CMB Probe of Particle Dark Matter and Primordial Black Hole

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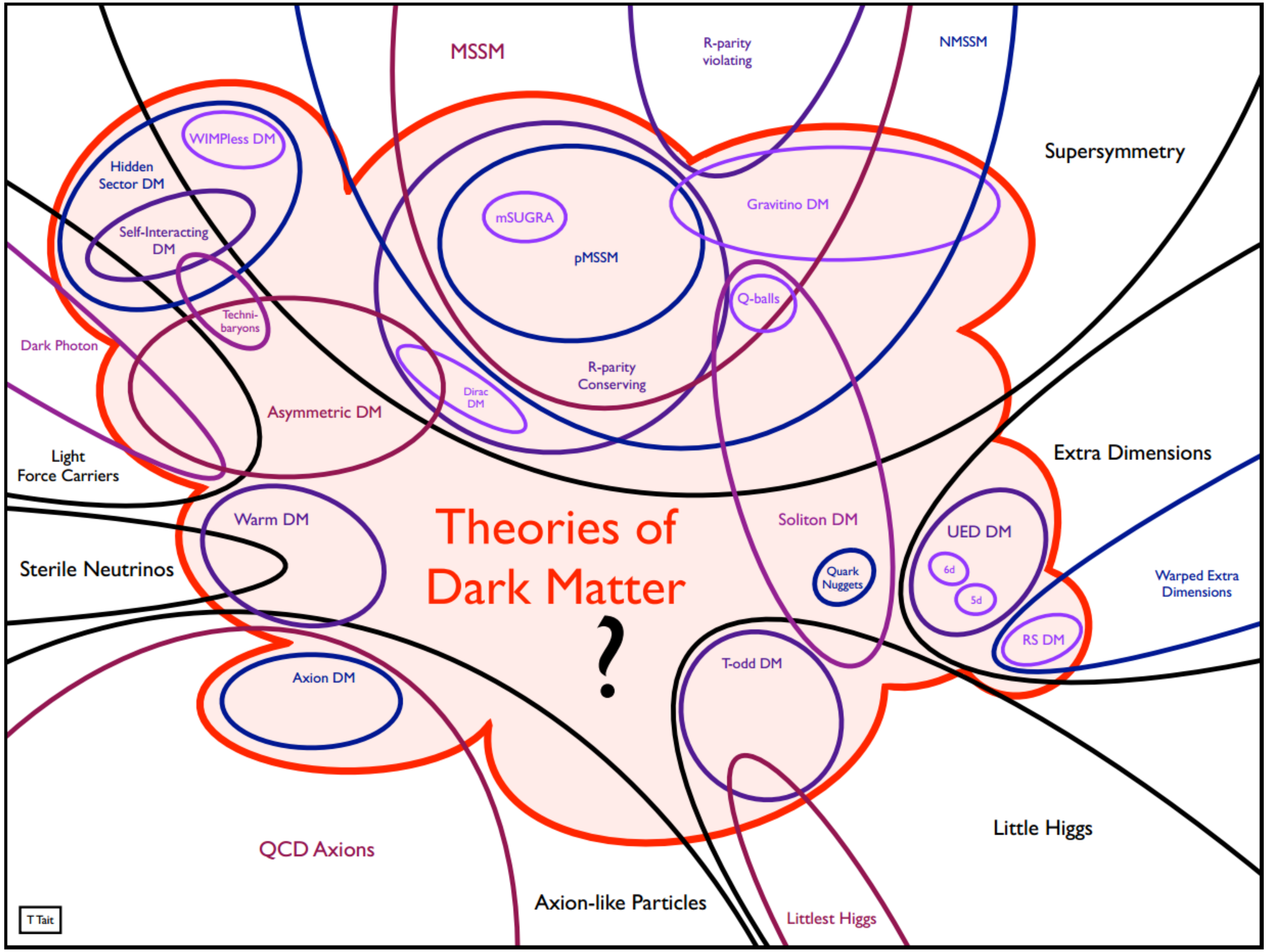
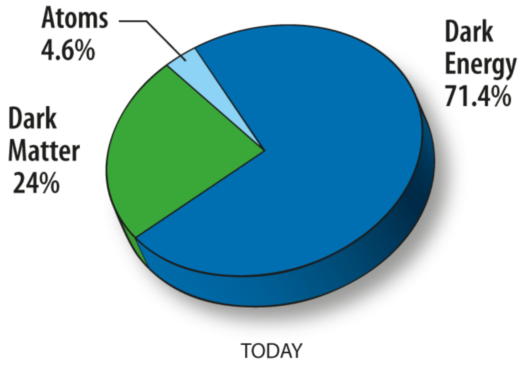
ArXiv 2002.03380 2011.12244

PowerPoint

What is Dark Matter





What we know

1. Gravitational Interactive
2. Negligible interaction with Baryonic Matter
3. Stable
4. Dynamically Cold

Possibilities

1. New Particle(s)
2. Primordial Black Hole (PBH)
3. Modified Gravity

. . .

PBH

Important probe of the very early universe !

Formation

(Very early universe)

1. Density Fluctuation

2. Inflationary Perturbation

3. Cosmological Phase Transition

4. Collapsing Domain Wall Bubble

5. Collapsing Cosmic String

. . .

Mass Range

$$M \sim \frac{c^3\,t}{G} \sim 10^{15} \left(\frac{t}{10^{-23}\,\mathrm{s}}\right) \mathrm{g}.$$

Anywhere between

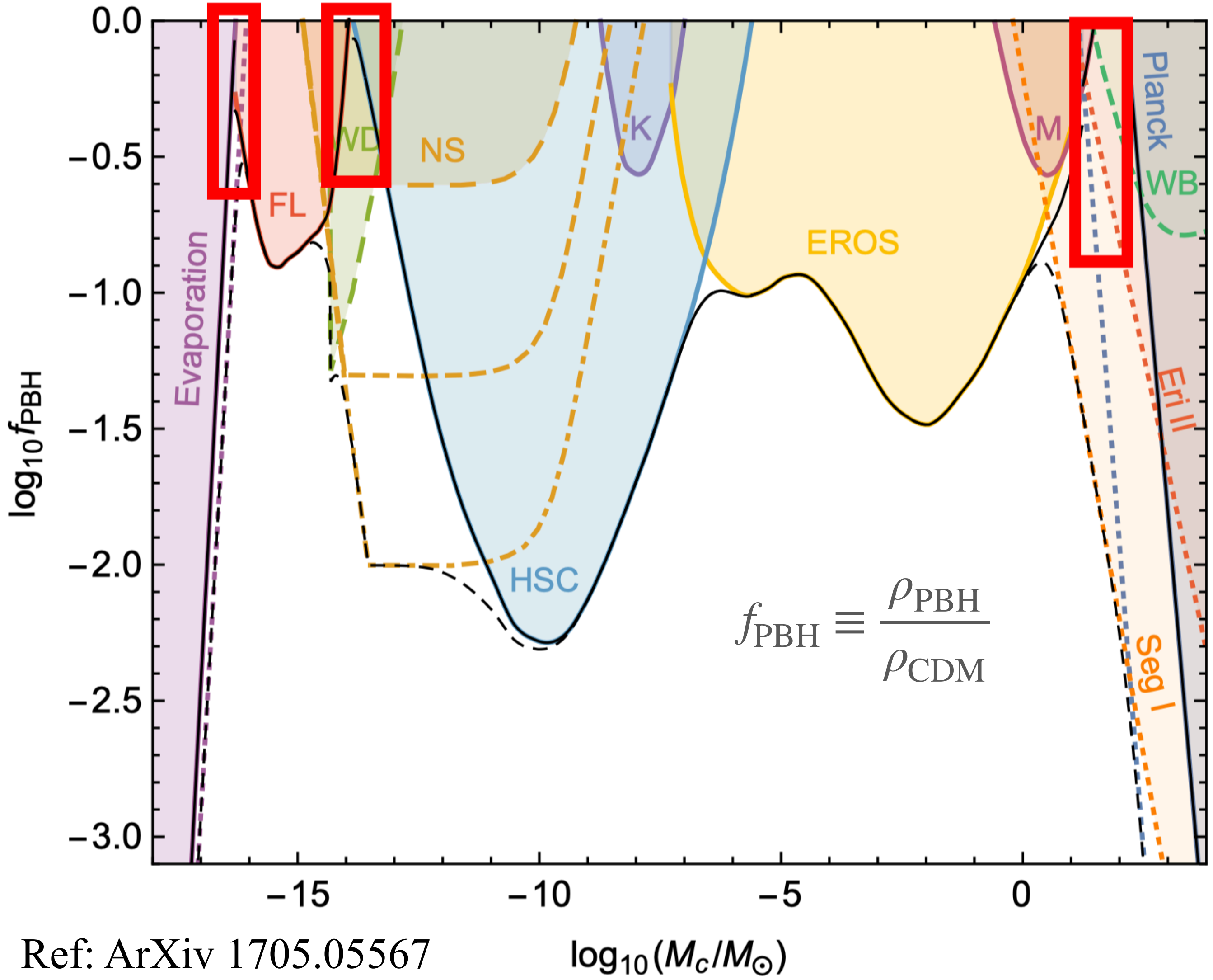
$$10^{-5}\mathrm{g} \;\sim\; 10^5 M_\odot$$

Theories

- Quantum Gravity

- Inflation

PBH Current Status



Ref: ArXiv 1705.05567

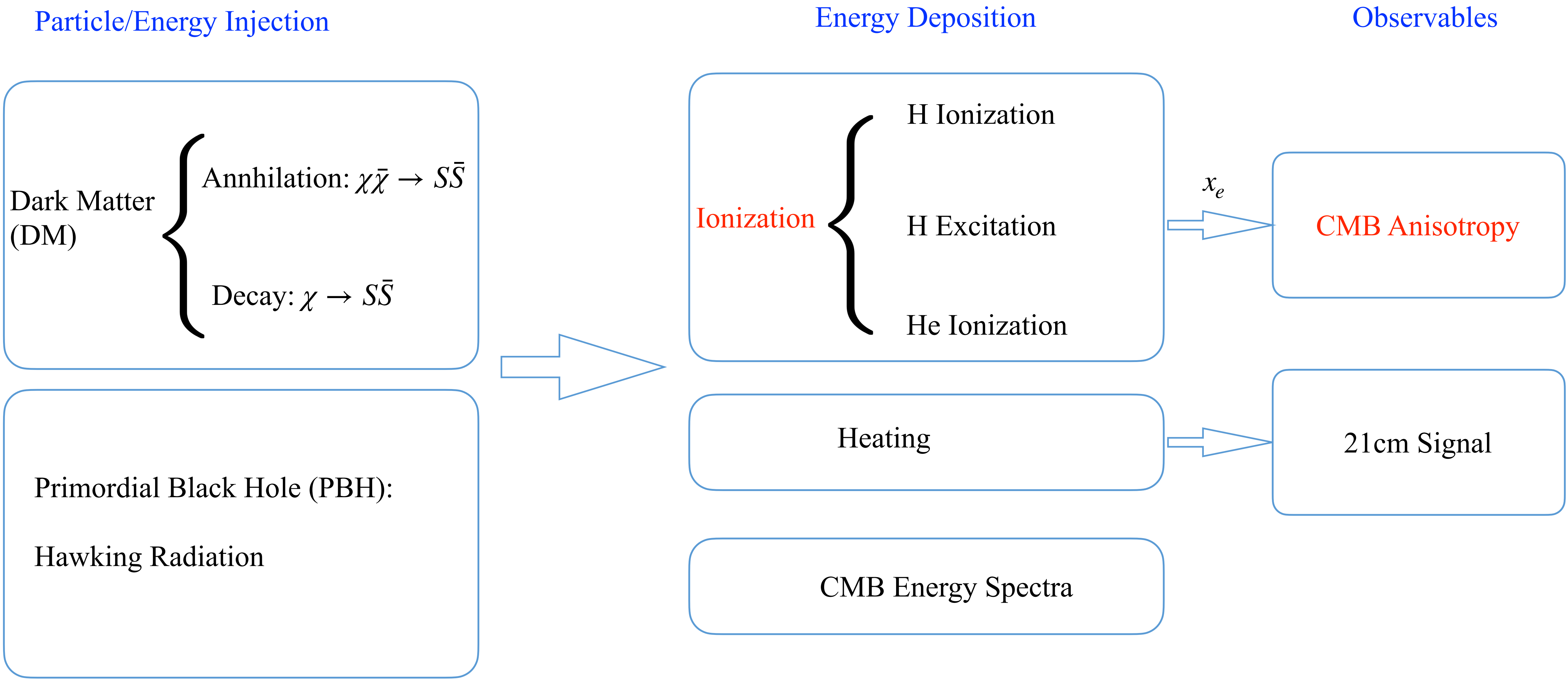
Mechanism

- Gravitational Lensing
- Gravitational Wave
- Accretion
- Hawking Radiation
- …

Only 3 Mass Windows Left

Our Window: $10^{13} \sim 10^{17}$g

Overview


Particle/Energy Injection
Energy Deposition
Observables
Dark Matter (DM)
Annhilation: $\chi\bar{\chi} \to S\bar{S}$
Decay: $\chi \to S\bar{S}$
Primordial Black Hole (PBH):
Hawking Radiation
Ionization
H Ionization
H Excitation
He Ionization
Heating
CMB Energy Spectra
x_e
CMB Anisotropy
21cm Signal

Can DM Ionize the Universe?

Energy required (unit comoving volume):

$$\Delta E = n_H \times 13.6eV = 13.6eV \cdot \frac{\Omega_b \rho_{cr}}{m_p}$$

DM density

$$\Delta \rho_c = \rho_c (1 - e^{-t/\tau}) = \rho_{cr} \Omega_c t / \tau$$

Assuming

$$\Delta E = f \times \Delta \rho_c$$

$$f \sim 0.1$$

Lower Bound:

$$\tau \sim 1.5 \times 10^{25} s$$

Upper bound:

$$\frac{\Delta \rho_c}{\rho_c} \sim \frac{t}{\tau} \sim 3 \times 10^{-8}$$

Dark Matter Injection

$$\textbf{Dark Matter:} \left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{INJ}} = R \times E_{\mathrm{n}}$$

Decay:

$$R^{\mathrm{dec}} = \Gamma_\chi n_\chi e^{-\Gamma_\chi t},\ E_{\mathrm{n}}^{\mathrm{dec}} = m_\chi \quad \Longrightarrow \quad \left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{dec}}_{\mathrm{INJ}} = \Gamma_\chi \Omega_\chi (1+z)^3 \rho_{\mathrm{c}}$$

Annihilation (s-wave):

$$R^{\mathrm{ann}} = \mathrm{g}\ n_\chi^2 \langle\sigma v\rangle,\ E_{\mathrm{n}}^{\mathrm{ann}} = 2m_\chi \quad \Longrightarrow \quad \begin{cases} \text{Homogeneous} & \left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{ann}}_{\mathrm{INJ}} = \frac{\langle\sigma v\rangle}{m_\chi} \Omega_\chi^2 (1+z)^6 \rho_{\mathrm{c}}^2 \\ \text{Clustered} & \left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{ann,boosted}}_{\mathrm{INJ}} = [1+B(z)] \left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)^{\mathrm{ann}}_{\mathrm{INJ}} \end{cases}$$

Boost Factor

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

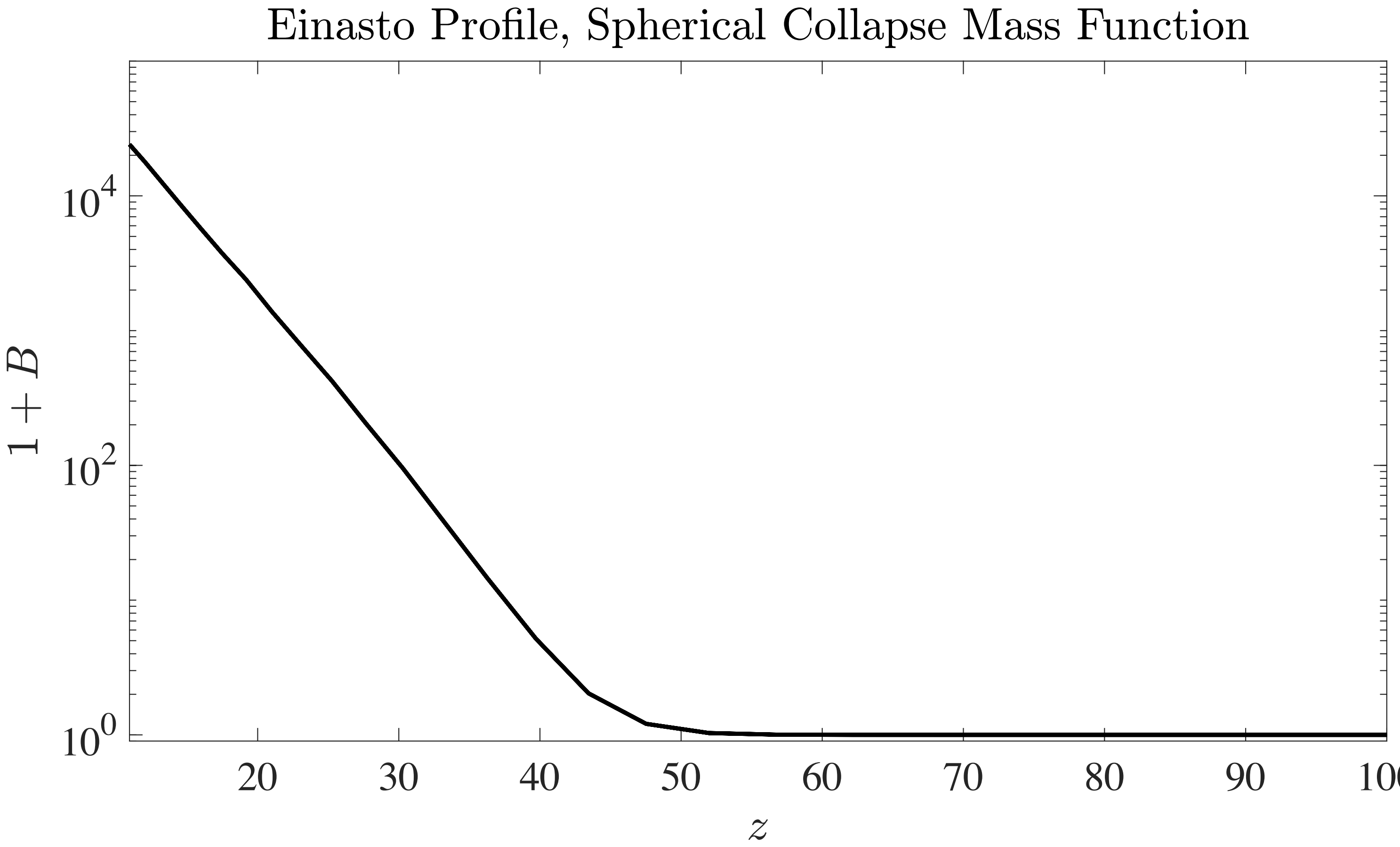
Boost Factor

$$B_{\mathrm{h}}(M) = \frac{4\pi}{\bar{\rho}_{\mathrm{h}}^2 V_{\mathrm{h}}(M)} \int_0^{r_{200}} \mathrm{d}r \rho^2(r) r^2$$

Halo Profile

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

Halo Mass Function



$$\rho(r) = \rho_{-2} \exp\left(-\frac{2}{\alpha_{\mathrm{e}}}\left[\left(\frac{r}{r_{-2}}\right)^{\alpha_{\mathrm{e}}} - 1\right]\right)$$

$$\frac{\mathrm{d}n}{\mathrm{d}\ln M} = \frac{1}{2} f(\nu) \frac{\rho_{\mathrm{DM}}}{M} \frac{\mathrm{d}\ln(\nu)}{\mathrm{d}\ln M}$$

$$f(\nu) = A\sqrt{\frac{2q\nu}{\pi}}\left[1 + (q\nu)^{-p}\right] \mathrm{e}^{-q\nu/2}$$

PBH Injection : Hawking Radiation

Particle Spectra:

$$\frac{dN}{dEdt} = \frac{1}{2\pi} \frac{\Gamma_s}{\exp(E/T_{BH}) - (-1)^{2s}}$$

Temperature

$$T_{\rm BH} = 1.06\text{TeV}\frac{10^{10}\text{g}}{M}$$

Mass Loss:

$$\dot{M} = -5.34 \times 10^{25} F(M) M^{-2} \text{g/s}$$

$F(M): 1 \sim 15$

$$\left(\frac{\mathrm{d}E}{\mathrm{dVd}t}\right)^{\rm MMD}_{\rm INJ} = -\dot{M} \cdot n_{\rm PBH}$$

Monochromatic Distribution:

$$n_{\rm PBH} = f_{\rm PBH} \frac{\Omega_{\rm DM}\rho_{\rm cr}(1+z)^3}{M}$$

$$f_{\rm PBH} \equiv \Omega_{\rm PBH}/\Omega_{\rm DM}$$

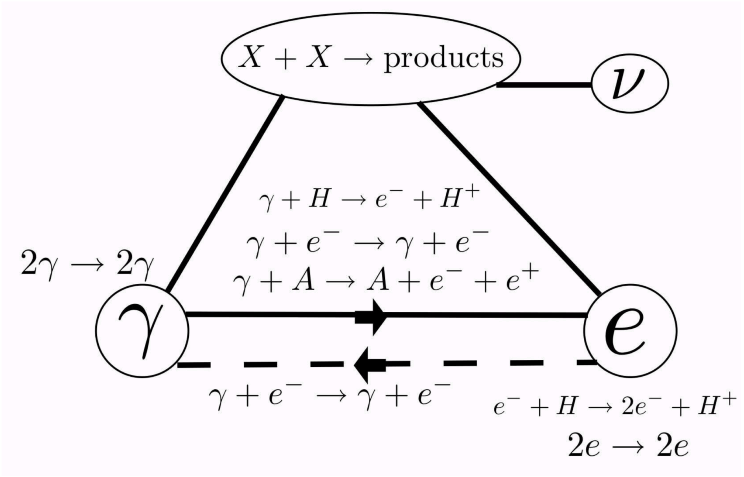
Extended Distribution:

$$\left(\frac{\mathrm{d}E}{\mathrm{dVd}t}\right)_{\rm INJ} = \int dM \Psi(M) \left(\frac{\mathrm{d}E}{\mathrm{dVd}t}\right)^{\rm MMD}_{\rm INJ}$$

$$\Psi(M) \equiv \frac{1}{\rho_{\rm PBH}} \frac{\mathrm{d}\rho_{\rm PBH}(M)}{\mathrm{d}M}$$

Deposition Efficiencies

$$\left(\frac{dE}{dtdV}\right)_{c,\mathrm{dep}} = f_c(z)\left(\frac{dE}{dtdV}\right)_{\mathrm{inj}}$$



- EM cascade
- Pair Production
- Compton Scattering
- Inverse CS

…

Dependencies
1. Redshift
2. Injection history
3. $e^{\pm}, \gamma$ Spectra
4. Particle Channel

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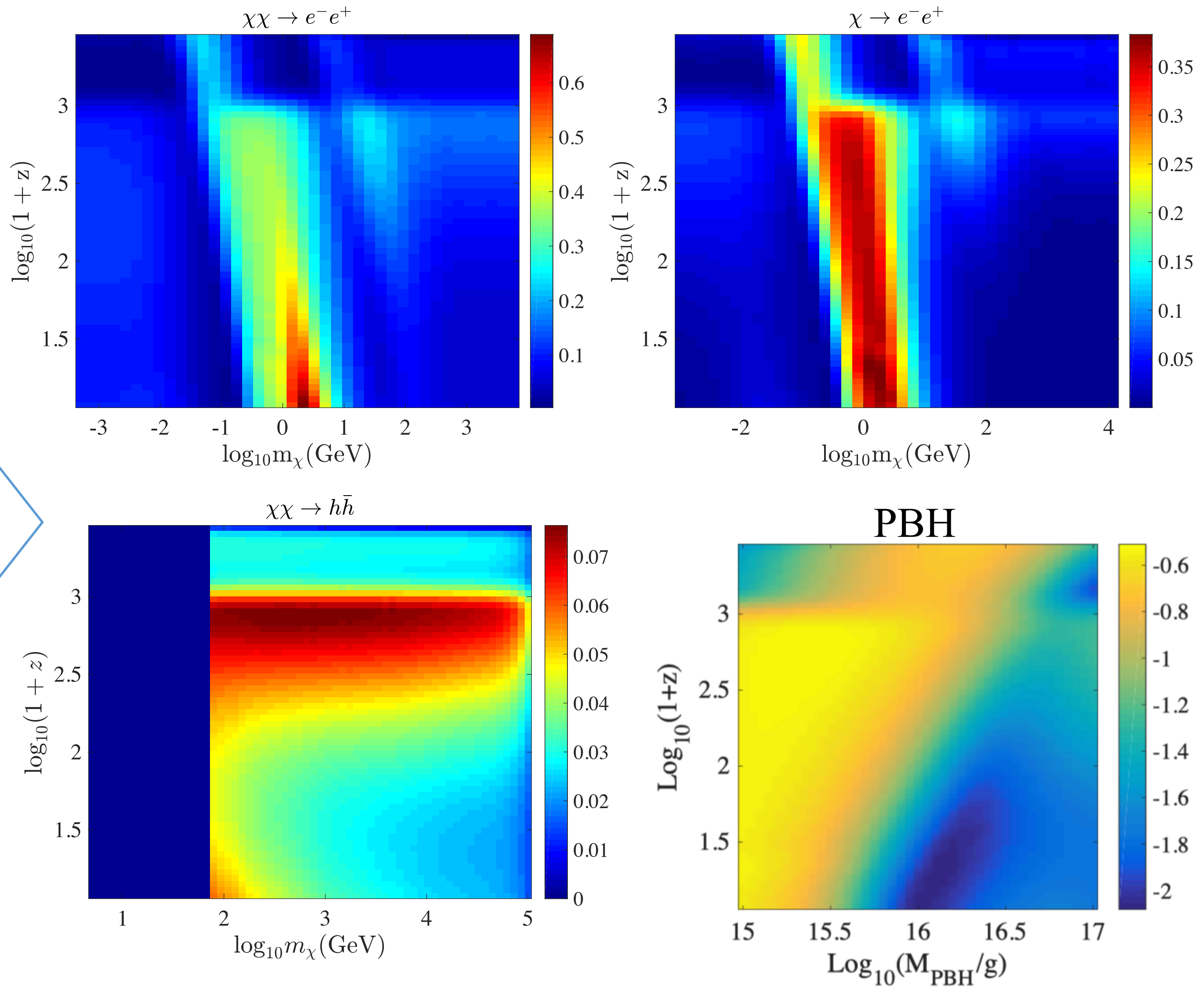
Examples
(H Ionization)



Modified Recombination

$$\frac{\mathrm{d}x_{\mathrm{e}}}{\mathrm{d}z} = \left(\frac{\mathrm{d}x_{\mathrm{e}}}{\mathrm{d}z}\right)_0 - \frac{I_\chi}{(1+z)H(z)} \qquad (16)$$

$$\frac{\mathrm{d}T_{\mathrm{IGM}}}{\mathrm{d}z} = \left(\frac{\mathrm{d}T_{\mathrm{IGM}}}{\mathrm{d}z}\right)_0 - \frac{2}{3k_B(1+z)H(z)}\frac{K_{\mathrm{h}}}{1+f_{\mathrm{He}}+x_{\mathrm{e}}}$$

From ground state (n=1)

Ionization Terms:

$$I_\chi = I_{\chi i} + I_{\chi\alpha}$$

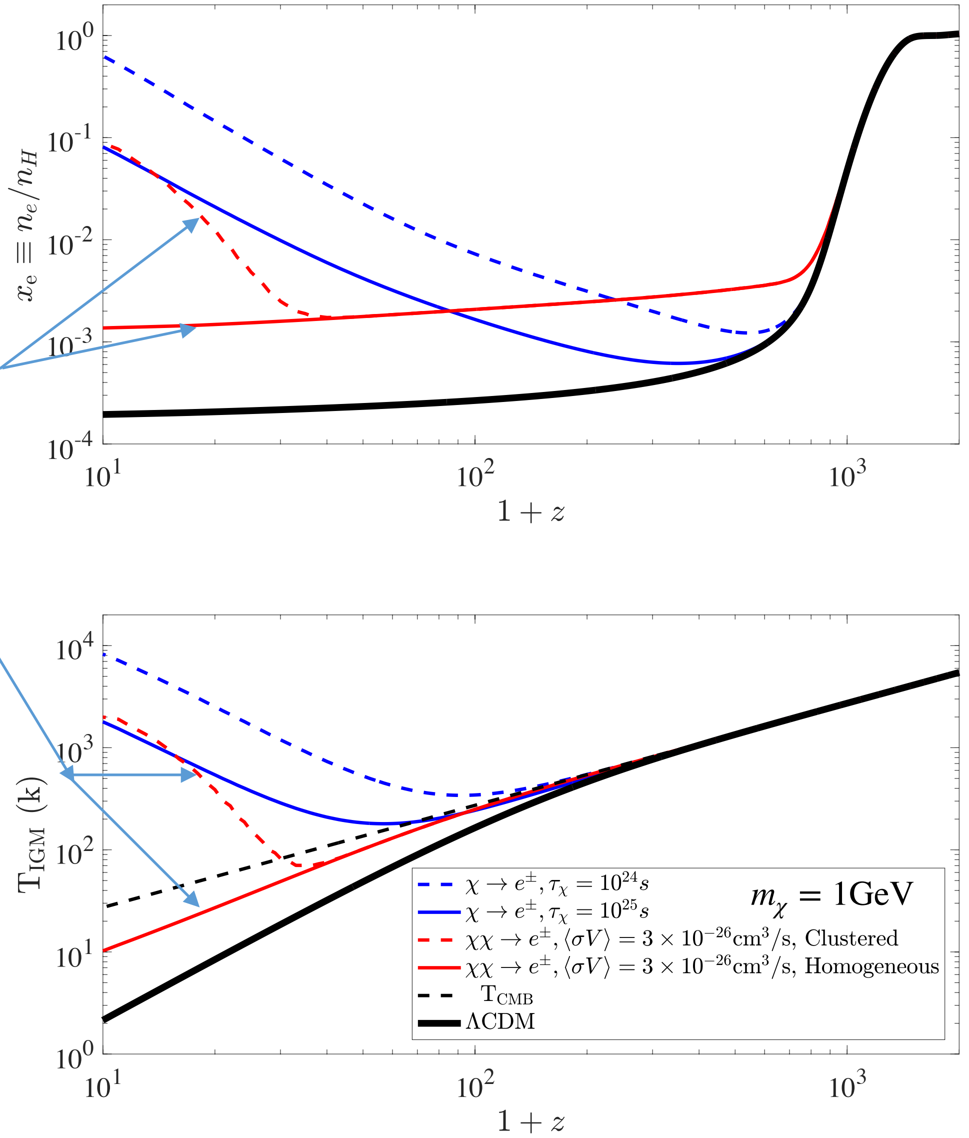
$$\begin{cases} I_{\chi i}(z) = \dfrac{1}{n_{\mathrm{H}}(z)E_i}\left(\dfrac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{DEP},i} \\ I_{\chi\alpha}(z) = \dfrac{1-C}{n_{\mathrm{H}}(z)E_\alpha}\left(\dfrac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{DEP},\alpha} \end{cases}$$

From excited state (n=2)

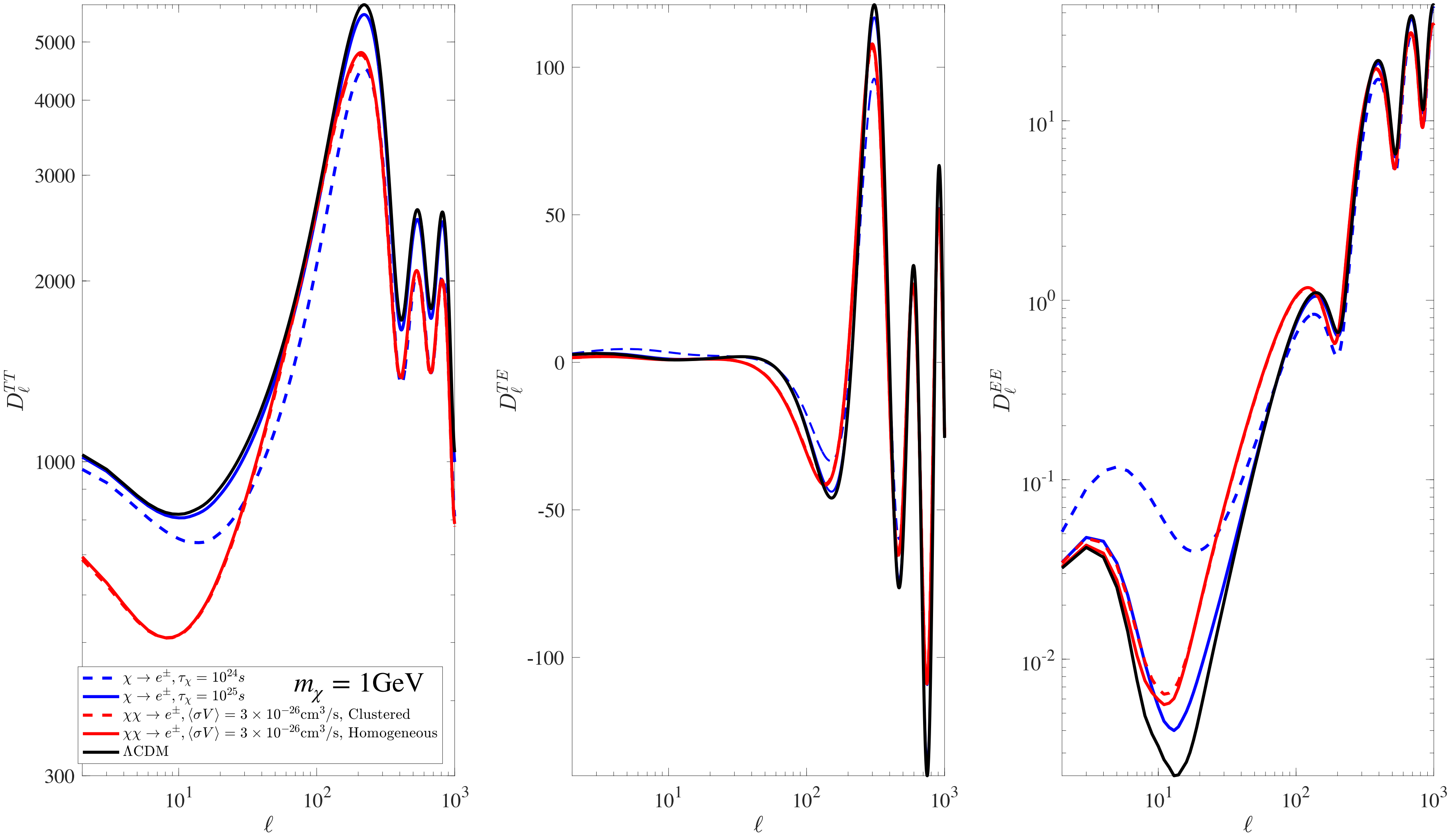
Heating Term:

$$K_{\mathrm{h}}(z) = \frac{1}{n_{\mathrm{H}}(z)}\left(\frac{\mathrm{d}E}{\mathrm{d}V\mathrm{d}t}\right)_{\mathrm{DEP},h}$$

Halo Boost



CMB Signature



Increase Compton Scattering

& Width of Surface of Last Scattering

1. Suppress small scale (high ℓ) correlations
2. Enhance Low-L correlations;
3. Shift EE and TE peak location

Insensitive to Halo Boost

Forecast Datasets

Chi^2

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

Data

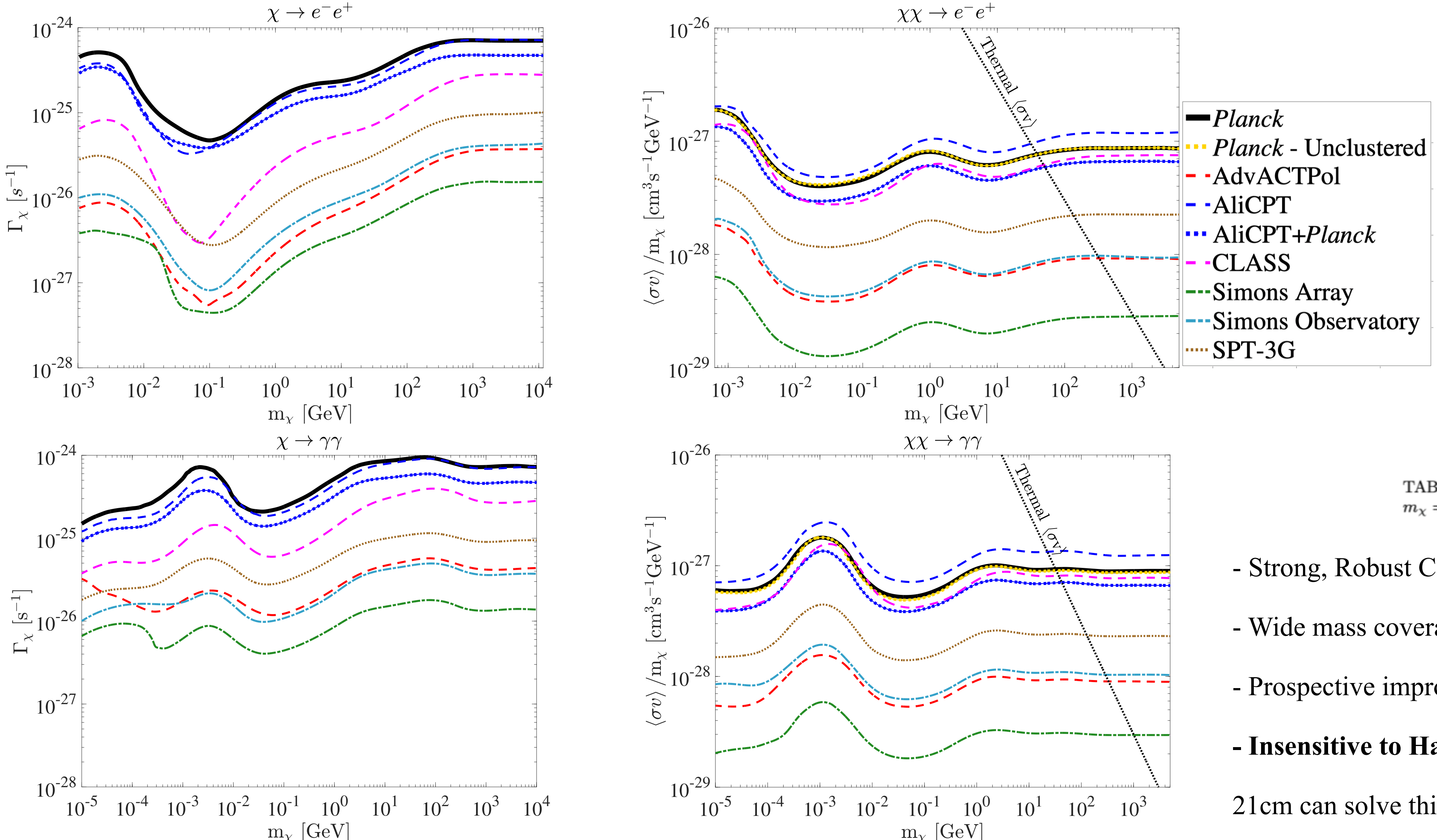
$$\hat{C}_\ell = \underbrace{\bar{C}_\ell}_{\Lambda\mathrm{CDM}} + \underbrace{N_\ell}_{\text{Noise}}$$

$$N_\ell^{\rm EE} = \left[\sum_\nu \frac{1}{N_{\ell,\nu}^{\rm EE}}\right]^{-1}, \quad N_\ell^{\rm TT} = N_\ell^{\rm EE}/2$$

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

Experiment	ν[GHz]	$\omega_{\rm E,\nu}^{-1/2}$ [μK-arcmin]	$\theta_{\rm FWHM}$[arcmin]	$f_{\rm sky}$[%]	$\ell_{\rm min}$	$\ell_{\rm max}$
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			
CMB-S4 [70, 71]	95	2.9	2.2	62	30	3000
	145	2.8	1.4			
PICO [68, 69]	90	2.09	9.5	70	2	4000
	108	1.70	7.9			
	129	1.53	7.4			
	155	1.28	6.2			

DM Constraints (ArXiv 2002.03380)



Experiment	$\chi\chi \to e^+e^-$	$\chi\chi \to \gamma\gamma$
Planck	6.25	9.24
Planck - Unclustered	6.17	9.00
AdvACTPol	0.65	0.93
AliCPT	8.02	13.32
AliCPT+*Planck*	4.58	6.91
CLASS	4.85	8.26
Simons Array	0.20	0.31
Simons Observatory	0.68	1.08
SPT-3G	1.59	2.41

TABLE III. 95%C.L upper-bound on $\langle\sigma v\rangle / m_\chi$ (in 10^{-28} $cm^3 s^{-1} GeV^{-1}$) for $m_\chi = 10$GeV.

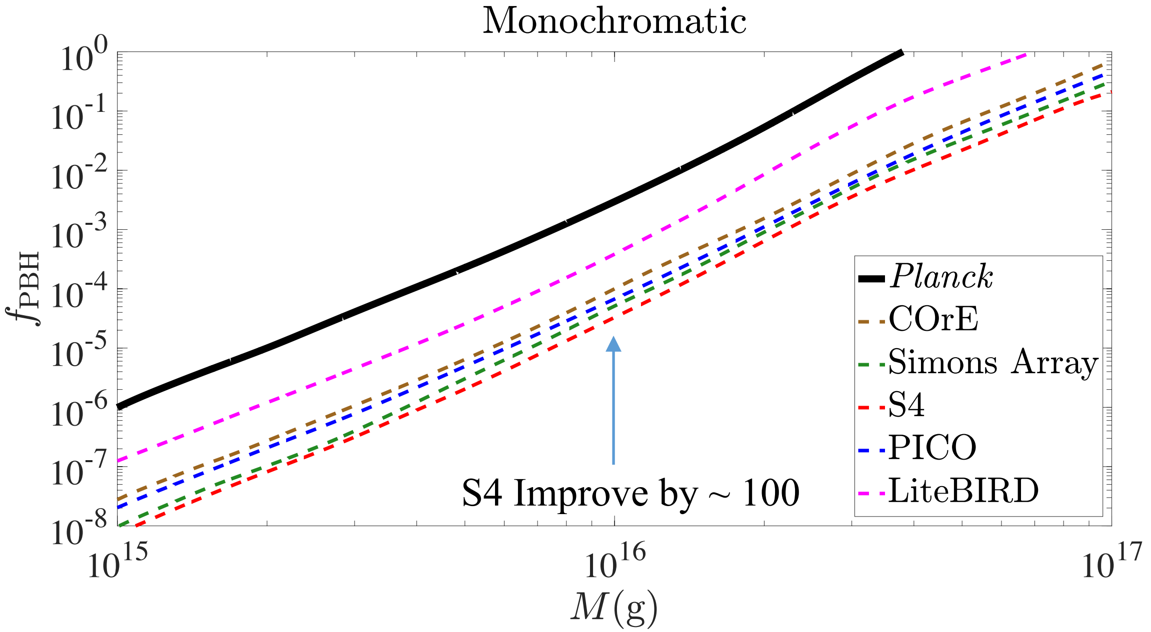
Experiment	$\chi \to e^+e^-$	$\chi \to \gamma\gamma$
Planck	23.61	85.02
AdvACTPol	0.68	4.66
AliCPT	20.77	78.31
AliCPT+*Planck*	16.00	53.07
CLASS	5.51	29.74
Simons Array	0.35	1.49
Simons Observatory	0.92	4.18
SPT-3G	2.20	9.88

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

- Strong, Robust Constraints (think about cosmic ray)
- Wide mass coverage : KeV (WDM) to TeVs (CDM)
- Prospective improvements by about a factor of 100
- **Insensitive to Halo Boost (Curse/Blessing?)**

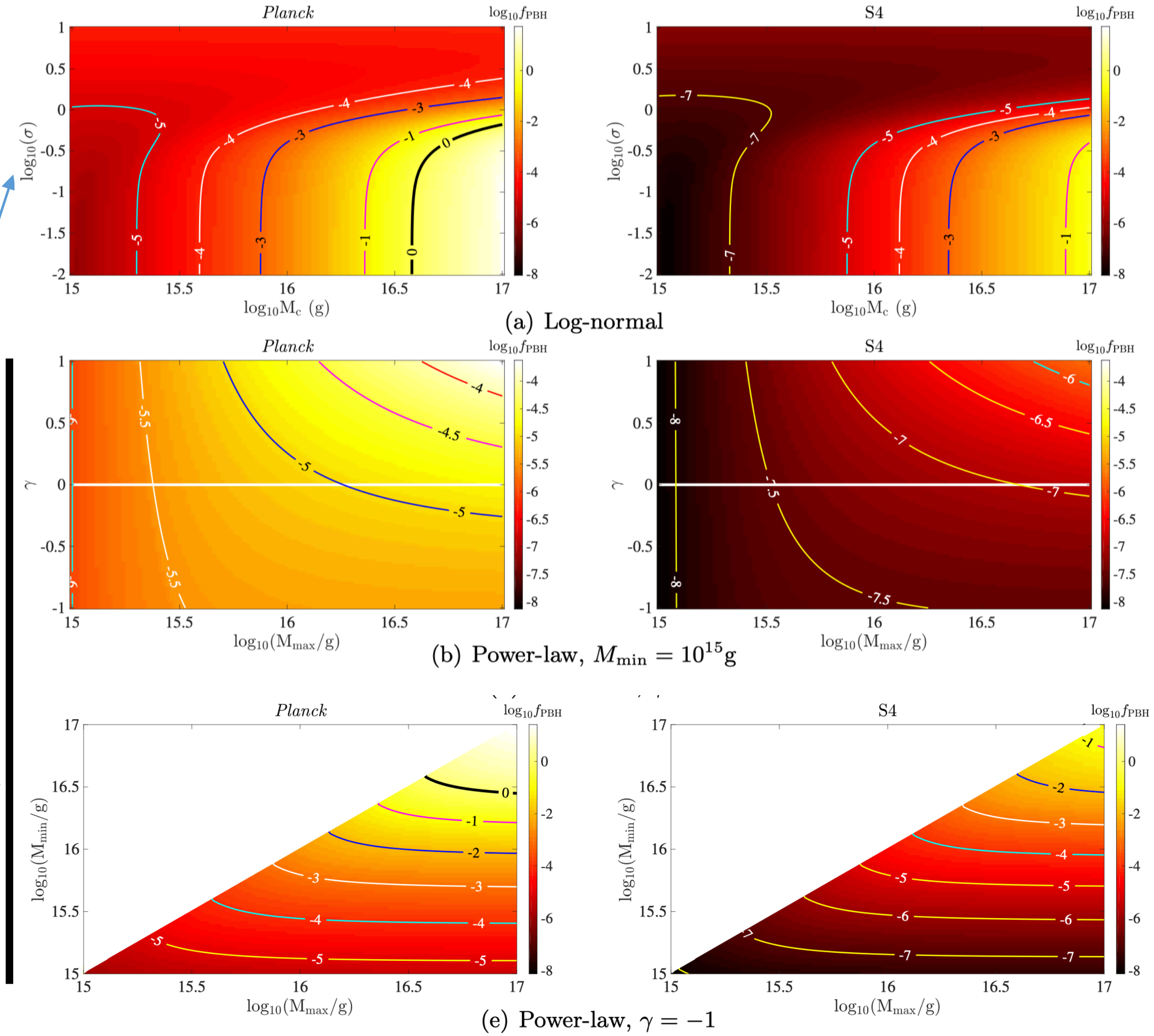
21cm can solve this problem!

PBH Constraints (2011.12244)



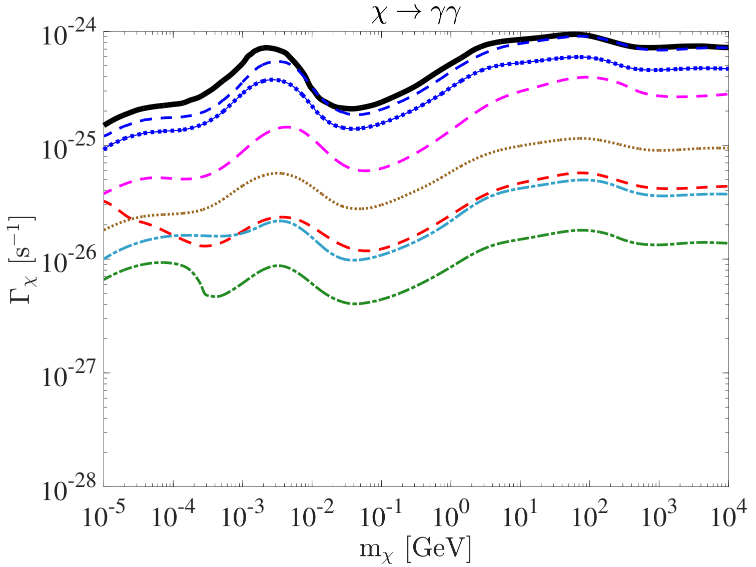
$$\Psi(M') = \frac{1}{\sqrt{2\pi}\sigma M'} \exp\left(-\frac{(\log[M'/M])^2}{2\sigma^2}\right)$$

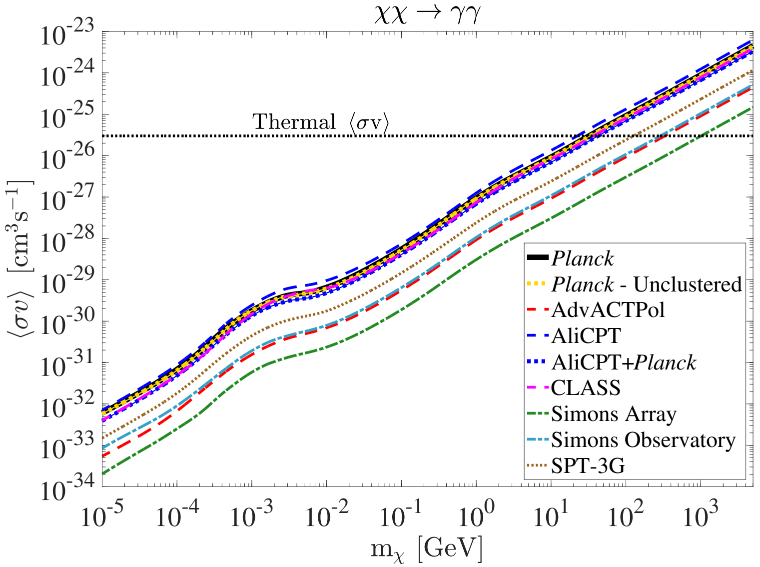
$$\Psi(M') \propto M'^{\gamma-1} \; (M_{\rm min} < M' < M_{\rm max})$$

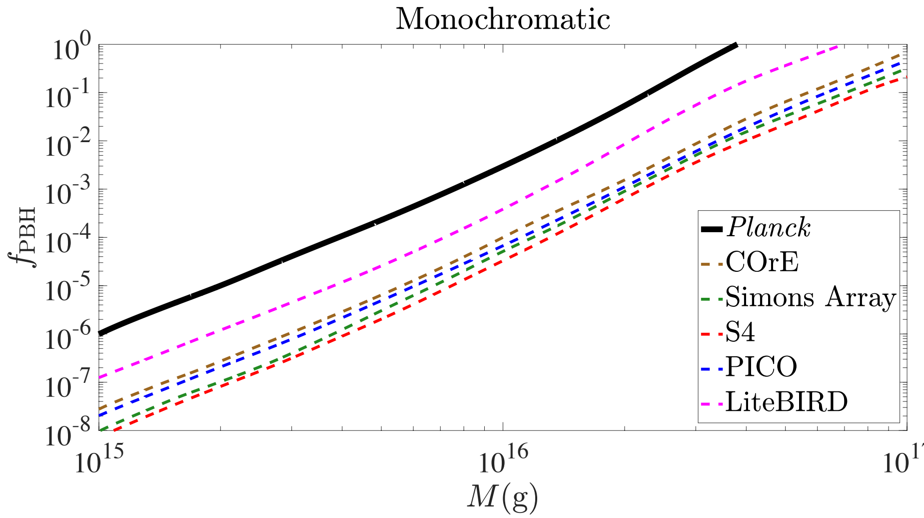


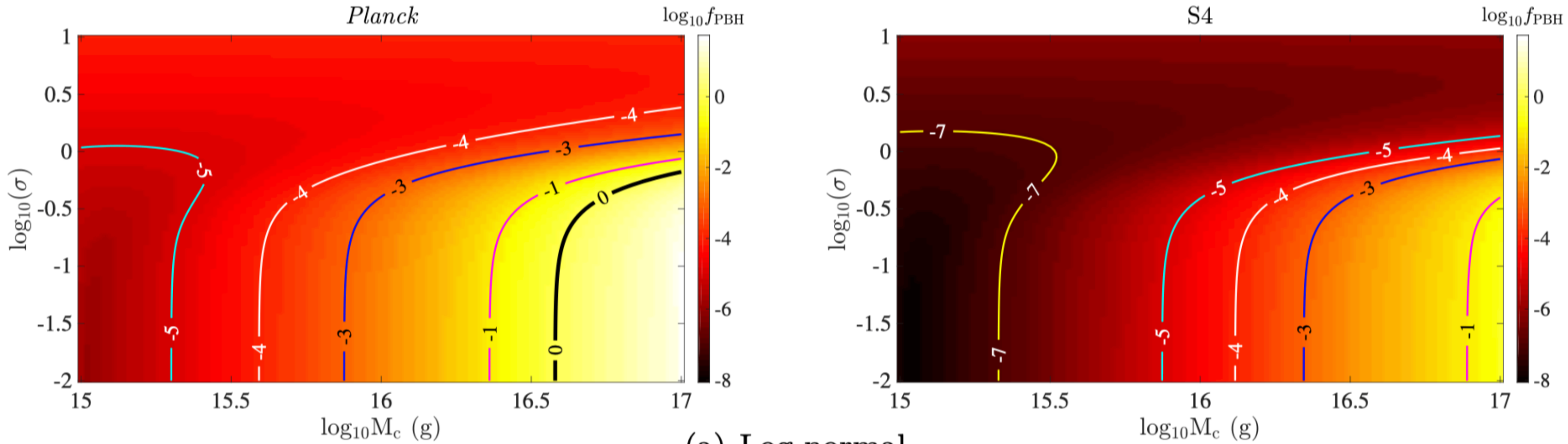
$10^{15} \sim 10^{17}$g window can be ruled out

Thank you!









(a) Log-normal

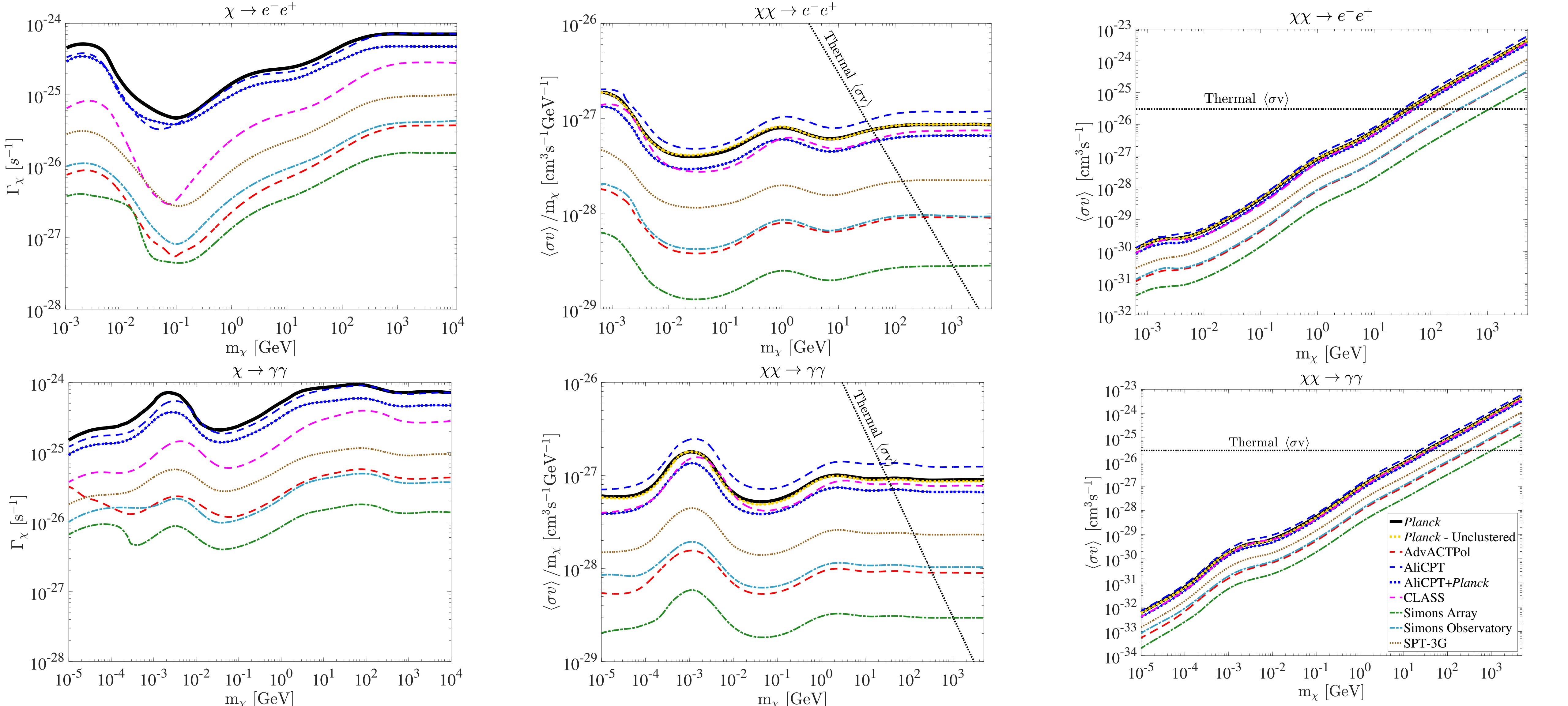
1. CMB can set robust and stringent DM/PBH bounds
2. Prospective improvement by 100 for future experiment
3. Stay tuned for the first 21cm light - SKA, HERA

Energy

Injection and Deposition

from DM

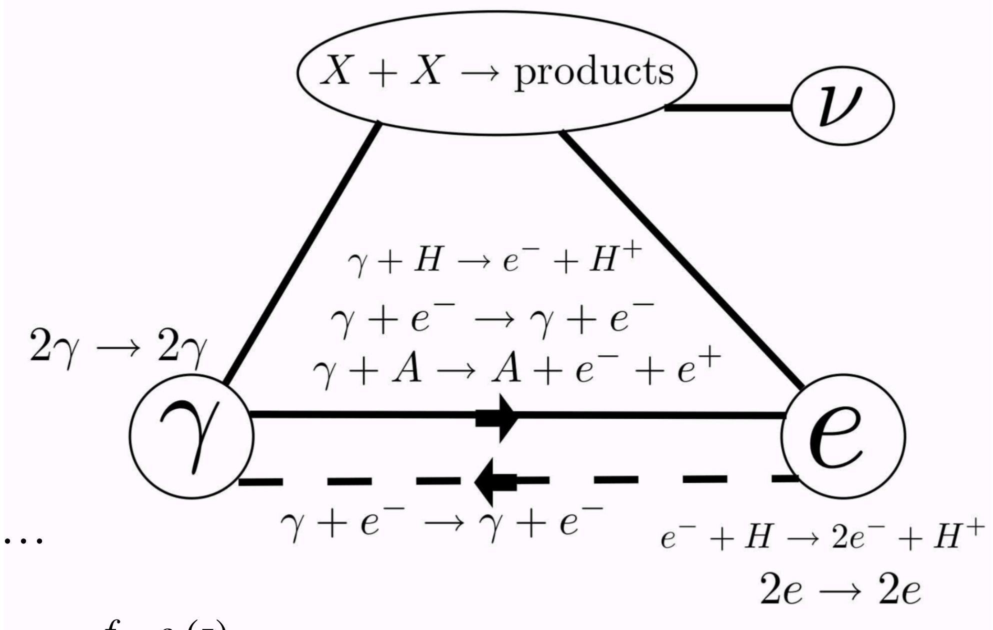
DM Constraints (ArXiv 2002.03380)



IGM Interaction

Most SM particles are either unstable or inactive.

Only $e^{\pm}, \gamma$ need to be accounted for.



$I^s \equiv \dfrac{\mathrm{d}N^s}{\mathrm{d}E\mathrm{d}V\mathrm{d}t}$

DM: $I^s = \dfrac{\mathrm{d}N^s}{\mathrm{d}E} \times R$

Pythia, HERWIG, PPPC4DMID…

PBH

Monochromatic

$$I^{s,\delta}(M,t) = \frac{dN^s}{d\epsilon dt}(M,t) \times \frac{f_{\mathrm{BH}}\rho_c(z)}{M'}$$

$$\frac{dN^s}{d\epsilon dt}(M,\epsilon) = \sum_i \int d\epsilon_i \frac{dN^s}{d\epsilon}(\epsilon,\epsilon_i)\frac{dN_i}{d\epsilon_i dt}(M,\epsilon_i)$$

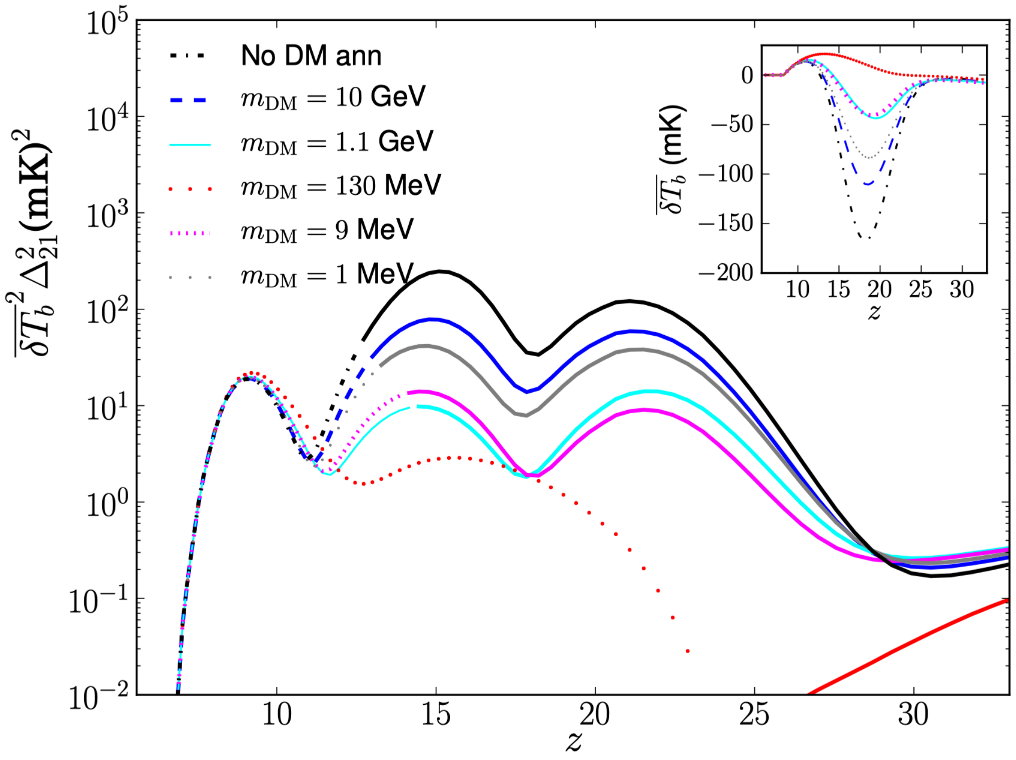
Extended

$$I^s = \int_0^\infty dM \cdot \Psi(M) \cdot I^{s,\delta}(M,z)$$

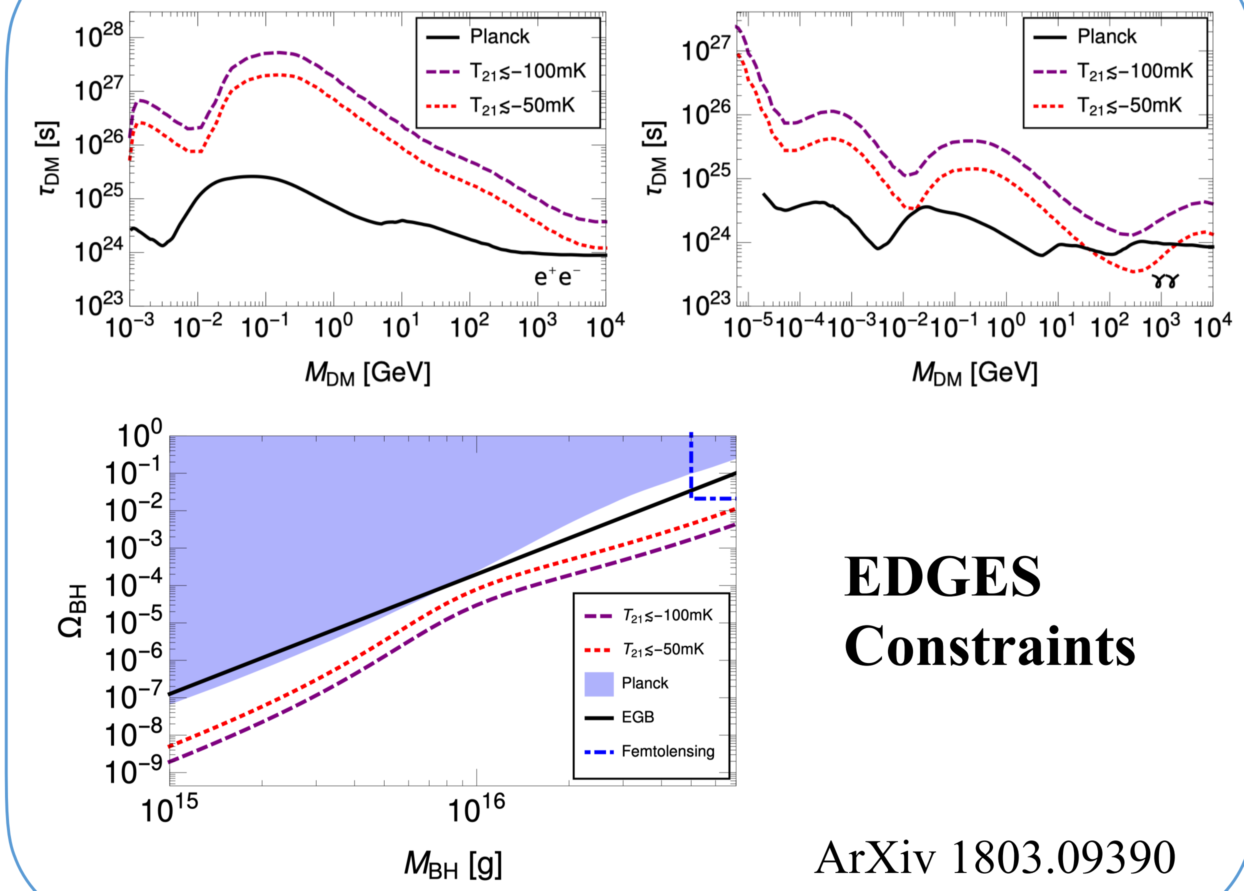
21cm Probe

$$\delta T_b(\nu) \simeq 27\, x_{\rm HI}\,(1+\delta_b)\left(1-\frac{T_{\rm CMB}}{T_S}\right)\left(\frac{1}{1+H^{-1}\partial v_r/\partial r}\right)\left(\frac{1+z}{10}\right)^{1/2}\left(\frac{0.15}{\Omega_m h^2}\right)^{1/2}\left(\frac{\Omega_b h^2}{0.023}\right)\ \mathrm{mK}$$

DM&PBH



ArXiv 1603.06795



EDGES Constraints

ArXiv 1803.09390

Deposition Efficiency

Dependent on:
1. Deposition channel
2. Redshift
3. Injection energy
4. Injection history
5. Particle species

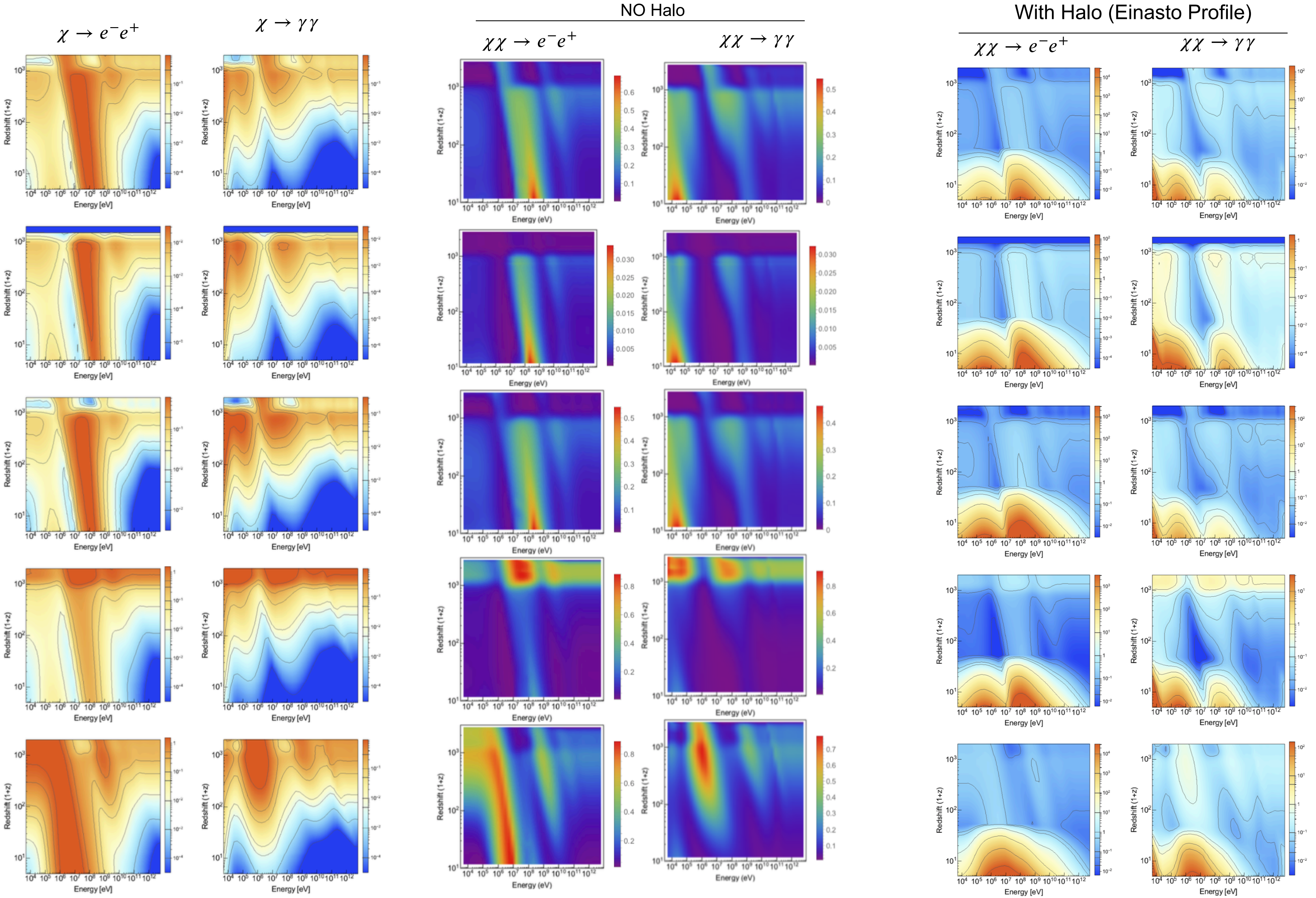
H Ionization

He Ionization

H Excitation

Heating

Low Energy Photon

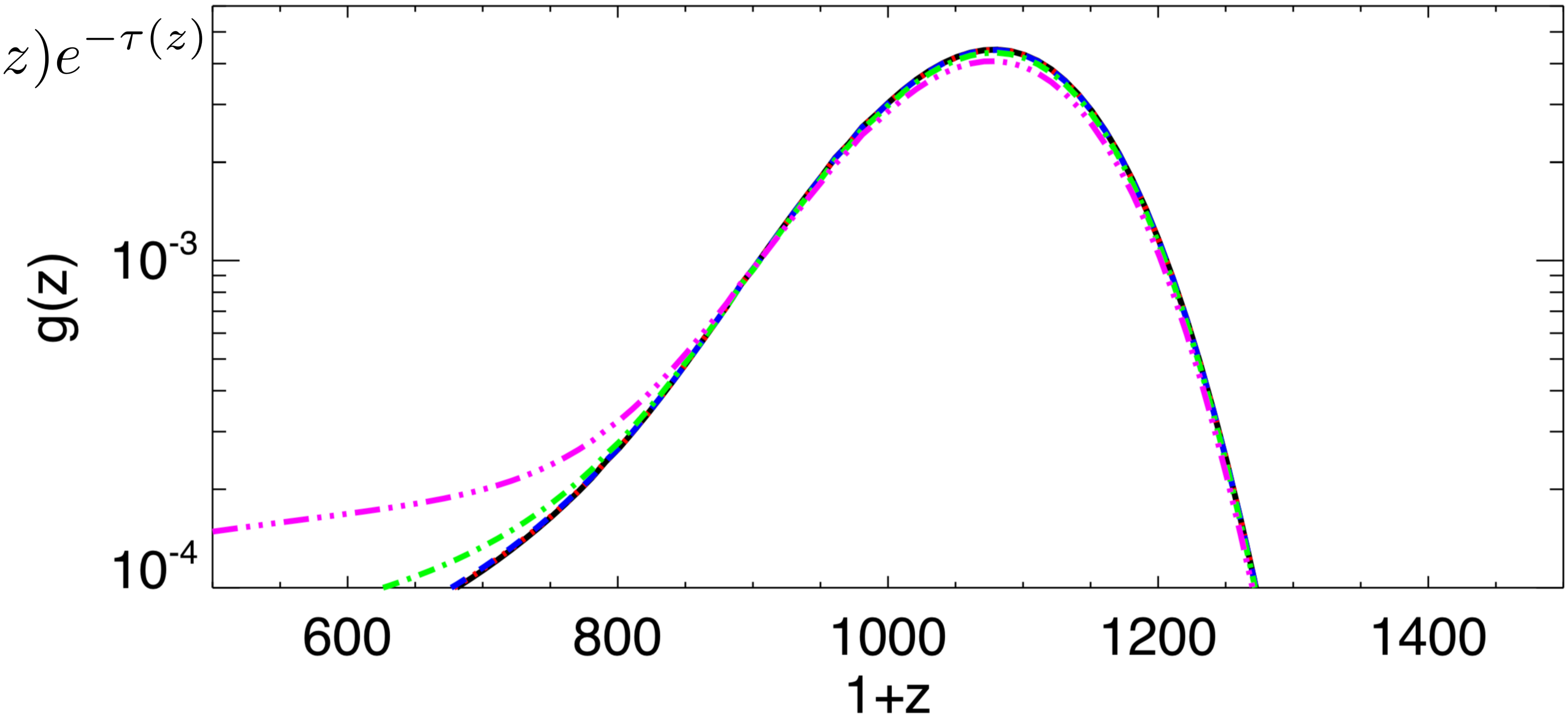


Courtesy
Of
Tracy Slatyer

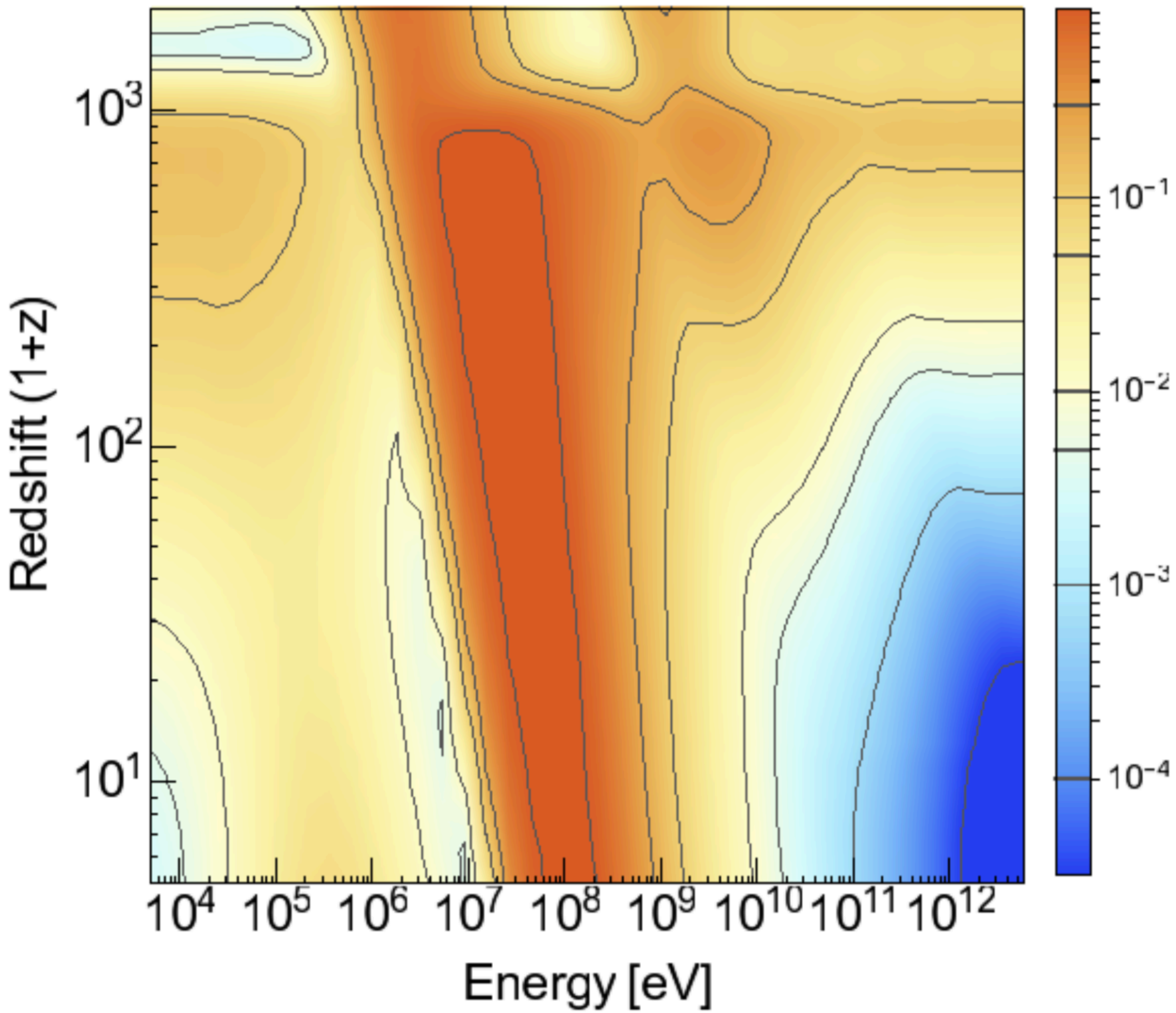
Width of laster scattering surface

Visibility function: probability that a photon last scattered between z and z + dz

$$g(z) \equiv \tau'(z)e^{-\tau(z)}$$



Stripe on e^-e^+ Deposition Eff Figs



Location : 1 ~ 100 MeV

Electrons in this energy range upstater CMB photons to ~ 10 eV - KeV energies, where they can efficiently ionize hydrogen.