- An absorption profile centered at 78 megahertz in the sky-averaged spectrum
EDGES experiment (https://www.nature.com/articles/nature25792)

- Possible interaction between baryons and DM particles revealed by the first stars
Barkana (https://www.nature.com/articles/nature25791)

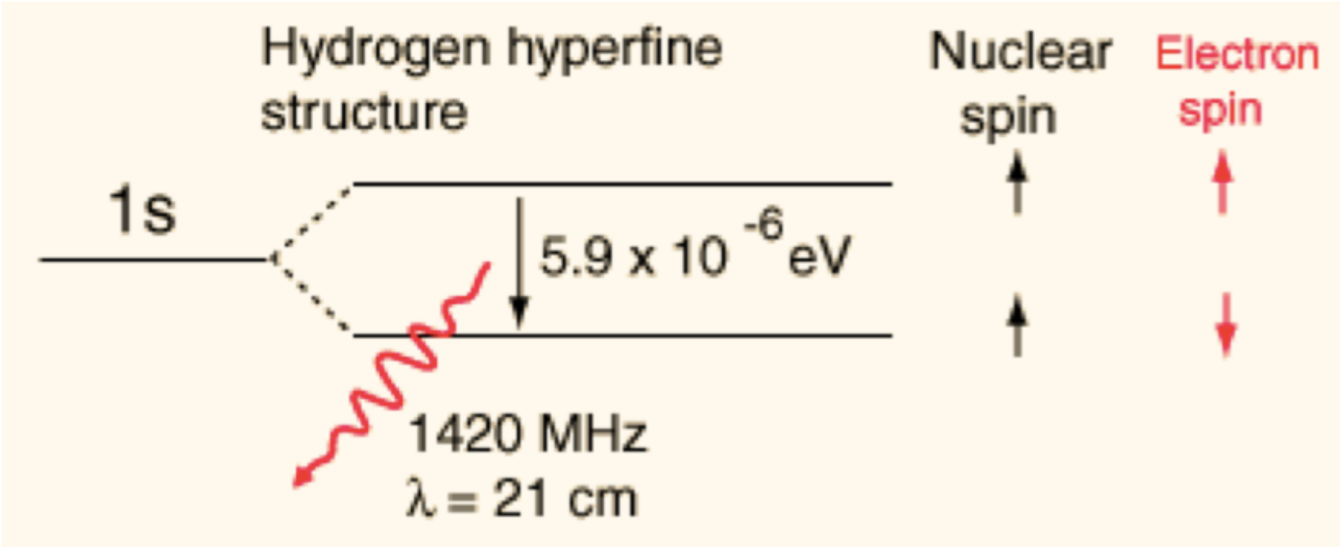
- Severely Constraining Dark Matter Interpretations of the 21-cm Anomaly
berlin et al. (https://arxiv.org/abs/1803.02804)

- The 21 cm transition and the IGM
- The EDGES signal
- Barkana’s interpretation
- Berlin et al. Interpretation

Jean-Marc Le Goff (CEA Saclay, DPhP) Cosmo-club, 10 April 2018

The 21 cm transition

- Hydrogen hyperfine structure:



- spin temperature T_S : $\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp \frac{-\Delta E}{kT_S}$

- signal : brilliance temperature $\delta T_b \approx 21\text{mK}\, x_{\text{H}_\text{I}} \left(1 - \frac{T_\gamma}{T_S}\right) \sqrt{\frac{1+z}{10}}$

IGM history

- 1100 > z > 150: Thomson scattering on residual e^- => $T_{gas} = T_{CMB}$

  collisional coupling $T_S = T_{gas}$

- 150 > z > 80:

  gas decoupled from CMB

  $T_{CMB} \sim 1/a$ and $T_S = T_{gas} \sim 1/a^2$

- 80> z > 30 :

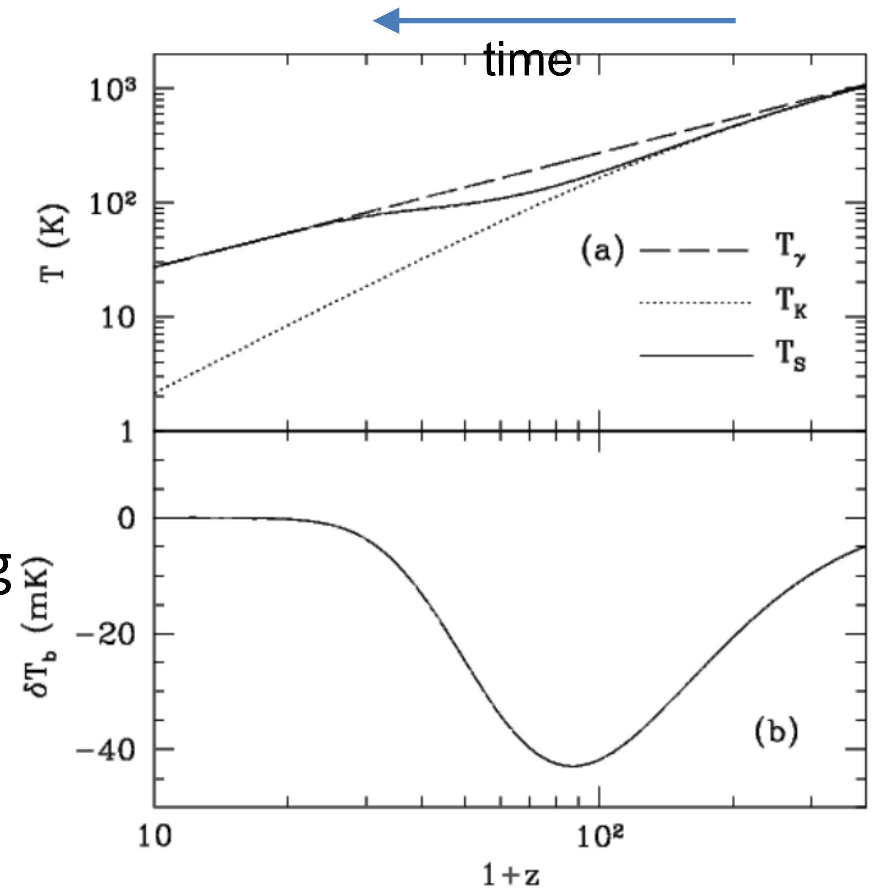
  collisional coupling ineffective

  $T_S \to T_{CMB}$ due to radiative coupling

- signal : brilliance temperature

$$\delta T_b \approx 21\mathrm{mK}\, x_{\mathrm{H_I}} \left(1 - \frac{T_\gamma}{T_S}\right) \sqrt{\frac{1+z}{10}}$$

absorption ($T_S < T_{CMB}$) or emission ($T_S > T_{CMB}$)

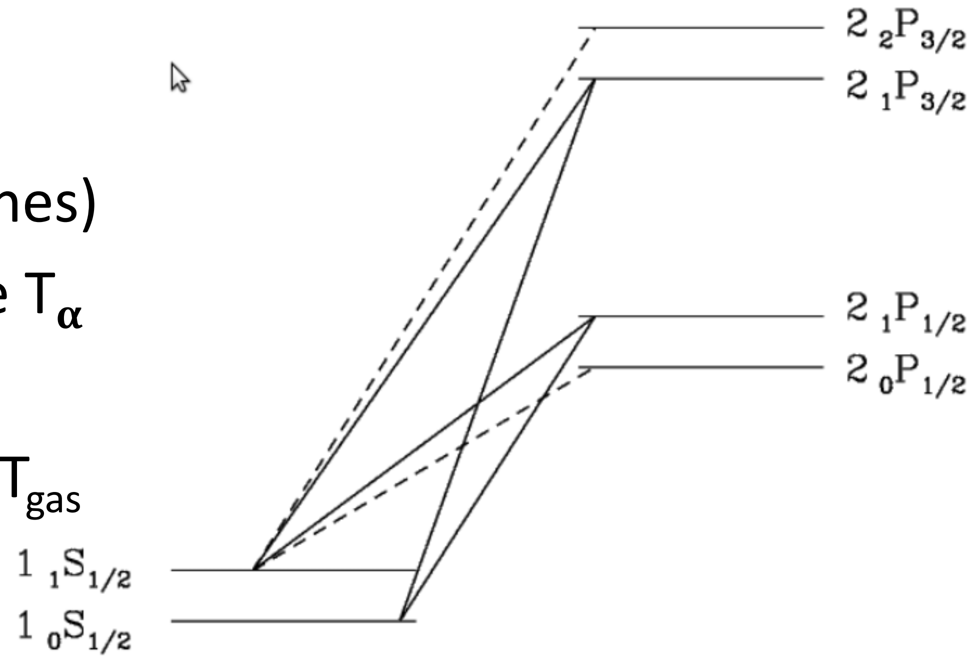


Ly-α pumping (Wouthuysen - Field)

- z ~ 30 : cosmic down

  => Ly-**α** (n=1 <-> n=2, 4 lines)
- lines ratio -> color temperature T_α
- gas optically thick =>

  equilibrium with the gas: $T_\alpha \to T_{gas}$

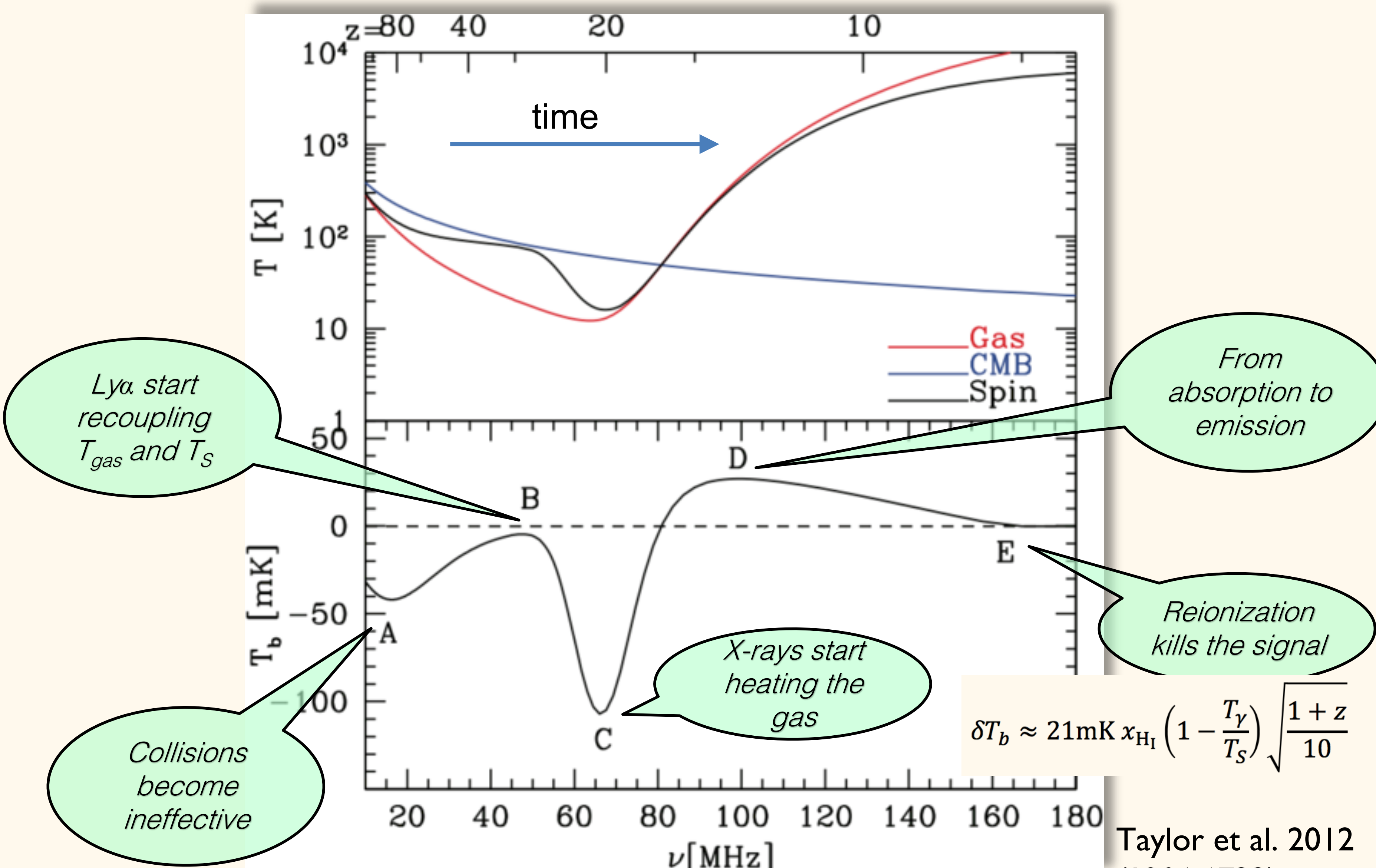


$$T_S^{-1} = \frac{T_\gamma^{-1} + x_c T_{gas}^{-1} + x_\alpha T_\alpha^{-1}}{1 + x_c + x_\alpha}$$

- when x_α increases $T_S \to T_\alpha \to T_{gas}$

  Ly-**α** is recoupling the spin to the gas

IGM history



$$\delta T_b \approx 21\mathrm{mK}\, x_{\mathrm{H_I}} \left(1 - \frac{T_\gamma}{T_S}\right) \sqrt{\frac{1+z}{10}}$$

Taylor et al. 2012 (1206.6733)

The EDGES experiment

- MRO western Australia

(Site for SKA precursor)

- began August 2015
- high band 90-200 MHz

$\boldsymbol{\nu} = 1420 /(1+z)$ (14>z>6)

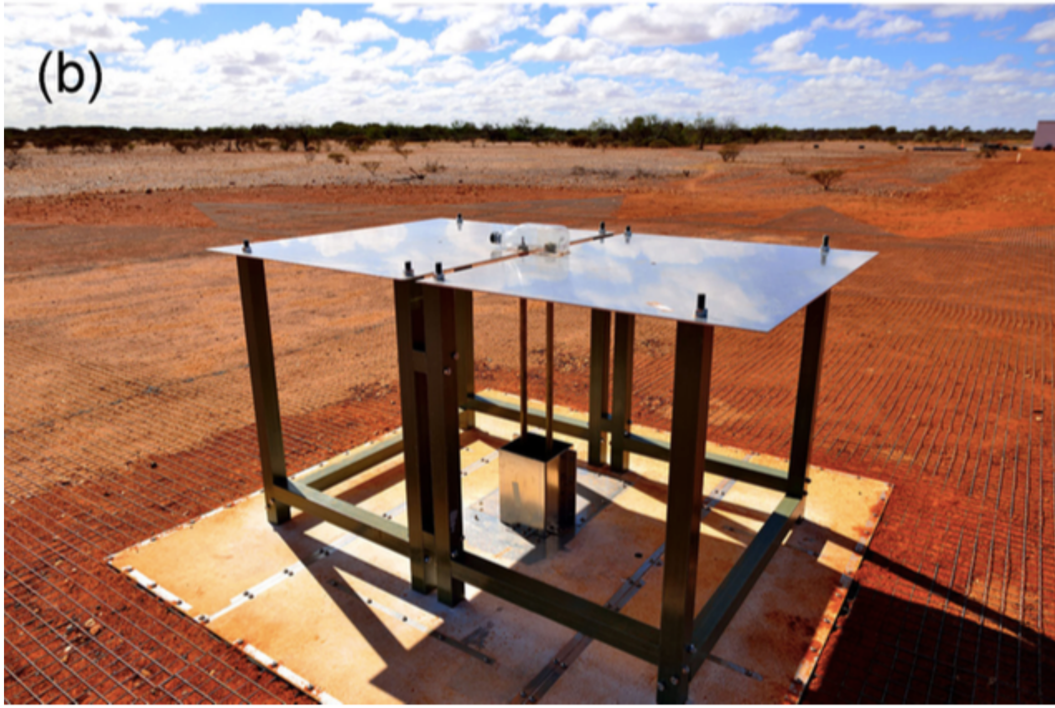
- 2 low band 50-100 MHz

(27>z>13)

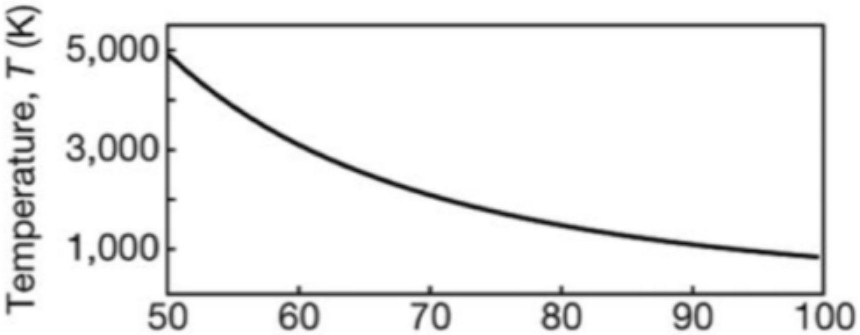
- radio-receiver

single-polar dipole-like antenna

- metal ground plane
- measure sky averaged signal



Fit the data



- physically-motivated fit :

Galactic synchrotron + ionospheric absorption (b_3) and emission (b_4)

$$T_{\mathrm{F}}(\nu) = b_0\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5+b_1+b_2\log(\nu/\nu_{\mathrm{c}})} \mathrm{e}^{-b_3(\nu/\nu_{\mathrm{c}})^{-2}} + b_4\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2}$$

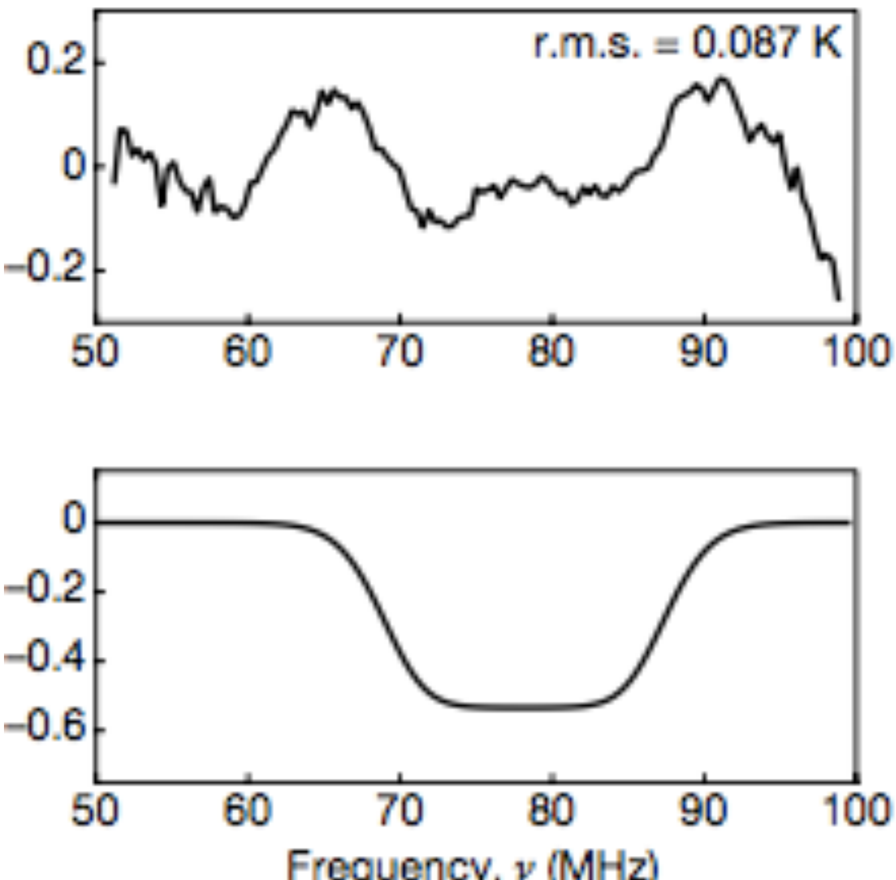
- linear approximation to it , centered on $\boldsymbol{\nu}_c$ = 75 MHz (5 param)

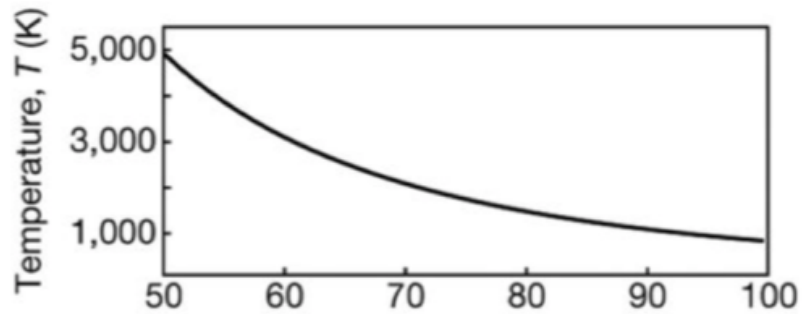
$$T_{\mathrm{F}}(\nu) \approx a_0\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5} + a_1\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5}\log\left(\frac{\nu}{\nu_{\mathrm{c}}}\right) + a_2\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2.5}\left[\log\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)\right]^2 + a_3\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-4.5} + a_4\left(\frac{\nu}{\nu_{\mathrm{c}}}\right)^{-2}$$

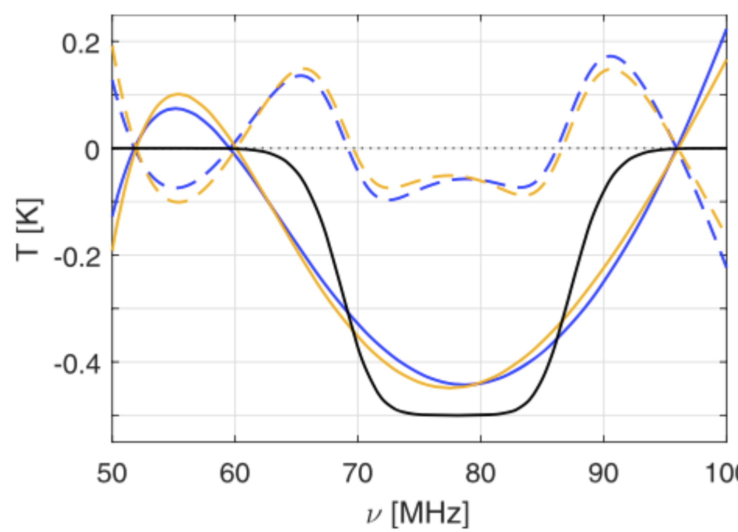
- alternative fit $$T_{\mathrm{F}}(\nu) = \sum_{n=0}^{N-1} a_n \nu^{n-2.5}$$ (N=4,5,6)

residuals

•

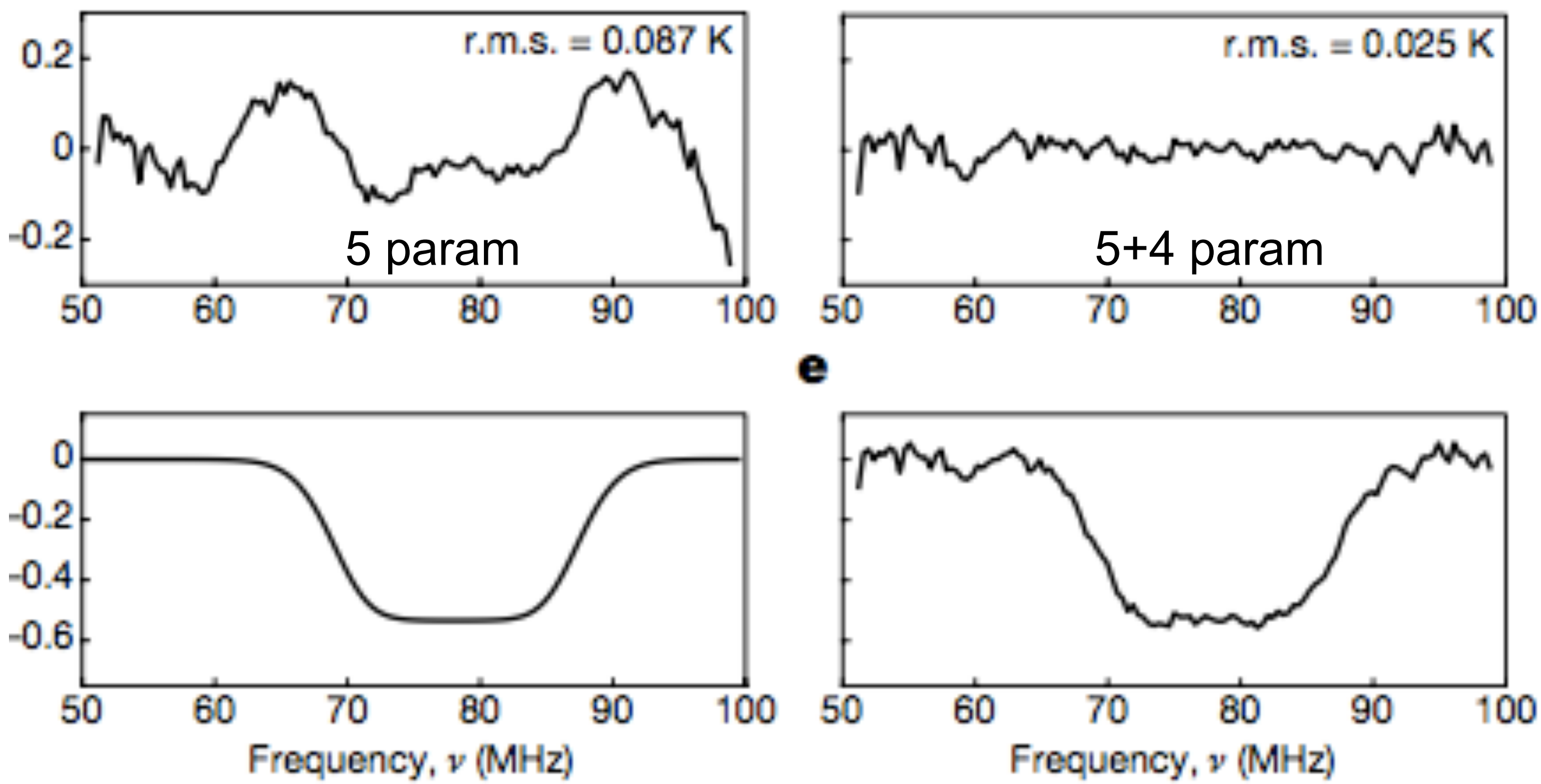






new fit

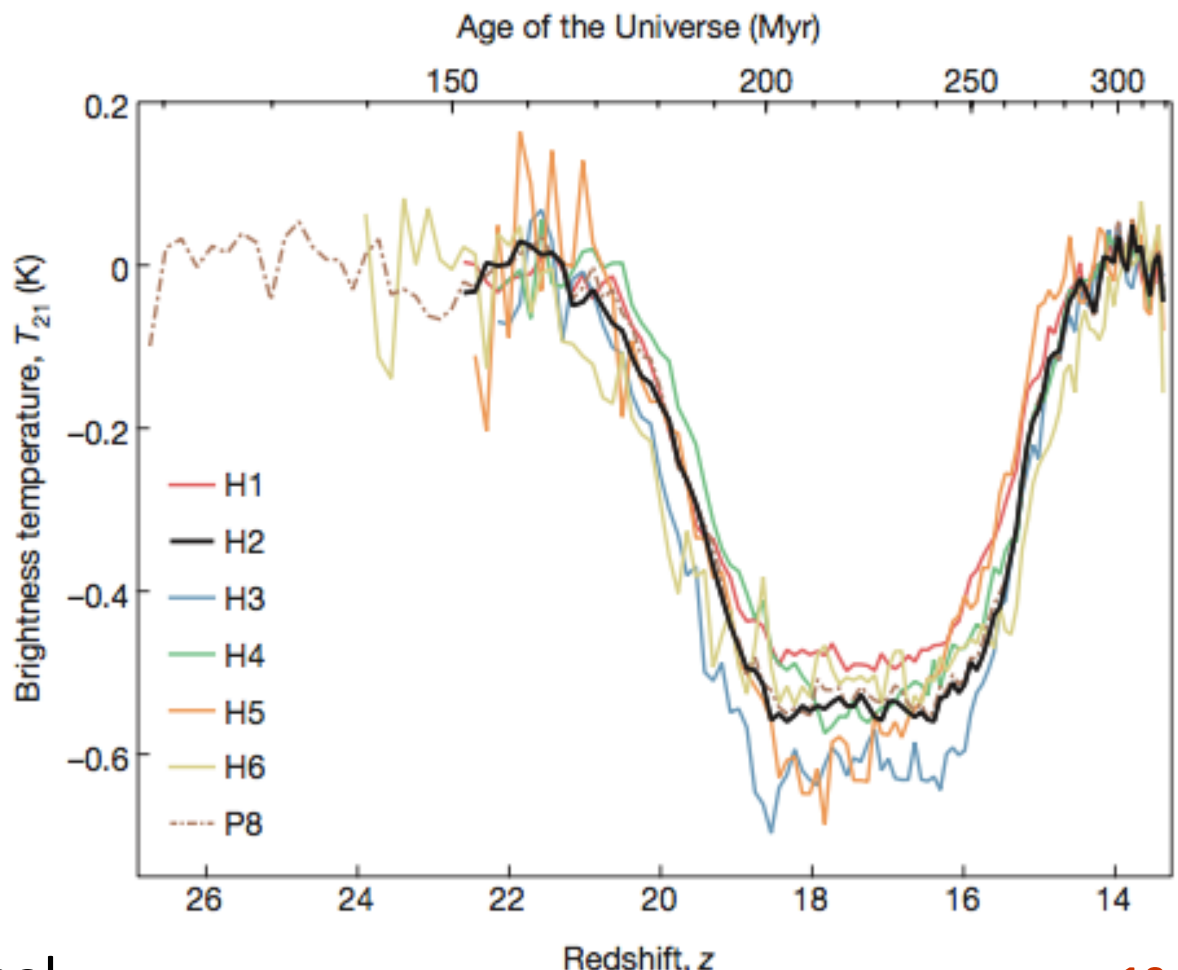
- add a 4 param function to fit the trough



- $\boldsymbol{\nu}_c$ =78 ± 1 MHz, FWHM = 19^{+4}_{-2} MHz, A= $0.5^{+0.5}_{-0.2}$ K (99%)
- absorption with S/N = 37

Hardware and processing tests

- ground plane
- NS/EW
- balun shield
- moon, sun, Galaxy
- solar and sidereal time
- data over 2 years
- 2 calib. techniques
- 2 pipelines
- beam correction
- beam model
- foreground fit
- 90-200 MHz has no signal



alternative explanations

Alternative astronomical or atmospheric mechanisms all excluded for various reasons :

- H II regions and Radio-frequency recombination lines
  not concentrated in Galactic plane, inconsistent spectra
- Earth's ionosphere
  no diurnal variations
- Hydroxyl radical and nitric oxide
  max 0.1 mK

=> signal due to 21 cm absorption

Signal due to 21 cm absorption

- absorption at ν = 1420 /(1+z) MHz => 20 > z > 15 : expected
- U shape not expected: strong initial flux of Ly-α ?
- Amplitude requires $T_{CMB} / T_S > 15$ while at most 7 is expected

- earlier gas decoupling (z=250 instead of 150) excluded by Planck

- T_{CMB} > 104 K instead of 2.725 (1+z) = 46 K at z=17

DM decay or annihilation, primordial BH,

primordial B field would also increase T_{gas} and T_S

- T_S < 3.2 K, interacting with something cooler: CDM ?

Experimental perspectives

Many similar experiments underway

- LEDA, SCI-HI, PRIZM, SARAS2

best would be

- in space (no atmosphere and ionosphere -> simpler foreground)
- lunar farside (surface or orbiting the moon)

Spatial fluctuations with interferometer

- HERA operational in the next 2 years:

  power spectrum of EDGE signal

- SKA

Barkana's interpretation

- best case x_{H1} =1, T_S=T_{gas} ,no astrophysical heating : A = 209 mK
- various ideas to increase absorptions fail: density fluctuations, much larger abundance of early haloes (~ no effect), lower residual electron fraction (constrained by CMB observations)

  => must be CDM

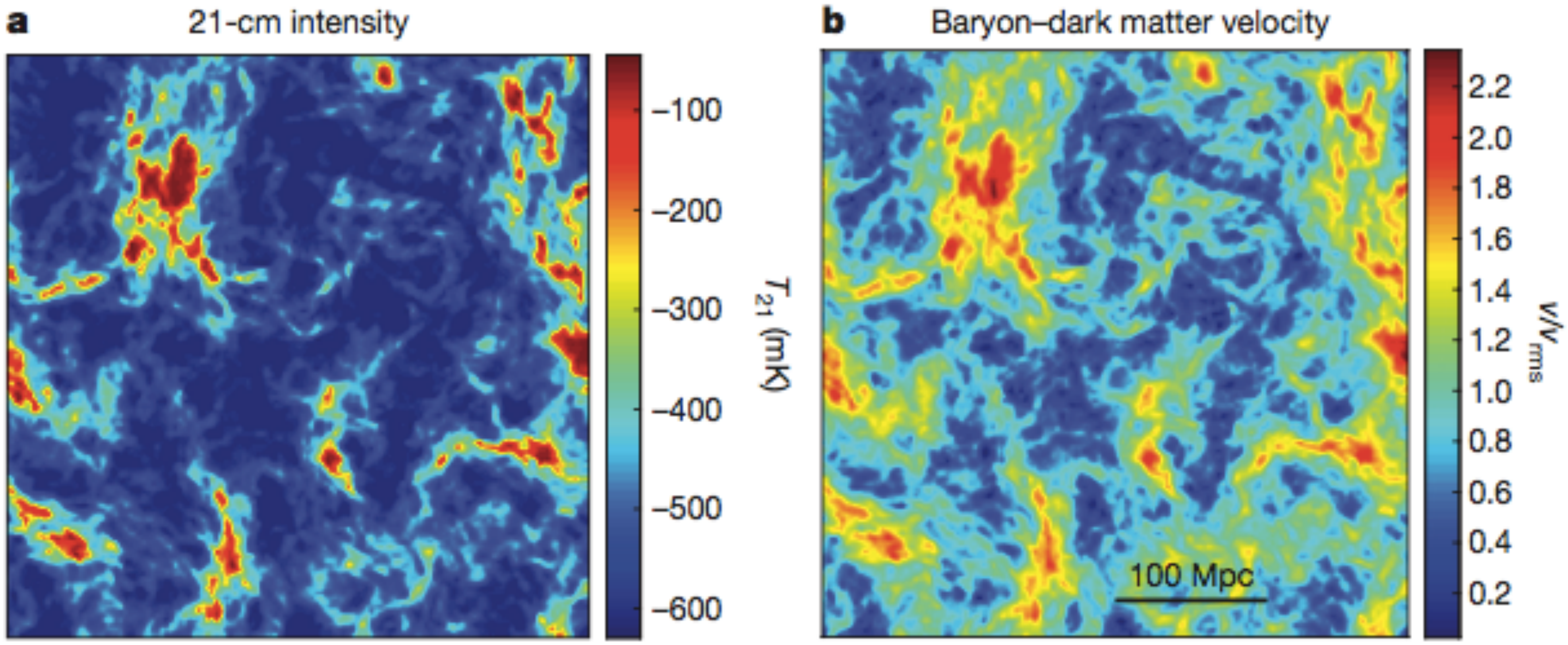
- assume velocity-dependent baryon-DM cross-section:

$$\sigma(v) = \sigma_c \left(\frac{v}{c}\right)^{-4} = \sigma_1 \left(\frac{v}{1\,\mathrm{km\,s^{-1}}}\right)^{-4}$$

- similar to Coulomb but millicharge model probably excluded
- assume mon-standard coulomb-like interaction

Computation of 21 cm signal

- DM follow only gravity, baryons coupled to photons => relative "streaming velocity" due to DM



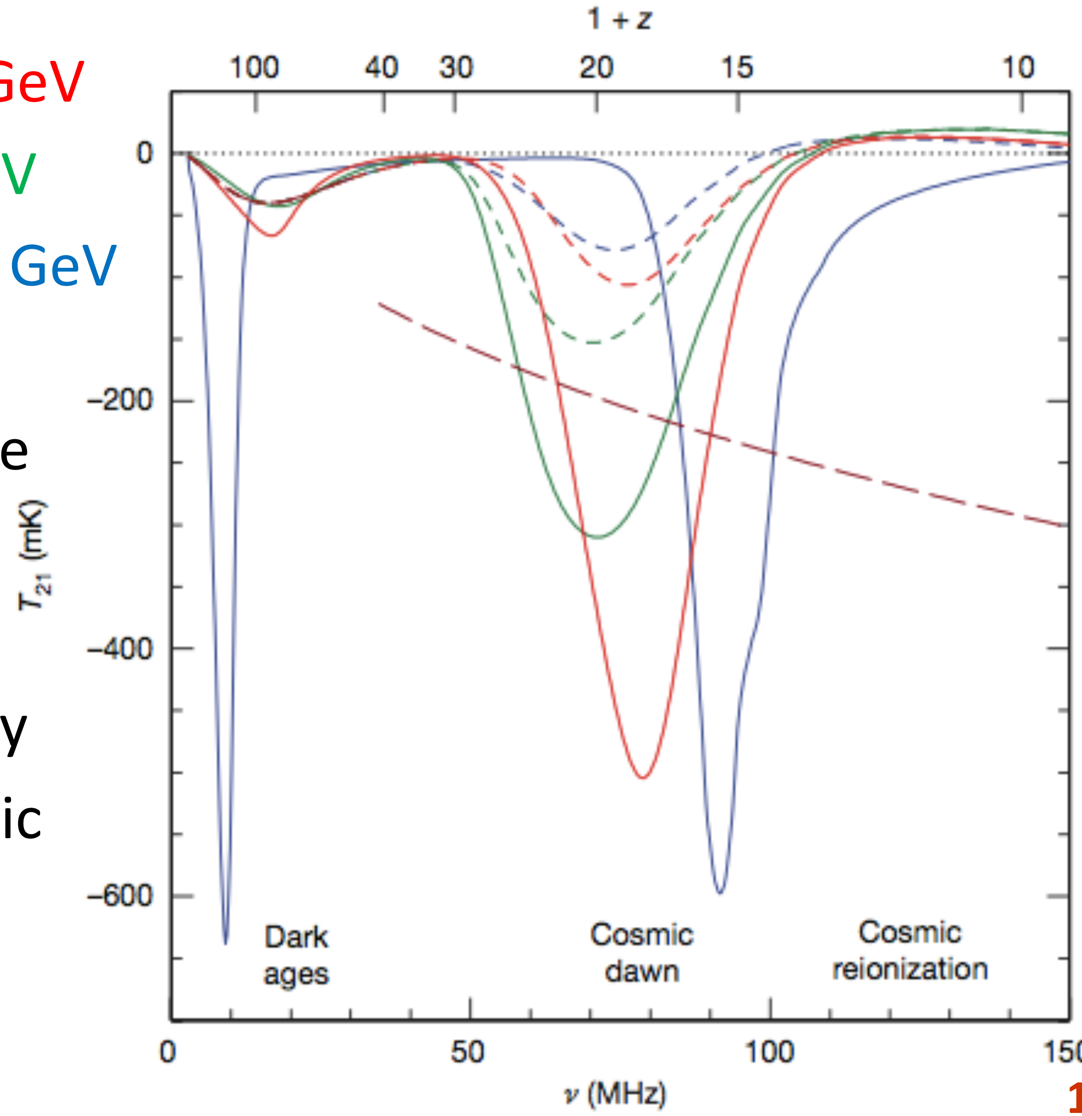
- spatial average => global 21 cm signal (many ingredients in the calculation)

results

- $\boldsymbol{\sigma}_1$ = 8 10^{-20} cm^2 $m_\varkappa$= 0.3 GeV
- $\boldsymbol{\sigma}_1$ = 3 10^{-19} cm^2 $m_\varkappa$= 2 GeV
- $\boldsymbol{\sigma}_1$ = 1 10^{-18} cm^2 $m_\varkappa$= 0.01 GeV

- red amplitude comparable to data but not shape

- signal in dark ages unlikely to be observable (ionospheric distortions and Galactic synchrotron 40 times larger)



Constraints on DM

black curves for

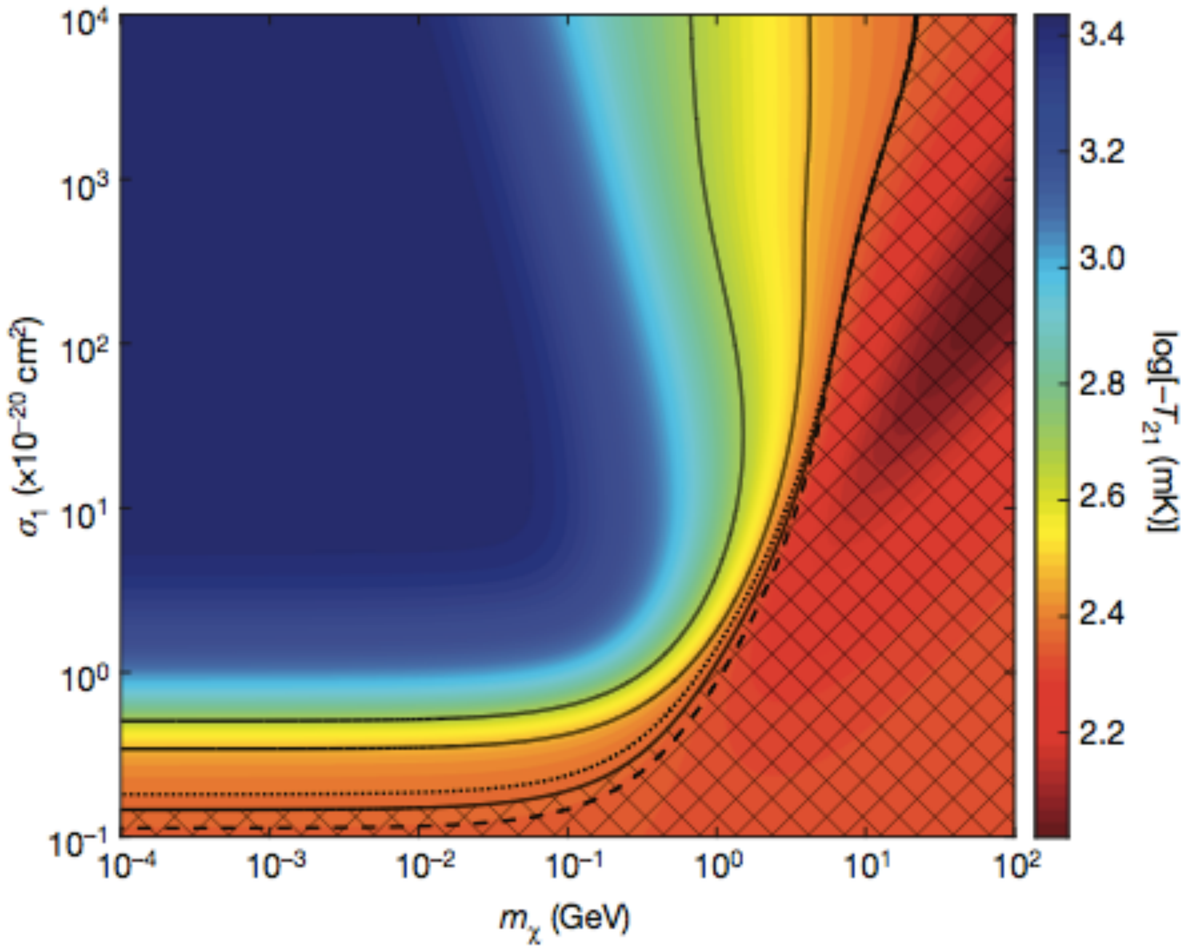
A= 231, 310, 500 mK

A < 231 mK

excluded region

favors small $m_{\varkappa}$

and high cross section



Severely Constraining Dark Matter Interpretations of the 21-cm Anomaly

- if **σ** is velocity independent, we cannot explain EDGES signal
- effect of DM baryon interaction maximized for **σ** ~ v^{-4}

  => interaction mediated by a particle

  with $m_{med} << T$ at $z = 17$,   i.e. $m_{med} < 10^{-3}$ eV
- \- experimental constraints on 5th force in this mass range

  \- this mediator would contribute too much

  to density of radiation at recombination

  => no new mediator

=> only possibility are models in which DM carries a "millicharge"

- Then they spend all the article discussing millicharge model
- But Barkana says : millicharge is excluded so we assume a non-standard Coulomb-like interaction

Constraints on millicharge

- $\varepsilon = e_\chi / e$ millicharge

- CMB

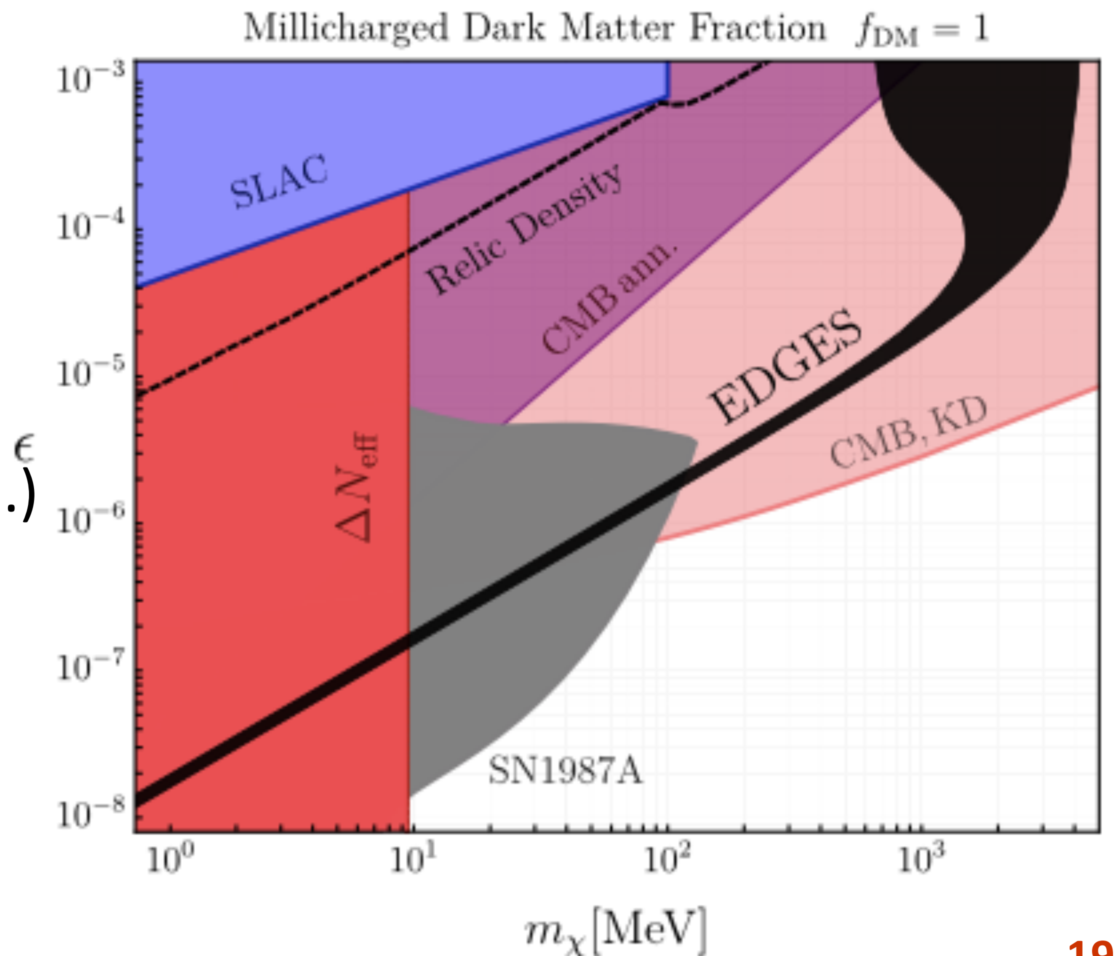
+ SN1987A

+ BBN (ΔN_{eff})

+ SLAC miilicharge exp

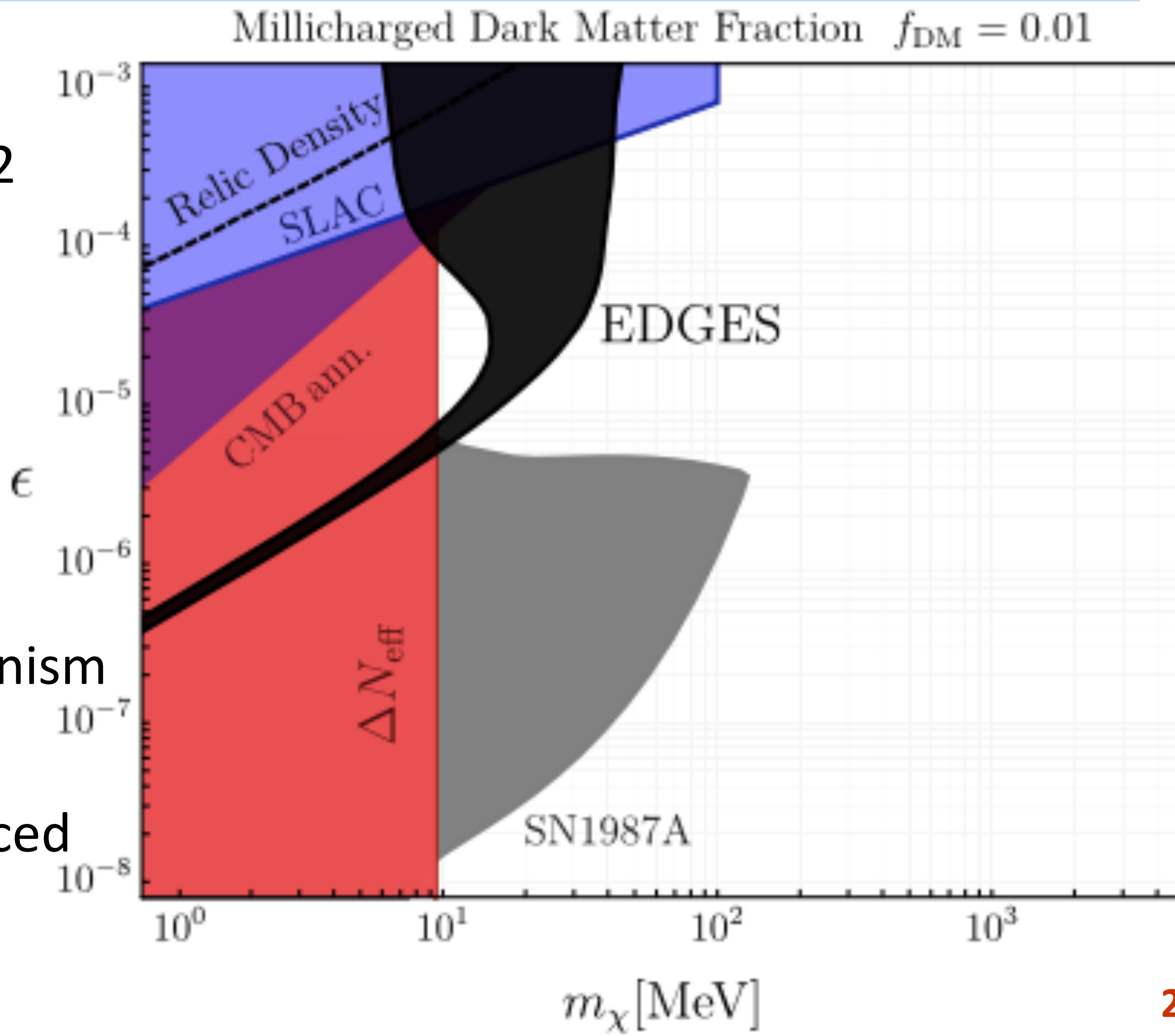
+ DM annihilation (CMB ann.)

=> $f_{DM} = 1$ impossible



Constraints on millicharge

- Only possibility $0.003 < f_{DM} < 0.02$
- $\varepsilon = 10^{-4} - 10^{-6}$
- m_χ 10 -80 MeV
- depletion mechanism needed to avoid being overproduced



Many other papers

Increase CMB T

- Population of high-z black holes [Ewall-Wice+ (2018)]
- Soft photon emission from light dark matter [Fraser+ (2018)]
- Resonant oscillation of dark photons into RJ photons [Pospelov+ (2018)]
- Phenomenological connection to ARCADE-2 excess? [Feng & Holder (2018); Chluba (2015)]

Earlier gas decoupling due to early DE (Hills & Baxter 2018):

Vanilla version excluded by CMB, may be highly tuned versions

Today on ArXiv: Heating of the intergalactic medium by the cosmic microwave background during cosmic dawn

Summary

- 21 cm signal $\propto$ (T_S – T_{CMB})
- EDGES sees an absorption around 78 MHz with S/N=37
- position consistent with Wouthuysen-Field effect at cosmic dawn
- however the amplitude is at least twice has much as expected
- Seems to mean T_S and then T_{gas} lower
- Barkana: this is due to cooling by a non-standard Coulomb-like interaction with CDM
- Berlin et al.: only possible model is millicharge

  this model can only give f_{CDM} ~ 1%
- note: if DM interacts with hadrons, it probably also annihilates to hadrons an heats gas
- experimental confirmation soon ?