New Physics and 21 cm Observations

Josef Pradler

with Pospelov, Ruderman, Urbano, PRL 2018, arXiv:1803.07048

ÖAW AUSTRIAN ACADEMY OF SCIENCES

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

Invisibles Workshop KIT
Sept 06 2018

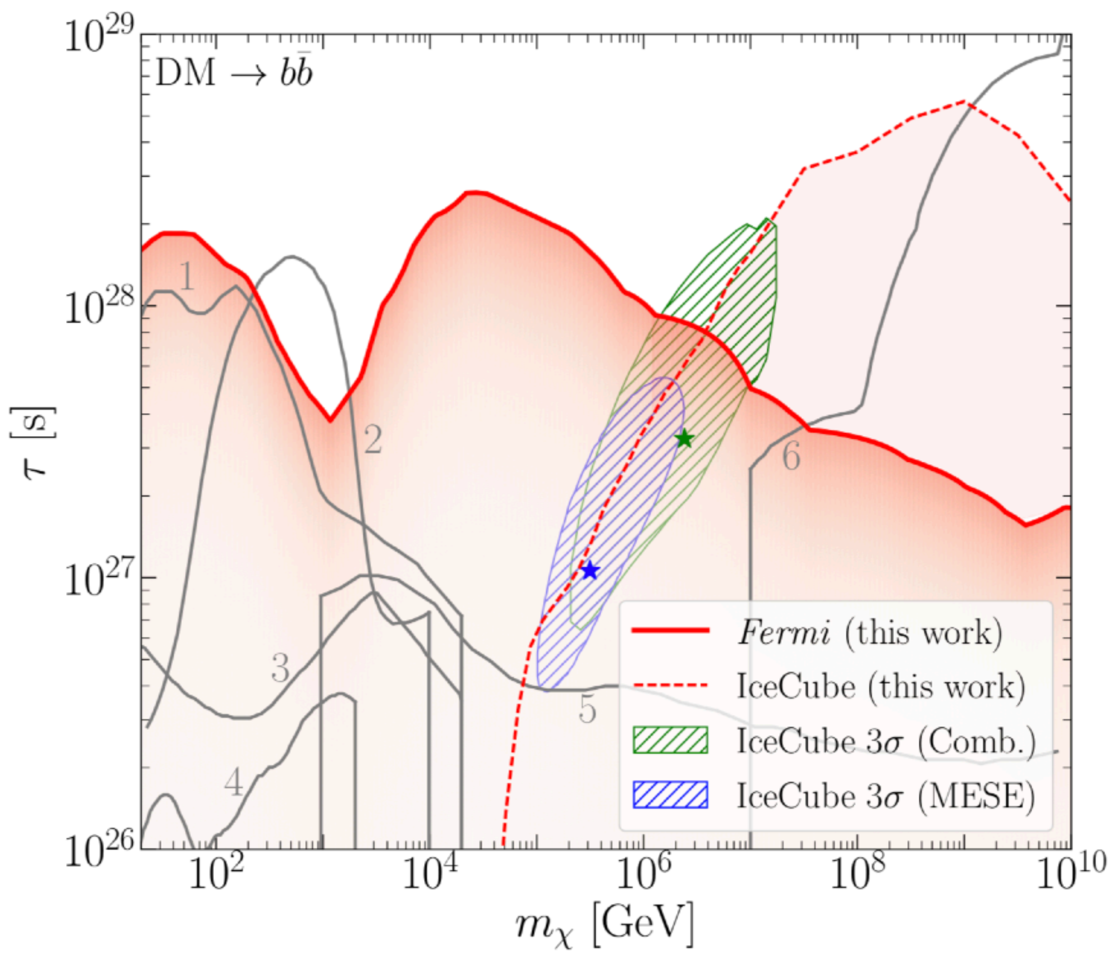
Plan

- Introduction - on the stability of Dark Matter
- DM decay can introduce dark radiation (DR) content
- Cosmological 21cm signal and (anomalous) EDGES observation and the at redshift z=17-20
- Prospects of explaining anomaly in terms of new physics - concrete successful model is offered
- Outlook / Conclusions

DM decay into visible states

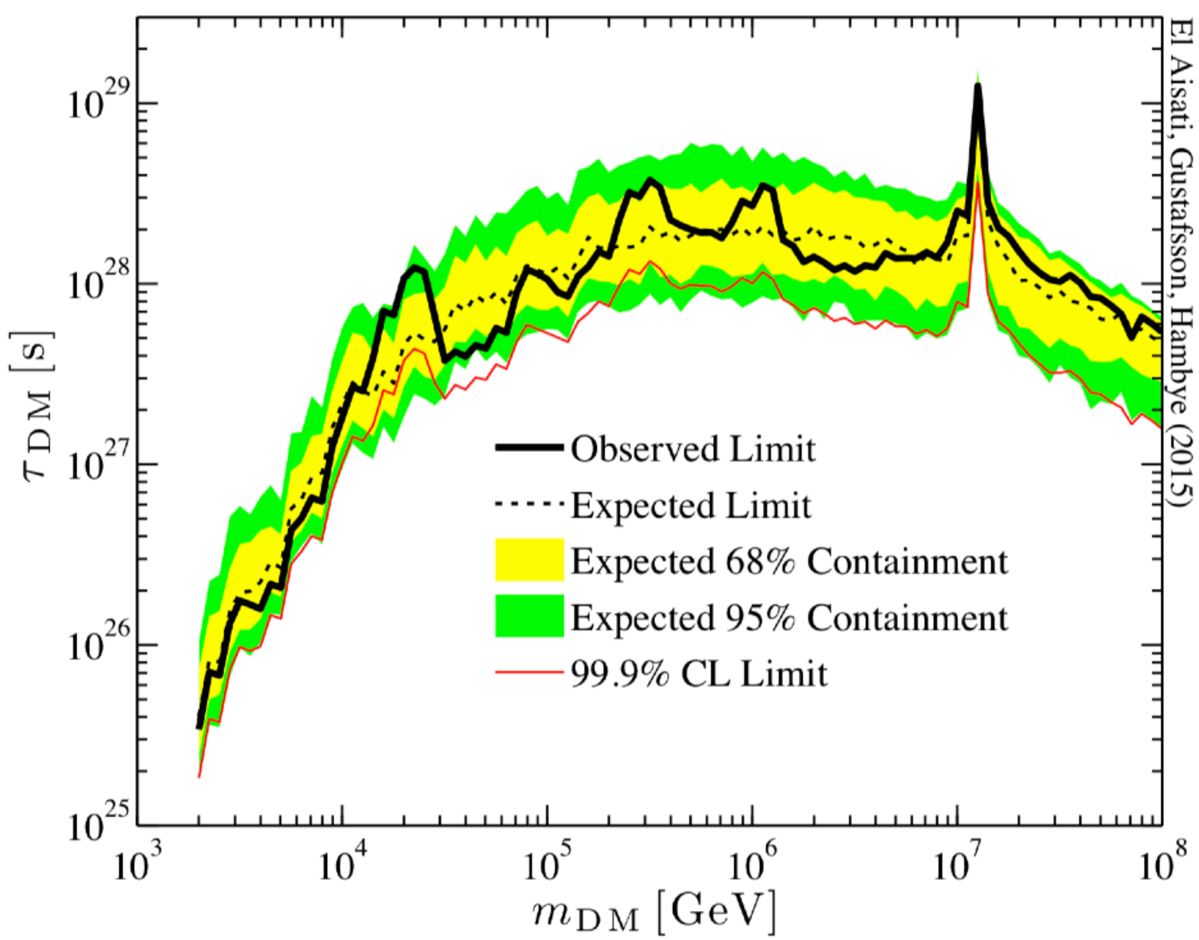
Indirect detection searches require the lifetime of **WIMP-DM** to exceed the age of universe by a large factor, (10^9 - 10^{11}) t_0, through visible decay products

gamma-rays



Cohen et al PRL 2016

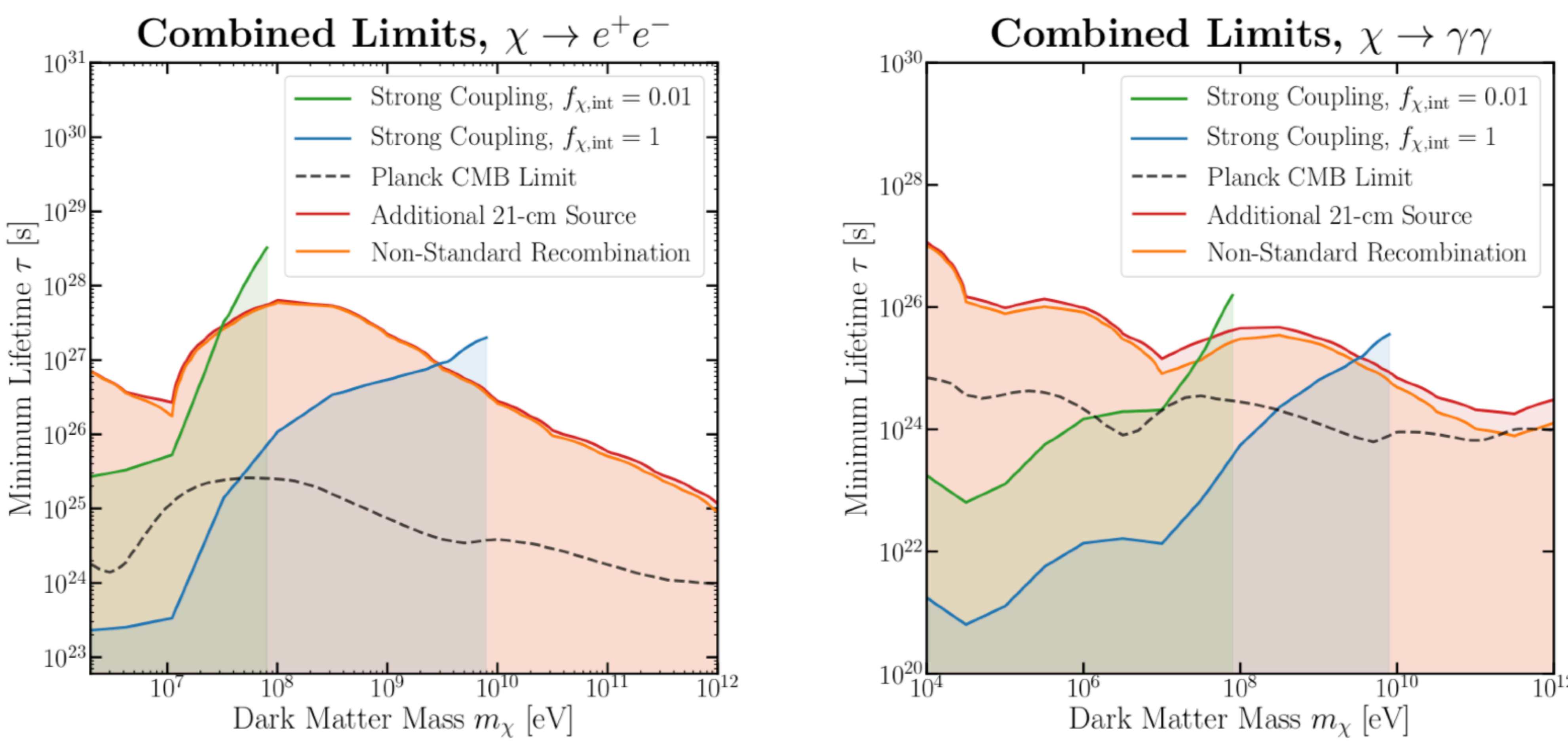
neutrinos



El Aisati, Gustafsson, Hambye PRD 2015

DM decay into visible states

Since recently, 21cm cosmology (tentatively) requires the lifetime of **sub-GeV DM** to exceed the age of universe by a large factor, $(10^9 - 10^{11})\, t_0$



Liu, Slatyer 2018

see also Clark et al 2018; Mitridate, Podo 2018

DM decay into *dark states?*

Any **direct** sensitivity through a smaller branching fraction into SM states will strongly depend on the details of the model

Consider, e.g. DM decay $X \to \chi\bar{\chi}$

=> $X \to \chi\bar{\chi}e^+e^-$ decay is highly suppressed

$$\mathrm{Br}_{X\to\chi\bar{\chi}e^+e^-} \leq 10^{-3} G_\chi^2 m_X^4 \sim 10^{-13} \quad (m_X = 1\,\mathrm{GeV},\, G_\chi = G_F)$$

Our Universe has the chance to be permeated by **dark radiation** that is sourced by DM decay (or annihilation). What are the direct tests for it?

DM decay into *dark states?*

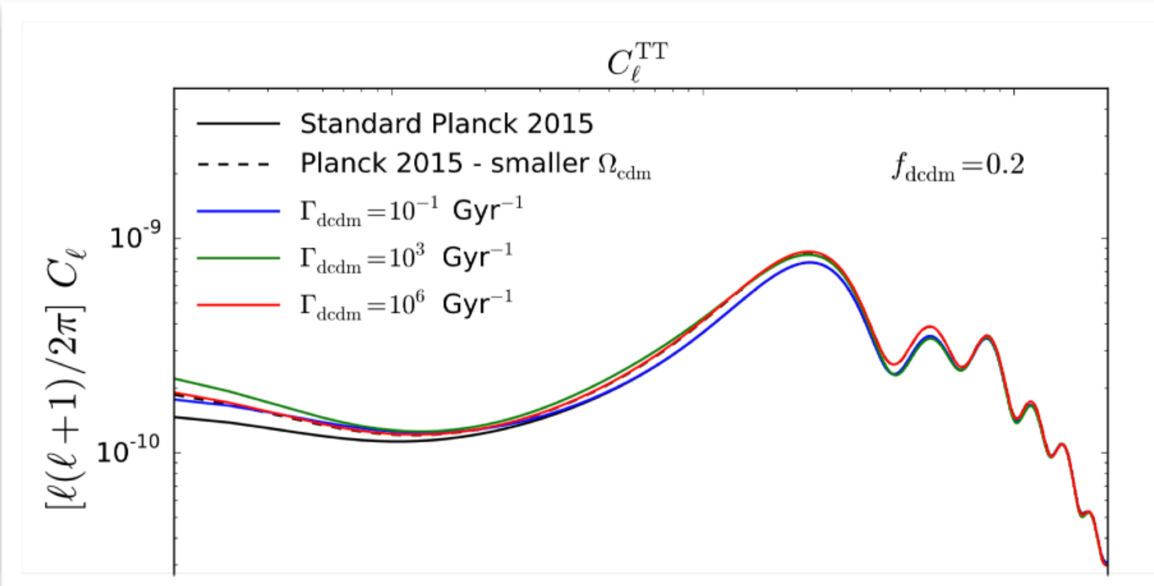
Cosmology remains a sensitive probe of DM decays, irrespective of DM mass and interaction, but through gravity.

CMB (late-time ISW) and lensing constrains

$$f_{\rm dm} < \text{few}\,\% \qquad (\tau_{\rm dm} < \tau_U)$$

$$f_{\rm dm}/\tau_{\rm dm} \lesssim 1/12\tau_U \qquad (\tau_{\rm dm} > \tau_U)$$

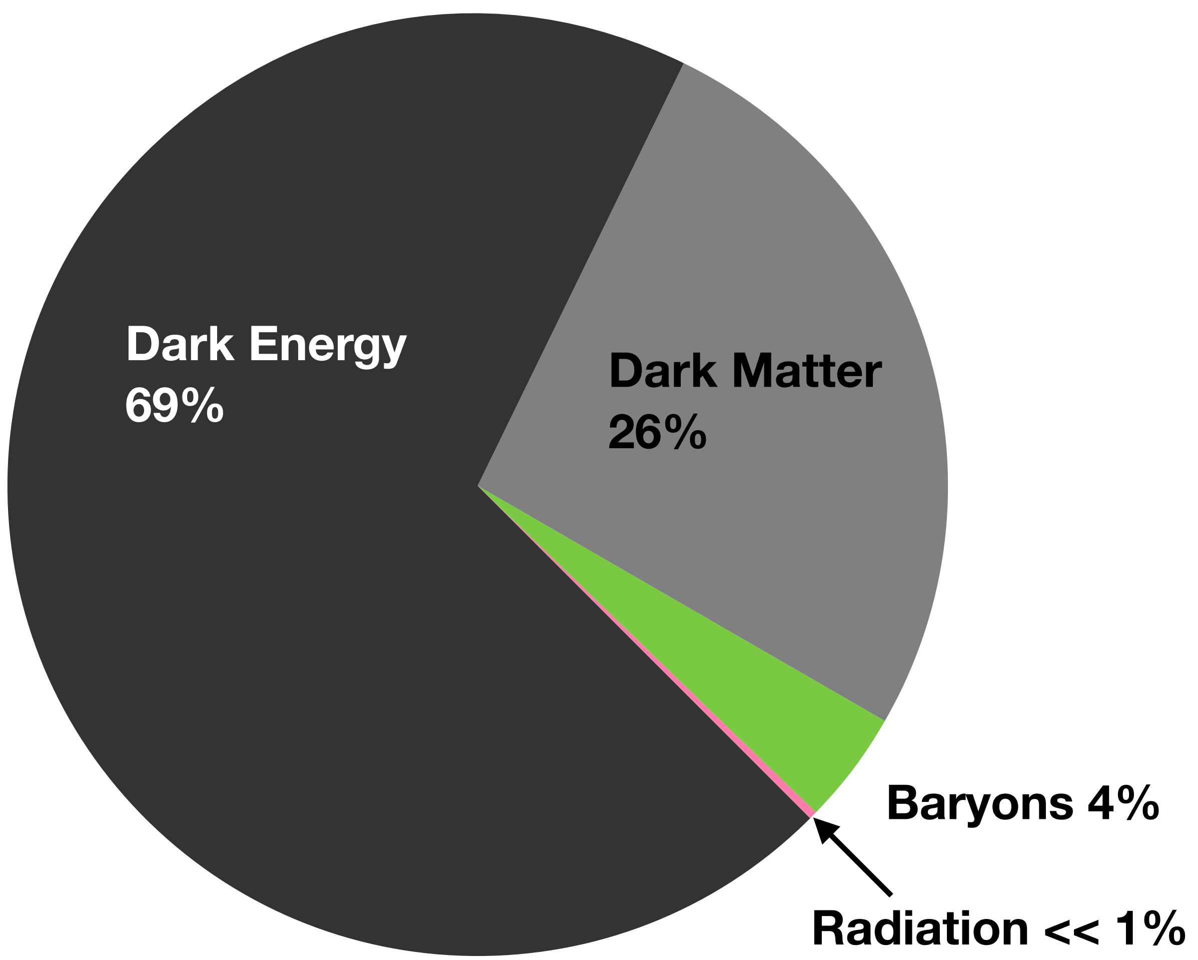
Poulin, Serpico, Lesgourges 2016
see also Berezhiani, Dolgov, Tkachev 2015



There are also constraints on structure formation with residual “kicked DM state” in place

e.g. Wang, Peter at al. 2014

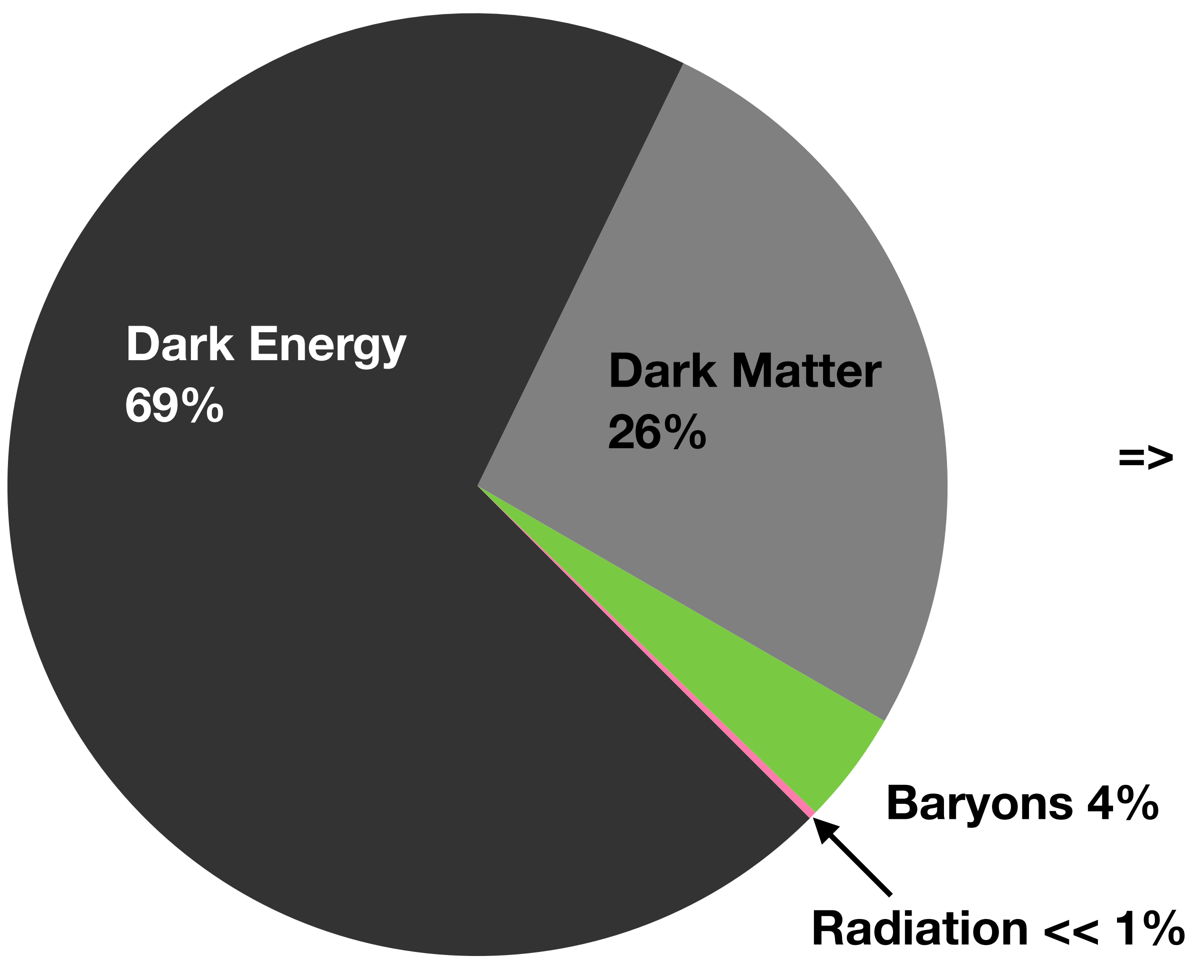
Late Dark Radiation



CMB-inferred

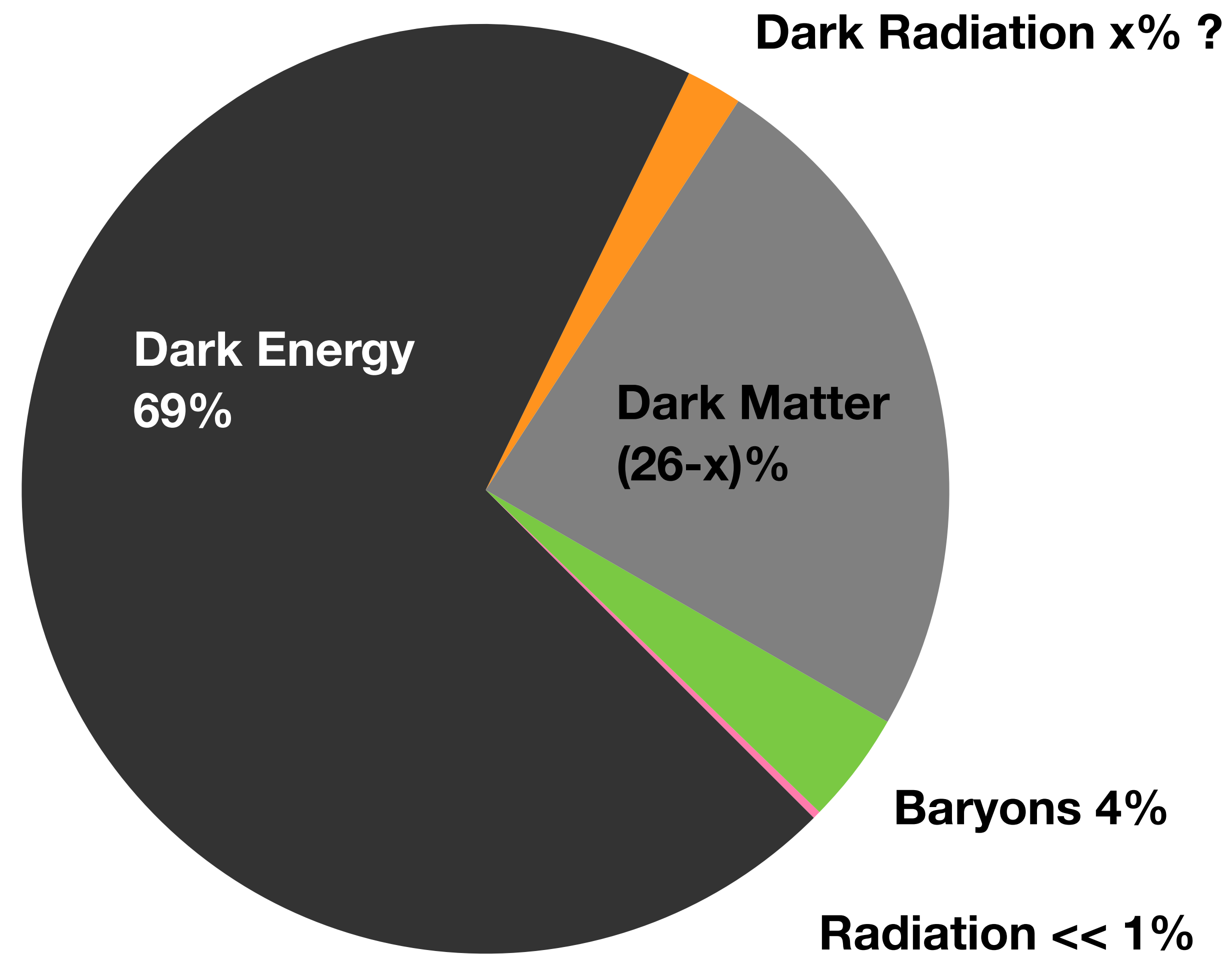
$\rho_{\rm DR}/\rho_\gamma < 0.15$ Planck

Late Dark Radiation



CMB-inferred

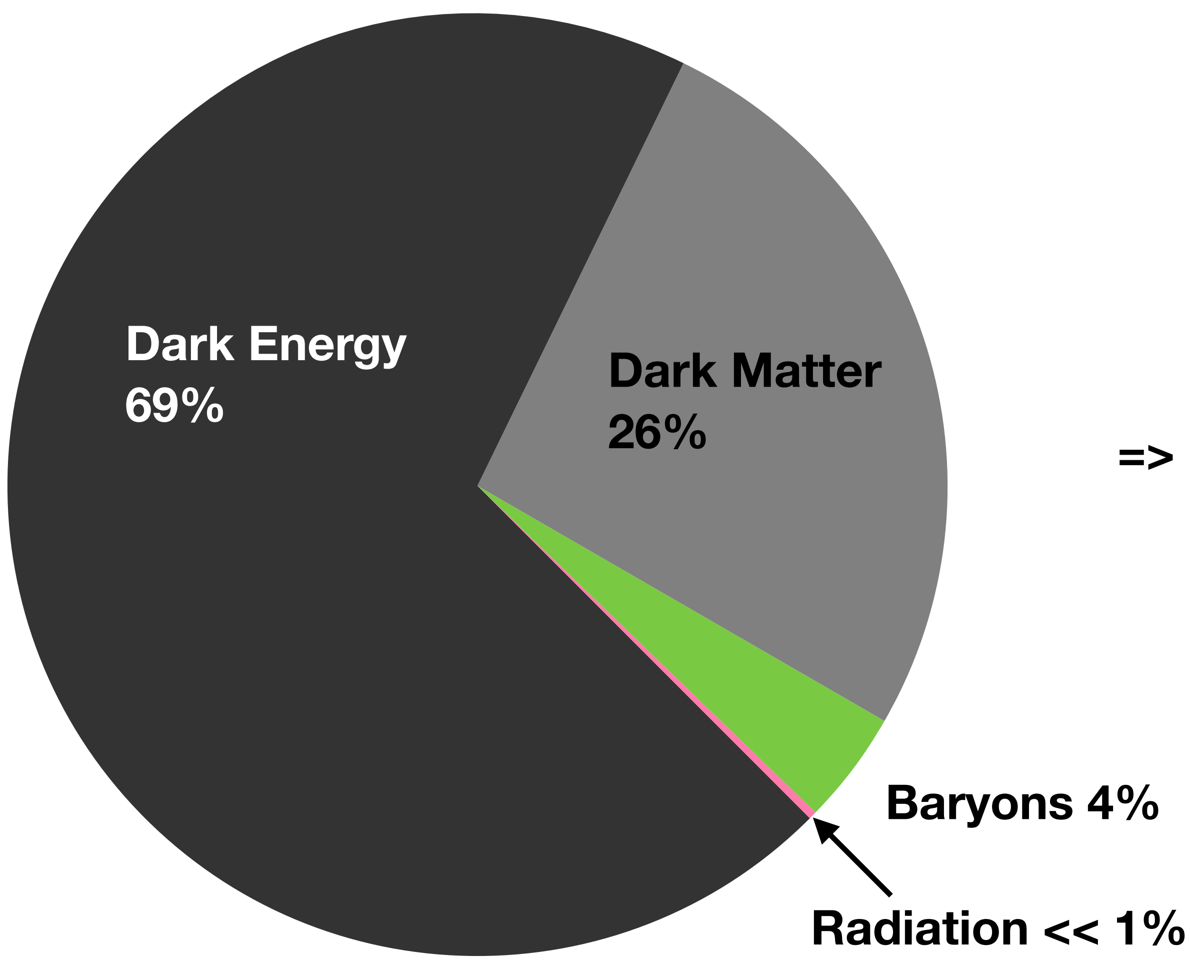
=>



Low redshift Universe

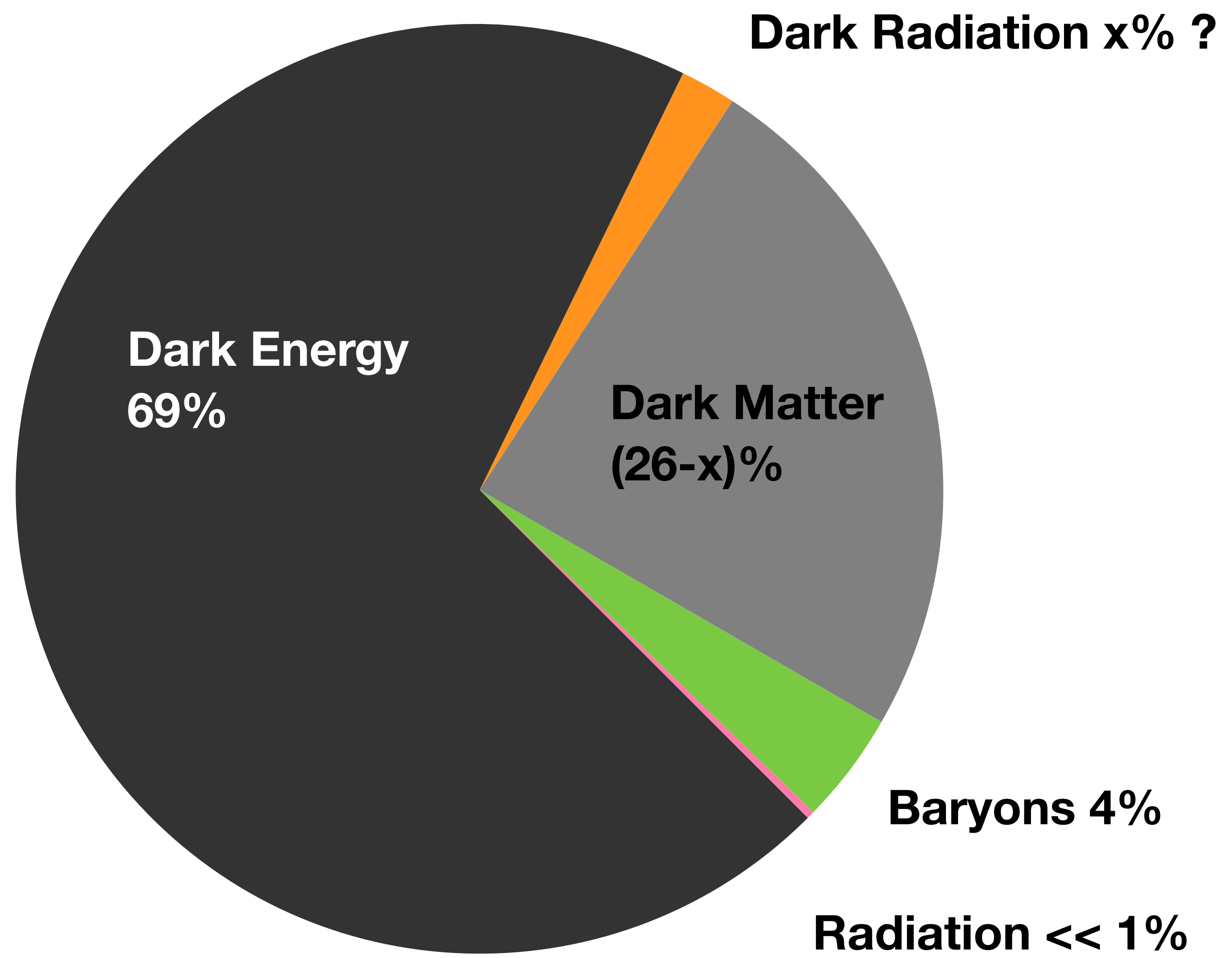
$\rho_{\rm DR}/\rho_\gamma < 0.15$ Planck

Late Dark Radiation



CMB-inferred

=>

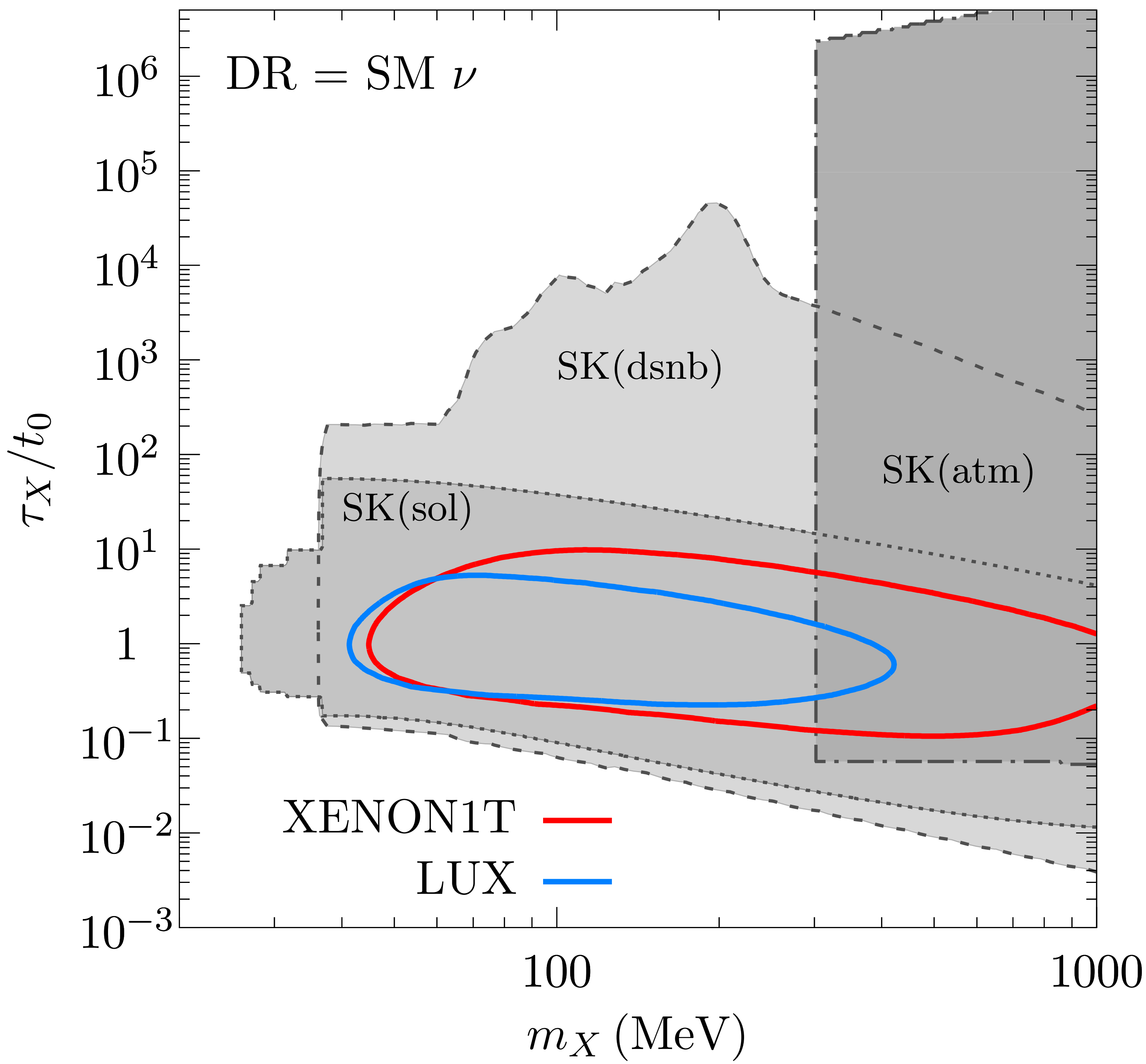


Low redshift Universe

$\rho_{\mathrm{DR}}/\rho_\gamma < 0.15$ Planck

OPTION 1: $n_{\mathrm{DR}} \ll n_\gamma, \quad E_{\mathrm{DR}} \gg E_\gamma$

Late DR in SM neutrinos



Option 1

DR in SM neutrinos ν

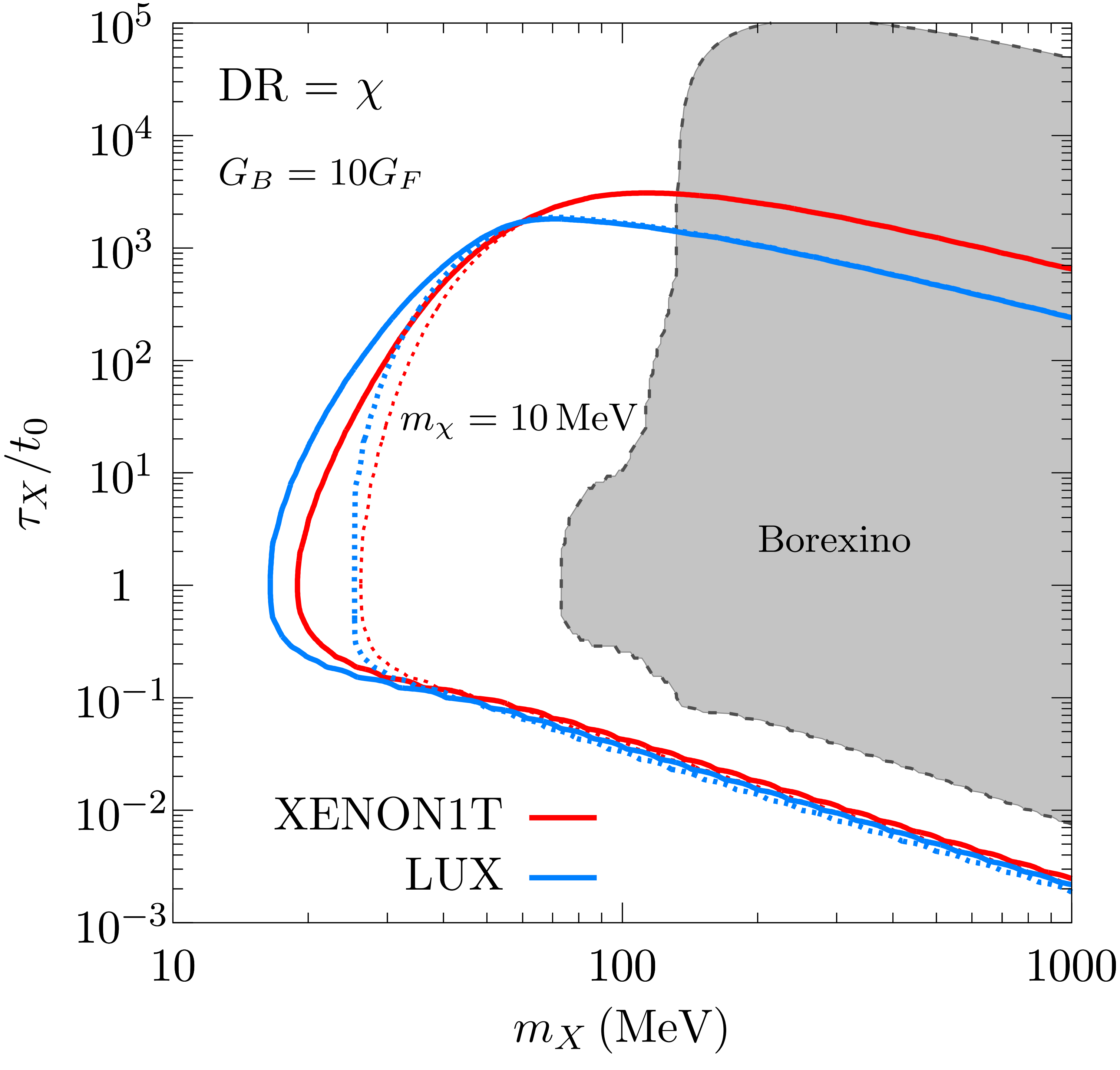
=> if flux is saturated then neutrino floor ~2 orders of magnitude away from current direct detection sensitivity

=> neutrino floor is raised to by ~2 orders of magnitude for a 30 GeV WIMP

[Nikolic, JP in prep]

Cui, Pospelov, JP 2017

Late DR in a new species



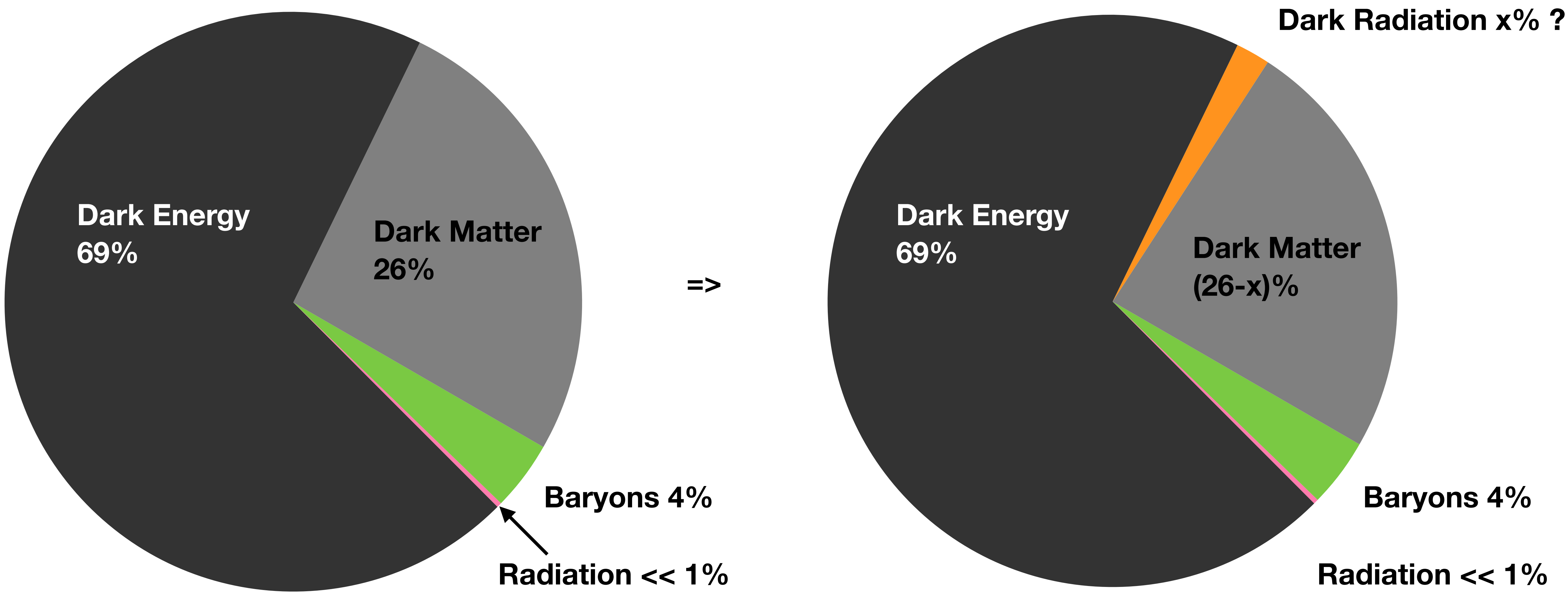
Option 2

new neutrino interacting with baryonic current

Borexino limit derived from elastic scattering on protons

Cui, Pospelov, JP 2017

Late Dark Radiation



CMB-inferred

Low redshift Universe

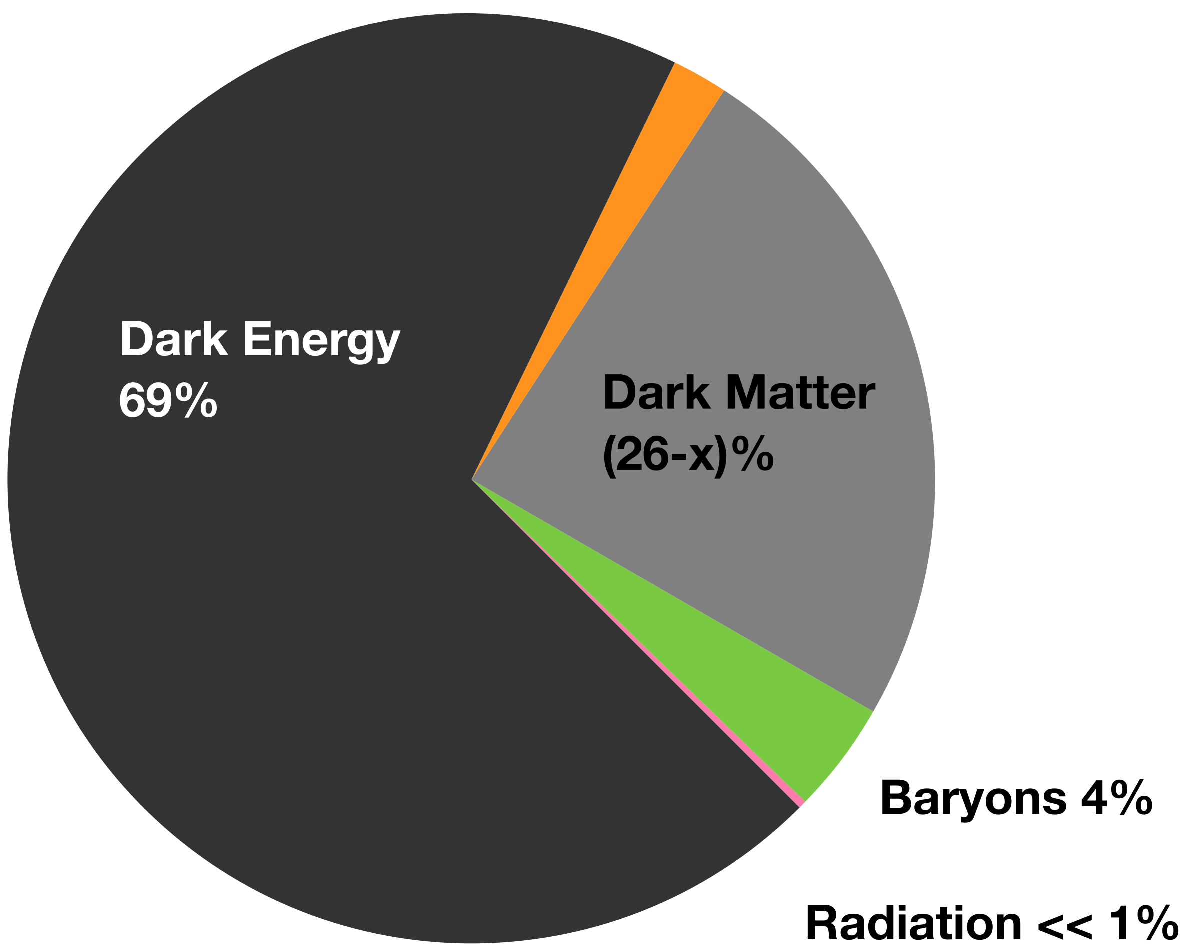
$\rho_{\rm DR}/\rho_\gamma < 0.15$ Planck

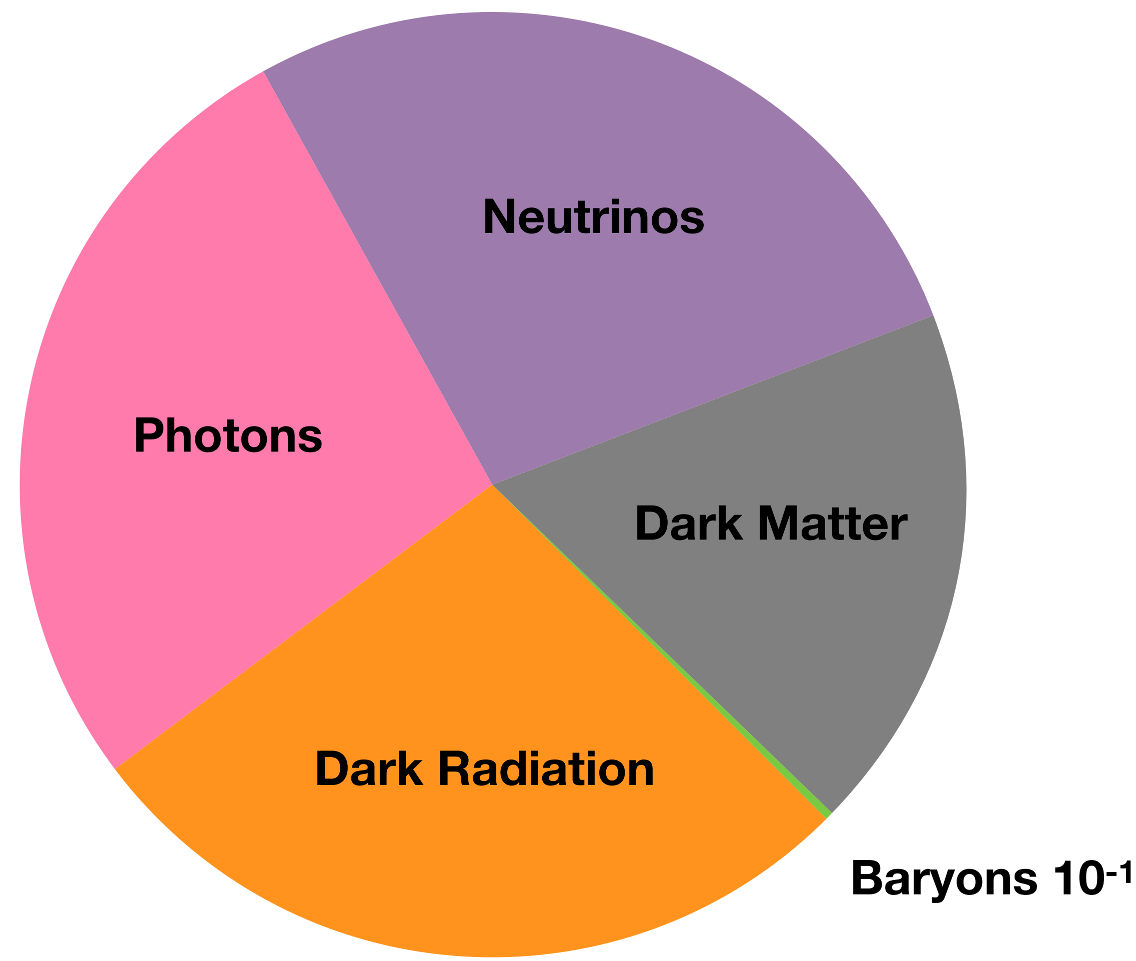
OPTION 2: $\omega_{\rm DR} \ll \omega_{\rm CMB}, \quad n_{\rm DR} > n_{\rm CMB},$

$\omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}$

Universe in “numbers”

Energy budget **vs.** **Number budget?**





Dark Radiation can be dominant

NB: any DE number density was subtracted…

Signatures of very soft DR?

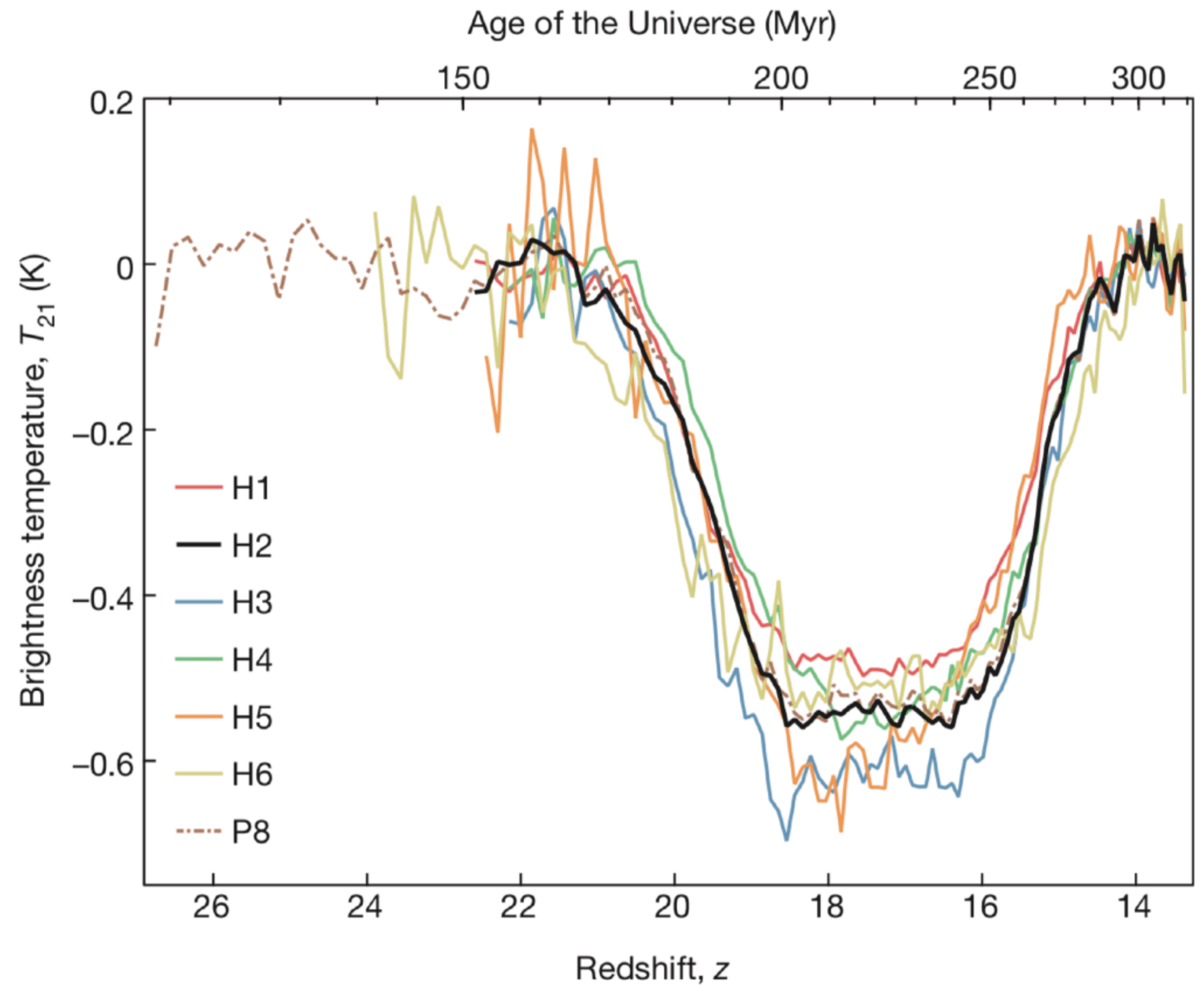
Light fields often have their interactions enhanced at high energies and suppressed at low energies, e.g.

- Neutrinos that have Fermi-type interactions with atomic constituents
- Axions with effective dimension 5 interactions with fermions and gauge bosons.

=> This type of dark radiation (DR) very difficult to see directly

However, **21cm cosmology** could provide new insights.

EDGES result



What is measured in 21 cm cosmology is a brightness temperature

$$T_{21}(z) = \frac{\tau(T_s - T_{\rm r})}{1+z}$$

$$\simeq 23\,\mathrm{mK}\,x_H(z)\left[1 - \frac{T_r(z)}{T_s(z)}\right]\sqrt{\frac{1+z}{10}}$$

Zaldarriaga, Furlanetto, Hernquist 2004

=> EDGES collaboration has measured anomalously low value (3.8 sigma)

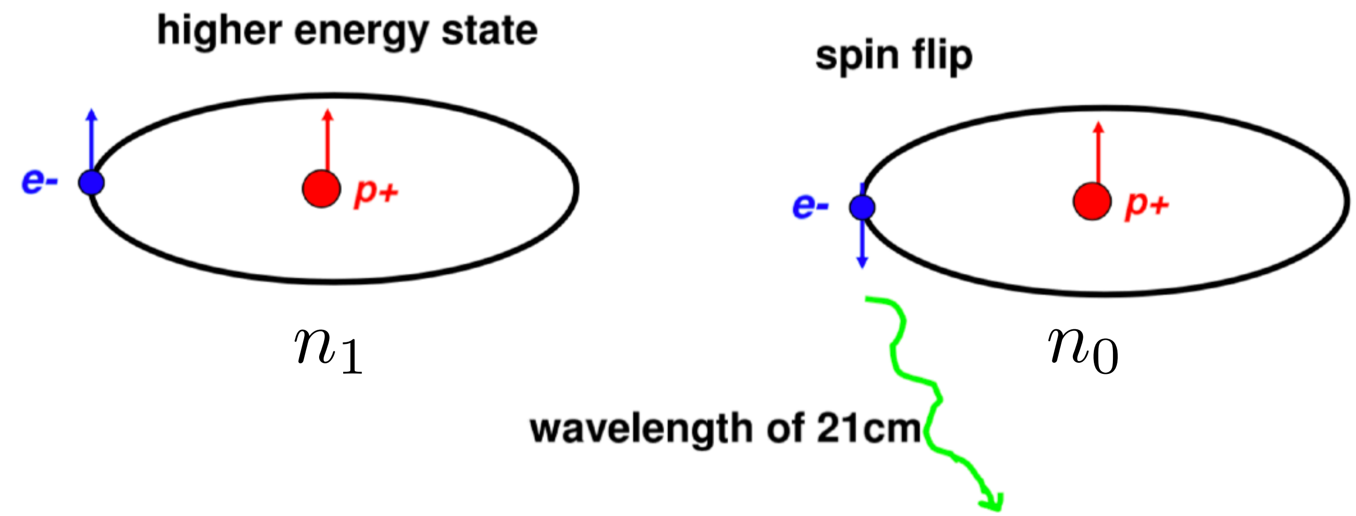
$$T_{21}(z \simeq 17) = -0.5K \quad (16 < z < 20)$$

Bowman et al 2018

H hyperfine transition

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left\{-\frac{T_\star}{T_s}\right\}$$

T_s spin temperature



$$21\,\text{cm} \quad \text{or} \quad 1.4\,\text{GHz} \quad \text{or} \quad 6\,\mu\text{eV}$$

$$\dot{n}_0 + 3Hn_0 = -n_0(C_{01} + B_{01}I_\nu) + n_1(C_{10} + A_{10} + B_{10}I_\nu)$$

collisions

Einstein coefficients

intensity of photons with 21cm wavelength

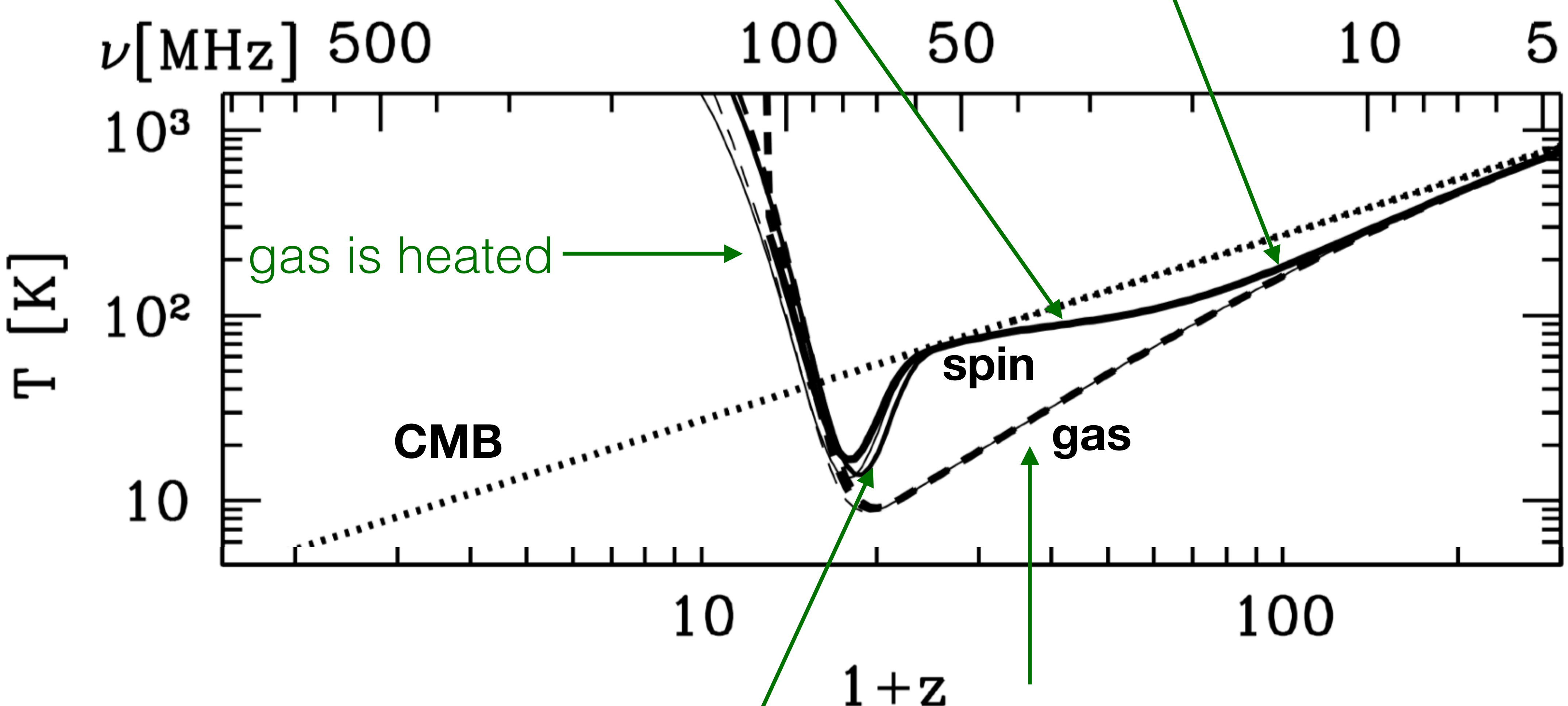
$$I_\nu = T\omega^2/2\pi^2$$

In reality, evolution is very complex, once Ly_α & X-ray photons become available!

see Venumadhav, Dai, Kaurov, Zaldarriaga 2018

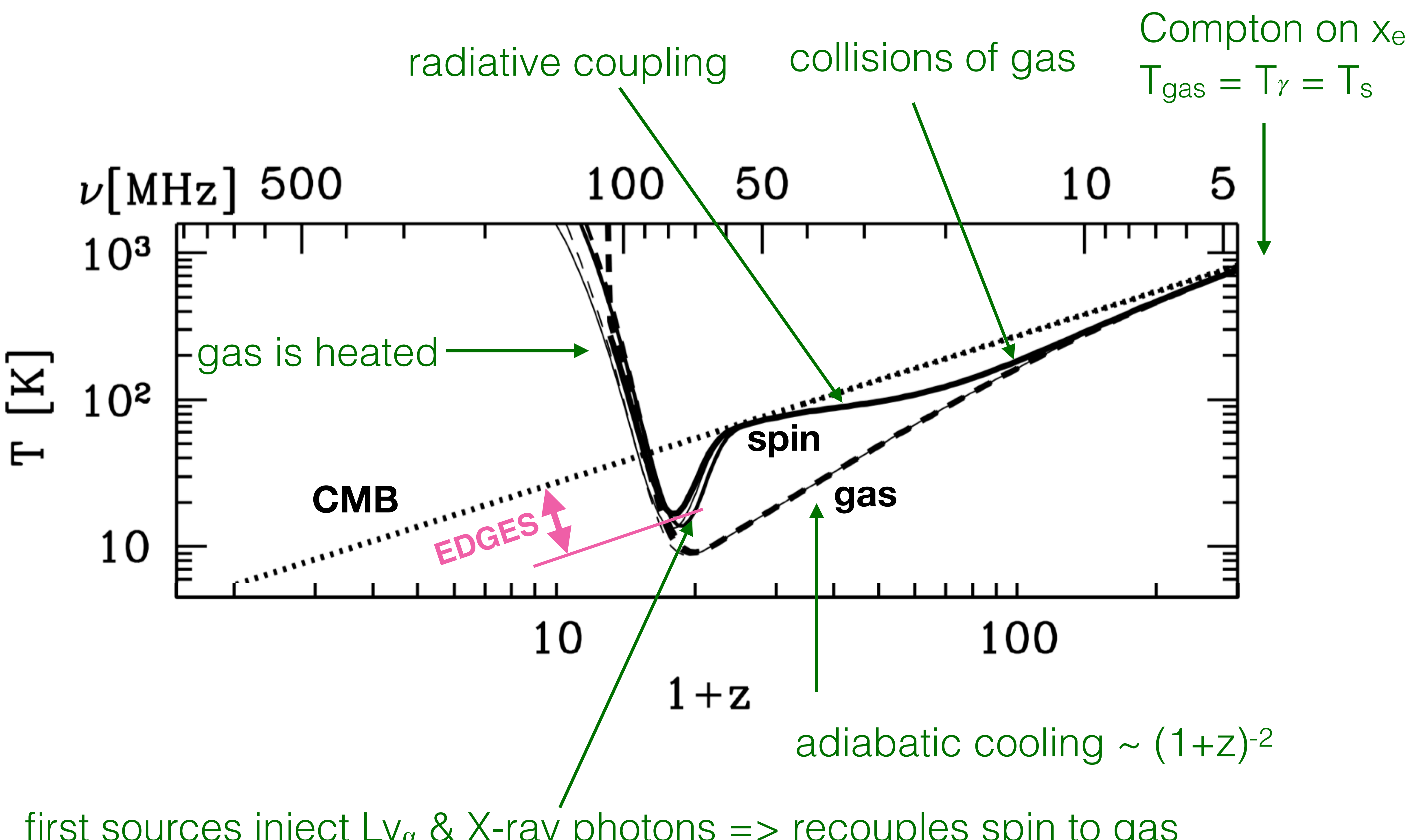
Evolution of spin temperature

see, e.g., Loeb, Pritchard 2012



Evolution of spin temperature

see, e.g., Loeb, Pritchard 2012



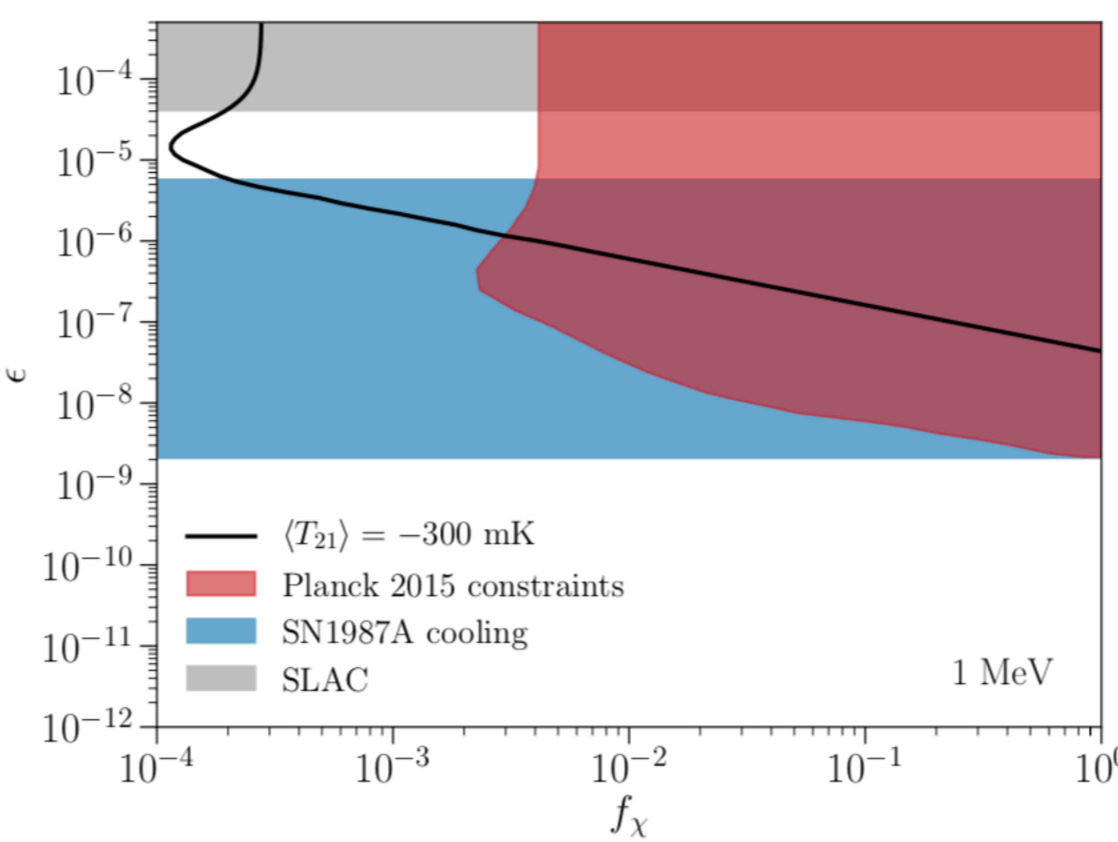
Principal options in changing T_{21}

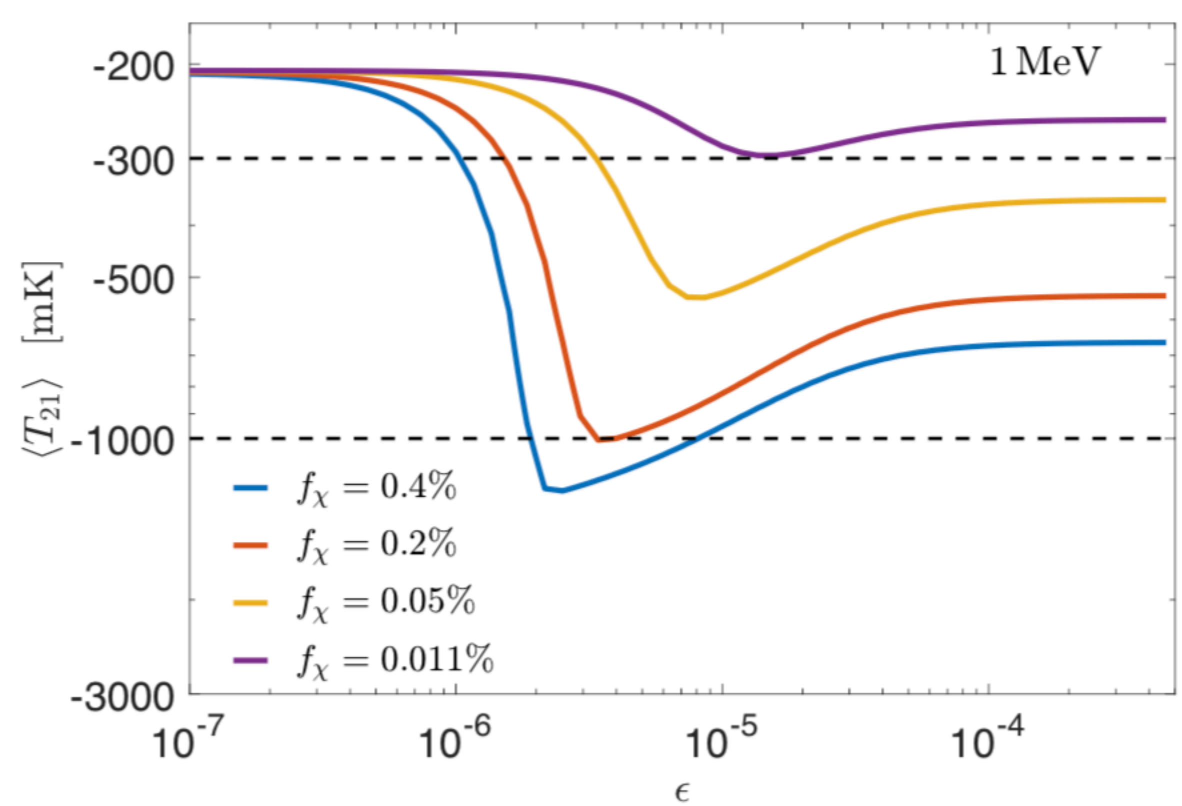
$$T_{21}(z) \simeq 23\,\mathrm{mK}\, x_H(z) \left[1 - \frac{T_r(z)}{T_s(z)}\right] \sqrt{\frac{1+z}{10}}$$

Barkana;
Munoz, Loeb;
Barkana et al;
Berlin et al; …

1. Make baryons colder by coupling it to colder DM fluid

DM-baryon/electron cross section needs to be enhanced by 1/v^4 (i.e. massless mediator, Coulomb-like.) Milli-charged DM constraints apply; sub-% population may still do it.





Kovetz et al;

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Colin, Baxter;
Falkowski, Petraki;

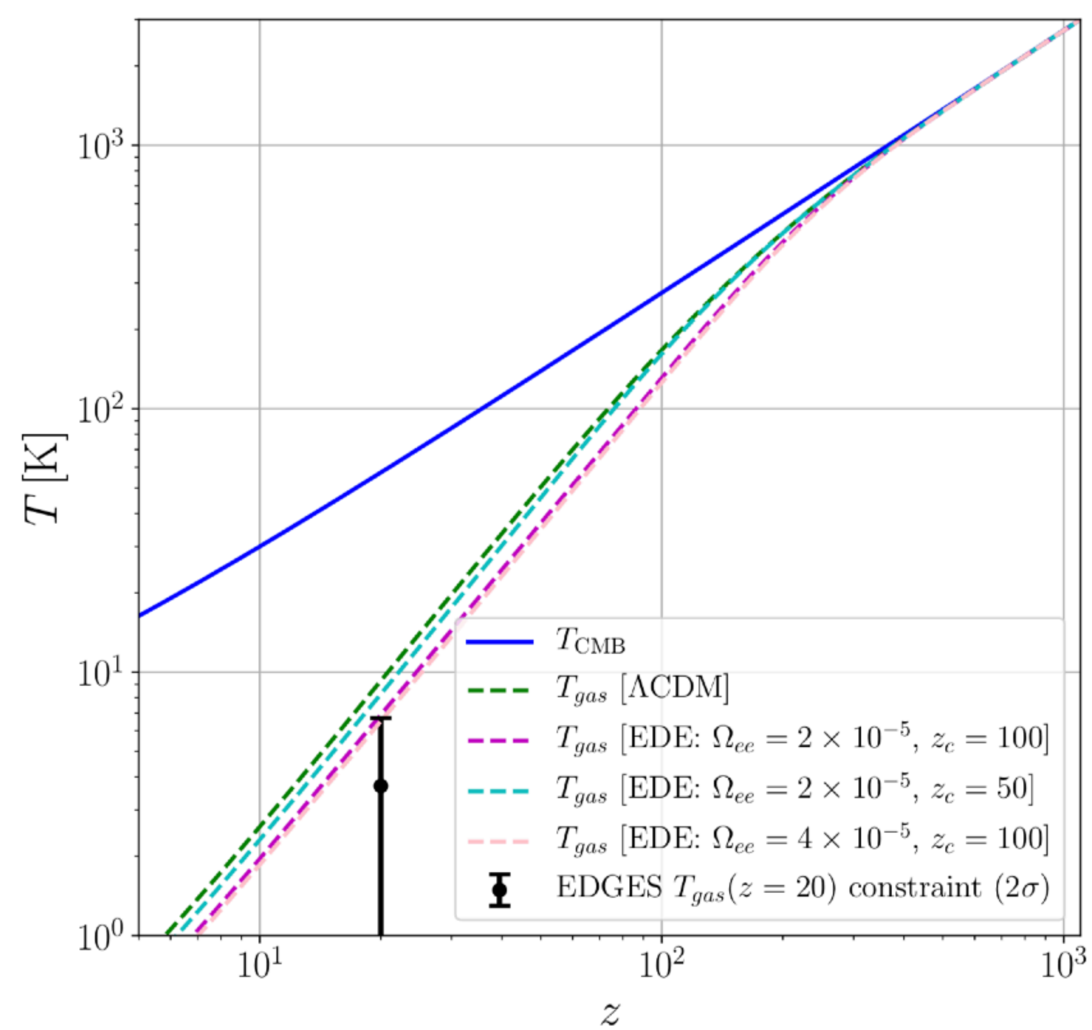
2. Change the timing of baryon-photon decoupling

=> Baryons have more time to cool (e.g. via early dark energy domination or charge sequestration, i.e., $n_e < n_p + 2\, n_\alpha$)

=> highly fine-tuned
(if not impossible to arrange)

Example: early dark energy domination excluded by CMB power spectrum (ISW); also increases tension in H_0

Colin, Baxter;



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Feng, Holder;
Tallin group;
our paper;
Moroi, Nakayama, Tang;

3. Add photons into the 21cm wavelength band at z~17

=> raises "effective T_{CMB}" in the low-energy **Rayleigh Jeans (RJ)** tail of the CMB

$$\frac{dn_{\rm CMB}}{d\omega} = \frac{\omega^2}{\pi^2}\frac{1}{e^{\omega/T}-1} \to \frac{T\omega}{\pi^2} \qquad \Rightarrow \qquad T \sim \frac{1}{\omega}\frac{dn_{\rm CMB}}{d\omega}$$

=> those extra photons engage in the H hyperfine transition

=> needs a careful modification of the CMB, that is only operative in the IR (disfavors direct DM decay into photons)

Rough criterion: double the amount of RJ photons at $x \equiv \omega_{21}/T_{\rm CMB} = 10^{-3}$

Principal options in changing T_{21}

$$T_{21}(z) \simeq 23\,\mathrm{mK}\, x_H(z)\left[1 - \frac{T_r(z)}{T_s(z)}\right]\sqrt{\frac{1+z}{10}}$$

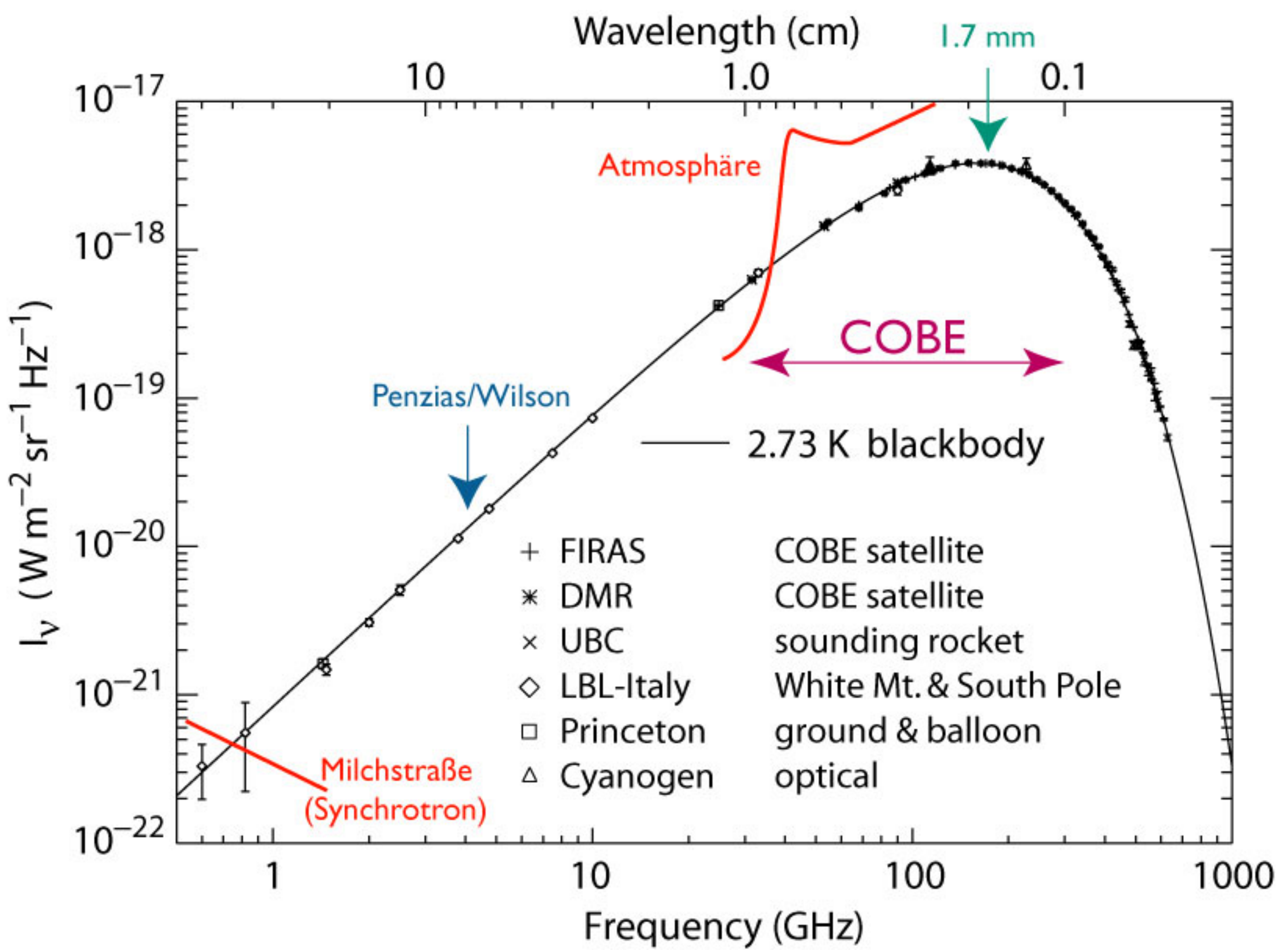
3. Add photons into the 21cm wavelength band at z~17

$$x = \frac{\omega_{21}}{T_{\rm CMB}} \simeq 10^{-3}$$

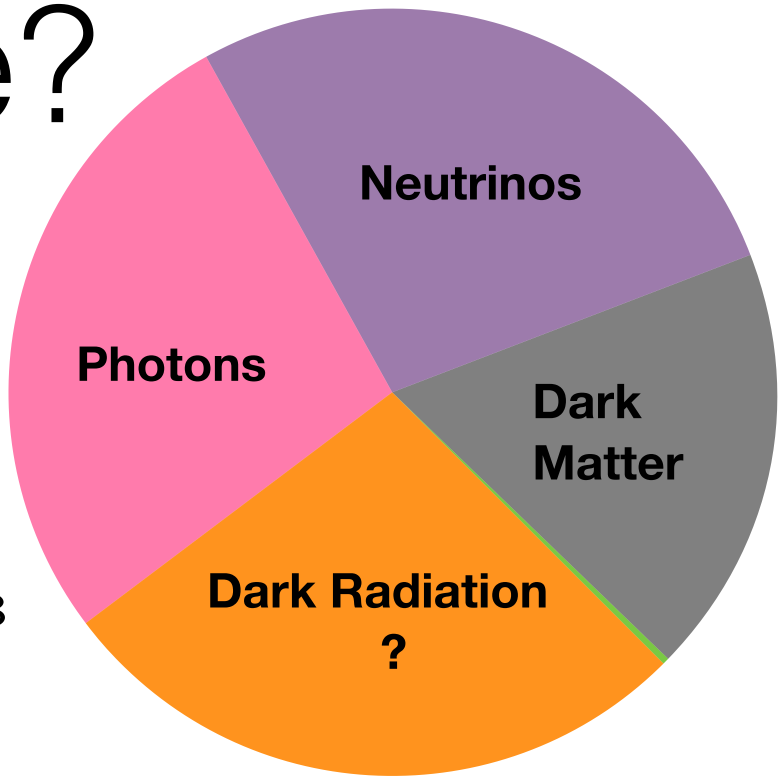
CMB not measured at x ~ 10^{-3}
i.e below 100 MHz;
swamped by foregrounds

=> room to accommodate primordial extra photons

=> will affect 21cm signal



How much DR is possible?



Number of CMB photons in the RJ tail until ω_{max}

$$n_{\rm RJ} = \frac{1}{\pi^2}\int_0^{\omega_{\rm max}} \frac{\omega^2 d\omega}{\exp[\omega/T]-1} \simeq \frac{T\omega_{\rm max}^2}{2\pi^2} \simeq 0.21\, x_{\rm max}^2\, n_{\rm CMB}$$

For $x_{\rm max} \sim 10^{-3}$ $\quad \frac{n_{\rm RJ}}{n_{\rm CMB}} \sim 10^{-6}$ $\quad x = \omega/T$

For example, $x_{\rm max} = 10^{-3}$, and saturating the permissible numbers:

$$n_{\rm DR} \lesssim 10^2\, n_{\rm CMB}, \quad \text{early DR with } \Delta N_{\rm eff} = 0.5$$

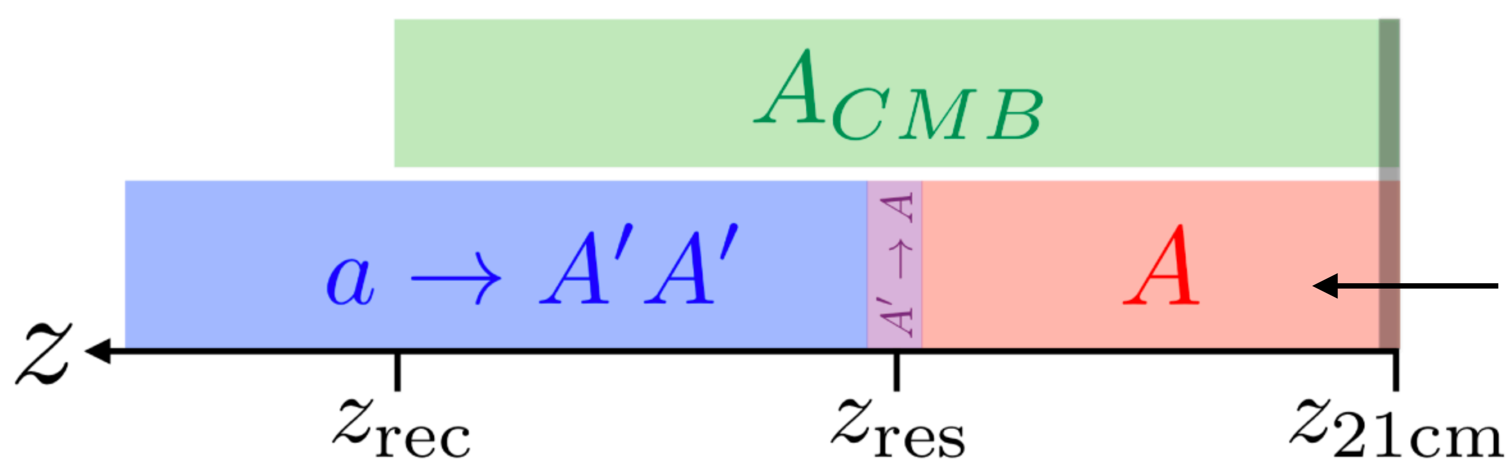
$$n_{\rm DR} \lesssim 10^5\, n_{\rm CMB}, \quad \text{late decay of } 0.05\, \rho_{\rm DM}$$

=> it is possible to add many more dark quanta in the RJ tail without running into immediate problems with cosmology

Modification of the RJ tail of the CMB

Main idea:

CMB released



extra photons

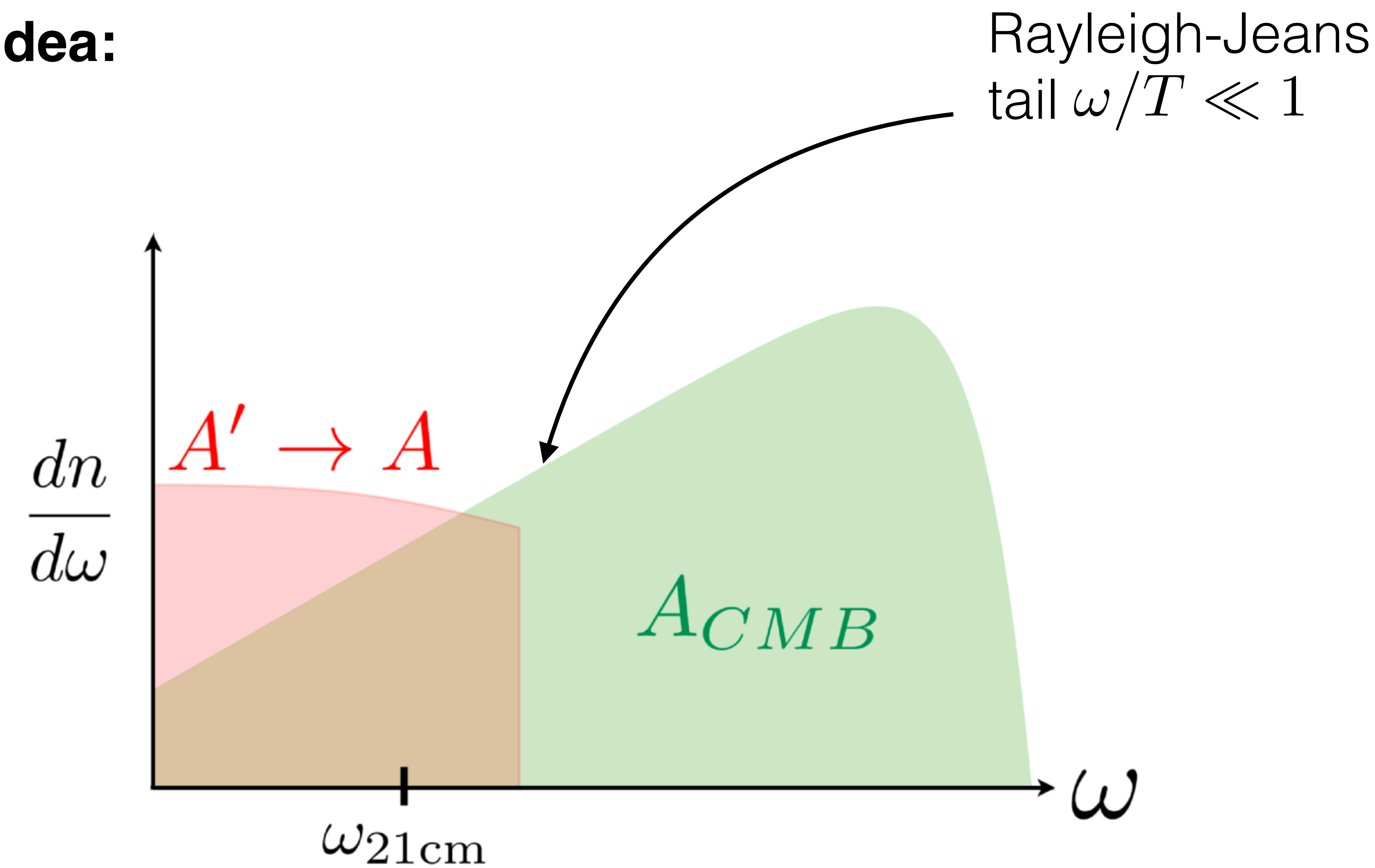
A’ continuously
sourced by decay of a

Resonant conversion of
A’ into ordinary photons A

happens when $m_A = m'_A(z)$

Modification of the RJ tail of the CMB

Main idea:



$$\frac{dn_A}{d\omega} \to \frac{dn_A}{d\omega} \times P_{A\to A} + \frac{dn_{A'}}{d\omega} \times P_{A'\to A}$$

DM decay into dark photons

Axion-like particle together with dark photon:

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

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

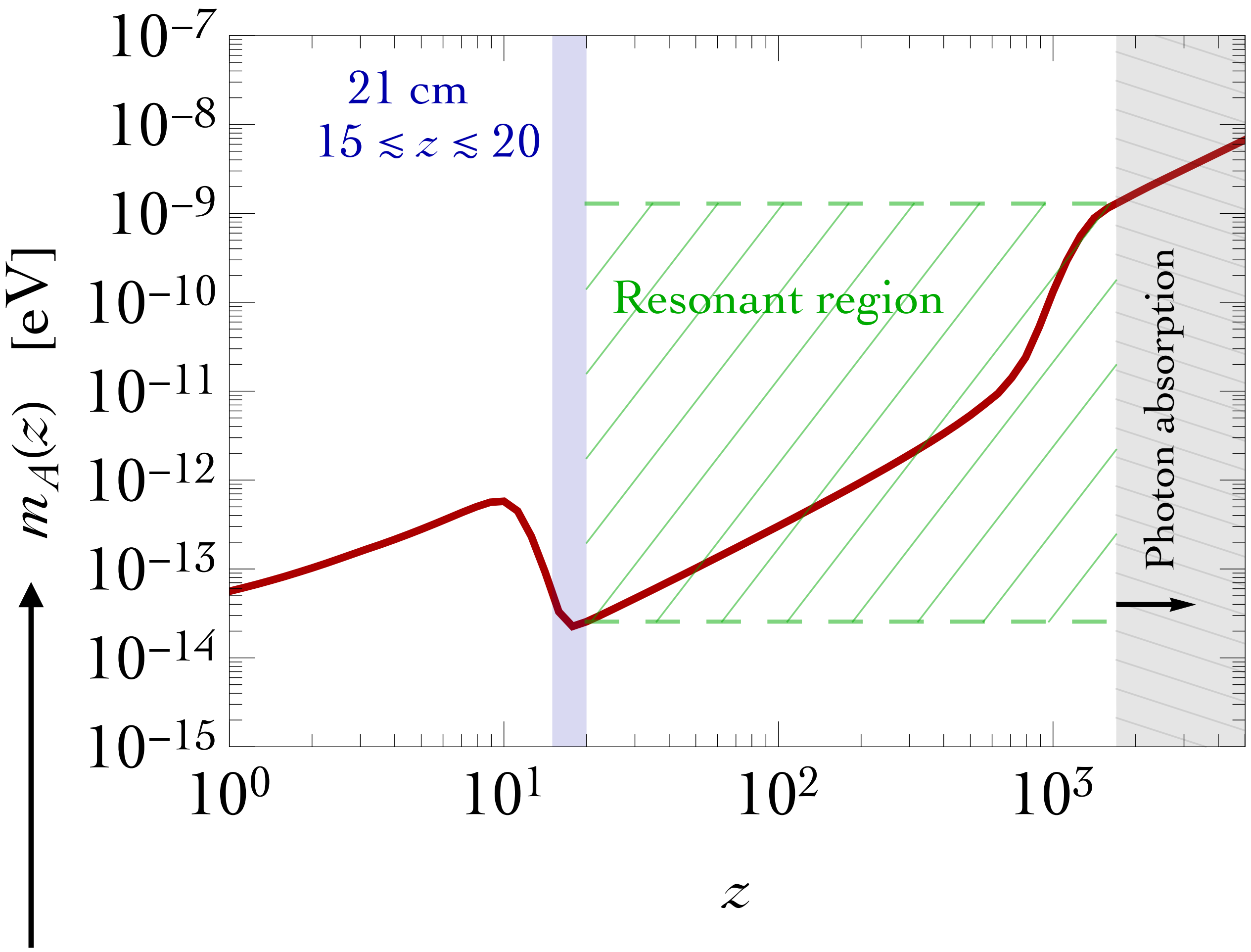
Lifetime can be anything from much shorter to much longer than the age of the Universe

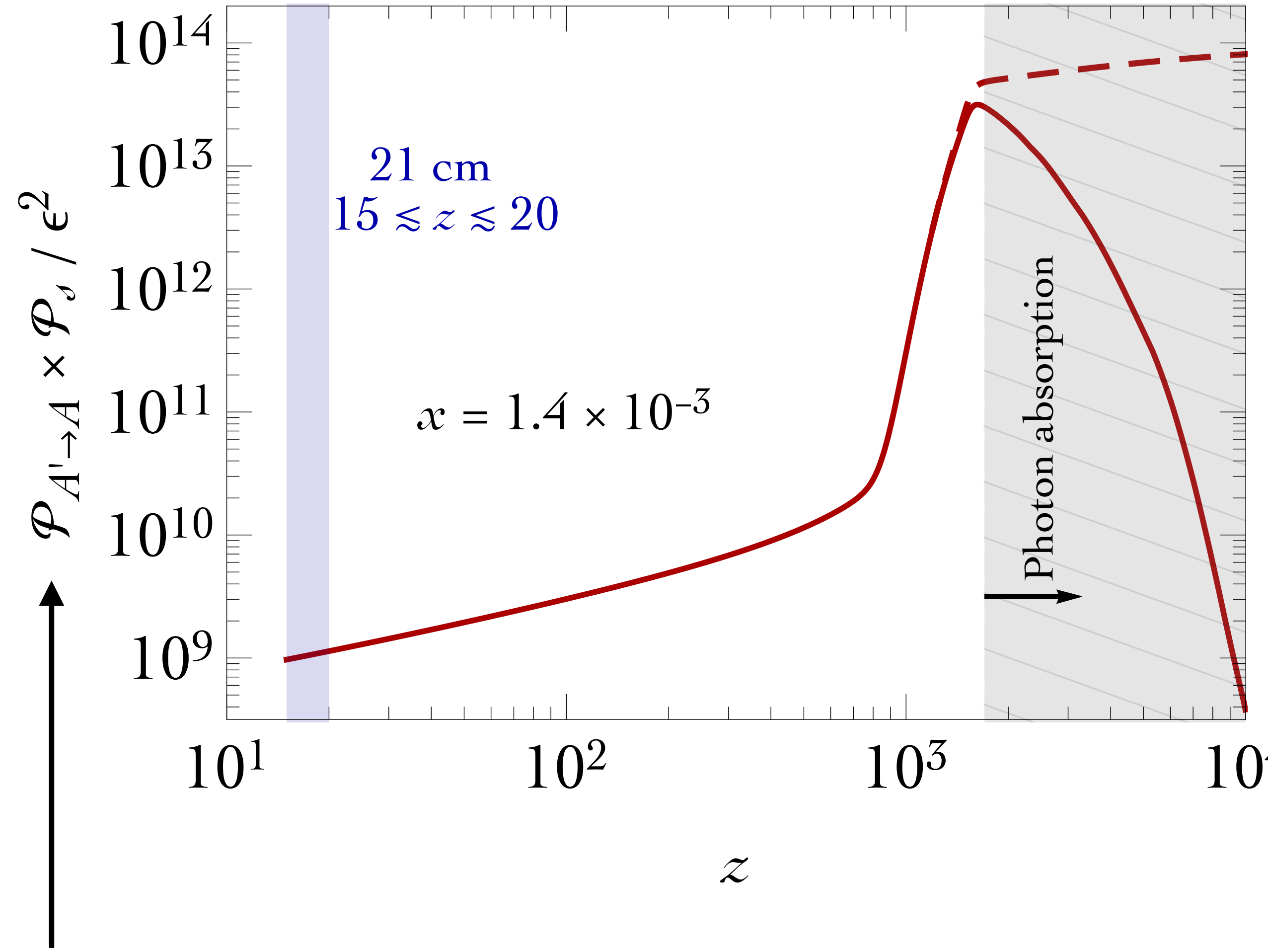
$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times 10^{-4}}{\tau_{\rm U}}\left(\frac{m_a}{10^{-4}\,{\rm eV}}\right)^3\left(\frac{100\,{\rm GeV}}{f_a}\right)^2$$

Axion decay to two normal photons does not work because $f_a > 10^9\ \mathrm{GeV}$ and the rate is tiny.

Dark photon - photon conversion

$$m'_A = m_A(z)$$





photon plasma freq.

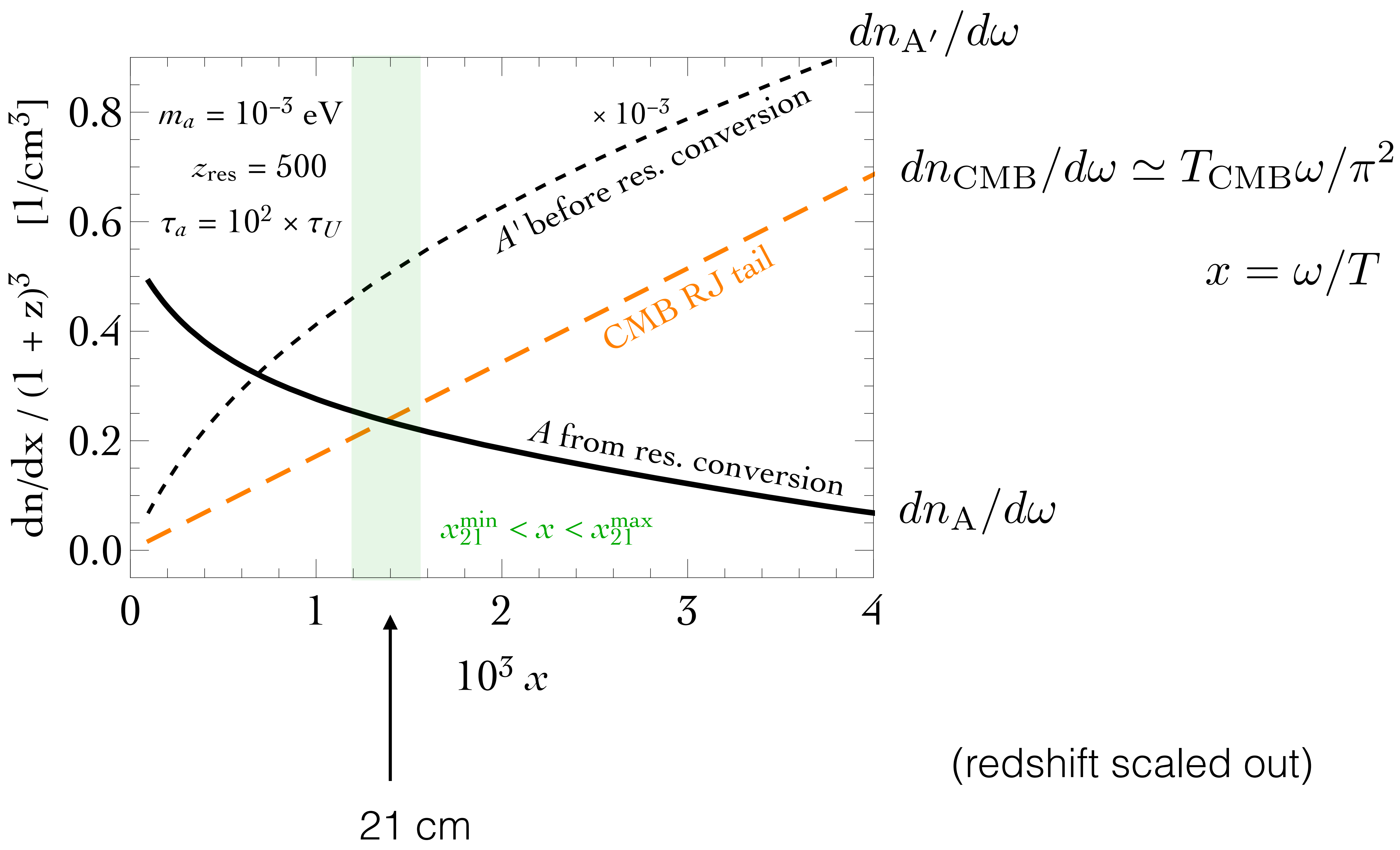
$$m_A(z) \simeq 1.7 \times 10^{-14}\mathrm{eV} \times (1+z)^{3/2} X_e^{1/2}(z)$$

transition probability

$$P_{A \to A'} = P_{A' \to A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \times \left| \frac{d \log m_A^2}{dt} \right|_{t=t_{\rm res}}^{-1}$$

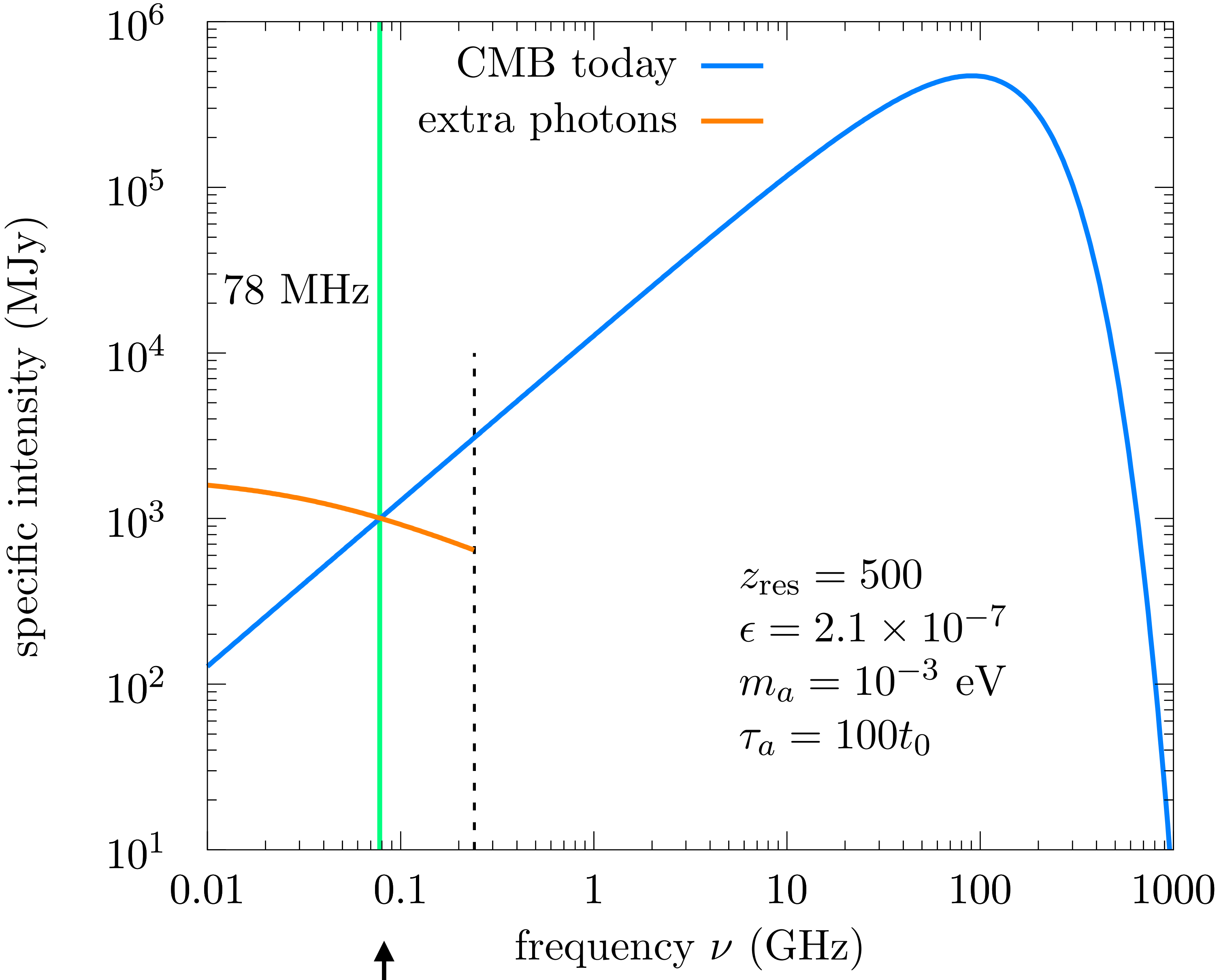
see also [Mirizzi, Redondo, Sigl 2009]

Spectra at 21cm wavelength



(redshift scaled out)

CMB today



21 cm at z=17

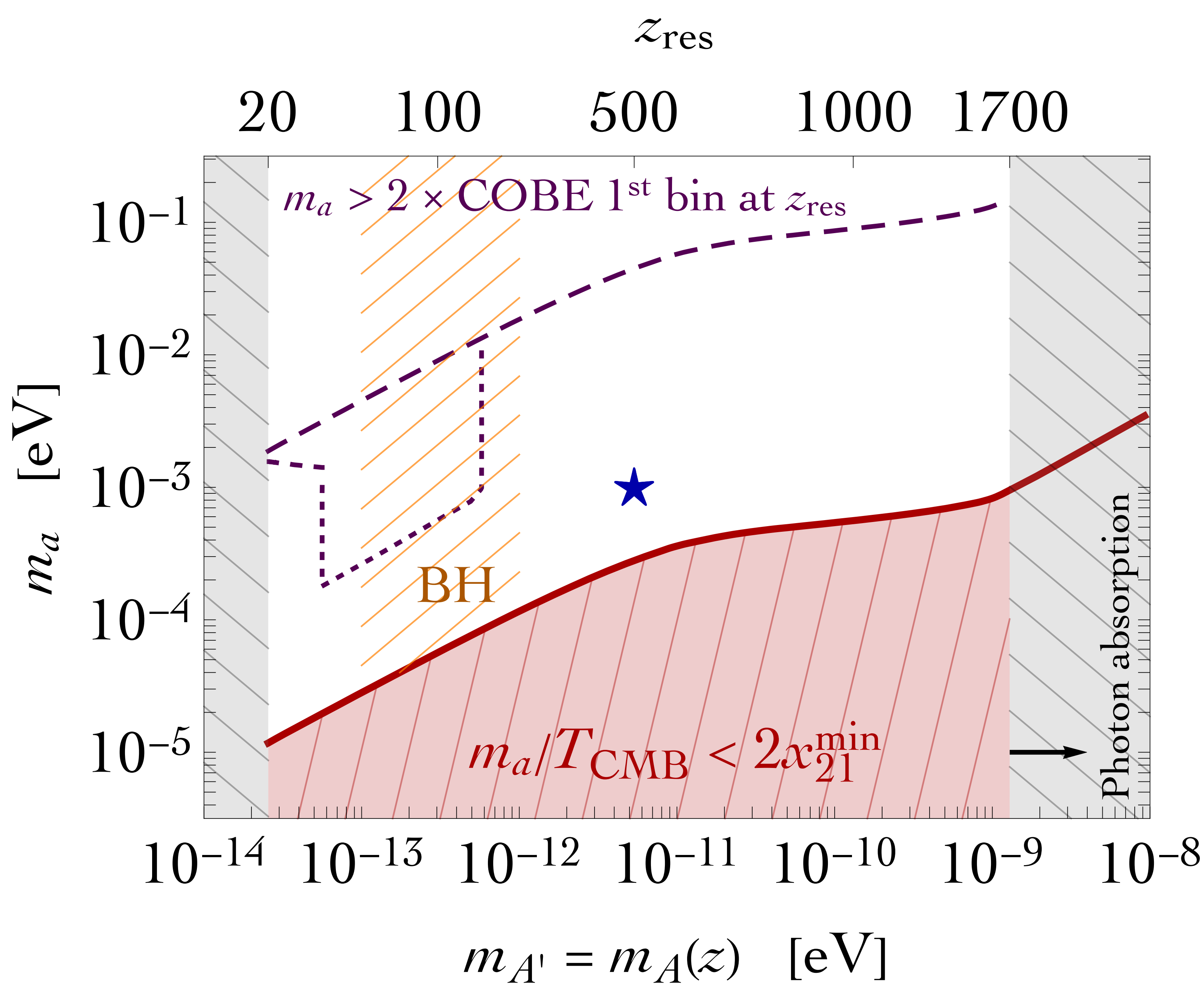
Constraint on spectral CMB distortion

$$P_{A' \to A} \propto \frac{1}{\omega}$$

biases conversion towards the IR

=> good - makes it safe(r) against strong COBE/FIRAS limit on spectral CMB distortion for x > 0.2

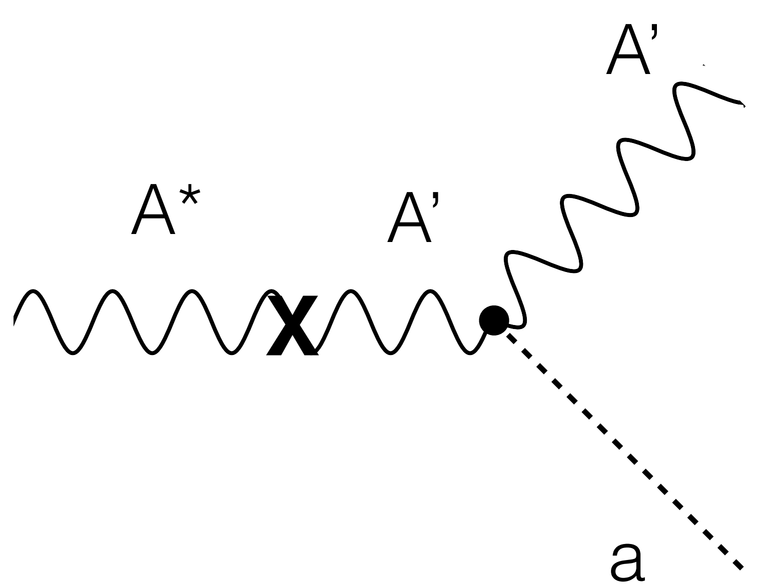
NB: axion-photon conversion $\propto \omega$



Stellar energy loss constraint

Very light fields (< keV) are most notably constrained through astrophysics. Constraints can be divided into ones that vanish as $m_{A'} \to 0$ and those that don't. For example, direct A' production is suppressed by $(m'_A/m_A)^2$.

Photons (plasmons) can decay to dark photon and axion $A^* \to A'a$



$$Q_{A^* \to A'a} = \frac{\epsilon^2 m_A^4 n_T}{96\pi f_a^2}$$

=> compare with neutrino emission from a dipole moment

$$Q_{A^* \to \nu\bar{\nu}} = \frac{\mu^2 m_A^4 n_T}{24\pi}$$

=> HB limit $\mu \leq 3 \times 10^{-12}(e/2m_e)$ [Raffelt, Haft 93]

$m_A =$ plasma freq.

$$\epsilon/f_a < 2 \times 10^{-9}\,\mathrm{GeV}^{-1}$$

DM lifetime vs. photon count

Example:

Fixing progenitor mass

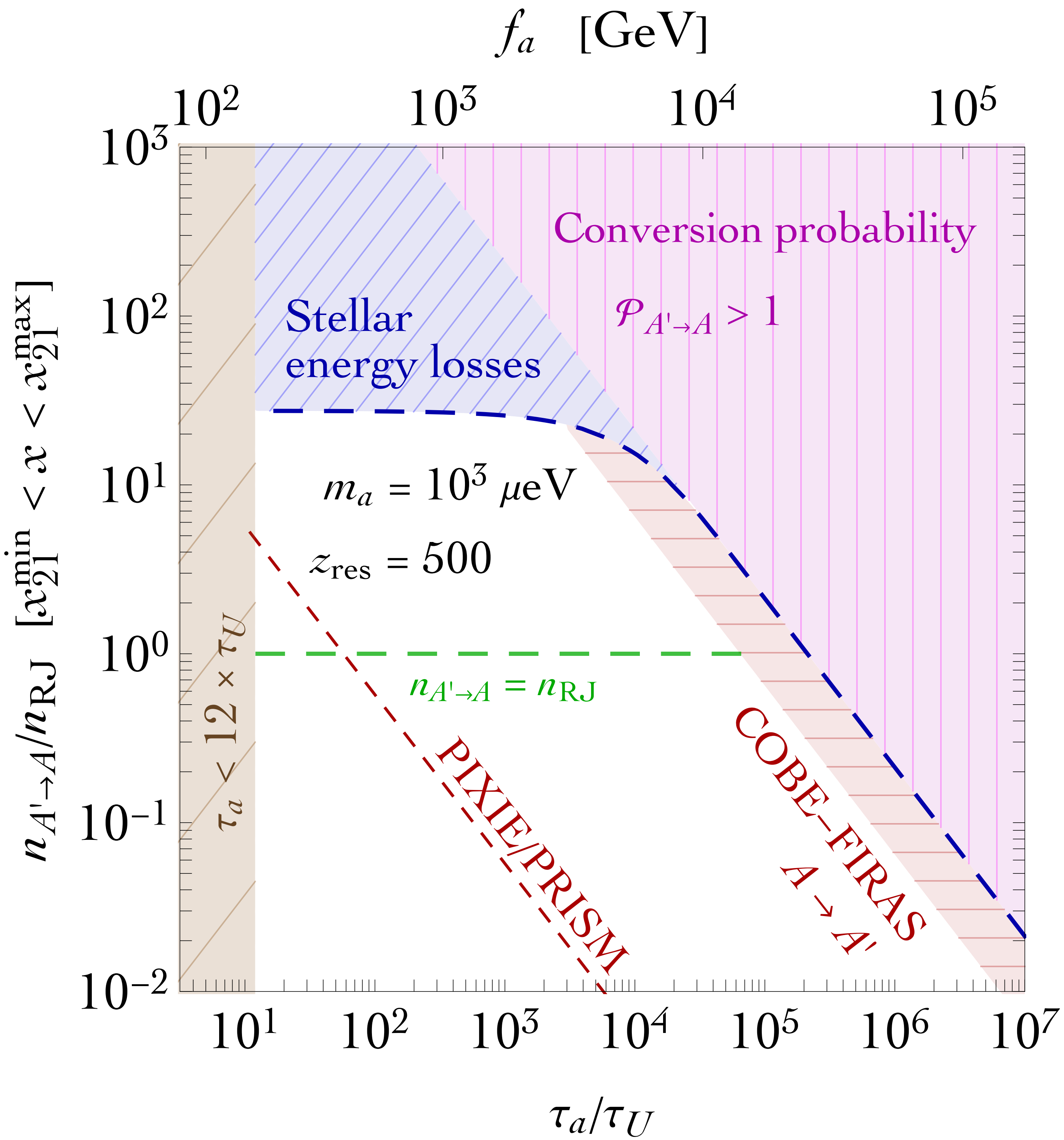
$m_a = 10^{-3}\,\mathrm{eV}$

and DP mass such that

$z_{res} = 500$

we obtain the possible enhancement in the photon count at $x = 10^{-3}$

green line: count doubled
=> EDGES amplitude explained

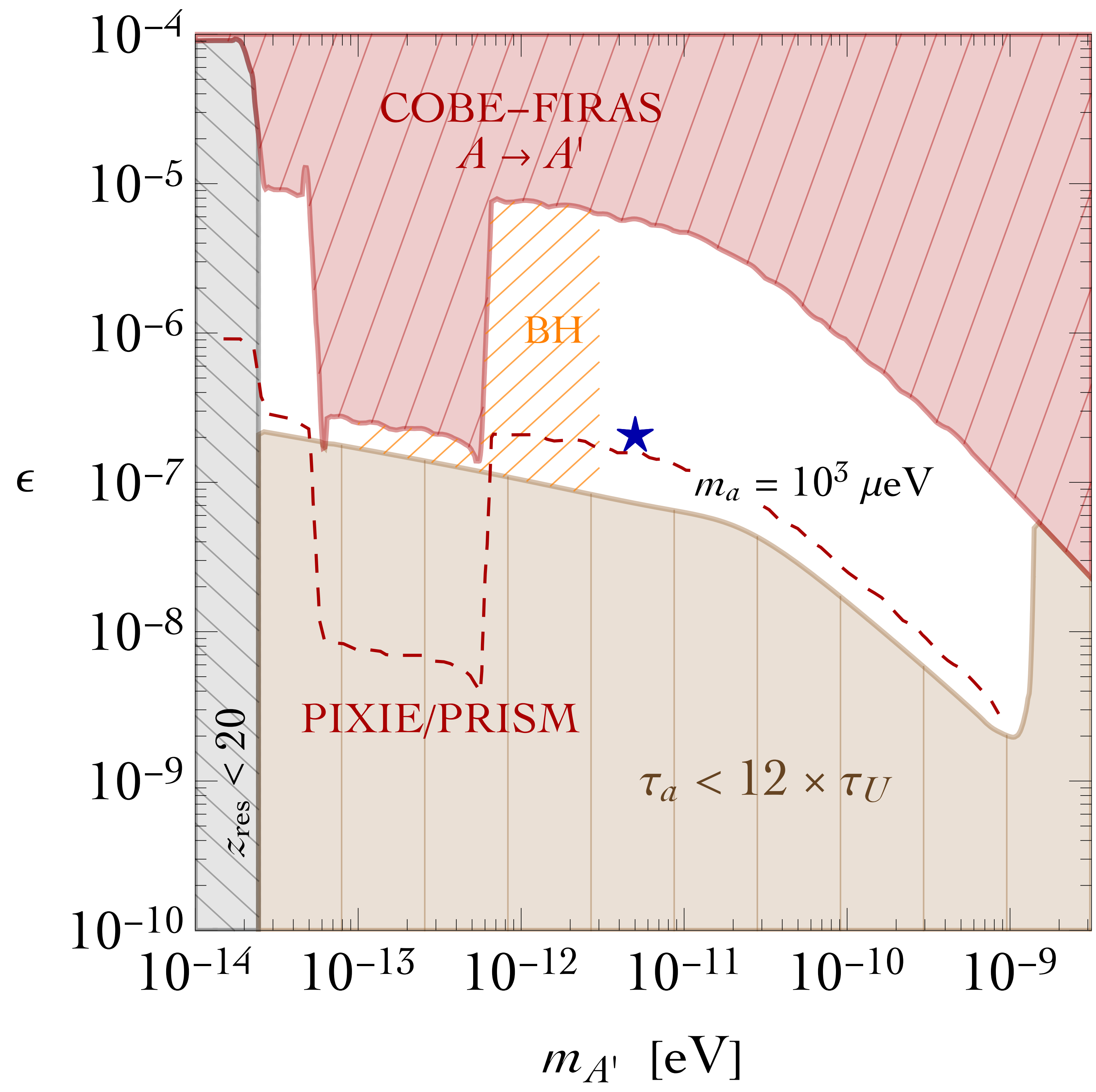


Kinetic Mixing vs. DP mass

Imposing $n_{A' \to A}/n_{\rm RJ} = 1$, i.e. requiring that EDGES amplitude is explained, and for one value of axion mass

=> yields parameter space in DP mass vs. epsilon

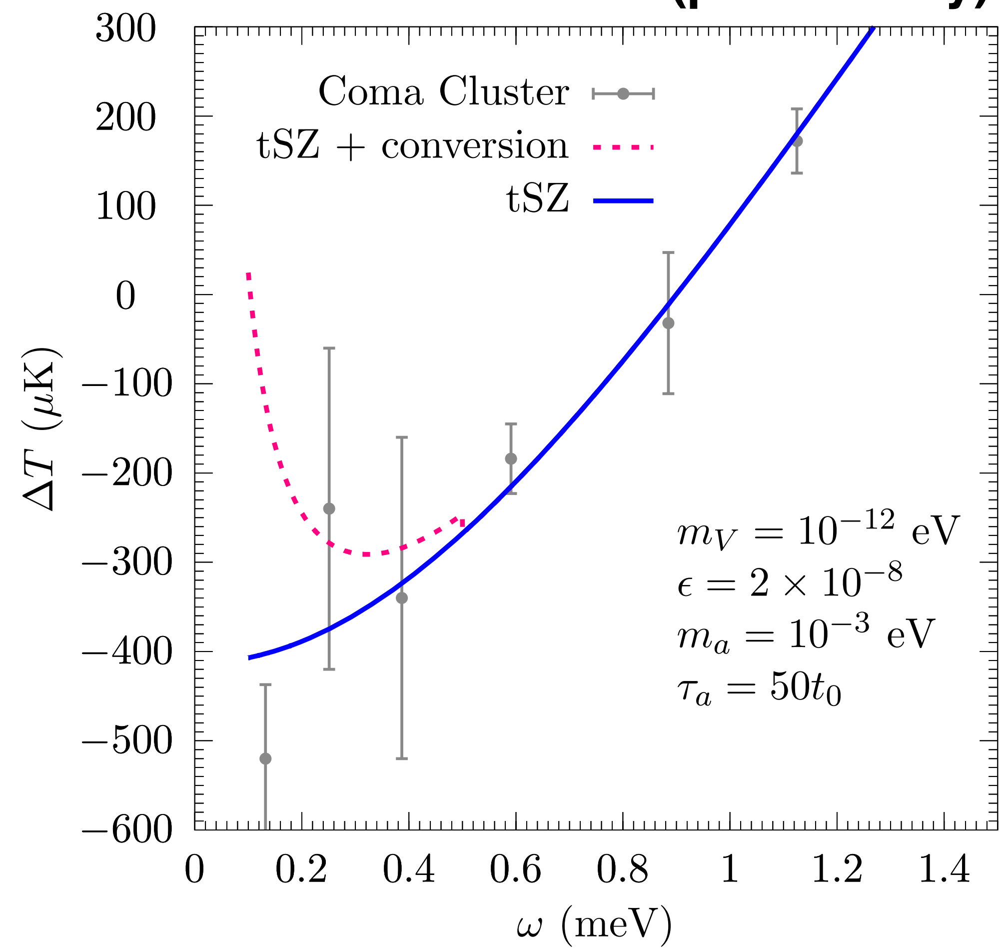
=> much allowed.



Outlook

- Further constraints on the model will exist from conversions in the low-z Universe, e.g.
  - from thermal SZ-effect measurements in specific Clusters
  - from “lines” from axion decay inside clusters today

(preliminary)

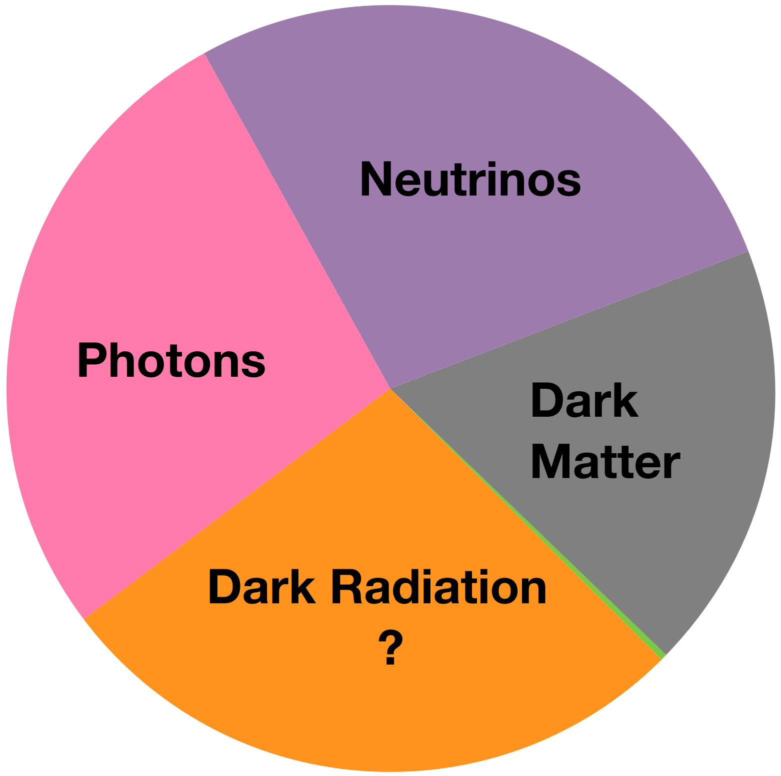


- Interesting connection to ARCADE 2 radio observations. Measurement of (extragalactic) sky temperature in the range 3-8GHz show excess [compare FIRAS > 13 GHz]

- Can we learn more about EDGES, e.g. by considering the shape? (steep turn-on of the feature)

[in preparation]

Conclusions



- Cosmic pie-chart in number densities is largely unwritten. Our Universe could be filled with dark radiation, and when the energy of quanta is small, it can be so in large numbers.

- There is a class of models = dark photon sourcing particles, that supply an extra population of cosmological photons through resonant conversion.

  => can account for EDGES signal

- presented, concrete model has plenty of parameter space. Additional constraints from the low-z Universe will apply (currently under investigation)

Independently of whether EDGES result will persist, 21 cm cosmology offers a new tool for testing the physics of the dark sector.