Dark Matter & the CMB

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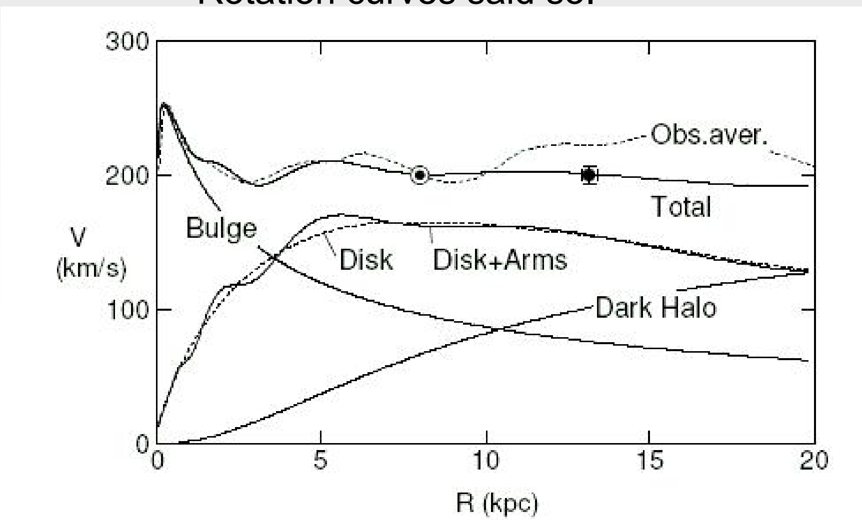
Outline

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

Dark matter out there…

Rotation curves said so.

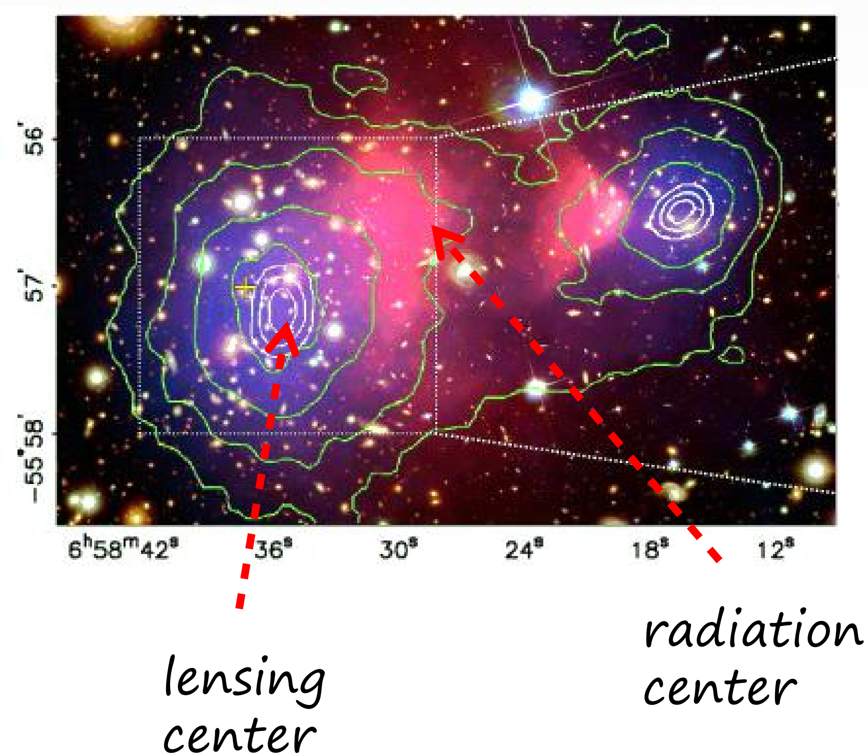


SCIENCE

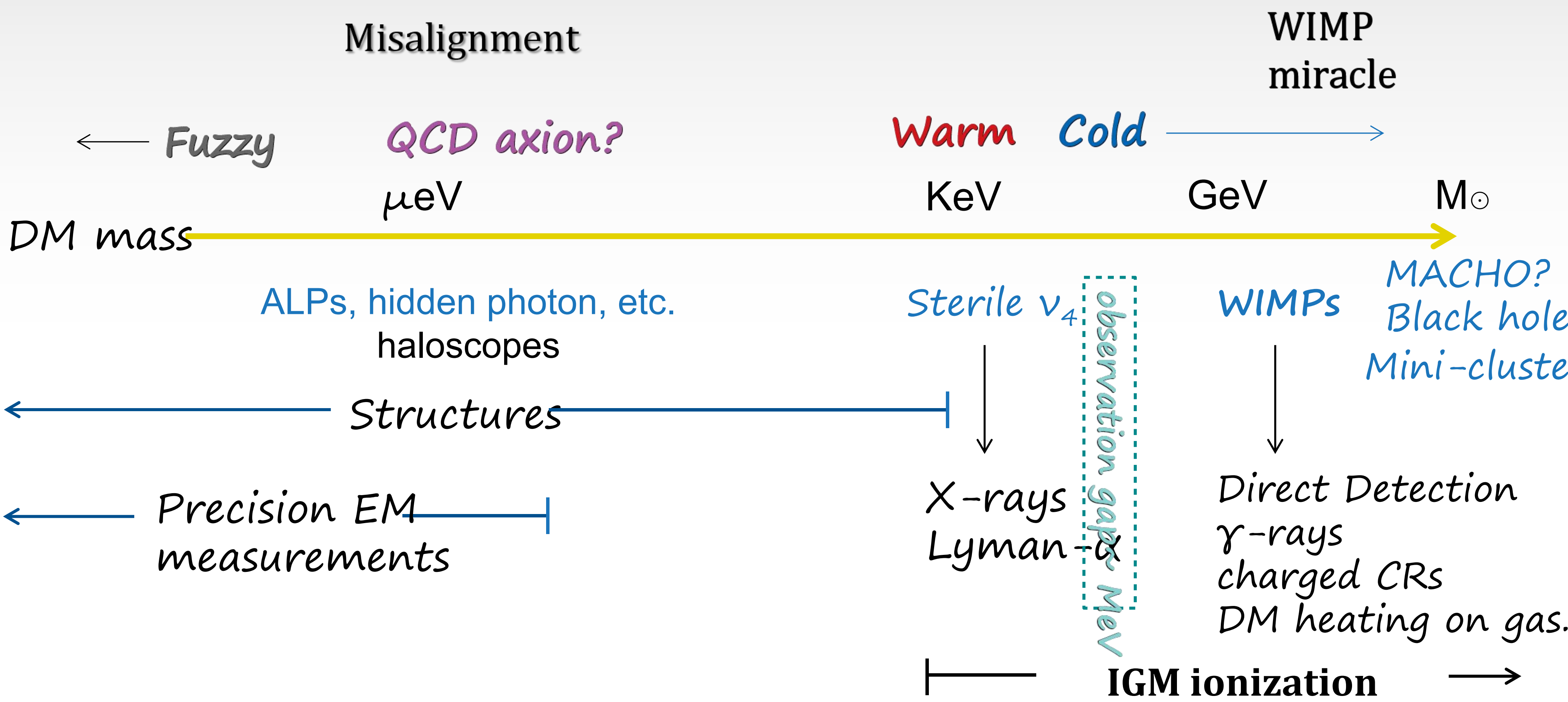
Heart of darkness: Scientists probe dark matter near Milky Way's core

DM got'be `matter', right?

1E0657-56 'Bullet cluster'

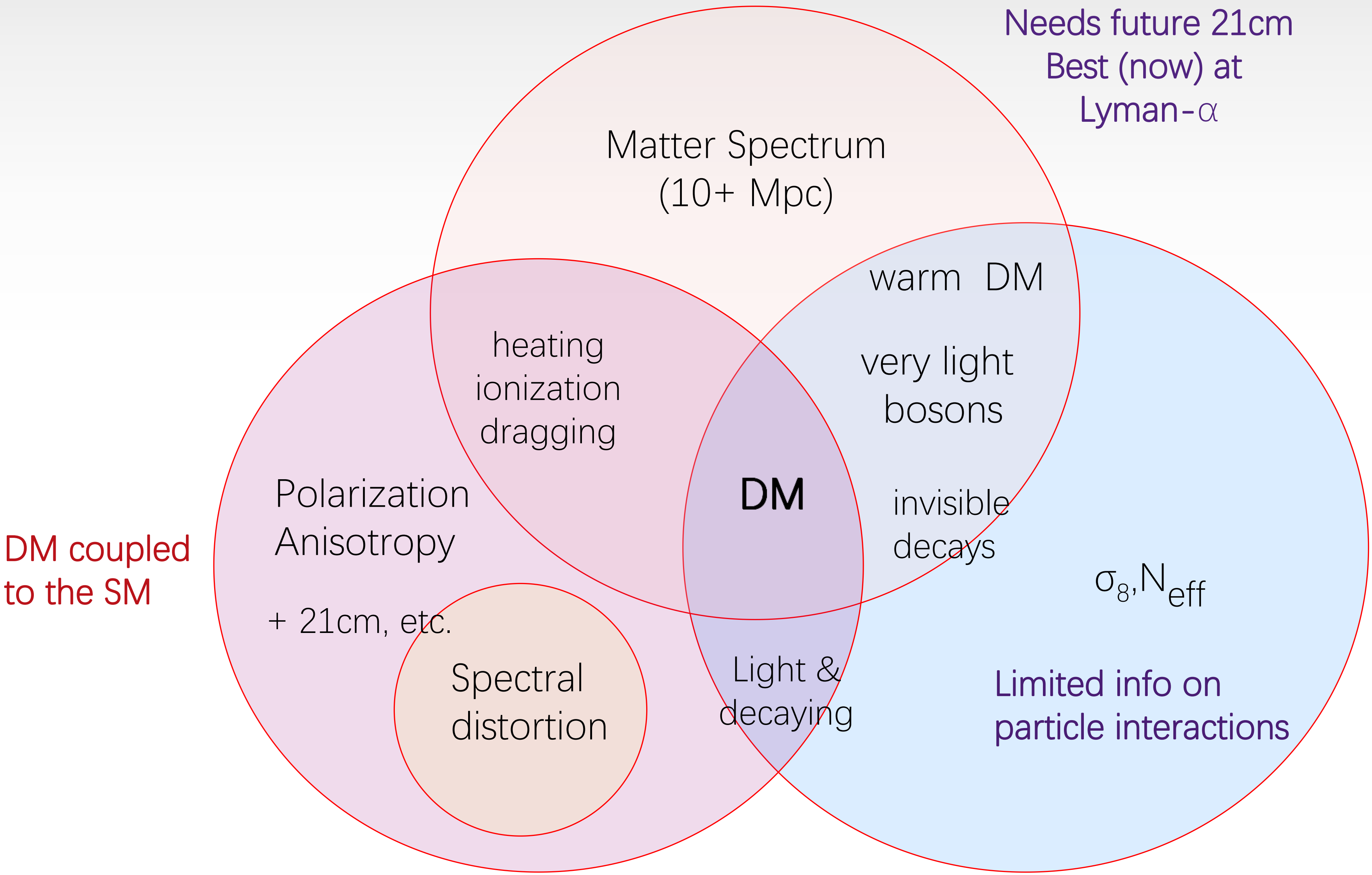


Theory orders are placed.



CMB covers a wide DM mass range!

CMB and Dark Matter – how?



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

DM probes from the CMB

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  `coupled' DM, early/steady energy injection,
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- 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 (line search: $\tau > 10^{28}$ s)
IGM ionization pre-EoR (PLANCK)	$\tau > 10^{24}$ s
IGM heating pre-EoR (21cm,projected)	$\tau > 10^{26}$ s

The `standard' ionization history

Standard ionization evolution (pre-EoR)

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

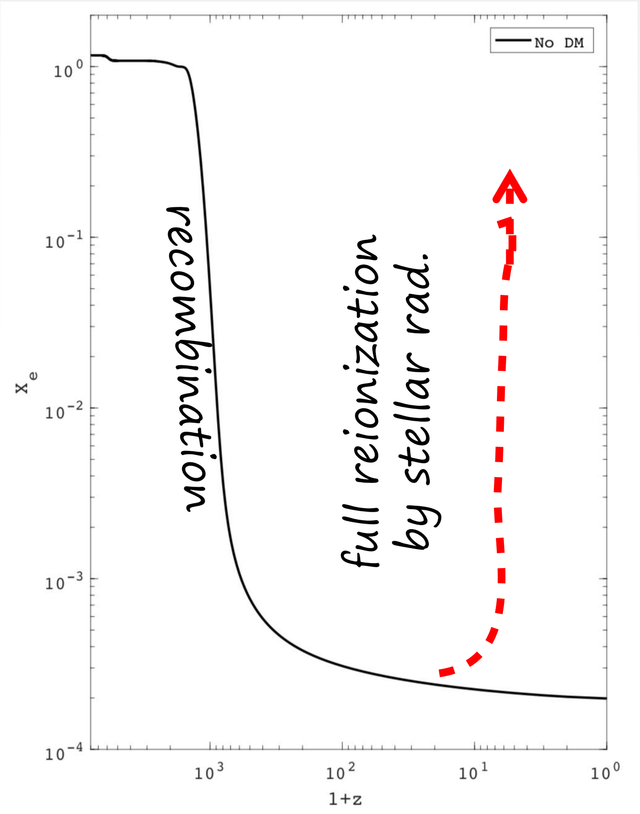
Ionization rate (by radiation field):

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

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

"Deposit Channels"

ionization from ground state

ionization from excited states

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

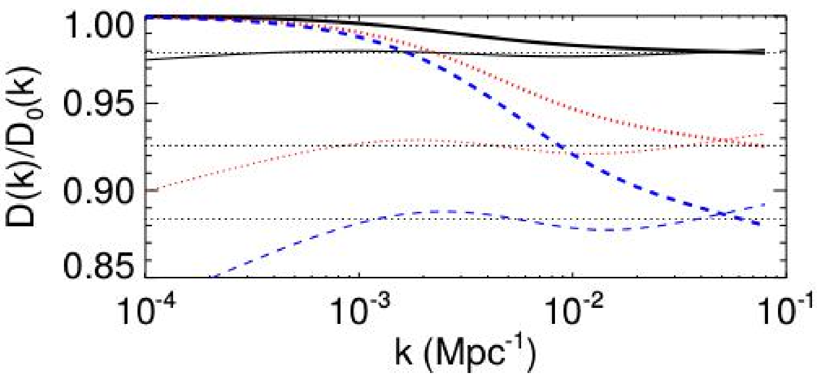
SM: H atom ionization and recombination

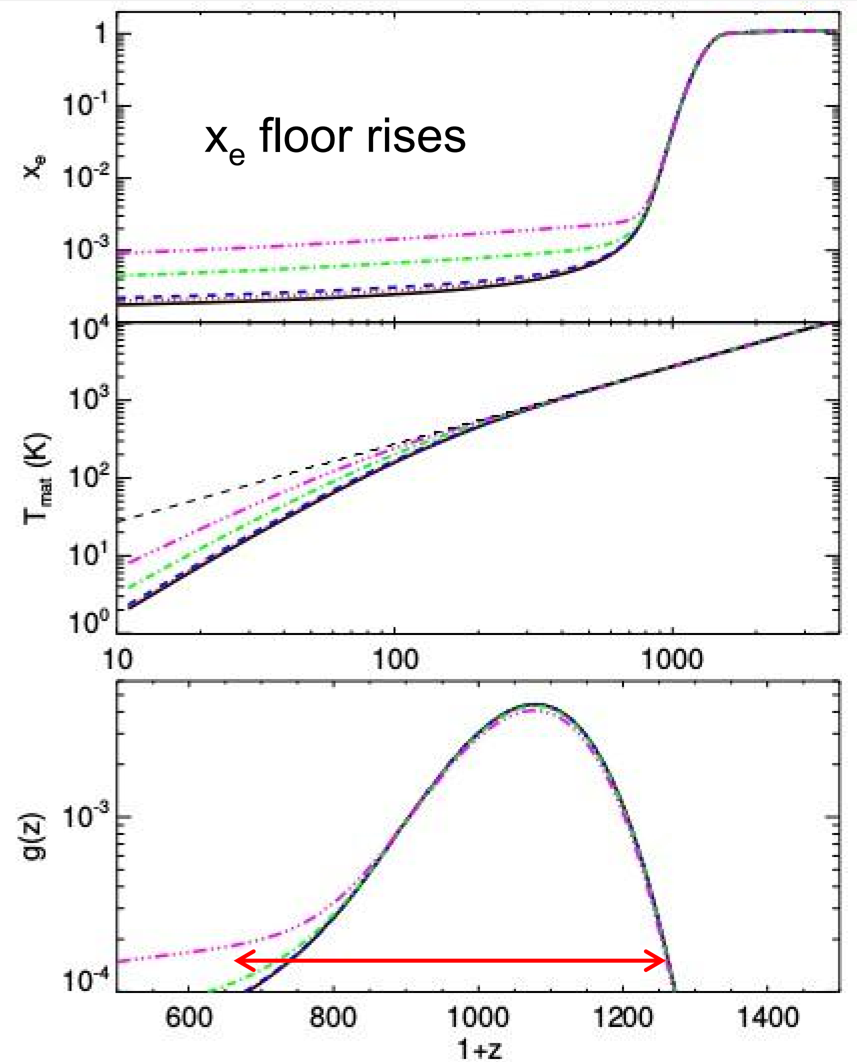
(+ other channels)

The `perturbed' ionization history

Ionization enhances photon scattering

in the damping function:





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,

$\sim (z+1)^6$

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

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

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

DM Decay: a steady rate, unaffected by structure formation

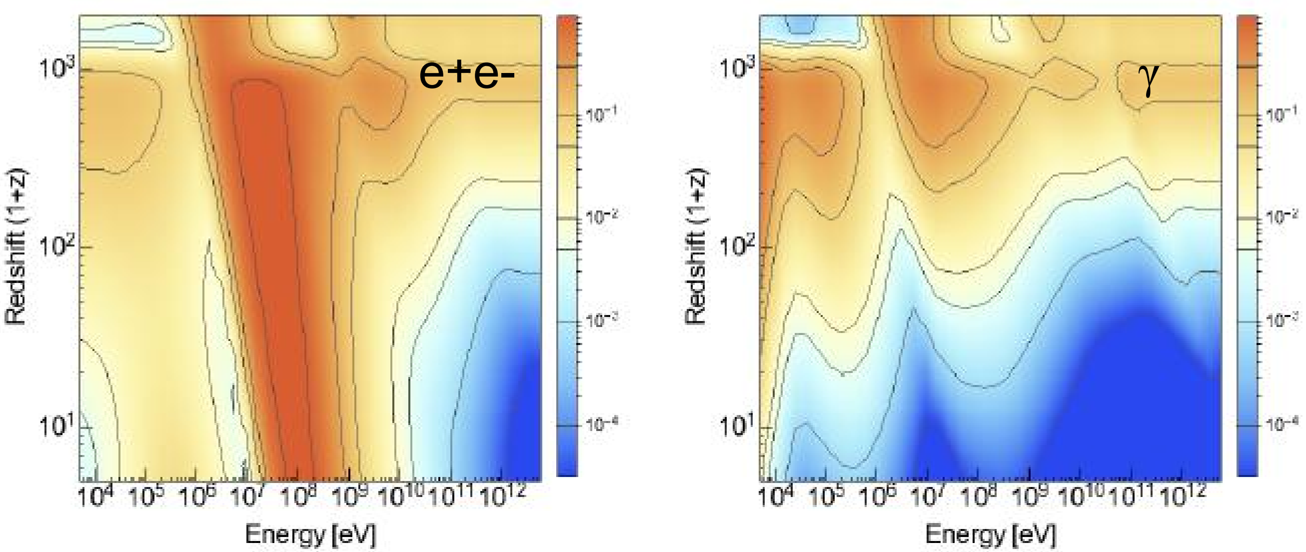
$\sim (z+1)^3$

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 ter[m]
Lyman-α photons, etc.

Also see:
Belotsky, Kirillov 2015

- Compute a history-dependent deposit “efficiency” f (E,z)

$$f_c \equiv \left(\frac{dE_{tot}}{dV dt}\right)_{DEP} \Big/ \left(\frac{dE_{tot}}{dV dt}\right)_{INJ}$$

(from sim.) (from theory)

$$f_{\rm c}(z_{\rm i}) \approx \frac{\sum_s \sum_{\rm j} \sum_{\rm k} E^s_{\rm j} I^s(z_k, E^s_j) {\rm d}V(z_{\rm k}) {\rm d}t(z_{\rm k}) T^s_{\rm c,ijk} {\rm d}E^s_{\rm j}}{\sum_s \sum_{\rm j} E^s_{\rm j} I^s(z_i, E^s_j) {\rm d}E^s_{\rm j} {\rm d}V(z_{\rm i}) {\rm d}t(z_{\rm i})}$$

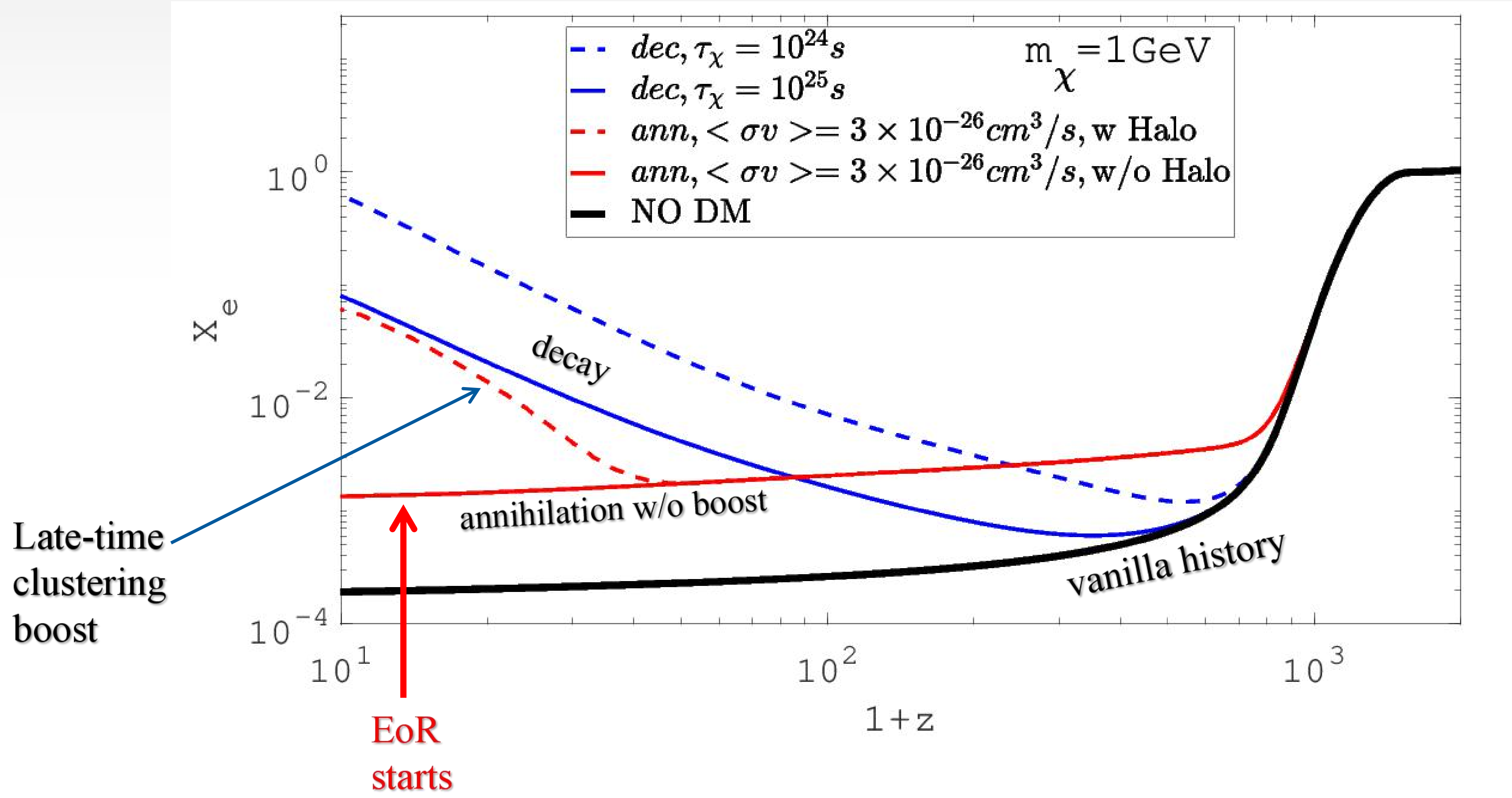
- Averaged over injection spectra *(j)* and species *(s)* and integrated over all previous redshift $(z_k > z_i)$
- Electrons are more effective than gamma rays at large energy
- Photons extends to (much) lower mass range

Simulated eff. T_{ijk}
`DarkHistory’
Liu, Ridgway, Slatyer, 19’

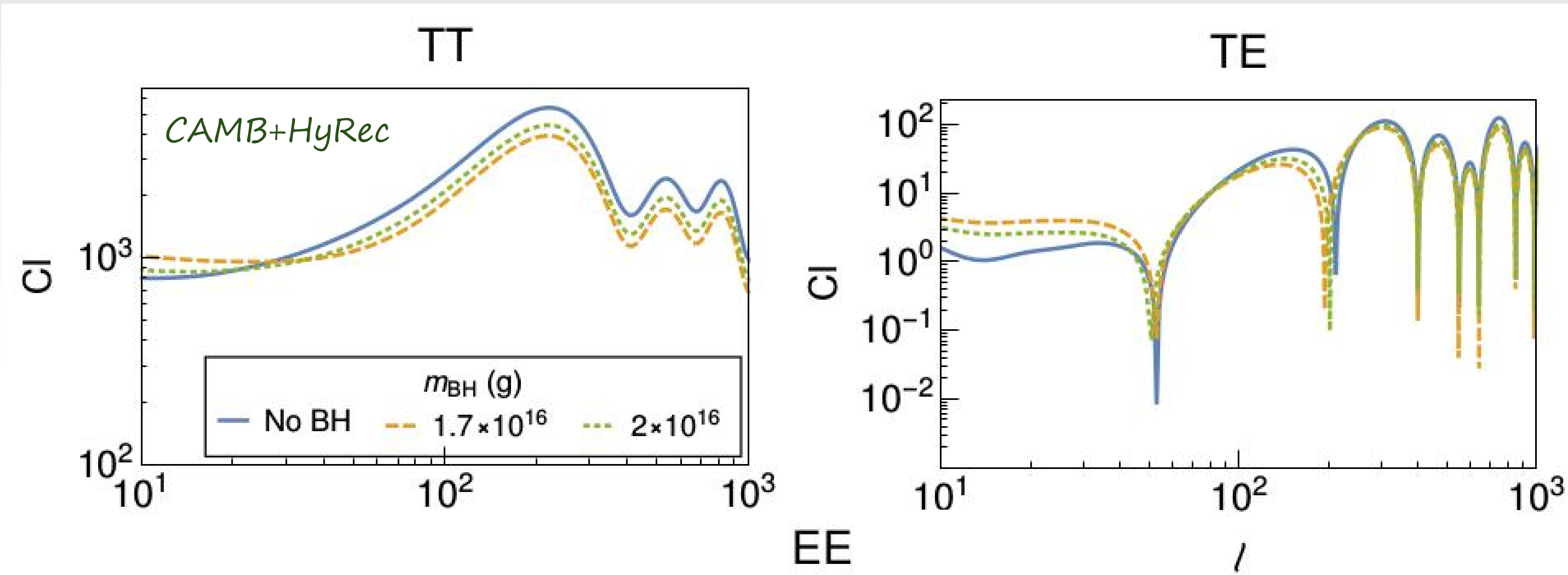
DM: impact on xe

Annihilation: raises the x_e floor,

Decay: steady rise in x_e

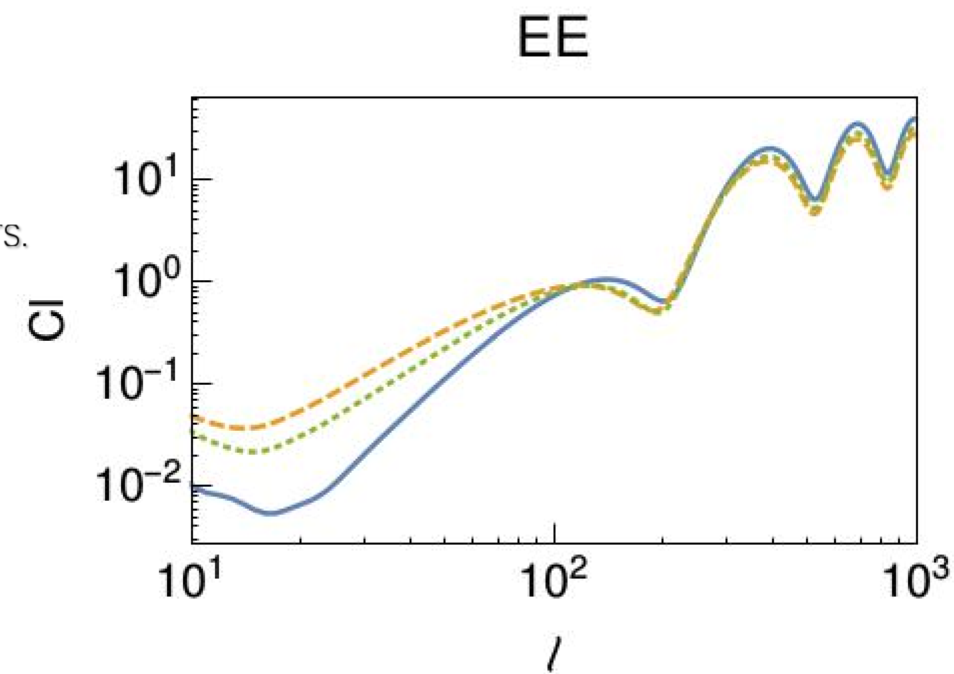


Xe on CMB C_l: damping & pol. peak shift



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

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



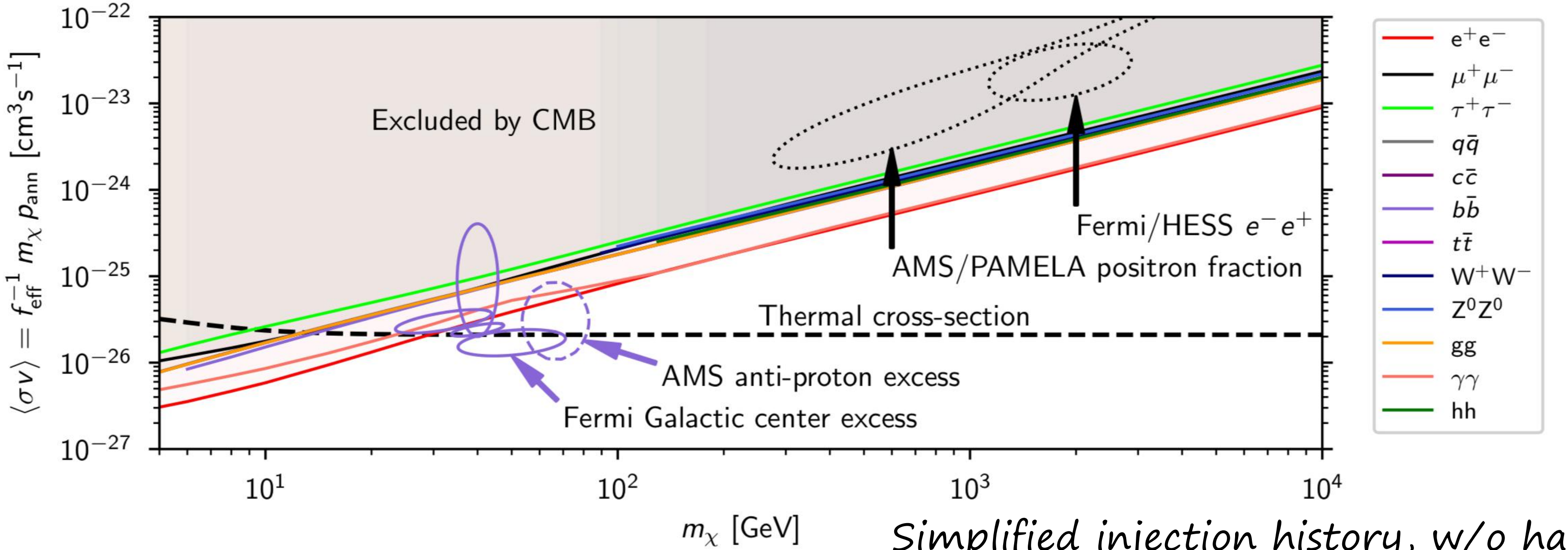
LSS broadening increases polarization perturbation amplitudes

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

* enhances damping

Current limits: WIMP annihilation

Planck Collaboration: Cosmological parameters

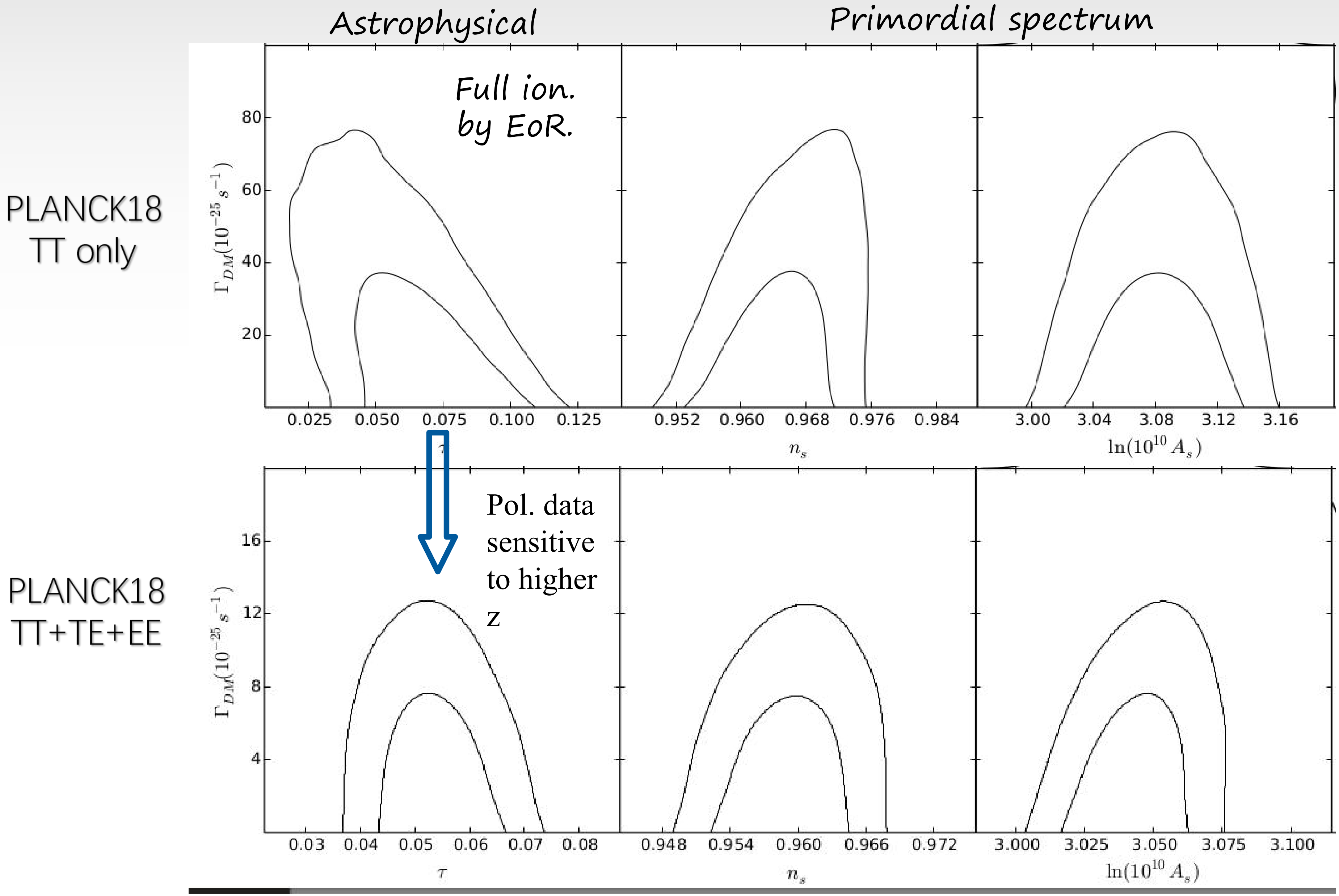


Simplified injection history, w/o halo boost

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 $p_{\rm ann} < 3.2 \times 10^{-28}\,{\rm cm}^3\,{\rm s}^{-1}\,{\rm GeV}^{-1}$. 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:
`Cosmological parameters'
Thermal WIMP mass limit: 10~30 GeV

PLANCK 18: Pol. data lifts EoR degeneracy



Pol. EE peak shifts make the call

Astrophysical ionization ~ EoR saturation

Overall anisotropy spectral shape

	TT	TT,TE,EE
τ	-0.22	-0.04
n_s	0.59	0.14
$\ln(10^{10} A_s)$	0.17	0.27
$\Omega_b h^2$	0.17	0.07
$\Omega_c h^2$	-0.08	0.16
$100\theta_{MC}$	-0.37	-0.28

TABLE I. Linear correlation coefficients between $\langle \sigma v \rangle / m_\chi$ and cosmological parameters corresponding to Fig.3.

Data: PLANCK18

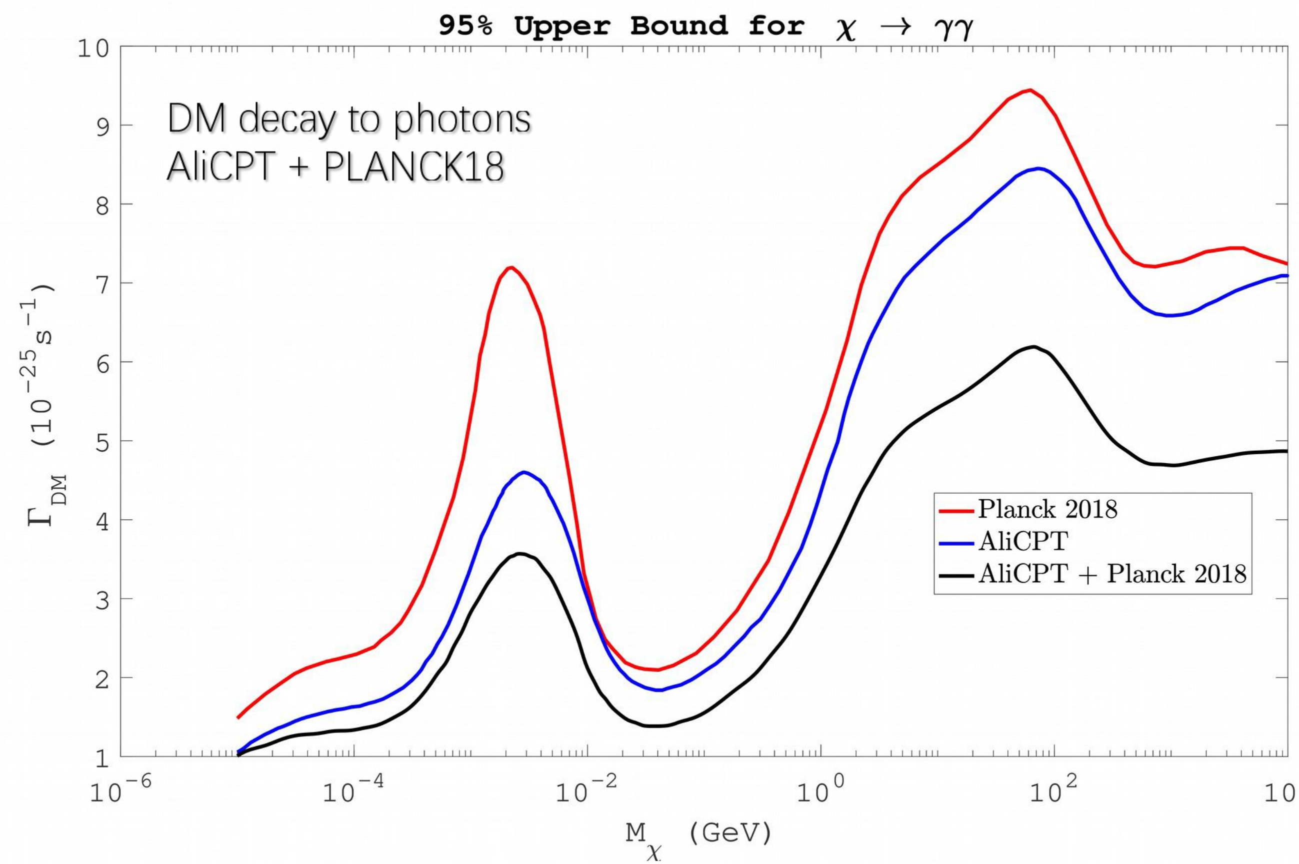
Polarization ani. C_l
TE, EE peak location shift sensitive to higher z (~recombination) effects

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

AliCPT: China's upcoming CMB pol. observatory



by Junsong Cang

Stat: Noise + CV

~ 40% improvement in combined analysis
(for DM sensitivities)

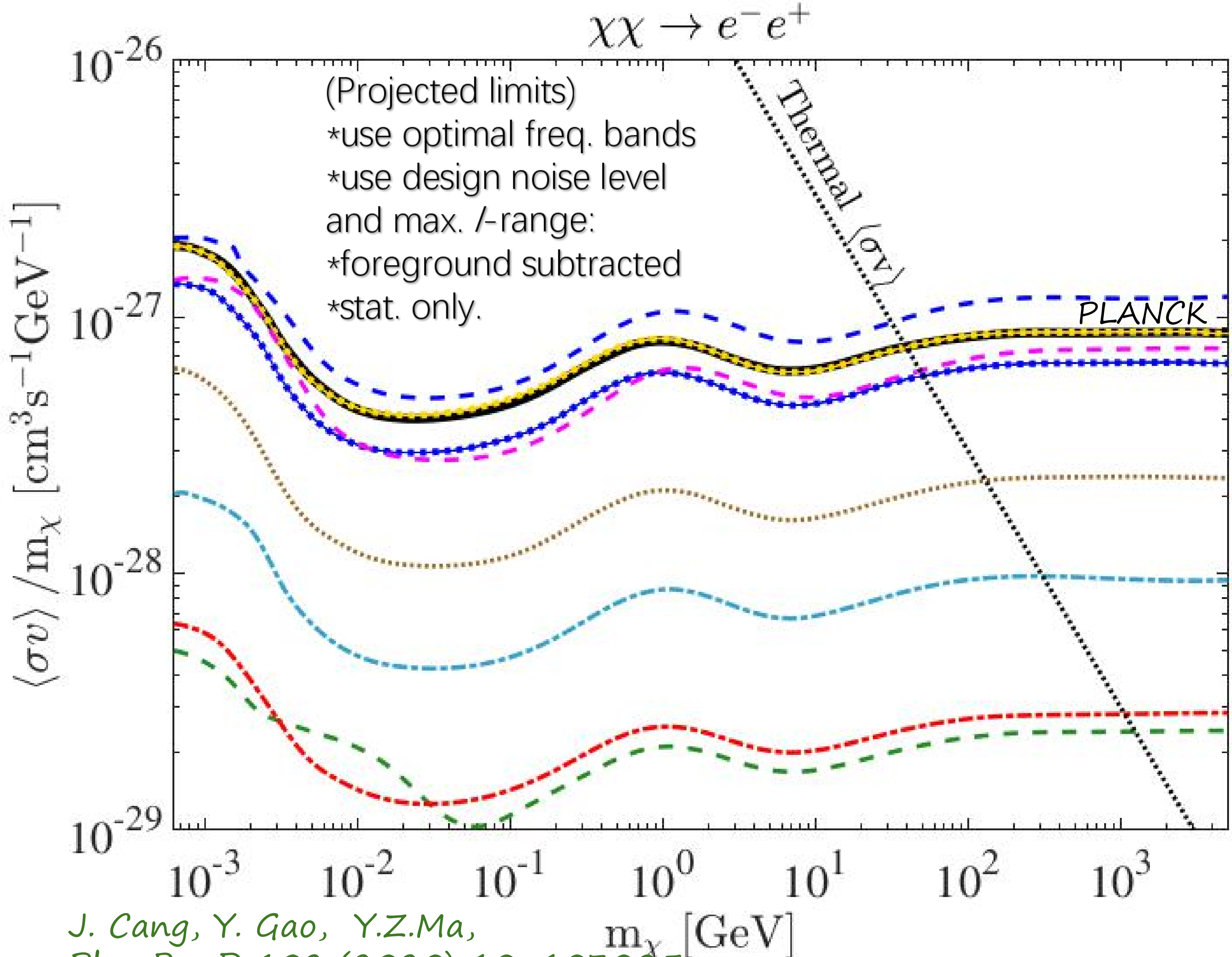
$$N^{EE}_{l,f} = \frac{l\ (l+1)}{2\ \pi}\ \omega_{EE}\ e^{l(l+1)\frac{\theta_f^2}{8ln2}} \qquad (1)$$

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

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)

Forecast on Thermal WIMP mass (ee channel)

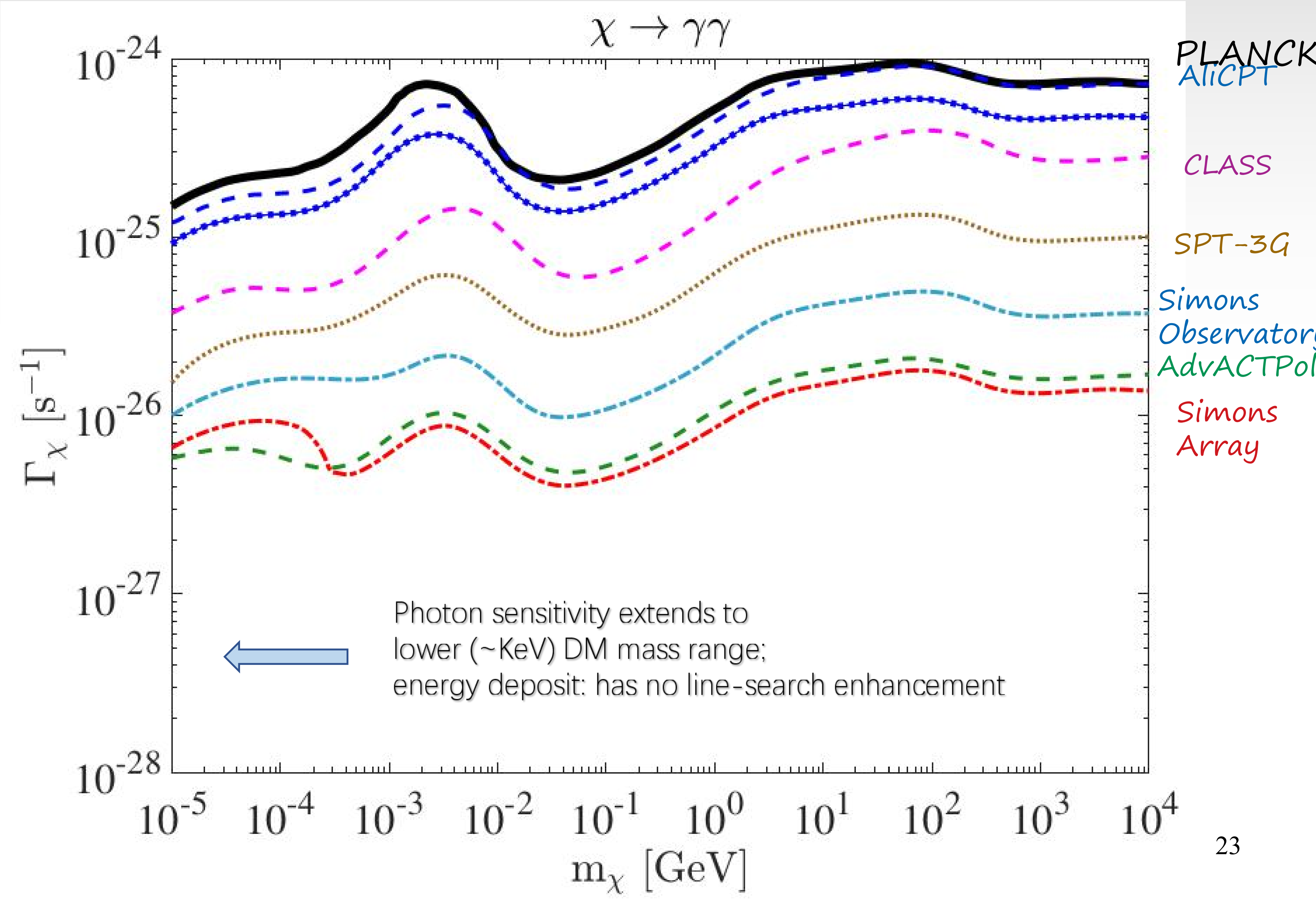
~ Keck/BICEP3



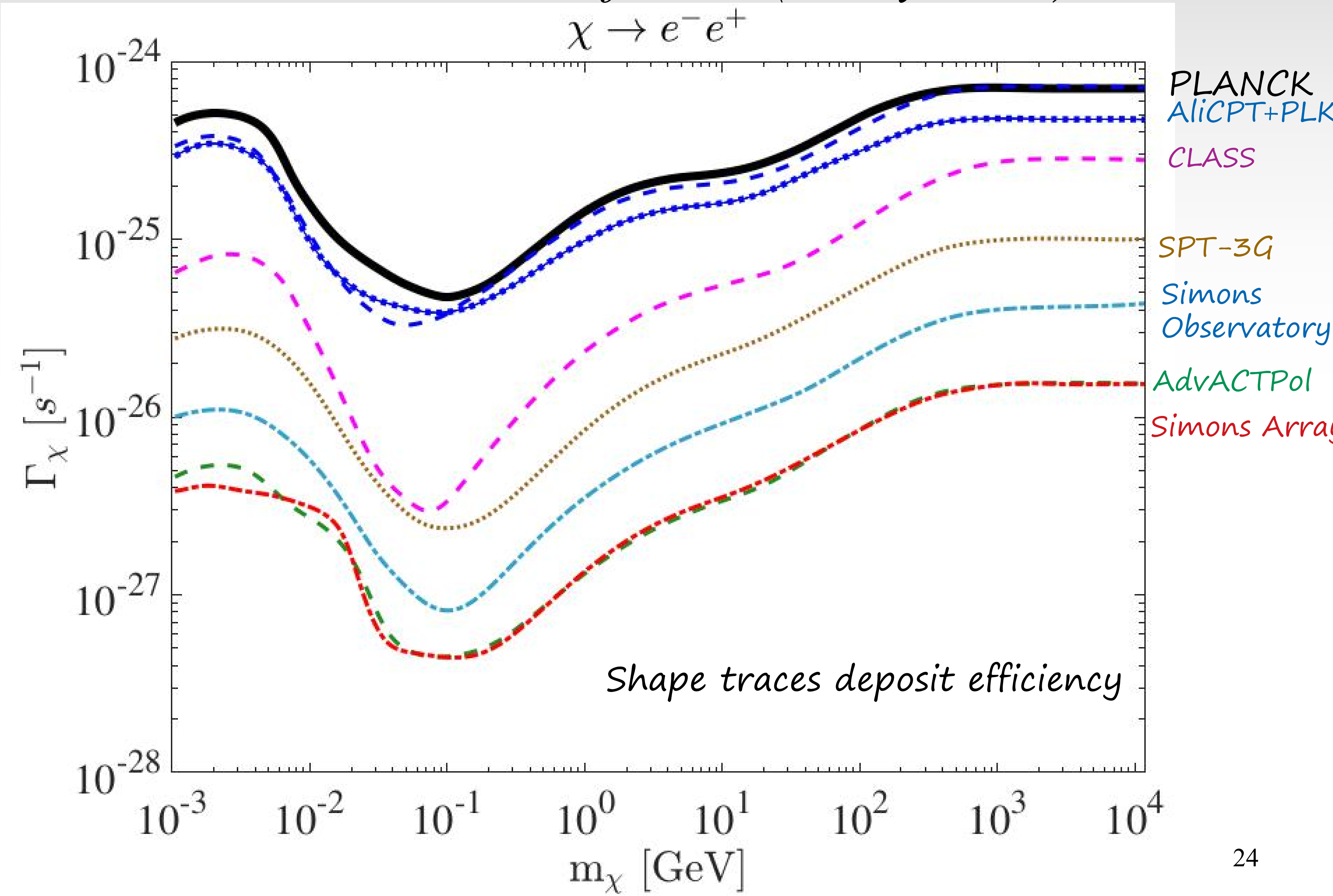
AliCPT
PLANCK
CLASS
AliCPT+PLK
SPT-3G
Simons Observatory
Simons Array
AdvACTPol

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

Forecast on WIMP lifetime (decay to photons)



Forecast on WIMP lifetime (decay to ee)



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.

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

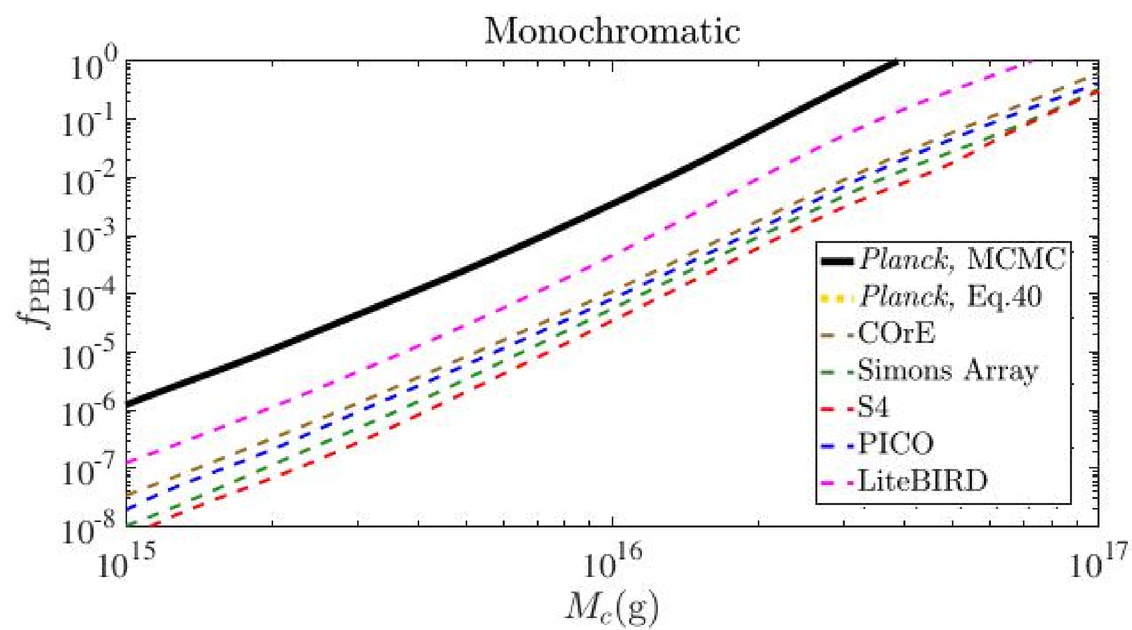
TABLE III. Expected 95% C.L. lower limit on m_χ (in GeV) assuming a thermal relic's annihilation cross-section $\langle \sigma v \rangle = 3 \times 10^{-26}$ cm^3/s.

Low mass PBHs, radiation

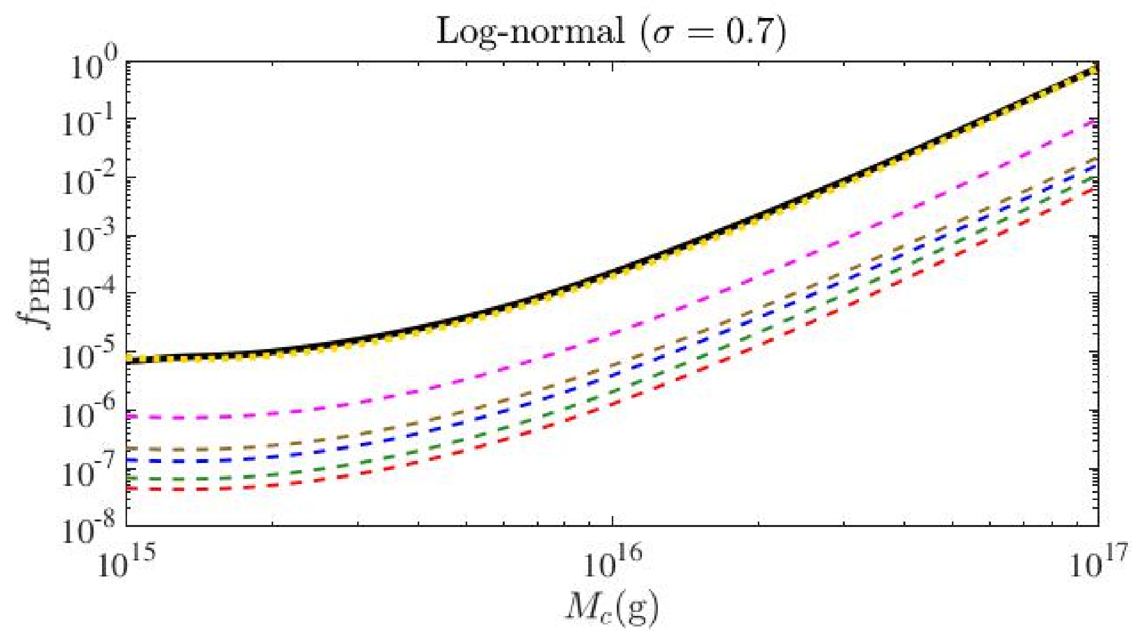
PBH's Hawking radiation has a $dE/dt \sim (1+z)^3$ history

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 & 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

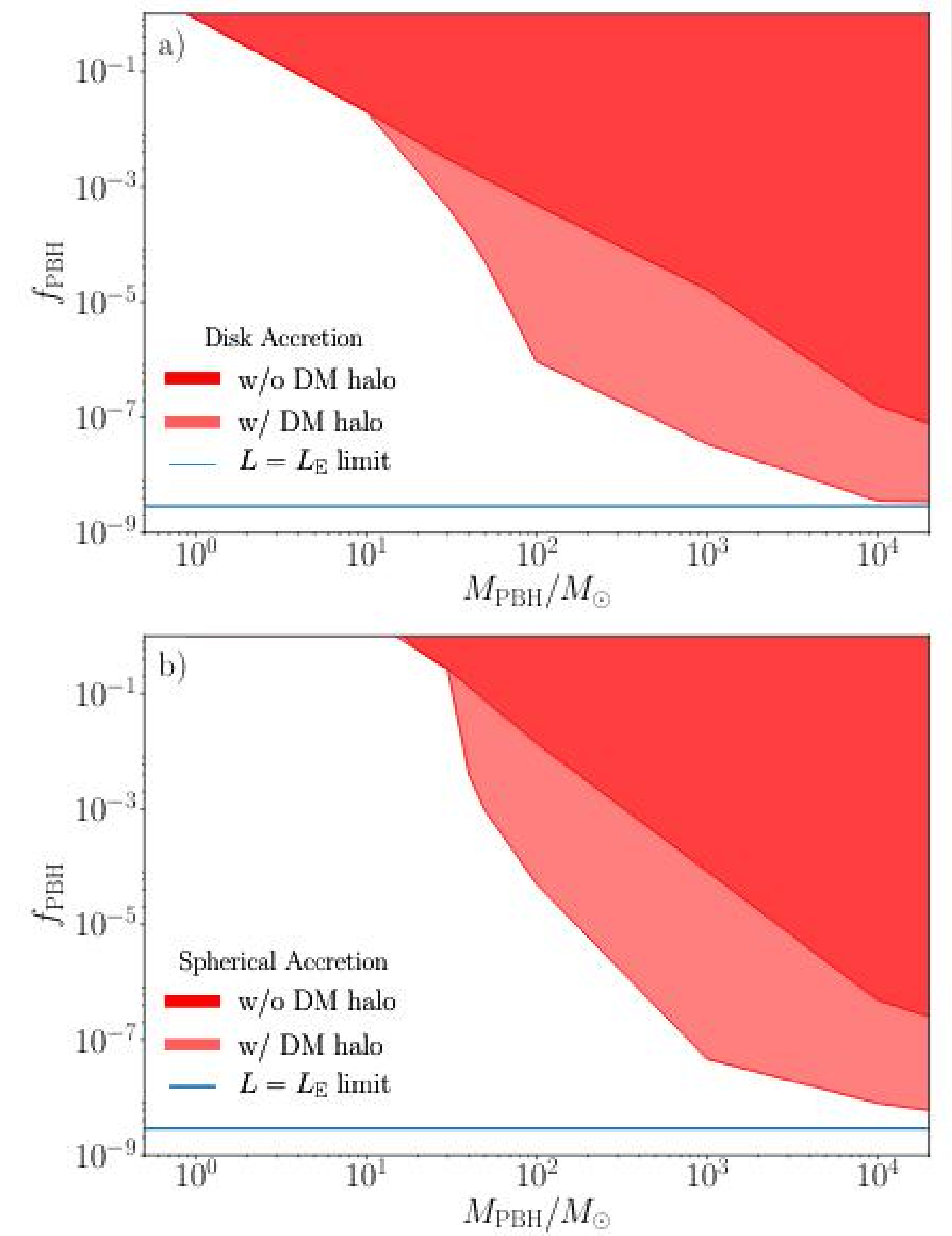
BH accretion radiation (solar-supermassive)

Masive BHs
10 -10^4 M_{sun}

CMB constraint on ionization radiation

PLK18 data

Serpico, Poulin, Inman, Kohri, 2002.10771



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

- Mostly via extra ionization, breaks degeneracy in τ – looks good!
- (Annihilation) Not very sensitive to clustering boost

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

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

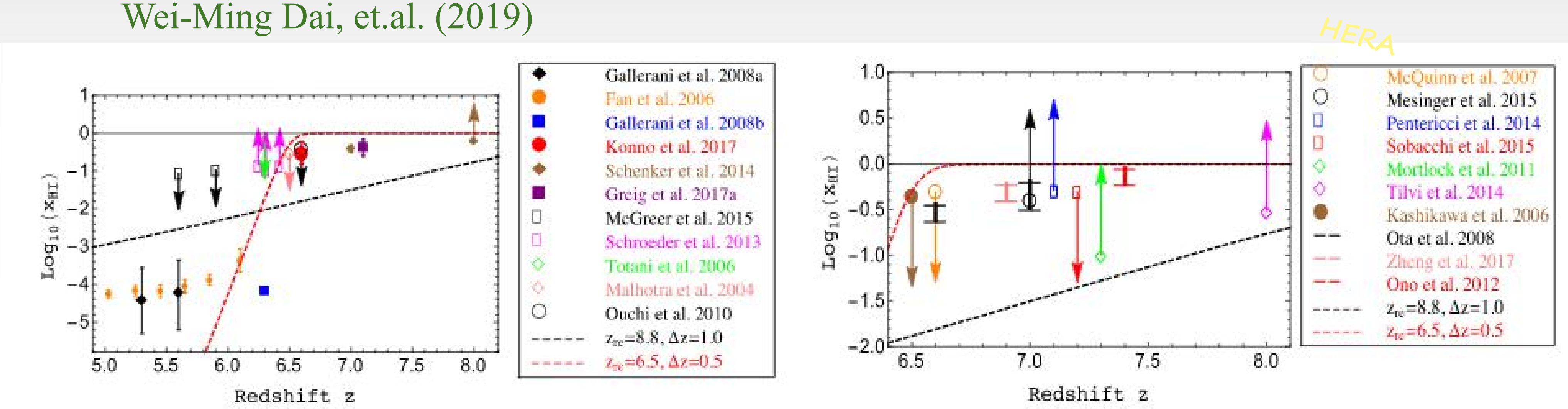
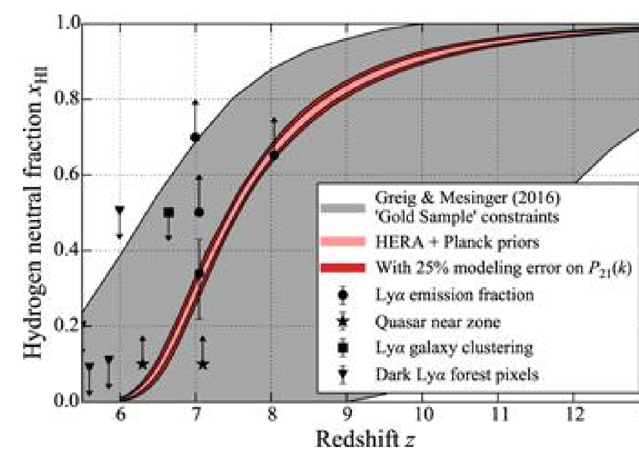


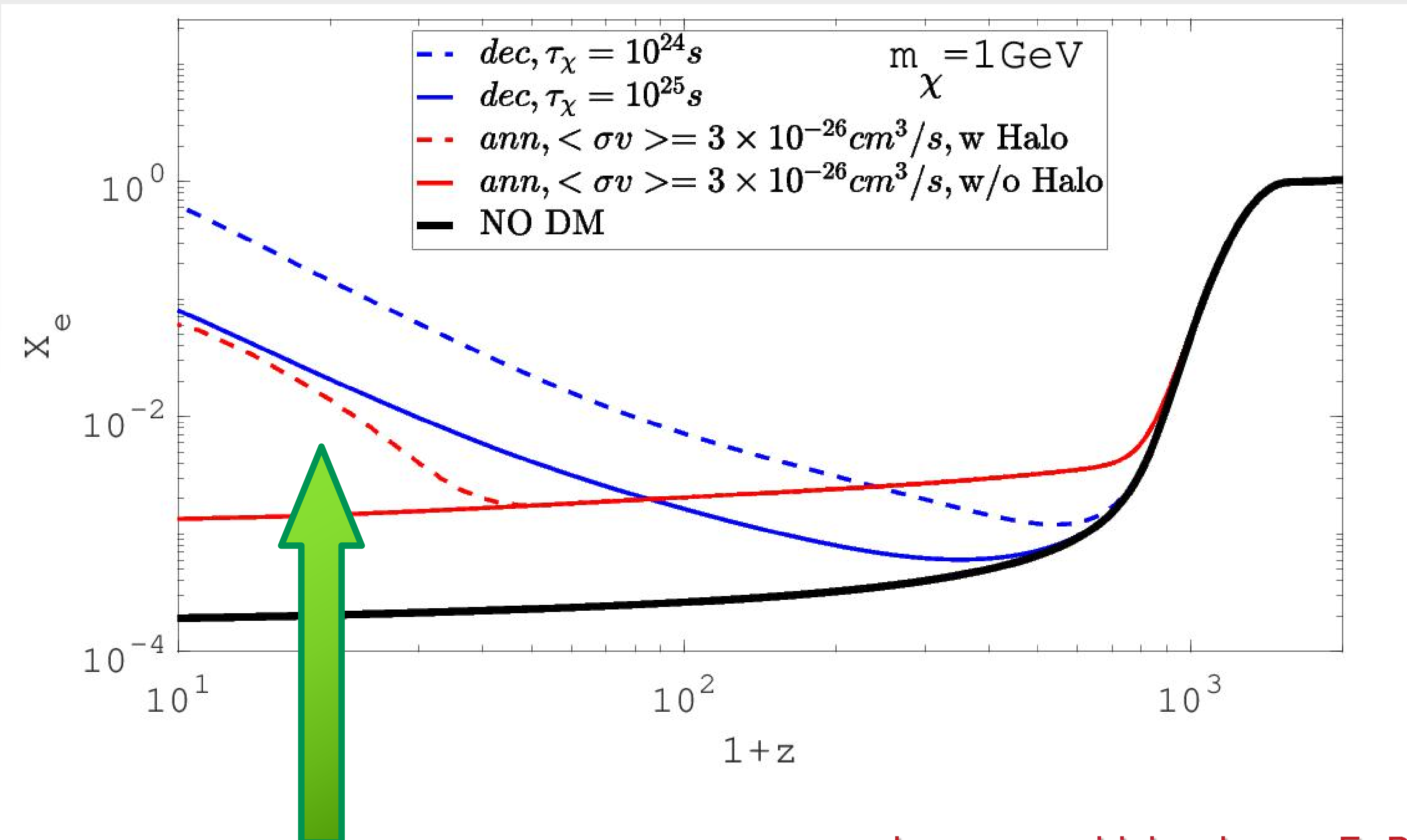
FIG. 4: The state-of-the-art measurement on $x_{\rm HI}(z)$, taken from Table I. The black and red dashed lines are two examples of the "tanh" model which cannot fit the data very well.

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

EoR uncertainty needs future exp. input



DeBoer et.al. 2017

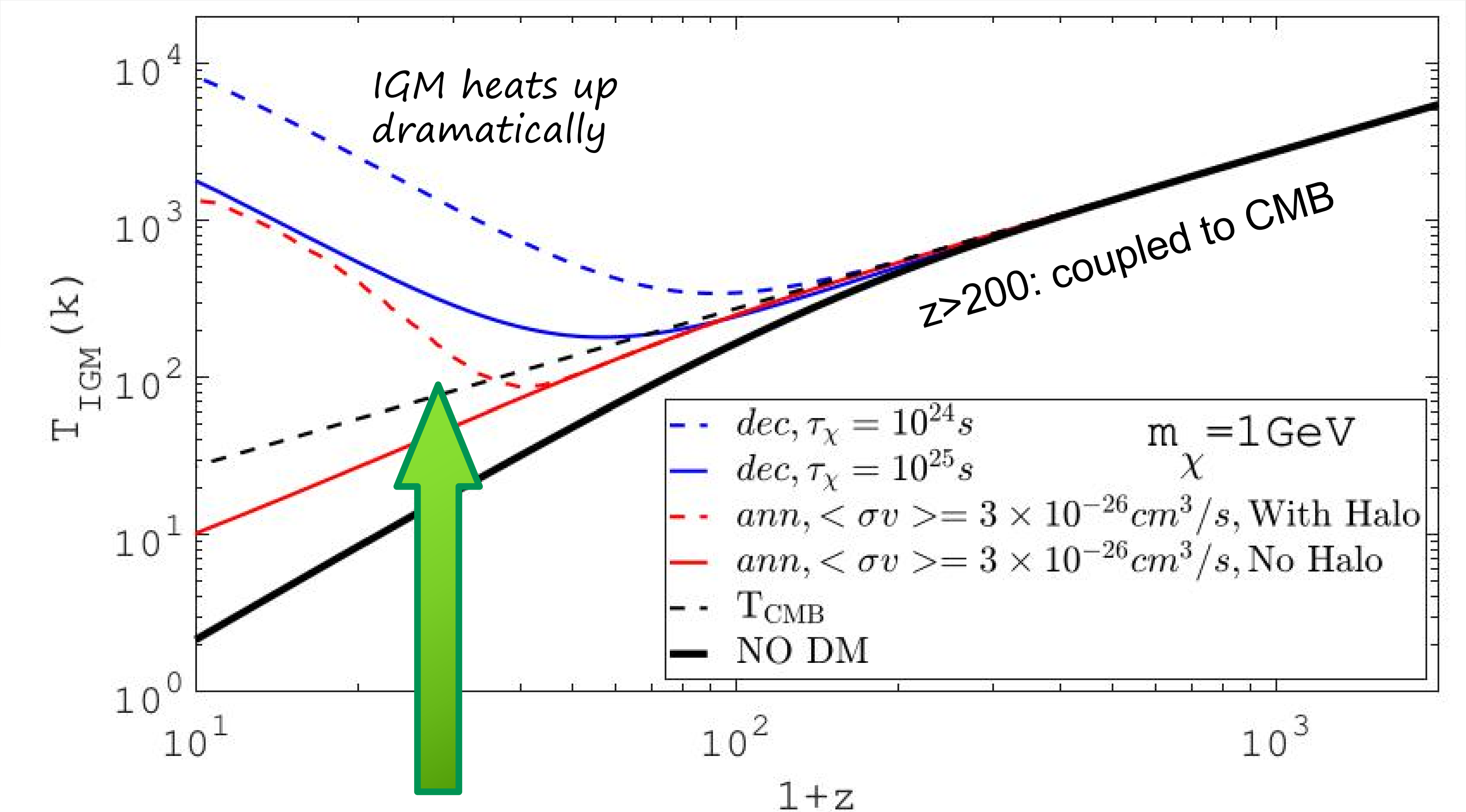


Remember this bump?

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^{2-3} near EoR

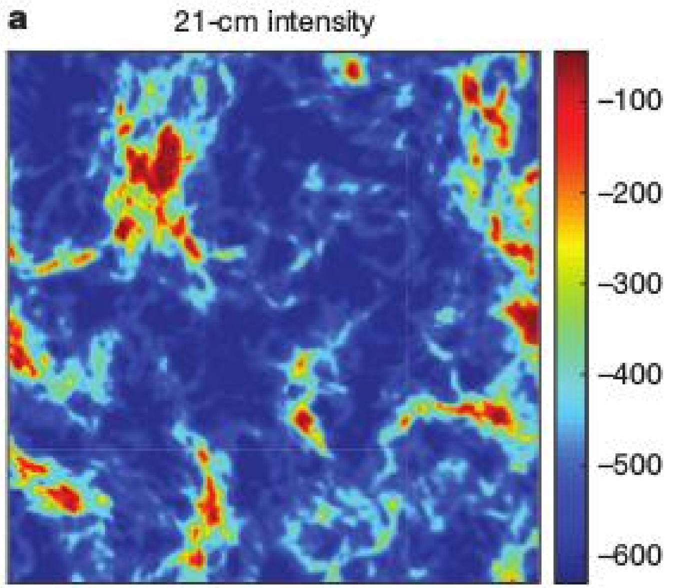
IGM heating with DM

- Injected particles raise IGM temperature

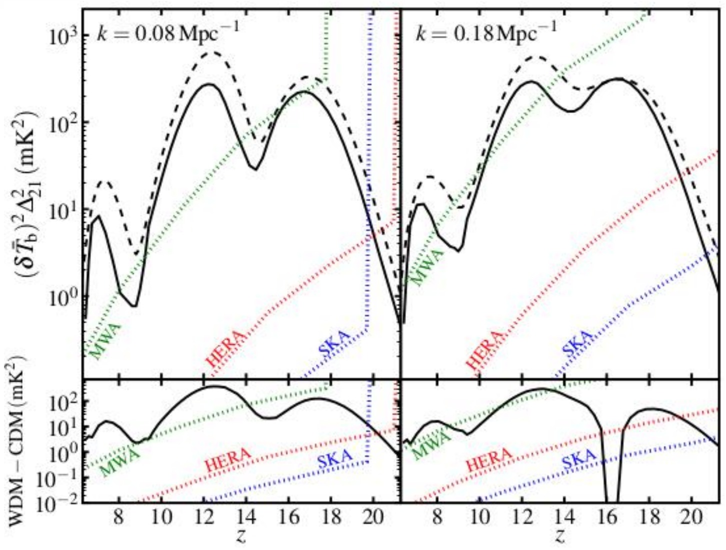
Scattering with
bkg radiation
$\propto T_{CMB} - T_{IGM}$

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

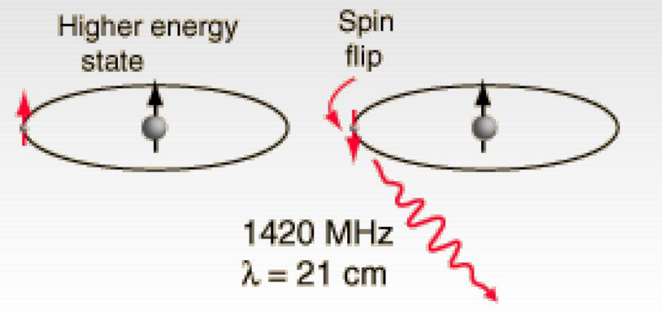


Simulated T21 map w DM,
Rennan Barkana, nature25791



Projected power spectrum sensitivities
(from SKA white paper)

Neutral Hydrogen 21cm line



Hyper-fine split between the singlet
and triplet states of neutral Hydrogen atom

Spontaneous 21cm transition very slow: 10^7 yr

$$N_1/N_0 = 3\ \mathrm{e}^{-0.068\mathrm{K}/T_\mathrm{S}}$$

Spin temperature determined by relative effectiveness
between 21cm transitions, conversions by kinetic collisions,
coupling to the CMB and Lyman-α photons.

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

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

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

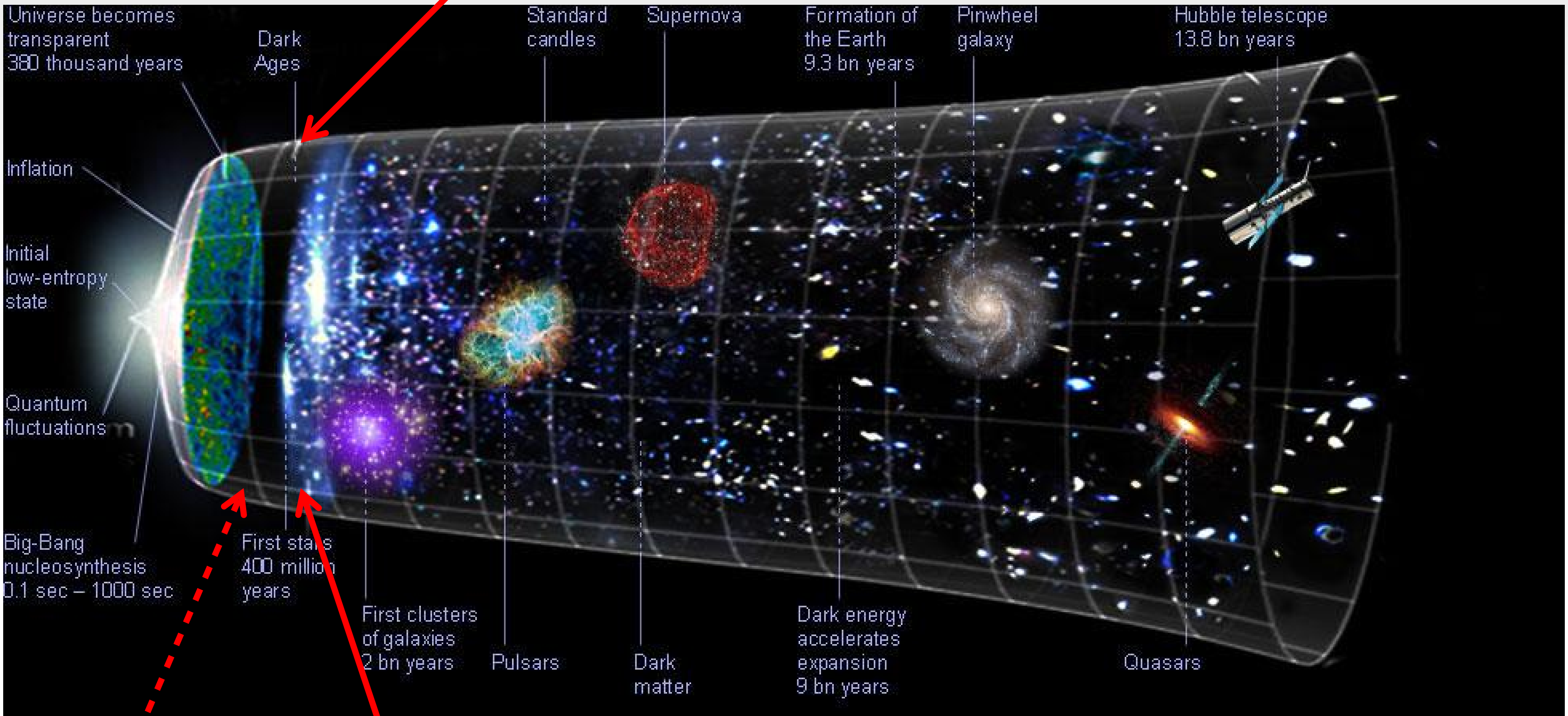
CMB develops [dark] absorption lines by
running through neutral Hydrogen gas clouds
with $T_S < T_{CMB}$.

→ Slices of high-z universe

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.

ionization

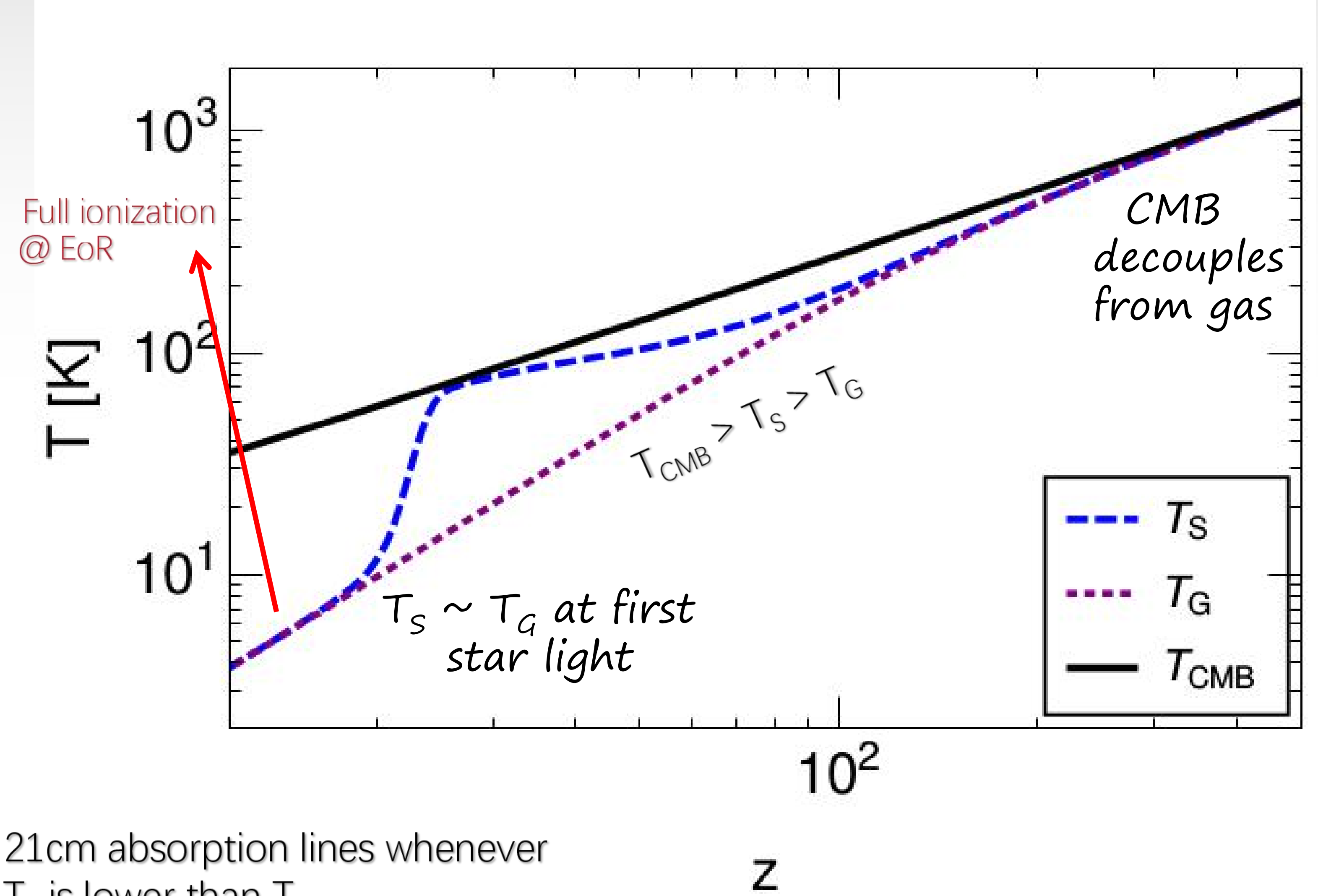
Gas density distribution

Optical depth: Cosmology model-dependent

Gas spin temperature against CMB

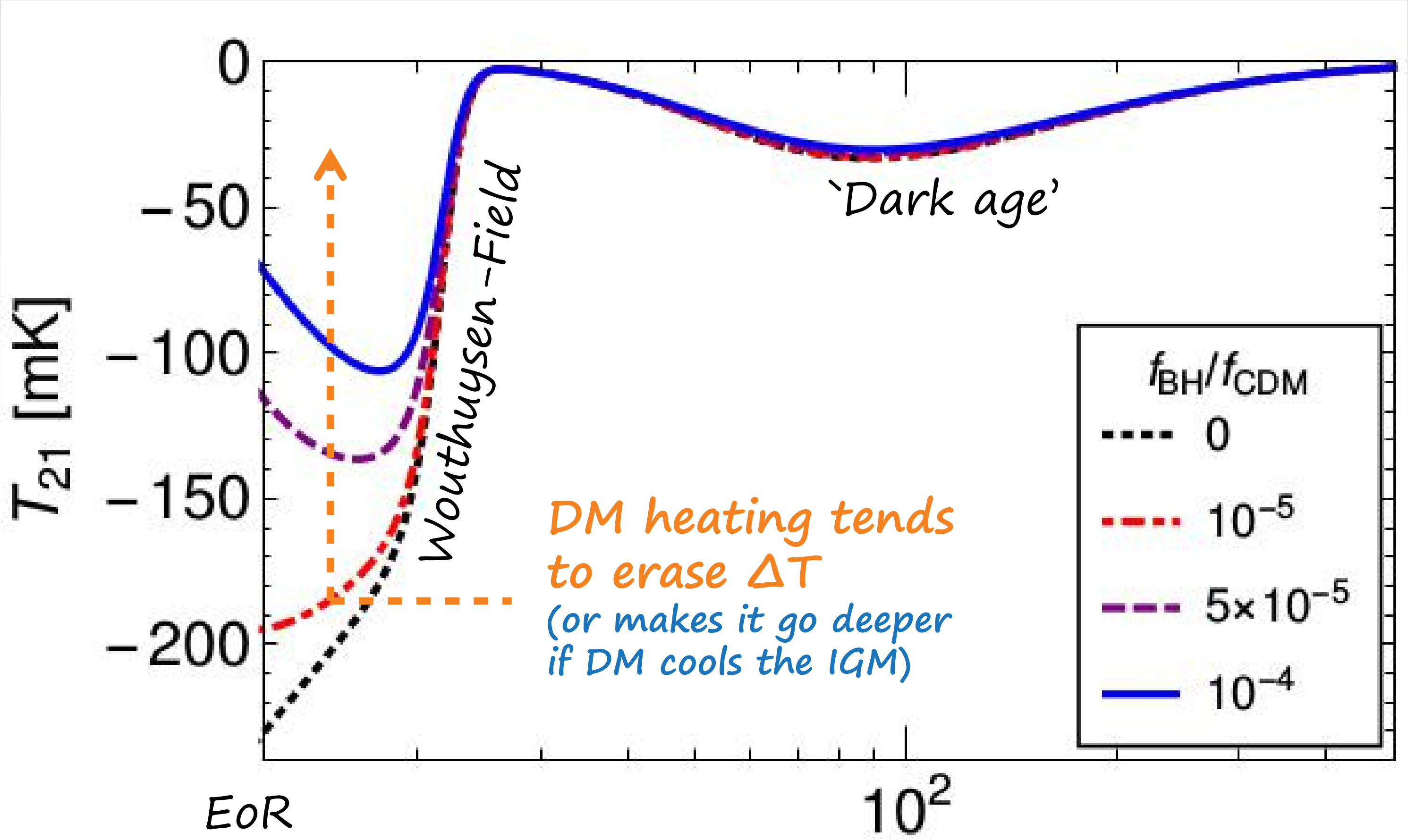
Wouthuysen-Field: $T_{spin} \sim T_{lya} \sim T_{GAS}$ at cosmic dawn

Temperature evolution



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

DM induced heating can suppress / erase the 21cm signal



The average `brightness temperature' z

EDGES: claim of 21cm

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

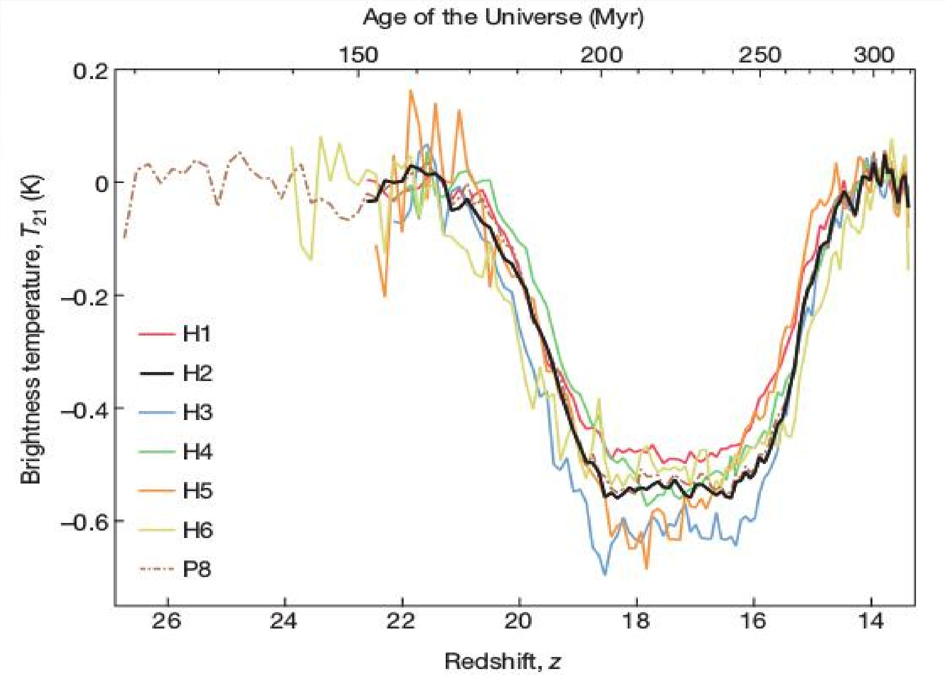
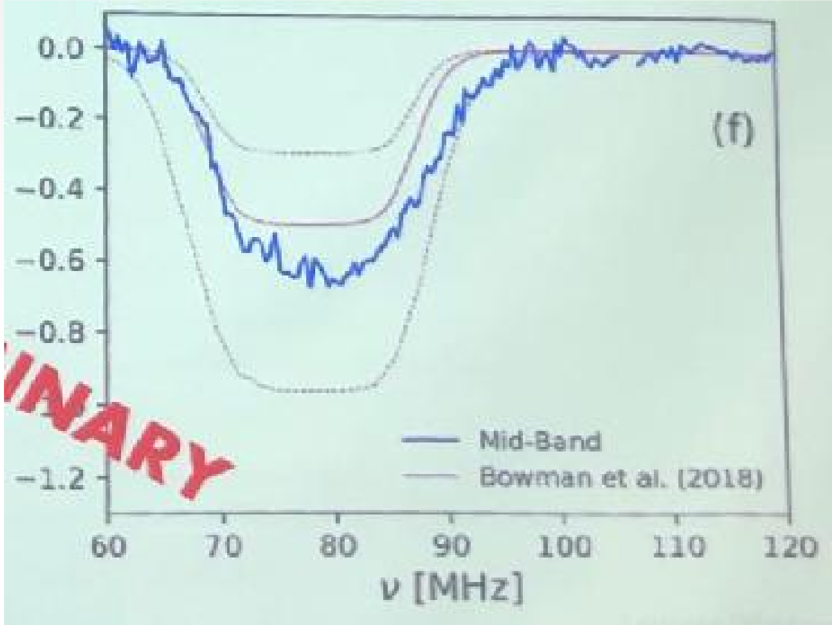
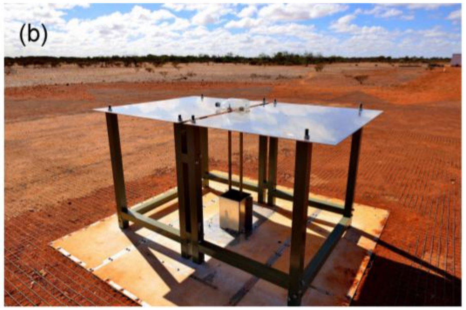


Figure 2 | Best-fitting 21-cm absorption profiles for each hardware case.

2020 (summer)





EDGES: A Discovery near 78 MHz?

~ Twice the LCDM signal !

LOFAR & MWA (by 2020
Upper limits only.

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 releases energy)

Raises gas temperature by energy injection: reduces 21cm signal

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

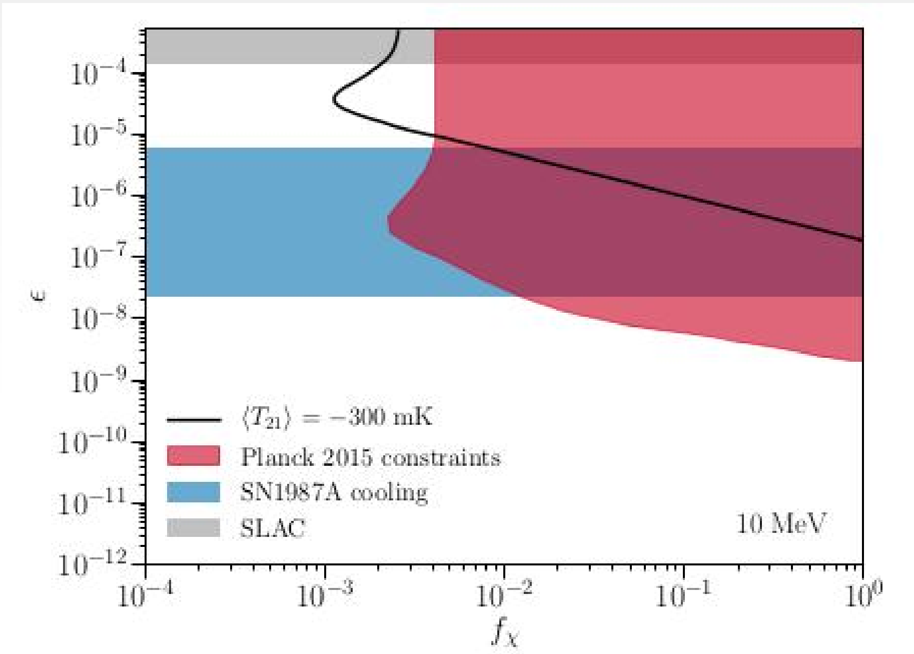
CMB uncertainties

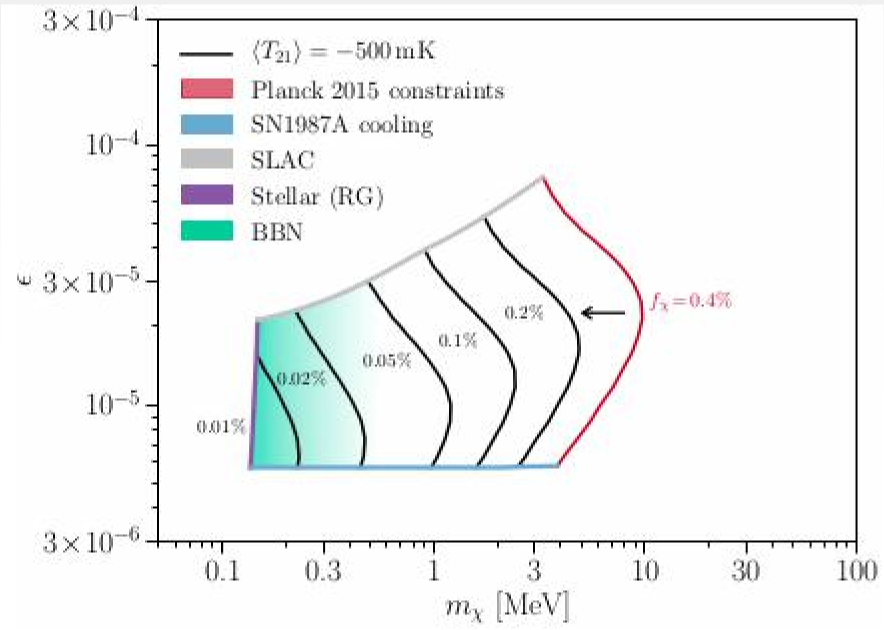
Large uncertainty
at low frequency;
radio-frequency *new physics

Non-standard cosmology
Modified Friedmann Eq.
Dynamic DE, etc

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

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'

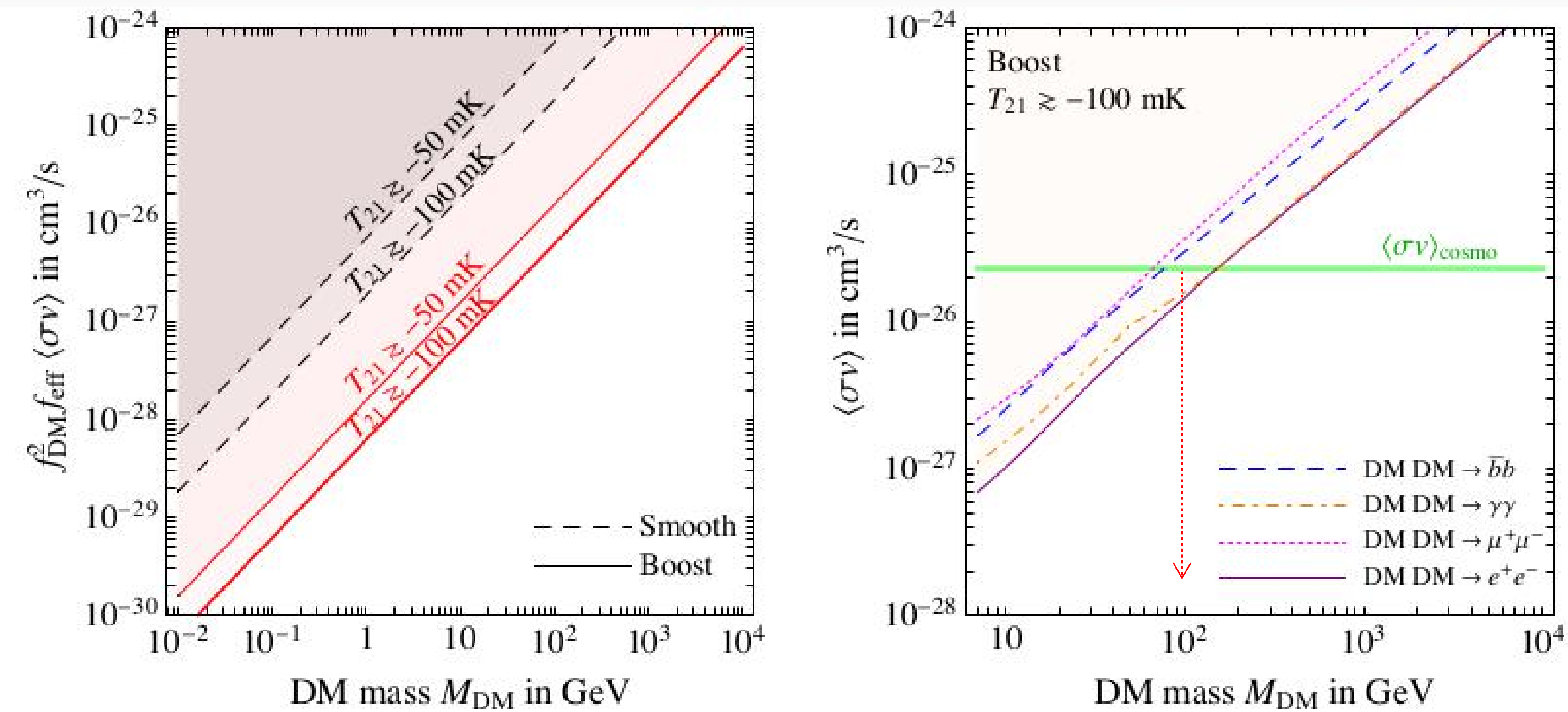
* subleading abundance is OK if millicharged DM also has long-range force with the rest of DM (H.Liu, Outmezguine, Redigolo, Volansky 1908.06986)

Discovery of 21cm means high WIMP sensitivity

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

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

Excluding vanilla thermal wimp below 1

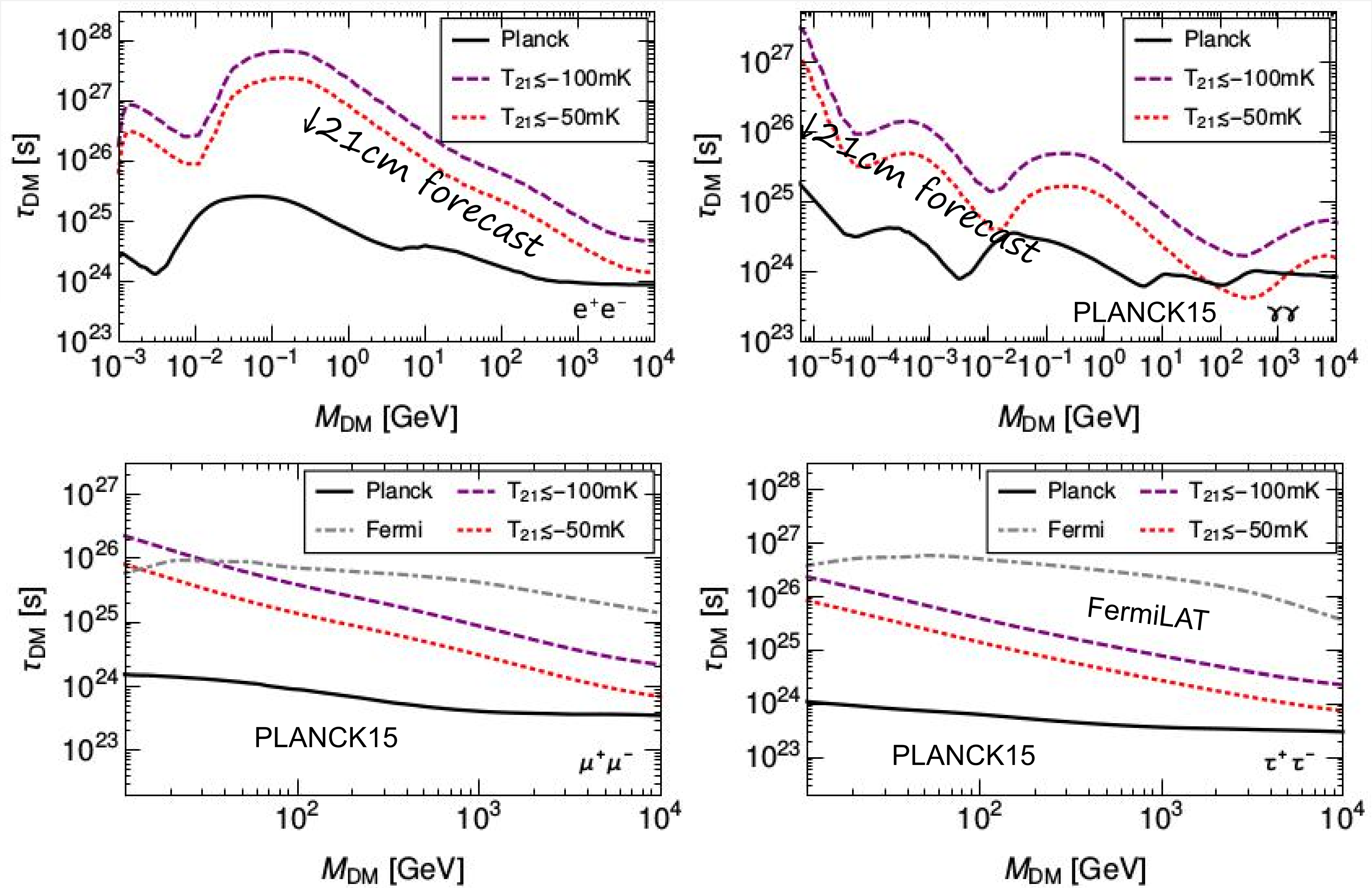


Unlike CMB pol., 21cm is **VERY sensitive** to DM clustering boost

WIMP lifetime bound @ 21cm discovery

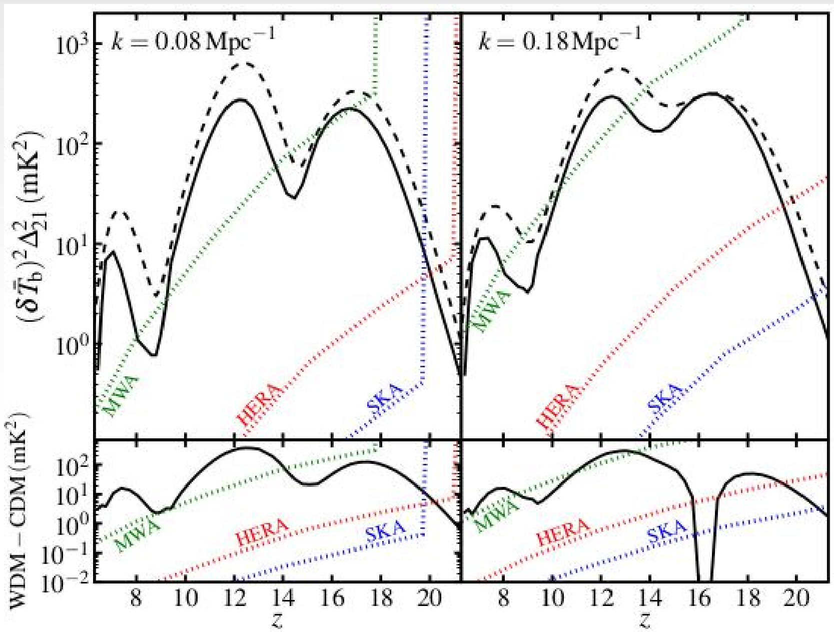
Limit on T_{GAS} rise:
ΔT_{21} < +100 or +150 mK at z=17

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



Decay: unaffected by clustering.

21cm has great expectations…



中国签约参与SKA项目

实验建设:SKA 一期项目的总的预计为6.5 亿欧元,相当于50亿人民币左右。将由中国、南非、英国、澳大利亚、荷兰、意大利、葡萄牙,加拿大、德国、印度等共同承担。
*中国出资规模占重要比例。
*中电集团54研究所负责133盏天线建造。

21cm with DM: Inhomogeneous heating…

- w/o DM: inhomogeneity from matter fluctuations
- w DM: x_e, T also become inhomogeneous
  esp. for ρ^2 enhanced annihilation & quick E deposit
- Potential correction to 21cm spectrum (v.s. global signal)

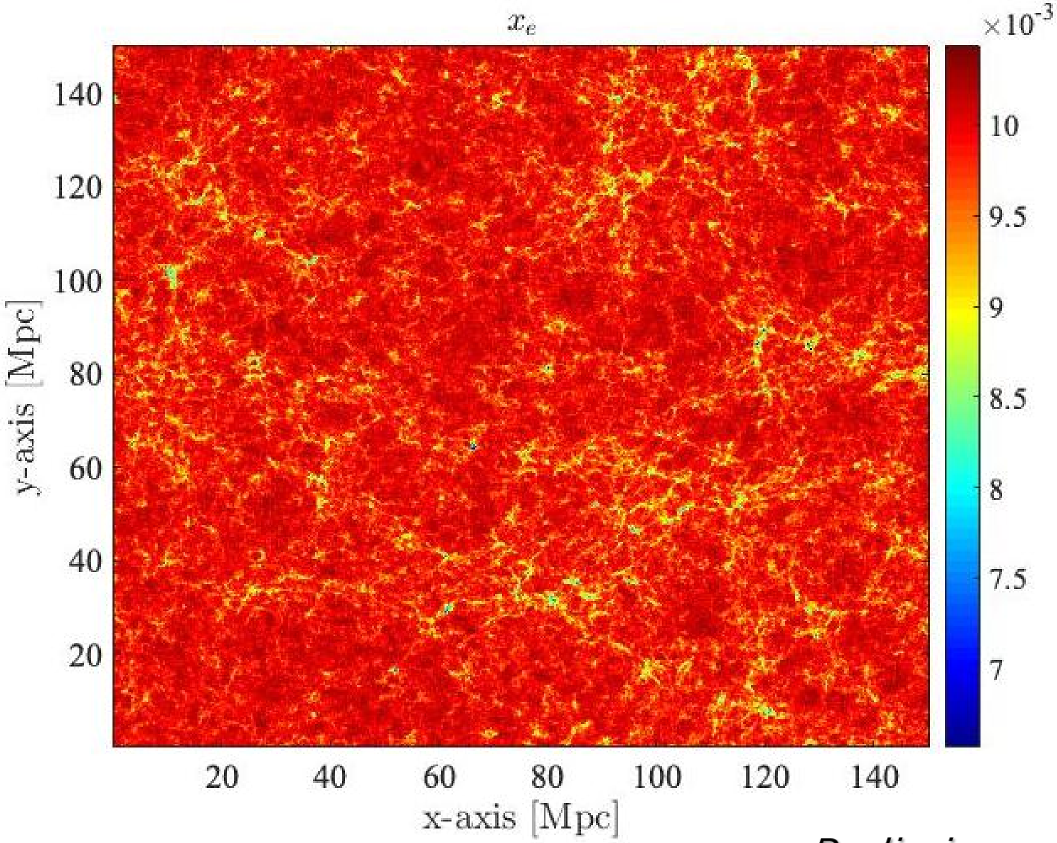
SM | DM energy deposit

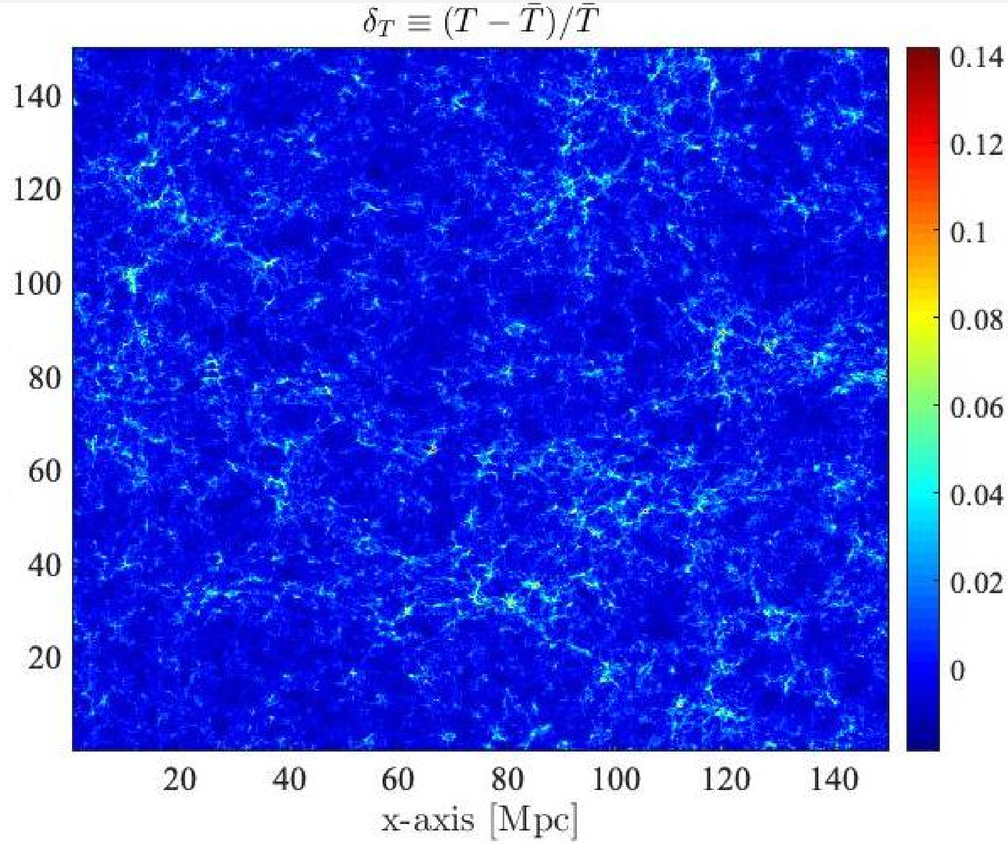
$$\frac{dx_e}{dt} = C\left(\beta(1-x_e)e^{-E_\alpha/k_BT} - x_e^2 n_H \alpha\right) + \frac{1}{n_H E_i} J_{d,i} + \frac{1-C}{n_H E_\alpha} J_{d,\alpha}$$

+ transport terms, etc.

$$\frac{dT}{dt} = \frac{2T}{1+z}\frac{dz}{dt} + \frac{8\sigma_T a_R T_\gamma^4}{3m_e c^2}\frac{x_e}{f_b}(T_\gamma - T) + \frac{2}{3k_B n_H f_b} J_{d,h}$$

x_e & T inhomogeneity potentially affect the 21cm power spectrum



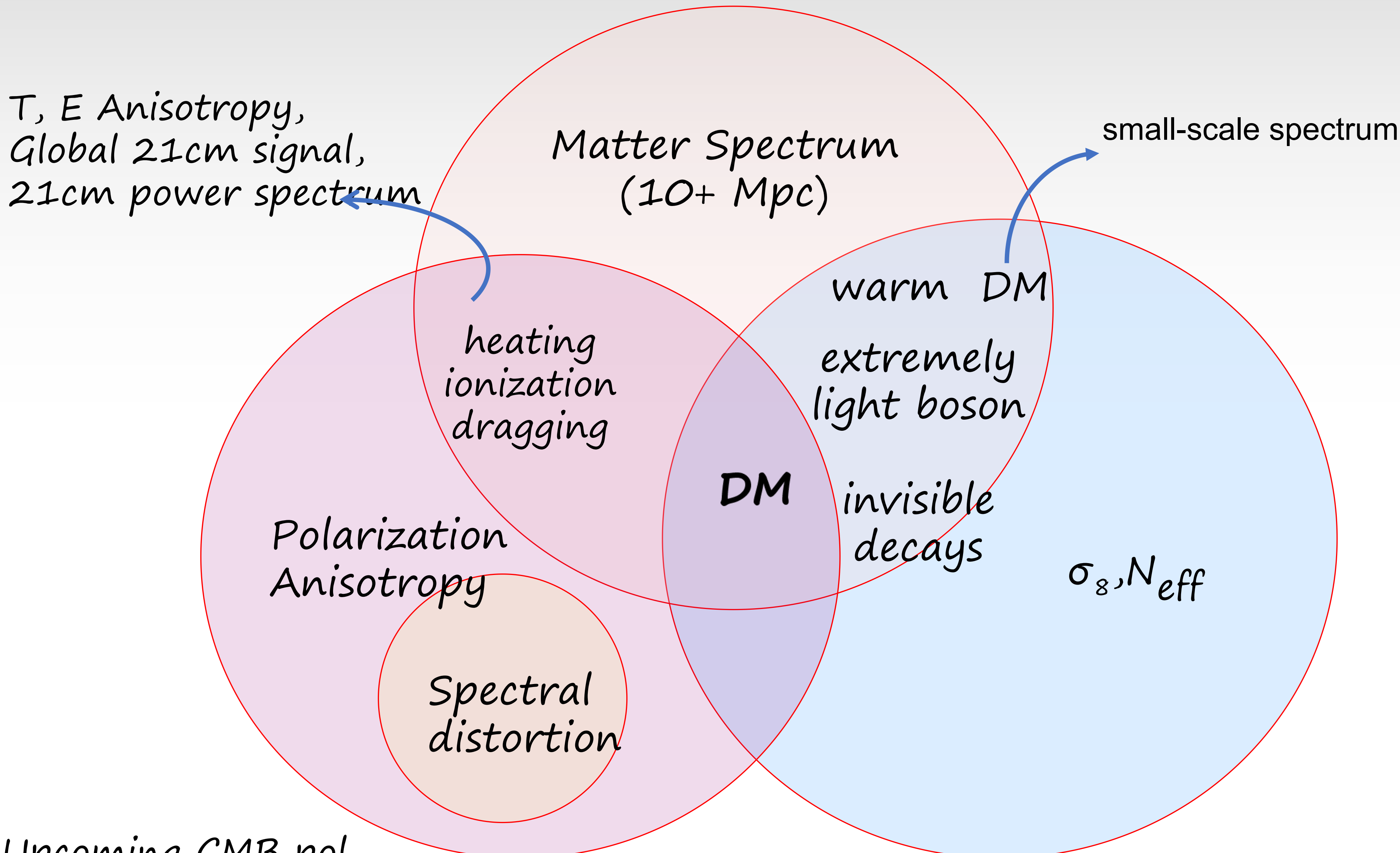


Preliminary

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

J.Cang, Y.Gao, Y-Z.Ma, in progress

Dark Matter and CMB

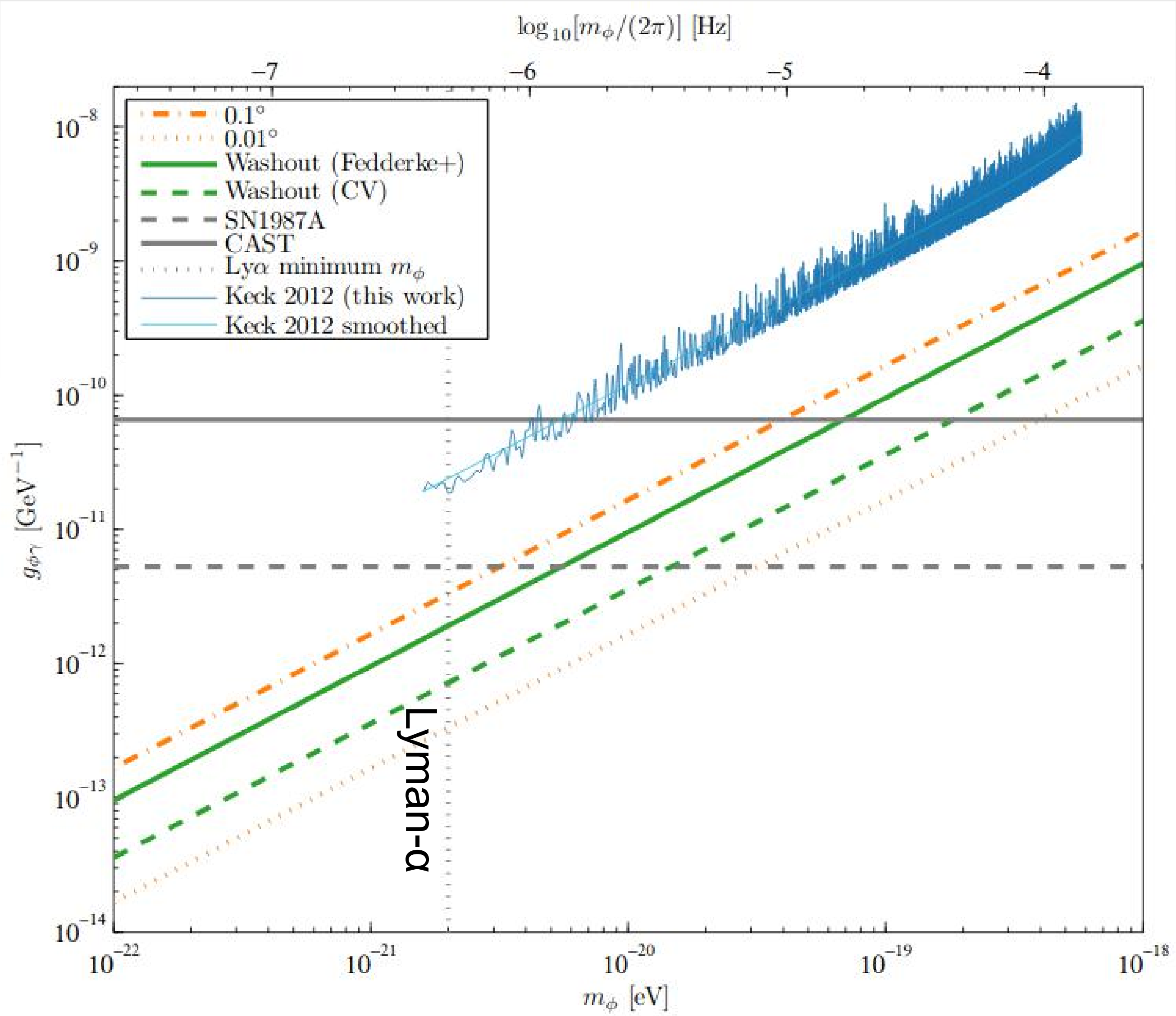


Upcoming CMB pol.

AdvACTPol, AliCPT, Simons Obs., SPG3, S4, etc. & 21cm coming close?

BACKUP: light bosonic DM

CMB on very light bosonic DM



CAST

stellar

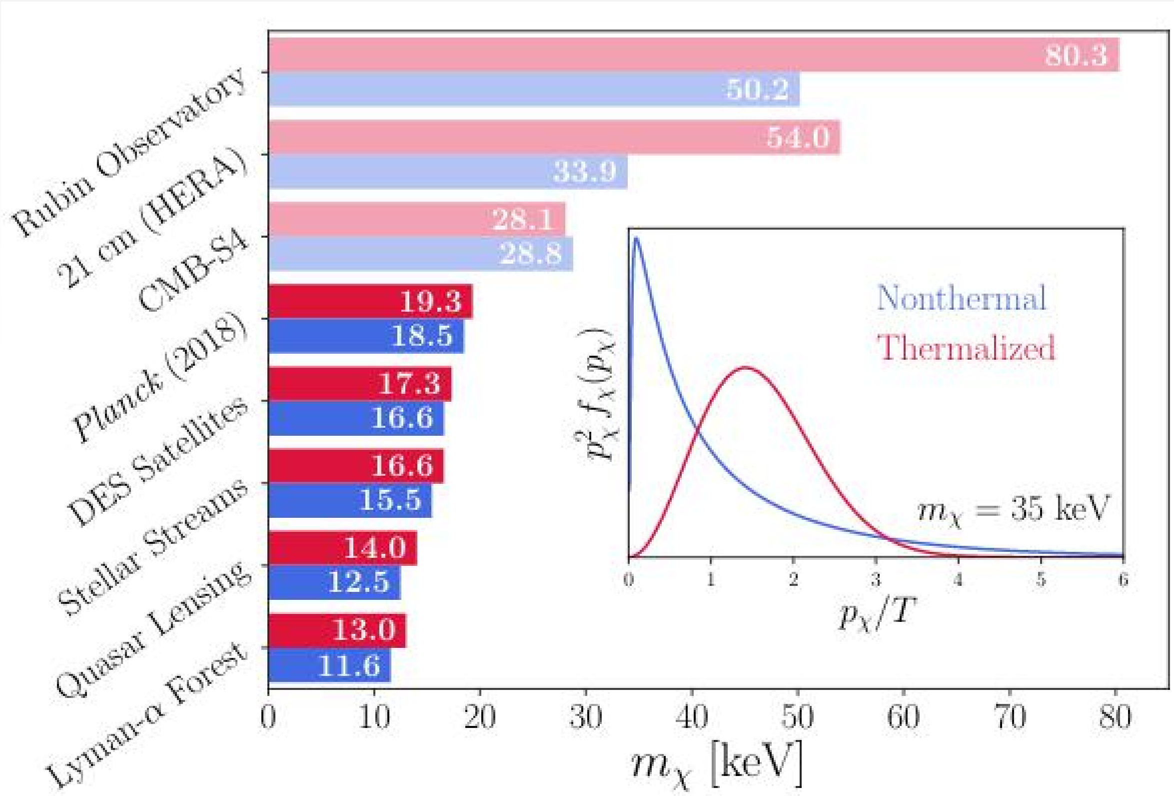
BICEP/KECK3 (2011.03483) CMB polarization rotations

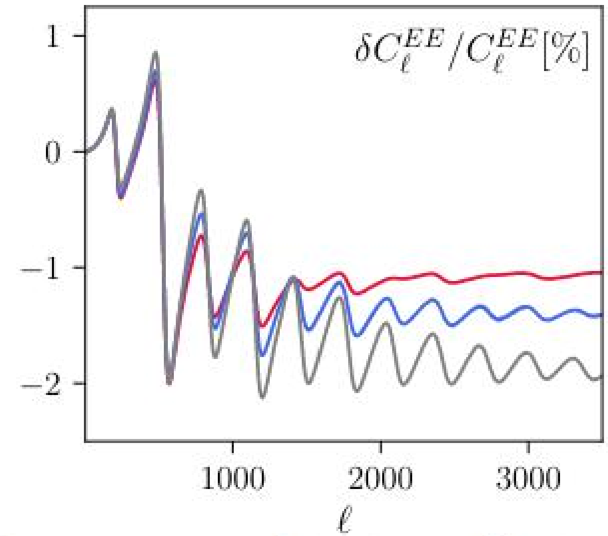
BACKUP: partially coupled DM

Effect 3: DM `couples' to matter

Nonthermal DM at lower velocities:
"Dragging" on baryo

Dvorkin, Lin, Schutz, 2011.0





DM – matter scattering at low velocity: $\langle v\sigma \rangle \sim v^{-n}$
Corrections in TT, EE, and lensing spectra

FORECAST Method

Forecast likelihood

$$-2\ln\mathcal{L}(\{C_\ell\}|\{\hat{C}_\ell\}) =$$
$$f_{\rm sky} \times \sum_\ell (2\ell+1)\{\mathrm{Tr}[\hat{C}_\ell C_\ell^{-1}] - \ln|\hat{C}_\ell C_\ell^{-1}| - 2\}$$

$$C_\ell \equiv \begin{bmatrix} C_\ell^{TT} & C_\ell^{TE} \\ C_\ell^{TE} & C_\ell^{EE} \end{bmatrix}$$

$$\hat{C}_\ell \equiv \begin{bmatrix} \bar{C}_\ell^{TT} + N_\ell^{TT} & \bar{C}_\ell^{TE} \\ \bar{C}_\ell^{TE} & \bar{C}_\ell^{EE} + N_\ell^{EE} \end{bmatrix}$$

$$N_\ell^{\rm EE} = \left[\sum_\nu \omega_{E,\nu} \exp\left(-\ell(\ell+1)\frac{\theta^2_{\rm FWHM,\nu}}{8\ \ln 2}\right)\right]^{-1}$$
$$N_\ell^{\rm TT} = \frac{1}{2}\ N_\ell^{\rm EE}$$

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	$f_{\rm sky}$	$\ell_{\rm min}$	$\ell_{\rm max}$	ν (GHz)	δP (μK-arcmin)	$\theta_{\rm FWHM}$ (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