21-cm observation-hints of dark matter?

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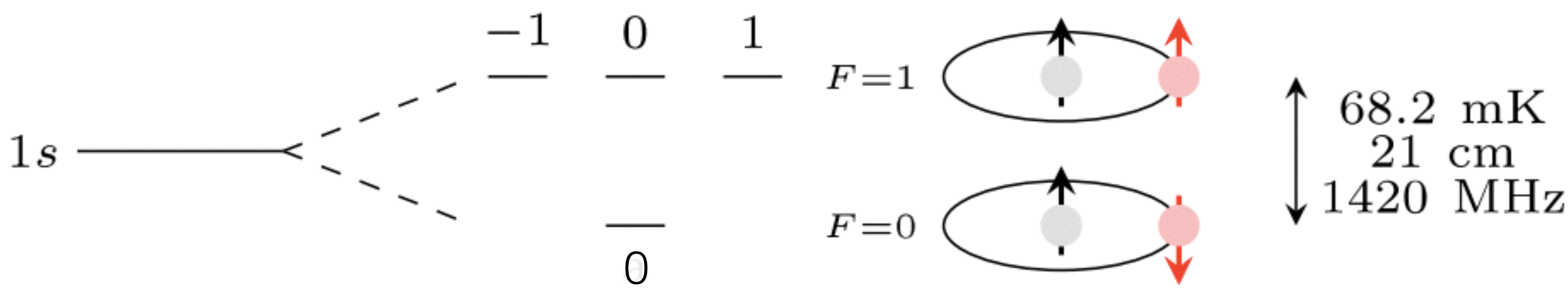
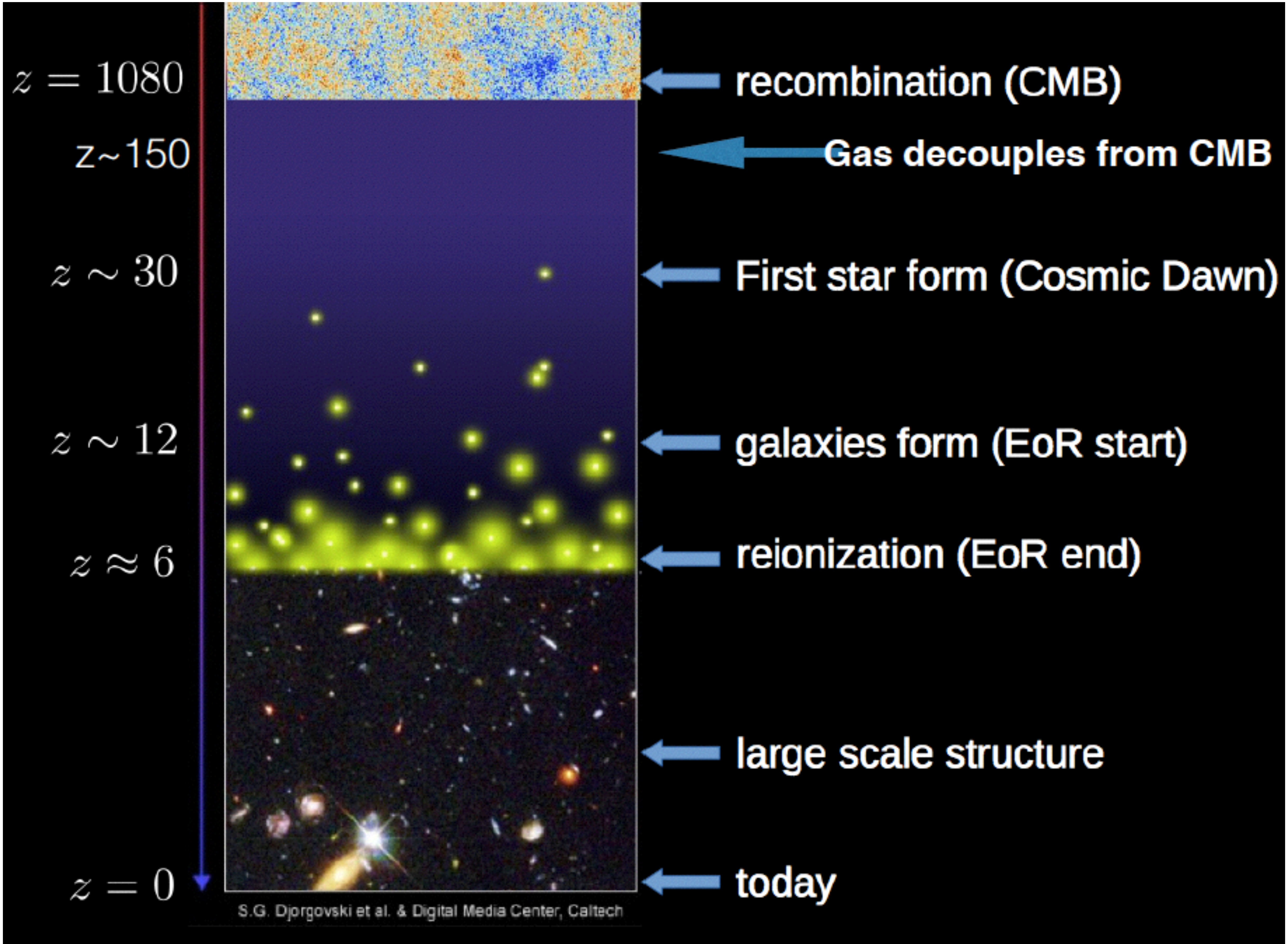
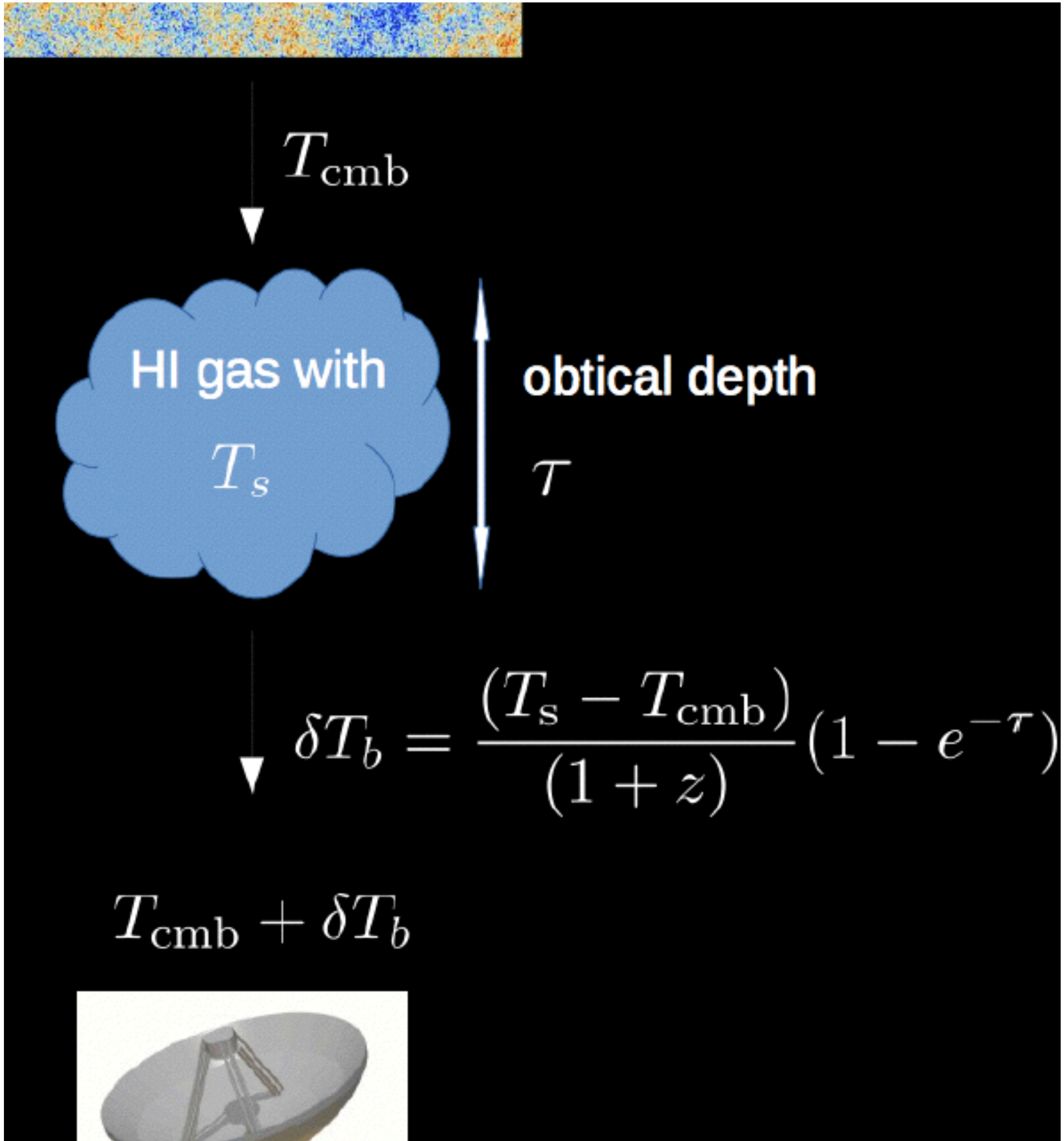
The 21cm line of atomic hydrogen



$$E_{10} \simeq \frac{4}{3}\frac{g_e e}{2m_e}\frac{g_p e}{2m_p}\frac{\alpha^3 m_e^3}{\pi}$$

$$= 5.9 \times 10^{-6}\ \mathrm{eV} \simeq 0.068\ \mathrm{K} \simeq 2\pi/21\ \mathrm{cm}$$


$z = 1080$
$z \sim 150$
$z \sim 30$
$z \sim 12$
$z \approx 6$
$z = 0$
recombination (CMB)
Gas decouples from CMB
First star form (Cosmic Dawn)
galaxies form (EoR start)
reionization (EoR end)
large scale structure
today
S.G. Djorgovski et al. & Digital Media Center, Caltech



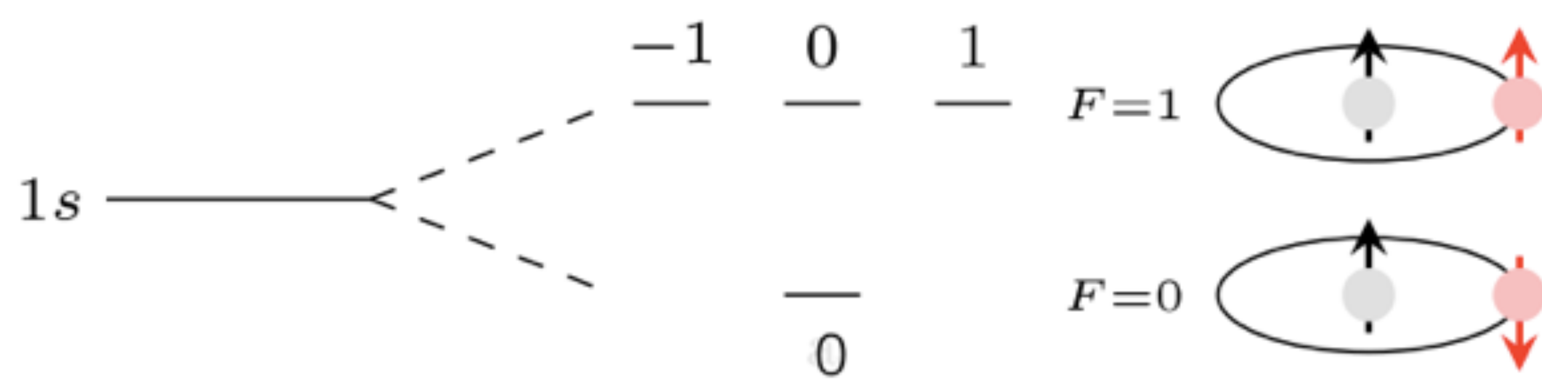
$T_{\rm cmb}$
HI gas with
T_s
obtical depth
τ
$\delta T_b = \frac{(T_{\rm s} - T_{\rm cmb})}{(1+z)}(1 - e^{-\tau})$
$T_{\rm cmb} + \delta T_b$

21-cm radio signal

- First observations from galactic HI in 1951.
- First observations at the cosmological scales - Bowman et al (EDGES) Nature Letters 555 (2018) 67
- Dark matter interpretation -Barkana, Nature 555 (2018) 71

Spin temperature is defined by the ratio

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} e^{-T_*/T_s} \simeq 3\left(1 - \frac{T_*}{T_s}\right) \qquad T_* = E_{21}/k_B = 0.068K$$



Detailed balance equation for HI number density in J=0 and J=1 states

$$n_0\left(C_{01}+P_{01}+A_{01}N_\gamma\right)=n_1\left(C_{10}+P_{10}+A_{10}(1+N_\gamma)\right)$$

Gas collisions

UV -photons from early stars

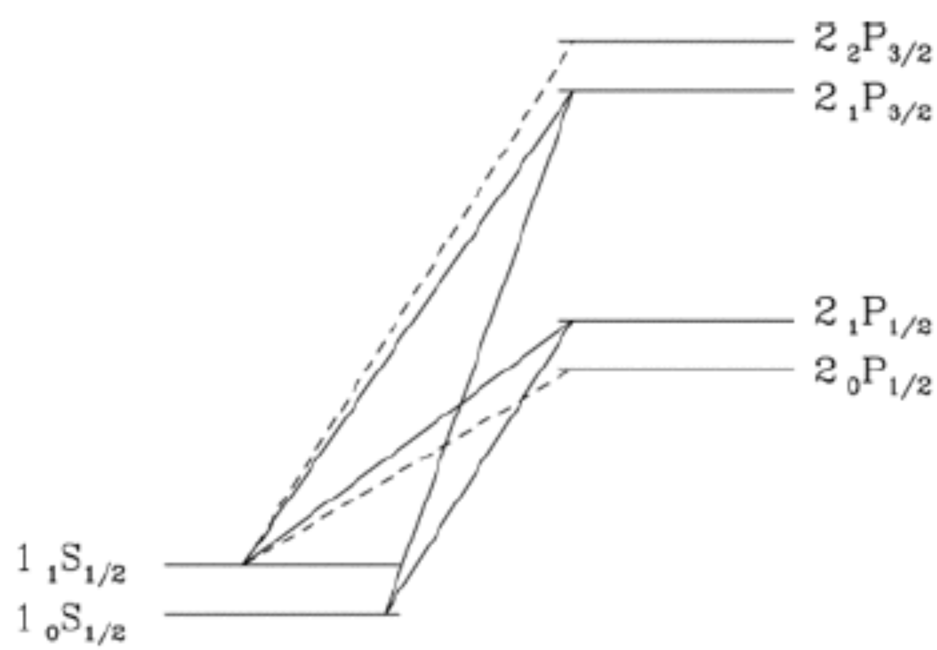
CMB photon absorption

Transitions rates caused by collisions with gas (mainly HI)

$$C_{01} = \frac{g_1}{g_0} C_{10}\, e^{-T_*/T_K} \simeq 3\, C_{10} \left(1 - \frac{T_*}{T_K}\right)$$

Transitions caused by UV-photons (Wouthuysen-Field effect)

$$P_{01} = \frac{g_1}{g_0} P_{10}\ e^{-T_*/T_c} \simeq 3\, P_{10} \left(1 - \frac{T_*}{T_c}\right)$$



Einstein emission and absorbtion coefficients

$$A_{01} = \frac{g_1}{g_0} A_{10} = 3\,A_{10}$$

$$N_\gamma = (e^{T_*/T_\gamma} - 1)^{-1} \simeq T_\gamma/T_*.$$

$$A_{10} = \frac{(2\pi)^3\,\alpha\,\nu_{21}^3}{3m_e^2} = 2.869 \times 10^{-15}\,s^{-1}$$

Rate of spin transitions induced by CMB photons

$$A_{10}\,\frac{T_\gamma}{T_*} \simeq 10^{-4}\,yr^{-1}\left(\frac{z+1}{30}\right)$$

Putting all this in the detailed balance equation

$$n_0\left(C_{01}+P_{01}+A_{01}N_\gamma\right)=n_1\left(C_{10}+P_{10}+\ A_{10}(1+N_\gamma)\right)$$

Lower gas temperature
to lower spin temperature

$$\Rightarrow \quad T_s - T_\gamma = \frac{x_{col}(T_K - T_\gamma) + x_\alpha(T_c - T_\gamma)}{1 + x_{col}}$$

$$x_{col} \equiv \frac{C_{10}}{A_{10}}\frac{T_*}{T_K}\,, \quad x_\alpha \equiv \frac{P_{10}}{A_{10}}\frac{T_*}{T_c}$$

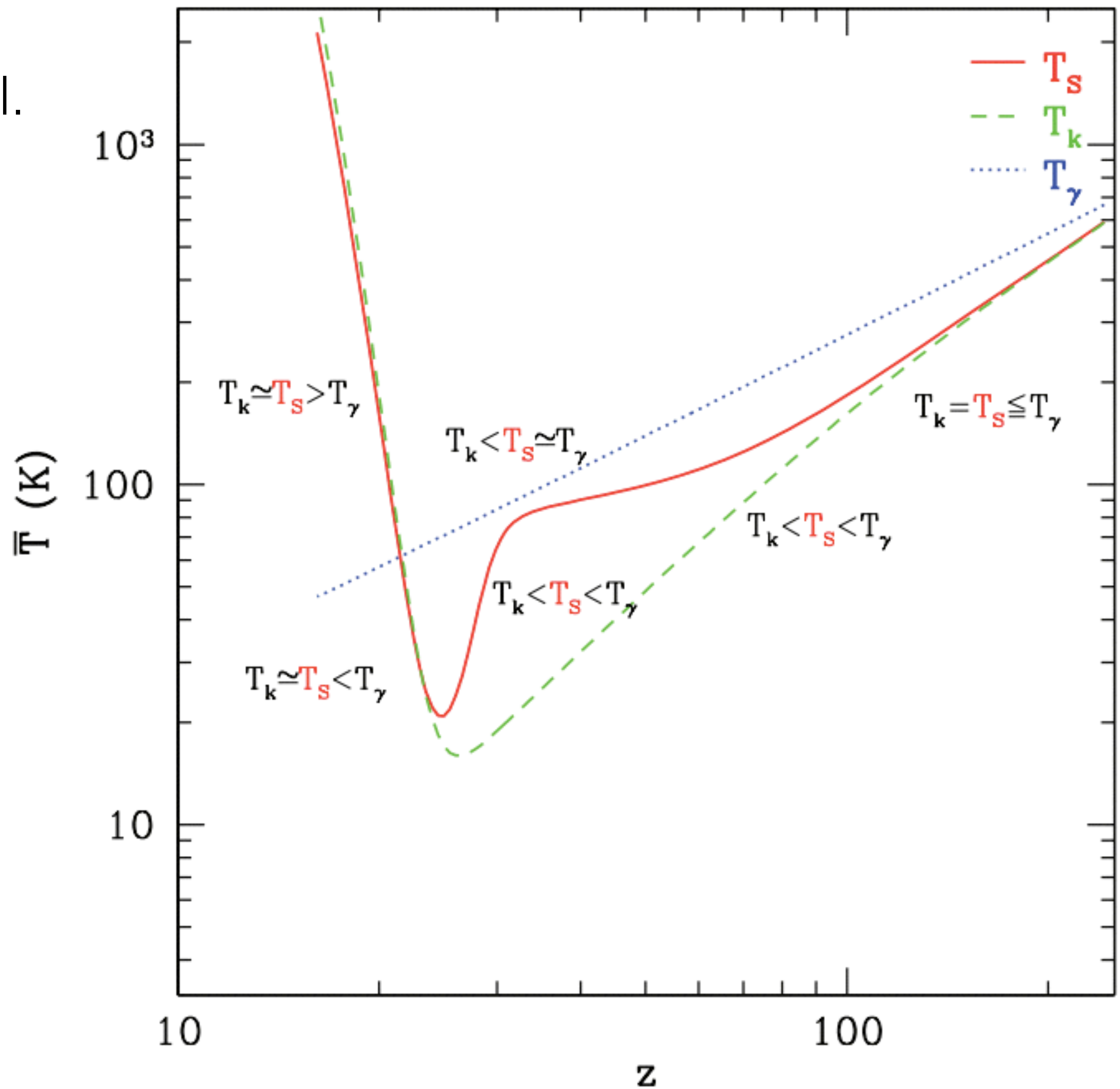
21-cm brightness temperature

$$T_{21} = \frac{T_s - T_\gamma}{1+z}\left(1 - e^{-\tau}\right) \simeq \frac{T_s - T_\gamma}{1+z}\tau$$

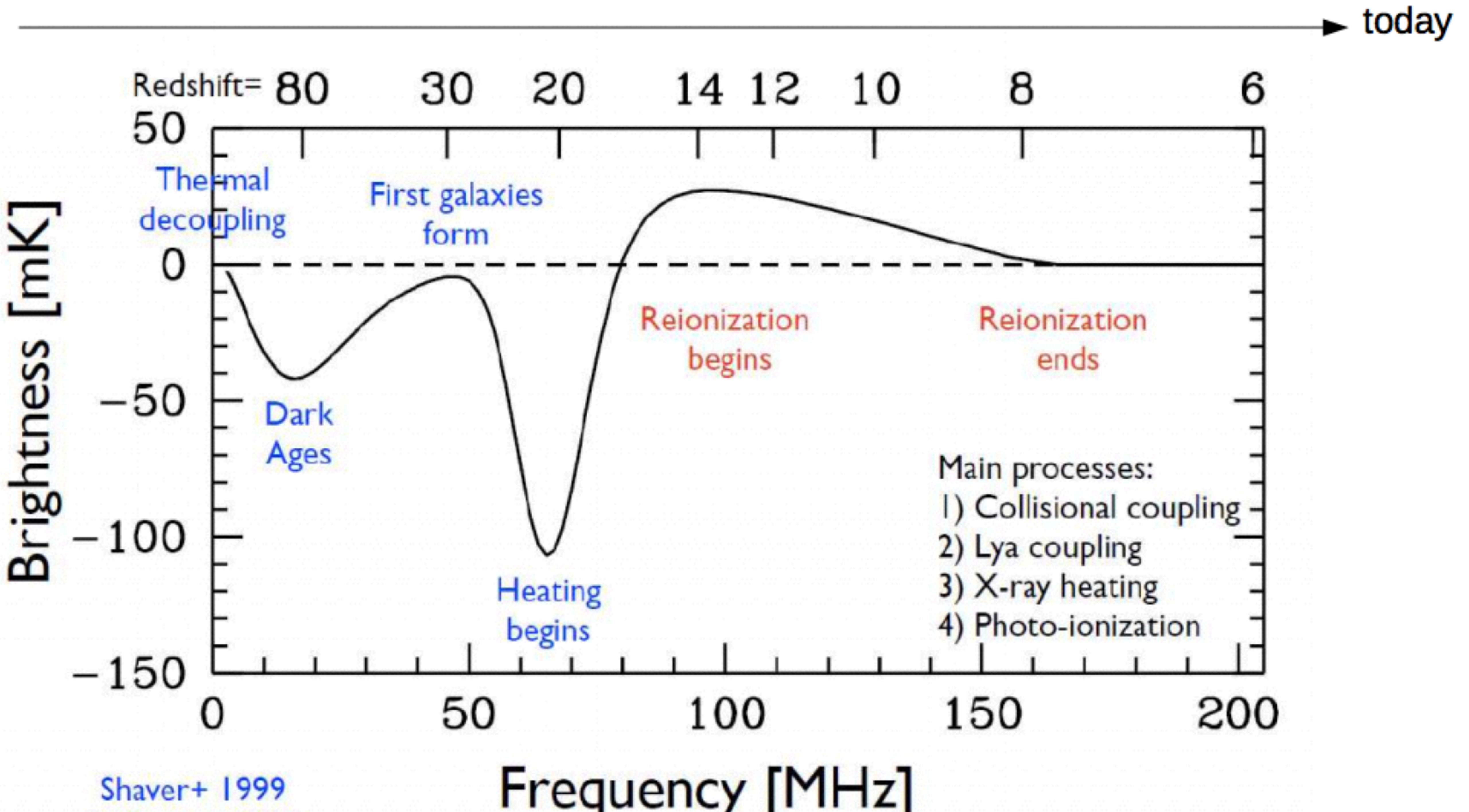
Optical depth

$$\tau \simeq \frac{3\lambda_{21}^2 A_{10} n_{\rm H}}{16 T_s H(z)}$$

21CMFAST
Messinger et al.
MNRAS 2011

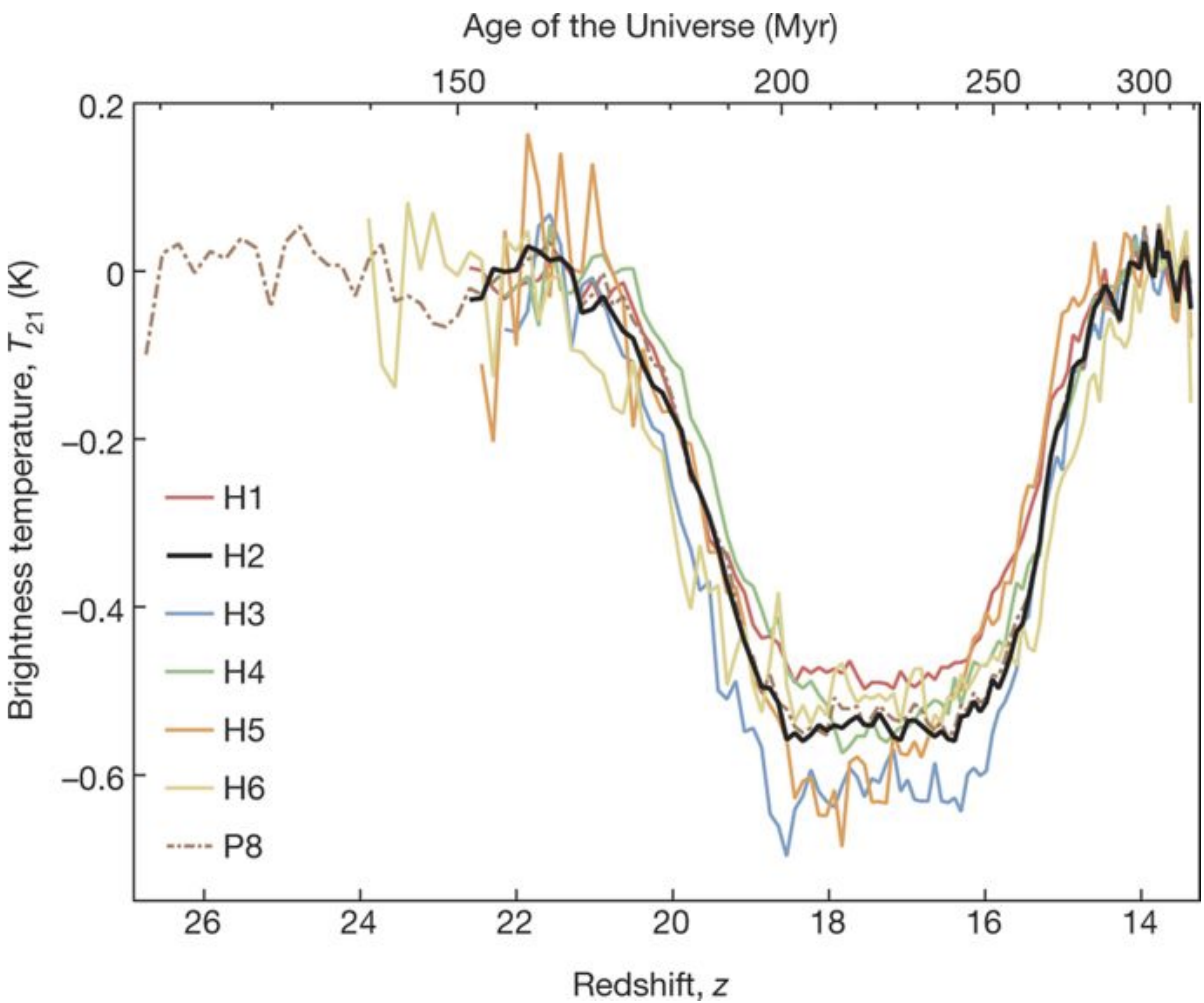


$$
\begin{aligned}
T_{21} &= \frac{T_s - T_\gamma}{1+z}\left(1 - e^{-\tau}\right) \\
&\simeq \frac{T_s - T_\gamma}{1+z}\,\tau
\end{aligned}
$$



Shaver+ 1999
Furlanetto 2006
Pritchard & Loeb 2010

First 21-cm observation , Bowman et al , Nature 2018



$$T_{21}^{SM}(z = 17) \gtrsim -220 \text{ mK}$$

$$T_{21}^{EDGES}(z \simeq 17) = -500^{+200}_{-500} \text{ mK}$$

Predicted spin temperature $T_s(z = 17) \geq 6.8\,K$

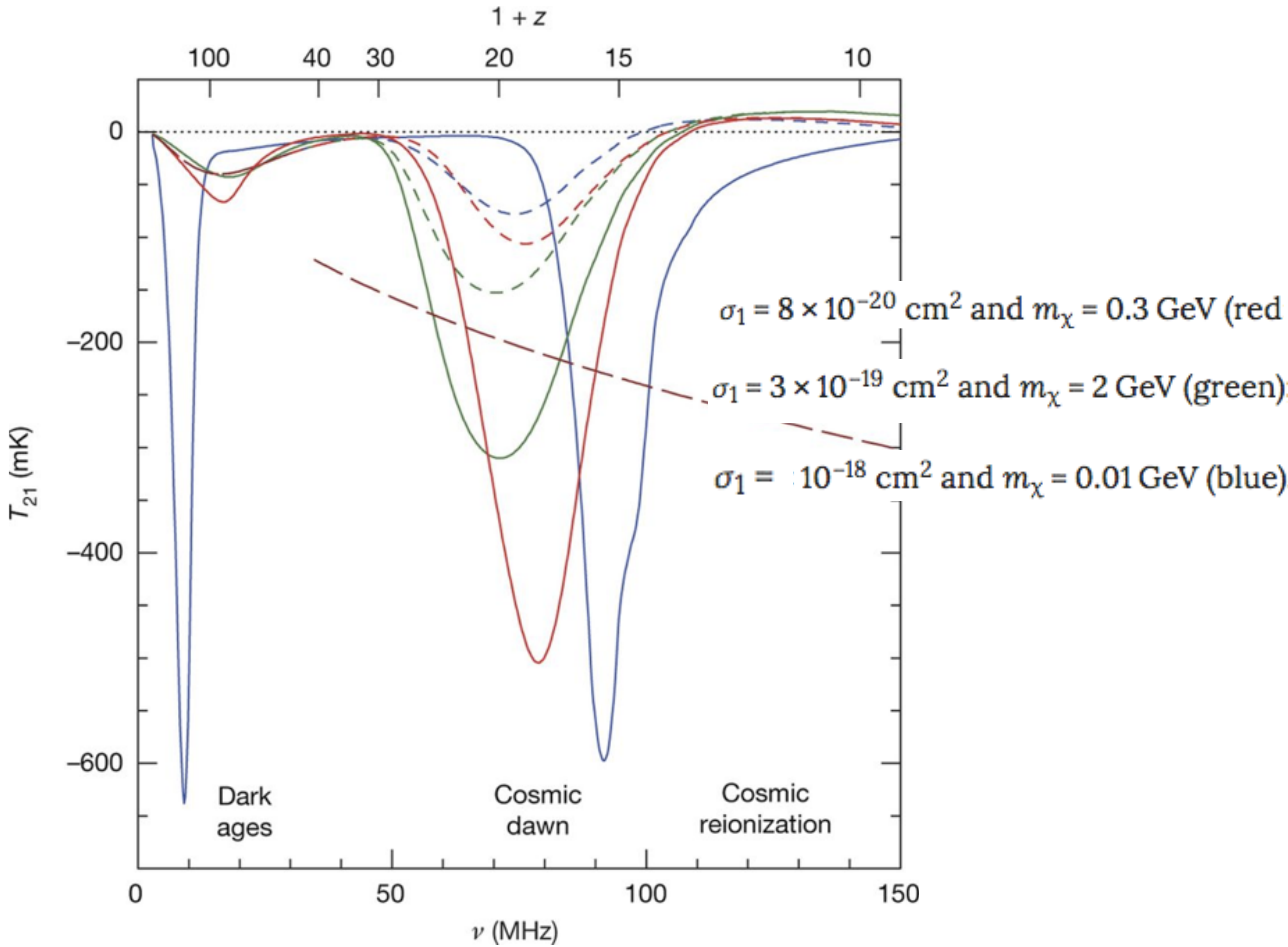
Spin temperature implied by EDGES

$$T_s(z = 17) = 3.26^{+1.94}_{-1.58}\,K$$

Barkana et al 1803.03091

Three ways of explaining excess dip observed by EDGES

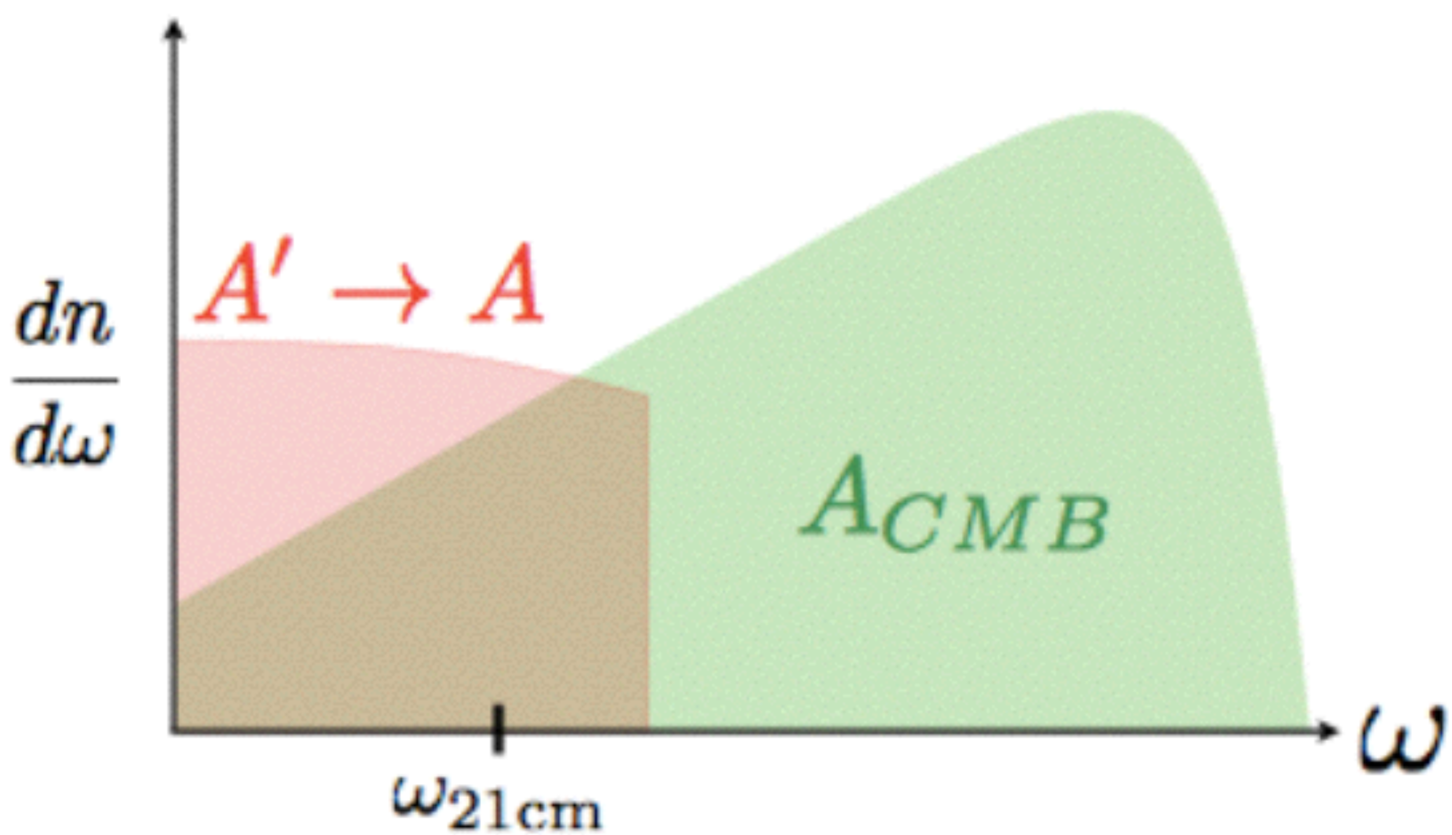
- Interaction of protons with CDM to lower gas temperature.
- Generate excess CMB at ~ 79 MHz by axion-photon conversion, axion decay, dark photon mixing etc.
- Lower spin temperature by spin flip interactions.



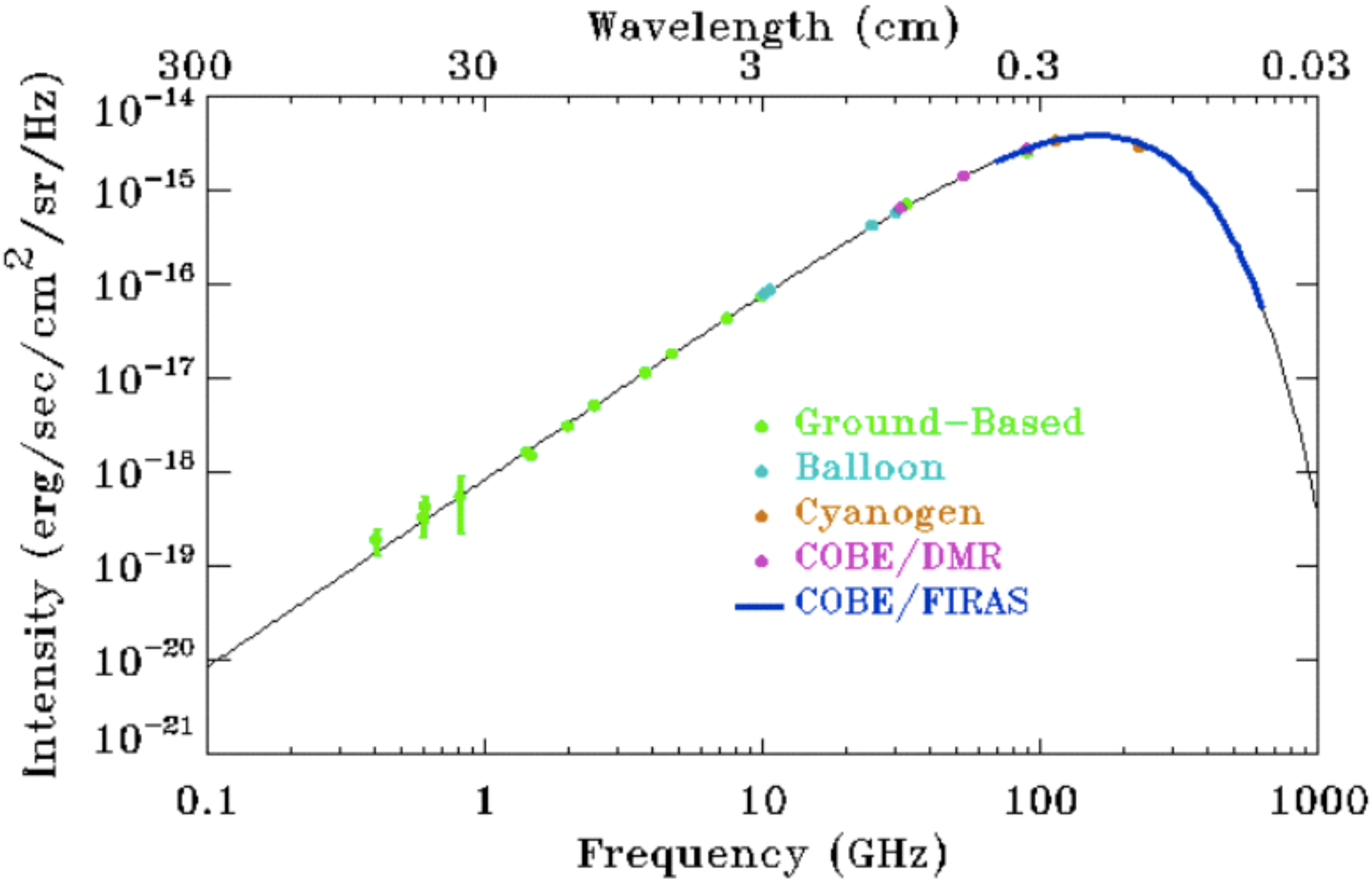
Baryon-DM interaction ?

Barkana, Nature, 2018

Pospelov, Pradler, Ruderman, Urbano (2018)
Resonant conversion of dark photons to 21-cm photons.



CMB spectrum not well tested at 85 MHz region



Pospelov et al (2018)

- Light DM a, decaying to two dark photons via an ALP coupling:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{a}{4f_a}F'_{\mu\nu}\tilde{F}'^{\mu\nu} + \mathcal{L}_{AA'}$$

- Dark photon mixes with EM via "familiar' kinetic mixing

$$\mathcal{L}_{AA'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2\,.$$

The decay rate of $a \to 2A'$ is

$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times 10^{-4}}{\tau_{\rm U}}\left(\frac{m_a}{10^{-4}\,\text{eV}}\right)^3\left(\frac{100\,\text{GeV}}{f_a}\right)^2.$$

QCD Axions

Axion mass

$$m_a = \frac{m_\pi f_\pi}{f_a} \frac{\sqrt{m_u m_d}}{m_u + m_d} \simeq 5.9\mu\text{eV} \left(\frac{10^{12}\,\text{GeV}}{f_a} \right)$$

Axion dark matter density

$$\Omega_a = 0.15 \left(\frac{10^{12}\,\text{GeV}}{f_a} \right)^{7/6} \theta_1^2$$

HI spin flip by resonant axion emission into axion BEC
Lambiase & SM (2018)

Axion-electron coupling

$$H_{int} = \frac{g_f}{2f_a}\left(\nabla a \cdot \vec{S} + \frac{\partial_t a}{m_f}\vec{p} \cdot \vec{S}\right)$$

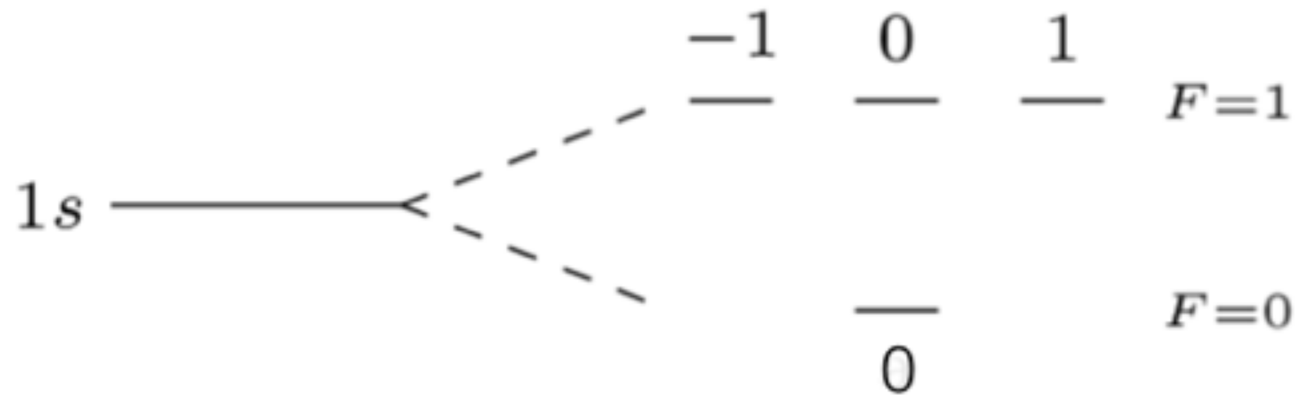
Sikivie (2014)

First term can cause spin flip by axion emission/absorbtion by electron or proton in HI

Auriol, Davidson, Raffelt 1808.09456

- Axion coupling too weak to give observable effect.
- Spin flip process raises spin temperature not lowers it.

Spin temperature from spin flip



$$\frac{n_1}{n_0} \equiv 3\ e^{-T_*/T_s}$$

If $\{J=0, M=0\} \leftrightarrow \{J=1, M=0,\pm 1\}$ are in equilibrium

$$n_1 = 3\,n_0 \quad \text{therefore} \quad T_s \to \infty$$

True for photon mediated transitions

However …for axion mediated spin flips

$$\frac{g_e}{f_a}\langle J=1, M=0,\pm 1|\vec{p}_a\cdot\vec{S}_e|J=0, M=0\rangle$$

$$\langle J=1, M=0|S_z^e|J=0, M=0\rangle = \frac{1}{2},$$
$$\langle J=1, M=\pm 1|S_z^e|J=0, M=0\rangle = 0.$$

J=0 state connects to only one of the J=1 states

If axion spin flip is the most dominant process

$$n_1/n_0 = 1$$

and the spin temperature goes towards

$$T_s = -T_* \ (\ln[1/3])^{-1} = 0.062\,\mathrm{K}$$

We need $T_s \sim 1.68\ K$

Taking into account all processes (including axions)

$$T_s = \frac{A_{10}T_\gamma + C_{10}T_* + P_{10}T_* + \Gamma^a_{10}T_*}{A_{10} + C_{10}\frac{T_*}{T_k} + P_{10}\frac{T_*}{T_c} + \frac{2}{3}\Gamma^a_{10}}$$

Transition by axion emission/absorption

Transition amplitude

$$\mathcal{M}_{01} = \frac{g_f}{2f_a}|p_a|\frac{1}{\sqrt{2E_aV}}\langle N_p|a_p|N_p+1\rangle$$
$$= \frac{g_f}{2f_a}|p_a|\frac{1}{\sqrt{2E_aV}}\sqrt{N_p}$$

Decay width

$$\Gamma^a_{10} = \frac{1}{16\pi^2}\left(\frac{g_f}{f_a}\right)^2 p^3_{10}N_p.$$

Numerical value

$$\Gamma_{10}^{a} = 6.2 \times 10^{-27} g_f^2\, p_{10}^3\, N_p \quad \mathrm{GeV}^{-2}$$

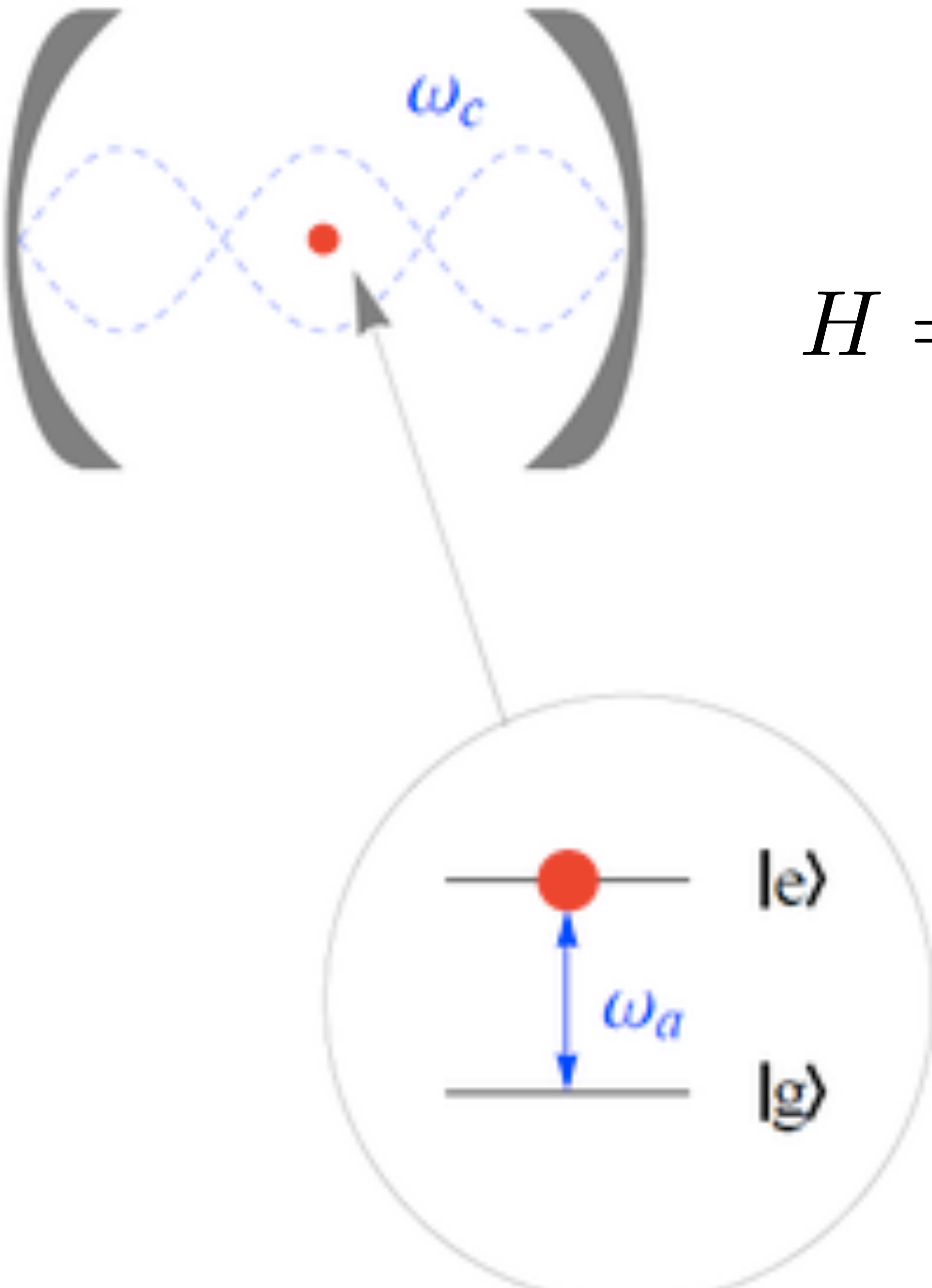
$$p^3 N_p \;=\; (2\pi)^3 n_p \;=\; (2\pi)^3 (\rho_a / m_a)$$

$$\Gamma_{10}^{a} \;\simeq\; 10^{-46}\, \mathrm{eV}.$$

Rate for photon induced transitions

$$\gamma = A_{10} N_\gamma \simeq A_{10} \frac{T_\gamma}{T_*} = 1.36 \times 10^{-27} \left(\frac{z+1}{18} \right) \mathrm{eV}$$

We need effects first order in f_a …coherent spin flip



Jaynes-Cummings model

$$H = \frac{\omega_a}{2}\sigma_z + \omega_c a^\dagger a + \lambda\left(\sigma^+ a + \sigma^- a^\dagger\right)$$

$$= \begin{pmatrix} \frac{1}{2}\omega_a + \omega_c n & \lambda(n+1)^{1/2} \\ \lambda(n+1)^{1/2} & -\frac{1}{2}\omega_a + \omega_c(n+1) \end{pmatrix}$$

Spin-oscillations in axionic bath

$$H = \begin{pmatrix} \frac{1}{2}(E_{10} - E_a) & \Omega \\ \Omega & -\frac{1}{2}(E_{10} - E_a) \end{pmatrix}$$

Axion induced transition frequency

$$\Omega = \lambda(N_p + 1)^{1/2} = \frac{g_f p_a}{2 f_a \sqrt{2E_a}} \left(\frac{N_p + 1}{V}\right)^{1/2} = \frac{g_f p_a}{2 f_a \sqrt{2E_a}} \sqrt{n_p}$$

Mixing angle

$$\theta = \frac{1}{2} \tan^{-1} \left(\frac{2\Omega}{E_{10} - E_a}\right)$$

1-0 transition amplitude by axion emission

$$\mathcal{M}_{10} = \frac{g_f}{2f_a}|p_a|\frac{1}{\sqrt{2E_aV}}\langle N_p+1|a_p^\dagger|N_p\rangle = \frac{g_f}{2f_a}|p_a|\frac{1}{\sqrt{2E_aV}}\sqrt{N_p+1}$$

$$H = E_{10}\,\frac{1}{2}\sigma_z + E_a a^\dagger a + \lambda\left(\sigma^+ a + \sigma^- a^\dagger\right)$$

$$= \begin{pmatrix} \frac{1}{2}E_{10} + E_a N_p & \lambda(N_p+1)^{1/2} \\ \lambda(N_p+1)^{1/2} & -\frac{1}{2}E_{10} + E_a(N_p+1) \end{pmatrix}$$

Transition probability

$$P_{10}^a(t) = \frac{\Omega^2}{(E_{10} - E_a)^2 + \Omega^2} \sin\left[\sqrt{(E_{10} - E_a)^2 + \Omega^2}\ t\right]$$

Taking into account decoherence due to photon process

$$\bar{P}_{10}^a = \int_0^\infty dt e^{-\gamma t} P_{10}^a(t)$$

$$= \frac{1}{2} \frac{\Omega^2}{\gamma^2 + \Omega^2 + (E_{10} - E_a)^2}$$

$$E_{10} = E_a = \sqrt{m_a^2 + p_a^2} \quad \text{for any} \quad m_a$$

Axion induced transition rate

$$\Omega = \lambda(N_p+1)^{1/2} = \frac{g_f p_a}{2 f_a \sqrt{2E_a}} \left(\frac{N_p+1}{V}\right)^{1/2}$$

$$= \frac{g_f}{2 f_a \sqrt{2E_{10}}} \left(E_{10}^2 - m_a^2\right)^{1/2} \sqrt{n_p}$$

$$= 0.77 \times 10^{-24} \sqrt{n_p}\ \mathrm{eV}^{-1/2} \left(\frac{\sqrt{E_{10}^2 - m_a^2}}{0.9 E_{10}}\right) \left(\frac{g_f\ 10^{12}\mathrm{GeV}}{f_a}\right)$$

Number of thermal axions at z=17

$$n_p = 0.45 \times 10^{-3} \mathrm{eV}^3$$

Rate for photon induced transitions

$$\gamma = A_{10} N_\gamma \simeq A_{10} \frac{T_\gamma}{T_*} = 1.36 \times 10^{-27} \left(\frac{z+1}{18} \right) \text{eV}$$

Axion process competitive with the photon process!

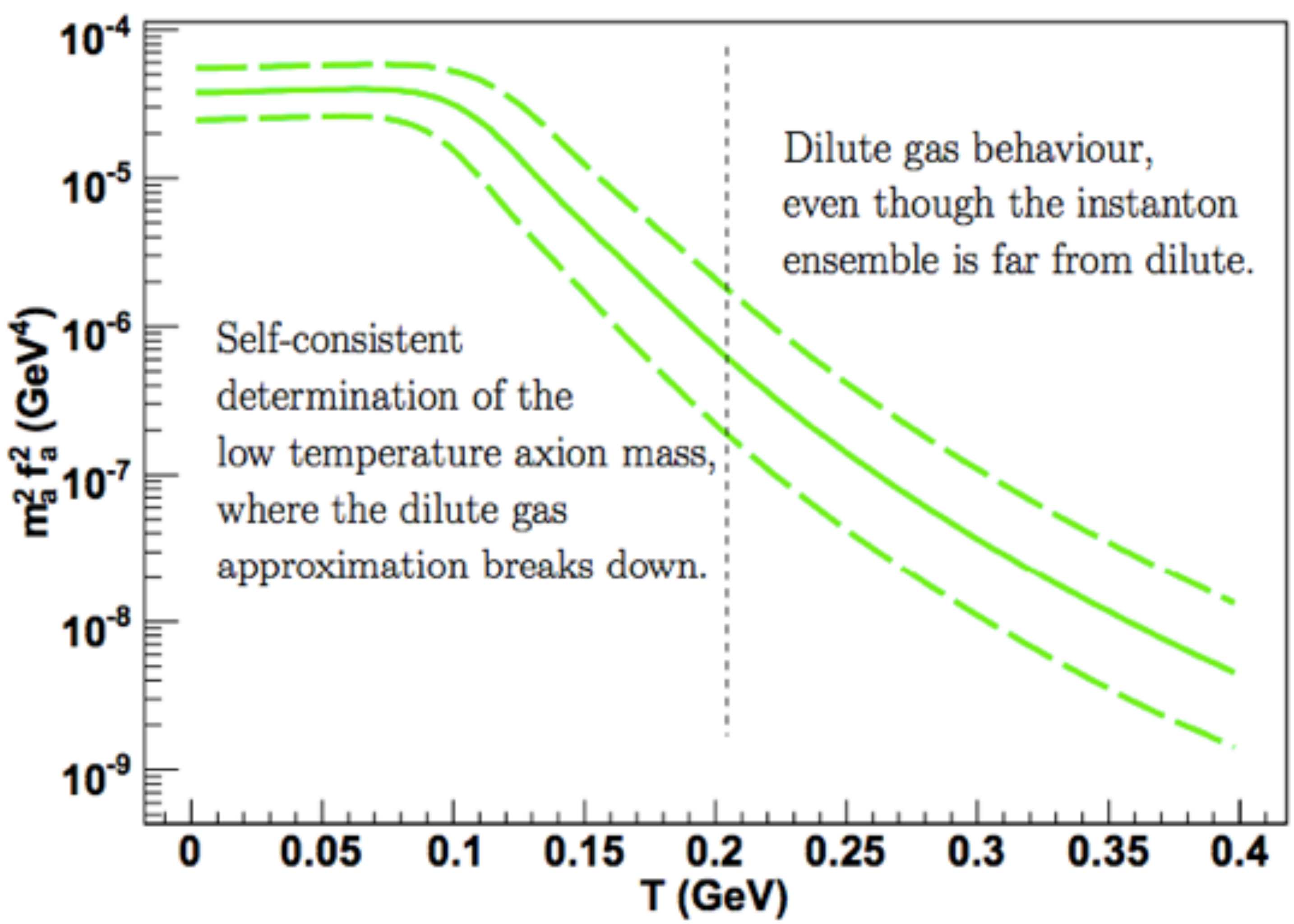
Thank You

Axion mass depends upon the temperature

In the low temperature regime the axion mass can be approximated by

$$m_a^2 f_a^2 = 1.46\,10^{-3}\Lambda^4 \frac{1+0.50\,T/\Lambda}{1+(3.53\,T/\Lambda)^{7.48}},\ 0 < T/\Lambda < 1.125\,,$$

$$\Lambda = 400\,\mathrm{MeV}$$



Olivier Wantz, E.P.S. Shellard arXiv:0910.1066

$$\text{If} \quad m_a(T) = E_{10} \quad \text{at} \quad T < 1eV$$

$$\text{Mixing angle} \quad \theta = \frac{\pi}{4} \text{ at some earlier era}$$