Dark Matter Search in the CMB

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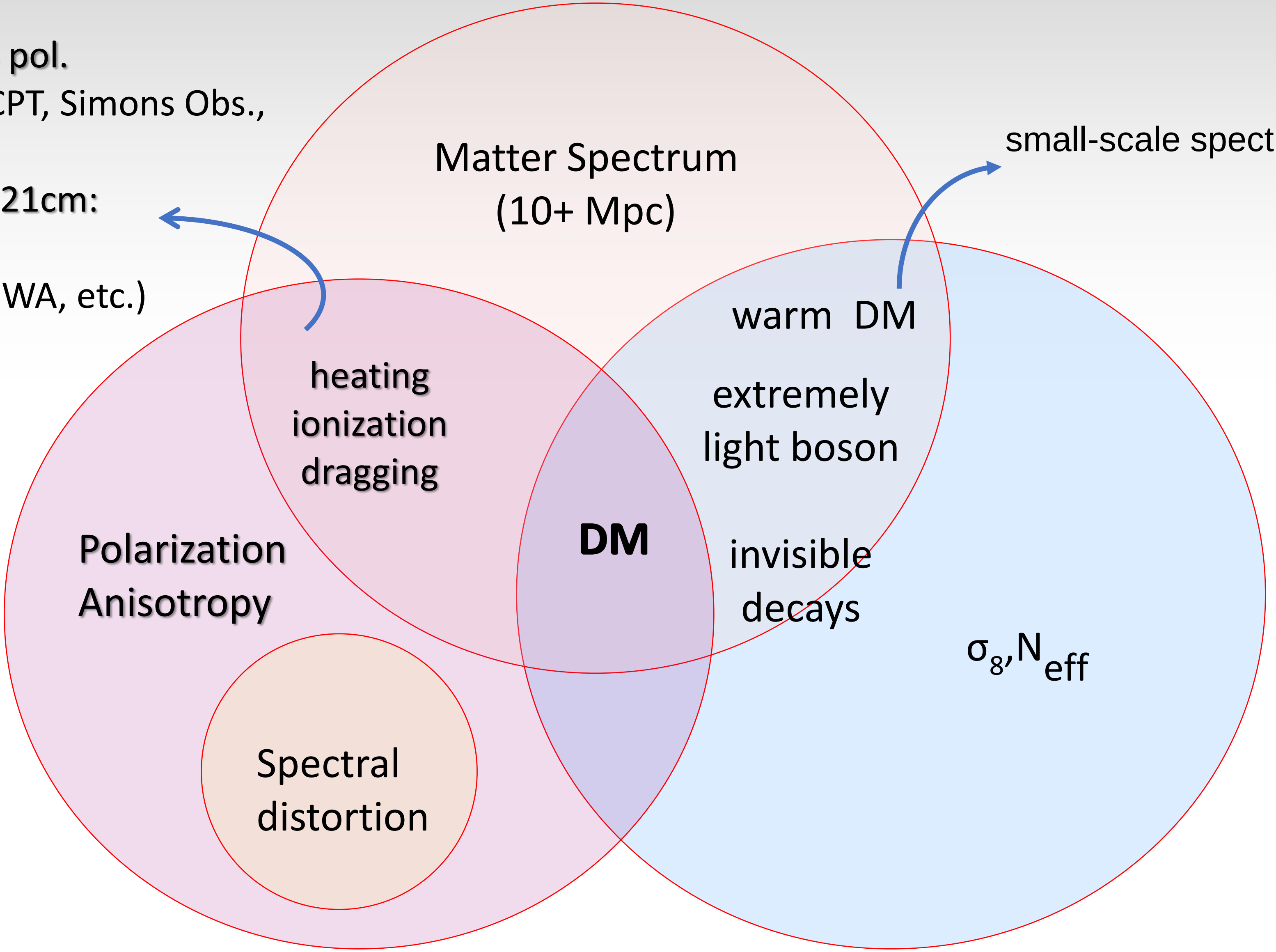
Outline

- Particle Dark Matter Effects on the CMB
- DM ↔ CMB anisotropies (Ionization)
- DM ↔ 21cm (Temperature) update
- PBH formation ↔ CMB ? update

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.)



Matter Spectrum
(10+ Mpc)

small-scale spectrum

warm DM

extremely
light boson

invisible
decays

$\sigma_8, N_{\mathrm{eff}}$

heating
ionization
dragging

DM

Polarization
Anisotropy

Spectral
distortion

DM coupled
to the SM

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):

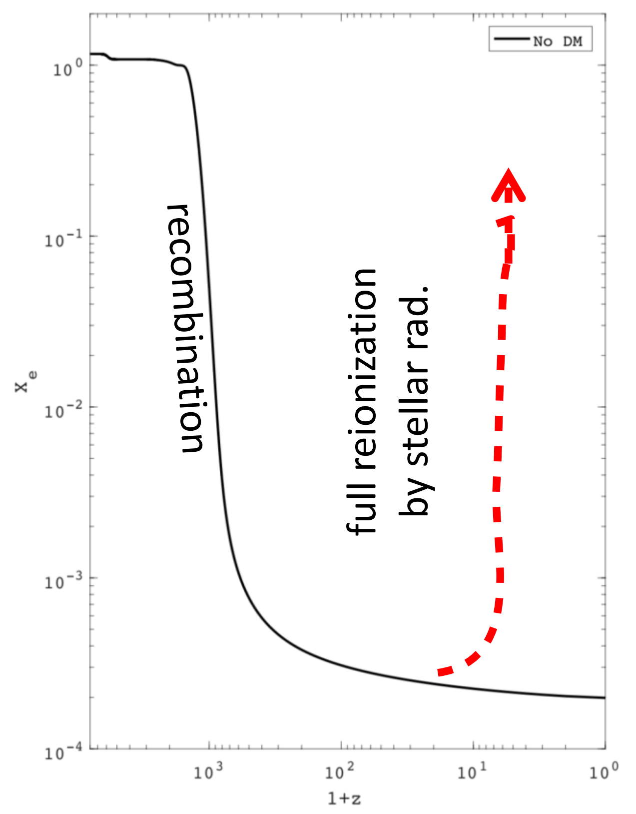
$$\beta \equiv \langle \sigma v \rangle \left(\frac{m_e T}{2\pi}\right)^{3/2} e^{-\epsilon_0/T}$$

Equilibrium 10^{-4} – 10^{-3} ionization fraction can be sensitive to new physics:

* Energy release ($e^{\pm}, \gamma$, etc)
* Kinetic collisions from NP.
* Anything new, e.g. extra soft ioniziations?

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

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

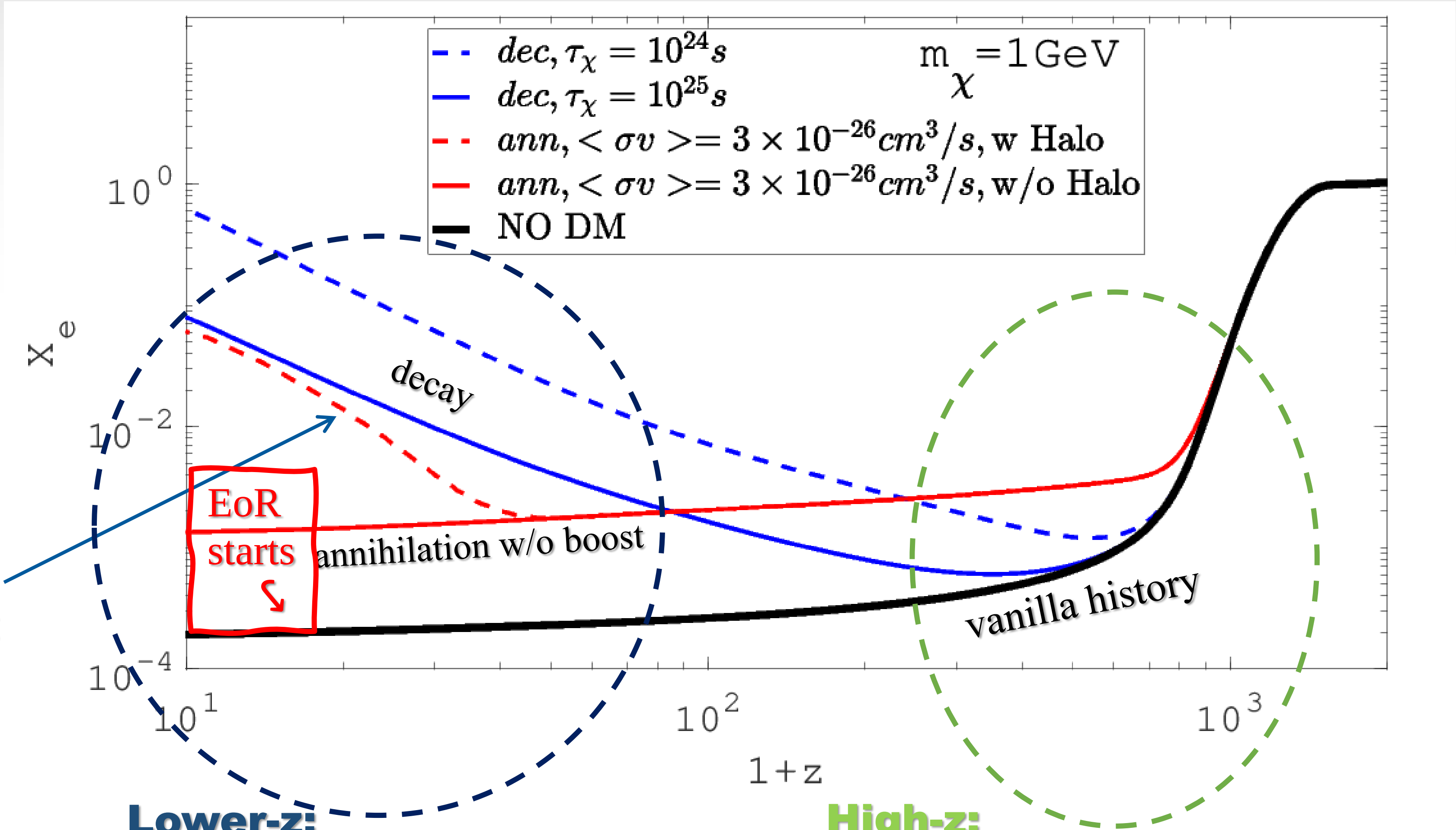


x_e reduces to a 10^{-4} floor during the cosmic dark age and returns to unity during EoR

DM windows in x_e history

Annihilation: raises the x_e floor,

Decay: steady rise in x_e



Late-time clustering boost

Lower-z: Sensitive to 21cm requires T_{gas} info.

High-z: Sensitive to CMB EE,ET pol.

Impact from steady (high-energy) injection

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

Possible Observations:	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 cosmic data Also need more theory work …

Formalism: NP ionization

- Extra amount of free electrons
- Enhanced CMB scattering → Damping on C_l

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

"Deposit Channels"

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

ionization from ground state

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

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)

Redshift dependence in injection rate

- Energy deposit rate can build up overtime
- NP processes ⟺ (different) injection history

DM Annihilation: fast during high z,

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

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

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

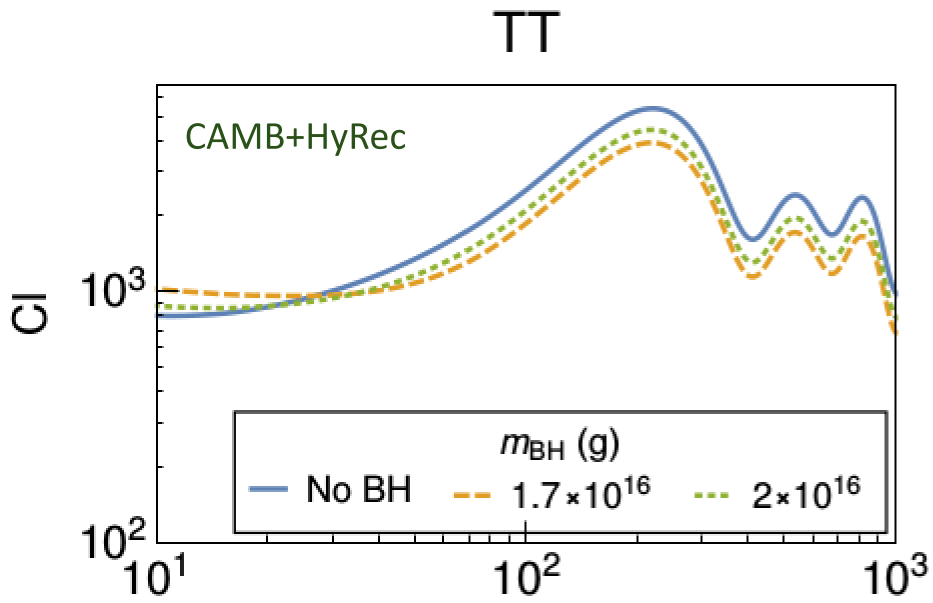
$$B(z) = \frac{\Delta_{\rm c}\rho_{\rm c}}{\rho_{\rm DM}^2} \int_{M_{\rm min}}^{\infty} M B_{\rm h}(M) \frac{\mathrm{d}n}{\mathrm{d}M} \mathrm{d}M$$

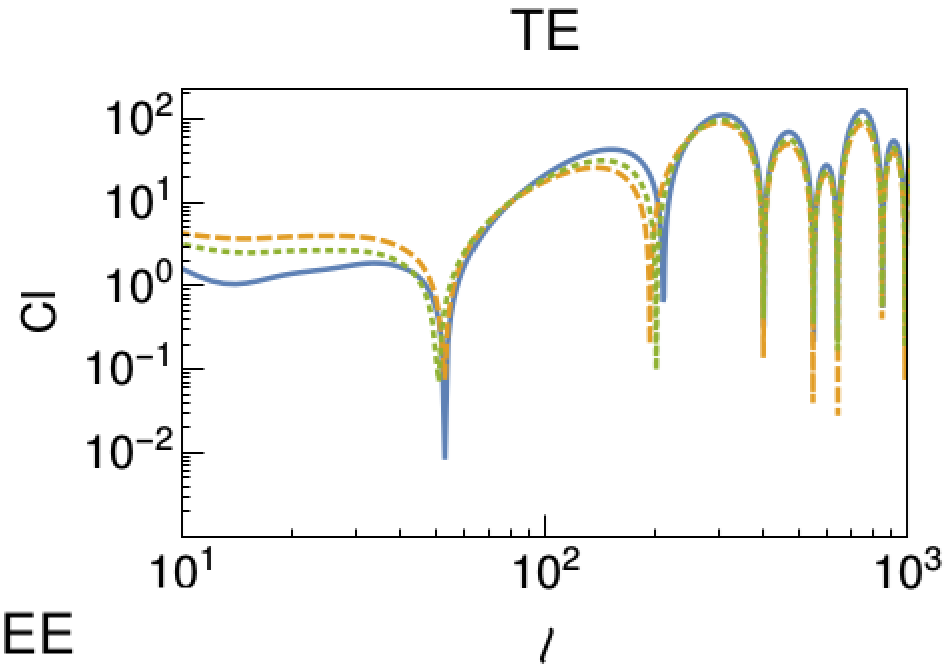
Velocity dependence: requires special treatment:
(i) redshift dep.
(ii) halo *J*- factor

DM Decay: a steady rate, unaffected by structure formation

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

Xe on CMB C_l: damping & pol. peak shift

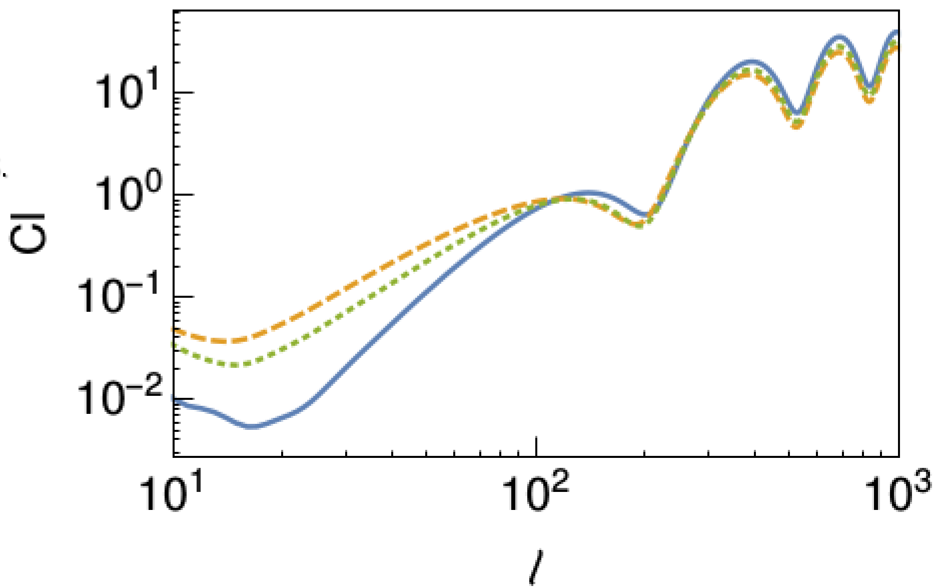




Large l damping may be degenerate to cosmological parameters.

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

EE



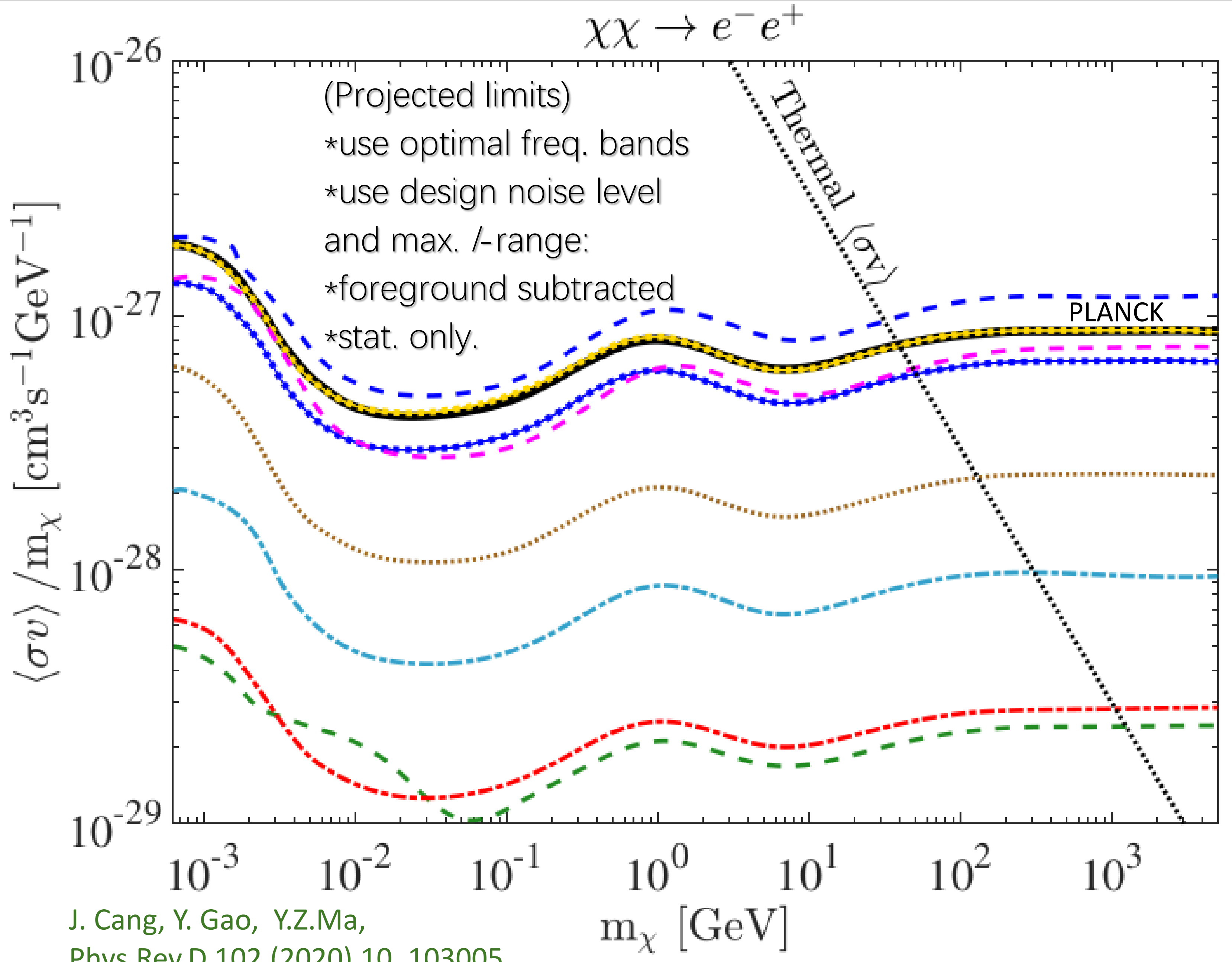
LSS broadening increases polarization perturbation amplitudes

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

- enhances damping

Forecast on Thermal WIMP mass (ee channel)

~ Keck/BICEP3



AliCPT

PLANCK

CLASS

AliCPT+PLK

SPT-3G

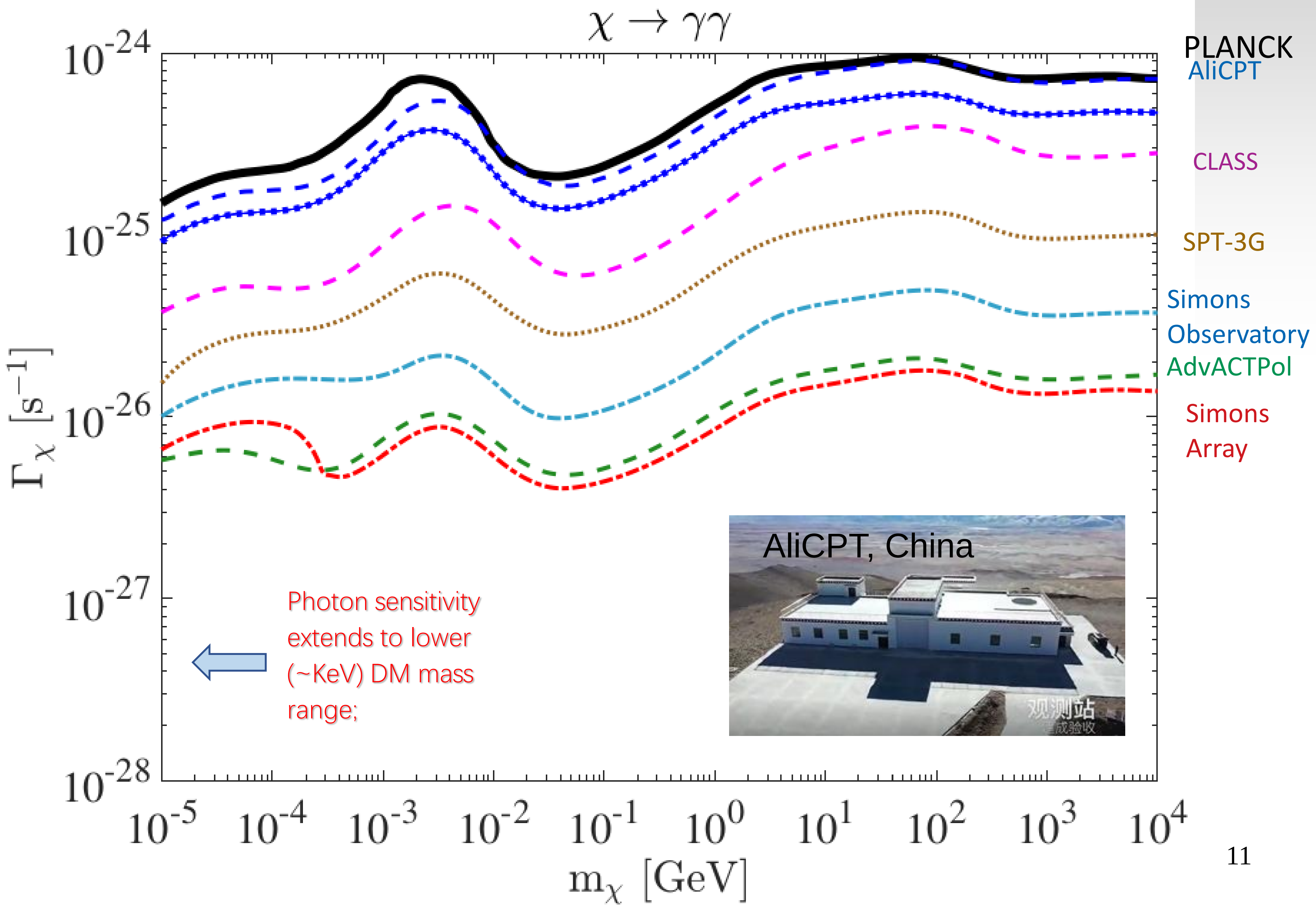
Simons Observatory

Simons Array

AdvACTPol

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

Forecast on WIMP lifetime (decay to photons)



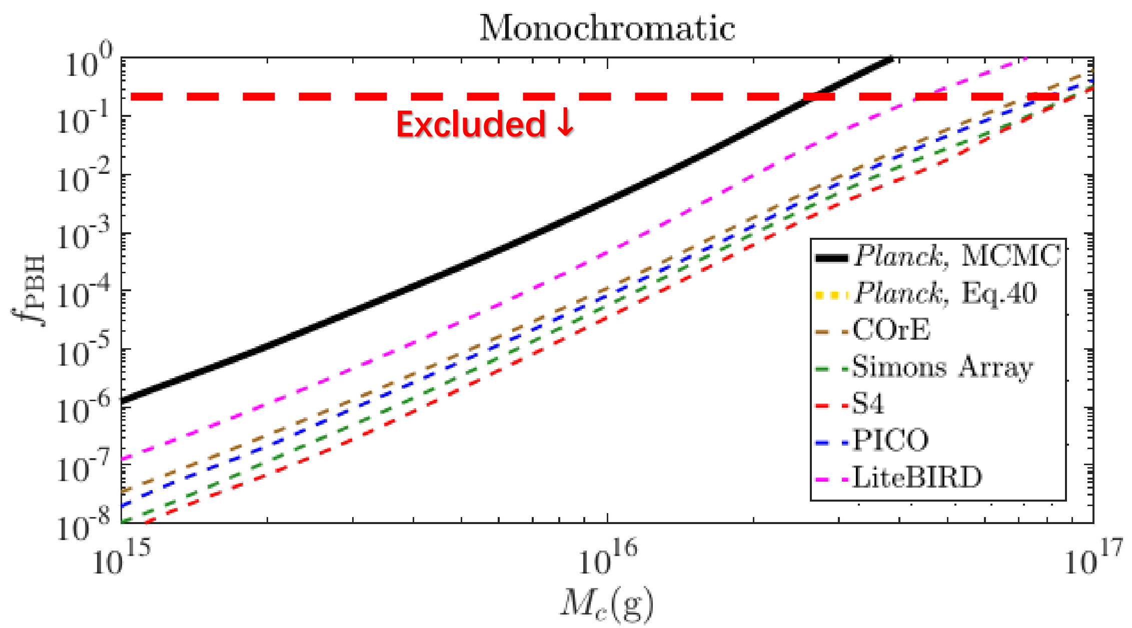
Photon sensitivity extends to lower (~KeV) DM mass range;

Evaporating PBHs, (low-mass)

PBH’s Hawking radiation has a dE/dt~$(1+z)^3$ history

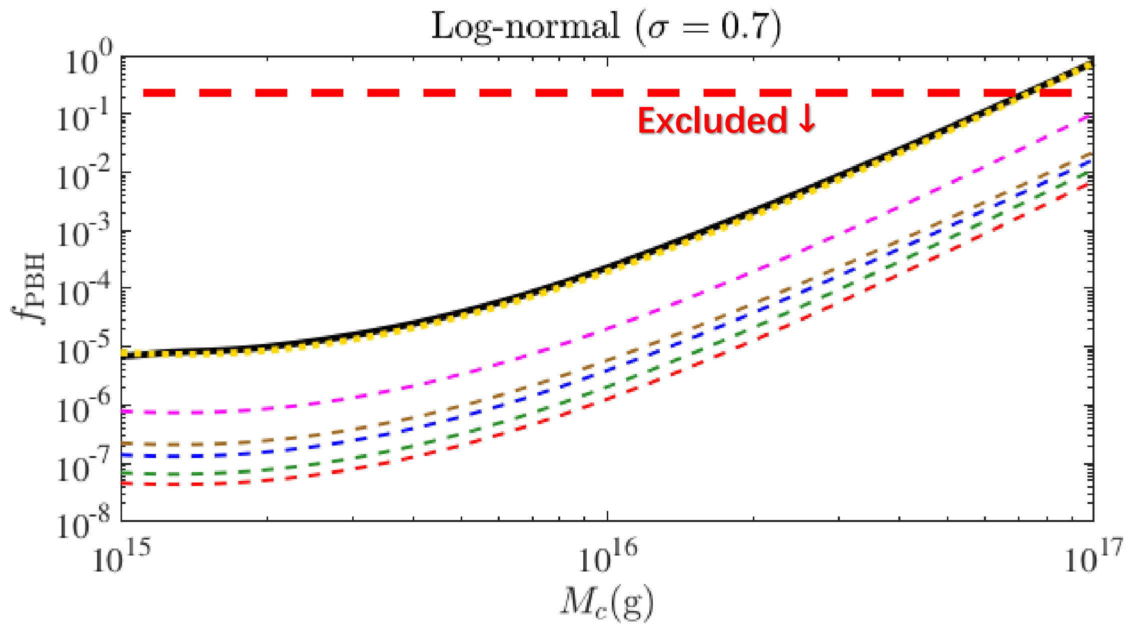
Significant sensitivity in relevant mass range:
$M_{BH} = 10^{14\text{ - }17}$ g

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


Monochromatic

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

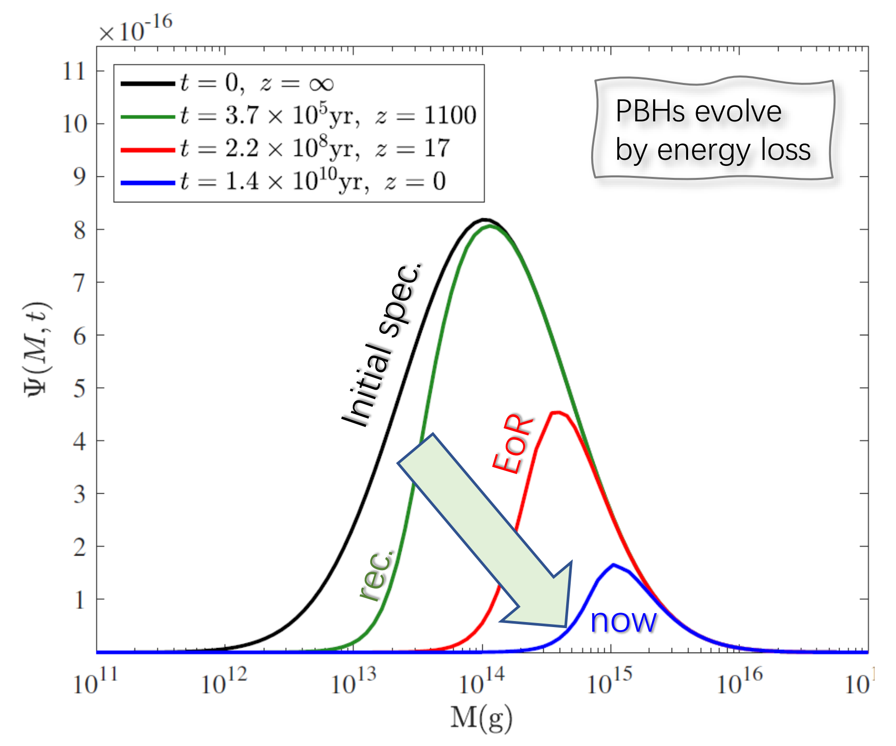

Log-normal ($\sigma = 0.7$)

Spinning & Very low-mass PBHs

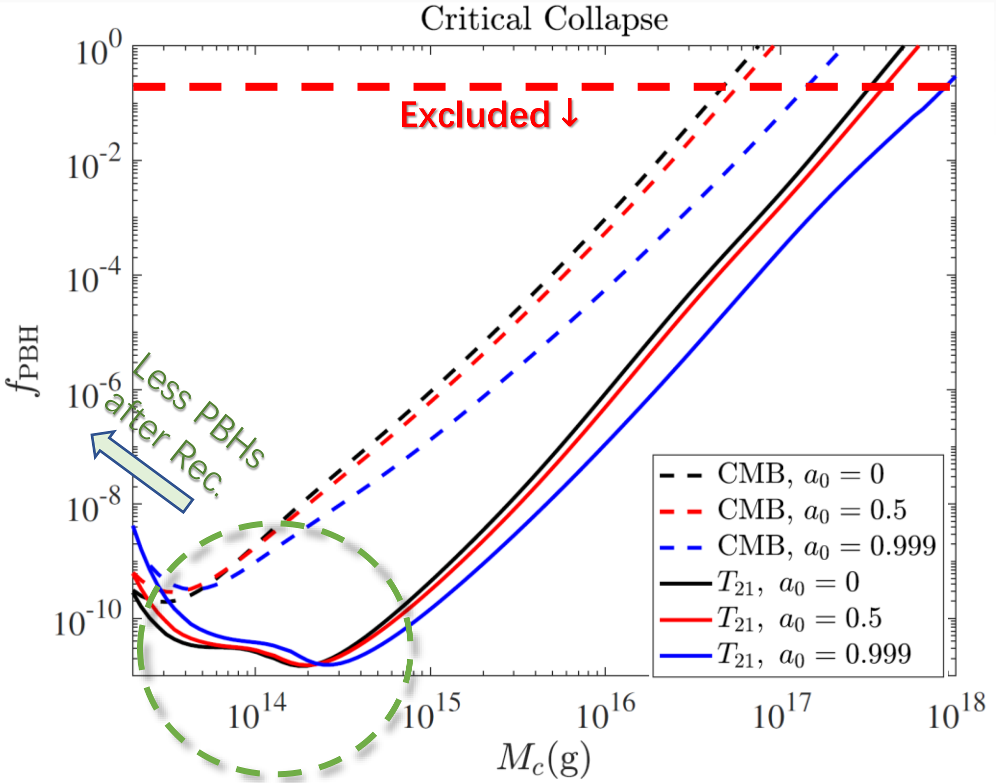
$m_{PBH} = 10^{13} - 10^{17}$ g

Significant PBH spin and mass evolution
→ Non-trivial injection and x_e history

lifetime < AOU:
“total” evaporation during dark age



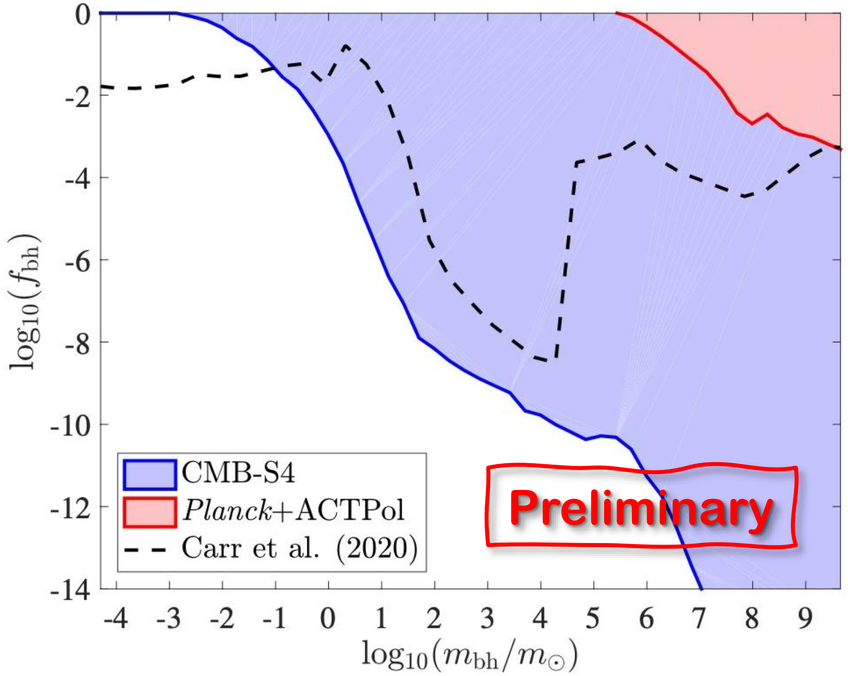
J. Cang, Y.Gao, Y-Z. Ma, 2108.13256

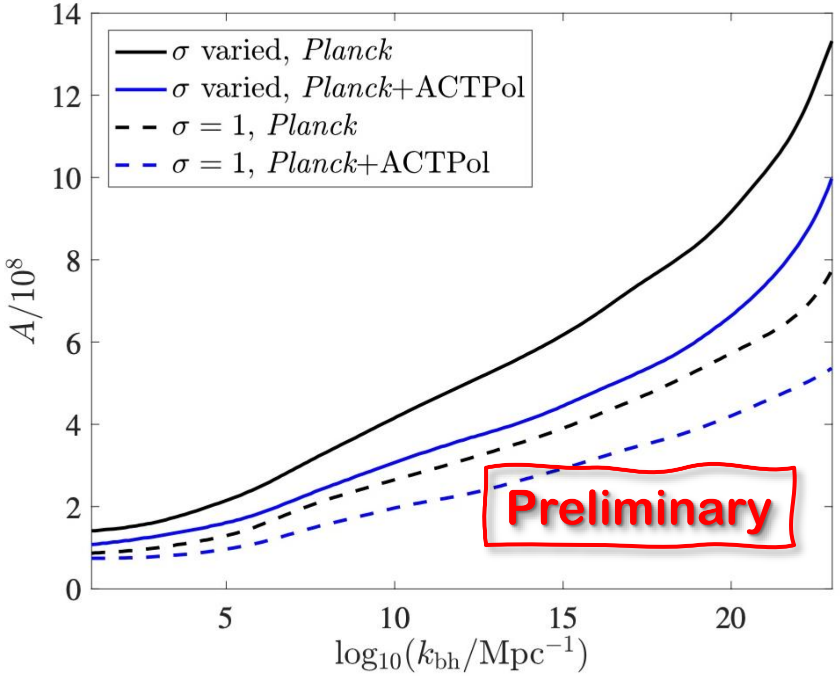


“Bad range” for
a mass spectrum

N_{eff} limits on PBHs

Future CMB N_{eff} offers stringent sensitivity on very early PBH formation

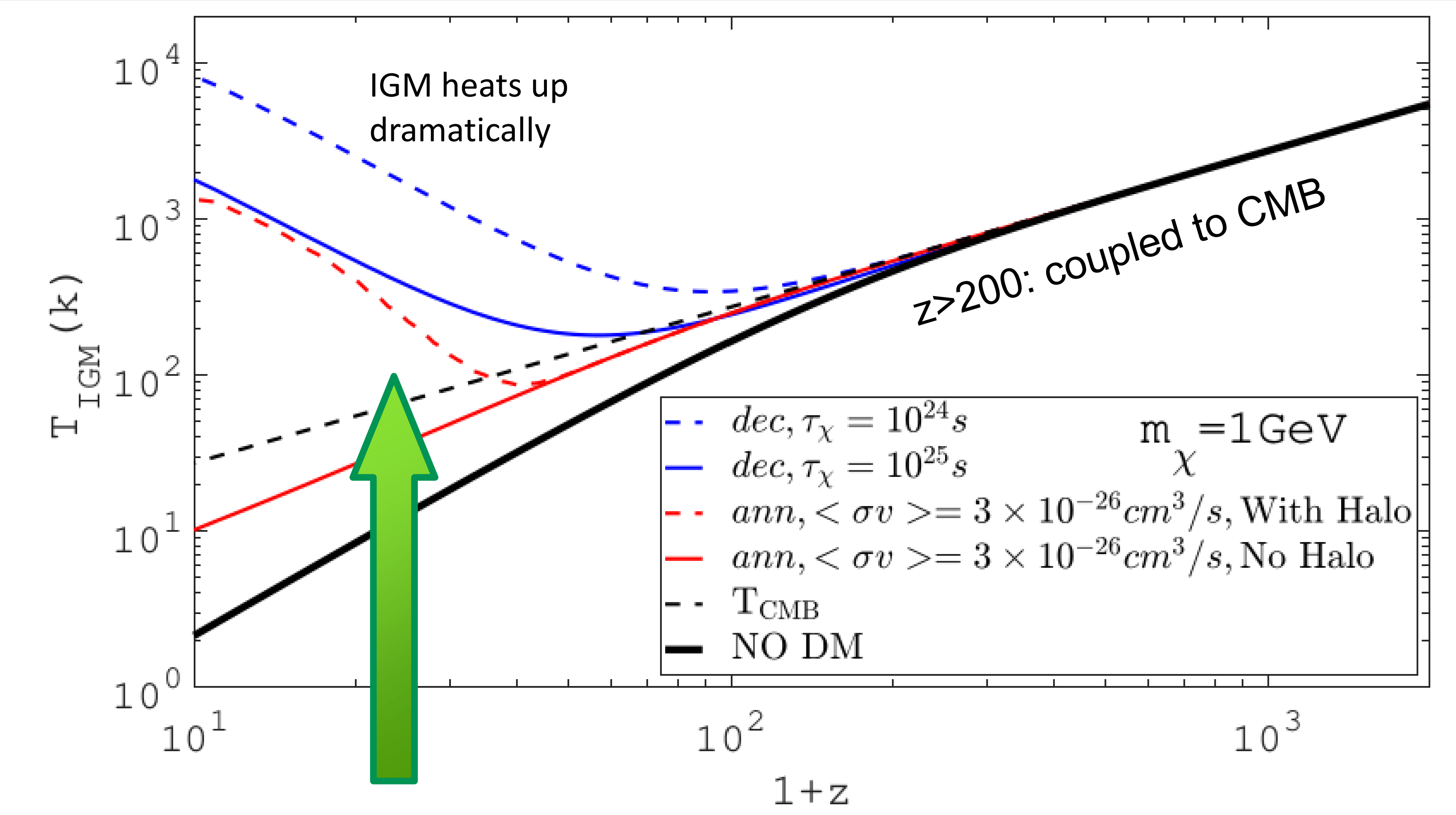




Promising forecast for stellar-mass and super-massive PBHs.

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

21cm : *IGM temperature*

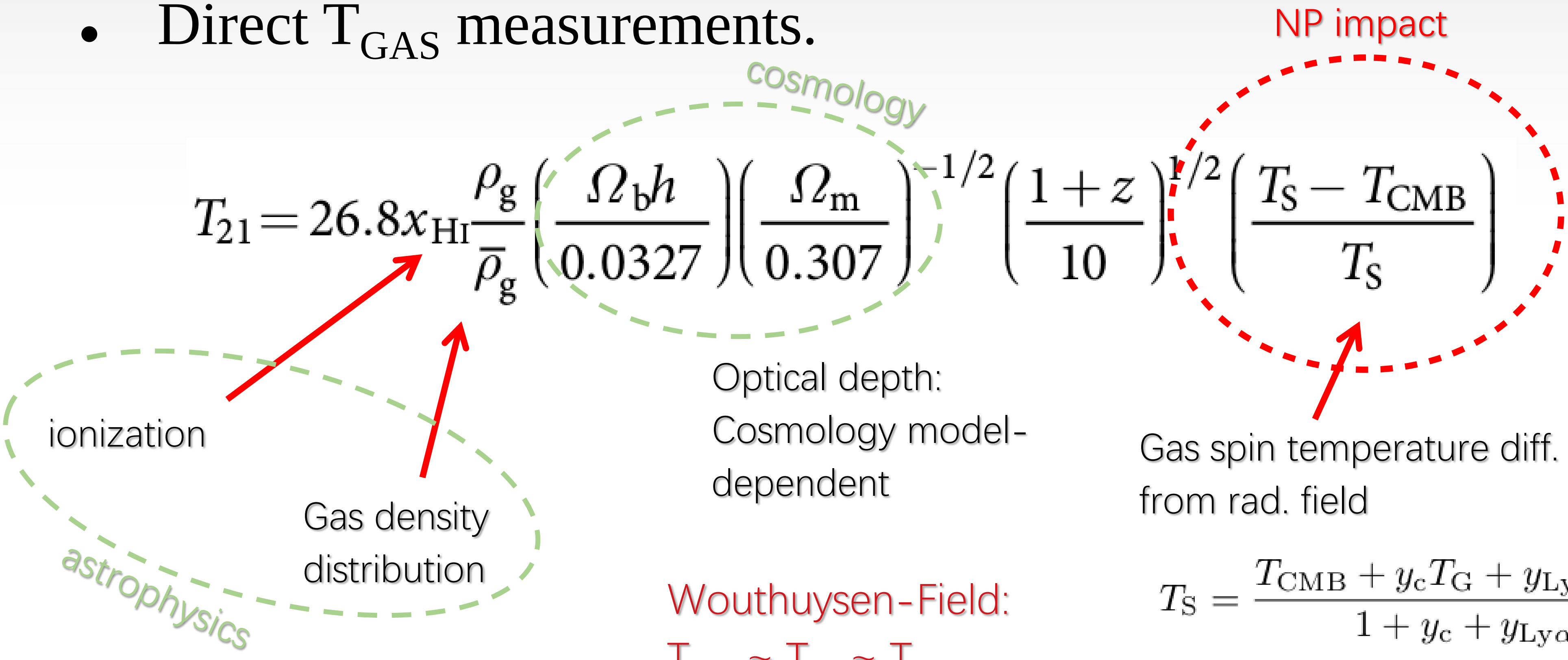


Severe x_e washout by astrophysics.
21cm comes to rescue!

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

Formalism: T_{21} dependencies...

- 21cm brightness relies on IGM temperature evolution
- Direct T_{GAS} measurements.



NP impact

cosmology

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

ionization

Gas density distribution

astrophysics

Optical depth: Cosmology model-dependent

Gas spin temperature diff. from rad. field

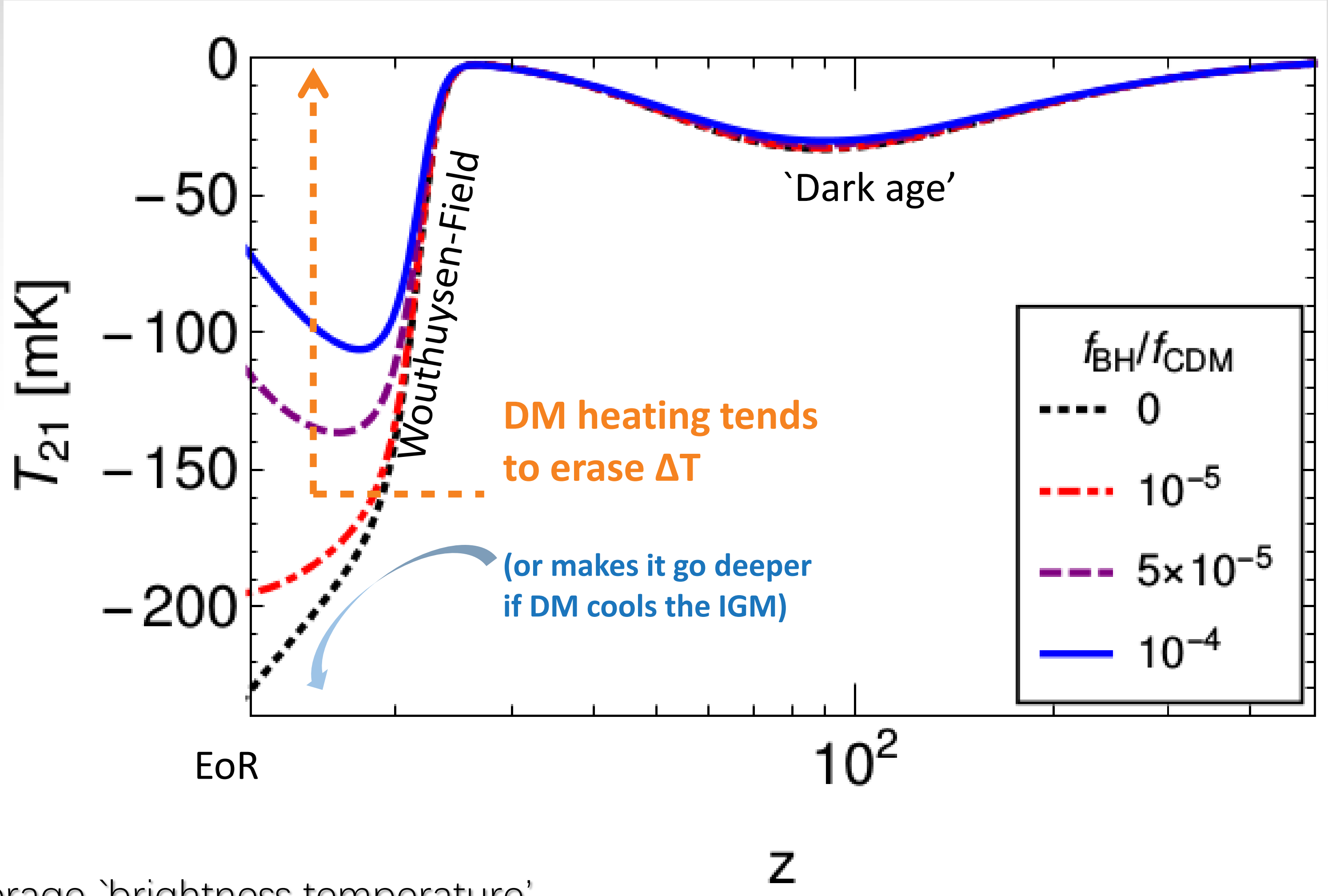
Wouthuysen-Field:
$T_{spin} \sim T_{lya} \sim T_{GAS}$
at cosmic dawn

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

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

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

Extra heating can erase the 21cm signal



DM heating tends to erase ΔT

(or makes it go deeper if DM cools the IGM)

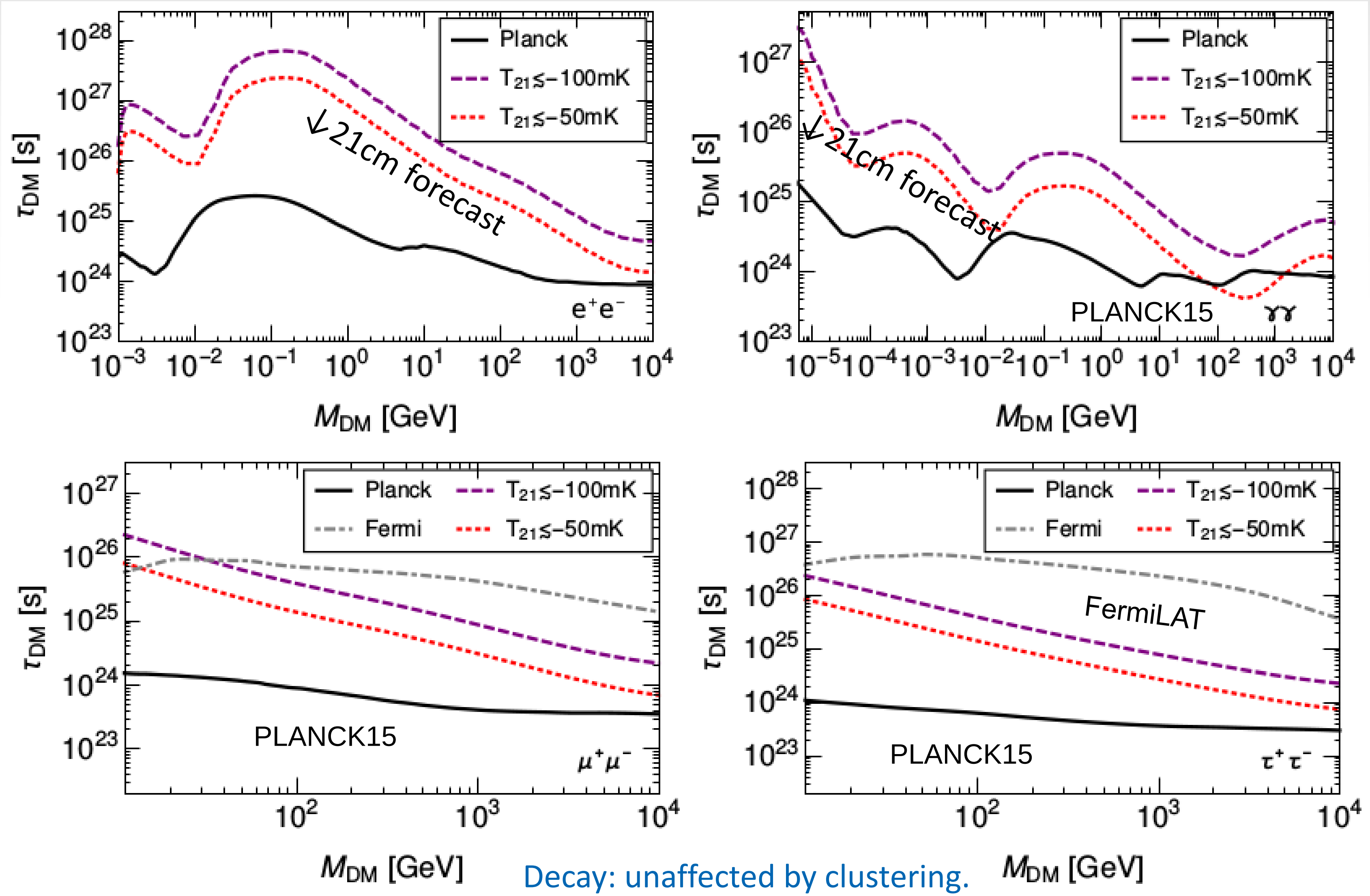
The average `brightness temperature'

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

WIMP limits: 21cm can do better than CMB pol.

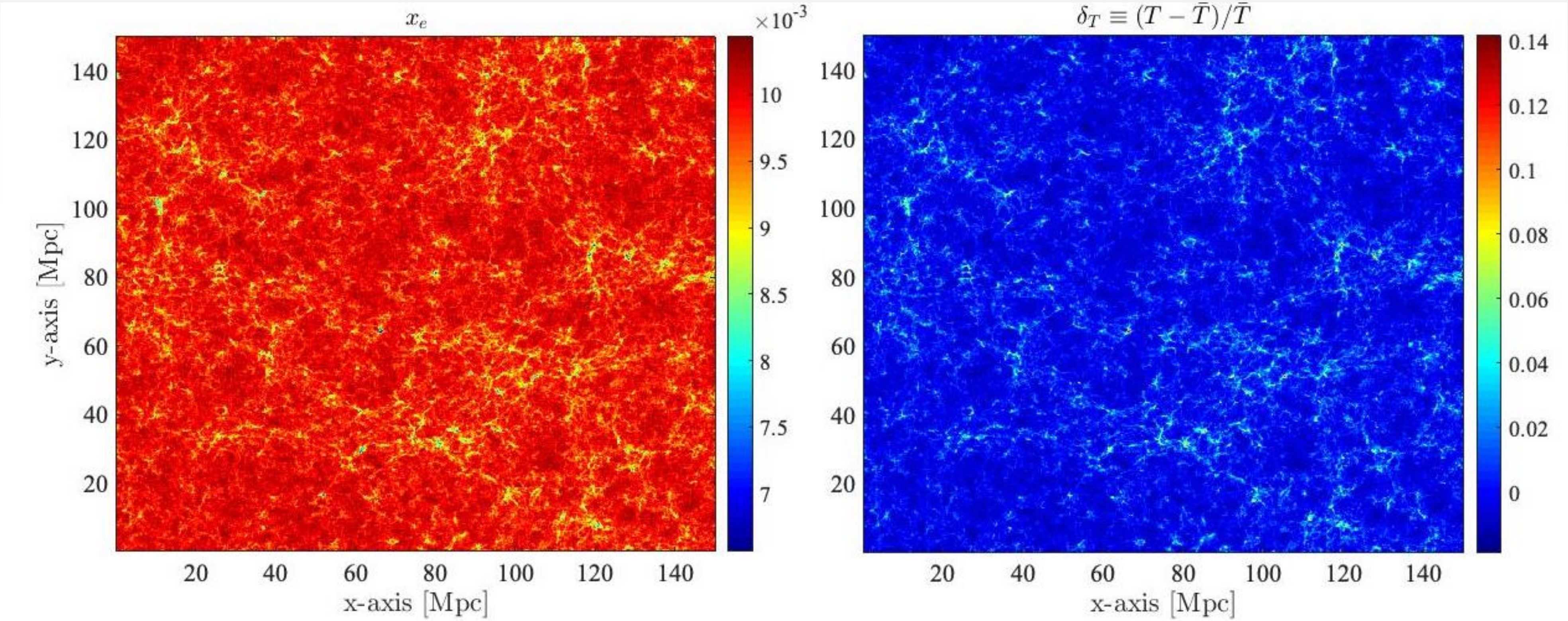
Limit on T_{GAS} rise:
$\Delta T_{21} < +100$ or $+150$ mK at z=17

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



Decay: unaffected by clustering.

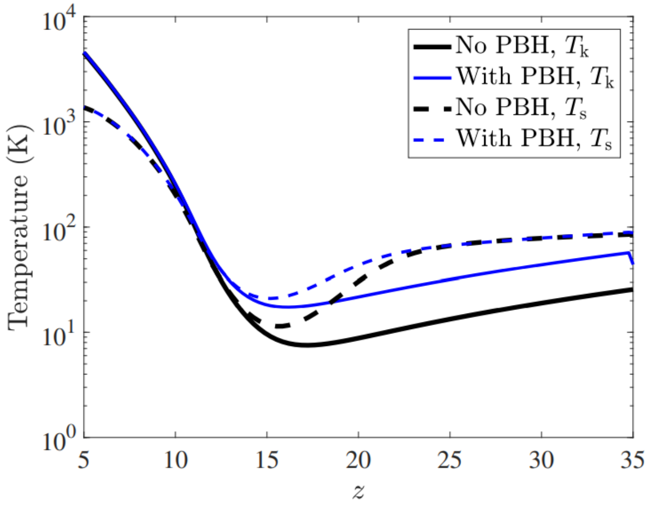
x_e, T inhomogeneity impact 21cm power spectrum

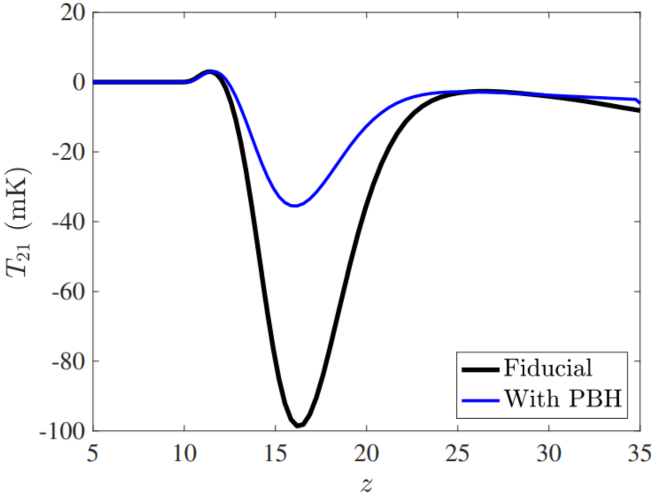


Enhanced x_e & T inhomogenuity in patchy reionization (on a Mpc grid)

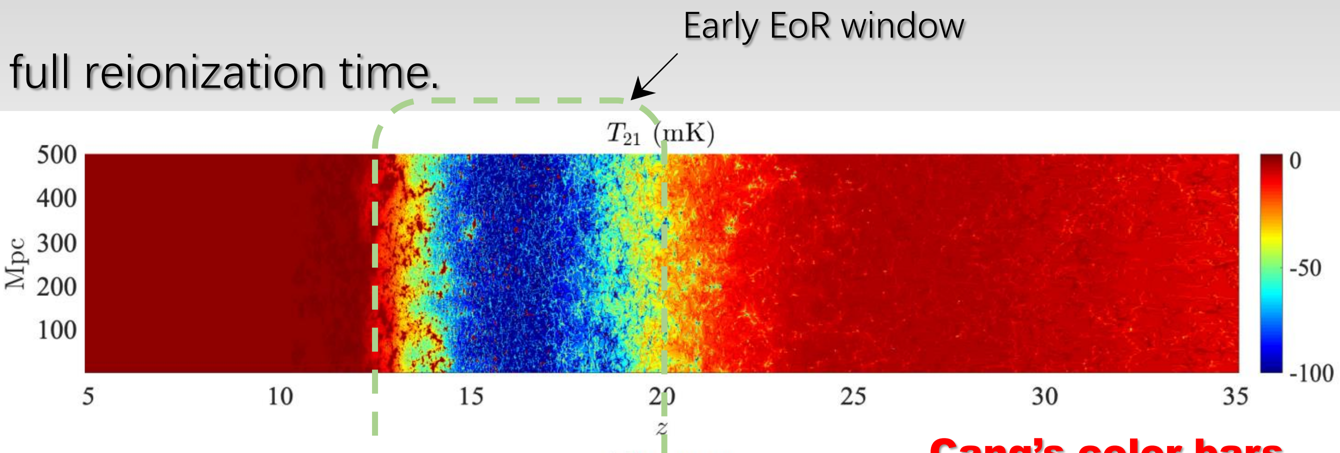
21cm：venture into the nonlinear regime

Spatial T_{21}, T_{gas} evolution towards full reionization time.



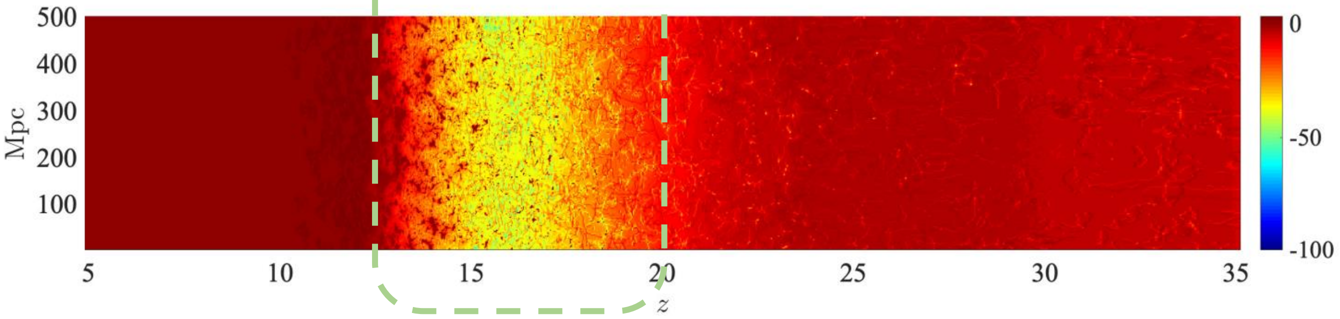


Early EoR window



(a)No PBH

Cang's color bars



(b)With PBH

↑ Show-case: Scale-depend evolution: $T(k^{-1},z)$

$m_{bh} = 10^{14}$ g, $f_{bh} = 5 \times 10^{-10}$

DM/PBH corrections in both global T_{21} and realistic $T_{21}(k,z)$ spectra are expected.

(collaborative work in progress.)

backups

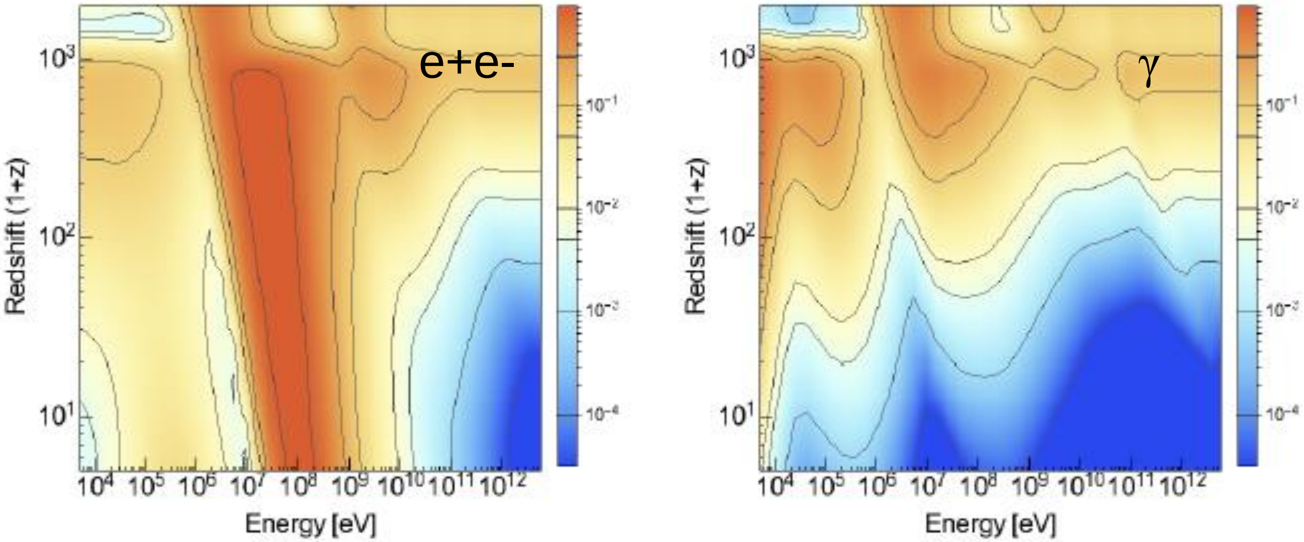
Lagged energy deposition

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

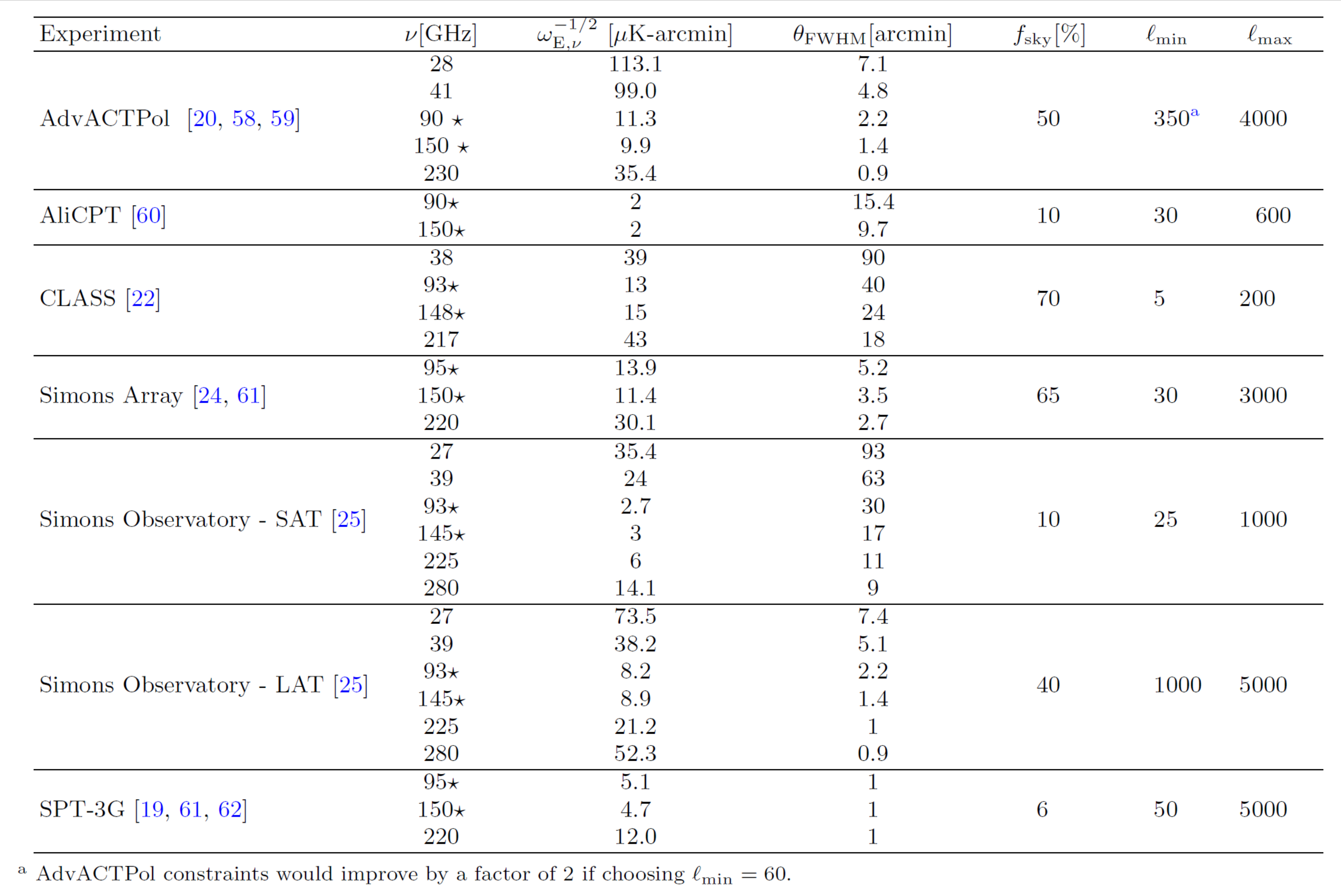
Numerical calculation

Implemented into
HyRec codes:

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

Also see:
Belotsky, Kirillov 2015

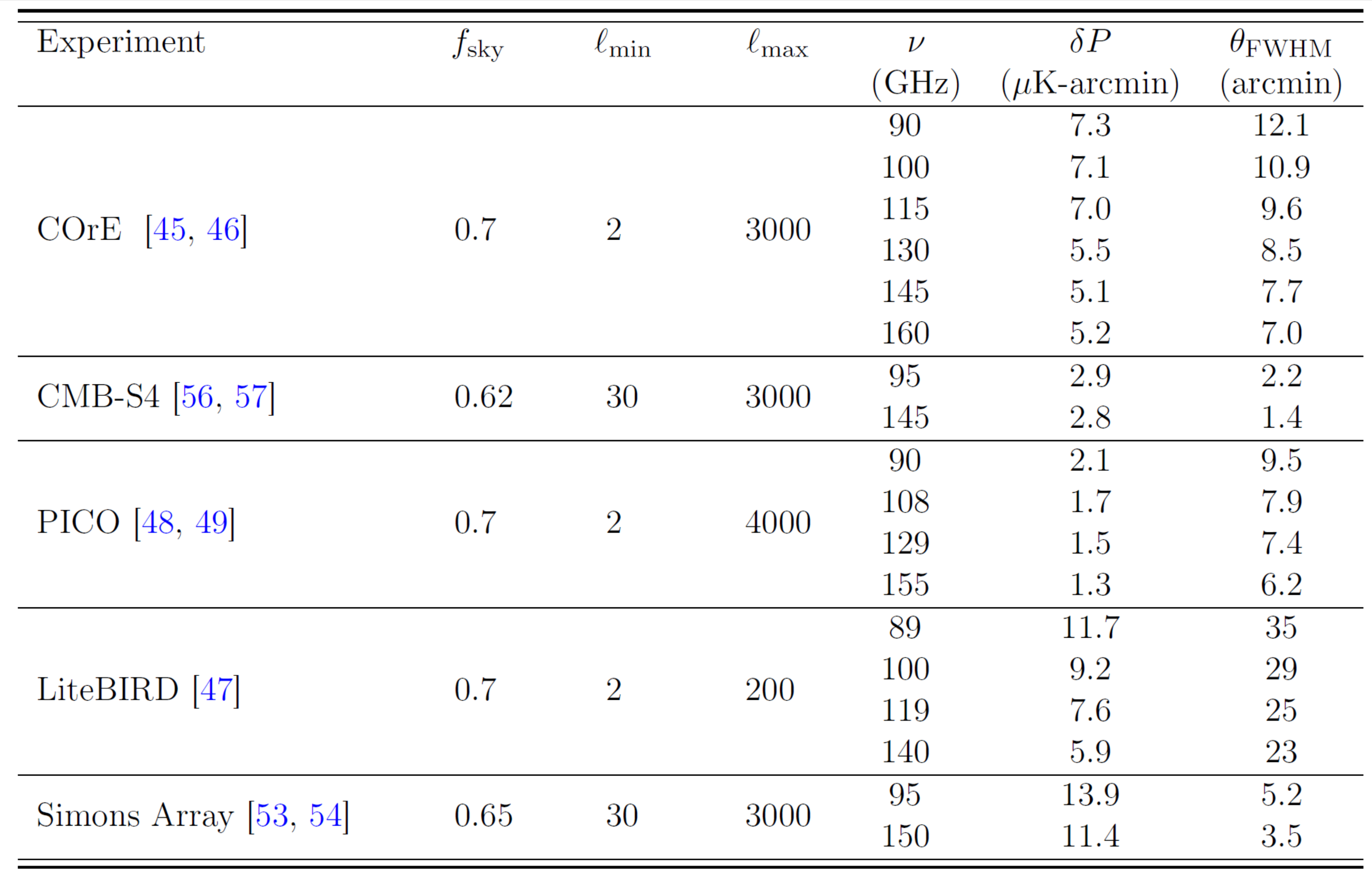
Exp. specifications (DM)



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 $\star$	11.3	2.2			
	150 $\star$	9.9	1.4			
	230	35.4	0.9			
AliCPT [60]	90$\star$	2	15.4	10	30	600
	150$\star$	2	9.7			
CLASS [22]	38	39	90	70	5	200
	93$\star$	13	40			
	148$\star$	15	24			
	217	43	18			
Simons Array [24, 61]	95$\star$	13.9	5.2	65	30	3000
	150$\star$	11.4	3.5			
	220	30.1	2.7			
Simons Observatory - SAT [25]	27	35.4	93	10	25	1000
	39	24	63			
	93$\star$	2.7	30			
	145$\star$	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$\star$	8.2	2.2			
	145$\star$	8.9	1.4			
	225	21.2	1			
	280	52.3	0.9			
SPT-3G [19, 61, 62]	95$\star$	5.1	1	6	50	5000
	150$\star$	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