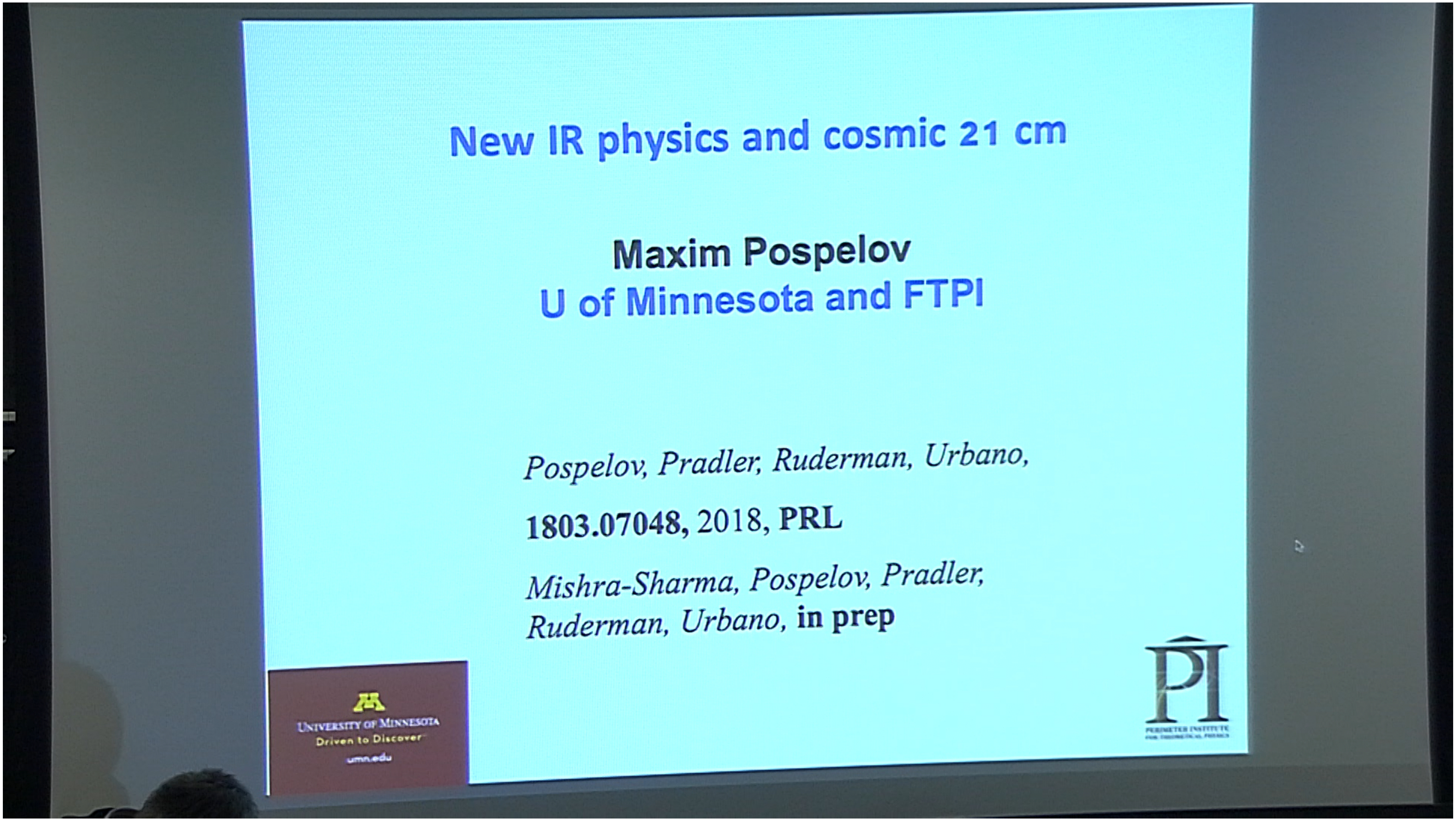
Title: New Physics in the Rayleigh-Jeans tale of the CMB and cosmic 21cm signal

Speakers: Maxim Pospelov

Collection: Cosmological Frontiers in Fundamental Physics 2019

Date: September 03, 2019 - 11:30 AM

URL: http://pirsa.org/19090022


New IR physics and cosmic 21 cm
Maxim Pospelov
U of Minnesota and FTPI
Pospelov, Pradler, Ruderman, Urbano,
1803.07048, 2018, PRL
Mishra-Sharma, Pospelov, Pradler,
Ruderman, Urbano, in prep
University of Minnesota
Driven to Discover
umn.edu
Perimeter Institute

Plan

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

2. Cosmic 21 cm physics by an amateur. Bigger picture. EDGES thought-provoking results. [If correct]: weird dark matter or weird CMB? [e.g. modified CMB Planck distribution.]

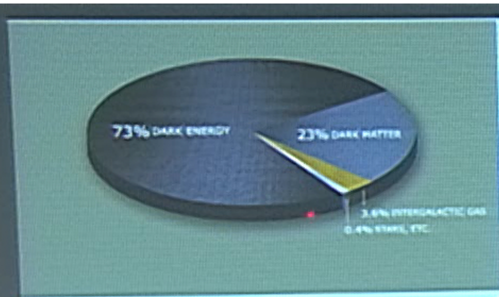
3. Weird DM: millicharged particles in the sub-100 MeV range. (new constraints from neutrino experiments)

4. Weird CMB: dark radiation → enhancement of Rayleigh-Jeans tail.

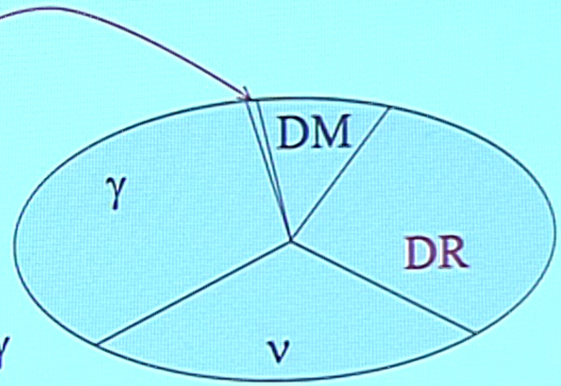
$$\omega_{\rm DR} \ll \omega_{\rm CMB}\ , \quad n_{\rm DR} > n_{\rm RJ}\ , \quad \omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}\ .$$

5. Conslusions

2



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

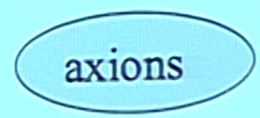


Atoms

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 3

New IR degrees of freedom = light (e.g. sub-eV) beyond-Standard-Model states

Let us *classify* possible connections between Dark sector and SM using standard particle physics tools.

4

Light weakly coupled new physics

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

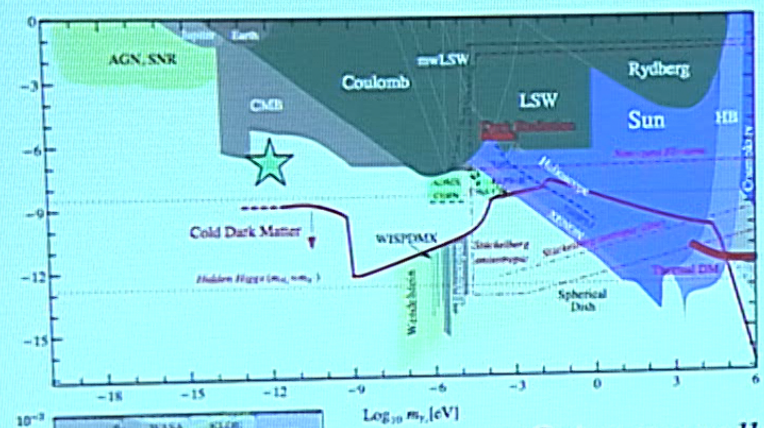
$J_\mu^{\,A}\, \partial_\mu a / f$ axionic portal

……….

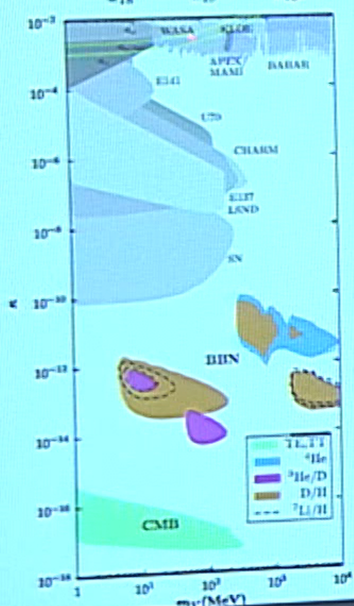
$$\mathcal{L}_{\text{mediation}} = \sum_{k,l,n}^{k+l=n+4} \frac{\mathcal{O}_{\text{med}}^{(k)} \mathcal{O}_{\text{SM}}^{(l)}}{\Lambda^n},$$

5

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 $m_{A'}$.*

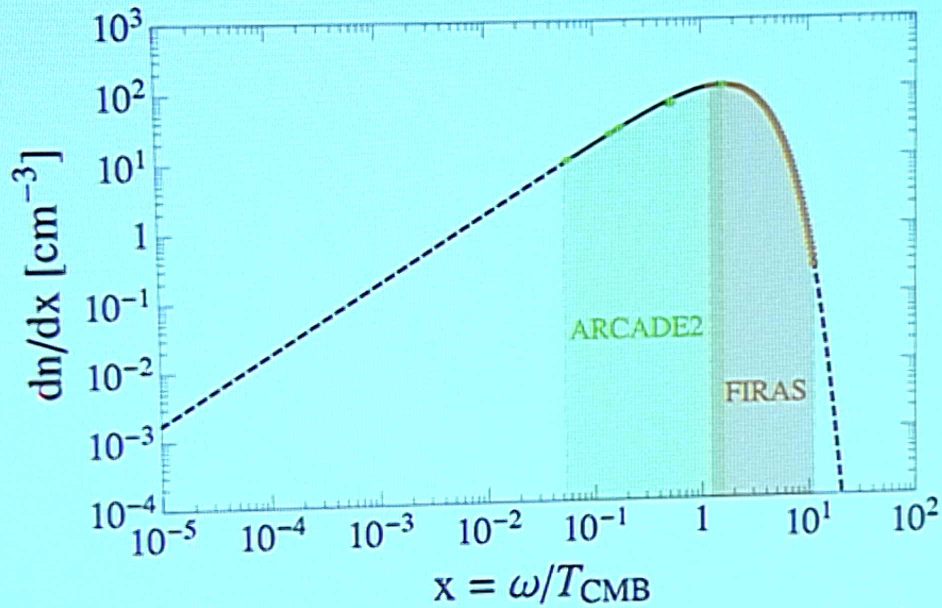


Going to smaller couplings: new primordial nucleosynthesis and CMB constraints from late decays of dark photons, (our group, Fradette et al, 2014)

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, $m_A = m_{A'}$)

6

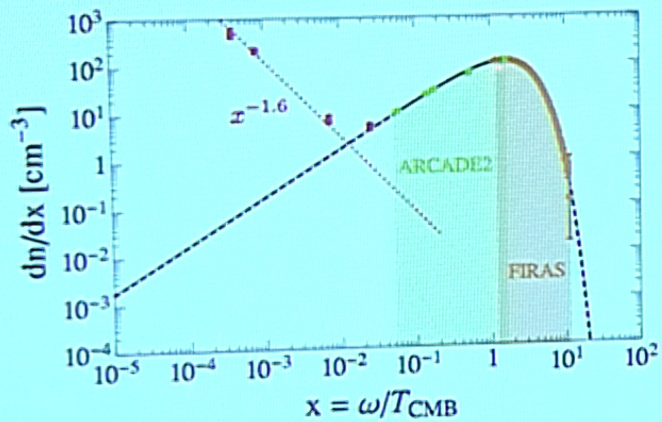
CMB Planckian spectrum

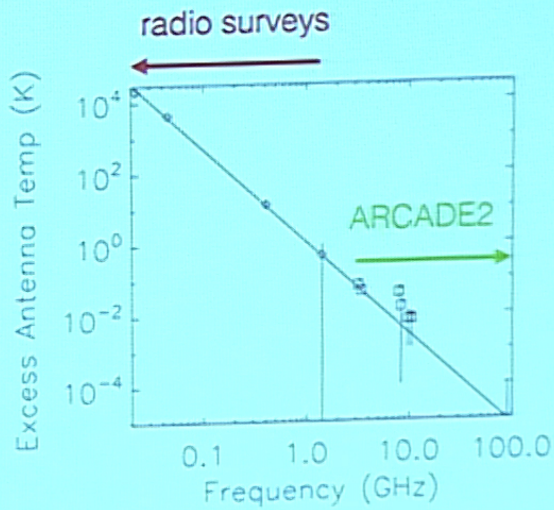


- FIRAS on COBE has measured the spectrum near its maximum to 1 part in 10^4 accuracy. $x \equiv \omega/T_{CMB}$
- The CMB anisotropy program by many experiments have proceeded on solid footing.
- 21 cm physics wants to use small x part of this plot

7

Radio Excess





- ARCADE 2, **0901.0555**

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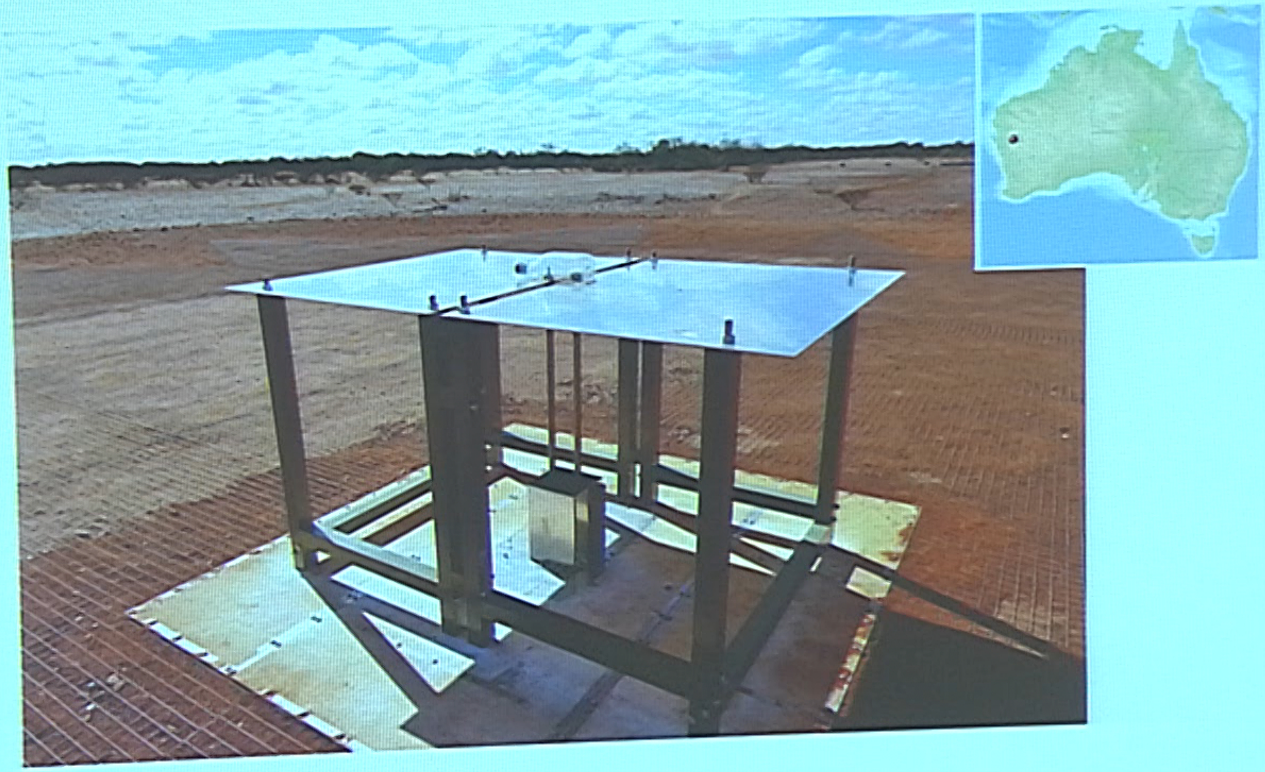
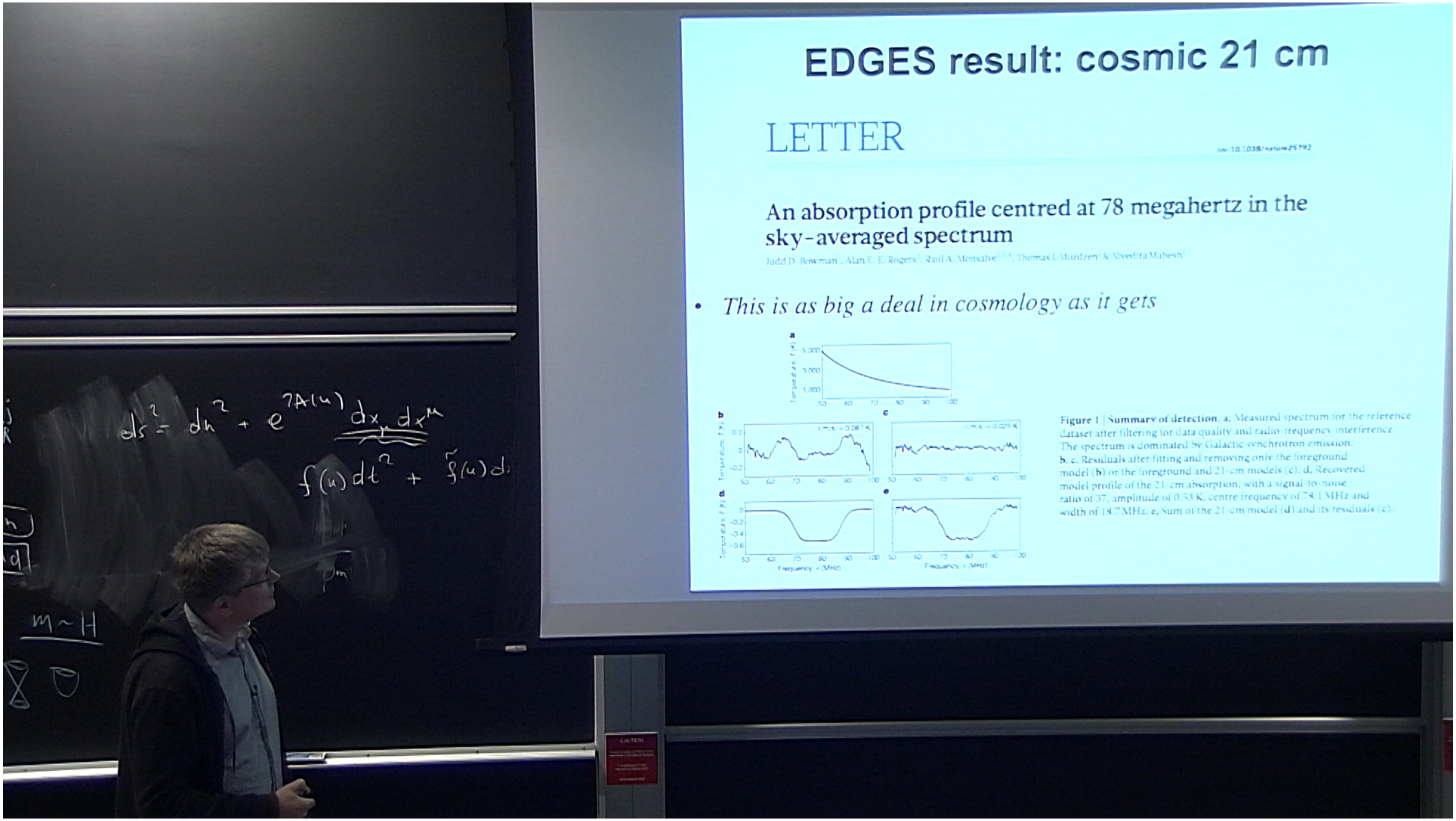
EDGES

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
An absorption profile centred at 78 megahertz in the sky-averaged spectrum
This is as big a deal in cosmology as it gets

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*

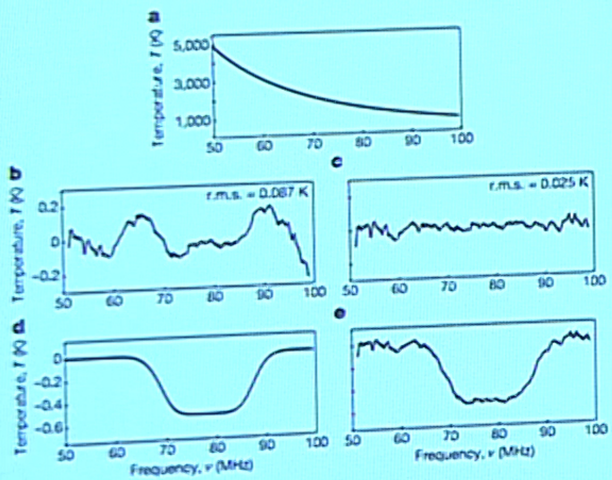
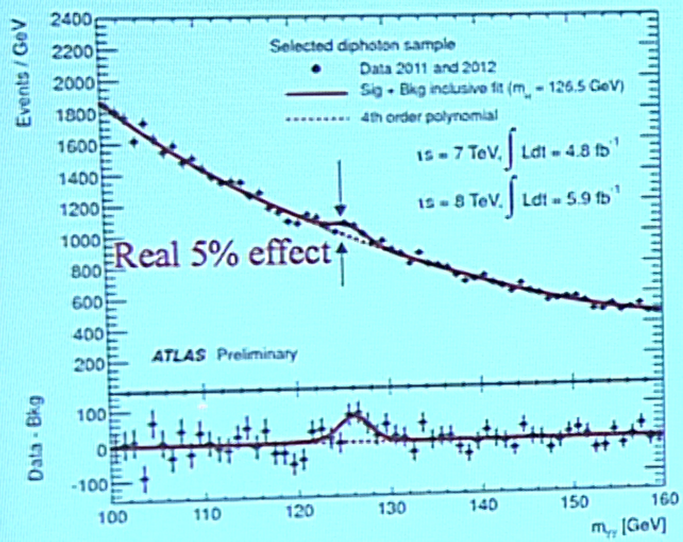


Figure 1 | Summary of detection. a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b, c,** Residuals after fitting and removing only the foreground model (**b**) or the foreground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

Remember this?



The Higgs discovery in 2gamma channel (small 5% effect) is the result of a "bump hunt" over smooth, not exactly predicted background.

EDGES result: cosmic 21 cm

LETTER

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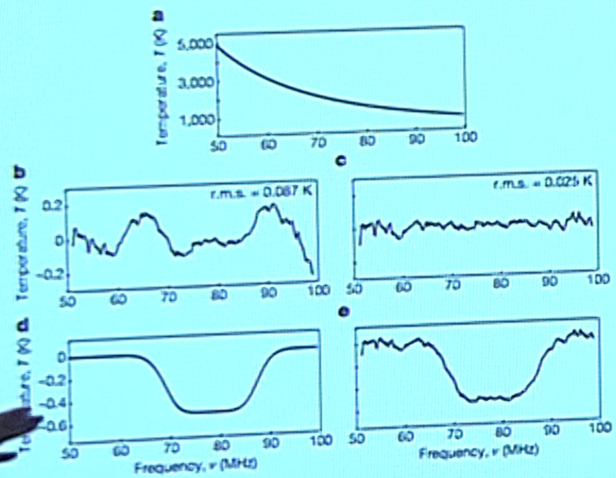
An absorption profile centred at 78 megahertz in the sky-averaged spectrum

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 skepticism expressed in the literature about the instrument itself, data analysis and possible sources of backgrounds. Collaboration has not conceded any of that. Recent data (Mosalve, LaThuile talk) with new antenna are consistent.



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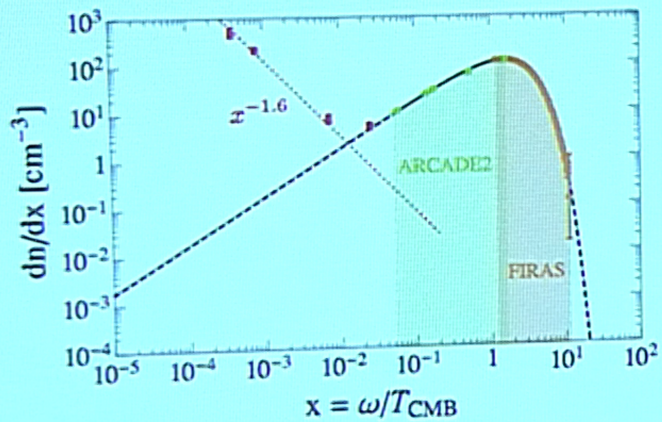
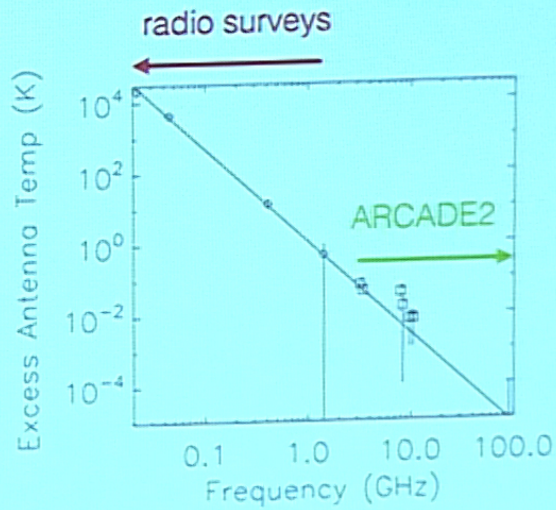
Radio Excess





- ARCADE 2, **0901.0555**

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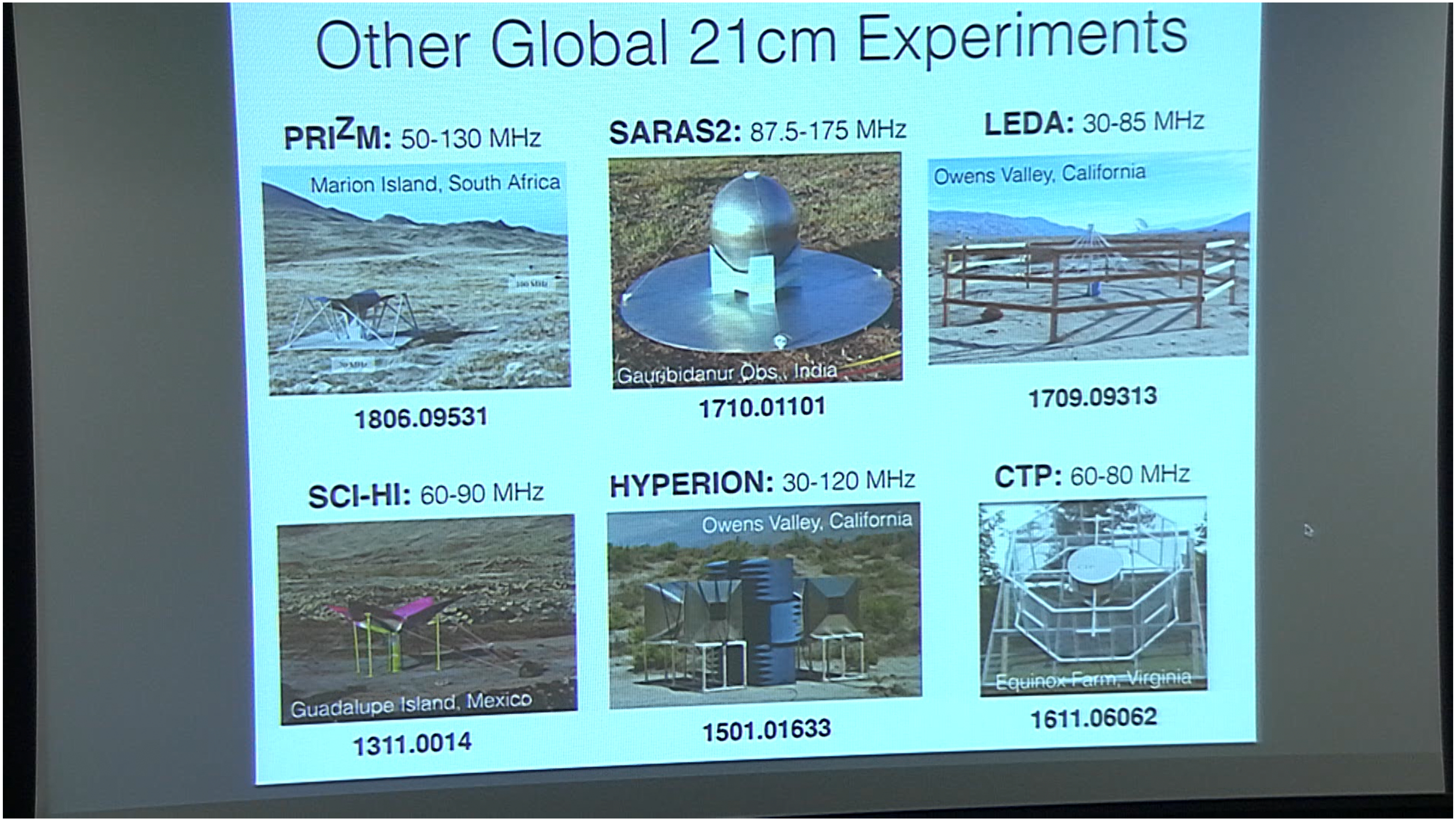
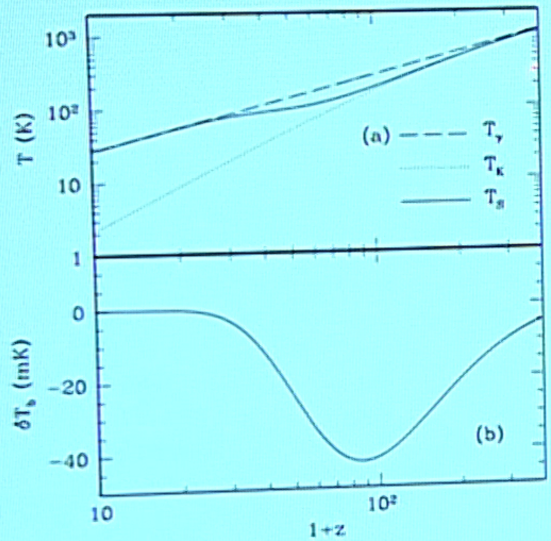
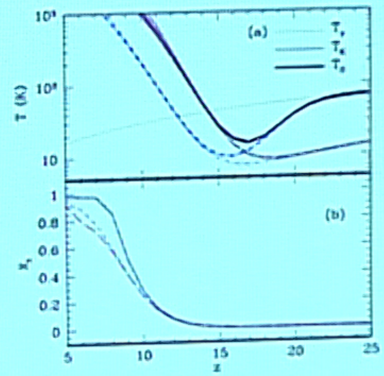

Other Global 21cm Experiments
PRIZM: 50-130 MHz
Marion Island, South Africa
1806.09531
SARAS2: 87.5-175 MHz
Gauribidanur Obs., India
1710.01101
LEDA: 30-85 MHz
Owens Valley, California
1709.09313
SCI-HI: 60-90 MHz
Guadalupe Island, Mexico
1311.0014
HYPERION: 30-120 MHz
Owens Valley, California
1501.01633
CTP: 60-80 MHz
Equinox Farm, Virginia
1611.06062

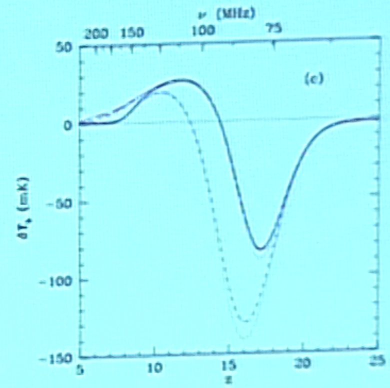
Interpretation of observation

- (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:

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

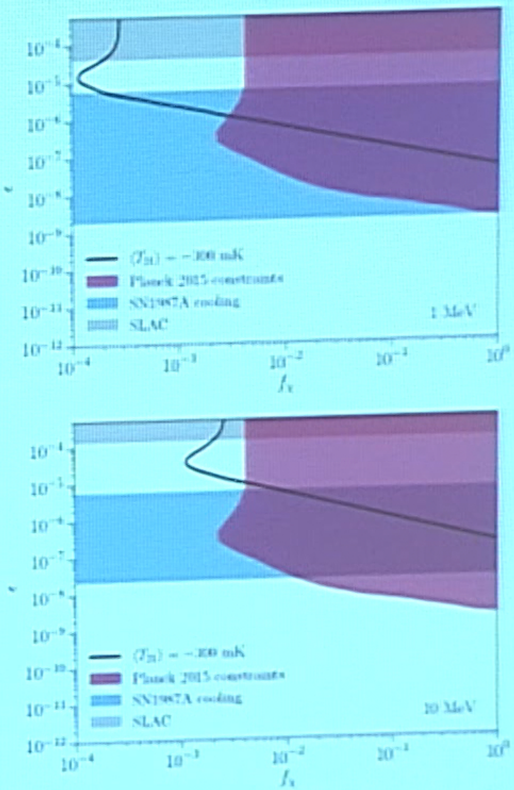
- Notice that these are all measured cosmological parameters, except the spin temperature, but it *cannot drop below baryonic temperature*!

- 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.

Millicharge explanations are very constrained

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



Kovetz et al, 2018

Speculations aimed to explain EDGES

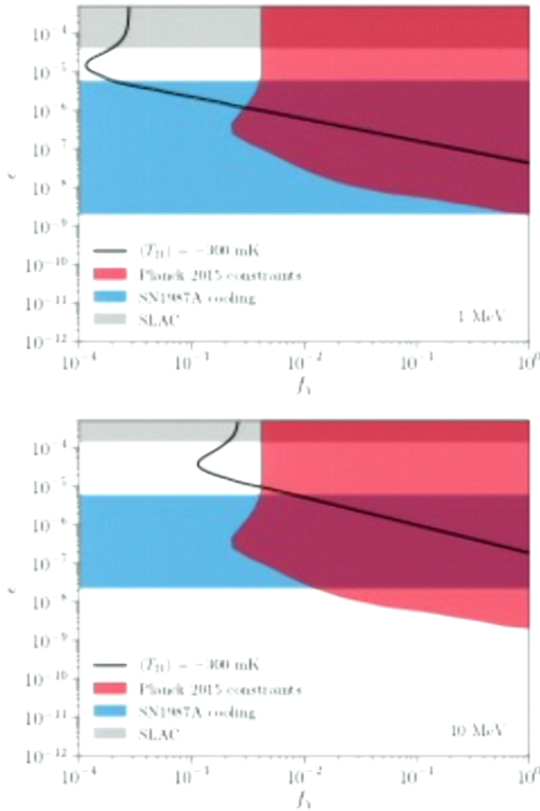
"DM does it to me"? But it cannot be "normal" WIMP or axion with the interactions that are too weak.

- 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*. Fraser et al, 2018; Pospelov et al, 2018

Millicharge explanations are very constrained

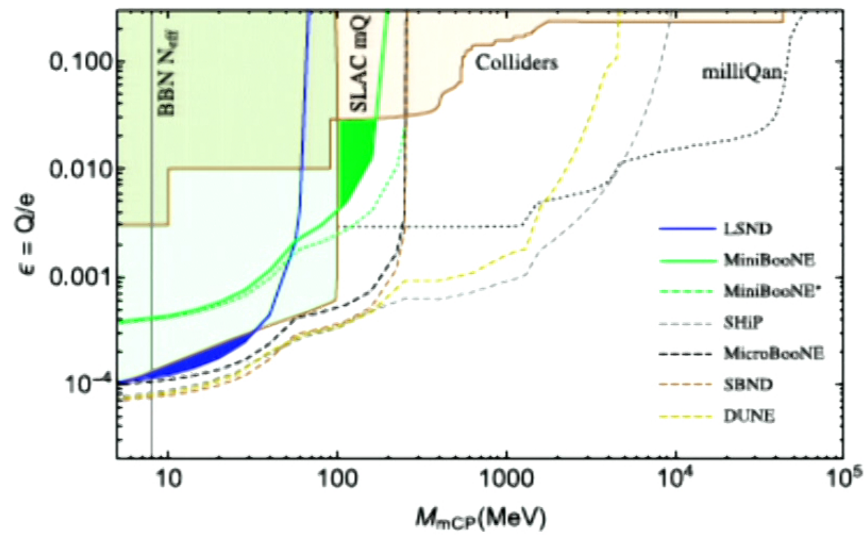
- CMB and BBN constrains
- Direct experimental constraints
- Energy injection constraints
- Direct detection constraints (?)
- Astrophysics constraints



Kovetz et al, 2018

Direct experimental constraints on millicharged particles

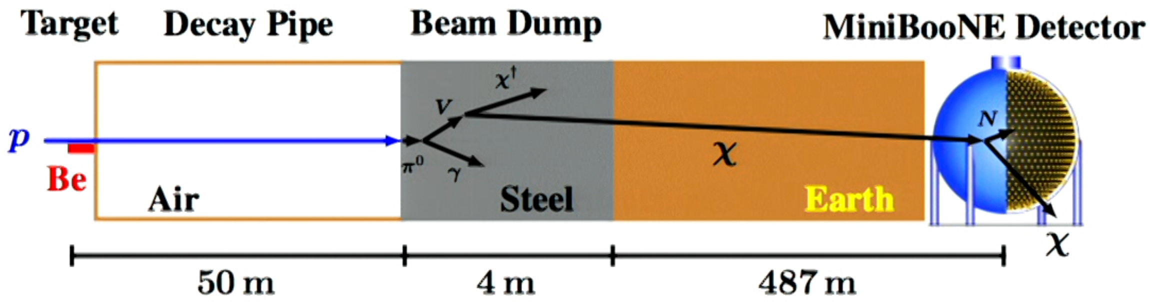
- Magill, Plestid, MP, Tsai, 2018. Best constraints in the 10 MeV range come from the LSND experiments (nu-e scattering)

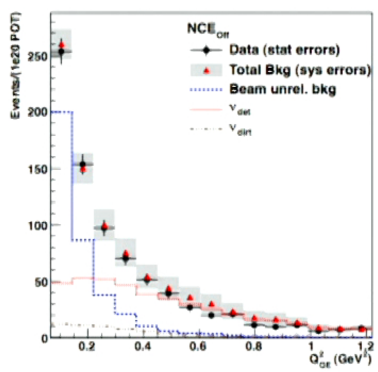


- *Further progress can be achieved through dedicated milliQan type experiments.*

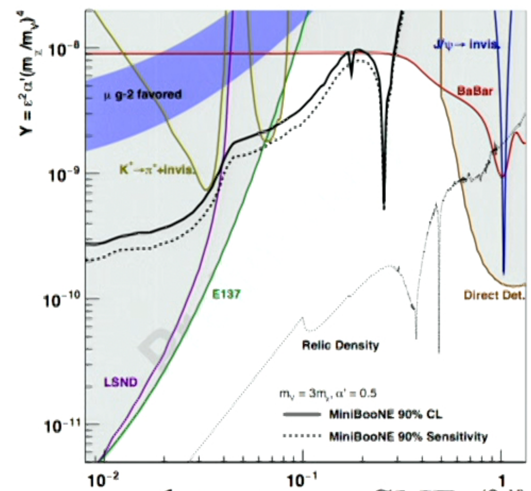
Neutrino and beam dump experiments can be recast as constraints on millicharge

arXiv:1702.02688, PRL 2017





	#events	uncertainty
BUB	697	
ν_{det} bkg	775	
ν_{dirt} bkg	107	
Total Bkg	1579	14.3% (pred. sys.)
Data	1465	2.6% (stat.)



Subject to future improvement with much closer new detector at SNB

22

New proposal at Fermilab

PROPOSAL FOR EXPERIMENTAL RESEARCH
DOE/SC PROGRAM OFFICE: **High Energy Physics (HEP)**
DOE/SC PROGRAM OFFICE TECHNICAL CONTACT: **Dr. Kathleen Turner**
FUNDING OPPORTUNITY FOA NUMBER: **DE-FOA-0002112**
ADMINISTRATIVE POINT OF CONTACT: **Hema Ramamoorthi**, 630-840-6723, hema@fnal.gov
PAMS LoI #: **LOI-0000025681**

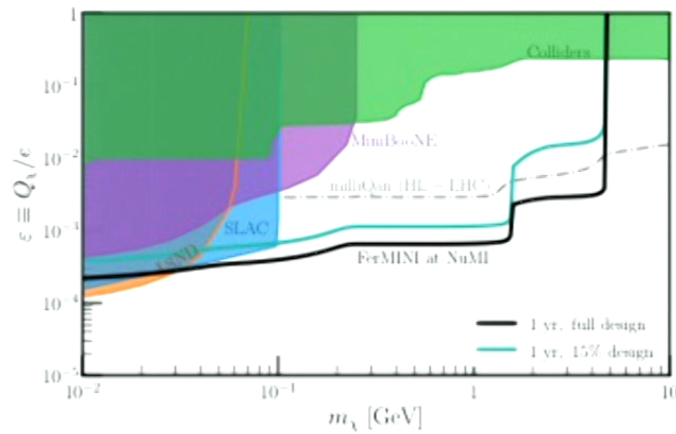
TRACK #1, PRD #1

APPLICANT/INSTITUTION: FERMI NATIONAL ACCELERATOR LABORATORY
PO BOX 500
BATAVIA, IL 60510-5011

FerMINI: Fermilab Search for Minicharged Particles

Principal Investigators:

A. HAAS (NYU), C.S. HILL (OSU), J.F. HIRSCHAUER* (FNAL)
D.W. MILLER (Chicago), D. STUART (UCSB),
Y.-D. TSAI (FNAL)

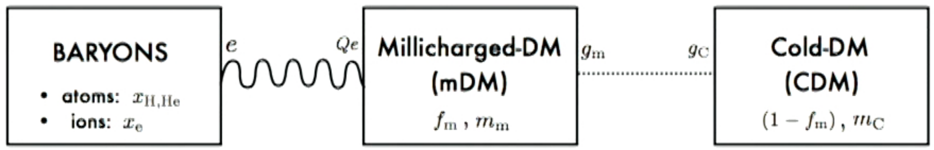


We propose to install a new MilliQan-style detector in the MINOS cavern at Fermilab.

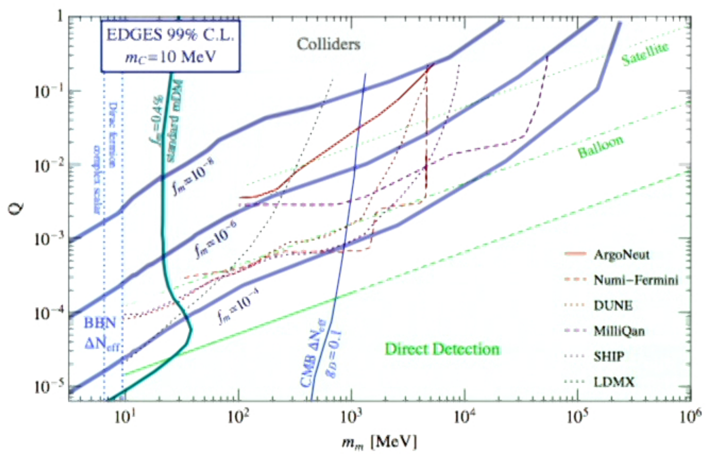
Would signficantly increase the reach, but unlikely to close EDGES r.o.i.

Modified model with extra cooling

H. Liu et al, 2019 arXiv:1908.06986v1



Main challenges in the previous mQ proposal – very few particles – hard to "store" heat. New proposal – extract heat with mQ and pass it to other DM particles that have strong rescattering rate on mQ.



Far less constrained scenario: smaller concentrations and larger masses of mQ particles are allowed.

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 $n_{CMB} = 0.24\ T^3$,

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

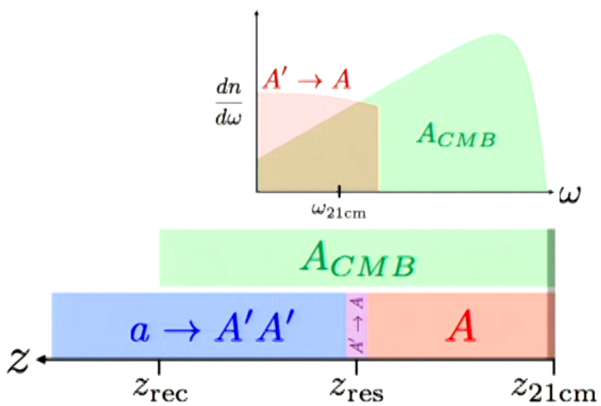
- What if there existed *early* DR that we could take to saturate as much as $N_{eff} = 0.5$ or alternatively, there is late decay of DM to DR, and we take up to 5% of DM to convert?

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

- 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.



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

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

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.
- I am going to explore $\omega_{\rm DR} \ll \omega_{\rm CMB}\ , \quad n_{\rm DR} > n_{\rm RJ}\ , \quad \omega_{\rm DR} n_{\rm DR} \ll \rho_{\rm tot}\ .$
- 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

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

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. $\tau_{\rm a} > 10^{20}\ \tau_{\rm U}$)

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

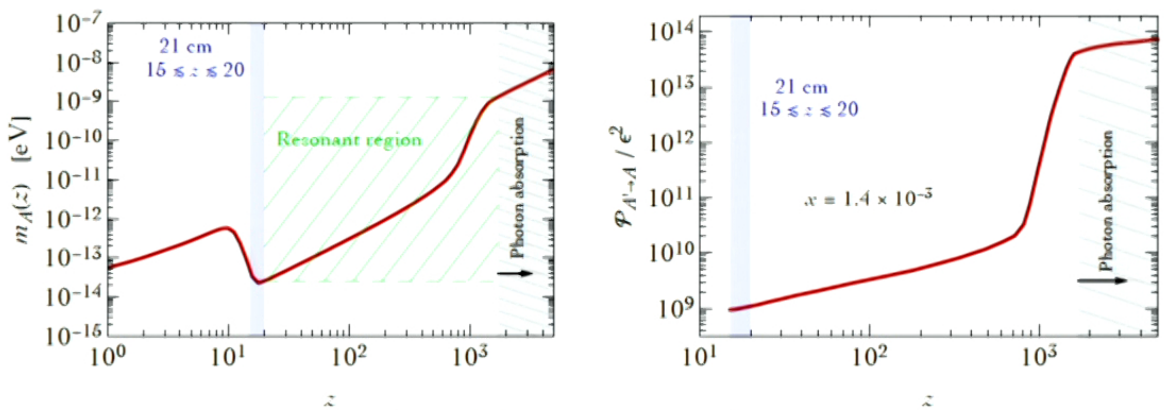
Resonance occur when $m_{A'} = \omega_{pl}(z)$

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)

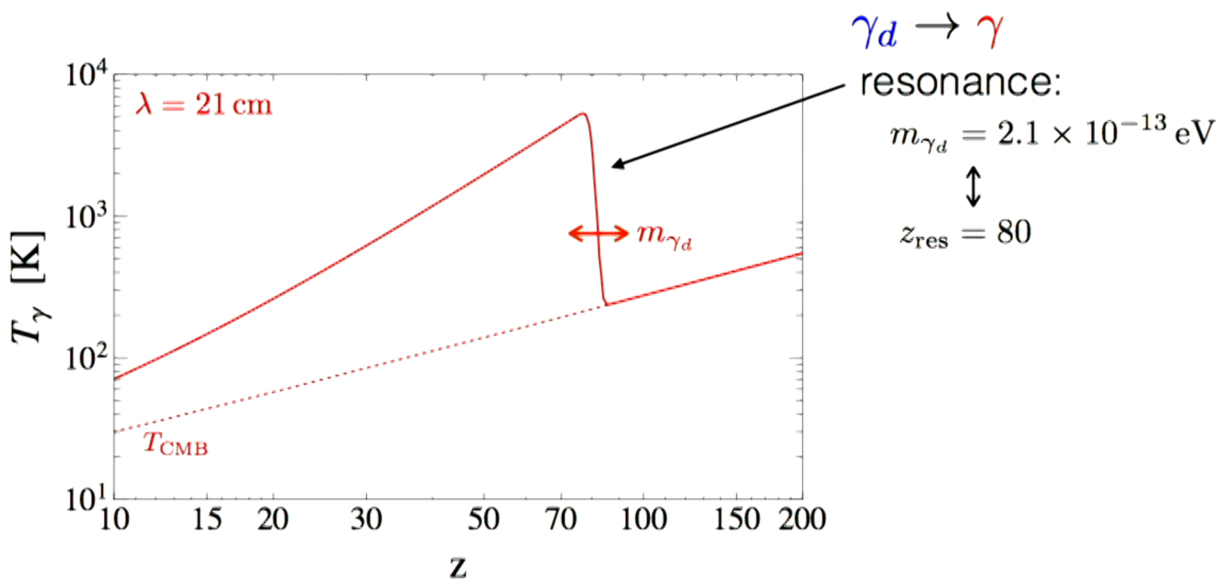
$$m_A(z) \simeq 1.7\times 10^{-14}\,\mathrm{eV}\times(1+z)^{3/2}X_e^{1/2}(z)$$



Most importantly, $P \sim \varepsilon^2\times10^{10}$, not $P\sim\varepsilon^2$!

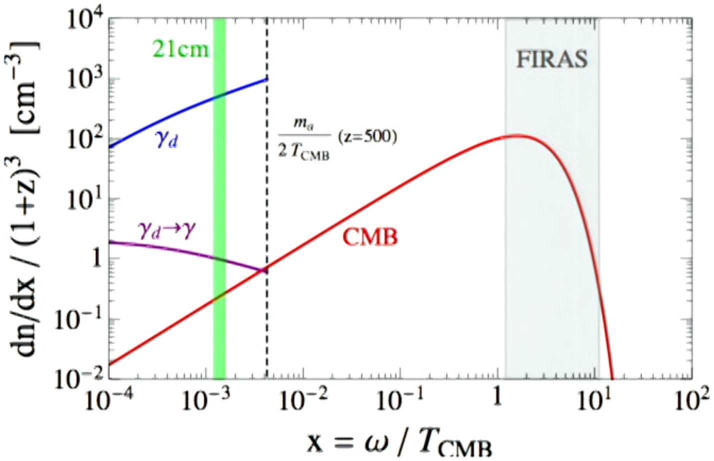
Number of CMB photons can be drastically increased at a given redshift

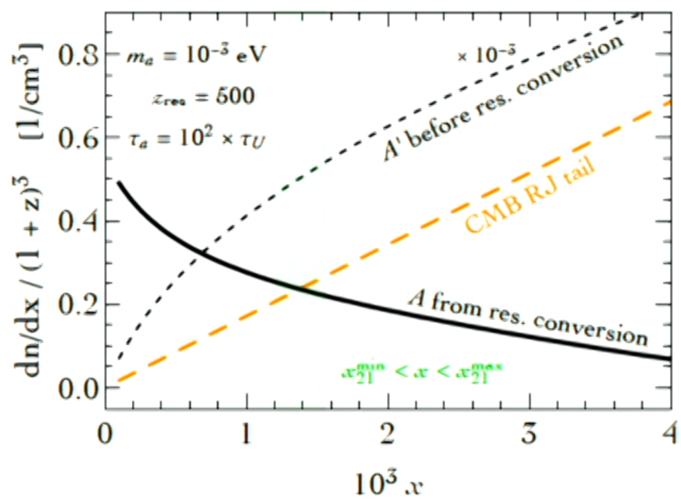
Resonance Edge



RJ tail of the CMB spectrum

- For one specific point on parameter space (1 meV DM, z=500 resonance, lifetime = 100 ages of Universe)





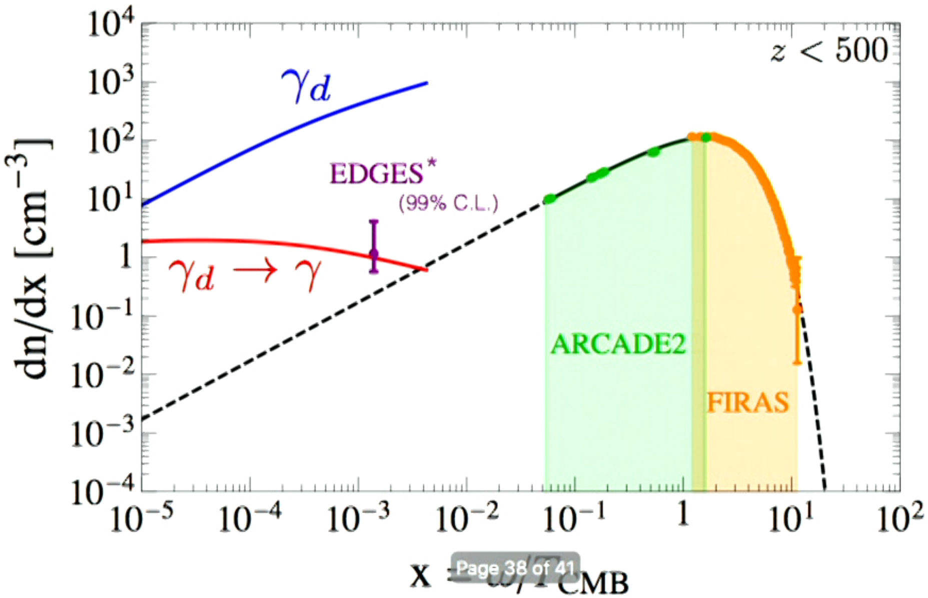
- Green band – interesting for 21 cm range of x, $x \in (x_{21}^{\rm min}, x_{21}^{\rm max}) = (1.2, 1.6) \times 10^{-3}$

Further developments

More accurate modelling of the absorption feature: Ruderman, Urbano

Photon and Dark Photon Spectra

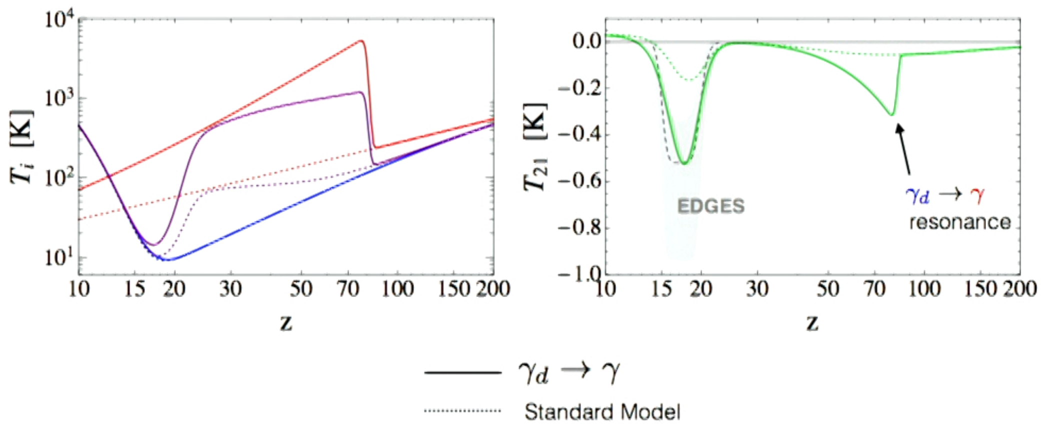
ex. parameters: $m_a = 10^{-3}\,\mathrm{eV}$ $\quad \tau_a = 1.4 \times 10^{12}\,\mathrm{y}$ $\quad m_{\gamma_d} = 5 \times 10^{-12}\,\mathrm{eV} \longleftrightarrow z_{\mathrm{res}} = 500$ $\quad \epsilon = 4 \times 10^{-7}$



*assuming a model of the gas temperature

New prediction: additional sharp feature

21cm at High Redshift



Curtesy of S. Mishra-Sharma

New prediction: additional sharp feature

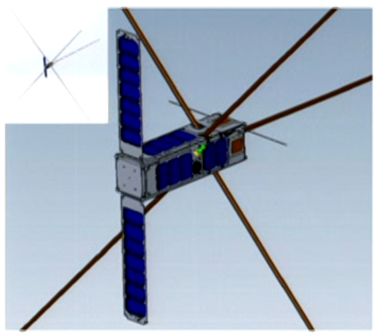
21cm from the Far Side of the Moon?

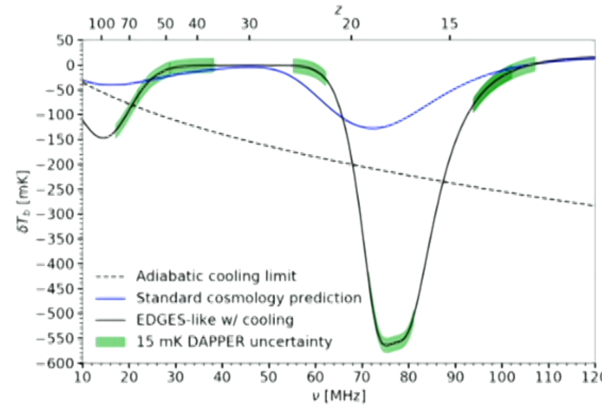
DAPPER: Dark **A**ges **P**olarimeter **P**athfind**ER**

$f = 15 - 30$ MHz

$46 \leq z \leq 93$

lunar orbit to reduce
earth-based radio





Jack Burns *et. al.*, Astro2020 White Paper, **1902.06147**

Curtesy of S. Mishra-Sharma

40

Conclusions

1. IR frontier is a modification of SM by light and weakly coupled BSM fields. ALPs or dark photons with small mass are an example.

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

3. *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.

4. 21 cm cosmological signal, then, provides the key test of such models with beyond-SM sectors composed of light fields.