The photon as new physics messenger

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The photon as new physics messenger

In cosmology, most information has been brought to us through photons; especially true what regards the properties of the dark sector

=> in this talk, we consider new physics where photons directly point back to dark sector physics

1. Cosmological 21cm photons as probe of new very light physics

   M. Pospelov, J. Ruderman, A. Urbano, PRL 2018, arXiv:1803.07048

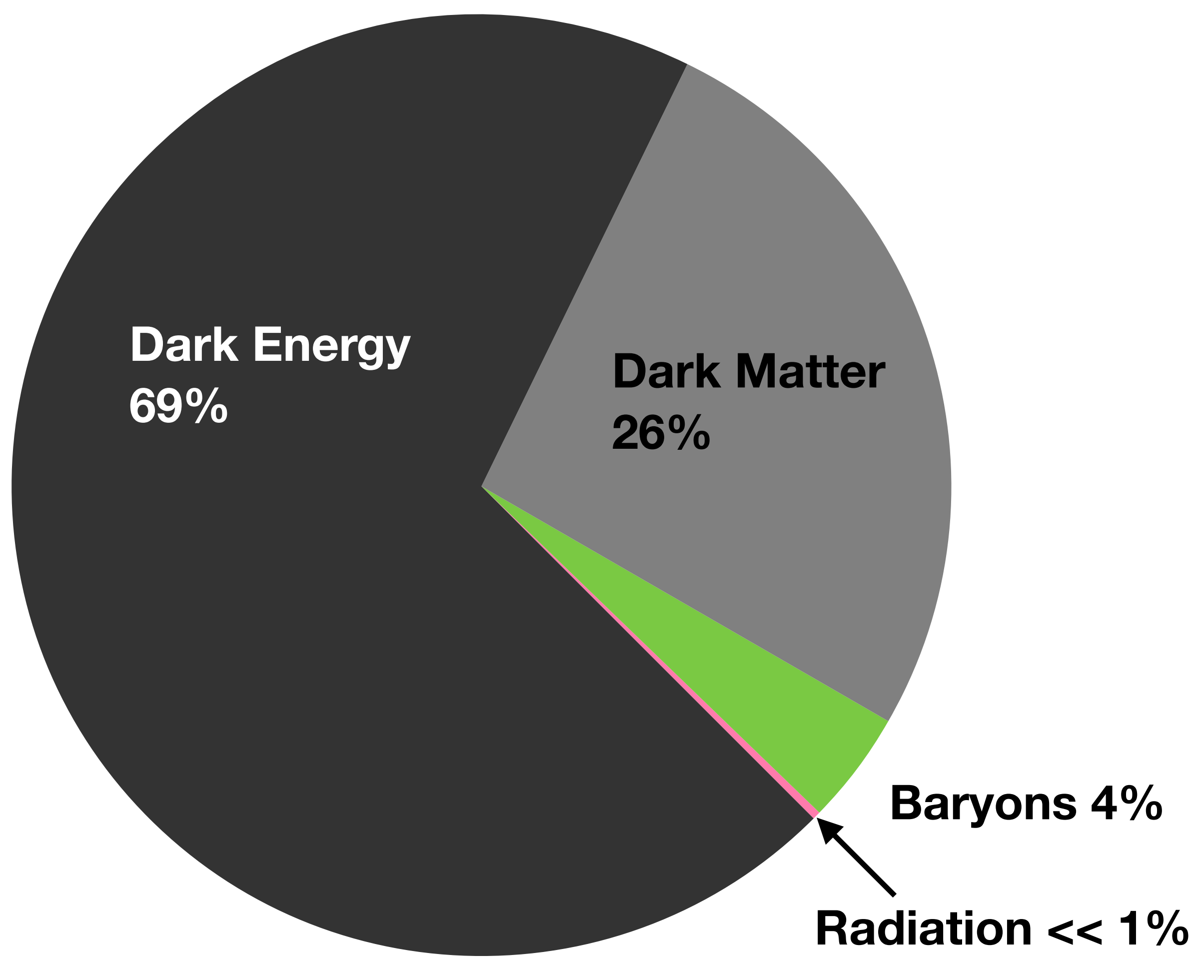
2. "Photon-portal" to new physics - direct dark state photon couplings

   X. Chu, JP, L. Semmelrock, PRD 2019 arXiv:1811.04095
   X. Chu, J.-L. Kuo, JP, L. Semmelrock, in preparation

New Physics under the lamppost?

The cosmic piechart

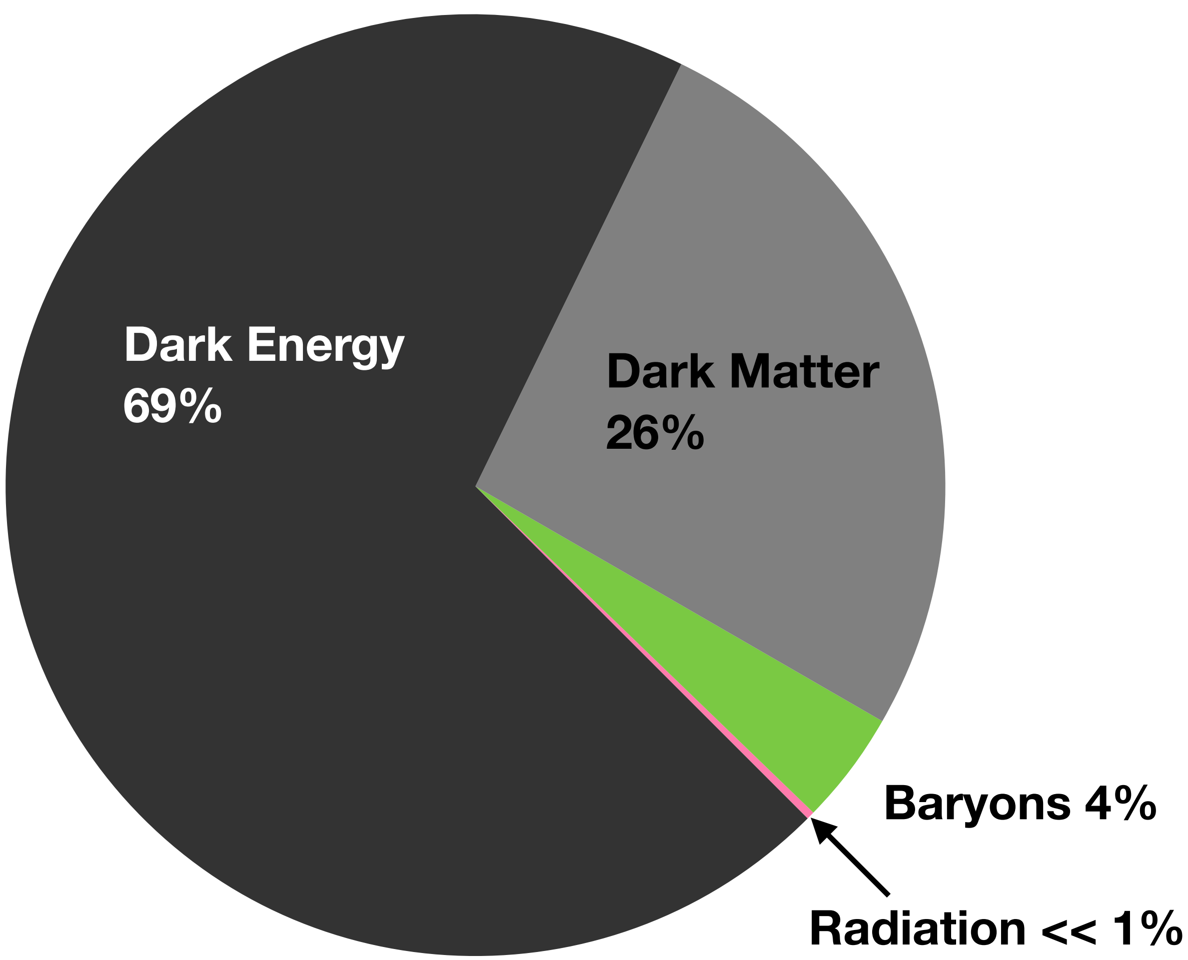
Energy budget



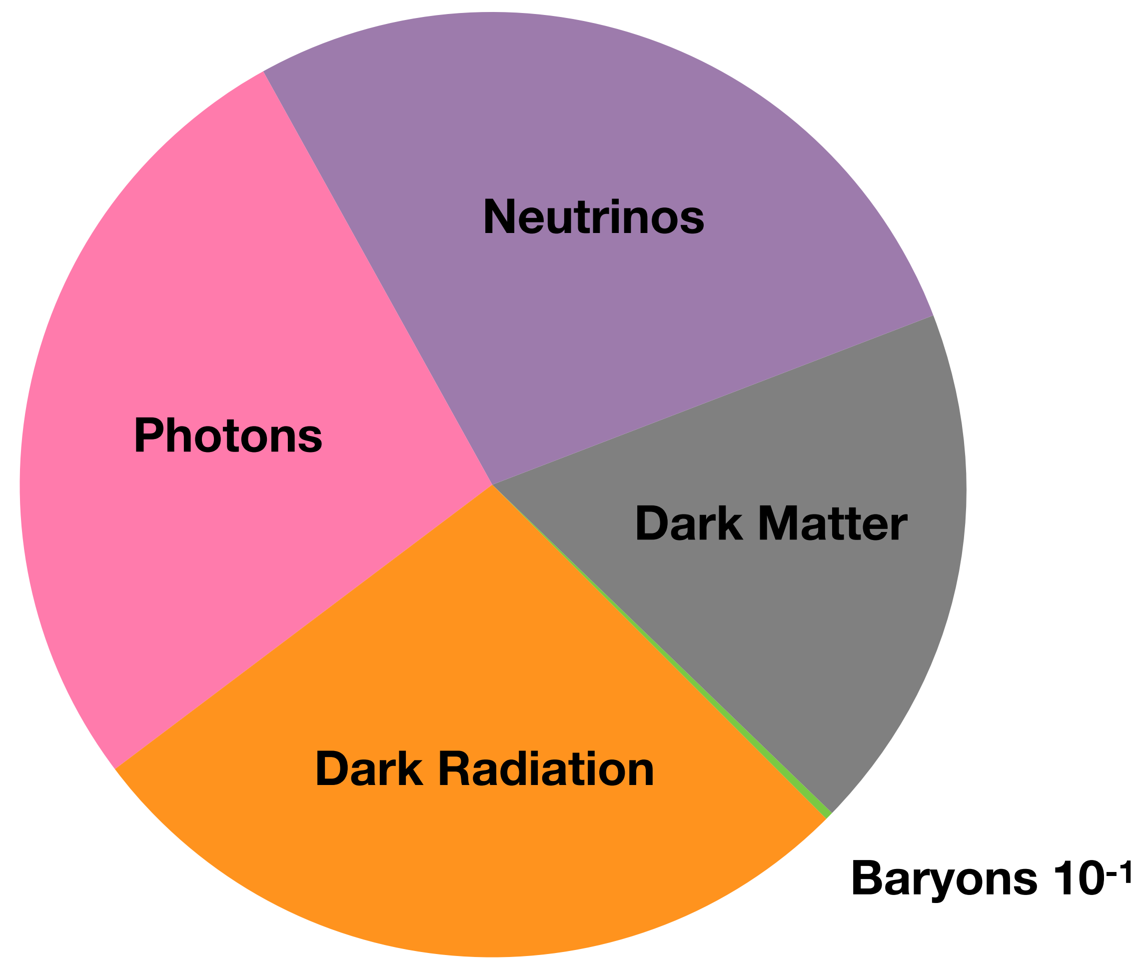
CMB-inferred

The cosmic piechart

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

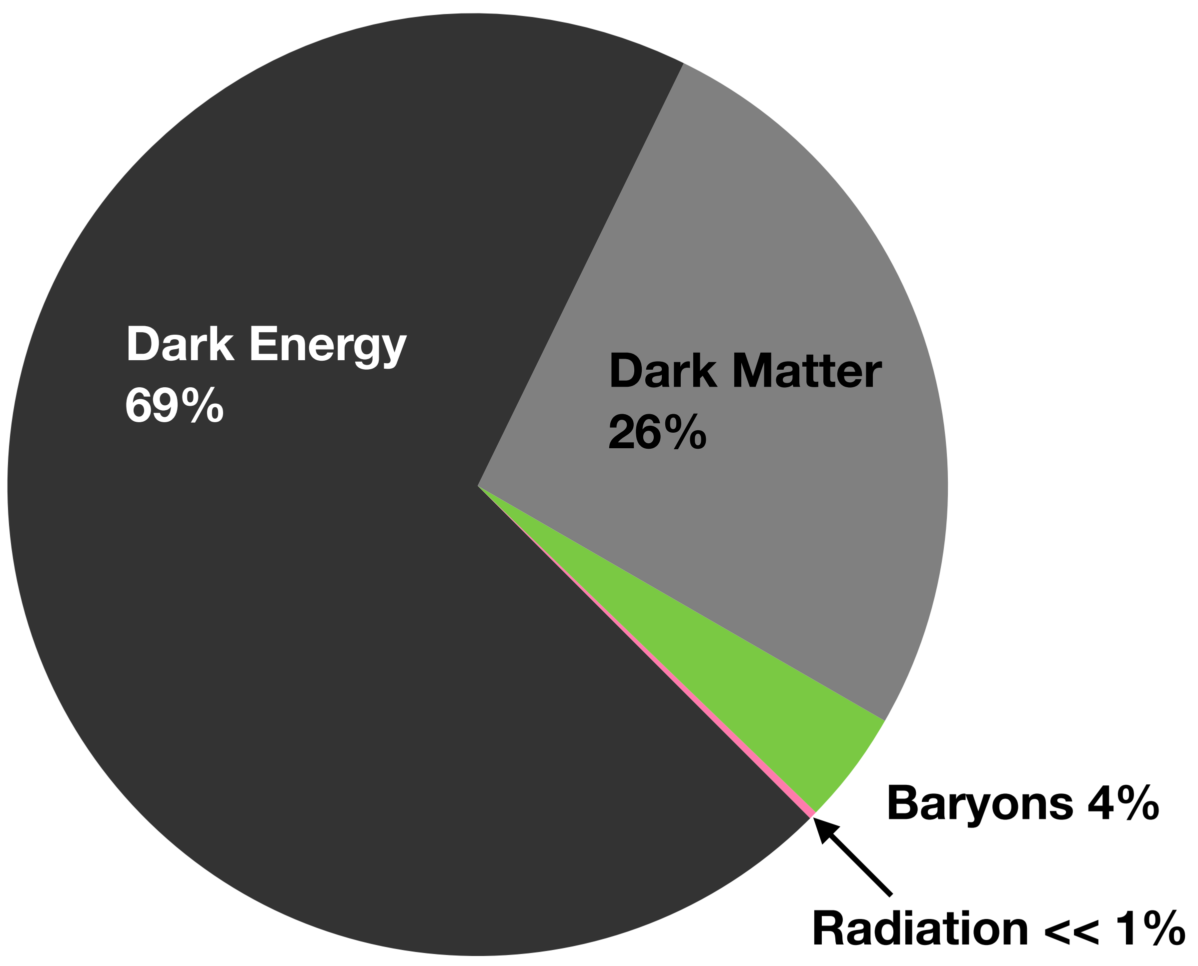


CMB-inferred



Dark Radiation can be dominant

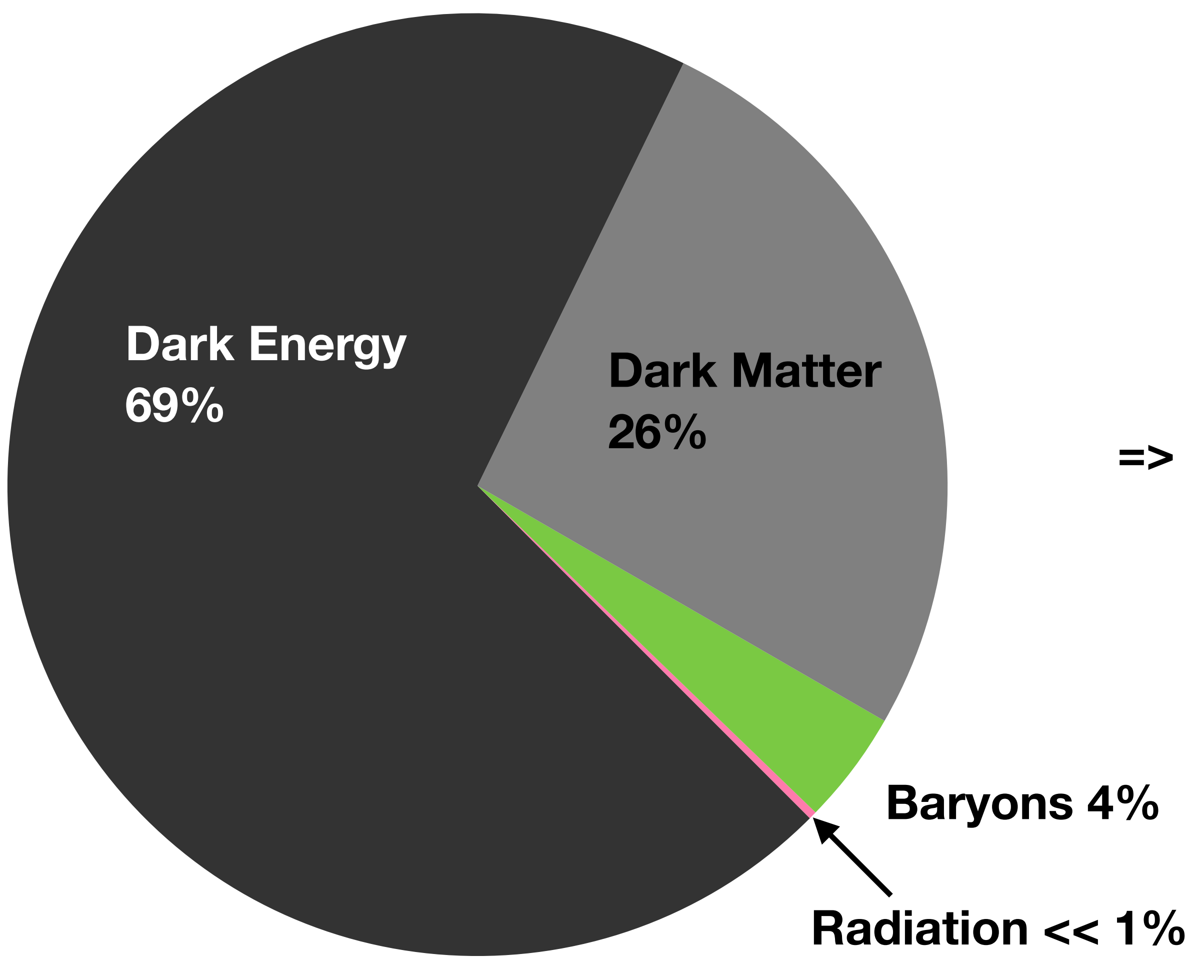
The cosmic piechart



CMB-inferred

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

The cosmic piechart



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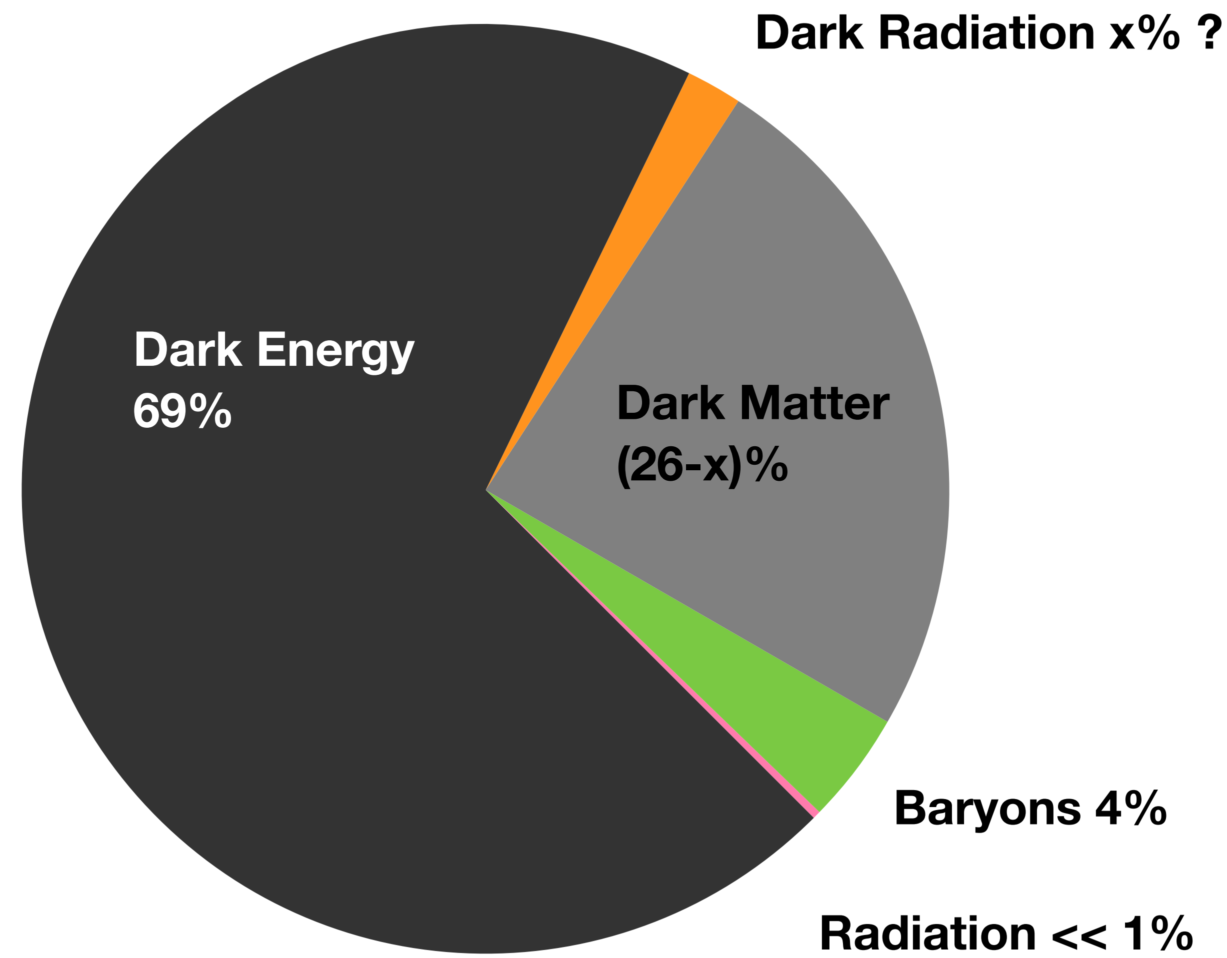
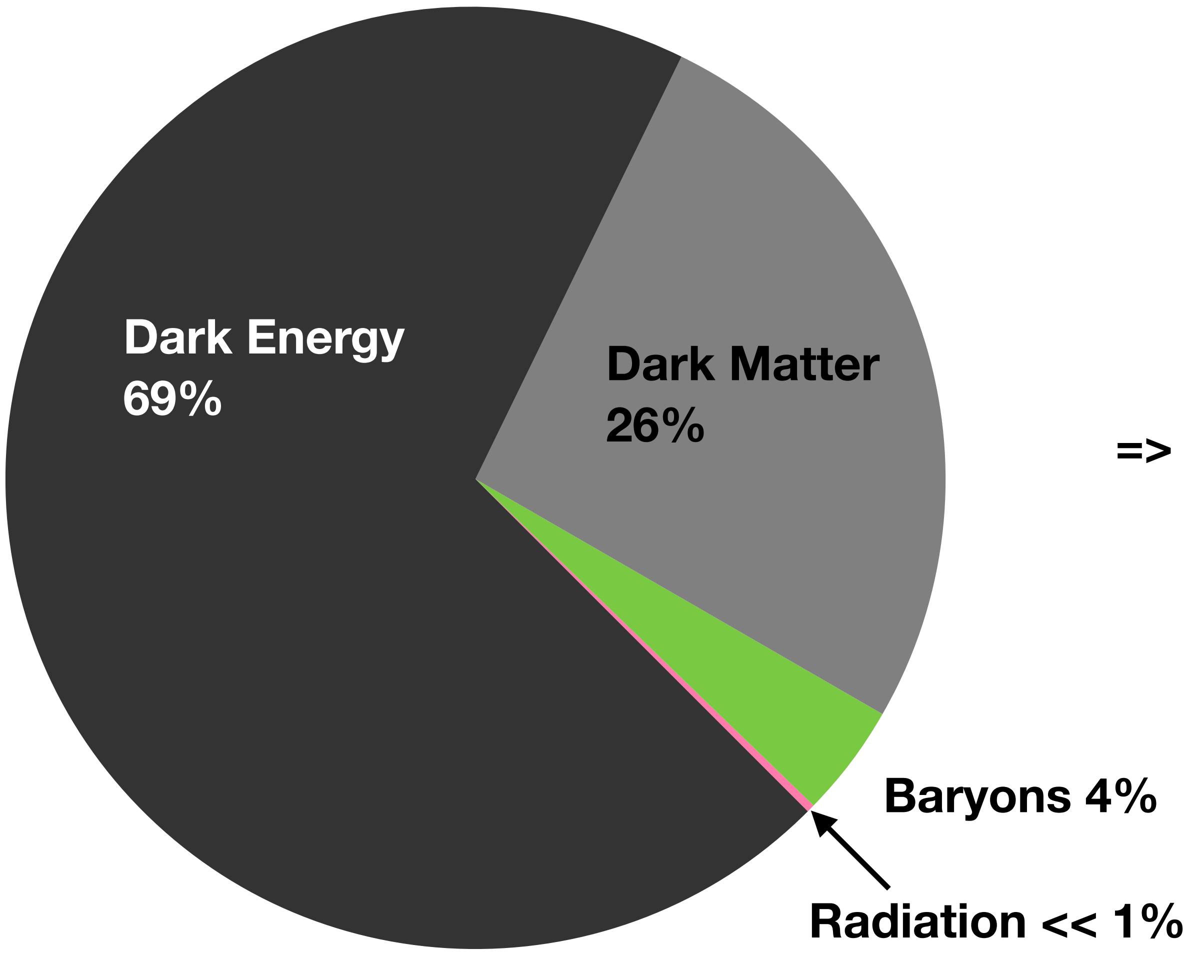


CMB-inferred

Low redshift Universe

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

The cosmic piechart



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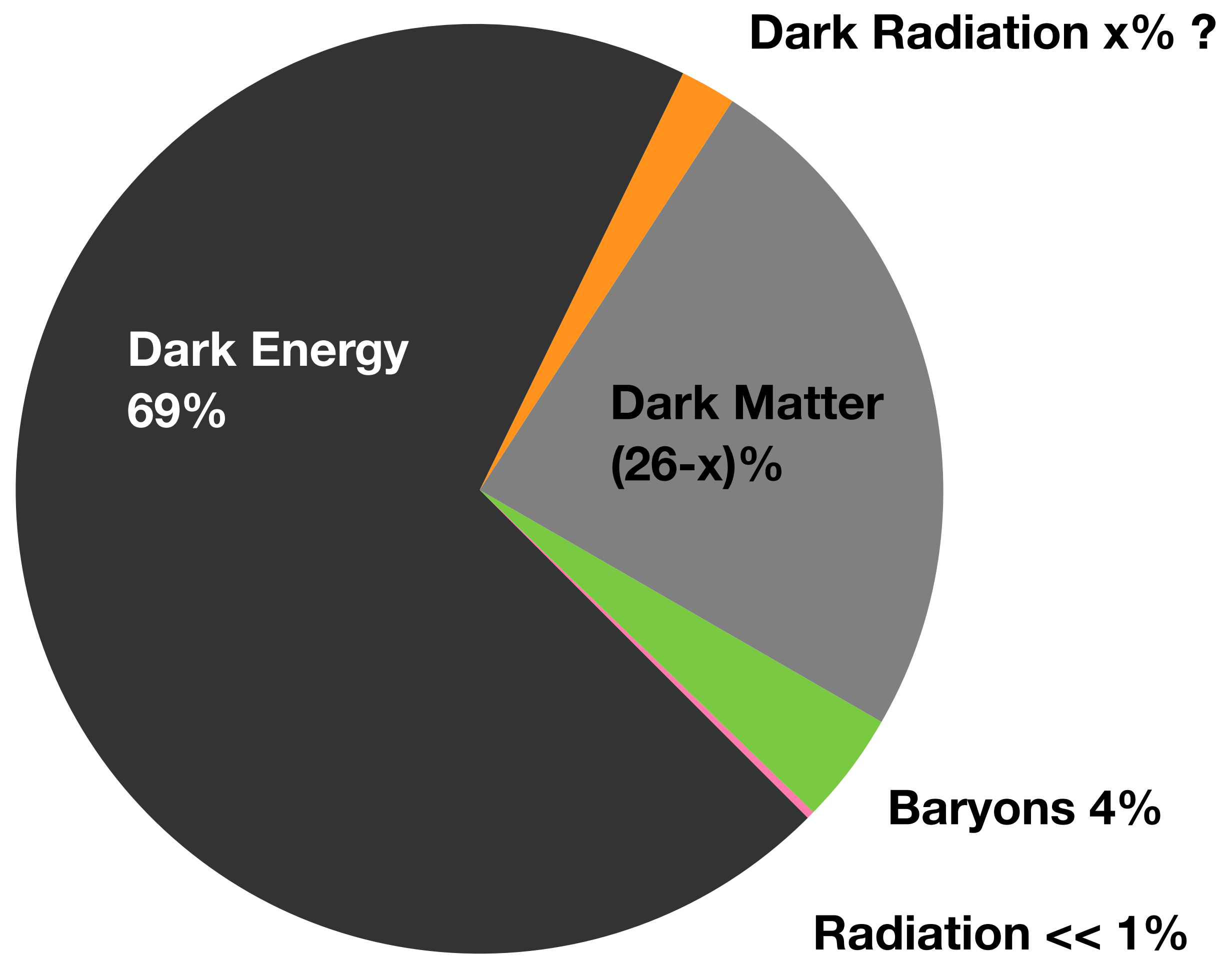


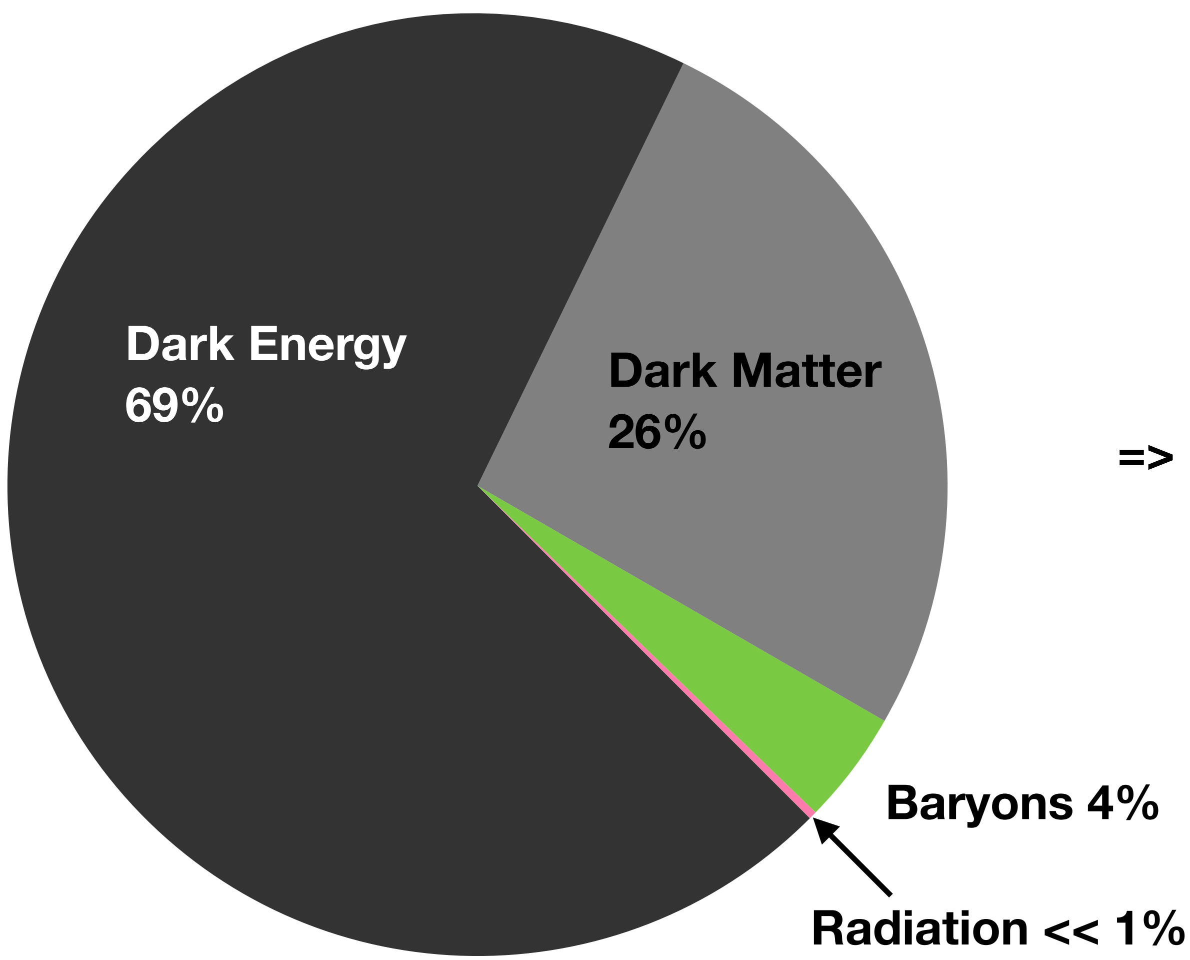
CMB-inferred

Low redshift Universe

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

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

The cosmic piechart



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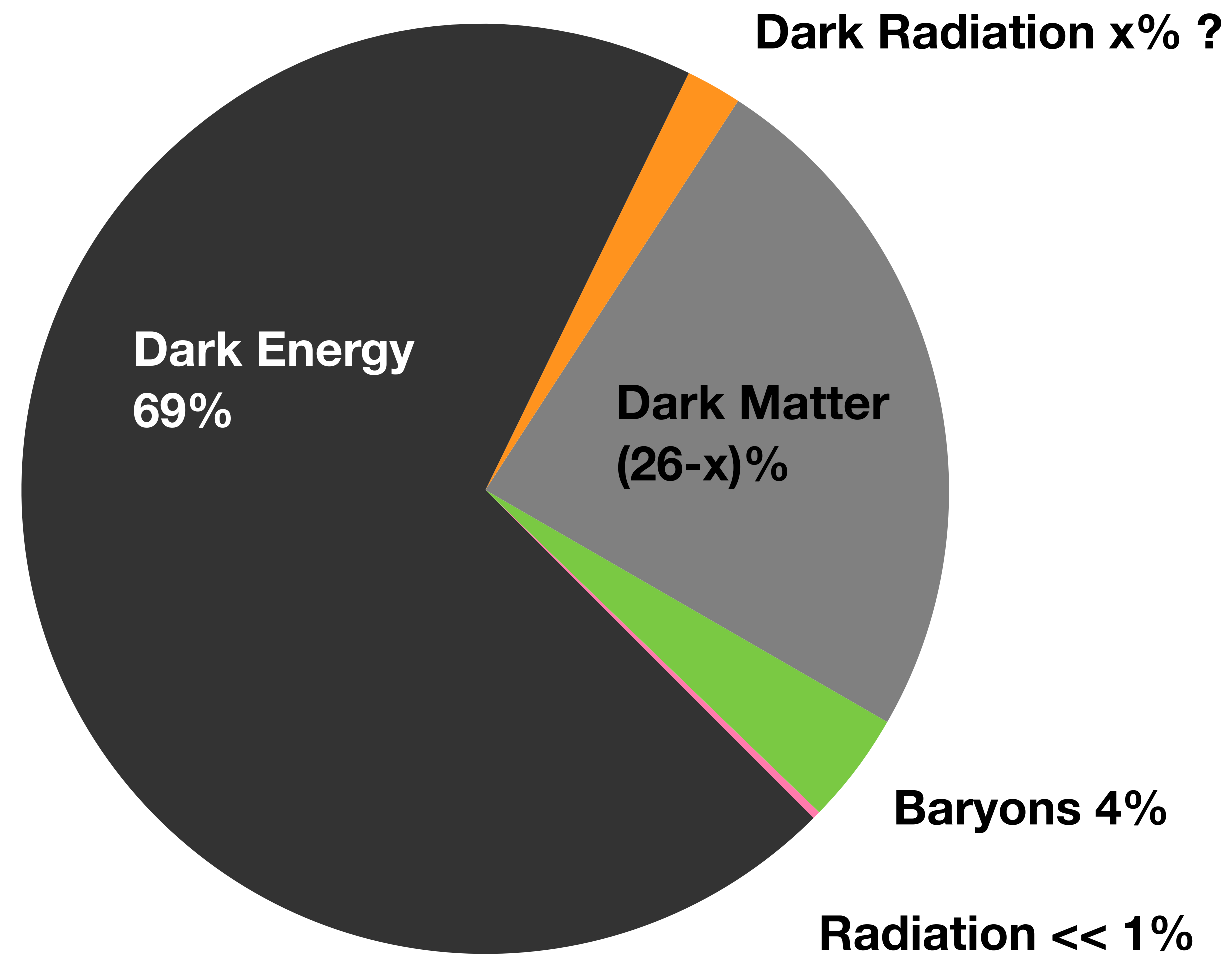


CMB-inferred

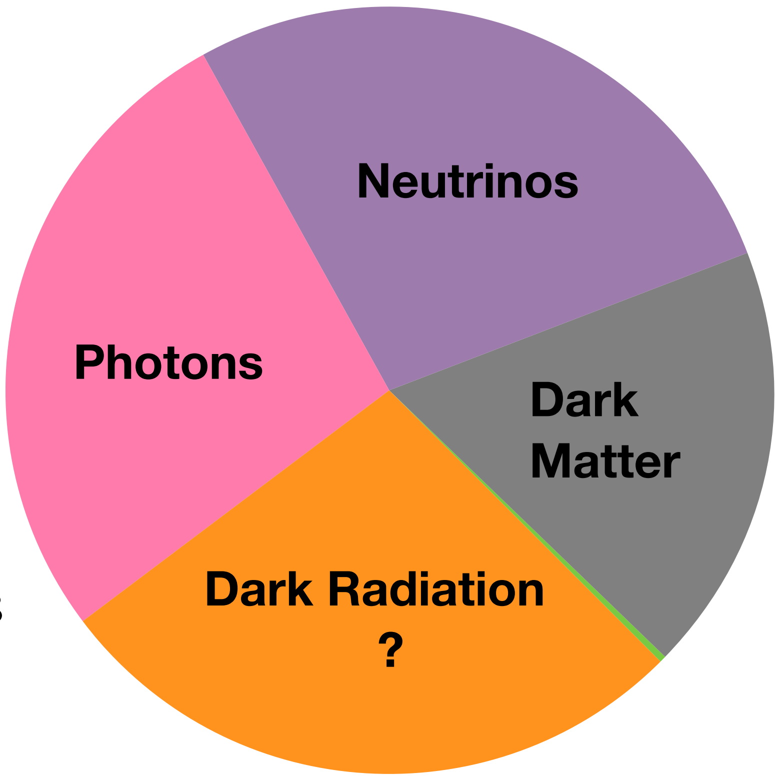
Low redshift Universe

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

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

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

How much 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

Direct sensitivity to *dark radiation?*

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 $X \to \chi\bar{\chi}$

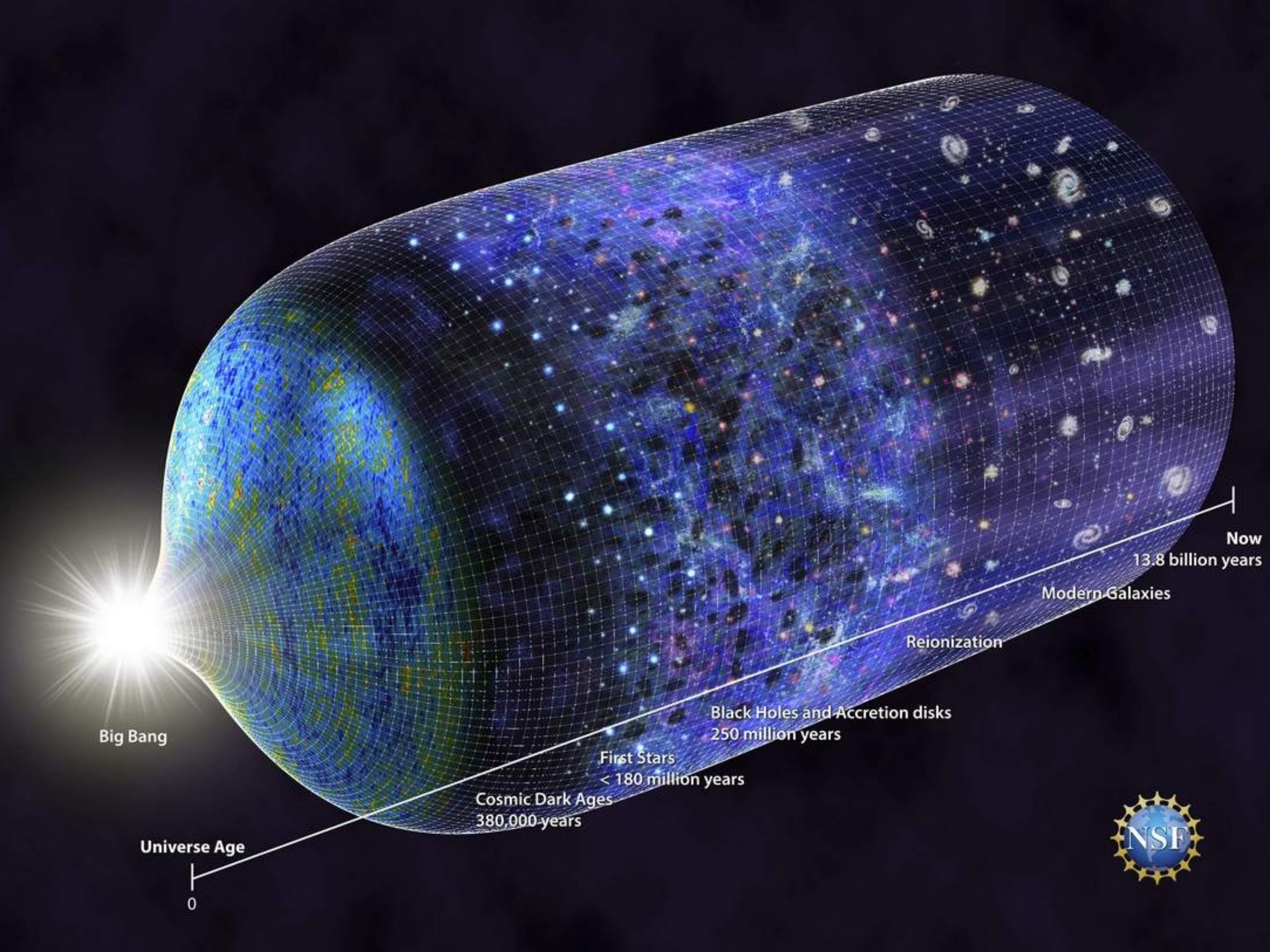
=> $X \to \chi\bar{\chi}e^+e^-$ decay is highly suppressed

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

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?

1. *If dark radiation is a dark photon*

=> 21cm cosmology! The new game in town.

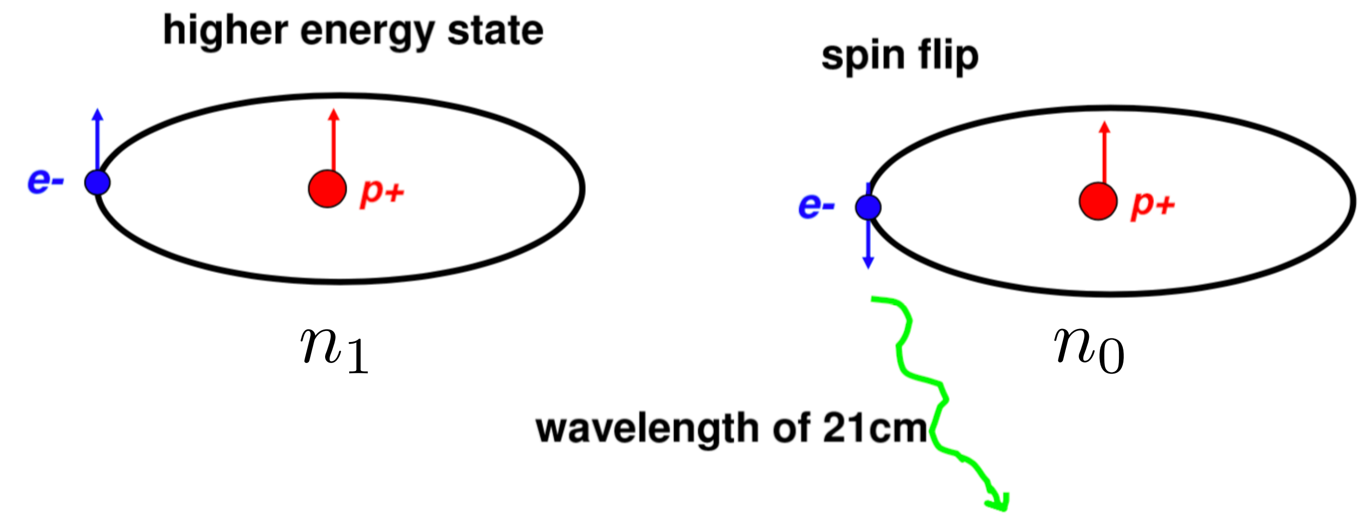


Big Bang
Universe Age
0
Cosmic Dark Ages
380,000 years
First Stars
< 180 million years
Black Holes and Accretion disks
250 million years
Reionization
Modern Galaxies
Now
13.8 billion years
NSF

21 cm 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

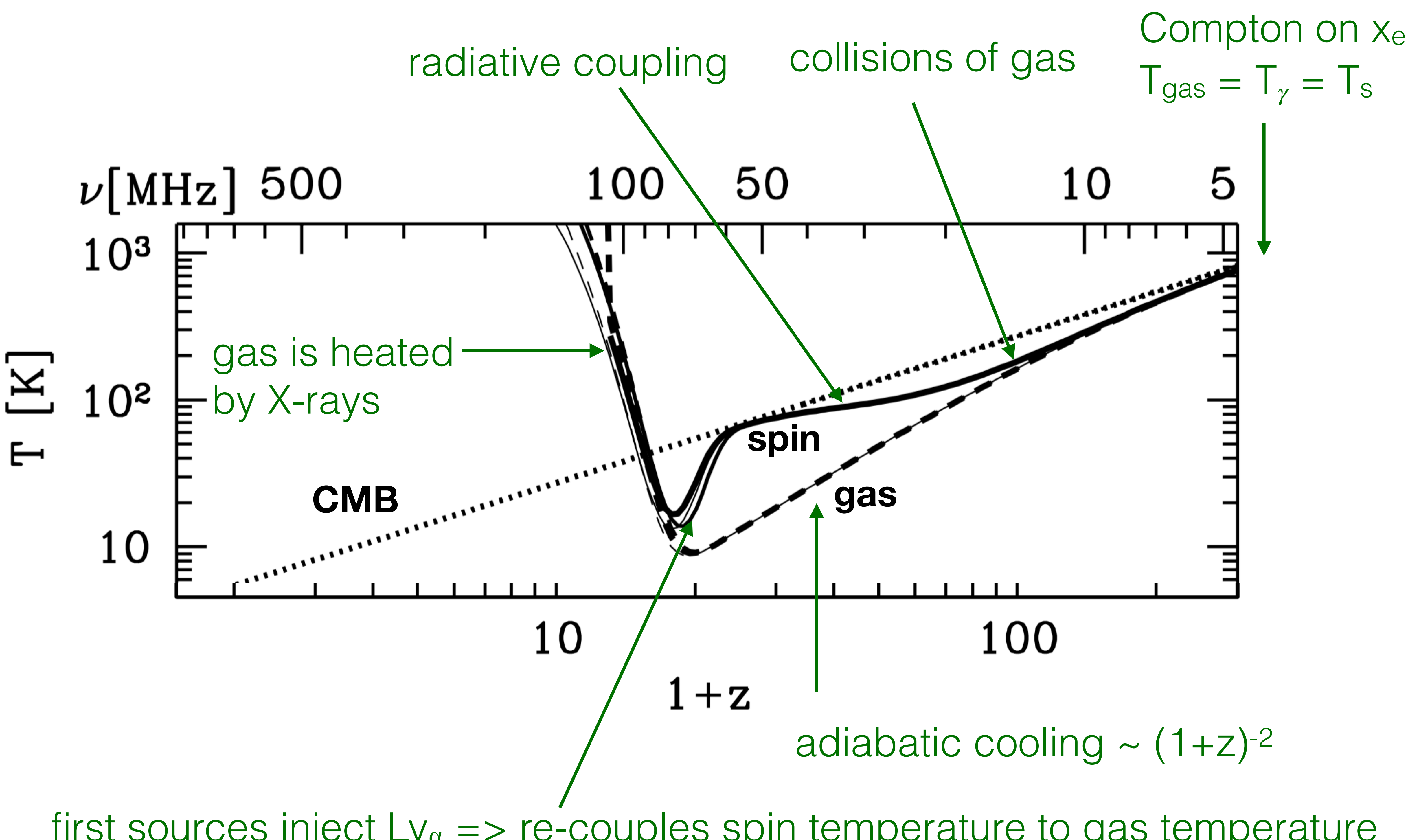
$$I_\nu = T\omega^2/2\pi^2$$

In reality, evolution is very complex, once Ly_α & X-ray fluxes are generated by stars.

see Venumadhav, Dai, Kaurov, Zaldarriaga 2018

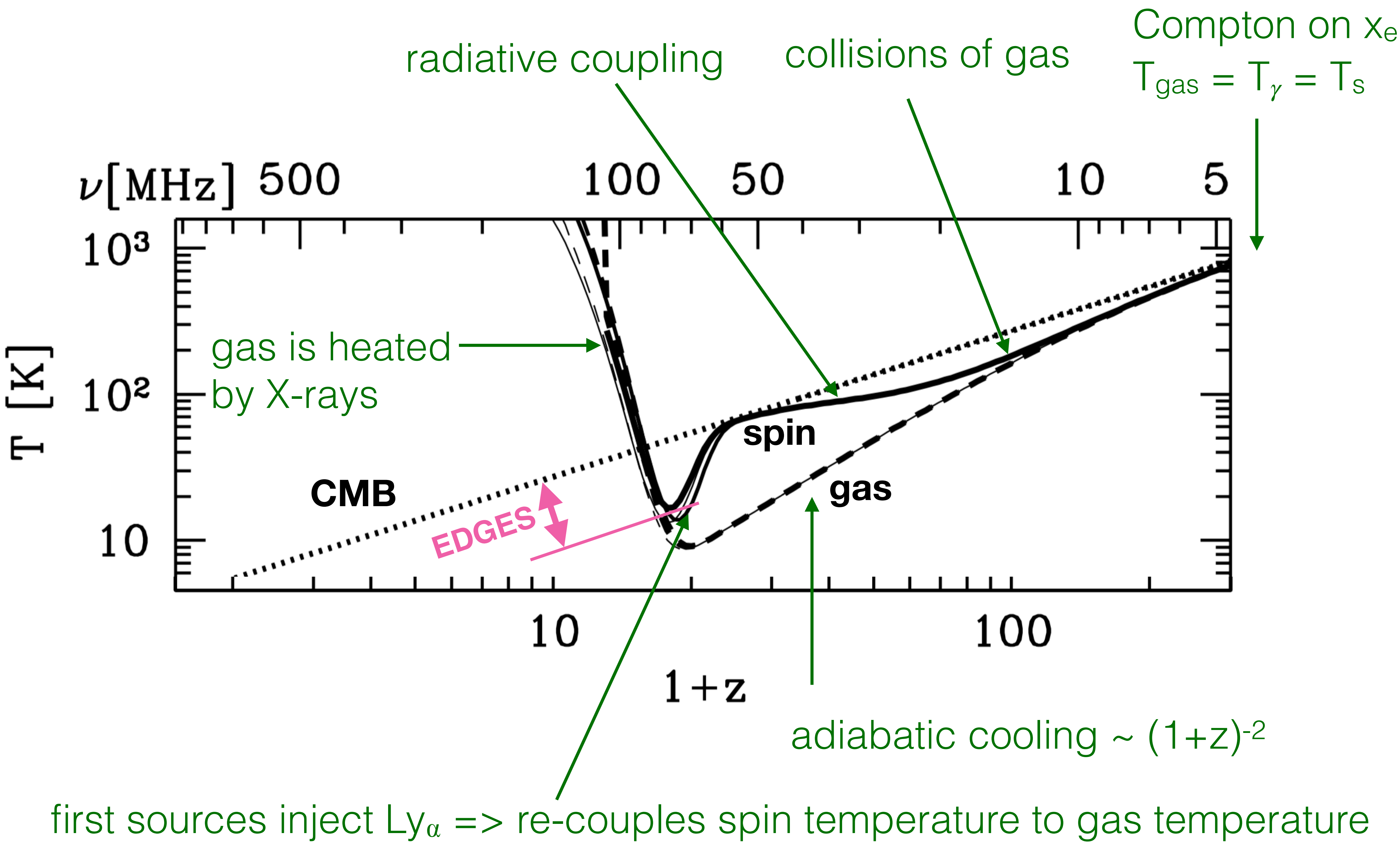
Evolution of spin temperature

see, e.g., Loeb, Pritchard 2012



Evolution of spin temperature

see, e.g., Loeb, Pritchard 2012



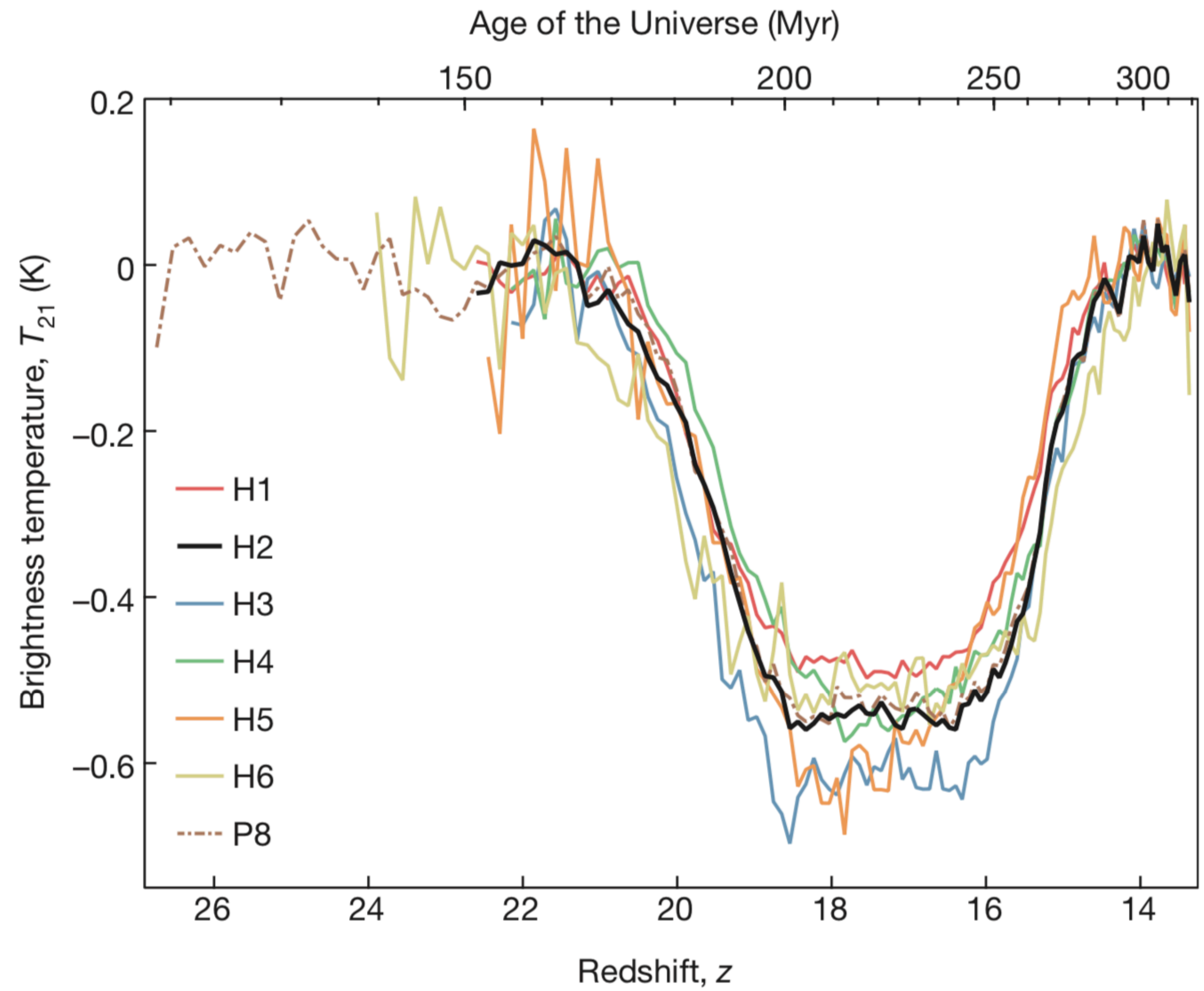
EDGES result

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

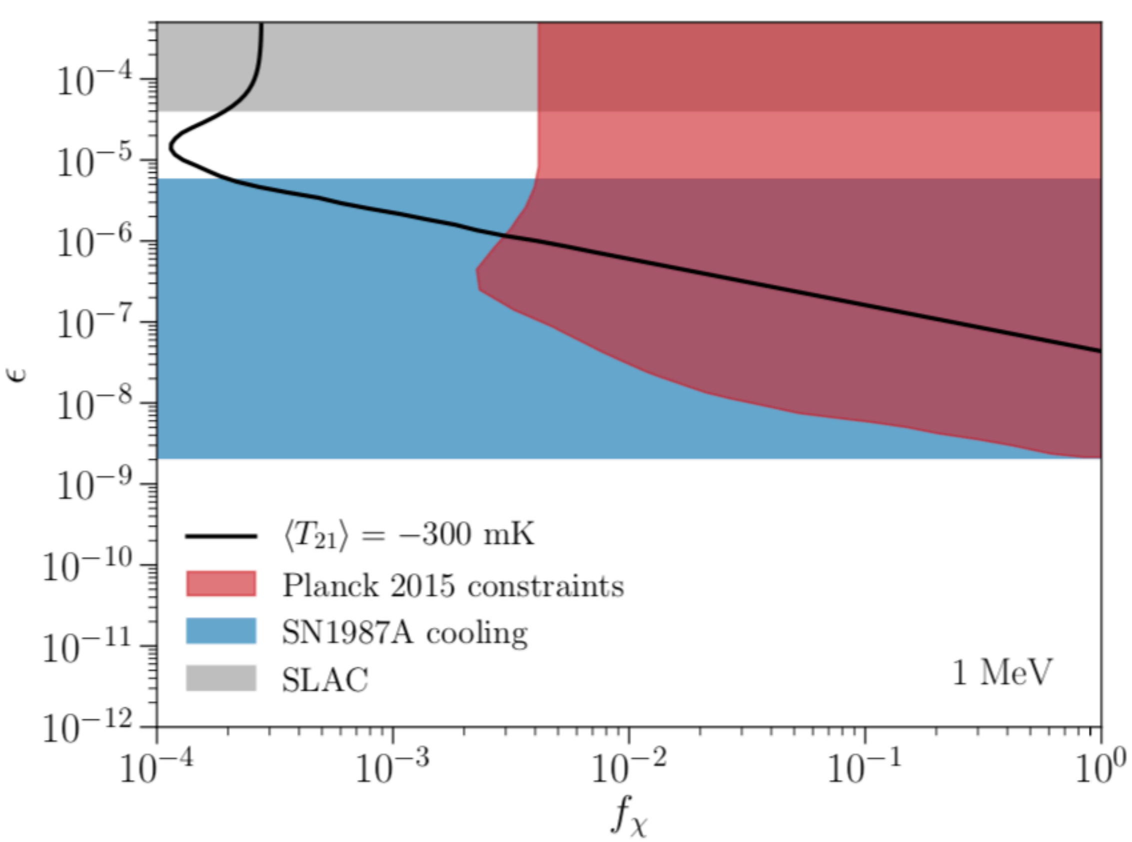
Principal options in changing T_{21}

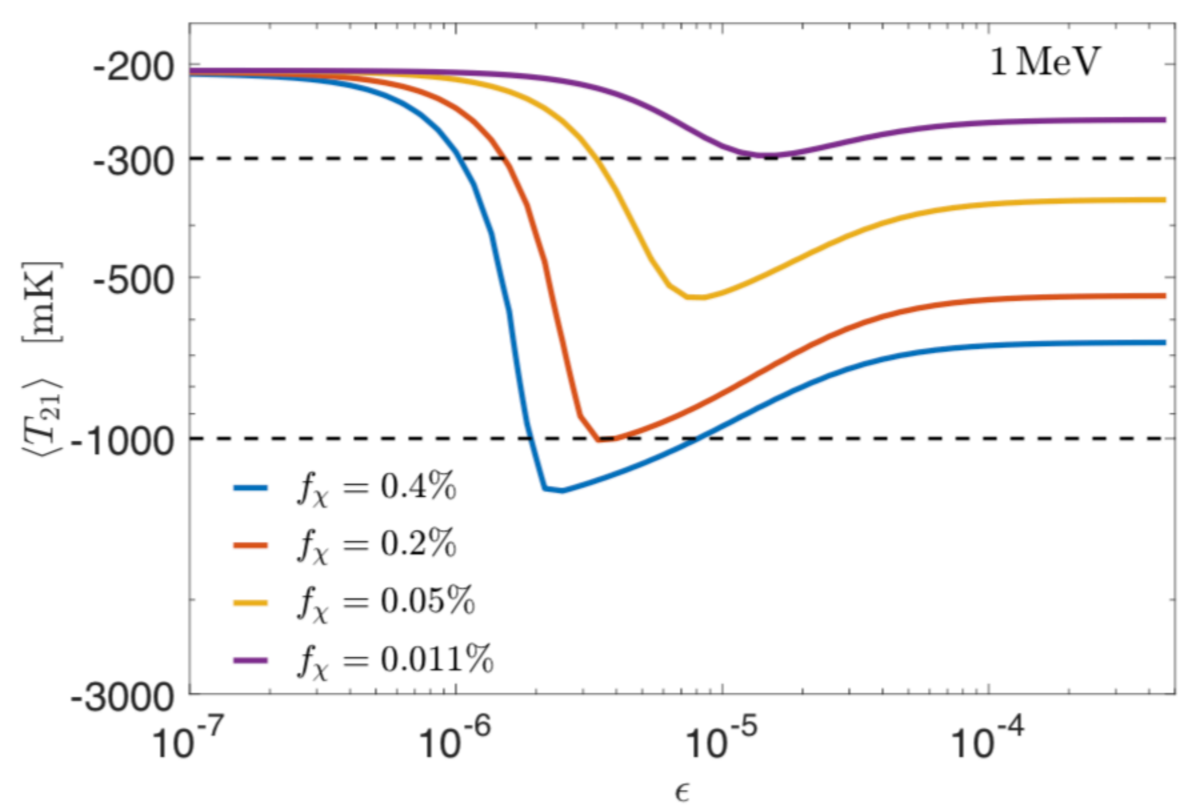
$$T_{21}(z) \simeq 23\,\mathrm{mK}\,x_H(z)\left[1-\frac{T_r(z)}{T_s(z)}\right]\sqrt{\frac{1+z}{10}}$$

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;

Principal options in changing T_{21}

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

2. 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

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

=> 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 $x \equiv \omega_{21}/T_{\mathrm{CMB}} = 10^{-3}$

Principal options in changing T_{21}

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

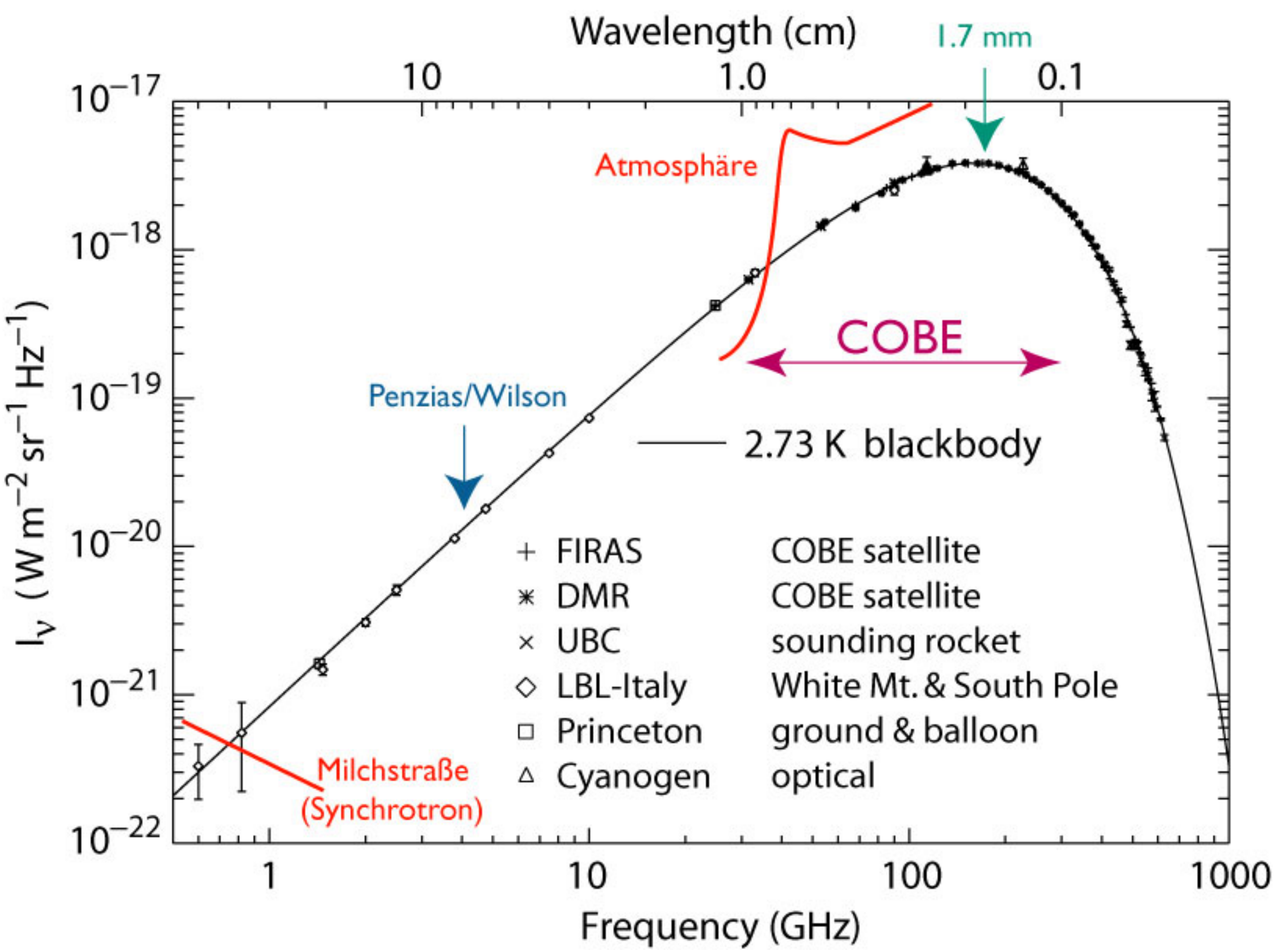
2. Add photons into the 21cm wavelength band at z~17

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

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

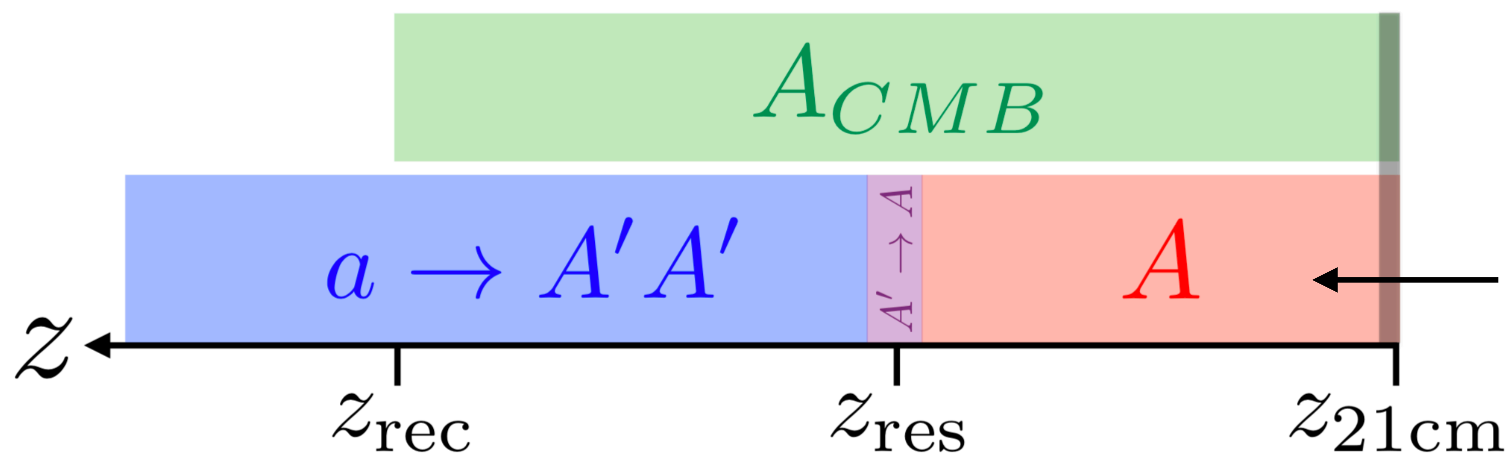


Extra photons in the CMB

dark radiation = dark photons

Our main idea:

CMB released



extra photons

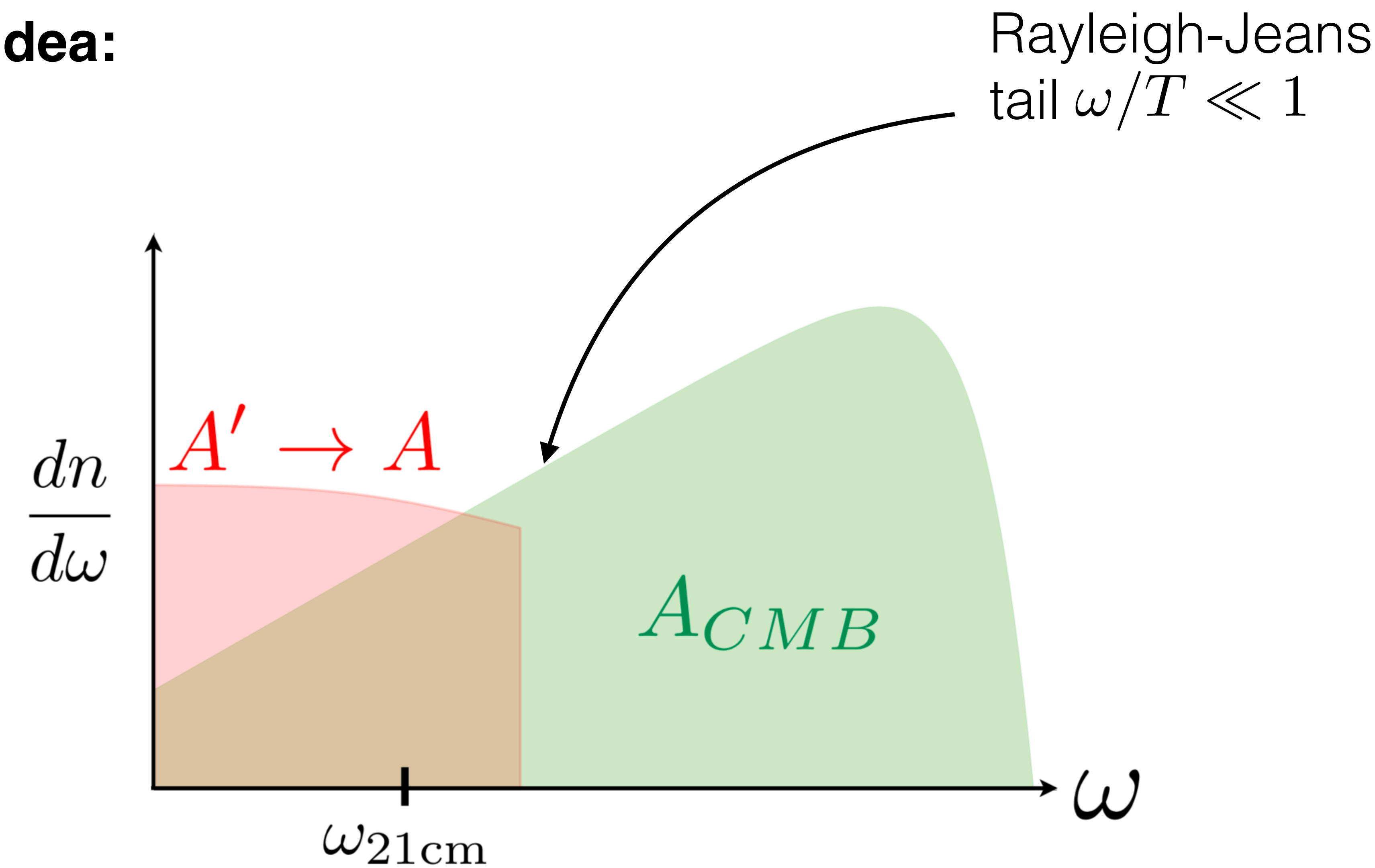
A' continuously sourced by decay of a

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:

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

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

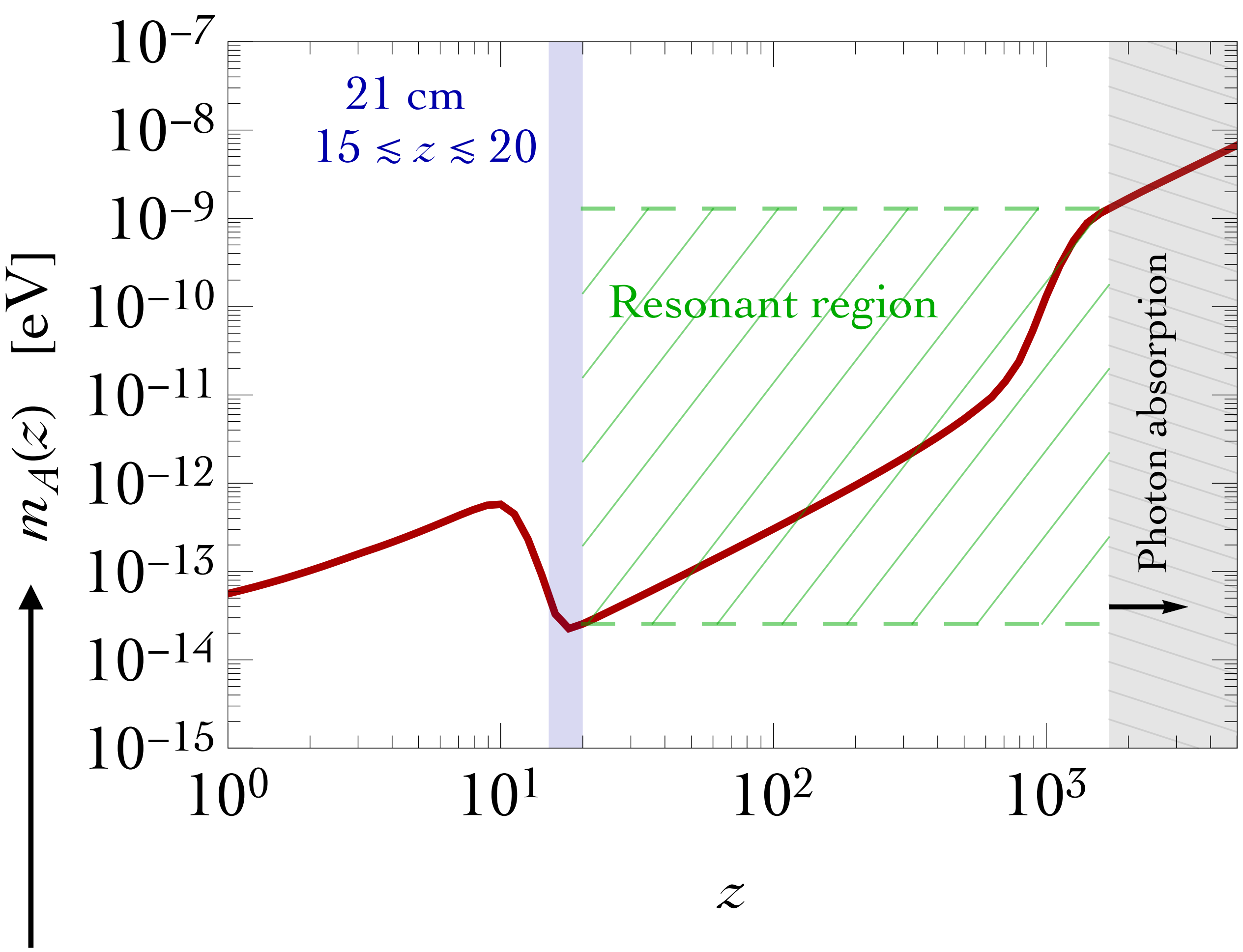
Lifetime can be anything from much shorter to much longer than the age of the Universe

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

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

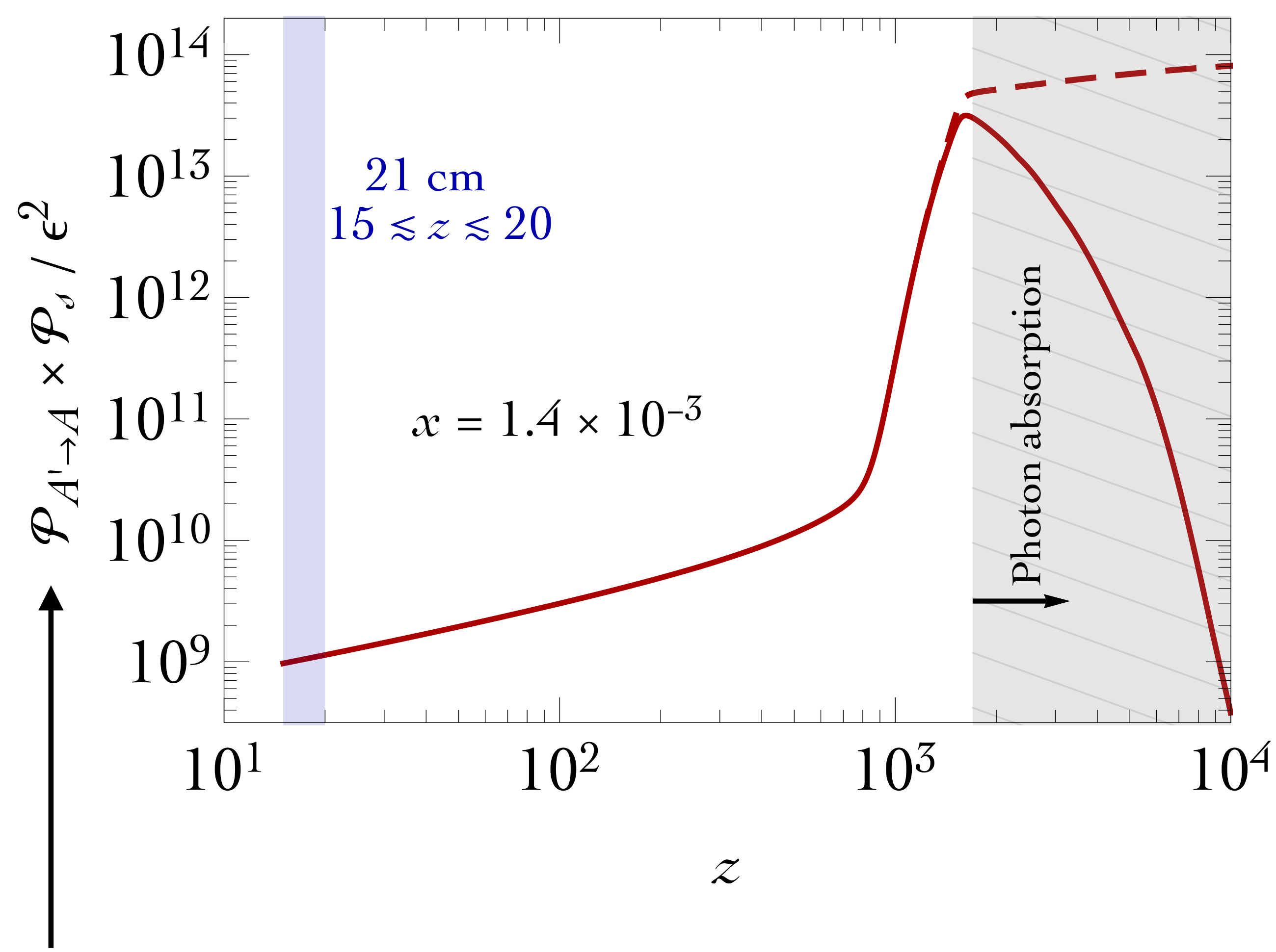
Dark photon - photon conversion

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



photon plasma freq.

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

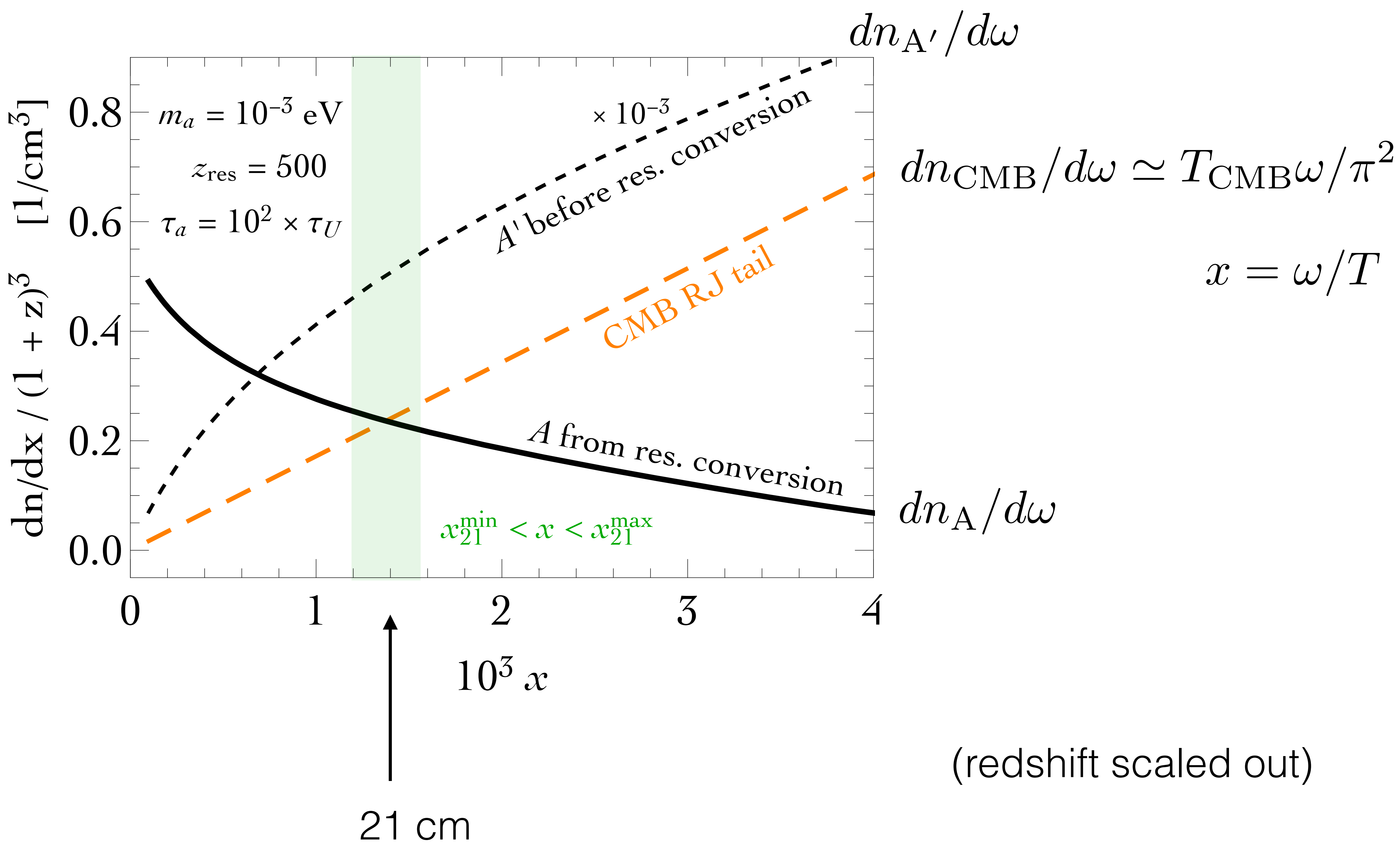


transition probability

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

see also [Mirizzi, Redondo, Sigl 2009]

Spectra at 21cm wavelength



(redshift scaled out)

DM lifetime vs. photon count

Example:

Fixing progenitor mass

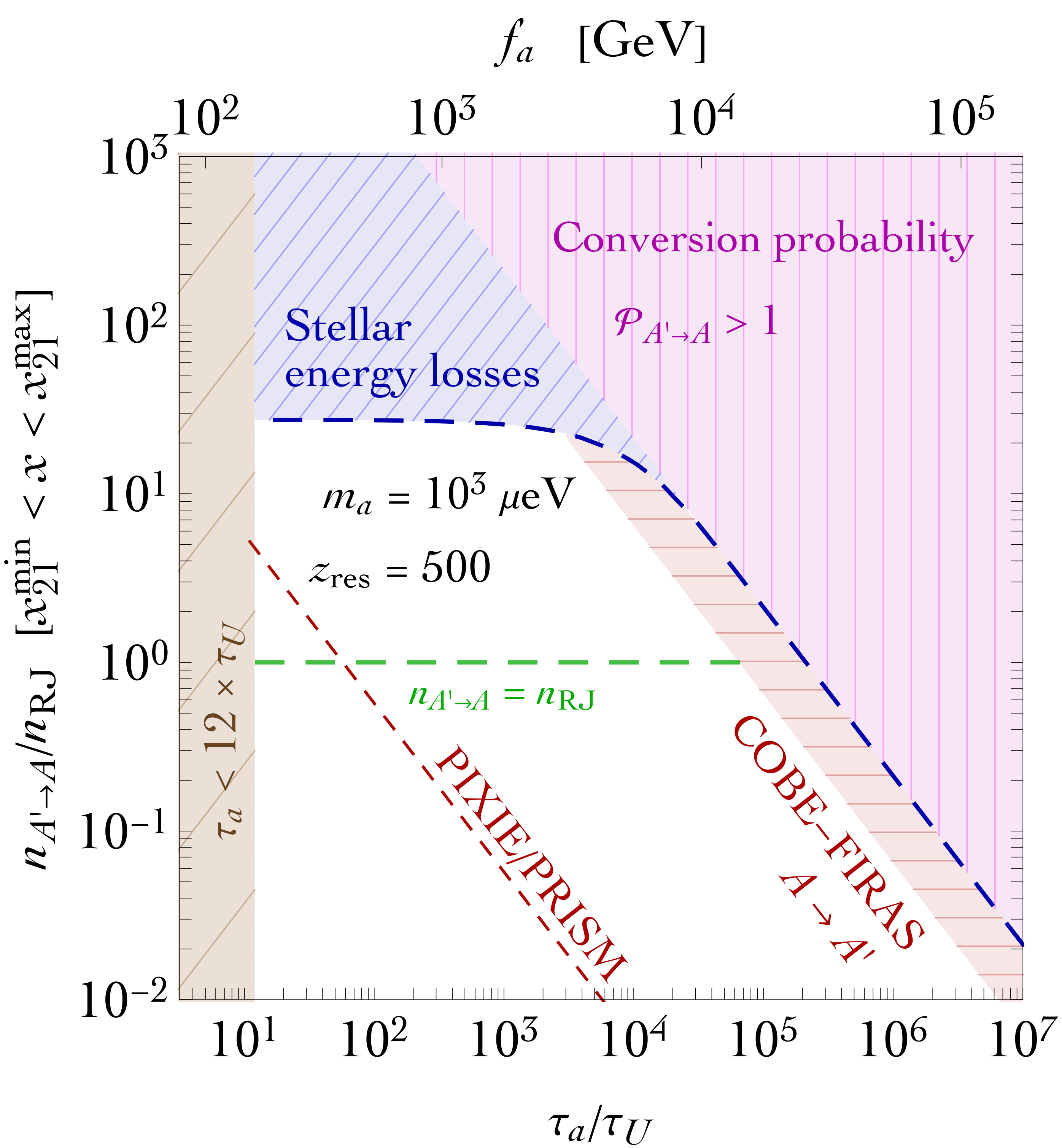
$m_a = 10^{-3}\,\mathrm{eV}$

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

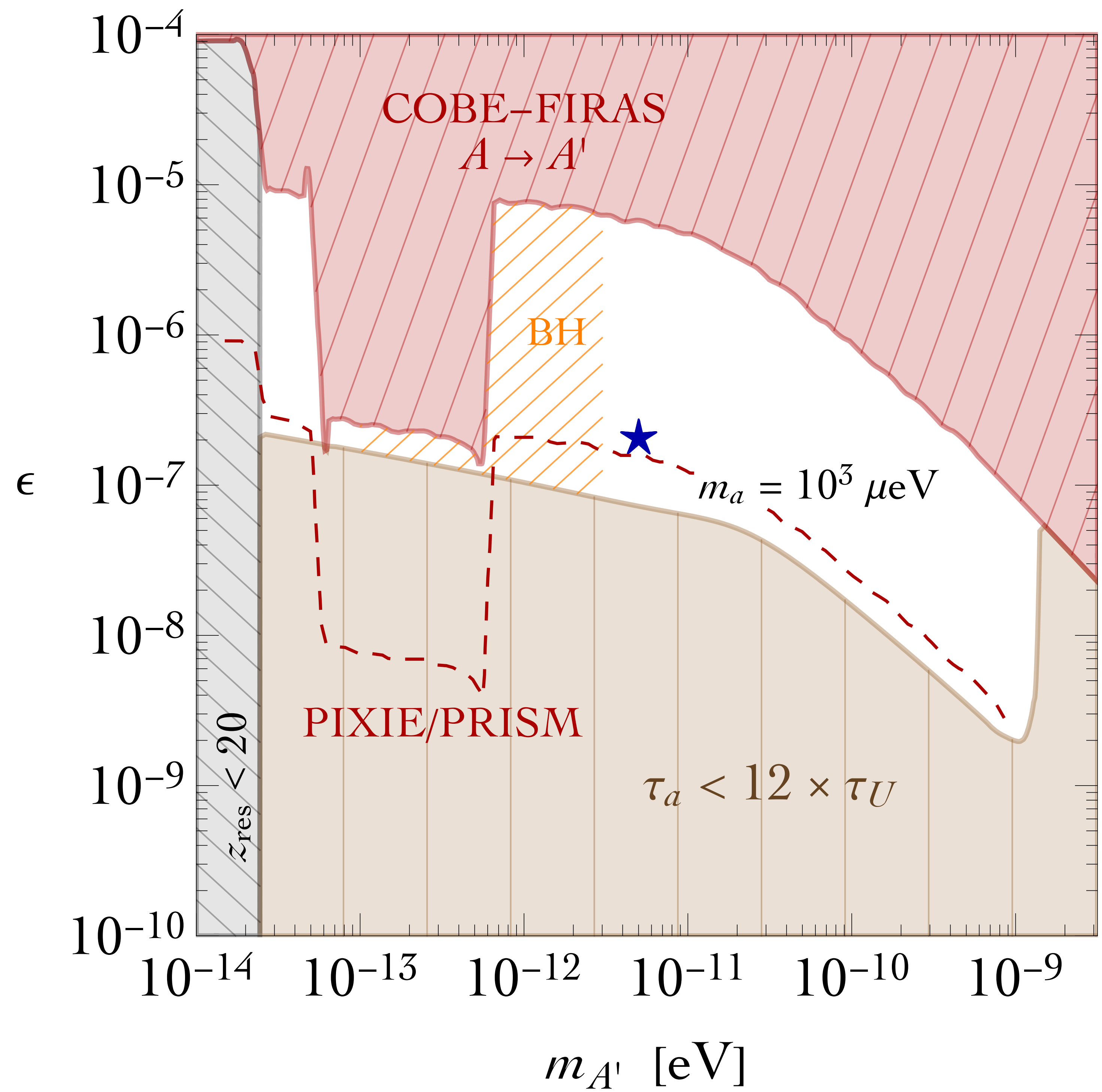


Kinetic Mixing vs. DP mass

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

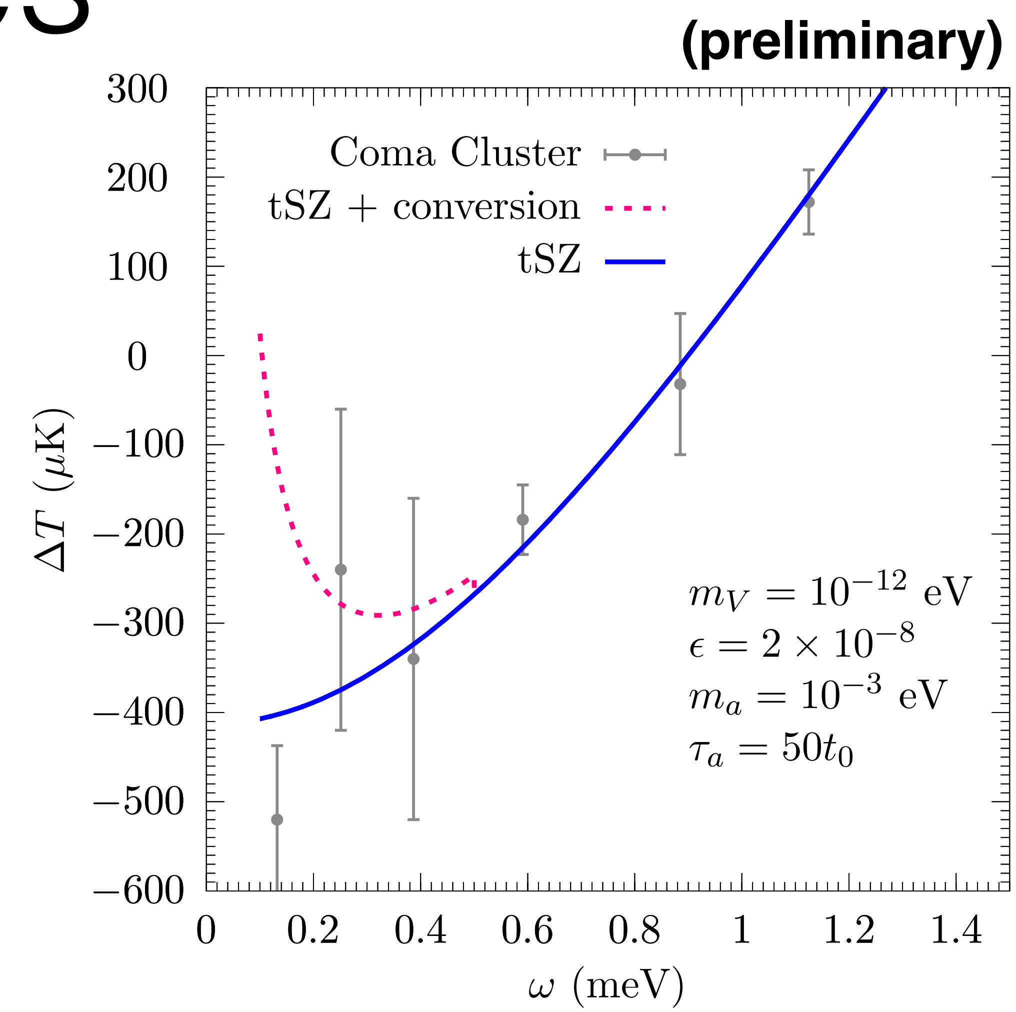
=> yields parameter space in DP mass vs. epsilon

=> much allowed.



Additional signatures

- 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 DM haloes today

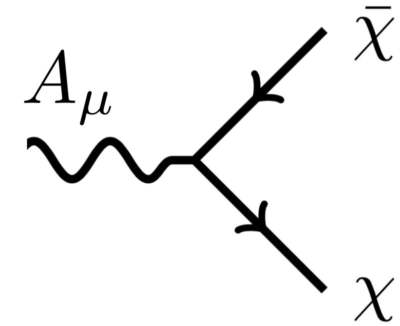


- Interesting connection to ARCADE 2 radio observations. Measurement of (extragalactic) sky temperature in the range 3-8GHz show excess [compare FIRAS > 13 GHz]

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

② Dark States with EM-interactions

Electromagnetic neutral particles χ can interact with the photon through higher-dimensional operators



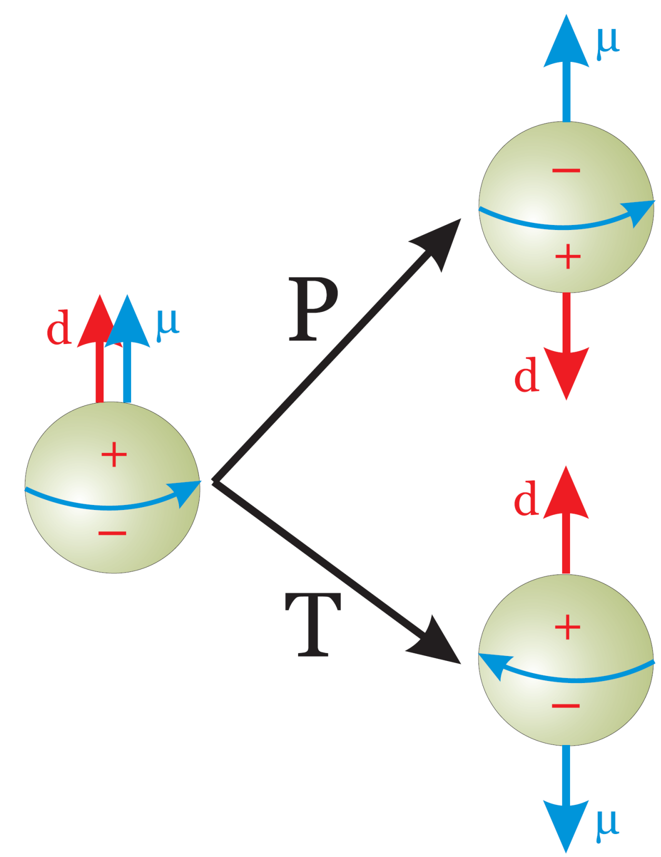
For a Dirac particle, best known are magnetic and electric dipole moments

$$H_{\rm MDM} = -\mu_\chi(\vec{B}\cdot\vec{\sigma}_\chi)$$

P and T even

$$H_{\rm EDM} = -d_\chi(\vec{E}\cdot\vec{\sigma}_\chi)$$

P and T odd => CP violating



Dark States with EM-interactions

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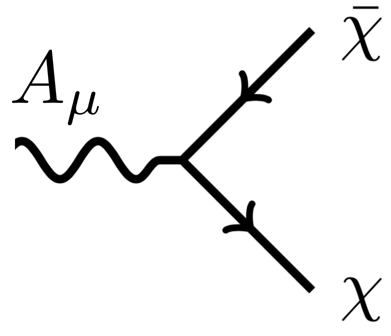


Charge radius interaction and anapole moments

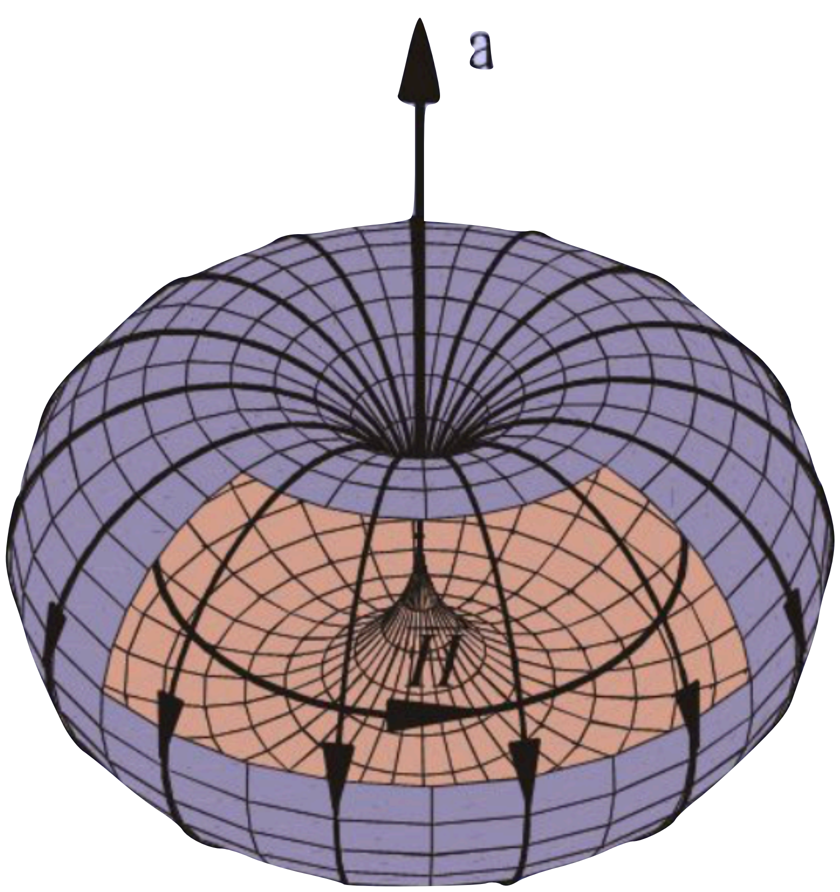
$$H_{\rm AM} = -a_\chi(\vec{J} \cdot \vec{\sigma}_\chi)$$

Zel'dovich 1958

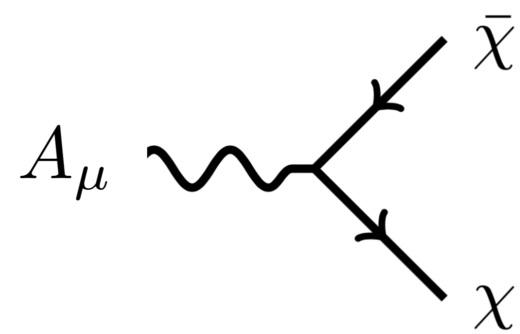
P odd but CP even

$$H_{\rm CR} = -b_\chi(\vec{\nabla} \cdot \vec{E})$$

P and T even



Dark States with EM-interactions



Effective operators

millicharge (ϵQ):	$\epsilon e\, \bar{\chi}\gamma^\mu \chi A_\mu,$	dim 4
magnetic dipole (MDM):	$\frac{1}{2}\mu_\chi\, \bar{\chi}\sigma^{\mu\nu}\chi F_{\mu\nu},$	
electric dipole (EDM):	$\frac{i}{2}d_\chi\, \bar{\chi}\sigma^{\mu\nu}\gamma^5\chi F_{\mu\nu},$	dim5
anapole moment (AM):	$a_\chi\, \bar{\chi}\gamma^\mu\gamma^5\chi\partial^\nu F_{\mu\nu},$	
charge radius (CR):	$b_\chi\, \bar{\chi}\gamma^\mu\chi\partial^\nu F_{\mu\nu}.$	dim6

NB: Millicharged states at the intensity frontier have previously been discussed

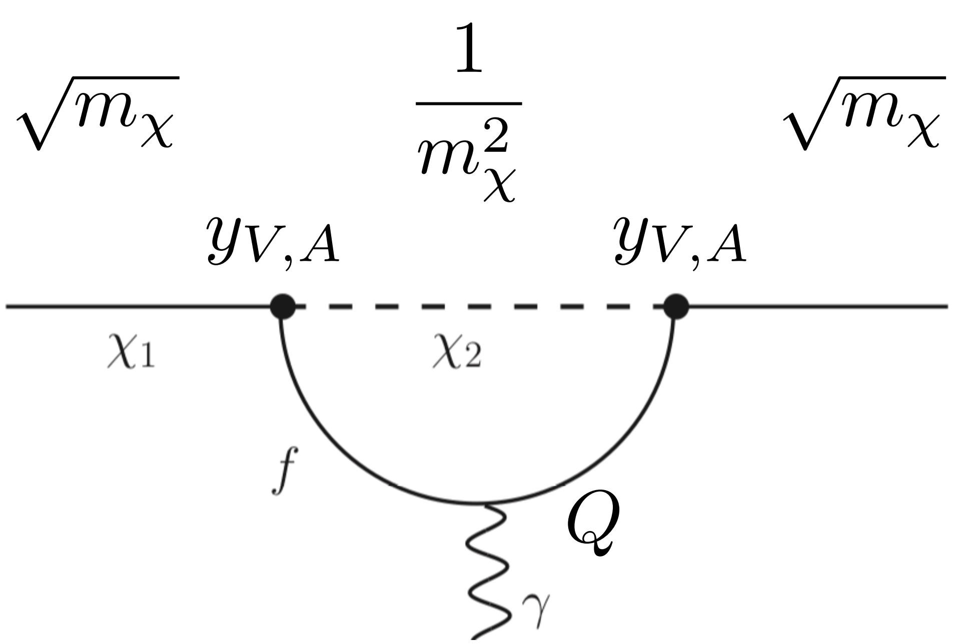
Prinz et 1998; recent refs Magill et al 2018; Berlin et al 2018,

Origin of form factor interactions

a) compositeness

e.g. Bagnasco, Dine, Thomas 1994; Foadi, Frandsen, Sannino 2009; Antipin, Redi, Strumia, and Vigiani 2015

b) radiatively (possibly enhanced by mass degeneracies)



$$\mu_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \qquad d_\chi \sim \frac{Q\,\mathrm{Im}[\mathrm{y_V y_A^*}]}{m_\chi}$$

$$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{M^2}$$

or $$a_\chi,\, b_\chi \sim \frac{Q|y_{A,V}|^2}{m_\chi} \times \frac{1}{\Delta m}$$

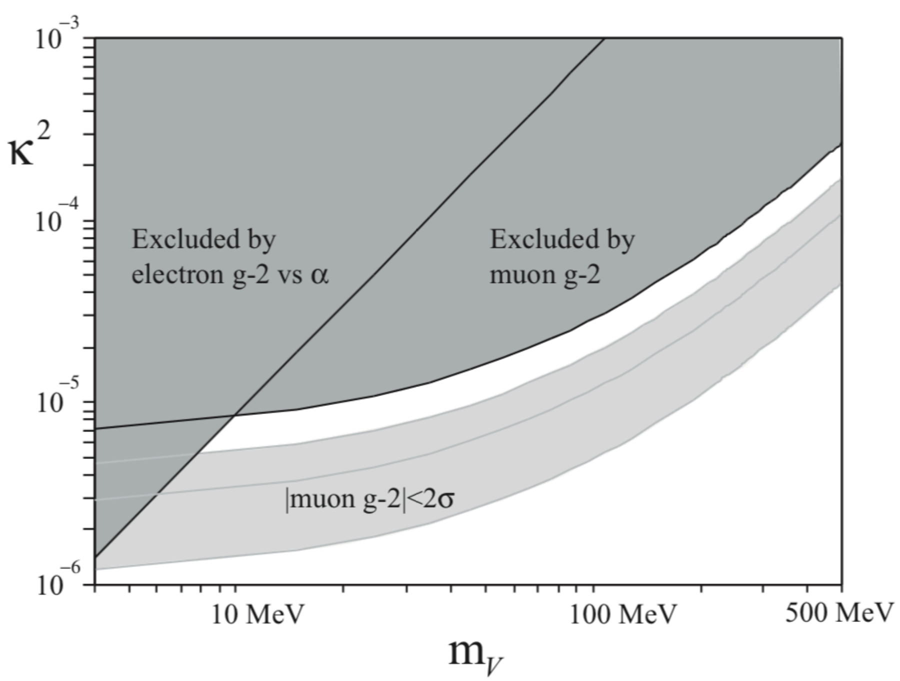
see also recent ref. Kavanagh, Panci, Ziegler 2018

Muon g-2

- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

- Prospective solutions became a driver for intensity frontier efforts, think: dark photon.



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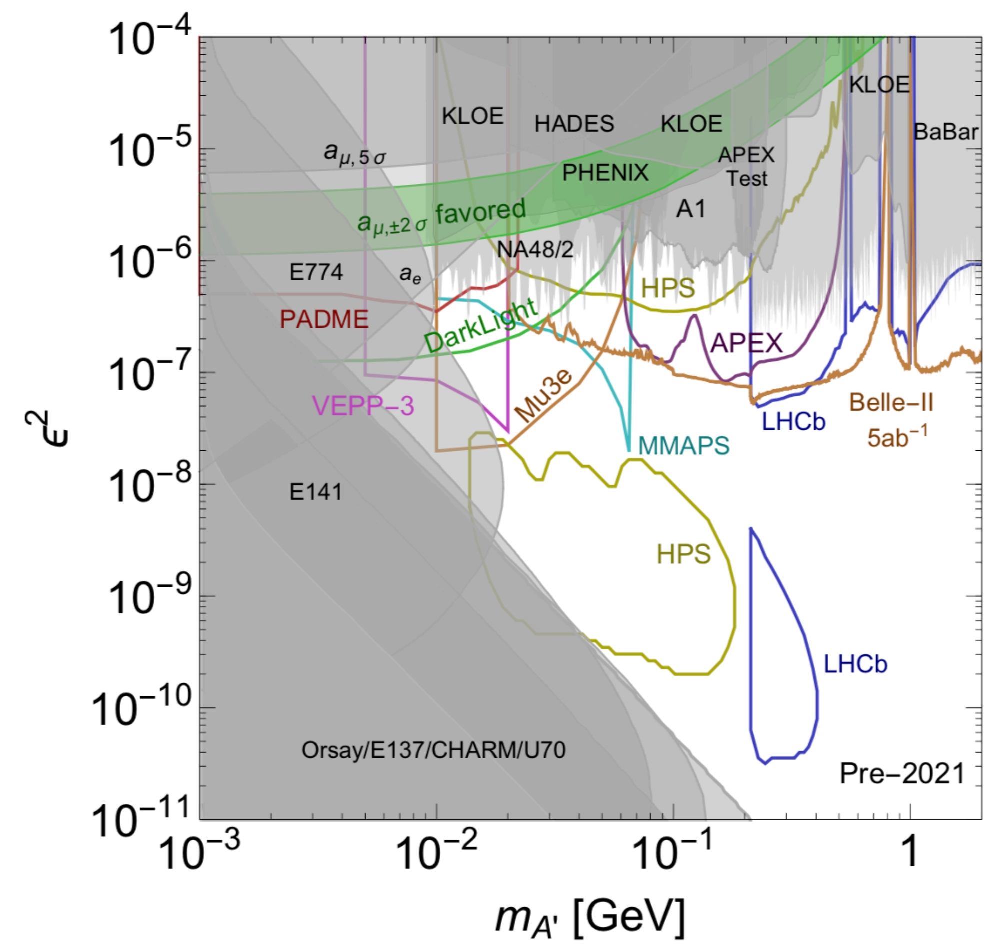


Pospelov 2009

2016 Dark Sectors **Community Report**

Muon g-2

- Muon g-2 puzzle: (3-4)σ tension between SM prediction and measurement

$$\Delta a_\mu = a_\mu^{\rm exp} - a_\mu^{\rm SM} = (290 \pm 90) \times 10^{-11}$$

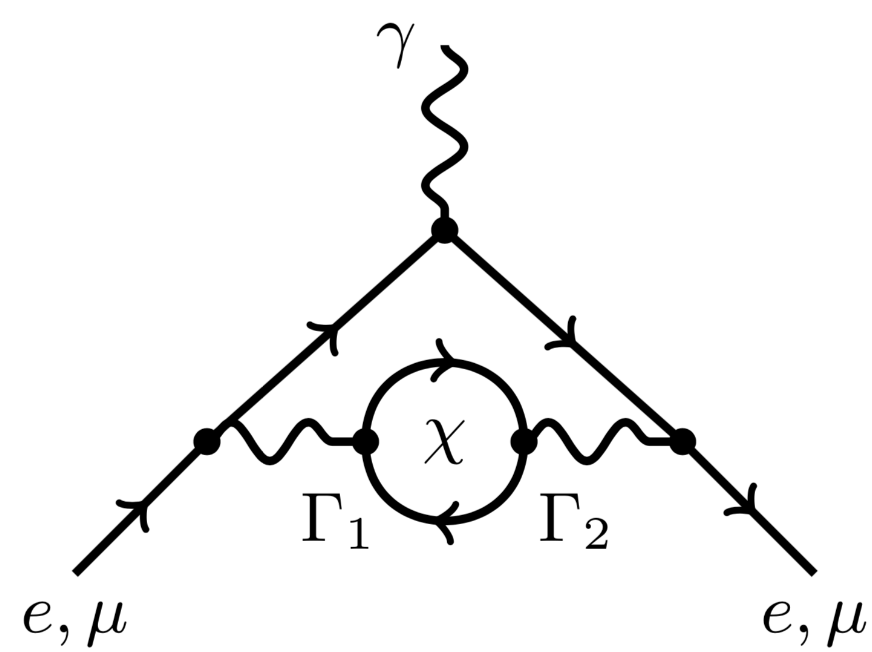
- For form-factor interactions, contributions enter through the vacuum polarization

e.g. use dispersion relation + unitarity

$$\Delta a_\mu = \frac{1}{4\pi^3} \int_{4m_\chi^2} ds\, \sigma_{e^+e^- \to \chi\bar{\chi}}(s) K(s)$$

solution to g-2 for

$$|\mu_\chi|,\ |d_\chi| \sim \text{few} \times 10^{-3} \mu_{\rm B}$$



=> we shall see, that it is excluded by BaBar

Precision tests

- In EW theory, G_F, m_W and m_Z are related and receive calculable quantum corrections, summarized in the Δr parameter

$$\Delta r_{\rm obs} = 1 - \frac{A_0^2}{M_W^2 s_w^2} = 0.03492 \pm 0.00097$$

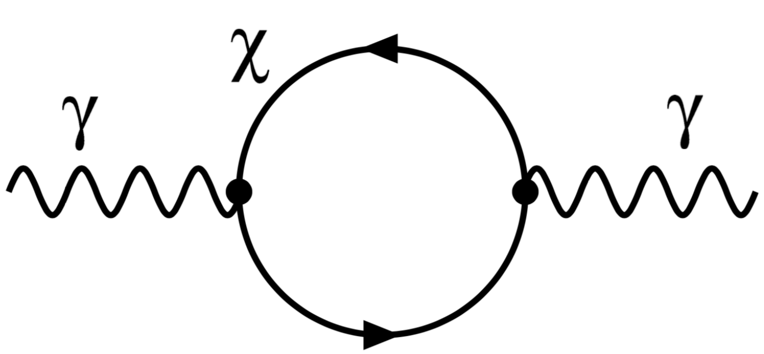
$$A_0 = (\pi\alpha/\sqrt{2}G_F)^{1/2}$$

$$s_w^2 = 1 - M_W^2/M_Z^2$$

$$-0.0038 < \Delta r_{\rm new} < 0.00018$$

(tighter upper limit from 1.8 tension)

Running of α contributes $\Delta r_{\rm new} \simeq \Pi(-M_Z^2) - \Pi(0)$



$$|\mu_\chi| \text{ or } |d_\chi| \; < 3.2 \times 10^{-6} \mu_B$$

(saturating upper limit)

$$|a_\chi| \text{ or } |b_\chi| \; < 3.2 \times 10^{-5}/\text{GeV}^2$$

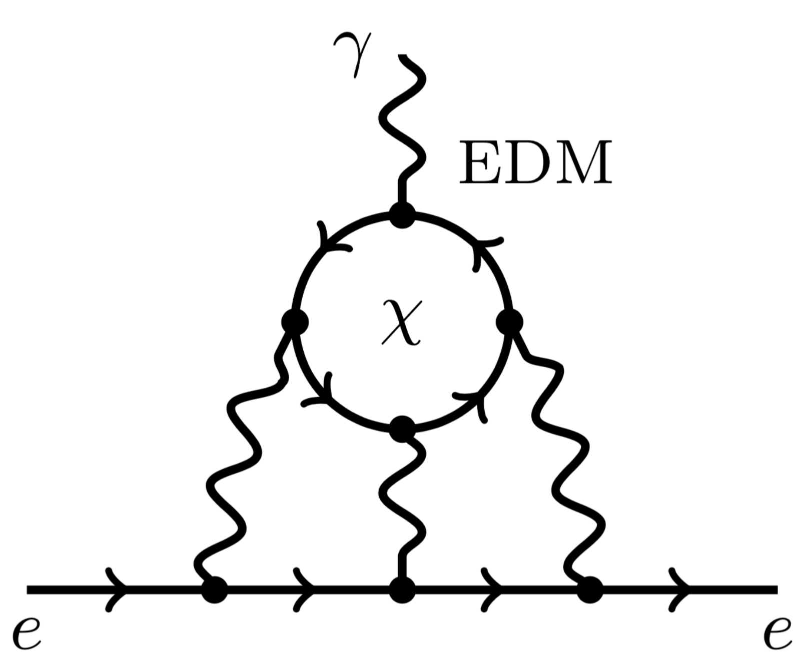
(saturating lower limit)

EDMs

- Recently, ACME collaboration improved bound on electron EDM

$$|d_e| < 1.1 \times 10^{-29}\, e\,\mathrm{cm} \ = 6 \times 10^{-19} \mu_B$$

- Dark states may induce an EDM operator via insertion of dark d_χ



3 loop it is

$$d_e \sim e^3 m_e d_\chi \times (\mathrm{mass})^{-1}$$

$$(\mathrm{mass})^{-1} \sim \epsilon^3 e^3/m_\chi, \mu_\chi^3 m_\chi^2, \\ d_\chi^2 \mu_\chi m_\chi^2,\ b_\chi d_\chi^2 m_\chi^3 \ldots$$

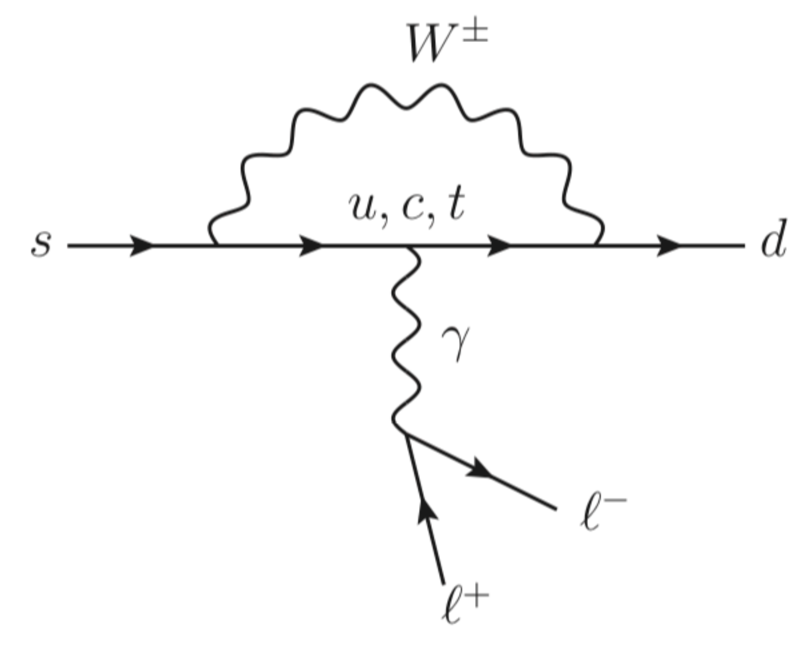
e.g. dim-5 operators only:

$$(10^{-5} - 10^{-6})\, \mu_B \sqrt{\mathrm{GeV}/m_\chi}$$

Rare Meson Decays

- χ pair-production through γ^* in flavor changing s->d and b->s transition closely related to $K^+ \to \pi^+ l^+ l^-$ and $B^+ \to K^+ l^+ l^-$

e.g. for Kaons



$$\frac{\Gamma(K^+ \to \pi^+ \bar{\chi}\chi)}{\Gamma(K \to \pi e^+ e^-)} \simeq 1.9 \times 10^4 \left(\frac{\mu_\chi \text{ or } d_\chi}{\mu_B}\right)^2$$

$$\frac{\Gamma(K^+ \to \pi^+ \bar{\chi}\chi)}{\Gamma(K \to \pi e^+ e^-)} \simeq 2.6 \times 10^4 \left(\frac{a_\chi \text{ or } b_\chi}{\text{TeV}^2}\right)^2$$

constrained from $\text{Br}(K^+ \to \pi^+ + \text{inv}) \lesssim 4 \times 10^{-10}$ E949; see also NA62

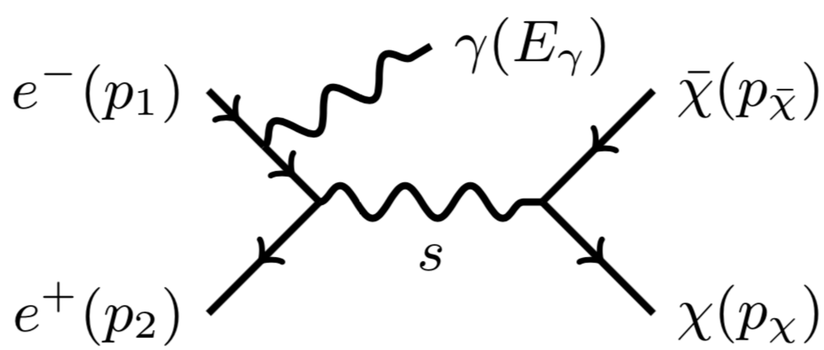
$$|\mu_\chi| \text{ or } |d_\chi| \lesssim 3 \times 10^{-4} \mu_B$$

$$|a_\chi| \text{ or } |b_\chi| \lesssim 0.2\,\text{GeV}^{-2}$$

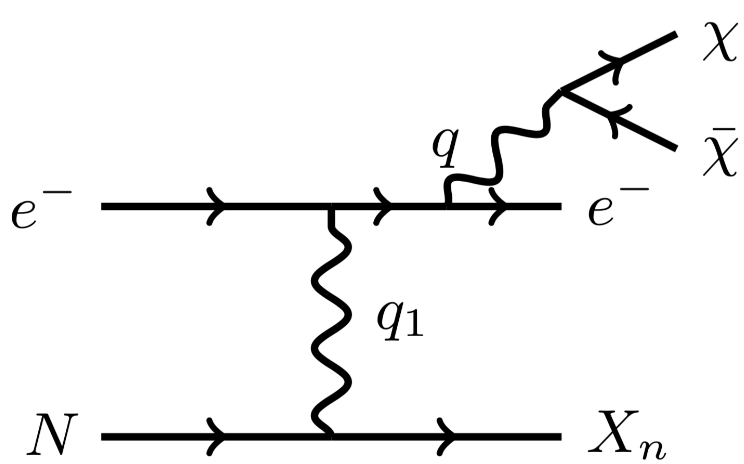
likewise for $\text{Br}(B^+ \to K^+ + \text{inv}) \lesssim 7 \times 10^{-5}$ BaBar 2003

A target for the intensity frontier

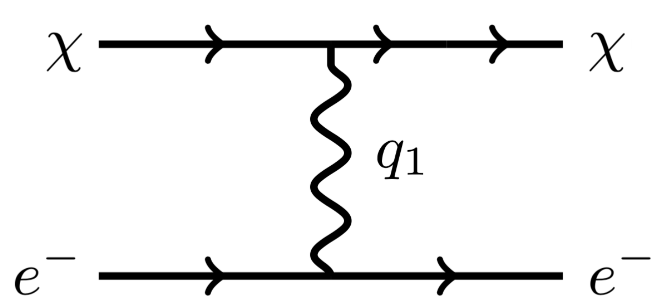
e.g. utilizing electron beams



1. search for missing momentum in e^+e^- colliders such as BaBar, Belle, Belle-II and BESIII



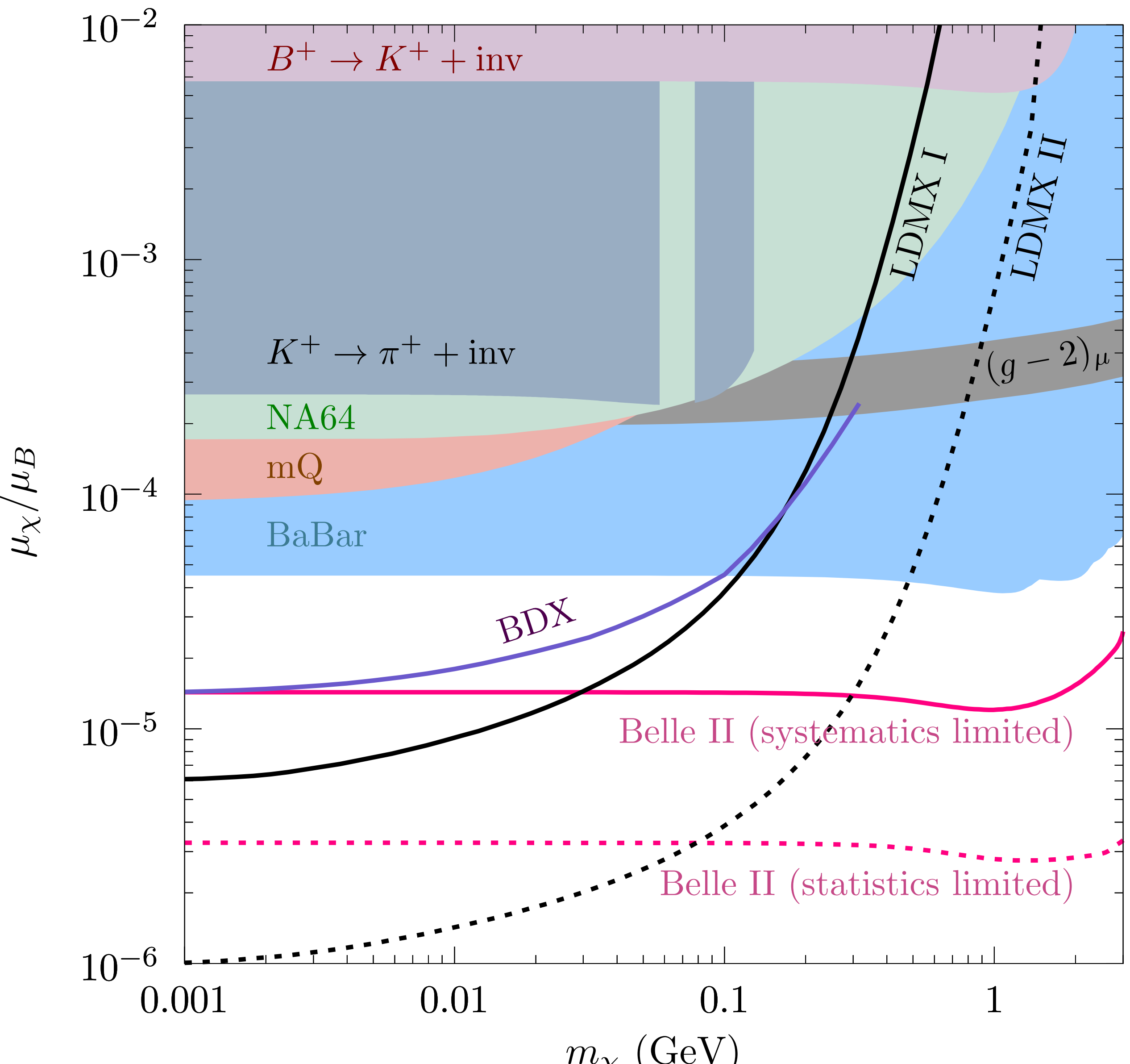
2. search for missing energy in e^- fixed-target experiments such as NA64 and LDMX



3. direct search for χN or χe^- scattering of χ particles produced in e^- fixed-target experiments mQ, BDX (at SLAC or Mainz)

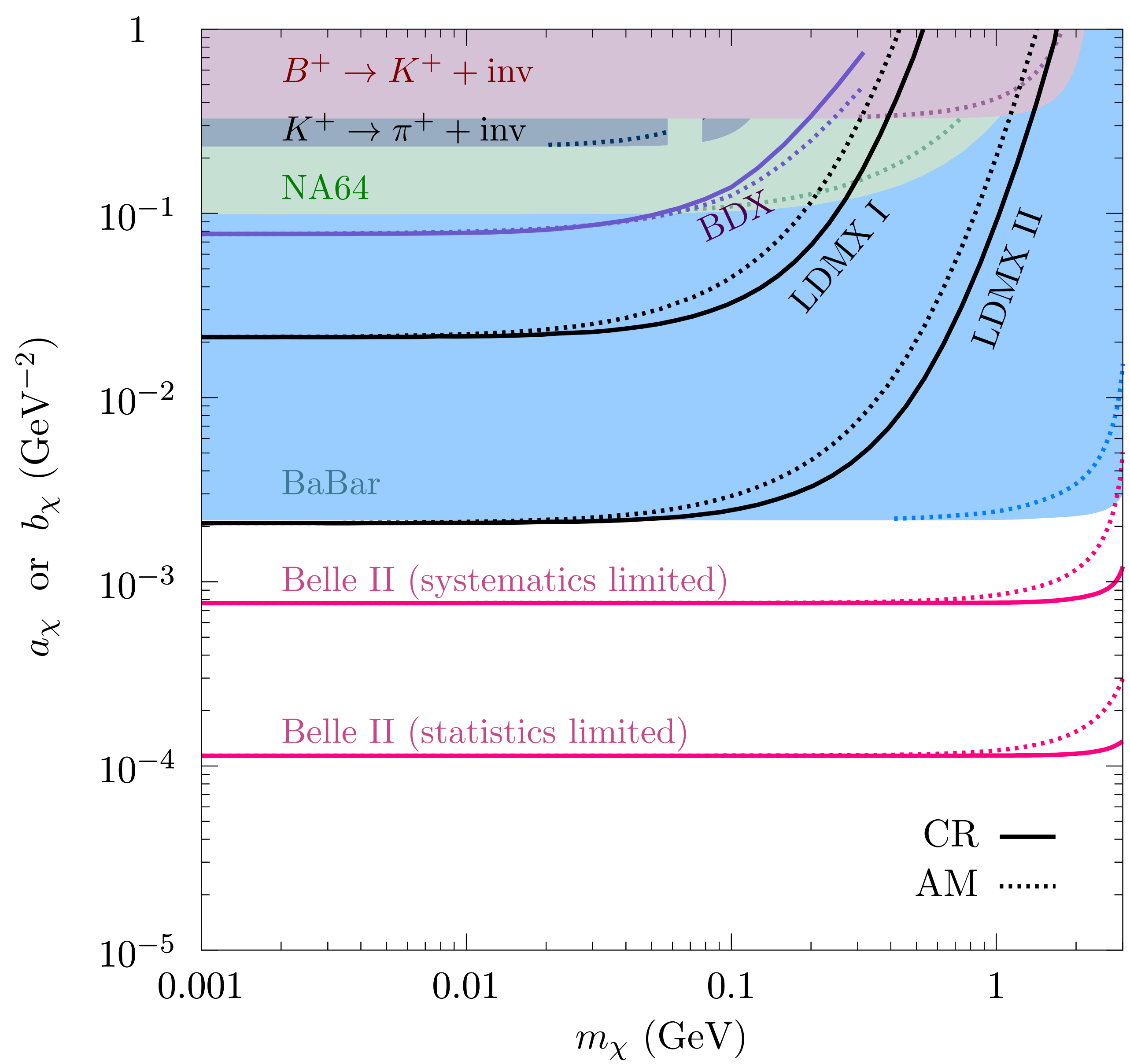
Direct sensitivity

dim-5
magnetic or electric dipole



$\mu_B \simeq 2 \times 10^{-11}\, e\,\text{cm}$

dim-6
anapole / charge radius

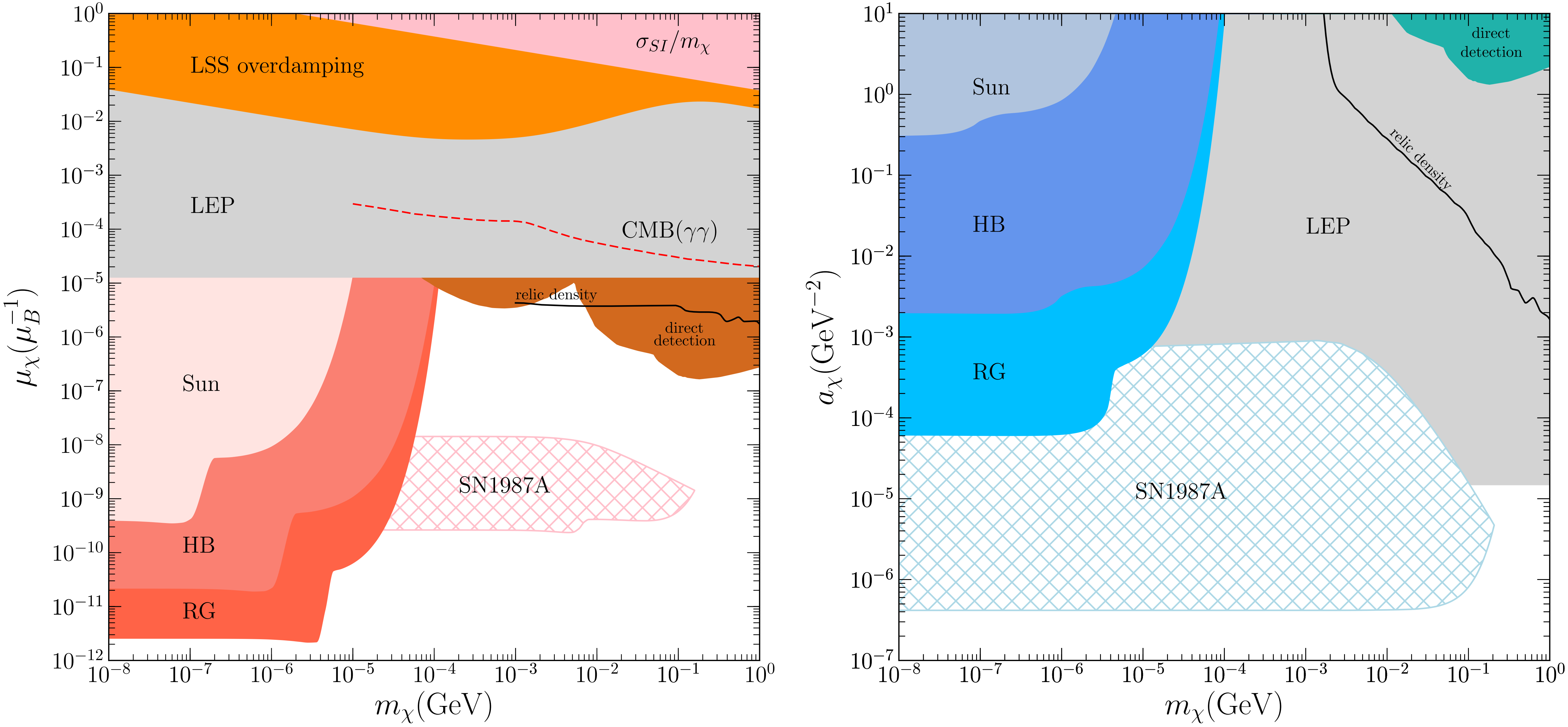


LDMX I: $4\text{x}10^{14}$ EOT, 4 GeV beam on W
LDMX II: $3.2\text{x}10^{15}$ EOT, 8 GeV beam on Al

mQ: $8.4\text{x}10^{18}$ EOT, 29.5 GeV beam on W
BDX: $3.2\text{x}10^{22}$ EOT, 11 GeV beam on Al

Form-factor "landscape"

in preparation with X. Chu, J.-L. Kuo, L. Semmelrock



=> see Jui-Lin Kuo's poster

Photon as New Physics Messenger

1 **21cm cosmology is new probe non-standard population of soft photons, sourced by new physics processes**

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;
Dark photon sourcing particles, that supply an extra population of cosmological photons through resonant conversion => can account for EDGES signal

2 **Neutral sub-GeV dark sector particles may directly talk to the photon through electromagnetic interactions**

We are filling the "landscape" in form factor coupling and dark sector mass; another science case that lines up with much activity on the "intensity frontier" and the exploration of light dark sector physics