

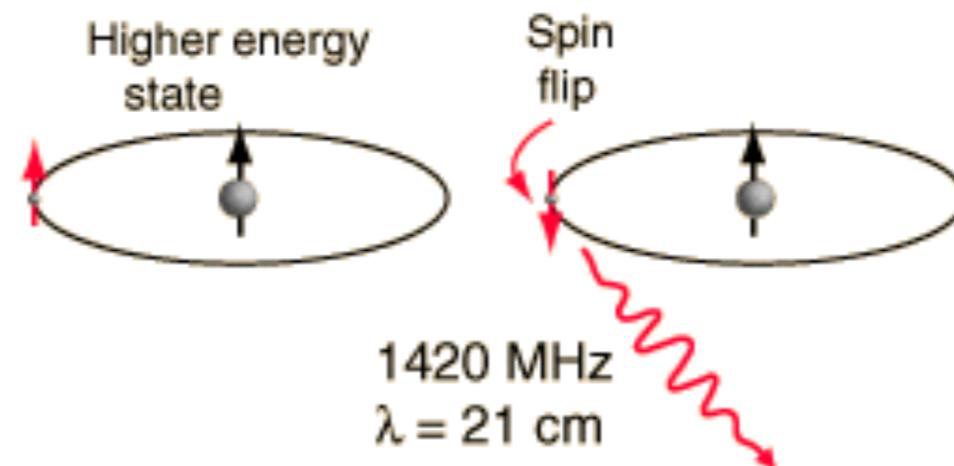
# The physics of the HI 21 cm line

## Observing the early Universe

Marta B. Silva

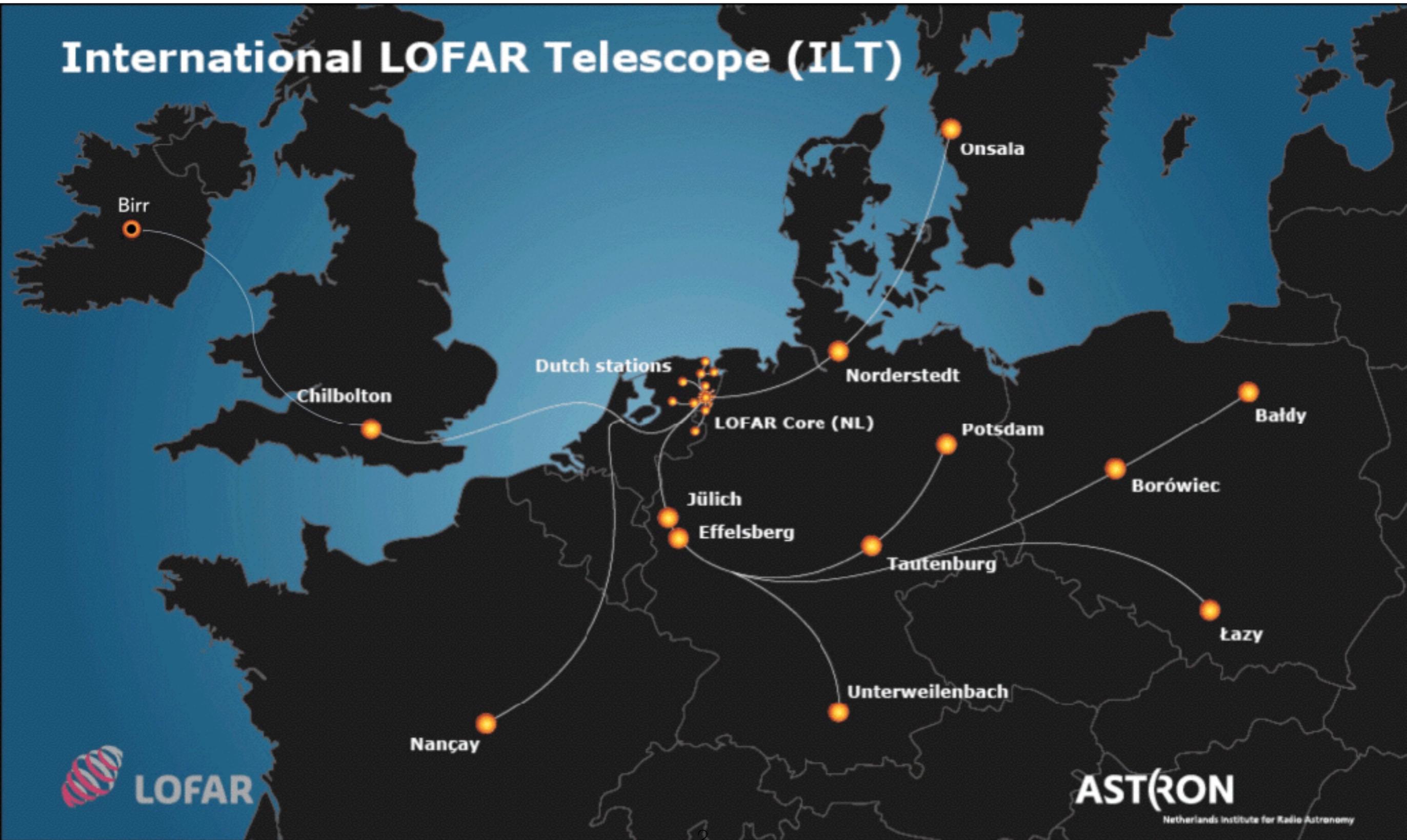
*Kapteyn Astronomical Institute  
University of Groningen, The Netherlands*

6<sup>a</sup> Escola Avançada de Astrofísica do INPE  
Cosmologia de 21 cm no século 21



# Low Frequency Array (LOFAR)

## International LOFAR Telescope (ILT)



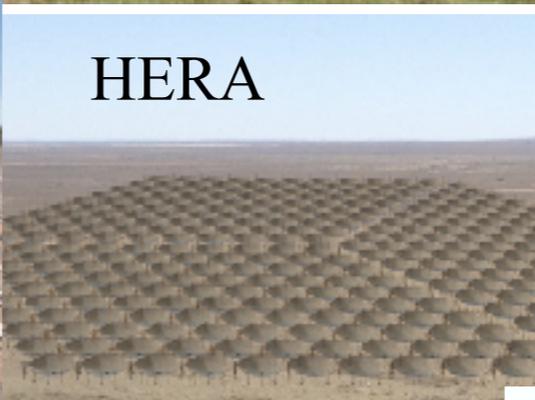
# LOFAR

Low band: 30 - 80 MHz  
High Band: 115-189 MHz



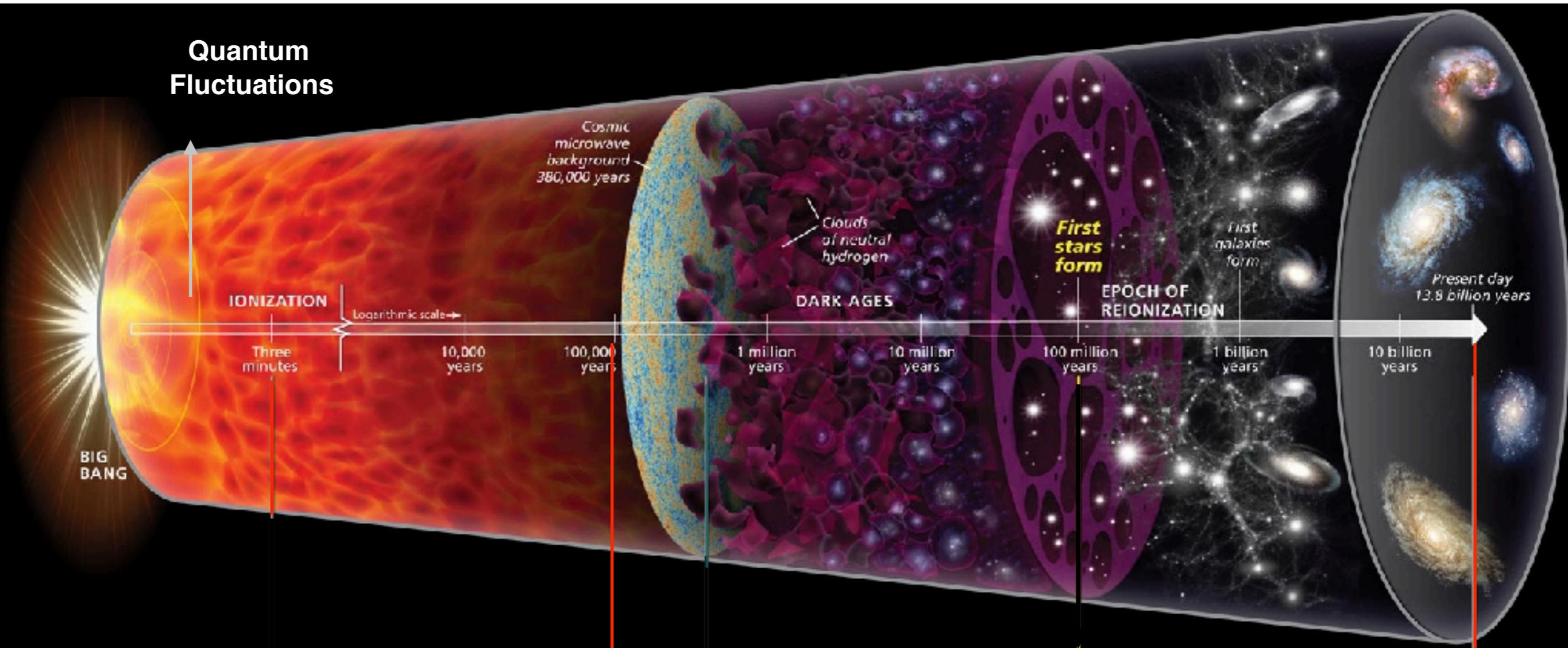
# 21 cm line

## A hot topic in today's astronomy



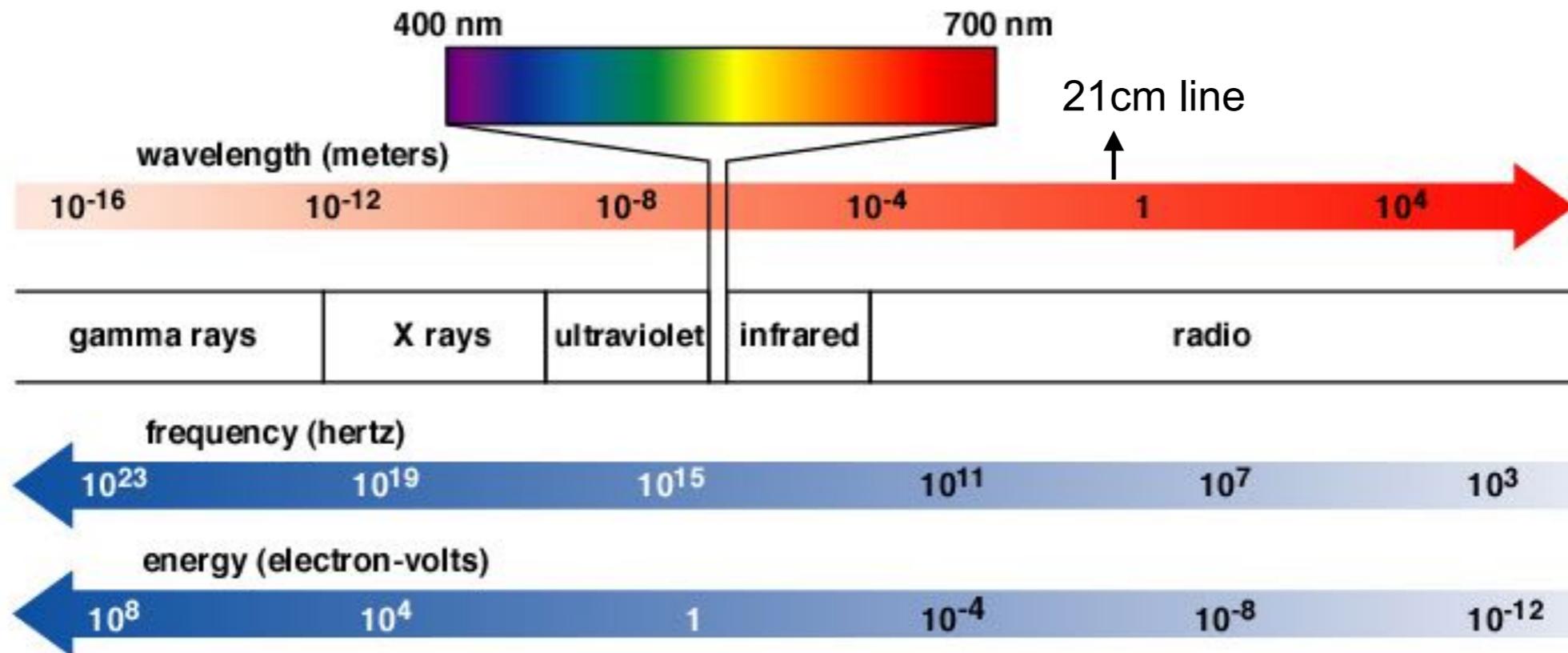
**Why is this line so important?**

# The first light in the Universe

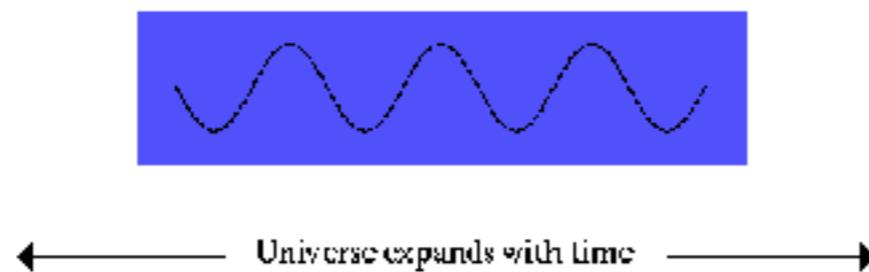


**Timeline for 21cm line transition**

# The electromagnetic spectrum



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$$\lambda_0 = 21 \text{ cm}$$

$$\lambda_{\text{obs}} = \lambda_0 (1+z)$$



# The HI 21 cm line

## The first light in the Universe

### Lecture 1

- i) The 21 cm line
- ii) CMB Formation
- iii) The mean 21 cm line signal

### Lecture 2

- iv) Cosmic Dawn/  
The First Stars
- v) Reionization
- vi) Observing the EoR

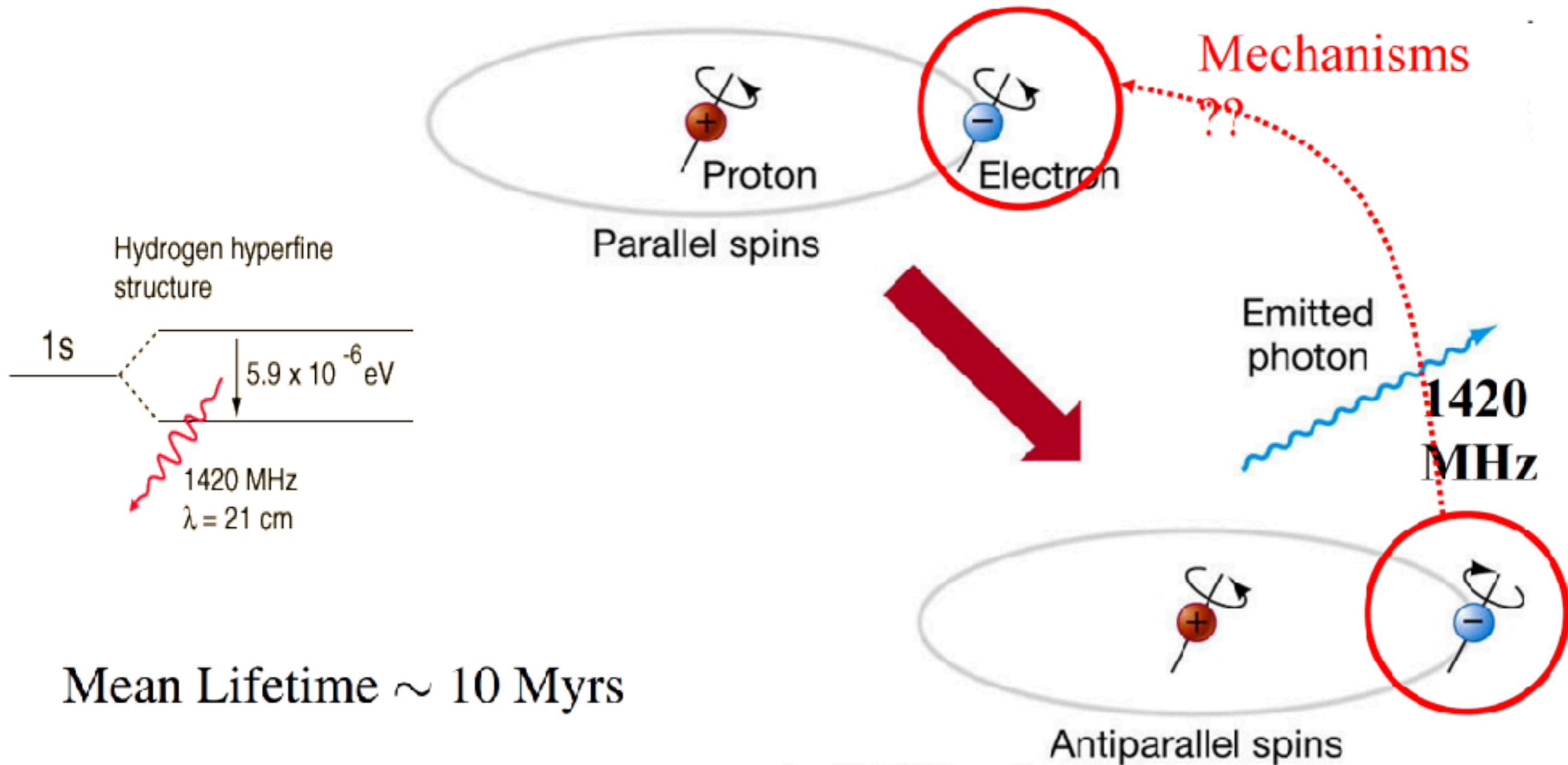
### Lecture 3

- vii) Impact of the EoR on the CMB
- viii) Other probes of the EoR
- viV) 21 cm line in the post EoR

# Lecture 1

- i) The 21 cm line
- ii) CMB Formation
- iii) The mean 21cm line signal
- iv) Structure formation

# The 21-cm line from neutral hydrogen



# 21 cm line Brightness Temperature

$$\delta T_b \approx 28\text{mK} (1 + \delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{\frac{1}{2}}$$

The diagram illustrates the mapping of terms in the equation to Astrophysics and Cosmology. A blue box labeled "Astrophysics" is connected by a vertical line to the term  $x_{HI} \frac{T_s - T_{CMB}}{T_s}$ . A red box labeled "Cosmology" is connected by lines to the terms  $(1 + \delta)$ ,  $\frac{\Omega_b h^2}{0.02}$ , and  $\left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{\frac{1}{2}}$ .

# Brightness Temperature

Rayleigh-Jeans approximation

$$h\nu \ll kT$$

$$T_b(\nu) \approx I_\nu c^2 / 2k_B \nu^2$$

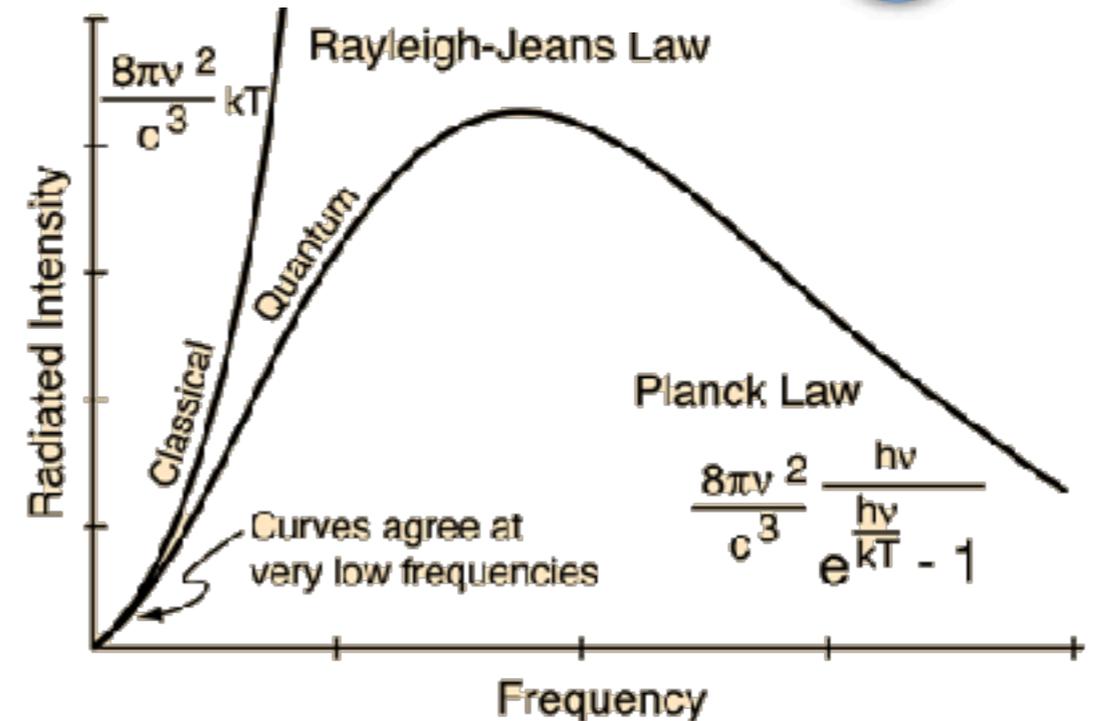
Apparent brightness

$$T_b(\nu) = T'_b(\nu_0) / (1 + z)$$

$$\nu_0 = 1420.4057 \text{ MHz}$$

$$\nu = \nu_0 / (1 + z)$$

$$E = h_p \nu = h_p \nu_0 / (1 + z)$$



Credit: <http://hyperphysics.phy-astr.gsu.edu/hbase/mod6.html>

$$\lambda = c/\nu$$

# Brightness Temperature

Apparent brightness

$$T_b(\nu) = T'_b(\nu_0)/(1 + z)$$

$$\nu_0 = 1420.4057 \text{ MHz}$$

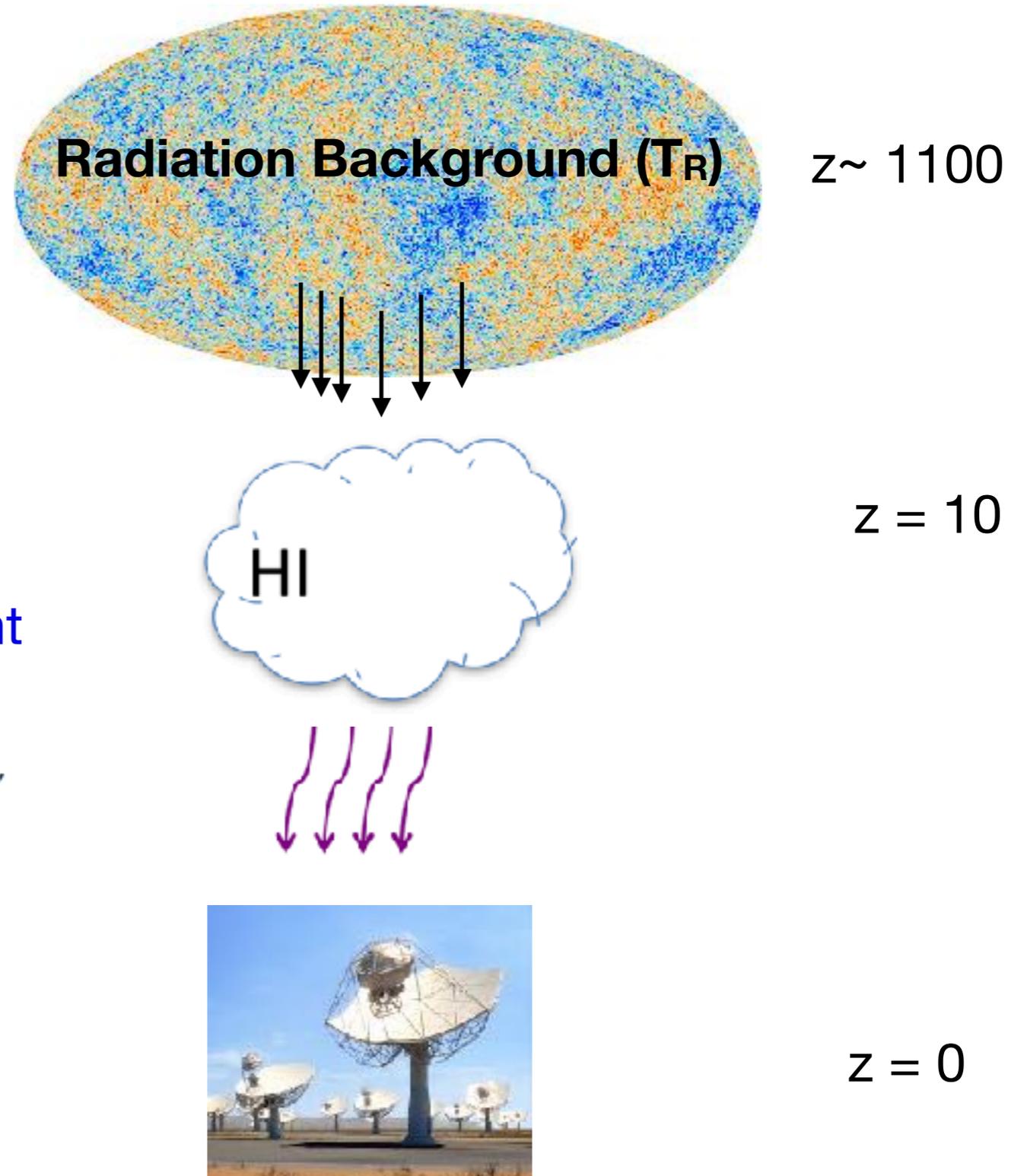
$$\nu = \nu_0/(1 + z)$$

Radiative transfer along a line of sight

$$T'_b(\nu) = T_{\text{ex}}(1 - e^{-\tau_\nu}) + T'_R(\nu)e^{-\tau_\nu}$$

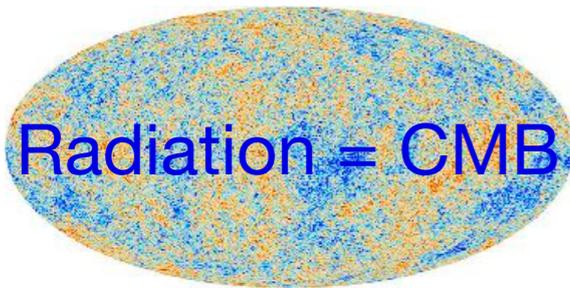
$$\tau_\nu \equiv \int ds \alpha_\nu \text{ (optical depth)}$$

Integral along the path of  
the absorption coefficient



# Brightness Temperature

$$T'_b(\nu) = T_{\text{ex}}(1 - e^{-\tau\nu}) + T'_R(\nu)e^{-\tau\nu}$$



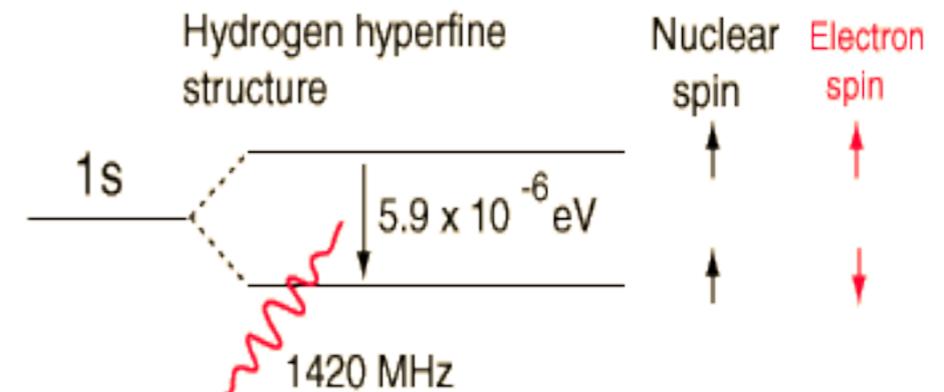
$$T_R = T_\gamma$$

$$T_\gamma(z) = T_\gamma(0)(1 + z)$$

$$T_\gamma(0) = 2.73 \text{ K}$$

## Spin Temperature

$$T_{\text{exc}} = T_S$$



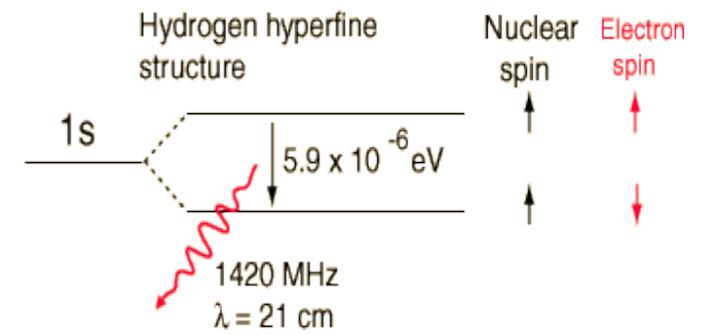
$$\frac{n_1}{n_0} = 3 \exp(-T_*/T_S)$$

$$T_* \equiv E_{10}/k_B = 0.068 \text{ K}$$

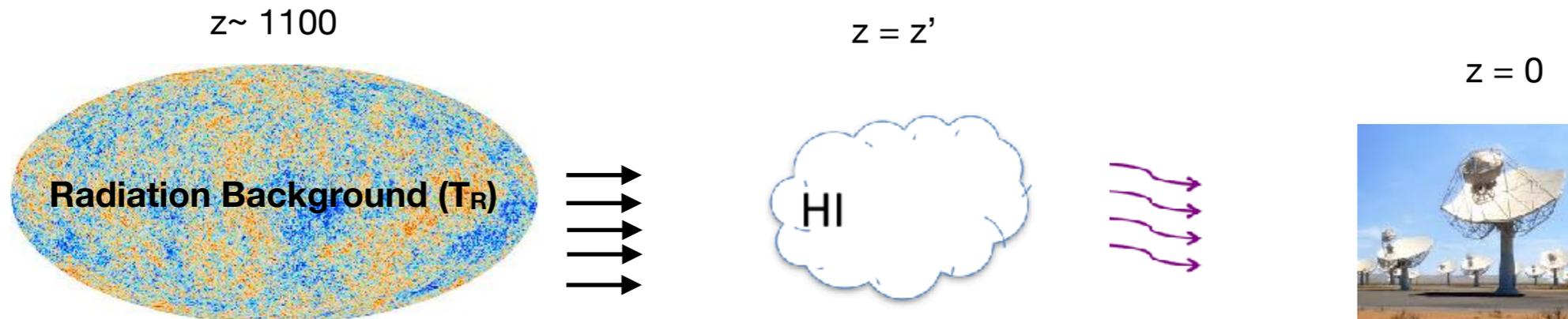
# Tb: Optical depth

$$T'_b(\nu) = T_{\text{ex}}(1 - e^{-\tau_\nu}) + T'_R(\nu)e^{-\tau_\nu}$$

$$\tau_\nu \equiv \int ds \alpha_\nu$$



$$\tau_\nu = \tau_{21 \text{ cm}}$$

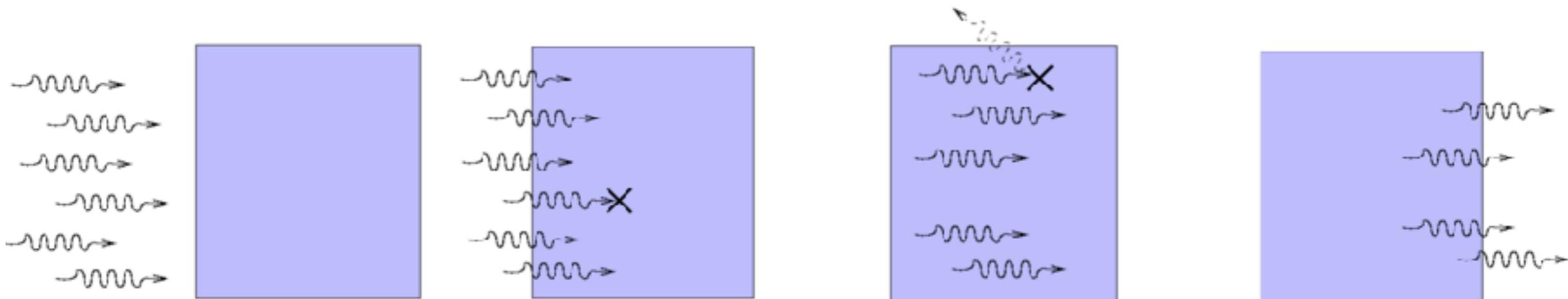


Incident radiation ( $I_0$ )

Absorbed radiation

Scattered radiation

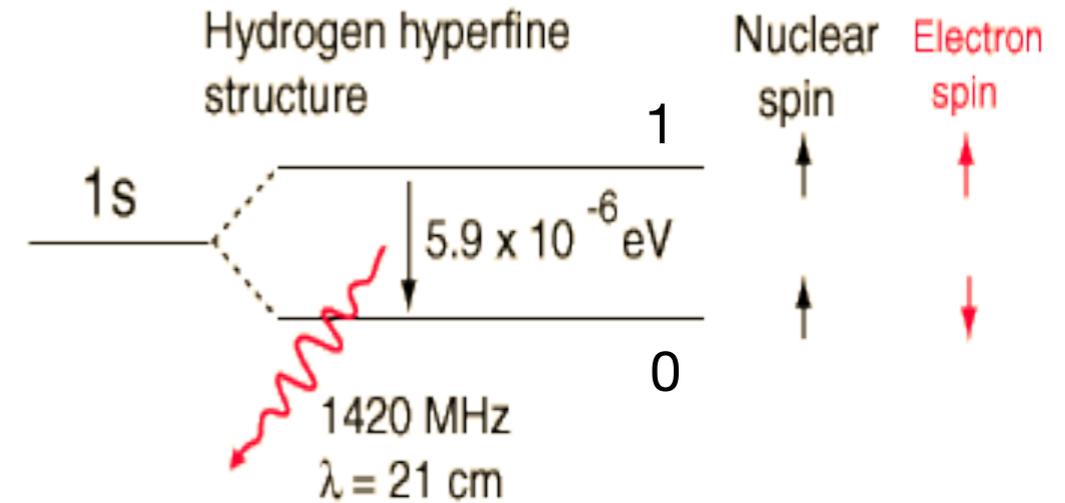
Observed radiation ( $I$ )



# Tb: Optical depth

$$T'_b(\nu) = T_{\text{ex}}(1 - e^{-\tau_\nu}) + T'_R(\nu)e^{-\tau_\nu}$$

$$\tau_\nu = \tau_{21 \text{ cm}}$$



$$\tau_\nu \equiv \int ds \alpha_\nu$$

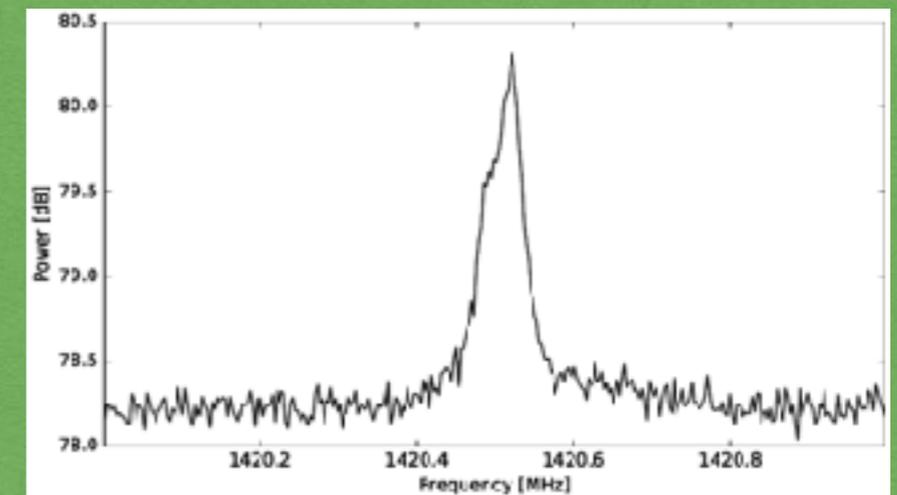
$$\tau_\nu = \int ds \sigma_{01} (1 - e^{-E_{10}/k_B T_S}) \phi(\nu) n_0$$

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

$$\tau_{\nu 0} = \frac{3}{32\pi} \frac{hc^3 A_{10}}{k_B T_S \nu_0^2} \frac{x_{\text{HI}} n_H}{(1+z) (dv_{\parallel}/dr_{\parallel})}$$

$$\approx 0.0092 (1 + \delta) (1 + z)^{3/2} \frac{x_{\text{HI}}}{T_S} \left[ \frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right]$$

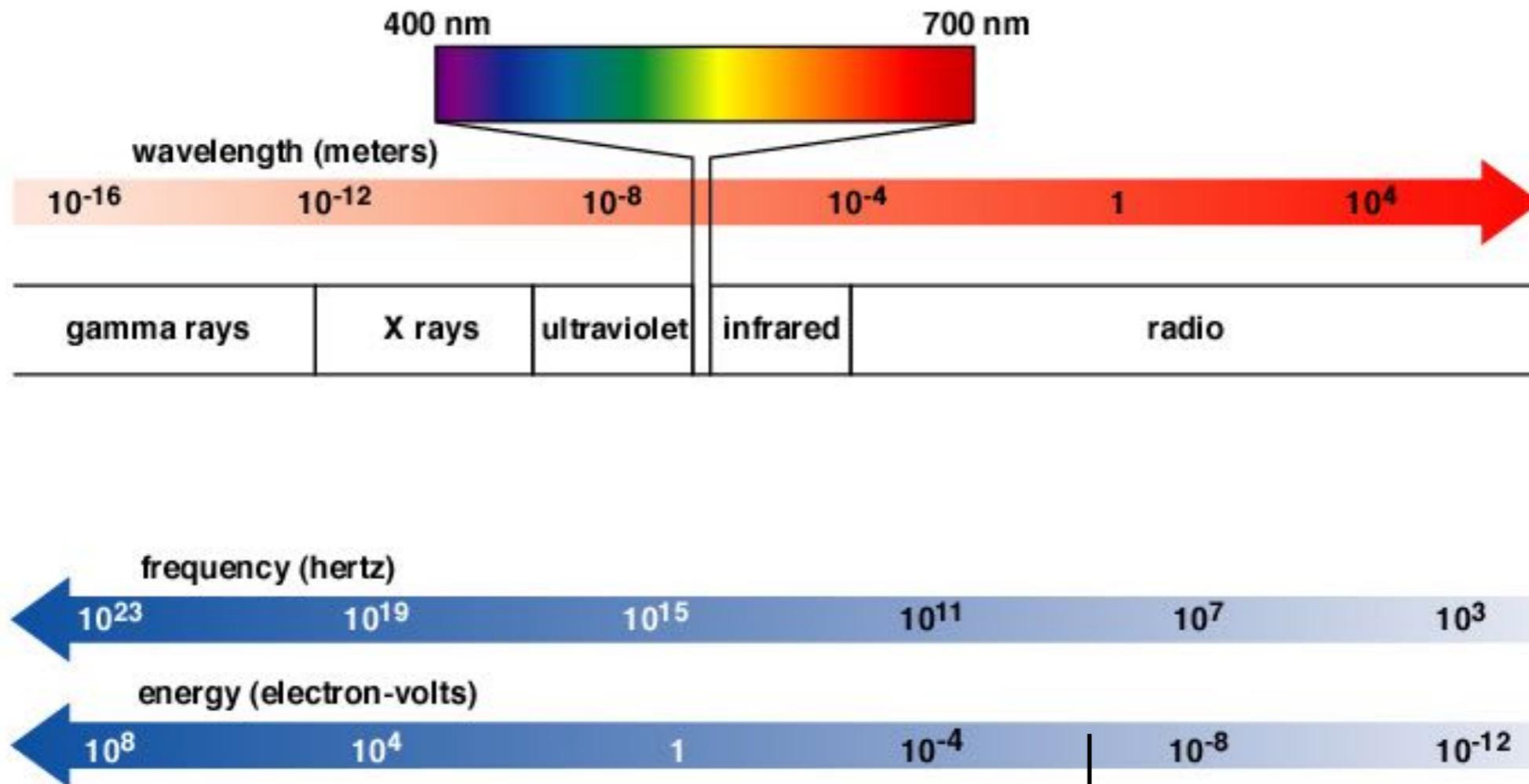
$$\sigma_{01} \equiv \frac{3c^2 A_{10}}{8\pi\nu^2} \quad (\text{Cross section})$$



credit: DC Price 2016

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

# The energy of the 21cm radiation



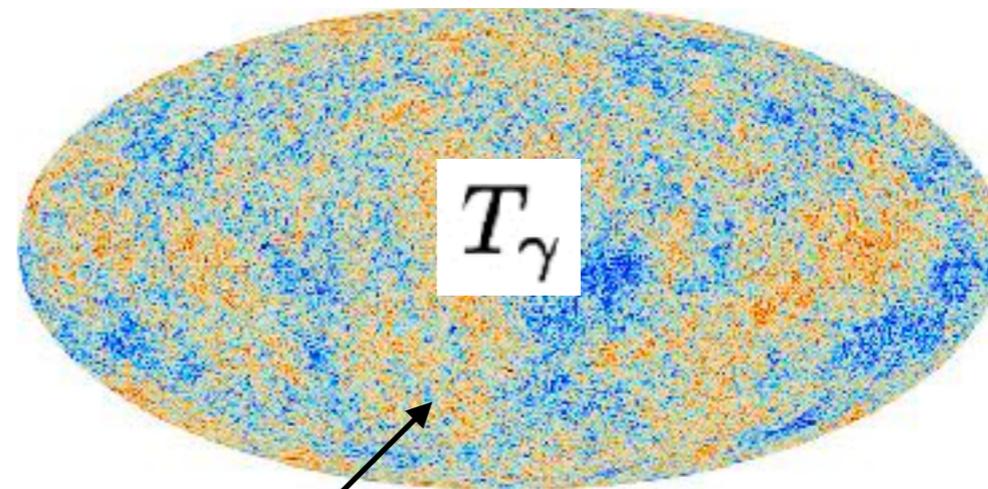
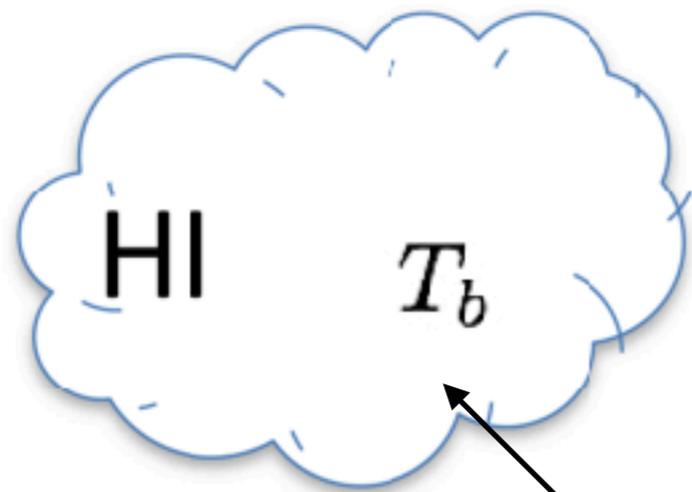
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$$E_{21\text{cm}} = 5.9 \times 10^{-6} \text{ eV}$$

# $\delta T_b$ : The Brightness Temperature

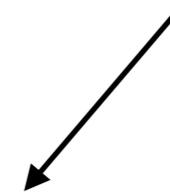
$$T_b(\nu) = T_S (1 - e^{-\tau_\nu}) + T_\gamma(\nu) e^{-\tau_\nu}$$

$$\delta T_b(\nu) \equiv T_b - T_\gamma = (T_S - T_\gamma) (1 - e^{-\tau_\nu})$$



# 21 cm line Brightness Temperature

$$\begin{aligned}\delta T_b(\nu) &= \frac{T_S - T_\gamma(z)}{1+z} (1 - e^{-\tau_{\nu 0}}) \approx \frac{T_S - T_\gamma(z)}{1+z} \tau_{\nu 0} \\ &\approx 9 x_{\text{HI}} (1 + \delta) (1+z)^{1/2} \left[ 1 - \frac{T_\gamma(z)}{T_S} \right] \left[ \frac{H(z)/(1+z)}{dv_{\parallel}/dr_{\parallel}} \right] \text{ mK}\end{aligned}$$



If we assume this is 0  
(Except for the Hubble flow the gas is not moving in the direction of the line of sight)

# 21 cm line Brightness Temperature

$$\delta T_b \approx 28\text{mK} (1 + \delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{\frac{1}{2}}$$

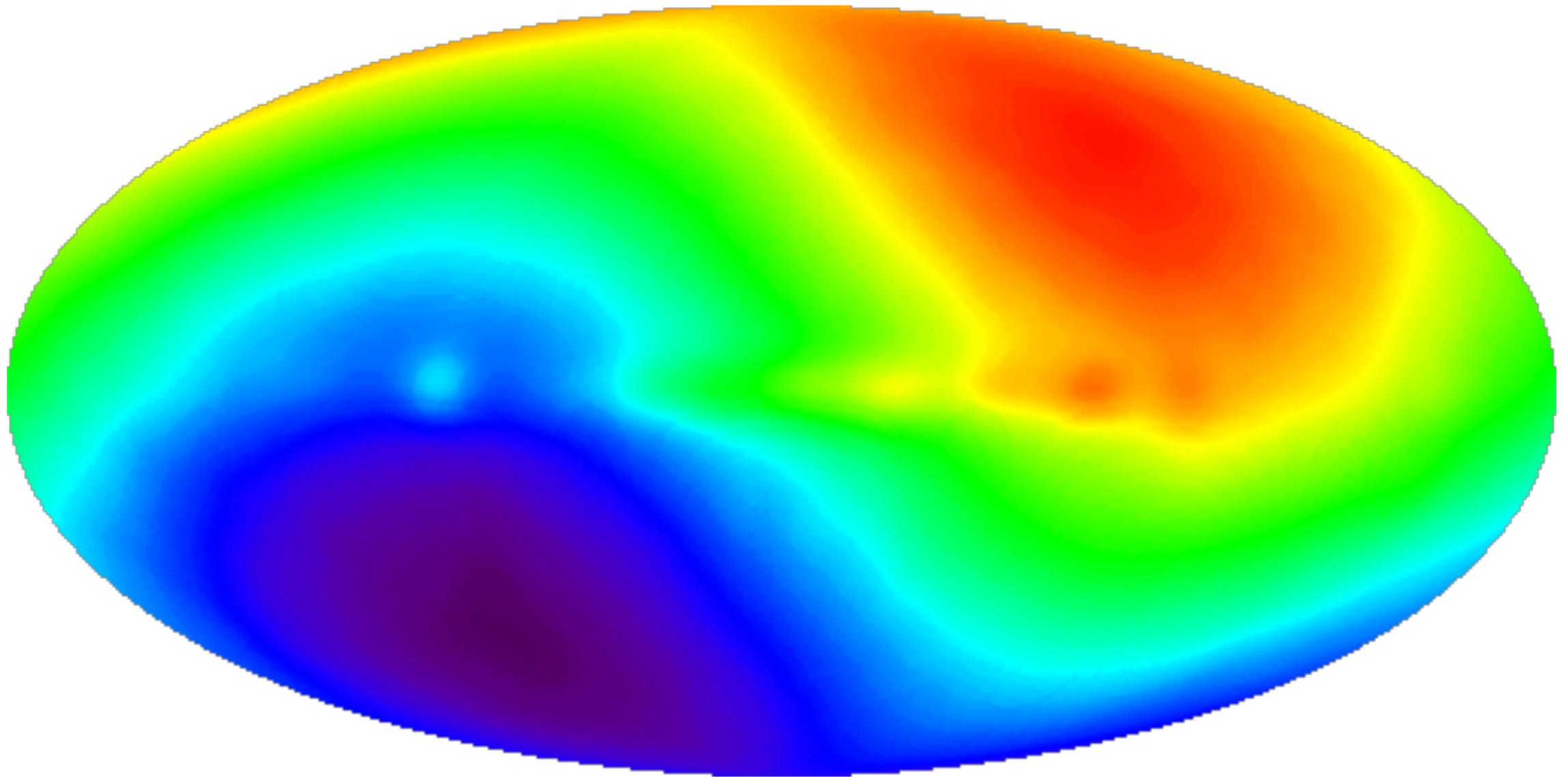
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**How do we constrain cosmology  
in the early Universe?**

# The Cosmic Microwave Background (CMB)

**Raw image:**

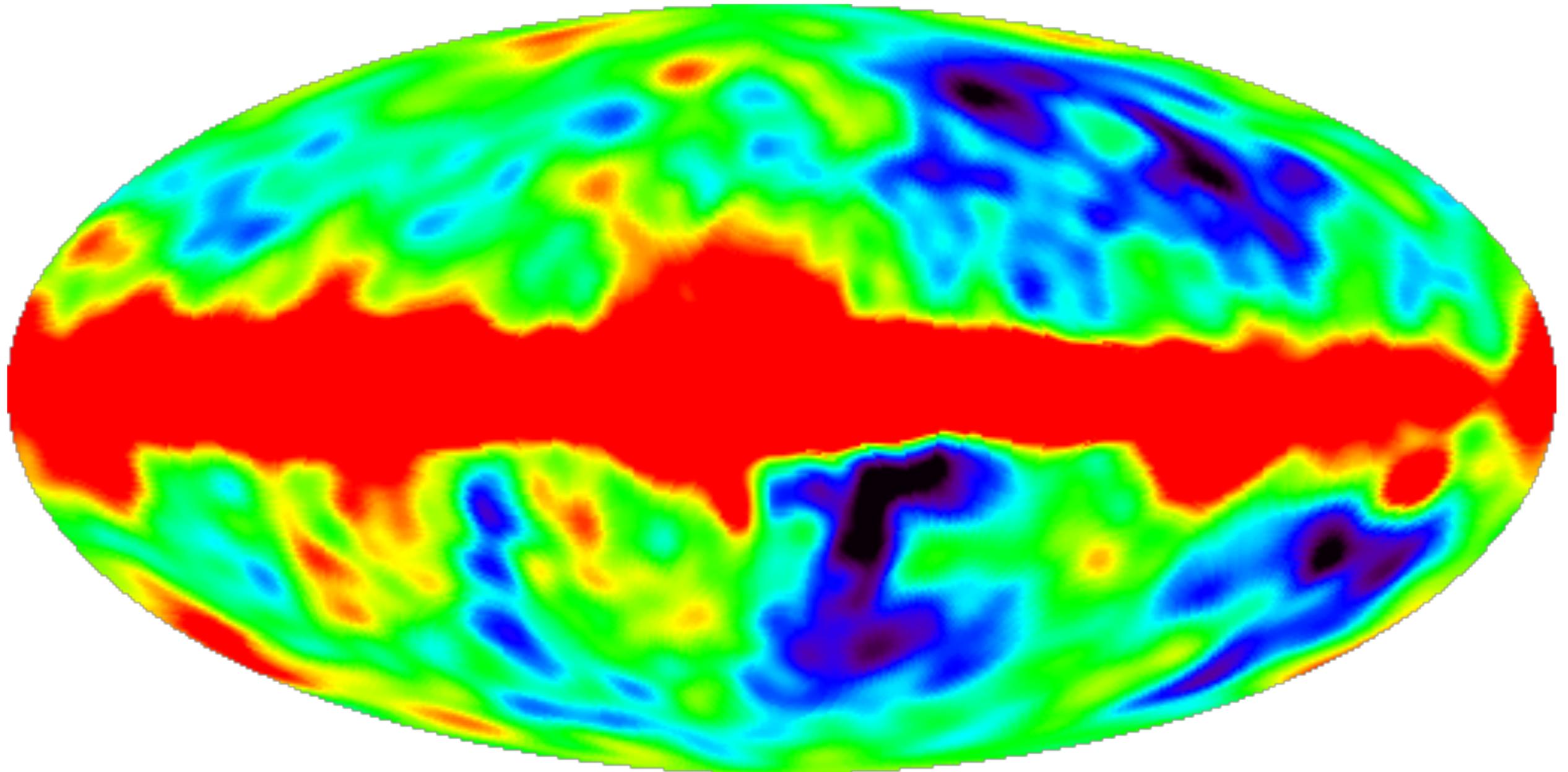
Typical dipole appearance because our Galaxy is moving in a particular direction



# The Cosmic Microwave Background (CMB)

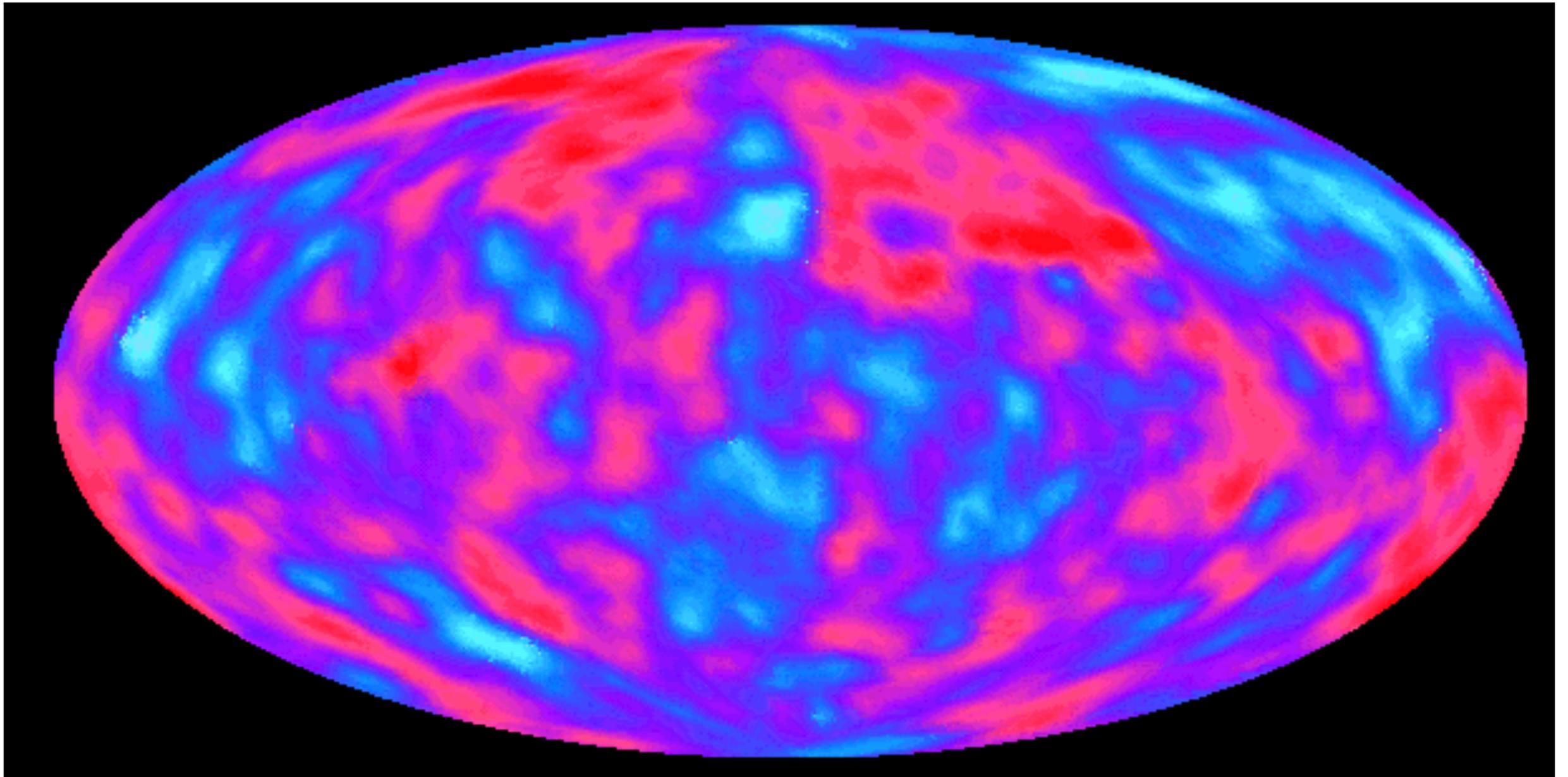
After removing the Galaxy's motion:

Map dominated by the far-infrared emission from gas in our own Galaxy

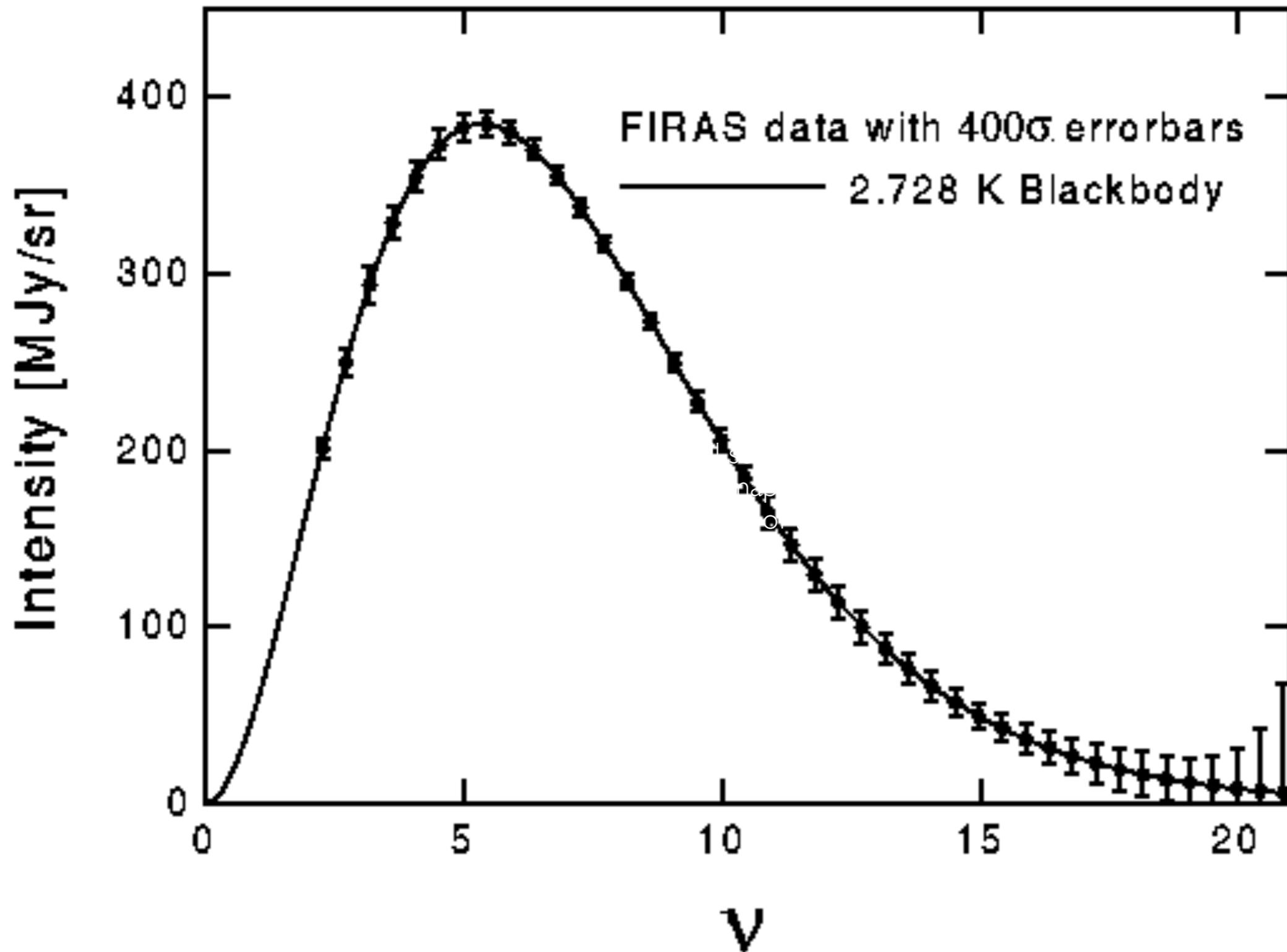


# The Cosmic Microwave Background (CMB)

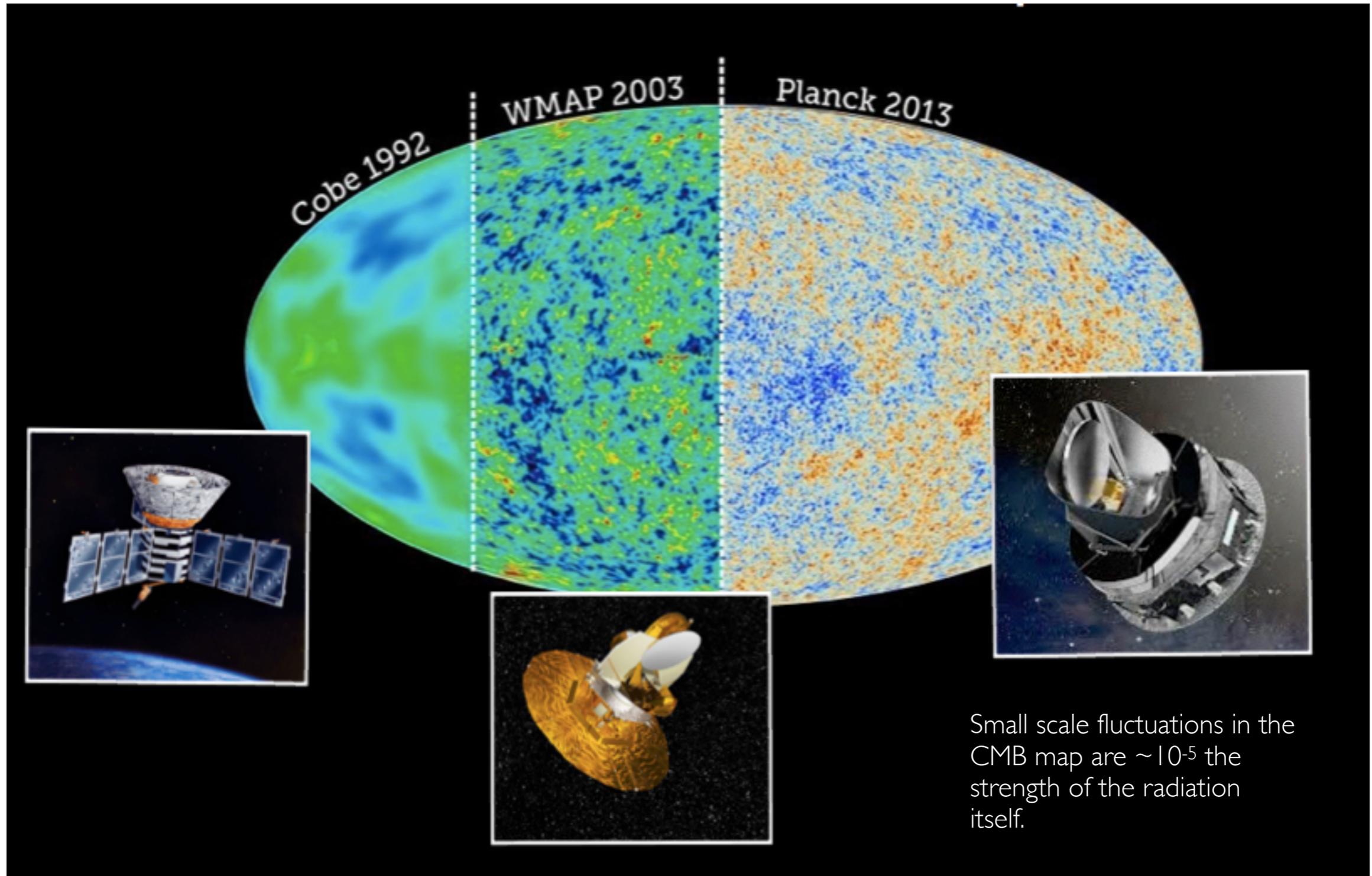
After removing our galaxy emission:



# The Cosmic Microwave Background (CMB)

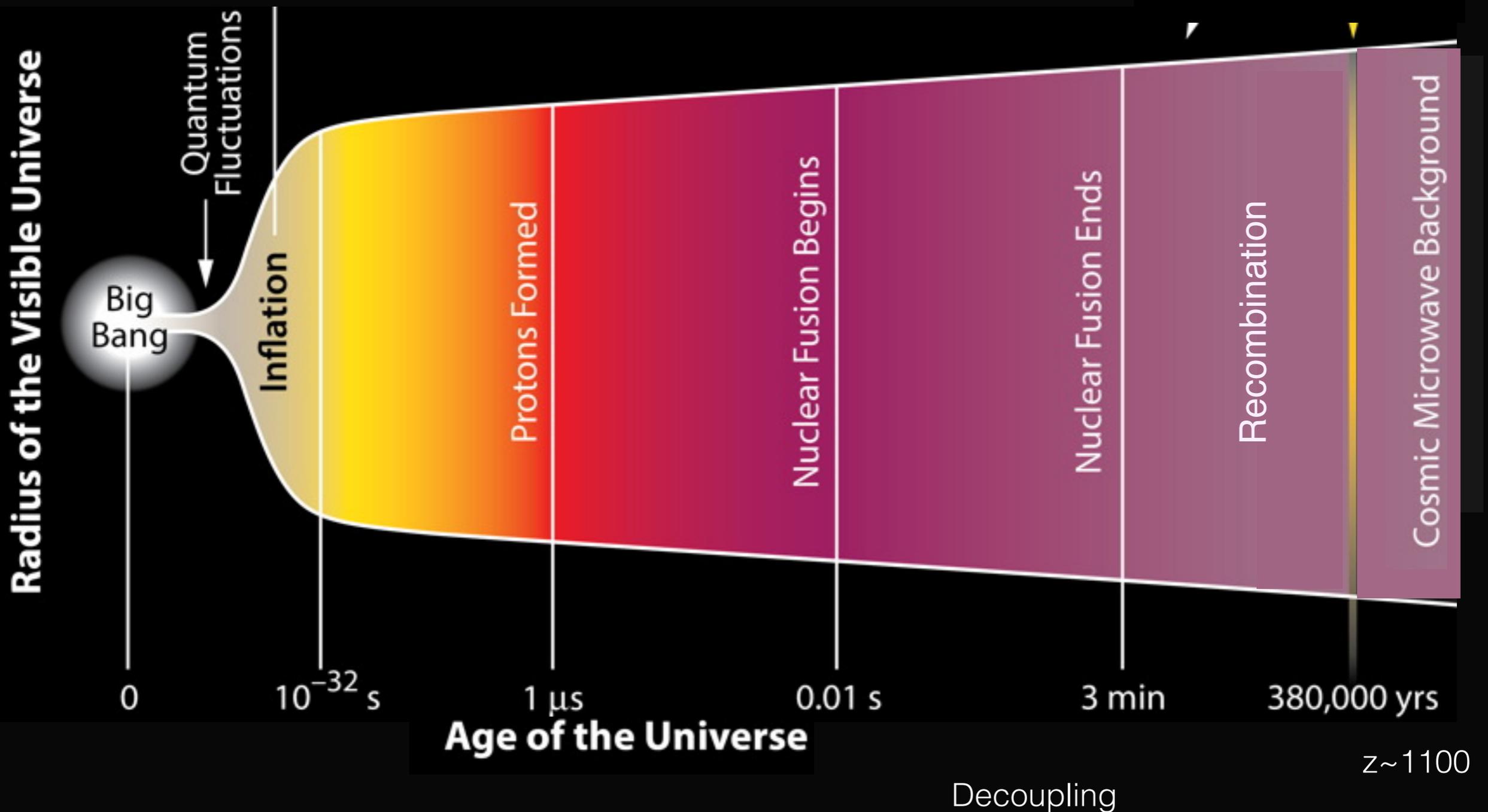


# The Cosmic Microwave Background (CMB)

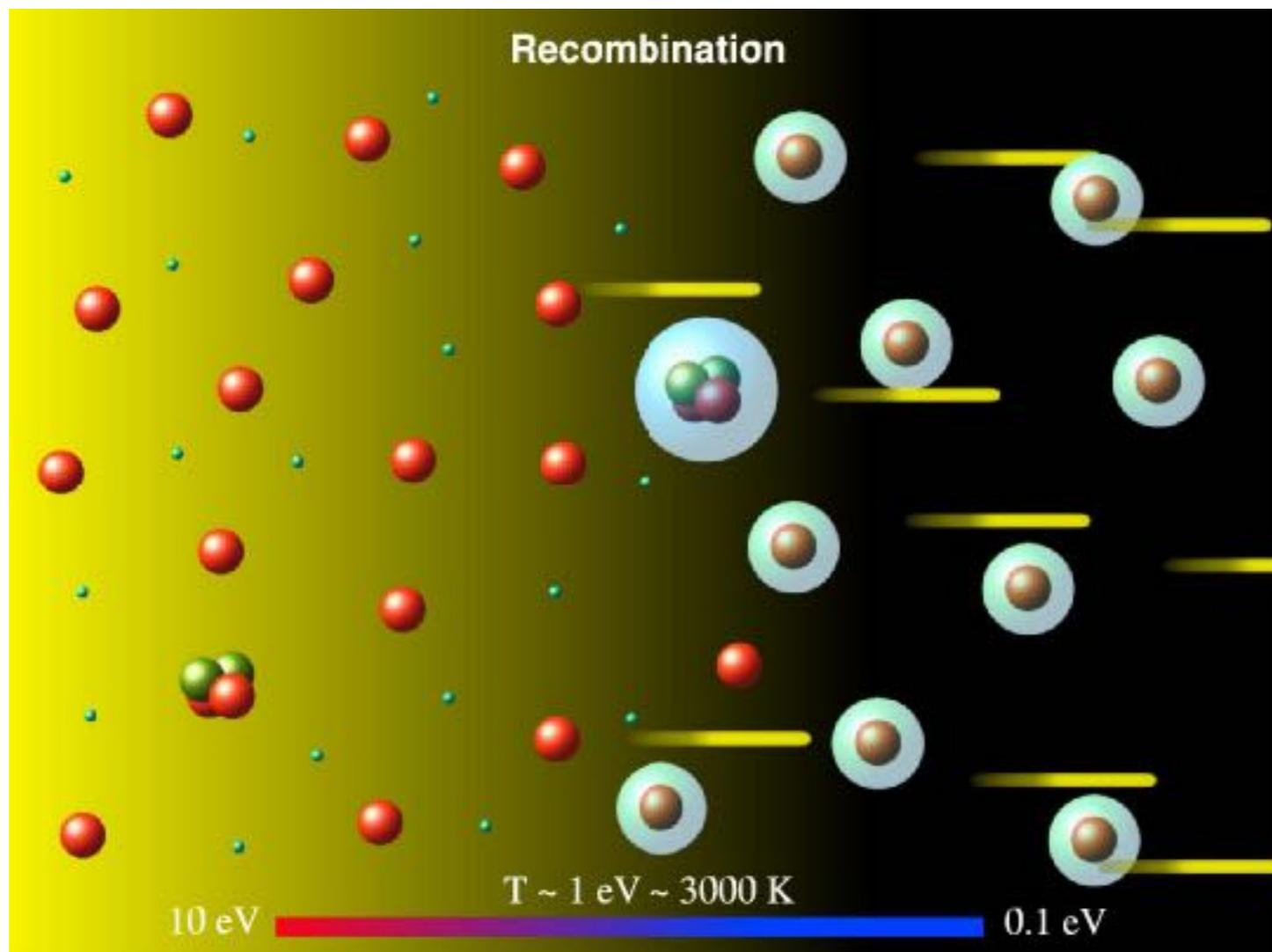


**Where does this radiation come from?**

# From the Big Bang to the Epoch of Recombination



# Recombination and Photon decoupling



Recombination to an excited state followed by photon emission



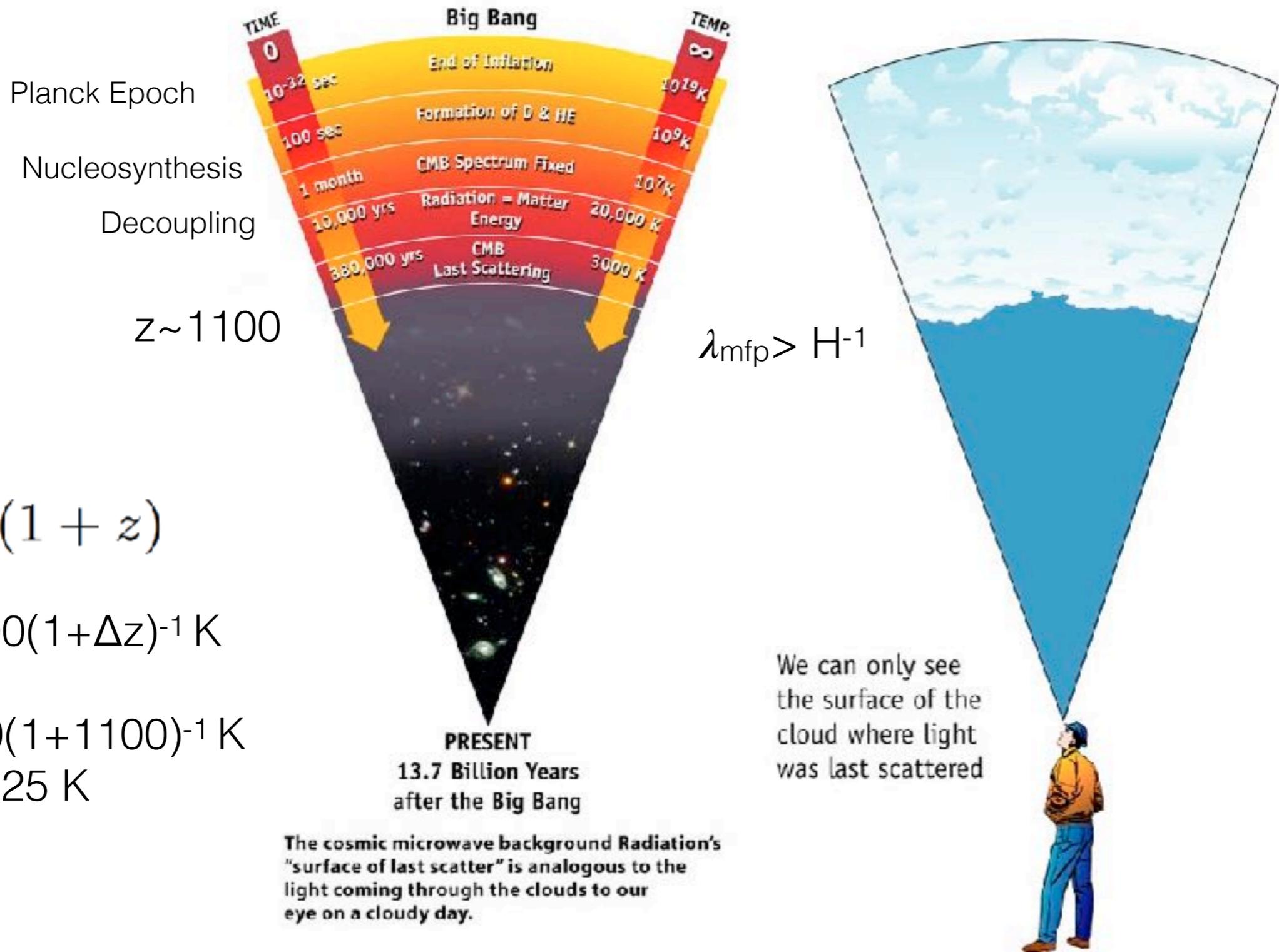
When the photon mean free path became bigger than the rate of expansion of the Universe

$$\lambda_{\text{mfp}} > H^{-1}$$



Photon Decoupling  
(CMB formation)

# The Cosmic Microwave Background (CMB)



$$T_{\text{CMB}} \propto (1 + z)$$

$$T_{\text{CMB},z} = 3000(1+z)^{-1} \text{ K}$$

$$T_{\text{CMB},0} = 3000(1+1100)^{-1} \text{ K} = 2.725 \text{ K}$$

The cosmic microwave background Radiation's "surface of last scattering" is analogous to the light coming through the clouds to our eye on a cloudy day.

# The 21 cm line Brightness Temperature

$$\delta T_b \approx 28\text{mK} (1 + \delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{\frac{1}{2}}$$

$$\delta T_b = T_b - T_{CMB}$$

$$T_s = T_{CMB} \Rightarrow \delta T_b = 0$$

No signal

$$T_s > T_{CMB} \Rightarrow \delta T_b > 0$$

Signal in emission

$$T_s < T_{CMB} \Rightarrow \delta T_b < 0$$

Signal in absorption

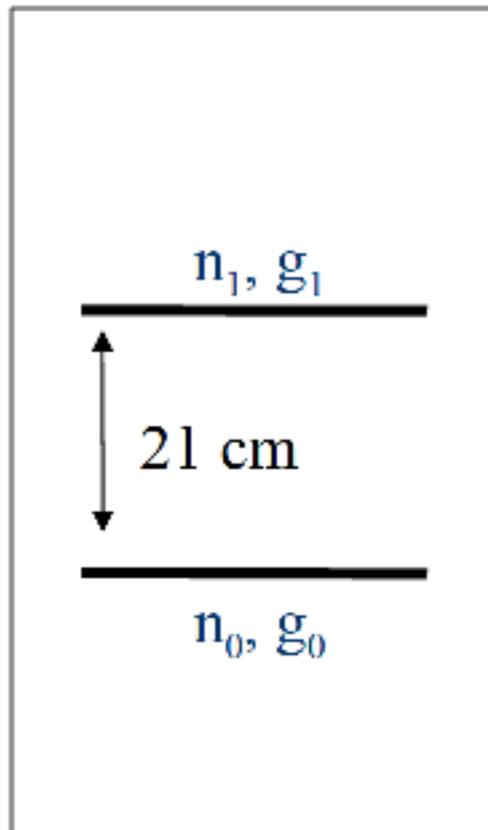
# The Spin Temperature

$$\delta T_b \approx 28\text{mK} (1 + \delta) x_{HI} \frac{T_s - T_{CMB}}{T_s} \frac{\Omega_b h^2}{0.02} \left[ \frac{0.24}{\Omega_m} \left( \frac{1+z}{10} \right) \right]^{\frac{1}{2}}$$

- The value of the  $T_s$  is given by:

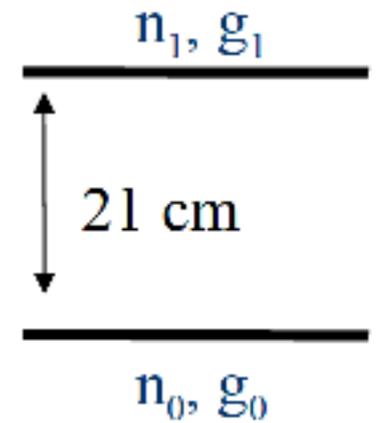
$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

Field 1958  
 Madau et al 98  
 Ciardi&Madau 2003

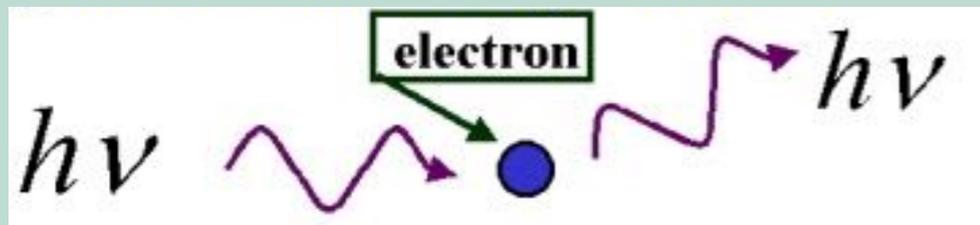


# The Spin Temperature

$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

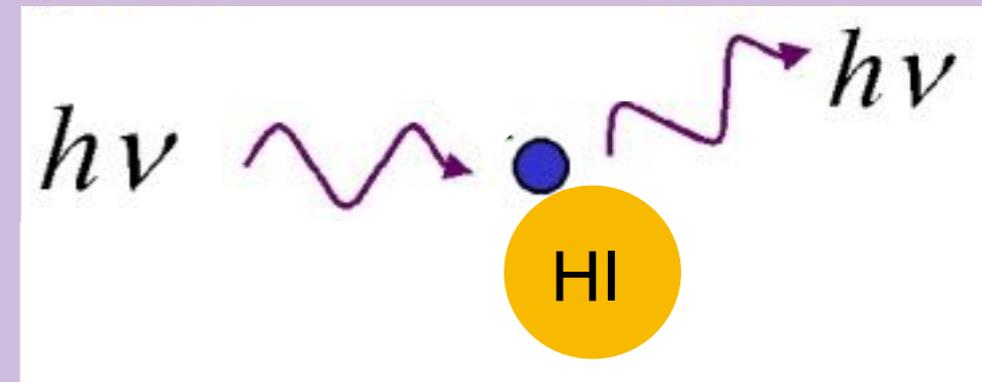


## Coupling to the CMB

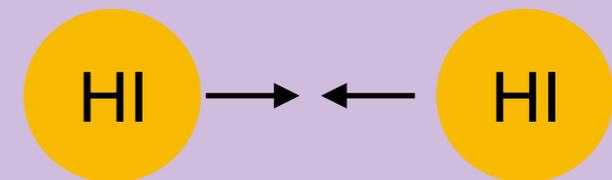


Thomson scattering of CMB photons (low energy photons) by free electrons

## Coupling to the gas



Scattering of Ly $\alpha$  photons



Collision with other HI atoms, electrons and protons

# Temperature Evolution

In a Universe expanding adiabatically

$$T_{\text{CMB}} \propto (1 + z)$$

$$T_{\text{CMB},z} = T_{\text{CMB},z=1100} (1 + \Delta z)^{-1} \text{ K}$$

$$T_{\text{CMB},z} = 3000 (1 + 1100 - z)^{-1} \text{ K}$$

$$T_{\text{CMB}}(0) = 2.73 \text{ K}$$

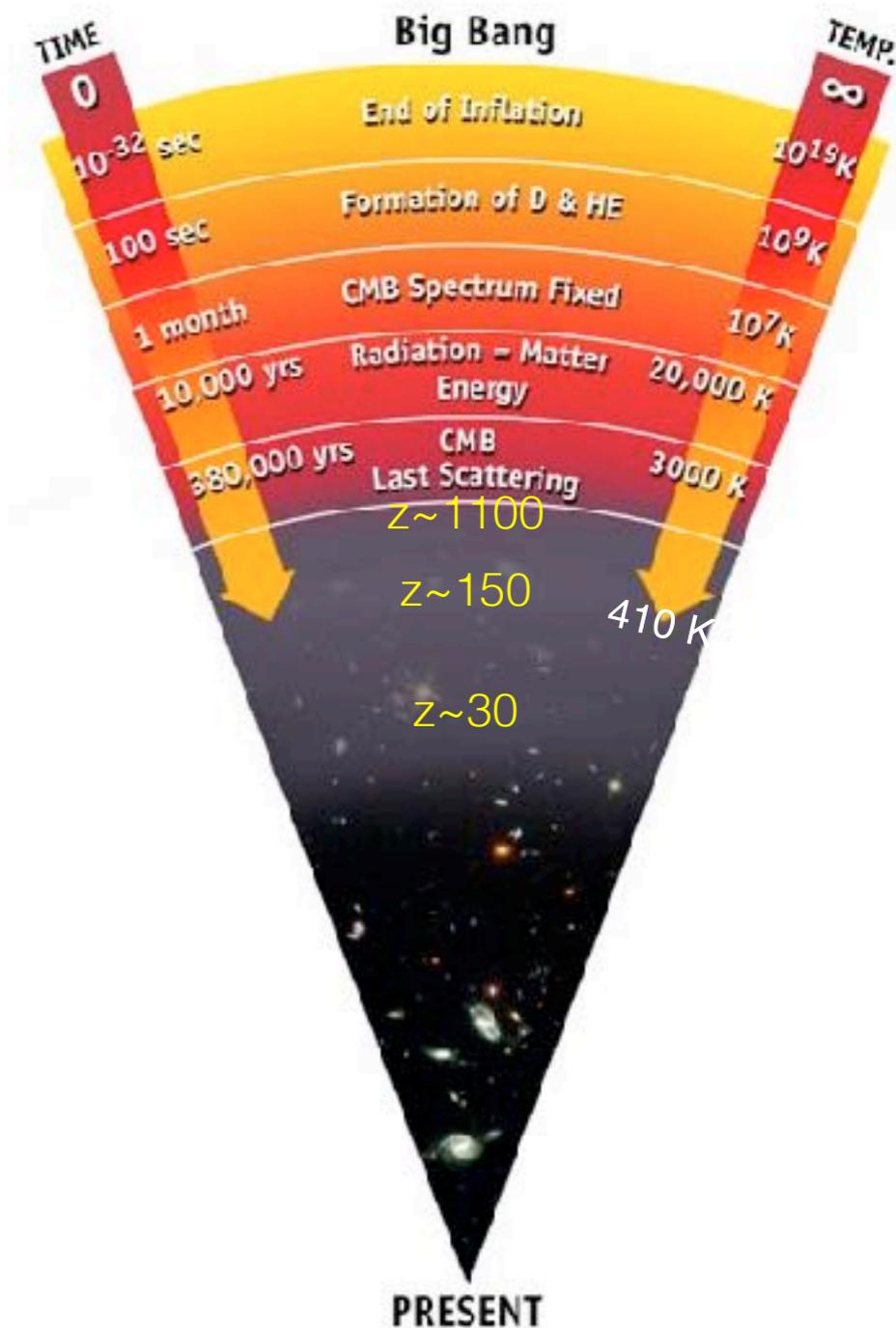
$T_{\text{K}}$  coupled to  $T_{\text{CMB}}$  through Thomson scattering of residual free electrons

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

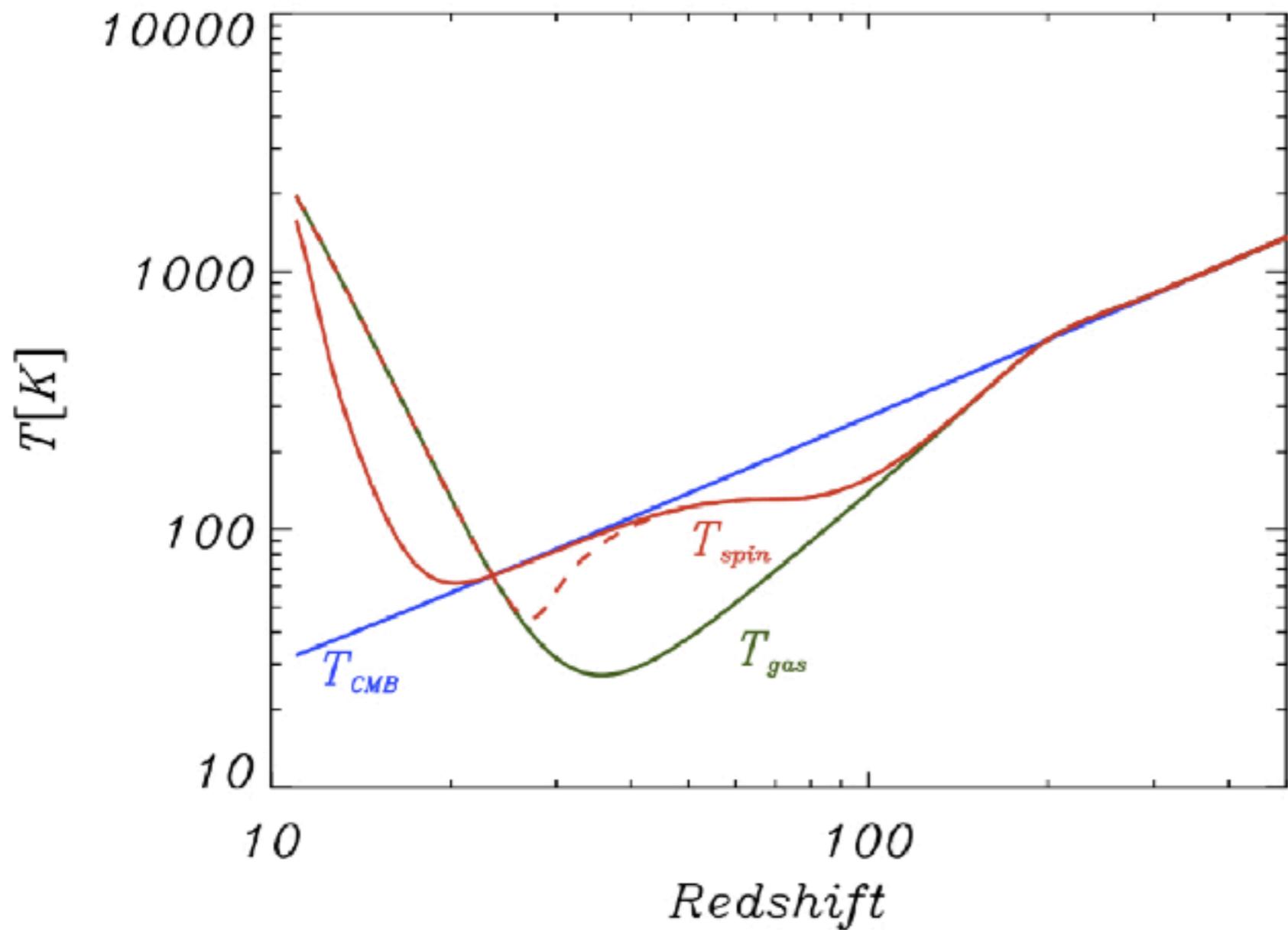
$$T_{\text{K}} \propto (1 + z)^2$$

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

$T_{\text{K}}$  will increase with the onset of Star Formation



# The global evolution of TS



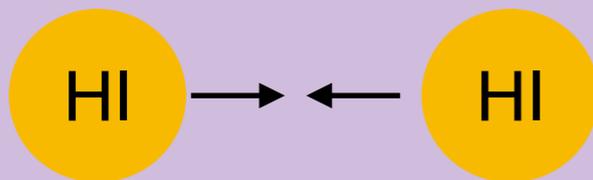
$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

Loeb & Zaldarriaga 2004, Pritchard & Loeb 2008,  
Baek et al. 2010, Thomas & Zaroubi 2010

# The global evolution of $T_s$ : Collisional and radiative coupling to $T_k$

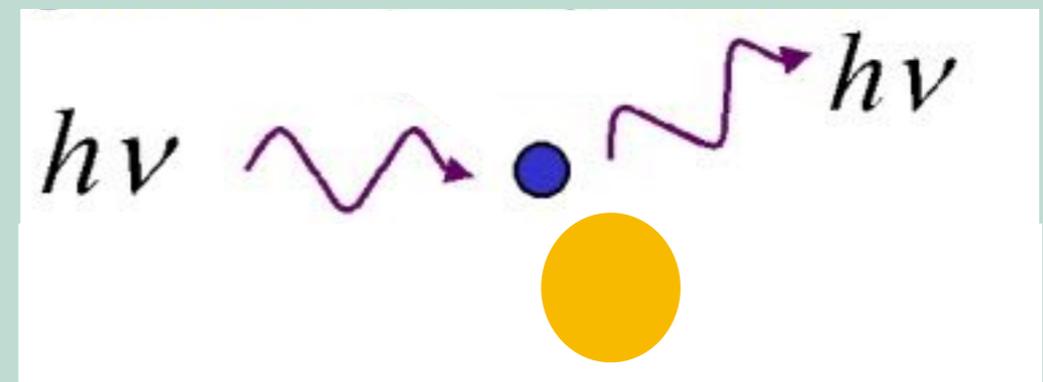
$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

Collision with other HI atoms,  
electrons and protons

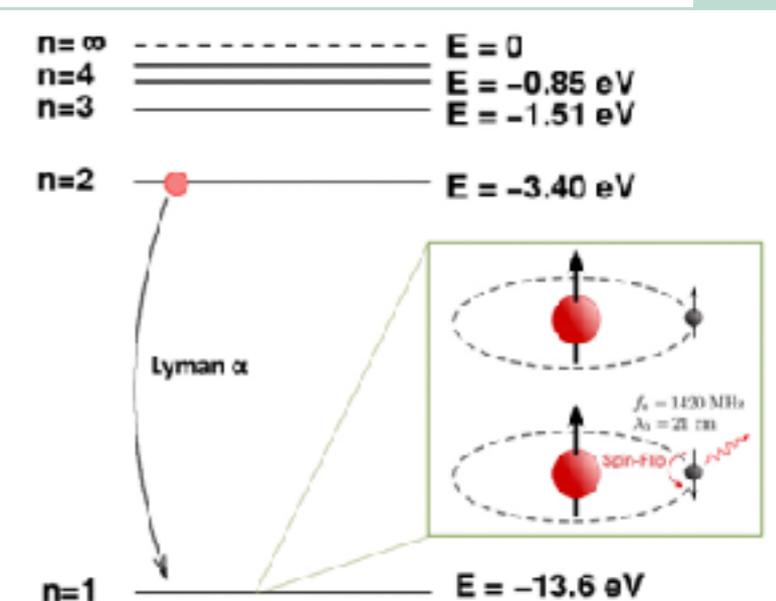


Important when the  
densities are high

Scattering Ly $\alpha$  photons

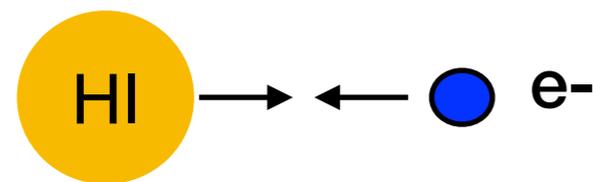
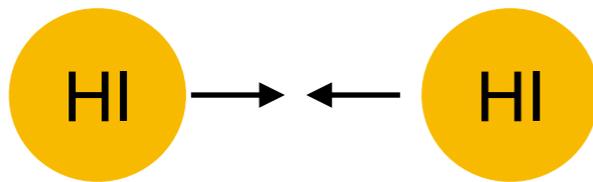


Ly $\alpha$  photons are  
emitted by stars



# Collisional coupling: $x_c$

Collision with other HI atoms,  
electrons and protons



$$y_c = \frac{4T_\star}{3A_{10}T_\gamma} \left[ \kappa_{1-0}^{HH}(T_k)n_H + \kappa_{1-0}^{eH}(T_k)n_e \right]$$

Spontaneous emission  
coefficient

tabulated coefficients  
for collisions

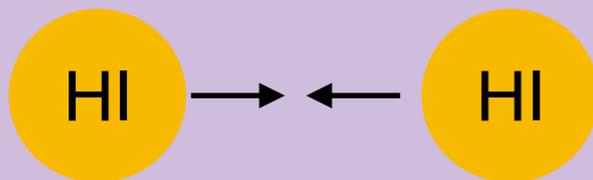
$$T_\star \equiv hc/k\lambda_{21\text{cm}} = 0.0628 \text{ K}$$

Important coupling mechanism  
when the densities are high

# The global evolution of TS: Collisional and radiative coupling

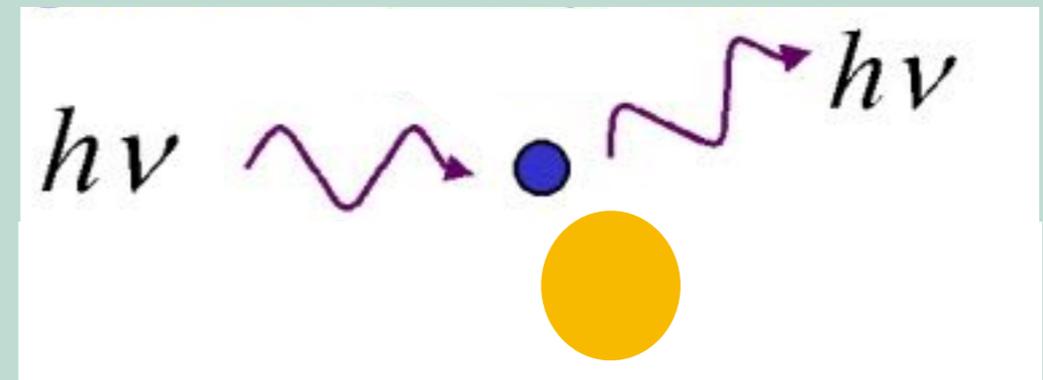
$$T_s^{-1} = \frac{T_{CMB}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$

Collision with other HI atoms,  
electrons and protons

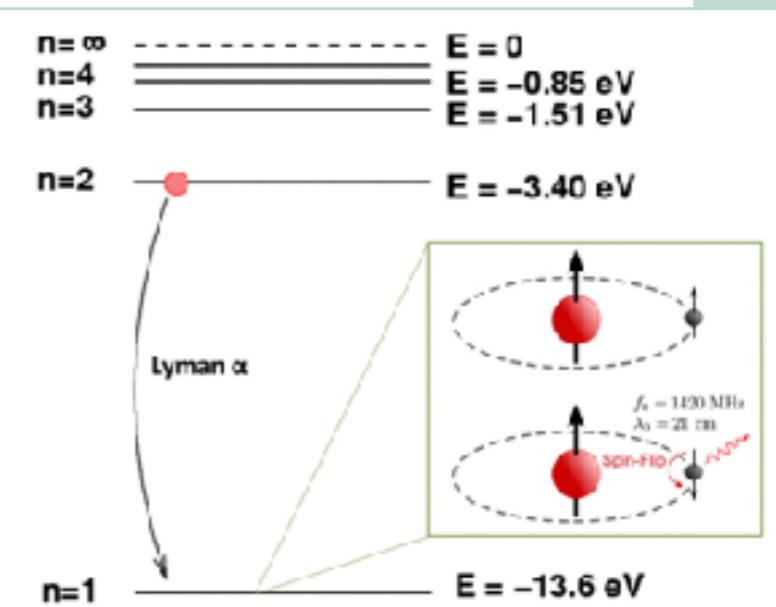


Important when the  
densities are high

Scattering Ly $\alpha$  photons

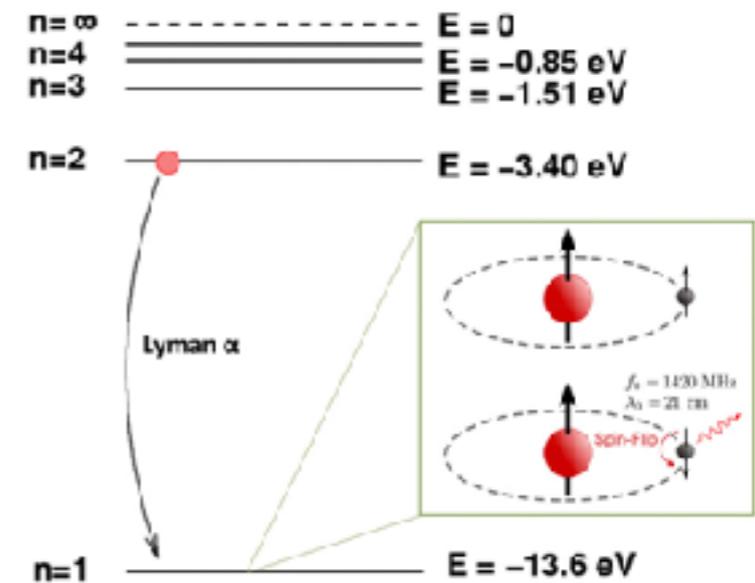


Ly $\alpha$  photons are  
emitted by stars



# The Lyman-alpha line

**Very important line!!!**

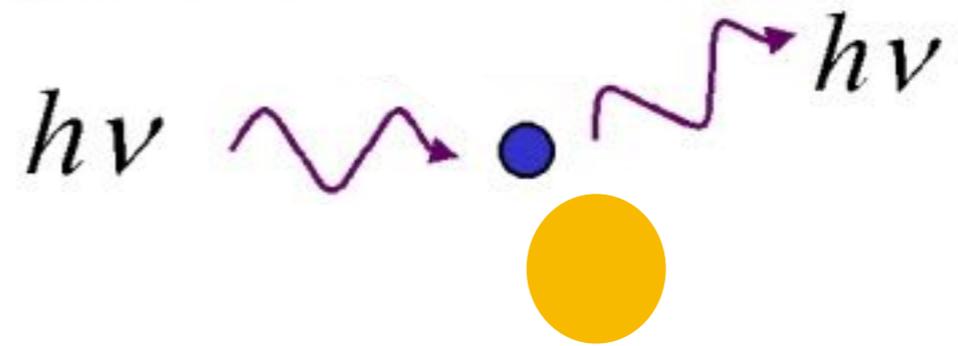
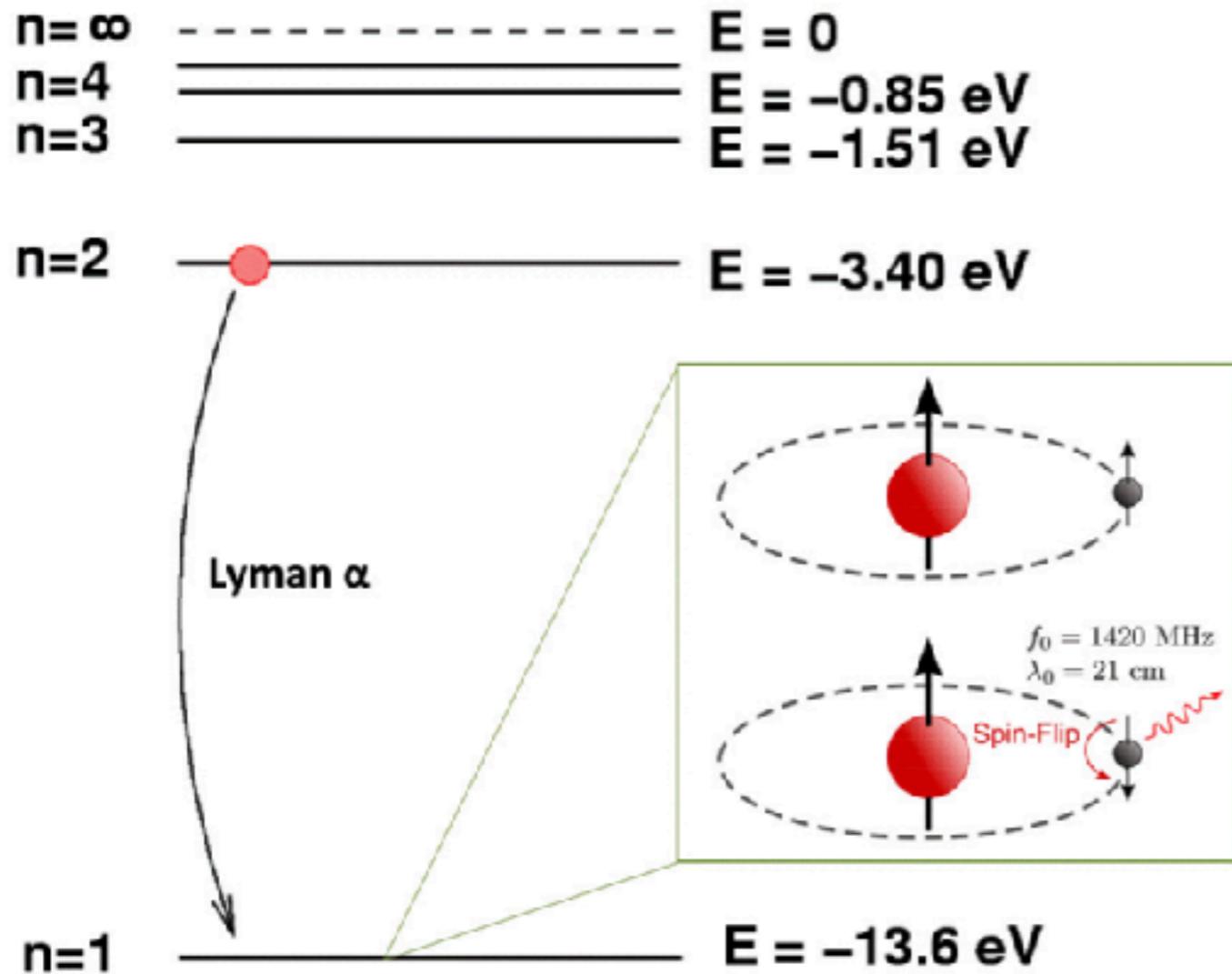


Couples the 21 cm line Spin Temperature to the Gas Temperature

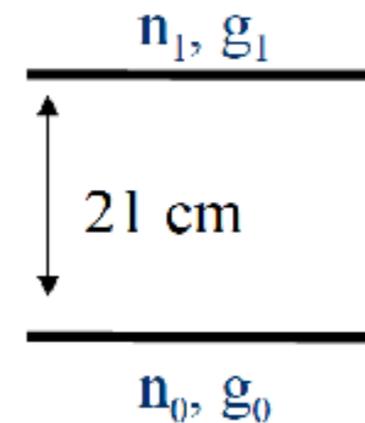
Main cooling line for star formation

Independent tracer of the high redshift Universe

# The Lyman-alpha transition: $X_\alpha$

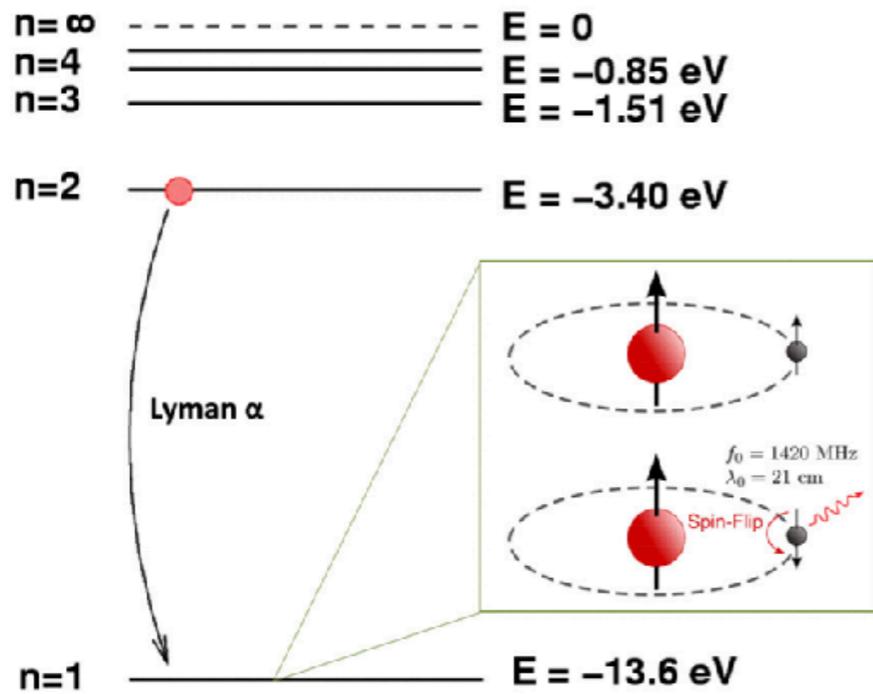


Radiative coupling of TS to TK due to scattering (absorption and reemission) of Ly $\alpha$  photons



The Ly $\alpha$  line has a huge cross section: It is absorbed and reemitted multiple times in a hydrogen cloud

# The Lyman-alpha transition: $\chi_\alpha$

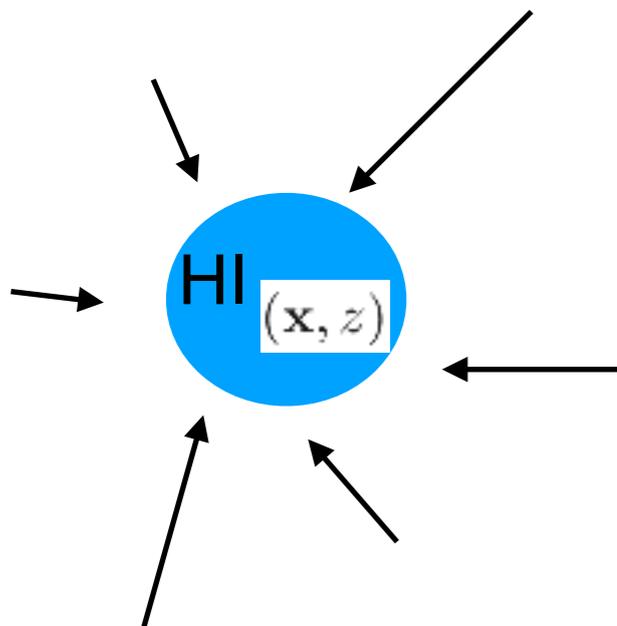


$$\chi_\alpha = \frac{S_\alpha J_\alpha}{J_c}$$

$$J_c \equiv \frac{16\pi^2 T_\star e^2 f_\alpha}{27 A_{10} T_\gamma m_e c}$$

$$\approx 5.552 \times 10^{-8} (1+z) \quad \text{m}^{-2} \text{s}^{-1} \text{Hz}^{-1} \text{sr}^{-1}$$

$$T_\star \equiv hc/k\lambda_{21\text{cm}} = 0.0628 \text{ K}$$

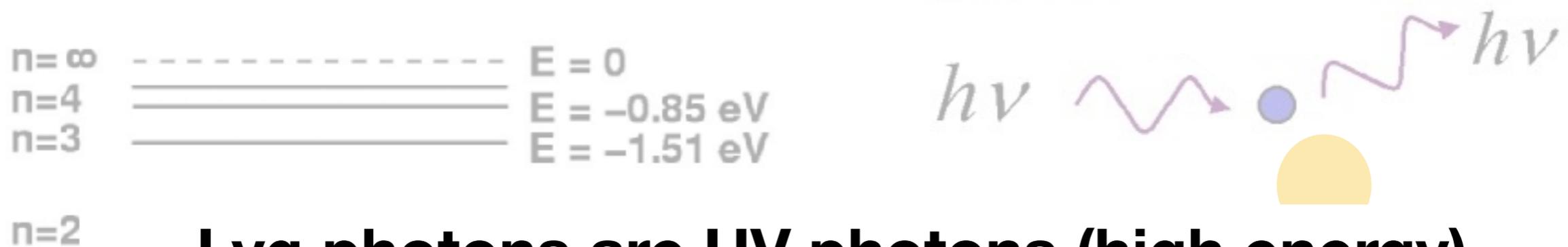


$$J_\alpha(\mathbf{x}, z) = \frac{(1+z)^2}{4\pi} \sum_{n=2}^{n_{\max}} f_{\text{rec}}(n) \times$$

$$\times \int \frac{d\Omega'}{4\pi} \int_0^{x_{\max}(n)} dx' \epsilon_\alpha(\mathbf{x} + \mathbf{x}', \nu'_n, z')$$

$$J_\alpha(z) = \frac{(1+z)^2}{4\pi} \sum_{n=2}^{n_{\max}} f_{\text{rec}}(n) \int_z^{z_{\max}(n)} \frac{cdz'}{H(z')} \epsilon_\alpha(\nu'_n, z')$$

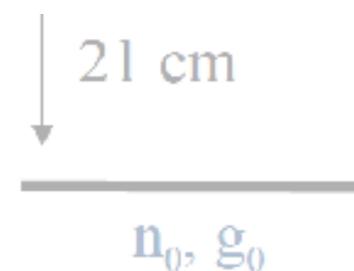
# The Lyman-alpha transition: $\chi_\alpha$



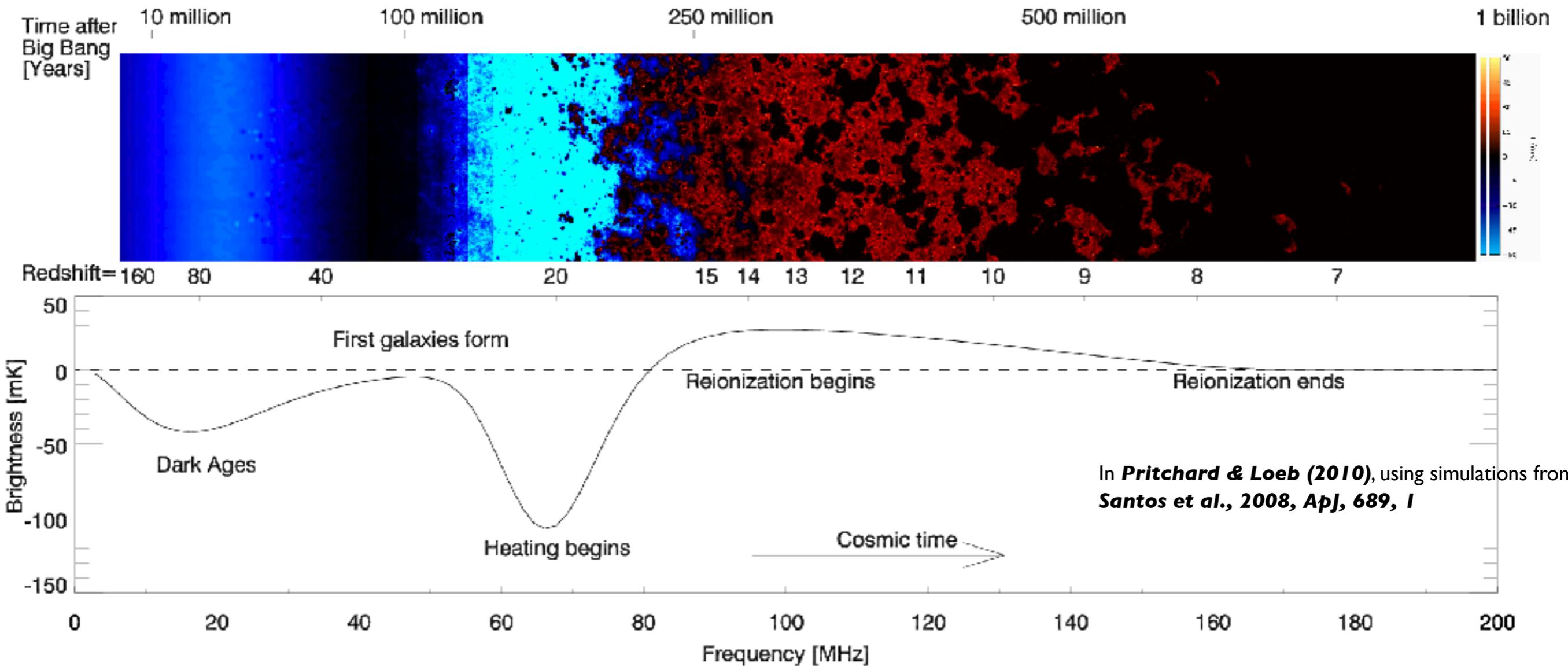
**Ly $\alpha$  photons are UV photons (high energy) emitted by stars**



**So they only contribute to  $T_s$  after stars are formed**

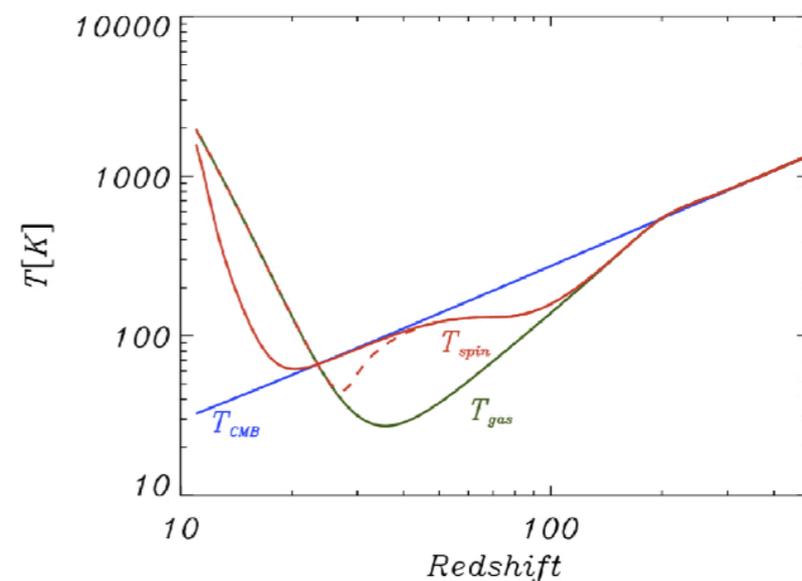


# The global 21 cm signal

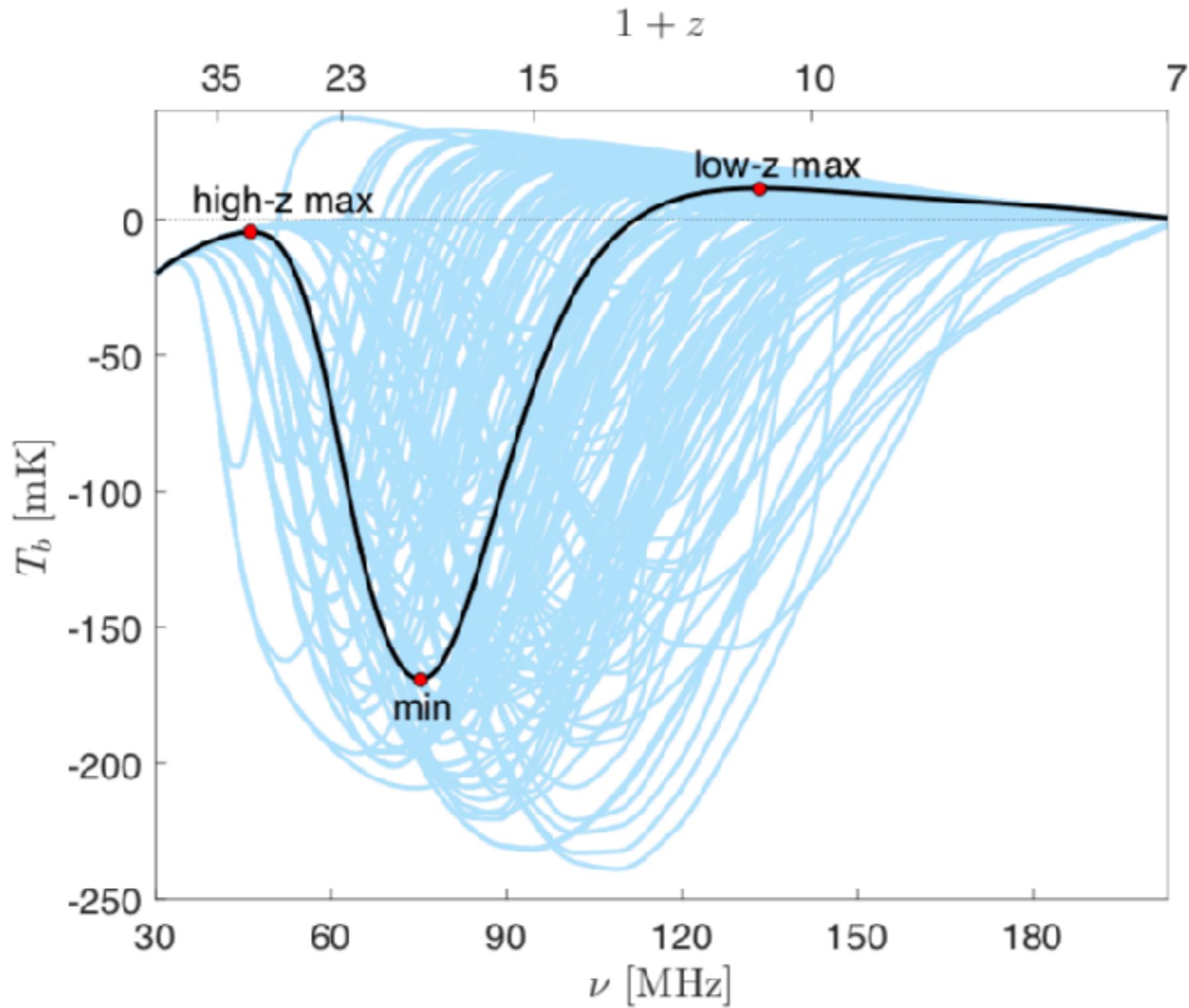


$$\delta T_b = \propto \frac{T_S - T_{\text{CMB}}}{T_S}$$

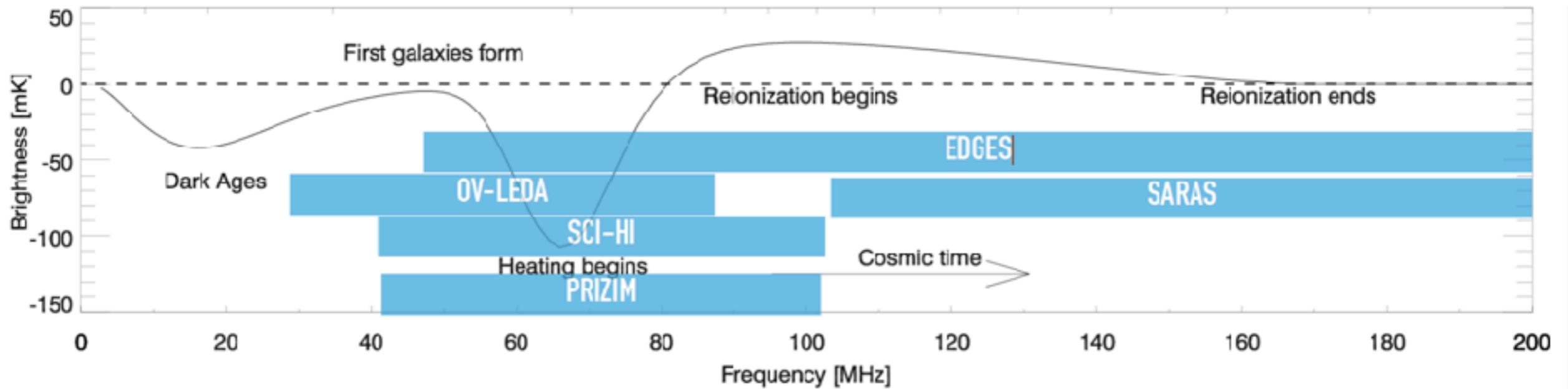
$$T_s^{-1} = \frac{T_{\text{CMB}}^{-1} + x_c T_k^{-1} + x_\alpha T_k^{-1}}{1 + x_c + x_\alpha}$$



# The global 21 cm signal



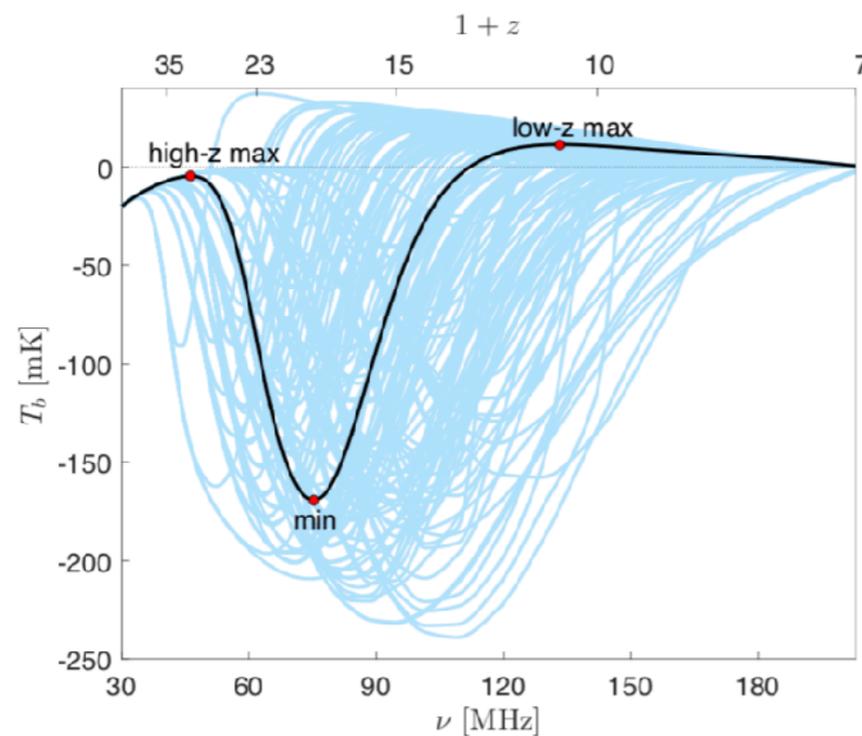
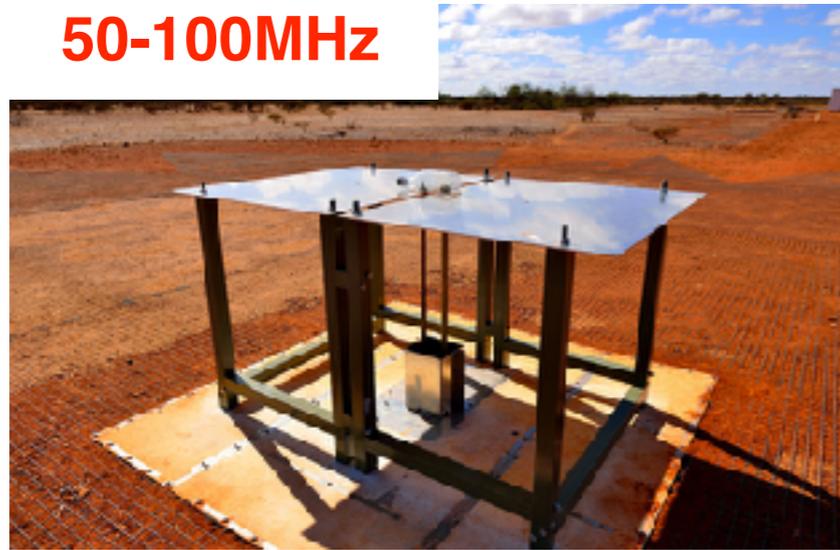
# High-z 21 cm Projects Under Way



# EDGES

## Experiment to Detect the Global Epoch of Reionization Signature

50-100MHz

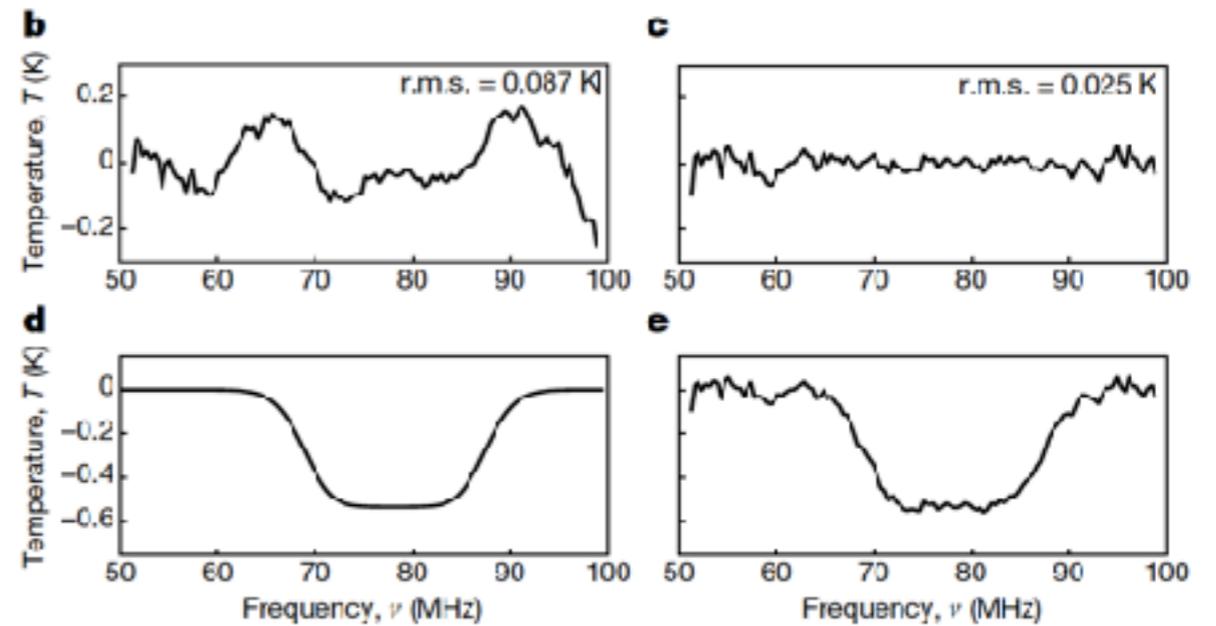
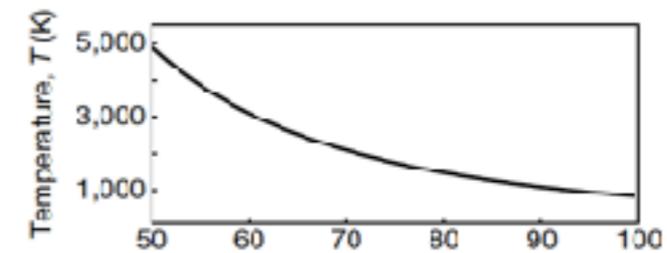


## LETTER

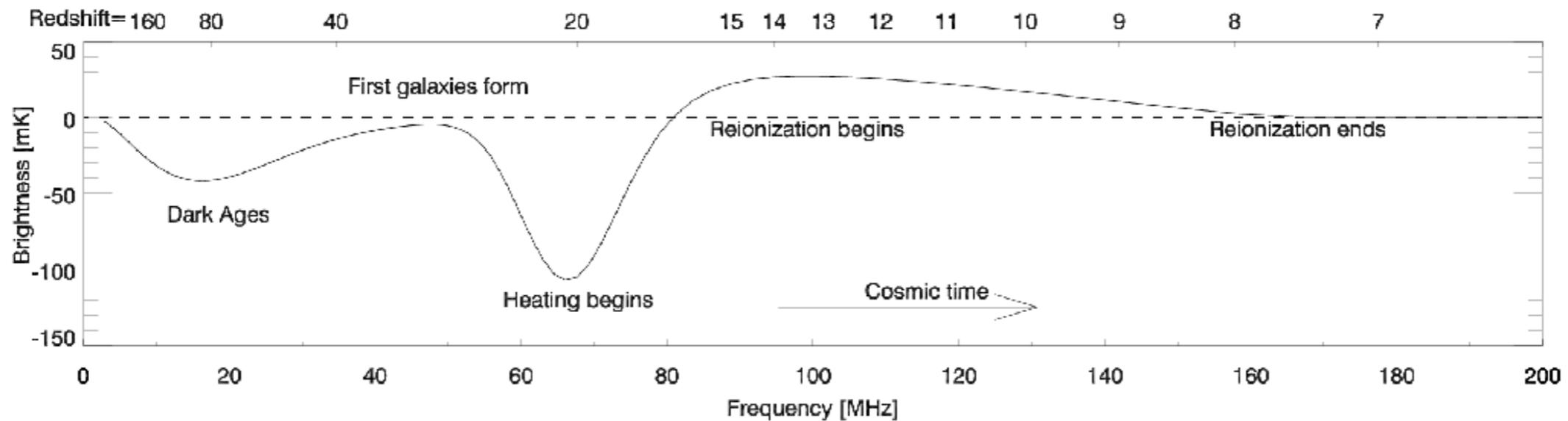
doi:10.1038/nature25792

### An absorption profile centred at 78 megahertz in the sky-averaged spectrum

Judd D. Bowman<sup>1</sup>, Alan E. E. Rogers<sup>2</sup>, Raul A. Monsalve<sup>1,3,4</sup>, Thomas J. Mozdzen<sup>1</sup> & Nivedita Mahesh<sup>1</sup>



# How could this feature absorption be so strong?



Thermal equilibrium at  $z \approx 200-150 \Rightarrow T_K = T_{\text{CMB}}$

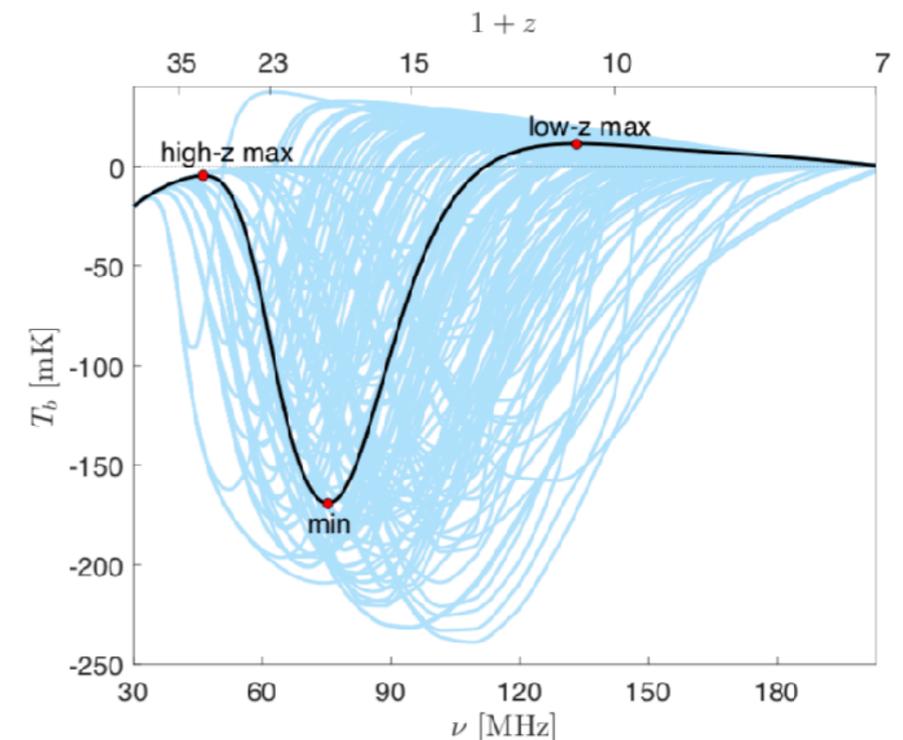
$$T_{\text{gas}} \propto (1+z)^2$$

$$\delta T_b \propto \frac{T_S - T_{\text{CMB}}}{T_S}$$

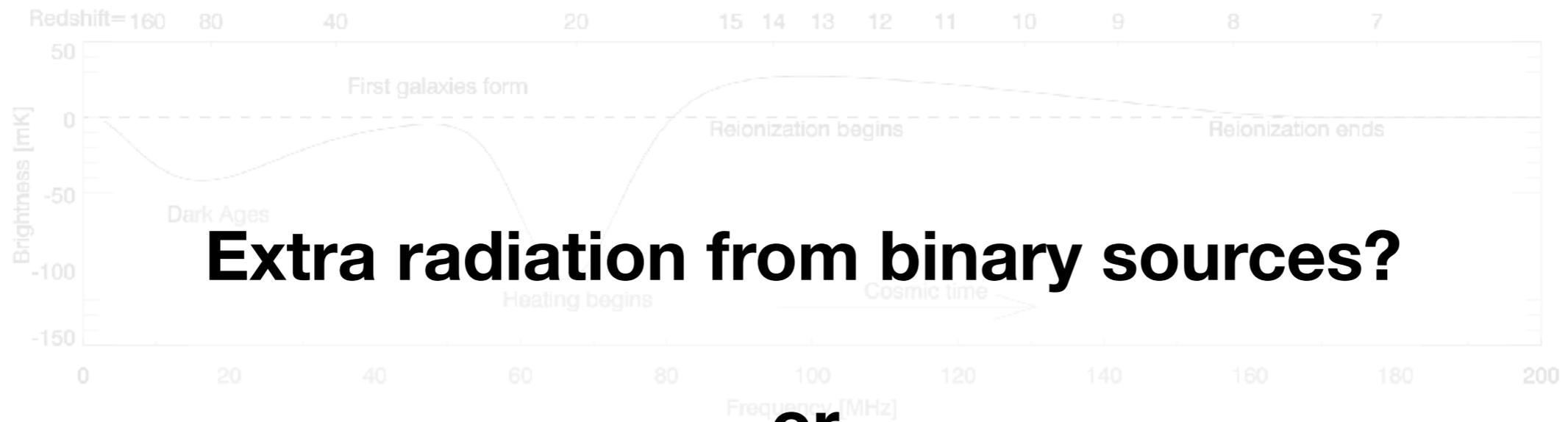
$$T_R \propto (1+z)$$

$$\delta T_{21}(z) \propto \left[ 1 - \frac{T_R(z)}{T_S(z)} \right]$$

$$\delta T_{21} \propto \frac{x_\alpha + x_c}{1 + x_\alpha + x_c} \left( 1 - \frac{T_R}{T_{\text{gas}}} \right)$$



# How could this feature absorption be so strong?



**Extra radiation from binary sources?**

or

Thermal equilibrium at  
 $z \approx 150 \Rightarrow T_K = T_{\text{CMB}}$

$$T_{\text{gas}} \propto (1+z)^2$$

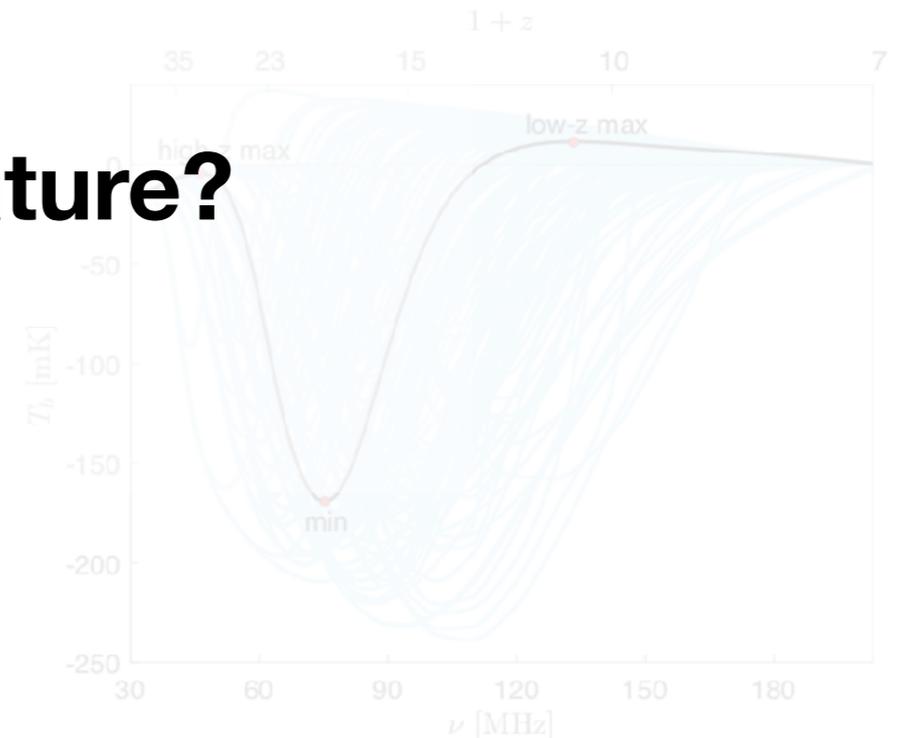
**A colder gas Temperature?**

$$\delta T_b \propto \frac{T_S - T_{\text{CMB}}}{T_S}$$

$$T_R \propto (1+z)$$

$$\delta T_{21}(z) \propto \left| 1 - \frac{T_R(z)}{T_S(z)} \right|$$

$$\delta T_{21} \propto \frac{x_\alpha + x_c}{1 + x_\alpha + x_c} \left( 1 - \frac{T_R}{T_{\text{gas}}} \right)$$

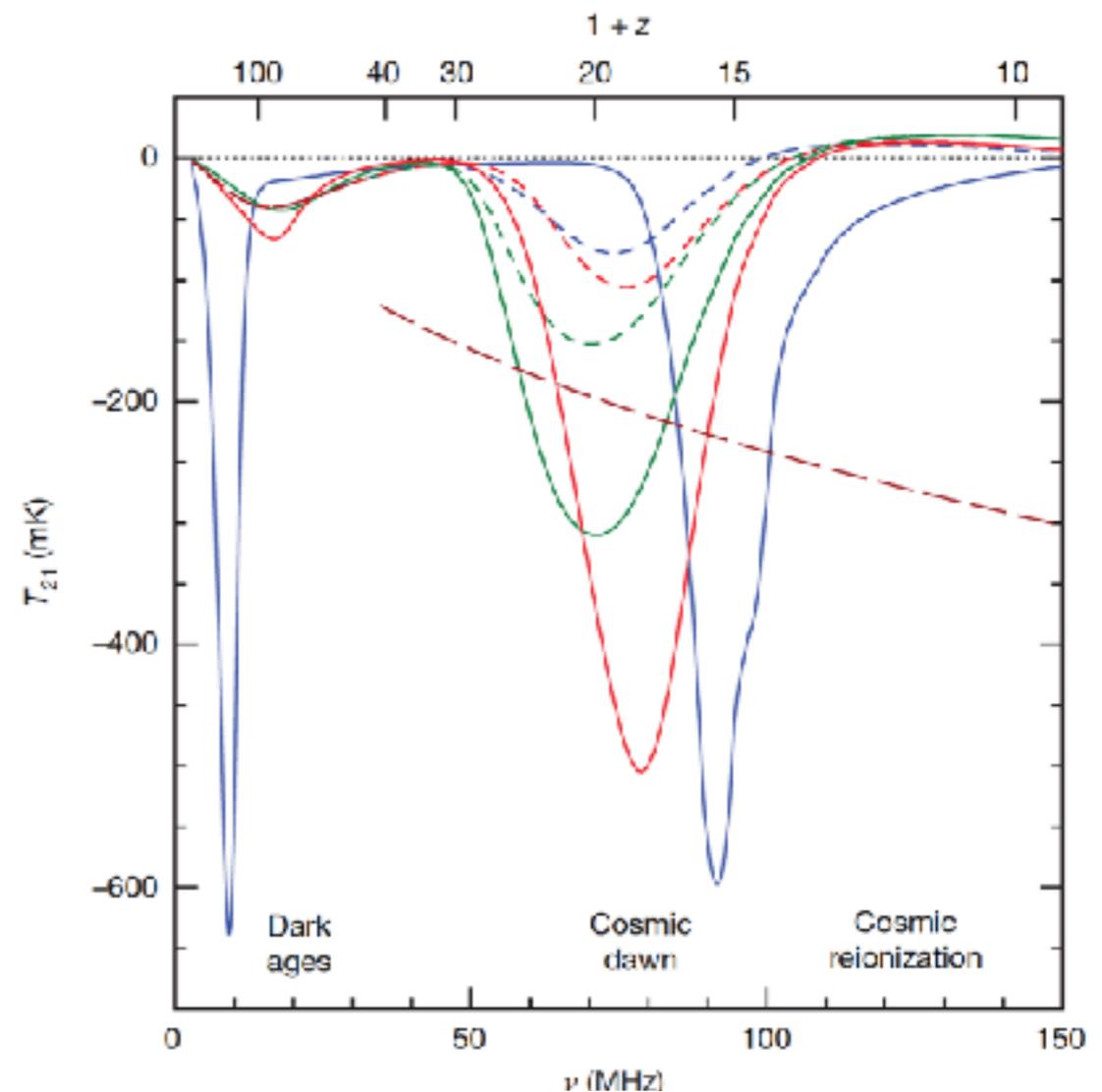


# Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana<sup>1</sup>

The cosmic radio-frequency spectrum is expected to show a strong absorption signal corresponding to the 21-centimetre-wavelength transition of atomic hydrogen around redshift 20, which arises from Lyman- $\alpha$  radiation from some of the earliest stars<sup>1–4</sup>. By observing this 21-centimetre signal—either its sky-averaged spectrum<sup>5</sup> or maps of its fluctuations, obtained using radio interferometers<sup>6,7</sup>—we can obtain information about cosmic dawn, the era when the first astrophysical sources of light were formed.

The recent detection of the global 21-centimetre spectrum<sup>5</sup> reveals a stronger absorption than the maximum predicted by existing models, at a confidence level of 3.8 standard deviations. Here we report that this absorption can be explained by the combination of radiation from the first stars and excess cooling of the cosmic gas induced by its interaction with dark matter<sup>8–10</sup>. Our analysis indicates that the spatial fluctuations of the 21-centimetre signal at cosmic dawn could be an order of magnitude larger than previously expected and that the dark-matter particle is no heavier than several proton masses, well below the commonly predicted mass of weakly interacting massive particles. Our analysis also confirms that dark matter is highly non-relativistic and at least moderately cold, and primordial velocities predicted by models of warm dark matter are potentially detectable. These results indicate that 21-centimetre cosmology can be used as a dark-matter probe.



# DM

## LETTER

doi:10.1038/nature25791

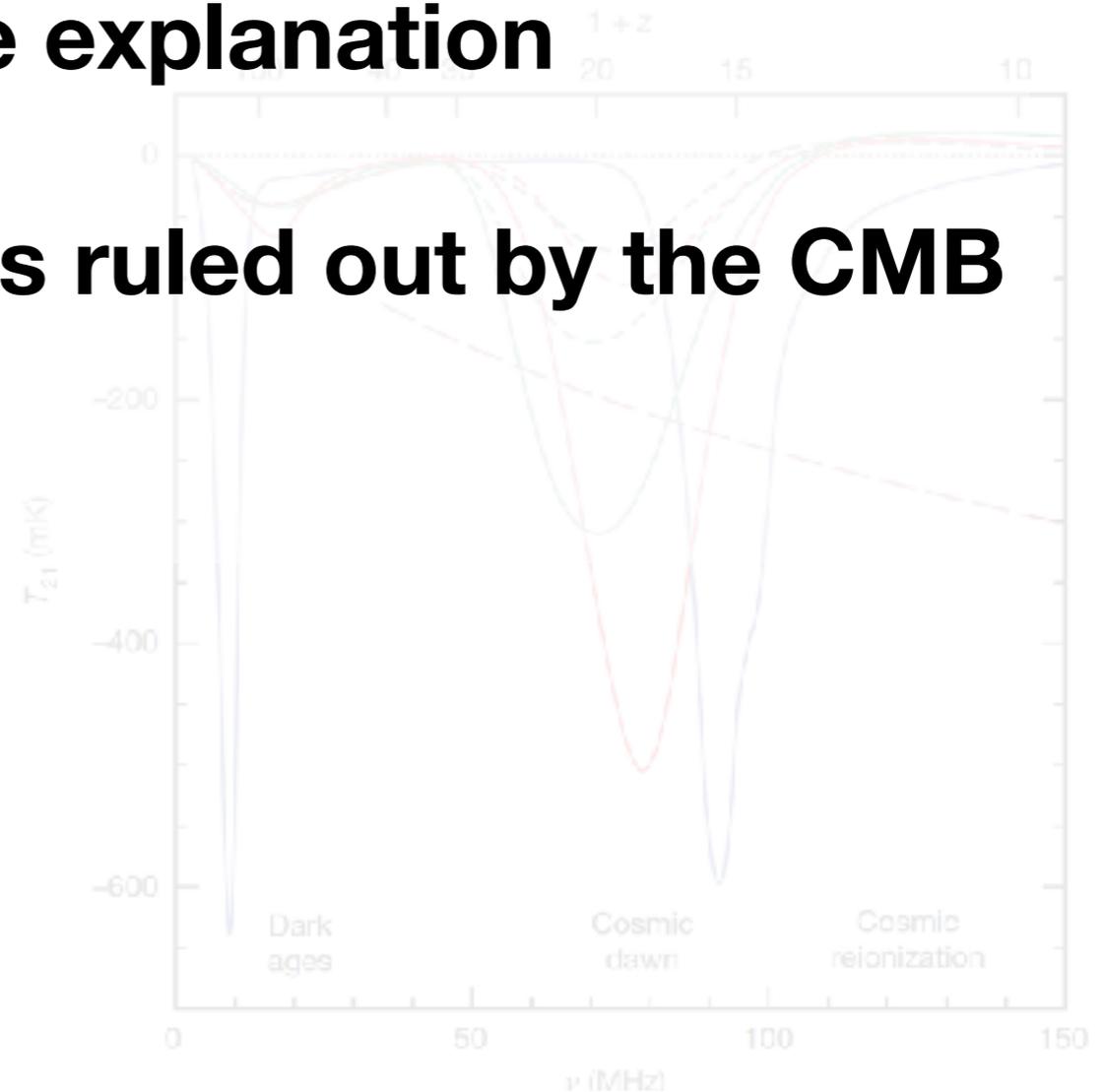
### Possible interaction between baryons and dark-matter particles revealed by the first stars

Rennan Barkana<sup>1</sup>

#### Not a possible explanation

The cosmic radio-frequency spectrum is expected to show a strong absorption signal corresponding to the 21-centimetre-wavelength transition of atomic hydrogen around redshift 20, which arises from Lyman- $\alpha$  radiation from some of the earliest stars<sup>1-4</sup>. By measuring the global 21-cm spectrum<sup>5</sup> or maps of its fluctuations, obtained using radio interferometers<sup>6,7</sup>—we can obtain information about cosmic dawn, the era when the first astrophysical sources of light were formed. The recent detection of the global 21-centimetre spectrum<sup>5</sup> reveals a stronger absorption than the maximum predicted by existing models, at a confidence level of 3.8 standard deviations. Here we report that this absorption can be explained by the combination of radiation from the first stars and excess cooling of the cosmic gas induced by its interaction with dark matter<sup>8-10</sup>. Our analysis indicates that the spatial fluctuations of the 21-centimetre signal at cosmic dawn could be an order of magnitude larger than previously expected and that the dark-matter particle is no heavier than several proton masses, well below the commonly predicted mass of weakly interacting massive particles. Our analysis also confirms that dark matter is highly non-relativistic and at least moderately cold, and primordial velocities predicted by models of warm dark matter are potentially detectable. These results indicate that 21-centimetre cosmology can be used as a dark-matter probe.

**This type of interaction is ruled out by the CMB**



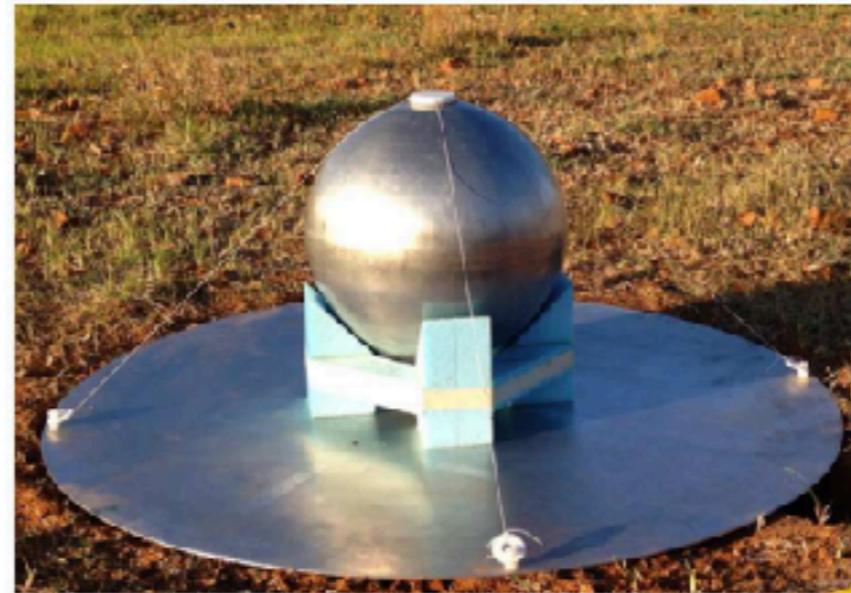
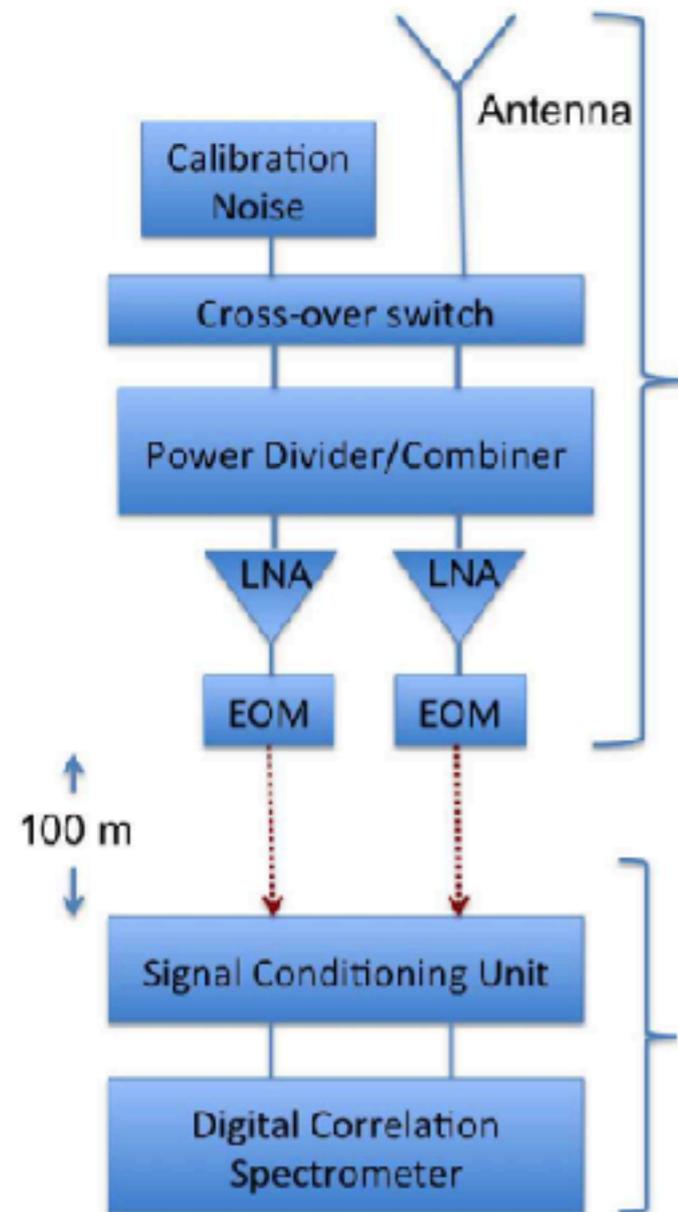
**Is the detection real?**

# Discussion

- **Is it a real detection?**
  - **Foreground removal artefact due to the simple polynomial foreground model**
  - **Multi path propagation**
  - **Ionosphere**
  - **Absorption line in the galaxy**

**To be confirmed soon!!!**

# SARAS 2

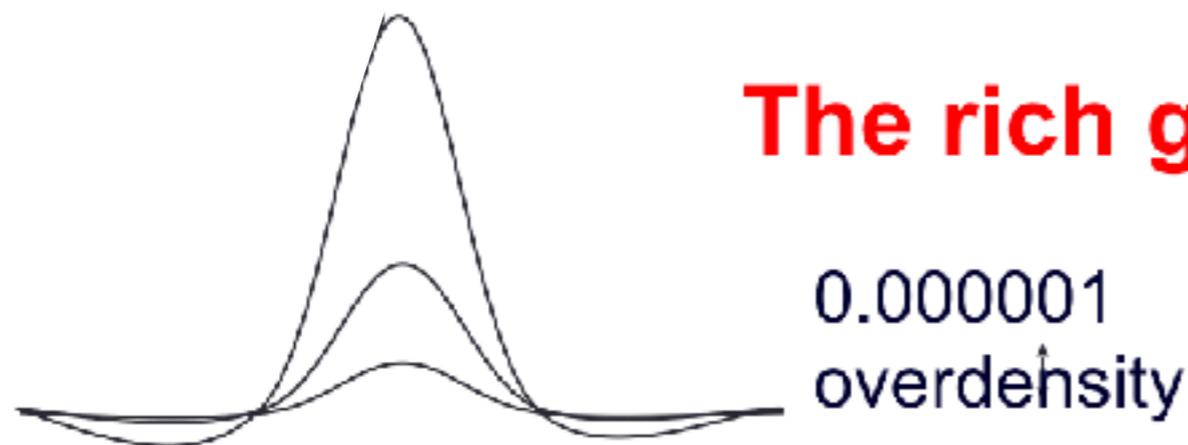


Spectral radiometer designed for measuring the all-sky global 21-cm spectral distortions, located in Southern India

**Figure 1.** SARAS 2: In the schematic, LNA refers to Low-Noise Amplifiers while EOM are Electro-Optical Modulators. The upper right image shows the sphere-disk monopole, with the sphere supported using styrofoam, cotton strings and teflon fasteners. The lower right image shows the spectrometer.

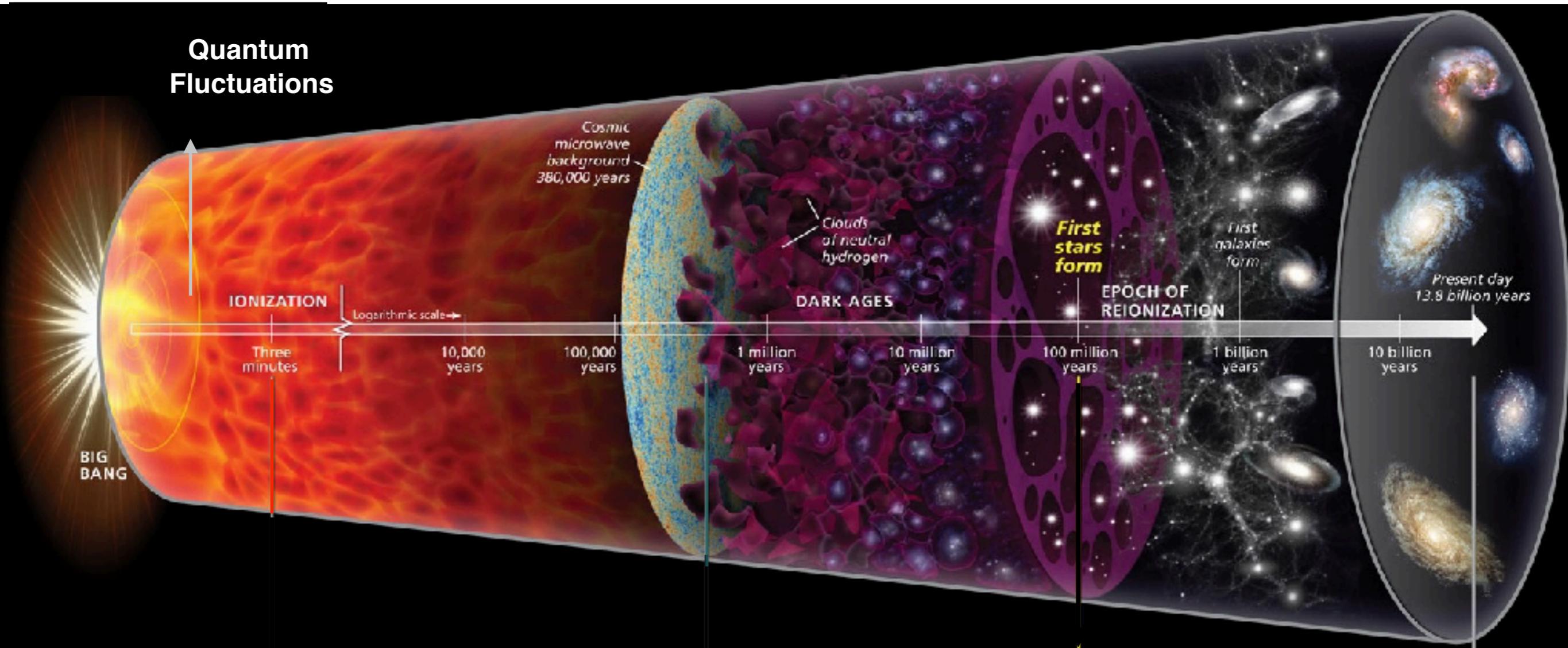
# Next: The first light sources

From quantum fluctuations  
to the first bound structures



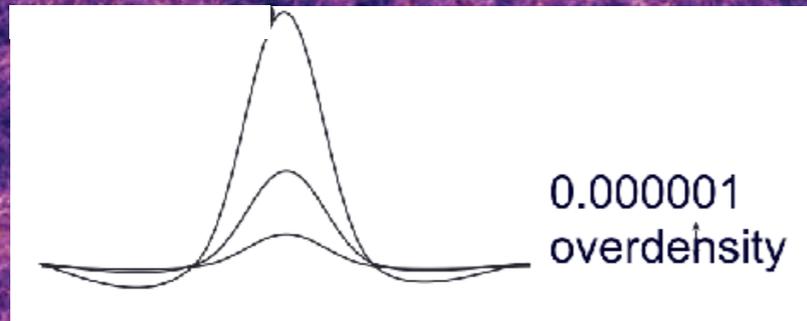
**The rich gets richer and the poor gets poorer**

# The first light in the Universe

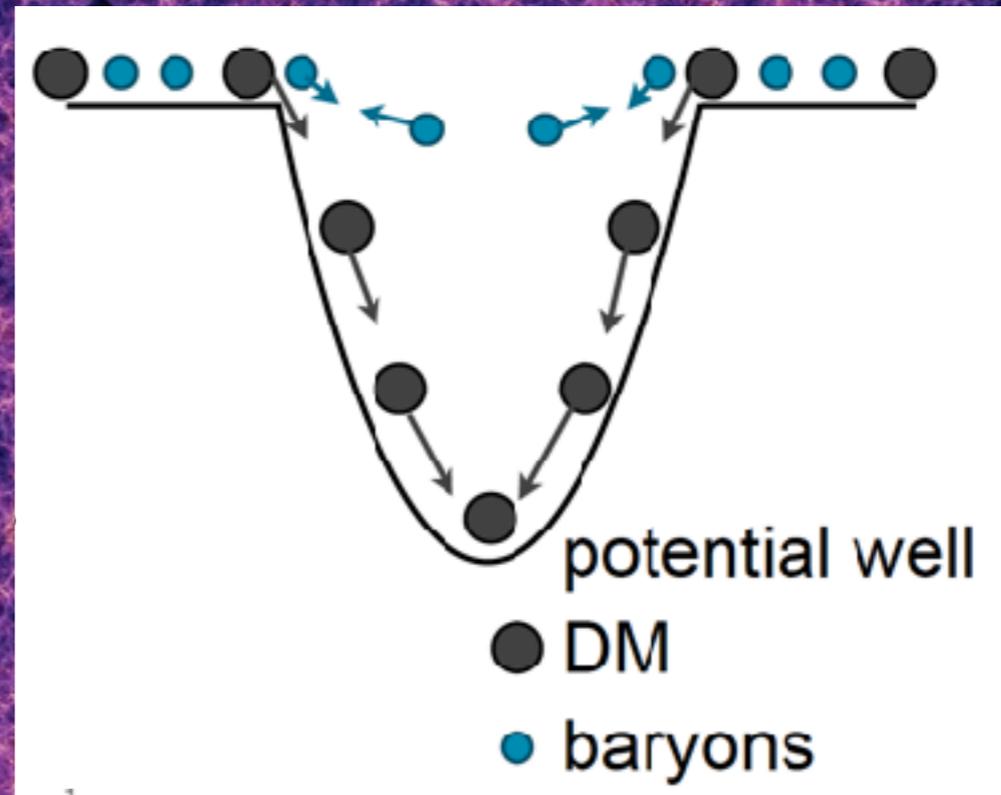


**Quantum fluctuations evolve into classic density fluctuations and later into large scale structure**

# From density fluctuations to star formation



Overdense regions become more and more overdense and form DM halos



First Stars formed in the peaks of the density field

# Structure Formation: Dark Matter halos

i) First density fluctuations are gaussian  
(confirmed by the CMB)

ii) The Universe is flat

$$\delta = \frac{\rho - \bar{\rho}}{\bar{\rho}} \quad \bar{\rho} = \Omega_m \rho_{\text{crit}}$$

$$\rho_c = \frac{3H^2}{8\pi G} = 10^{-26} \text{ kg/m}^3$$

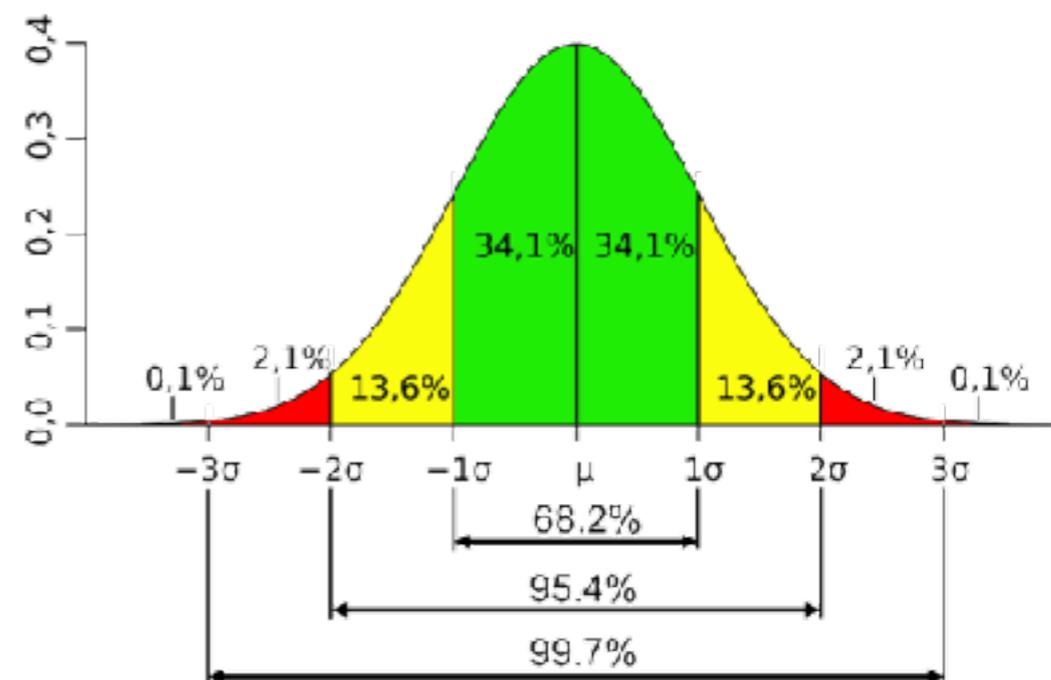
(10 hydrogen atoms per cubic metre)

Fluctuations become non linear at  $\delta \approx 1$

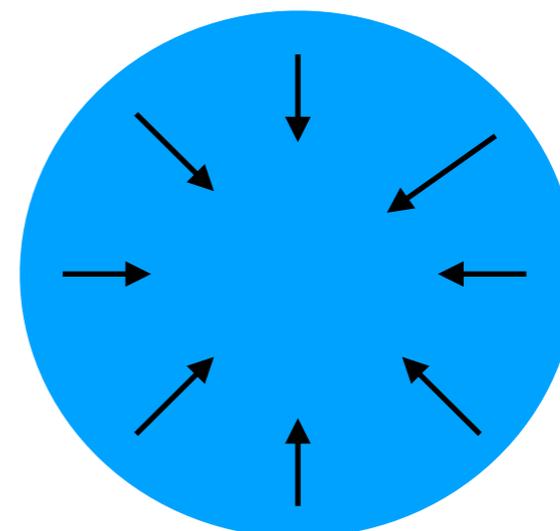
iii) For non-linear fluctuations



Spherical collapse  
(Press & Schechter formalism)

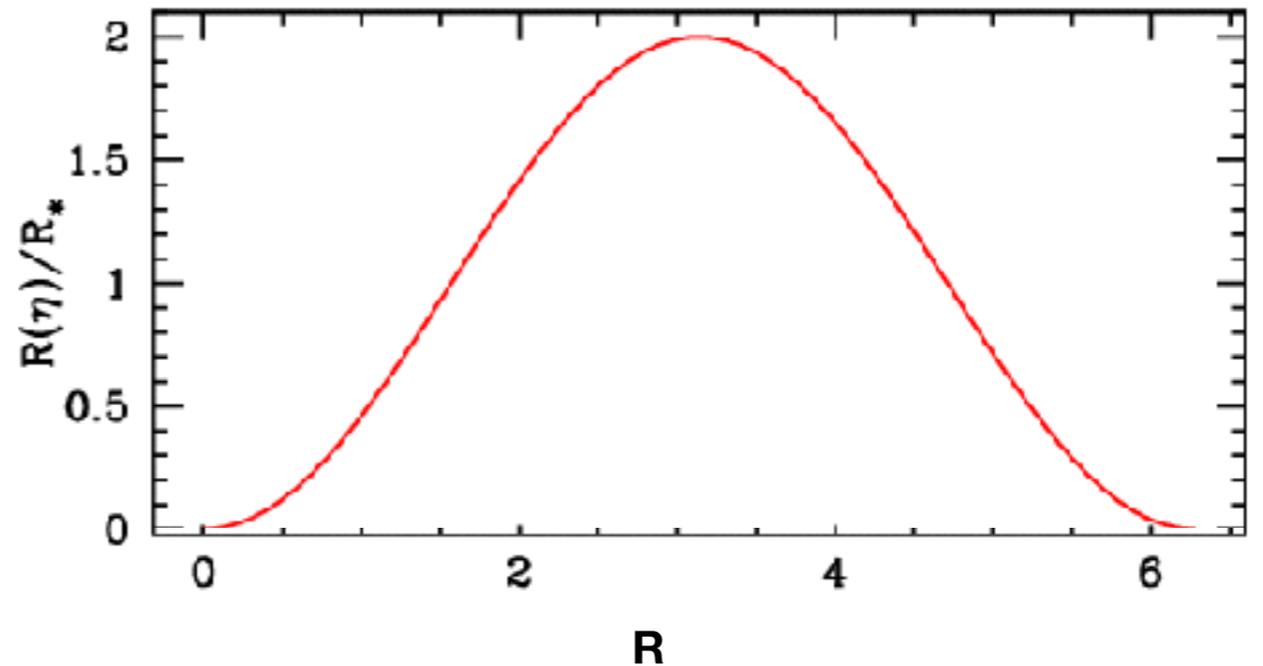


Credit - <https://kanbanize.com/blog/normal-gaussian-distribution-over-cycle-time/>



# Dark Matter Halos Formation

- Consider a spherically symmetric overdensity in an expanding background
- By Birkhoff's Theorem, it can treat as an independent and scaled version of the Universe
- Initial expansion with Hubble flow, turnaround, collapse and virialisation

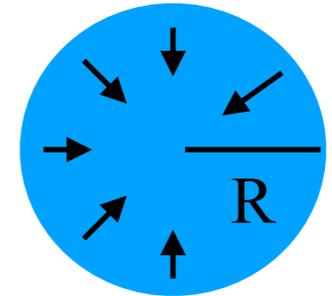


Credit - Chris Power

# Spherical collapse: Press & Schechter Formalism

Mass-density field smoothed over a scale  $R$  correspondent to a mass  $M$  is also Gaussian

$$P(\delta > \delta_{\text{crit}}|M) = \frac{1}{\sigma(M)\sqrt{2\pi}} \int_{\delta_{\text{crit}}}^{\infty} d\delta' \exp\left(-\frac{\delta'^2}{2\sigma^2(M)}\right)$$



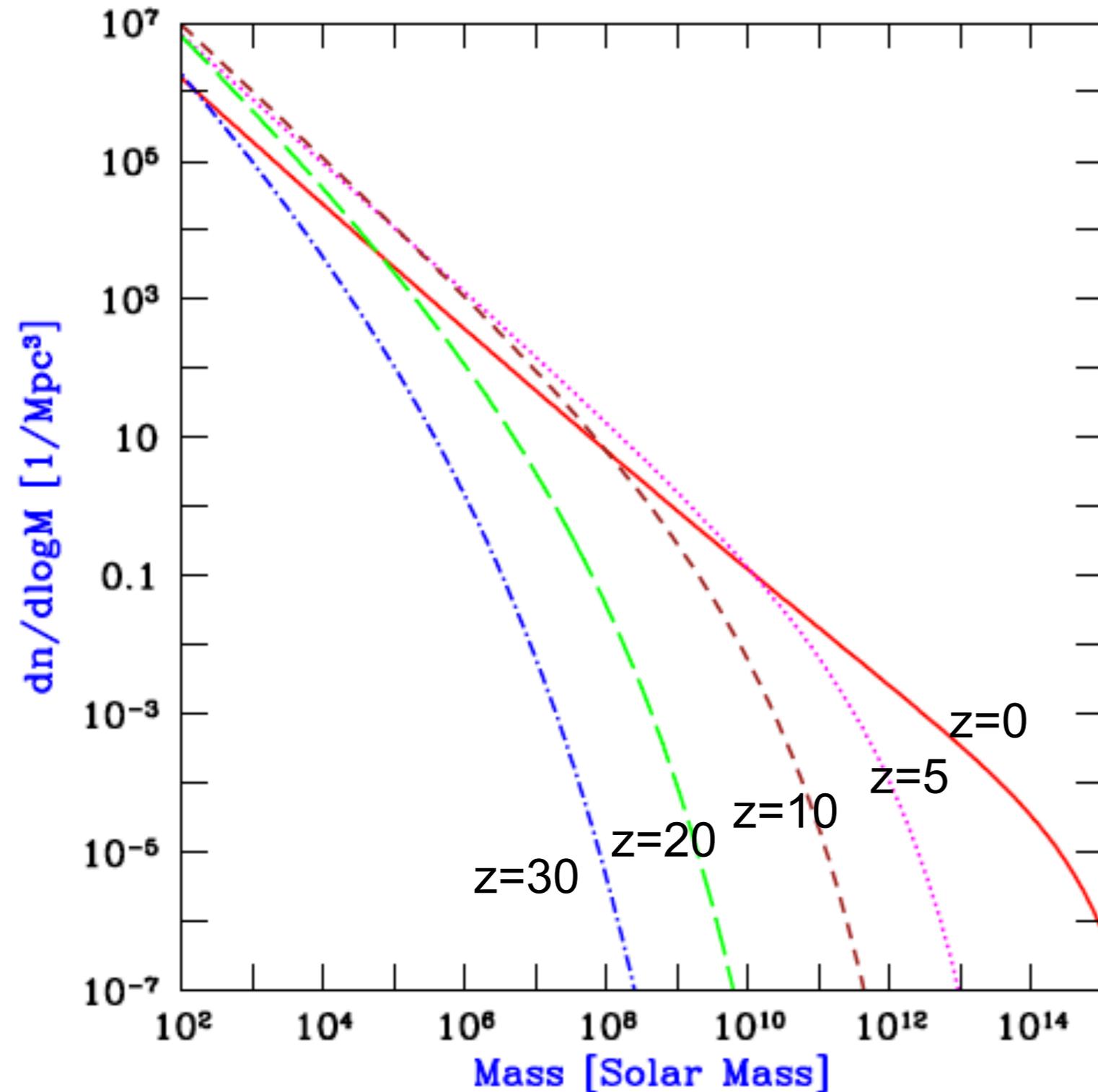
$\sigma^2(M)$  denotes the variance of the mass-density field smoothed over scale  $M$

$$P(> M) = P(\delta > \delta_{\text{crit}}|M) = \frac{1}{2} \left[ 1 - \text{erf}\left(\frac{\nu}{\sqrt{2}}\right) \right] \quad \nu \equiv \frac{\delta_{\text{crit}}}{\sigma(M)}$$

Letting  $dn$  be the comoving number density of halos of mass between  $M$  and  $M + dM$

$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M} \frac{-d(\ln \sigma)}{dM} \nu_c e^{-\nu_c^2/2}$$

# Spherical collapse: Press & Schechter Formalism



$$\frac{dn}{dM} = \sqrt{\frac{2}{\pi}} \frac{\rho_m}{M} \frac{-d(\ln \sigma)}{dM} v_c e^{-v_c^2/2}$$

$$v \equiv \frac{\delta_{\text{crit}}}{\sigma(M)}$$

# **“Let there be Light”**

## **The first stars and Galaxies**

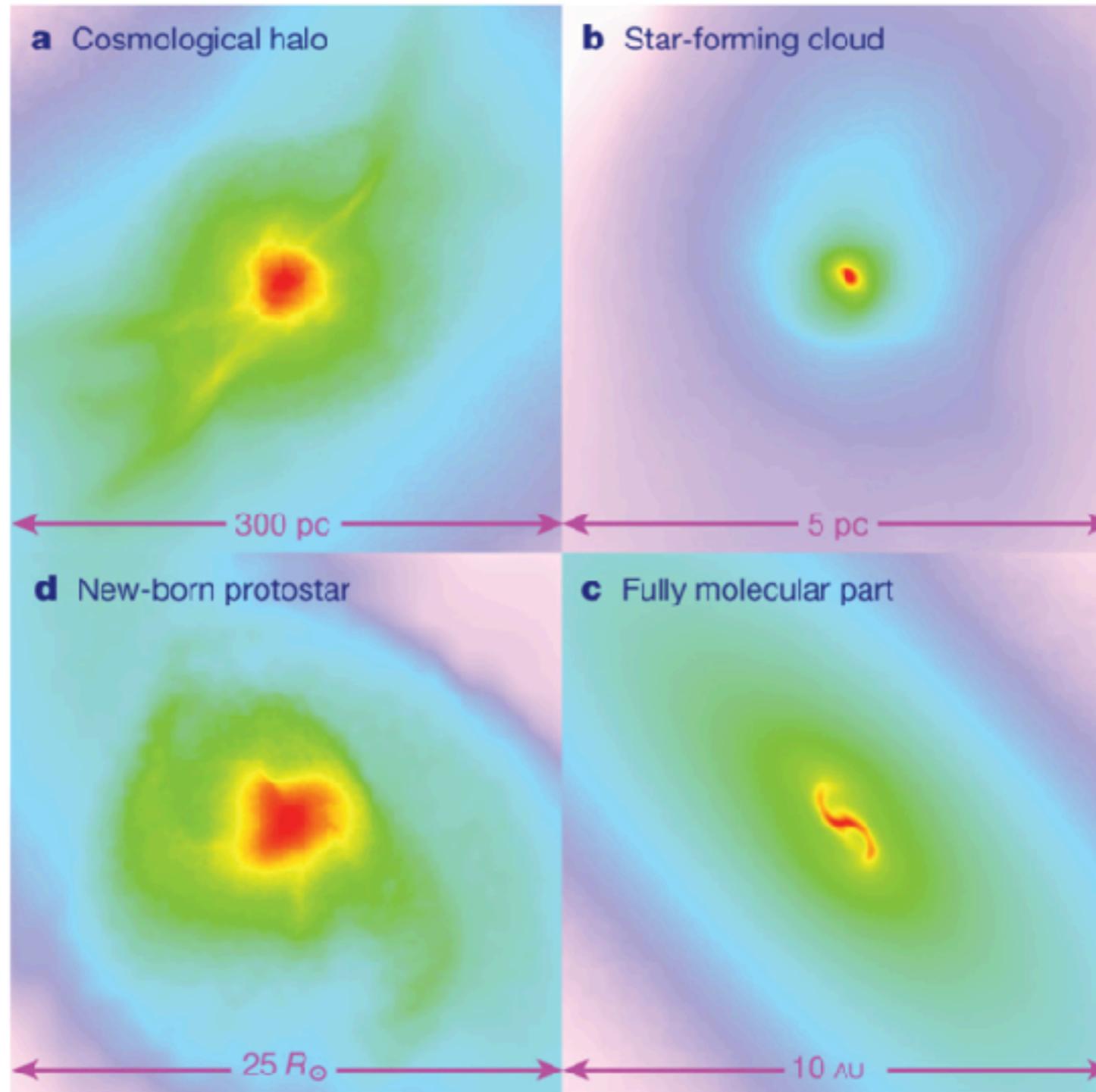
**POP III stars : Formed from primordial gas with only Hydrogen and Helium**

**Cooling without metals**

**The fragmentation issue**

**Impact on the IGM of the first stars**

# Stellar Formation in a Halo



$$1 \text{ pc} = 3.086 \times 10^{16} \text{ m}$$

$$1 R_{\odot} = 6.09 \times 10^{15} \text{ m}$$

$$1 \text{ AU} = 1.496 \times 10^{11} \text{ m}$$

Projected gas distribution around a primordial protostar.

# Star Formation in a Halo: Stability of gas clouds

## Mean densities:

Sun:  $1.4 \text{ g cm}^{-3}$

MW at solar radius:  $10^{-23} \text{ g cm}^{-3}$

Present day average:  $5 \times 10^{-31} \text{ g cm}^{-3}$

## Stability of spherical gas cloud: Jeans criterion

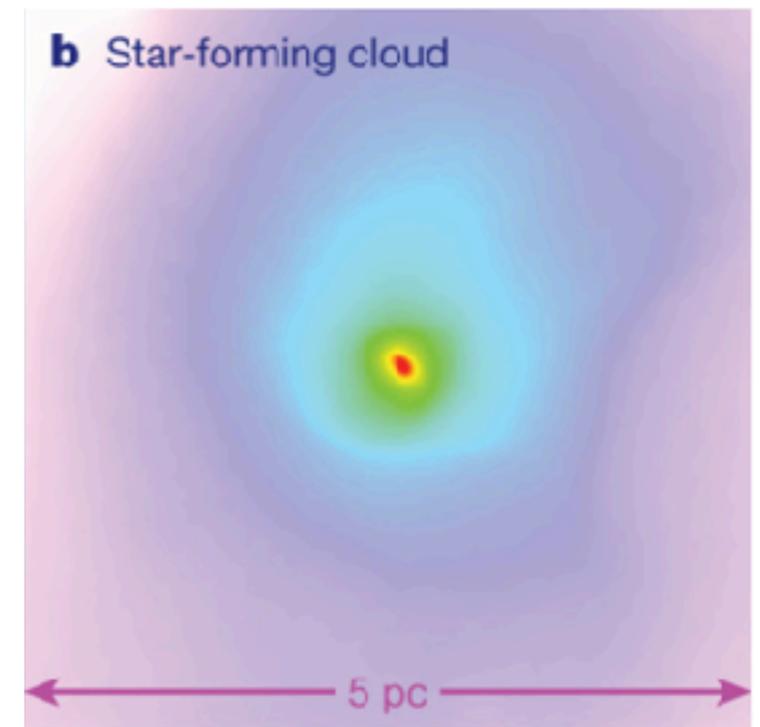
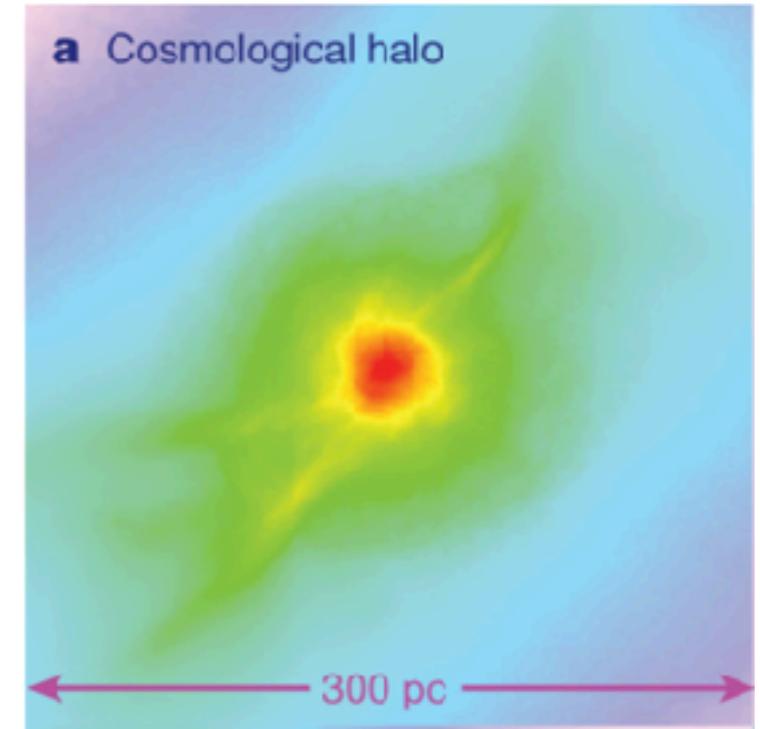
Jeans mass is the critical mass needed  
to form a bound object

### Gravity vs Gas pressure

$$\begin{aligned}
 M_J &= \frac{\pi^{5/2}}{6} \left( \frac{1}{G} \right)^{3/2} \rho^{-1/2} c_s^3 \\
 &= \frac{\pi^{5/2}}{6} \left( \frac{k}{G} \right)^{3/2} \left( \frac{1}{\mu m_H} \right)^2 n^{-1/2} T^{3/2} \\
 &\approx 50 M_\odot \mu^{-2} \left( \frac{n}{1 \text{ cm}^{-3}} \right)^{-1/2} \left( \frac{T}{1 \text{ K}} \right)^{3/2}
 \end{aligned}$$

$\mu \approx 1.22$  for primordial atomic gas

$\mu \approx 2.33$  for molecular gas.



# Star Formation in a Halo: Cooling

The Jeans Mass scales with redshift and cosmological parameters as:

$$M_J \approx 5 \times 10^3 M_\odot \left( \frac{\Omega_m h^2}{0.14} \right)^{-1/2} \left( \frac{\Omega_b h^2}{0.022} \right)^{-3/5} \left( \frac{z+1}{10} \right)^{3/2}$$

The gas needs not only to be bound but also to cool to form stars

$$M_{\text{cool}} \approx 6 \times 10^5 M_\odot h^{-1} \Omega_m^{-1/2} \left( \frac{\mu}{1.22} \right)^{-3/2} \left( \frac{z+1}{10} \right)^{3/2}$$

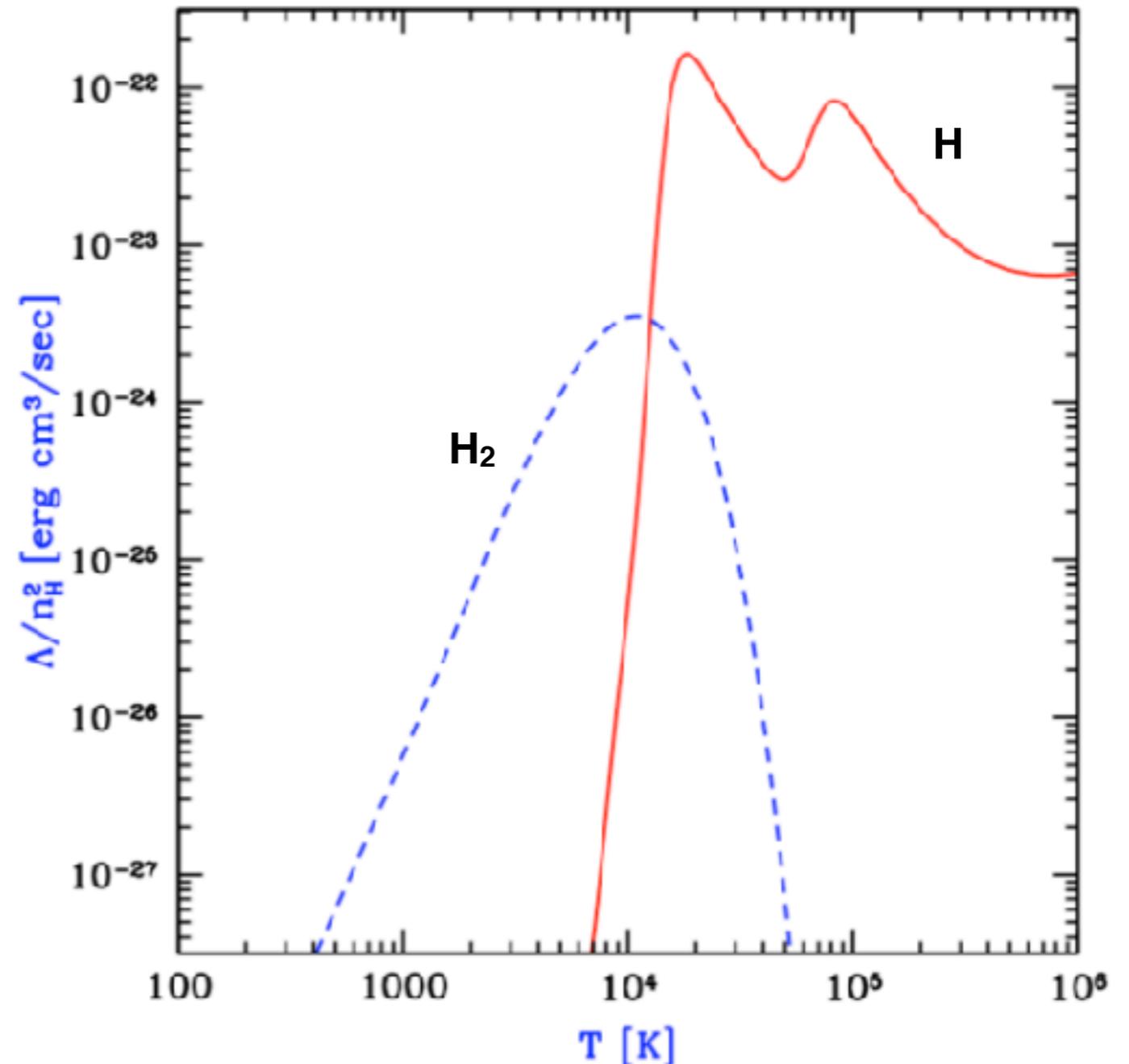
If  $M < M_{\text{cool}}$  the gas does not cool sufficiently fast (within a Hubble time)

For  $z < 40$   $M_{\text{cool}} > M_J \Rightarrow$  Many halos do not form stars

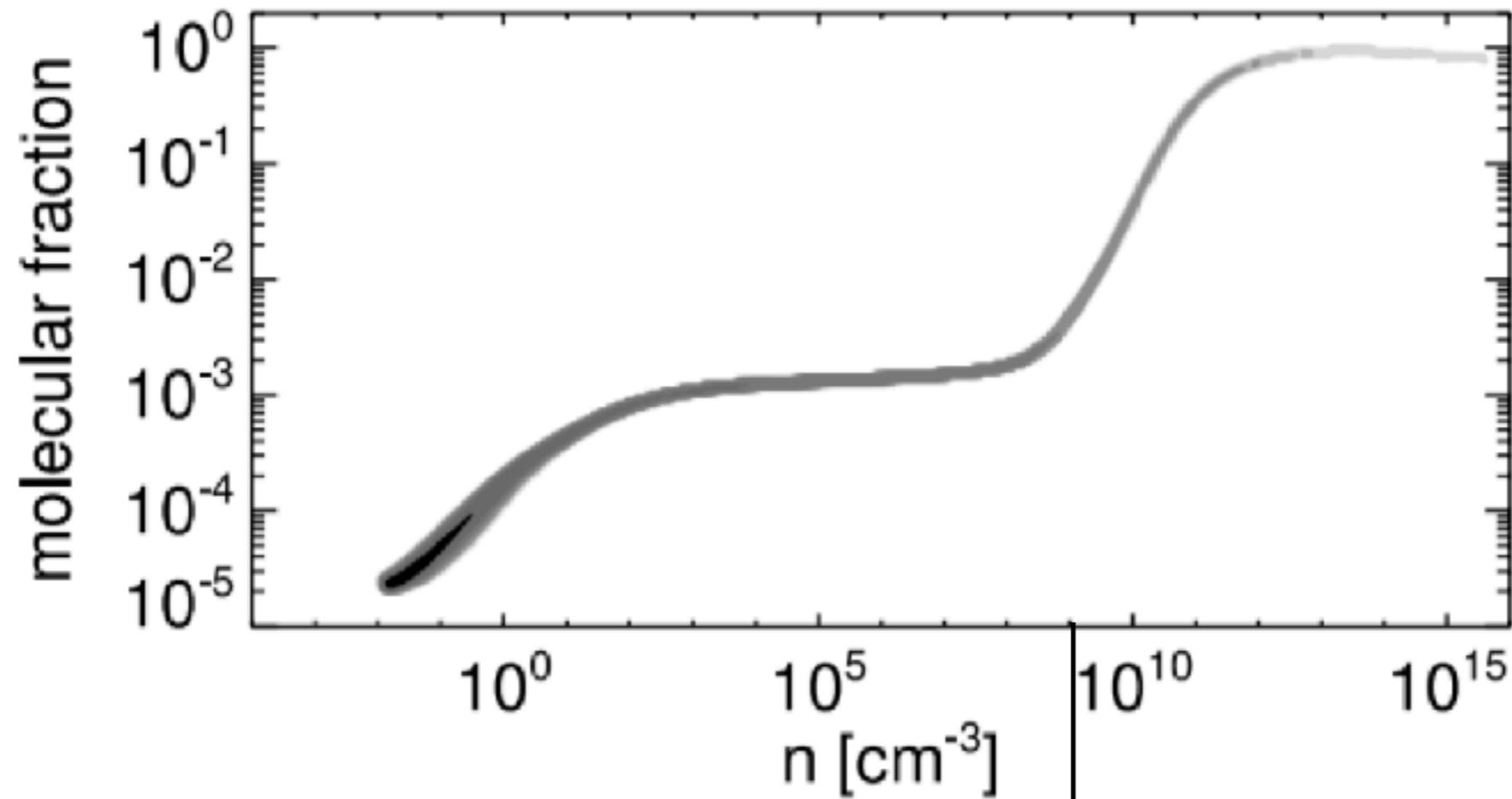
# Cooling rate of Primordial gas

Radiative Cooling for HI alone starts at  $T=10^4\text{K}$  which corresponds to Lyman-alpha transition

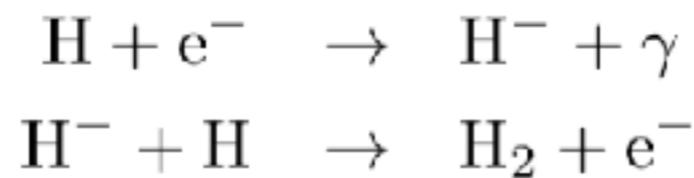
H<sub>2</sub> has vibrational and rotational modes that allow cooling at lower temperatures



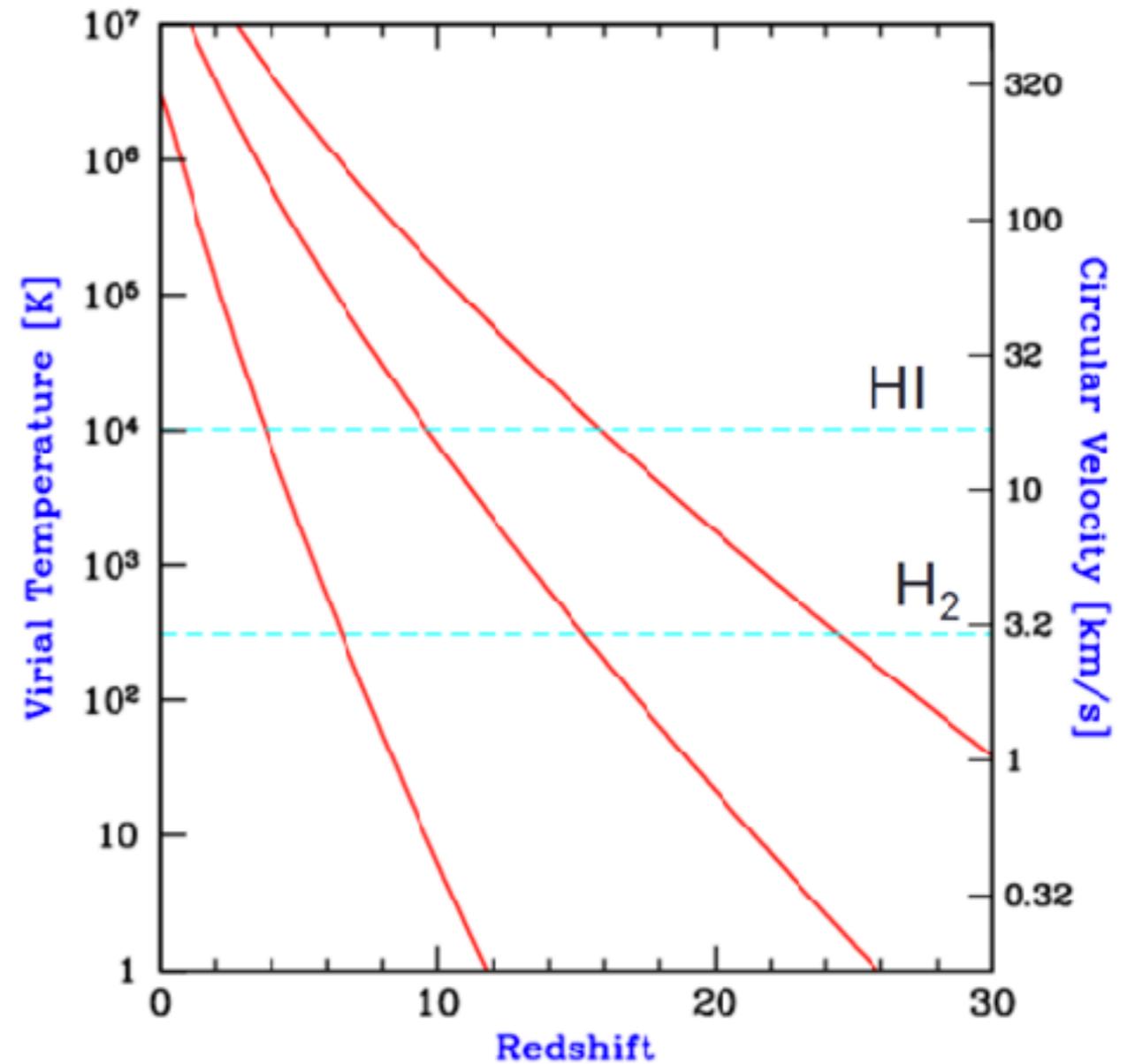
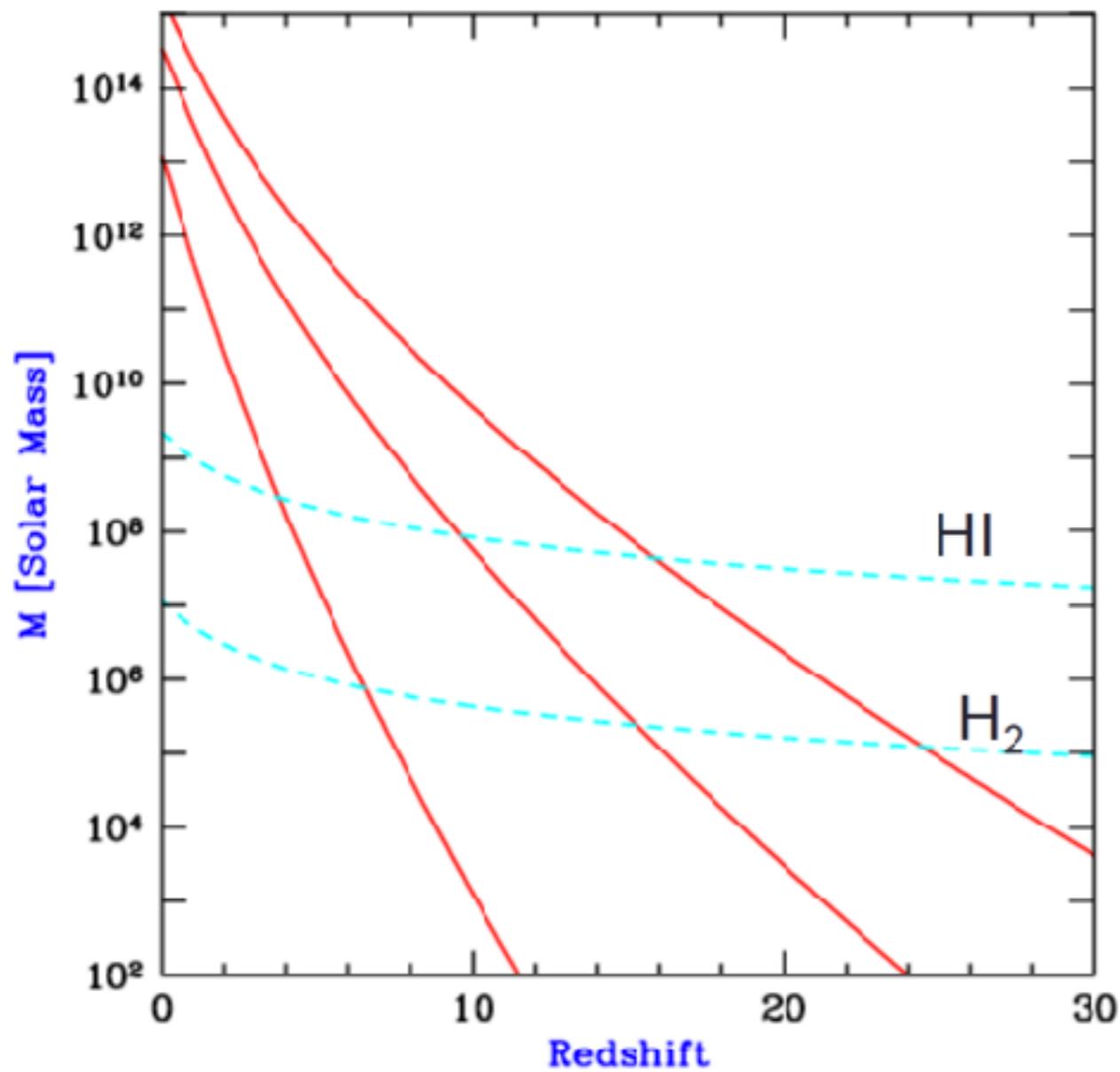
# Molecular gas: H<sub>2</sub> formation



Credit: Yoshida 2006



# Properties of collapsing halos



$1 - \sigma$ ,  $2 - \sigma$ , and  $3 - \sigma$  fluctuations (in order from bottom to top)

# Stellar Formation in a Halo



**Huge dynamic range**  
**Computational challenging**

$\frac{2}{c}/2$

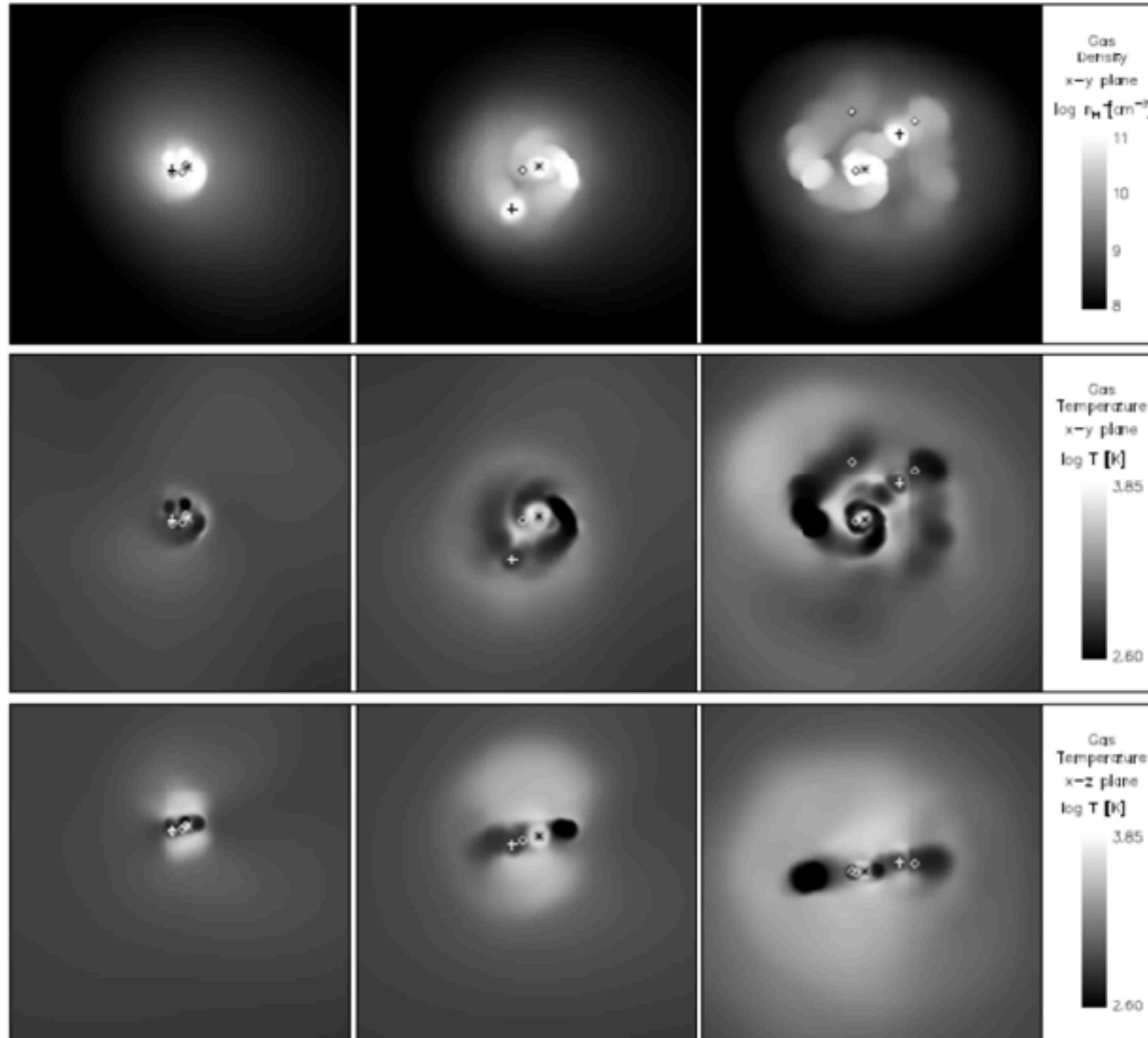
**Initially thought to be only one massive  
star forming per halo**



Projected gas distribution around a primordial protostar.

Bromm *et al.* 2009

# Fragmentation



Size: 5000 AU