Early cosmology constraints on new feebly-interacting physics

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Plan

1. *Introduction.*

2. BBN and CMB constraints on dark photons and a Higgs-portal scalar. Application for the displaced decay searches at the LHC.

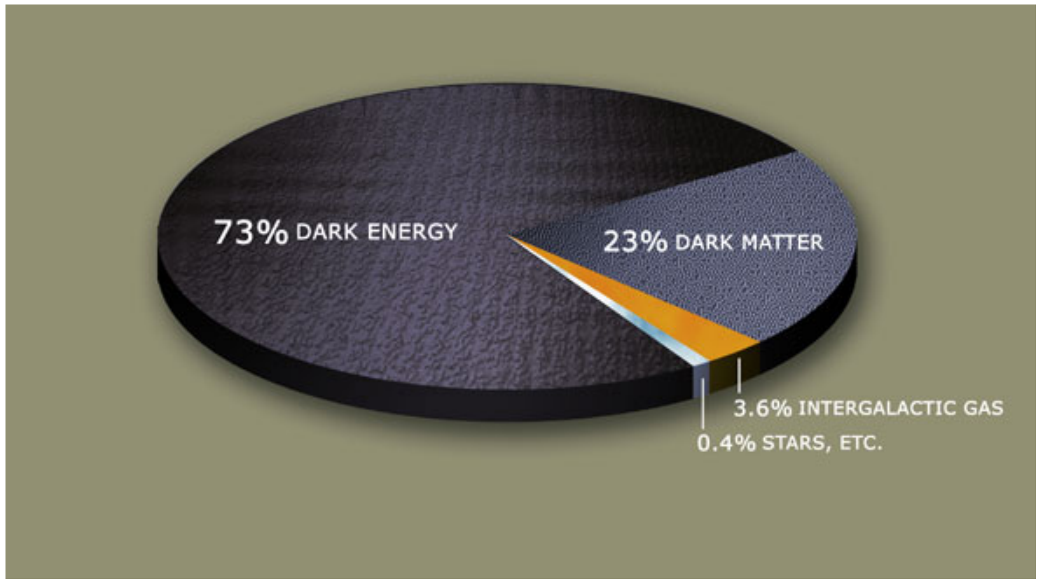
3. An exciting start to cosmological 21 cm physics: EDGES thought-provoking results. [If correct]: unusual dark matter or unusual CMB?

4. New physics models at the "infrared frontier".

5. Conclusions

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?

Cosmological Constraints on new physics is a very mature field

PHYSICAL REVIEW VOLUME 92, NUMBER 6 DECEMBER 15, 1953

Physical Conditions in the Initial Stages of the Expanding Universe*,†

RALPH A. ALPHER, JAMES W. FOLLIN, JR., AND ROBERT C. HERMAN
Applied Physics Laboratory, The Johns Hopkins University, Silver Spring, Maryland
(Received September 10, 1953)

The detailed nature of the general nonstatic homogeneous isotropic cosmological model as derived from general relativity is discussed for early epochs in the case of a medium consisting of elementary particles and radiation which can undergo interconversion. The question of the validity of the description afforded by this model for the very early super-hot state is discussed. The present model with matter-radiation interconversion exhibits behavior different from non-interconverting models, principally because of the successive freezing-in or annihilation of various constituent particles as the temperature in the expanding universe decreased with time. The numerical results are unique in that they involve no disposable parameters which would affect the time dependence of pressure, temperature, and density.

The study of the elementary particle reactions leads to the time dependence of the proton-neutron concentration ratio, a quantity required in problems of nucleogenesis. This ratio is found to lie in the range $\sim 4.5:1-\sim 6.0:1$ at the onset of nucleogenesis. These results differ from those of Hayashi mainly as a consequence of the use of a cosmological model with matter-radiation interconversion and of relativistic quantum statistics, as well as a different value of the neutron half-life.

One of the first correct papers on primordial nucleosynthesis. It notices the difference for Dirac and Majorana neutrinos. n/p for Dirac is larger. Poor accuracy of predictions is due to very uncertain τ_n

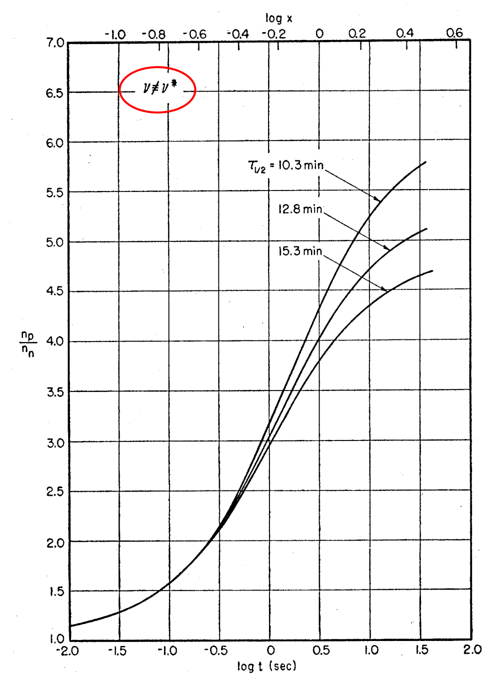


FIG. 2. The proton-neutron concentration ratio *versus* time and temperature ($x=m_ec^2/kT$) in the case of the Dirac neutrino (distinguishable neutrino and antineutrino) for the Robson neutron half-life value of 12.8 min, plus-and-minus the probable error.

Early Universe cosmology provides benchmark constraints on new physics

To name a few:

- Prevents most popular light WIMP (DM → SM annihilation) dark matter scenarios to lower the mass scale below ~ few MeV. Sensitivity via Neff from CMB, He/H, D/H etc.
- Prevents residual decays and annihilations of relic BSM particles if too much energy is injected (e.g. sensitive to ~0.1 eV per baryon injection of visible at the CMB epoch via modification of TT, EE etc angular correlations)
- Prevents altering the CMB spectral shape at ~ 1 part in 10^4 level further constraining decaying/annihilating particles at $z\sim10^5$ and below.
- Prevents independent uncorrelated fluctuations of different components of primordial fluids.

etc

Modern cosmology has some problems/tension in the data

To name a few:

- *Hubble tension*. Cosmology points to a lower value of Hubble expansion rate today than what is measured via SN + distance ladder.
- *Lithium problem*. Something does go wrong/missing when local determination of ^{7}Li/H is compared with the BBN prediction (the latter is a factor of ~3 higher). While it is possible that post-BBN, and specifically stellar, depletion of lithium is at play, it is also possible that the new physics modified the BBN outcome.
- First claim of the global 21cm absorption feature (*EDGES*) is at odds with the standard cosmological model.

etc

Cosmological constraints on “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)

LHN 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

……….

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

Production and decay of extremely weakly coupled dark photon

Let us study ~ a few MeV mass new particle V with coupling $e\varepsilon \sim 10^{-18}$

Let us introduce a new notation, $\alpha_{\text{eff}} \sim \alpha\, \varepsilon^{2} \sim 10^{-38}$

Production cross section for the $e^+e^- \to V\gamma$ process is

....

$$\sigma_{\text{prod}} \sim \frac{\pi\alpha\alpha_{\text{eff}}}{E^2_{\text{c.m.}}} \sim 10^{-66} \quad \text{cm}^2$$

It is hard to believe at first:

Not only such a model can be tested – as it turns out it can be robustly excluded by the data ! Constraints from "freeze-in"

(First application to HNL, Adams, Sarkar, Sciama, 1998)

Constraints on very dark photons

- The production cross section is ridiculously small, but in the early Universe at $T > m_V$, in fact, *every colliding pair of particles can produce such V*, and there is a lot of time available for this.
- Once produced such particles *live for a very long time*, and decay in the "quiet" Universe, depositing non-thermal amounts of energy and changing physics of primordial matter after recombination.
- Precision determination of optical depth during the CMB, position of Doppler peaks and the slope of the Silk diffusion tale provide tight restrictions on the amount of energy injected.
- Due to BBN we also have a pretty good evidence that the Universe in fact once was at least T ~ a few MeV hot…..
- Fradette, Pradler, MP, Ritz, arxiv:1407.0993, constraints on "very dark photons"

Filling out details….

- Lifetime against the decay of V to electron-positron pairs

$$\tau_V \simeq \frac{3}{\alpha_{\rm eff} m_V} = 0.6\ {\rm mln\ yr} \times \frac{10\,{\rm MeV}}{m_V} \times \frac{10^{-35}}{\alpha_{\rm eff}}$$

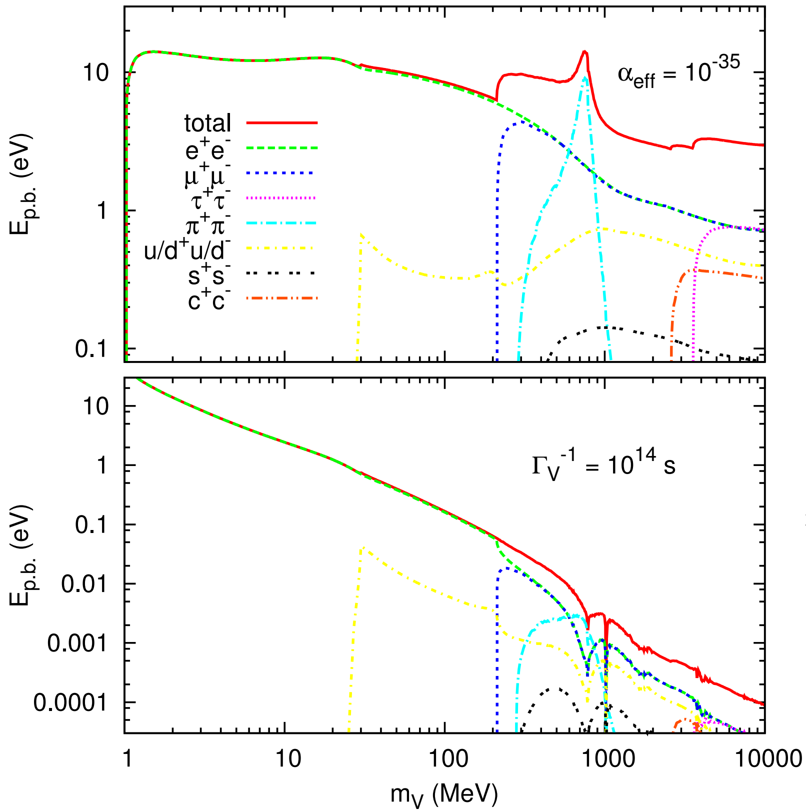
- $e^+e^- \rightarrow V$ in the early Universe leads to the energy stored per baryon

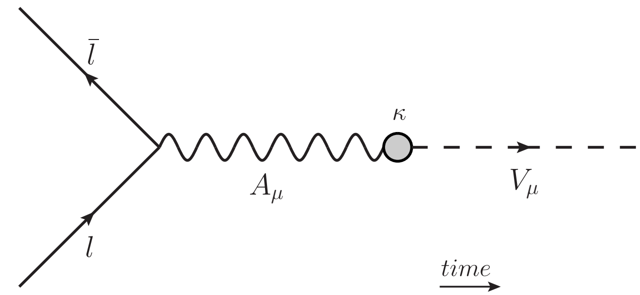
$$E_{\rm p.b.} \sim \frac{m_V \Gamma_{\rm prod} H^{-1}_{T=m_V}}{n_{b,T=m_V}} \sim \frac{0.1\alpha_{\rm eff} M_{\rm Pl}}{\eta_b} \sim \alpha_{\rm eff} \times 10^{36}\,{\rm eV}$$

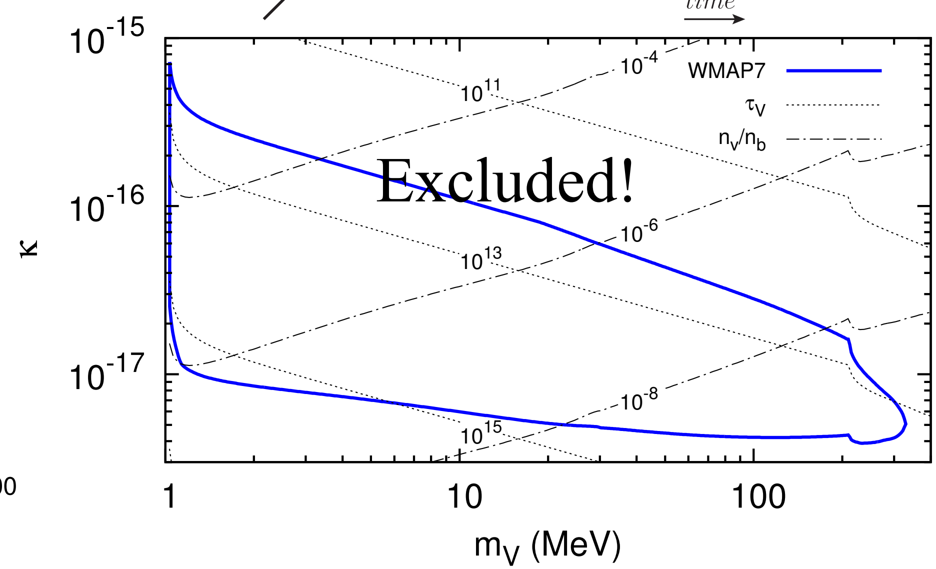
$$\text{for} \quad \Gamma_V^{-1} = 10^{14}{\rm s}.$$

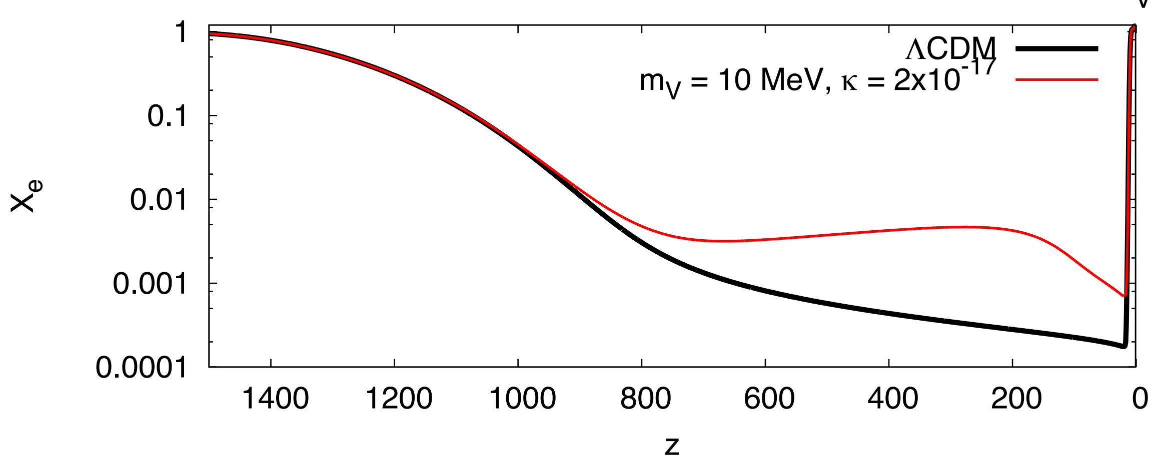
- Planck mass in numerator, and $1/\eta_b \sim 10^9$ provide huge enhancement.
- Once injected back to the medium via $V \rightarrow e^+e^-$ ~ 1/3 of the stored energy leads to ionization. E.g. 1 eV per baryon recreates $X_e \sim$ few 10^{-2} – which would be in gross conflict with CMB physics.

Dark photon changes ionization history

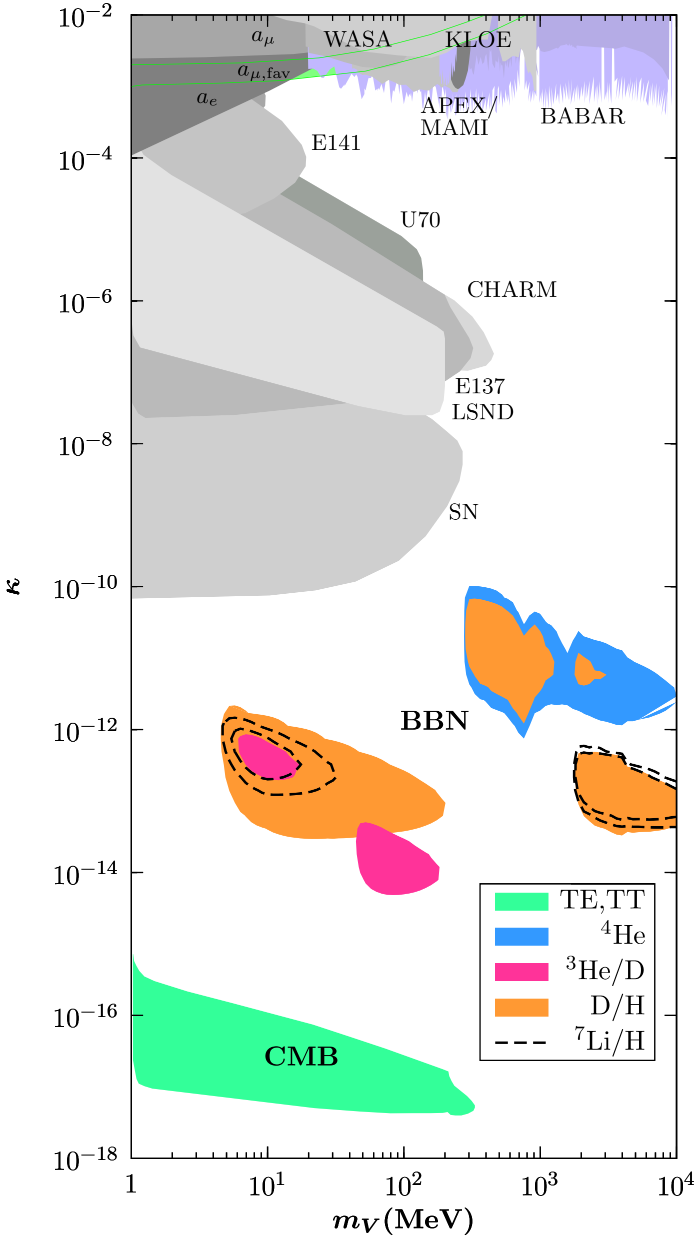








Constraints on dark photons



- 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)

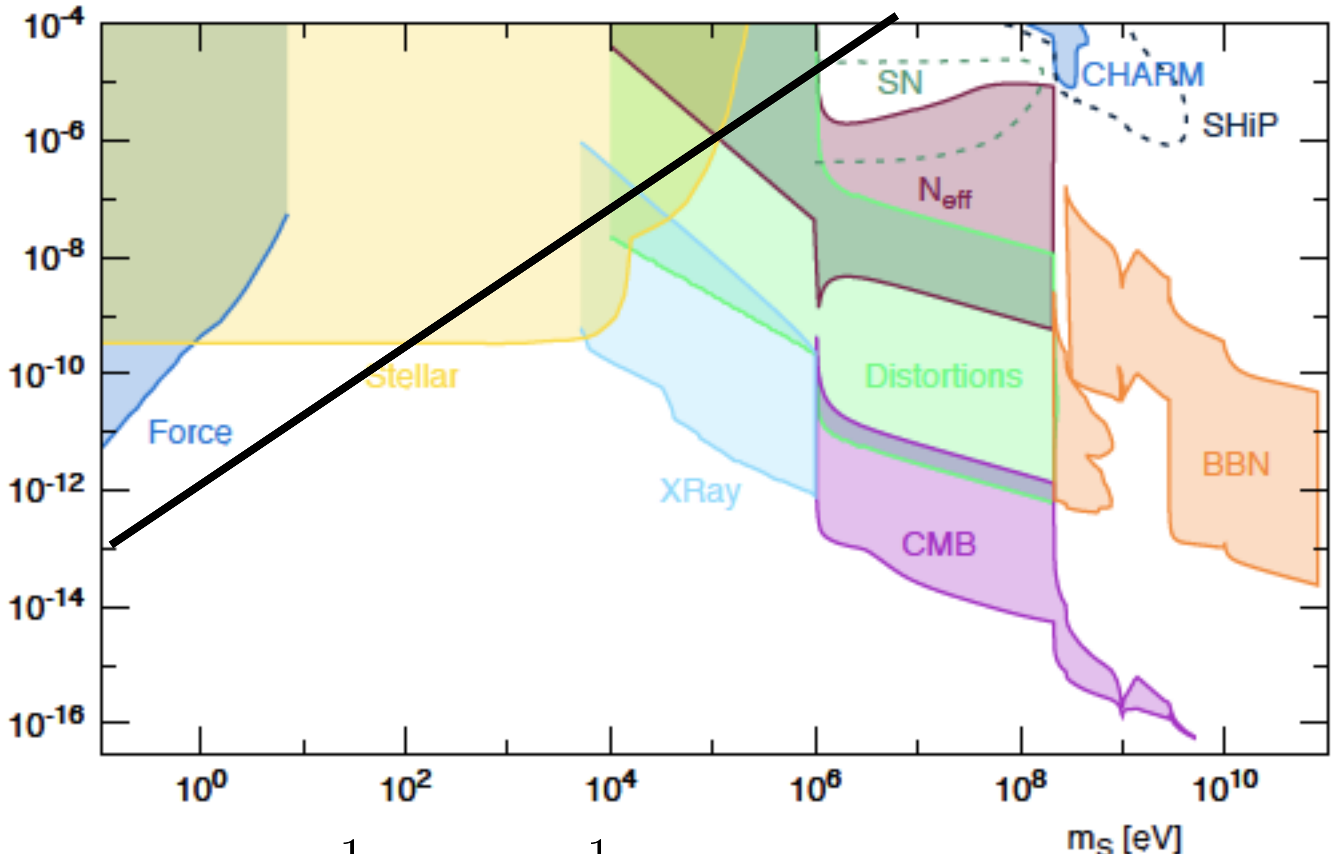
Freeze-in yield

Production Channel i	$Y_i^{v\gg 0}$	$Y_i^{v\gtrsim 0}$	Y_i^{sym}	Y_i^{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 ~50% accuracy. Big improvements over earlier works (that were ok up to factor of ~30)

Results significantly constrain technically natural corner

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

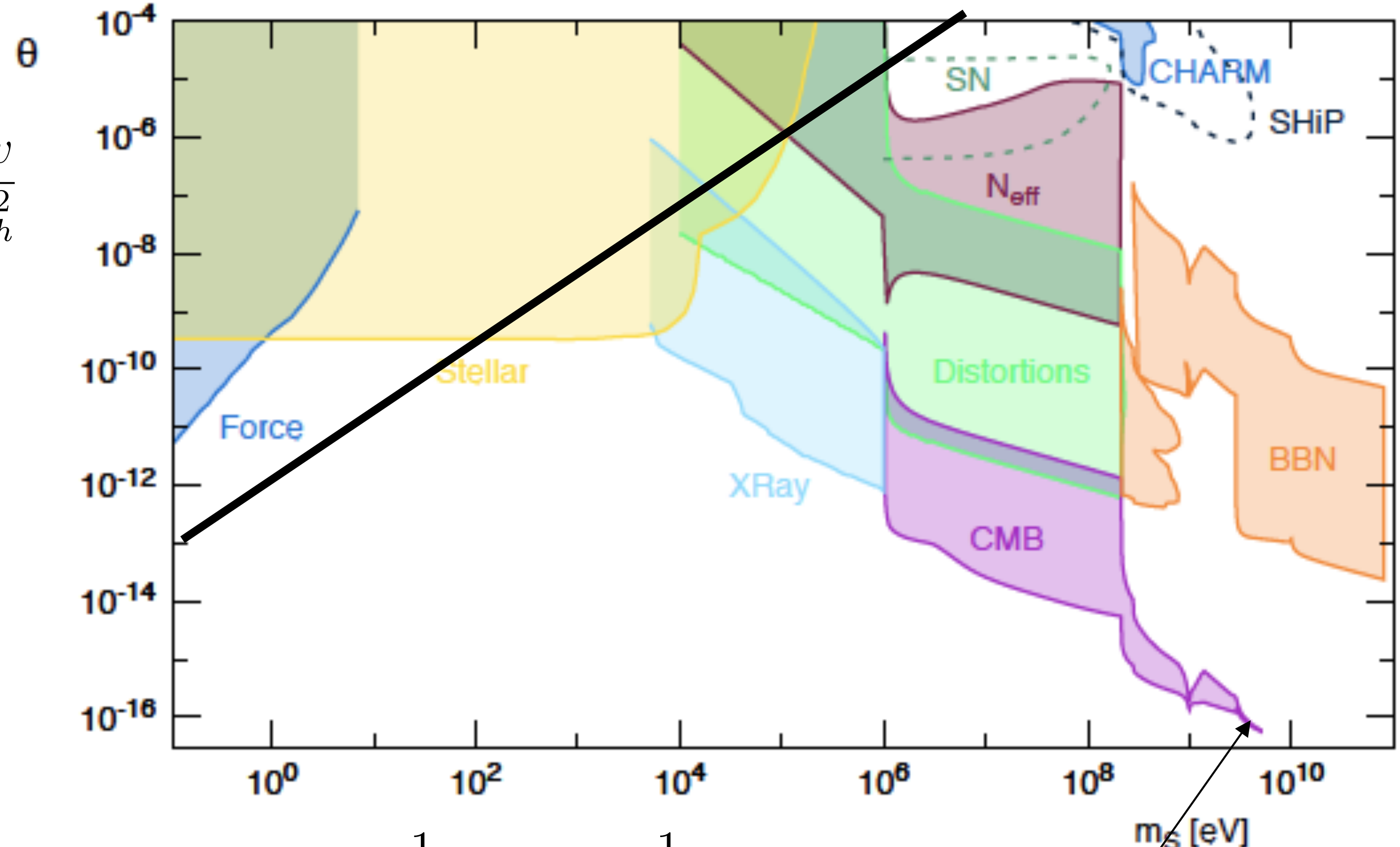


$$\mathcal{L}_{\text{Higgs portal}} = \frac{1}{2}(\partial_\mu S)^2 - \frac{1}{2} m_S^2 S^2 - ASH^\dagger H$$

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).

Results significantly constrain technically natural corner

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



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

Coupling of a new state S to electron here is ~ 10^{-22}. Similar to gravitational coupling of NR electron.

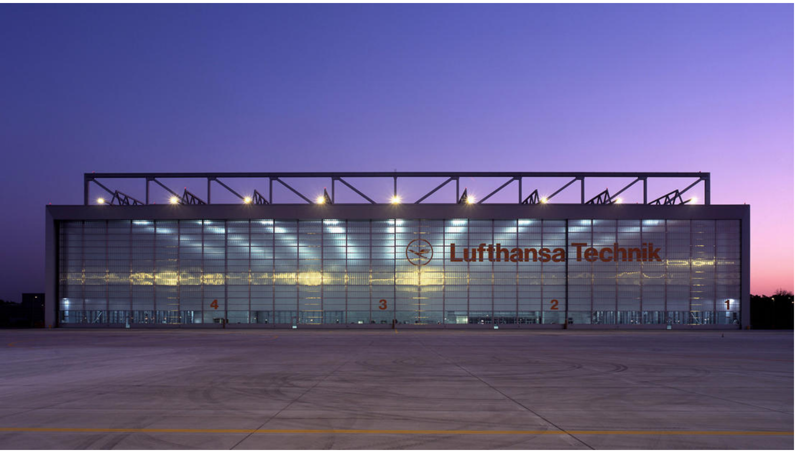
Higgs portal and light scalars at the LHC

- **I will consider λ_S sizeable and A parameter (mixing) to be small.**

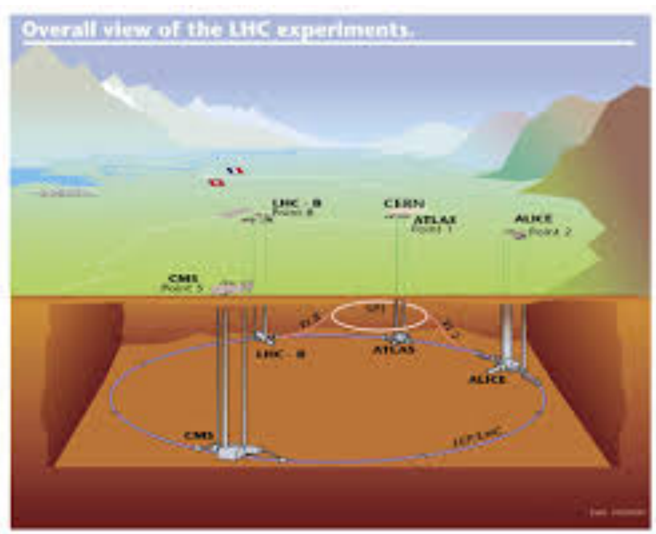
$$\mathcal{L}_{H/S} = \mu^2 H^\dagger H - \lambda_H \left(H^\dagger H\right)^2 - V(S) - ASH^\dagger H - \lambda_S S^2 H^\dagger H + \text{kin. terms.}$$

- 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, due to λ_S followed by S decay.
- What if S are so long-lived that they decay at really macroscopic distance away? BBN comes to rescue to set limits on maximum lifetimes.

MATHUSLA proposal (staring from Chou, Curtin, Lubatti, 1606.06298)



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.



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

- 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

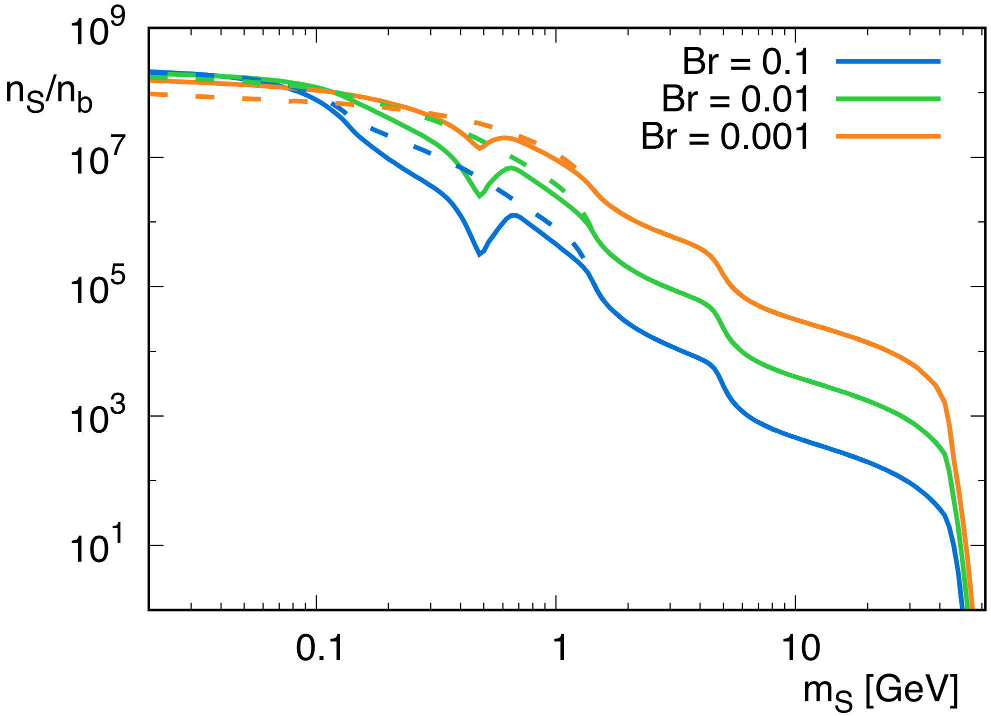
$$\Gamma_{h\to SS} = \frac{\lambda_S^2 v^2}{8\pi m_h}\sqrt{1-\frac{4m_S^2}{m_h^2}},$$

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

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

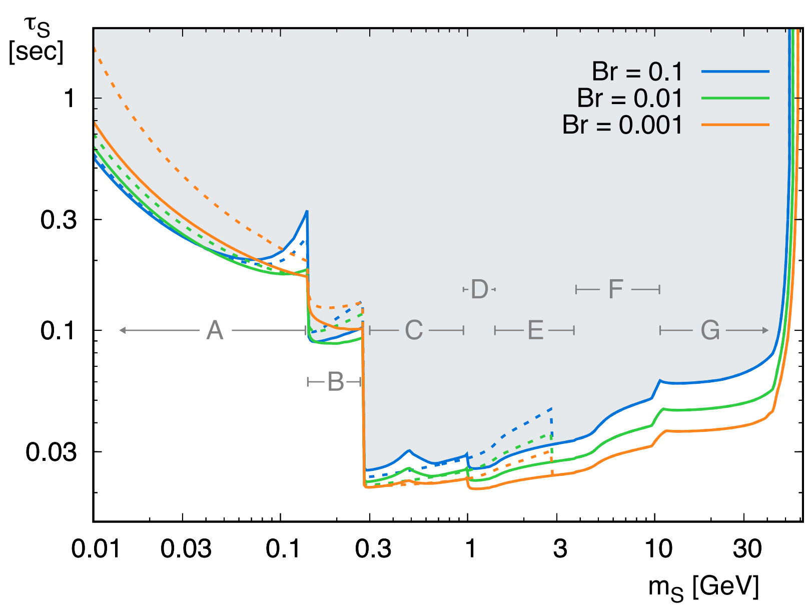
Cosmological metastable abundance

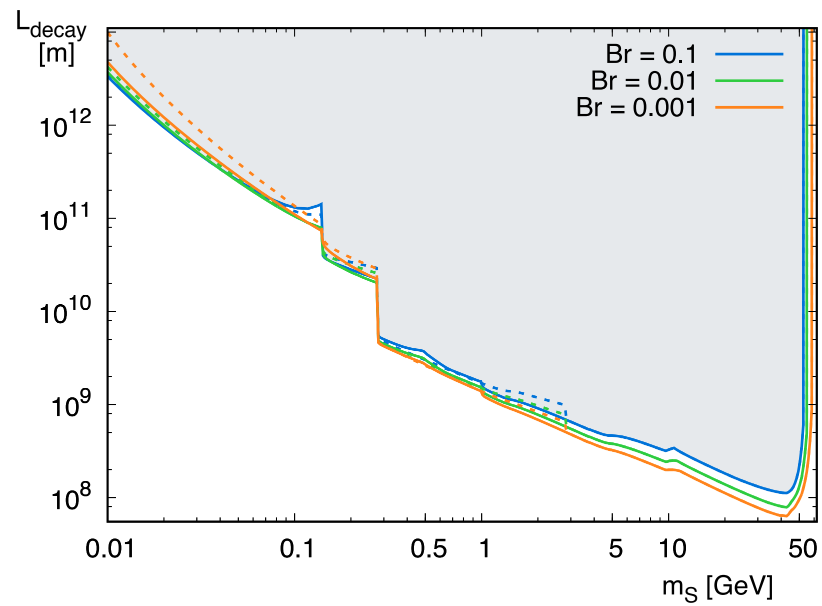
- In the early Universe, the number density is depleted as for the usual WIMP:
- However, because Higgs mediation is relatively inefficient, the abundance you are stuck with is large. [The smaller H→SS branching is, the MORE of these particles survive in the early U]



Constraints on lifetime come mostly from n/p enrichment

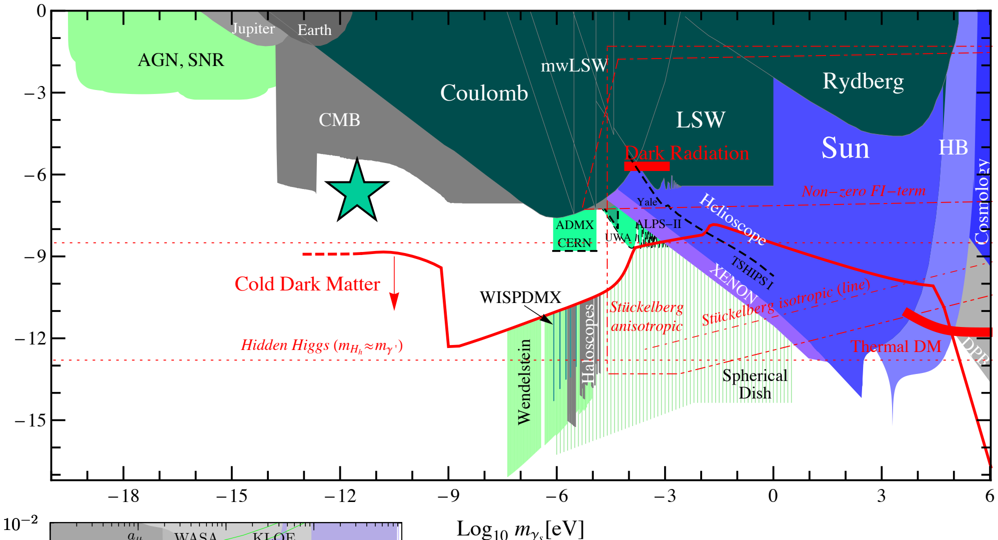
- Decay products (nucleons, kaons, pions) induce extra p→n transitions and quite generically increase n/p. This is very constrained.

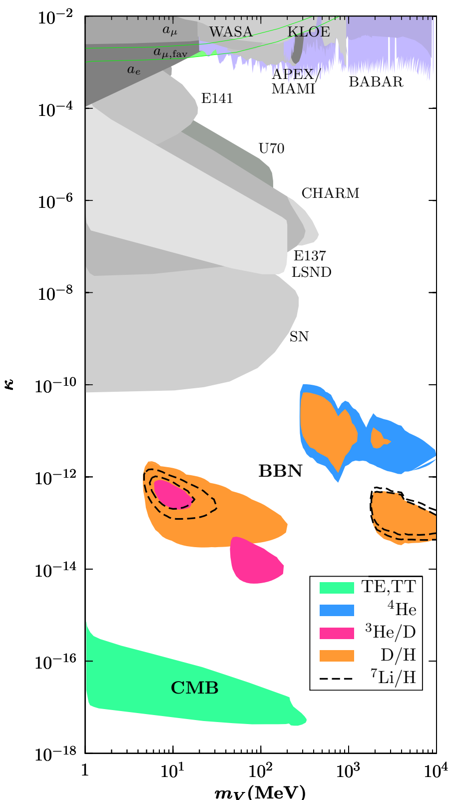




- For a ~ GeV scale particle, and energy of 200 GeV (broadly consistent with being a decay of the Higgs at 13 or 14 TeV energy), the minimum probability to decay in 100m detector is ~ 10^{-6}. If the branching of H→SS is sizeable, then it is a detectable signal.

Constraints on dark photon in broad mass range





Going to small mass range (our group, An et al, 2013, has derived correct stellar energy loss constraints.) *Notice weakening of bounds at small $m_{A'}$*

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

EDGES result: cosmic 21 cm

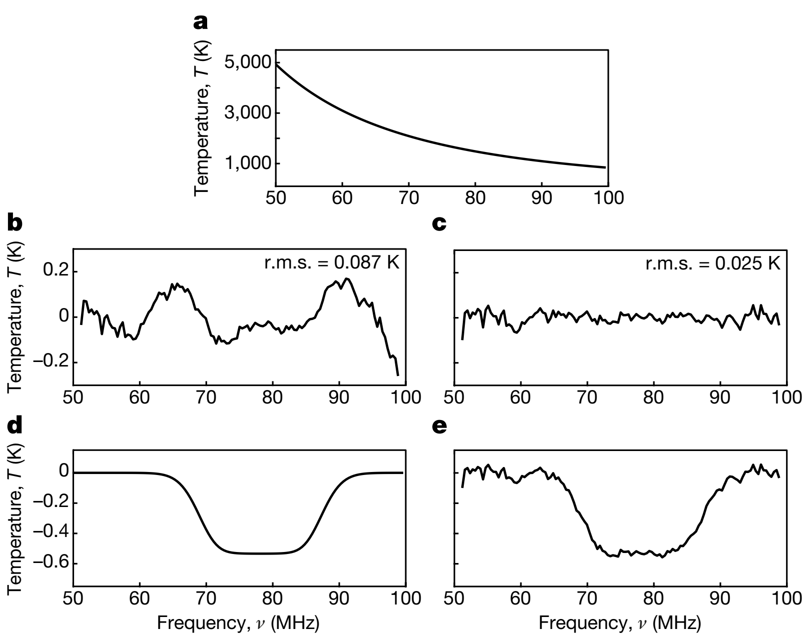
LETTER

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*

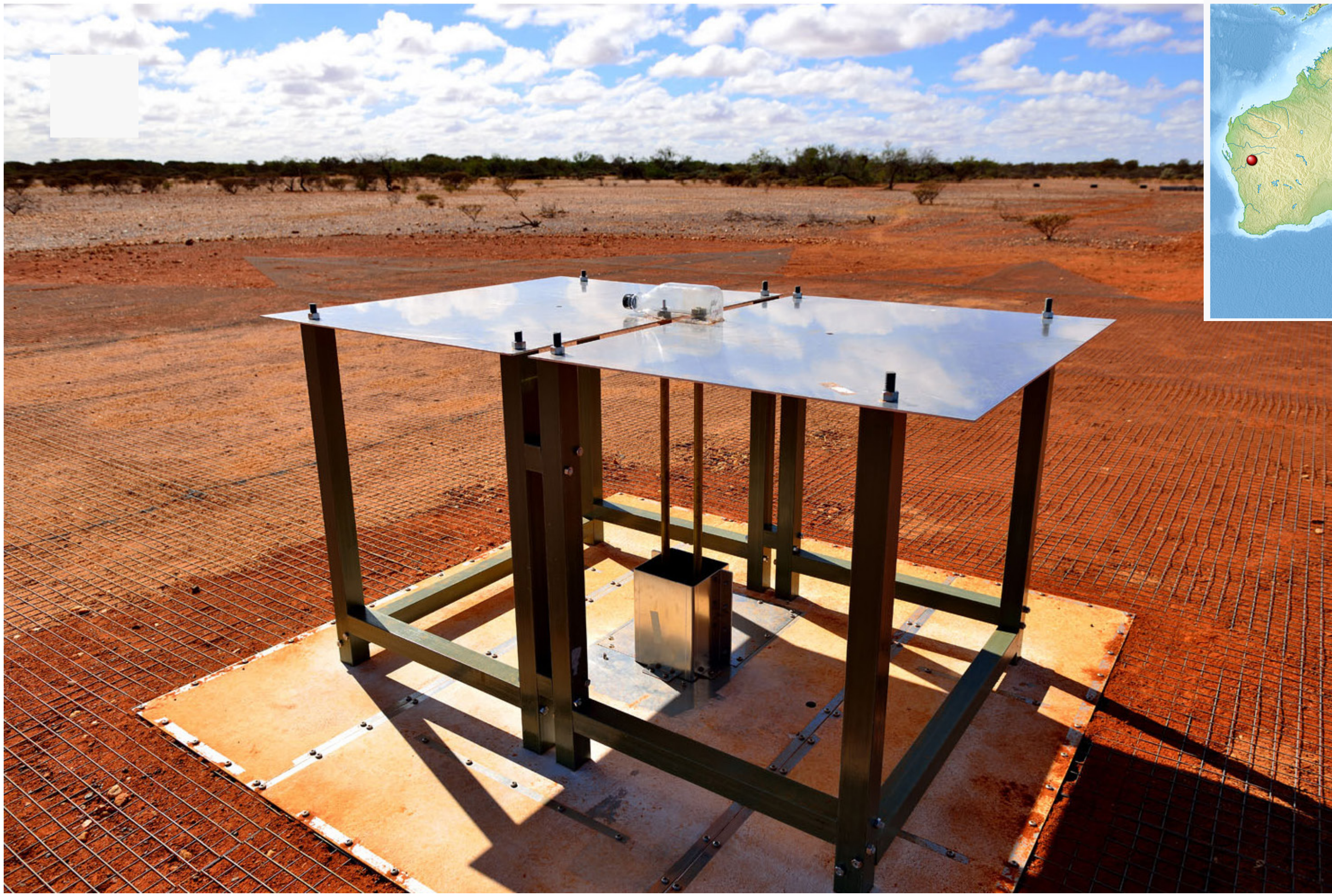


There is plenty of skepticism expressed in the literature about the instrument itself, data analysis and possible sources of backgrounds. For now, the collaboration has not conceded any of that.

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**).

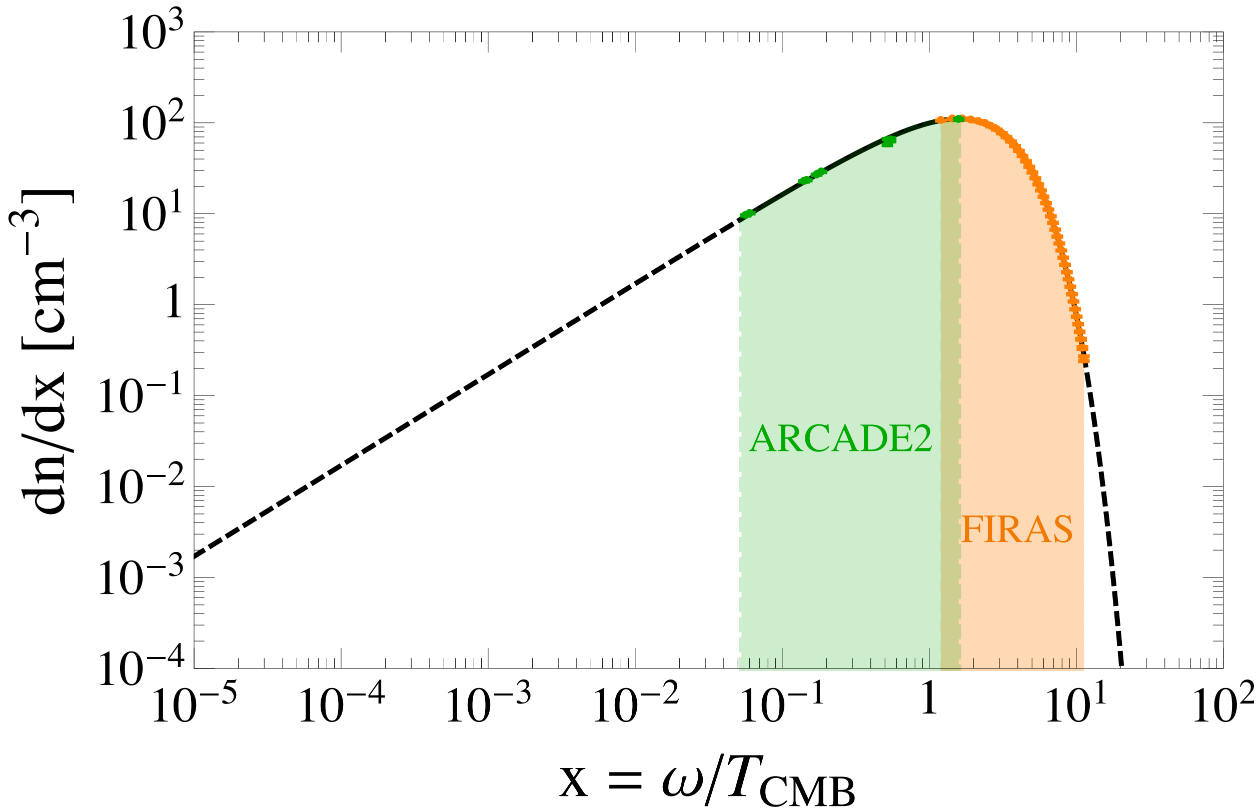
EDGES

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



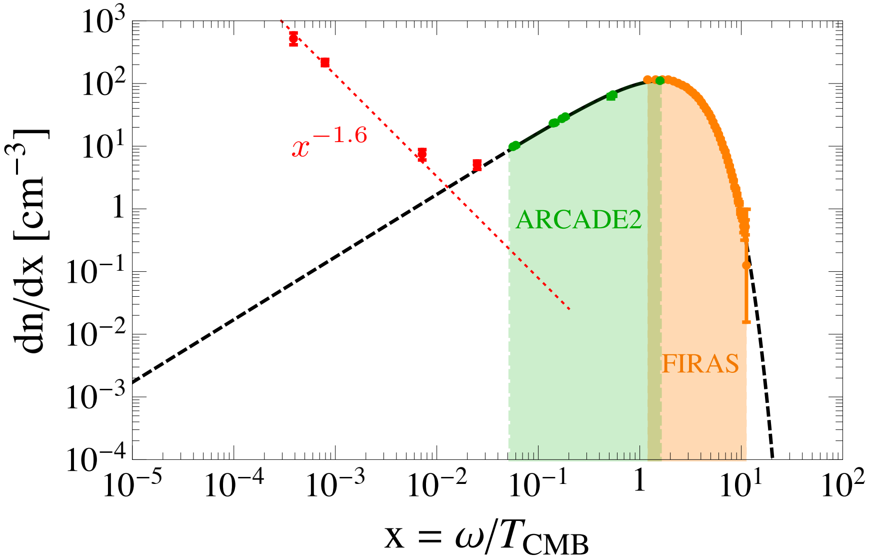
Bowman *et. al.* Nature **555**, 67 (2018)

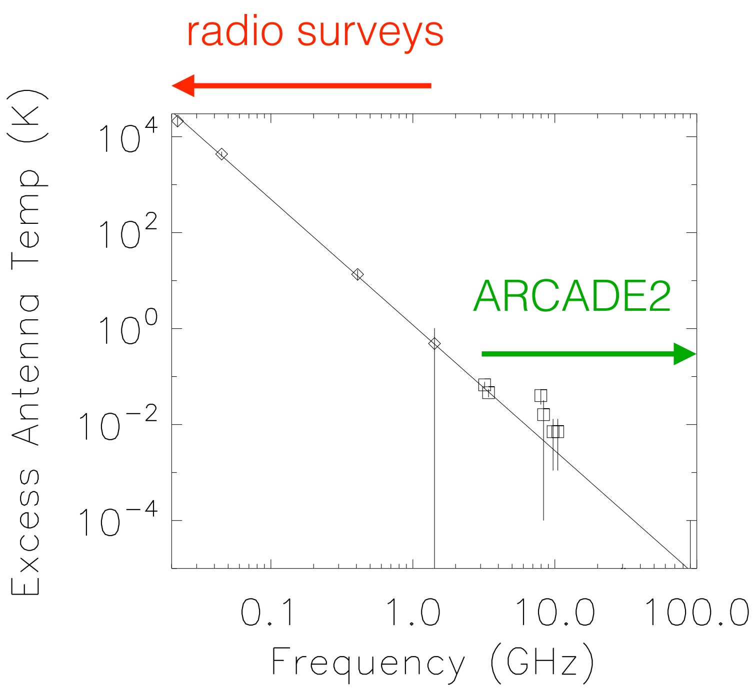
CMB Planckian spectrum



- 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



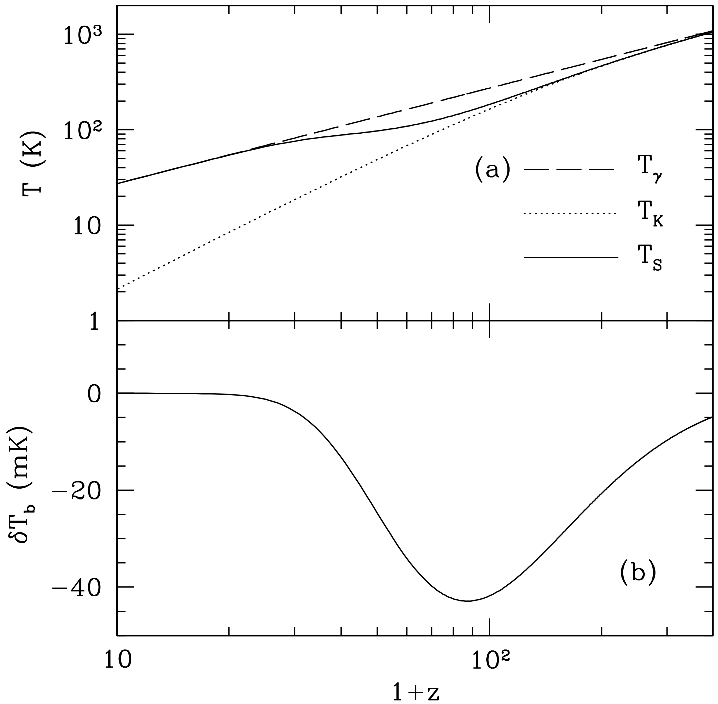


- ARCADE 2, **0901.0555**

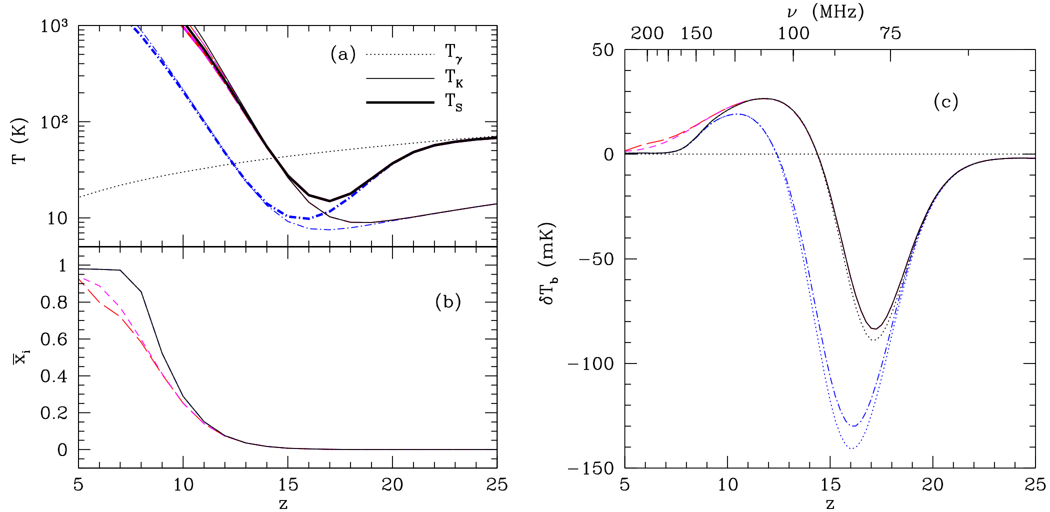
We do not have an independent probe of primordial part of the spectrum x ~ 10^{-3}, as it is fully covered by radio excess.

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.

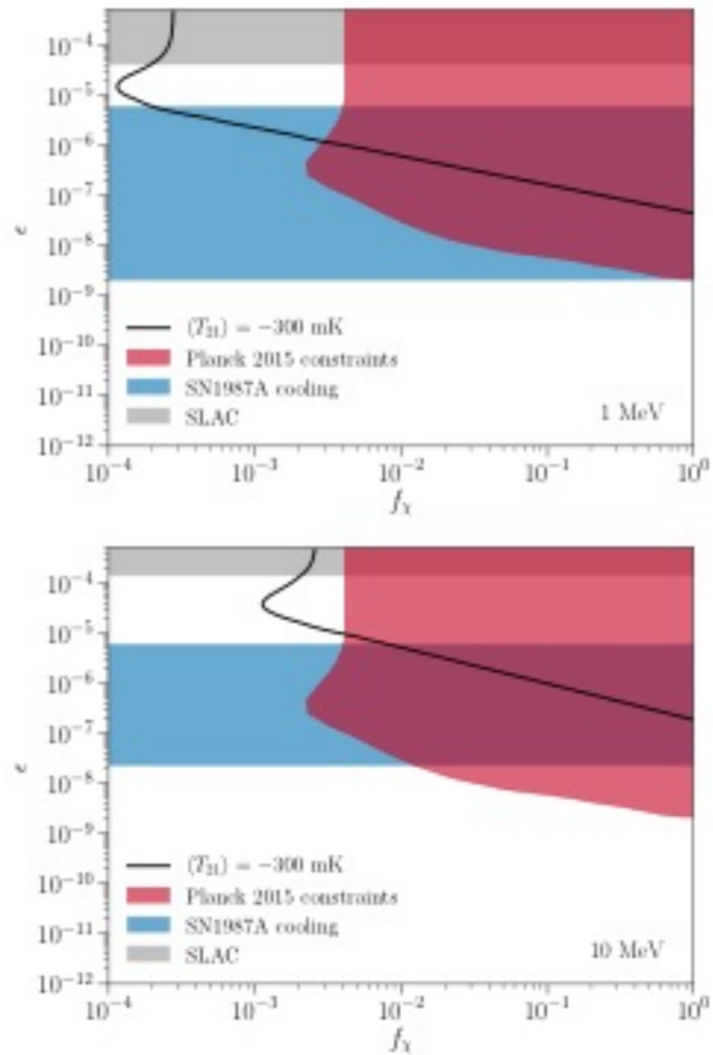
- Approach 1: *Cool the baryonic kinetic temperature even more*.

- 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*.

Millicharge explanations are very constrained

- CMB and BBN constrains
- Direct experimental constraints
- Energy injection constraints
- Direct detection constraints (?)
- Astrophysics constraint

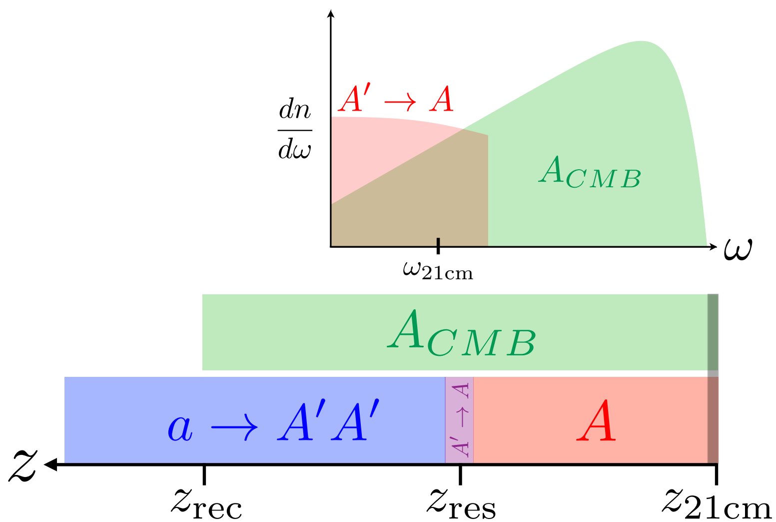
However, 10 MeV mass, 10^{-4}-10^{-5} charge and 1% abundance is not yet excluded. Constraints can be further relaxed if main part of DM is also light, and strongly coupled to MCPs. (H. Liu et al, 2019)



Kovetz et al, 2018

Making more IR photons

- 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.



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

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

Example of new physics model

MP, Pradler, Ruderman, Urbano, 2018, PRL

- 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. $\tau_a > 10^{20}\ \tau_{\mathrm{U}}$)

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

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

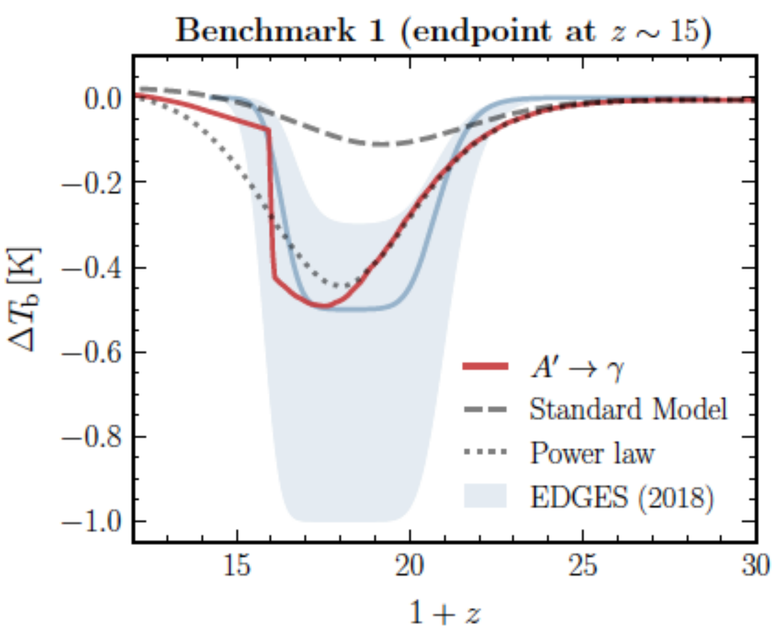
$\omega_{pl} \ll m_{A'}$, vacuum oscillation, $\theta_{eff} = \varepsilon$ (and $\omega^2_{pl} = 4\pi\alpha\, n_e / m_e$)

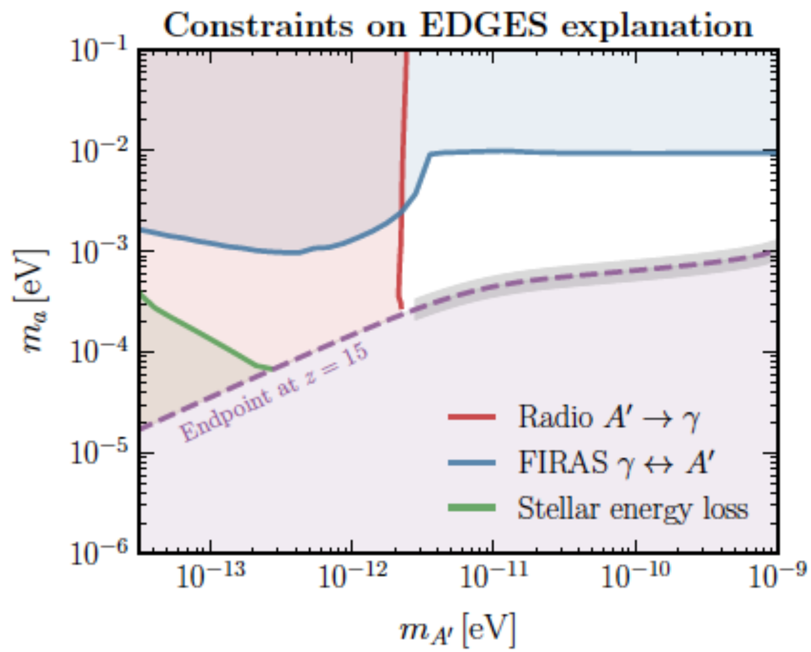
$\omega_{pl} \gg m_{A'}$, in-medium oscillations, $\theta_{eff} = \varepsilon \times (m_{A'}^2 / \omega_{pl}^2(z))$

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

Parameter space of the model that can fit EDGES excess

- Typical ε is on the order of 10^{-7}. A. Caputo et al, 2020, to appear.





Dark sector model with an ALP of ~1 meV mass, and dark photon of ~ 0.01-1 neV, can generate an excess photons in the IR tail of the CMB, and fit EDGES anomalous observations.

Conclusions

1. Cosmological constraints are derived on the entire mass-mixing plane for scalars coupled through the super-renormalizable portals, and on dark photons.
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. *We have an 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.
4. 21 cm cosmological signal, then, provides the key test of such models with beyond-SM sectors composed of light fields.