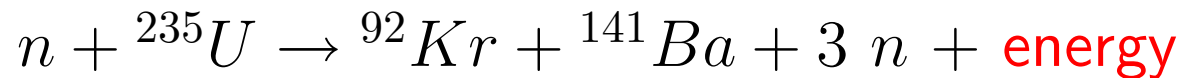
Energy Source: Fuel

- combustion

burn fuel (carbon)



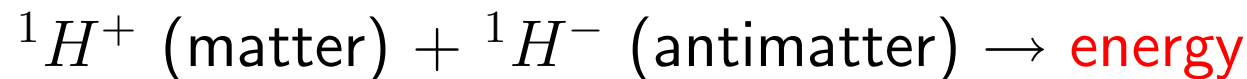
- nuclear fission



- nuclear fusion



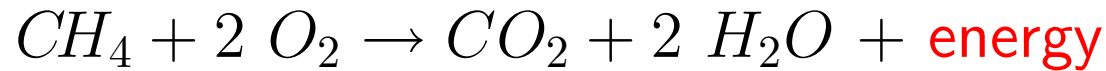
- antimatter annihilation



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

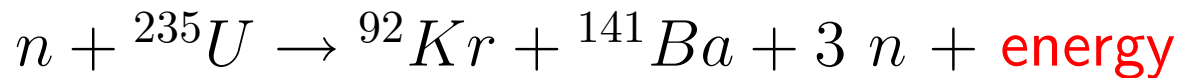
Energy Source: Fuel "Efficiency"

- combustion



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

- nuclear fission



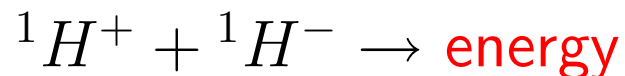
energy = 0.8 MeV / a.unit

- nuclear fusion

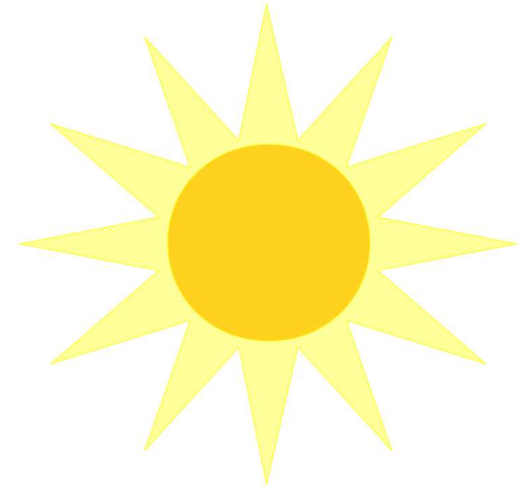


energy = 3.5 MeV / a.unit

- annihilation

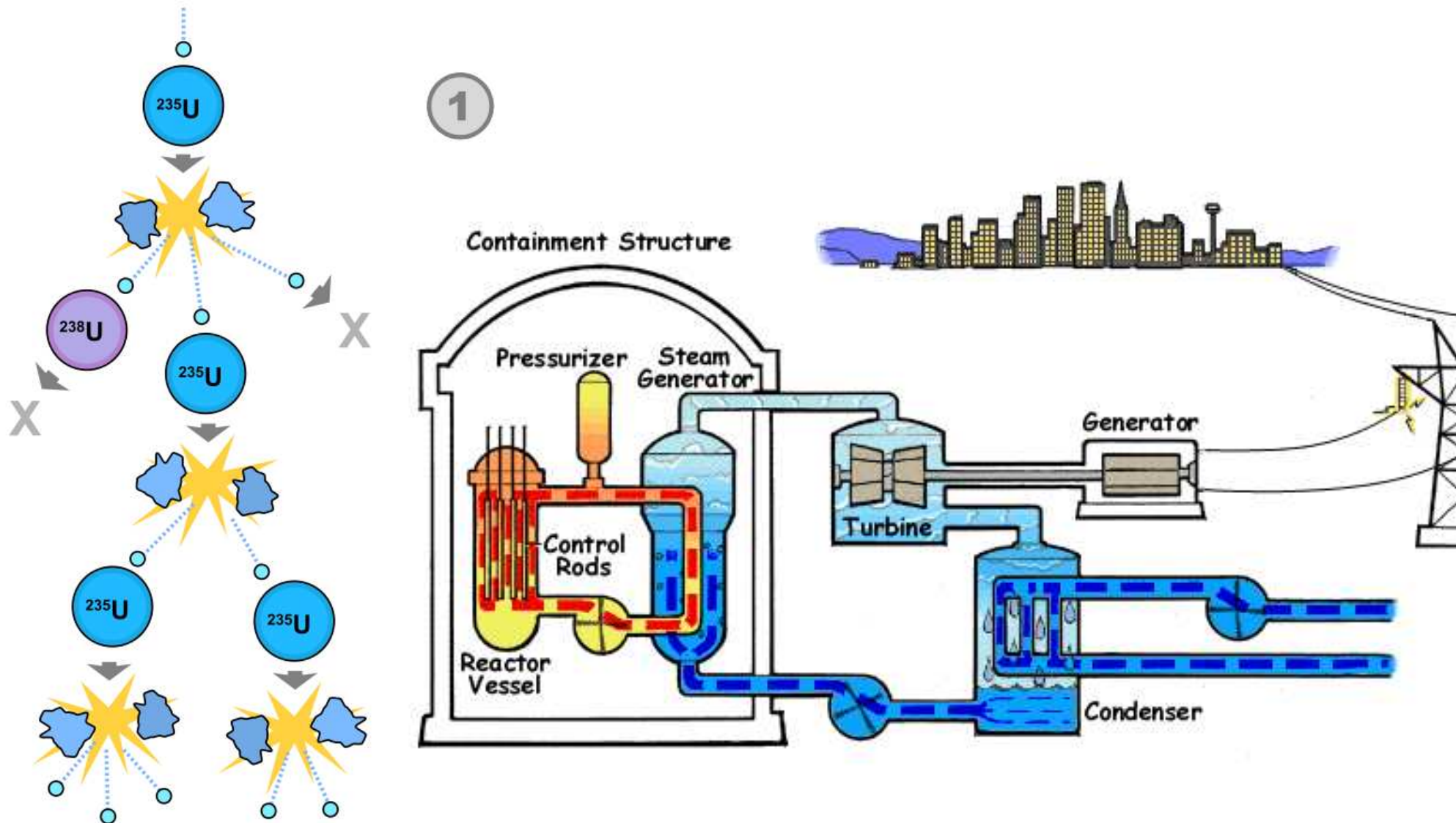


energy = 938 MeV / a.unit



Nuclear Energy: Present

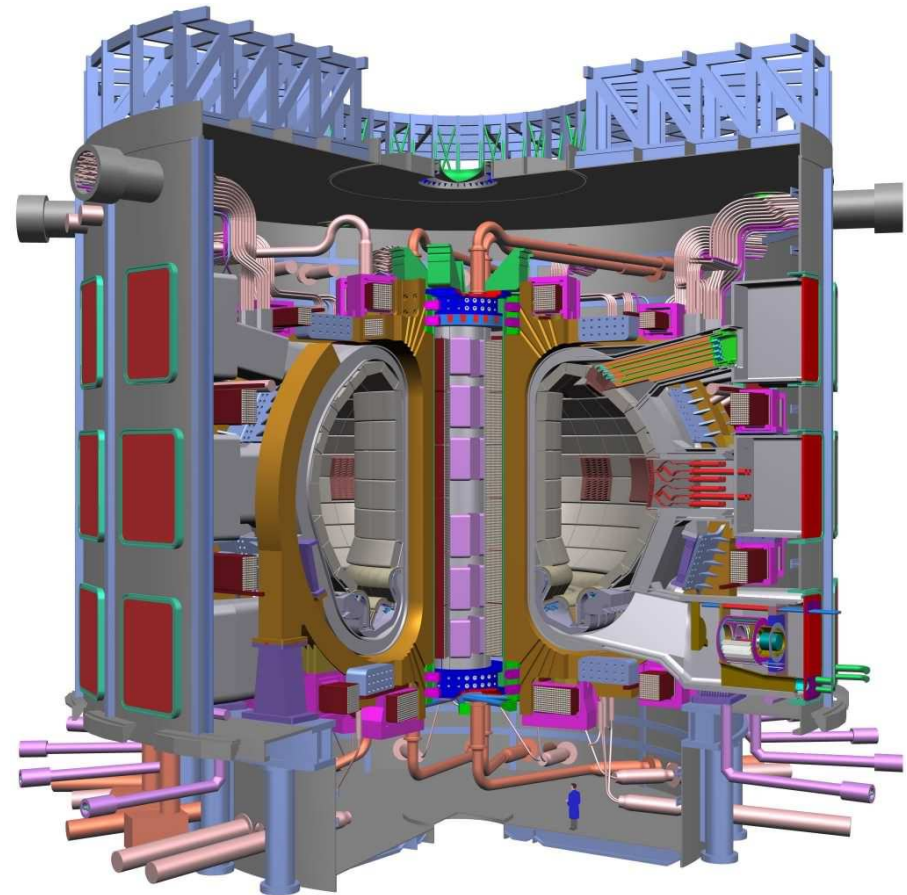
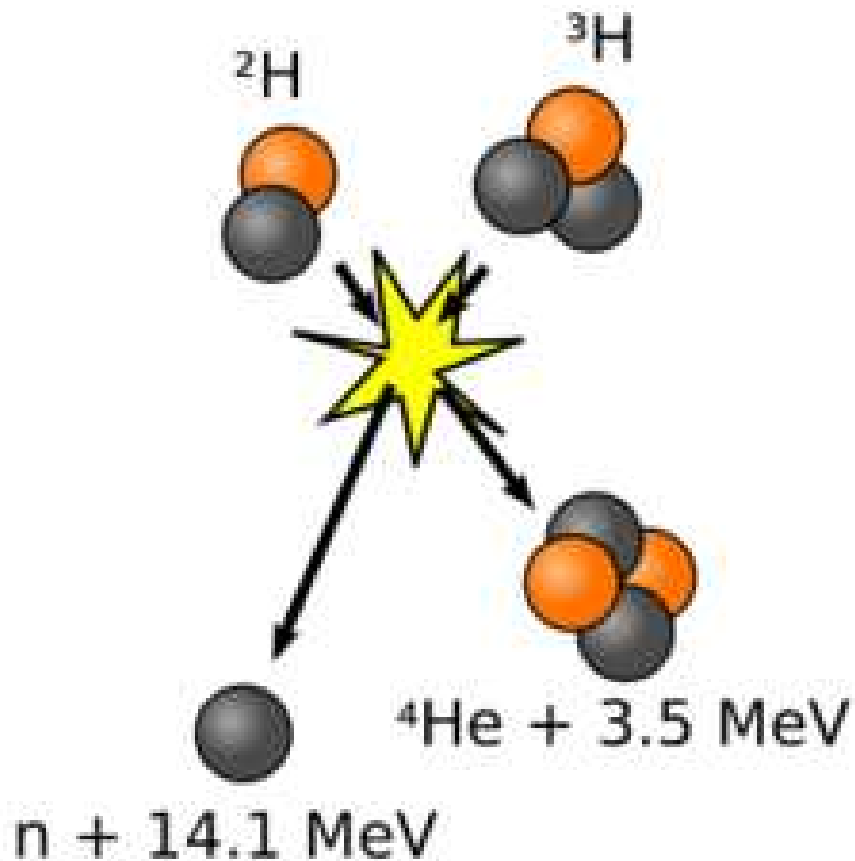
- Nuclear fission reactor



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

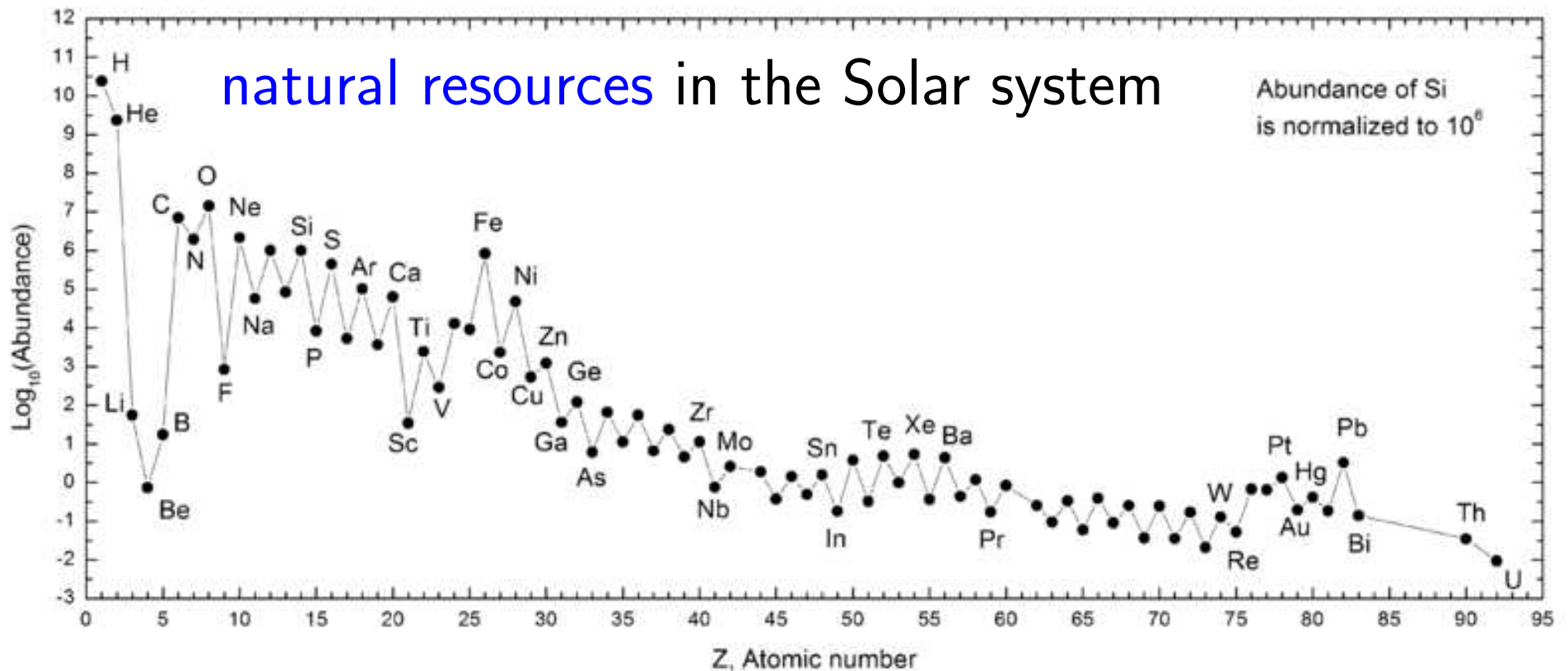


Sub-Nuclear Energy: Antimatter (?)

- 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...

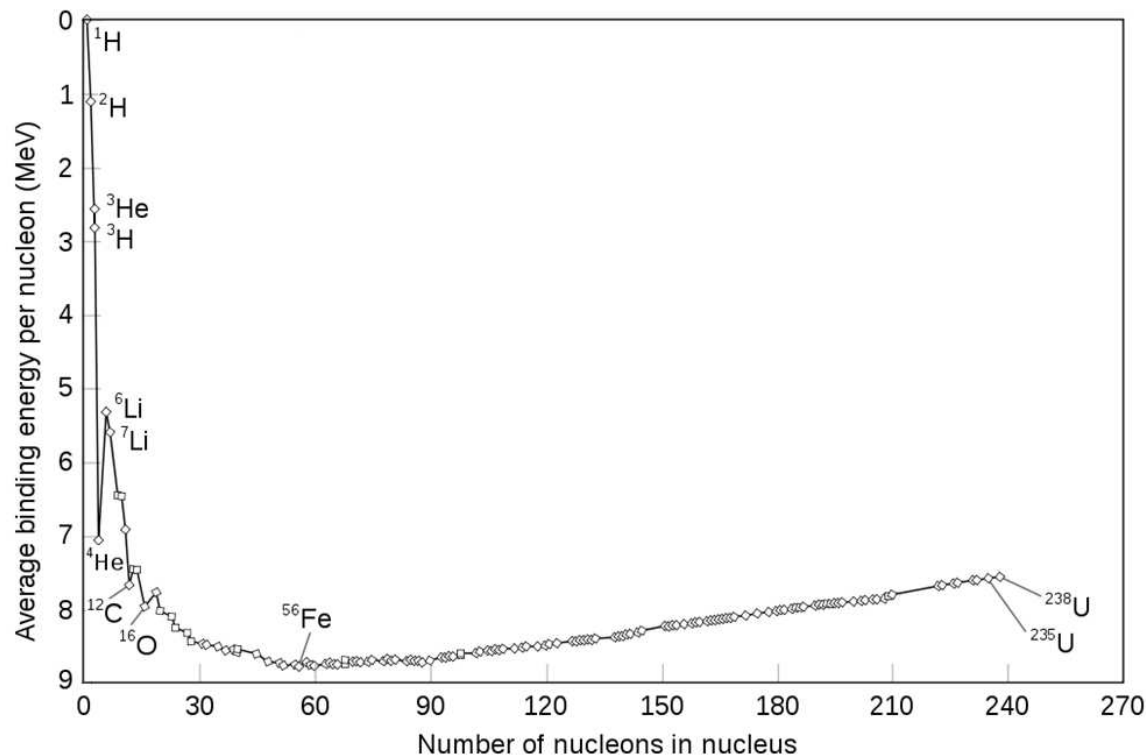
Natural Resources in the Solar System

- **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



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



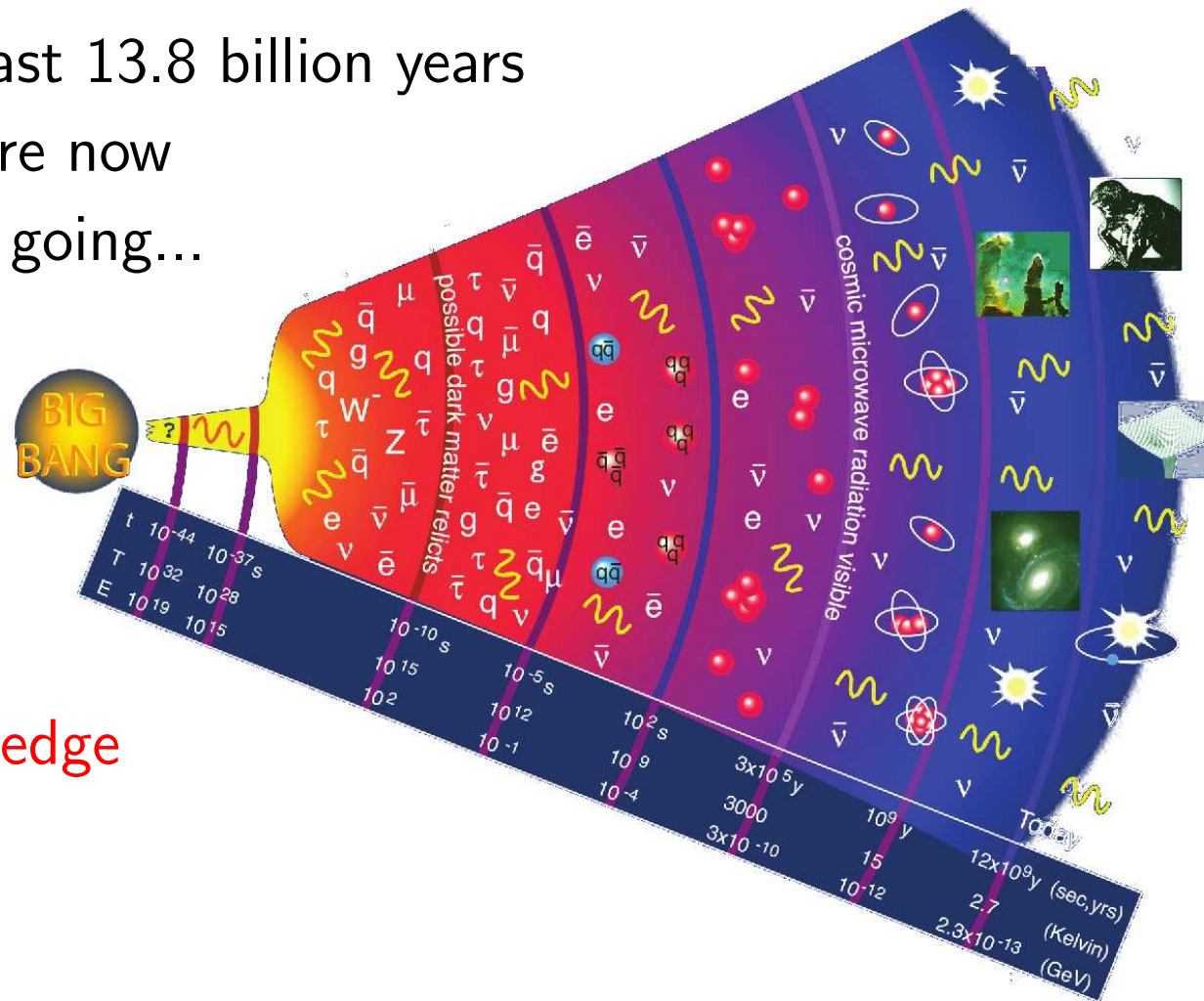
Nuclear Energy: Conclusion

- 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

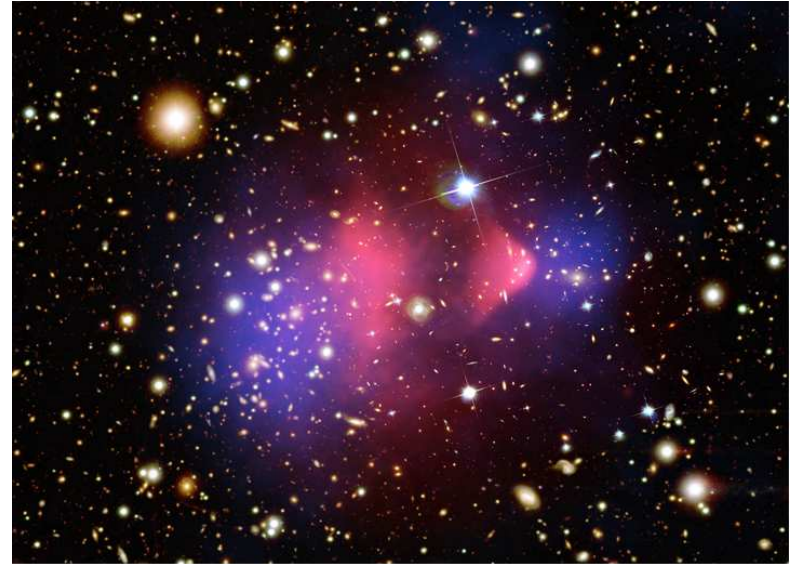
Discovery of a Higgs Boson

- 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**



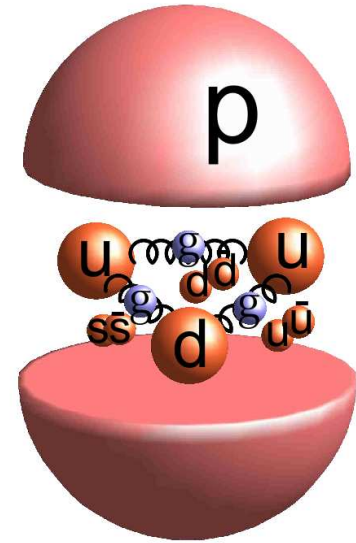
The dark questions: What we do not see

- 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?



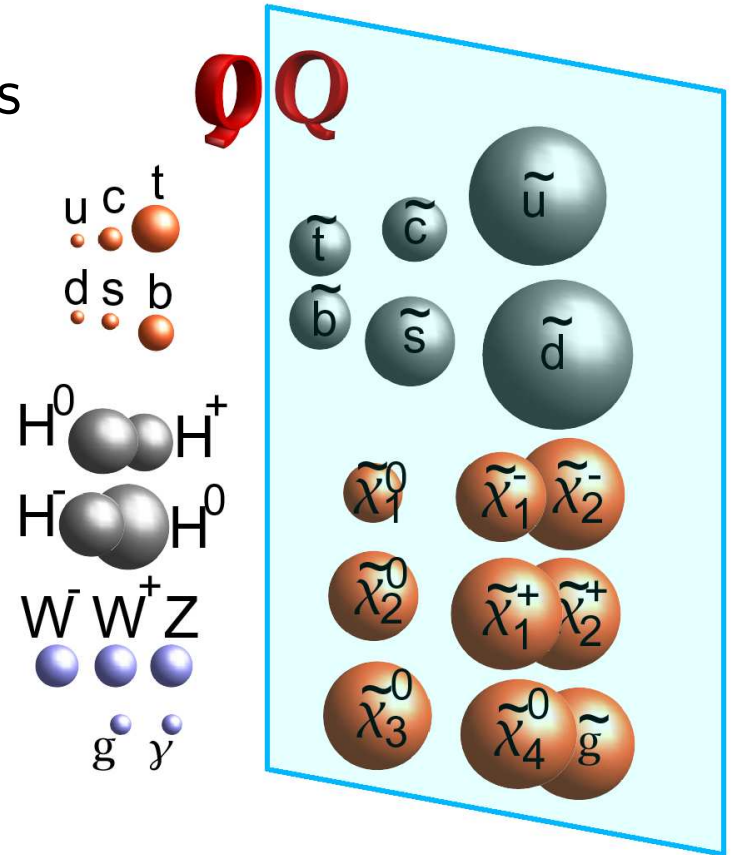
The light questions: What we do see

- 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 $<1 \text{ eV}$ to $>10^{11} \text{ eV}$
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?



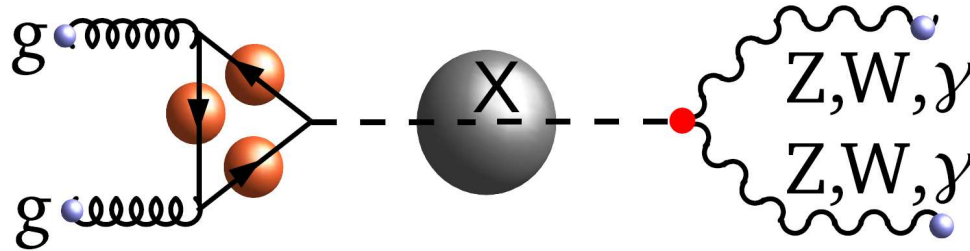
Looking for answers

- 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...**

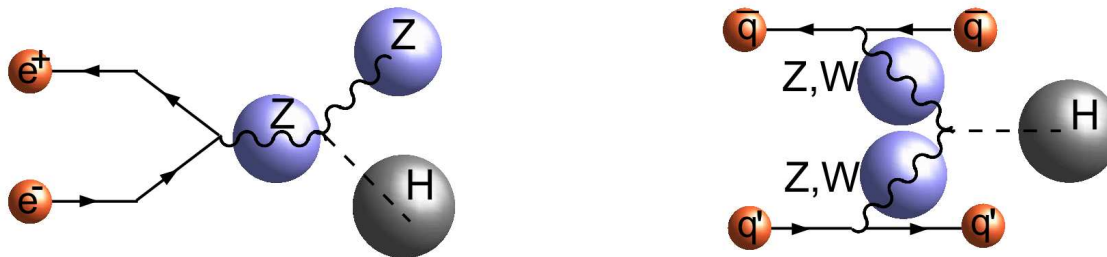


Two paths to reach

- We have seen this



- We are now guaranteed to have these



- Two paths to proceed

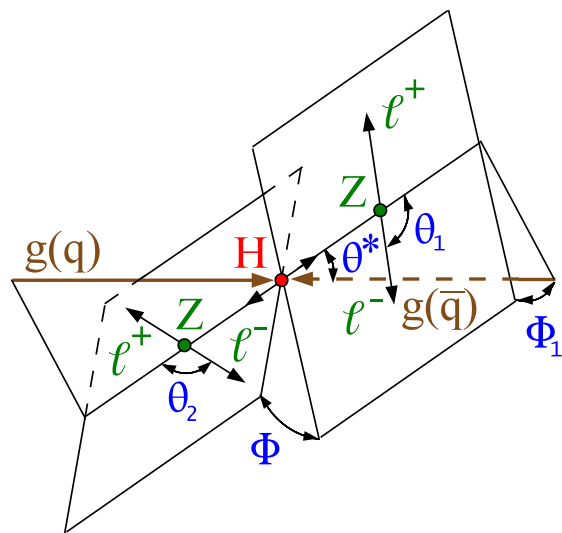
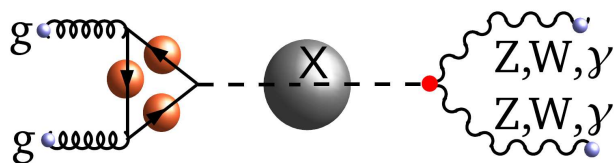
- (1) precision measurements of **new state** of matter-energy (**H**)
- (2) reaching higher in mass+sensitivity for **other states** (**X**)

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

We have the knowledge and technology

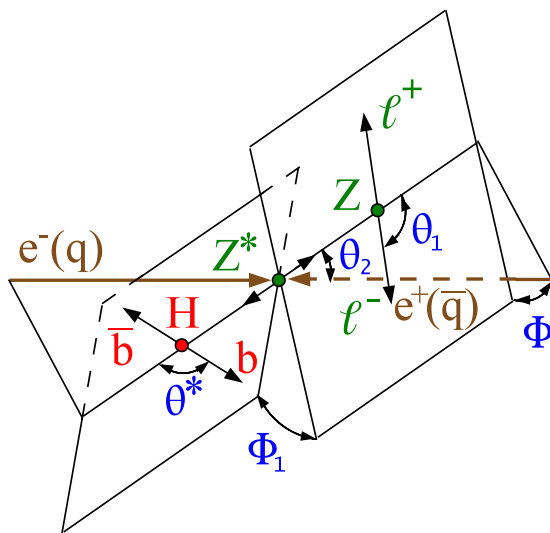
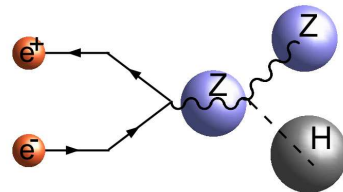
- LHC pp

$$gg \rightarrow H$$



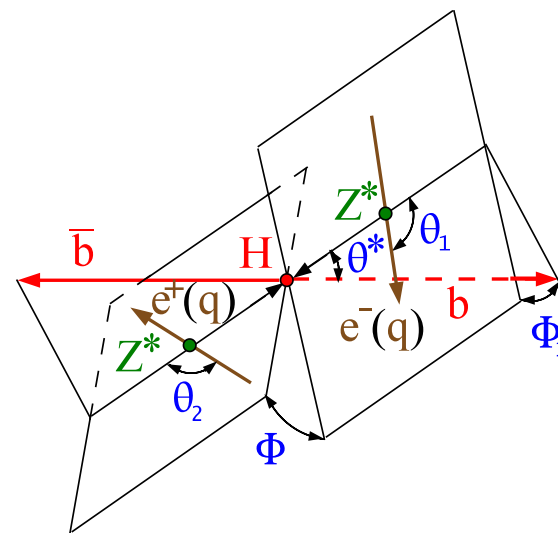
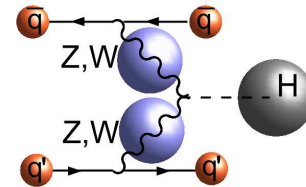
- H-factory ~ 250 GeV

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



- ILC ~ 1 TeV

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



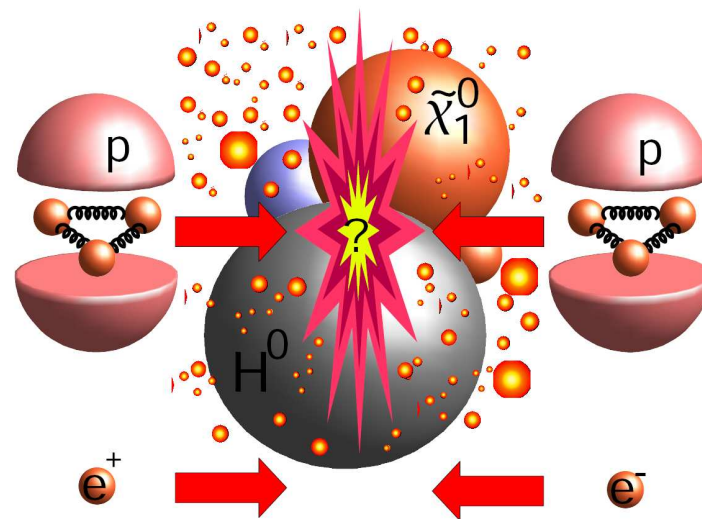
- With complementary approaches

- 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 $pp \sim 100$ 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

 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: Axel Zambach, Copyright © Nobel Media AB

Saul Perlmutter




Photo: Belinda Pratten, Australian National University

Brian P. Schmidt




Photo: Hornwood 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"*.

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

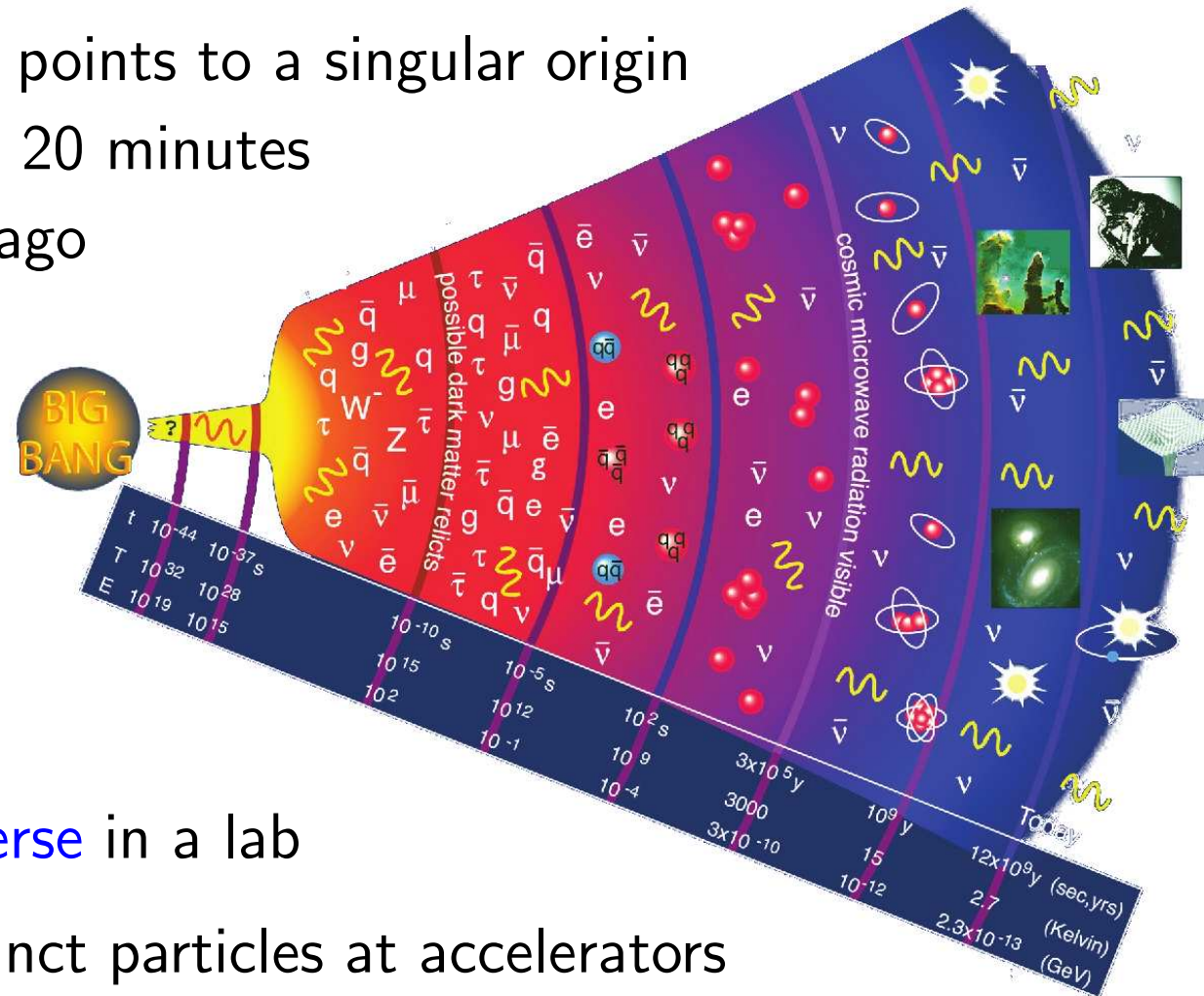
- like a bank account balance:
when you take all your money out
there is a **minimum balance** left

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



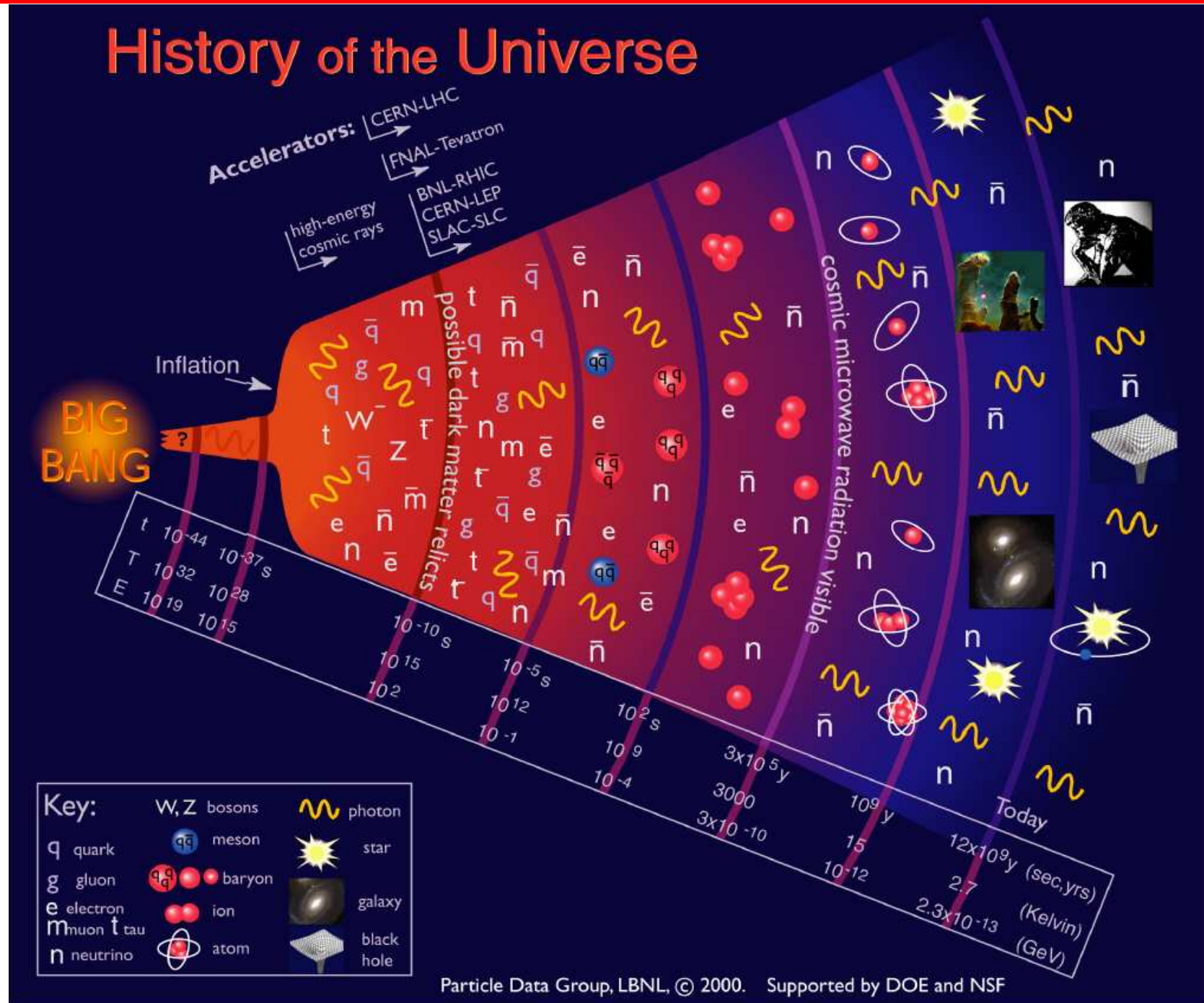
Start from the Beginning: The Big Bang

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



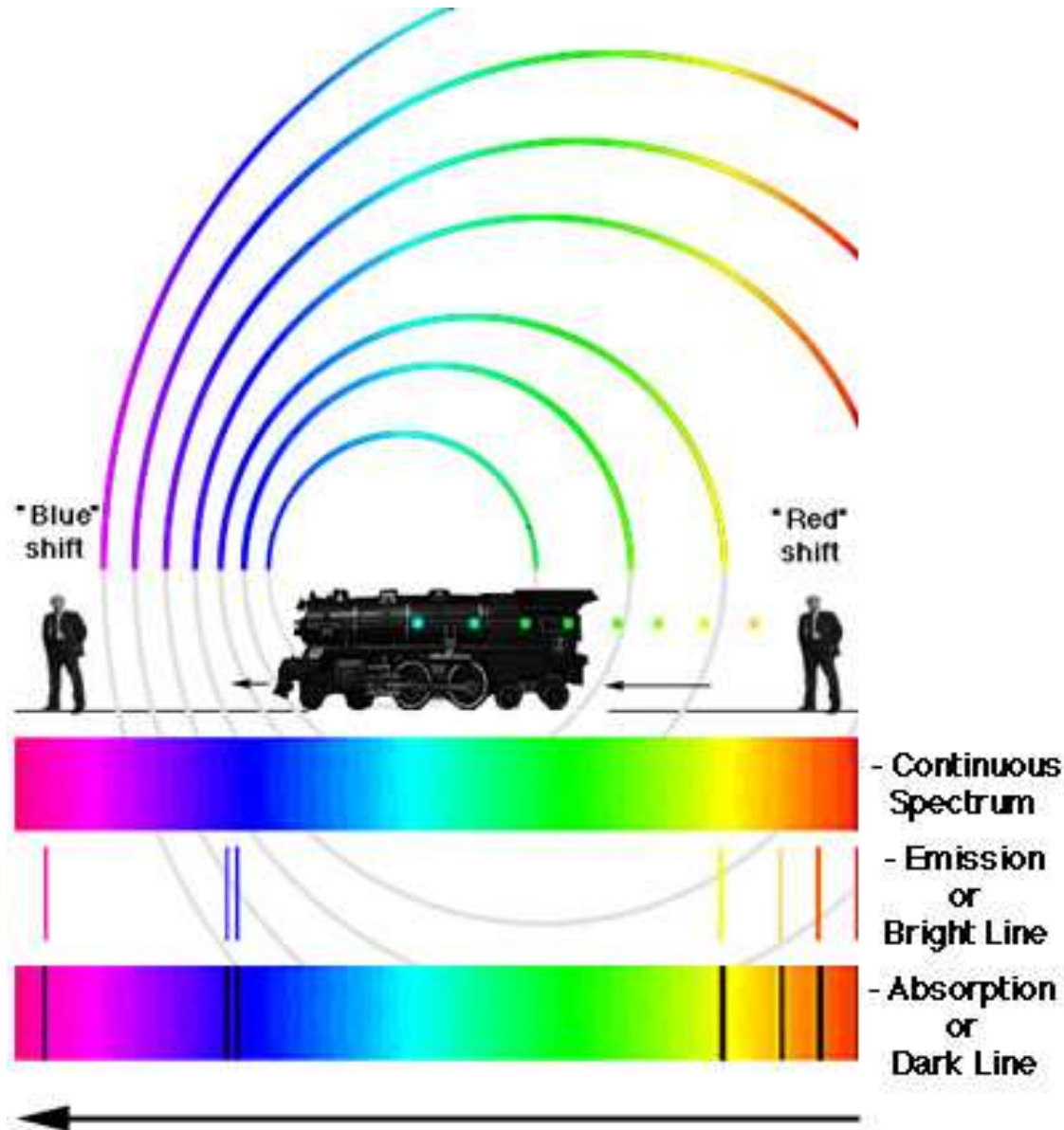
- Recreate early **Universe** in a lab
 - re-create now extinct particles at accelerators
 - re-create conditions and understand laws

The Big Bang



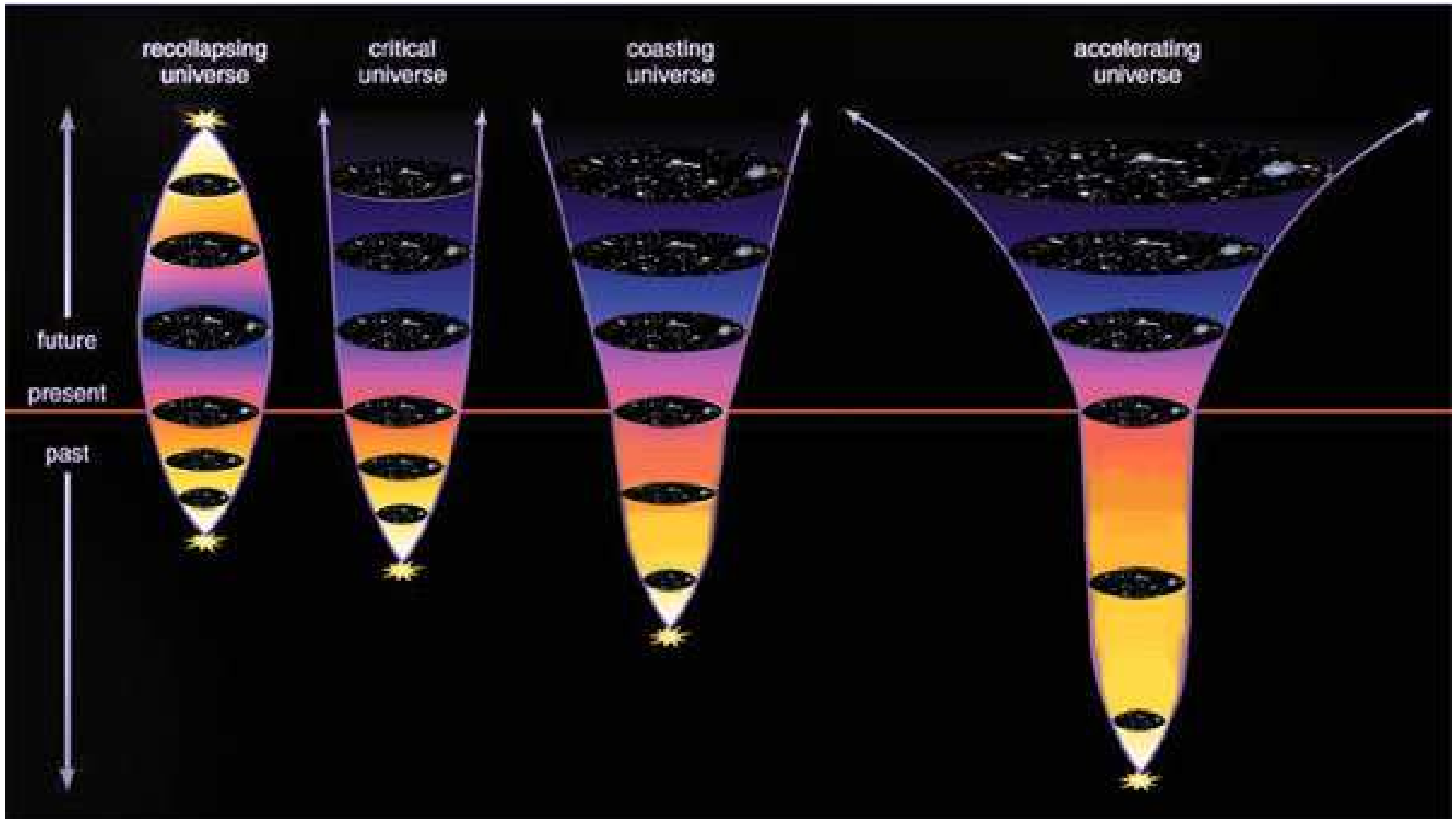
Expanding Universe

- Observe stars as trains moving AWAY from us



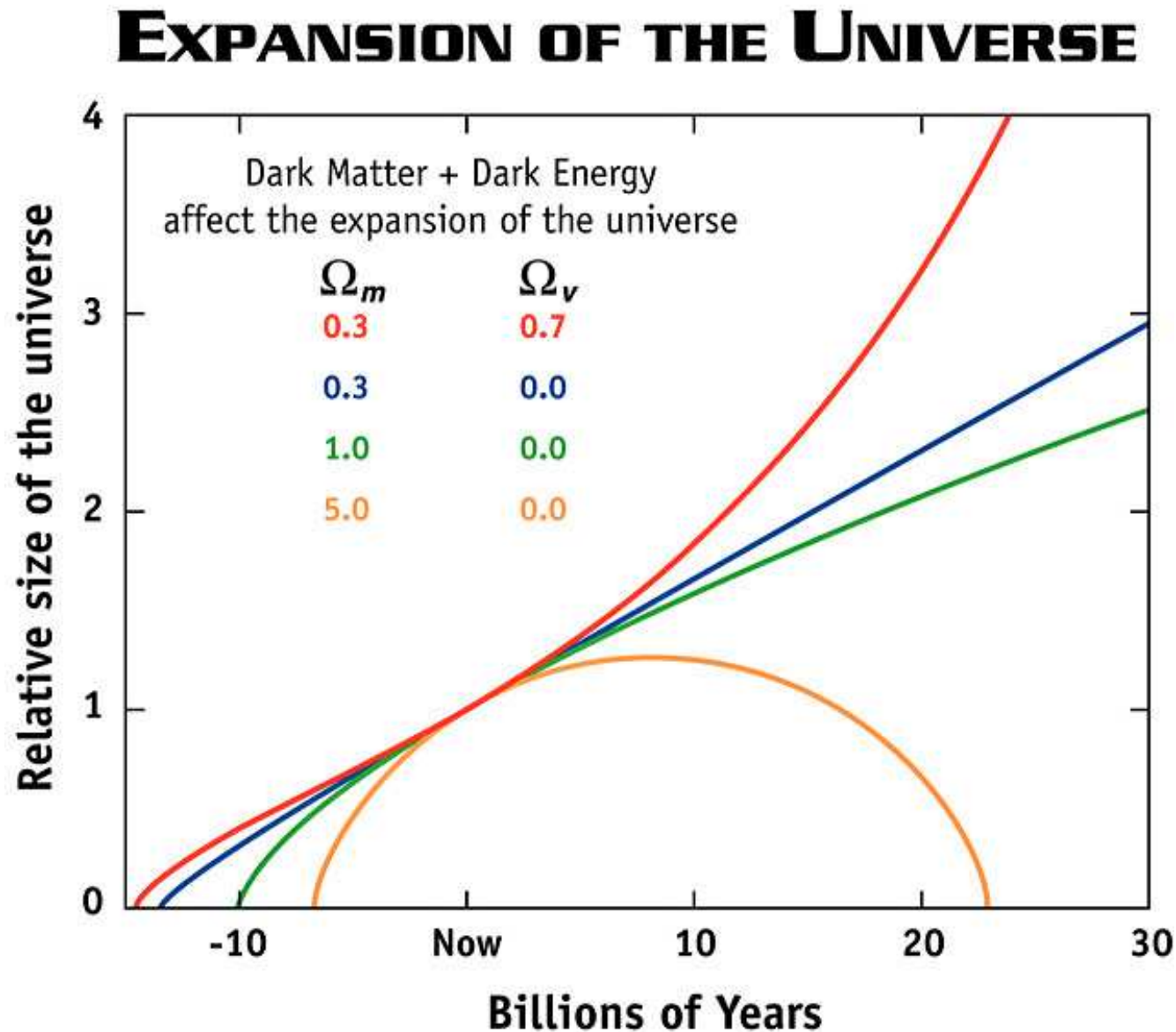
Will Universe Expand Forever?

- 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

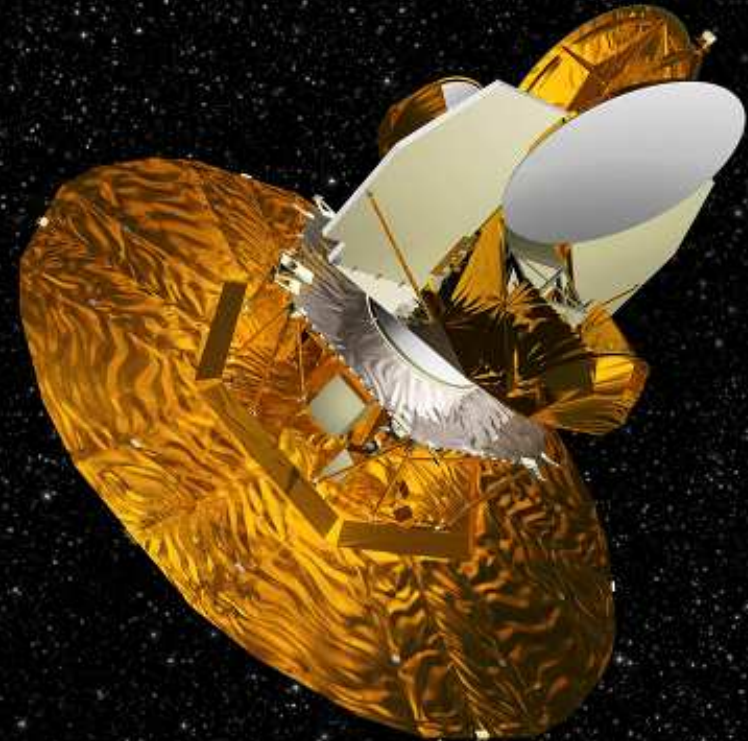


Example: WMAP Explorer Mission

Wilkinson Microwave Anisotropy Probe

launched by NASA in 2001

Headed by Prof. C. Bennett, JHU



Example: Hubble Space Telescope

launched by NASA in 1990

operated by Space Telescope Science Institute

replace by James Webb Space Telescope in 2018

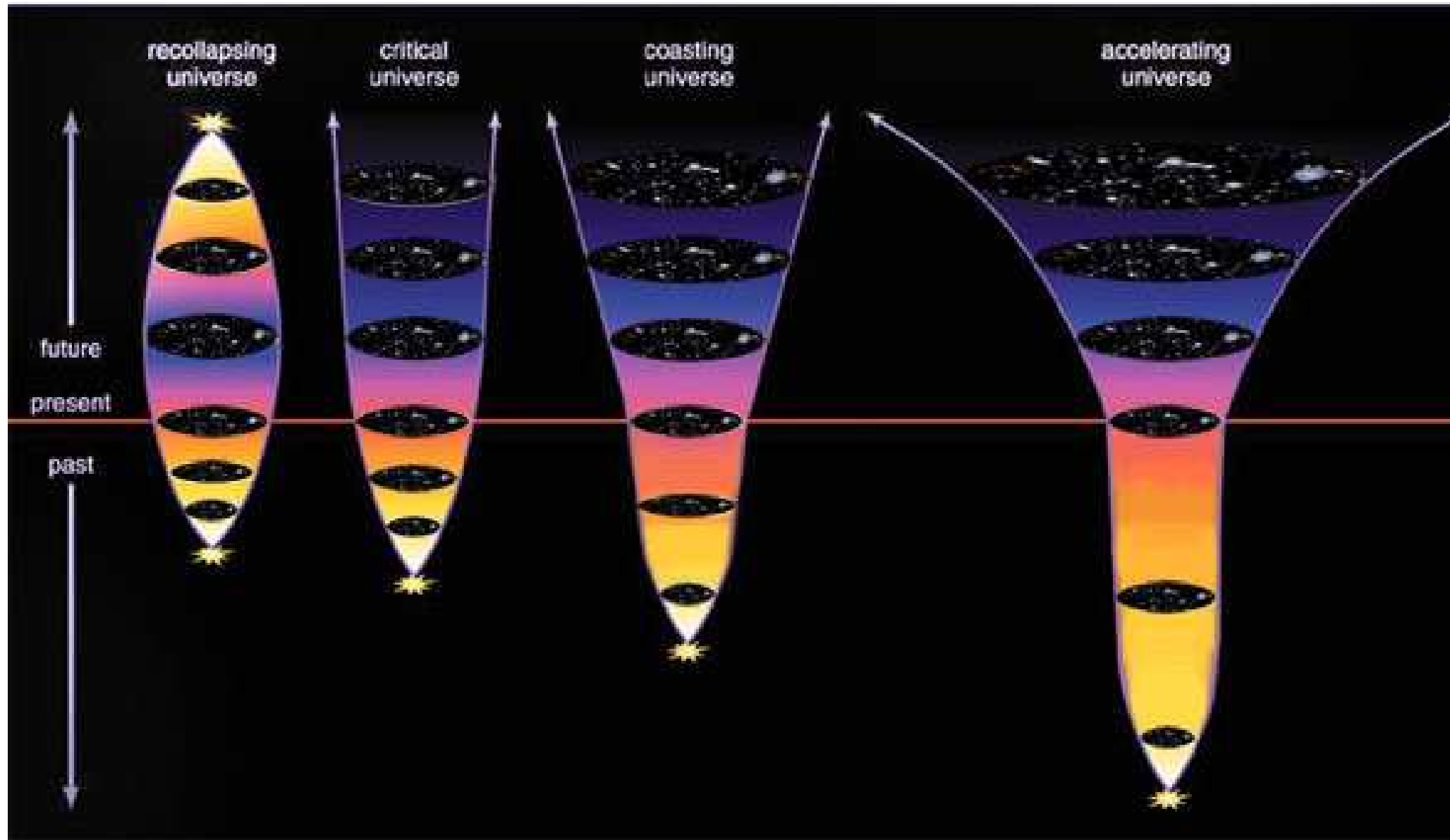


Gravity Should Slow Expansion

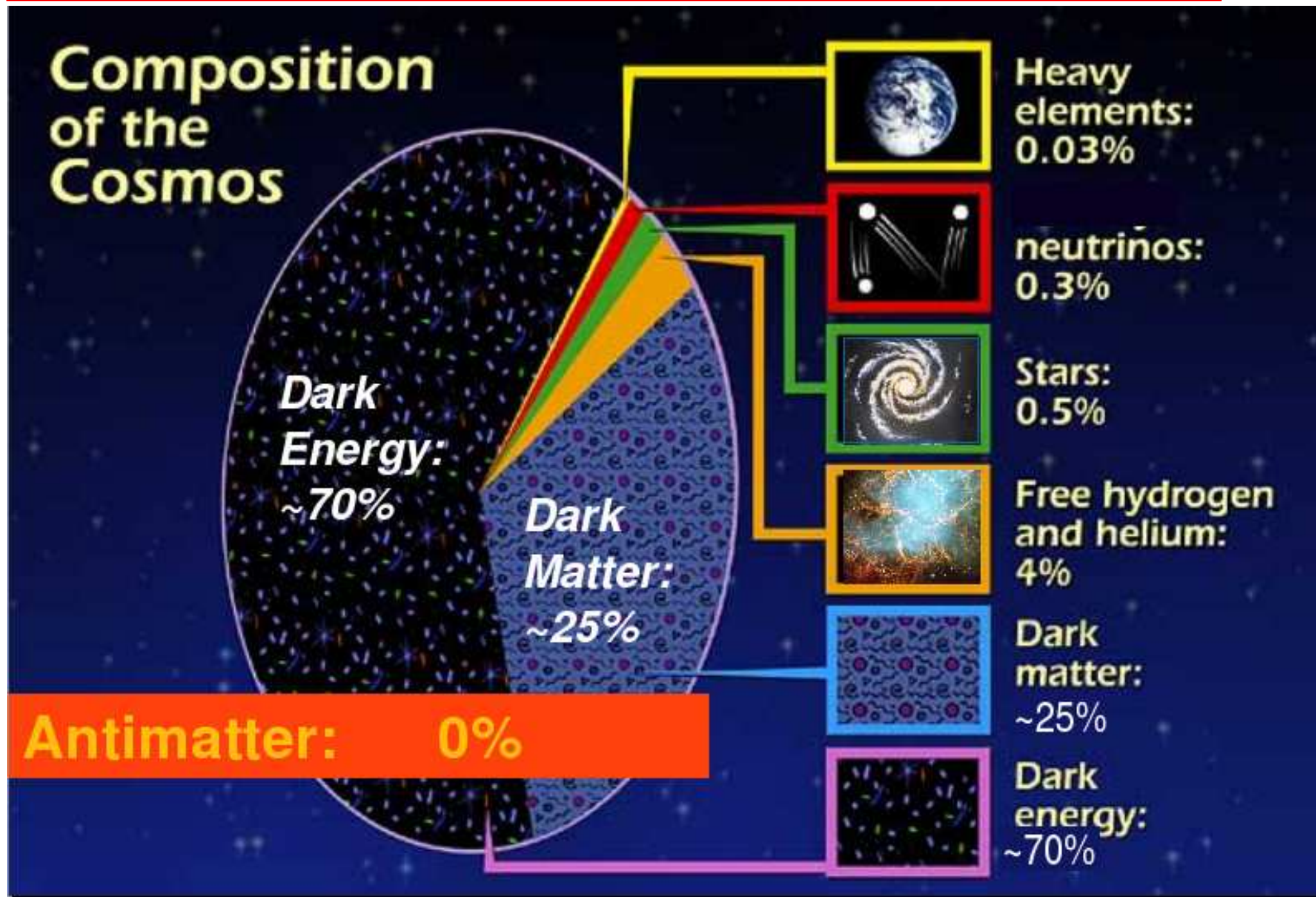


Expansion is Accelerating

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



Puzzles of the Universe

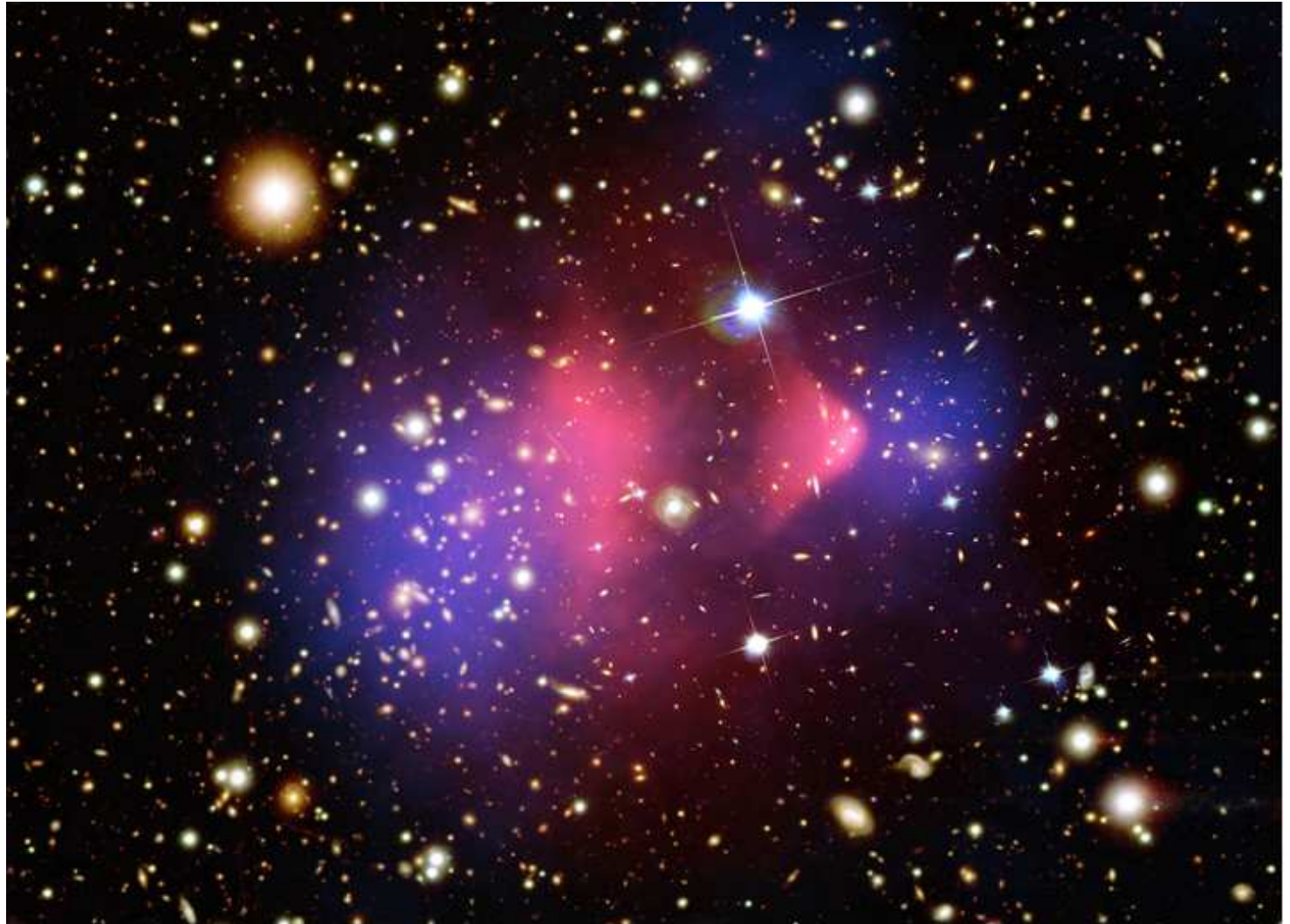


Puzzles of the Universe

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

Dark Matter

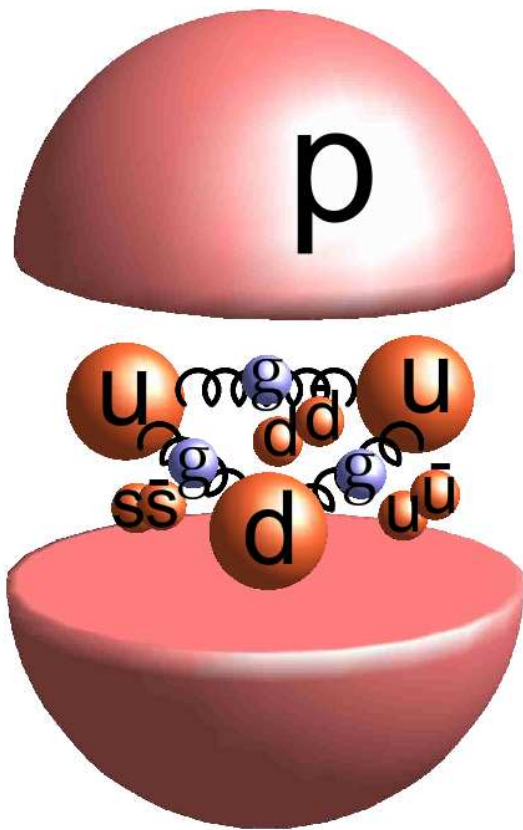
- Dark matter (25%) – "dark" does not emit light, unknown
 - left over from Big Bang, may create in accelerators...



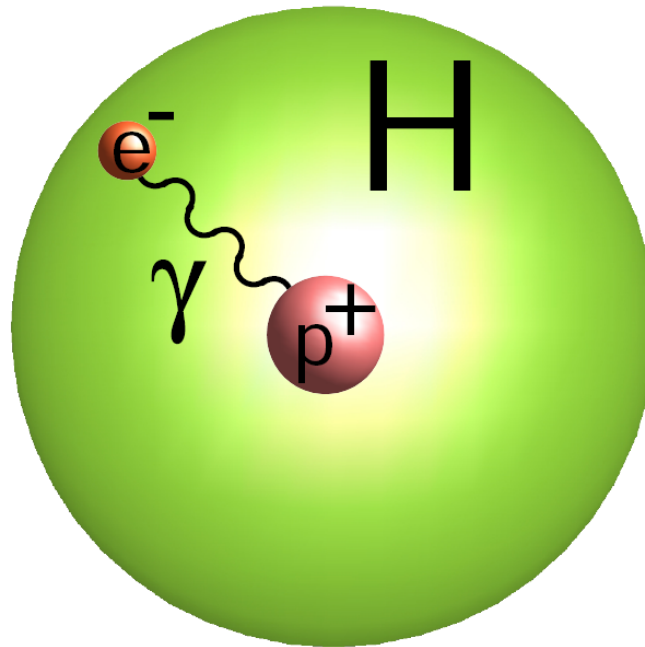
(Galaxy cluster 1E 0657-66: X-ray, Optical, Grav. Lensing)

Ordinary Matter in Big Bang

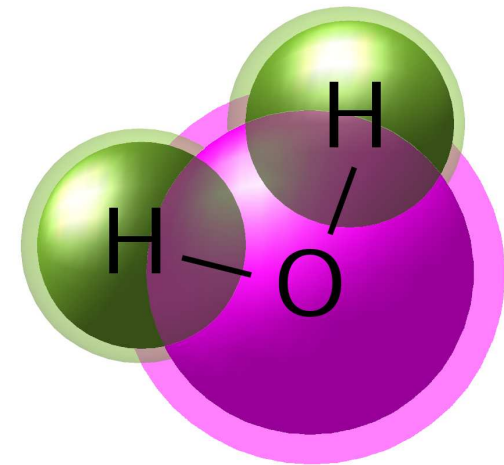
- Quark-gluon soup **fraction of a second** after Big Bang
 - **within minutes** protons and neutrons formed
 - **billions of years** to create all known elements



proton/neutron



atom



molecule

Periodic Table of Matter

PERIODIC TABLE																	
Atomic Properties of the Elements																	
<p>Frequently used fundamental physical constants</p> <p>For the most accurate values of these and other constants, visit physics.nist.gov/constants</p> <p>1 second = 9 192 631 770 periods of radiation corresponding to the transition between the two hyperfine levels of the ground state of ^{133}Cs</p> <p>speed of light in vacuum c 299 792 458 m s⁻¹ (exact)</p> <p>Planck constant h 6.626 1 × 10⁻³⁴ J s ($\hbar = h/2\pi$)</p> <p>elementary charge e 1.602 2 × 10⁻¹⁹ C</p> <p>electron mass m_e 9.109 4 × 10⁻³¹ kg</p> <p>$m_e c^2$ 0.5110 MeV</p> <p>proton mass m_p 1.672 6 × 10⁻²⁷ kg</p> <p>fine-structure constant α 1/137.036</p> <p>Rydberg constant R_∞ 10 973 732 m⁻¹</p> <p>$R_\infty hc$ 3.289 842 × 10¹⁵ Hz</p> <p>Boltzmann constant k 1.380 7 × 10⁻²³ J K⁻¹</p>																	
<p>Legend:</p> <p>■ Solids</p> <p>■ Liquids</p> <p>■ Gases</p> <p>■ Artificially Prepared</p>																	
<p>NIST National Institute of Standards and Technology</p> <p>Technology Administration, U.S. Department of Commerce</p> <p>Physics Laboratory physics.nist.gov</p> <p>Standard Reference Data Group www.nist.gov/srd</p>																	
Group 1 IA	2 IIA											13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
1 H Hydrogen 1.00794 1s 13.5984												5 B Boron 10.811 1s ² 2s ² 2p ¹ 8.2980	6 C Carbon 12.0107 1s ² 2s ² 2p ² 11.2603	7 N Nitrogen 14.0067 1s ² 2s ² 2p ³ 14.5341	8 O Oxygen 15.9994 1s ² 2s ² 2p ⁴ 13.6181	9 F Fluorine 18.9984032 1s ² 2s ² 2p ⁵ 17.4228	10 Ne Neon 20.1797 1s ² 2s ² 2p ⁶ 21.5645
2 Li Lithium 6.941 1s ² 2s ¹ 5.3917	4 Be Beryllium 9.012182 1s ² 2s ² 9.3227											13 Al Aluminum 26.981538 [Ne]3s ² 3p ¹ 5.9858	14 Si Silicon 28.0855 [Ne]3s ² 3p ² 8.1517	15 P Phosphorus 30.973761 [Ne]3s ² 3p ³ 10.4867	16 S Sulfur 32.059 [Ne]3s ² 3p ⁴ 10.3600	17 Cl Chlorine 35.453 [Ne]3s ² 3p ⁵ 12.6676	18 Ar Argon 39.948 [Ne]3s ² 3p ⁶ 15.7596
3 Na Sodium 22.989770 [Ne]3s ¹ 5.1391	12 Mg Magnesium 24.3050 [Ne]3s ² 7.6462	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIII	9 VIII	10 VIII	11 IB	12 IIB	13 IIIA	14 IVA	15 VA	16 VIA	17 VIIA	18 VIIIA
19 K Potassium 39.0983 [Ar]4s ¹ 4.3407	20 Ca Calcium 40.078 [Ar]4s ² 6.1132	21 Sc Scandium 44.955910 [Ar]3d ¹ 4s ² 6.5615	22 Ti Titanium 47.887 [Ar]3d ² 4s ² 6.8281	23 V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462	24 Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹ 6.7665	25 Mn Manganese 54.938049 [Ar]3d ⁵ 4s ² 7.4340	26 Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9024	27 Co Cobalt 58.933200 [Ar]3d ⁷ 4s ² 7.8810	28 Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6398	29 Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹ 7.7204	30 Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ² 9.3942	31 Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹ 5.9993	32 Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	33 As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7866	34 Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	35 Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	36 Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996
4 K Potassium 39.0983 [Ar]4s ¹ 4.3407	20 Ca Calcium 40.078 [Ar]4s ² 6.1132	21 Sc Scandium 44.955910 [Ar]3d ¹ 4s ² 6.5615	22 Ti Titanium 47.887 [Ar]3d ² 4s ² 6.8281	23 V Vanadium 50.9415 [Ar]3d ³ 4s ² 6.7462	24 Cr Chromium 51.9961 [Ar]3d ⁵ 4s ¹ 6.7665	25 Mn Manganese 54.938049 [Ar]3d ⁵ 4s ² 7.4340	26 Fe Iron 55.845 [Ar]3d ⁶ 4s ² 7.9024	27 Co Cobalt 58.933200 [Ar]3d ⁷ 4s ² 7.8810	28 Ni Nickel 58.6934 [Ar]3d ⁸ 4s ² 7.6398	29 Cu Copper 63.546 [Ar]3d ¹⁰ 4s ¹ 7.7204	30 Zn Zinc 65.409 [Ar]3d ¹⁰ 4s ² 9.3942	31 Ga Gallium 69.723 [Ar]3d ¹⁰ 4s ² 4p ¹ 5.9993	32 Ge Germanium 72.64 [Ar]3d ¹⁰ 4s ² 4p ² 7.8994	33 As Arsenic 74.92160 [Ar]3d ¹⁰ 4s ² 4p ³ 9.7866	34 Se Selenium 78.96 [Ar]3d ¹⁰ 4s ² 4p ⁴ 9.7524	35 Br Bromine 79.904 [Ar]3d ¹⁰ 4s ² 4p ⁵ 11.8138	36 Kr Krypton 83.798 [Ar]3d ¹⁰ 4s ² 4p ⁶ 13.9996
5 Rb Rubidium 85.4678 [Kr]5s ¹ 4.1771	38 Sr Strontium 87.62 [Kr]5s ² 5.6949	39 Y Yttrium 88.90585 [Kr]4d ¹ 5s ² 6.2173	40 Zr Zirconium 91.224 [Kr]4d ² 5s ² 6.6339	41 Nb Niobium 92.90638 [Kr]4d ⁴ 5s ¹ 6.7589	42 Mo Molybdenum 95.94 [Kr]4d ⁵ 5s ¹ 7.0924	43 Tc Technetium (98) [Kr]4d ⁵ 5s ² 7.28	44 Ru Ruthenium 101.07 [Kr]4d ⁷ 5s ¹ 7.3605	45 Rh Rhodium 102.90550 [Kr]4d ⁸ 5s ¹ 7.4589	46 Pd Palladium 106.42 [Kr]4d ¹⁰ 5s ⁰ 8.3369	47 Ag Silver 107.8682 [Kr]4d ¹⁰ 5s ¹ 7.5762	48 Cd Cadmium 112.411 [Kr]4d ¹⁰ 5s ² 8.9938	49 In Indium 114.818 [Kr]4d ¹⁰ 5s ² 5p ¹ 5.7864	50 Sn Tin 118.710 [Kr]4d ¹⁰ 5s ² 5p ² 7.3439	51 Sb Antimony 121.760 [Kr]4d ¹⁰ 5s ² 5p ³ 8.6084	52 Te Tellurium 127.60 [Kr]4d ¹⁰ 5s ² 5p ⁴ 9.0099	53 I Iodine 126.90447 [Kr]4d ¹⁰ 5s ² 5p ⁵ 10.4513	54 Xe Xenon 131.293 [Kr]4d ¹⁰ 5s ² 5p ⁶ 12.1298
6 Cs Cesium 132.90545 [Xe]6s ¹ 3.8939	56 Ba Barium 137.327 [Xe]6s ² 5.2117		72 Hf Hafnium 178.49 [Xe]4f ¹⁴ 5d ² 6s ² 6.8251	73 Ta Tantalum 180.9479 [Xe]4f ¹⁴ 5d ³ 6s ² 7.5496	74 W Tungsten 183.84 [Xe]4f ¹⁴ 5d ⁴ 6s ² 7.8640	75 Re Rhenium 186.207 [Xe]4f ¹⁴ 5d ⁵ 6s ² 7.8335	76 Os Osmium 190.23 [Xe]4f ¹⁴ 5d ⁶ 6s ² 8.4382	77 Ir Iridium 192.217 [Xe]4f ¹⁴ 5d ⁷ 6s ² 8.6670	78 Pt Platinum 195.078 [Xe]4f ¹⁴ 5d ⁹ 6s ¹ 8.9588	79 Au Gold 196.96655 [Xe]4f ¹⁴ 5d ¹⁰ 6s ¹ 9.2255	80 Hg Mercury 200.59 [Xe]4f ¹⁴ 5d ¹⁰ 6s ² 10.4375	81 Tl Thallium 204.3833 [Hg]6p ¹ 6.1082	82 Pb Lead 207.2 [Hg]6p ² 7.4167	83 Bi Bismuth 208.98038 [Hg]6p ³ 7.2855	84 Po Polonium (209) [Hg]6p ⁴ 8.414	85 At Astatine (210) [Hg]6p ⁵ 8.414	86 Rn Radon (222) [Hg]6p ⁶ 10.7485
7 Fr Francium (223) [Rn]7s ¹ 4.0727	88 Ra Radium (226) [Rn]7s ² 5.2784		104 Rf Rutherfordium (261) [Rn]5f ¹⁴ 6d ² 7s ² 6.0 ?	105 Db Dubnium (262) [Rn]5f ¹⁴ 6d ³ 7s ² 6.0 ?	106 Sg Seaborgium (266) [Rn]5f ¹⁴ 6d ⁴ 7s ² 6.0 ?	107 Bh Bohrium (264) [Rn]5f ¹⁴ 6d ⁵ 7s ² 6.1941	108 Hs Hassium (277) [Rn]5f ¹⁴ 6d ⁶ 7s ² 6.2657	109 Mt Meitnerium (268) [Rn]5f ¹⁴ 6d ⁷ 7s ² 6.0260	110 Uun Ununnilium (281) [Rn]5f ¹⁴ 6d ⁸ 7s ² 5.9738	111 Uuu Unununium (272) [Rn]5f ¹⁴ 6d ⁹ 7s ² 5.9914	112 Uub Unbium (285) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 6.1979		114 Uuq Ununquadium (289) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 6.2817		116 Uuh Ununhexium (292) [Rn]5f ¹⁴ 6d ¹⁰ 7s ² 6.50		
<p>Lanthanides</p> <p>57 La Lanthanum 138.9055 [Xe]5d¹6s² 5.5789</p> <p>58 Ce Cerium 140.116 [Xe]4f¹5d¹6s² 5.5387</p> <p>59 Pr Praseodymium 140.90705 [Xe]4f³6s² 5.473</p> <p>60 Nd Neodymium 144.24 [Xe]4f⁴6s² 5.5250</p> <p>61 Pm Promethium (145) [Xe]4f⁵6s² 5.582</p> <p>62 Sm Samarium 150.36 [Xe]4f⁶6s² 5.6437</p> <p>63 Eu Europium 151.964 [Xe]4f⁷6s² 5.6704</p> <p>64 Gd Gadolinium 157.25 [Xe]4f⁷5d¹6s² 6.1498</p> <p>65 Tb Terbium 158.92534 [Xe]4f⁹6s² 5.8638</p> <p>66 Dy Dysprosium 162.500 [Xe]4f¹⁰6s² 5.9389</p> <p>67 Ho Holmium 164.93032 [Xe]4f¹¹6s² 6.0215</p> <p>68 Er Erbium 167.259 [Xe]4f¹²6s² 6.1077</p> <p>69 Tm Thulium 168.93421 [Xe]4f¹³6s² 6.1843</p> <p>70 Yb Ytterbium 173.04 [Xe]4f¹⁴6s² 6.2542</p> <p>71 Lu Lutetium 174.967 [Xe]4f¹⁴5d¹6s² 5.4259</p>																	
<p>Actinides</p> <p>89 Ac Actinium (227) [Rn]6d¹7s² 5.17</p> <p>90 Th Thorium 232.0381 [Rn]6d²7s² 6.3067</p> <p>91 Pa Protactinium 231.03688 [Rn]5f²6d¹7s² 5.89</p> <p>92 U Uranium 238.02891 [Rn]5f³6d¹7s² 6.1941</p> <p>93 Np Neptunium (237) [Rn]5f⁴6d¹7s² 6.2657</p> <p>94 Pu Plutonium (244) [Rn]5f⁶7s² 6.0260</p> <p>95 Am Americium (243) [Rn]5f⁷7s² 5.9738</p> <p>96 Cm Curium (247) [Rn]5f⁸7s² 5.9914</p> <p>97 Bk Berkelium (247) [Rn]5f⁹7s² 6.1979</p> <p>98 Cf Californium (251) [Rn]5f¹⁰7s² 6.2817</p> <p>99 Es Einsteinium (252) [Rn]5f¹¹7s² 6.42</p> <p>100 Fm Fermium (257) [Rn]5f¹²7s² 6.50</p> <p>101 Md Mendelevium (258) [Rn]5f¹³7s² 6.58</p> <p>102 No Nobelium (259) [Rn]5f¹⁴7s² 6.95</p> <p>103 Lr Lawrencium (262) [Rn]5f¹⁴7p¹ 4.9 ?</p>																	

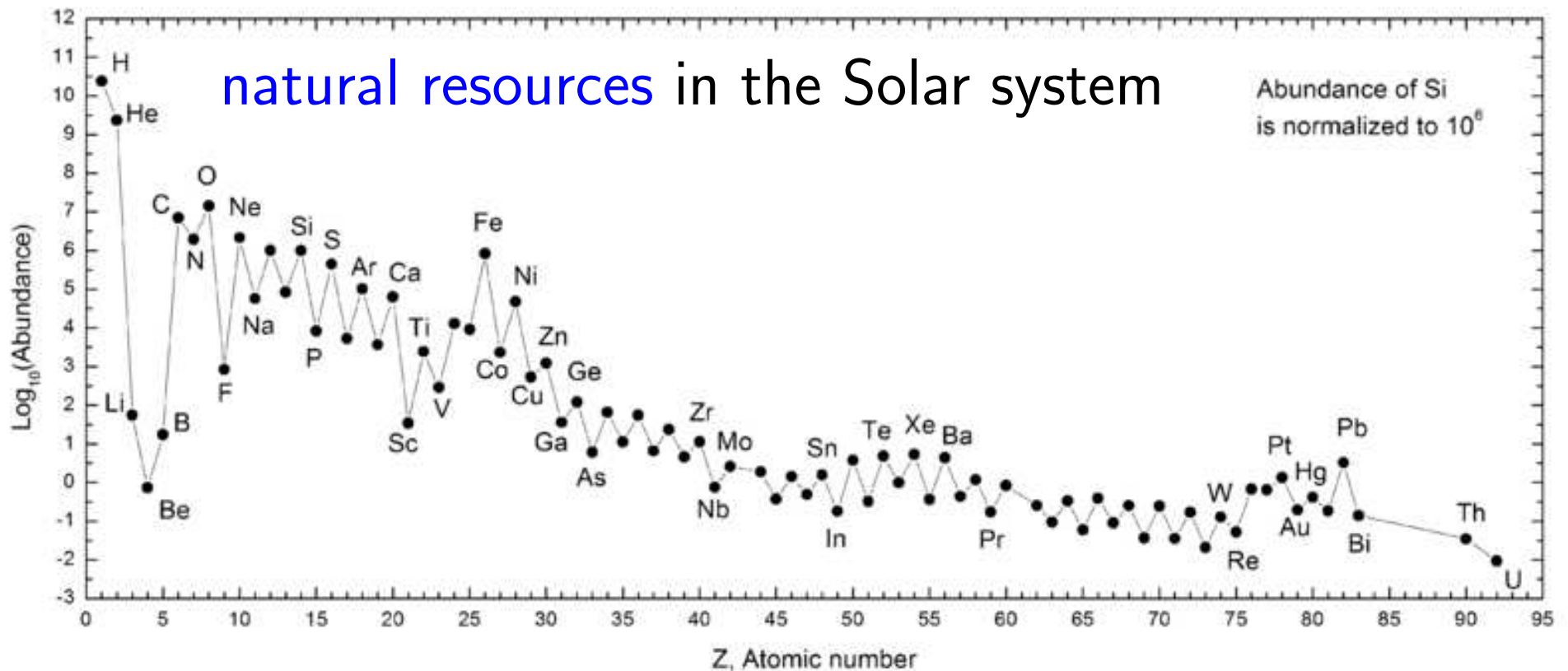
[†]Based upon ¹²C. () indicates the mass number of the most stable isotope.

For a description of the data, visit physics.nist.gov/data

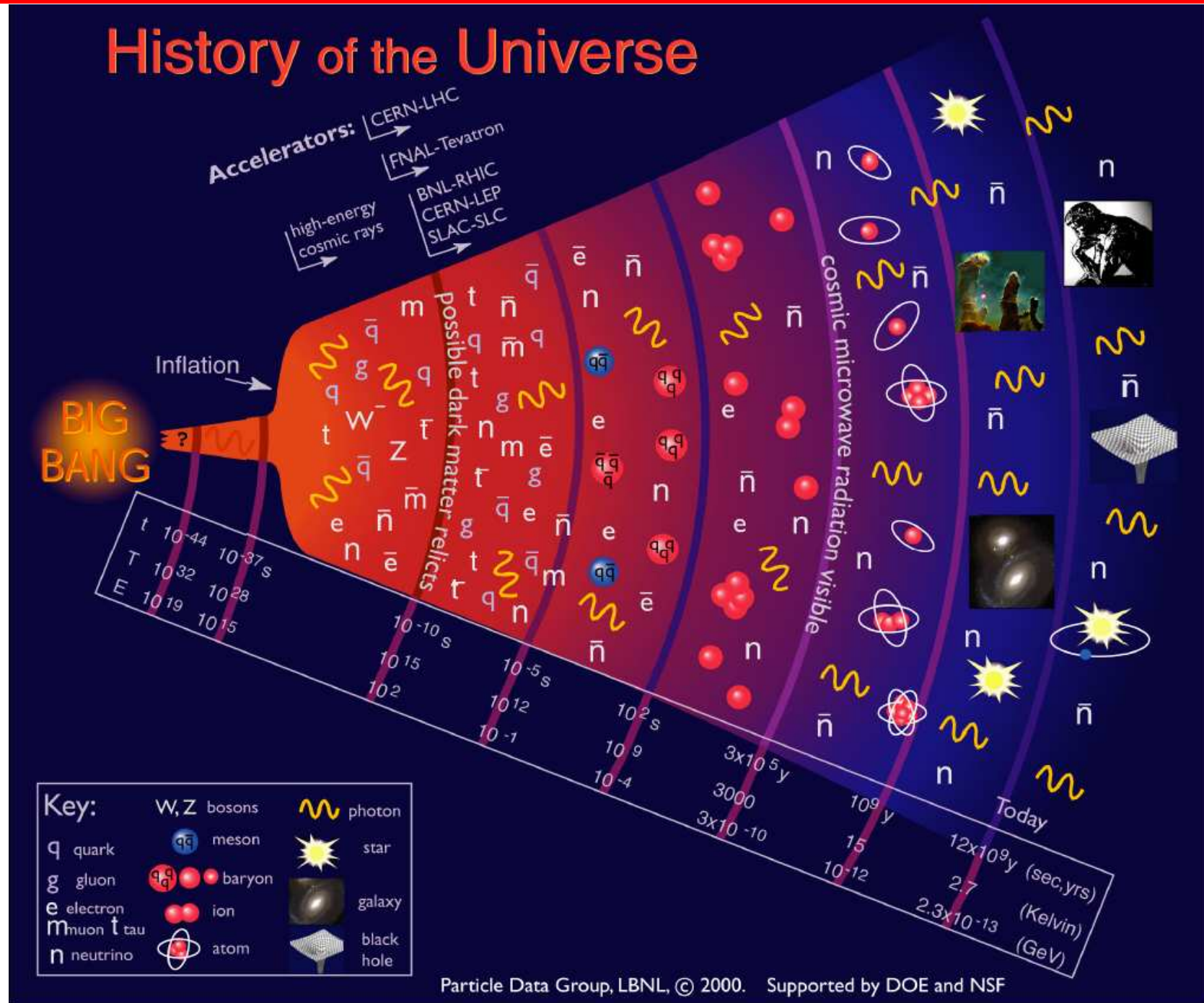
NIST SP 966 (September 2003)

Formation of All Elements

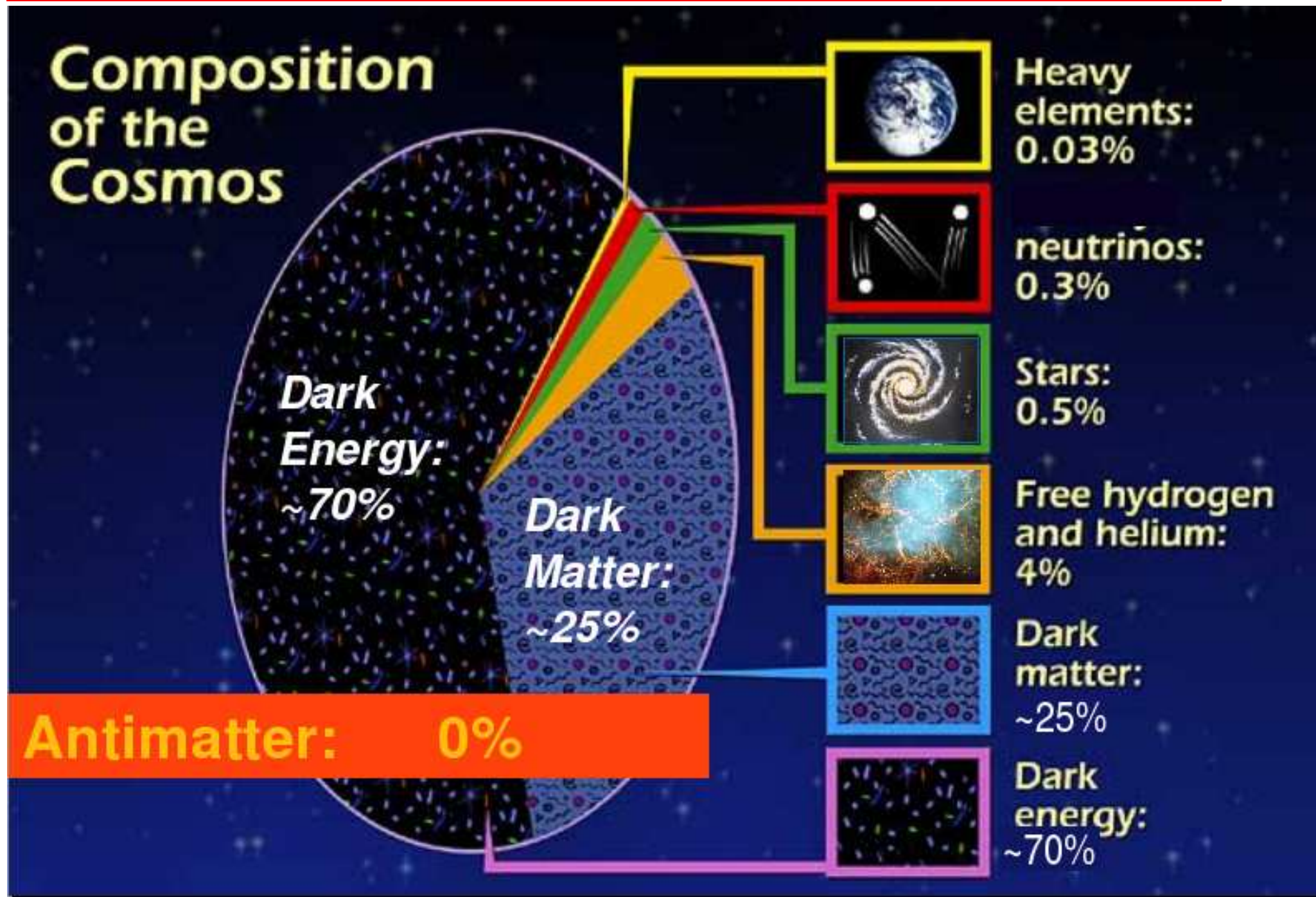
- Success of **Big Bang** theory – predict formation of elements
 - light elements (H, He) in early moments
 - heavy elements (C – U) in fusion within stars
- Nuclear energy – in the gluon soup binding the quarks



The Big Bang



Puzzles of the Universe



Puzzles of the Universe

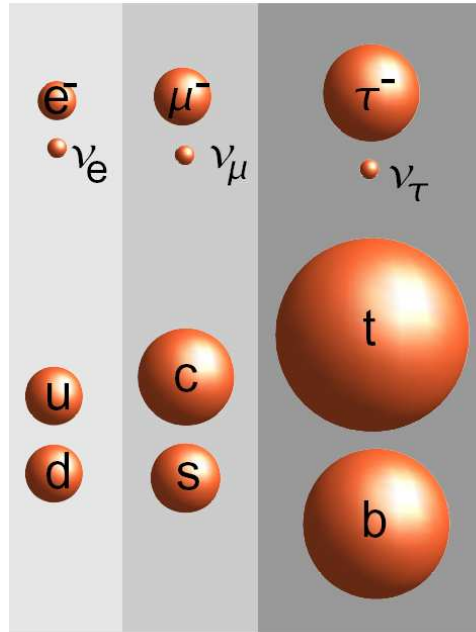
- Dark energy ($\sim 70\%$)
 - do not know what it is; explain accelerated expansion
- Dark matter ($\sim 25\%$)
 - does not emit light, but seen with gravity
- Ordinary matter ($\sim 5\%$)
 - the only thing we knew until recently: from Hydrogen to Uranium
- Ordinary antimatter ($\sim 0\%$)
 - equal 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

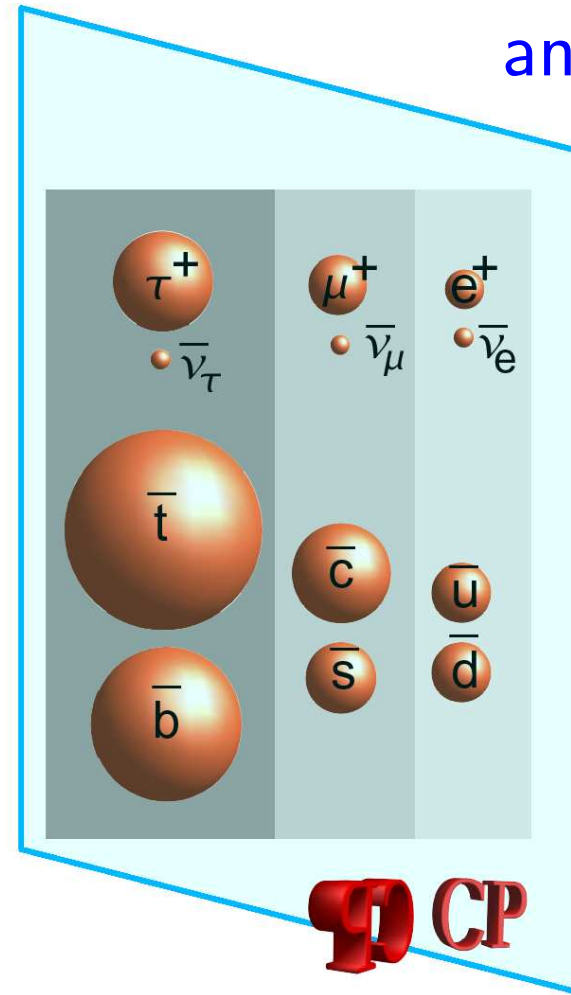
- matter

leptons

quarks



anti-matter



- Produced equal in Big Bang

energy \rightarrow 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. Moritz

Makoto Kobayashi



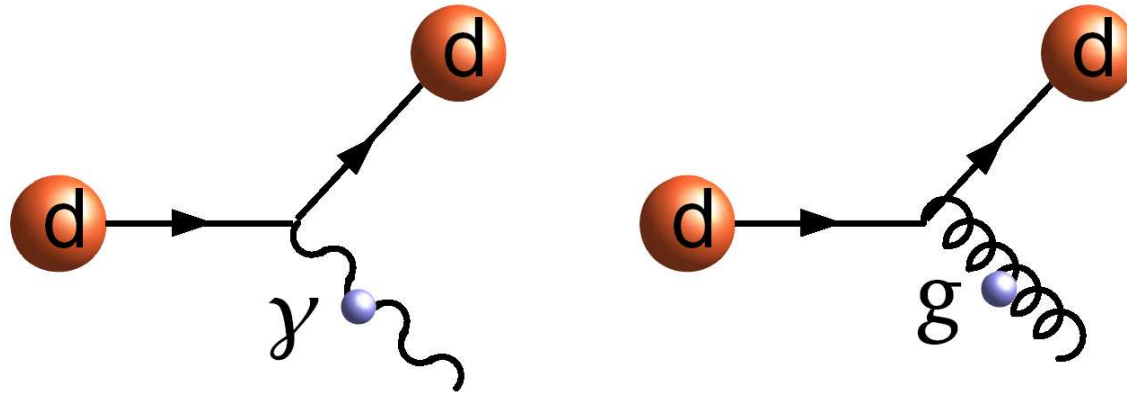
© The Nobel Foundation Photo: U. Moritz

Toshihide Maskawa

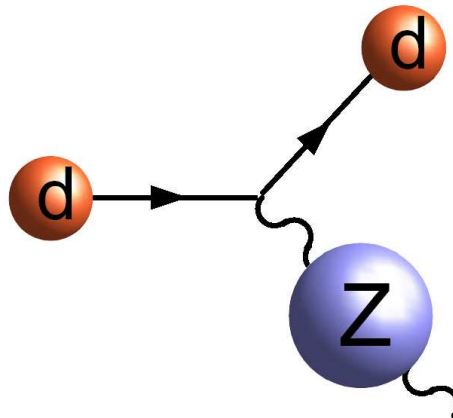
The Nobel Prize in Physics 2008 was divided, one half awarded to Yoichiro Nambu "for the discovery of the mechanism of spontaneous broken symmetry in subatomic physics", the other half jointly to Makoto Kobayashi and Toshihide Maskawa "for the discovery of the origin of the broken symmetry which predicts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



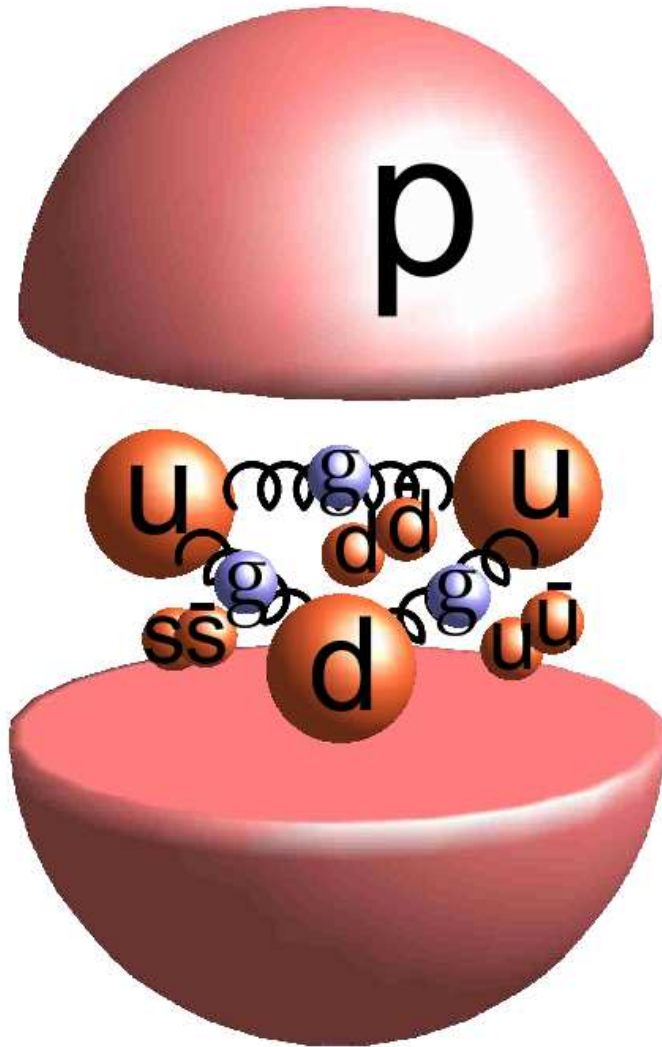
Idea - the Higgs Field

- 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-gluon soup energy:
 $m_p c^2 = 938 \text{ MeV}$

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

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

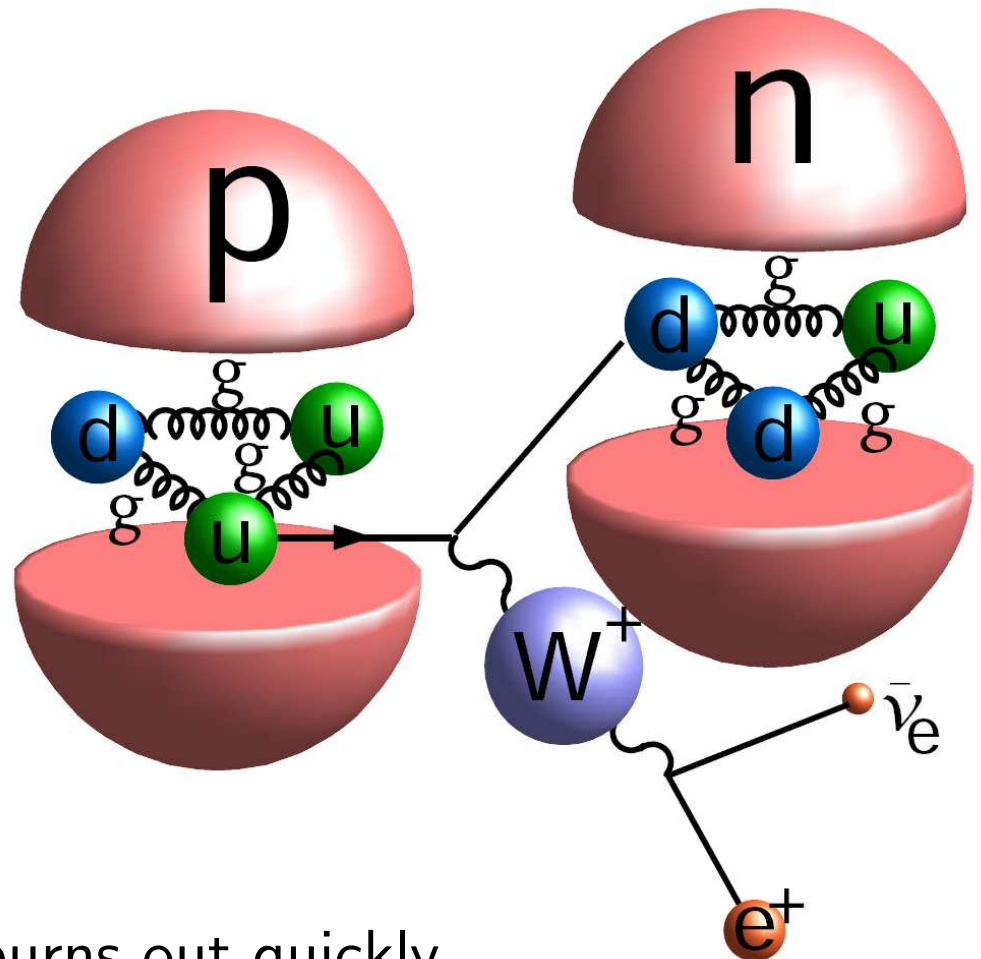
- Origin of Sun light

starts from Weak fusion

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

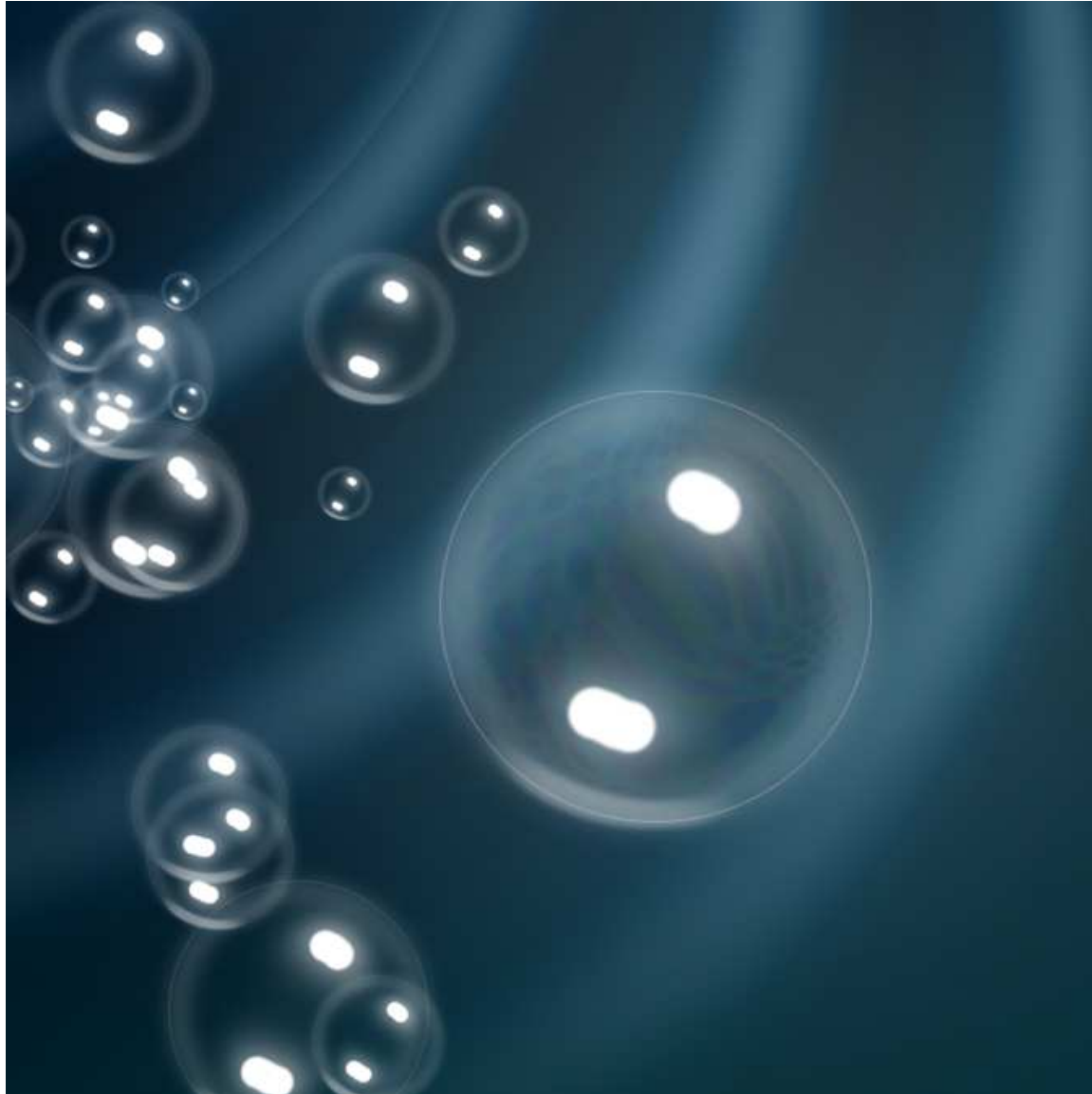
slow burning due to heavy W^+

Remove the Higgs field – Sun burns out quickly



News from the Large Hadron Collider

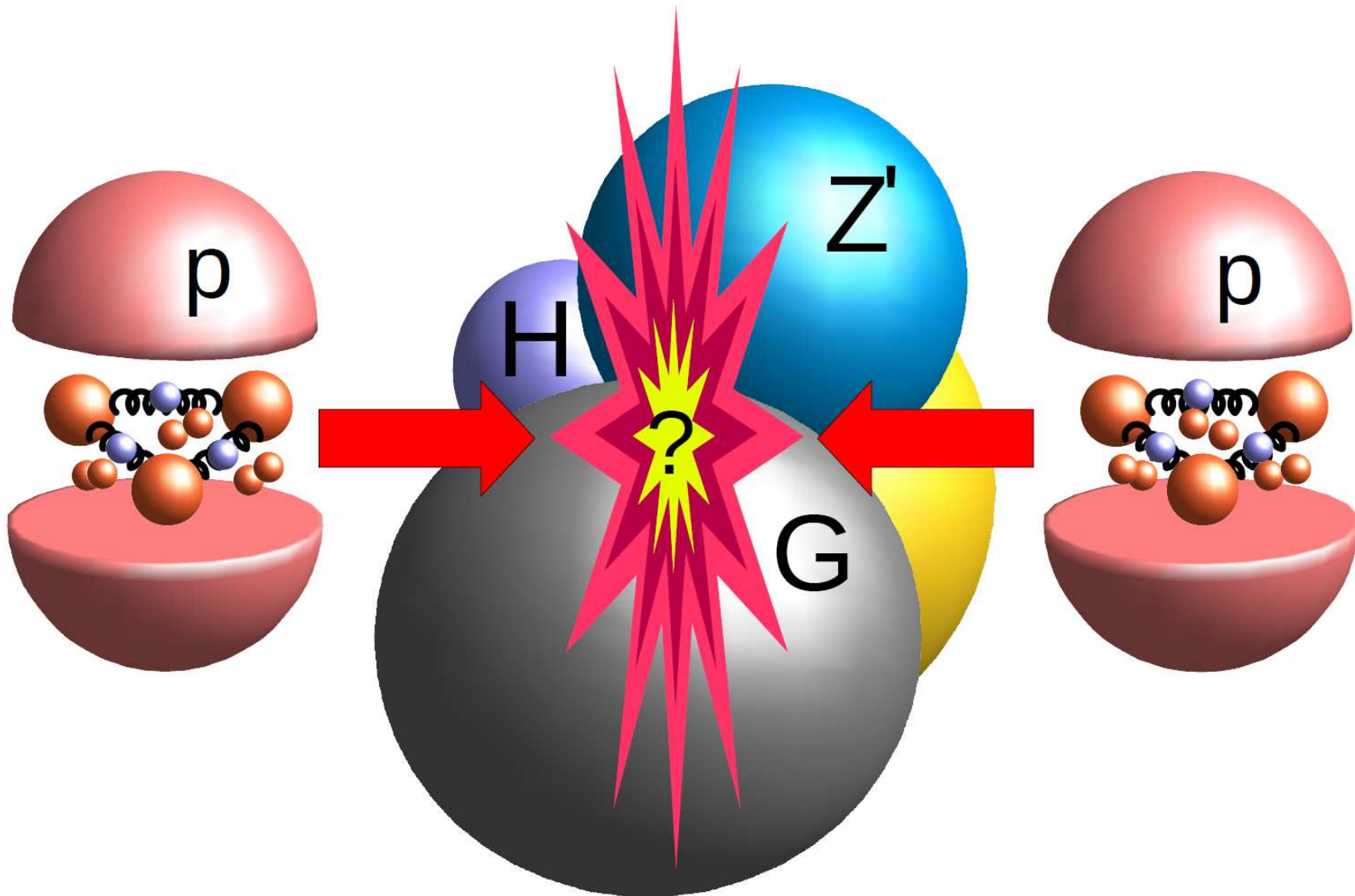
- Idea: if the **Higgs field** exists, like soap:
 - blow into the soap, create a **bubble** (Higgs boson)



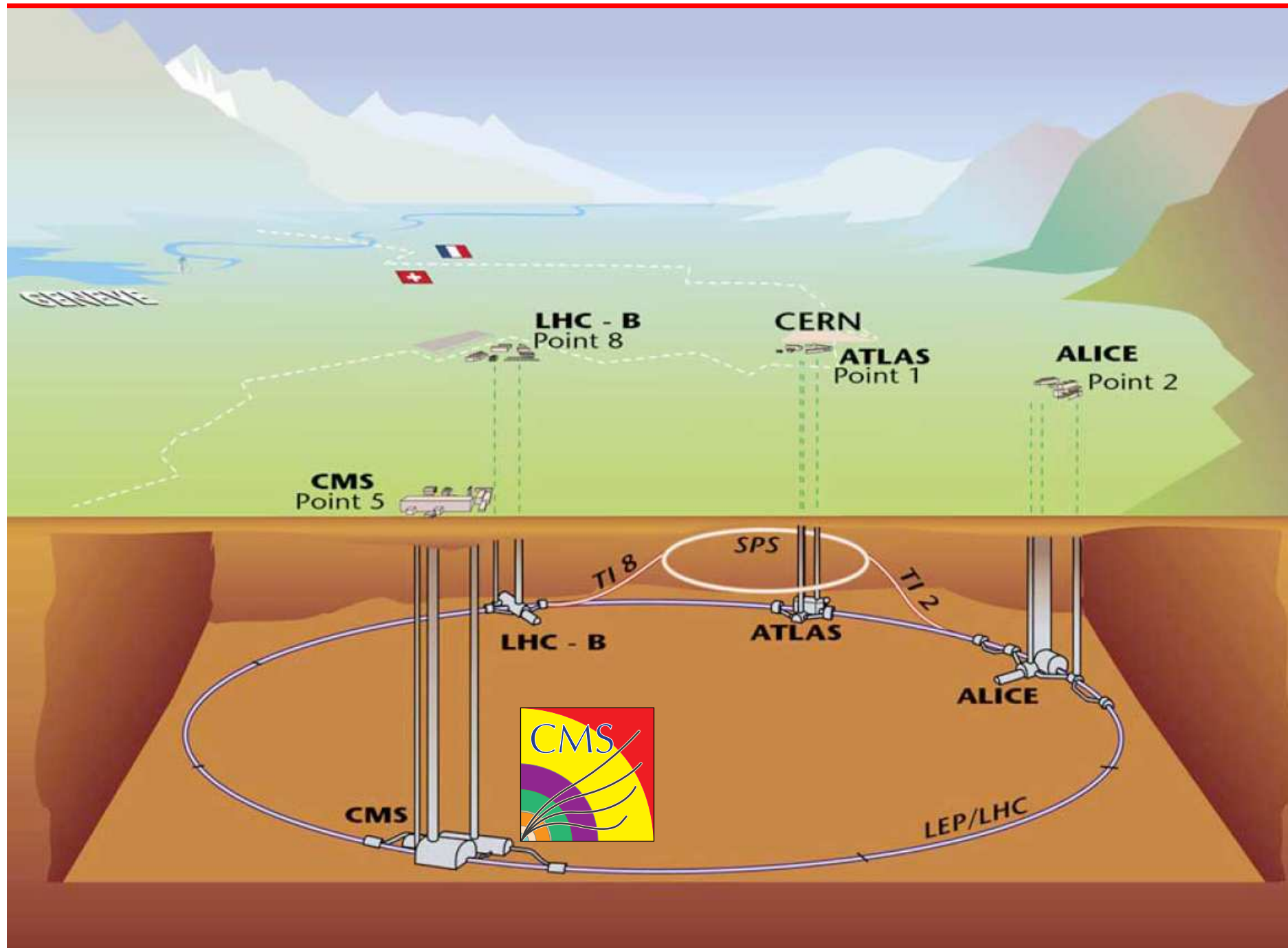
The Large Hadron Collider

The Large Hadron Collider

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



The Large Hadron Collider



The Large Hadron Collider

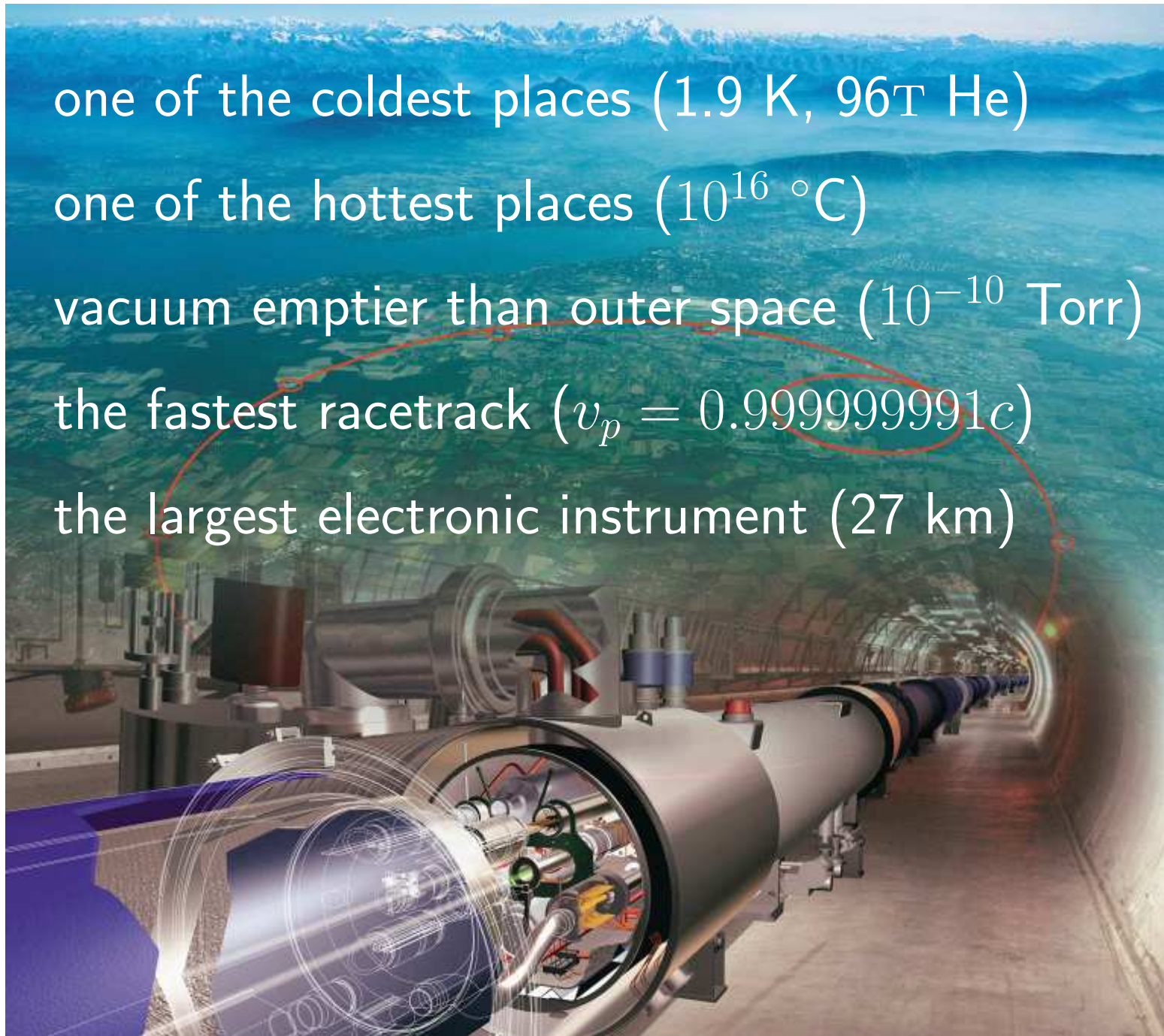
one of the coldest places (1.9 K, 96T He)

one of the hottest places (10^{16} °C)

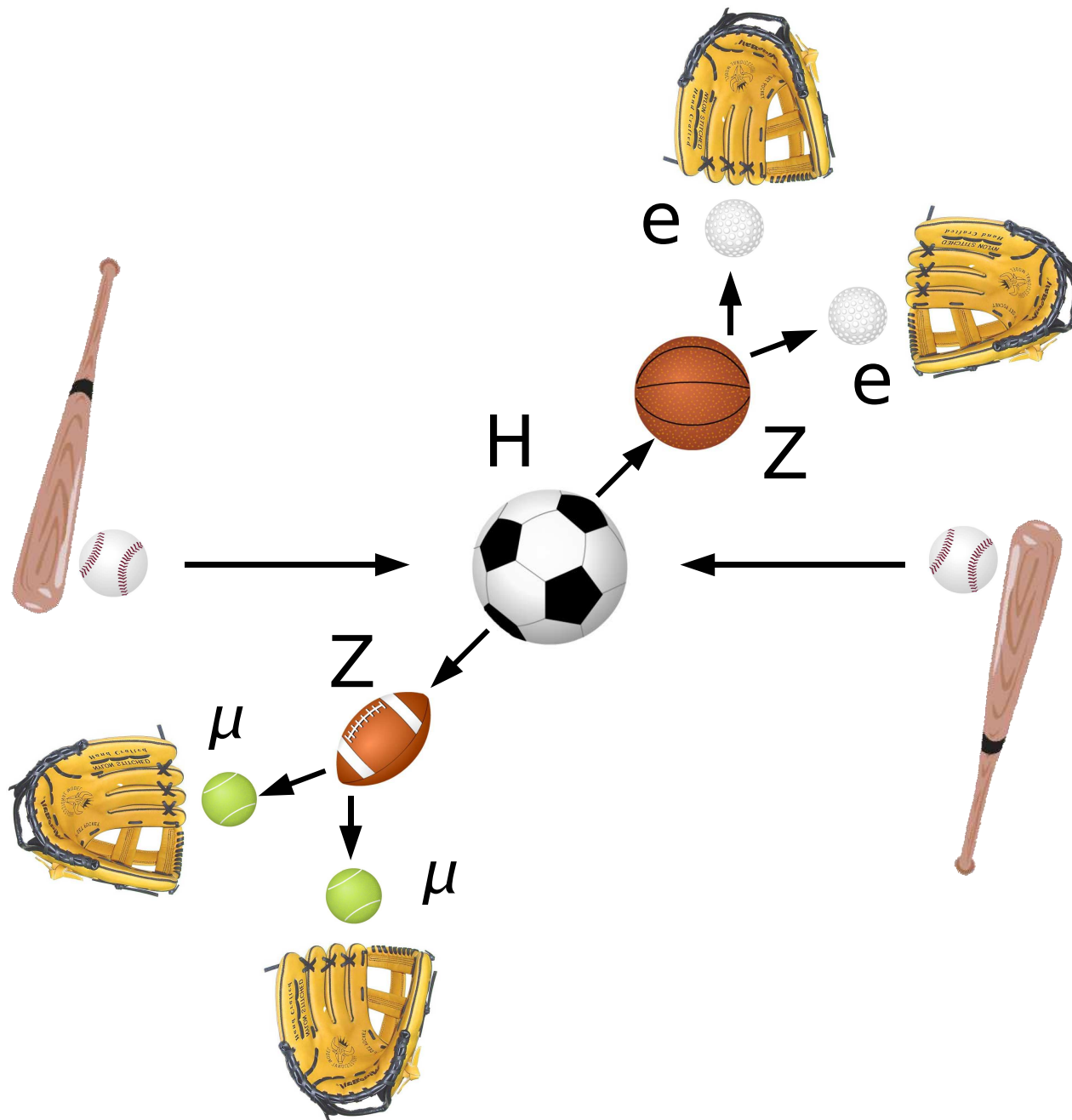
vacuum emptier than outer space (10^{-10} Torr)

the fastest racetrack ($v_p = 0.9999999991c$)

the largest electronic instrument (27 km)

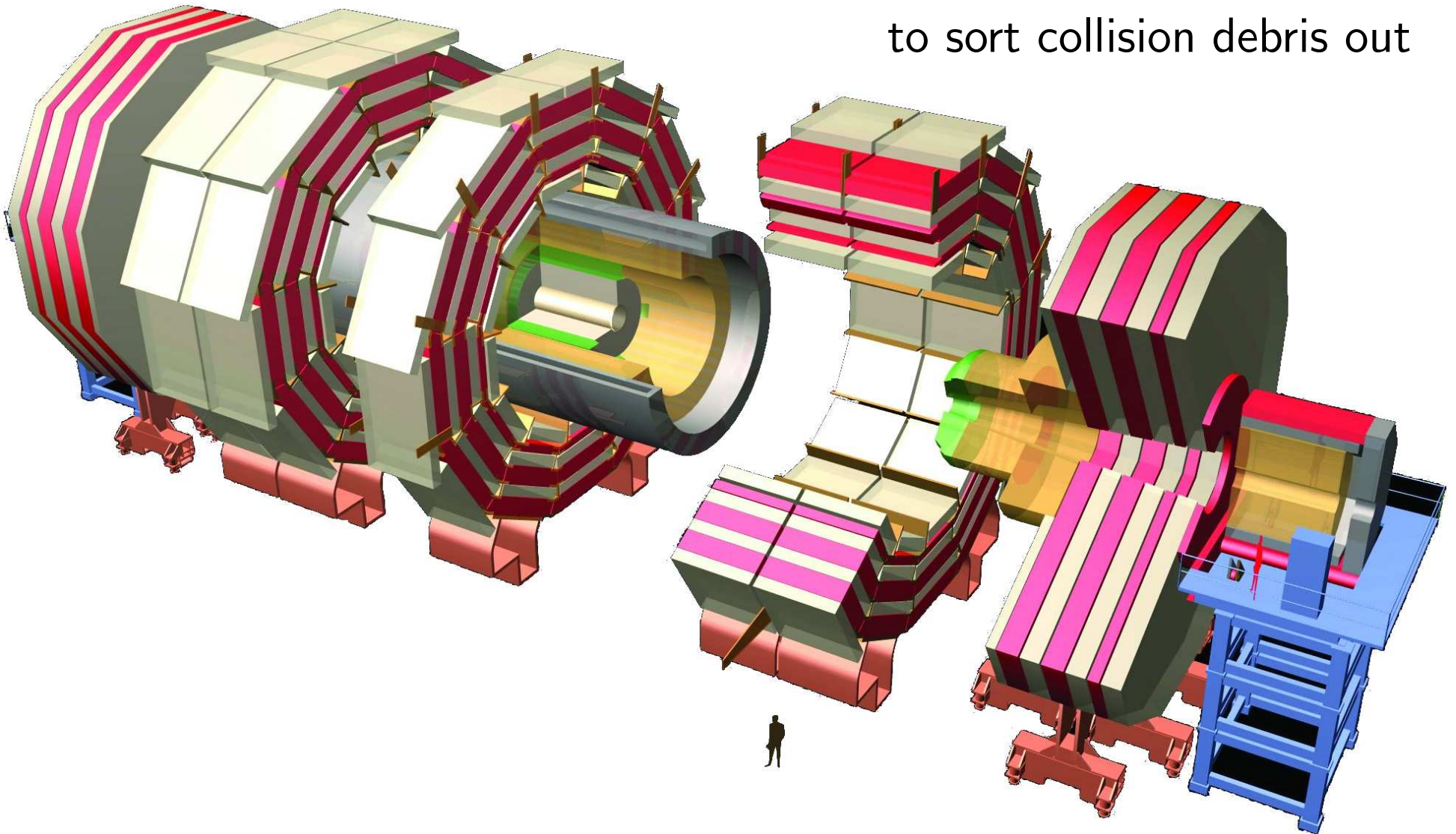


The Large Hadron Collider



Example: the CMS Detector

- Complex detector
to sort collision debris out



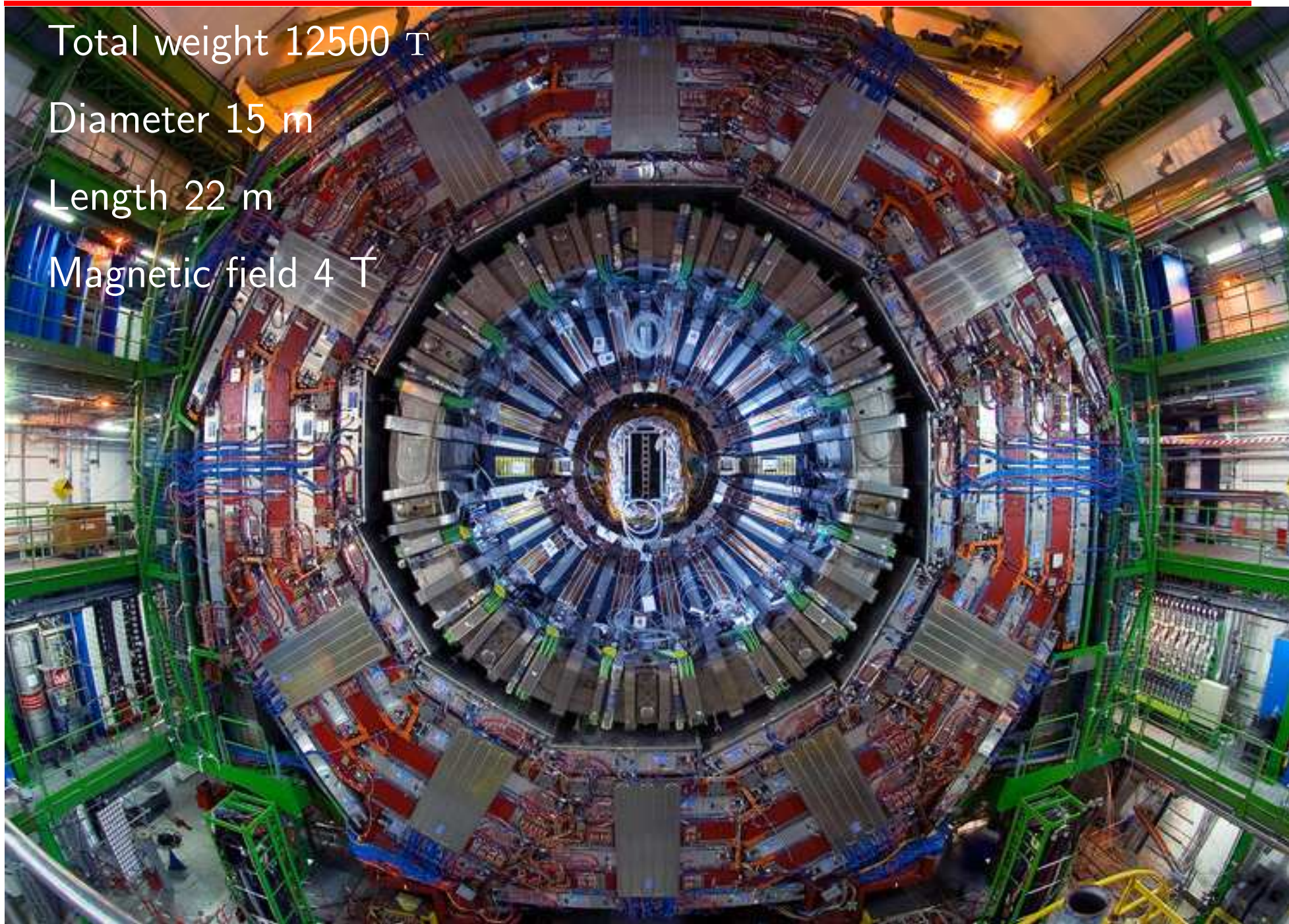
The CMS Detector

Total weight 12500 T

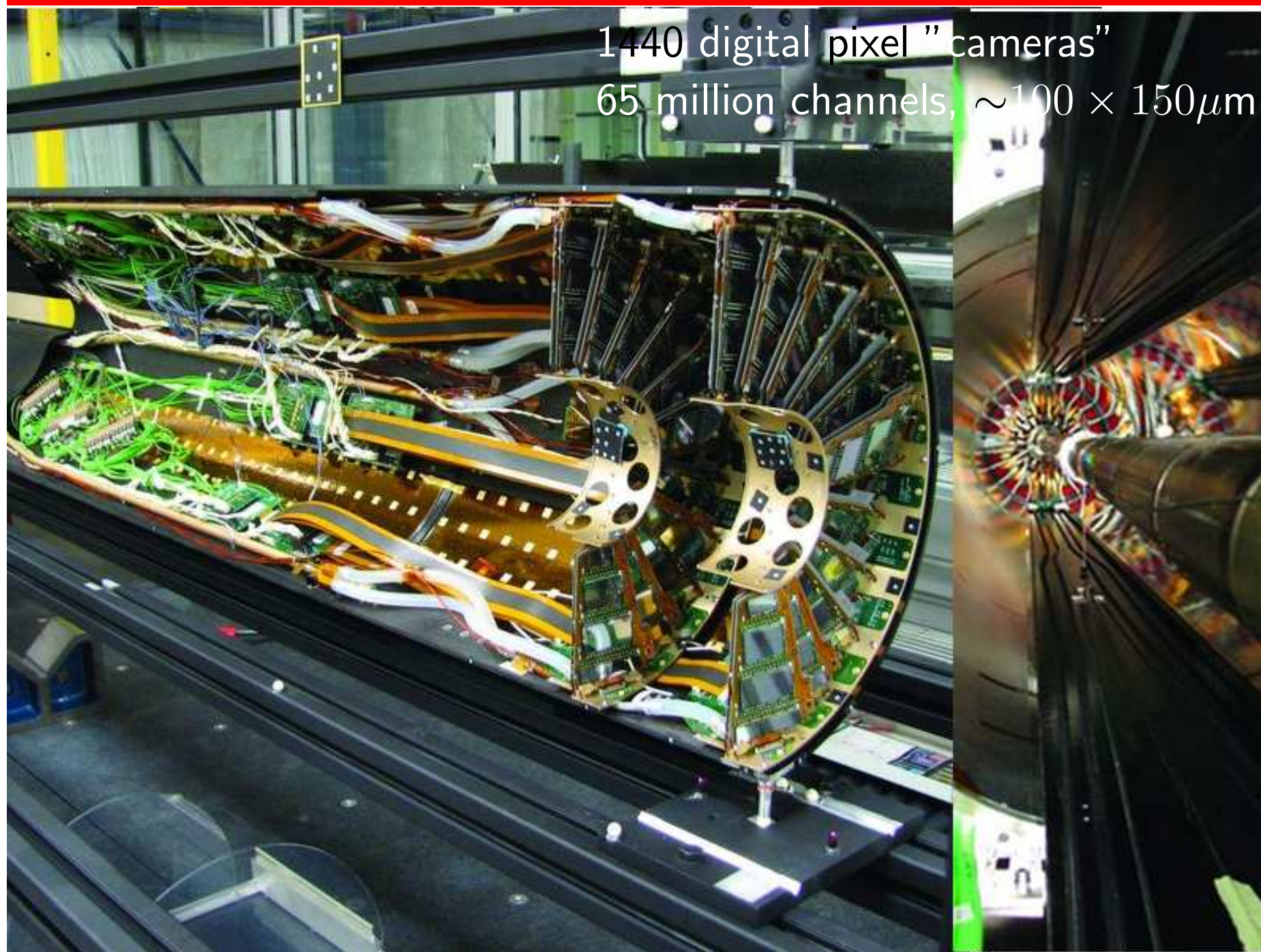
Diameter 15 m

Length 22 m

Magnetic field 4 T

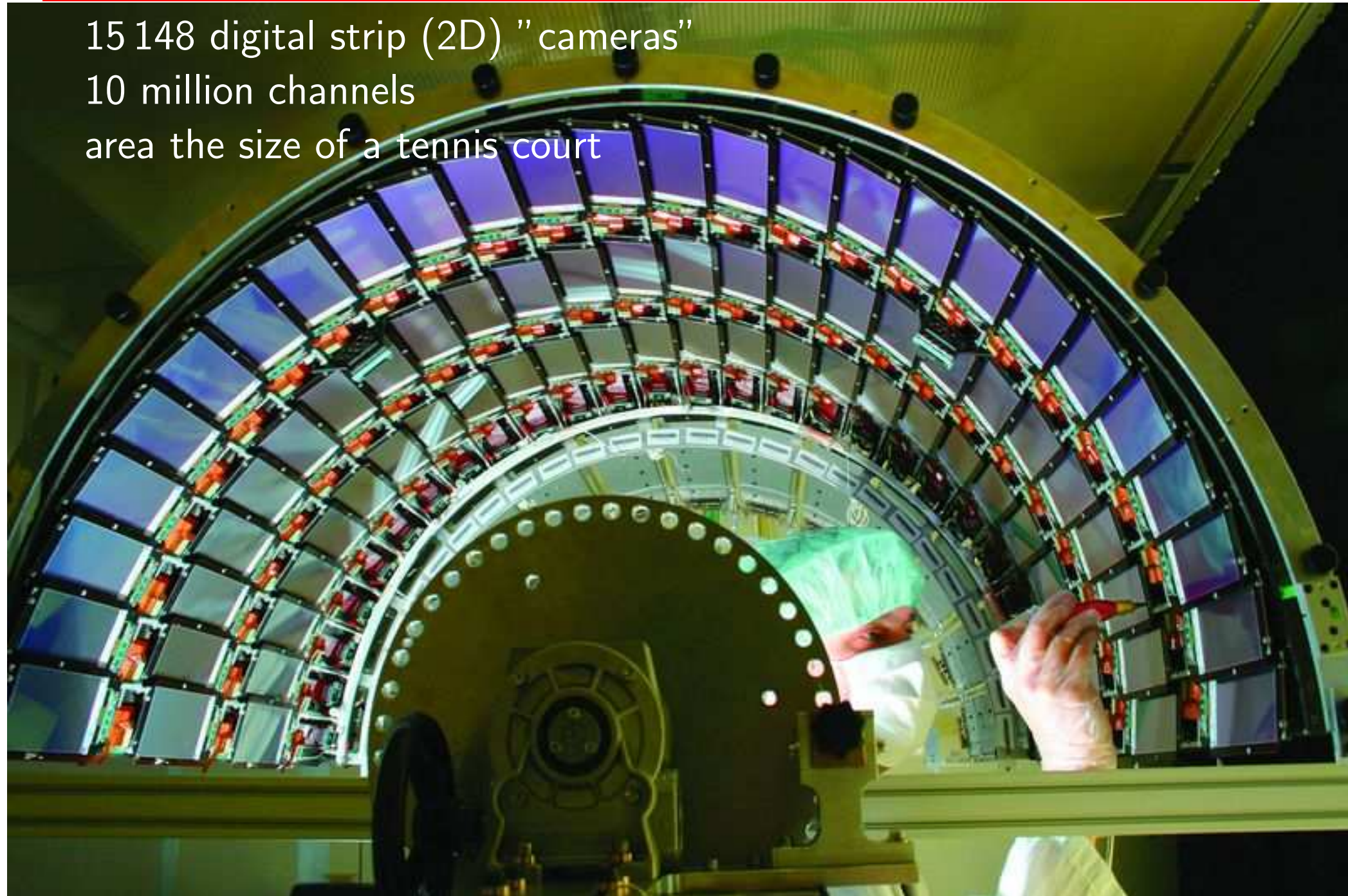


The Silicon Pixel Detector



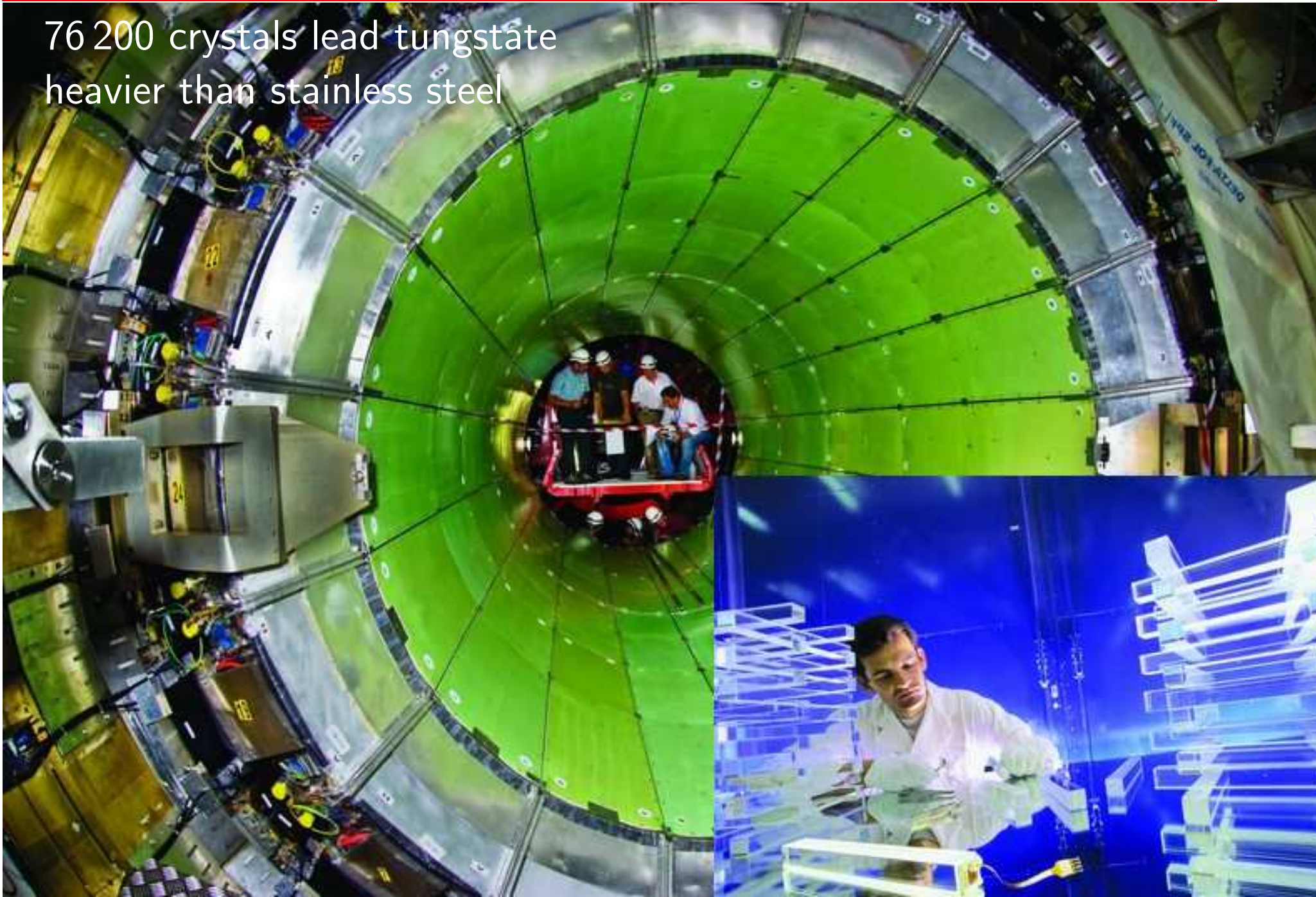
The Silicon Strip Detector

15 148 digital strip (2D) "cameras"
10 million channels
area the size of a tennis court



Electromagnetic Calorimeter

76 200 crystals lead tungstate
heavier than stainless steel

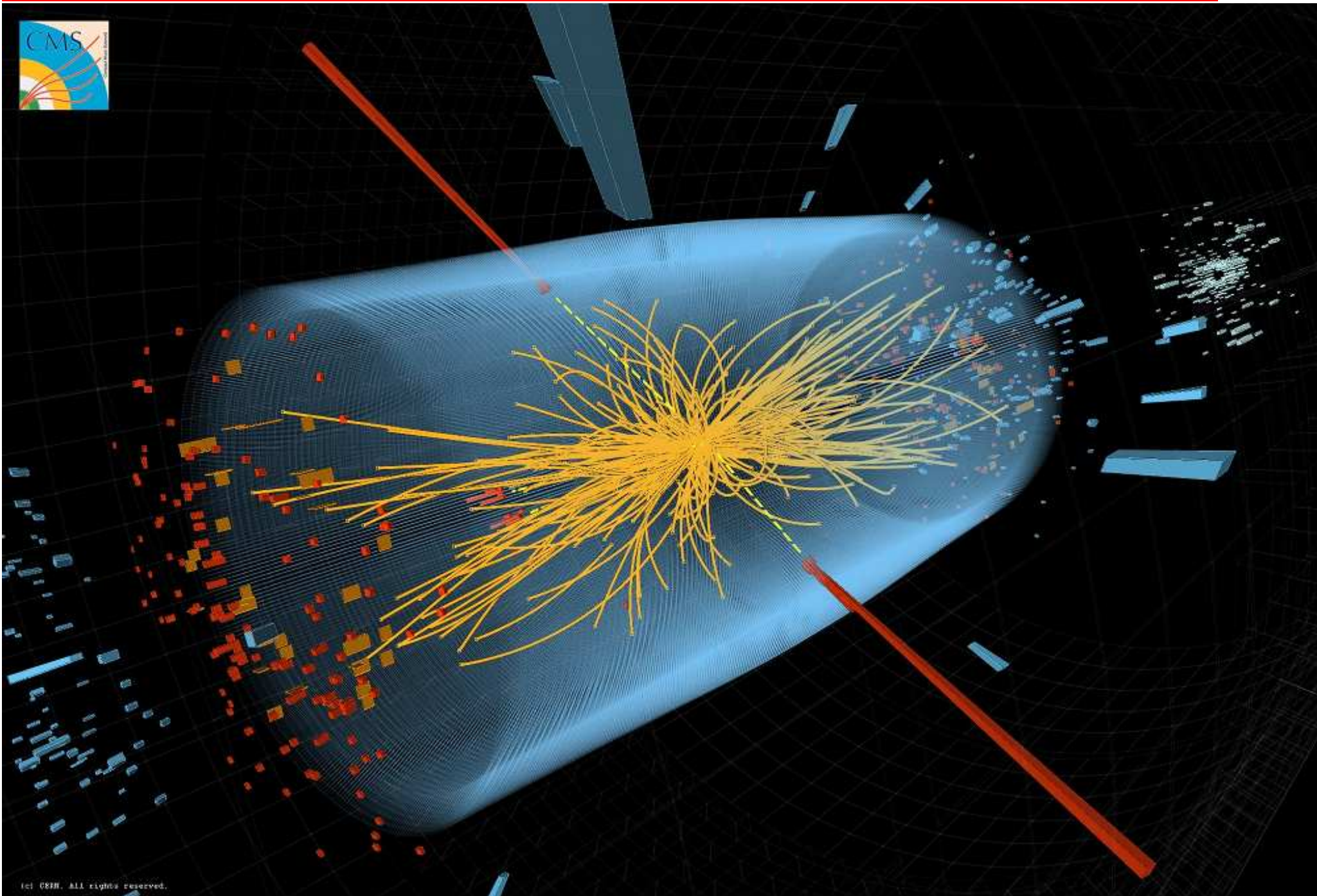


Hadronic Calorimeter and Muon System

>1 million WWII brass shells \Rightarrow HCAL absorber
HCAL scintillator \Rightarrow light signal
1400 Muon chambers in iron "return yoke," 2 million wires



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

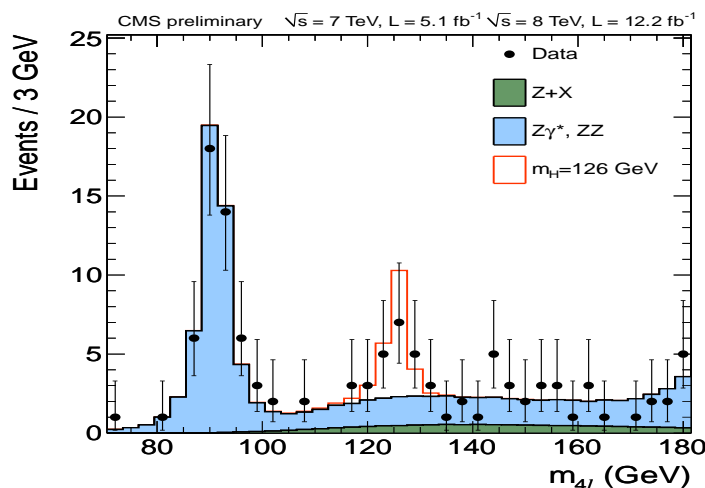
Petabyte = Million Gigabytes
1 Gigabyte \simeq 1 CD
- Flow of data from one experiment alone (CMS):
 - > 300 trillion **proton-proton** collisions in 2011
 - > 3 billion "**events**" recorded on disk in 2011



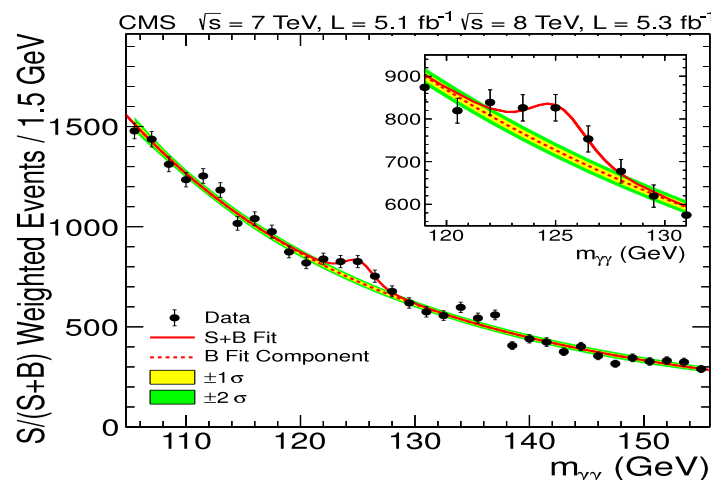
Discovery of a Higgs-like Boson

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

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



$$X \rightarrow \gamma\gamma$$

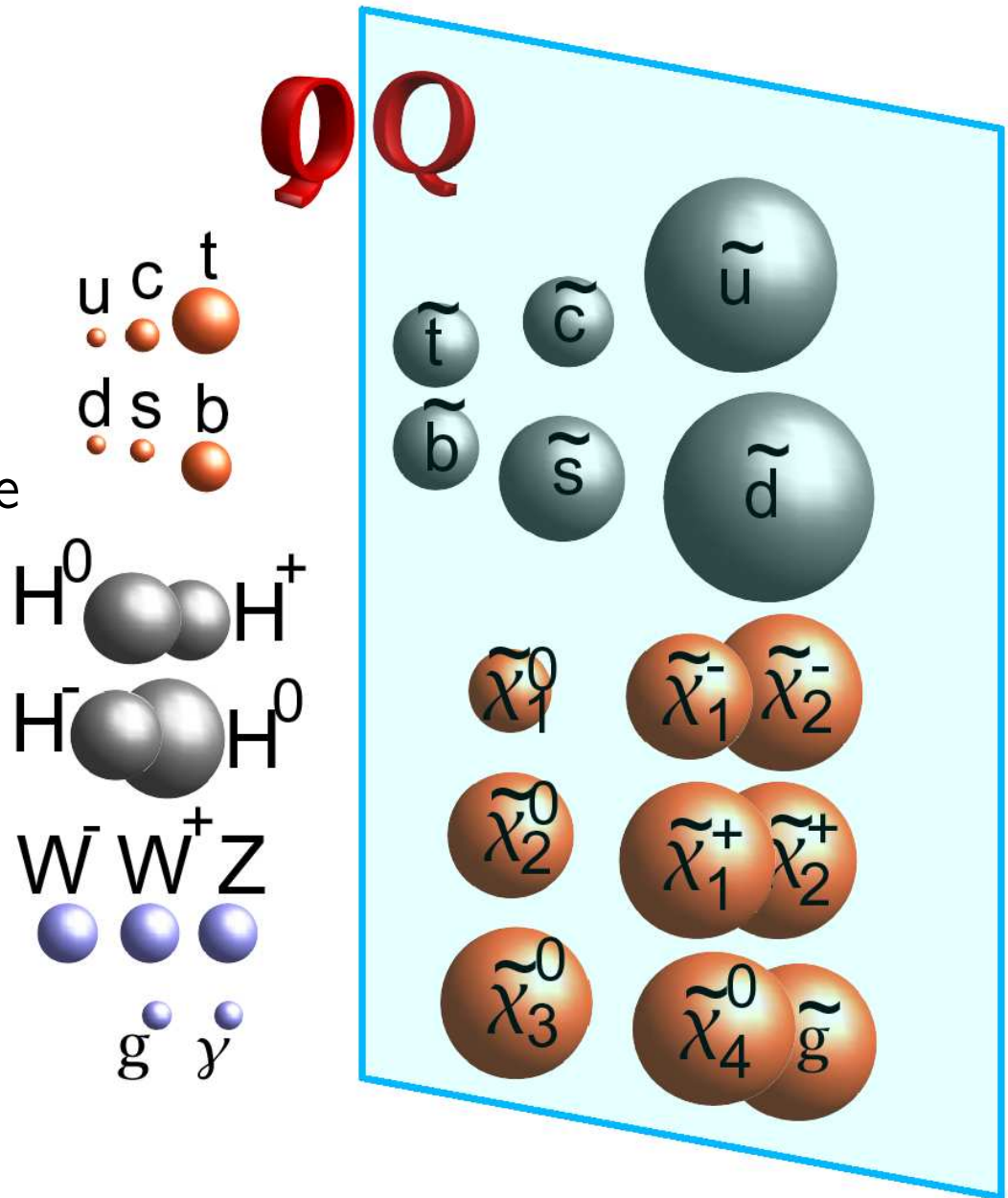


- it is a **boson**, $\text{spin} \neq 1 \Rightarrow \text{spin} = 0$ or 2 ... nothing like this before (!)
even if composite, not from known objects (!)
 - quantum numbers: $J^P = 0^-$ excluded ($> 95\%$ CL),..
 - couples to **fermions** (matter) and **bosons** similar to SM **Higgs boson**
- Need to go **deeper** and **broaden** 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 ($\sim 70\%$)
 - leads to accelerated expansion of the Universe (what is it?)
- Dark matter ($\sim 25\%$)
 - behaves differently from ordinary matter (what is it?)
- Ordinary matter ($\sim 5\%$)
 - from Hydrogen to Uranium – our natural resources
- Antimatter ($\sim 0\%$)
 - disappeared after the Big Bang (why?)
- Higgs field or something alike
 - origin of mass (how?)