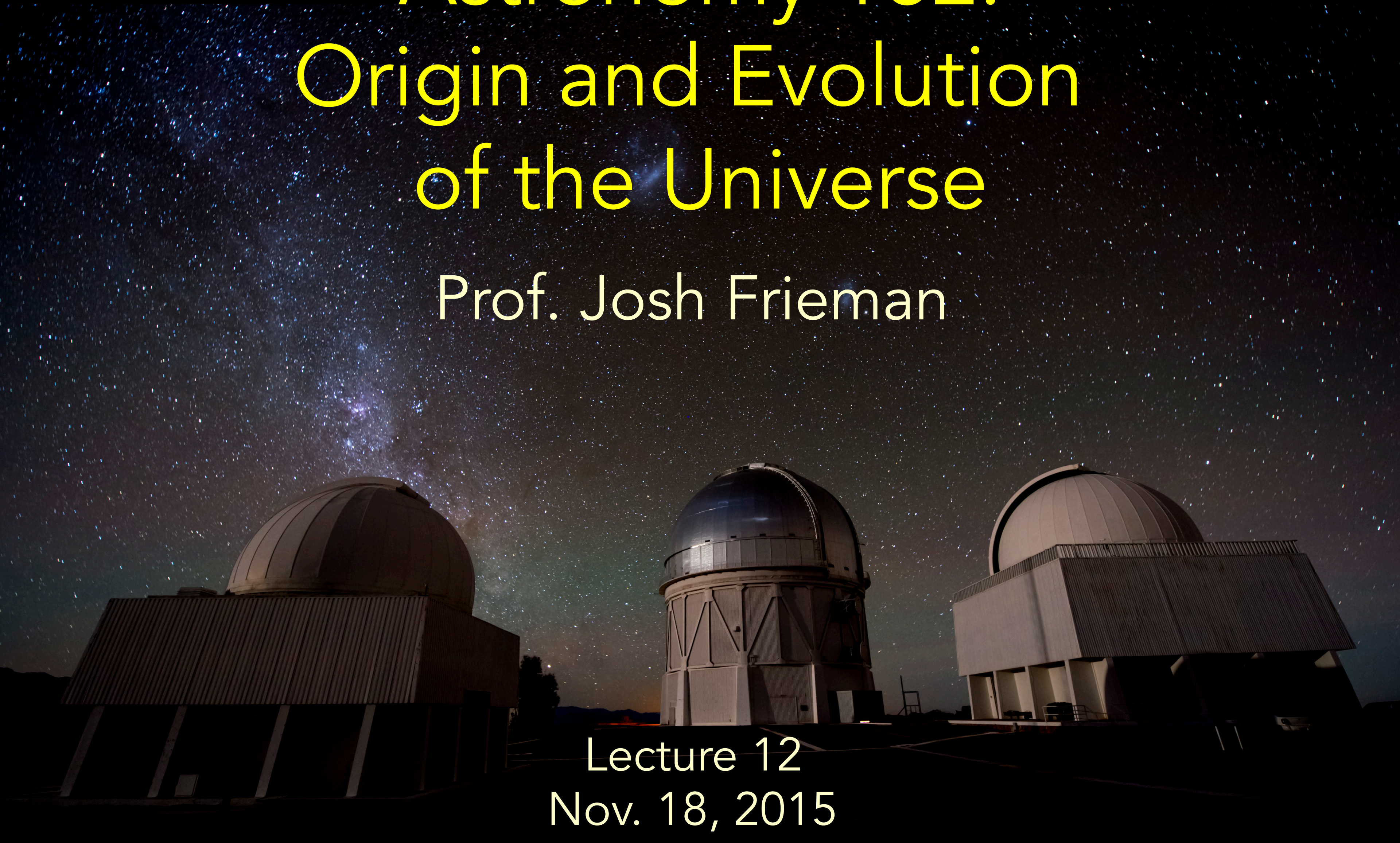
Astronomy 182: Origin and Evolution of the Universe

Prof. Josh Frieman



Lecture 12

Nov. 18, 2015

Today

- Big Bang Nucleosynthesis and Neutrinos
- Particle Physics & the Early Universe
  - Standard Model of Particle Physics
  - Relic Dark Matter particles
  - Baryogenesis

Assignments

- This week: read Hawley and Holcomb, Chapter 12 .
- This Friday: Essay 4 due on HH, Chapter 12.
- Final project: choose a topic in cosmology from popular books or an article in the reputable press: Scientific American, NY Times, Astronomy Magazine, Discover, Science News,…write a 3-page essay in the style of a newspaper or magazine article on that theme, *in your own words.*

Some Possible Project Topics

- Recent Measurements of the Cosmic Expansion Rate
- 100th Anniversary of General Relativity
- Einstein's Views on the Cosmological Constant
- Evidence for Black Holes in the Universe
- Experiments searching for Dark Matter
- Cosmic Surveys constraining the nature of Dark Energy (DES, eBOSS, DESI, LSST, WFIRST, Euclid,…)
- Theories of Dark Energy
- Theories of Modified Gravity to explain Cosmic Acceleration
- Experiments Measuring the Cosmic Microwave Background (Planck, SPT, ACT, BICEP,…)
- (Testing) Theories of Primordial Inflation
- Computer Simulations of the formation and evolution of large-scale structure and galaxies

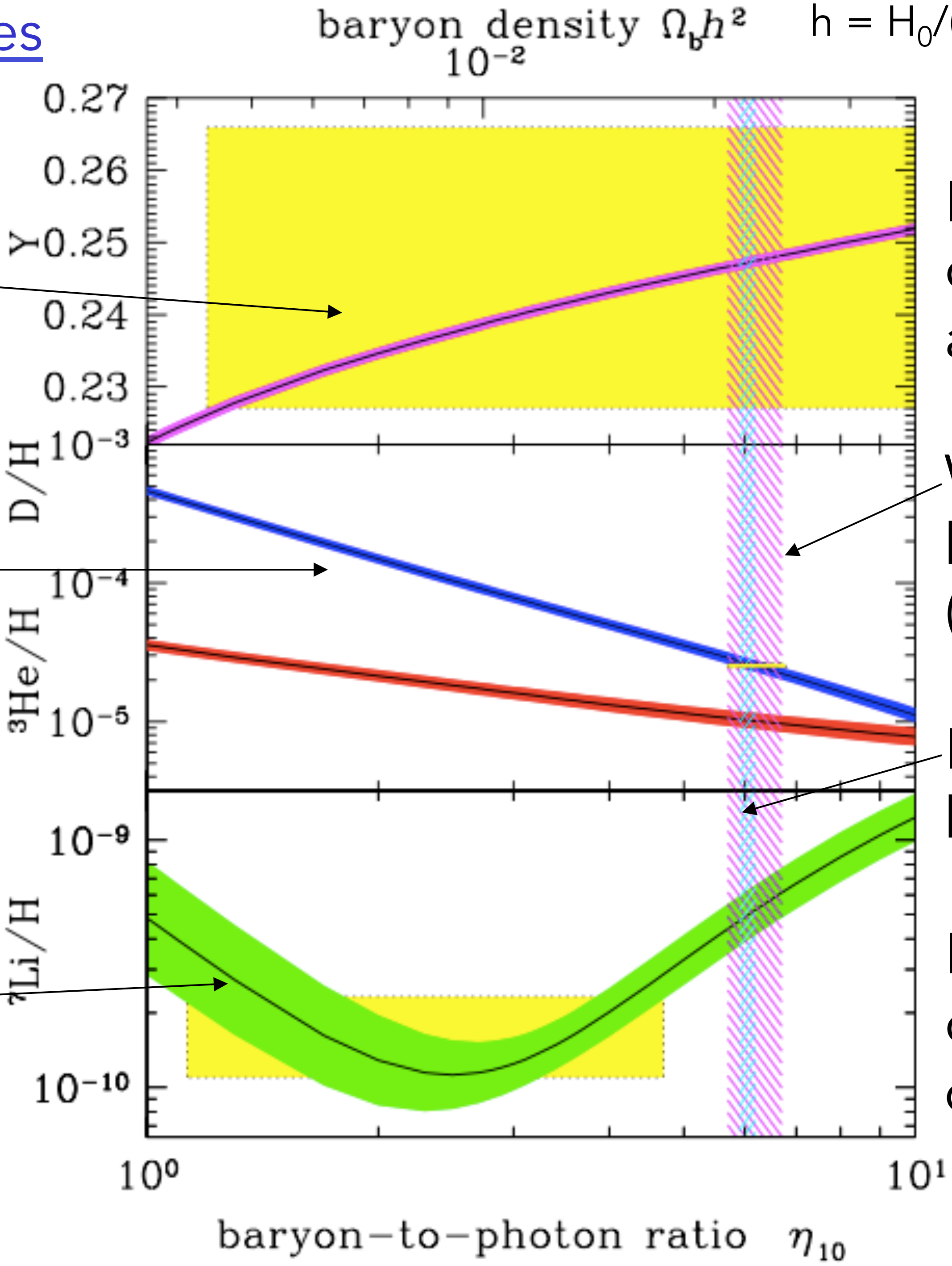
Cosmic History

- Going back in time from the present toward the Big Bang, first significant epoch we reached was Hydrogen recombination/ photon decoupling at t ~ 380,000 years (T ~ 3000 deg).

- Continuing back, the next major epoch is that of Big Bang Nucleosynthesis (BBN), at t ~ 3 minutes (T ~ 10^9 deg).

BBN abundances

h = H_0/(100 km/sec/Mpc)



Fraction of baryonic mass in He^4

Deuterium to Hydrogen ratio

Lithium to Hydrogen ratio

Boxes: observed abundances

Wide vertical band: BBN (mainly D)

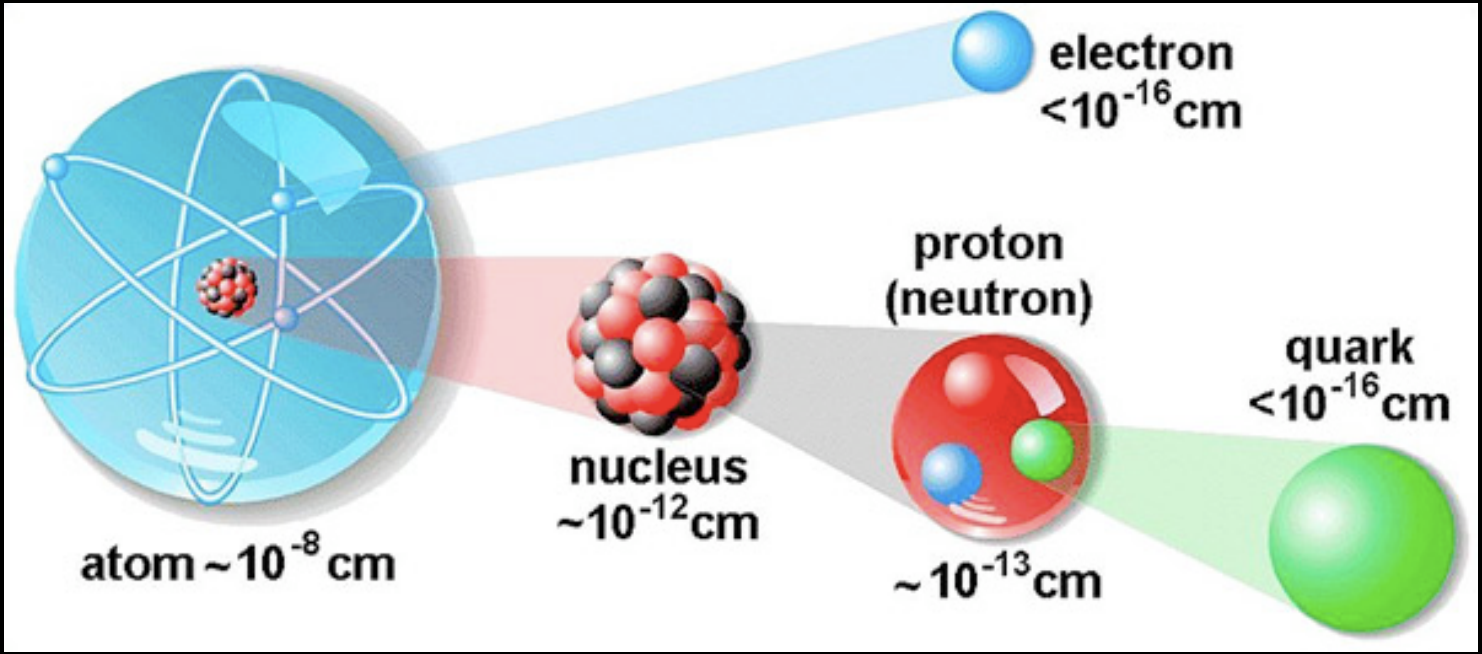
Narrow band: CMB

Lithium in old stars is discordant

BBN as a Probe of Particle Physics

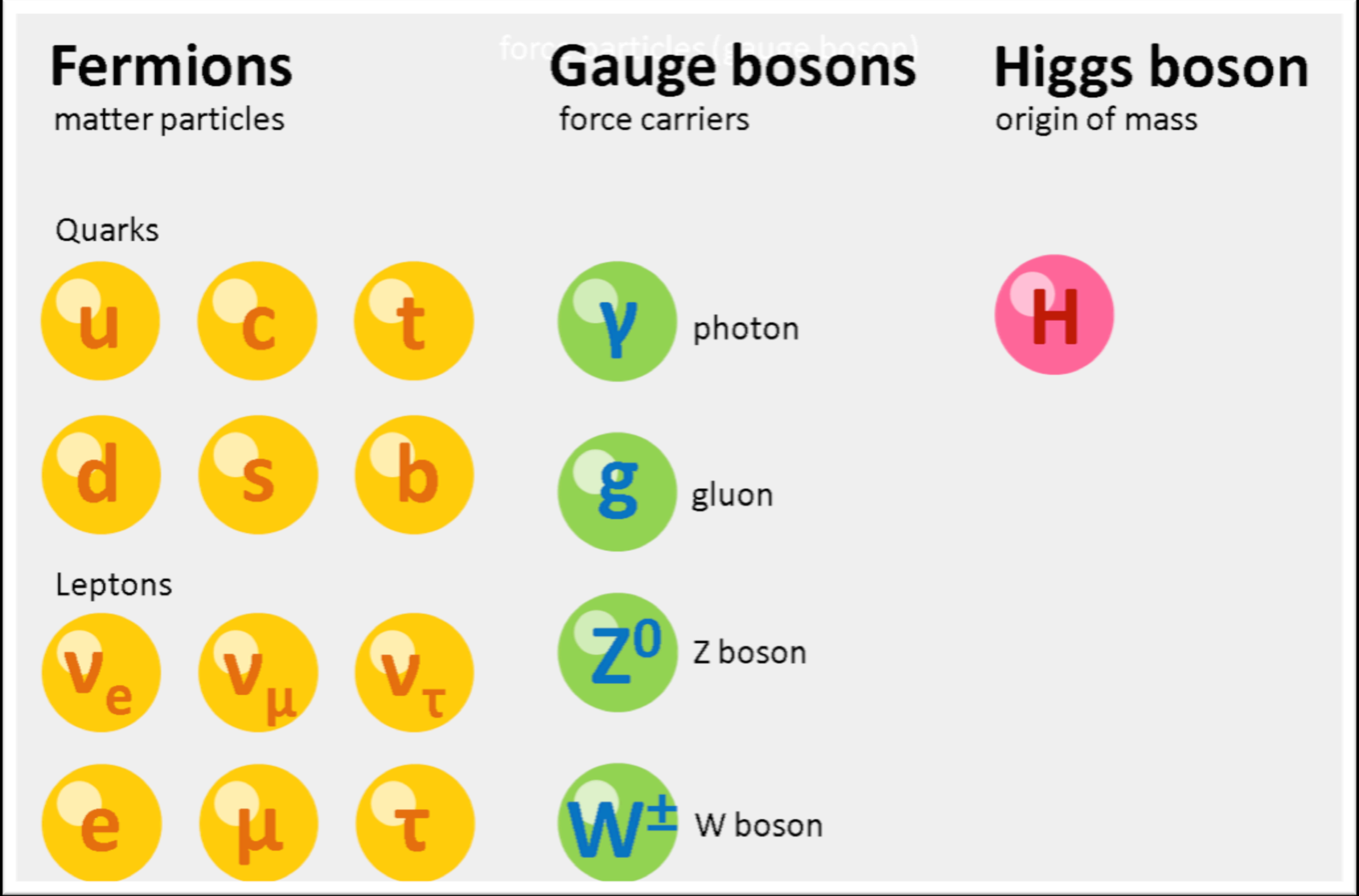
- Observed light element abundances (except for Lithium) agree with predictions of Hot Big Bang Cosmology, nuclear physics (which determines fusion reaction rates), and the Standard Model of Particle Physics and are concordant with measurements of the CMB anisotropy.
- We can therefore use BBN as a “laboratory” to constrain physical phenomena not described by (i.e., that are beyond) the Standard Model of Particle Physics.
- Example: neutrinos and other relativistic particle species

The Structure of Baryonic Matter



1 1/10,000 1/100,000 1/100,000,000

Particles of the Standard Model



Fermions
matter particles

Quarks

Leptons

Gauge bosons
force carriers

photon

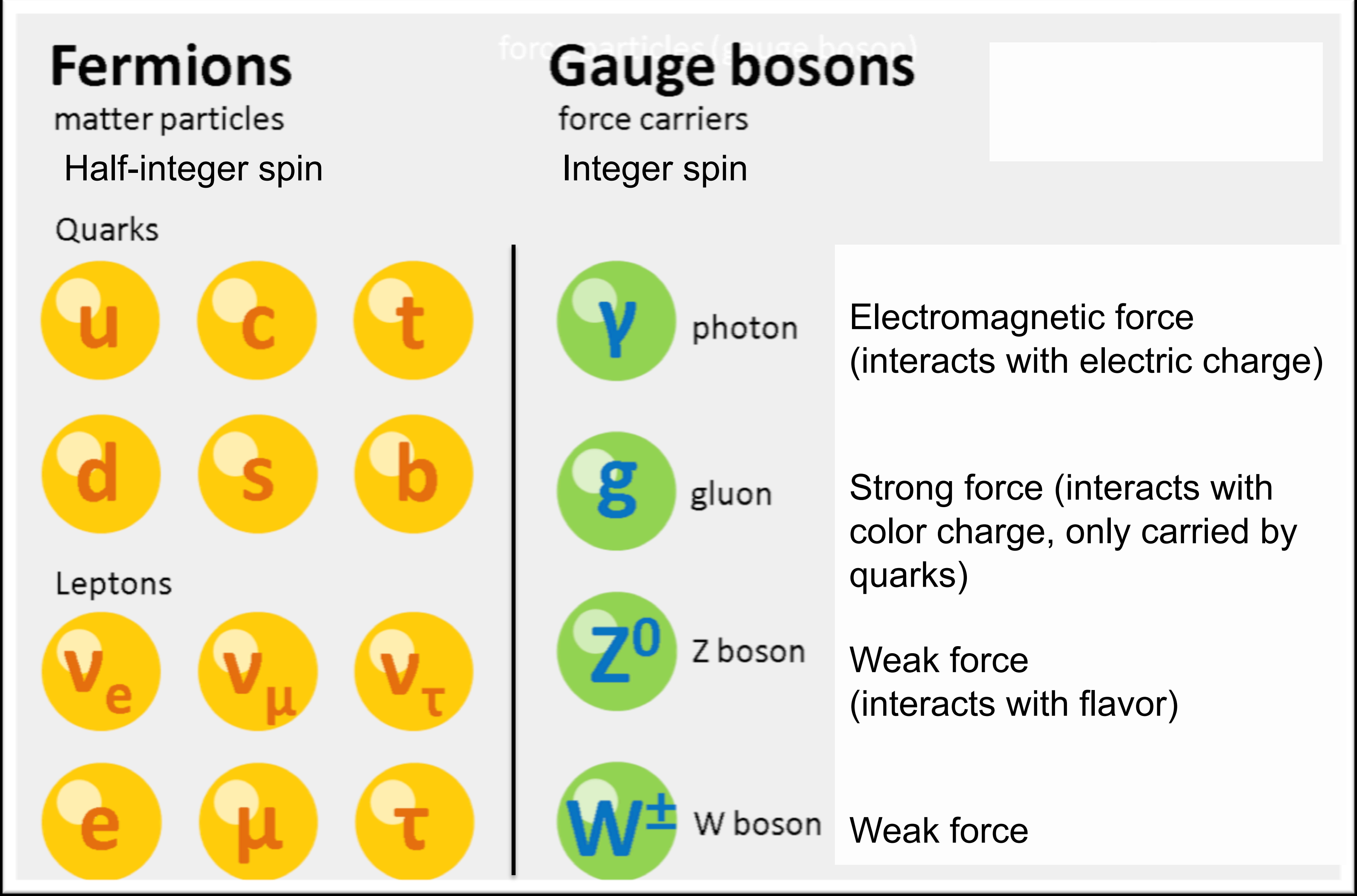
gluon

Z boson

W boson

Higgs boson
origin of mass

Particles of the Standard Model



Fermions

matter particles

Half-integer spin

Gauge bosons

force carriers

Integer spin

Electromagnetic force (interacts with electric charge)

Strong force (interacts with color charge, only carried by quarks)

Weak force (interacts with flavor)

Weak force

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

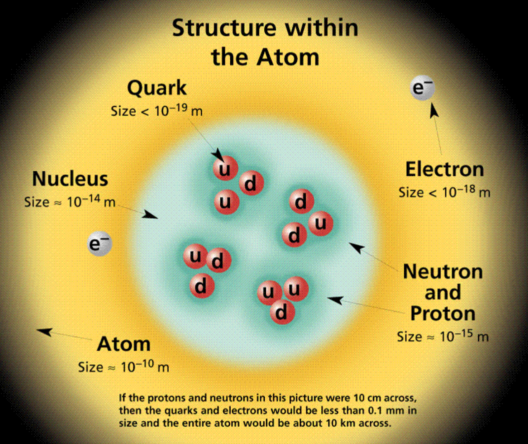
Quarks spin = 1/2

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 ħ, 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	Electromagnetic	Strong	
		(Electroweak)		Fundamental	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
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
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.

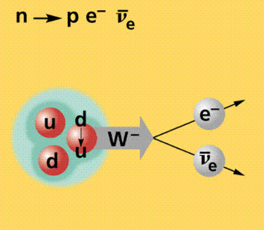
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

Matter and Antimatter

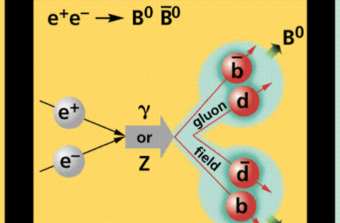
For every particle type there is a corresponding antiparticle type, denoted by a bar over the particle symbol (unless + or – charge is shown). Particle and antiparticle have identical mass and spin but opposite charges. Some electrically neutral bosons (e.g., Z^0, γ, and $\eta_c = c\bar{c}$, but not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

Figures

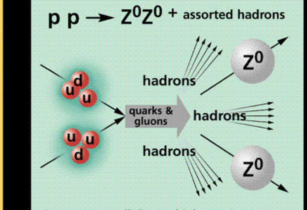
These diagrams are an artist's conception of physical processes. They are ***not*** exact and have ***no*** meaningful scale. Green shaded areas represent the cloud of gluons or the gluon field, and red lines the quark paths.



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:
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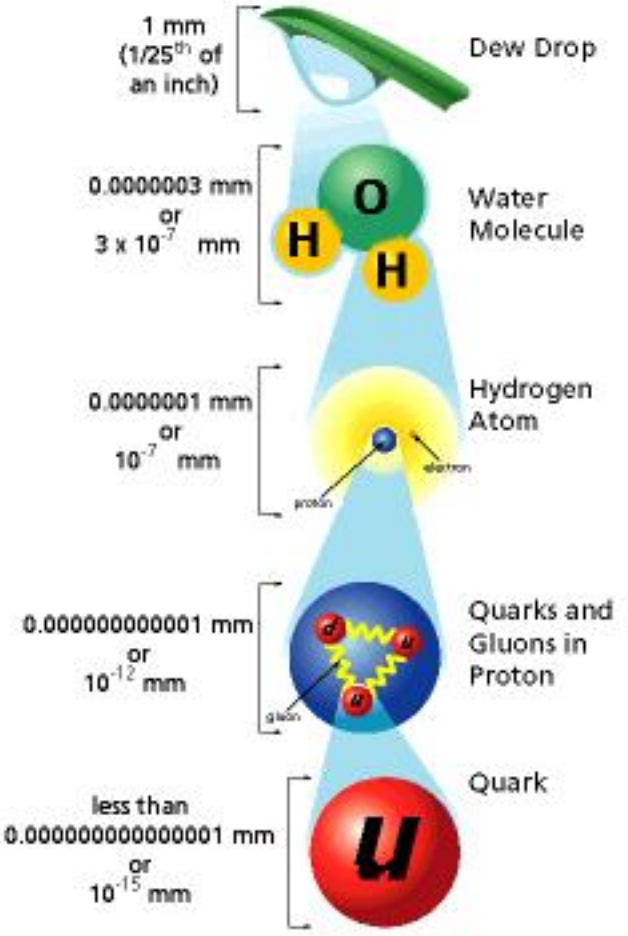
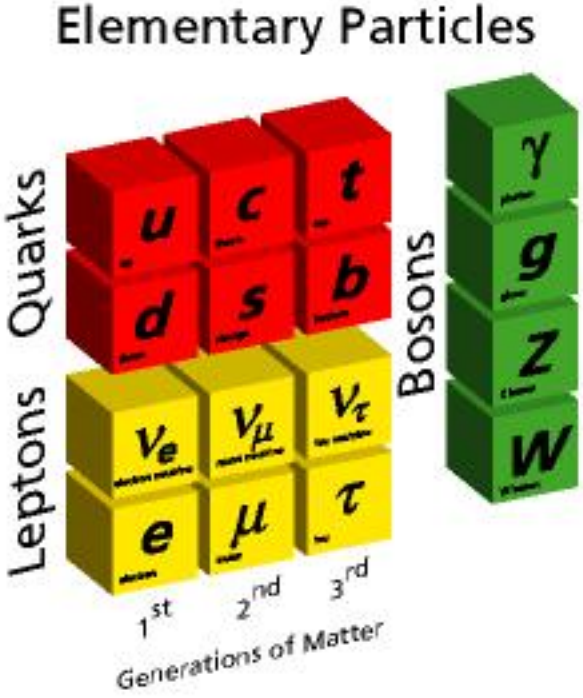
Particles of the Standard Model





Photon
Gluon

Protons and neutrons each composed of 3
up (u) and down (d) quarks, `held together’ by gluons

Cosmic Neutrinos

- Massless (or extremely light), electrically neutral particles that only interact via the Weak Force (with W, Z bosons)
- Standard Model includes 3 massless neutrinos: ν_e ν_μ ν_τ
- In the early Universe, they are produced in weak interactions between quarks and leptons and should be about as abundant as the photons of the CMB.
- They form a Cosmic Neutrino Background (CNB) analogous to the Cosmic Microwave (Photon) Background.
- Just as CMB photons decouple around t_{rec}=380,000 years or T_{rec}~3000 deg K, cosmic neutrinos decouple (stop interacting) at t_F~1 second or T_F~10^{10} K. Thus, if we could observe this CNB, it would give us a snapshot of the Universe when it was 1 second old. So far, haven't come up with a way to detect CNB neutrinos *directly* (they have very low energy and interact very weakly).

Cosmological (Massless) Neutrinos

Neutrinos are in equilibrium with the primeval plasma through weak interaction reactions. They decouple from the plasma at a temperature

$$T_{dec} \approx 1MeV$$

We then have today a Cosmological Neutrino Background at a temperature:

$$T_\nu = \left(\frac{4}{11}\right)^{1/3} T_\gamma \approx 1.945K \rightarrow kT_\nu \approx 1.68 \cdot 10^{-4} eV$$

slightly colder than the CMB

With a density of:

$$n_f = \frac{3}{4}\frac{\varsigma(3)}{\pi^2} g_f T_f^3 \rightarrow n_{\nu_k,\bar{\nu}_k} \approx 0.1827 \cdot T_\nu^3 \approx 112 cm^{-3}$$

for a relativistic neutrino translates in a extra radiation component of:

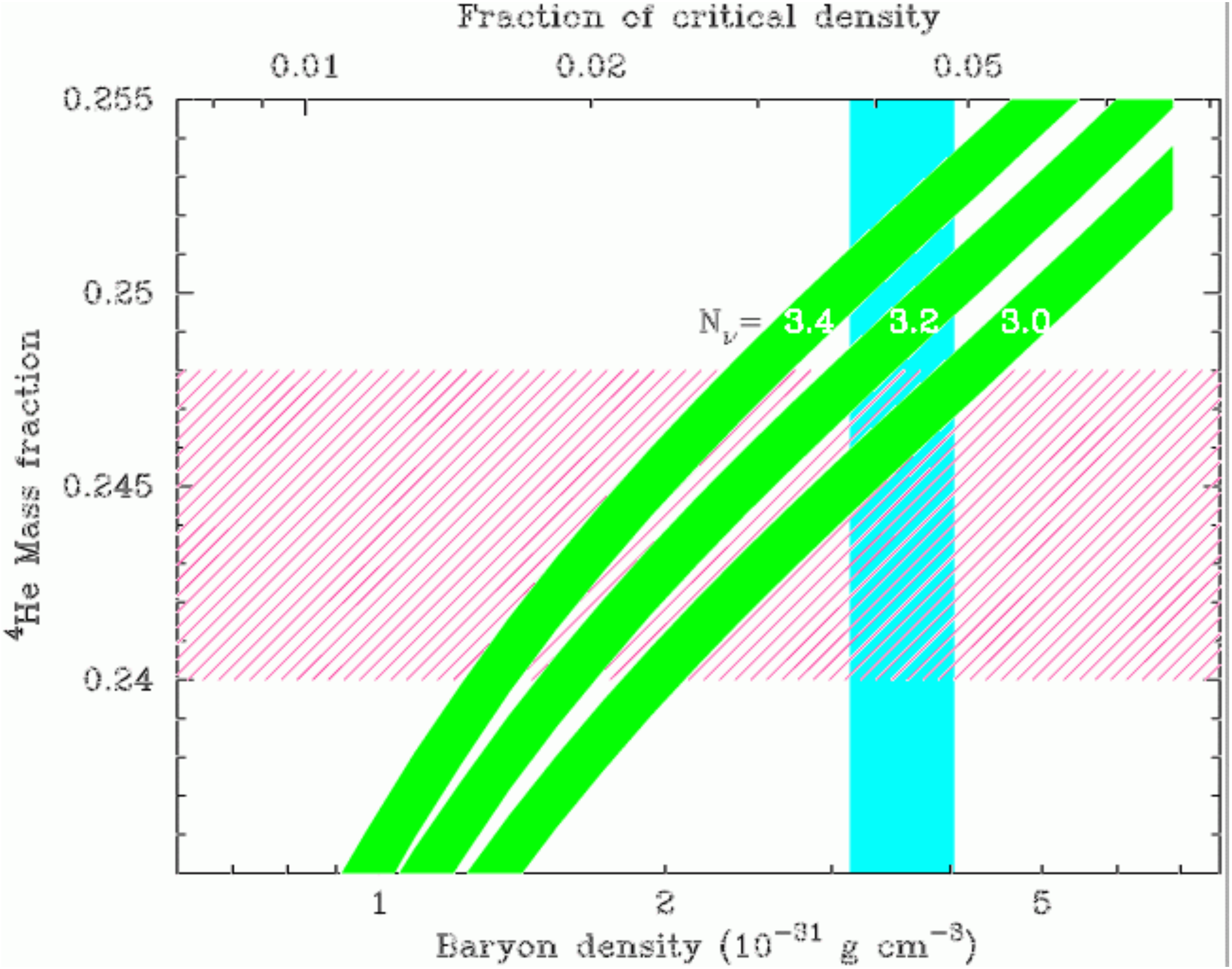
$$\Omega_\nu h^2 = \frac{7}{4}\left(\frac{4}{11}\right)^{4/3} N_{eff}^\nu \Omega_\gamma h^2$$

Standard Model predicts:

$$N_{eff}^\nu = 3.046$$

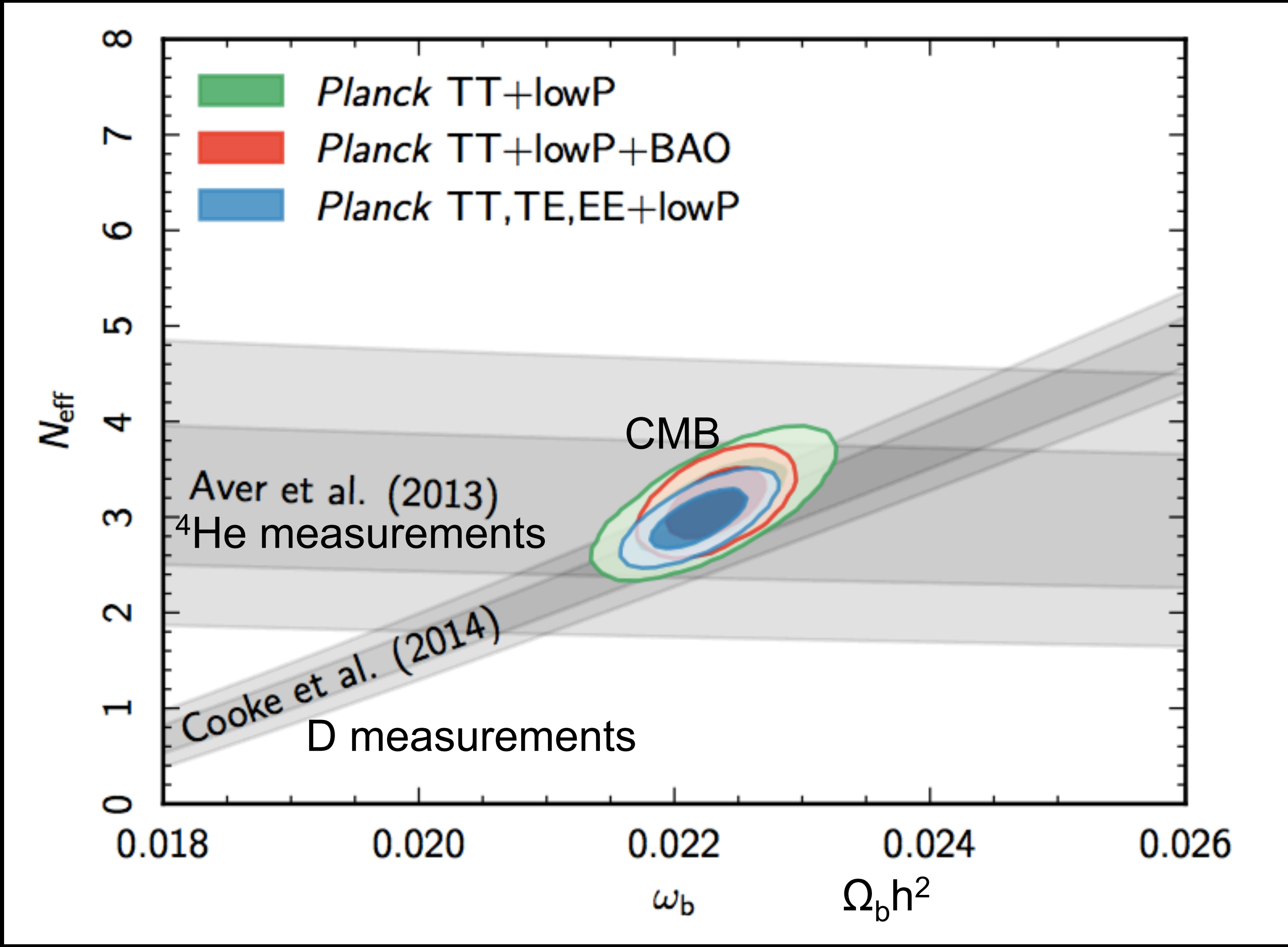
BBN and Neutrinos

- Energy density of neutrinos is comparable to the energy density of photons during BBN, and together they dominate over massive particles.
- The expansion rate (at fixed temperature) during BBN is determined by the total number of massless (or relativistic) species: more massless particles → higher density → higher expansion rate
- BBN involves competition between weak interaction rates and cosmic expansion rate: changing the expansion rate H(T) will change light element abundances, particularly ^{4}He.
- Agreement of BBN predictions with observed element abundances thus constrains the number of species of light particles (e.g., the number of light neutrinos), N_{eff}.


Fraction of critical density
0.01
0.02
0.05
0.255
0.25
0.245
0.24
^{4}He Mass fraction
N_ν = 3.4
3.2
3.0
1
2
5
Baryon density (10^{-31} g cm^{-3})

CMB, BBN and Neutrinos

- Standard Model with N_{eff}=3 light neutrinos fits: evidence for Cosmic Neutrino Background!
- Little room left for additional light particles



Cosmology & Particle Physics

- The BBN constraint on neutrino properties was historically one of the first examples of the symbiotic interaction between cosmology & particle physics, a major theme over the last 35 years.

- Cosmology: to understand the early Universe, we need to understand physics at the highest energies

- Particle Physics: since accelerators cannot reach the highest energy scales, cosmology can constrain the physical laws at very high energies: probe physics beyond the Standard Model.

Logarithmic view of Cosmic History

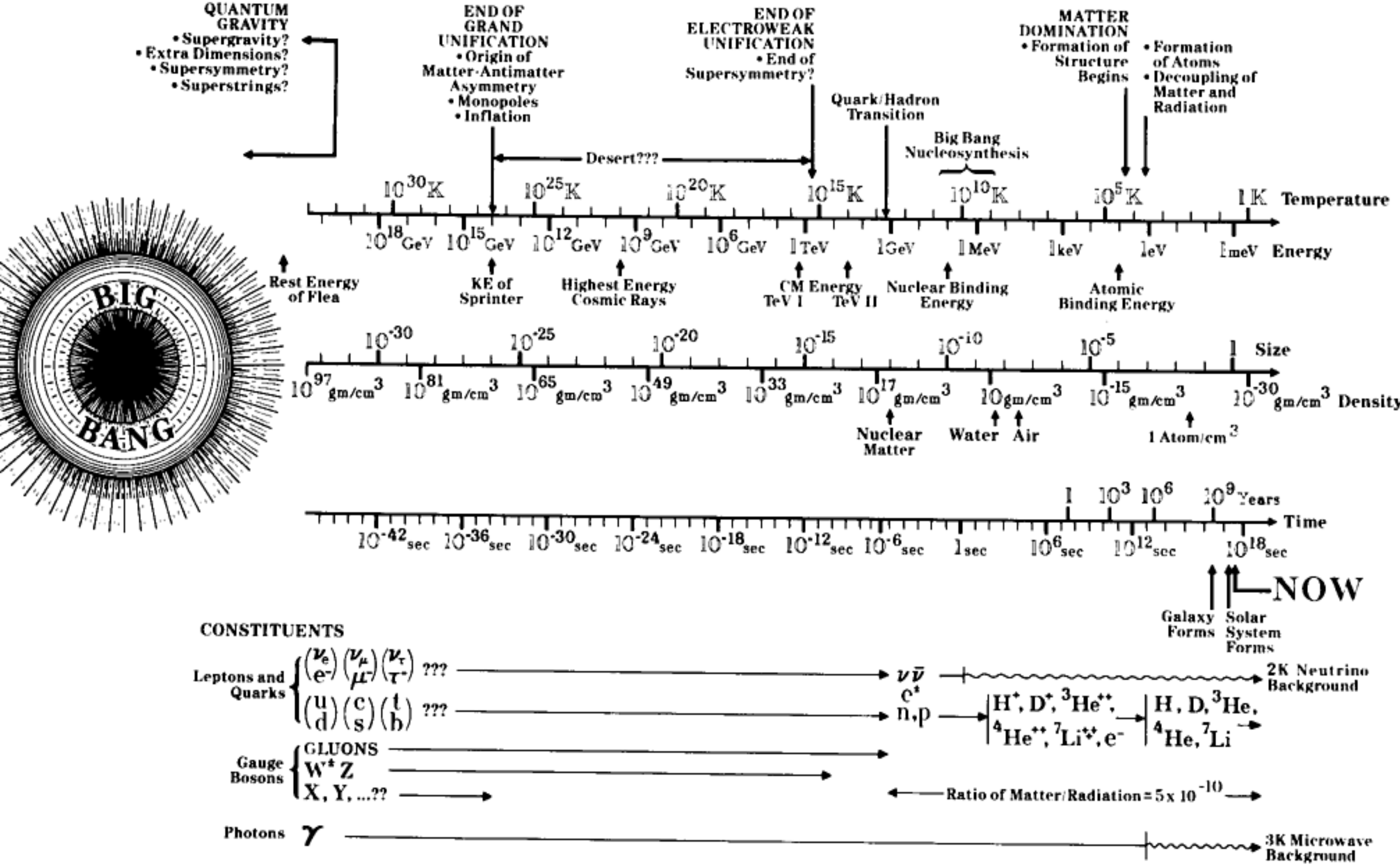


Fig. 1.5.

Cosmology & Particle Physics:
Offspring of the Marriage

- In addition to the light nuclei and the thermal Cosmic Microwave Background Radiation, there are a number of more speculative but well-motivated relics from the Hot Big Bang.
- Two prime examples:
  - Cold Dark Matter particles
  - Asymmetry between matter & anti-matter in the Universe (baryon asymmetry)

- Later, we will discuss what is perhaps the most remarkable child of this marriage: the Inflationary Scenario.

Non-baryonic Dark Matter

- Evidence on the amount of Dark Matter from Big Bang Nucleosynthesis and CMB indicates 25% of the Universe is in an exotic Dark Matter component, made of some as-yet undiscovered elementary particle.

- In order for it to be dark matter, this particle should be at most weakly interacting (i.e., interact with W, Z bosons, not photons) and have an abundance in the Universe of $\Omega_{\text{dark matter}} = 0.25$.

- Models of Elementary Particle Physics provide a number of Dark Matter candidates, hypothetical particles with these requisite properties.

(Some) Dark Matter Candidates

Neutrinos (mass ~ few electron Volts ~ 10^{-5} electron's mass) known to exist, should be as abundant as CMB photons.

Weakly Interacting Massive Particles (WIMPS) (mass ~ 10-100 x proton mass) Favorite candidate of particle physics theorists

Axions (mass ~ 10^{-5} electron Volts ~ 10^{-10} electron mass) Hypothetical particle that arises in theories that seek to explain certain features of the strong interactions

Note: these candidates involve physics beyond the well-tested Standard Model of Particle Physics. Thus, determining the nature of the Dark Matter should tell us about fundamental physics.

Dark Matter Properties: Clustering

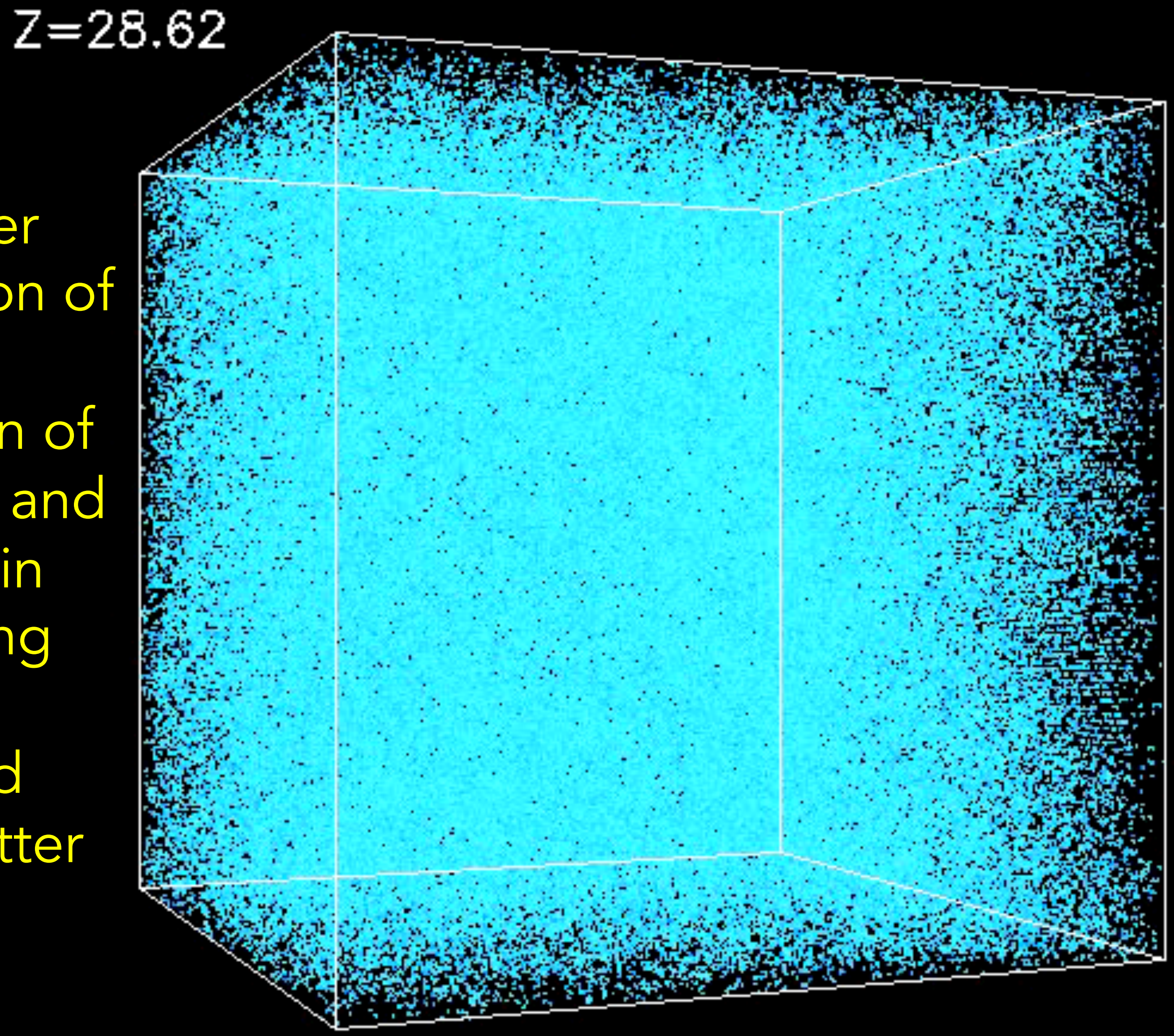
Three `types' of Dark Matter distinguished by the objects they can be found in:

- Cold DM: clusters on all scales; particles slowly moving,… Candidates: WIMPs, axions, …
- Hot DM: these particles moved at near the speed of light early on, and can only cluster in objects as big as clusters (or larger): would not expect to find them in individual galaxy halos.
  Candidate: neutrinos
- Warm DM: clusters on scales of galaxies or larger.
  Candidate: heavy neutrinos (in certain cases)

Dark Matter & Large-scale Structure

These 3 different types of DM (cold, hot, warm) lead to different scenarios for the formation of galaxies and large-scale structures in the Universe.

Observations of the large-scale distribution of galaxies (from galaxy surveys) indicate that the bulk of the DM is cold (or at most slightly warm).



Computer Simulation of the formation of Galaxies and Clusters in Expanding Universe with Cold Dark Matter

Relic Cold Dark Matter WIMPs

- In the early Universe, consider a Weakly Interacting Massive Particle interacting with other particles via the Weak Interaction. At very high temperatures (very early times), when the typical thermal (kinetic) energy per WIMP is much larger than its rest mass, $k_BT >> m_{WIMP}c^2$, they move at essentially the speed of light and are as abundant as the background radiation photons.

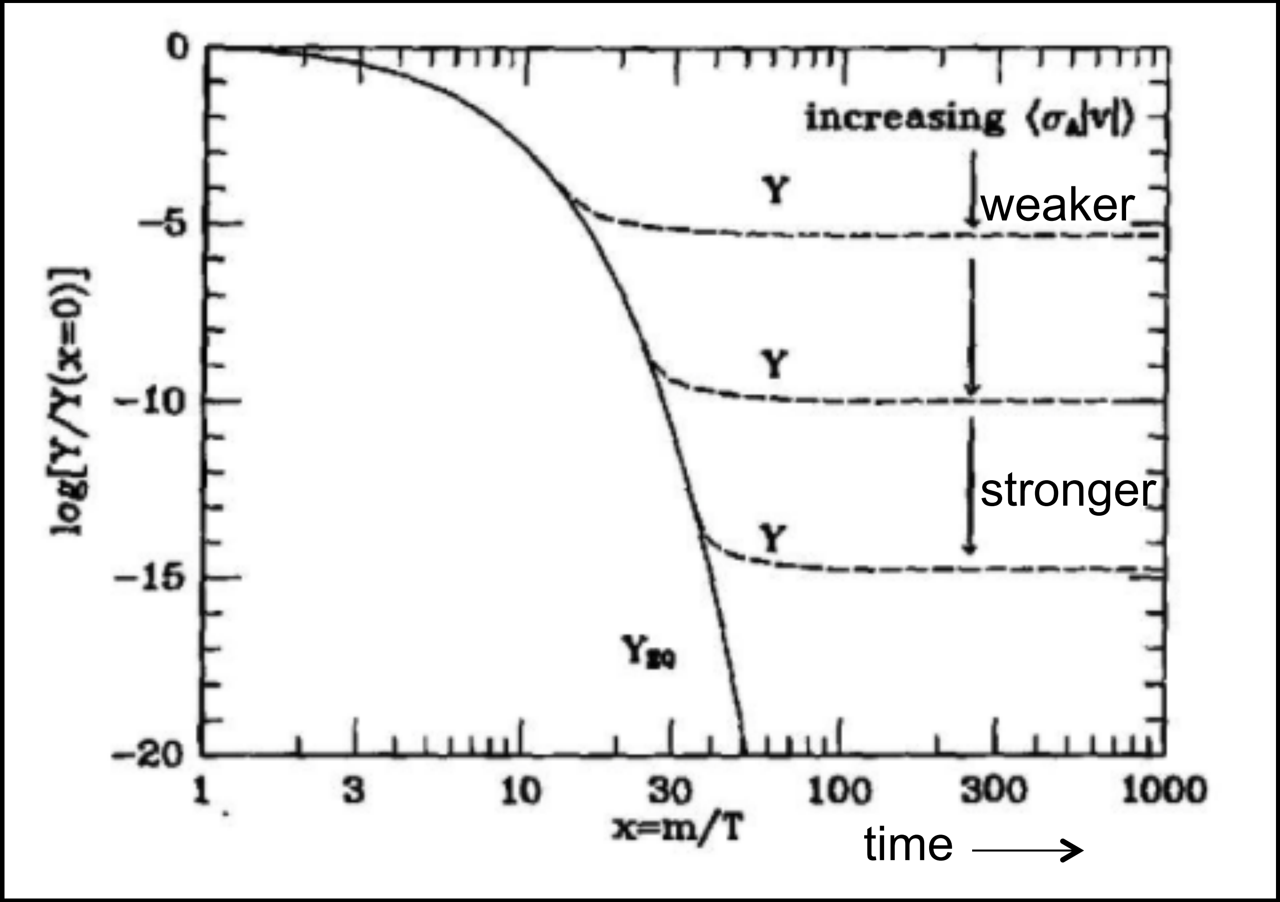
- A critical interaction is the annihilation of a WIMP and anti-WIMP into another weakly interacting particle (and anti-particle) and the inverse of this reaction: the creation of a WIMP/anti-WIMP pair.

Relic WIMPs

- When the temperature drops below the rest mass of the WIMP, $k_B T < m_{WIMP} c^2$, the rate of annihilation of WIMP/anti-WIMPs becomes larger than their rate of production: the abundance of WIMPs falls compared to photons.
- At a certain point, the abundance of WIMPs and anti-WIMPs has dropped so low, that they can no longer find each other to annihilate. The WIMPs “freeze out” of thermal equilibrium (analogous to freeze-out of weak interactions just before BBN) and their abundance relative to photons thereafter remains fixed.

Relic WIMPs

WIMP abundance relative to photons



Abundance at freeze-out determined by strength of the annihilation interactions: stronger→lower.

Relic WIMPs

- Recall for baryons, Ω_b=0.05 from BBN and CMB. This corresponds to a baryon to photon ratio:

$$n_{baryon}/n_{photon} = 6 \times 10^{-10}$$

- For WIMPs with characteristic Weak Interaction rates, their abundance relative to photons at freeze-out is of order

$$n_{WIMP}/n_{photon} \sim 3 \times 10^{-9} (m_{proton}/m_{WIMP})$$

or

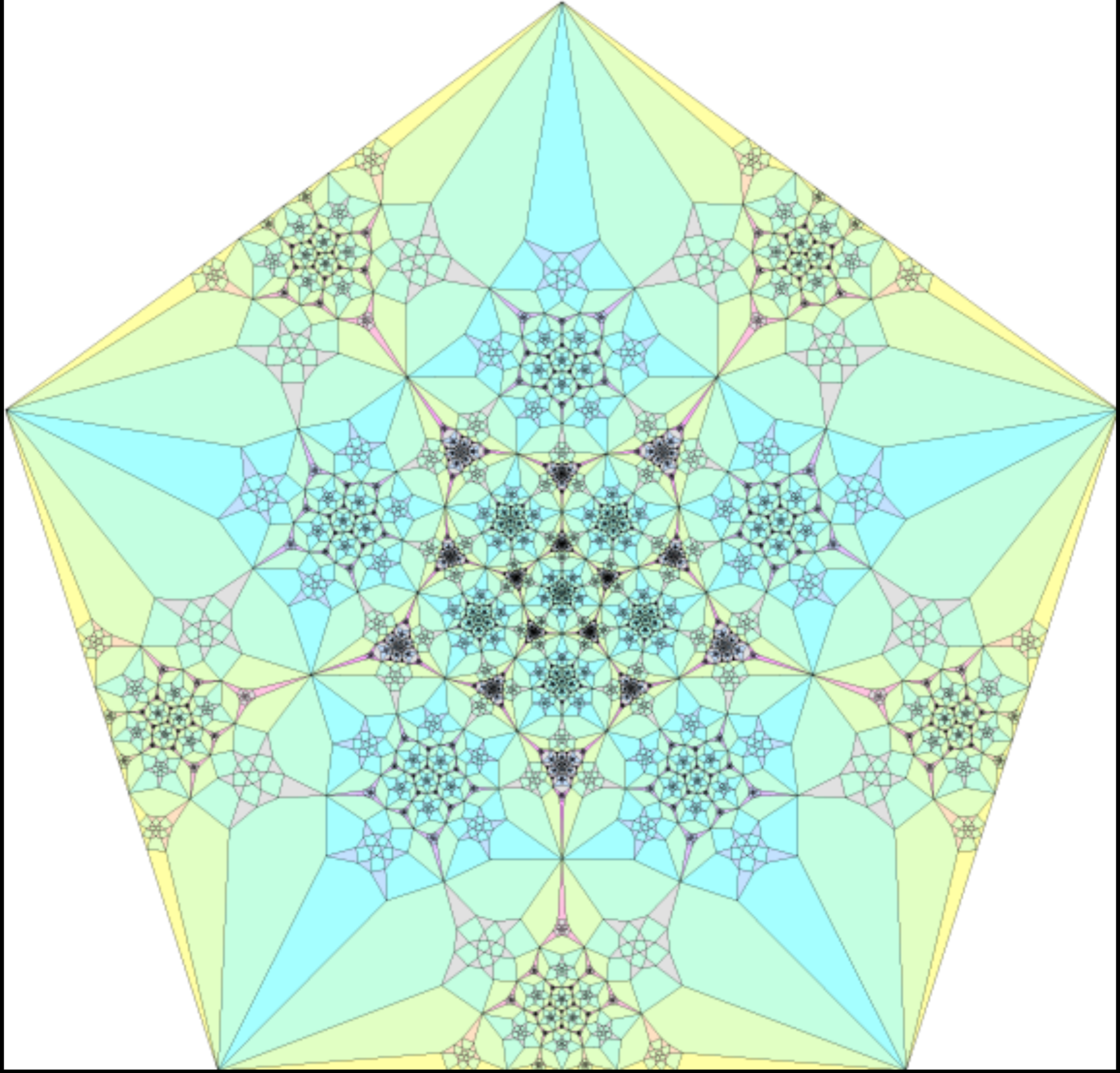
$$\Omega_{WIMP} \sim 0.25$$

so WIMPs are `natural' Dark Matter candidates! This is sometimes called the 'WIMP miracle'.

What is the WIMP?

- It can’t be one of the elementary particles of the Standard Model (quarks or leptons): they make up only 5% of the critical density, and we need 25%.
- It must come from (and would thus be evidence for) physics beyond the Standard Model.

Symmetries in Nature



Symmetries and Conservation Laws

- Certain systems in Nature exhibit symmetries in space and time:
  - rotational invariance (e.g., of a sphere)
  - spatial or time translation invariance
  - reflection (left-right) symmetry
- **Noether's theorem:** for systems with symmetry, there are corresponding quantities that are *conserved* in time. Example: spatial translation invariance ←→ conservation of momentum.

Emmy Noether

External and Internal Symmetries

- External symmetries in space and time:
  - rotational invariance (e.g., of a sphere)
  - spatial or time translation invariance
  - reflection (left-right) symmetry
- Internal symmetries (not involving spatial transformations):
  - Elementary particles exhibit many such symmetries, and there are associated conservation laws. Example: gauge-invariance of the electromagnetic field ←→ conservation of electric charge

Symmetry & Unification

well-tested

1800's: electricity & magnetism given a unified description in Maxwell's theory of Electromagnetism
1930's: Initial Theory of Weak Interactions (Fermi)
1960's: Electromagnetic & weak interactions unified in electroweak theory (Glashow, Weinberg, Salam)
1970's: Theory of Strong Interactions (QCD)
1970's: Standard Model of Particle Physics

speculative

1970's: Electroweak & strong interactions unified in Grand Unified Theories (GUTs)
1980's-20??: Unify electroweak, strong, and gravitational interactions in Superstring Theory

Unification of Forces

Strong	**Electromagnetic**	**Weak**	**Gravity**
hadrons: p, n; pions: $\pi^{\pm}, \pi^{0}$; (QCD: quarks, gluons)	charged particles: e^{-}, μ^{-}, τ^{-}; p; $\pi^{\pm}$	p, n, π; e, μ, τ;, neutrinos: ν_e, ν_μ, ν_τ	all particles (always attractive)
nuclear binding; energy in stars	atoms, crystals, molecules; light; chemical energy	decays: $n \rightarrow pe^{-}\bar{\nu}_e$; element synthesis	weight; binding of solar system, stars, galaxies
	$\leftarrow \quad E + B \quad \rightarrow$ (Maxwell)		
← QCD →	← Electroweak $(SU(2) \times U(1))$ →		
← Grand Unification (GUT)? →			
← Superstring? →			

Symmetry and the Standard Model

- Weak & Electromagnetic interactions arise from a common Electroweak symmetry. This model now very precisely tested and confirmed in particle physics experiments at accelerators.

- But the manifestations of these two interactions appear to be very different:
  - Electromagnetism: photon is massless--> EM force has infinite range
  - Weak interaction: W,Z bosons are massive (~100 times proton mass) → weak force short range
- Why are they so different?

Spontaneous Symmetry Breaking

Symmetries of the theory may not be manifest in Nature: they can be <u>broken</u>.

Everyday Examples:

- Pencil balanced on its end is rotationally symmetric, looks the same from any angle. But when it falls, it must do so in a particular direction, thus breaking the rotational symmetry.

- People sitting at a round table must choose which glass to drink from, the one on their left or their right. Each is possible: initially, the system is left-right symmetric. However, once someone chooses, the symmetry is broken.

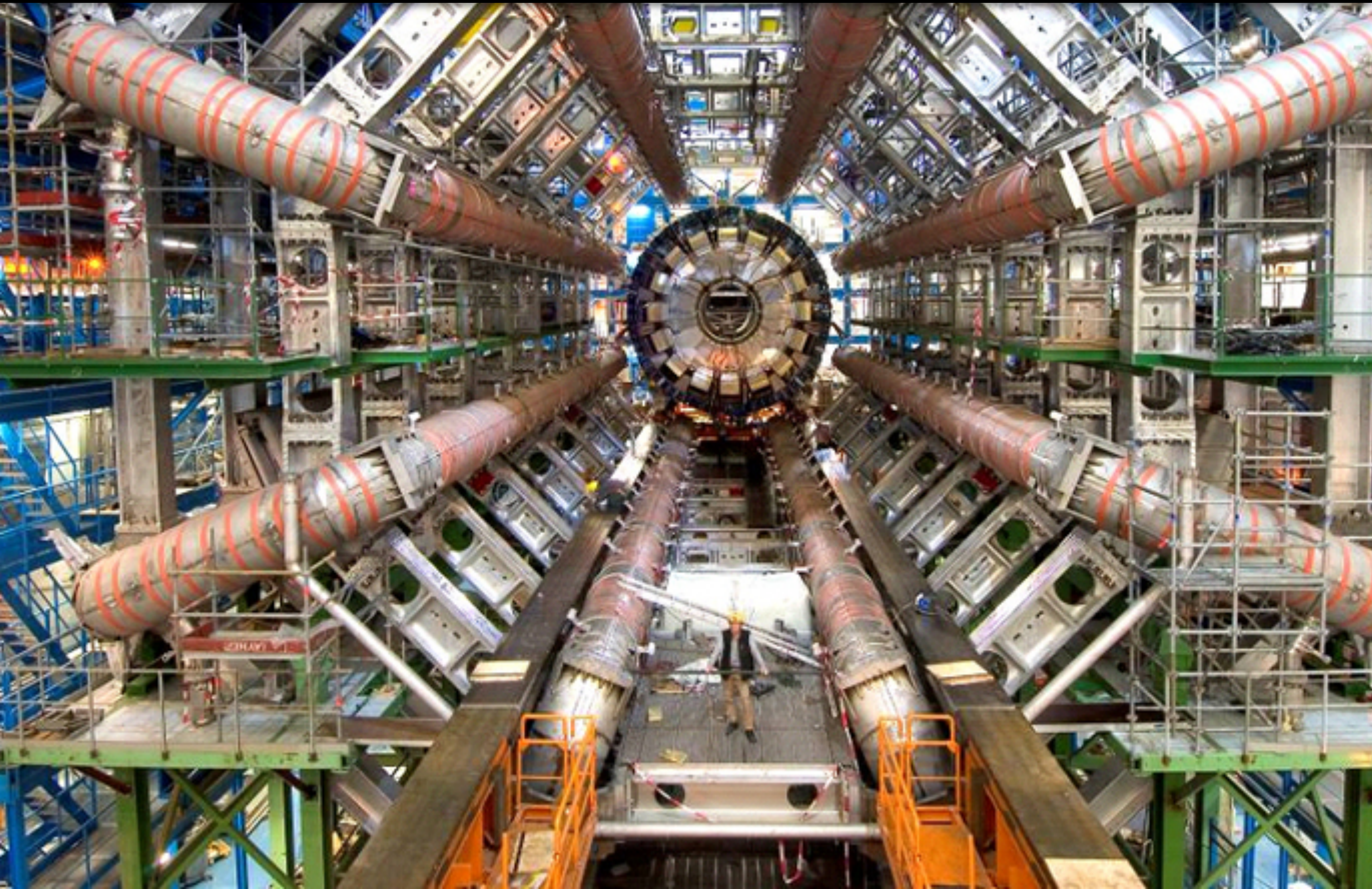
Higgs Boson & Symmetry Breaking

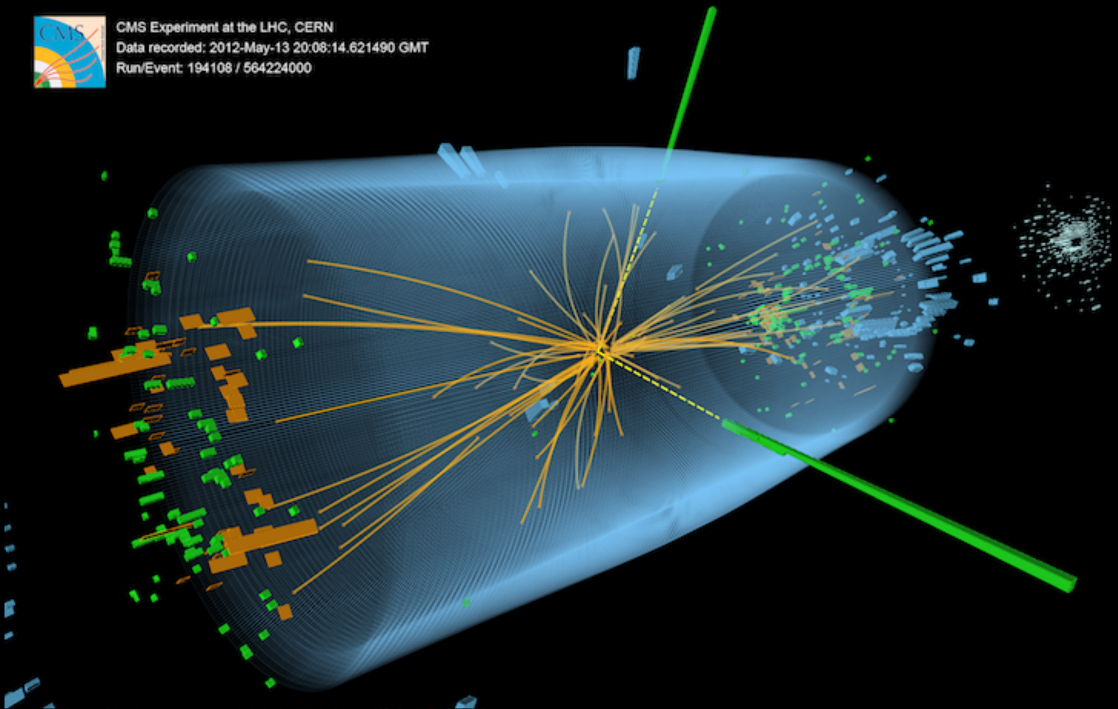
Higgs Boson: spin-zero particle (scalar field) that breaks the electroweak symmetry and differentiates the electromagnetic from the weak interactions.

The Higgs interacts with and gives mass to the W and Z Bosons and to all other elementary matter particles, but leaves the photon massless. Can think of it as a kind of `medium' through which elementary particles move. It is a `field' (like an electromagnetic or gravitational field) but with the same value throughout all of space.

Like the photon of electromagnetism, the Higgs field has an associated particle, the Higgs boson, with a mass about 130 times the proton mass.

Large Hadron Collider now operating in Switzerland.
This is where the Higgs Boson was discovered in 2012.




CMS Experiment at the LHC, CERN
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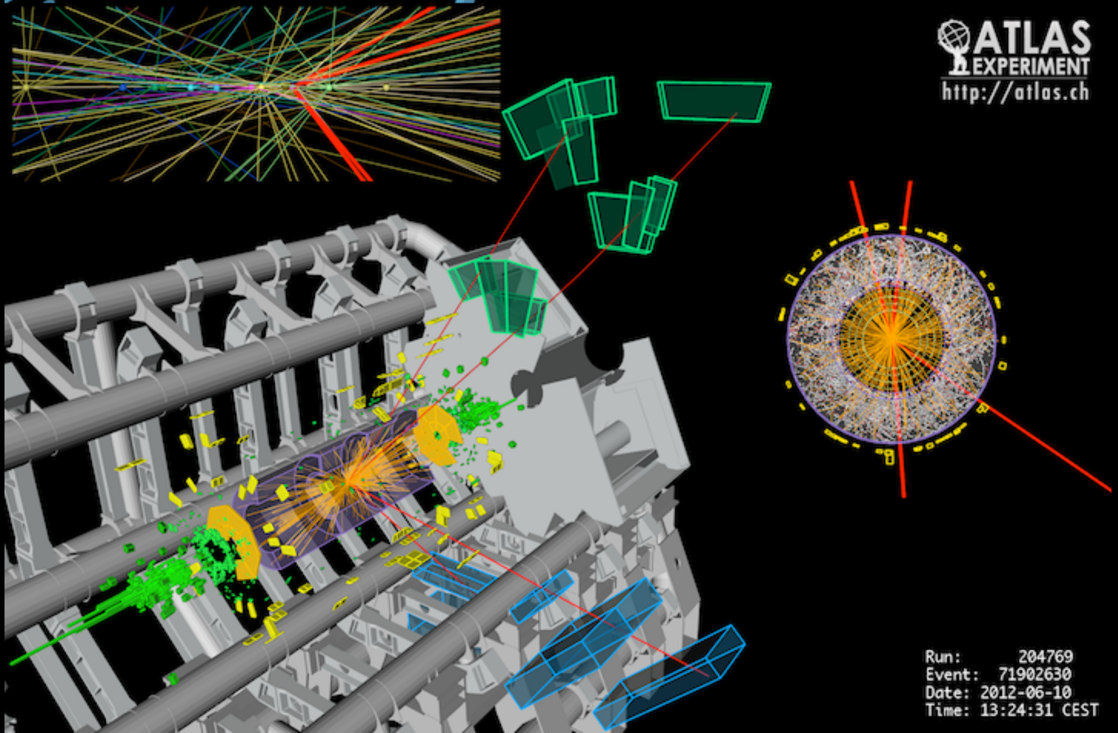
ATLAS
EXPERIMENT
http://atlas.ch
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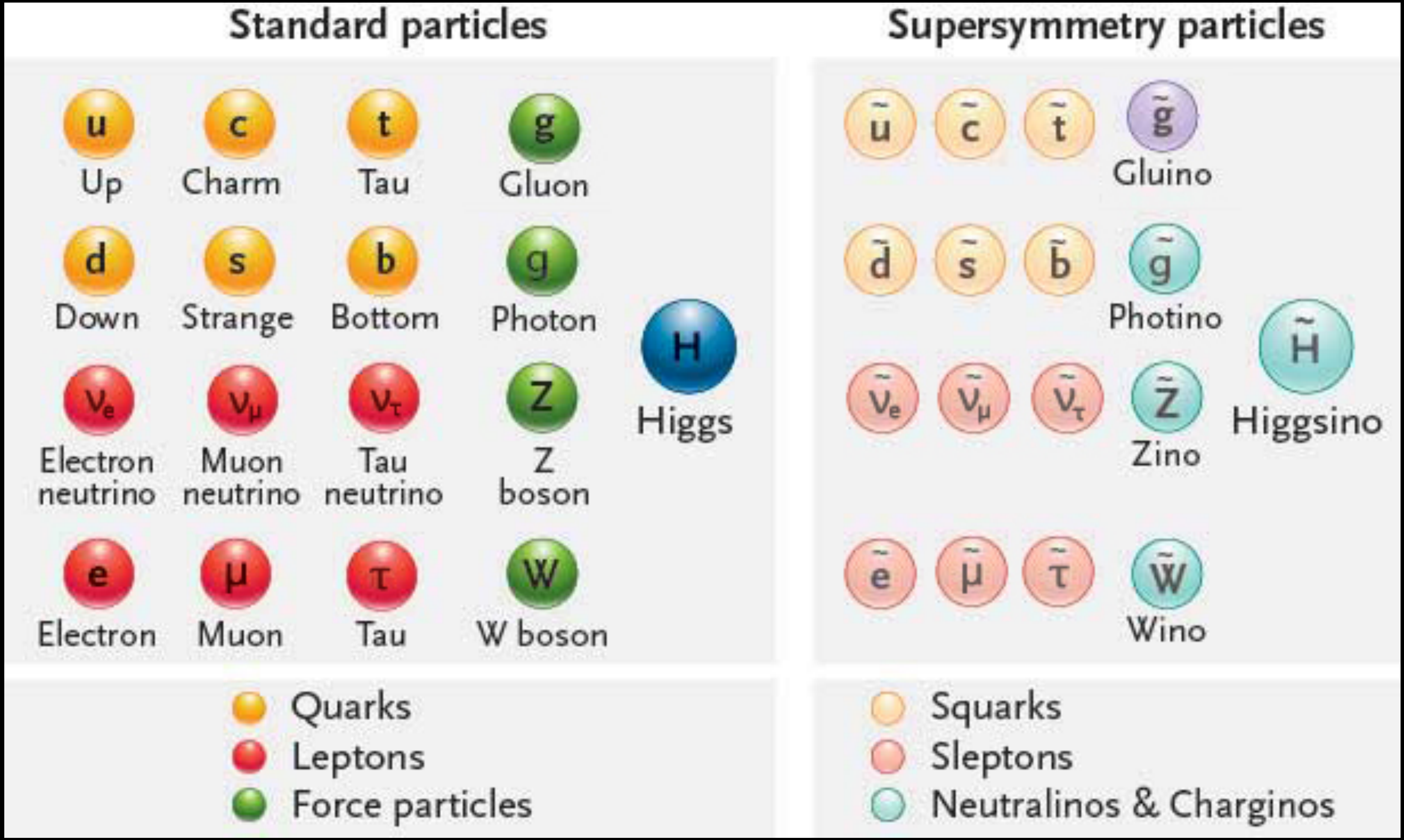
Supersymmetry (SUSY)

- Hypothetical symmetry between fermions and bosons.
- For every particle of the Standard Model, there would be a supersymmetric partner particle with different spin.
- Each particle and its SUSY partner would have the same mass.
- Such SUSY particles have not (yet) been seen at the LHC: they must be heavier than Standard Model particles: SUSY must be a *broken symmetry* in nature (or it may just not be a symmetry of nature at all).

Supersymmetry (SUSY)



The lightest neutralino particle is expected to be stable (doesn't decay) and would be a natural WIMP candidate. Dark matter experiments searching for them.

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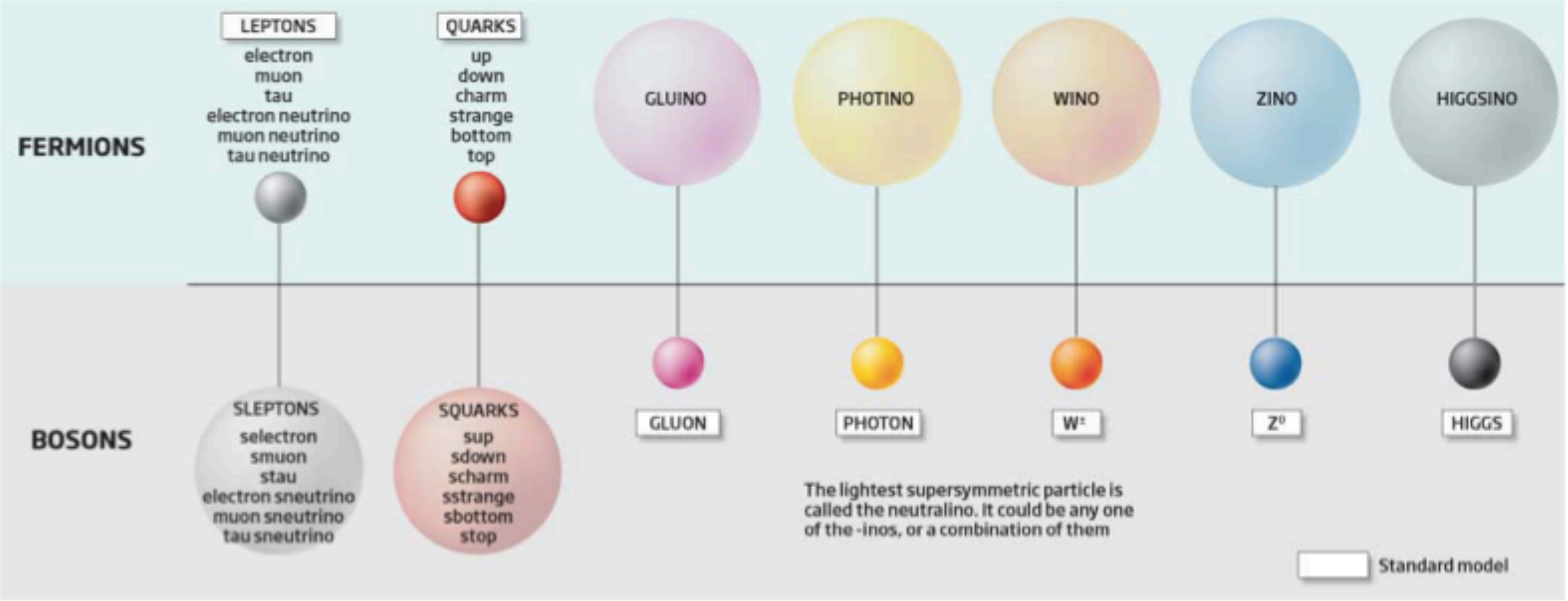

The lightest supersymmetric particle is called the neutralino. It could be any one of the -inos, or a combination of them

Figure 2 - Particles in supersymmetric theories
http://www.newscientist.com/data/images/archive/2734/27341202.jpg

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SUPERsymmetry

THE SEARCH FOR A HIDDEN WORLD OF SUPER PARTICLES

All the matter that makes up the visible Universe is made up of particles that, in turn, are made up of smaller elementary particles...

...but, what if each of these particles has a super-secret super alterego?

Supersymmetry (also known as **SUSY**) is a theory that predicts that for every elementary particle we can see, there is a hidden **super particle** version that we haven't seen yet.

The super particles will have similar properties to their normal versions, but their **mass** and **'spin'** will be different.

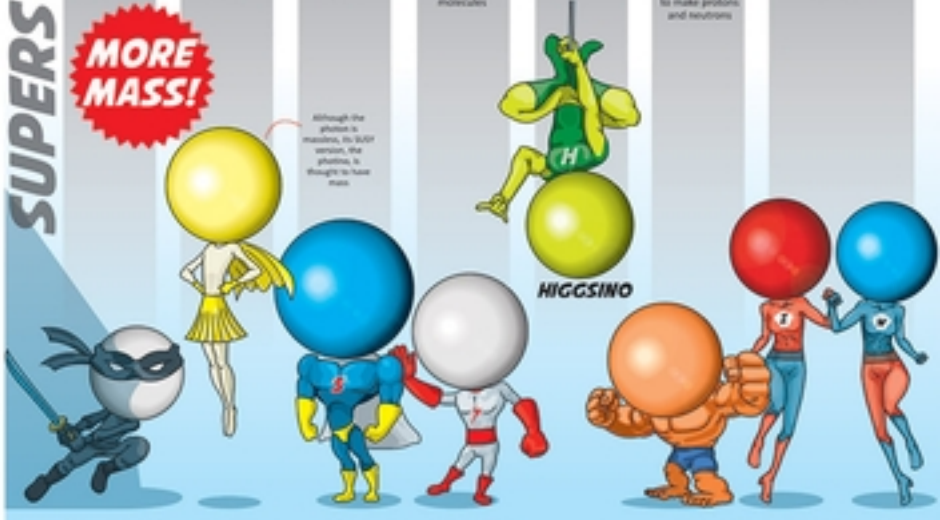
Each super particle will have **more mass** than its 'normal' version. So, for every **quark**, there will be a heavier 'super quark', called a **squark**, hidden from view

NORMALS

NEUTRINO	PHOTON	QUARK	ELECTRON	HIGGS	GLUON	Z BOSON & W BOSON
This is a particle ninja. It has no electric charge and barely interacts with other particles.	This is a particle of light. It has no mass and carries the electromagnetic force	The protons and neutrons that make up an atom's nucleus are made of quarks.	This negatively-charged particle orbits an atom's nucleus and allows atoms to bond to form molecules	The Higgs is responsible for giving the other elementary particles their mass.	This carries the strong nuclear force. It is the particle glue that holds quarks together to make protons and neutrons	These carry the weak nuclear force. They are responsible for allowing atoms to decay into lighter chemical elements.

SUPERS

MORE MASS!

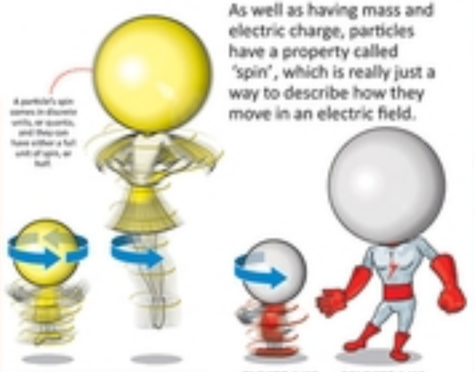


Although the photon is massless, its SUSY version, the photino, is thought to have mass.

The massive SUSY particles could provide some of the missing **'dark matter'** that scientists are searching for.

LESS SPIN!

A super particle will have a half unit less **'spin'** than its normal counterpart.



As well as having mass and electric charge, particles have a property called 'spin', which is really just a way to describe how they move in an electric field.

A particle's spin comes in discrete units, or quanta, and they can have either a full unit of spin, or half.

PHOTONS ARE SPIN-ONE PARTICLES

PHOTINOS ARE SPIN-HALF PARTICLES

ELECTRONS ARE SPIN-HALF PARTICLES

SELECTRONS HAVE NO SPIN AT ALL

In the weird world of particle physics, spin isn't much like spin as you might know it. For example, although a spin-one particle only needs to make one revolution to get back to its starting point, a spin-half particle has to make two revolutions to get back to where it started.

So, if you were a spin-half particle facing your friend, and you made one full revolution, when you came to a stop, your friend would still be looking at the back of your head!

The Theoretical Appeal of SUSY

- Explain hierarchy of energy scales in particle physics: W, Z bosons orders of magnitude lighter than GUT scale
- Coupling constant unification at GUT scale

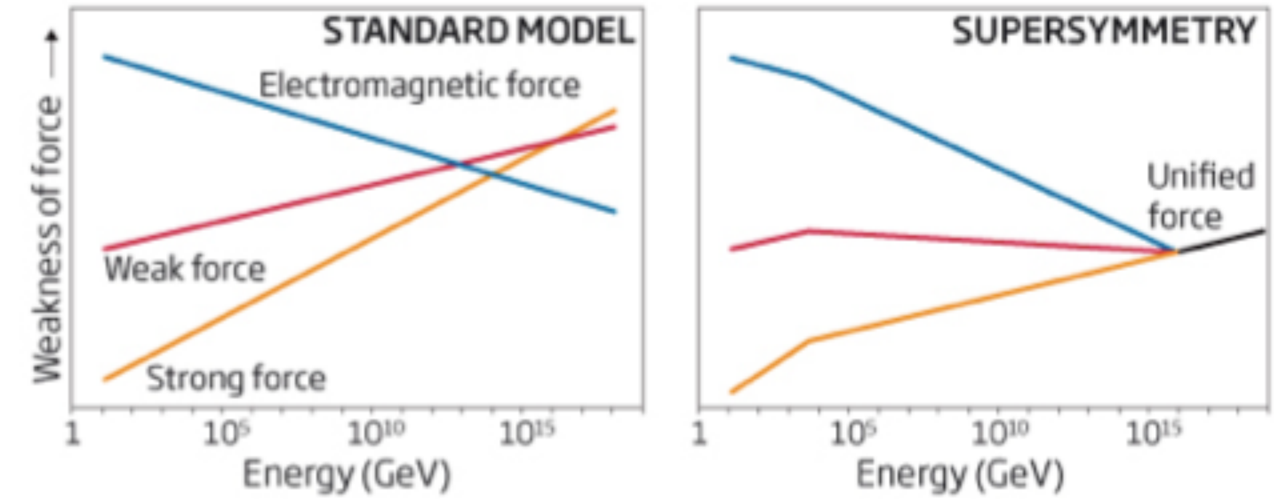
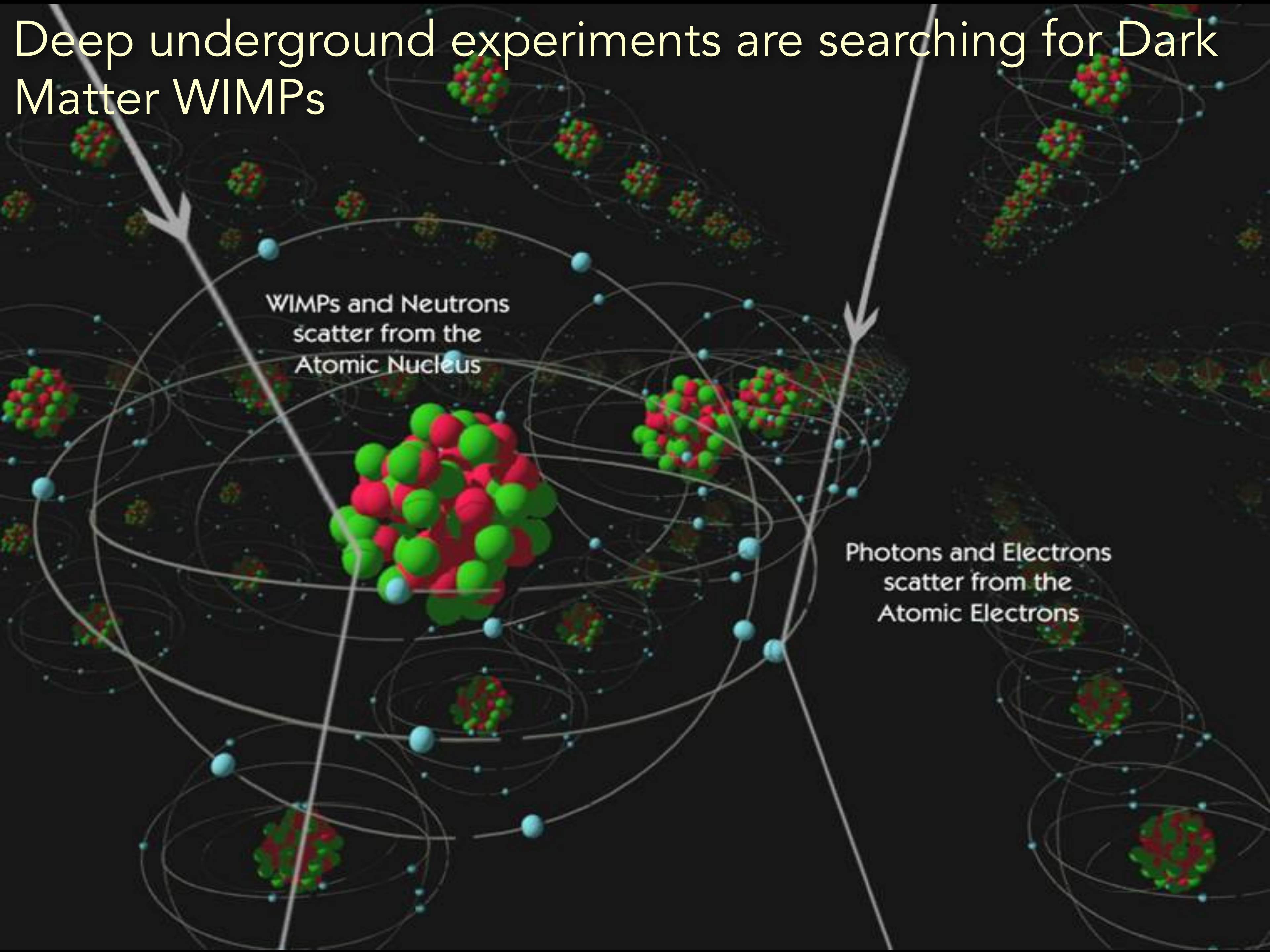
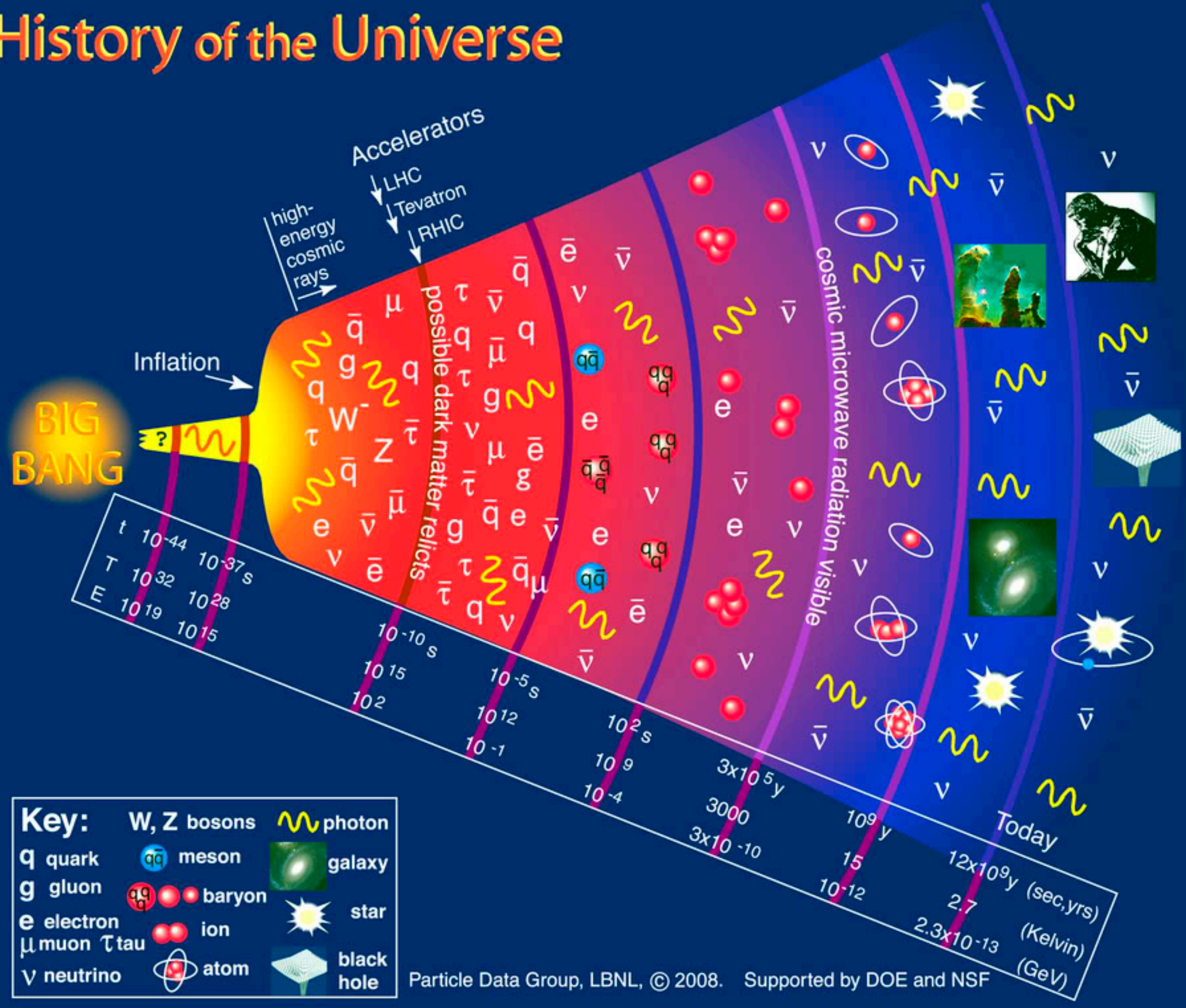


Figure 3 – Force unification in the Standard Model compared to supersymmetry
http://www.newscientist.com/data/images/ns/cms/dn20248/dn20248-2_534.jpg

Deep underground experiments are searching for Dark Matter WIMPs



History of the Universe



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