Cosmological Signatures of New Light Particles/Dark Sector

Maxim Pospelov
Perimeter Institute/U of Victoria

Fradette, Pospelov, 2017; Fradette, Pospelov, Pradler, Ritz 2018; Pospelov, Pradler, Ruderman, Urbano, 2018.

University of Victoria | British Columbia Canada

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Plan

1. *Introduction:* Portal to dark sector.

2. General cosmo constraints on super-renormalizable portal.

3. Constraints on the lifetime of the Higgs portal scalars from BBN, relevant for rare Higgs decay searches.

4. Ultralight sectors, and possible connection to 21 cm physics.

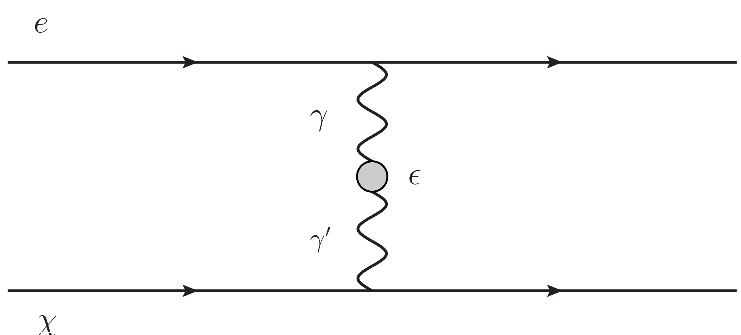
5. Conclusions

Dark sector example

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

$$\mathcal{L}_{\psi,A} = -\frac{1}{4} F_{\mu\nu}^2 + \bar{\psi}[\gamma_\mu (i\partial_\mu - eA_\mu) - m_\psi]\psi$$

$$\mathcal{L}_{\chi,A'} = -\frac{1}{4} (F'_{\mu\nu})^2 + \bar{\chi}[\gamma_\mu (i\partial_\mu - g' A'_\mu) - m_\chi]\chi,$$



Millicharge if $m_{A'} \rightarrow 0$

- "Effective" charge of the "dark sector" particle χ is $Q = e \times \varepsilon$ (if momentum scale $q > m_V$). At $q < m_V$ one can say that particle χ has a non-vanishing *EM charge radius*, $r_\chi^2 \simeq 6\epsilon m_V^{-2}$.
- Dark photon can "communicate" interaction between SM and dark matter. Very light χ can be possible.
- *Enables models of light Dark Matter, including MeV-to-GeV scale WIMP*

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

……….

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

Dark sectors = light weakly coupled states that may include DM and/or its mediators.

Comprehensive strategy to go after dark sectors:

US Cosmic Visions: New Ideas in Dark Matter 2017 : Community Report

Marco Battaglieri (SAC co-chair),[1] Alberto Belloni (Coordinator),[2] Aaron Chou (WG2 Convener),[3] Priscilla Cushman (Coordinator),[4] Bertrand Echenard (WG3 Convener),[5] Rouven Essig (WG1 Convener),[6] Juan Estrada (WG1 Convener),[3] Jonathan L. Feng

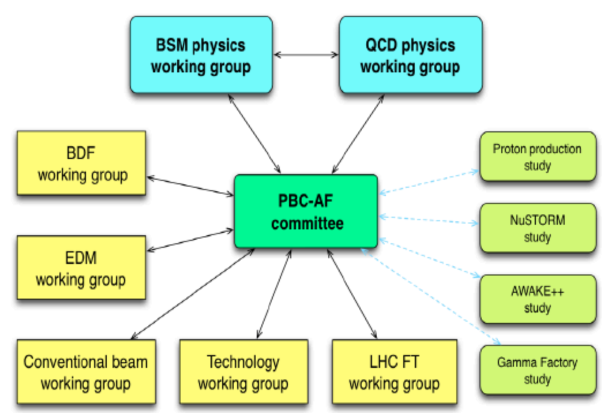
arXiv:1707.04591v1 [hep-ph] 14 Jul 2017

… very long list of authors

Dark Sectors 2016 Workshop: Community Report

Jim Alexander (VDP Convener),[1] Marco Battaglieri (DMA Convener),[2] Bertrand Echenard (RDS Convener),[3] Rouven Essig (Organizer),[4,*] Matthew Graham (Organizer),[5,†] Eder Izaguirre (DMA Convener),[6] John Jaros (Organizer),[5,‡] Gordan

CERN PBC exercise led by Lamont, Jaeckel, Valee



The Higgs portal idea

- The Higgs field is the simplest realization of mass generation for gauge fields and fermions of the SM.
  The lowest fully gauge invariant dimension operator that you can build out the Higgs field is 2 :

$$H^{+}H = v^2+2vh+h^2$$

Recall that dim≤4 operators do not require extra UV physics (i.e. no extra particles required, self-consistent)

"Standard WIMP" (Silveira, Zee++) in form of a scalar S can be obtained from the d=4 operator

$$S^2 H^{+}H = S^2\,(v^2+2vh+h^2)$$

(Light) Higgs-like particle through the super-renormalizable portal

Example: new particle admixed with a Higgs. (I keep the lowest dim op.)

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

After (Higgs Field = vev + fluctuation h), the actual Higgs boson mixes with S.

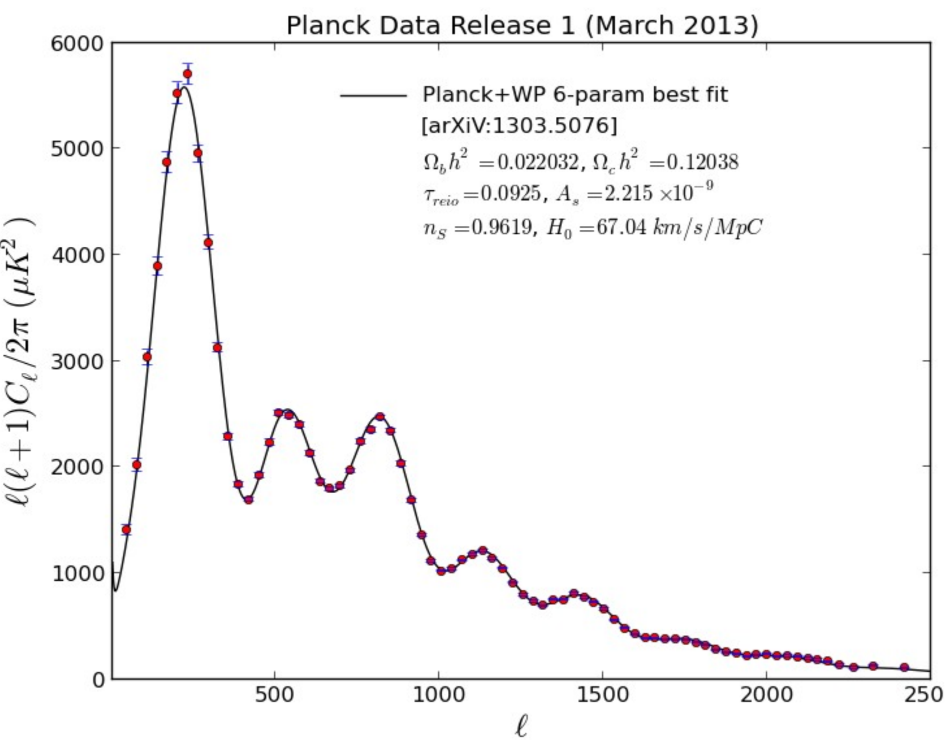
Mixing angle: $$\theta = \frac{Av}{m_h^2}$$

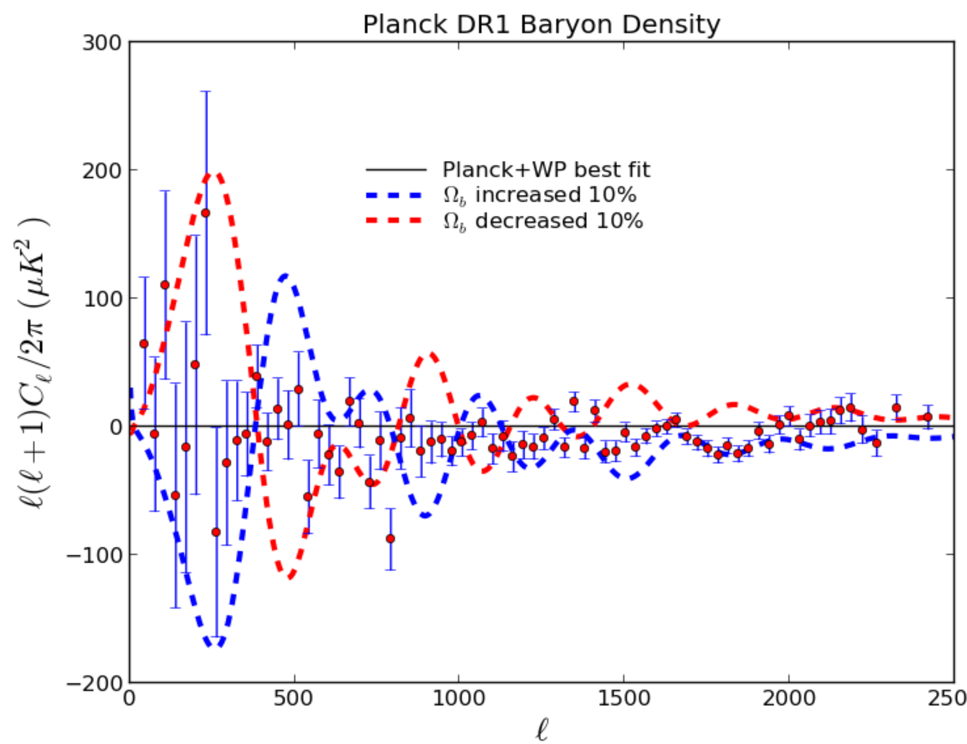
The model is technically natural as long as A is not much larger than m_S (corrections go as $\Delta m_S^2 \sim A^2 * \log$)

Low energy: new particle with Higgs couplings multiplied by θ. Mixing angle and mass can span many orders of magnitude.

New effects in Kaon and B-decays, 5^{th} force, and cosmology.

CMB is an important source of constraints



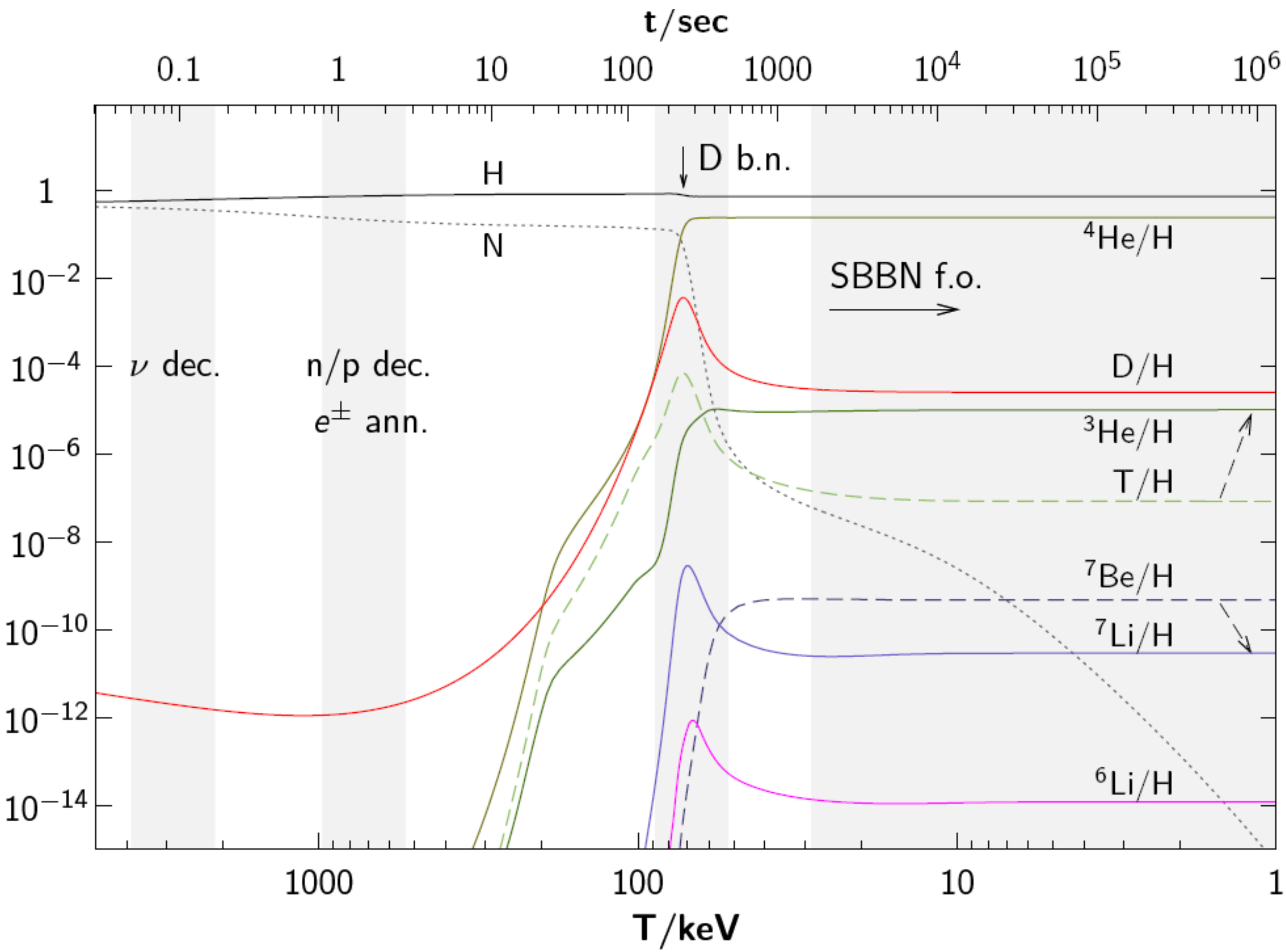


Parameter	Value (68%)
$\Omega_b h^2$	0.02207±0.00027
$\Omega_c h^2$	0.1198±0.0026 (is it high?)
$100\theta_*$ (acoustic scale at recombination)	1.04148±0.00062 (~ 500 parts per million accuracy)
τ	0.091±0.014 (WMAP seeded)
$\ln(10^{10}A_s)$	3.090±0.025
n_s	0.9585±0.0070 (<1 at > 5 σ)

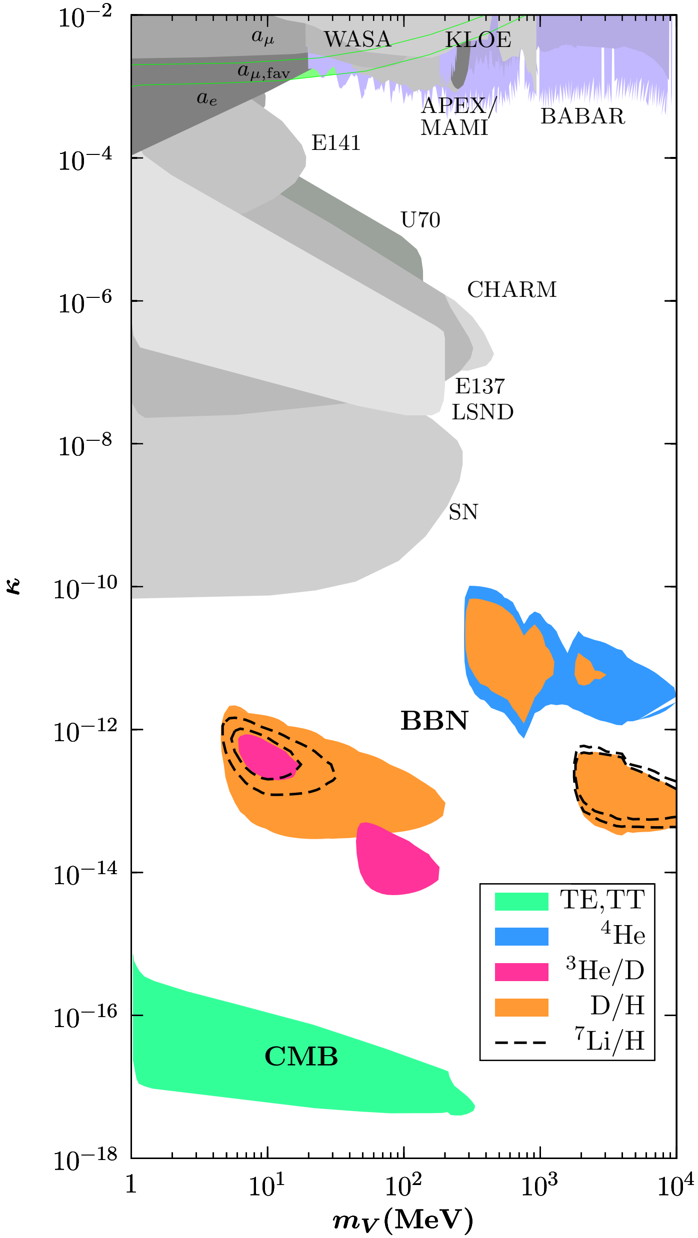
Parameter	Value (95%)
Ω_K	-0.0005±0.006
$\Sigma\, m_\nu$ (eV)	<0.23
N_{eff}	3.30±0.54
Y_P	0.267±0.040

Planck data (Figures from Kinney, Natoli talks ~5yr ago)

BBN is important source of constraints



Constraints on dark photons



- We rule out significant fraction of dark photon parameter space.
- These new limits are inevitable: only rely on thermal production and require that the Universe was T~ 0.3 m_V hot.
- Non-thermal component of $< V_\mu >$ (so-called "vacuum misalignment") will only make limits stronger. Existence of "dark Higgs" can only make limits stronger.
- After 2014, limits/sensitivity can be further improved with Planck polarization data.
- (Fradette, MP, Pradler, Ritz, 2014)

Generalization to Higgs-mixed scalars

- Basic idea is the same: freeze-in production in the very early Universe, $T > m_S$.
- Late decays via mixing with the Higgs
- Because of the Higgs portal, the production peaks at T close EW scale.
- The sensitivity is enhanced compared to dark photons: small mass dark photons decouple, but small mass S scalars do not. Production due to e.g. top Yukawa, decay due to e.g. electron Yukawa. Expect more sensitivity!
- (Fradette, MP, Pradler, Ritz, 2018, PRD)

Comparing sterile neutrino, dark photon, and singlet Higgs freeze-in production

- Sterile neutrino N: $T_{max} \sim 100$ MeV;

- Dark photon V: $T_{max} \sim 0.4\, m_V$;

- Singlet scalar S: $T_{max} \sim M_W$

* You can also have inflationary production of bosons (V or S)

* Previous papers on freeze-out through Higgs portal (Berger et al, 2016, T. Flacke et al, are good within ~ 2 orders of magnitude.)

Freeze-in yield

Production Channel i	$Y_i^{v\gg 0}$	$Y_i^{v\gtrsim 0}$	$Y_i^{\rm sym}$	$Y_i^{\rm tot}$ $[10^{10}\theta^2]$
$t\bar{t} \to gS$	2.11	0.93	0	6.29 - 8.11
$tg \to tS$ $(\times 2)$	4.17	0.90		
$t\bar{t} \to hS$	0.41	0.08	0.03 - 0.05	1.72 - 2.01
$t\bar{t} \to ZS$	0.44	0.11		
$t\bar{b} \to W^+S$ $(\times 2)$	0.82	0.11		
$th \to tS$ $(\times 2)$	0.38	0.13	0.14 - 0.21	14.40 - 17.77
$tZ \to tS$ $(\times 2)$	1.46	0.77		
$tW \to bS$ $(\times 2)$	3.66	1.43		
$bW \to tS$ $(\times 2)$	8.70	1.11		
$Zh \to ZS$	0.26	0.10	0.01 - 0.02	8.68 - 10.93
$ZZ \to hS$	0.33	0.17		
$WW \to hS$	0.57	0.25		
$WW \to ZS$	3.47	0.89		
$Wh \to WS$ $(\times 2)$	0.46	0.16		
$WZ \to WS$ $(\times 2)$	3.57	0.69		
$hh \to hS$	0.01	< 0.01	0	
Total	30.81	7.84	0.19 - 0.28	31.1 - 38.8

Freeze-in yield is given by $3*10^{-9}\ \theta^2$ with ~100% accuracy. Big improvements over earlier works (that were ok up to factor of ~30)

Emissivities around EW transition need to be treated carefully

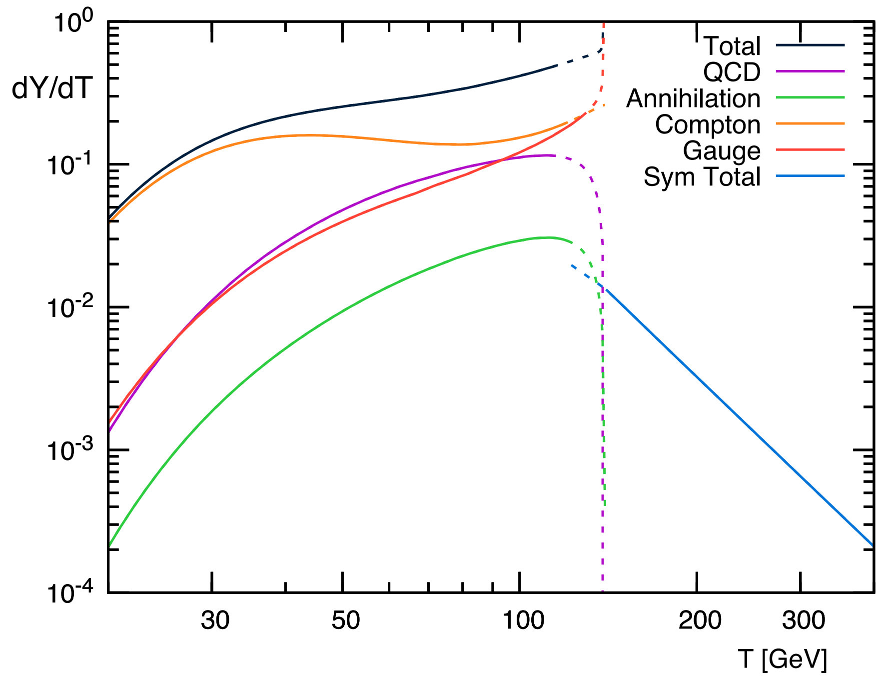
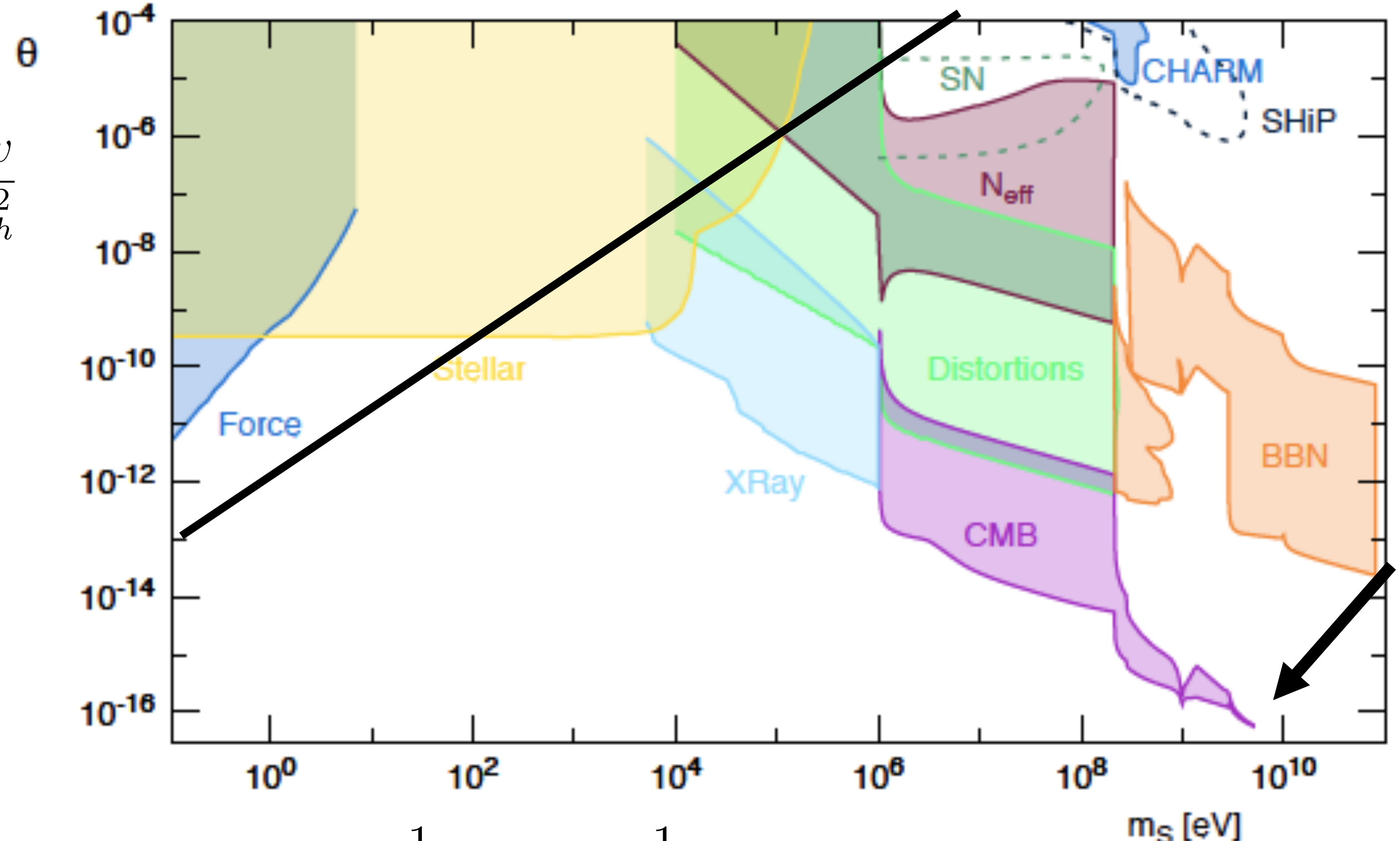


FIG. 5. Total S freeze-in emissivity and the contribution from each production channel category as a function of temperature for $\theta = 10^{-5}$.

- Neither the approximation of $m_{SM}(v) = m_{SM}((v(T))$ nor approximation of thermal masses is adequate if one aims at "precise" calculation.

Constraints significantly constrain technically natural corner



$$\theta = \frac{Av}{m_h^2}$$

Coupling of a new state S to electron here is ~ 10^{-22}, very similar to m_e/M_{Pl} (Sensitive to graviton-strength couplings)

$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2}m_S^2 S^2 - ASH^\dagger H$$

A < O(1-to-10)*mS is what you expect for not having additional tuning issues in m_S. θ< O(1-to-10)*mS/(100 GeV).

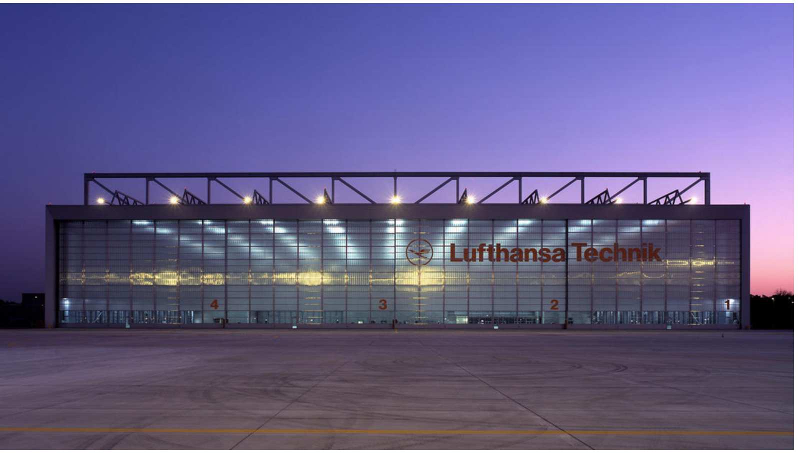
Higgs portal and light scalars at the LHC

- Fradette, MP, 2017
- **Will consider λ_S to be sizeable and A parameter (mixing) small.**

$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

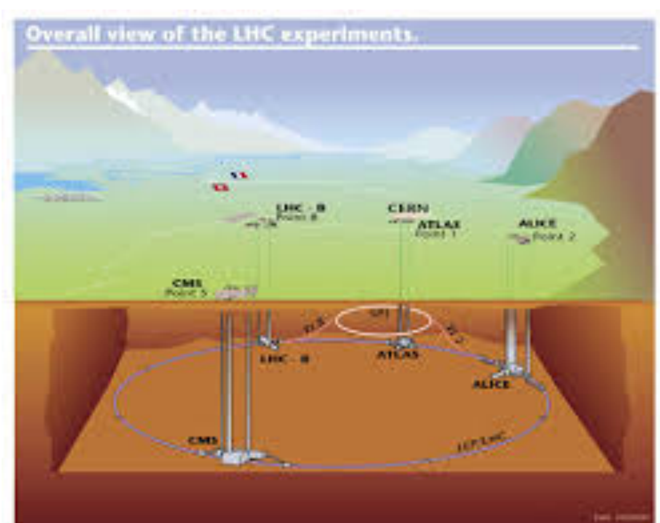
- If quadratic and linear coupling co-exist, then the LHC offers nice ways of probing this sector for light-ish S: At the LHC, we will be concerned with H→ S+S, followed by S decay.
- *What if S are so long-lived that they decay at really macroscopic distance away?*

MATHUSLA proposal.



Industrial size O(200 m) hollow detector to be put on the surface, near the forward region of a particle detector at the LHC, e.g. CMS.

D. Curtin et al., 2019



Time correlation between events at the LHC and decay vertex inside a large detector can drastically cut the number of background cosmic events

Higgs portal and light scalars

Fradette, Pospelov, PRD 2017 (= "BBN contract" for MATHUSLA)

- At the LHC, we will be concerned with H→ S+S, followed by S decay.
- Consider "an almost" Z_2 symmetric case to maximize the depletion of S in the early universe, and minimize its decay:

$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

Defines lifetime

Defines H decay and S abundance

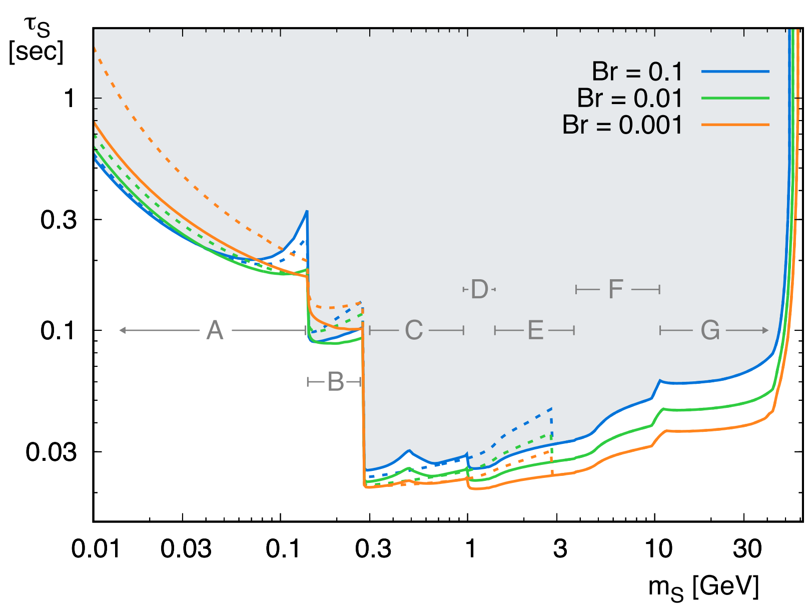
$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

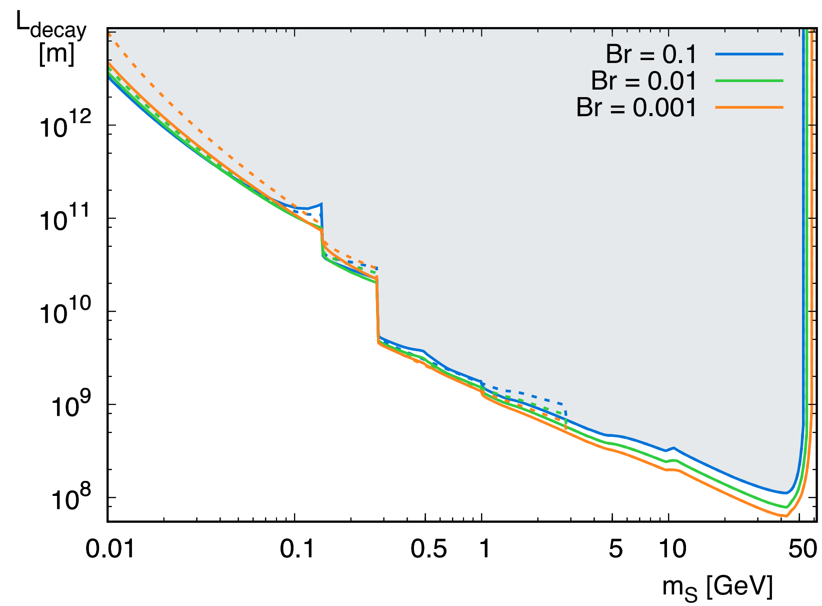
$$Br(h\to SS) = \frac{\Gamma_S}{\Gamma_S+\Gamma_{SM}} \simeq 10^{-2}\left(\frac{\lambda_S}{0.0015}\right)^2,$$

$$\sigma v(s) = \frac{8\lambda_S^2 v^2}{(s-m_h^2)^2+m_h^2\Gamma^2_{\text{SM}+S}}\frac{\Gamma_{\text{SM}}^{m_h\to\sqrt{s}}}{\sqrt{s}}, \qquad \langle\sigma v\rangle = \frac{\int_{4m_S^2}^{\infty} ds\, \sigma v(s)\, s\sqrt{s-4m_S^2}K_1\left(\frac{\sqrt{s}}{T}\right)}{16Tm_S^4K_2^2\left(\frac{m_S}{T}\right)}.$$

Constraints on lifetime – good news for Mathusla type ideas

- Decay products (nucleons, kaons, pions) induce extra p→n transitions and quite generically increase n/p. This is very constrained.

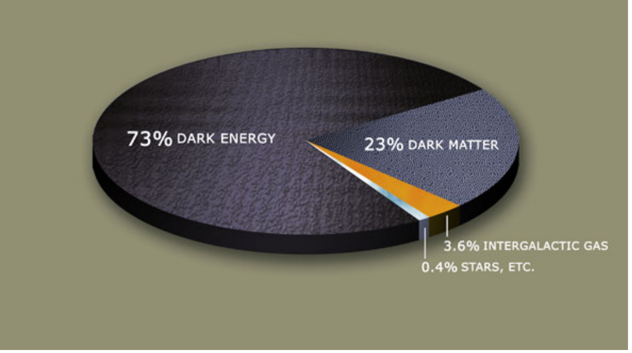




- For a ~ GeV scale particle, and energy of 200 GeV (broadly consistent with being a decay of the Higgs at 13 or 14 TeV energy), the minimum probability to decay in 100m hangar is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

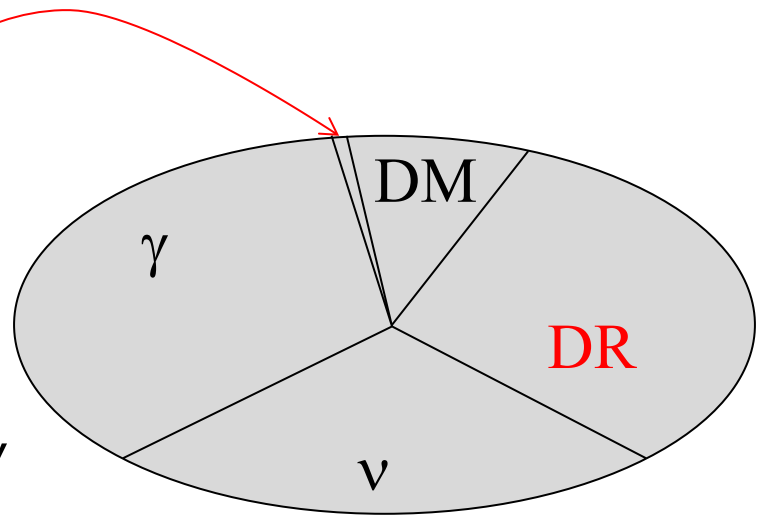
Ultra light particles at late time cosmology

- A lot of focus in the last few years has been on ultra-light dark matter (e.g. $m_a \sim 10^{-22}$ eV) with de Broglie wave length comparable to the size of the smallest halos.
- My main interest is that some models of ultralight particles like dark photons can be decoupled at early Universe, and recouple later, modifying late time photon spectra
- In some other basis, the on-shell dark photon coupling can be written to as $\varepsilon FF'$ but as $\varepsilon m_{A'}^2 AA'$. At early times, $(m_{A'}/T)$ suppression, and at late time – possible resonance (when plasma frequency is equal to dark photon mass, $m_A = m_{A'}$)



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

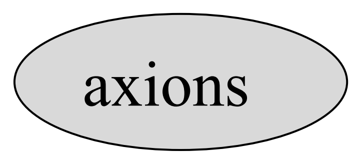
Atoms



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

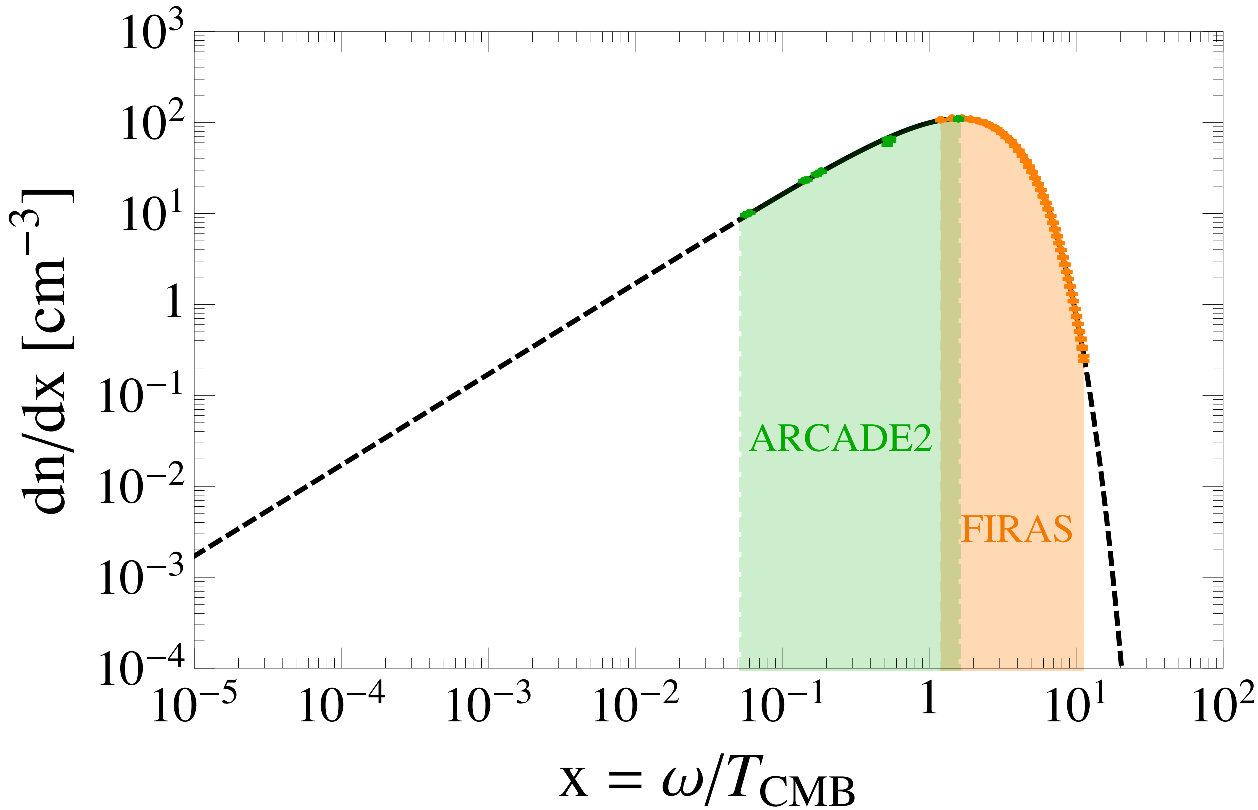
We have no idea about DM number densities. (WIMPs ~ 10^{-8} cm^{-3}; axions ~ 10^{9} cm^{-3}. Dark Radiation – Who knows! Can be dominant while being a subdominant component of ρ).

Number density chart for axionic universe:



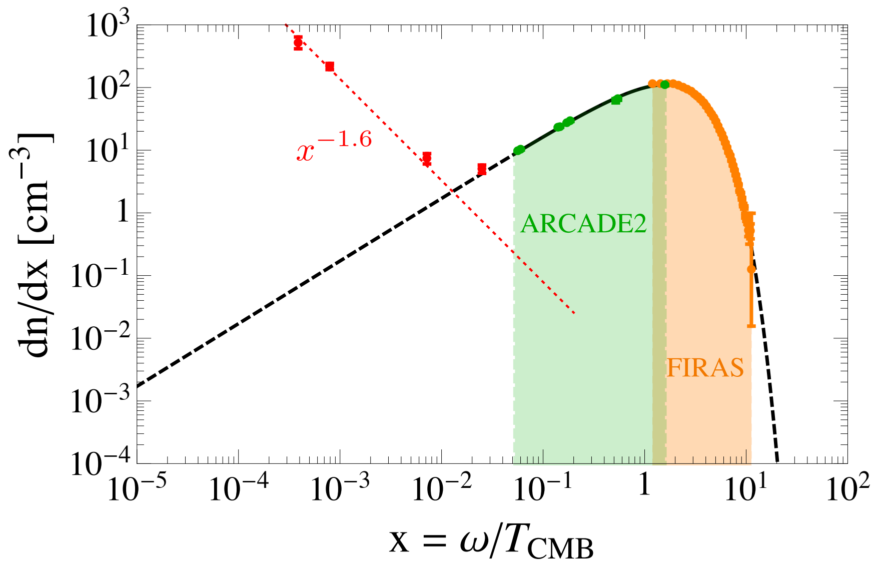
DR can be present in A. large number of quanta, B. be negligible in the energy balance, C. Can affect CMB and 21 cm due to coupling to γ

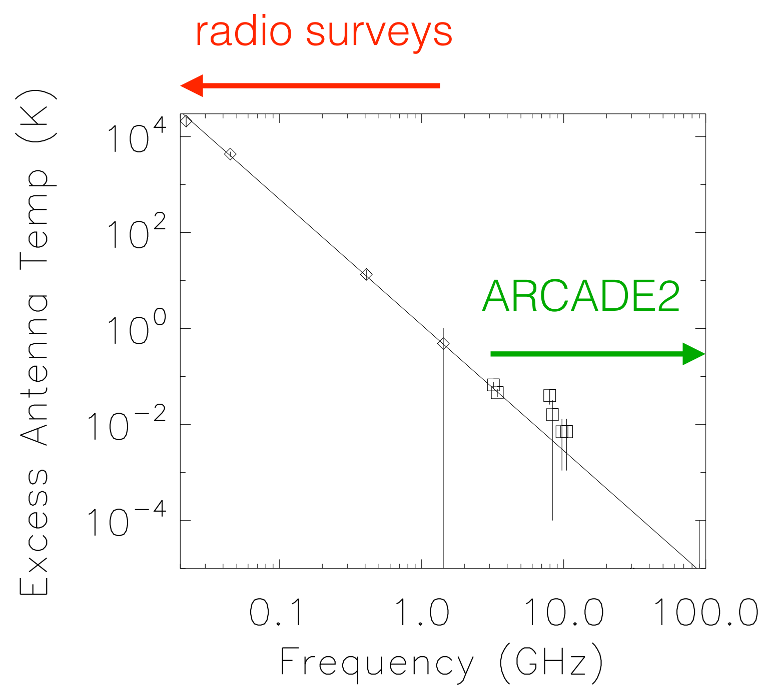
CMB Planckian spectrum



- FIRAS on COBE has measured the spectrum near its maximum to 1 part in 10^4 accuracy. $x \equiv \omega/T_{\rm CMB}$
- The CMB anisotropy program by many experiments have proceeded on solid footing.
- 21 cm physics wants to use small x part of this plot

Radio Excess

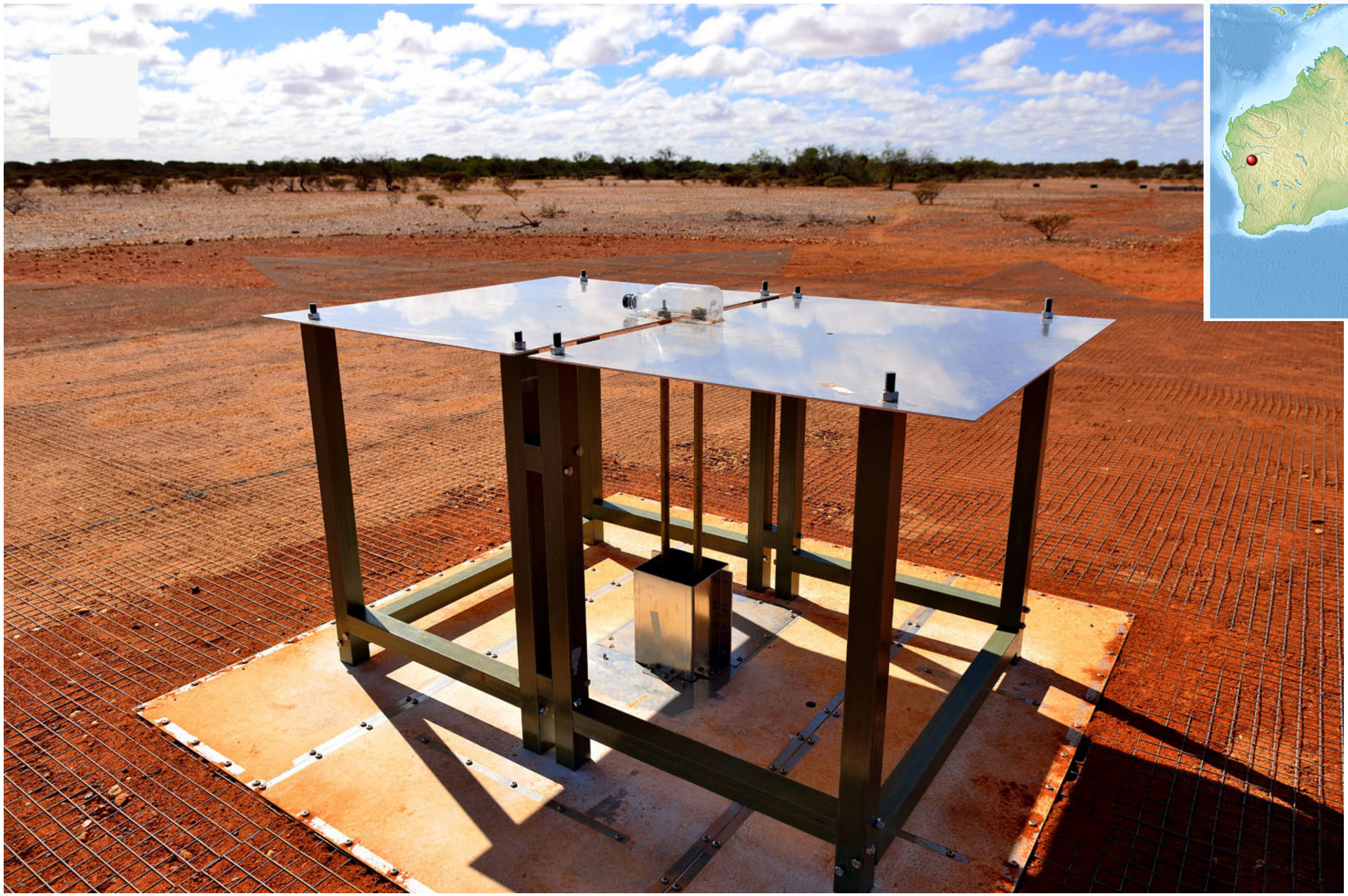




- ARCADE 2, **0901.0555**

EDGES

Experiment to **D**etect the **G**lobal **E**poch of Reionization **S**ignature



Bowman *et. al.* Nature **555**, 67 (2018)

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, if it gets confirmed by other groups, to be a real cosmological effect.*

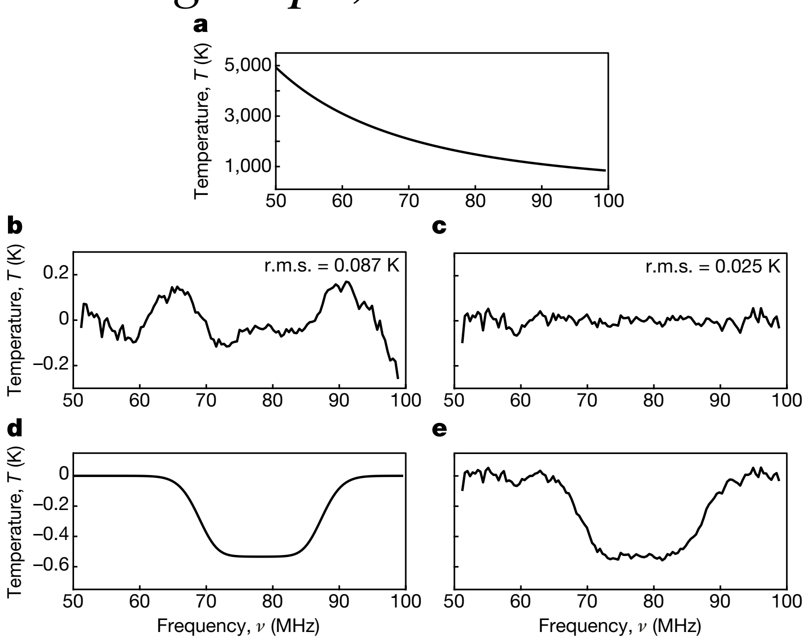


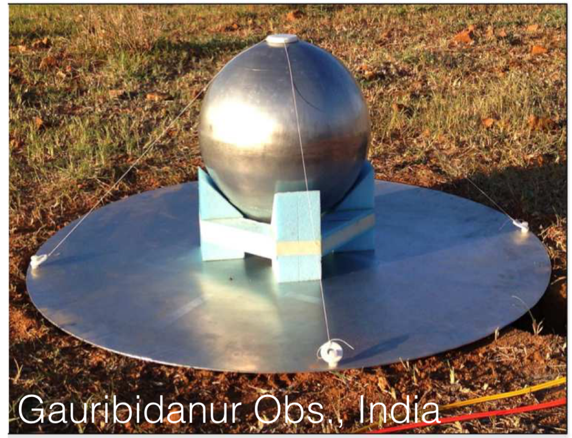
Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b**, **c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground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

Other Global 21cm Experiments

PRI^{Z}M: 50-130 MHz

1806.09531

SARAS2: 87.5-175 MHz



1710.01101

LEDA: 30-85 MHz

1709.09313

SCI-HI: 60-90 MHz

1311.0014

HYPERION: 30-120 MHz

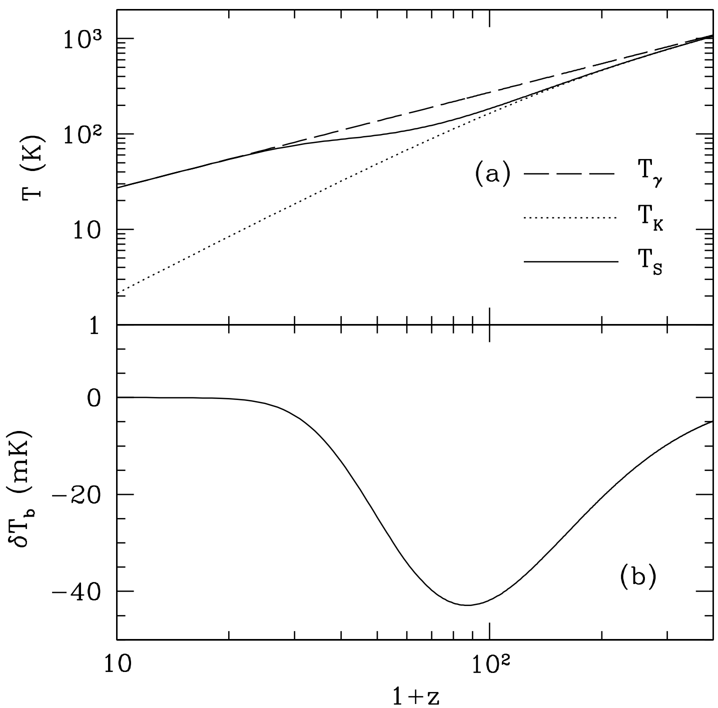
1501.01633

CTP: 60-80 MHz

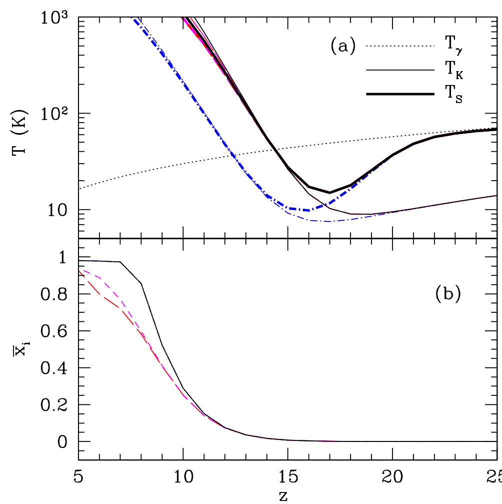
1611.06062

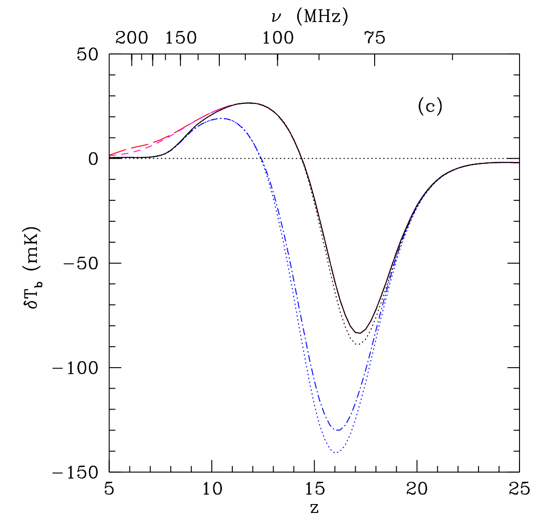
Interpretation of observation

- (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

"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*.

Alternative path for enhancing 21 cm signal – more Rayleigh-Jeans photons

- Feng, Holder, 2018: only a small fraction (e.g. ~1%) of the current "Arcade" excess – if it is a pre-existing condition (exists at z~20) – could give an enhanced 21 cm monopole signatures.

- After EDGES, several papers with: general discussion (Fraser et al.), first concrete model realization (our paper), and further ideas in this direction (Moroi, Nakayama, Tang).

How much quanta does RJ tail has?

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

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

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

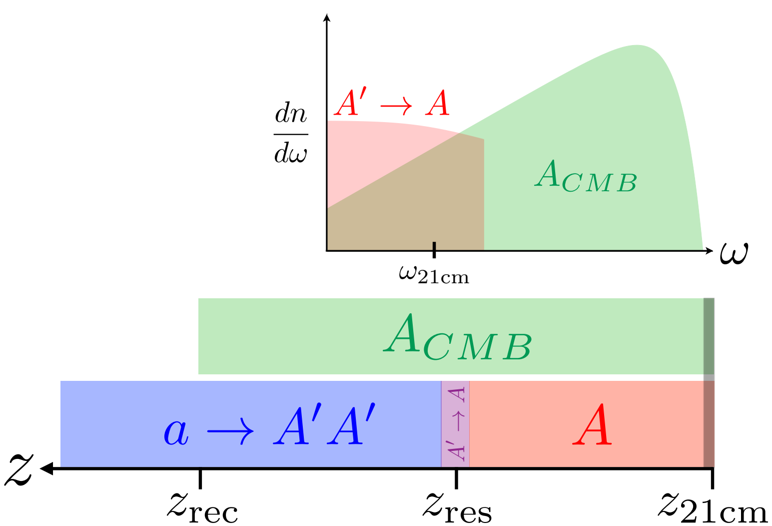
- What if there existed *early* DR that we could take to saturate as much as $N_{eff} = 0.5$ or alternatively, there is late decay of DM to DR, and we take up to 5% of DM to convert?

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

- 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.



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

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

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.
- We suggest this regime: $\omega_{\rm DR} \ll \omega_{\rm CMB}\ , \quad n_{\rm DR} > n_{\rm RJ}\ , \quad \omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}\ .$
- Before Planck, DR has been invoked as a remedy for $\Delta\ N_{eff} > 0$; It’s been speculated that 10% of DM→DR decay is responsible for H_0 tension (Berezhiani et al, 2015).

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

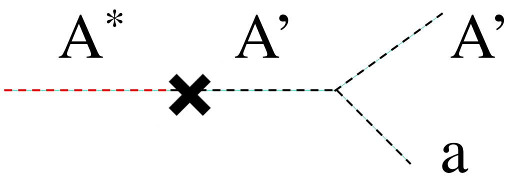
$$\mathcal{L}_{AA'} = -\frac{1}{4}F_{\mu\nu}^2 - \frac{1}{4}(F'_{\mu\nu})^2 - \frac{\epsilon}{2}F_{\mu\nu}F'_{\mu\nu} + \frac{1}{2}m_{A'}^2(A'_\mu)^2 \,.$$

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

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

“direct” decay of DM into photons is very constrained. f_a is limited above 10^{10} GeV (and e.g. $\tau_a > 10^{20}\ \tau_U$)

Constraints from stellar `cooling`

- Direct production of dark photons is suppressed by $(m_{A'}/m_A)^2$.
- $\gamma^* \rightarrow$ 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 $\gamma^* \rightarrow$ to *νν* 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→2photons 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

$$\Gamma_a = \frac{m_a^3}{64\pi f_a^2} = \frac{3\times \overset{10^{-18}}{\cancel{10^{-4}}}}{\tau_{\rm U}}\left(\frac{m_a}{10^{-4}\,{\rm eV}}\right)^3\left(\frac{\overset{10^9\ \mathrm{GeV}}{\cancel{100\,{\rm GeV}}}}{f_a}\right)^2.$$

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

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

Effective mixing

$\varepsilon\, m_{A'}^2 /(m_{A'}^2 - \omega_{pl}^2(z))$

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

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

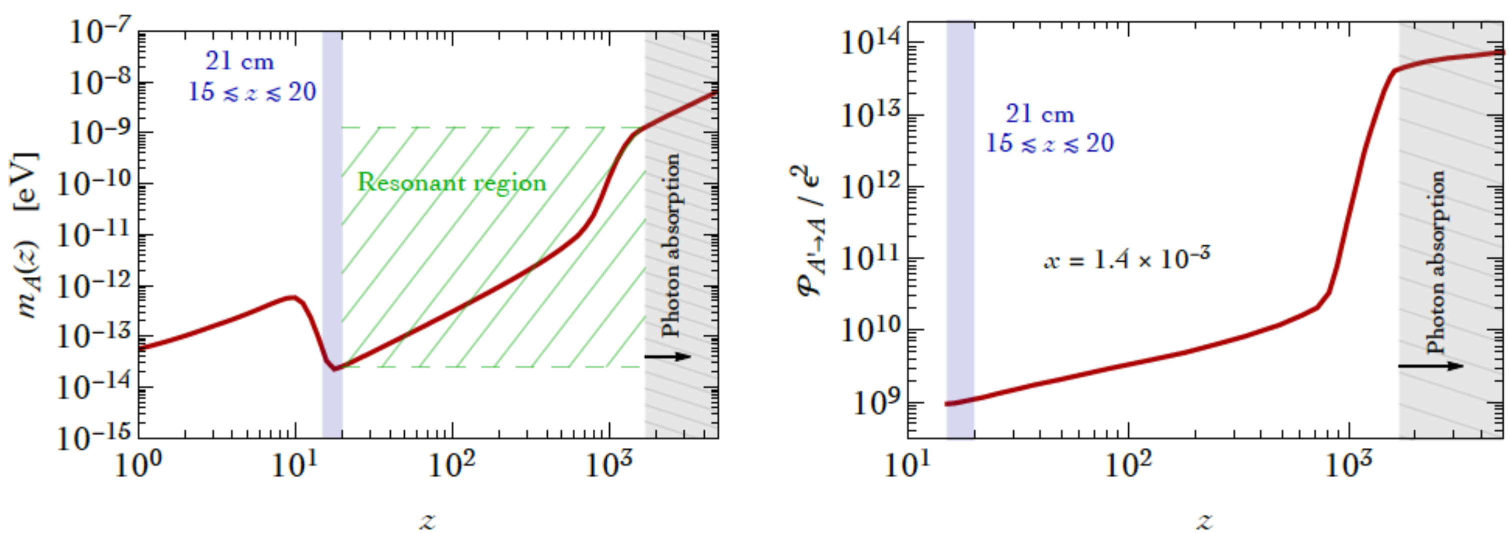
Resonance occur when $m_{A'} = \omega_{pl}(z)$

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 → $\gamma\gamma$ 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

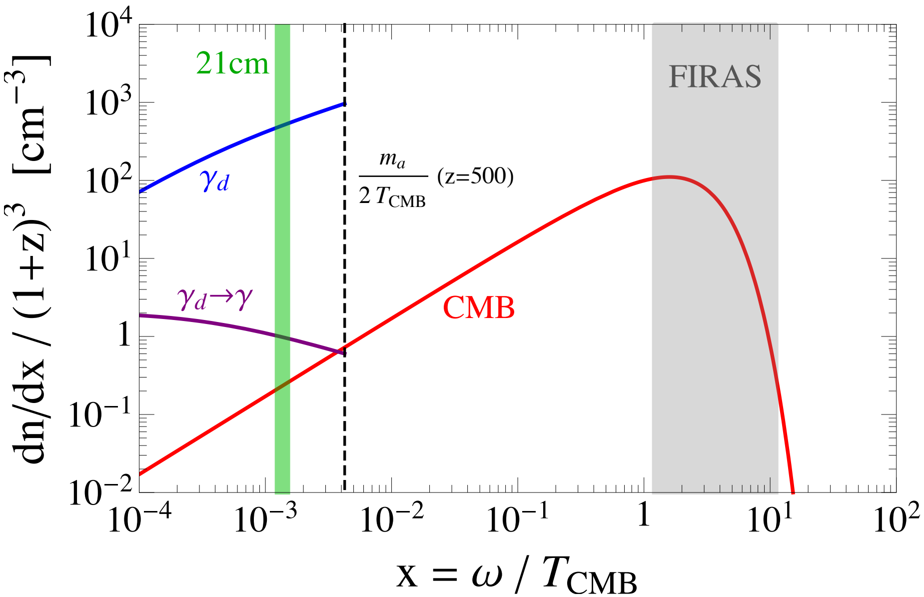
- DM → $\gamma'\gamma'$, followed by $\gamma' \to \gamma$ idea works because resonant conversion probability is huge, $P_{\gamma' \to \gamma}/\varepsilon^2 \sim 10^{10}$ or more!

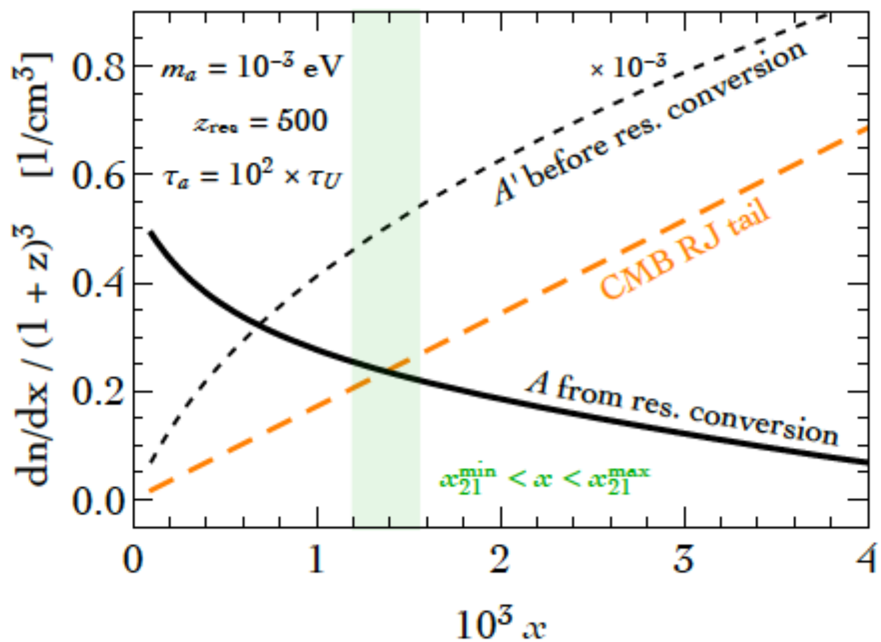
- Also, the oscillation probability is $\sim \omega^{-1}$, making the probability three orders of magnitude larger for 21 cm relevant photons compared to $x \sim O(1)$.

- 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).

RJ tail of the CMB spectrum

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

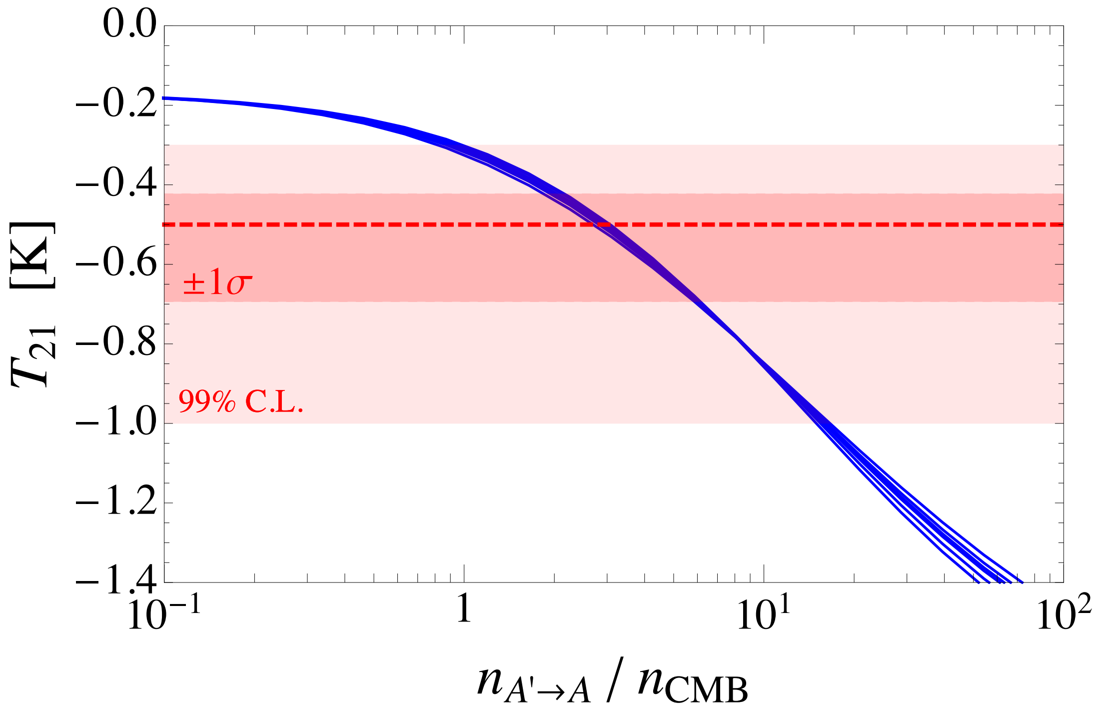




- Green band – interesting for 21 cm range of x, $x \in (x_{21}^{\mathrm{min}}, x_{21}^{\mathrm{max}}) = (1.2, 1.6) \times 10^{-3}$

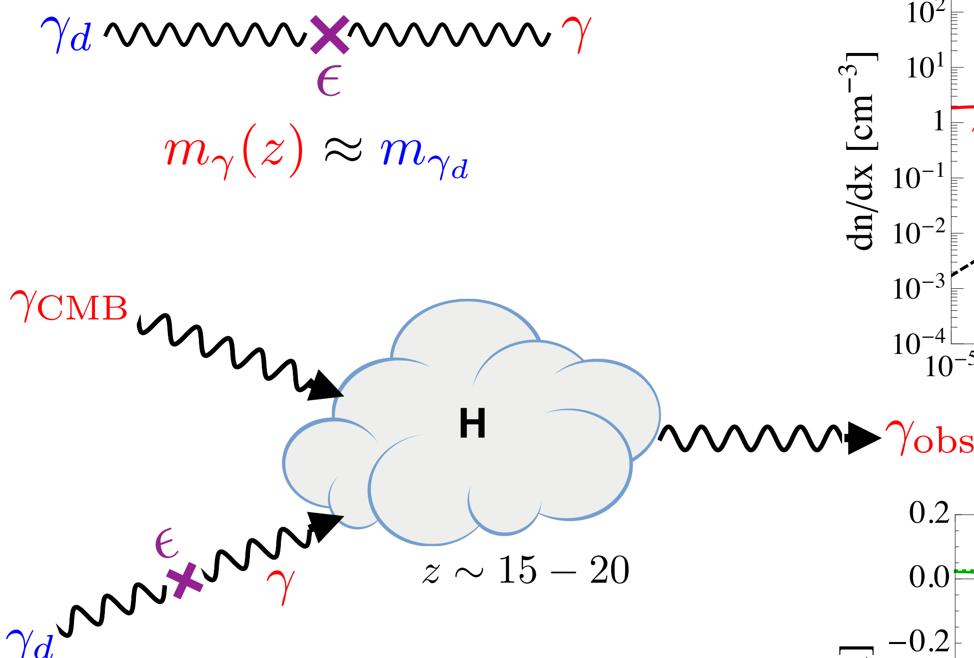
Further developments

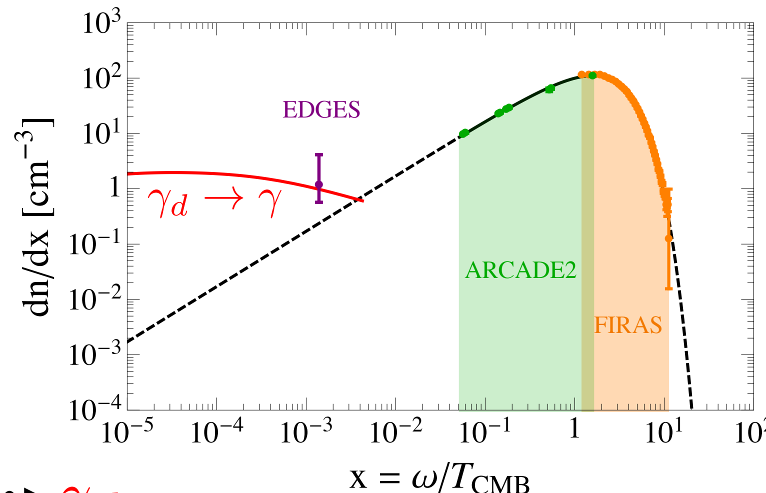
- Varying the spectral form of the extra injected photon spectrum, and comparing it with EDGES signal strength, we derive the required degree of enhancement,

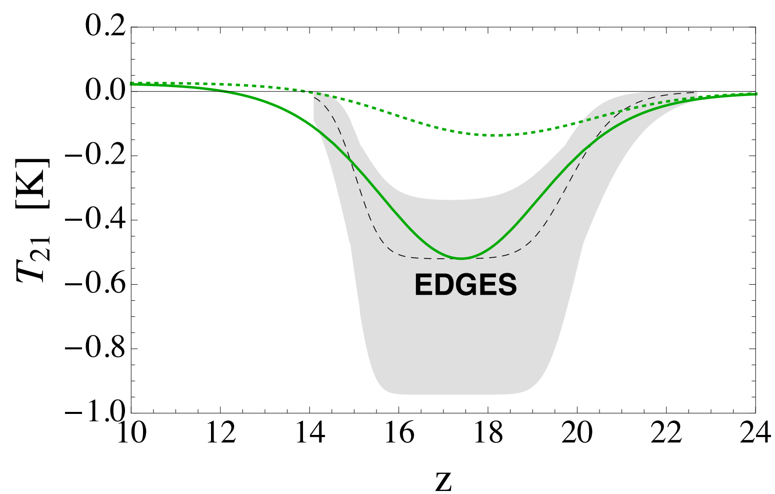


- Model dependence is rather weak. Typically need 2-20 enhancement
- Strong dependence of how you treat EDGES feature.

Take Away


γ_d
ϵ
γ
$m_\gamma(z) \approx m_{\gamma_d}$
$\gamma_{\rm CMB}$
H
$\gamma_{\rm obs}$
ϵ
γ
γ_d
$z \sim 15 - 20$


EDGES
$\gamma_d \to \gamma$
ARCADE2
FIRAS
dn/dx [cm^{-3}]
x = $\omega/T_{\rm CMB}$


EDGES
T_{21} [K]
z

Conclusions

1. Cosmological constraints are derived on the entire mass-mixing plane for scalars mixed with Higgs. Depending on the mass, the limits reach down to the strength of couplings similar to gravitons (m_e/M_{Pl}). Large area of "natural" parameter space is probed.
2. *Constraints are derived on the lifetime of the Higgs portal scalars from BBN, relevant for rare Higgs decay searches. Lifetime is generically < 0.1 sec. Good news for a Mathusla-style project*
3. IR frontier is a modification of SM by light and weakly coupled BSM fields. ALPs or dark photons with small mass are an example.
4. *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.*
5. 21 cm cosmological signal, then, provides the key test of such models with beyond-SM sectors composed of light fields.