Hydrogen 21cm absorption line limits on dark matter and primordial black holes

& recent highlights

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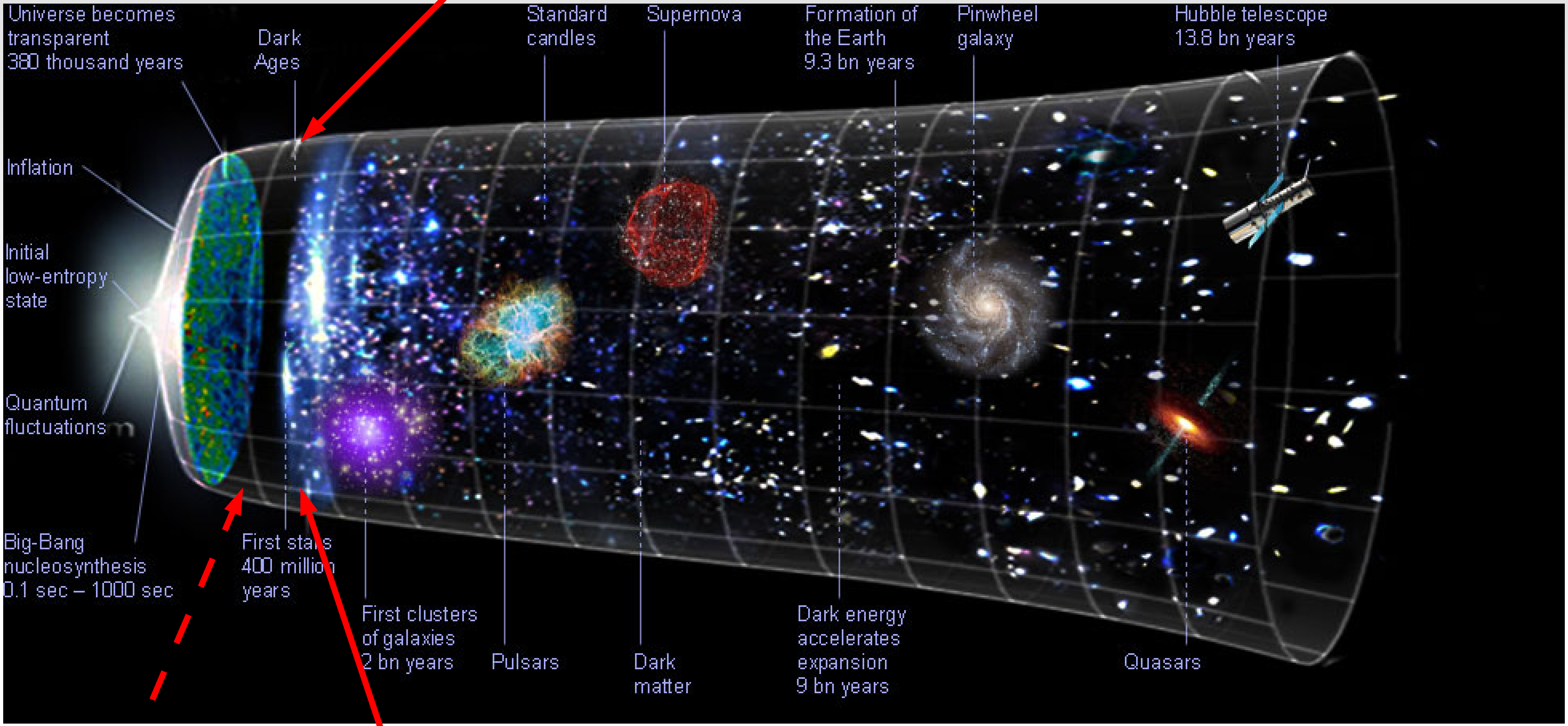
CMB 21cm absorption signals on passing through intergalactic gas: **neutral Hydrogen presence & T_s cooler than CMB**

Dark age window



philosophy-of-cosmology.ox.ac.uk

Gas temperature decouples from CMB z~200

Early reionization window (first discovery claim from EDGES)

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

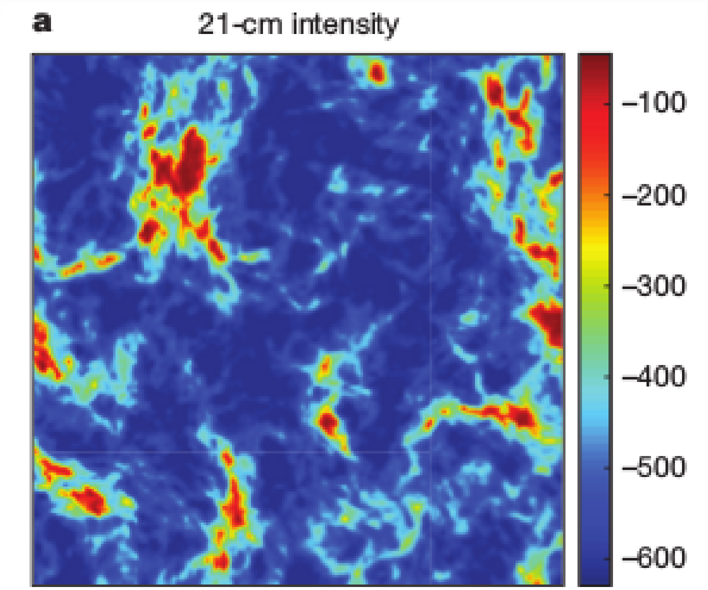
Outline

- EDGES signal - first reionziation epoch measurement?
- Brief review of ideas
- Proof-of-principle bound on energy injections

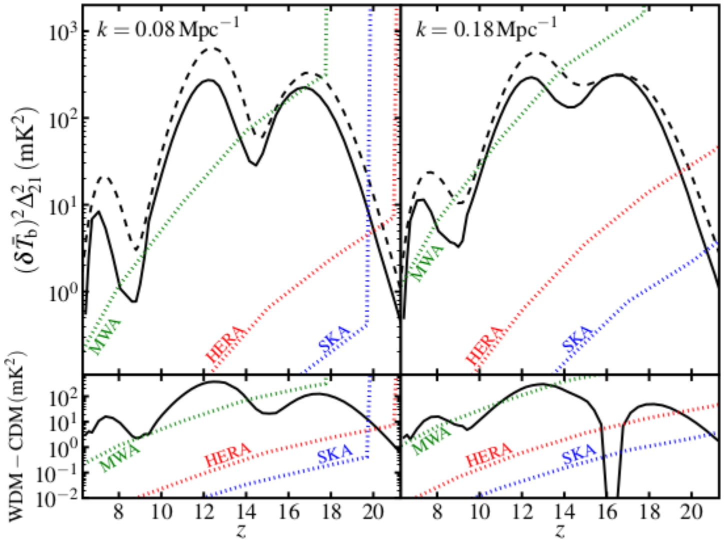
Information from 21cm data …

- The cosmological reionization history:
  Ionization fraction x_e, mean temperature T_G
- Distribution of neutral Hydrogen gas
  temperature map & power spectrum P(k)

at [a] reionization
epoch, 10<z<30
[b] z<1 galactic gas
emissions

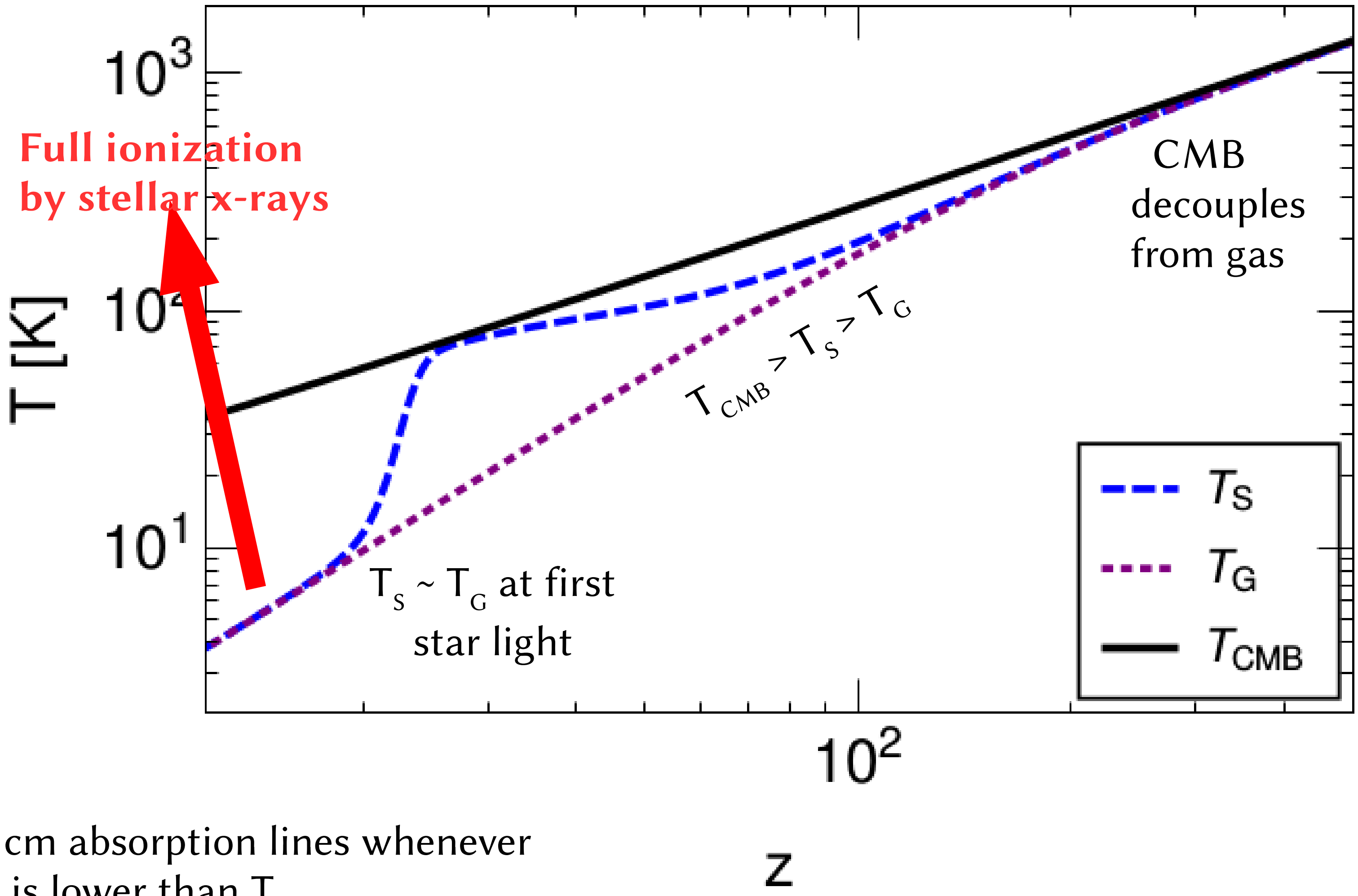


Simulated T21 map, (z=17, 384 Mpc), w DM, Rennan Barkana, nature25791



Projected power spectrum sensitivities (from SKA white paper)

Reionization in the Standard Astrophysics



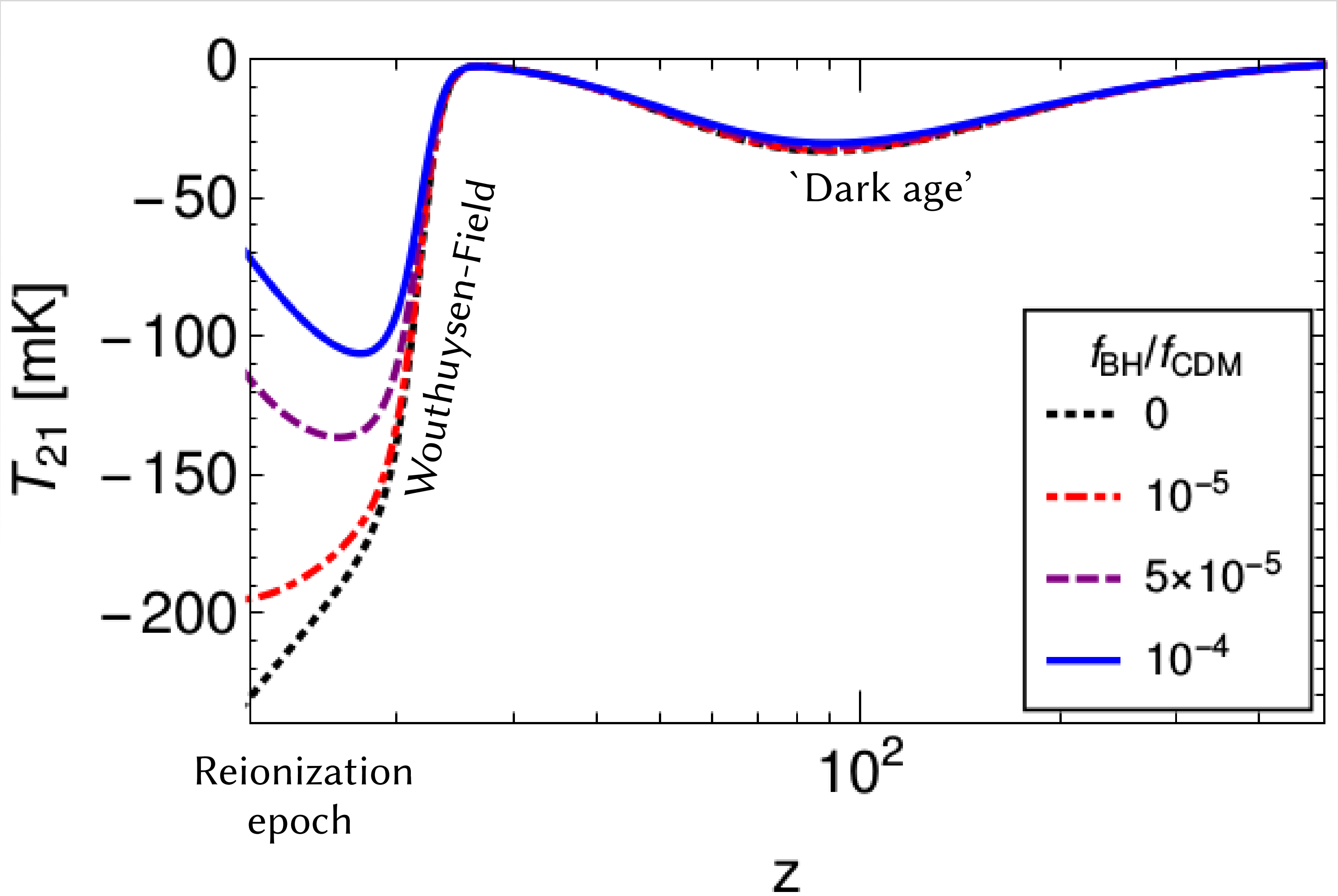
Full ionization by stellar x-rays

CMB decouples from gas

$T_{CMB} > T_S > T_G$

$T_S \sim T_G$ at first star light

21cm absorption lines whenever T_S is lower than T_{CMB}.
Temperature sim. with HyRec



`Dark age'

Wouthuysen-Field

Reionization epoch

The average `brightness temperature',
ignoring over-density and comoving velocity gradients

$$T_{21} \approx 0.023\mathrm{K} \cdot x_{\mathrm{H_I}}(z) \left(\frac{0.15}{\Omega_{\mathrm{m}}} \cdot \frac{1+z}{10} \right)^{\frac{1}{2}} \frac{\Omega_{\mathrm{b}} h}{0.02} \left(1 - \frac{T_{\mathrm{CMB}}}{T_{\mathrm{S}}} \right)$$

First claim of observation: The EDGES 21cm result

J. D. Bowman, A. E. E. Rogers, R. A. Monsalve,
T. J. Mozdzen, and N. Mahesh, Nature 555, 67 (2018).

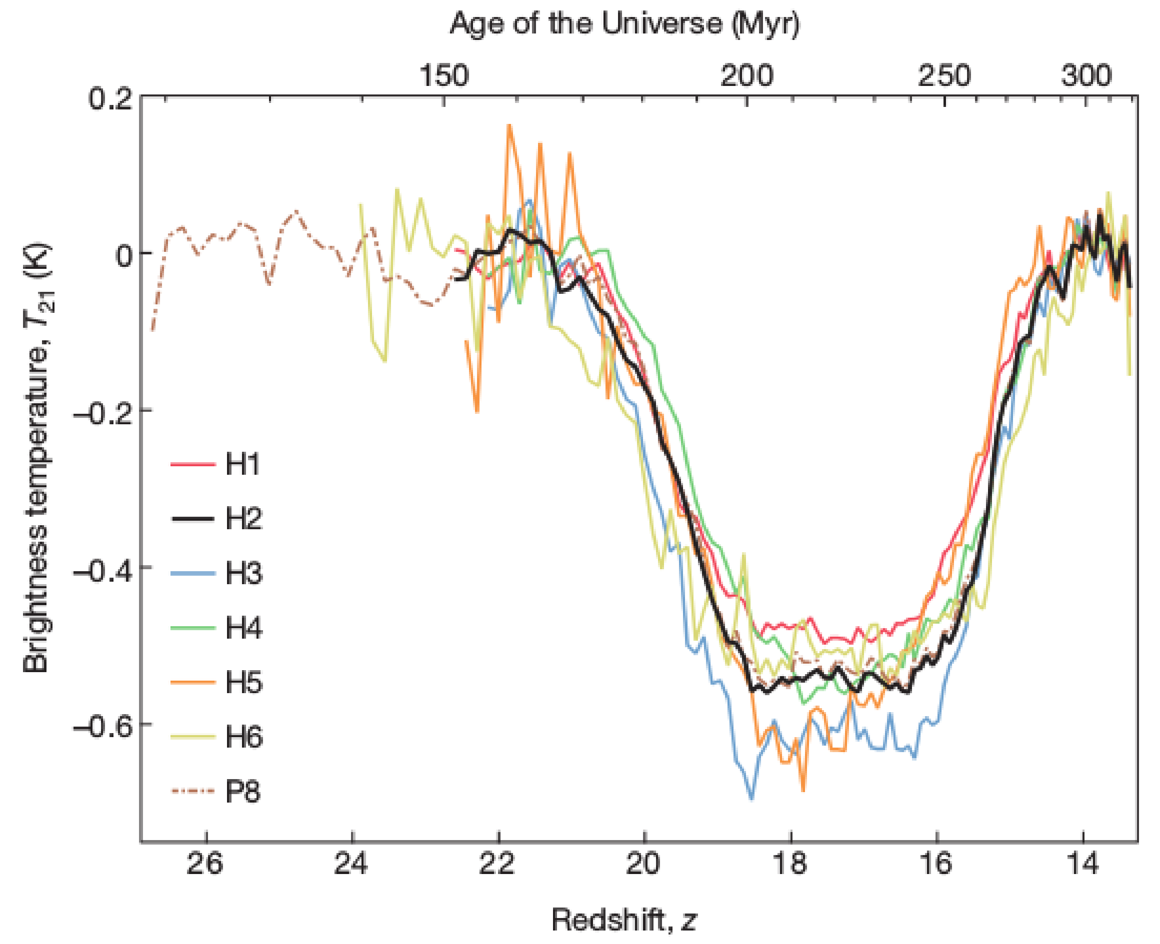
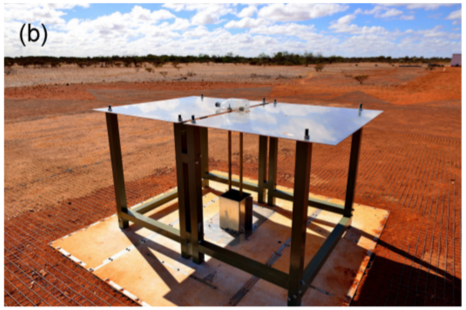


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

EDGES:
Discovery
near 78 MHz?

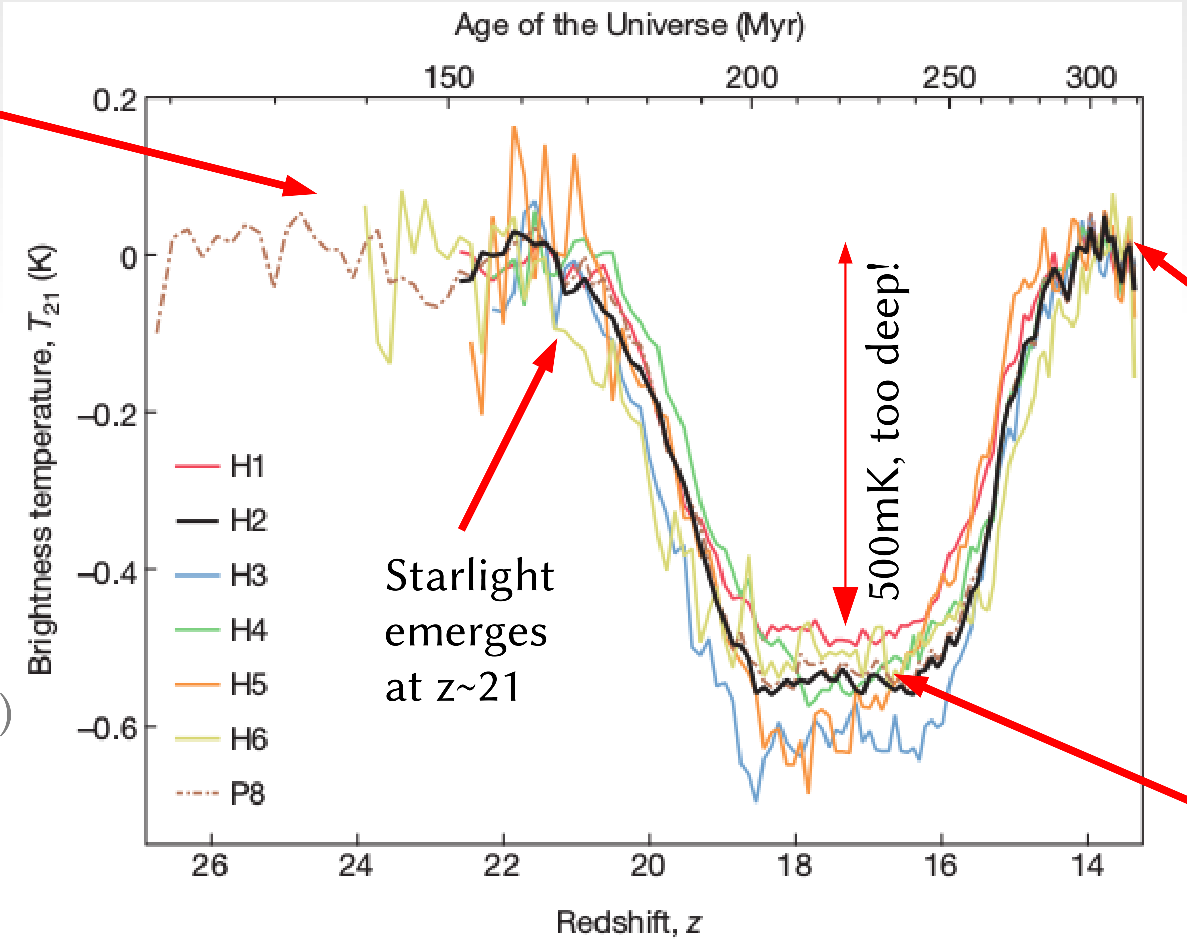


21cm frequency:
1420 MHz / (1+z)

First claim of observation: The EDGES 21cm result

J. D. Bowman, A. E. E. Rogers, R. A. Monsalve,
T. J. Mozdzen, and N. Mahesh, Nature 555, 67 (2018).

$T_S \sim T_{CMB}$
no signal
for z>21



500mK, too deep!

Starlight
emerges
at z~21

Full ionization
at z~14?

How can this be a
flat valley?

For ΛCDM (non-)
interpretations,
see S.Witte, et.al
1804.03888

Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

T_{21} dependences...

- The 21cm brightness temperature

$$T_{21} = 26.8\, x_{\mathrm{HI}} \frac{\rho_{\mathrm{g}}}{\bar{\rho}_{\mathrm{g}}} \left(\frac{\Omega_{\mathrm{b}} h}{0.0327}\right) \left(\frac{\Omega_{\mathrm{m}}}{0.307}\right)^{-1/2} \left(\frac{1+z}{10}\right)^{1/2} \left(\frac{T_{\mathrm{S}} - T_{\mathrm{CMB}}}{T_{\mathrm{S}}}\right)$$

Gas distribution

Cosmological model
dependence:
optical depth, etc

$$T_{21} \propto \frac{1}{H(z)} \left(1 - \frac{T_\gamma(z)}{T_s(z)}\right)$$

Gas spin
temperature
against bkg
(CMB)

How is the (particle) dark matter involved?

Yeah

DM cooling

Lower gas temperature via collisions: more 21cm signal

Explains the EDGES data
*needs large scattering xsec

DM heating

Raises gas temperature by energy injection: reduces 21cm signal

Most stringent bounds on DM annihilation, decays & other energy injections

Nay

CMB uncertainties

Large uncertainty at low frequrency; new physics at radio-frequencies

Non-standard cosmology:

Modified Friedmann Eq.

Many papers on dark matter after EDGES!

- Dark matter can cool down T_G via collision
- Dark matter can affect T_S via SD scattering

Barkana, et.al. :
A millicharged DM
with $\sigma \sim v^{-4}$

- Non-CDM affects the 21cm temperature & power spectrum

M. Sitwell, et.al, MNRAS, 438, 2664

- Dark matter, or black holes, can indirectly ruin the 21cm signal if they have emissions, and …

G. D'Amico, et.al.,1803.03629 (DM annihilation)
S. Clark, et.al. 1803.09390 (DM decay & PBH rad.)
K. Cheung, et.al, 1803.09398 (DM annihilation)
A. Hektor, et.al,1803.09697 (PBH accretion)
T. Slatyer, C.-L. Wu, 1803.09734 (DM ann. & decay)

- enhance ionized fraction of gas, affect CMB propagation

T. Slatyer, 1506.03811
T. Slatyer and C.-L. Wu, 1610.06933.
S. Clark, et.al. 1612.07738

DM cooling theories:
enhancing the 21cm signal

The scattering (H, He cooling, etc)
mediator must be screened by
SM particles

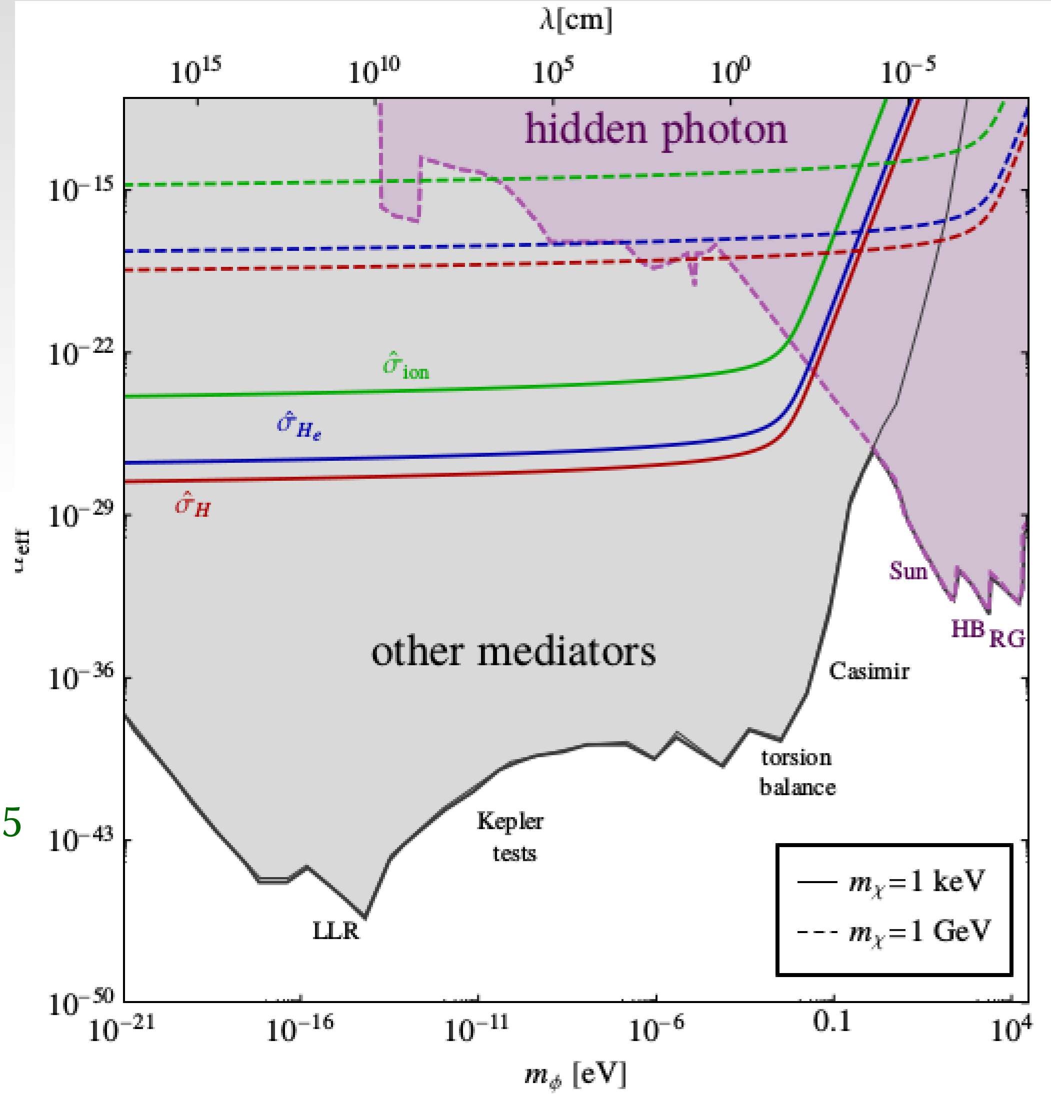
viable candidates: photon & friends

R. Barkana, et.al. 1803.03091

A few more DM cases,

S. Fraser et.al 1803.03245

Z. Kang, 1803.04928

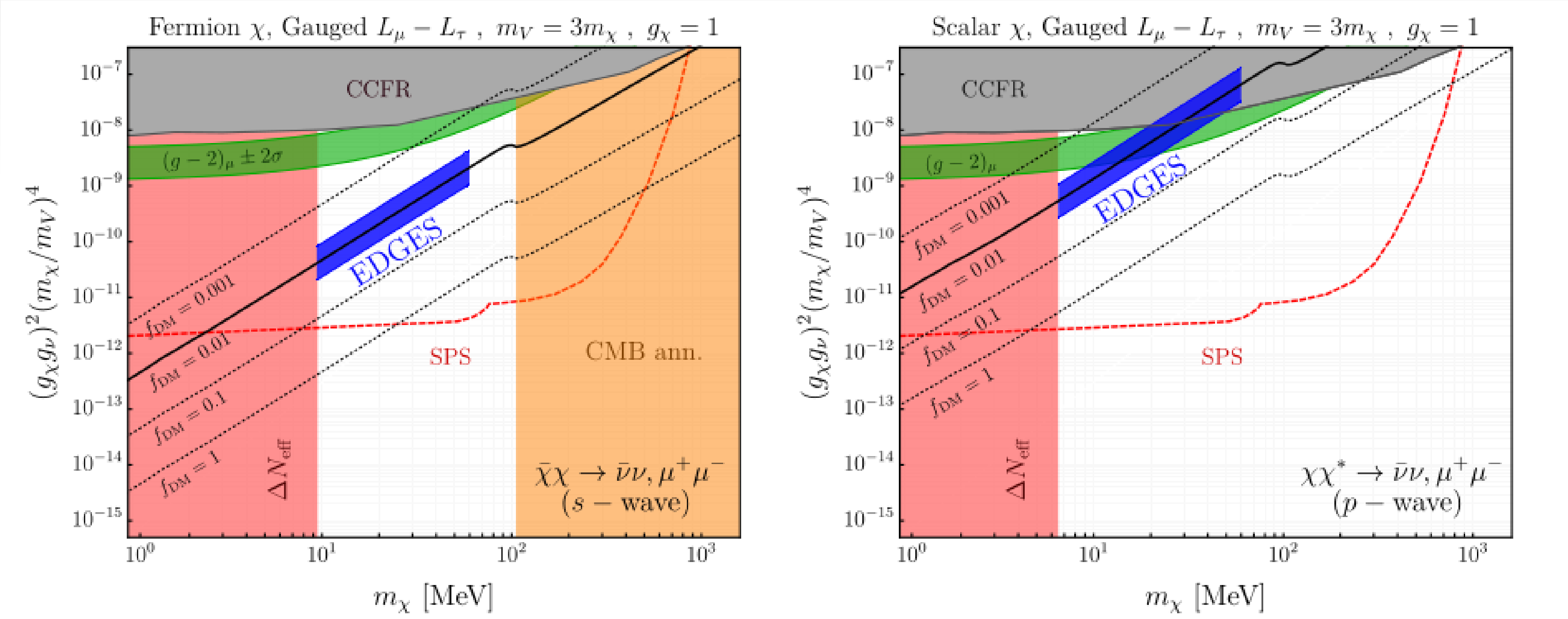


Dark matter as an explanation to the EDGES data

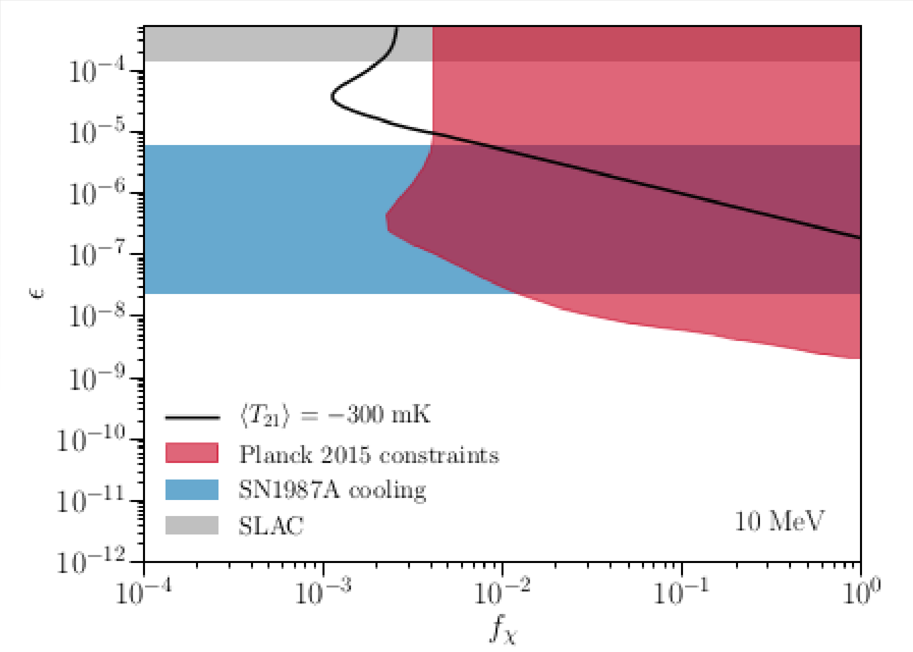
Cooling $\mathrm{H_I}$ gas needs a very large scattering cross-section need to avoid constraint from direct detection

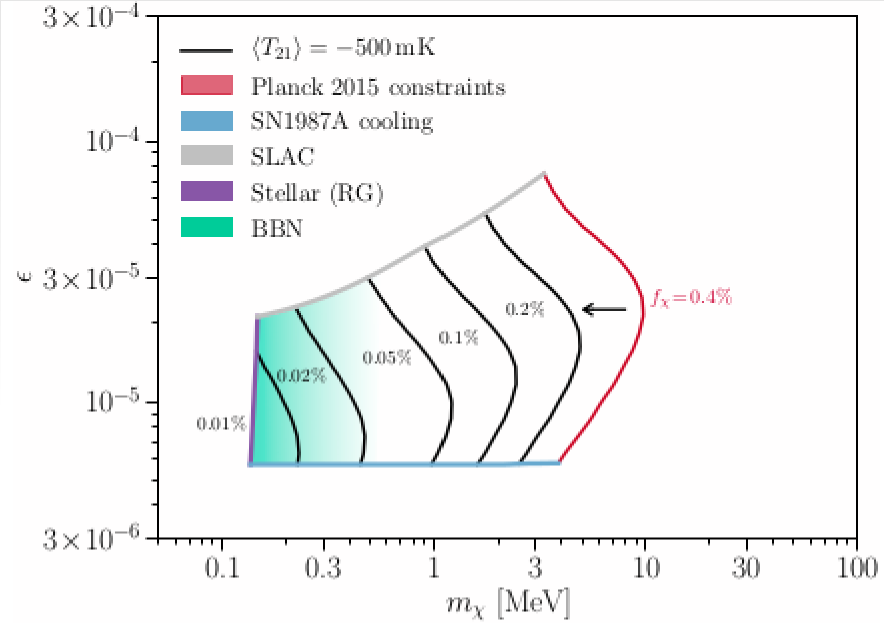
→ velocity dependence?

R. Barkana, et.al. 1803.03091



Millicharged DM need to be at percent level abundance, and relic density requires alternative annihiliation / depletion procecess A.Berlin, et.al. 1803.02804





Milli-charged DM constrained to lighter than 85 MeV
and tiny fractions of relic density
for 100% relic desnity, σ_0 constrained to $<10^{-42}$cm^2.

E.D.Kovertz, et.al. 1807.11482

A few non-DM scenarios:

Earlier T_G-T_{CMB} decoupling

Charge sequestration:

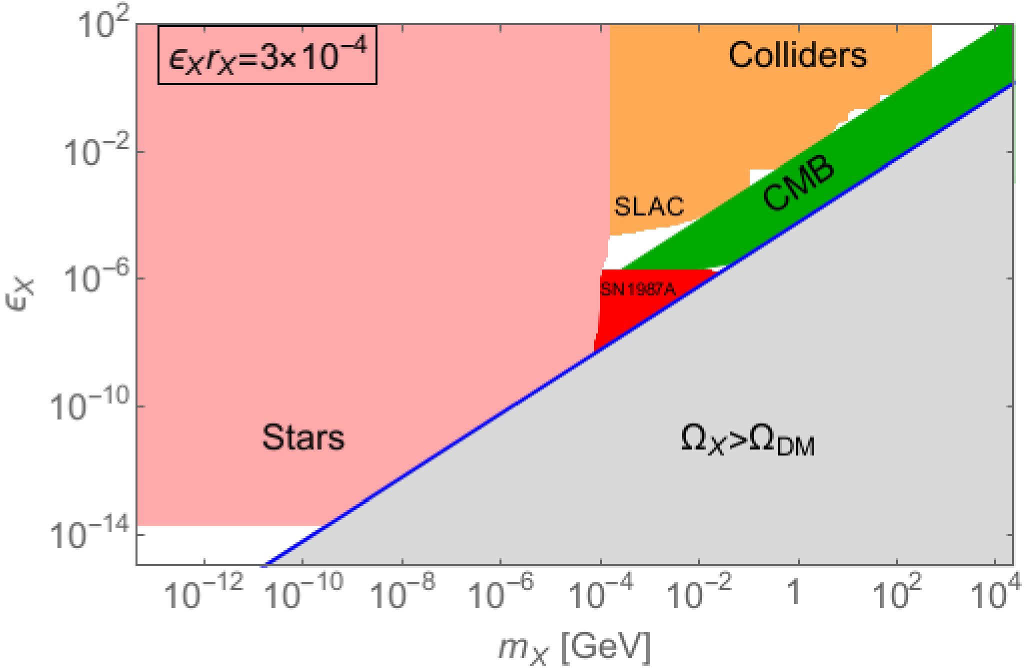
A. Falkowski, K. Petraki, 1803.10096

A negatively charged (-ϵ), stable particle to replace some electrons in the Universe

- * reduces x_e during recombination
- * fasten CMB – HI decoupling

$$x_p = x_e + \epsilon_X r_X$$

$$x_p \equiv n_p/n_B,\ x_e \equiv n_e/n_B,\ r_X \equiv n_X/n_B$$

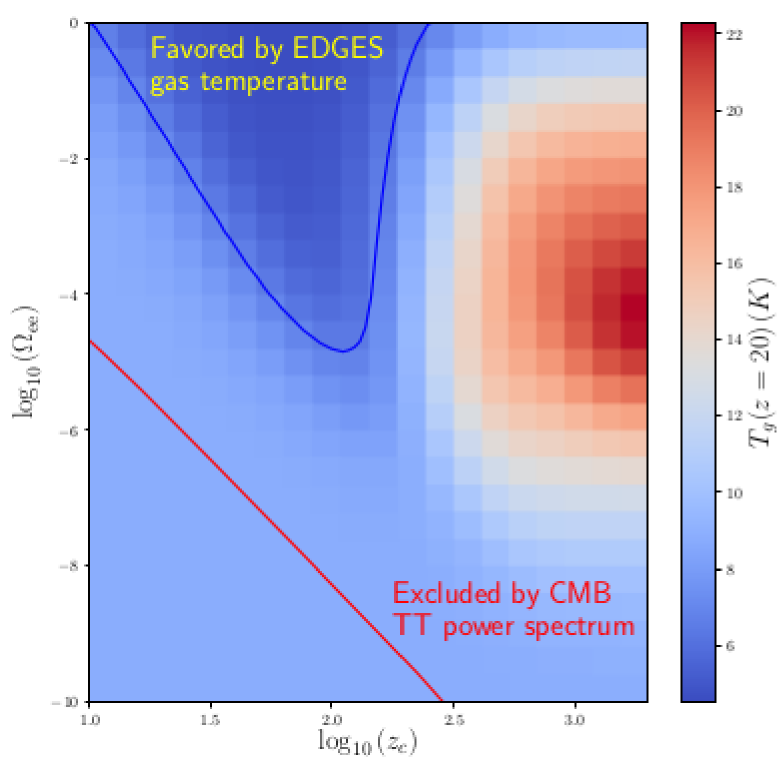


\`Early' dark energy?

J. Colin Hill, E. Baxter. 1803.07555

Addition dark energy component with *w*=-1 and it decays away by z_c ~ 20-1000.

- * faster expansion rate \`early on'
- * Earlier CMB – HI decoupling



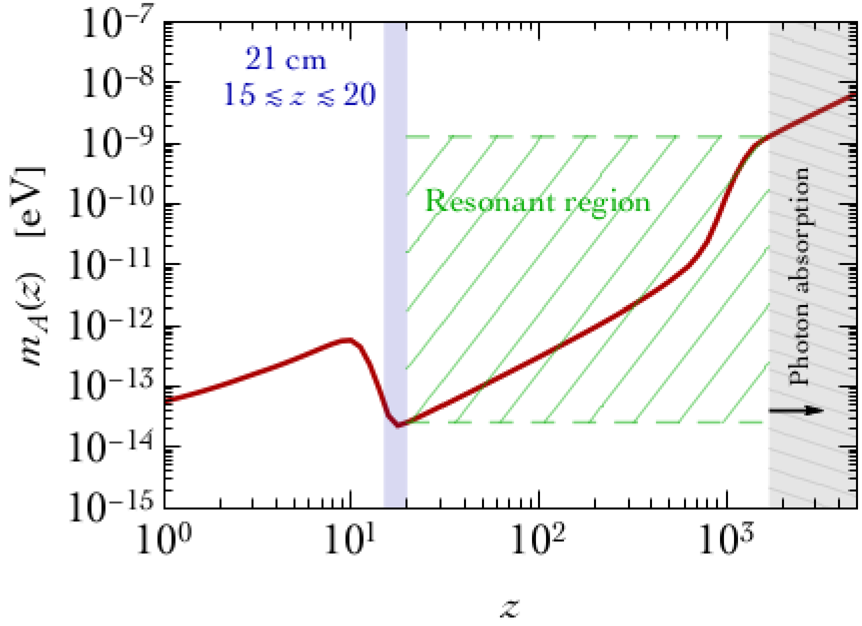
A few non-DM scenarios: low-freq. uncertainties

Modification in CMB:

M. Pospelov, et.al. 1803.07048

Order~1 increase in the Raileigh-Jeans tail of CMB: e.g. osc. with a very light dark photon A’ via mixing $\epsilon F'_{\mu\nu} F_{\mu\nu}$

Can be of interest in precision 21cm tests, when A’ - A oscillate resonantly at the effective A mass (in plasma) $m_A \sim m_{A'}$



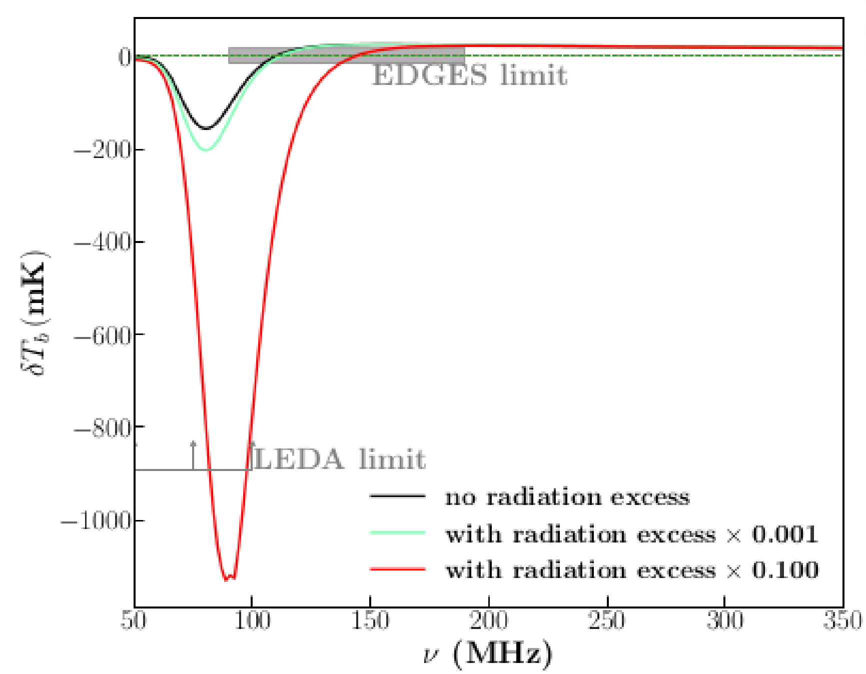
Radio-wavelength backgrounds

C. Feng, G. Holder. 1801.05396

other than CMB is detected by ARCADE

– non black body CMB, enhancing the signal

– EDGES can place a bound on early rad. fields



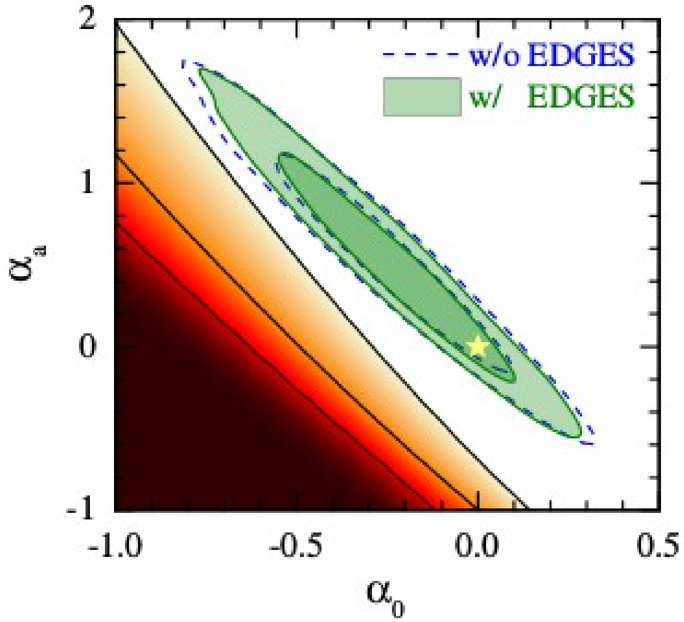
Other exortics..

- New physics contribution to CMB uncertainty

ALP conversion to CMB: T.Moroi, K.Nakayama, Y.Tong, 1804.10378
Mirror sector radiation to CMB: D.A.Sierra, C.S.Fong, 1805.02685

- Modified cosmology / Friedmann equation H(z)

Vacuum Energy – Dark Matter interaction: Y.Wang G-B. Zhao, 1805.11210
Dark Energy – Dark Matter interaction: B.Yue, Y.Xu, B.Wang, 1807.05541



A global fit with
DE/VE-DM
interaction model
Y.Wang G-B. Zhao, 1805.11210

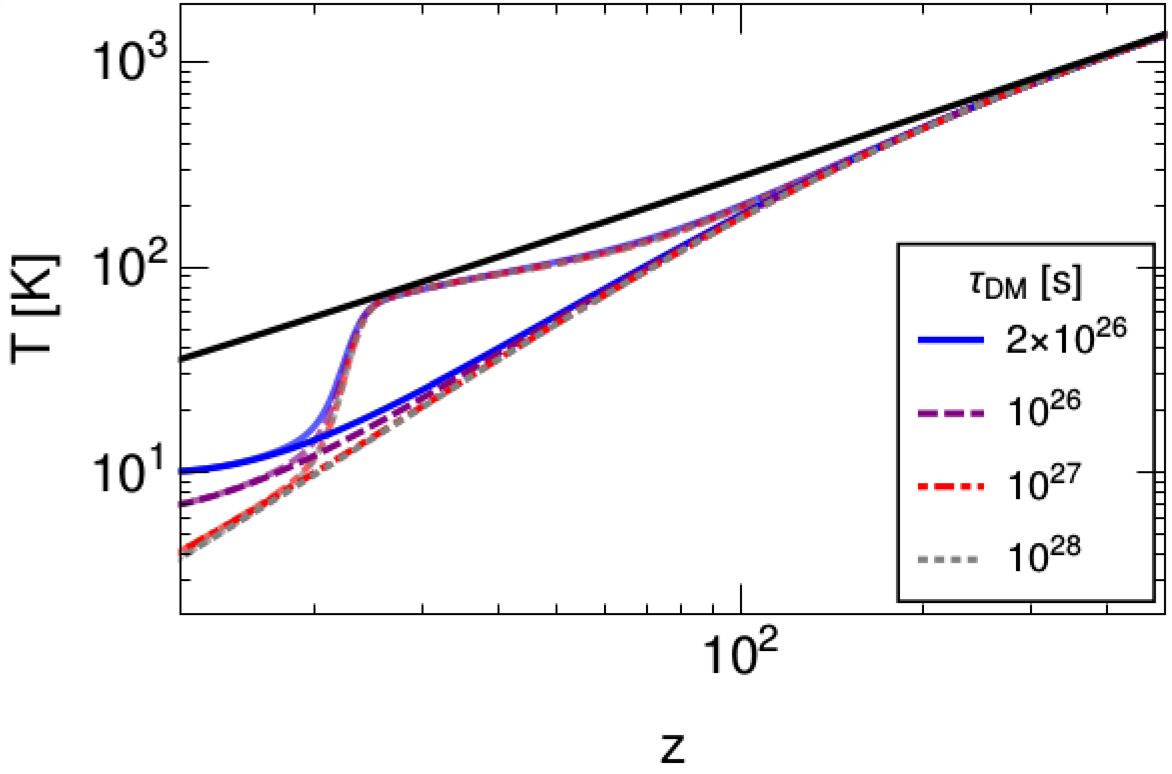
$$\dot{V} = 3\alpha H \frac{\rho_{\rm dm} V}{\rho_{\rm dm} + V}$$

DM heating story:
use the 21cm signal as a constraint

- Injection of energy into intergalactic gas suppresses 21cm during reionization epoch
- The observation of (any) 21cm signal means an upper limit
- EDGES may have a lot systematics, future 21cm experiments awaits.

Energy injection effects

- (Historic, cumulative) high-energy injection of electrons/photons
- Increased x_e
- Later CMB – gas decoupling
- Higher T_G
- May reduce or wipe out the 21cm signal



Injection & absorption

- Injected high-energy particles lose energy by scattering, ionization, excitations, etc...

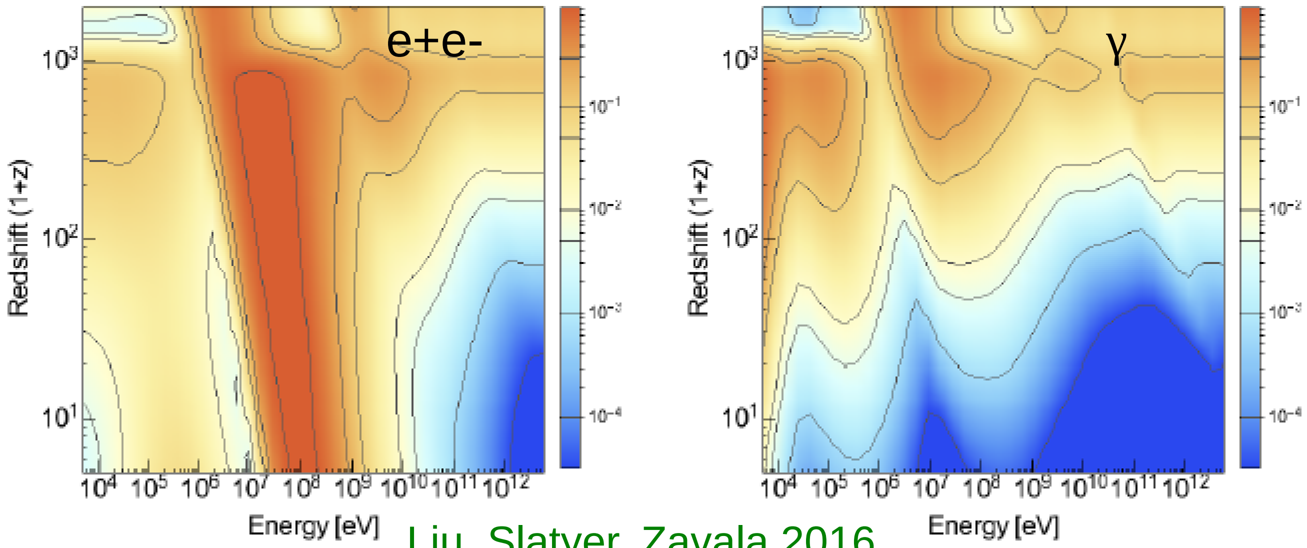
Not all energy is immediately deposited into the environment (gas, CMB, etc) if particles are too energetic:

* accumulative over earlier injection
* efficiency reduces at later time

Numerical calculation

Implemention into **CAMB, HyRec** codes: new physics excitation, scattering terms, Lyman-α photons, etc.

Energy “fraction” into ionization (of H)

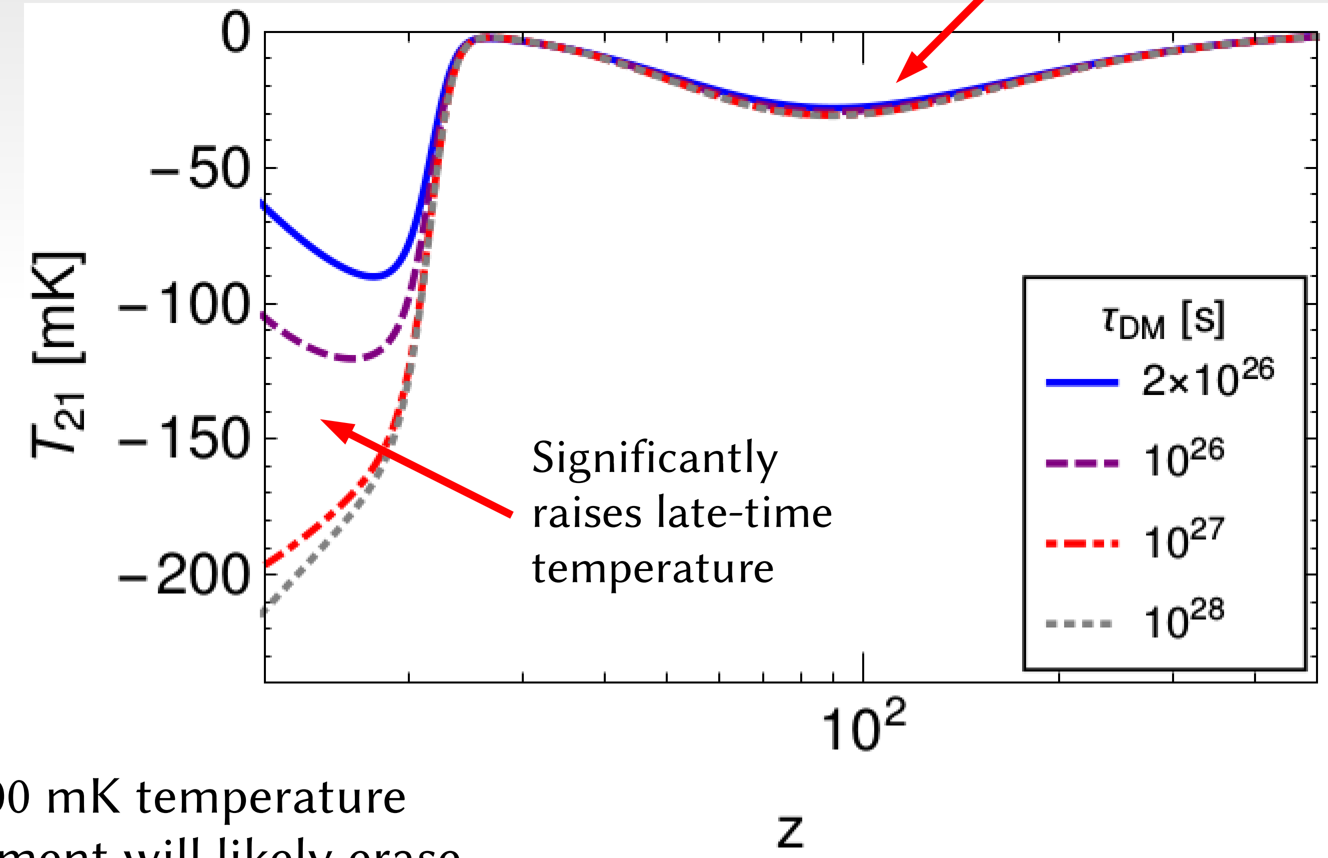


Liu, Slatyer, Zavala 2016

Also see:
Belotsky, Kirillov 2015

21cm signal suppression by injection

Limited early time effects
leave `dark age' alone



Significantly
raises late-time
temperature

Assuming
100% DM
decays as
DM⟶ e+e-

A 100~200 mK temperature enhancement will likely erase the expected 21cm signal in standard astrophysics

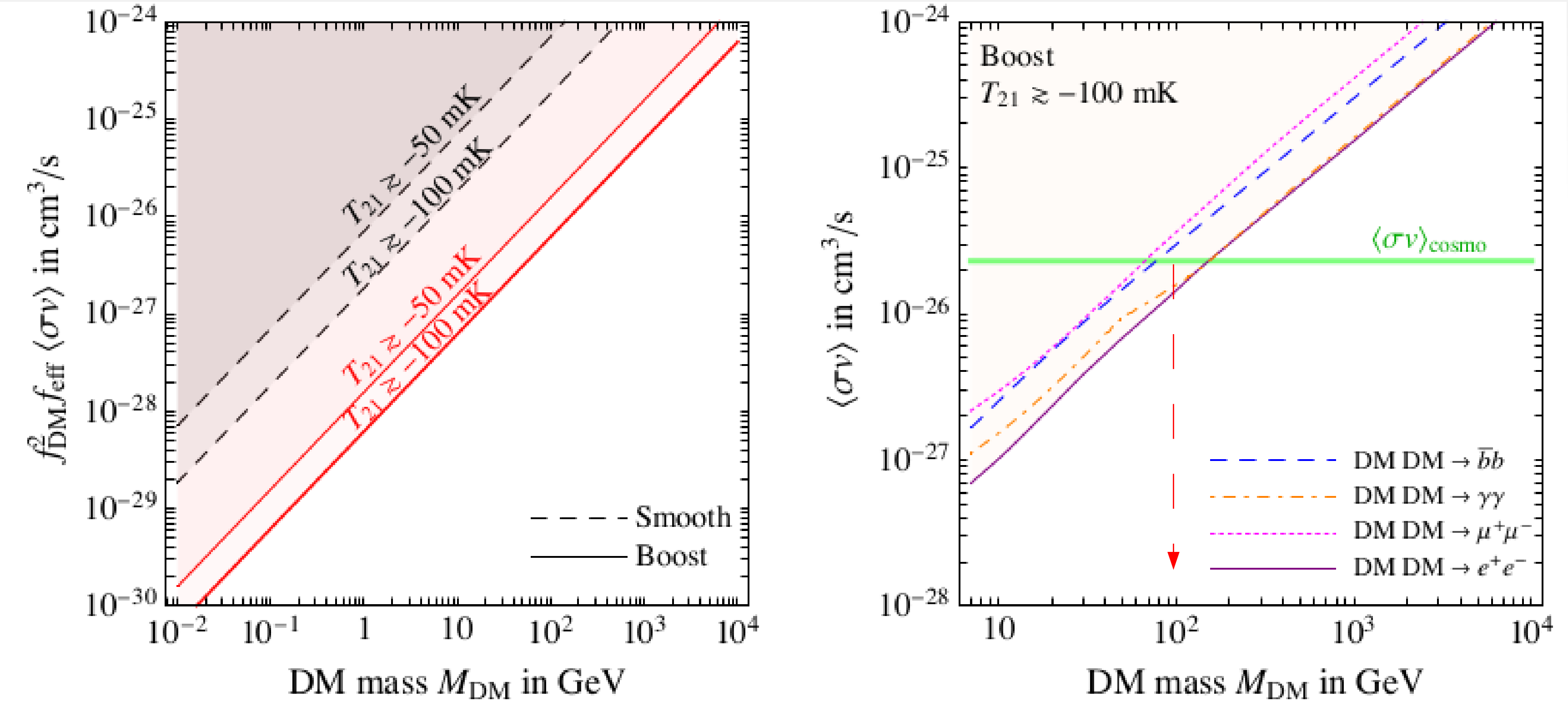
EDGES T_{21} uncertainty:
+200 mK by 95% up-fluctuation

The observation of 21cm signal as an upper limit

On DM annihilation rates:
by requiring injection induced
ΔT_{21} < +100 or +150 mK

G. D’Amico, P. Panci, A. Strumia 1803.03629

Excluding vanilla thermal wimp below 10^2 GeV?

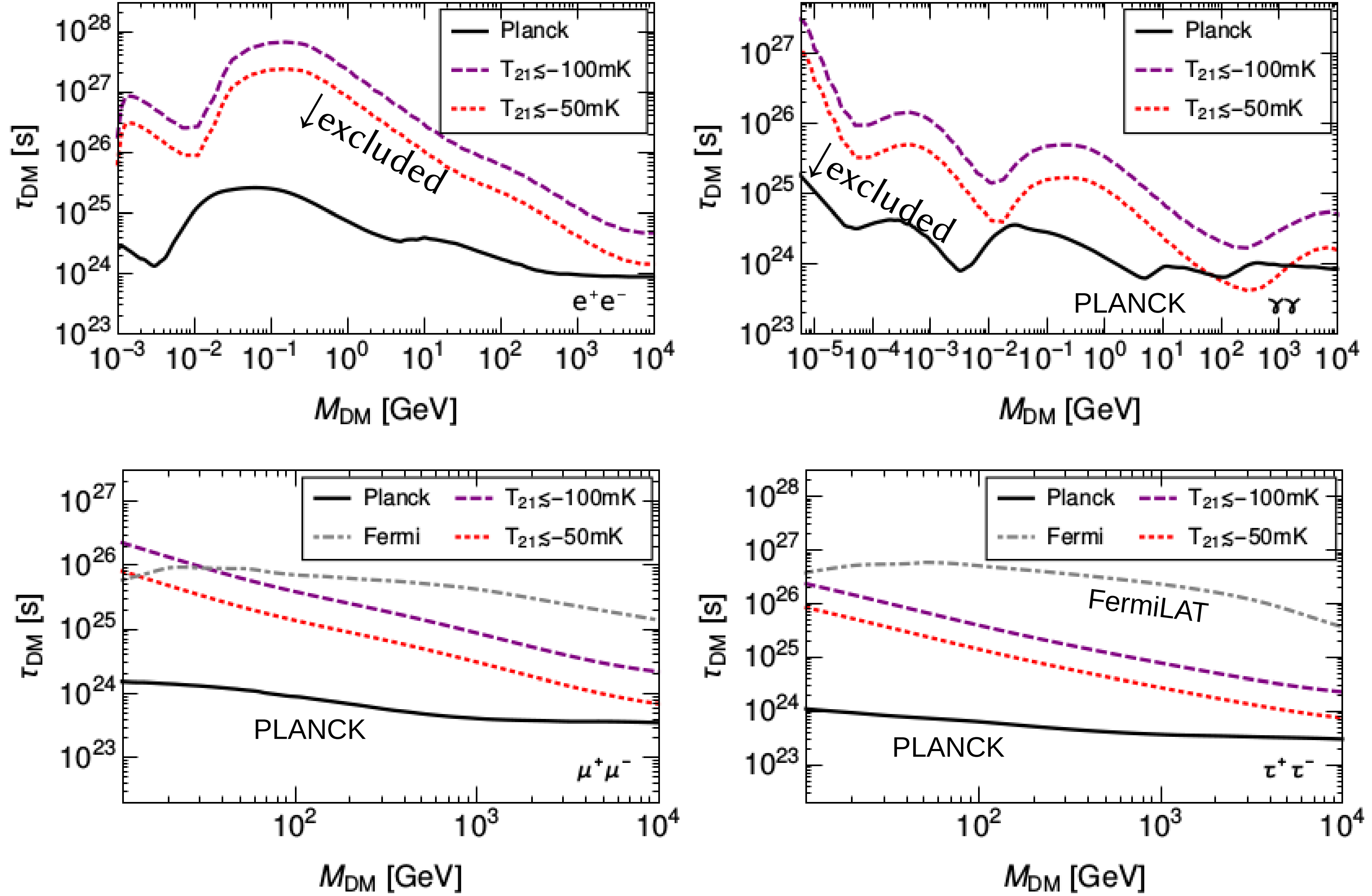


Annihilation: over-density boost B~217 at z~20

Lower limit on DM decay lifetime

$\Delta T_{21} < +100$ or $+150$ mK at $z=17$

* 3.5 KeV line allowed by 21cm



S.Clark, B.Dutta, Y.Gao, Y.-Z.Ma, L.E.Strigari, 1803.09390

Lower limit on DM decay lifetime

$\Delta T_{21} < +100$ or $+150$ mK at $z=17$
Gives 1-2 orders of magnitude better bounds on DM injection in comparison to PLANCK TT+TE+EE+lowP data

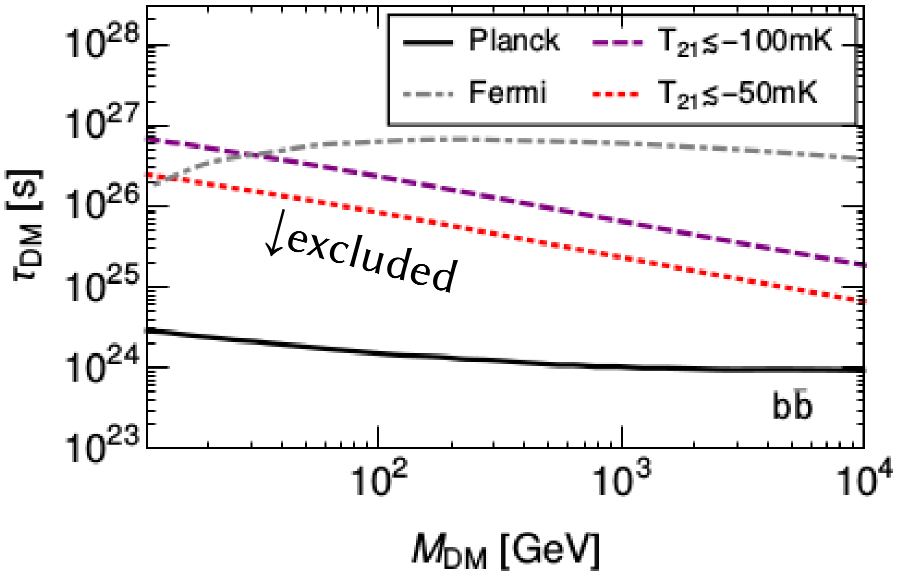
Lower sensitivity at large DM mass due to poorer effective energy loss efficiency

O(0.1-1) correction from cosmological parameter variations (PLANCK)

S. Clark, B. Dutta, Y. Gao, Y.-Z. Ma, L.E.Strigari, 1803.09390

Photon line signals:

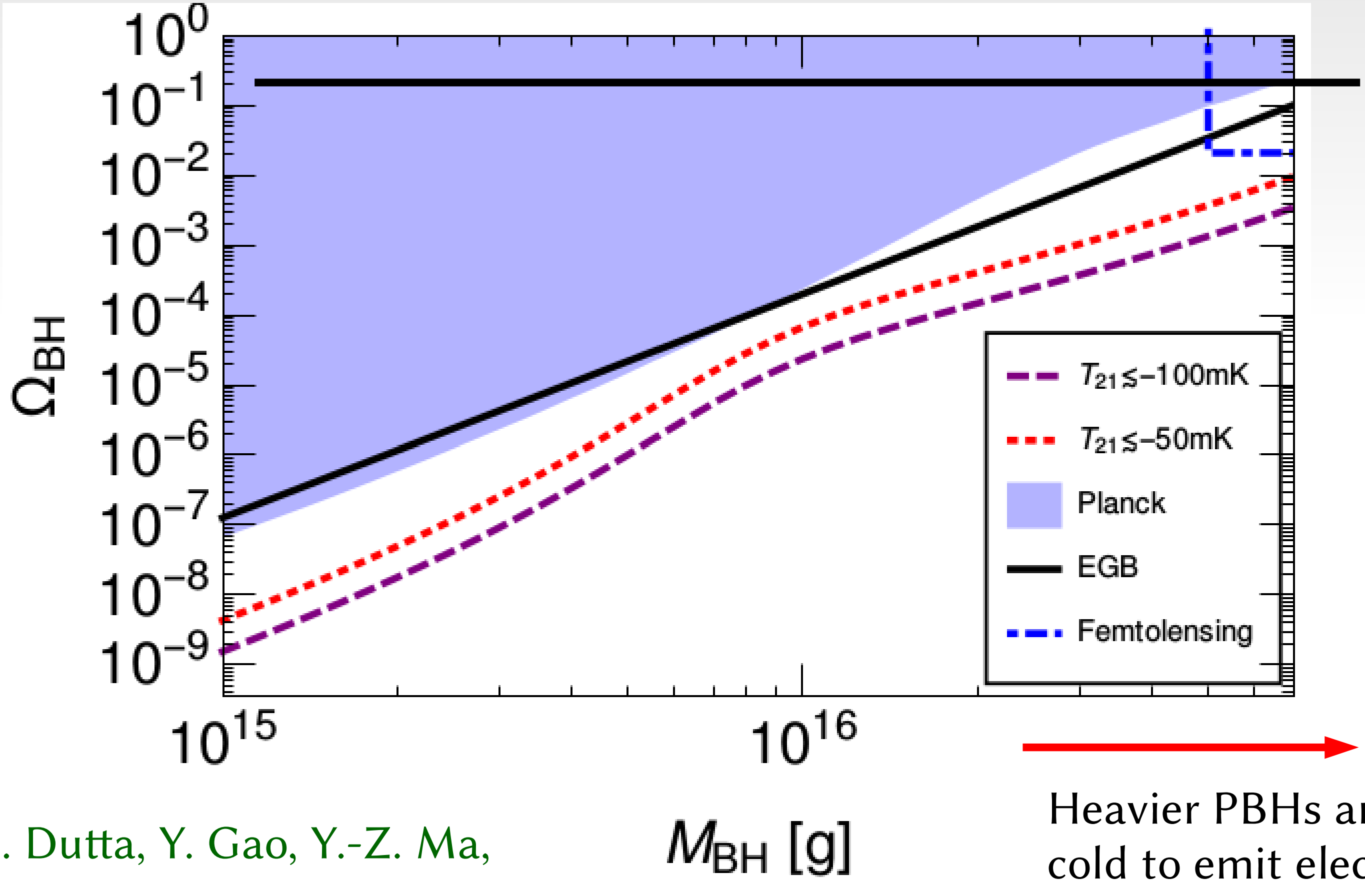
Very good limit in KeV range. Testing the 3.5 KeV line needs O(mK) T_{21} sensitivity
Comparable to X-ray line search ~10^{26}s in (sub) MeV range.
Less than Fermi-LAT's pass8 ~10^{29}s in GeV range.



Upper limit on primordial BH’s Hawking radiation

ΔT_{21} < +100 or +150 mK at z=17

Applicable to long-lived ($m > 10^{15}$g), evaporating black holes



relic density

Heavier PBHs are too cold to emit electrons and have lower (~M^{-3}) evaporation rate

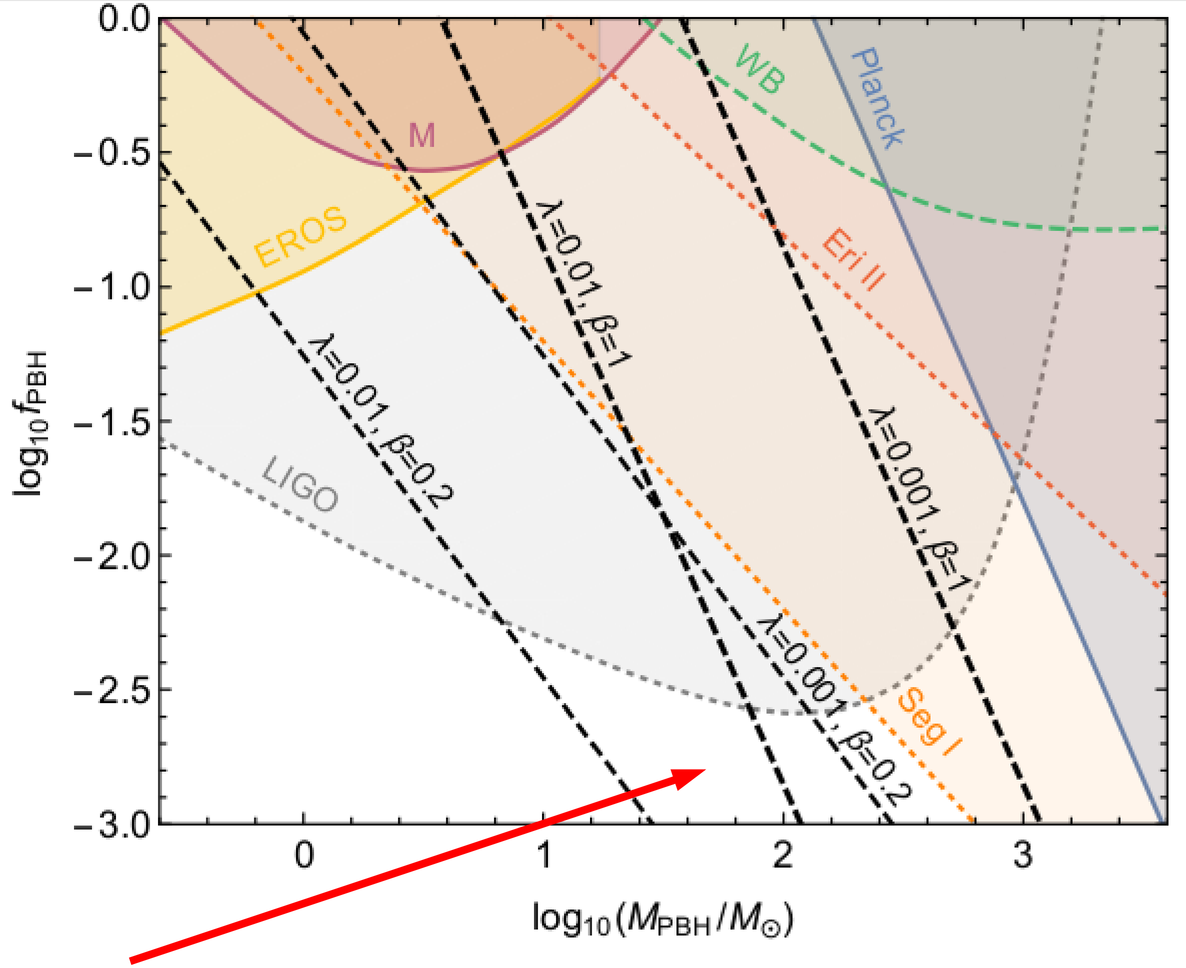
S. Clark, B. Dutta, Y. Gao, Y.-Z. Ma, L.E.Strigari, 1803.09390

Upper limit on massive PBH's accretion

X-ray emission from BH accretion, immediate energy deposition

Limit set by $T_G(z\sim17.2)=8K$
Improvement over PLANCK by 1-2 orders of mag.

A. Hektor, G. Hütsi, L. Marzola, M. Raidal, V. Vaskonen, H. Veermäe, 1803.09697



Complementing the LIGO

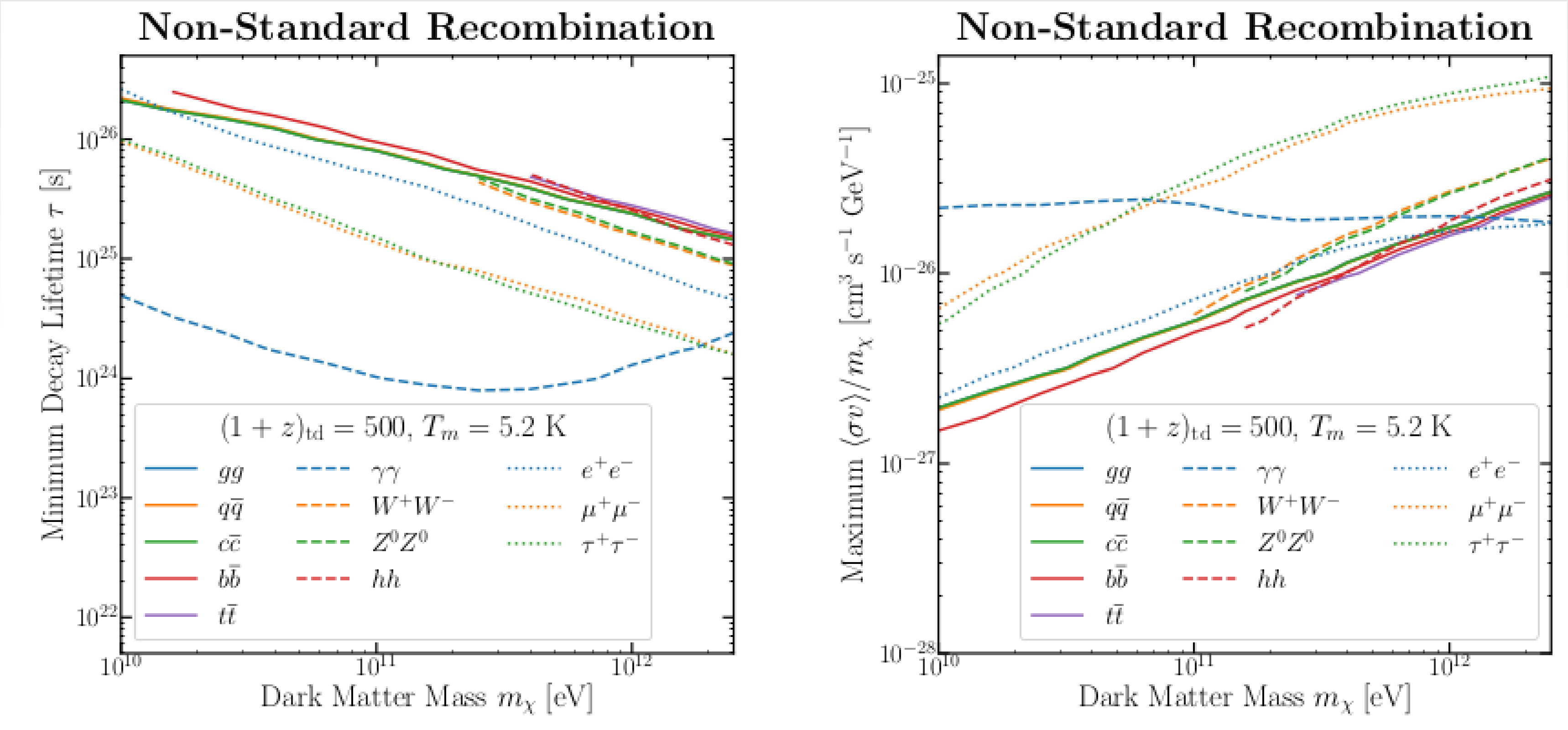
Summary

- EDGES results can be interpreted in many ways
- Existence of reionization epoch 21cm signal imposes a strong limit on historic energy injection
- Like CMB, injection bounds extend to low energy/mass
- 21cm bounds on DM, PBH are very powerful, even at the current proof-of-principle estimates
  --- comparable to Fermi-LAT (DM ann.)
  --- better than PLANCK (DM decay & PBHs)
- Future 21cm experiments (HERA, MWA, SKA) await.

Backup: more DM injection fits

Limits on DM annihilation & decays

$T_G(z=17.2)$ = 5.2K limit, no cooling

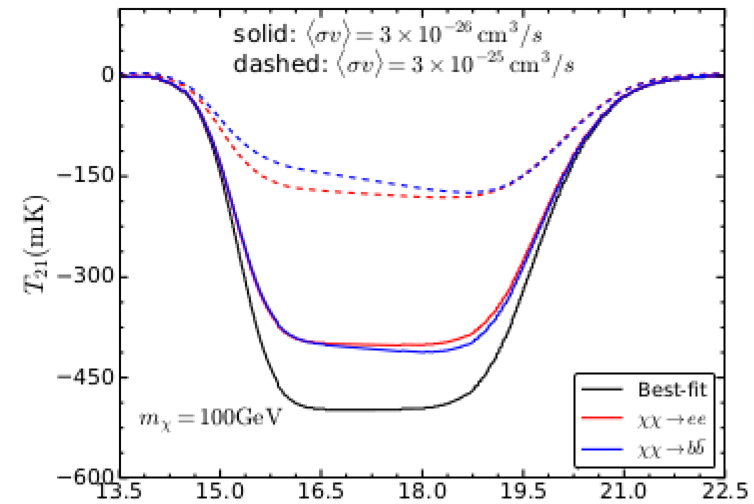


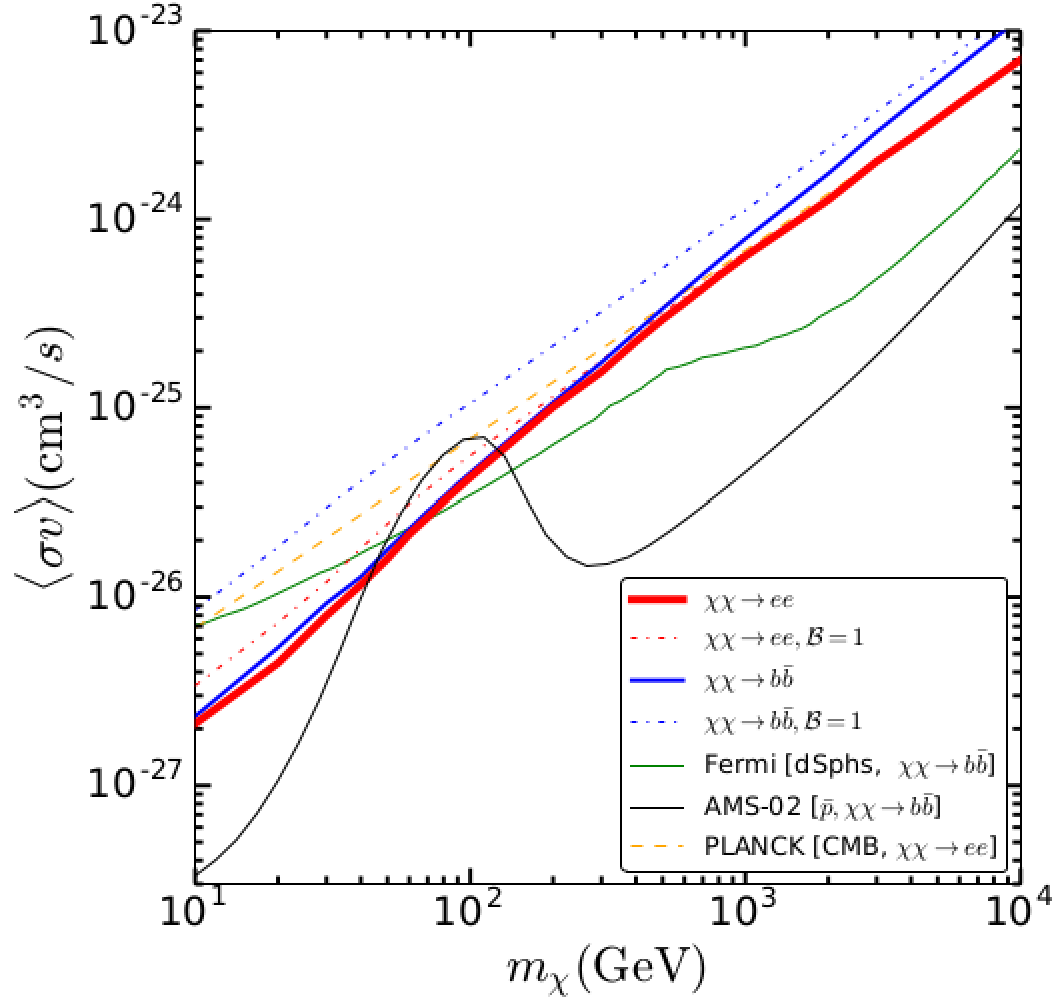
H. Liu, T. R. Slatyer, 1803.09739

Upper limit on DM annihilation

Fitting to the EDGES T_{21} history..

K. Cheung, J-L Kuo, K-W Ng, Y-L S Tsai, 1803.09398





Backup: Injection corrections

Extra contributions to ionization & heating

- Reduce neutral hydrogen fraction

$$\frac{dx_e}{dz} = \left(\frac{dx_e}{dz}\right)_{\rm orig} - \frac{1}{(1+z)H(z)}\left(I_{Xi}(z) + I_{X\alpha}(z)\right)$$

Ionization: $I_{Xi}(z) = f_i(E,z)\dfrac{dE/dVdt}{n_H(z)E_i}$

Lyman-α excitation $I_{X\alpha}(z) = f_\alpha(E,z)(1-C)\dfrac{dE/dVdt}{n_H(z)E_\alpha}$

- IGM temperature

$$\frac{dT_{\rm IGM}}{dz} = \left(\frac{dT_{\rm IGM}}{dz}\right)_{\rm orig} - \frac{2}{3k_B(1+z)H(z)}\frac{K_h}{1+f_{\rm He}+x_e}$$

$$K_h(z) = f_h(E,z)\frac{dE/dVdt}{n_H(z)}$$

- Wouthuysen-Field

$$T_{\rm S} = \frac{T_{\rm CMB} + y_{\rm c}T_{\rm G} + y_{{\rm Ly}\alpha}T_{{\rm Ly}\alpha}}{1 + y_{\rm c} + y_{{\rm Ly}\alpha}},$$

$$y_{\rm c} = \frac{C_{10}}{A_{10}}\frac{T_\star}{T_{\rm G}},$$

$$y_{{\rm Ly}\alpha} = \frac{P_{10}}{A_{10}}\frac{T_\star}{T_{{\rm Ly}\alpha}},$$

For Lyman-alpha during reionization,
See B. Ciardi and P. Madau, astro-ph/0303249

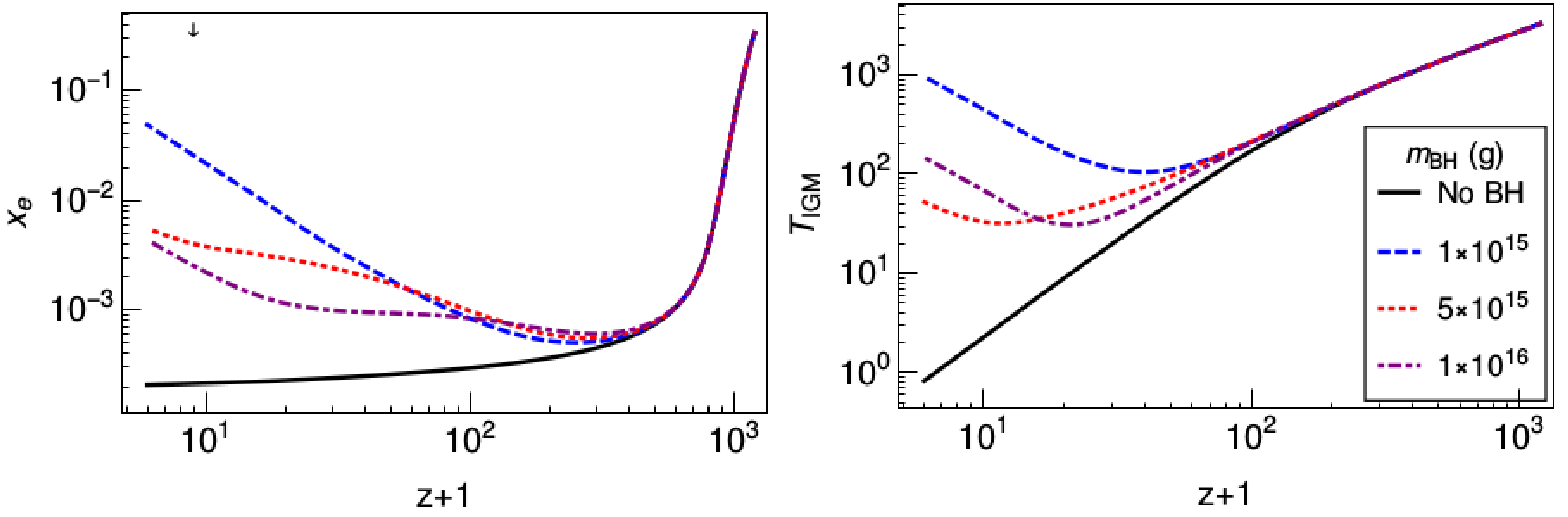
- Energy deposit rate (ionization, excitations, heating)

$$
\begin{aligned}
I_{X_\mathrm{i}}(z) &= \frac{f_\mathrm{i}(E,z)}{\mathrm{H}_H(z)E_\mathrm{i}}\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t},\\
I_{X_\alpha}(z) &= (1-C)\frac{f_\alpha(E,z)}{n_\mathrm{H}(z)E_\alpha}\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t},\\
K_\mathrm{h}(z) &= \frac{f_\mathrm{h}(E,z)}{n_\mathrm{H}(z)}\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\\
C &= \frac{1+K\Lambda_{2s,1s}n_\mathrm{H}(1+x_\mathrm{e})}{1+K\Lambda_{2s,1s}n_\mathrm{H}(1-x_\mathrm{e})+K\beta_\mathrm{B}n_\mathrm{H}(1-x_\mathrm{e})}.
\end{aligned}
$$

- The `effective’ rate *f*(E,z) is cumulative of historic injection
- Electrons are more effective in energy deposit
- *f* is averaged over injection spectra and species

$$
f_c(m_\mathrm{DM},z) = \frac{\sum_s \int f_c(E,z,s)E(\mathrm{d}N/\mathrm{d}E)_s\mathrm{d}E}{\sum_s \int E(\mathrm{d}N/\mathrm{d}E)_s\mathrm{d}E},
$$

- Ionization history can be a powerful test (at z>7) on \`prolonged’ electron & gamma ray injection from new physics



Num. computation by HyRec

Backup: PBHs (CMB)

Hawking radiation, `lifetime' and BH mass

- BH evaporates at a temperature

Hawking 75'

$$T_{PBH} = \frac{1}{8\pi G M} = 1.06\mathrm{TeV} \times \frac{10^{10}\mathrm{g}}{M_{PBH}}$$

- with a peak energy of radiation

$$E_\gamma = 5.71 T_{PBH}\,,\ E_\nu = 4.22 T_{PBH}\,,\ E_{e^\pm} = 4.18 T_{PBH}$$

Mass loss rate:

$$\dot{M}_{10} = -5.34 \times 10^{-5} \left(\sum_i f_i \right) M_{10}^{-2}\ \mathrm{s}^{-1}$$

lifetime:

$$\tau(M) \sim \frac{G^2 M^3}{\hbar\, c^4} \sim 10^{64} \left(\frac{M}{M_\odot} \right)^3 \mathrm{yr}$$

- BH evaporation can be a good source of cosmic rays, injection particle species determined by BH mass

A steady radiation injection below ~100 MeV

- Relevant for PBH mass above 10^{15} g, or peak radiation energy below muon mass
- Hawking evaporation after recombination yields (mostly) e+e- and gamma rays
- For M>>10^{15}g, mass loss negligible during the age of the Universe
- A steady and long-lasting injection of radiation that scales as $(1+z)^3$

Extra-galactic source

Of Hawking evaporation rate

$$\dot{M}_{10} = -5.34 \times 10^{-5} \left(\sum_i f_i \right) M_{10}^{-2}\ \mathrm{s}^{-1}$$

into light (massless) species,

$$f_0 = 0.267, \quad f_1^{\gamma} = 0.06, \quad f_{3/2} = 0.02,$$
$$f_2^{g} = 0.007, \quad f_{1/2}^{\nu} = 0.147, \quad f_{1/2}^{e^{\pm}} = 0.142$$

J.MacGibbon, PRD, 1991

and photons & electrons affects the environment with unit volume injection rate, +redshift

$$\begin{aligned} \frac{dE}{dV\,dt} &= \dot{M}_{PBH}\,\eta(E_i, z)\, n_{PBH} \\ &= \frac{\dot{M}_{10}}{M_{10}} \rho_{cr}(z)\Omega_{PBH}(z)\eta_i(E, z) \end{aligned}$$

$\Gamma^{-1} \sim M/M$

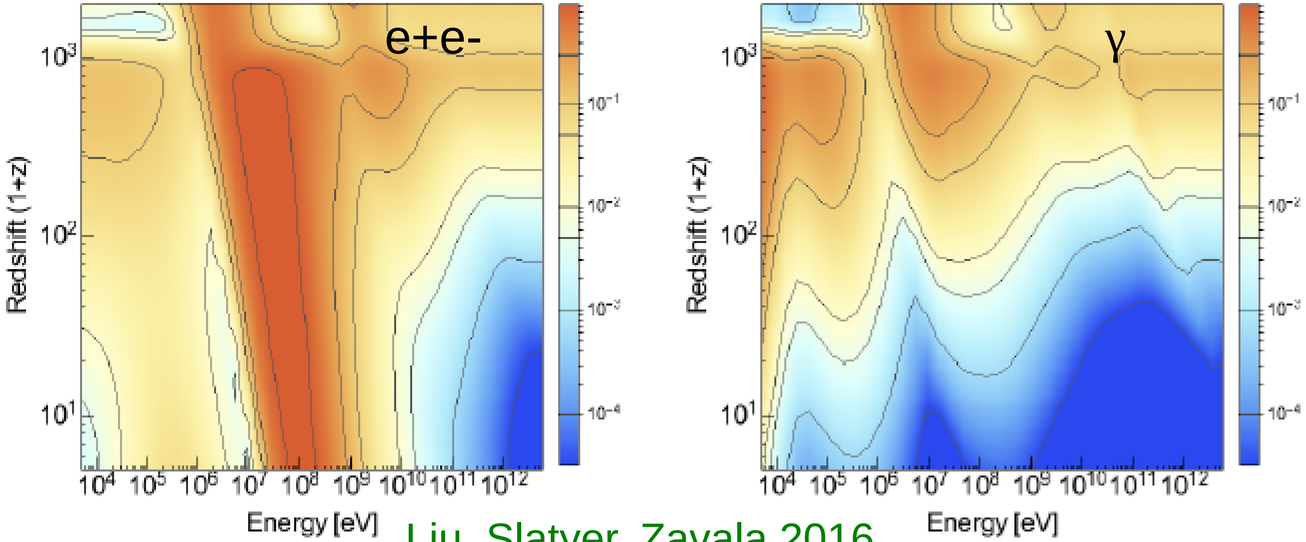
$$\left.\frac{dE}{dV\,dt}\right|_{\mathrm{BH}} = \frac{\dot{M}_{10}}{M_{10}} \rho_{cr}(z)\Omega_{PBH}(z)\eta(E_{PBH}, z)$$

Injection vs absorption

- photons interact via Compton scattering & absorptions
- electrons lose energy by inverse C. scattering & ionization

Not all energy is efficiently absorbed by the environment (gas) esp. if particles are too energetic

Energy “fraction” into ionization (of H)

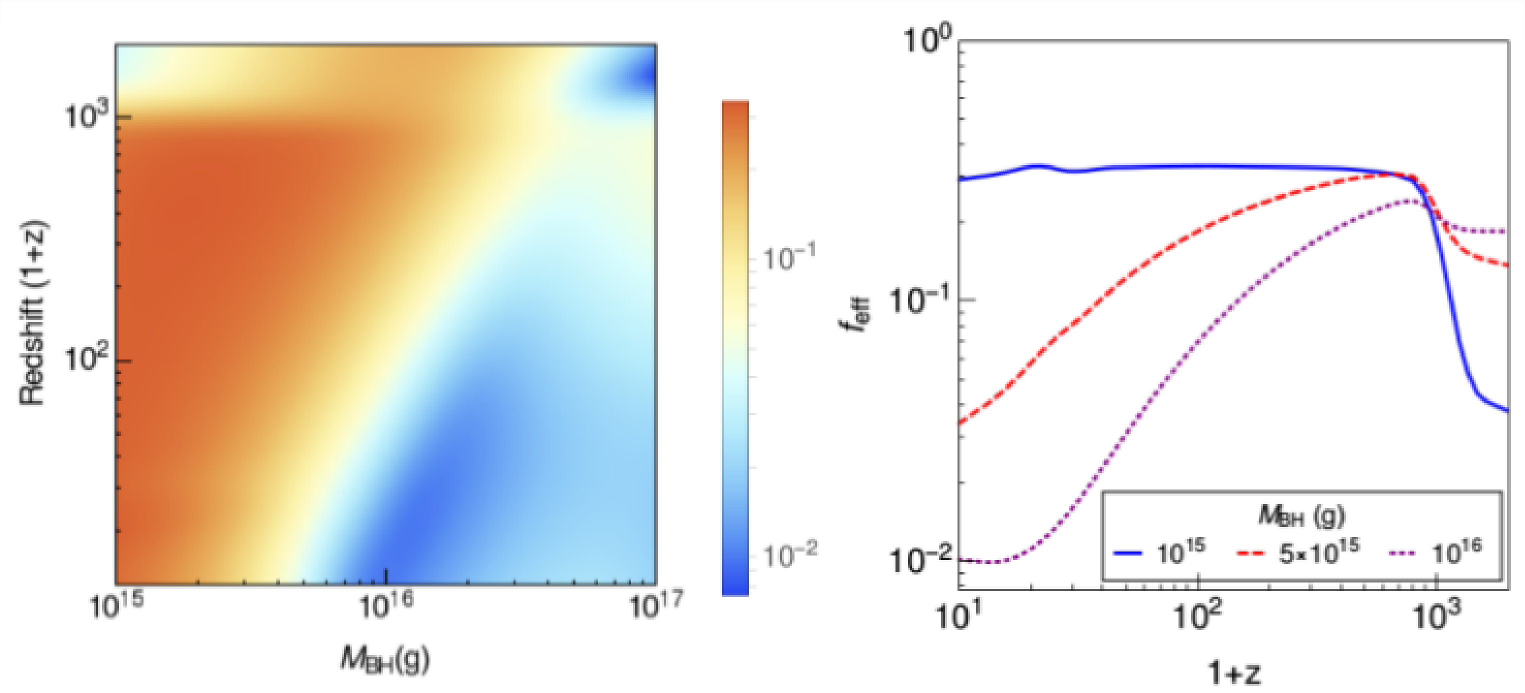


Liu, Slatyer, Zavala 2016

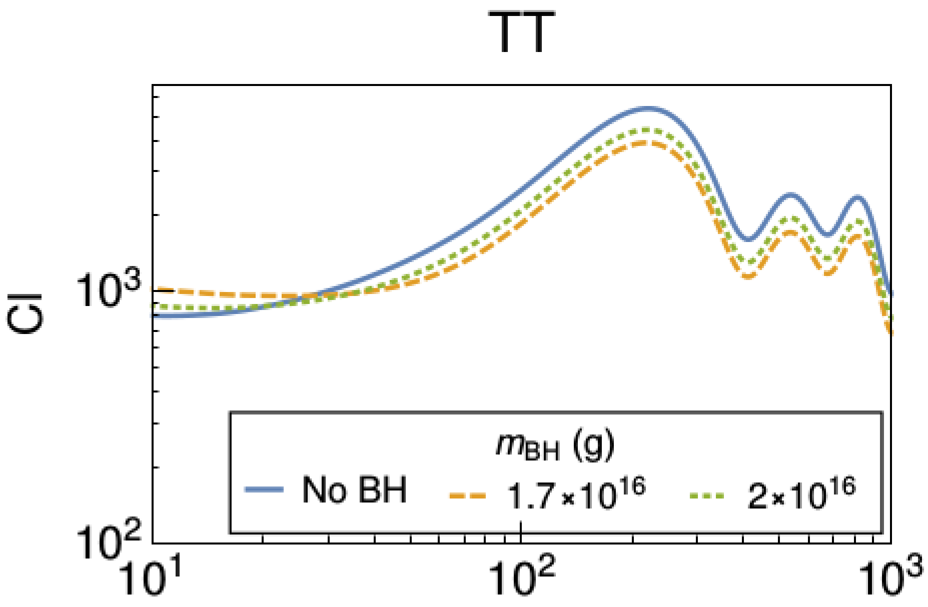
Also see:
Belotsky, Kirillov 2015

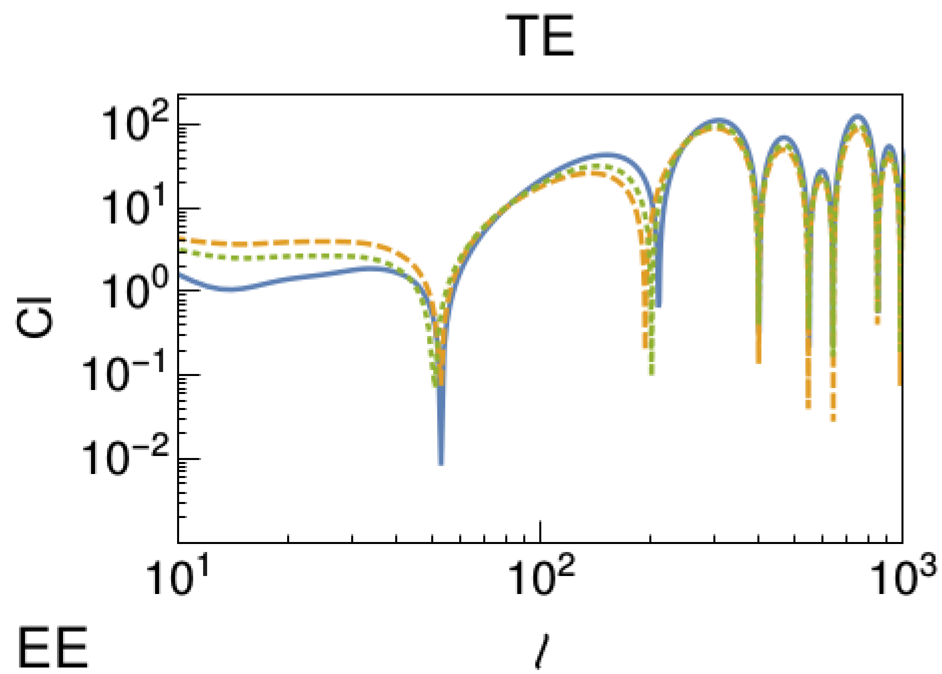
BH Effective absorption efficiencies

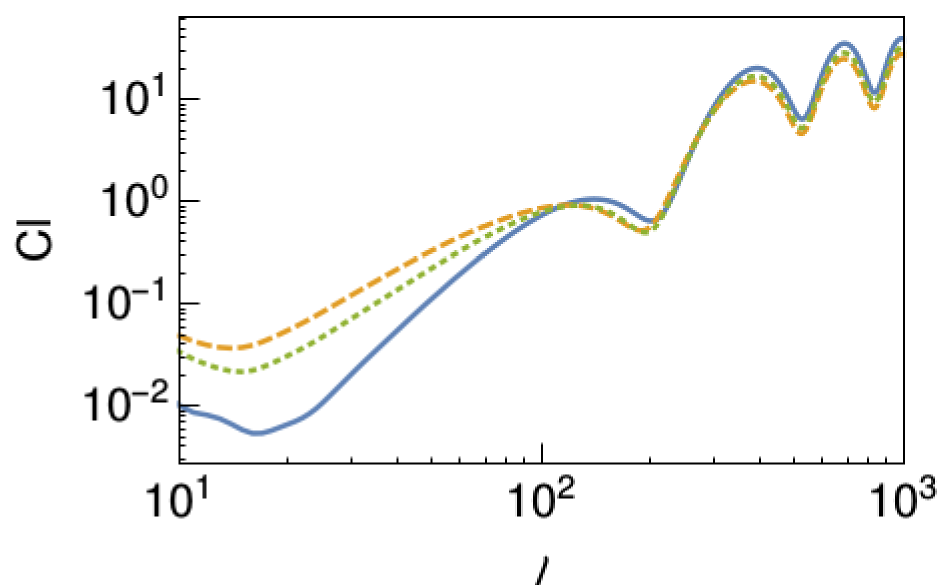
- Average over injection (BH radiation) energy spectrum and particle species
- Delayed injection: integrated over earlier z (up to CMB)



Impact on the CMB Cls

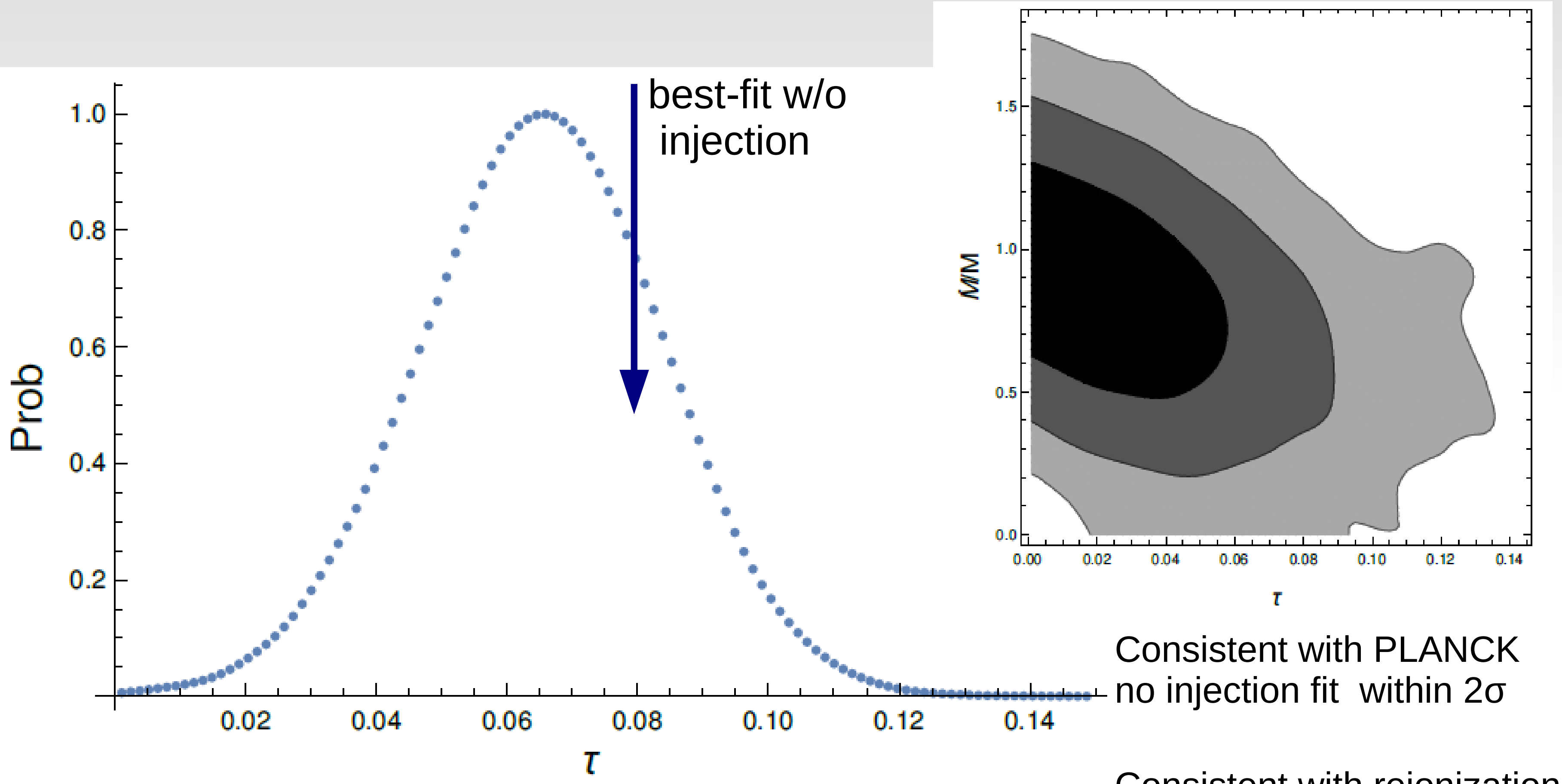






CAMB+HyRec+
CosmoMC+
PLANCK data kit

Reduced optical depth



best-fit w/o injection

Consistent with PLANCK no injection fit within 2σ

PLANCK: temperature + polarization

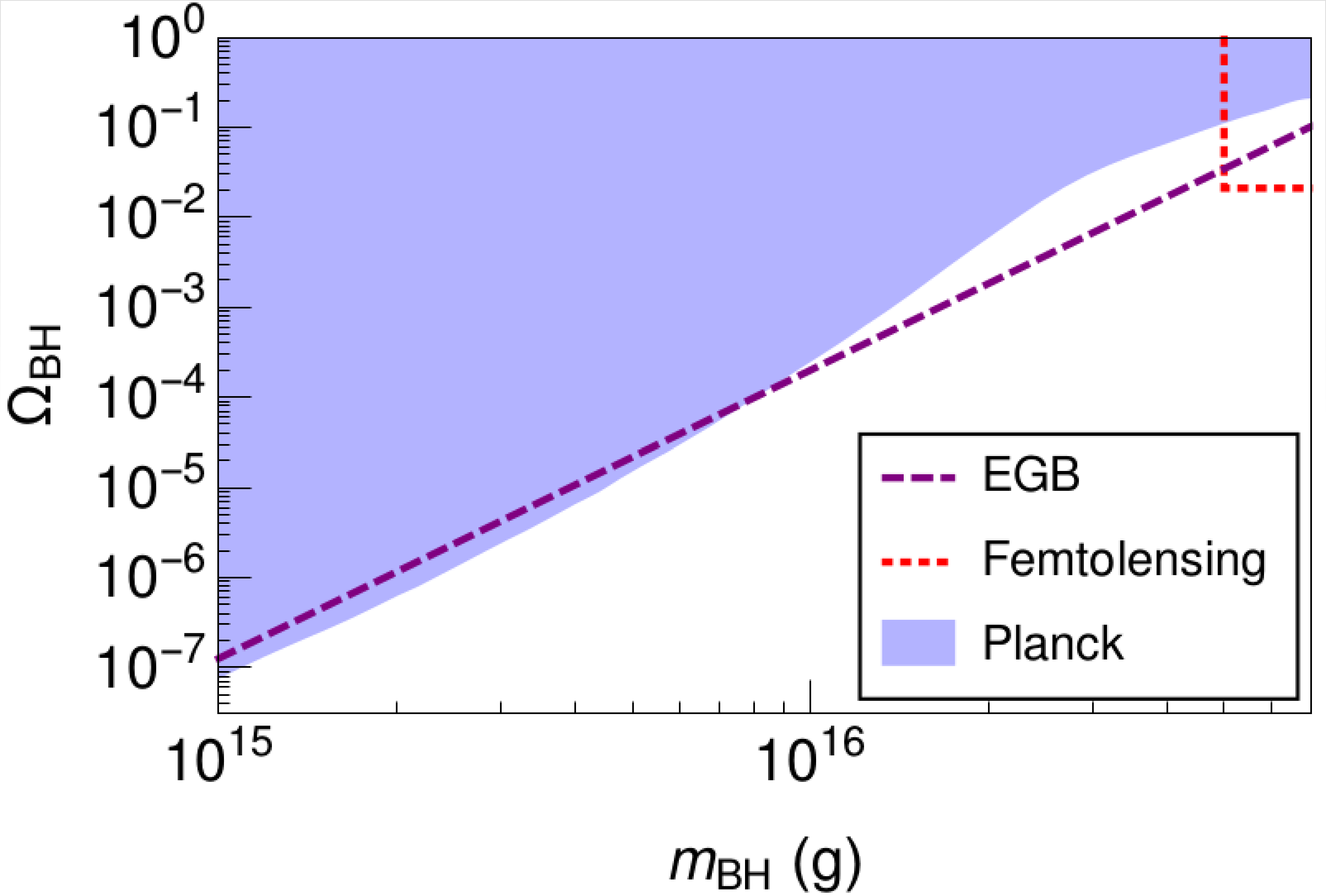
Consistent with reionization z ≤ 6

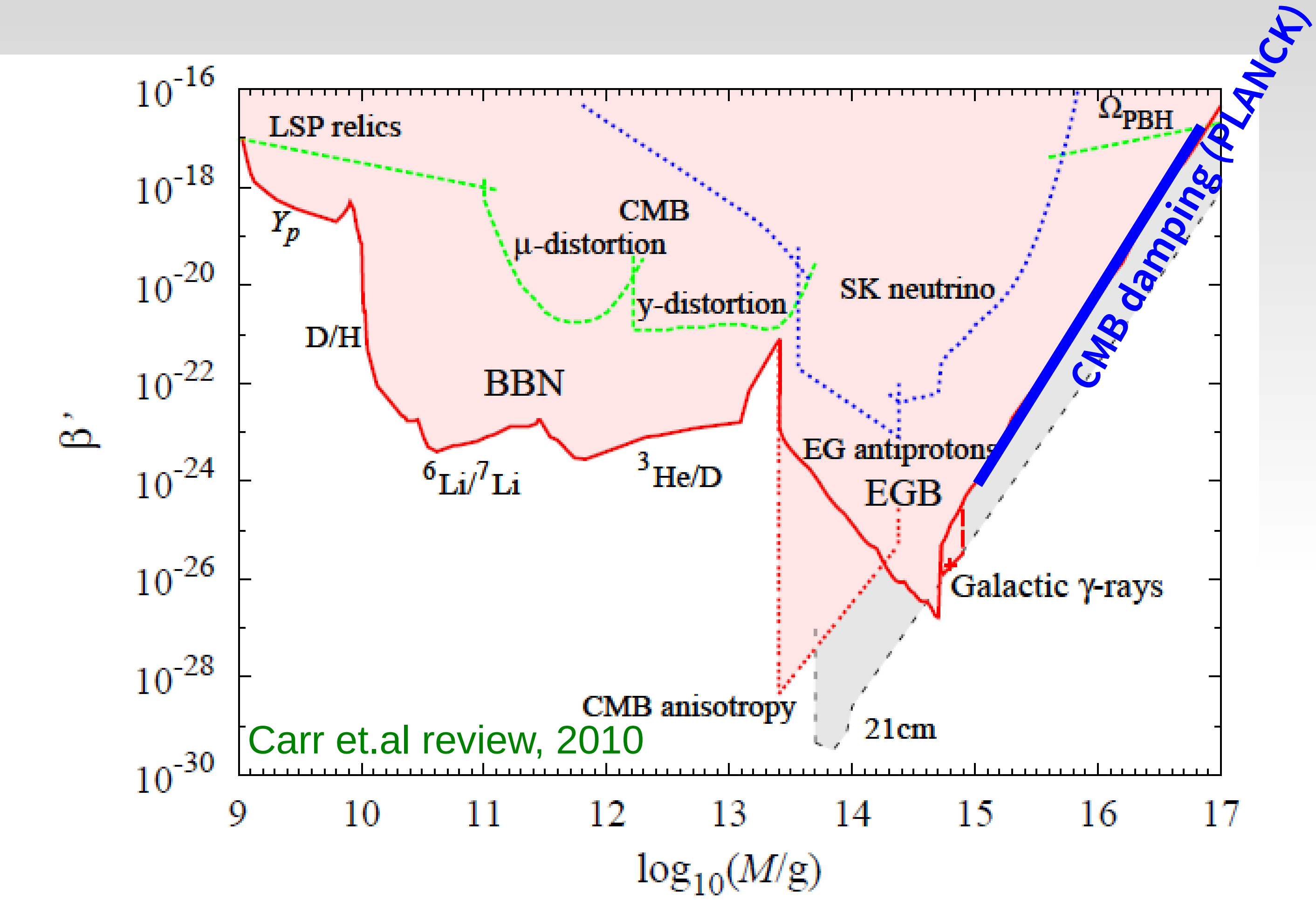
DM Decay: $\tau > 10^{24}$ s

Liu, Slatyer, Zavala 2016

Need polarization data to break degeneracy

PLANCK constraint on PBH as `relic' abundance



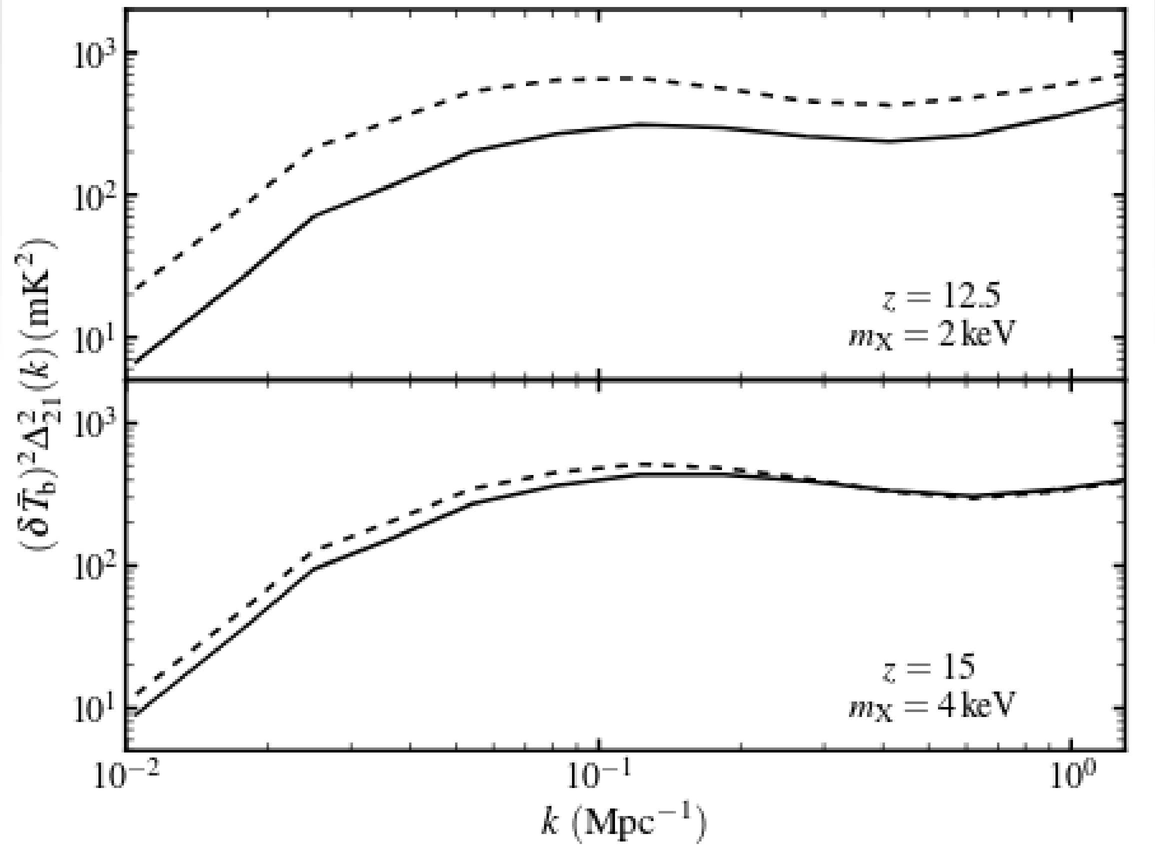


Simple scaling, assume no entropy production after PBHs and $\Omega_r \sim 10^{-4}$ at CMB time, also β' ~ β:

$$\Omega_{\rm PBH} \simeq \beta\, \Omega_{\rm r}\, (1+z) \sim 10^6\, \beta \left(\frac{t}{1\,{\rm s}}\right)^{-1/2} \sim 10^{18}\, \beta \left(\frac{M}{10^{15}\,{\rm g}}\right)^{-1/2} \qquad (M > 10^{15}\,{\rm g})\,.$$

Backup: 21cm prospects

SKA: Reionization epoch power spectrum



SKA white paper

Warm versus Cold DM at 21cm

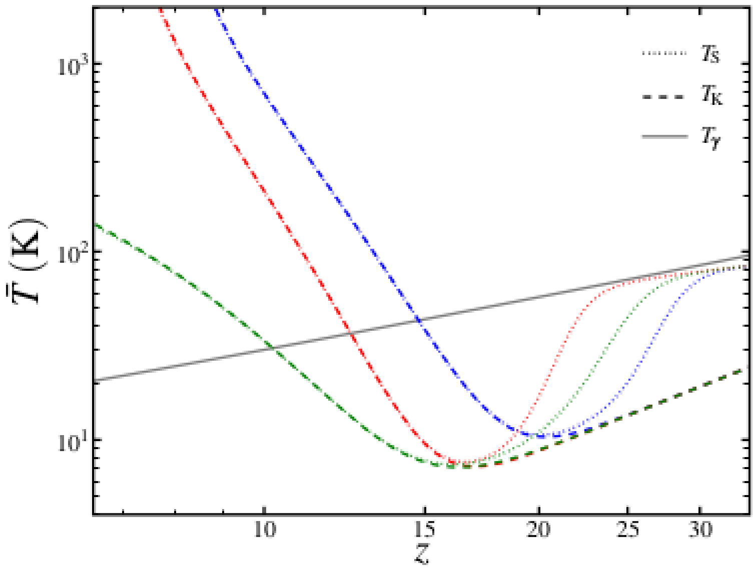


Figure 3. Mean spin temperatures $\bar{T}_S$ for CDM and WDM models. The dotted curves show $\bar{T}_S$ for our fiducial CDM model (blue), WDM with $m_X = 3\,\mathrm{keV}$ (red), and CDM with $f_*/f_{*\mathrm{fid}} = 0.1$ (green). In addition, the mean kinetic temperature $\bar{T}_K$ of each model is plotted with a dashed curve in the same colour used for $\bar{T}_S$. The grey solid line is the CMB temperature. Figure taken from (Sitwell et al., 2014).

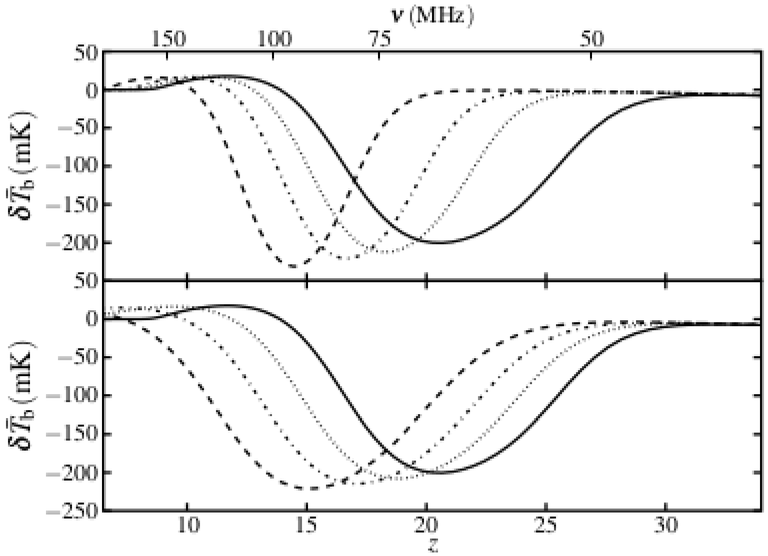
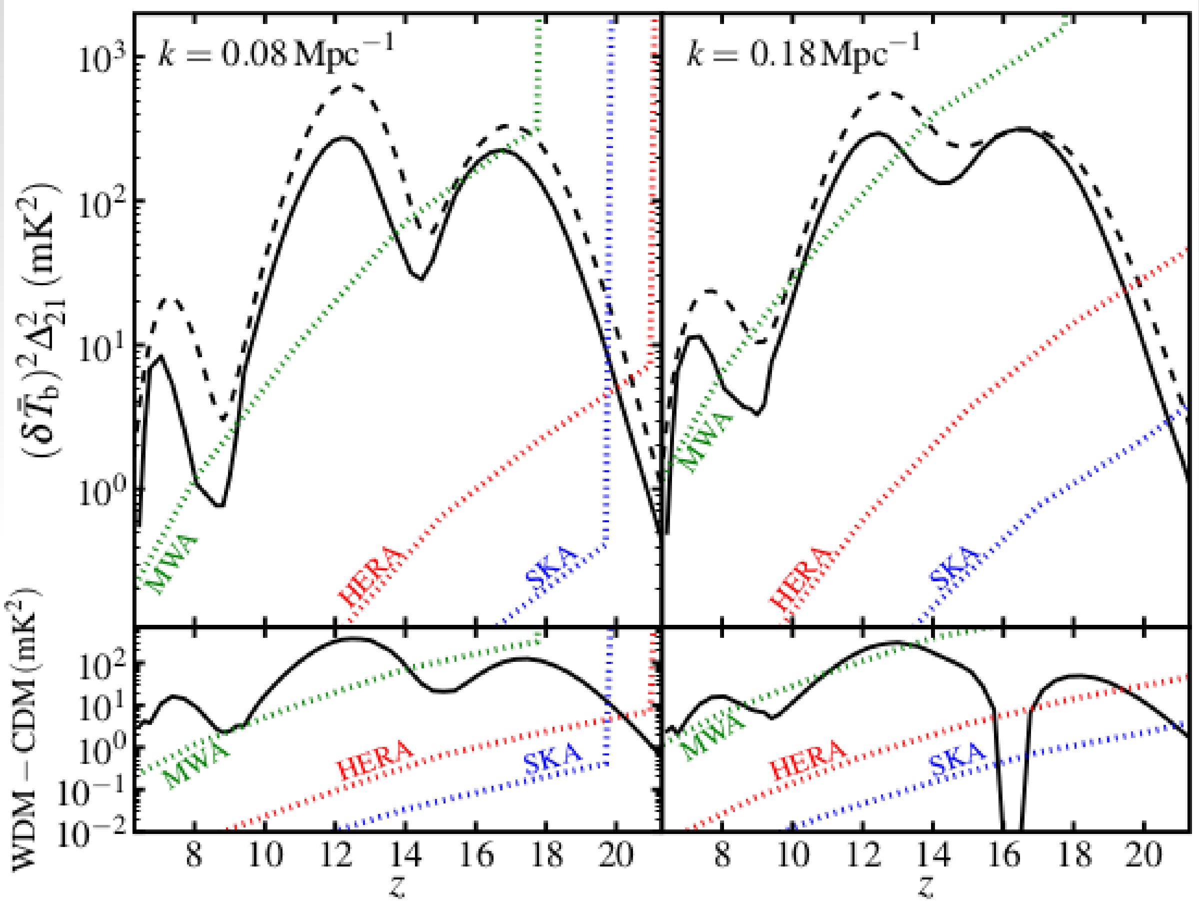


Figure 4. Mean 21 cm brightness temperature $\delta\bar{T}_b$. The solid curve is the fiducial CDM model. The upper plot shows the results of WDM runs where the dashed, dotted-dashed, and dotted curves are for $m_X = 2, 3, 4$ keV, respectively. The lower plot shows CDM runs where the dashed, dotted-dashed, and dotted curves are for CDM models with $f_*/f_{*\mathrm{fid}} = 0.03, 0.1, 0.5$, respectively. Figure taken from Sitwell et al. (2014).

SKA white paper



M. Sitwell, A. Mesinger, Y.-Z Ma,
K. Sigurdson, 2014 MNRAS, 438, 2664