

21st century & 21 cm cosmology

VERÃO QUÂNTICO 2021

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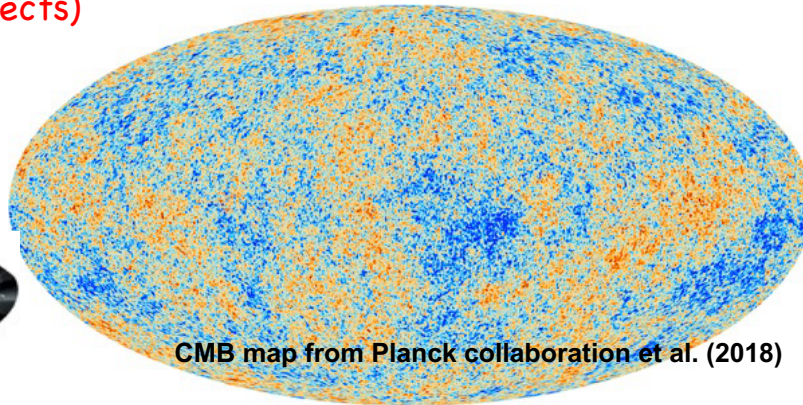
October 2021

Plan of the lectures

- **21 cm cosmology**
- 21 cm observations
- the BINGO project

Era of precision cosmology

- Cosmology is now in a golden area with plenty of data (Planck, SDSS, DES and other large surveys)
- There are still a few key questions to be answered!
 - Inflation ($t < 10^{-32}$ s) – maybe CMB with B-mode polarization results
 - What is the nature of Dark Matter?
 - What is the nature of Dark Energy?
 - Dark energy (EUCLID, HETDEX, DESI, LSST – DoE flagship projects)



CMB map from Planck collaboration et al. (2018)

C.A. Wuensche (2021)

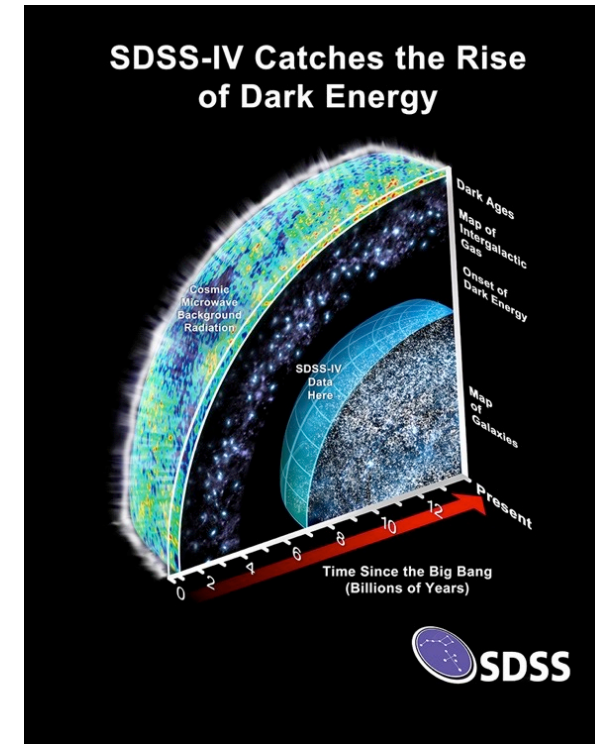
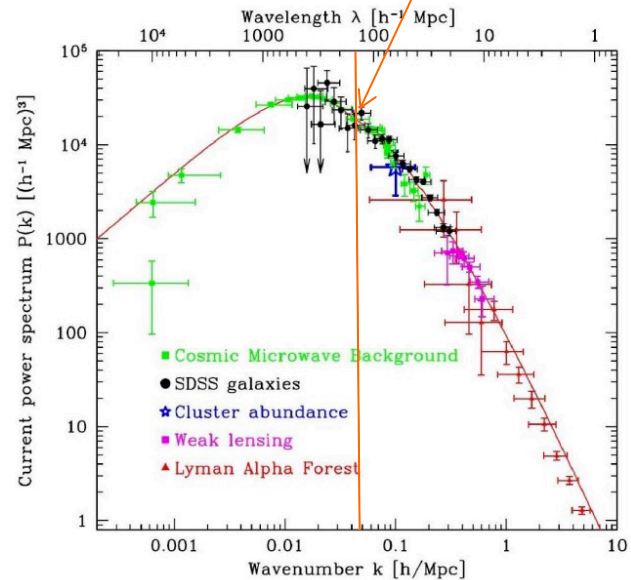
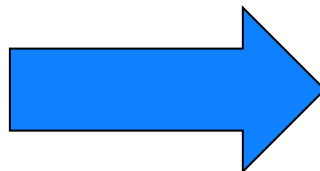
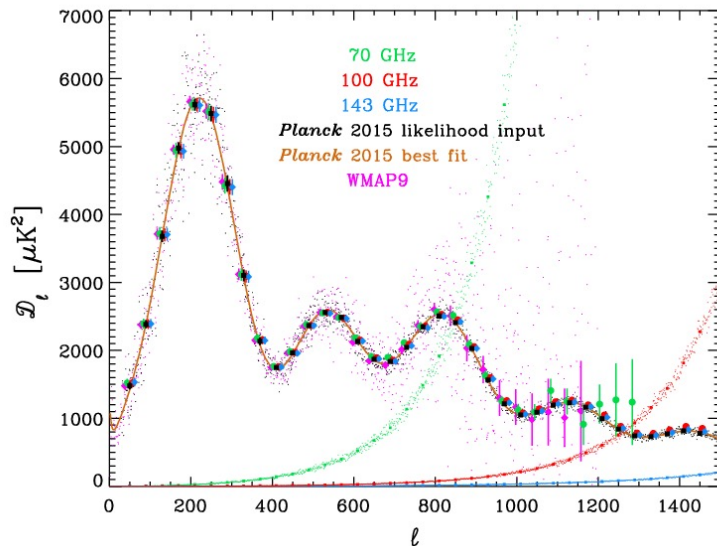
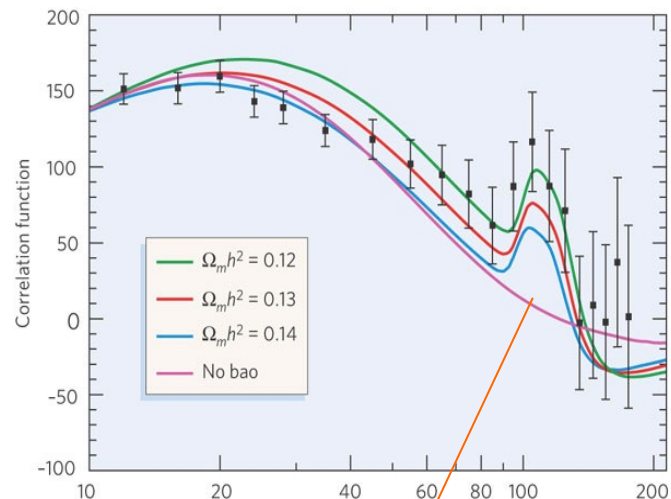
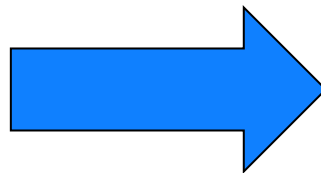
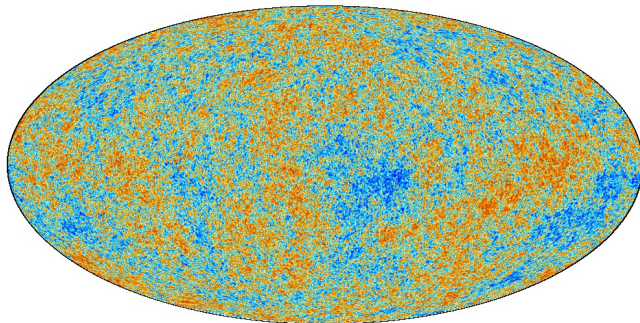


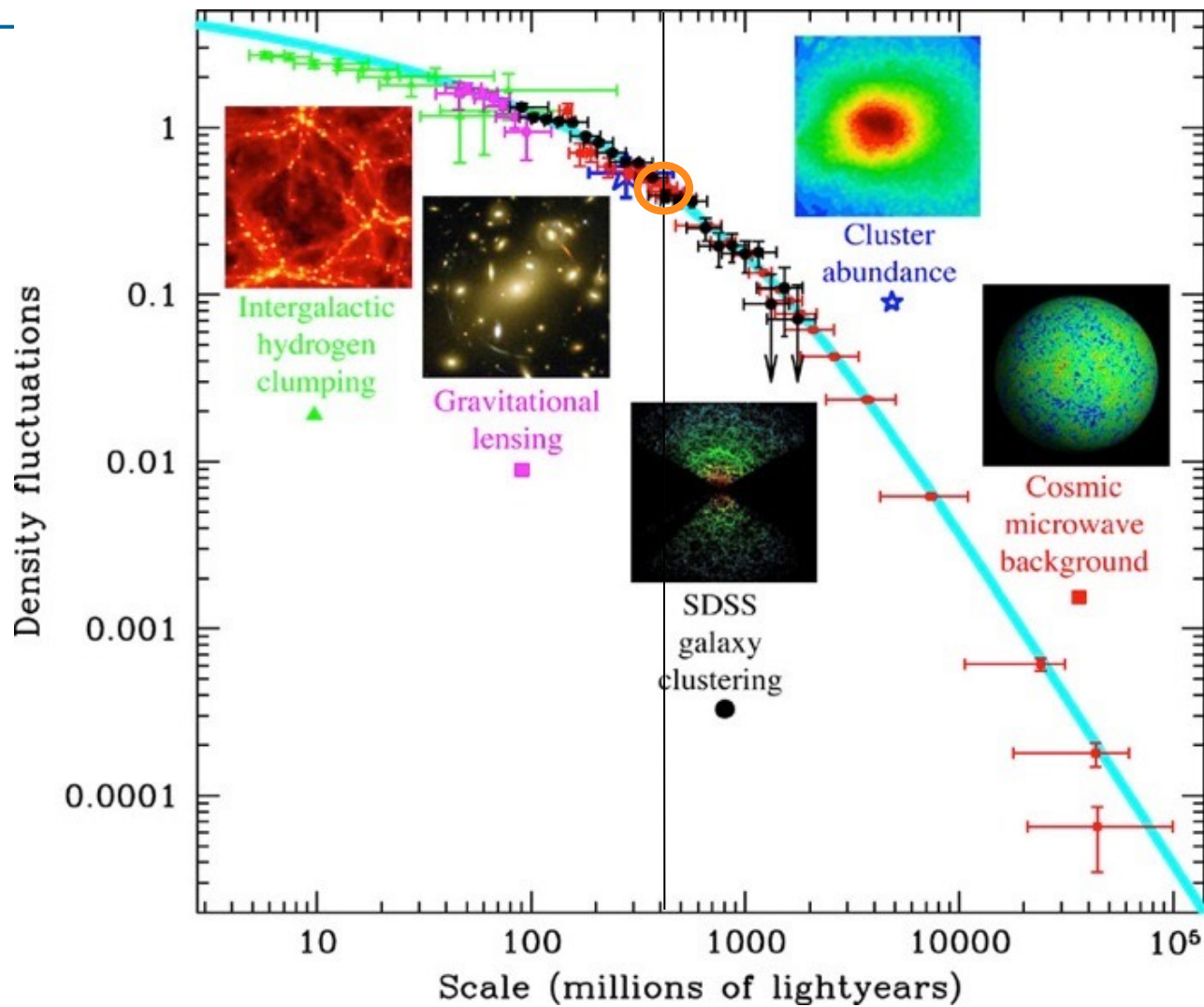
Image Credit: Dana Berry / SkyWorks Digital Inc. and the SDSS collaboration.

Dark Energy Observation program

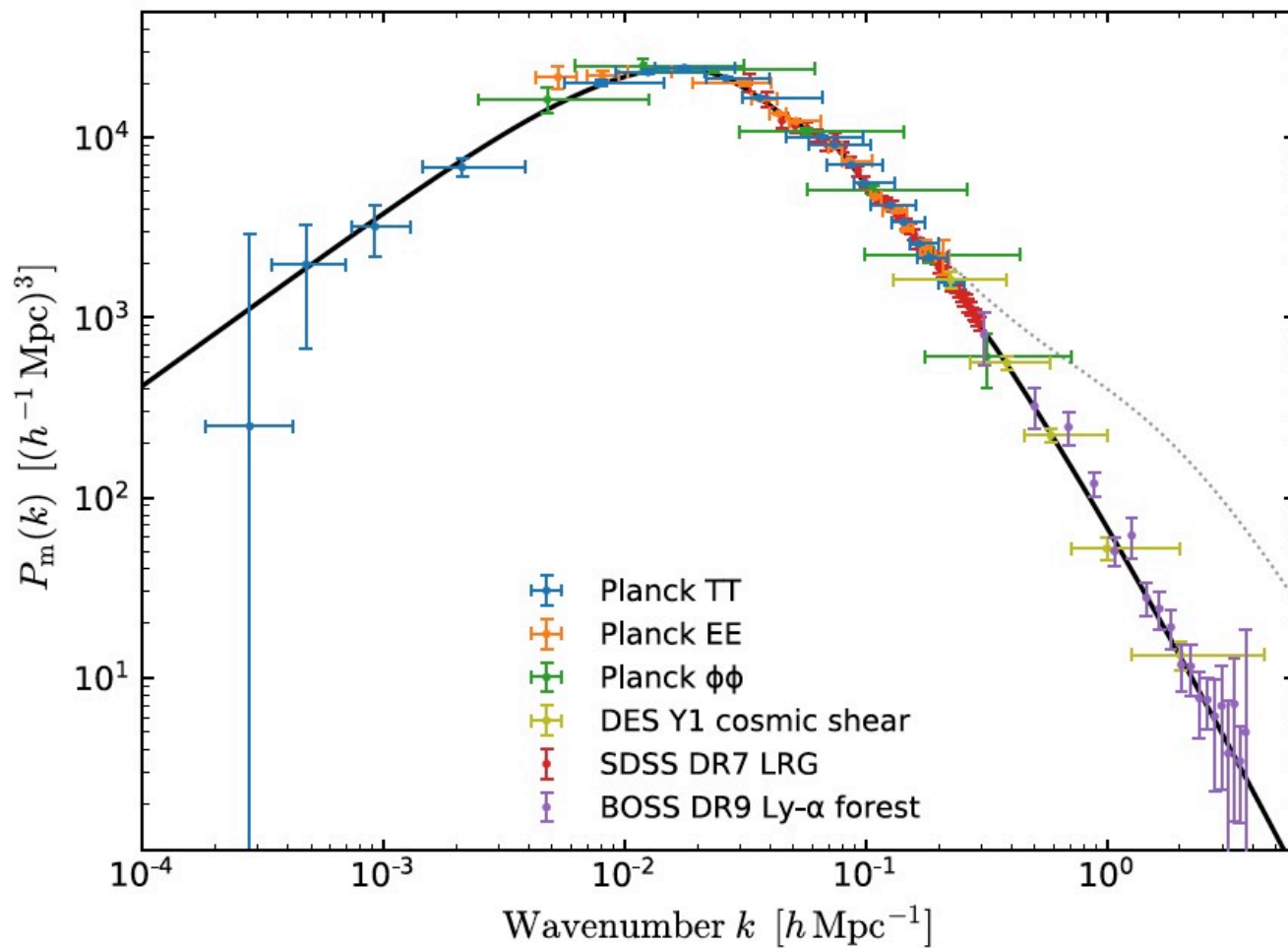
- Instruments: JWST, SKA, LSST, Euclid, DESI
- Observational targets
 - Galaxy Cluster Counting
 - Targets: SZ and X-ray cluster surveys
 - SN Ia
 - Targets: Large, low- z , SN survey
 - Weak Gravitational Lensing
 - Targets: optical surveys and 21 cm interferometric measurements
 - Baryon Acoustic Oscillations
 - Targets: $D(z)$, $H(z)$

Temperature x matter fluctuations



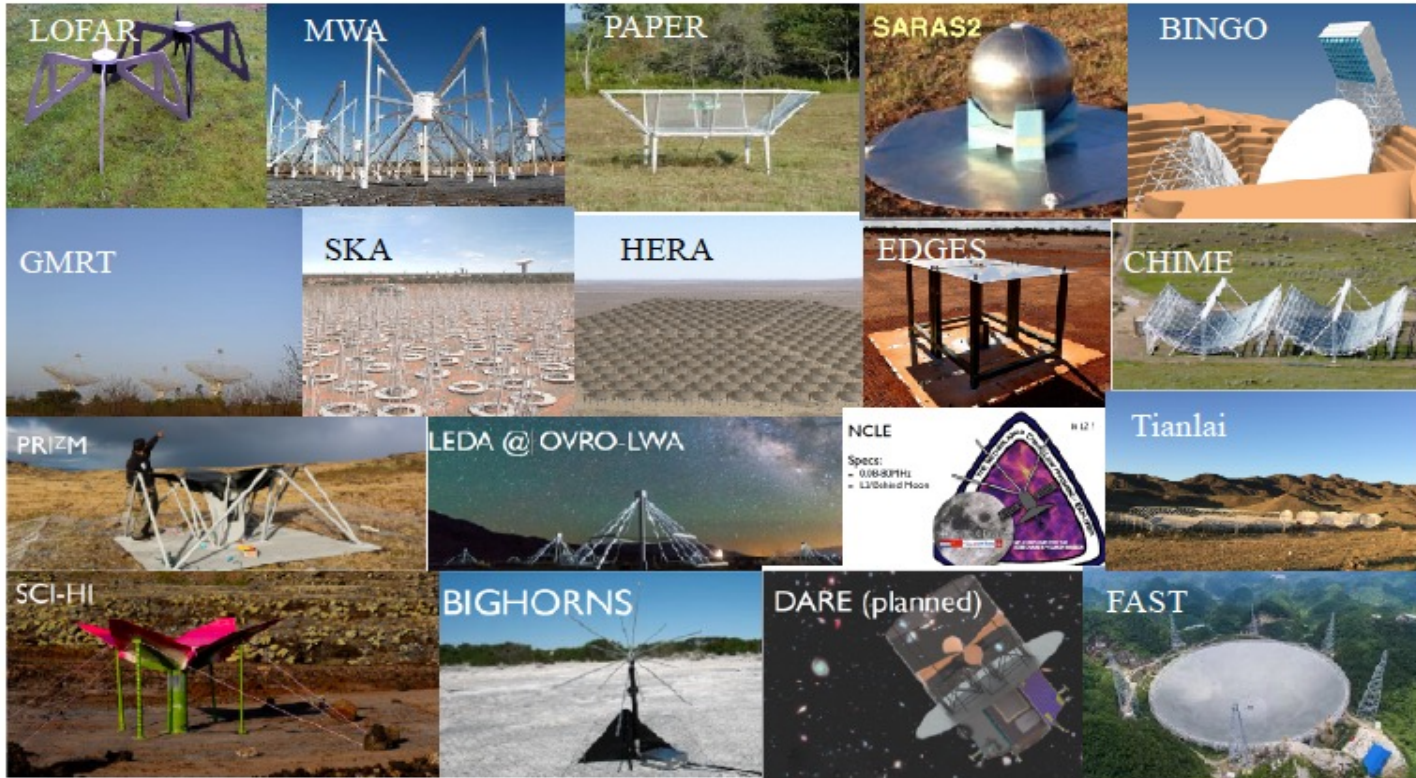


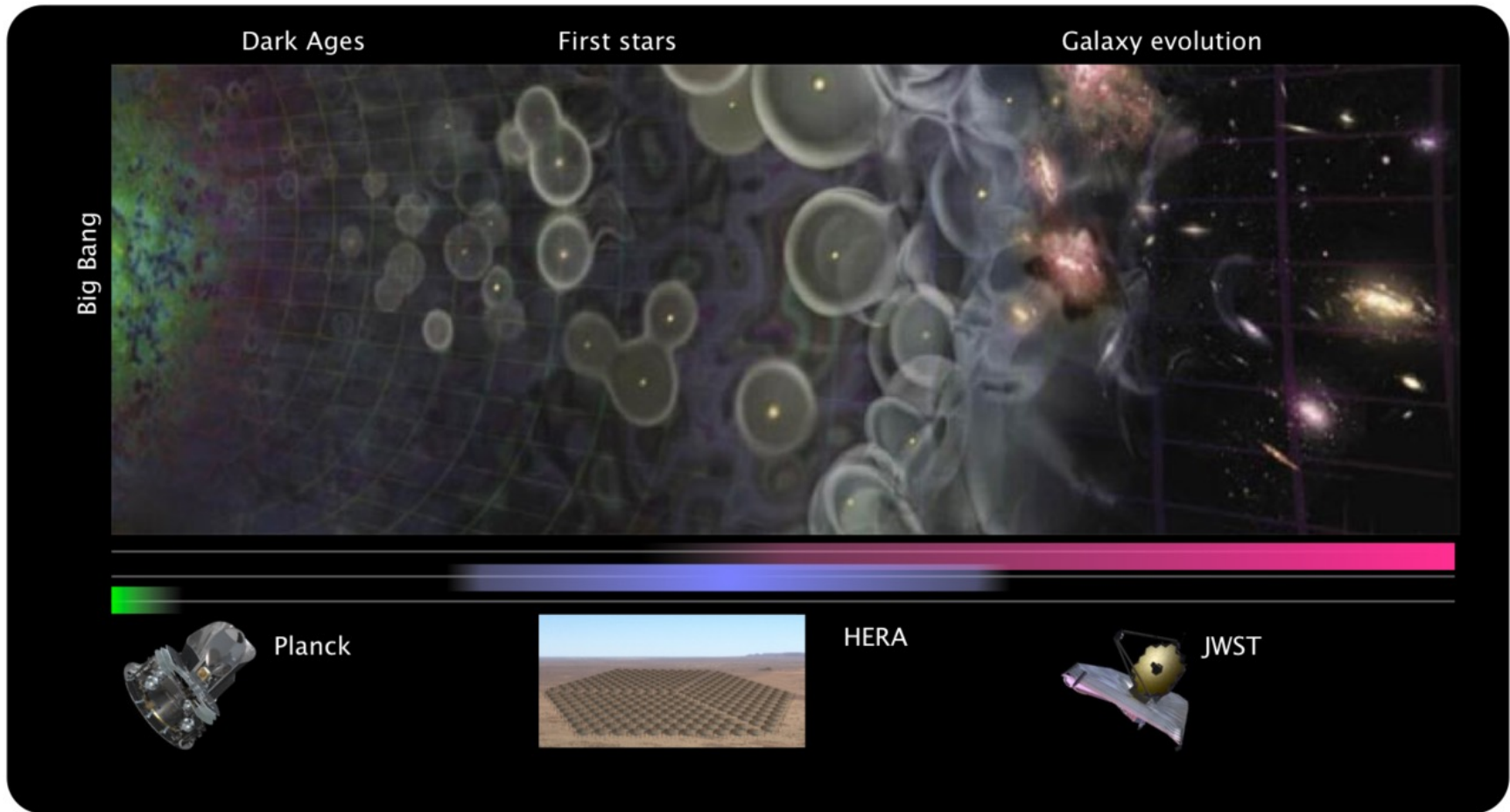
Credit: Max Tegmark



21 cm cosmology/astrophysics

A hot topic in today's astronomy





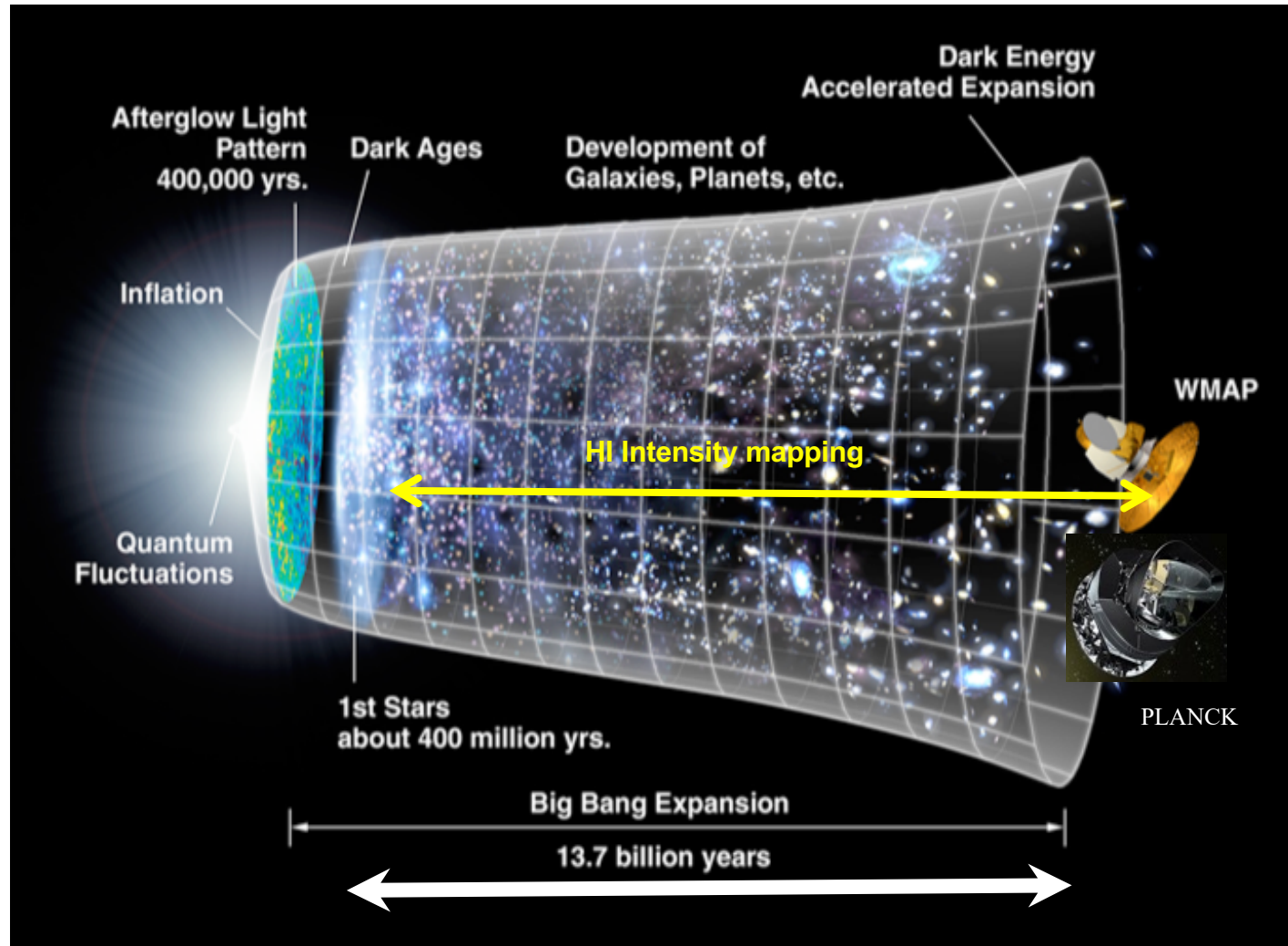
Credit: <http://danielcjacobs.com/research/21cm-cosmology/>

The BIG (BANG) picture

- The Universe evolved from a gaussian, almost uniform distribution where photons and electrons were coupled by Thomson interaction
- Dark matter halos were already collapsing under gravitational effect, dragging baryons into them
- Very small density fluctuations in the CMB temperature distribution evolved to gravitationally collapse into the large scale structure that today form the “cosmic web”

$$\frac{\delta\rho}{\rho} \sim 10^{-5} \rightarrow \frac{\delta\rho}{\rho} \gg 1$$

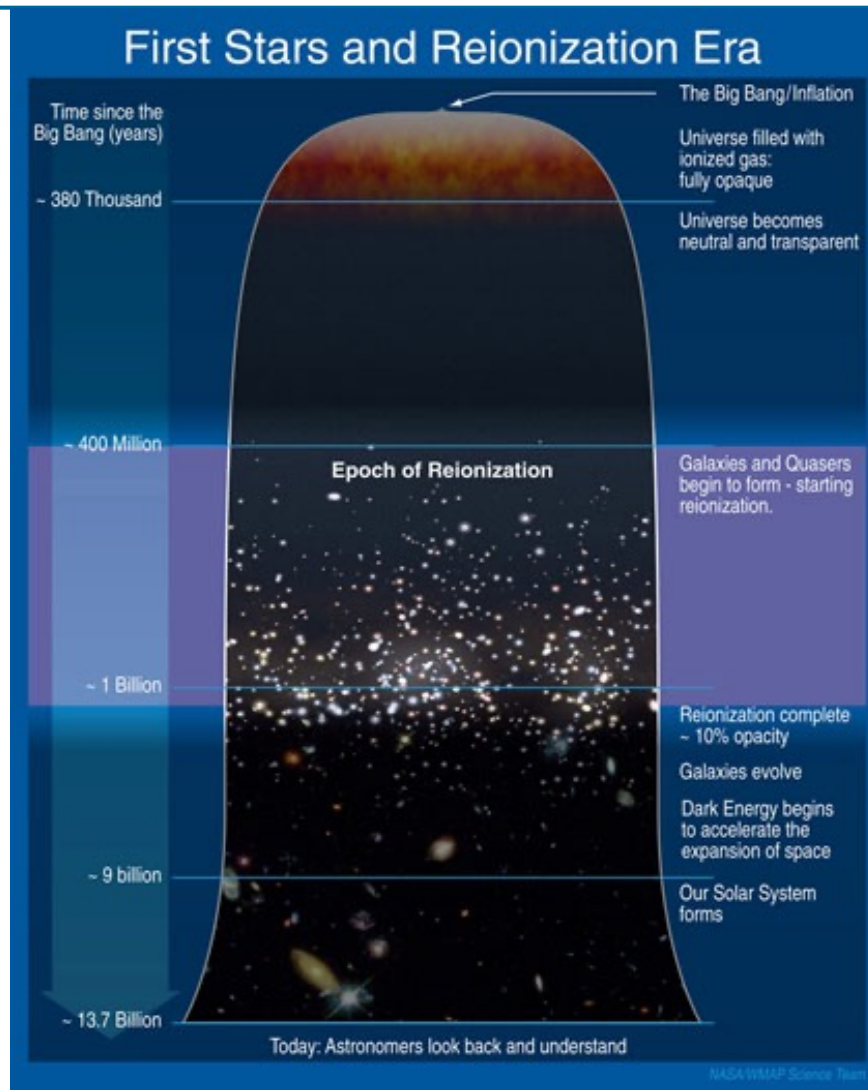
- Yet to be studied and understood: the so-called “Dark Ages”, that roughly cover the redshift interval $1100 > z > 6$

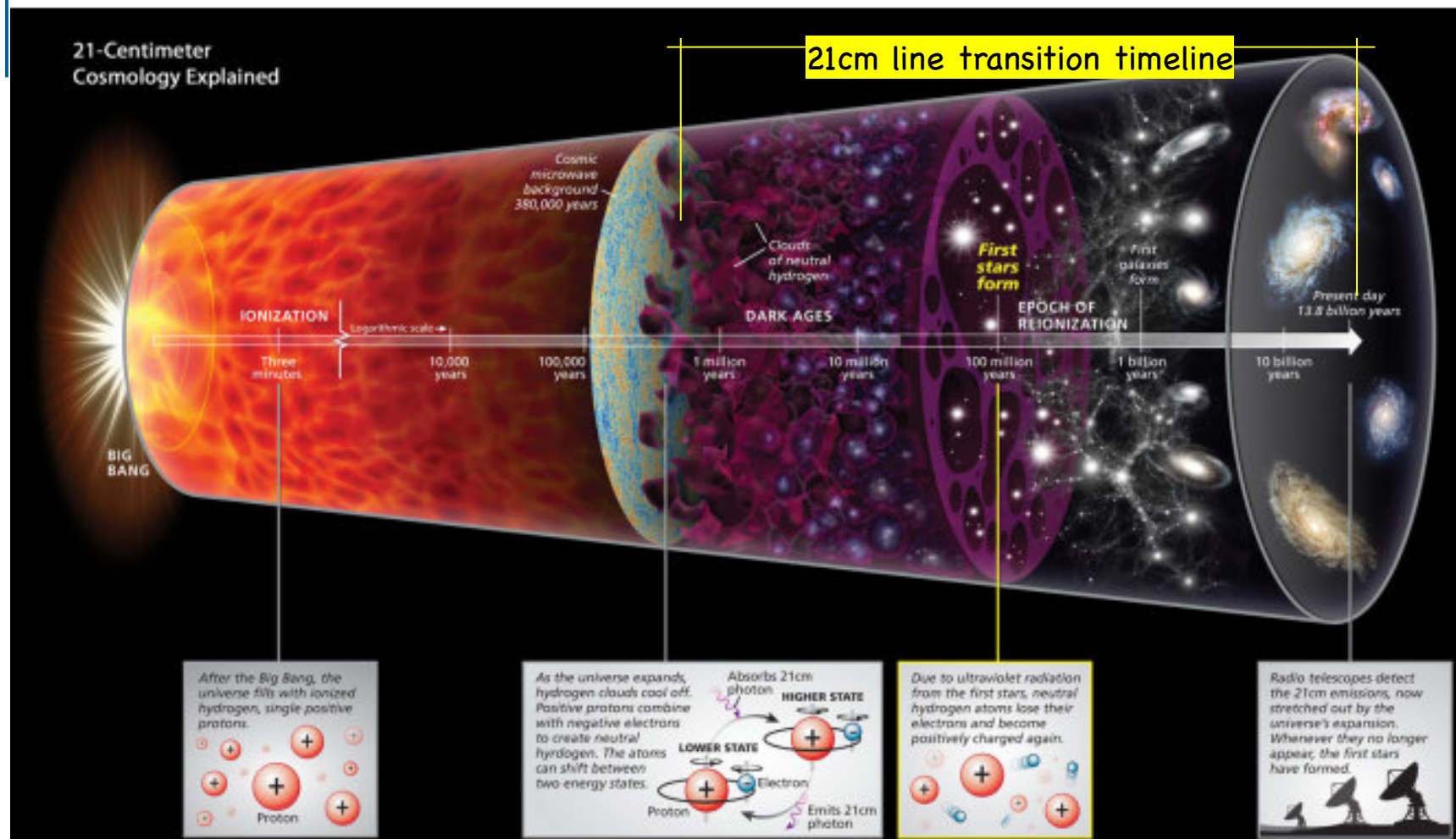


The BIG (BANG) picture

- The Dark Ages most importante aspects:
 - Transition from linear to non-linear regime in the density perturbations
 - Possibility to directly detect PopIII stars
 - Study the first quasars and stars and their influence in the neighborhood
 - Connect CMB physics with Large Scale Structure (LSS) physics
- Main physical processes after recombination and before the non-linear regime
 - Expansion
 - Gravity pull
 - Interaction between residual electrons and photons

21 cm cosmology is probably our best bet to study these phenomena in the Universe history





Credit: <https://www.discovermagazine.com/the-sciences/chasing-the-universes-first-generation-of-stars>

The Astrophysics during the Dark Ages

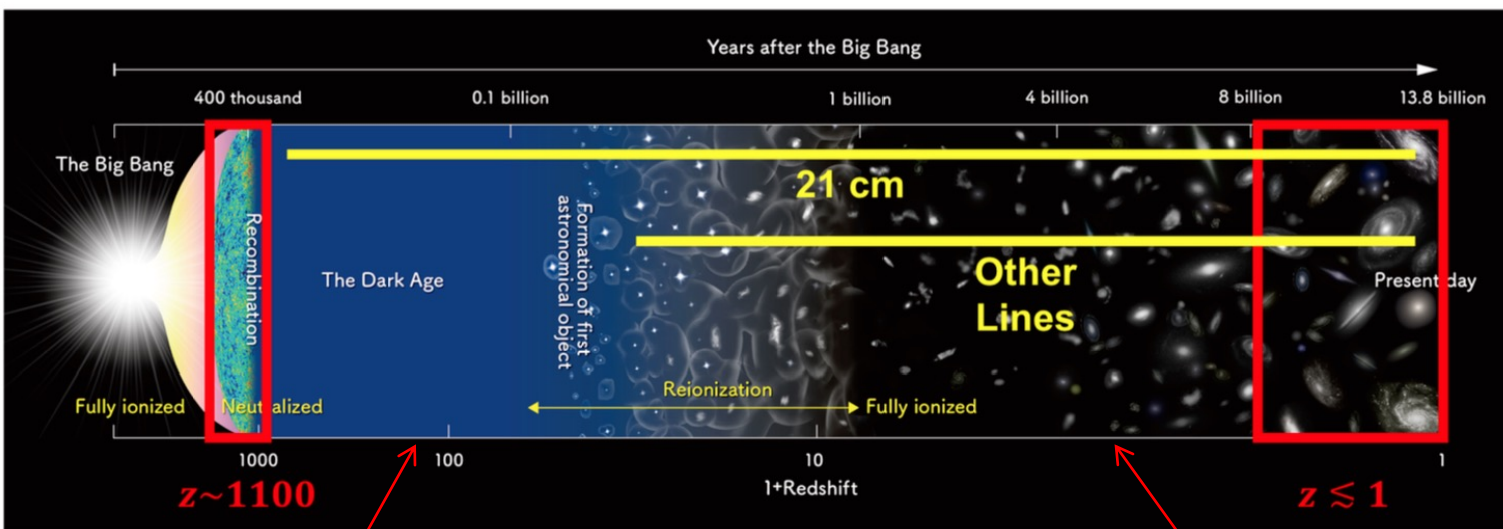
- Matter cluster and collapse to form Pop III stars and the first quasars
- These are powerful sources of high-energy photons that “reionize” the InterGalactic Medium (IGM) => THIS IS THE SO-CALLED REIONIZATION or COSMIC DAWN
- Once the Universe is ionized, it becomes transparent to UV ($\text{Ly-}\alpha$) photons and the young star-forming galaxies can then be observed
- The neutral Universe suffers a “REIONIZATION” and most of the existing gas today is ionized

21 cm cosmology (HI)

- Physics of the early Universe is reasonably well understood from $10^{-6} \text{ s} < t < 3.8 \times 10^5 \text{ yrs}$ (**decoupling**)
- Physics after Cosmic Dawn ($t \sim 180 \times 10^6 \text{ yrs}$) is again reasonably well understood
- HI “is formed” at decoupling and starts to disappear after Cosmic Dawn
- History of matter evolution can be traced via HI distribution (and its “disappearance”) from $z=20$ to $z=0$
 - $0 < z < 2$ – Matter to Dark Energy transition
 - $2 < z < 6$ – Structure formation...
 - $6 < z < 20$ – HII to HI...

For reference:

$Z = 0.5$	$\Rightarrow$	$t = 8,63 \text{ Gy}$
$Z = 2$	$\Rightarrow$	$t = 3,32 \text{ Gy}$
$Z = 6$	$\Rightarrow$	$t = 0.94 \text{ Gy}$
$Z = 20$	$\Rightarrow$	$t = 0,18 \text{ Gy}$



$Z = 200$

$Z = 6$

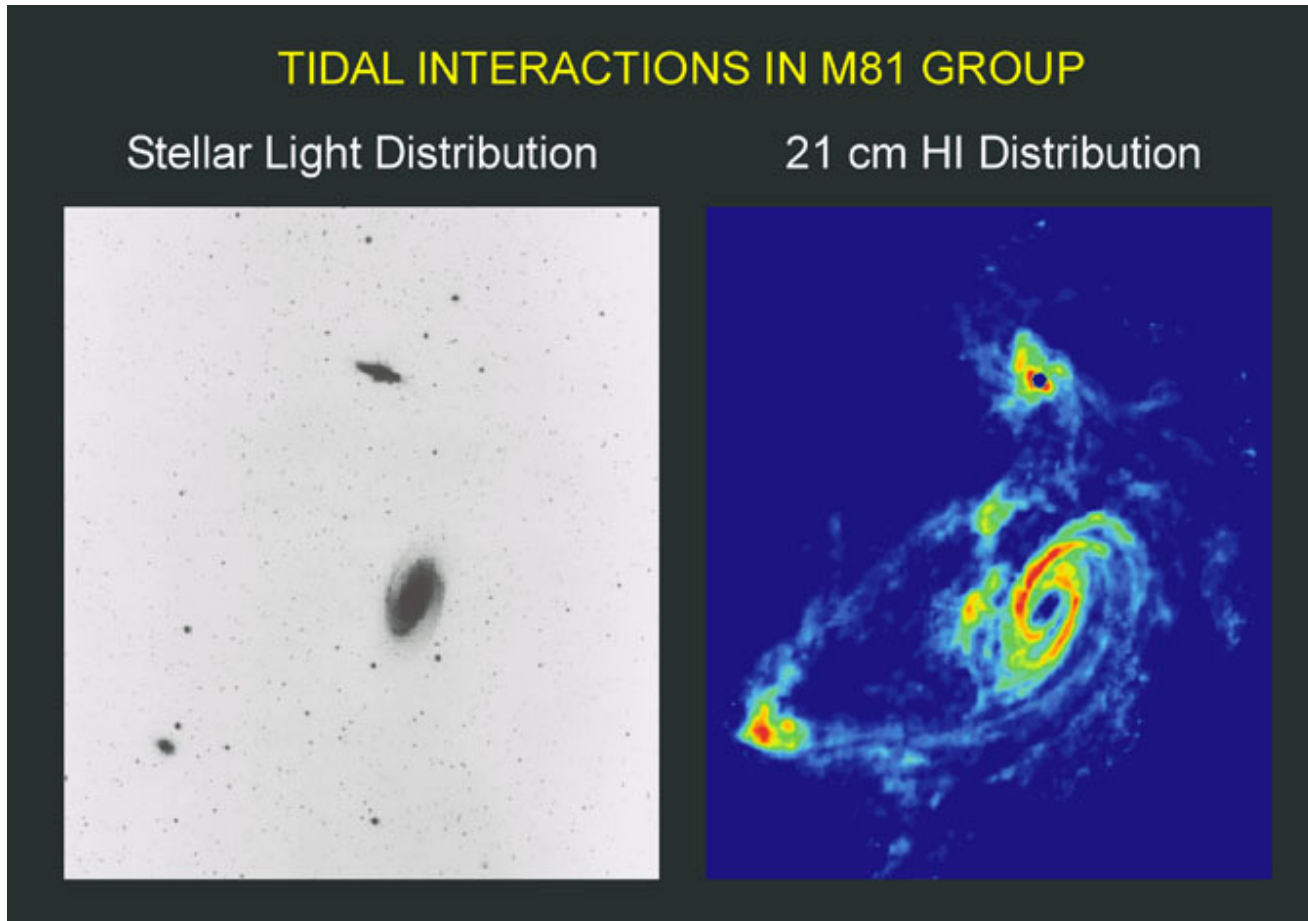
Kovetz et al. 2017 (arXiv:1709.09066)

THE BASICS

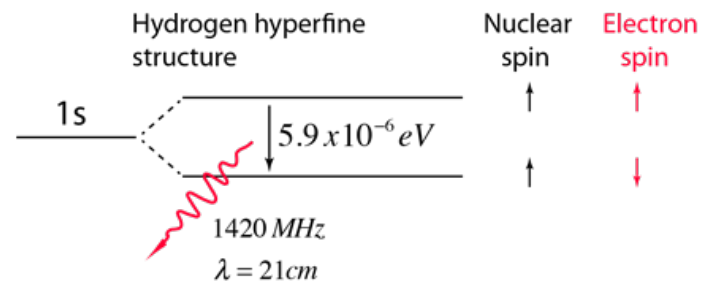
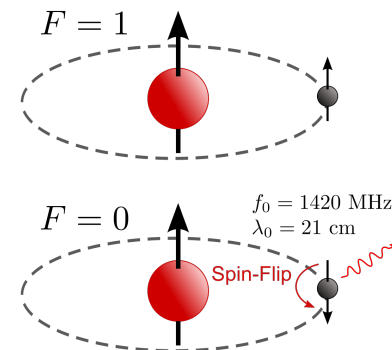
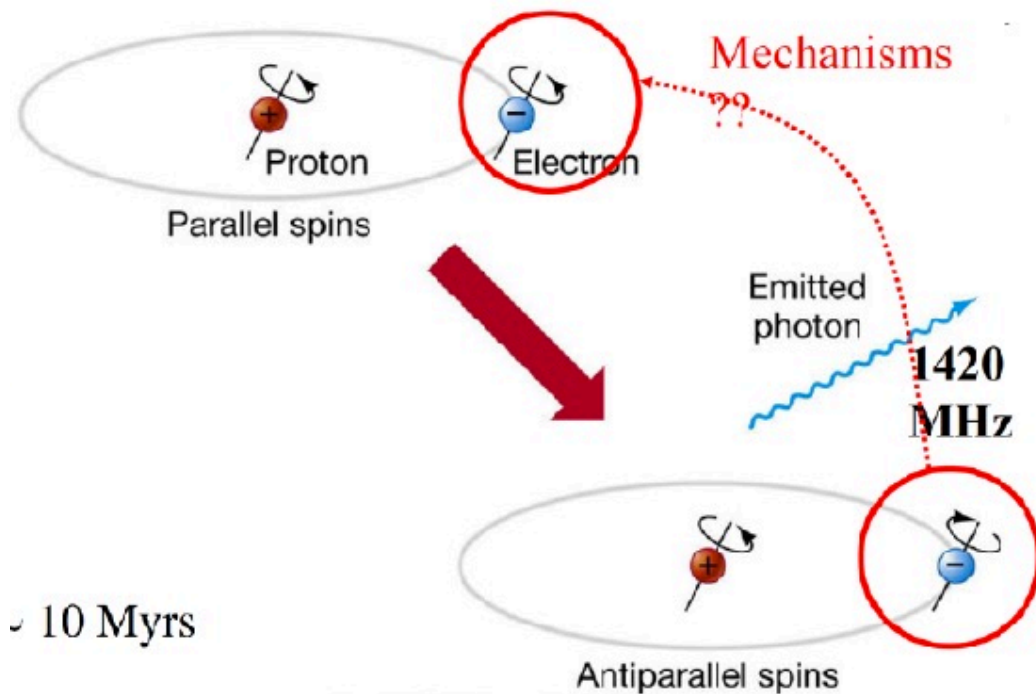
Atomic Hydrogen 21 cm line

- H is the most abundant element in the Universe
- Neutral H (HI) is most important, BUT:
 - **Very difficult to detect in cosmological distances**
- 21 cm “forbidden” transition line
 - 1 atom emits a photon every 10^{15} s (~ 30 Myr), so it should be a very weak signal
 - But.... There are zillions of H atoms in the Universe!
 - **Frequency: 1420.406 MHz ($\Rightarrow$ wavelength ≈ 21.106 cm – radio)**
- Observed since 1950s’ but only restricted to the Galaxy and neighbor galaxies ($z < 0.1$)
- **Doppler shift of HI line gives direct information of velocity and distance**
- Redshift of interest starts at frequencies < 1 GHz

Atomic Hydrogen 21 cm line

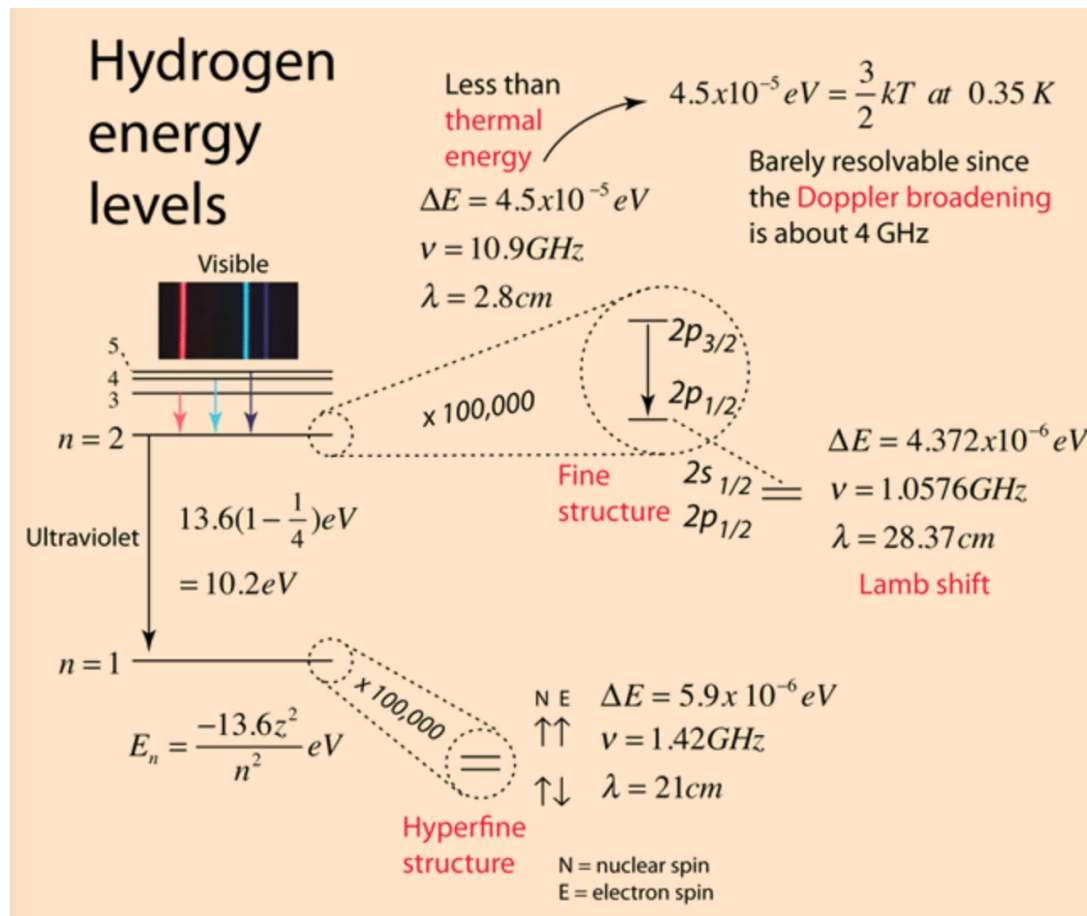


Atomic Hydrogen 21 cm line



BUT THERE ARE ALSO ABSORPTIONS...

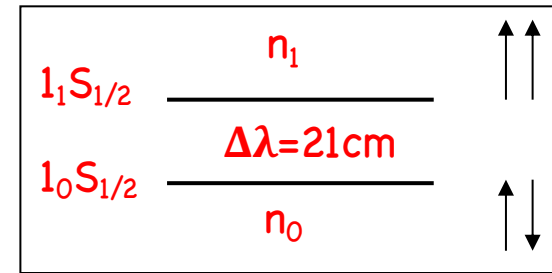
Atomic Hydrogen 21 cm line



The transition

- And we should consider the population distribution for the following cases:

- ☐ Spontaneous emission
- ☐ Stimulated emission
- ☐ Absorption



$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left[\frac{T_*}{T_S}\right]$$

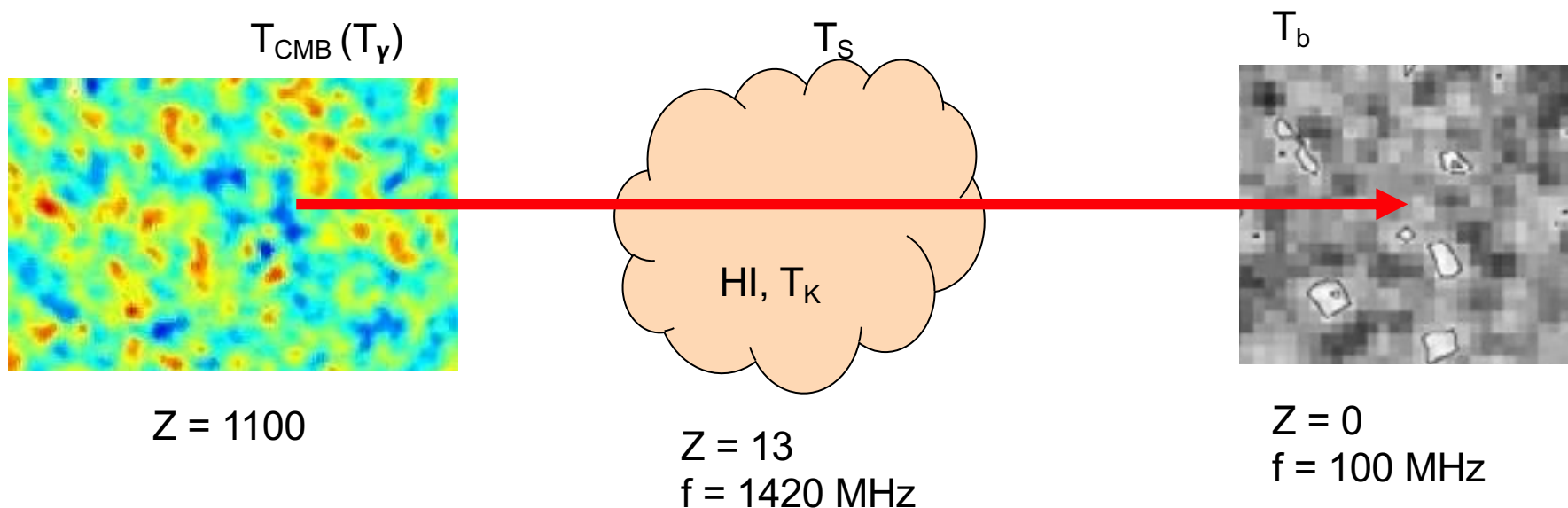
$$g_1=3$$

$$g_0=1$$

- The spin temperature (T_S) is the relevant variable and it changes according to the epoch (background temperature changes).

The basic idea...

$$T_b = T_b(0) e^{-\tau_\nu} + T_S(1 - e^{-\tau_\nu}),$$



$$T'_b(z) = T_b(z)(1 + z) = T_S e^{-\tau_\nu} + T_\gamma(z)(1 - e^{-\tau_\nu}).$$

The formalism

- In our context, T_b is what we observe and its original intensity is redshifted due to the expansion. In the HI cloud, we identify T_{CMB} with T_γ

$$T'_b(z) = T_b(z)(1 + z) = T_S e^{-\tau_\nu} + T_\gamma(z)(1 - e^{-\tau_\nu}).$$

- We are interested in the fluctuations that appear in the brightness temperature

$$\delta T = T_b - T_\gamma$$

- Considering a small optical depth, which happens as the Universe expands and the scattering agents decrease:

$$\delta T_b(z) = \frac{T_S - T_\gamma(z)}{1 + z} \tau_{\nu_0}$$

The formalism

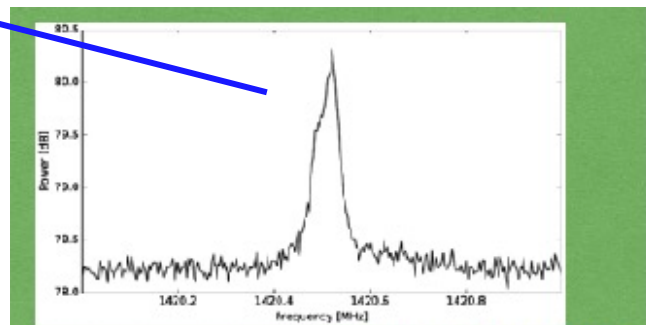
- The optical depth $\tau_{\nu 0}$ for a hydrogen cloud can be expressed in terms of emission coefficient A_{10} and will include the variation with the Hubble flow

$$\tau_{\nu} = \int ds \sigma_{01} (1 - e^{E_{10}/k_B T_S}) \phi(\nu) n_0$$

Line profile. Various factors account for its shape

$$\approx \sigma_{01} \left(\frac{h\nu}{k_B T_S} \right) \left(\frac{N_{HI}}{4} \right) \phi(\nu)$$

HI column density



credit: DC Price 2016

$$\sigma_{01} = \frac{3cA_{10}}{8\pi\nu^2}$$

Spontaneous emission coefficient

$$\phi(\nu) \sim c/[sH(z)\nu]$$

The formalism

- We expect to see the variation of IGM properties changing with the Hubble flow and the velocity broadening of region with **linear dimension s**

$$\Delta V \sim s H(z), \text{ so that } \phi(\nu) \sim c/sH(z)\nu$$

$$N_{HI} = x_{HI}n_H(z)s$$

- Combining the above expressions, we get an expression for $\tau_{\nu 0}$ in a cosmological context

$$\begin{aligned} \tau_0 &= \frac{3}{32\pi} \frac{hc^3 A_{10}}{k_B T_S \nu_0^2} \frac{x_{HI} n_H}{(1+z) dv_{\parallel}/dr_{\parallel}} \\ &\approx 0.0092(1+\delta)(1+z)^{3/2} \frac{x_{HI}}{T_S} \left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right] \end{aligned}$$

Kelvin

The temperature of the 21 cm line transition

$$\delta T_b(\nu) \approx \underbrace{9X_{HI}(1 + \delta_b) \left[1 - \frac{T_{\gamma(z)}}{T_S} \right]}_{\text{Astrophysics}} \underbrace{(1+z)^{1/2} \left[\frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right]}_{\text{Cosmology}} \text{ mK}$$

Labels for the equation components:
 - Fraction of HI: points to X_{HI}
 - Radiation field temperature: points to $T_{\gamma(z)}$
 - Baryon fractional overdensity: points to δ_b
 - Spin temperature: points to T_S
 - LoS velocity gradient: points to $dv_{\parallel}/dr_{\parallel}$

- These are the fluctuations we expect to measure and is a direct application of the radiative transfer equation.
 - T_S is driven by the radiation field and fluctuates around $T_{\gamma(z)}$. The difference will define which is the dominant process: **absorption**, **emission** or a zero variation
 - For high- z clouds, $T_{\gamma(z)} = T_{\text{CMB}}$ (mostly emission)
 - For lower- z clouds, $T_{\gamma(z)} = T_{\text{Ly-}\alpha}$ (high- z radio sources, absorption)

A detailed derivation can be found in Furlanetto, Oh & Briggs (Phys. Rep. 2006)

The temperature of the 21 cm line transition

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

$T_\gamma \Rightarrow$ CMB

$T_\alpha \Rightarrow$ Wouthuysen-Field coupling

$T_K \Rightarrow$ gas kinetic temp (scattering)

$x_i \Rightarrow$ coupling constants

- T_S is dominated by different sources along the history of the Universe:
 - CMB interaction (mostly absorption, but also stimulated emission)
 - Collisional coupling with e^- , p and other H atoms
 - Ly- α scattering (the Wouthuysen-Field effect)
- The coupling constants define which process dominates in a given epoch

$$T_S \sim T_\alpha \sim T_K$$



W-F



recoils

Remember that $E_{21} = kT_{21}$
 $E_{21} = 5.9 \times 10^{-6}$ eV, $T_{21} = 0.068$ K

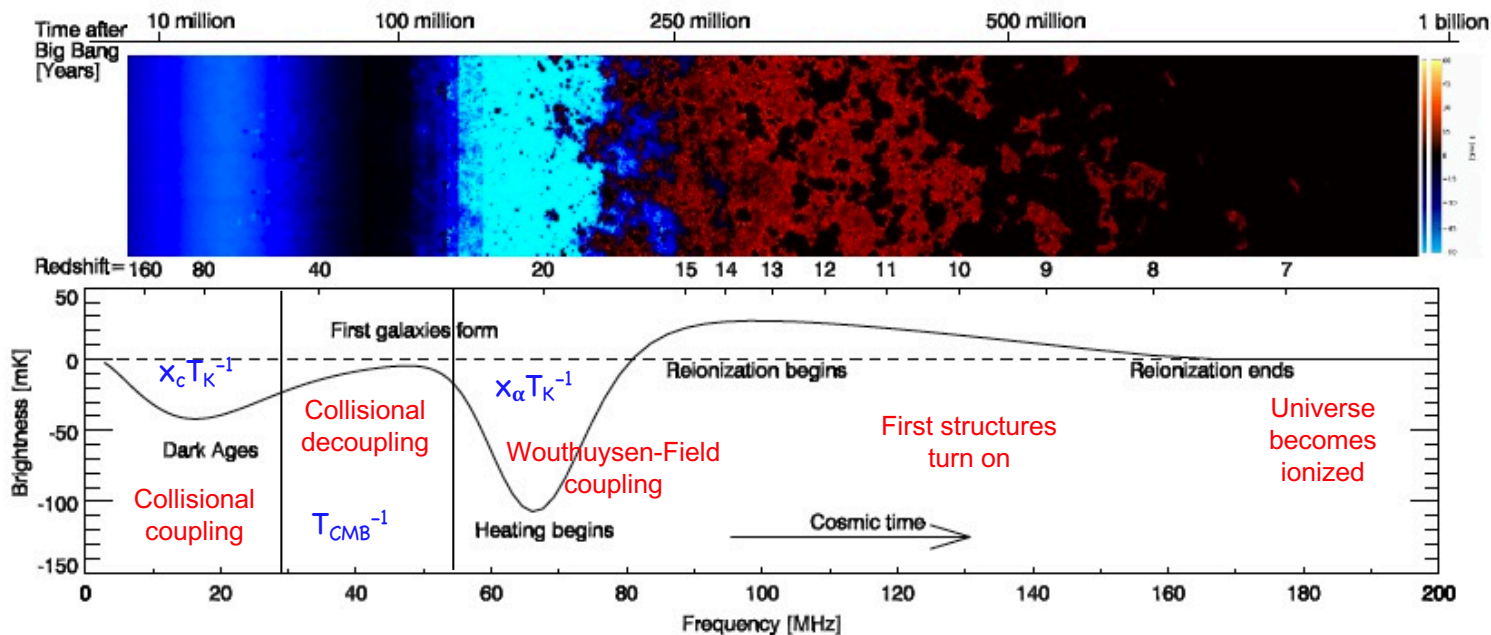
The temperature of the 21 cm line transition

$T_S = T_{CMB} \rightarrow \delta T_b = 0$ No signal

$T_S > T_{CMB} \rightarrow \delta T_b > 0$ Emission

$T_S < T_{CMB} \rightarrow \delta T_b < 0$ Absorption

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



The temperature of the 21 cm line transition

- We must note that, despite all the quantities related to T_S are referred to as “temperatures”, they are not actually thermodynamic temperatures.
 - T_R and T_b are radio intensity measurements
 - T_S measures the relative occupation numbers of the two hyperfine levels
 - T_α is a “color” temperature describing the photon distribution in the vicinity of the Ly- α transition.
 - True thermodynamic temperatures:
 - T_{CMB} – Cosmic Microwave Background temperature
 - T_K - kinetic temperature of the gas

THE PHYSICAL PROCESSES THAT PRODUCE THE 21 CM LINE

CMB Interactions

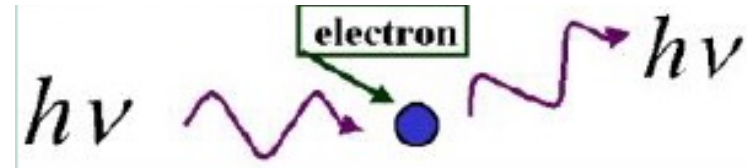
- CMB temperature evolves with z
- T_K is coupled to T_{CMB} ($\propto (1+z)$) through Thomson scattering of residual free electrons
- There is no α -coupling constant in this case

$$T_K \approx T_{CMB} \text{ down to } z \sim 200 - 150$$

$$T_K \propto (1+z)^2$$

$$T_K = T_{K,z=150}(1 + \Delta z)^{-2} K$$

Thomson scattering of CMB photons by e^-

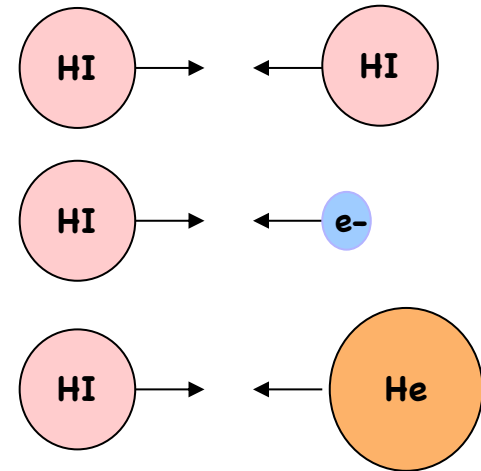


Collisional coupling

- Coupling to the gas, i is the colliding species (H-H, H-e⁻, H-He...)
- κ is the rate coefficient for spin excitation/de-excitation with species i
- C and A are the relevant Einstein coefficients
- **Quite efficient at high densities**

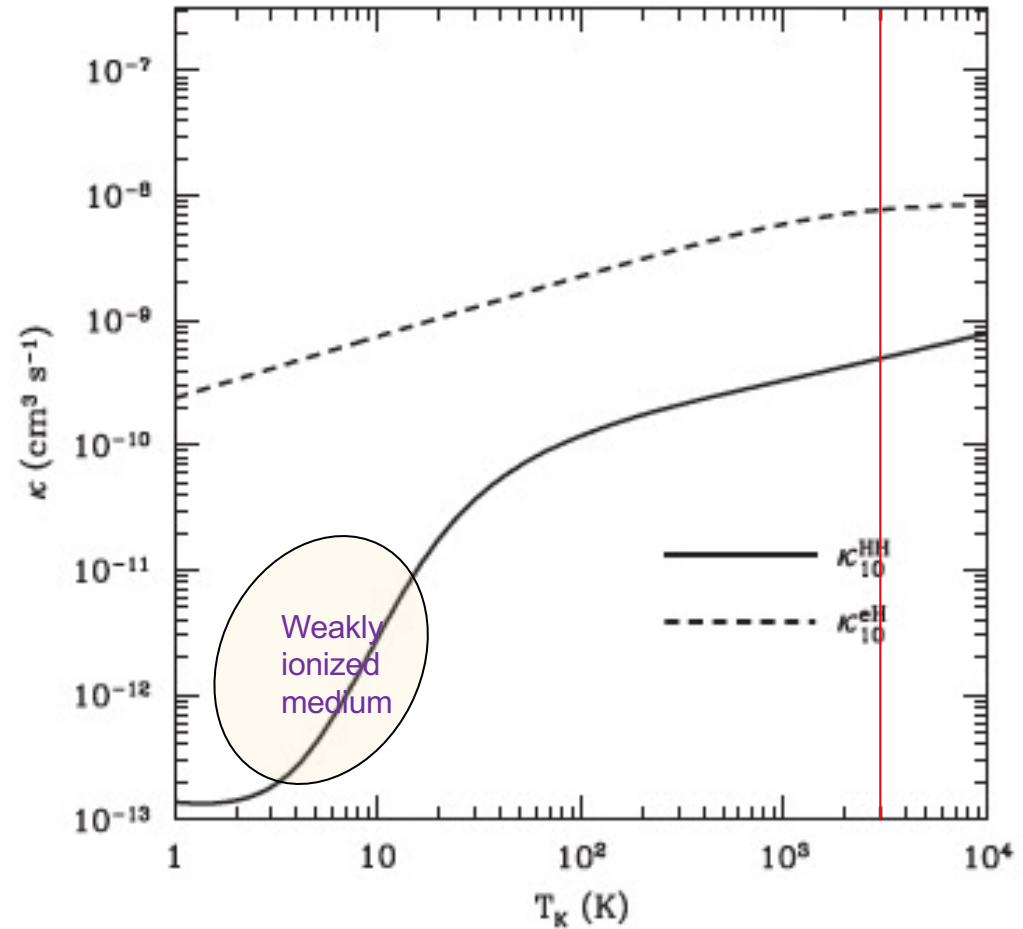
$$x_c^i \equiv \frac{C_{10}^i T_*}{A_{10} T_\gamma} = \frac{n_i \kappa_{10}^i T_*}{A_{10} T_\gamma}$$

Obs: Lots of quantum mechanics involved, through scattering theory. Spin exchange is the main issue in the HI - e⁻ collisions



Collisional coupling

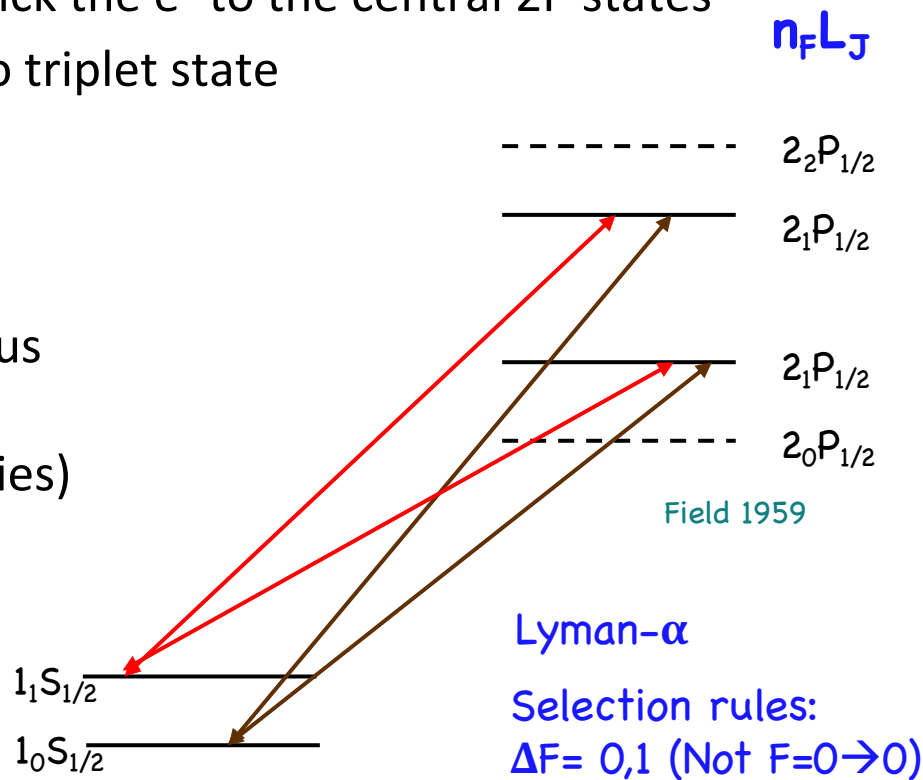
- De-excitation rates for H-H and H-e⁻
- Rates also proportional to densities
- Red line marks the (equivalent) temperature of recombination



Credit: Furlanetto, Oh & Briggs (Phys. Rep. 2006)

Wouthuysen-Field Effect

- Specific transitions powered by Ly- α photons
- Excitation from singlet state can kick the e- to the central 2P states
- Selection rules allow decay only to triplet state
- H atoms change hyperfine states through absorption and spontaneous re-emission of a Ly- α photon (or through down-cascading the Ly-series)



Wouthuysen-Field Effect

■ Coupling to the Ly- α radiation field means decoupling from the CMB field

■ T_S is now driven by a much more energetic radiation field

■ The coupling constant x_α is described by:

$$x_\alpha = \frac{4}{27} \frac{P_\alpha}{A_{10}} \frac{T_*}{T_{CMB}}$$

□ the scattering probability of a Ly- α photon, P_α

$$P_\alpha = 4\pi\chi_\alpha \int d\nu J_\nu(\nu)\phi_\alpha(\nu)$$

□ the “color temperature” of the Ly- α radiation field, T_*

□ local absorption cross section

$$\sigma_\nu = \chi_\alpha \phi_\alpha(\nu)$$

□ oscillation strength of the Ly- α transition

$$\chi_\alpha = \pi e^2 / m_e c$$

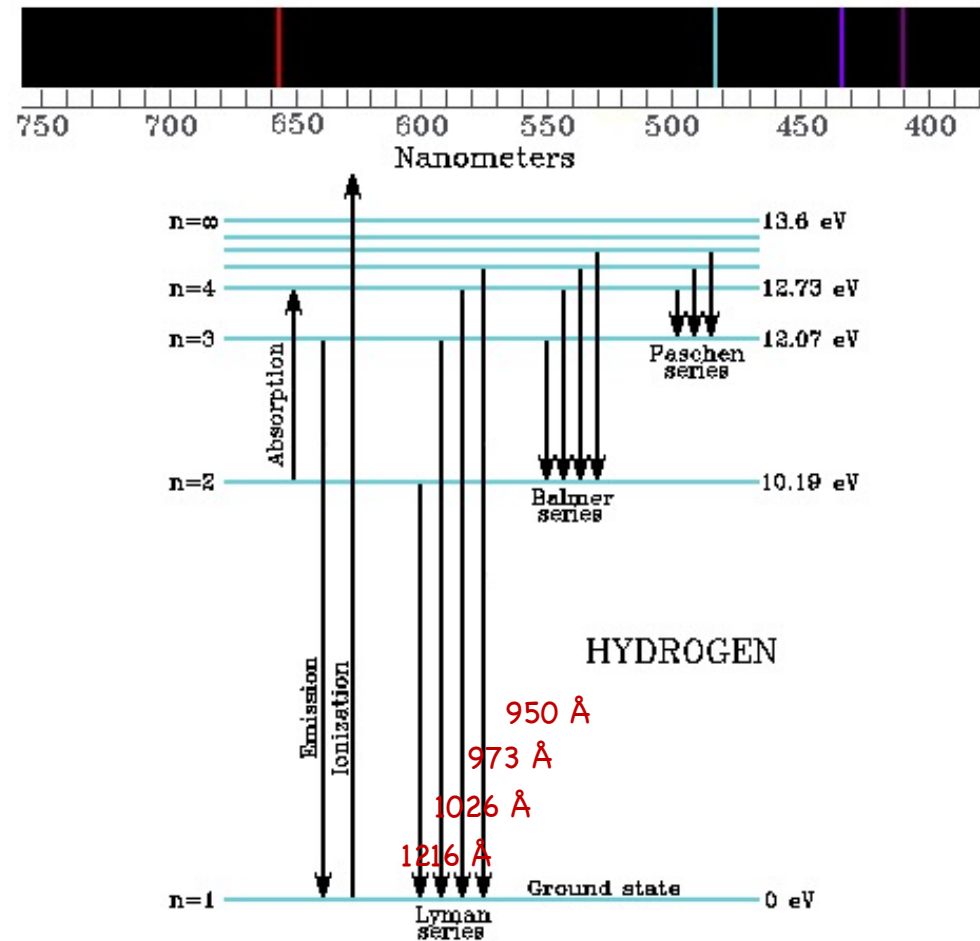
□ Ly- α absorption profile

$$\phi_\alpha(\nu)$$

□ angle-averaged specific intensity, (by number)

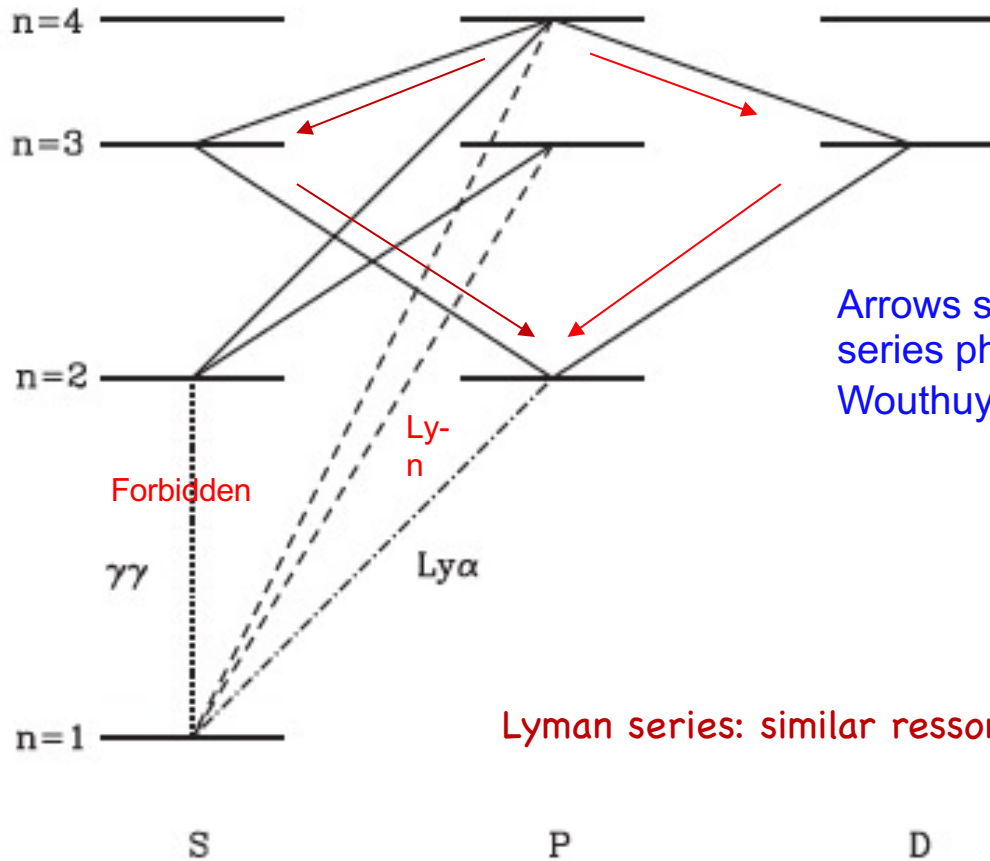
$$J_\nu(\nu)$$

Electron Energy Levels in Hydrogen



Credit: http://www.physics.louisville.edu/cldavis/phys111/davis/notes/ap_hslines.html

The Lyman-n possibilities of transitions



Arrows show the "recycling path" of a Ly-n series photon back into a Ly- α photon => Wouthuysen-Field effect back into the game

Lyman series: similar resonances to Ly- α but different couplings

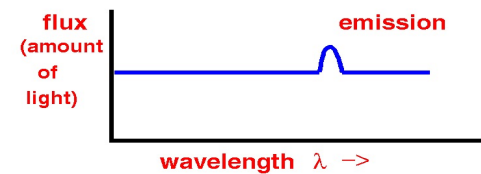
Why is the Ly- α line so important?

- It couples the 21cm line spin temperature to the gas kinetic temperature, through the Ly- α resonance
- It is essential to cool down the IGM, through photon absorption
- Its high intensity can be used as an independent tracer of structure in the high- z Universe ($z > 3$)
- Very high cross-section ($\sim 10^5$ scatterings before redshifting out of Ly- α resonance)
- Since the Ly- α is in the UV range, they contribute to ionization of the IGM, but only after the first generations of stars are formed.

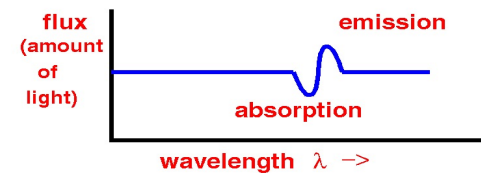
The global evolution of T_s

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

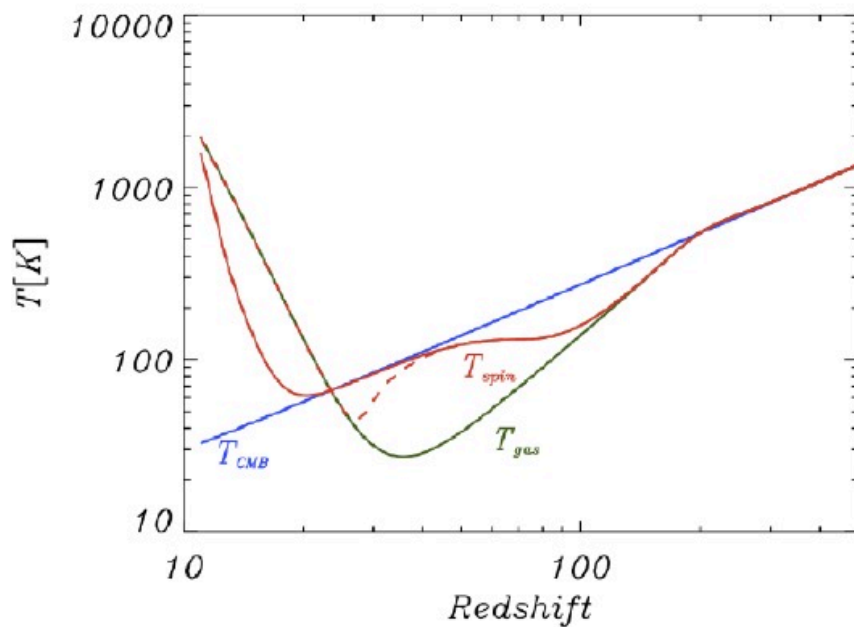
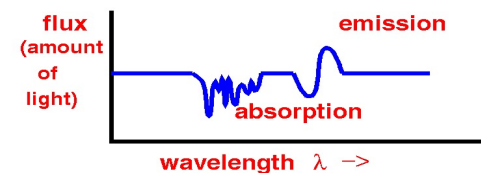
No absorbing clouds



One absorbing cloud close by



Several absorbing clouds



Refs: Loeb & Zaldarriaga, 2004; Pritchard & Loeb 2008, Baek et al, 2010

Credit: <https://w.astro.berkeley.edu/~john/lya.html>

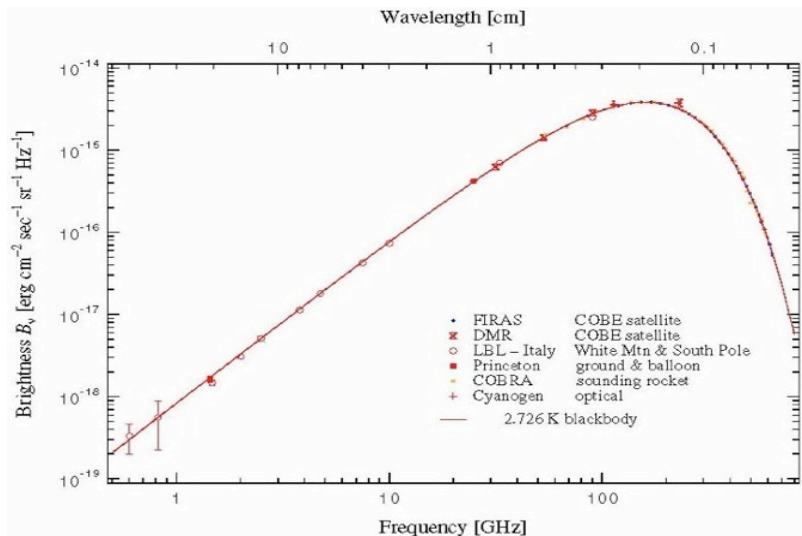
COSMOLOGY CONNECTIONS

Cosmology in the early Universe

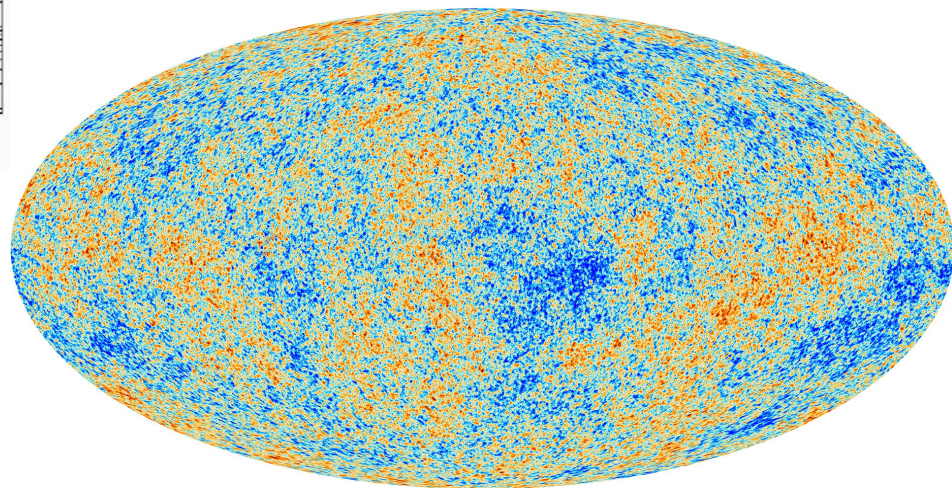
- The Cosmic Microwave Background is the superb (and only) tool to directly probe the early Universe
- Oldest electromagnetic signal that can be observed
- “Portrait” of the Universe $\sim 380,000$ years after the BIG BANG
- Blackbody spectrum with temperature $T = 2.725 (\pm 0.001)$ K
- Temperature fluctuations ($\Delta T \sim 10^{-5}$ K), sourced to primordial density fluctuations, reveal details of the physics of the formation of structures in the Universe
- Observable characteristics:
 - ☐ spectral distribution
 - ☐ angular distribution
 - ☐ polarization

CMB spectrum: energetics

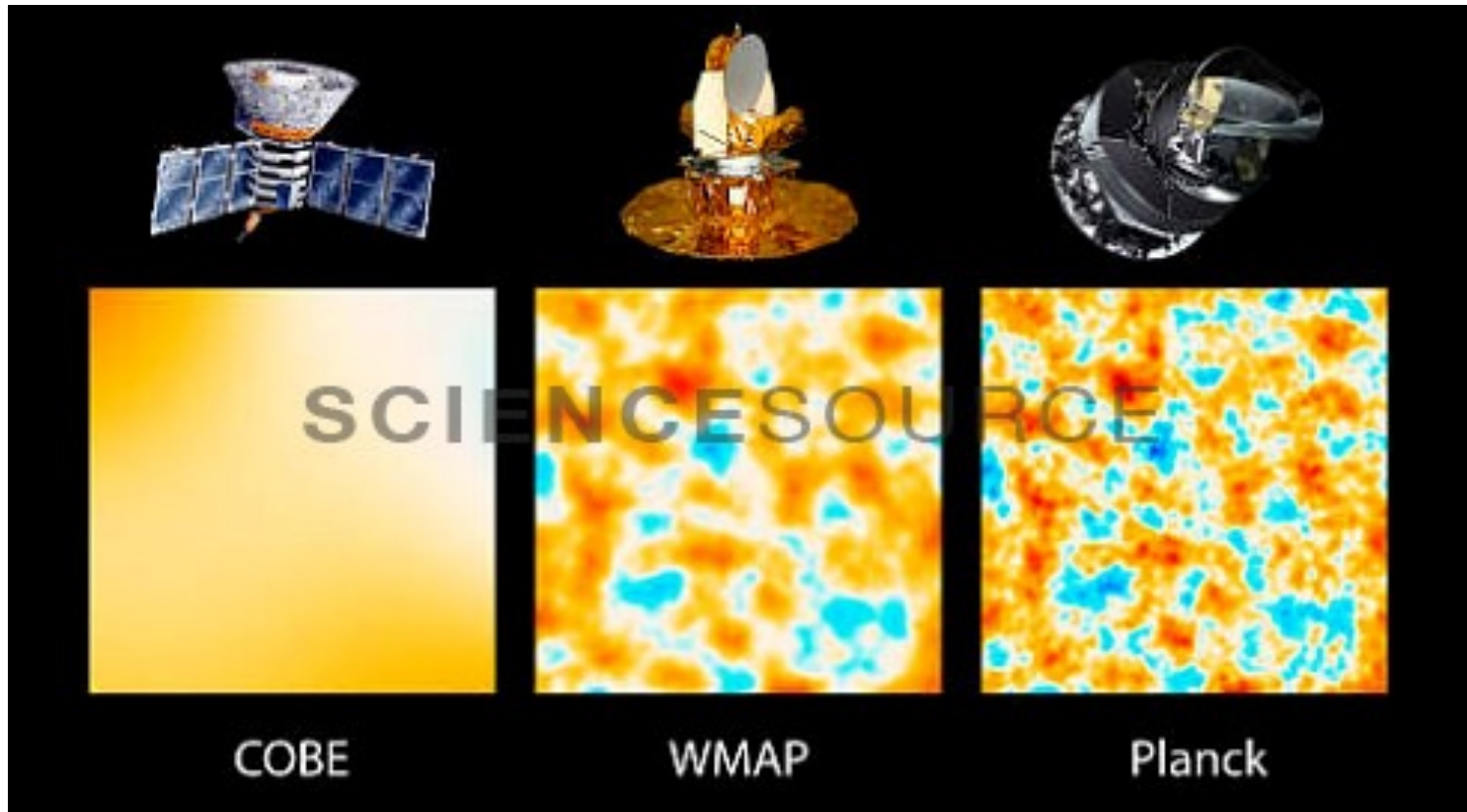
- Phase Transitions (Unification Theories)
- Decay of fossil particles (Dark Matter)
- Reionization (first stars)



- Distribution of density fluctuations
- Global cosmological parameters
- Inflation physics

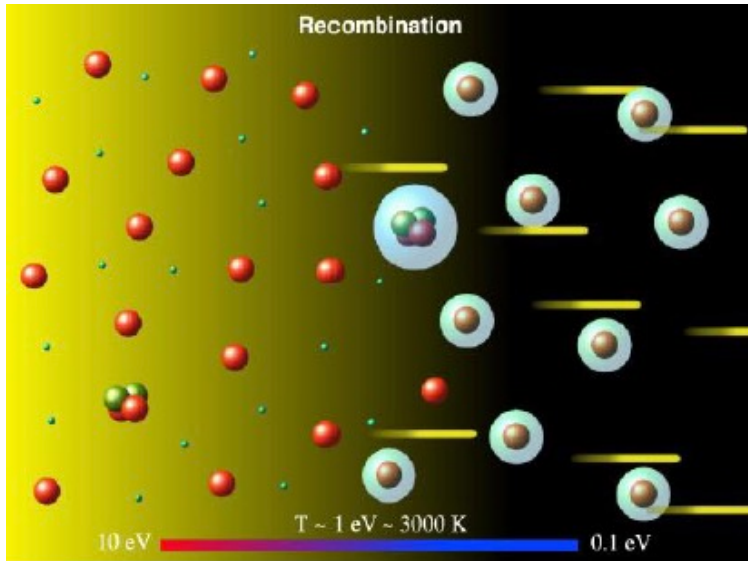


CMB temperature fluctuations: dynamics



CMB creation

- Photons and matter are coupled through Thomson scattering by photons
- Temperature decreases, electrons and protons (neutrons) combine to produce neutral atoms
- Mean free path of photons becomes $> H^{-1}$
- Photons decouple from matter at **$z=1100$**



$$T_{CMB}(z) = T_{cmb}(z=0)(1+z)$$

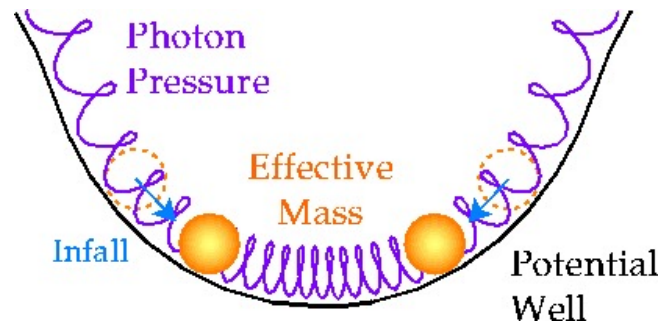
$$T_{CMB}(z=0) = 2.725K$$

$$T_{cmb}(z=1100) \approx 3000K$$

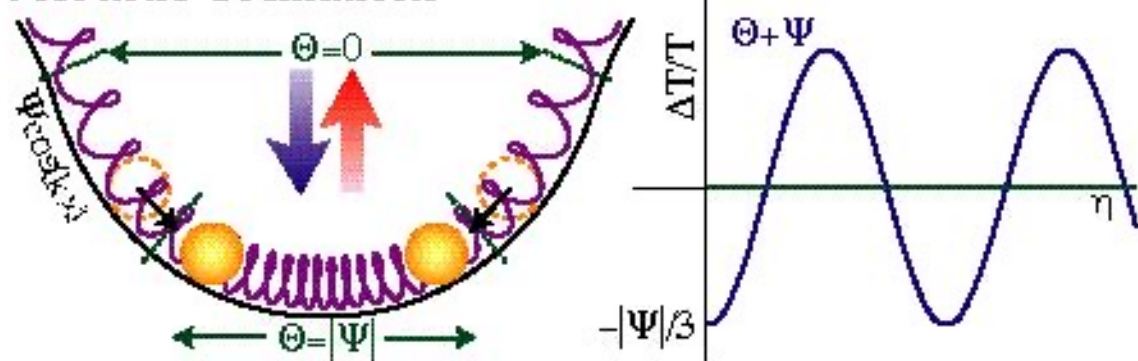
Source of density fluctuations

- Matter-radiation coupling can be modeled by a damped harmonic oscillator $\Rightarrow$ acoustic waves

- ☐ Baryons: mass $\rightarrow$ collapse
- ☐ Photons: resistance to collapse
- ☐ Density (not displacement): variable
- ☐ Expansion (H_0): damping term
- ☐ Gravity: main driving force



Acoustic Oscillations

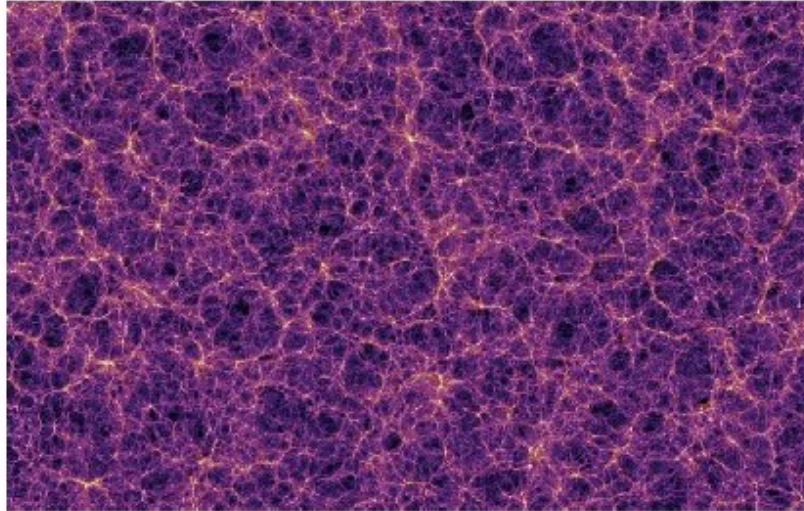
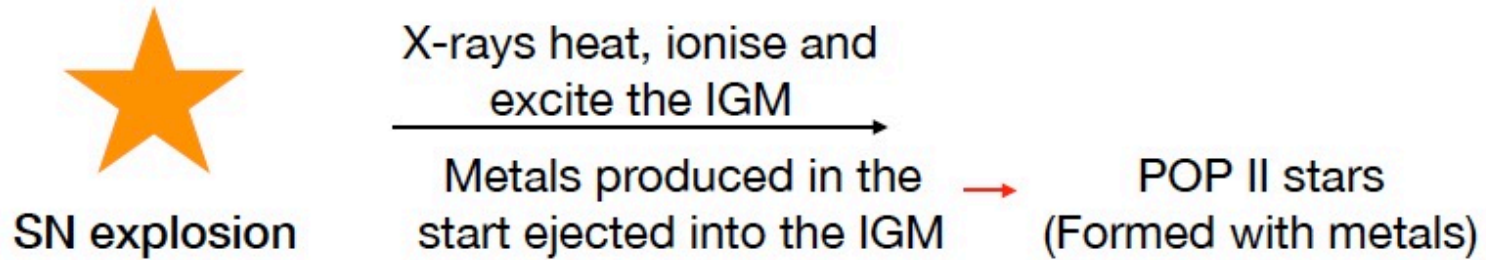


Reionization/Cosmic Dawn

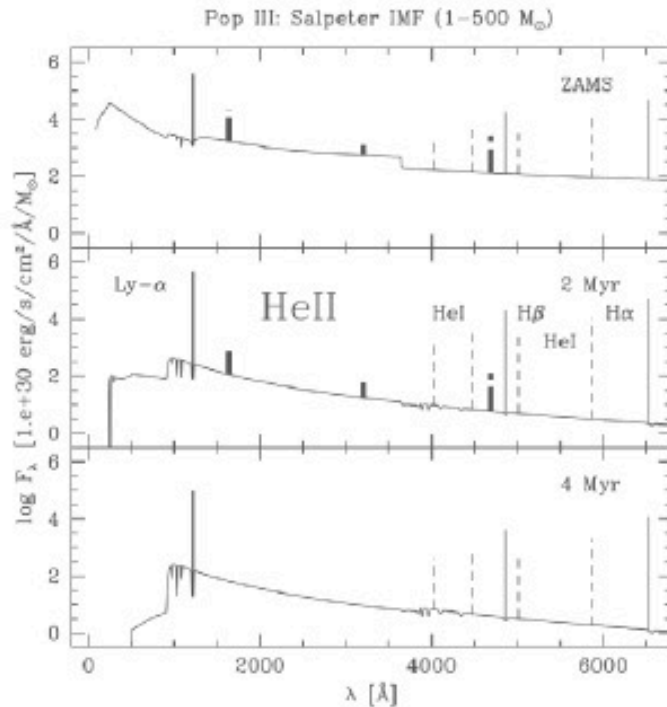
- Birth of first (**Pop III**) stars, in primordial mini-halos
- IMF is highly uncertain ($0.1 < M/M_{\text{sun}} < 1000$)
- Cooling through
 - neutral hydrogen $\rightarrow$ HI, $T > 10^4$ K
 - molecular hydrogen $\rightarrow$ H₂, $T > 200$ K
- Cause the chemical enrichment of the Universe, when supernova IIa exploded and flooded the IGM with metals
- Ionize its surroundings
- Produce of Lyman-Werner photons (11.2 to 13.6 eV) that photodissociate H₂

M_{ini}	lifetime
1000.	
500.00	1.899E+06
400.00	1.974E+06
300.00	2.047E+06
200.00	2.204E+06
120.00	2.521E+06
80.00	3.012E+06
60.00	3.464E+06
40.00	3.864E+06
25.00	6.459E+06
15.00	1.040E+07
9.00	2.022E+07
5.00	6.190E+07

Chemical enrichment



IGM ionization (surroundings)

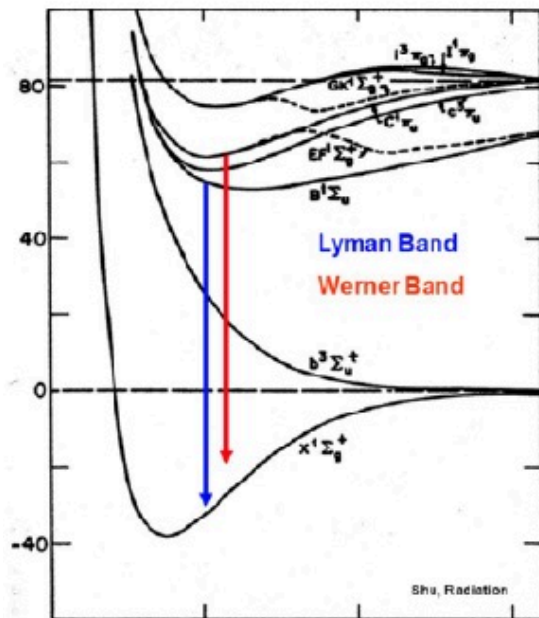


Hydrogen ionising energy
 $E_{\text{ion}} = 13.6$ eV

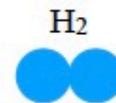
Not enough stars to ionise
 the IGM

After stars stop producing
 ionizing photons the gas
 recombines

Lyman-Werner radiation



UV Electronic
Transitions:
 H_2



H_2 gets excited and often
vibrates and breaks into $H + H$

- Lyman-Werner photons destroy $H_2 \Rightarrow$ No more SF in small halos
- Regions with a high Lyman-Werner background only form stars by atomic cooling $\Rightarrow$ stable SF at $T_{\text{vir}} = 10^4$ K

Pop III Stars and the IGM environment

- Production of X-ray and UV photons have a different impact to
 - UV is mostly for ionization
 - X-ray contributes (+/- 1:1:1) to excitation, ionization and heating
- The mean free path l of an X-ray photon can be computed through its cross-section σ
 - $n_H = 2.2 \times 10^{-7} (1+z)^{-3} \text{ cm}^{-3}$
 - $\sigma_0 = 6 \times 10^{-18} \text{ cm}^2$
 - $E_0 = 13.6 \text{ eV}$
- For $z = 20$ and $E=E_0 \rightarrow \langle l \rangle = 0.22 \text{ kpc}$
- For $z=20$ and $E=1 \text{ keV} \rightarrow \langle l \rangle = 0.1 \text{ Mpc}$
- For $z=6$ and $E = 1 \text{ keV} \rightarrow \langle l \rangle = 285 \text{ Mpc}$

$$\langle l_E \rangle = \frac{1}{n_H \sigma_H(E)}$$

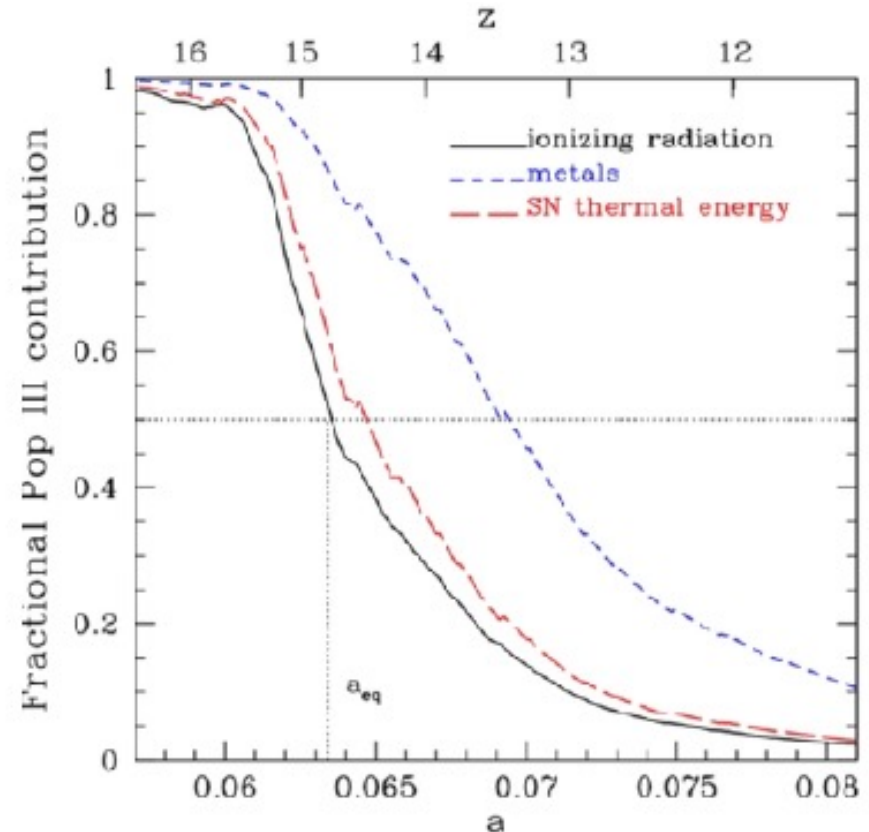
$$\sigma_H(E) = \sigma_0 \left(\frac{E_0}{E} \right)^3$$

Pop III Stars and the IGM environment

- The duration of Pop III era in a given galaxy is very short (100 – 200 Myr)
- Pop III lifetime: UV emission (affects only the star surroundings)
- Pop III supernovae: X- and γ -ray emission (further impact in the IGM)

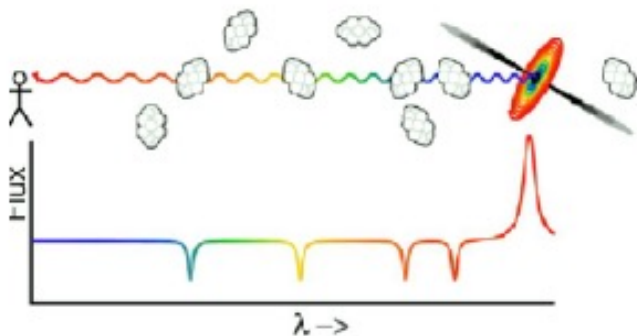
Main sources of ionizing photons:

- Stars: POP II + POP III
- Quasars + QSO's
- DM decay + annihilations



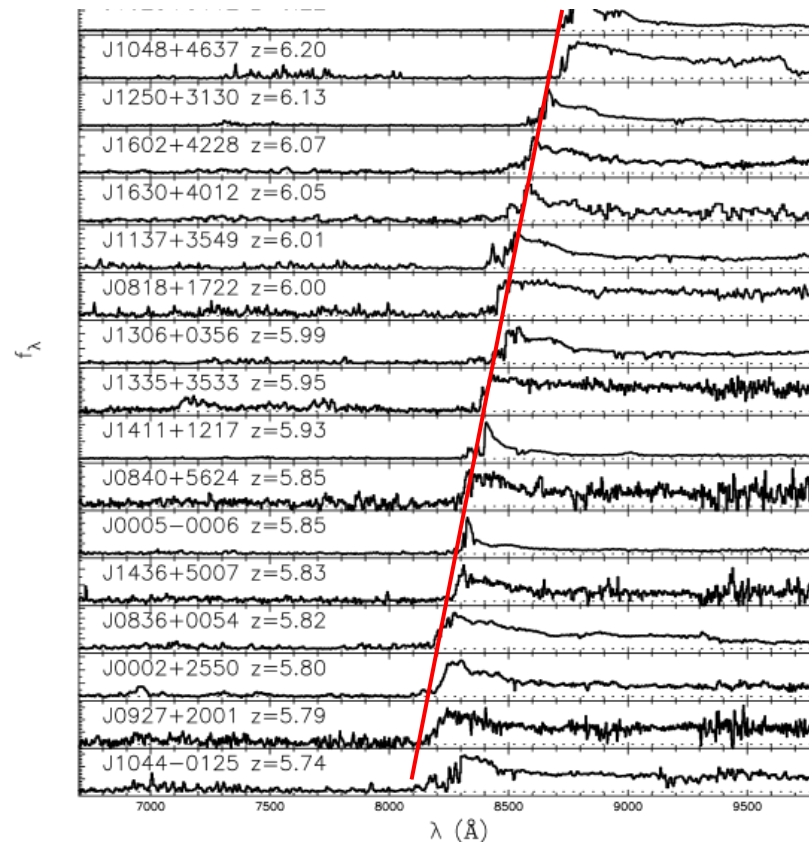
More on reionization

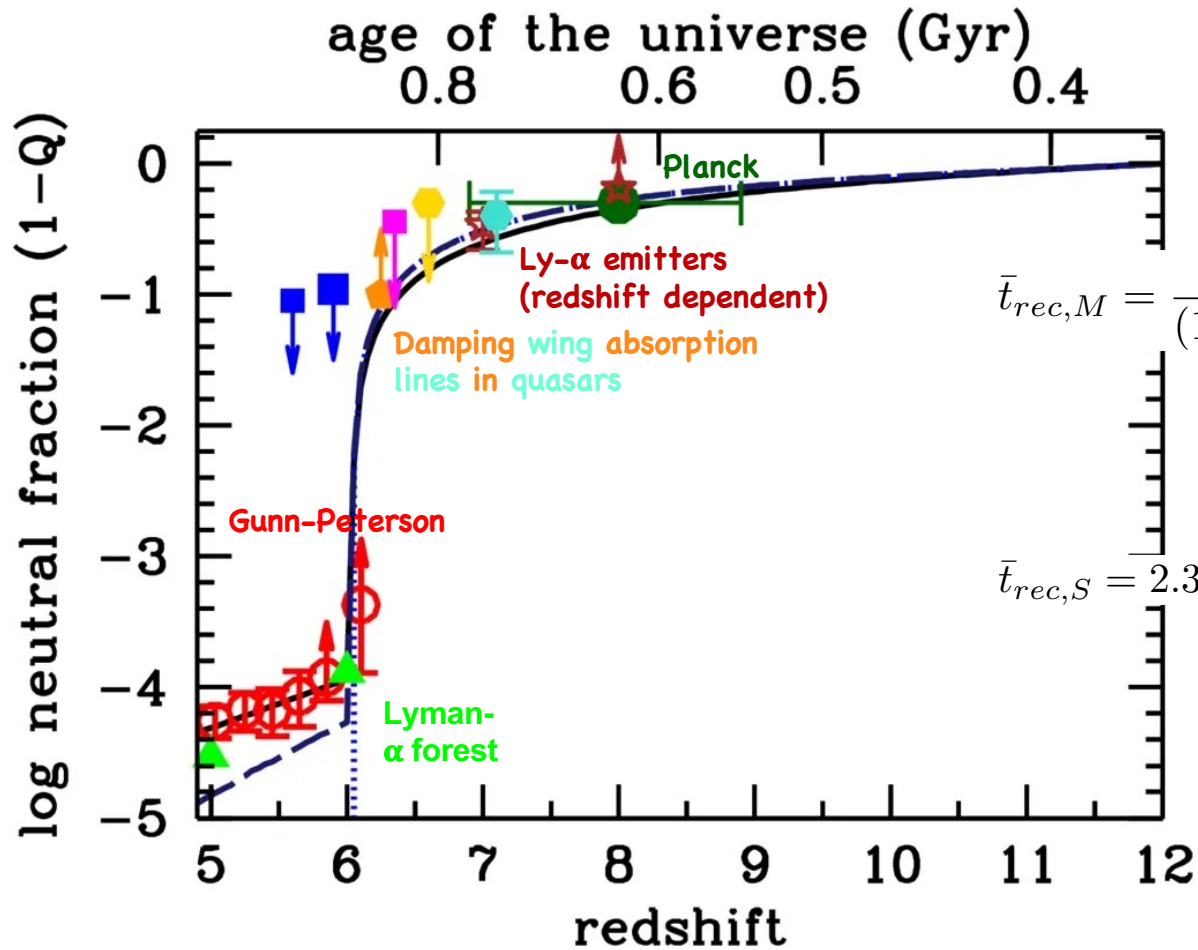
- The spectra of quasars help estimate the end of reionization, through the Gunn-Peterson effect (trough)



Moderate resolution spectra of 19 SDSS quasars at $5.74 < z < 6.42$.

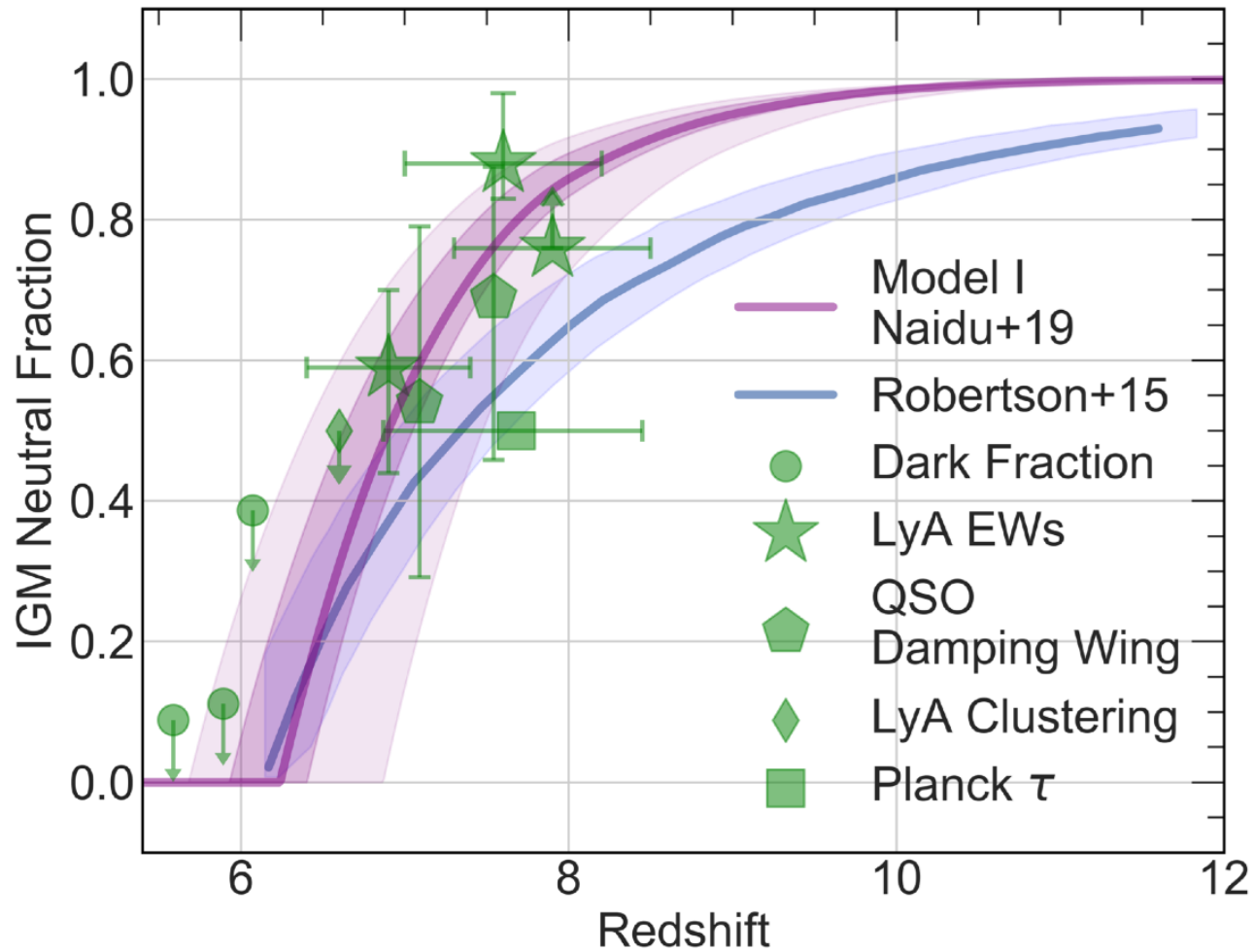
Adapted from Fan et al. (2006b)





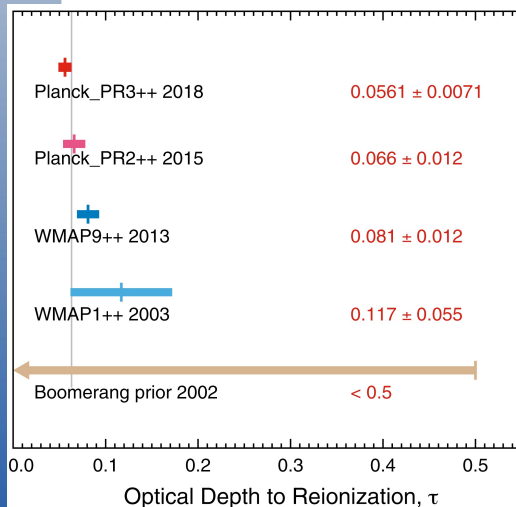
$$\bar{t}_{rec,M} = \frac{1}{(1 + \chi) \langle n_H \rangle \alpha(T_0) C_R}$$

$$\bar{t}_{rec,S} = 2.3[(1 + z)/6]^{-4.35} \text{ Gyr}$$

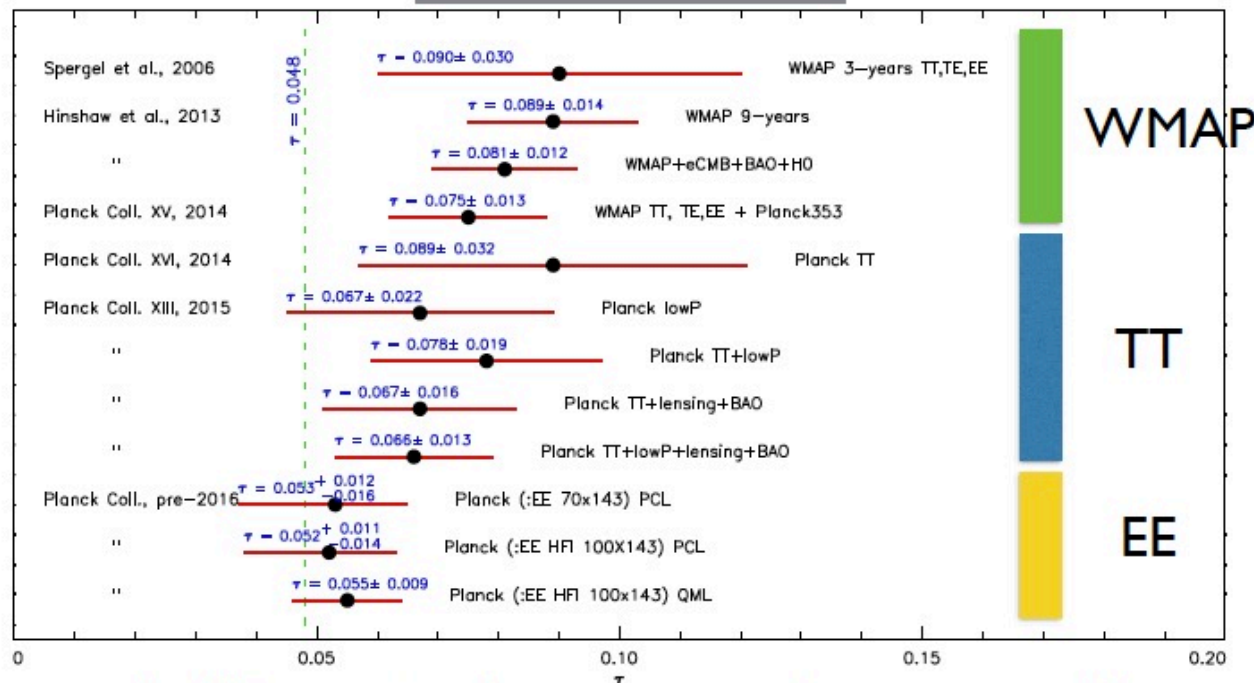


- The optical depth to reionization, τ , measures the line-of-sight free-electron opacity to CMB radiation.

$$\tau = \sigma_T \int \bar{n}_e(z) \frac{dl}{dz} dz,$$



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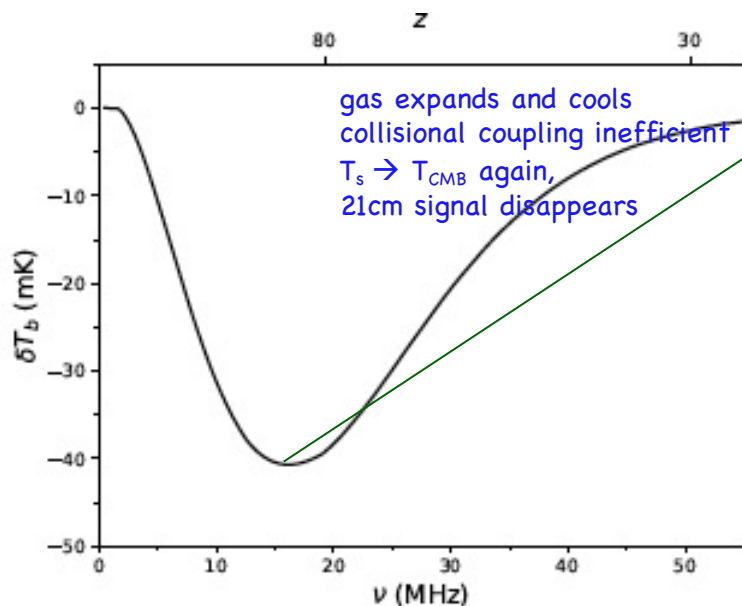
From J. Pritchard (2017)

Lower values for tau pushes the epoch of formation of the first stars to earlier times!!!

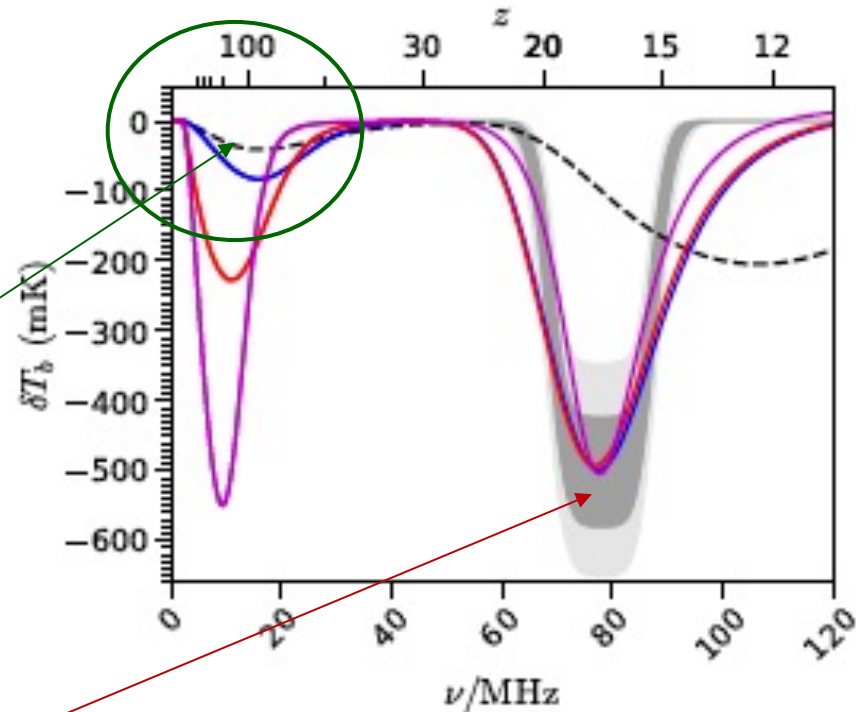
Planck Collaboration (2016)

Global 21 cm signal during Dark Ages

Heating the IGM $\rightarrow$ decreasing of the 21cm amplitude: **SENSITIVE PROBE OF COSMOLOGY AT THESE TIMES**



High medium density
collisional coupling is relevant
 $T_s \rightarrow T_{\text{gas}}$



EDGES result: double the absorption depth (amplify the 21cm signal) and suggestion of the presence on interacting Dark Matter interacting with photons to explain the additional cooling (Bowman et al. Nature (2018))

For reference along the forthcoming slides

The CMB power spectrum is given by
$$C_l = 4\pi \int \Delta_\zeta^2(k) \left| \frac{\Theta_l(k)}{\zeta(k)} \right|^2 d \ln k$$

The spherical harmonic multipole l is (heuristically...) associated with a typical angular size given by
$$\theta \sim \frac{\pi}{l} = \frac{180}{l}$$

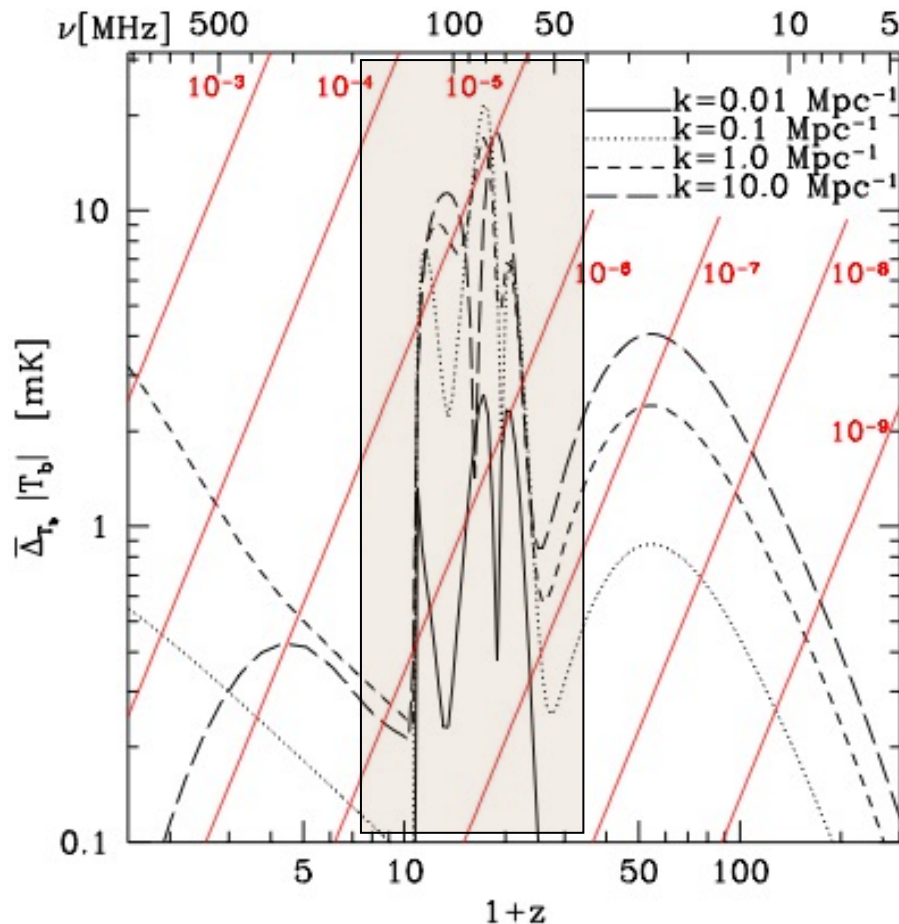
A more realistic correspondence is obtained when associating l with a comoving length scale
$$x \sim r\theta \sim \frac{\pi r}{l}$$

And hence with a wavenumber
$$k = \frac{2\pi}{\lambda} \sim \frac{\pi}{x} \sim \frac{l}{r}$$

For $l \gg 1$ (Liddle et al. arXiv:0607275)
$$l \sim 14000 \frac{k}{\text{Mpc}^{-1}}$$

The above works for 21cm “order-of-magnitude” scale estimation. But bear in mind that, in C_l computation, many k modes must be included

The power spectrum during the Dark Ages



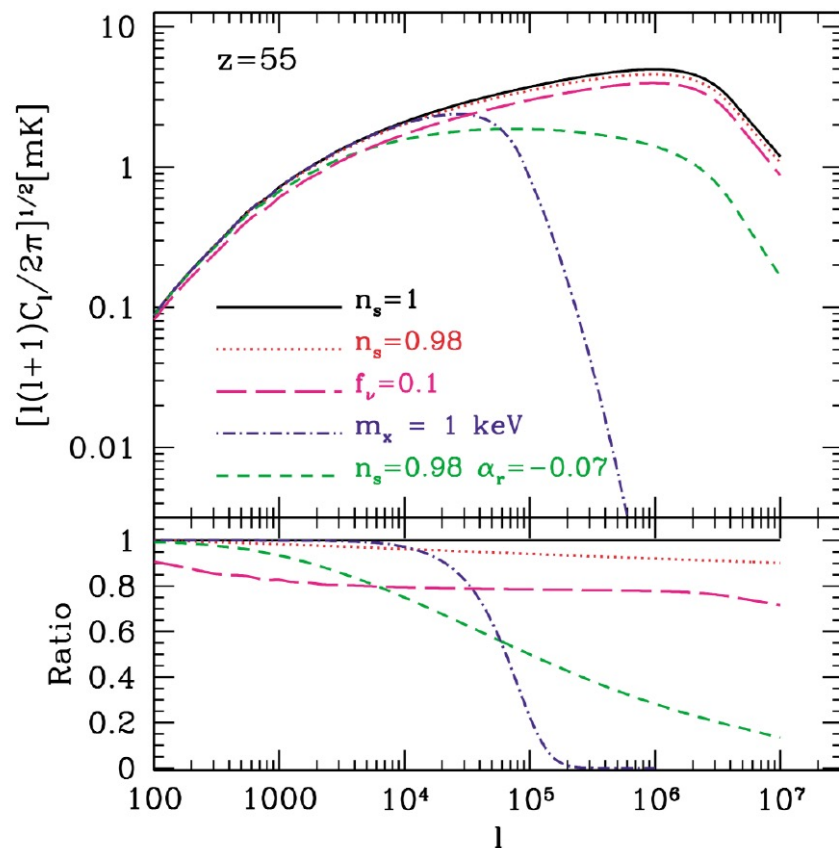
21-cm brightness temperature fluctuations at several different wavenumbers (for Λ -CDM)

Red diagonal lines $\rightarrow$ comparison to foreground brightness temperature (from Galactic synchrotron)

$$k = \frac{2\pi}{\lambda}$$

For reference:

The power spectrum during the Dark Ages



Upper: Testing alternative cosmologies

- Deviations from $n=1$
- Possibility of a running n
- Massive neutrinos
- Warm DM ($m=1 \text{ keV}$)

• Lower: residuals from top

The power spectrum during the Dark Ages - summary

- 21cm measurements can cover a large fraction of the Hubble volume, with frequency choice directly setting the redshift interval
- Its measurements at higher redshifts probe the Universe still in a linear (or weakly non-linear), where power spectrum analysis can be directly associated with cosmological parameters
- Other highlights
 - Larger dynamic range in amplitude for PS measurements
 - CMB measurements offer stringent constraints that can best be improved by larger-volume surveys, such as 21cm surveys. The clean, small-scale Dark Ages signal is an excellent opportunity to further constrain the existence of non-Gaussianity in the density power spectrum
 - Various cosmological parameters are best measured at small scales
 - The extraordinary statistical precision of a 21-cm Dark Ages measurement would also allow us to identify deviations from a featureless primordial power spectrum that might be imprinted by complex models of inflation

To be continued....