Dark Matter Search in the CMB

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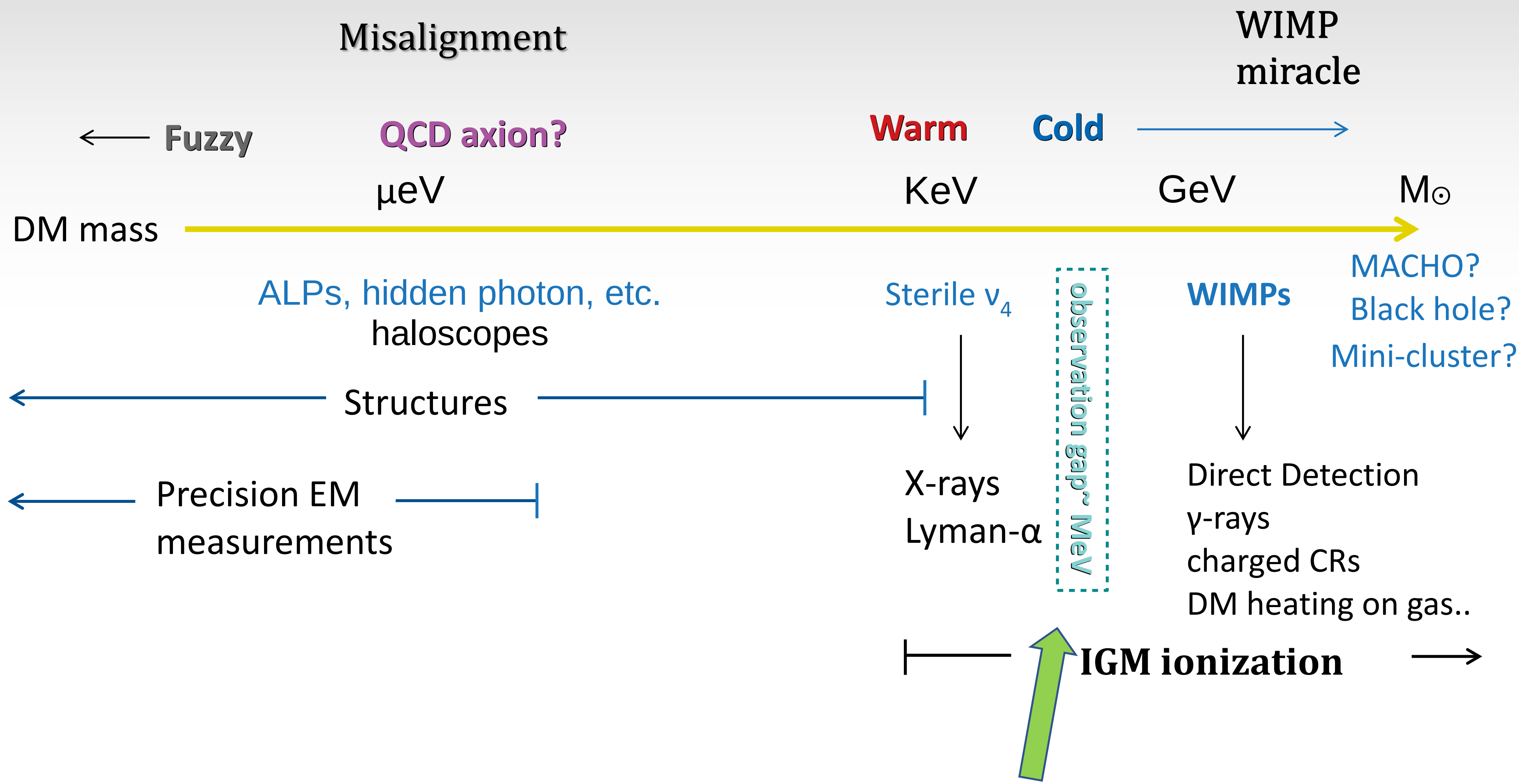
Outline

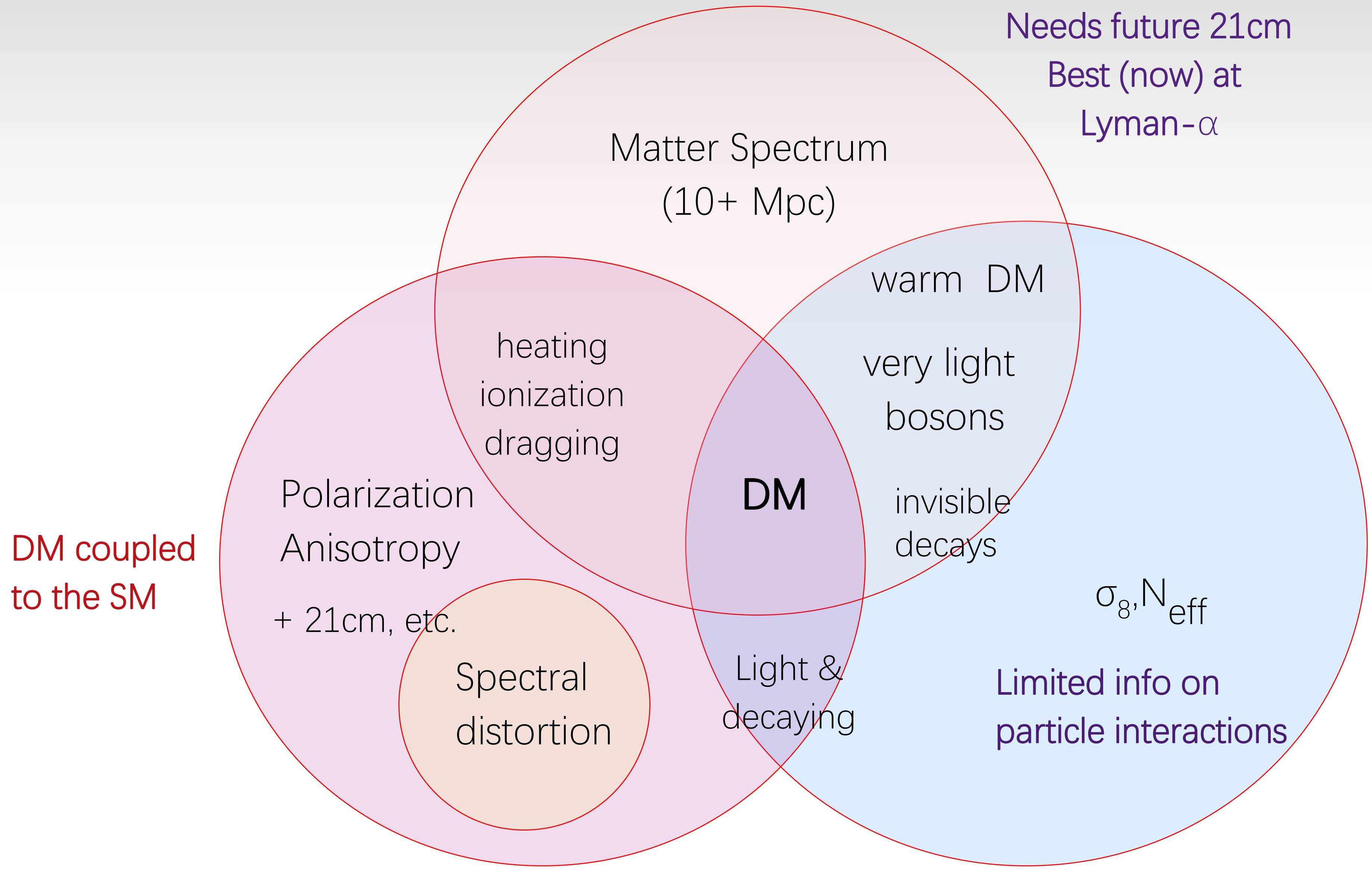
- Particle Dark Matter Effects on the CMB
- DM ↔ CMB anisotropies (Ionization)
- DM ↔ 21cm (Temperature)
- Forecasts for DM and PBHs
- Inhomogeneity from DM heating

Theory orders are placed.



CMB covers a wide DM mass range! **~MeV opportunity**

CMB & Dark Matter



DM probes from the CMB

- CMB spectral distortion:
  `coupled' DM, early/steady energy injection,
  DM-photon conversion, etc
- CMB polarization:
  pol. rotation in CPV medium
- CMB derivatives:
  21cm maps of matter power-spectrum:
  spatial & temperature distributions

Impact from steady (high-energy) injection

- Deposit energy into IGM during the dark age of Universe
- (1) Ionize (fraction of) the IGM; (2) Heats the IGM
- A small energy budget for a large impact

	On decay lifetime:
Continuum Indirect Search (Fermi-LAT, etc):	$\tau > 10^{26}$ s (lines: $\tau > 10^{28}$ s)
IGM ionization pre-EoR (PLANCK)	$\tau > 10^{24}$ s
IGM heating pre-EoR (21cm,projected)	$\tau > 10^{26}$ s (existence) Higher precision by data

The `standard' ionization history

Standard ionization evolution (pre-EoR)

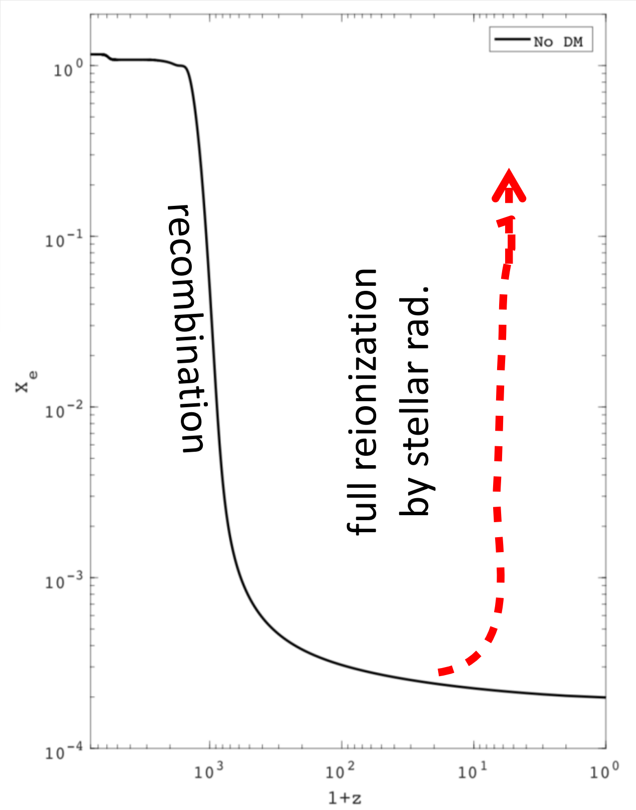
$$\frac{dX_e}{dt} = \left\{(1 - X_e)\beta - X_e^2 n_b \alpha^{(2)}\right\}$$

Ionization rate (by radiation field):

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

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 during EoR

DM Effect 1: ionization

- More free electrons
- More CMB scattering → Damping on C_l

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

"Deposit Channels"

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

SM: H atom ionization
and recombination

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

ionization from
ground state

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

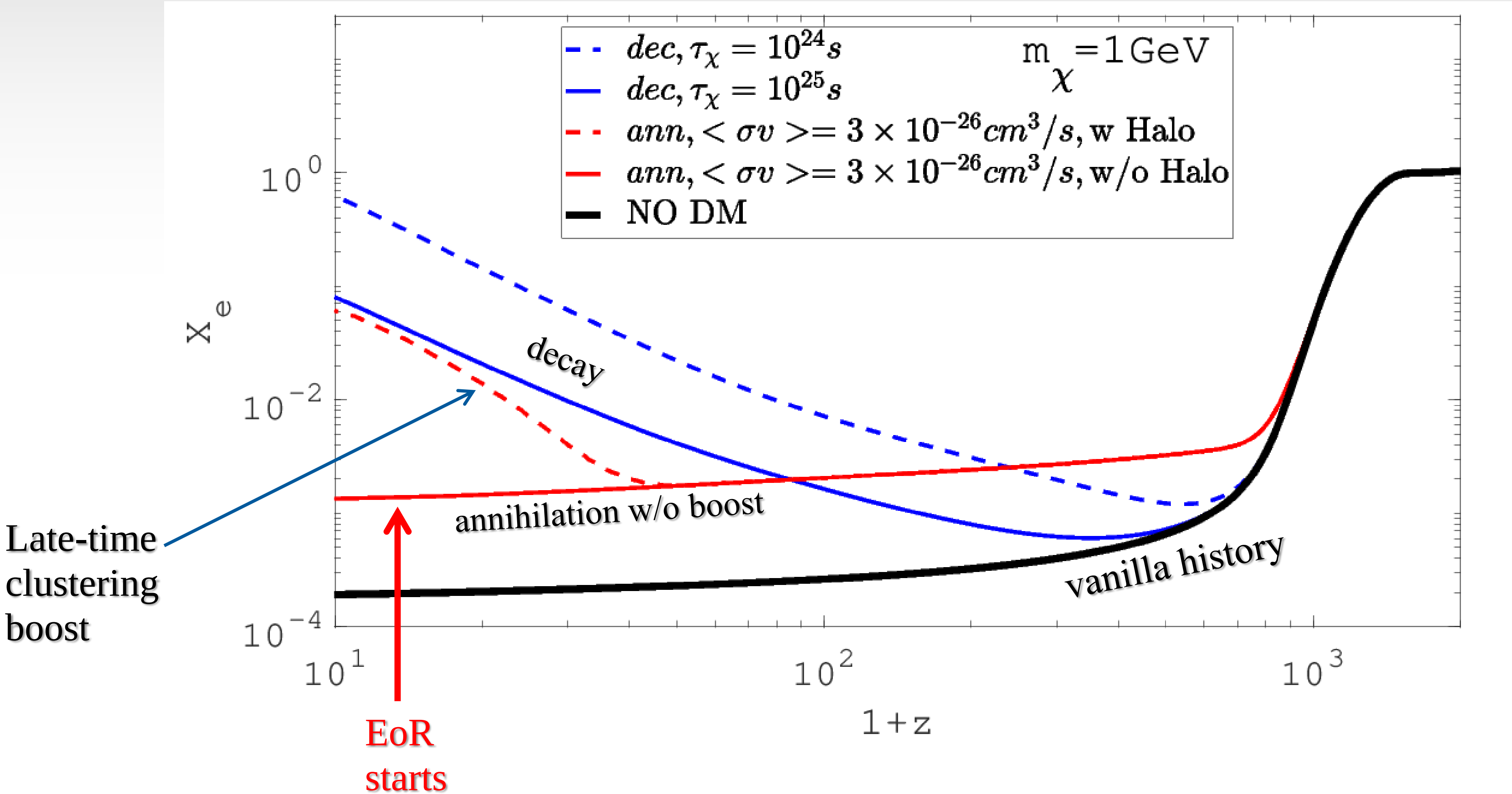
ionization from
excited states

(+ other channels)

DM: impact on x_e

Annihilation: raises the x_e floor,

Decay: steady rise in x_e



The `perturbed' ionization history

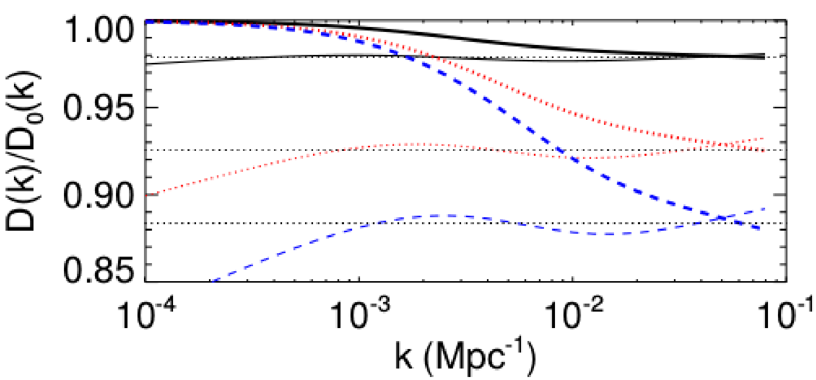
Ionization enhances photon scattering

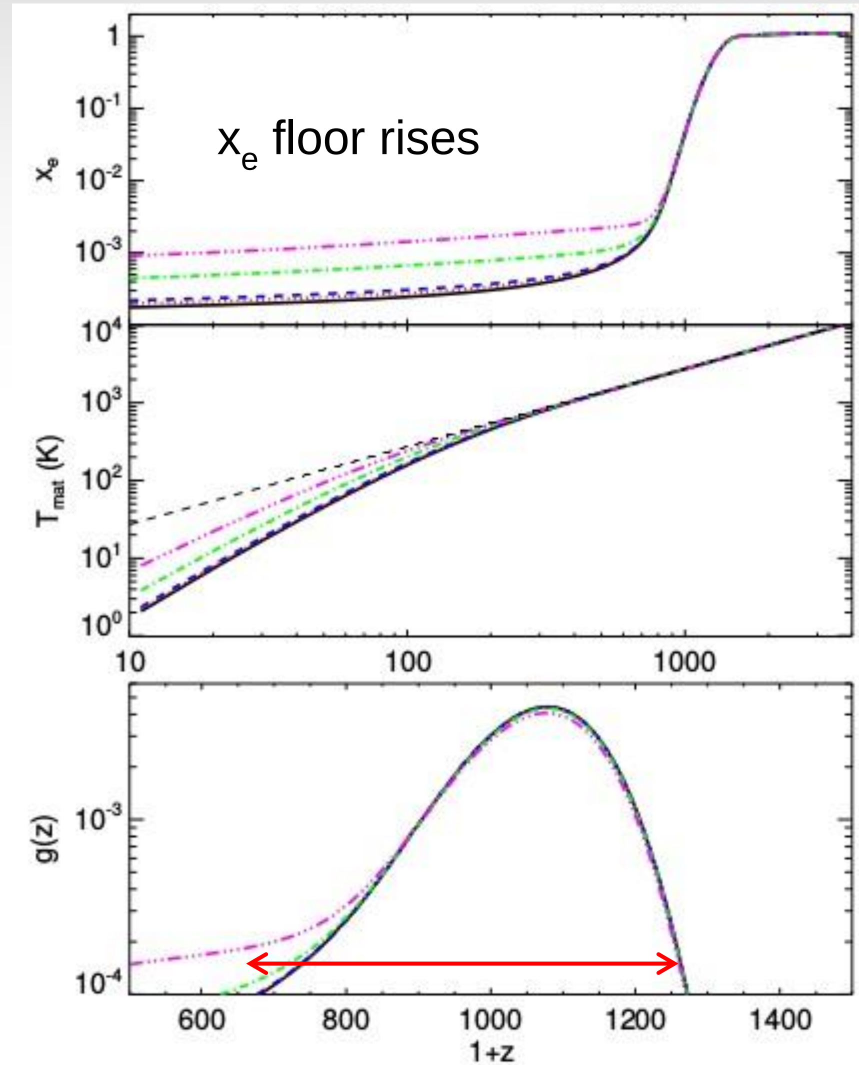
$$C_l = 4\pi A \int_0^\infty d(\ln k)\, k^{n_s} D^2(k) T^2(k)$$

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"

Redshift dependence in injection rate

- Annihilation and/or Decay of WIMPs
- Energy release during dark ages

DM Annihilation: fast during high z,

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

Late time density clustering boosts the annihilation rate after z~O(50)

$$\left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{INJ}}^{\mathrm{ann,boosted}} = [1+B(z)]\left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{INJ}}^{\mathrm{ann}}$$

$$B(z) = \frac{\Delta_{\mathrm{c}}\rho_{\mathrm{c}}}{\rho_{\mathrm{DM}}^2}\int_{M_{\mathrm{min}}}^{\infty} M B_{\mathrm{h}}(M)\frac{\mathrm{d}n}{\mathrm{d}M}\mathrm{d}M$$

DM Decay: a steady rate, unaffected by structure formation

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

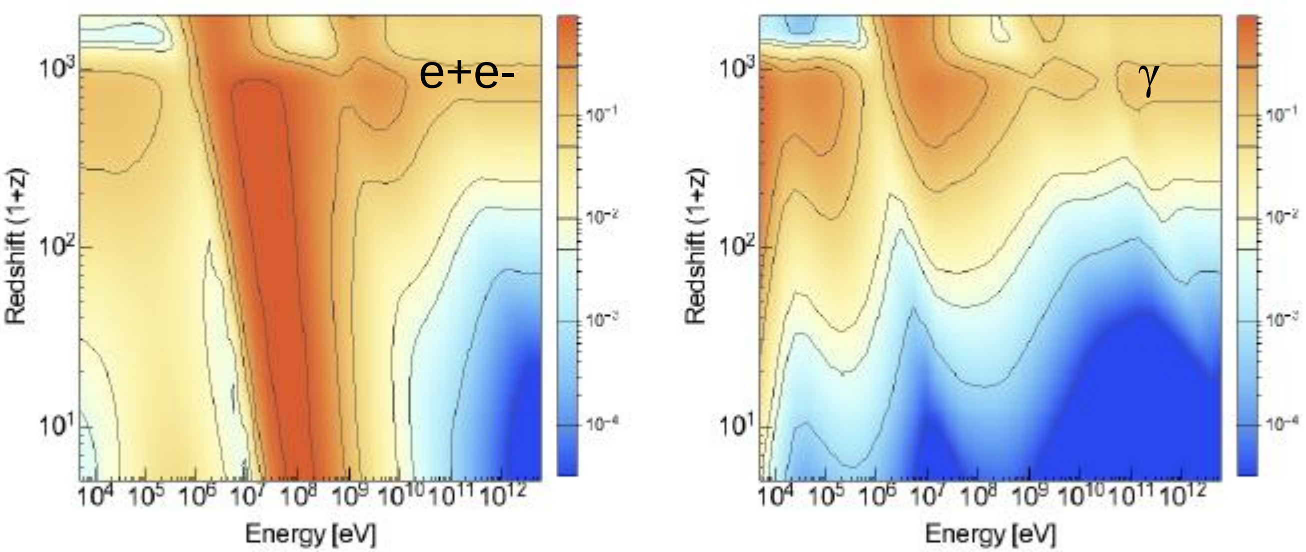
Lagged energy deposition

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

Not instantaneously deposited into the IGM
if particles are energetic (E >> KeV):

* accumulative over earlier injection
* efficiency reduces at later time

Energy "fraction" into ionization (of H)



Liu, Slatyer, Zavala, 2016

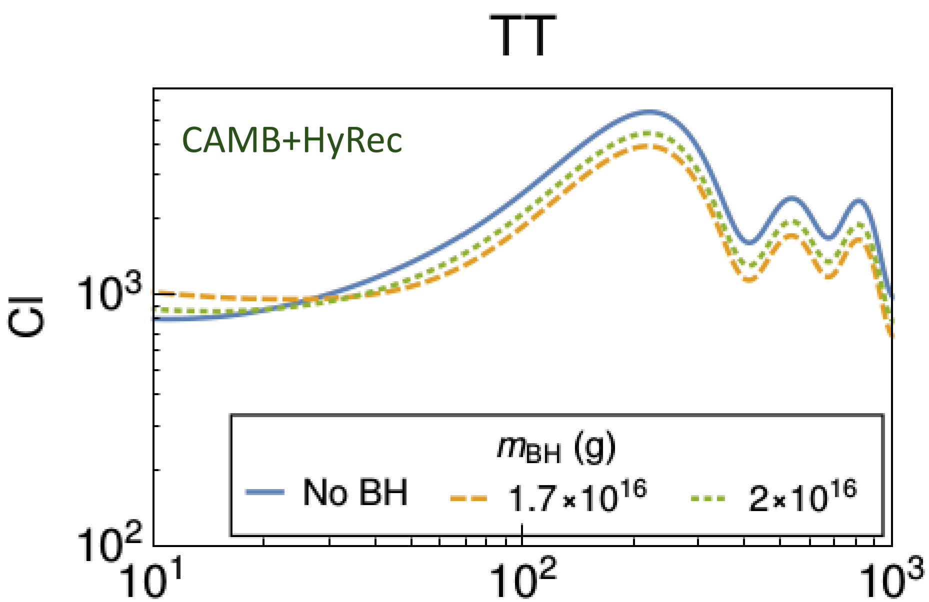
Numerical calculation

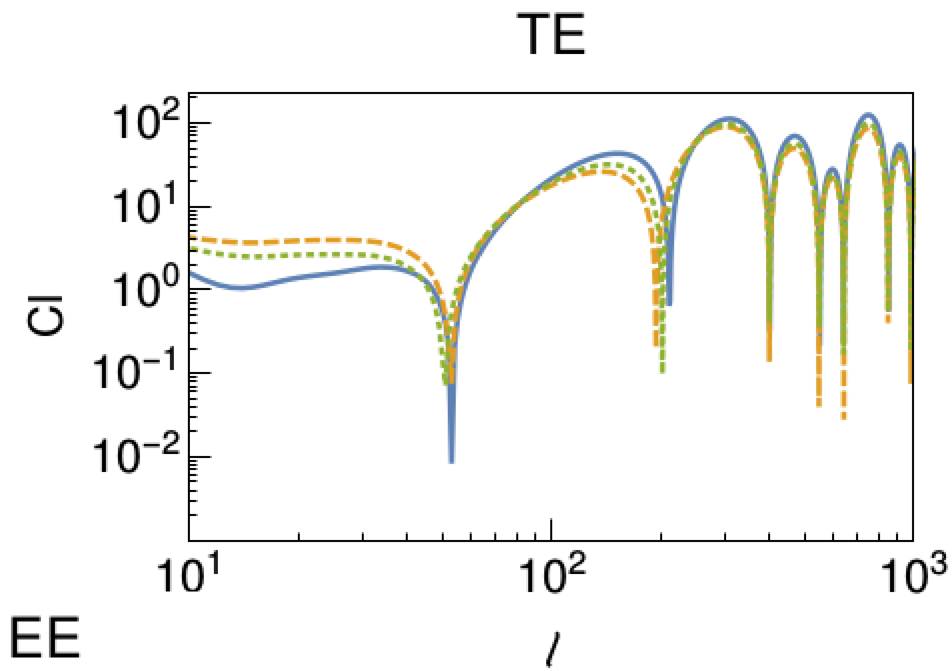
Implemented into
HyRec codes:

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

Also see:
Belotsky, Kirillov 2015

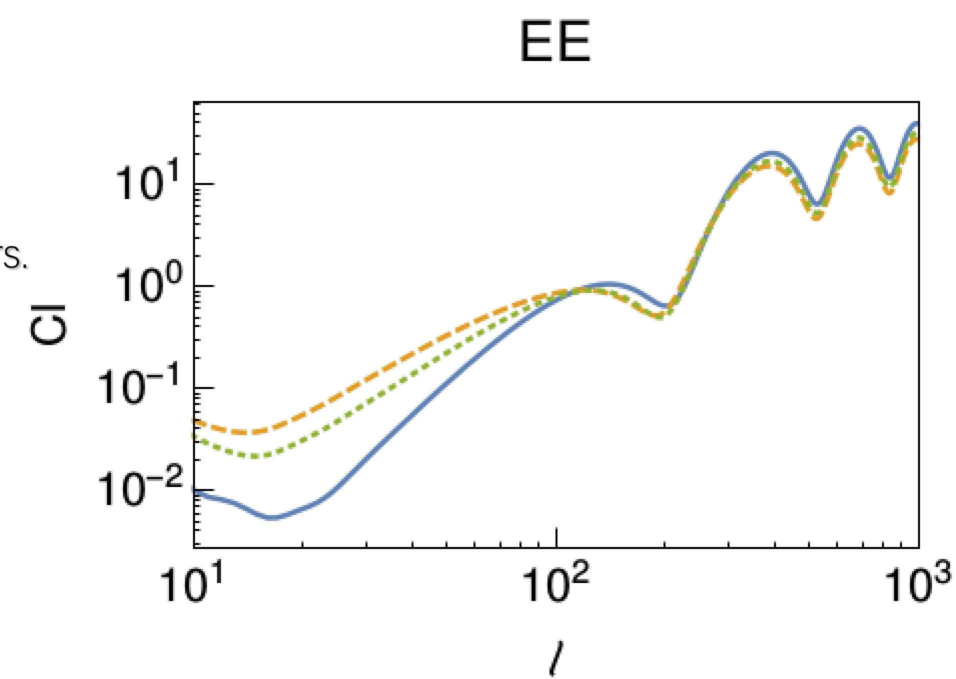
Xe on CMB C_l: damping & pol. peak shift





Large l damping may be degenerate to cosmological parameters.

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

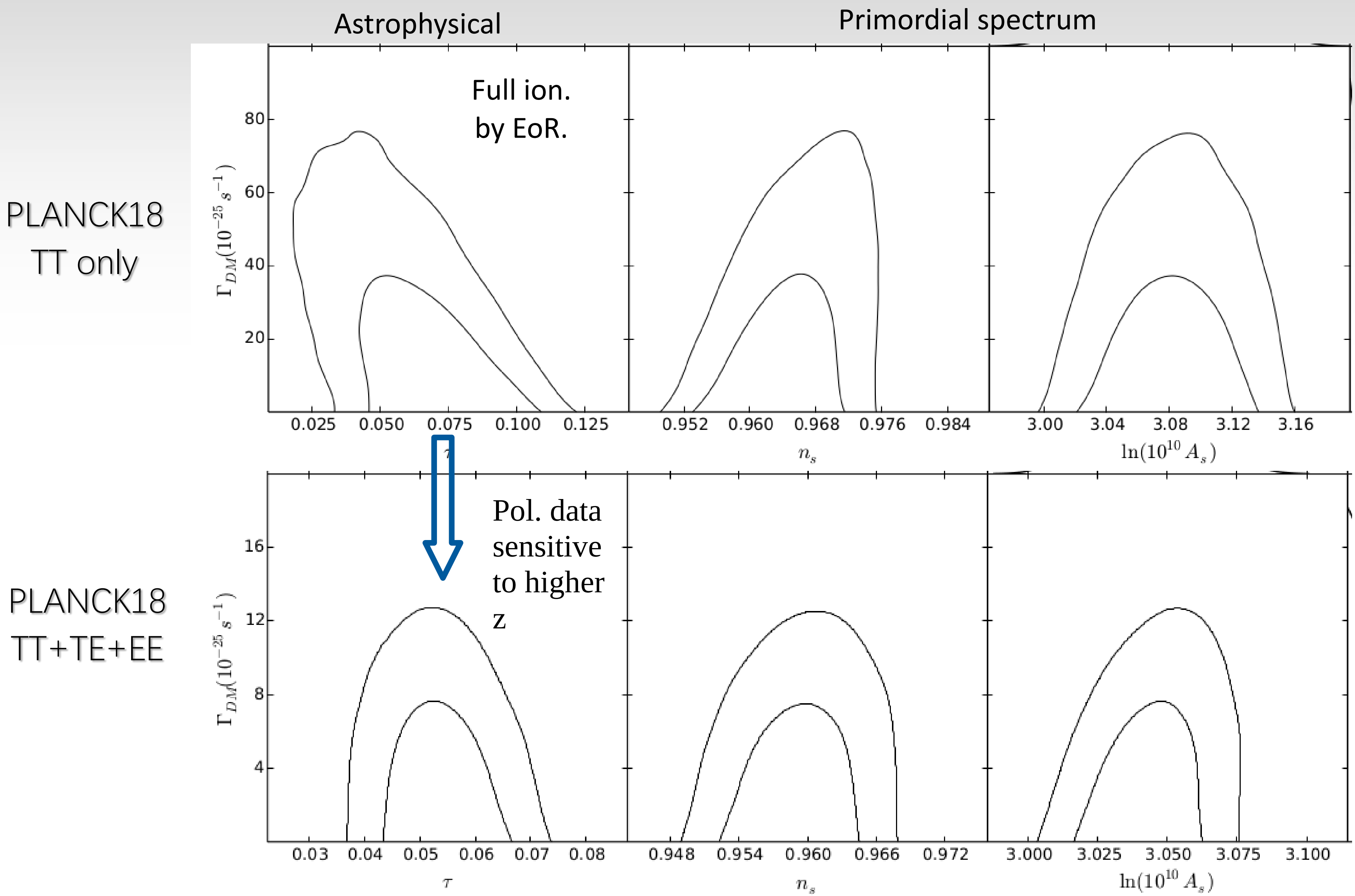


LSS broadening increases polarization perturbation amplitudes

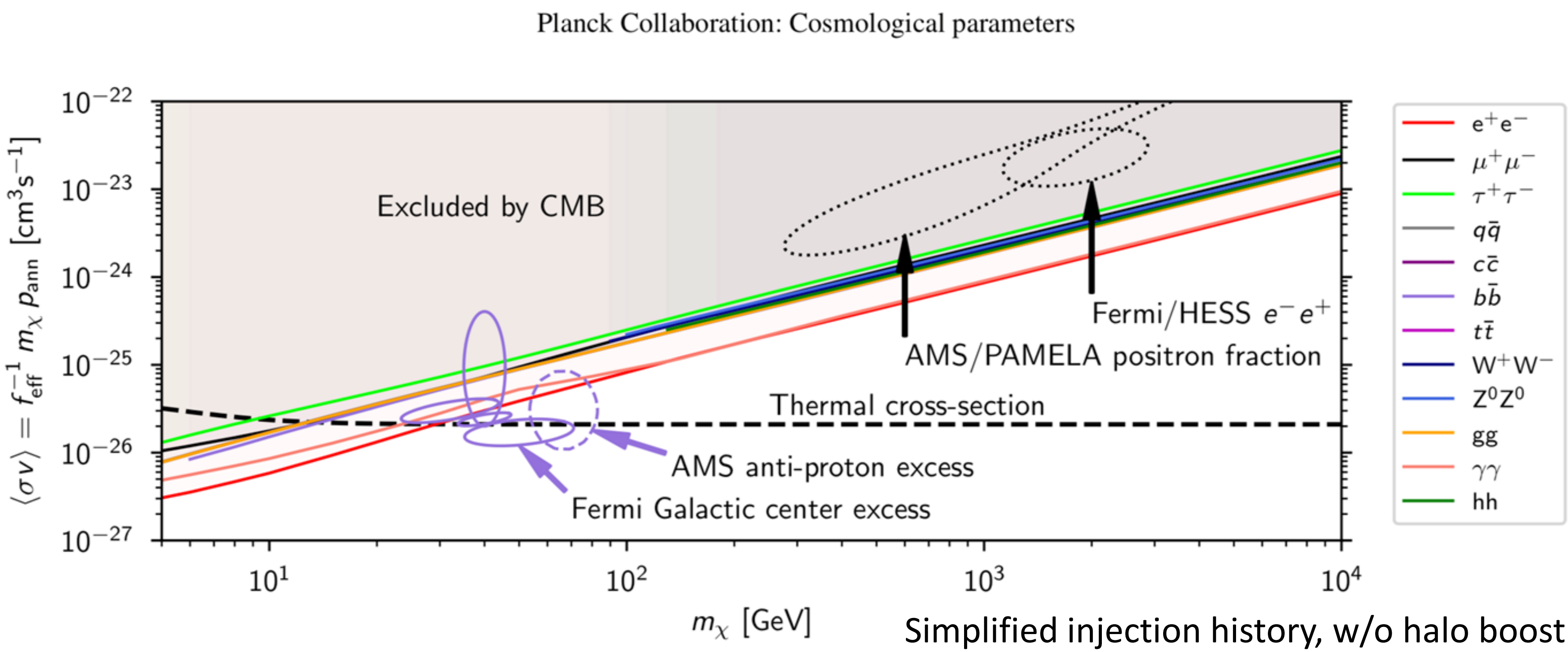
* visible shift in E pol. peaks by enhanced monopole to quadrature ratio

* enhances damping

PLANCK 18: Pol. data lifts EoR degeneracy



Current limits: WIMP annihilation



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.

PLANCK 18:
`Cosmological parameters'
Thermal WIMP mass limit: 10~30 GeV

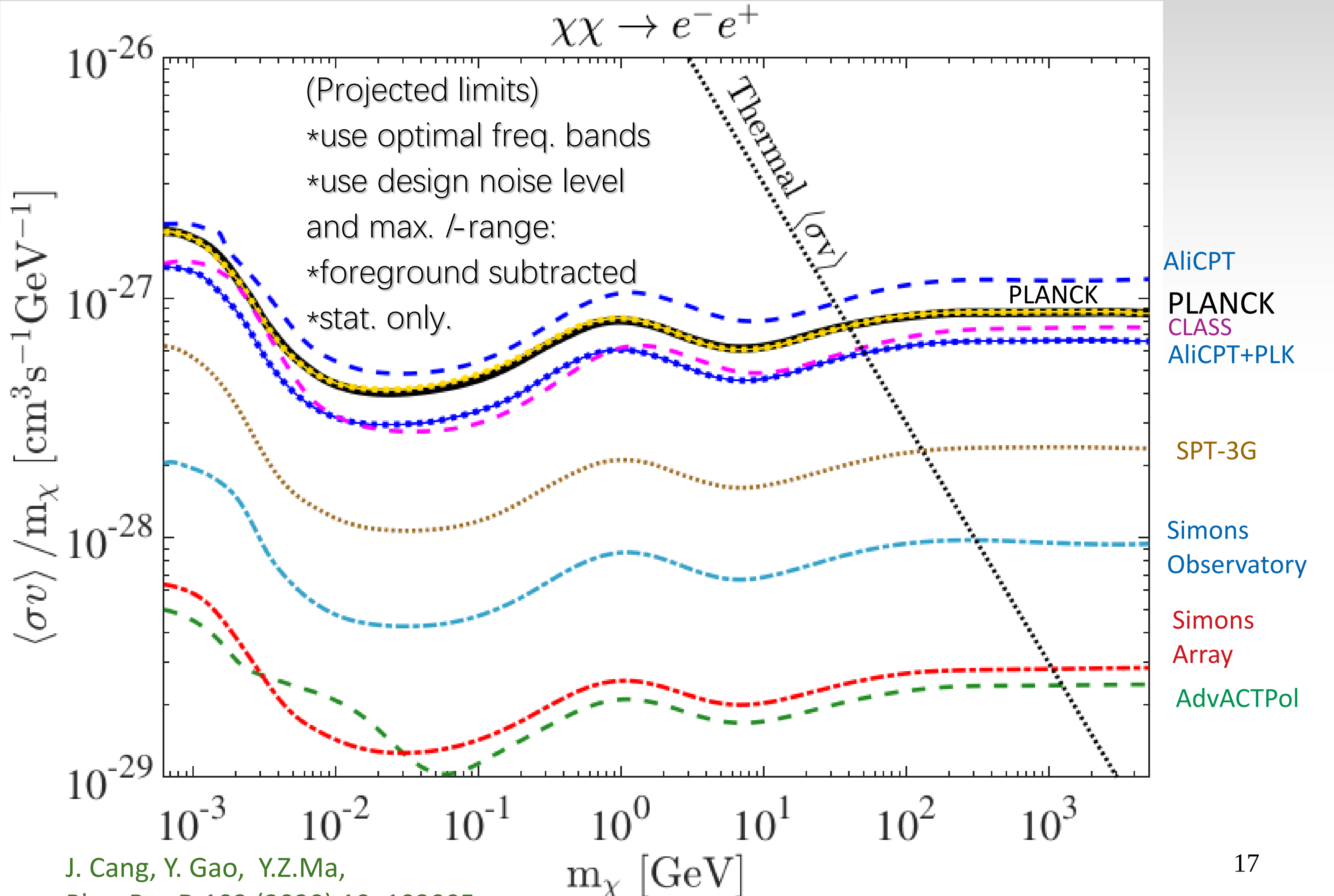
Near future: How about more pol. data

实验	$\sigma_{P,\nu}$（μk'）	$\theta_{FWHM,\nu}$（'）	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

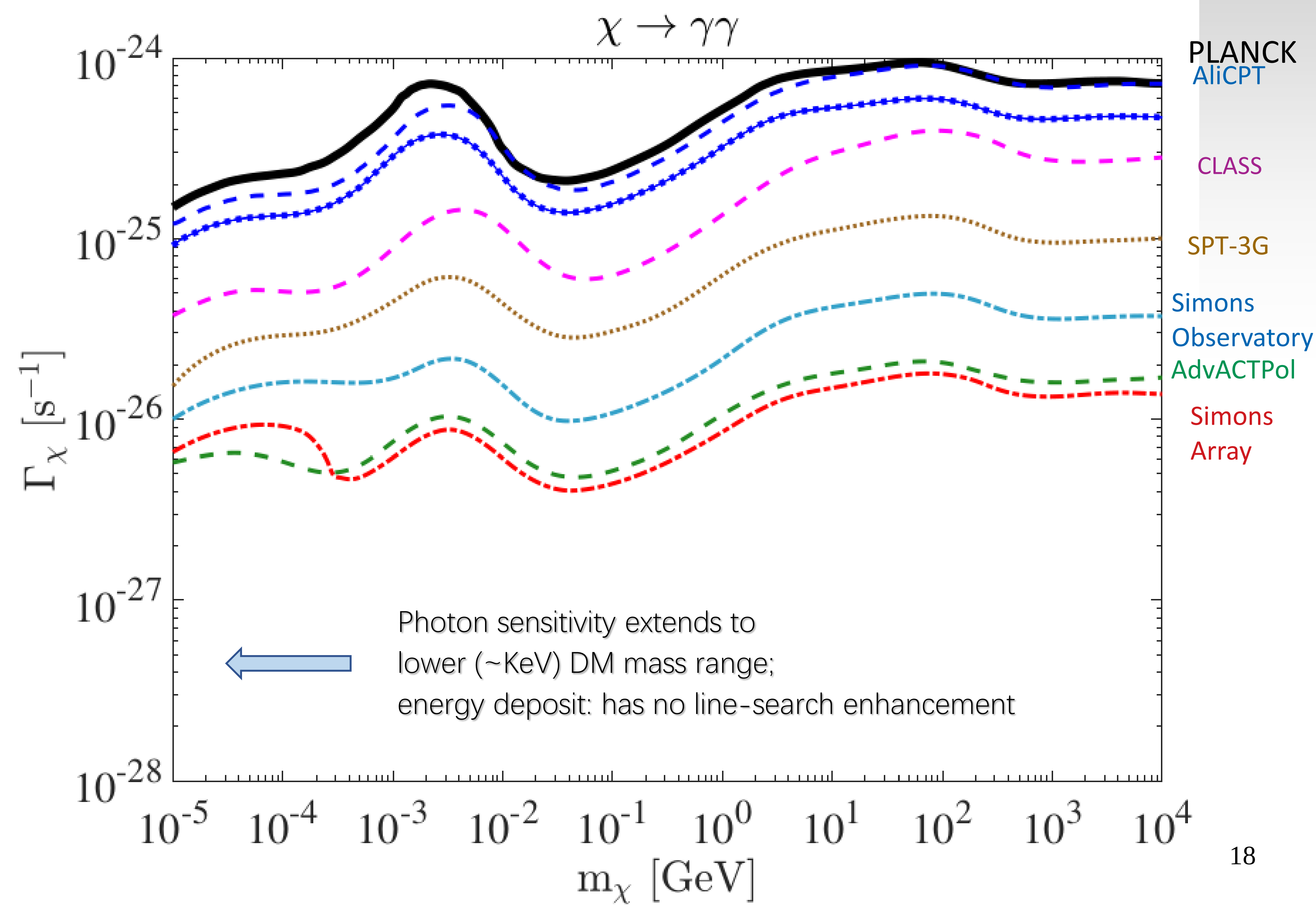
Forecast on Thermal WIMP mass (ee channel)

~ Keck/BICEP3



J. Cang, Y. Gao, Y.Z.Ma,
Phys.Rev.D 102 (2020) 10, 103005

Forecast on WIMP lifetime (decay to photons)



Stat.-only estimates on up-coming observations (no FG)

Experiment	$\chi \to e^+e^-$	$\chi \to \gamma\gamma$
Planck	24	85
AdvACTPol	0.68	4.7
AliCPT	21	78
AliCPT+*Planck*	16	53
CLASS	5.5	30
Simons Array	0.35	1.5
Simons Observatory	0.92	4.2
SPT-3G	2.2	9.9

TABLE II. 95% C.L. upper limit on Γ_χ (in 10^{-26} s^{-1}) at $m_\chi = 10$ GeV.

Lower bounds on DM decay lifetime (null-signal)

Experiment	$\chi\chi \to e^+e^-$	$\chi\chi \to \gamma\gamma$
Planck	39	32
Planck - Unclustered	39	33
AdvACTPol	330	330
AliCPT	32	22
AliCPT+*Planck*	51	42
CLASS	49	37
Simons Array	1.1×10^3	1.0×10^3
Simons Observatory	310	290
SPT-3G	140	130

TABLE III. Expected 95% C.L. lower limit on m_χ (in GeV) assuming a thermal relic's annihilation cross-section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s.

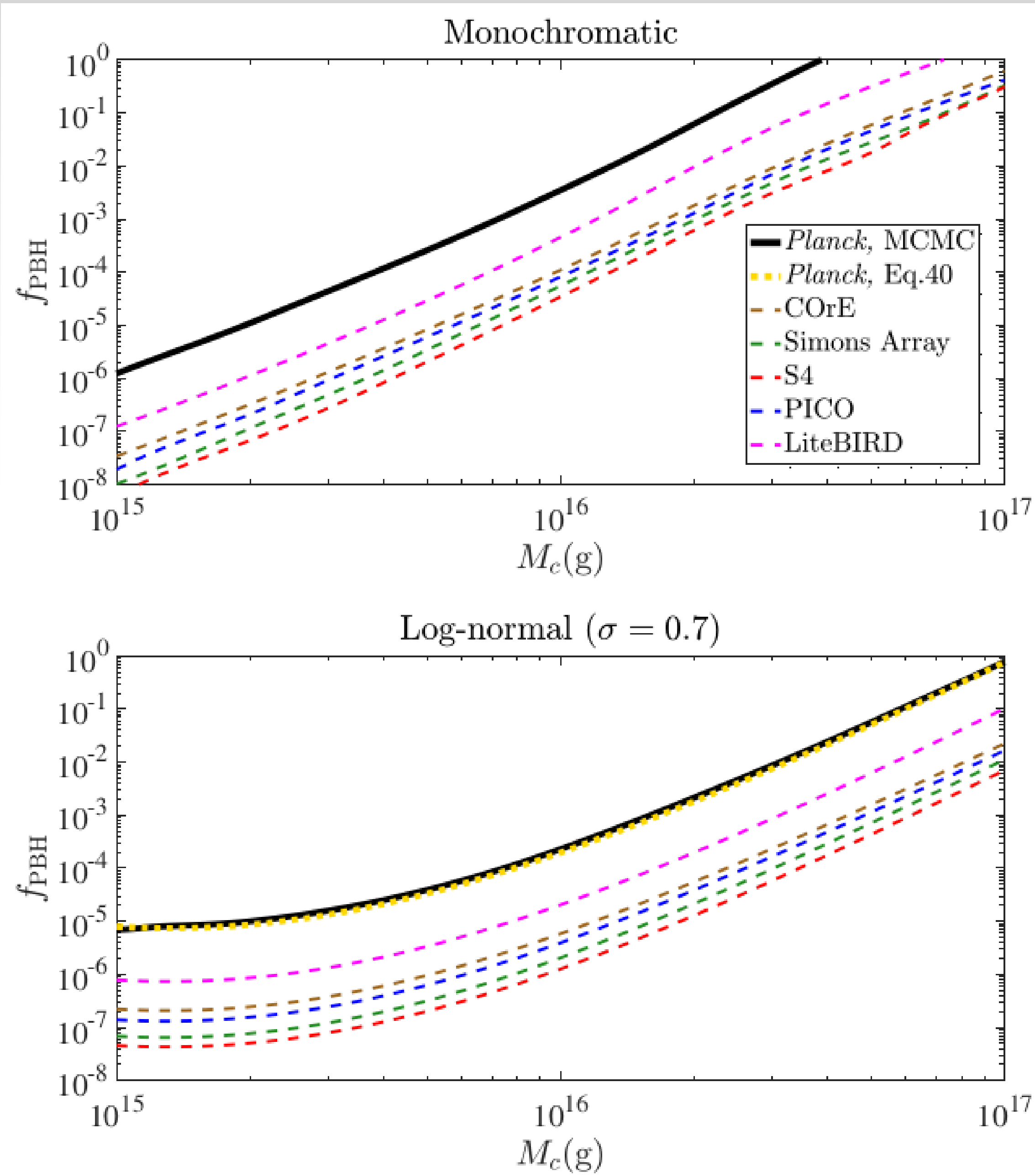
Lower bounds on \`vanilla' thermal DM mass (null-signal)

Evaporating PBHs, (low-mass)

PBH's Hawking radiation has a $dE/dt \sim (1+z)^3$ history

Significant sensitivity in relevant mass range: $M_{BH} = 10^{14-17}$ g

PLANCK15 constraint:
S.Clark., B.Dutta., Y.Gao, Y-Z.Ma, L.E. Strigari, 1612.07738



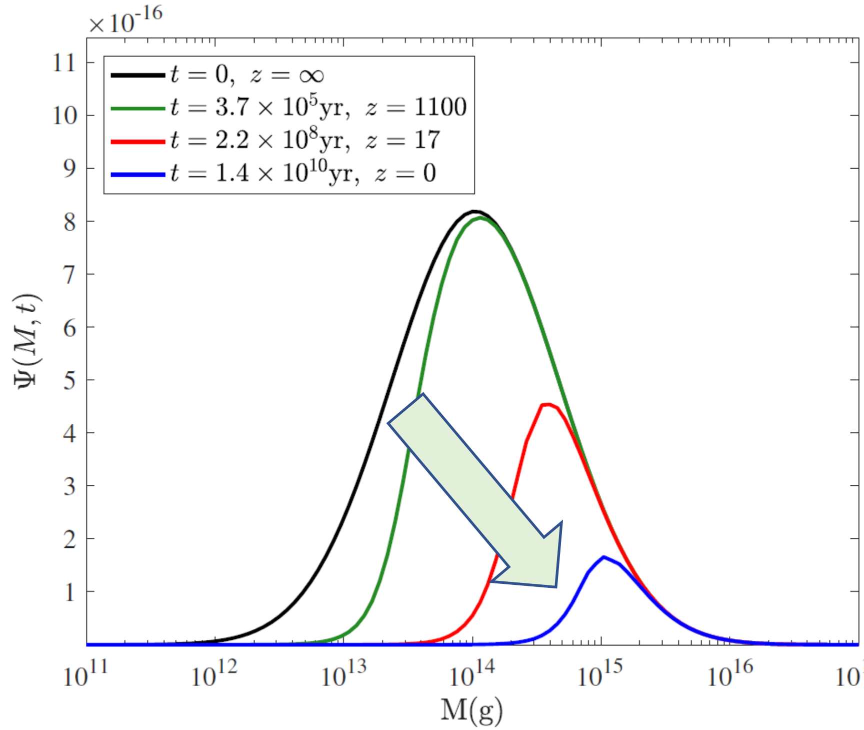
PLANCK18 limits & forecasts:
Extended BH mass distributions, see:
J.Cang., Y.Gao., Y-Z. Ma., 2011.12244

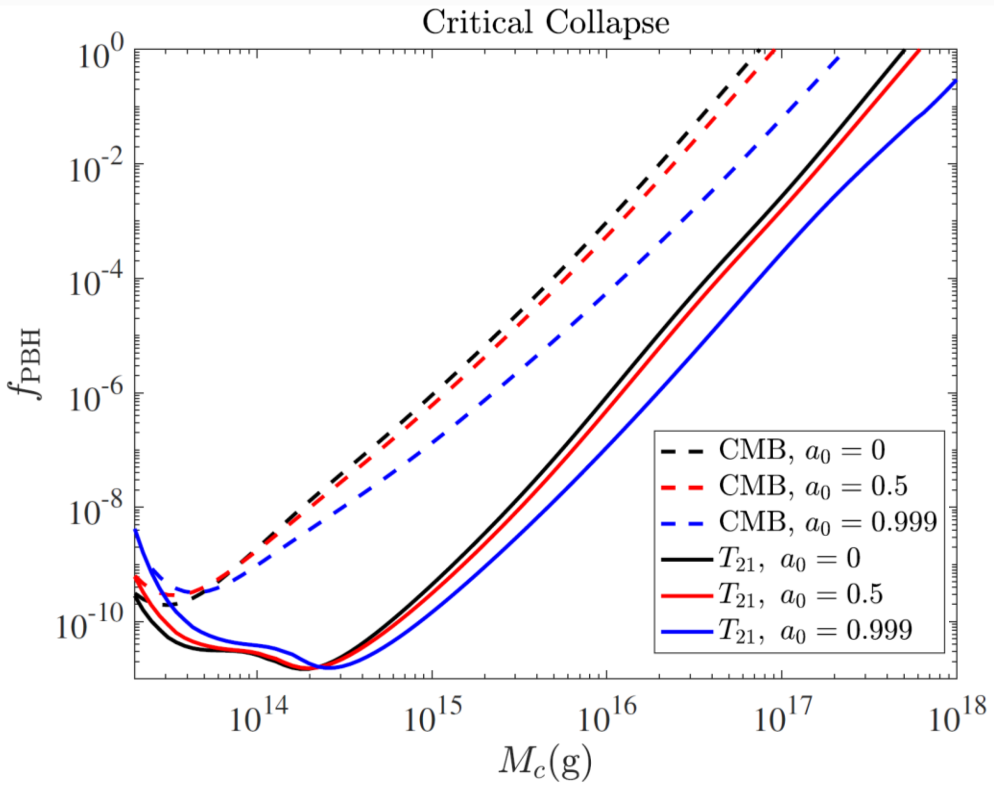
Experiment	Scaling Factor
Planck	1
COrE	37
CMB-S4	113
PICO	53
LiteBIRD	7
Simons Array	80

Spinning & lower mass (evaporating) PBHs

m_{PBH} = 10^{13} - 10^{17} g

lifetime < AOU:
evolving mass spectrum





J. Cang, Y.Gao, Y-Z. Ma, appearing soon.

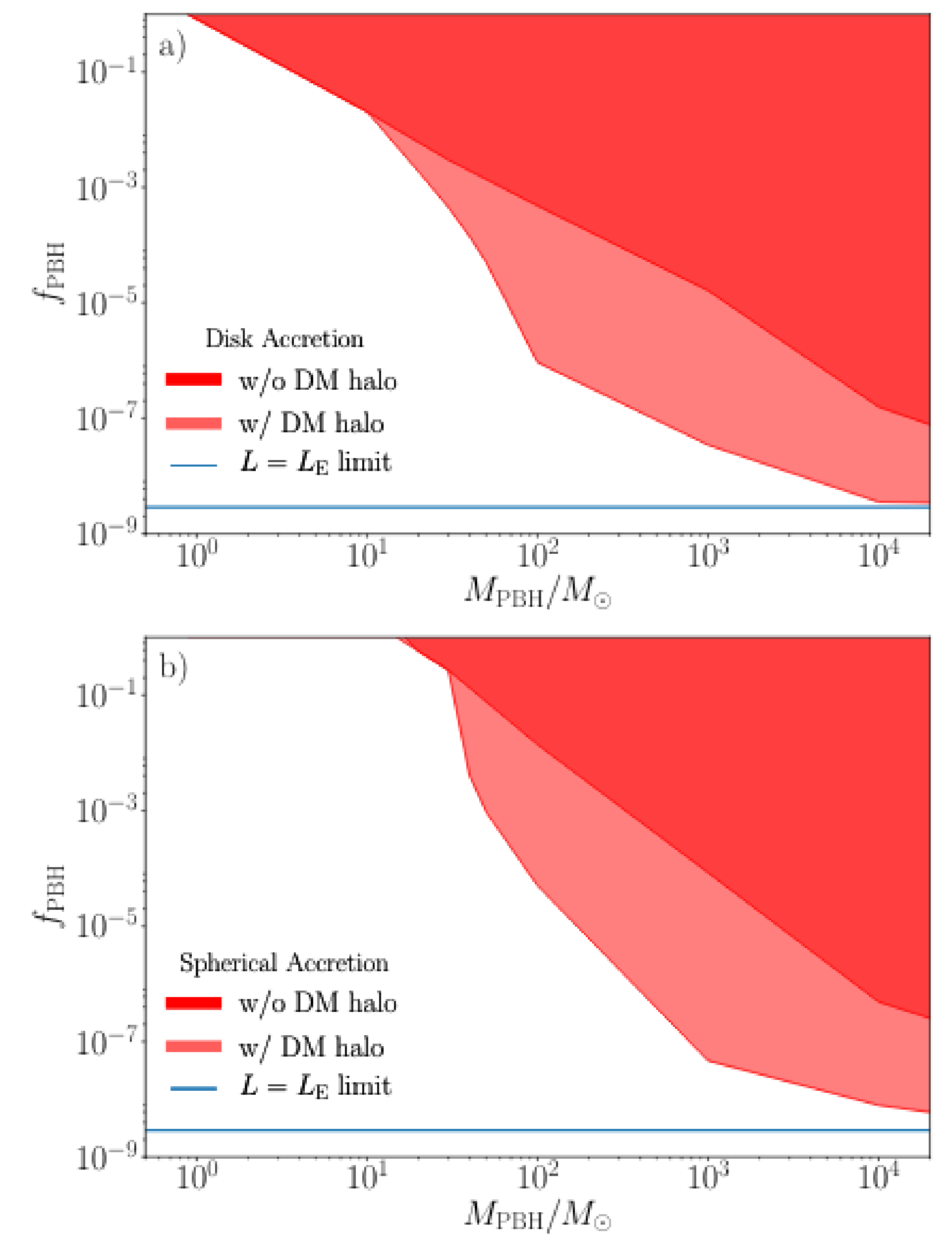
BH accretion radiation (solar-supermassive)

Masive BHs
10 -10^4 M_{sun}

CMB constraint
on ionization
radiation

PLK18 data

Serpico, Poulin,
Inman, Kohri,
2002.10771



Remaining Issue: EoR uncertainty (τ) washes out late-time DM injection

Wei-Ming Dai, et.al. (2019)

HERA

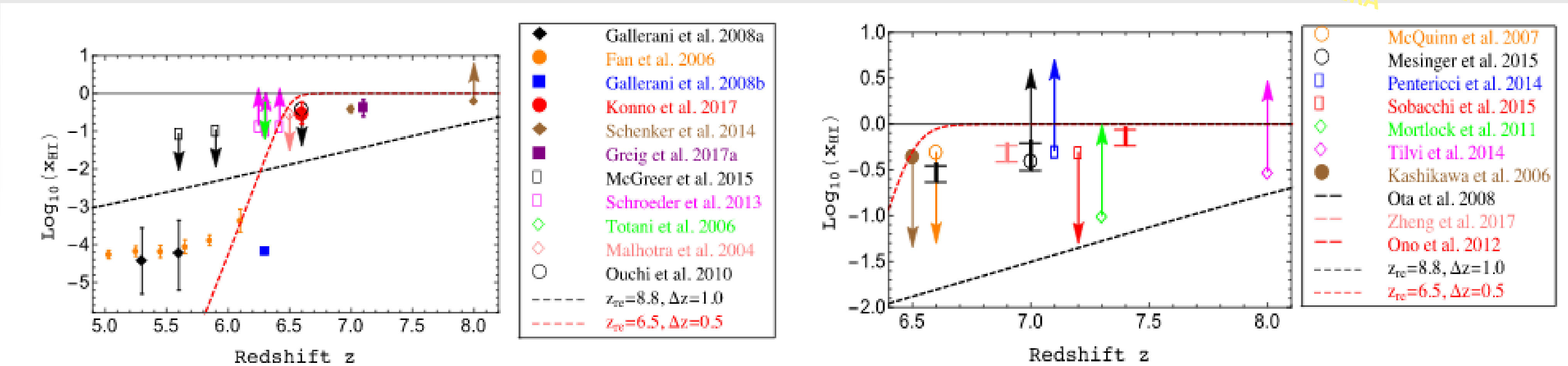
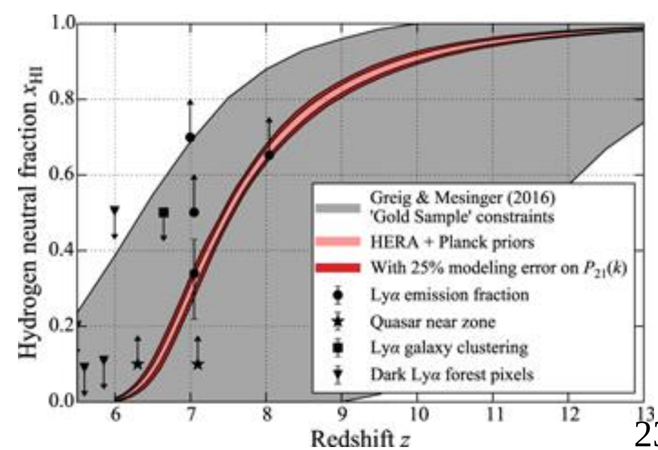


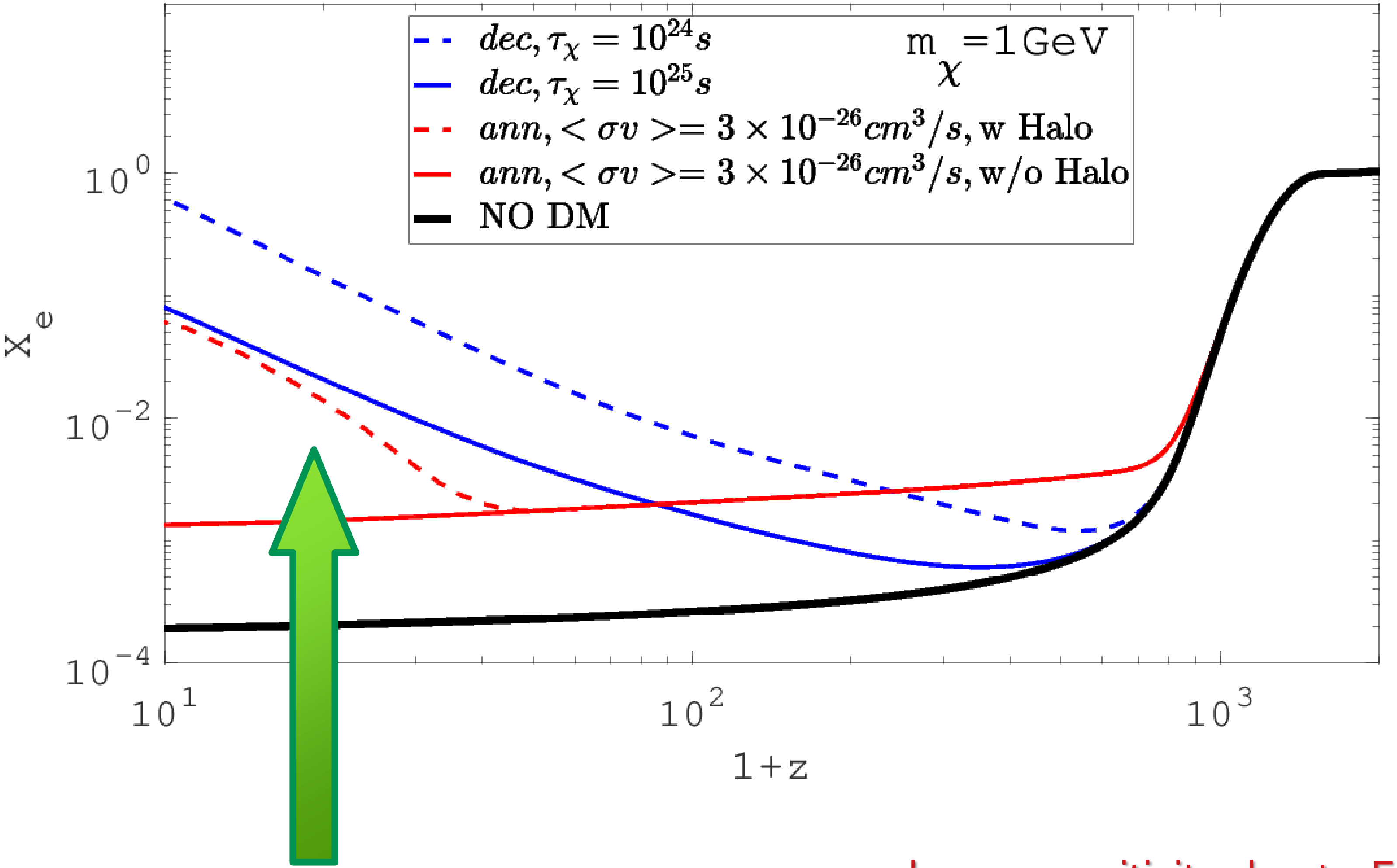
FIG. 4: The state-of-the-art measurement on $x_{\rm HI}(z)$, taken from Table I. The black and red dashed lines are two examples of the "tanh" model which cannot fit the data very well.

Current Pol. data sensitivity MOSTLY
derives from injection right-after recombination time

EoR uncertainty needs future exp. input



DeBoer et.al. 2017

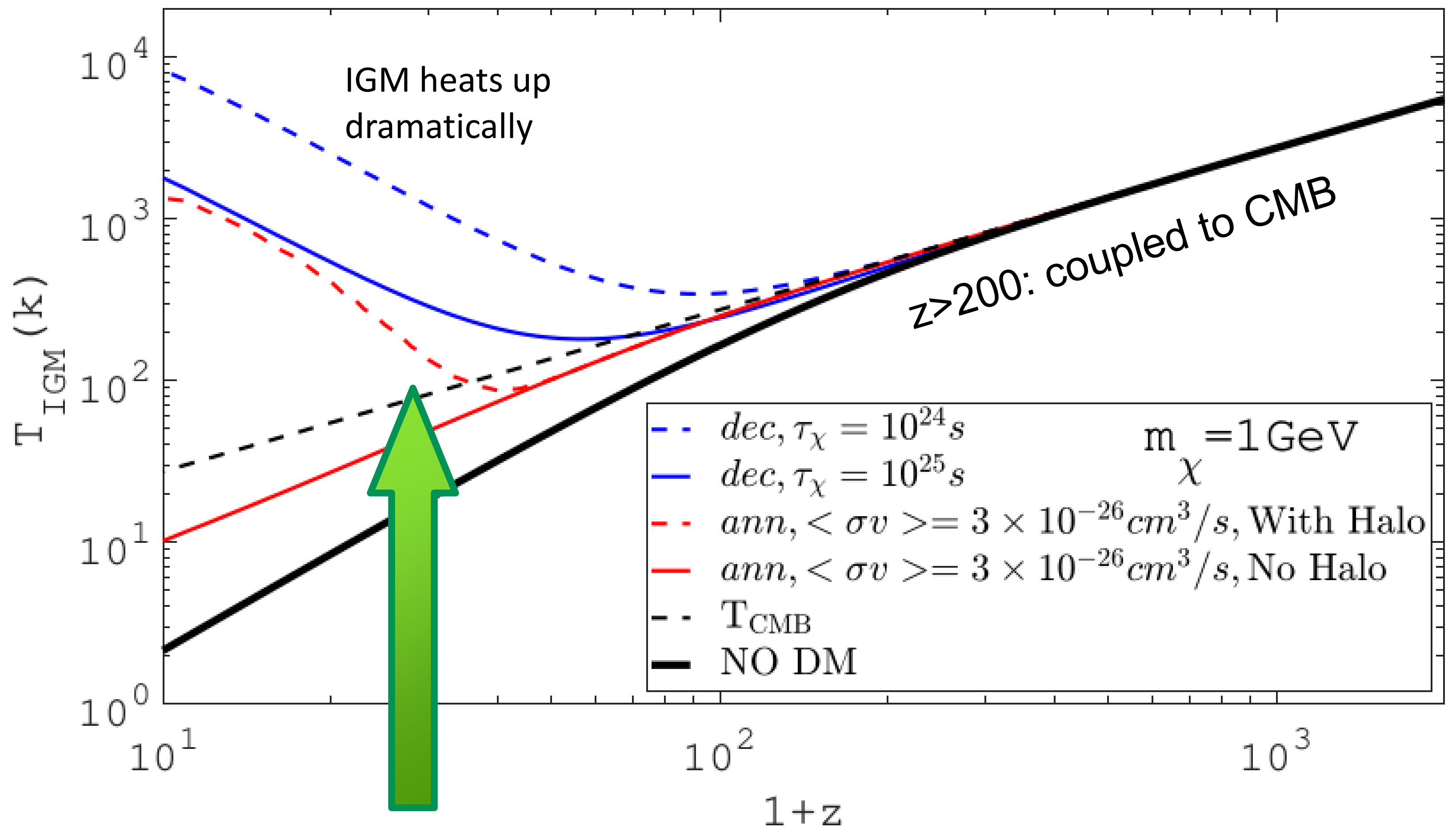


Remember this bump?

poor low-z sensitivity due to EoR

We need a late-time handle.

DM effect #2: IGM temperature

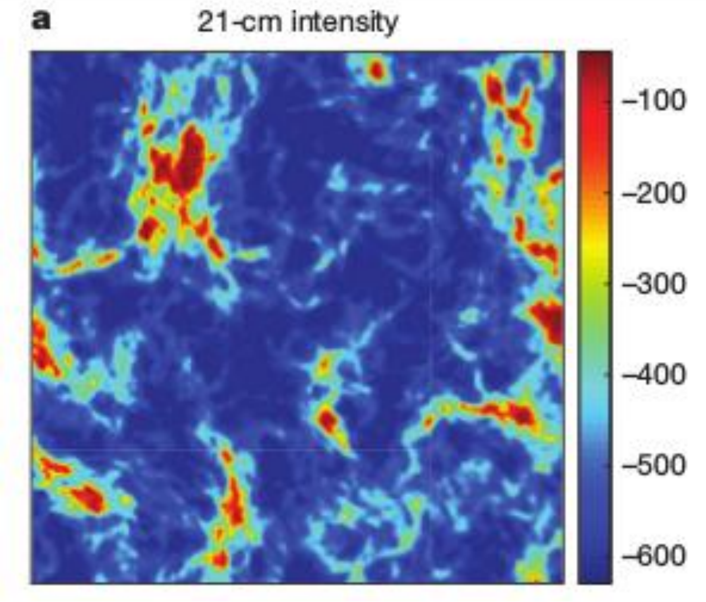


Early EoR observation will be helpful!

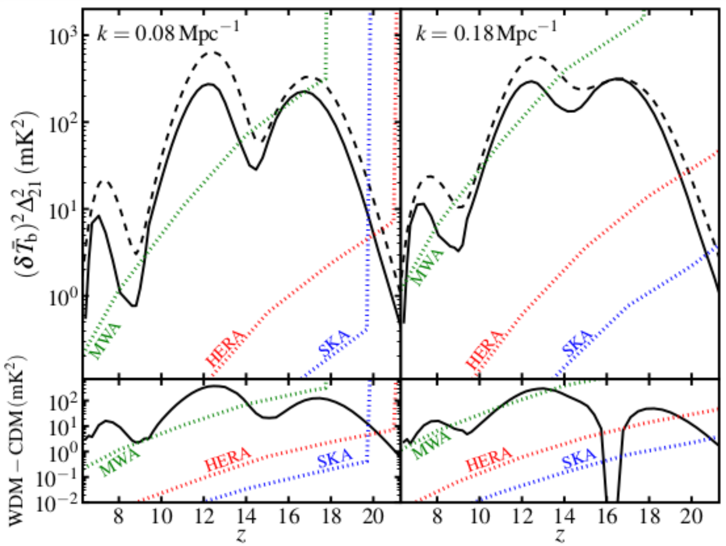
T_{IGM} can rise by $10^{2\text{-}3}$ near EoR

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



Simulated T_{21} map w DM,
Rennan Barkana, nature25791

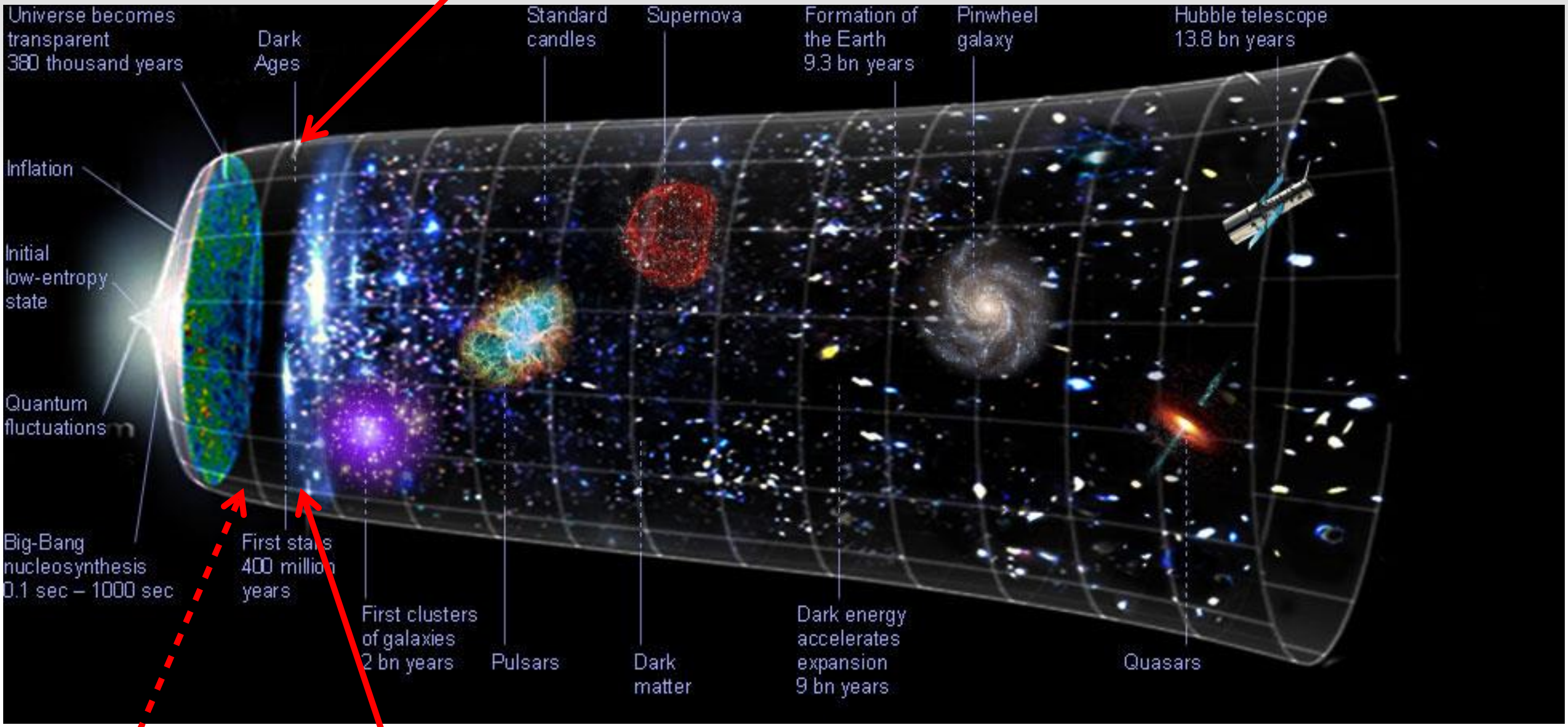


Projected power spectrum sensitivities
(from SKA white paper)

CMB's 21cm absorption windows

(1) neutral Hydrogen presence (2) T_S cooler than the 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 T_{GAS} measurements.

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

ionization

Gas density distribution

Optical depth: Cosmology model-dependent

Gas spin temperature diff. from rad. field

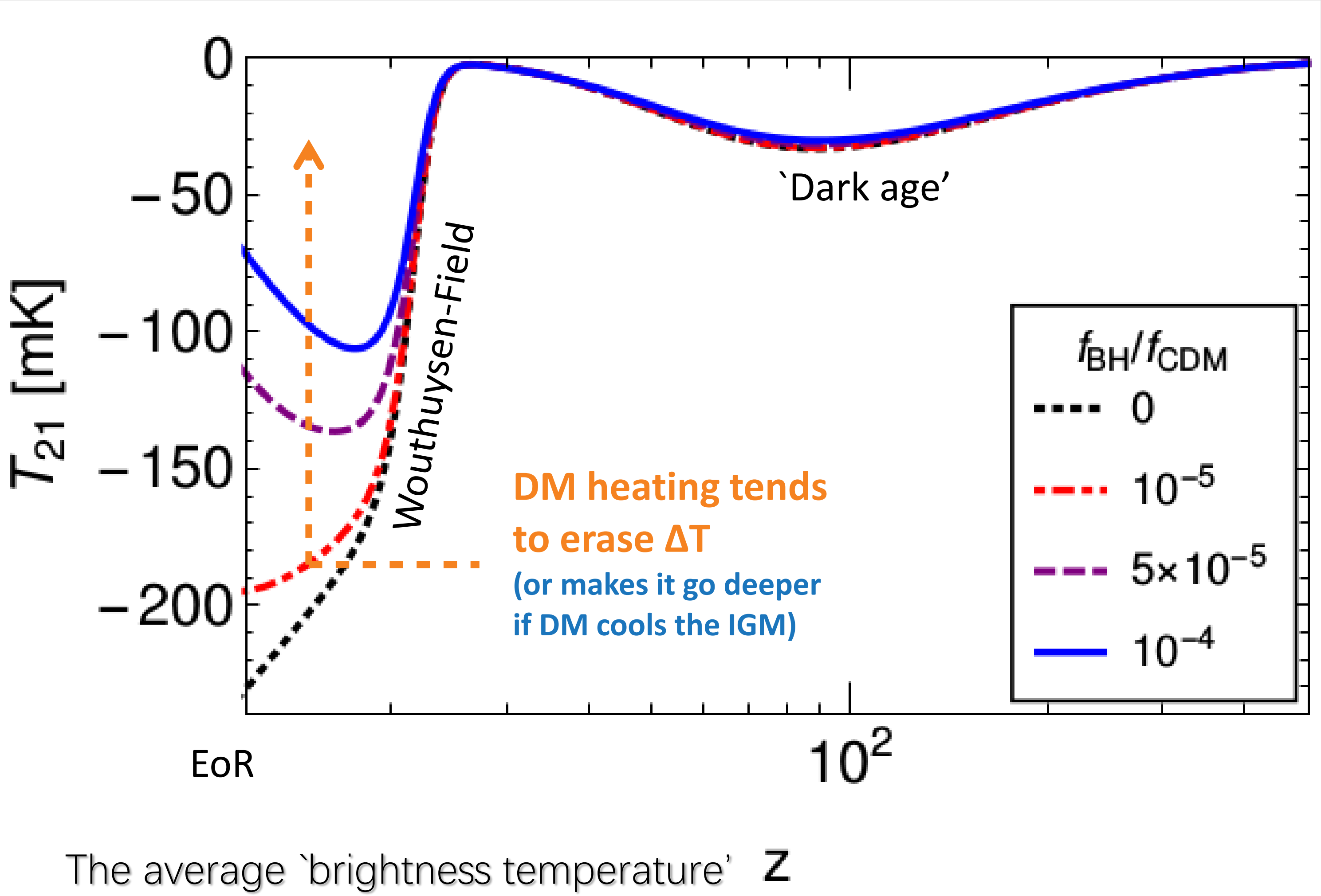
Wouthuysen-Field: $T_{spin} \sim T_{lya} \sim T_{GAS}$ at cosmic dawn

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

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

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

DM induced heating can suppress / erase the 21cm signal



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

EDGES: glimpse of 21cm era?

EDGES 2018

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

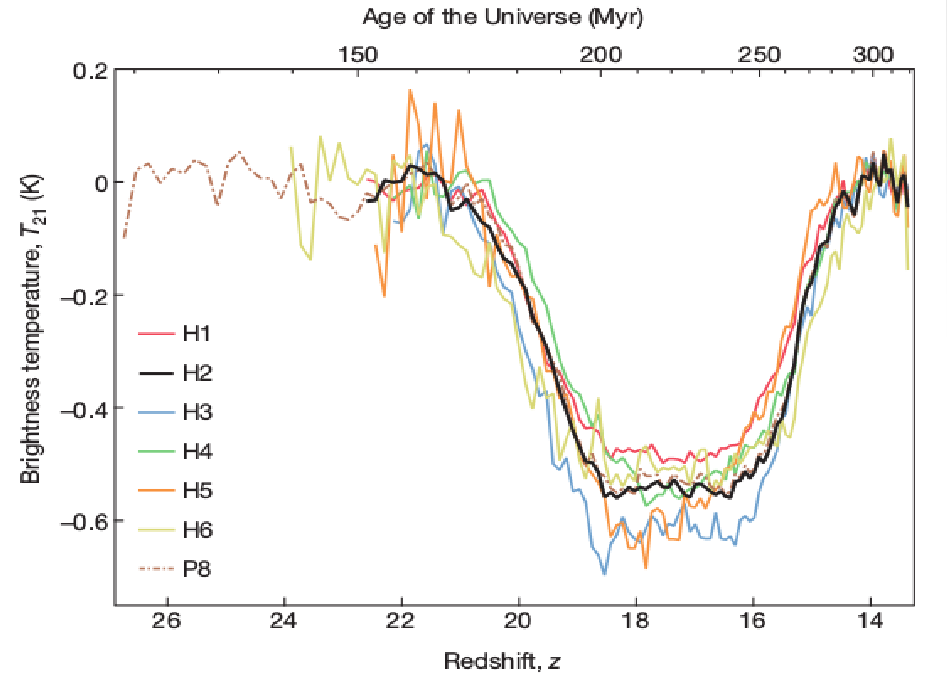
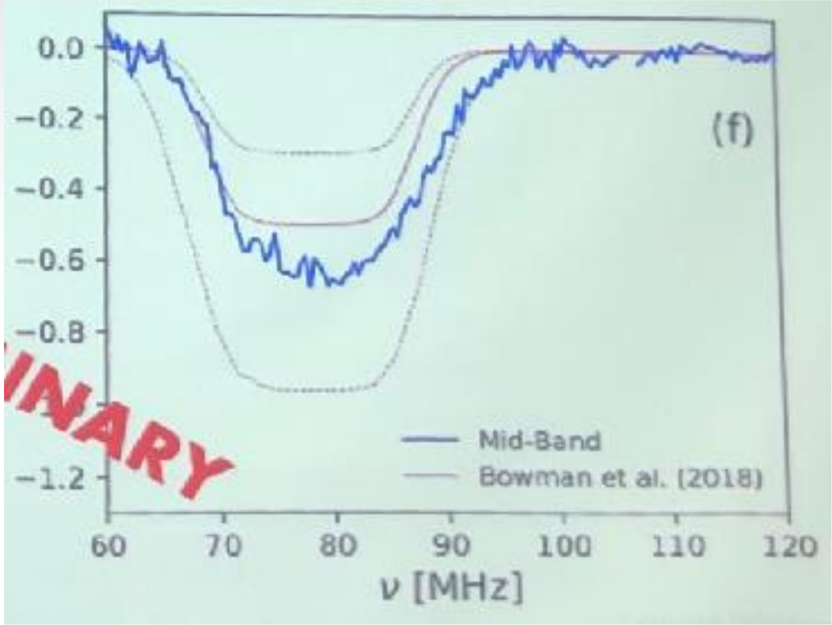
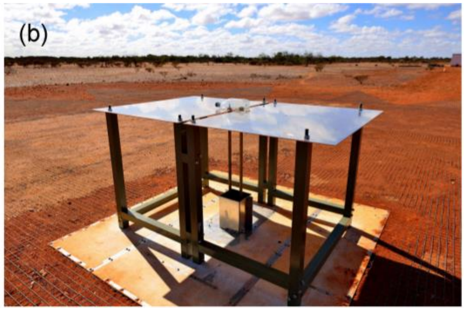


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

2020 (summer)





EDGES: A Discovery near 78 MHz?

~ Twice the LCDM signal !

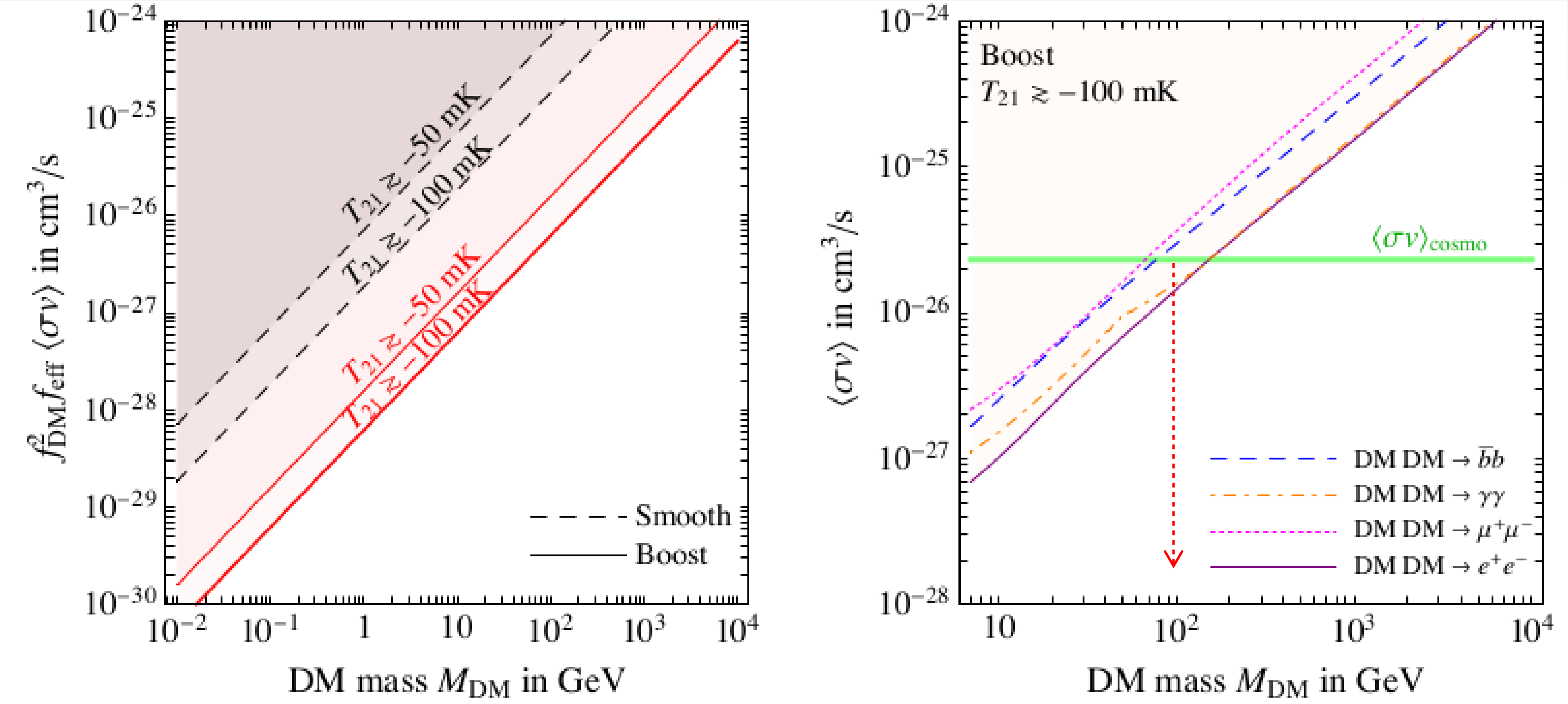
LOFAR & MWA (by 2020)
Upper limits only.

Discovery of 21cm means high WIMP sensitivity

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?

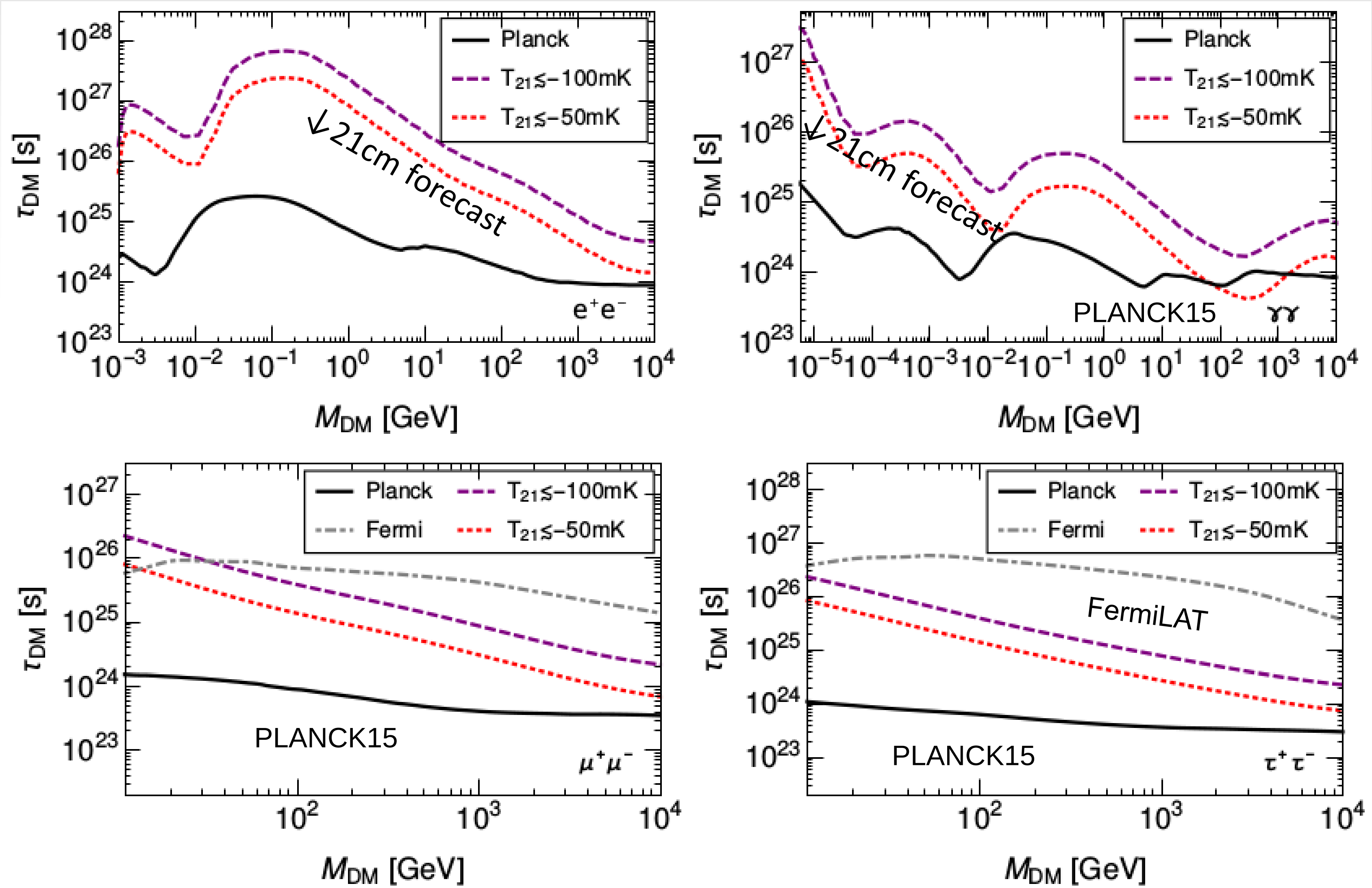


Unlike CMB pol., 21cm is **VERY sensitive** to DM clustering boost

WIMP lifetime sensitivity @ 21cm discovery

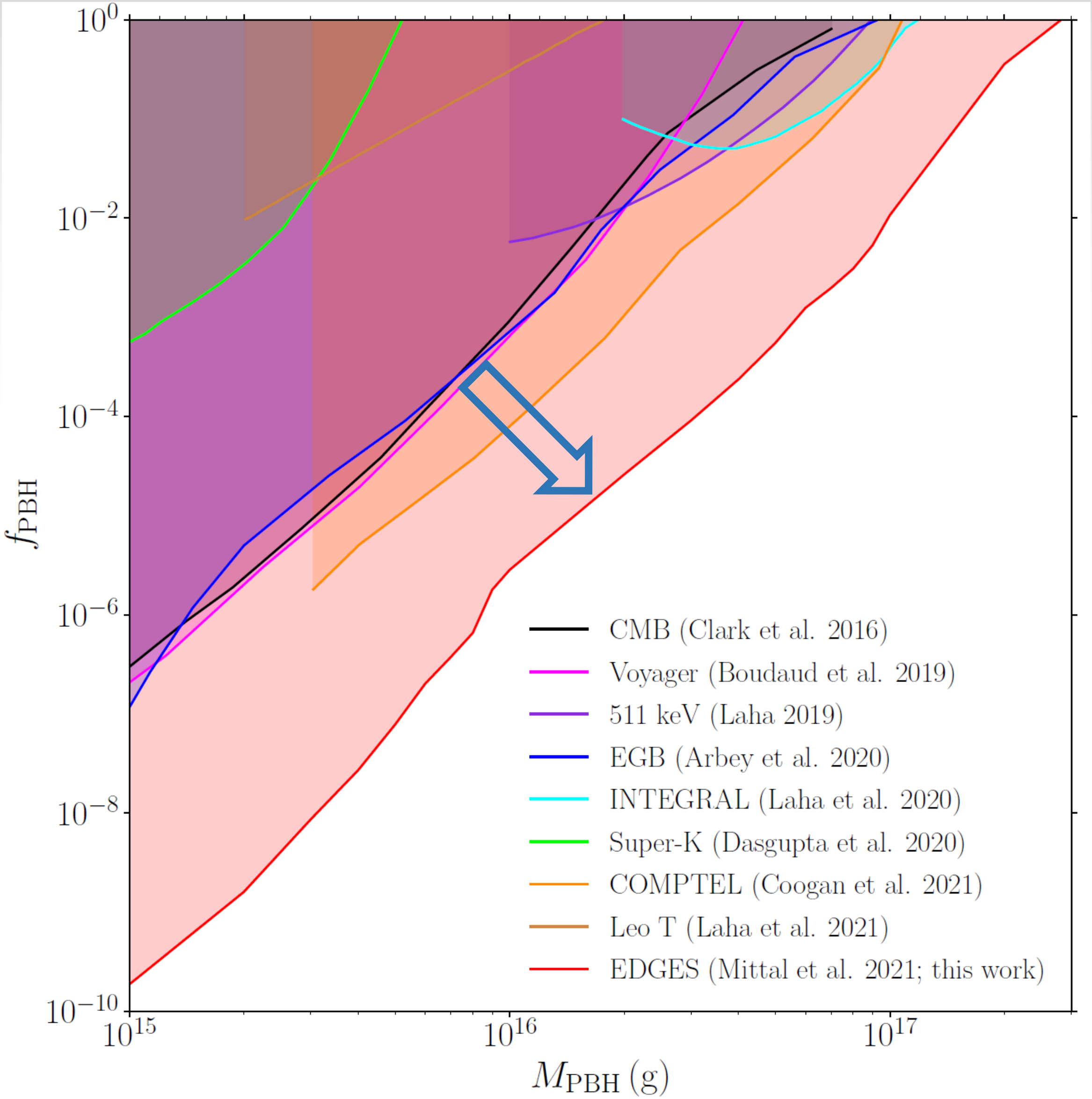
Limit on T_{GAS} rise:
ΔT_{21} < +100 or +150 mK at z=17

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



Decay: unaffected by clustering.

*Better sensitivity if **real data** kicks in.*

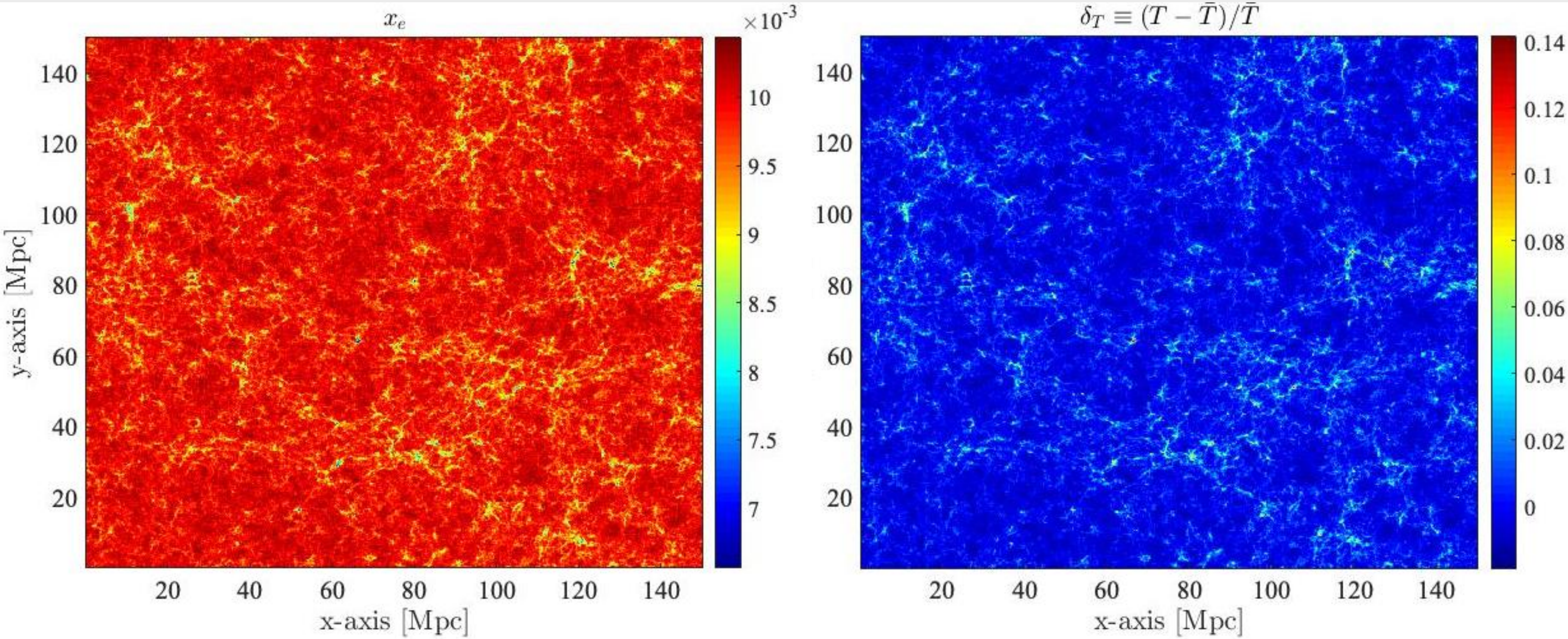


Fit to EDGES data
with X-ray heating model.

Mittal, et.al, 2107.02190

x_e, T inhomogeneity impact 21cm power spectrum

Modified DM energy deposit equation:
inhomogeneous heating terms
+ transport terms

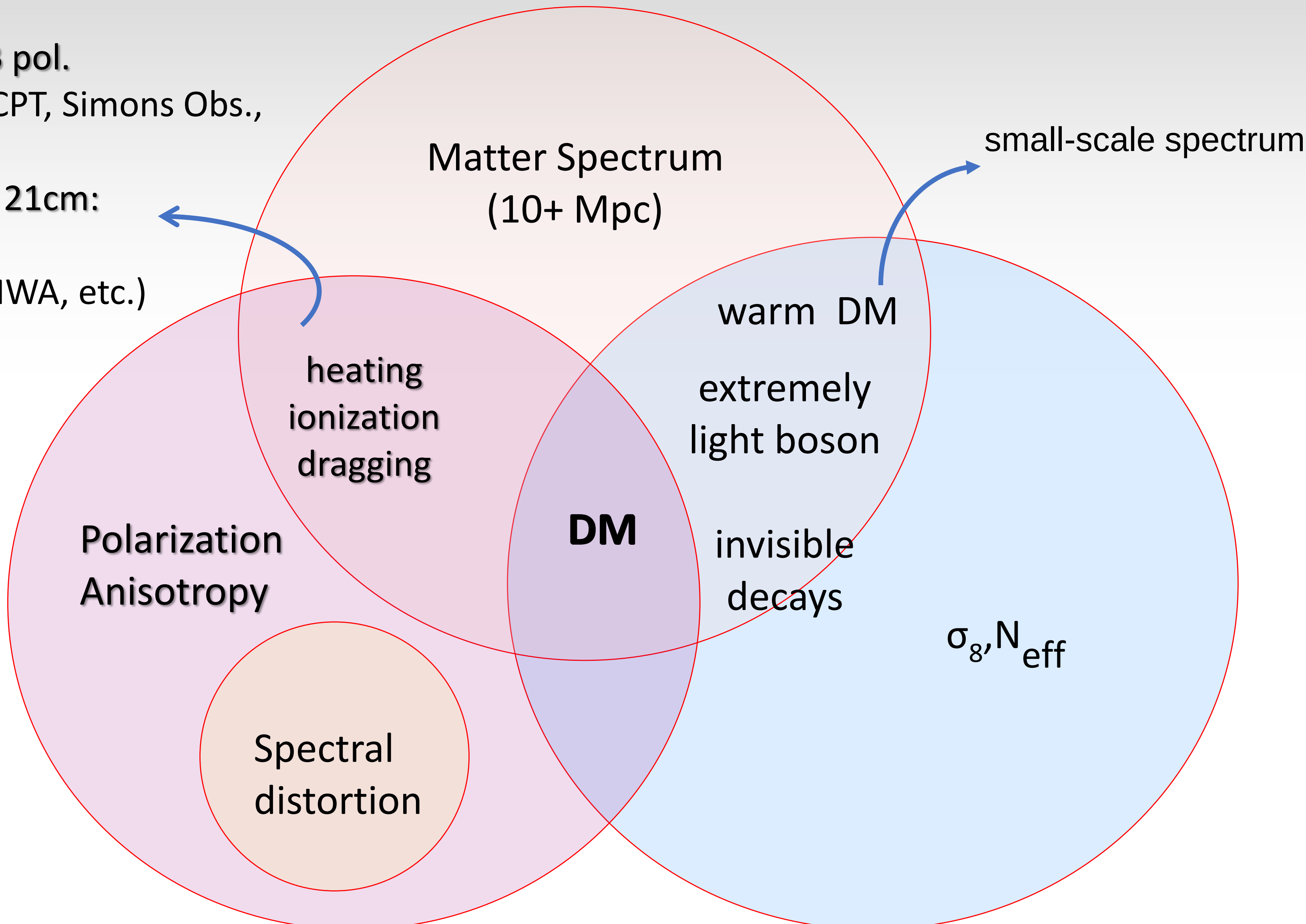


preliminary : (Mpc/pixel, deposit terms only, instantaneous deposition)

J.Cang, Y.Gao, in progress (stay tuned!)

CMB & 21cm: capable of EW, TeV scale DM search.

Upcoming CMB pol.
AdvACTPol, AliCPT, Simons Obs., SPG3, S4, etc..
Very promising 21cm: coming closer?
(EDGES, SKA, MWA, etc.)



backups

Exp. specifications (DM)

Experiment	ν[GHz]	$\omega_{\mathrm{E},\nu}^{-1/2}$ [μK-arcmin]	θ_{FWHM}[arcmin]	f_{sky}[%]	ℓ_{min}	ℓ_{max}
AdvACTPol [20, 58, 59]	28	113.1	7.1	50	350[a]	4000
	41	99.0	4.8			
	90 ⋆	11.3	2.2			
	150 ⋆	9.9	1.4			
	230	35.4	0.9			
AliCPT [60]	90⋆	2	15.4	10	30	600
	150⋆	2	9.7			
CLASS [22]	38	39	90	70	5	200
	93⋆	13	40			
	148⋆	15	24			
	217	43	18			
Simons Array [24, 61]	95⋆	13.9	5.2	65	30	3000
	150⋆	11.4	3.5			
	220	30.1	2.7			
Simons Observatory - SAT [25]	27	35.4	93	10	25	1000
	39	24	63			
	93⋆	2.7	30			
	145⋆	3	17			
	225	6	11			
	280	14.1	9			
Simons Observatory - LAT [25]	27	73.5	7.4	40	1000	5000
	39	38.2	5.1			
	93⋆	8.2	2.2			
	145⋆	8.9	1.4			
	225	21.2	1			
	280	52.3	0.9			
SPT-3G [19, 61, 62]	95⋆	5.1	1	6	50	5000
	150⋆	4.7	1			
	220	12.0	1			

[a] AdvACTPol constraints would improve by a factor of 2 if choosing $\ell_{\mathrm{min}} = 60$.

Exp. specifications (PBH)

Experiment	f_{sky}	ℓ_{min}	ℓ_{max}	ν (GHz)	δP (μK-arcmin)	θ_{FWHM} (arcmin)
COrE [45, 46]	0.7	2	3000	90	7.3	12.1
				100	7.1	10.9
				115	7.0	9.6
				130	5.5	8.5
				145	5.1	7.7
				160	5.2	7.0
CMB-S4 [56, 57]	0.62	30	3000	95	2.9	2.2
				145	2.8	1.4
PICO [48, 49]	0.7	2	4000	90	2.1	9.5
				108	1.7	7.9
				129	1.5	7.4
				155	1.3	6.2
LiteBIRD [47]	0.7	2	200	89	11.7	35
				100	9.2	29
				119	7.6	25
				140	5.9	23
Simons Array [53, 54]	0.65	30	3000	95	13.9	5.2
				150	11.4	3.5