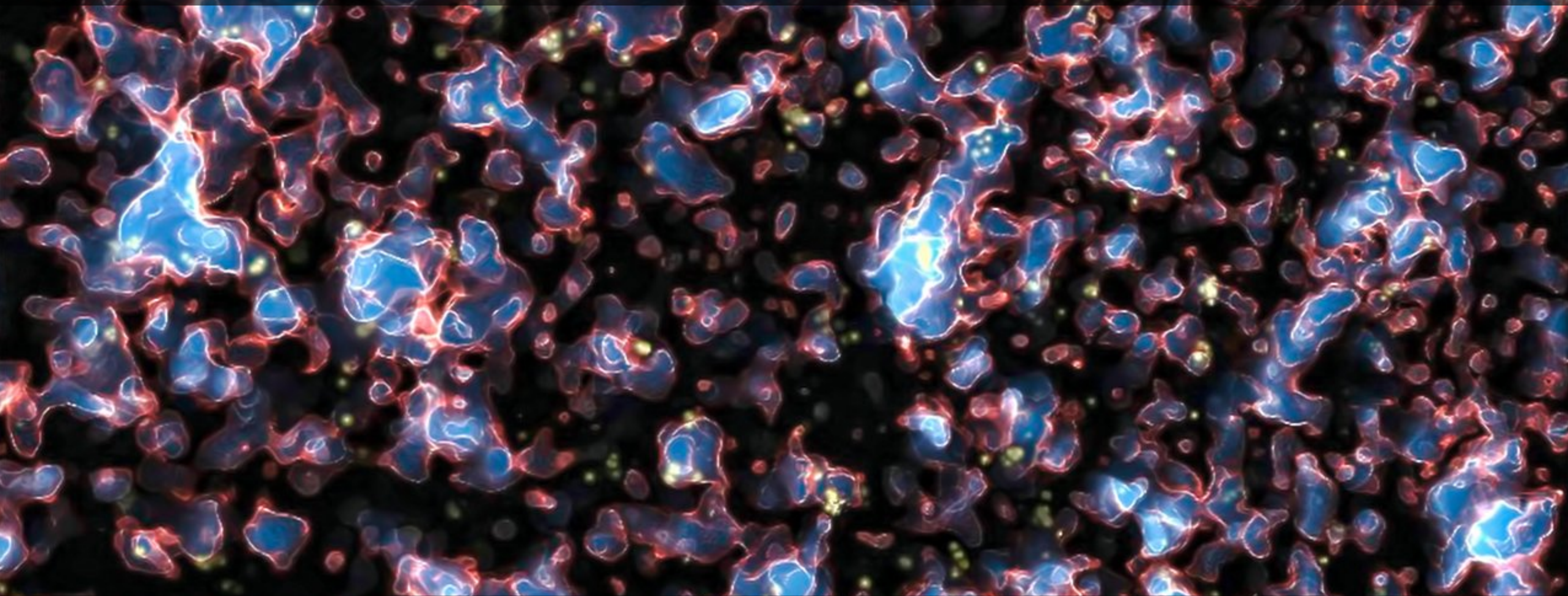


Constraining long-lived dark sector particles with CMB and Lyman- α

Sonali Verma [ULB Brussels] | Rencontres de Physique des Particules, 11th March 2026



Based on [arxiv: 2602.10078](https://arxiv.org/abs/2602.10078) in collaboration with Laura Lopez-Honorez

See Y. Gouttenoire's talk for $z > 1000$

Recombination

Neutral

$z \sim 1000$

CMB

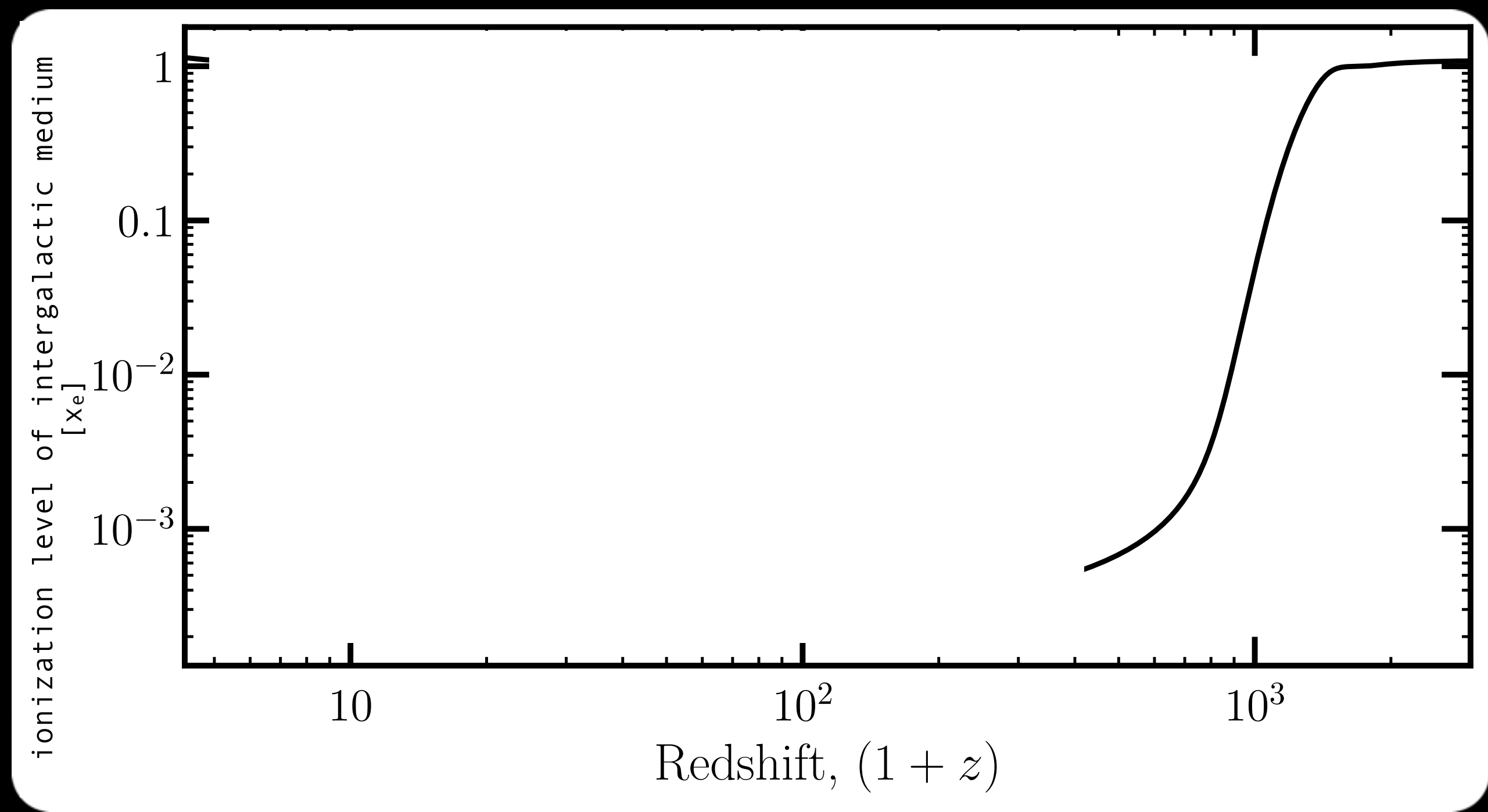


Recombination

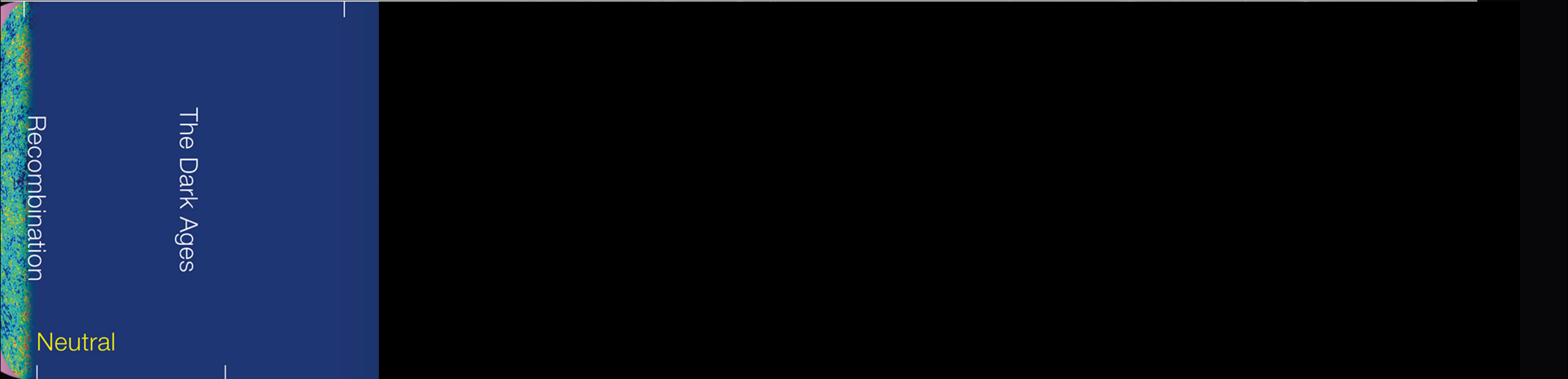
Neutral

$z \sim 1000$

CMB

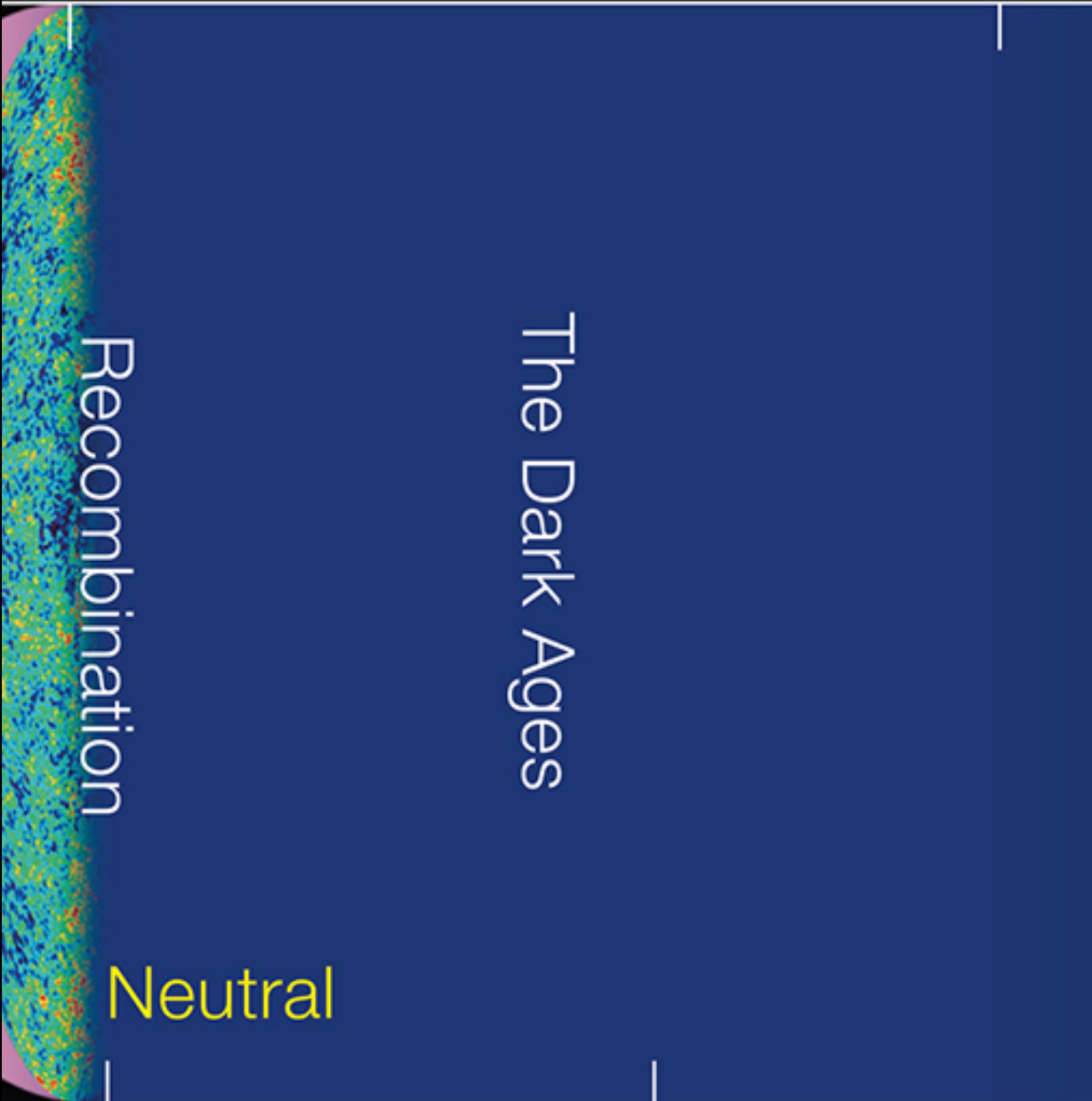


CMB probes e.g. WMAP,
Planck



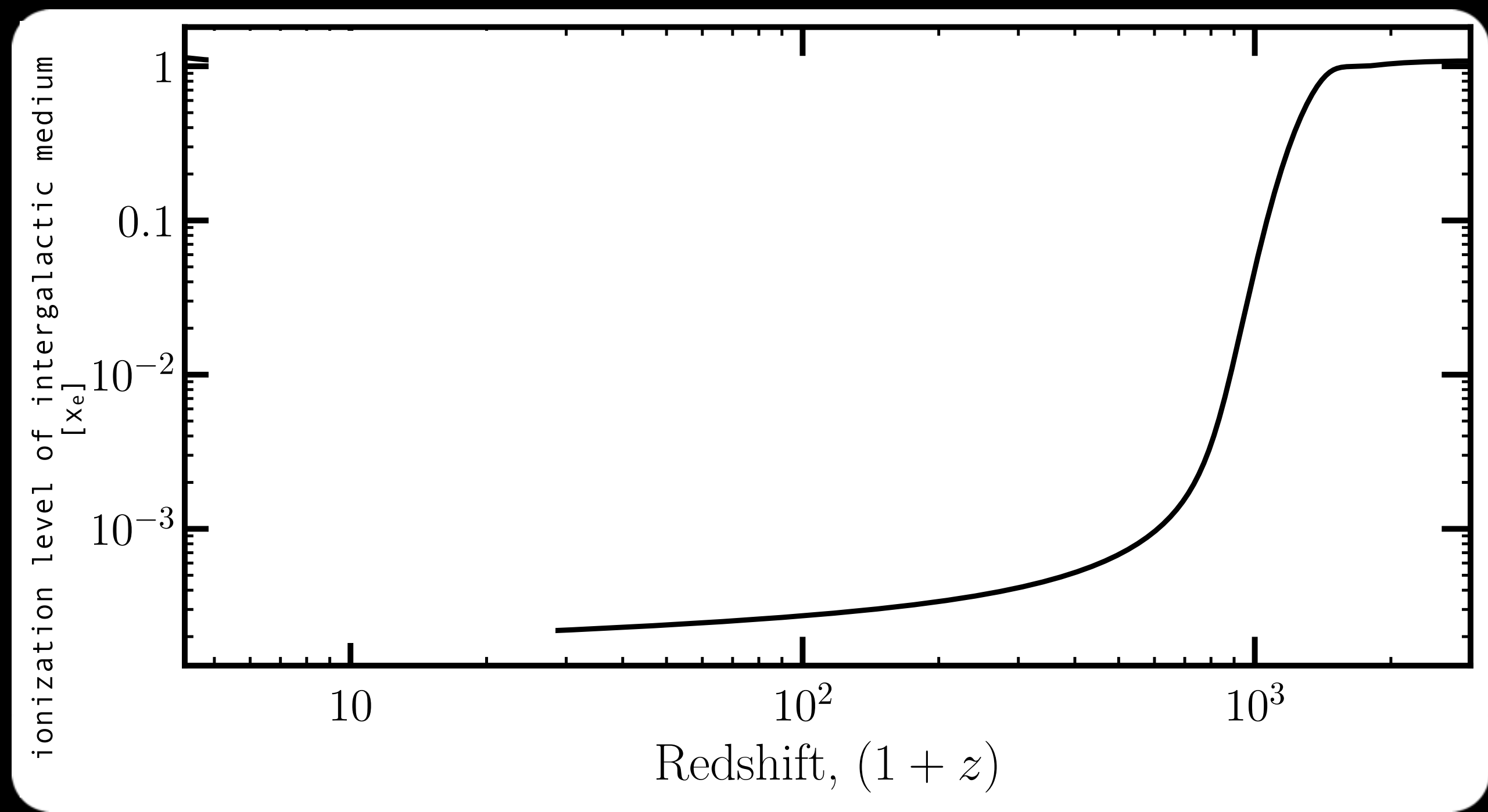
$z \sim 1000$

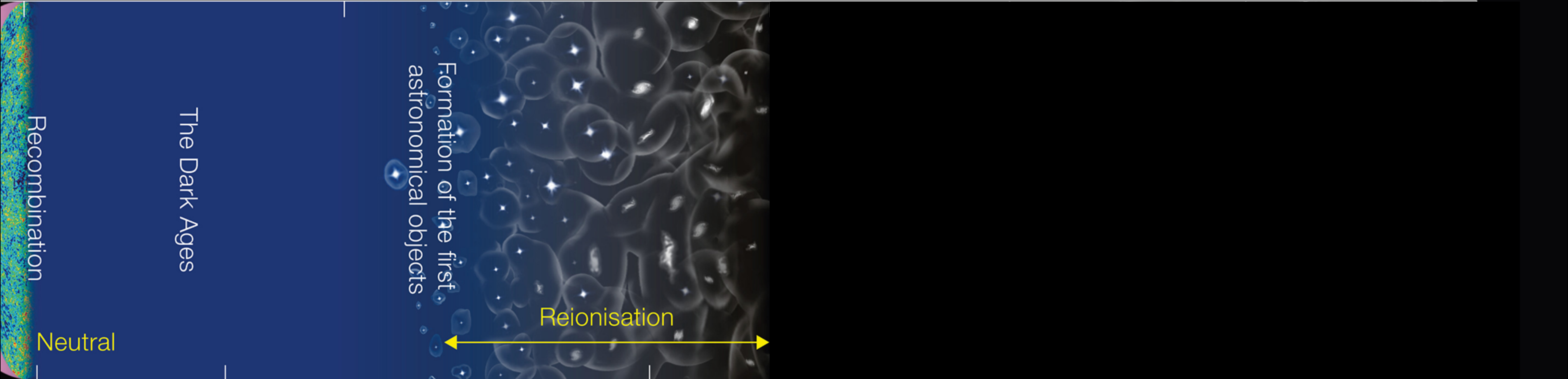
CMB Dark Ages



$z \sim 1000$

CMB Dark Ages





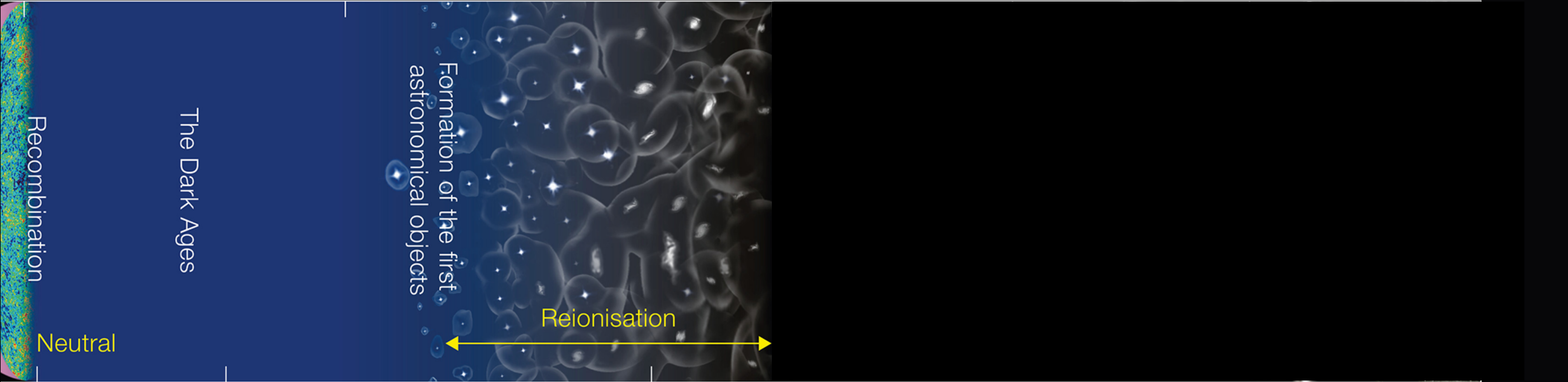
$z \sim 1000$

$z \sim 30$

CMB

Dark Ages

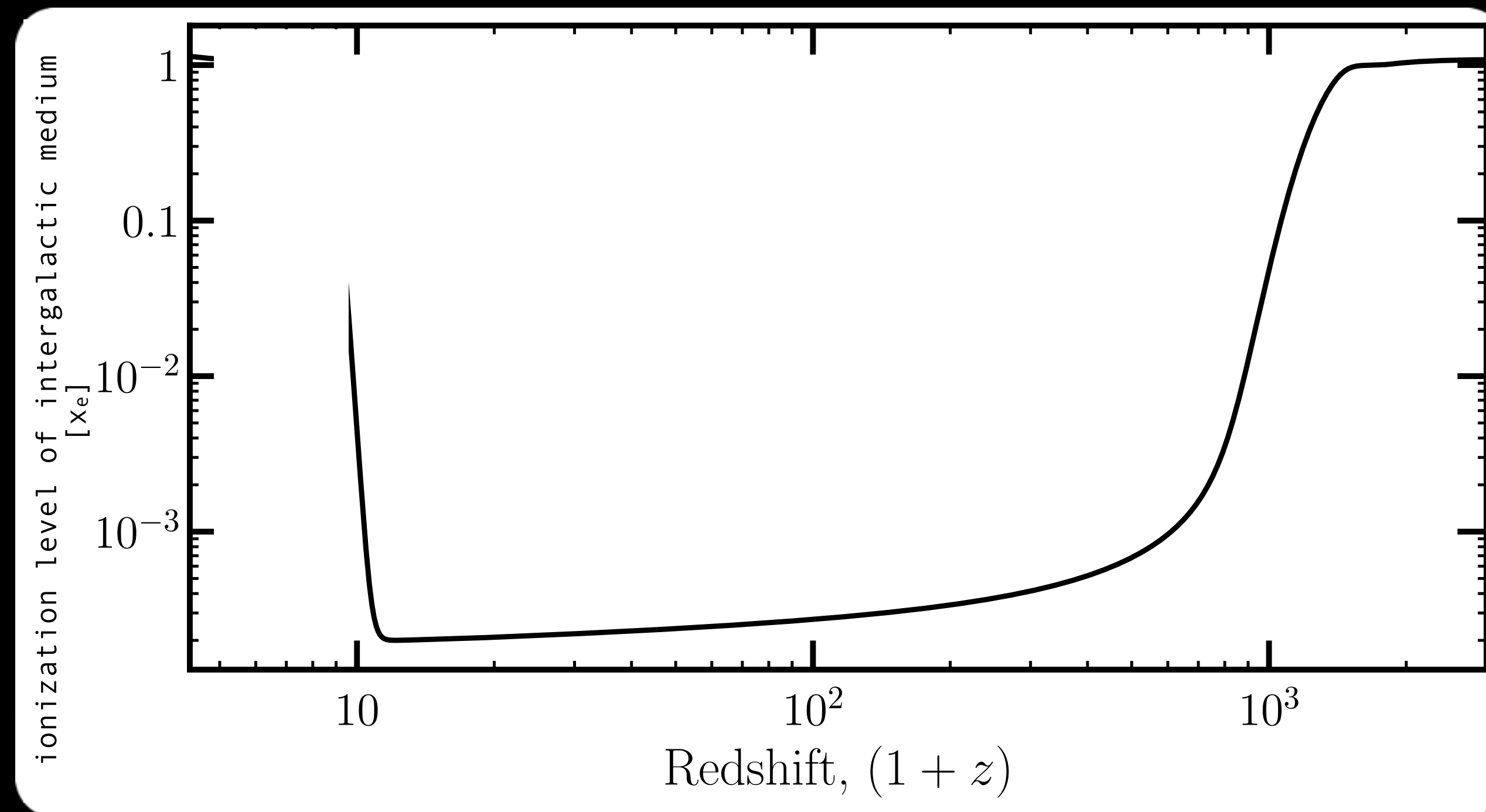
Cosmic Dawn



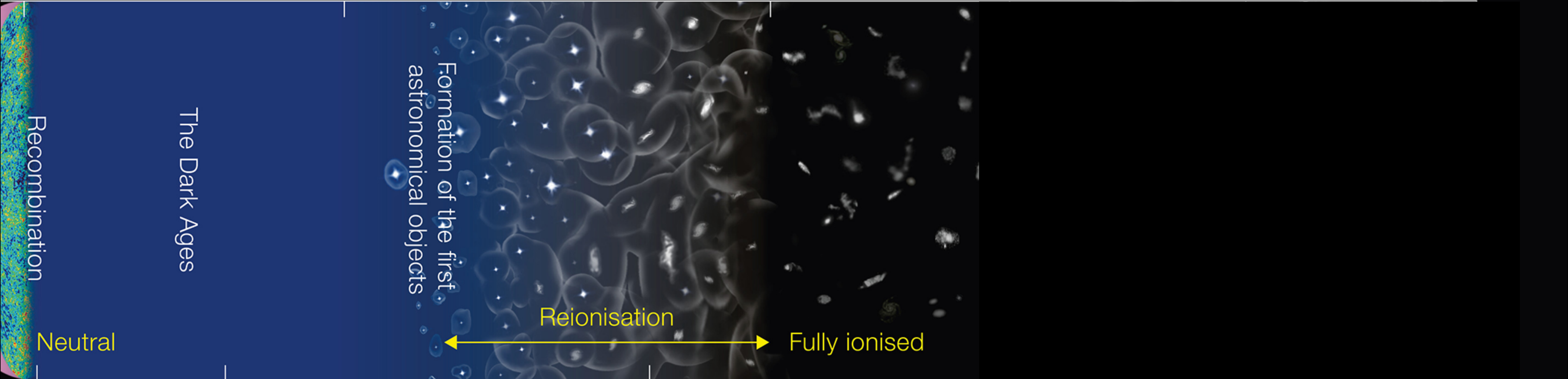
$z \sim 1000$

CMB

Dark Ages



Upcoming 21-cm signal from
HERA, SKA, SARAS...



$z \sim 1000$

$z \sim 30$

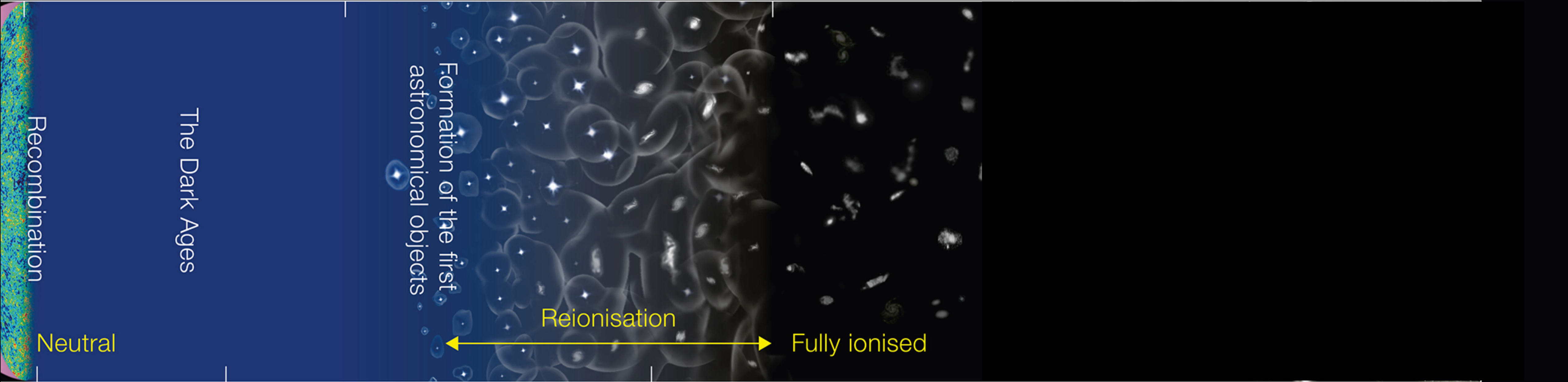
$z \sim 5$

CMB

Dark Ages

Cosmic Dawn

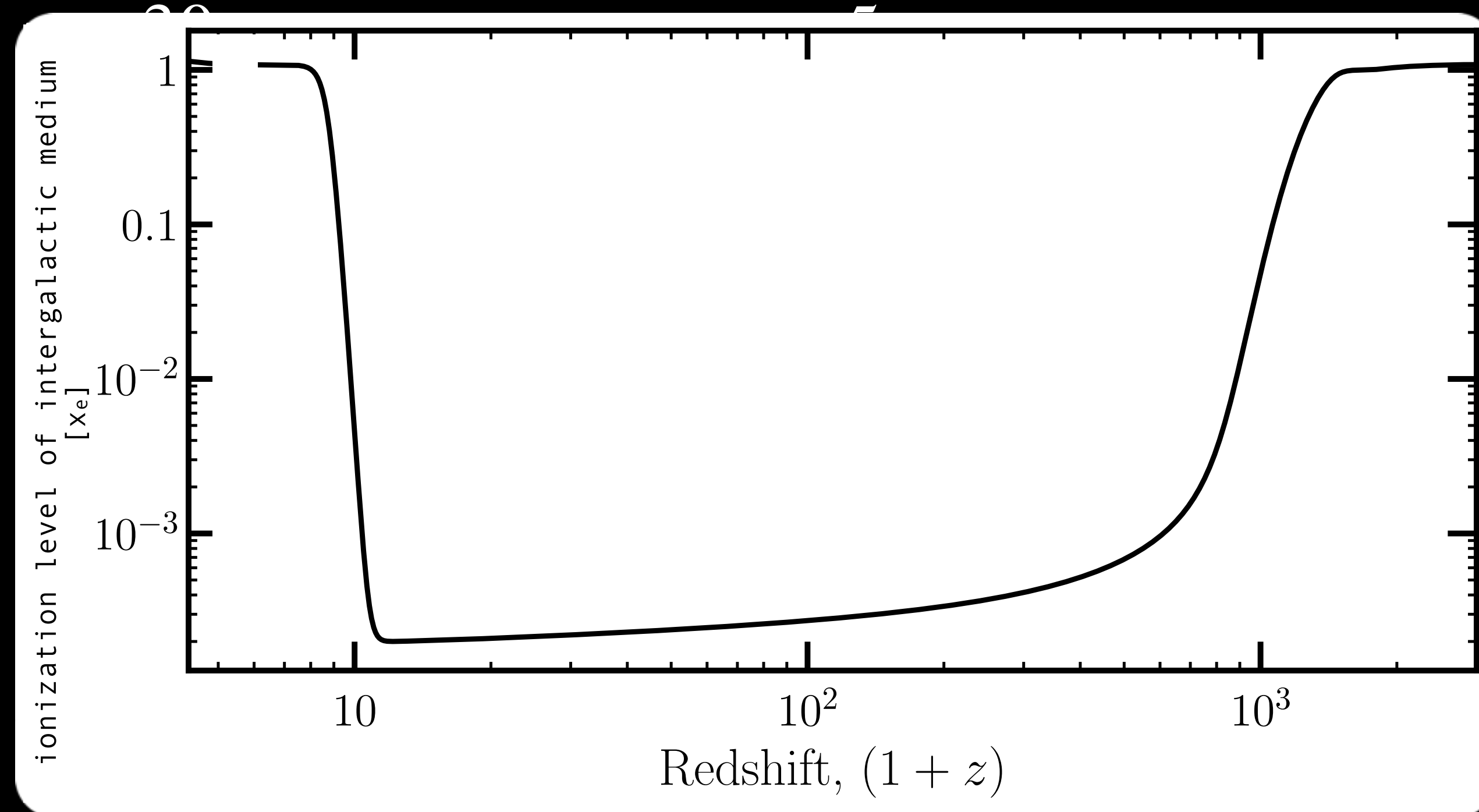
Reionization over



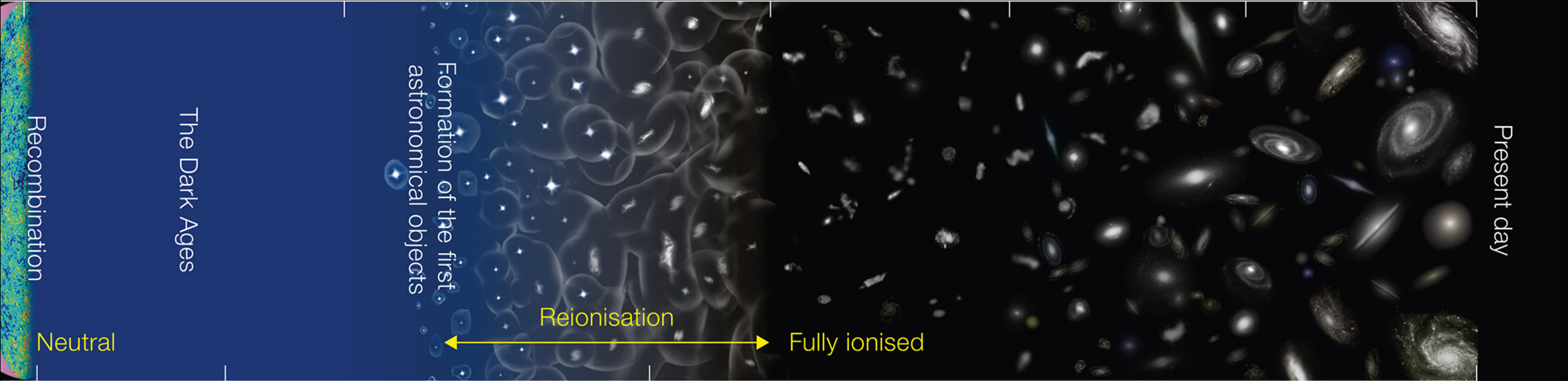
$z \sim 1000$

CMB

Dark Ages



Lyman-alpha
spectra of quasars



Present day

Formation of the first
astronomical objects

Reionisation

Fully ionised

The Dark Ages

Recombination

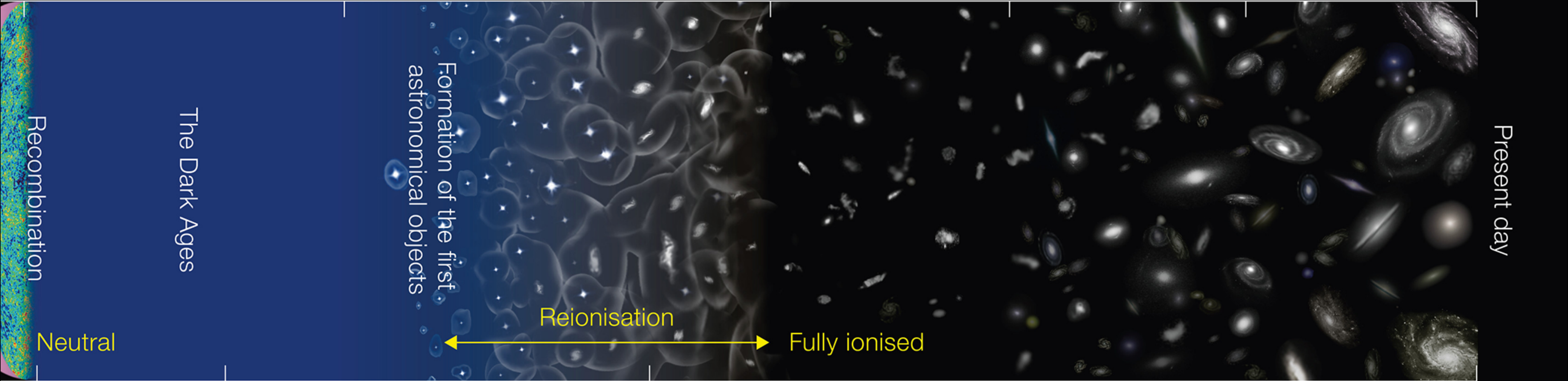
Neutral

$z \sim 1000$

$z \sim 30$

$z \sim 5$

CMB Dark Ages Cosmic Dawn Reionization over



$z \sim 1000$

$z \sim 30$

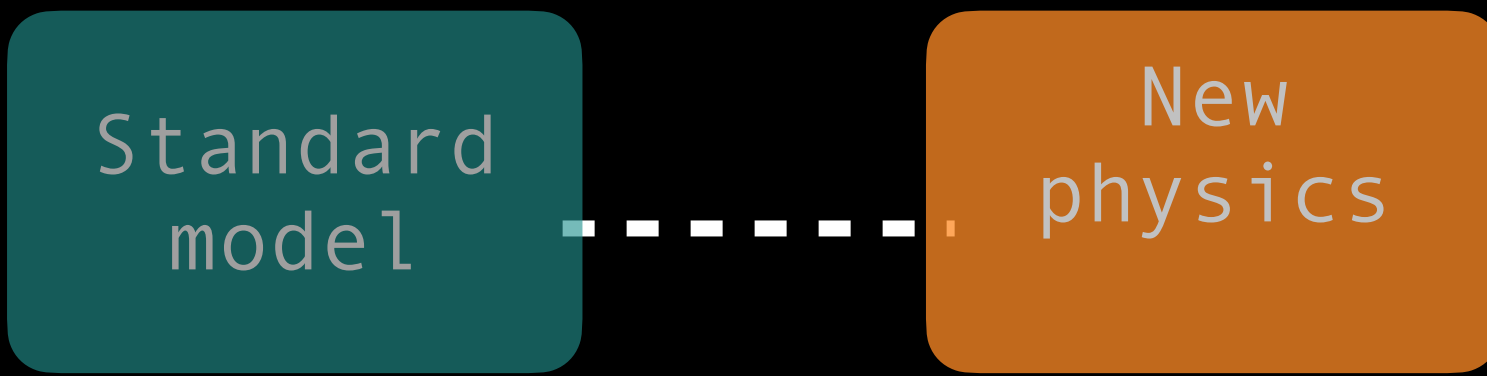
$z \sim 5$

CMB

Dark Ages

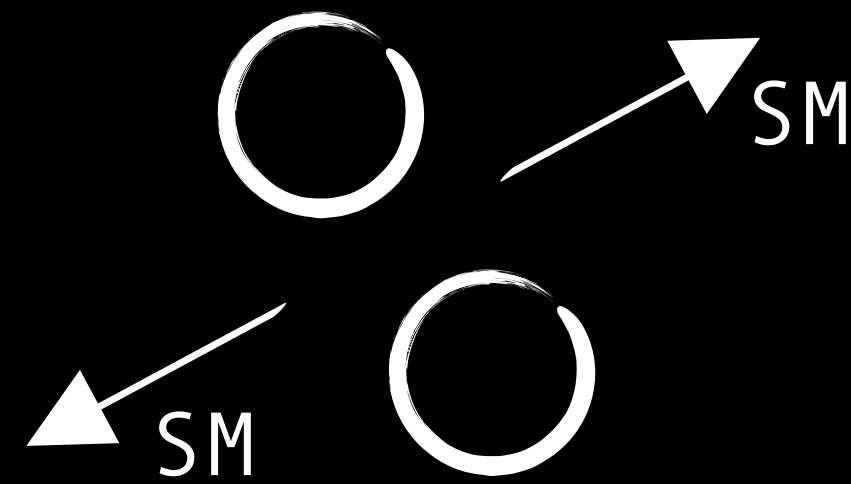
Cosmic Dawn

Reionization over



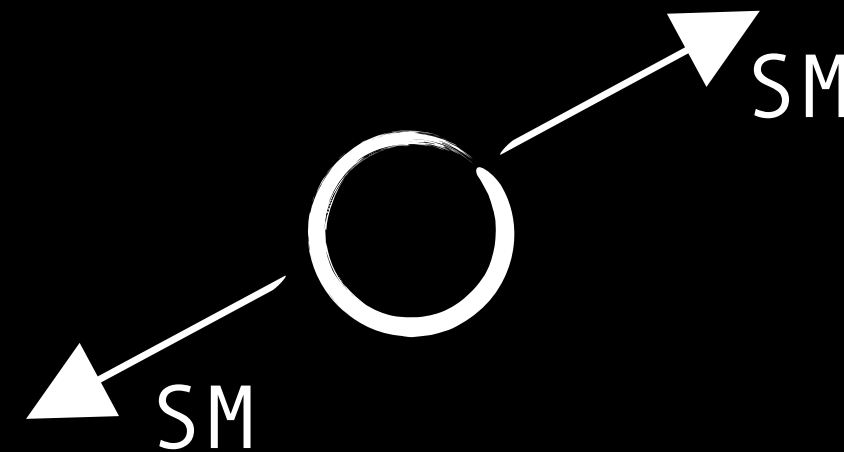
$$\tau > t_0$$

Dark matter [DM] annihilation



for CMB, see e.g.: [\[Adams '98\]](#), [\[Chen et al. '03\]](#), [\[Padmanabhan '05\]](#), [\[Slatyer et al. '09\]](#), [\[Slatyer '15\]](#), [\[Slatyer and Wu '16\]](#), [\[Diamanti et al. '13\]](#)...

Dark matter decay

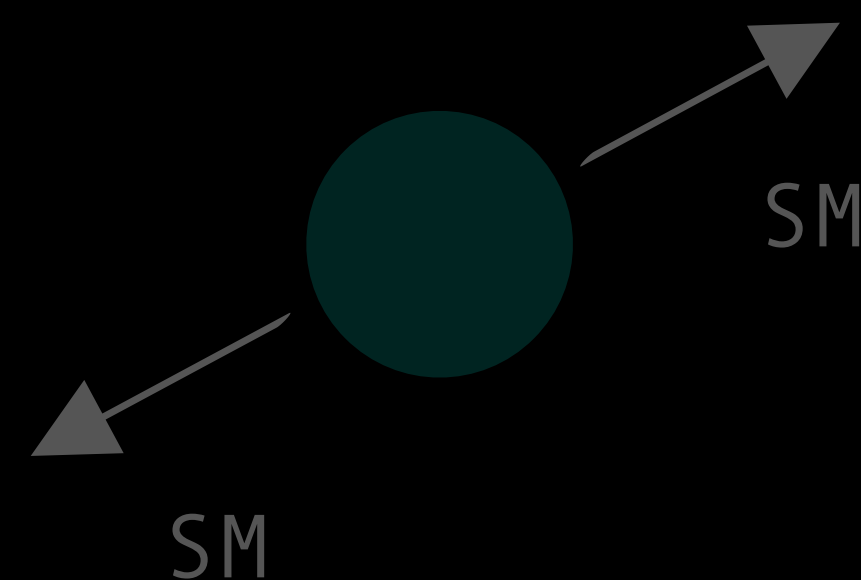


for reionization, see e.g.: [\[Cirelli et al '09\]](#), [\[Liu et al '20\]](#) [\[Liu et al '16\]](#), [\[Capozzi et al' '23\]](#)...

$$\tau < t_0$$

Dark sector [DS] decay

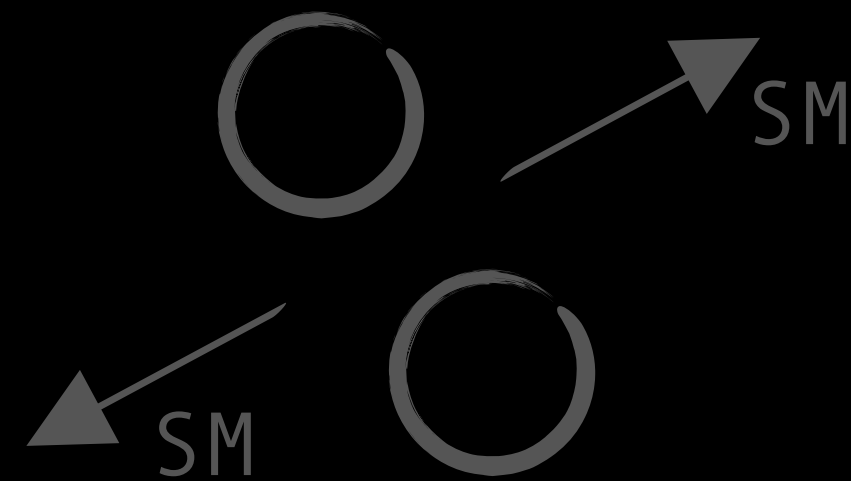
$$f_{DS} = \frac{\Omega_{DS}}{\Omega_{DM}} \ll 1$$



For CMB: e.g. [\[Poulin, Lesgourges, Serpico '16\]](#), [\[Acharya, Khatri '19\]](#), [\[Lucca et al. '19\]](#), [\[Slatyer and Wu '16\]](#)

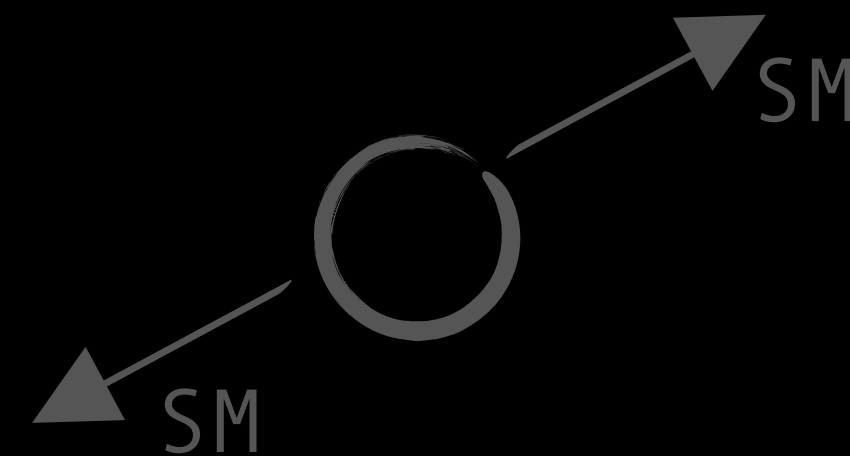
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Dark matter [DM] annihilation



for CMB, see e.g.: [\[Adams '98\]](#), [\[Chen et al. '03\]](#), [\[Padmanabhan '05\]](#), [\[Slatyer et al. '09\]](#), [\[Slatyer '15\]](#), [\[Slatyer and Wu '16\]](#), [\[Diamanti et al. '13\]](#)...

Dark matter decay



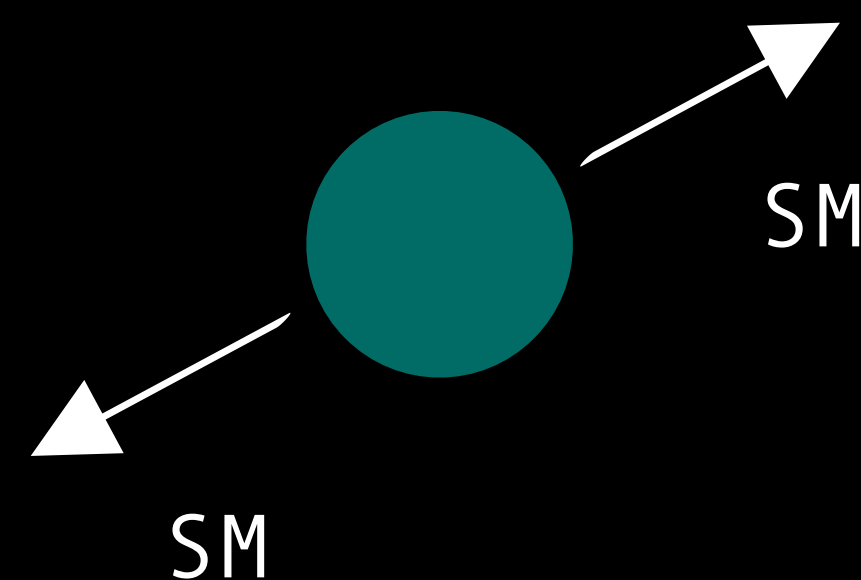
for reionization, see e.g.: [\[Cirelli et al '09\]](#), [\[Liu et al '20\]](#) [\[Liu et al '16\]](#), [\[Capozzi et al' '23\]](#)...

$$\tau < t_0$$

Dark sector [DS] decay

:This talk:

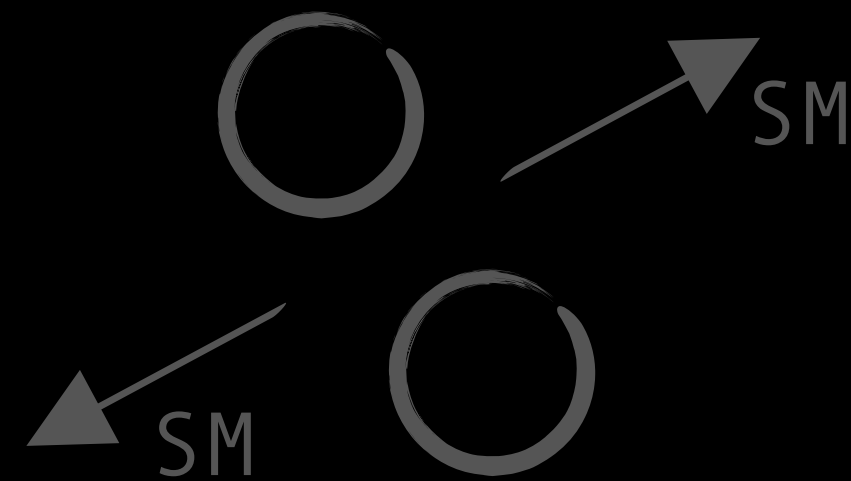
$$f_{DS} = \frac{\Omega_{DS}}{\Omega_{DM}} \ll 1$$



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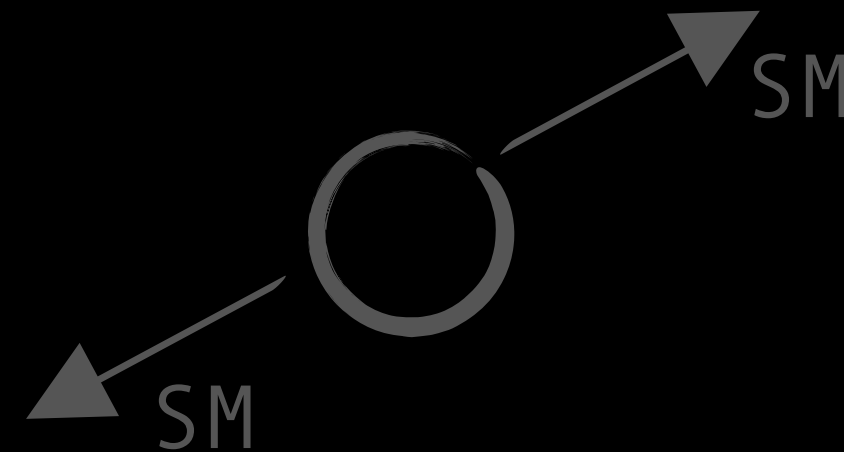
$$\tau > t_0$$

Dark matter [DM] annihilation



for CMB, see e.g.: [\[Adams '98\]](#), [\[Chen et al. '03\]](#), [\[Padmanabhan '05\]](#), [\[Slatyer et al. '09\]](#), [\[Slatyer '15\]](#), [\[Slatyer and Wu '16\]](#), [\[Diamanti et al. '13\]](#)...

Dark matter decay



for reionization, see e.g.: [\[Cirelli et al '09\]](#), [\[Liu et al '20\]](#) [\[Liu et al '16\]](#), [\[Capozzi et al' '23\]](#)...

$$\tau < t_0$$

Dark sector [DS] decay

$$f_{DS} = \frac{\Omega_{DS}}{\Omega_{DM}} \ll 1$$

For CMB: e.g. [\[Poulin, Lesgourges, Serpico '16\]](#), [\[Acharya, Khatri '19\]](#), [\[Lucca et al. '19\]](#), [\[Slatyer and Wu '16\]](#)

Axion Like Particles (ALPs)

e.g. [\[Langhoff et al. '22\]](#)

Dark photon (*DP*)

e.g. [\[Caputo et al. '25\]](#)

Evaporating Primordial BHs

For CMB: see e.g. [\[Poulin et al' 16\]](#), [\[Acharya et al. '20\]](#)...
For recent limits from Lyman-alpha: see [\[Khan et al. '25\]](#), [\[Saha et al. '24\]](#), see also [\[Kim '20\]](#) for LeoT heating

Previous works

$\tau > t_0$

[Planck 2015]



Dark matter [DM] annihilation

Dark matter decay

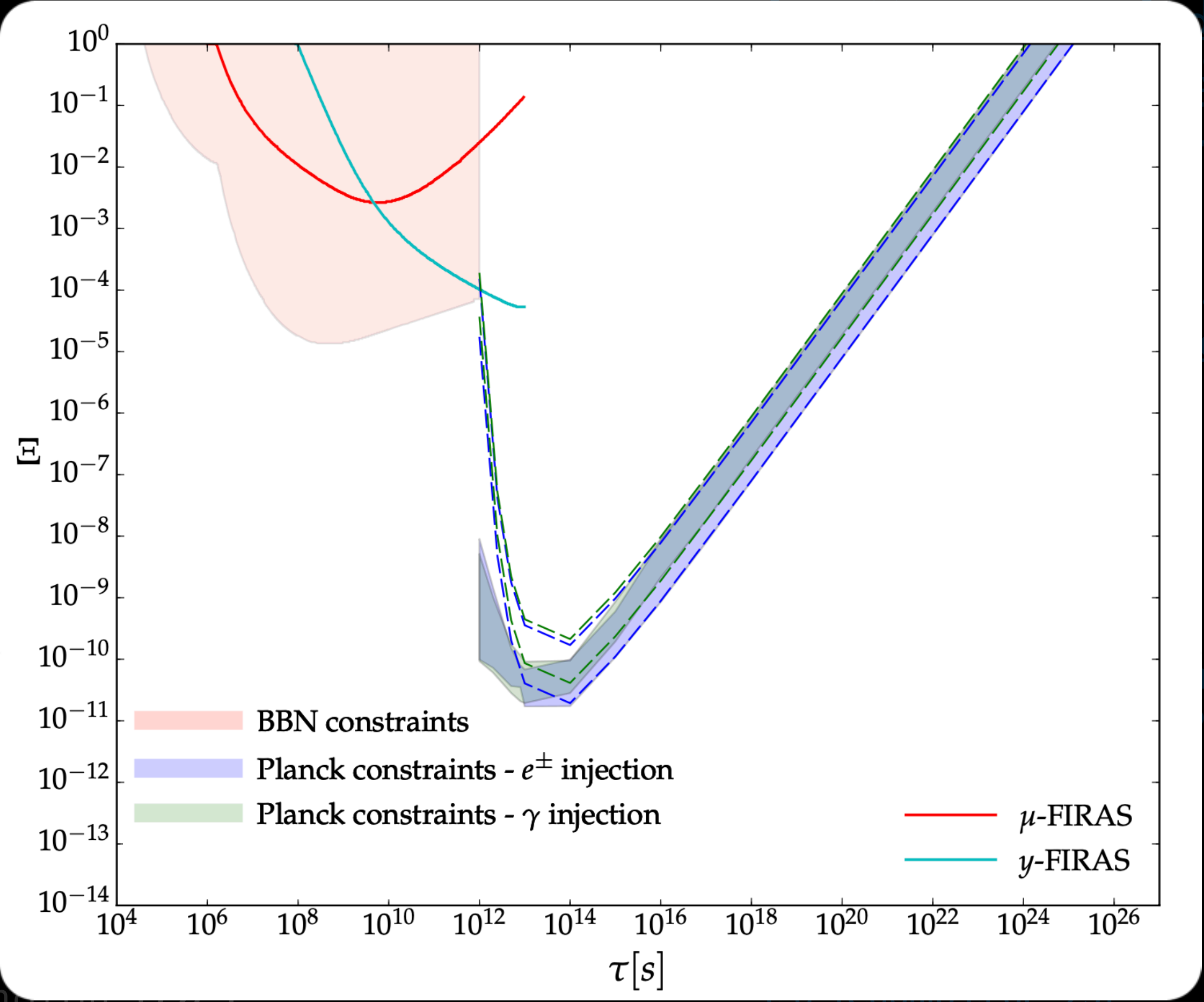
$\tau < t_0$

Dark sector [DS] decay

Axion Like

Dark photon (A')

Evaporating Primordial BHs



[Lams '98], [Chen et al. '03],
[Slatyer et al. '09], [Slatyer '15],
[Diamanti et al. '13]...

e.g.: [Cirelli et al '09], [Liu et al
[Lopez et al' '23]...

[Poulin, Lesgourges, Serpico '16],
[Lucca et al. '19], [Slatyer

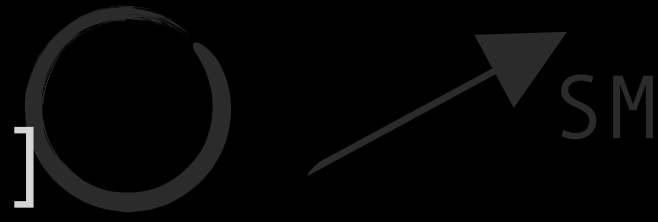
[Poulin, Lesgourges, Serpico '16]

For CMB: see e.g. [Poulin et al' 16], [Acharya et al. '20]...
For recent limits from Lyman-alpha: see [Khan et al. '25],
[Saha et al. '24], see also [Kim '20] for LeoT heating

Can we say something more from Lyman-alpha measurements at $z \sim 5$?

L. Lopez-Honorez and SV [arxiv: 2602.10078]

[Planck 2015]



Dark matter [DM] annihilation

Dark matter decay

$$\tau < t_0$$

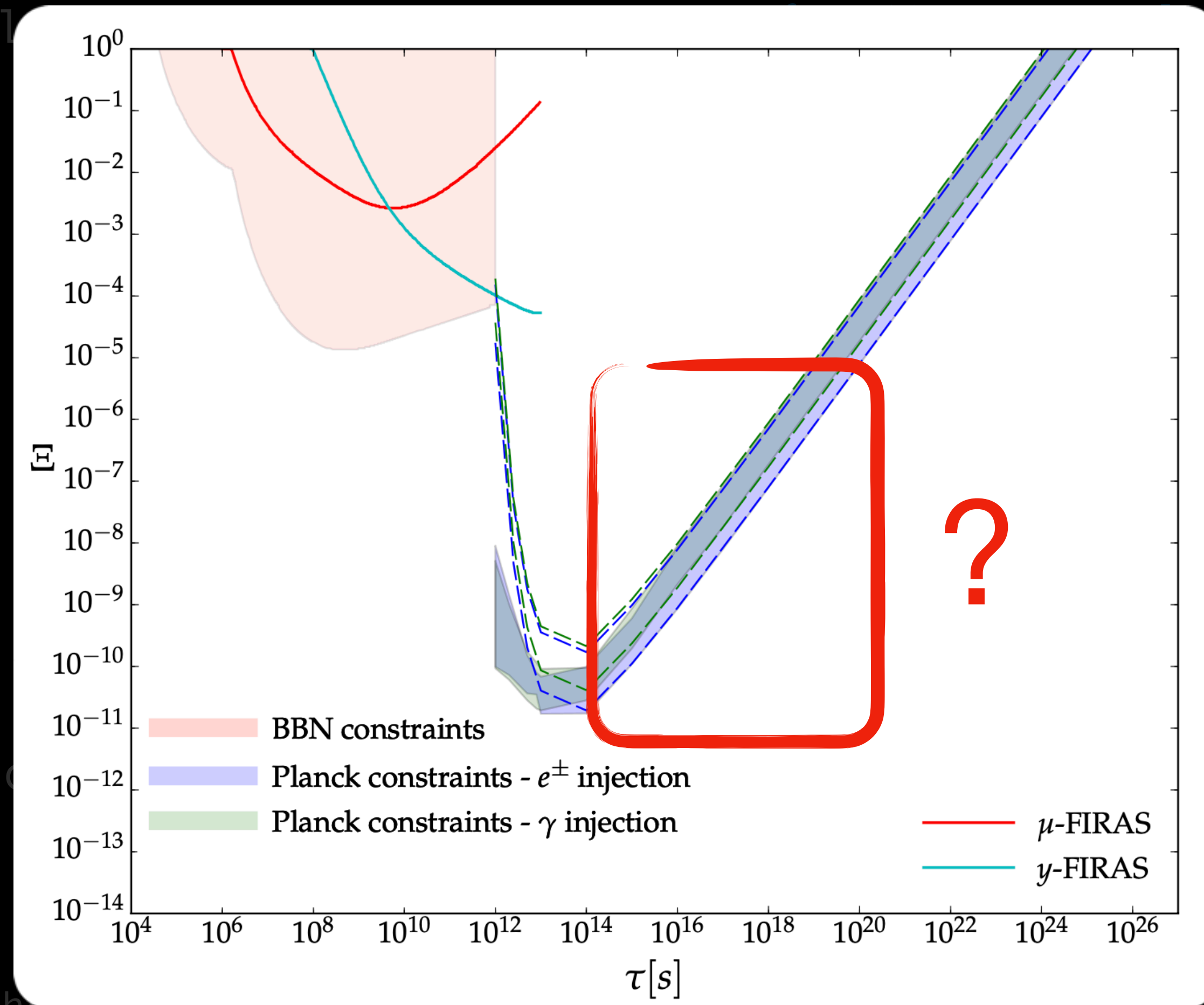
Dark sector [DS] decay

Axion Like

Dark photon (A')

Evaporating Primordial BHs

DS fractional abundance



[Poulin, Lesgourges, Serpico '16]

For CMB: see e.g. [Poulin et al' 16], [Acharya et al. '20]...
For recent limits from Lyman-alpha: see [Khan et al. '25],
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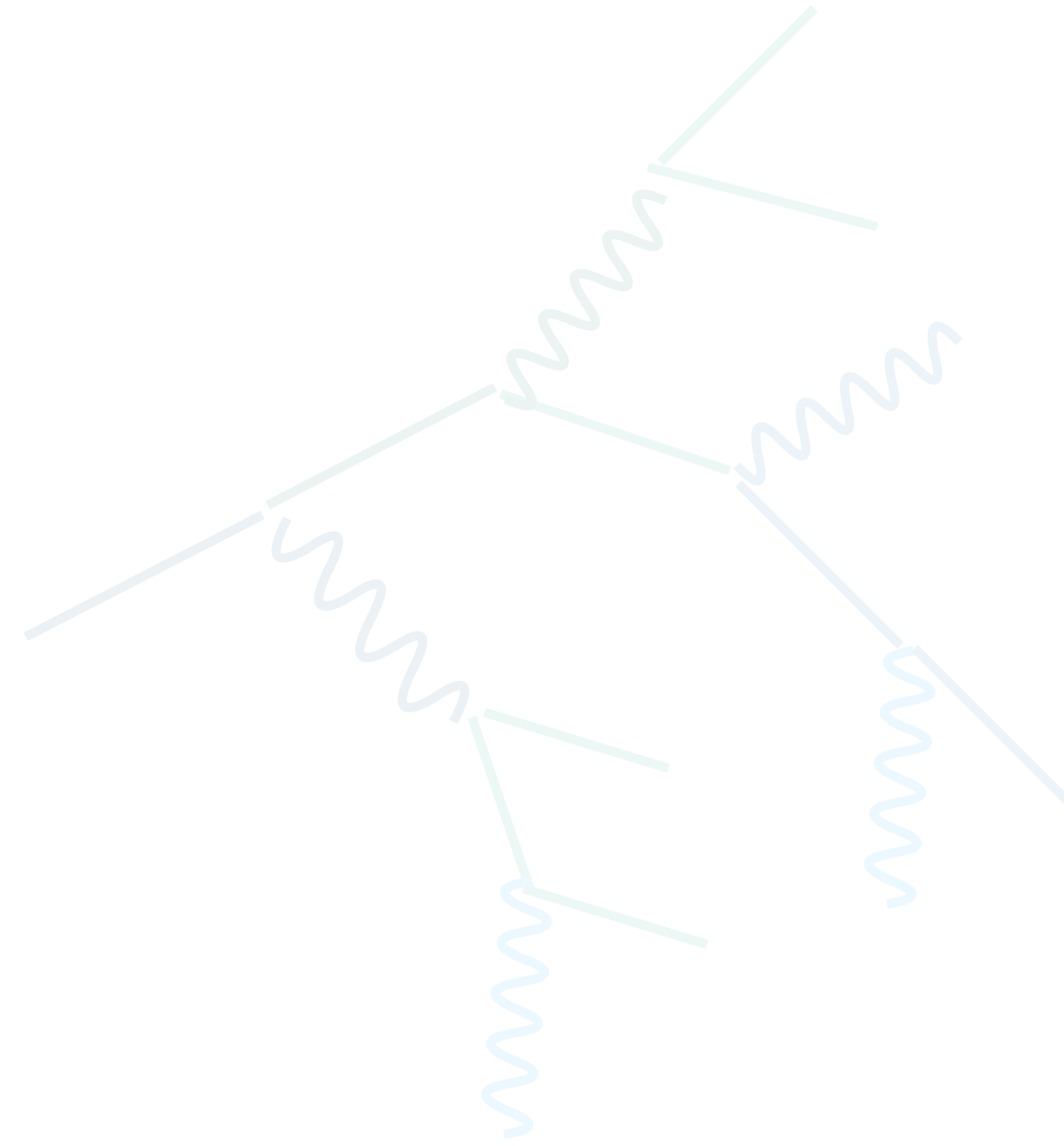
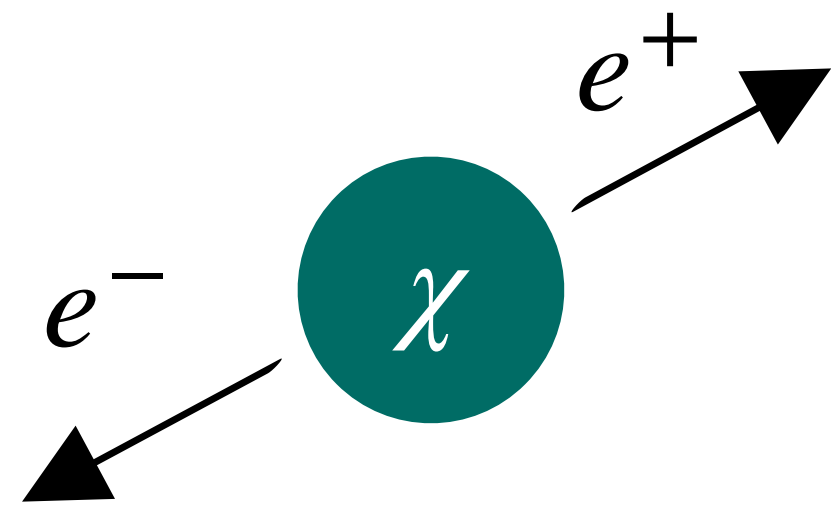
[Lams '98], [Chen et al. '03],
[Slatyer et al. '09], [Slatyer '15],
[Diamanti et al. '13]...

e.g.: [Cirelli et al '09], [Liu et al
[Lopez-Honorez et al' '23]...

[Poulin, Lesgourges, Serpico '16],
[Lucca et al. '19], [Slatyer

Energy injection from dark sectors

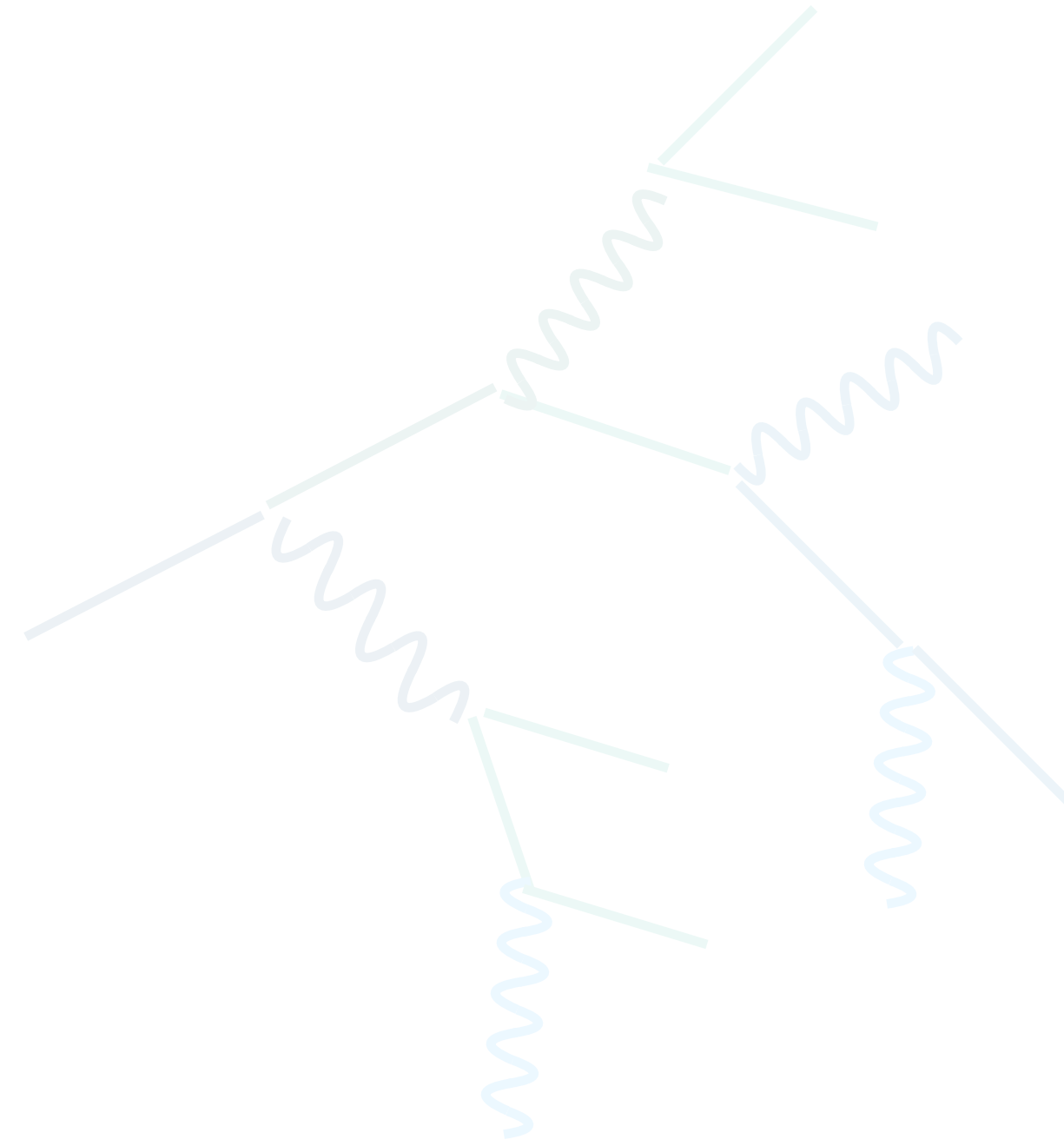
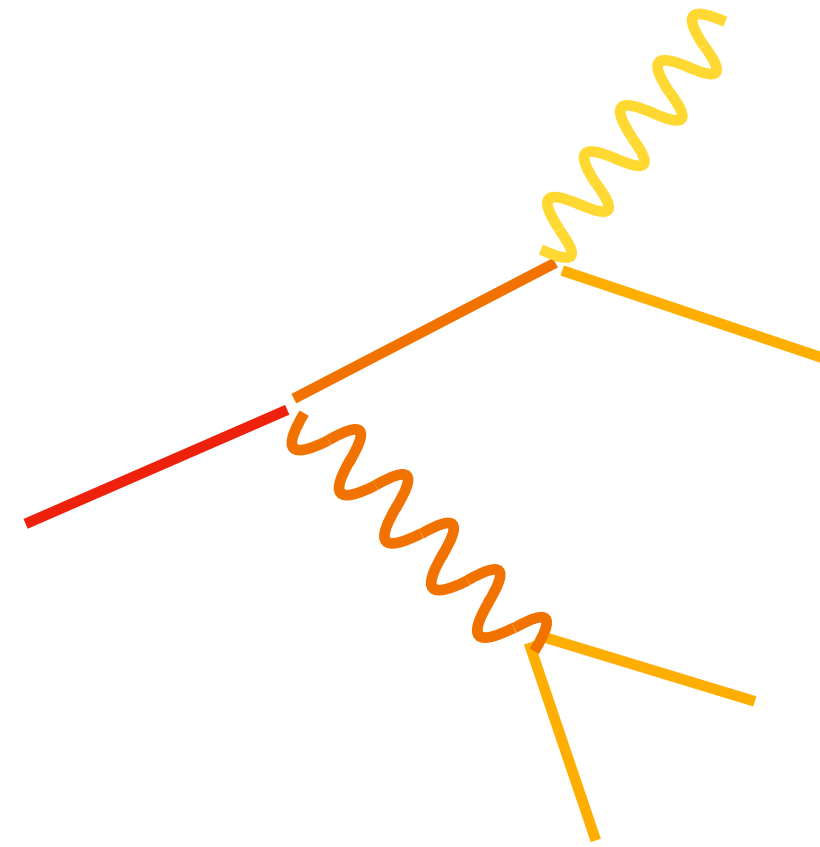
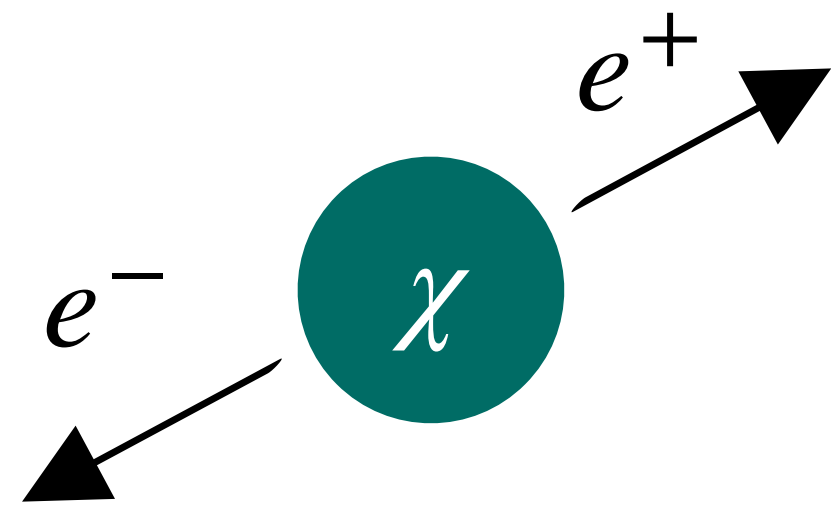
Dark sector particle



$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

Dark sector particle

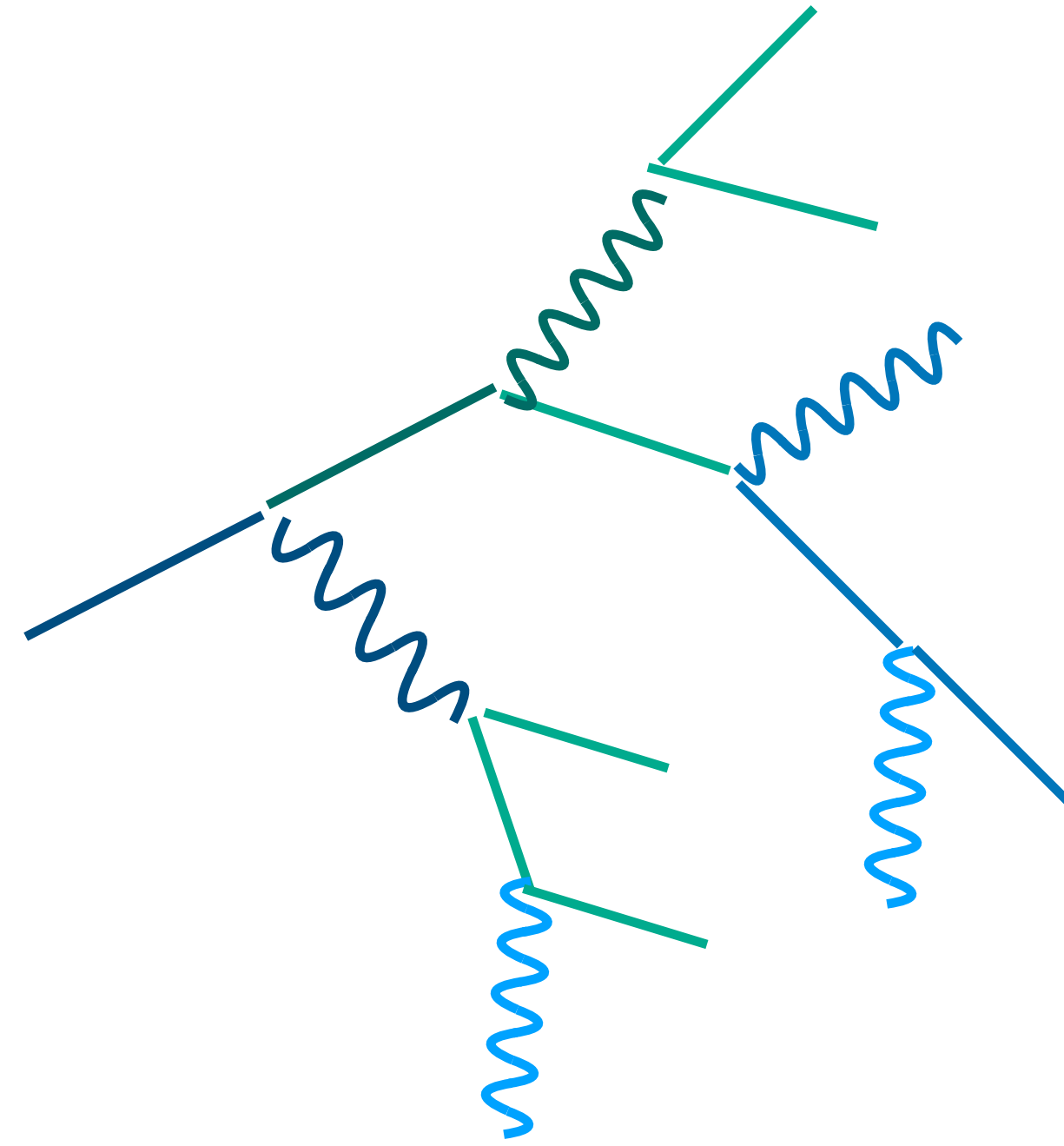
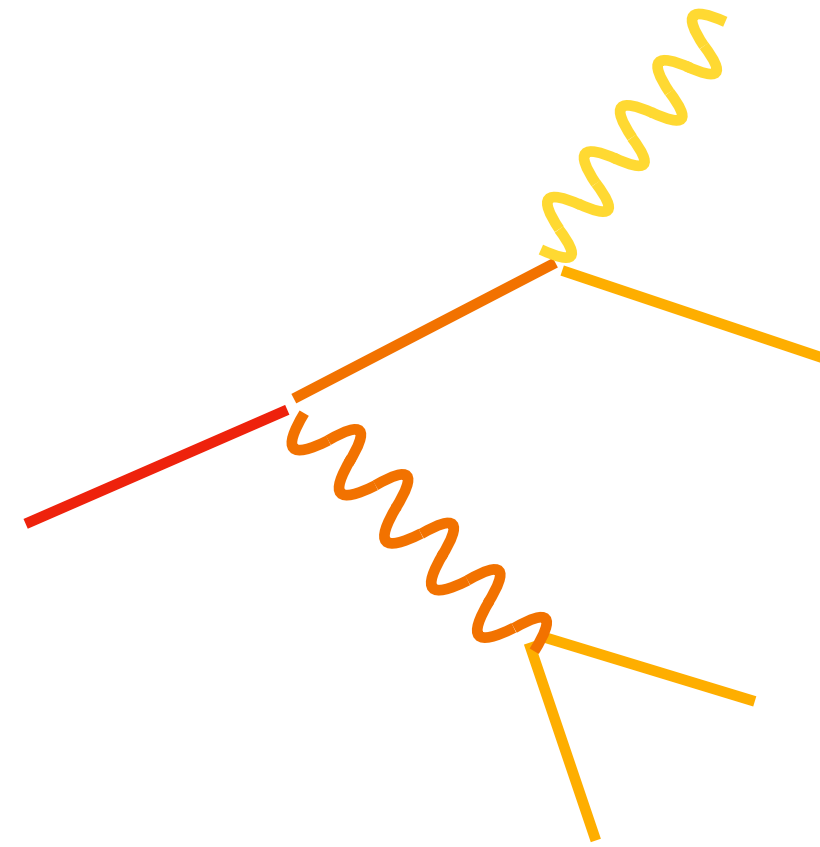
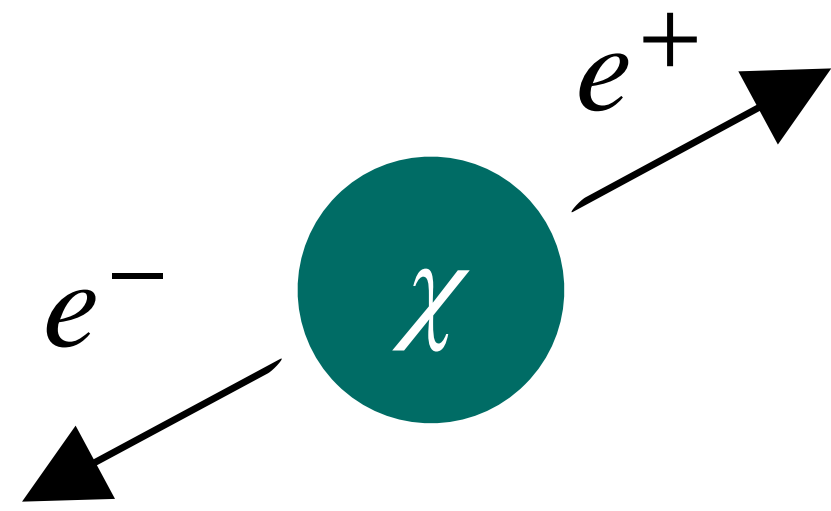


$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

Injected particles will **cascade** giving rise to an e.m. shower

Dark sector particle

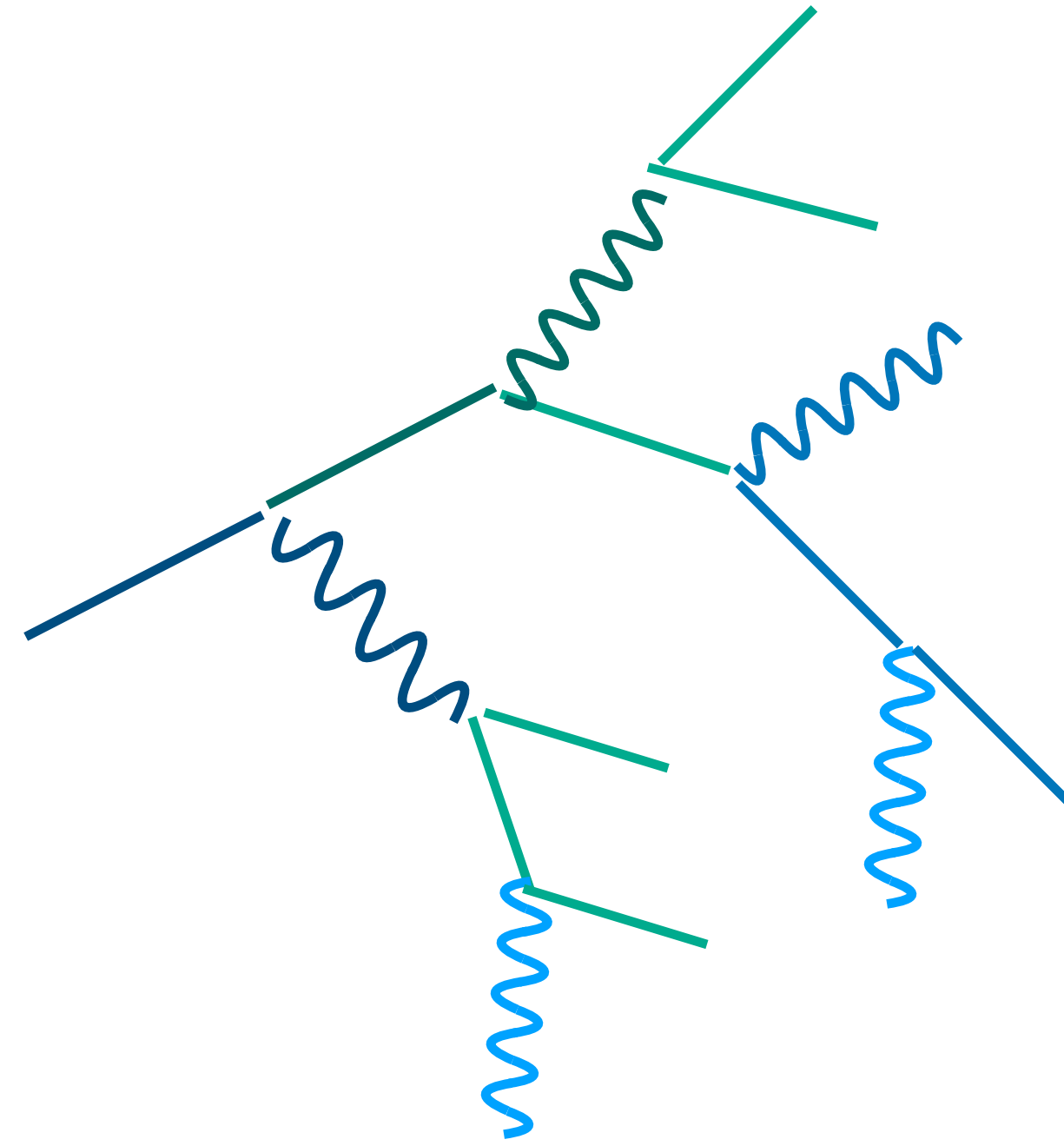
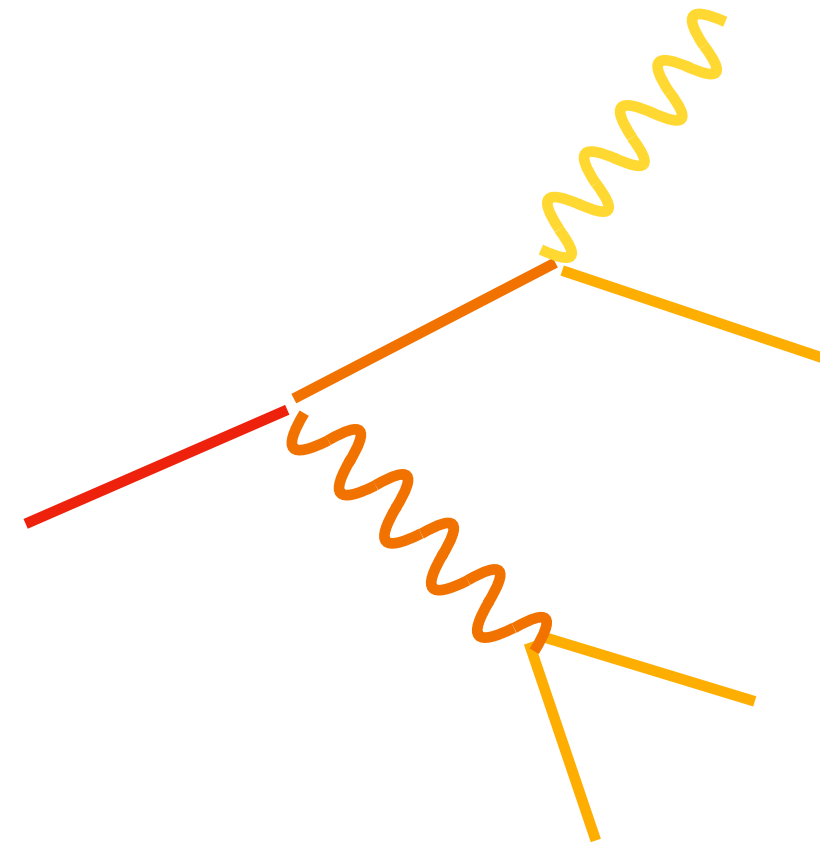
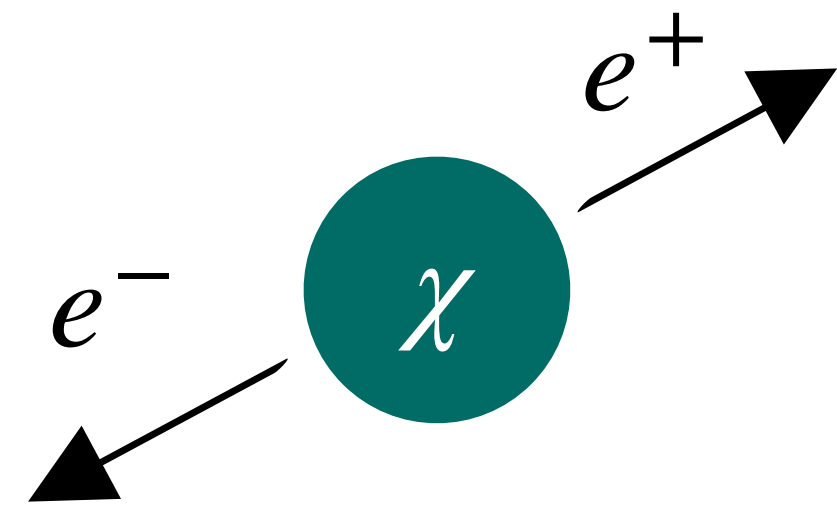


$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

With time, # secondary particles increases, average energy decreases

Dark sector particle

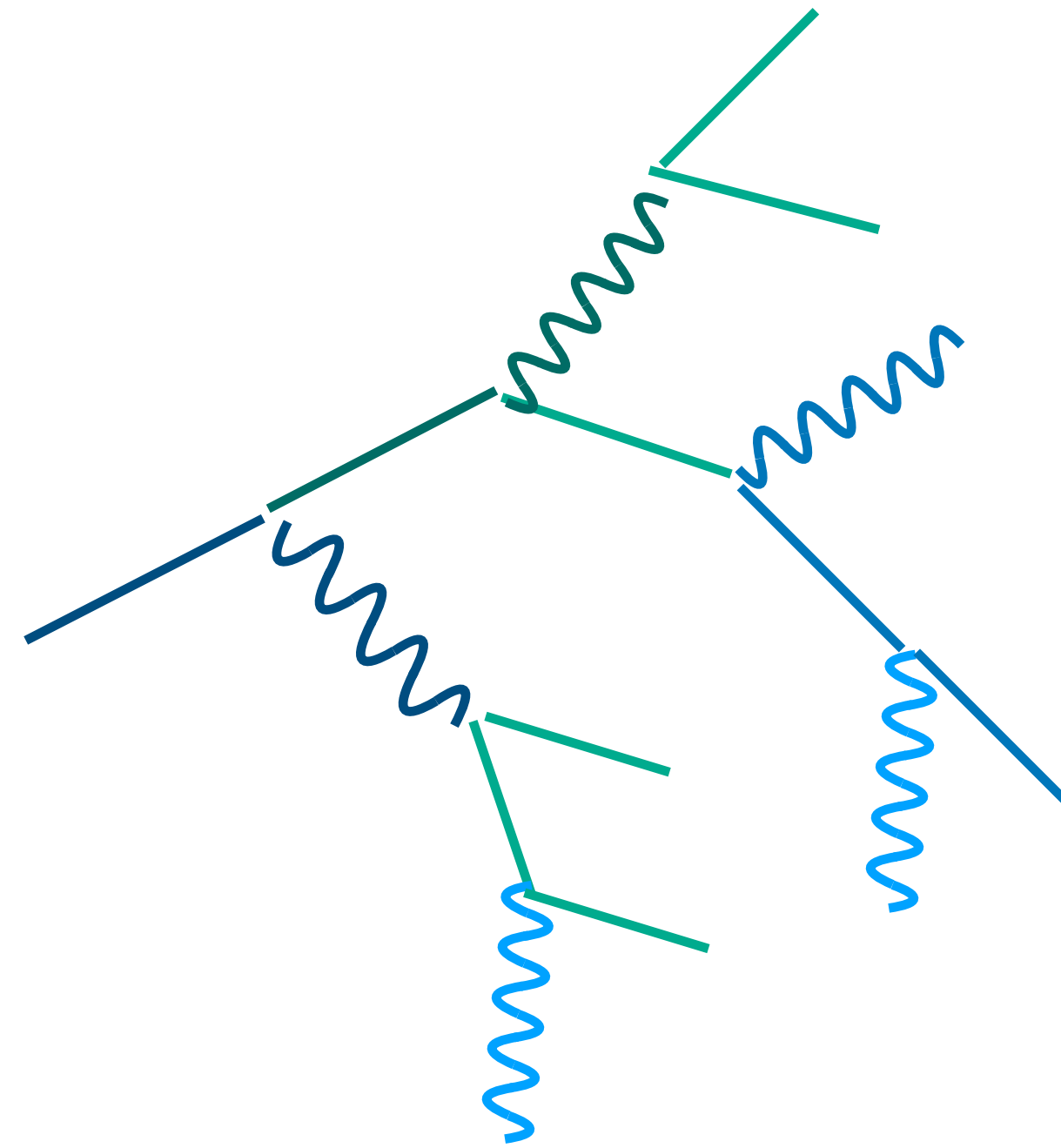
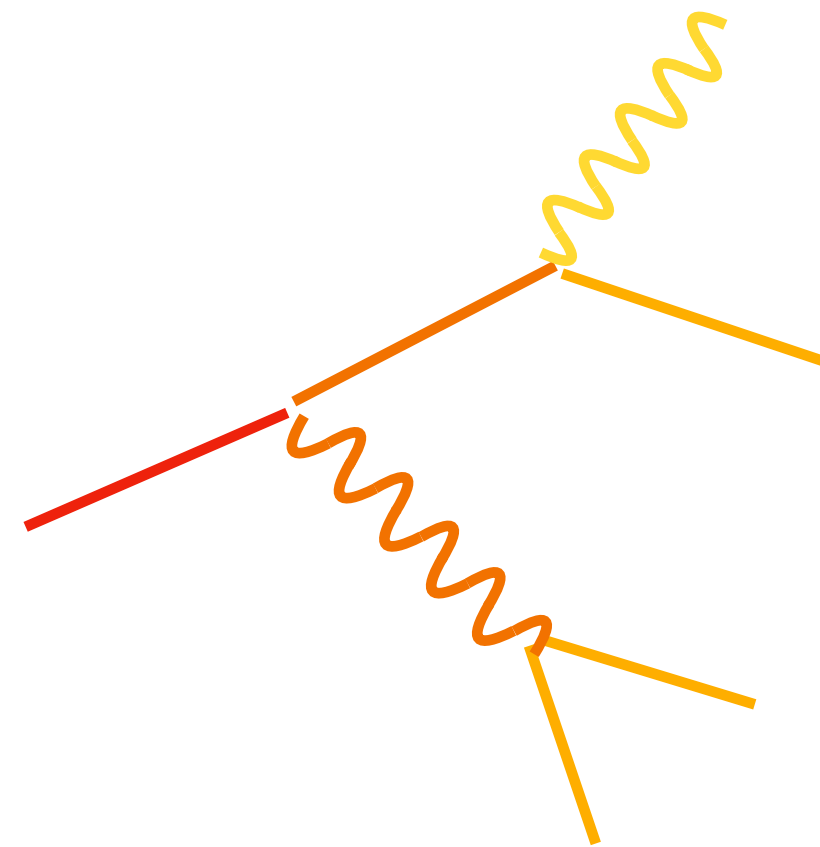
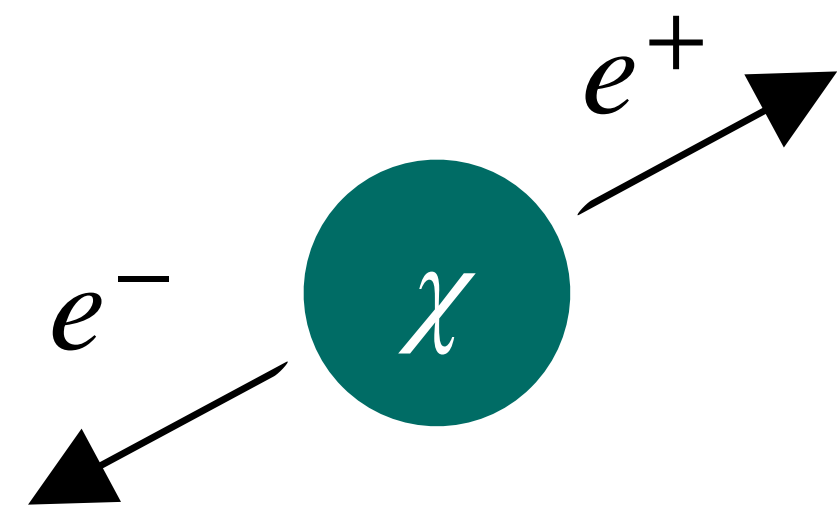


$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

Once cooled enough, particles interact with the **atoms** in the intergalactic medium [IGM]

Dark sector particle



$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

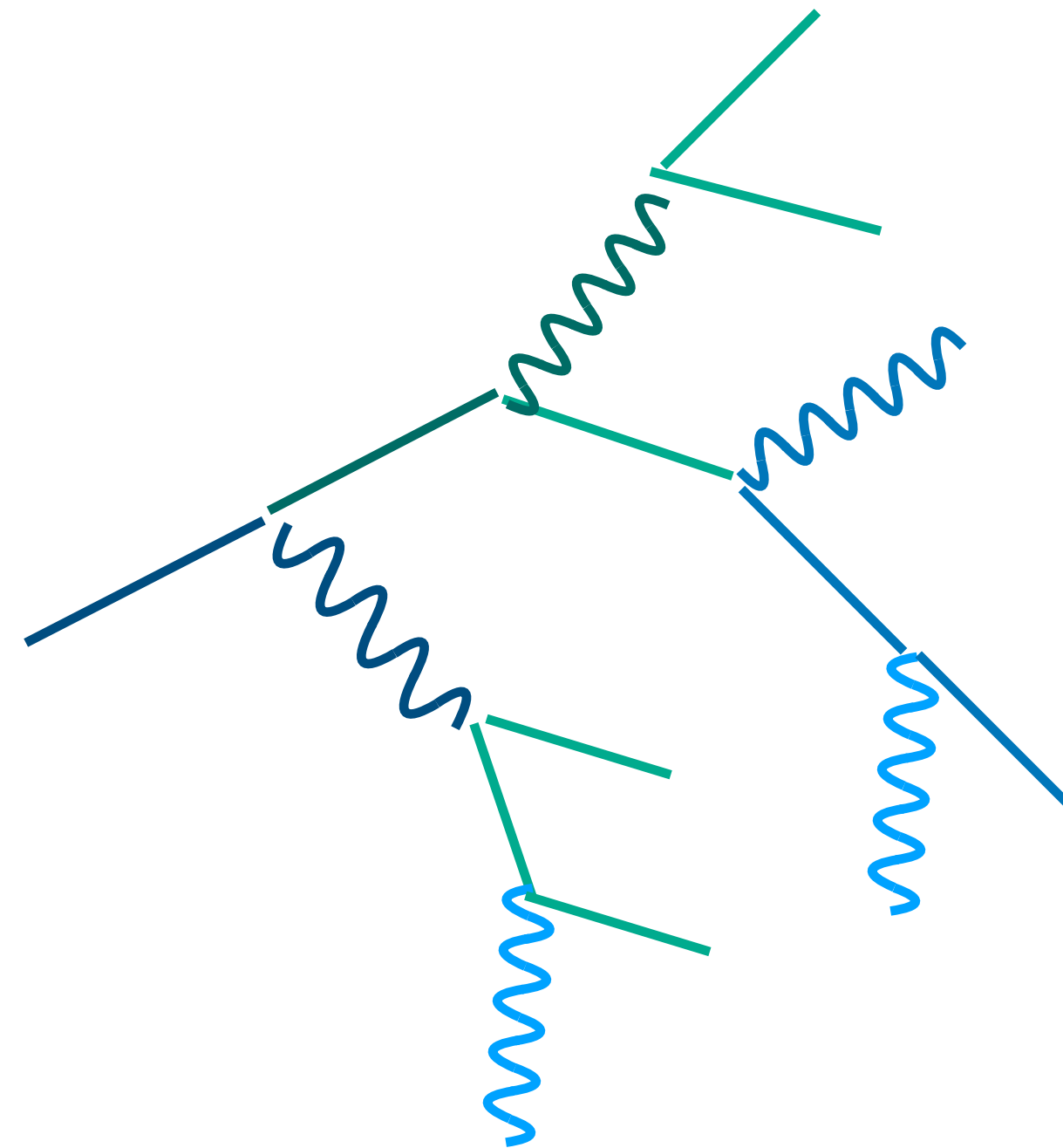
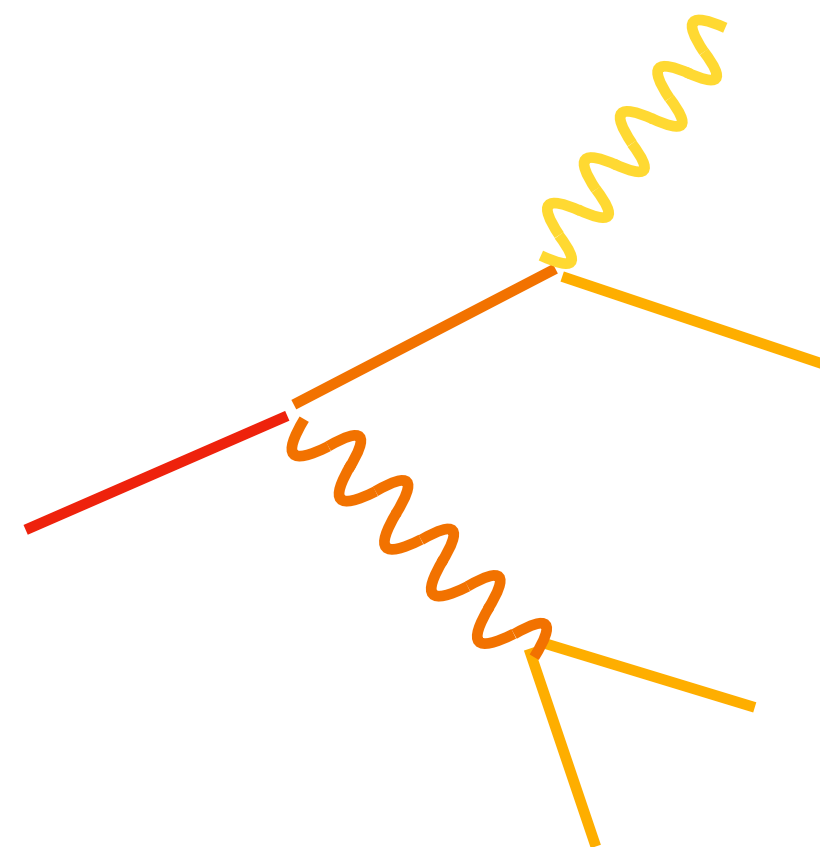
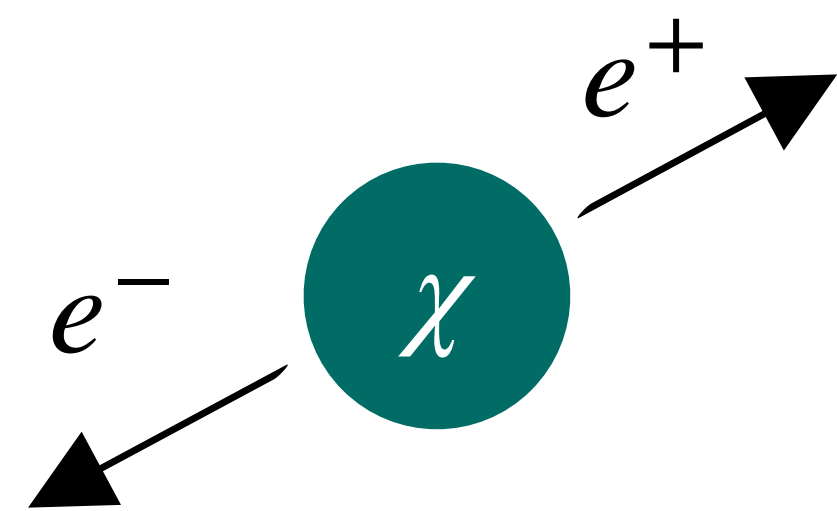
Once cooled enough, particles interact with the **atoms** in the intergalactic medium [IGM]

Increased Ionization $(\Delta x_e)_{DS}$

Heating of the intergalactic medium $(\Delta T_m)_{DS}$

modified DarkHistory - to include DS injection

Dark sector particle



$$e^- + \gamma \rightarrow e^- + \gamma$$

$$\gamma + H \rightarrow e^- + p^+$$

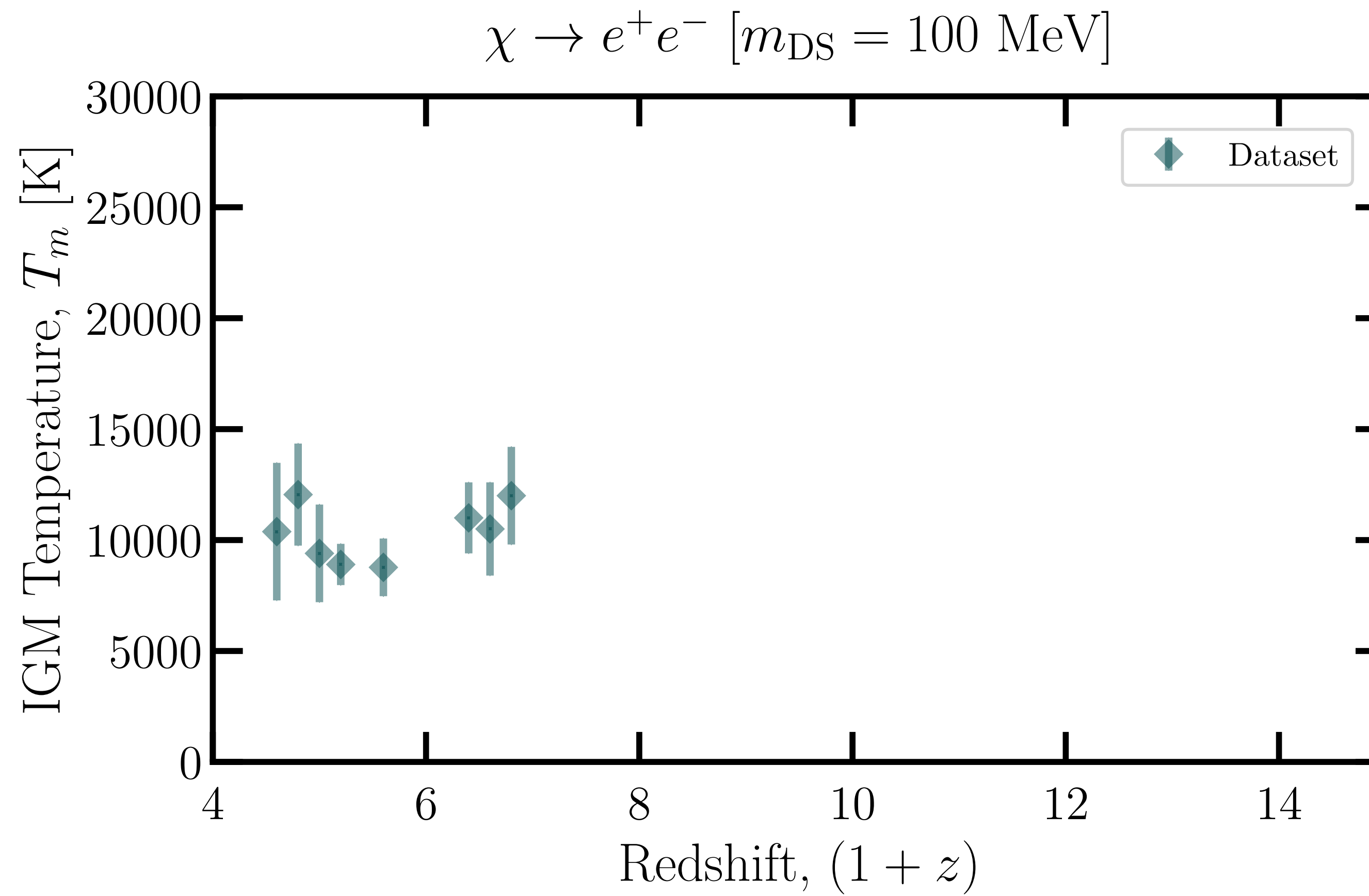
Once cooled enough, particles interact with the **atoms** in the intergalactic medium [IGM]

$$\text{Energy actually deposited} = f_{\text{channel}}(z, E, x_e) \times \text{Energy injected by decay}$$

Energy deposition fraction* - not all particles are good ionizers!

modified DarkHistory - to include DS injection

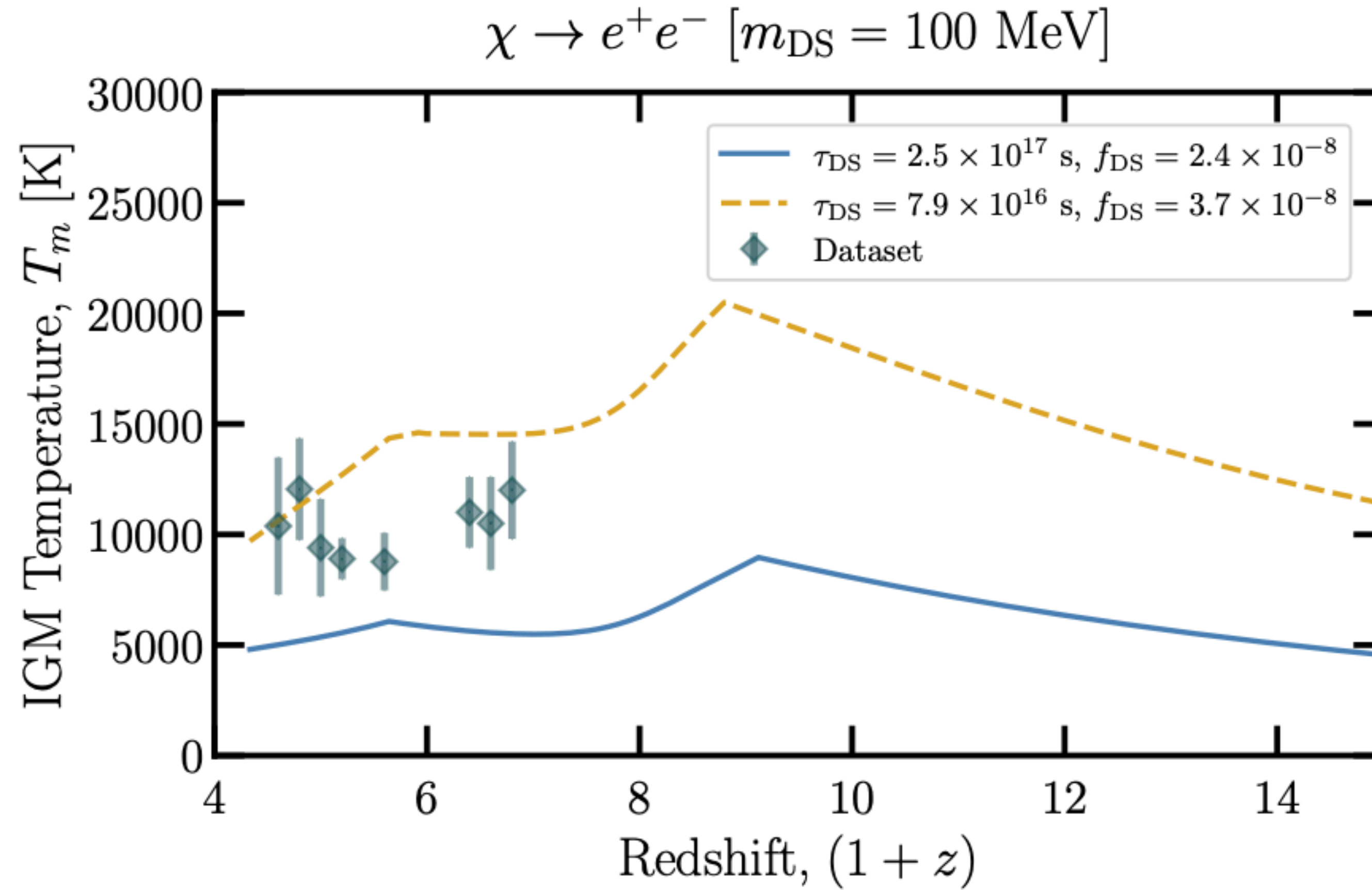
[New] Constraints from Lyman- α IGM measurements



IGM temperature dataset from [Gaikwad et al.], [Walther et al.]

see [Liu et al '20] for DM case

L. Lopez-Honorez and **SV** [arxiv: 2602.10078]

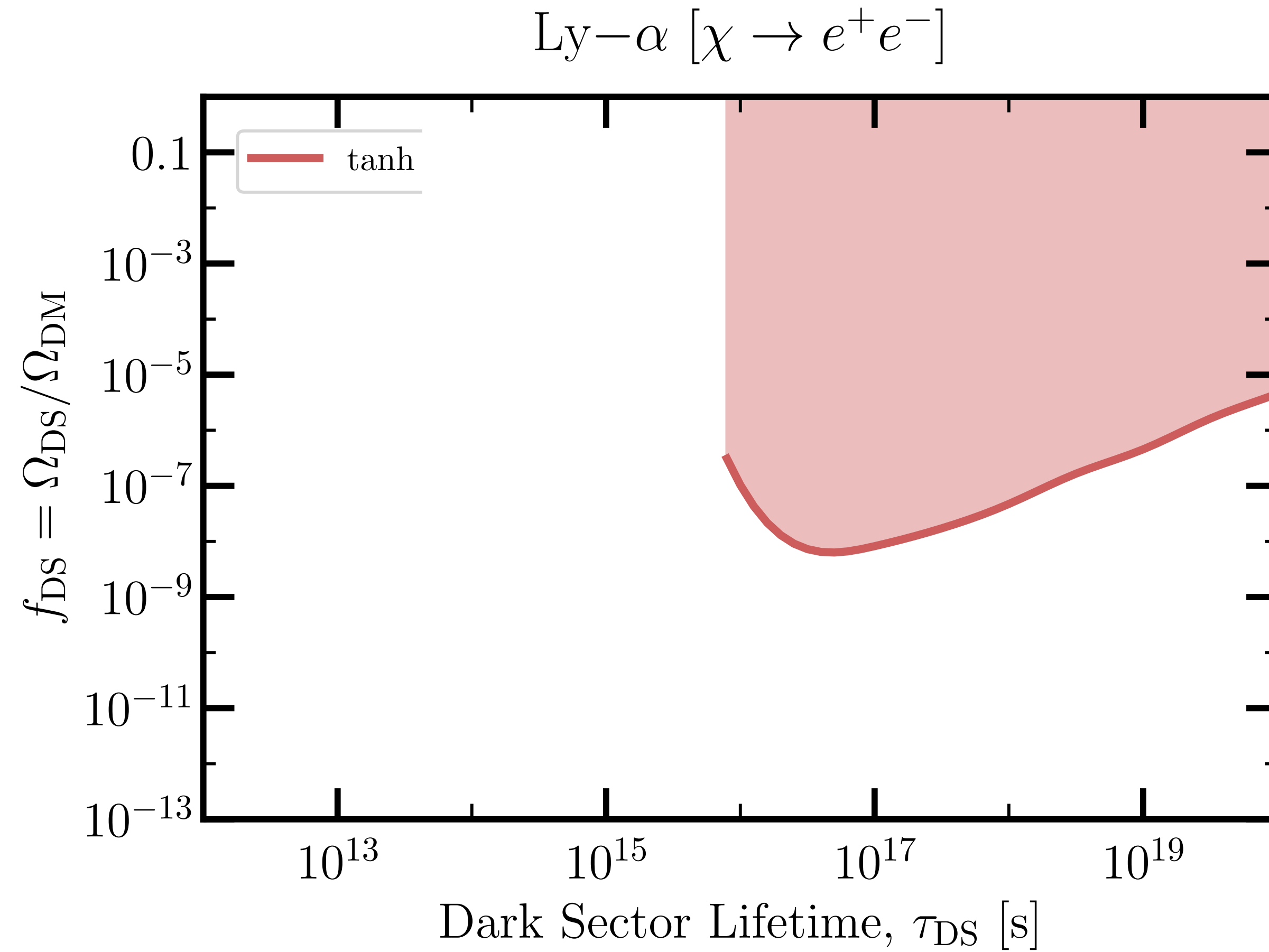


IGM temperature dataset from [Gaikwad et al.], [Walther et al.]

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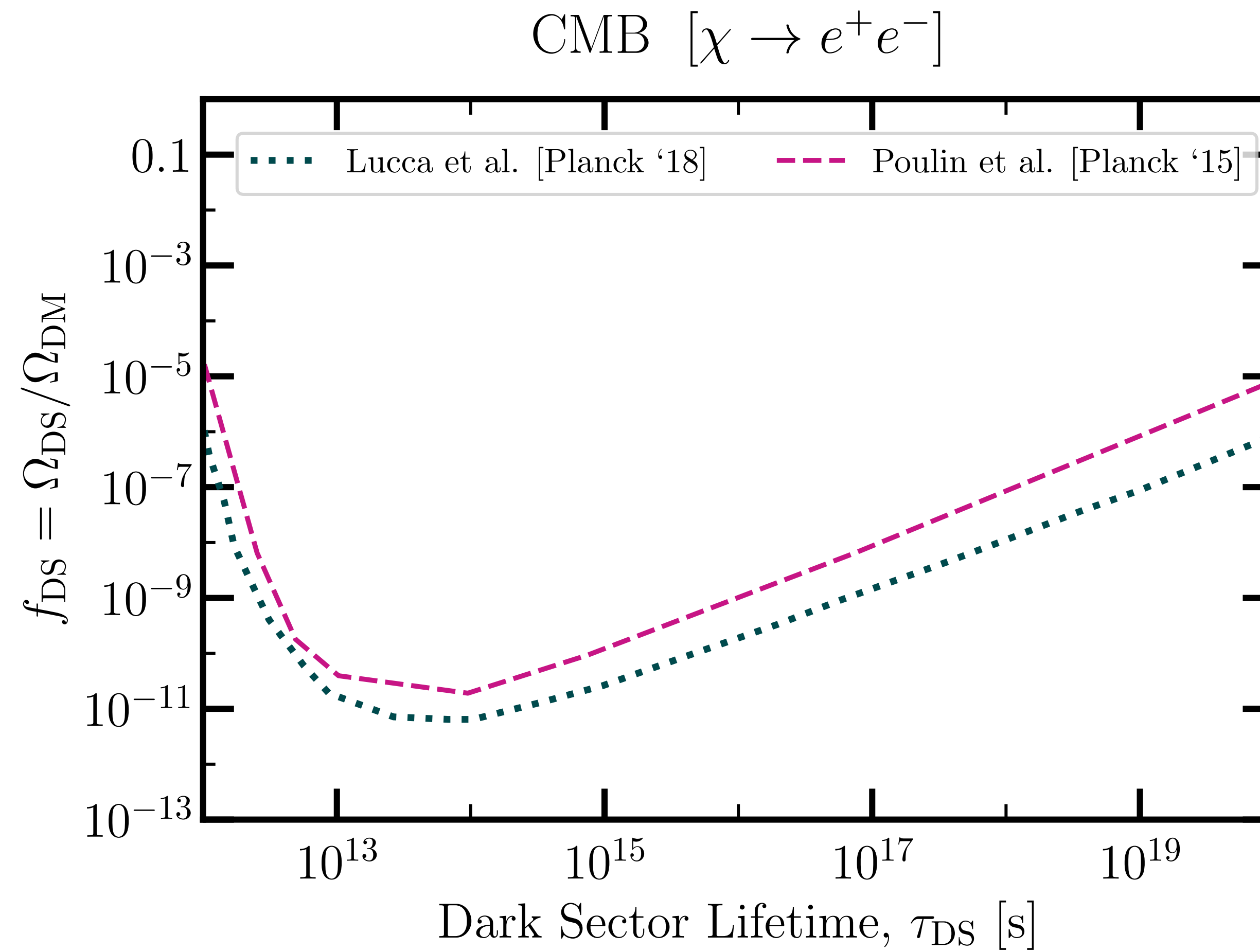
Our constraints from Lyman- α IGM temperature measurements

L. Lopez-Honorez and **SV** [arxiv: 2602.10078]



[Revisiting] Constraints from CMB

Existing limits from full CMB anisotropy analysis

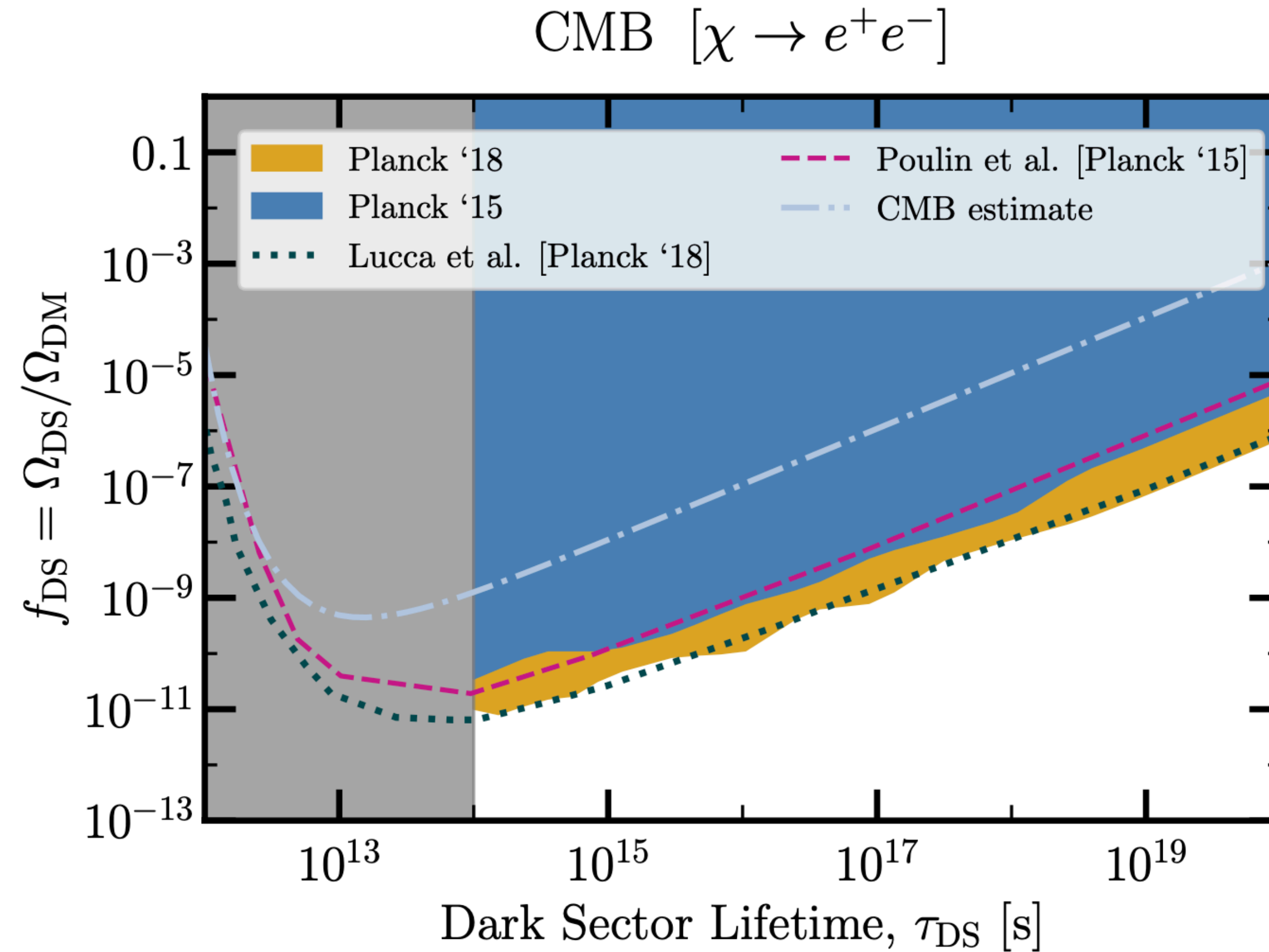


[Poulin, Lesgourgues, Serpico '16]

[Lucca, Schöneberg, Hooper, Lesgourgues, Chluba '19]

Our constraints from Planck's optical depth to reionization measurements

L. Lopez-Honorez and SV [arxiv: 2602.10078]



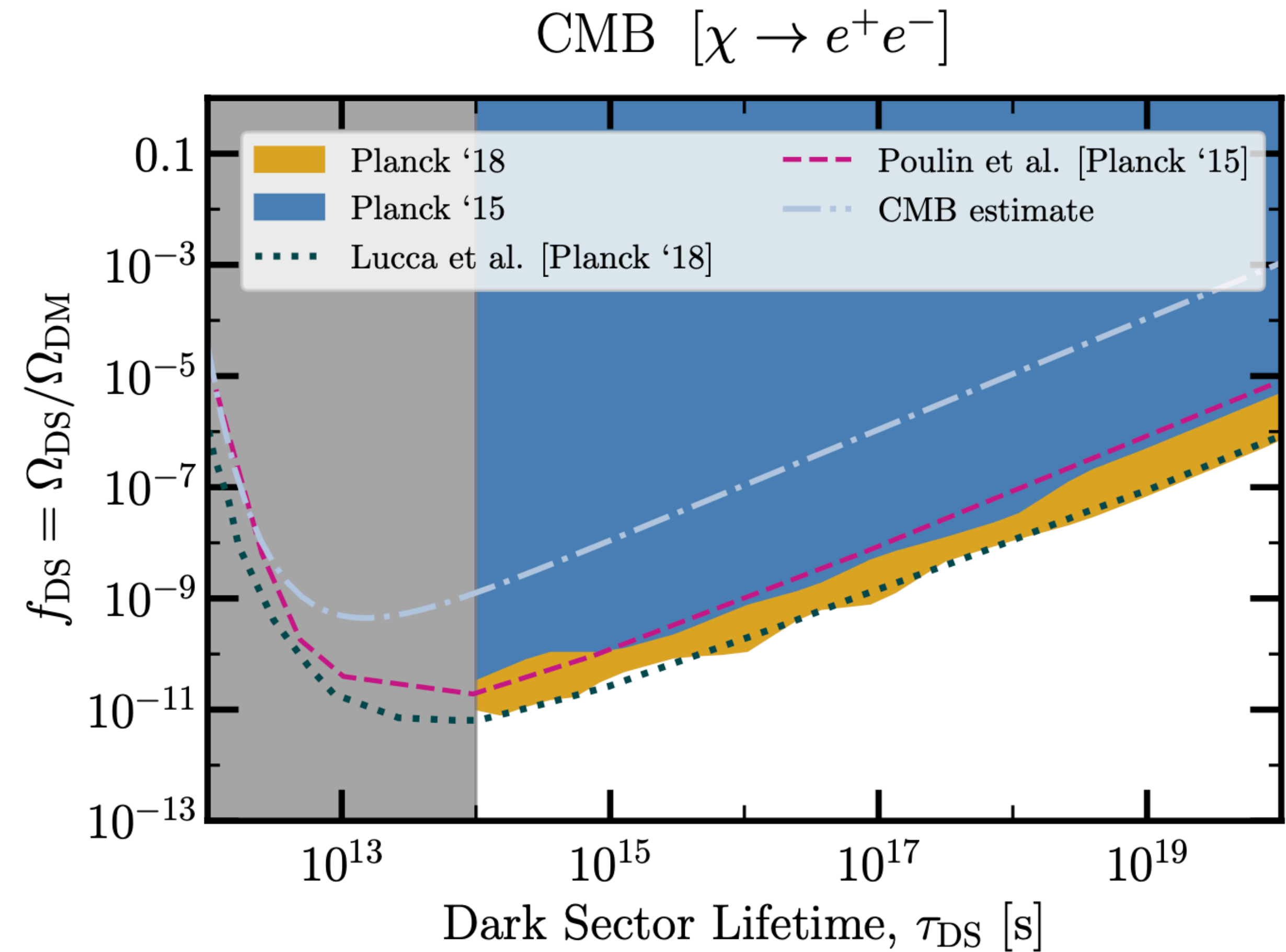
[Poulin, Lesgourges, Serpico '16]

[Lucca, Schöneberg, Hooper, Lesgourges, Chluba '19]

See also [Poulin et al. '15], [Capozzi et al. 2023]

estimates from optical depth to reionization give good agreement with CMB full bounds

L. Lopez-Honorez and SV [arxiv: 2602.10078]



[Poulin, Lesgourgues, Serpico '16]

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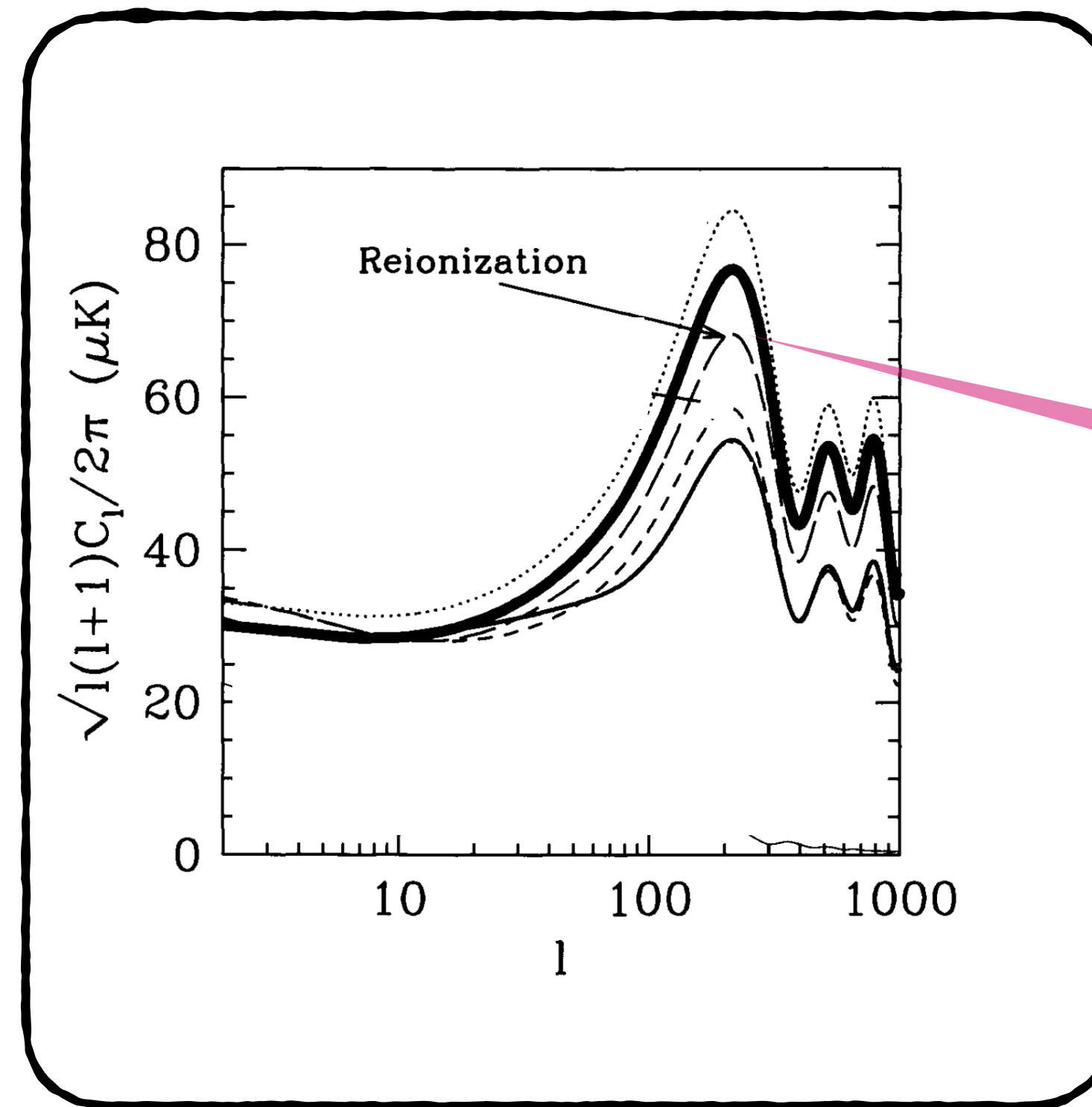
estimates from **optical depth to reionization** give good agreement with CMB full bounds

$$\tau_{reion} = n_H(0)\sigma_T \int_0^{z_{max}} dz x_e(z) \frac{(1+z)^2}{H(z)}$$

e.g. Aghanim et al [Planck Collaboration 2018]

optical depth to reionization

$$\tau_{reion} = n_H(0)\sigma_T \int_0^{z_{max}} dz x_e(z) \frac{(1+z)^2}{H(z)}$$

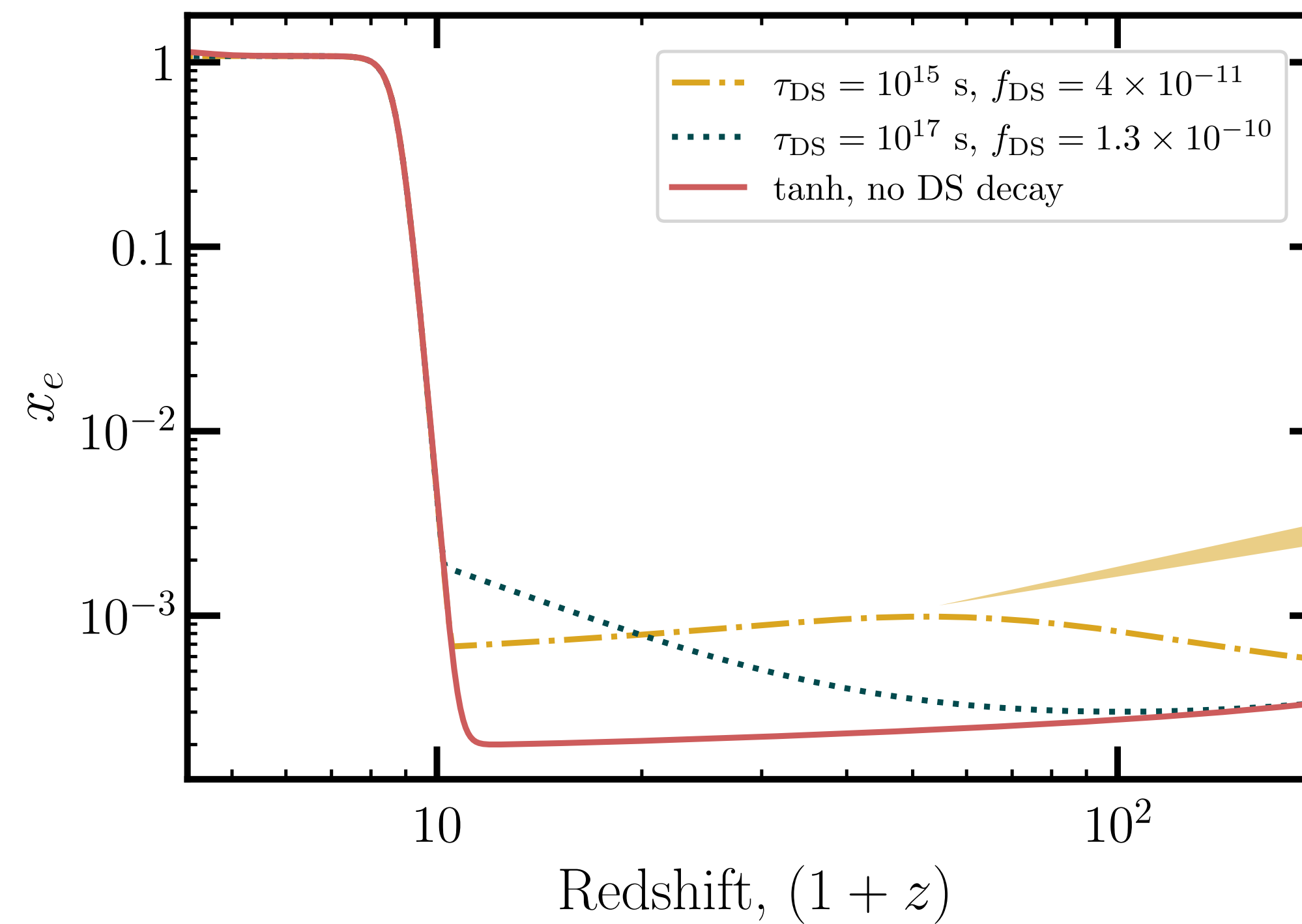


Free electrons around reionization will damp the CMB anisotropies $\sim e^{-2\tau_{reion}}$

[Figure adapted from Dodelson's Modern Cosmology]

optical depth to reionization

$$\tau_{reion} = n_H(0)\sigma_T \int_0^{z_{max}} dz x_e(z) \frac{(1+z)^2}{H(z)}$$



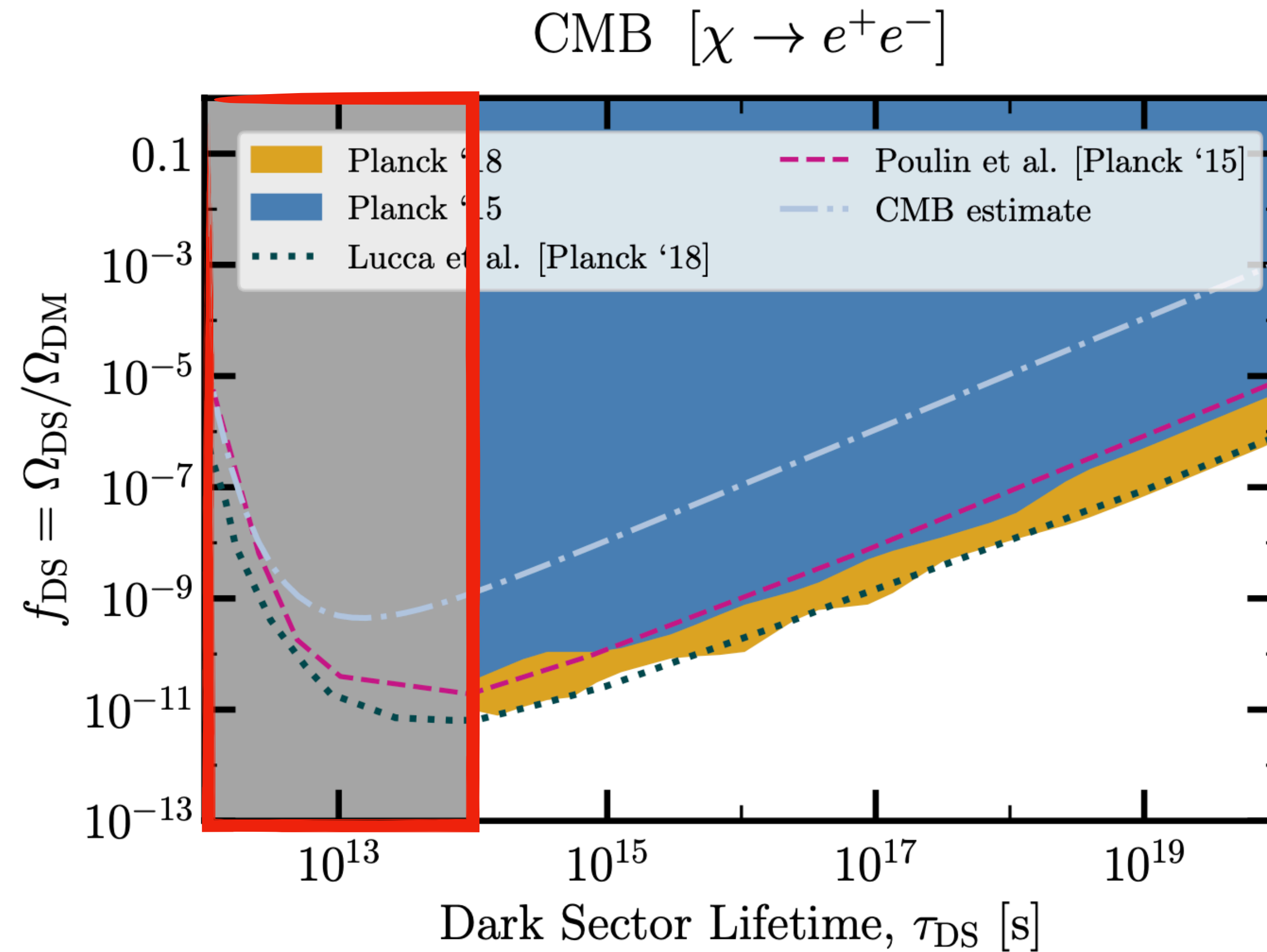
Decays from dark sector with lifetime $> 10^{14}$ s will enhance ionization level/optical depth

Planck 2018 measurement: $\tau_{reion} = 0.054 \pm 0.007$

[Aghanim et al \[Planck Collaboration 2018\]](#)

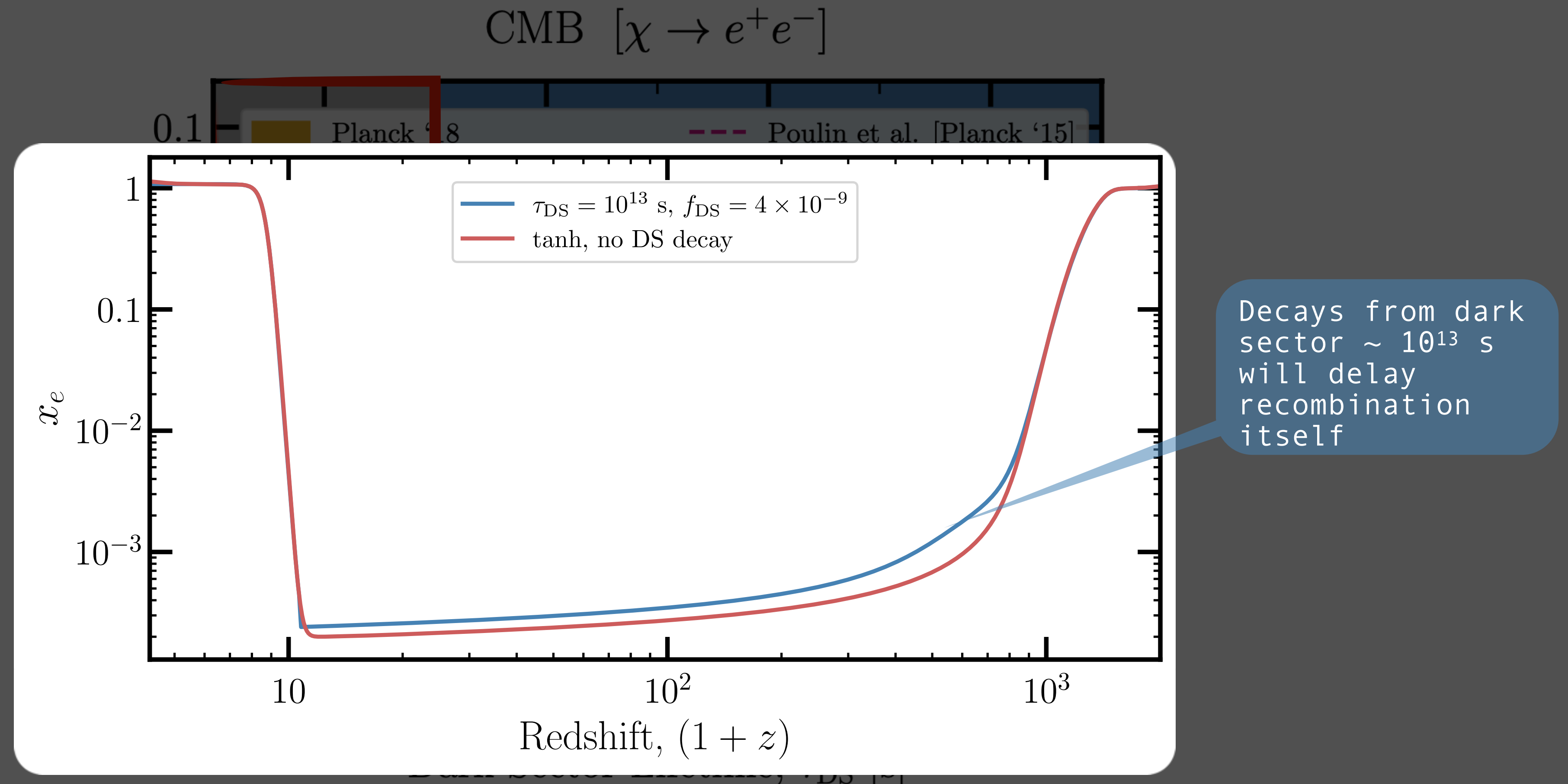
Our constraints from Planck's τ_{reion} measurements

L. Lopez-Honorez and SV [arxiv: 2602.10078]



Our constraints from Planck's τ_{reion} measurements

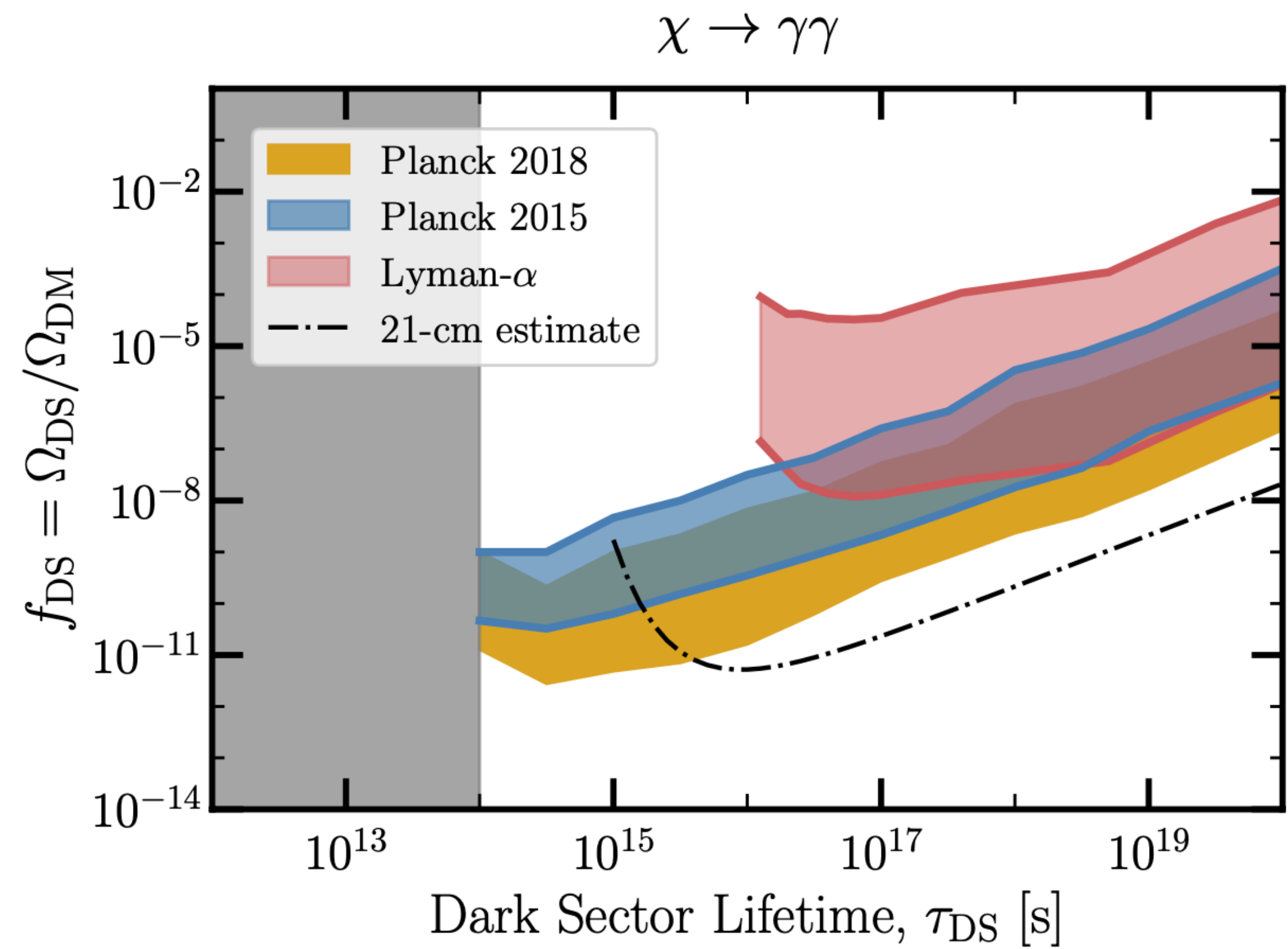
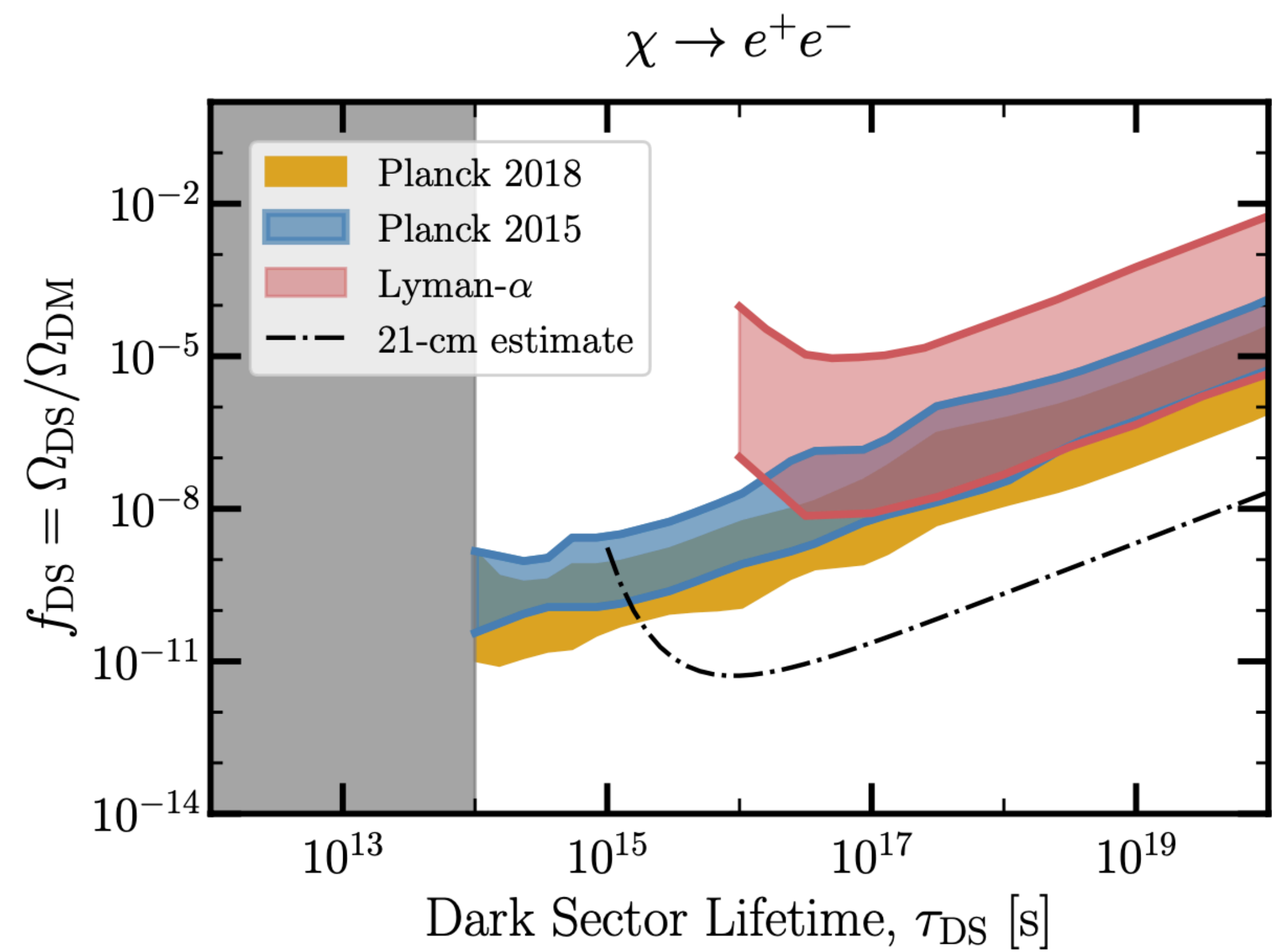
L. Lopez-Honorez and SV [arxiv: 2602.10078]



CMB bounds based on optical depth to reionization should be reliable for late-decaying DS

See also [Poulin et al. 2016], [Capozzi et al. 2023]

Combined constraints



- IGM temperature measurements from $\text{Ly}\alpha$ can probe late energy injection
- $\text{Ly}\alpha$ constraints are complementary to CMB, competitive with Planck '15
- Upcoming 21-cm signal probes will improve limits from current probes

Back-up

Modification in IGM observables from DS energy injection

$$\Delta x_e \simeq \frac{1}{n_b} \frac{1}{E_{\text{ion}}} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

$$\Delta T_{\text{m}} \simeq \frac{1}{n_b} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

Modification in IGM observables from DS energy injection

$$\Delta x_e \simeq \frac{1}{n_b} \frac{1}{E_{\text{ion}}} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

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$$\left(\frac{dE}{dV dz} \right)^{\text{DS, inj}} = f_{\text{DS}} e^{-t/\tau_{\text{DS}}} \rho_{\text{DM}}^0 \frac{1}{\tau_{\text{DS}}} \frac{(1+z)^2}{H(z)}$$

DS fractional abundance

DS lifetime

Modification in IGM observables from DS energy injection

$$\Delta x_e \simeq \frac{1}{n_b} \frac{1}{E_{\text{ion}}} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

$$\Delta T_m \simeq \frac{1}{n_b} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

$$\left(\frac{dE}{dV dz} \right)^{\text{DS, inj}} = f_{\text{DS}} e^{-t/\tau_{\text{DS}}} \rho_{\text{DM}}^0 \frac{1}{\tau_{\text{DS}}} \frac{(1+z)^2}{H(z)}$$

DS fractional abundance

DS lifetime

$$\Delta x_e(z = 1000) \sim 10^{-3} \left(\frac{f_{\text{DS}}}{10^{-9}} \right) \left(\frac{\rho_{\text{DM}}^0/\rho_b^0}{5} \right) \left(\frac{5 \times 10^{13} \text{ s}}{\tau_{\text{DS}}} \right)$$

DS decay can modify free electron fraction at $\mathcal{O}(10^{-3})$ level at CMB

Modification in IGM observables from DS energy injection

$$\Delta x_e \simeq \frac{1}{n_b} \frac{1}{E_{\text{ion}}} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

$$\Delta T_{\text{m}} \simeq \frac{1}{n_b} \left(\frac{dE}{dV dz} \right)^{\text{DS, inj}}$$

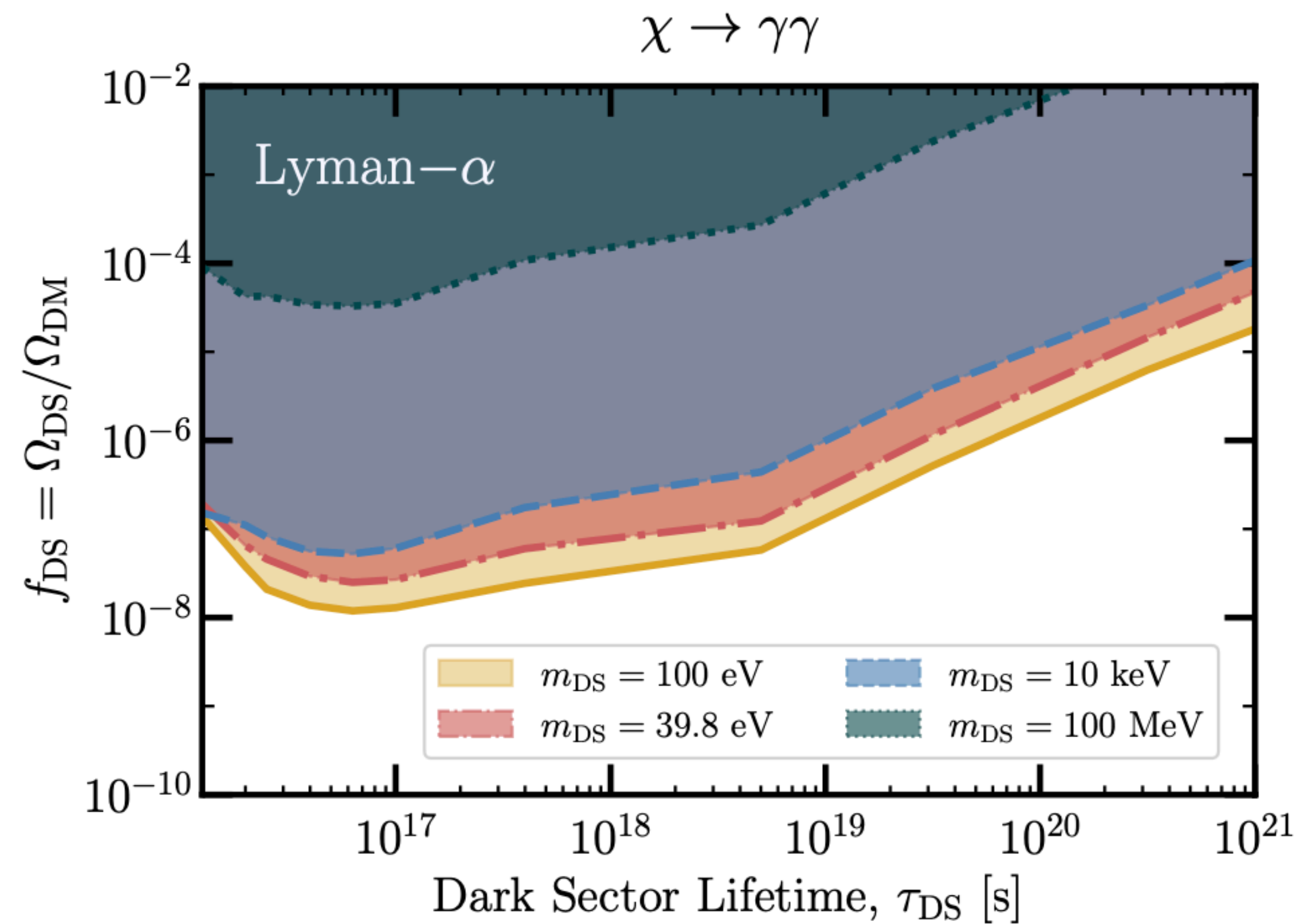
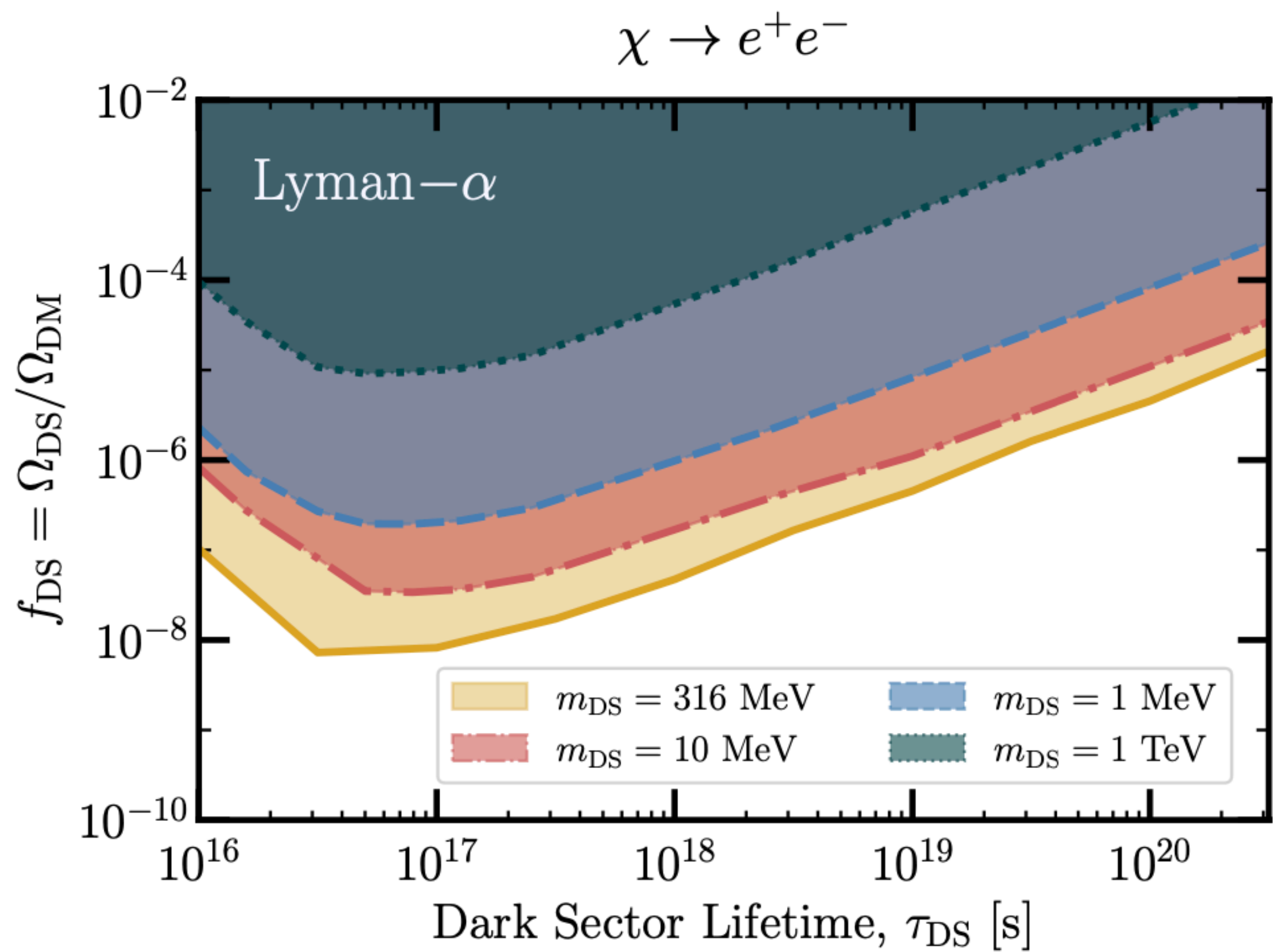
$$\left(\frac{dE}{dV dz} \right)^{\text{DS, inj}} = f_{\text{DS}} e^{-t/\tau_{\text{DS}}} \rho_{\text{DM}}^0 \frac{1}{\tau_{\text{DS}}} \frac{(1+z)^2}{H(z)}$$

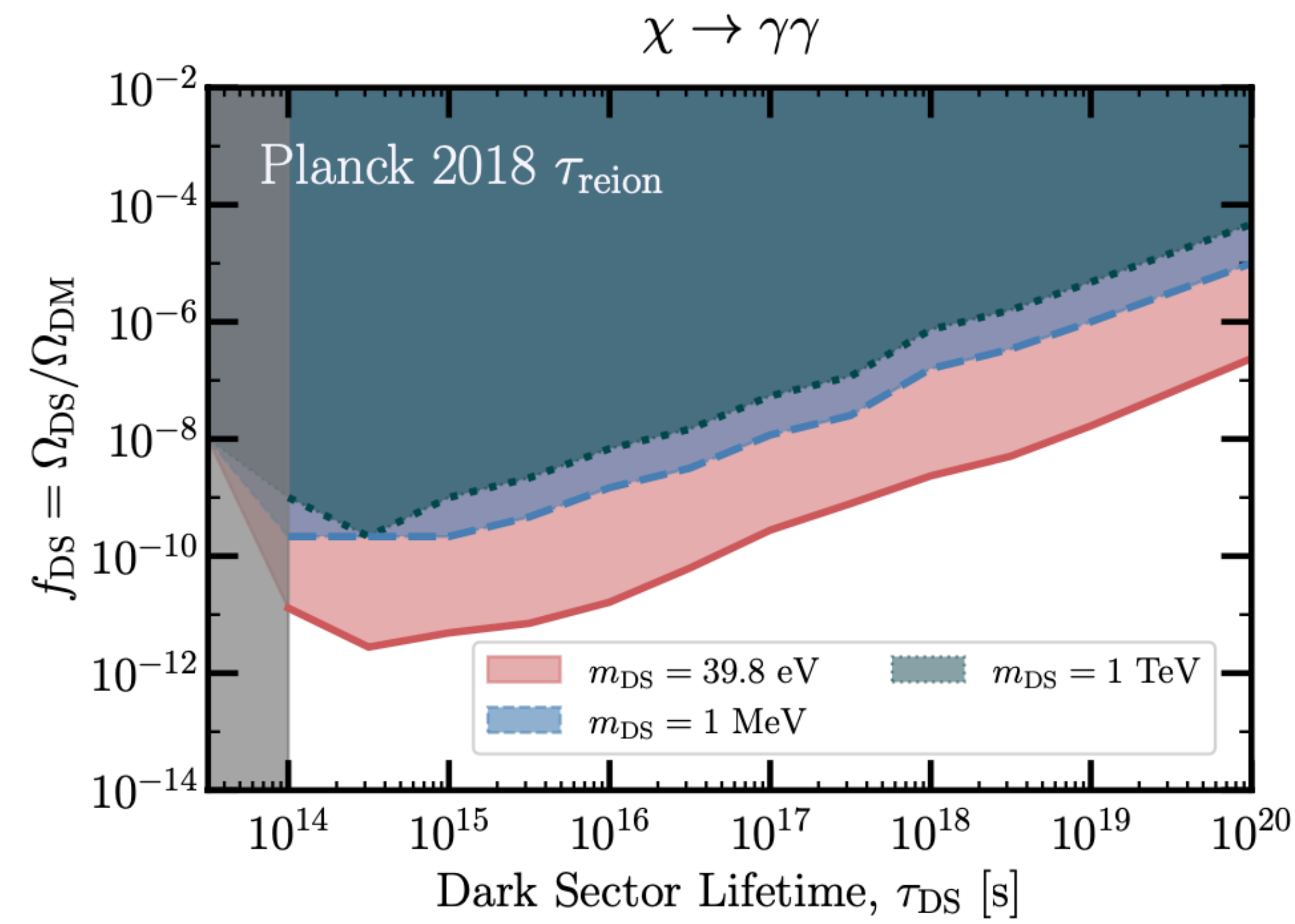
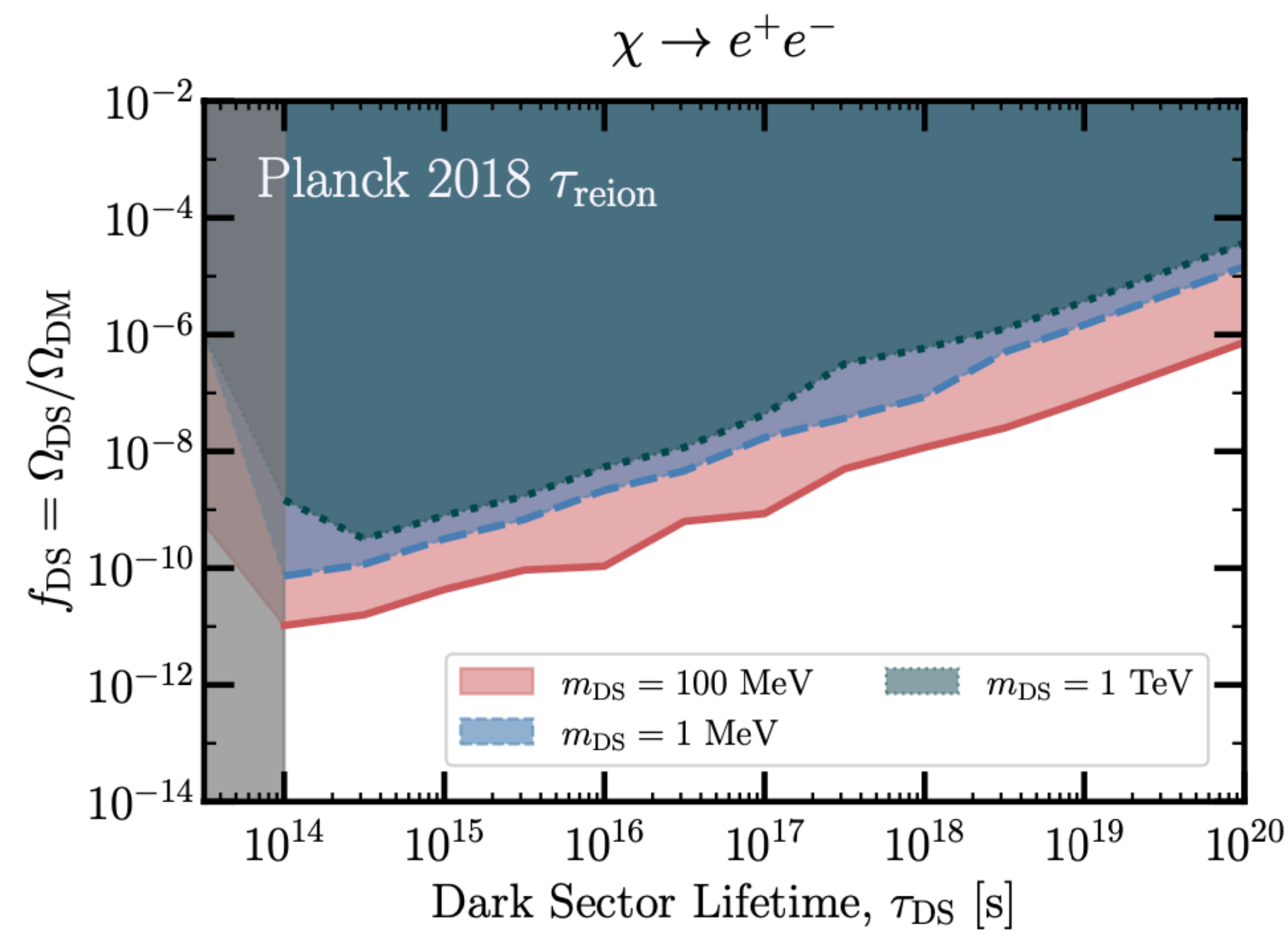
DS fractional abundance

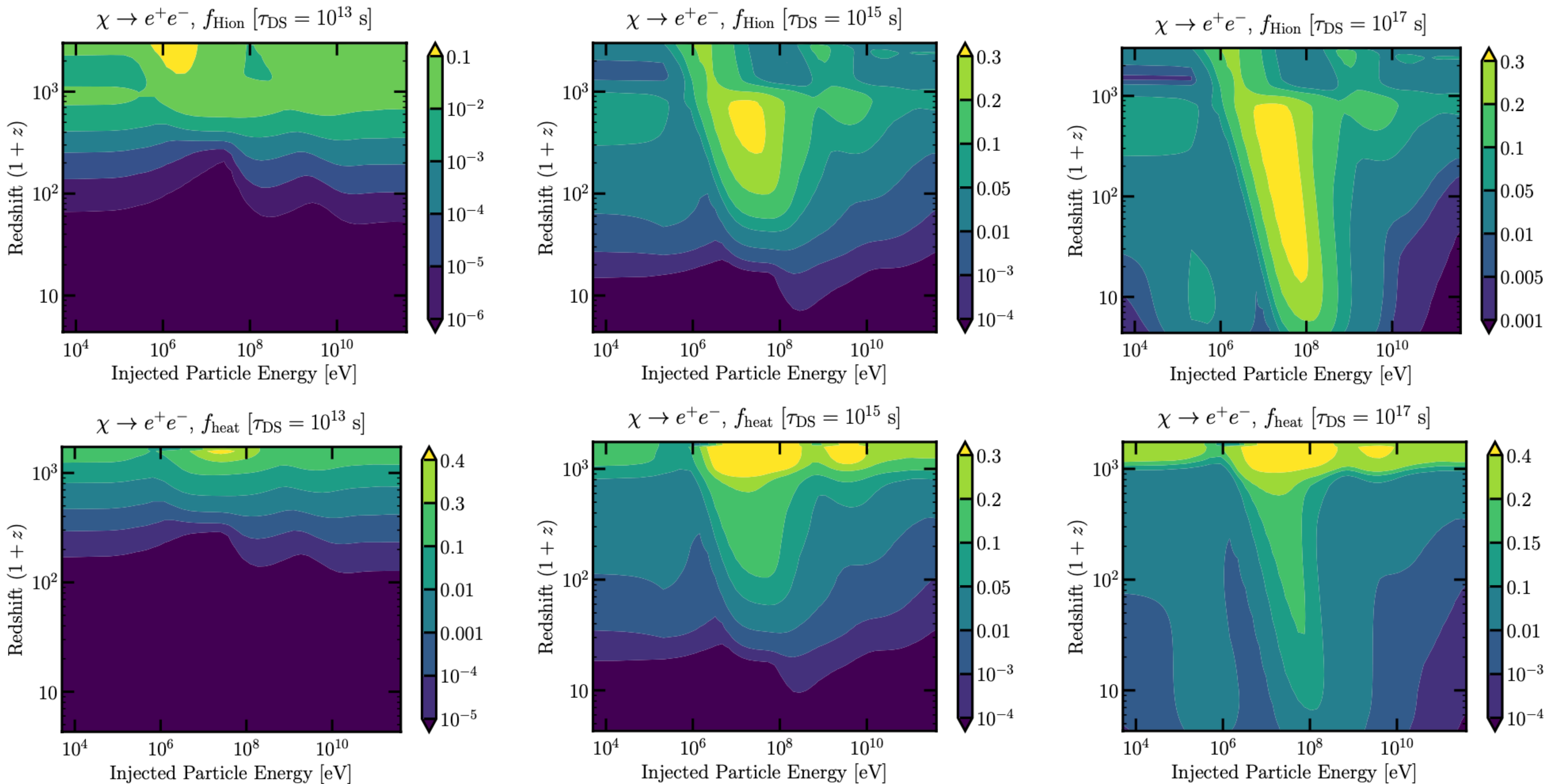
DS lifetime

$$\Delta T_{\text{m}}(z=5) \sim 10^4 \text{ K} \left(\frac{f_{\text{DS}}}{10^{-9}} \right) \left(\frac{\rho_{\text{DM}}^0/\rho_{\text{b}}^0}{5} \right) \left(\frac{6 \times 10^{16} \text{ s}}{\tau_{\text{DS}}} \right)$$

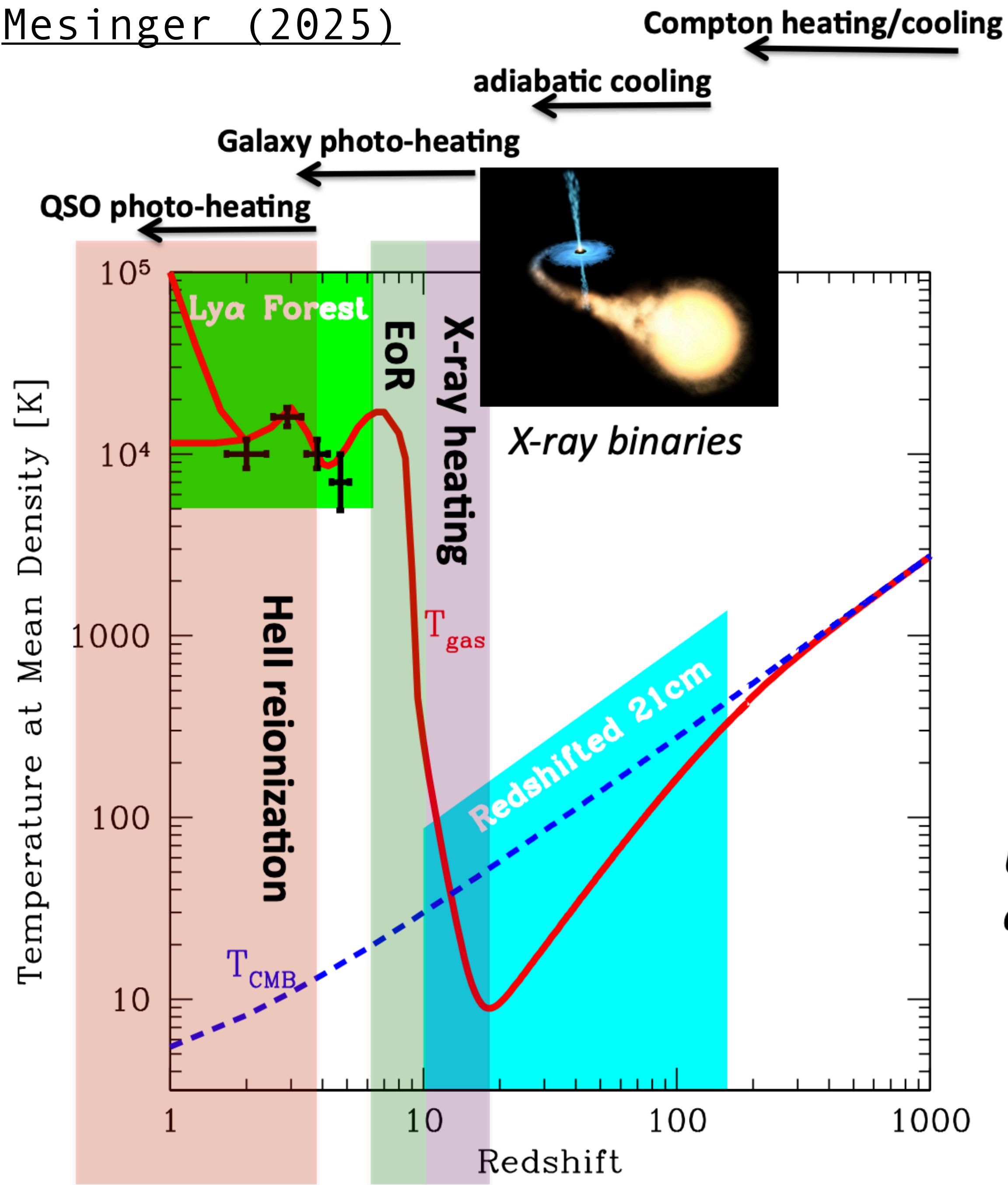
DS decay can modify IGM temperature probed by Ly α already







Credits: Mesinger (2025)

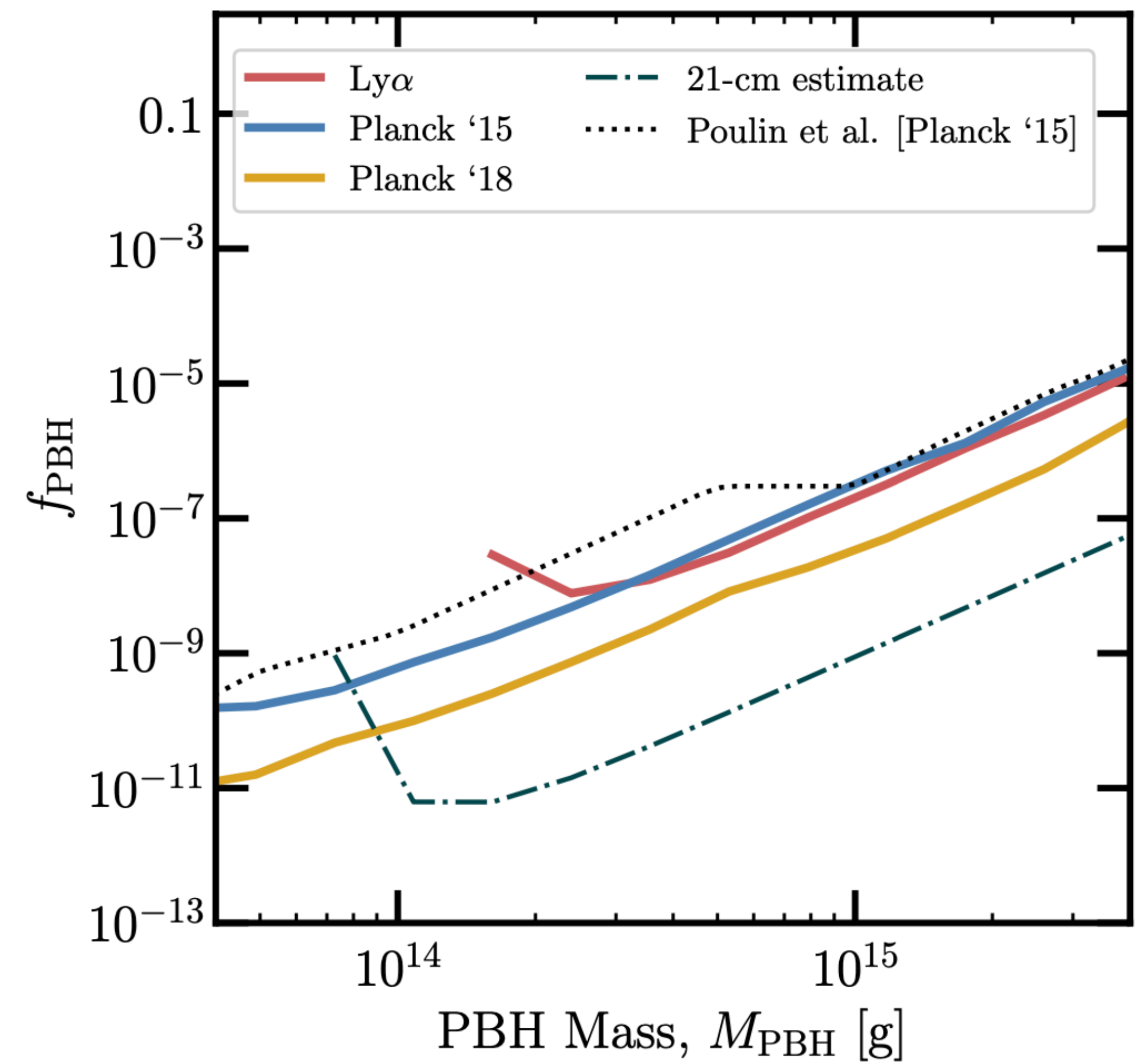


What about the heating history?

Until recently, only constrained at $z < \sim 5$

adapted from McQuinn (2016)

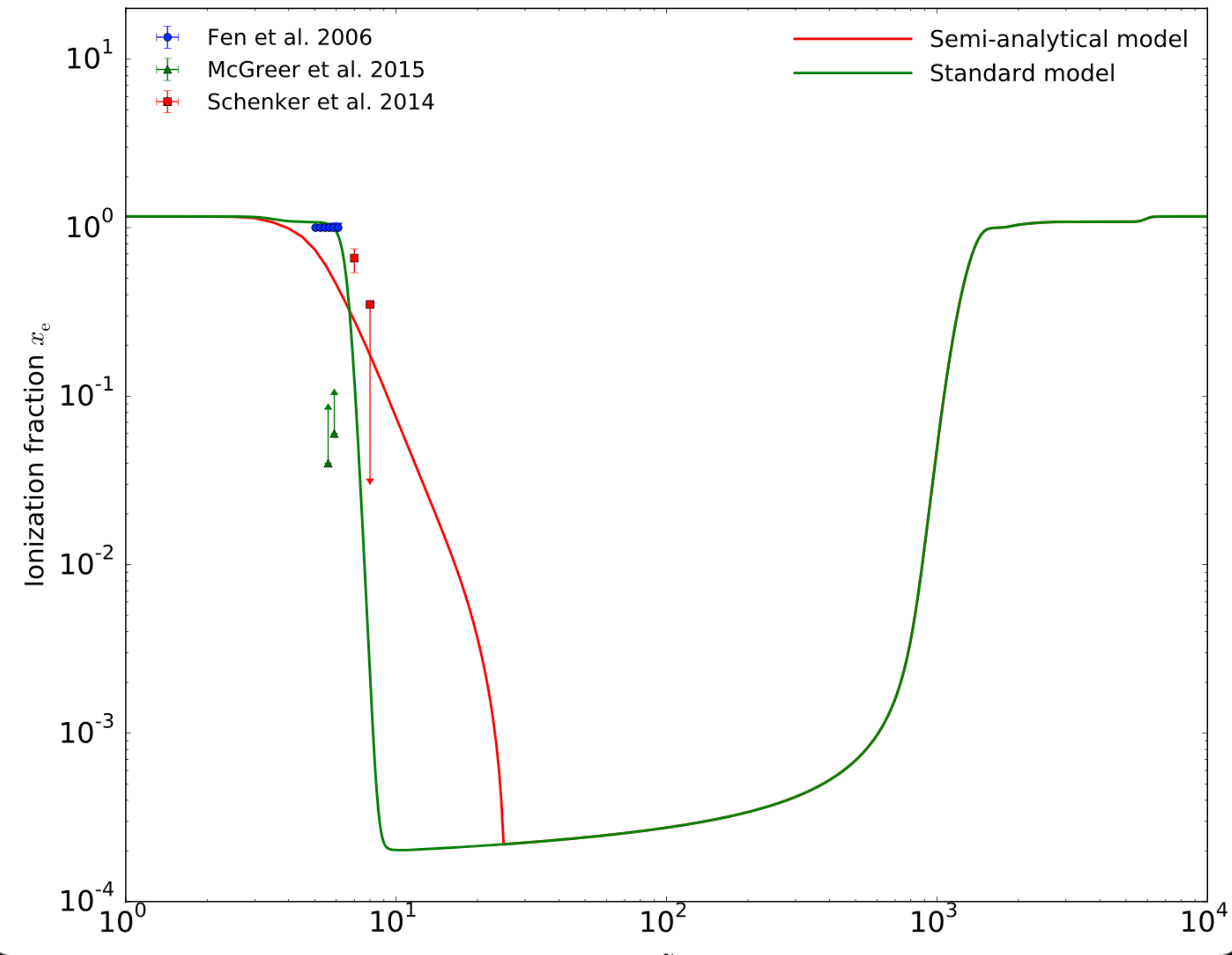
Translation to evaporating Primordial Black Holes



What will energy injection do to CMB?

[Poulin et al. 2016](#)

$$\chi \rightarrow e^+e^-/\gamma\gamma$$



Recombination

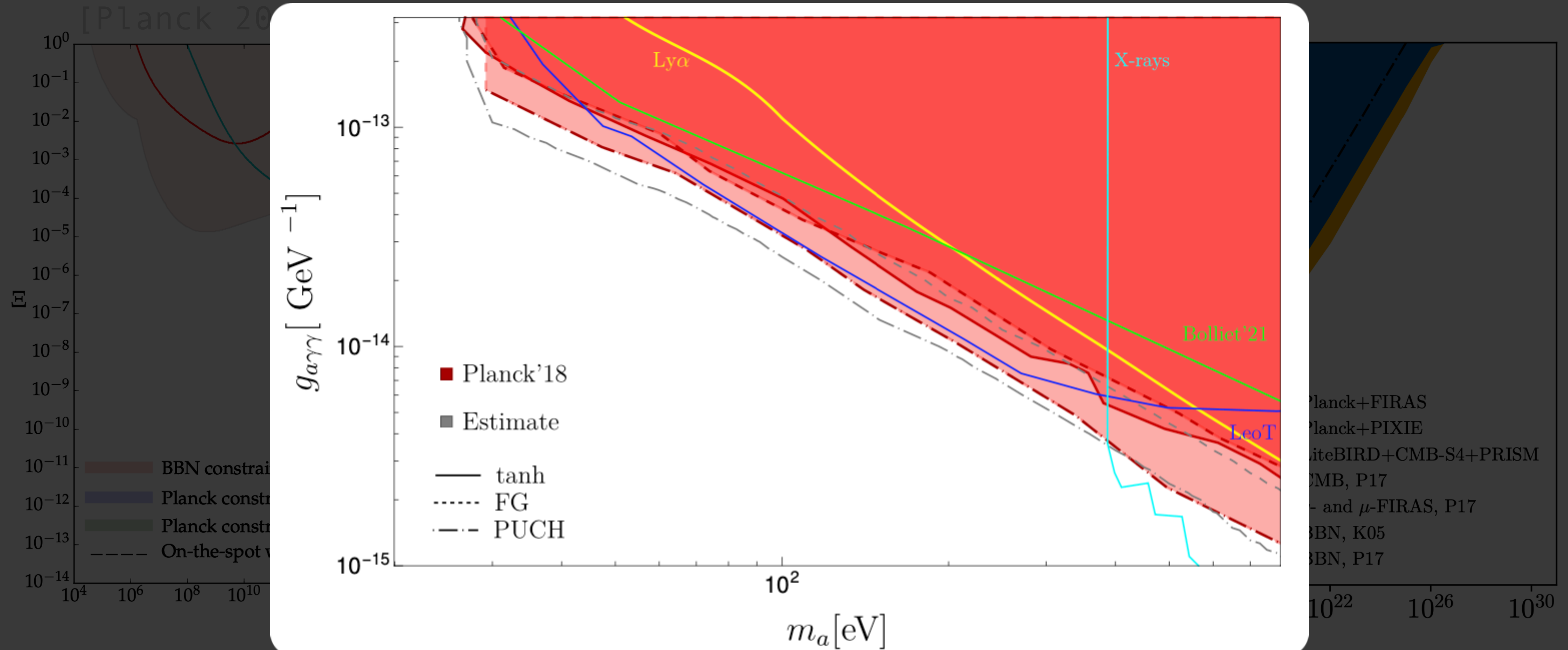
Neutral

$z \sim 1000$

at with atoms in gas

estimates from optical depth to reionization give good agreement with CMB full bounds

[Capozzi, Ferreira, Lopez-Honorez, Mena '23]



[Poulin, Lesgourgues, Serpico '16]

[Lucca, Schöneberg, Hooper, Lesgourgues, Chluba '19]