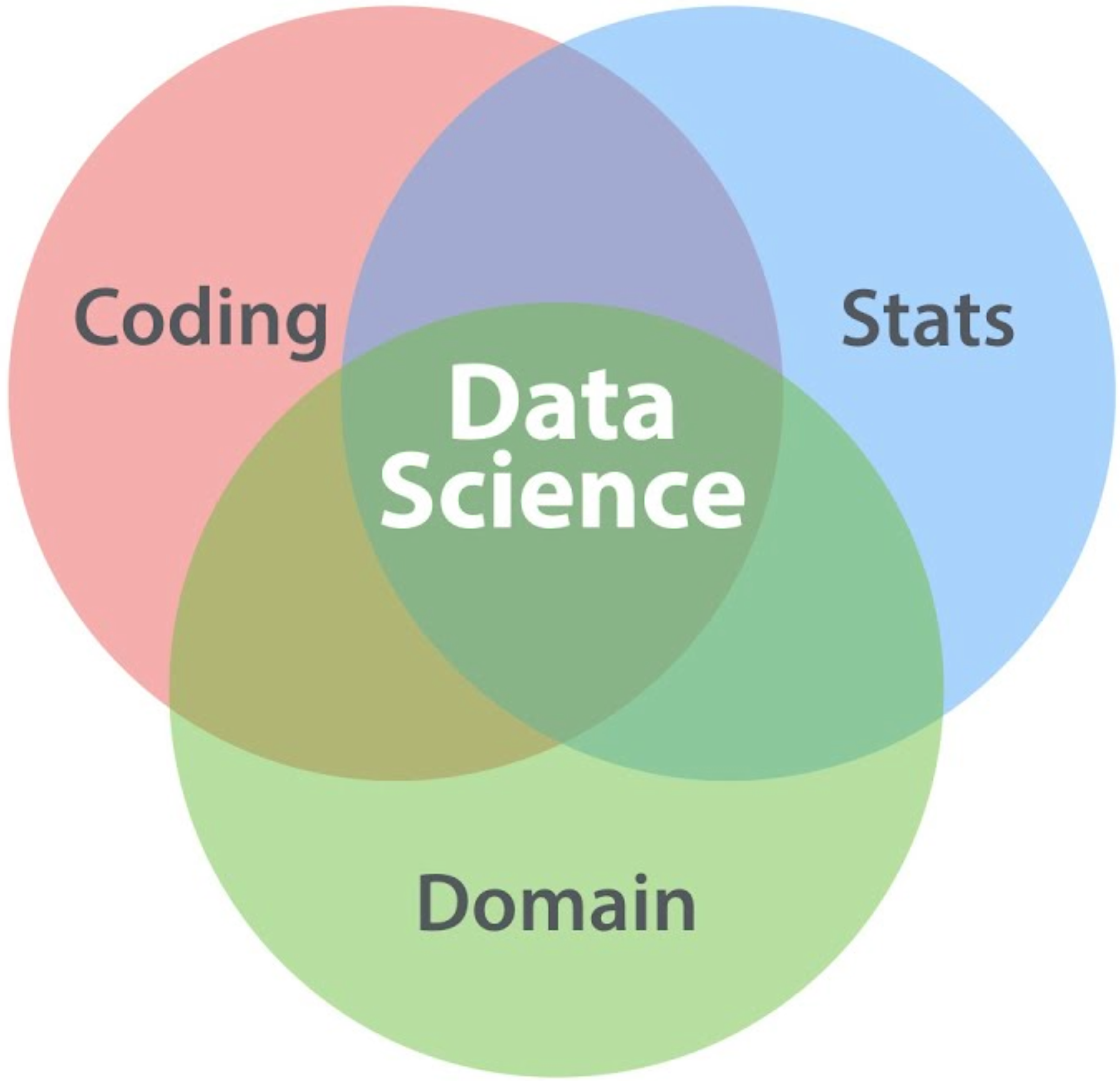
Python for Data Science 2

Lecture 13

Amir Farbin

Domain

- Scientists these days are more are more gaining their insights from applying data science to their problems.
  - As a result they generally become good data scientists.
    - Apply the Data Science to other fields
- Data Science is generally applied to a domain.
- A “Generic” Data Scientists needs to be able to understand enough about a domain to formulate and tackle problems in that domain.
- We’ll be using examples from my domain (Particle Physics aka High Energy Physics)…
  - Plan ~3 Lectures on HEP



Big (Fundamental) Questions

The Universe

When did the Universe begin/how big is it?

What is the Universe made of?

How did the Universe evolve?

Telescopes: look far into space (back into time). Study stars, black-holes, gases, galaxies, galaxy clusters, quasars, super-novas, gamma-ray bursts, etc ...

Cosmic Microwave background: study the after-glow of the big bang.

Physical Laws

What is matter?

What are the forces?

Why are things as the are?

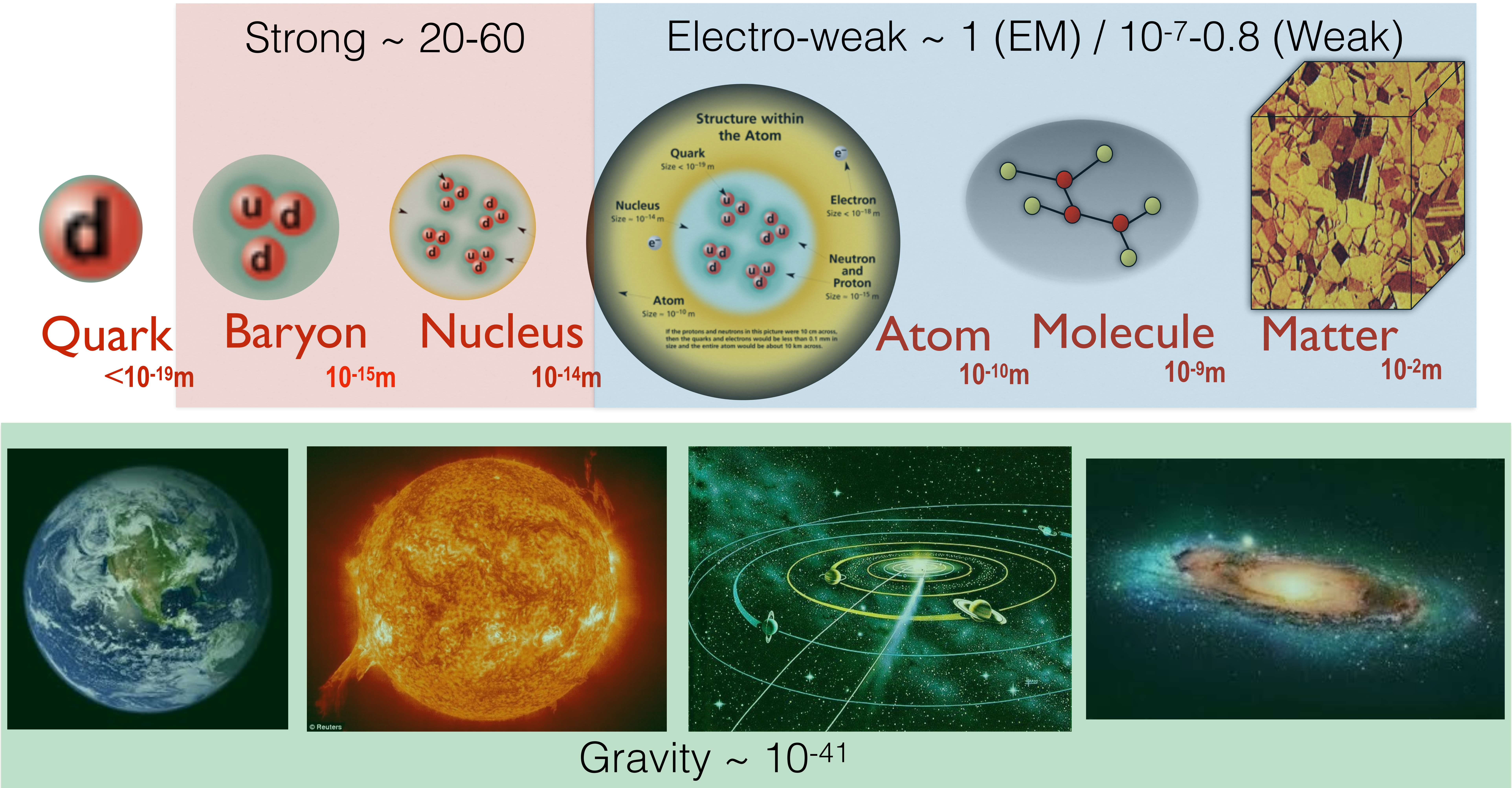
Particle Accelerators + Detectors: "microscope". The faster the particles the better the resolution.

Specialized Detectors: study or search for particles (eg neutrinos, ultra-high energy cosmic rays, axions) from various sources

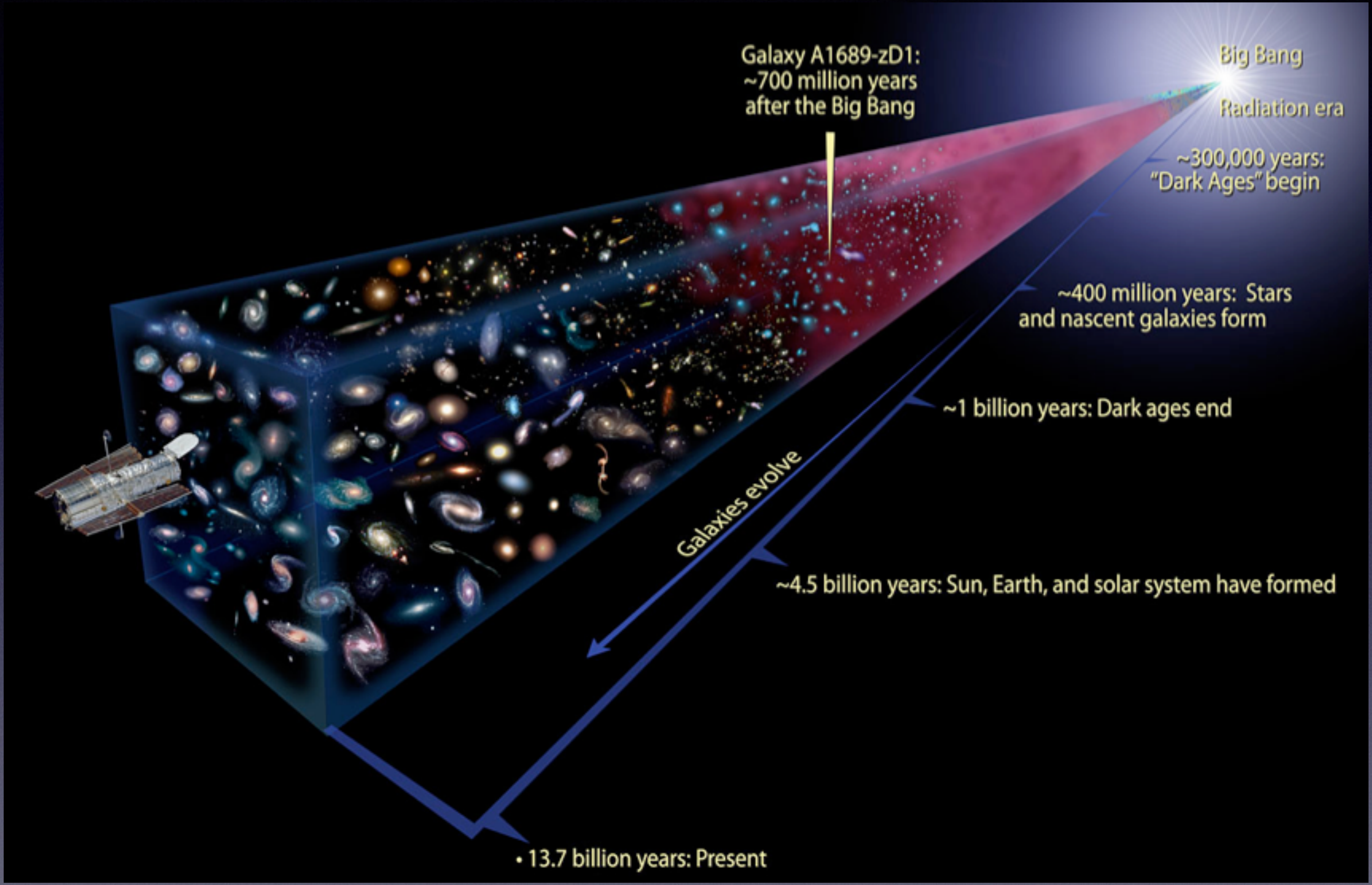
Big Bang

Building a Universe…

- Each "structure" is due to some fundamental force.
  - The stronger the force the smaller the structure.
  - The weaker the force the larger the structure.



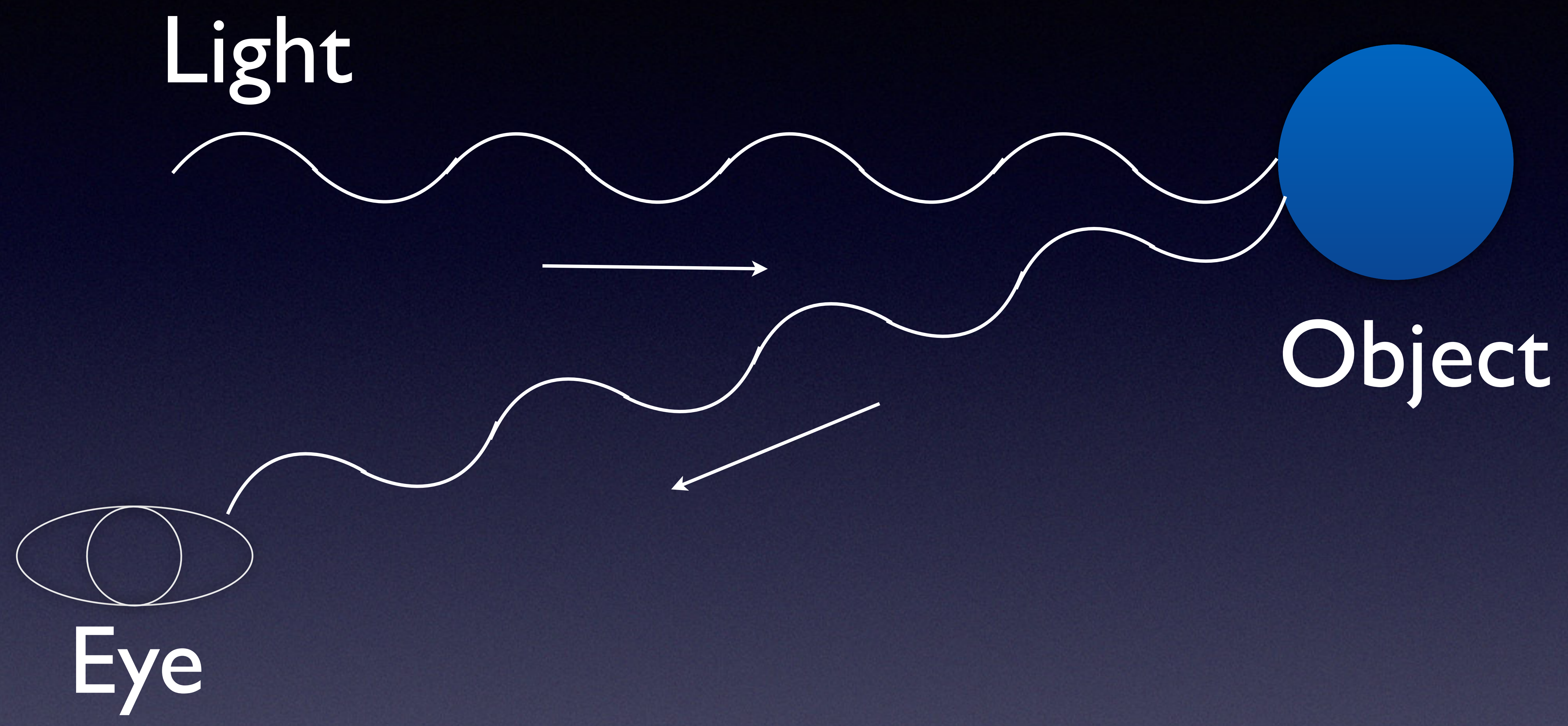
Emergence of Structure



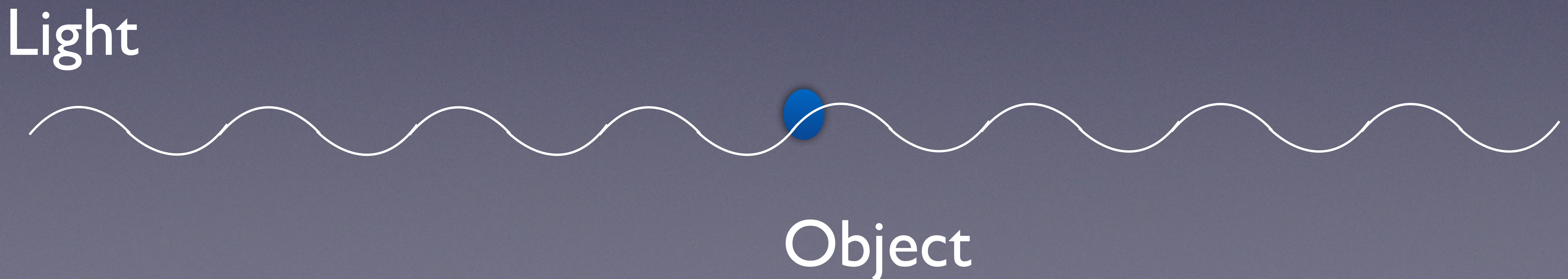
Science of the Smallest Scales (Highest Energies)

How do we “see”?

Wavelength < Object



Wavelength > Object



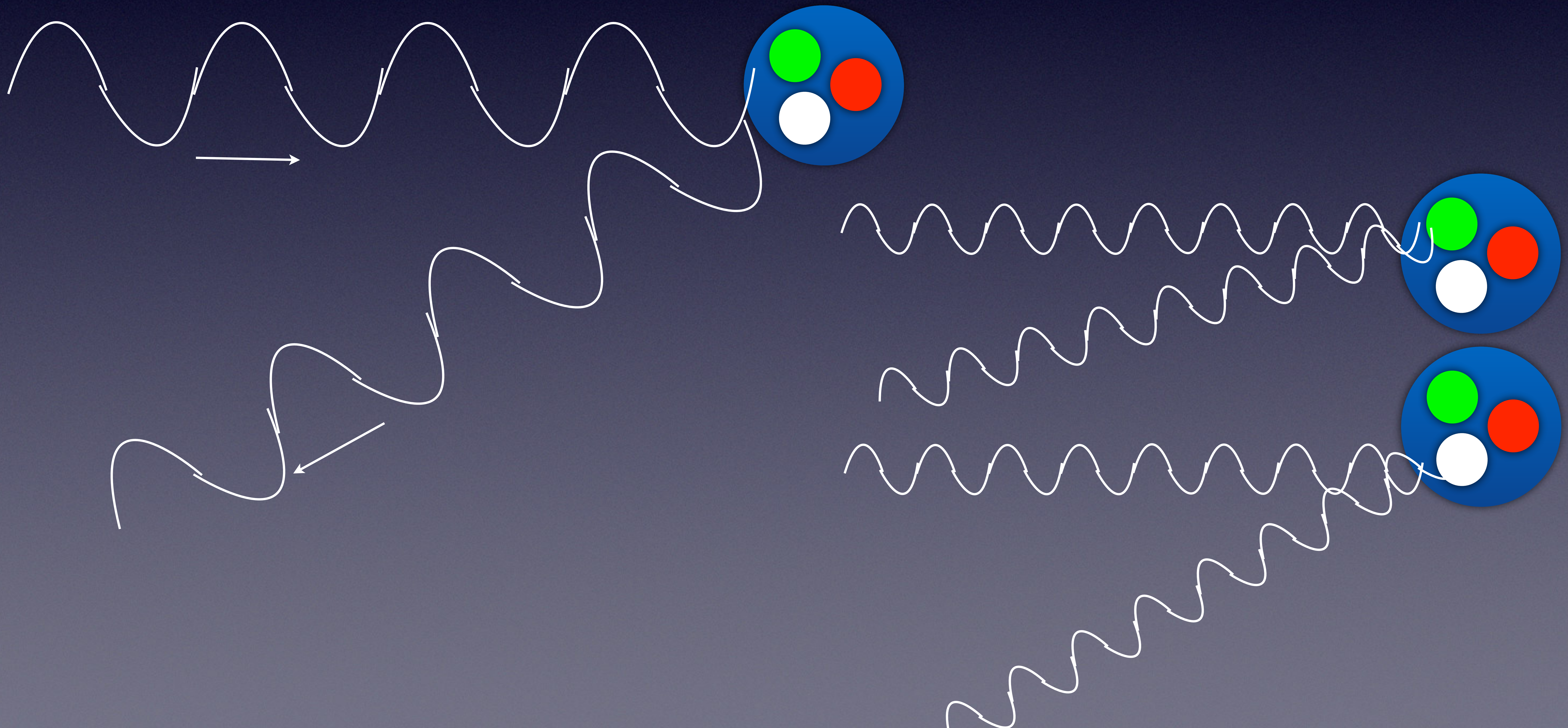
“Seeing”

- To see smaller and smaller objects, we have to use smaller and smaller wavelengths
  - Smaller wavelength = Higher Frequency = Higher Energy

  - So we need High Energies to see very small distances.
- Our eyes can see only certain wavelengths.
  - We need special detectors that can “see” these wavelengths
  - Actually, we don’t have to use light... we can use other particles.
    - Easier to get other particles to higher energies... and then see them.
    - All small particles behave like waves and particles. (Wave particle duality / de Broglie wave-length)

Fundamental or Composite

- When we try to look at an object closely, the most basic question is:
  - Is it make of other smaller things (aka is it a composite particle) or not (aka fundamental)?



Making Matter!

- Einstein's Relativity tells us $E=mc^2$... or Mass and Energy are the same thing.
  - Energy in the form of mass is very potent...
    - So turning mass to energy gives us a lot of energy (nuclear reactors, bombs, ...)
    - Conversely takes a lot of energy to make mass.
- But... as we turn up the energy of our particles to "see" smaller and smaller distances, we starting having enough energy to make new particles.
- Heavy particles don't live long... they "decay" into lighter particles... so we don't have them around naturally.
  - But we can create them (using high energies)... and see them decay.
  - We've made 1000's of new particles... but just a few are fundamental.

Standard Model of

FUNDAMENTAL PARTICLES AND INTERACTIONS

The Standard Model summarizes the current knowledge in Particle Physics. It is the quantum theory that includes the theory of strong interactions (quantum chromodynamics or QCD) and the unified theory of weak and electromagnetic interactions (electroweak). Gravity is included on this chart because it is one of the fundamental interactions even though not part of the "Standard Model."

FERMIONS

matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	–1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	–1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	–1

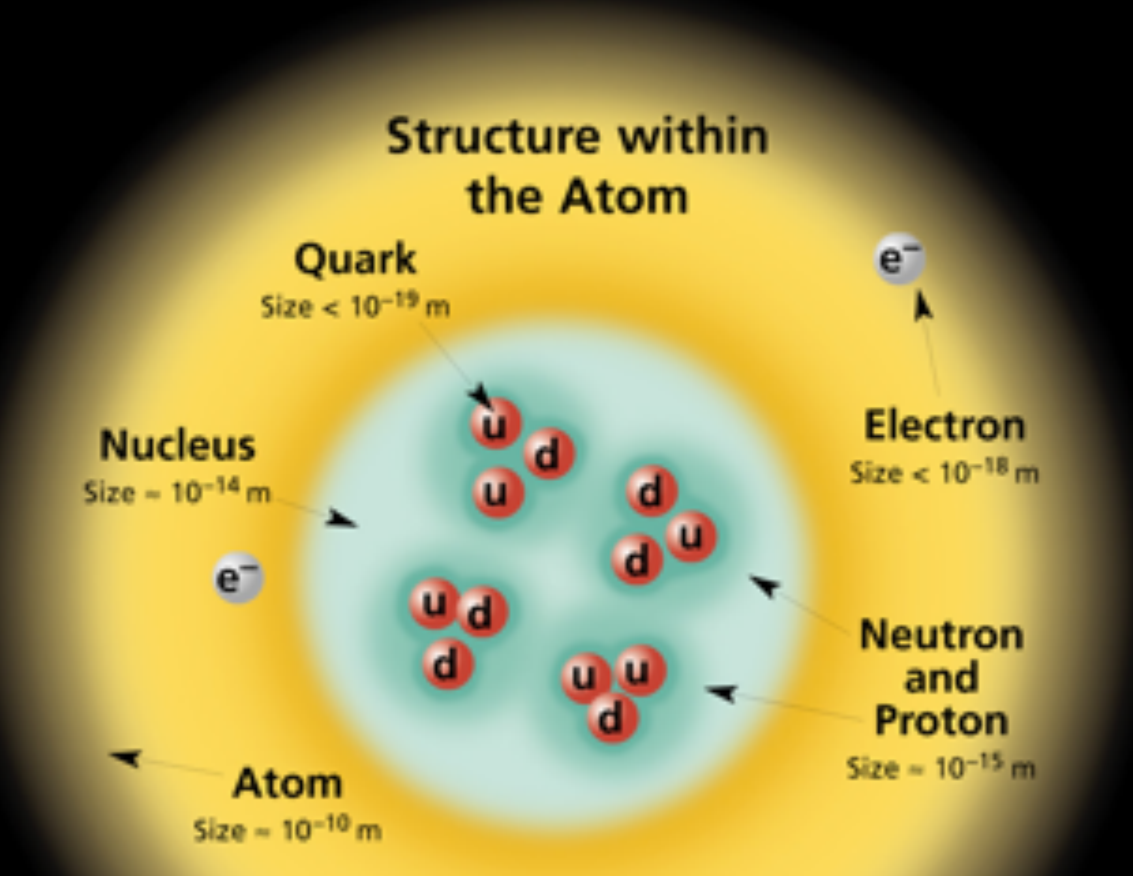
Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	–1/3
c charm	1.3	2/3
s strange	0.1	–1/3
t top	175	2/3
b bottom	4.3	–1/3

Spin is the intrinsic angular momentum of particles. Spin is given in units of $\hbar$, which is the quantum unit of angular momentum, where $\hbar = h/2\pi = 6.58\times10^{-25}$ GeV s $= 1.05\times10^{-34}$ J s.

Electric charges are given in units of the proton's charge. In SI units the electric charge of the proton is 1.60×10^{-19} coulombs.

The **energy** unit of particle physics is the electronvolt (eV), the energy gained by one electron in crossing a potential difference of one volt. **Masses** are given in GeV/c^2 (remember $E = mc^2$), where 1 GeV $= 10^9$ eV $= 1.60\times10^{-10}$ joule. The mass of the proton is 0.938 GeV/c^2 $= 1.67\times10^{-27}$ kg.



If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

BOSONS

force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

Color Charge

Each quark carries one of three types of "strong charge," also called "color charge." These charges have nothing to do with the colors of visible light. There are eight possible types of color charge for gluons. Just as electrically-charged particles interact by exchanging photons, in strong interactions color-charged particles interact by exchanging gluons. Leptons, photons, and ***W*** and ***Z*** bosons have no strong interactions and hence no color charge.

Quarks Confined in Mesons and Baryons

One cannot isolate quarks and gluons; they are confined in color-neutral particles called **hadrons**. This confinement (binding) results from multiple exchanges of gluons among the color-charged constituents. As color-charged particles (quarks and gluons) move apart, the energy in the color-force field between them increases. This energy eventually is converted into additional quark-antiquark pairs (see figure below). The quarks and antiquarks then combine into hadrons; these are the particles seen to emerge. Two types of hadrons have been observed in nature: **mesons** $q\bar{q}$ and **baryons** qqq.

Residual Strong Interaction

The strong binding of color-neutral protons and neutrons to form nuclei is due to residual strong interactions between their color-charged constituents. It is similar to the residual electrical interaction that binds electrically neutral atoms to form molecules. It can also be viewed as the exchange of mesons between the hadrons.

PROPERTIES OF THE INTERACTIONS

Property \ Interaction	Gravitational	Weak (Electroweak)	Electromagnetic (Electroweak)	Strong: Fundamental	Strong: Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
Strength relative to electromag for two u quarks at: 3×10^{-17} m	10^{-41}	10^{-4}	1	60	Not applicable to quarks
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2

Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

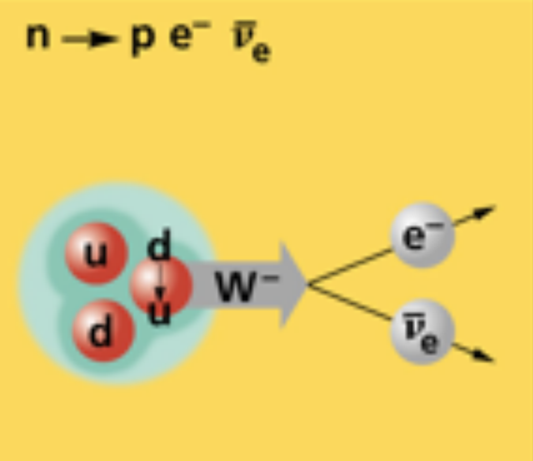
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

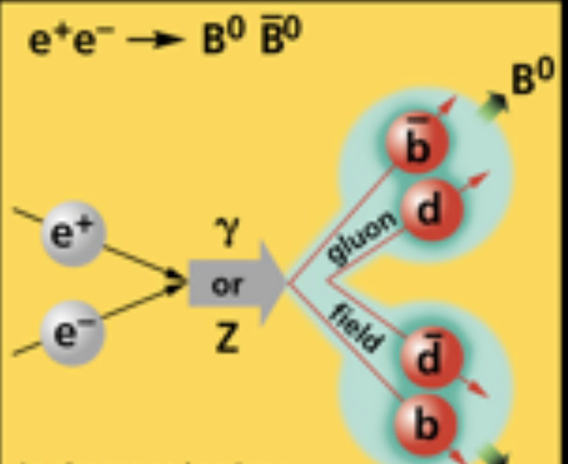
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not $K^0 = d\bar{s}$) are their own antiparticles.

Figures

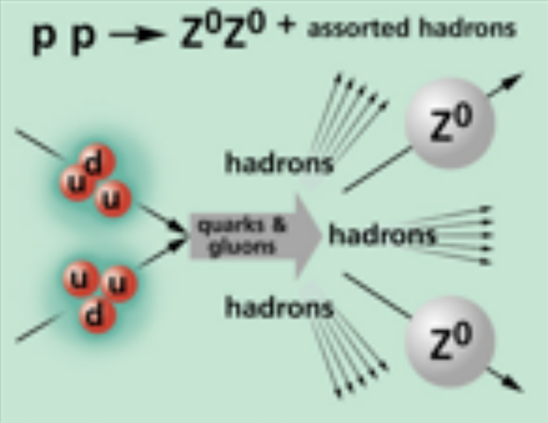
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



A neutron decays to a proton, an electron, and an antineutrino via a virtual (mediating) W boson. This is neutron β decay.



An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

The Particle Adventure

Visit the award-winning web feature *The Particle Adventure* at
http://ParticleAdventure.org

This chart has been made possible by the generous support of:

U.S. Department of Energy
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Stanford Linear Accelerator Center
American Physical Society, Division of Particles and Fields
BURLE INDUSTRIES, INC.

http://CPEPweb.org

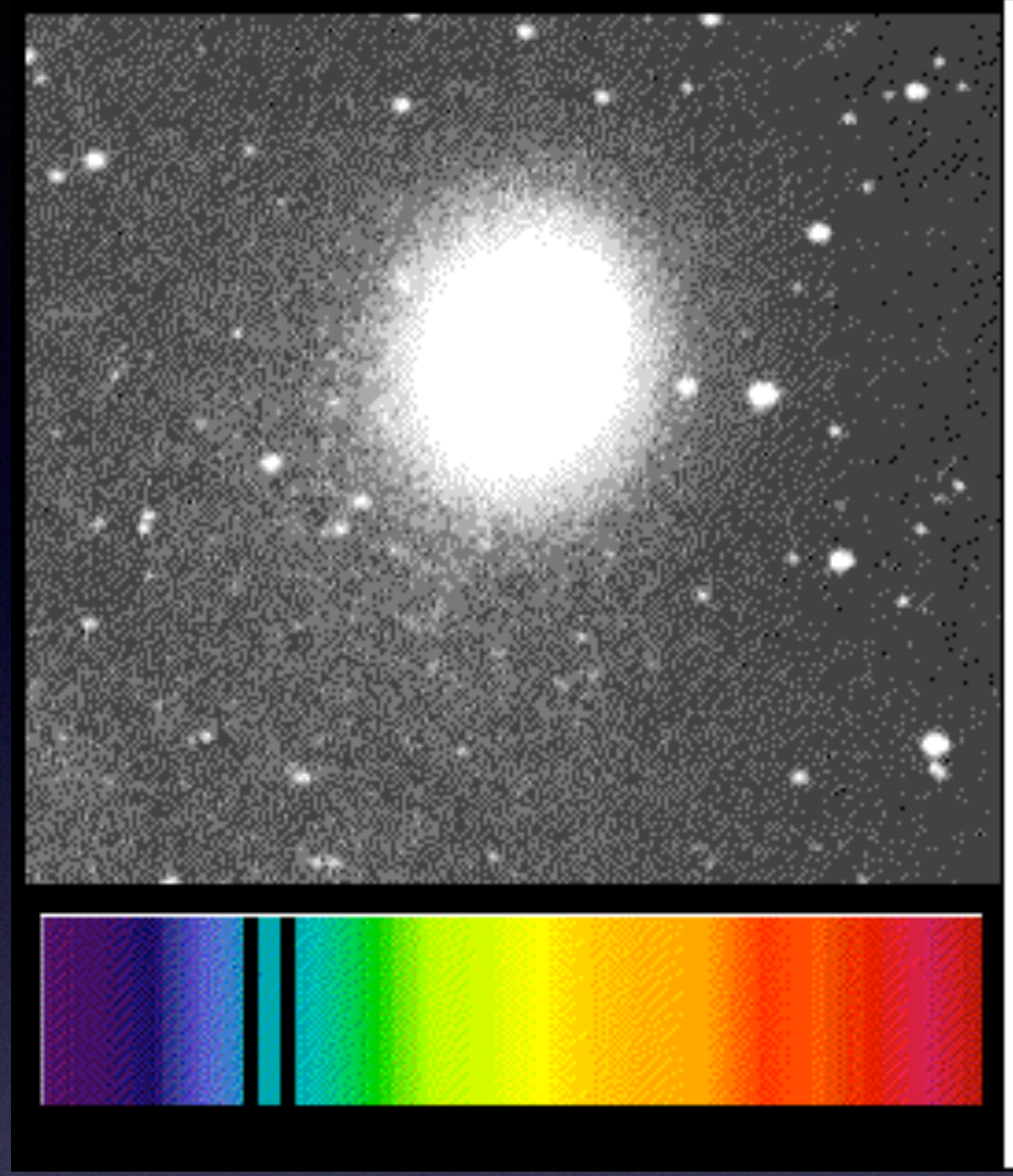
Science of Largest Scales

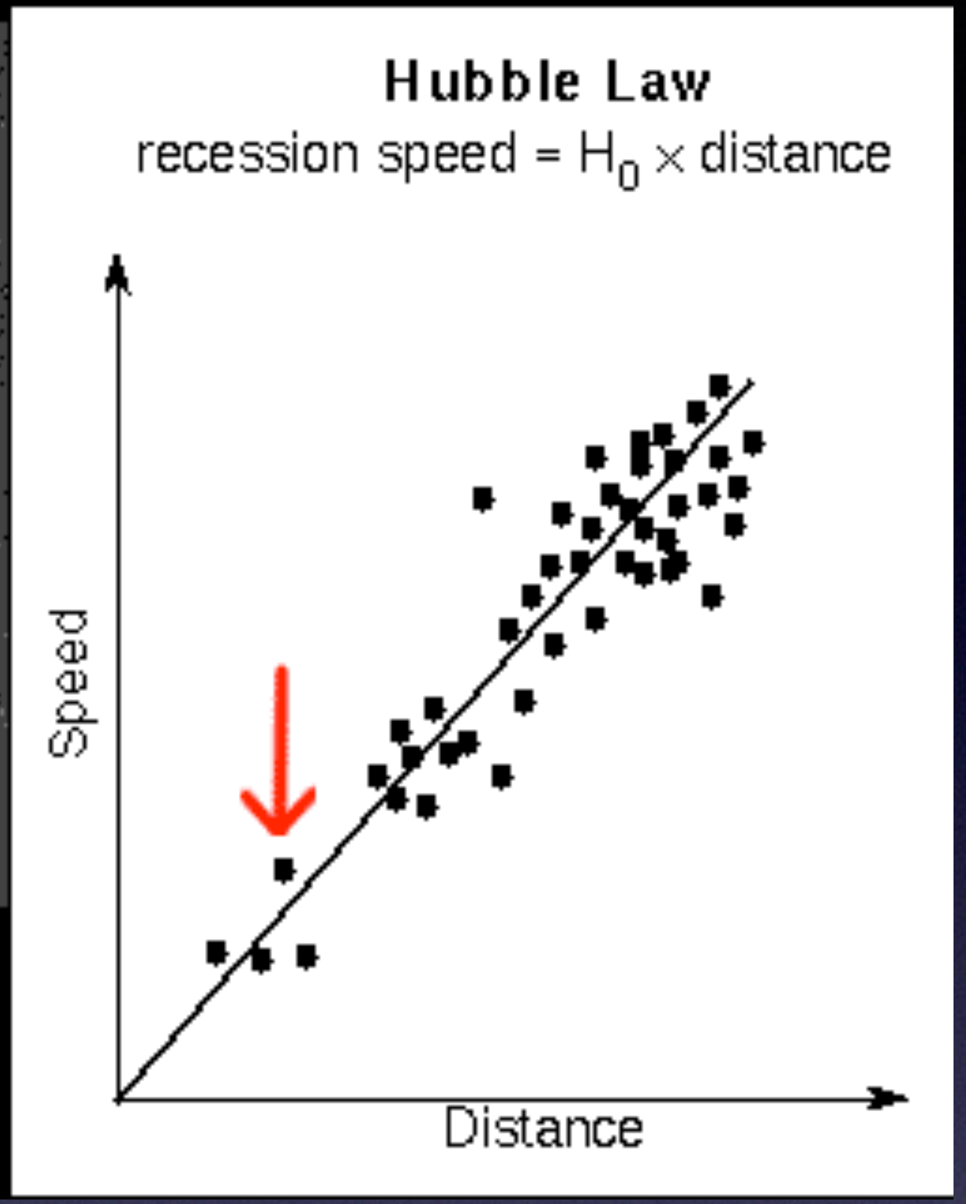
Telescopes!

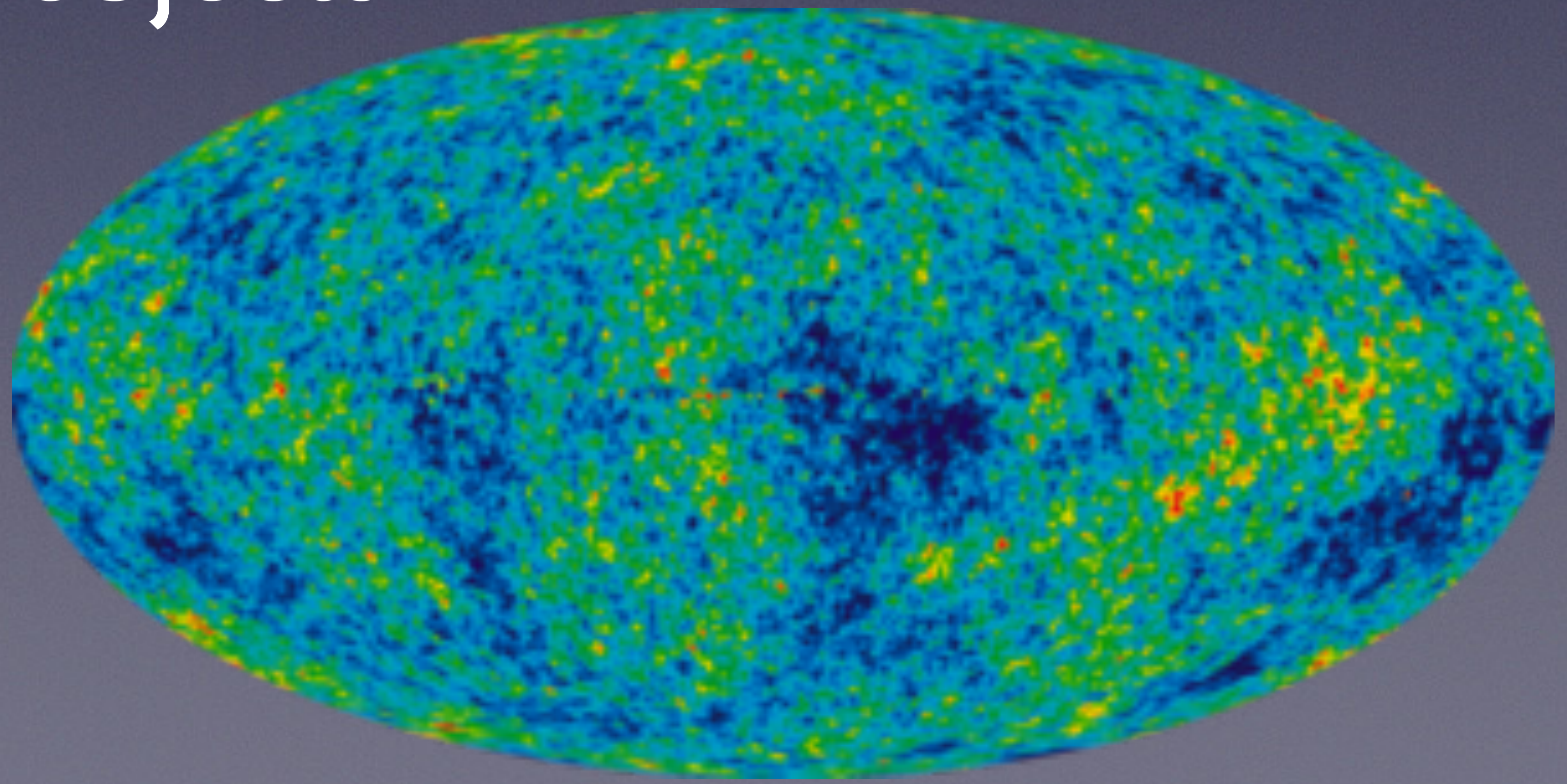
- If we look at the sky carefully we see that
  - We live on a planet, which is part of our solar system.
  - Our sun is one of billions in our galaxy
  - Our galaxy is one of billions in the Universe.
- Since Light takes time to travel
  - If you look at the sun, you see it as it was 8 mins ago!
  - The further away we look, the further back in time we see!
- So if we look far enough, we can see the beginning of the Universe.
  - It’s difficult to see far objects... they are very faint.

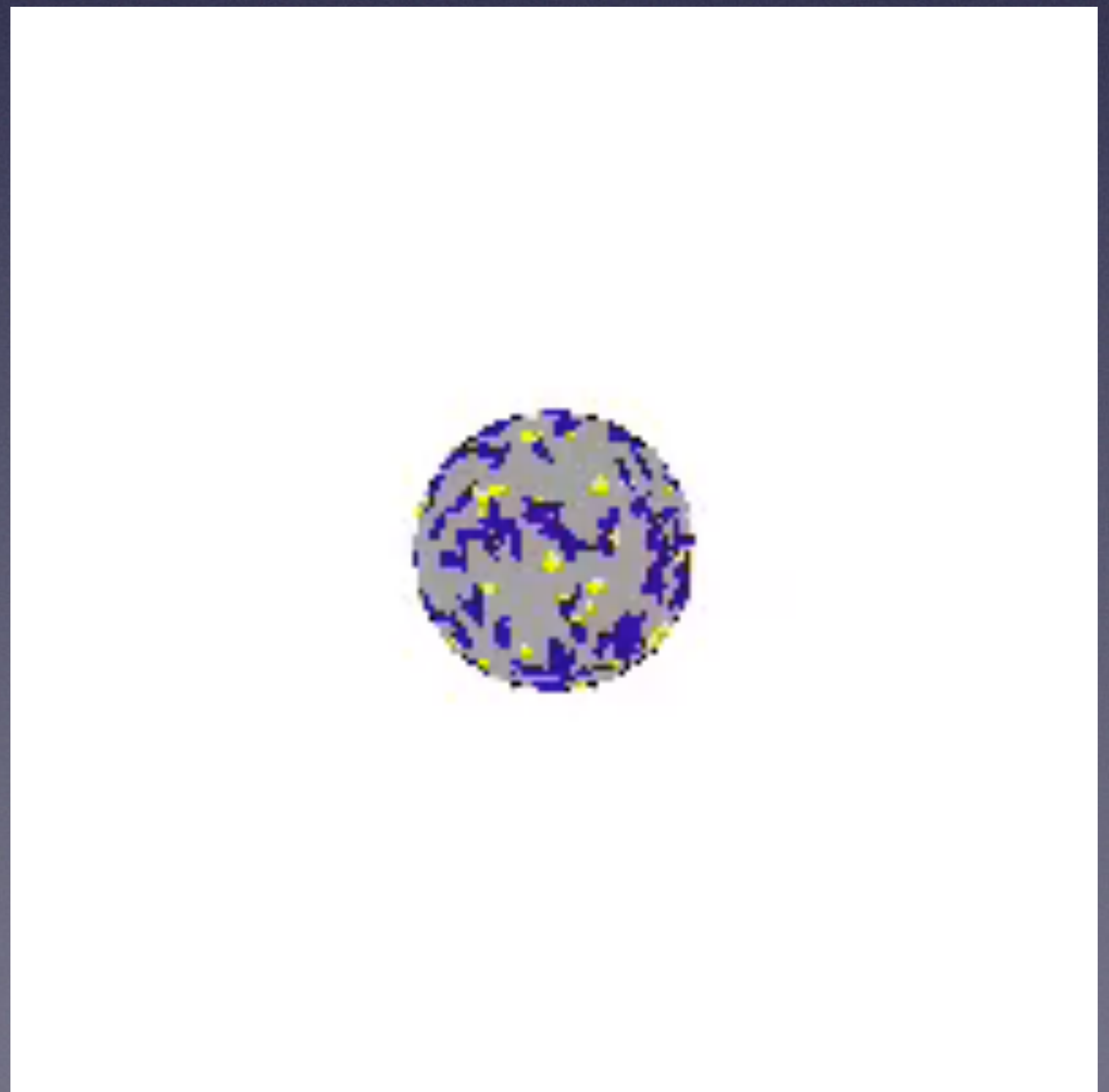
The Universe

- The Universe is Expanding!
  - Hubble
  - Cosmic Microwave Background
- The Universe Started 13.4 Billion Years Ago
  - Measure distance to furthest objects









Expanding Universe

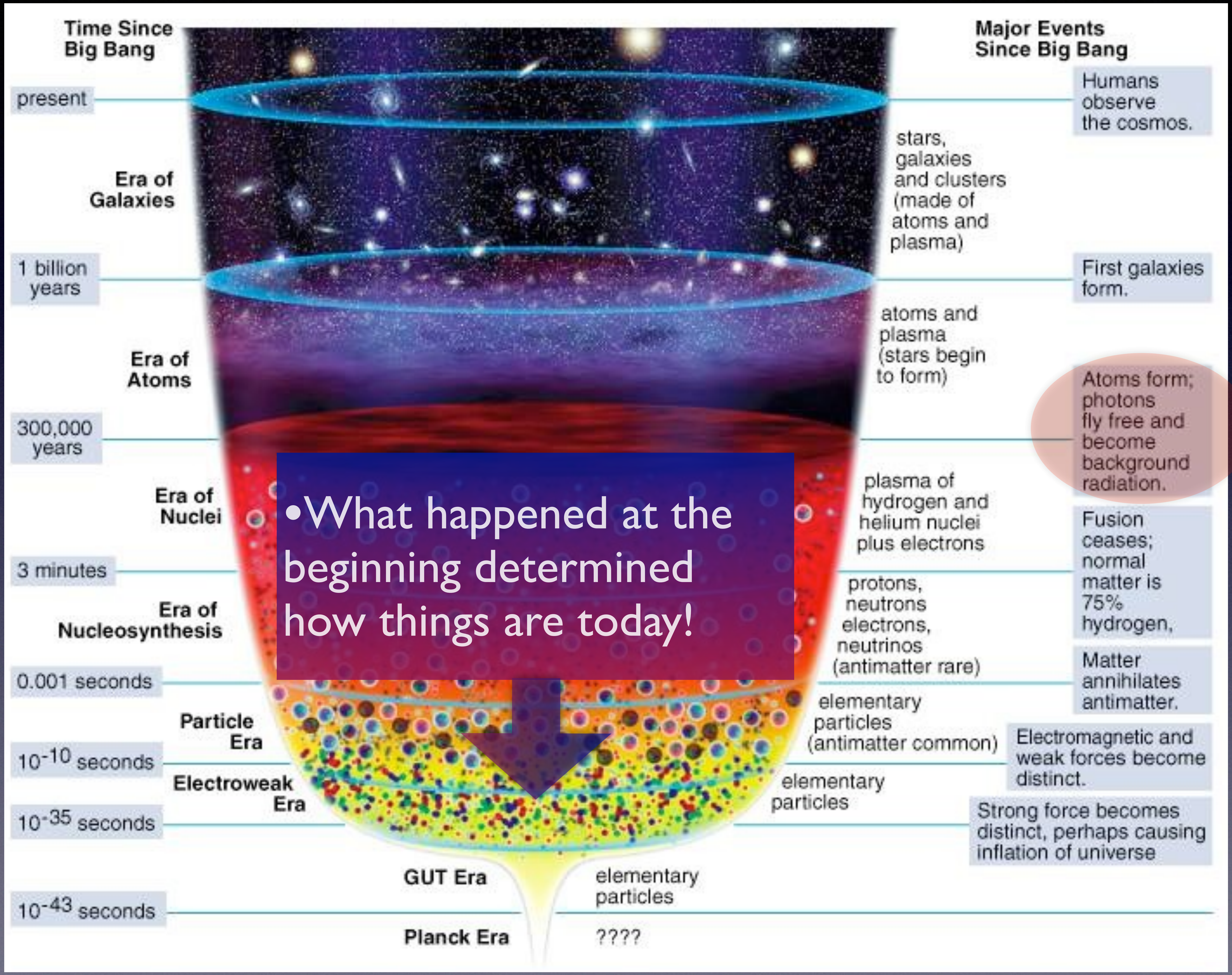
- What happens if you take a lot of stuff and squeeze it together?
  - That's what gravity does to hydrogen gas in space...
    - the result are stars like our sun.
  - As you squeeze things together, they get hot (ie more energetic)
- Now think about the Universe...
  - If the Universe is expanding, it use to be much smaller than now.
  - So all of the stuff in the Universe was squeezed together.
    - So it was much hotter.
    - If we go back long enough, it was so hot that exotic were particles routinely made.

History of the Universe

Today

13.4 Billion Years

“Beginning”



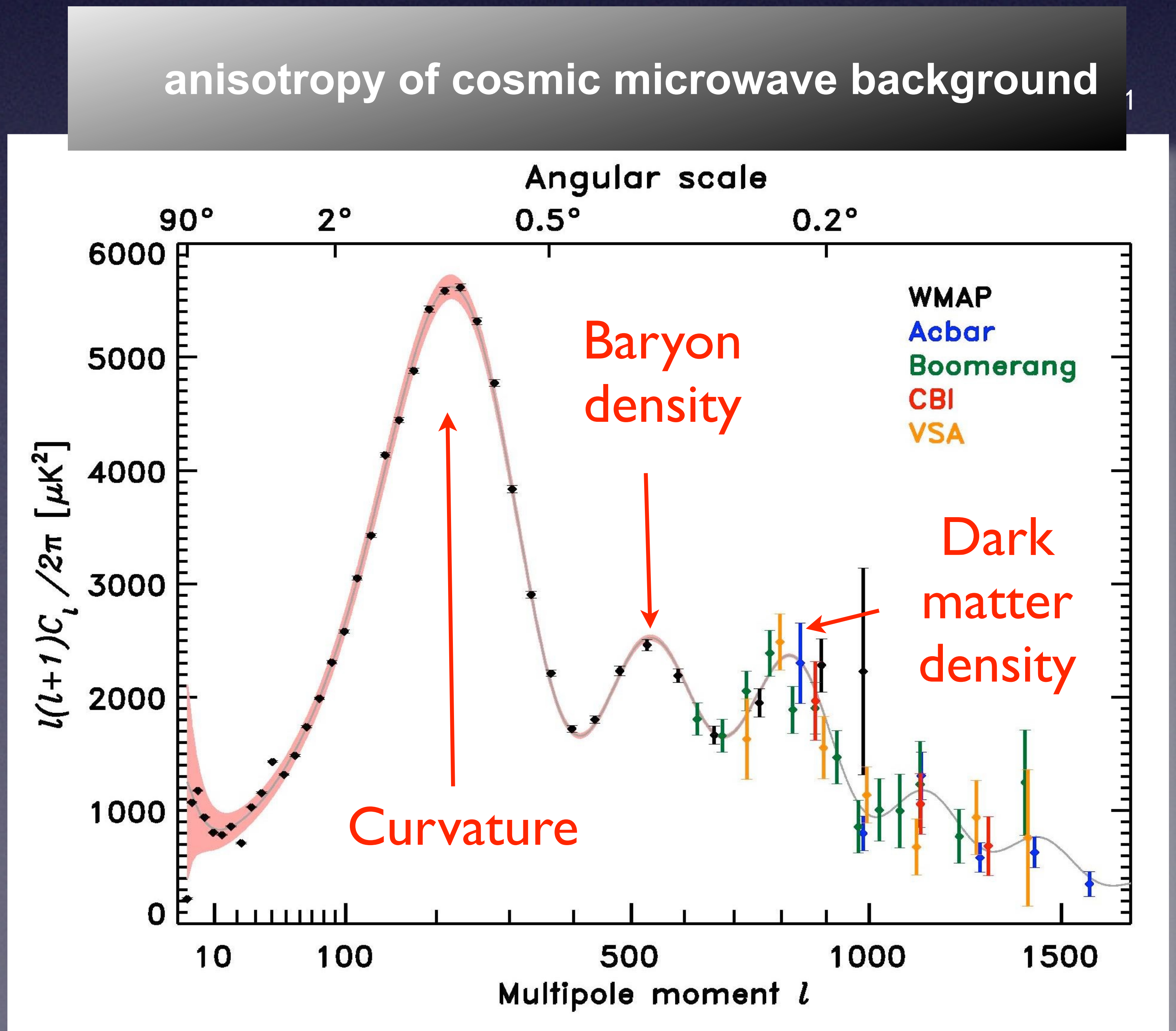
- What happened at the beginning determined how things are today!

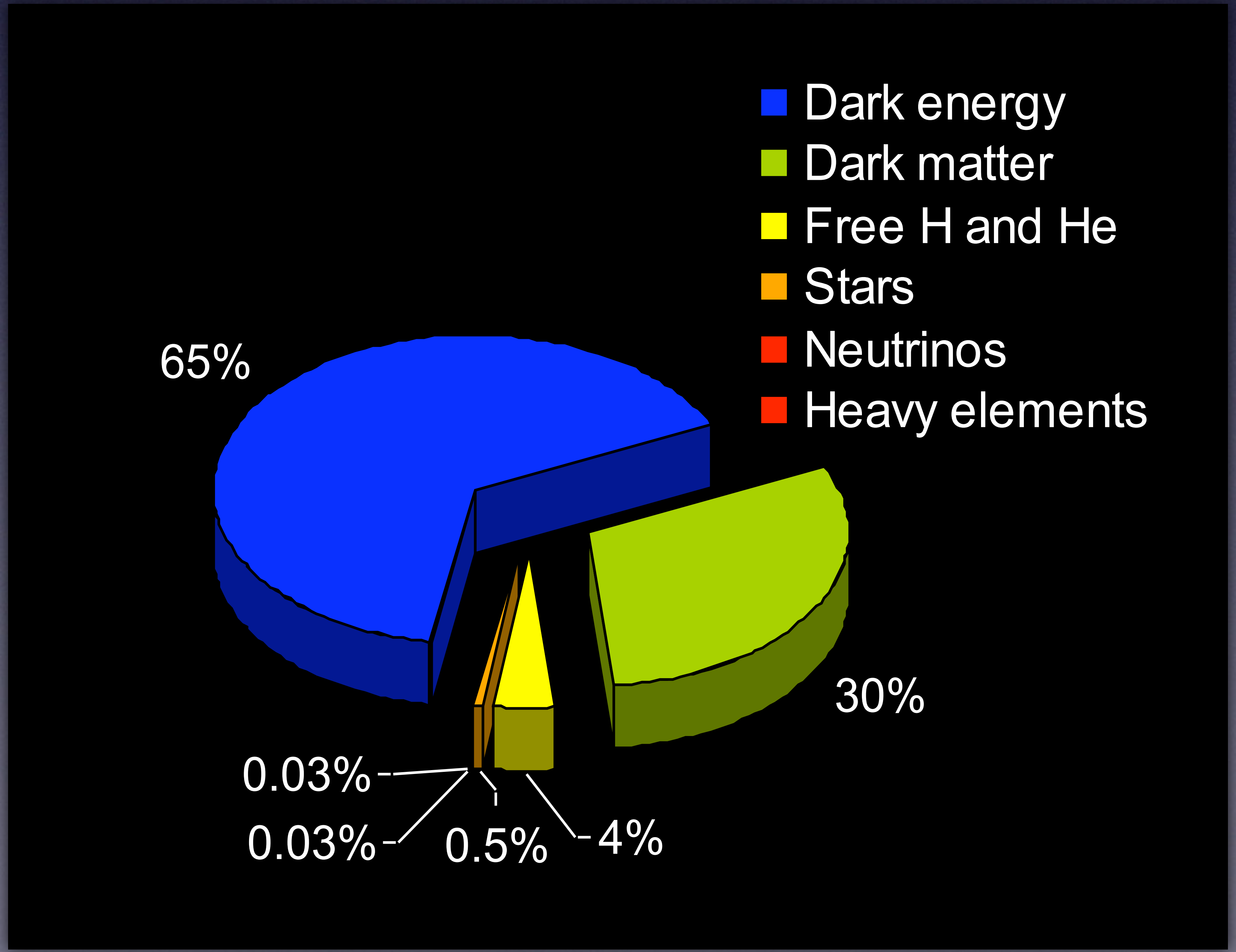
3 Cosmic Mysteries

- Phenomena whose existence is certain due to large-scale observation, but never been captured or produced in a lab.
  - *Dark Matter...* known since 1933
    - Rotation Curves
    - Gravitational Lensing
    - Bullet Cluster
    - Early Galaxies
  - *Dark Energy...* known since 1998
    - Supernovae
  - *Inflation...* "confirmed" in early 2000s. "The Universe is Flat!"
    - Cosmic Microwave Background
- Need to particle physics to understand the nature of these phenomena.
- Dark Matter is the key: "Dark Matter Miracle"

What is in the Universe?

- Convergence of various observations tell us that < 5% of the universe is made of stuff we understand!
  - It's mostly Dark Matter and Dark Energy
  - The Density of Dark Matter in the Universe suggests that it's made of particles with mass ~ 0.1 - 1 TeV





Recreating the Early Universe

- In the early universe, really energetic particles collided, making other particles... which then decayed... and then collided... etc.
- We can recreate those collisions and produce some of the same particles...
  - Maybe we can make Dark Matter (probably)
  - But there are other good reasons...

Was the Universe an accident?

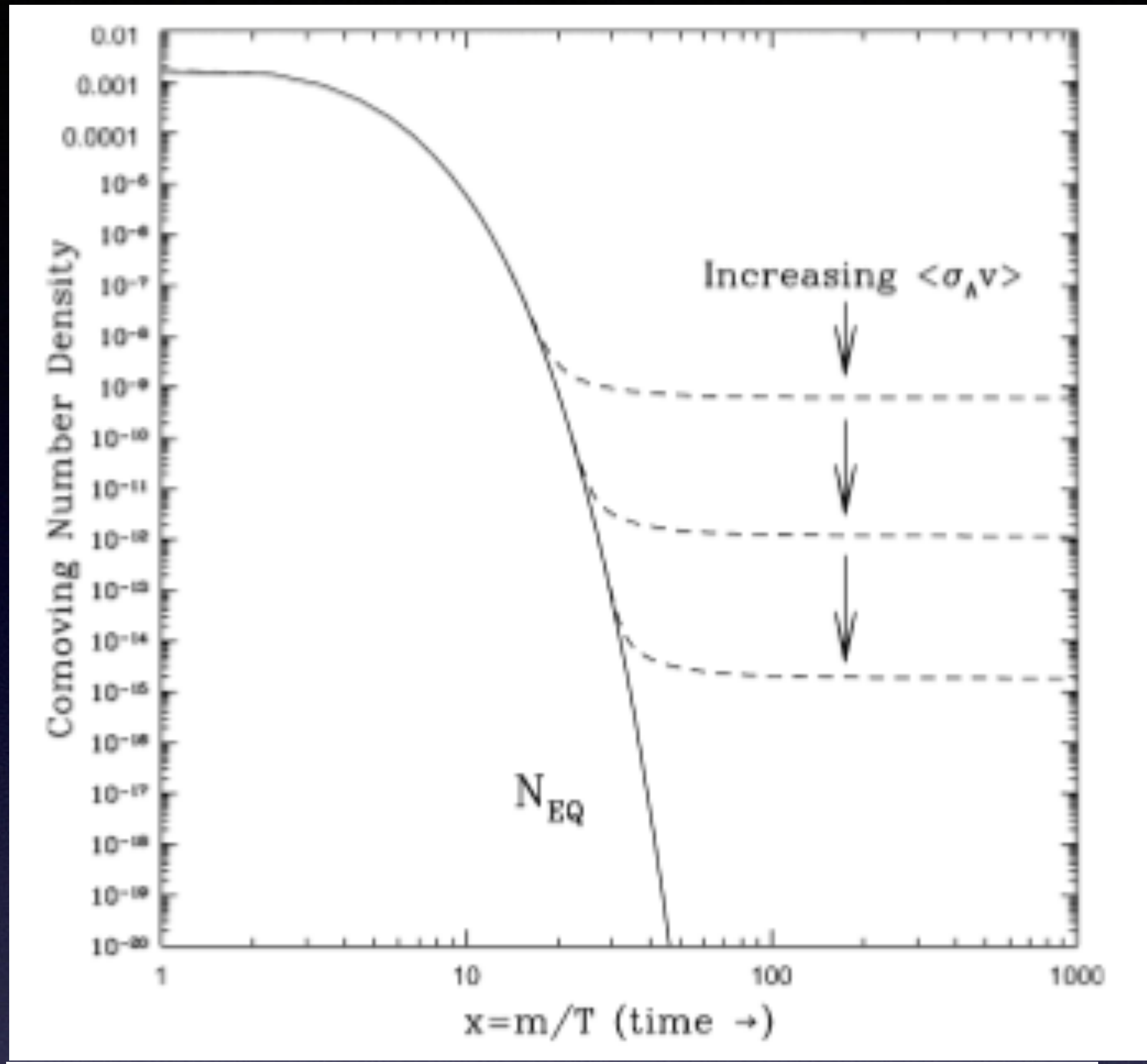
Artificial Intelligence studying LHC data on Supercomputers may find the answer.

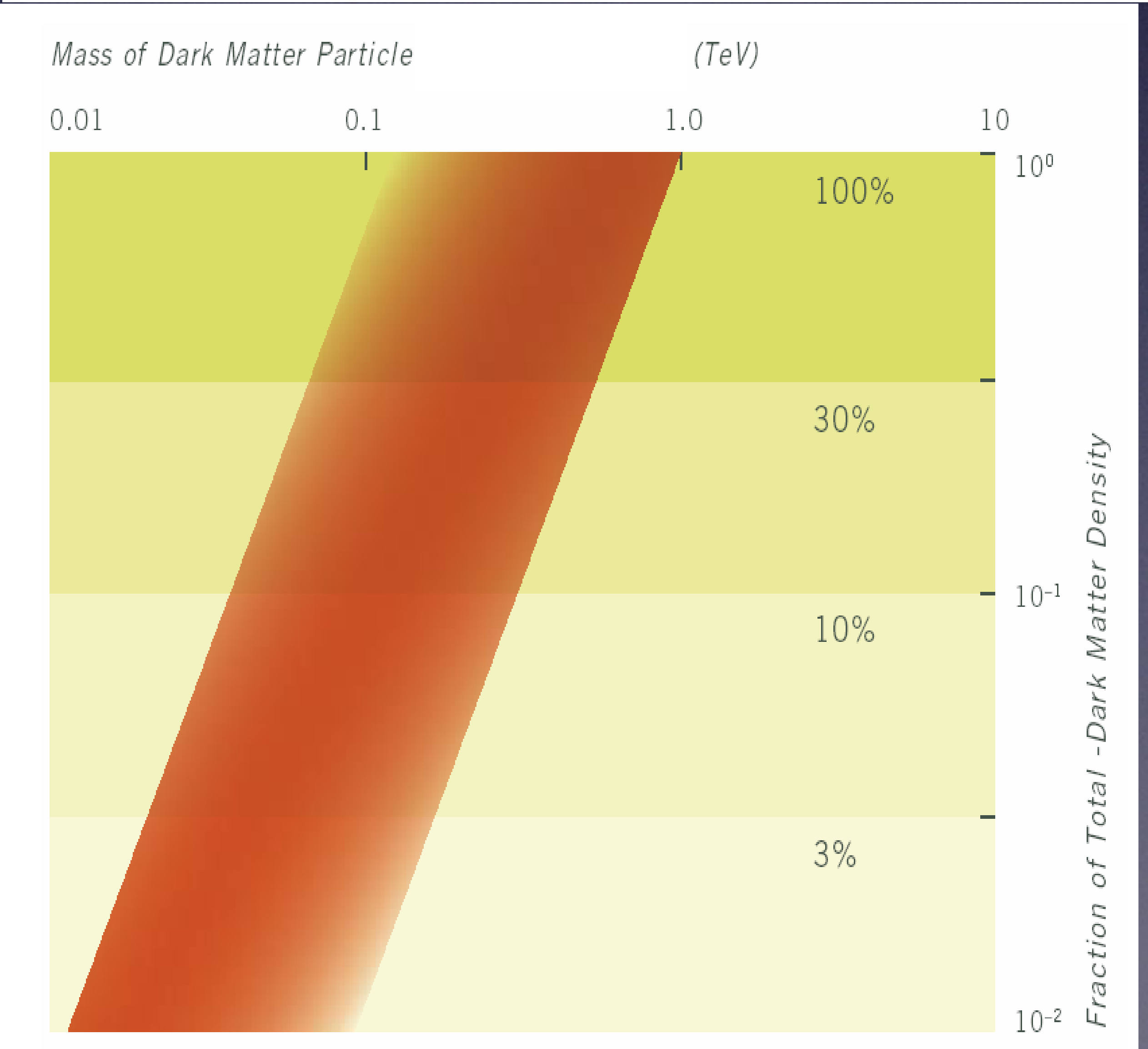
Reasons for Building the LHC

- Physics at 1 TeV
  - Find the Higgs (Finish the SM)
  - Dark Matter
  - Hierarchy Problem
    - Fine-tuning
  - Gauge Unification

Dark Matter

- Dark Matter must interact (to be created)
- The higher the cross-section (~mass^{-2}), the lower its abundance in the universe.
- If DM interacts with Electroweak strength (~ EW mass Scale) then the DM density is about what we observe
- So from purely cosmological observations we conclude that Dark-matter particles should have mass of 0.1 - 1 TeV.





HEPAP LHC/ILC Subpanel (2006)

[band width from k = 0.5 – 2, S and P wave]

Fine-tuning

- Our existence depends on physical constants being very precisely tuned. For example:
  - **Force of Gravity**… must be within 1 part in 10^{60}.
  - *and* **Cosmological Constant** (dark energy)… must be within 1 part in 10^{120}.
    - Or the Universe would either blow itself apart or collapse.
- **Distribution of mass energy in early Universe** must be smoothly distributed by 1 part in $(10^{10})^{123}$.
  - Or we wouldn't get structures we see today.
- The observed **Higgs mass** (observed by LHC in 2012) is naively due to a fine-tuning of 1 part in 10^{16}.
  - Or Forces and masses would be very different.

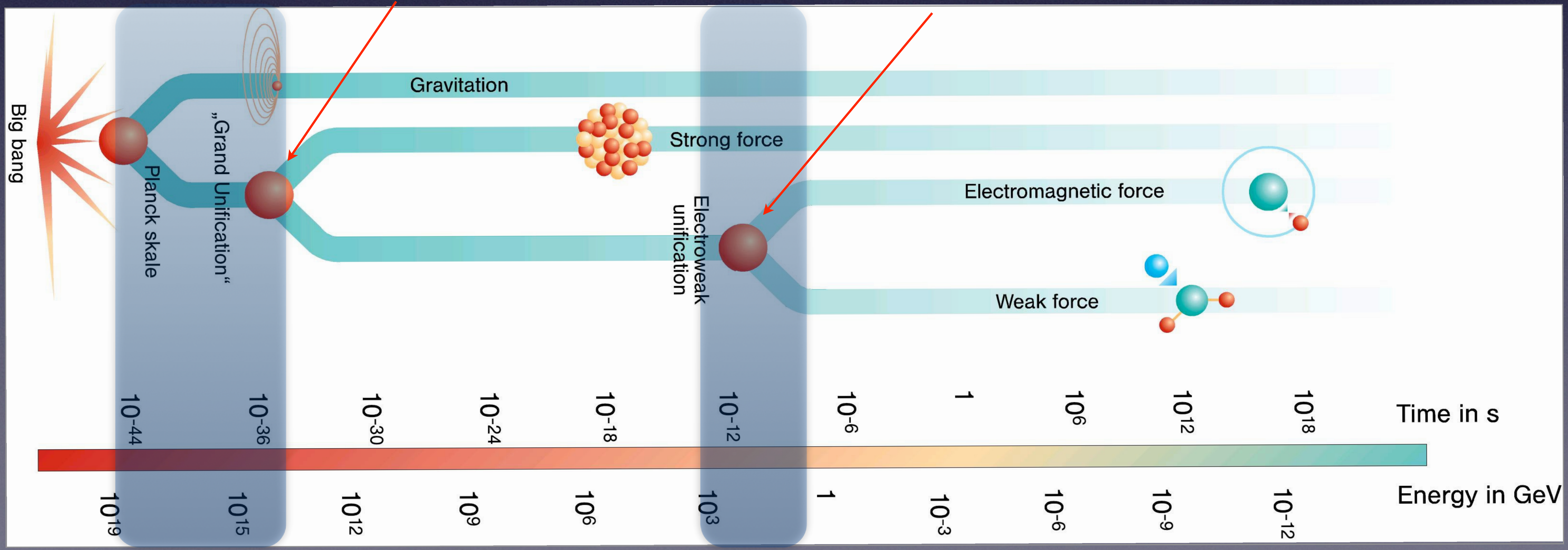
How?

- ***Chance***- very very unlikely to get these parameters…
  - perhaps:
    - *multiverse*- there are lots of Universes.
    - *anthropic principle*- we are in a Universe in which we can exist.
- ***Naturalness***- Small numbers don't in nature.
  - There is some symmetry, force, or structure that control the constants…
  - A aesthetic principle that constants should be of order 1.
    - Therefore any observed small/fine-tuned number is due to some phenomena.
  - For example for the Higgs mass, it can be Supersymmetry, extra-dimensions, additional sub-structure.
  - We can imminently test this at the LHC.
- ***Design?***

Hierarchy Problem

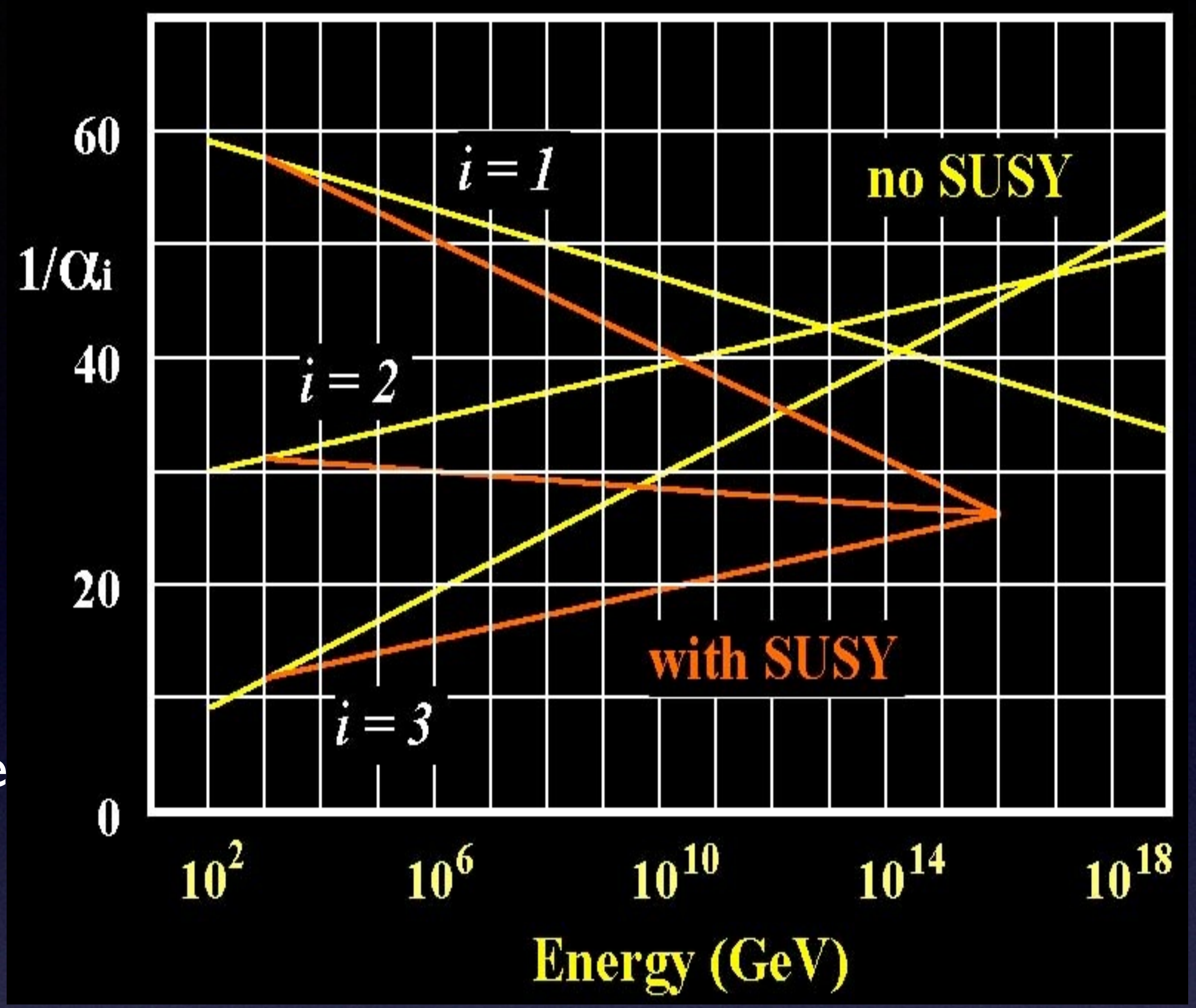
- At the heart of the Standard Model is a particle called the Higgs (which we haven't seen yet...)
  - For the SM to work, the Higgs mass has to be < 1 TeV
  - But the SM predicts the Higgs mass to be around the mass where something new happens.
  - So for SM to work... something new has to happen ~ 1 TeV

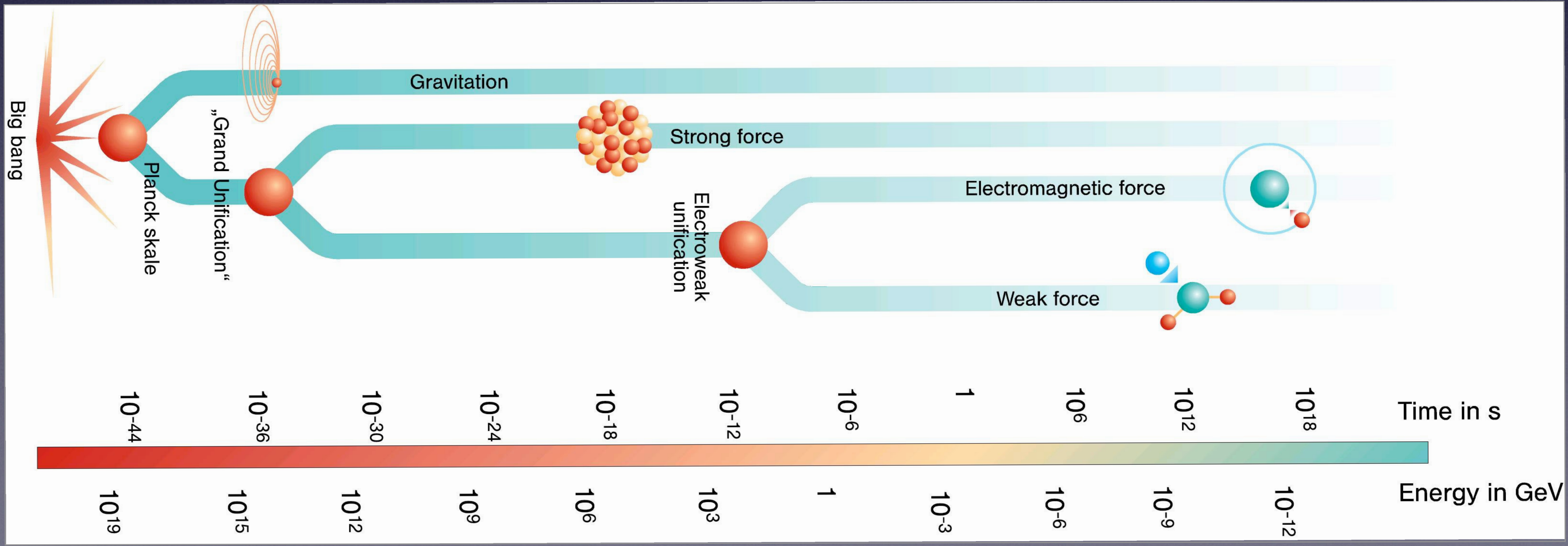
Higgs Mass w/o New Physics Where Higgs Mass Needs to be



Unification

- We know about 4 Forces...
  - We don’t know why Gravity is so much weaker than the others.
  - 2 of them Unify (Electromagnetic and weak)
    - It means that at high enough energies, they look like one force (have the same strength).
  - We have theories that Unify strong force too... and we can see the effects at 1 TeV!
- Planck Scale... where we think Gravity should unify.





How do we probe 1 TeV?

- Cross 2 beams of particles with ~ 1 TeV of energy
  - $E=mc^2$
- Methods:
  - Linear Collider- Energy ~ length
  - Circular collider
    - recirculate the beam
    - Energy ~ radius/magnetic field
- What kind of particles?
  - Electron/Positrons
    - Radiate away energy in circular collider
      - LEP up the CM energy of 209 GeV
    - Linear Collider is requires more space
      - SLC
- Proton/Anti-proton
  - Hadrons made of quarks, so ~ 1/3 of energy goes into collisions
  - Hard to get enough Anti-protons
    - TeVatron ~ E_{CM} = 1.98 TeV
- Proton/Proton
  - SSC- 40 TeV- Canceled
  - Large Hadron Collider- in the old LEP tunnel
    - 7 TeV Now
    - 14 TeV Design
    - Higher Intensity than SSC

The LHC

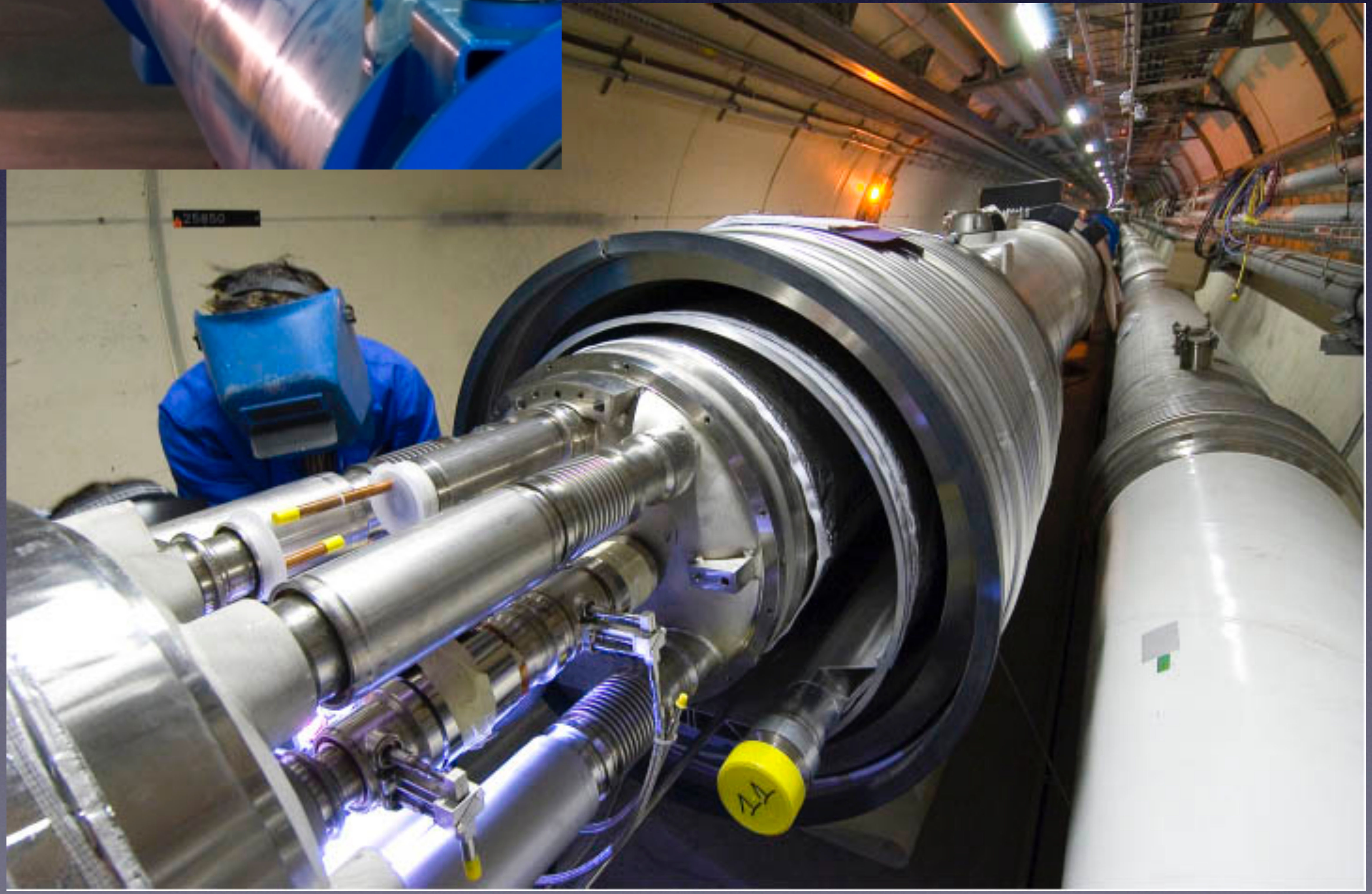
• pp collisions 7+7 TeV $\Rightarrow \sqrt{s}$ = 14 TeV

27 km

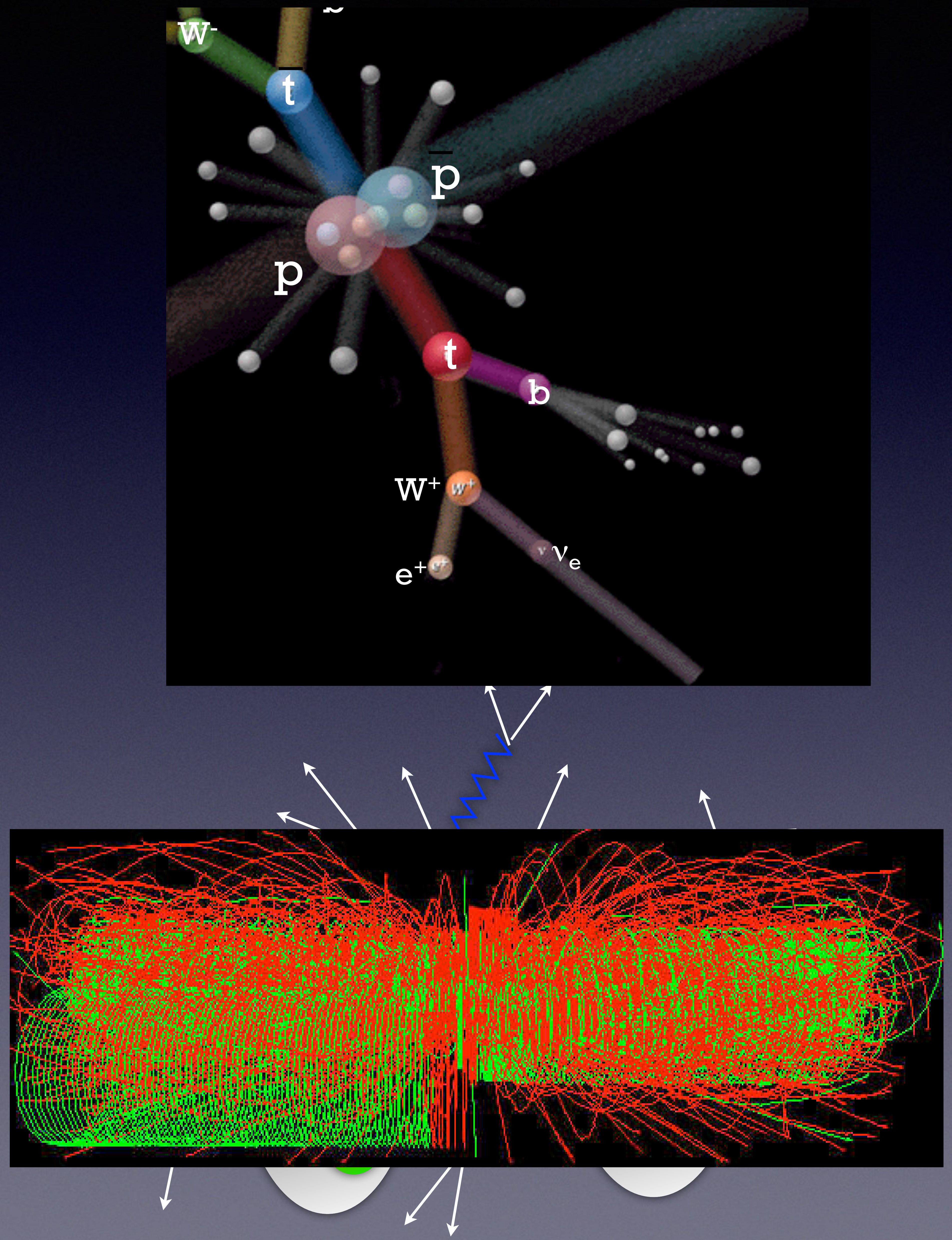
2835 Bunches, 10^{11} protons/bunch:

• $L_{design} = 10^{34}\ cm^{-2}\ s^{-1}$ (after 2009)

• $L_{initial} \leq$ few x $10^{33}\ cm^{-2}\ s^{-1}$ (until 2009)

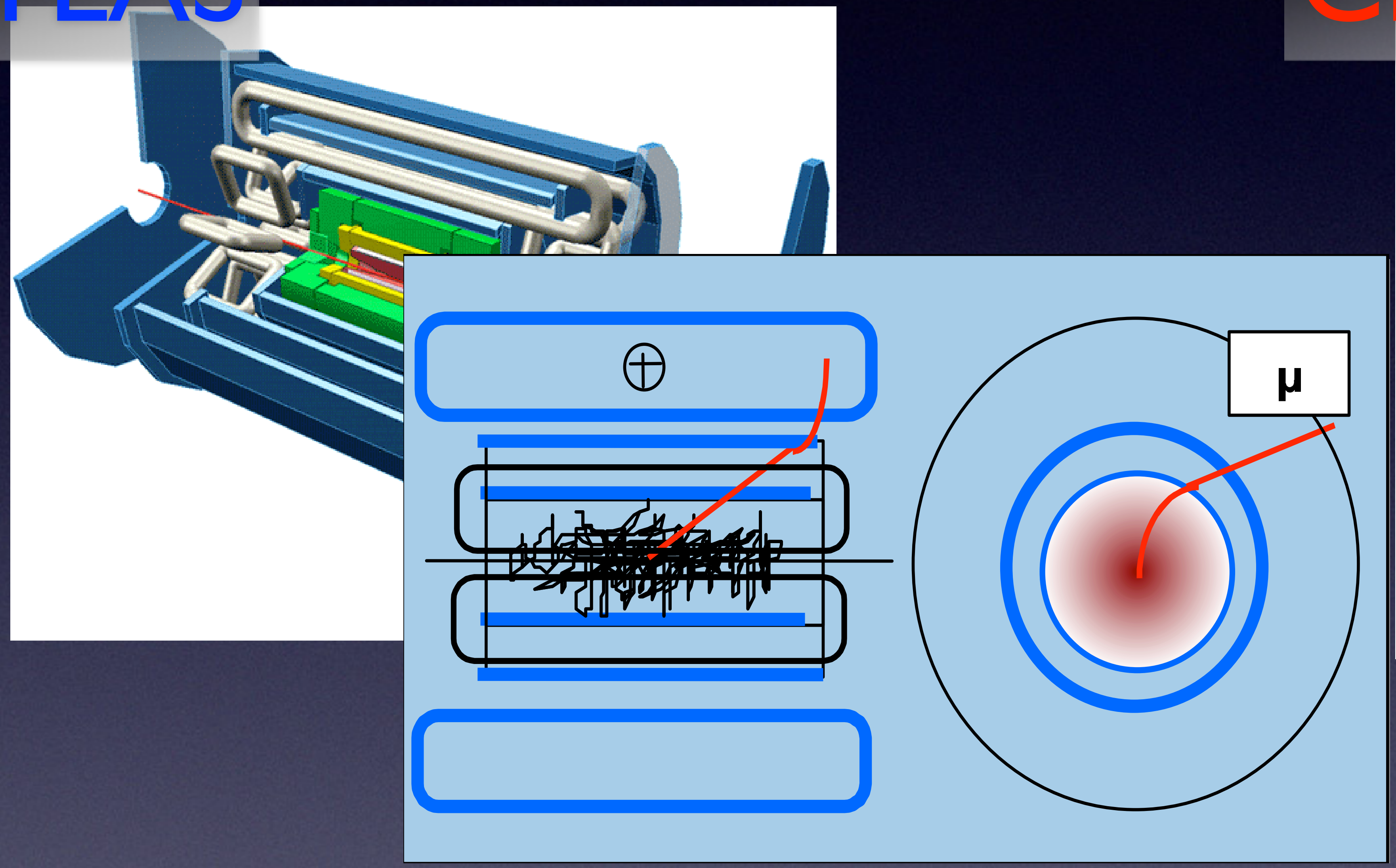



LHC Environment

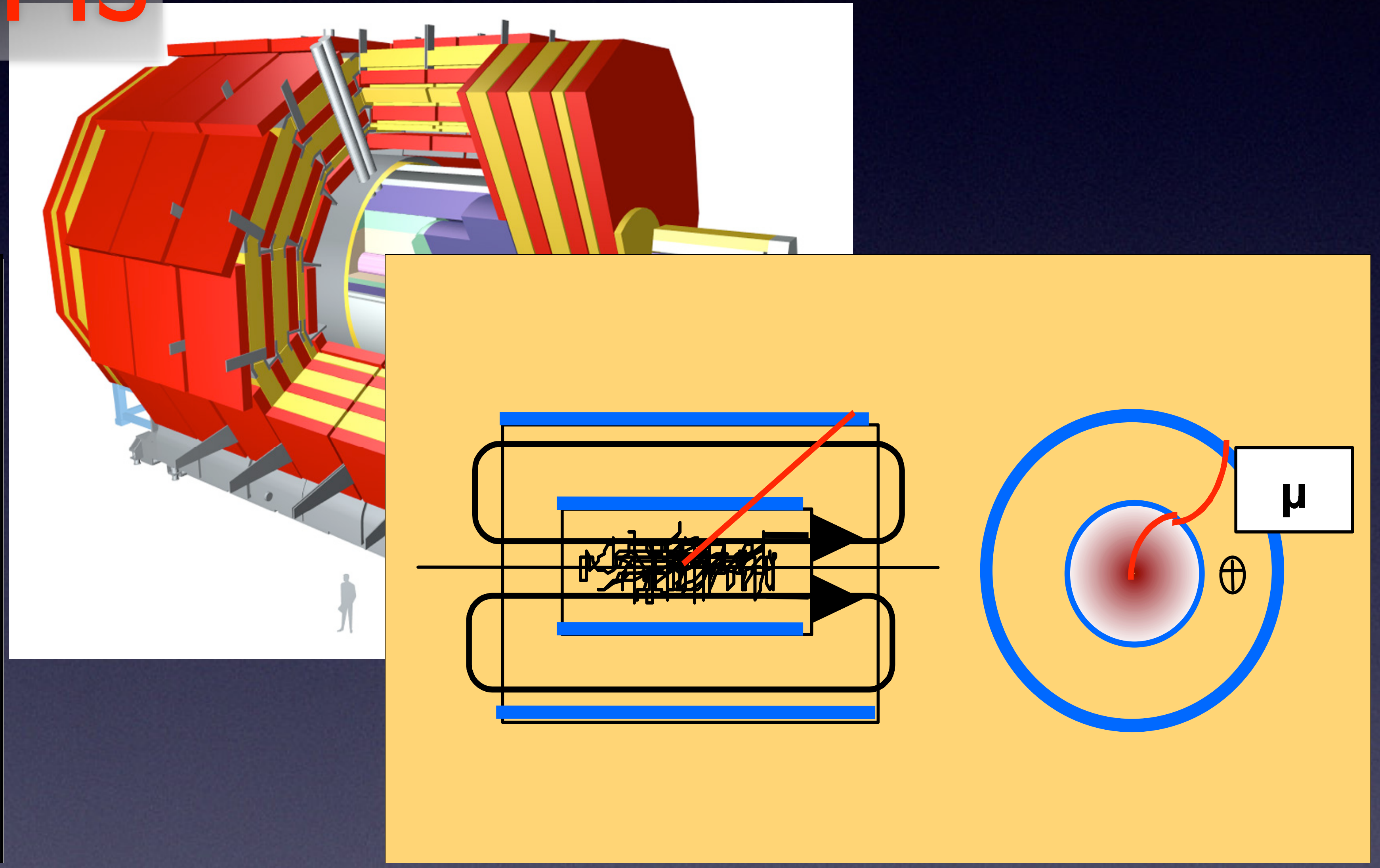


The LHC General-purpose Detectors

ATLAS



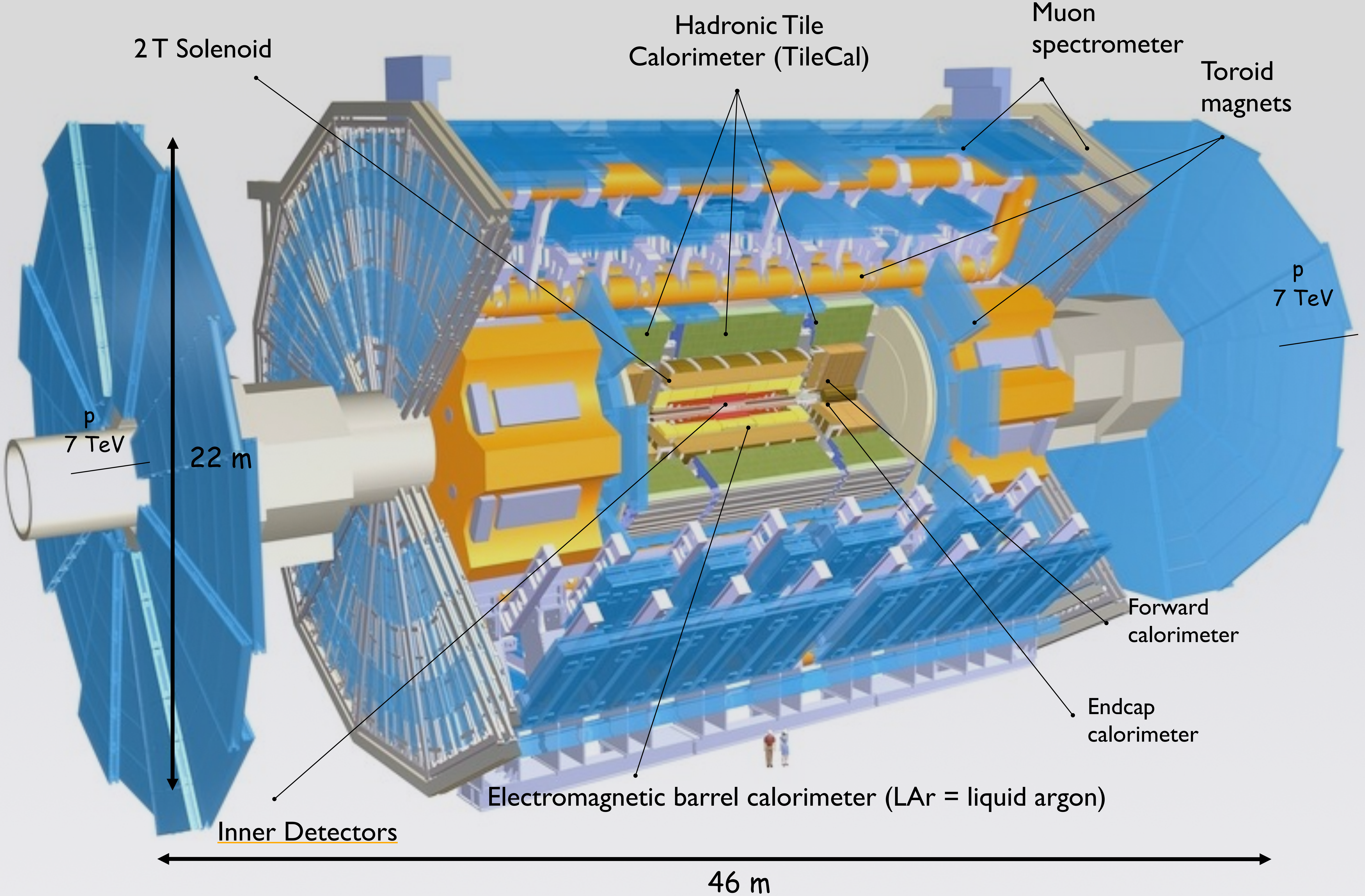
CMS



- Solenoid (2T) + Large Toroidal Magnate System
- Standalone muon tracking
- Calorimeters outside solenoid

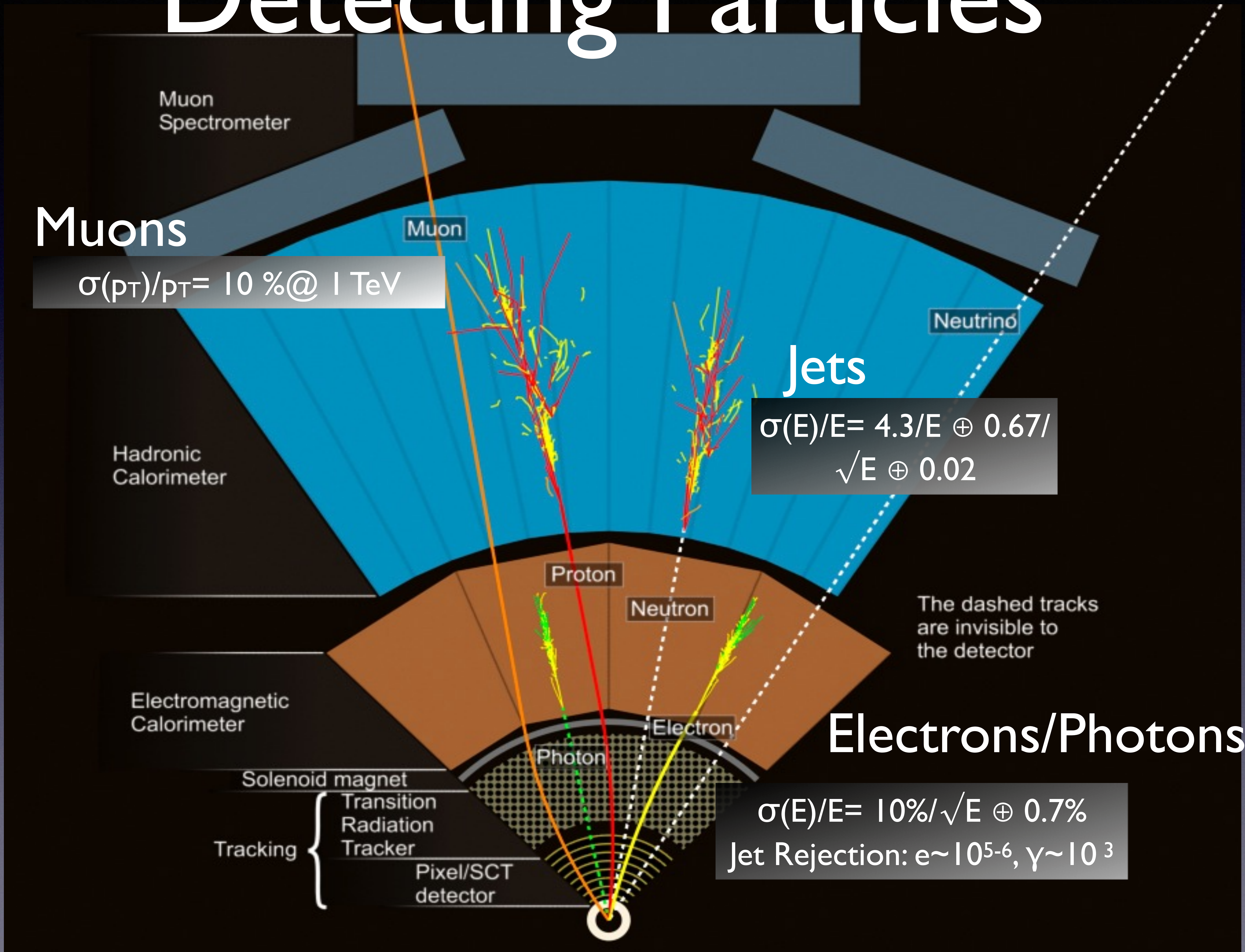
- Powerful Solenoid (4T)
- Muon bend in return flux
- Calorimeters inside solenoid⇒constraint on HCal

ATLAS



Total mass ~ 7000 tonnes, installed 92 m underground.

Detecting Particles



Muons

$\sigma(p_T)/p_T = 10\ \%@\ 1\ \text{TeV}$

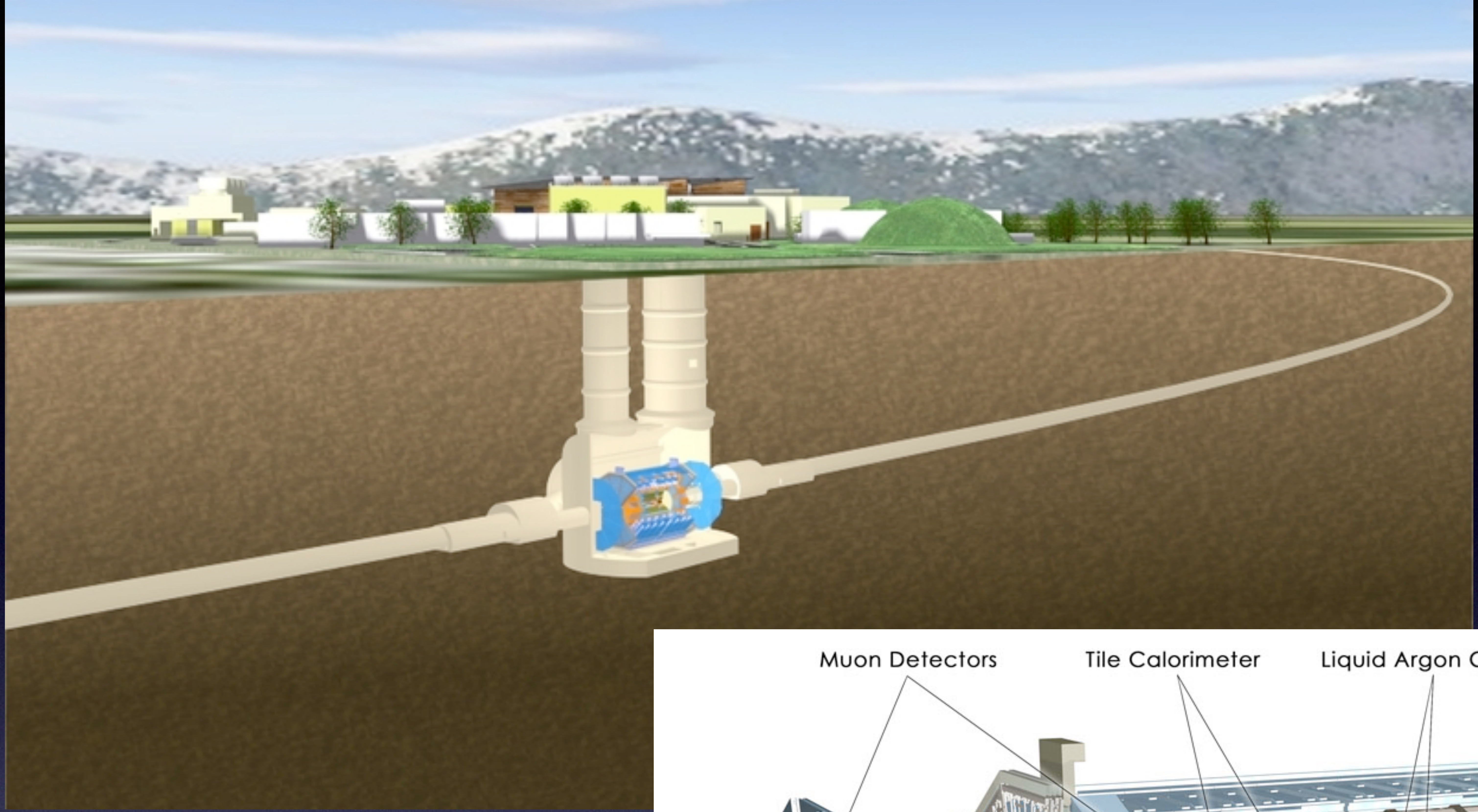
Jets

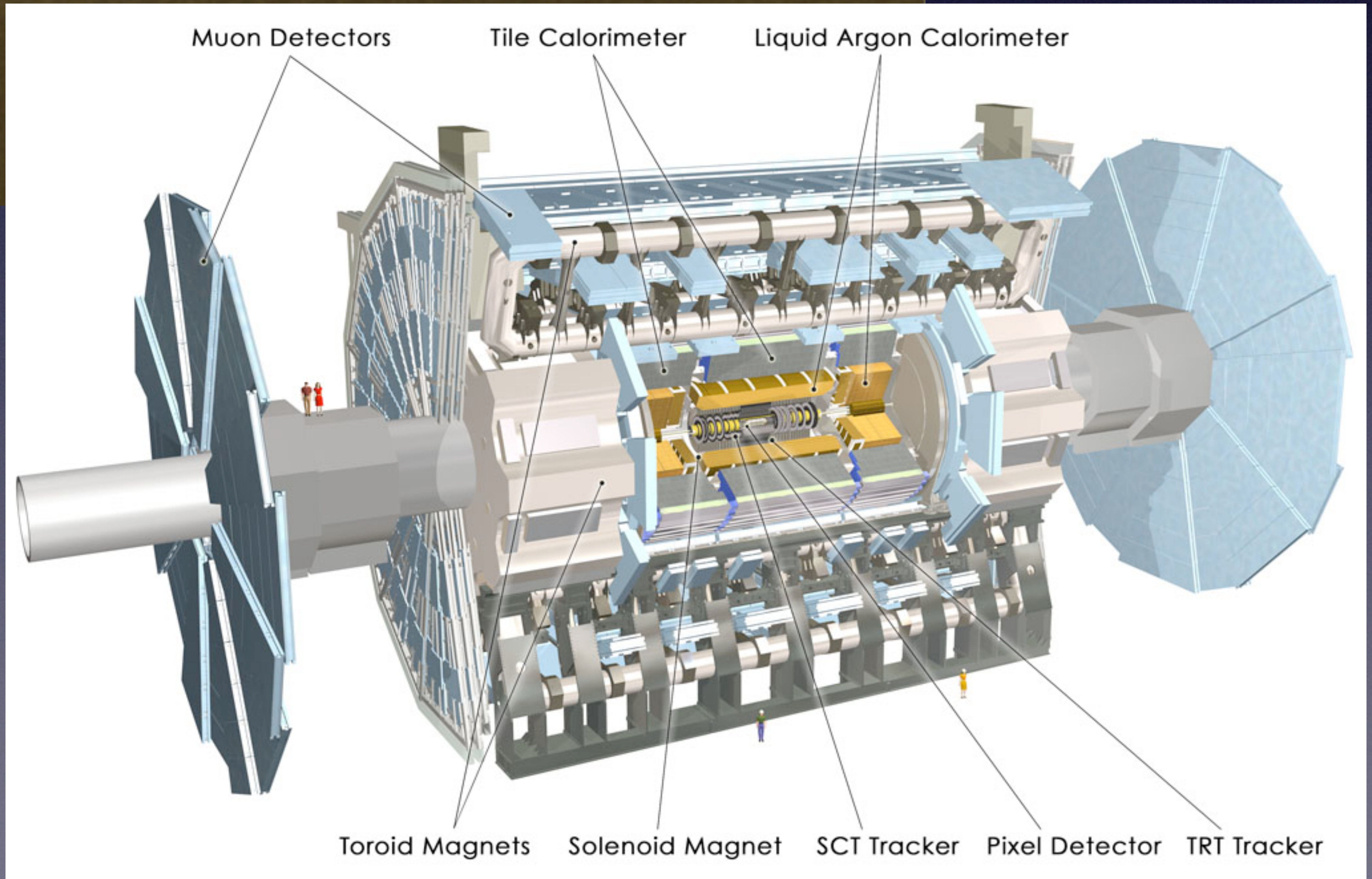
$\sigma(E)/E = 4.3/E \oplus 0.67/\sqrt{E} \oplus 0.02$

Electrons/Photons

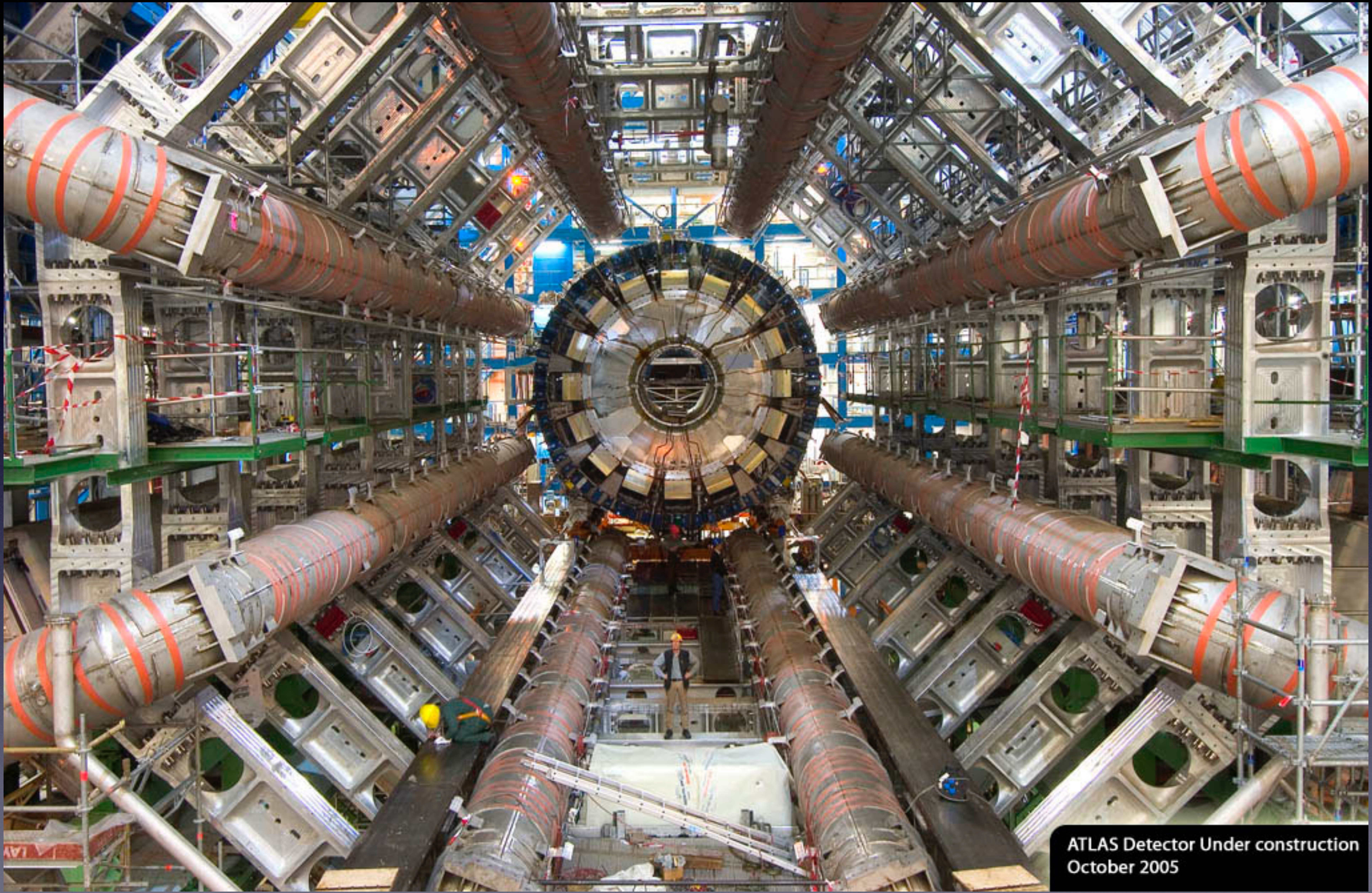
$\sigma(E)/E = 10\%/\sqrt{E} \oplus 0.7\%$

Jet Rejection: $e \sim 10^{5\text{-}6}$, $\gamma \sim 10^{3}$

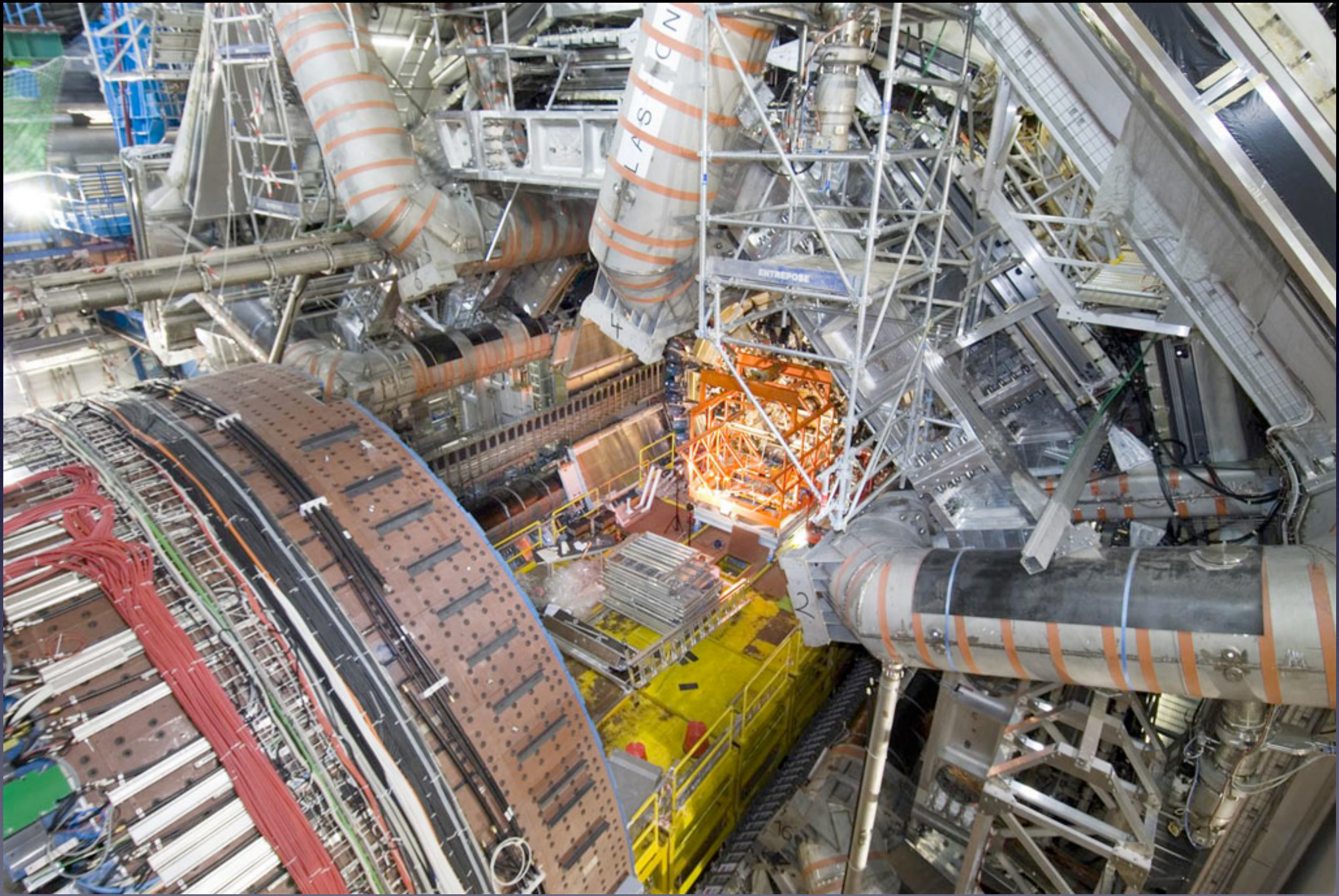


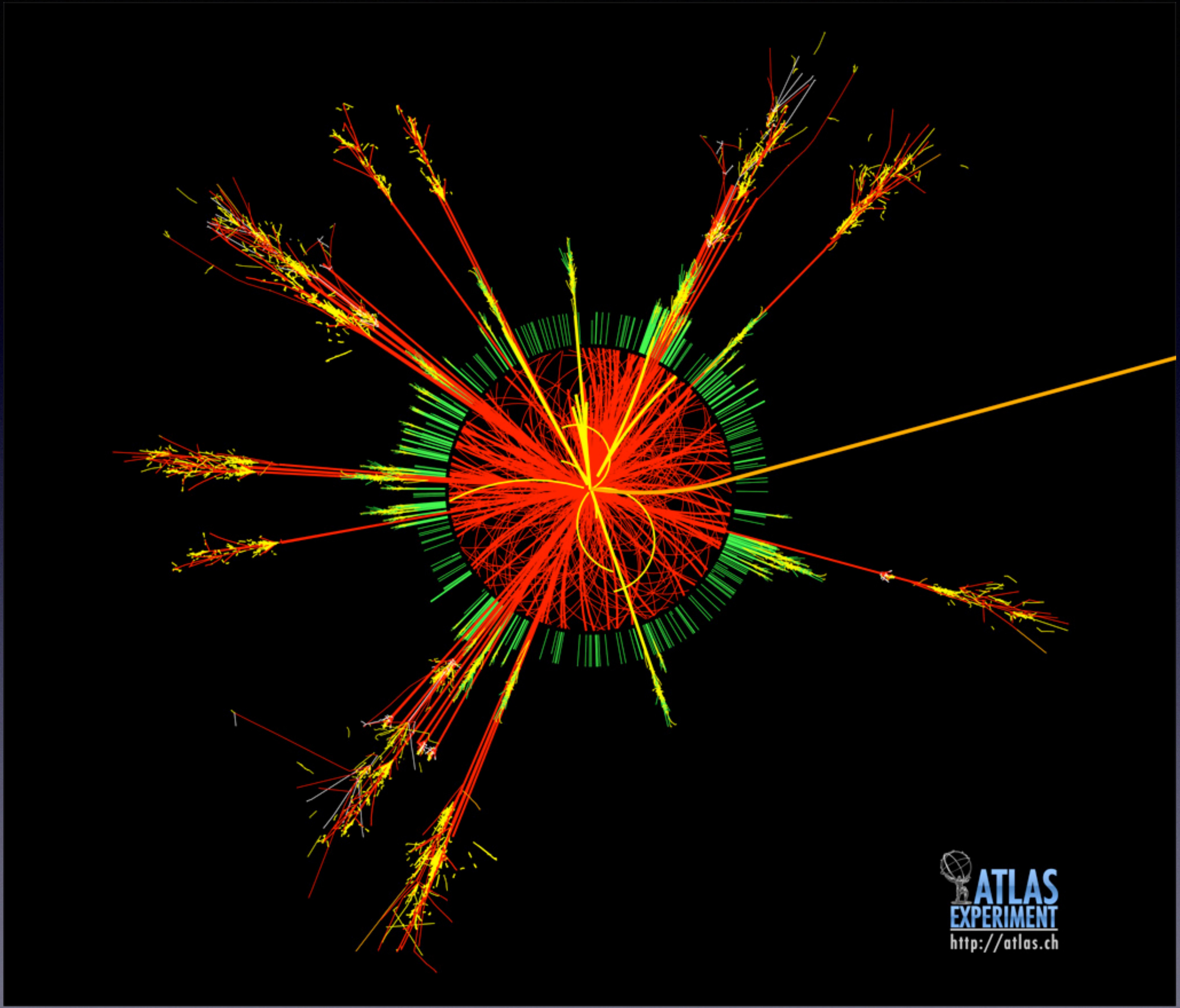

Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

3000 Collaborators

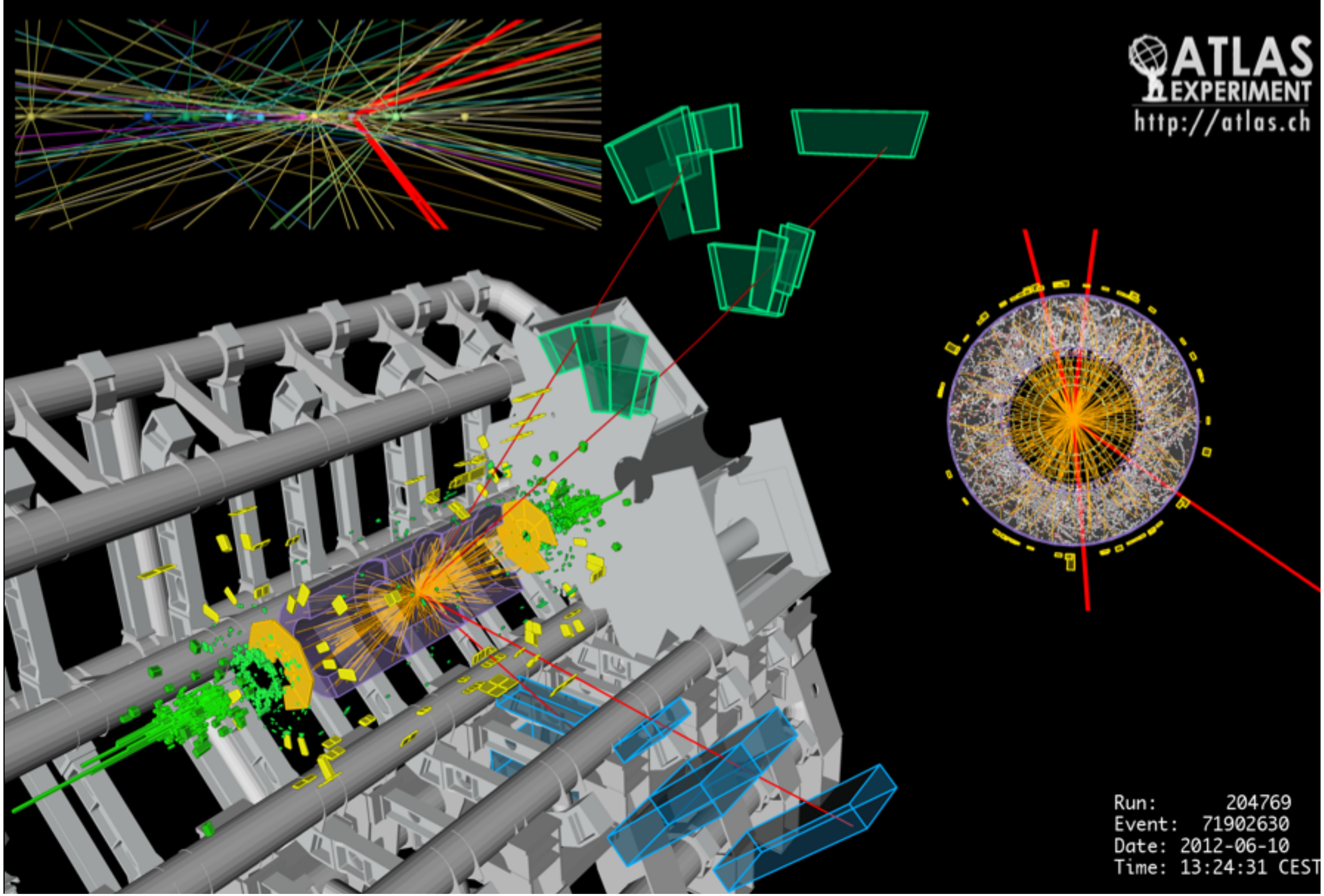


ATLAS Detector Under construction
October 2005




ATLAS
EXPERIMENT
http://atlas.ch

$$H \to ZZ \to 4l$$


ATLAS
EXPERIMENT
http://atlas.ch
Run: 204769
Event: 71902630
Date: 2012-06-10
Time: 13:24:31 CEST

What could we "see"?

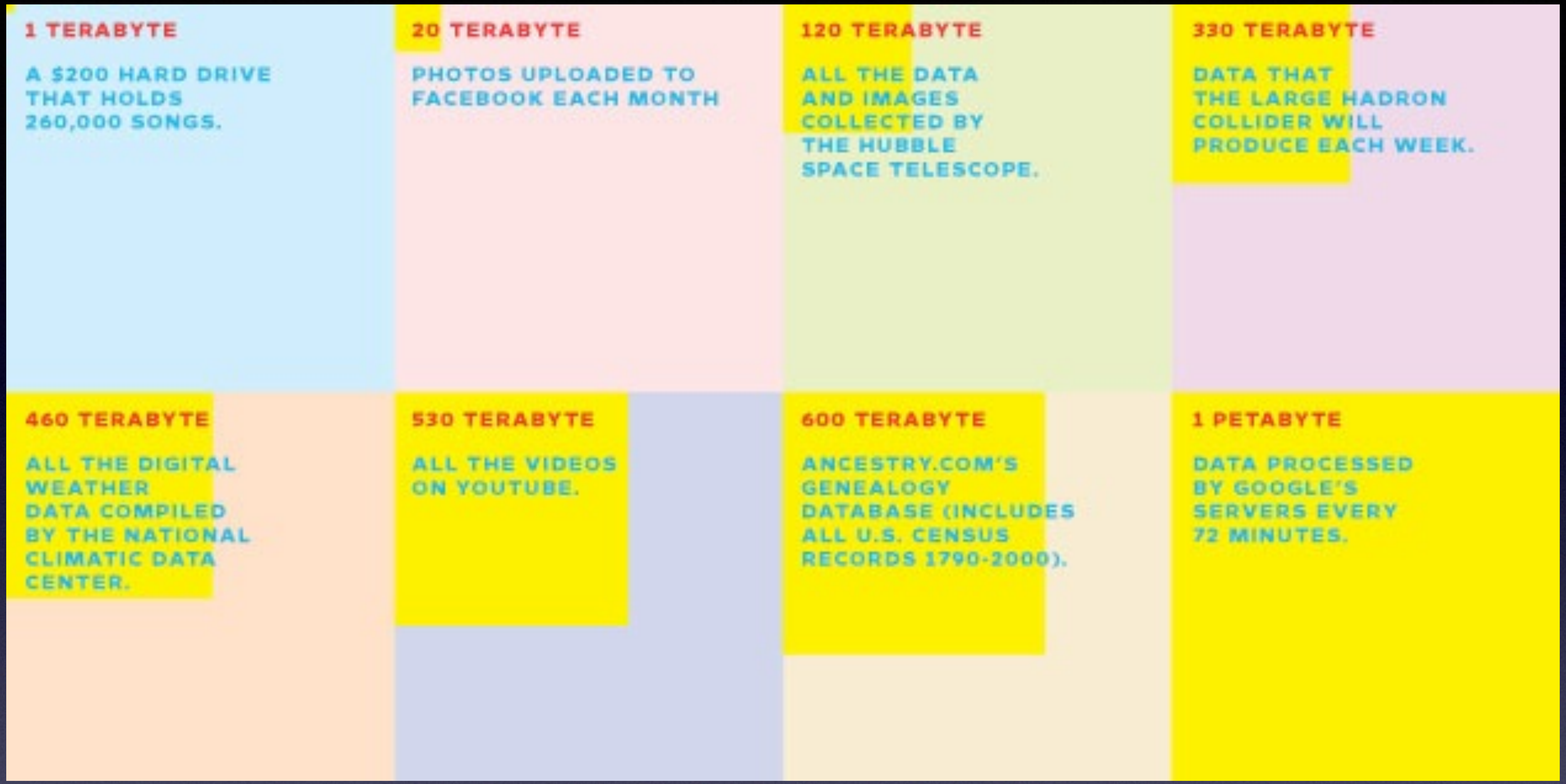
- Recall:
  - SM breaks down ~ 1 TeV
  - Lots of things unexplained by SM.
- Theorists have been thinking about ways to solve the problems of the SM for > 30 years.
- Many ideas have been proposed and disproven.
- Best candidates for what we'll see at LHC:
  - Super-symmetry: every particle has a heavier super-partner. Adding these partners make the calculations come out. They also help unify all forces & Provide a dark matter candidate.

- Extra-dimensions: there may be more than 4 dimensions... and gravity might be weak because unlike other forces, it propagates in the other dimensions.
  - If this is true, LHC might make black-holes
- We hope for a big needle in a haystack.

HEP Computing

- The web was invented at CERN!
  - Particle Physics is one of the largest users of the internet for many decades... 2 reasons:
    - We work in large collaborations, spread around the world.
    - We have lots of data... need to access it remotely, or move it to local computers.
  - The html protocol was developed at CERN for particle physicists in the early 1990's.
    - First web site: CERN... first in US: SLAC (Stanford Linear Accelerator Center)

LHC Computing



- LHC Produces lots of data
- Too expensive to have all of the computers in one place.
- So computers are spread around the world... building a GRID of computing resources.
- UTA is one of six Tier 2 sites for ATLAS in the US.
- As much effort goes into the software/computing side as the detector...

- To understand the most fundamental phenomena in nature, the Physicists application of the scientific method:

1. Build Models

  - The **Standard Model of HEP** describes the building blocks of matter and their interactions.
    - SM requires the existence of a set of fundamental particles with very specific properties.
      - Tested and validated through experiments, including some of the most precise measurements ever.
    - Yet, has **failures**, e.g. no Dark Matter. Not compatible with Gravity.
    - And, has **inconsistencies**: e.g. both SM predicts the Higgs mass to be big and requires it to be small. (Known as the Hierarchy problem…
  - Models are **expressed mathematically**
    - Ideally build on a minimal set of rules (principles/laws)
    - SM Mathematical Framework: Quantum Field Theory- Way beyond this class.
      - Renormalization: encapsulating unknown (effects at high energy) in measurable parameters.
      - SM is a Model with **19 parameters**. Masses of particles. Strengths of forces. etc…
        - None are fundamental like speed of light or Planck's constant.

2. **Build new model that tackle inconsistencies**.

3. **Create experiments (target weaknesses in the model)**

Our Mathematical Models

Classical:
Calculus (Infinitesimal)
Object (a particle) described by x, y, z, α,β,γ
and their derivatives (ie momentum).

Atomic scales

Quantum Mechanics:
Probabilistic
A particle described by a complex wave-function P(x, y, z, α,β,γ + derv).

Relativity explains Electromagnetic Unification. EM fields inherently relativistic.

General Relativity:
Tensor Calculous
Gravity = Curvature of Space Time.
Gravity weak, so curvature ignorable on small scales.

Relativistic QM Requires Creation of Particles... leads to Fields

Classical Field Theory:
eg Electrodynamics
Interaction of particles with a dynamic field
A(x, y, z).

Relativistic Particles

Quantum Field Theory:
eg: QED, Standard Model
Particles = Fields.
Gauge Symmetries = the classical dynamic Fields = Particles = Electroweak
Calculate Probability of interaction.

Building the SM

Field Theory + Quantum Mechanics + Relativity = Quantum Field Theory

Ingredients

1. Leptons + Quarks

FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2		
Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2		
Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

2. Three Local Gauge Symmetries

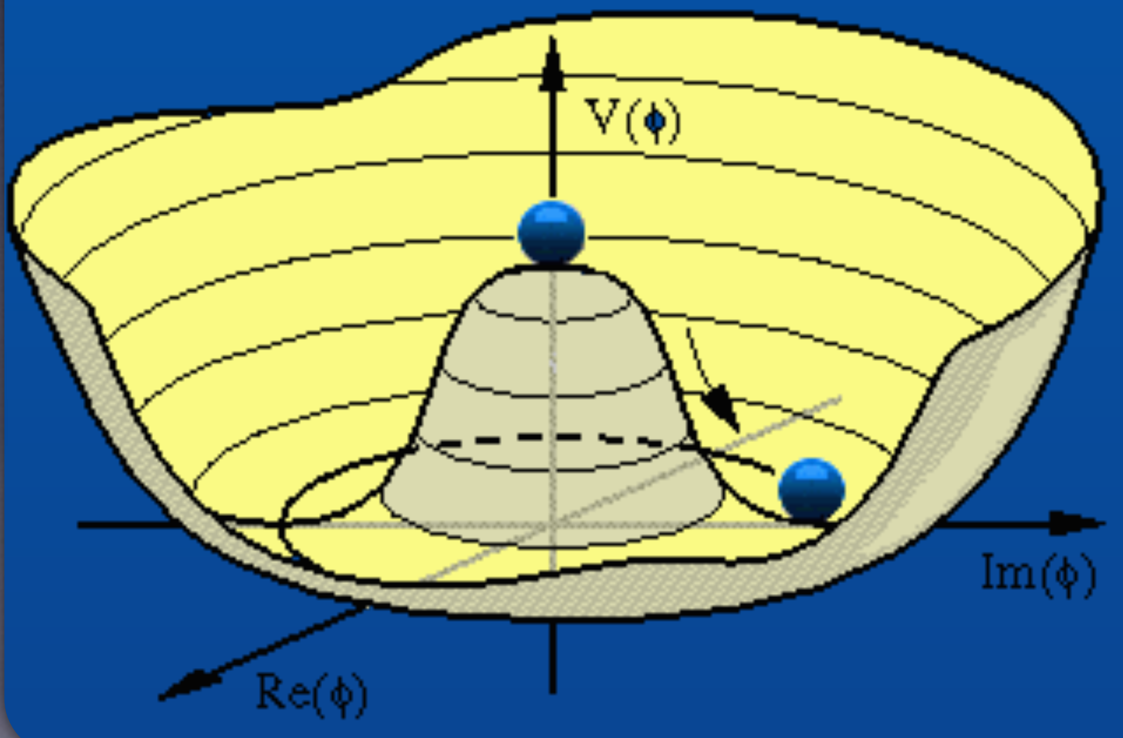
- Each Symmetry implies existence of a new set of boson (spin 1) fields
- These bosons "carry" the Forces

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	−1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

3. Higgs Mechanism

- Every particle interacts with a scalar (spin 0) field
- This field has non-zero Vacuum Expectation Value
  - Breaks symmetry between E&M and Weak Forces
  - Gives masses to all particles w/o breaking Gauge Symmetries



Standard Model

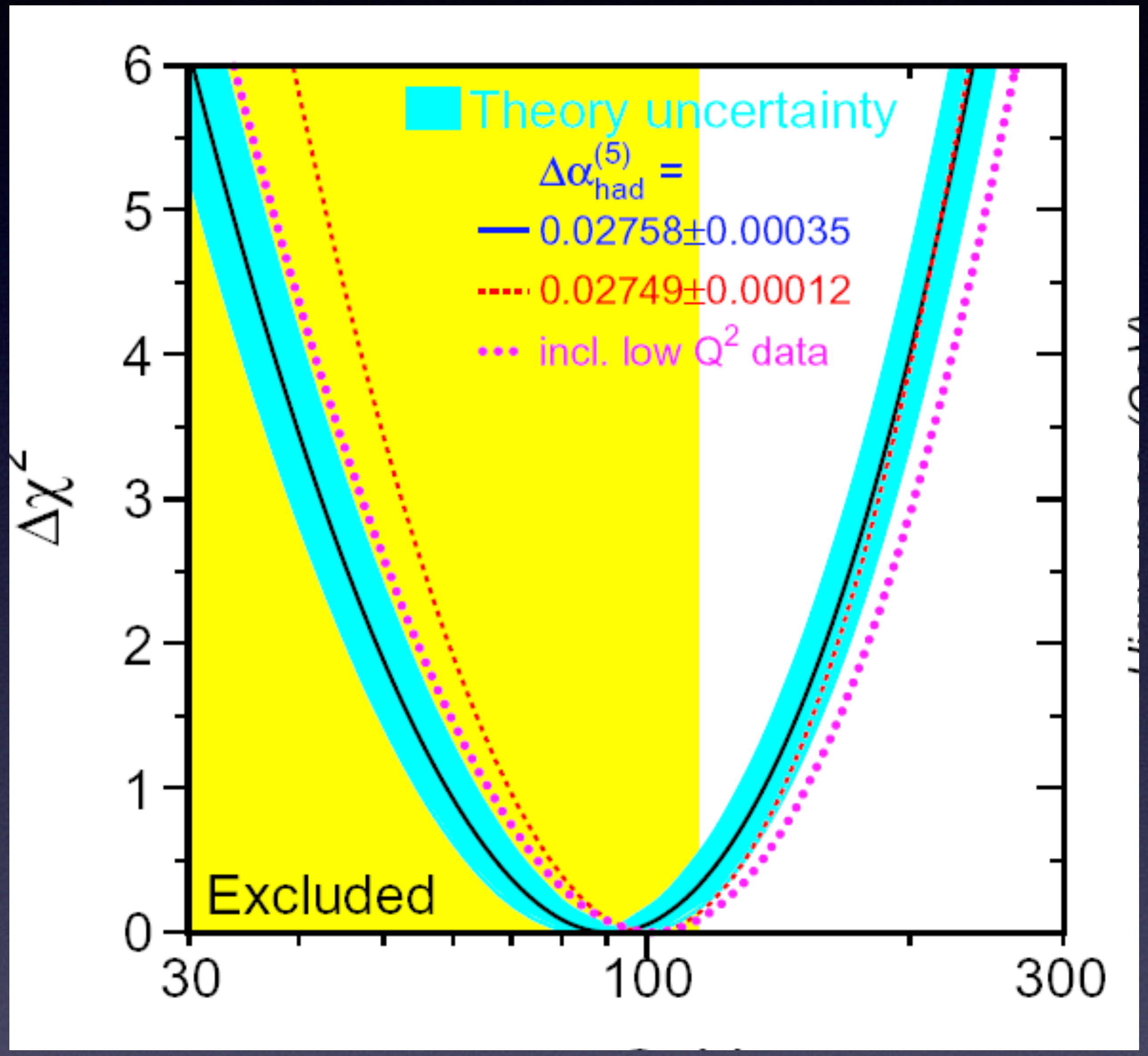
Agreement with all experimental results so far

- Why Look Beyond the Standard Model?
  - Takes 19 parameters (eg Masses)... Why these values?
  - Still looking for the Higgs particle.
  - Gravity not included! Why gravity is so much weaker than everything else?
  - Misses a lot of the Universe: No Dark matter candidate. Can't explain Dark Energy.
  - Doesn't have enough asymmetry between matter/anti-matter to explain why we exist!
- At ~ 1 TeV of energy, some of the SM predictions don't make sense. So something ***new*** has to happen at 1 TeV.

Hierarchy Problem

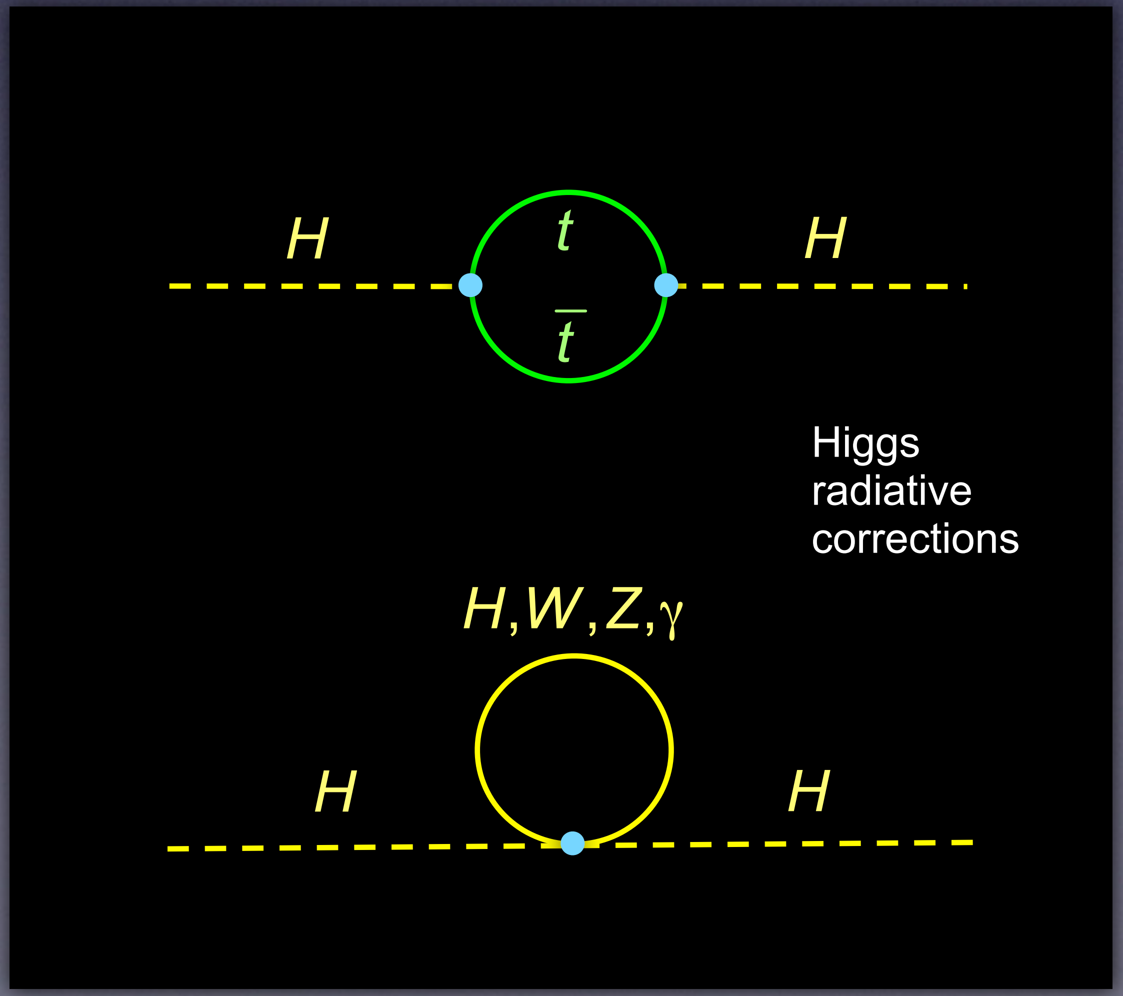
m_H=Higgs Mass
~ EW Symmetry
Breaking

Measurements: Electroweak
m_H < 1 TeV



m_H Calculation:
Radiative Corrections

Cut-off Scale (Λ)



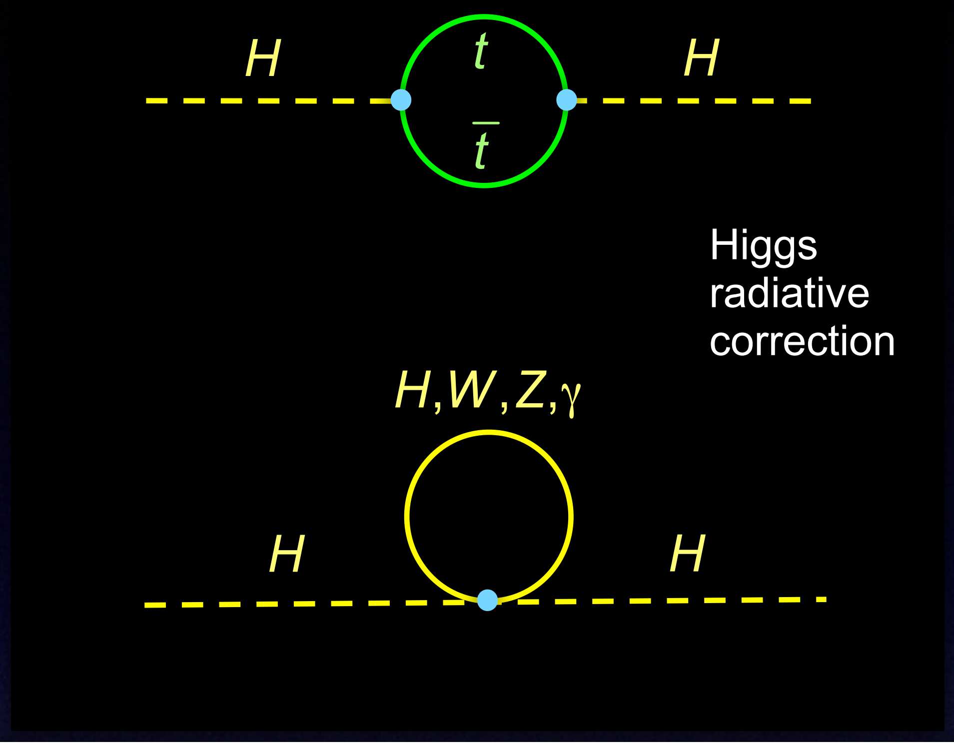
GUT Scale
Planck Scale

Quadratic Divergence
$m_H \sim m_{GUT}$ or m_{pl}

Naturalness

$m_H^2 = m_0^2 + \delta m_0^2$

Measured = Bare + Correction



$$\delta m_H^2 \propto \int_0^\infty d^4k \frac{k^2 + m_f^2}{\left(k^2 + m_f^2\right)^2} + \dots \xrightarrow{\text{cut-off}} \int_0^{\Lambda_{\text{cut-off}}} (\dots) \propto \Lambda^2_{\text{cut-off}}$$

We input Bare

But $\delta m_H^2 \sim \Lambda^2$ (ie large)

If m_H(Measured) < 1 TeV,

but $\Delta m_H \sim m_{GUT}$ or m_{Pl}

Need in part in 10^{16} cancellation

between m_H^2(Bare) + δm_H^2

So we must fine-tune the value of bare