WIMP sensitivity from CMB measurements

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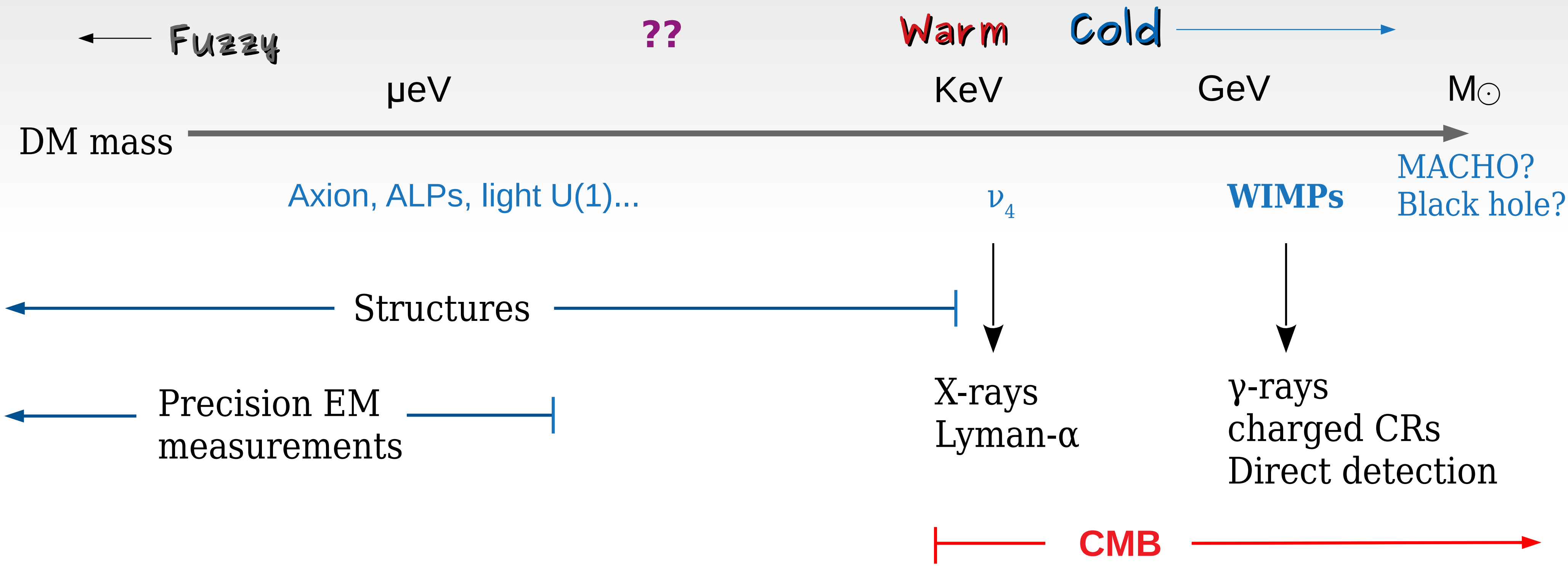
Outline

- WIMP induced energy injection after Recombination
- Impacts on ionization & temperature
- Ionization: CMB temp. & pol. maps
- Temperature (& ion.): 21cm

Forecasts for upcoming CMB pol. experiments

Dark matter mass range



CMB covers a wide DM mass range!

Fills a gap between indirect
X-ray and γ-ray searches
(also good for massive radiating objects)

WIMP `means' energy injection

- Annihilation (required) Decay (optional) for thermal WIMP
- Energy release during dark ages

Annihilation: fast during high z, (plus late-time boost)

$$\frac{dE}{dV\,dt} = \rho_c^2 c^2 \Omega_{\rm DM}^2 (1+z)^6 p_{\rm ann}(z) \qquad \sim (z+1)^6$$

Decay: a steady rate, unaffected by structure formation

$$\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t} = \Gamma_{\rm DM} \cdot \rho_{\rm c,0} \Omega_{\rm DM} (1+z)^3 \qquad \sim (z+1)^3$$

Primordial Black holes: Hawking evaporation at mostly constant rate similar to DM decay, soft in radiation energy

$$\left.\frac{dE}{dV\,dt}\right|_{\rm BH} = \frac{\dot{M}_{10}}{M_{10}} \rho_{cr}(z) \Omega_{PBH}(z) \eta(E_{PBH}, z) \quad \sim (z+1)^3$$

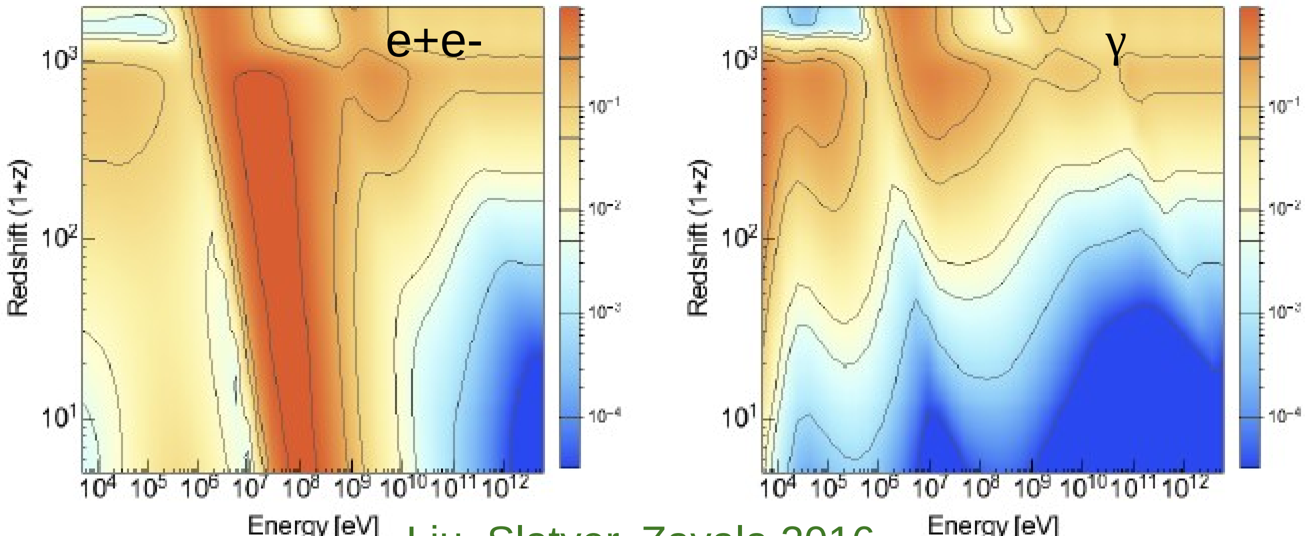
Injection & absorption

- 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

Energy “fraction” into ionization (of H)



Liu, Slatyer, Zavala 2016

Numerical calculation

Implemented into **HyRec** codes:

new physics induced excitation, scattering terms, Lyman-α photons, etc.

Also see:
Belotsky, Kirillov 2015

- The `effective' deposit fraction f(E,z)

Absorption/injection ratio is cumulative of historic injection:

Higher at late time (low z) & low E
Instant absorption at very low E

- Averaged over injection spectra and species *s*

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

- Electrons are more effective than gamma rays at large energy
- Photons emissions extends to (much) lower DM mass range
- Protons from cascades are negligible

Energy deposit: ionization & heating

- Raises ionization fraction

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

Extra ionization

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

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

- Raises IGM temperature

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

& gas heating

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

The cosmic ionization history

Standard ionization evolution is obtained by solving the Boltzmann equation for electrons:

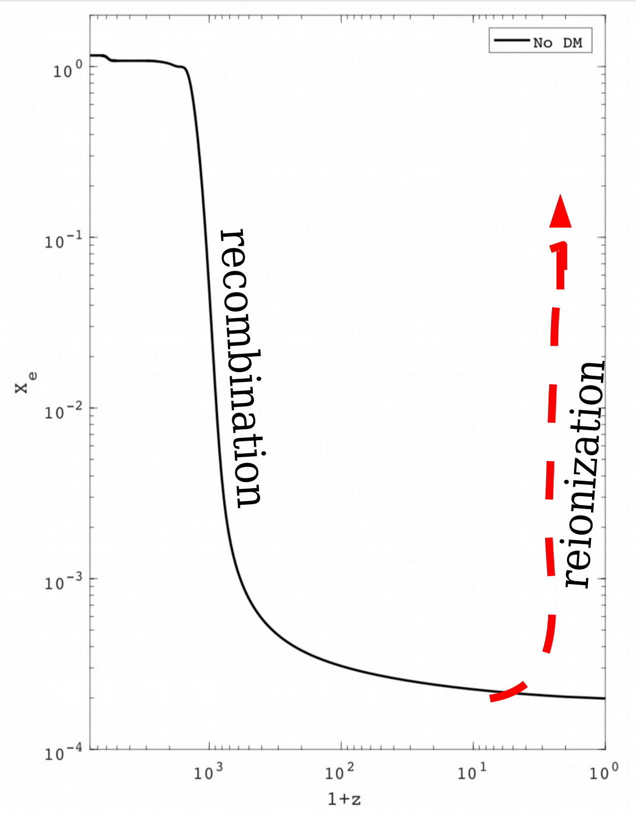
$$\frac{dX_e}{dt} = \left\{(1 - X_e)\beta - X_e^2 n_b \alpha^{(2)}\right\}$$

Ionization rate:

$$\beta \equiv \langle \sigma v \rangle \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\epsilon_0/T}$$

Recombination: $\alpha^{(2)} \equiv \langle \sigma v \rangle$

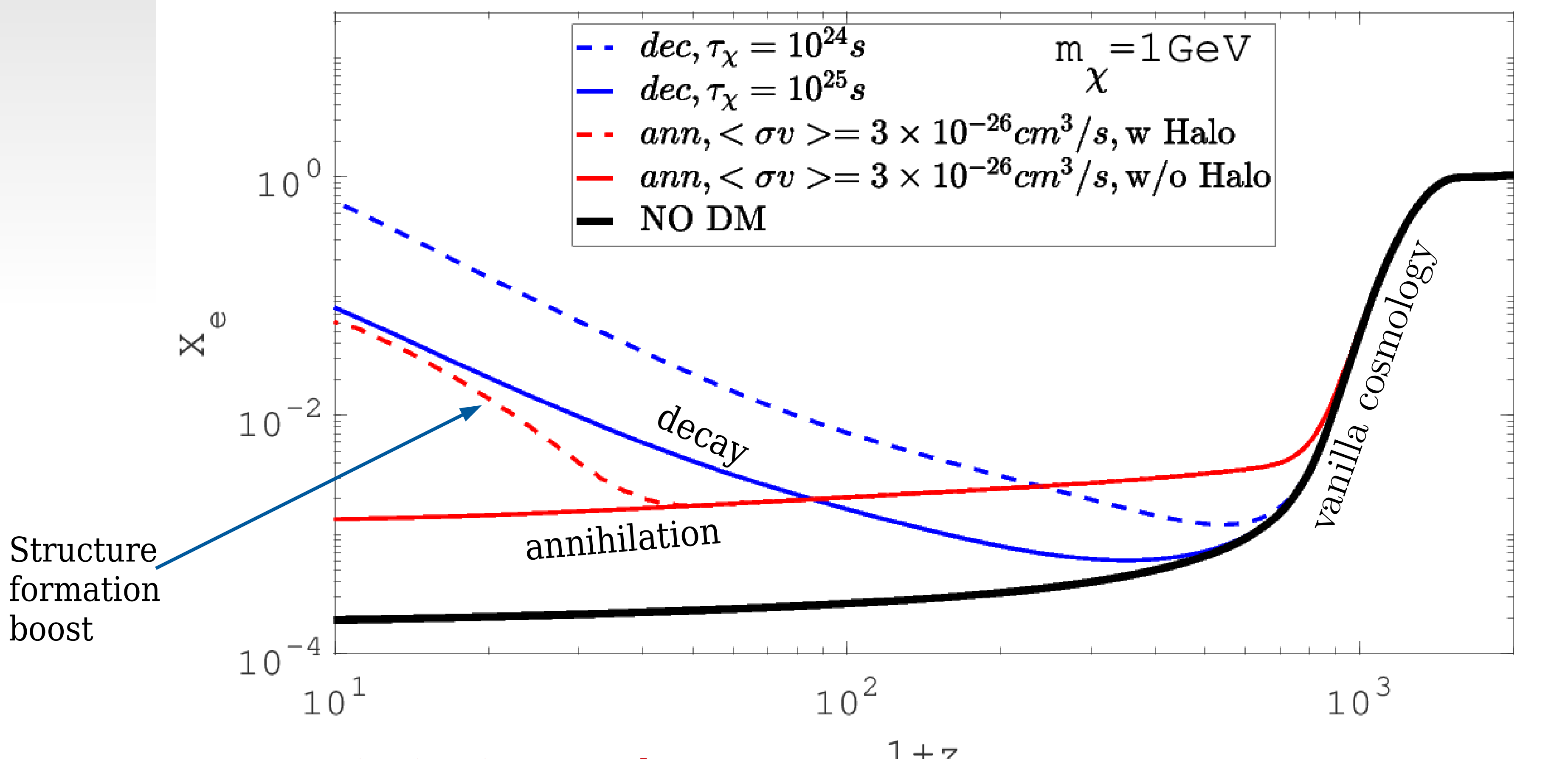
Approx. capture rate to a non-ground state $\alpha^{(2)} = 9.78 \frac{\alpha^2}{m_e^2} \left(\frac{\epsilon_0}{T}\right)^{1/2} \ln\left(\frac{\epsilon_0}{T}\right)$



x_e reduces to a 10^{-4} floor during the cosmic dark age and returns to unity @EoR

Ionization fraction: x_e

Annihilation: raises the x_e floor, Decay: steady rise in x_e



Reionization not shown

Free electrons: the CMB Cls

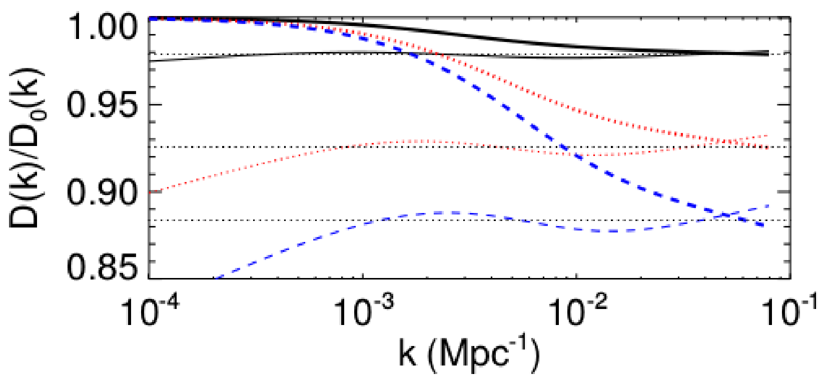
Increased ionization enhances photon scattering

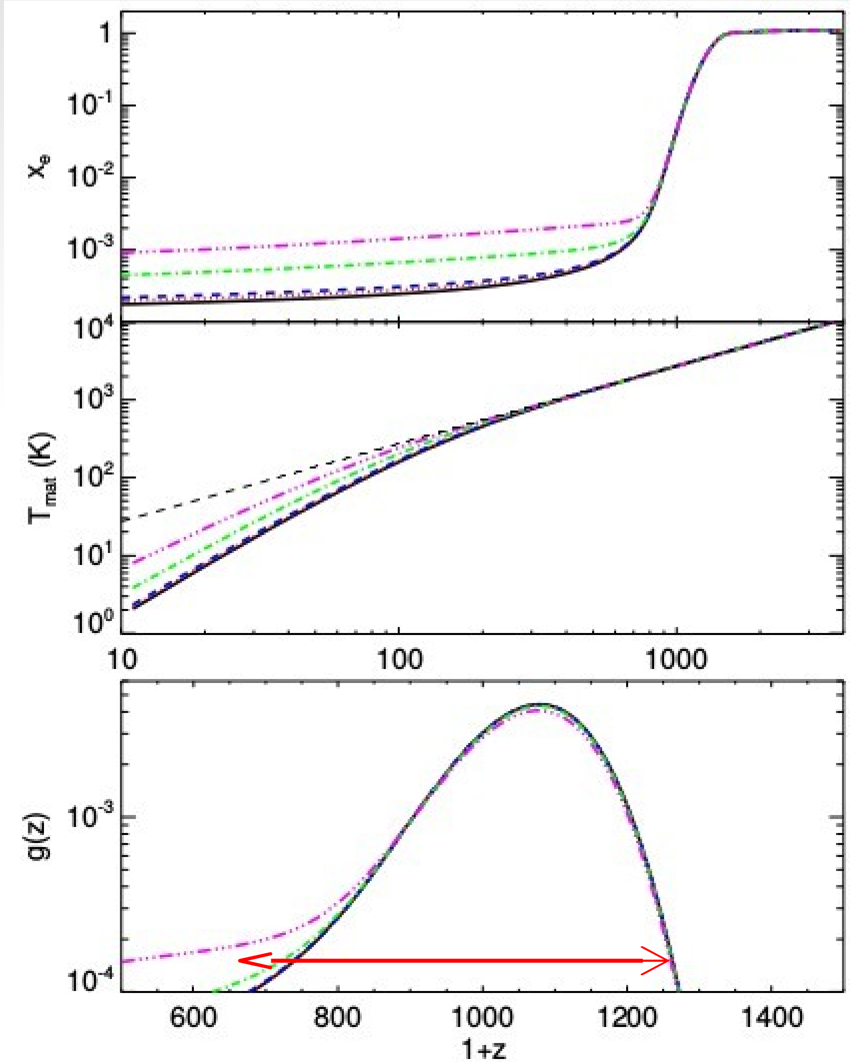
$$C_l = 4\pi A \int_0^\infty d(\ln k)\, k^{n_s} D^2(k) T^2(k)$$

in the damping function:

$$D(k) = \int dz\, g(z) \exp\left(-\frac{k^2}{k_D^2(z)}\right)$$

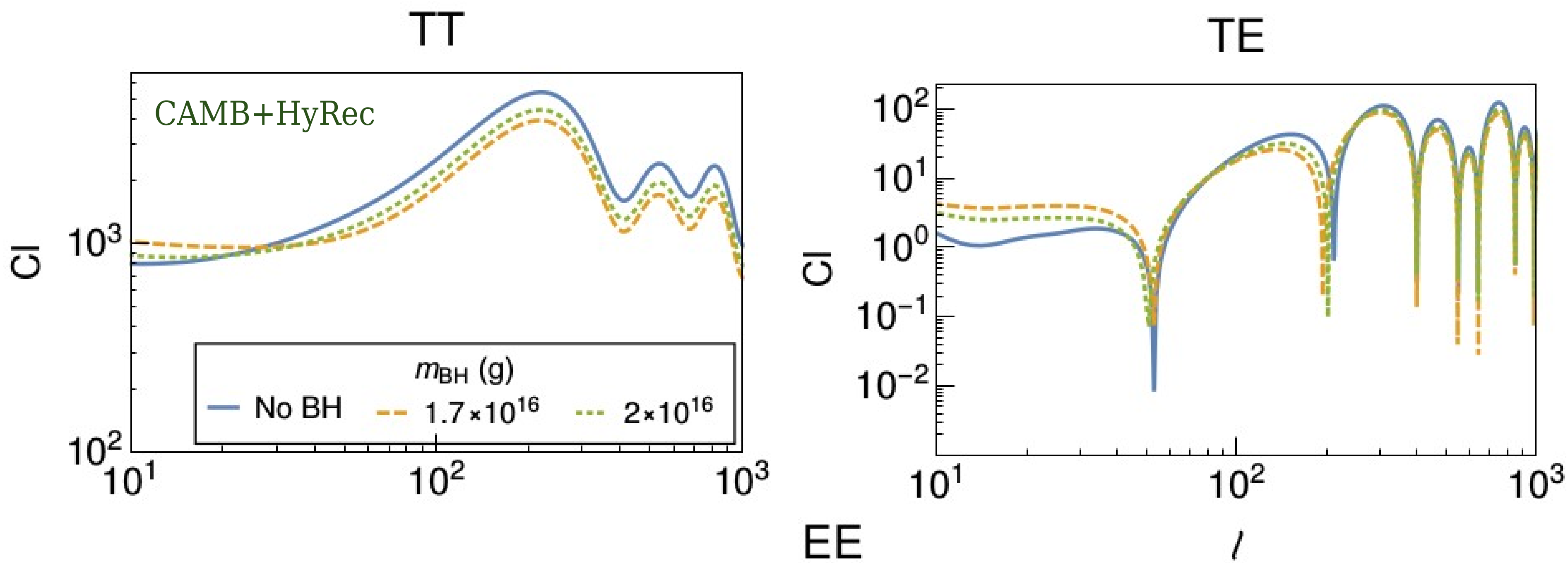
$$\frac{1}{k_D^2} = \int_z^\infty dz\, \frac{c}{H^2(z)} \frac{1}{6(1+R)\tau'(z)} \left[\frac{R^2}{(1+R)} + \frac{16}{15}\right]$$





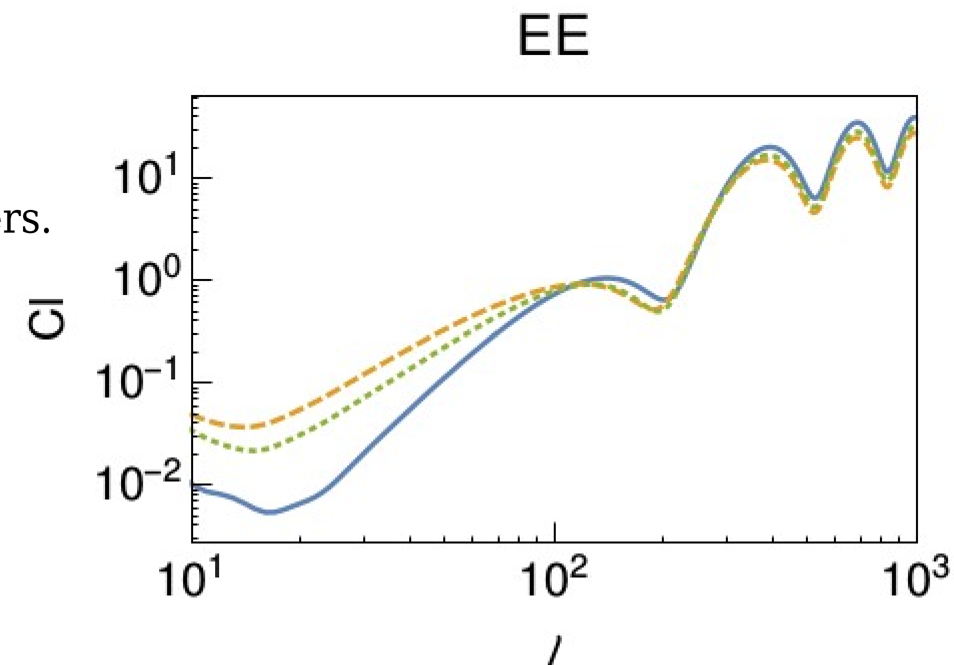
Continuous energy deposit:
"Broadens the last scattering surface"

Impact on the CMB Cls



Large *l* damping may be degenerate to cosmological parameters.

Low *l* , esp. peak shift in polarization spectra are more effective

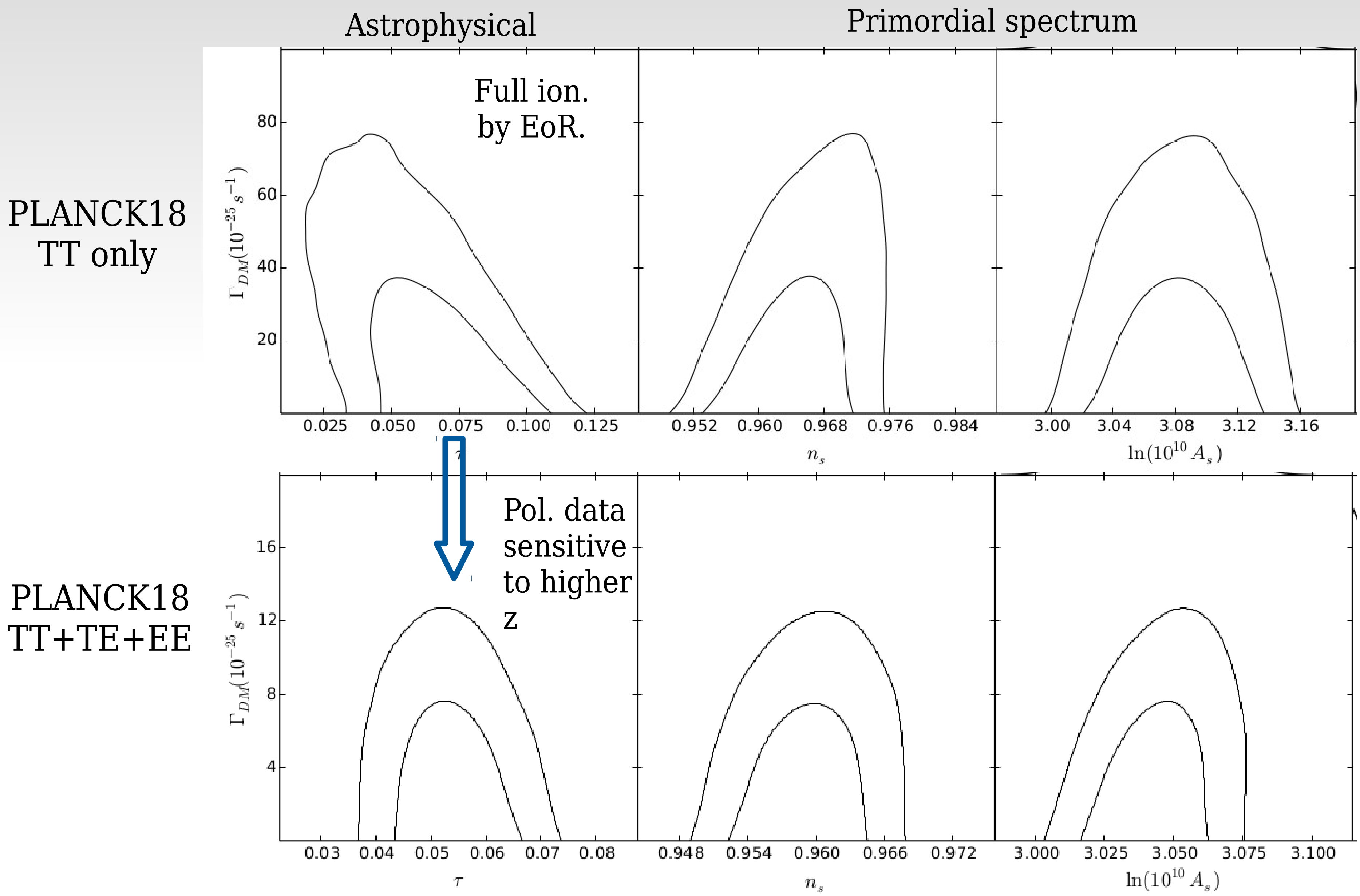


LSS broadening increases polarization perturbation amplitudes

* **shifts the E pol. peaks** by enhanced monopole to quadrature ratio

* enhances damping

Degeneracy with Cosmological Parameters



Polarization helps breaking degeneracy

Data: PLANCK18
(DM decay scenario)
Fit by CosmoMC

Astrophysical ionization ~ EoR saturation → τ

Overall anisotropy spectral shape → n_s

	TT	TT+TE+EE
τ	-0.53	-0.12
n_s	0.39	0.15
A_s	0.07	0.24
$\Omega_b h^2$	0.02	0.10
$\Omega_c h^2$	-0.02	0.01
$100\theta_{\rm MC}$	-0.13	-0.10

TABLE I. Correlation coefficients between Γ_{DM} and base ΛCDM parameters.

Polarization ani. C_l

TE, EE peak location shift sensitive to higher z (~recombination) effects

Major degeneracy: EoR history

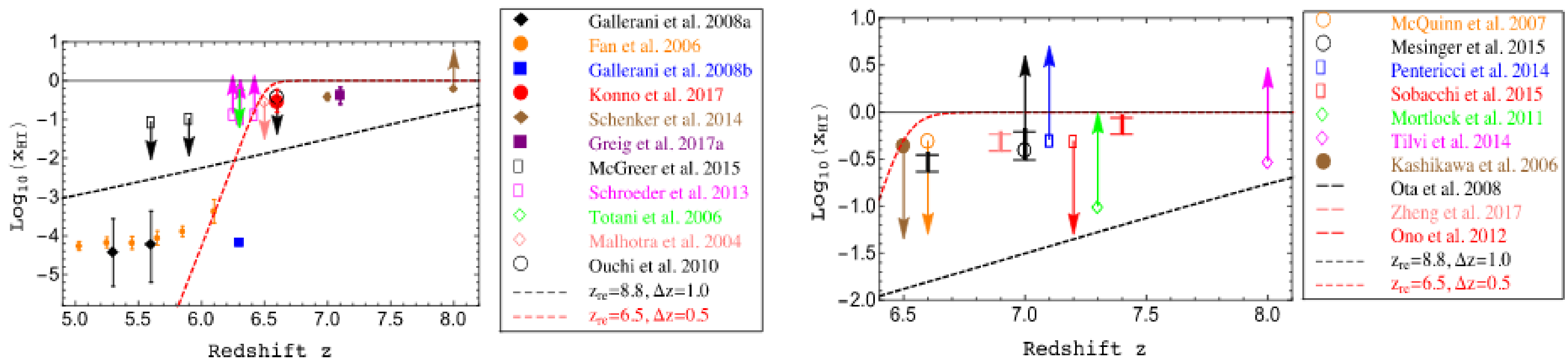


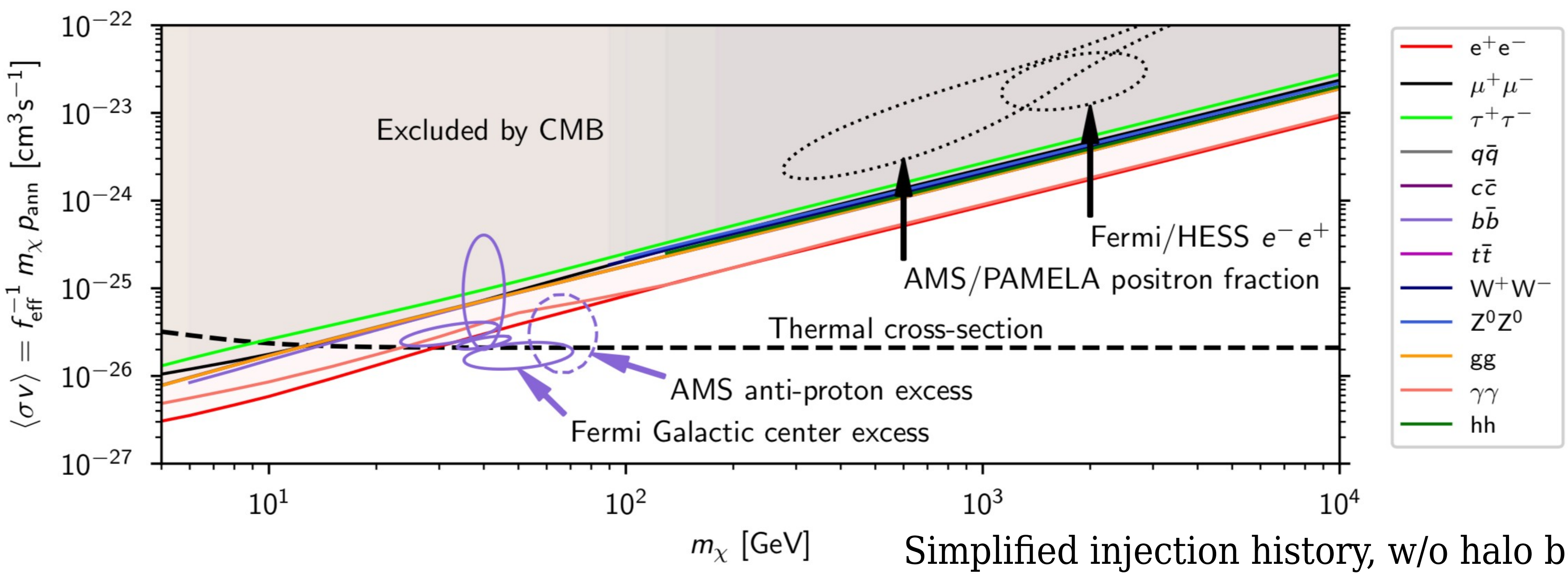
FIG. 4: The state-of-the-art measurement on $x_{\rm HI}(z)$, taken from Table I. The black and red dashed lines are two examples of the "tanh" model which cannot fit the data very well.

Wei-Ming Dai, Yin-Zhe Ma, Zong-Kuan Guo, Rong-Gen Cai PRD 99, (2019) 04352

Astrophysical energy injection has similar effects as that from DM.

Current limits: WIMP annihilation

Planck Collaboration: Cosmological parameters



Simplified injection history, w/o halo boost

Fig. 46. *Planck* 2018 constraints on DM mass and annihilation cross-section. Solid straight lines show joint CMB constraints on several annihilation channels (plotted using different colours), based on $p_{\rm ann} < 3.2 \times 10^{-28}\,{\rm cm^3\,s^{-1}\,GeV^{-1}}$. We also show the $2\,\sigma$ preferred region suggested by the AMS proton excess (dashed ellipse) and the *Fermi* Galactic centre excess according to four possible models with references given in the text (solid ellipses), all of them computed under the assumption of annihilation into $b\bar{b}$ (for other channels the ellipses would move almost tangentially to the CMB bounds). We additionally show the $2\,\sigma$ preferred region suggested by the AMS/PAMELA positron fraction and *Fermi*/H.E.S.S. electron and positron fluxes for the leptophilic $\mu^+\mu^-$ channel (dotted contours). Assuming a standard WIMP-decoupling scenario, the correct value of the relic DM abundance is obtained for a "thermal cross-section" given as a function of the mass by the black dashed line.

DM interpretations, also see
H.Liu, T. R. Slatyer, J. Zaval, 16'

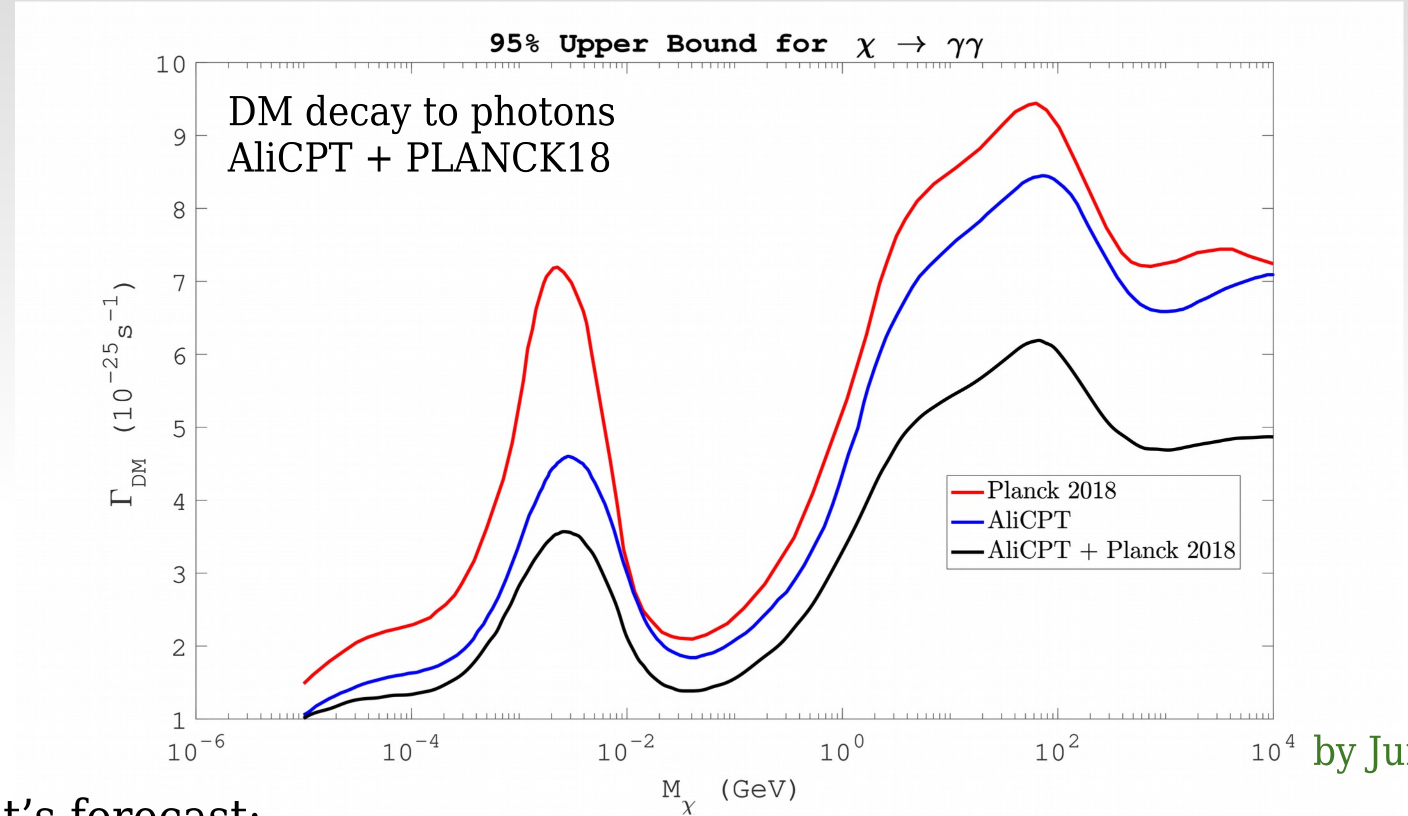
PLANCK 18:
`Cosmological parameters'

Upcoming CMB pol. experiments

实验	$\sigma_{P,v}$（μk'）	$\theta_{FWHM,v}$(')	观测频率(GHz)	参考文献 arXiv 号	实验状态
AliCPT	2.06 2.06	15.37 9.73	95 150	1710.03047	在建
AdvACTPol	7.8 6.9 25	2.2 1.3 0.9	90 150 230	1406.4794v2	运行中
CLASS	39 10 15 43	90 40 24 18	38 93 148 217	1408.4788	运行中
Simons Array	13.9 11.4 30.1	5.2 3.5 2.7	95 150 220	1502.01983	运行中
SPT-3G	6 3.5 6	1 1 1	95 150 220	1407.2973	运行中
Simons Observatory - Small Aperture Telescope	13.35 24 2.69 2.97 5.594 14.14	91 63 30 17 11 9	27 39 93 145 225 280	1808.07445	在建，预计 2020 年建成
Simons Observatory - Large Aperture Telescope	73.5 38.18 8.2 8.91 21.21 52.32	91 63 30 17 11 9	27 39 93 145 225 280	1808.07445	在建，预计 2020 年建成

+ BICEP3 data available

IHEP's contribution



by Junsong Cang

Theorist's forecast:

Stat.+ Noise

$$C_l^{CMB} + N_l + C_l^{FG} + C_l^{Others}$$

$$N_{l,f}^{EE} = \frac{l\,(l+1)}{2\,\pi}\,\omega_{EE}\,e^{l(l+1)\frac{\theta_f^2}{8ln2}} \quad (1)$$

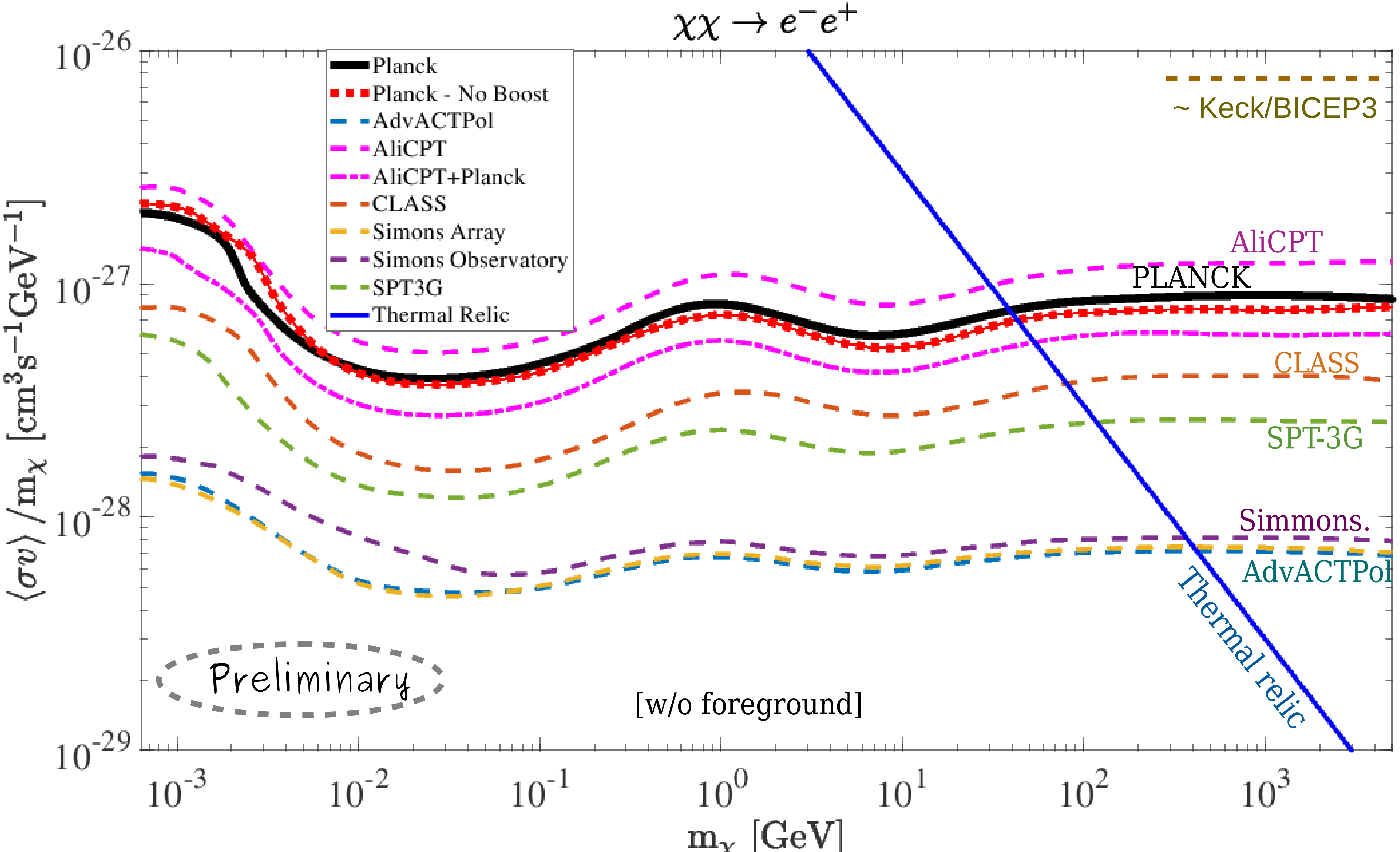
$$N_{l,f}^{TT} = \frac{l\,(l+1)}{2\,\pi}\,\omega_{TT}\,e^{l(l+1)\frac{\theta_f^2}{8ln2}} \quad (2)$$

~ 40% relative improvement from PLANCK18

Sensitivity traces energy deposit efficiency

w/o foreground, combining frequencies;
(TT TE EE) for AliCPT & PLANCK
5 year run, Noise Equiv. Temp. ~ 350 μK√s,
noise_muk_arcmin = 1.1 (T) 1.56 (E)

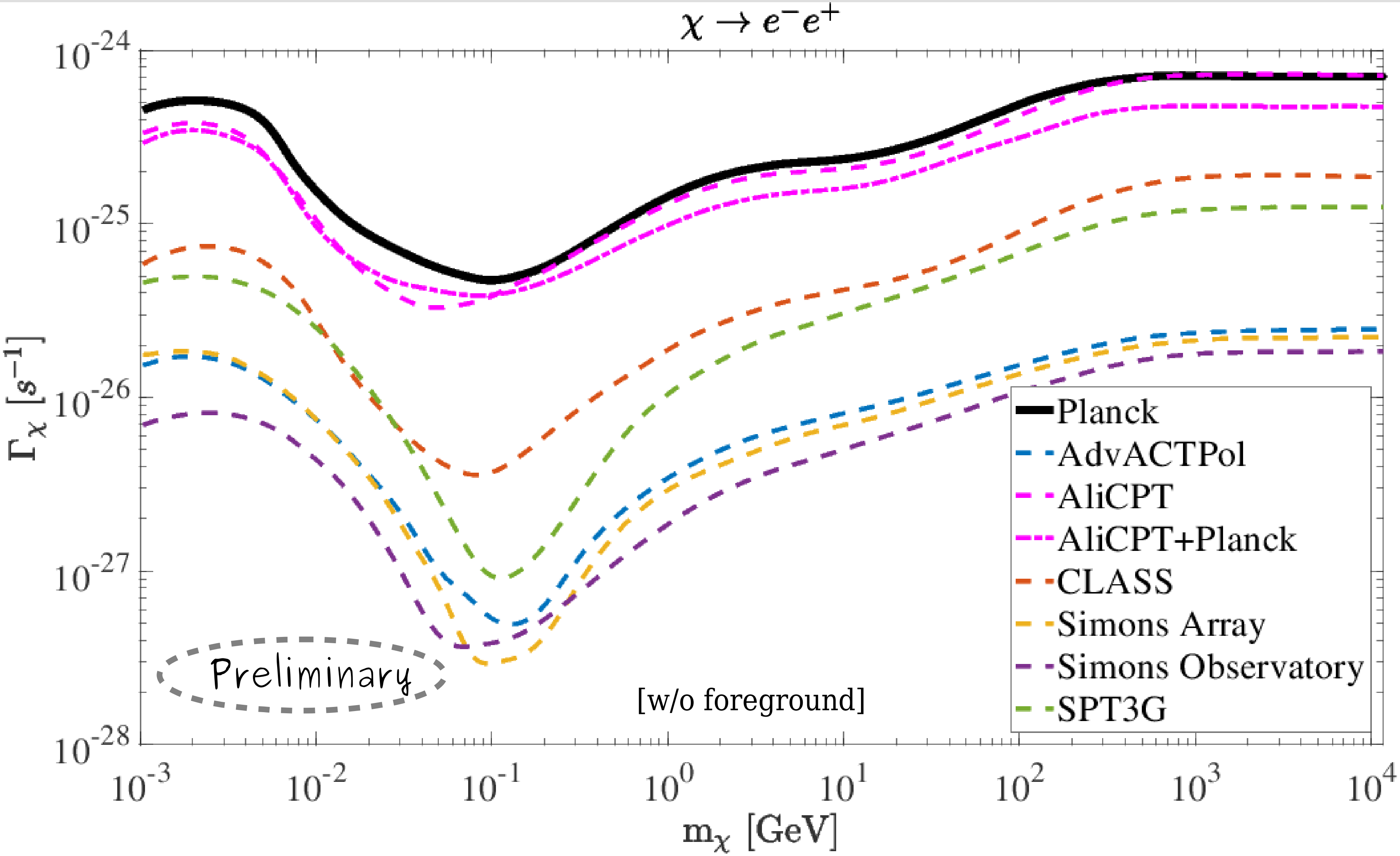
WIMP prospects: annihilation



J. Cang, Y. Gao, 1912.XXXXX.

WIMP prospects: decay (to e+e-)

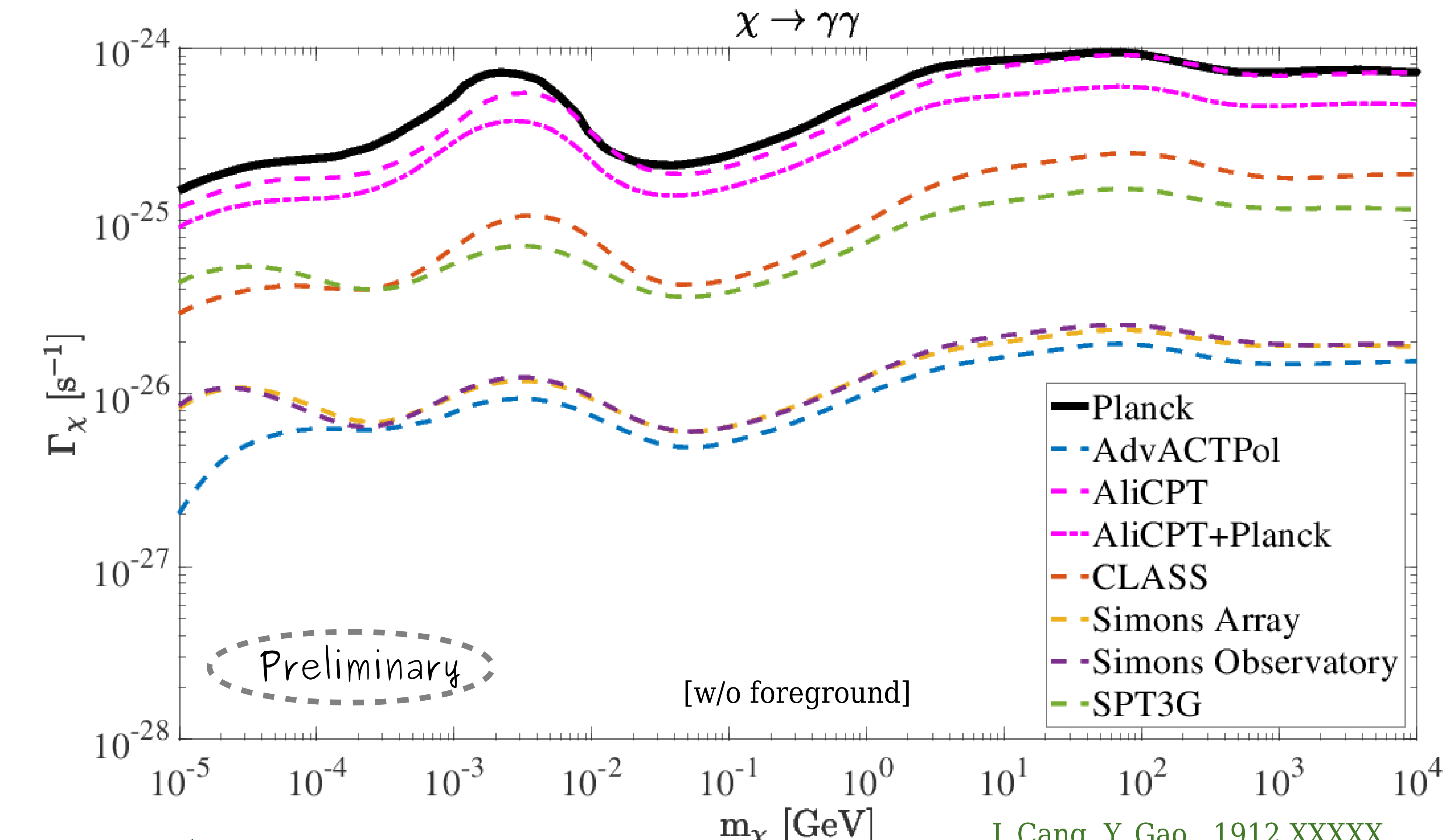
← Keck/BICEP3



Shape traces deposit efficiency

J. Cang, Y. Gao, 1912.XXXXX.

WIMP prospects: decay (to γγ)

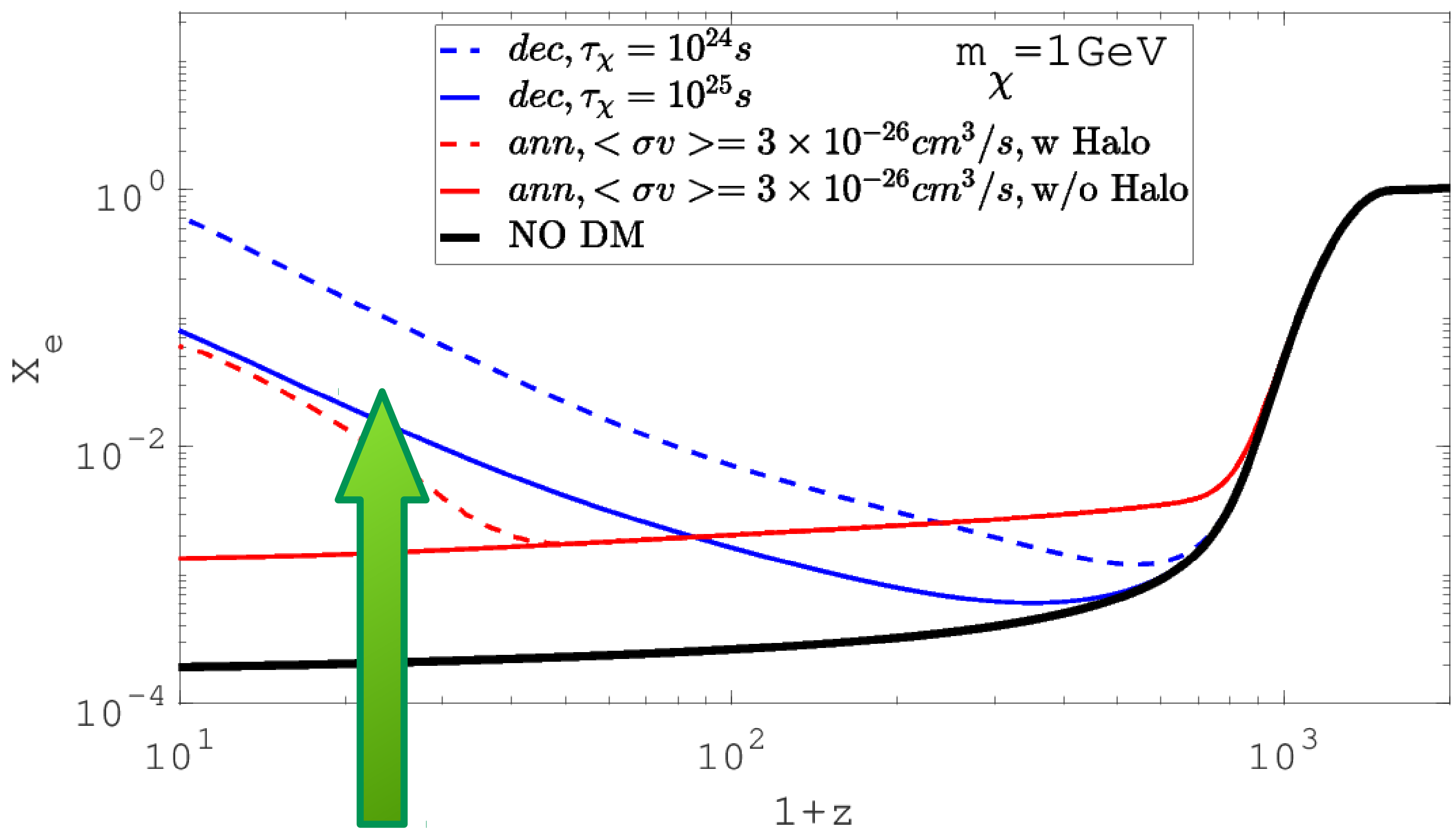


J. Cang, Y. Gao, 1912.XXXXX.

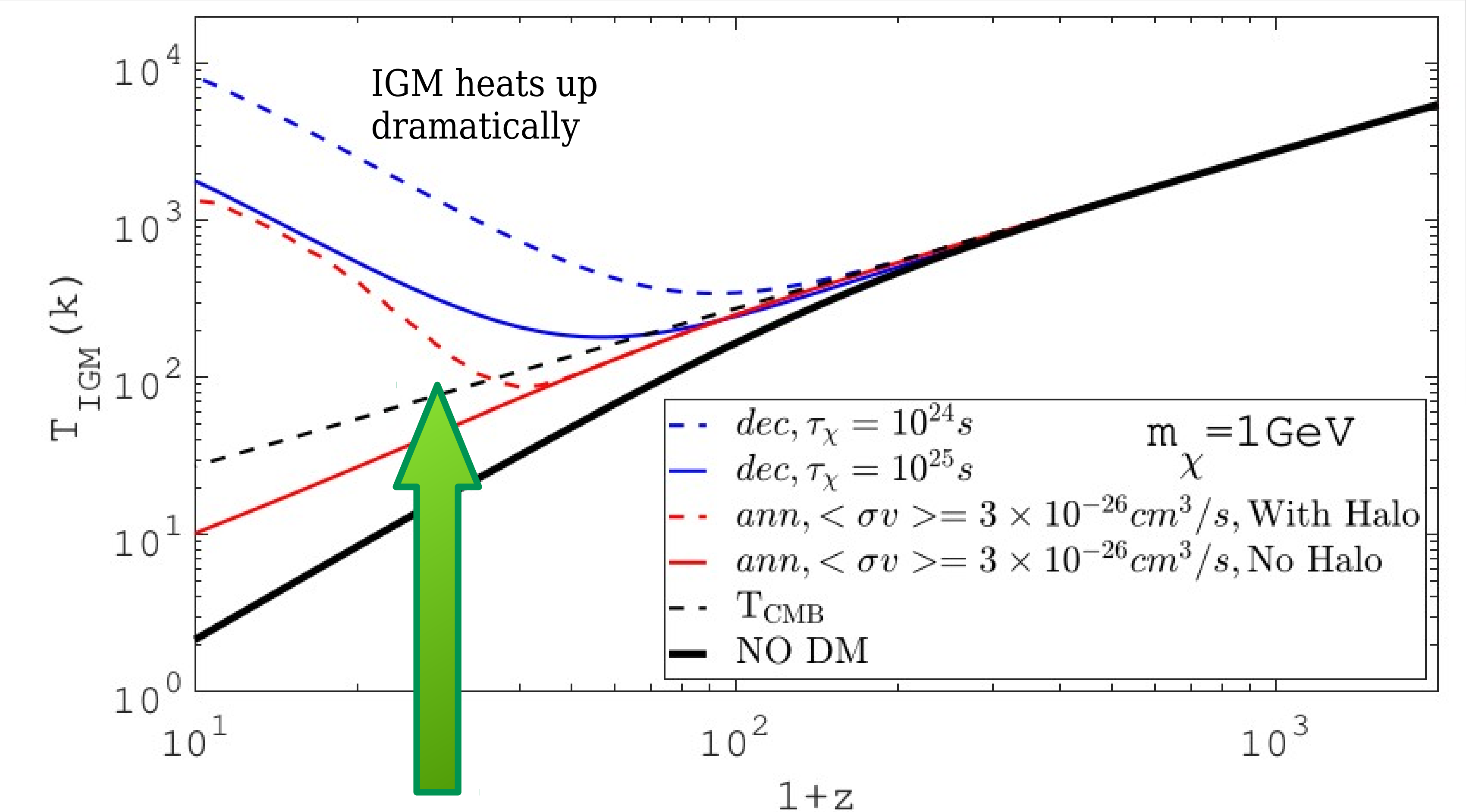
Photon channel extends to lower (~KeV) DM mass

About (E-mode) Pol. Sensitivity...

- Mostly via extra ionization.
- Breaks degeneracy in τ – looks good! ☺
- (Annihilation) Not all that sensitive to clustering boost 😐
- Due to saturation by EoR, may not fully reveal late-time rise in x_e and IGM temperature ☹



Early EoR observation will be helpful!



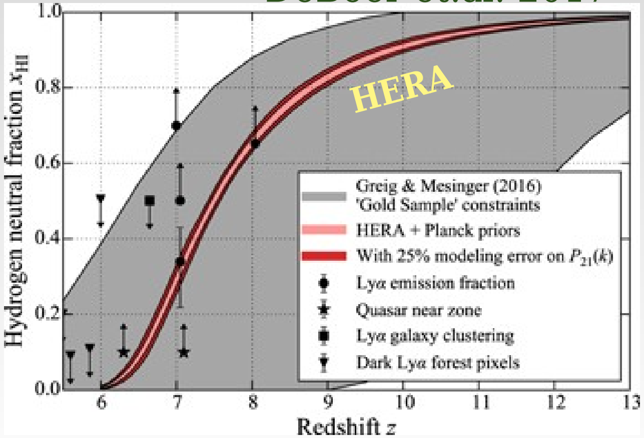
Early EoR observation will be helpful!

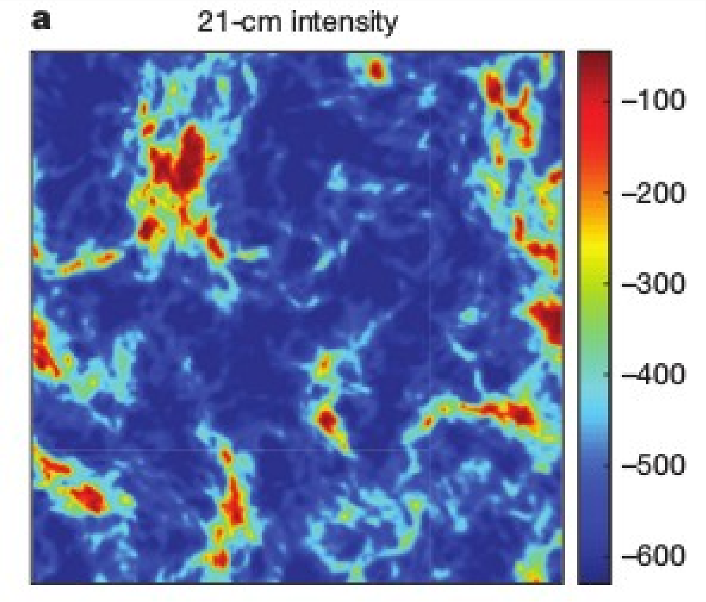
T_{IGM} ⟶ '21cm' signal

We may hear a lot from 21cm ...

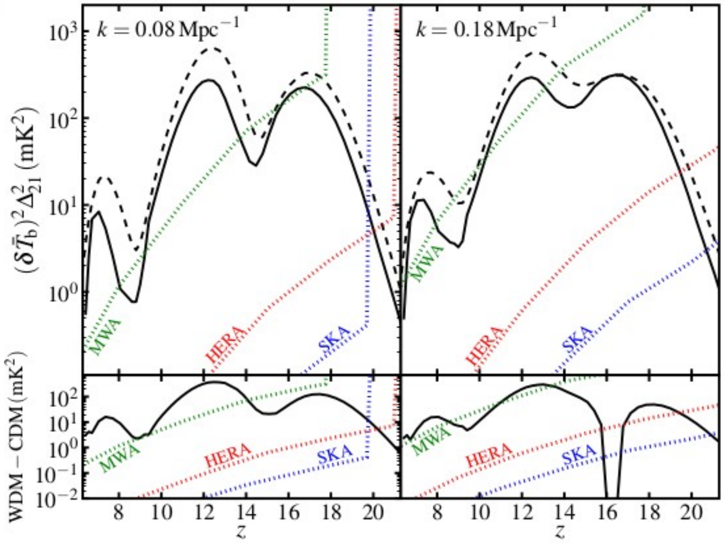
- **Precision reionization history**:
  Ionization fraction x_e, mean temperature T_G
- **Distribution of neutral Hydrogen gas**
  temperature map & power spectrum P(k)

DeBoer et.al. 2017





Simulated T21 map w DM,
Rennan Barkana, nature25791

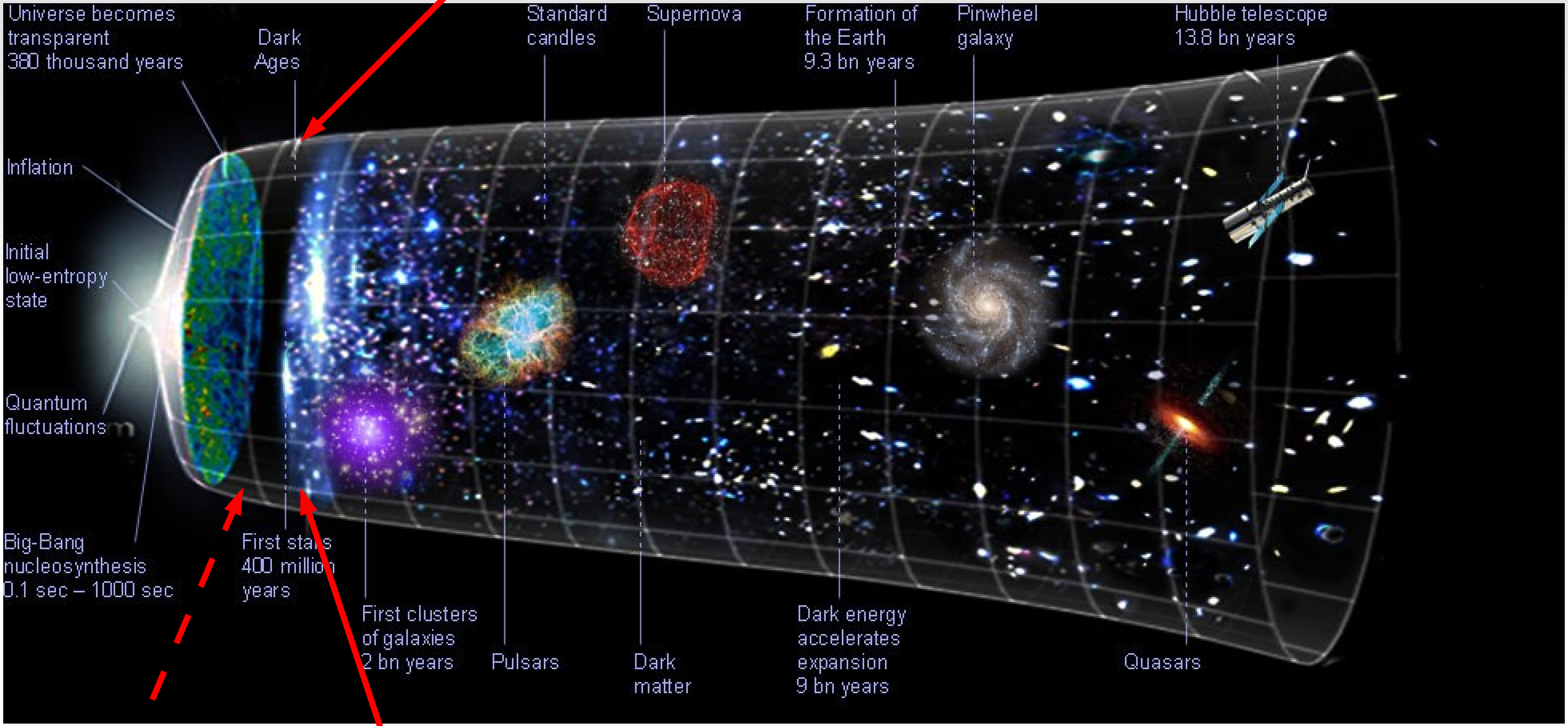


Projected power spectrum sensitivities
(from SKA white paper)

CMB's 21cm absorption needs:

(1) neutral Hydrogen presence (2) T_s cooler than CMB

Dark age window



Picture from: 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).

T_{21} dependencies...

- 21cm brightness relies on IGM temperature evolution
- Direct x_e, T measurements.

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

ionization

Gas density distribution

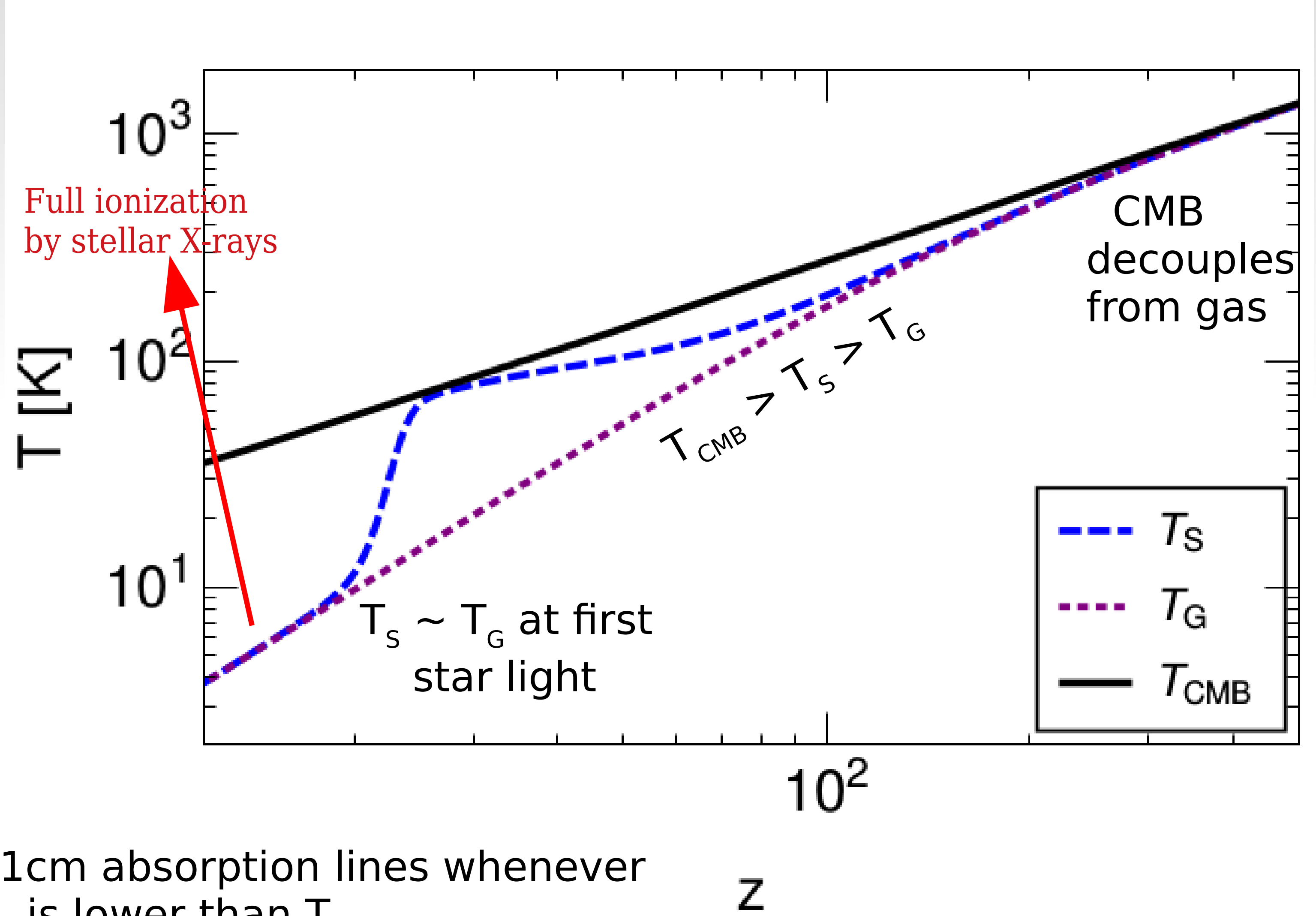
Cosmological model

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

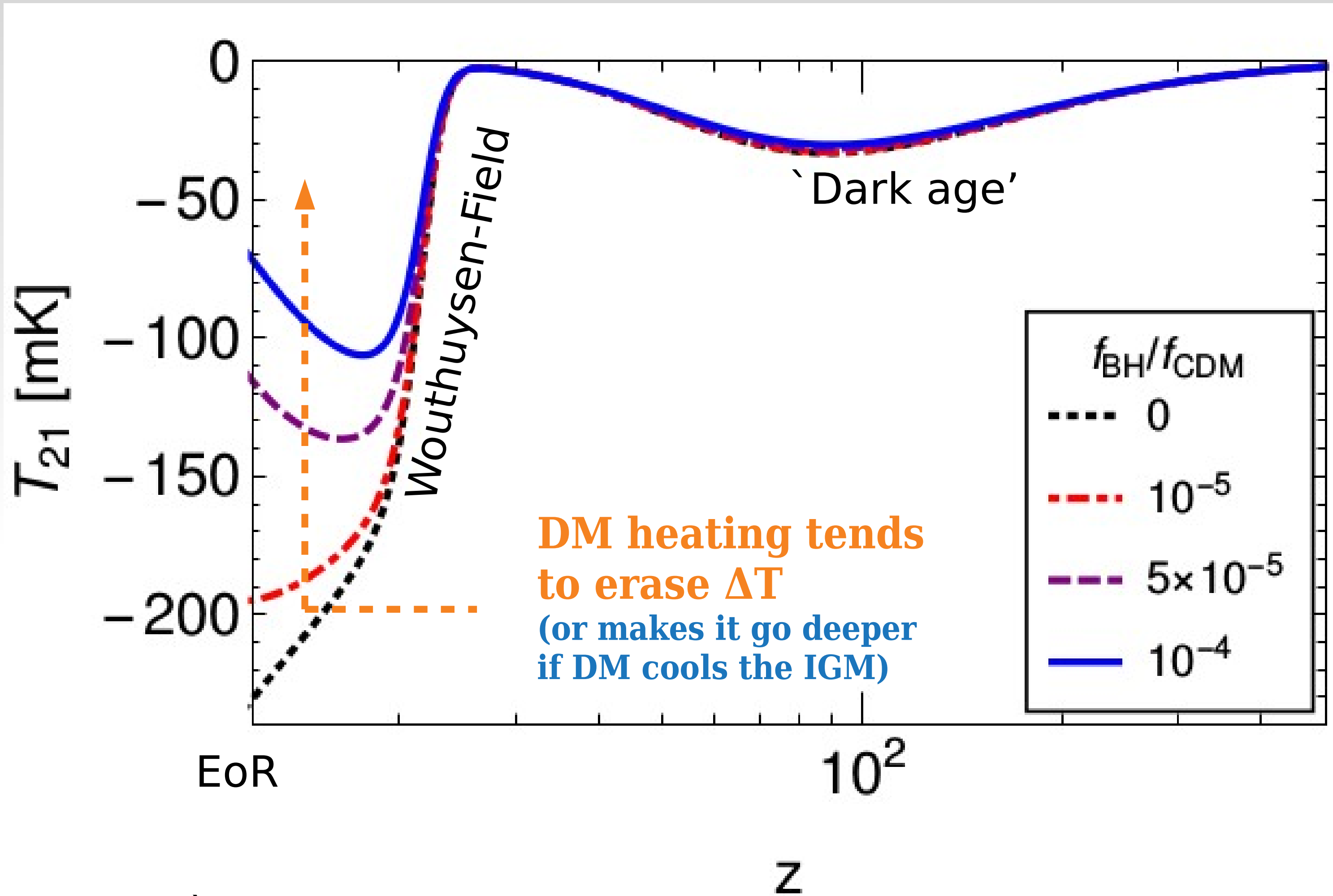
Gas spin temperature against bkg (CMB)

T_S~T_{IGM} at cosmic dawn

Temperature evolution



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



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

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

EDGES: First claim of 21cm

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

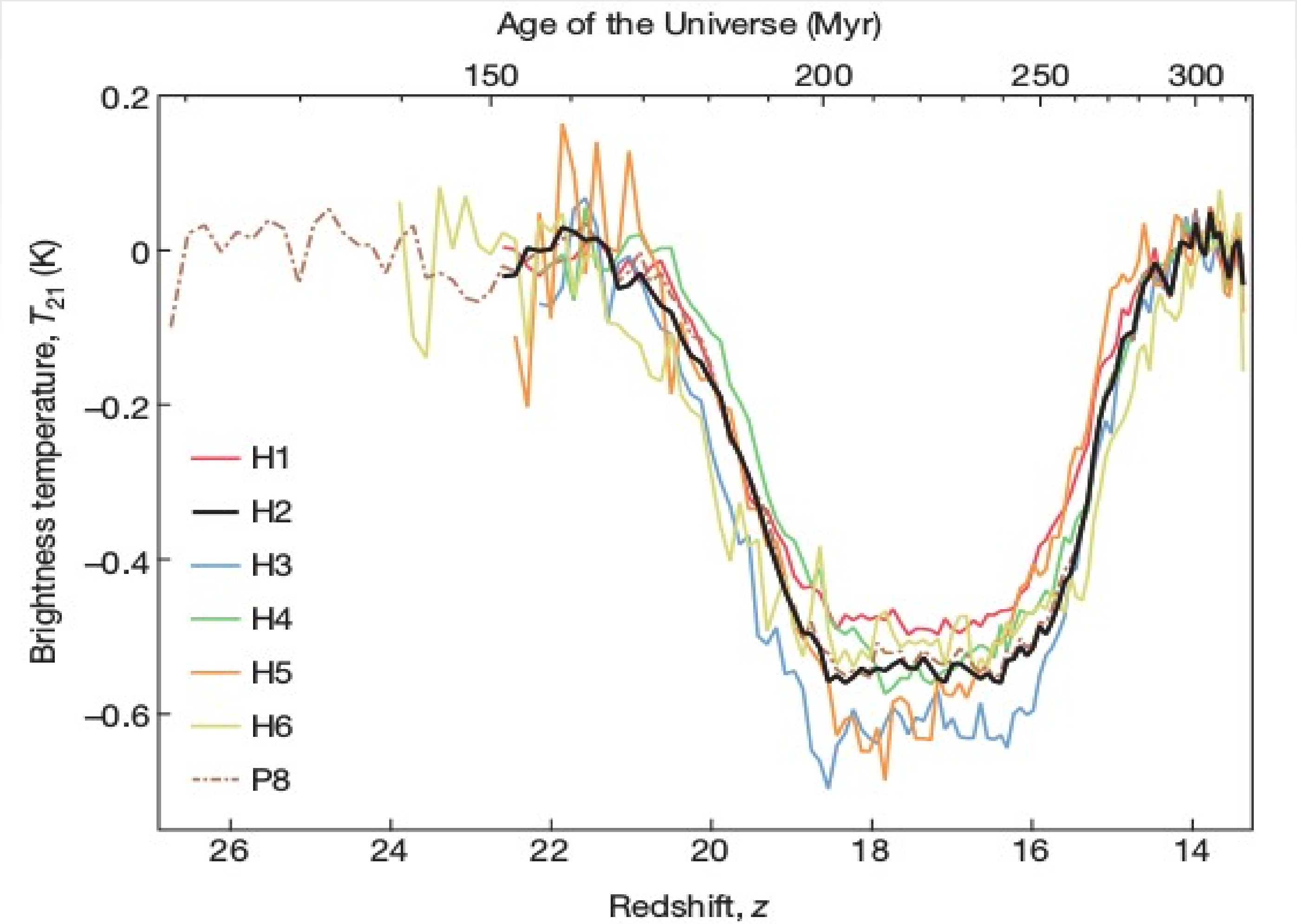
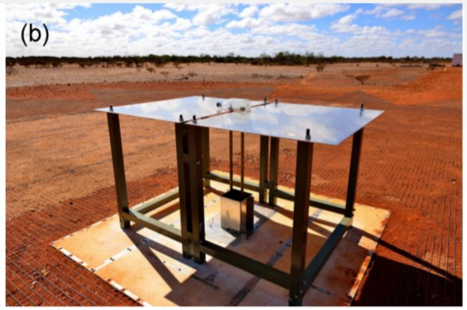


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.



EDGES: A Discovery near 78 MHz?

Freq.= 1420 MHz / (1+z)

~Twice the predicted signal !

WIMP involvement?

DM cooling
(DM is cooler)

Lower gas temperature via collisions: more 21cm signal

Explains the EDGES data
*needs large scattering xsec

DM heating
(DM injects energy)

Raises gas temperature by energy injection: reduces 21cm signal

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

Yeah

Nay

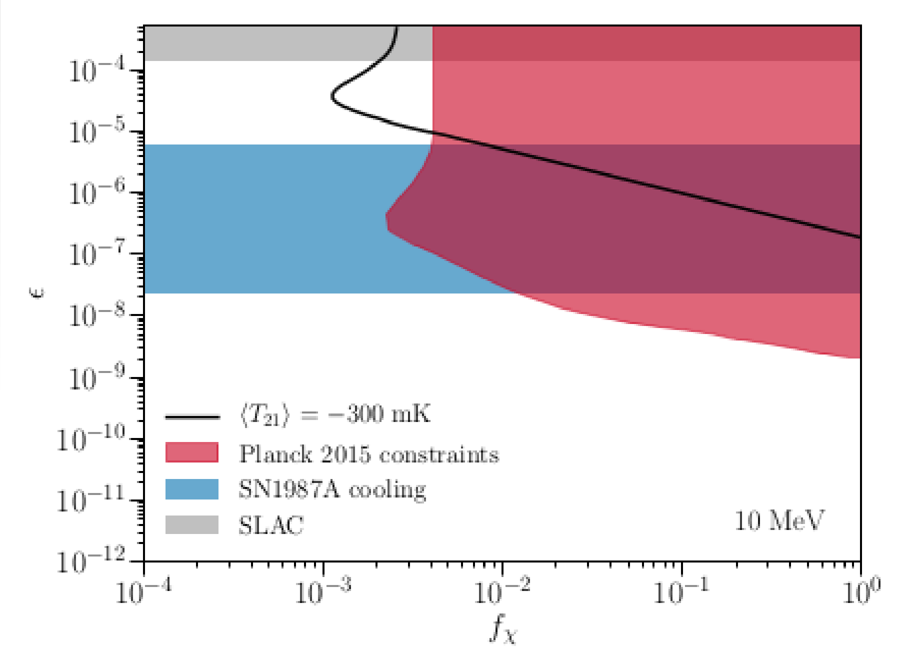
CMB uncertainties

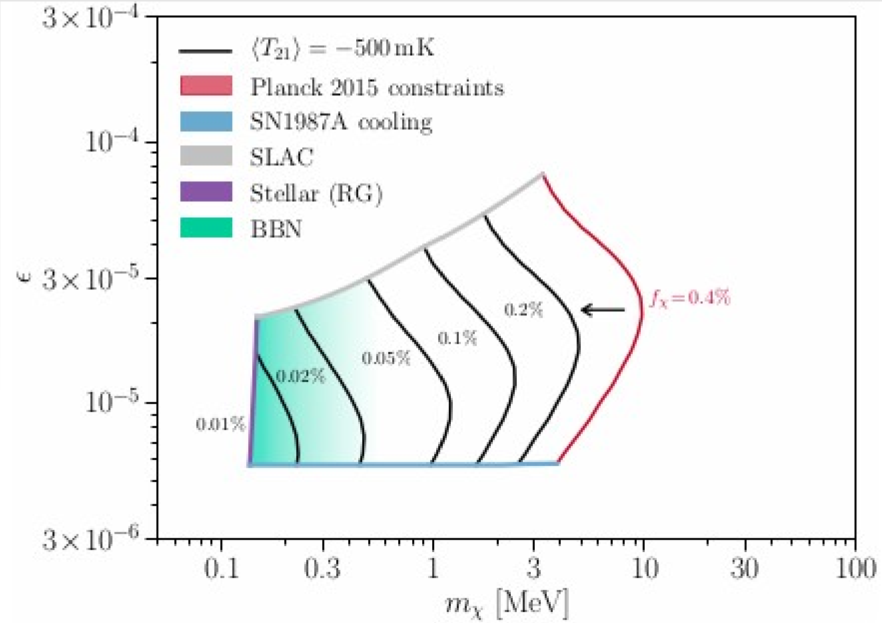
Large uncertainty at low frequency;
radio-frequency
new physics, like ALP

Non-standard cosmology

Modified Friedmann Eq.

WIMP cooling as an explanation to the EDGES data





Milli-charged DM constrained to MeV range and
tiny (<1%) fractions of relic density E.D.Kovertz, et.al. 18'

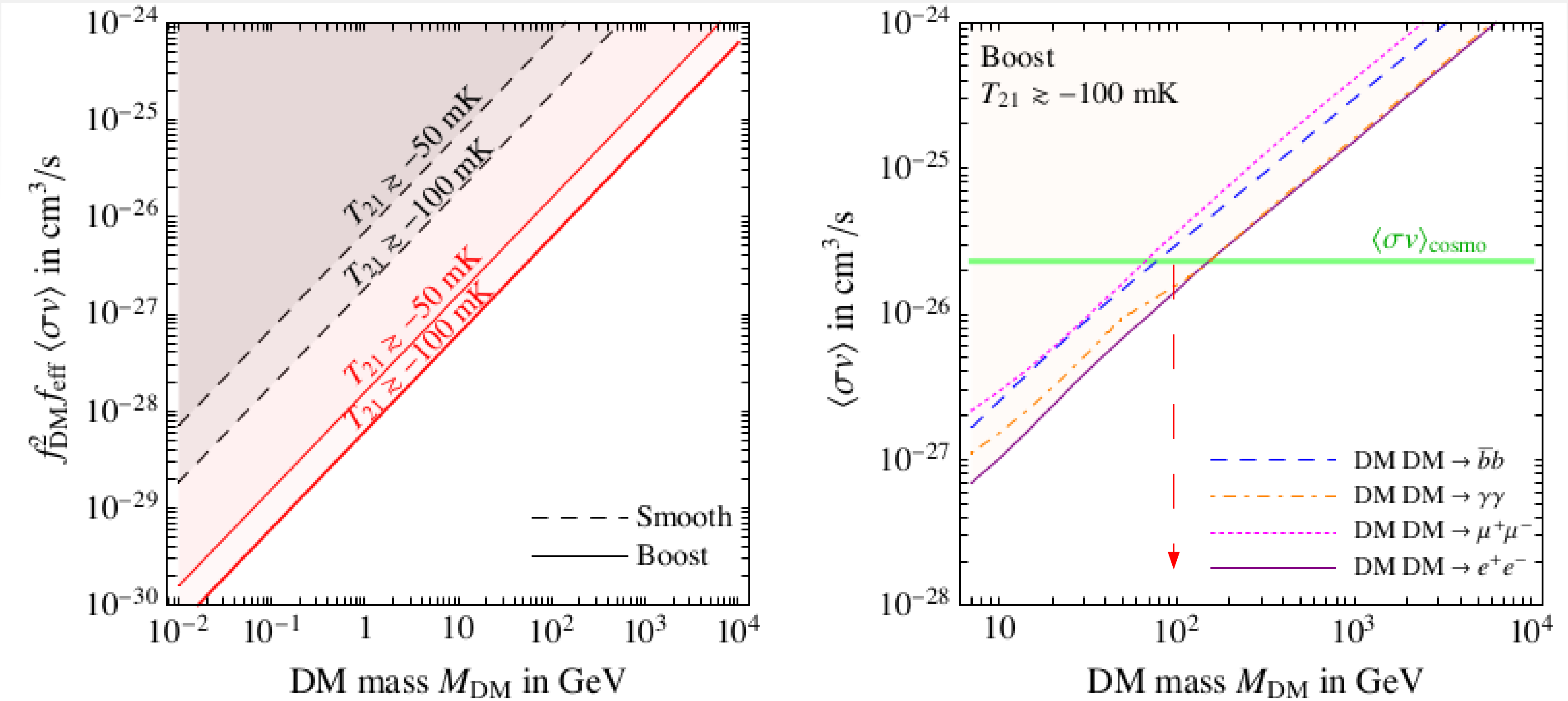
* subleading abundance is OK if millicharged DM also has long-range force with the rest of DM (H.Liu, Outmezguine, Redigolo, Volansky 1908.06986)

Discovering 21cm means a WIMP constraint

On DM annihilation rates:
by requiring injection induced
$\Delta T_{21} < +100$ or $+150$ mK

G. D'Amico, P. Panci, A. Strumia 18'

Excluding vanilla thermal wimp below 10^2 GeV?

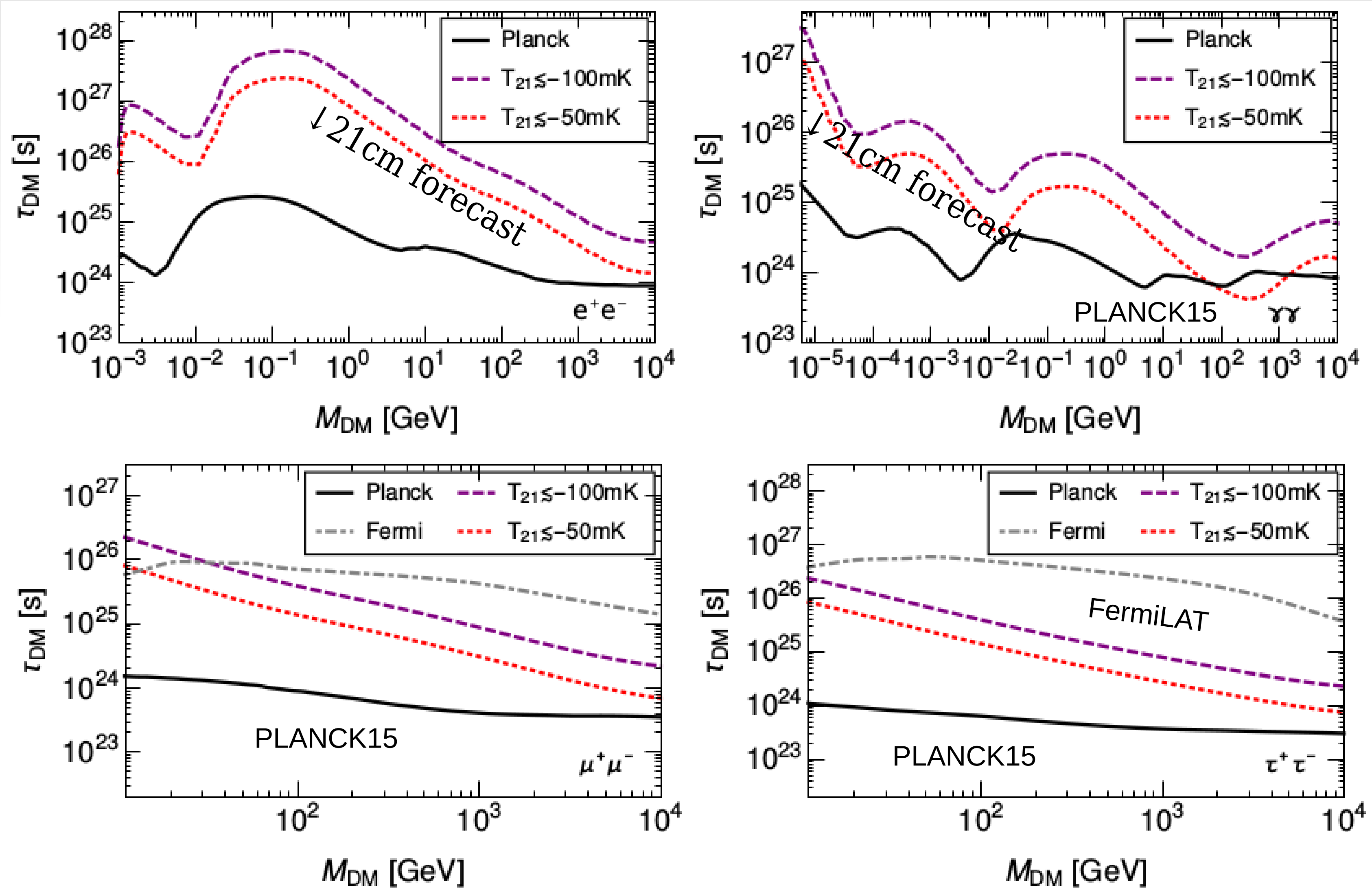


Unlike CMB pol., 21cm is **VERY sensitive** to DM clustering boost

WIMP lifetime bound @ 21cm discovery

Limit on T_{GAS} rise:
ΔT_{21} < +100 or +150 mK at z=17

S.Clark, B.Dutta, Y.Gao, Y.-Z.Ma, L.E.Strigari, 18'



Decay: unaffected by clustering.

Summary

CMB Pol. anisotropy

* sensitive to ionization
* degenerate to EoR
* C_l sensitive to higher-z effects
* Great improvement from TT-alone
* Not very sensitive to clustering
* Discovered – precision obs.
* Derived effects from xe, T

Global 21cm signal (Dawn)

* sensitive to IGM temperature
* breaks EoR degeneracy
* sensitive to clustering
* HUGE foreground ($> 10^5$)
  – signal not confirmed yet
* Direct xe, T measurement

Common features:

* Based on energy deposits
* Wide WIMP mass range coverage (esp. btw X-ray and γ-ray)
* Future sensitivity to weak scale WIMP annihilation
* VERY tight limits on **long-lifetime** visible WIMP decays
* **Rosy prospects** from future radio-astro experiments.