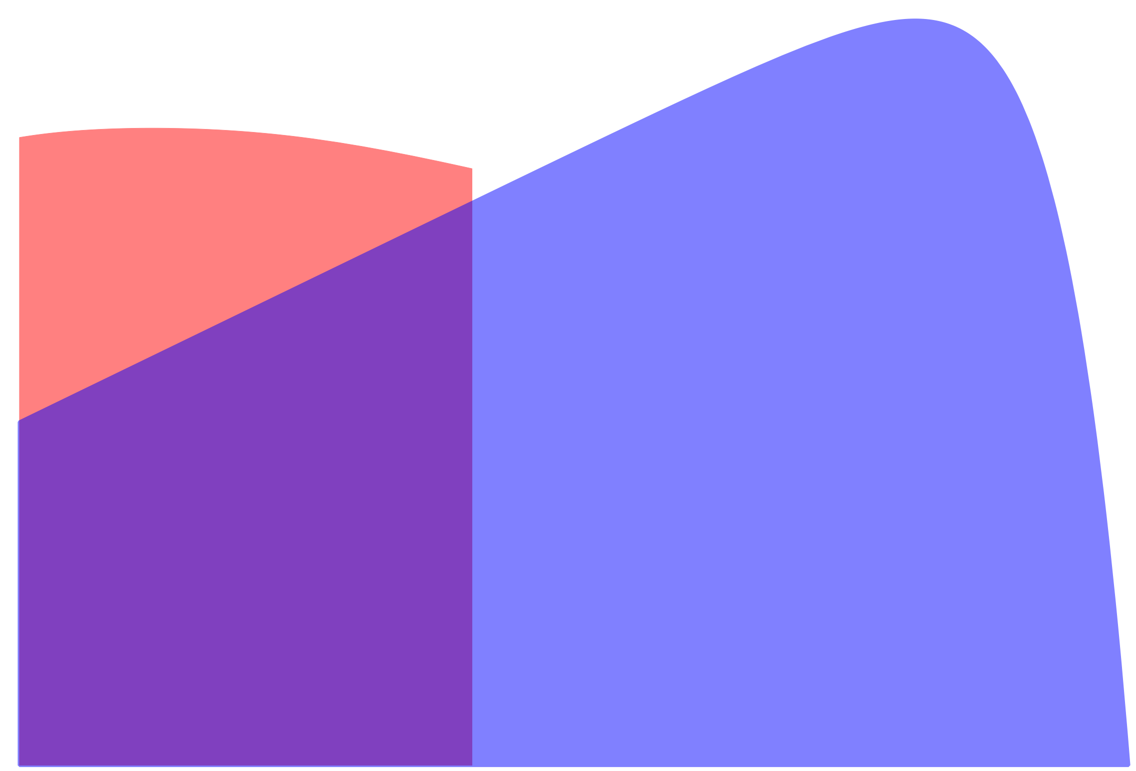
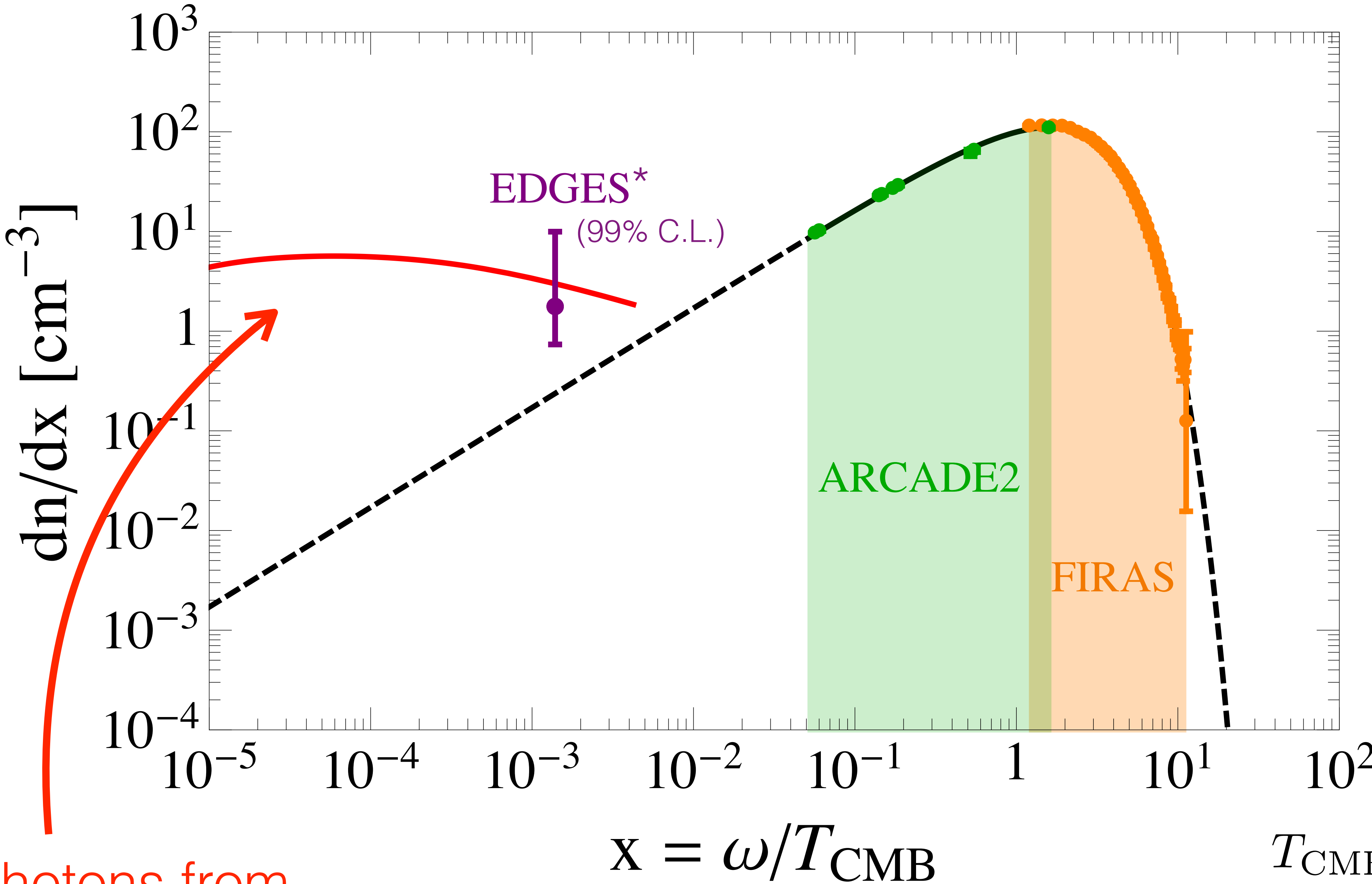
21cm Probes Dark Radiation

Josh Ruderman
(NYU, CERN)
@PPC2018, 8/24



Pospelov, Pradler, JTR, Urbano, **1803.07048 & *to appear***

Soft Spectral Distortion from Dark Radiation



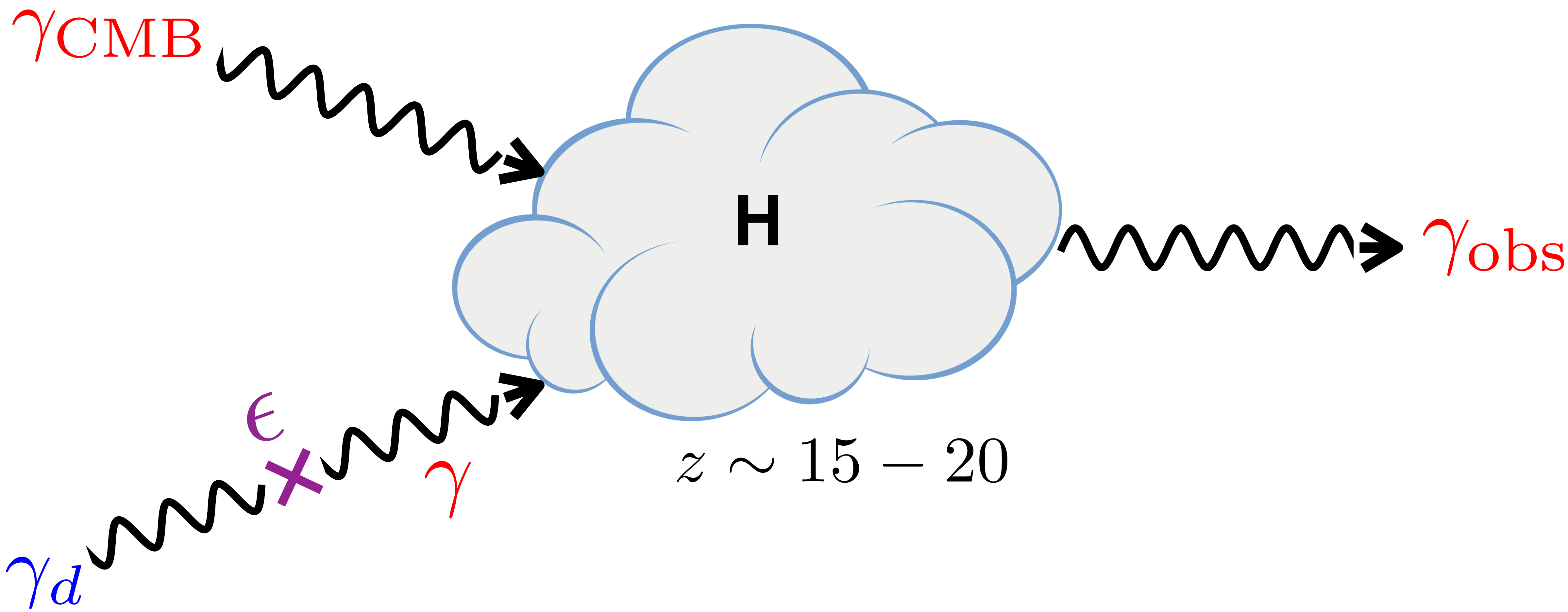
new photons from dark radiation

$\gamma_d \rightarrow \gamma$

Bowman *et. al.* Nature **555**, 67 (2018)

*assuming a model for gas heating

21cm Cosmology

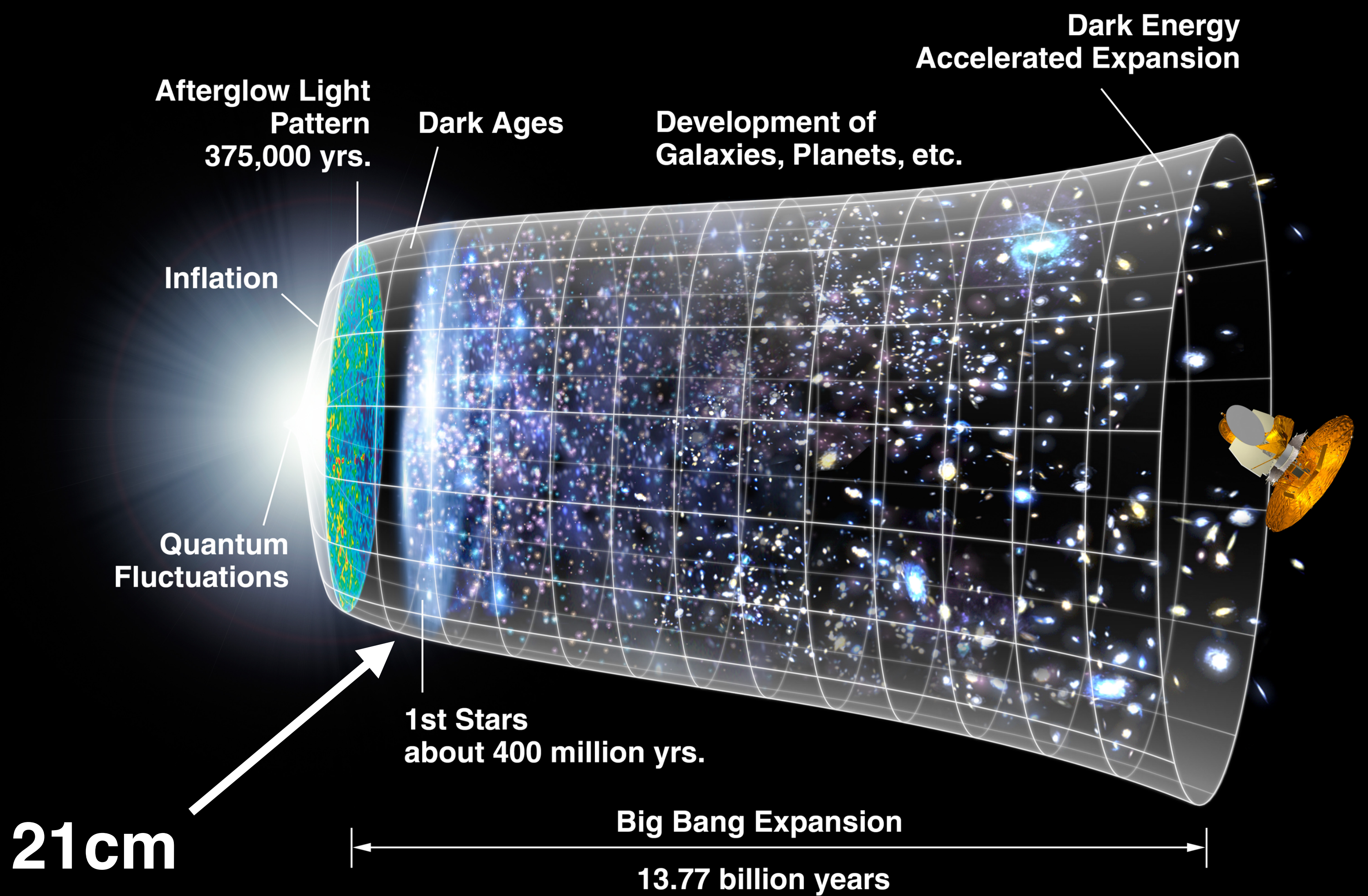


Plan

I. 21cm Primer

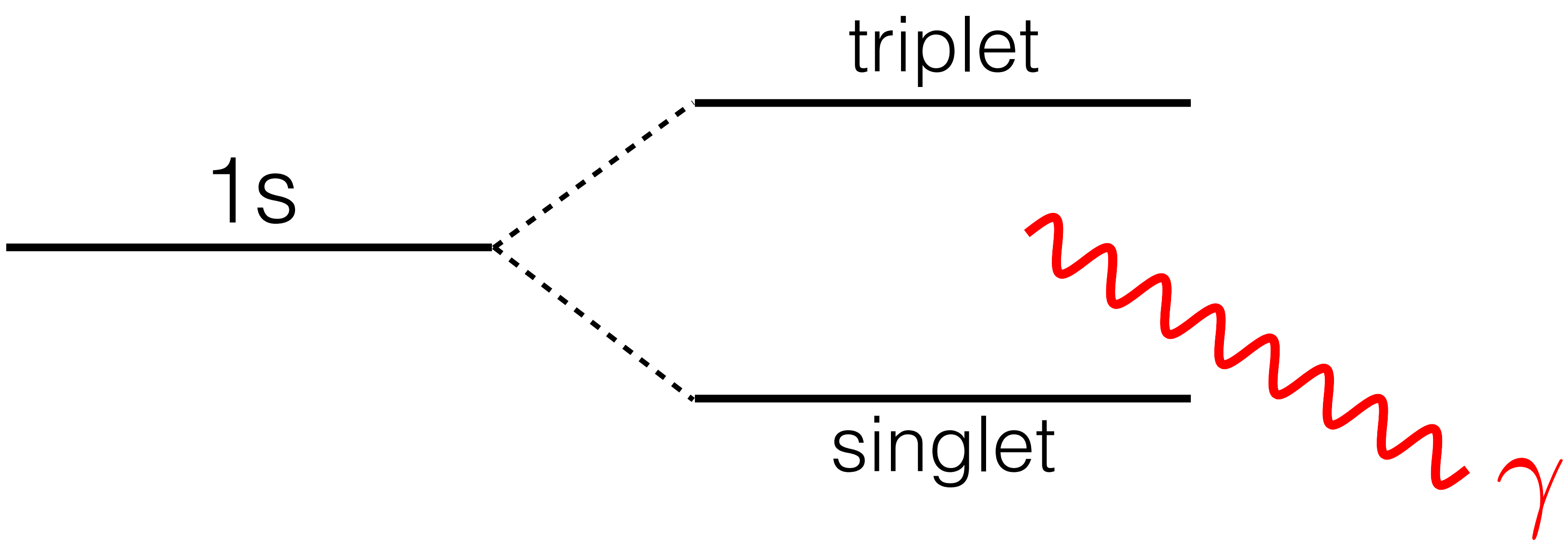
II. $\gamma_d \to \gamma$

I. 21cm Primer



21cm Line of Hydrogen

- hyperfine splitting of hydrogen 1s:

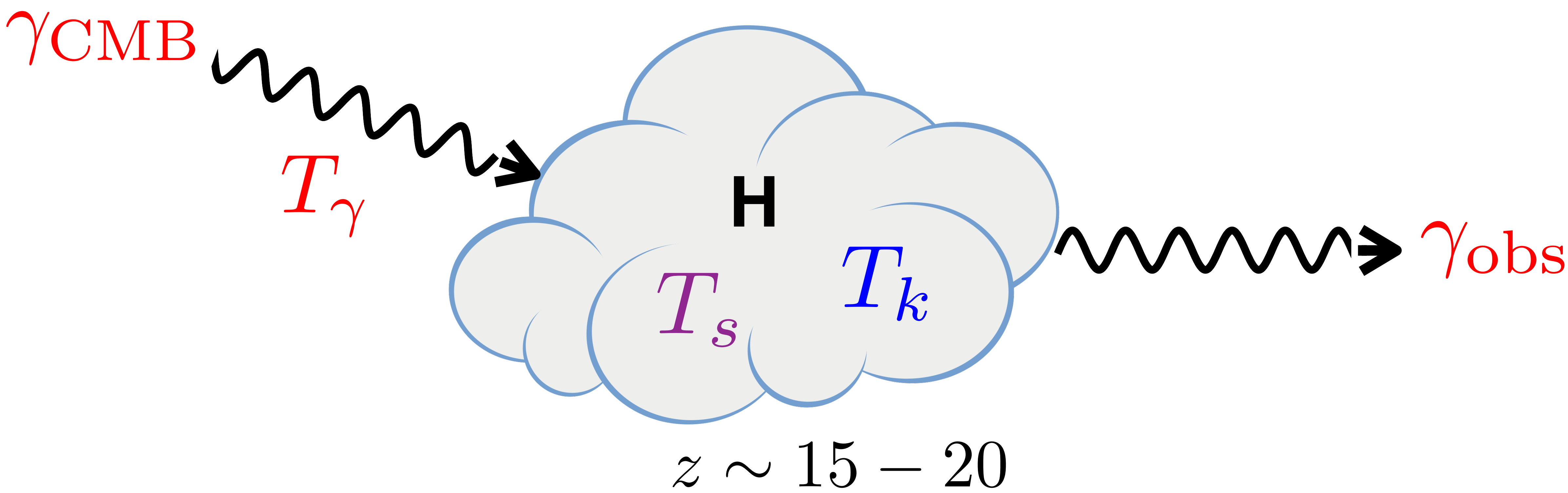


$$\lambda = 21\,\text{cm}$$
$$\omega_{21} = 5.9\,\mu\text{eV}$$

- redshift: $\omega_{\text{obs}} = \dfrac{\omega_{21}}{1+z}$

- hydrogen spin temperature: T_S $\qquad \dfrac{n_t}{n_s} = 3\,e^{-\omega_{21}/T_S}$

Temperatures and Absorption



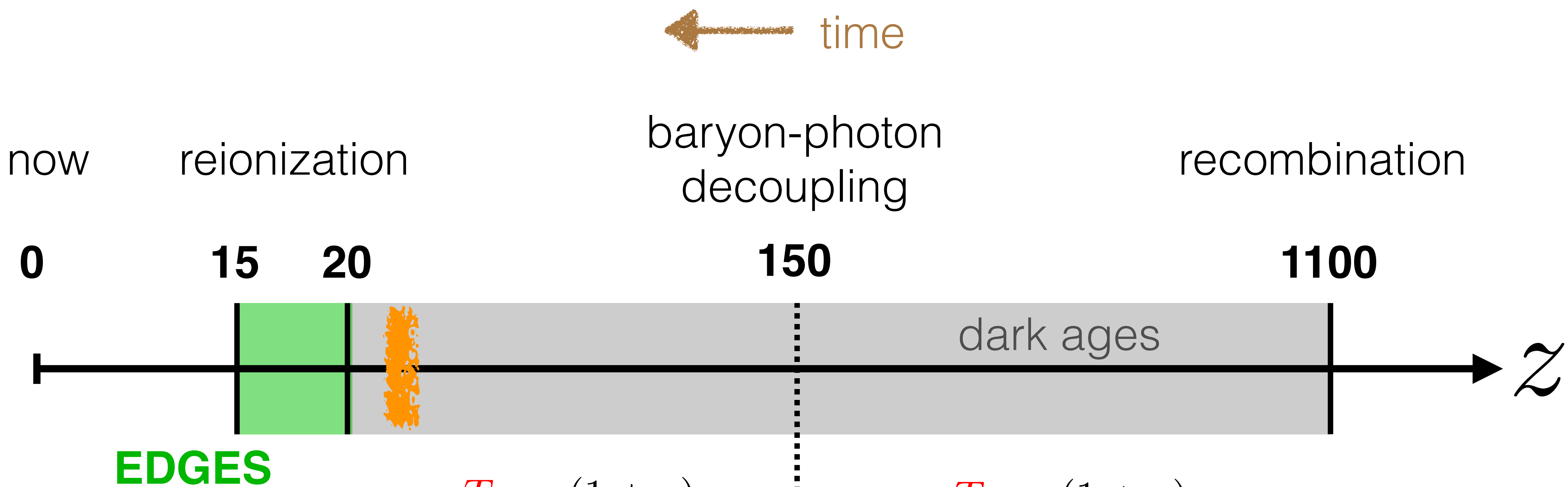
temperatures:
T_γ, T_k, T_s

- photon: $T_\gamma = T_{\rm CMB}$
- hydrogen kinetic: T_k
- hydrogen spin: T_s

absorption:

$$\Delta T_{21}(z) = 32\,{\rm mK} \times \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right)\sqrt{\frac{1+z}{18}}$$

Temperature Evolution



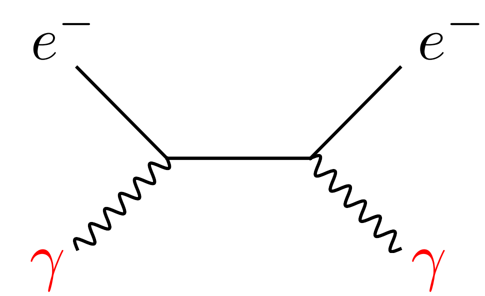
$T_\gamma \propto (1+z)$

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

$$T_k \leq T_s \leq T_\gamma$$

$T_\gamma \propto (1+z)$

$$T_{s,k} \approx T_\gamma$$

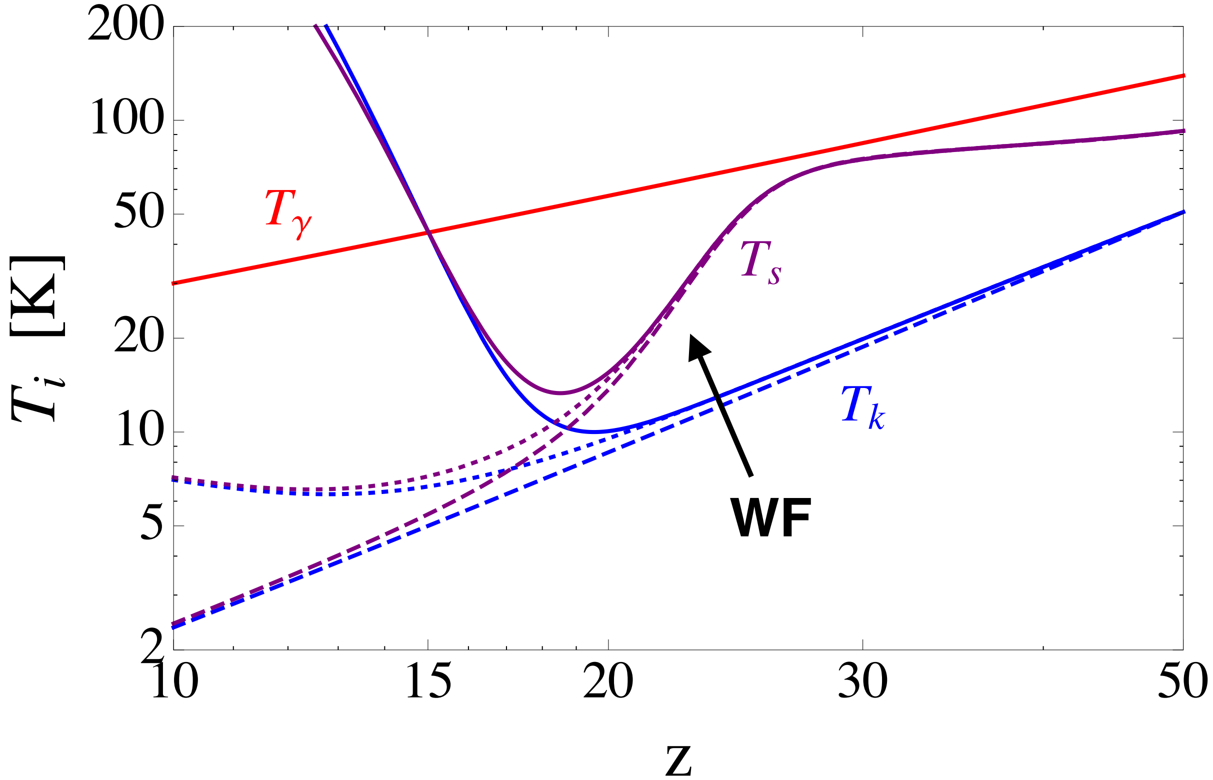


Woutuysen-Field Effect:

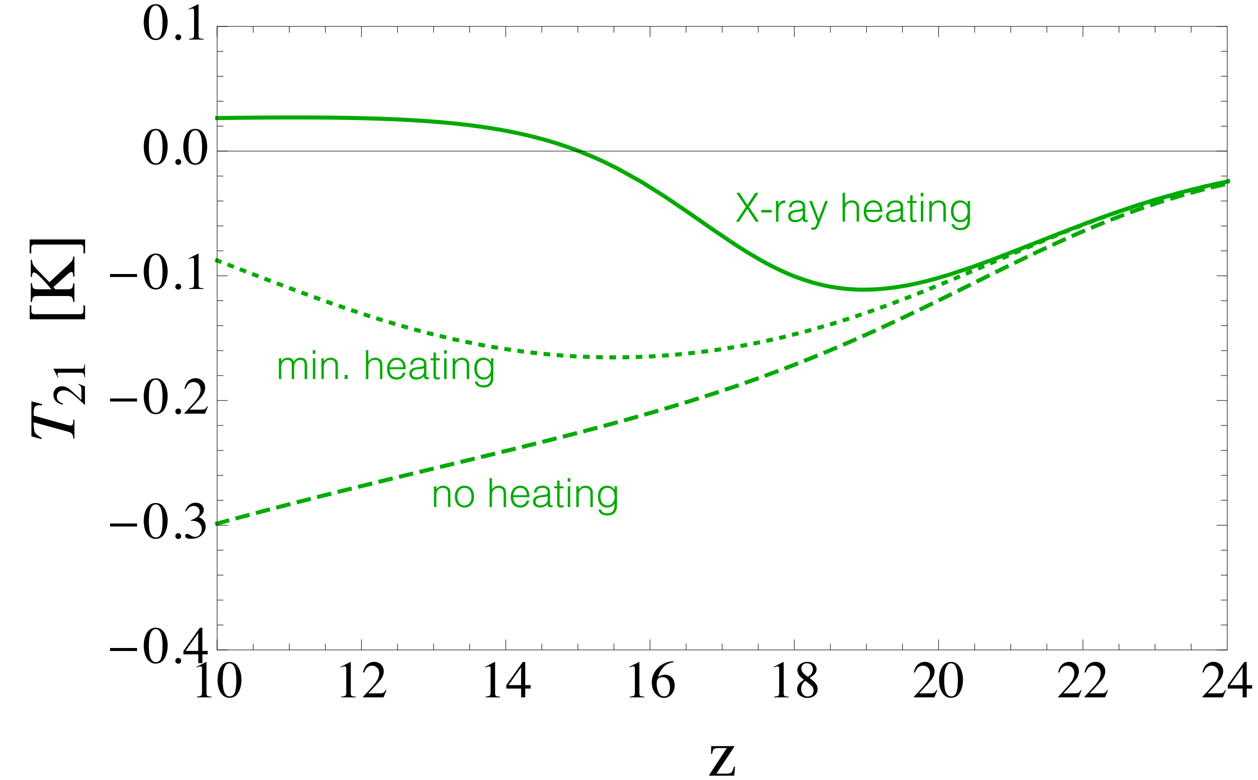
UV light from first stars couples: $T_s \rightarrow T_k$

Temperatures and Absorption

temperature evolution



21cm absorption



- - - - - without gas heating

·········· minimal gas heating

——— with X-ray heating

WF

$$T_s^{-1} = \frac{x_{\rm CMB} T_\gamma^{-1} + \tilde{x}_\alpha T_c^{-1} + x_c T_k^{-1}}{x_{\rm CMB} + \tilde{x}_\alpha + x_c}$$

adiabatic cooling

minimal heating

X-ray heating

$$(1+z)\frac{dT_k}{dz} = 2T_k - \frac{\mathcal{E}_{\rm Comp} + \mathcal{E}_{{\rm Ly}\alpha} J/J_0 + \mathcal{E}_{\rm CMB} + \mathcal{E}_X}{1+f_{\rm He}+x_{\rm e}} T_k$$

evolution equations from: Venumadhav, Dai, Kaurov, Zaldarriaga, **1804.02406**

EDGES

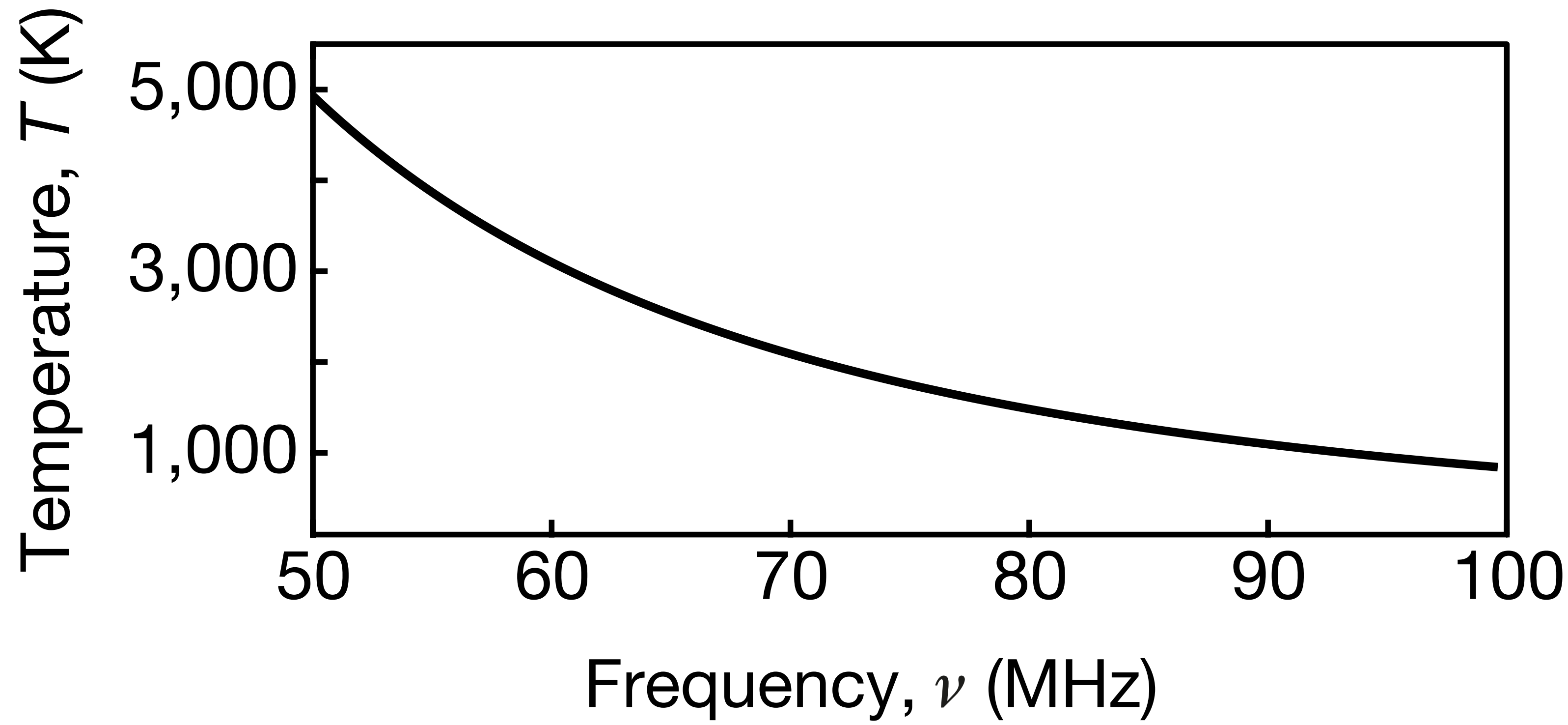
Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature

Bowman *et. al.* Nature **555**, 67 (2018)

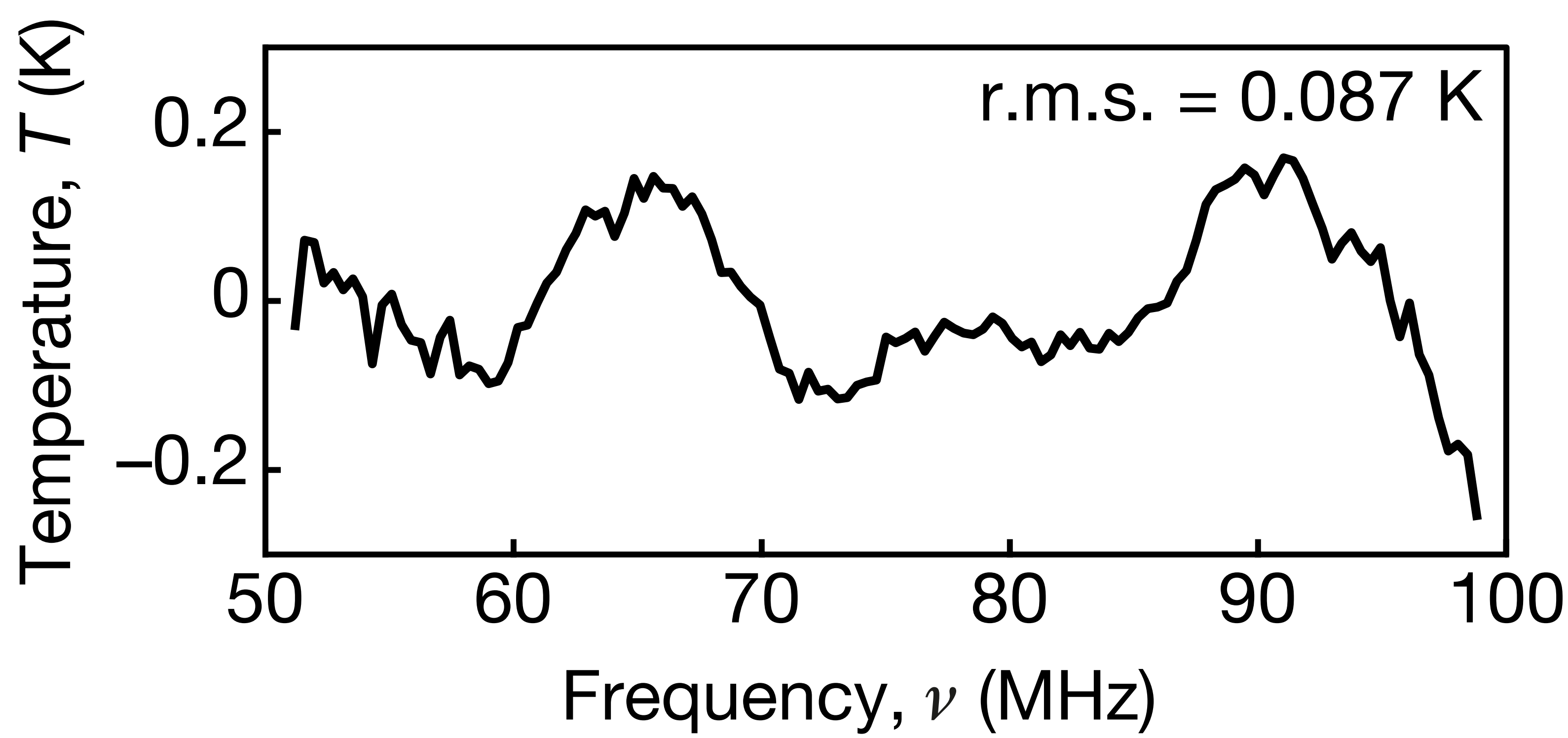
EDGES

Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature

measured spectrum:



residuals
(foregrounds only):

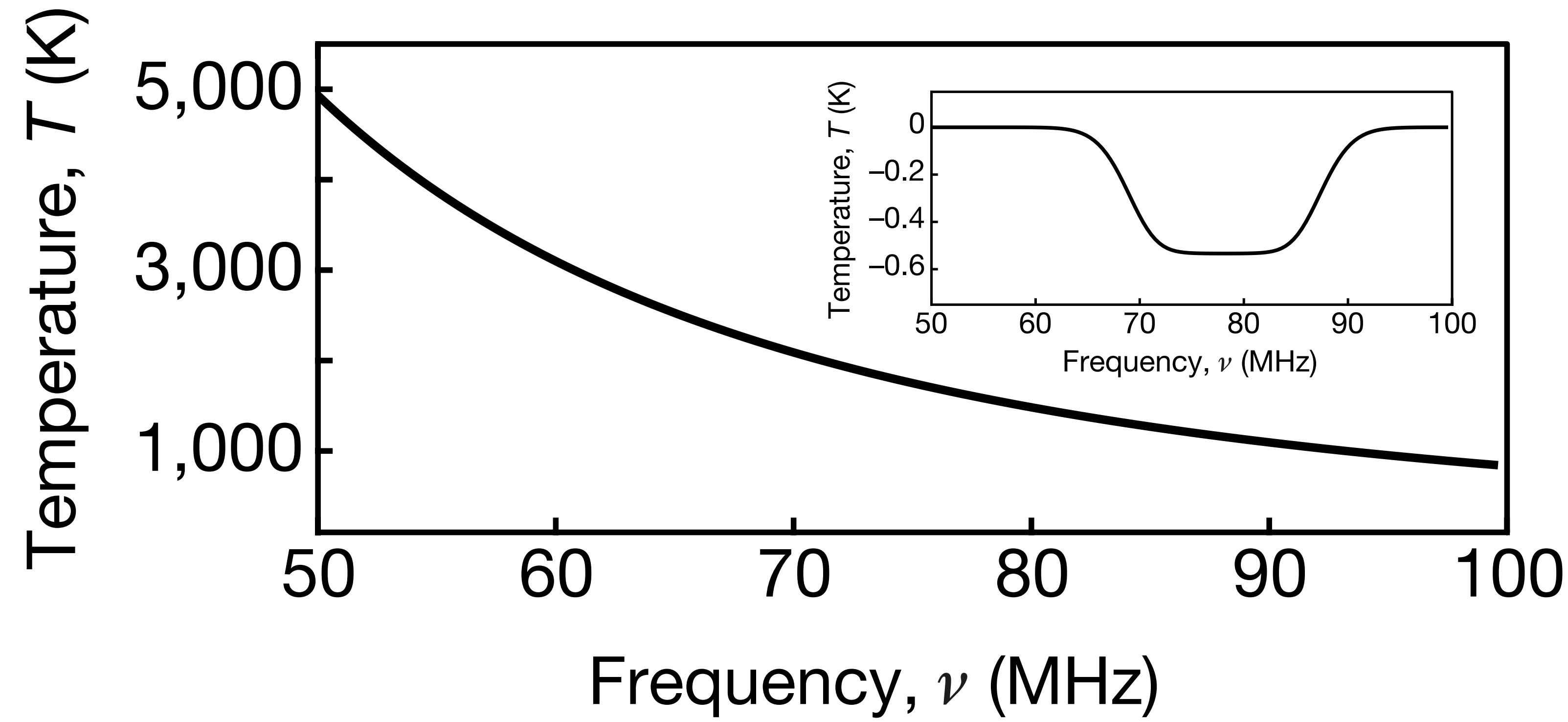


Bowman *et. al.* Nature **555**, 67 (2018)

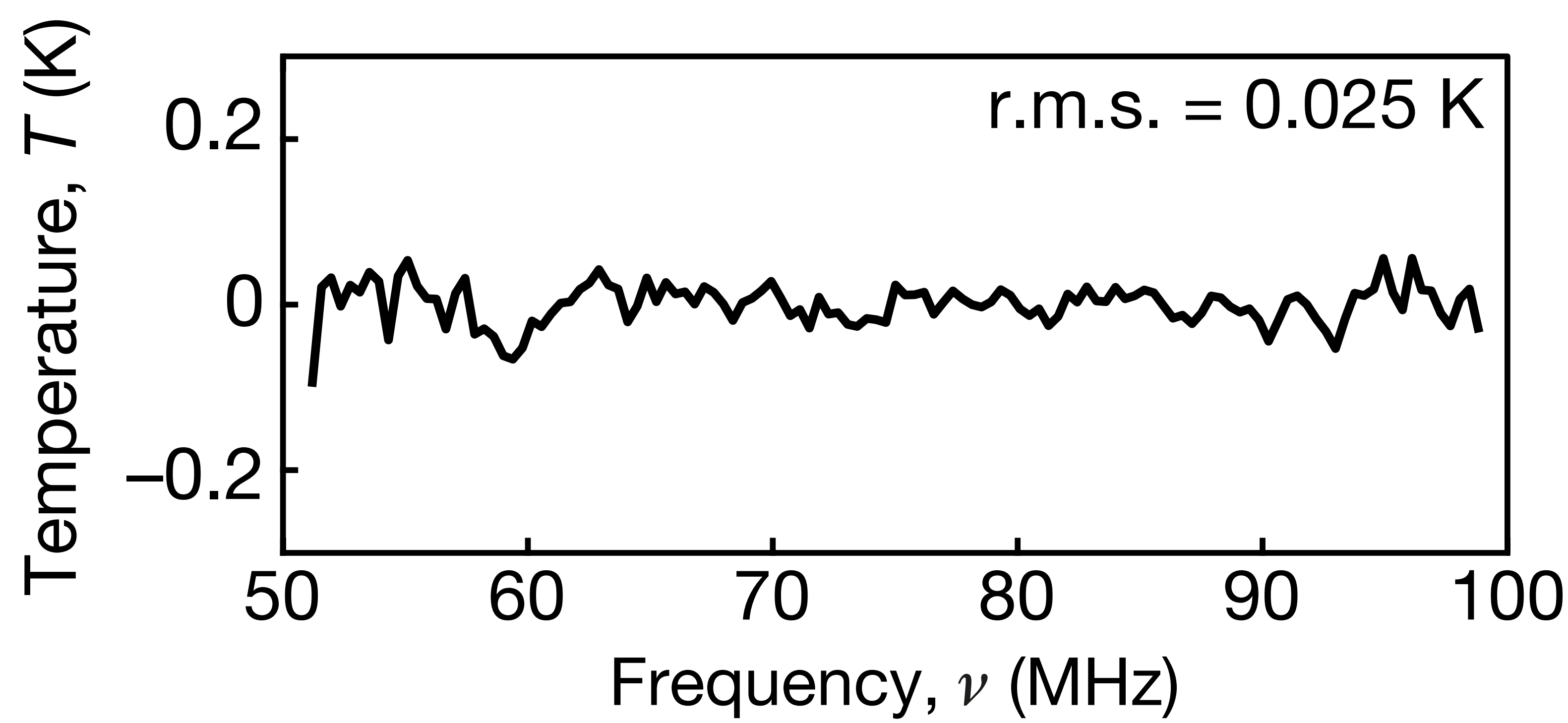
EDGES

Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature

measured spectrum:



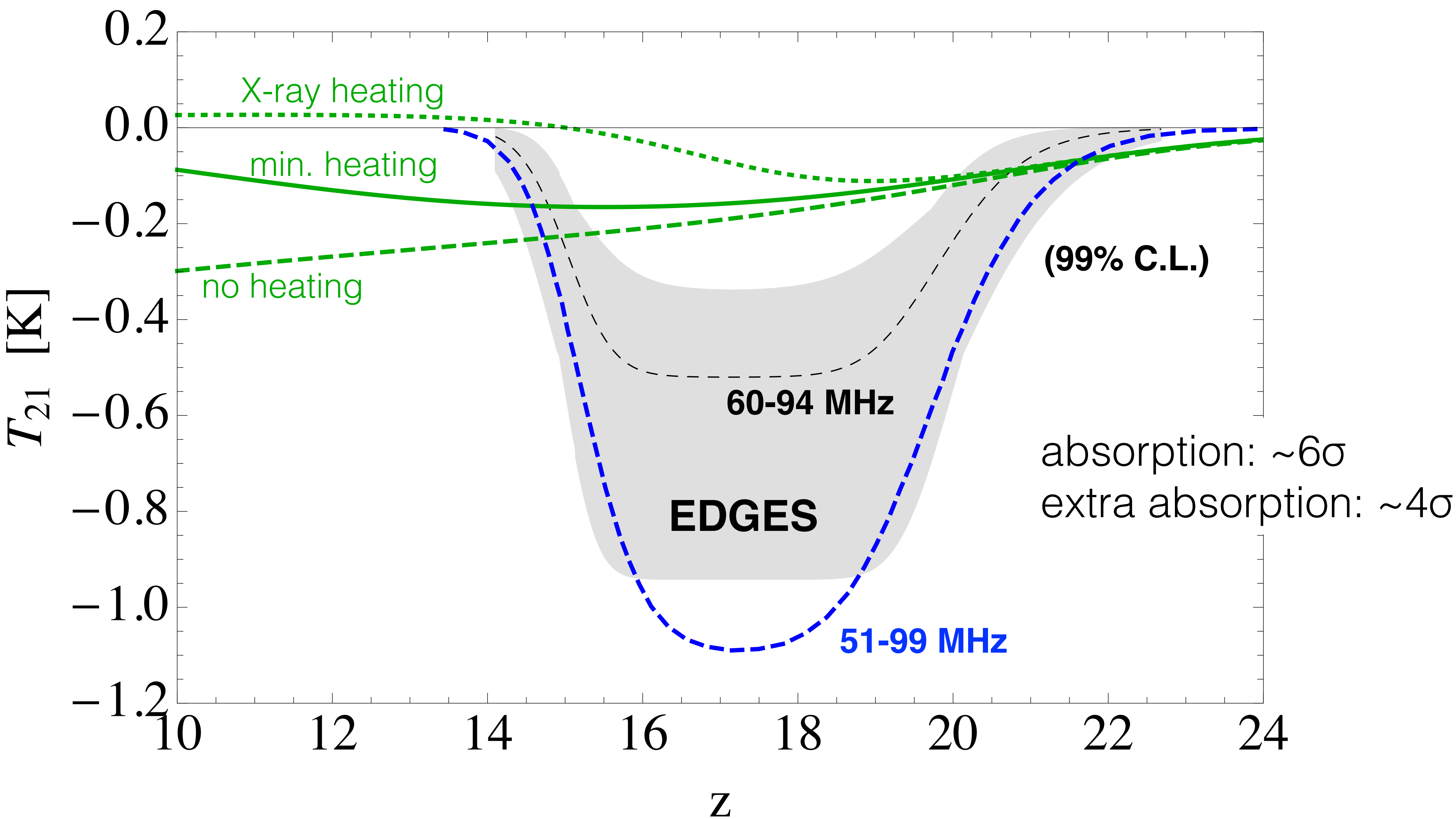
residuals
(including absorption):



Bowman *et. al.* Nature **555**, 67 (2018)

EDGES

Experiment to **D**etect the **G**lobal **E**poch of **R**eionization **S**ignature



- foreground variations: Hills, Kulkarni, Meerburg, Puchwein, **1805.01421**

21cm Probes New Particle Physics

increasing 21cm absorption with new physics:

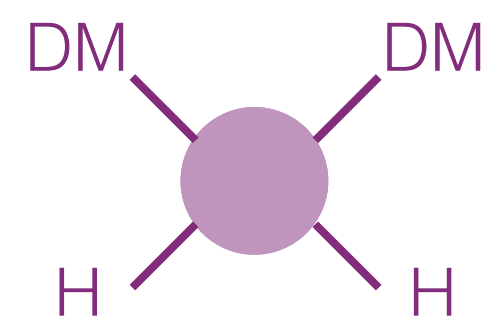
$$T_{21} \propto 1 - \frac{T_\gamma}{T_s}$$

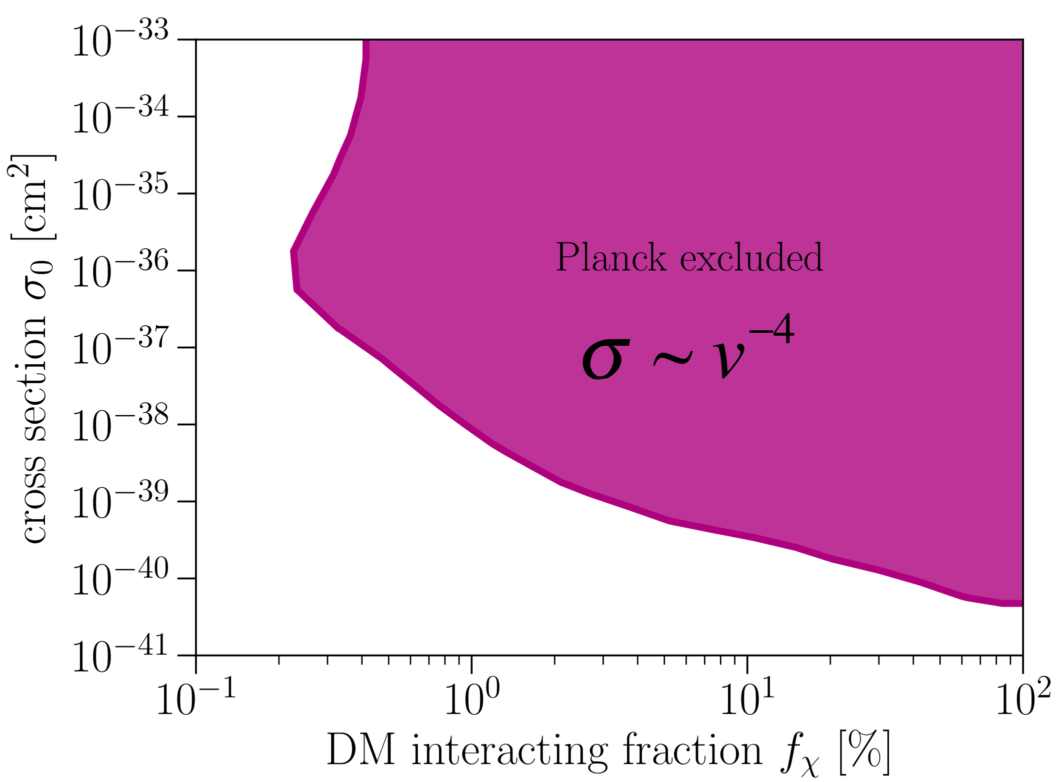
add photons $T_\gamma > T_{\mathrm{CMB}}$

(easy!)

cool baryons

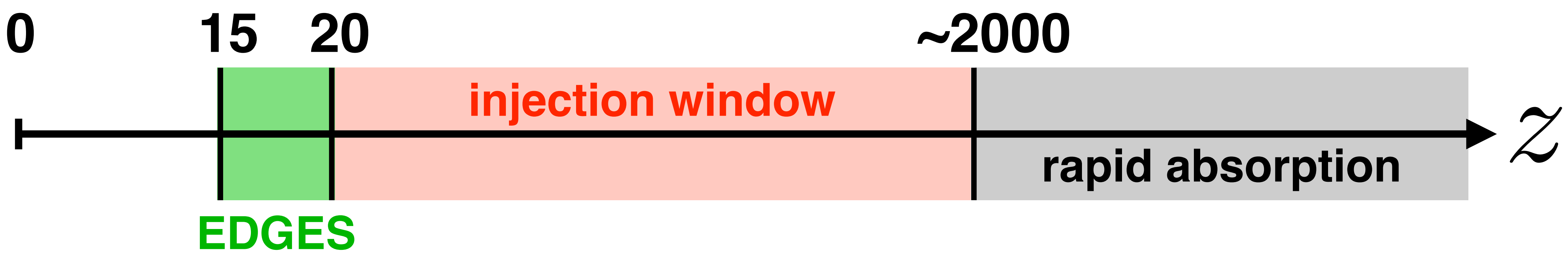
(hard)



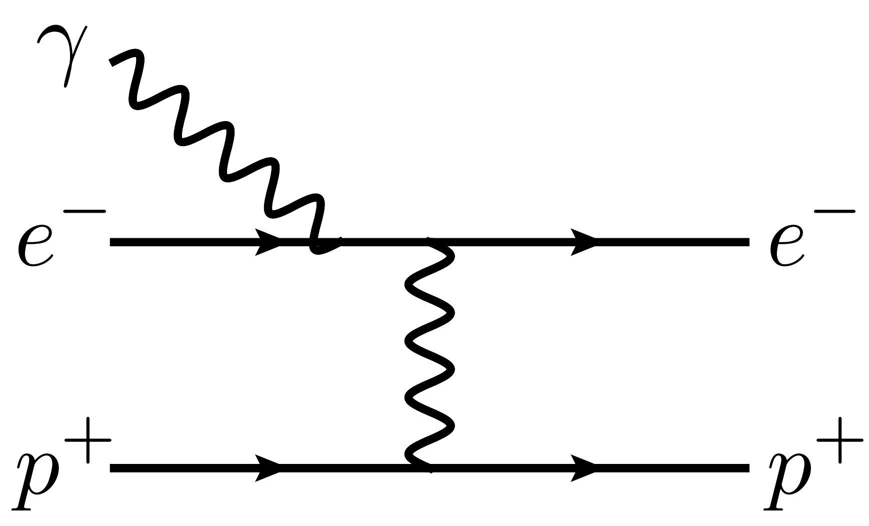


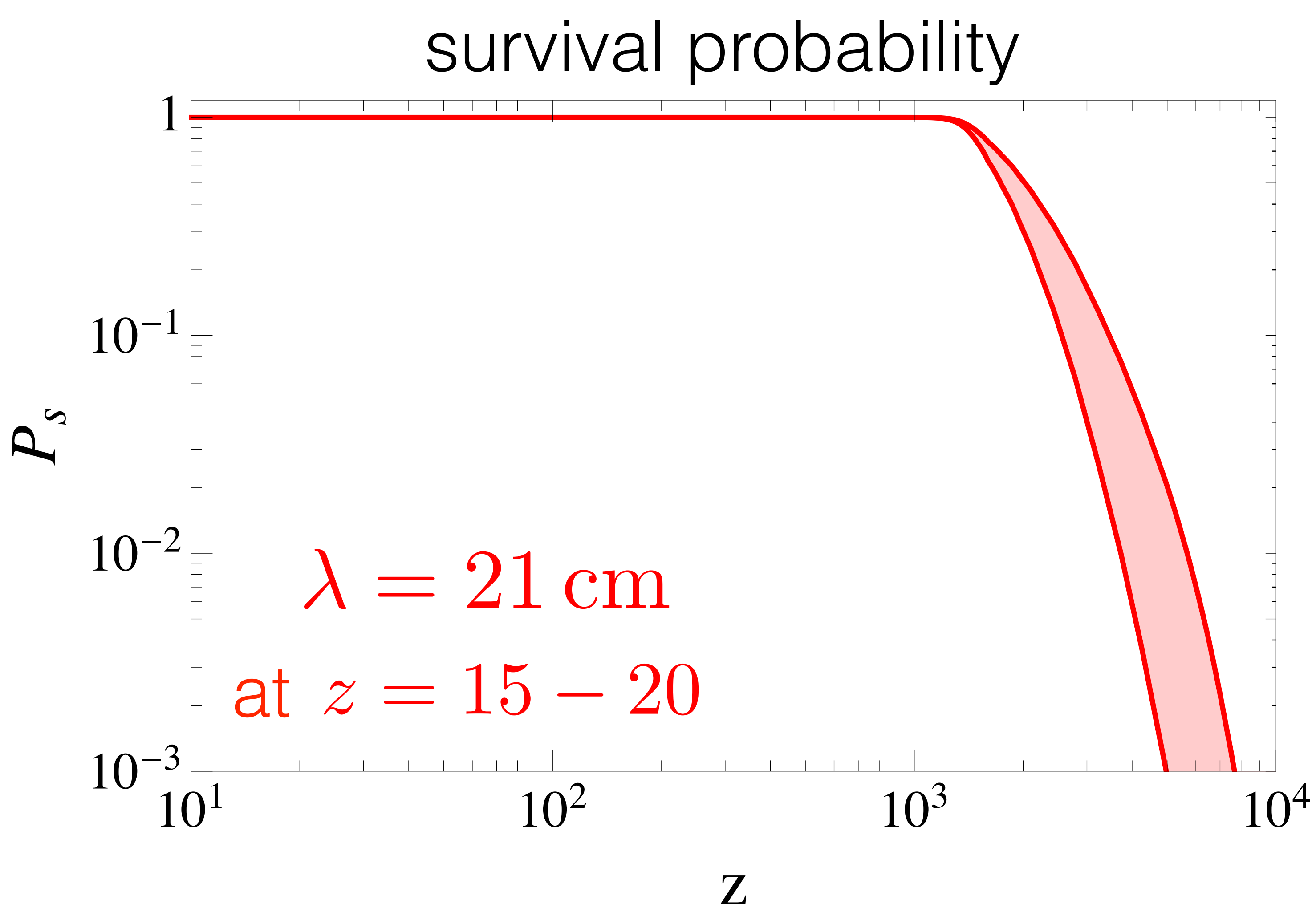
see Vera's talk

When to Add 21cm Photons



free-free absorption:

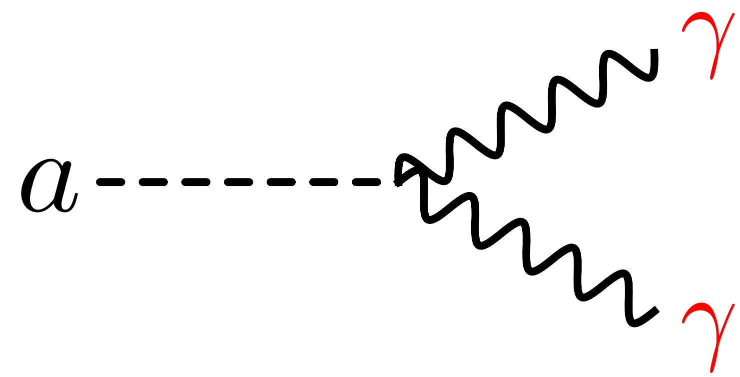




Chluba, **1506.06582**

What if dark matter decays to photons?

ex) $\frac{1}{f}\, a\, F \tilde{F}$



$$10^{-5}\,\mathrm{eV} < m_a < 10^{-3}\,\mathrm{eV}$$

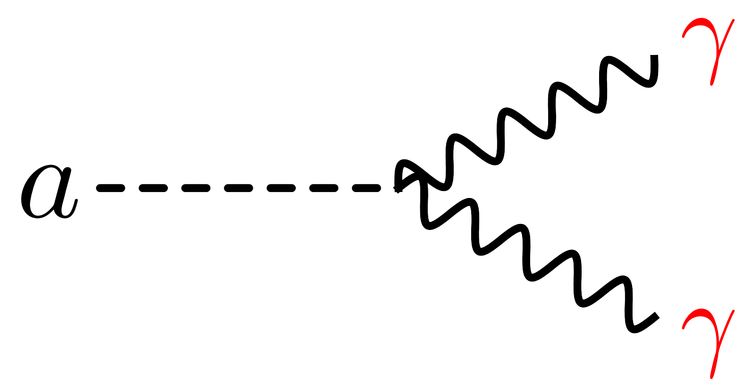
$\uparrow$ $\lambda > 21\,\mathrm{cm}$

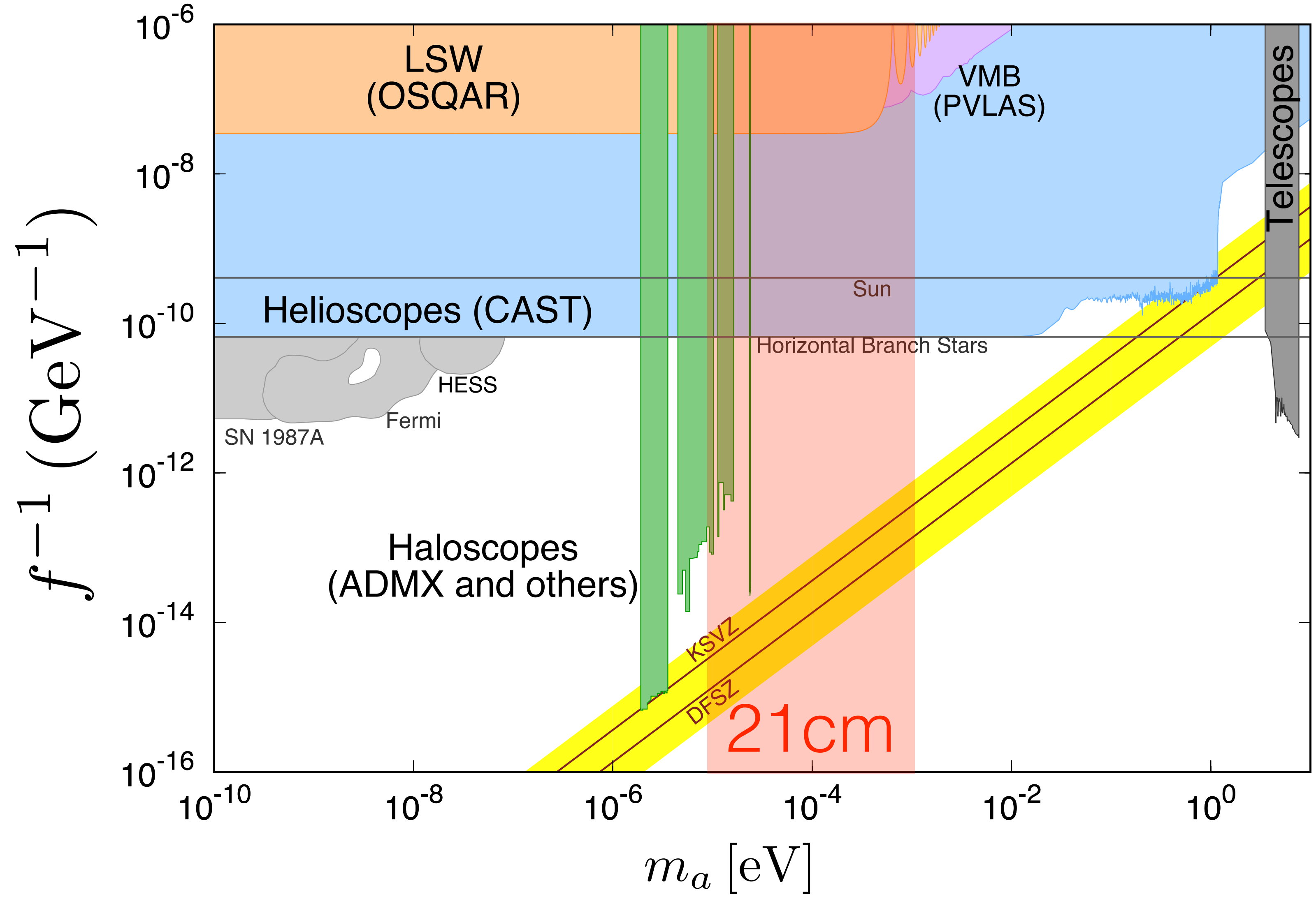
$\uparrow$ 21cm photons absorbed

Fraser *et. al.*, **1803.03245**

What if dark matter decays to photons?

ex) $\frac{1}{f}\, a\, F\tilde{F}$





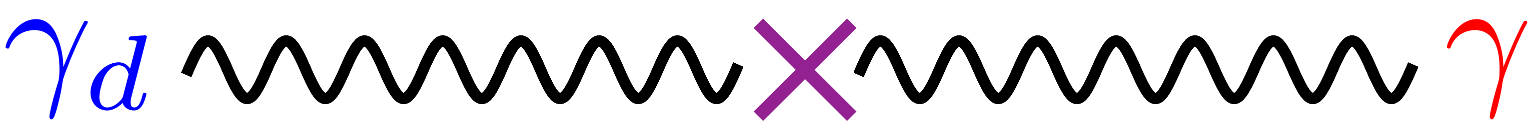
$f > 10^{10}\ \mathrm{GeV}$

↓

$$\left.\frac{n_{a\to\gamma\gamma}}{n_\gamma^{\mathrm{CMB}}}\right|_{21\ \mathrm{cm}} \lesssim 10^{-12}$$

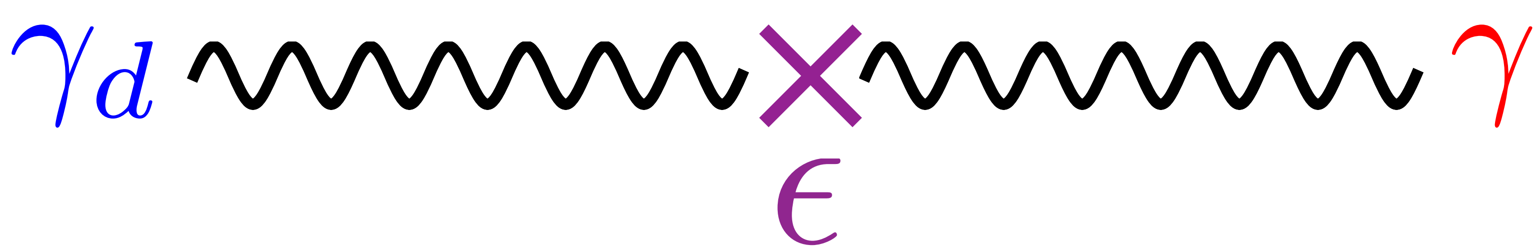
Fraser *et. al.*, **1803.03245**

II. $\gamma_d \to \gamma$



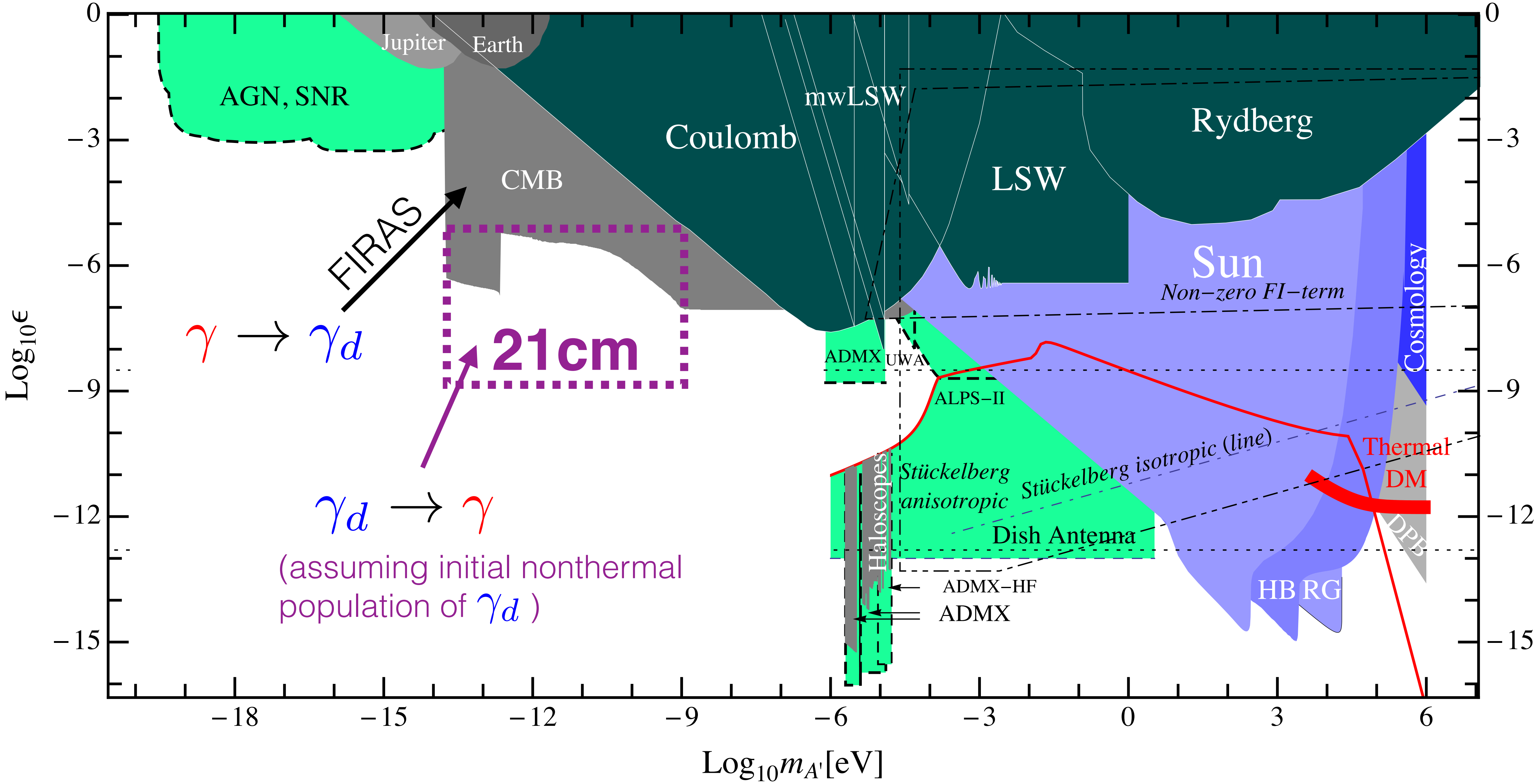
Kinetic Mixing Portal

$$-\frac{\epsilon}{2} F^{d}_{\mu\nu} F^{\mu\nu} + \frac{m^2_{\gamma_d}}{2} \gamma_d^2$$



Holdom, Phys. Lett. **166B**, 196 (1986)

$$(\epsilon, m_{\gamma_d})$$



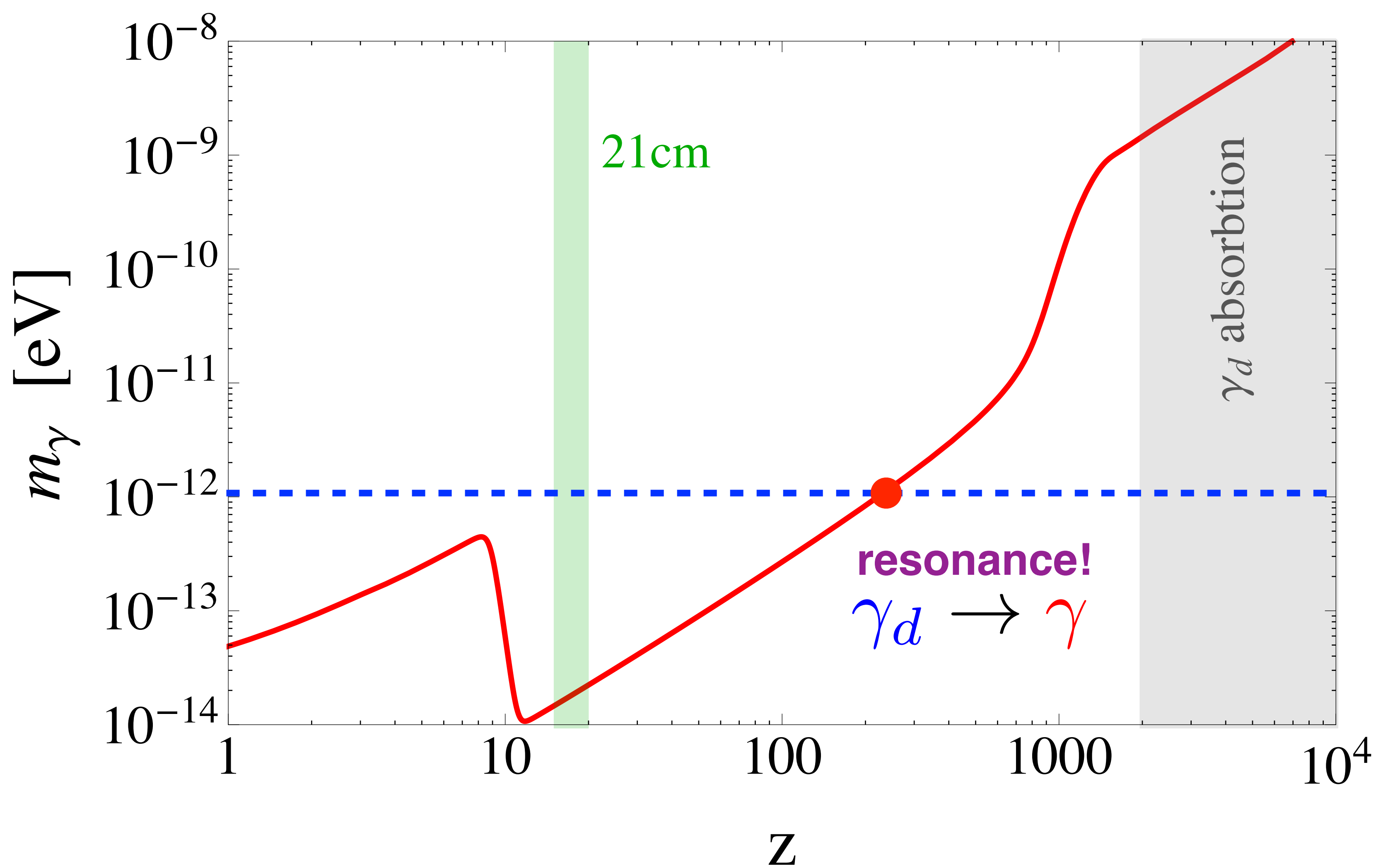
Essig *et. al.*, Snowmass, **1311.0029**

Resonant $\gamma_d \to \gamma$ Oscillations

$$m_\gamma(z) \approx m_{\gamma_d}$$

γ_d ~~~~×~~~~ γ

$$m_\gamma(z) = \sqrt{\frac{4\pi\alpha\, n_e(z)}{m_e}} = 1.6 \times 10^{-14}\,\text{eV} \times (1+z)^{3/2} \sqrt{x_e(z)}$$



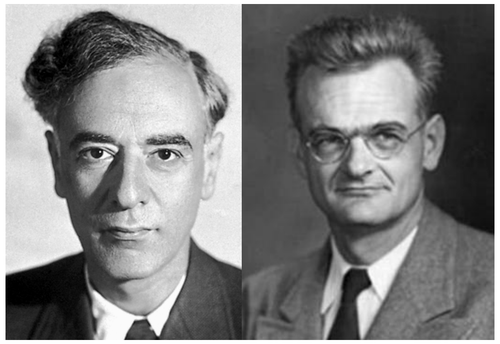
ex)

$m_{\gamma_d} = 10^{-12}\,\text{eV}$

Mirizzi, Redondo, Sigl, **0901.0014**

Oscillation Probability

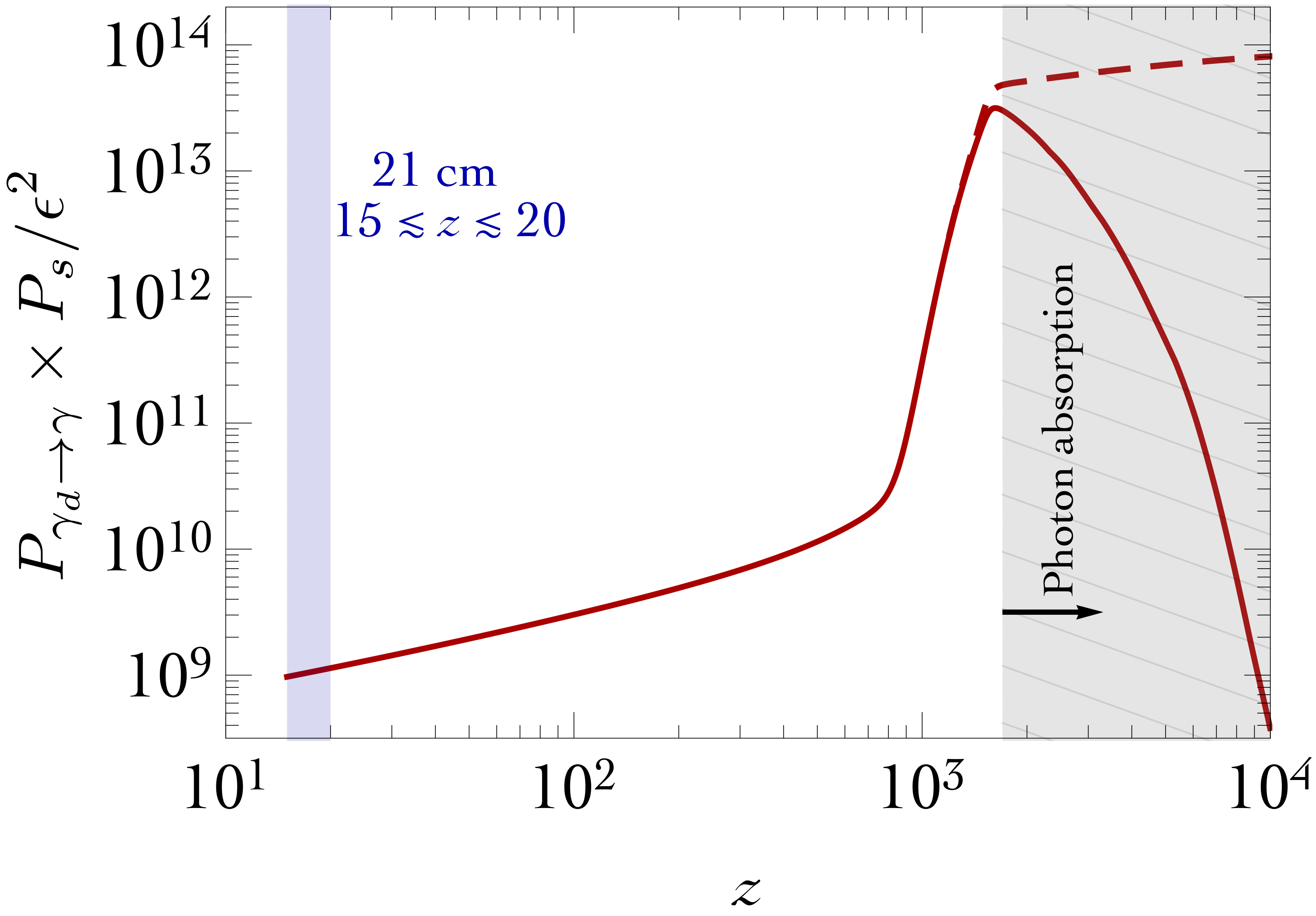
Landau-Zener formula for non-adiabatic level crossing



$$P_{\gamma_d \to \gamma} = \frac{\pi \epsilon^2 m_{\gamma_d}^2}{\omega} \left| \frac{d \log m_\gamma^2}{dt} \right|^{-1}$$

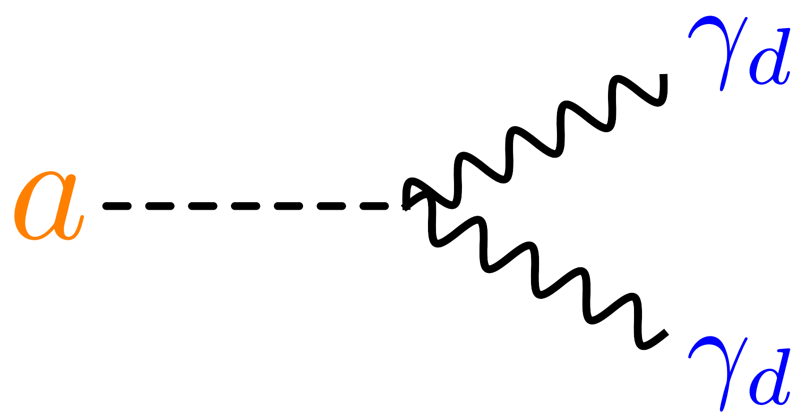
$$\propto \frac{m_{\gamma_d}^2}{\omega H_0} z^{-5/2} \epsilon^2$$

10^{-33} eV

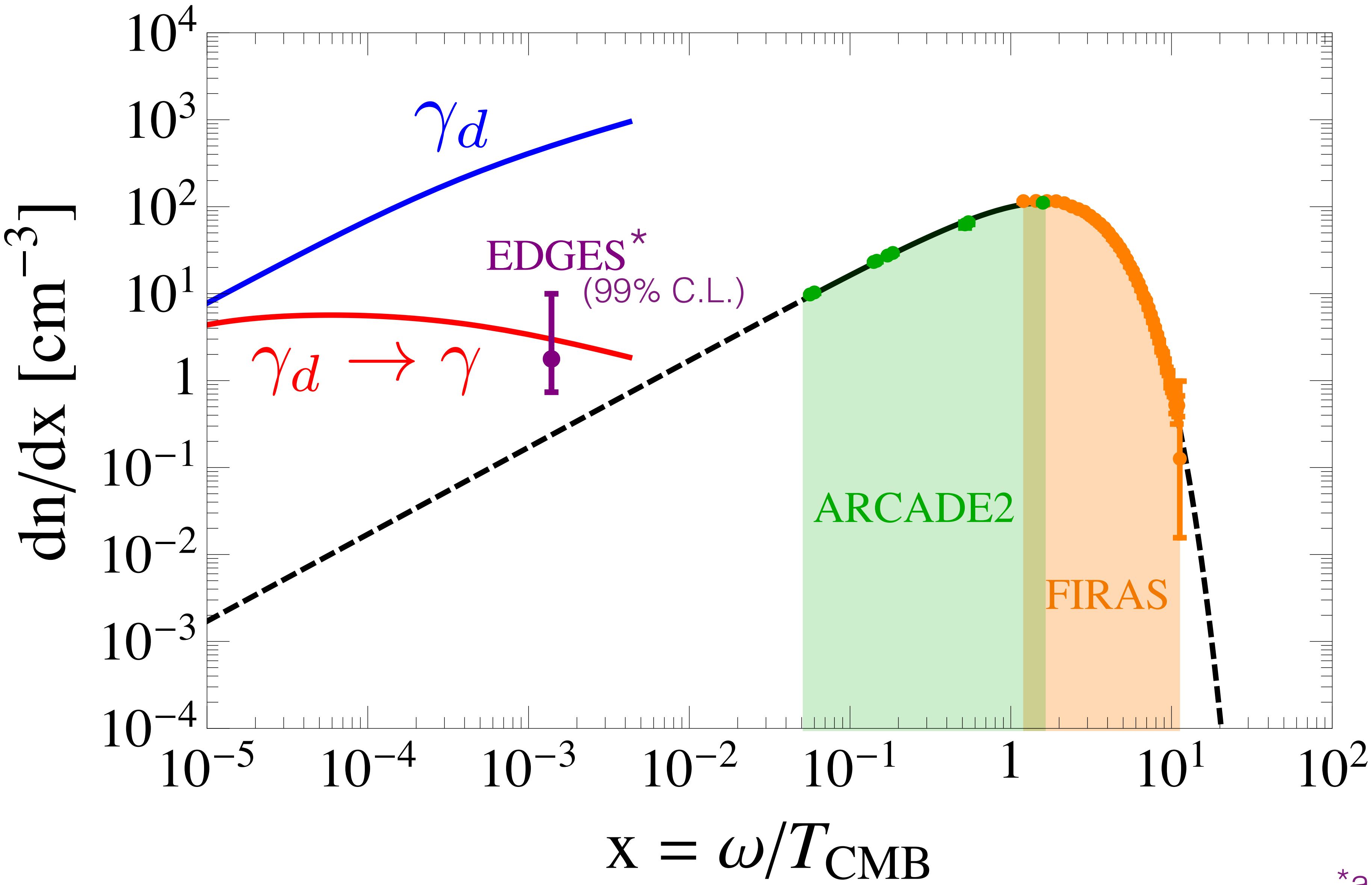


Mirizzi, Redondo, Sigl, **0901.0014**

Dark Matter Decays to Dark Photons



$$\frac{1}{f} a F_d \tilde{F}_d$$



$m_a = 10^{-3}\,\text{eV}$

$\tau_a = 1.4 \times 10^{12}\,\text{y}$

$m_{\gamma_d} = 5 \times 10^{-12}\,\text{eV}$

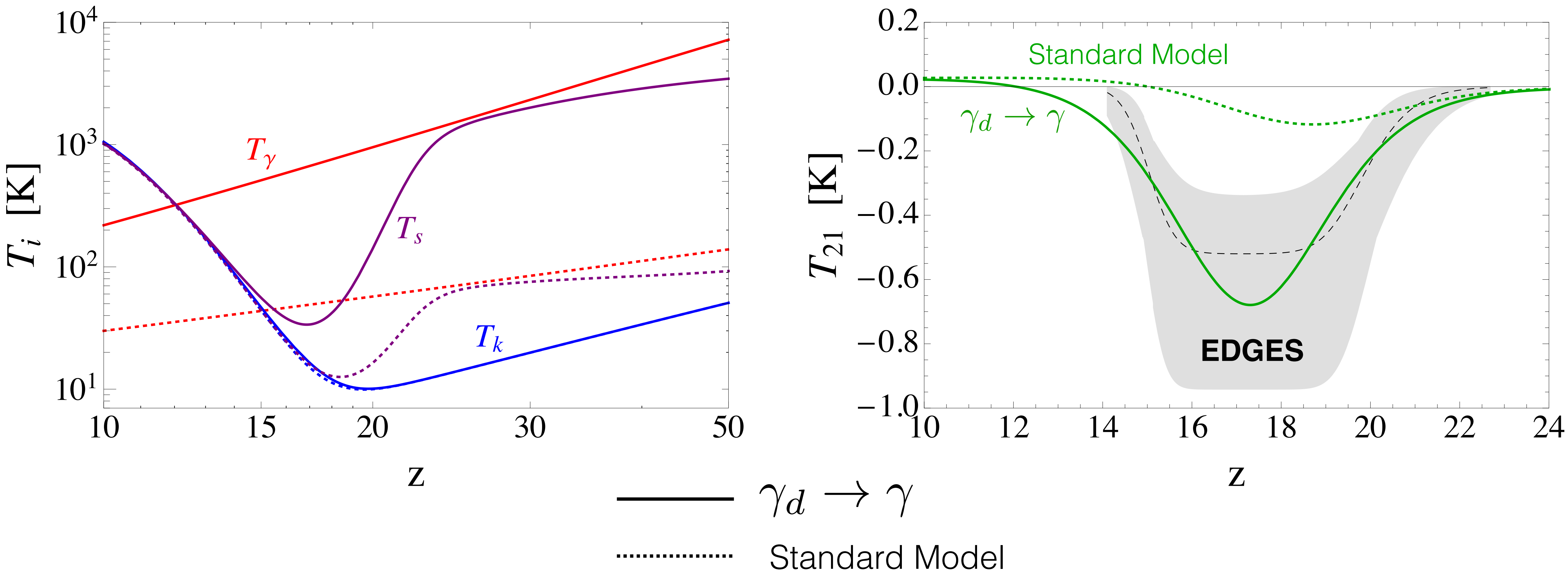
$\epsilon = 7 \times 10^{-7}$

*assuming a model for gas heating

21cm Absorption with Extra Soft Photons

temperature evolution

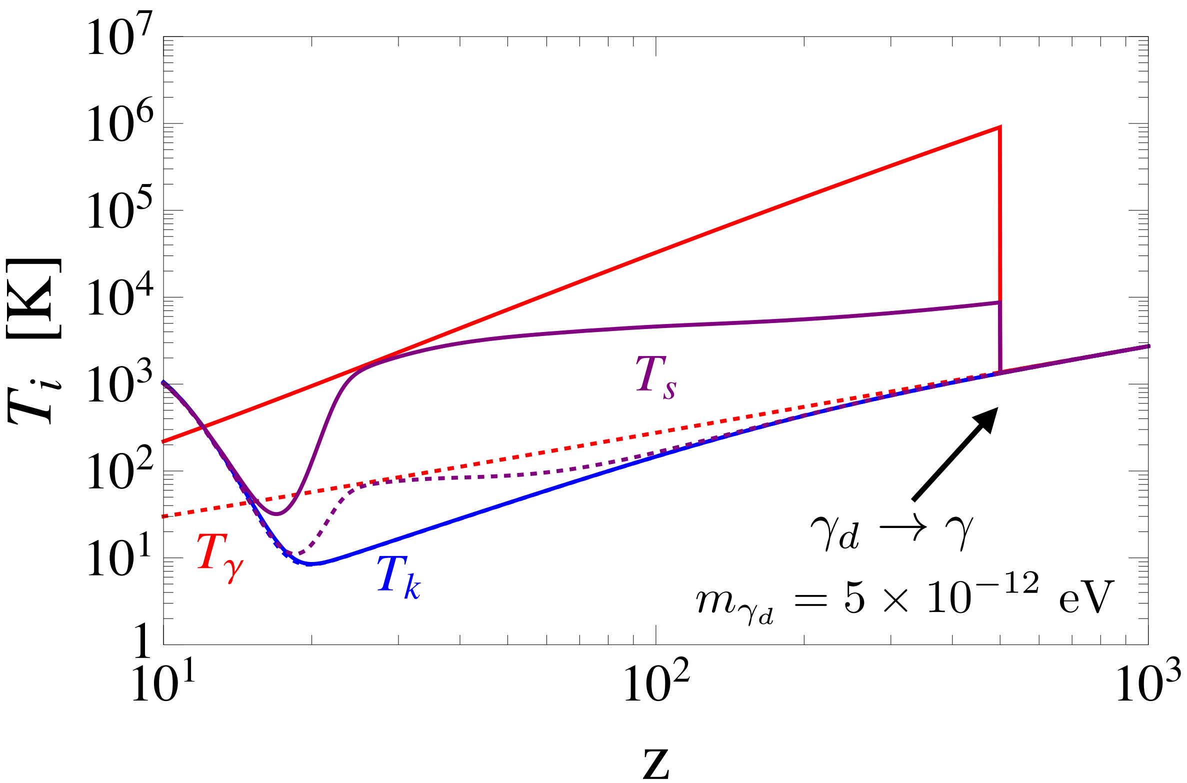
21cm absorption



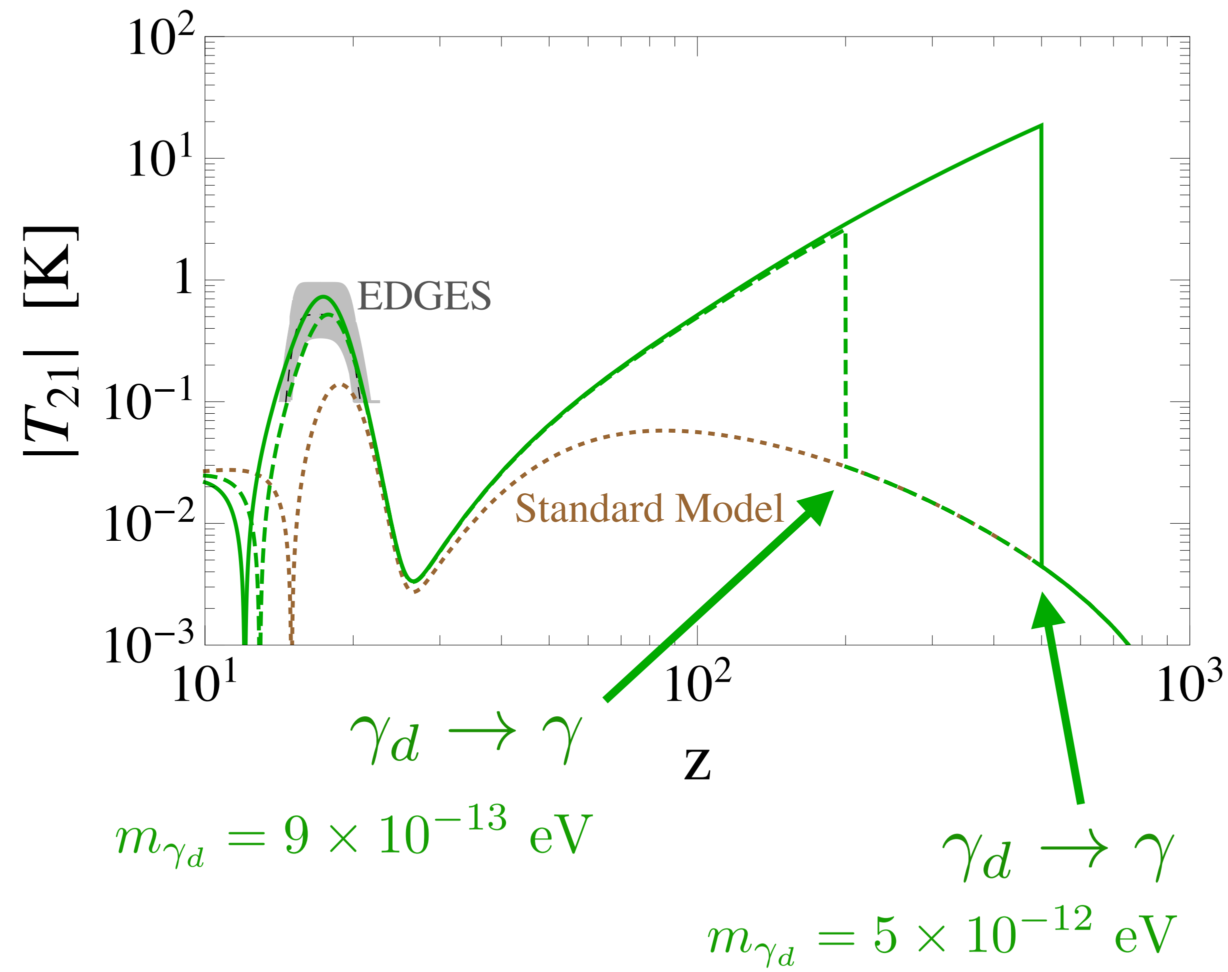
X-ray heating and Lyman-α from large halos: $T_{\rm vir} > 2 \times 10^5$ K

21cm at High Redshifts

temperature evolution



21cm absorption

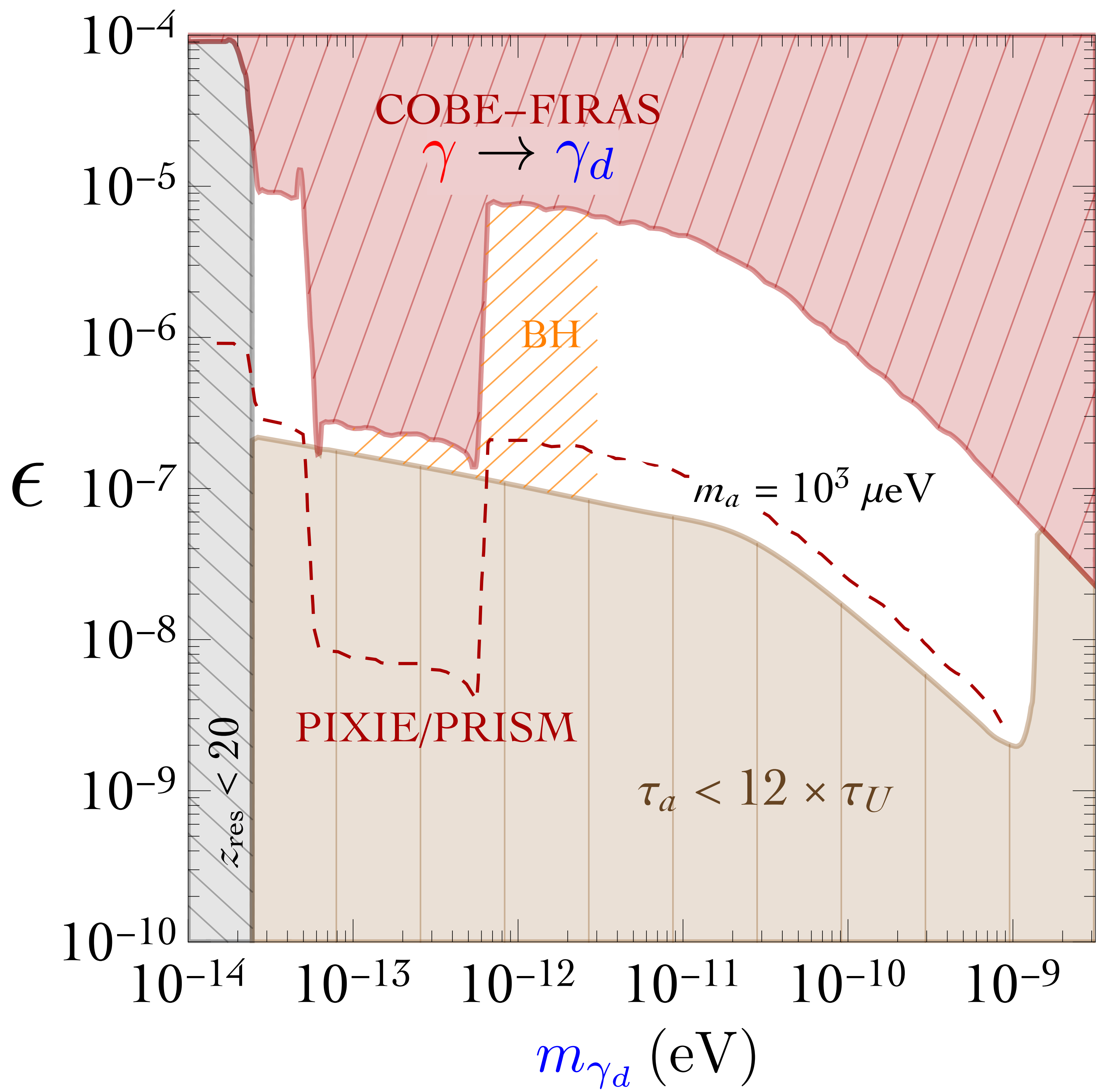


prediction: large excess with an **edge**

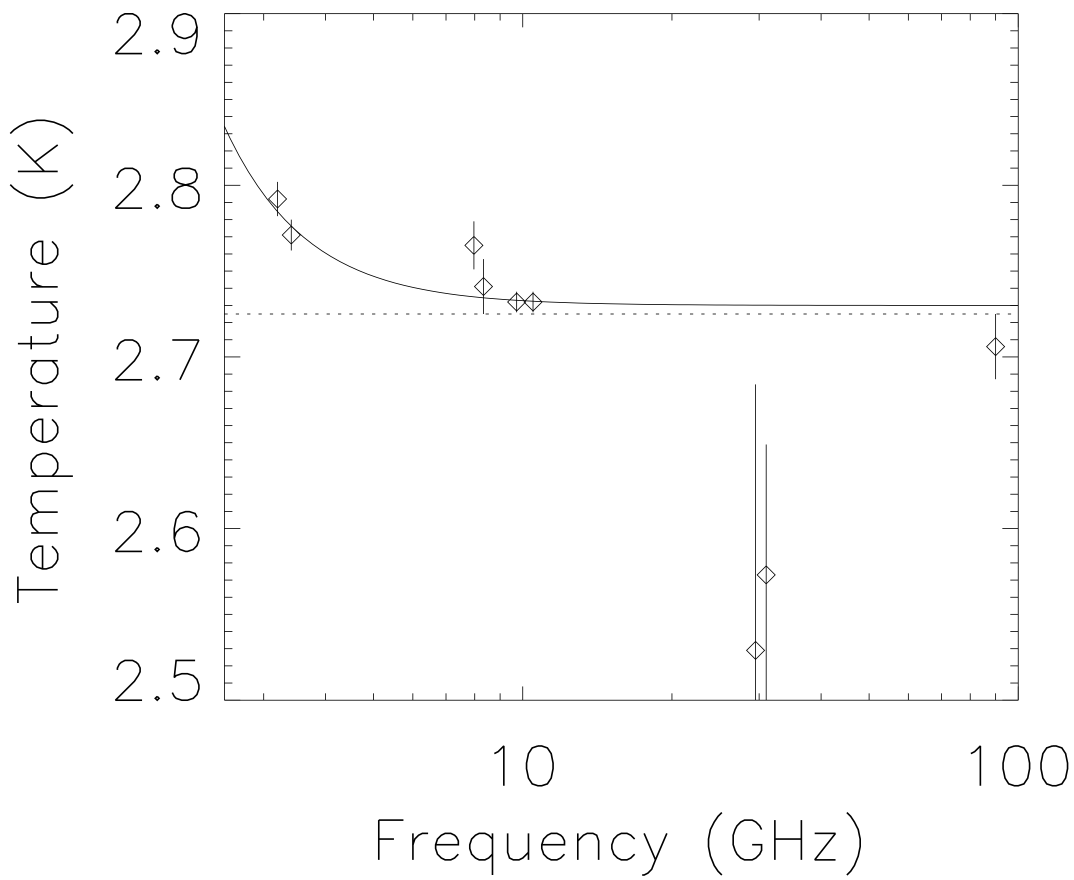
Dark Photon Parameter Space

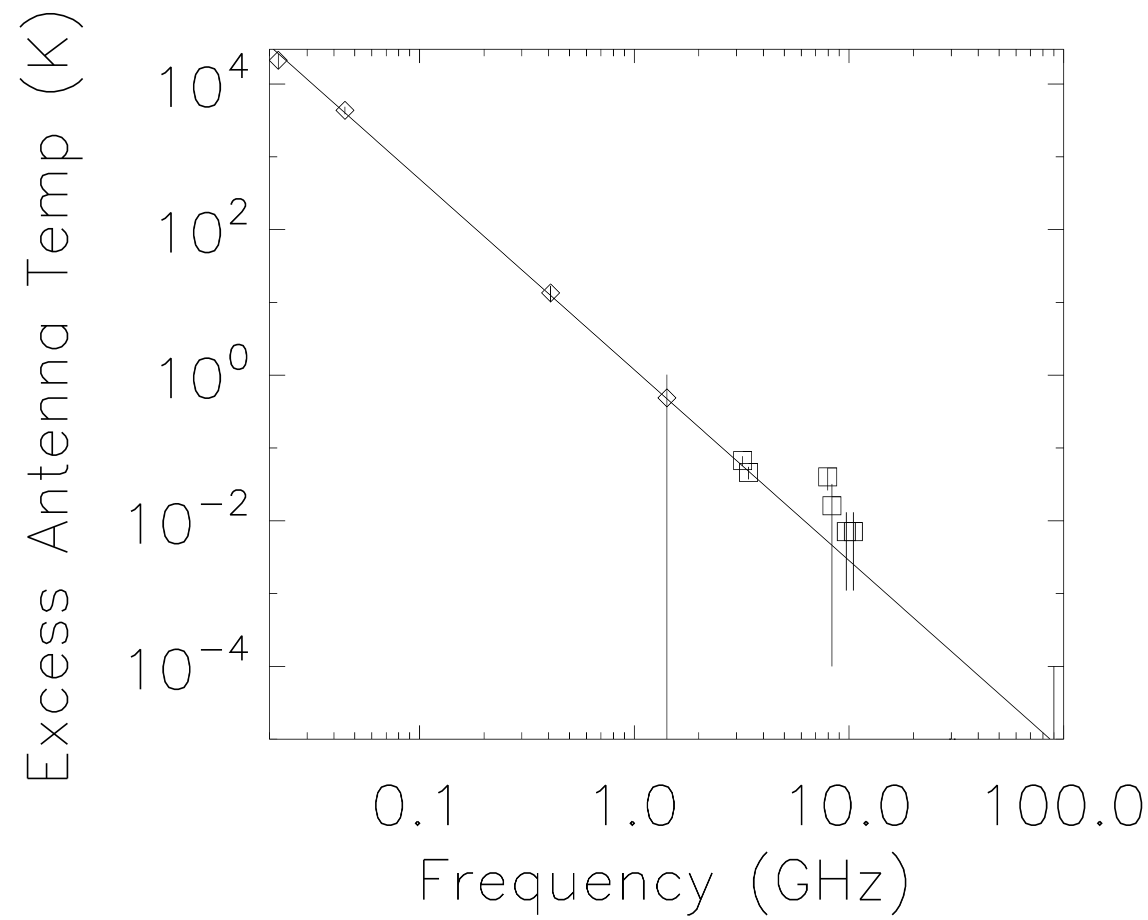
$m_a = 10^{-3}\,\mathrm{eV}$

choose τ_a
such that $n_{\gamma_d \to \gamma} = n_{\mathrm{CMB}}$
at 21cm



ARCADE Excess

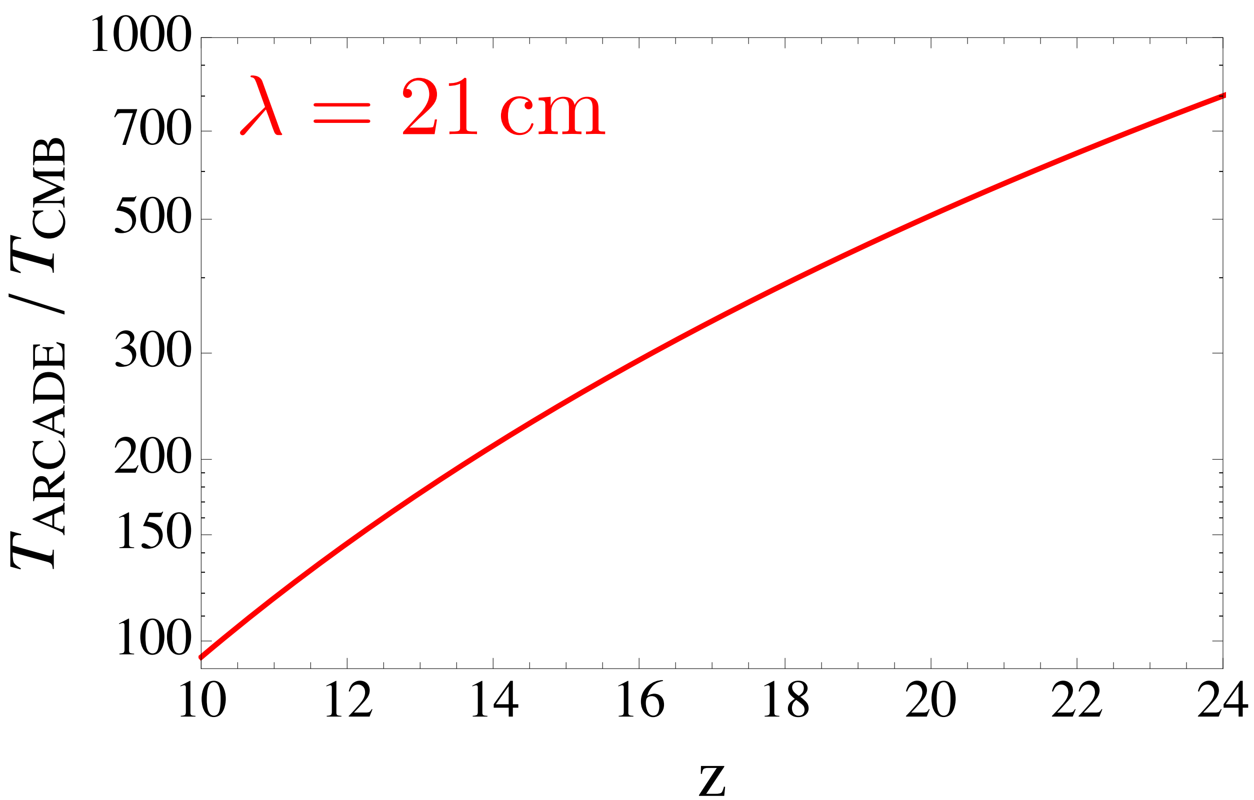


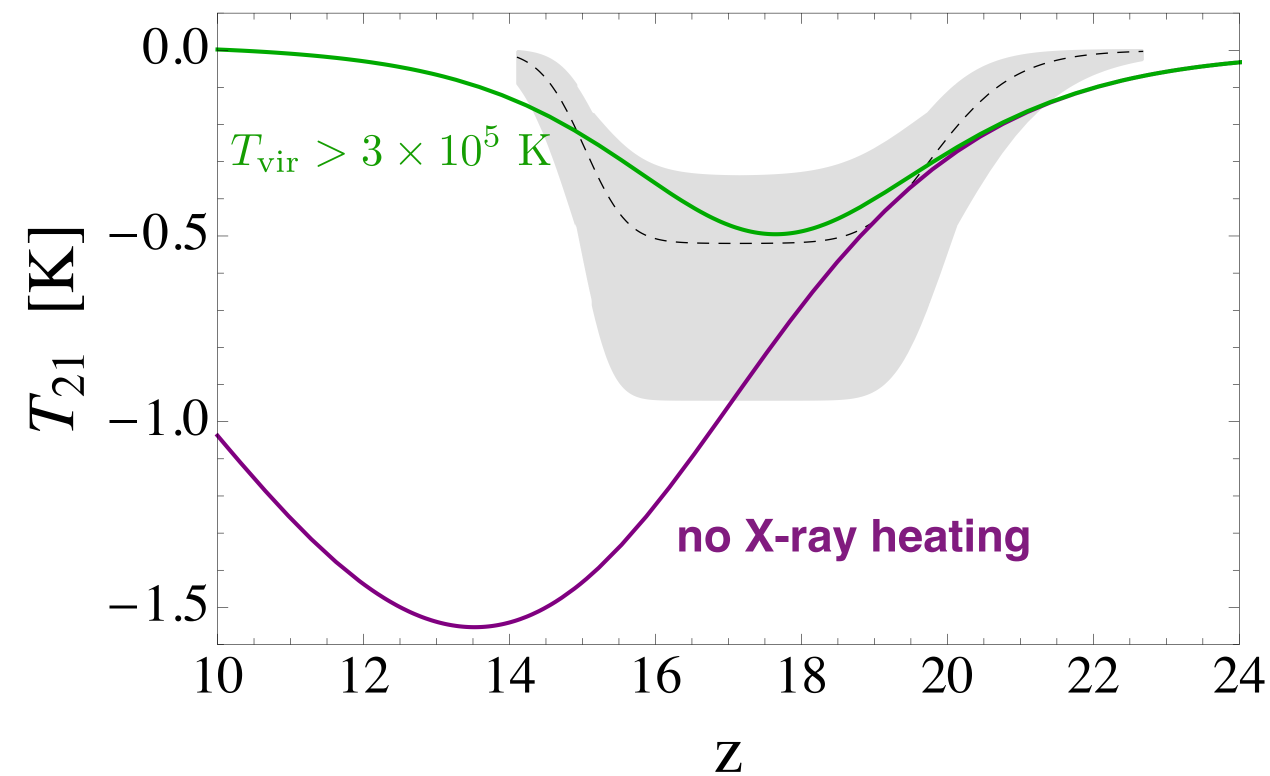


Source	Frequency GHz	Temperature K	Uncertainty K
Roger	0.022	21200	5125
Maeda	0.045	4355	520
Haslam	0.408	16.24	3.4
Reich	1.42	3.213	.53
ARCADE 2	3.20	2.792	0.010
ARCADE 2	3.41	2.771	0.009
ARCADE 2	7.97	2.765	0.014
ARCADE 2	8.33	2.741	0.016
ARCADE 2	9.72	2.732	0.006
ARCADE 2	10.49	2.732	0.006
ARCADE 2	29.5	2.529	0.155
ARCADE 2	31	2.573	0.076
ARCADE 2	90	2.706	0.019

- ARCADE 2, **0901.0555**

EDGES from ARCADE Excess



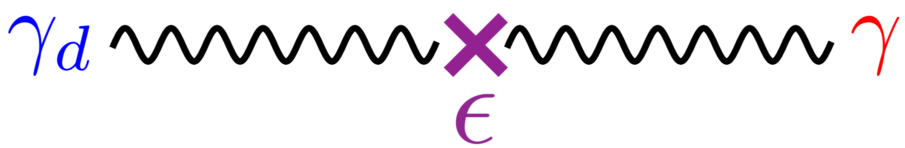


- ARCADE predicts too much 21cm absorption without X-ray heating

Feng, Holder, **1802.07432**

- EDGES and ARCADE are compatible if there is large X-ray heating

Take Away



$$m_\gamma(z) \approx m_{\gamma_d}$$