Broadband 21 cm cosmological signal from dark matter spin-flip interactions

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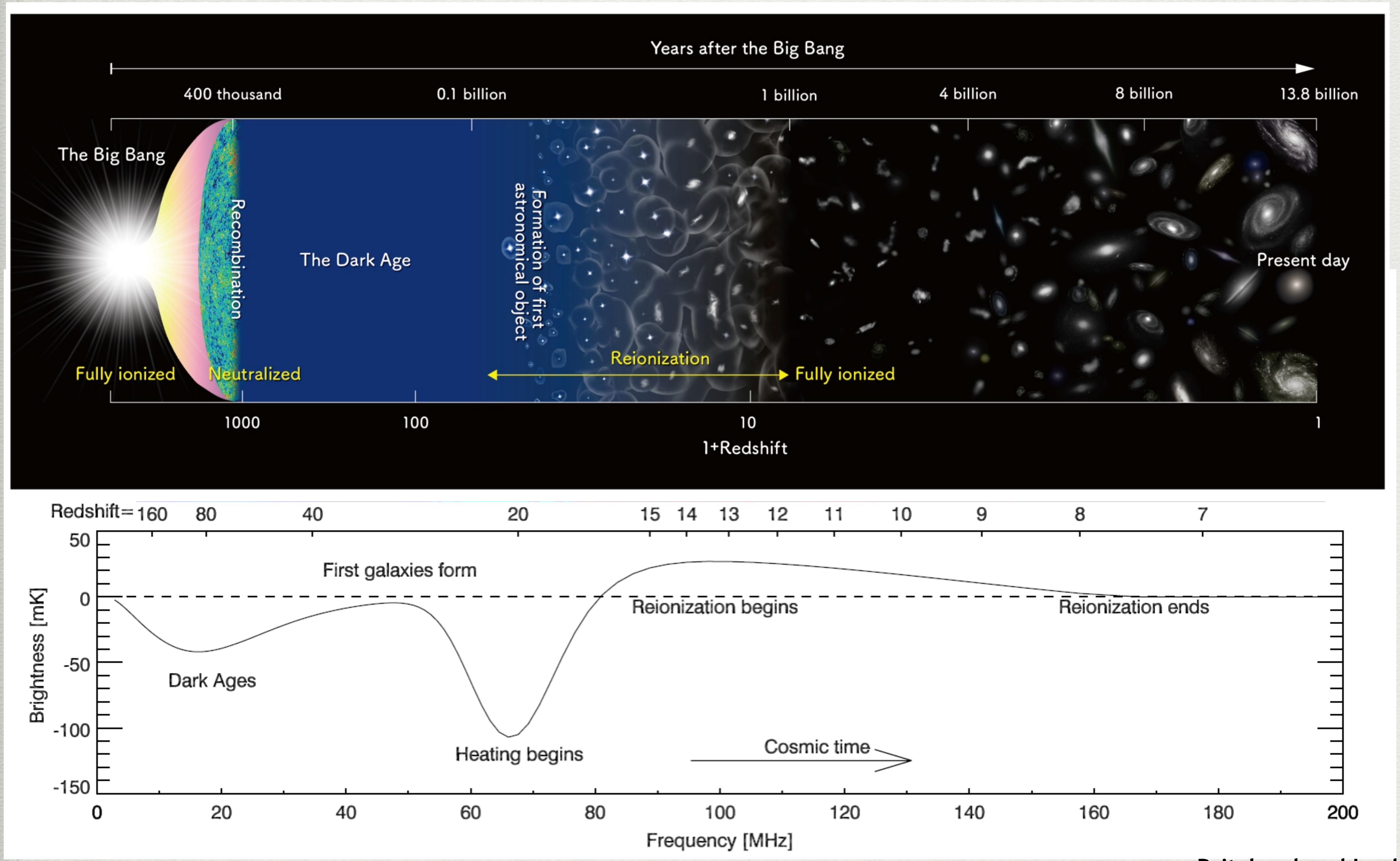
21 cm signal in standard cosmology



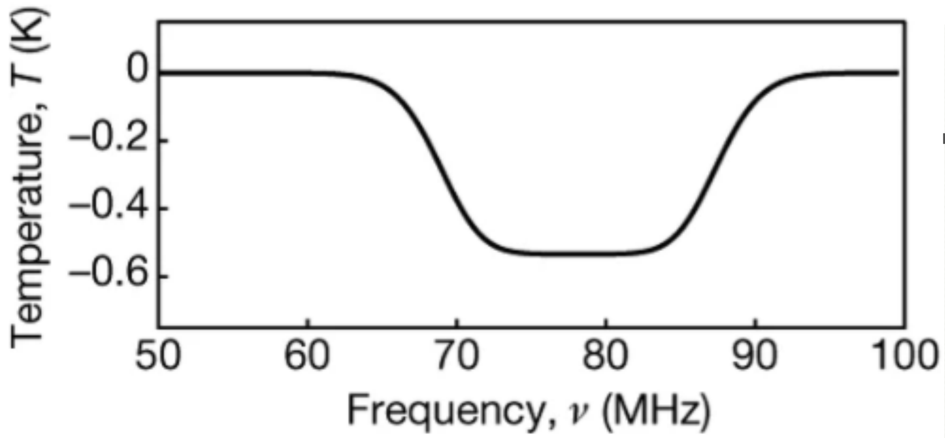
Pritchard and Loeb 2012

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]

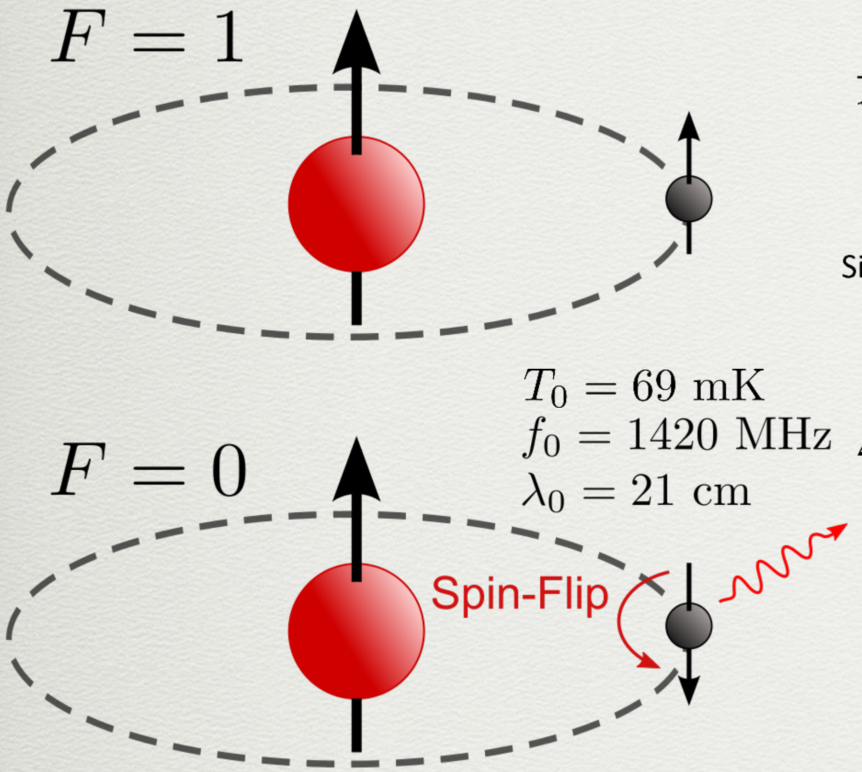


→ EDGES experiment

Goal of the work: Look for BSM models that can explain the predicted 21 cm signal and also could be tested in future experiments.

Dark matter spin flip model

Spin temperature of neutral hydrogen and Differential Brightness temperature



$T_0 = 69$ mK
$f_0 = 1420$ MHz $\Delta = 5.9\ \mu$eV
$\lambda_0 = 21$ cm

$\frac{1}{\sqrt{2}} \uparrow\downarrow - \downarrow\uparrow$

Singlet State S = 0

$\uparrow\uparrow$

$\frac{1}{\sqrt{2}} \uparrow\downarrow + \downarrow\uparrow$

$\downarrow\downarrow$

Triplet State S = 1

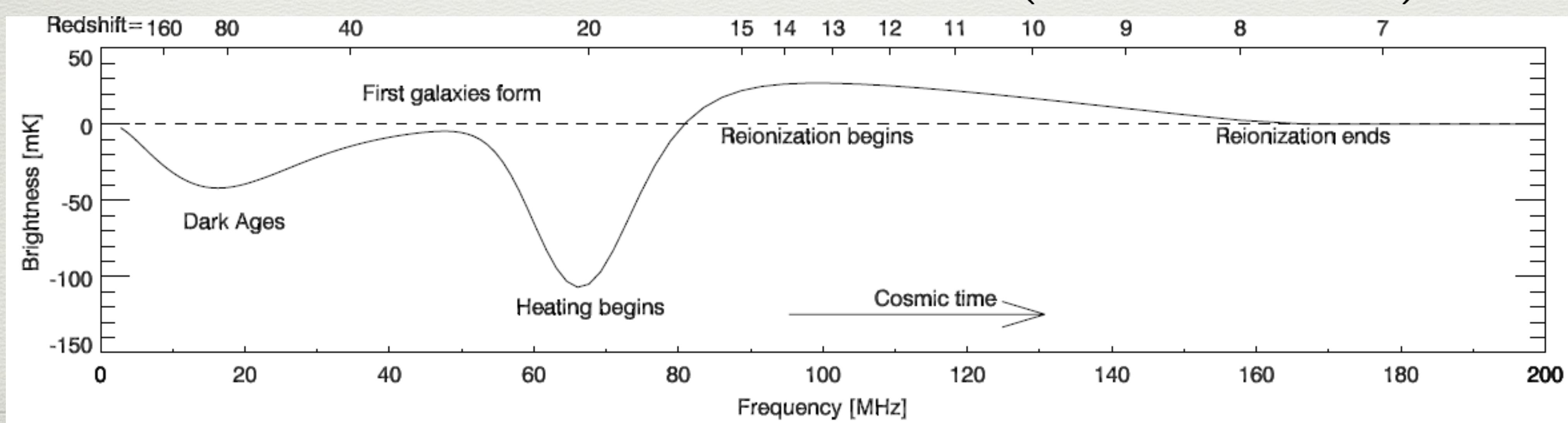
$$\frac{n_1}{n_0} = 3e^{-\frac{\Delta}{T_s}}$$

T_s parameter that describes the relative population of singlet and triplet states

$\delta T_b > 0$ net **emission** if $T_s > T_{CMB}$,

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

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



Determininating T_s

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

CMB Excitation

Collisional Excitation

Lyman-α from first stars

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

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

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

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

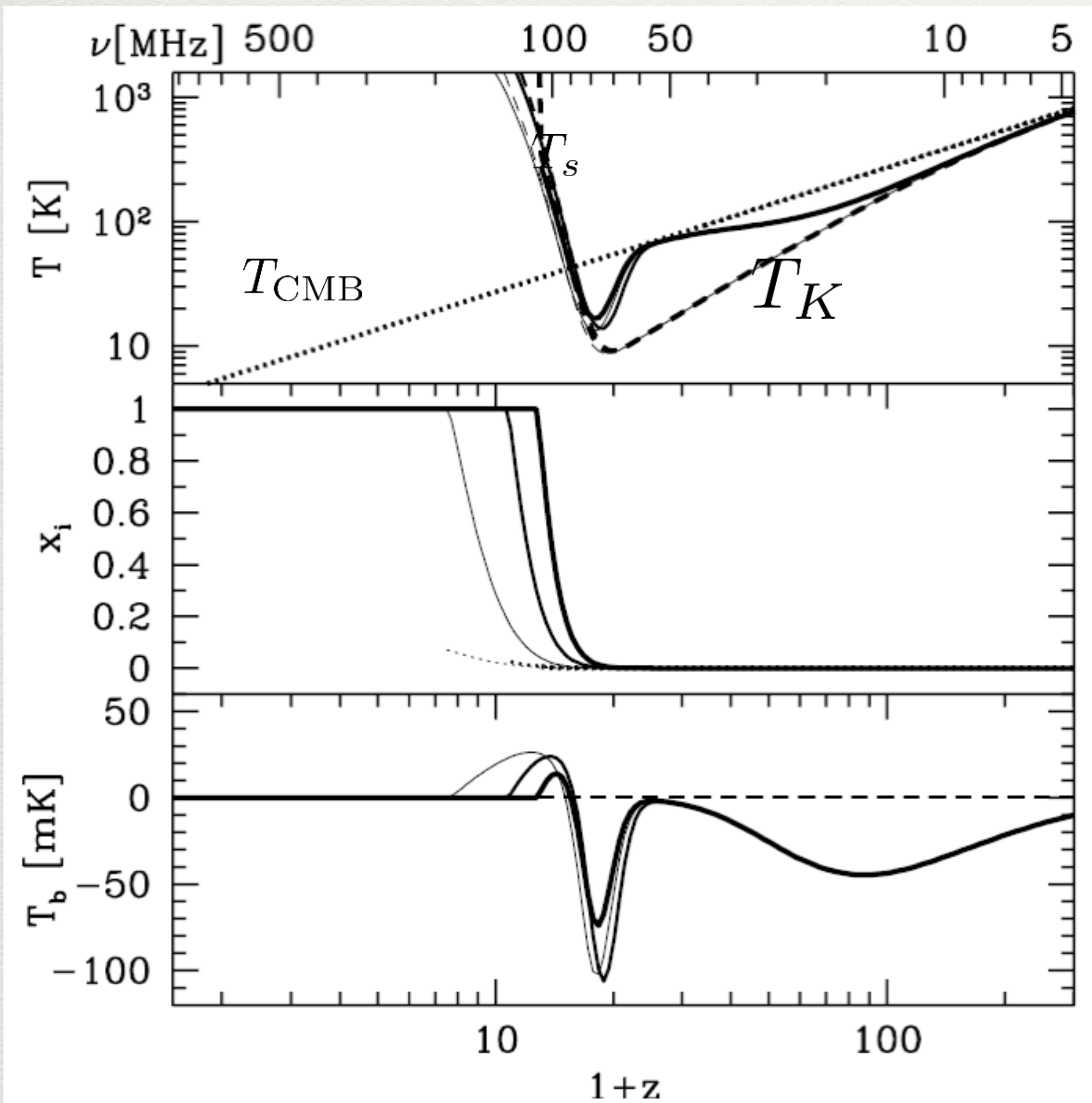
$x_C = \frac{C_{10}}{B_{10}}$ → Collisional coupling

$x_\alpha = \frac{P_{10}}{B_{10}}$ → Lyman-α coupling

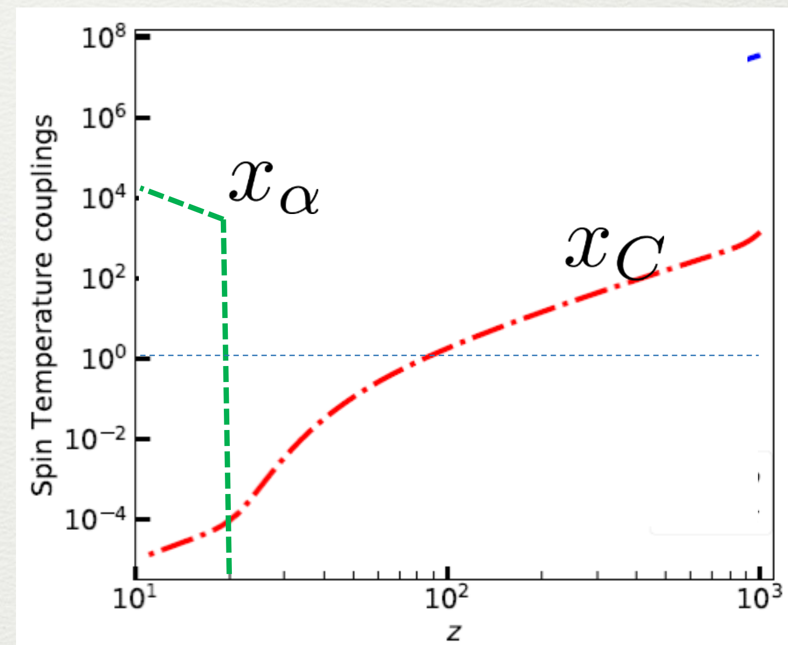
Evolution of the spin temperature

$1 - x_{HI}$

δT_b

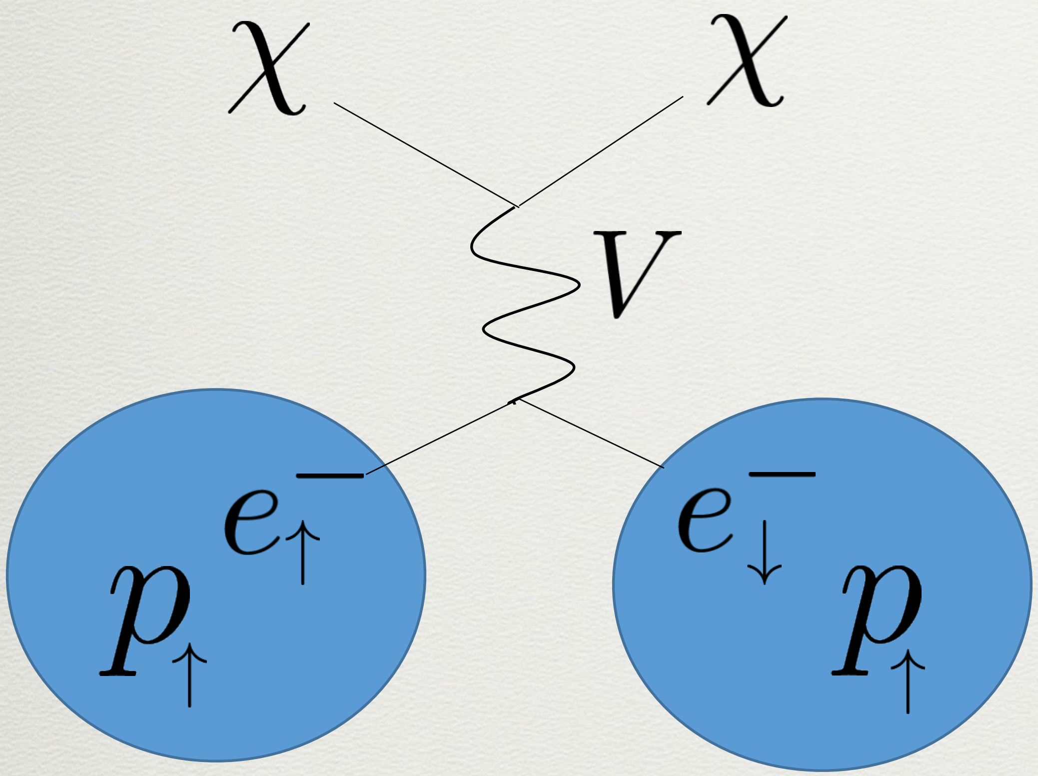


Pritchard and Loeb 2012



Dark matter spin-flip interaction model

$$\mathcal{L} = ig_\chi \overline{\chi}\gamma^\mu\gamma^5\chi V_\mu + ig_e\overline{e}\gamma^\mu\gamma^5 e V_\mu$$



5 parameters: $\alpha_\chi, \alpha_e, m_\chi, f, m_V$

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

Two distinct effects:

1. Direct change of spin temperature

$$D_{01} \quad D_{10}$$

2. Energy transfer between the dark matter and gas

$$\Gamma_H \quad \Gamma_\chi$$

Forward scattering and spin-flip cross-section

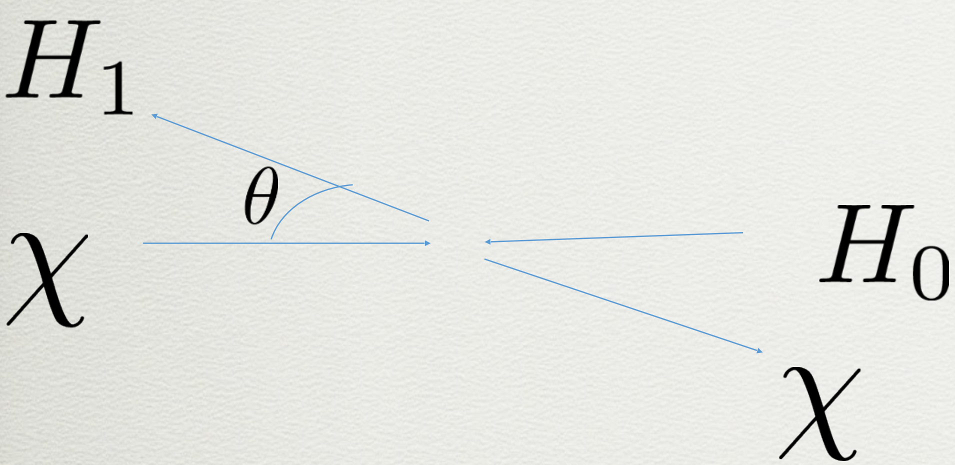
$$V(r) = \frac{g_\chi g_e}{r} e^{-m_V r} (\vec{S}_e \cdot \vec{S}_\chi)$$

Elastic, massless mediator

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

Singularity cut-off by mediator mass or threshold momentum

$$m_V \ll p_{\rm th} = \sqrt{2\Delta\mu} \qquad m_V \ll \frac{p_{\rm th}^2}{\sqrt{2\mu T_{\rm eff}}} \propto \Delta \sqrt{\frac{\mu}{T_{\rm eff}}}$$



$$\langle v^2 \rangle = \langle v_H^2 \rangle + \langle v_\chi^2 \rangle \qquad \mu = \frac{m_H m_\chi}{m_H + m_\chi}$$

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

$$\sigma = 4\pi \frac{\alpha_e \alpha_\chi}{\Delta^2}$$

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

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

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

$$\Gamma_H \propto n_\chi \langle \bar{\sigma} v \rangle$$

Modified rate balance and spin-temperature

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

- B_{01}: CMB Excitation
- C_{01}: Collisional Excitation
- P_{01}: Lyman-α from first stars
- D_{01}: ***Dark matter spin flip interactions***

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

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

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

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

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

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

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

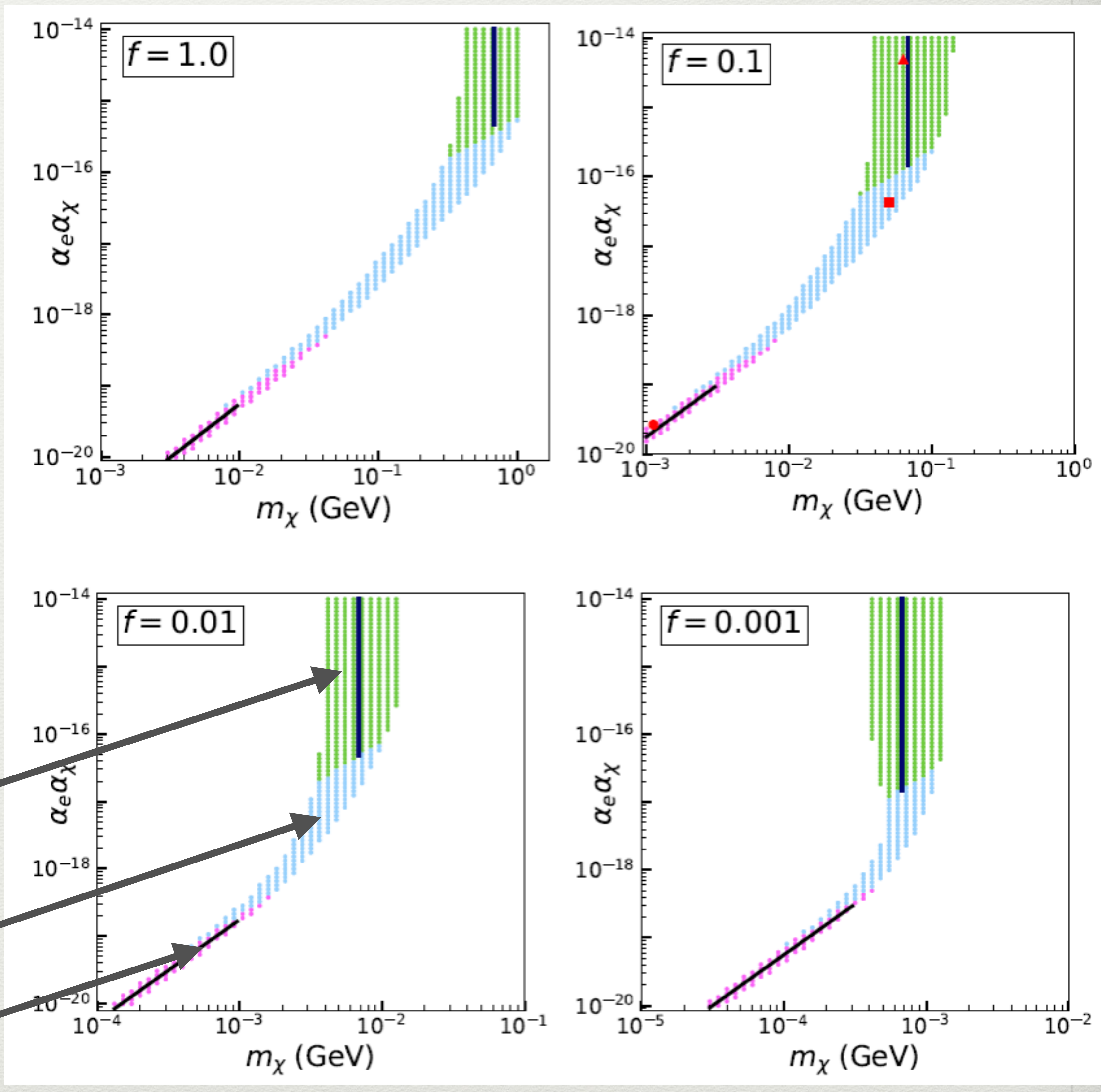
$$T_{\rm eff} = \mu\left(\frac{T_K}{m_H} + \frac{T_\chi}{m_\chi}\right) \qquad \mu = \frac{m_H m_\chi}{m_H + m_\chi}$$

Parameter space of the model

- We get a strong broadband absorption signal
  - Strong: $T_{eff} << T_{cmb}$
  - Broadband: $x_D >> 1$

- Benchmark parameter space gives rise to a benchmark value of

  $\delta T_b(z = 17) = - 500$ mK

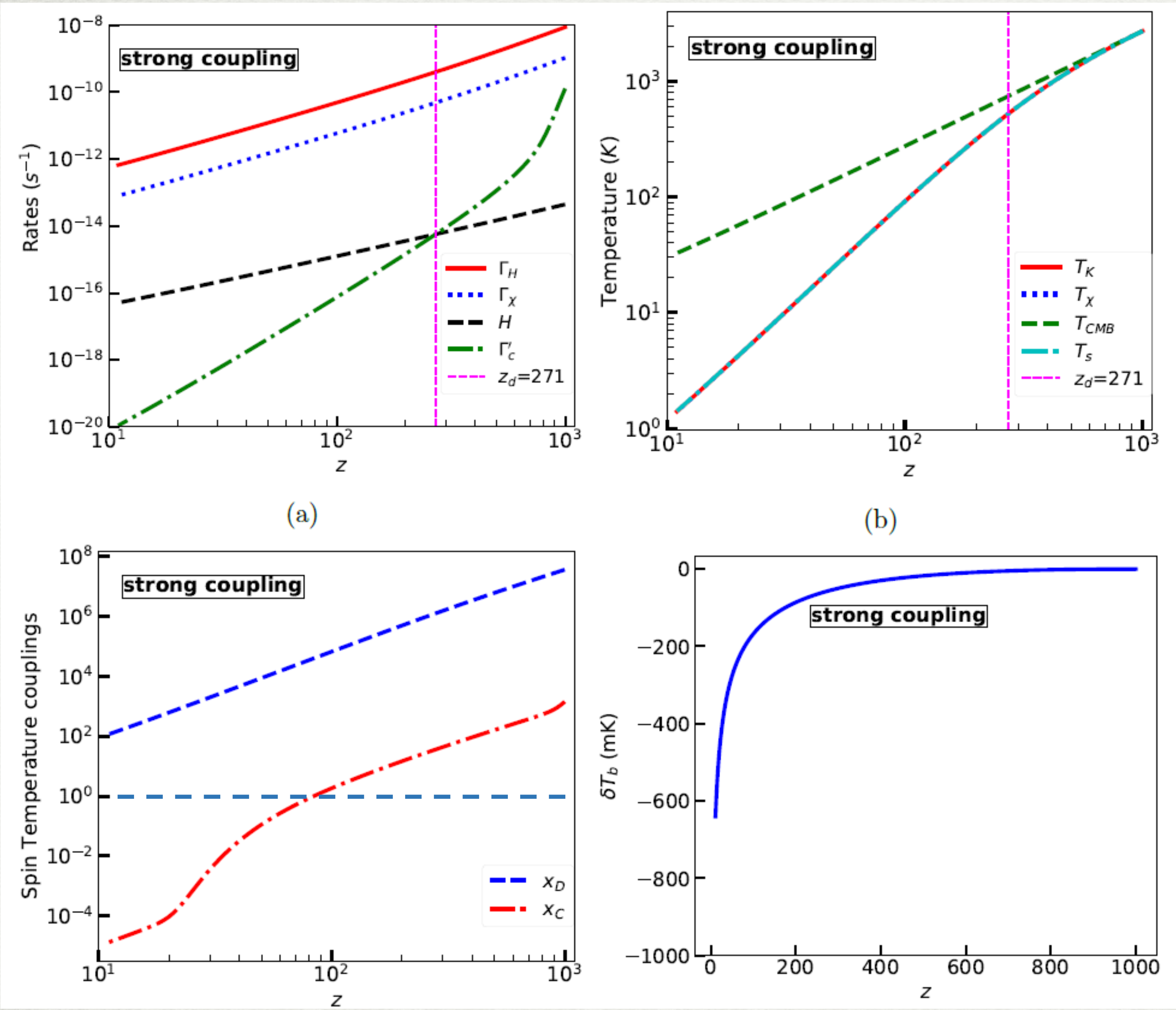


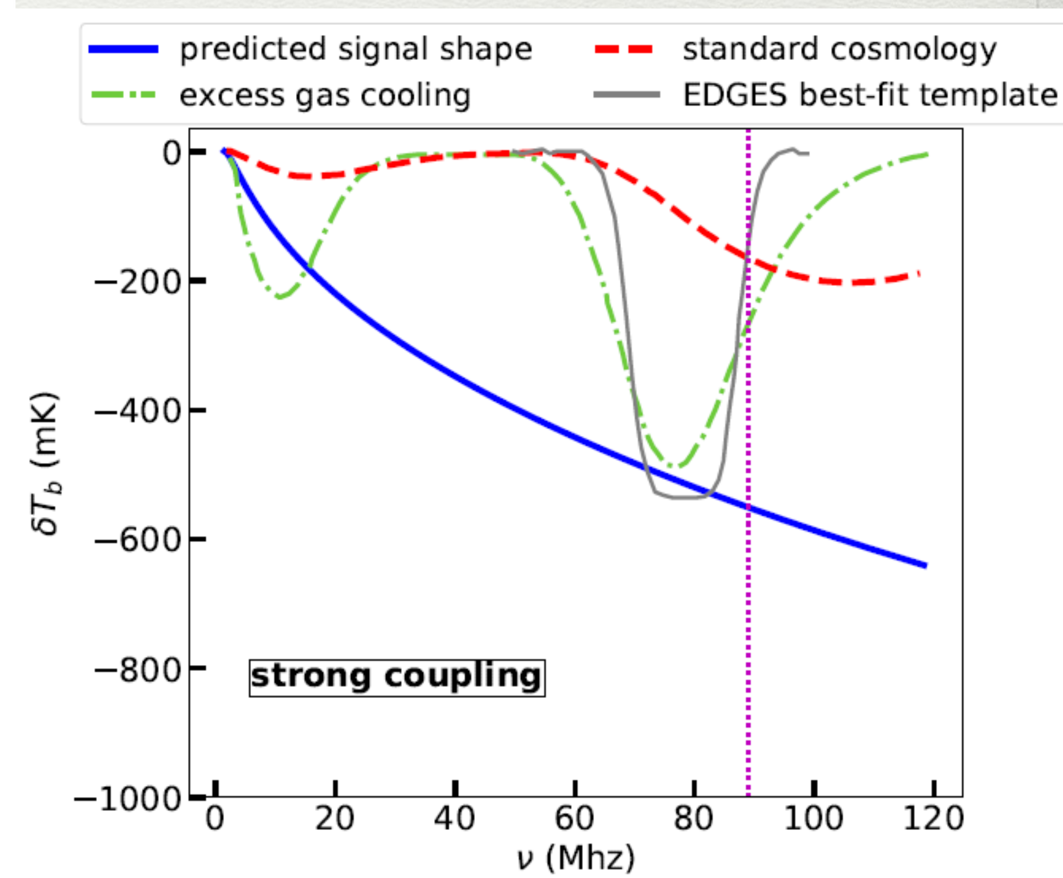
Strong coupling

Intermediate coupling

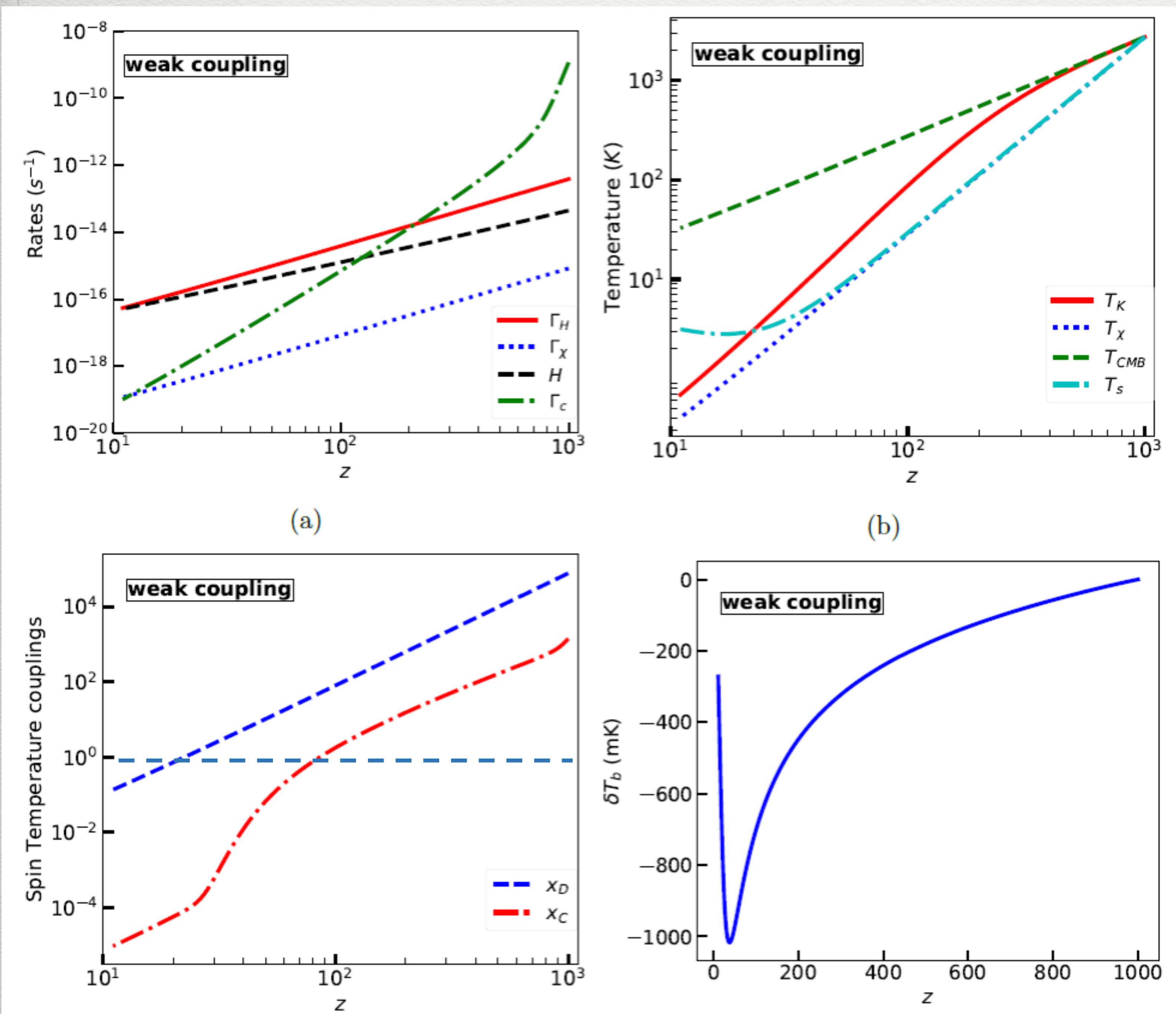
Weak coupling

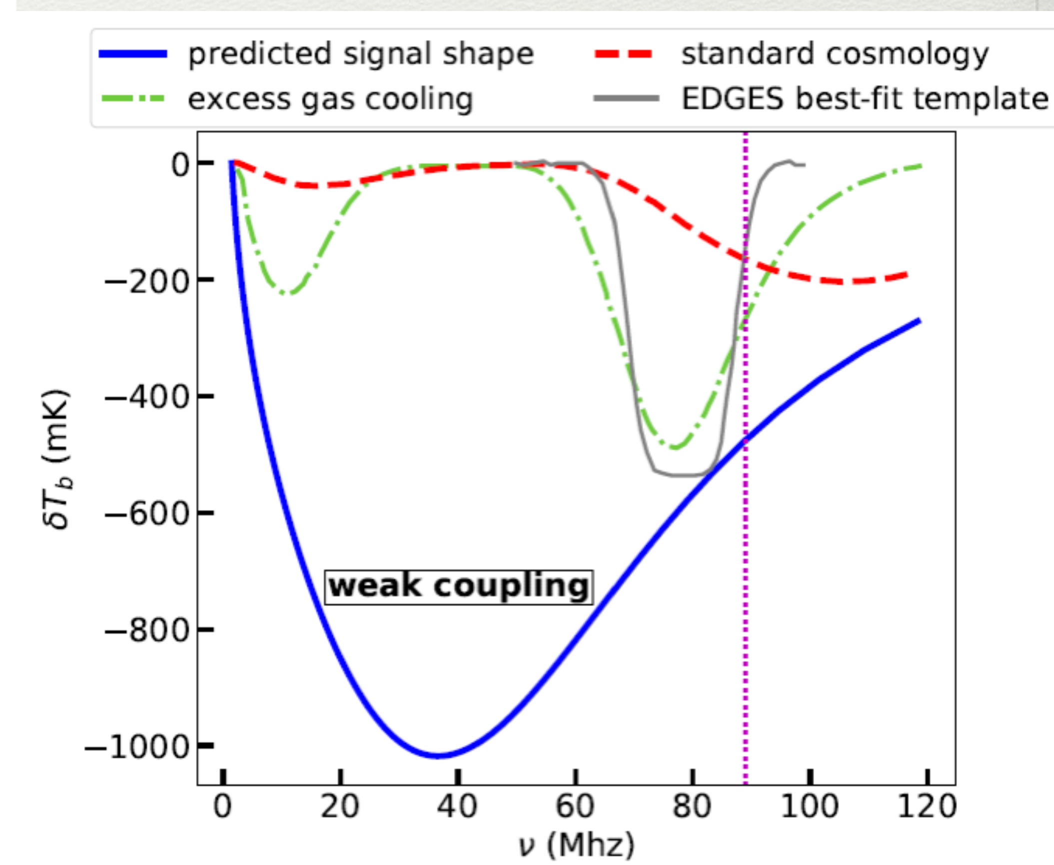
Strong coupling benchmark



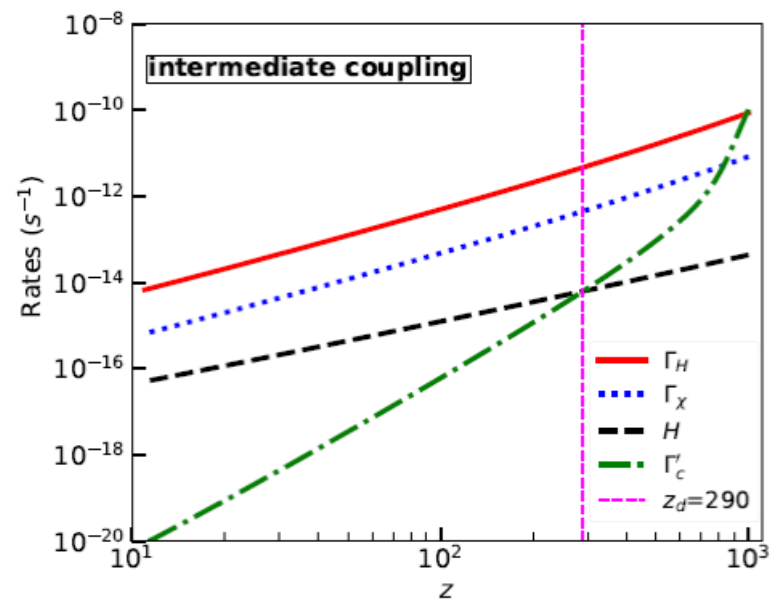


Weak coupling benchmark

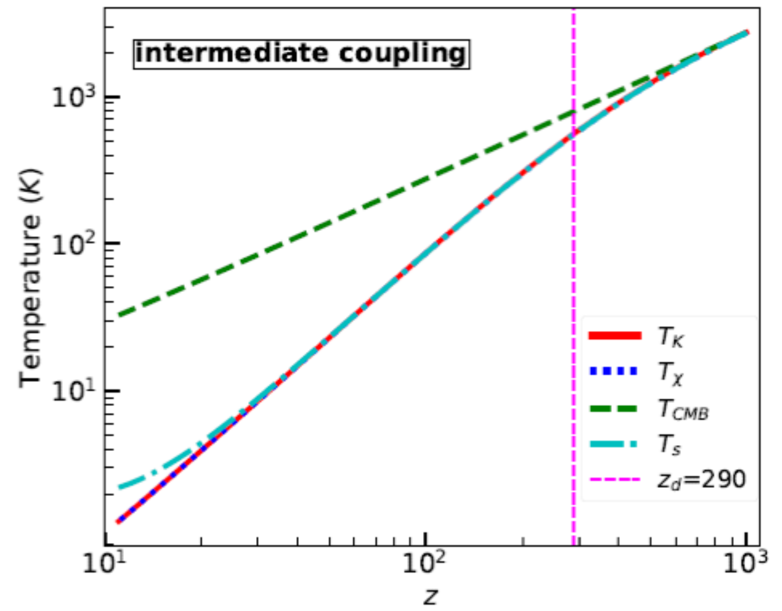




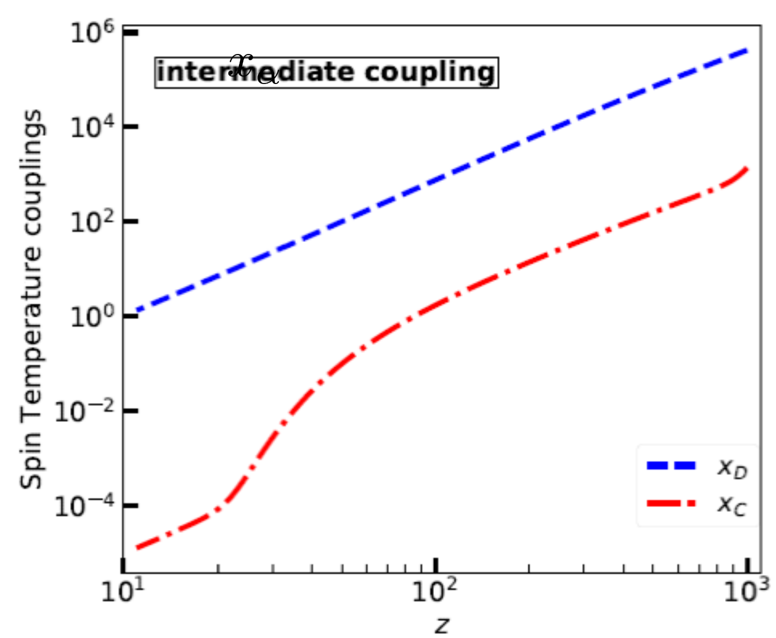
Intermediate coupling benchmark

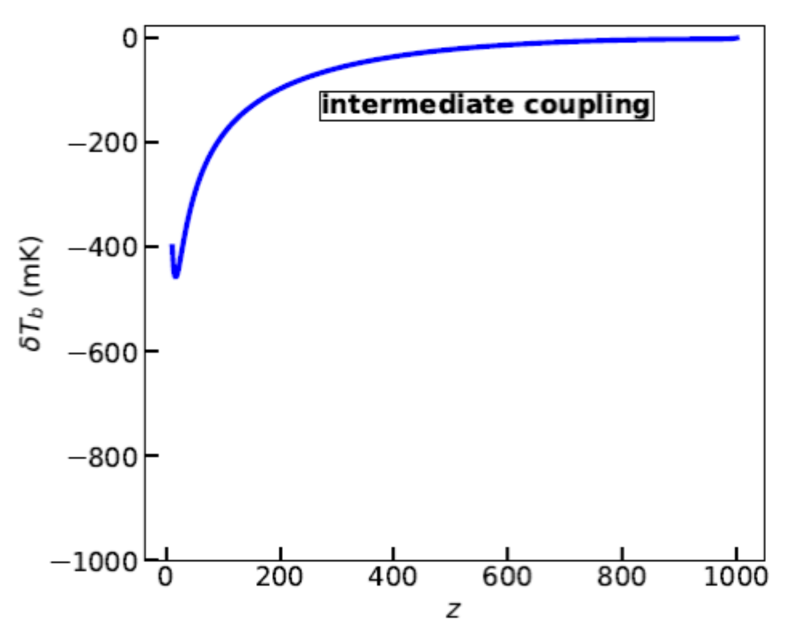


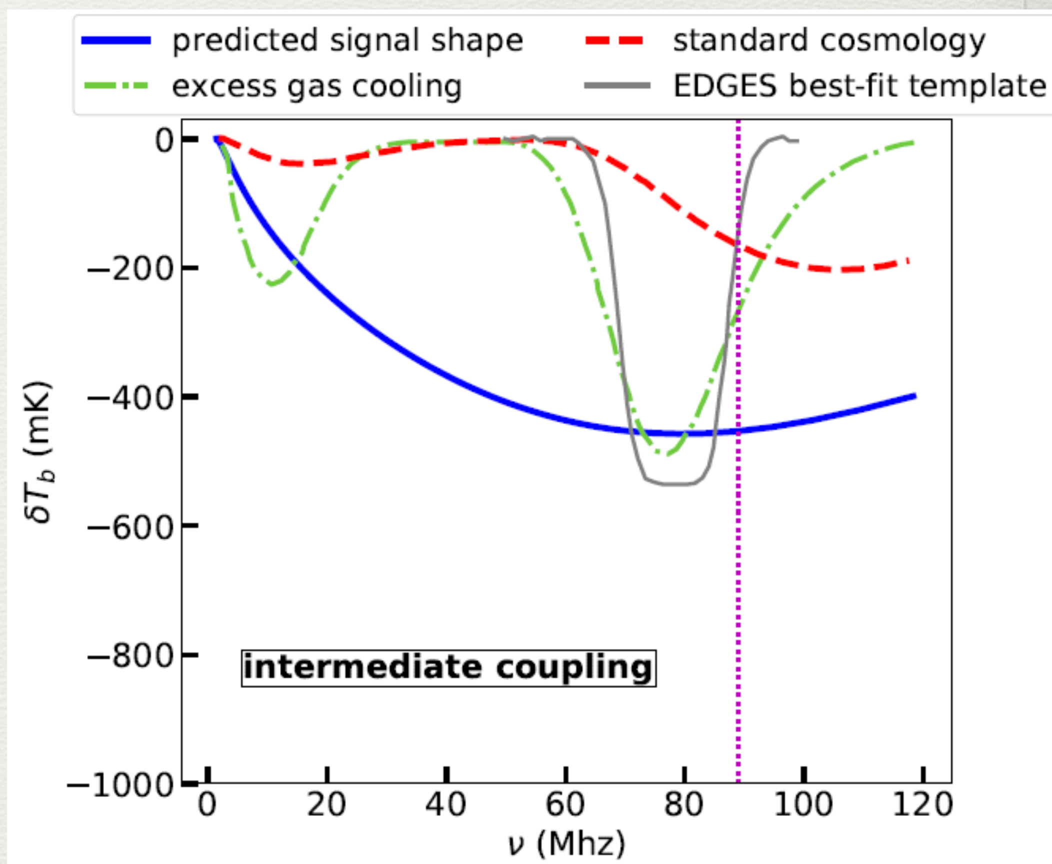
(a)



(b)

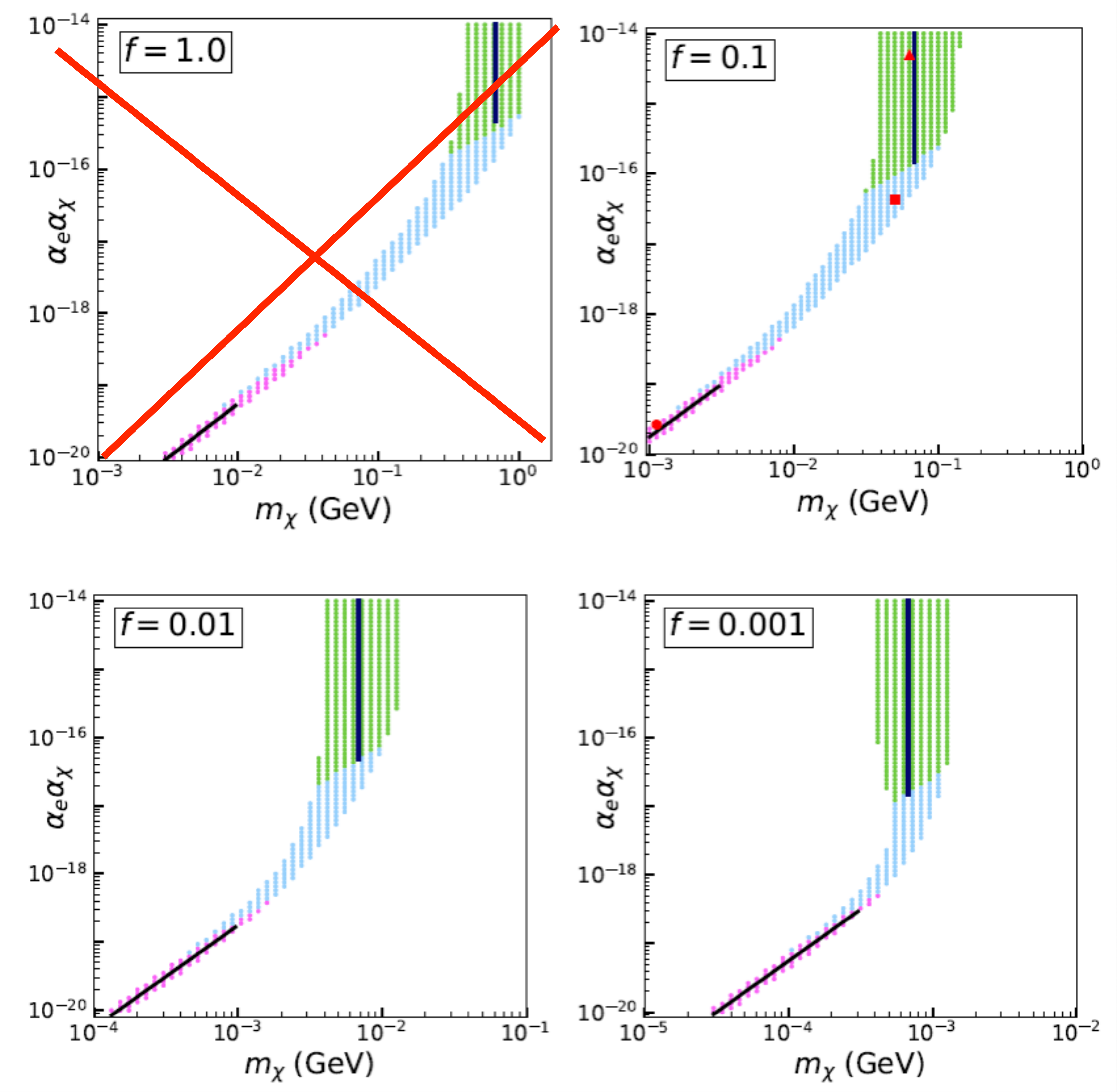




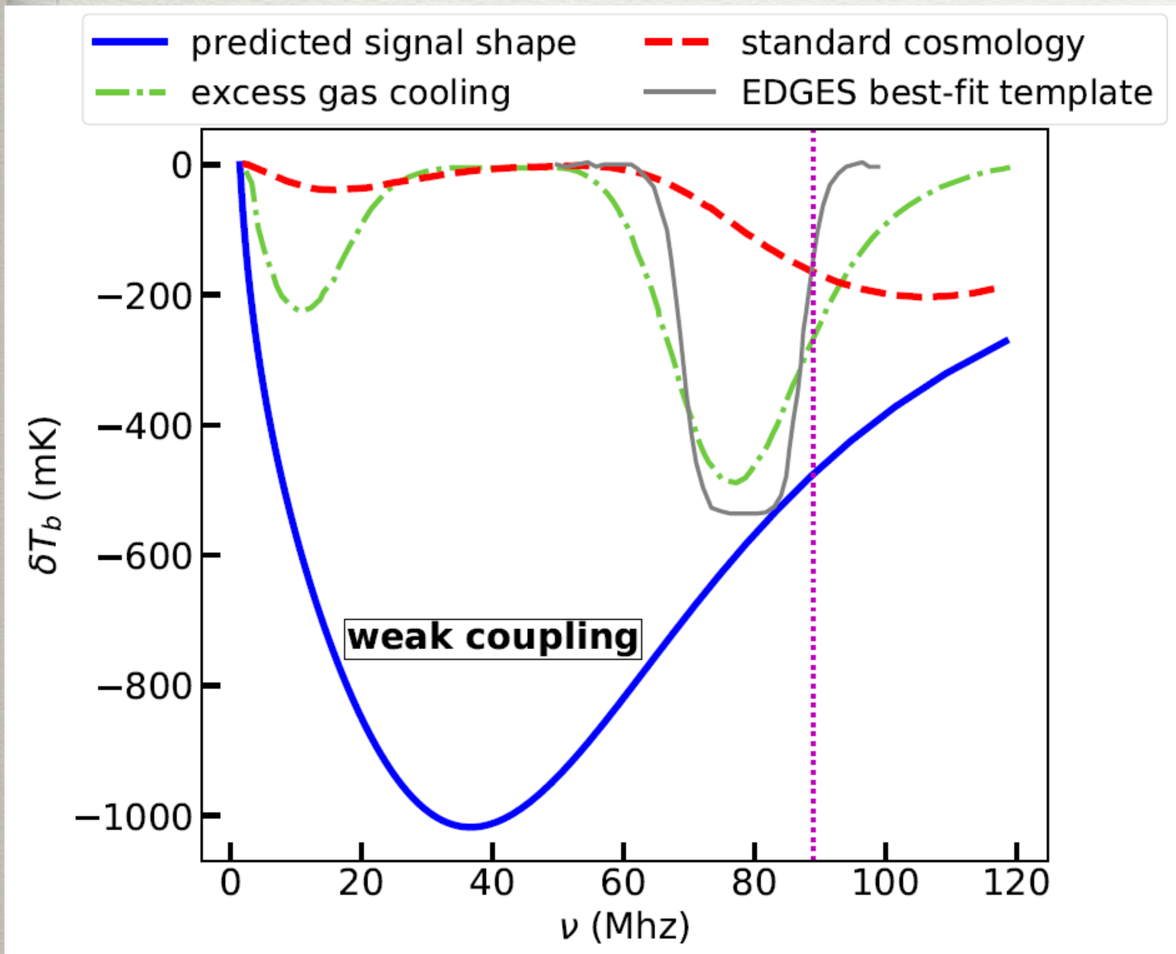


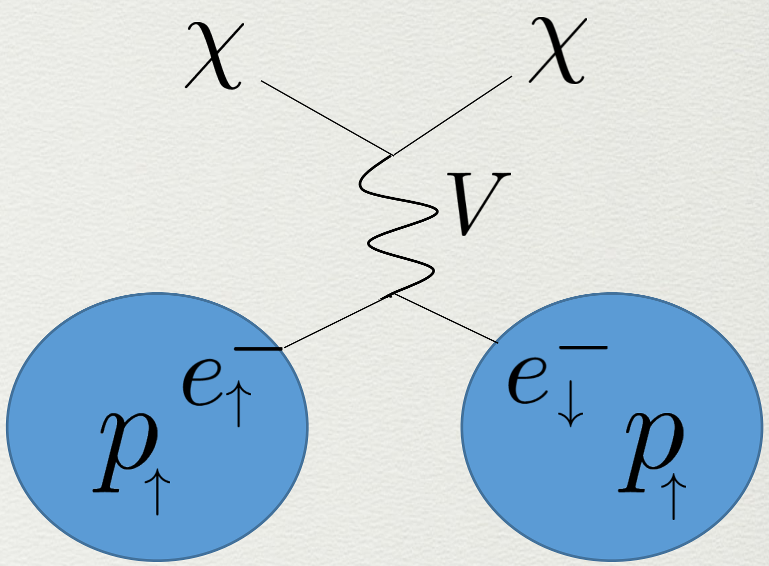
Constraints:

- Light mediator
  - **Short range forces mm-nm scale**
  - *Collider searches*
  - *Stellar cooling* ΔN_{eff}
  - Extra-radiation species
- Cosmological constraints
  - **Kinetic decoupling**
  - Self-interaction
  - Freeze-out



Key Results





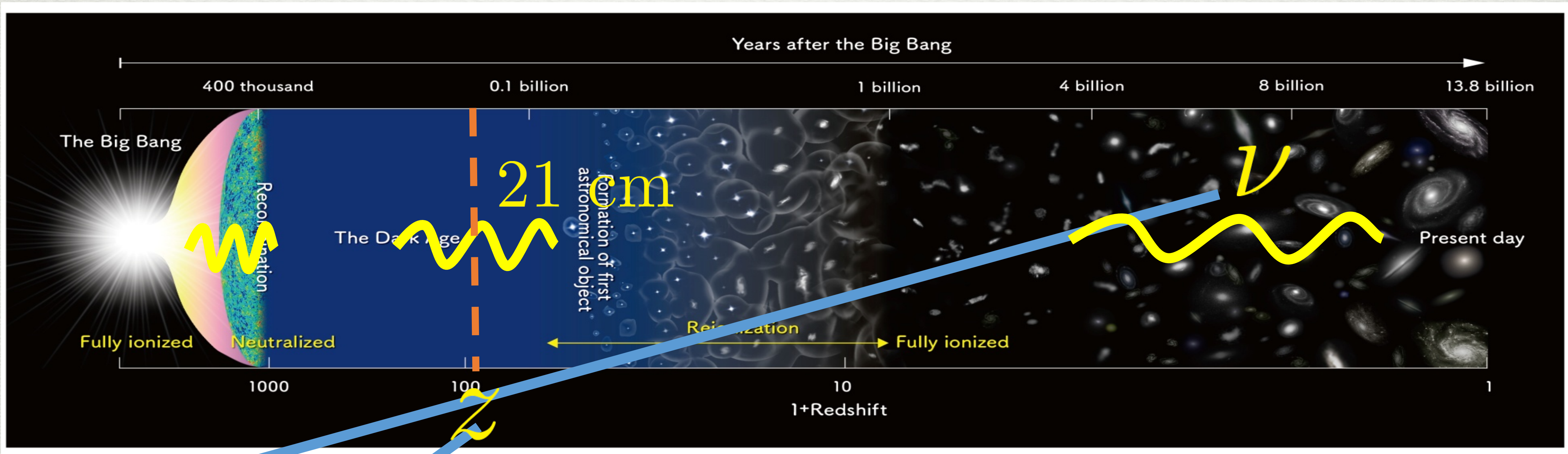
- **New testable prediction**

<u>Single, strong, broadband global 21 cm signal-unlike anything predicted in standard cosmology or excess cooling models!</u>

- Independent probes of the gas temperature in weak and intermediate coupling scenarios

Standard cosmology/excess cooling models	Dark matter spin flip model
Two distinct band-limited absorption features	Single broadband absorption feature
Localized near 20 Mhz (z ~ 70), 90 Mhz (z ~ 15)	From 1.4 Mhz (z~1000) - 90 Mhz (z ~ 15)
Weak or strong	Strong
Spin temperature traces gas temperature	Spin temperature not necessarily track gas temperature

Back up



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

$$I_\nu = 2k_B T \frac{\nu^2}{c^2}$$

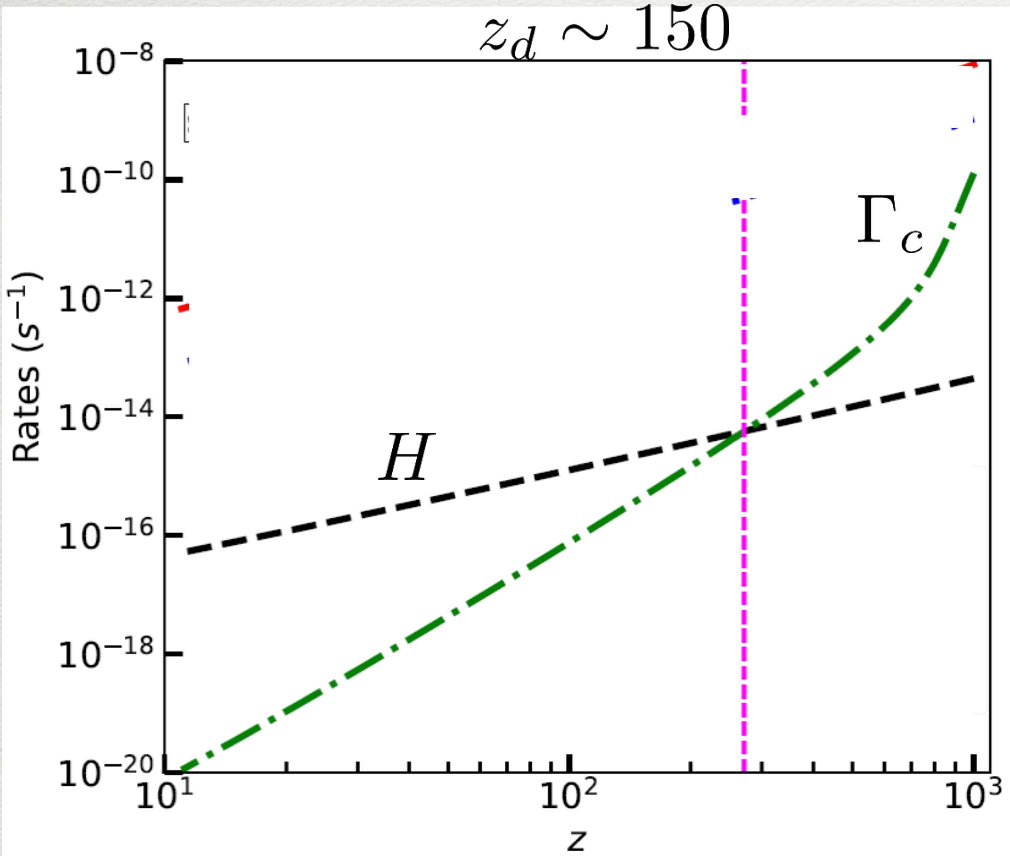
Blackbody expectation

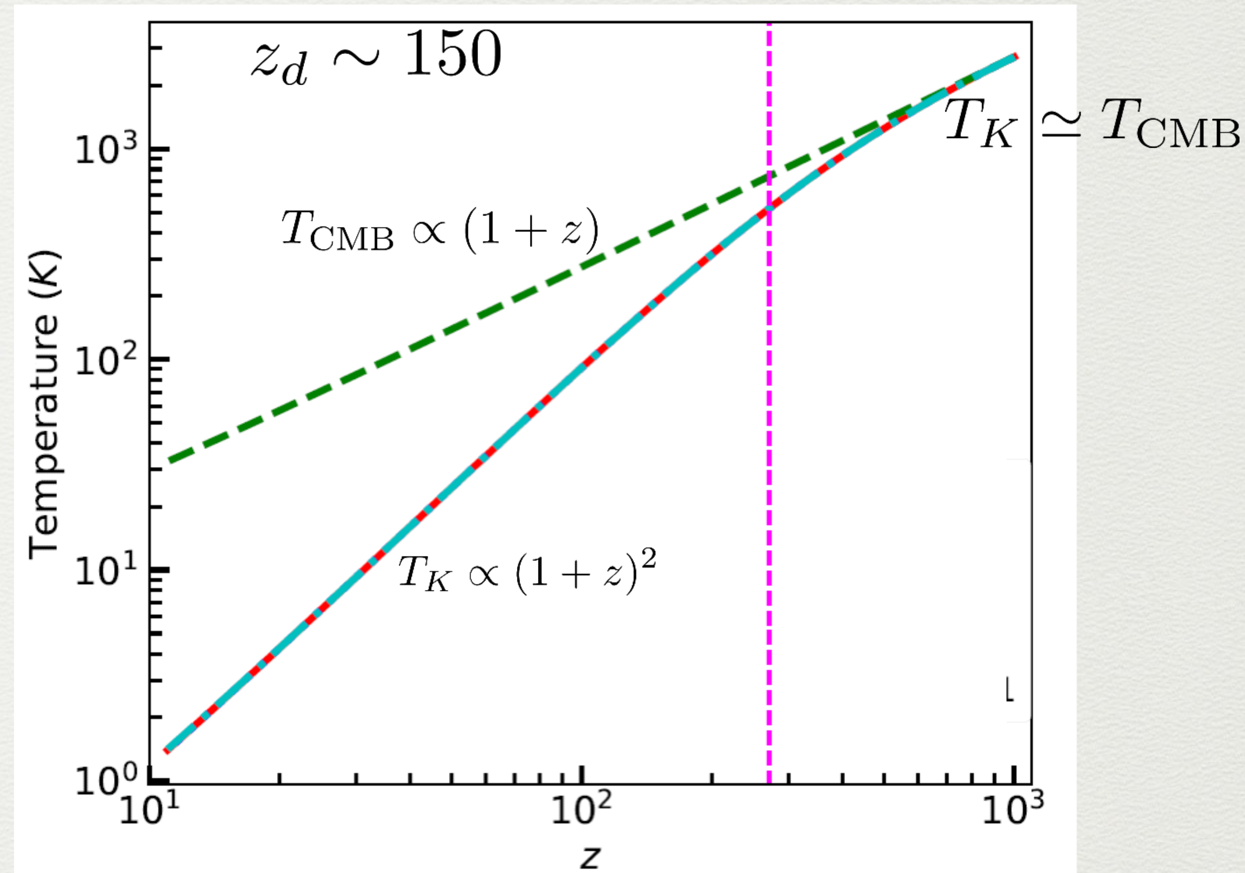
$$T_b \equiv \frac{c^2}{2k_B\nu^2} I_\nu$$

$$\delta T_b \propto I_\nu^{\mathrm{measured}} - I_\nu^{\mathrm{CMB}}$$

measure of net absorption or emission at different redshifts

Evolution of the gas kinetic temperature





Compton scattering rate

$$\frac{dT_K}{d\log(1+z)} = +2T_K - \frac{\Gamma_c}{H}(T_{\rm CMB} - T_K)$$

$$\Gamma_c = \frac{8a_r\sigma_T}{3m_ec}T^4_{\rm CMB}(z)\frac{x_e(z)}{(1+0.08+x_e(z))}$$

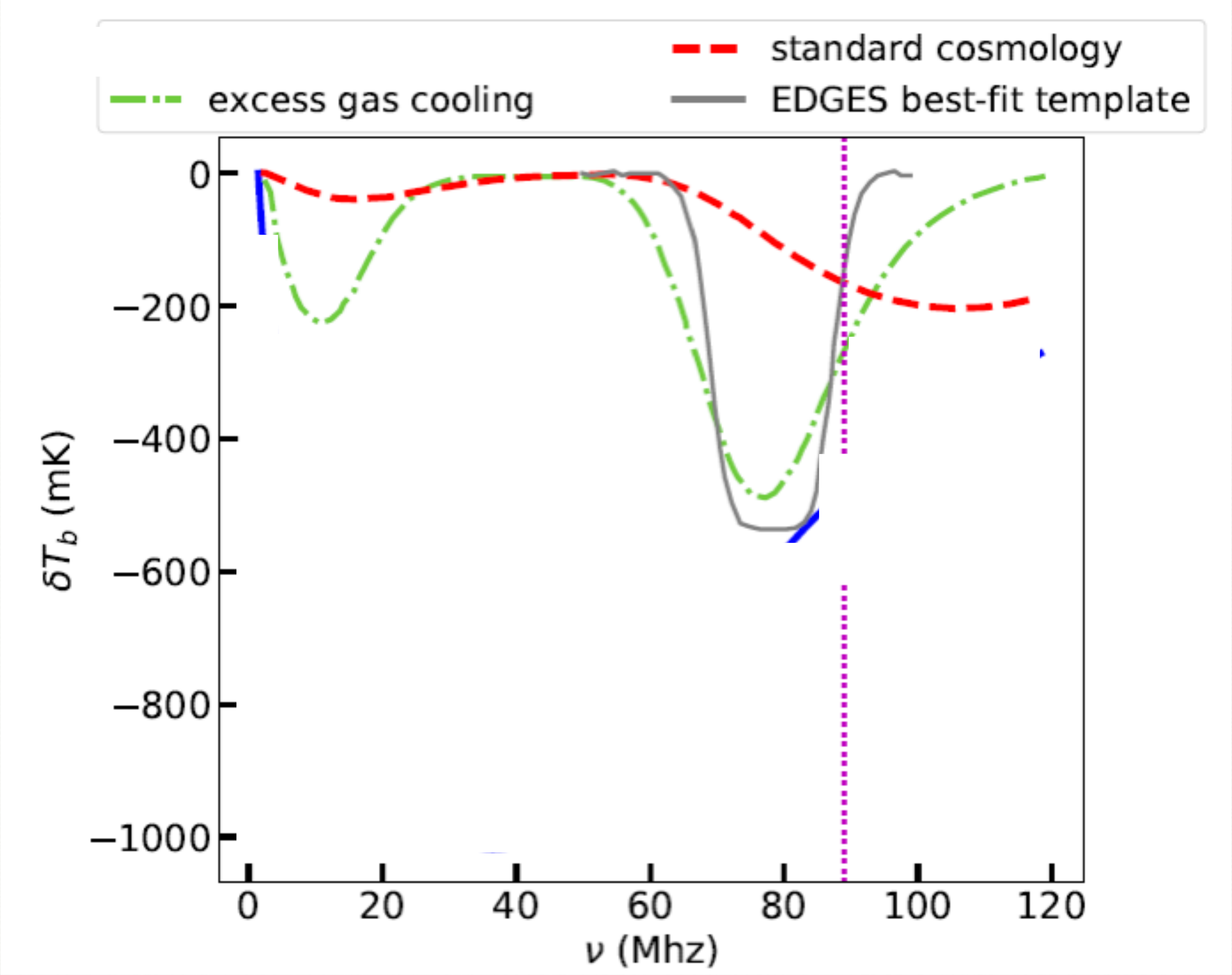
$$= 7.4\times10^{-20}\left(\frac{1+z}{1+10}\right)^4 \times \frac{x_e(z)}{2\times10^{-4}}\frac{1.08}{(1+0.08+x_e(z))}s^{-1}$$

In standard cosmology

$$T_K(z=17) \sim 6.8 \ \ \text{K}$$

$$T_s^{\rm EDGES}(z=17) \sim 3.3 \ \ \text{K}$$

Excess gas cooling models



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

Constraints:

- Light mediator
  - **Short range forces mm-nm scale**
  - *Collider searches*
  - *Stellar cooling*
  - Extra-radiation species $\Delta N_{\rm eff}$
- Cosmological constraints
  - **Kinetic decoupling**
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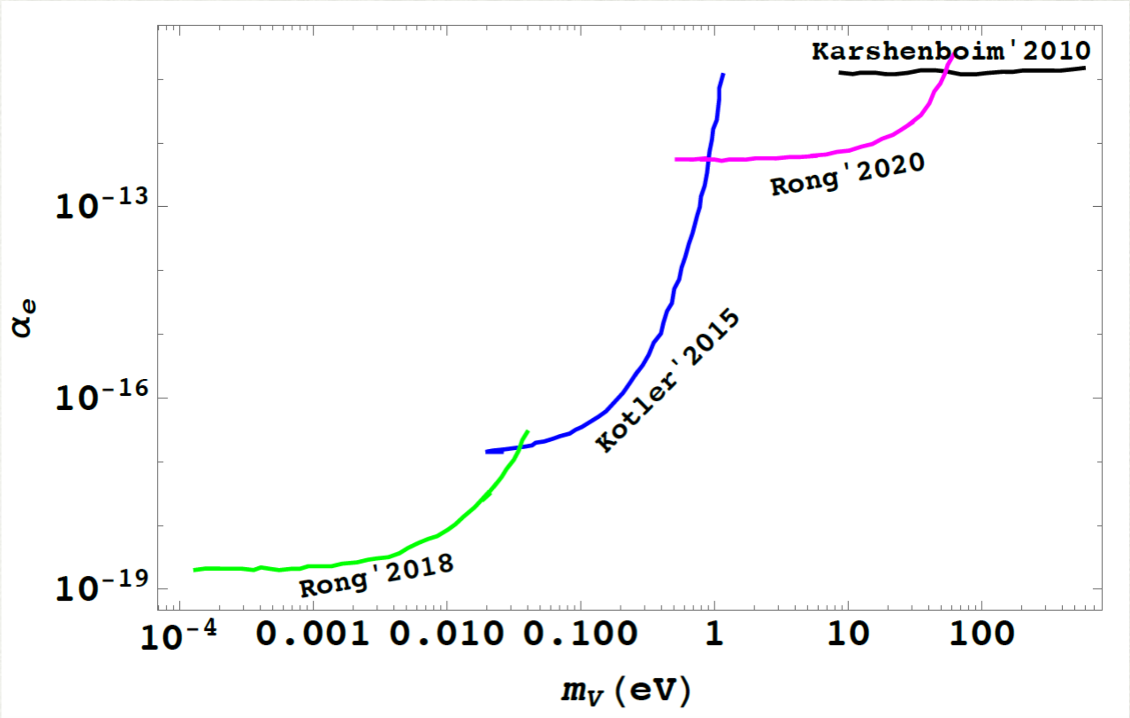

$$0.1\ \text{eV}\sqrt{\frac{\alpha_\chi \alpha_e}{10^{-18}}}\left(\frac{\mu}{0.1\ \text{GeV}}\right) \lesssim m_V \lesssim 2.3\ \text{eV}\sqrt{\left(\frac{1000\ \text{K}}{T_{\rm eff}}\right)\left(\frac{\mu}{0.1\ \text{GeV}}\right)}$$