

Particle Physics: Cosmology

Edward Dunton

Week 12: December 15, 2018
Columbia University Science Honors Program



Course policies

- Classes from 10:00 AM to 12:30 PM (10 min break at ~ 11:10 AM).
- **Attendance record counts.**
 - Up to four absences
 - Lateness or leaving early counts as half-absence
 - Send email notifications of all absences to shpattendance@columbia.edu
- Please, no cell phones during class
- **Please, ask questions!**
- Lecture materials + Research Opportunities + Resources to become a particle physicist

<https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram>

Schedule

Month	Day	Lecture	Teacher
September	22	Introduction	Yeon-jae
	29	History of Particle Physics	Yeon-jae
October	6	Special Relativity	Edward
	13	Quantum Mechanics	Edward
	20	Experimental Methods	Edward
	27	The Standard Model – Overview	Yeon-jae
November	3	The Standard Model – Limitations	Yeon-jae
	10	Neutrino Theory	Edward
	17	Neutrino Experiment	Edward
	24	No classes, SHP break	
December	1	LHC and Experiments	Yeon-jae
	8	The Higgs Boson and Beyond	Yeon-jae
	15	Particle Cosmology	Edward

LAST WEEK...

THE HIGGS BOSON AND BEYOND

What is the Higgs Boson?



- While developing the modern theory of particle physics, physicists soon realized they had found a problem.
- By the same mechanism as the **massless photon** arises from Quantum Electrodynamics, a set of **massless bosons** arise when the theory is extended to include the weak nuclear force.

The Problem:

The short-range characteristic of the nuclear force makes it fundamentally different from electromagnetism...

**The bosons appear to be massless in theory,
but Nature tells us they have mass!**



The Higgs Mechanism

- What made us so sure about the Higgs mechanism?
 - After all, physicists searched for it for decades!

There are consequences to the Higgs mechanism, which we can measure:

1. It predicts massive W^+ , W^- and Z^0 bosons
 - The W^+ , W^- bosons should have a mass of 80.390 ± 0.018 GeV
 - The Z^0 boson should have a mass of 91.1874 ± 0.0021 GeV

However, the mass of the Higgs boson itself is not predicted by the SM...

Measurements:

- ✓ 80.387 ± 0.019 GeV
- ✓ 91.1876 ± 0.0021 GeV

Mass

- How much of your mass is made up of that “fundamental” mass?
 - You've got about 7×10^{27} atoms in you.
 - In terms of quarks, you're about 123×10^{27} up and down quarks.
Adding those masses up, you get to $\sim 0.4 \times 10^{27}$ GeV.
 - That is ~ 0.7 kg!
- 99% of our mass (and the mass of everything else we see) comes from the binding energy of our nuclei.



1 GeV

~



+



+



0.002 GeV + 0.002 GeV + 0.002 GeV

Symmetries

- **Emmy Noether:** any symmetry of a physical system has an associated conservation law.
- *“...certainly one of the most important mathematical theorems ever proved in guiding the development of modern physics, possibly on a par with the Pythagorean theorem.”* — Hill, Lederman
- Physical laws are the same at all times:
 - Time symmetry → leads to energy conservation.



NOT from nobelprize.org

Symmetries and particles

- All of these things are related to a hugely important symmetry in particle physics known as **gauge symmetry**.
- In QM, wave functions are invariant under transformation like:

$$\psi \rightarrow \psi' = \psi e^{i\theta}$$

- This operation is called a **gauge transformation**.
- In particle physics, gauge invariance encodes the symmetry structure of conserved “charges” and the renormalizability of quantum theory.
- Now we can start to talk about why there is only one photon, but eight gluons, and why the weak force has three massive exchange particles.

The weak interaction

- If the gauge group of the weak nuclear force is $SU(2)$, then we expect to see **three massless weak bosons**.
- But we know the weak force is mediated by the W^\pm and the Z^0 , and **these are extremely massive!**
- In order to make a gauge invariant theory work for the weak nuclear force, we need to come up with a way to make heavy gauge bosons in a manner that doesn't destroy the consistency of the quantum theory.

The electroweak force



Sheldon Lee Glashow



Abdus Salam

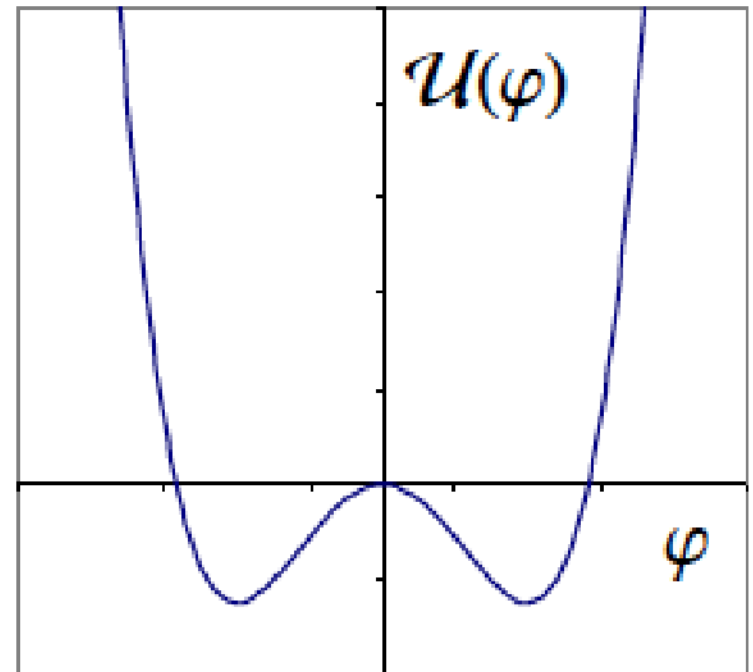


Steven Weinberg

- Glashow, Salam and Weinberg in the late 1960s:
 - The weak force and electromagnetism appear very different at low energies, but GSW hypothesized that at higher energies these are really just **different aspects of the same electroweak interaction**, with a single characteristic charge, e .
 - At high energies, these forces would look the same.
 - At lower energies, the symmetry between these forces is *spontaneously broken*.

Lagrangian mechanics

- To get a correct interpretation of the Lagrangian, and to be able to use perturbative (Feynman) calculations, we need to find one of its minima (*a ground state*) and look at small fluctuations about that minimum.

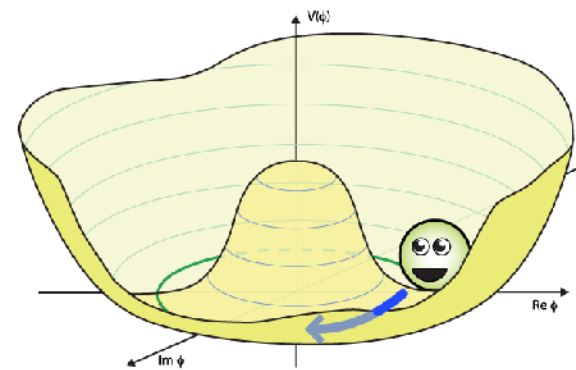
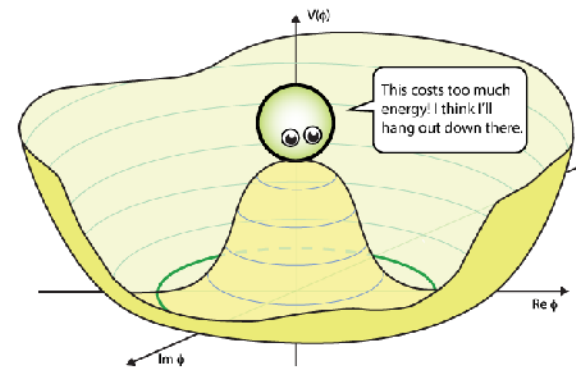
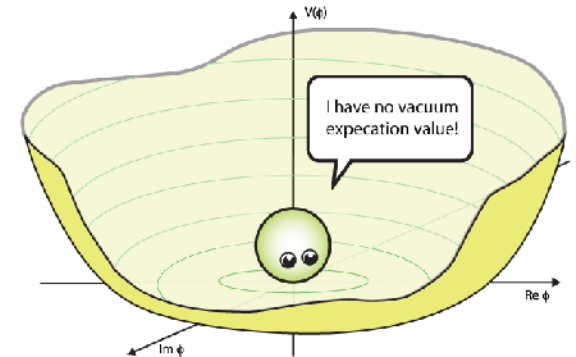
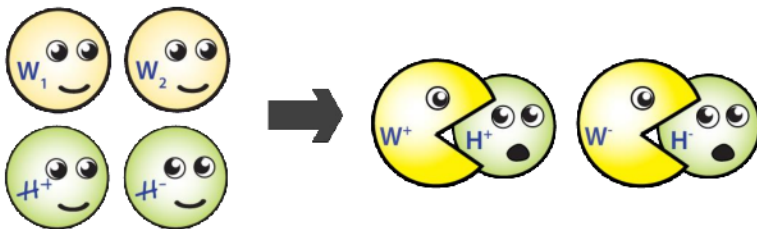
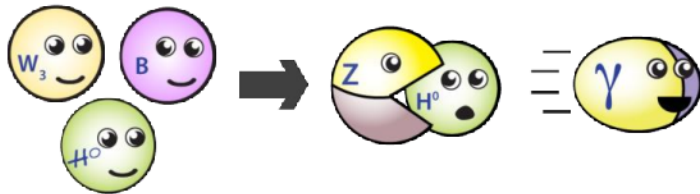
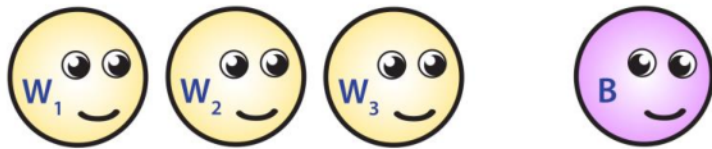


Calculation must be formulated in terms of deviations from one or the other of these ground states.

Symmetry breaking

- The phenomenon we have just considered is called *spontaneous symmetry breaking*.
- Why symmetry breaking?
 - Our choice of a ground state “breaks” the obvious reflection symmetry of the original Lagrangian.
- What about the spontaneous part?
 - The choice of a ground state is arbitrary in this system. There is no external agency that favors one over the other, or even forces the choice to begin with.

The Higgs mechanism



The Higgs mechanism

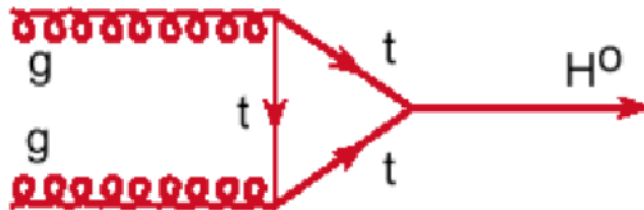
- Now let's come back to our question of a few minutes ago...
- Why are the gauge bosons of the weak nuclear force massive when $SU(2)$ symmetry says you should expect 3 massless bosons?
- Answer: when the gauge symmetry of a Lagrangian is spontaneously broken, the expected massless bosons become massive!

The Higgs mechanism

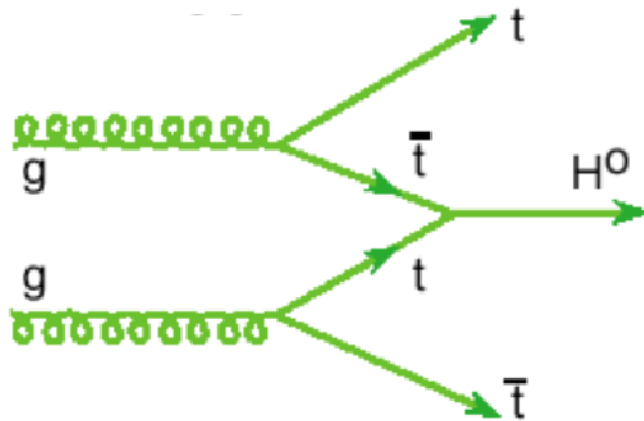
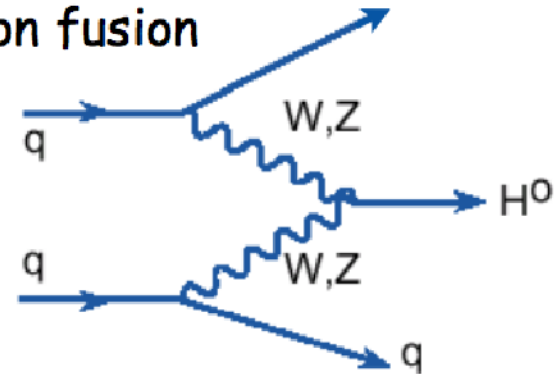
- ...the resulting theory has massive gauge bosons and the nice properties of a fully invariant gauge theory (albeit the symmetries are hidden).
- Physically, the expected massless bosons acquire mass by interacting with a newly apparent massive scalar field called the Higgs field.
 - **This is the Higgs mechanism.**

Higgs production at the LHC

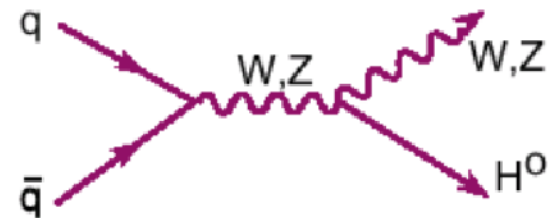
1. Gluon fusion



2. Vector boson fusion



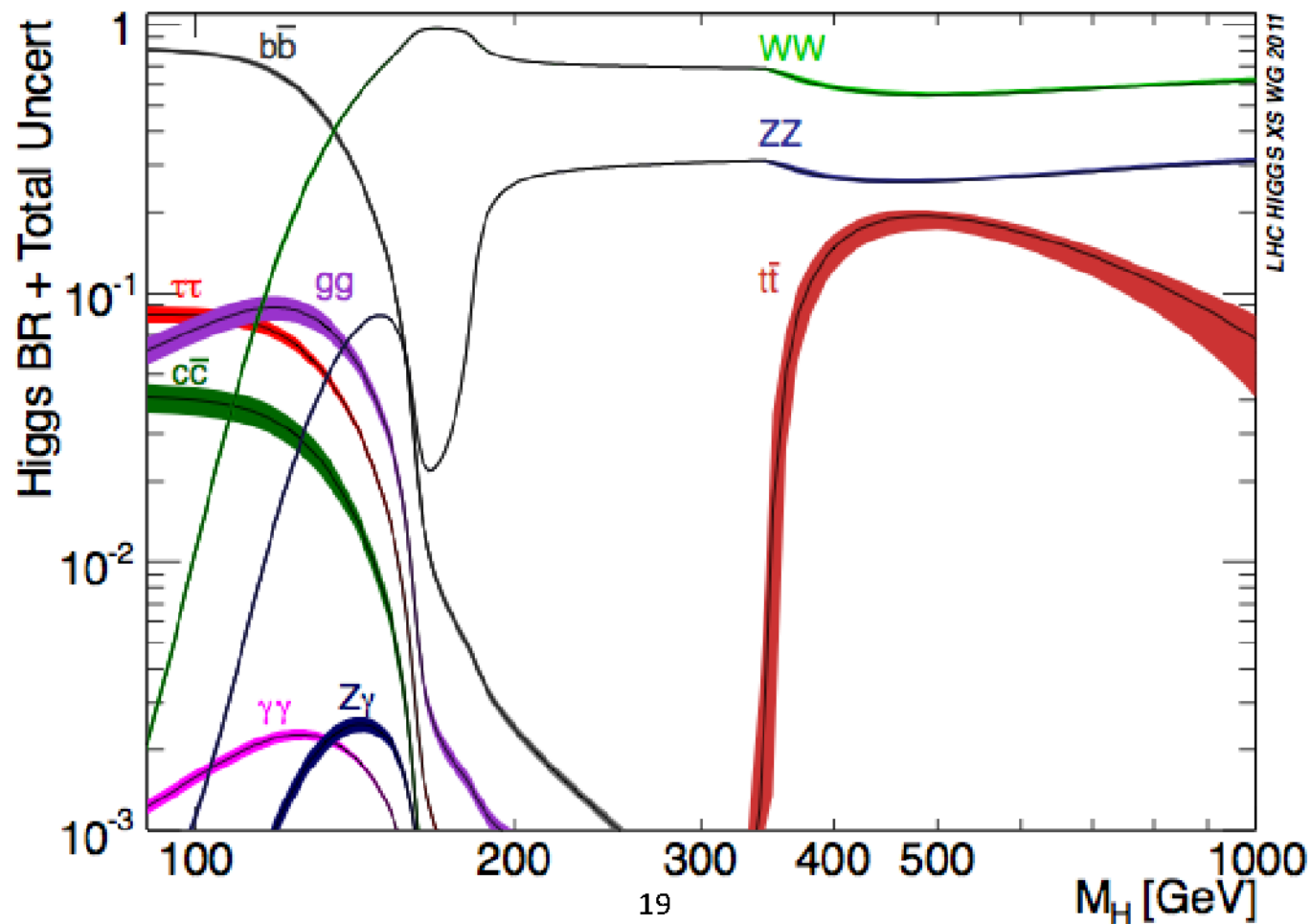
3. $t\bar{t}$ -fusion



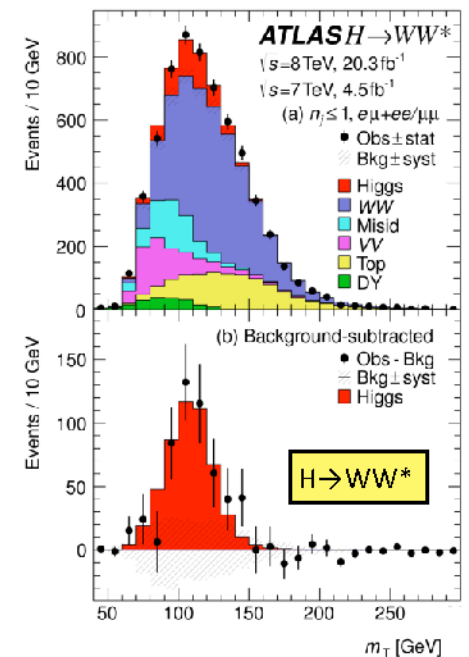
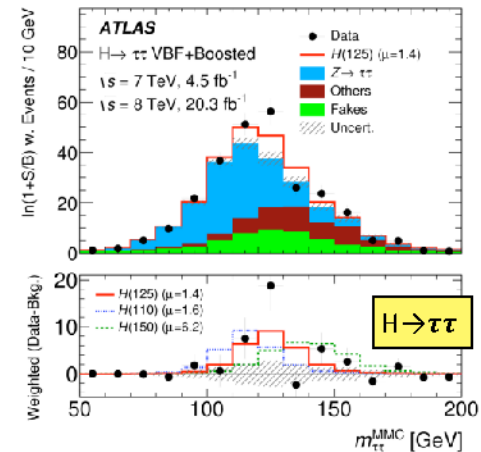
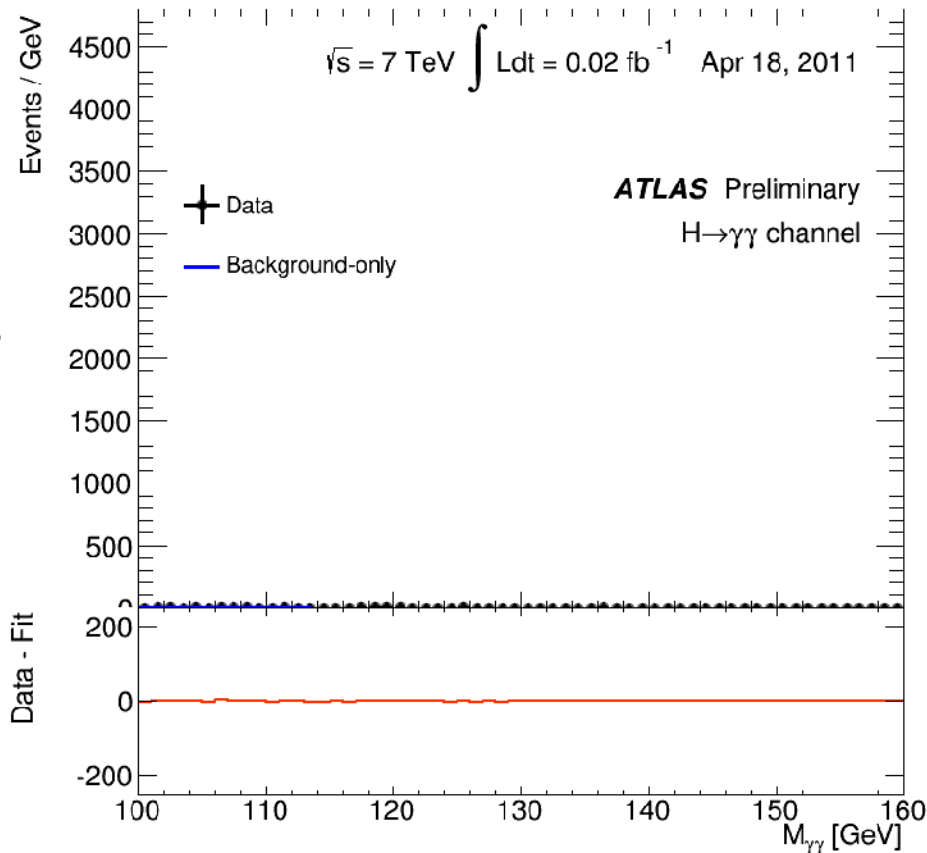
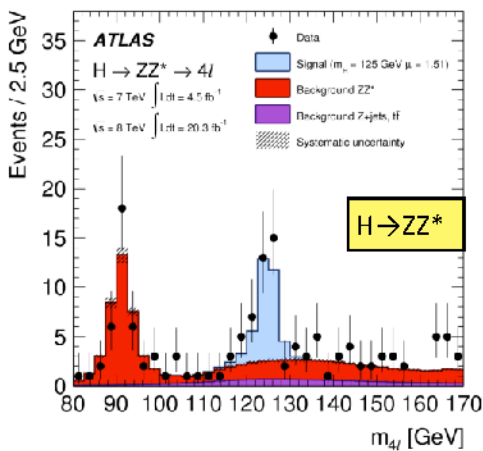
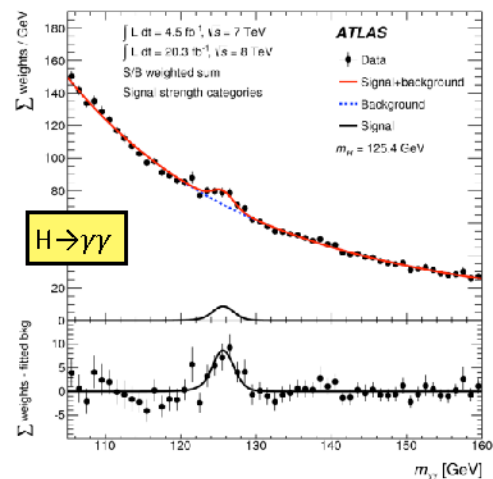
4. Associated production

Higgs decay

- Once we produce a Higgs boson, what can it decay into?



The Higgs Discovery (by ATLAS+CMS)



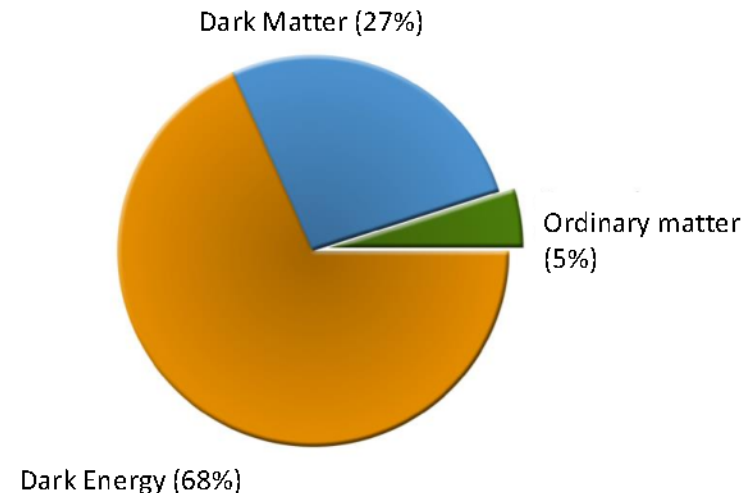
Where are we now?

The Higgs boson discovery was a groundbreaking achievement.

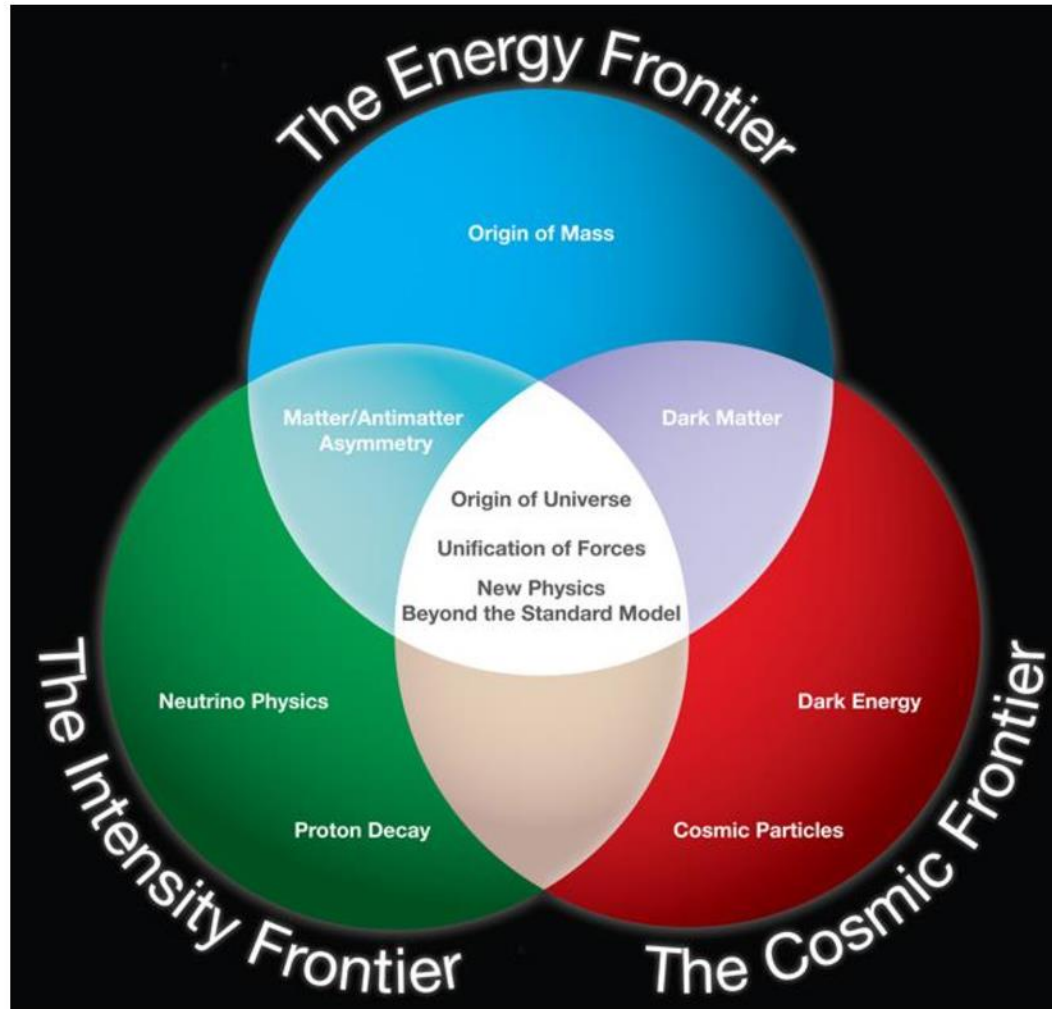
... but the Standard Model is an incomplete description of our Universe.

Plenty of open questions...

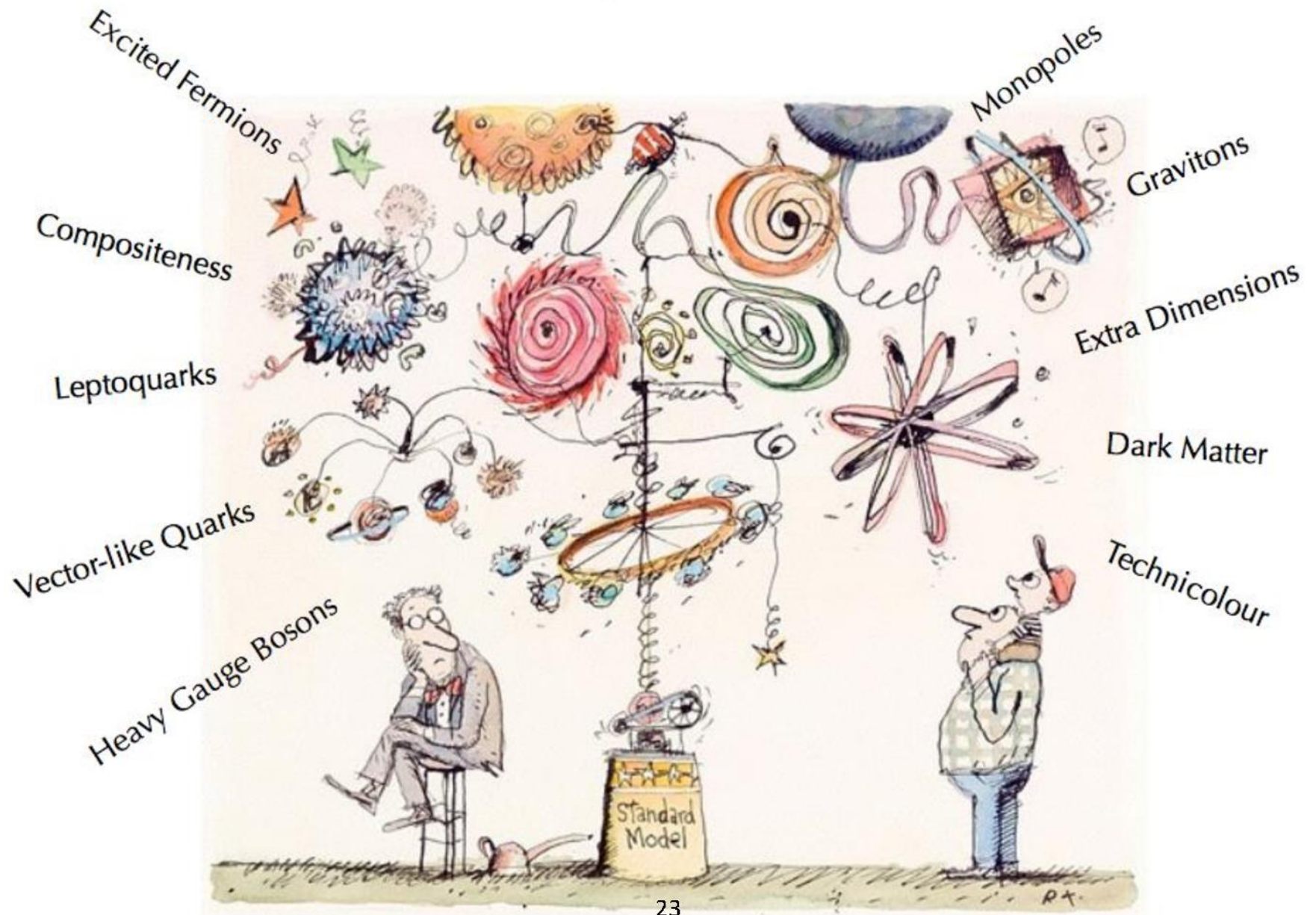
- What happened to all the antimatter?
- What is most of our Universe made of?
- What is dark energy?
- How does gravity come in?
- No explanation for masses of particles.
- No explanation for the number of generations.



Many paths to discovery...

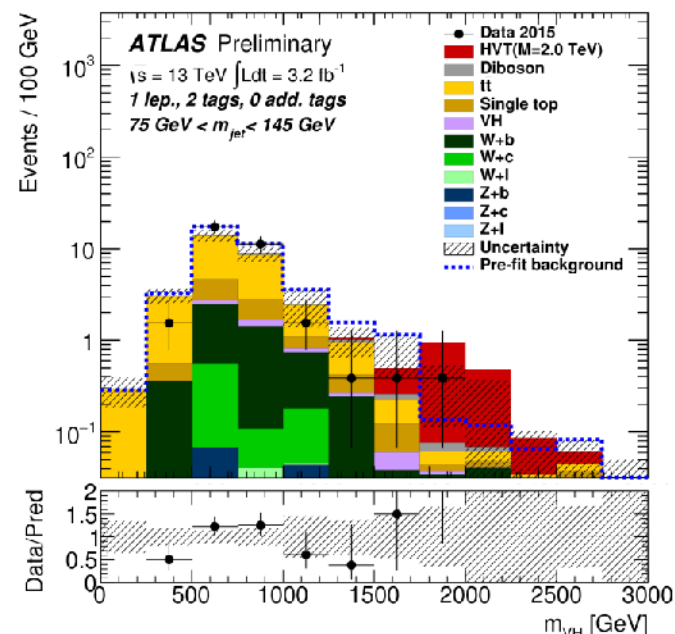
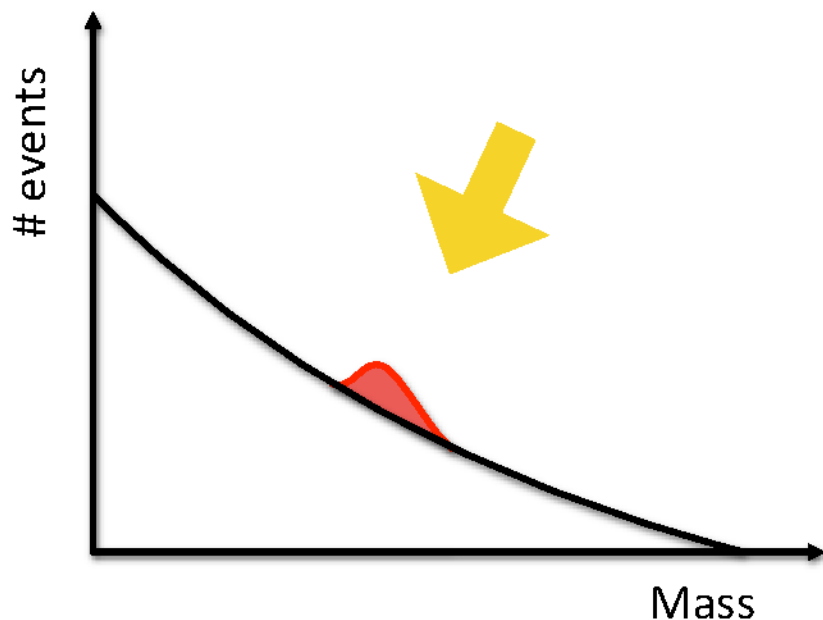


Searches for New Physics

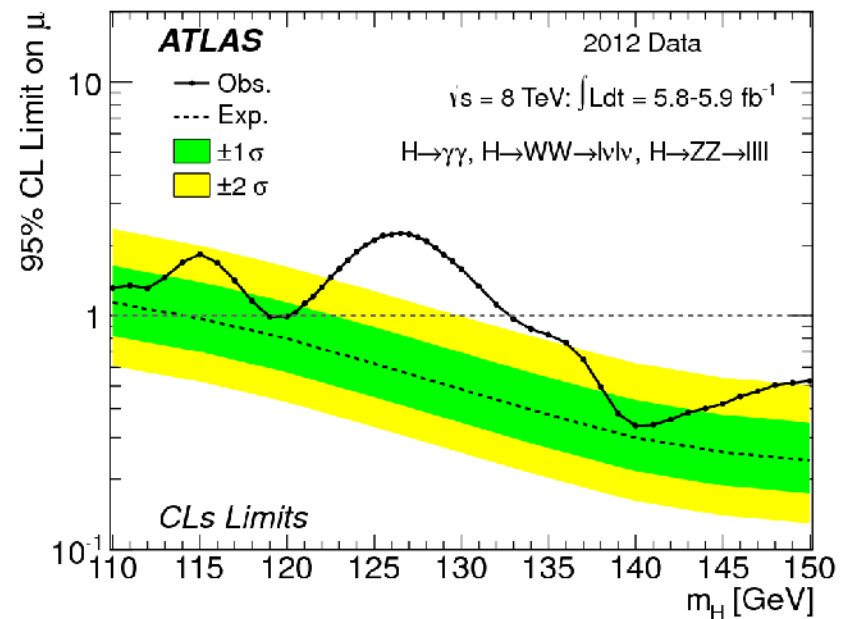
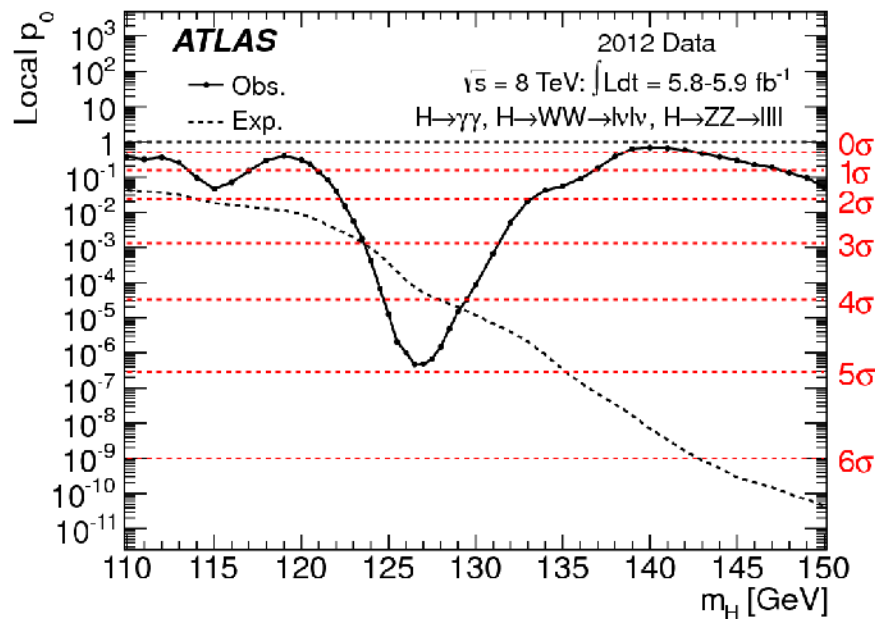


How to make a search?

- We can't identify a single event as coming from a specific process.
- What we can do is perform a **statistical analysis** to understand if e.g. the data collected agrees with what the SM predicts
- A set of event selection cuts are applied to reduce the amount of background events while keeping as many signal events as possible



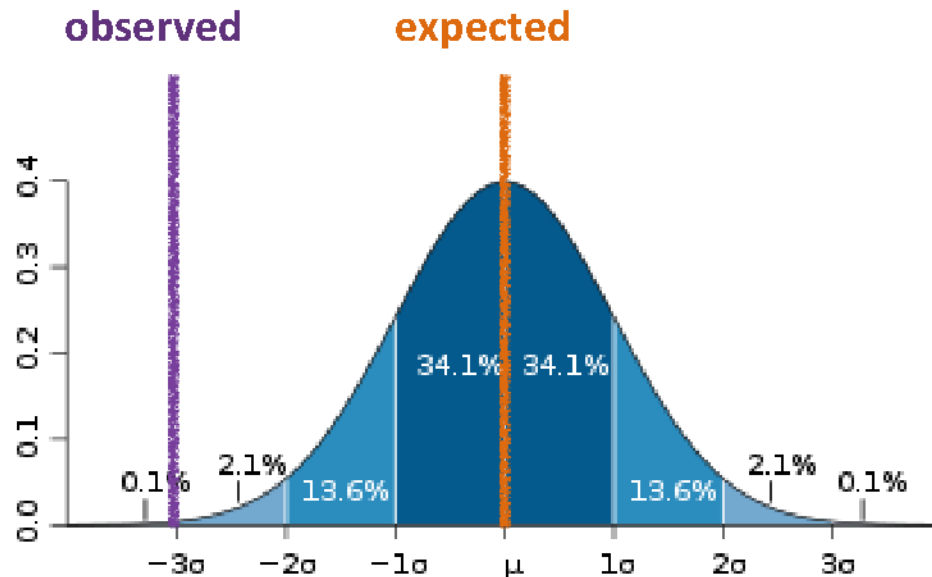
How do we test an hypothesis?



- When we are searching for new particles we first see small “bump”.
 - We need to be able to quantify how big that bump is.
- We test the hypothesis that it is just a background fluctuation causing the excess of events.

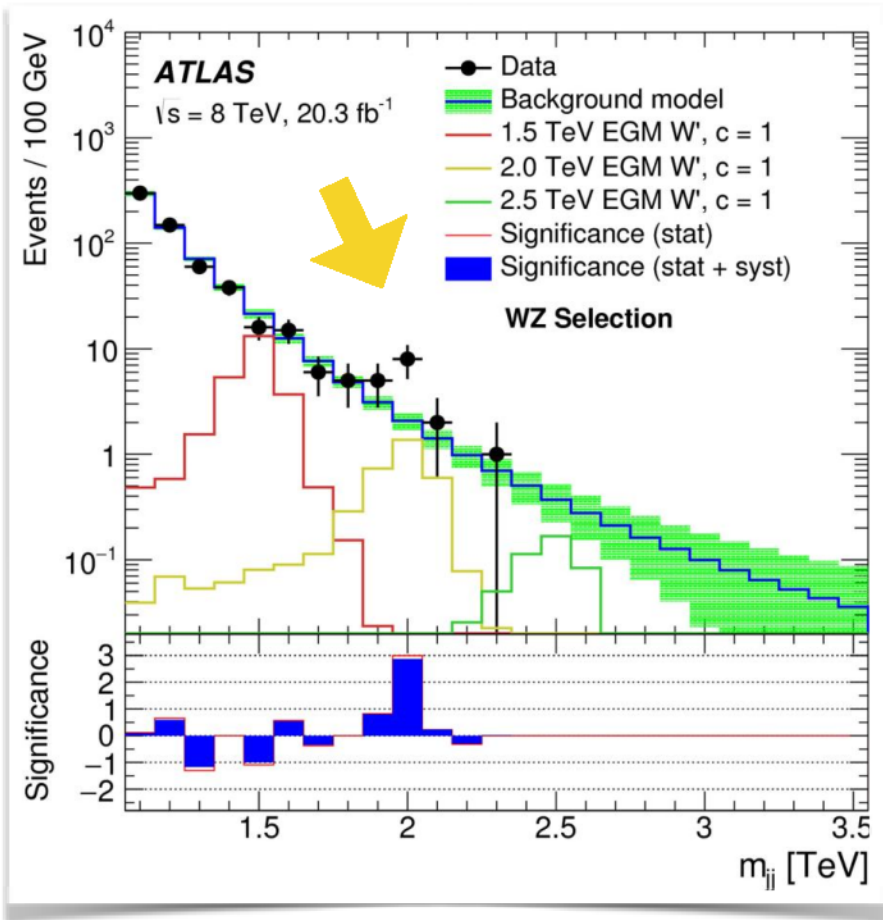
Aside: standard deviation

- Most measurements obey normal distribution statistics.
- If one observes a large deviation from expectation, one can quantify the level of disagreement based on the probability of such observation:

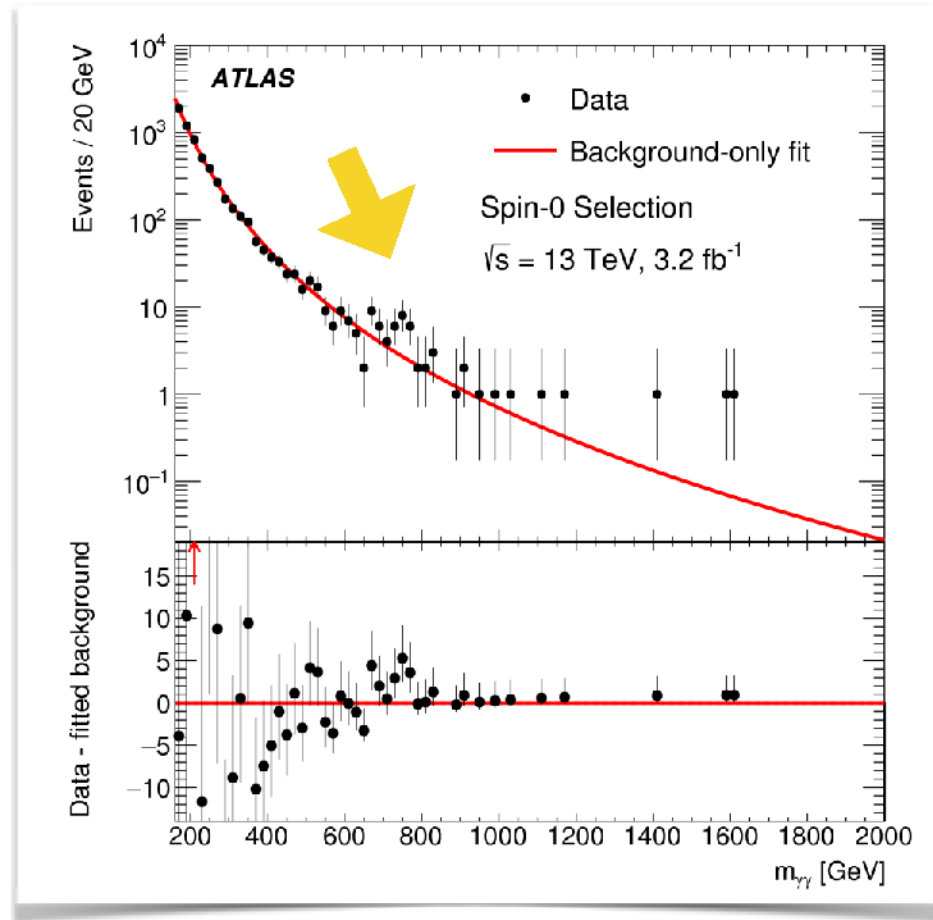


The significance of this particular measurement being in disagreement with expectation is $>3\sigma$.

Exciting hints / statistical fluctuations?



Invariant mass of a W and Z bosons



Invariant mass of two photons

Summary

- The physics programme of the LHC experiments is vast and exciting!
- It presents several challenges, from engineering to computing, which put CERN at the forefront of science and technology.
- The discovery of the Higgs Boson by ATLAS and CMS marks a new era of Particle Physics.
- The Standard Model, despite its successes, has glaring limitations... and there are many paths to discovery!

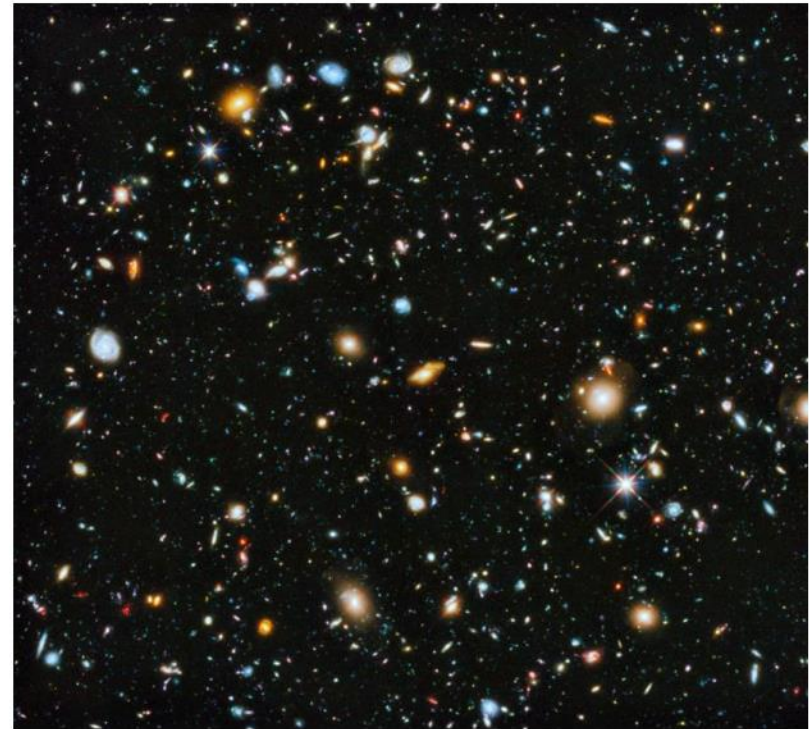
COSMOLOGY

THIS CLASS

- The Standard Model... of **Cosmology**
 - **Finite** and **infinite** universes
 - The **Hubble Law** and the expansion of the universe
- The **Big Bang**: Evidence
 - Hubble **expansion**
 - **Cosmic microwave background**
 - Other evidence: cosmic **abundances** of the light elements, and **large scale structure** of the universe
- **Dark Matter** and **Dark Energy**
 - **Unobserved** matter: how we know it's there
 - Standard Model **candidates** for dark matter particles
 - Why dark matter may be **outside** the Standard Model

COSMOLOGY

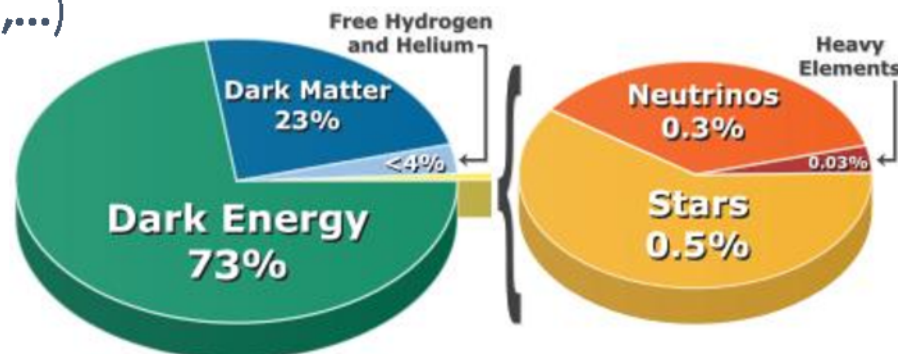
- Cosmology is the study of the origin and evolution of the universe.
- Major questions:
 - What is the nature of the universe? Is it **infinite** in size? In age?
- Cosmological Principle
 - The main idea of cosmology is that the laws of physics are the **same** all over the universe. All observers measure the same physical laws.
 - “Atoms in α -Centauri are the same as atoms on Earth; and Maxwell’s equations in M100 are the same as they are in our galaxy”.



Hubble Ultra Deep Field 2014.

THE CURRENT PICTURE OF THE UNIVERSE

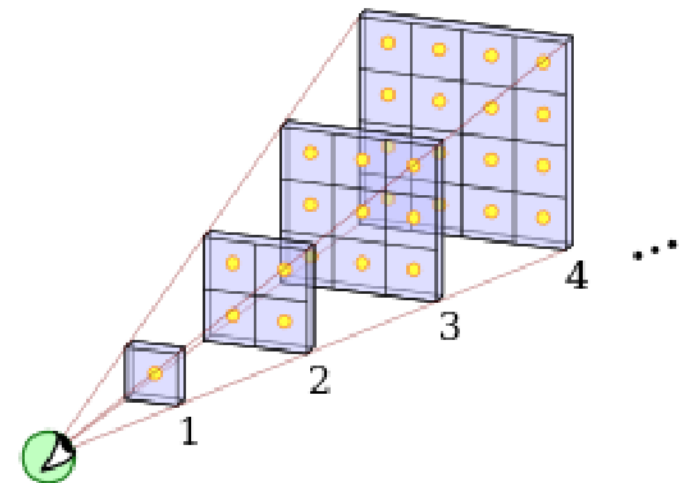
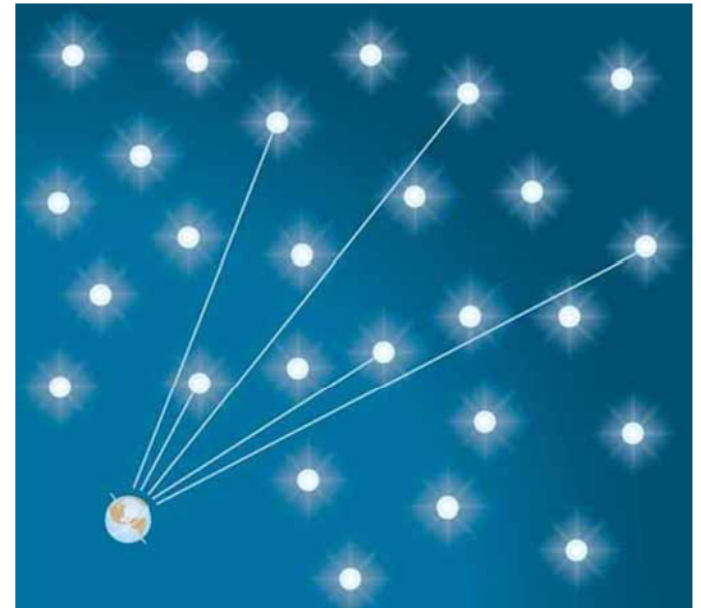
- Measurements indicate that the universe is about 13.8 billion years old.
- It began as a hot, dense **singularity**, but has since expanded to a truly enormous size.
- We really don't know what the universe is made of. Quarks, leptons, and photons compose **about** 5% of the energy density of the universe.
- How do we know all this? Particle physics! (And also astronomy, gravitation,...)



THE INFINITE UNIVERSE: OLBER'S PARADOX

- What is the nature of the universe? Is it infinite in size? In age?
- Suppose the universe is infinite in size and age. What would it **look** like?
- Suppose also that the sky is uniformly filled with stars (as Newton believed).
- Then the entire sky should glow with **infinite brightness**, even at night.
- The fact that the sky is dark (Olber's Paradox, c. 1823) suggests the universe must be finite in age or extent.

In an infinite universe uniformly filled with stars, starlight falls off like $1/r^2$, but star count increases like r^2 , so the entire looks bright.



THE STATIC UNIVERSE (UP TO 1916)

- For hundreds of years, physicists held onto ingrained beliefs that the universe is a **static** system (fixed size? finite age?).
- Newtonian physics does not predict a changing universe.
- Then in 1916, Einstein's general relativity suggested that the universe could be **expanding** or **contracting**.
- But Einstein didn't like this result, so he put a fudge factor into his equations (the **cosmological constant Λ**) to ensure that the universe stay a fixed size.
- Too bad for Einstein: the universe has turned out to be a very dynamic place!

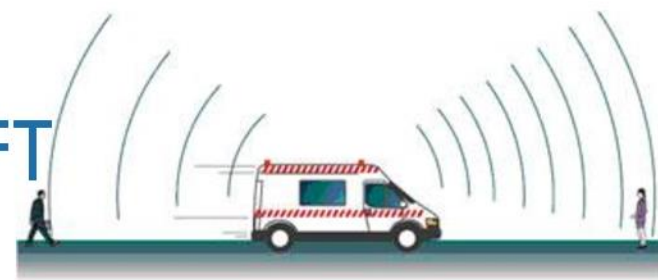


HUBBLE AND THE EXPANDING UNIVERSE

- In 1929, E. Hubble noticed that distant astronomical objects appear more **red** than nearby luminous bodies.
- That is, the spectral lines of nearby galaxies are systematically shifted to longer (**redder**) wavelengths.
- They are said to have a redshift.
- Moreover, more distant objects always exhibit a larger redshift.
- A very unexpected observation!



INTERPRETING THE REDSHIFT

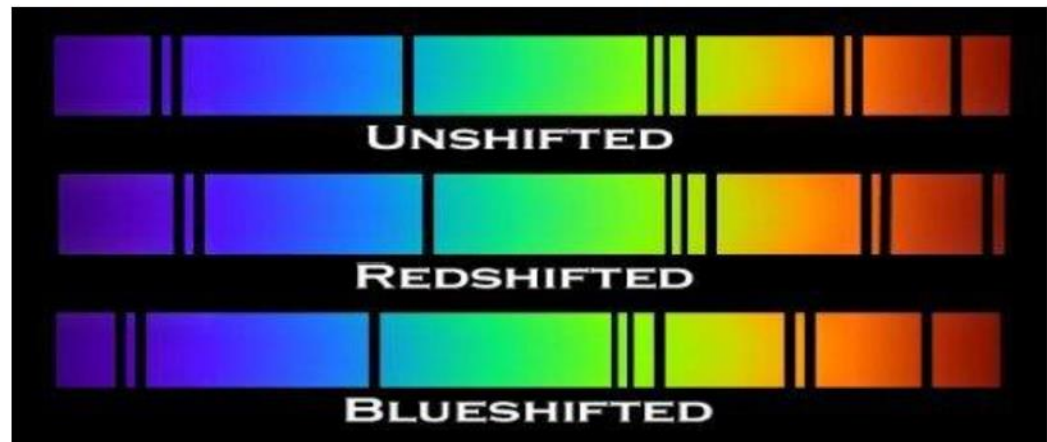


- How did Hubble interpret the redshifting of spectral lines?
- The phenomenon could be explained in terms of the Doppler shift of light waves.
- If a radiating source of waves is receding from an observer, its wavelength appears to be stretched.
- For visible light (see formula below), longer wavelengths means lines are at the red part of the spectrum. (Note: $\beta = v/c$ is the recession velocity.)

$$\lambda' = \lambda (1 + z)$$

Observed \nearrow \uparrow Emitted

$$z = (1 + \beta) \gamma - 1$$

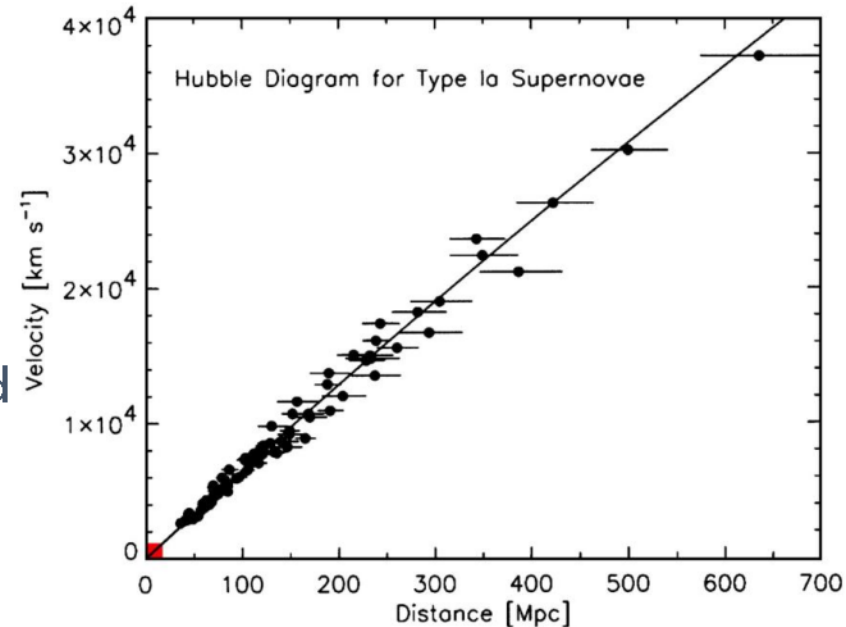


RECESSION OF THE COSMOS

- Hubble concluded that galaxies are **redshifted** because they are **receding** from us.
- When Hubble plotted the **velocity** of moving objects as a function of their **distance** from Earth, he noticed a **linear relationship**.
- **Hubble Law**: objects are moving away from earth at a velocity proportional to their distance:

$$v = Hr$$

Hubble constant



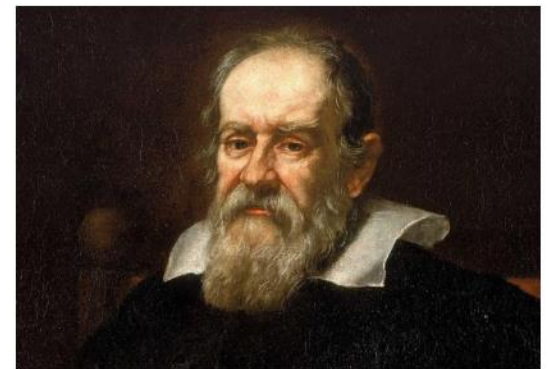
Velocity of distant objects as a function of distance from Earth.
NOTE: (1 Mpc = 3.09 x 10¹⁹ km).

INTERPRETING THE HUBBLE LAW

- Hubble's plot suggests that the universe is expanding from a point centered near the Earth.
- One might suggest that the Earth is at the center of a "cosmic explosion" that is blowing debris in all directions.
- But that would be a bizarre **coincidence**: the Earth just happens to be at the center of the expanding universe!
- **Copernican Principle**: the Earth is not a special observation point. It is unlikely that we just happen to be at a privileged vantage point.



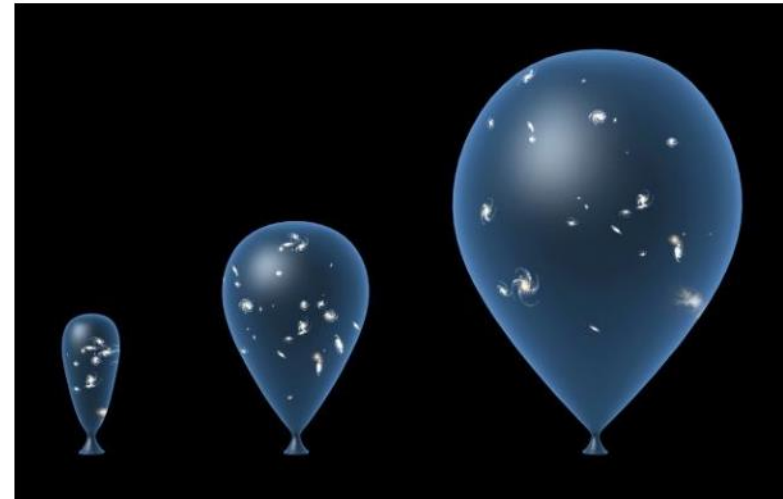
Center of the Universe
Wallace, Idaho



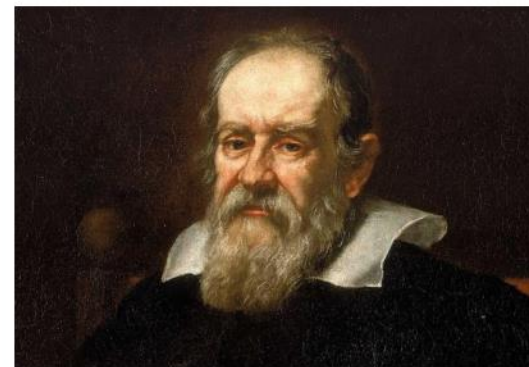
Sad Galileo...

INTERPRETING THE HUBBLE LAW

- A more likely, though perhaps harder to understand, explanation for the Hubble plot is that **all points** in the universe are moving away from each other!
- To understand this, think of how the distance between points on the **surface of a balloon** grows as the balloon blows up. Such an **expansion** produces a Hubble plot.



If the universe we know is compressed onto two spatial dimensions (the surface of a balloon), then no point on the balloon is special. As the balloon grows, recession velocities increase according to the Hubble Law.



Happy Galileo!

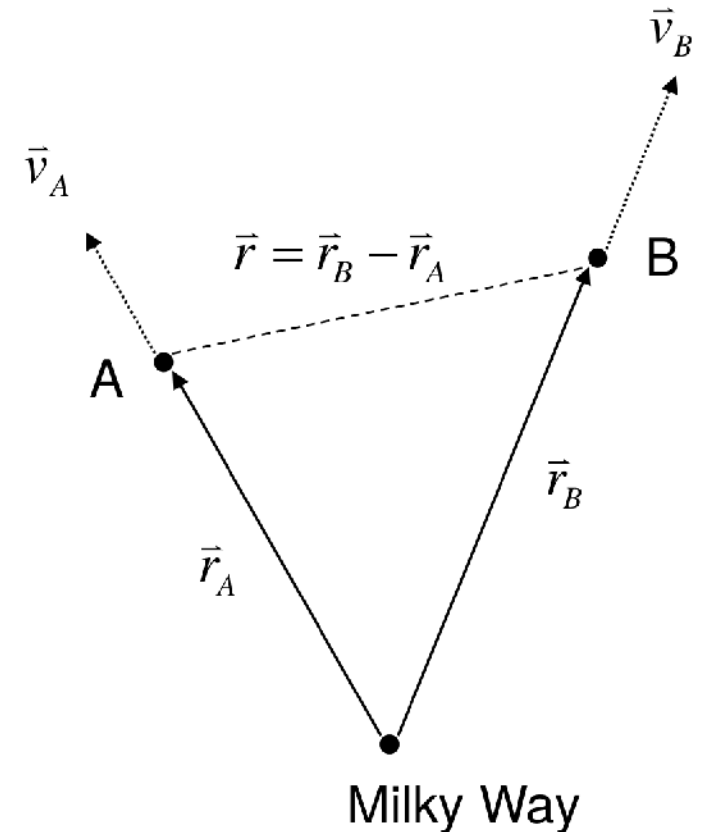
INTERPRETING THE HUBBLE LAW

- How do two objects A and B move with respect to the Milky Way?

$$\left. \begin{aligned} \vec{v}_A &= H_0 \vec{r}_A \\ \vec{v}_B &= H_0 \vec{r}_B \end{aligned} \right\} \text{HubbleLaw}$$

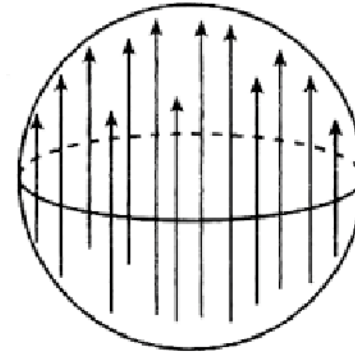
- How does A see B moving?

$$\begin{aligned} \vec{v}_{BA} &= \vec{v}_B - \vec{v}_A \\ &= H_0 (\vec{r}_B - \vec{r}_A) \\ &= H_0 \vec{r}_{BA} \\ &= H_0 \vec{r} \end{aligned}$$

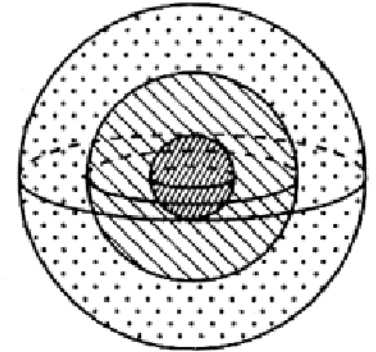


COSMOLOGICAL PRINCIPLE

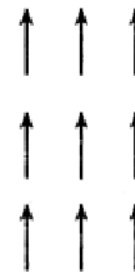
- Hubble Law is consistent with the Cosmological Principle: the universe is **homogeneous** and **isotropic** (to lowest-order).
- Isotropic: same in all **directions**.
- Homogeneous: same in all **locations**.
- That is, there is no special vantage point in the universe.
On **large** scales, the universe is uniform and boring.



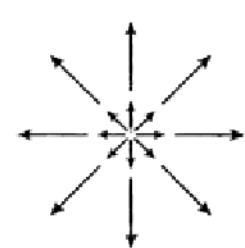
Homogeneous
Not isotropic



Isotropic
Not homogeneous



Homogeneous
Not isotropic



Isotropic
Not homogeneous

EXPANSION AND HUBBLE'S CONSTANT

- If the universe is growing like an expanding balloon, then all distances get expanded by a time dependent factor:

$$r(t) = a(t) r_0$$

The diagram shows the equation $r(t) = a(t) r_0$ with three arrows pointing to its components: an orange arrow from 'Distance at time t' to $r(t)$, a green arrow from 'Scale factor' to $a(t)$, and a teal arrow from 'Distance at time t_0 (today)' to r_0 .

- Hence, the velocity of recession is:

$$\begin{aligned} v(t) &= \dot{a} r_0 \\ &= \dot{a} \left(\frac{a}{a} \right) r_0 = \left(\frac{\dot{a}}{a} \right) a r_0 = \left(\frac{\dot{a}}{a} \right) r(t) \\ &= H r(t) \end{aligned}$$

$$H = \frac{\dot{a}}{a}$$

$$\dot{x} = \frac{dx}{dt}$$

EXPANSION AND HUBBLE'S CONSTANT

- So, the Hubble constant H tells us the **rate of expansion** of the universe by giving us the rate of change of the scale factor a .
- NOTE: only **cosmological** distances are expanding; local scales don't change. Atoms, trees, and planets do not stretch over time(!).
- NOTE: the recessional velocity $v(t)$ can be larger than c !
- H must be experimentally measured. Its value today is*:

$$H_0 = 67.8 \pm 0.9 \text{ km s}^{-1} \text{ Mpc}^{-1}$$

$$1 \text{ pc} = 3.09 \times 10^{13} \text{ km} \approx 3 \text{ light-years}$$

* Planck 2015

THE BIG BANG

- If cosmological distances are expanding according to a scale factor $a(t)$, what did the universe look like when $t=0$?
- In standard cosmology, the origin of the expansion is the so-called **Big Bang**, postulated by Lemaitre (1923) and Gamow (1948).
- The Big Bang model makes the strong postulate that the universe originated as a **singularity** of effectively infinite energy density at a point in spacetime.
- Since mass/energy should always be conserved, the universe got **less dense** (and **cooled off**) as it **expanded**.

THE FRIEDMANN EQUATION

- So the universe evolves in time. Its time evolution is described by the classical field theory due to A. Einstein called general relativity (GR).
- Einstein's field equations in GR look like:

$$G_{\mu\nu} = \frac{8\pi G_N}{c^4} T_{\mu\nu}$$

Geometry of spacetime
(gravitational potential)

Distribution of mass and energy in spacetime

- For a homogeneous and isotropic universe, the solution to Einstein's equations is the Friedmann equation (1922):

$$H^2 = \left(\frac{\dot{a}}{a}\right)^2 = \frac{8\pi G_N \rho}{3} - \frac{\kappa c^2}{a^2} + \frac{\Lambda}{3}$$

"Kinetic energy" density

"Potential energy" density
(dust, gas, photons, neutrinos, ...)

Total energy density
(curvature)

Einstein's fudge factor
Cosmological constant

INTERPRETING THE FRIEDMANN EQUATION

- The Friedmann equation actually has a pretty intuitive **interpretation** (energy conservation)...
- Suppose the universe is filled with nonrelativistic (cool) matter, like dust and gas.
- Consider a sphere of expanding matter:
 - It has radius $a(t)$ and density ρ , and so contains a total mass $M = (4/3) \pi a^3 \rho$.
- A point mass m stuck on the surface of the sphere has **total energy**:
$$\frac{1}{2} m \dot{a}^2 - \frac{m M G_N}{a} = \text{constant} = -\frac{1}{2} \kappa c^2 m$$
- If $M = (4/3) \pi a^3 \rho$ (and ignoring Λ) we recover the Friedmann equation!

INTERPRETING THE FRIEDMANN EQUATION

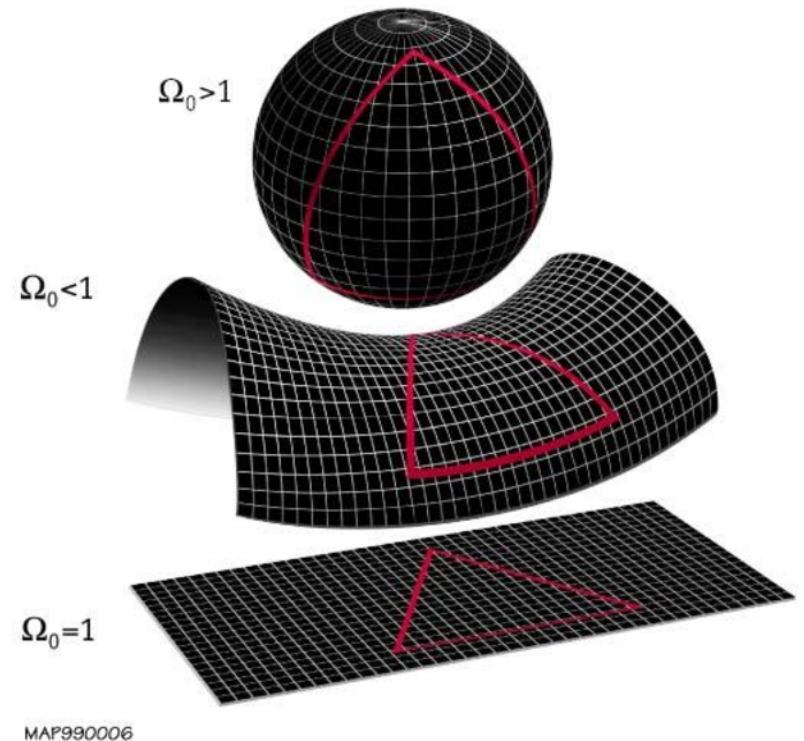
- Looking now at the Friedmann equation (assuming $\Lambda=0$):

$$H^2 - \frac{8\pi G_N \rho}{3} = -\frac{\kappa c^2}{a^2}$$

- We see that if $\kappa=-1$, the total energy (or curvature) of the universe is positive. Hence, the “kinetic term” dominates, and the universe **expands without limit**.
- If $\kappa=+1$, the curvature term is negative, and the universe will reach a **maximum radius** and then **contract back to zero**.
- When $\kappa=0$, the kinetic and potential energies **just balance** such that the universe has no curvature (it is flat).
- NOTE: Einstein **inserted** the term Λ to force the total energy to vanish for any value of κ , thus ensuring the universe could never spontaneously collapse. After Hubble’s observation of expansion in 1929, Einstein called this fudge the biggest **mistake** of his career.

CURVATURE AND SCALE FACTOR

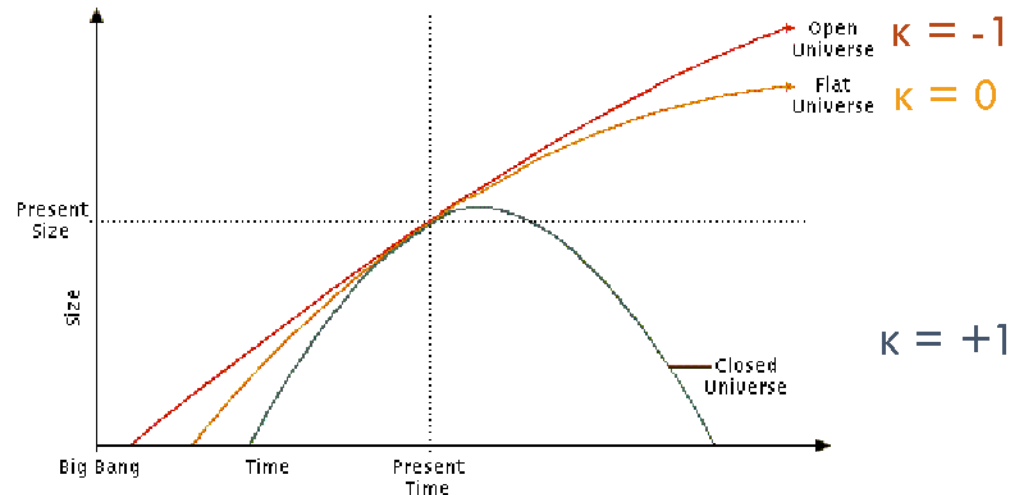
- The scale factor a varies differently in time for different κ values.
- The number κ has a geometric interpretation as the “Gaussian curvature” of space.
- At the present time, the universe is still expanding, so we are not exactly sure what kind of universe we live in.
- BUT: experiments suggest that we are very close (within 0.2%) to the $\kappa = 0$ curve – the so-called flat universe of standard Euclidean geometry.



Relation of the parameter κ to “curvature” of the universe, for a closed, open, and flat geometry. Note that in a closed universe, an explorer moving in a straight line (geodesic) would eventually return to his point of origin.

POSSIBLE ISOTROPIC UNIVERSES

- Gaussian curvature κ is clearly related to the time evolution of the scale factor a .
- Solving for a , one can show that the universe can evolve in three ways:
 1. **Open**: the universe expands without limit.
 2. **Flat**: the universe expands and (asymptotically) reaches a fixed size.
 3. **Closed**: the universe eventually contracts back into a singularity.
- Experiments suggest we are closest to the $\kappa = 0$ curve.
- Or, perhaps by chance, we are living in a time when the universe just looks flat.



JARGON: THE DENSITY PARAMETER Ω

- If $\kappa=0$ and $\Lambda=0$, we can ask what is the **critical density** that just closes the universe? From the Friedmann equation, this works out to be:

$$\rho_c = \frac{3H_0^2}{8\pi G_N} \approx 8.6 \times 10^{27} \text{ kg/m}^3 \approx 5 \text{ H atoms / m}^3$$

- The ratio of the actual density of all energy in the universe to the critical density is often given by a number Ω called the **closure or density parameter**:

$$\Omega = \frac{\rho}{\rho_c} = 1 + \frac{\kappa c^2}{H^2 a^2}, \quad \begin{cases} \kappa < 0 \Rightarrow \Omega < 1 \\ \kappa = 0 \Rightarrow \Omega = 1 \\ \kappa > 0 \Rightarrow \Omega > 1 \end{cases}$$

- So, for a flat universe, $\Omega = 1$. Experimentally, we find that*:

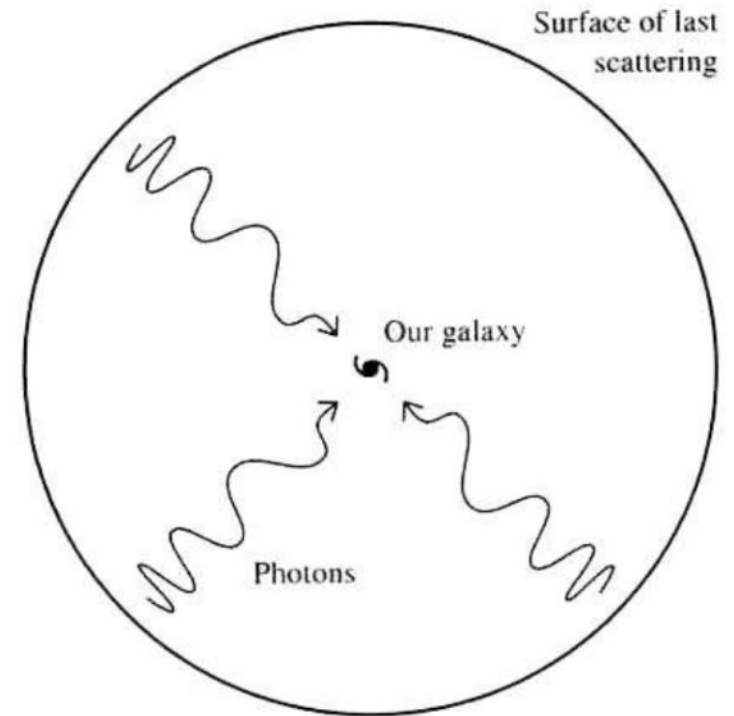
$$\Omega = 1.002 \pm 0.005$$

suggesting that our universe happens to be almost exactly flat.

EVIDENCE FOR THE BIG BANG

BIG BANG EVIDENCE: THE AFTERGLOW

- The expansion of the universe suggests that it began in some kind of explosion. What else supports this idea?
- In the 1940's, G. Gamow suggested that the universe originated as a hot, dense fireball.
- Gamow recognized that this fireball would be full of extremely high energy radiation (like gamma-ray photons and neutrinos).
- Hence, if a Big Bang occurred, there should exist relic photons from the explosion, though their energies would be cooled (redshifted) by expansion.



Radiation from the early universe appears to originate on the surface of a sphere centered on our galaxy. If observers exist in other galaxies, they will see photons coming from the surface of a different sphere centered around their location. (From A. Liddle, Wiley, 2003)

OBSERVATION OF THE CMB

- The Big Bang got a boost in the 1960s when two scientists – A. Penzias and R. Wilson of Bell Labs – made an unusual observation.
- Penzias and Wilson were attempting to calibrate a microwave receiver in New Jersey.
- They noticed that their signal exhibited background noise that they couldn't eliminate, despite strenuous efforts.
- After much investigation, they realized that the noise was coming from all parts of the sky.



Robert Wilson (left) and Arno Penzias (right) in front of their microwave horn at Bell Labs in New Jersey (1965). They initially believed their background noise was due to pigeons nesting inside the device.

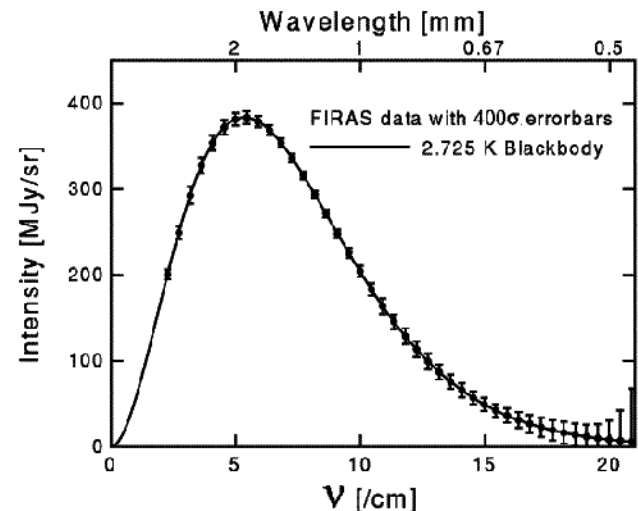
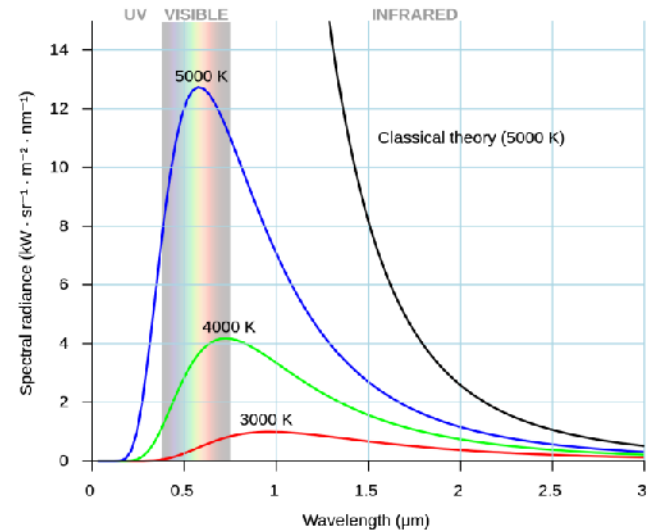


COSMIC MICROWAVE BACKGROUND

- When Penzias and Wilson reported their microwave measurements, cosmologists realized that this background signal could correspond to **relic radiation** from the Big Bang.
- The microwave background is far **too intense** to be of stellar origin. In addition, it is **isotropic**, meaning that it has equal intensity in all parts of the sky.
- A relatively easy thermodynamics calculation shows that if the universe is about **14 billion years old** (as supported by other astronomical observations), the **relic radiation should have cooled to microwave energies**.
- Hence, the cosmic microwave background (**CMB**) is important **evidence** in support of the Big Bang.

THE PERFECT BLACKBODY SPECTRUM

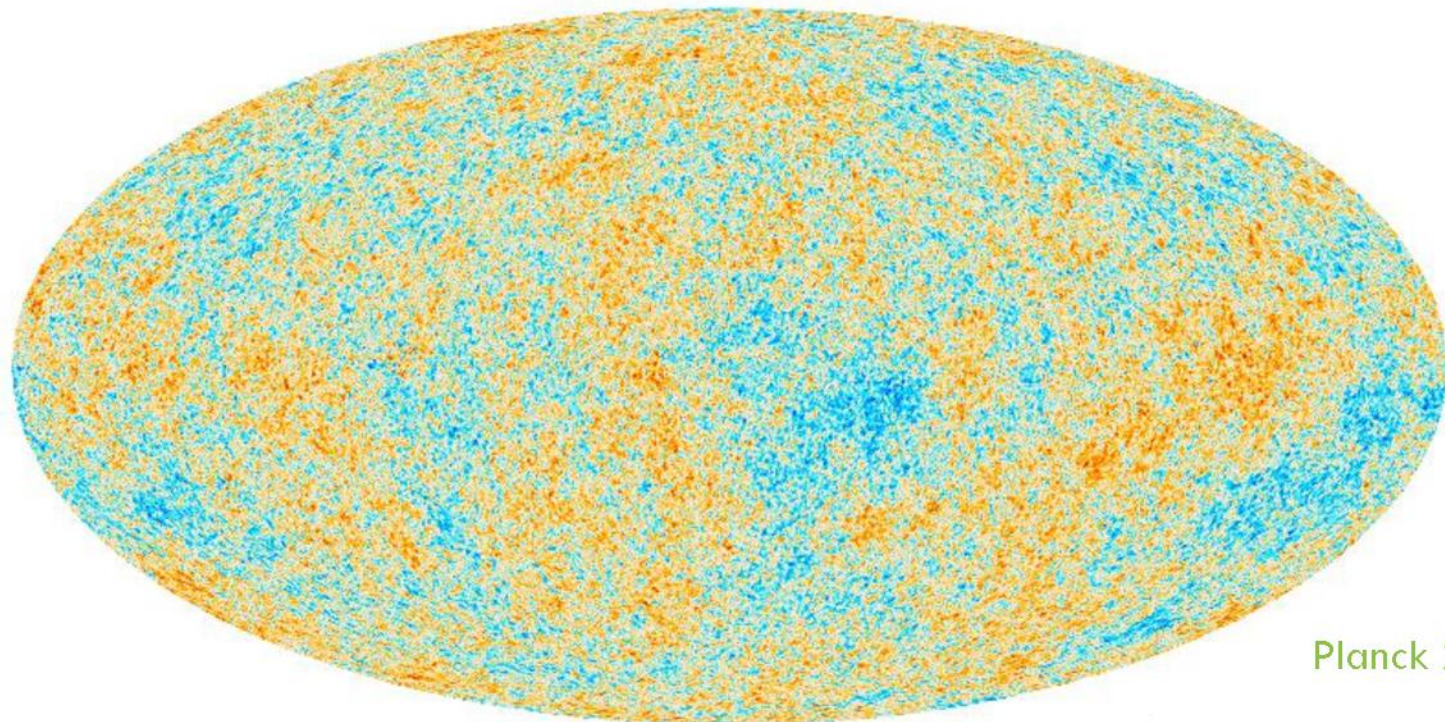
- How do we **know** that the CMB is the relic radiation of the Big Bang?
- Careful satellite measurements have shown that the CMB is a **blackbody spectrum** peaking at **2.73 °K**.
- RECALL: hot objects emit blackbody radiation as they cool.
- CMB is the radiation emitted by the universe as it **cools off** from the Big Bang explosion.



COBE measurement of CMB spectrum (1992)

ISOTROPY AND HOMOGENEITY

- CMB measurements also support the assertion that the universe is **isotropic** and **homogeneous** at large scales.
- Temperature maps of the CMB show that there is very **little variation** across the sky. That is, the universe is roughly the same temperature in all directions. Only **sub-mK** to **μK** variations are observed (however these turn out to be very significant...).



Planck 2013

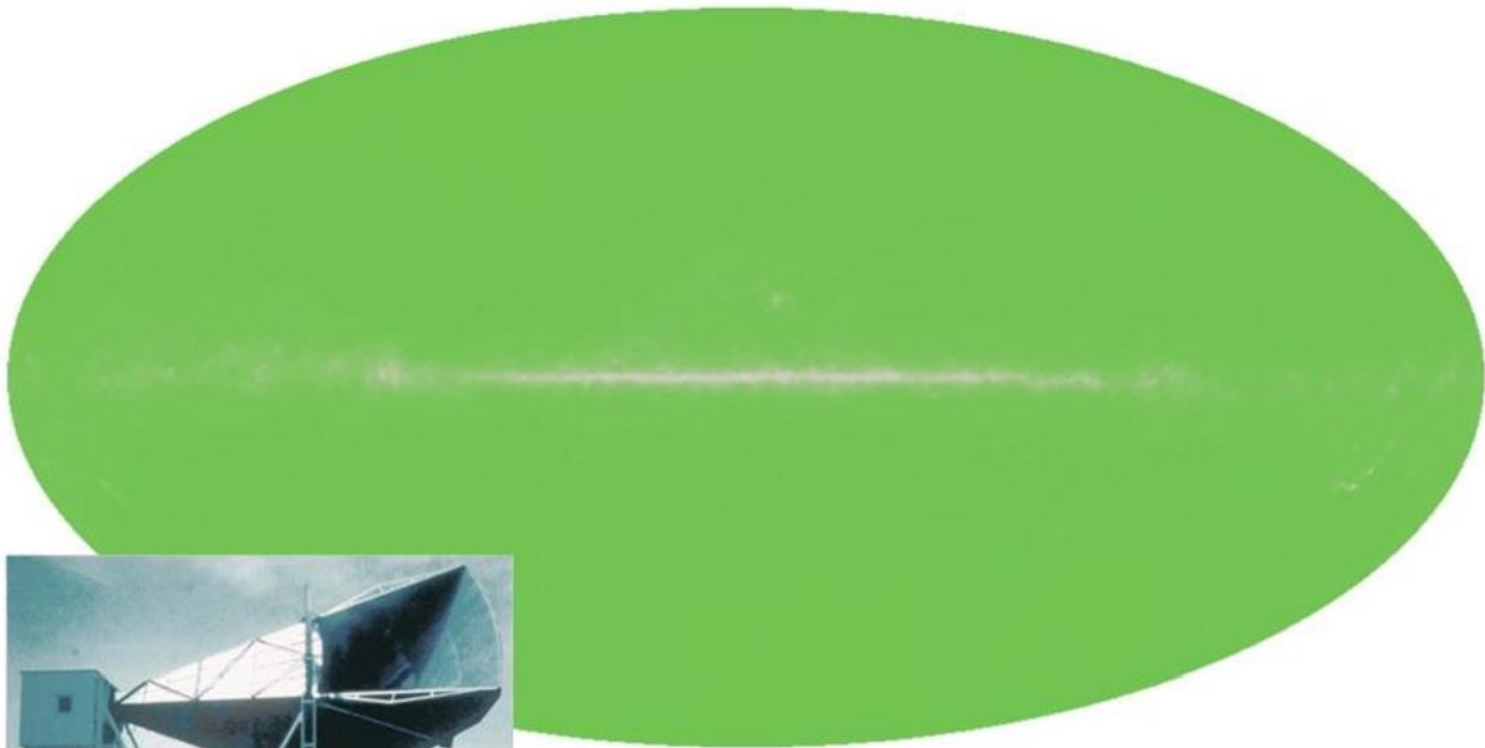
-500 500 μK_{CMB}

ORIGINS OF THE CMB

- How did the **photons** in the **CMB** actually arise?
- They were **created** in the Big Bang, along with the other fundamental particles.
- Originally all of these particles were in a state of **thermal equilibrium**, continually **annihilating** each other and present in **roughly equal numbers**.
- **Photons** constantly **scattered off** the other free, **charged particles**. But as the universe cooled, these other particles “froze” into **bound states**: first into **nuclei**, then into **atoms**.
- After this point ($\sim 380,000$ years), the relic photons could **propagate freely** without scattering. They still make it to us as the CMB.

MEASURING THE CMB

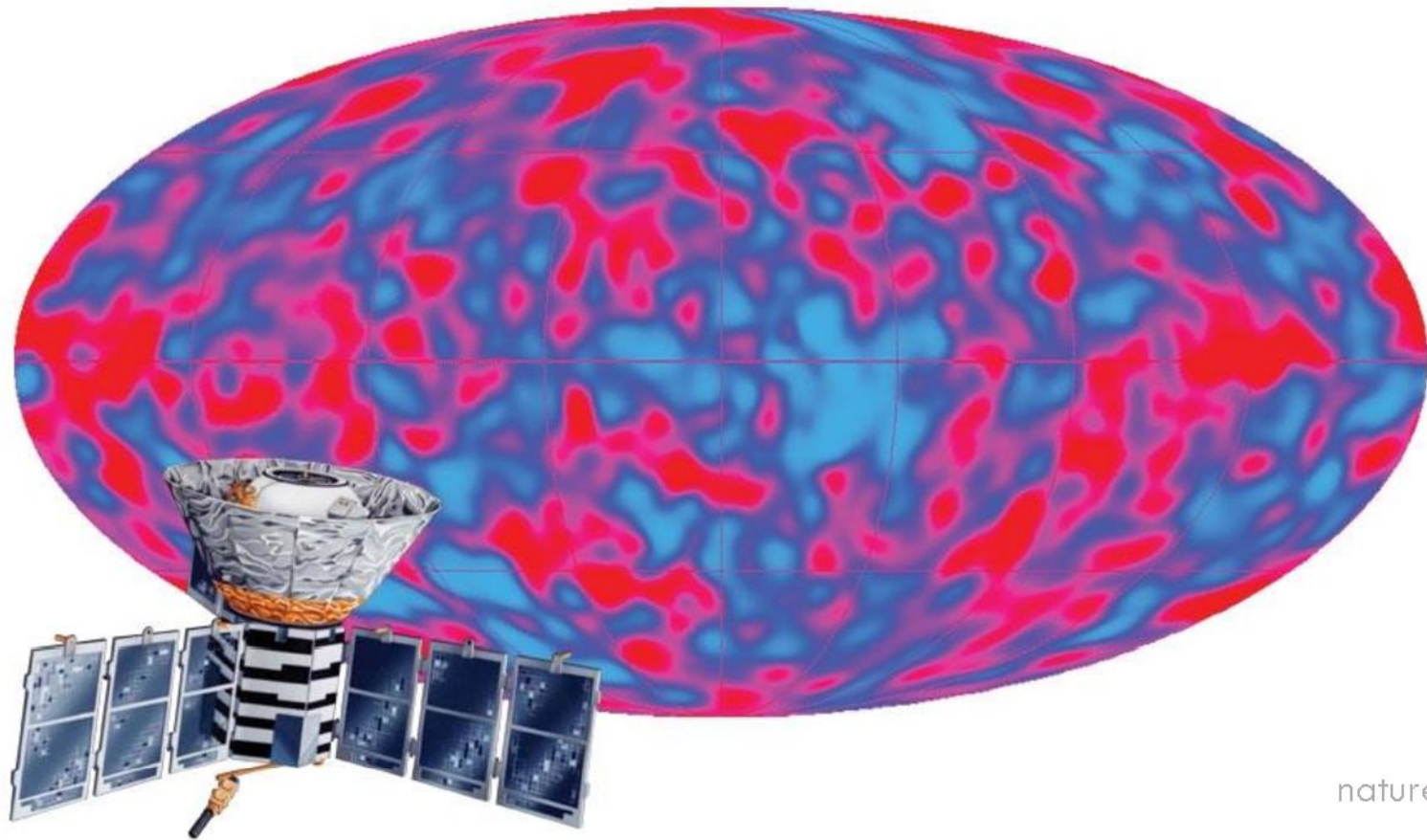
- Penzias & Wilson 1964 – 1965
- Earth-based (New Jersey) microwave telescope



nature

MEASURING THE CMB

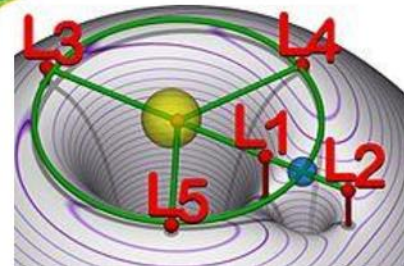
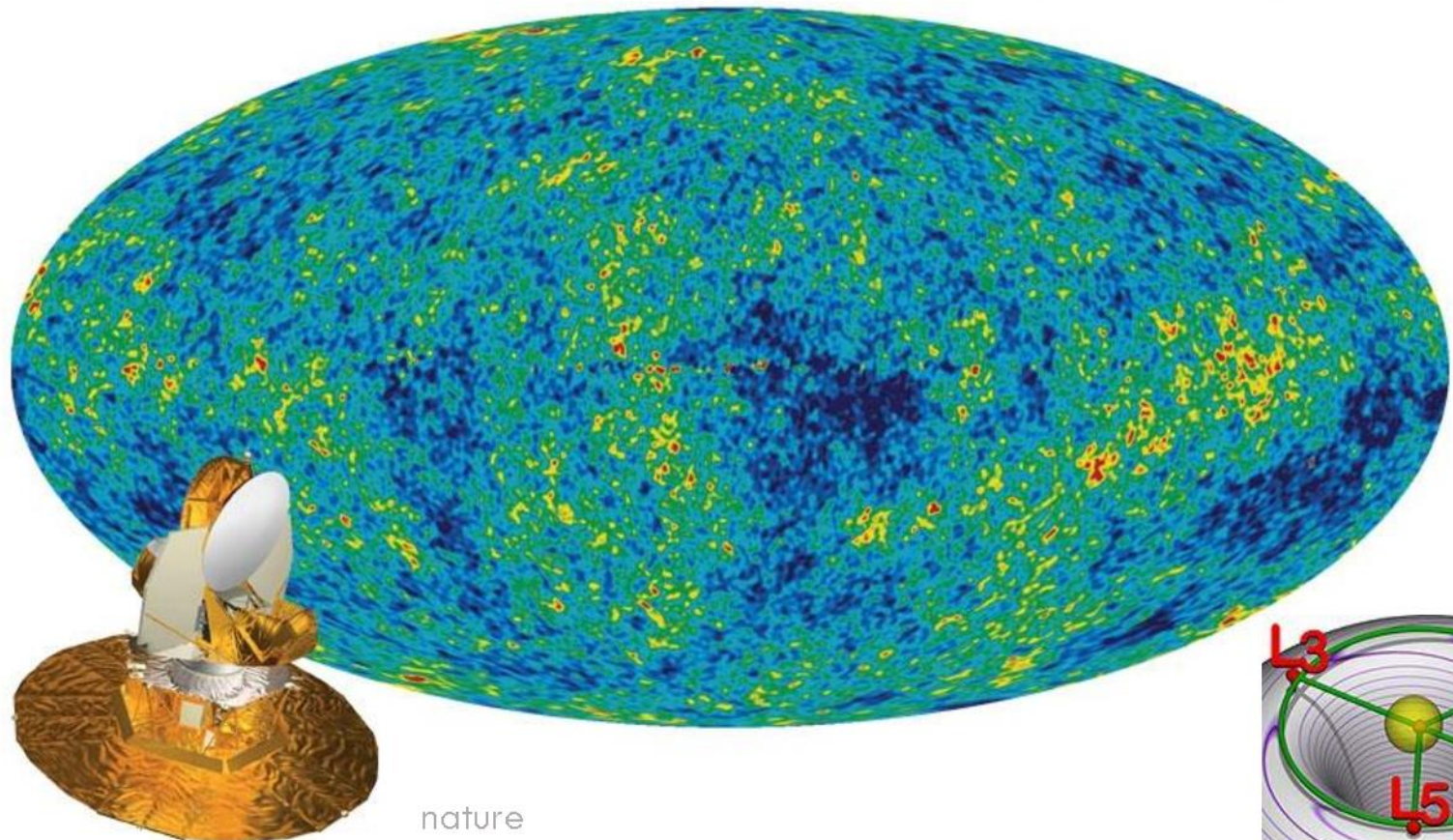
- Cosmic Background Explorer (COBE) 1989 – 1993
- Satellite in geosynchronous orbit



nature

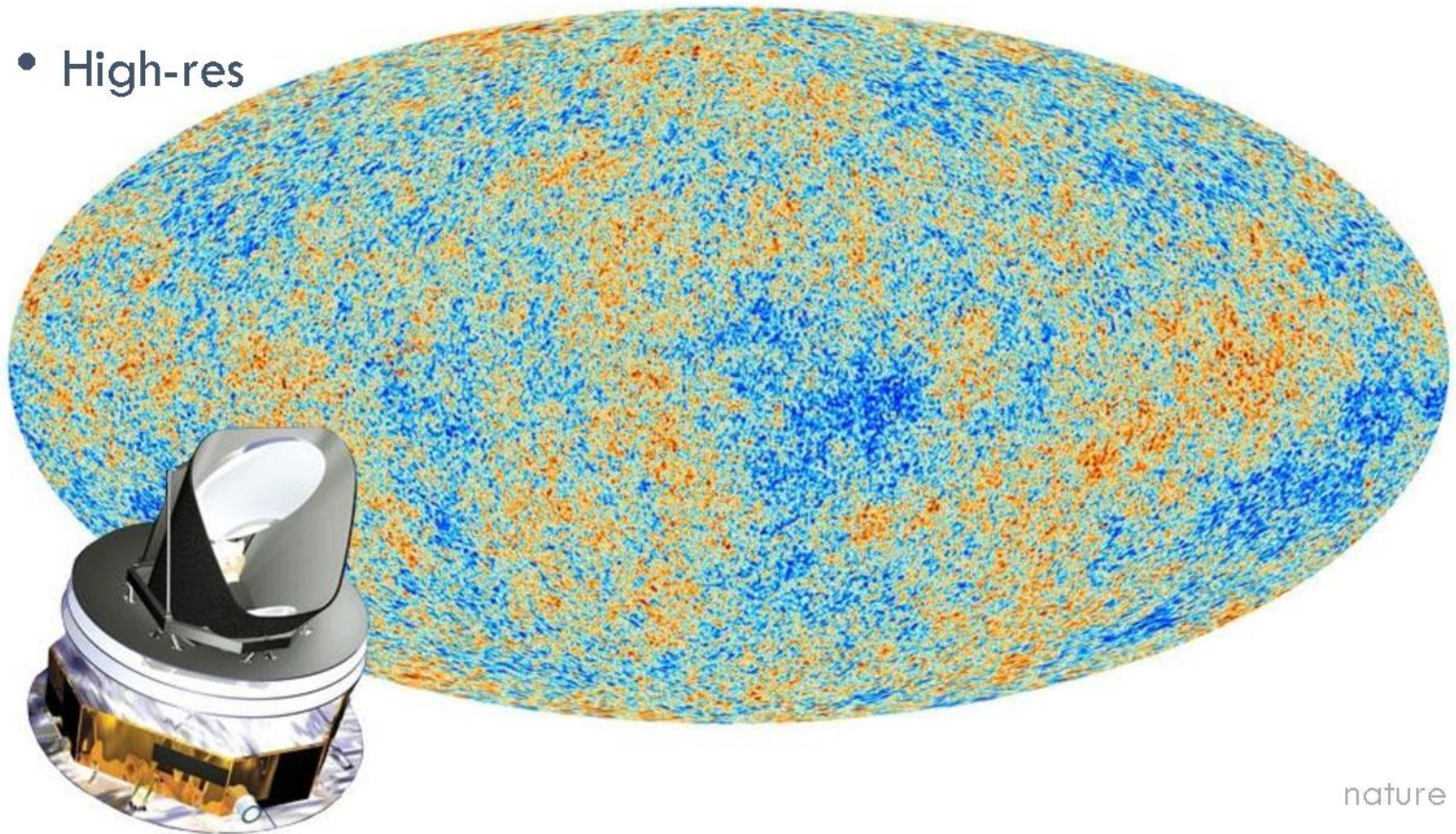
MEASURING THE CMB

- Wilkinson Microwave Anisotropy Probe (WMAP) 2001 - 2010
- Satellite in Earth's sun shadow (Lagrangian point 2: L2)



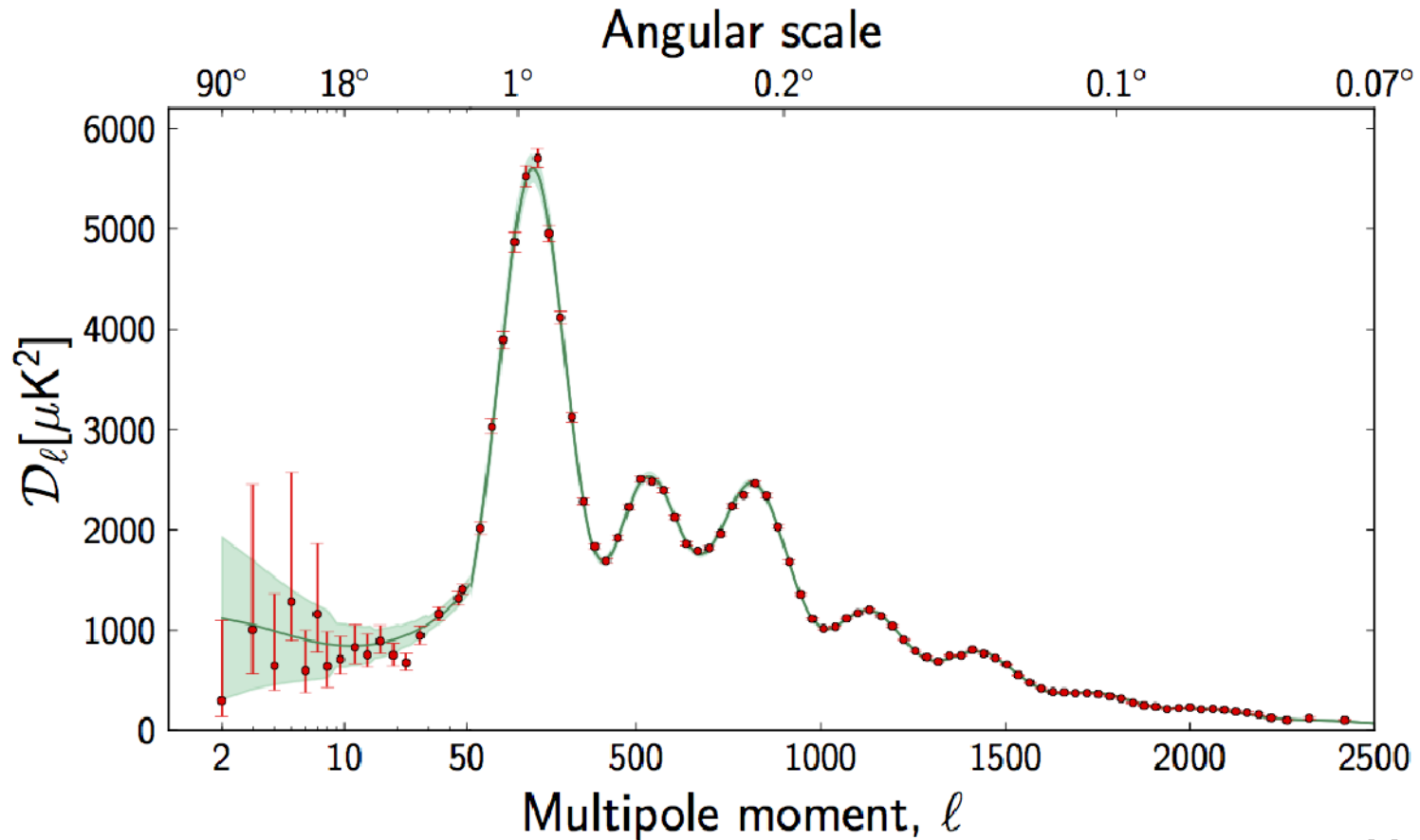
MEASURING THE CMB

- Planck space telescope 2009 - 2013
- Satellite at Lagrangian point 2
- High-res



MEASURING THE CMB

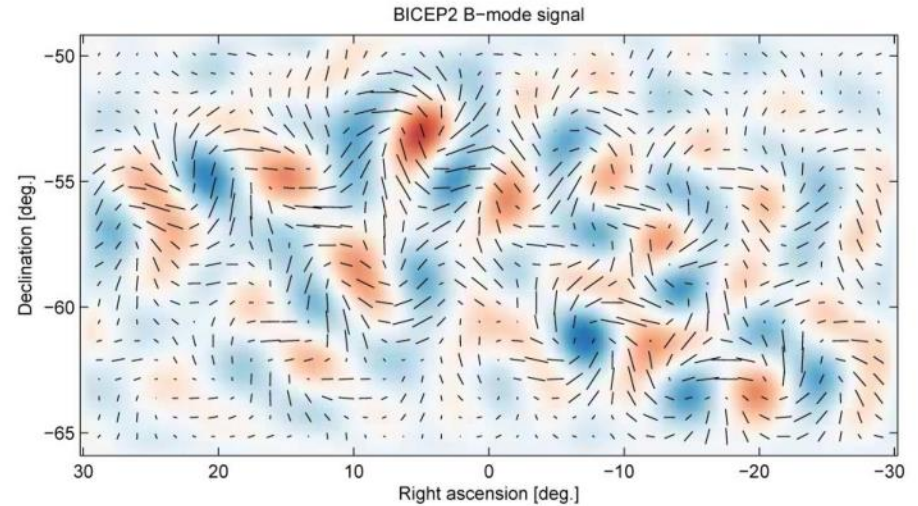
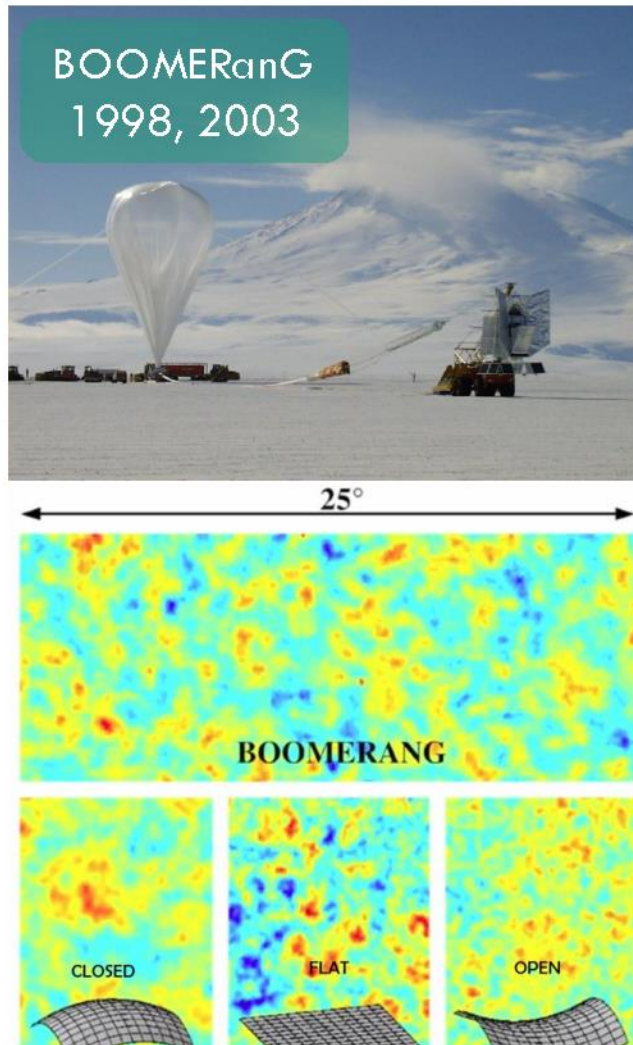
- Cosmological model fit to Planck's 2013 data



Planck 2013

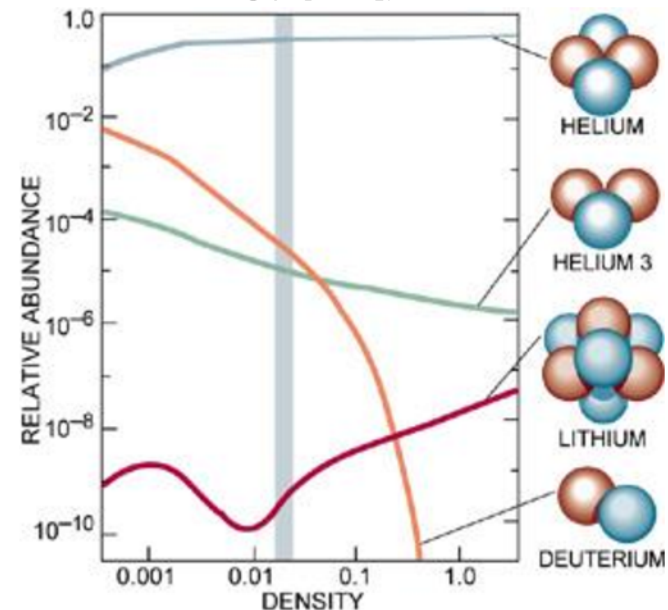
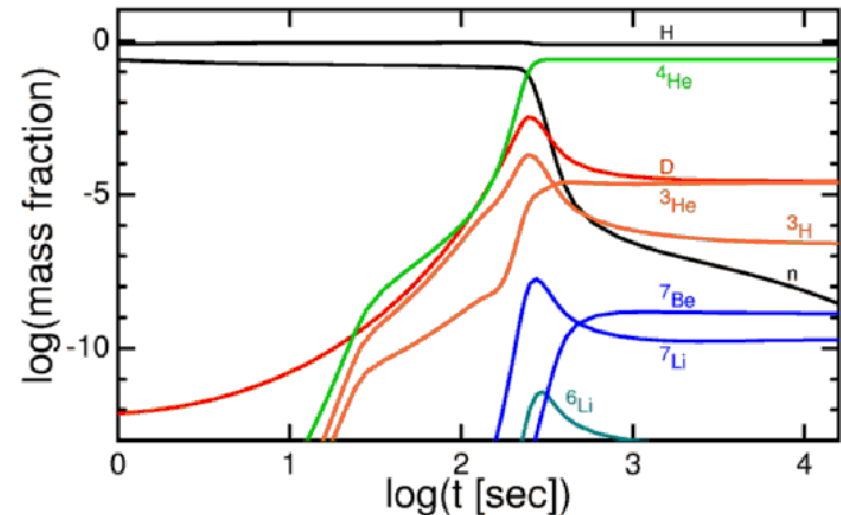
MEASURING THE CMB

MODERN EARTH-BASED EXPERIMENTS

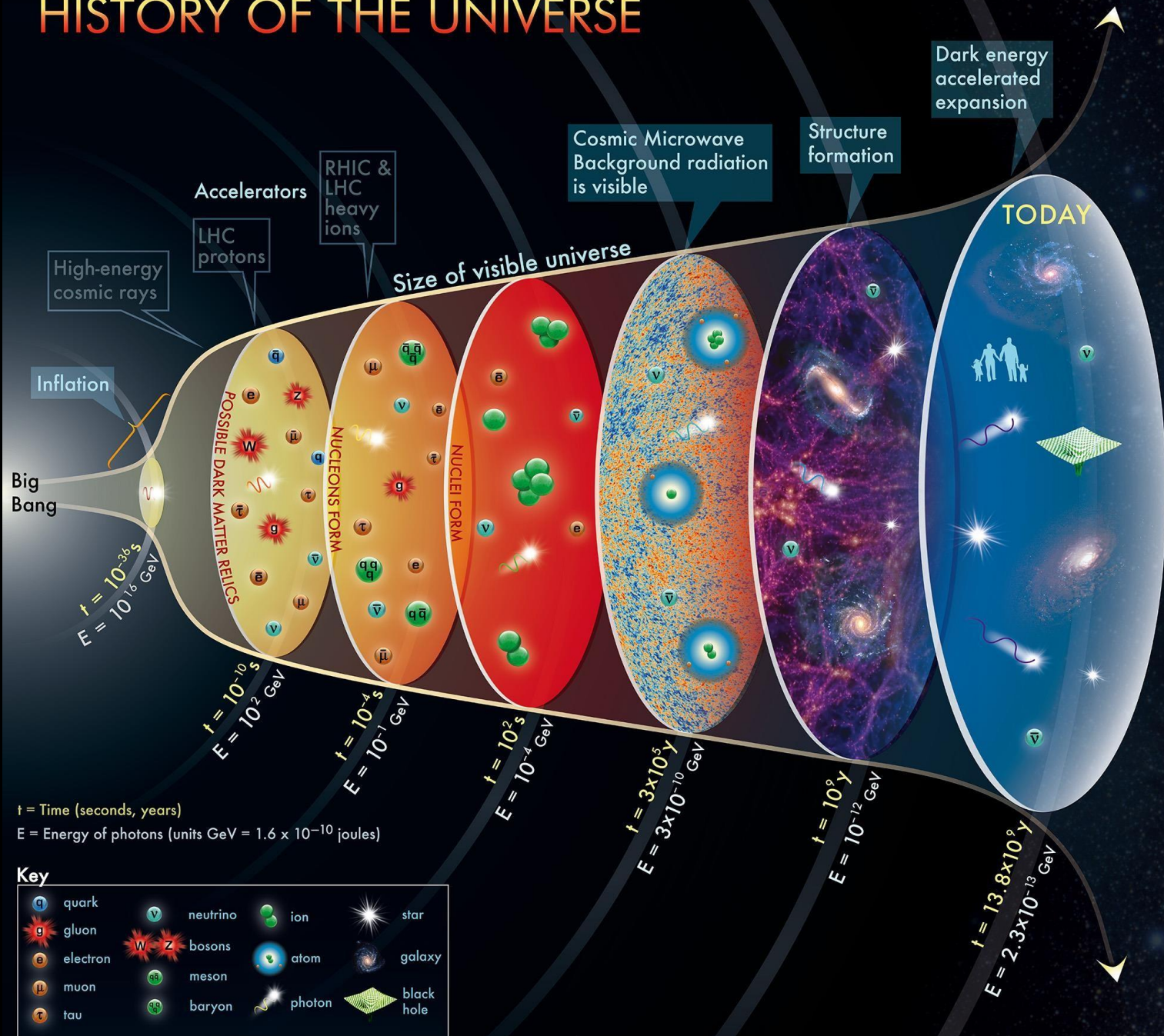


BIG BANG NUCLEOSYNTHESIS

- Another key piece of evidence in support of the Big Bang model is the **abundance** of **light elements** in the Universe.
- In the Big Bang model, light elements such as **d**euterium, **h**elium, **l**ithium should have been produced by fusion of **h**ydrogen (protons!) during the first ~20 minutes of the life of the Universe.
- The **predicted** primordial abundances of these elements has been **precisely confirmed** by experiment.



HISTORY OF THE UNIVERSE

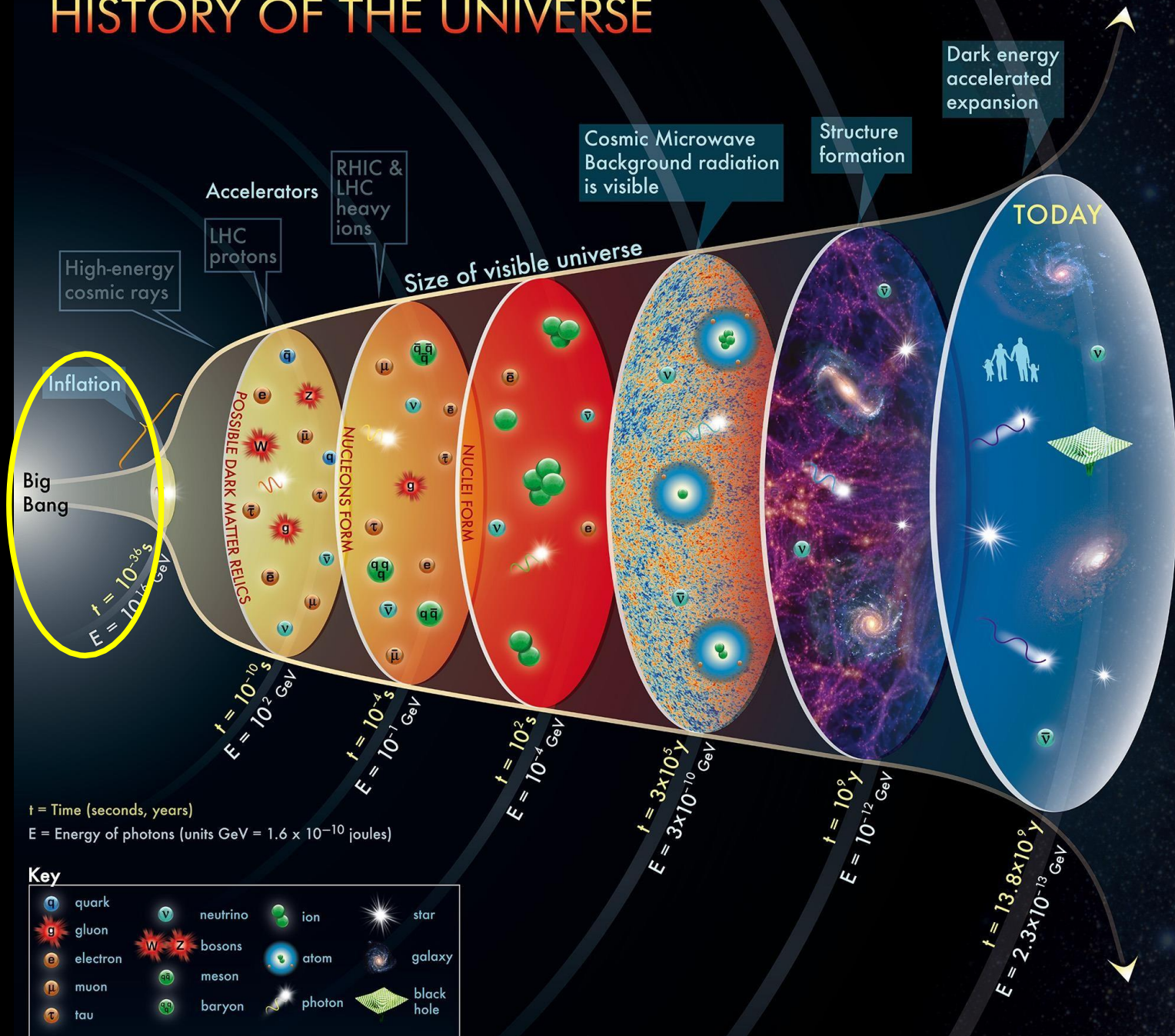


The concept for the above figure originated in a 1986 paper by Michael Turner.

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HISTORY OF THE UNIVERSE



t = Time (seconds, years)

E = Energy of photons (units GeV = 1.6×10^{-10} joules)

Key

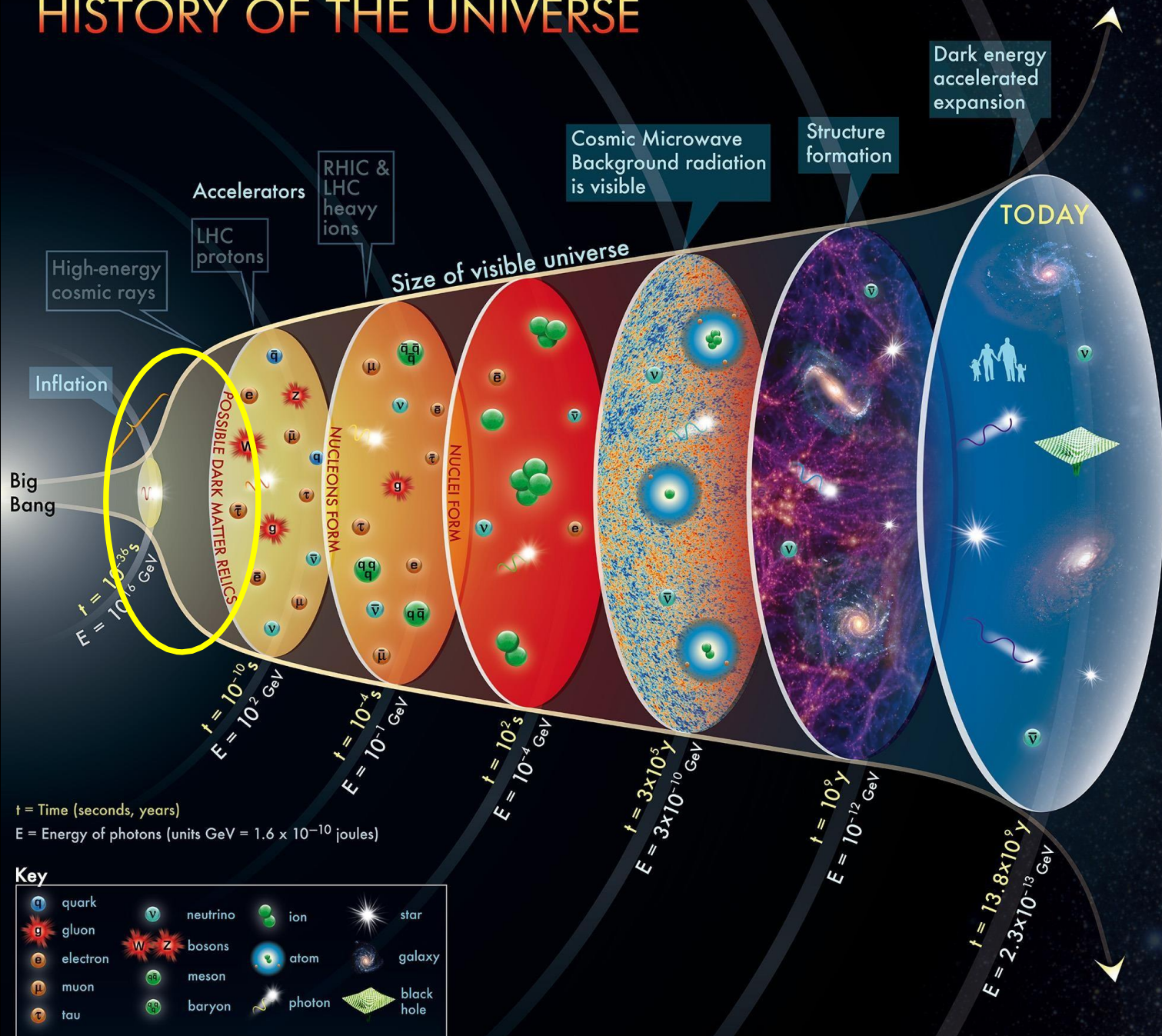
	quark		neutrino		ion		star
	gluon		bosons		atom		galaxy
	electron		meson		photon		black hole
	muon		baryon				
	tau						

The concept for the above figure originated in a 1986 paper by Michael Turner.

UNIVERSE 10^{-37} SECONDS AFTER BIG BANG

- **Quantum gravity** dominates the universe from 10^{-44} seconds. What did things look like? **Unknown**.
- At around 10^{-37} seconds, there is good evidence to indicate that the universe underwent a brief phase of VERY rapid expansion, called **inflation**.
- Inflation involves an **exponential expansion**, during which the universe should have grown by a factor of at least 10^{26} !
- It, or something like it, seems to be **required** in order to produce a universe that is **flat, homogeneous** and **isotropic**.

HISTORY OF THE UNIVERSE



t = Time (seconds, years)

E = Energy of photons (units $\text{GeV} = 1.6 \times 10^{-10}$ joules)

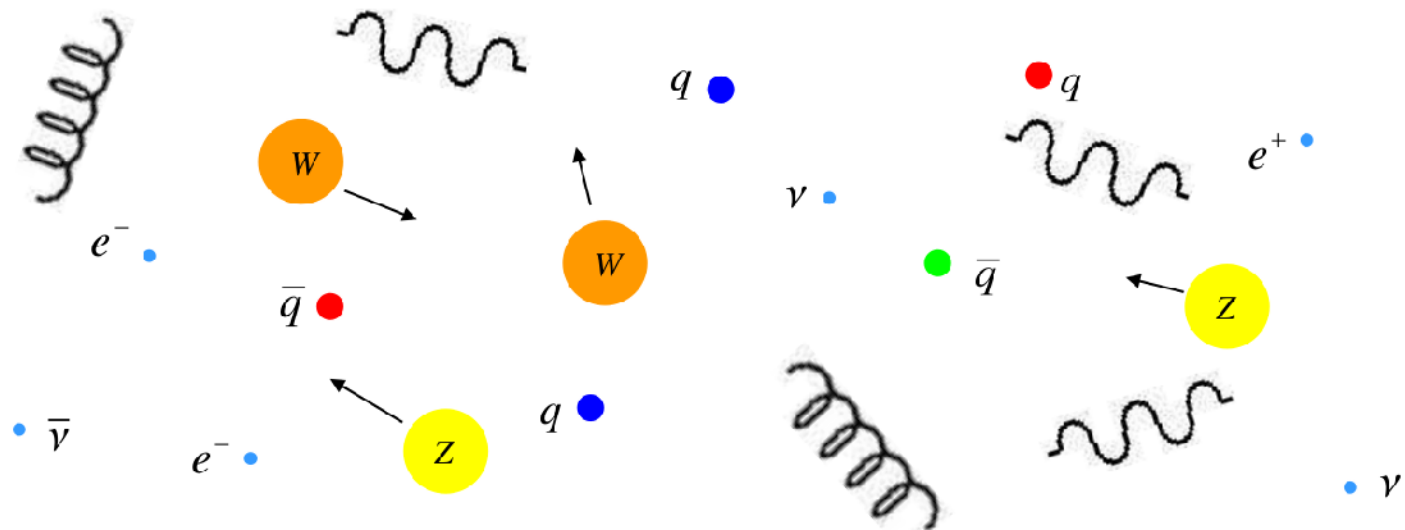
Key

	quark		neutrino		ion		star
	gluon		bosons		atom		galaxy
	electron		meson		photon		black hole
	muon		baryon				
	tau						

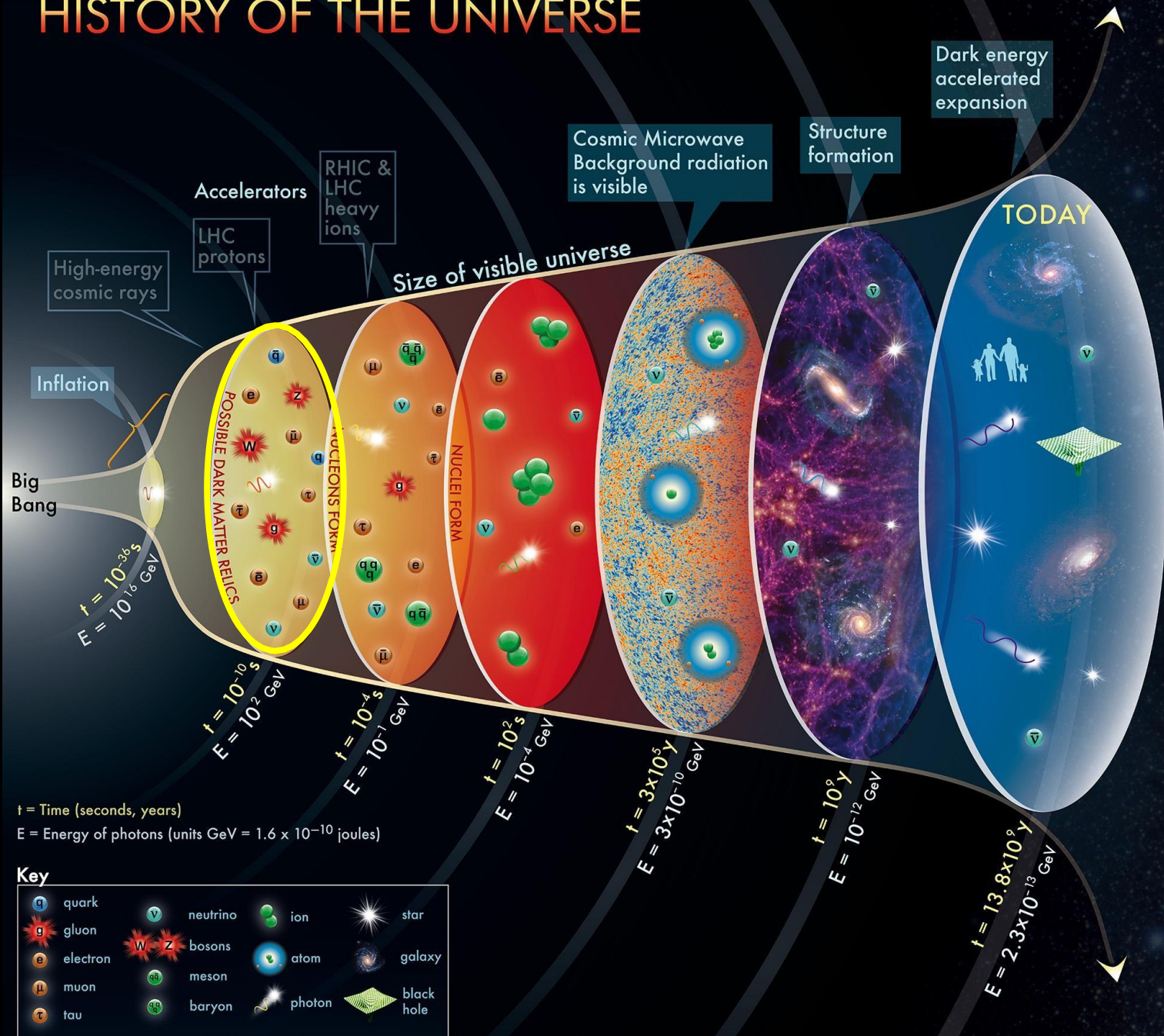
The concept for the above figure originated in a 1986 paper by Michael Turner.

UNIVERSE 10^{-27} SECONDS AFTER BIG BANG

- After 10^{-27} s, possible higher level symmetries are broken, creating the interactions observed in today's accelerators.
- The **W**'s and **Z**'s form; these scatter off the highly relativistic free quarks and leptons in the primordial plasma.



HISTORY OF THE UNIVERSE



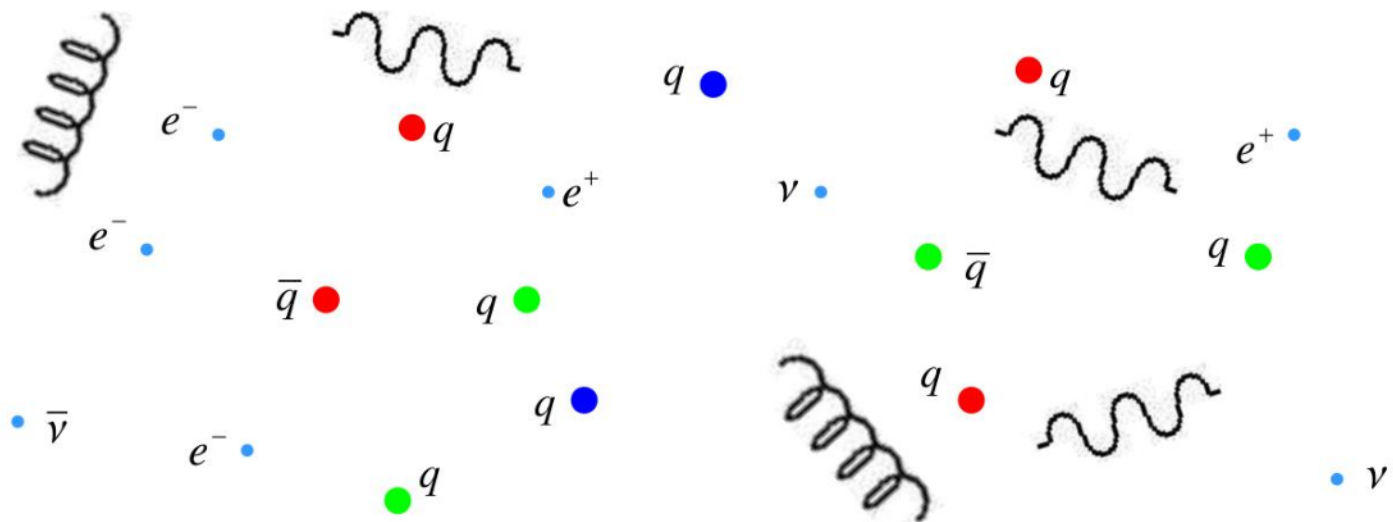
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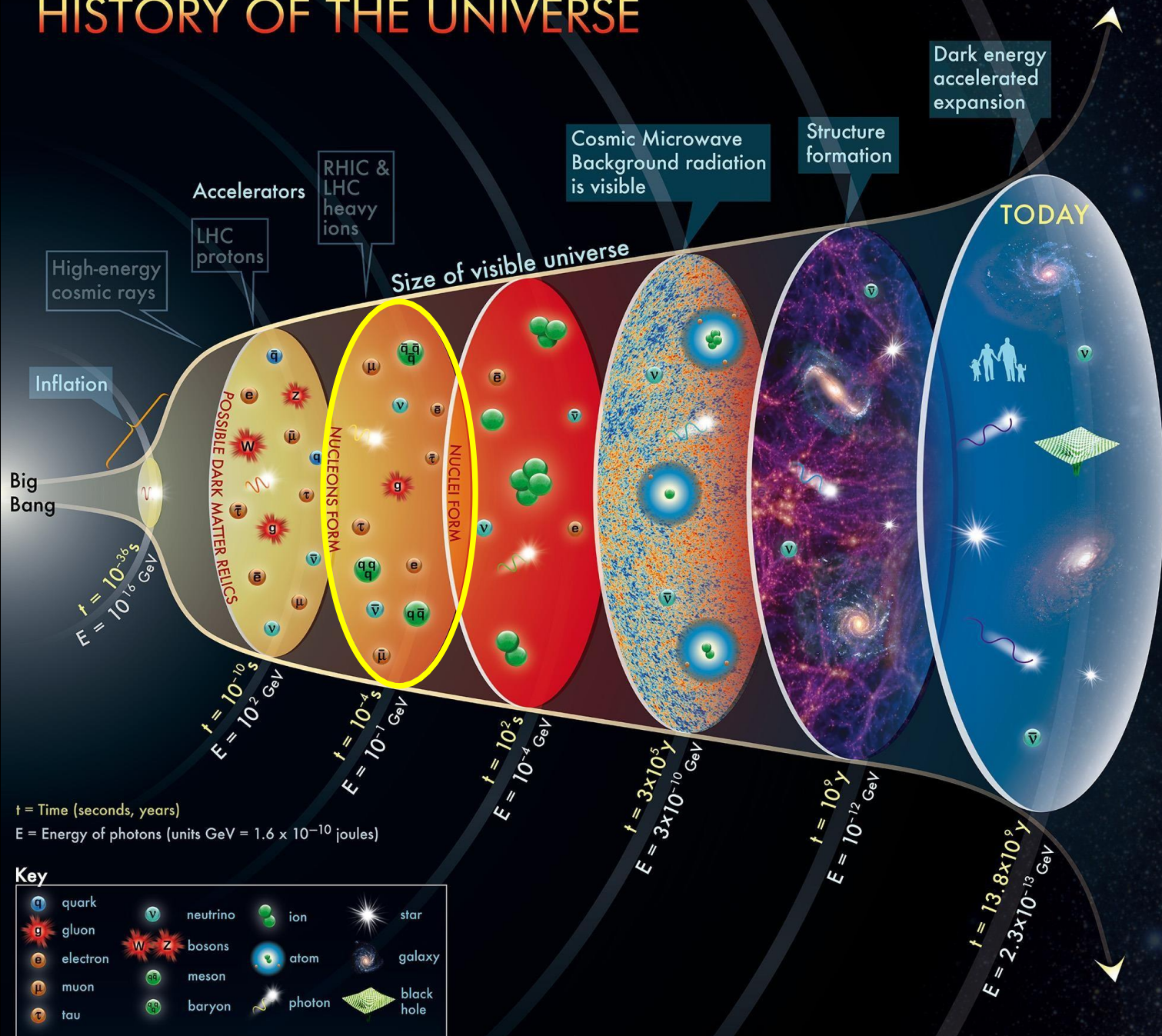
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UNIVERSE 10^{-10} SECONDS AFTER BIG BANG

- Universe cools to the point that reactions like $e^+e^- \rightarrow W^+W^-$ can **no longer replenish** the population of **W's** and **Z's**.
- The free **W's** and **Z's** disappear, and the **quarks** and **antiquarks** start to **annihilate**, creating the present **matter surplus** (we are still **unclear** on how this happened)



HISTORY OF THE UNIVERSE



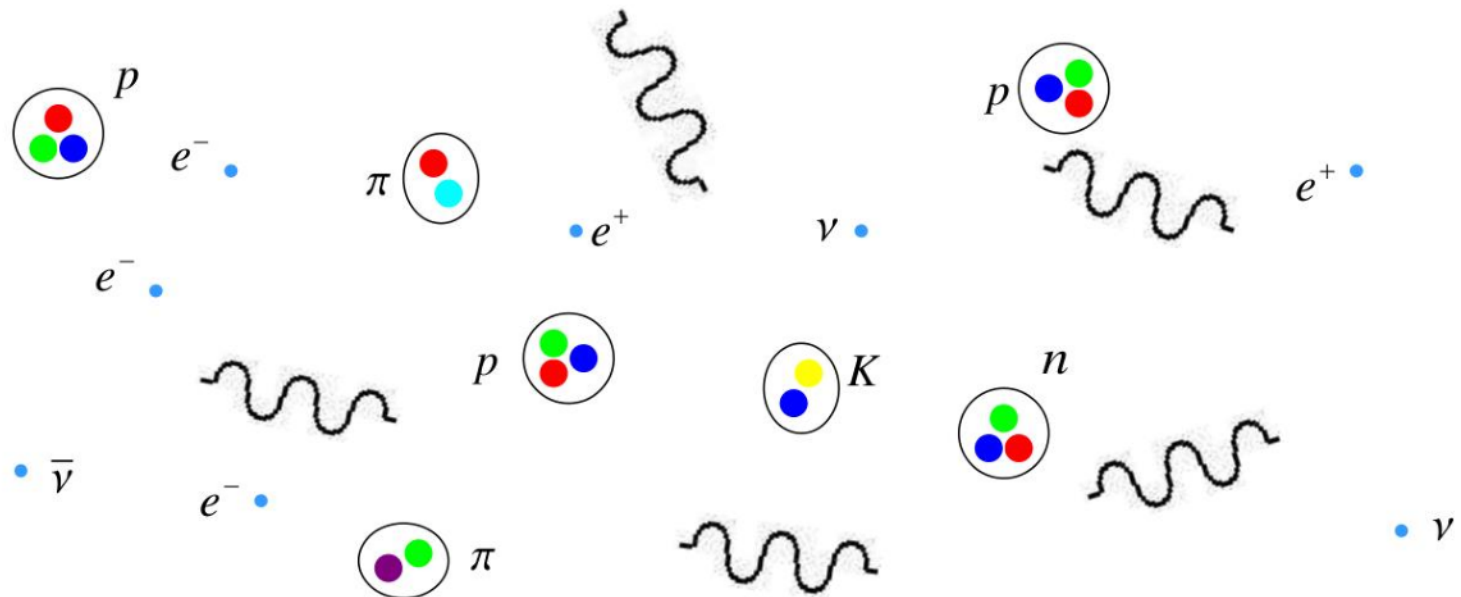
The concept for the above figure originated in a 1986 paper by Michael Turner.

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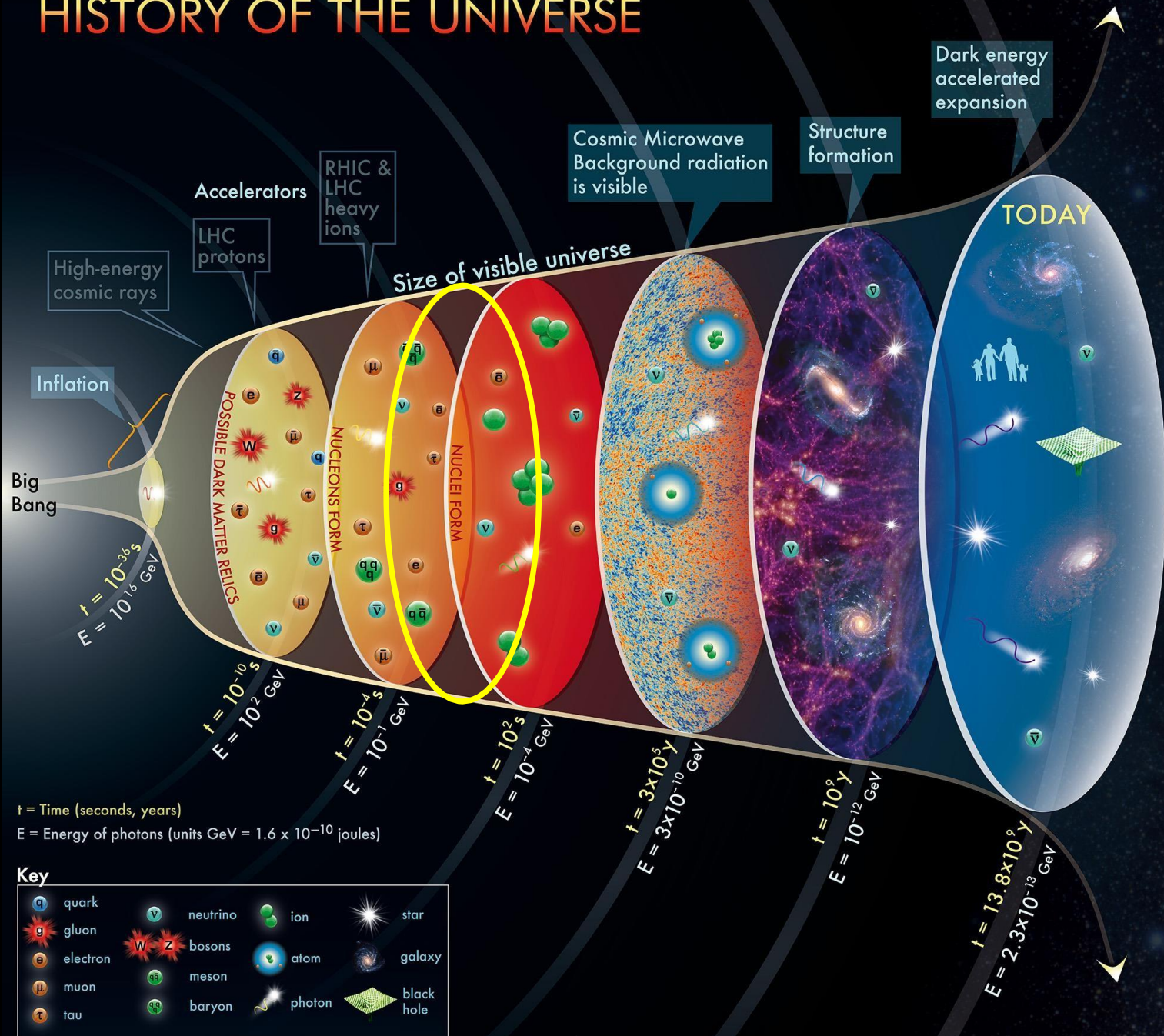
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UNIVERSE 10^{-5} SECONDS AFTER BIG BANG

- Universe cools to the point that the **quark-gluon** plasma can **bind** into stable **baryons** and **mesons**.
- It is during this period that the **protons**, **neutrons**, and other familiar **hadrons** form.



HISTORY OF THE UNIVERSE



The concept for the above figure originated in a 1986 paper by Michael Turner.

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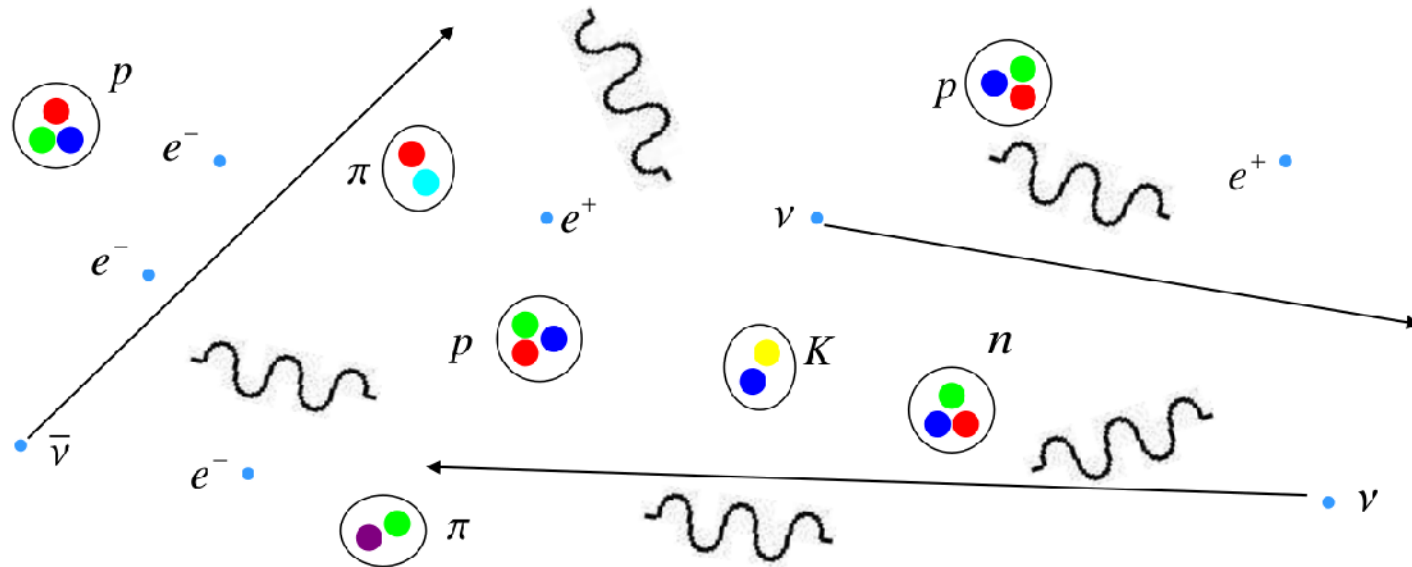
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UNIVERSE 10^{-2} SECONDS AFTER BIG BANG

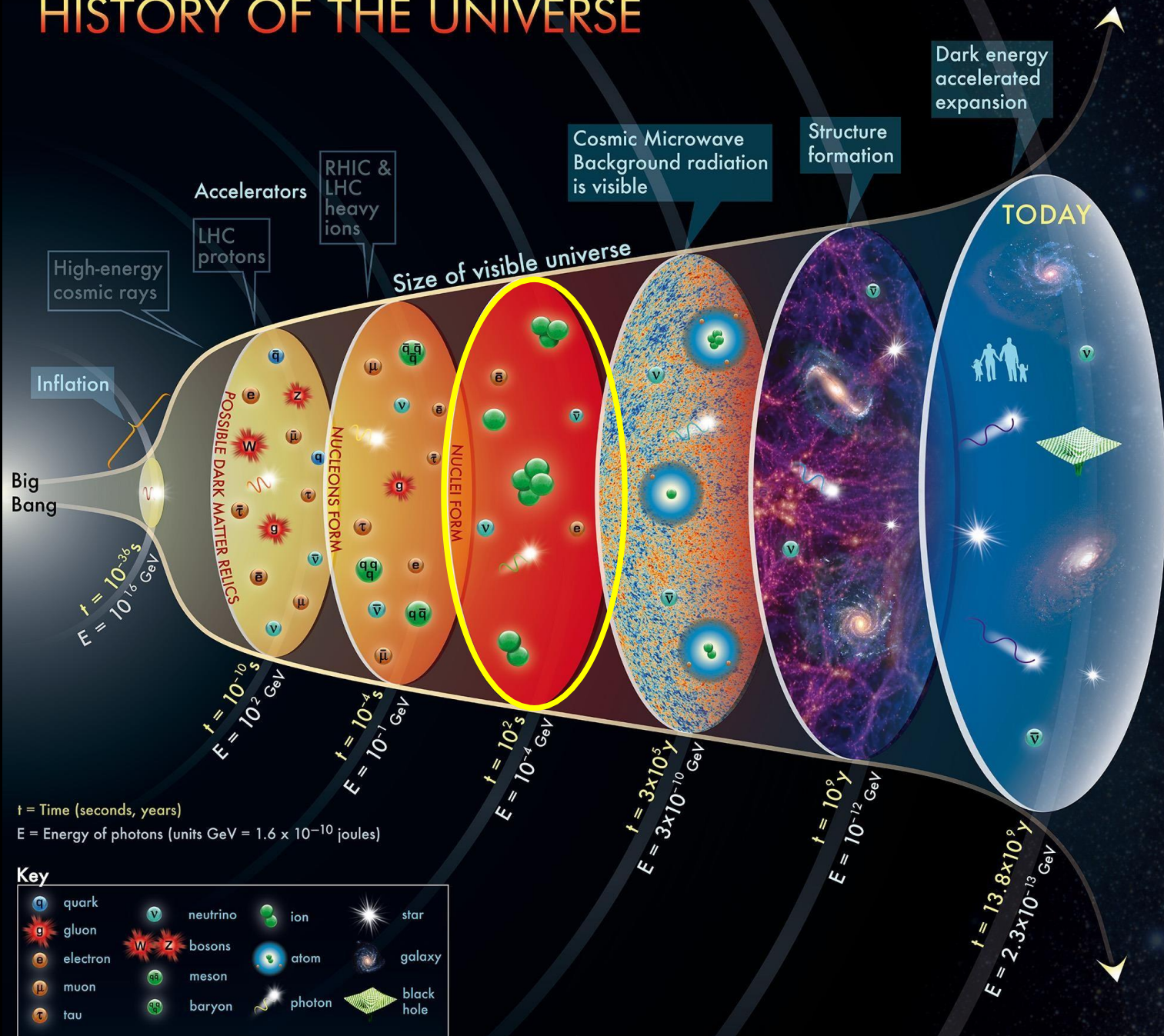
- Cooling continues; eventually **neutrinos stop annihilating** via reaction:

$$\nu + \bar{\nu} \rightarrow e^{-} + e^{+}$$

- The **neutrinos no longer interact**, and can move freely through the universe, creating the **cosmic neutrino background**.



HISTORY OF THE UNIVERSE



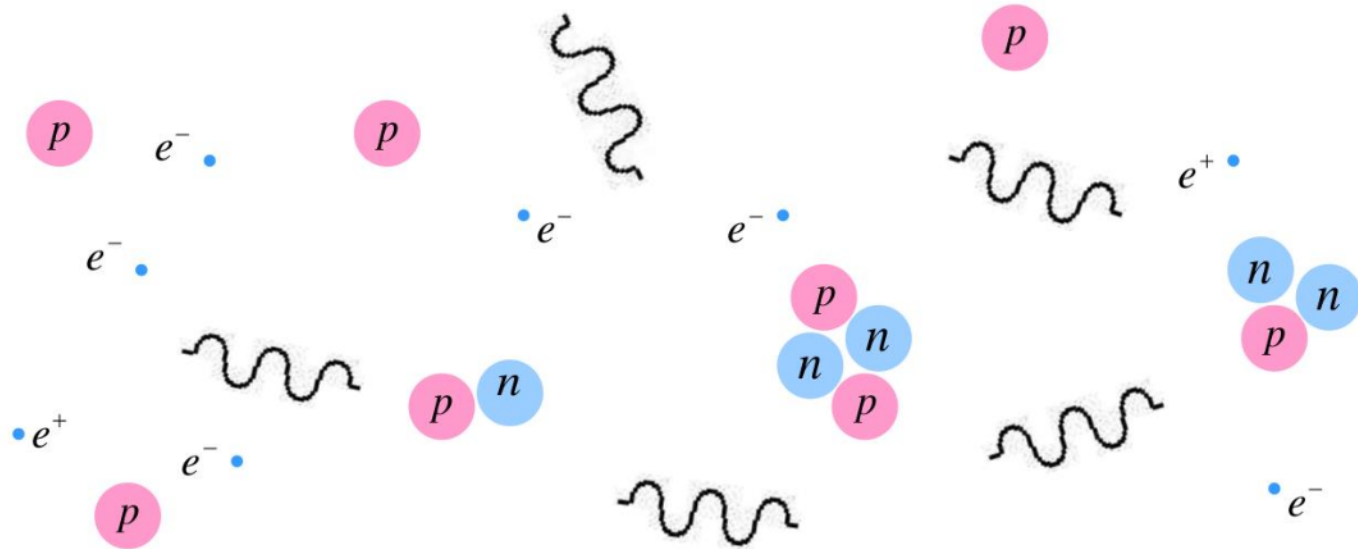
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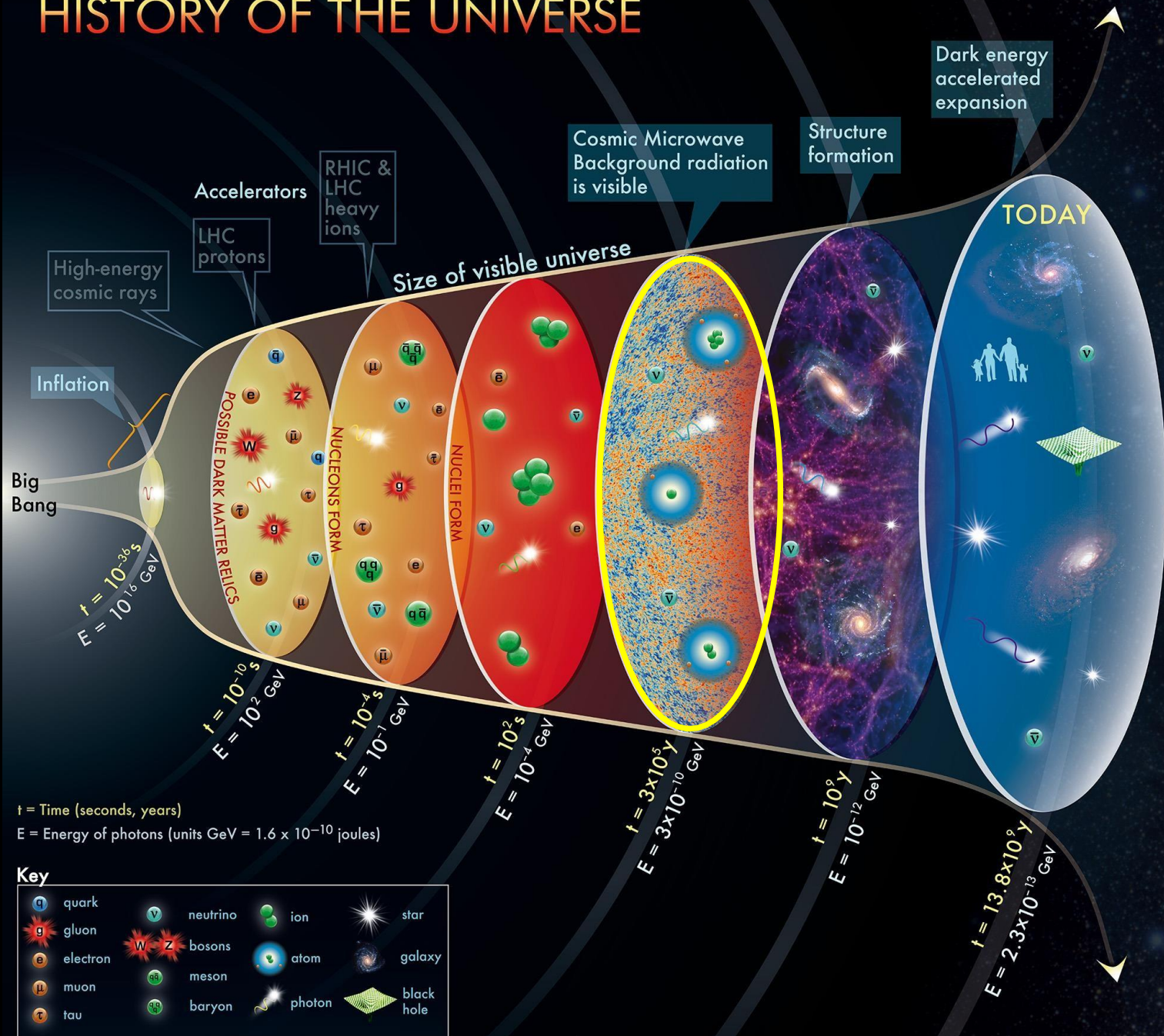
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UNIVERSE 100 SECONDS AFTER BIG BANG

- Big Bang nucleosynthesis: cool enough for stable atomic nuclei to form. Most electrons and positrons annihilate, forming photons.
- Photons scatter off remaining free electrons and prevent stable atoms from combining. Universe is “opaque”, since photons can’t travel far without getting scattered.



HISTORY OF THE UNIVERSE



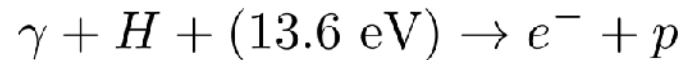
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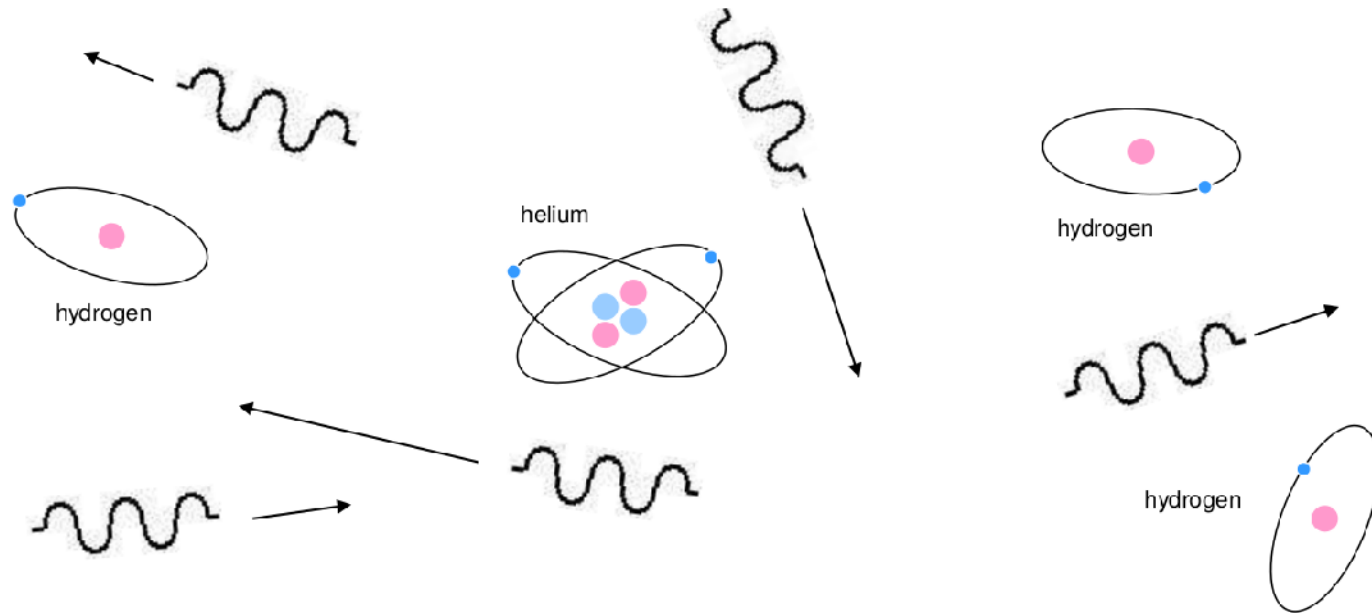
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UNIVERSE 10^5 YEARS AFTER BIG BANG

- After $\sim 380,000$ years, it gets cool enough for electrons to “recombine” with nuclei into stable atoms without getting instantly re-ionized via:



- There are no more free electrons to scatter relic photons; the photons stream freely through the “transparent” universe, creating the CMB.



DARK MATTER AND DARK ENERGY

THE MYSTERY OF DARK MATTER

- **Luminous** or otherwise directly detectable matter – stars, gas, dust – makes up only a **small fraction** of the universe.
- The other components of the universe are “**dark**” in the sense that **we have not detected them**.
- How do we know that ordinary matter makes up such a small part of the universe?
- And if we can't detect the other “stuff”, the dark components of the energy in the universe, how can we tell they are there?

DARK MATTER HAS MASS

- Let's answer the second question first.
- There is stuff in the universe that we cannot observe directly; it **neither emits, reflects, nor absorbs radiation**.
- However, if the stuff has mass-energy, it creates a **gravitational** field.
- Hence, by measuring the **gravitational pull** of invisible objects on **visible material**, we can **infer** the amount of mass present in the entire system.
- This method is used throughout astronomy to determine the existence of dim stars, extrasolar planets, etc.

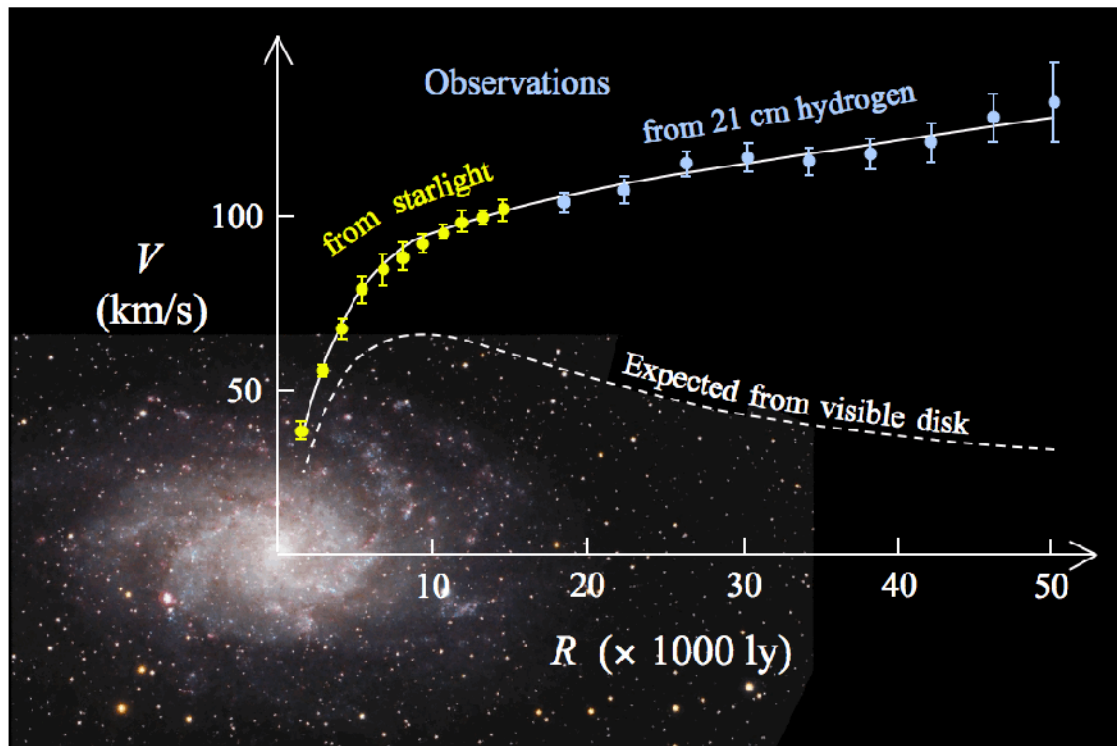
EXPECTED GALACTIC DYNAMICS

- The **gravitational** signal of invisible matter is most clearly evident on **galactic** scales.
- Many galaxies look like spirals – they have a thin disc and a central hub.
- For a star **inside** the hub, **Newtonian gravitation** suggests that its rotational velocity should vary as $v \propto r$.
- For a star **outside** the hub (in the disc), the rotational velocity varies as $v \propto r^{-1/2}$.



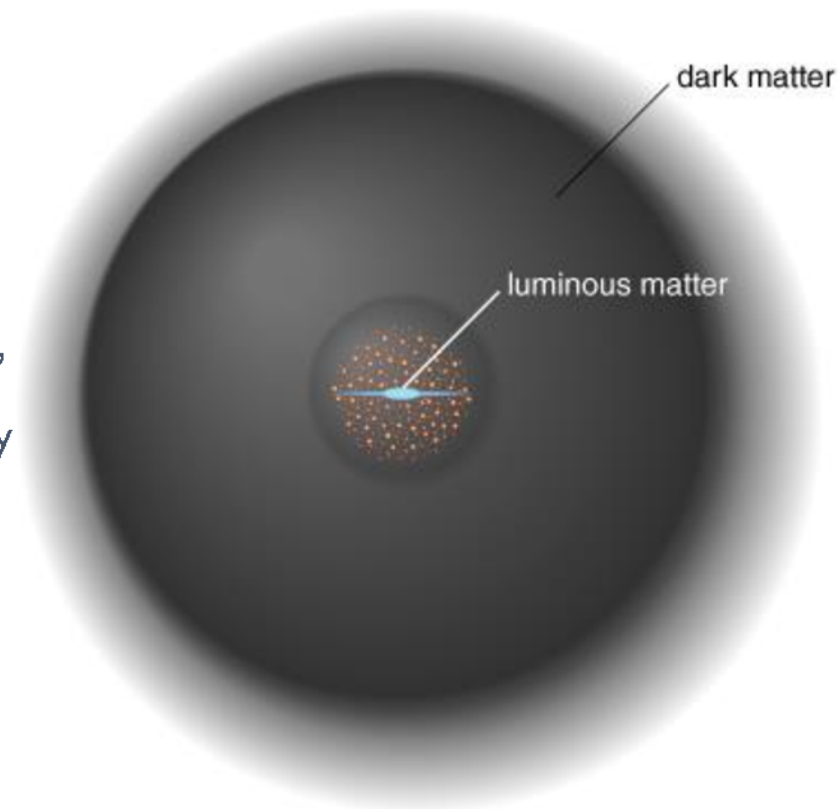
ACTUAL GALACTIC DYNAMICS

- Contrary to expectations, however, the rotation curves of observed galaxies do not match our predictions.
- Where have we gone wrong?



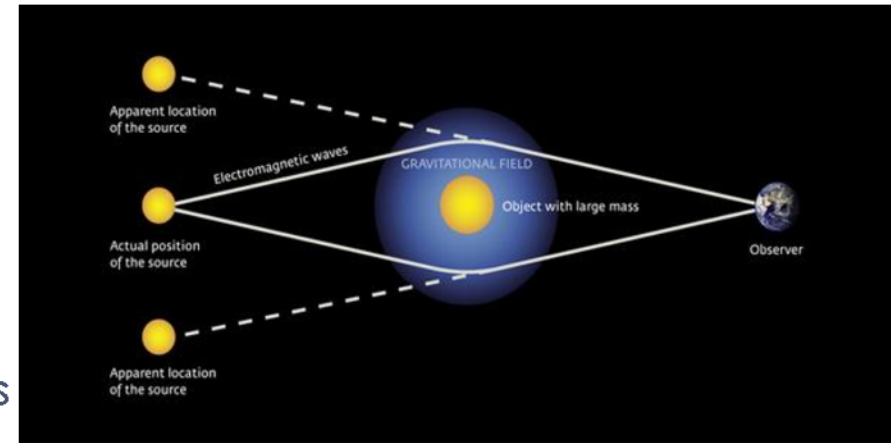
TRUE GALACTIC MATTER DISTRIBUTION

- How to **fix** the rotation curve:
 1. **Junk** Newton's Laws.
 2. Alter our **assumption** that all of the galaxy's matter is contained in the hub and disc.
- Probably, the second method is preferable. So, we assume **that in addition** to the luminous dust and gas in the spiral, there is a spherical "**halo**" of **dark matter** we can't see, except by its gravitational influence on the stars we observe.
- **RESULT:** the **halo fixes the rotation curve!** But now we have to detect this stuff.



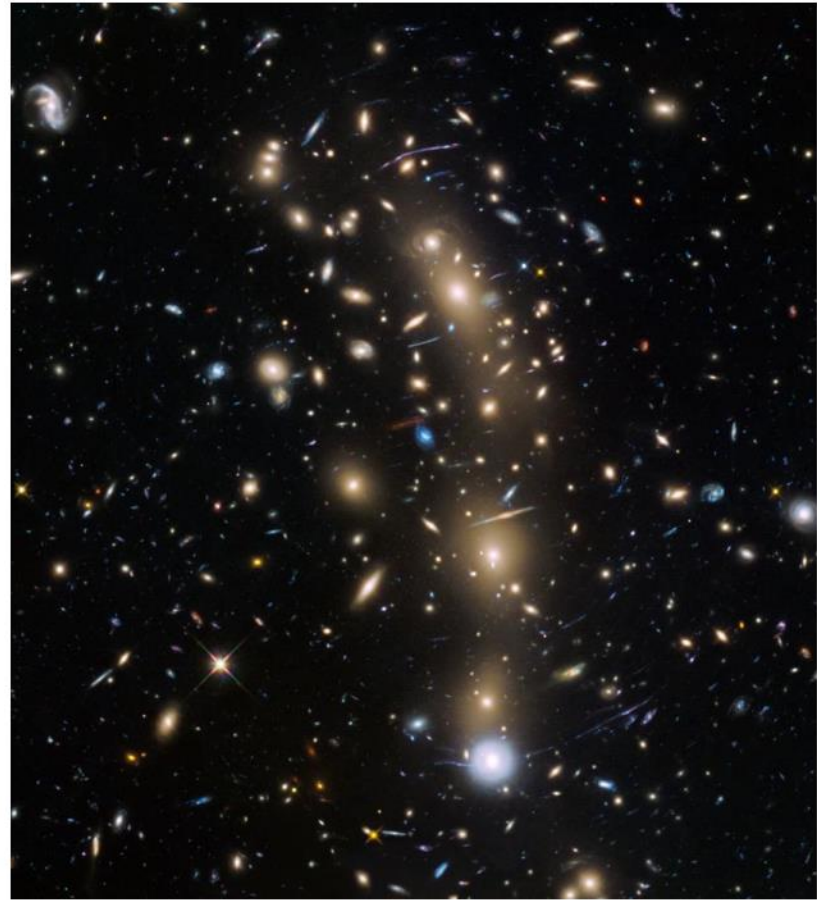
MORE EVIDENCE FOR DARK MATTER

- There are **other** significant ways to observe dark matter besides the rotation curves of spiral galaxies.
- The most important is a phenomenon called **gravitational lensing**.
- In General Relativity, massive objects **deform** spacetime. A photon moving around a massive object can therefore get **deflected** and travel along the warped geometry.
- If a **massive** object is in our line of sight, it can **focus light rays** from a glowing body just like a converging lens in optics.



EXAMPLE OF LENSING

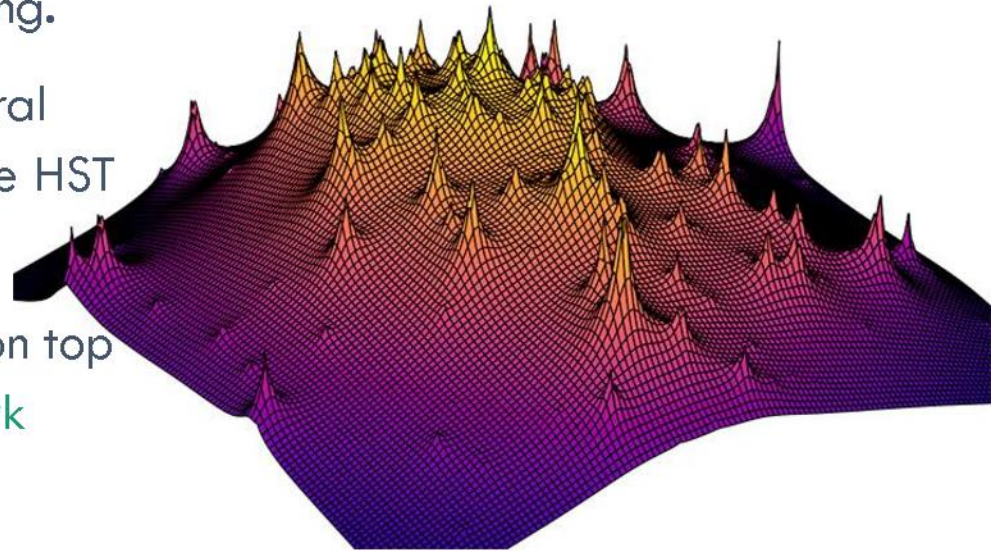
- Pictures from the Hubble Space Telescope provide **ample evidence** for gravitational lensing.
- In the HST picture of the cluster MACS J0416, the bright **arcs** are gravitationally **distorted** images of galaxies more distant than the cluster.
- The **amount** of lensing and distortion suggests that much of the mass of the cluster is actually concentrated in dark matter.
- NOTE: several of the arcs are multiple images of a single galaxy located behind the cluster.



The cluster MACS J0416, as seen by the HST. The foreground material in the cluster (bright yellow spiral galaxies + dark matter) have distorted and deflected light from galaxies in the background.

EXAMPLE OF LENSING

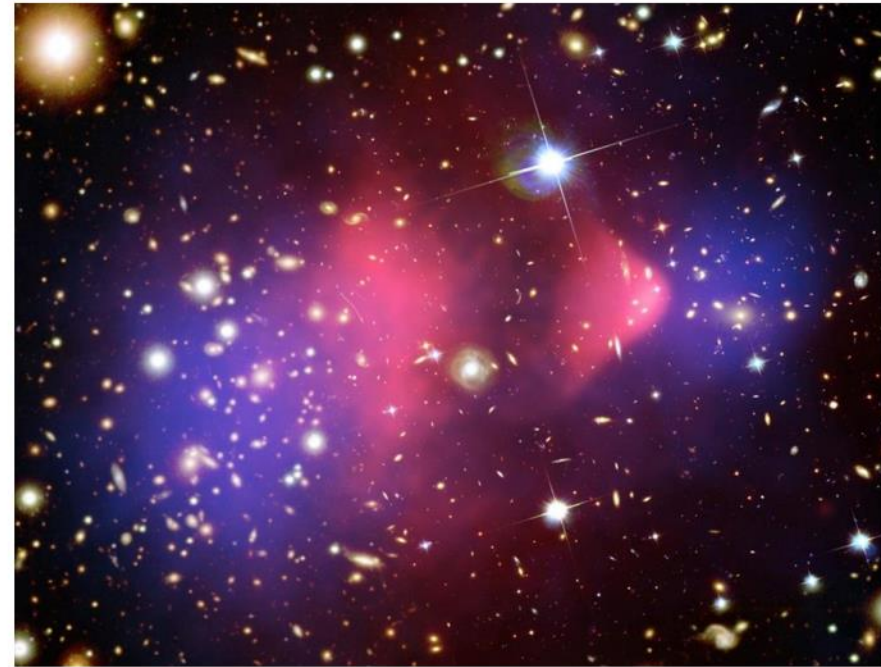
- The plot on the right shows the **mass distribution** in MACS J0416, as **inferred** from gravitational lensing.
- The **spikes** correspond to the spiral **galaxies** in the foreground of the HST image.
- Note how the spikes are riding on top of a **large bump of invisible dark matter**.
- Hence, we **conclude** that most of the cluster's mass is dark matter; only a small part is concentrated in luminous material.



Reconstructed mass distribution of the cluster MACS J0416.

THE BULLET CLUSTER

- The Bullet cluster (and a few others similar to it) is one of the most **compelling** pieces of evidence for dark matter.
- It consists of two galaxy clusters undergoing a violent **collision**.
- The “**standard**” matter interacts violently, **clustering in the middle** of the collision and emitting **X-ray** radiation.
- The **dark matter** components have passed through each other **unaffected**.



The Bullet cluster. Very hot gas imaged in X-ray is shown in pink. The distribution of dark matter as inferred from gravitational lensing is shown in blue.

WHAT IS DARK MATTER?

- The astronomical evidence shows that much of the universe is filled with dark matter – while $\Omega = 1$, $\Omega_{\text{DM}} = 0.26$ – it's 1/4 of the cosmos! But what is this stuff?
- There are several possibilities:
 1. The dark matter is **baryonic**, like you, your clothing, and the chair you're sitting in. It is just **normal material**, but is hard to detect because it's not luminous.
 2. The dark matter is **nonbaryonic**, and can be **cold** (nonrelativistic) or hot (relativistic). It is not the ordinary “stuff” we are made of, and so is hard to detect because it only interacts gravitationally.
- **Big Bang Nucleosynthesis** and **CMB** analyses say **baryons only make up 4.8%** of the material in the universe; the rest of the dark matter must be **nonbaryonic**!
- Wild as it seems, it turns out that most dark matter is likely nonbaryonic; in fact, it probably consists of **particles** that **are not part of the Standard Model**.

WEAKLY INTERACTING MASSIVE PARTICLES

- If most dark matter is nonbaryonic, then we have a number of possible **candidate particles** to choose from.
- One solution is to simply **invent a particle** with the **right properties**. From observations, we know that such a particle must be:
 1. **Stable** – it has survived since the Big Bang;
 2. **Weakly interacting** – it does not reflect or scatter light;
 3. **Massive** – it is heavy enough to generate the observed gravitational effects (lensing, rotation curves, ...).
- Hence, physicists have hypothesised a new particle: the **WIMP**, or weakly interacting massive particle.
- The WIMP could be a **supersymmetric** particle (nice!).

WEAKLY INTERACTING MASSIVE PARTICLES

- WIMPs do not belong to the Standard Model, but there is widespread belief that they could be incorporated into a supersymmetric theory of particle physics, in particular WIMPs and the **lightest SUSY particle** share many significant properties.
- Cosmic WIMPs are expected to have a **mass** near **$100 \text{ GeV}/c^2$** , (to within a factor of 10 or so), and velocities similar to that of luminous material in galaxies.
- In other words, WIMPs are “**cold dark matter**,” stuck in **nonrelativistic** Newtonian motion.
- Currently, experimentalists are trying very hard to **detect WIMPs** via elastic scattering from nuclei. No luck yet (although one controversial signal)!

AXIONS

- Another nonbaryonic dark matter candidate is the **axion**, a hypothetical, **light**, neutral pseudoscalar particle with a mass of about $1\text{-}100\text{ }\mu\text{eV}/c^2$.
- The idea for axions originated in **QCD**, where they were a byproduct of invoking a broken **symmetry** in the theory.
 - And **explain** why there is **no CP** violation in strong interactions!
- Ordinarily, this would be an annoyance, but it turns out that these axions are actually a **convenient dark matter candidate**, so we like them.
- Because they are so light, axions – if they exist – would have been produced in **huge numbers** in the early universe, and they would be **stable**. Like WIMPs, relic axions are expected to be nonrelativistic “**cold dark matter**.”
- Although more active in the past, there is a research programme dedicated to the search for axions. No luck yet.

WHY NOT NEUTRINOS?

- Finally, a potentially plausible dark matter candidate is our old friend, the light and stable **neutrino**.
- In the early universe, neutrinos were created in large quantities by the reaction:

$$e^{-} + e^{+} \rightarrow \nu + \bar{\nu}$$

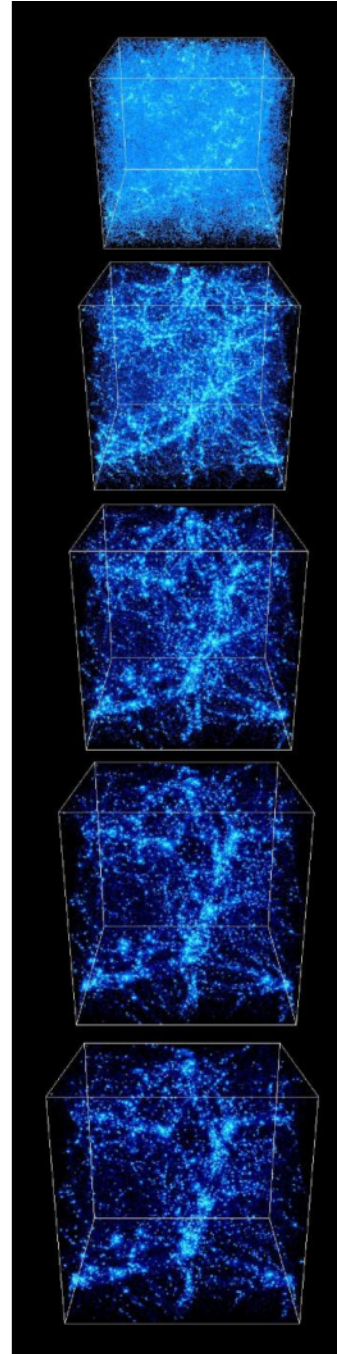
- These neutrinos quickly decoupled from matter, so it seems very likely that they are **still floating around**.
- There should be a **cosmic neutrino background** (CNB?), and in CMB analyses indicate that this is the case.
- Naturally, the primary advantage of the neutrino model is that these particles are actually **known to exist**.
- However, there are significant technical **objections...**

WHY NOT NEUTRINOS?

- Why are neutrinos **non-ideal** candidates for dark matter?
- Basically, the problem is that they were **too energetic** during the early universe.
- That is, when the neutrinos **decoupled** from matter, the **temperature** of the universe was **very high**: $k_B T \approx 3 \text{ MeV}$.
- Since the neutrinos started out in **equilibrium** with other particles, their average energies were about 3 MeV.
- Hence, the relic neutrinos started out as **relativistic** particles; and they would have been “**hot dark matter**”.

STRUCTURE AND DARK MATTER

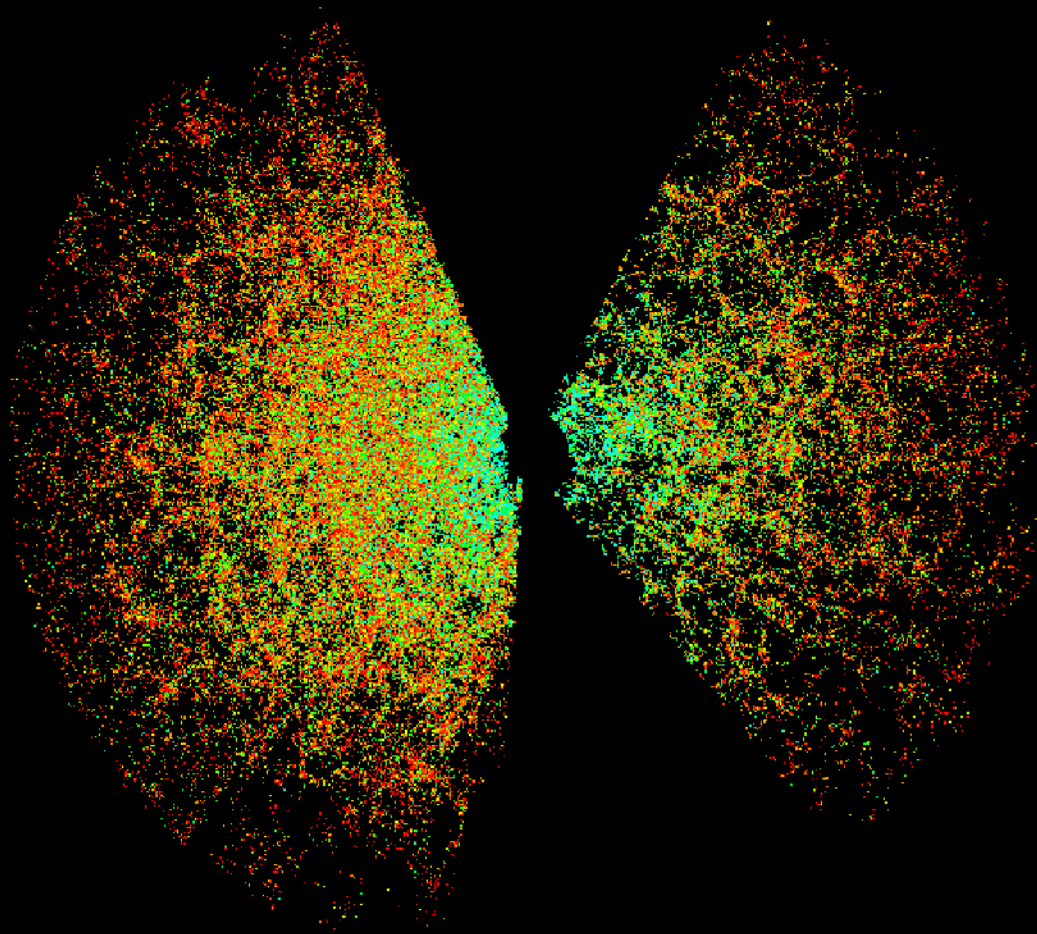
- Who cares if the dark matter in the early universe was relativistic? **Why is this a problem?**
- The issue starts like this: the early universe was filled with a **hot, dense gas**. Like any dense material, this gas was filled with small density fluctuations – **sound waves**.
- As the universe expanded and cooled, these density fluctuations began to **condense** into larger **objects**.
- That is, as **distance** scales **increased**, **gravity** became the **dominant** force. Regions of higher mass/energy density began to gravitationally attract large amounts of material.
- The density fluctuations got **bigger and bigger**, eventually turning into **the large scale structures** we see in the universe today: galaxies, clusters of galaxies, and superclusters of clusters.



FORMATION OF LARGE SCALE STRUCTURE

- The evidence for small density fluctuations in the early universe comes from the CMB.
- The μK anisotropies in the CMB sky map are actually the manifestation of compression waves (sound) moving through the young universe.
- Density variations (sound waves) in the early universe appear as small anisotropies in the CMB sky map.
- Eventually the compression waves condensed into extended, gravitationally bound objects, like the filamentary superclusters and large voids visible in the sky survey at right.

LARGE SCALE STRUCTURE OF THE UNIVERSE

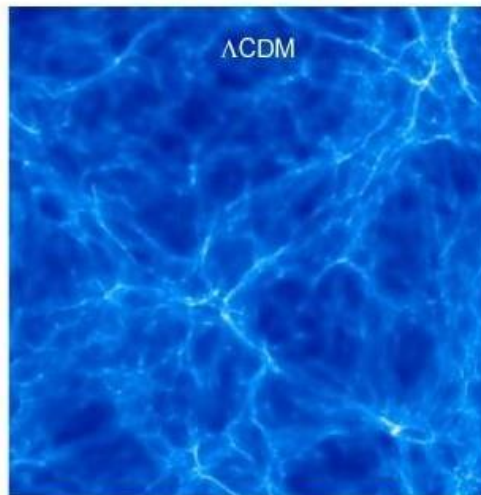


Sloan Digital Sky Survey

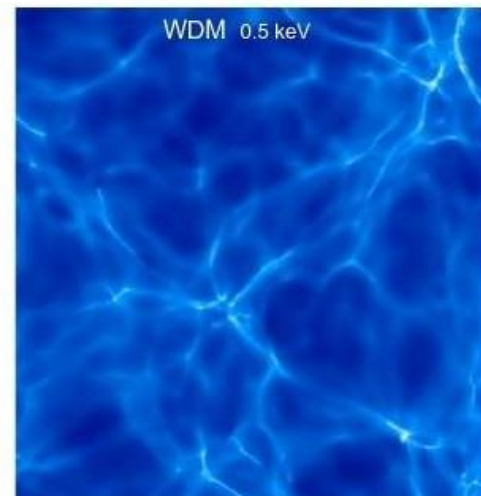
WHY DARK MATTER IS “COLD”

- Large-scale structure and CMB measurements tell us that $\Omega_m = 0.31$; **matter** is **31%** of the universe. **Most** of this stuff is **dark**.
- Computer simulations suggest the **structures** we see today could only **form** if the dark matter was **cold**.
- **Hot** dark matter would have “**ironed out**” primordial density fluctuations in the early universe, **destroying** the structures we observe today.
- The **neutrinos**, which were **relativistic** during the early universe, can only make up a **small portion** of Ω_m . **WIMPs** remain the favorite dark matter candidate.

cold dark matter



warm dark matter



SUMMARY OF MATTER/DENSITY “BUDGET”

- The universe is **composed** of many **types** of **matter** and energy. These all add up to form the **total energy density** of the universe.
- A convenient way to **summarize** the composition of the cosmos is in the parameter Ω , which is related to the **geometry** of the universe.
- You can **add up** the mass-energy contributions of various types of matter – photons, baryons, neutrinos, cold dark matter – to get the **total Ω** for the whole universe:

$$\Omega = \Omega_{\text{photons}} + \Omega_{\text{baryons}} + \Omega_{\text{DM}} + \dots$$

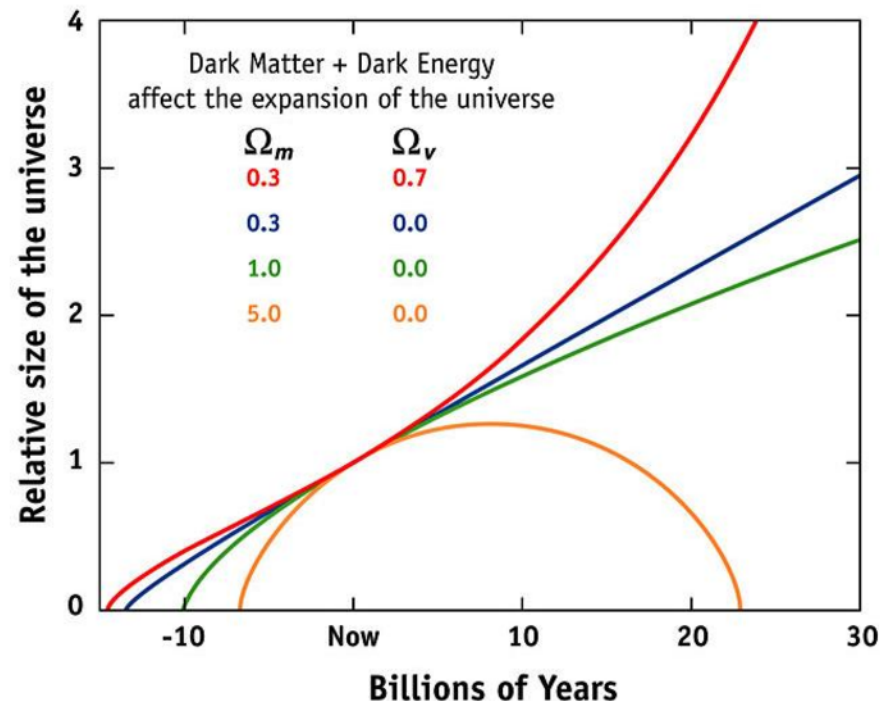
- **CMB** measurements suggest that today, $\Omega = 1.002 \pm 0.005$, meaning that the universe seems to be **geometrically flat**.

WHERE'S THE MISSING STUFF?!?!?!?

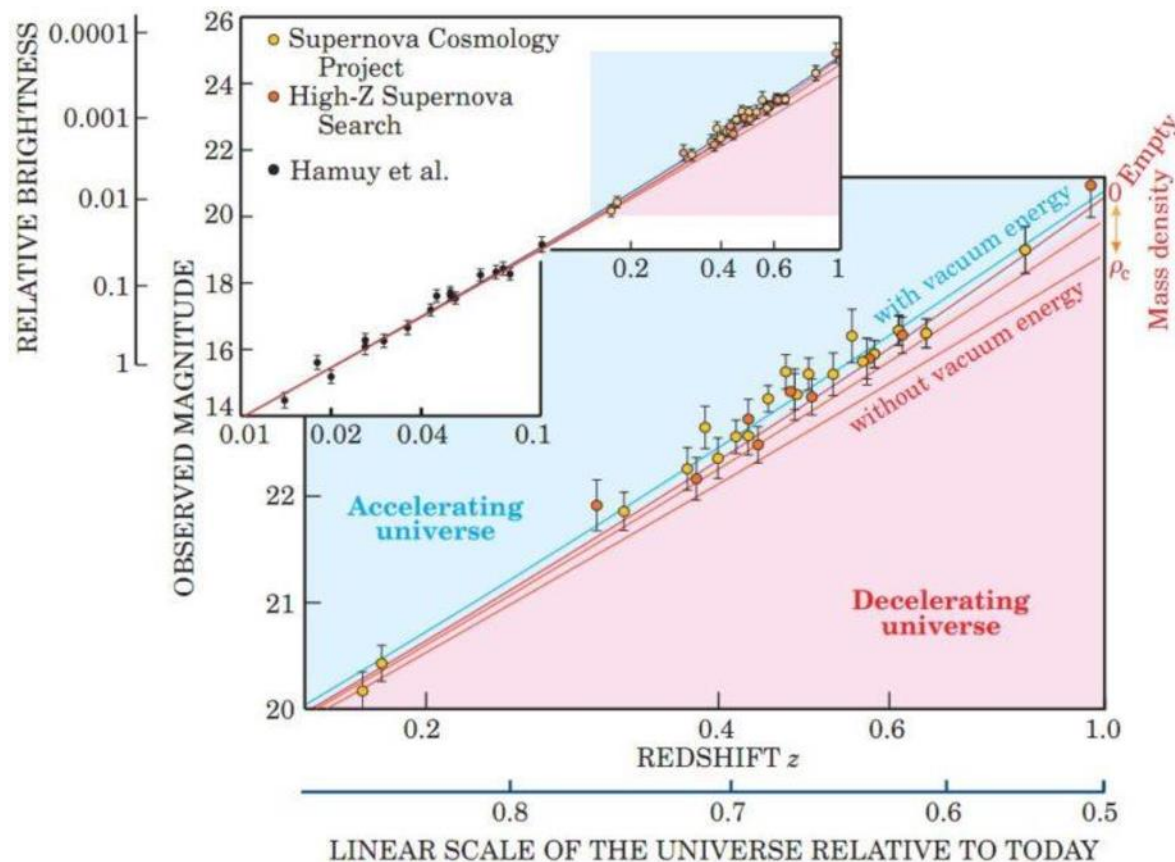
- If $\Omega = 1.002 \pm 0.005$, and putting all the matter in the universe together only gives you $\Omega_m = 0.3$, then where is the **other 70%** of the mass-energy in the universe?
- Currently, measurements appear to suggest that the other 70% of the universe is bound up in a **repulsive** energy field that is **forcing the universe apart**.
- This field, which is **accelerating** the current **expansion** of the universe, is known in cosmology and particle physics as “**dark energy**” or “**vacuum energy**”.

WHAT IS THE DARK ENERGY?

- Dark energy has something to do with the energy of the **QM vacuum**. In every bit of spacetime – even an empty bit – there exists some **intrinsic energy** (about 6 keV cm^{-3}).
- Unlike matter/radiation, vacuum energy density (probably) **does not diminish over time**; it will (probably) come to **dominate** the energy density of the cosmos; $\Omega = \Omega_{\Lambda}$.
- Dark energy tends to have a repulsive effect, **driving points** in spacetime **apart**, and accelerating the expansion of the universe. It may get to the point that galaxies, planets, molecules, and eventually even atoms are pulled apart.
- The “**Big Rip?**” Maybe in 15 billion years or so...



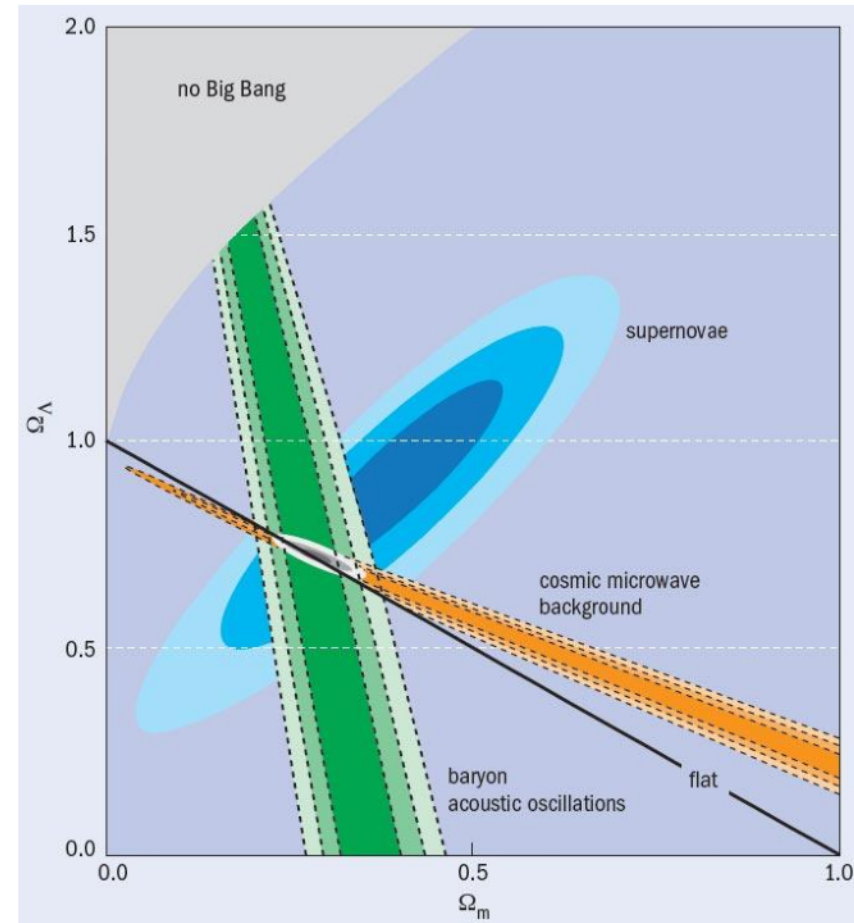
EVIDENCE FOR DARK ENERGY



- The **measurements** seem to suggest that the **expansion** of the universe is actually getting **faster** over time.
- Mathematically, this is equivalent to making the Λ term nonzero in the Friedmann equation. Was Einstein right all along...?

THE STANDARD MODEL OF COSMOLOGY

- Several **independent** measurements – of the **CMB**, large-scale **clusters**, and Type IA **supernovae** – **all** point to the following results:
- $\Omega \approx 1$; universe is **flat**.
- $\Omega_m \approx 0.3$; matter is **30%** of cosmos.
- $\Omega_\Lambda \approx 0.7$; **dark energy** is the rest.
- This is referred to as the **Λ CDM** model, and currently accepted as the “Standard Model” of cosmology



THE END