Testing Dark Matter Energy Injection in CMB measurements

& an AliCPT connection

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AliCPT symposium,
BNU 2019/09/07

- Dark matter impact on ionization/temperature
- CMB polarization as a good probe
- Experimental sensitivities

Dark Matter as a source of energy injection

- Extra amount of energy after/during recombination

Annihilation: Energy injection rate per unit time

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

Decay: relatively more energy injection at lower redshift

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

Primordial Black holes: evaporation at a near-constant rate similar to decay with relatively soft radiation energy

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

Energy deposit effects: ionization & heating

- Raises ionization fraction

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

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

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

- Raises IGM temperature

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

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

- Affects visibility function:

Correlation attenuation (esp. at large *l)*
Peak shifts in polarization spectra

Padmanabhan, Finkbeiner, 05

Acoustic & temperature peaks are less affected

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:

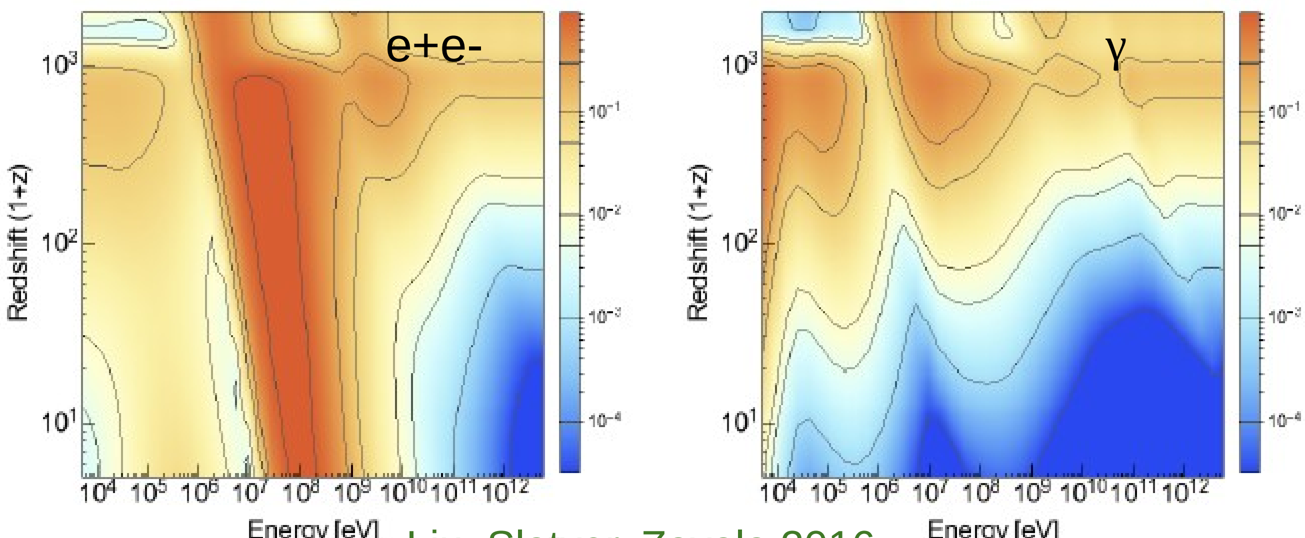
* accumulative over earlier injection
* efficiency reduces at later time

Numerical calculation

Implemented into **HyRec** codes:

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

Energy “fraction” into ionization (of H)



Liu, Slatyer, Zavala 2016

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

The cosmic ionization history

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

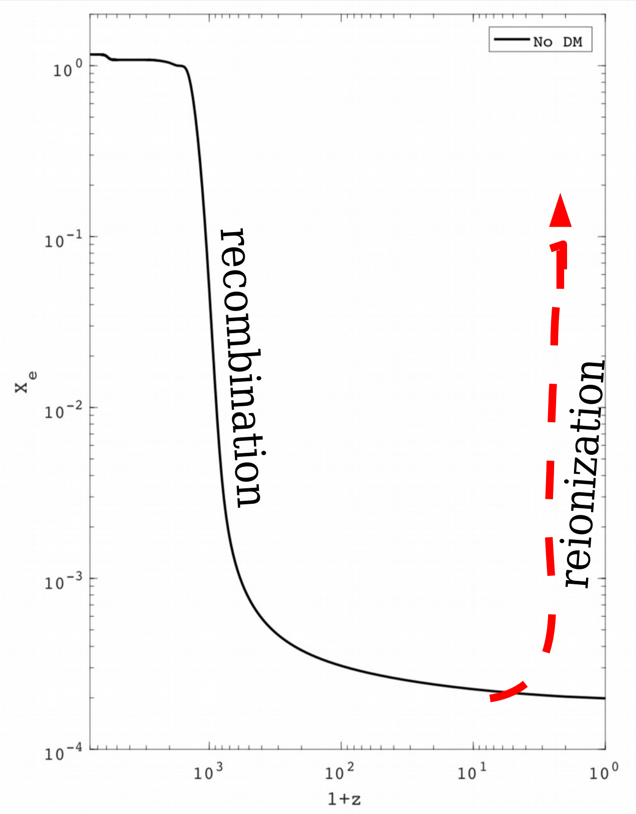
$$\frac{dX_e}{dt} = \left\{(1 - X_e)\beta - X_e^2 n_b \alpha^{(2)}\right\}$$

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 $\alpha^{(2)} = 9.78 \frac{\alpha^2}{m_e^2} \left(\frac{\epsilon_0}{T}\right)^{1/2} \ln\left(\frac{\epsilon_0}{T}\right)$



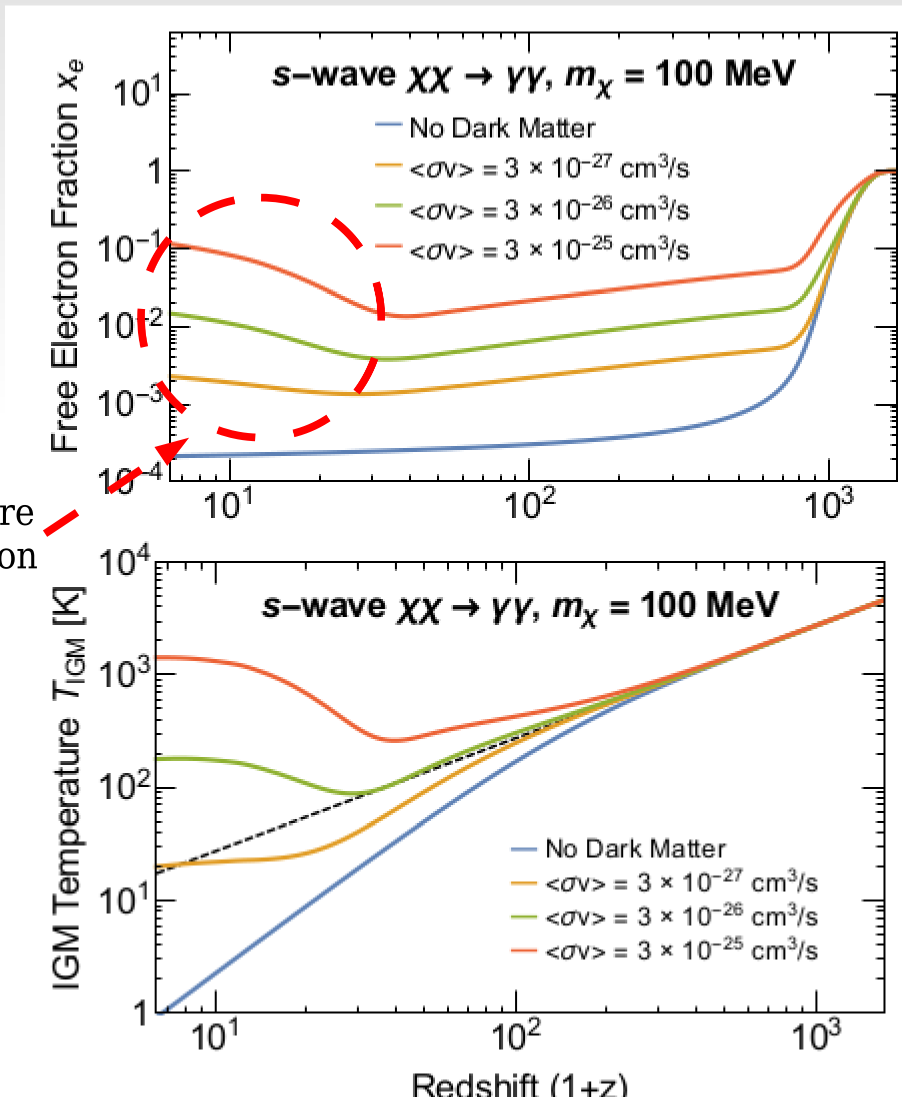
x_e reduces to a 10^{-4} floor during the cosmic dark age and returns to unity @EoR

Ionization fraction & temperatures

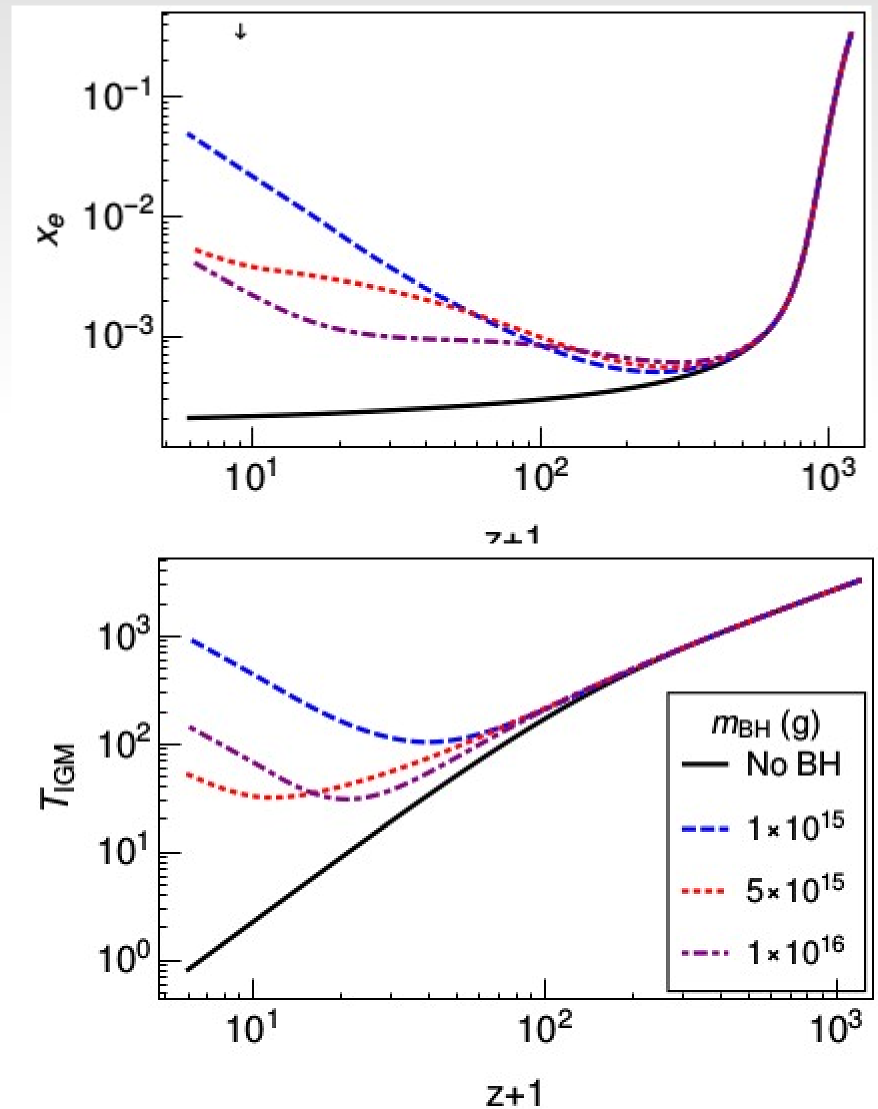
[*Exaggerated for illustration*]
Reionization not shown

Annihilation raises the x_e floor,
decay attends to be more important at low z

Structure formation boost



Liu, Slatyer, Zavala 2016



More free electrons: the CMB Cls

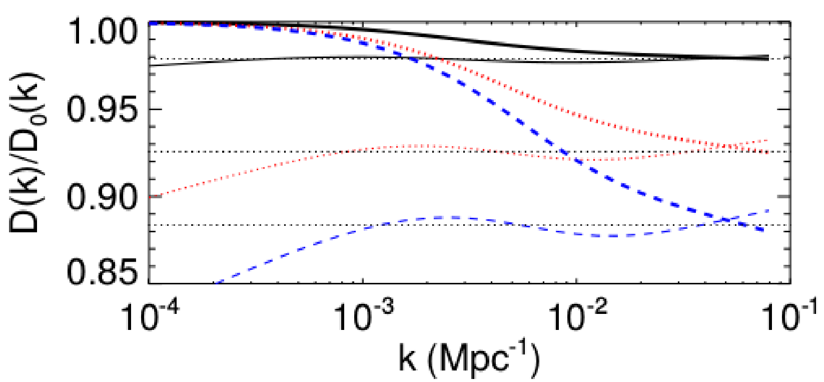
Increased ionization enhances photon scattering

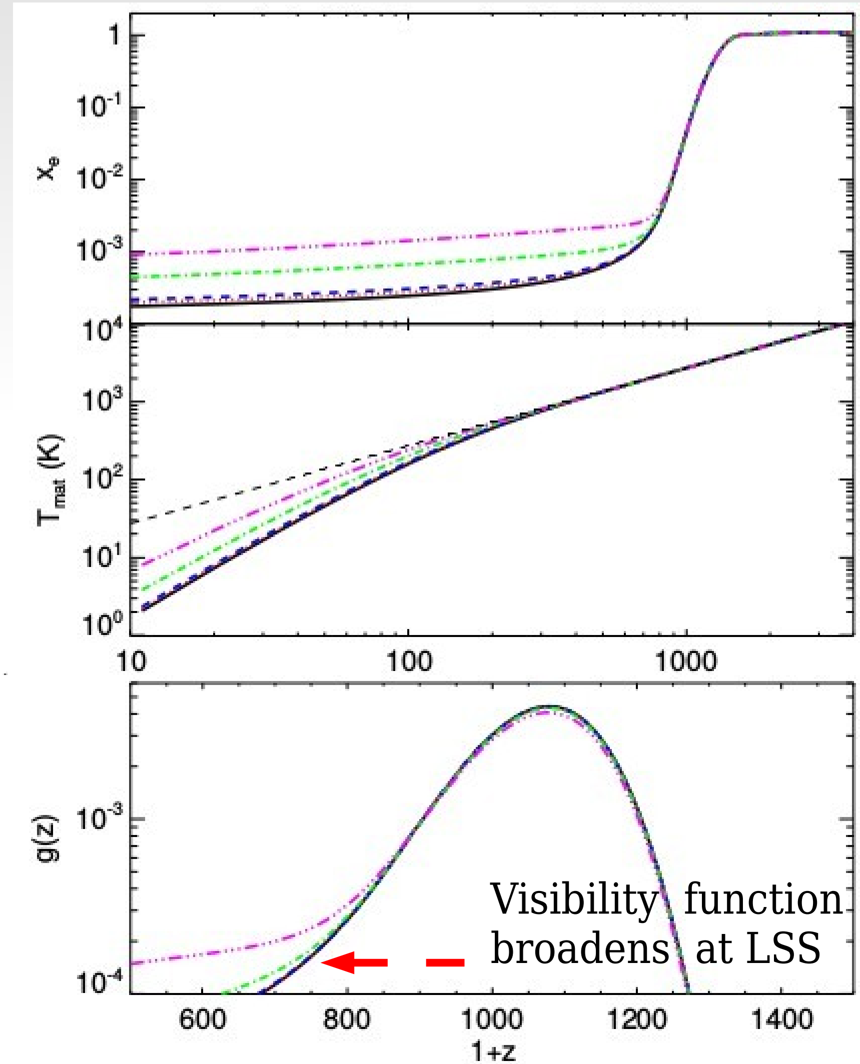
$$C_l = 4\pi A \int_0^\infty d(\ln k)\, k^{n_s} D^2(k) T^2(k)$$

And affects the damping function:

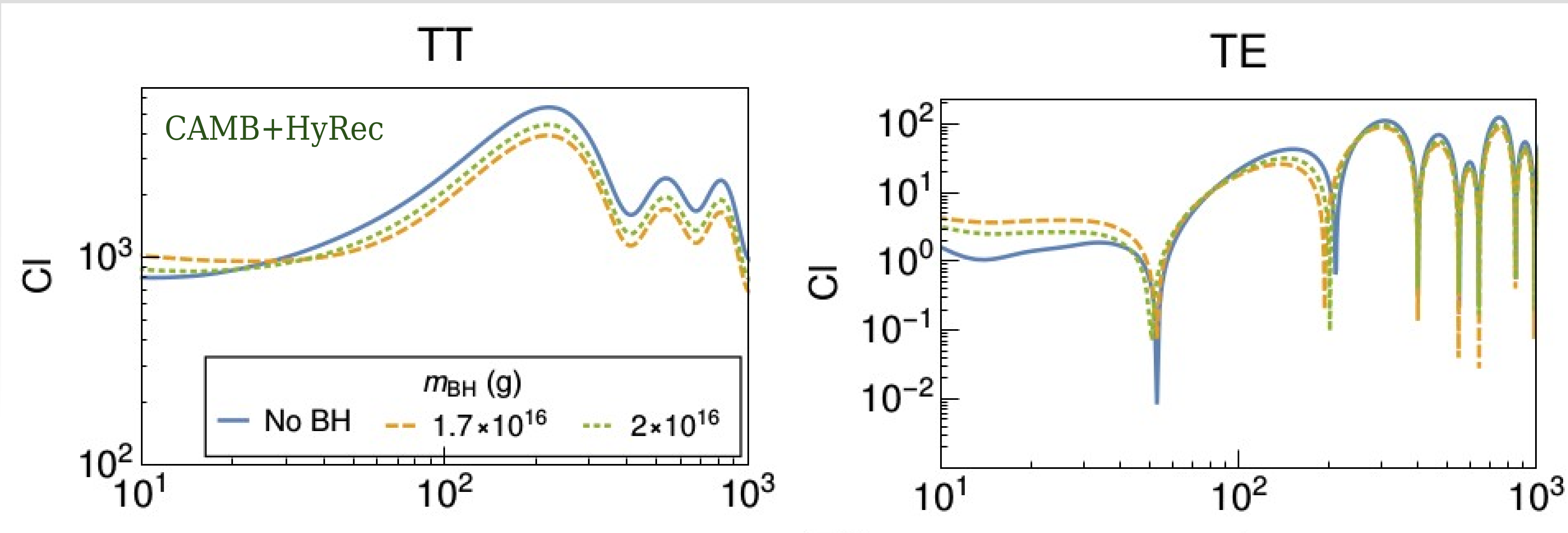
$$D(k) = \int dz\, g(z) \exp\left(-\frac{k^2}{k_D^2(z)}\right)$$

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



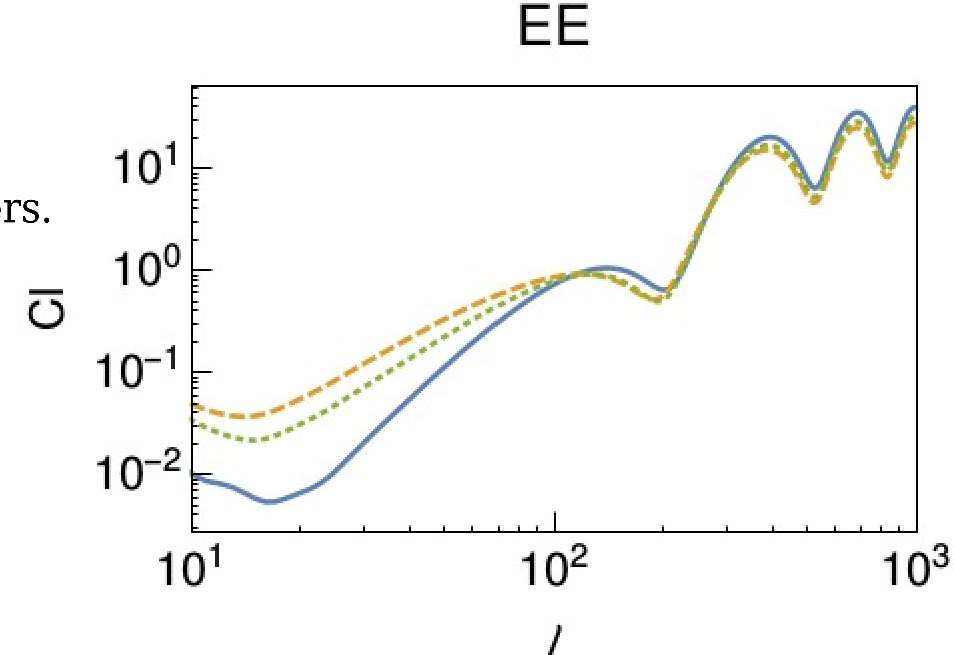


Impact on the CMB Cls



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

* more damping

Current limits: WIMP annihilation

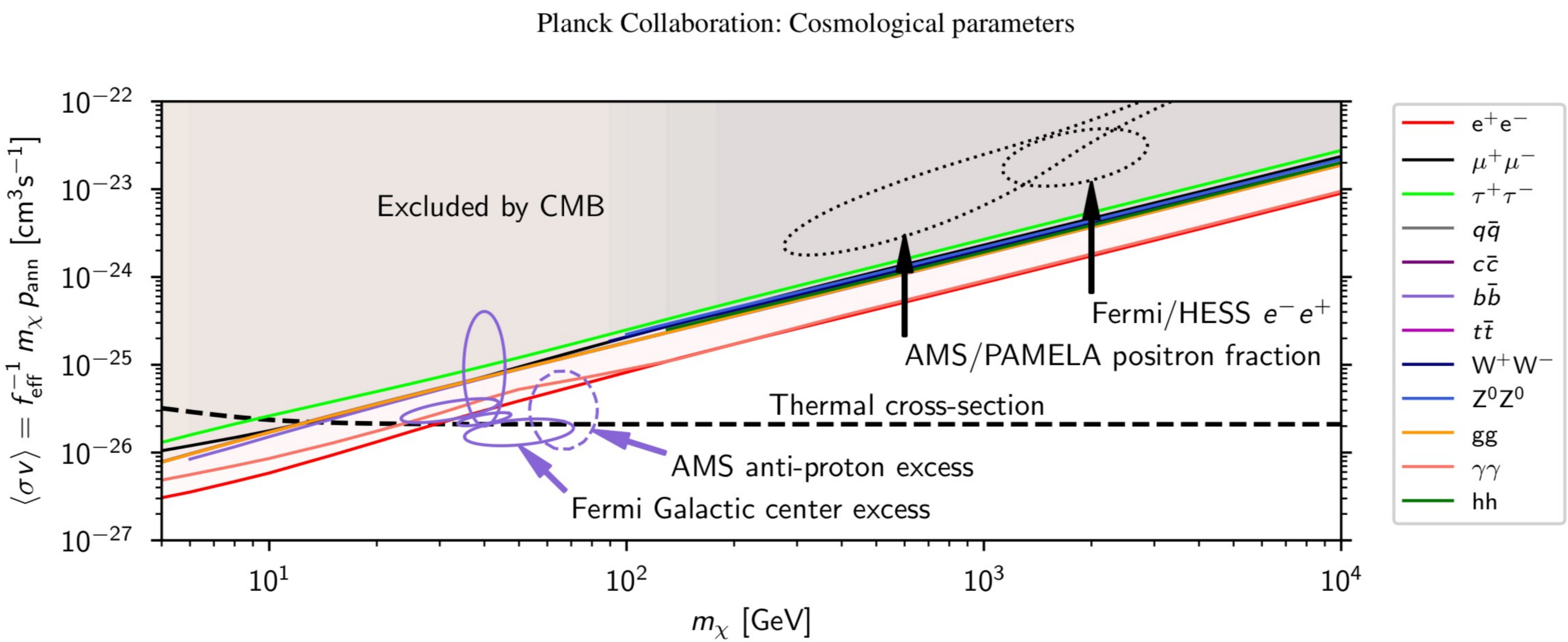
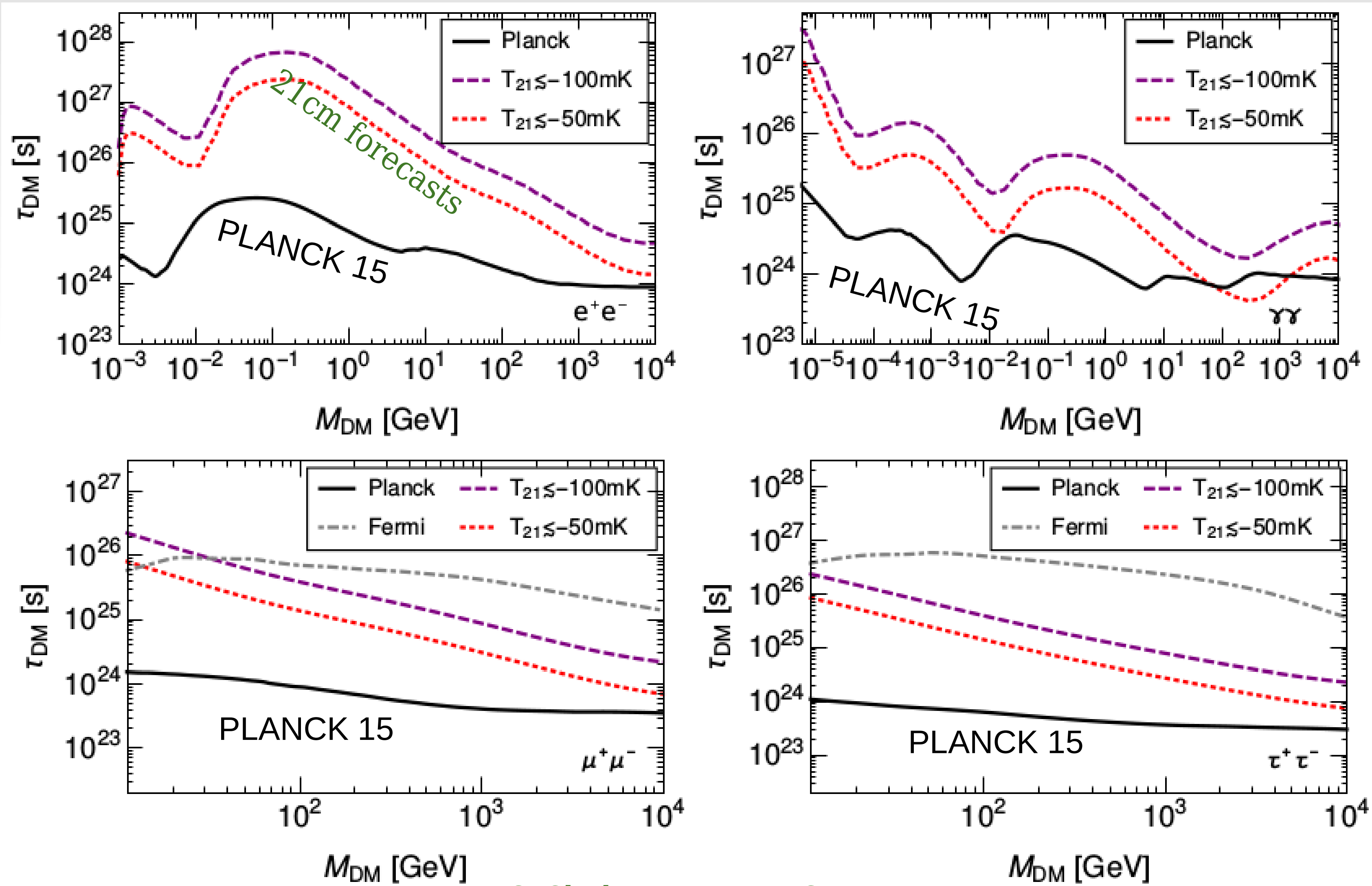


Fig. 46. *Planck* 2018 constraints on DM mass and annihilation cross-section. Solid straight lines show joint CMB constraints on several annihilation channels (plotted using different colours), based on $p_{\rm ann} < 3.2 \times 10^{-28}\,{\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-1}$. We also show the $2\,\sigma$ 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.

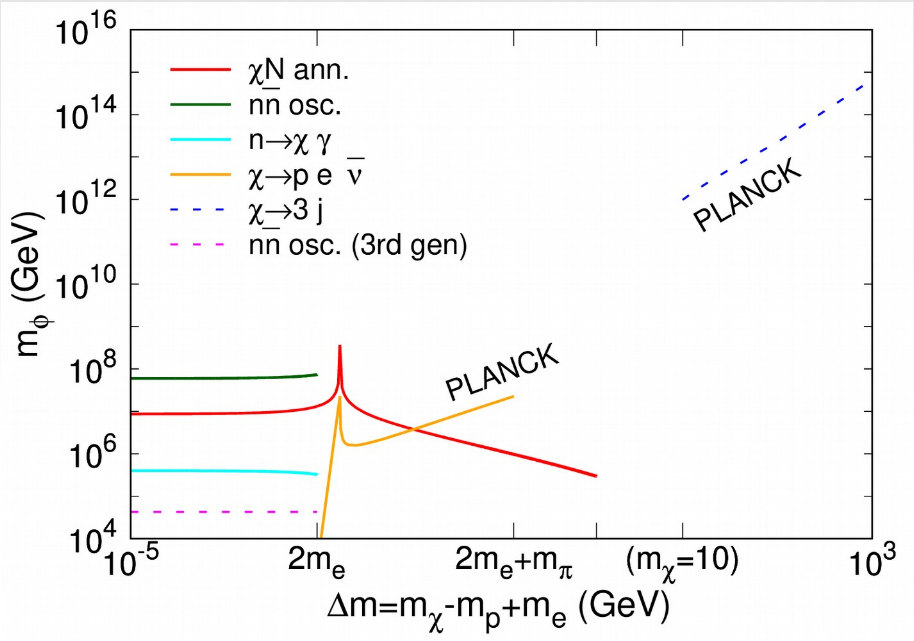
PLANCK 18

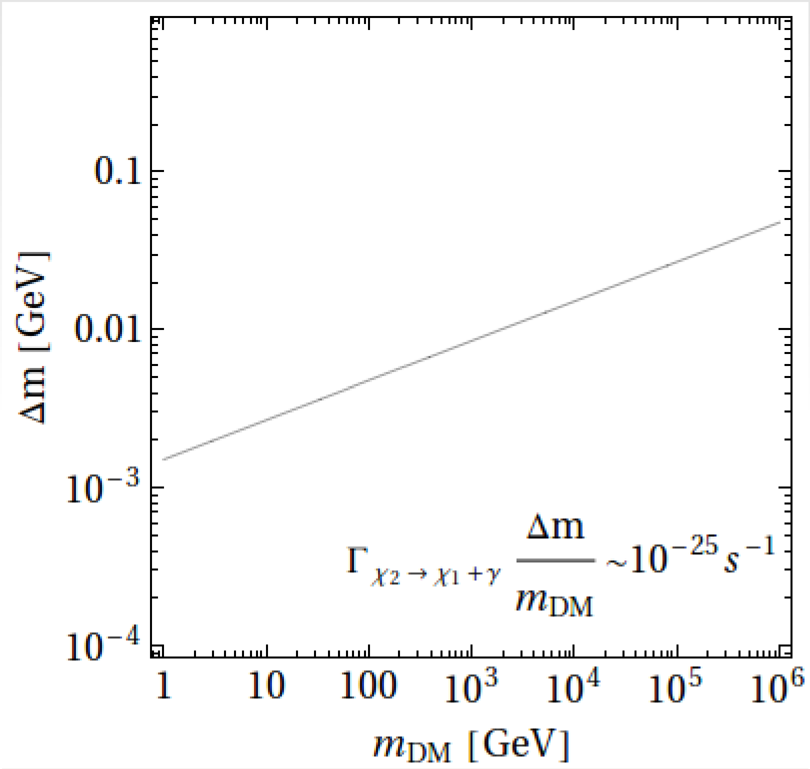
Limits on DM decay lifetime

* ← **3.5 KeV line: allowed**



S. Clark, B. Dutta, Y. Gao, Y.-Z. Ma,
L.E.Strigari, PRD98(2018) no.4, 043006





Non-symmetry protected
`dark' fermion decays:

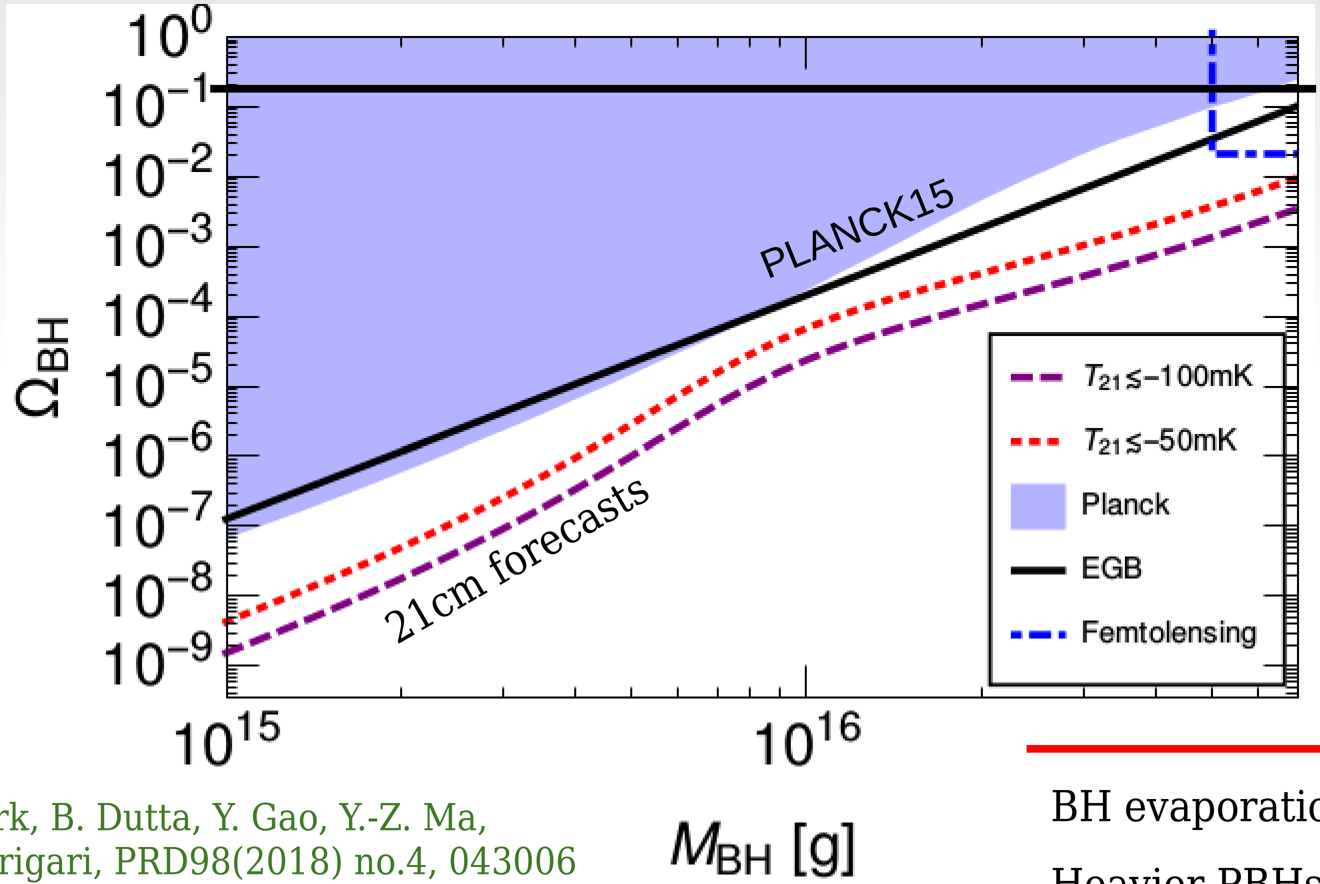
Leading limits for dim-6
$\mathbf{\Lambda^{-2}Nqqq}$ Baryon Number
Violating ($\mathbf{\Delta B}$=1) decay

M. Jin, Y. Gao, PRD 98 (2018) no.7, 075026

Dim-5 operator $\mathbf{\Lambda^{-1}}\bar{\chi}\sigma_{\mu\nu}\chi' F^{\mu\nu}$
decay $\chi\to\chi' + \gamma$:

$\Lambda > 10^{19}$ GeV for
MeV+ mass dark matter

Limit on primordial black holes



relic density

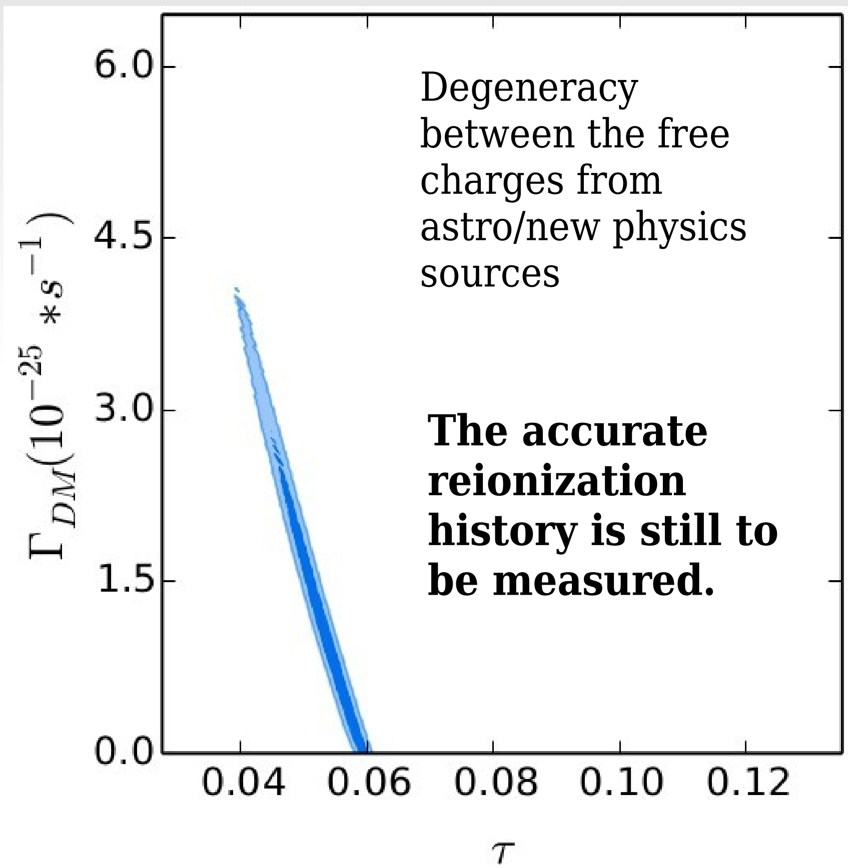
S. Clark, B. Dutta, Y. Gao, Y.-Z. Ma, L.E.Strigari, PRD98(2018) no.4, 043006

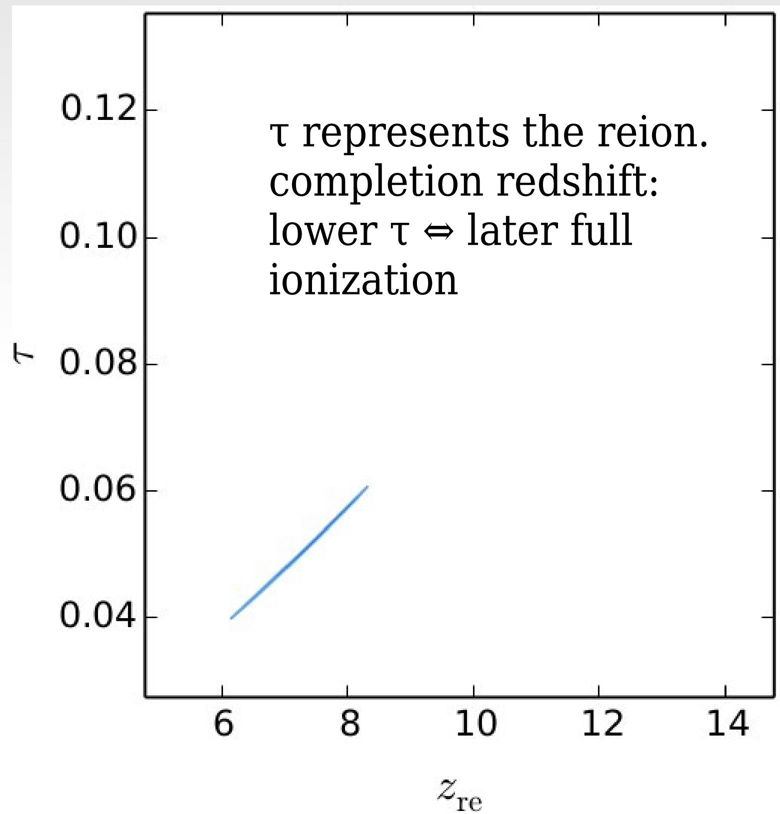
BH evaporation rate ~M^{-3}

Heavier PBHs are too cold to emit electrons;

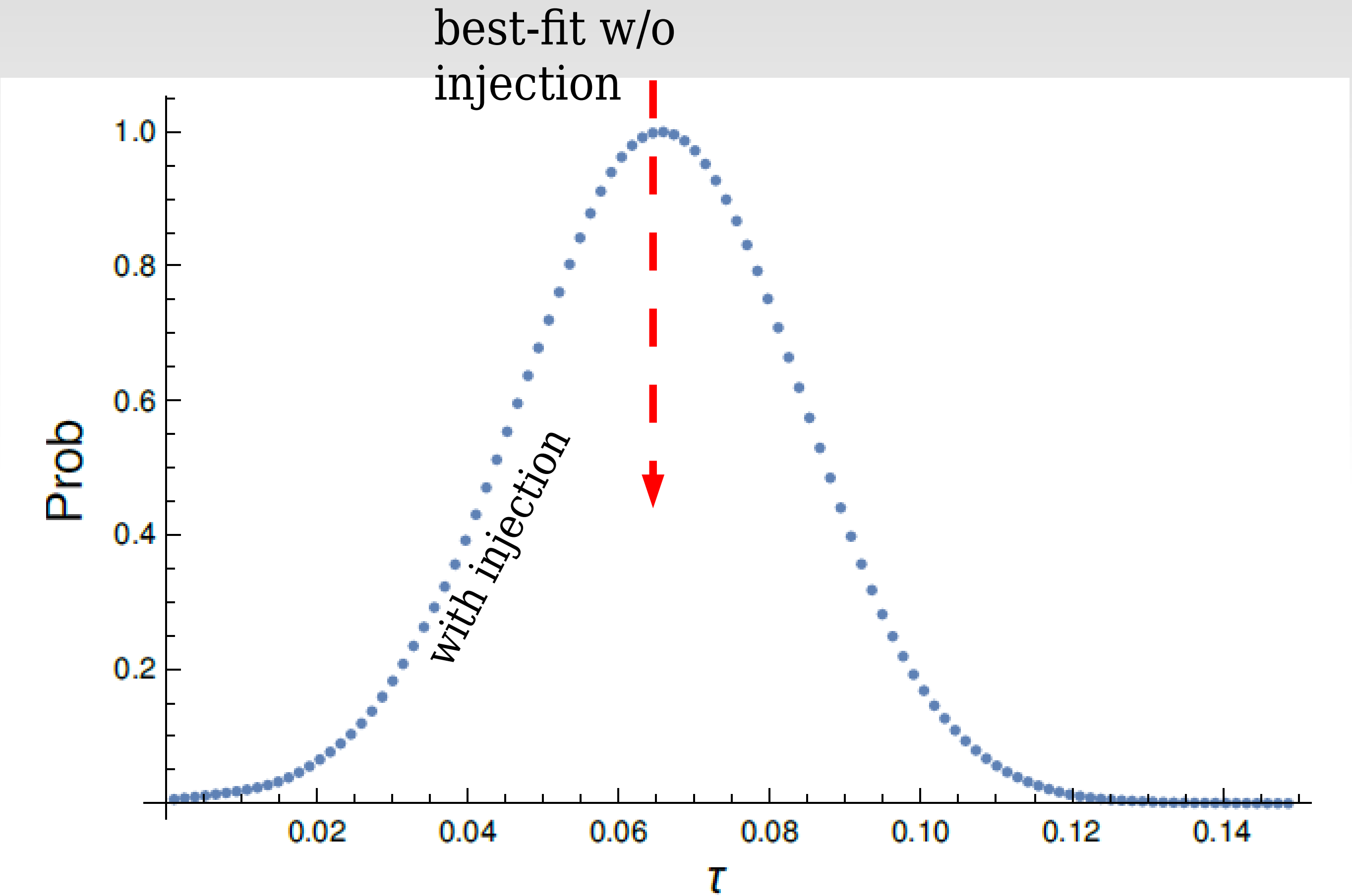
Major degeneracy: *Astrophysical & DM electrons*

(EoR)





More free e^+e^- : a small shift in effective optical depth



PLANCK 2015: temperature + polarization

How well do we know $x_e(z<20)$?

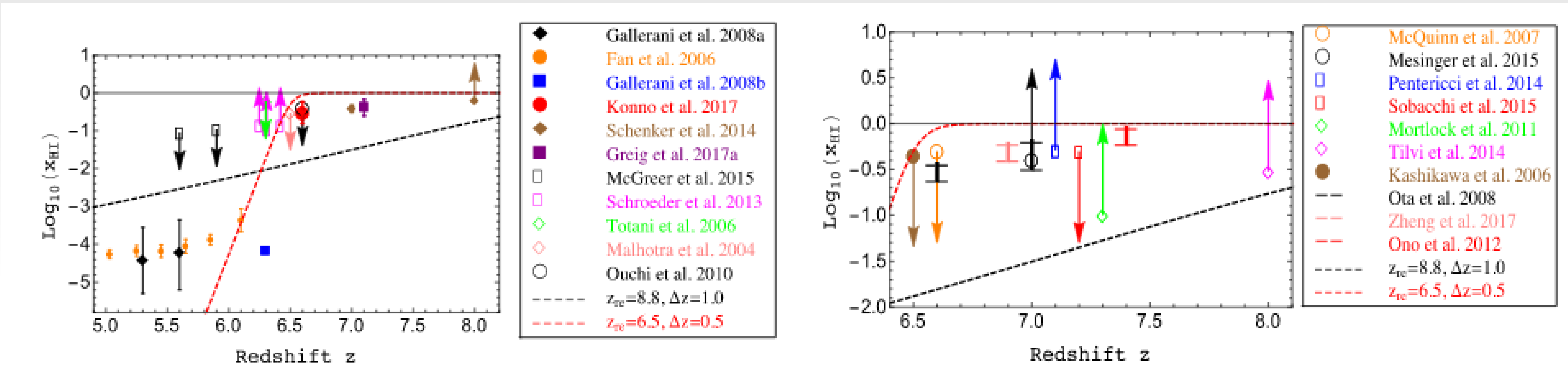
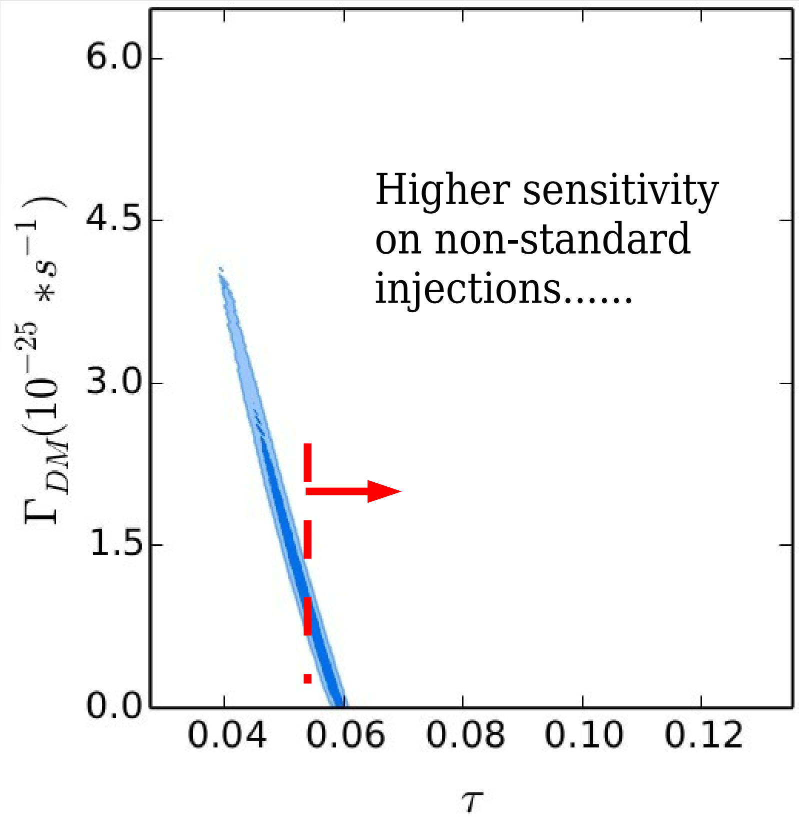
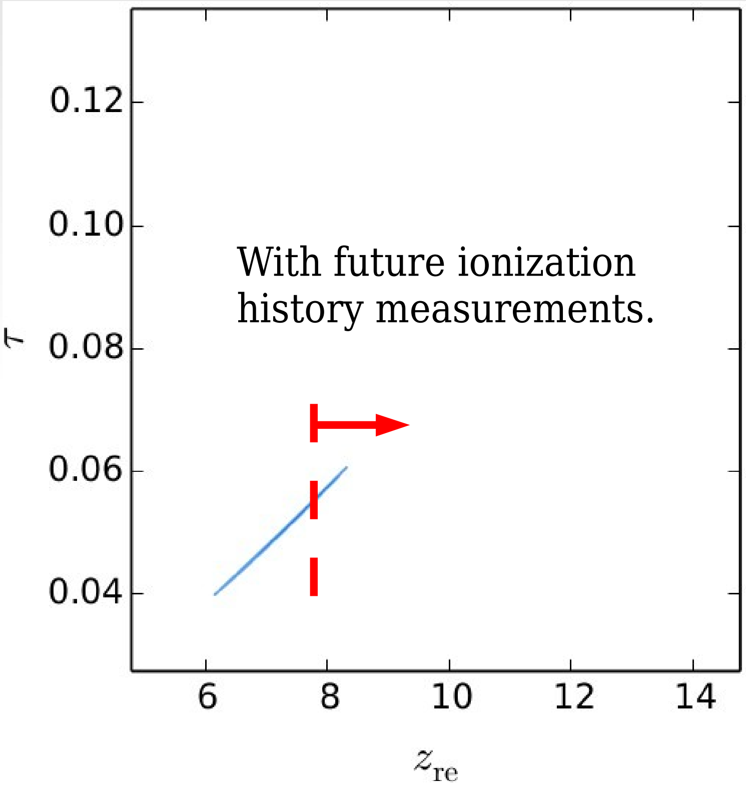


FIG. 4: The state-of-the-art measurement on $x_{\rm HI}(z)$, taken from Table I. The black and red dashed lines are two examples of the "tanh" model which cannot fit the data very well.

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

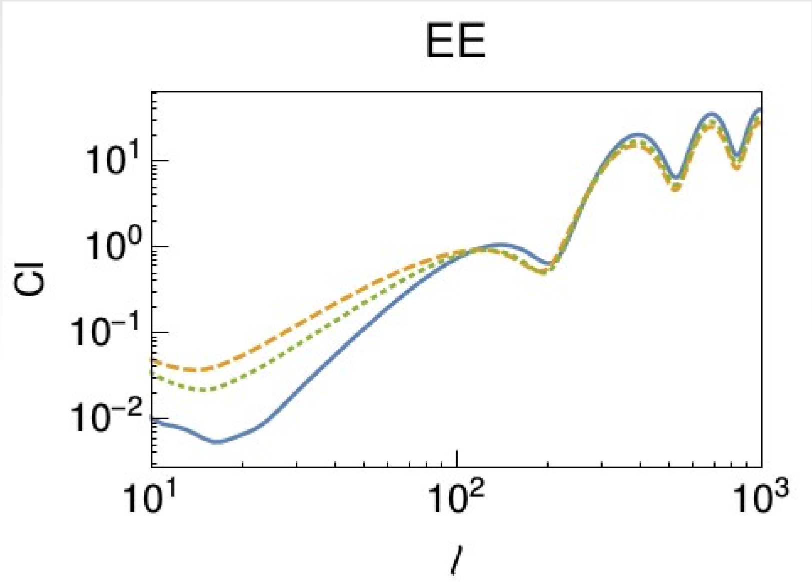
Future opportunity I : EoR measurement





EDGES **(Bowman, et.al. 2018)** hints for the dawn in 21cm?
Up-coming 21cm experiments: HERA, MeerKAT, SKA, etc..
Capable of measuring *both* **EoR history** & **matter temperature,** and more

Future Opportunity II: polarization data

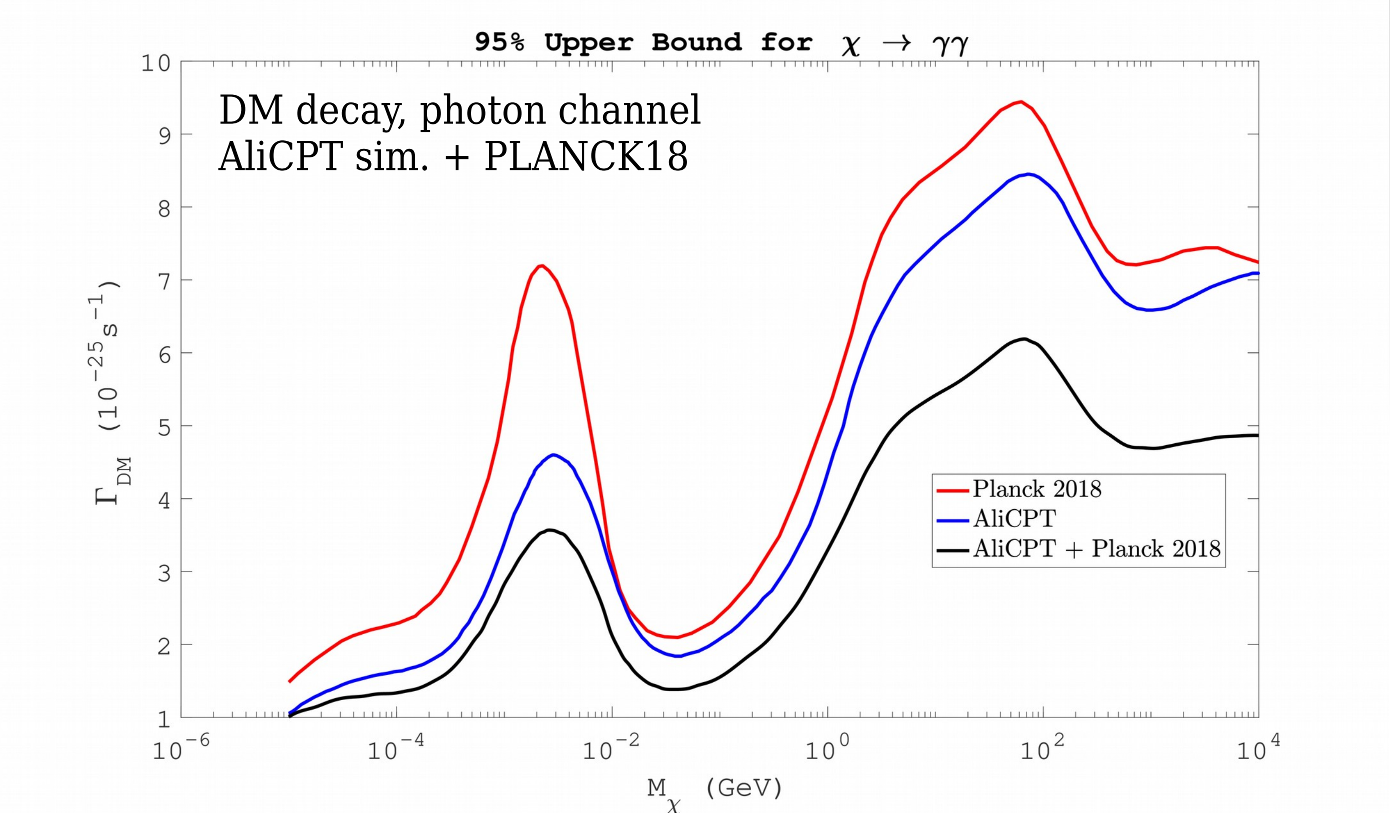


E spectral *peak shift* caused by near-recombination effects;
not degenerate with EoR uncertainty:

Improved E mode measurement helps test energy injections

A theorist's forecast

Junsong Cang, Yu Gao, in progress.



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

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

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

On ave. ~ 0.4 relative improvement w PLANCK18
Injection energy ~ 1/2 DM mass
Sensitivity traces cosmic 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)

Summary

- CMB polarization Cls: **very sensitive** to *post- recombination* new physics energy injections:
  WIMP annihilation & decay; PBH evaporation, etc.
- Wide mass coverage, best sensitivity in KeV-MeV range
- PLANCK(18) currently leading measurements
- E polarization data breaks degeneracy with EoR history uncertainty
- Future CMB/pol sensitivity? AliCPT, BICEP3, SPT-g3 ...

Stay tuned!