Presentation Schedule (RH114)

Dec 3 11:00-12:15

- Dean Montroy (ASU)
- Giovanna Cartagena (MIT)
- Franco Uribe Lavalle (Stanford)
- Olwyn Hagerty (UCLA)
- Alex Robinson (Caltech)
- Mason Winner (UA)
- Charles Dana (NAU)

Dec 5 11:00-12:15

- Govind Sarraf (UNM)
- Elizabeth Shields (NMSU)
- Madeline Ayling (UA)
- Sara Pezzaili (Harvard)
- Aniketh Sarkar (JHU)
- Emma Barney (UC Boulder)
- Louis Jencka (UC Boulder)

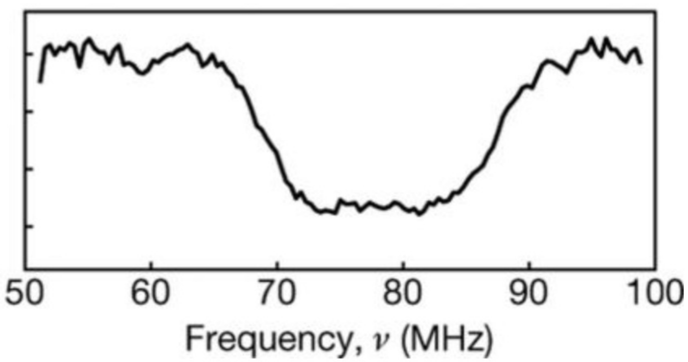
Dec 10 12:30-2:30

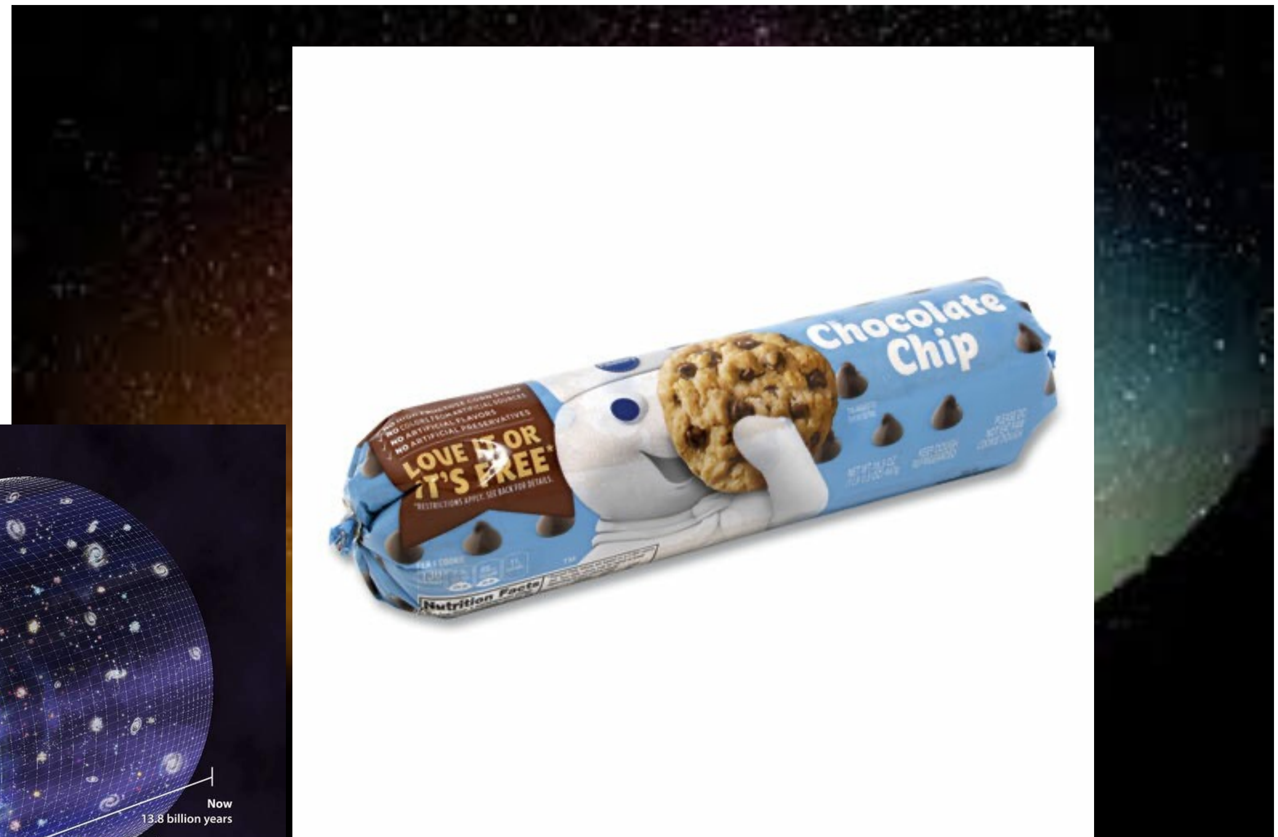
- Jacky Privette (Berkeley)
- Viktoria Aivaliotis (Caltech)
- Stephanie Paiva-Flynn (ASU)
- Juaquin Sanchez (UCLA)
- Santiago Armijo (Berkeley)
- Arnel Oczon (TTU)

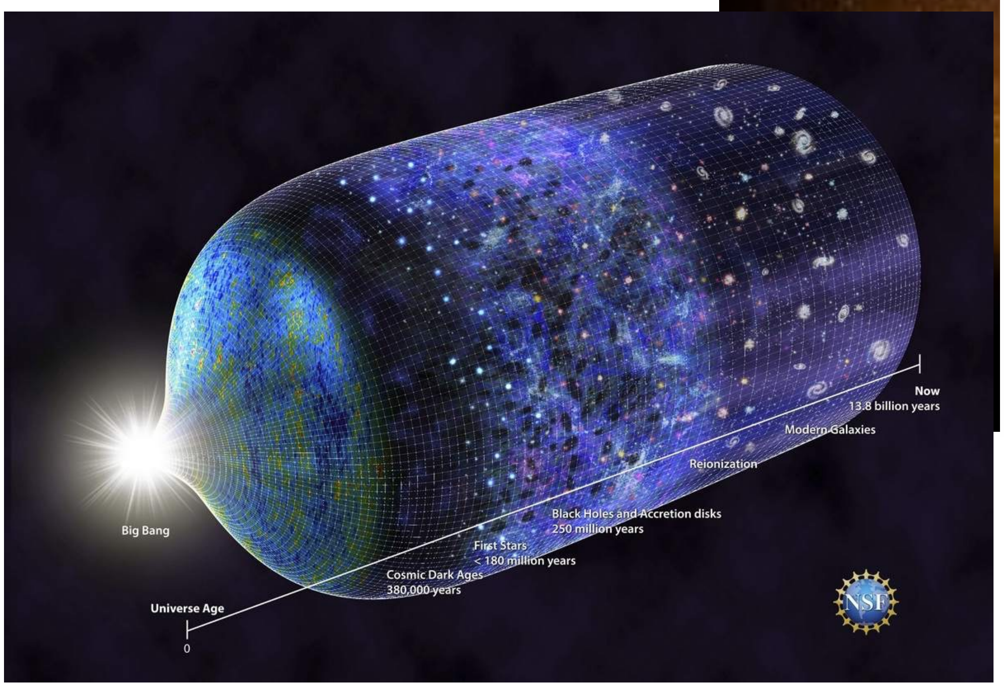
Powerpoint talk
Length = 7 min + 2 min Q&A

Send slides to me the day before and I will put them on a presentation laptop (mac).

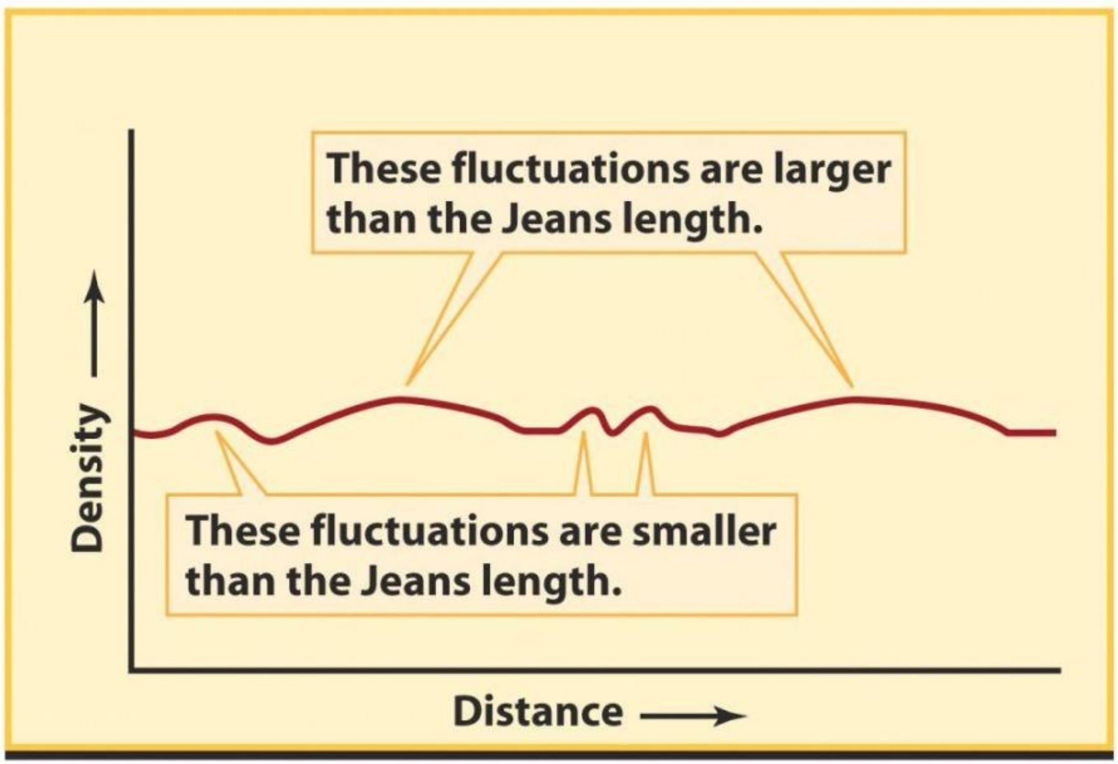
Cosmic Dawn


50
60
70
80
90
100
Frequency, ν (MHz)


Chocolate Chip
LOVE IT OR IT'S FREE
Nutrition Facts

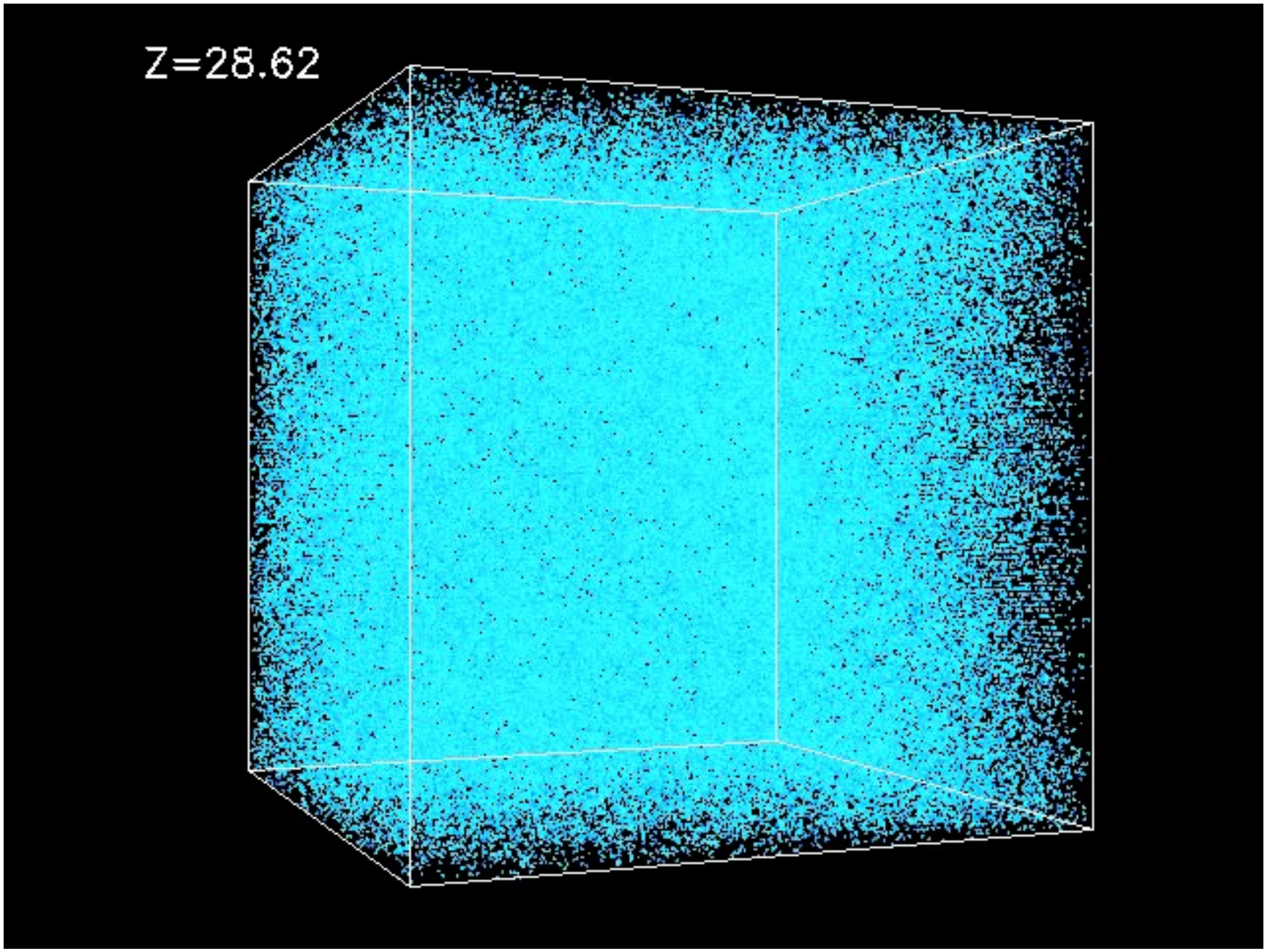

Now
13.8 billion years
Modern Galaxies
Reionization
Black Holes and Accretion disks
250 million years
First Stars
< 180 million years
Cosmic Dark Ages
380,000 years
Big Bang
Universe Age
0
NSF

- Anisotropies in the CMBR temperature indicate density ripples at the time of decoupling.
- These are seeds that grow to form galaxies.
- Which ripples will collapse first?

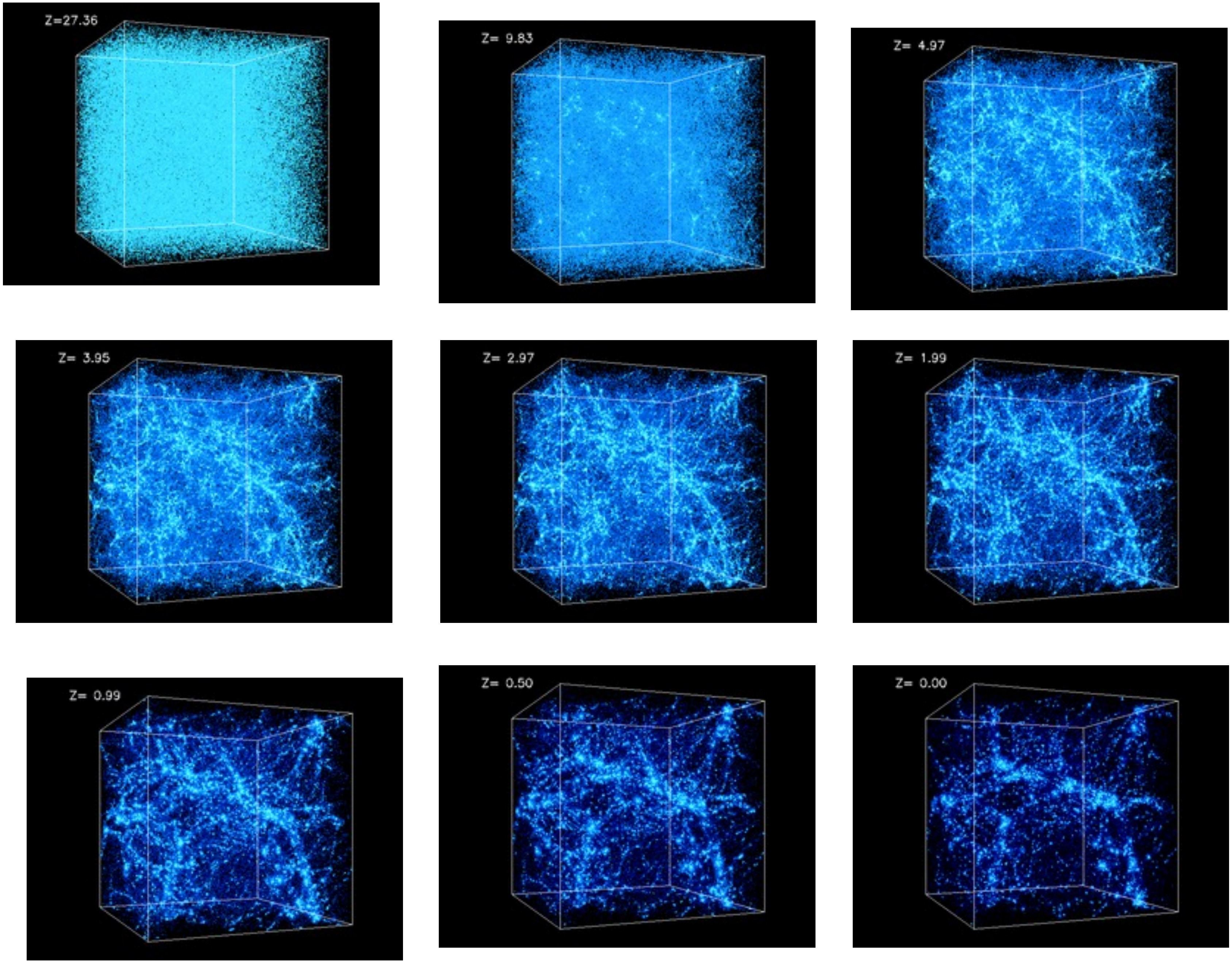


At an early time

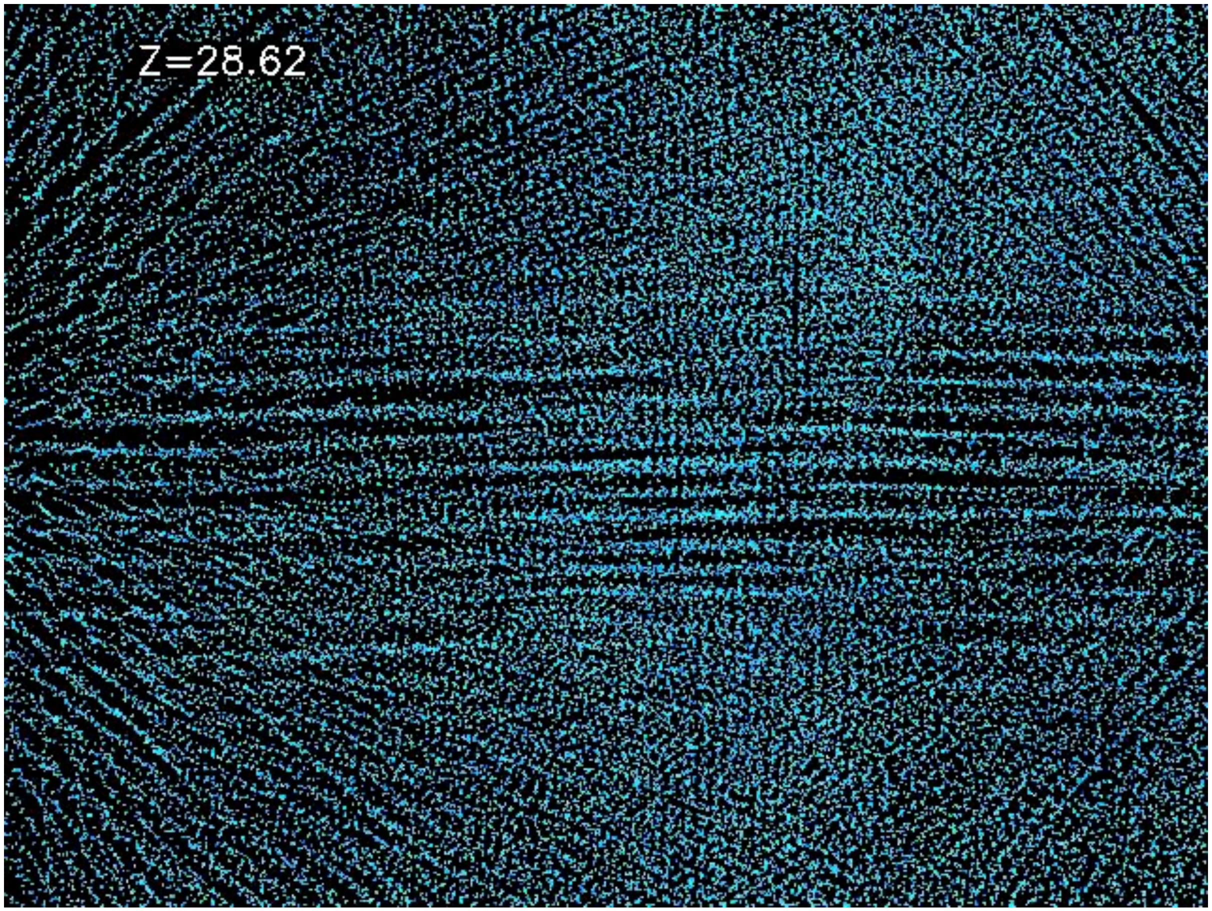
Structure formation simulation



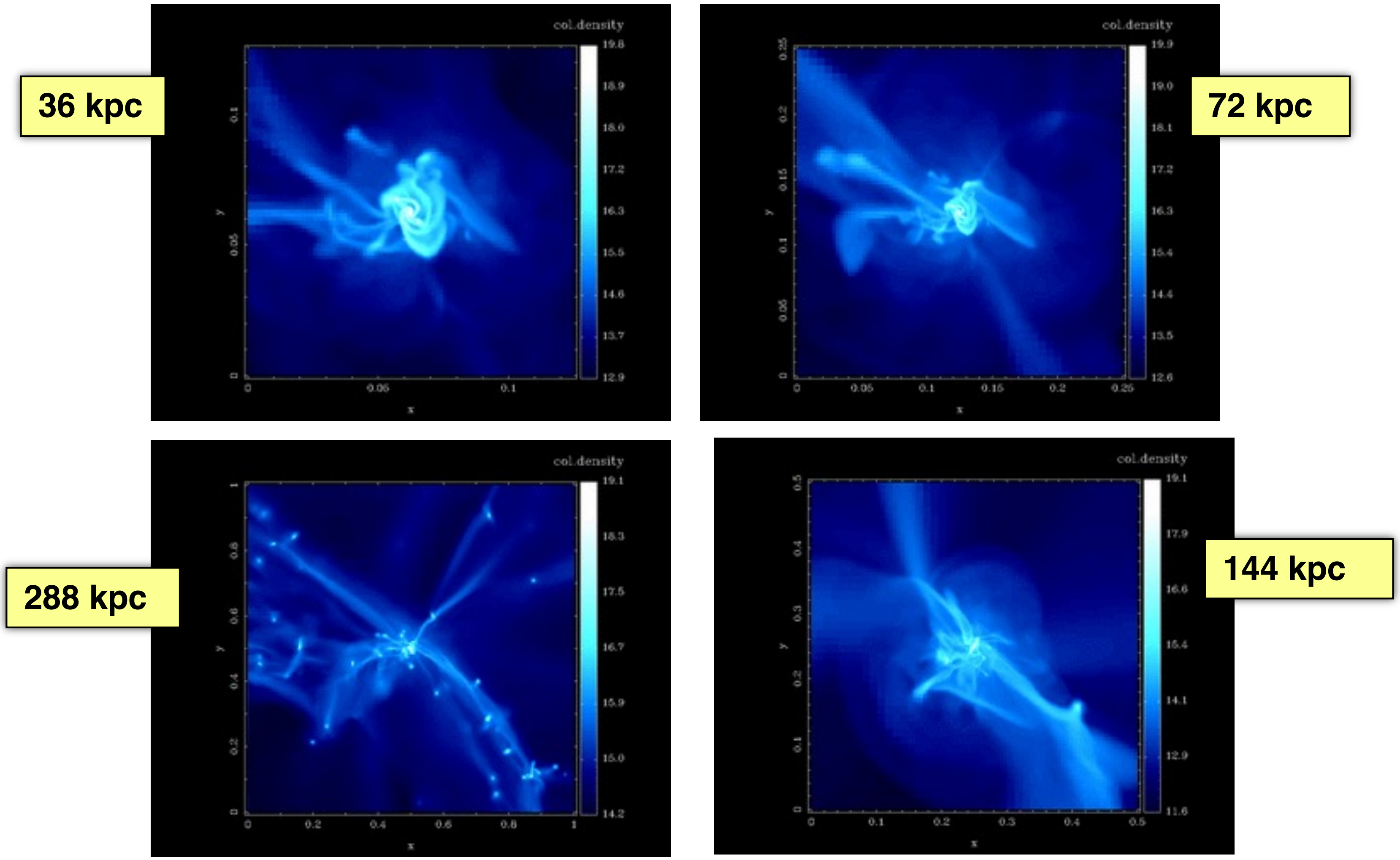
Filaments: formation ceases at z=1, why?



Groups of galaxies

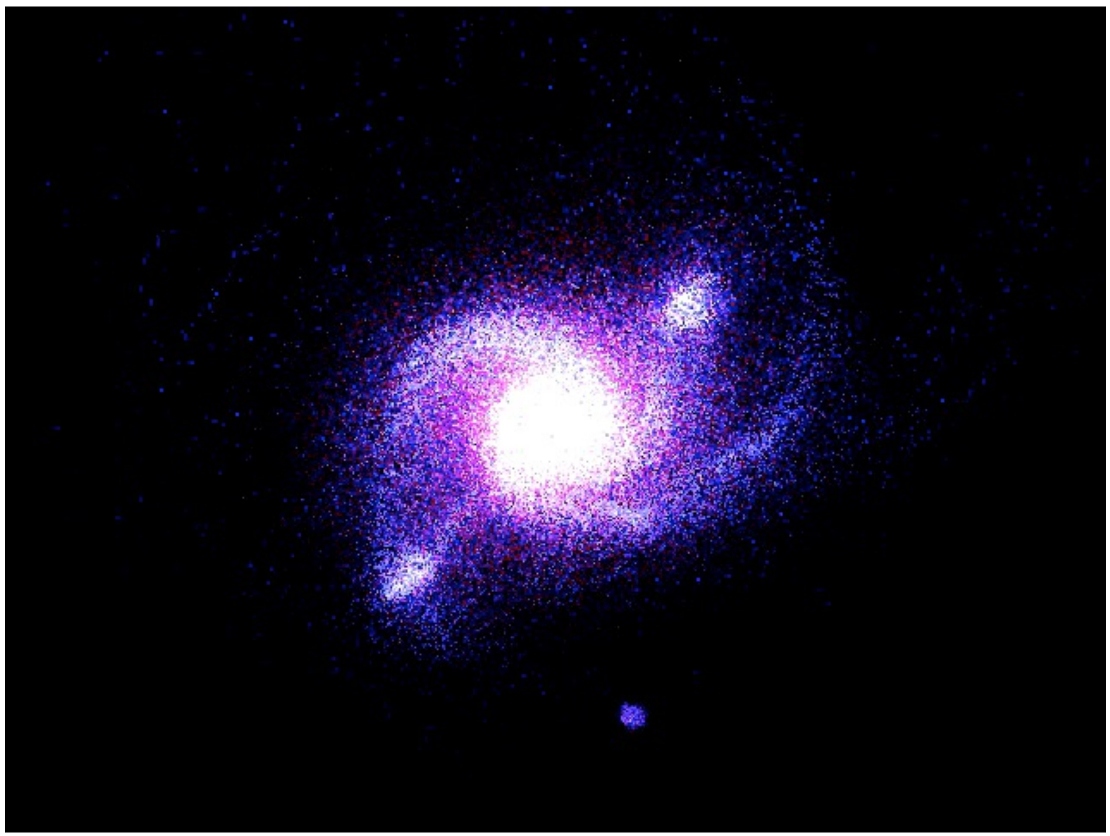


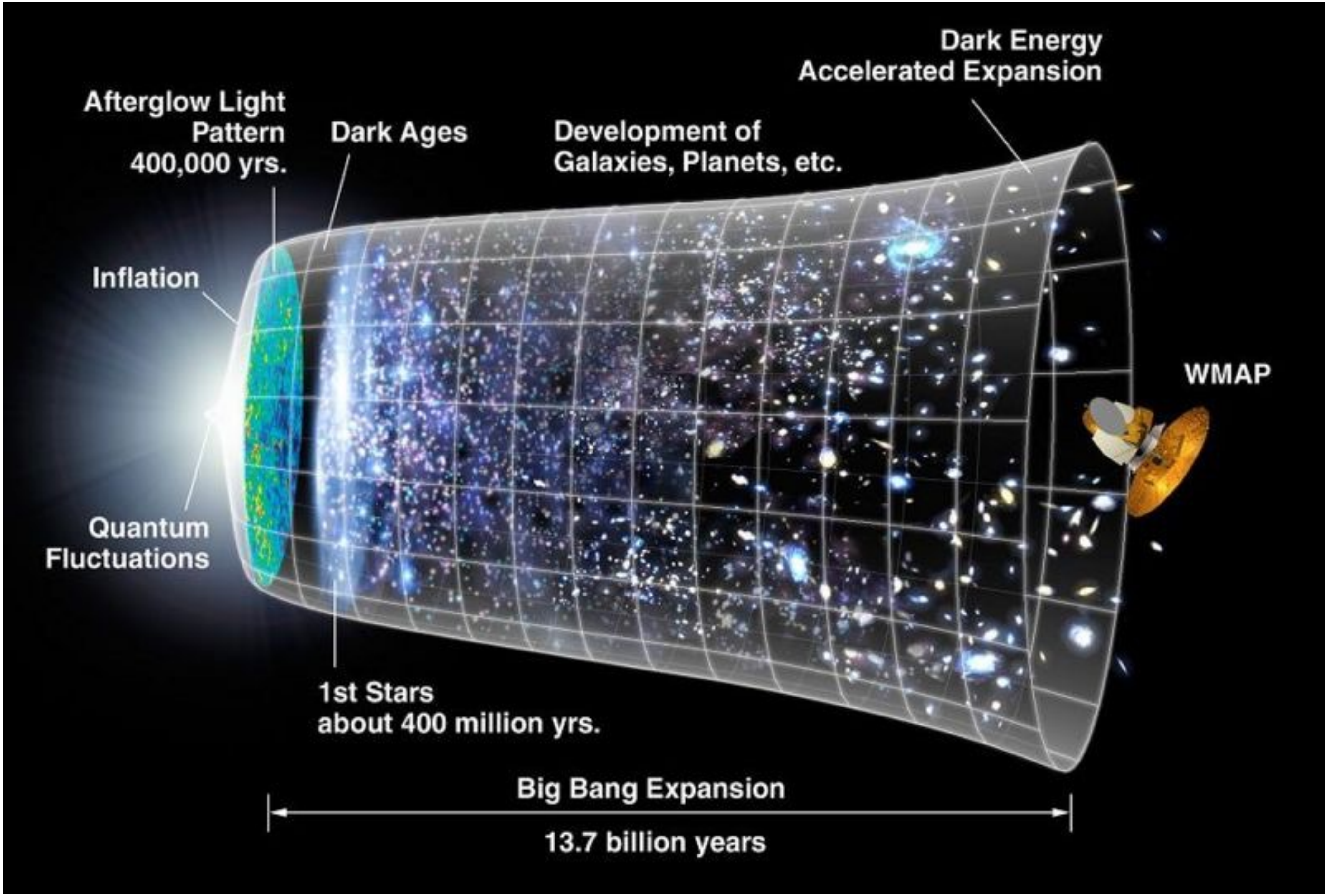
Formation of a galaxy



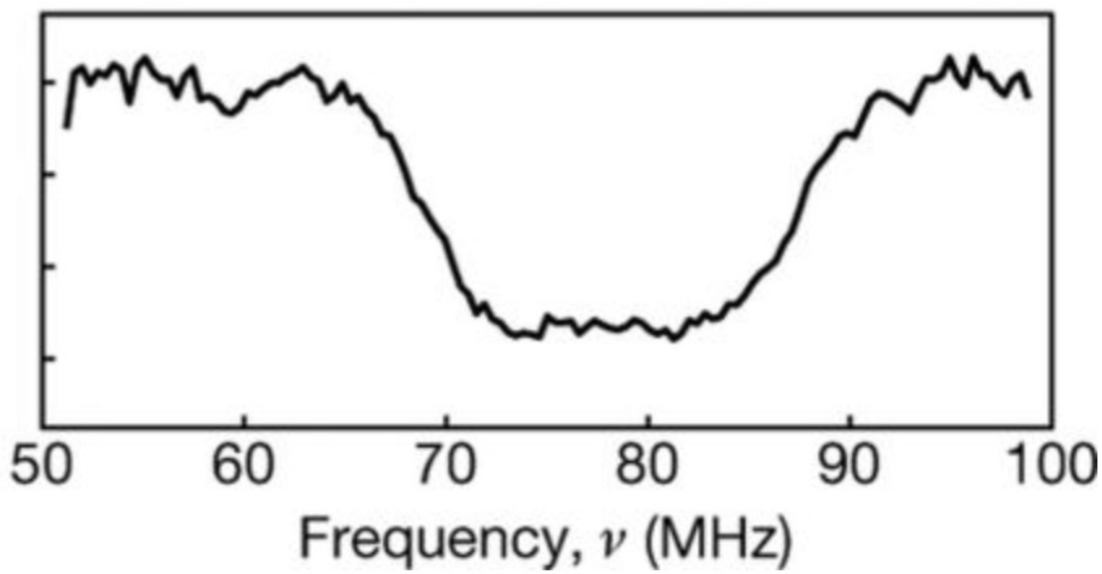
Forms in high density peaks where several large scale filaments intersect.

- Disk is forming stars actively.
- Unlike gas, stars can be heated by frequent collisions with other galaxies (common at these epochs).
- => stellar disk somewhat thicker than gas disk.




Dark Energy
Accelerated Expansion
Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years

Cosmic Dawn

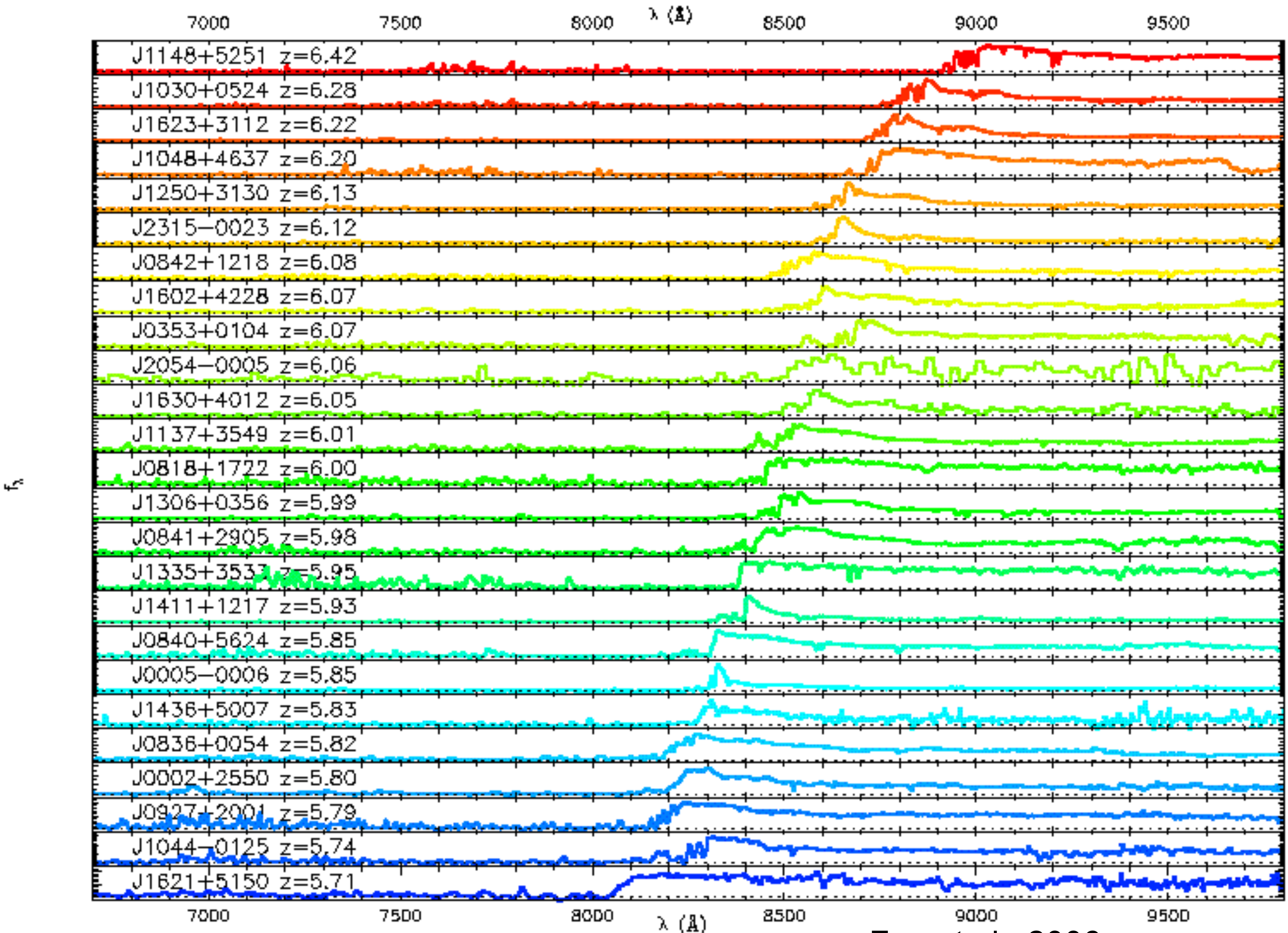


z=20 z=15

1+z = 1420 MHz / ν_obs

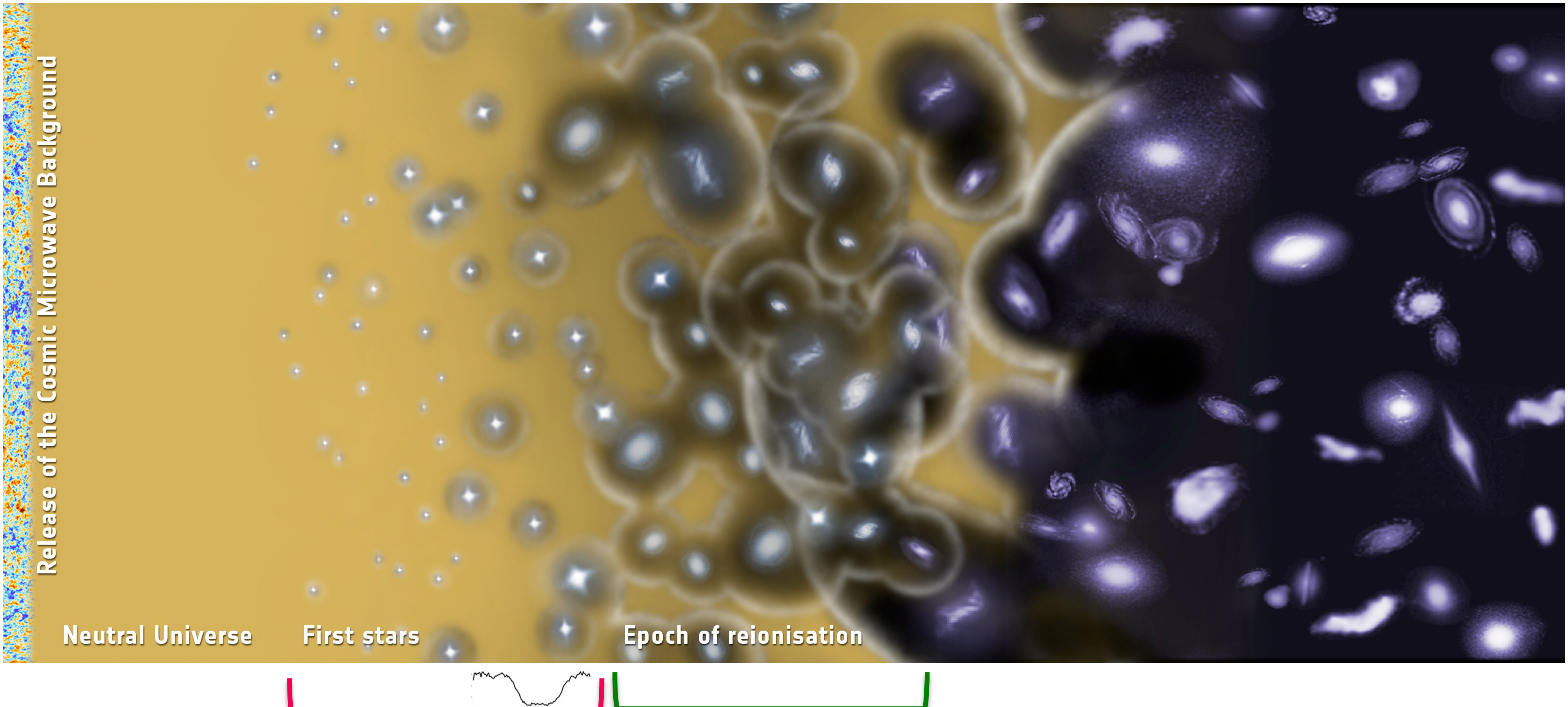
First stars at z=20 when universe is 180 Million years old

Bowman et al. 2018



Fan et al. 2006

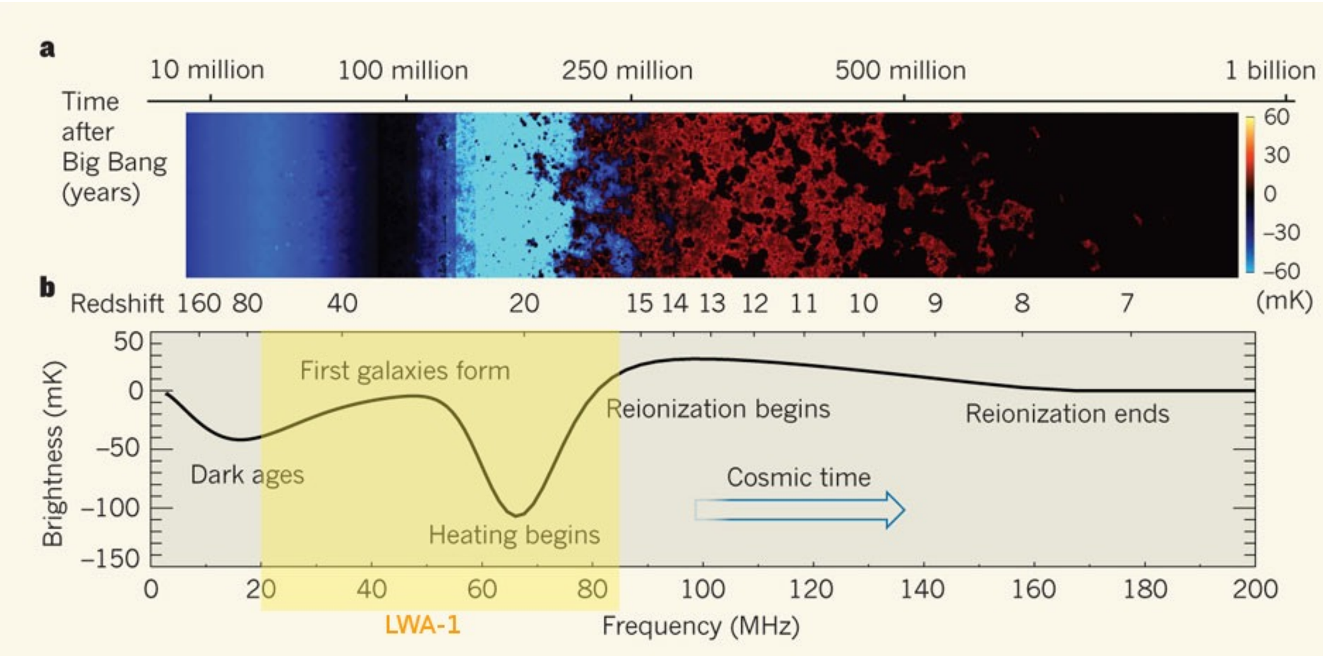
Epoch of Reionization



z =30-14
45-100 MHz

z = 14-6
100-200 MHz

Cosmic Dawn



The predicted brightness temperature of the 21cm line from the HI gas is displayed as a function of time, redshift & frequency.

Figure 1 from Pritchard & Loeb, 2010 Nature 469 772

$$\delta T_b \approx 27 x_{HI} \sqrt{\frac{1+z}{10}} \left(\frac{T_s - T_r}{T_s} \right) \text{ mK}$$

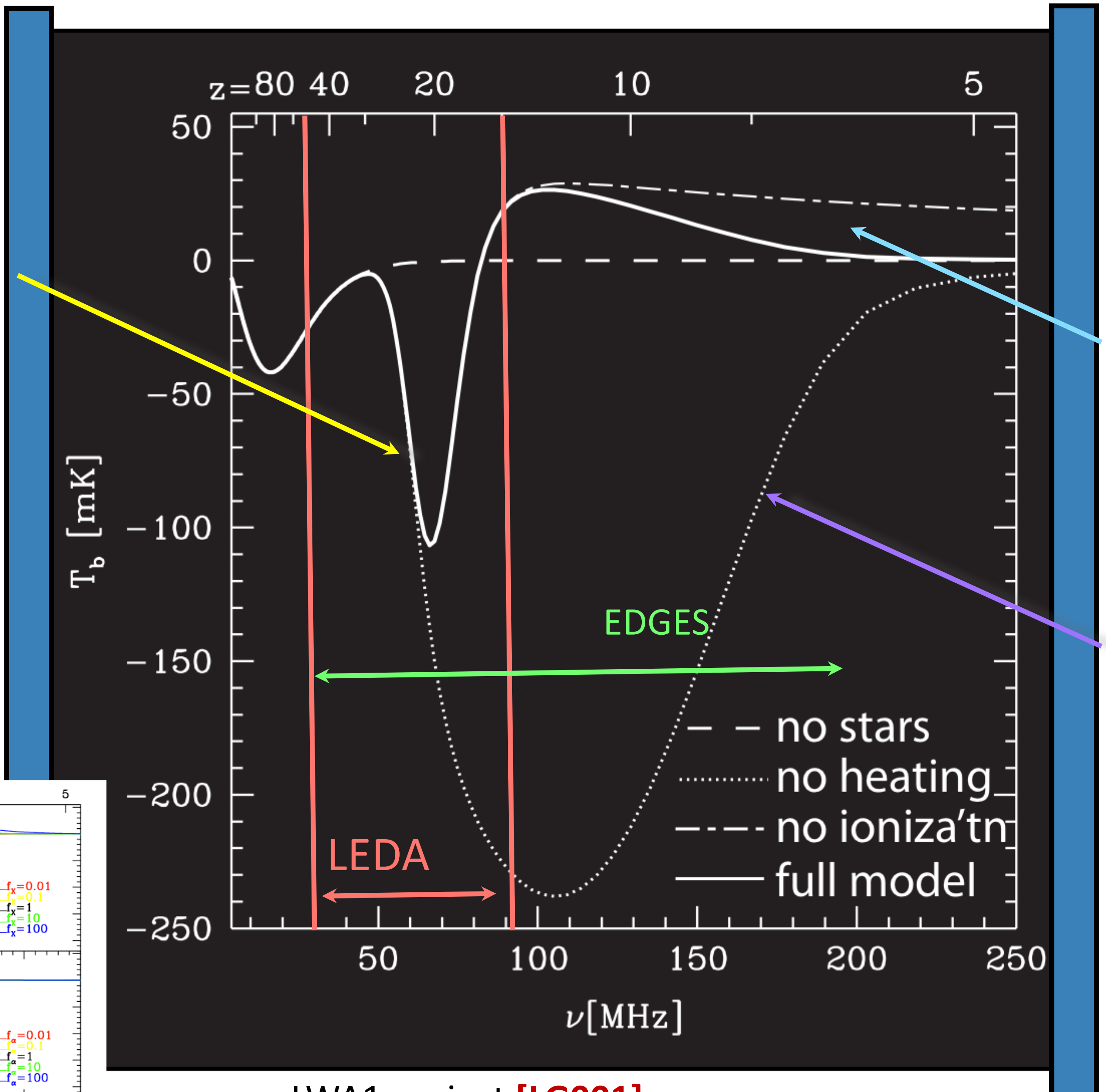
The Dark Ages through Cosmic Dawn encompasses the formation of the 1st galaxies & black holes. The LWA offers a unique window into this era.

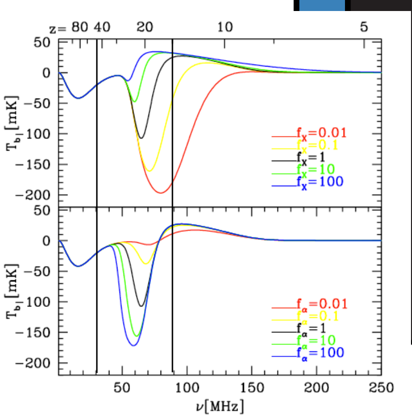
$$T_s^{-1} = \frac{T_\gamma^{-1} + x_\alpha T_\alpha^{-1} + x_c T_K^{-1}}{1 + x_\alpha + x_c}$$

CMB Photons   Lyman-α Photons   Collisions

Cosmic Dawn

Lyman-α photon production (likely from stars) determines magnitude of decoupling from the dashed curve



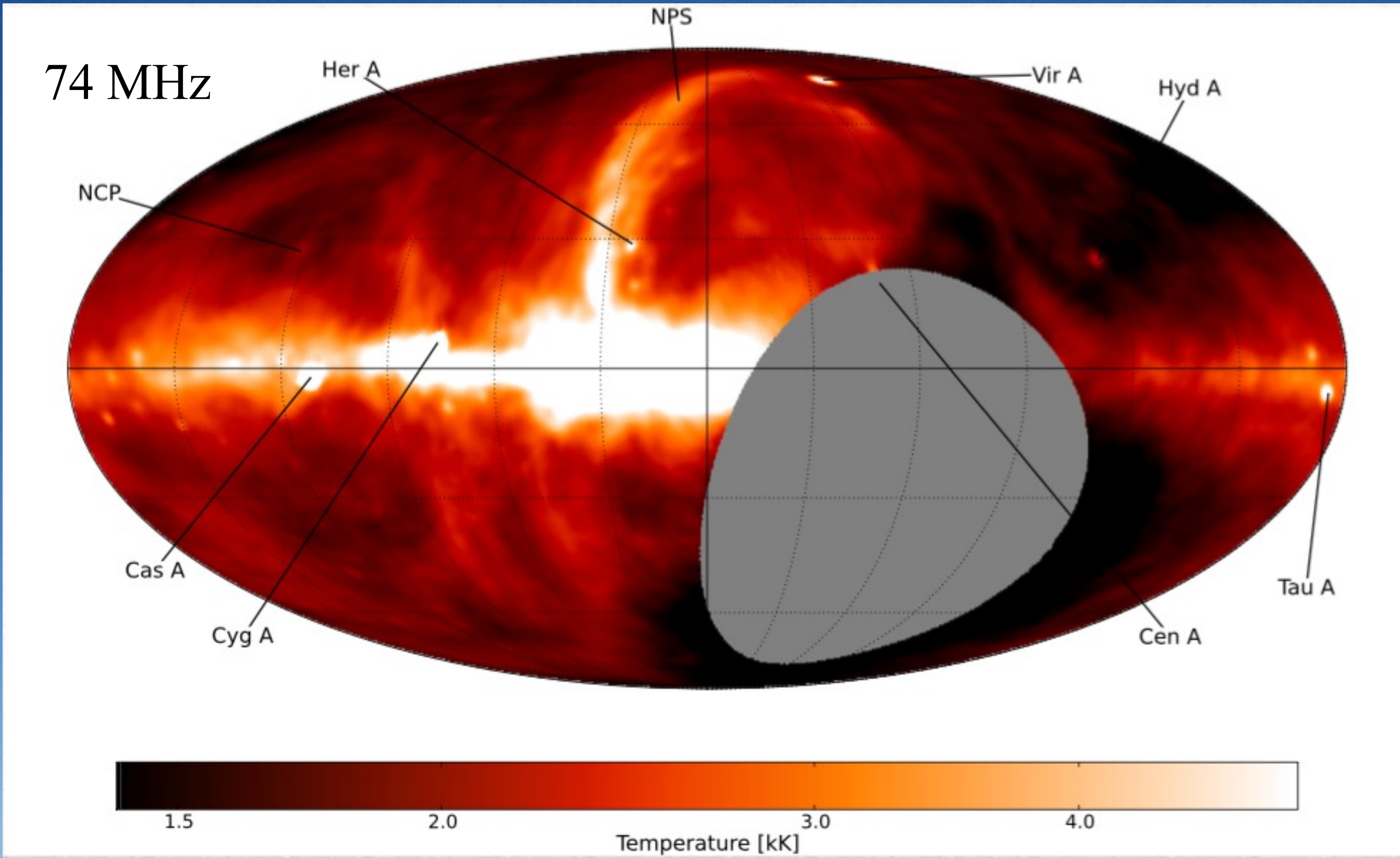


LWA1 project **[LG001]**

Production of ionizing photons determines the difference between dash-dot and solid curves

Case where IGM not reheated prior to reionization. It takes just 10^{-3} eV per baryon to significantly change this curve.

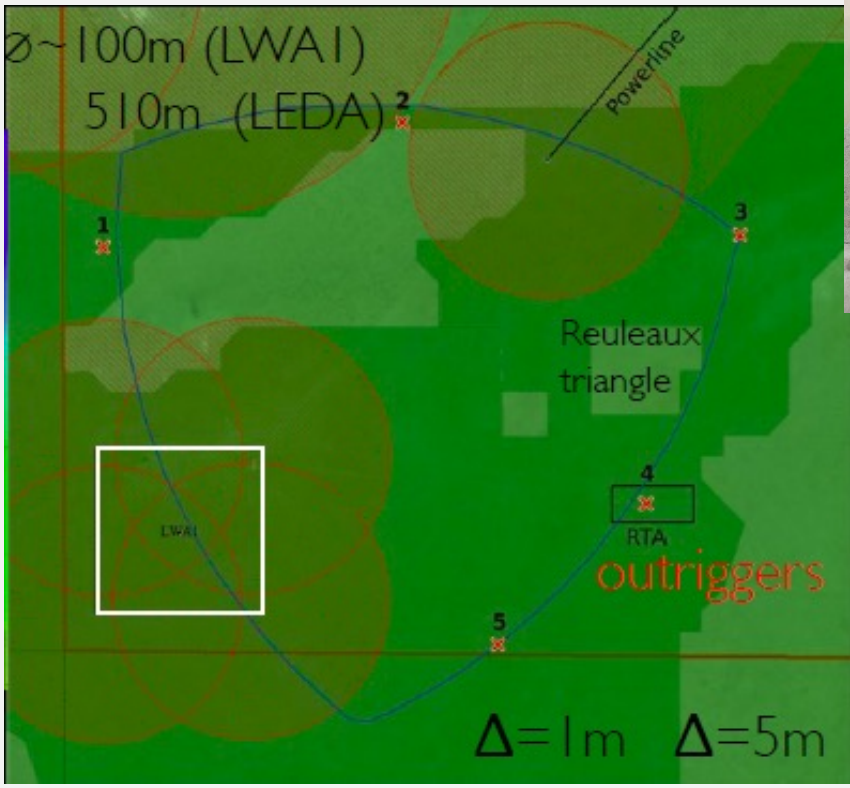
THE SKY



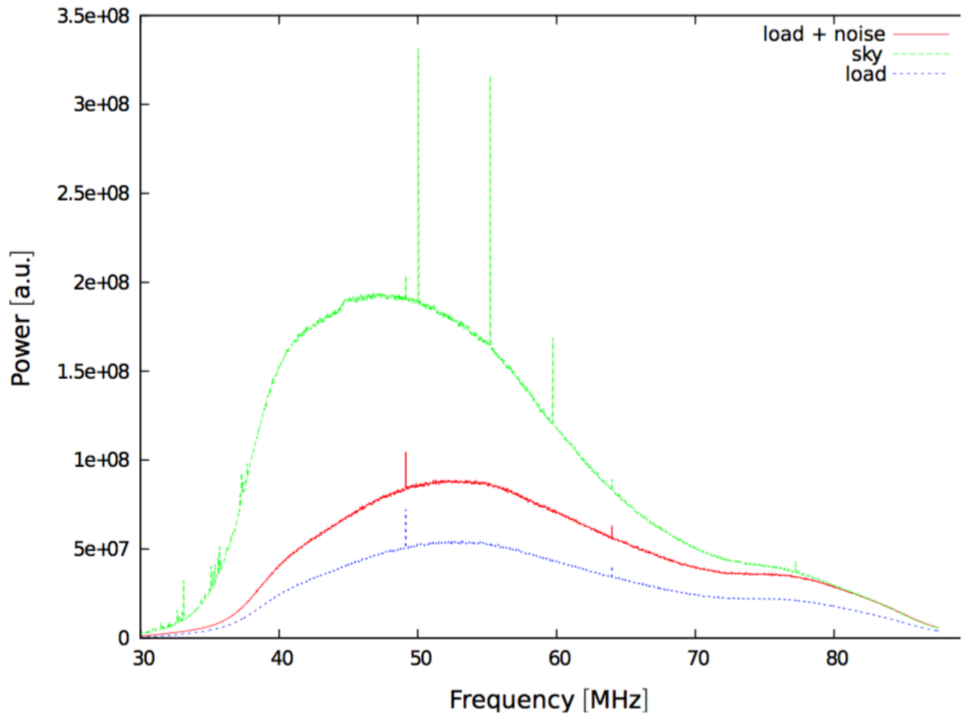
Dowell et al. 2017

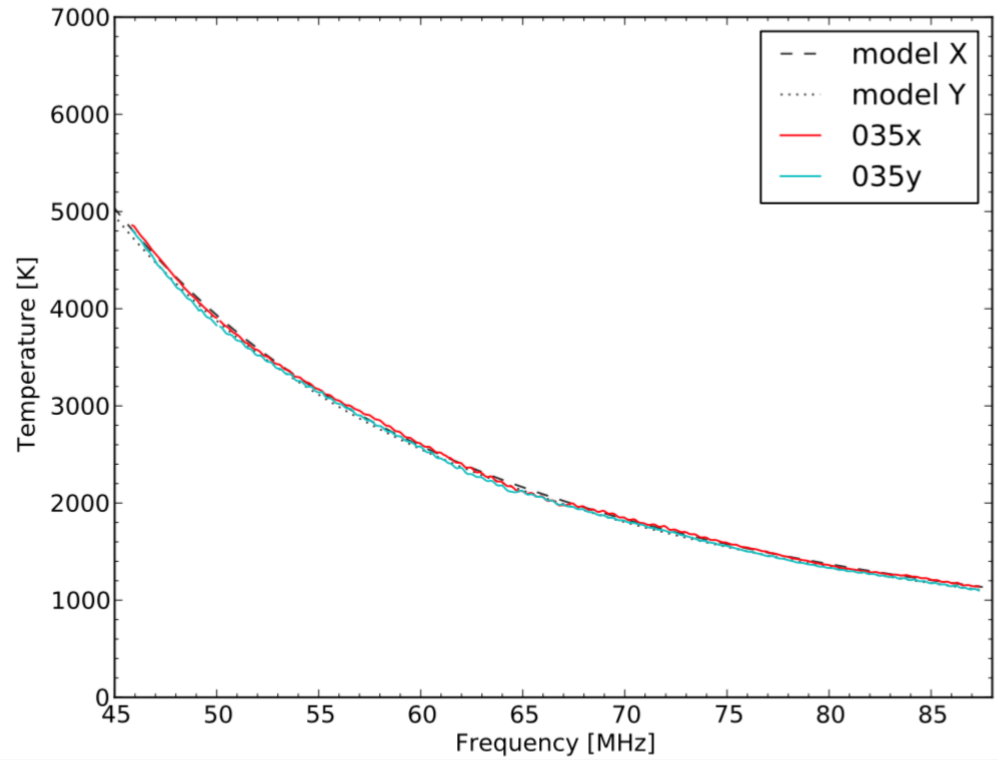
LEDA –outriggers for LWA1

Construction of 4 additional outriggers.



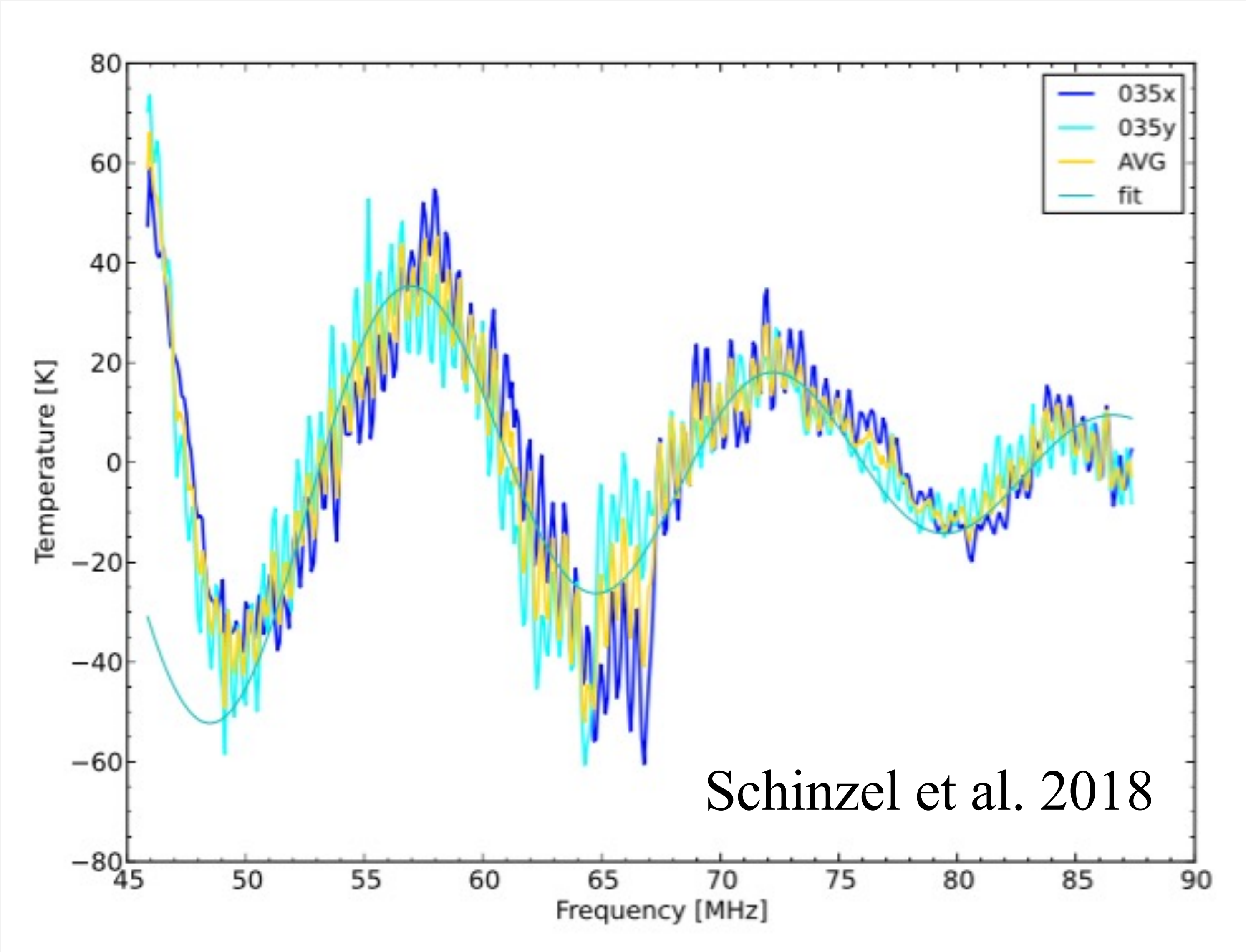
LEDA – results from NM



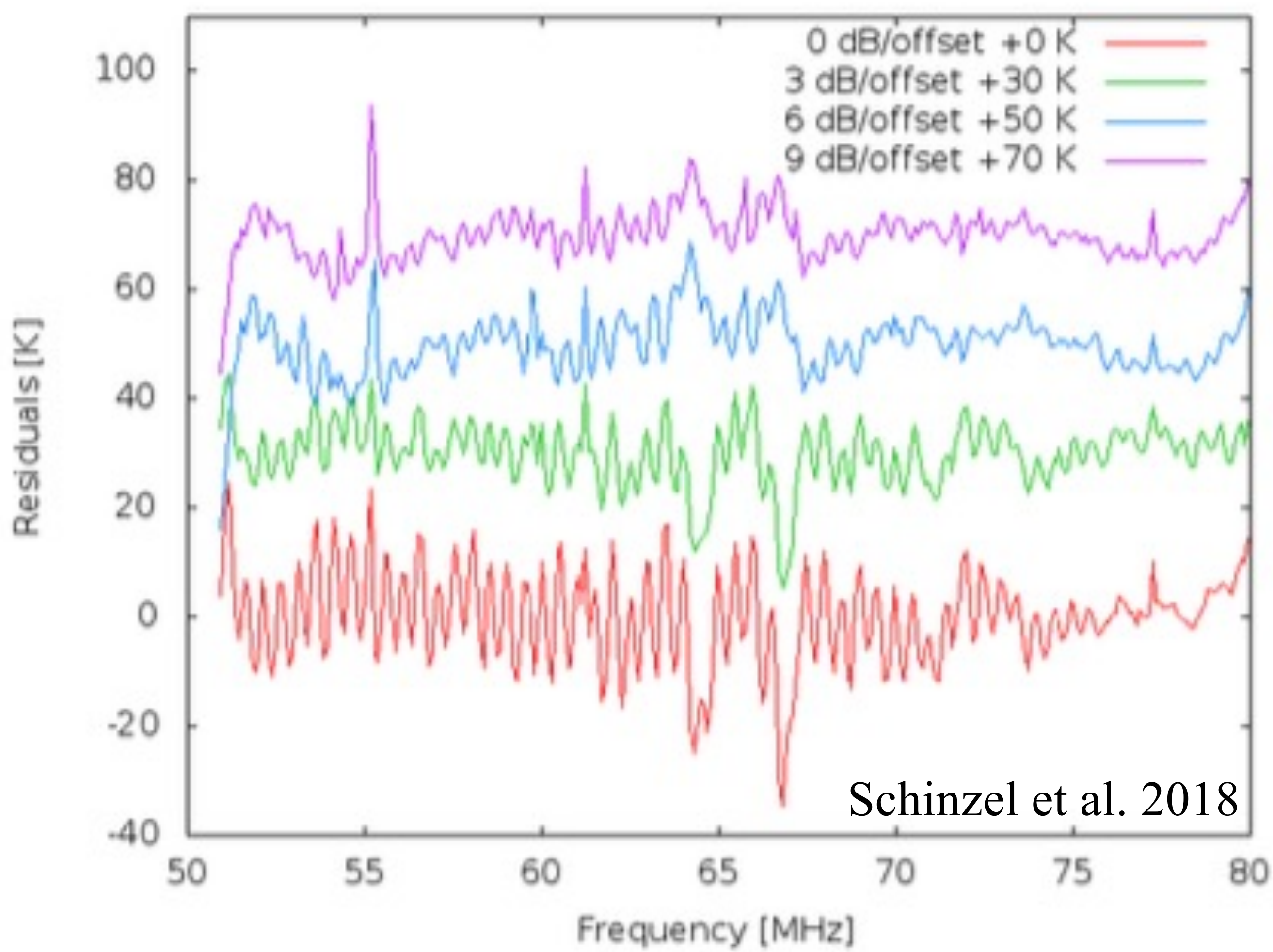


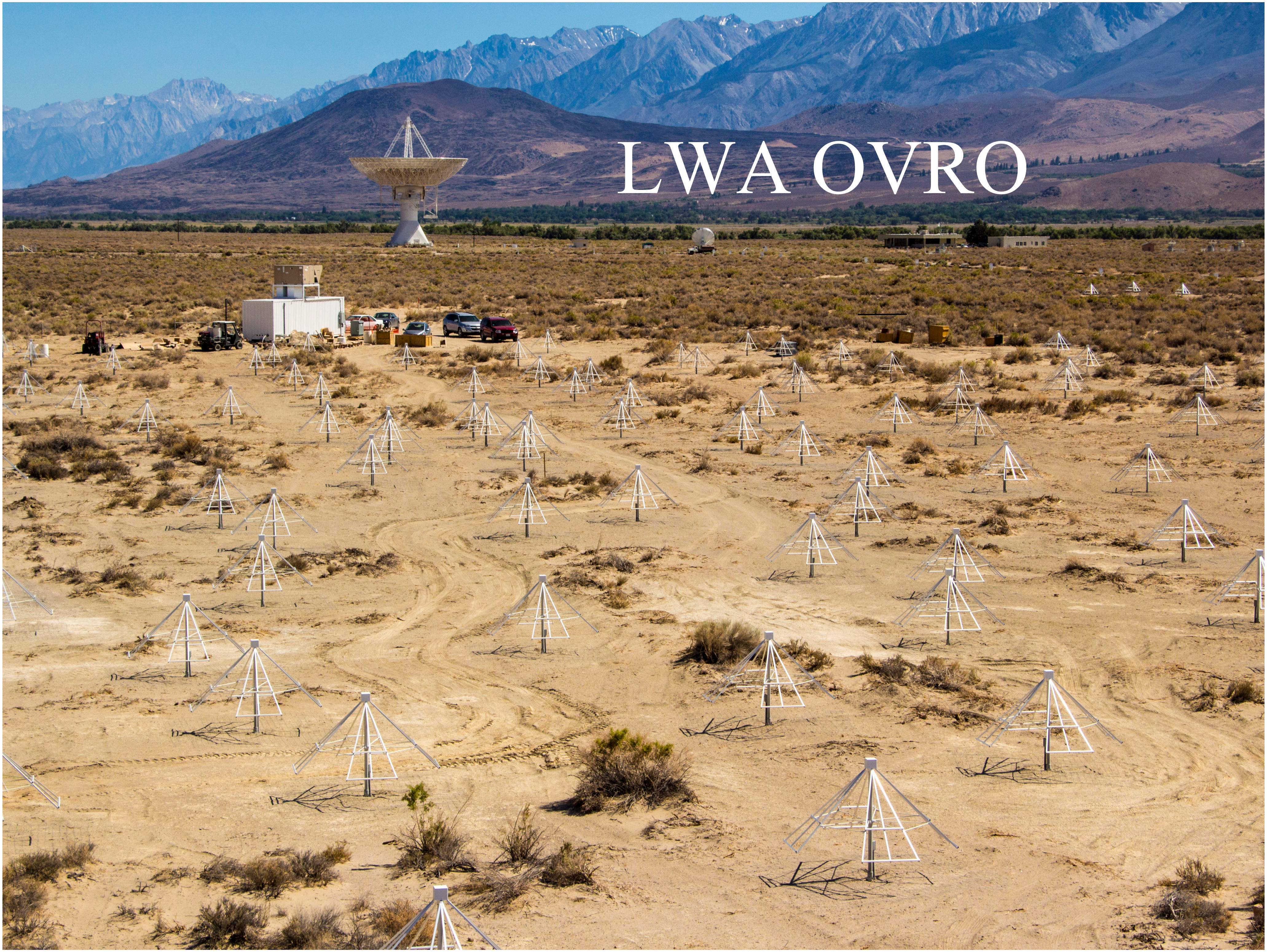
Schinzel et al. 2018

LEDA – results from NM

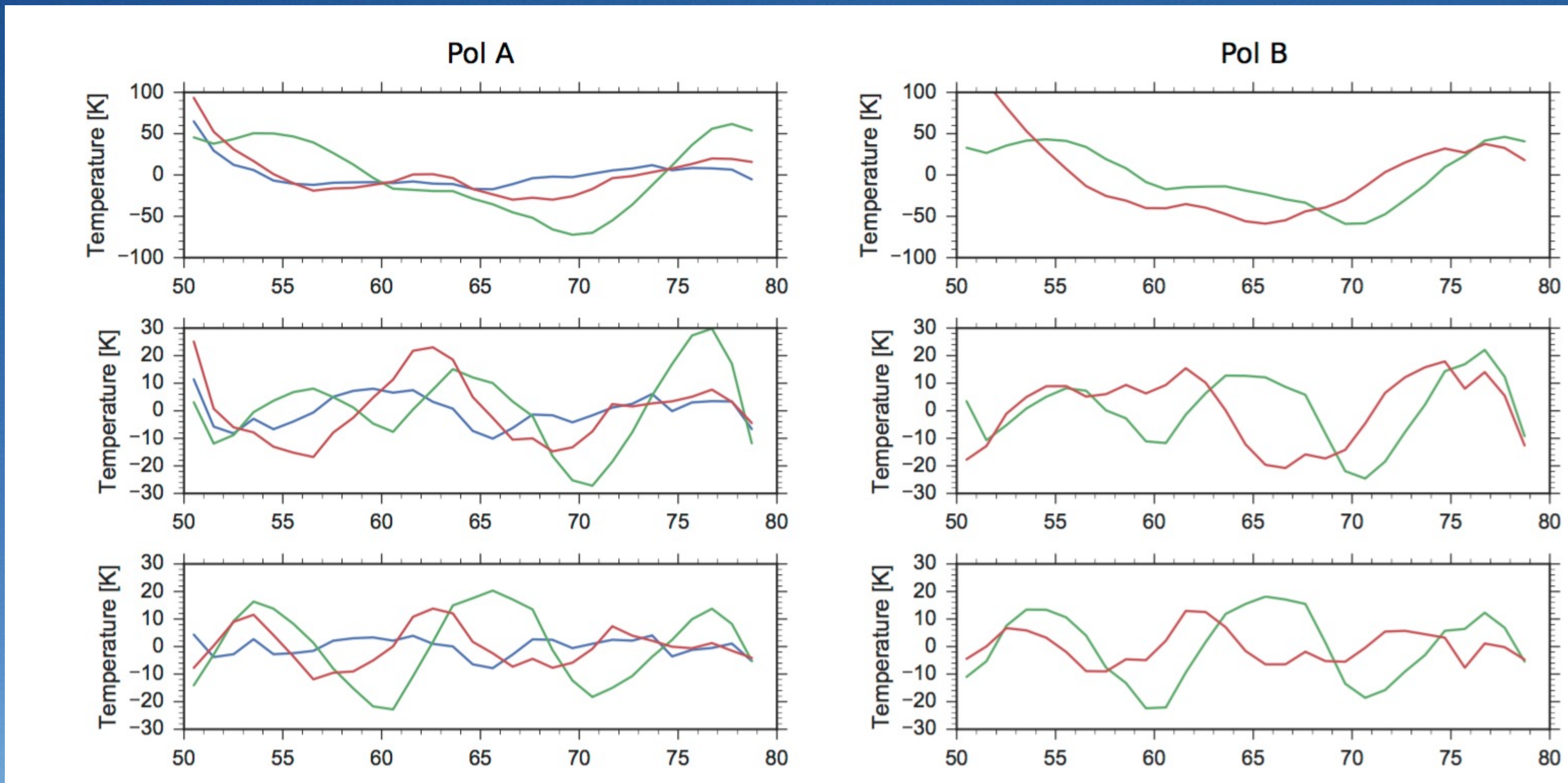


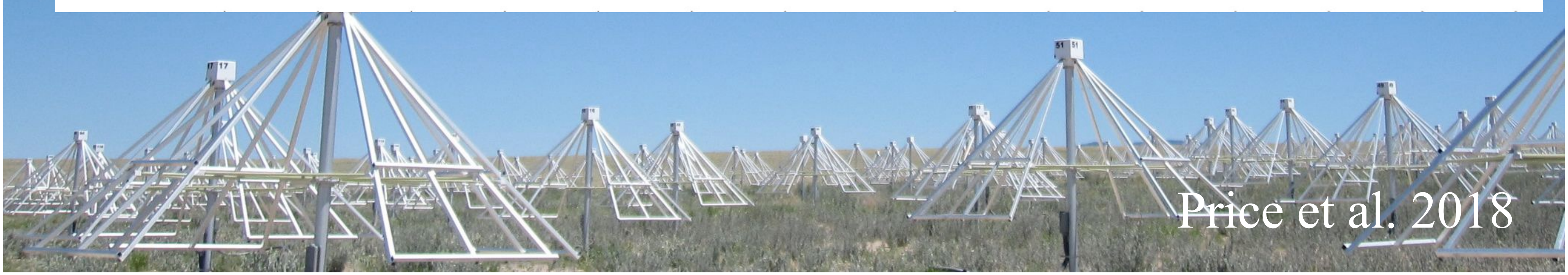
LEDA – results from NM




LWA OVRO

LEDA at OVRO

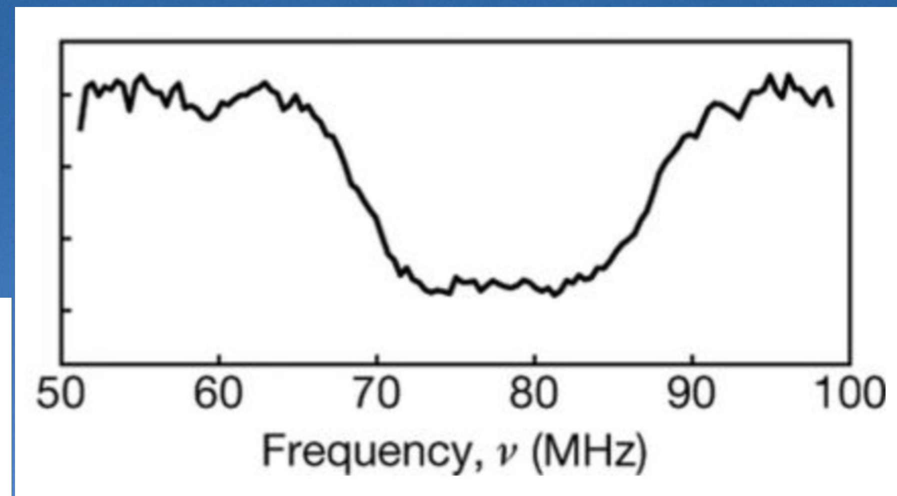


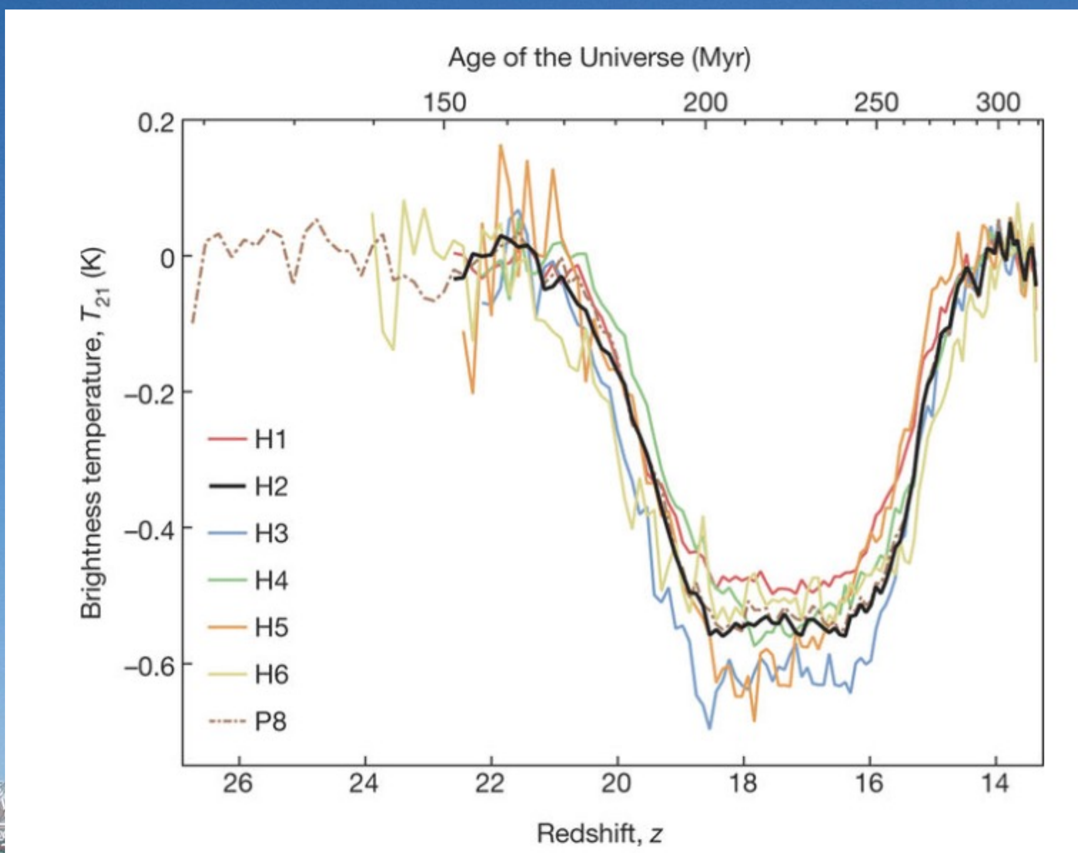


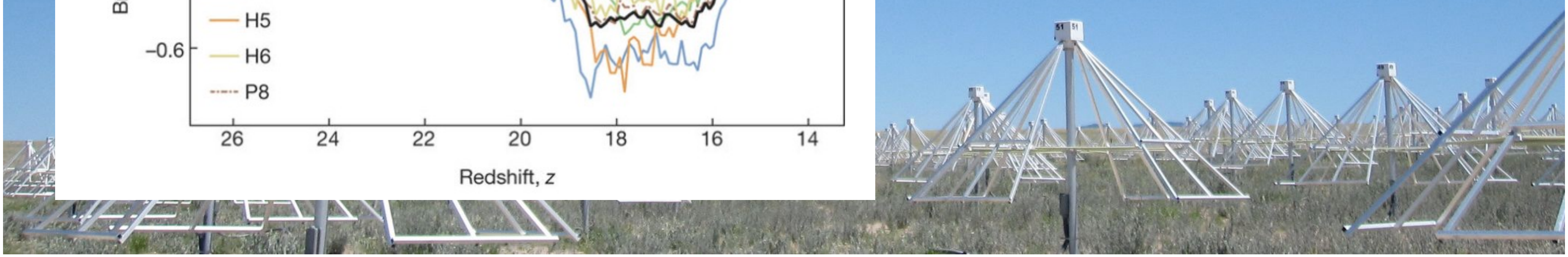
Price et al. 2018

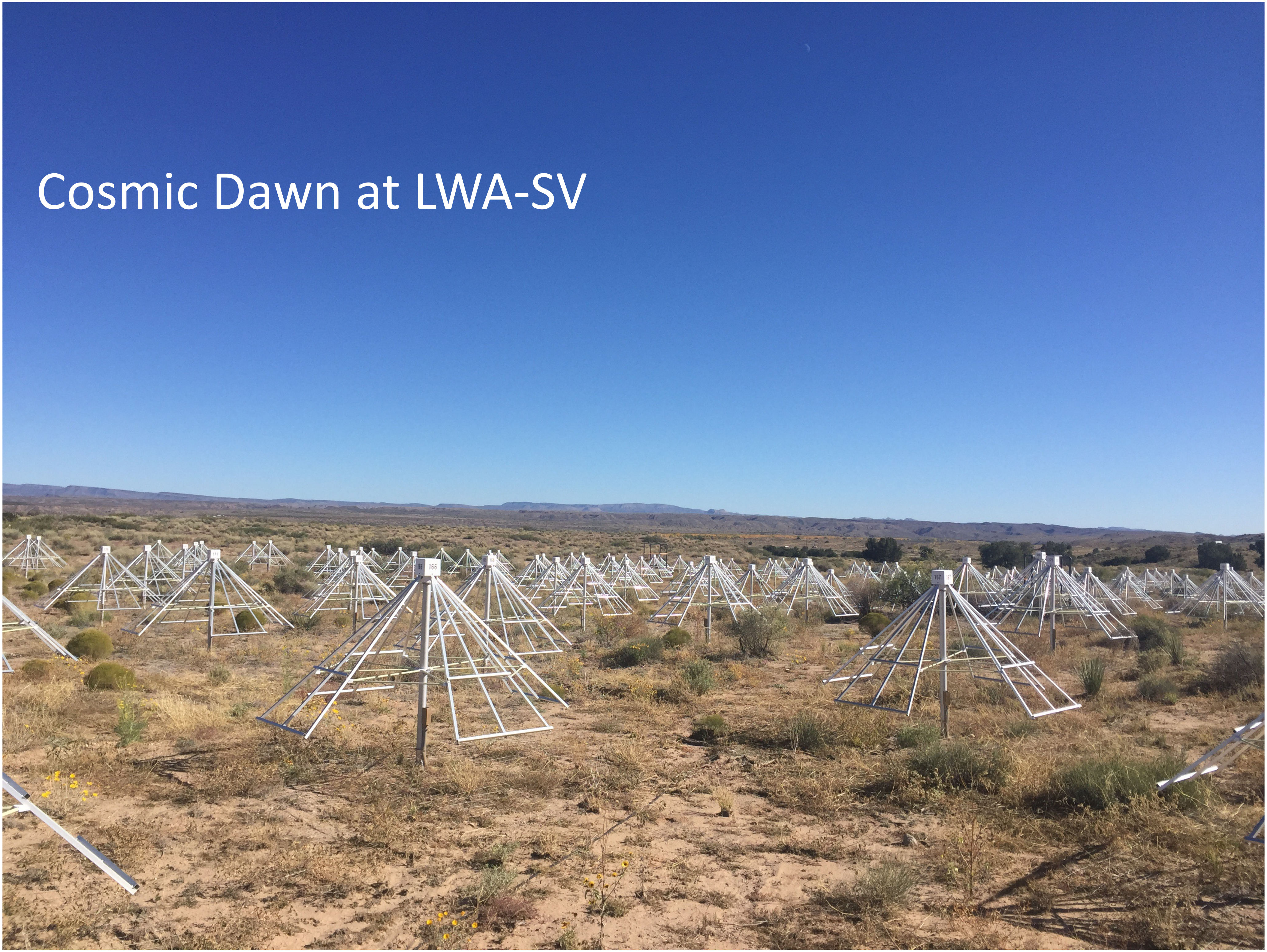
EDGES Detection of HI at z=17

Bowman et al. 2018

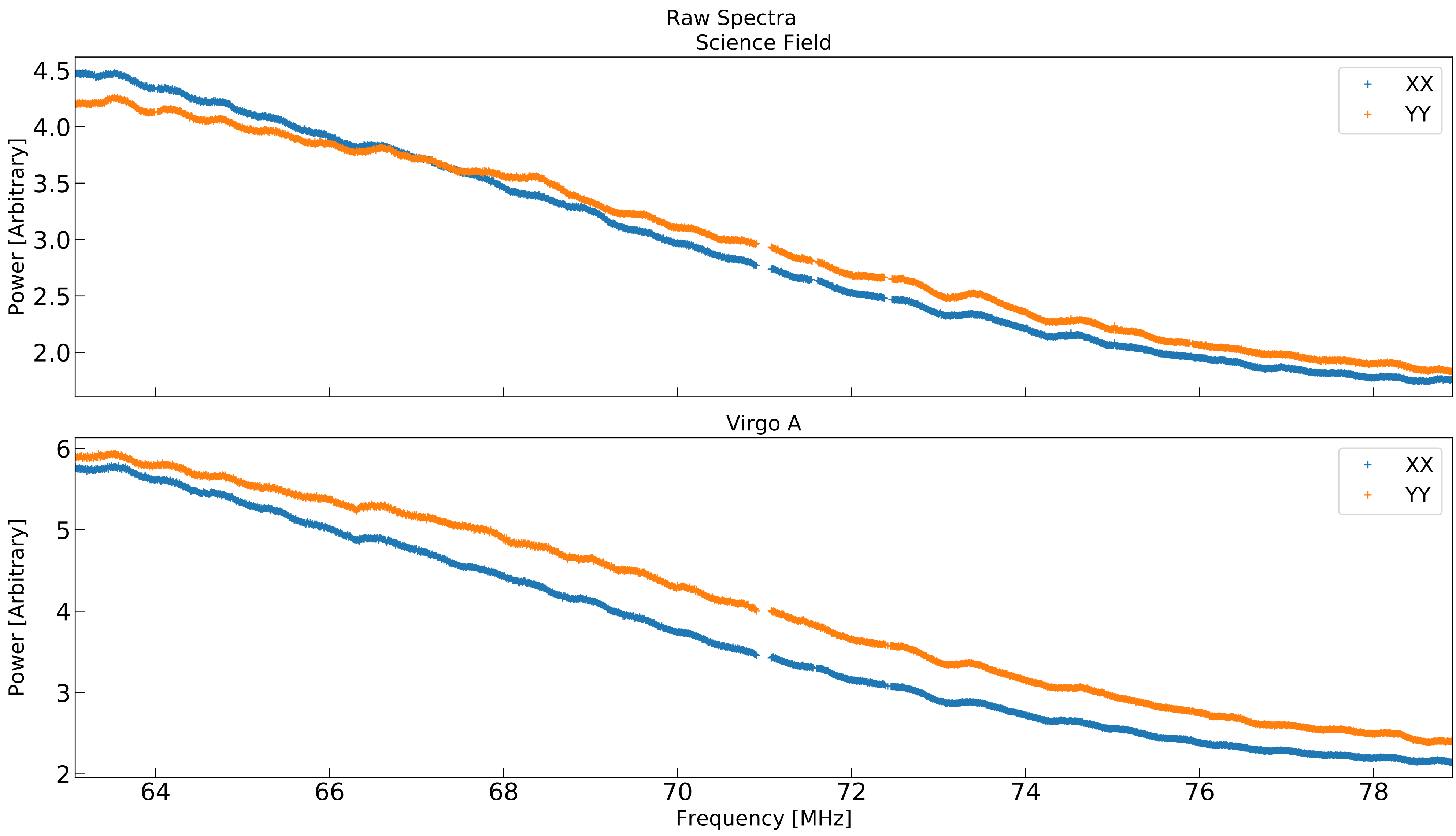




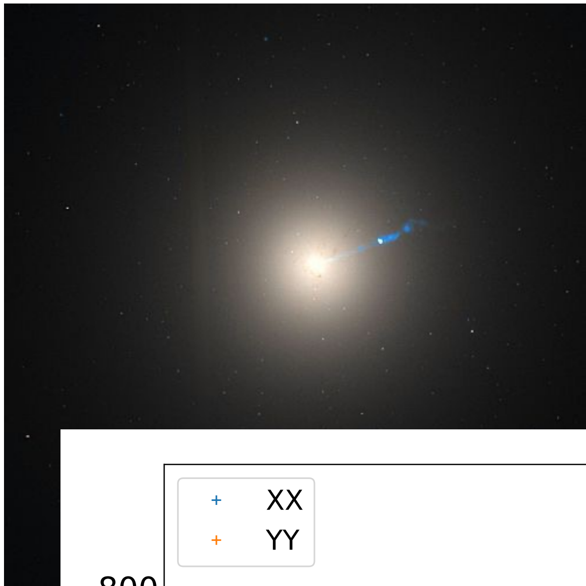


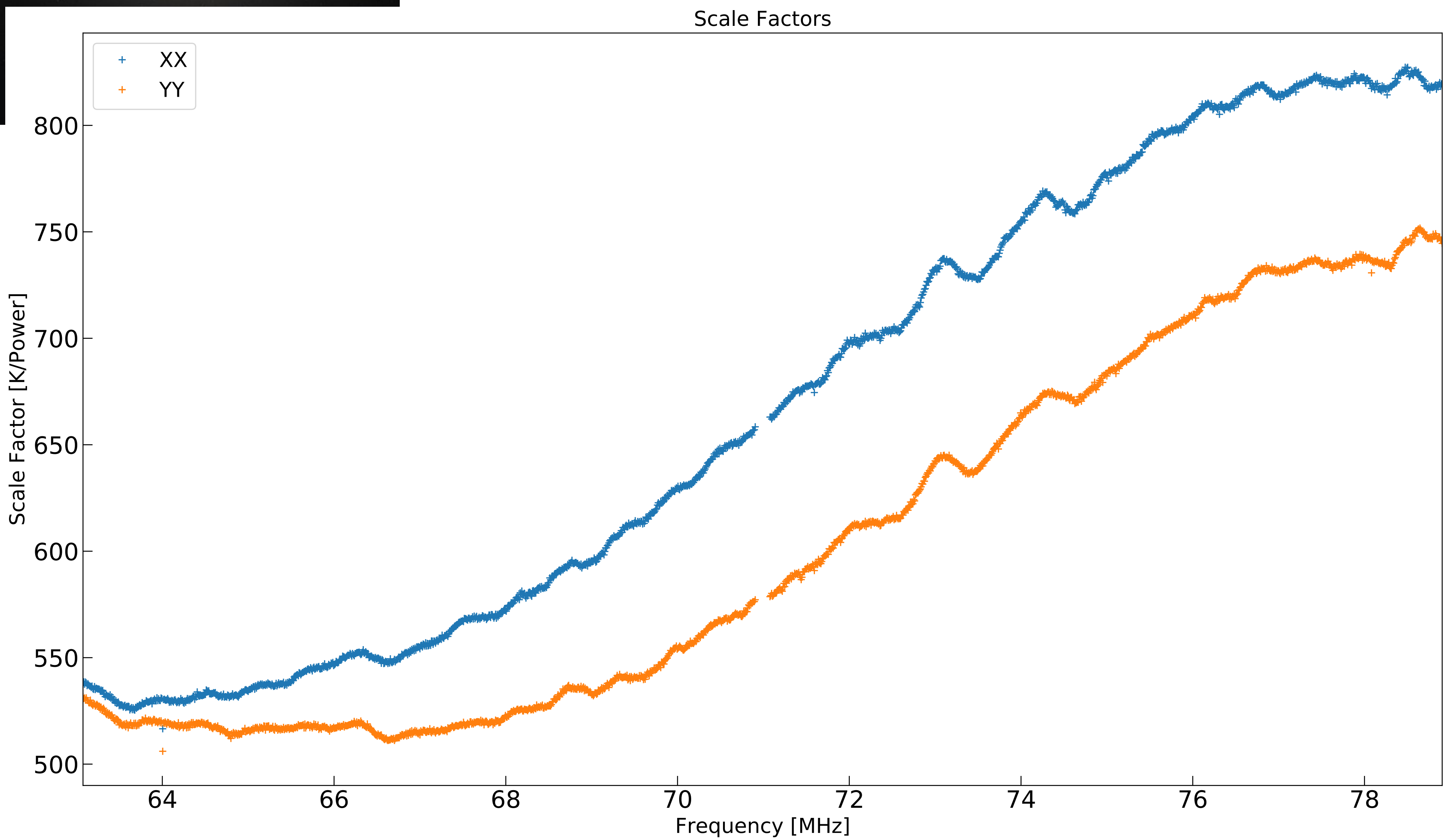

Cosmic Dawn at LWA-SV

LWA-SV Raw Spectra

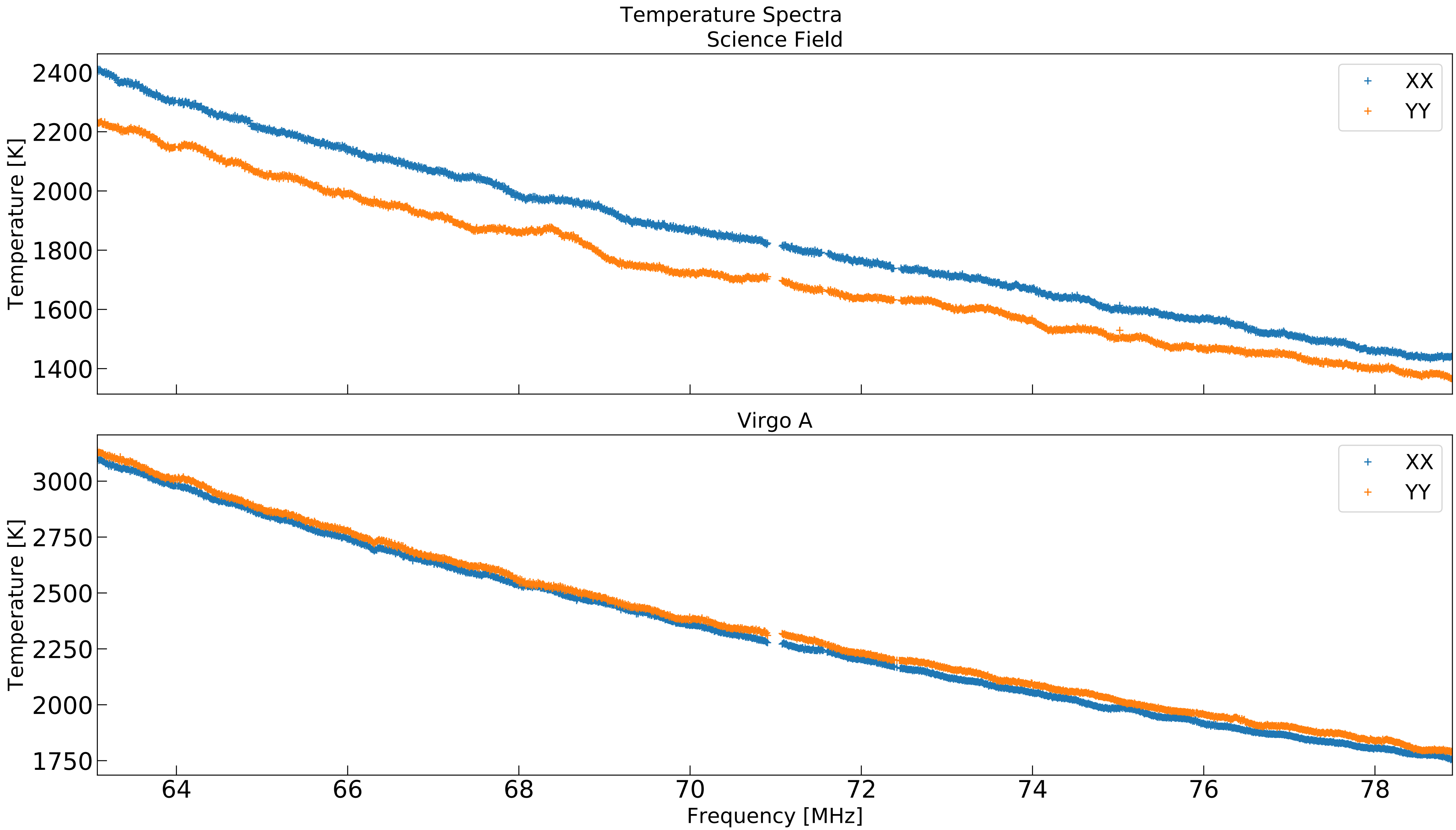


Temperature Calibration using Virgo A

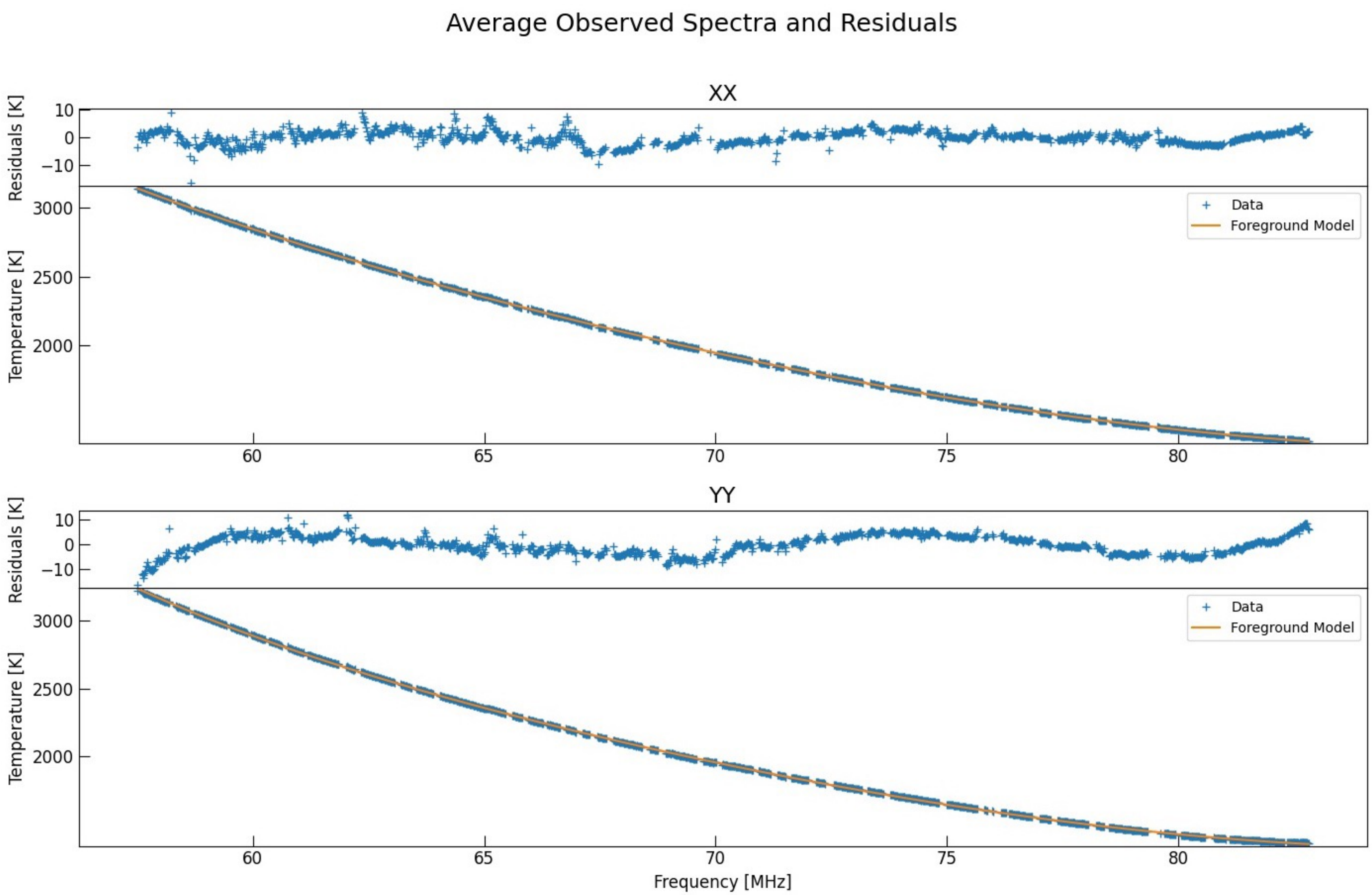




LWA-SV Calibrated Spectra



Limits from LWA-SV



rms

2.5 K

3.8 K

DiLullo et al. 2022

Temperature difference between the radiation and gas is higher than what standard astrophysics predicts.

Possibilities:

Gas is colder at $z \sim 17$ than in the standard picture.

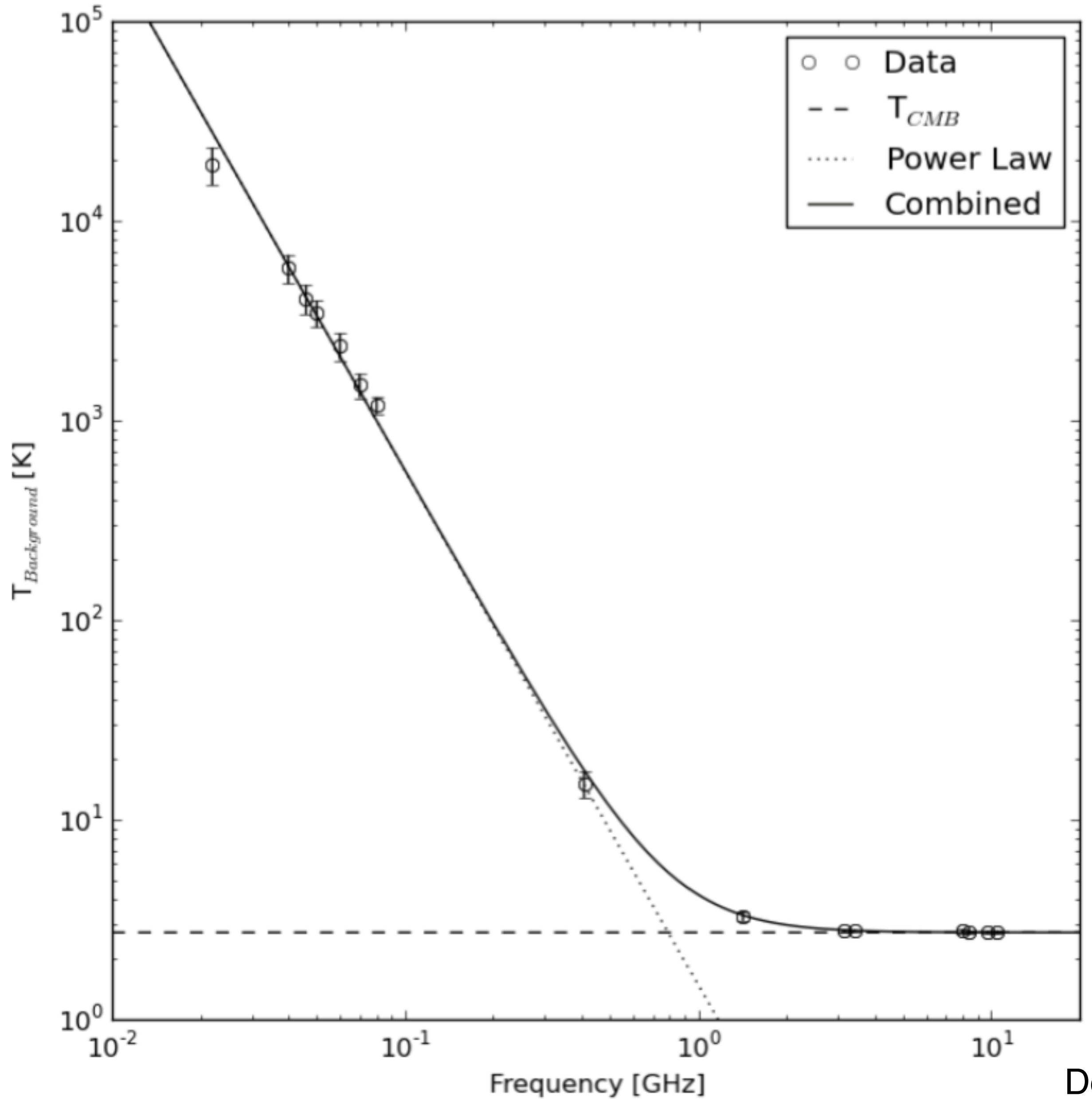
Astrophysics?
Not easy, astrophysical processes typically heat up the gas.

Baryon interaction with DM can further cool down the gas.

R. Barkana Nature 555, 71 (2018) [1803.06698 [astro-ph.CO]]
J. Munoz, A. Loeb 1802.10094 [astro-ph.CO]

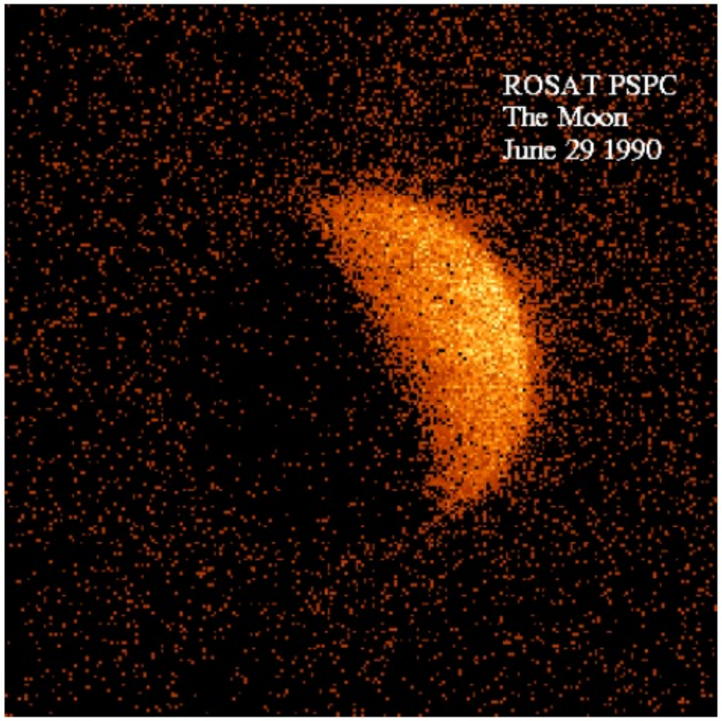
Or
Radiation is greater than just the CMB
Dowell & Taylor (2018) ApJL

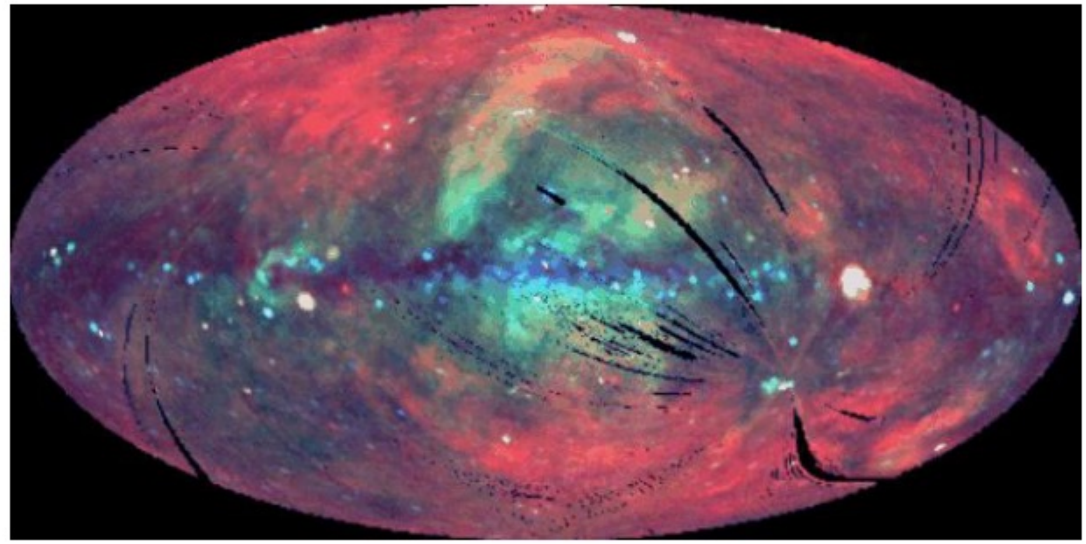
Extragalactic Radio Background



Dowell & Taylor (2018)

X-Ray Background

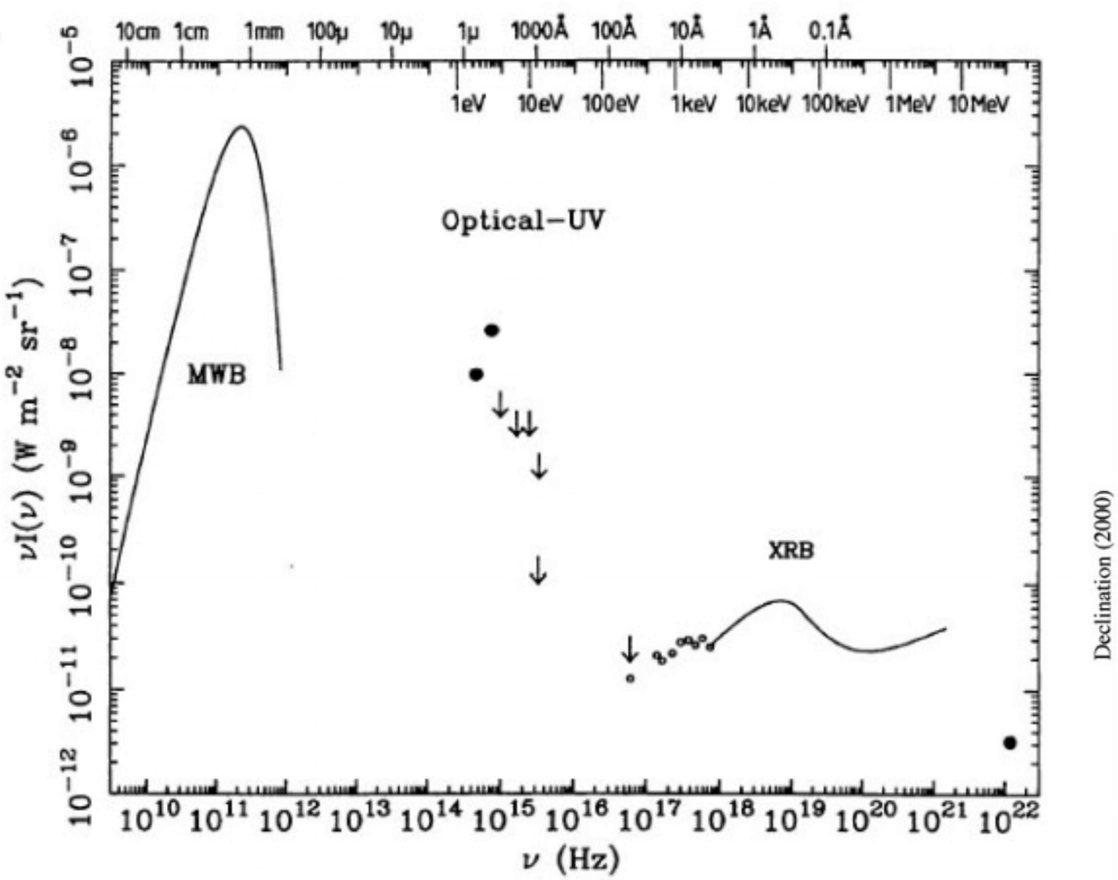




ROSAT all-sky

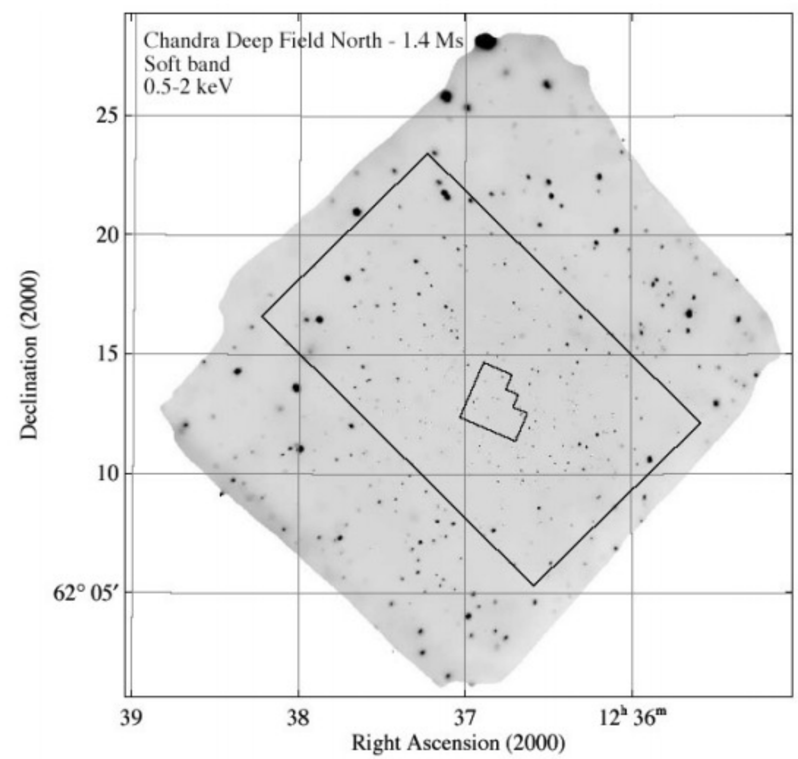
ROSAT image of the moon

X-Ray Background



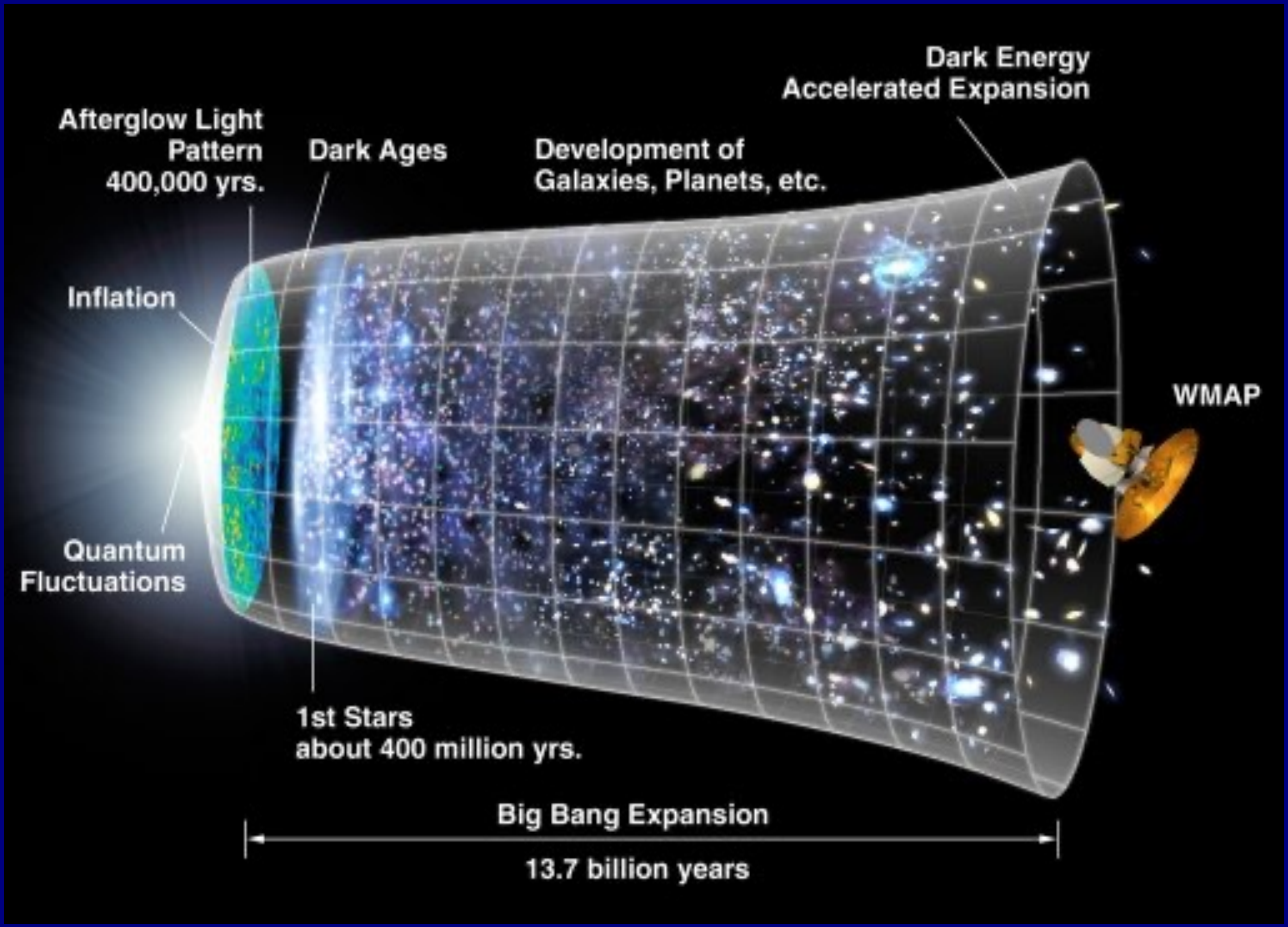
Fabian et al. 1992

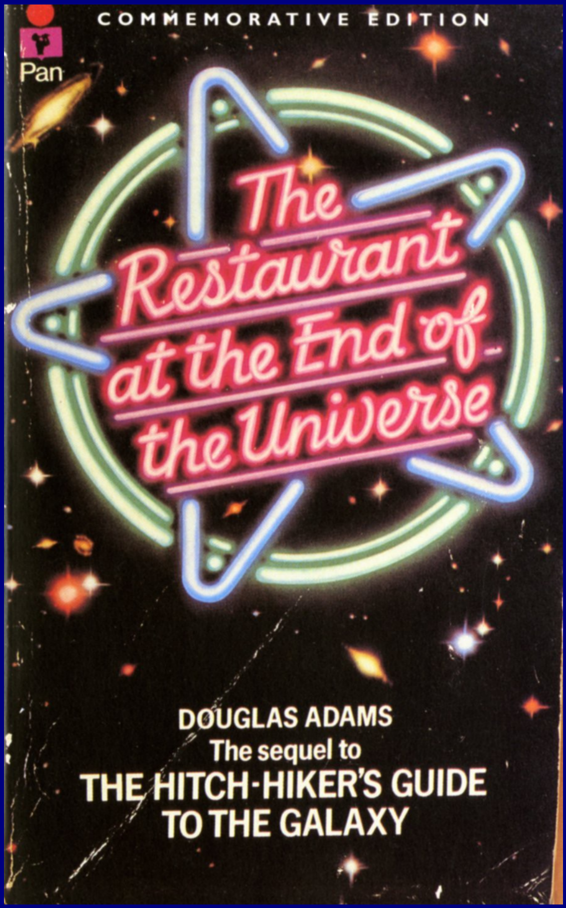
75% from 70 million sources spread evenly across the sky



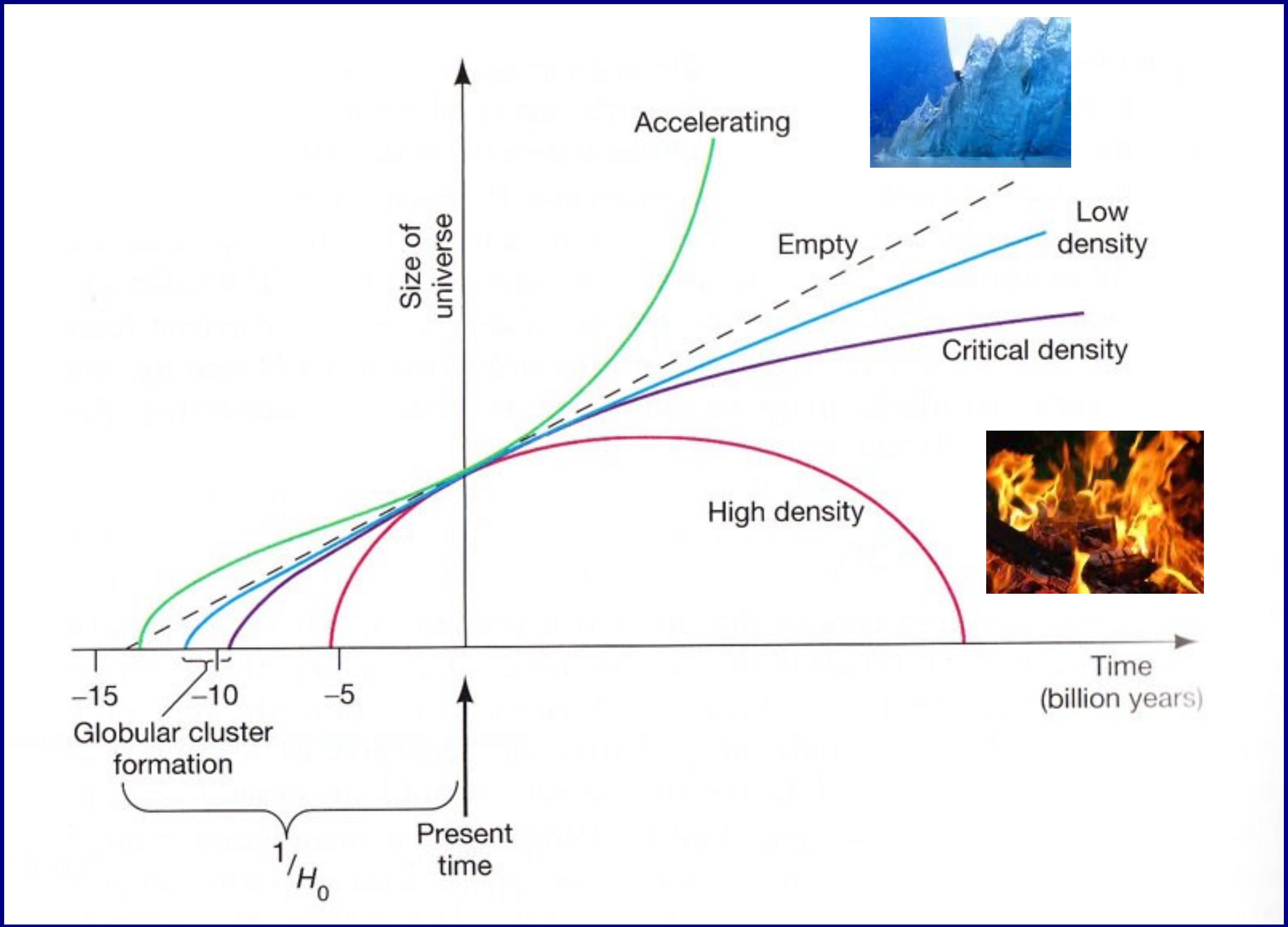
:The End of the Universe

How will the Universe end? Is this the only Universe? What, if anything, will exist after the Universe ends?





The Geometry of the Universe determines its fate



The Five Ages of the Universe

1) The Primordial Era

2) The Stelliferous Era

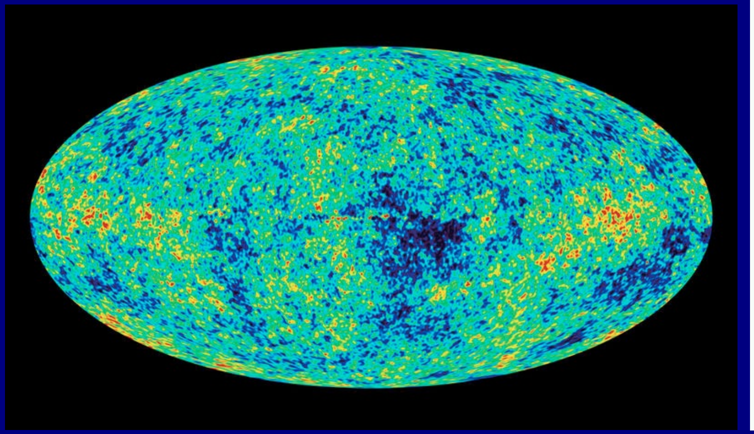
3) The Degenerate Era

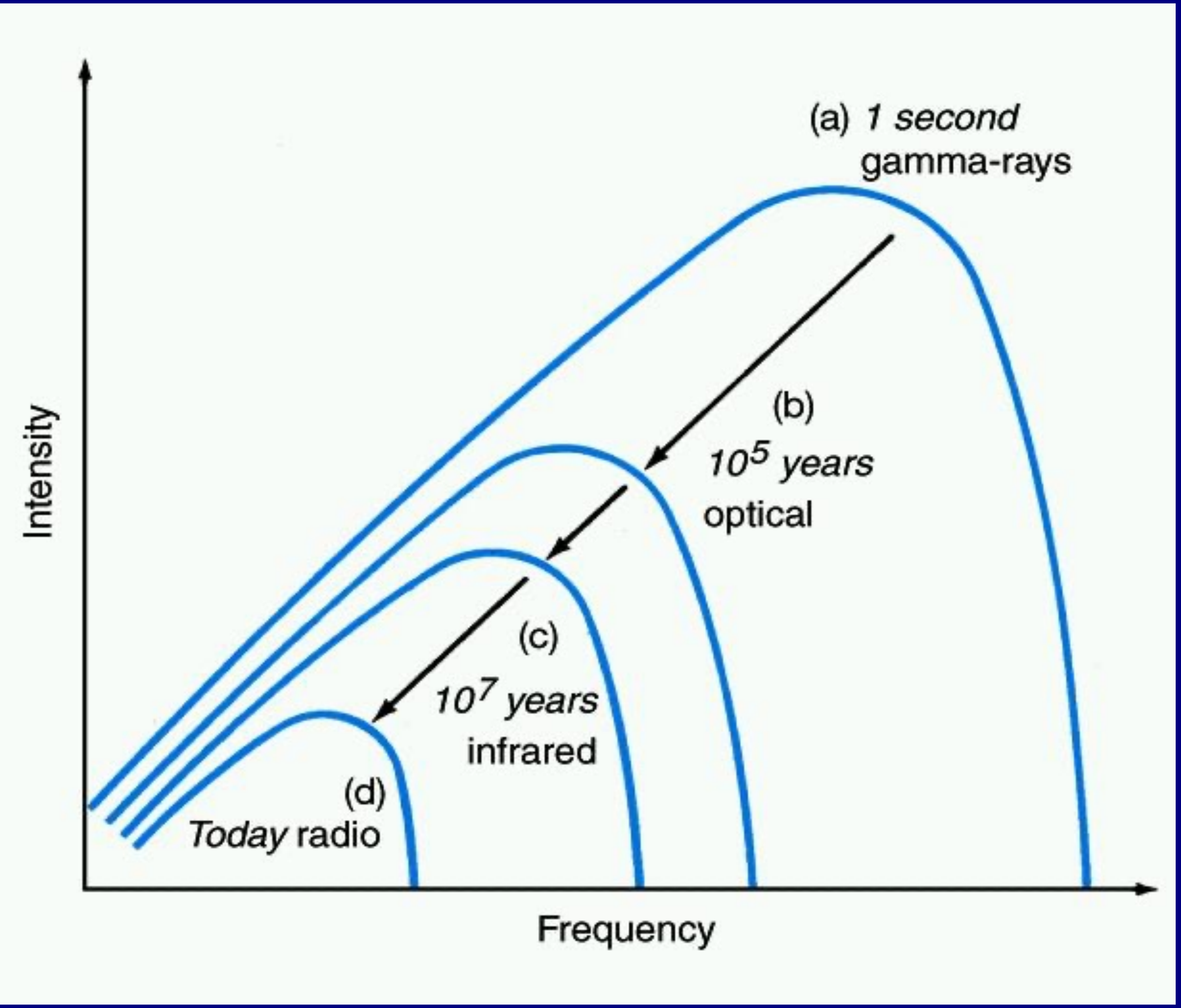
4) The Black Hole Era

5) The Dark Era

1. The Primordial Era: 10^{-45} - 10^{5} y

Something triggers the Creation of the Universe at t=0

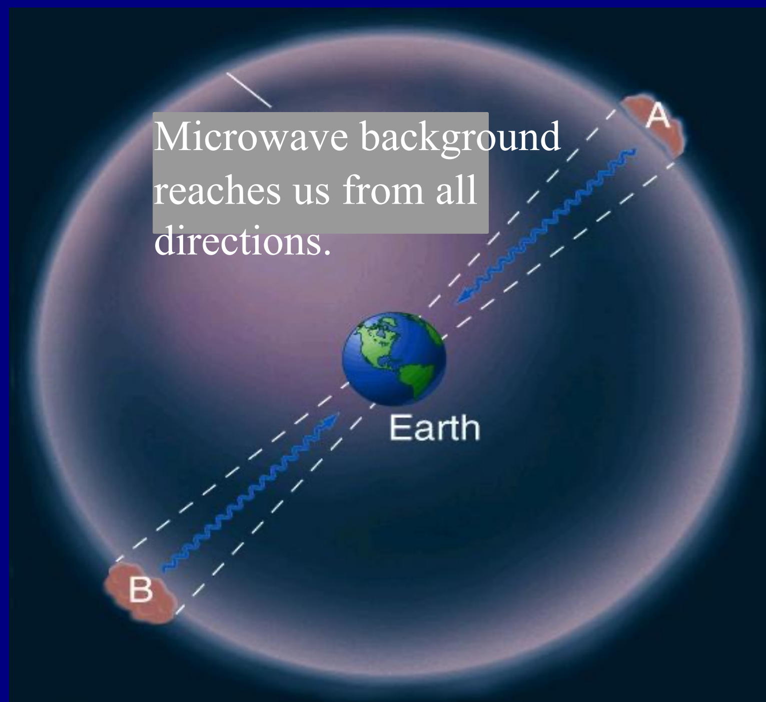




The Early Universe

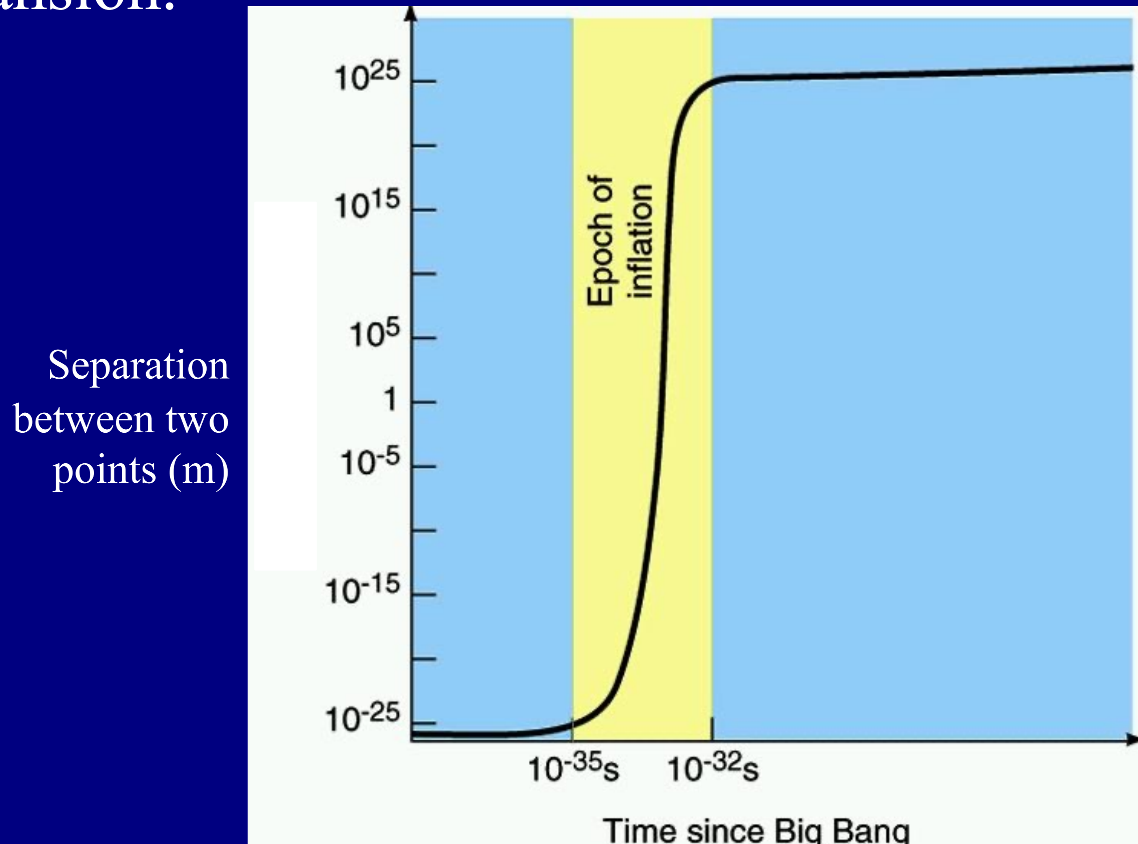
Inflation

A problem with microwave background:



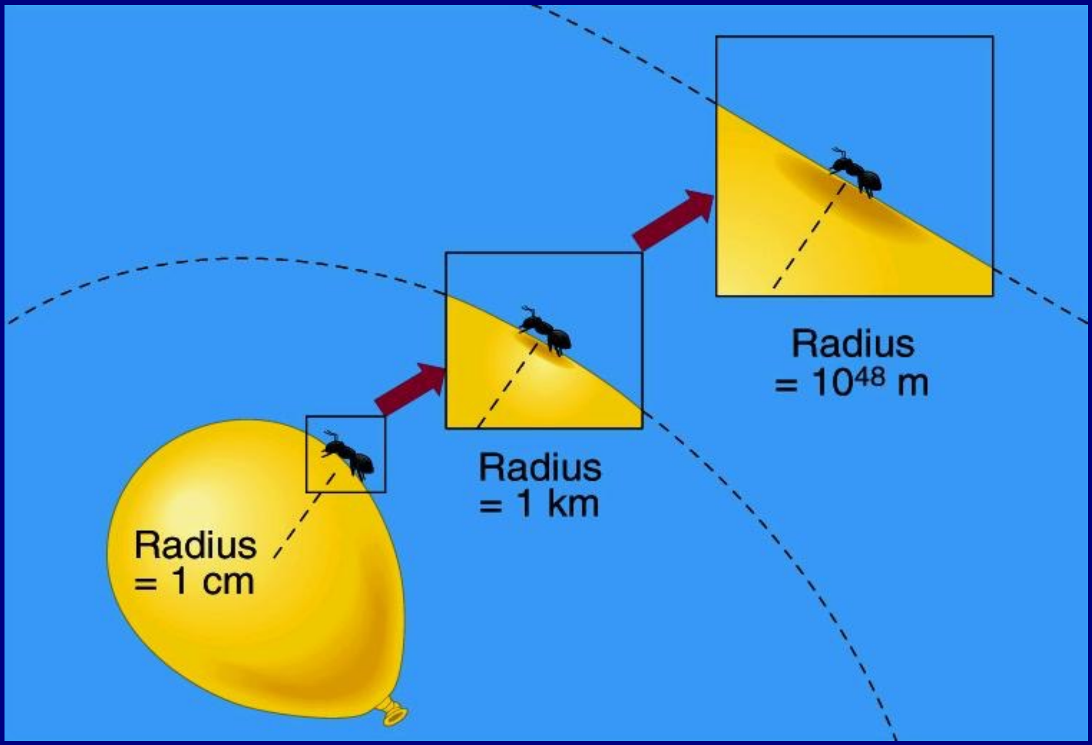
Temperature of background in opposite directions nearly identical. Yet even light hasn't had time to travel from A to B (only A to Earth), so A can know nothing about conditions at B, and vice versa. So why are A and B almost identical? This is "horizon problem"

Solution: Inflation. Theories of the early universe predict that it went through a phase of rapid expansion.



If true, would imply that points that are too far apart now were once much closer, and had time to communicate with each other and equalize their temperatures.

Inflation also predicts universe has flat geometry:



Microwave background observations seem to suggest that this is true.

2. The Stelliferous Era: 10^6 - 10^{14} y

Now = 13.8 billion years ~ 10^{10} y

How Long do Stars Live?

A star on Main Sequence has fusion of H to He in its core. How fast depends on mass of H available and rate of fusion. Mass of H in core depends on mass of star. Fusion rate is related to luminosity (fusion reactions make the radiation energy).

So,

$$\text{lifetime} \quad \alpha \quad \frac{\text{mass of core}}{\text{fusion rate}} \quad \alpha \quad \frac{\text{mass of star}}{\text{luminosity}}$$

Because $\text{luminosity} \quad \alpha \quad (\text{mass})^3$,

$$\text{lifetime} \quad \alpha \quad \frac{\text{mass}}{(\text{mass})^3} \quad \text{or} \quad \frac{1}{(\text{mass})^2}$$

So if the Sun's lifetime is 10 billion years, the smallest 0.1 M_{Sun} star's lifetime is 1 trillion years.

How Long do Galaxies Live?

Only as long as they can continue to manufacture stars. To do that the galaxy needs gas.

So,

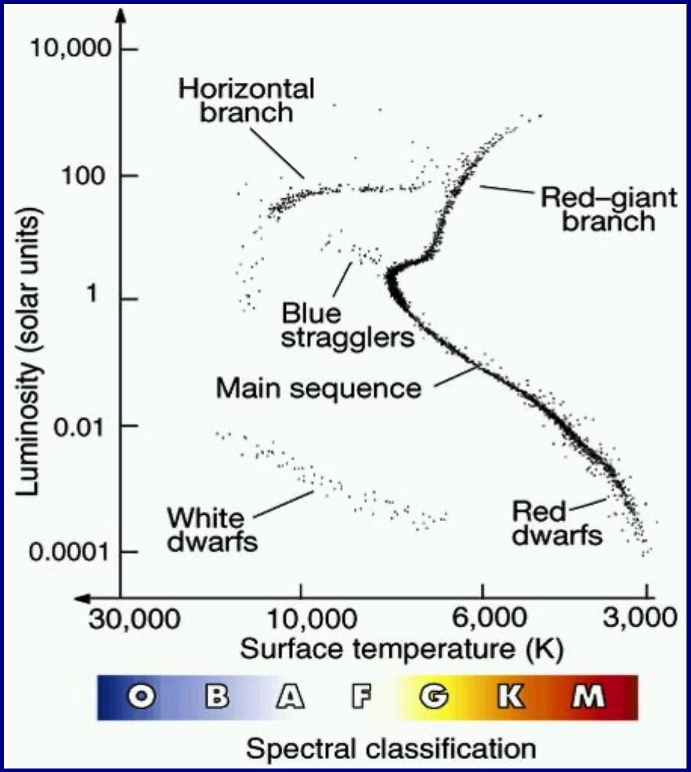
$$\text{lifetime} \quad \alpha \quad \frac{\text{Mass of gas}}{\text{star formation rate}} = \text{10 billion years (for MW)}$$

Galaxies with modest star formation rates can shine for perhaps 1 trillion years

3. The Degenerate Era: 10^{15} - 10^{39} y

Most stars leave behind a white dwarf

Mass between 0.1 and 1.4 M_sun



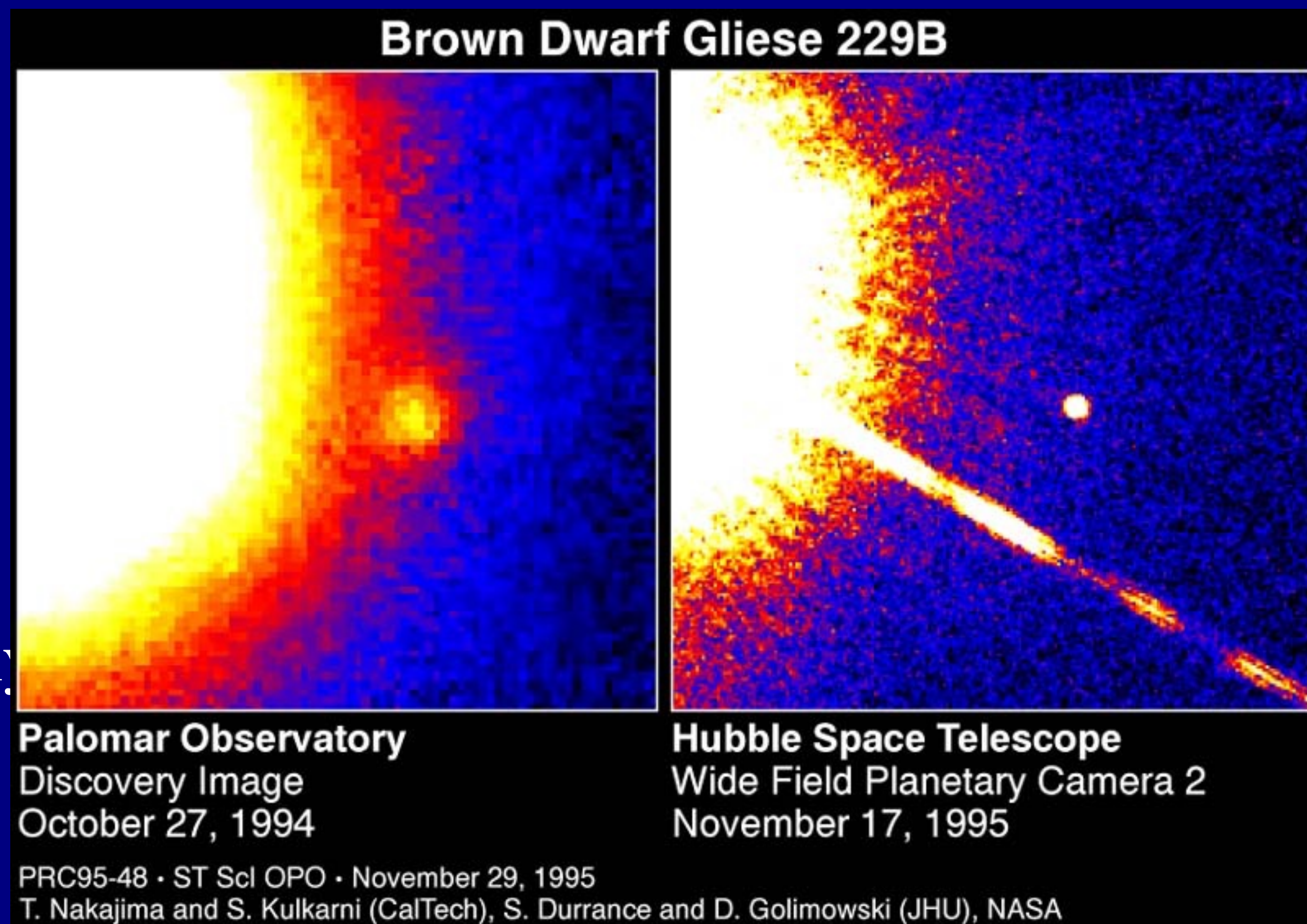
The Degenerate Era: 10^{15} - 10^{39} y

Some failed protostars never got hot enough to ignite hydrogen fusion:

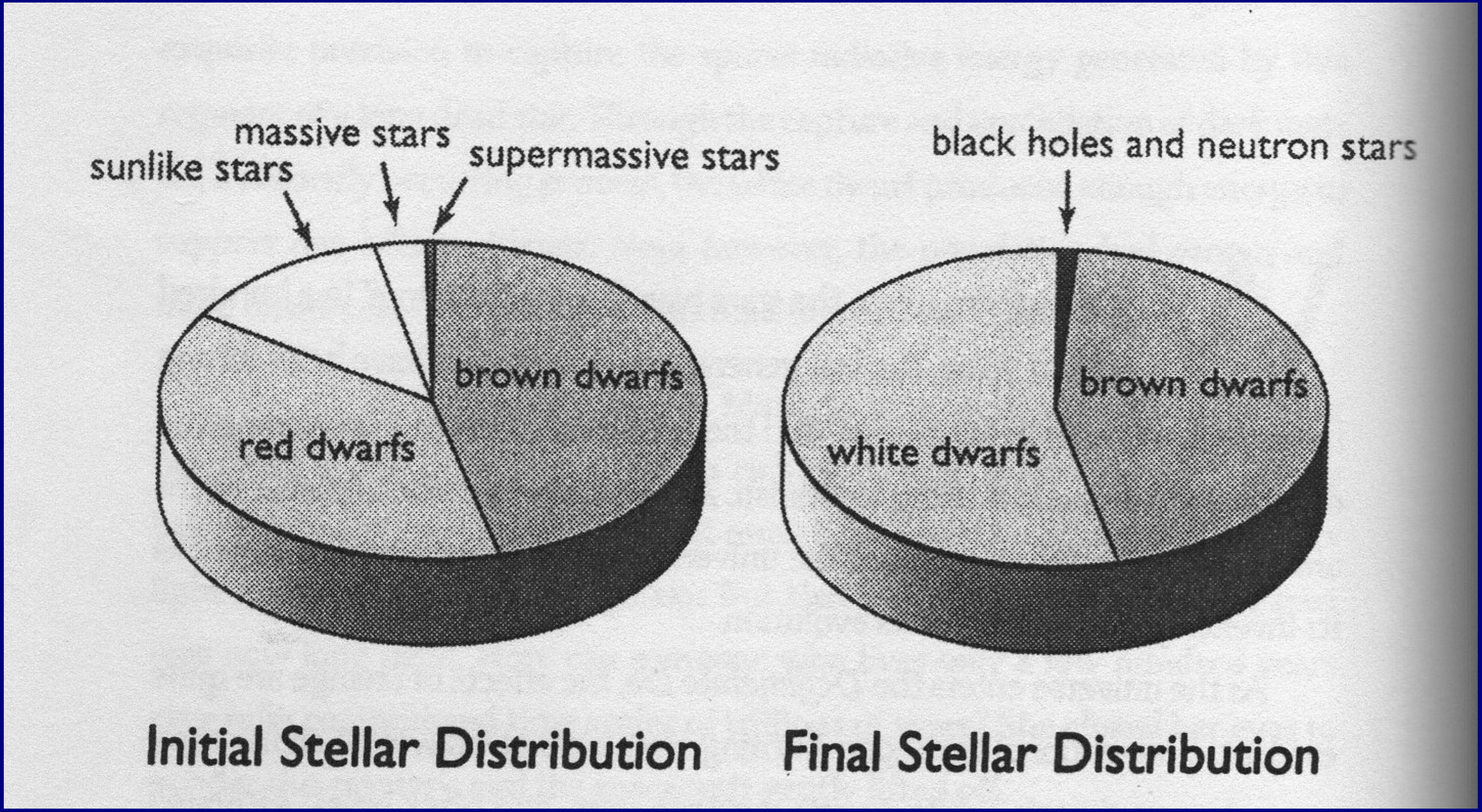
Brown Dwarfs

Mass < 0.08 M_sun

Brown dwarf collisions can create occasional warm spots in an increasingly cool universe



The Degenerate Era: 10^{15} - 10^{39} y

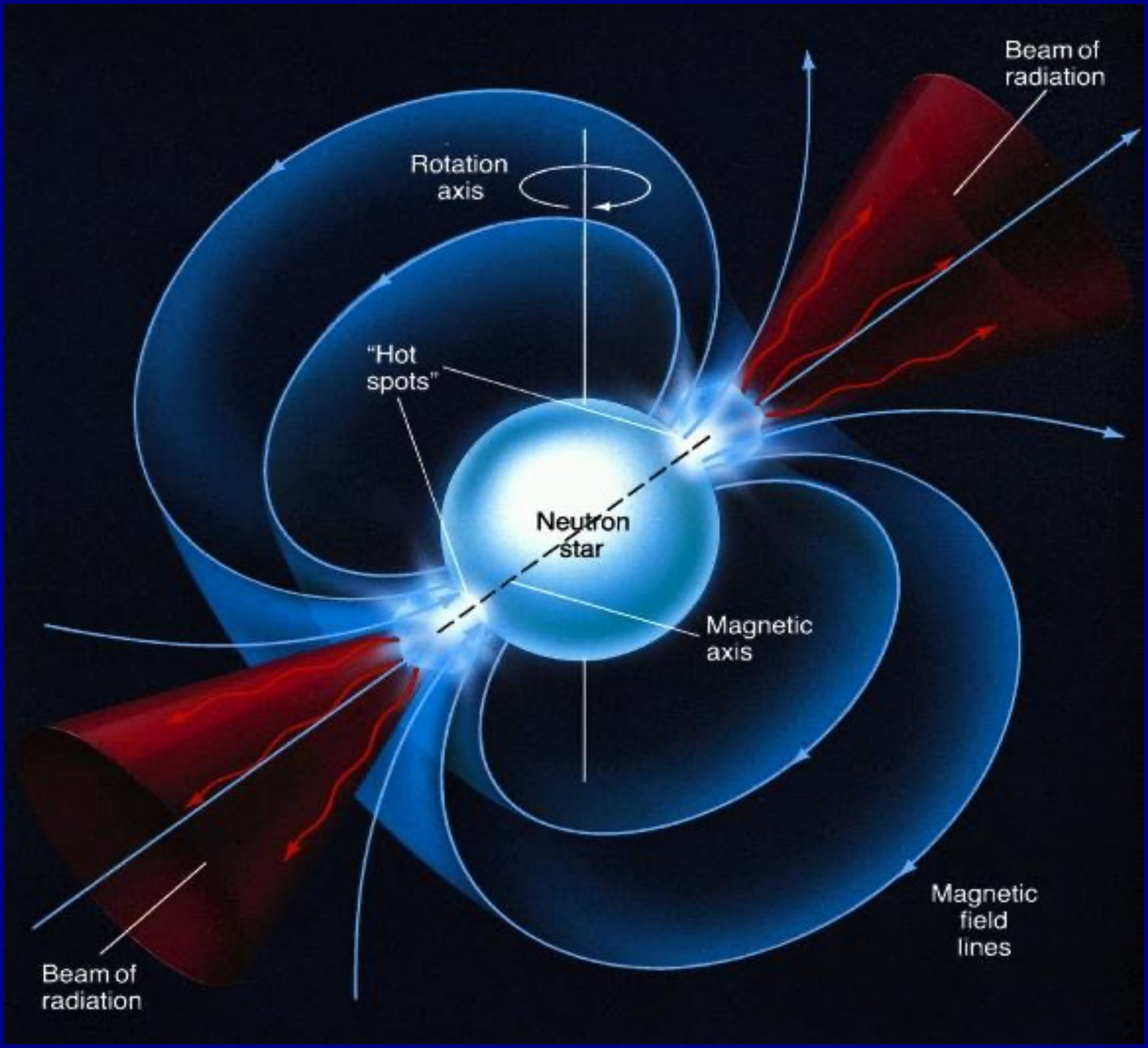


The Degenerate Era: 10^{15} - 10^{39} y

Neutron stars:

Cold and no longer pulsating

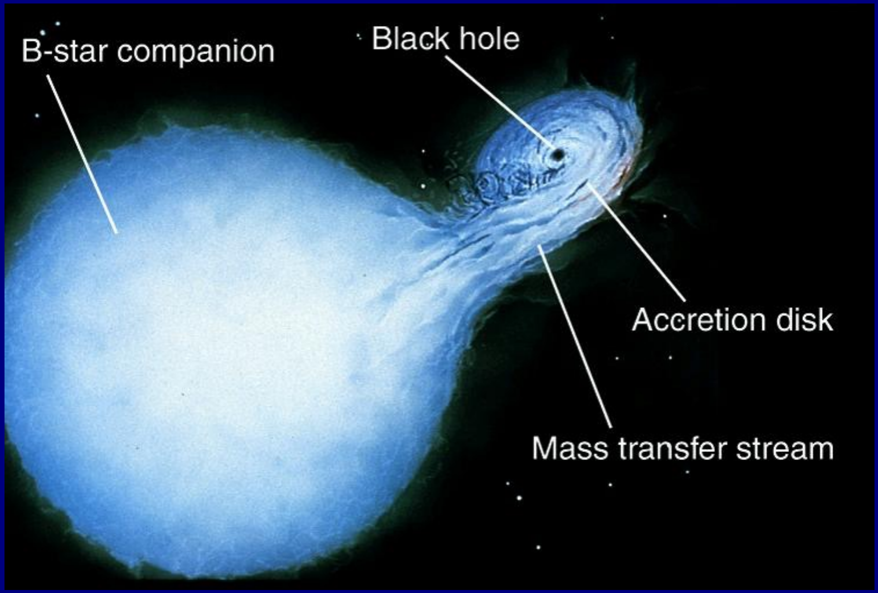
Mass ~ 1.5 M_sun



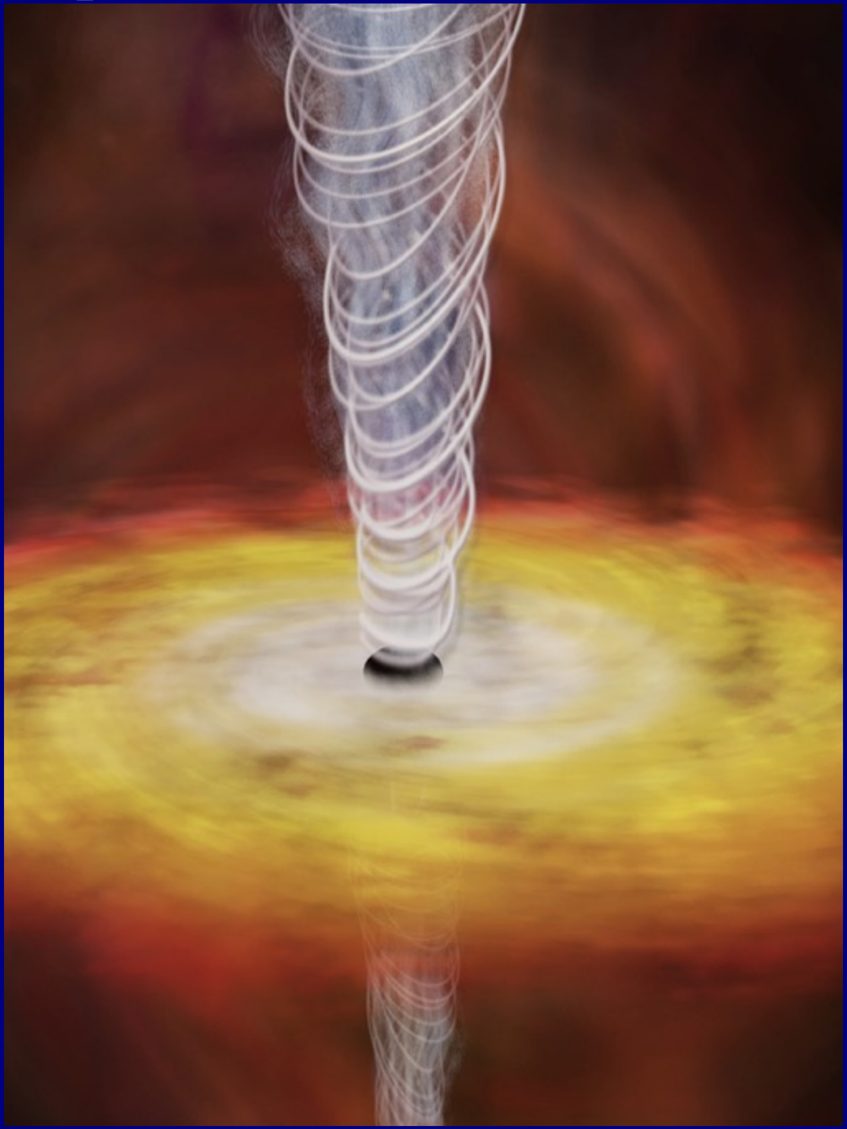
The Degenerate Era: 10^{15} - 10^{39} y

Black holes

Stellar mass black holes



Supermassive black holes



Galaxy evolution: dynamic relaxation during the Degenerate Era

Galaxies continue to merge to form large meta-galaxies (entire local group merges into a single galaxy); spirals merge --> ellipticals

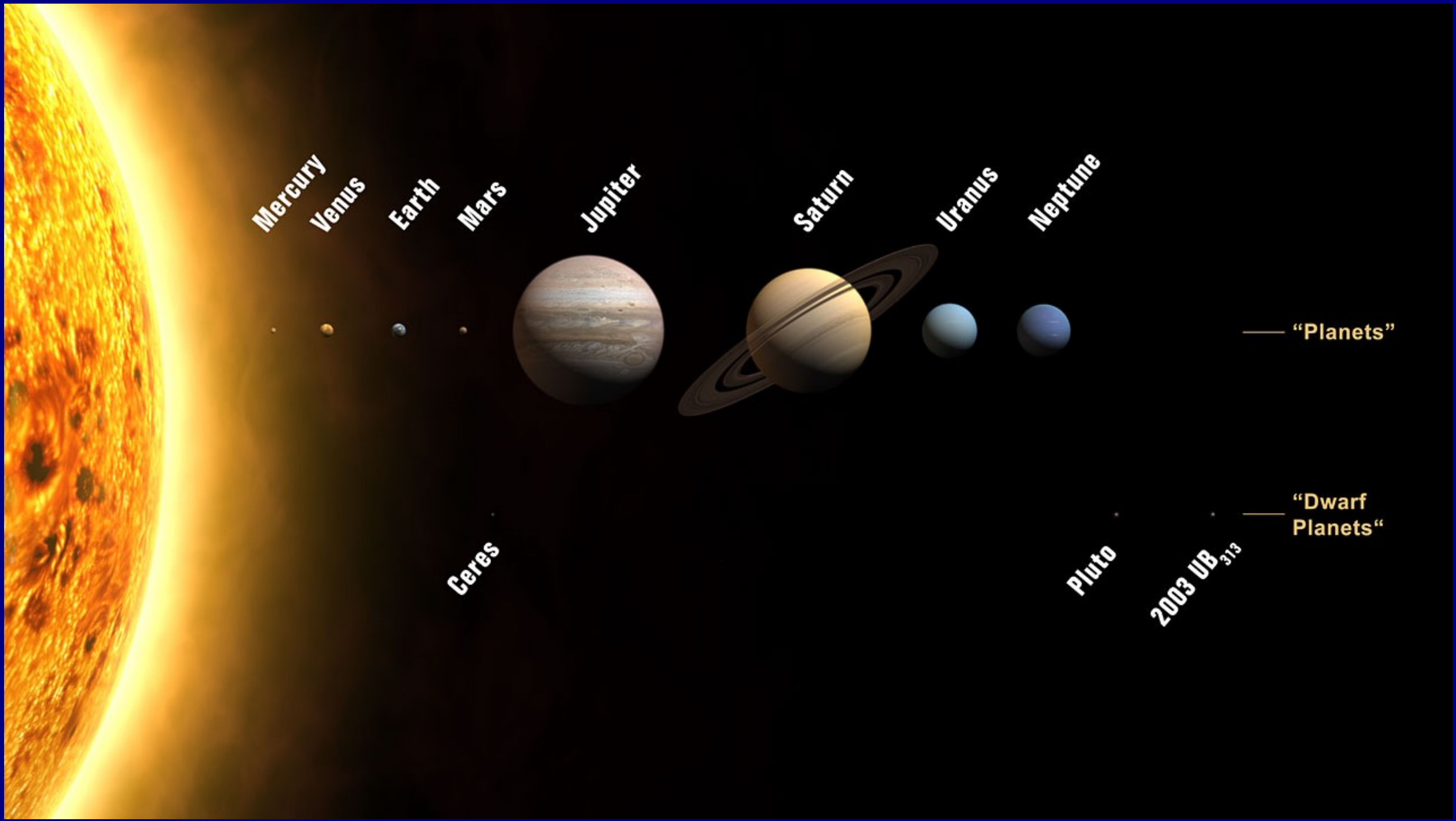
Massive remnants sink to the center of the galaxy

Less massive remnants get ejected from the galaxy (all the brown dwarfs are gone by 10^{20} y).

What happens to Solar systems like ours?

Inner planets are fried during end of stelliferous era
Planets are gradually stripped away during stellar encounters in the degenerate era

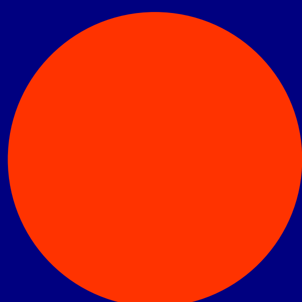
10^{17} 10^{15} 10^{12} y



Dark Matter?

Annihlation of WIMPs (Weakly Interacting Massive Particles)?

- In the halo of the galaxy
- In the cores of white dwarfs (power ~ 10^{15} Watts, 10^{-9} L_sun)



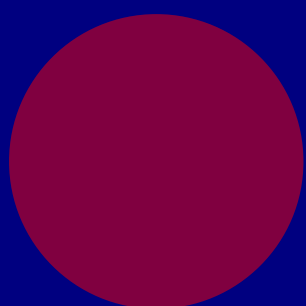
Surface temperature ~60 K

Steady energy source for ~10^{20} y

Proton Decay?

Predicted lifetime of protons (and neutrons) is 10^{37} y

- In white dwarfs (power ~ 400 Watts, 10^{-22} L_sun)



Surface temperature ~0.06 K

Composition changes to frozen H

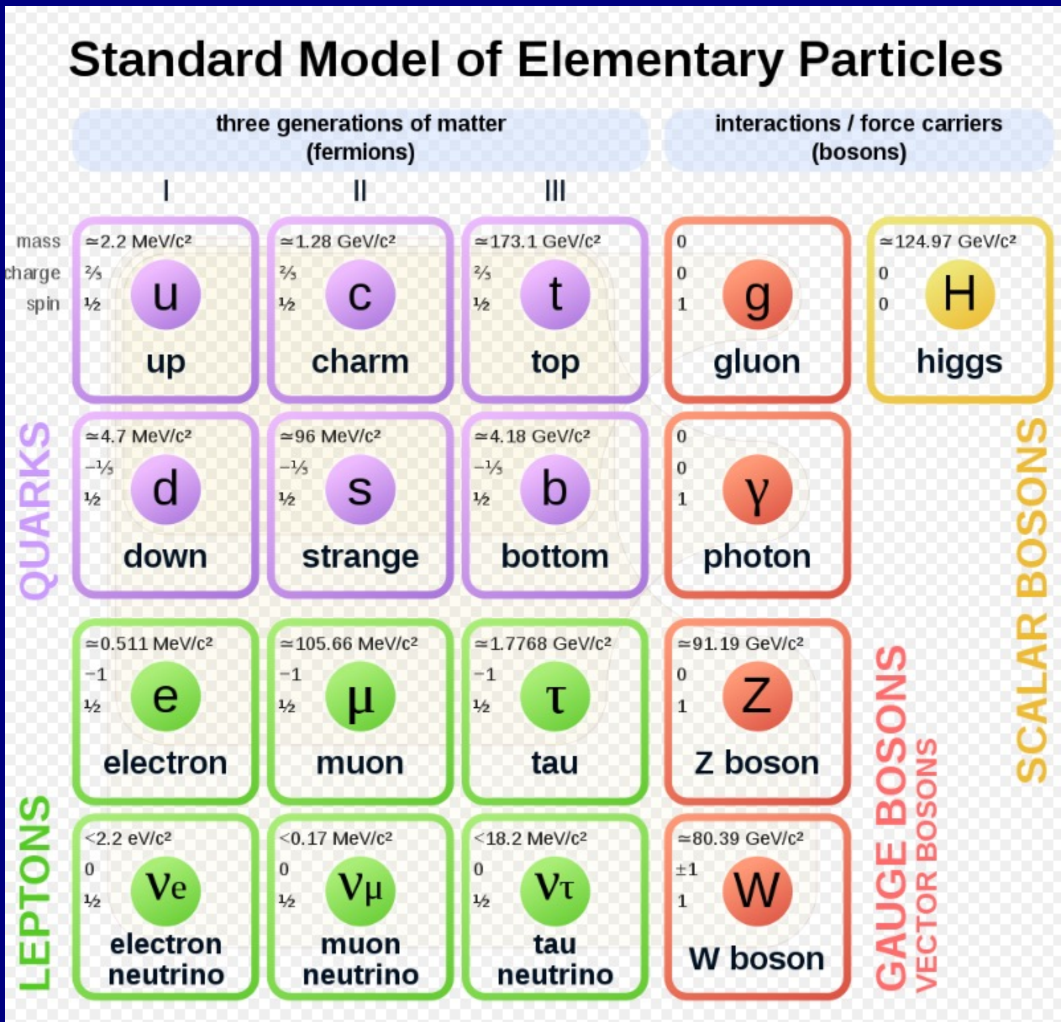
Star expands

Slow decay over ~10^{39} y

Eventual disintegration into photons

Neutron stars, planets, dust, all face the same fate.

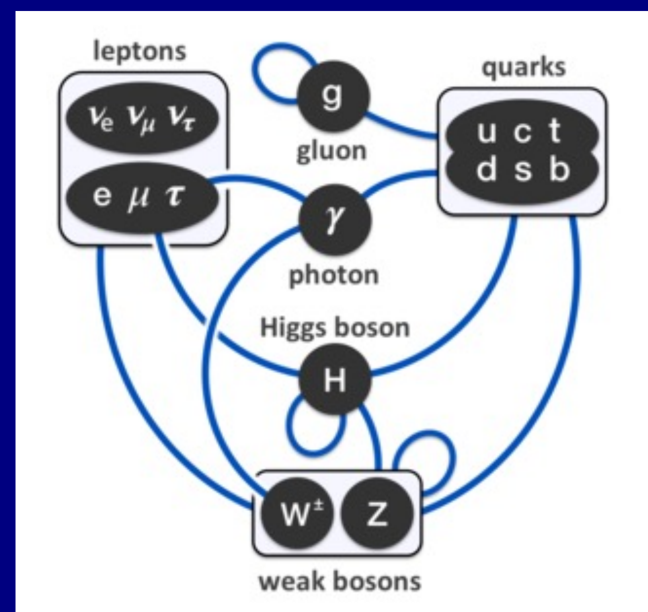
Do Neutrinos have a rest mass?



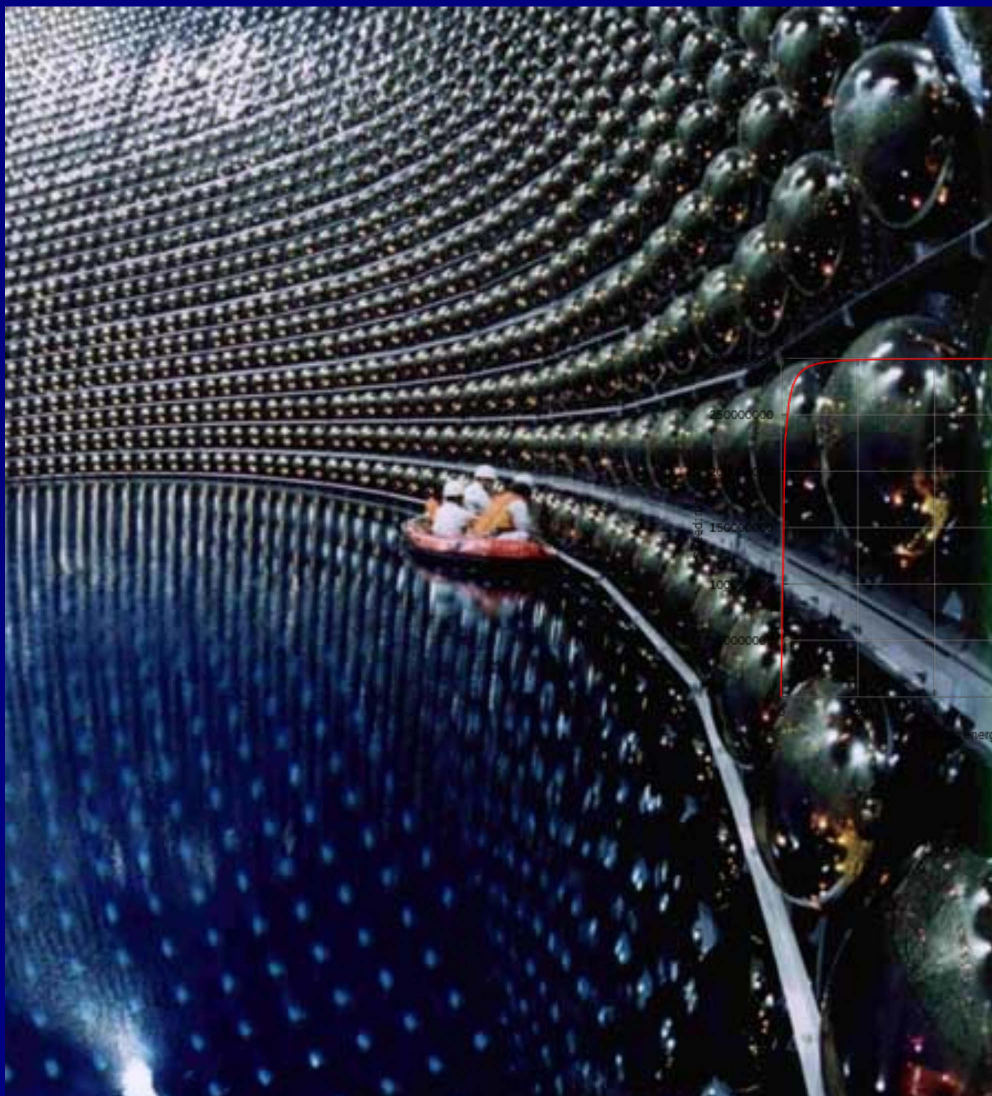
Not according to the standard model

Which has worked well but has issues:

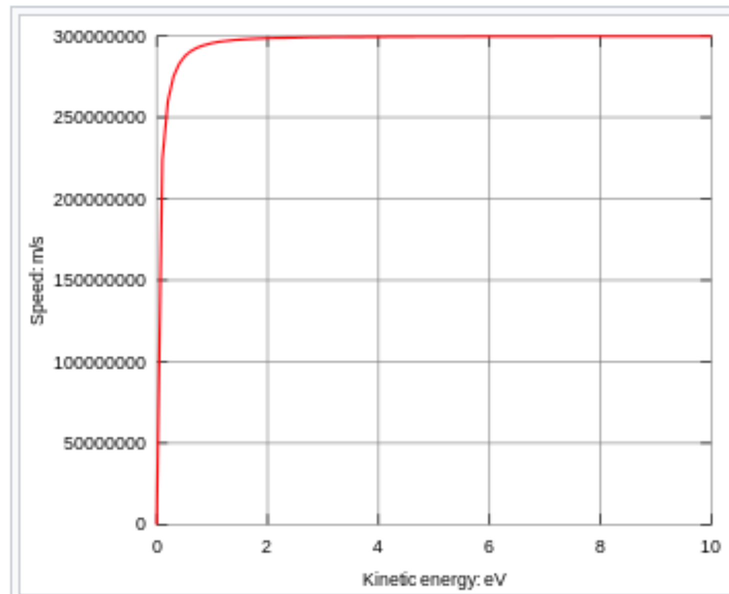
- Does not explain Baryon Asymmetry
- No dark matter/dark energy



Do Neutrinos have a rest mass?



Super-Kamiokande detects neutrino
Mixing so neutrinos have rest mass
At least > 0.05 eV but < 3 eV



Neutrino speed as a function of relativistic kinetic energy, with neutrino mass < 0.2 eV/c².

Energy	10 eV	1 KeV	1 MeV	1 GeV	1 TeV
$\lvert v-c \rvert / c$	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-14}$	$\lesssim 10^{-20}$	$\lesssim 10^{-26}$

4. The Black Hole Era: 10^{40} - 10^{100} y

Black holes inherit the Universe

- mostly in the form of stellar mass black holes

Some electrons, positrons, neutrinos and other particles remain

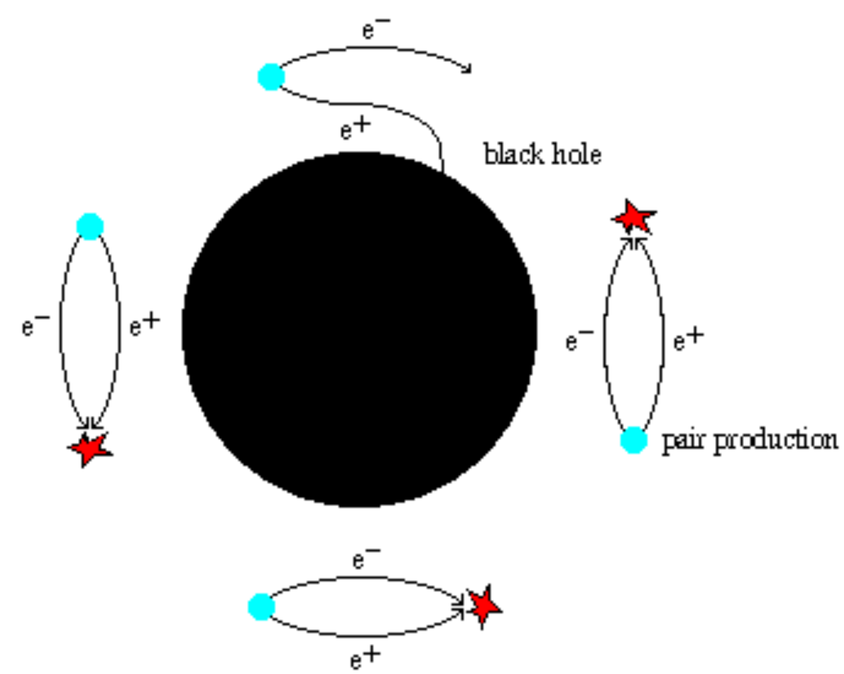
Planets, Stars and Galaxies are all long gone

4. The Black Hole Era: 10^{40} - 10^{100} y

Black holes eventually start to decay by Hawking Radiation

Hawking Radiation

the strong gravitational field around a black hole causes pair production



if a pair is produced outside the event horizon, then one member will fall back into the black hole, but the other member will escape and the black hole loses mass

Hawking radiation continued:

Effective Temperature ~ 1/mass

Universe cools with time, so that after 10^{21} y, the Universe is cooler than a 1 solar mass black hole (10^{-7} K)

After 10^{35} y, even 1 billion solar mass black holes have begun to evaporate.

Final stage of black hole radiation is explosive with 10^{6} kg of mass converted into energy

After 10^{100} y, even the most massive black holes are gone.

5. The Dark Era: $> 10^{101}$ y

Only some elementary particles and ultra-long-wavelength photons remain inside a vastly expanded Universe.

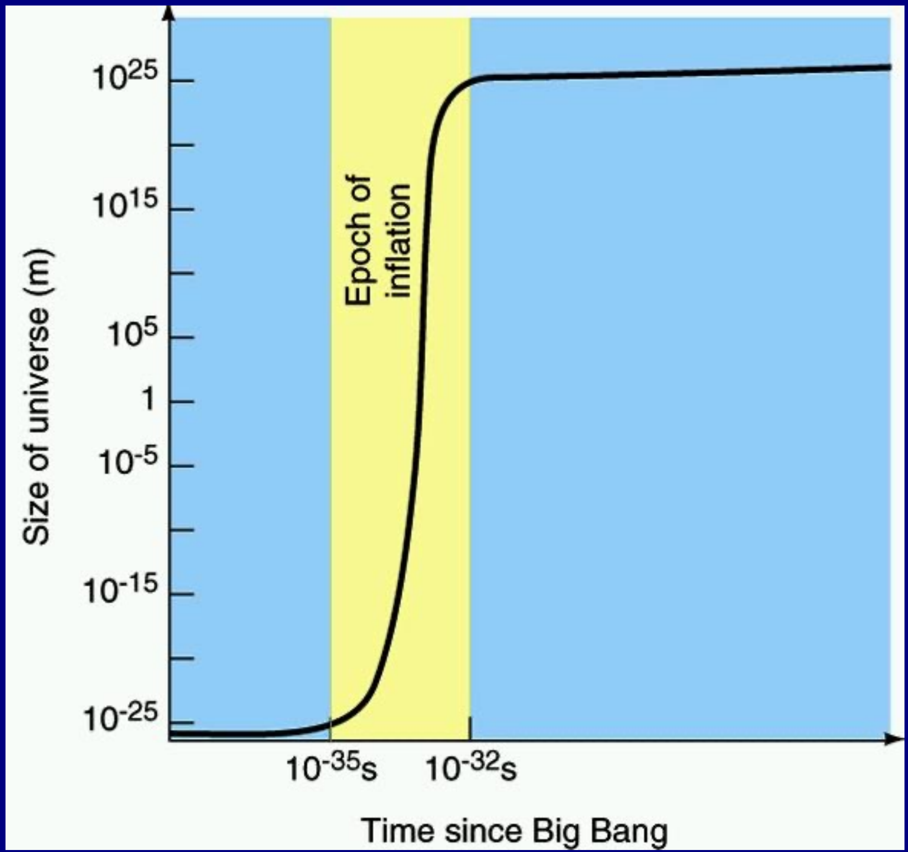
Density is unimaginably low. Our observable Universe now has a size of 10^{78} cubic meters. In the Dark Era there will be one electron every 10^{182} cubic meters.

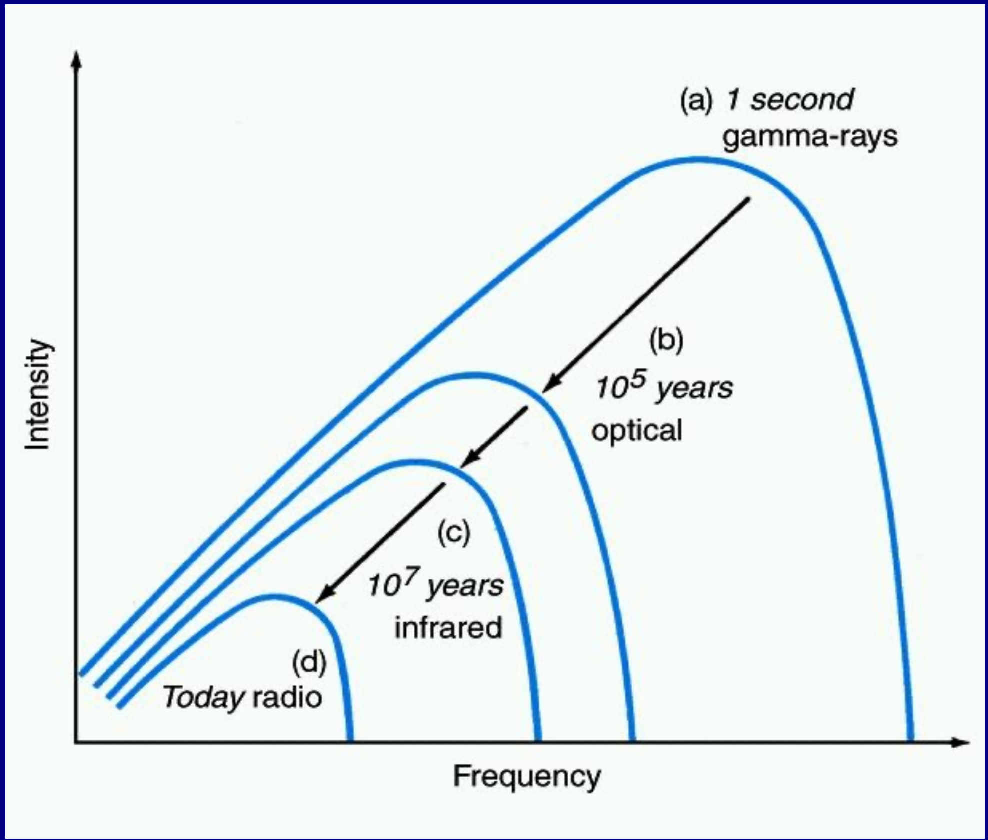
Heat death - nothing happens, no more sources of energy available

Or ….

1. The Primordial Era: 10^{-50} - 10^{5} y

Something triggers the Creation of a child Universe





Child Universe

Living on borrowed energy:

$E_{total} = mc^2 - 1/2\ m\ v_{esc}^2 = 0$

For a critical density Universe ($\Omega_0 = 1$)
Energy of expansion is about equal to energy in matter

Chaotic Inflation theory predicts multiple universes or “Hubble Volumes”
An Infinite Universe contains an infinite number of Hubble Volumes
There should be an infinite number of Universes similar to ours