The Big Bang Theory

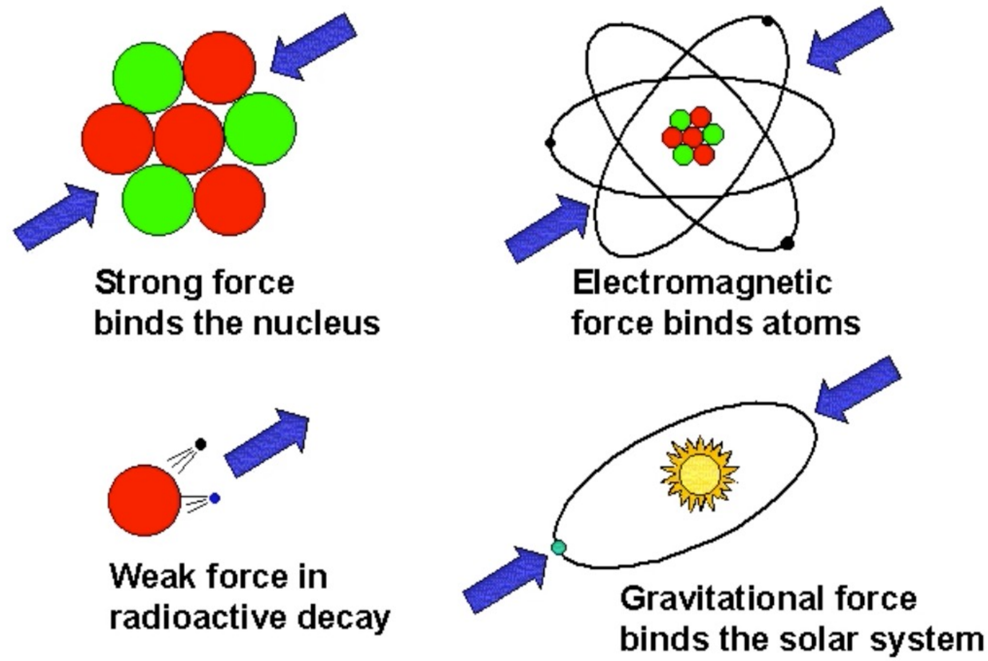
- The Big Bang theory is a detailed scientific model that describes conditions in the early universe and how they changed with time.

- 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

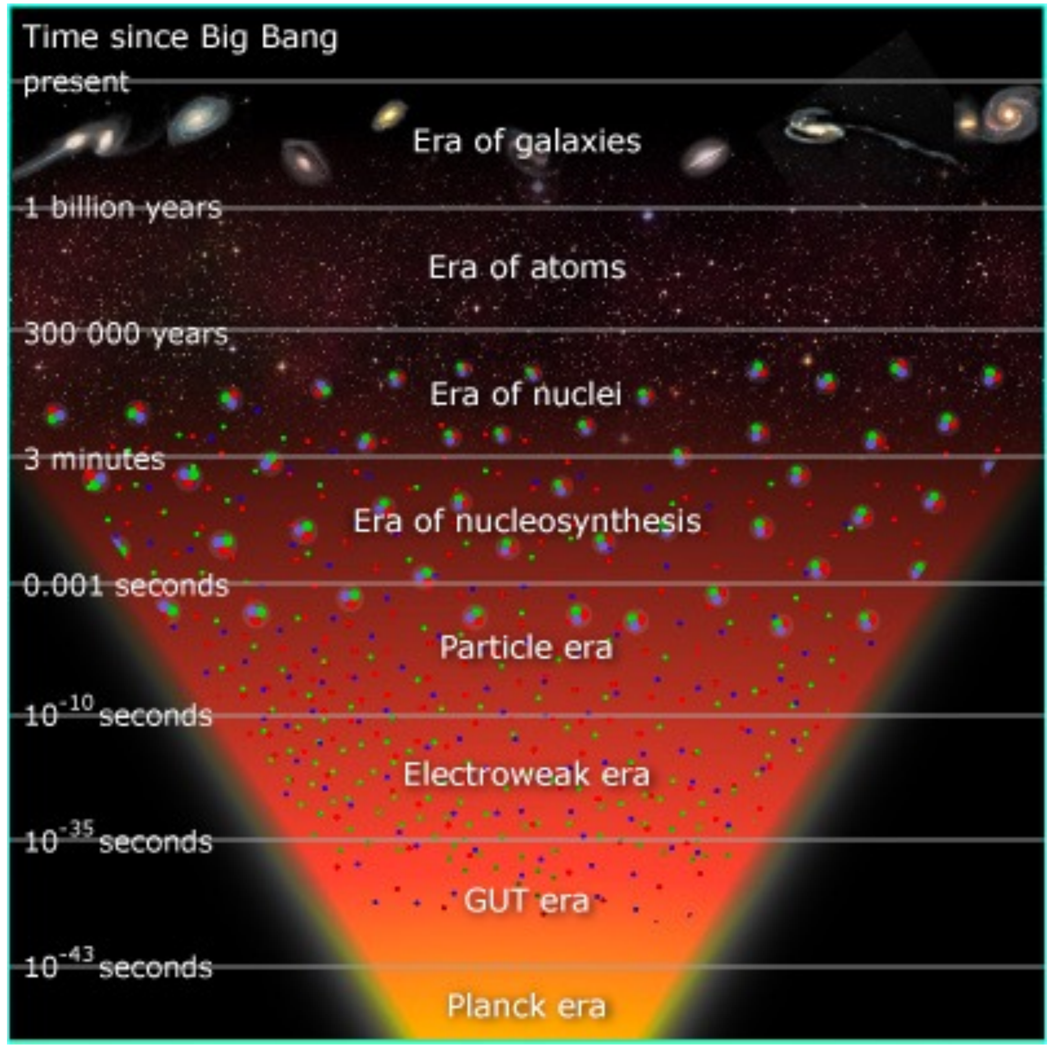
- For a brief instant after the Big Bang, the four forces may not have been distinct.



Big Bang Theory

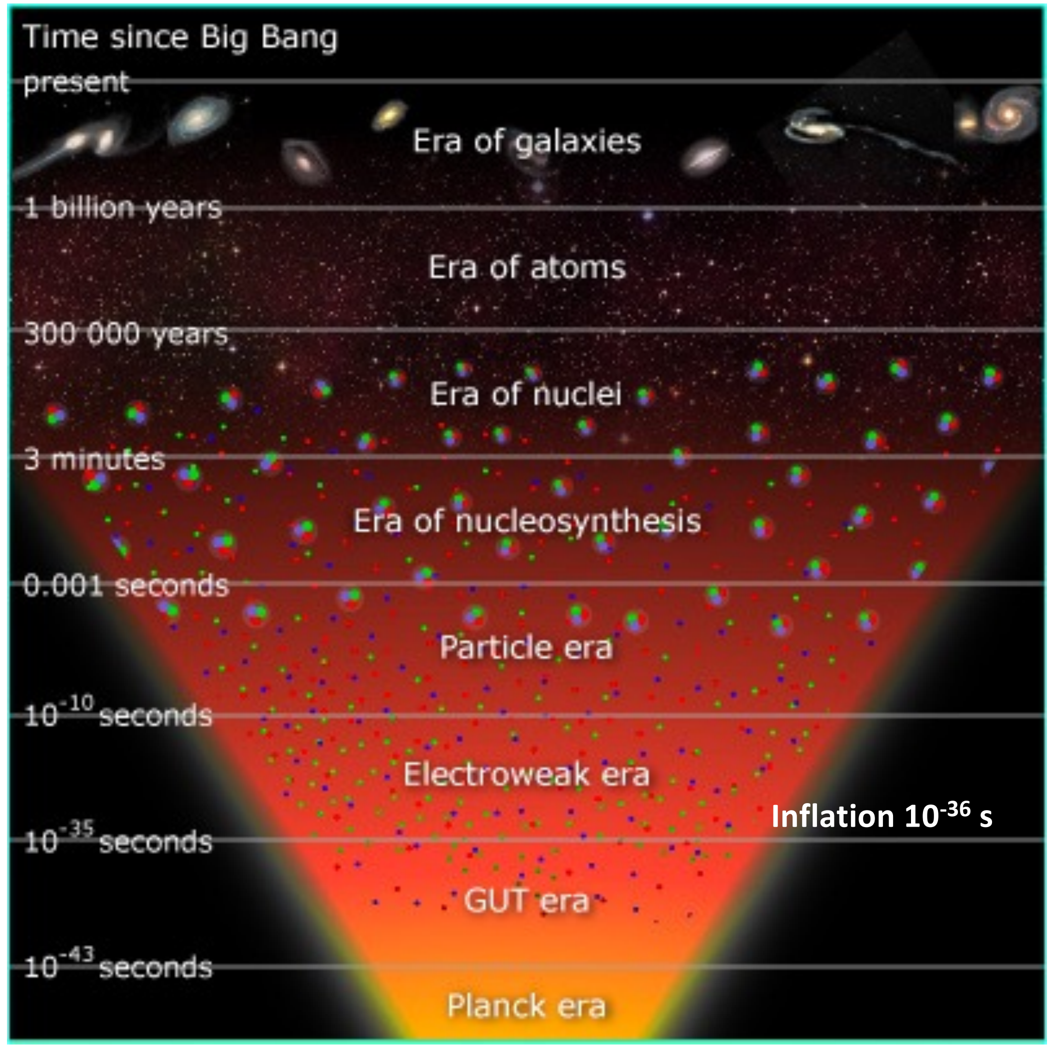
Radiation Dominated Eras:

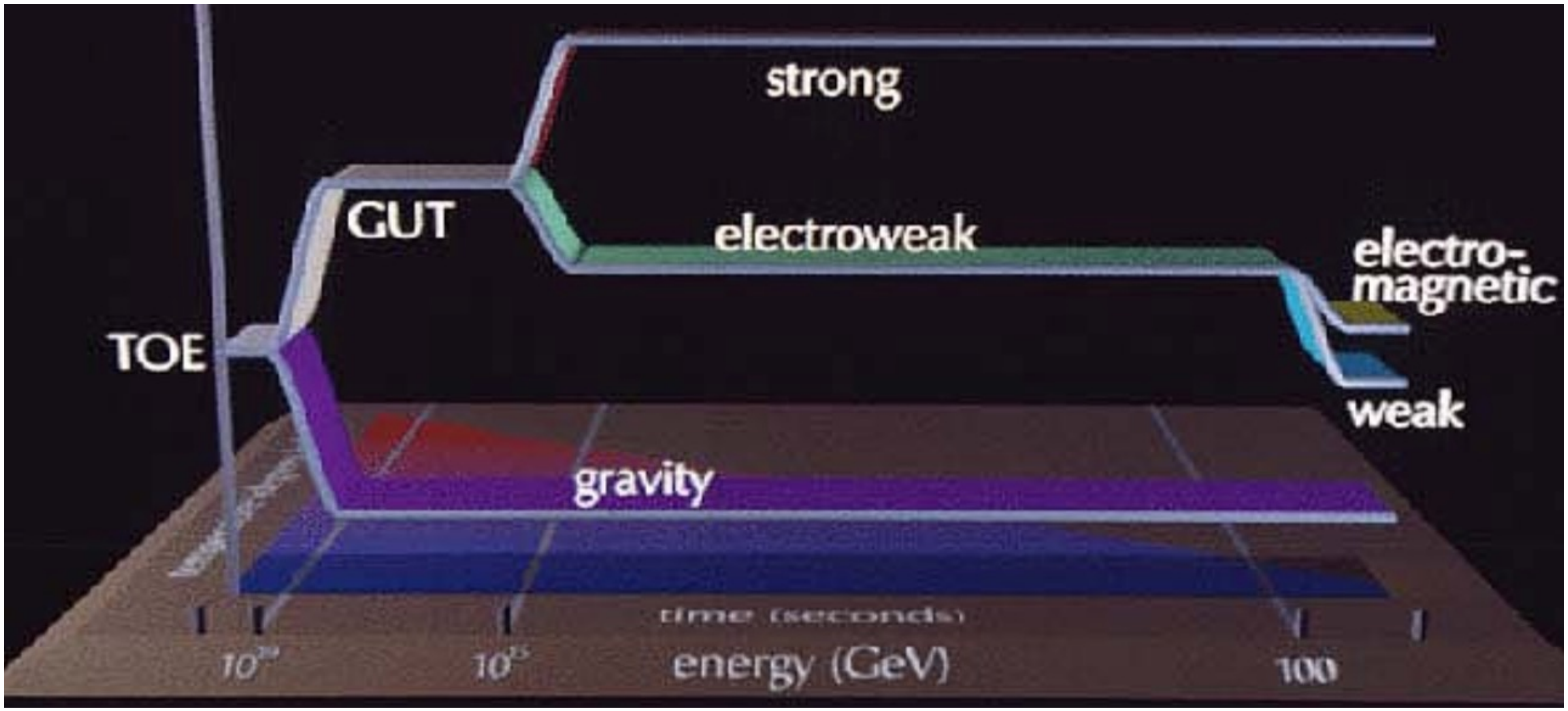
- First four eras were over in the first 0.001 seconds.
- Planck Era – the four forces may have been unified as one superforce.
- GUT (Grand Unified Theories) Era – gravity became distinct. The rest of the forces combined into GUT force.



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.

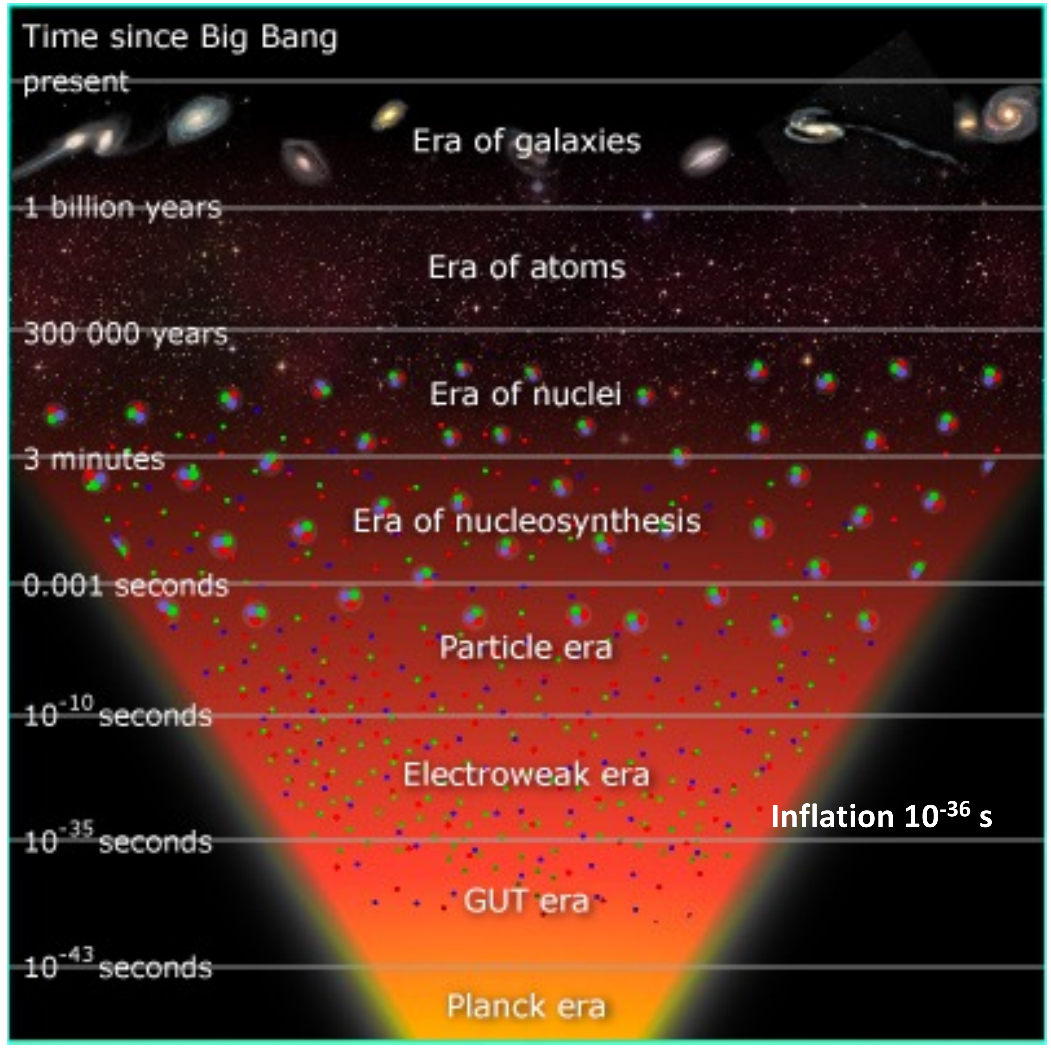



strong
GUT
electroweak
electro-
magnetic
TOE
weak
gravity
time (seconds)
10^{15}
energy (GeV)
100

Big Bang Theory

- Particle Era – spontaneous exchange of matter and energy continues.

At first we have a "soup" of particles: $\gamma, e\pm, \nu, anti\ \nu, q, anti\ q, n, p$



End of the Particle Era (t = 0.001 s)

- As the temp drops below rest mass energy of particles (T = To(1+z)):
  - $e\pm$ annihilate, but there are electrons now, meaning there was an imbalance between matter and antimatter.
  - Neutrons and protons decouple. Initially these reactions are in equilibrium, but favor protons since neutrons are more massive.
    - $n \leftrightarrow p + e^- + \bar{v}_e$
    - $n + e^+ \leftrightarrow p + \bar{v}_e$
    - $n + v \leftrightarrow p + e^-$

$$\frac{\#n}{\#p} = e^{-Q/kT} \qquad Q = (m_n - m_p)c^2 = 1.293\ MeV$$

At T ~ 10^{10} K (i.e. $kT = 1.293\ MeV$) the reactions “freeze out”

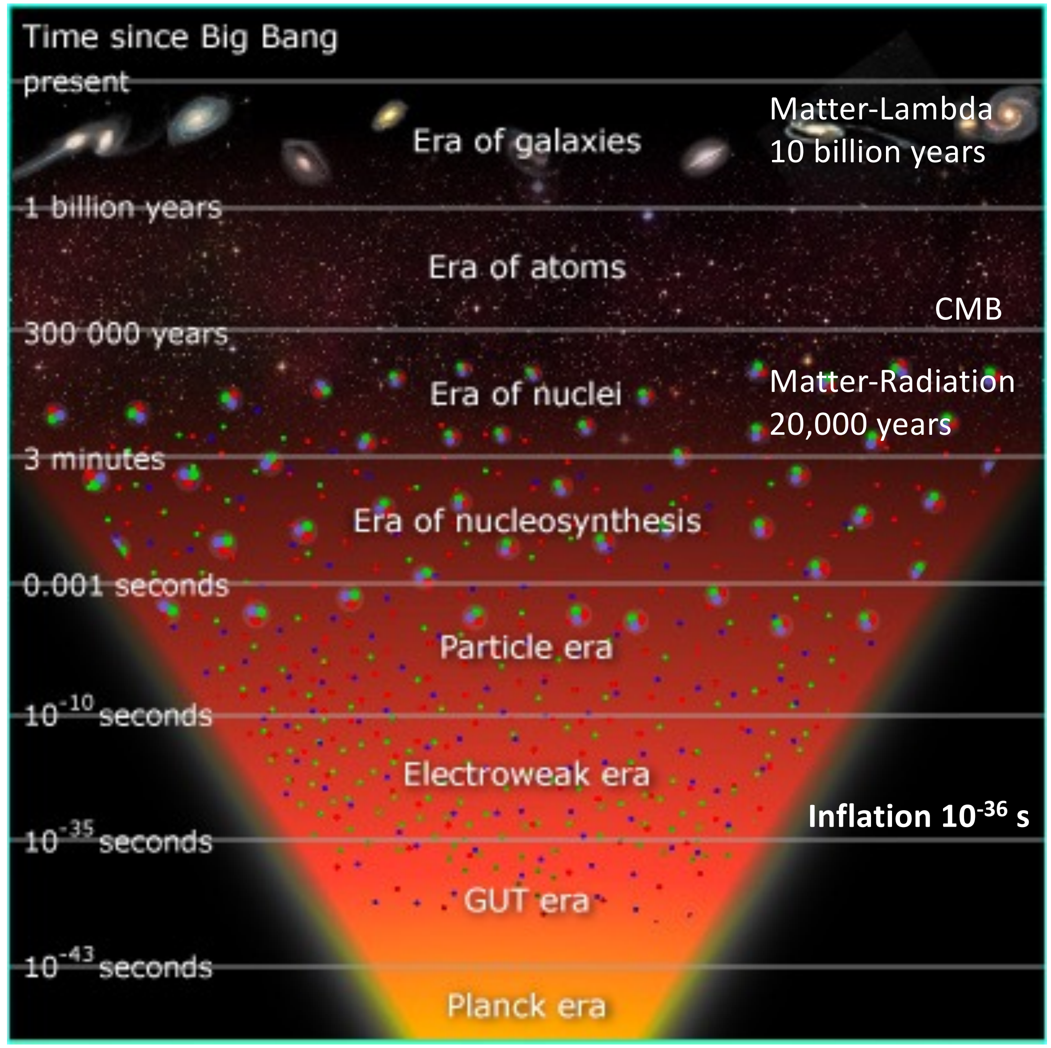
$$\frac{\#n}{\#p} = e^{-Q/1.293} = 0.22$$

Big Bang Theory

In 3 MINUTES !!!!:

- 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 – BAO
Ended after 380,000 years
Era of Recombination (atoms)



Big Bang Nucleosynthesis (formation of complex nuclei)

- t = 300 s, T = 10^9 K : Deuterium Production is favored (right wins:)

$$n + p \leftrightarrow {}^2H + \gamma$$

  - abundance of ${}^2H$ is governed by the Saha equation
  - depends critically on the number density of protons and neutrons (end of particle era)

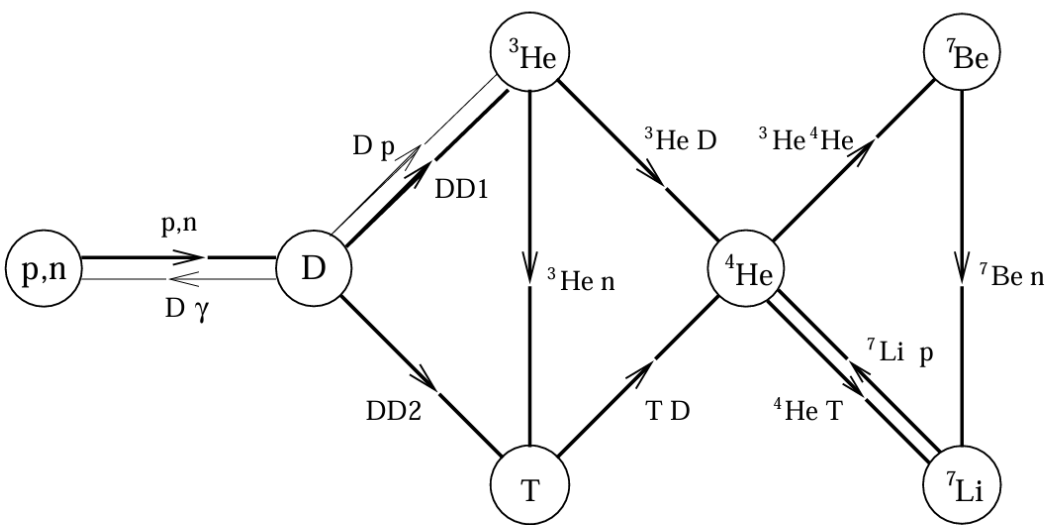
- Once Deuterium is present in significant abundances, *almost* all of it is transformed into Helium4 :

$$^2H + {}^2H \rightarrow {}^3He + n$$
$$^2H + {}^2H \rightarrow T + p$$

$$T + {}^2H \rightarrow \boldsymbol{{}^4He} + n$$
$$^3He + {}^2H \rightarrow \boldsymbol{{}^4He} + p$$

Big Bang Nucleosynthesis – freeze out

- As T drops, eventually Deuterium and He reactions "freeze out"
- Some other elements also form in trace amounts: ^{7}Li and ^{7}Be
- [but note that ^{7}Be is radioactive with a half-life of 53.28 days, decaying to ^{7}Li, so it isn't a primary Big Bang predictor, same with T]
- Nothing heavier formed because the universe cooled too quickly.



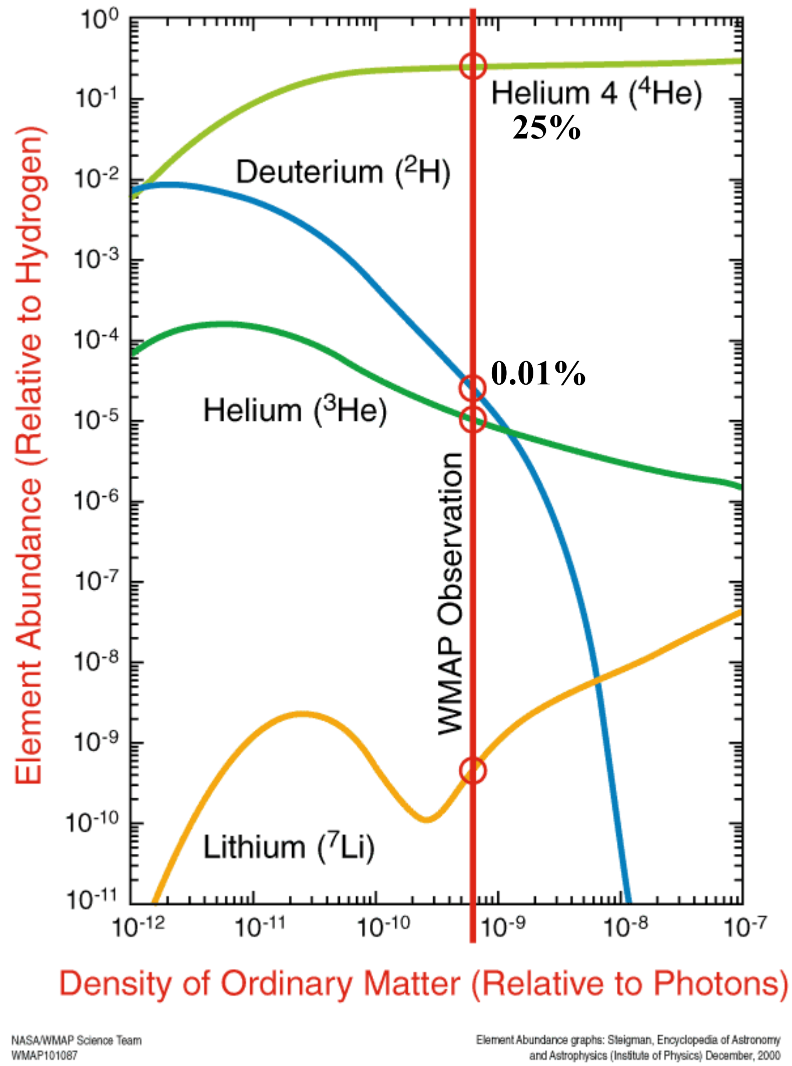
Mukhanov 2003
https://doi.org/10.48550/arXiv.astro-ph/0303073

Big Bang Nucleosynthesis

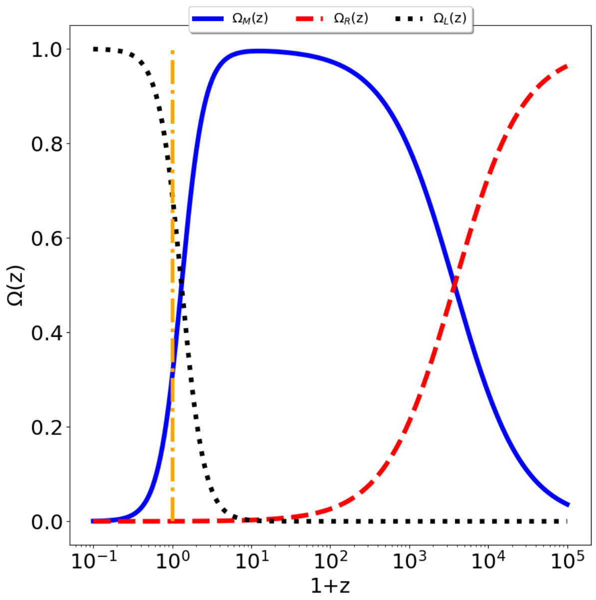
Resulting expected fractions of deuterium, Helium, Lithium in the universe depend on ratio of baryons to photons.

Radiation Dominated Era: Radiation Density sets the timing of the neutron/proton ratio freeze out. (to right, higher γ density, so earlier freeze out, so more neutrons and more time to form He)

<u>Baryon/photon density is constrained from the CMB, yielding abundances that match observations.</u>



Radiation Dominated Era



$$\boxed{T = T_0(R_0/R(t)) = T_0(1+z)}$$

Redshift is connected to TIME through the hubble parameter. (Look Back Time)

$$\int_0^z \frac{1}{H(z)} \frac{dz'}{(1+z')} = t_L$$

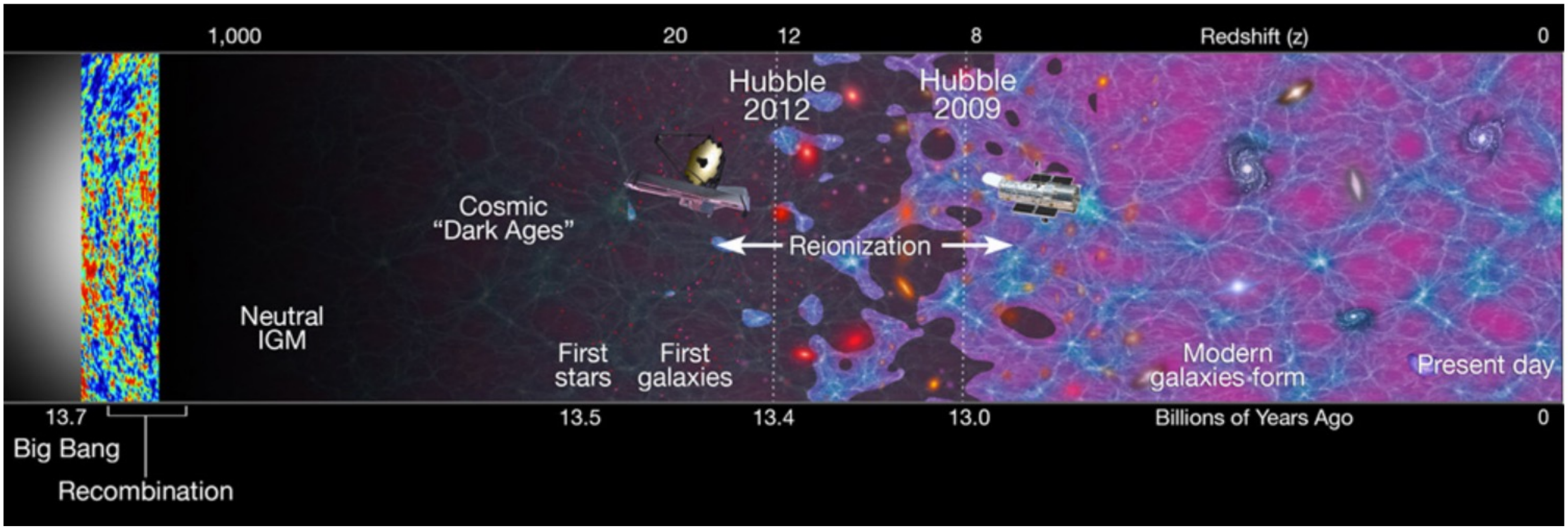
If Omega radiation increases this changes the TIMING of the temperature evolution – i.e. the timing of when proton and neutrons freeze out and so changing the time available for nucleosynthesis.

$$\boxed{H(t)^2 = H_o^2\left[\Omega_{m,o}(1+z)^3 + \Omega_{rad,o}(1+z)^4 + \Omega_{\Lambda,o} + (1-\Omega_o)(1+z)^2\right]}$$

Why can't He and D be explained by stars?

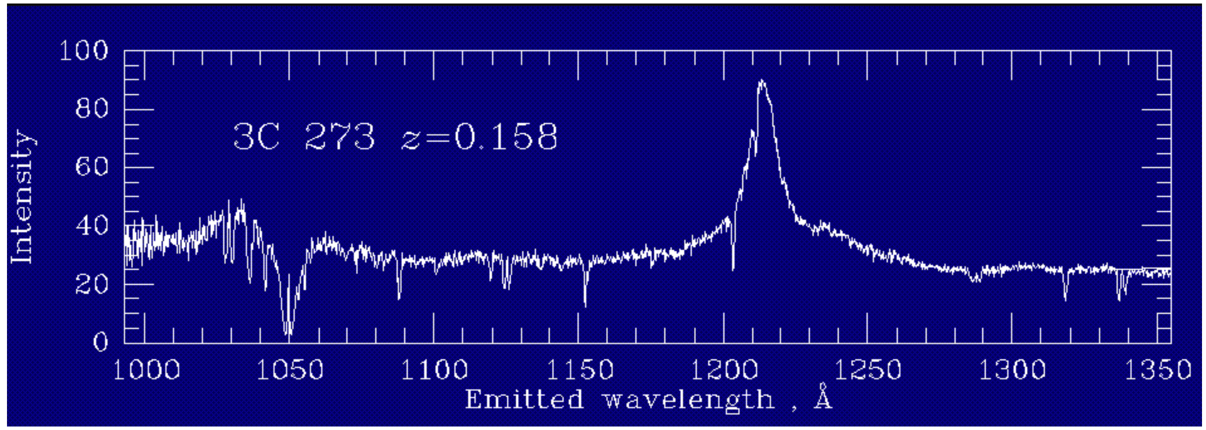
- G.Burbidge, M.Burbidge, Fowler, and Hoyle postulated that all elements were produced in stellar interiors or during SNe explosions
- BUT if true, there should only be a tiny amount of He around and NO Deuterium (destroyed in stellar interiors).
- The fact that Helium abundance is high (~25% pretty much everywhere) and Deuterium exists refutes this idea, supporting Big Bang Theory.

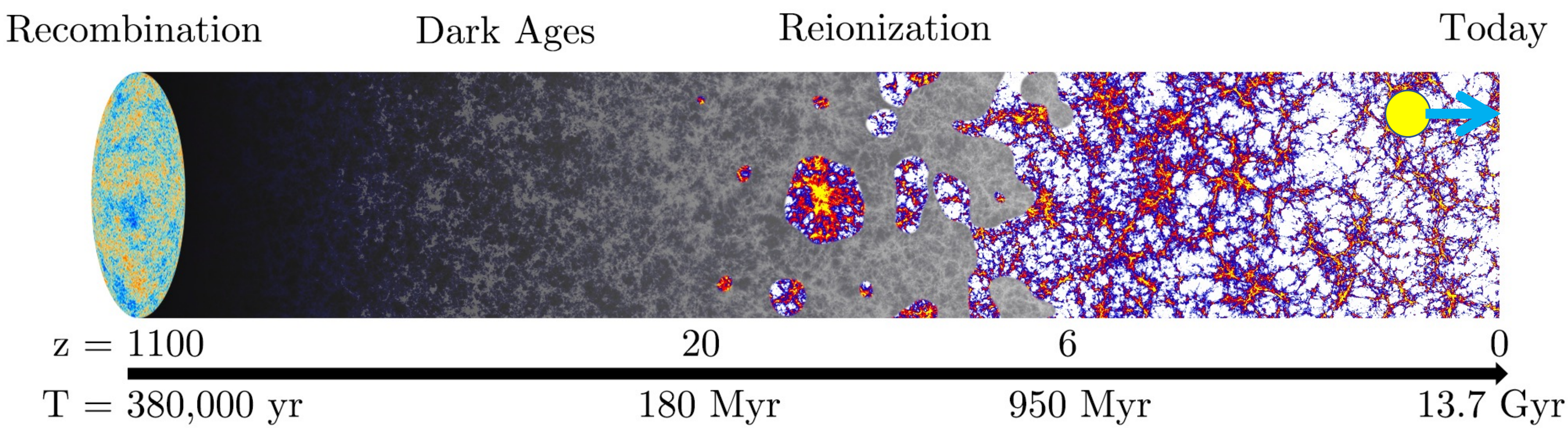
Reionization: post recombination the universe is neutral but starting at z~10 it starts to become ionized again. (occurs from z ~ 10-6)



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

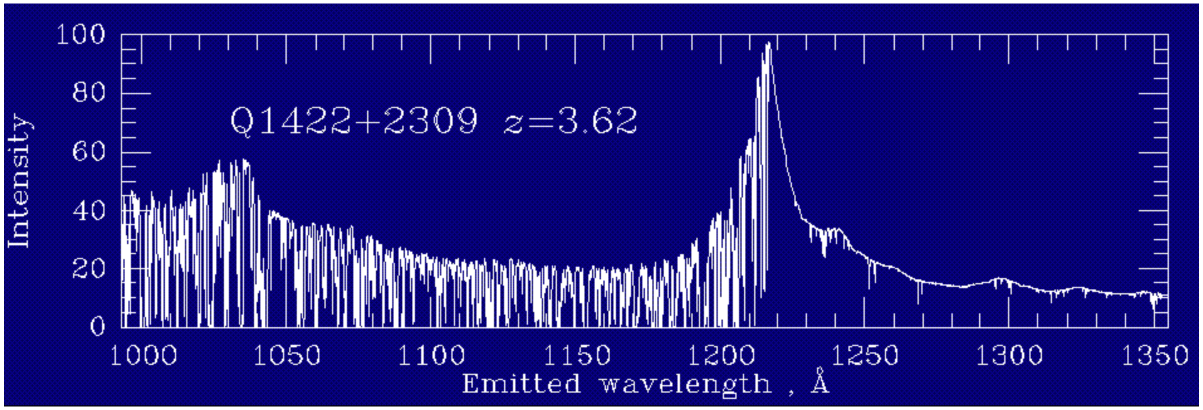
Low Z QSO

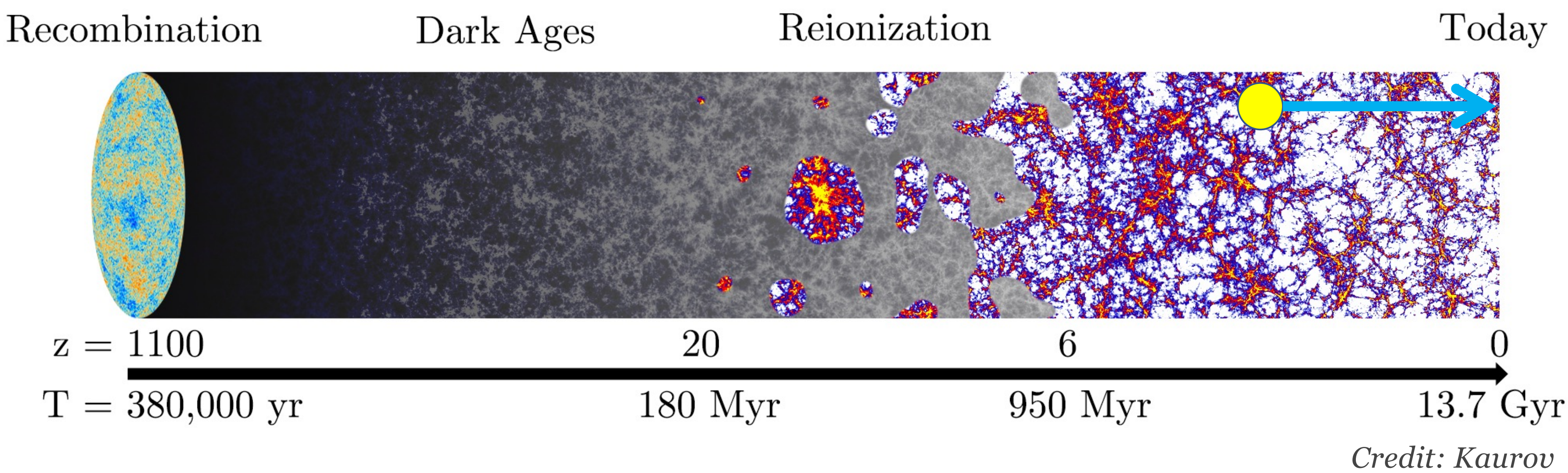




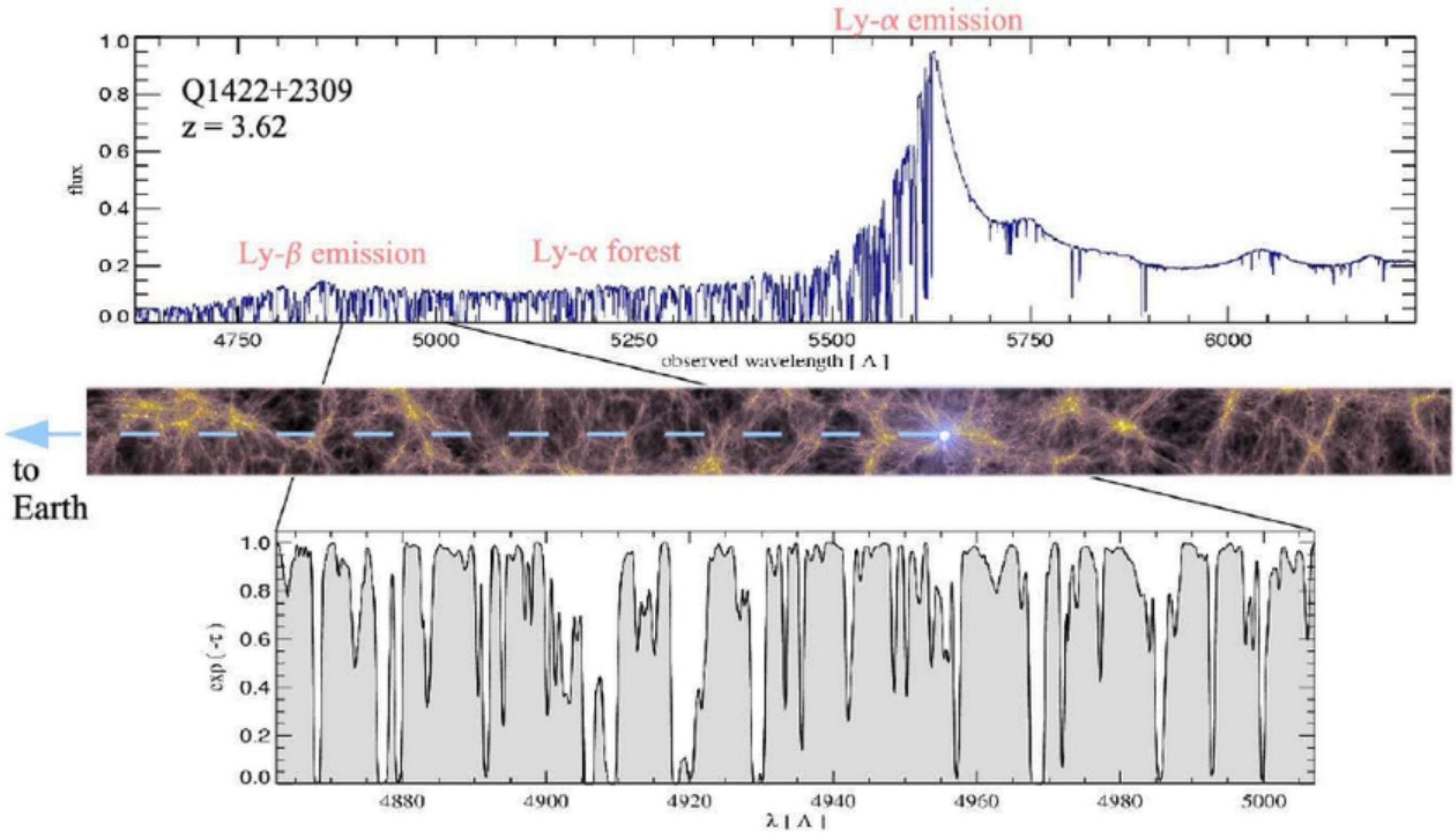
Credit: Kaurov

Mid Z QSO:
Lyman Alpha Forest

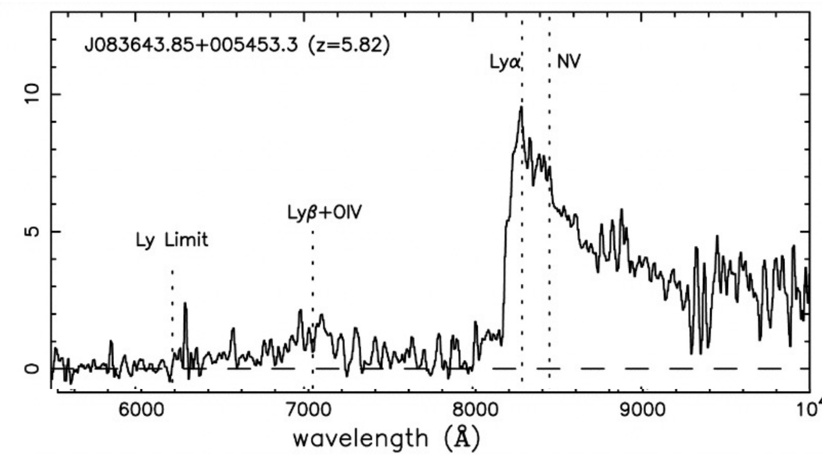




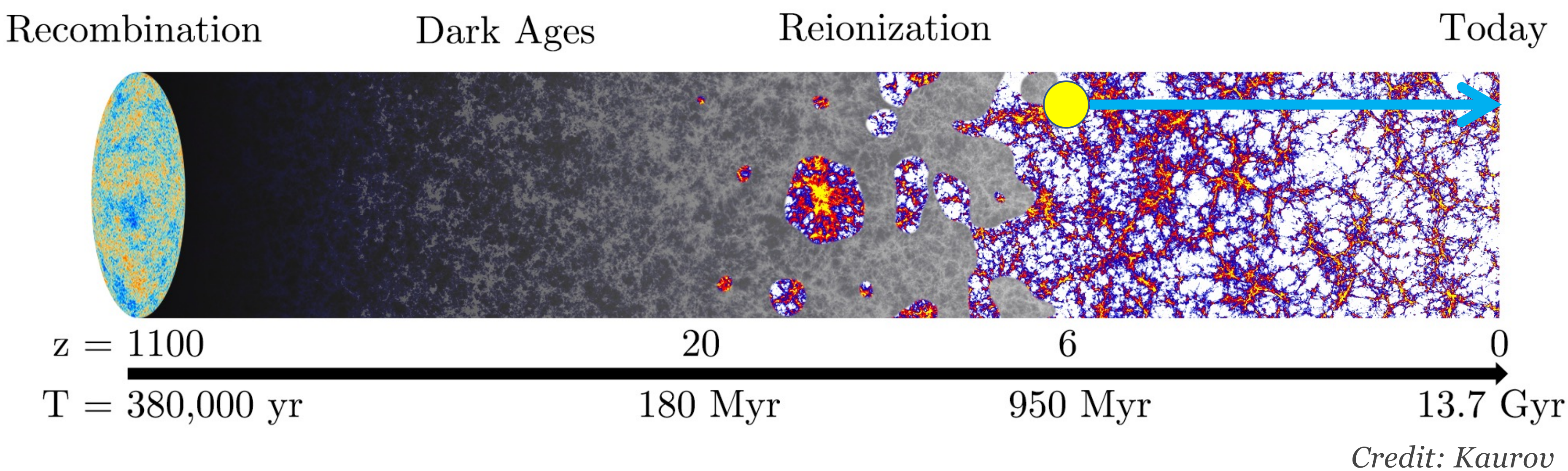
z=3.62 QSO spectrum, showing the Ly-alpha forest from intervening neutral H clouds:



High Z QSO:
Gunn Peterson Trough



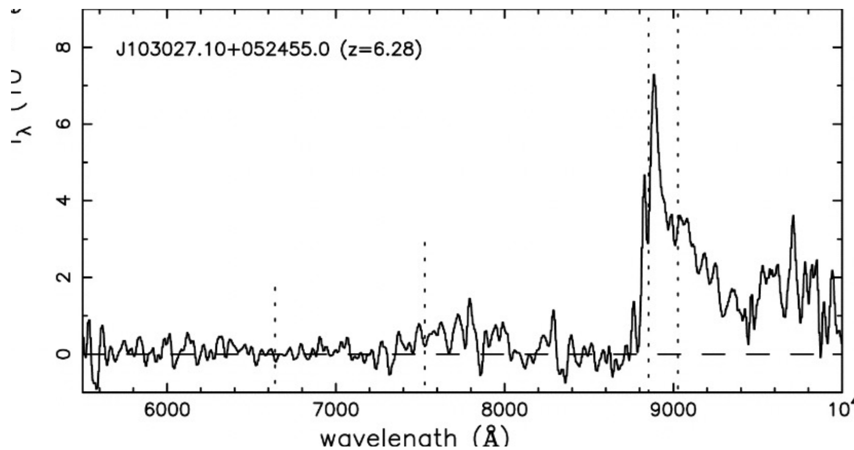
Fan+2002



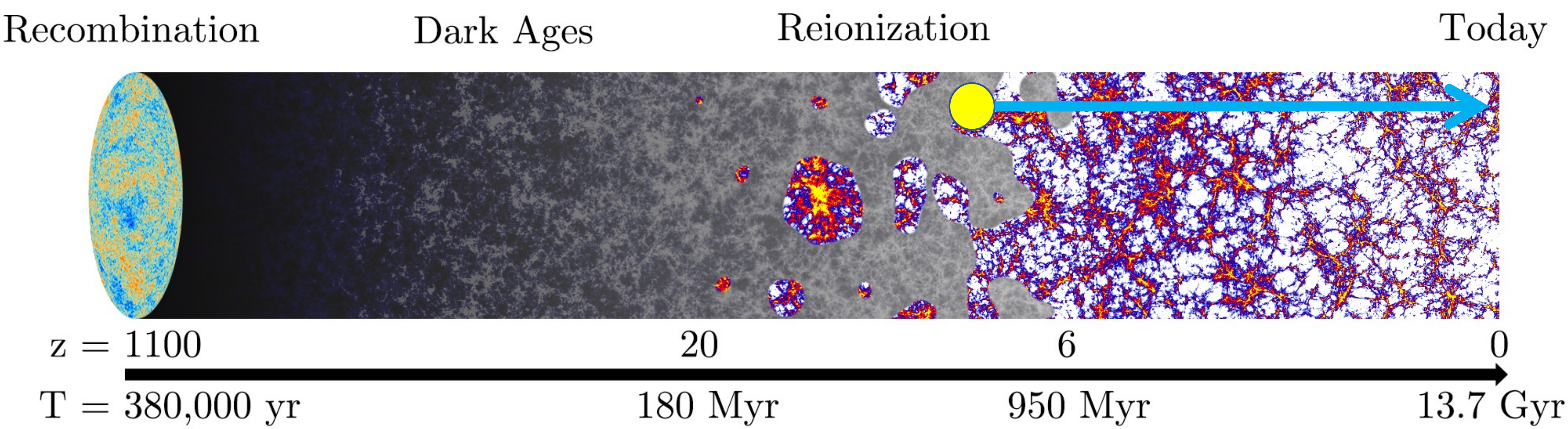
High Z QSO:
Gunn Peterson Trough

Shows up in QSOs around z~6 ….
Significant Hydrogen absorption.

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



Fan+2002

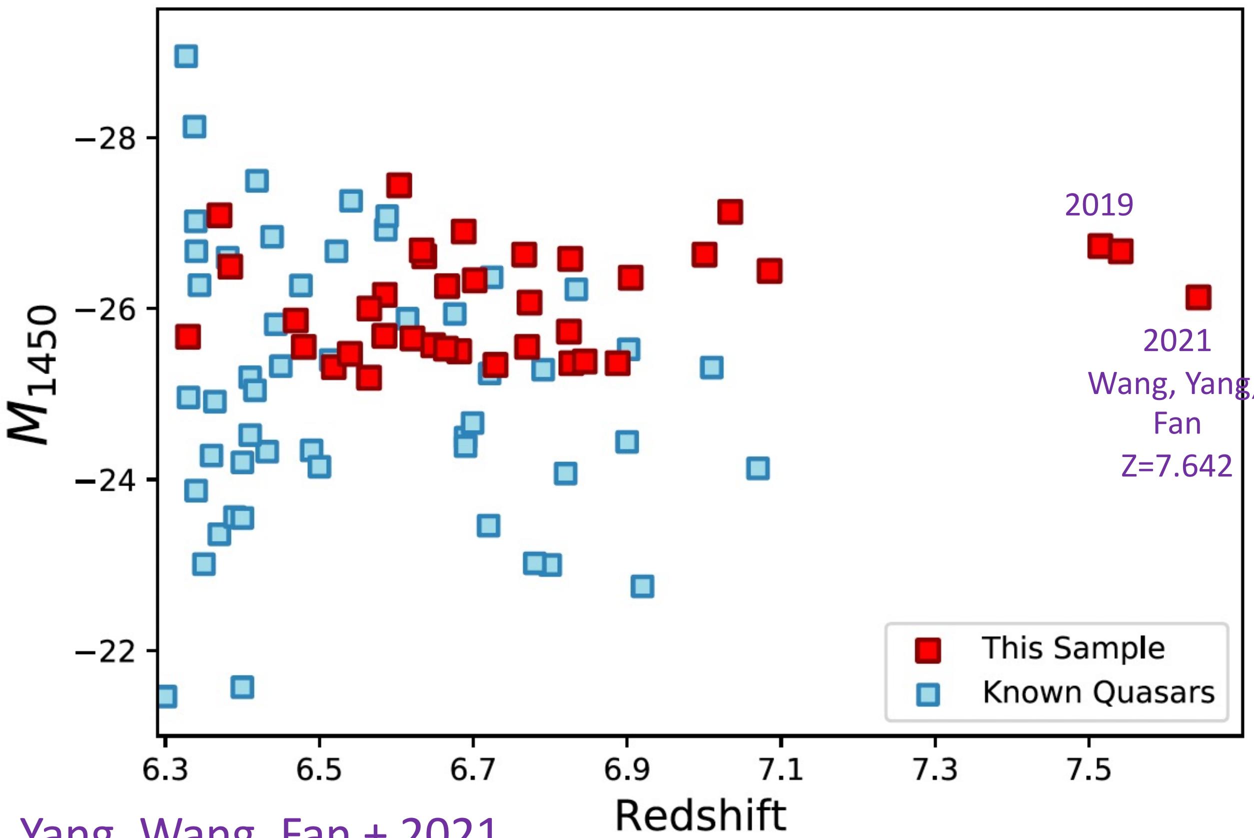


Credit: Kaurov

What were the sources of reionization?

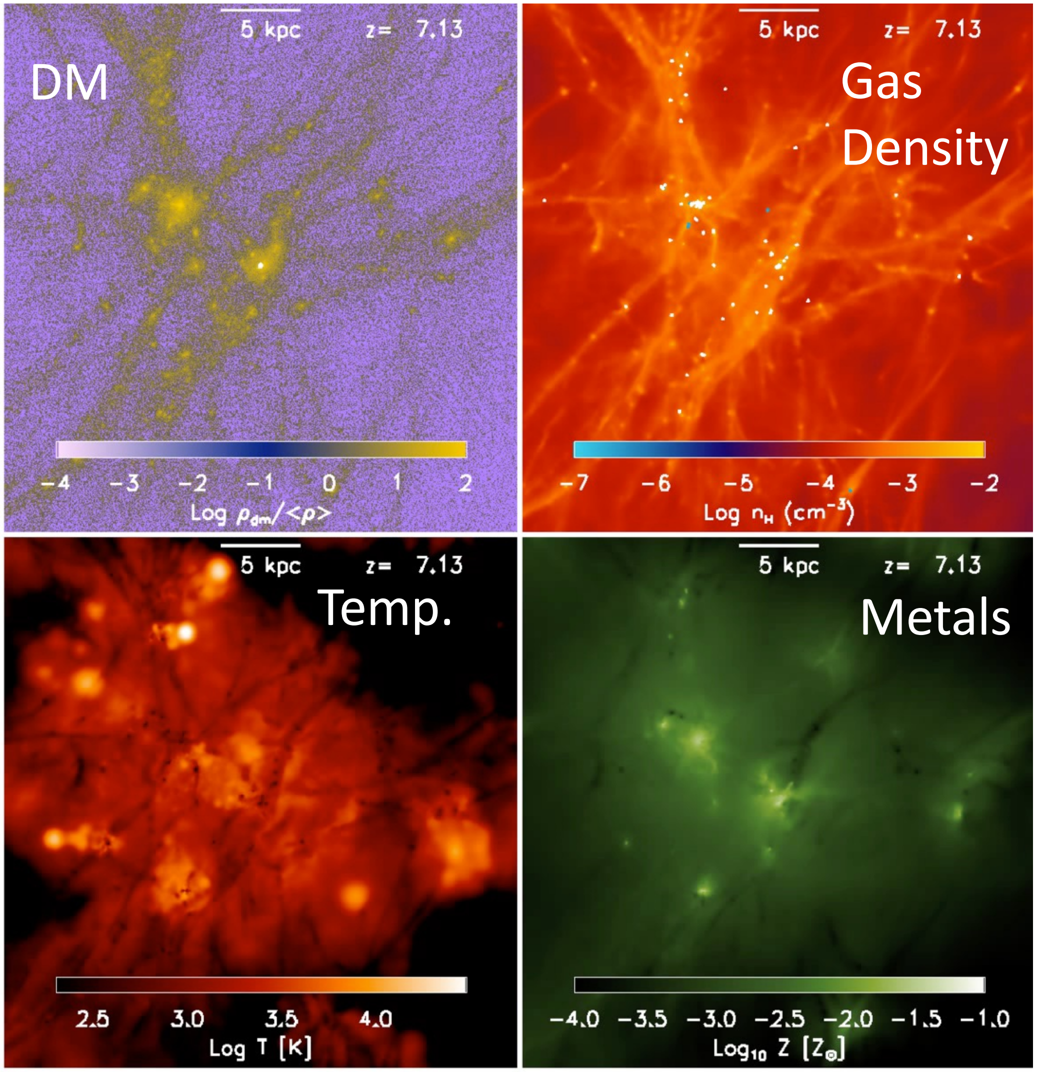
Quasars

The Astrophysical Journal, 923:262 (22pp), 2021 December 20



Yang, Wang, Fan + 2021

First Stars → Massive stars in low mass galaxies



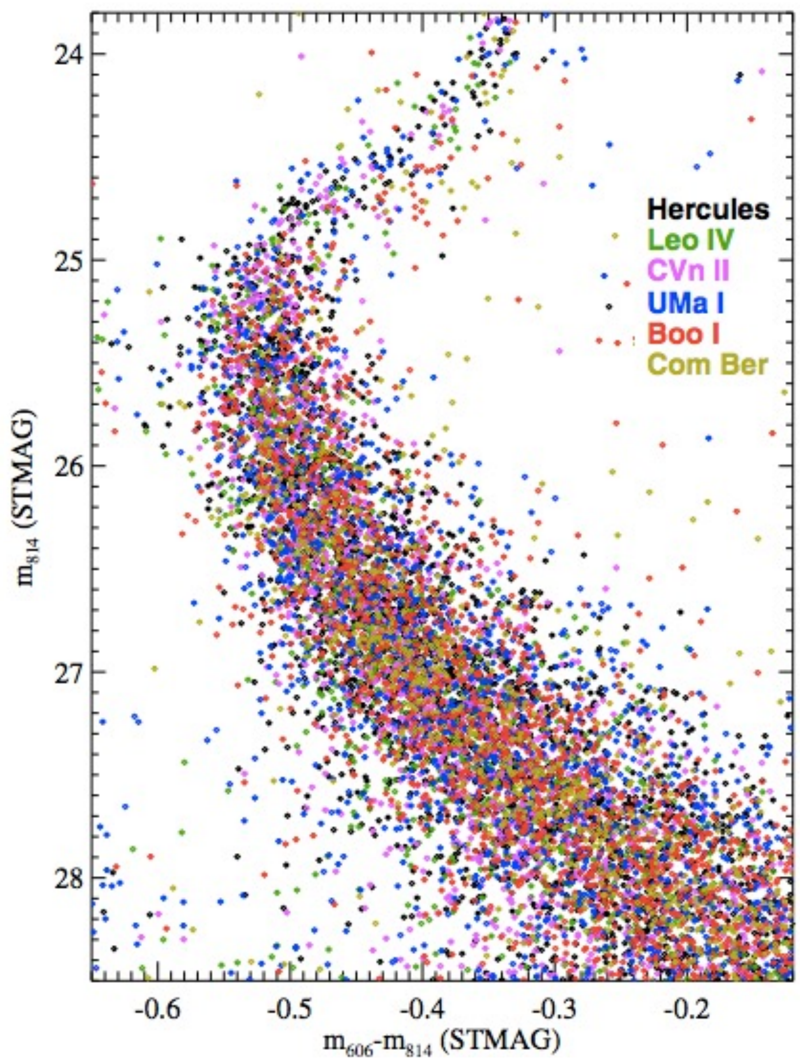
Jeon, Besla+2017

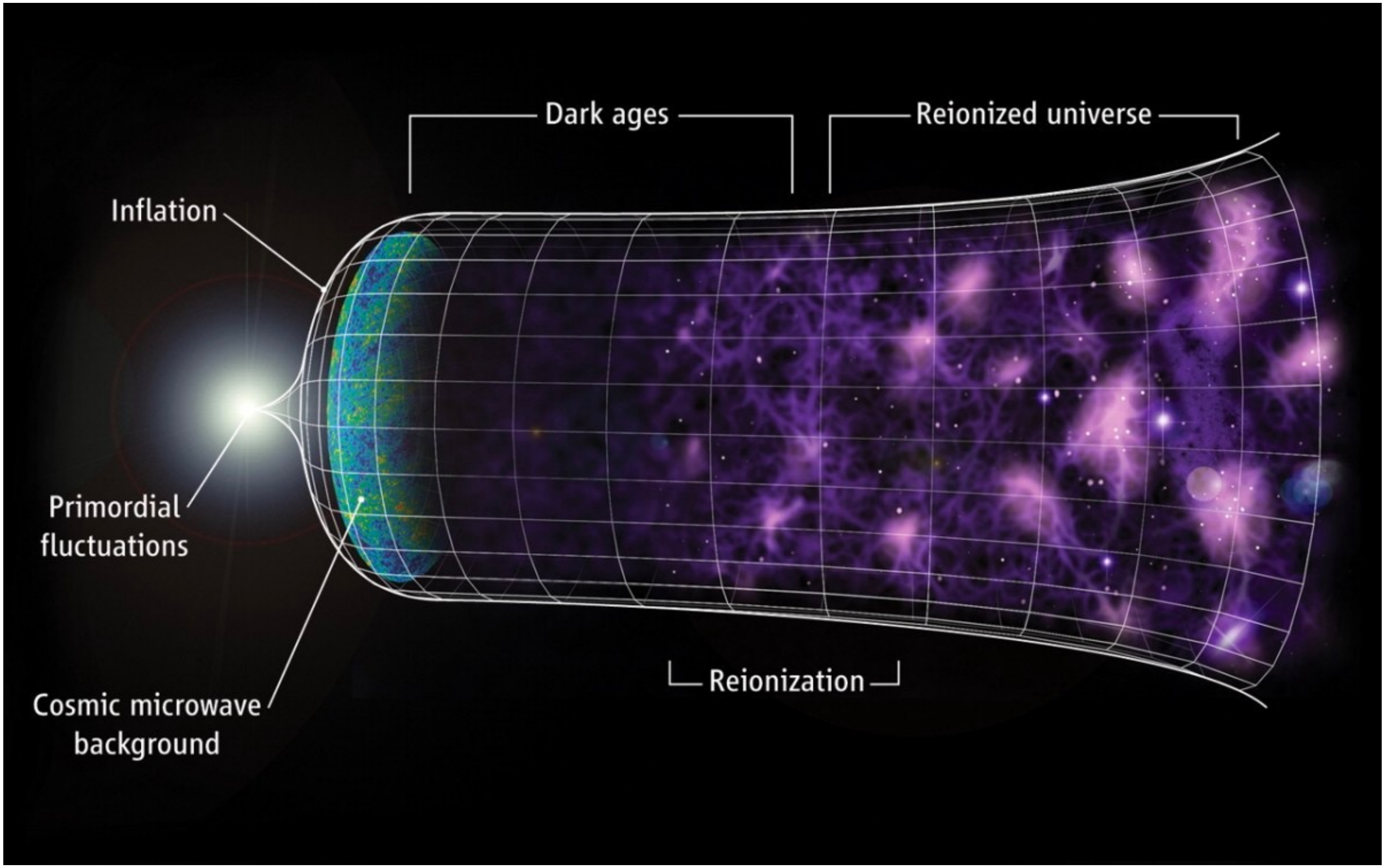
Brown +2014

CMD of each Ultra Fain 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




Dark ages
Reionized universe
Inflation
Primordial
fluctuations
Cosmic microwave
background
Reionization

End of Semester Survey