21 cm as probe of (signature of?) dark radiation

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Plan

1. *Introduction.* Dark matter; dark energy; … dark radiation, dark forces?

2. *Dark radiation of **numerous** soft quanta* in the Rayleigh-Jeans tail.

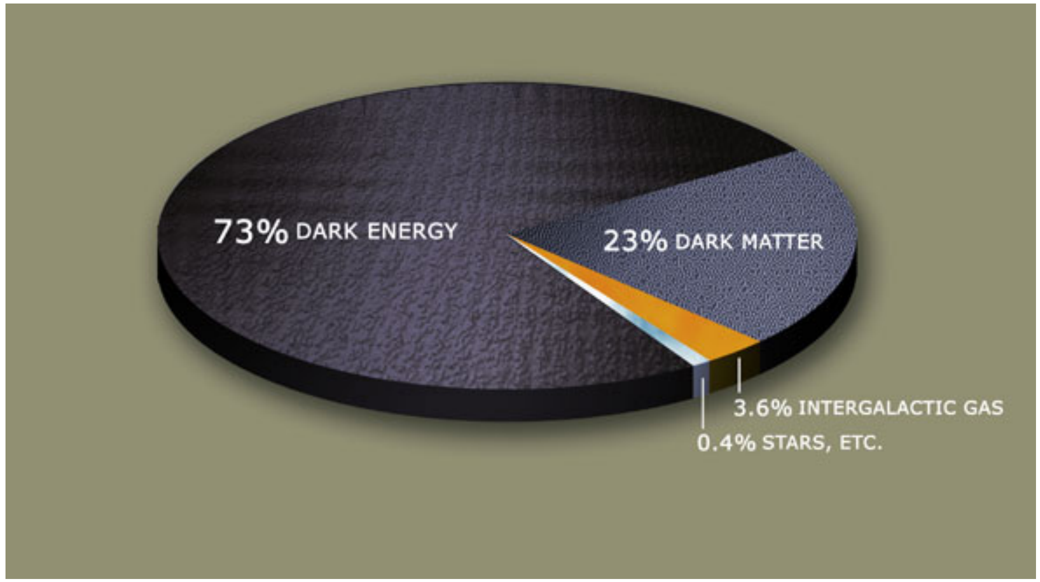
$$\omega_{\rm DR} \ll \omega_{\rm CMB} \ , \quad n_{\rm DR} > n_{\rm RJ} \ , \quad \omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot} \ .$$

3. Implication for EDGES result. Construction of specific model(s) for DR that can enhance the RJ tail, and *easily* account for strength of EDGES signal.

4. Future developments.

Cosmological surprises

Energy balance chart, z=0

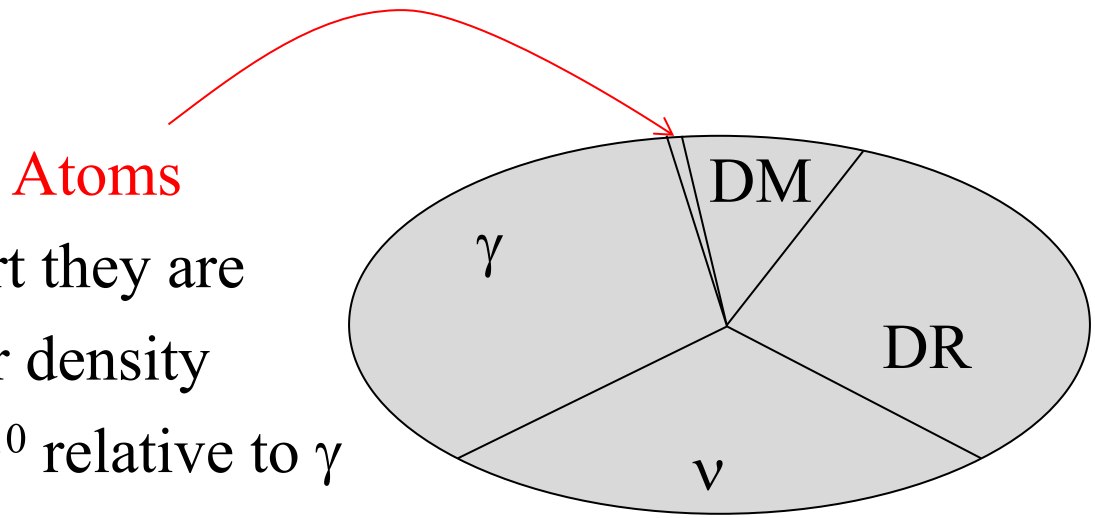


Existence of dark matter and dark energy calls into question whether there are other dark components:

Dark forces? Dark radiation?

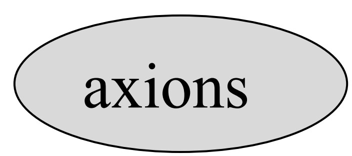
Is there a similar chart for *number densities*? Looks very different

In Energy chart they are 4%. In number density chart ~ 5 ×10^{-10} relative to γ



We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation – Who knows! Can be dominant while being a subdominant component of ρ).

Number density chart for axionic universe:



DR can be present in A. large number of quanta, B. be negligible in the energy balance, C. Can affect CMB and 21 cm due to coupling to γ

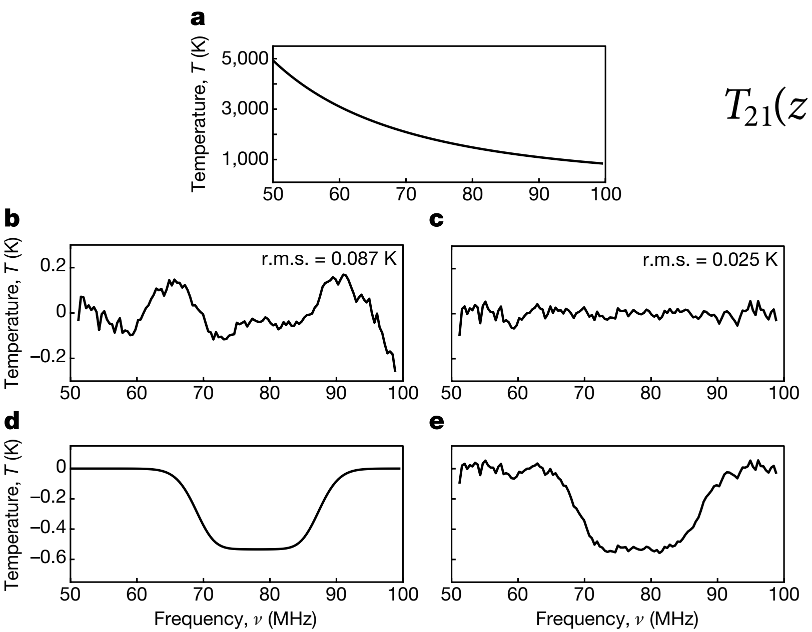
EDGES result: cosmic 21 cm

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]



$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground and 21-cm models (**c**). **d**, Recovered model profile of the 21-cm absorption, with a signal-to-noise ratio of 37, amplitude of 0.53 K, centre frequency of 78.1 MHz and width of 18.7 MHz. **e**, Sum of the 21-cm model (**d**) and its residuals (**c**).

$$\text{“}T_R\text{”} = \pi^2\, \omega^{-1} (dn_\gamma/d\omega)$$

EDGES result: too strong?

- The brightness of absorption/emission line:

$$T_{21}(z) \approx 0.023\ \mathrm{K} \times x_{\mathrm{HI}}(z)\left[\left(\frac{0.15}{\Omega_{\mathrm{m}}}\right)\left(\frac{1+z}{10}\right)\right]^{\frac{1}{2}}\left(\frac{\Omega_{\mathrm{b}}h}{0.02}\right)\left[1-\frac{T_{\mathrm{R}}(z)}{T_{\mathrm{S}}(z)}\right]$$

- Notice that these are all measured cosmological parameters, except the spin temperature, but it *cannot drop below baryonic temperature*

- EDGES (*and everyone else*) expected their result to be between -0.3 and 0 K. They got –0.6 K.

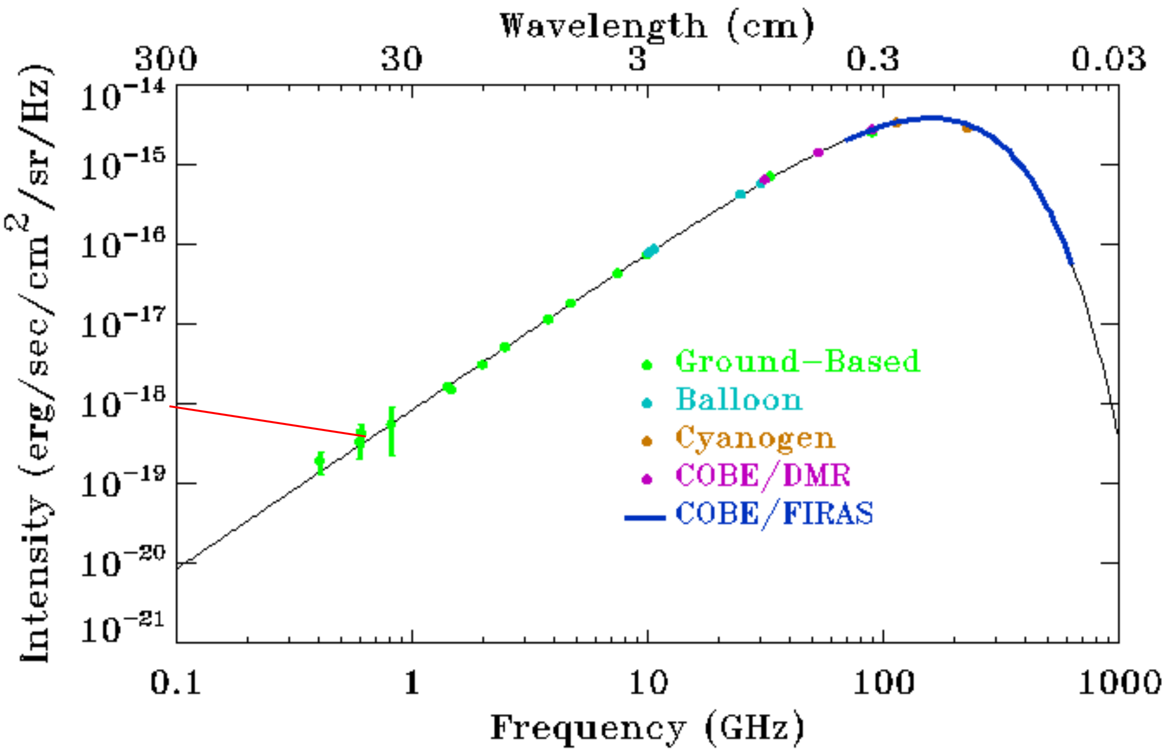
- The result is obviously important – first claimed detection of cosmic 21 cm. Moreover, if they are right about the strength of the coupling it is nothing but revolutionary, as "normal" ΛCDM cannot provide it.

Speculations aimed to explain EDGES

"DM does it to me"? But it cannot be "normal" WIMP or axion with the interactions that are too weak.

- Approach 1: *Cool the baryonic kinetic temperature even more*. (90% of attempts, Barkana; Munoz, Loeb et al; …) . Typically need DM-atom cross section to be enhanced as $\sigma \sim \sigma_0 v^{-4}$, which is Coulomb-like dependence. *Implication: a significant fraction of DM has a millicharge*. *Not clear if these models survive all the constraints*. (See also earlier paper Tashiro, Kadota, Silk, 2014)
- Approach 2: *Make more photons that can mediate F=0, F=1 transitions prior to z=20*. (That would raise "effective" T_{CMB} at the IR (or we call it RJ) tail). I.e. need a specific IR distortion of the CMB. *Almost impossible to arrange due to DM decay straight into photons*.
- Approach 3: Decouple protons from CMB earlier (Falkowski's talk)

CMB Planckian spectrum



$$x \equiv \omega/T_{\rm CMB}$$

- The Rayleigh-Jeans part of the spectrum at x ~ 10^{-3} is not measured – dominated by the foreground + diffuse emission. Part of it could be primordial.

- Yet there is a very important application/use of this part, as a background line for the hydrogen h.f. transition (aka 21 cm)

How much quanta does RJ tail has?

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

- Take $x_{max} \sim 2\ 10^{-3}$. The total number of such quanta is relatively small relative to $n_{CMB} = 0.24\ T^3$,

$$n_{RJ} / n_{CMB} \sim 10^{-6}.$$

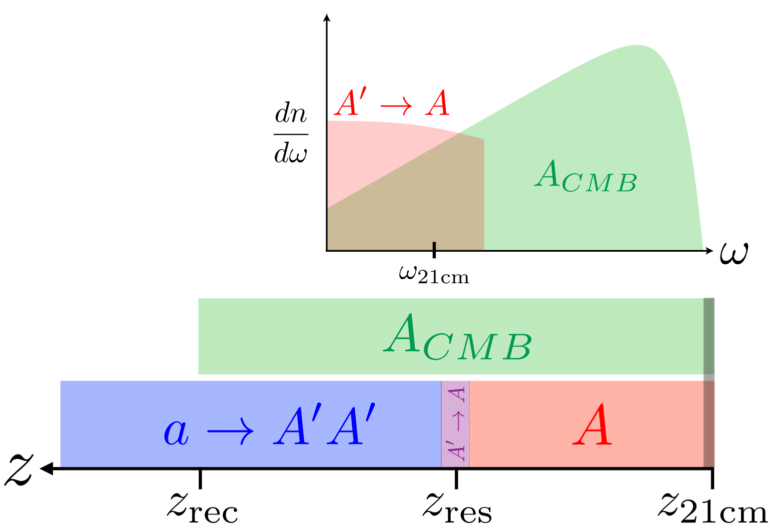
- What if there existed *early* DR that we could take to saturate as much as $N_{eff} = 0.5$ or alternatively, there is late decay of DM to DR, and we take up to 5% of DM to convert?

$$n_{\rm DR} \leq 1.5\times 10^2\, n_{\rm CMB}, \quad \text{early DR with } \Delta N_{\rm eff} = 0.5$$
$$n_{\rm DR} \leq 3.3\times 10^5\, n_{\rm CMB}, \quad \text{late decay of } 0.05\,\rho_{\rm DM}\ .$$

- It is easy to see that one could have 10^{11} more "dark" quanta in the RJ tail without running into problems of too much energy stored in DR. *Can we make them interacting DR quanta?*

Our proposal

- Step 1: Early (z > 20) decays (either of DM or of another DR species) create a *nonthermal* population of DR *dark photons A'*. Typical multiplicities are larger than n_{RJ}.
- Step 2: Dark photons can oscillate to normal photons. At some redshift z_{res}, a resonant conversion of A'→A occurs. This happens when plasma frequency becomes equal to $m_{A'}$.
- Step 3: *Enhanced* number of RJ quanta are available in the z = 15-20 window, making a deeper than expected absorption signal.



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

Example model we consider

- Light DM a, decaying to two dark photons via and ALP coupling:

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

- Dark photon mixes with EM via "familiar' kinetic mixing

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

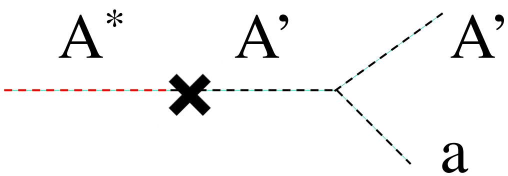
The decay rate of $a \to 2A'$ is

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

"direct" decay of DM into photons is very constrained. f_a is limited above 10^{10} GeV (and e.g. $\tau_{\rm a} > 10^{20}\ \tau_{\rm U}$)

Constraints from stellar `cooling`

- Direct production of dark photons is suppressed by $(m_{A'}/m_A)^2$.
- γ^* → to aA' production is possible due to combination of ε and f^{-1}.



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

- One can normalize it on known cases of γ^* → to $\nu\nu$ decays due to a possible neutrino magnetic moment, $Q = \mu^2 m_A^4 n_T (24\pi)^{-1}$
- Resulting bound: $\epsilon \times f_a^{-1} < 2 \times 10^{-9} \times \mathrm{GeV}^{-1}$

(with f's in the weak scale range, ε can be as large as 10^{-7}.)

Why simpler model a→2A does not work

(Fraser et al).

Take a simple axion-type model:

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{m_a^2}{2}a^2 + \frac{a}{4f_a}F_{\mu\nu}\hat{F}^{\mu\nu}$$

The decay rate of $a \to 2A$ is

10^{-18} $\quad$ 10^9 GeV

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

Limits of 10^9 GeV come from stellar energy losses + direct constraint on the coupling by *CAST experiment here at CERN*.

But a → 2 A’ → 2 photons may (and will) work due to a large enhancement in the A’→A oscillations during propagation due to a resonance.

Photon-dark photon mixing

- Polarization operator matrix Π for A-A' system.
- $\varepsilon F_{\mu\nu} F_{\mu\nu}' \rightarrow \varepsilon m_{A'}^2 A_\mu A_\mu'$ is the first step on-shell reduction.

- "Effective mass" matrix Π for A-A' system.

$$\begin{bmatrix} \omega_{pl}^2(z) & \varepsilon m_{A'}^2 \\ \varepsilon m_{A'}^2 & m_{A'}^2 \end{bmatrix}$$

$\omega_{pl} \ll m_{A'}$, vacuum oscillation, $\theta_{eff} = \varepsilon$ (and $\omega^2_{pl} = 4\pi\alpha\, n_e / m_e$)

$\omega_{pl} \gg m_{A'}$, in-medium oscillations, $\theta_{eff} = \varepsilon \times (m_{A'}^2 / \omega_{pl}^2(z))$

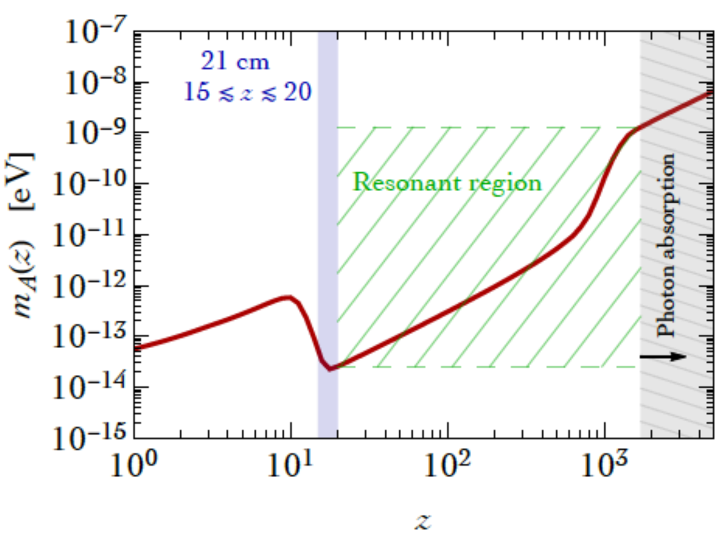
Resonance occur when $m_{A'} = \omega_{pl}(z)$

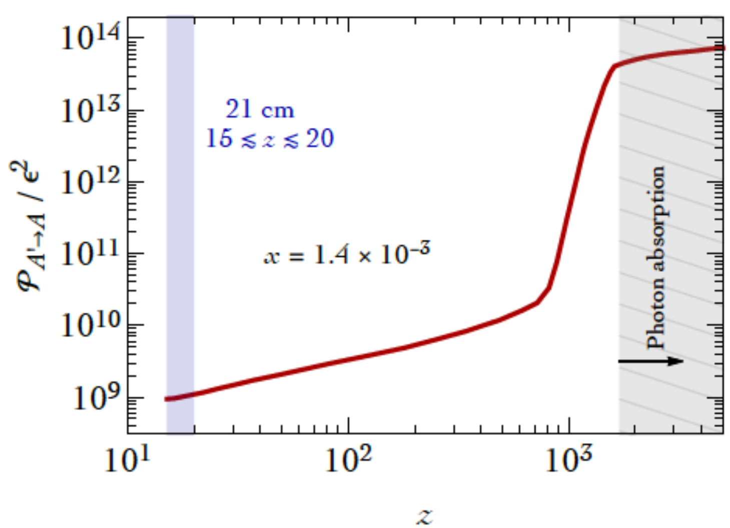
Resonant oscillations

$$P_{A\to A'} = P_{A'\to A} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \times \left| \frac{d \log m_A^2}{dt} \right|^{-1}$$

Considered in detail by Mirrizzi, Redondo, Sigl, 2009 (This is in the limit P<<1. For neutrino experts, this corresponds to MSW type oscillation with large degree of non-adiabaticity. Treated using the so-called Landau-Zenner approach, see e.g. S. Parke, 1986)

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





Most importantly, $P \sim \varepsilon^2 \times 10^{10}$, not $P \sim \varepsilon^2$!

Important points:

- DM $\rightarrow \gamma\gamma$ idea (to e.g. double RJ photon counts) would not work: once the stellar constraints are implemented, then there is not enough rate to create extra RJ photons

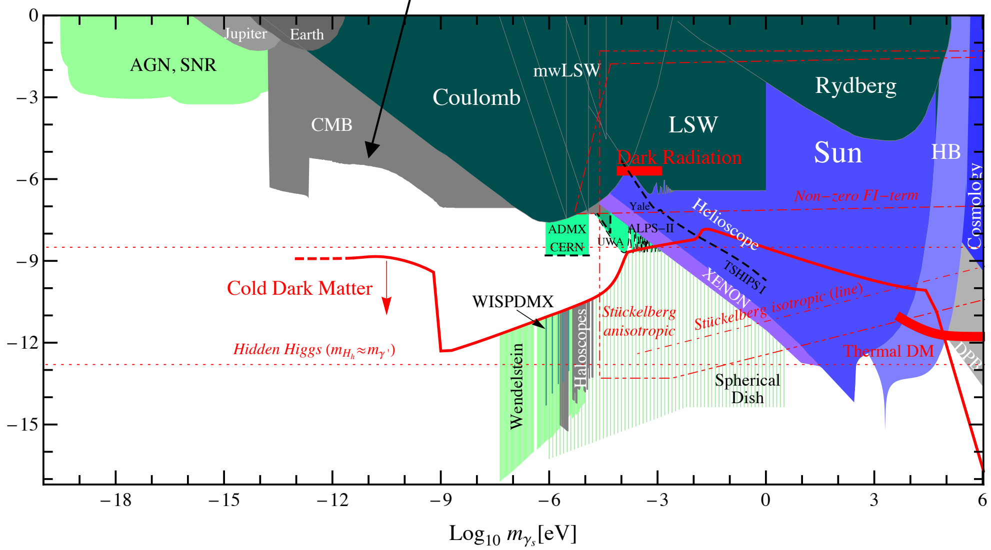
- DM $\rightarrow \gamma'\gamma'$, followed by $\gamma' \rightarrow \gamma$ idea works because resonant conversion probability is huge, $P_{\gamma' \rightarrow \gamma}/\varepsilon^2 \sim 10^{10}$ or more!

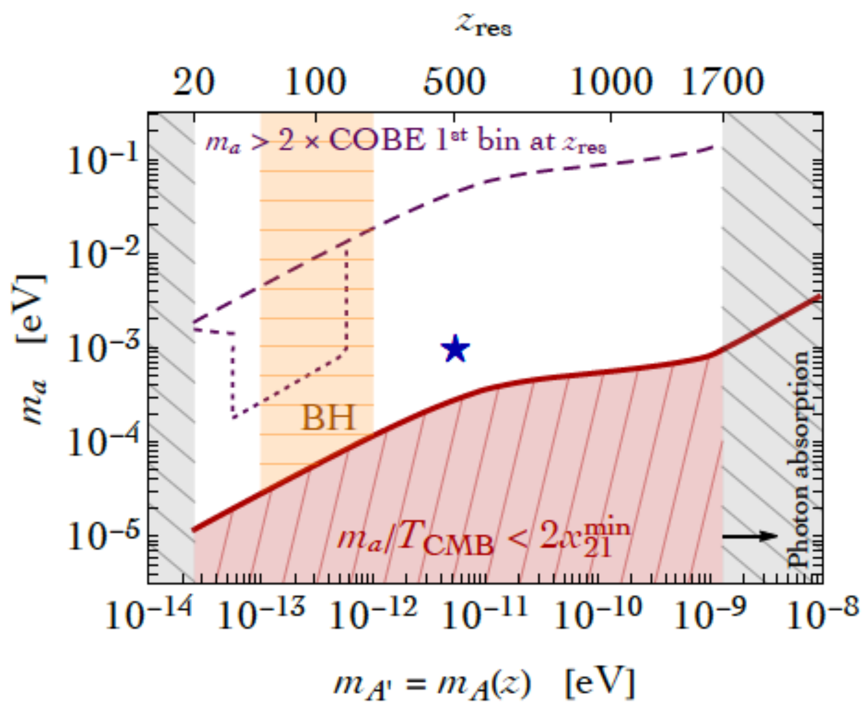
- Also, the oscillation probability is $\sim \omega^{-1}$, making the probability three orders of magnitude larger for 21 cm relevant photons compared to
  $x \sim O(1)$.

- The resonance is to occur between ~ 20 and 1700. Below – no effect on 21 cm, above – absorption of RJ photons by `free-free` processes (re-thermalization).

Constraints from spectral CMB distortions

- COBE/FIRAS measurement (NP 2006), perfect (1 part is 10^4) spectrum above x = 0.2

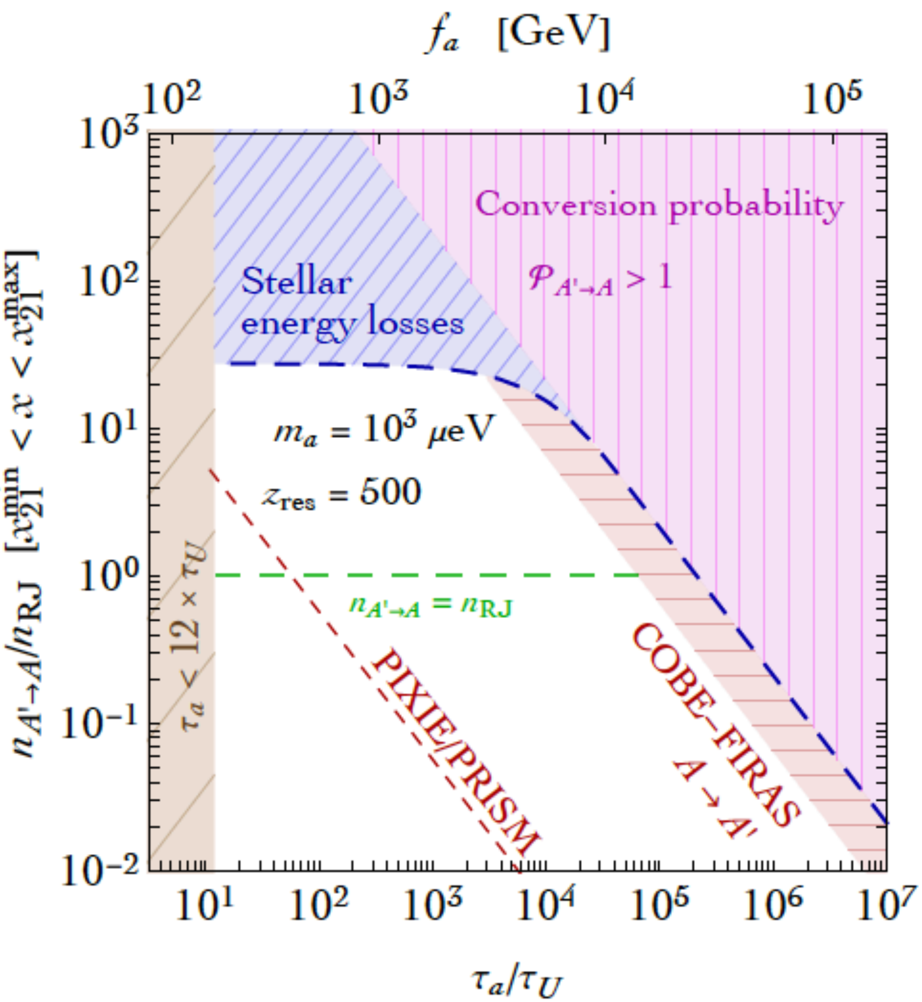




- Mixing angles as large as 10^{-7} are perfectly OK.

DM lifetime vs RJ counts

- Fixing the mass of decaying DM particles [as an example] to 10^{-3} eV, and resonant transition to occur at z=500, we scan different lifetimes:



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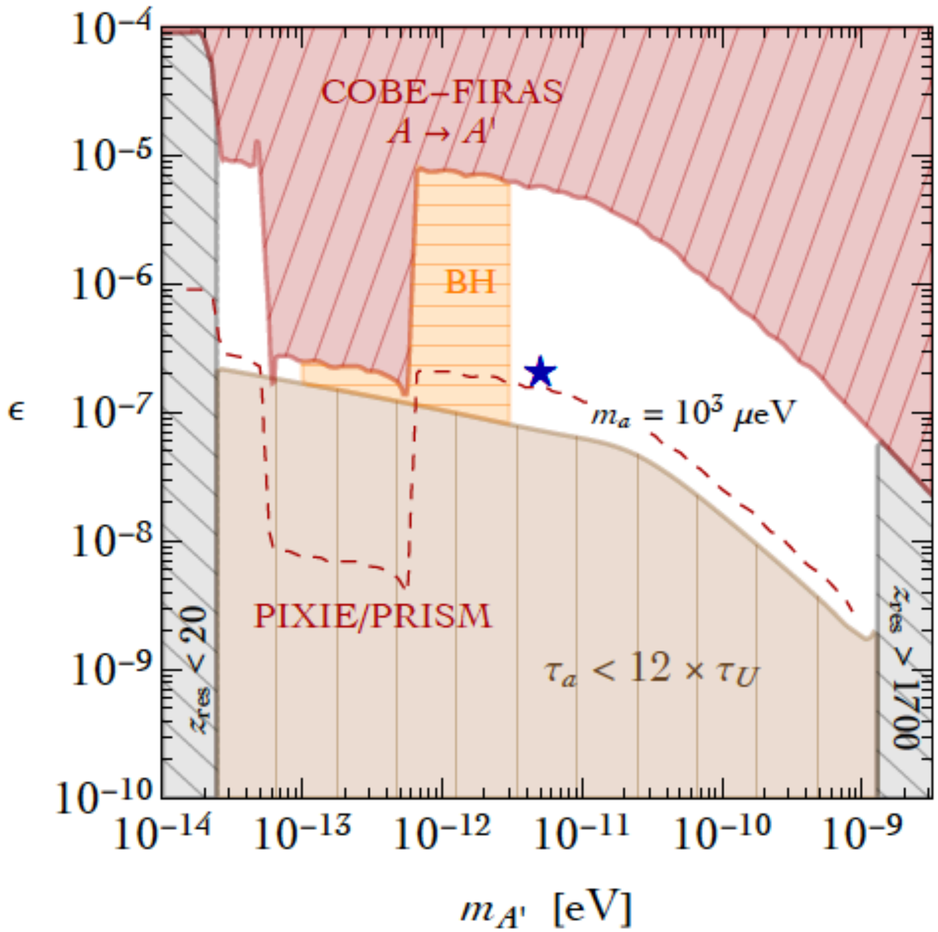
Along the green line one can double the actual RJ photon counts. Current limits from COBE are not super-restrictive. Future probes (PIXIE) could make it more restrictive.

Mixing angle – mass parameter space

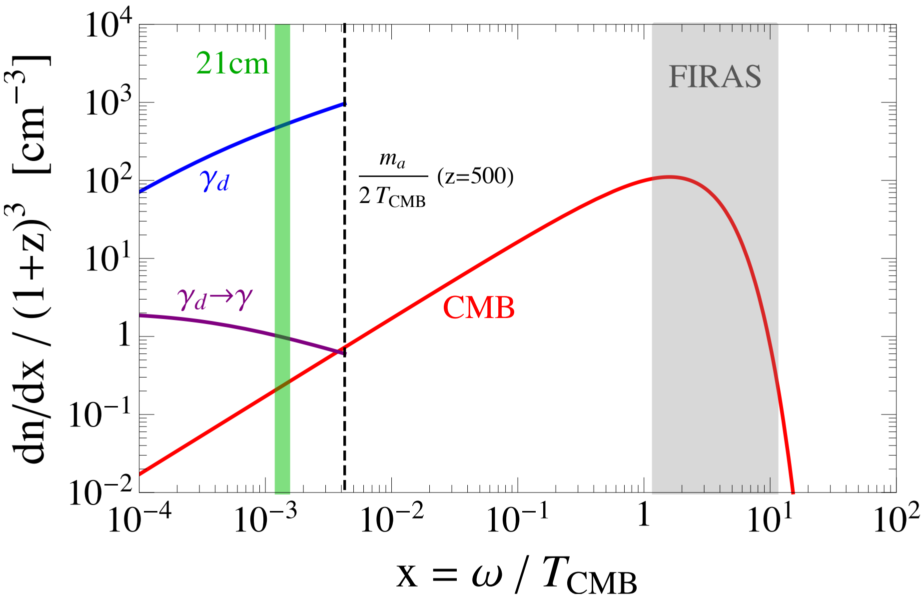
- Taking one parameter space point for DM *a* of meV mass, and *requiring RJ photon counts to double*:

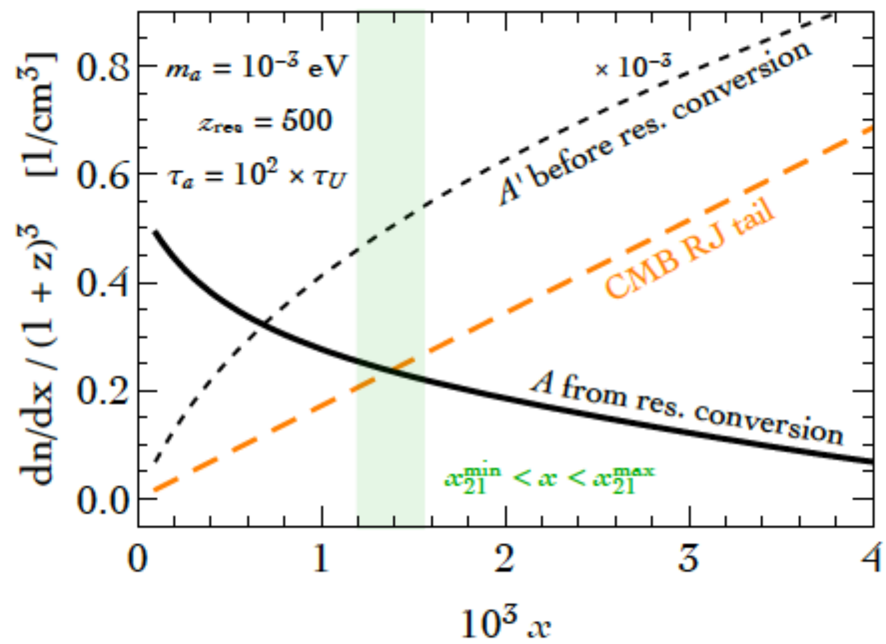


- Lot of parameter space is allowed. (BH super-radiance may be a limit)

RJ tail of the CMB spectrum

- For one specific point on parameter space (meV DM, z=500 resonance, lifetime = 100 ages of Universe)

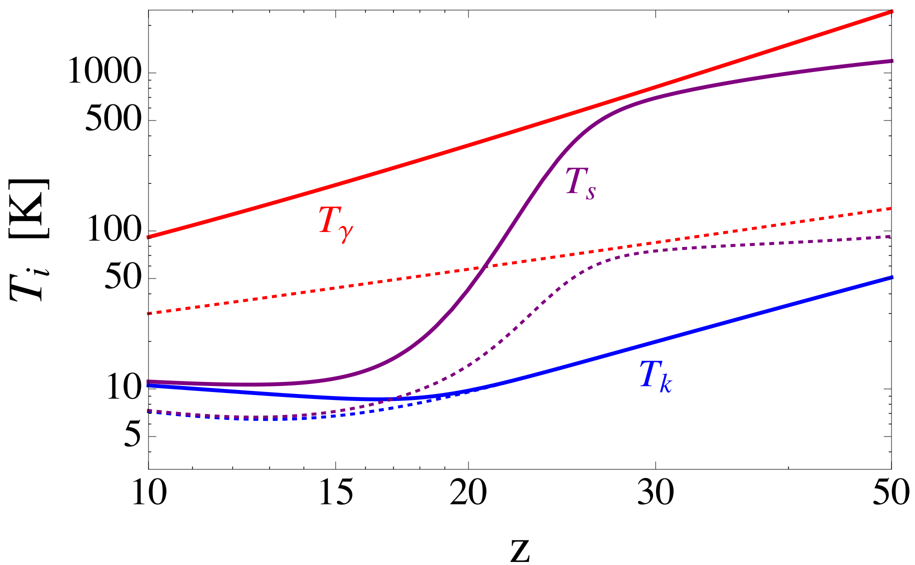


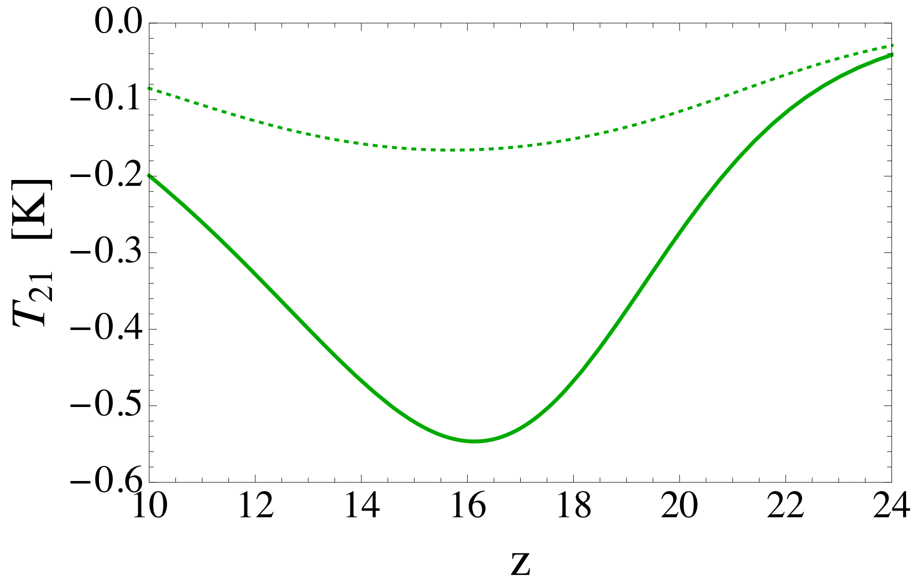


- Green band – interesting for 21 cm range of x, $x \in (x_{21}^{\rm min}, x_{21}^{\rm max}) = (1.2, 1.6) \times 10^{-3}$

Further developments

- Following Kaurov, Venumadhav, Dai, Zaldarriaga, 1805.03254, we implemented the mathematica code for calculating 21 cm spectra for different models with additional photon injection.



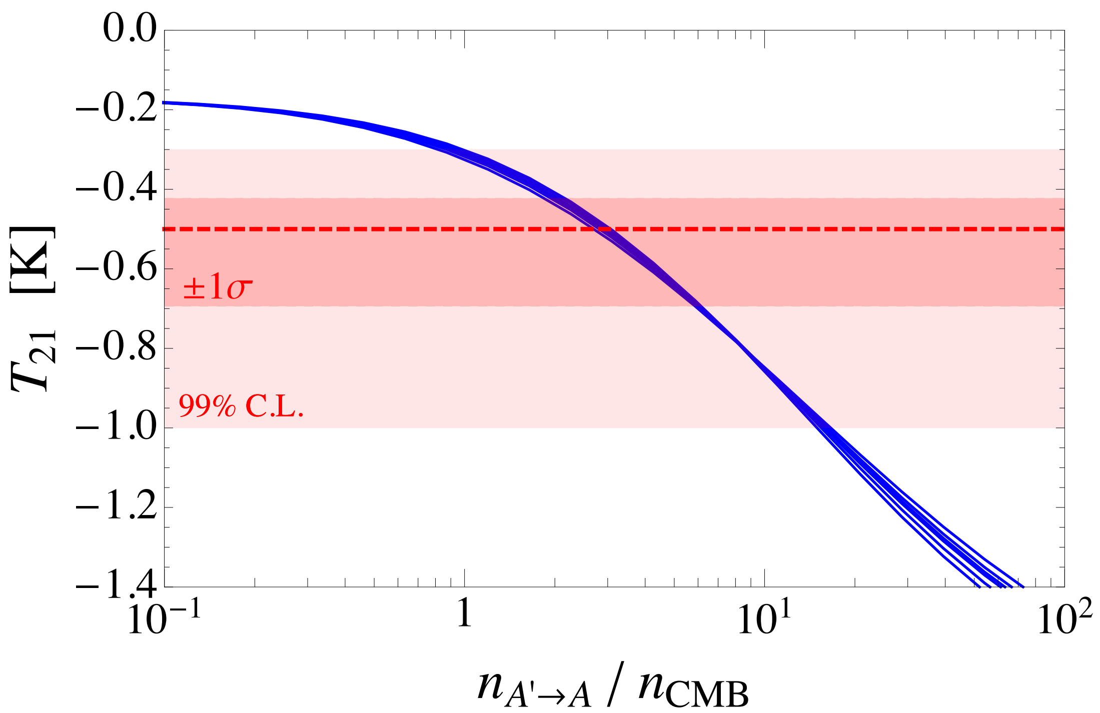


(dashed – "standard" curves, solid – with "extra" photons. Caveat – need to implement further x-ray heating, which will furnish a "termination" of the absorption feature.)

Using the strength of the EDGES signal, we can now estimate ourselves the required degree of enhancement in the RJ tail.

Further developments

- Varying the spectral form of the extra injected photon spectrum, and comparing it with EDGES signal strength, we derive the required degree of enhancement,



- Model dependence is rather weak. Typically need 2-20 enhancement
- Strong dependence of how you treat EDGES feature.

Other options for DR affecting 21 cm

- DR ALP oscillating into photons in the primordial magnetic field. (Moroi et al, 1804.10378, also our group, unpublished)
- Millicharge of neutrino fluid (which can be colder than baryons) ← does not seem to work given 10^{-14} e constraint on neutrino charges.
- Cascade decay of once thermal species (including neutrino decay, such as ν_2 → A' ν_1 followed by A'→A oscillations). Cascade decay make things increasingly softer.

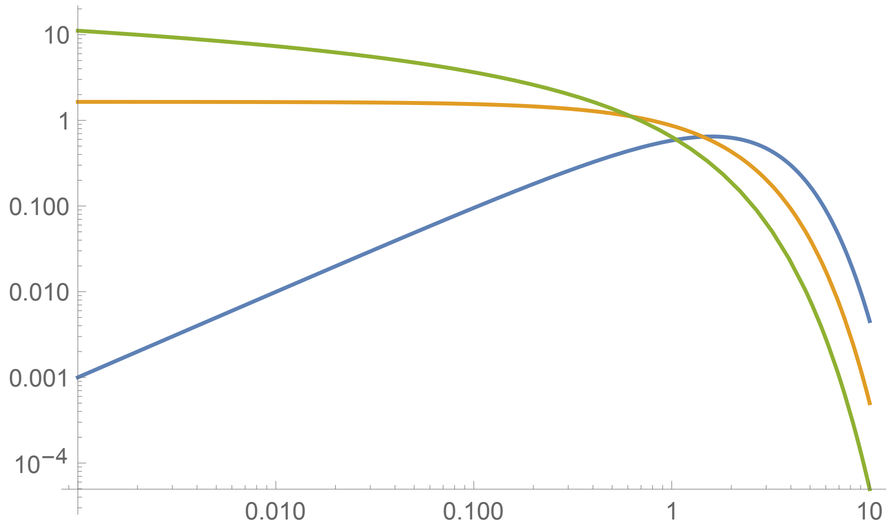


Figure 1: Blue: $x^2/(e^x - 1)$ distribution (i.e. Planckian); Brown: same after one decay; Green: same after two decays.

Conclusions

1. Dark Radiation is a generic possibility – and can contribute into relevant physics not only through total energy density but through its interactions.

2. *We have explicit class of models that can account for EDGES signal strength by supplying extra photons.* While sources of DR could vary (decay of DM, early decay of relics), the key feature is resonant conversion that transfers A' to normal EM sector.

3. 21 cm cosmological signal, then, provides the key test of such models with beyond-SM sectors composed of light fields.