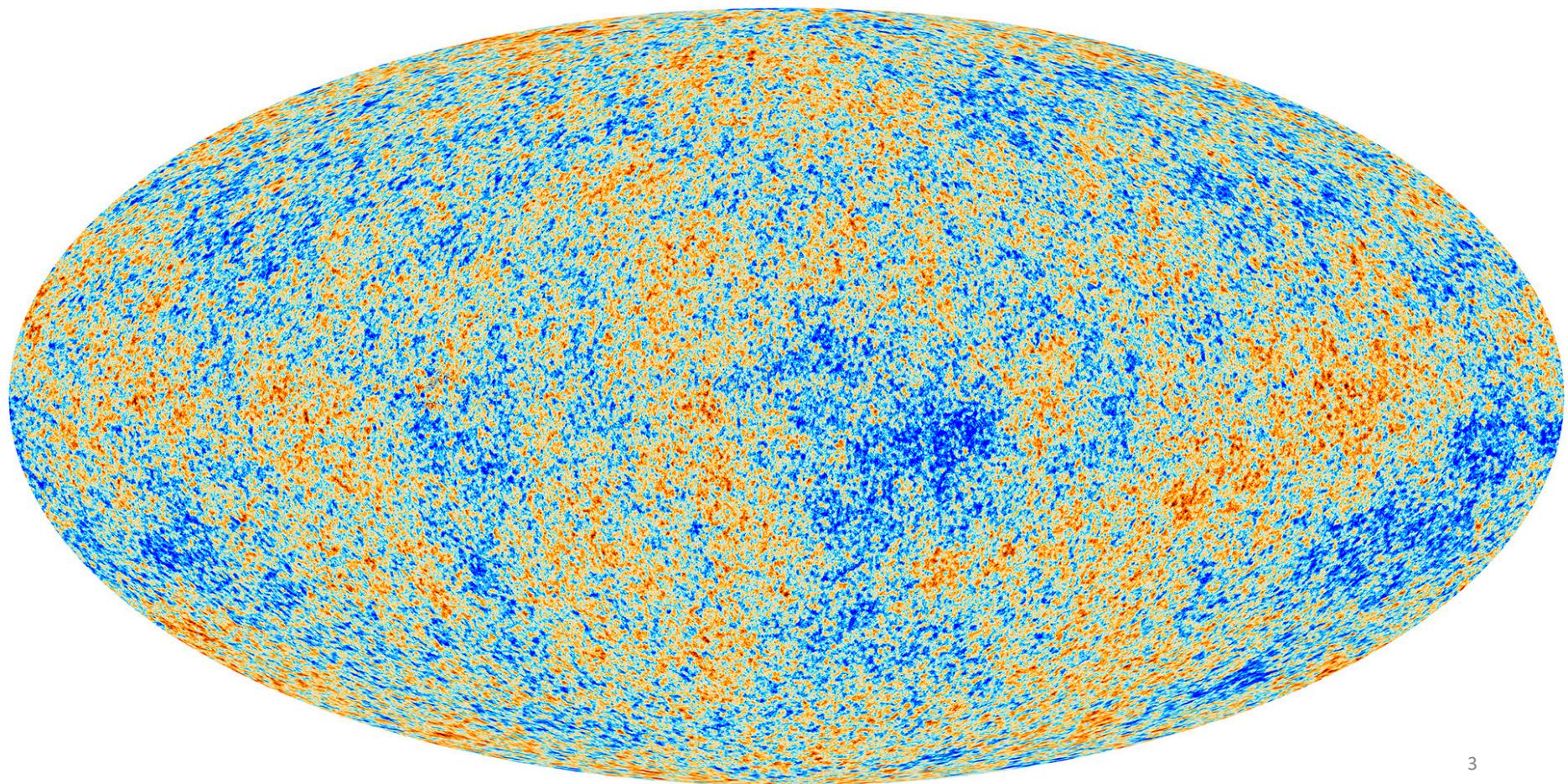
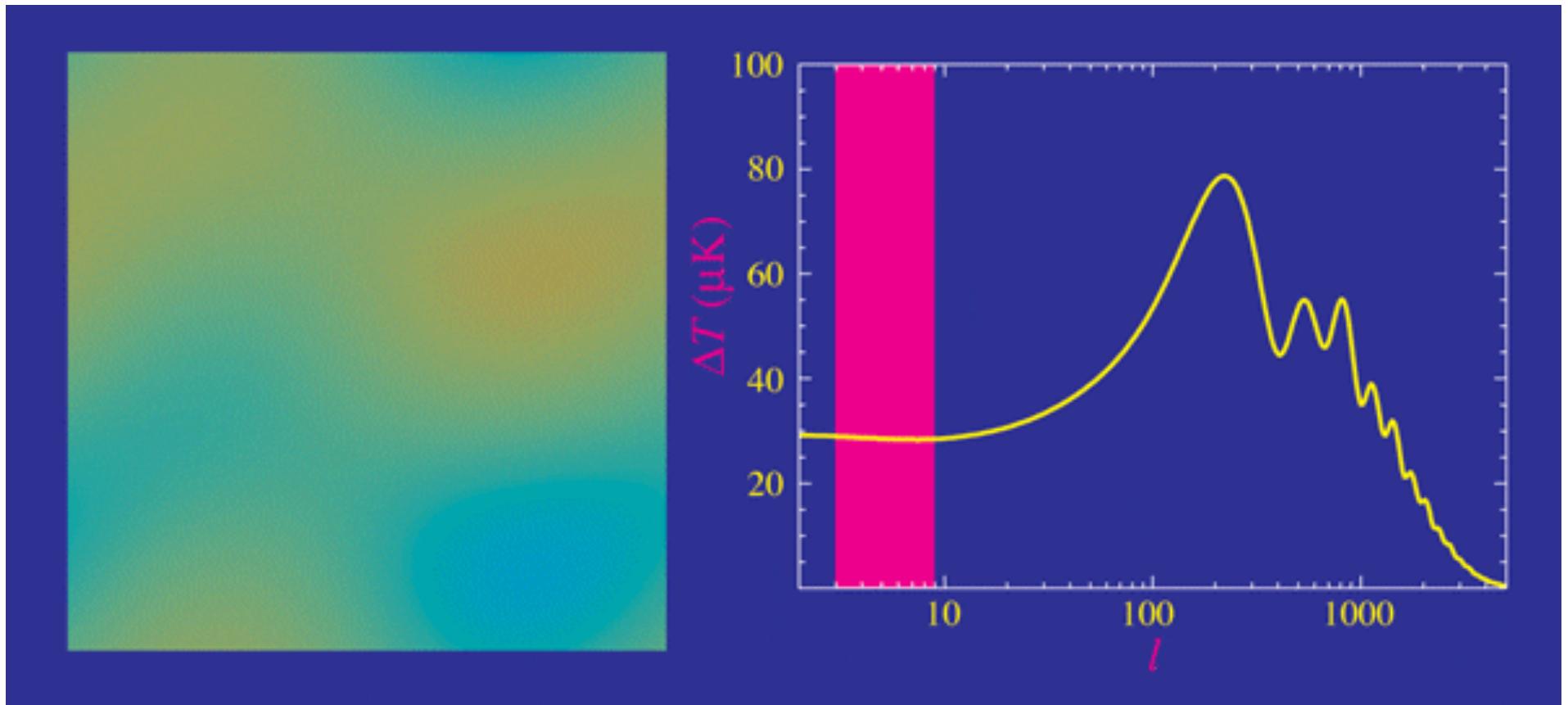


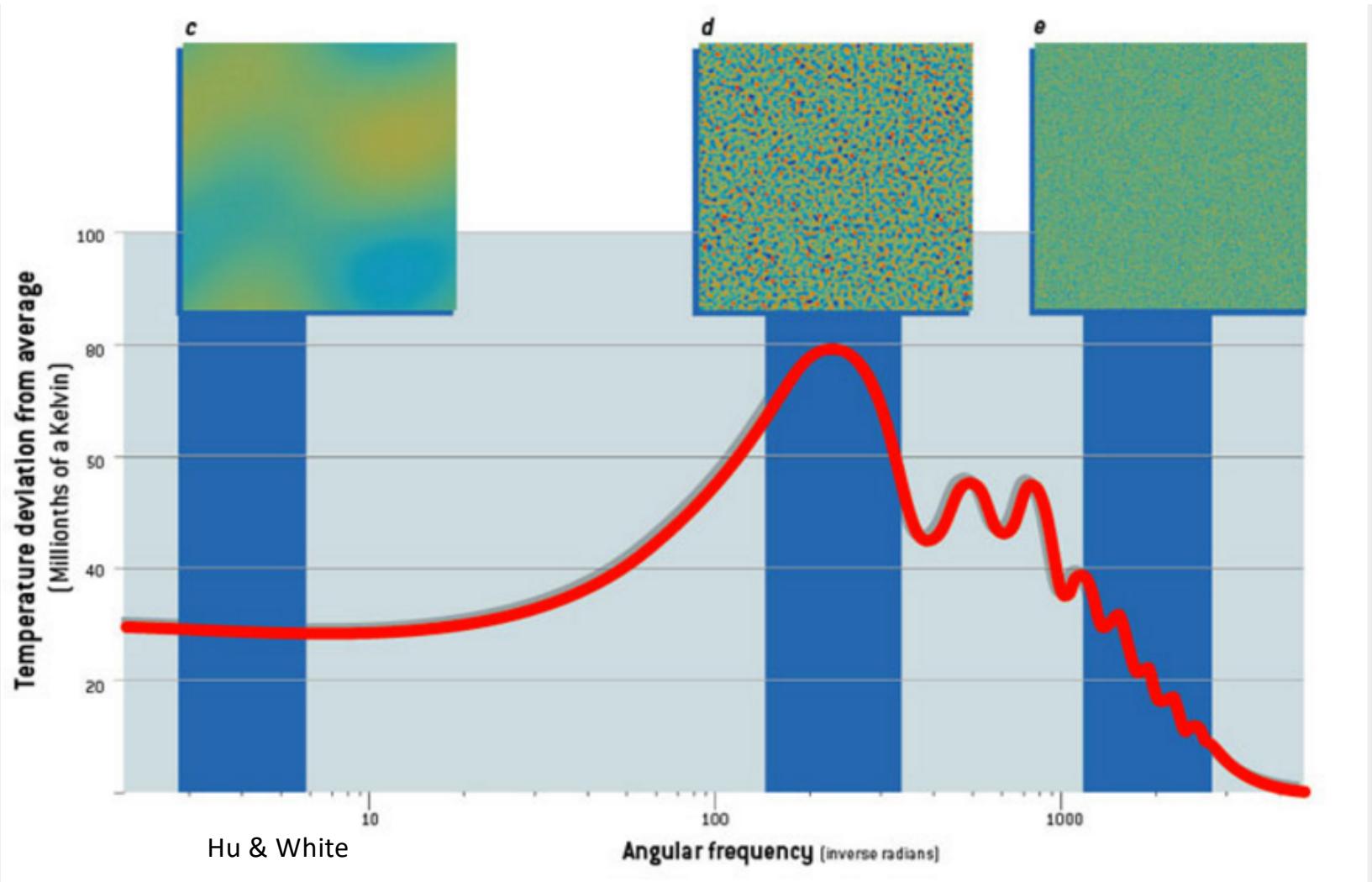
PLANCK 2015

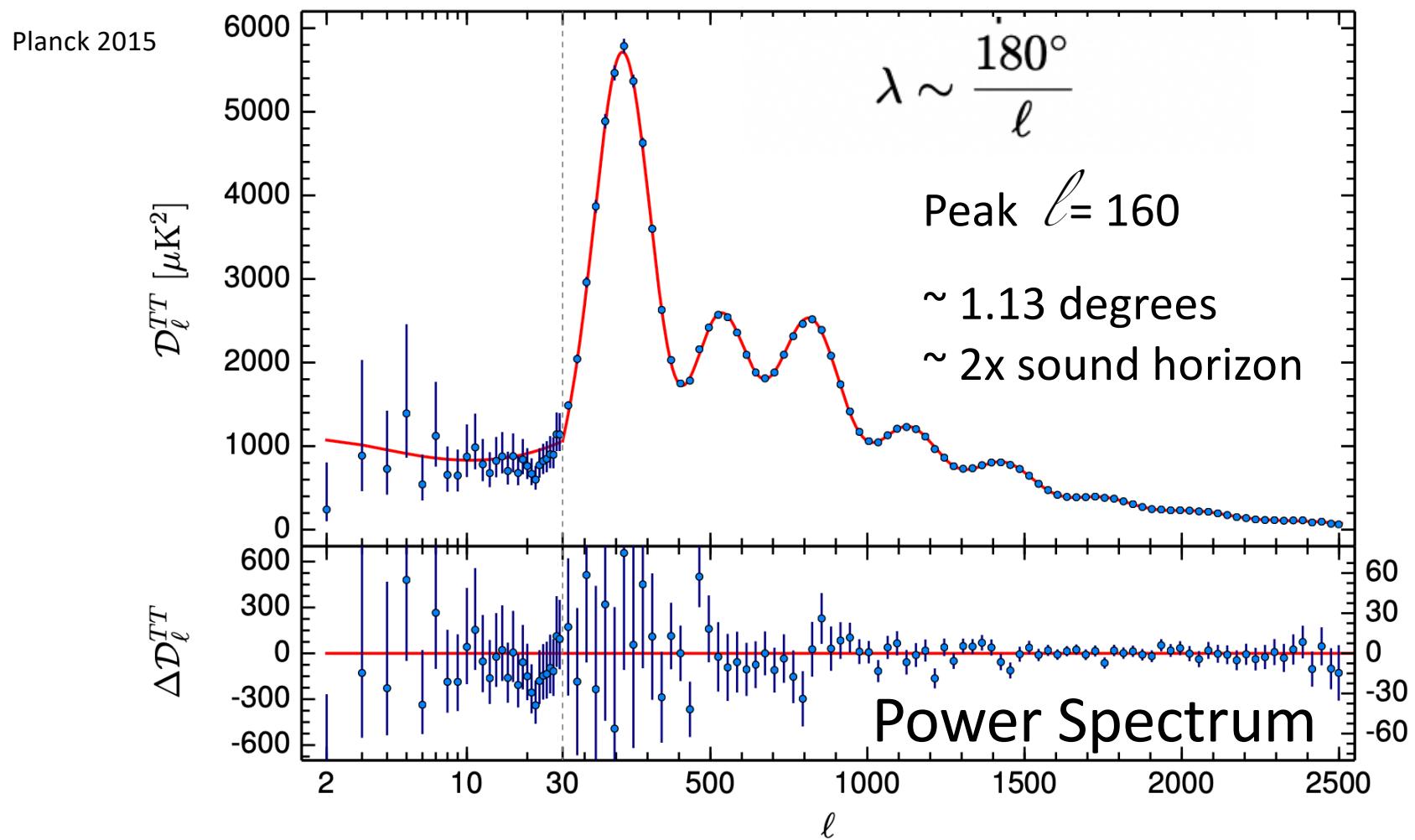


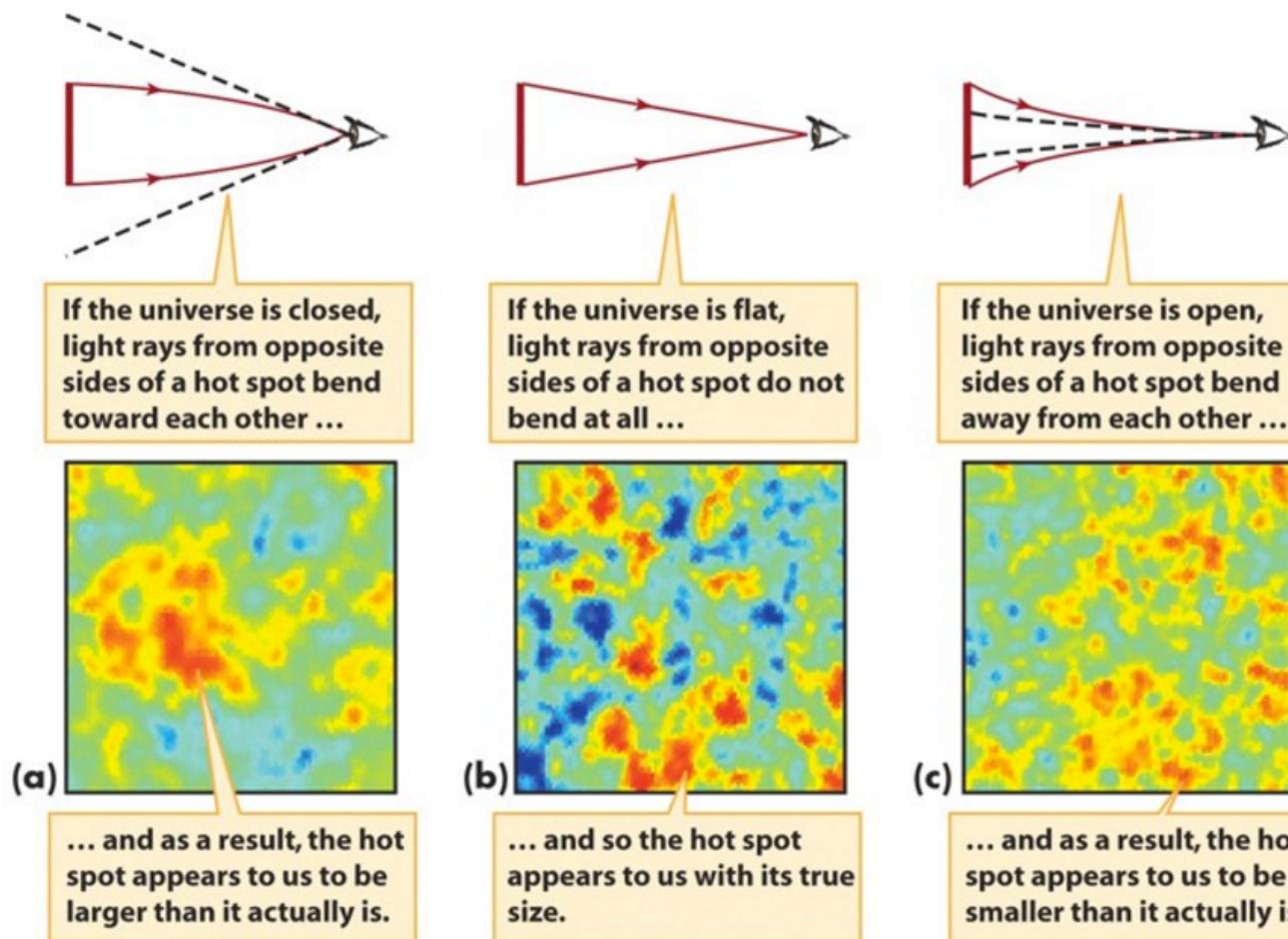


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<http://background.uchicago.edu/~whu/metaanim.html>

Power Spectrum







Curvature changes the angular size of the peaks

Curvature

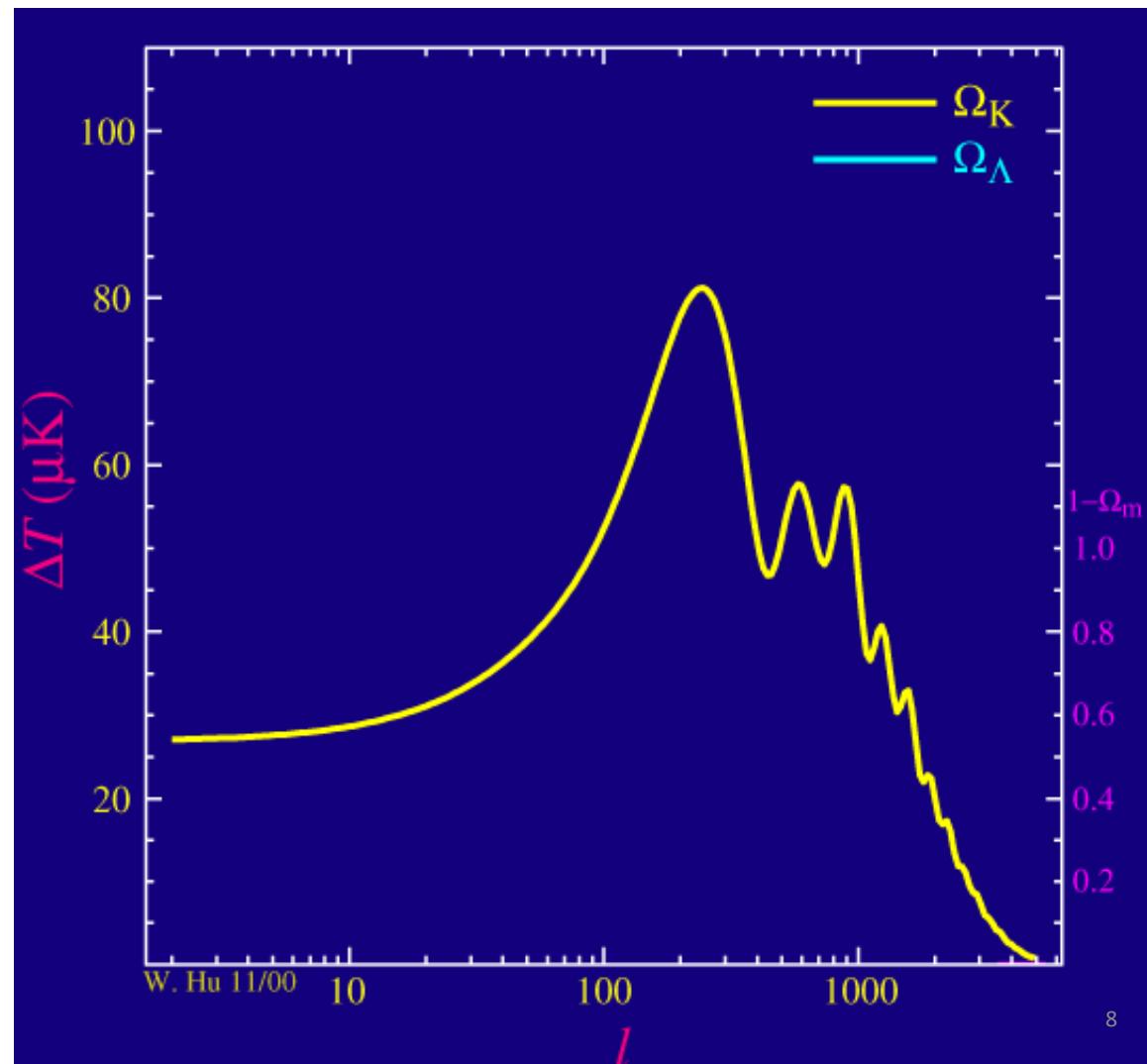
Location of the first peak tells us that

Curvature is flat

$$1 - \Omega_0 = \Omega_k = 0$$

(a flat universe is also expected from inflation)

Wayne Hu's Cosmology Tutorial



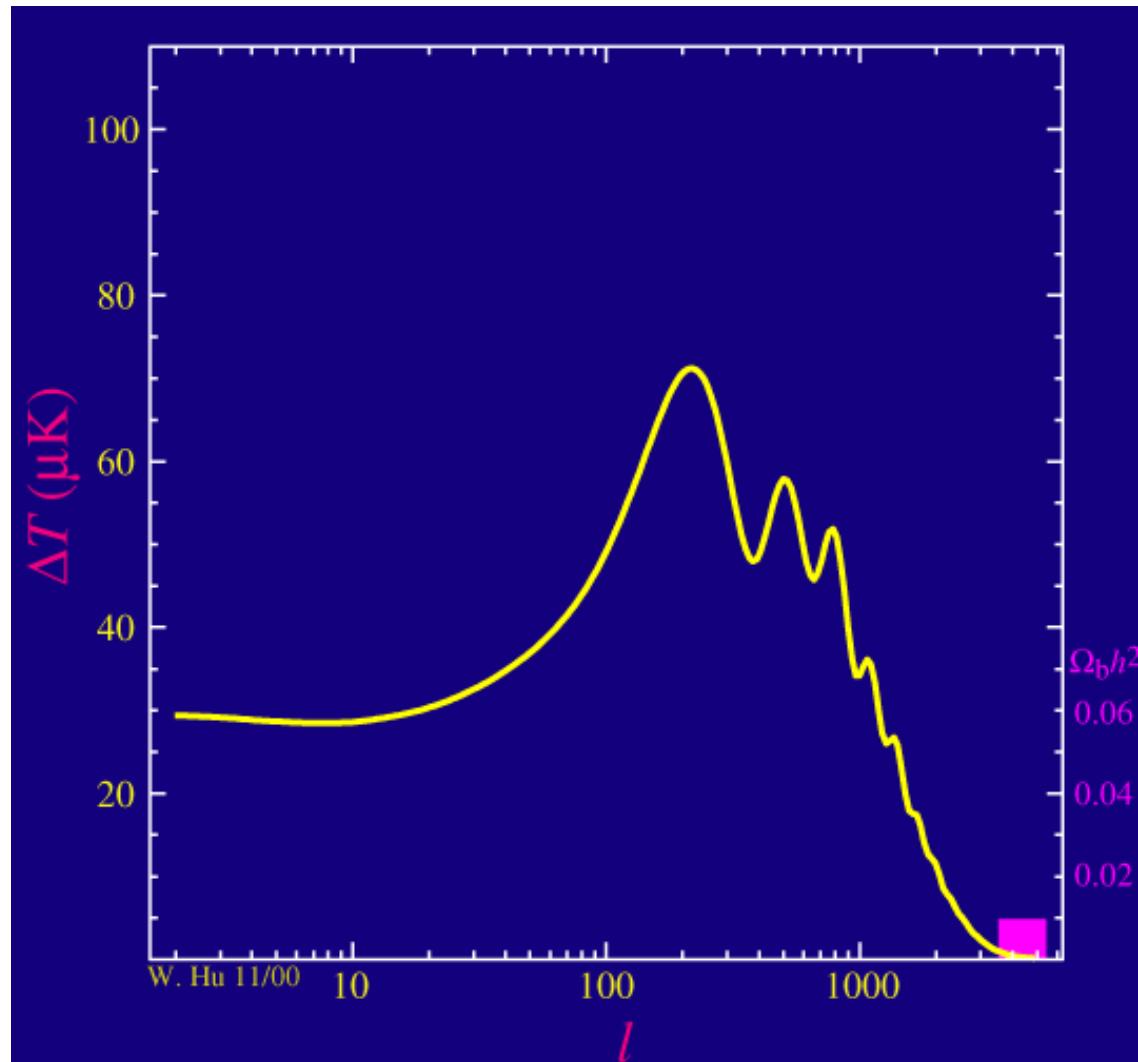
Baryon Density

$$\Omega_b h^2 \quad \rho_b / \rho_{\text{crit}}$$

$$0.02226 \pm 0.00023$$

The ratio of the observed even and odd peaks constrains the amount of normal matter in the universe.

The fact that the third peak is not much lower than the 2nd is good evidence that the baryon fraction must be low (i.e. that dark matter exists).



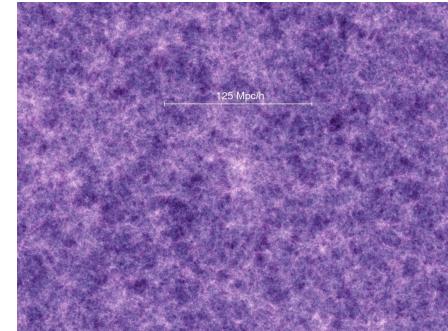
Acoustic Oscillations

Baryon-photon fluid falls into overdensities, heating up.

This increases radiation pressure, causing fluid to expand (rarefaction wave).

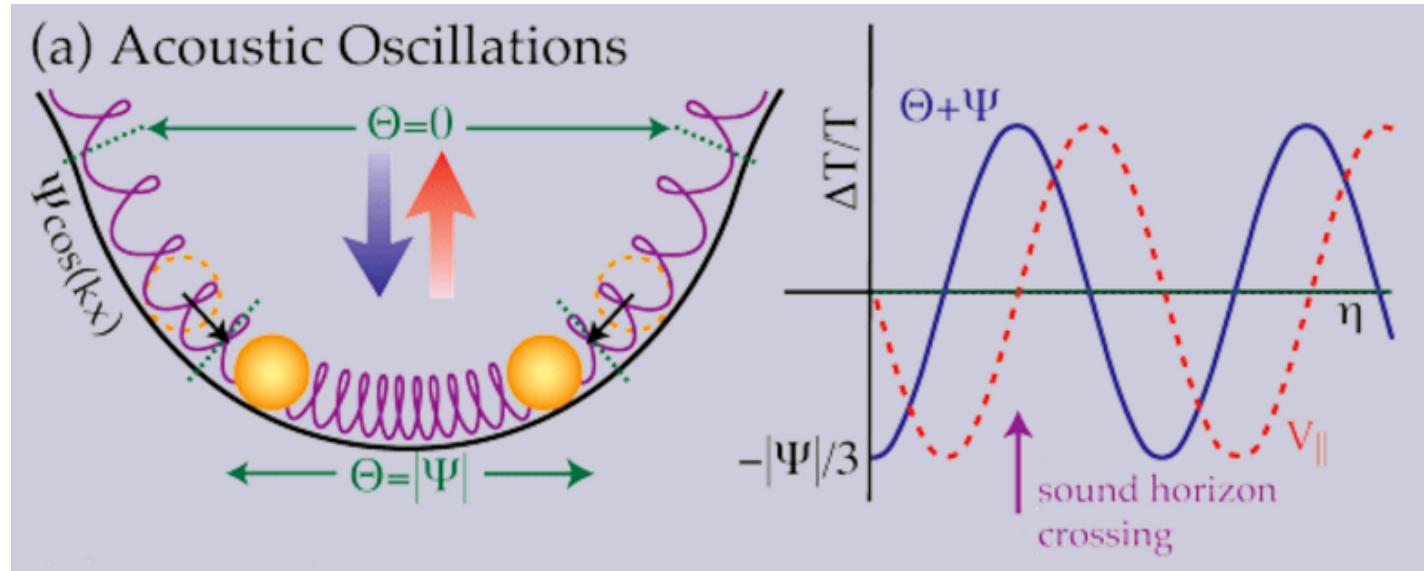
The fluid then cools and gravity wins again.

The fluid falls back into an overdensity and heat up.



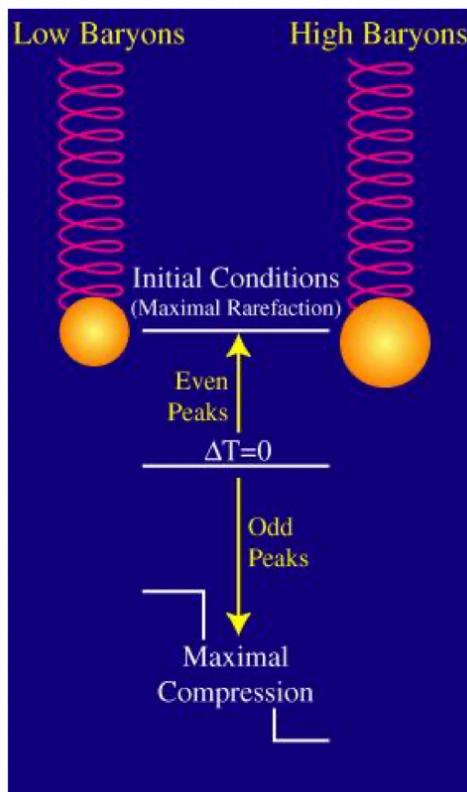
Called “acoustic oscillations”. The typical scale of these oscillations is the sound horizon distance.

At recombination, these oscillations “freeze” - if caught in a compressed state, it will give rise to a hot spot. else, cold spot.

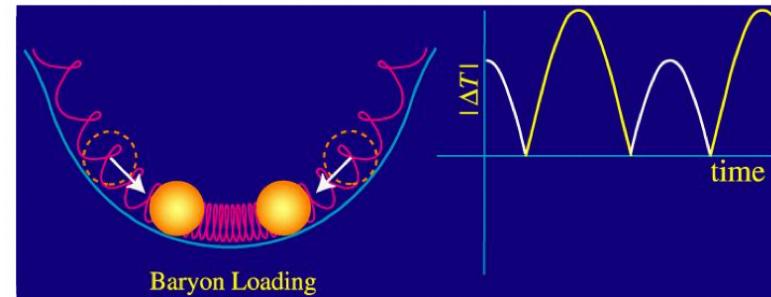


Constraining Baryon Density

More baryons increases the load



Increased load, adds to the potential at compression.
Compressions become stronger than Decompressions.



First and third peaks become stronger than the second and fourth,
depending on the load

(Remember dark matter won't do this – can't compress it!)

Courtesy Hans Eriksen

Total Matter Density

Impacts the amplitude of the first peak

$$\Omega_m h^2 \quad 0.09591 \pm 0.00045$$

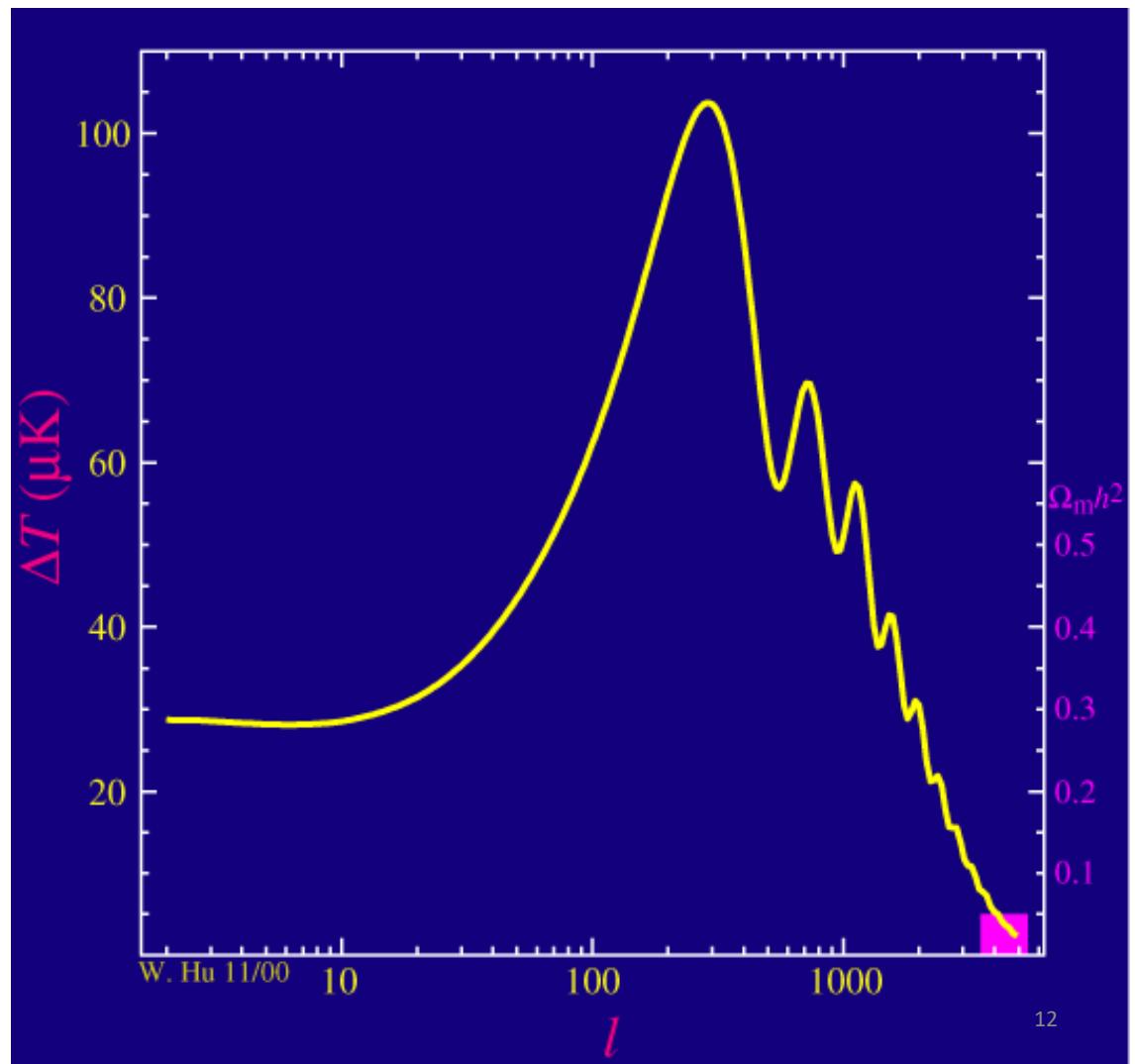
$$\Omega_m \quad 0.308 \pm 0.012$$

Therefore:

$$\frac{\Omega_b h^2}{\Omega_m h^2} = 0.157 \rightarrow \sim 16\%$$

$$\Omega_\Lambda \quad 0.692 \pm 0.012$$

Wayne Hu's Cosmology Tutorial



Benchmark Cosmology

$$\Omega_{m0} = 0.308 \pm 0.012 \quad \Omega_{\Lambda0} = 0.692 \pm 0.012 \quad \Omega_{\text{rad}0} = 8.24 \times 10^{-5} \quad H_o = 67.81 \pm 0.92$$

Energy density of the universe is currently 30% matter (16% of which is baryons) and 70% Dark Energy

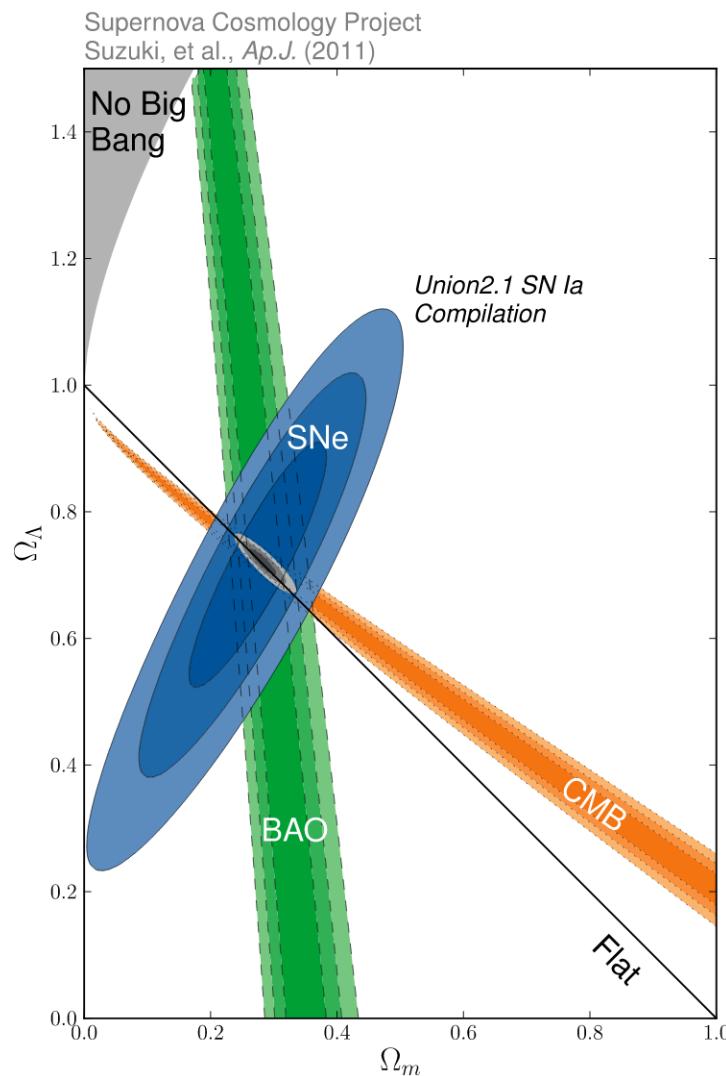
Lab 15

$$\Omega_{m0} = 0.308 \pm 0.012$$

$$\Omega_{\Lambda0} = 0.692 \pm 0.012$$

$$\Omega_{\text{rad}0} = 8.24 \times 10^{-5}$$

$$H_o = 67.81 \pm 0.92$$

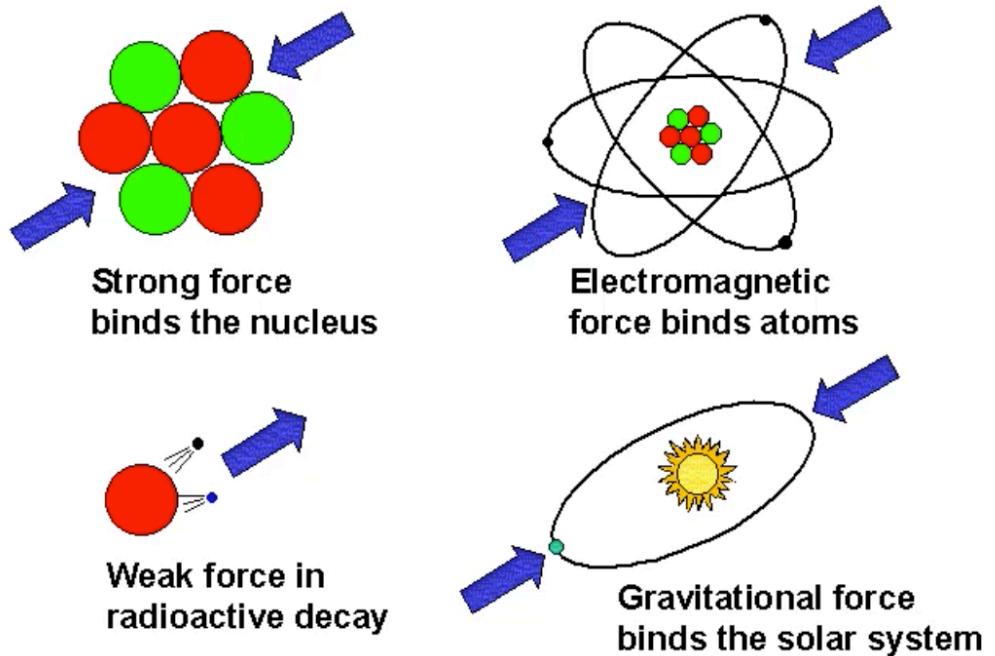


The Big Bang Theory

- The Big Bang theory is a detailed scientific model that describes conditions in the early universe and how they changed with time.
- The very early universe was so hot that energy could be transformed into matter and vice-versa.

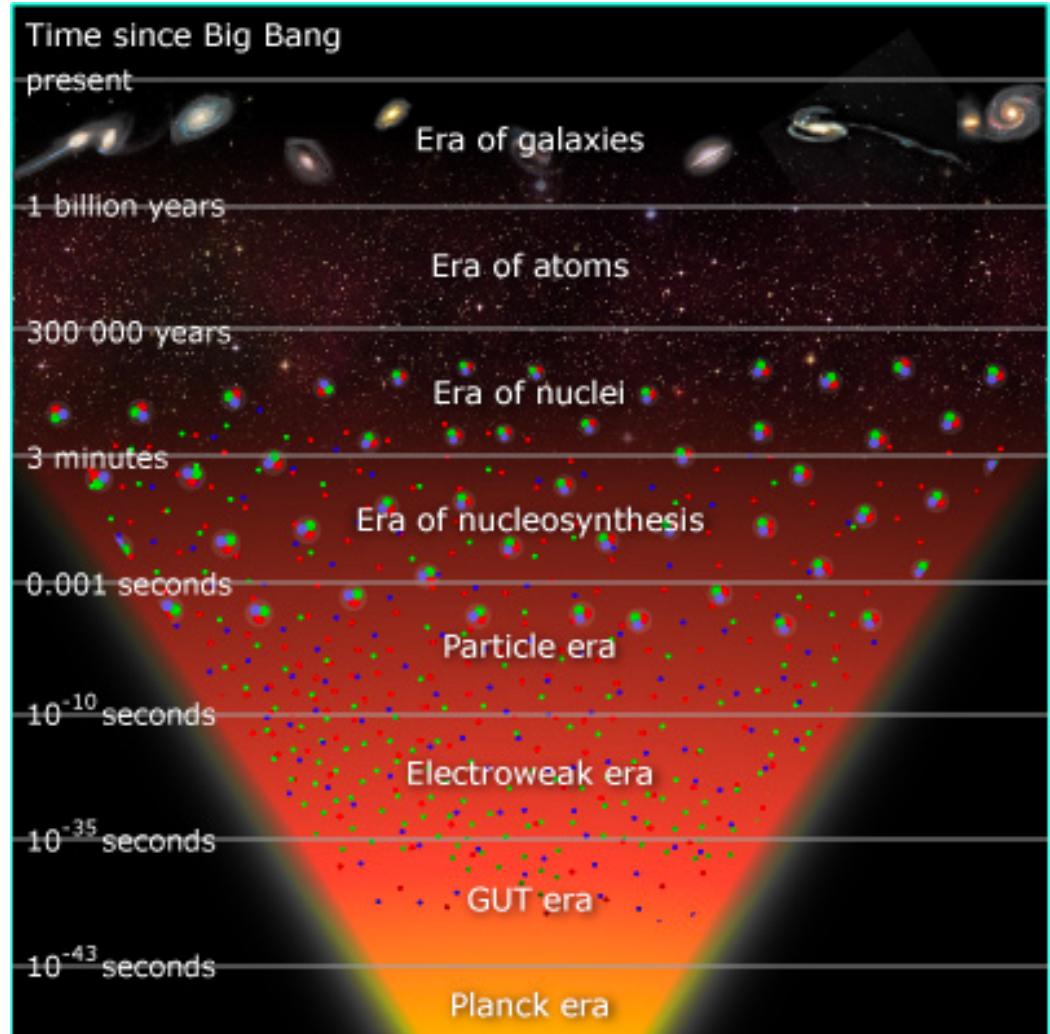
Fundamental Forces

- Four forces of nature:
 - Gravity
 - Electromagnetism
 - Strong force
 - Weak force
- For a brief instant after the Big Bang, the four forces may not have been distinct.



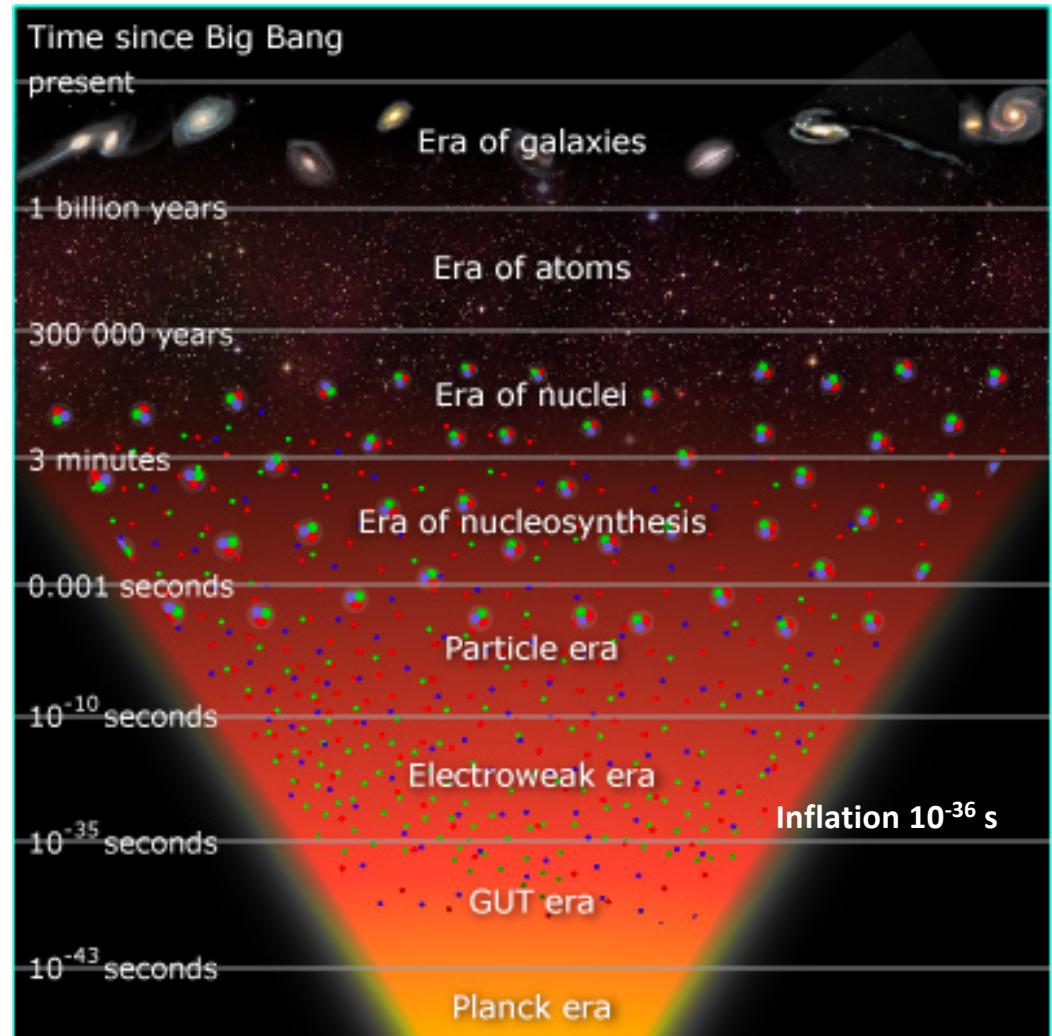
Big Bang Theory

- First four eras were over in the first 0.001 seconds.
- Planck Era – the four forces may have been unified as one superforce.
- GUT (Grand Unified Theories) Era – gravity became distinct. The rest of the forces combined into GUT force.



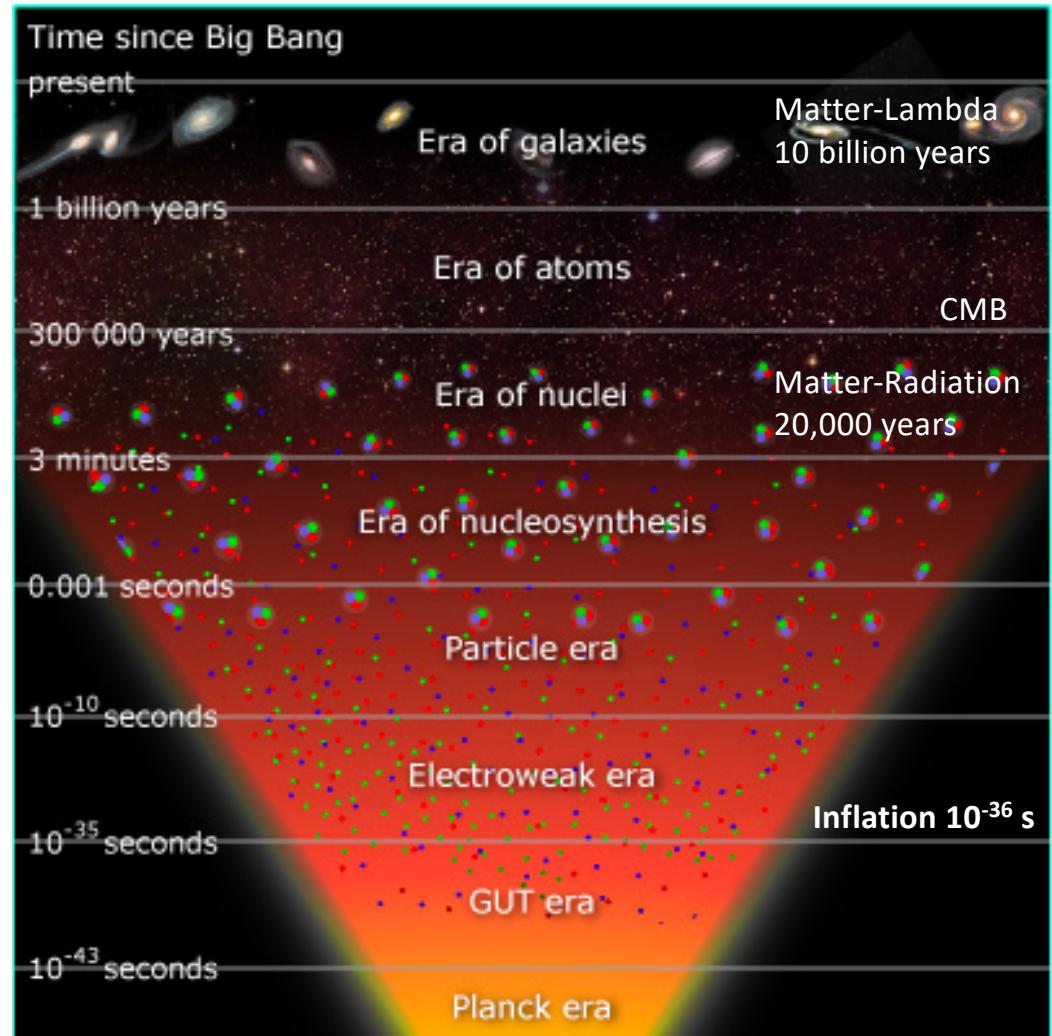
Big Bang Theory

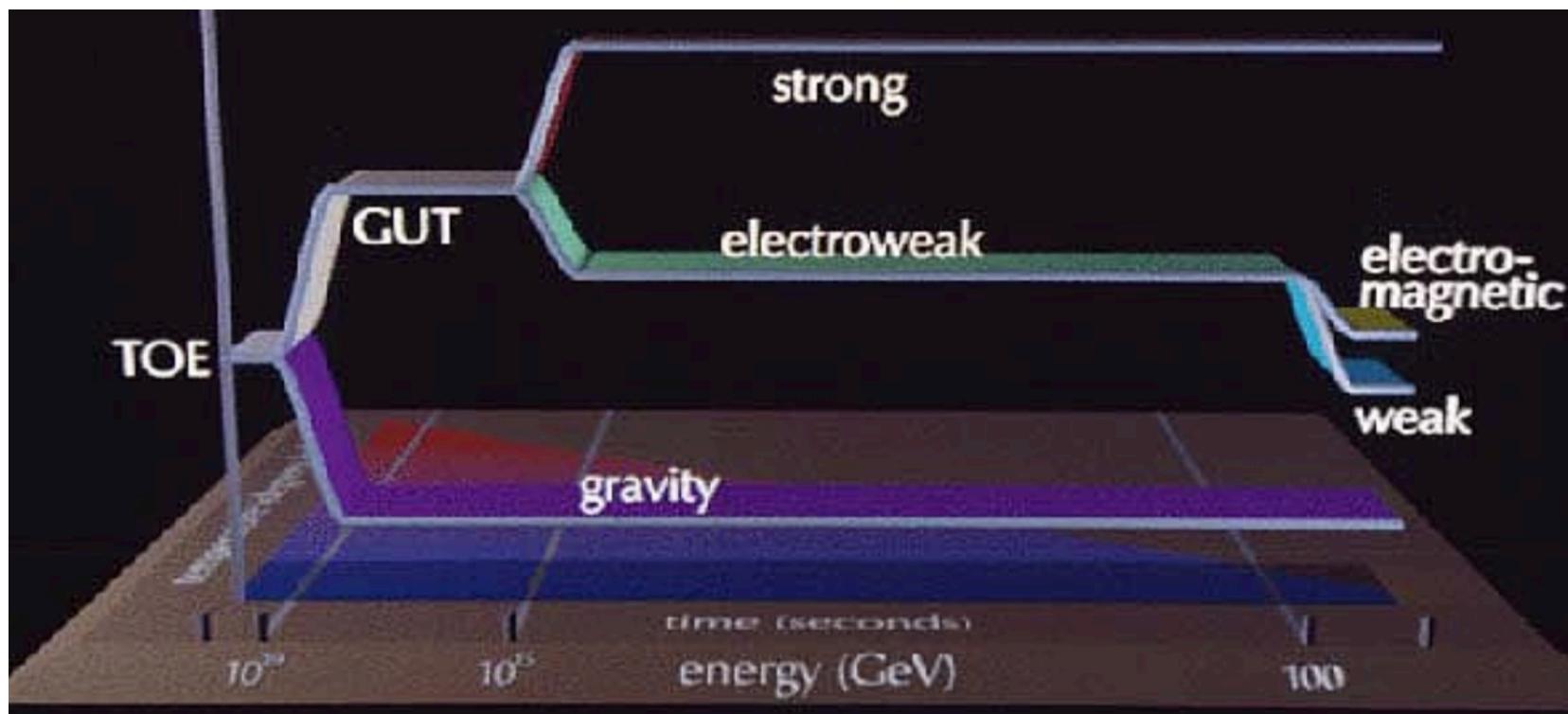
- End of GUT Era – GUT force split into strong force and electroweak force, resulting in inflation.
- End of Electroweak Era – four fundamental forces now distinct.
- Particle Era – spontaneous exchange of matter and energy continues.



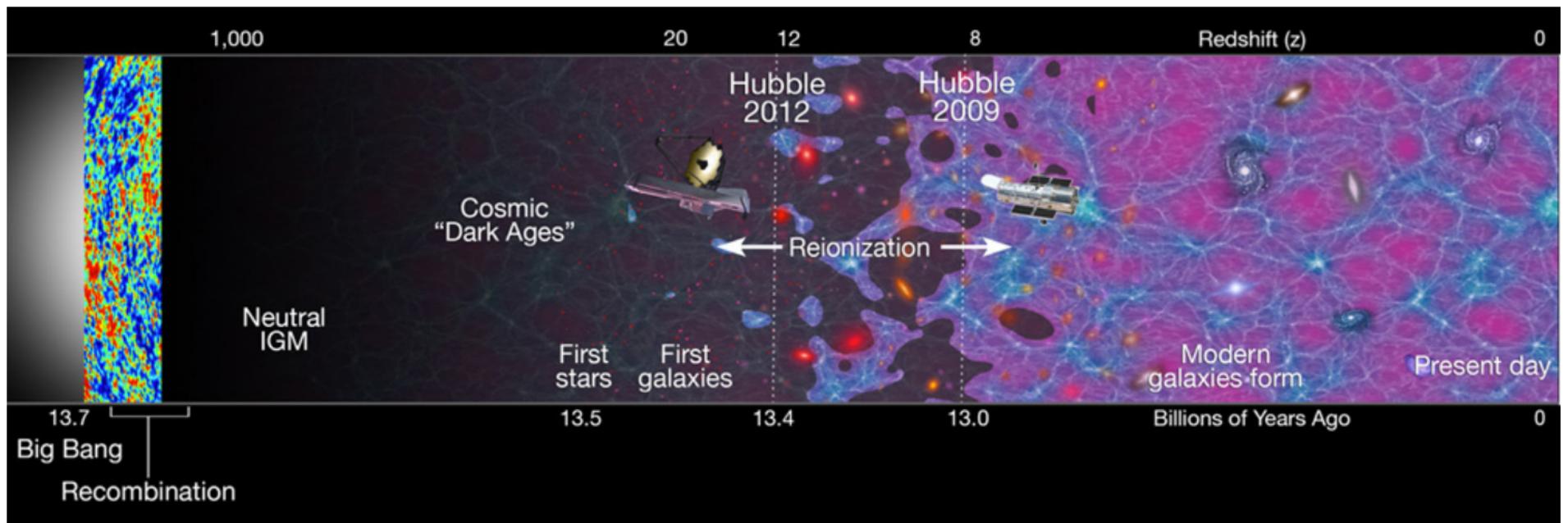
Big Bang Theory

- Particle Era ended when temperature fell to 1 trillion Kelvin.
- Era of Nucleosynthesis – fusion of protons and neutrons, resulting in 75% hydrogen and 25% helium in the universe.
Trace amounts of Deuterium and Lithium
- Era of Nuclei – hydrogen nuclei, helium nuclei, and electrons all moving independently.
Photon-Baryon Fluid
Ended after 380,000 years
Era of Recombination (atoms)



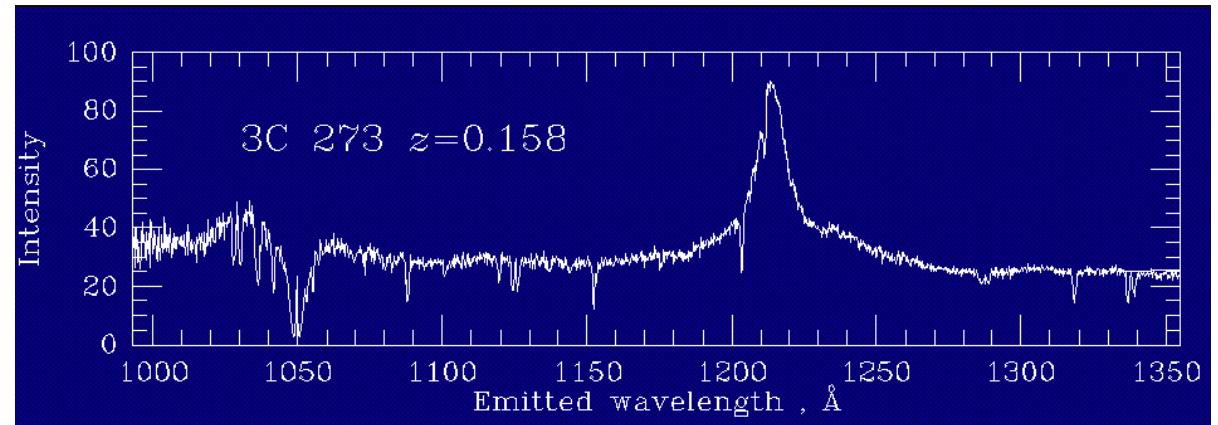


Reionization $z \sim 10-6$?



Reionization is Patchy: <https://www.youtube.com/watch?v=kifF3RYcfn0>

Low Z QSO

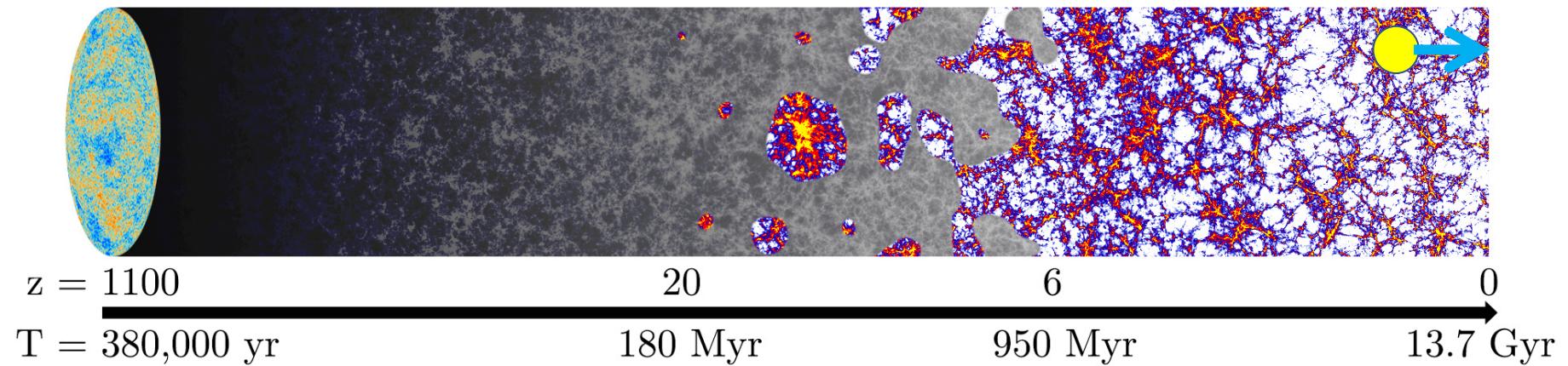


Recombination

Dark Ages

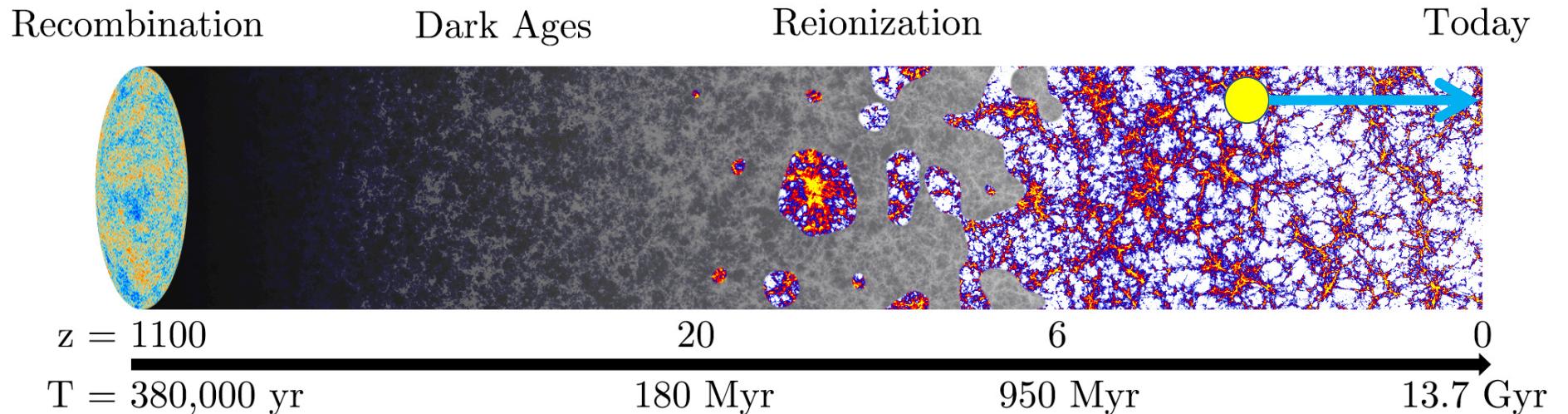
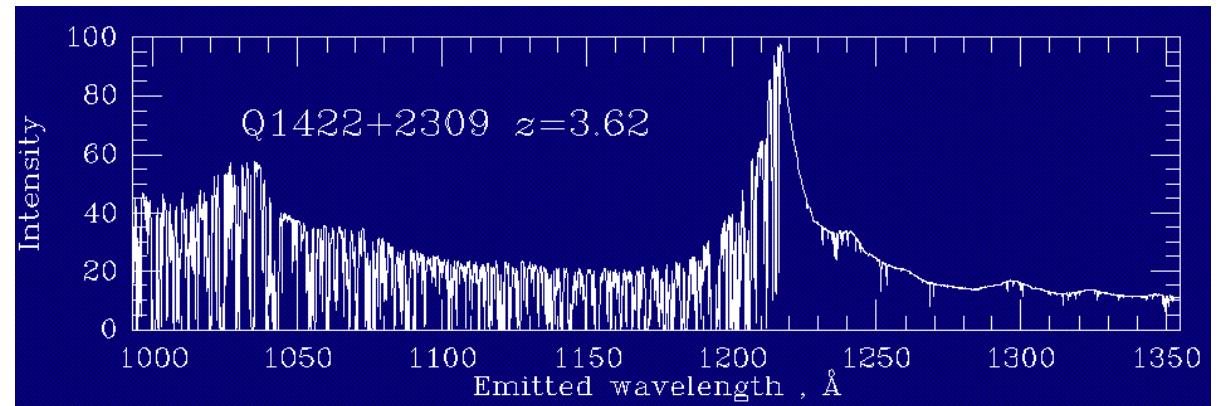
Reionization

Today



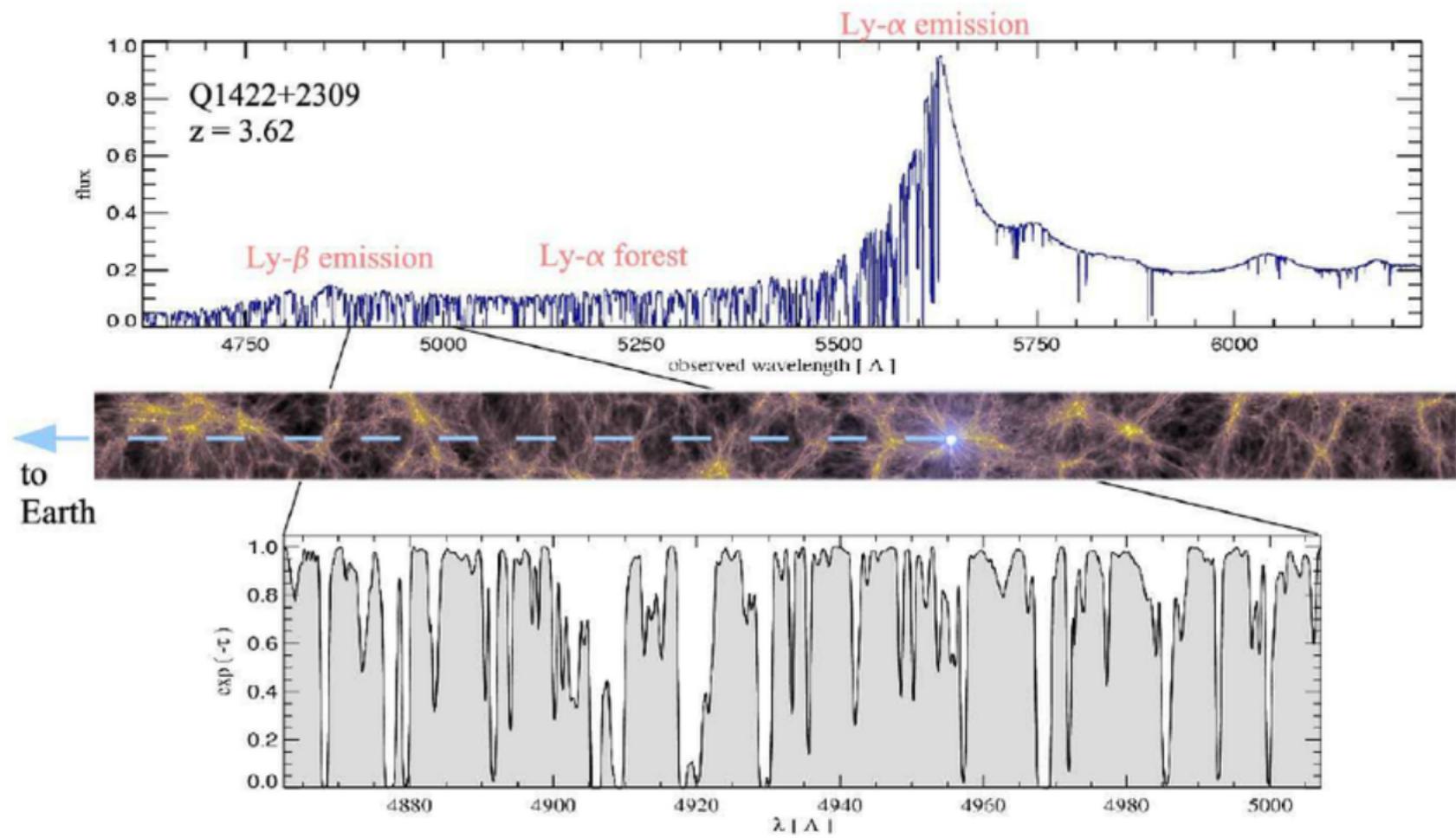
Credit: Kaurov

Mid Z QSO: Lyman Alpha Forest

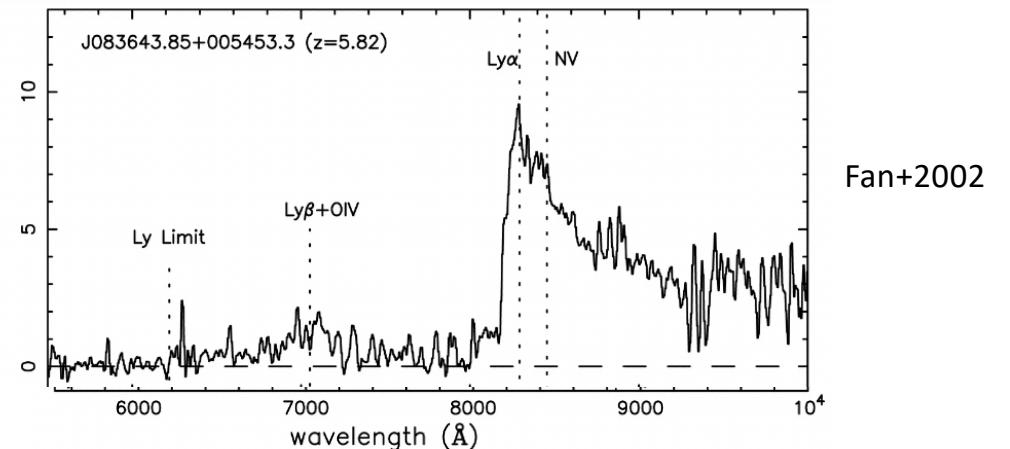


Credit: Kaurov

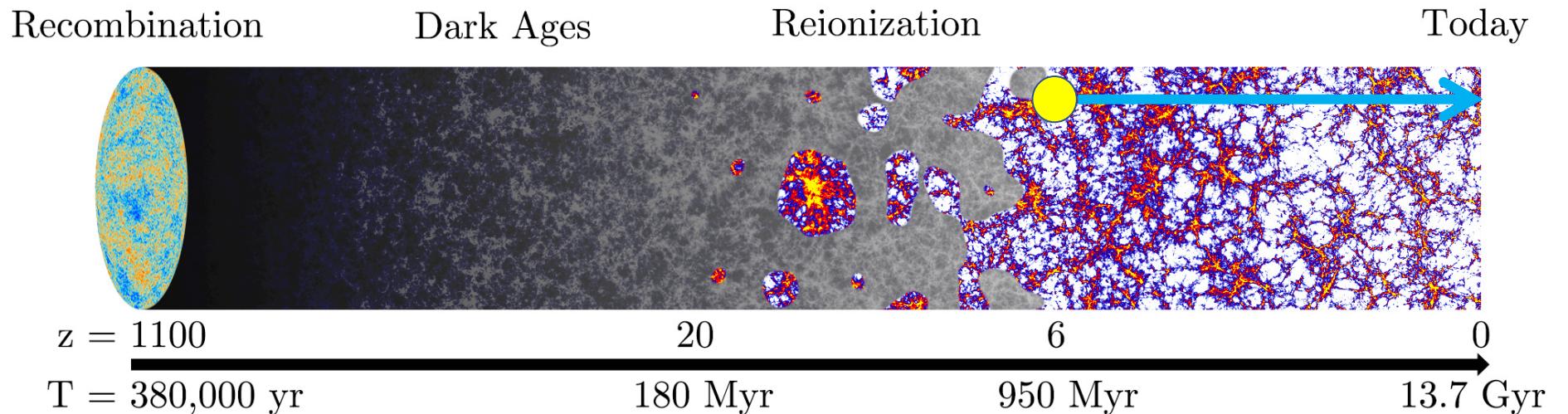
$z=3.62$ QSO spectrum, showing the Ly-alpha forest from intervening neutral H clouds:



High Z QSO: Gunn Peterson Trough



Fan+2002



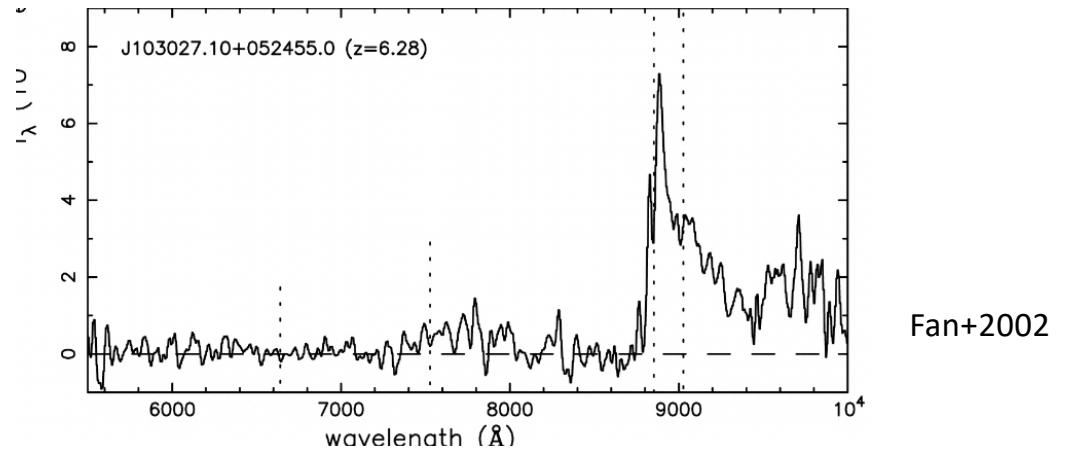
Credit: Kaurov

High Z QSO: Gunn Peterson Trough

Shows up in QSOs around $z \sim 6$

Significant Hydrogen absorption.

Suggests we're reaching the end of the Epoch of reionization.

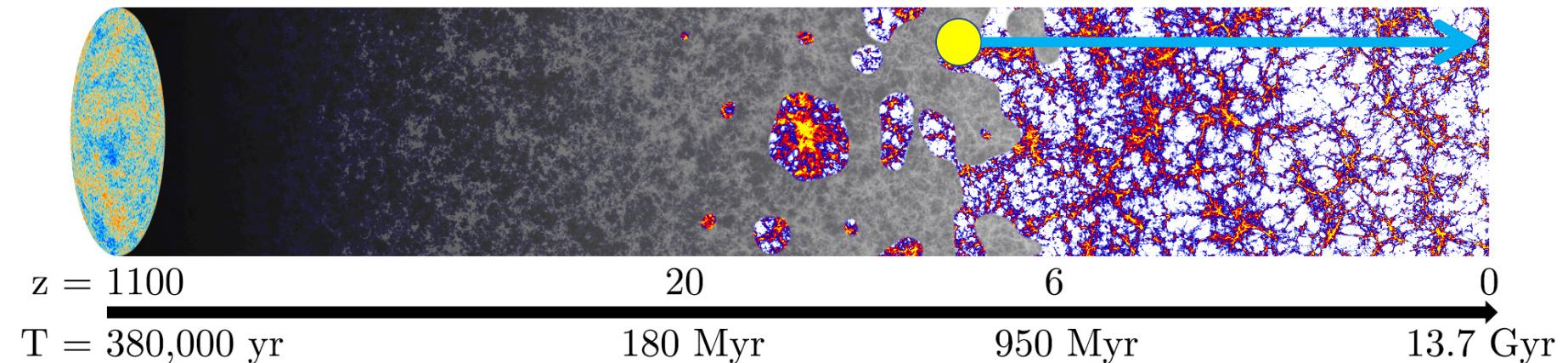


Recombination

Dark Ages

Reionization

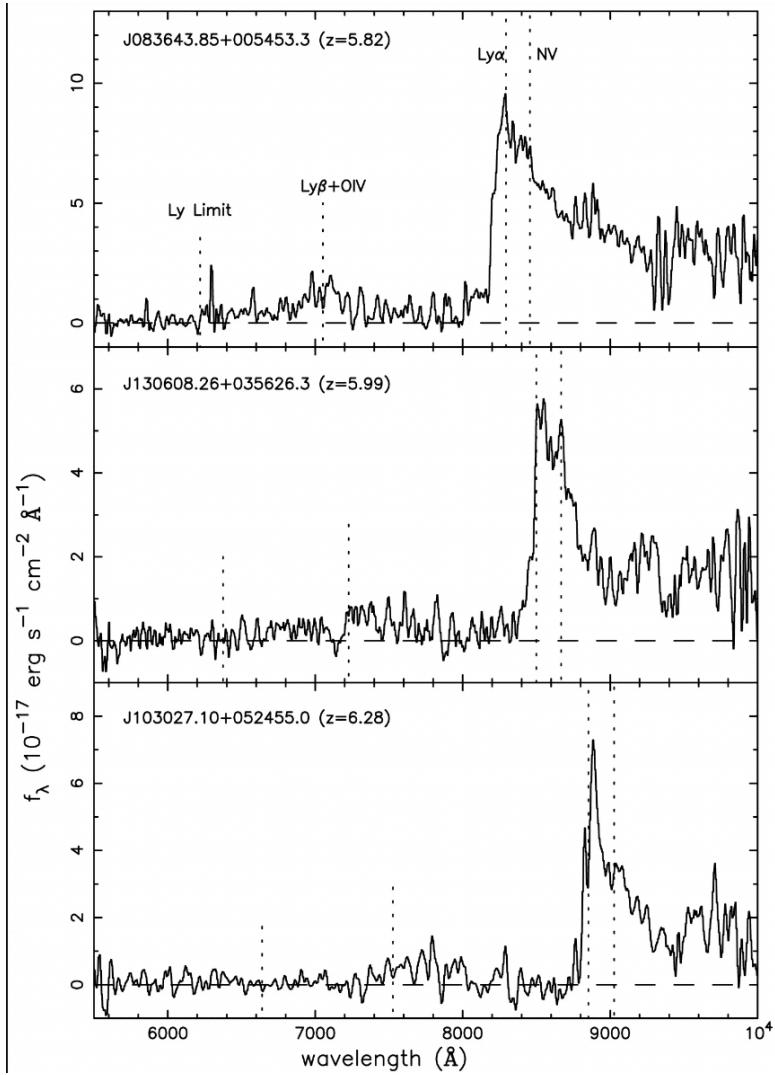
Today



Credit: Kaurov

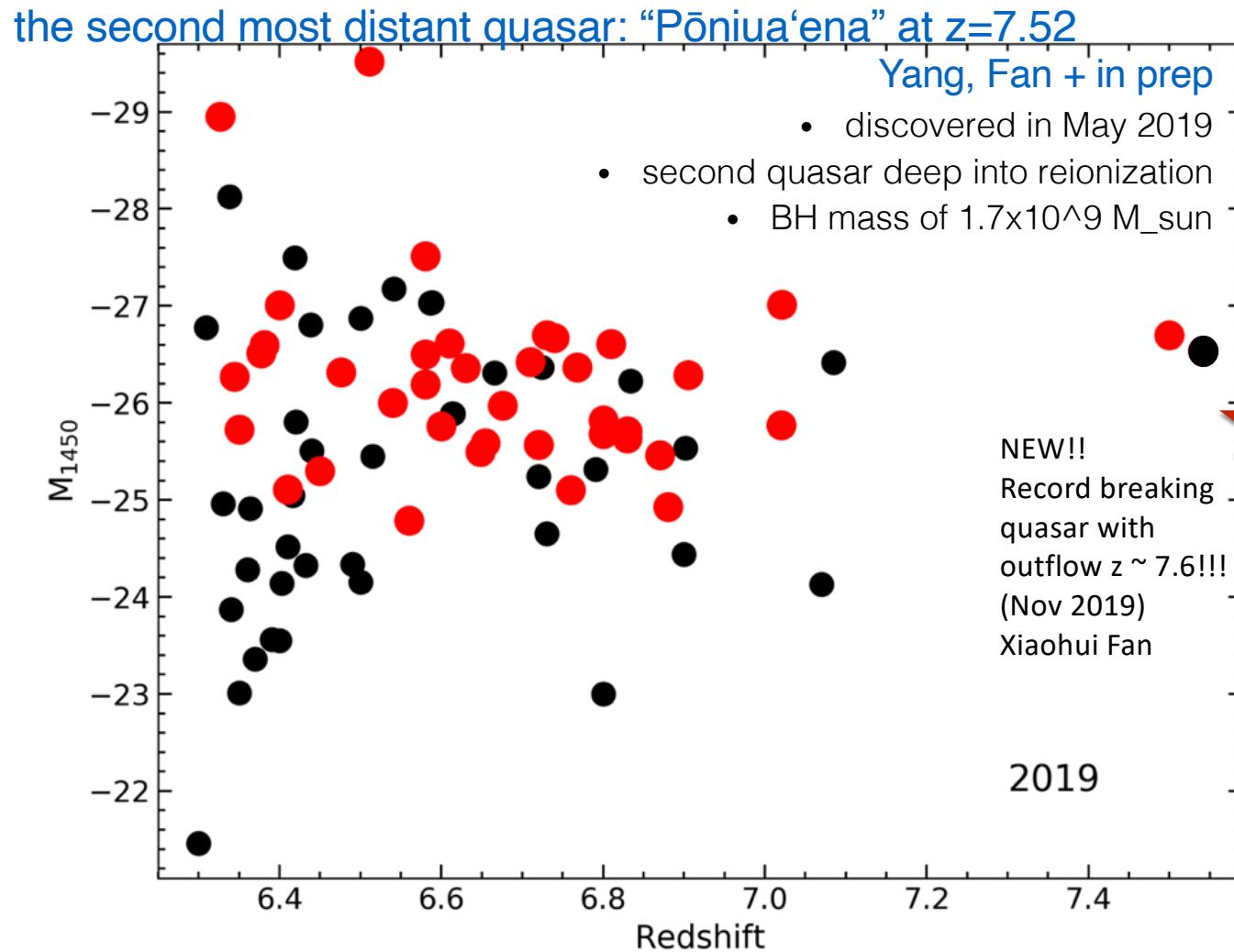
Gunn Peterson Trough

Fan+ 2002

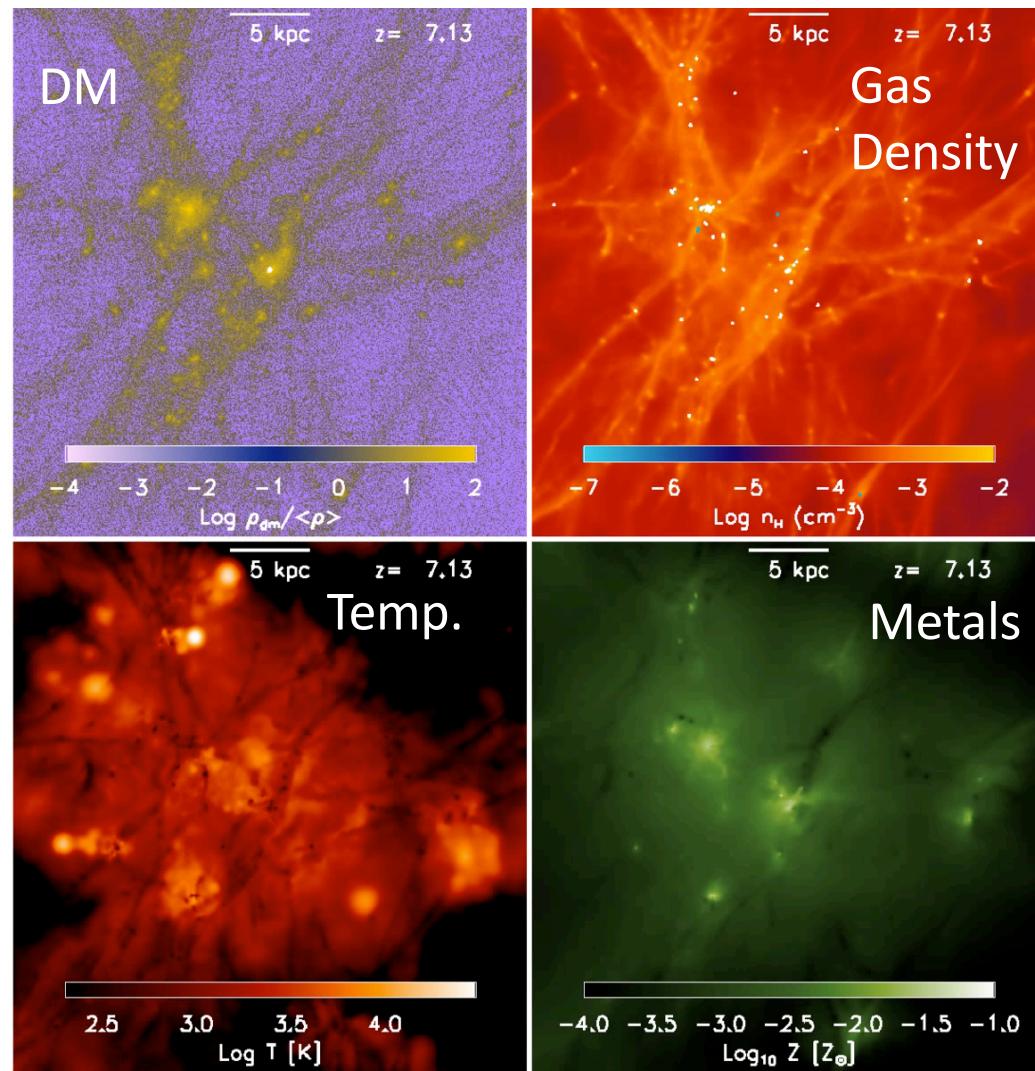


What were the sources of
reionization?

QSOs



First Stars →
Massive stars in low
mass galaxies



Jeon, Besla+2017

Brown +2014

CMD of each Ultra Faint Dwarf Galaxy (colored points) shifted to the distance and reddening of Hercules dwarf and zoomed into the CMD region most sensitive to age.

The similarities of the six CMDs imply that the UFD populations are extremely similar in age and metallicity.

A global event caused quenching

