Dark radiation, Rayleigh-Jeans tail, 21cm cosmology and all that

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Cui, Pospelov, Pradler, 2017, PRD to appear

Pospelov, Pradler, Ruderman, Urbano, 2018, subm to PRL

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PERIMETER INSTITUTE FOR THEORETICAL PHYSICS

Plan

1. *Introduction.* Cosmology as a tool of learning about new physics. Dark matter; dark energy; … dark radiation?

2. *Dark radiation of numerous soft quanta* in the RJ tail.

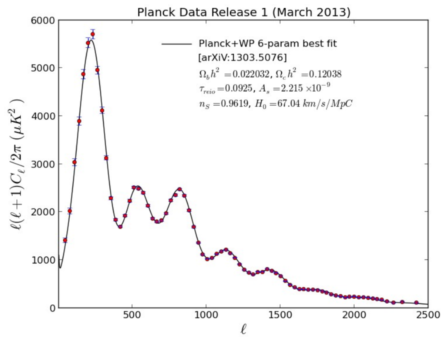
3. Implication for EDGES result

4. *Dark radiation of rare hard quanta*. Signals for direct DM detection.

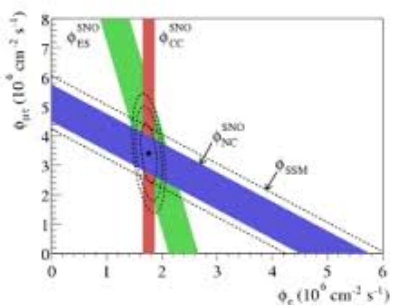
5. Conclusions

Clues for new physics

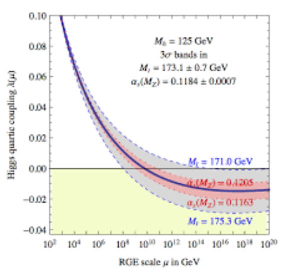
1. *Precision cosmology:* 6 parameter model (Λ-CDM) correctly describes statistics of 10^6 CMB patches. Existence of dark matter and dark energy. Strong evidence for inflation.



2. *Neutrino masses and mixing:* Give us a clue [perhaps] that there are new matter fields beyond SM. Some of them are not charged under SM.

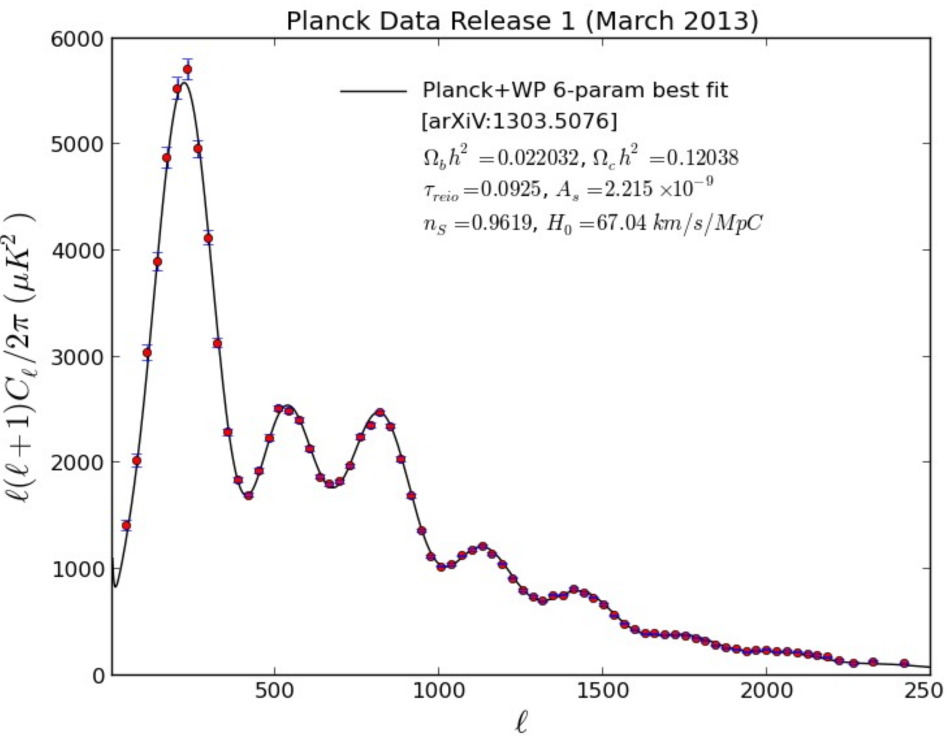


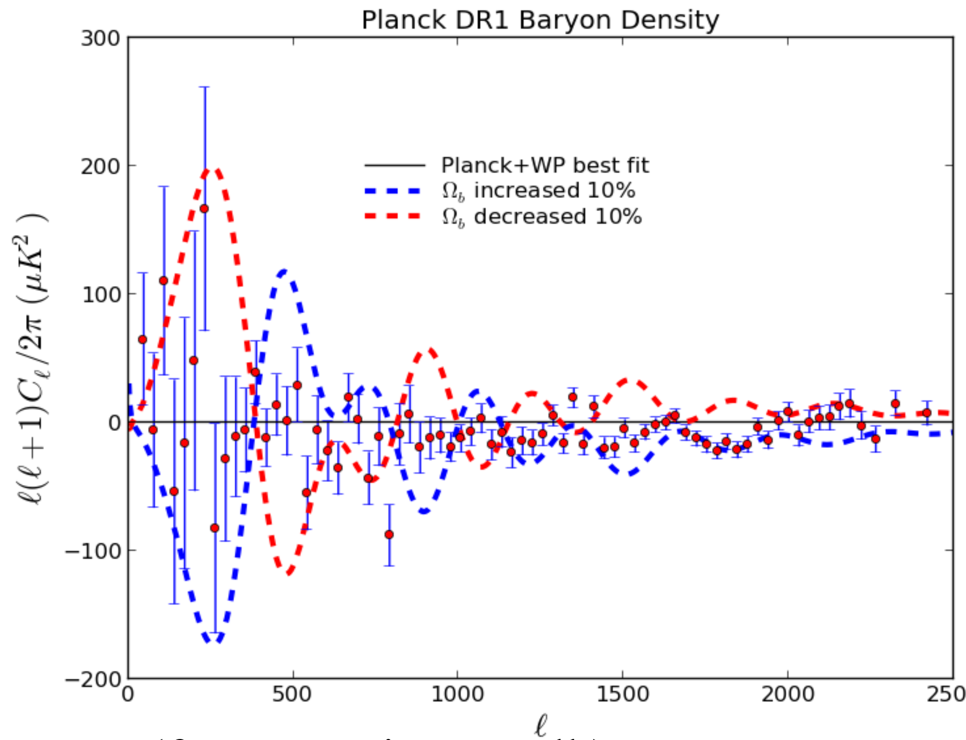
3. *Theoretical puzzles:* Strong CP problem, vacuum stability, hints on unification, smallness of m_h relative to highest scales (GUT, M_{Planck})



4. *"Anomalous results":* muon g-2, "proton radius puzzle", "cosmological lithium problem", small scale CDM problems…

Data from first Planck release in 2013



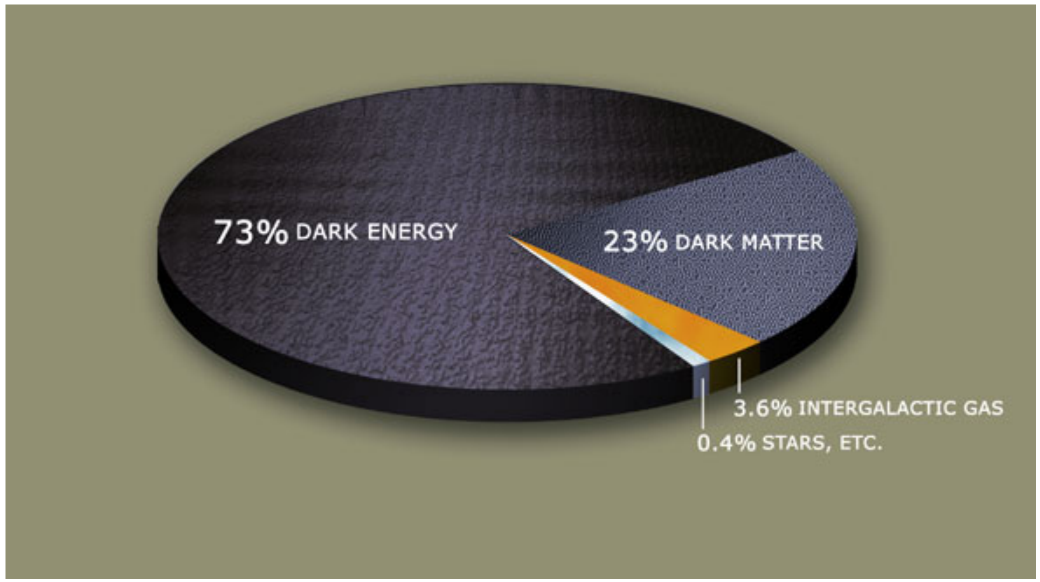


(from W Kinney talk)

Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

Parameter	Value (95%)
Ω_K	-0.0005±0.006
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

Cosmological surprises



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

Dark Forces? Dark radiation?

DM classification

At some early cosmological epoch of hot Universe, with temperature T >> DM mass, the abundance of these particles relative to a species of SM (e.g. photons) was

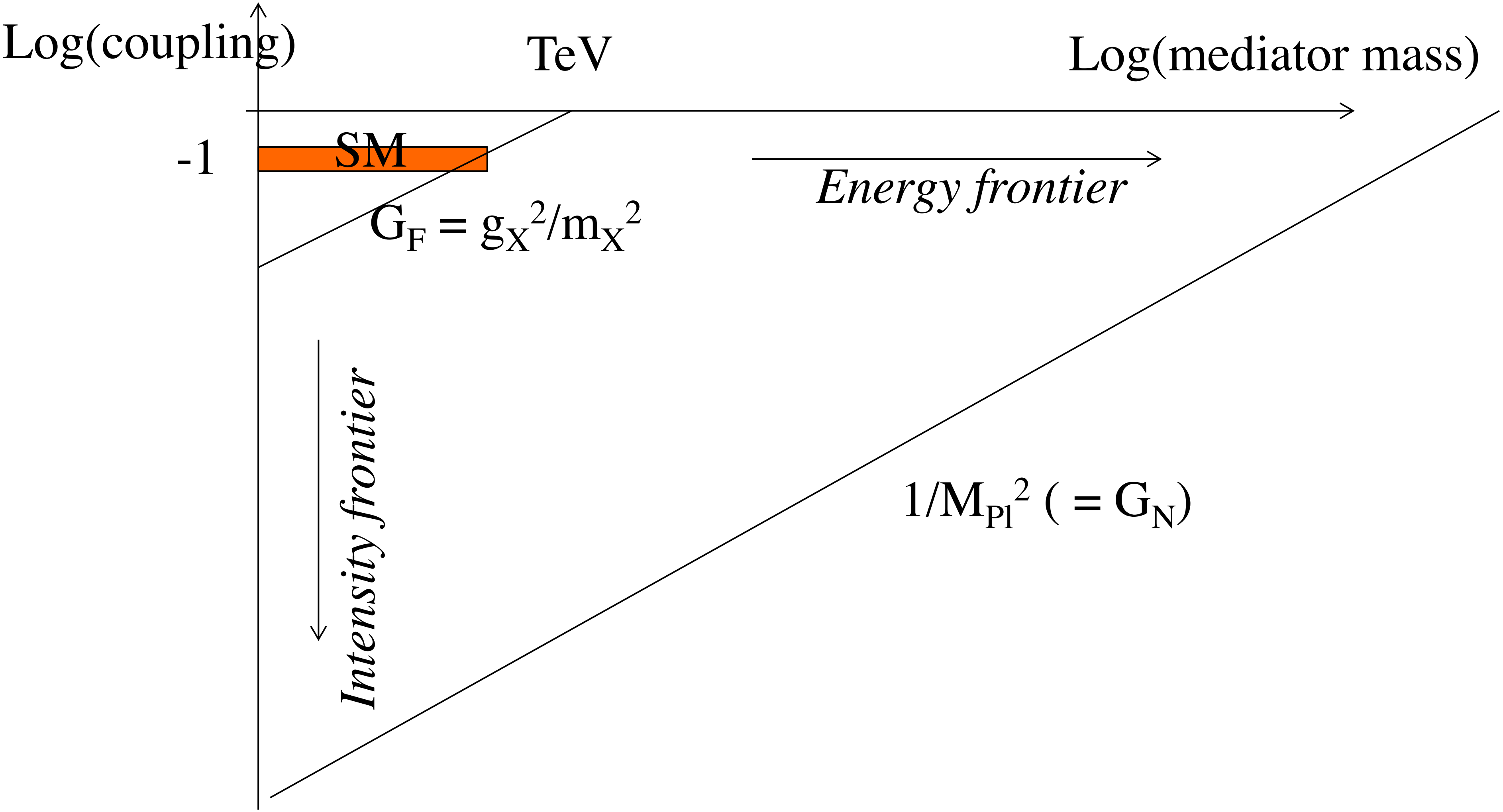
Normal: Sizable interaction rates ensure thermal equilibrium, $N_{DM}/N_\gamma = 1$. Stability of particles on the scale $t_{Universe}$ is required. *Freeze-out* calculation gives the required annihilation cross section for DM --> SM of order ~ 1 pbn, which points towards weak scale. These are **WIMPs**. Asymmetric DM is also in this category.

Very small: Very tiny interaction rates (e.g. 10^{-10} couplings from WIMPs). Never in thermal equilibrium. Populated by thermal leakage of SM fields with sub-Hubble rate (*freeze-in*) or by decays of parent WIMPs. [Gravitinos, sterile neutrinos, and other "feeble" creatures – call them **superweakly interacting MPs**]

Huge: Almost non-interacting light, m< eV, particles with huge occupation numbers of lowest momentum states, e.g. $N_{DM}/N_\gamma \sim 10^{10}$. "Super-cool DM". Must be bosonic. Axions, or other very light scalar fields – call them **super-cold DM**.

Coupling vs mass plot

In 2012-2013 LHC experiments discovered a new particle (Higgs boson) and a new force (Yukawa force). What do we know about forces in nature ?



Neutral "portals" to the SM

Let us *classify* possible connections between Dark sector and SM

$H^+H\,(\lambda\, S^2 + A\, S)$ Higgs-singlet scalar interactions (scalar portal)

$B_{\mu\nu} V_{\mu\nu}$ "Kinetic mixing" with additional U(1)' group

(becomes a specific example of $J_\mu^i A_\mu$ extension)

$LH\,N$ neutrino Yukawa coupling, N – RH neutrino

$J_\mu^i A_\mu$ requires gauge invariance and anomaly cancellation

It is very likely that the observed neutrino masses indicate that Nature may have used the *LHN* portal…

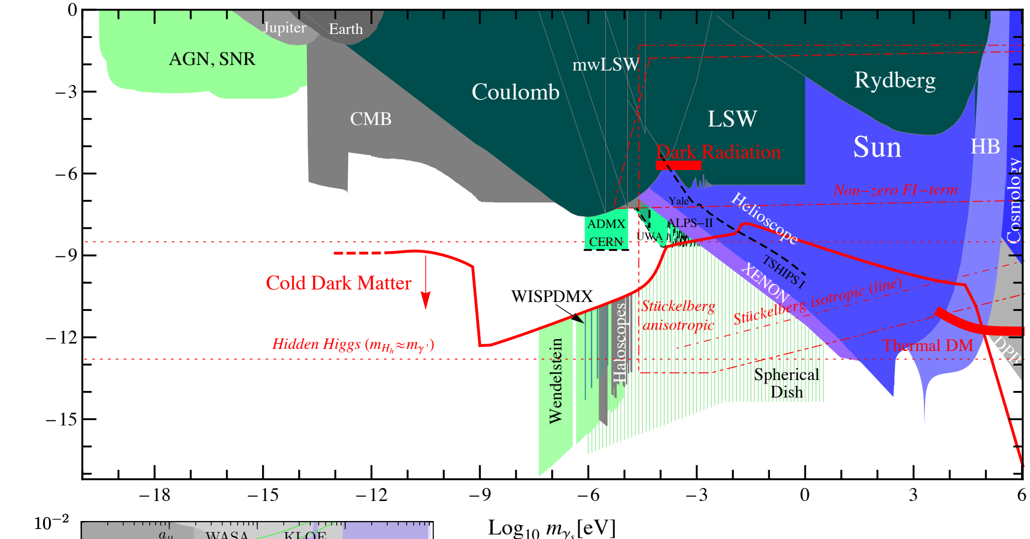
Dim>4

$J_\mu^A\ \partial_\mu a\,/f$ axionic portal

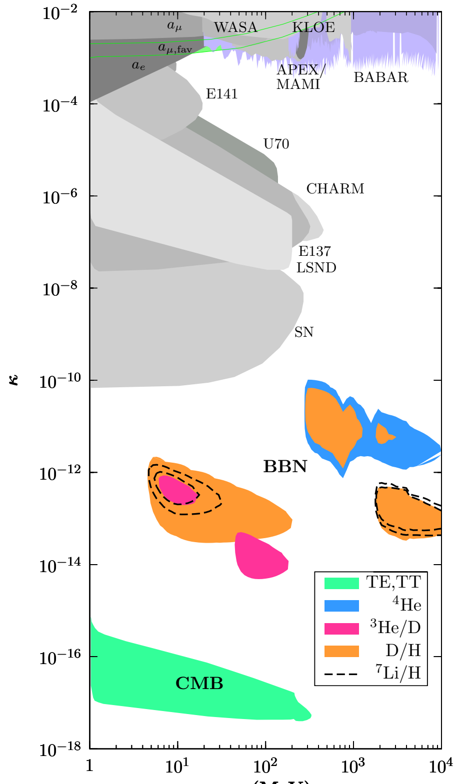
……….

$$\mathcal{L}_{\rm mediation} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\rm med}^{(k)}\mathcal{O}_{\rm SM}^{(l)}}{\Lambda^n},$$

Constraints on dark photon in broad mass range



Going to smaller mass range (our group, An et al, 2013, has derived correct stellar energy loss constraints)



Going to smaller couplings: new primordial nucleosynthesis and CMB constraints from late decays of dark photons, (our group, Fradette et al, 2014)

Dark Radiation?

- ”Dark radiation” existed in the form of neutrinos. At the time of the matter-radiation equality, about 40% of radiation energy density was encapsulated by neutrinos, and is fully captured by both BBN and CMB.
- New radiation like degrees of freedom ($p_{DR} = 1/3\ \rho_{DR}$) are limited by N_{eff}. SM predicts 3.04. Current limit is 3.04 +/- 0.3. *Strong constraint on fully thermalized species*.
- New DR? If not interacting with the SM – only through N_{eff}. However, if there is interaction, we have additional ways of probing DR.
- In this talk, I will cover two general cases for DR.

Two cases for Dark Radiation

- Case 1: numerous soft quanta

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

- Case 2: fewer hard quanta

$$n_{\rm DR} \ll n_\gamma, \ \ E_{\rm DR} \gg E_\gamma, \ \ \rho_{\rm DR}(\sim E_{\rm DR} n_{\rm DR}) \leq 0.1 \rho_{\rm DM}$$

First case for Dark Radiation

- Numerous soft quanta $\omega_{\rm DR} \ll \omega_{\rm CMB}$, $n_{\rm DR} > n_{\rm RJ}$, $\omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}$

Here $n_{\rm RJ}$ is the Rayleigh-Jeans tail of the CMB:

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

where $x \equiv \omega/T_{\rm CMB}$ is the frequency in units of temperature and $n_{\rm CMB}$ stands for total CMB number density, ~ $0.24 \times T^3_{\rm CMB}$

- Our model-building effort is partially motivated by the EDGES result, Bowman et al., Nature 2018. First claimed detection of cosmic 21 cm signal.
- The most useful energy units for the first part of the talk will be μeV.

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]

- *This is as big a deal in cosmology as it gets*

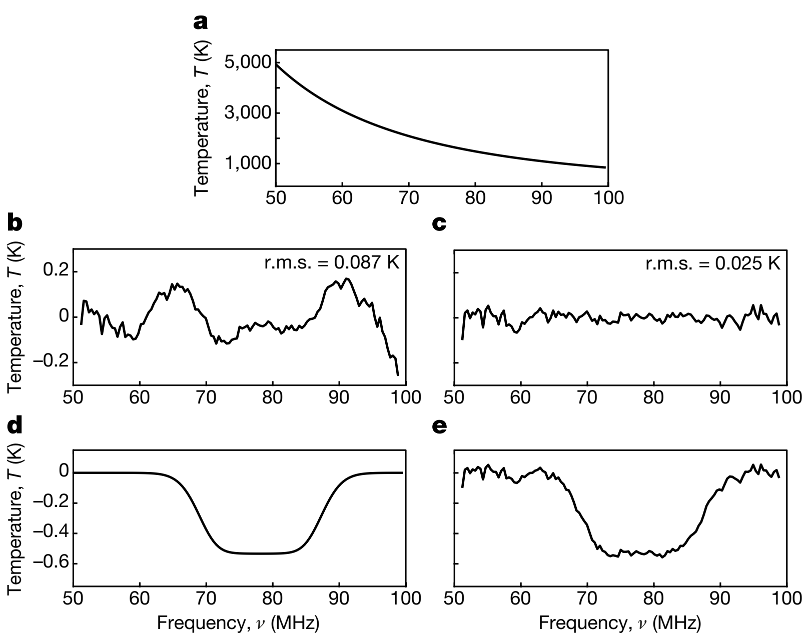
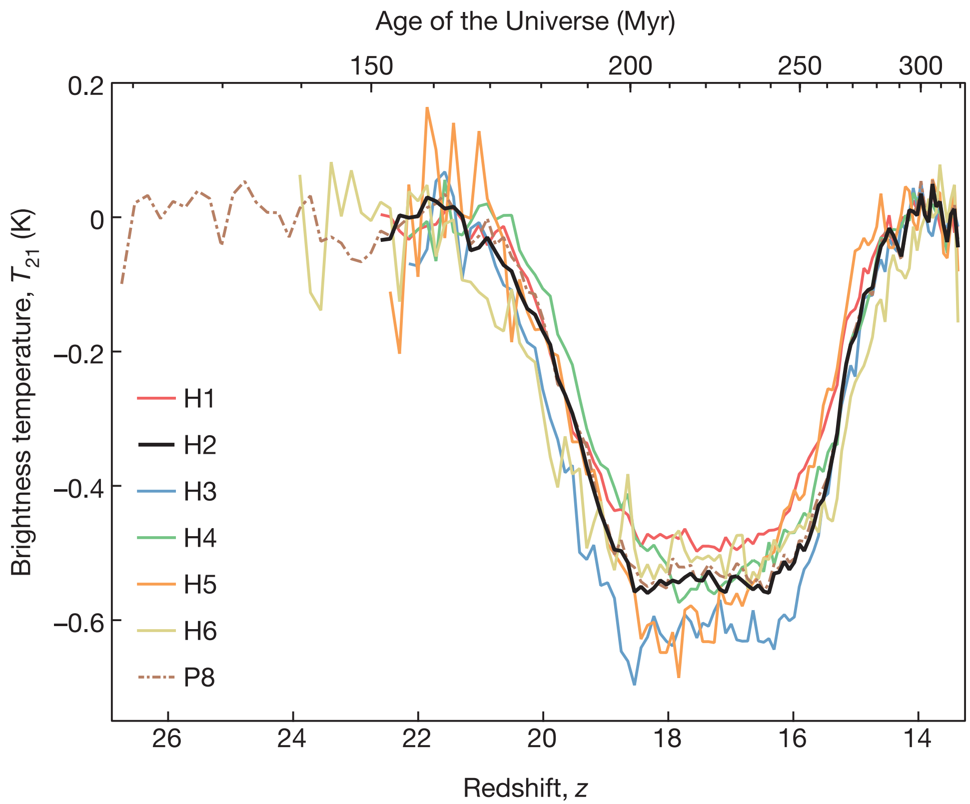


Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground 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**).

Interpretation of observation

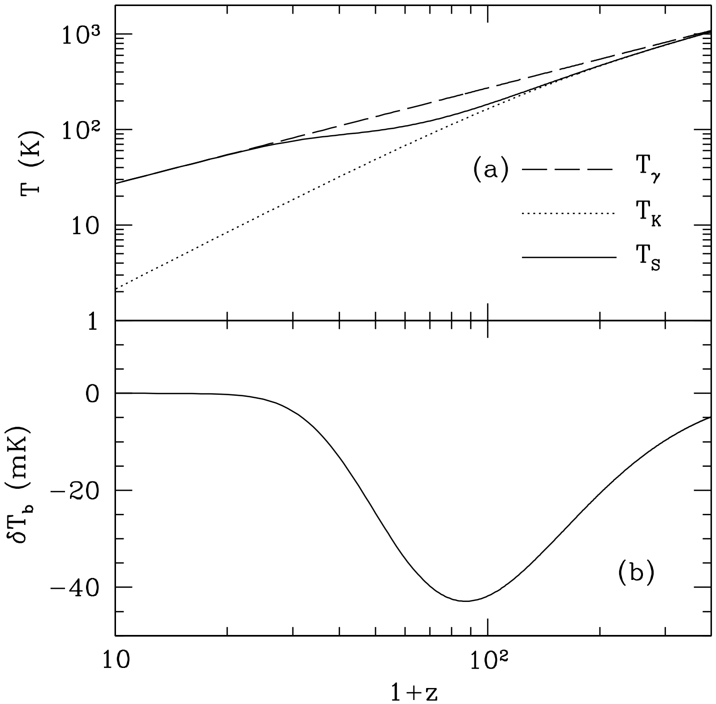
- We see the onset of CMB absorption by effectively colder F=0, F=1 hyperfine states of atomic hydrogen.



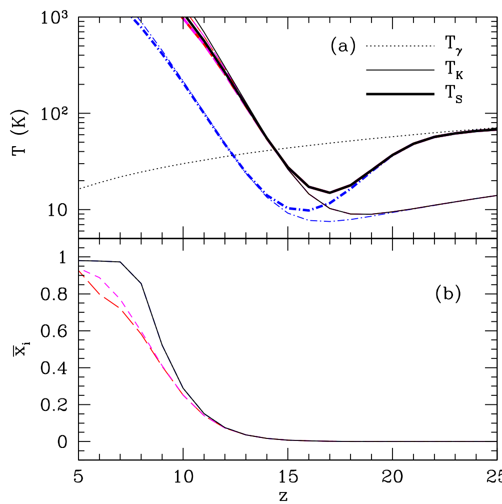
- The strength of the line is actually predicted by standard cosmology, see the literature decade ago, (summarized e.g. in Furlanetto et al, 2006, Phys. Rep.)

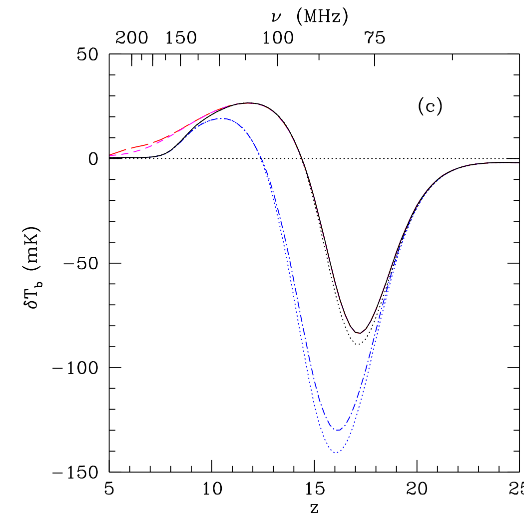
Interpretation of observation

- (Figures from Furlanetto et al, 2006, Phys. Rep.)



Naïve picture





Less naïve: first stars produce Lyman α photons that recouple spin and baryonic temperatures. Later – gas is heated and absorption switches to emission.

The most important point is that *T_s cannot drop below baryonic T_K* !

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

- Usual story: “DM does it to me”. But it cannot be “normal” WIMP or axion with the interactions that are super-weak.

- Approach 1: *Cool the baryonic kinetic temperature even more*. (90% of attempts, 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

- Approach 2: *Make more photons that can mediate F=0, F=1 transitions*. (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.

How much quanta does RJ has?

- Take $x_{max} \sim 2\ 10^{-3}$. The total number of such quanta is relatively small,

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

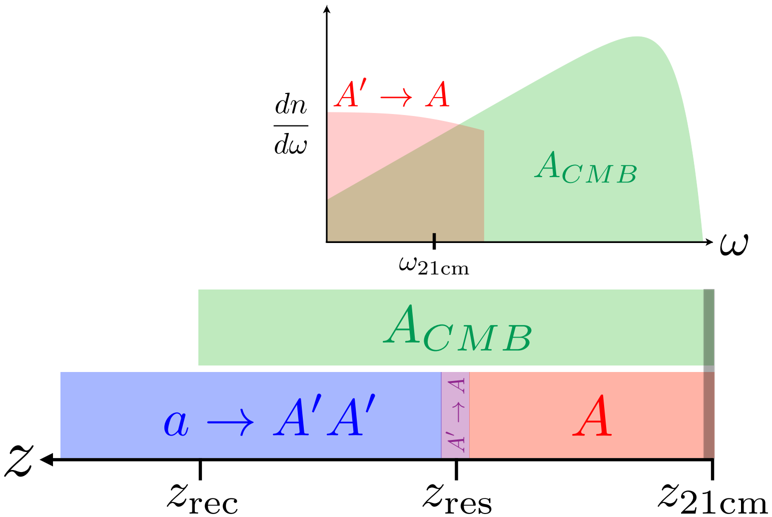
- What if there existed *early* DR that we could take to saturate as much as $N_{eff} = 0.5$ or alternatively, there is late decay of DM to DR, and we take up to 5% of DM to convert?

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

- 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 population of DR *dark photons A'*. Typical multiplicities are larger than n_{RJ}.
- Step 2: 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.



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

Specific 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

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

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

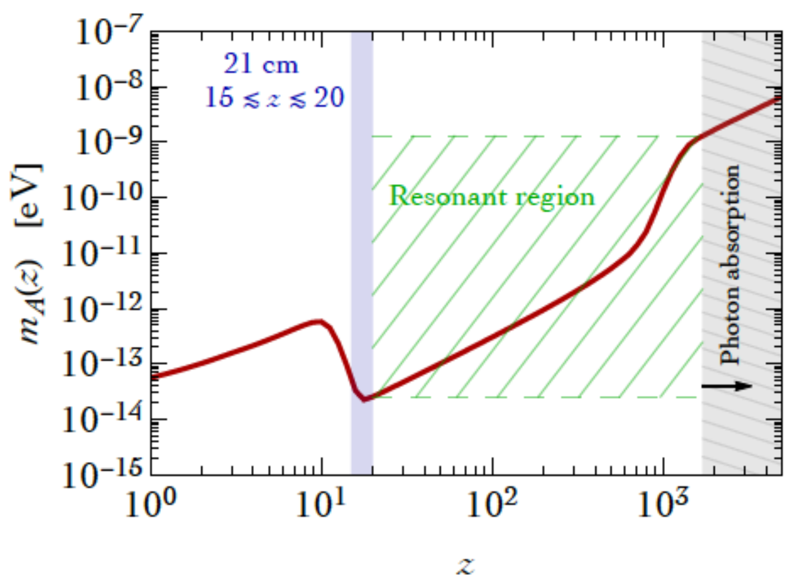
(with f's in the weak scale range, ε can be as large as 10^{-7}.)

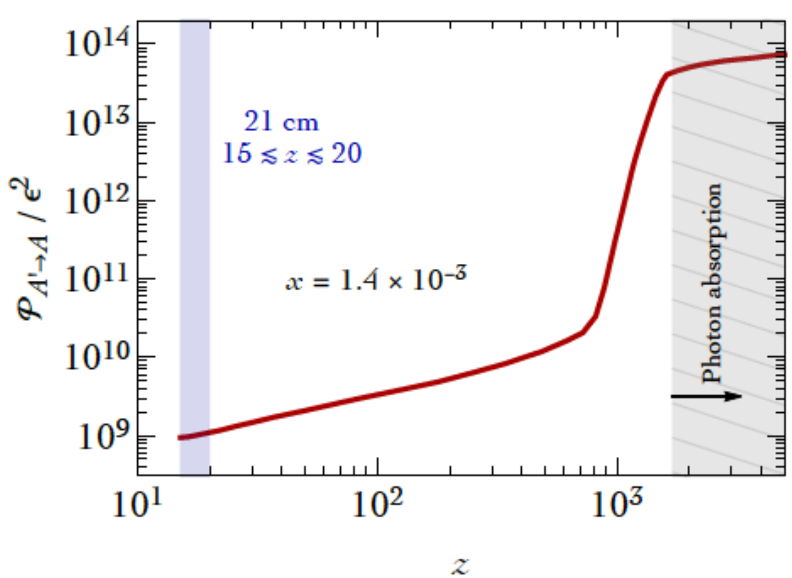
Resonant oscillations

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

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)

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





Important points:

- DM → γγ 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

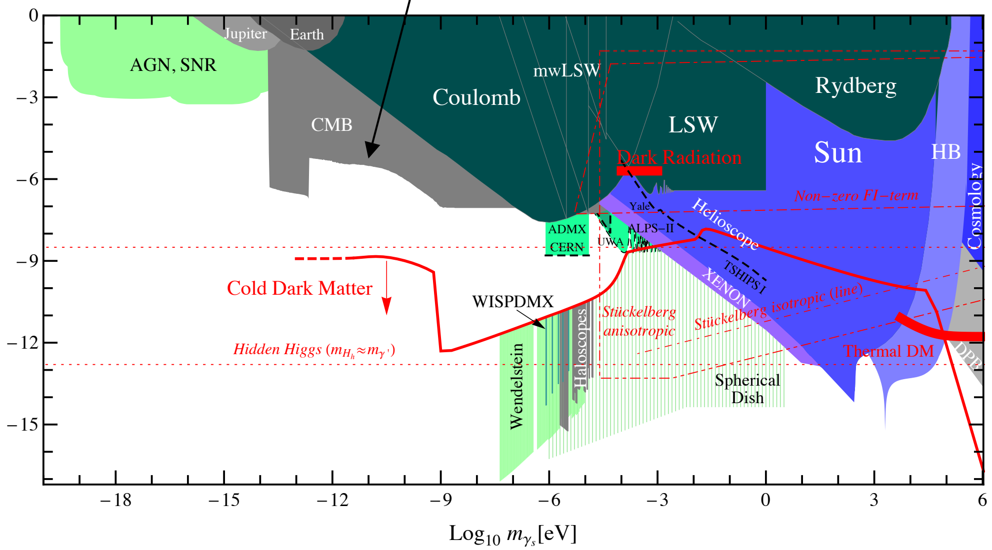
- DM → γ′γ′ , followed by γ′ → γ idea works because resonant conversion probability is huge, $P_{\gamma' \to \gamma}/\varepsilon^2 \sim 10^{10}$ or more!

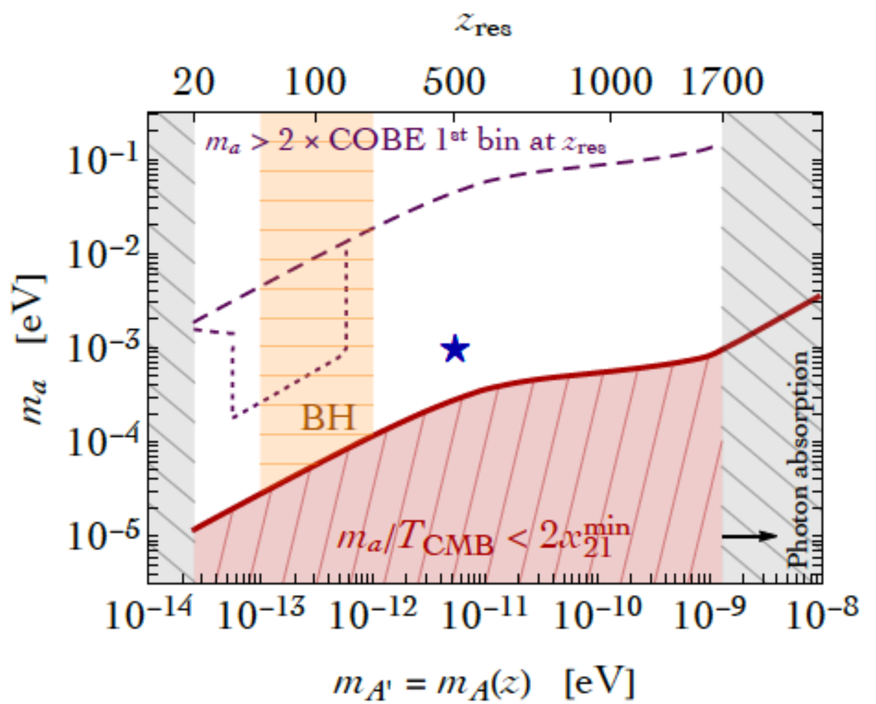
- Also, the oscillation probability is $\sim \omega^{-1}$, making the probability three orders of magnitude larger for 21 cm relevant photons compared to $x \sim O(1)$.

- 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

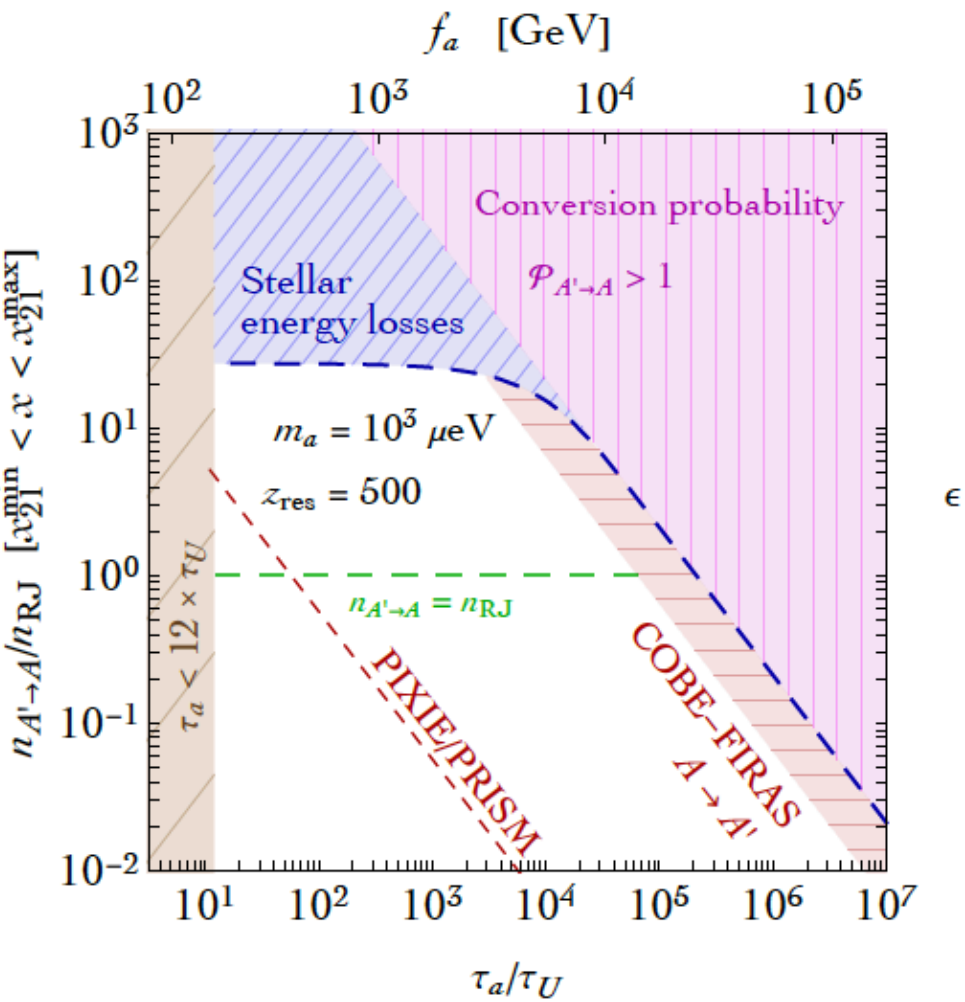




- Mixing angles as large as 10^{-6} are perfectly OK.

DM lifetime vs RJ counts

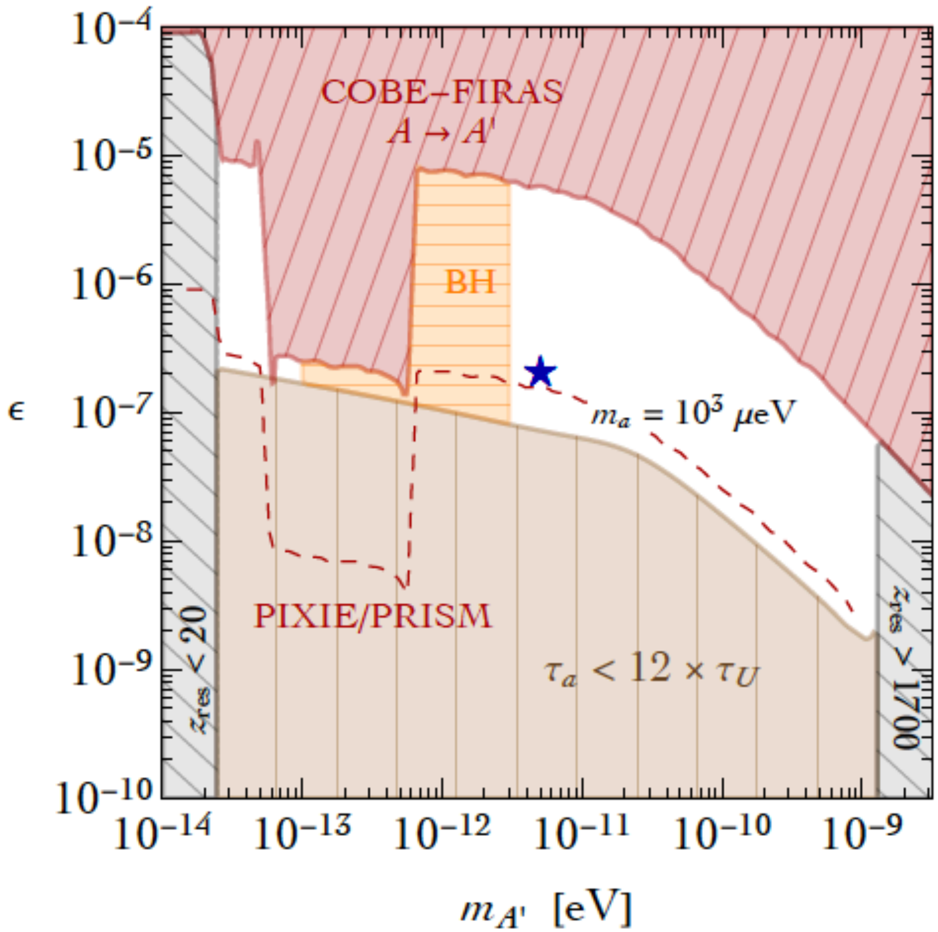
- Fixing the mass of decaying DM particles [as an example] to 10^{-3} eV, and resonant transition to occur at z=500, we scan different lifetimes:



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

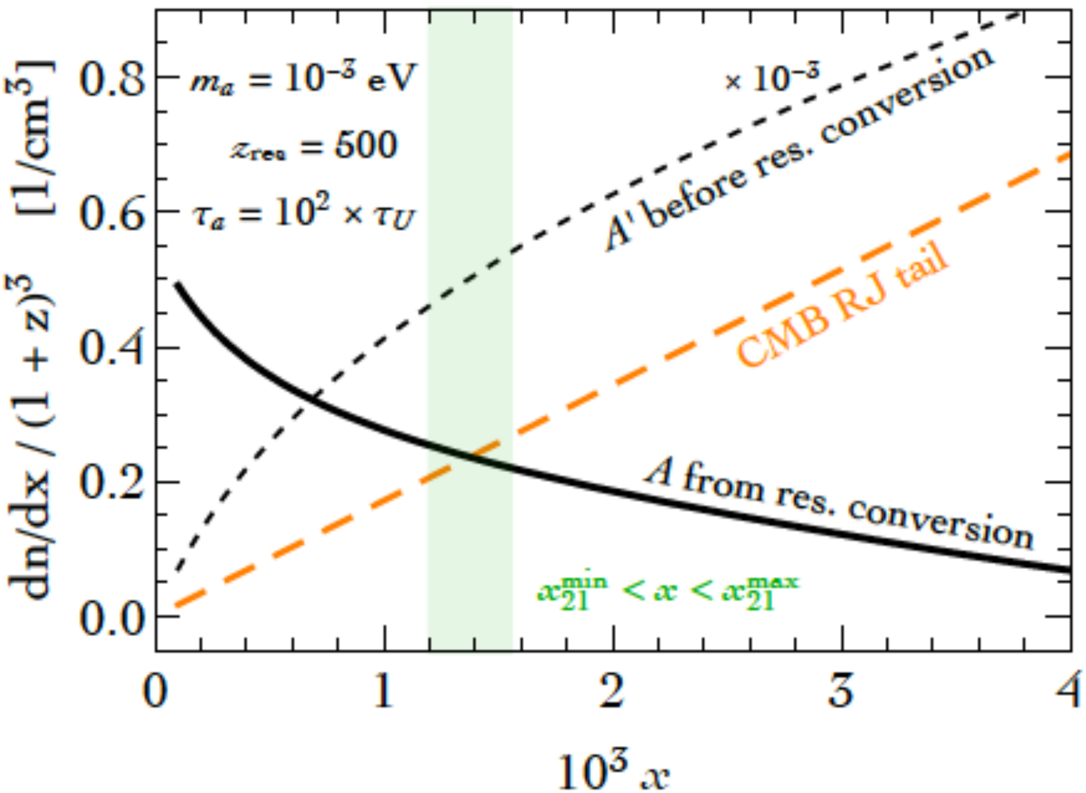
- Taking one parameter space point for DM *a* of meV mass, and *requiring RJ photon counts to double*:



- 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 $x \in (x_{21}^{\mathrm{min}}, x_{21}^{\mathrm{max}}) = (1.2, 1.6) \times 10^{-3}$

Other options to consider

- DR ALP oscillating into photons in the primordial magnetic field.
- 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 $\nu_2 \rightarrow A' \, \nu_1$ followed by A'→A oscillations). Cascade decay make things increasingly softer.

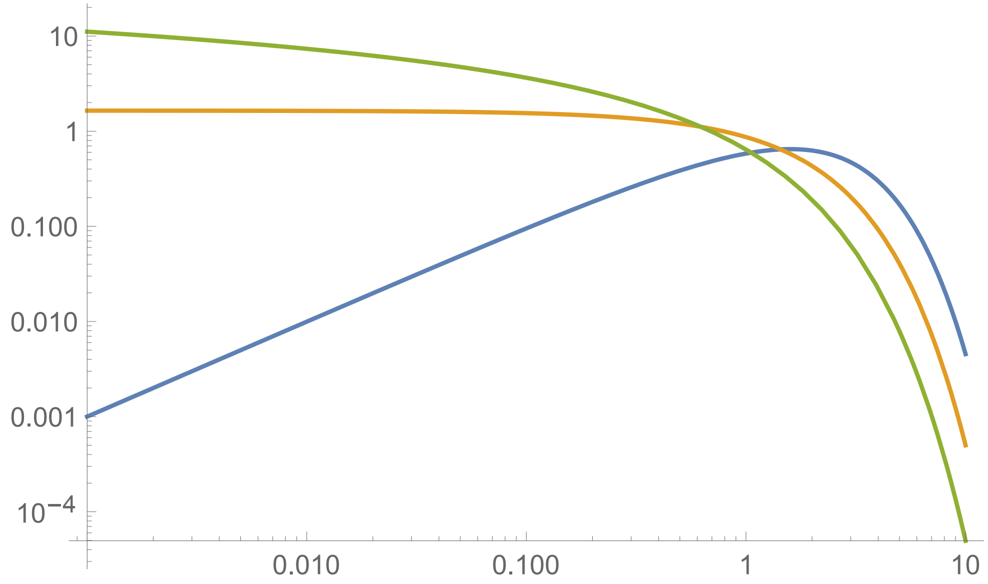


Figure 1: Blue: $x^2/(e^x - 1)$ distribution (i.e. Planckian); Brown: same after one decay; Green: same after two decays.

Two cases for Dark Radiation

- Case 1: numerous soft quanta

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

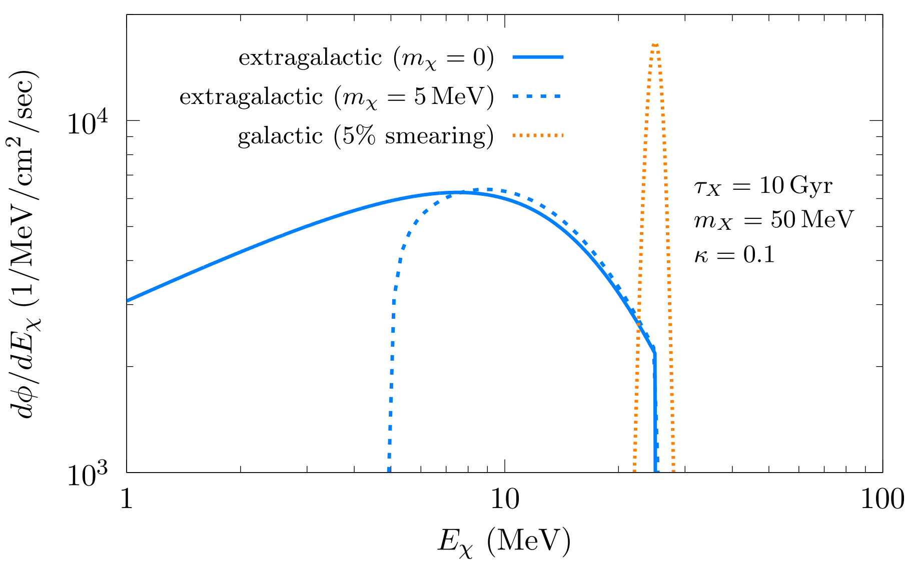
- Case 2: fewer hard quanta

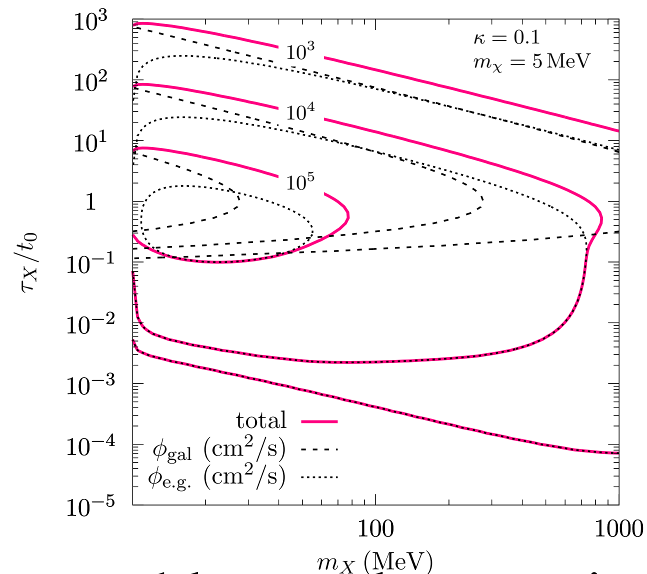
$$n_{\rm DR} \ll n_\gamma, \ \ E_{\rm DR} \gg E_\gamma, \ \ \rho_{\rm DR}(\sim E_{\rm DR} n_{\rm DR}) \leq 0.1 \rho_{\rm DM}$$

The idea to explore direct DM detection potential to look for DR.

- Scenario: A fraction of DM decays, producing fluxes of relativistic particles

- Typical spectra has a galactic and extra-galactic component:



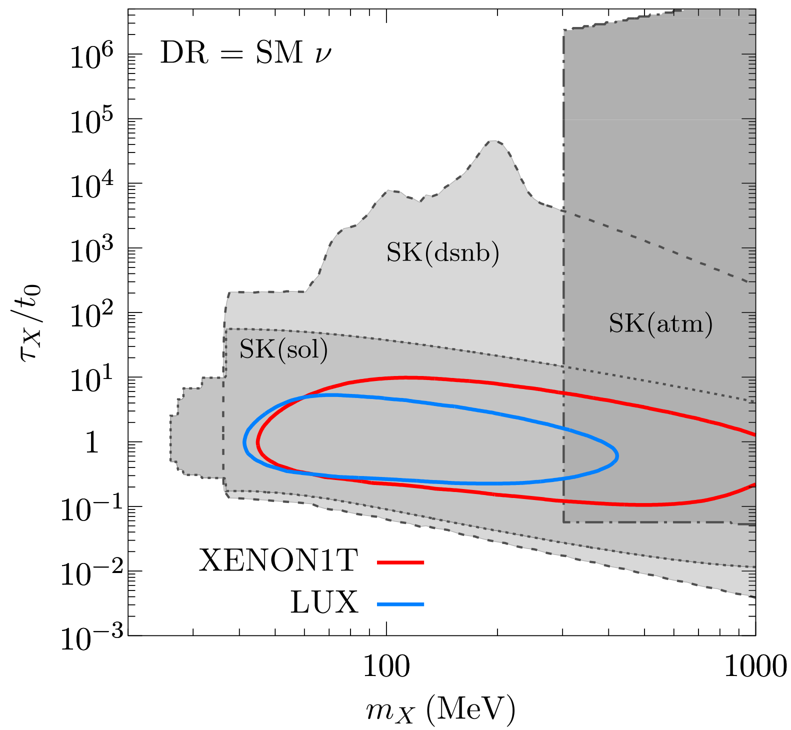


$$\phi_{\rm tot}^{\rm max} \sim \frac{10\,\mathrm{MeV}}{m_X} \times 10^6\,\mathrm{cm}^{-2}\mathrm{s}^{-1}.$$

- Could be comparable to solar neutrino fluxes, but more energetic creating DD sign.

Decay to SM neutrinos

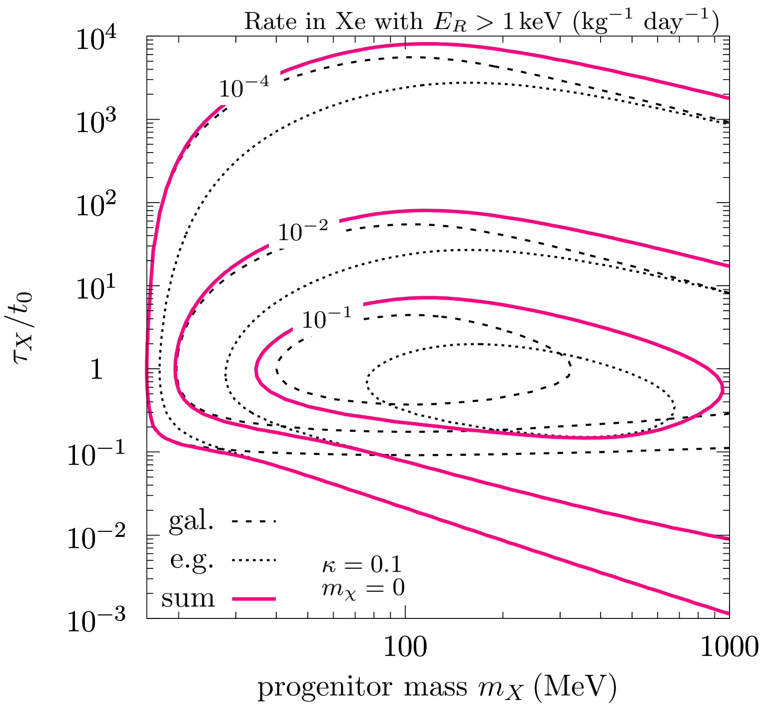
- A new population of SM neutrinos could be created by the DM decay. Constraints on electron antineutrinos by SK are very strong, but for neutrinos with E < 30 MeV the constraints are not that strong, and direct detection will soon become competitive.

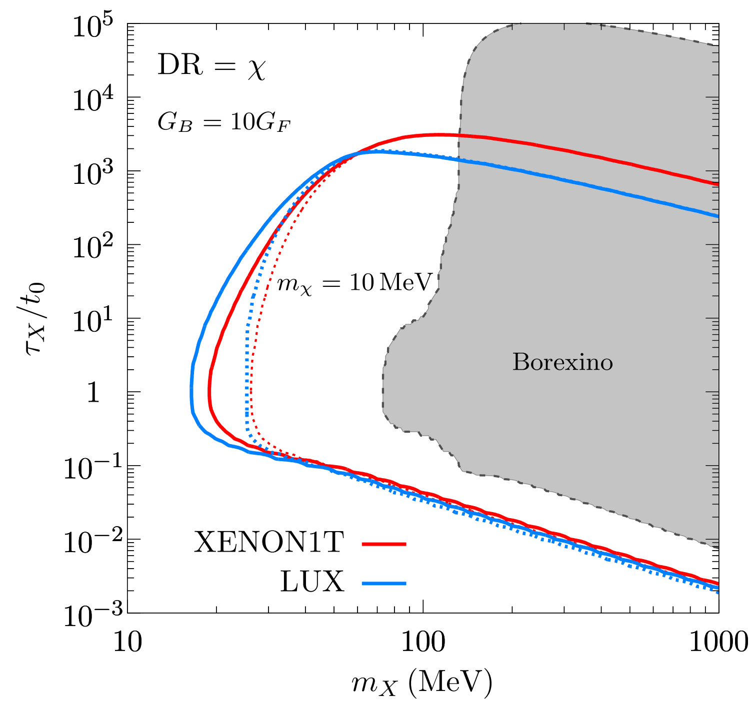


- With such hypothetical ν DR, the “neutrino floor” is at 10^{-47} cm^2.

Decay to DR coupled to baryons

- A new population of fermions that interact with baryonic current could be created by the DM decay. Constraints from SK are not strong, and direct detection is the most sensitive probe:





- Direct detection rates put significant constraints on models. Need more than 1 species do differentiate between DR and DM recoil.

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. RJ tail can be "built up" using the models of light decaying DM, that create quanta far more numerous than RJ tail of the CMB. Resonant conversion could then transfer A' to to normal EM sector. We can easily fit stronger-than-expected EDGES result without difficulities.

3. Interacting DR can be searched for in direct detection [of DM] experiments. The *maximum* strength signal from DR neutrinos will be reached relatively soon.

Photon-dark photon mixing

- Polarization operator matrix Π for A-A' system.