Small Scale Structures in Lambda Cold Dark Matter

Julio F. Navarro

- Lecture 1: Basic Cosmological Facts
- Lecture 2: Non-Linear Structures in LCDM
- Lecture 3: Galaxy Structure and LCDM
- Lecture 4: Small Scale Constraints to LCDM

The Cosmological Principle

Copernicus

Earth

Júpiter

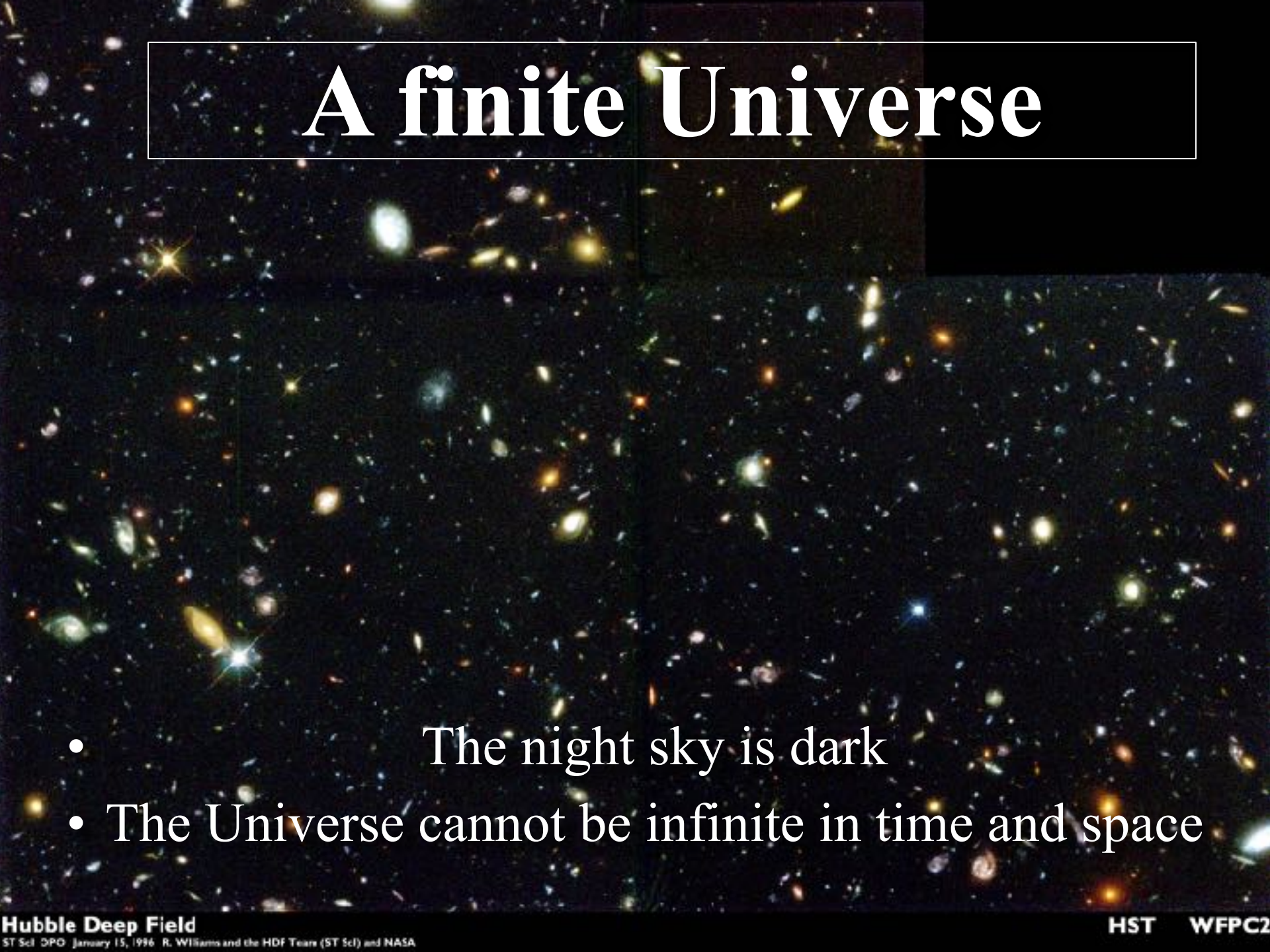
Venus

Sun

Mercury

- We are not privileged observers of the Universe
- The Universe must be homogeneous and isotropic
- There is a “cosmological time”

A finite Universe



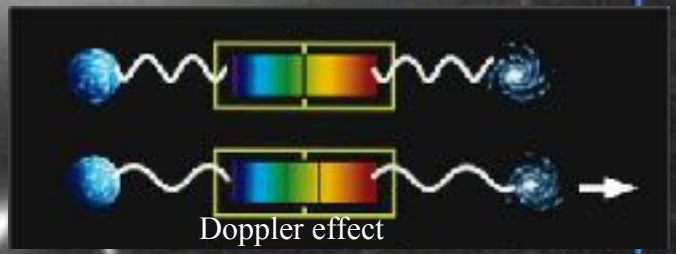
- The night sky is dark
- The Universe cannot be infinite in time and space

The expanding Universe

$H_o = 100$

$H_o = 67$

$H_o = 50$



Velocity V_c (km s^{-1})

13,000
12,000
11,000
10,000
9,000
8,000
7,000
6,000
5,000
4,000
3,000
2,000
1,000

0 20 40 60 80 100 120 140 160 180 200

Distance d (Mpc)

Universal expansion

- On cosmological scales the Universe is homogeneous and isotropic
- A possible visualization is to think of galaxies as populating a uniform grid in space
- As the Universe expands, the grid stretches without changing shape
- There is no centre. Every point in the grid is equivalent to any other



The expansion of the Universe

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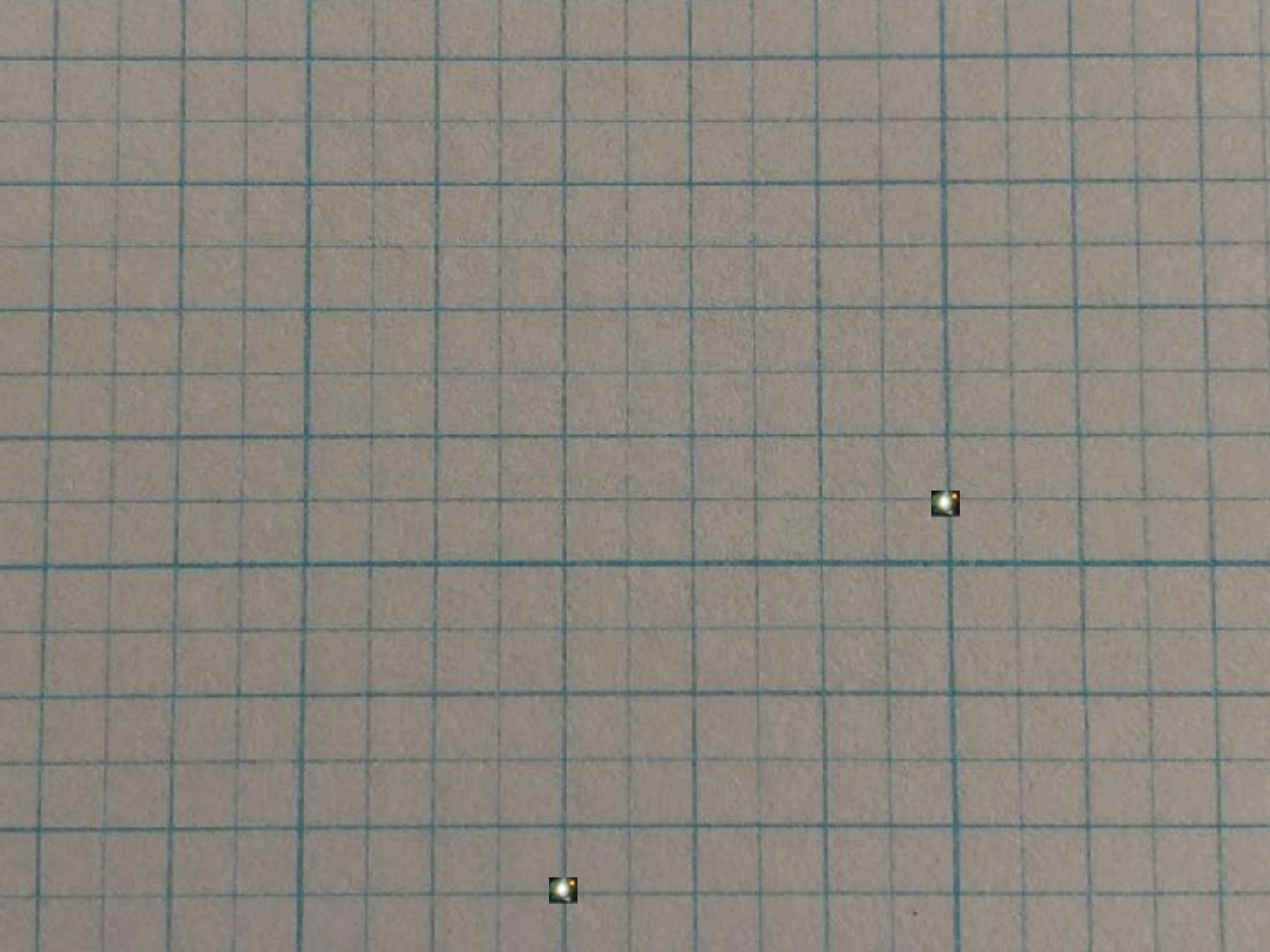
Universal Expansion + Theory of Relativity:
what happens if we look back in time?





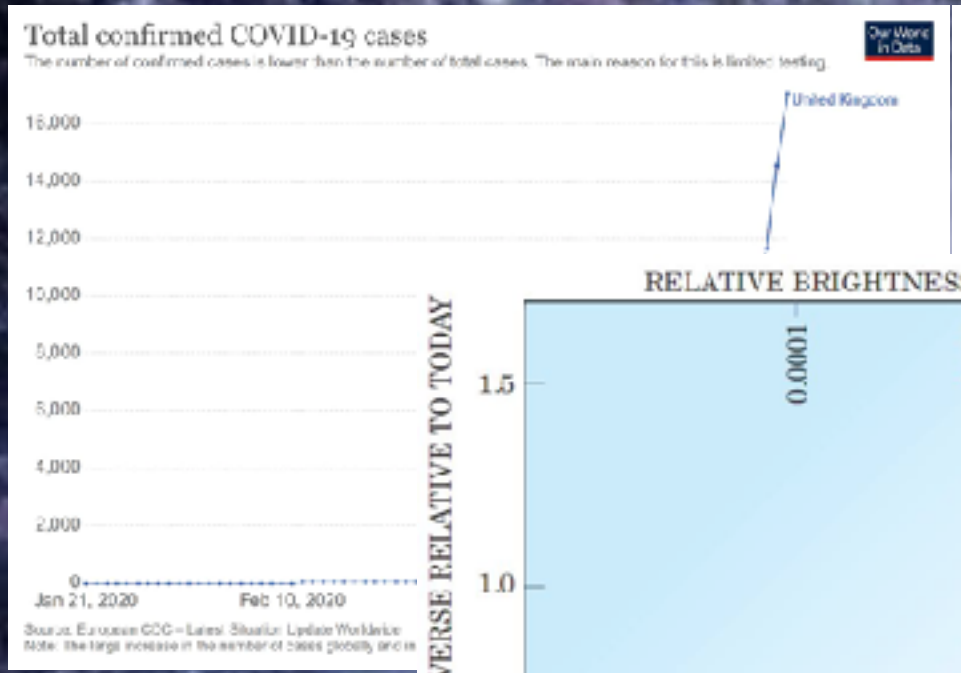


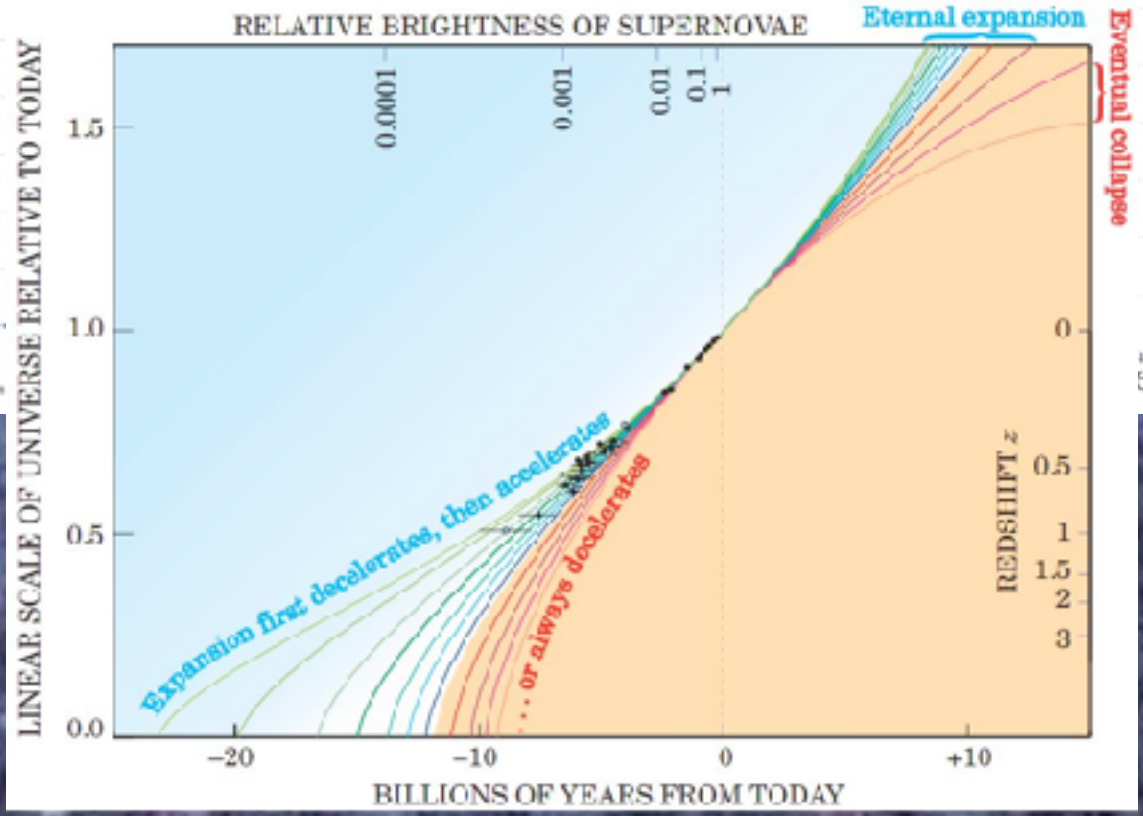
The Big Bang

- The “Big Bang” is the moment when the grid size approaches zero
- Looking back in time, the Universe compresses and heats up
- The early Universe was hot and dense



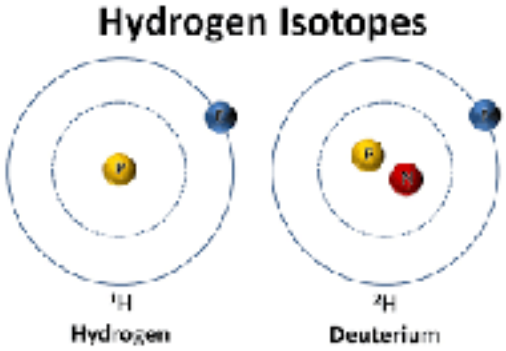
The Big Bang





Universal Expansion + Theory of Relativity

The Universe has a finite age



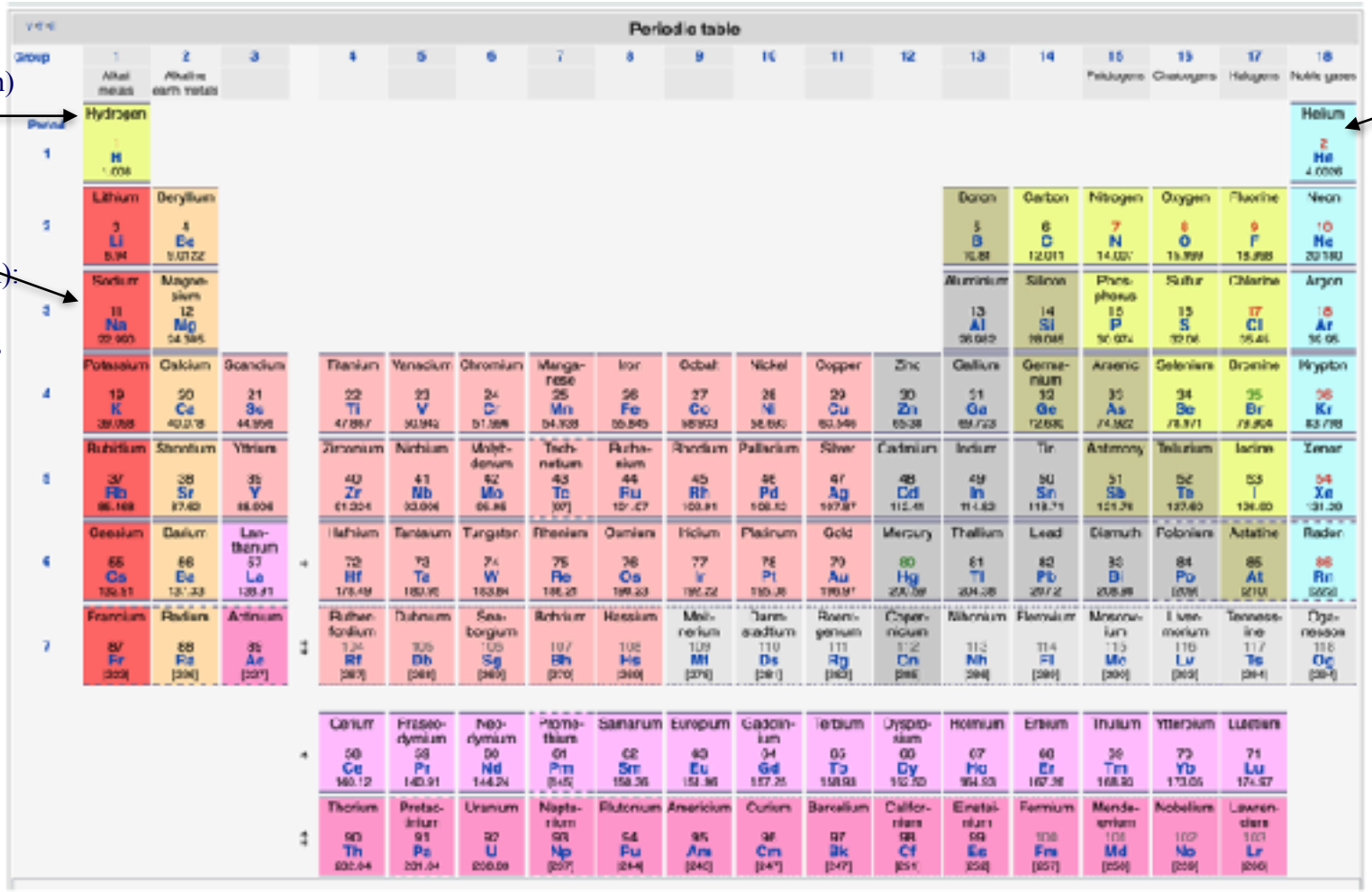
The matter content of the Universe

What is the world made of?

H (hydrogen)
1 proton

He (helium)
2 protons
2 neutrons

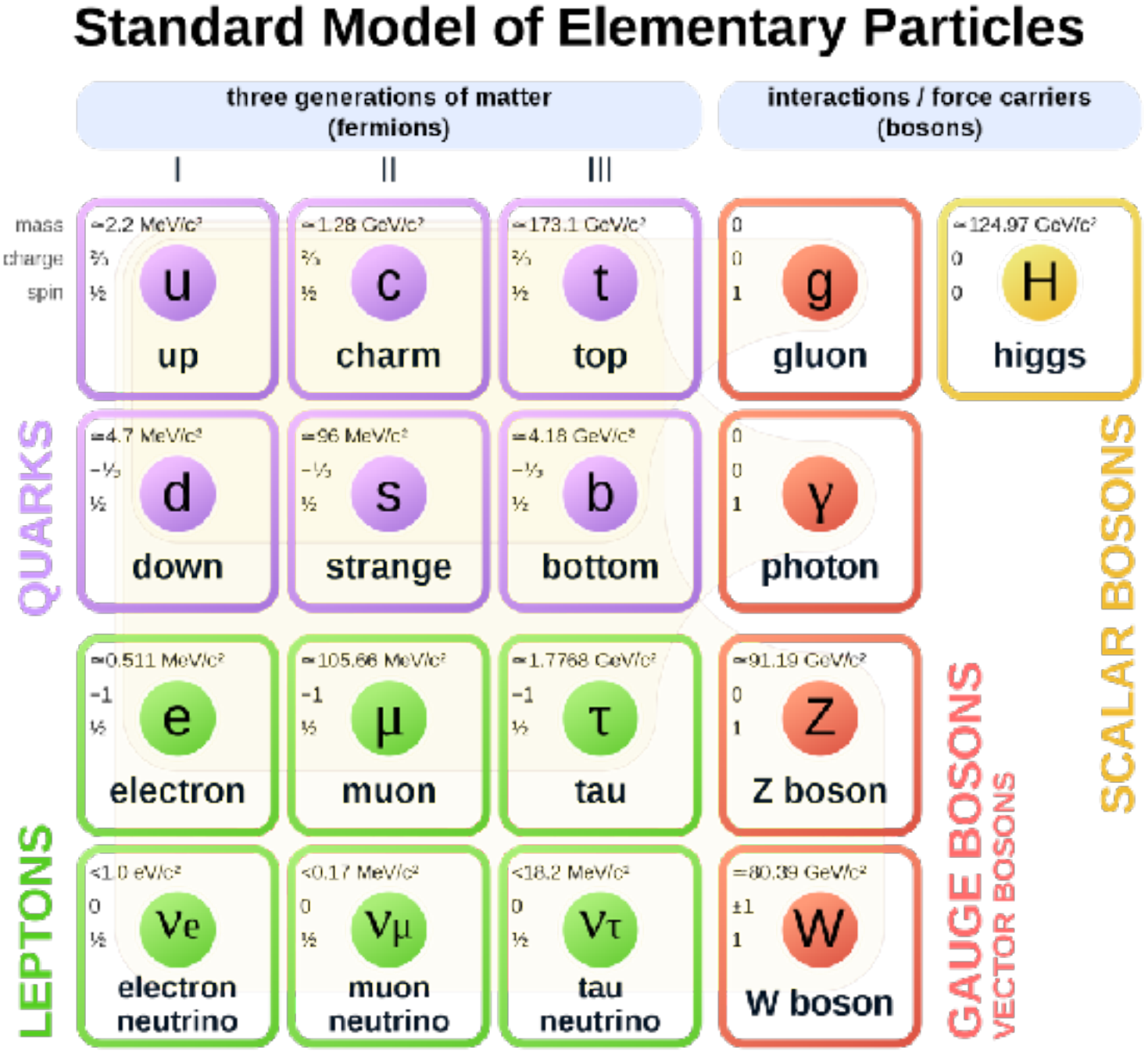
Na (sodium):
11 protons
12 neutrons



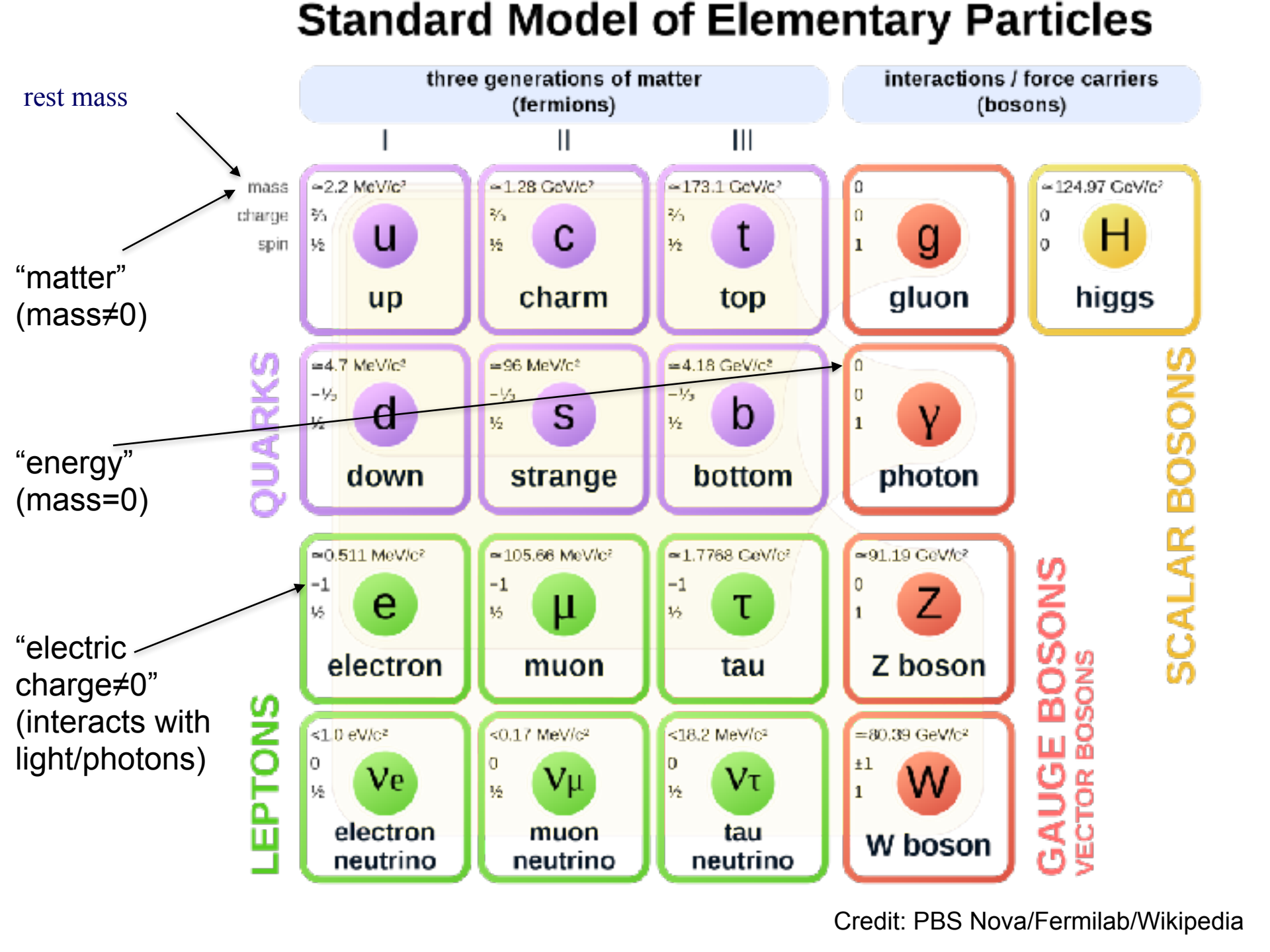
Heavier elements need neutrons

And their anti-particles!

Example: positron is same as electron, but with positive charge. They "annihilate" each other…



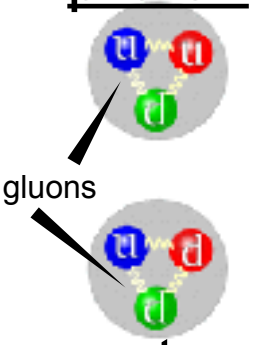
Credit: PBS Nova/Fermilab/Wikipedia



Credit: PBS Nova/Fermilab/Wikipedia

"**BARYONS**"
=3 quarks joined by gluons

<u>proton</u>



<u>neutron</u>

"matter"(mass≠0: "u"+"d" quarks+gluons

m_{proton}=938 MeV/c^2

"energy" (mass=0: photons, or "light")

Standard Model of Elementary Particles

three generations of matter (fermions)

interactions / force carriers (bosons)

I II III

mass
charge
spin

≈2.2 MeV/c²
⅔
½
u
up

≈4.7 MeV/c²
−⅓
½
d
down

≈0.511 MeV/c²
−1
½
e
electron

0
0
1
g
gluon

0
0
1
γ
photon

unstable

unstable

unstable

mass very small

QUARKS

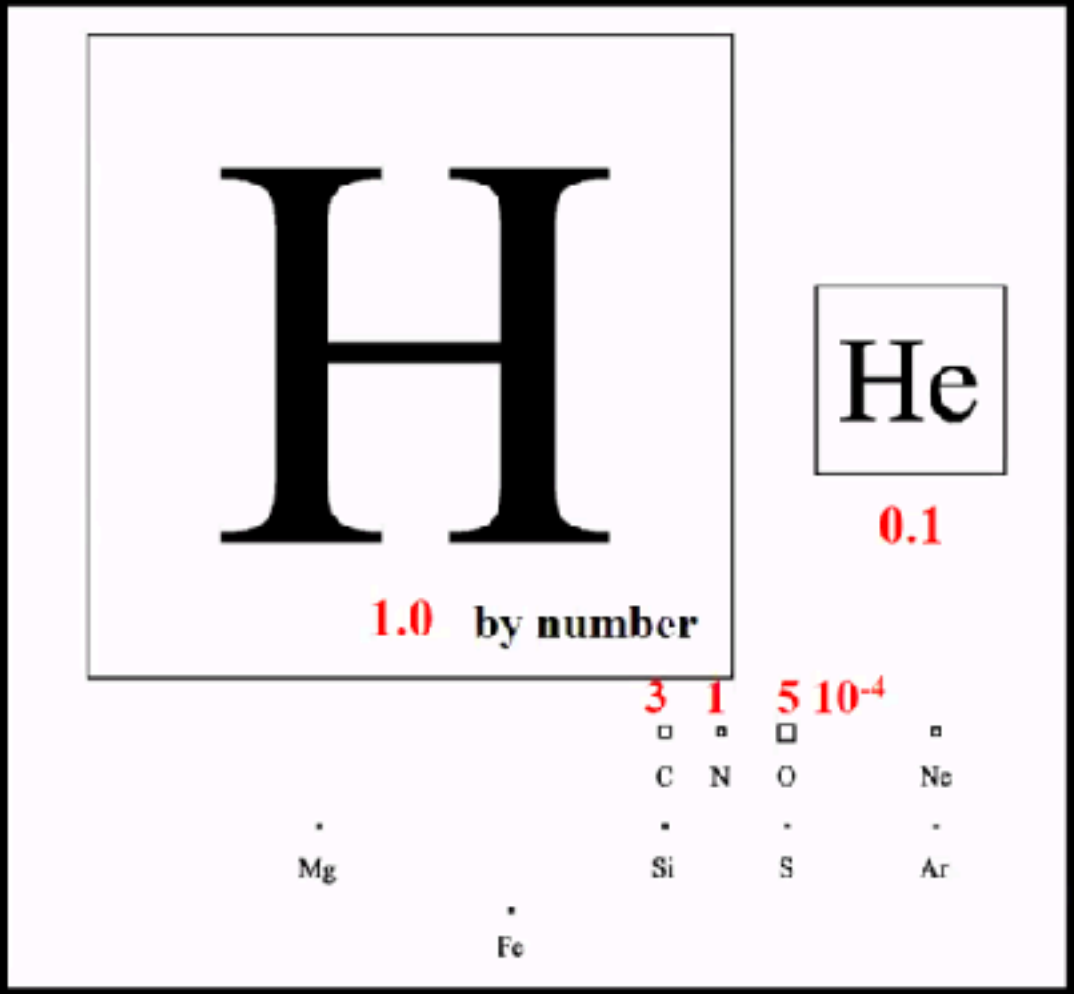
LEPTONS

GAUGE BOSONS
VECTOR BOSONS

SCALAR BOSONS

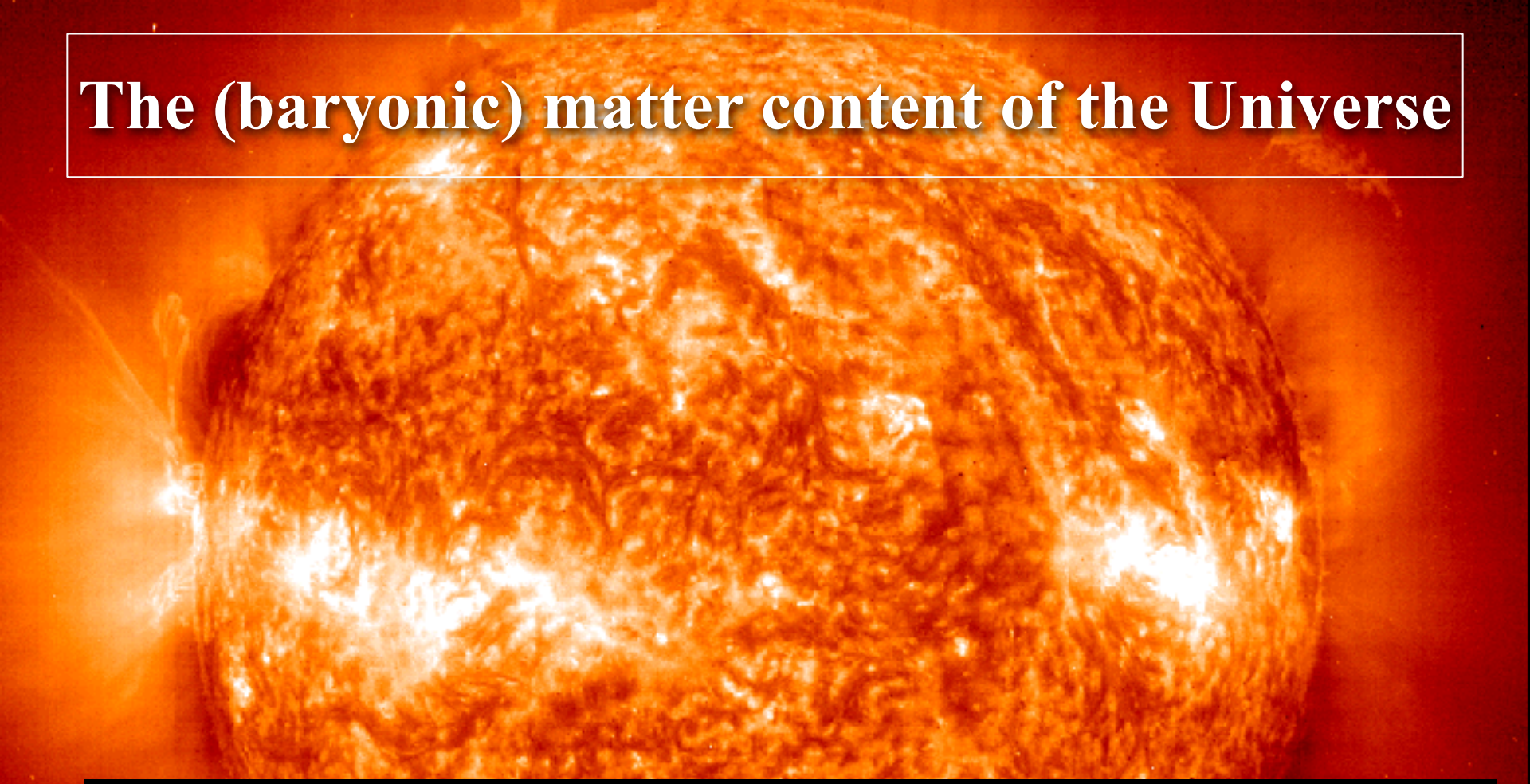
Credit: PBS Nova/Fermilab/Wikipedia

The astronomer's periodic table



- The Sun, like most stars, is a ball of Hydrogen and Helium
- Most atoms on Earth were synthesized in stars—we are "stardust" ("nuclear waste"?)

The (baryonic) matter content of the Universe



- In the Solar System, most of the mass is in the Sun
- The Sun, like most stars, is a ball of Hydrogen and Helium
- The light of a star is the result of the fusion of H and He into heavier nuclei
- Most atoms on Earth were synthesized in stars—we are "stardust" (or "nuclear waste"?)

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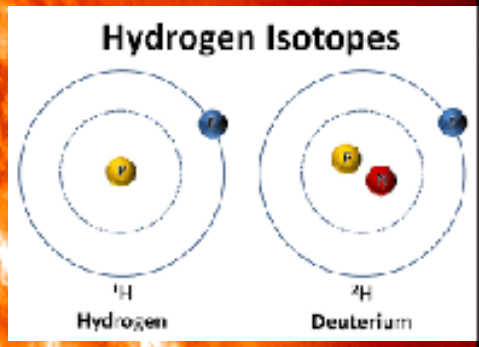
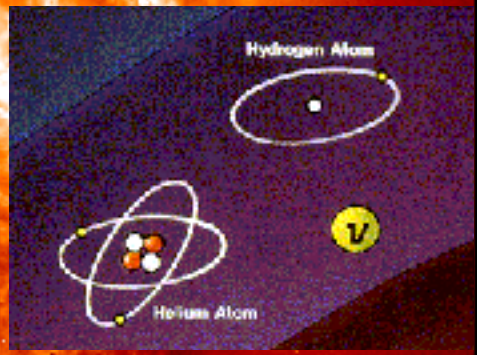
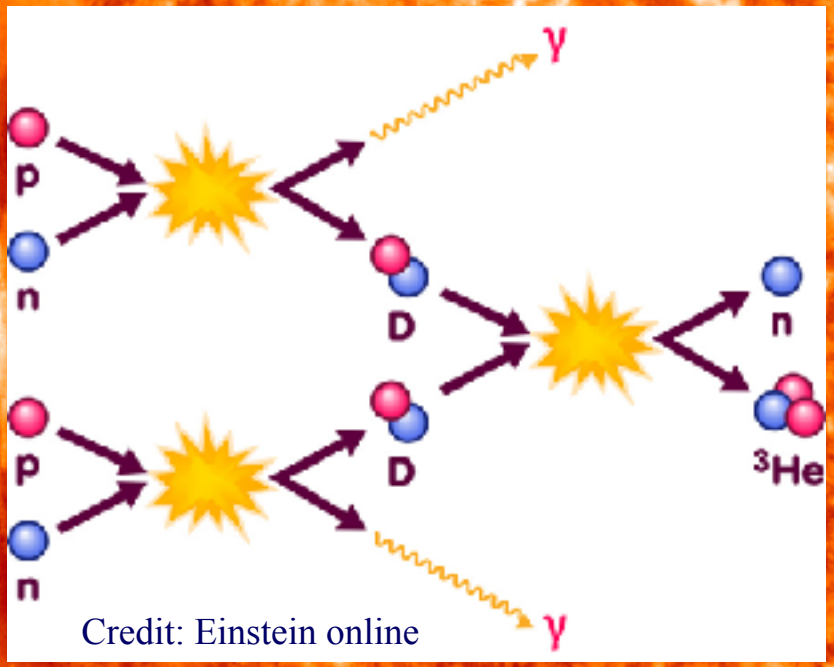


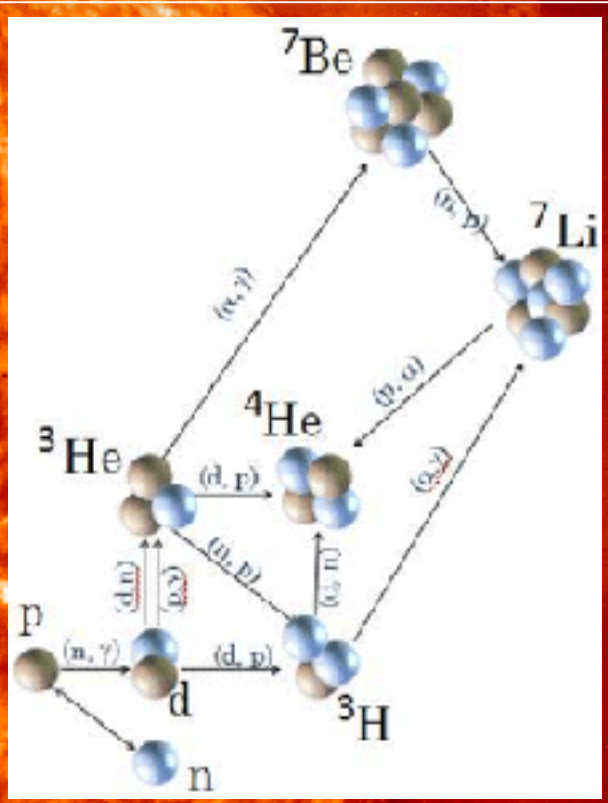


- Nuclear fusion only occurs in dense and hot regions, like the centre of a star
- Most of the observed Universe is Hydrogen and Helium
- Why, if the Universe was once hot and dense like a star?

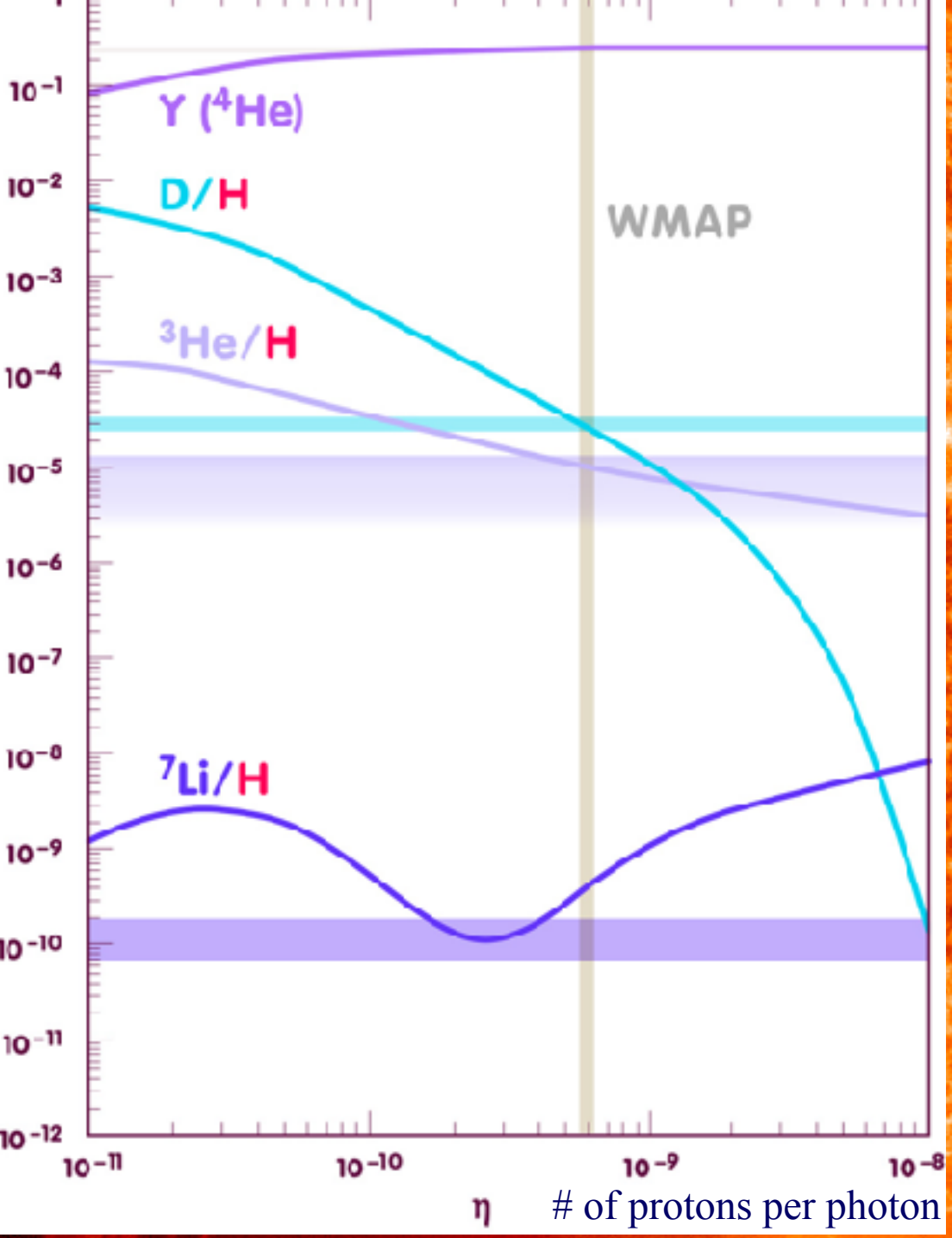
The (baryonic) matter content of the Universe



Credit: Einstein online



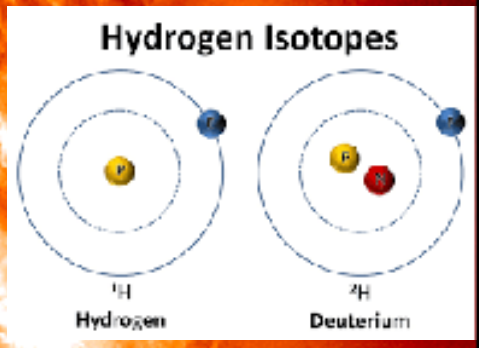
- The early Universe is too hot for heavy nuclei to exist: there were only neutrons, protons and light
- But the neutron (needed to form heavy nuclei) is unstable
- And deuterium (Hydrogen +neutron) is extremely fragile
- To not form heavy nuclei, the Universe must be full of light (>a billion photons per proton)

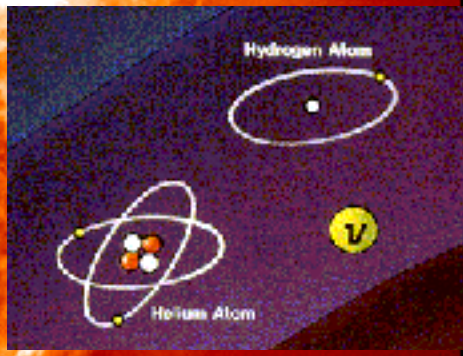


There must be light!

- The abundance of Helium (^{4}He), Deuterium (D), and other light elements allow us to measure the "matter/energy" ratio (baryons/light) of the Universe
- If we could measure the amount of light in the Universe, we could know the total amount of matter (baryonic)

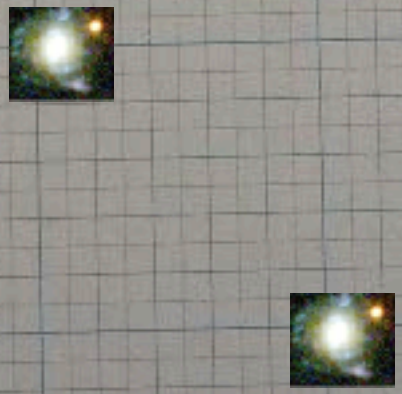
Where is that “cosmic light”?





The expansion of the Universe (backwards in time)

- The galaxy "grid" does not change as the Universe expands
- We can visualize the Universe as "static grid" where the density at each point increases as we go back in time
- Looking back in time, the Universe contracts and every point becomes denser and hotter



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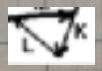
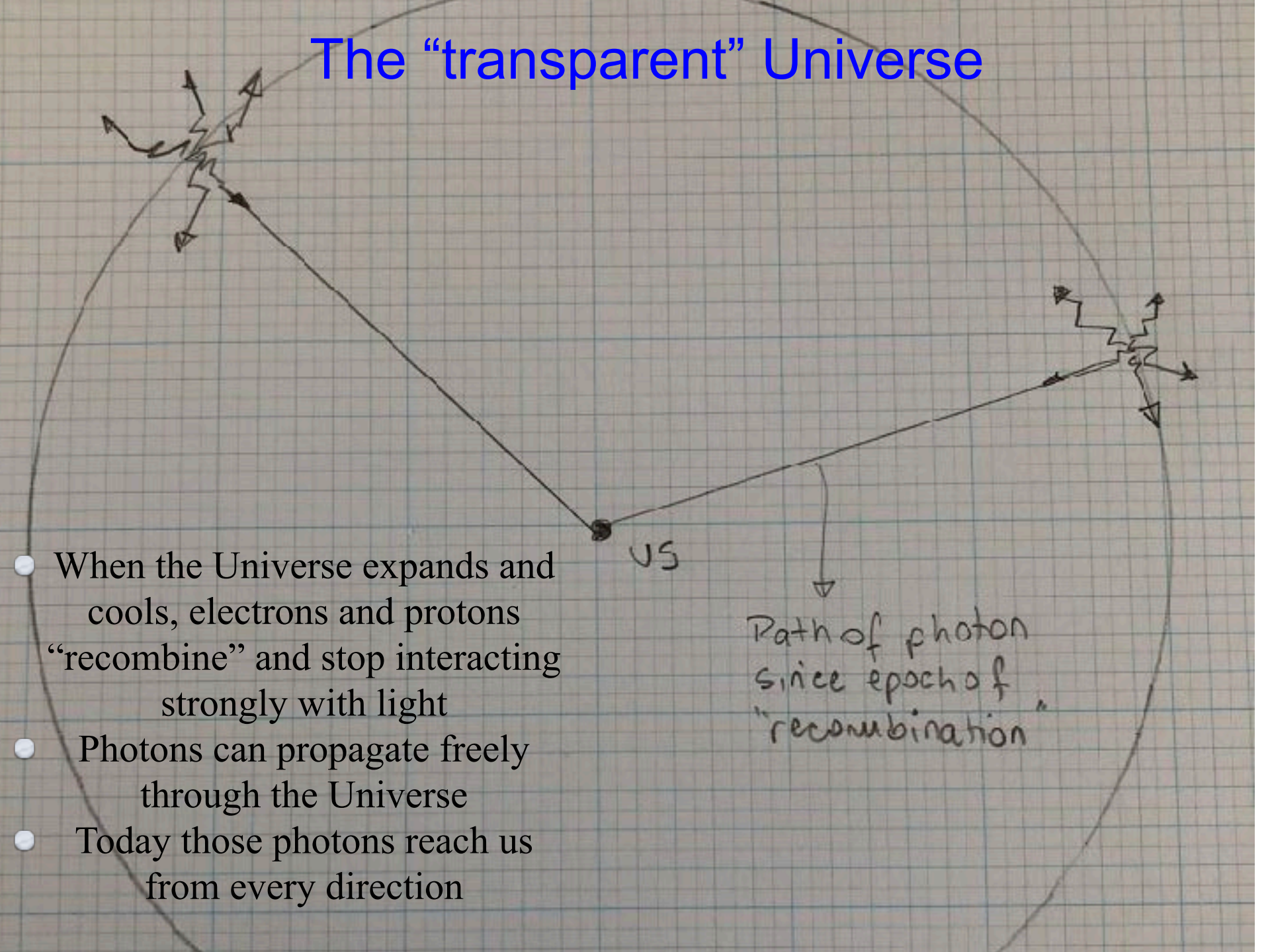
The “opaque” Universe

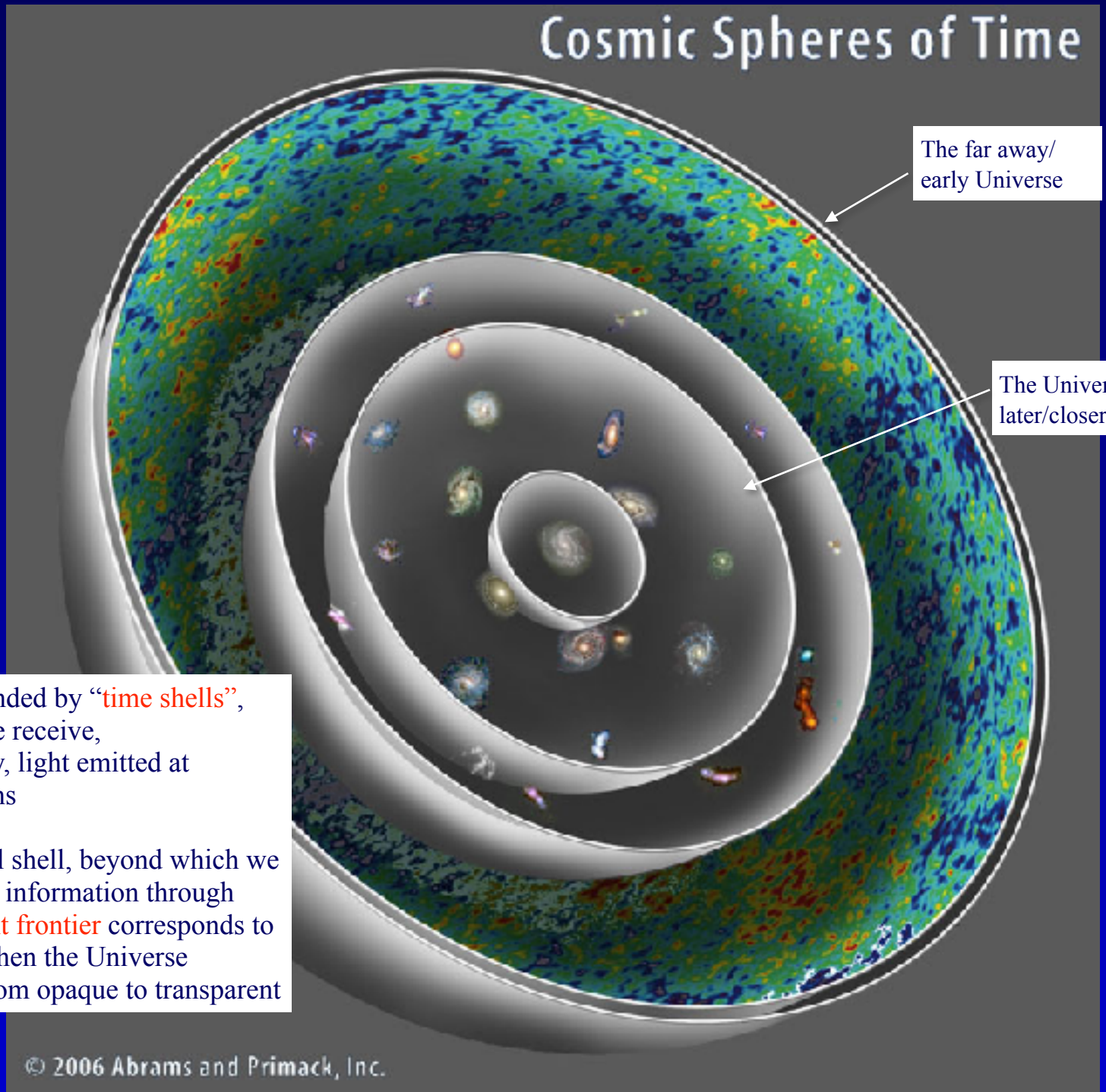
- At some point the Universe becomes so hot that electrons cannot remain attached to protons
- Free electrons interact with light and do not allow light to propagate freely. The early Universe is opaque, like a dense fog
- Photons cannot travel far from where they are



The “transparent” Universe



- When the Universe expands and cools, electrons and protons “recombine” and stop interacting strongly with light
- Photons can propagate freely through the Universe
- Today those photons reach us from every direction

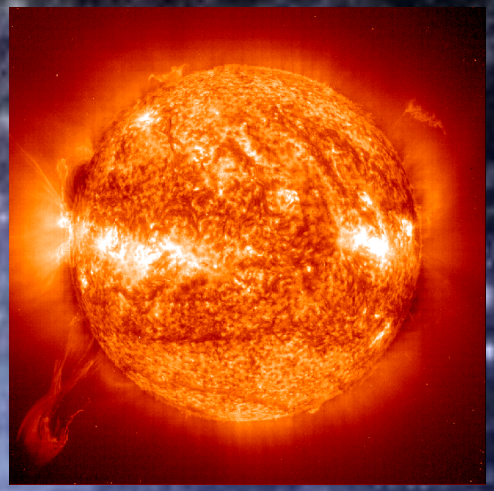


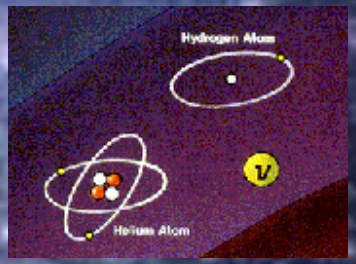
We are surrounded by "time shells", from which we receive, simultaneously, light emitted at different epochs

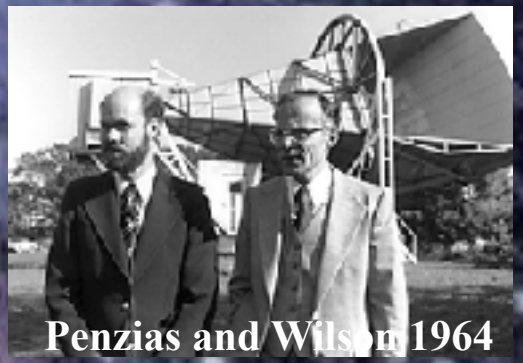
There is a final shell, beyond which we cannot receive information through light. This light frontier corresponds to the moment when the Universe transitioned from opaque to transparent

Summary of Basic Cosmological Facts

- The Universe expands
  - The Universe was once hotter and denser
  - There was a beginning of time: the Big Bang
- Most of the matter we see is hydrogen
  - Elements heavier than He are synthesized in stars
  - The Universe must be filled of light: the Cosmic Microwave Background
  - The Universe became opaque in the not too distant past



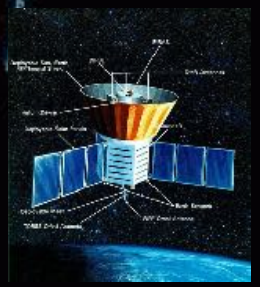




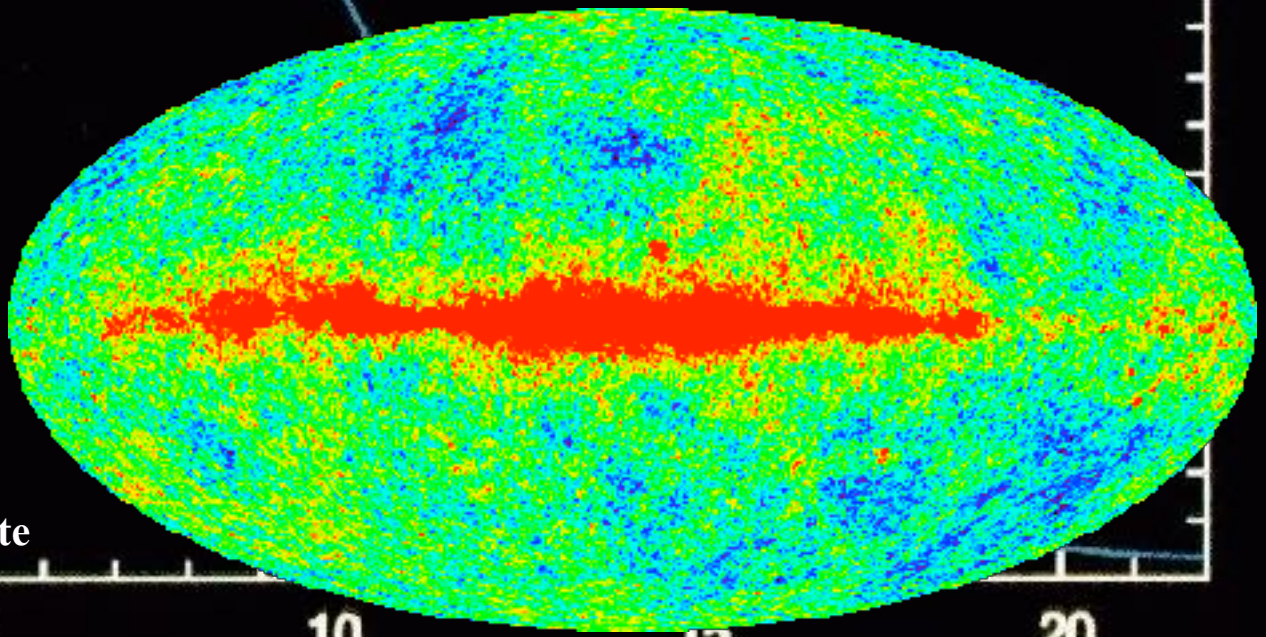
The Temperature of the Cosmic Microwave Background

A Planck function:

- the universe was once in thermal equilibrium
- Allows us to compute the number of photons in the Universe, and to infer from that its total baryonic mass.



The COBE satellite



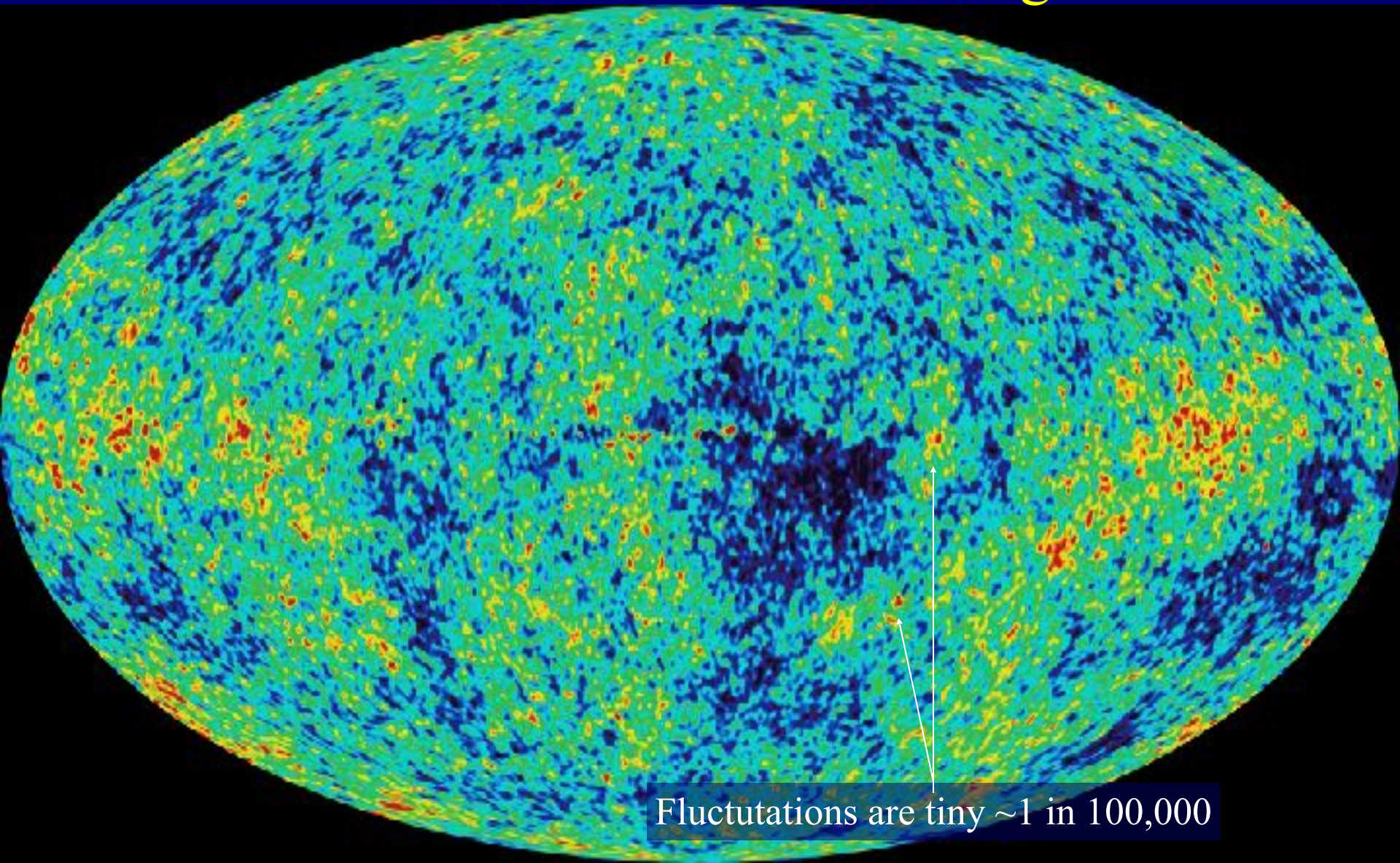
Intensity, 10^{-4} ergs / cm^2 sr sec cm^{-1}

1.2
1.0
0.8
0.6
0.4
0.2
0.0

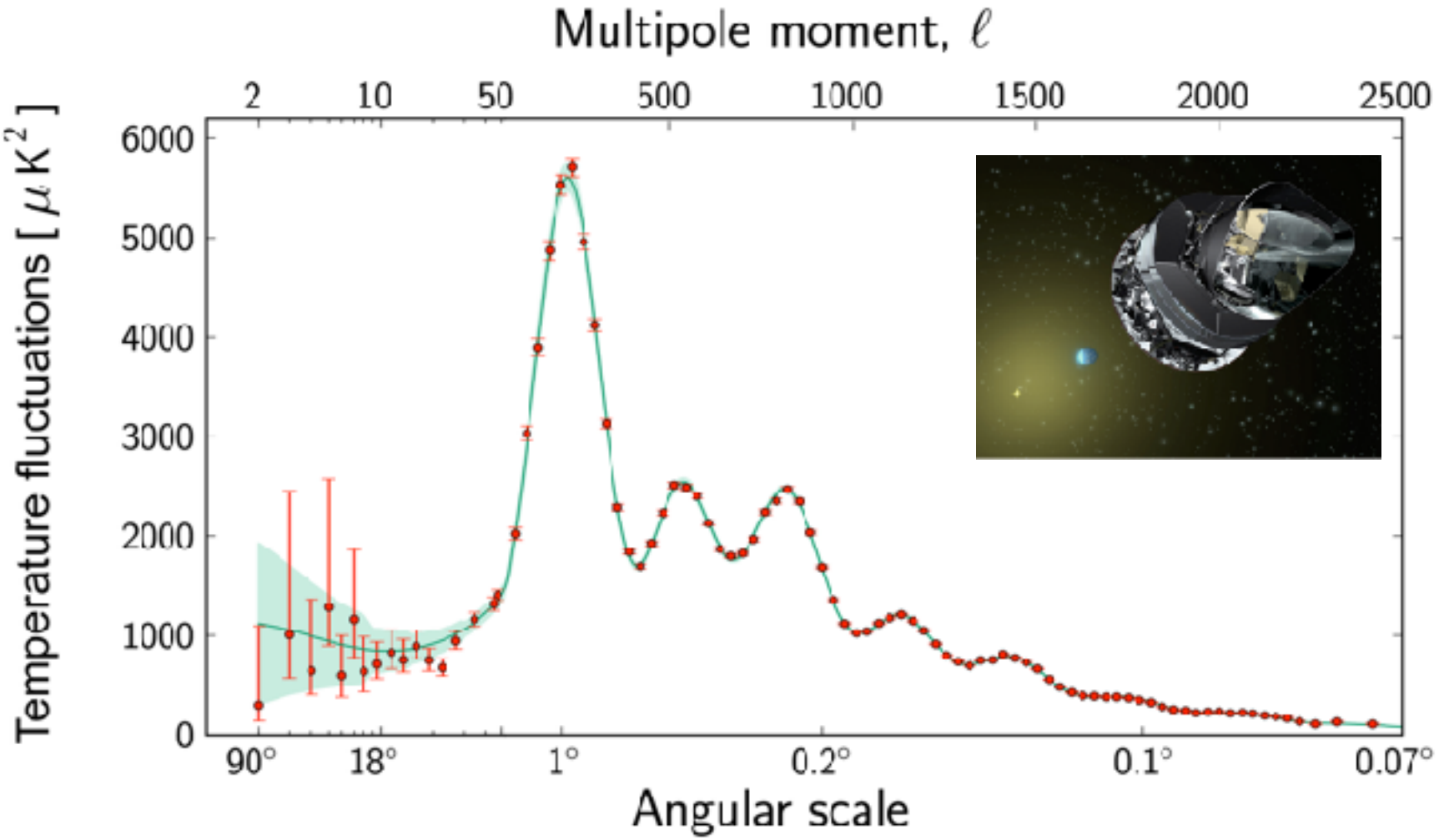
0
5
10
15
20

Waves / centimeter

WMAP Temperature Fluctuations in the Cosmic Microwave Background



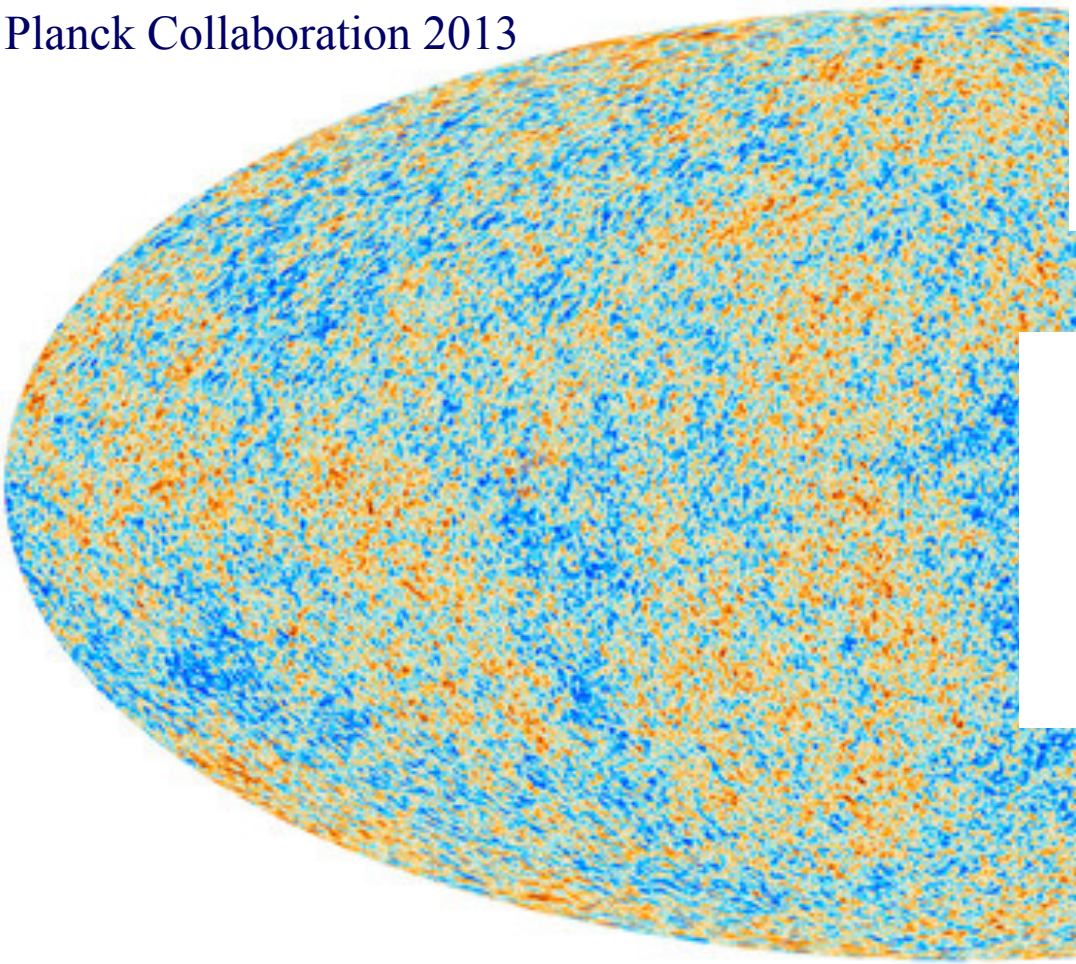
The Standard Model of Cosmology

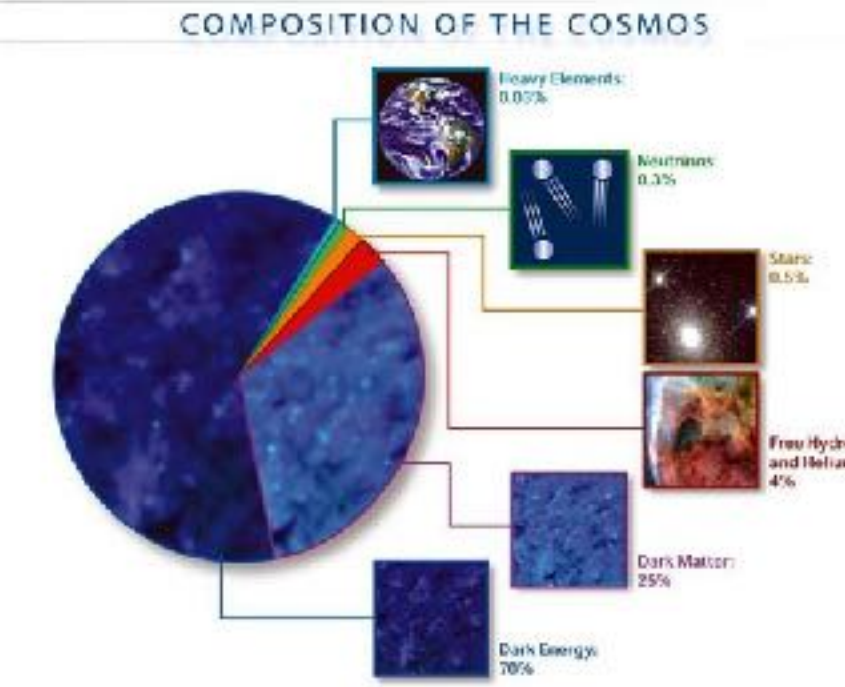


The Planck mission

The Standard Model of Cosmology

Planck Collaboration 2013



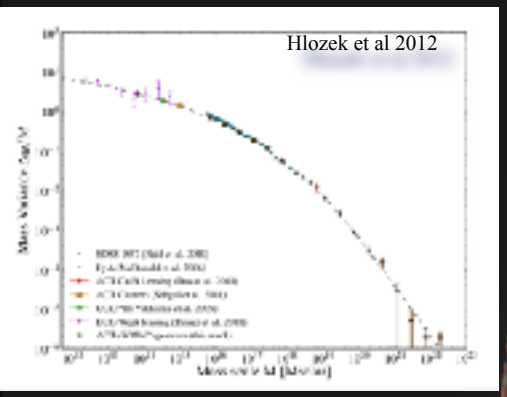


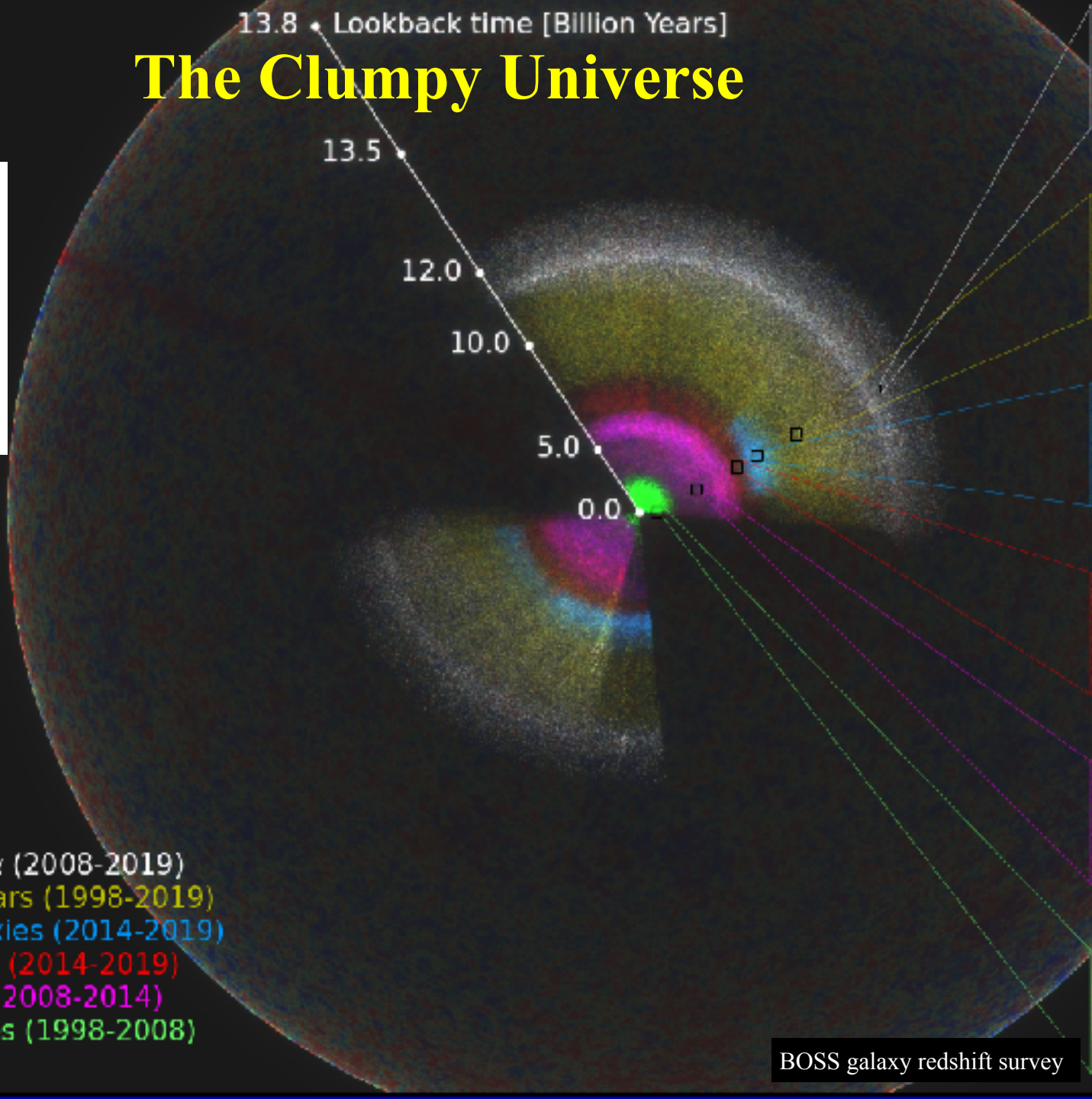
This is a universe that we can simulate!

Parameter	Best fit	68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073

SDSS

The Clumpy Universe





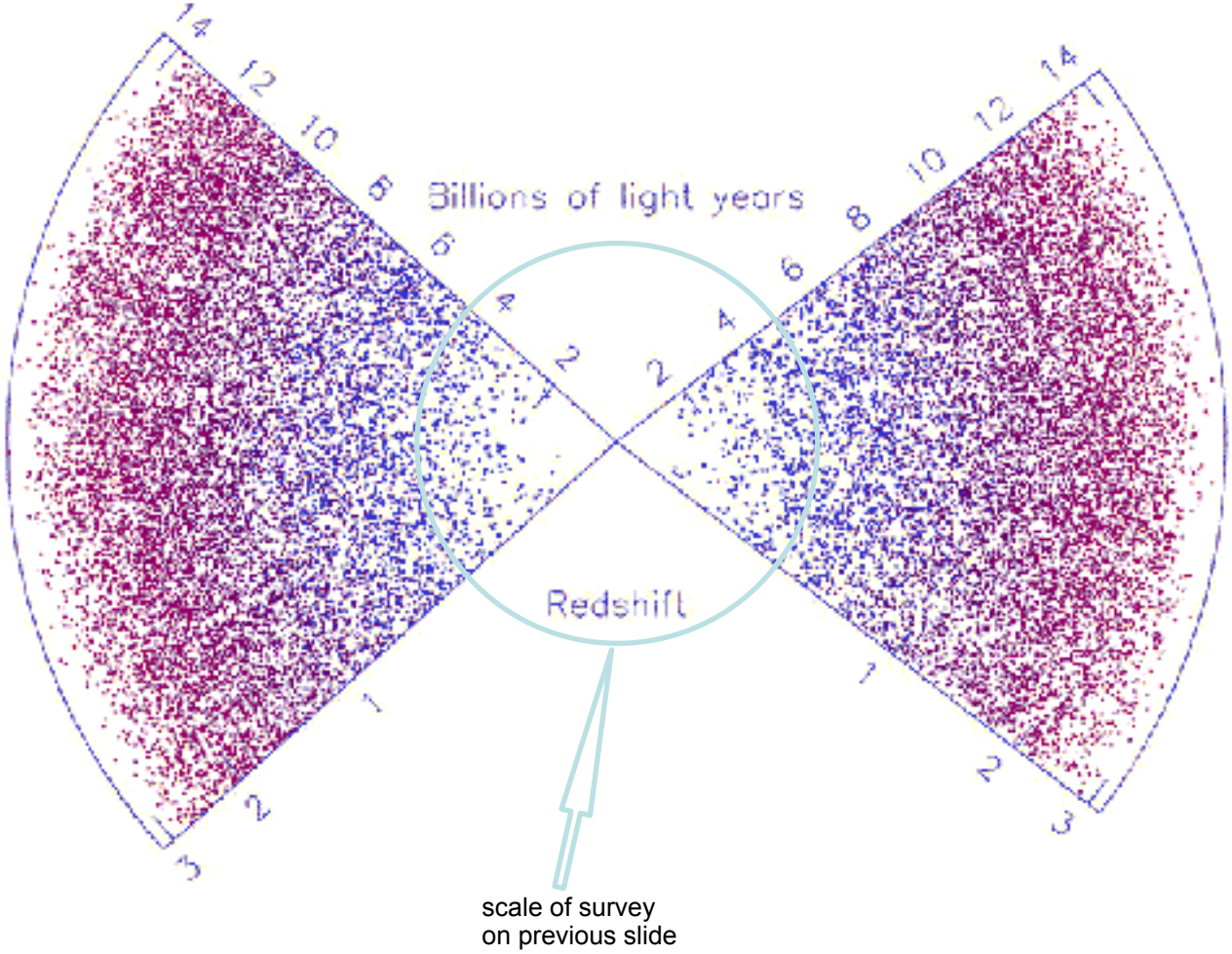
eBOSS + BOSS Lyman-α (2008-2019)
eBOSS + SDSS I-II Quasars (1998-2019)
eBOSS Young Blue Galaxies (2014-2019)
eBOSS Old Red Galaxies (2014-2019)
BOSS Old Red Galaxies (2008-2014)
SDSS I-II Nearby Galaxies (1998-2008)

BOSS galaxy redshift survey

The Clumpy Universe on large scales

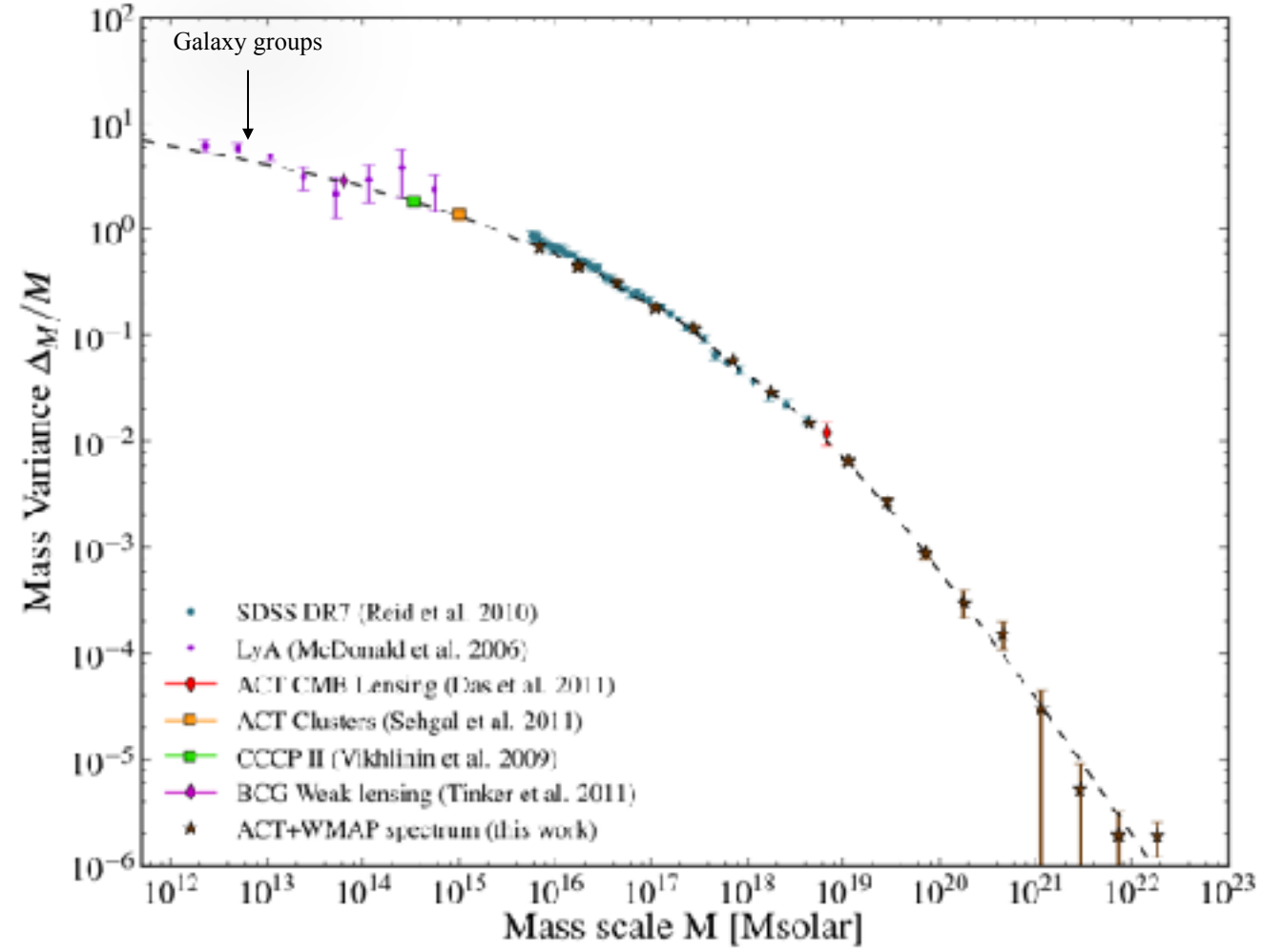
On large scales the Universe appears homogeneous and isotropic

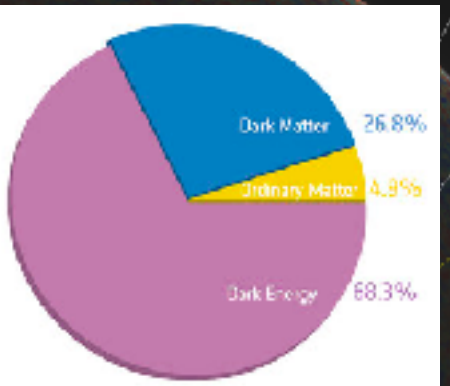
Quasar distribution on large scales from redshift surveys



The Universe is close to homogeneous and isotropic

The Clumpiness of the Universe as a function of scale



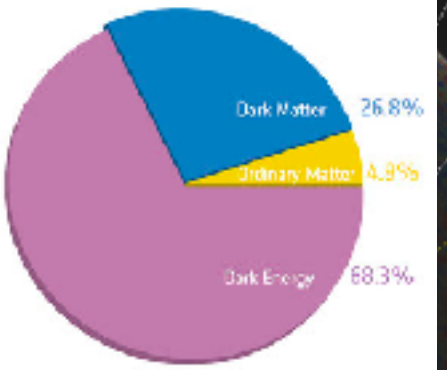


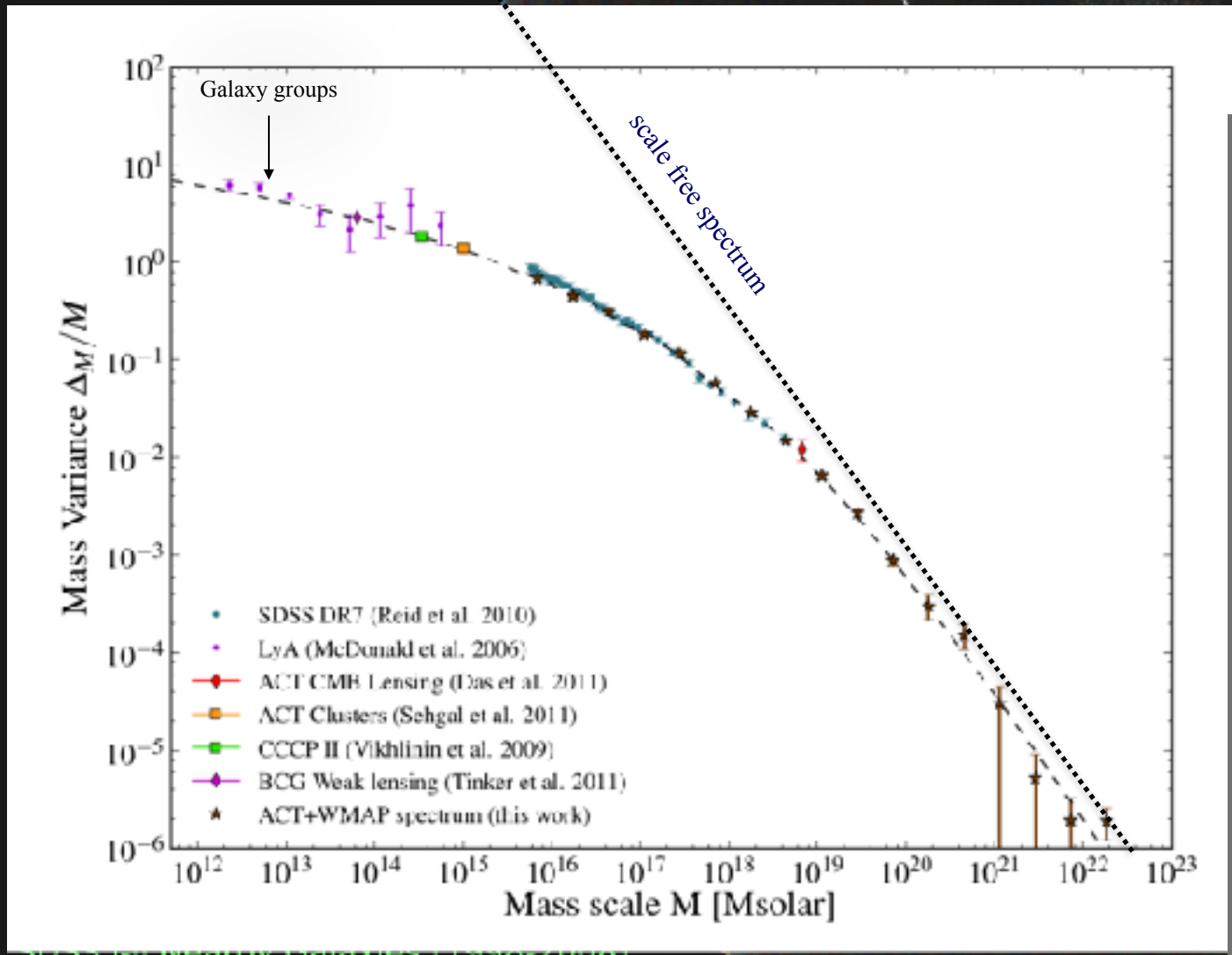
The power spectrum of density fluctuations over a wide range of scales is very well measured at various redshifts

Measurements on various scales trace a smooth curve if the Universal expansion started to accelerate in "recent" cosmological times

Hlozek et al 2012

The LCDM paradigm: Structure in the Universe in the Linear Regime





Hlozek et al 2012

The power spectrum of density fluctuations in the linear regime is very well matched by assuming that the initial density fluctuations are Gaussian and "scale free" and that the Universe is dominated by collisionless **Cold Dark Matter (CDM)**

This represents astonishing success!

End of Lecture 1