Dark radiation -
21cm signals and laboratory tests

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Neutrino **Oscillation** Workshop

- Introduction - dark radiation (DR) from dark matter (DM) decay
- **Neutrino** dark radiation from dark matter decay - laboratory tests

Cui, Pospelov, JP; PRD 2018, arXiv:1711.04531

- Dark photon dark radiation to photon **oscillation** - 21cm signals

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

- Outlook / Conclusions

Dark radiation from DM decay

Any **direct** sensitivity to DR in DM decay 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?*

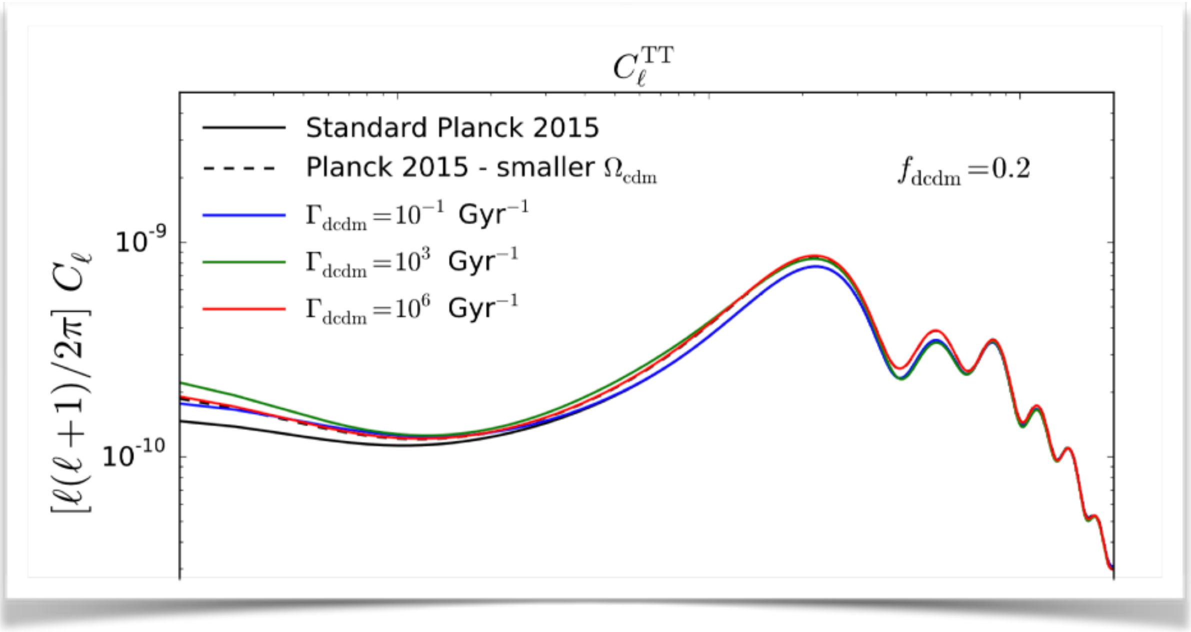
Cosmology remains a sensitive probe of DM decays, irrespective of DM mass and interaction, but through gravity.

CMB (late-time ISW) and lensing constrains

$$\begin{aligned} f_{\rm dm} &< \text{few}\,\% & (\tau_{\rm dm} < \tau_U) \\ f_{\rm dm}/\tau_{\rm dm} &\lesssim 1/12\tau_U & (\tau_{\rm dm} > \tau_U) \end{aligned}$$

Poulin, Serpico, Lesgourges 2016

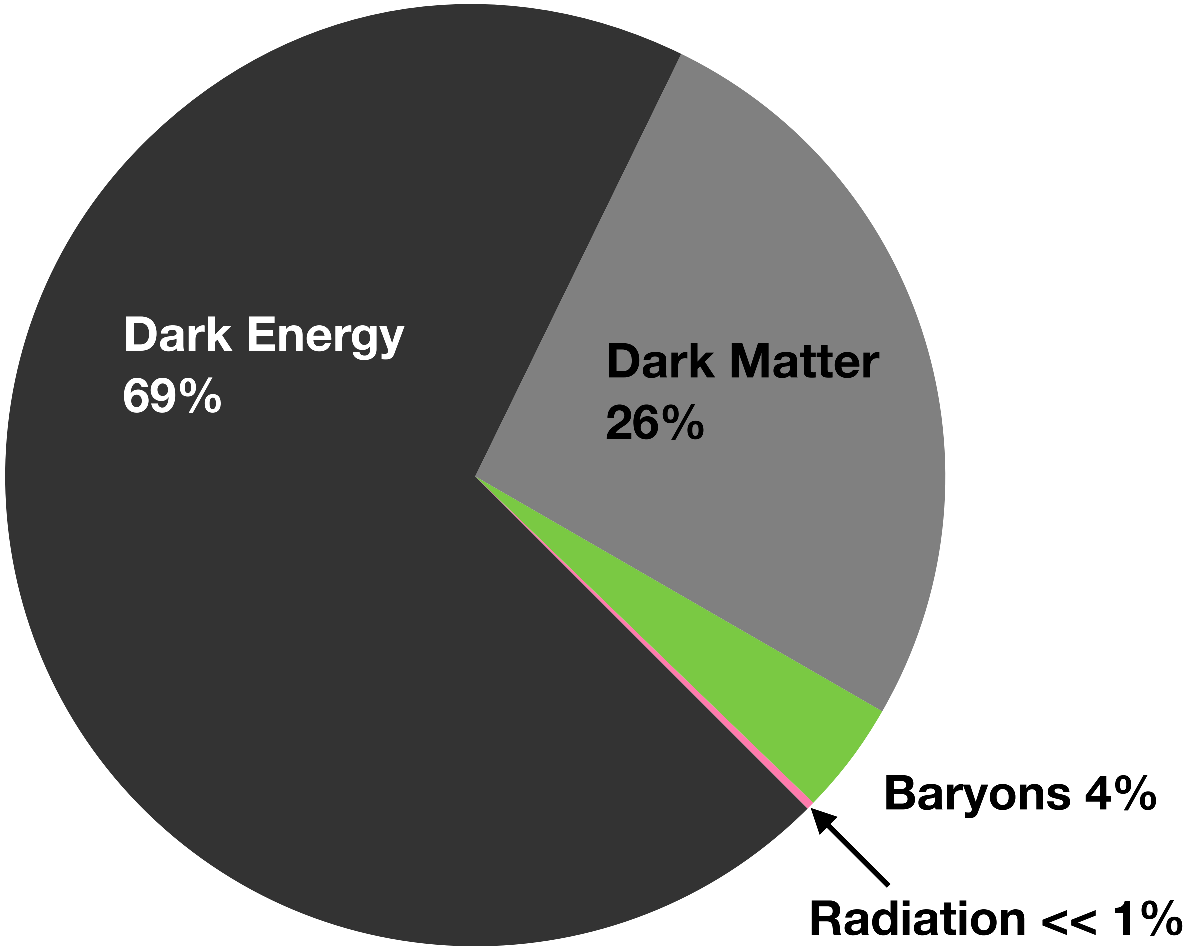
see also Berezhiani, Dolgov, Tkachev 2015



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

e.g. Wang, Peter at al. 2014

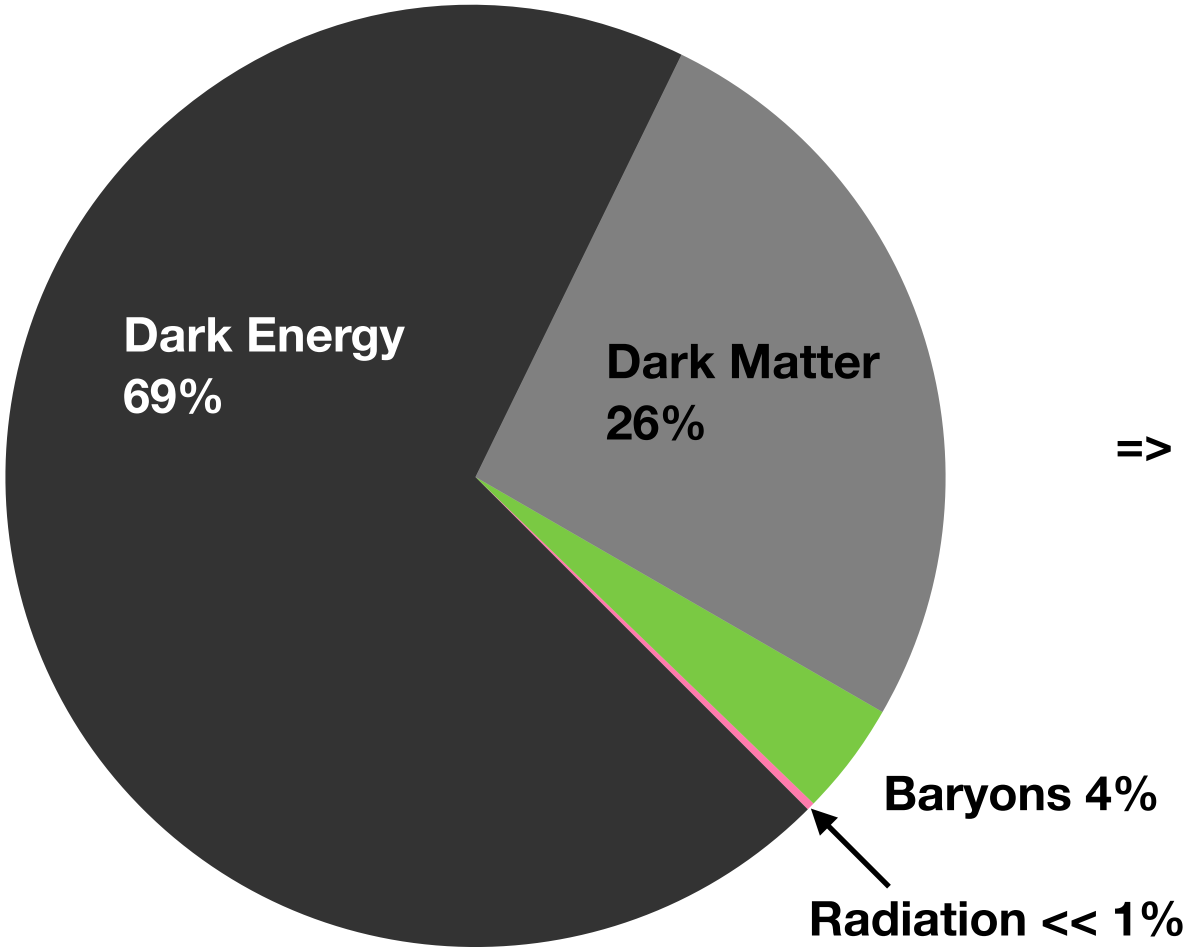
Late Dark Radiation



CMB-inferred

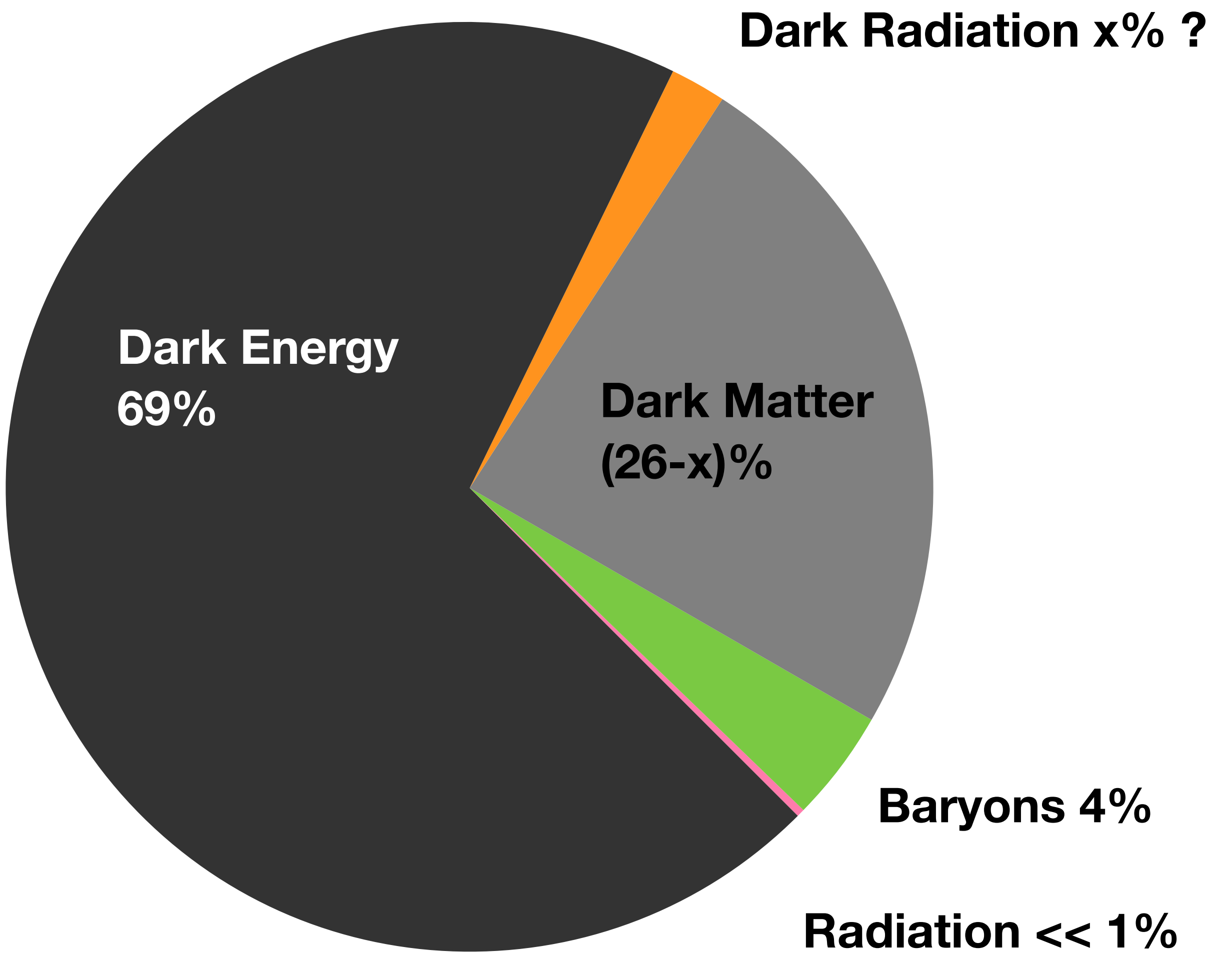
$\rho_{\mathrm{DR}}/\rho_\gamma < 0.15$ Planck

Late Dark Radiation



CMB-inferred

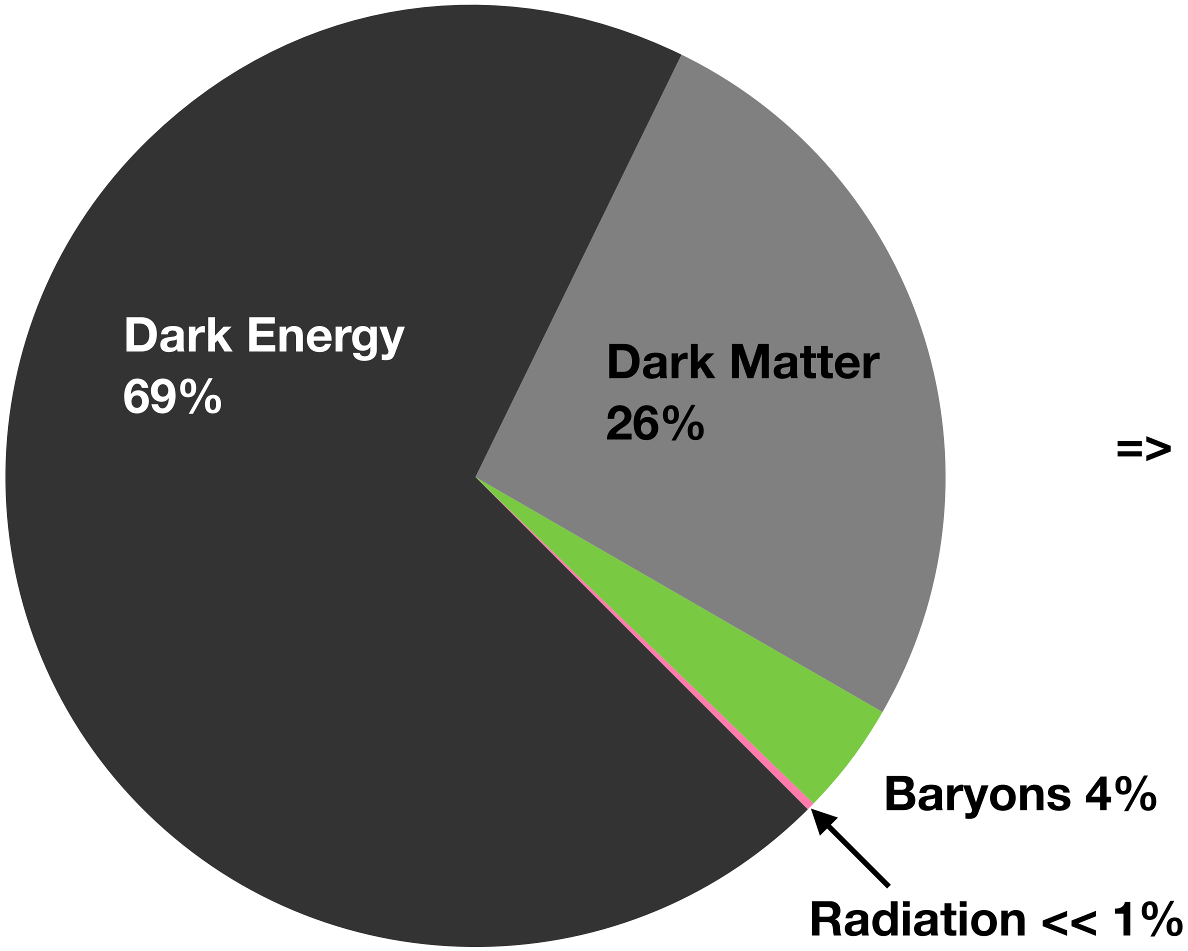
=>



Low redshift Universe

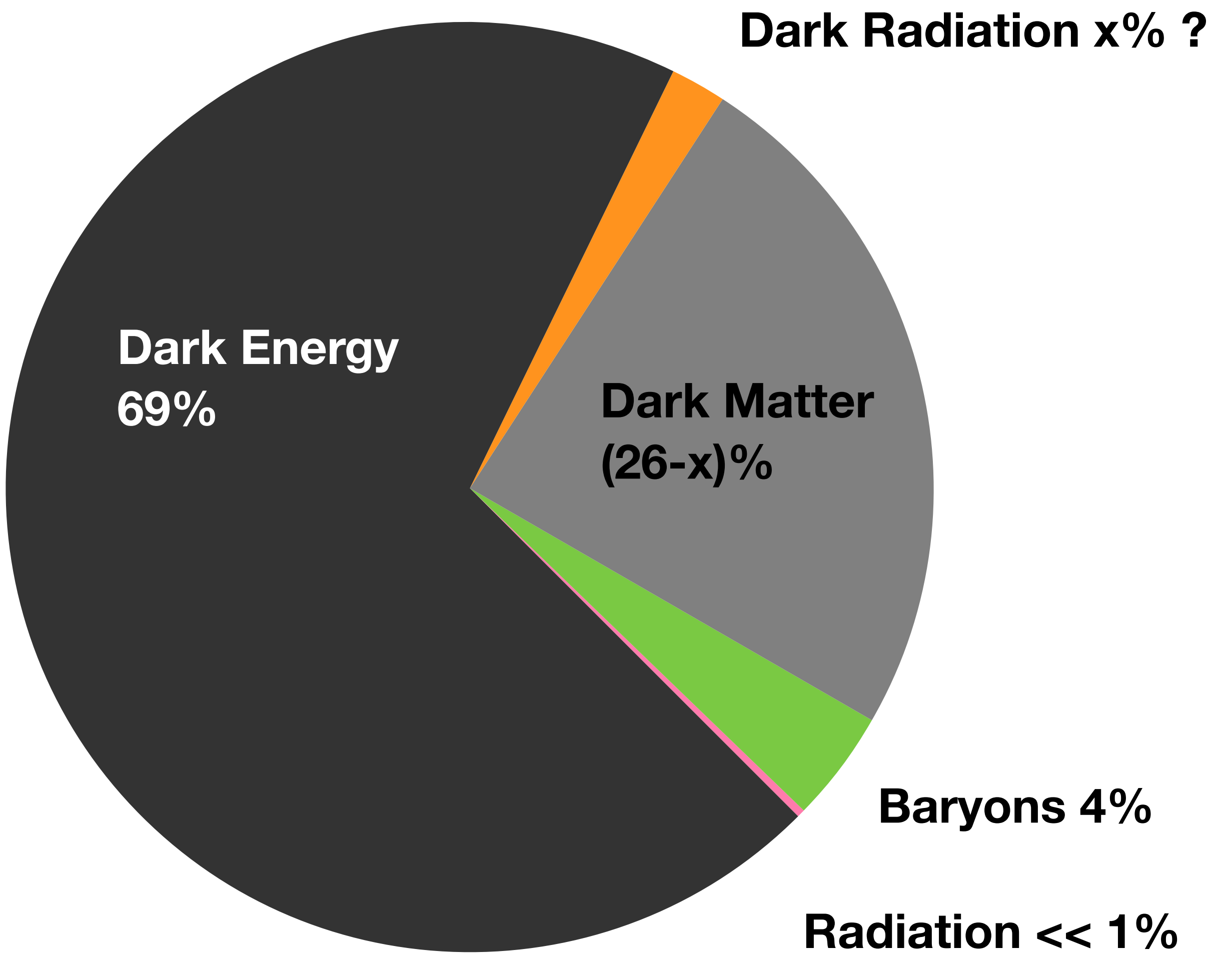
$\rho_{\mathrm{DR}}/\rho_{\gamma} < 0.15$ Planck

Late Dark Radiation



CMB-inferred

=>

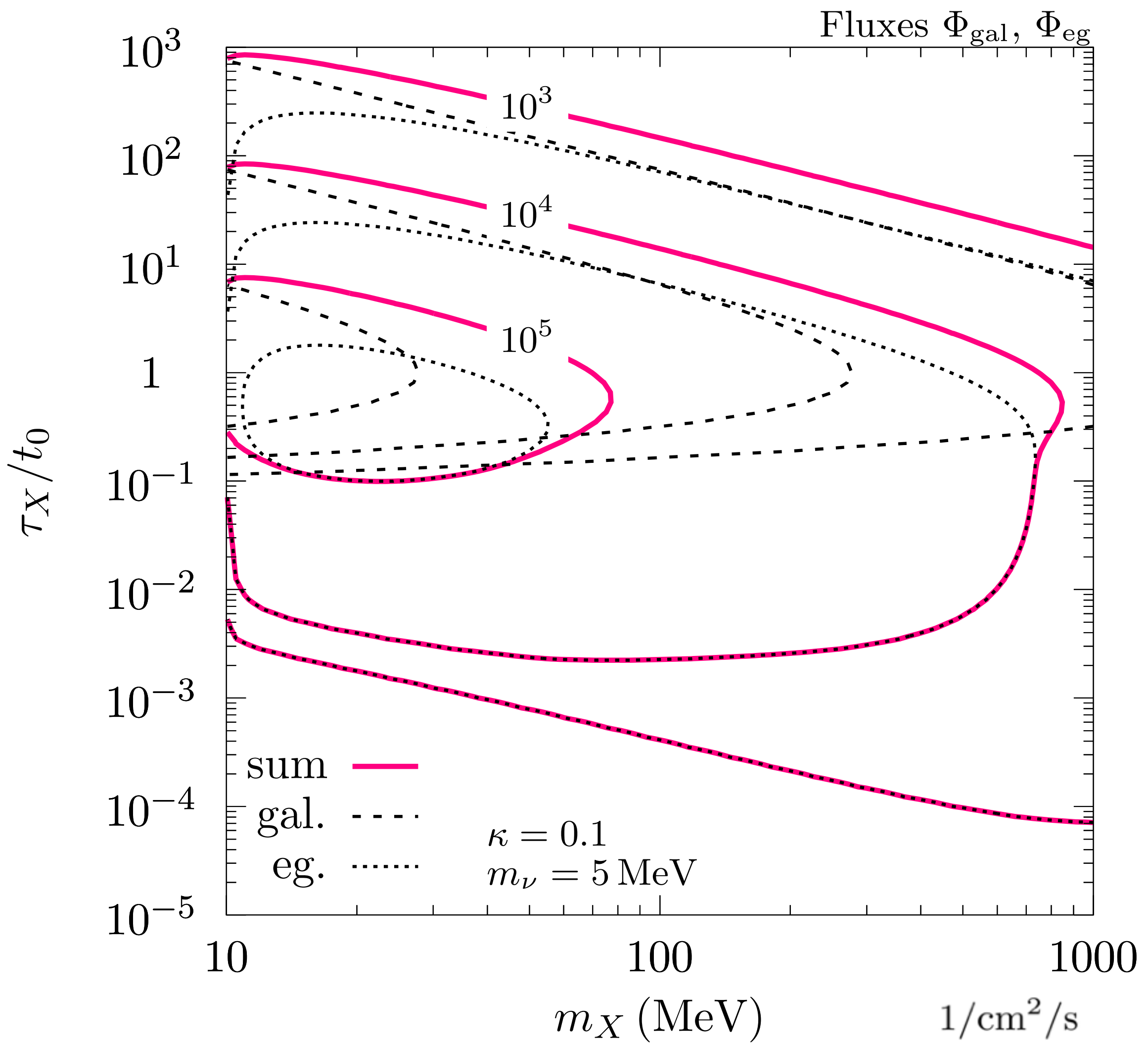


Low redshift Universe

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

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

Maximum fluxes from DM decay



Two sources:

galactic and extragalactic (cosmological)

Maximum flux $\Phi_{\rm tot}^{\rm max} \sim \dfrac{10\,\text{MeV}}{m_X} \times 10^6\,\text{cm}^{-2}\text{s}^{-1}$

=> much in excess of atmospheric nu-flux and DSNB at ~ 10 - 100 MeV

here: 10% decaying DM component

Late Dark Radiation in SM neutrinos

Benefits: no N_{eff} constraints for direct decay, interactions within SM are known, minimal setup

Decaying progenitor motivated by certain neutrino mass generation mechanism
Majoron $\phi \to \nu\nu \;\; (\bar{\nu}\bar{\nu})$

Φ breaks global lepton number, Goldstone mode is ϕ

$\mathcal{L} = y_1 \bar{L}^c H S_R + y_2 \Phi \bar{S}_L^c S_R + h.c.$ => $\mathcal{L}_{\phi\nu\nu} = i \frac{m_\nu^2}{\langle H \rangle^2} \frac{y_2}{y_1^2} (\nu\nu - \nu^c \nu^c)\phi$ $m_\nu = \frac{y_1^2 \langle H \rangle^2}{y_2 \langle \Phi \rangle}$

Chikashige, Mohapatra, Peccei 1981

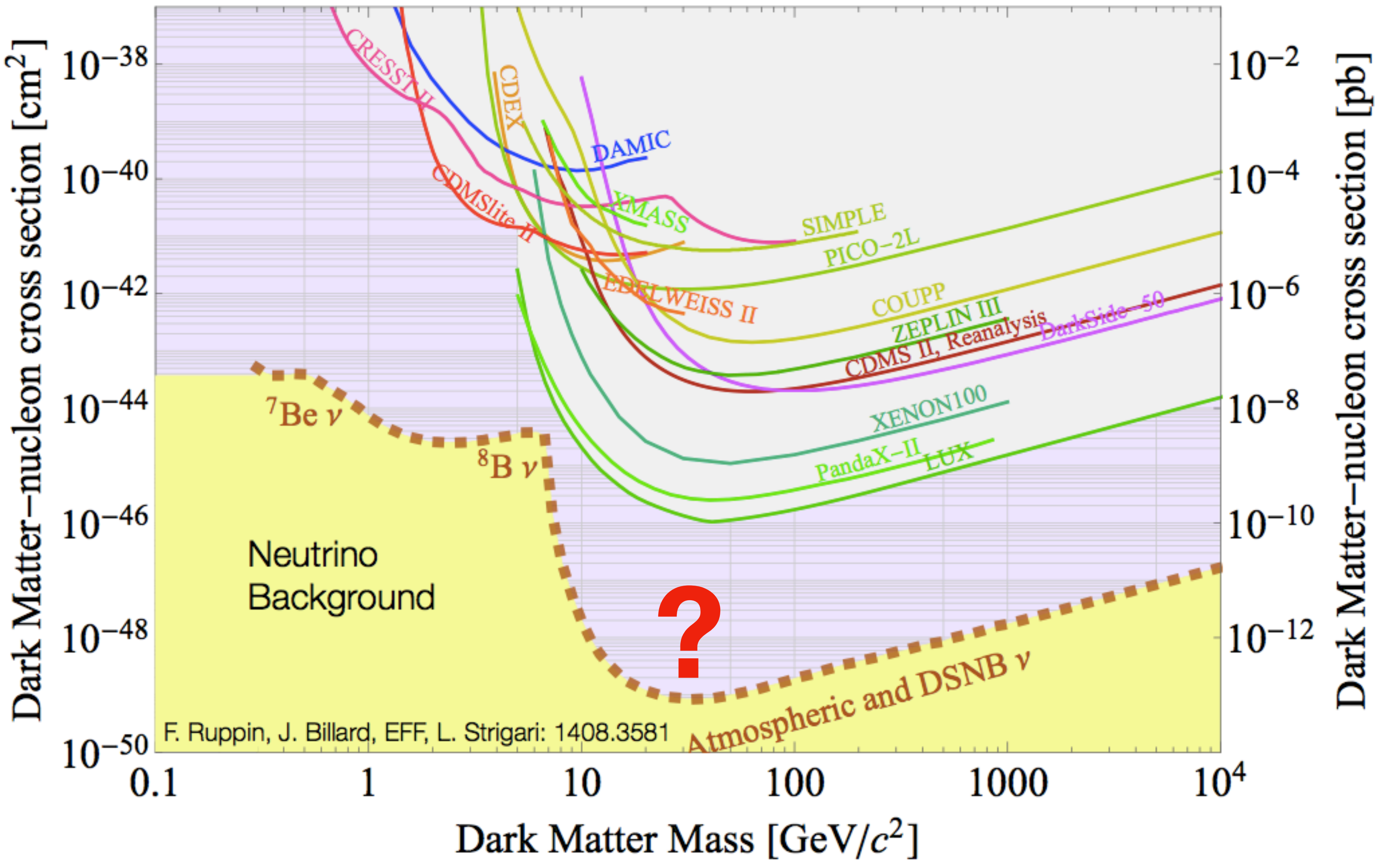
Mass of ϕ as pseudo-Goldstone uncertain, with contributions from Planck-scale suppressed operators; we take it $\mathrm{O}(10)\ \mathrm{MeV}$ noting a non-standard thermal history e.g. Berezinsky, Valle 1993

Late Dark Radiation in SM neutrinos

Opportunity: Injection of neutrinos at few 10’s of MeV poorly constrained

A 30 MeV neutrino gives signals in direct detection right in the region of largest sensitivity.

Neutrino floor can be raised in models that inject ν but not excessively $\bar{\nu}$

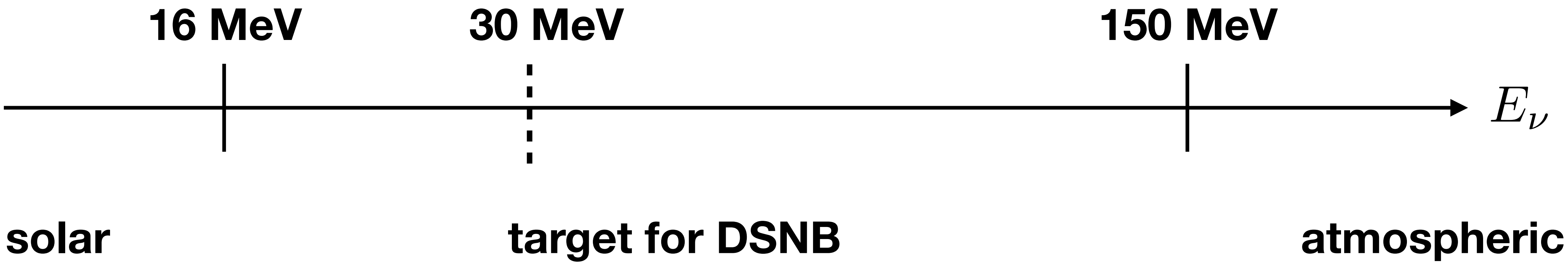


F. Ruppin, J. Billard, EFF, L. Strigari: 1408.3581

Late Dark Radiation in SM neutrinos

Measurements / Constraints:

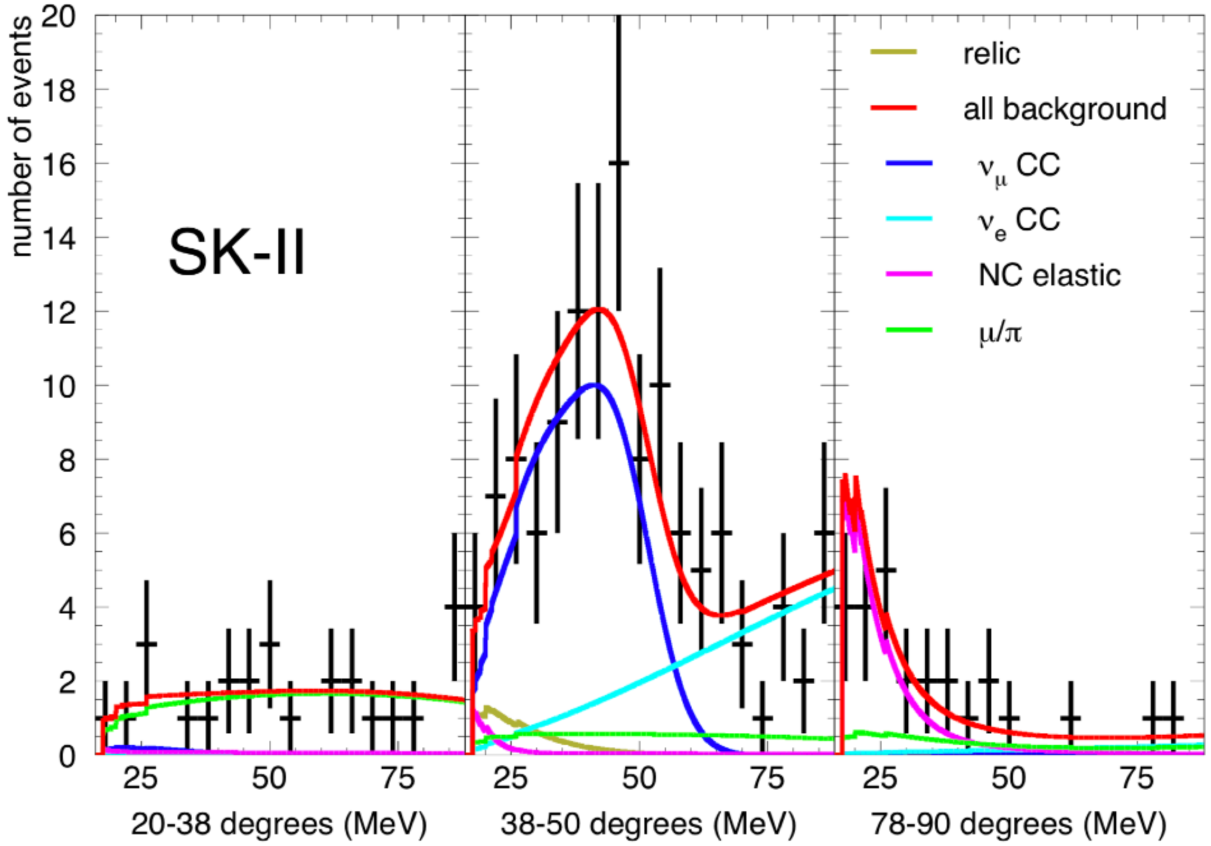
- E < 16 MeV: signal dominated by solar neutrinos (8B flux) in CC and NC scattering on electrons
- 16 MeV < E < 30 MeV: inverse beta decay $p+\bar{\nu}_e \rightarrow n+e^+$ with large visible energy
- 30 MeV < E < 150 MeV: reactions with neutrons inside nuclei no longer kinematically suppressed, e.g. ${}^{16}\mathrm{O} + \nu_e \rightarrow {}^{16}\mathrm{F} + e$
- E > 150 MeV: atmospheric neutrino flux well measured and concordant



Constraints from neutrino expts.

e.g. recasted Super-Kamiokande search for DSNB neutrinos

Super-K collaboration 2011

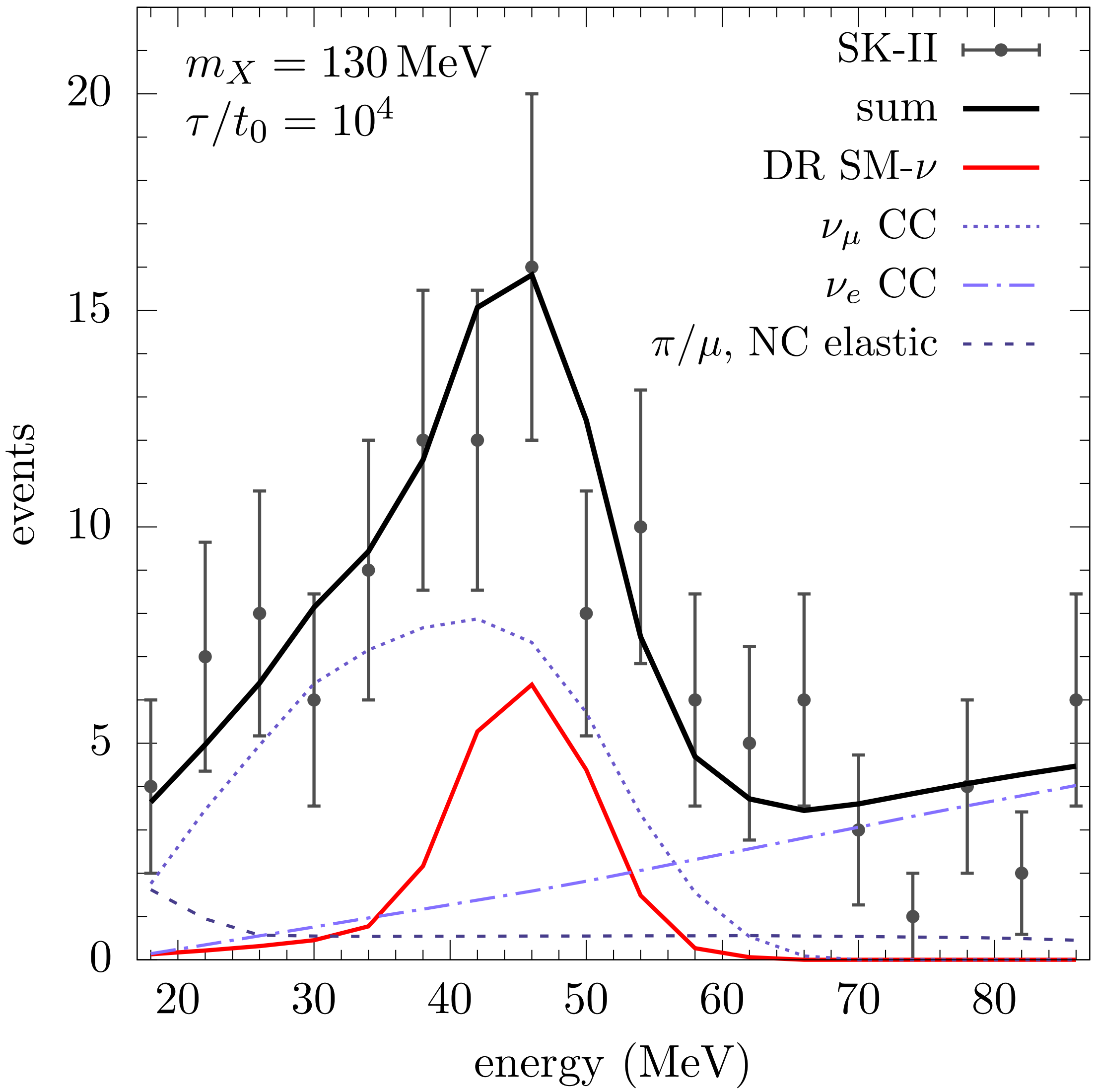


sideband

search-region
with fitted bkg.

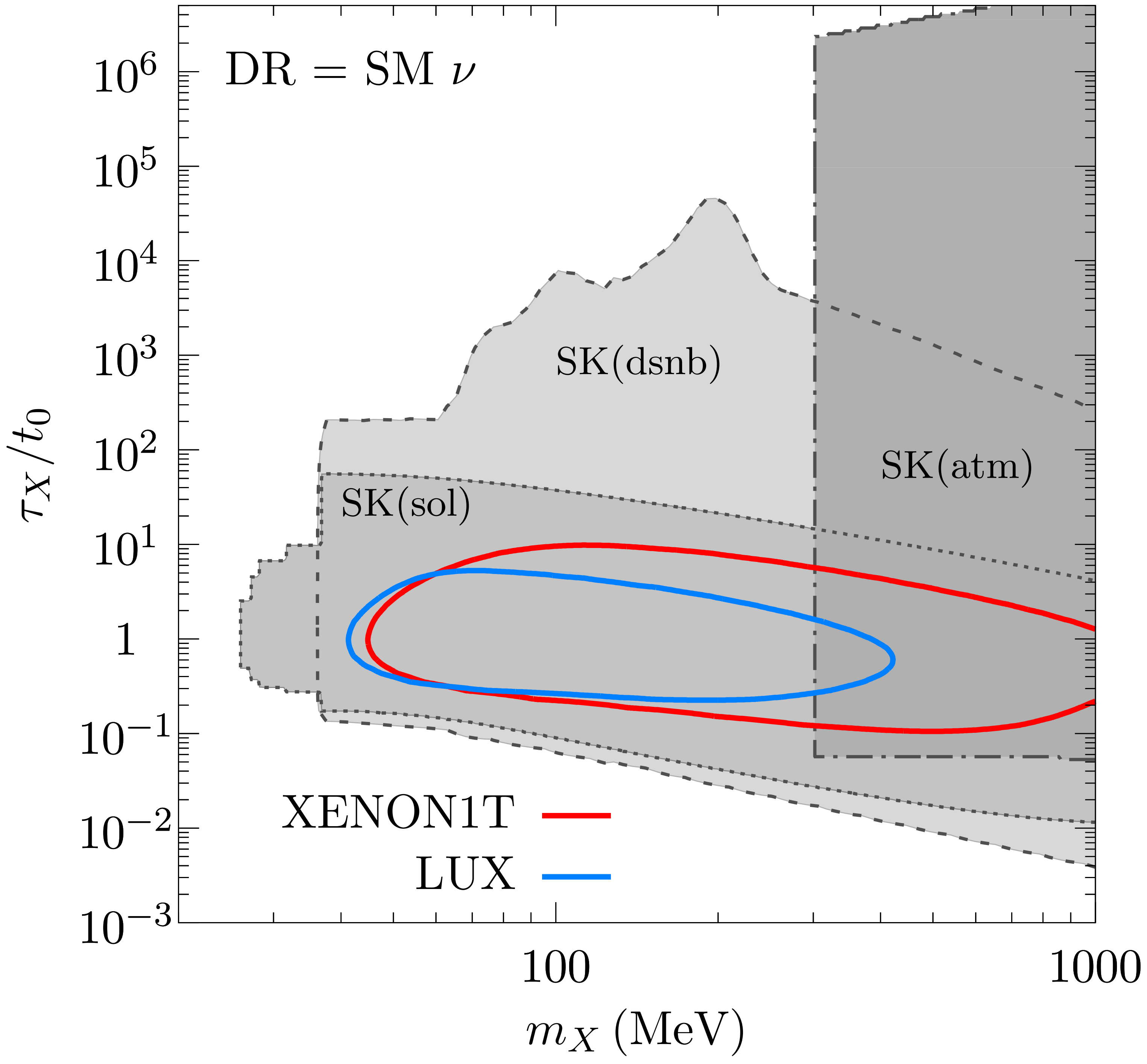
sideband

=>



e.g. $\phi_\nu(E_\nu \simeq 25\,\mathrm{MeV}) < 5 \times 10^2\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Late DR in SM neutrinos



Option 1

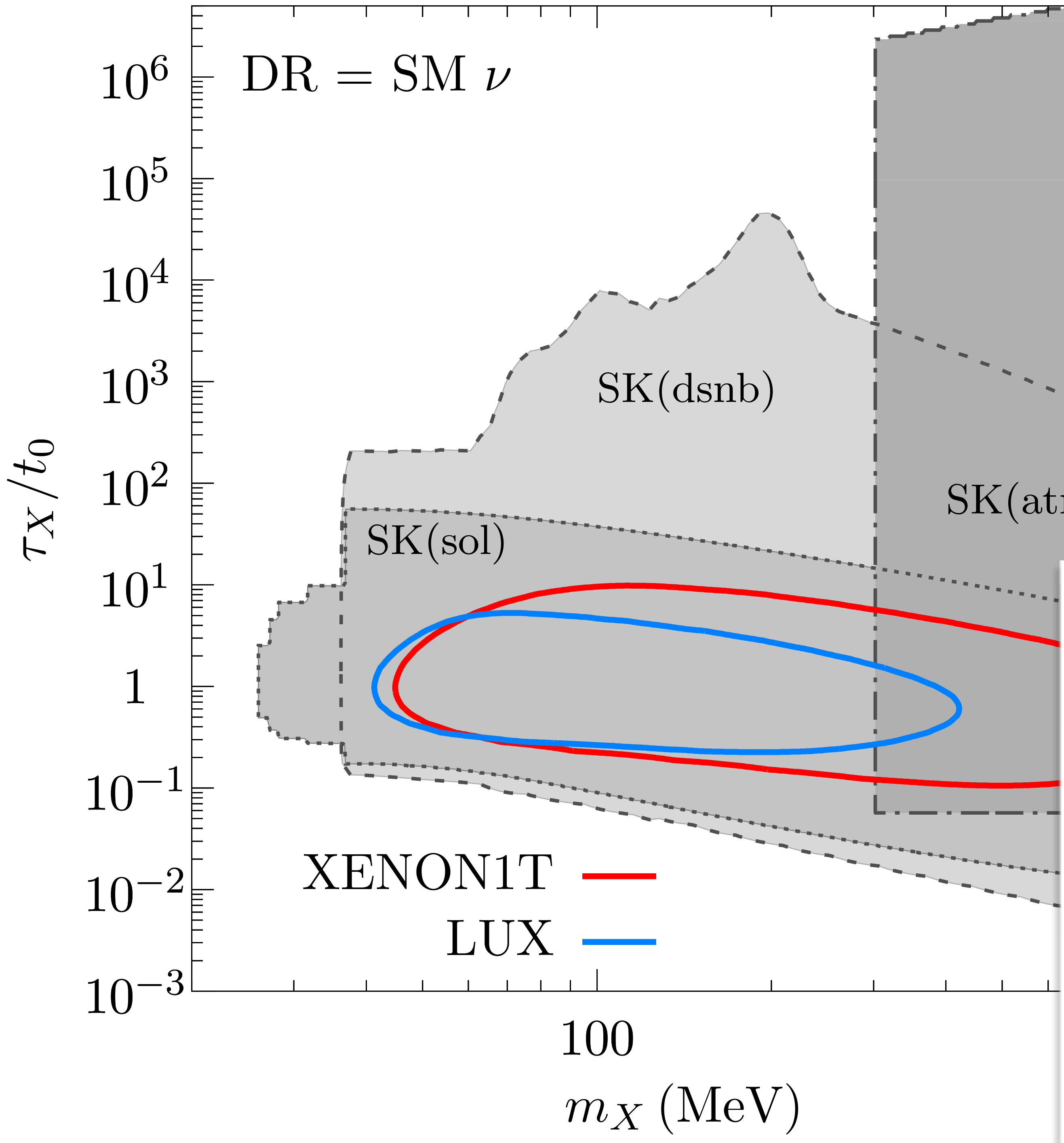
DR in SM neutrinos ν

=> 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

Cui, Pospelov, JP 2017

Late DR in SM neutrinos



Option 1

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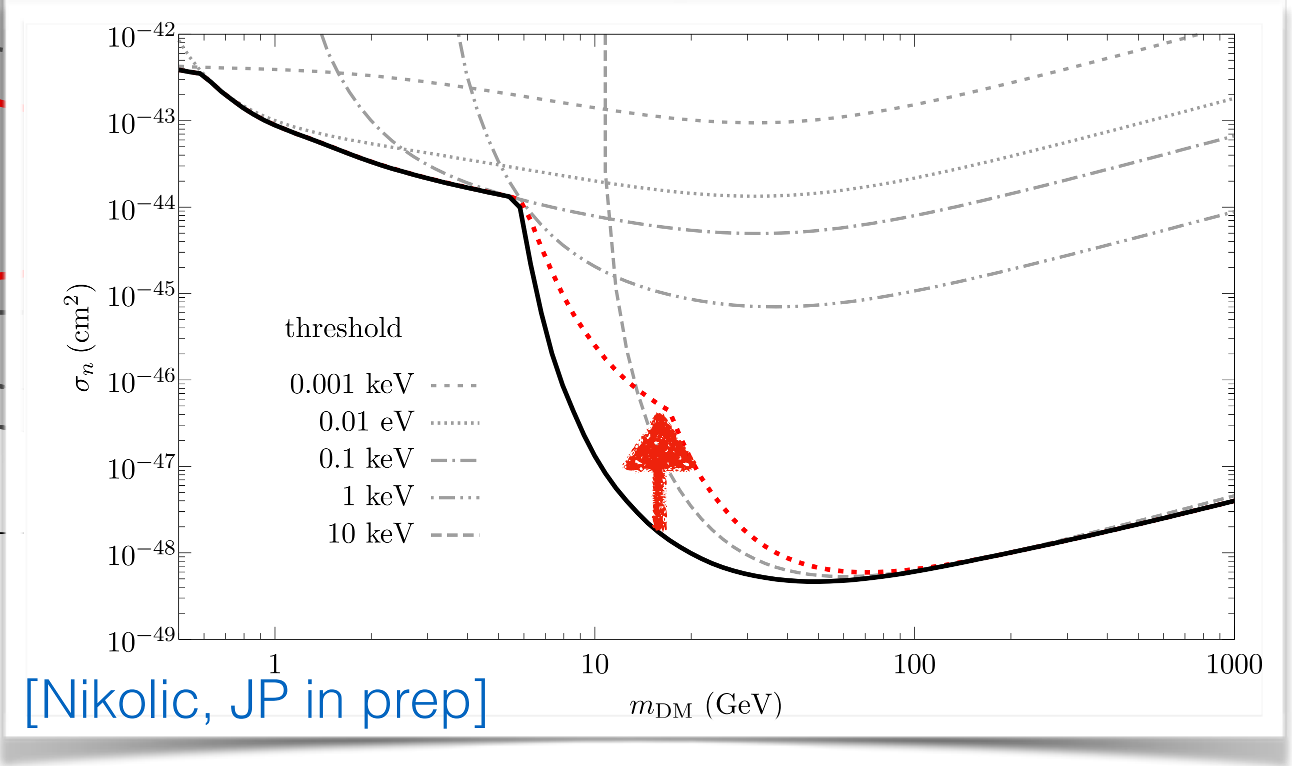
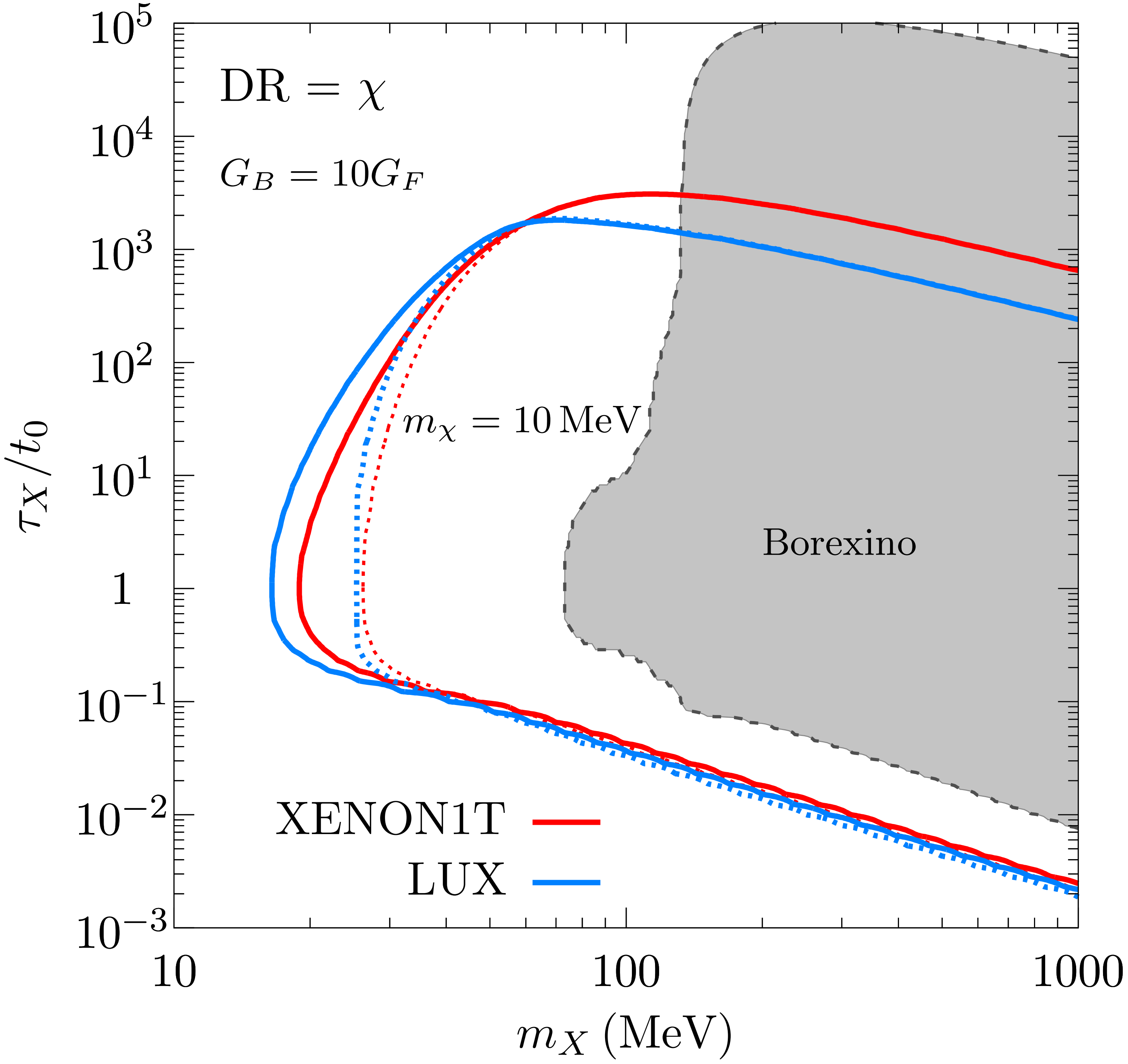


[Nikolic, JP in prep]

Late DR in a new species



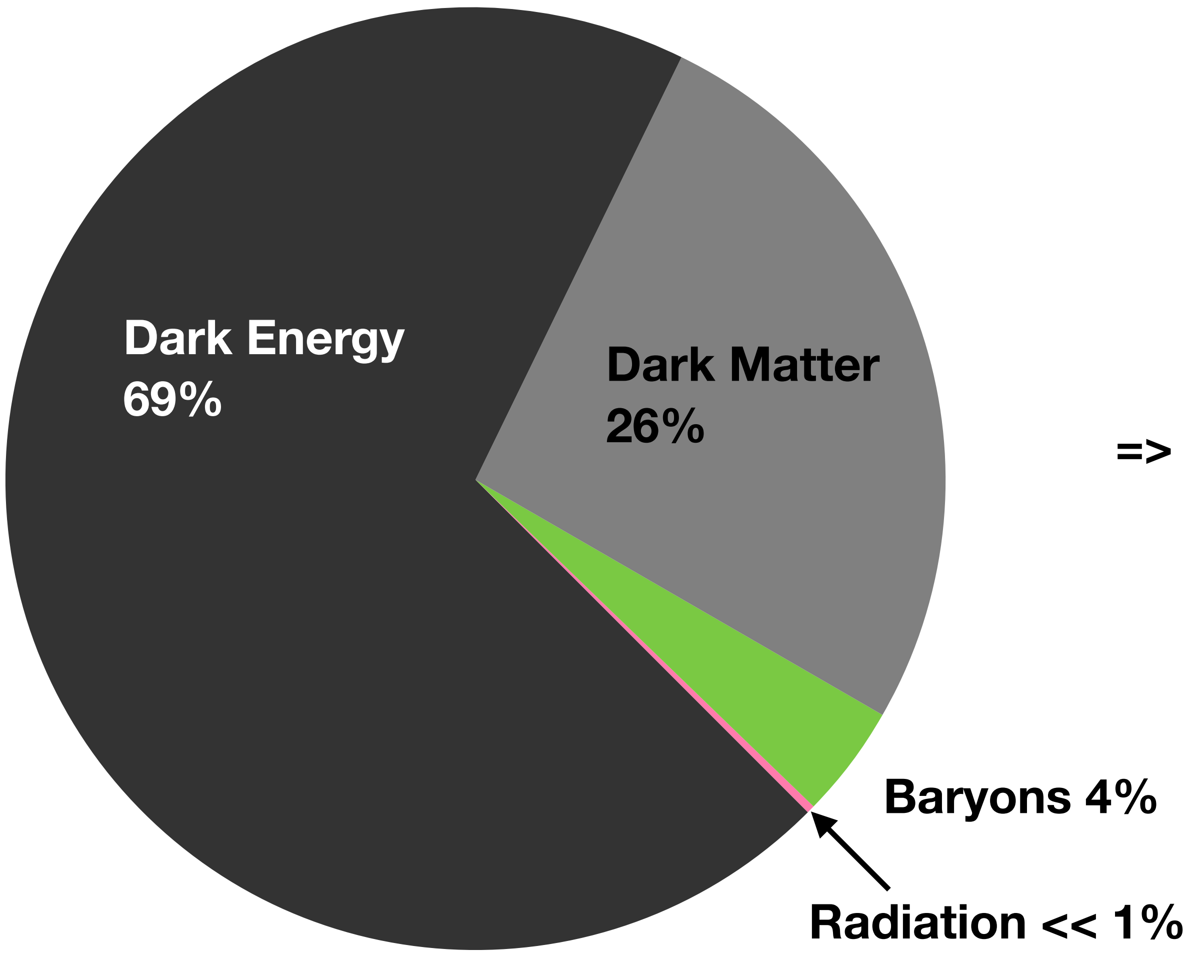
Option 2

new neutrino interacting with baryonic current

Borexino limit derived from elastic scattering on protons

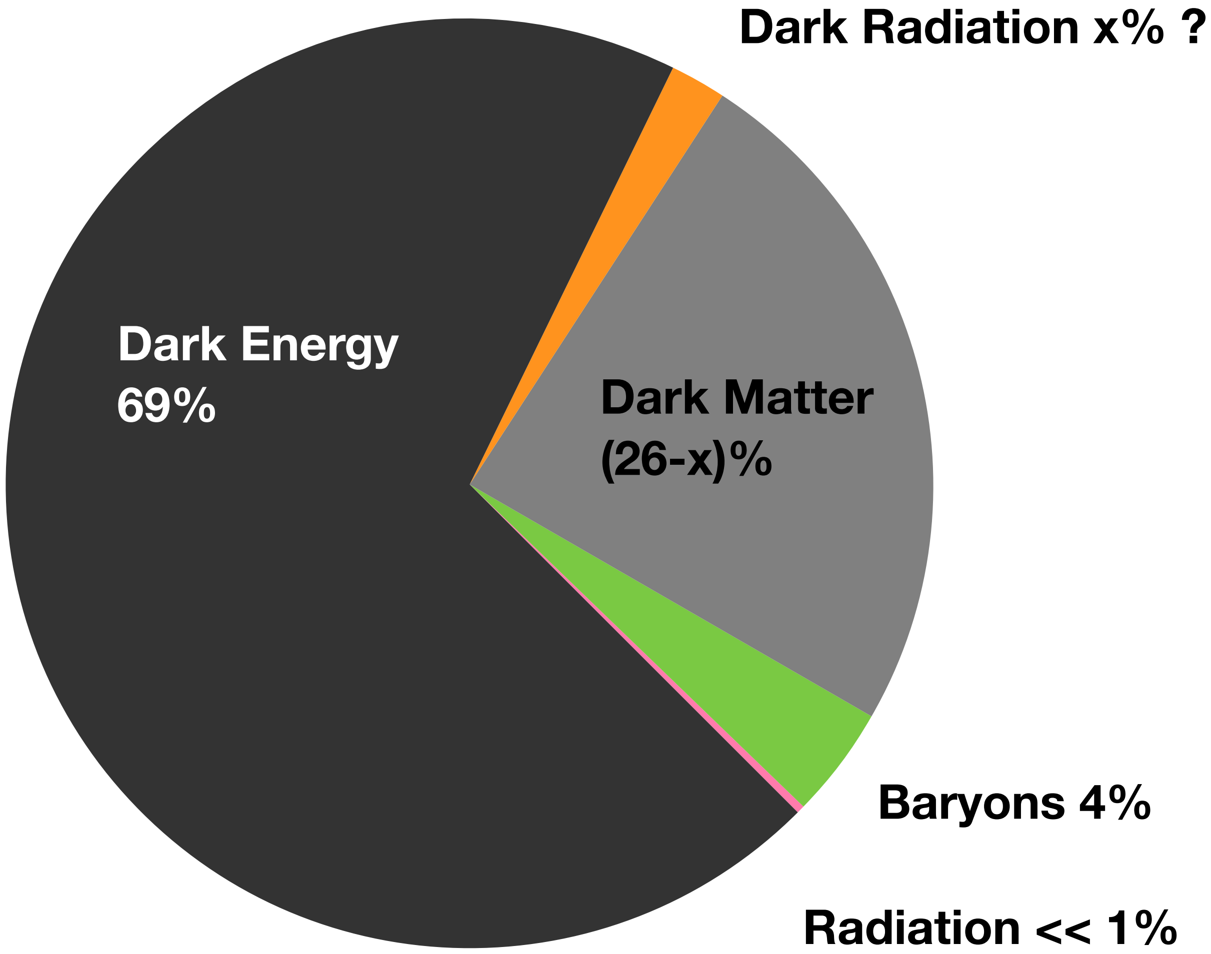
Cui, Pospelov, JP 2017

Late Dark Radiation



CMB-inferred

=>



Low redshift Universe

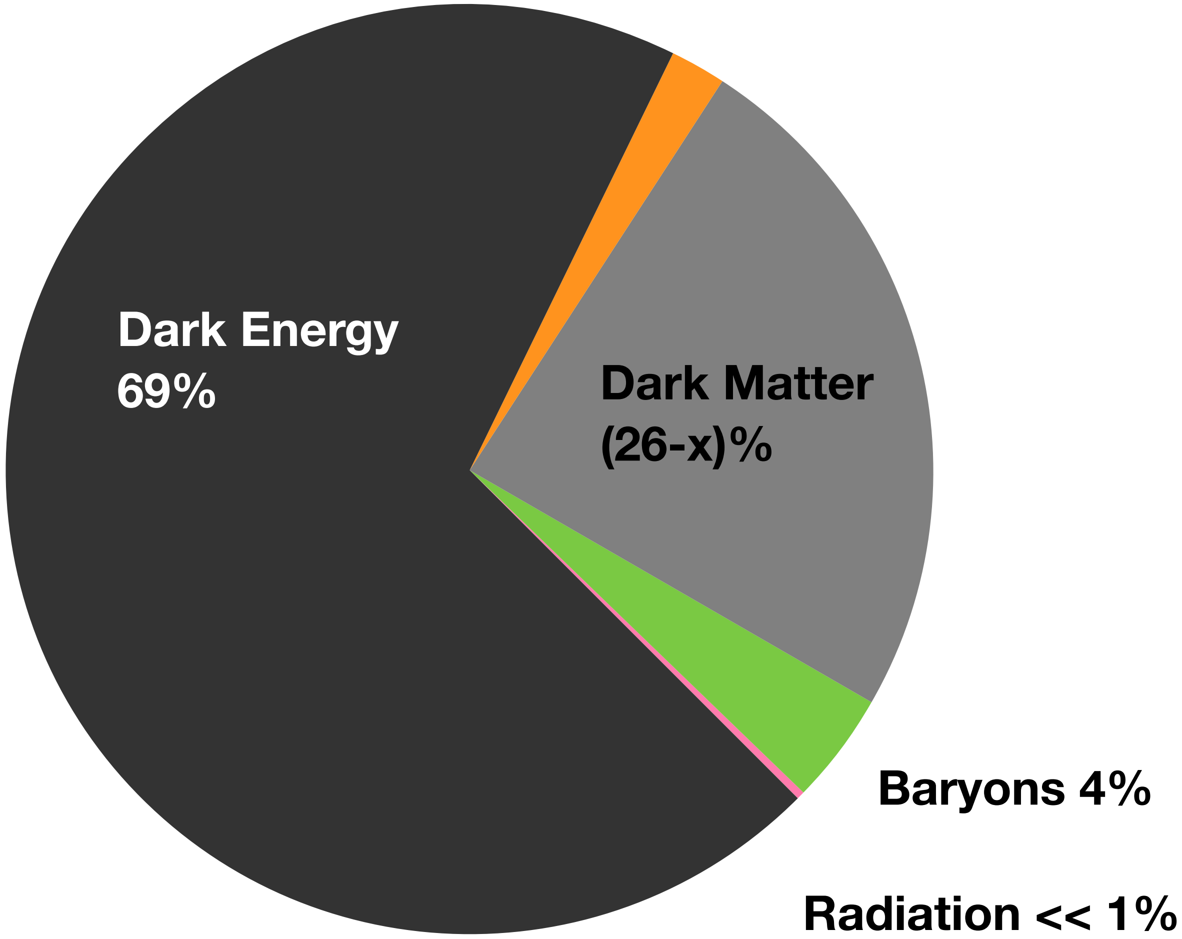
$\rho_{\mathrm{DR}}/\rho_\gamma < 0.15$ Planck

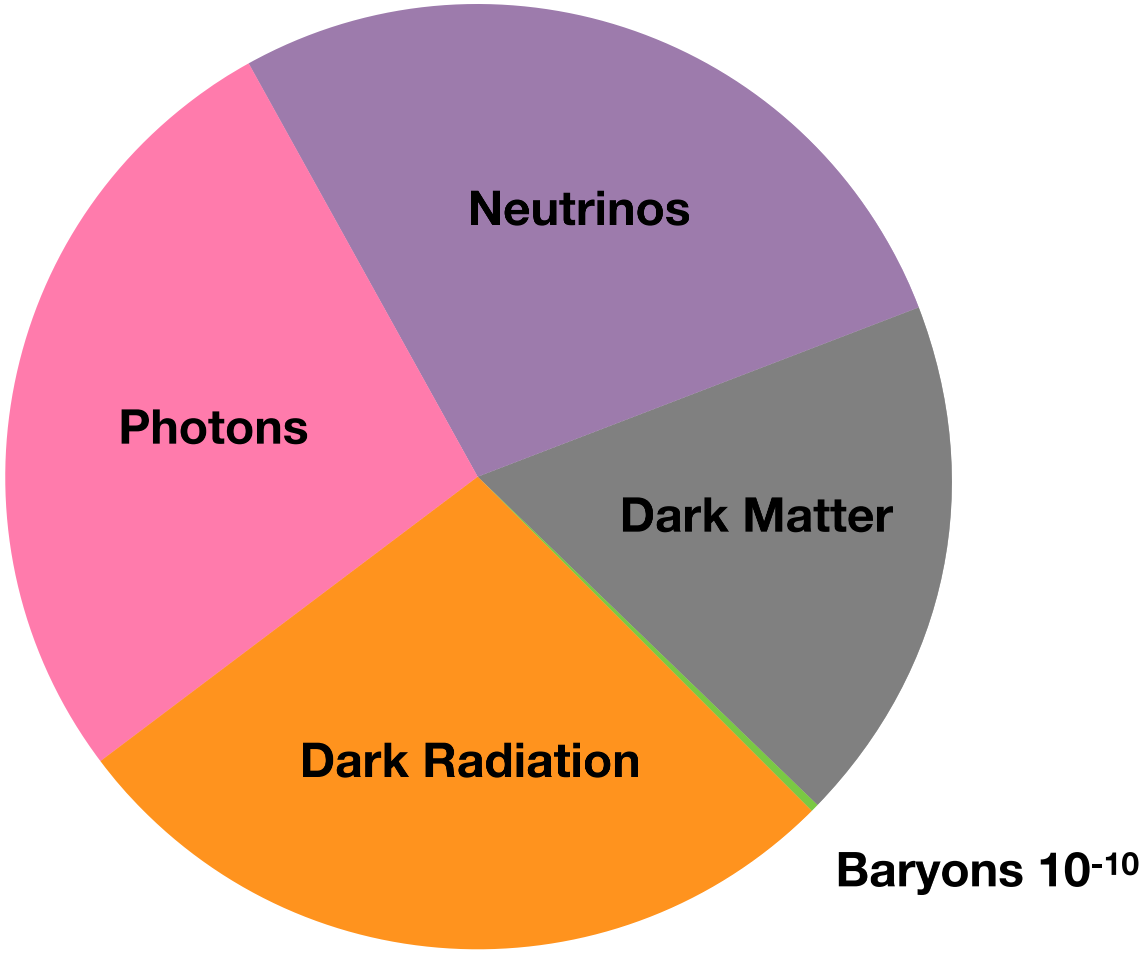
OPTION 2: $\omega_{\mathrm{DR}} \ll \omega_{\mathrm{CMB}}, \quad n_{\mathrm{DR}} > n_{\mathrm{CMB}},$

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

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?

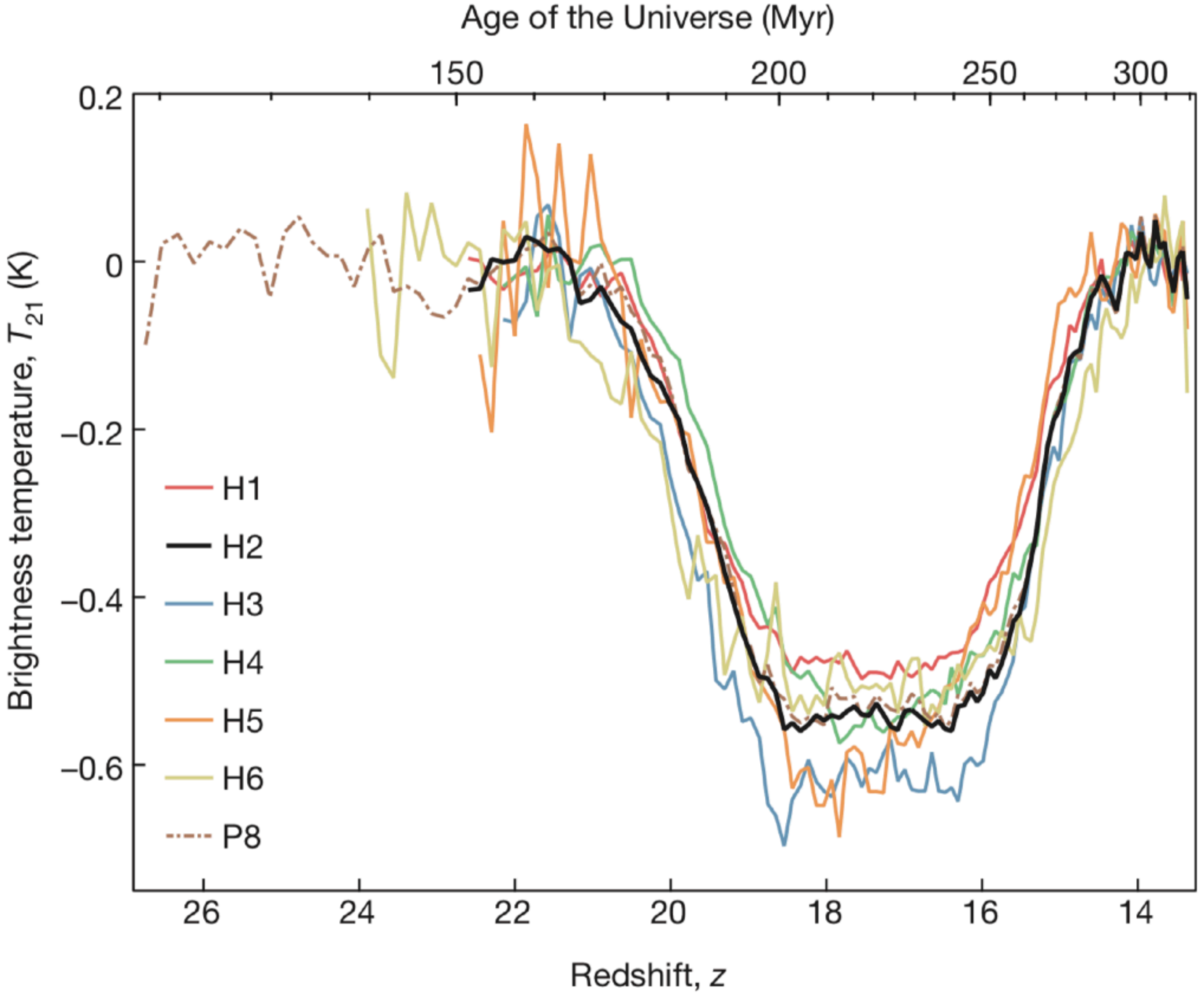
Light fields often have their interactions enhanced at high energies and suppressed at low energies, e.g.

- 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

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

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

Zaldarriaga, Furlanetto, Hernquist 2004

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

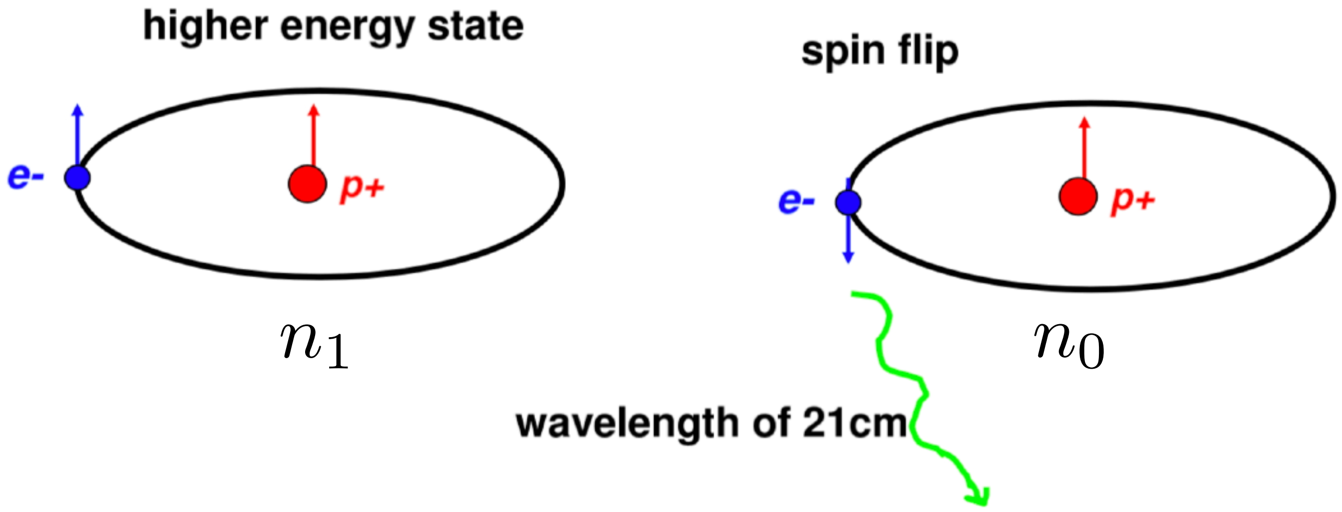
$$T_{21}(z \simeq 17) = -0.5K \quad (16 < z < 20)$$

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



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

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

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$_\alpha$ & X-ray photons become available!

see, e.g. Hirata 2005 and Venumadhav, Dai, Kaurov, Zaldarriaga 2018

Evolution of spin temperature

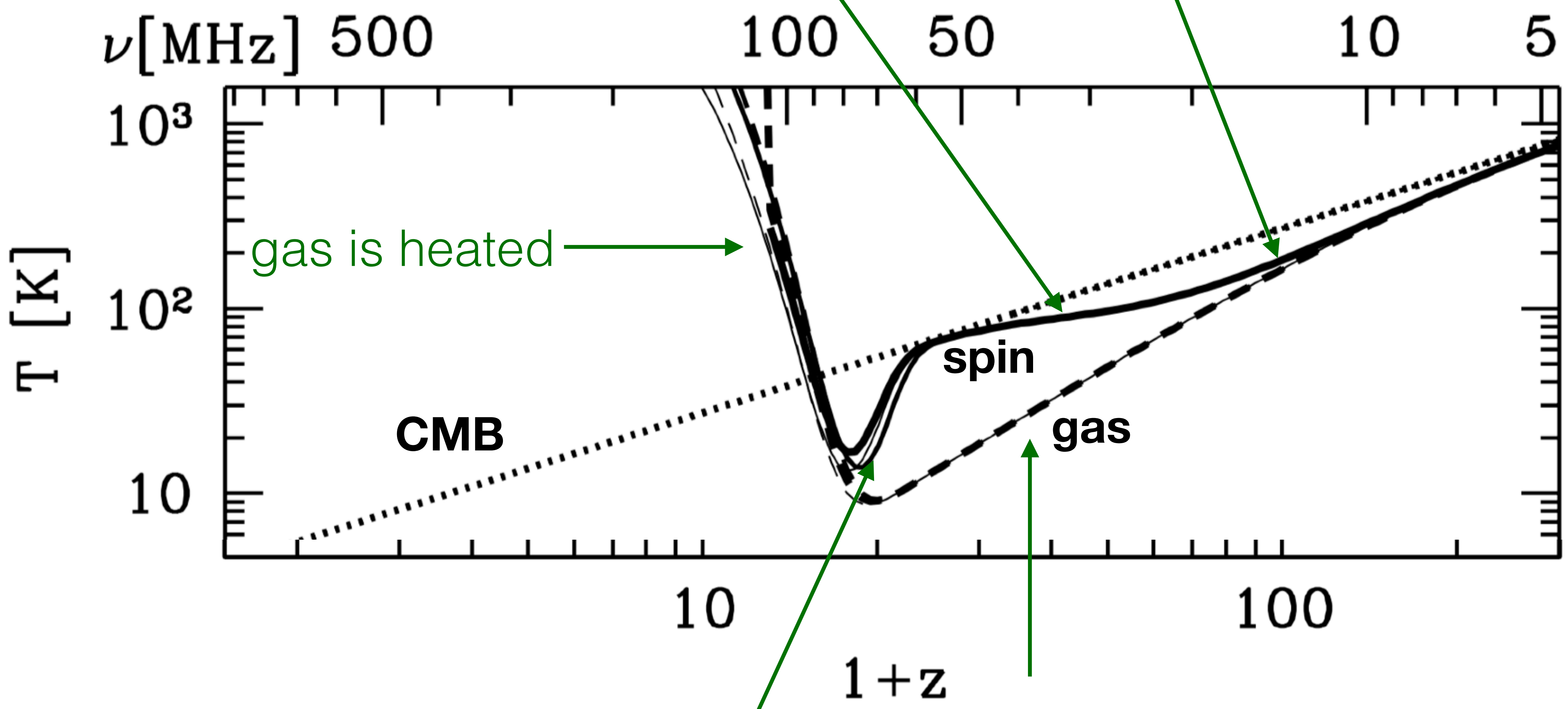
see, e.g., Loeb, Pritchard 2012

radiative coupling

collisions of gas

Compton on x_e

$T_{gas} = T_\gamma = T_s$



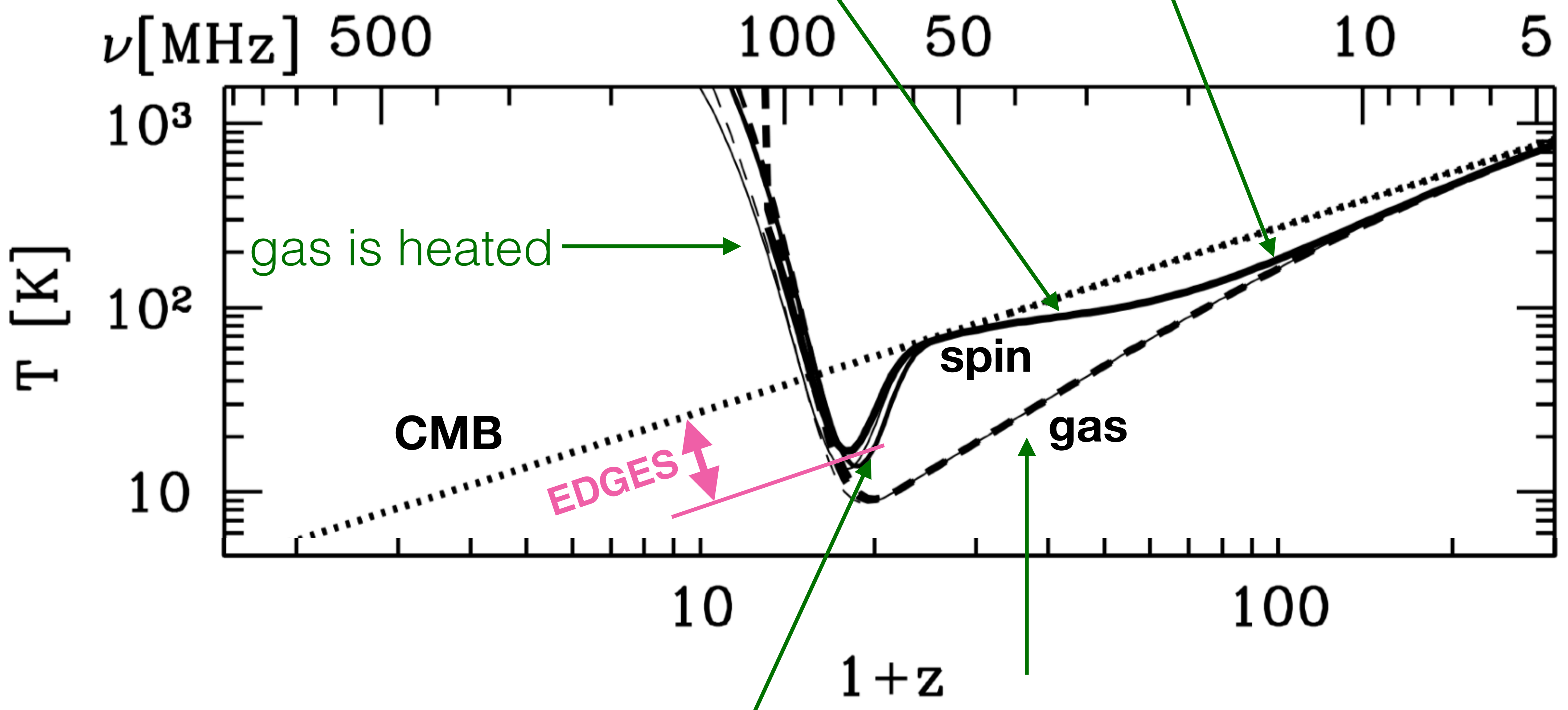
gas is heated

adiabatic cooling ~ $(1+z)^{-2}$

first sources inject Ly_α & X-ray photons => recouples spin to gas

Evolution of spin temperature

see, e.g., Loeb, Pritchard 2012



radiative coupling

collisions of gas

Compton on x_e
$T_{gas} = T_\gamma = T_s$

gas is heated

adiabatic cooling ~ $(1+z)^{-2}$

first sources inject Ly_α & X-ray photons => recouples spin to gas

How to change T$_{21}$?

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

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

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

=> raises “effective T$_{\rm CMB}$“ 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

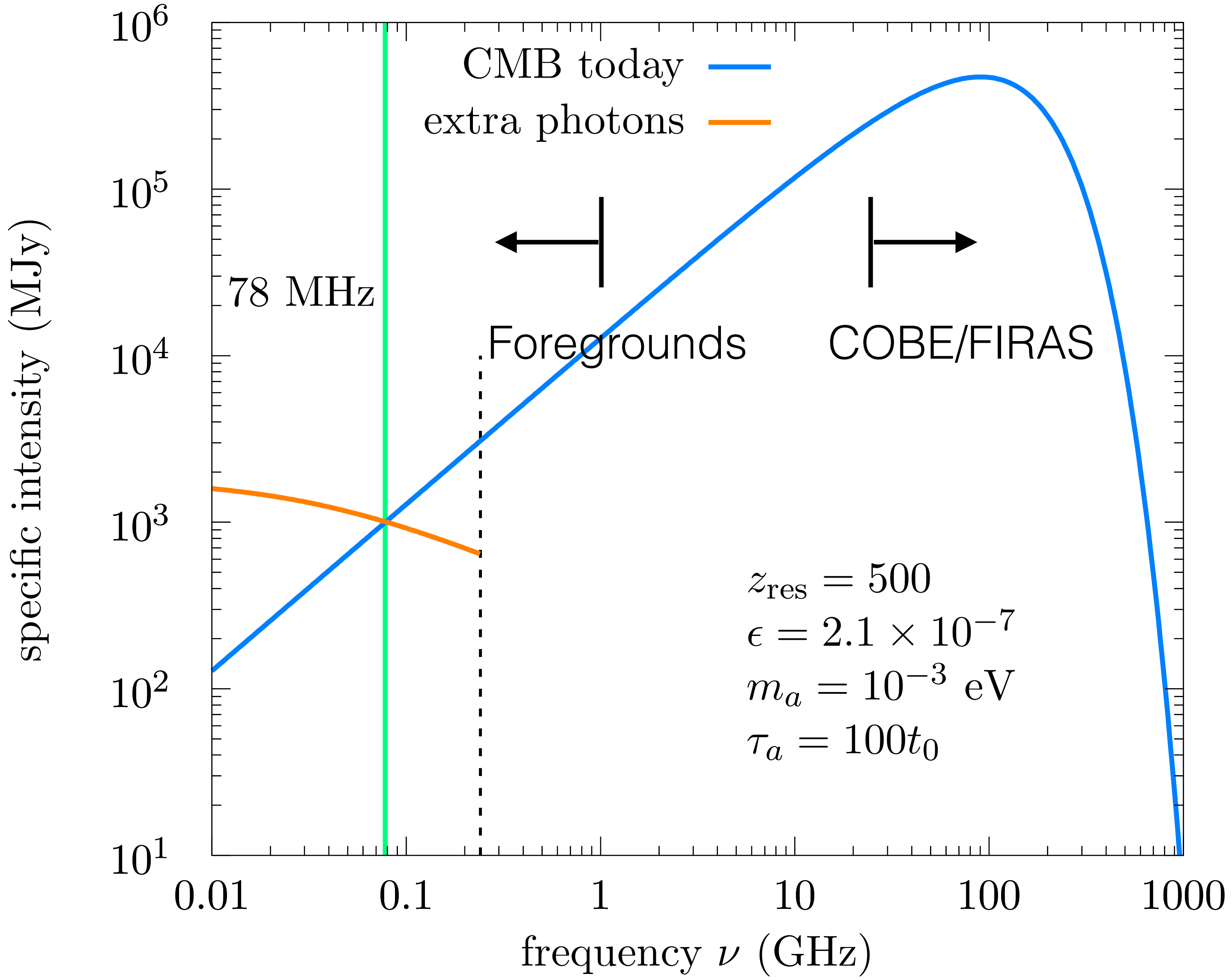
=> needs a careful modification of the CMB, that is only operative in the IR (disfavors direct DM decay into photons)

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

How to change T_{21}?

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

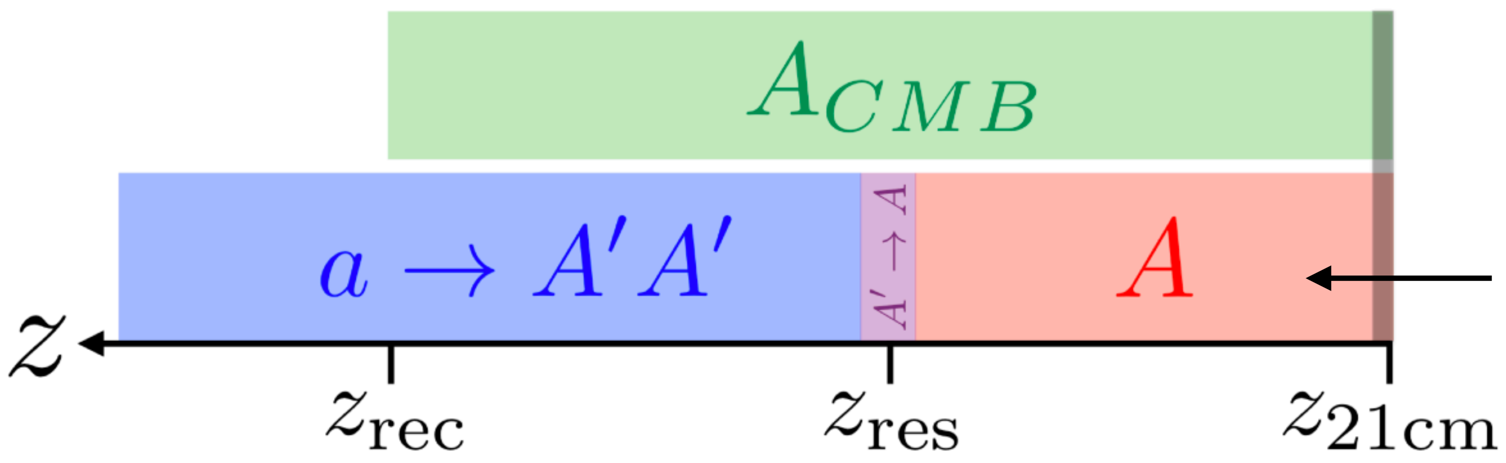
Add photons into the 21cm wavelength band at z~17



Modification of the RJ tail of the CMB

Main idea:

CMB released



extra photons

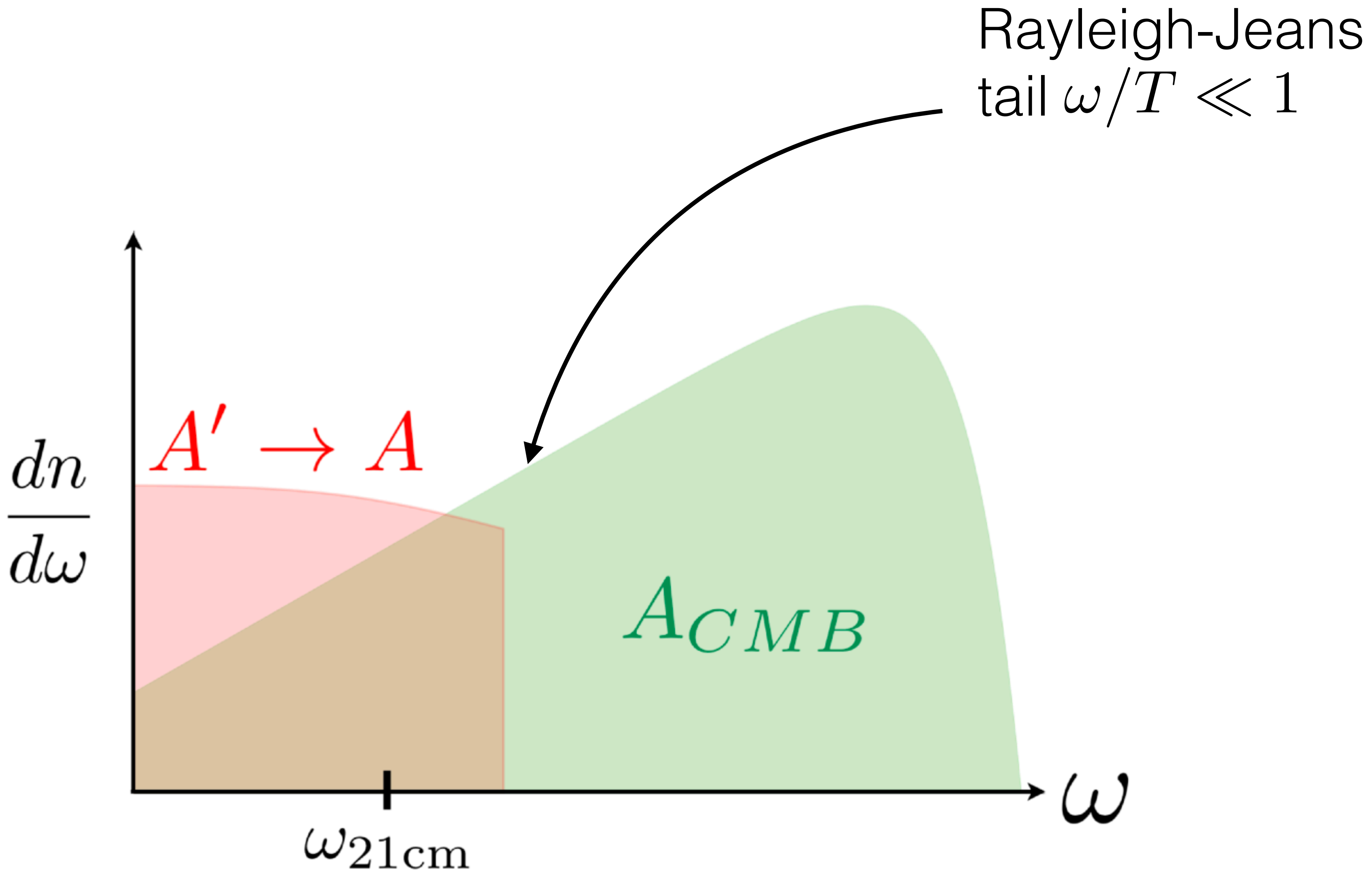
A’ continuously
sourced by decay of a

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:

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

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

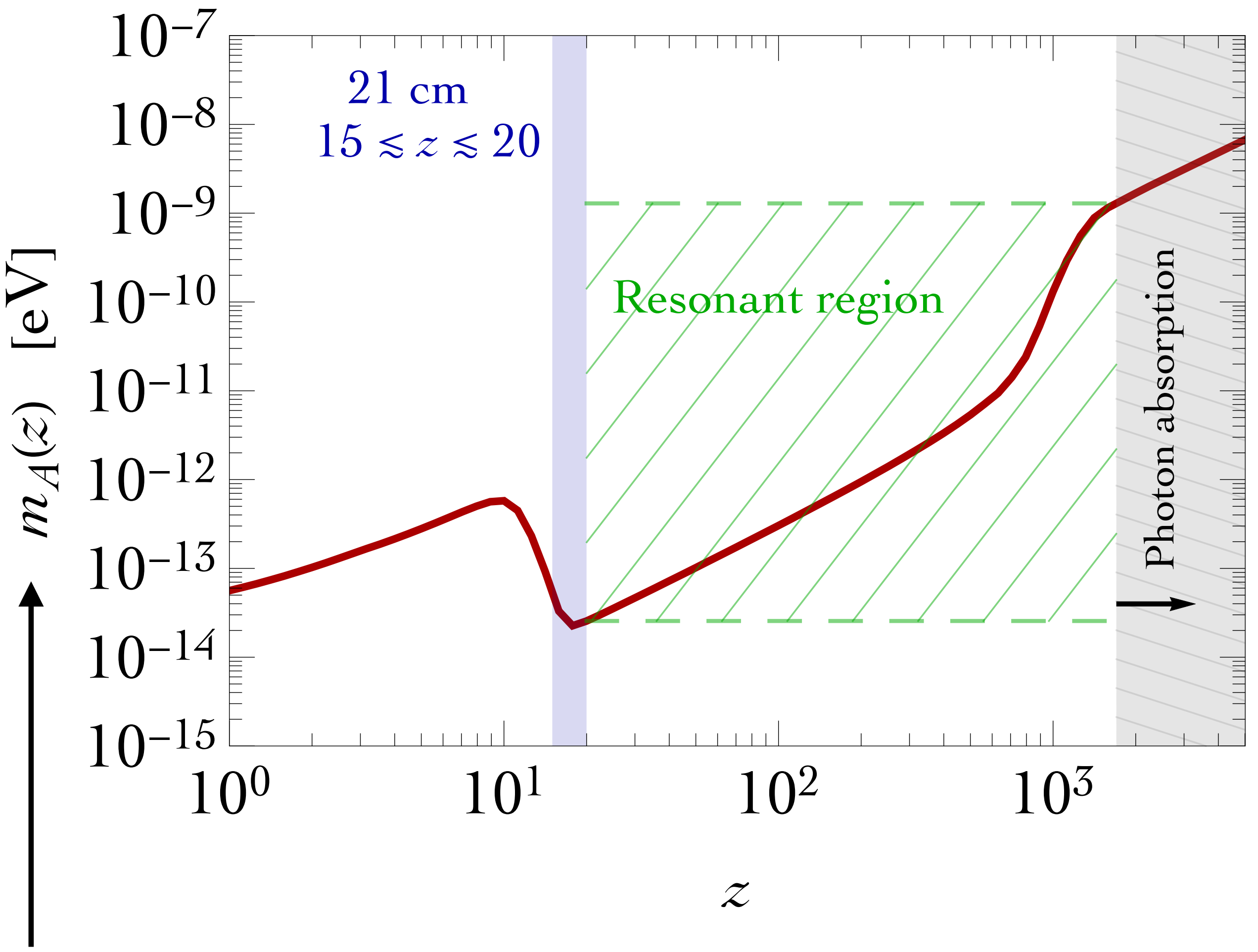
Lifetime can be anything from much shorter to much longer than the age of the Universe

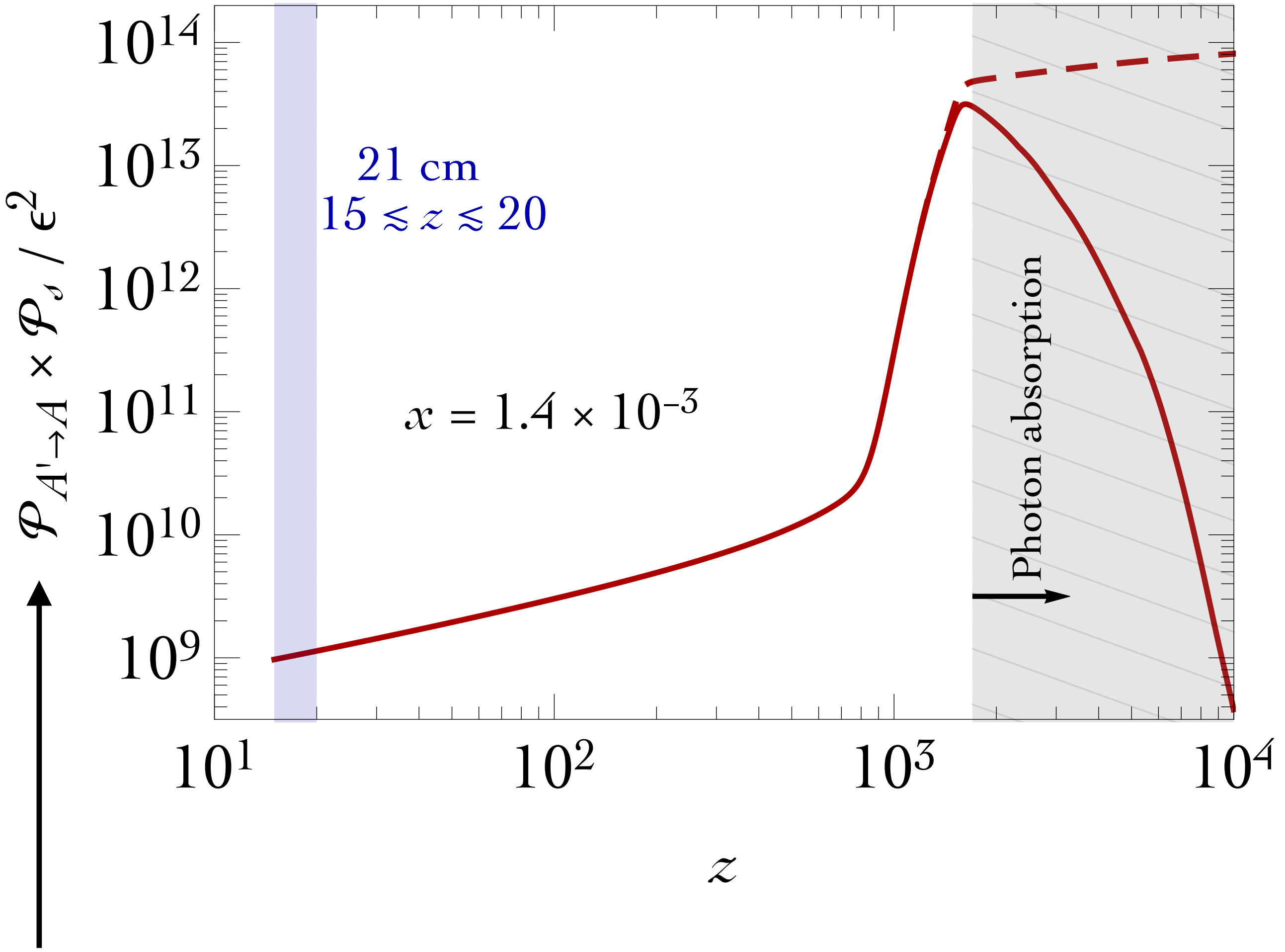
$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times 10^{-4}}{\tau_{\mathrm{U}}}\left(\frac{m_a}{10^{-4}\,\mathrm{eV}}\right)^3\left(\frac{100\,\mathrm{GeV}}{f_a}\right)^2$$

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.

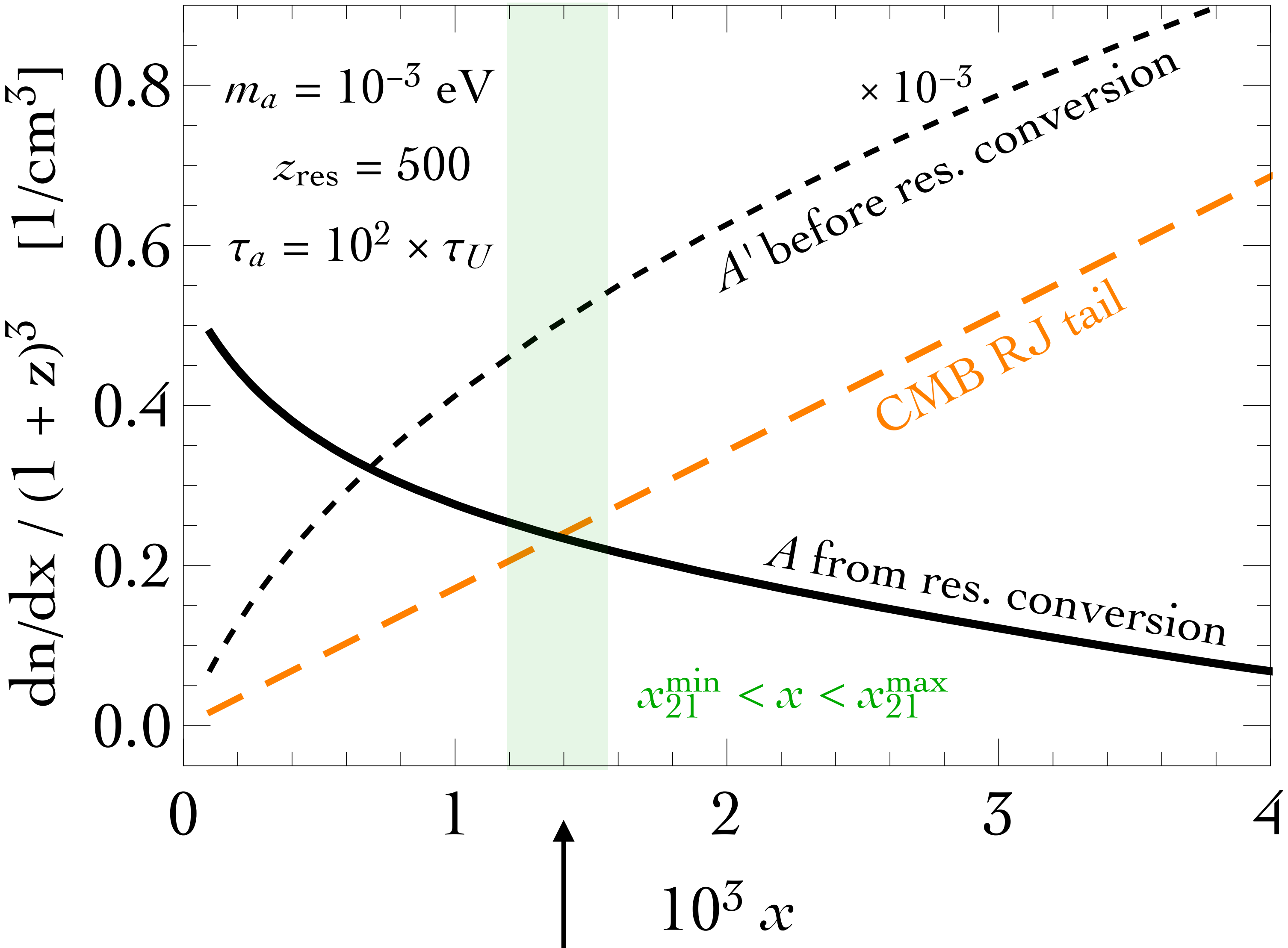
$$m_A(z) \simeq 1.7 \times 10^{-14}\mathrm{eV} \times (1+z)^{3/2} X_e^{1/2}(z)$$

transition probability

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

see also [Mirizzi, Redondo, Sigl 2009]

Spectra at 21cm wavelength



$dn_{\rm A'}/d\omega$

$dn_{\rm CMB}/d\omega \simeq T_{\rm CMB}\omega/\pi^2$

$x = \omega/T$

$dn_{\rm A}/d\omega$

21 cm

(redshift scaled out)

DM lifetime vs. photon count

Example:

Fixing progenitor mass

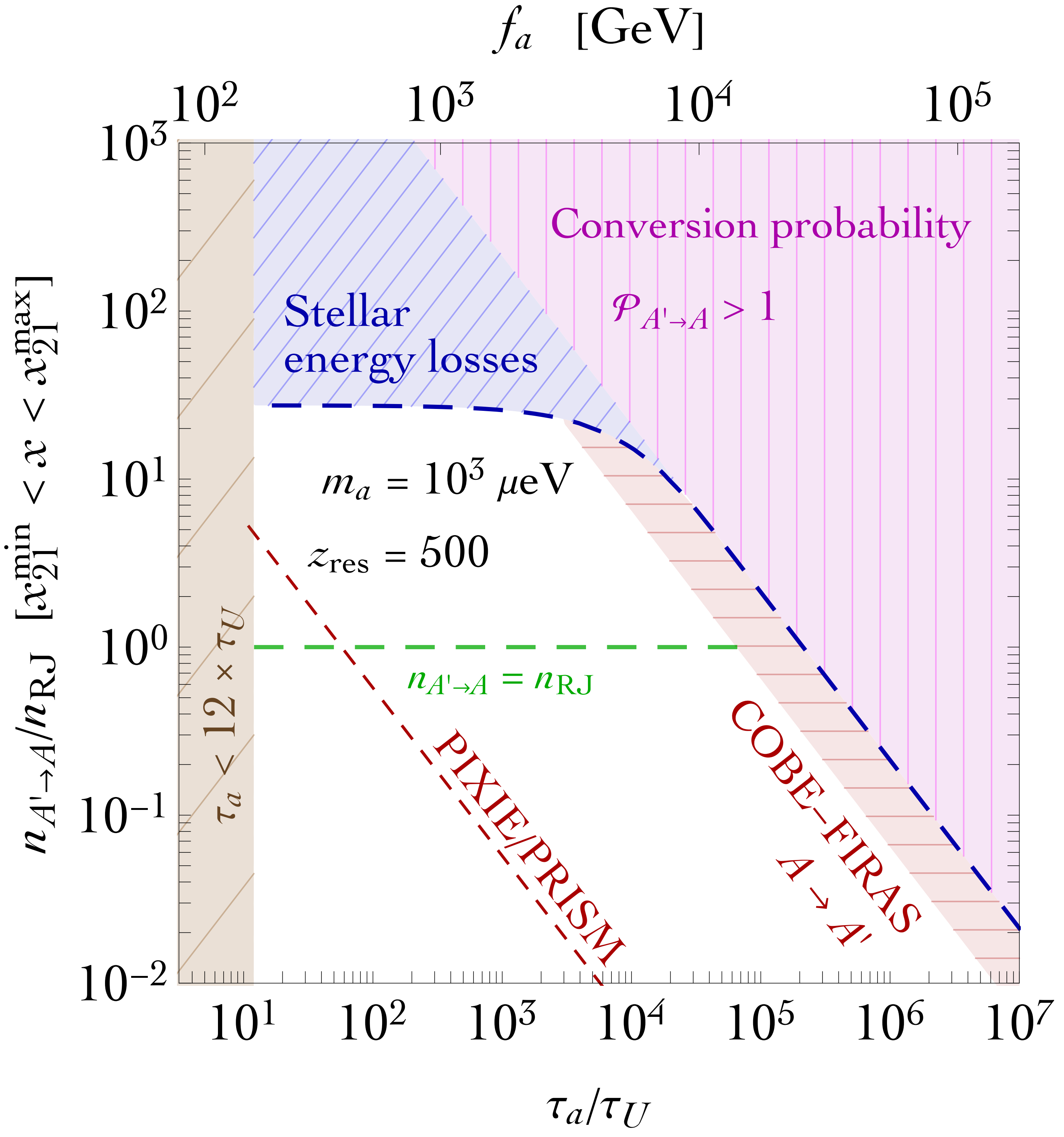
$m_a = 10^{-3}\,\mathrm{eV}$

and DP mass such that

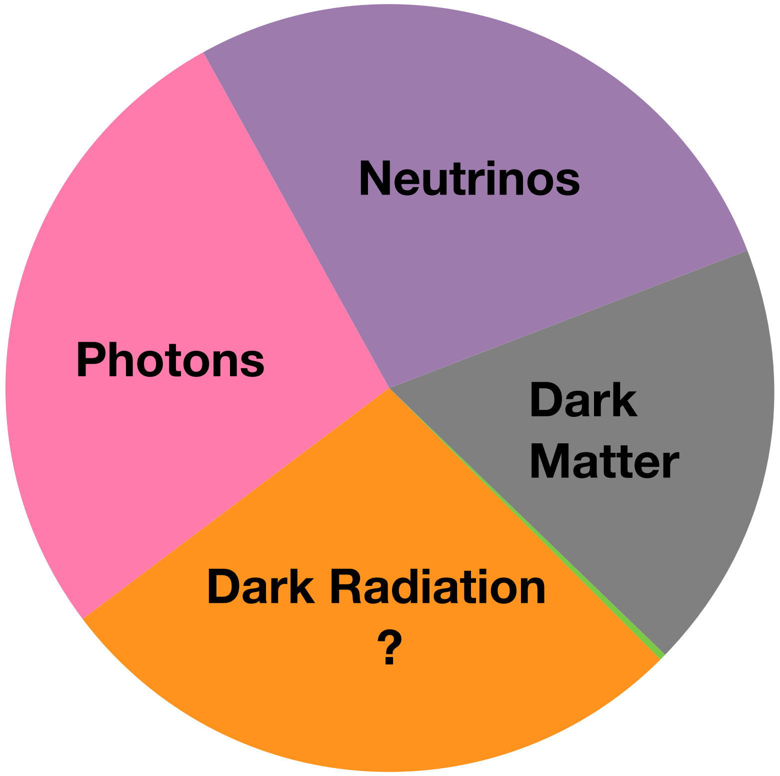
$z_{\mathrm{res}} = 500$

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

green line: count doubled
=> EDGES amplitude explained



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.

- DR in form of SM neutrinos with energies in the 30 MeV ballpark is constrained from superK and detectable in direct detection experiments; raises the neutrino floor

- 21 cm cosmology offers a new probe into the physics of very soft quanta; we identified a class of models = dark photon sourcing particles, that supply an extra population of cosmological photons through resonant conversion. Explanation of EDGES is possible.

Additional Material

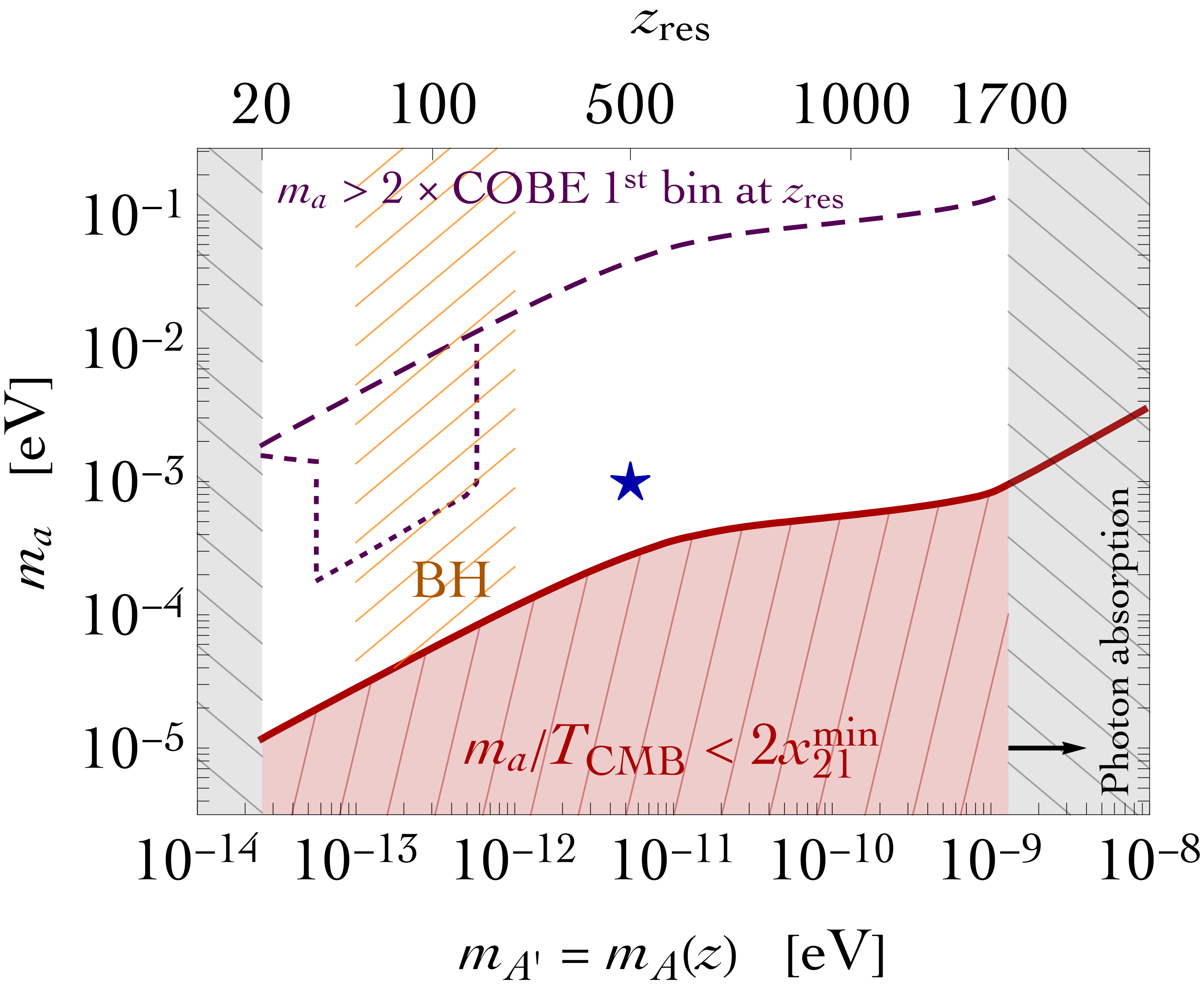
Constraint on spectral CMB distortion

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

biases conversion towards the IR

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

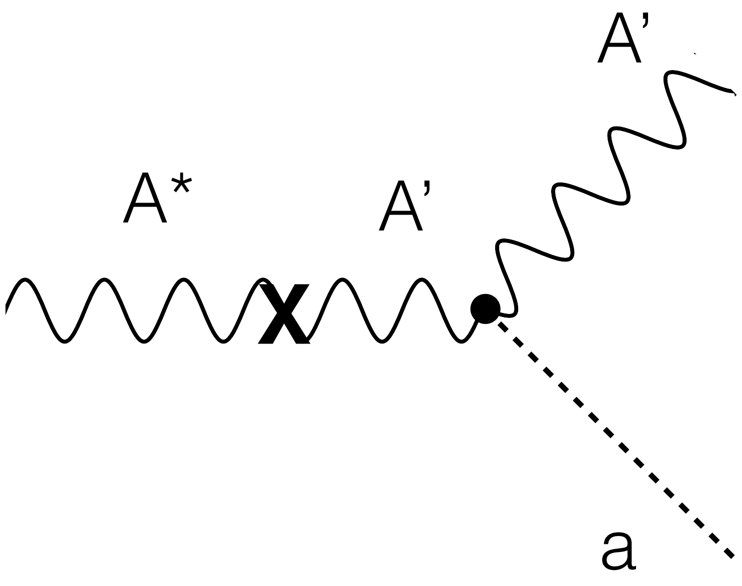
NB: axion-photon conversion $\propto \omega$



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.

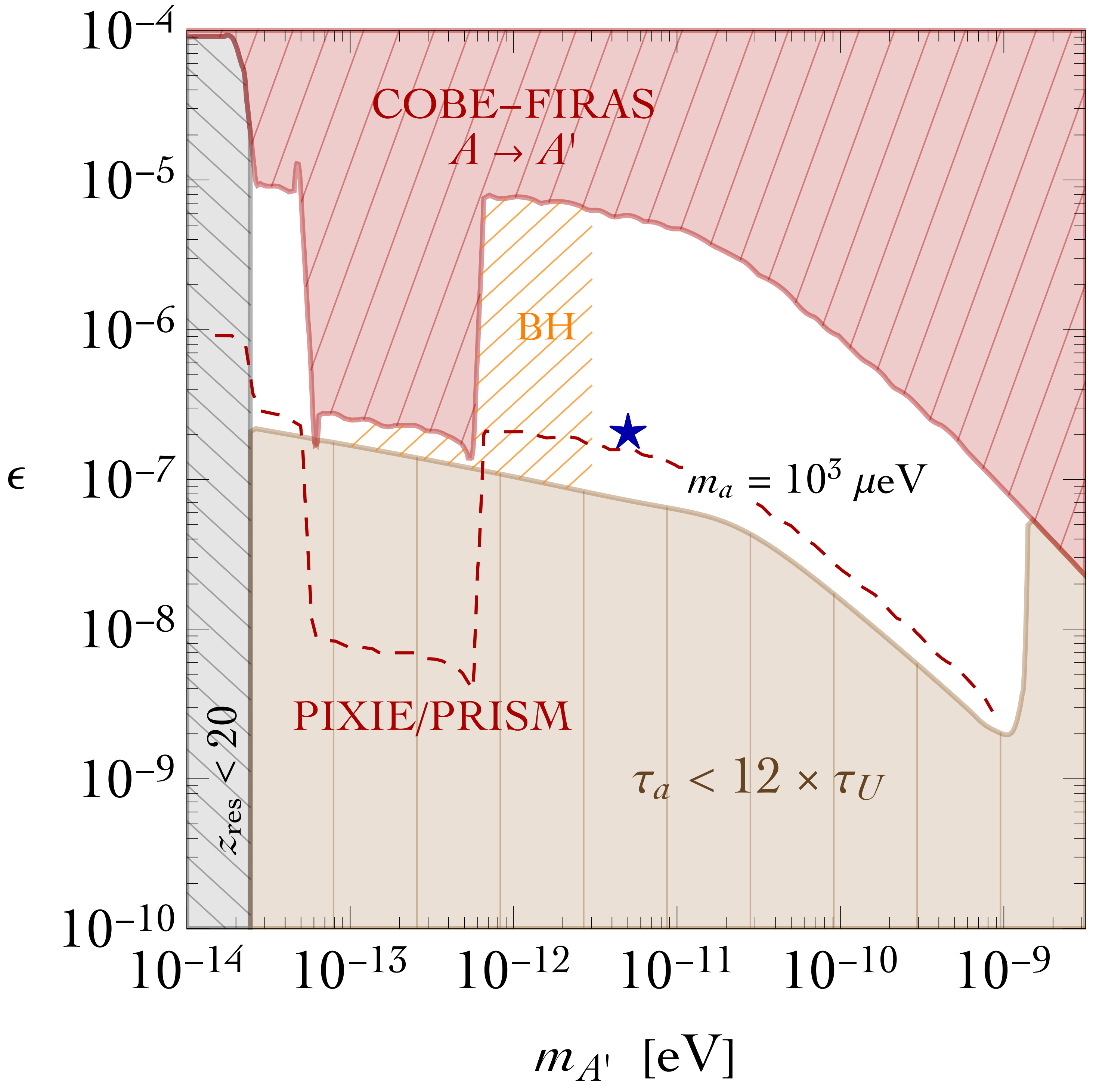
$$\epsilon/f_a < 2 \times 10^{-9}\,\mathrm{GeV}^{-1}$$

Kinetic Mixing vs. DP mass

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

=> yields parameter space in DP mass vs. epsilon

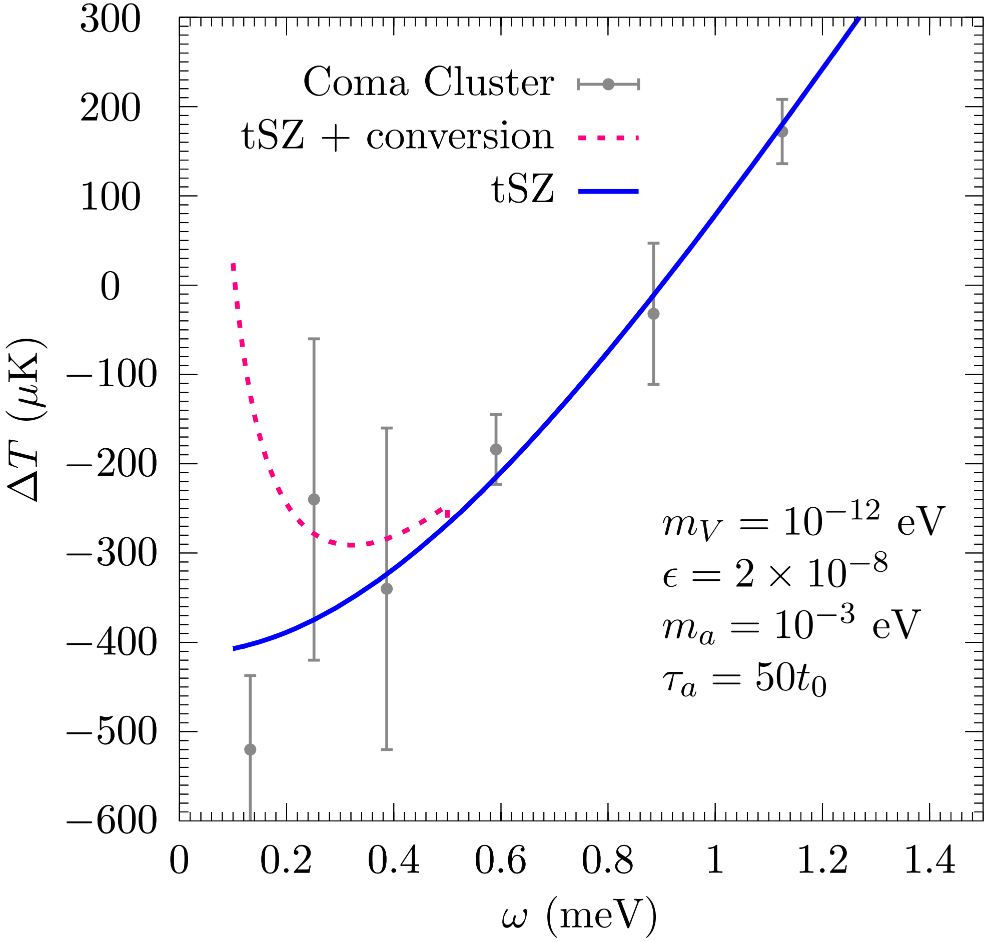
=> much allowed.



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]