21cm line in primordial clouds with full chemical computation

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Thesis supervisor : Denis Puy

JRJC SFP 2023 – Saint-Jean-de-Monts

How can 21cm neutral hydrogen line inform us about the Dark Ages ?

1) In the simple homogeneous expansion case

2) From the collapsing primordial structures

Plan

I) Overview of the cosmological context

II) 21cm physics

III) 21cm and chemistry in homogeneous Universe

IV) Collapsing primordial clouds and molecular thermal influence.

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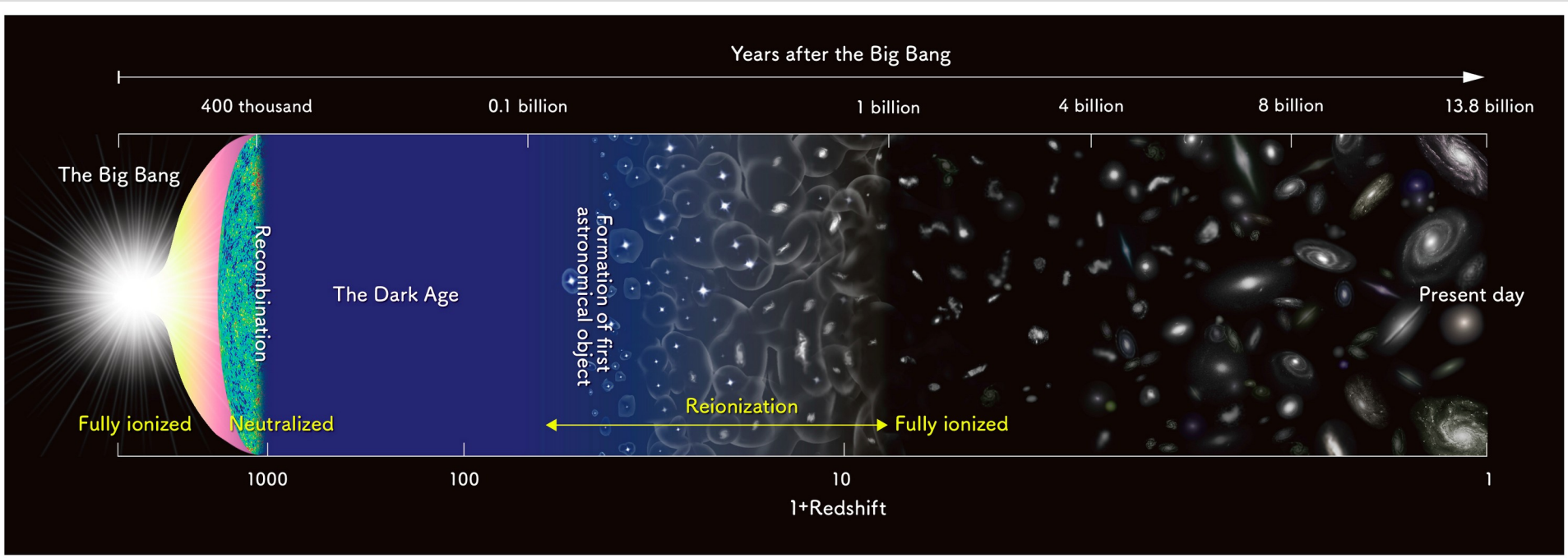
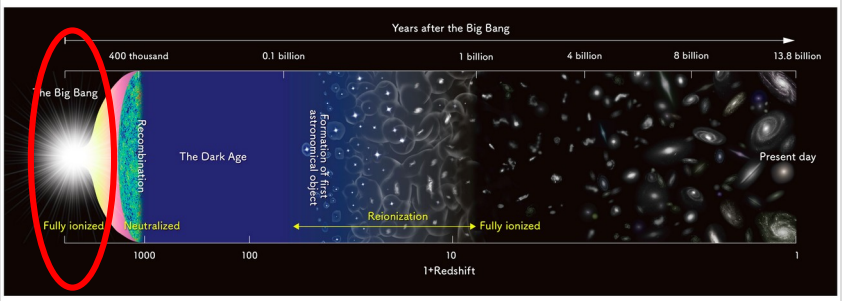
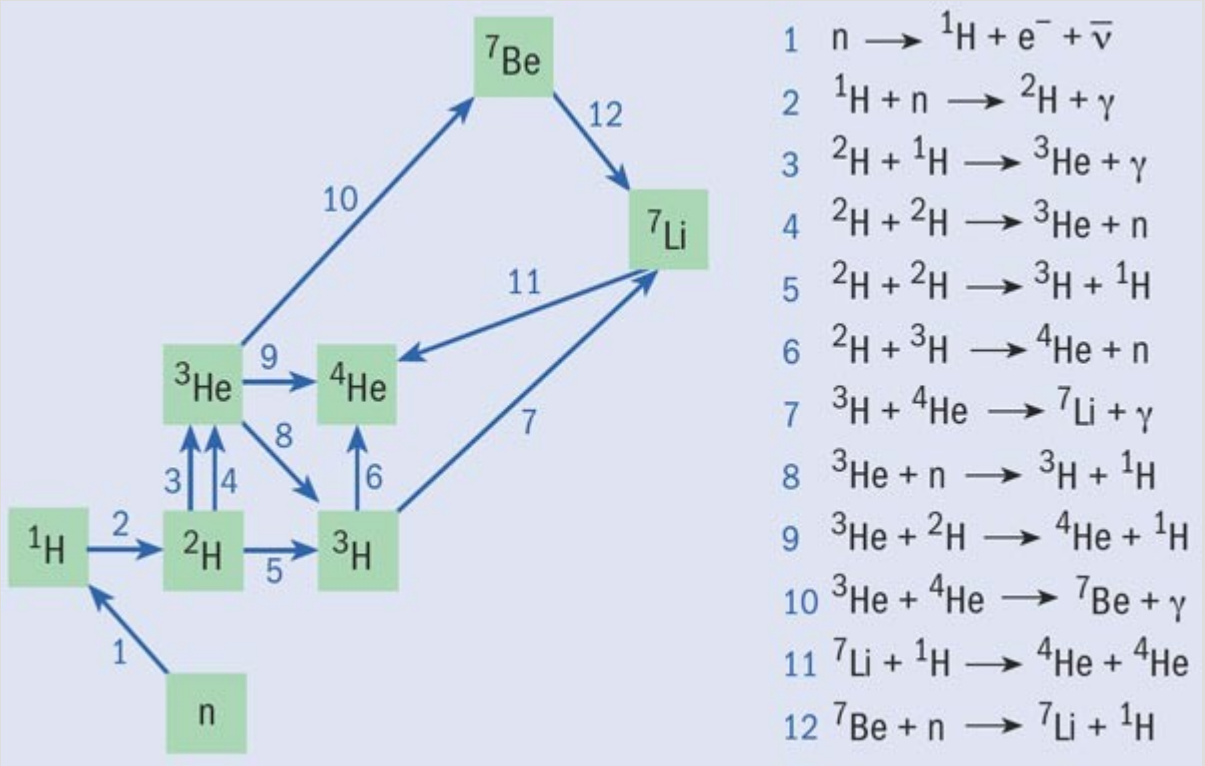
History of the universe



Credit : NAOJ

Big Bang Nucleosynthesis





1 $n \longrightarrow {}^{1}H + e^{-} + \bar{\nu}$

2 ${}^{1}H + n \longrightarrow {}^{2}H + \gamma$

3 ${}^{2}H + {}^{1}H \longrightarrow {}^{3}He + \gamma$

4 ${}^{2}H + {}^{2}H \longrightarrow {}^{3}He + n$

5 ${}^{2}H + {}^{2}H \longrightarrow {}^{3}H + {}^{1}H$

6 ${}^{2}H + {}^{3}H \longrightarrow {}^{4}He + n$

7 ${}^{3}H + {}^{4}He \longrightarrow {}^{7}Li + \gamma$

8 ${}^{3}He + n \longrightarrow {}^{3}H + {}^{1}H$

9 ${}^{3}He + {}^{2}H \longrightarrow {}^{4}He + {}^{1}H$

10 ${}^{3}He + {}^{4}He \longrightarrow {}^{7}Be + \gamma$

11 ${}^{7}Li + {}^{1}H \longrightarrow {}^{4}He + {}^{4}He$

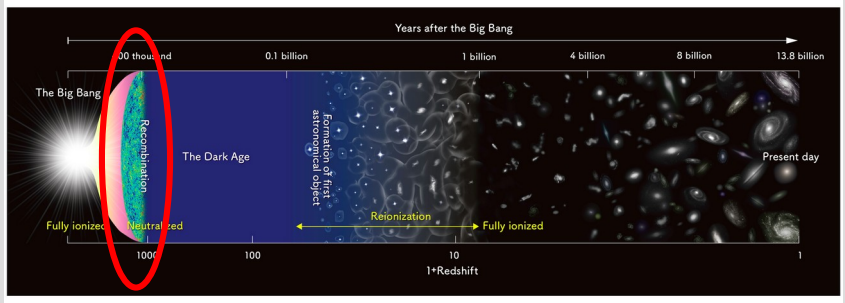
12 ${}^{7}Be + n \longrightarrow {}^{7}Li + {}^{1}H$

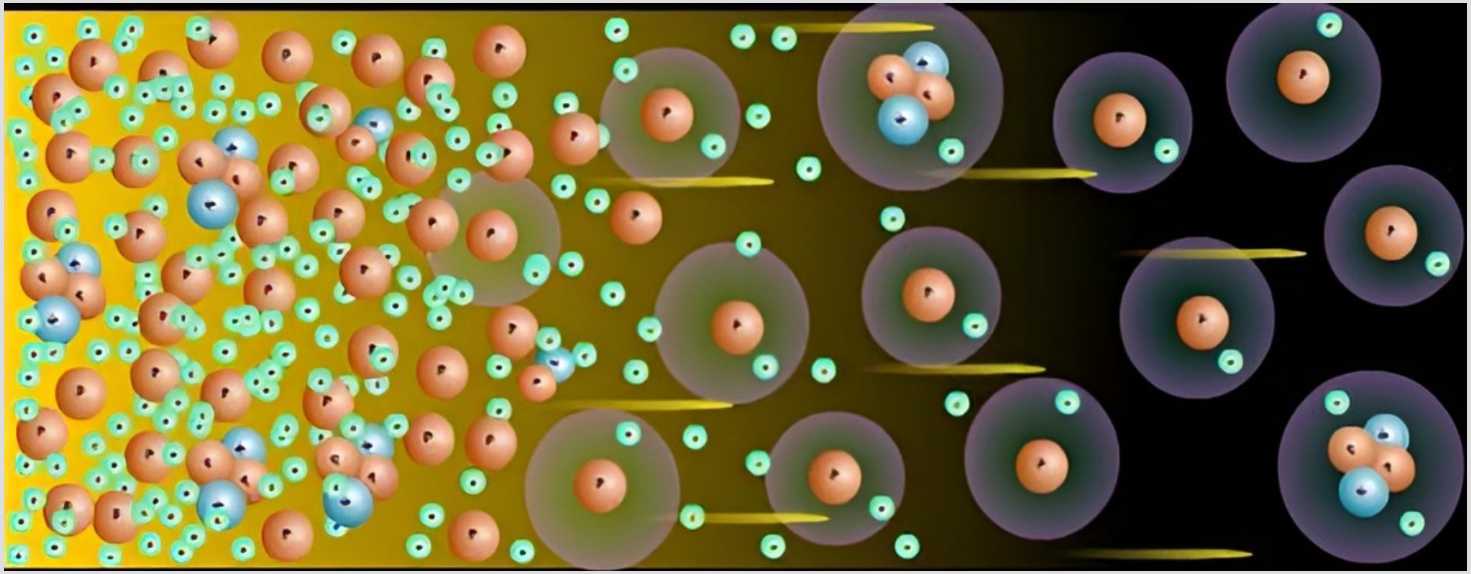
Production of the first nuclei :
H, **He**, **D**, **Li**…

Matter-radiation coupling :
Fully Ionized medium !

Credit : universe-review.ca

Recombination





Credit : bigatomicadventure

- **Matter-radiation coupling** becomes less effective because of the expansion

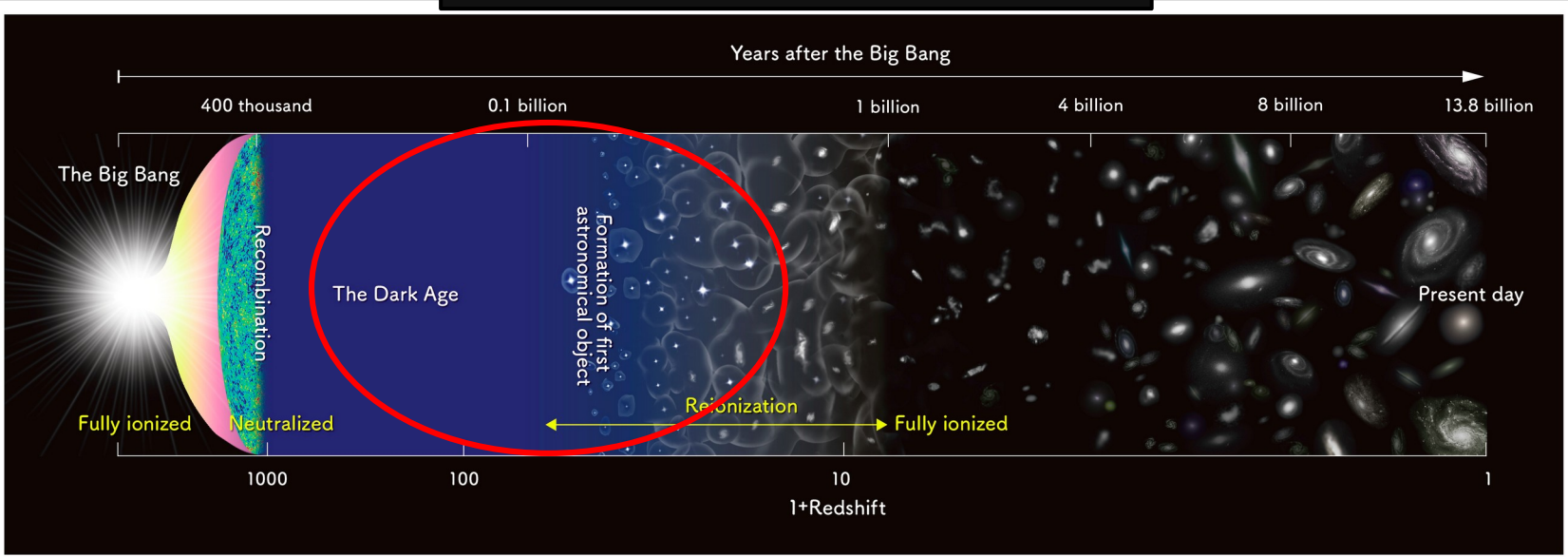
- **Neutral** atoms can now form !

$$z_{rec}(He) \sim 2550$$
$$z_{rec}(H) = z_{rec}(D) \sim 1400$$

Dark Ages

Dark Ages :

- Redshift ~ [1100-30]
- Gas is **neutral**
- More complex chemistry (molecules)



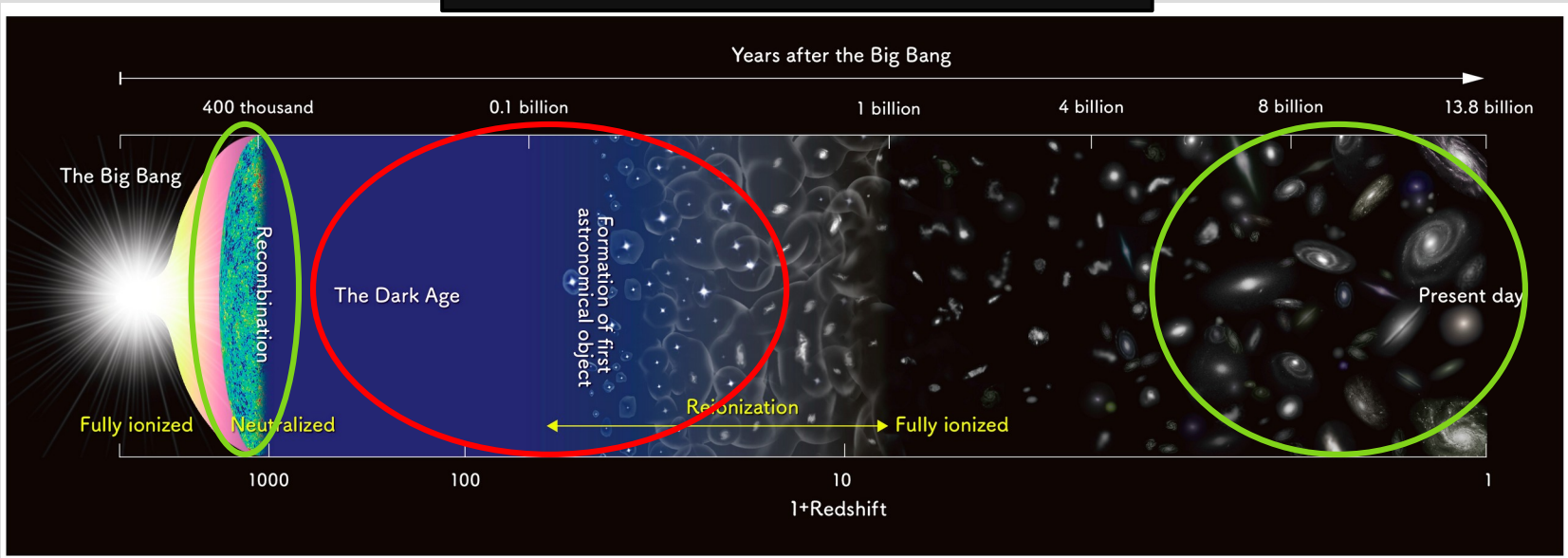
Dark Ages

Cosmic Microwave Background

Dark Ages :

- Redshift ~ [1100-30]
- Gas is **neutral**
- More complex chemistry (molecules)

Supernovae IA, galaxy surveys, gravitational lensing...



Dark Ages

Cosmic Microwave Background

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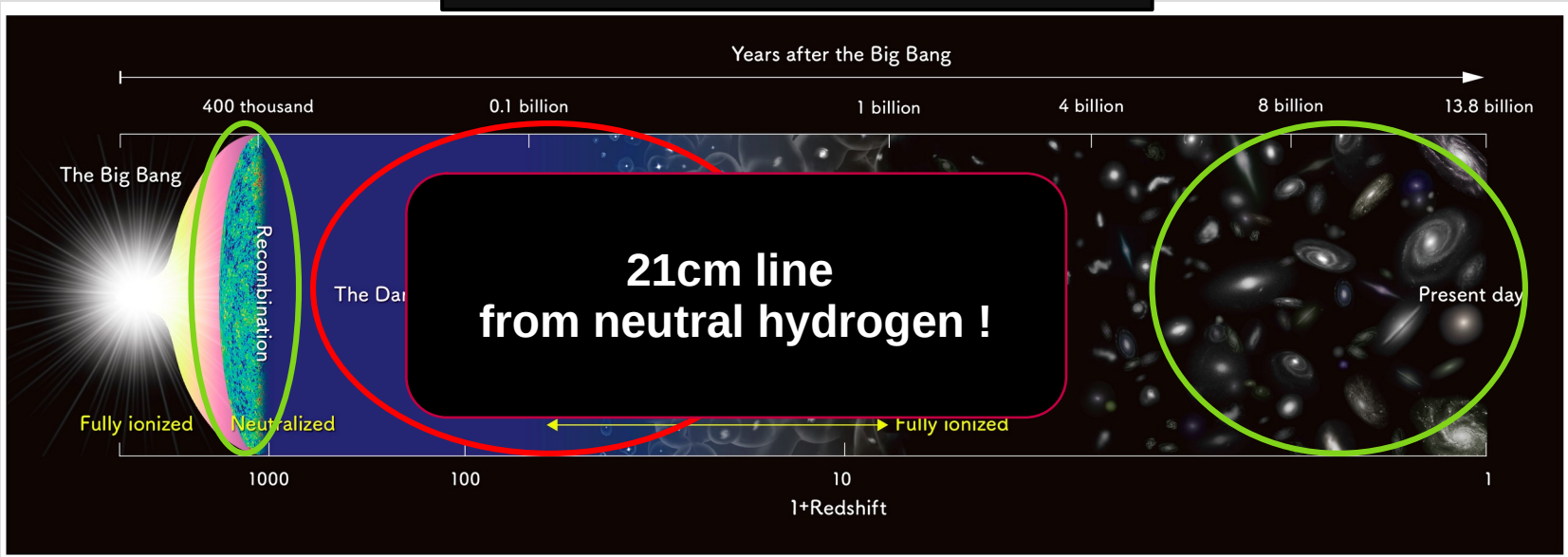

Hydrogen as a cosmological probe

Probes during **Dark Ages** and **Reionization**

Hydrogen as a cosmological probe

Probes during **Dark Ages** and **Reionization**

Scans large **volumes** **(space+redshift)**

Hydrogen as a cosmological probe

Probes during **Dark Ages** and **Reionization**

Sensitive to Standard and cosmology and thermal processes

Scans large **volumes** **(space+redshift)**

Plan

I) Overview of the cosmological context

II) 21cm physics

III) 21cm and chemistry in homogeneous Universe

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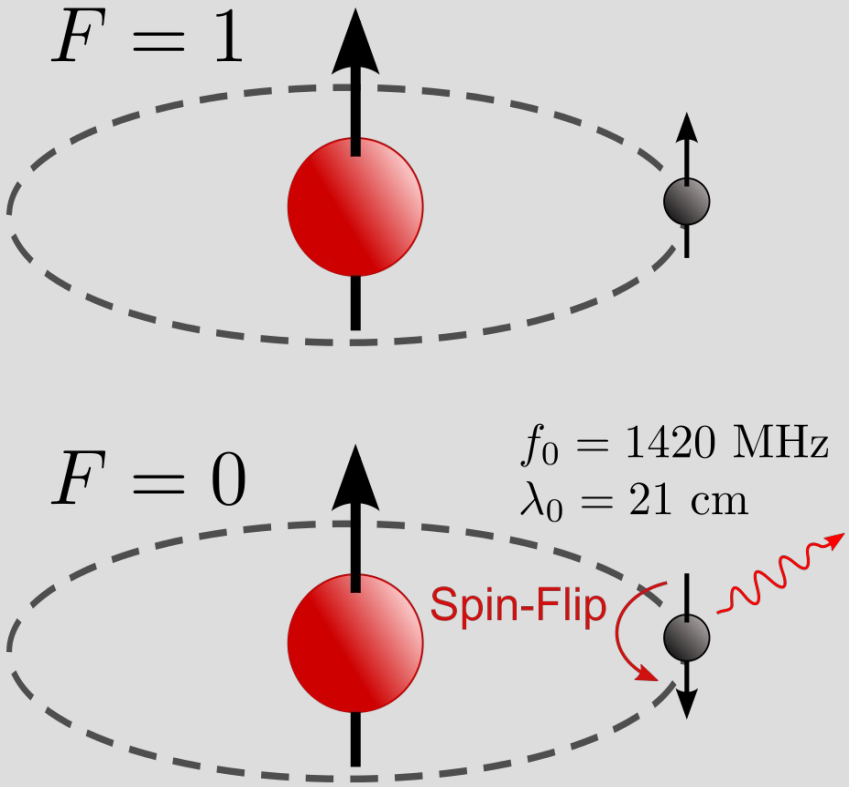
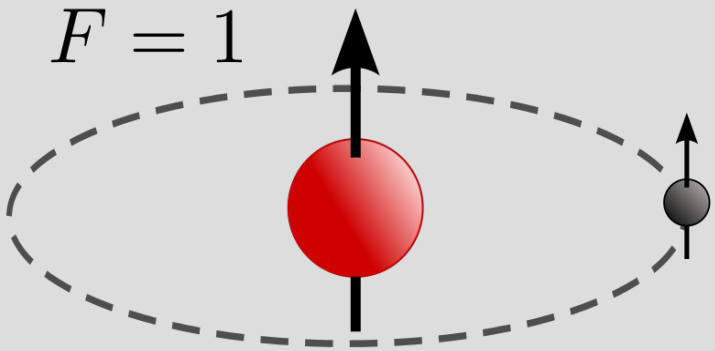
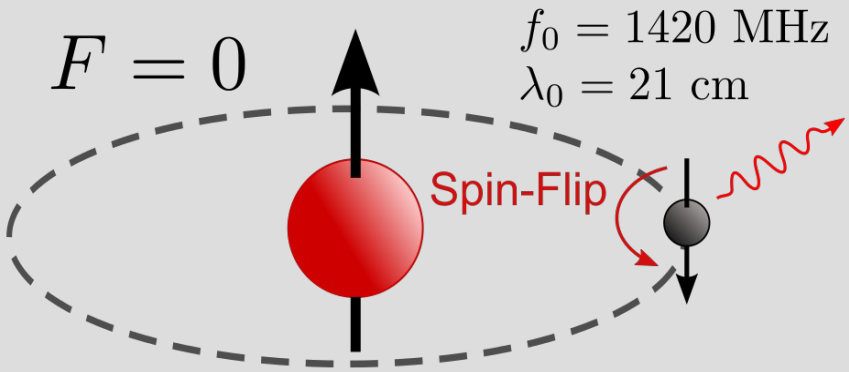
Recipe for 21cm transition



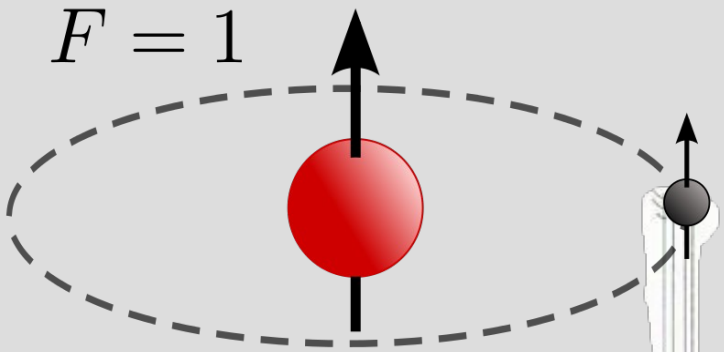
Recipe for 21cm transition

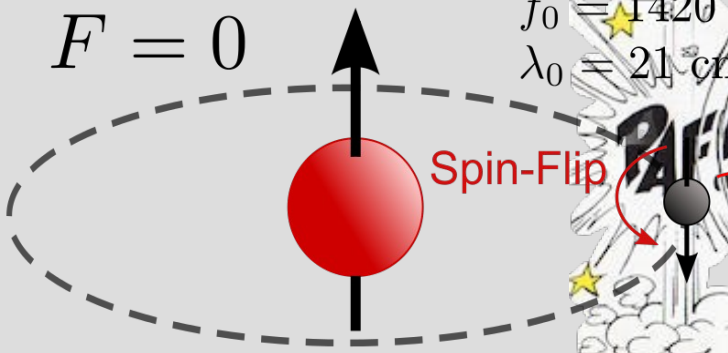




-Take hydrogen atoms in ground state (F=0)

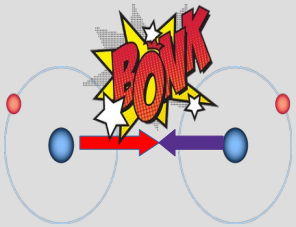
Recipe for 21cm transition





$f_0 = 1420$ MHz
$\lambda_0 = 21$ cm

H



H

-Take hydrogen atoms in ground state (F=0)
-Flip the electron spin (collisions, radiation) (F=1)

Recipe for ***Préfou à l'Arsenic***

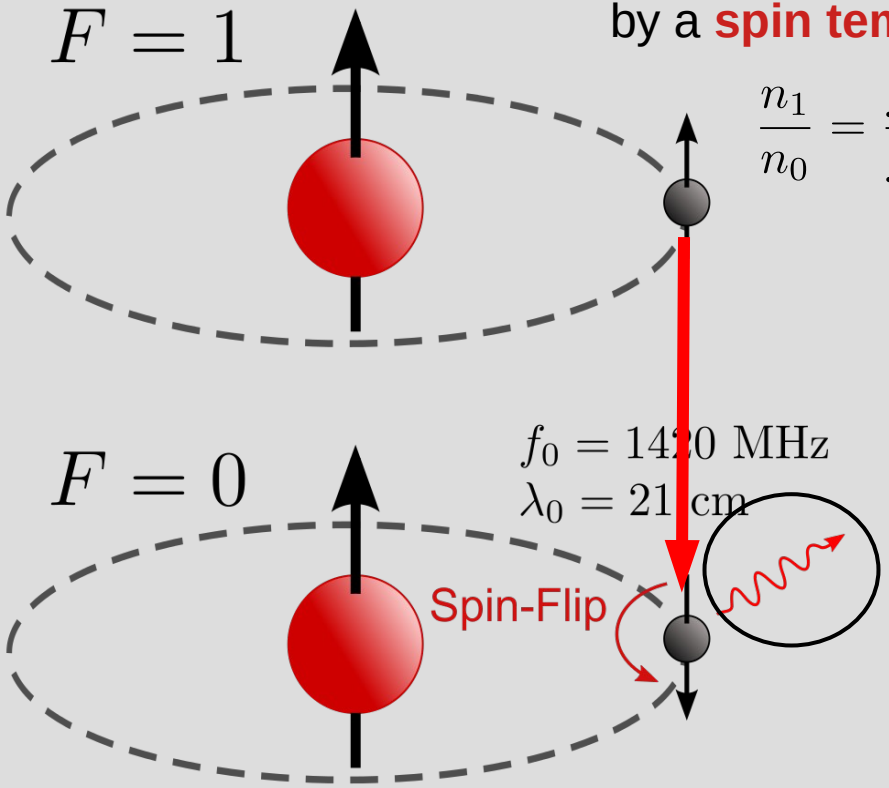
-Take hydrogen atoms in ground state (F=0)
-Flip the electron spin (collisions, radiation) (F=1)
- 6 **baguettes**
- add 8 **garlic cloves**
- 500g of **SALTED butter**
- a bit of **vitriol**

→ Delicous **PREFOU** for 20 persons !

Recipe for 21cm transition

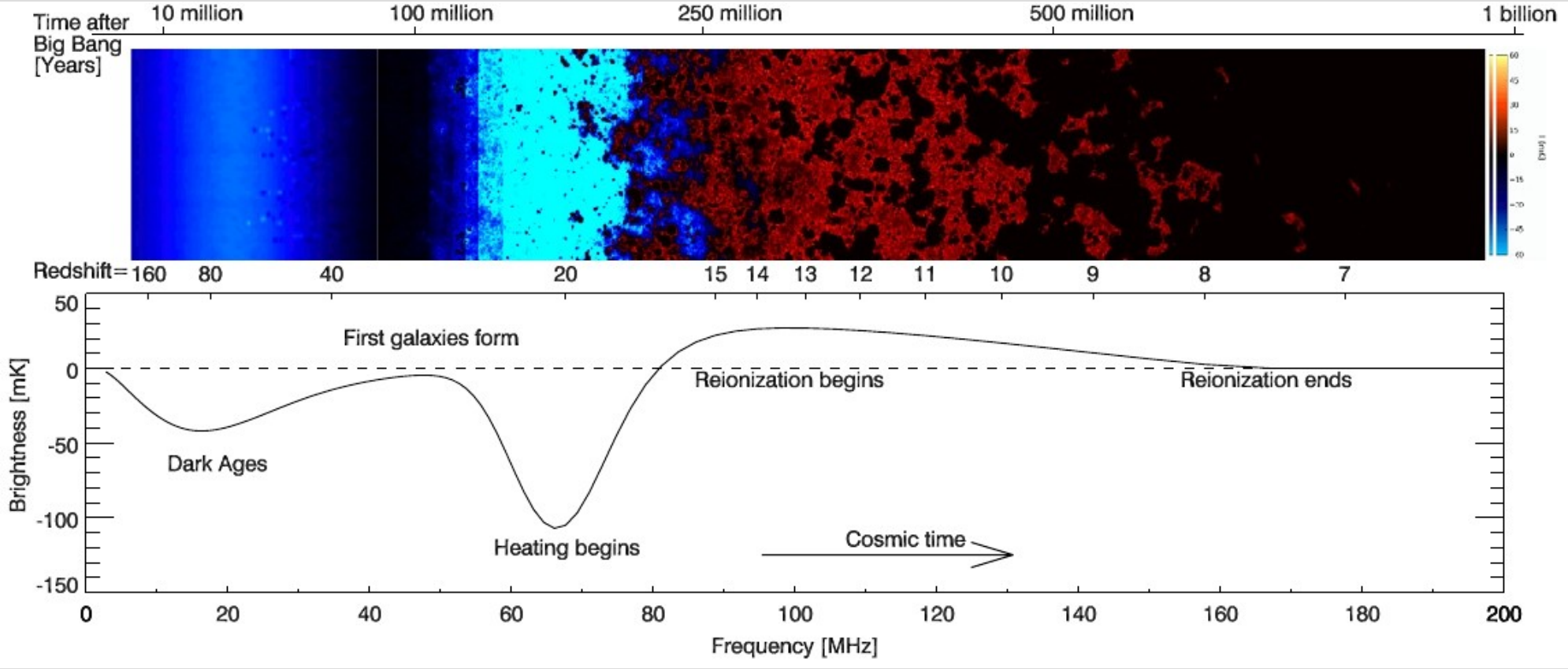
Relative populations described by a **spin temperature** :

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{h\nu_0}{k_b T_s}\right)$$



-Take hydrogen atoms in ground state (F=0)
-Flip the electron spin (collisions, radiation) (F=1)
-Return to ground state (F=0)
(Spontaneous → wait 11 million years
Stimulated → collision, radiation again)
→ **21cm photons are emitted !**

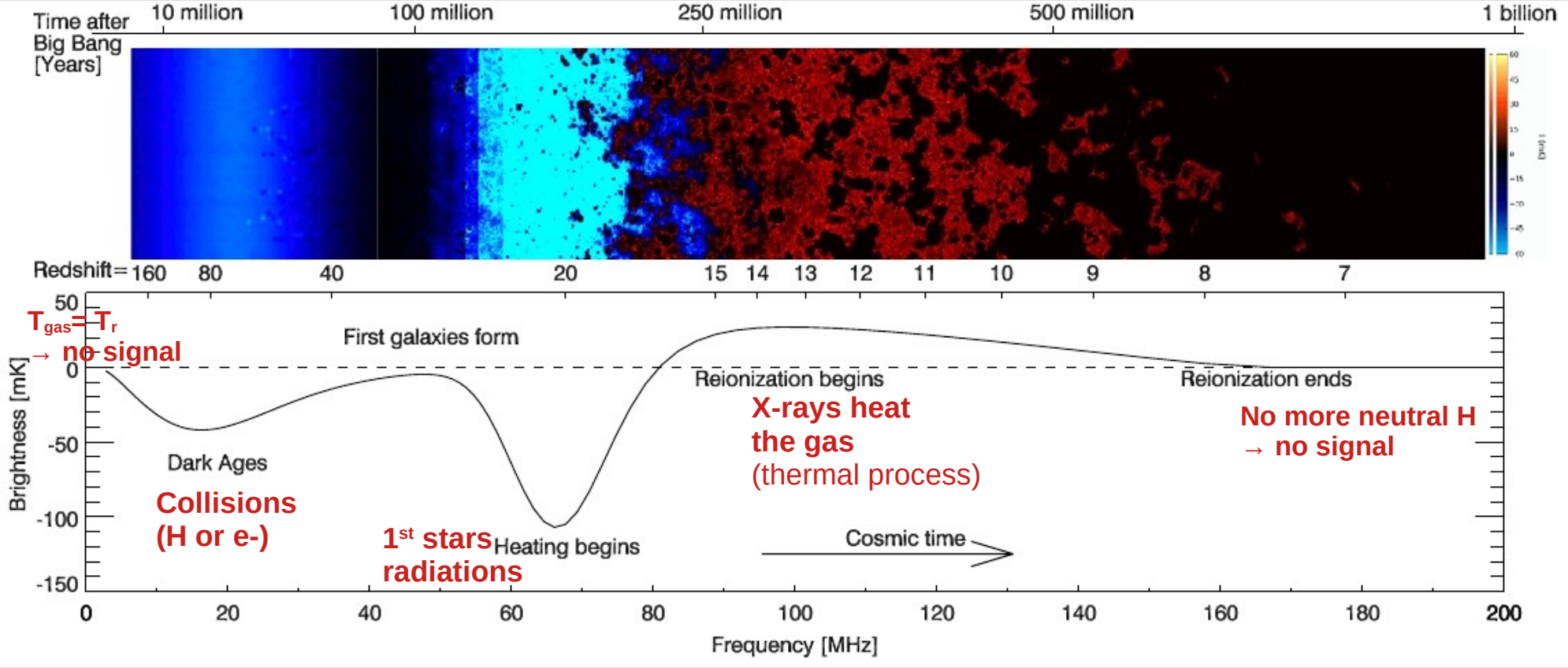
21cm brightness temperature



$$\delta T_b(\nu) \propto x_{HI}\left(1-\frac{T_r}{T_s}\right) mK$$

Credit :Pritchard & Loeb (2010)

21cm brightness temperature



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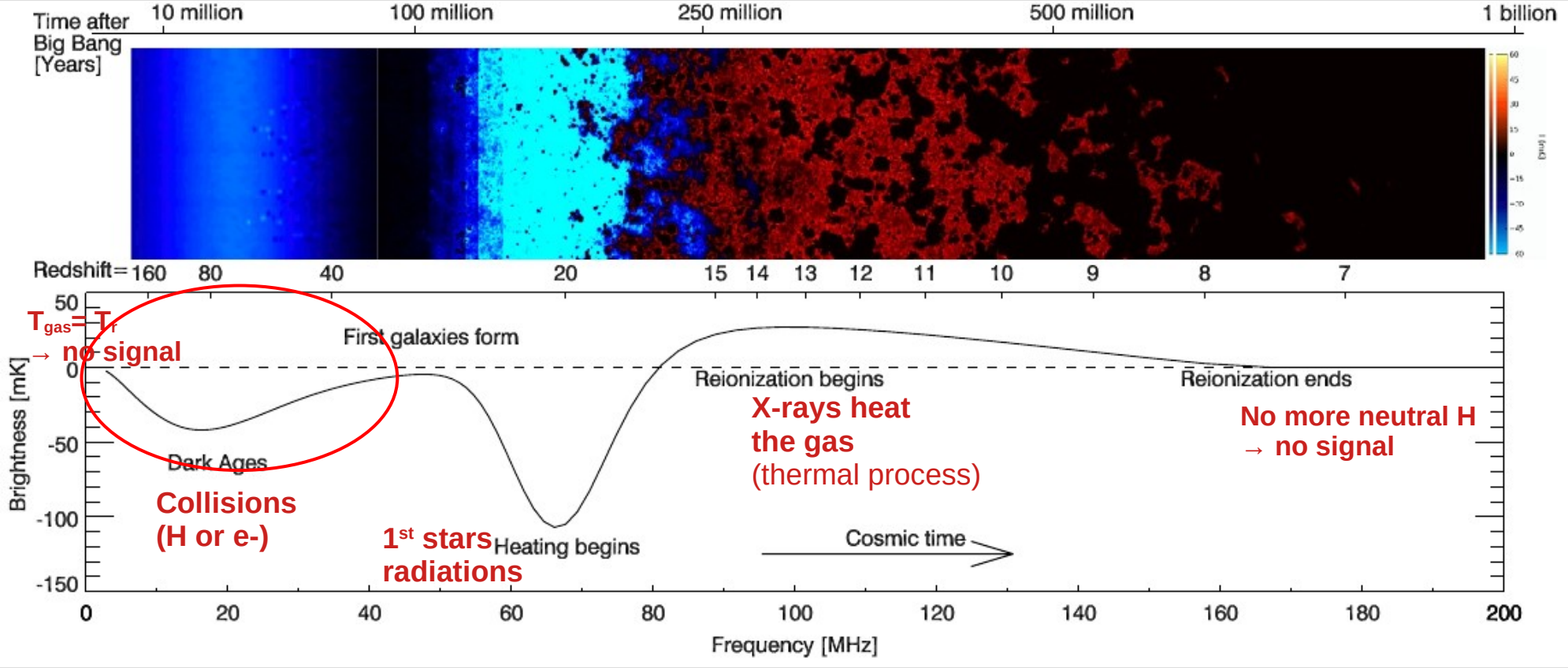

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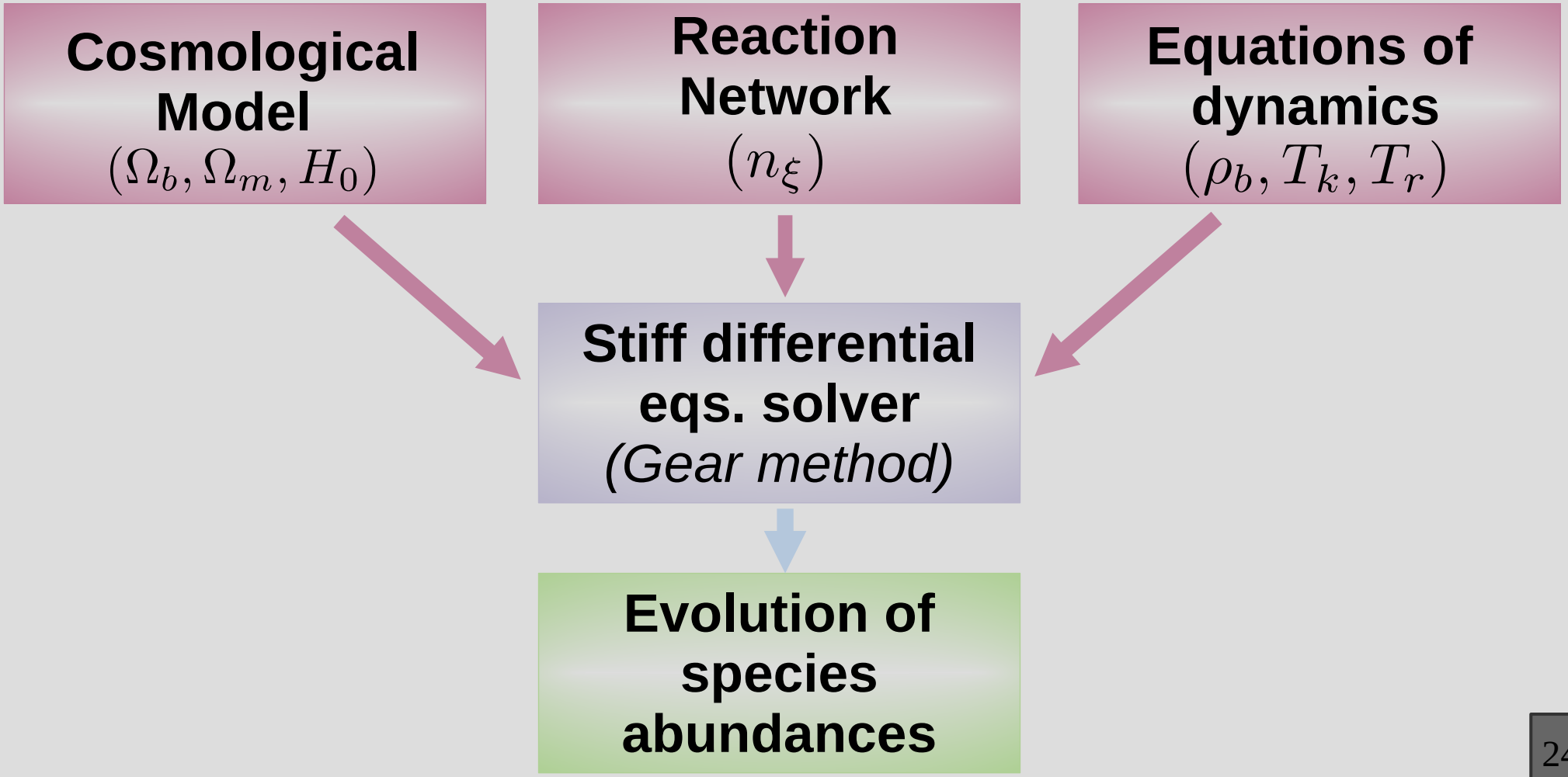
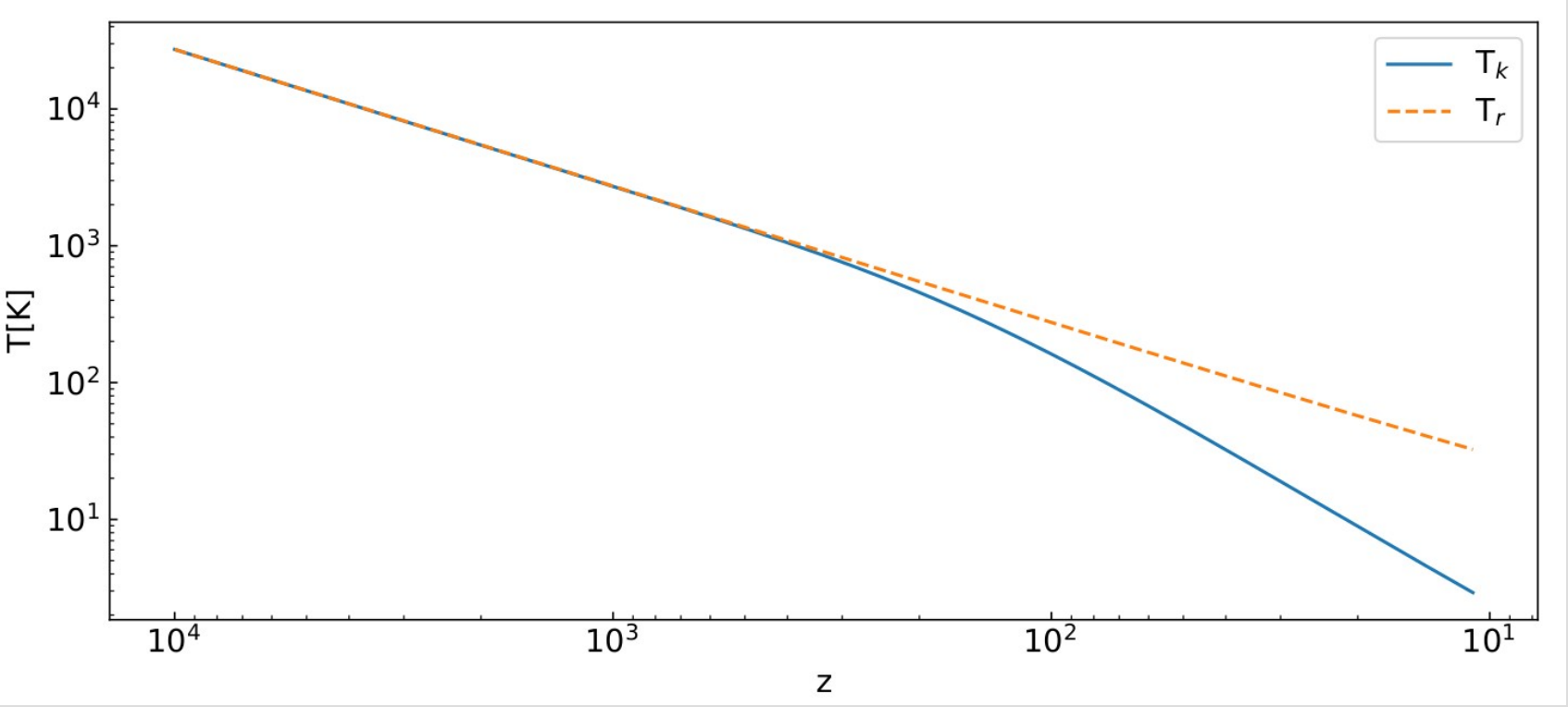
CHEMFAST code



Dynamics : **Temperatures**



Tk : Gas kinetic temperature

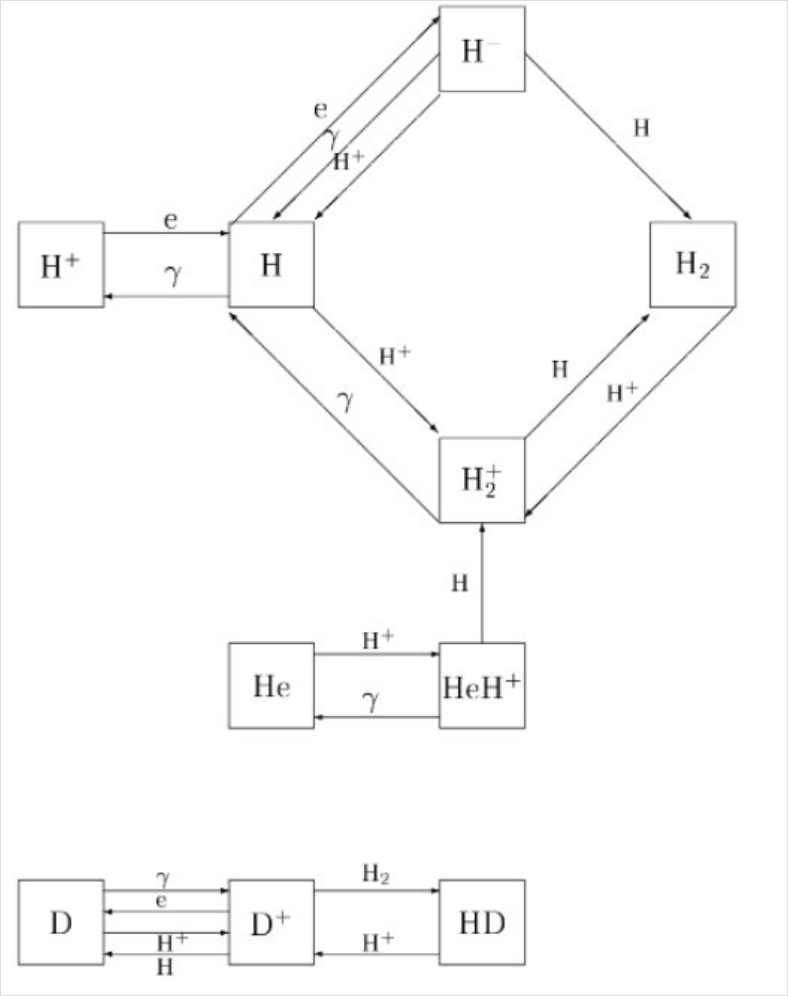
Tr :CMB radiation temperature

Radiation temperature : $T_r \propto (1+z)$

Gas temperature : $T_k \propto (1+z)^2 + Compton\ coupling$

Galli & Palla 1997

Reaction Network



- Only 3 major nuclei during Dark Ages : **H, He, D**

- Evolution of the numerical density of a ξ species

  Collisional processes : $\xi + \xi' \longleftrightarrow \xi_1 + \xi_2$

$$\left(\frac{dn_\xi}{dt}\right)_{chem} = \sum_{\xi_1,\xi_2} k_{\xi_1\xi_2} n_{\xi_1} n_{\xi_2} - \sum_{\xi'} k_{\xi\xi'} n_\xi n_{\xi'}$$

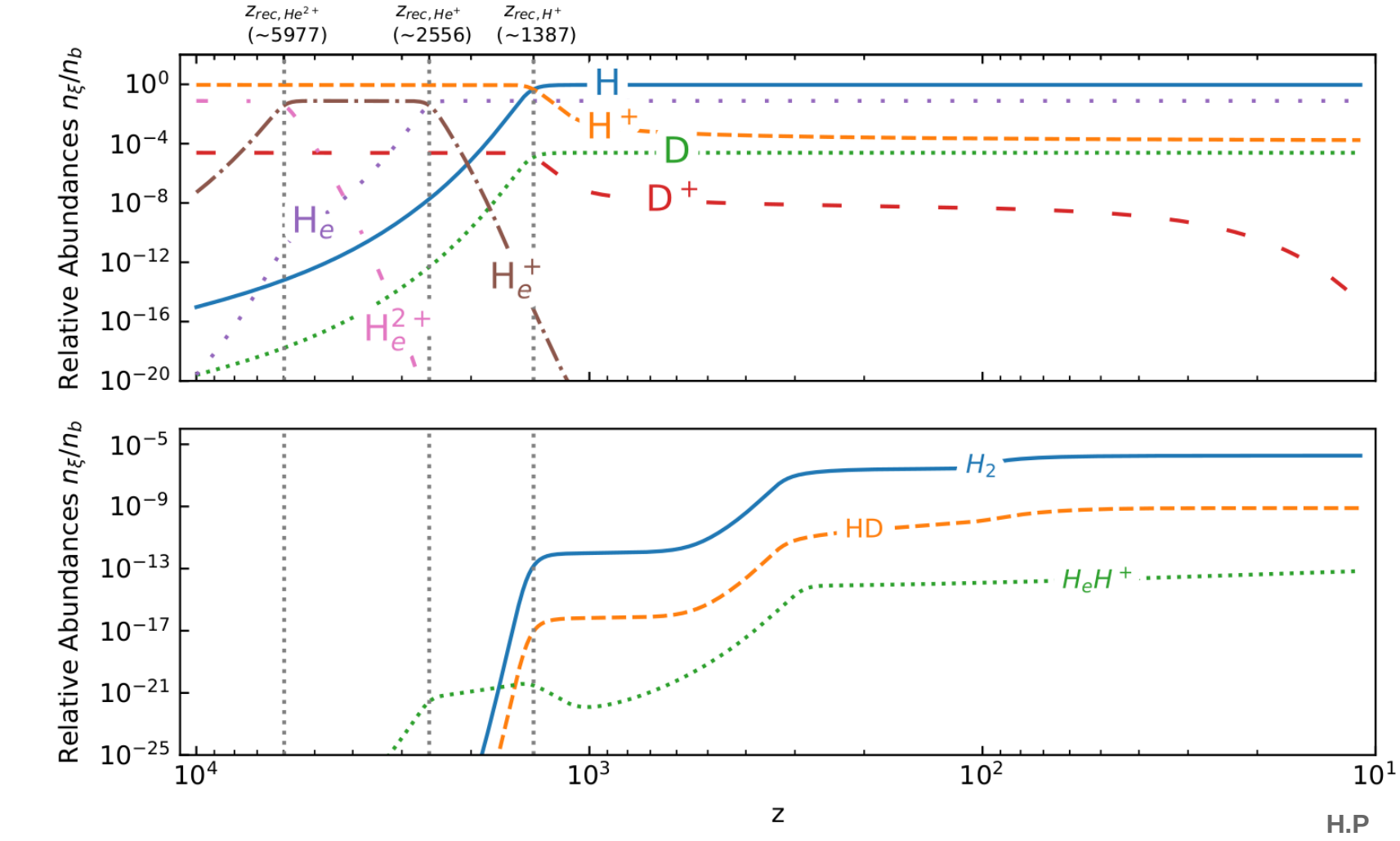
Formation $\xi_1 + \xi_2 \rightarrow \xi$

Destruction $\xi + \xi' \rightarrow \xi_1 + \xi_2$

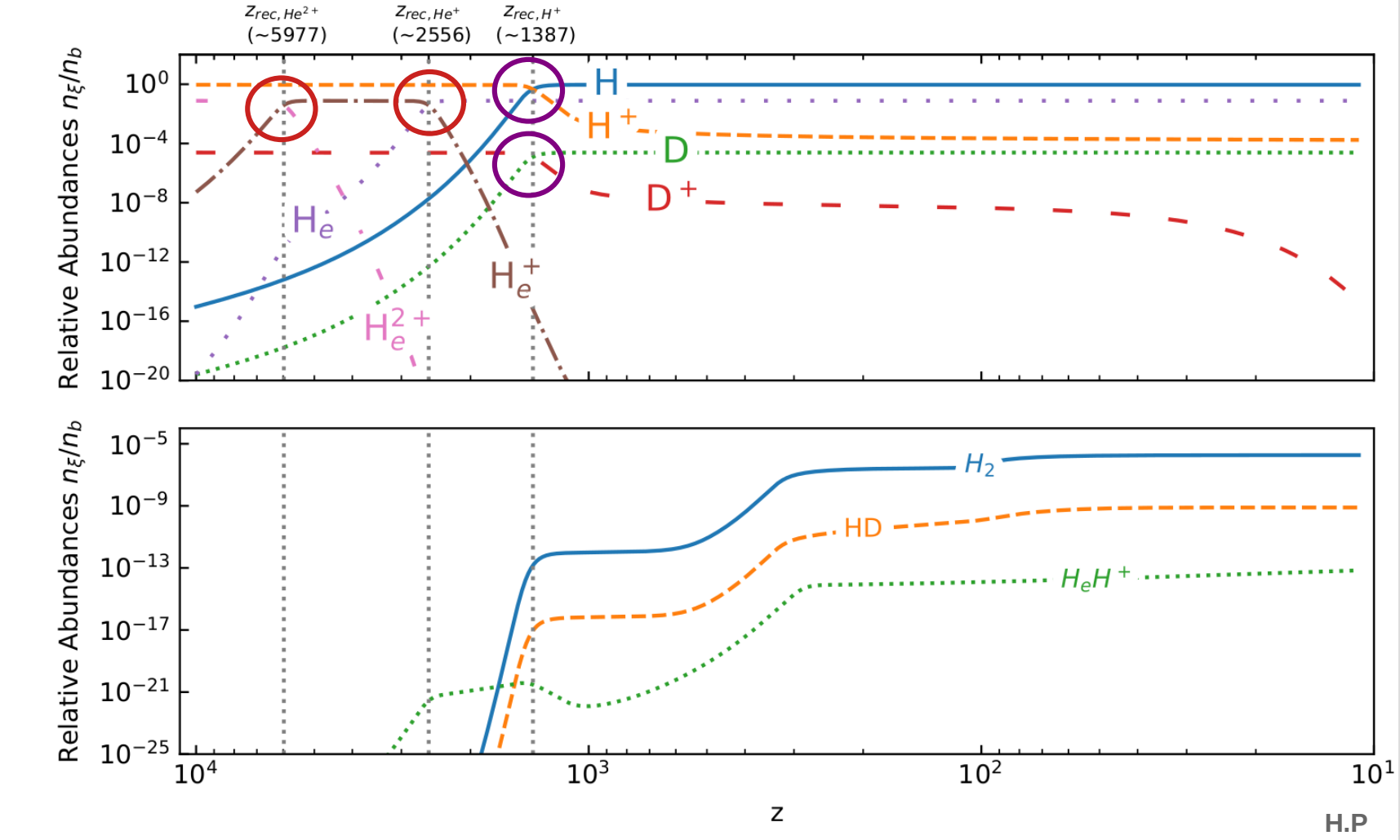
Electronic processes : $\xi + e^- \longleftrightarrow \xi_1 + \xi_2$

Photoprocesses : $\xi + \gamma \longleftrightarrow \xi_1 + \xi_2$

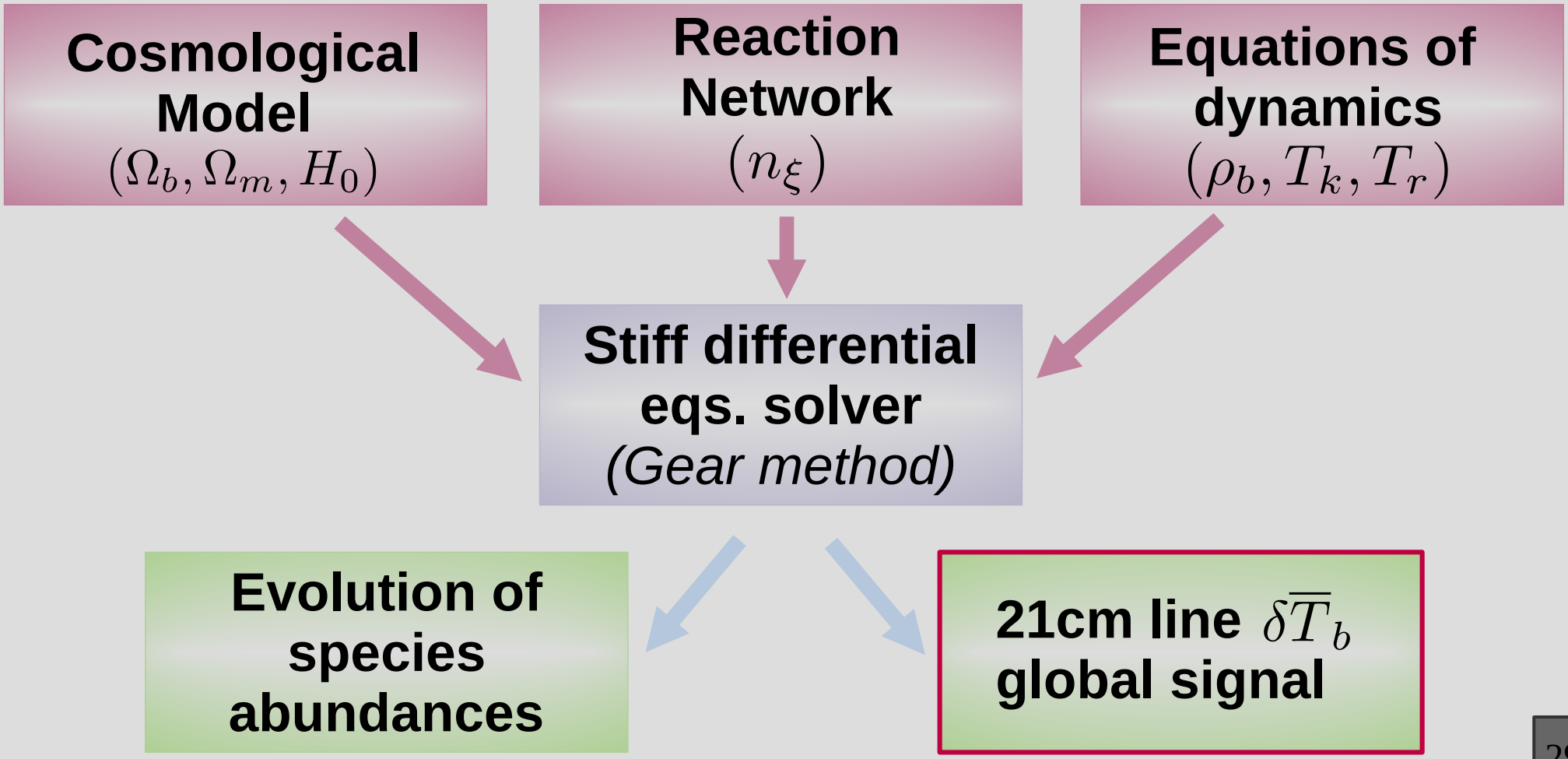
CHEMFAST : Abundances



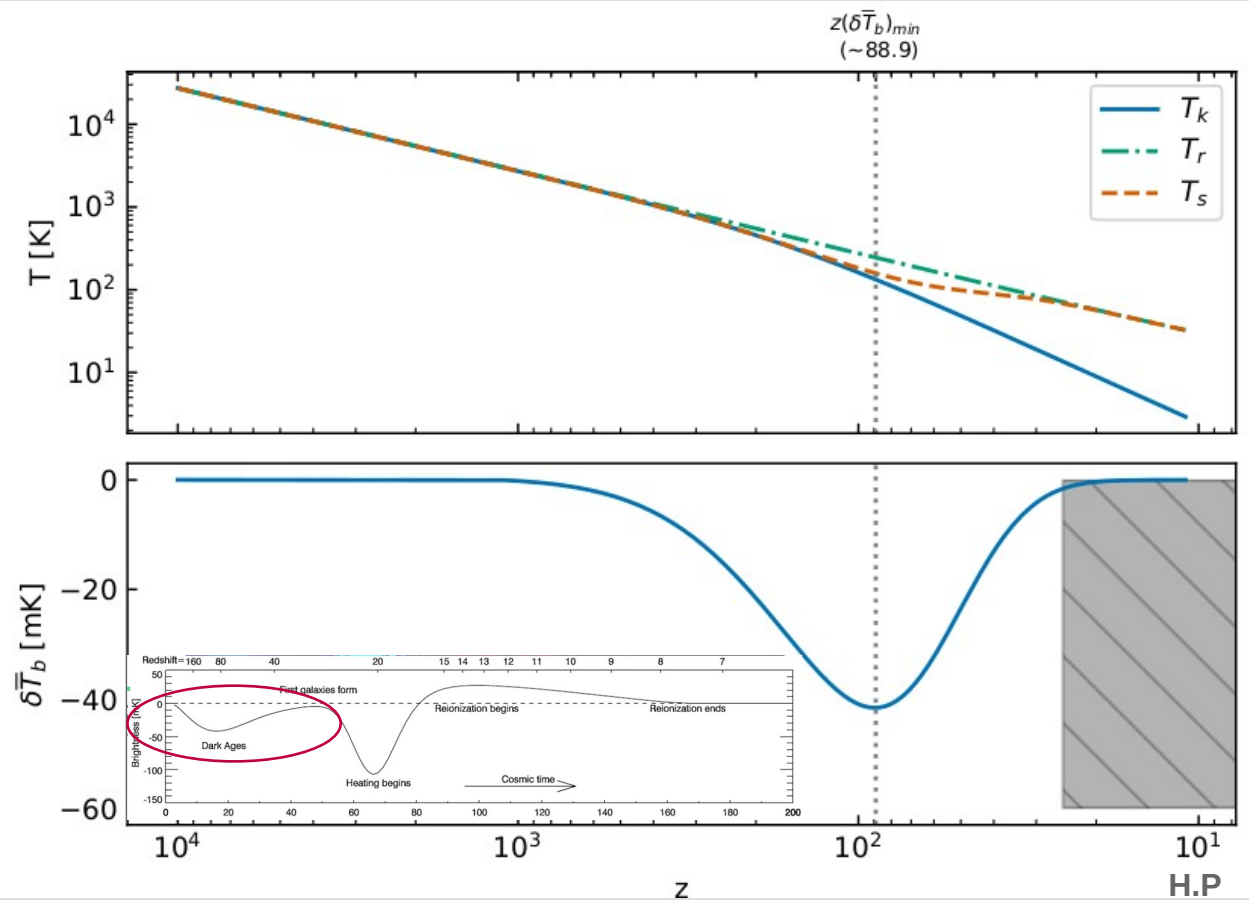
CHEMFAST : Abundances



CHEMFAST code



CHEMFAST : Results



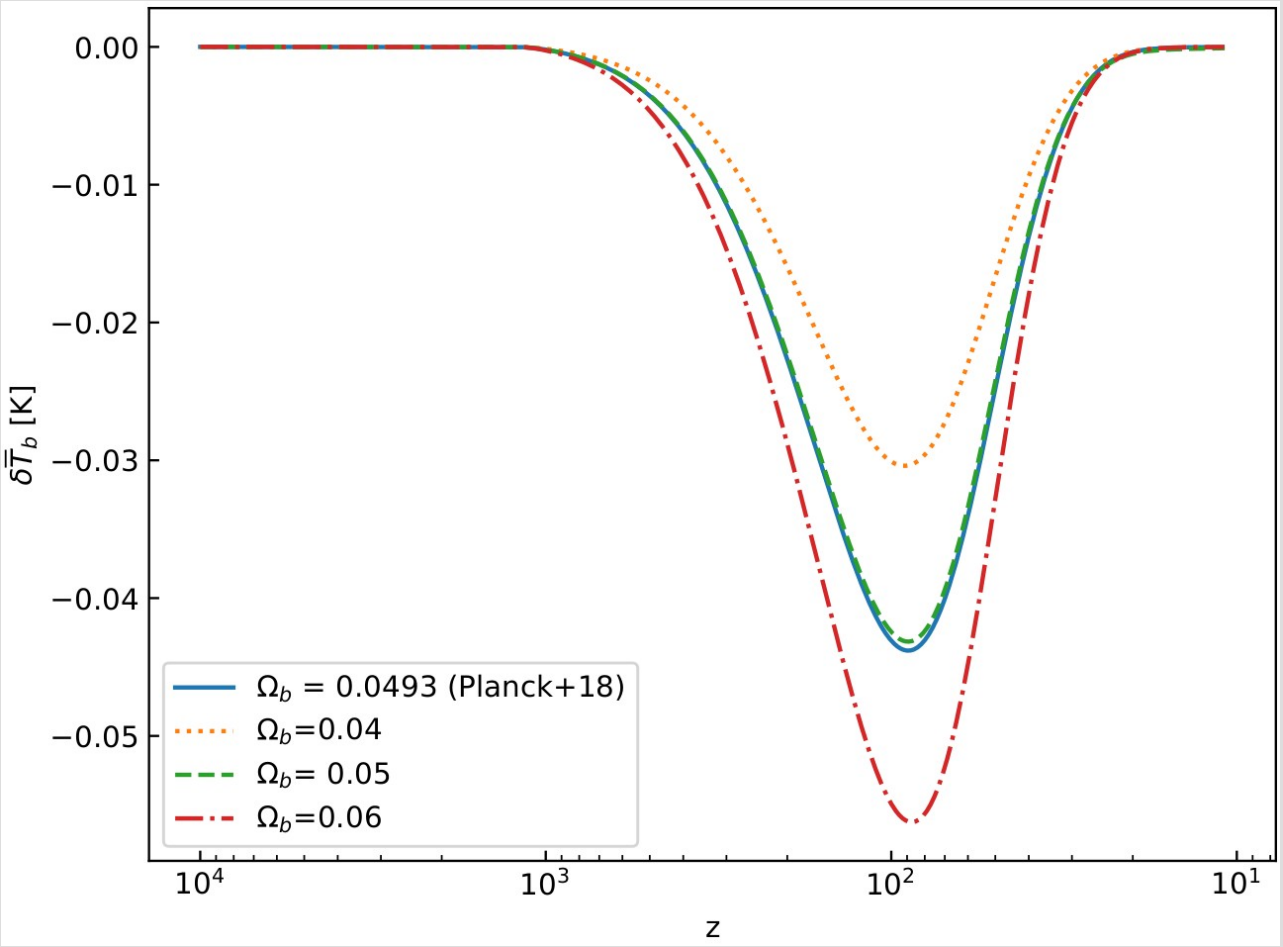
Ts : 21cm line spin temperature

Only **collisional** processes are considered !

$\delta\overline{T}_b$ *: Differential brightness temperature* ***(Global Signal)***

$$\delta T_b(\nu) \sim 27 x_{HI} \left(\frac{1+z}{10}\frac{0.15}{\Omega_m h^2}\right)^{1/2} \left(\frac{1-Y_p}{0.76}\right) \left(\frac{\Omega_b h^2}{0.023}\right) \left(1-\frac{T_r}{T_s}\right) mK$$

Ω_b influence on 21cm global signal



Ω_b controls baryon fraction → Hydrogen amount

More hydrogen and collisions → **More signal !**

First conclusions

- Our code follows species abundances for a given set of differential equations.
- We can compute 21cm global signal, which sensitive to cosmological parameters

Cosmological models can be constrained with 21cm line during the Dark Ages

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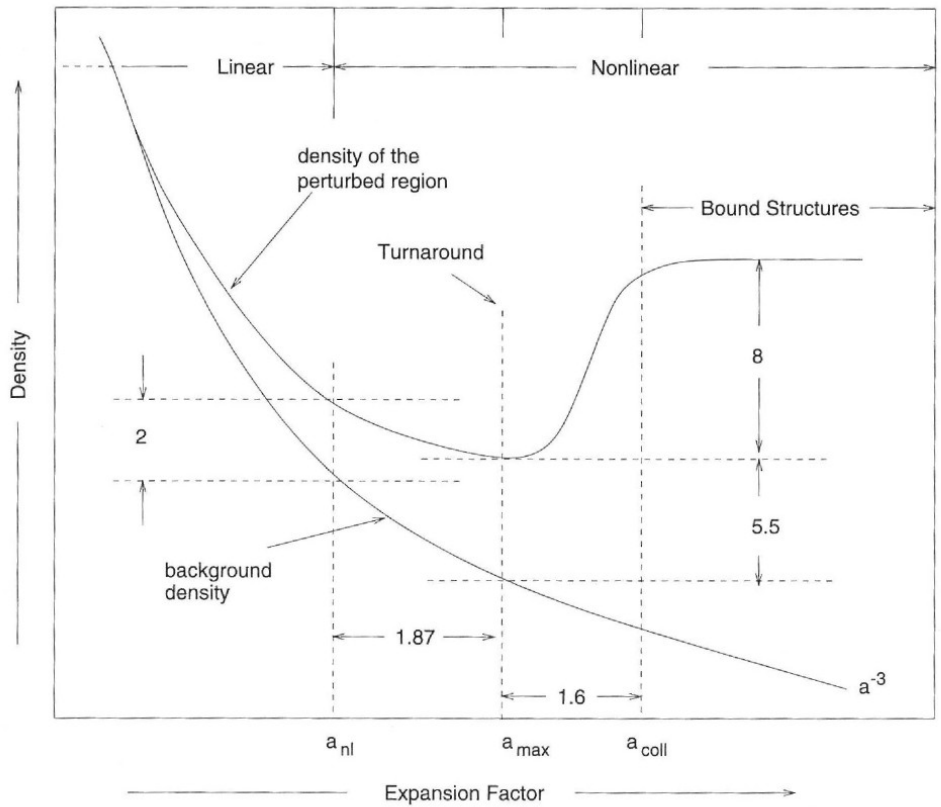
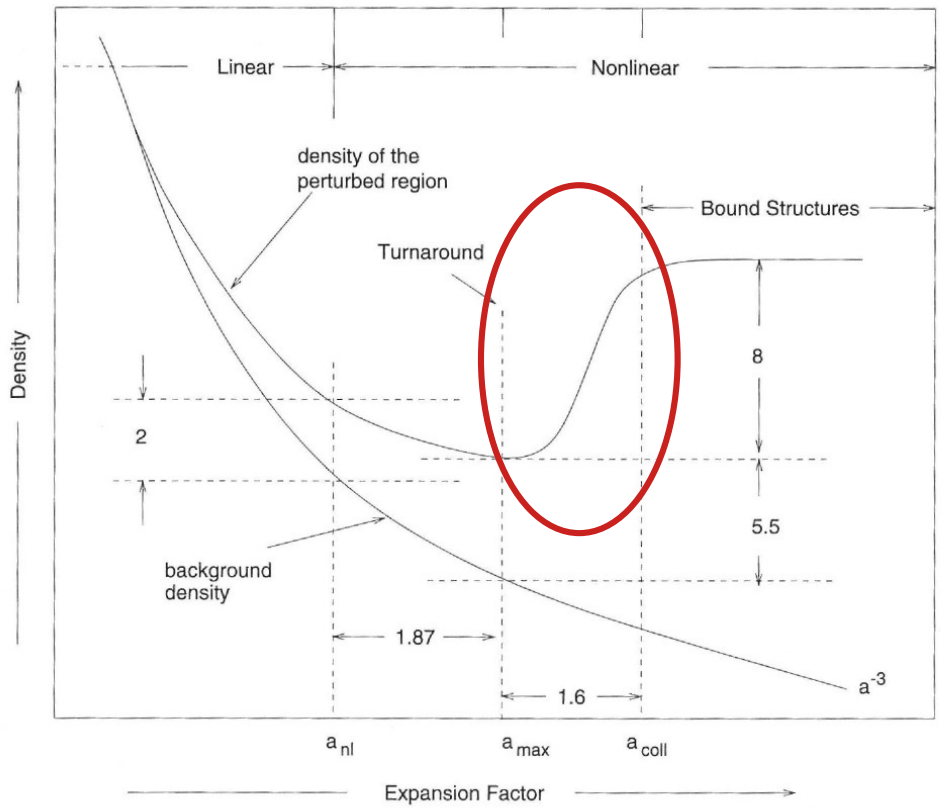
Collapse in expanding universe



Padmanabhan 2002

Collapse in expanding universe



Padmanabhan 2002

We start at **turnaround** (ta) redshift :

$$1 + z_{ta} \propto M^{\alpha}$$

1 free parameter : Cloud's mass **M**

Turnaround :
Gravity takes over expansion
$\rightarrow \delta\rho$ increases

Collapse model

- Cosmological model

$(\Omega_b, \Omega_m, H_0)$

- Basic hypothesis for the collapsing cloud :

Spherical
Homogeneous
Non rotating

- One free parameter to vary :

Mass of the collapsing cloud

- Follow the thermal influence of molecules :

Molecular thermal channel for T_k

Collapse model

- Cosmological model

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- Basic hypothesis for the collapsing cloud :

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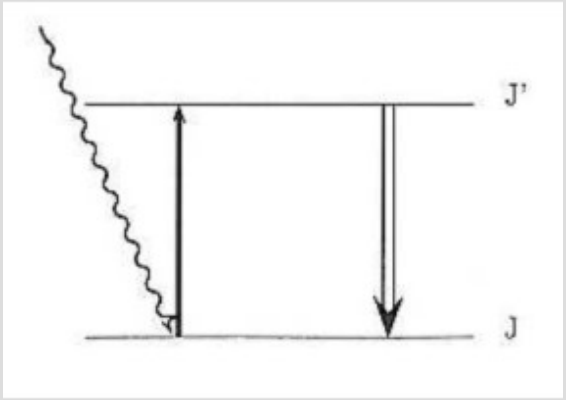
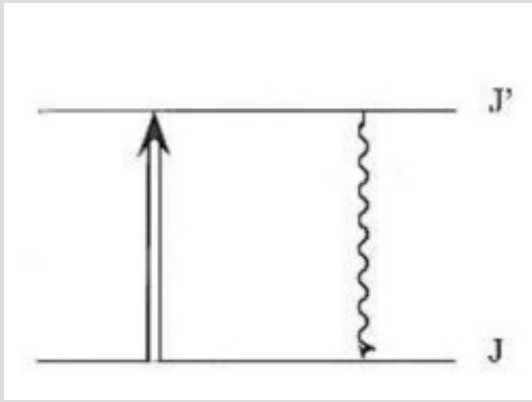
Molecular thermal channel for T_k

Molecular thermal functions

Rotational level transitions
for **H_2** and **HD molecules**





Heating :

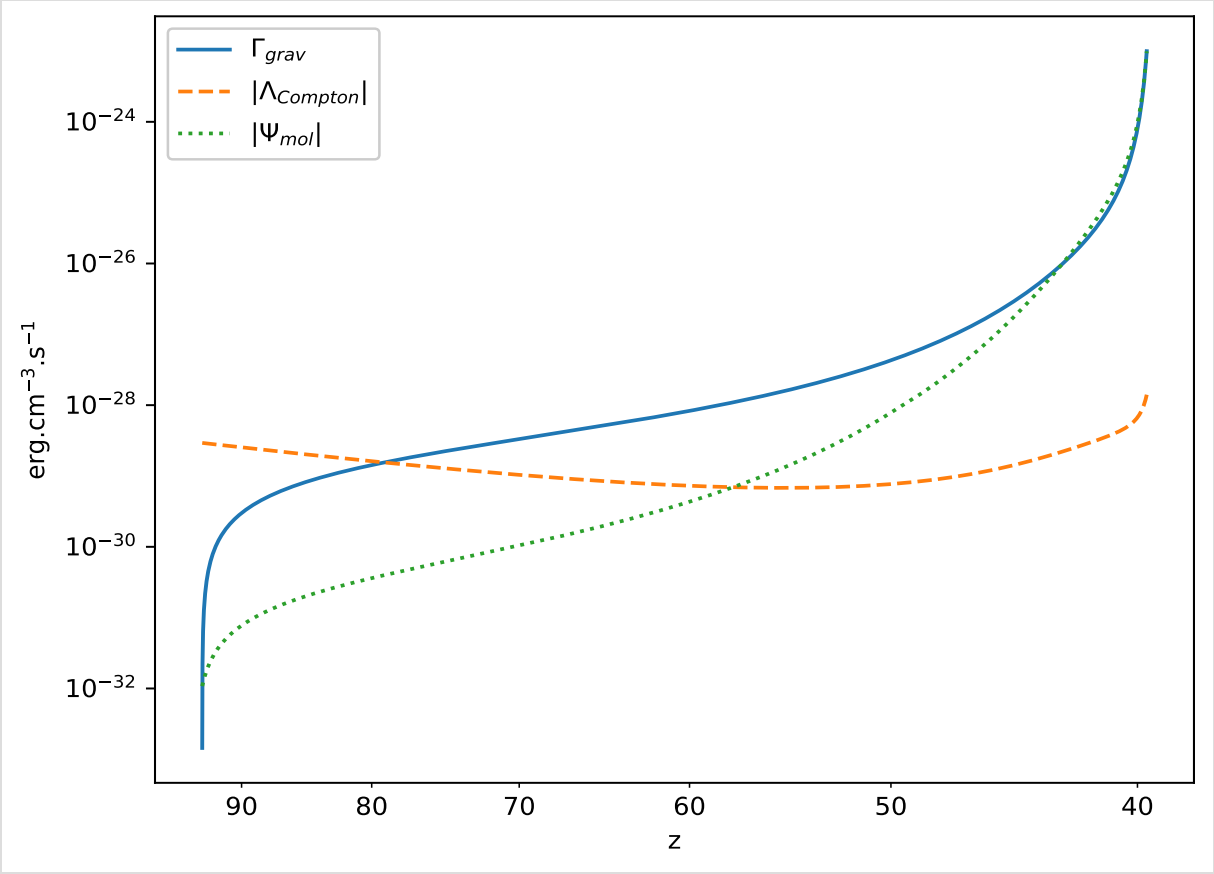
-External photon absorption
-Collisional de-excitation

Cooling :

-Collisional excitation
-Spontaneous or induced de-excitation with photon emission (lost for the medium)

Thermal Function : $\Psi = \text{Heating} - \text{Cooling}$ $[\text{ergs.cm}^{-3}.\text{s}^{-1}]$

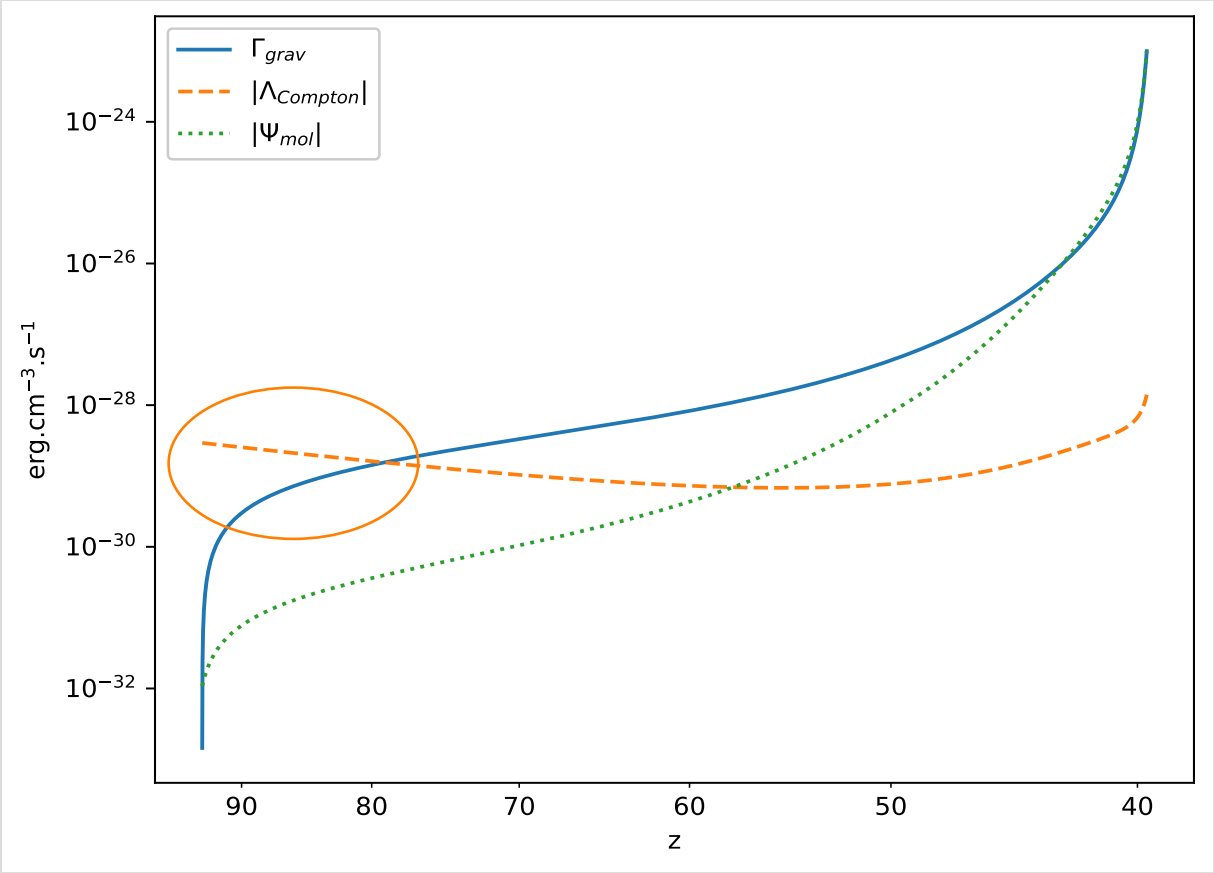
Thermal contributions to baryons temperature



$$\frac{dT_k}{dt} = -\frac{2T_k}{r}\frac{dr}{dt} + \frac{2}{3n_b k_b}\left(\Psi_{mol} + \Lambda_{Compton}\right)$$

Cloud's Mass : $10^8 M_\odot$

Thermal contributions to baryons temperature



1) **Compton interaction** couples gas to radiation

$$\frac{dT_k}{dt} = -\frac{2T_k}{r}\frac{dr}{dt} + \frac{2}{3n_b k_b}\left(\Psi_{mol} + \Lambda_{Compton}\right)$$

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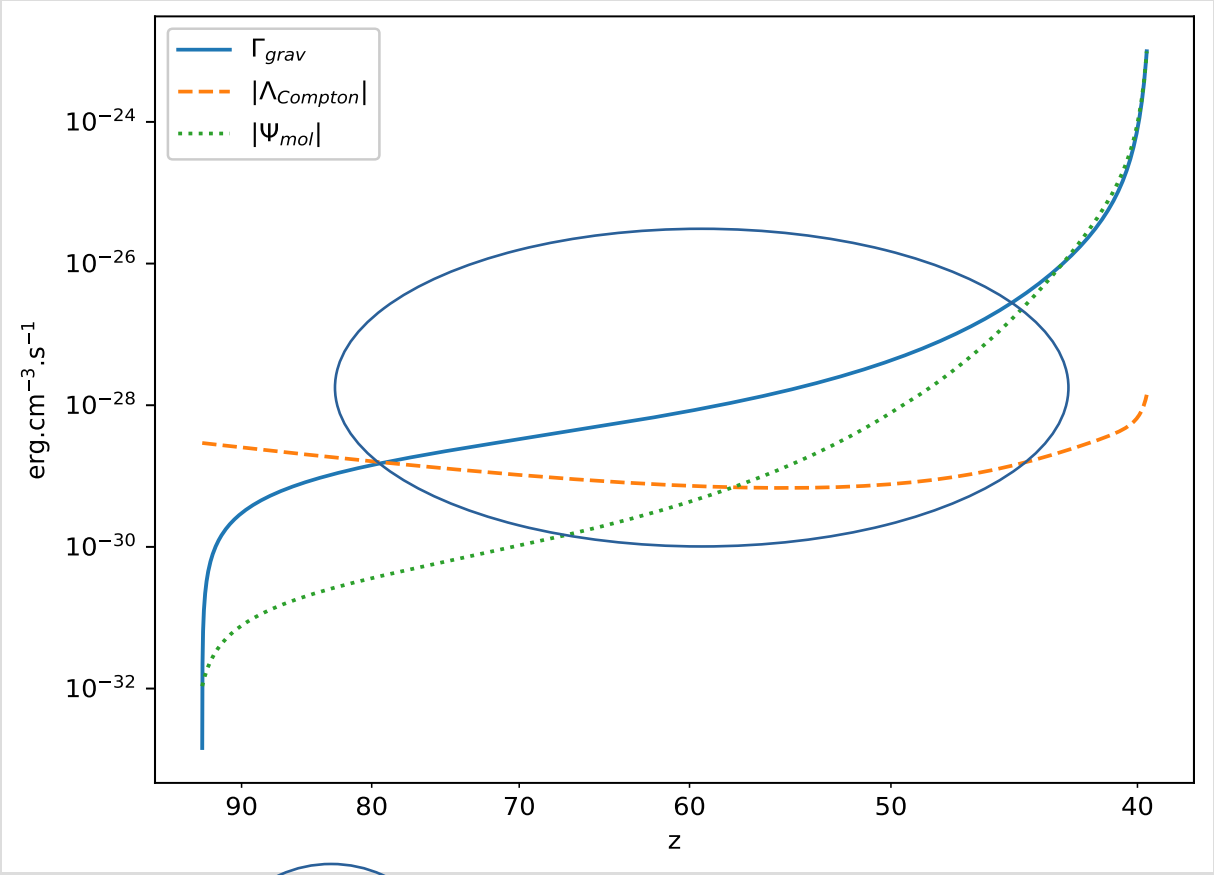

1) **Compton interaction** couples gas to radiation

2) **Gravitation** dominates and heat the gas

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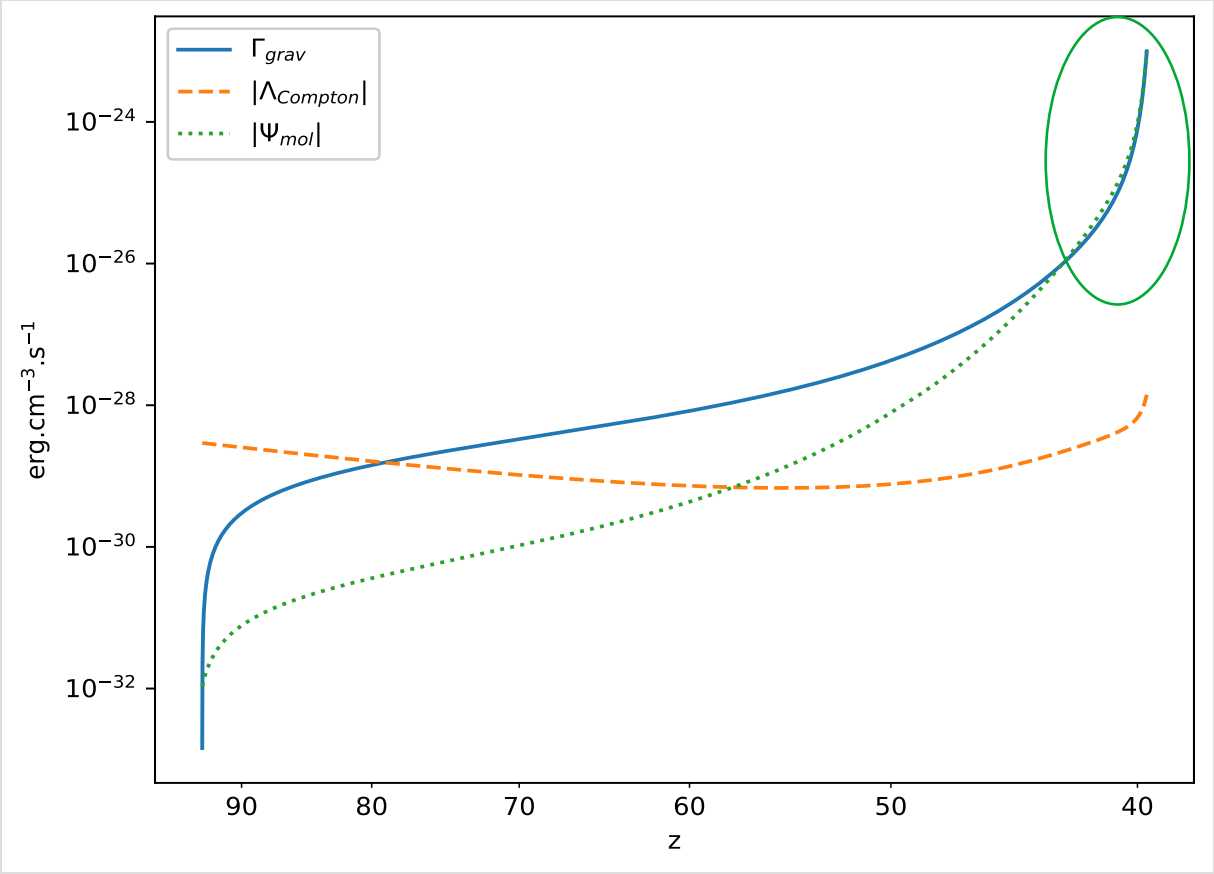


1) **Compton interaction** couples gas to radiation

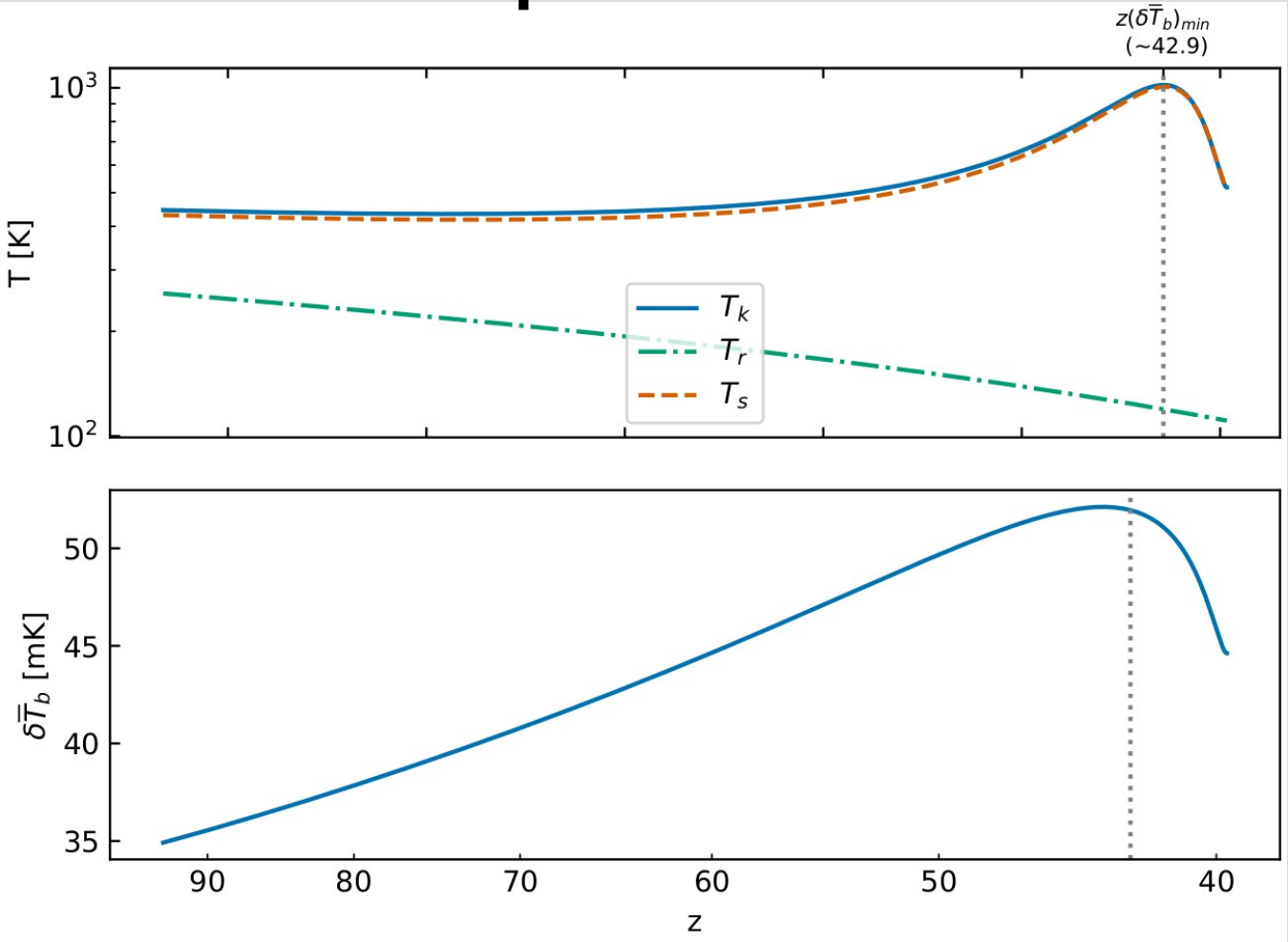
2) **Gravitation** dominates and heats the gas

3) **Molecular cooling** takes over gravitational heating !

Cloud's Mass : $10^8 M_\odot$

$$\frac{dT_k}{dt} = -\frac{2T_k}{r}\frac{dr}{dt} + \frac{2}{3n_b k_b}\left(\Psi_{mol} + \Lambda_{Compton}\right)$$

Temperatures in collapse



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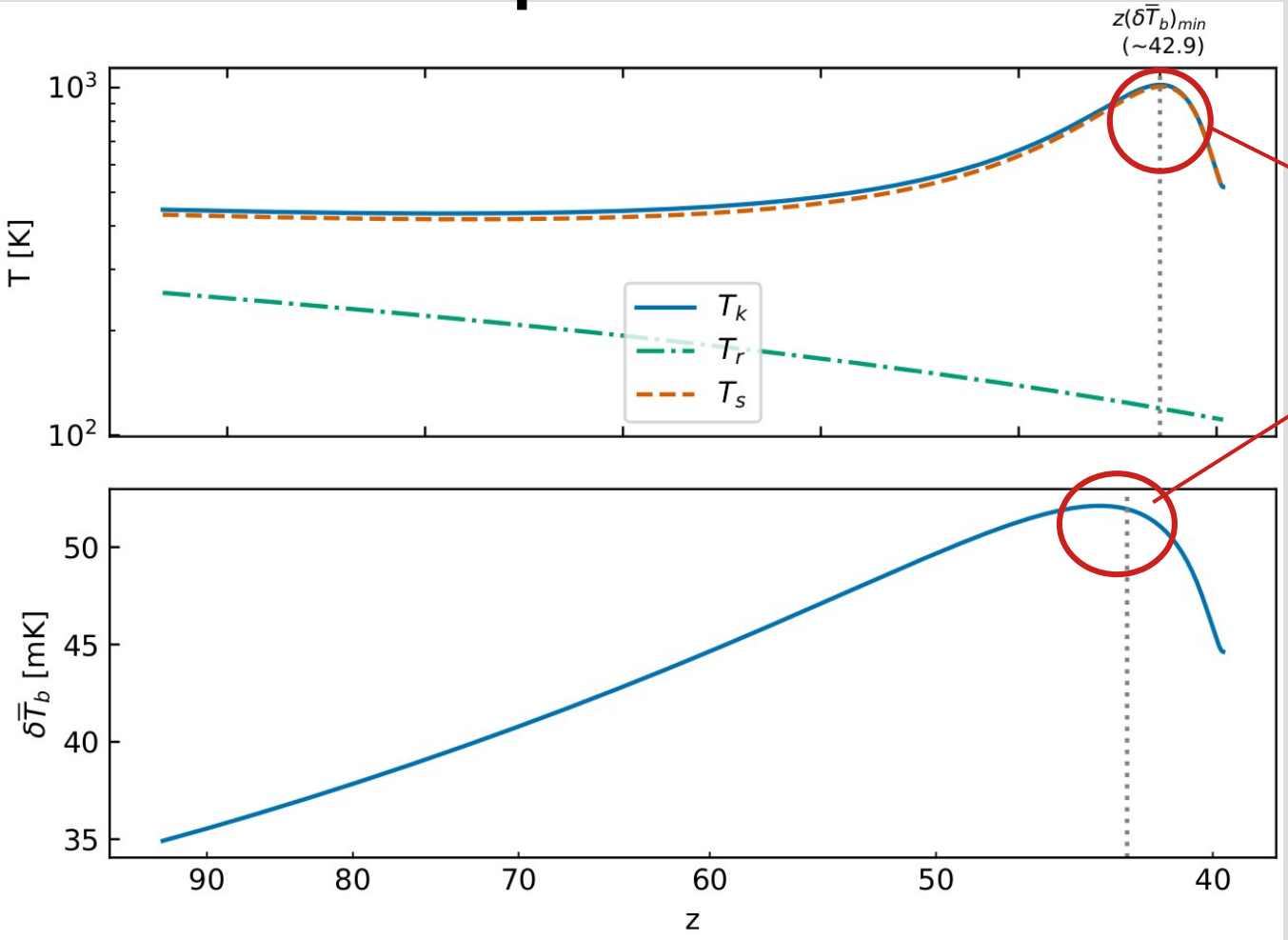

Effect of
Molecular cooling !

Cloud's Mass : $10^8 M_\odot$

Second conclusions

- Molecular processes strongly affect the gas temperature in collapsing primordial clouds
- They induce a very different 21cm line signature (at small scales) from the global signal.

Prospects :

- Evaluate the impact on the 21cm Power spectrum
- Study of thermal instabilities inside the collapsing cloud

BACKUP

OBSERVATIONS

21cm as a cosmological probe

Scans **Dark Ages** and **Reionization**
z~[200-6]

21cm as a cosmological probe

Scans **Dark Ages** and **Reionization**
z~[200-6]

Probes 3D volumes
(space+redshift)

Credit : Chapman+2019

21cm as a cosmological probe

Scans **Dark Ages** and **Reionization**
z~[200-6]

Exotic thermal processes
(extra radio background, Scattering DM)

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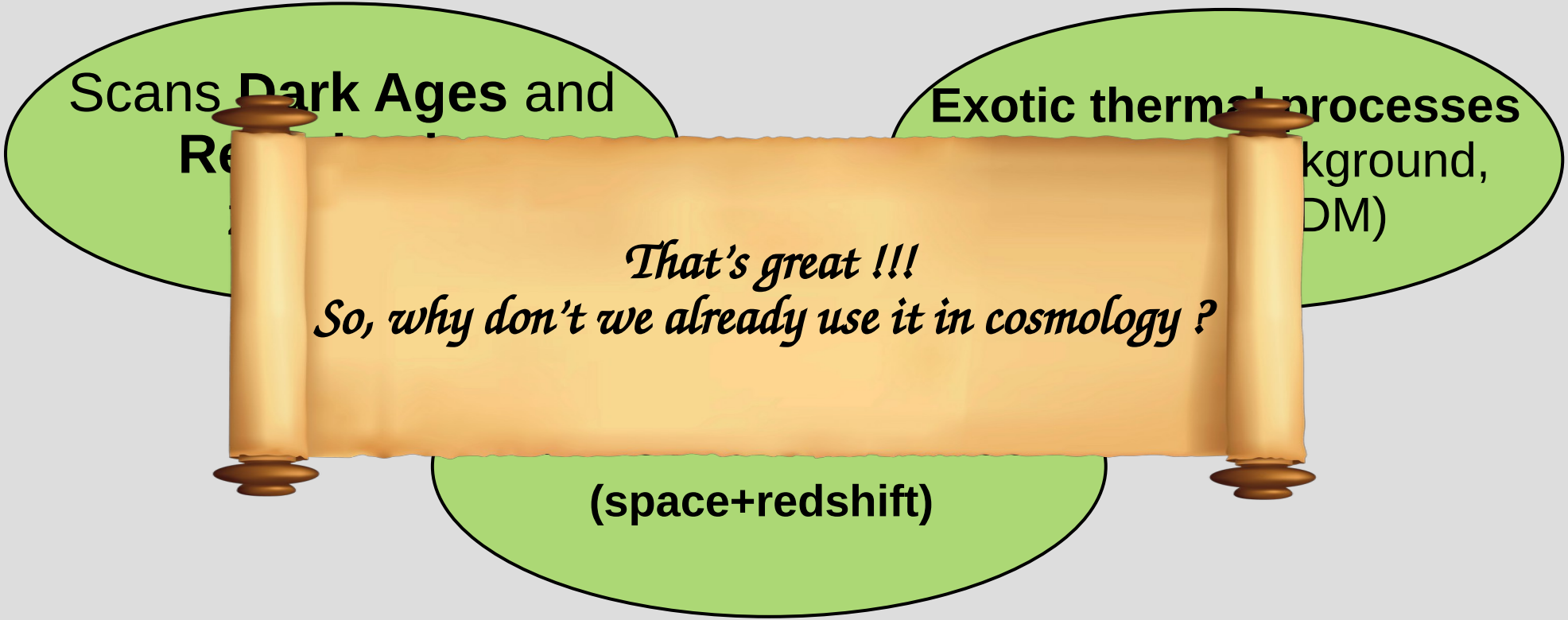
(space+redshift)

21cm as a cosmological probe



21cm as a cosmological probe

Galactic synchrotron emission

Exotic thermal processes
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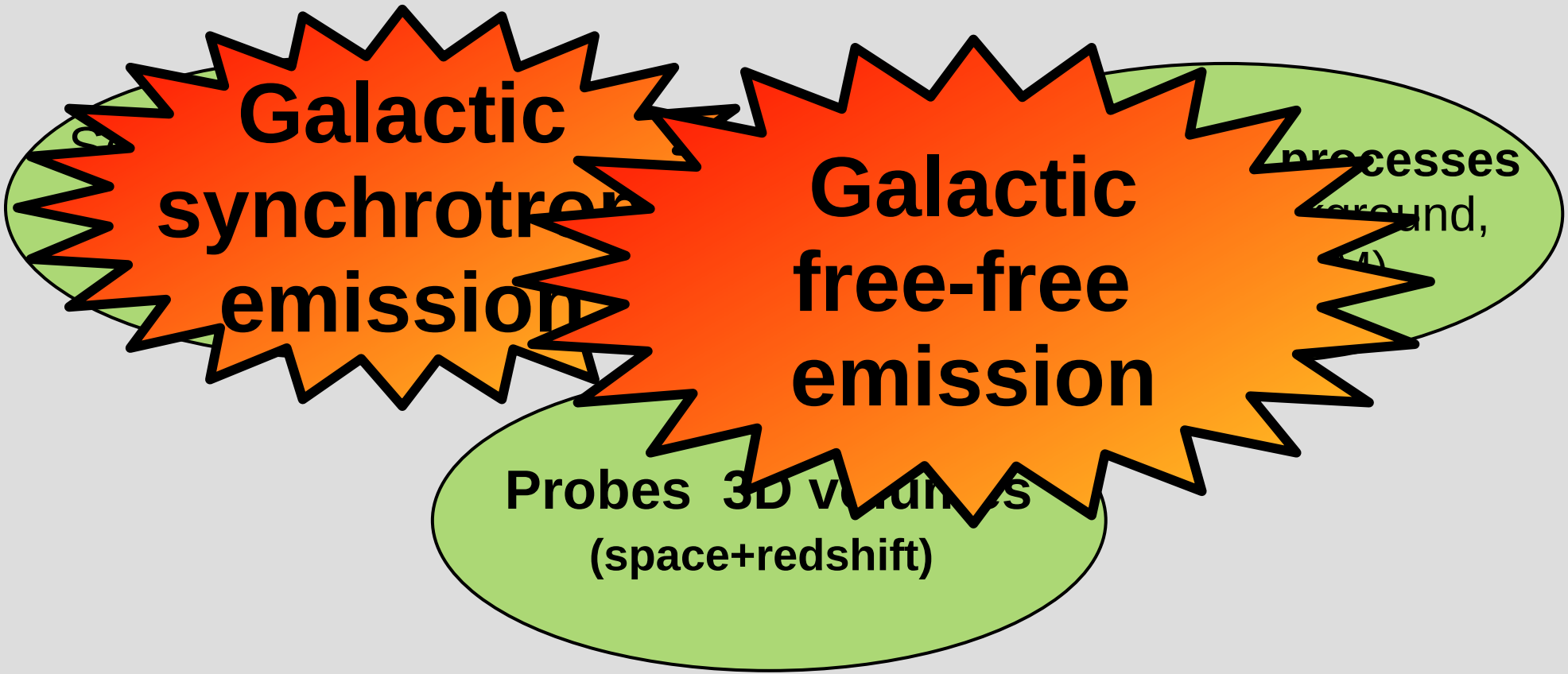
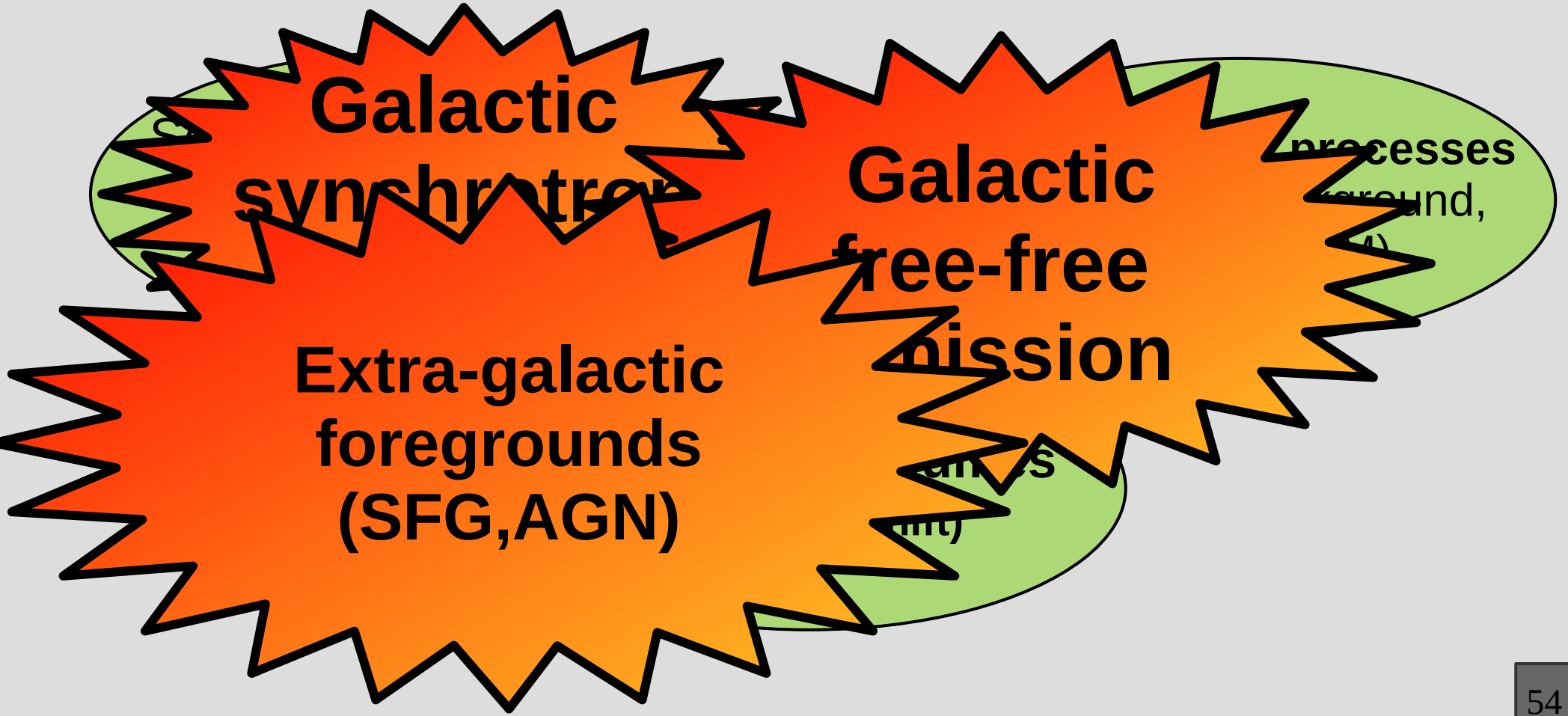
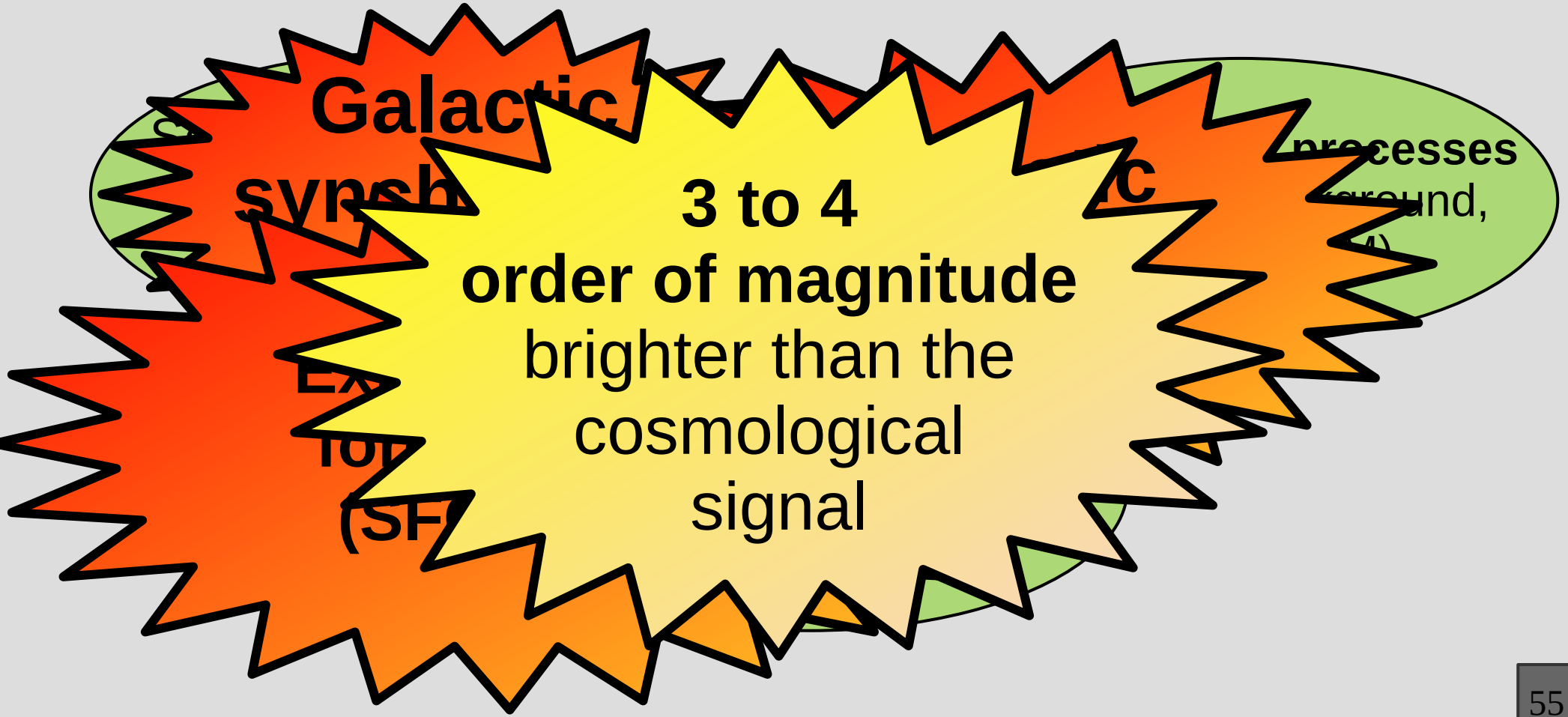


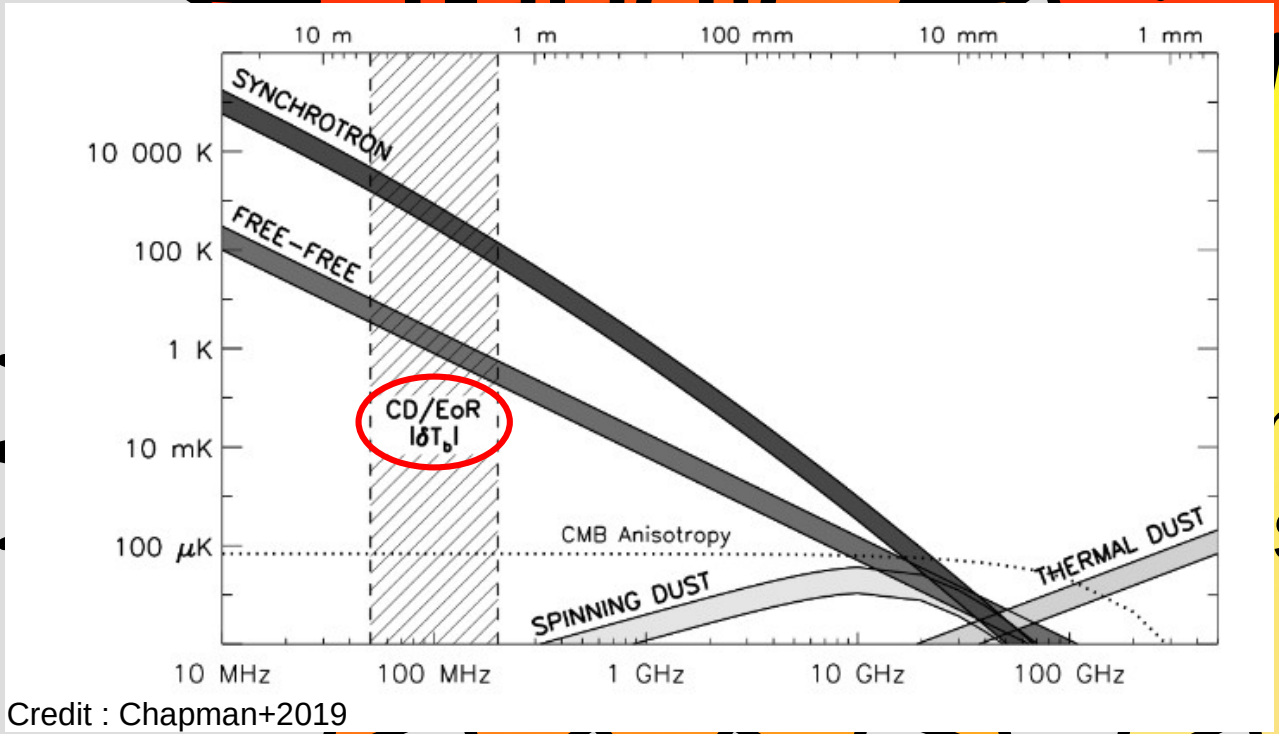
21cm as a cosmological probe



21cm as a cosmological probe



21cm as a cosmological probe

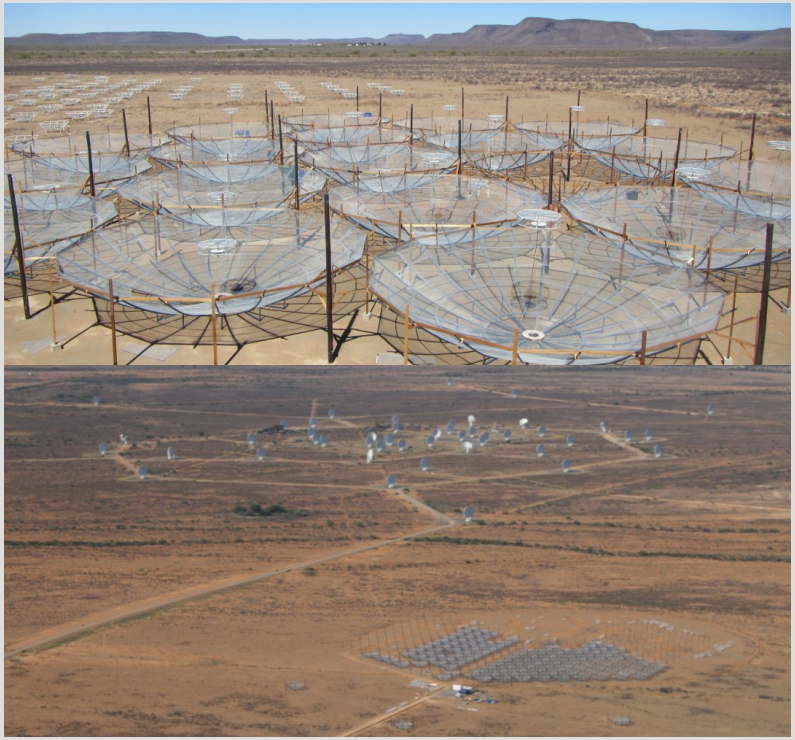


Credit : Chapman+2019

3 to 4
of magnitude
nter than the
smological
signal

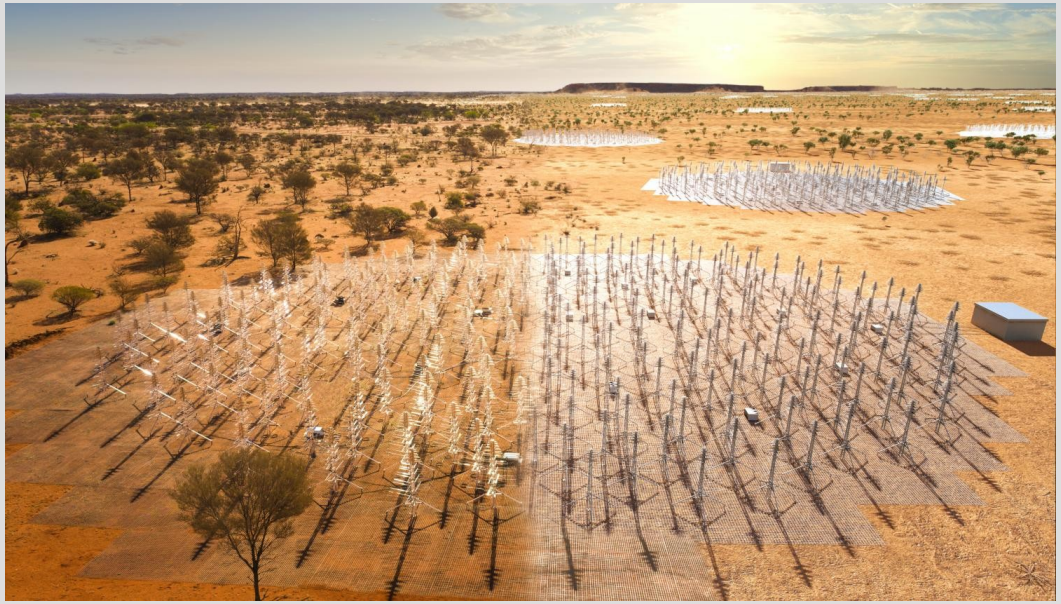
Observations on Earth

Credit : reionization.org



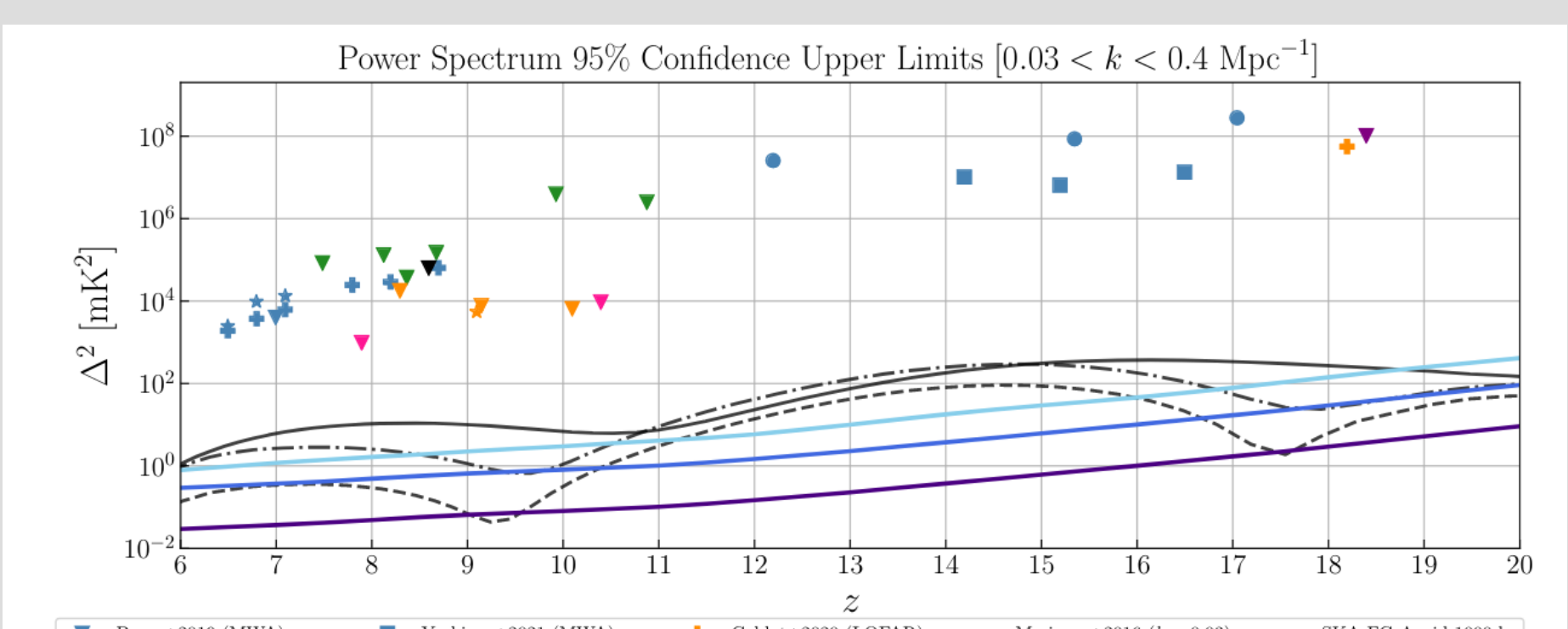
Hydrogen Epoch of Reionization Array (HERA) : 50-250MHz frequency band
Now running

Credit : skao.int



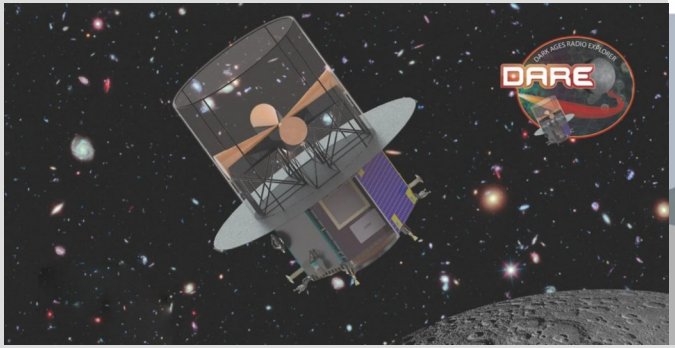
Square Kilometer Array–Low (SKA) :
50-350 MHz frequency band
Starting in ~2028 (?)

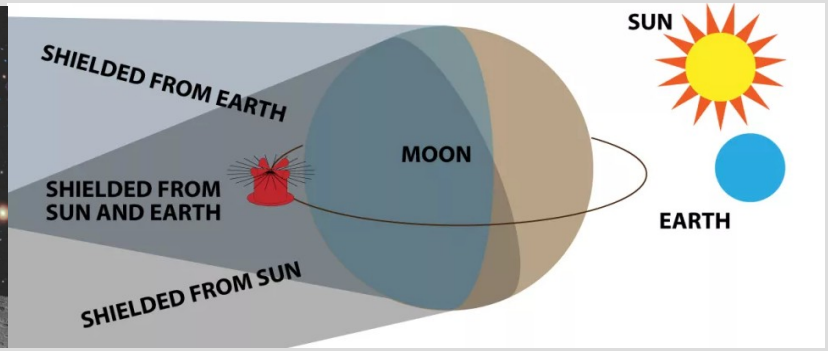
Observations on Earth



Credit : Barry+2022

Observation **not** on Earth

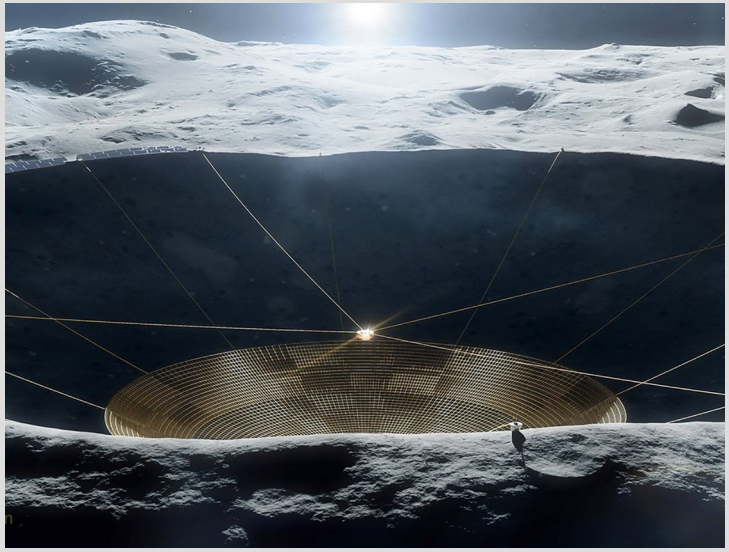




Dark Ages Radio Explorer (DARE)
40-120 MHz frequency band
Launch date : *soonish ?*

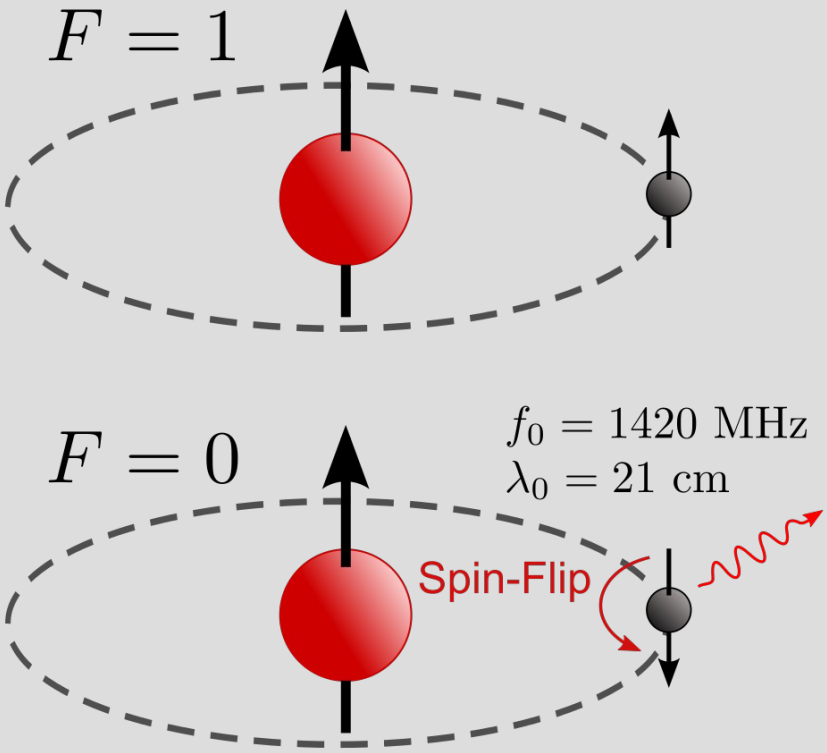
We need to observe from
The Dark Side of the Moon

Lunar Crater Radio Telescop (LCTR)
Lauch date : I'll be retired



21cm

21cm in a nutshell



Relative population of atoms in the two levels described by a **spin temperature :**

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{\mathrm{h}\nu_{21}}{\mathrm{k_b T_s}}\right)$$

Mechanisms compete in the spin temperature :

- **Absorption** & scattering of CMB photons
- **Collisions** with other **H** or free **e**$^-$ (*Dark Ages*)
- **Resonant Scattering** of Lyα photons (*Cosmic Dawn*)

Spin temperature

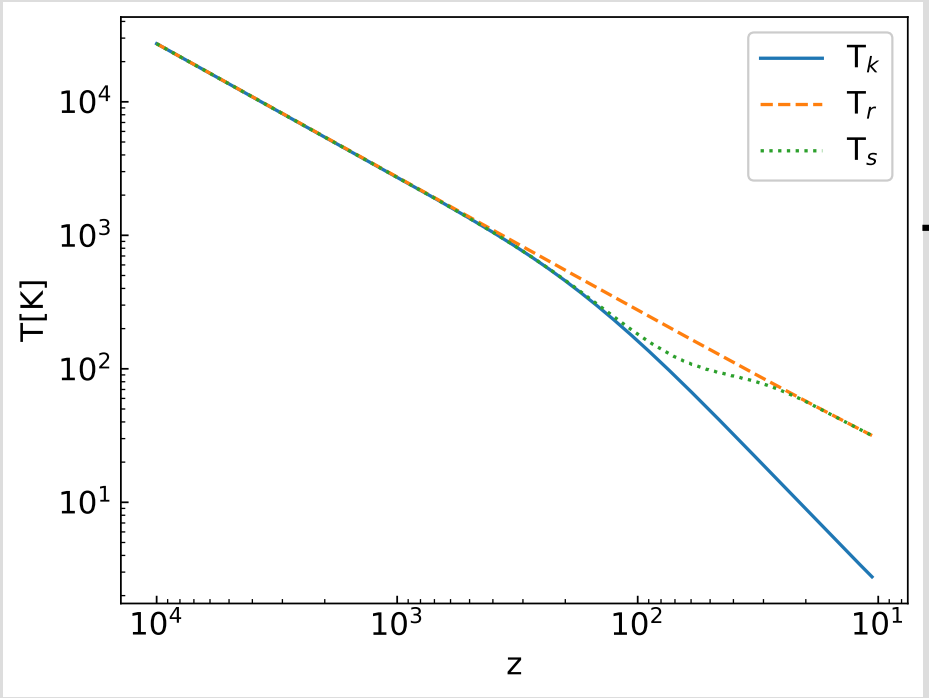
Collisions coupling coefficient :

$$x_c^i = \frac{C_{10}^i h\nu_{21}}{A_{10} k_b T_{CMB}}$$

$$T_s^{-1} \sim \frac{T_r^{-1} + x_c T_k^{-1}}{1 + x_c}$$

$T_r = T_{CMB}$

$(DarkAges)$



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

$$T_k \propto (1+z)^2 + Compton\ coupling$$

Spin temperature

Collisions coupling coefficient :

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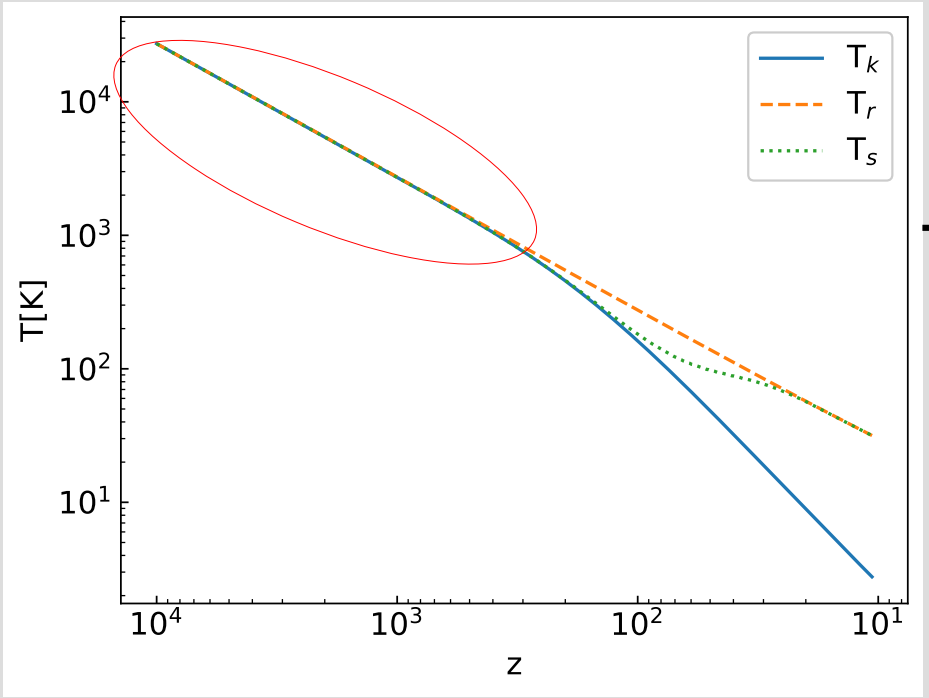

$$T_r \propto (1+z)$$

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1°) Before decoupling : $T_k = T_r \rightarrow T_s = T_r$

Spin temperature

Collisions coupling coefficient :

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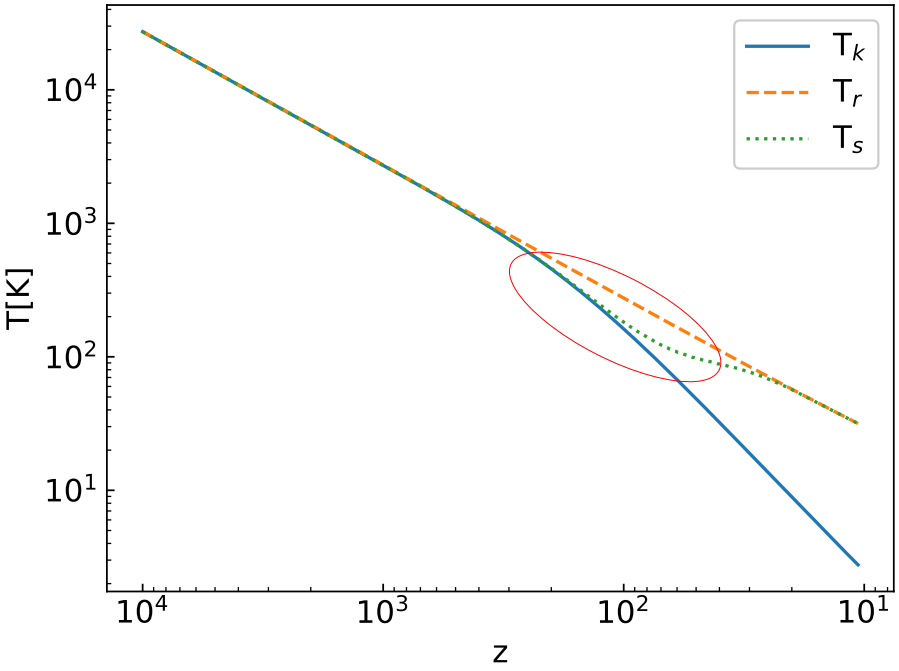

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1°) Before decoupling : $T_k = T_r \rightarrow T_s = T_r$

2°) After decoupling : $T_k \neq T_r, \quad x_c \gg 1$

Collision processus dominates : $T_s = T_k$

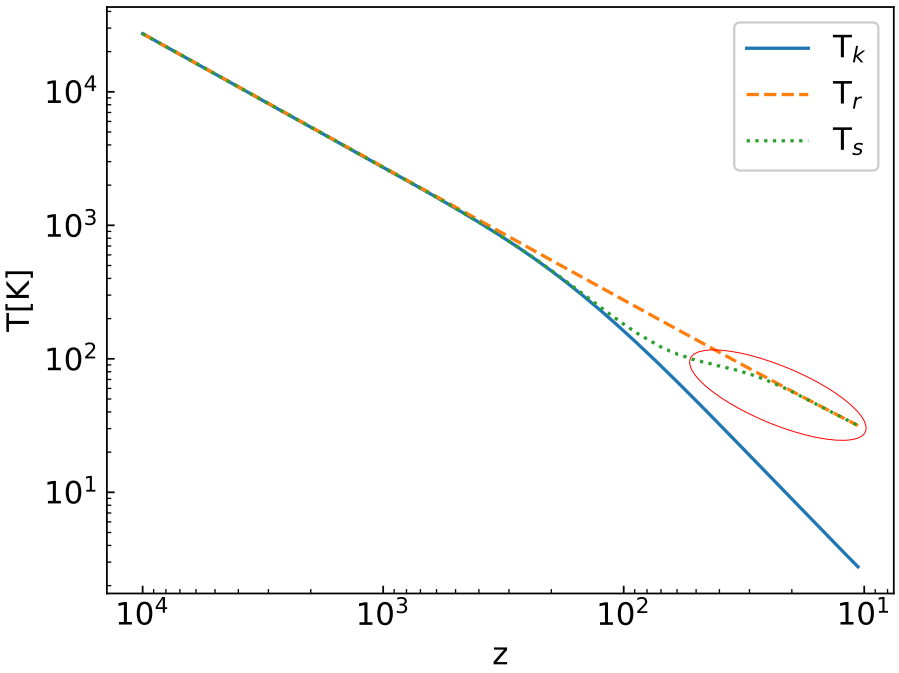
Spin temperature

Collisions coupling coefficient :

$$x_c^i = \frac{C_{10}^i h\nu_{21}}{A_{10} k_b T_{CMB}}$$

$$T_s^{-1} \sim \frac{T_r^{-1} + x_c T_k^{-1}}{1 + x_c}$$

$T_r = T_{CMB}$ $(Dark Ages)$



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2°) After decoupling : $T_k \neq T_r, \quad x_c \gg 1$

Collision processus dominates : $T_s = T_k$

3°) Around z~30 : expansion diluted baryons

→ Collisions are ineffectives

$$x_c << 1 \rightarrow T_s = T_r$$

CHEMFAST EQUATIONS

CHEMFAST : Equations

Integrate a set of **differential equations** over $10^4 > z > 10$

- Gas kinetic temperature : $\frac{dT_k}{dt} = -2HT_k + \frac{8\sigma_T a_r}{3m_e c} T_r^4 (T_r - T_m) x_e$
- Radiation temperature : $\frac{dT_r}{dt} = -HT_r$
- Species numerical density : $\left(\frac{dn_\xi}{dt}\right)_{chem} = \sum_{\xi_1,\xi_2} k_{\xi_1\xi_2} n_{\xi_1} n_{\xi_2} - \sum_{\xi'} k_{\xi\xi'} n_\xi n_{\xi'}$
- Mean numerical baryon density : $\frac{d\bar{n}_b}{dt} = -3H\bar{n}_b + \sum_\xi \left(\frac{d\bar{n}_\xi}{dt}\right)_{chem}$

Collapse equations

- Radiation temperature

$$\frac{dT_r}{dt} = -HT_r$$

- Gas temperature

$$\frac{dT_k}{dt} = -2T_k\frac{\dot{r}}{r} + \frac{2}{3n_b k_b}\Psi$$

- Radius

$$\ddot{r} = -\frac{GM}{r^2} + \frac{5k_b T_k}{\mu m_b r\left(1+\frac{\Omega_c}{\Omega_b}\right)}$$

- ξ species density

$$\frac{dn_\xi}{dt} = -3\frac{n_\xi}{r}\ddot{r} + \left(\frac{dn_\xi}{dt}\right)_{chem}$$

- Total baryon density

$$\frac{dn_b}{dt} = -3\ \frac{n_b}{r}\ddot{r} + \sum_\xi \left(\frac{dn_\xi}{dt}\right)_{chem}$$

Isothermal perturbations spectrum

$$\frac{\delta\rho}{\rho} = \left(\frac{M}{M_0}\right)^{-1/3} (1+z)^{-1}$$

$M_0 \sim 10^{15} h^{-1} \Omega_m M_{sun}$

(~mass of a supercluster today)

-**1 free parameter** in the model : **mass M of the cloud.**

-During M-domination : $\delta_{m,lin} \propto t^{2/3}$