2nd IITB-Hiroshima workshop

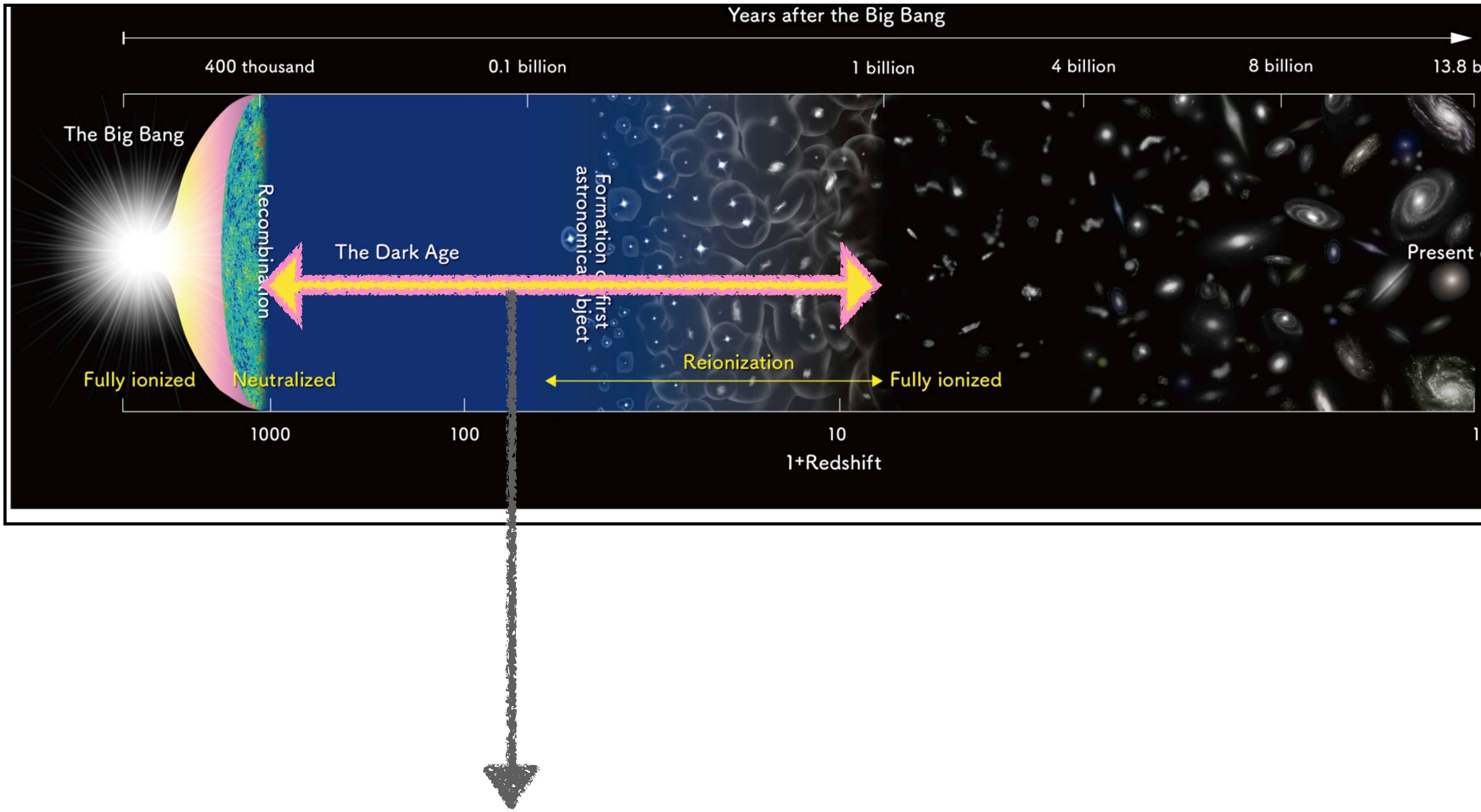
# Broadband Cosmological 21-cm signal from Dark Matter spin-flip Interactions

**Mansi Dhuria**

**IITRAM Ahmedabad**

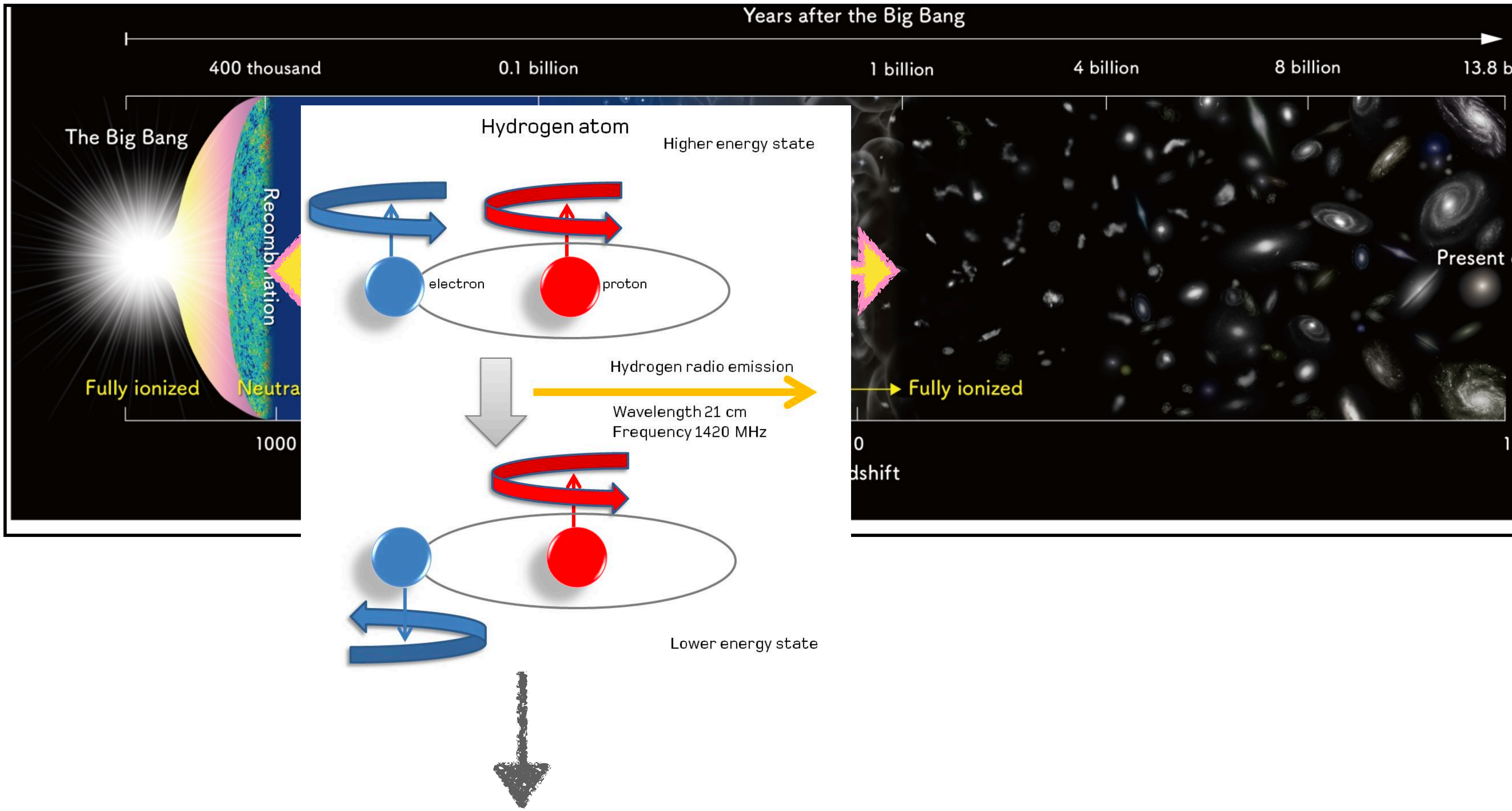
Based on JCAP 08 (2021) 041 (arXiv: astro-ph/2103.06303)
with Viraj Karambelkar, Vikram Rentala and Priyanka Sarmah

# Timeline of the universe...



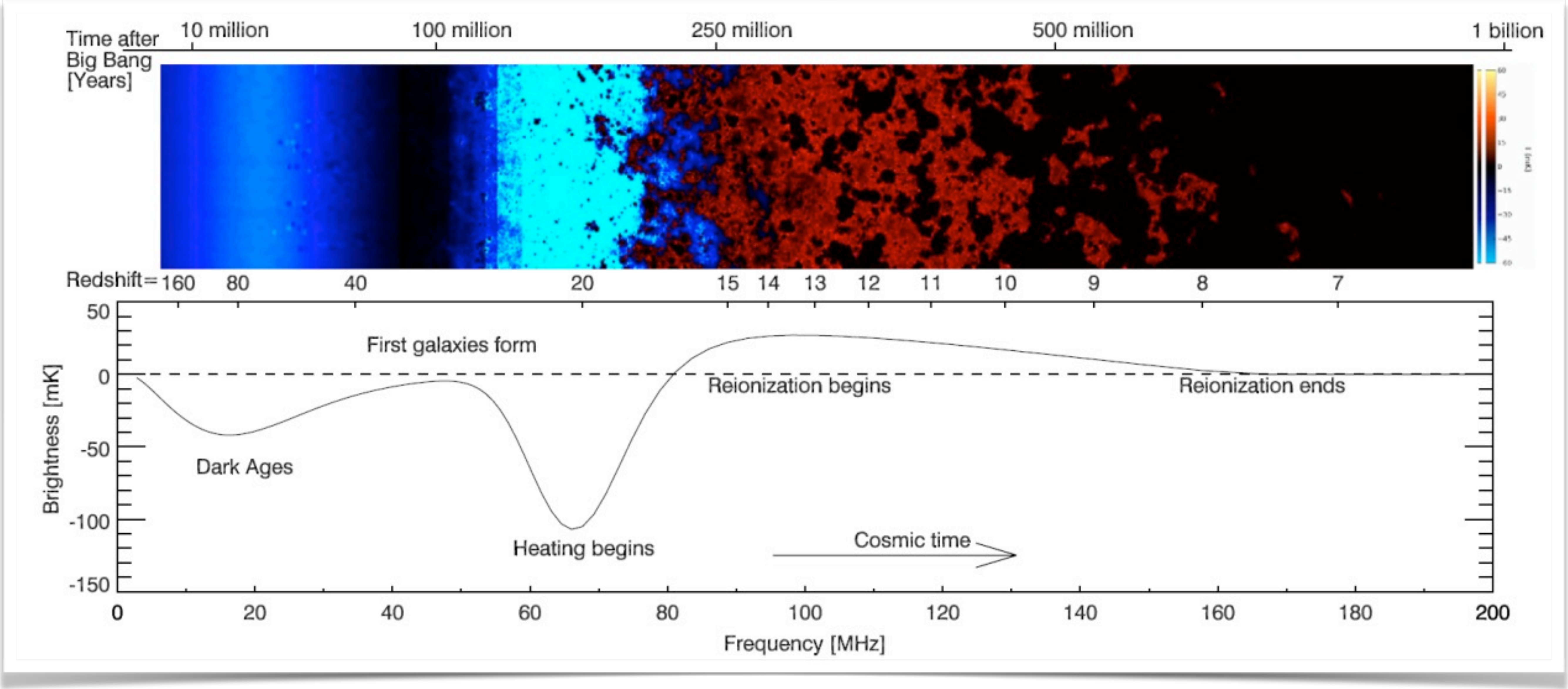

## Epoch of 21-cm Hydrogen

# Timeline of the universe…




# Epoch of 21-cm Hydrogen

# Global 21-cm signal in standard cosmology




Pritchard and Loeb 2012

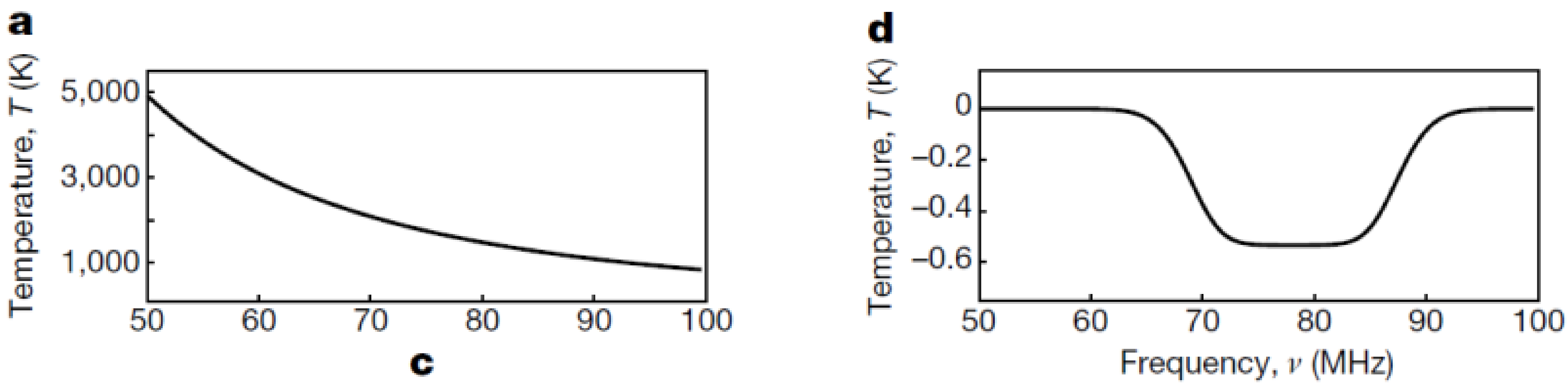
# Results from EDGES Global 21-cm Signal

LETTER

doi:10.1038/nature25792

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

Judd D. Bowman[1], Alan E. E. Rogers[2], Raul A. Monsalve[1,3,4], Thomas J. Mozdzen[1] & Nivedita Mahesh[1]



# Subsequent works...

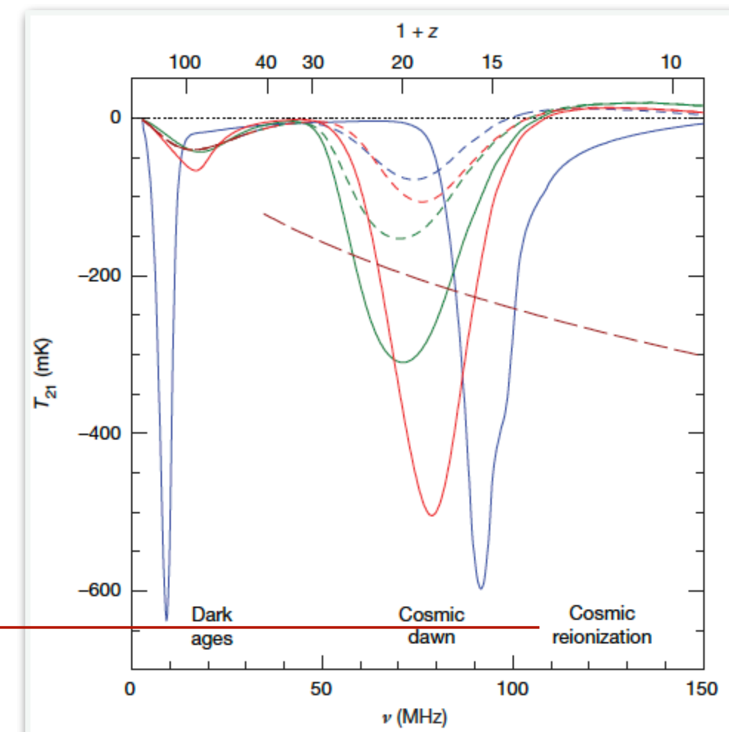
## Concerns about Modelling of the EDGES Data

Richard Hills, Girish Kulkarni, P. Daniel Meerburg, & Ewald Puchwein

ARISING FROM J. D. Bowman, A. E. E. Rogers, R. A. Monsalve, T. J. Mozdzen, & N. Mahesh *Nature* **555**, 67–70, (2018); https://doi.org/10.1038/nature25792.

## Excess cooling of Hydrogen due to its interaction with CDM:

**Barkana 2018,**
**Munoz and Loeb 2018,**
**Berlin, Hooper, Krnjaic, McDermott 2018,**
**Barkana, Outmezguine, Redigolo, Volansky, 2018**
**Kovetz et al 2018....**




## Other experiments:

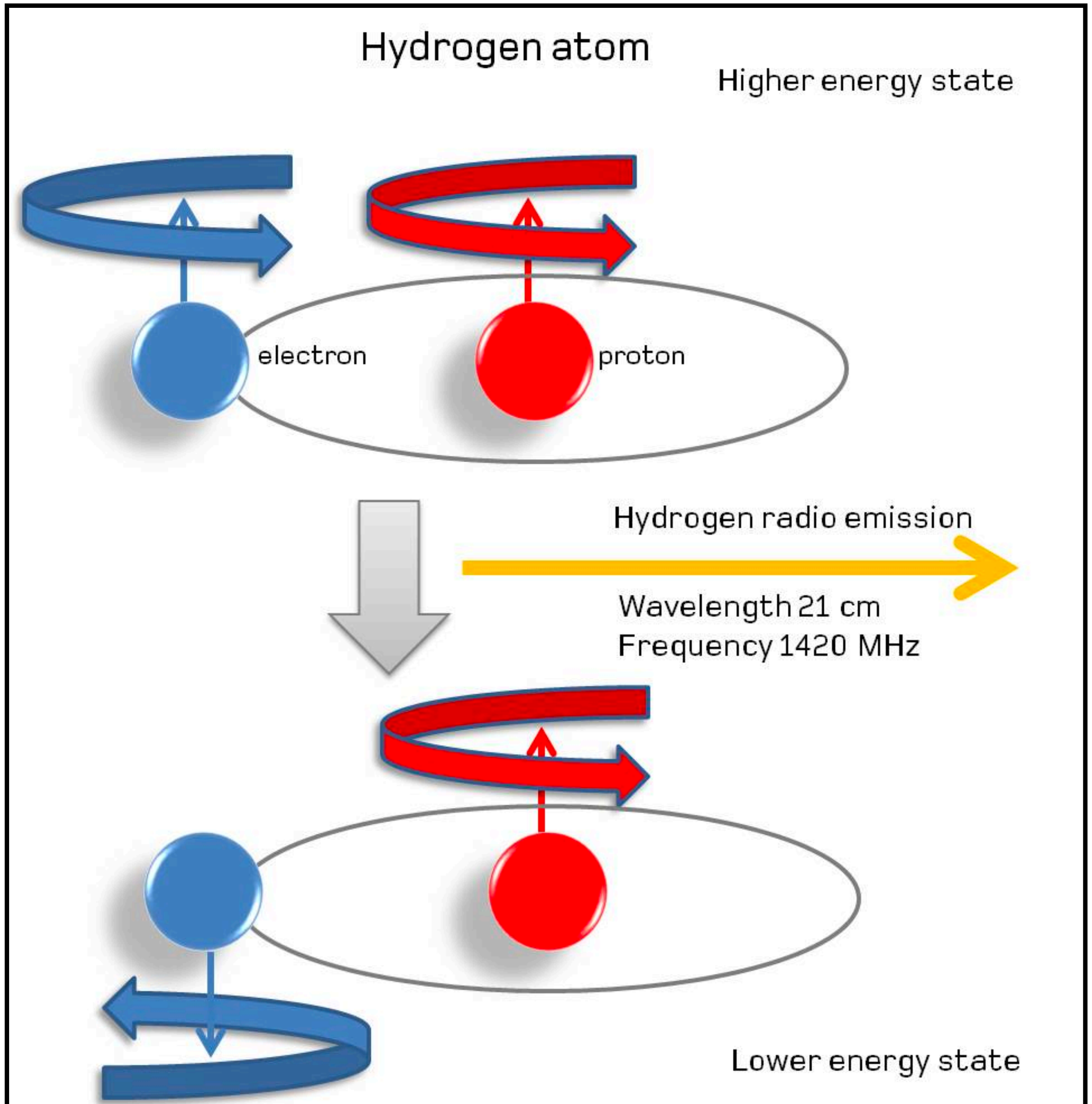
- **Low redshift-** **PRIZM, REACH, SARAS, SCI-HI, BIGHORNS (z ~15)**
- **Intermediate red-shift:** **LEDA (z~46), DAPPER (z~80)**
- **High red-shift:** **FARSIDE, PRATUSH, DARE, NCLE (z~1000)**

**Are there alternative predictions of the cosmological global 21-cm signal in Beyond Standard Model (BSM) physics that could be tested by future experiments?**

# Outline of the Talk

- Key parameters effecting the Cosmological 21-cm global signal.
- 21-cm signal in excess cooling models.
- **Template of the cosmological global 21-cm signal in DM-spin flip interaction model.**
- Constraints on the spin-flip coupling strengths.
- Summary of our results and future directions.

# 21-cm neutral hydrogen



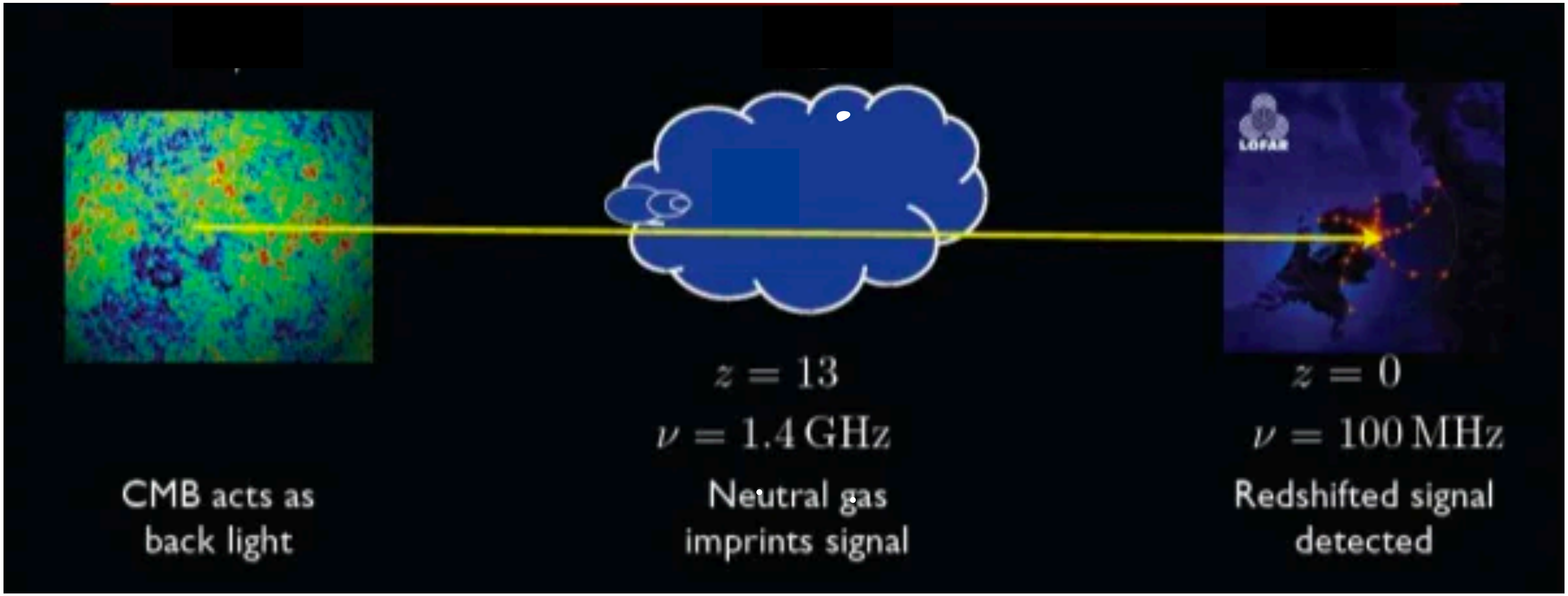

$$\frac{n_1}{n_0} = 3e^{-\frac{\Delta}{T_s}}$$

- $n_1$ - number of fermions in the singlet state

- $n_0$: Number of fermions in the triplet state

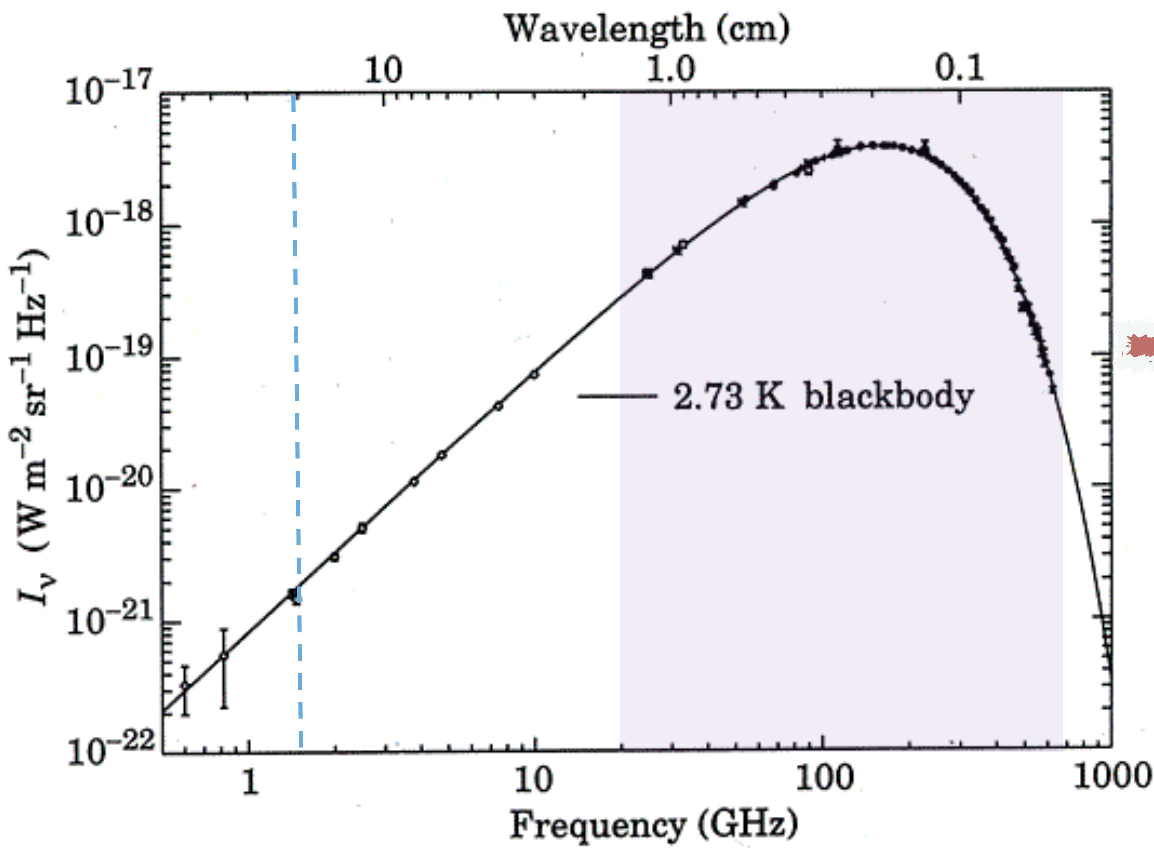
***$T_s$ - parameter describing the relative population of singlet and triplet states***

# Measuring 21-cm hydrogen




$$\nu = 1420/(1+z)\ \mathrm{MHz}$$

# Differential Brightness Temperature




$$I_\nu^{\mathrm{CMB}} = 2K_B T \frac{\nu^2}{c^2}$$

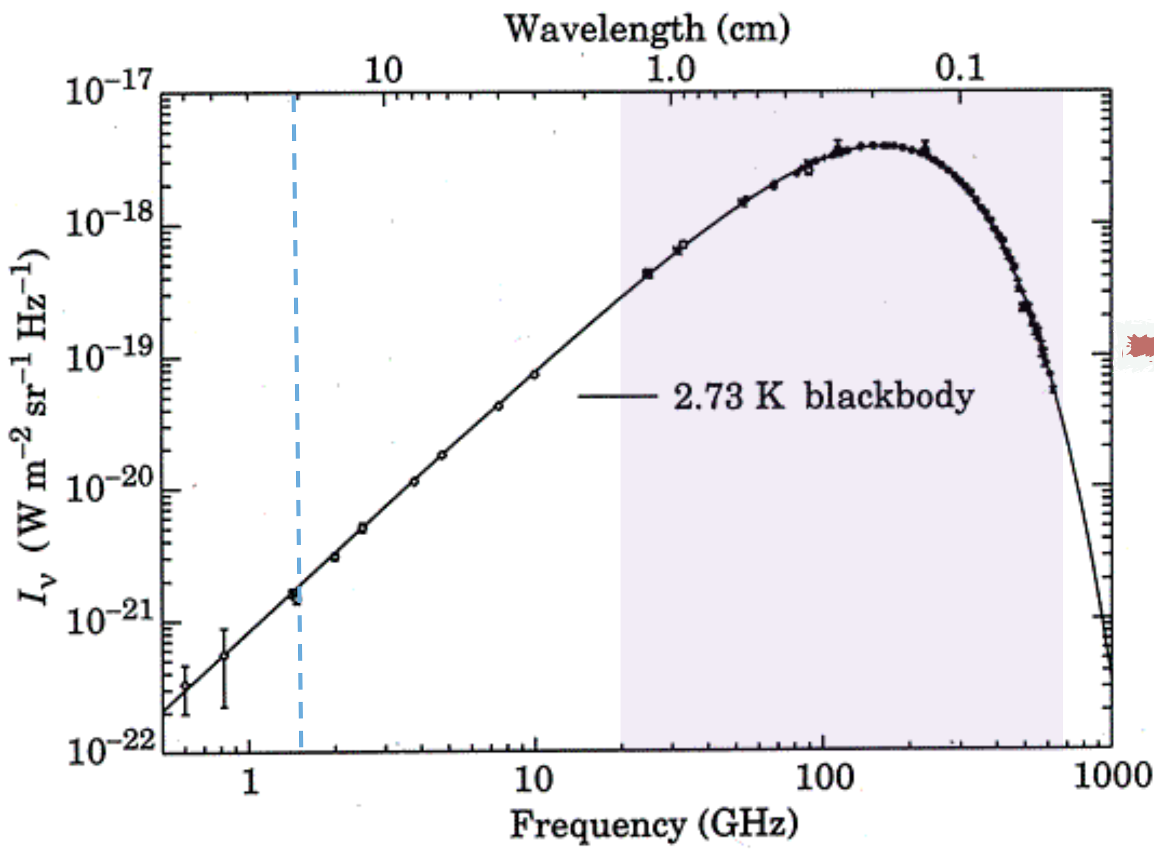
**Black Body expectation**

$$\delta T_b(z) \propto I_\nu^{\mathrm{measured}} - I_\nu^{\mathrm{CMB}} \propto x_{HI}(z) \left( \frac{T_s(z) - T_{\mathrm{CMB}}(z)}{T_s(z)} \right) \ \mathrm{mK}$$

$\delta T_b > 0$: net **emission** if $T_s > T_{CMB}$, i.e. more excited than needed to be in equilibrium with CMB

$\delta T_b < 0$: net **absorption** if $T_s < T_{CMB}$,

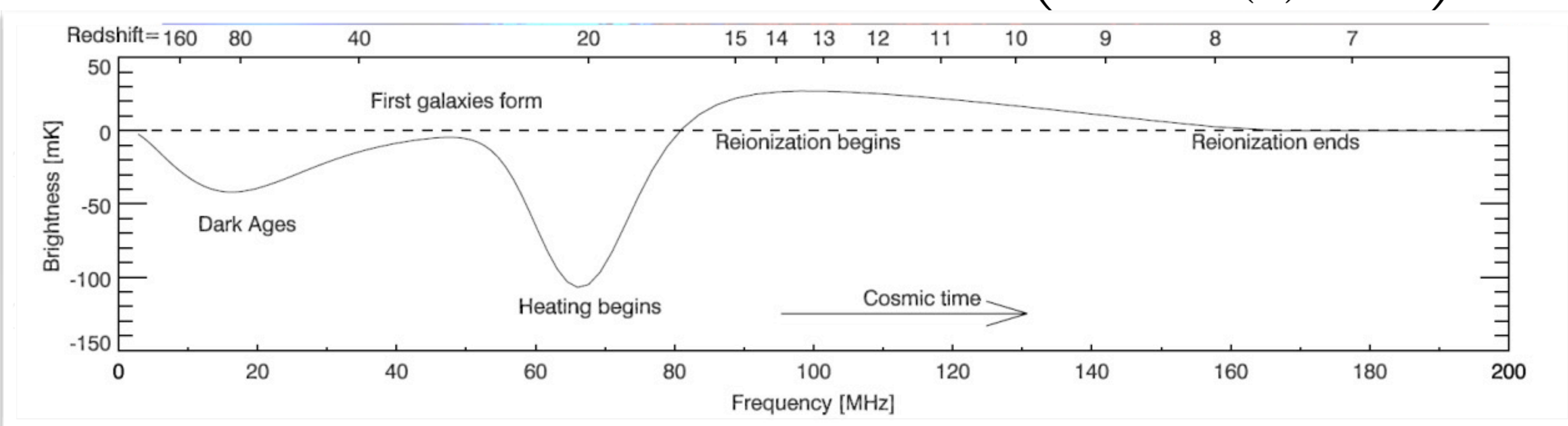
# Differential Brightness Temperature




$$I_\nu^{\rm CMB} = 2K_BT\frac{\nu^2}{c^2}$$

**Black Body expectation**

$$\delta T_b(z) \propto I_\nu^{\rm measured} - I_\nu^{\rm CMB} \propto x_{HI}(z)\left(\frac{T_s(z)-T_{\rm CMB}(z)}{T_s(z)}\right) \;\; {\rm mK}$$

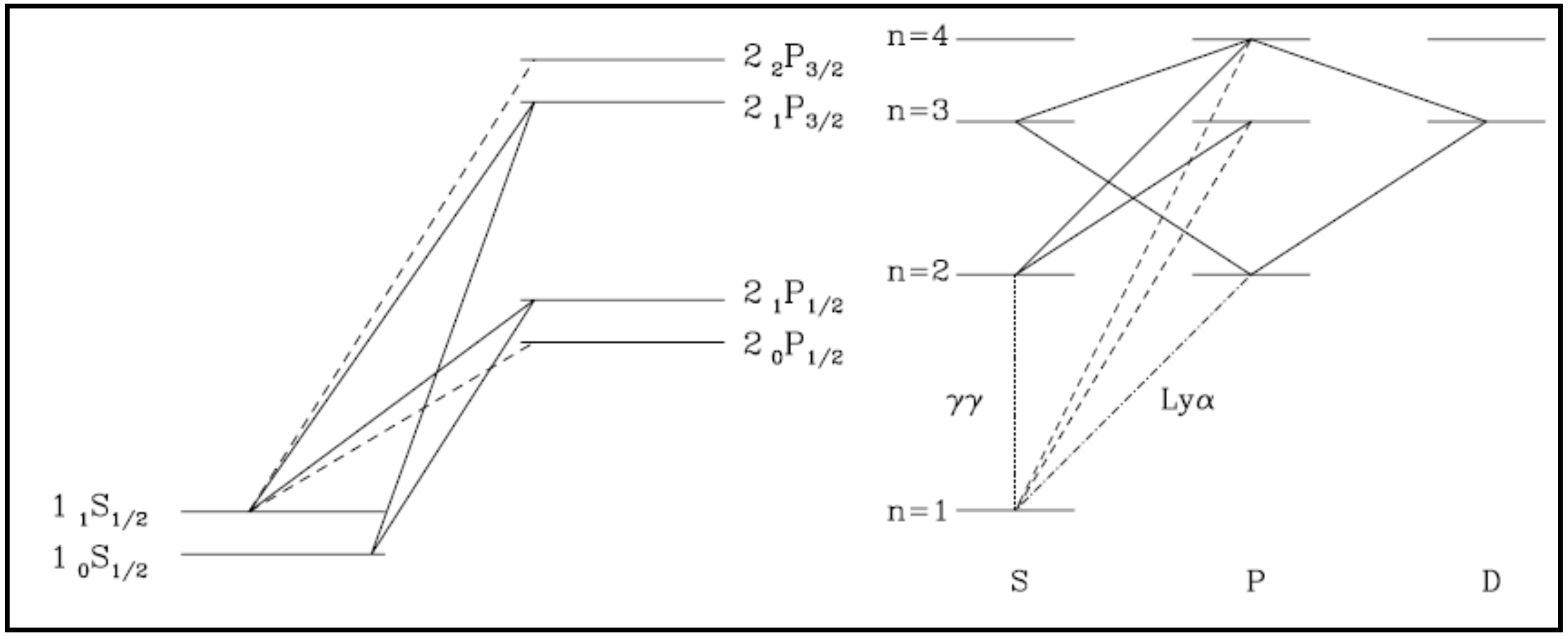


# Processes altering the spin temperature

- CMB excitations and de-excitations: **$A_{10}$ (spontaneous de-excitation), $B_{01}$(simulated excitation), $B_{10}$ (simulated de-excitation)**

- Collisional coupling H0 + (H,e,p): **$C_{01}$, $C_{10}$**

- Lyman-α photons from the first stars (Wouthuysen-Field effect): **$P_{01}$, $P_{10}$**



# Processes altering the spin temperature

$$n_0(B_{01} + C_{01} + P_{01}) = n_1(A_{10} + B_{10} + C_{10} + P_{10})$$

$$B_{10} = n_\gamma \langle \sigma(H_1 + \gamma \to H_0 + \gamma\gamma) v \rangle \simeq A_{10} \frac{T_{\rm CMB}}{\Delta}$$

$$\frac{n_1}{n_0} = 3e^{-\frac{\Delta}{T_s}} \simeq 3\left(1 - \frac{\Delta}{T_s}\right)$$

$$\frac{C_{01}}{C_{10}} = 3e^{-\frac{\Delta}{T_K}} \simeq 3\left(1 - \frac{\Delta}{T_K}\right)$$

$$\frac{P_{01}}{P_{10}} = 3e^{-\frac{\Delta}{T_c}} \simeq 3\left(1 - \frac{\Delta}{T_c}\right)$$

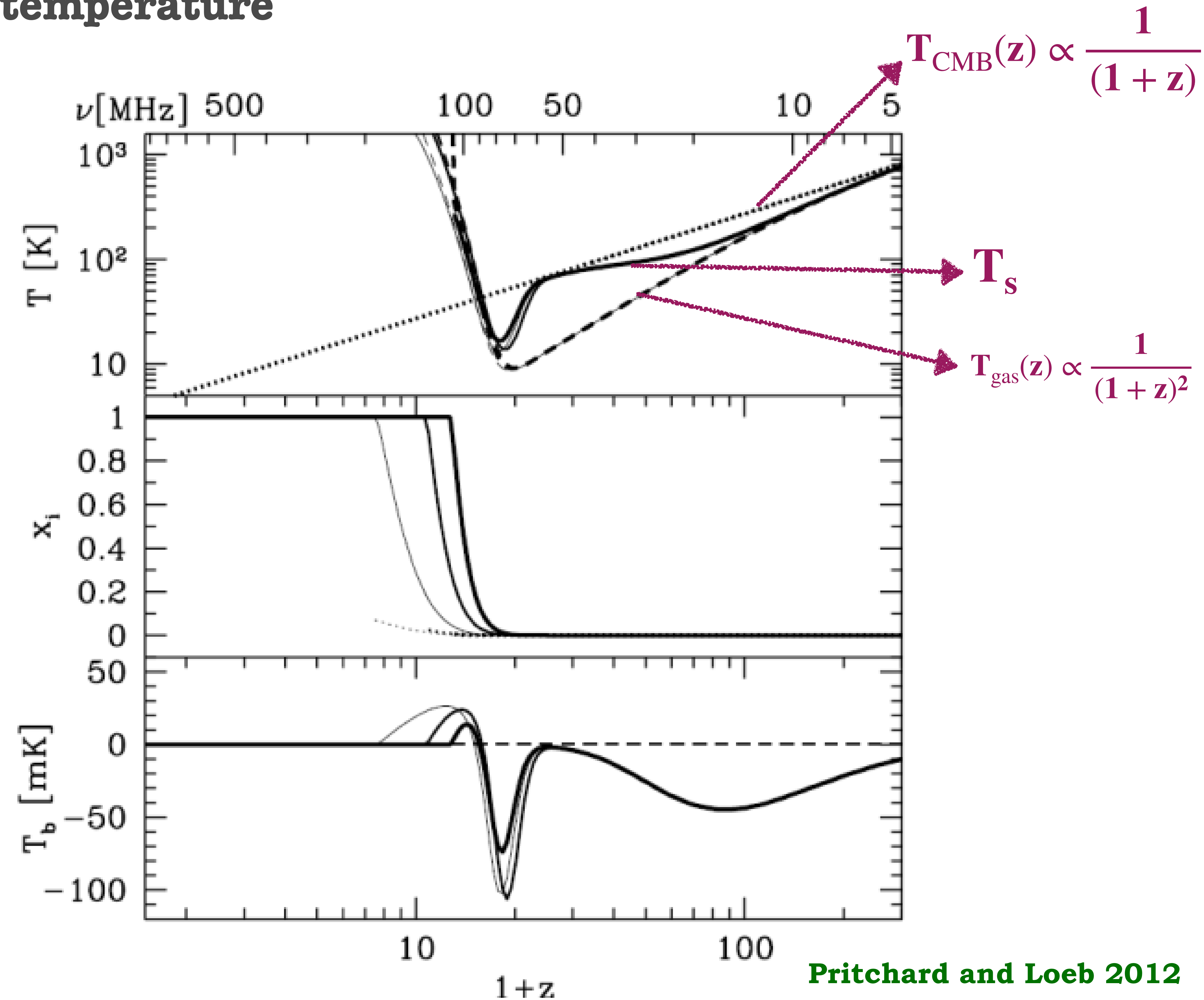
$A_{10} = (10 \ \ \text{million years})^{-1}$

$x_\alpha = \frac{P_{10}}{B_{10}}$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_c^{-1}}{1 + x_C + x_\alpha}$$

$x_C = \frac{C_{10}}{B_{10}}$

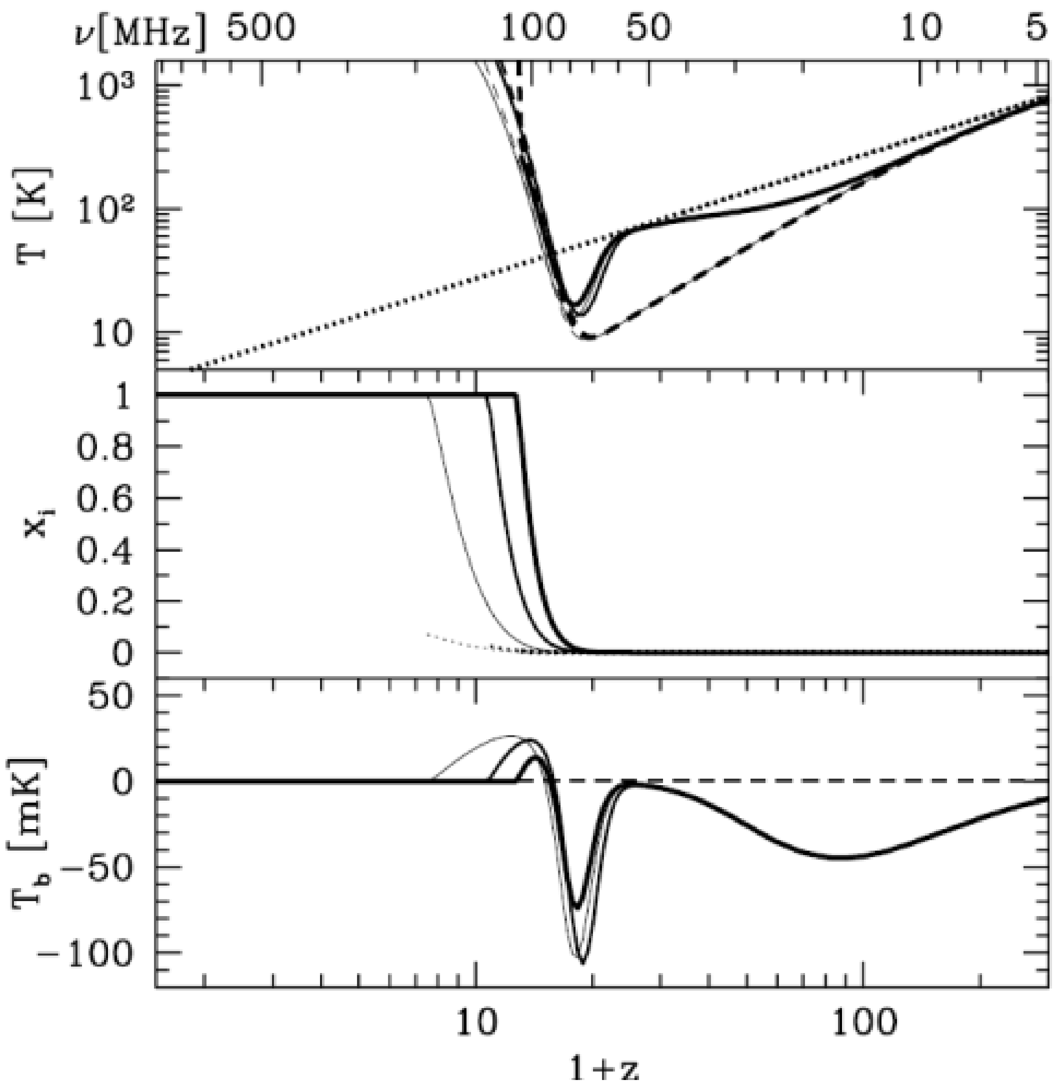
# Evolution of the Spin temperature, gas temperature and brightness temperature

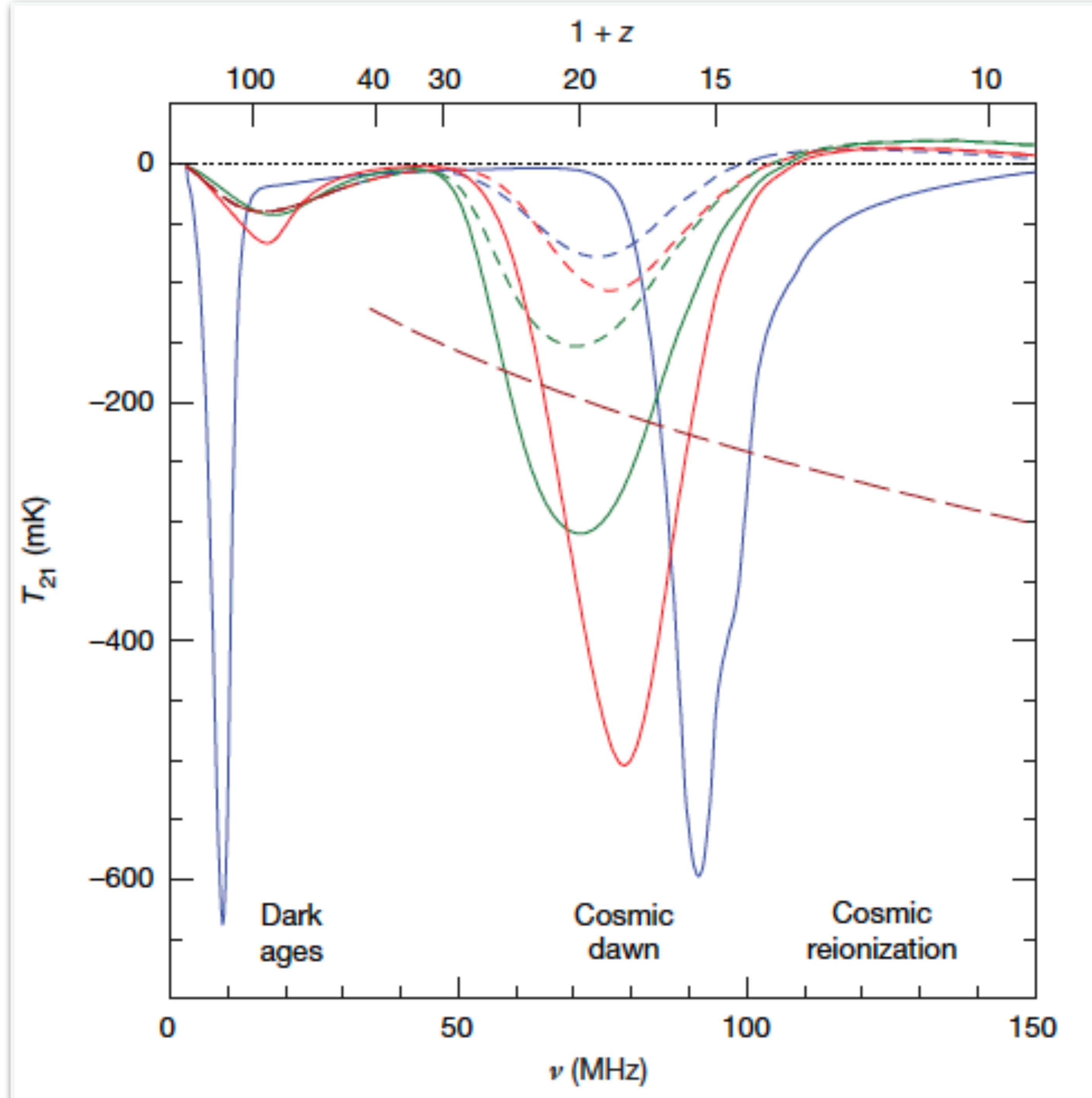



Pritchard and Loeb 2012

# Standard Cosmology/Excess Cooling Models

R. Barkana 2018



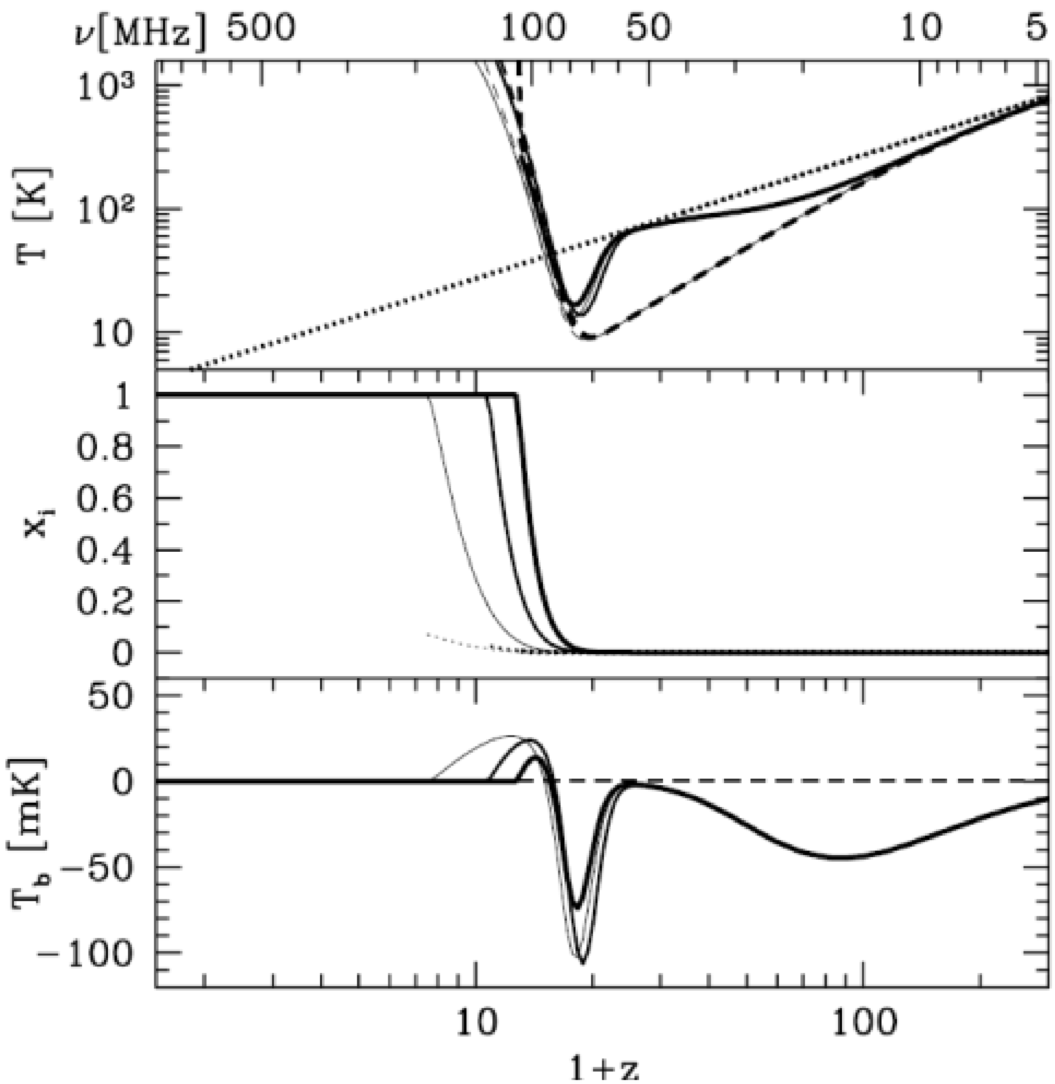

$\sigma_{\chi-H} \sim 8 \times 10^{-20}$ cm$^2$, $m_\chi \sim 0.3$ GeV

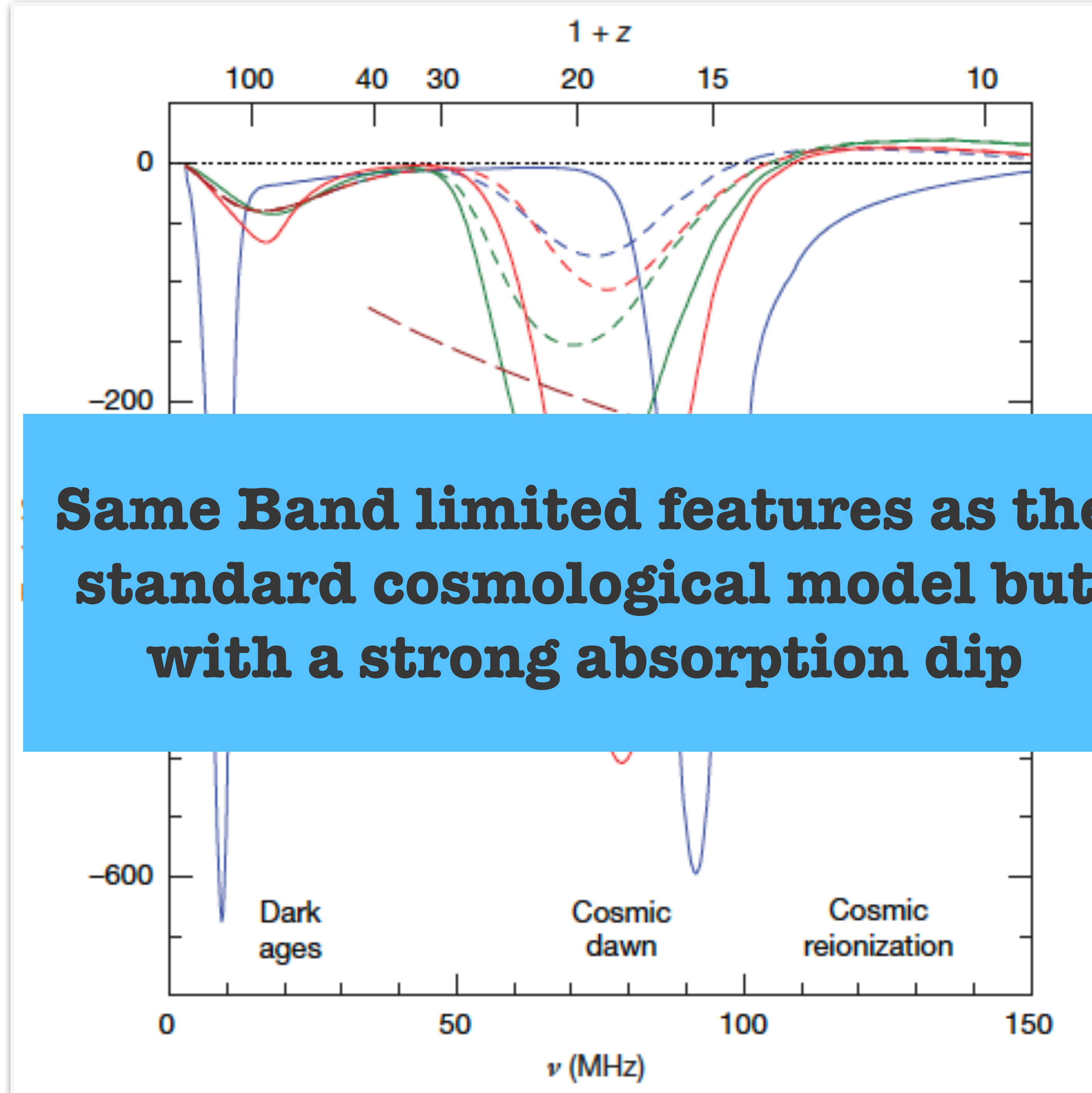
$\sigma_{\chi-H} \sim 3 \times 10^{-19}$ cm$^2$, $m_\chi \sim 2$ GeV

$\sigma_{\chi-H} \sim 3 \times 10^{-18}$ cm$^2$, $m_\chi \sim 0.01$ GeV

# Standard Cosmology/Excess Cooling Models

R. Barkana 2018




**Same Band limited features as the standard cosmological model but with a strong absorption dip**

$\sigma_{\chi-H} \sim 8 \times 10^{-20}$ cm$^2$, $m_\chi \sim 0.3$ GeV

$\sigma_{\chi-H} \sim 3 \times 10^{-19}$ cm$^2$, $m_\chi \sim 2$ GeV

$\sigma_{\chi-H} \sim 3 \times 10^{-18}$ cm$^2$, $m_\chi \sim 0.01$ GeV

**Are there alternative predictions of the cosmological global 21-cm signal in Beyond Standard Model (BSM) physics that could be tested by future experiments?**

↓

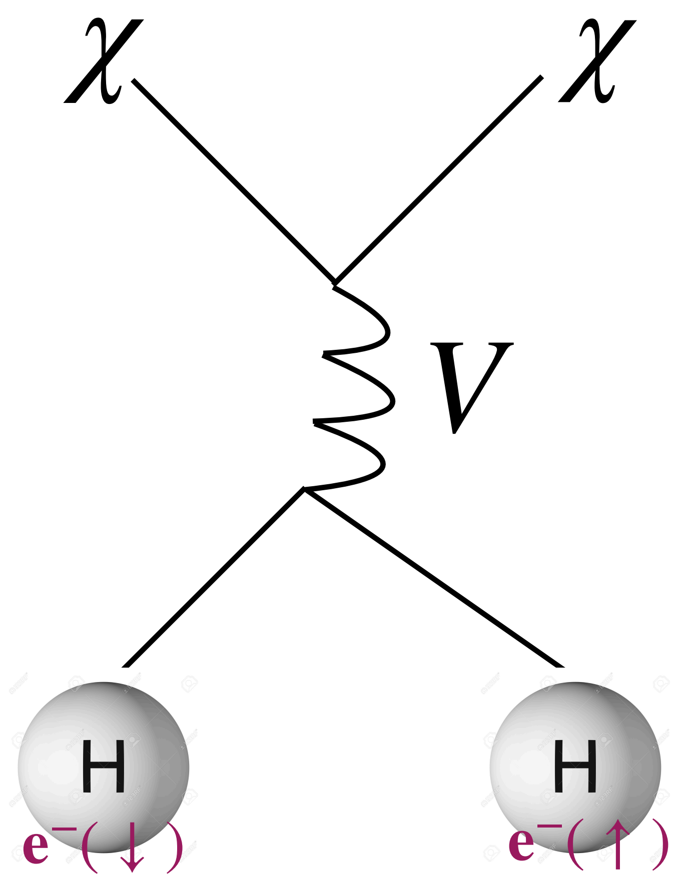
**Can we have other processes which could control the spin temperature?**

# Dark matter spin flip Interaction Model

# Spin-flip Interactions

$$\mathcal{L} = i g_\chi \overline{\chi} \gamma^\mu \gamma^5 \chi V_\mu + i g_e \overline{e} \gamma^\mu \gamma^5 e V_\mu$$

**t-channel scattering**




$$\chi + H_0 \leftrightarrows \chi + H_1$$

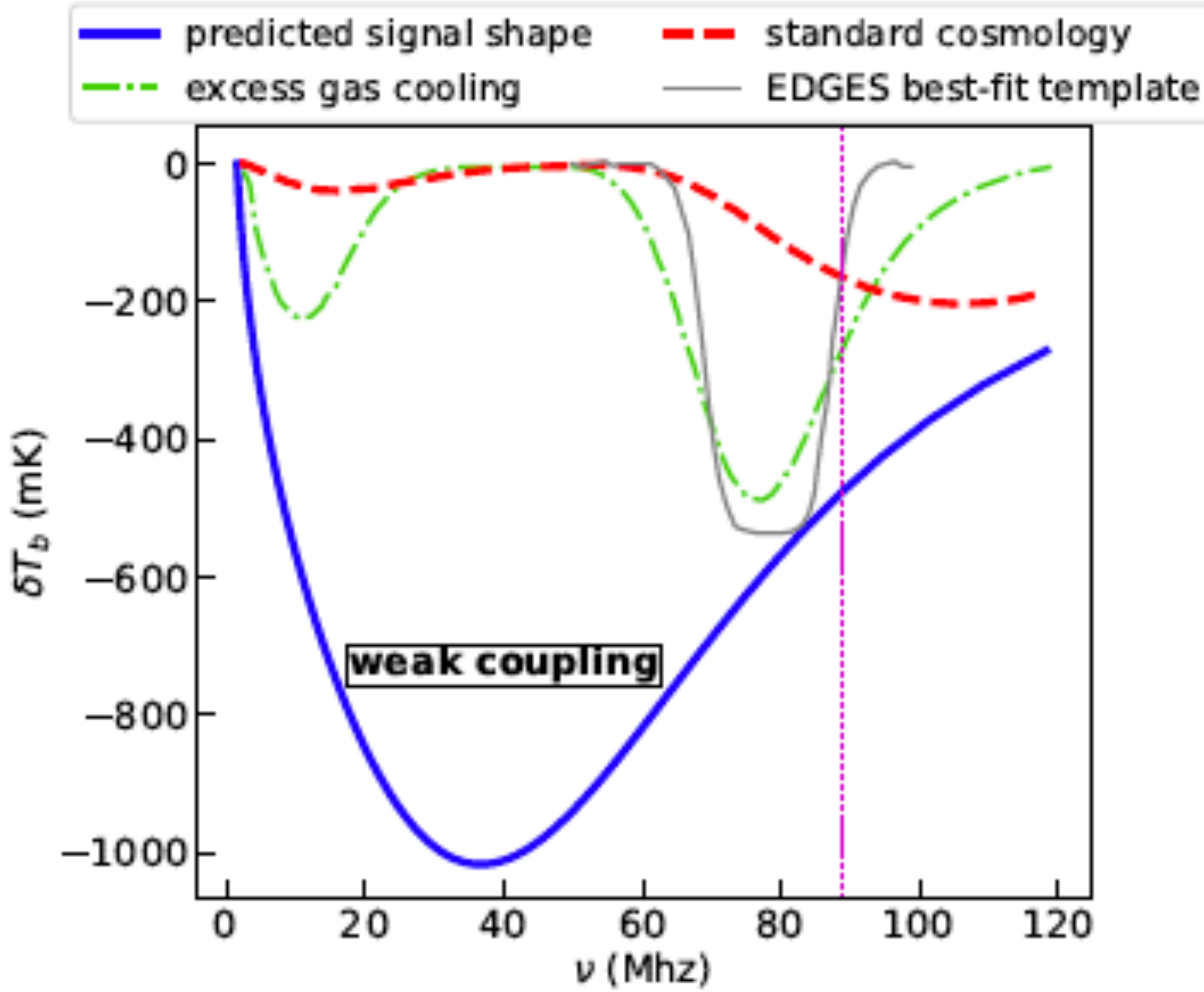
***The mechanisms altering the spin temperature are:***

- ***Direct spin flip interactions: D01, D10.***
- ***Energy exchange between Dark Matter and gas.***

***Five parameters:*** $\alpha_\chi, \alpha_e, m_\chi, f, m_V$

# Snapshot of our key results in comparison to Standard Cosmology/Excess cooling Models

- *Dominance of spin flip interactions over the energy transfer rate between gas and dark matter.*
- *Lower the spin-temperature over a large red-shift range leading to a single strong, broadband absorption signal ranging from 1.4 Mhz (z~1000) to 90 MHz (z~15).*
- *Spin-temperature does not necessarily track the gas temperature.*




**Other works: Lambiase and Mohanty 2018, Auriol et al 2018, Widmark 2019**

# Modified spin temperature

$$n_0(B_{01} + C_{01} + P_{01} + D_{01}) = n_1(A_{10} + B_{10} + C_{10} + P_{10} + D_{10})$$

$$\frac{D_{01}}{D_{10}} = 3e^{-\Delta/T_{\rm eff}} \simeq 3\left(1 - \frac{\Delta}{T_{\rm eff}}\right)$$

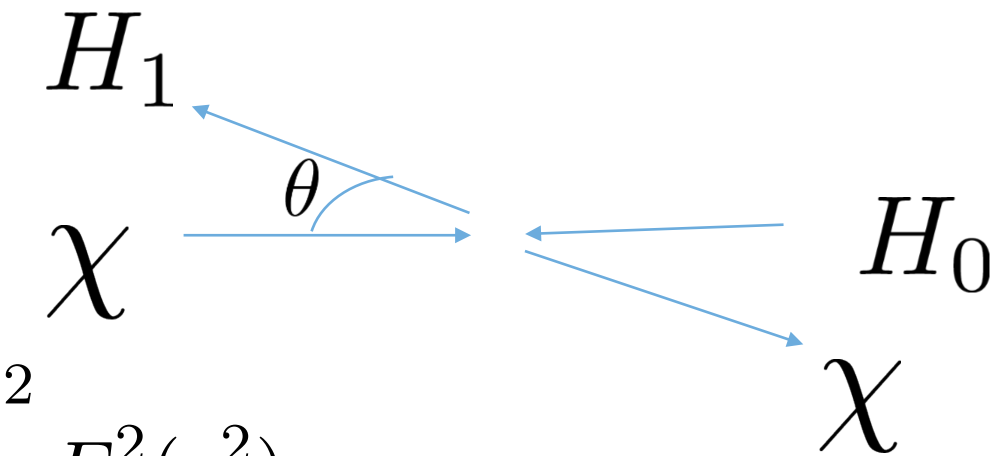
$$T_{\rm eff} = \mu\left(\frac{T_K}{m_H} + \frac{T_\chi}{m_\chi}\right)$$

$$\mu = \frac{m_H m_\chi}{m_H + m_\chi}$$

$$T_s^{-1} = \frac{T_{\rm CMB}^{-1} + x_C T_K^{-1} + x_\alpha T_c^{-1} + x_D T_{\rm eff}^{-1}}{1 + x_C + x_\alpha + x_D}$$

# Forward Scattering and Spin flip cross-section

**In the non-relativistic limit,**




$$V(r) = \frac{g_\chi g_e}{r} e^{-m_V r} (\vec{S}_e \cdot \vec{S}_\chi)$$

$$\sigma_{01} v_{\rm rel} \simeq \frac{3}{2\pi} g_\chi^2 g_e^2 \mu p' \int_{-1}^{1} d(\cos\theta) \left( \frac{1}{q^2 - m_V^2} \right)^2 F^2(q^2).$$

**For elastic scattering with massless mediator, the crossection scales as Rutherford scattering**

$$\frac{d\sigma}{d\Omega} \propto \frac{\alpha_e \alpha_\chi}{\mu^2 v^4 \sin^4 \frac{\theta}{2}}$$

$$\sigma_{01} \sim \frac{3}{4\pi} \frac{g_\chi^2 g_e^2}{\Delta^2}$$ **, assuming** $m_V^2 \ll p_{\rm th}^4 / p_c^2 \approx \sqrt{\frac{2\mu}{T_{\rm eff}}} \Delta$

# Spin flip Interactions vs Energy transfer rate

$$\sigma_{01} \sim \frac{3}{4\pi}\frac{g_\chi^2 g_e^2}{\Delta^2}$$ **, assuming** $$m_V^2 \ll p_{\rm th}^4/p_c^2 \approx \sqrt{\frac{2\mu}{T_{\rm eff}}}\Delta$$

$$T_{\rm eff} = \mu\left(\frac{T_K}{m_H} + \frac{T_\chi}{m_\chi}\right)$$

$$\mu = \frac{m_H m_\chi}{m_H + m_\chi}$$

- ***a nearly divergent scattering crosssection driven by the large probability for forward scattering. This divergence is cut-off by the tiny hyperfine mass-splitting between the singlet and triplet states***

$$D_{10} \propto n_\chi \langle \sigma v \rangle$$

- ***Small mass splitting Leads to a large cross-section for the spin-flip interaction.***

$$D_{10} = 3.01 \times 10^{-12}\left(\frac{f}{0.1}\right)\left(\frac{0.1\ \mathrm{GeV}}{m_\chi}\right)\left(\frac{\alpha_\chi}{10^{-2}}\right)\left(\frac{\alpha_e}{10^{-14}}\right)\left(\frac{0.1\ \mathrm{GeV}}{\mu}\right)^{\frac{1}{2}}\left(\frac{T_{\rm eff}}{10\ \mathrm{K}}\right)^{\frac{1}{2}}\left(\frac{1+z}{1+10}\right)^{3}\ \mathrm{s}^{-1}$$

# Spin flip Interactions vs Energy transfer rate

The energy transfer cross-section for the massless mediator in case of elastic scattering

$$\frac{d\overline{\sigma}}{d\Omega} \propto \frac{\alpha_e \alpha_\chi}{\mu^2 v^4 \sin^4 \frac{\theta}{2}} (1 - \cos\theta)$$

In our case of DM induced inelastic spin flip scattering,

$$\overline{\sigma} = 4\pi \frac{\alpha_e \alpha_\chi}{\Delta^2} \times \frac{\Delta}{T_{\rm eff}}$$

→ **Suppressed by hyperfine splitting parameter**

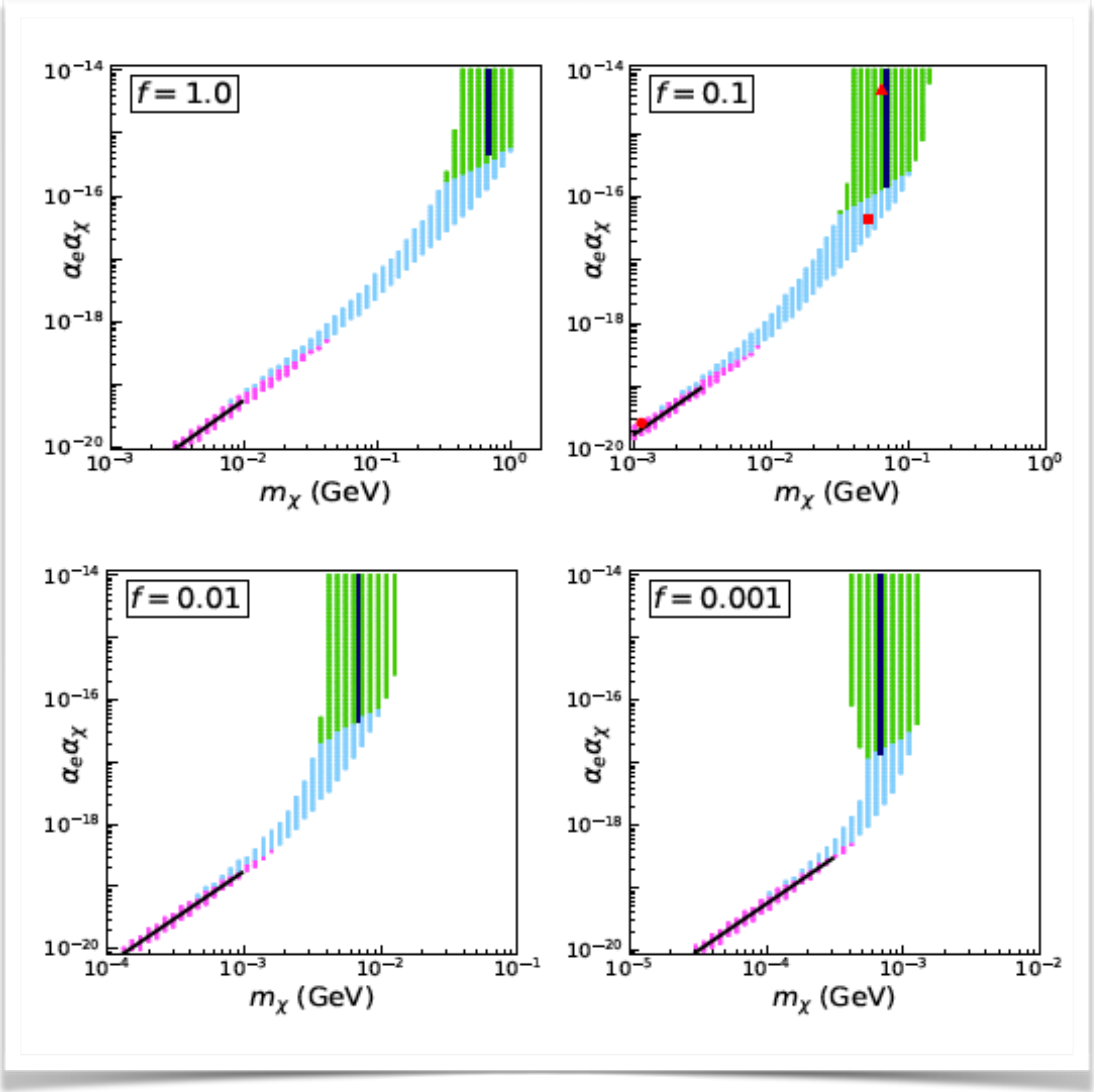
# Energy transfer rate

$$\frac{dT_\chi}{d\log(1+z)} = +2T_\chi - \frac{2}{3}\frac{\Gamma_\chi}{H}\left(T_K - T_\chi\right),$$
$$\frac{dT_K}{d\log(1+z)} = +2T_K - \frac{\Gamma_c}{H}(T_{\rm CMB} - T_K) - \frac{2}{3}\frac{\Gamma_H}{H}(T_\chi - T_K).$$

$$\Gamma_\chi \simeq n_H \left(\frac{\Delta\mu}{2MT_{\rm eff}}\right) 12\pi \frac{\alpha_\chi \alpha_e}{\Delta^2}\sqrt{\frac{8T_{\rm eff}}{\pi\mu}}.$$

$$\Gamma_H = n_\chi \left(\frac{\Delta\mu}{2MT_{\rm eff}}\right) \frac{3}{4\pi}\frac{g_\chi^2 g_e^2}{\Delta^2}\sqrt{\frac{8T_{\rm eff}}{\pi\mu}}$$

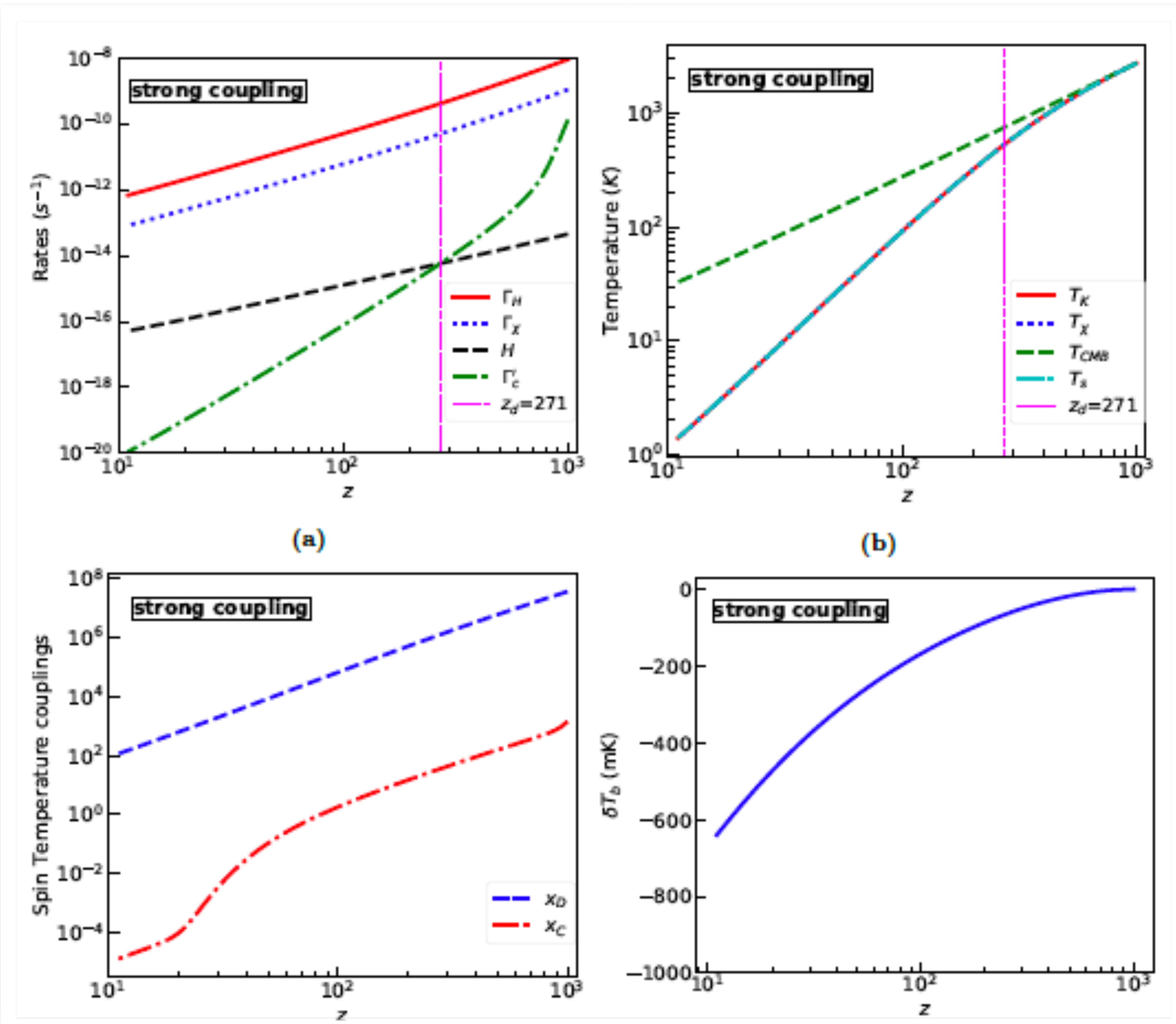
# Parameter Space of Interest

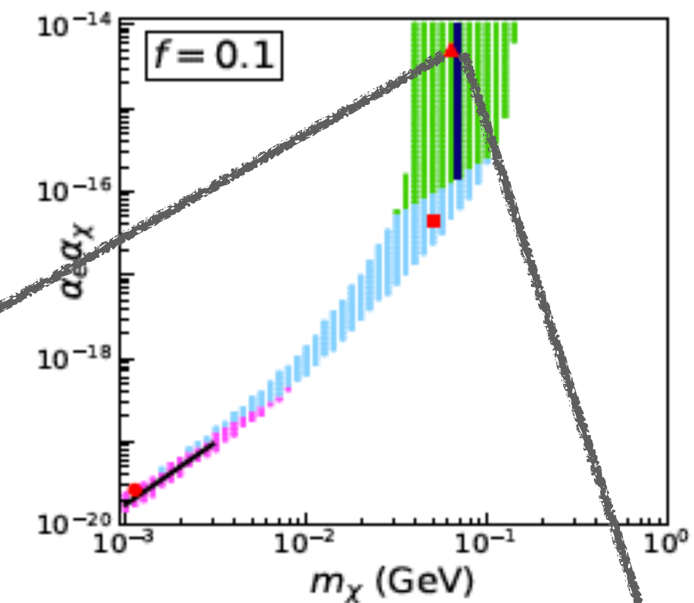


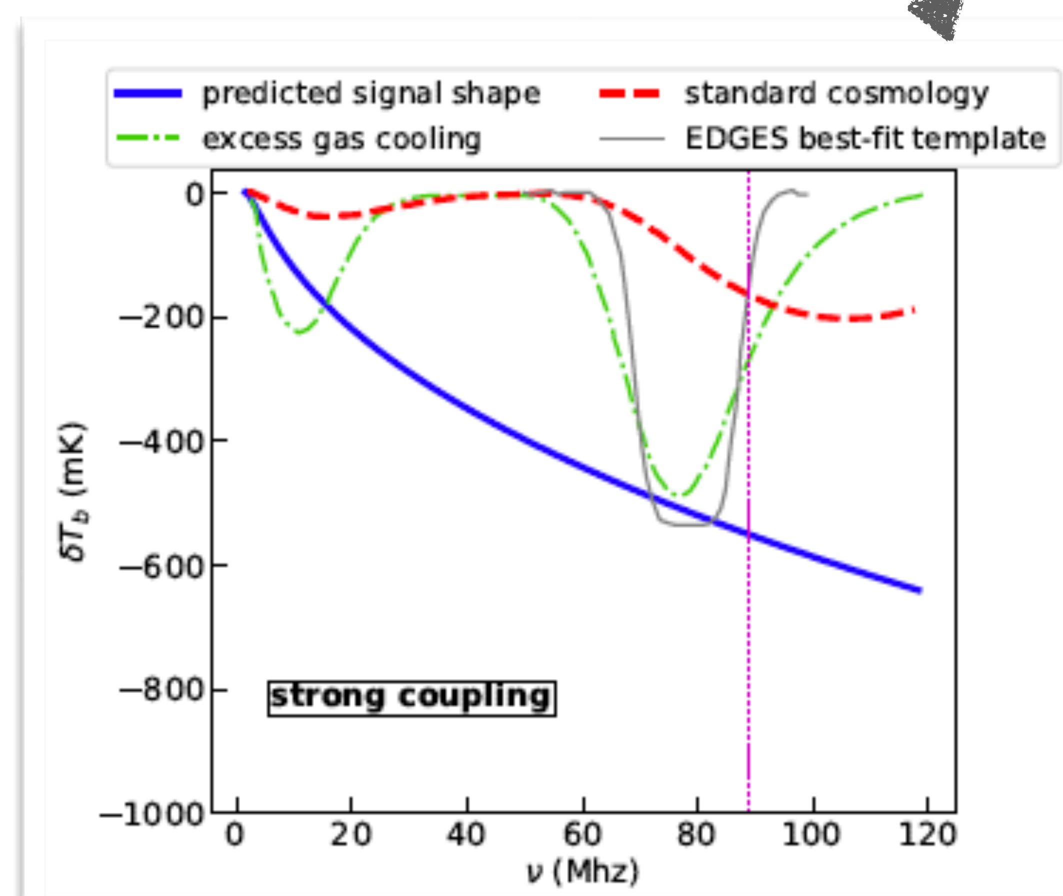

- Strong broadband absorption signal with **$T_{eff} << T_{cmb}$, and $x_D >> 1$**

- Benchmark parameter space giving rise to value of **$\delta T_b(z = 17) = -500$ mK**

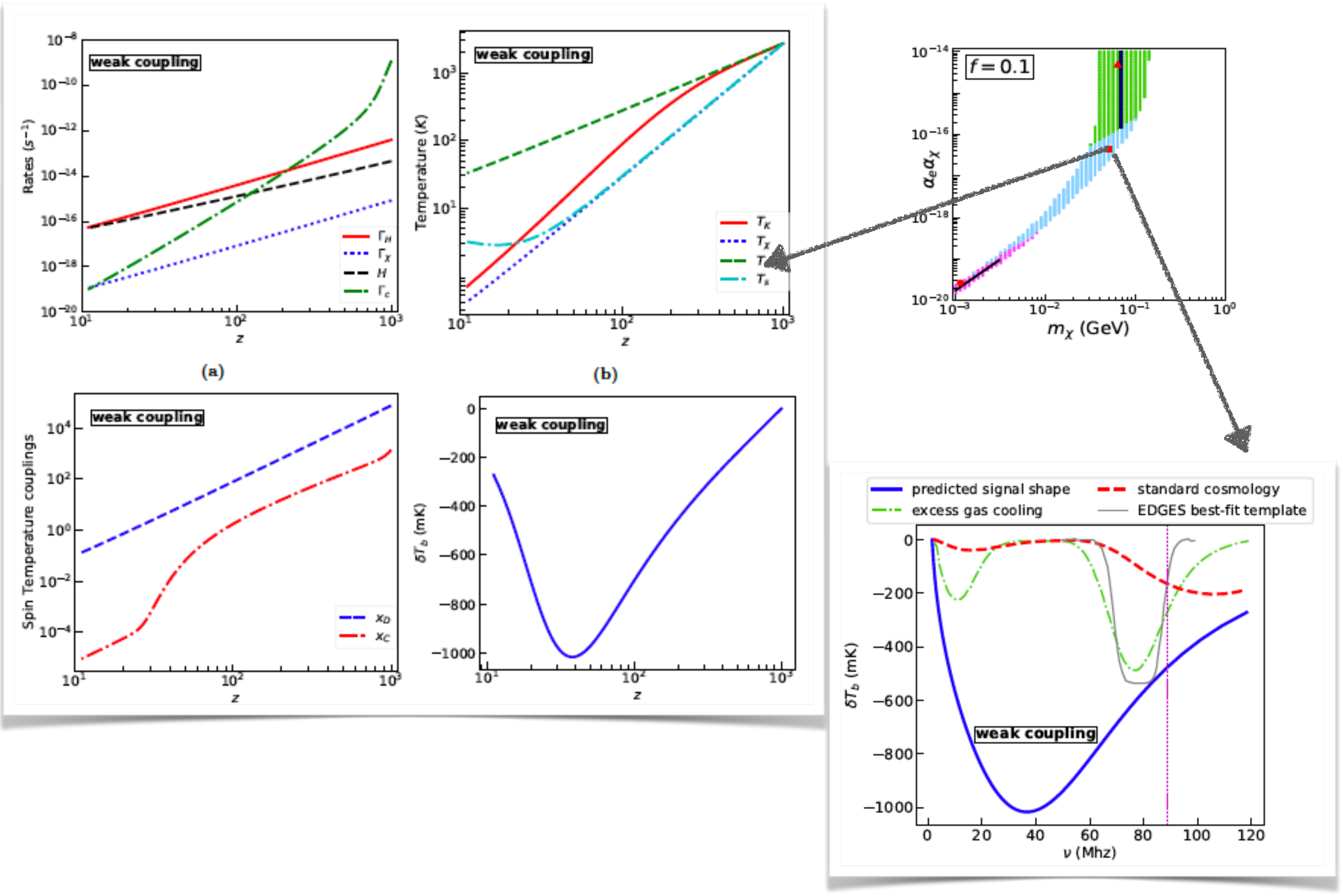
# Strong coupling Benchmark



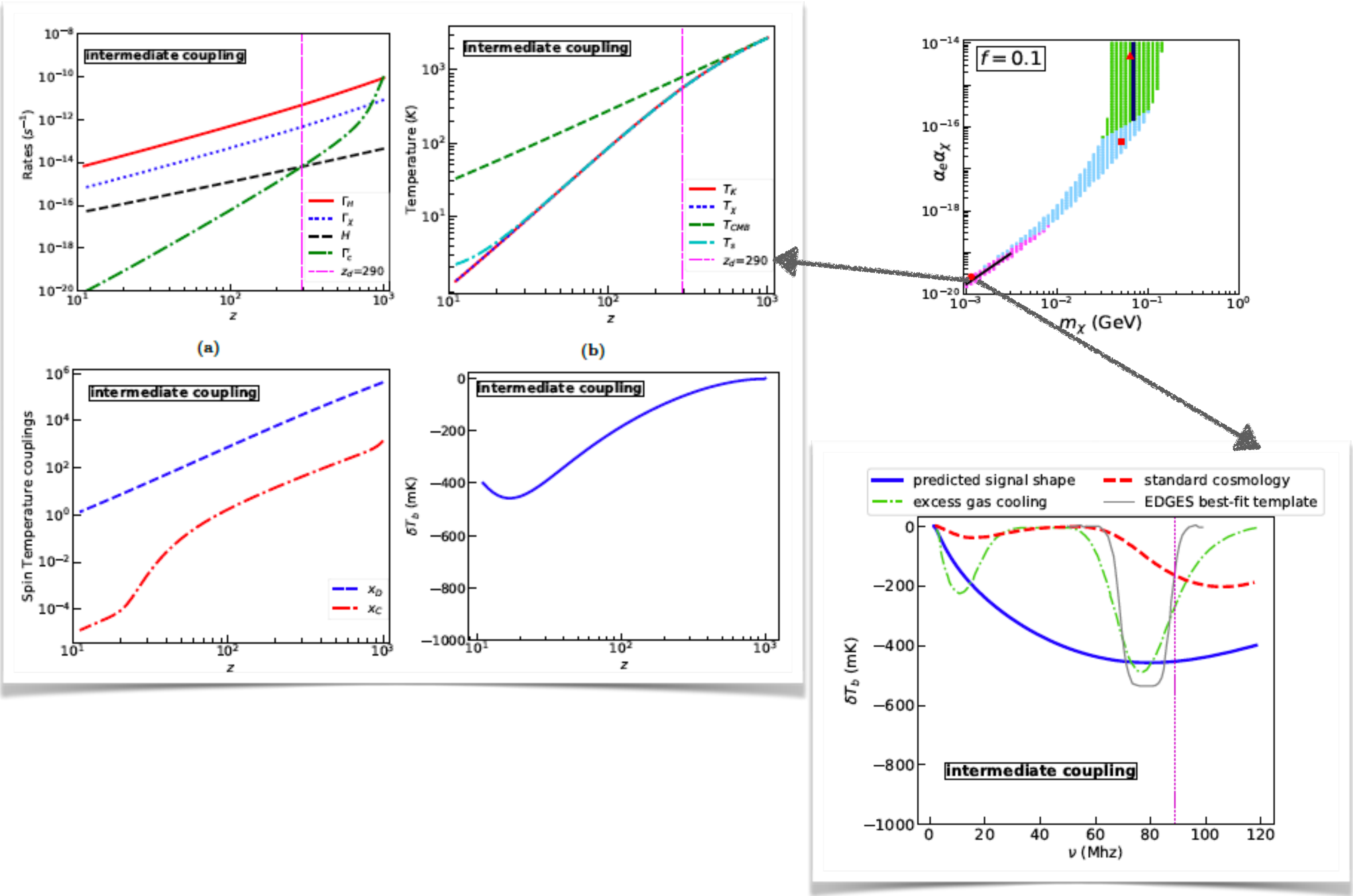



# Weak coupling Benchmark



# Intermediate coupling regime



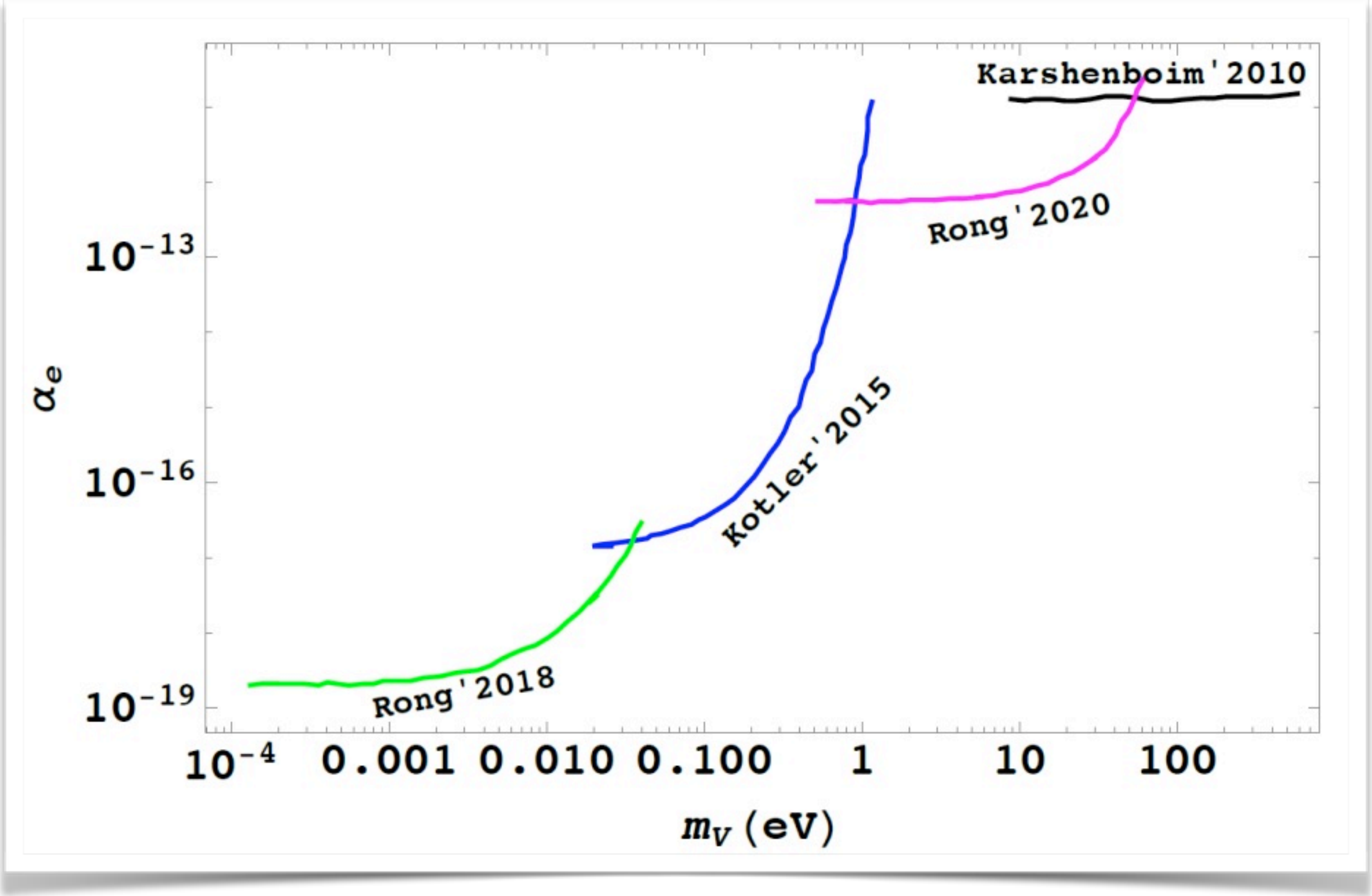
# Constraints

## Constraints on light mediator

- ☑ **Short range forces (mm-nm scale)**
- ☑ Collider searches
- ☑ Stellar cooling
- ☑ Extra-radiation species

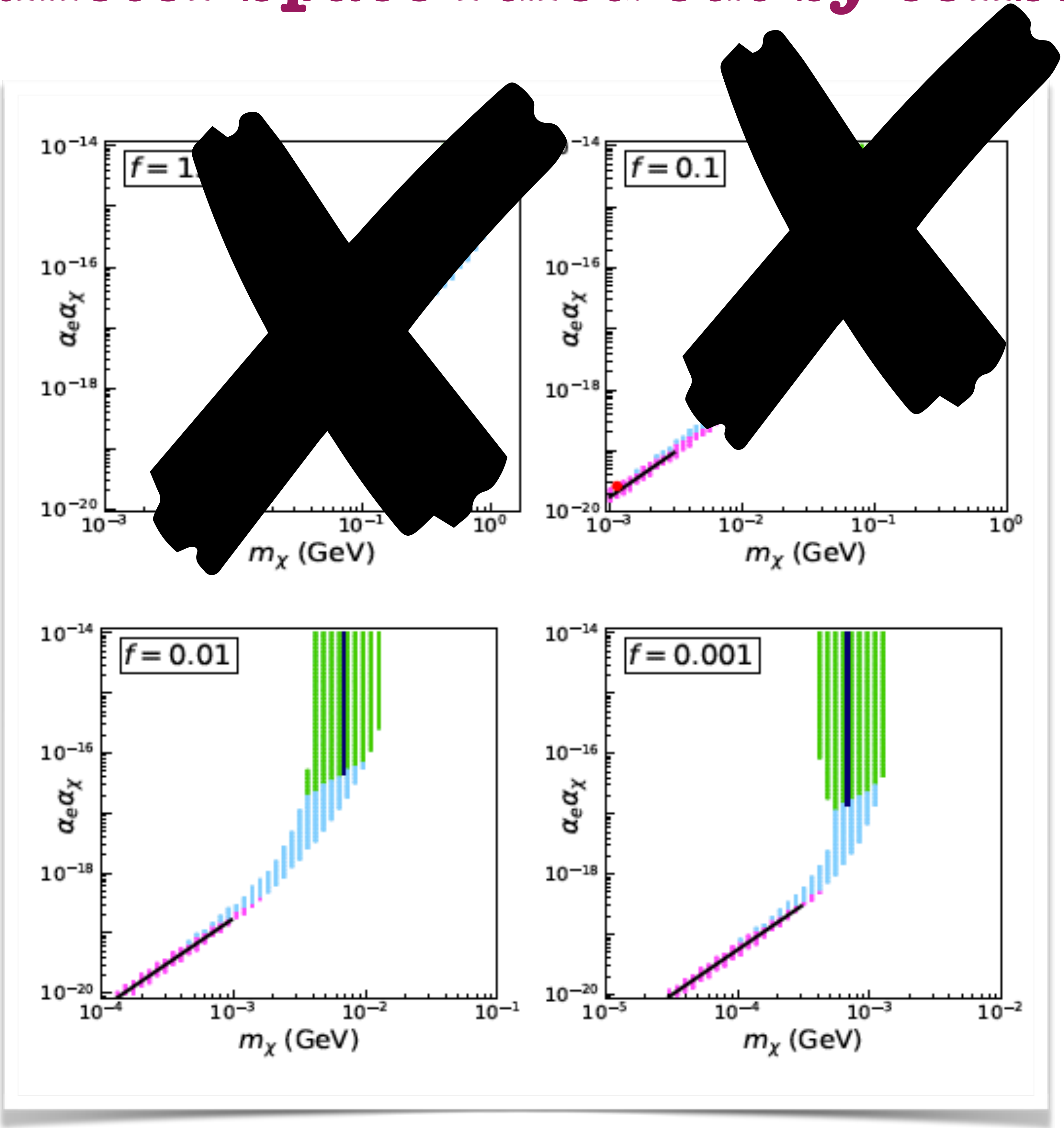
## Cosmological constraints

- ☑ **Kinetic decoupling**
- ☑ Self-interaction
- ☑ Freeze-out




$$0.1\ \text{eV}\sqrt{\frac{\alpha_\chi \alpha_e}{10^{-18}}\left(\frac{\mu}{0.1\ \text{GeV}}\right)} \lesssim m_V \lesssim 2.3\ \text{eV}\sqrt{\left(\frac{1000\ \text{K}}{T_{\text{eff}}}\right)\left(\frac{\mu}{0.1\ \text{GeV}}\right)}$$

# Parameter Space ruled out by constraints



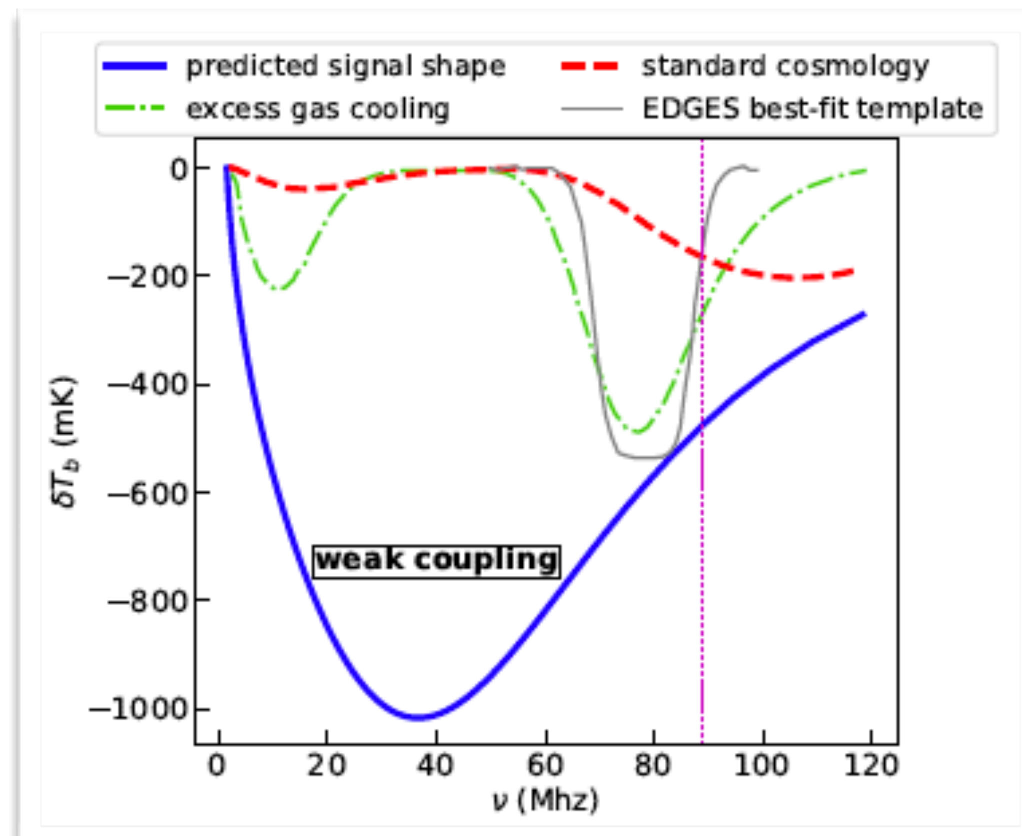
# Conclusions and testable predictions

- **Single, strong, broadband global 21 cm signal – unlike anything predicted in standard cosmology or excess cooling models!**

- Single broadband absorption feature From 1.4 Mhz (z˜1000) -Â 90 Mhz (z ˜ 15)

- Spin temperature is a tracer of DM temperature, not the gas temperature.

- Safe from laboratory and other constraints.



# Secondary tests

**Astrophysical probes:**

- Stochastic 21 cm signal (could be tested by future experiments such as SKA).
- Independent probe of the gas kinetic temperature.

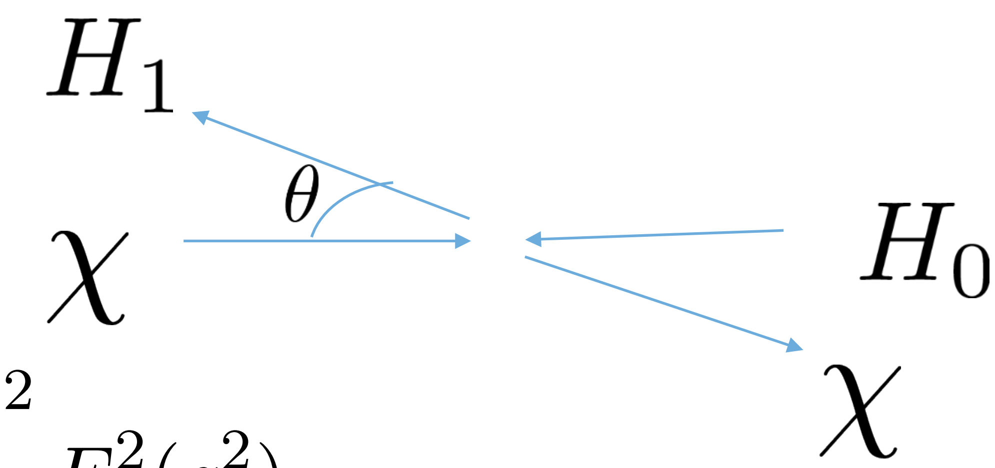
**Collider Probes:**

- UV completions with broken SM gauge symmetries, in order to evade constraint from Z decays, stellar cooling and extra radiation constraints.
- short-range forces between electrons on mm-nm scale.

Thanks for your kind attention

# Forward Scattering and Spin flip cross-section

**In the non-relativistic limit,**




$$V(r) = \frac{g_\chi g_e}{r} e^{-m_V r} (\vec{S}_e \cdot \vec{S}_\chi)$$

$$\sigma_{01} v_{\rm rel} \simeq \frac{3}{2\pi} g_\chi^2 g_e^2 \mu p' \int_{-1}^{1} d(\cos\theta) \left( \frac{1}{q^2 - m_V^2} \right)^2 F^2(q^2).$$

**For elastic scattering with massless mediator, the crossection scales as Rutherford scattering**

$$\frac{d\sigma}{d\Omega} \propto \frac{\alpha_e \alpha_\chi}{\mu^2 v^4 \sin^4 \frac{\theta}{2}}$$

$$\mathcal{I} = \int_{-1}^{1} d(\cos\theta) \left( \frac{1}{-p^2 - p'^2 - m_V^2 + 2pp' \cos\theta} \right)^2,$$

$$= \frac{2}{(p_{\rm th}^2 - m_V^2)^2 + 4 m_V^2 p^2},$$

$\sigma_{01} \sim \frac{3}{4\pi} \frac{g_\chi^2 g_e^2}{\Delta^2}$ **, assuming** $m_V^2 \ll p_{\rm th}^4 / p_c^2 \approx \sqrt{\frac{2\mu}{T_{\rm eff}}} \Delta$