Constraints on Dark Matter from the Cosmic Microwave Background

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U.S. Cosmic Visions:
New Ideas in Dark Matter
University of Maryland
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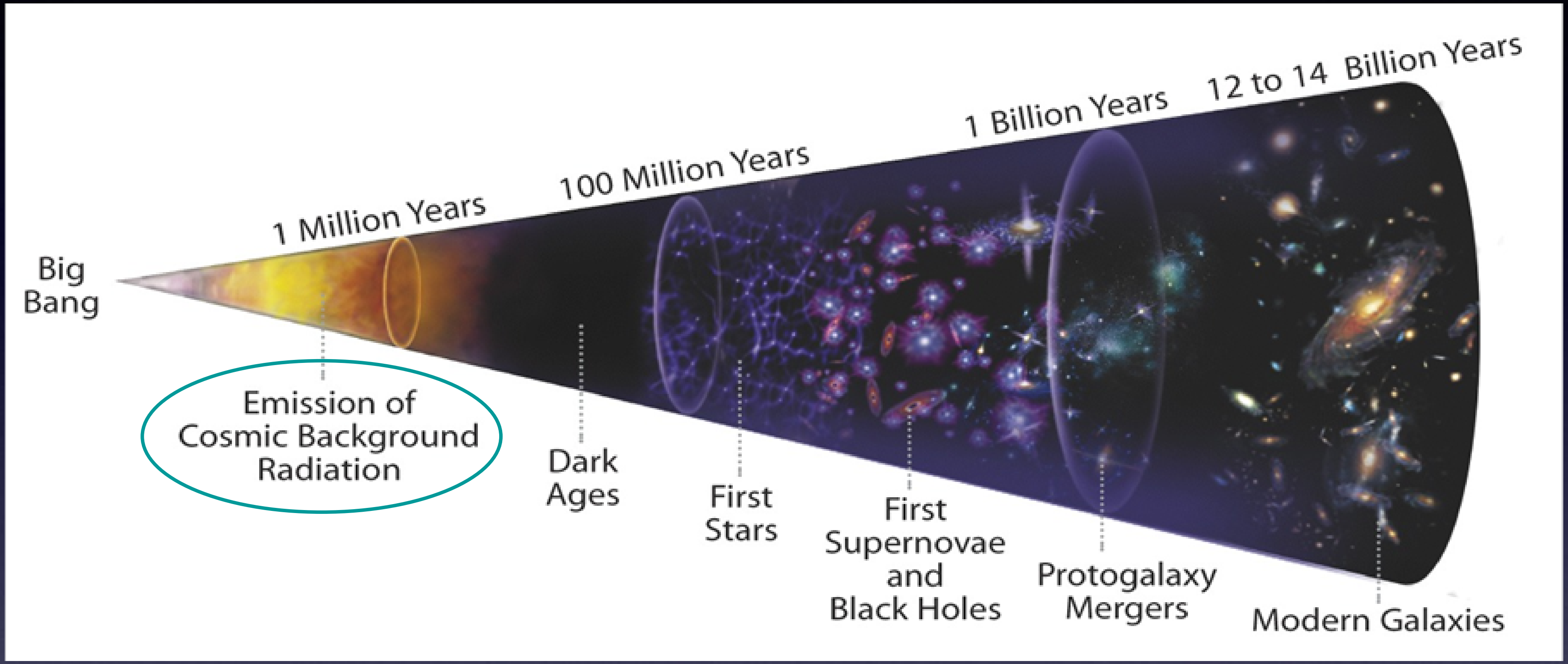
The cosmic dark ages



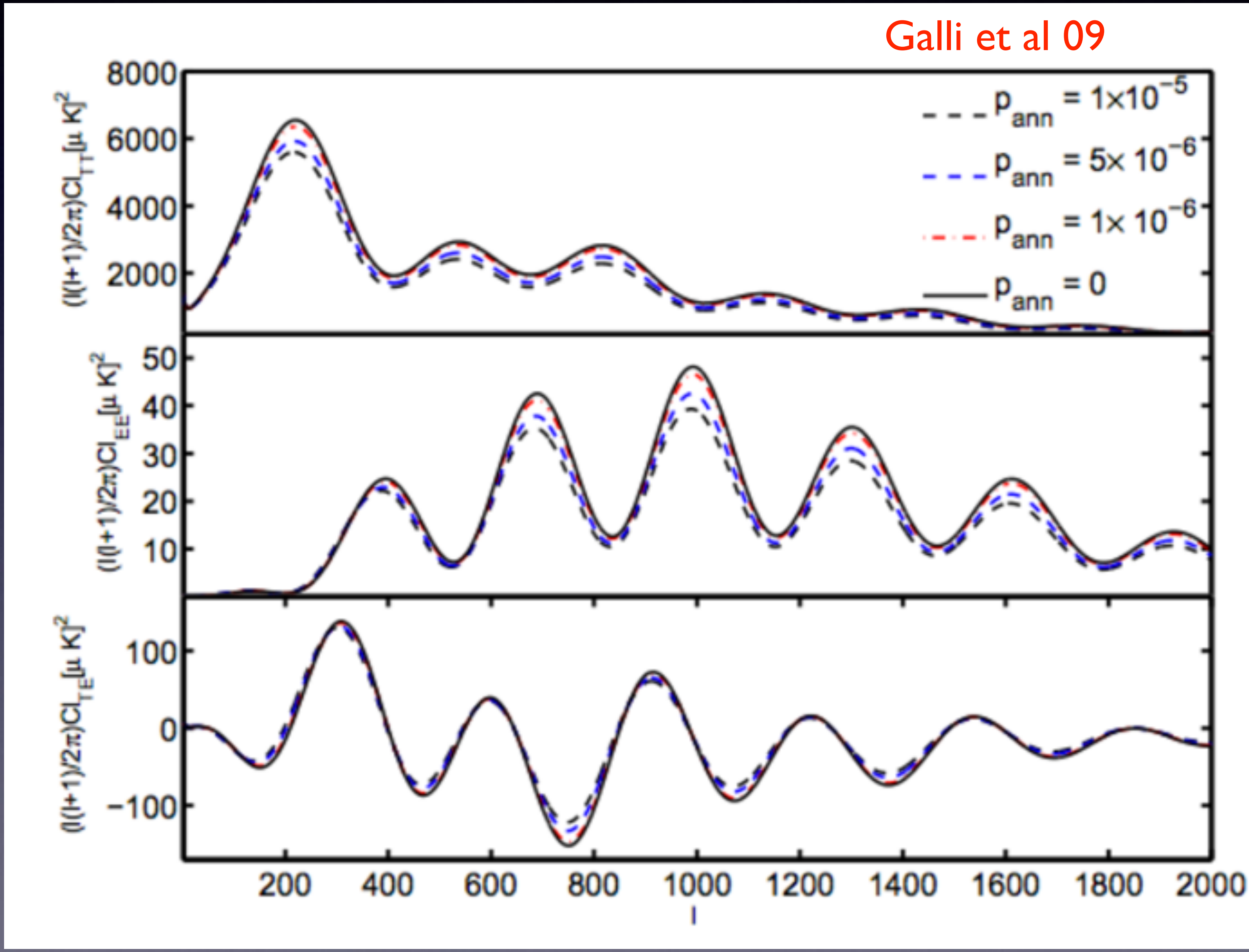
- Roughly z~10-1000, age of the universe ~400 000 years - 500 million years.
- For most of this period, matter fluctuations are small and perturbative; non-linear structure formation does not begin until $z < 100$. Thus any DM signals depend primarily on cosmological density of DM - well measured.
- Residual ionization fraction ~ few x 10^{-4}.
- Any ionization acts as a screen to the cosmic microwave background radiation - can be sensitively measured.

What can dark matter do?

- Consider the power from DM annihilation - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe.

Dark matter & the CMB

- Extra ionization from DM annihilation would suppress & distort temperature and polarization anisotropies in the CMB
- Consider large range of different DM annihilation products. Demonstrated in TRS '15 that effect on CMB is universal (for keV-TeV-energy annihilation products).



From theoretical models to imprint on the CMB

Dark matter model predicts annihilation/decay products

Annihilation/decay injects high-energy particles

↓ Decay with Pythia or similar program

High-energy photons + e^+e^- (others largely escape)

↓ Cooling processes (based on TRS et al 09, updated and improved in later work, interpolation tables now public)

Absorbed energy (ionization+excitation+heating)

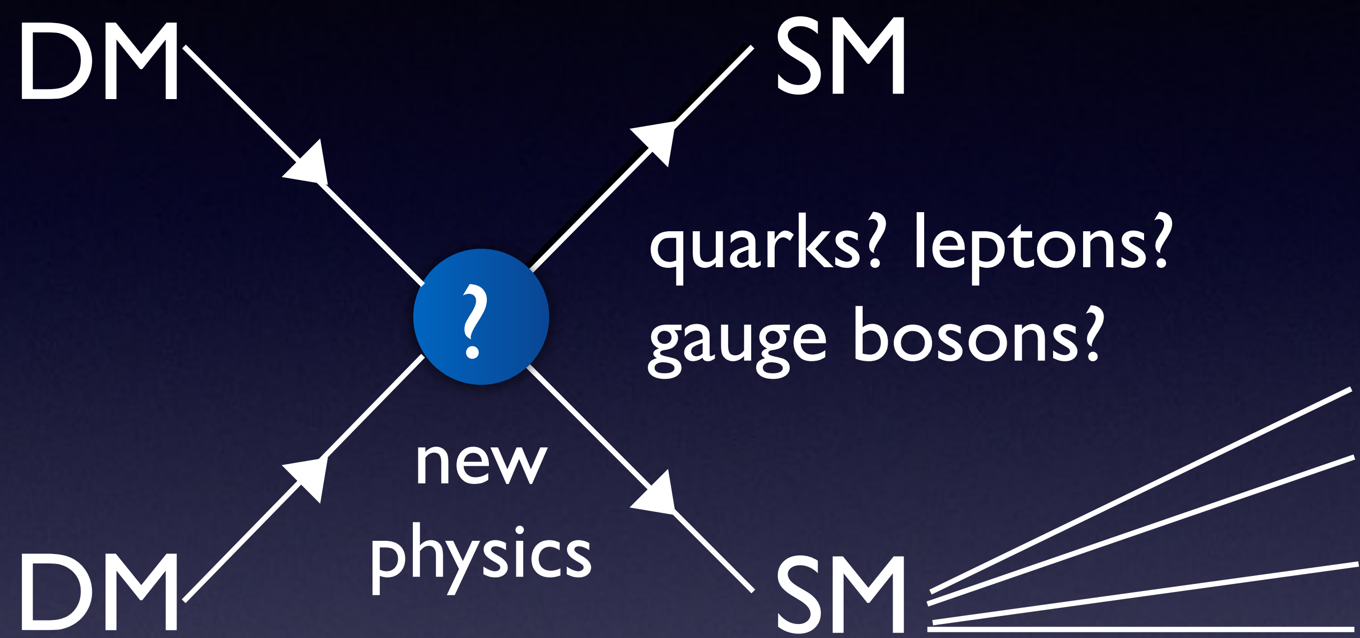
↓ Modify public recombination calculator (RECFAST, CosmoRec)

Cosmic ionization history

↓ Public CAMB/CLASS codes

Perturbations to CMB anisotropies

Annihilation



Cascading decays according to known SM processes

dark matter

known particles

long-lived known particles

$$\text{rate} = \frac{1}{2} n^2 \langle \sigma v \rangle = \frac{1}{2} \frac{\rho_{\text{today}}^2 \langle \sigma v \rangle}{m_\chi^2} (1+z)^6$$

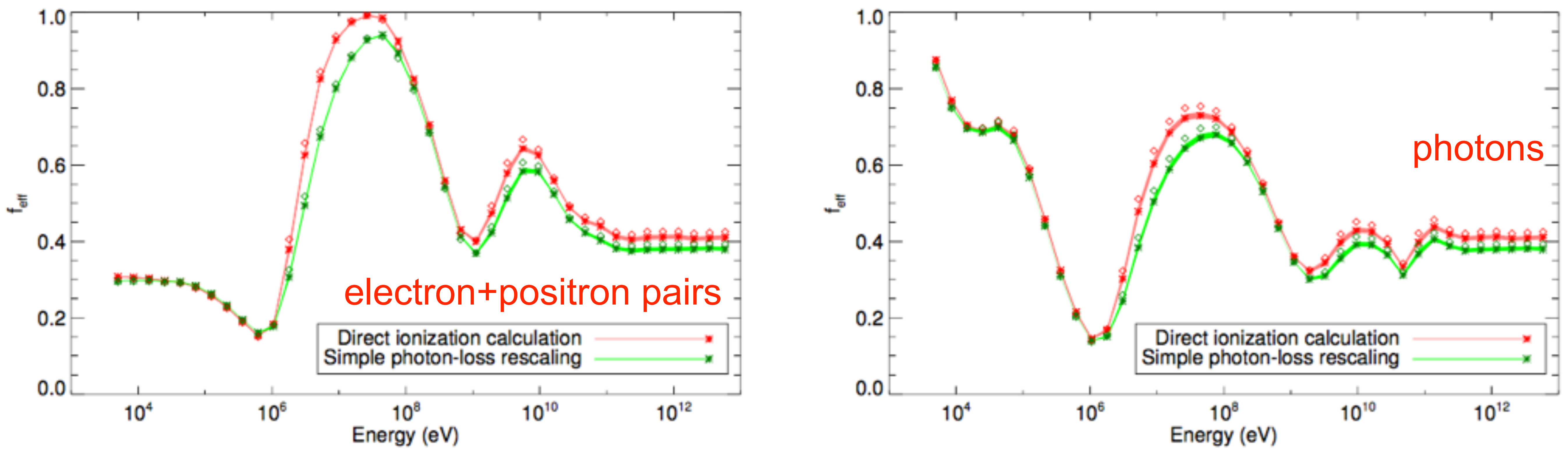
$$\text{energy injection} = \frac{\langle \sigma v \rangle}{m_\chi} \rho_{\text{today}}^2 (1+z)^6$$

spectrum of photons, positrons, electrons

(+ protons/antiprotons, but usually a small effect, see Weniger et al '13)

Efficiency factors

Phys. Rev. D 93, 023527 (2016)



- Result: all (s-wave, velocity-independent) annihilation, of keV-TeV DM, has the same effect on the CMB up to a normalization factor.
- We can compute this normalization/efficiency factor for all injection energies.
- Integrate over this curve to determine strength of CMB signal for arbitrary spectra of annihilation products.

Recipe for generic DM model

(with s-wave annihilation)

- Given DM mass and couplings, determine spectra of e+e- pairs and photons produced per annihilation:

$$\left(\frac{dN}{dE}\right)_\gamma, \left(\frac{dN}{dE}\right)_{e^+}$$

- Determine f_{eff} by average over photon and electron spectra:

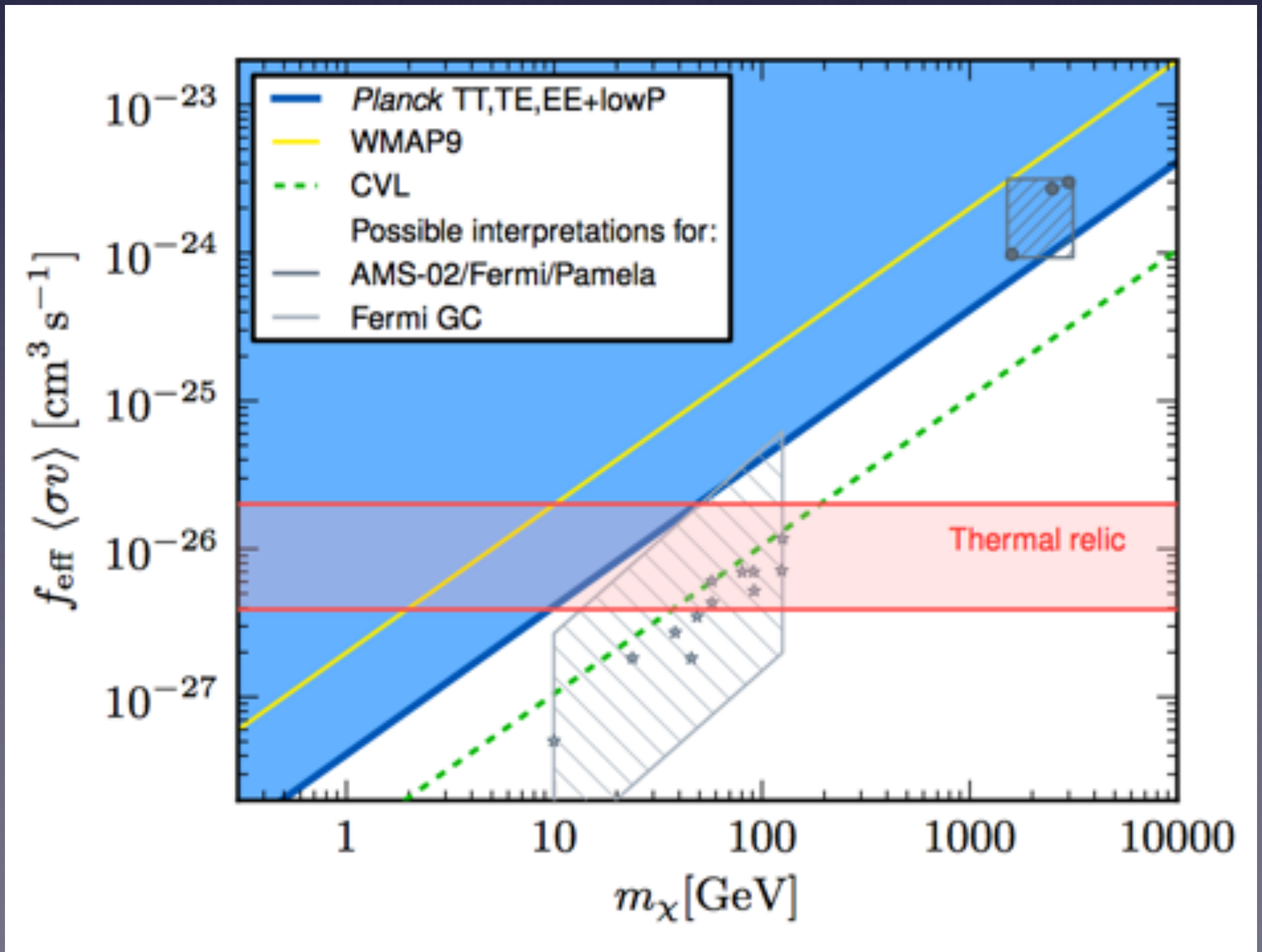
$$f_{\rm eff}(m_\chi) = \frac{\int_0^{m_\chi} E dE \left[2 f_{\rm eff}^{e^+e^-}(E) \left(\frac{dN}{dE}\right)_{e^+} + f_{\rm eff}^{\gamma}(E) \left(\frac{dN}{dE}\right)_\gamma\right]}{2m_\chi}$$

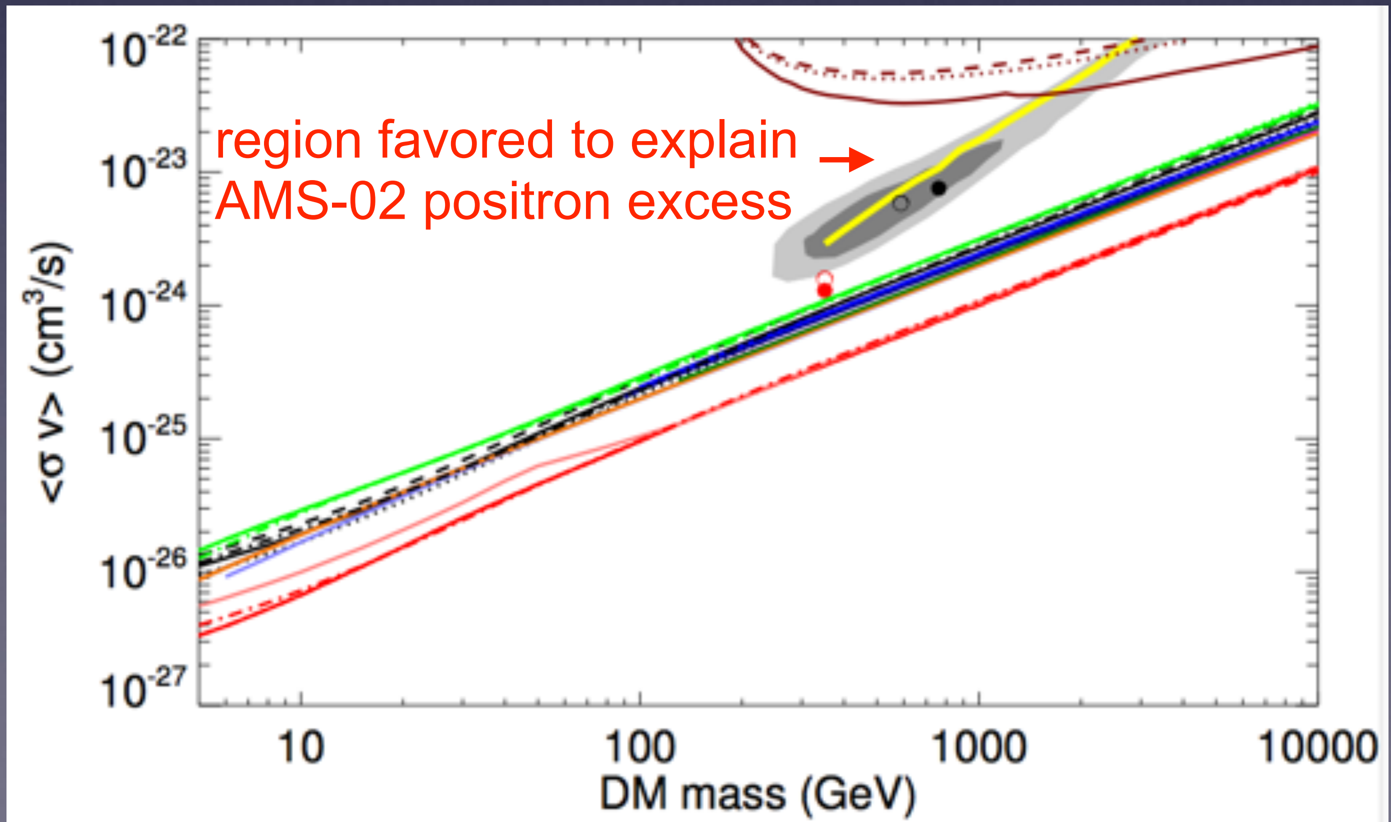
- Impose constraint derived by Planck team on annihilation parameter, via likelihood analysis:

$$f_{\rm eff} \frac{\langle \sigma v \rangle}{m_\chi} < 4.1 \times 10^{-28} {\rm cm}^3/{\rm s}/{\rm GeV}$$

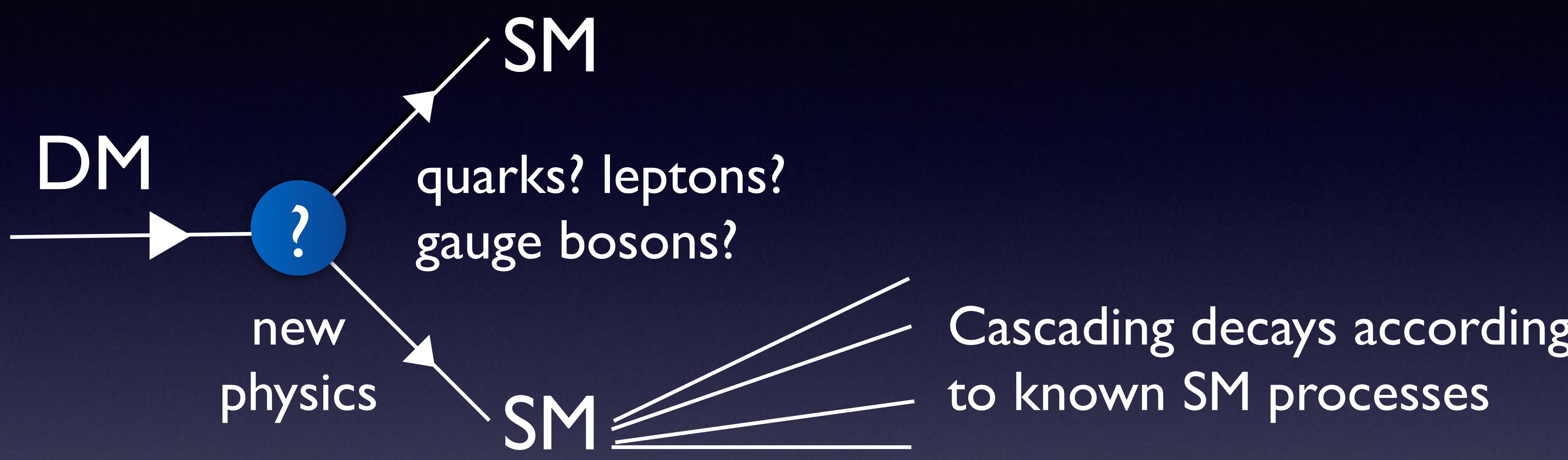
Limits from Planck

- Planck Collaboration '15 set bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 09.
- Left plot shows Planck bound, right plot shows resulting cross-section limits for a range of channels from Slatyer '15.
- These are general constraints; in terms of e.g. simple dark photon model, 1 GeV-100 TeV thermal-relic Dirac-fermion DM, annihilating into 1-100 MeV dark photons, appears to be ruled out (Cirelli et al 1612.07295).





Decay



dark matter → known particles

long-lived known particles → spectrum of photons, positrons, electrons

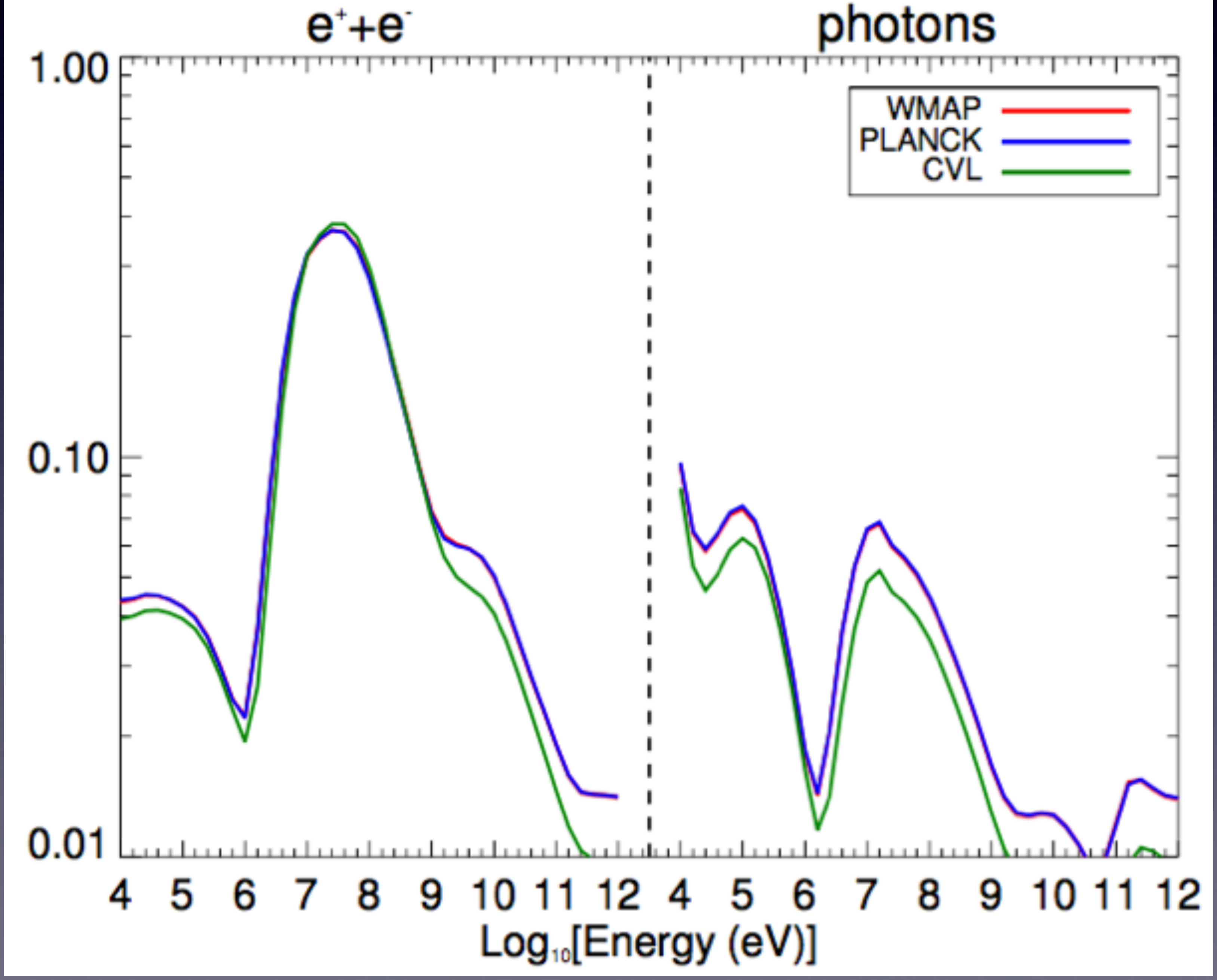
$$\text{rate} = \frac{n}{\tau} e^{-t/\tau} \approx \frac{\rho_{\text{today}}}{m_\chi \tau}(1+z)^3, \tau \gg t$$

$$\text{energy injection} \approx \boxed{\frac{1}{\tau}} \rho_{\text{today}}(1+z)^3, \tau \gg t$$

Efficiency factors (decay)

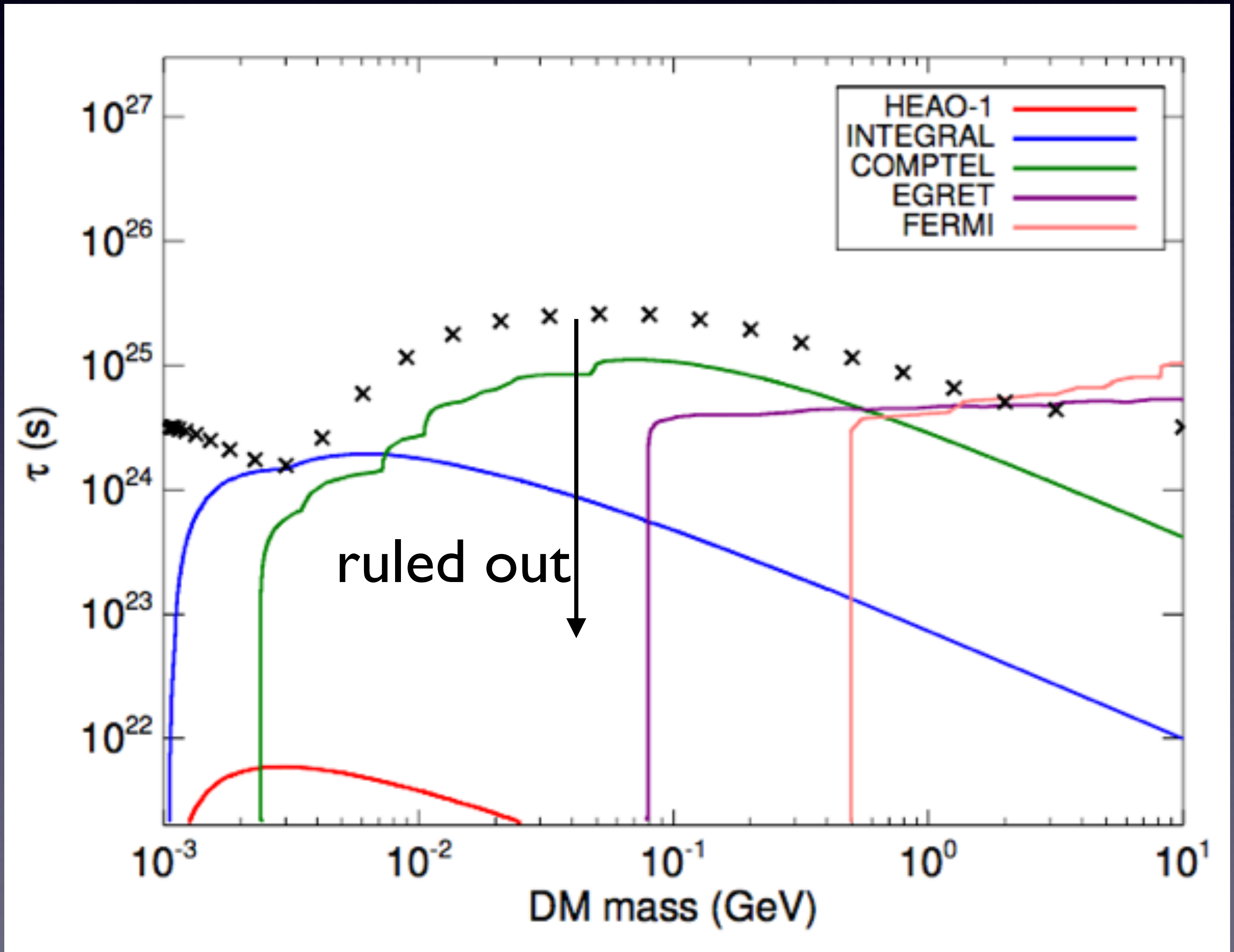
TRS and Wu, Phys. Rev. D 95, 023010 (2017)

- Can perform a similar analysis for decaying DM - again find a universal imprint on the CMB
- Can set constraints on DM decaying with a long lifetime, or other species decaying during the cosmic dark ages



Constraints on decay from Planck

- For long-lifetime decays, this method sets strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even 10^{-11} of the DM mass decaying (for lifetimes ~10^{14} s).
- See also Poulin et al 1610.10051.



Diffuse photon spectrum constraints from Essig et al '13

Complementarity

- These constraints are particularly effective, relative to other indirect searches:
  - For (annihilating) light dark matter
  - Where there is no telescope capable of seeing the bulk of the annihilation/decay products, due to their energy/spectrum; CMB acts ~as calorimeter
  - If annihilation/decay proceeds through intermediate dark-sector states, softening/broadening spectrum
  - When annihilation is enhanced at low velocities (e.g. by long-range interactions due to a light mediator, and/or formation of bound states)
  - If decay from a metastable state occurs during the cosmic dark ages; not observable today.
- They fail when (for example):
  - The (annihilating) DM is too heavy
  - Annihilation/decay is primarily to neutrinos
  - Annihilation is suppressed at low velocities / late times (as discussed this morning)

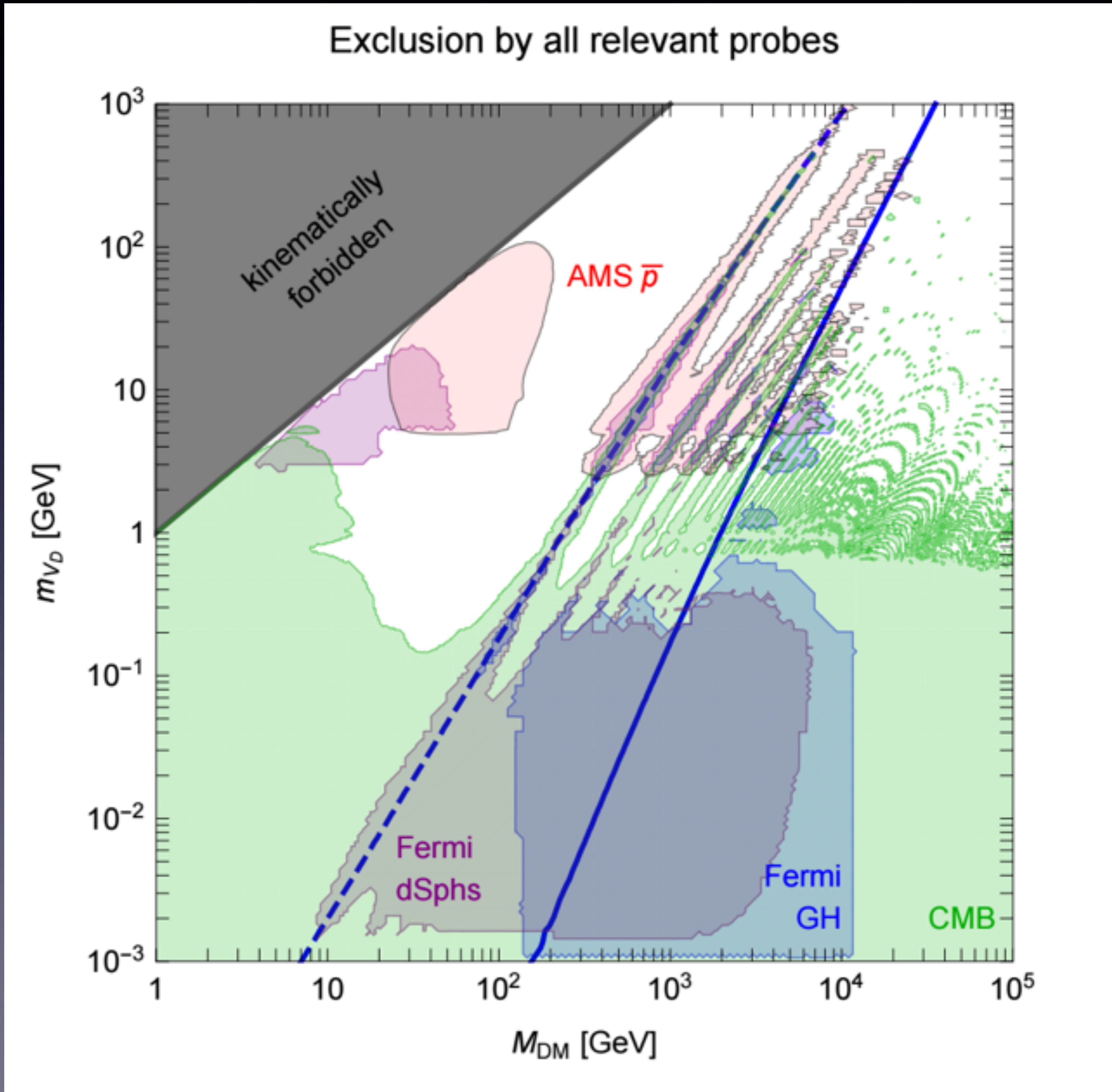
Ongoing work

- Exploring signatures beyond extra ionization: heating, distortion of the CMB energy spectrum.
- Accurate treatment of reionization epoch (initial work in Liu et al '16, & also by other groups).
- Could the heating of the universe by dark matter leave observable signatures in the 21cm line? (e.g. Evoli et al '14, Lopez-Honorez et al '16)
- Current assumption: all annihilation/decay products escape from the halos where DM is most dense.
  - Known to be not completely true - what are the effects on halos?
  - Could star formation history etc be affected?
- Exploring the sub-keV regime.
- Goal: comprehensive understanding of the possible effects of DM annihilation/decay in the early universe.

BONUS SLIDES

CMB constraints on dark photons

- Taken from Cirelli et al 1612.07295.
- Green region ruled out by CMB, assuming DM is a thermal relic and main annihilation channel is to dark photons (sets DM-dark photon coupling).
- Gray region = kinematically forbidden.
- Blue lines = boundary of region where bound states (a) exist and (b) are accessible by a dipole radiative transition.



CMB constraints on short-lifetime decays

- Long-lived particles could decay completely during cosmic dark ages
- Alternatively, decays from a metastable state to the final DM state could liberate some fraction of the DM mass energy
- CMB constrains the amount of power converted to SM particles in this way; width of band reflects variation with energy of SM products

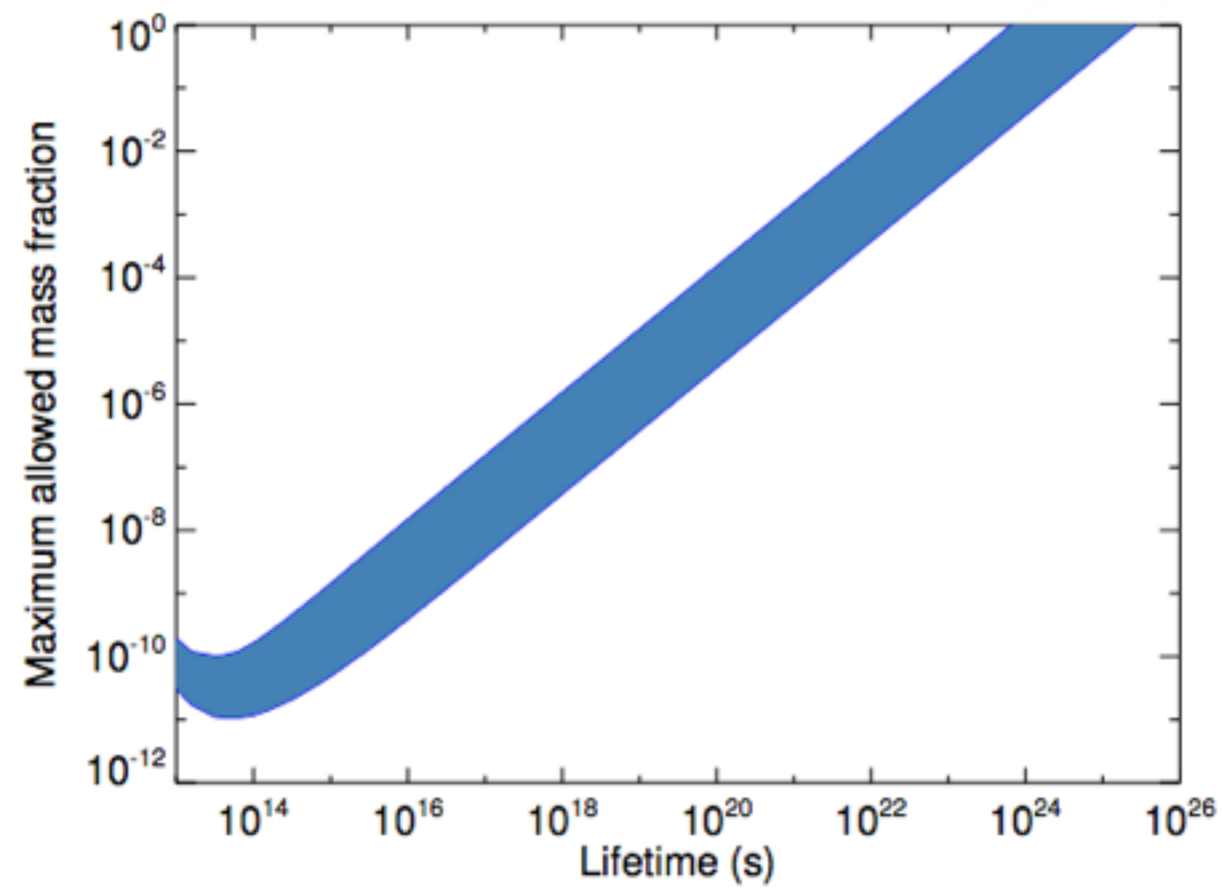
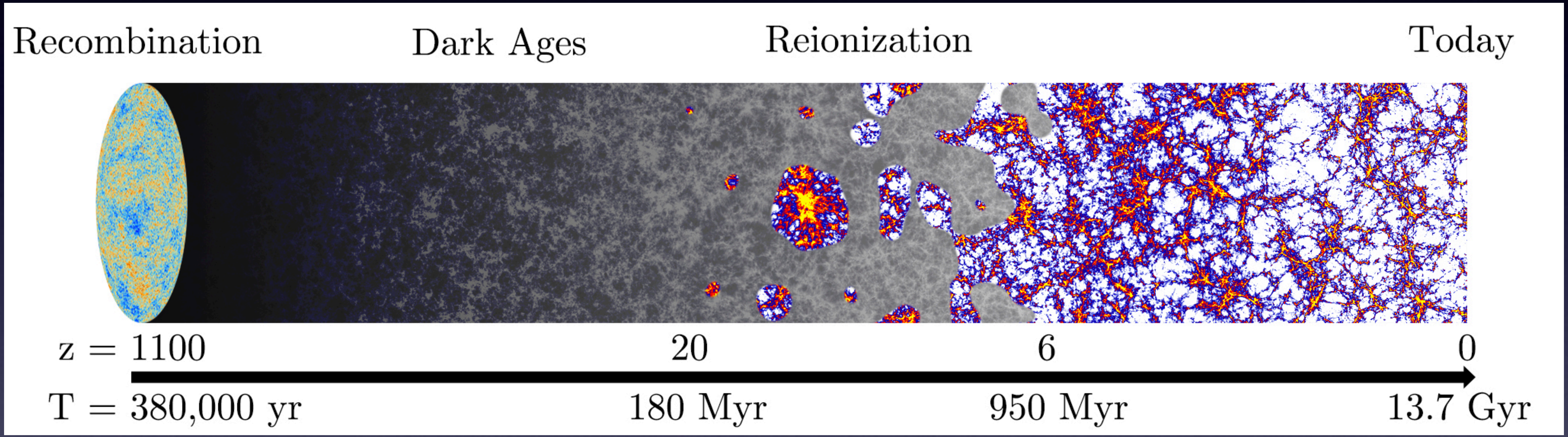


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime τ, for injections of 10 keV – 10 TeV photons and e^+e^- pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the MCMC bound for our reference model.

The epoch of reionization

Liu, TRS & Zavala PRD '16



- Around z~6-10, the universe became ~fully ionized again.
- Can DM annihilation or decay affect reionization?
- Can it affect the thermal history of our cosmos? Could DM annihilation/decay overheat the universe?

What we know about reionization

- Most recent results from Planck, May 2016, for cosmic reionization optical depth:

$$\tau = 0.058 \pm 0.012$$

- "The average redshift at which reionization occurs is found to lie between z = 7.8 and 8.8, depending on the model of reionization adopted… in all cases, we find that the Universe is ionized at less than the 10% level at redshifts above z =10."
- What limits does this set on DM annihilation? To what degree could DM contribute to the ionization history around reionization, consistent with these (and other) bounds?

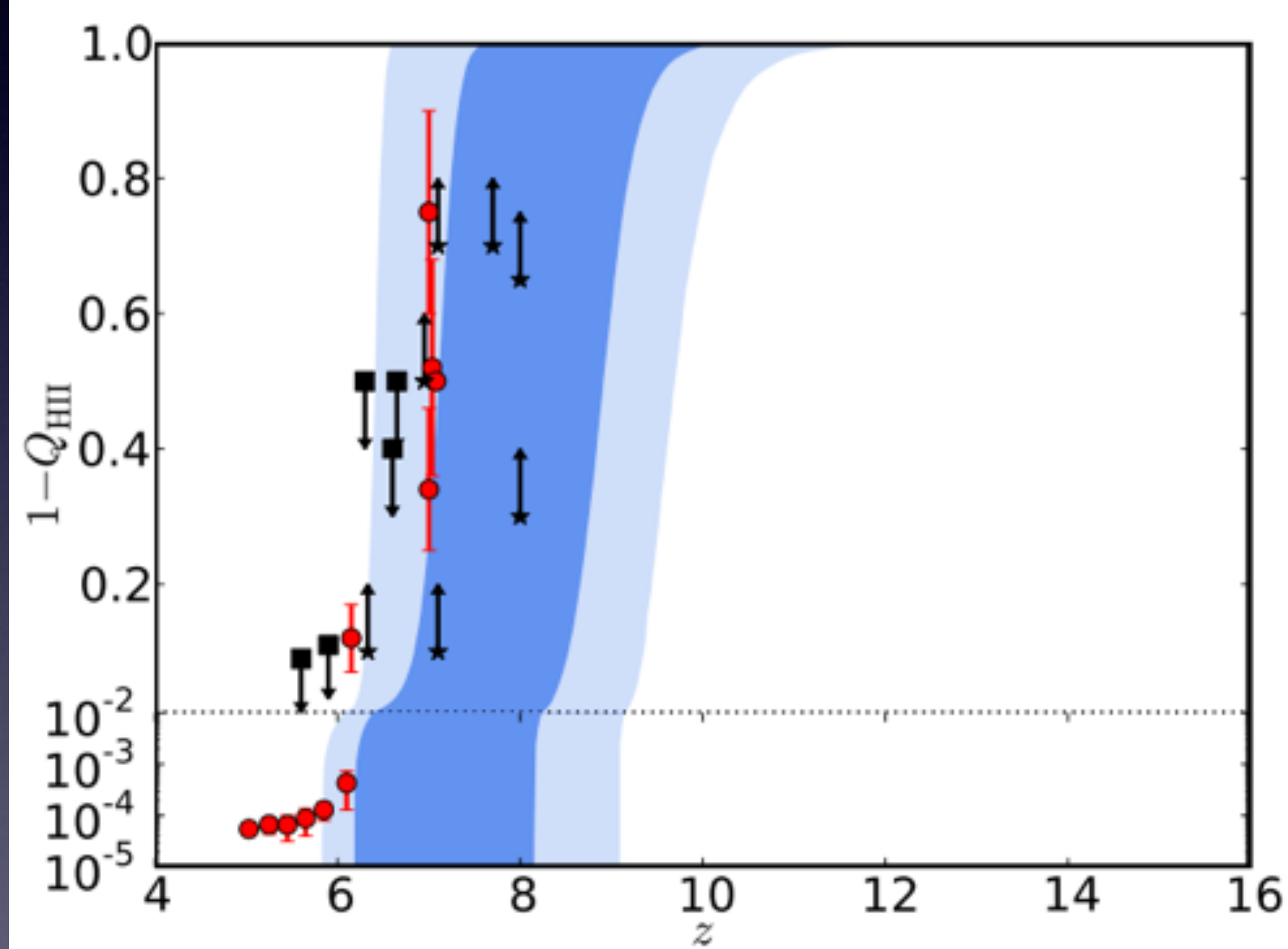


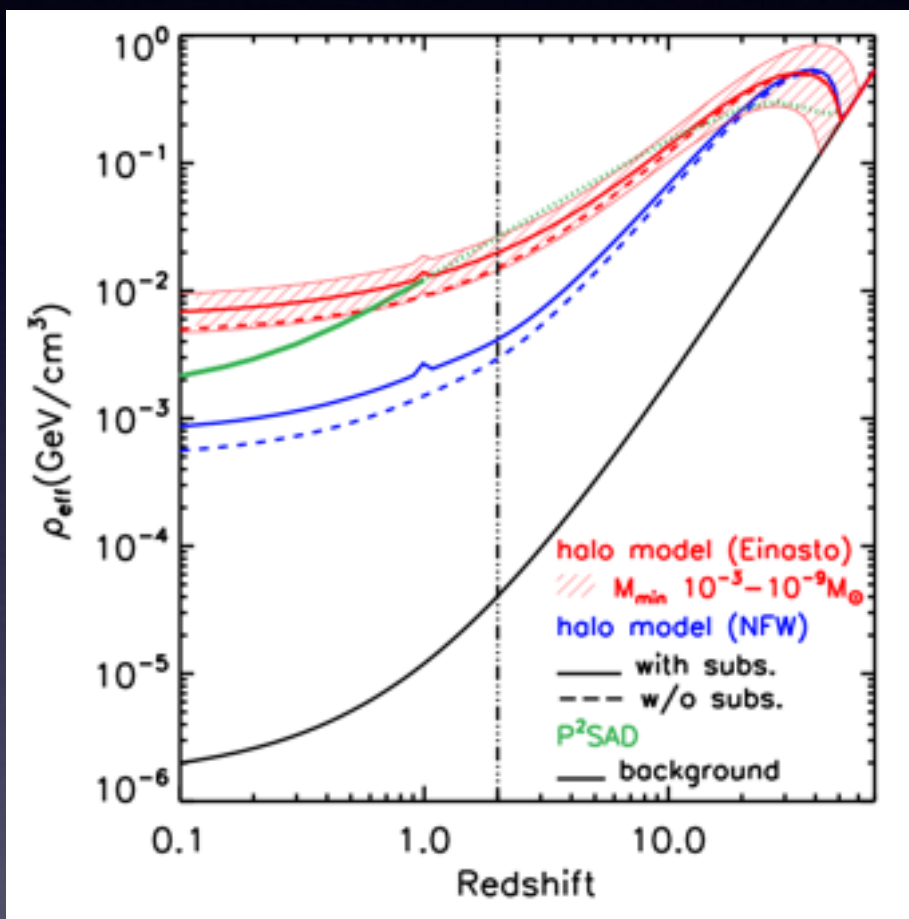
Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints compiled by Bouwens et al. (2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the 68 % and 95 % allowed intervals, respectively.

DM annihilation/decay in the epoch of reionization

- Previous studies include Belikov & Hooper 09, Cirelli et al 09, Diamanti et al 13, Poulin et al 15.
- We consider decays, s-wave annihilation, p-wave annihilation (velocity suppressed).
- Model dark matter structure formation at lower redshifts.
- Study heating of universe at redshifts < 10; understand impact of reionization on the cooling of annihilation products.
- Consider keV-TeV annihilation products, for ~model-independent results.
- Account for a range of independent constraints.

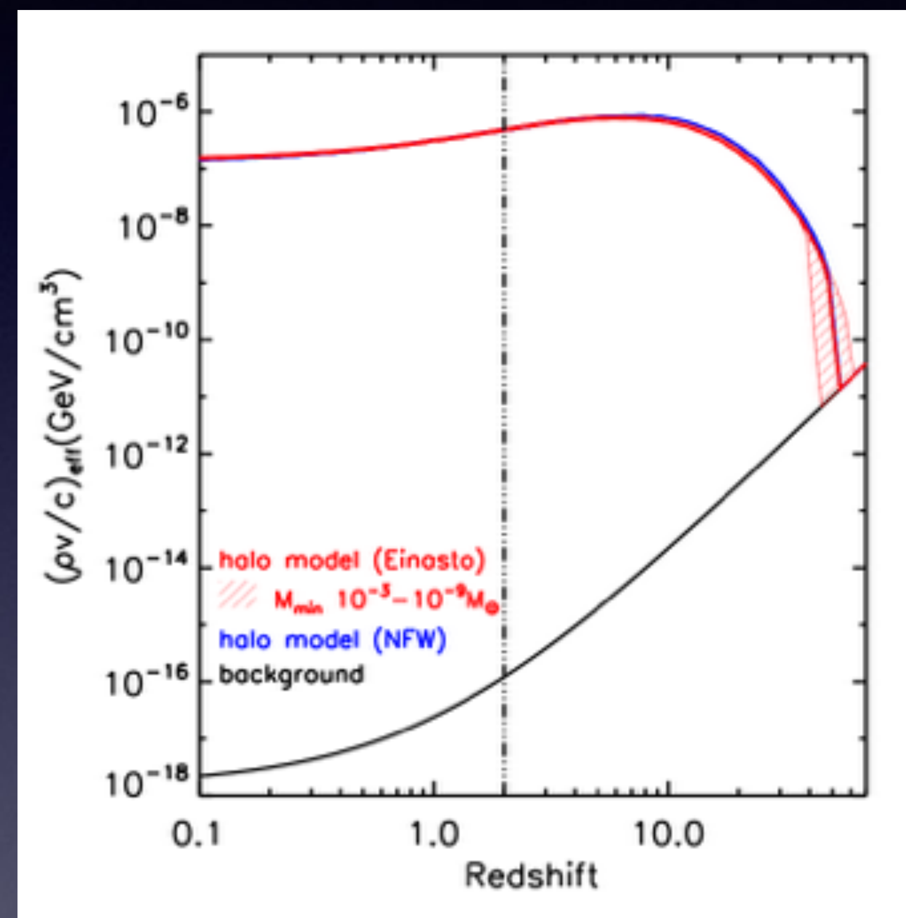
s-wave annihilation

$$\text{rate} \propto \rho^2$$



p-wave annihilation

$$\text{rate} \propto \rho^2 v^2$$



decay

$$\text{rate} \propto \frac{\rho}{\tau} e^{-t/\tau}$$

assume τ >> age of universe, rate follows DM density

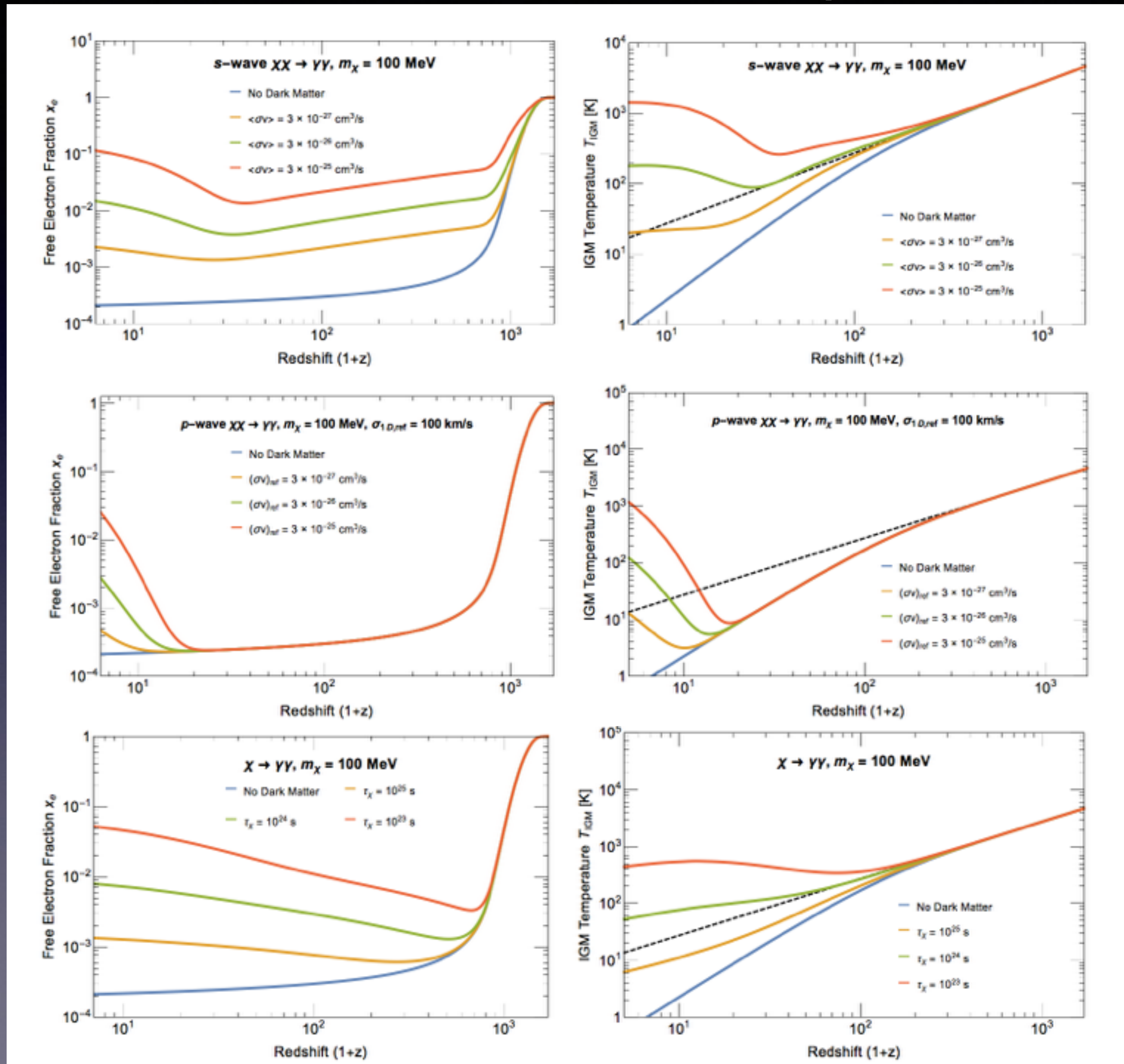
colored curves show effective average ρ, ρv, accounting for structure formation ionization

temperature

s-wave annihilation

p-wave annihilation

decay



Constraints

- CMB anisotropy bounds (discussed earlier) - limits changes to ionization history at high redshift. Strongly constrains s-wave annihilation, but less important for p-wave annihilation & decay.
- Total optical depth - limits integrated changes to ionization history. We used new Planck optical depth measurement and the fact that the universe is fully ionized after z=6:

$$\tau = 0.058 \pm 0.012, \quad \tau(z < 6) = 0.038, \quad \tau(z > 6) \leq 0.044 (2\sigma)$$

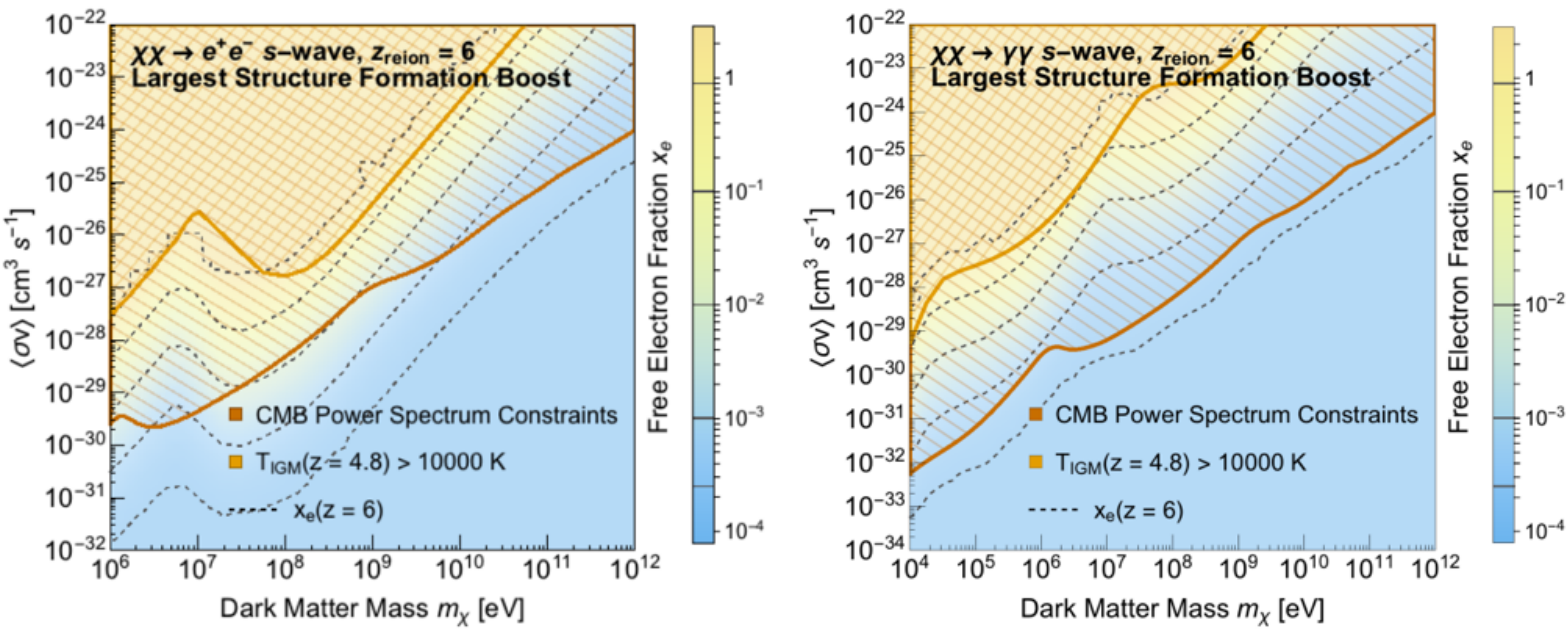
- Temperature after reionization (Becker et al '11, Bolton et al '11):

$$\log_{10}\left(\frac{T_{\mathrm{IGM}}(z = 6.08)}{\mathrm{K}}\right) \leq 4.21^{+0.06}_{-0.07} \qquad \log_{10}\left(\frac{T_{\mathrm{IGM}}(z = 4.8)}{\mathrm{K}}\right) \leq 3.9 \pm 0.1$$

- + bounds on decay and annihilation from present-day measurements of photon flux

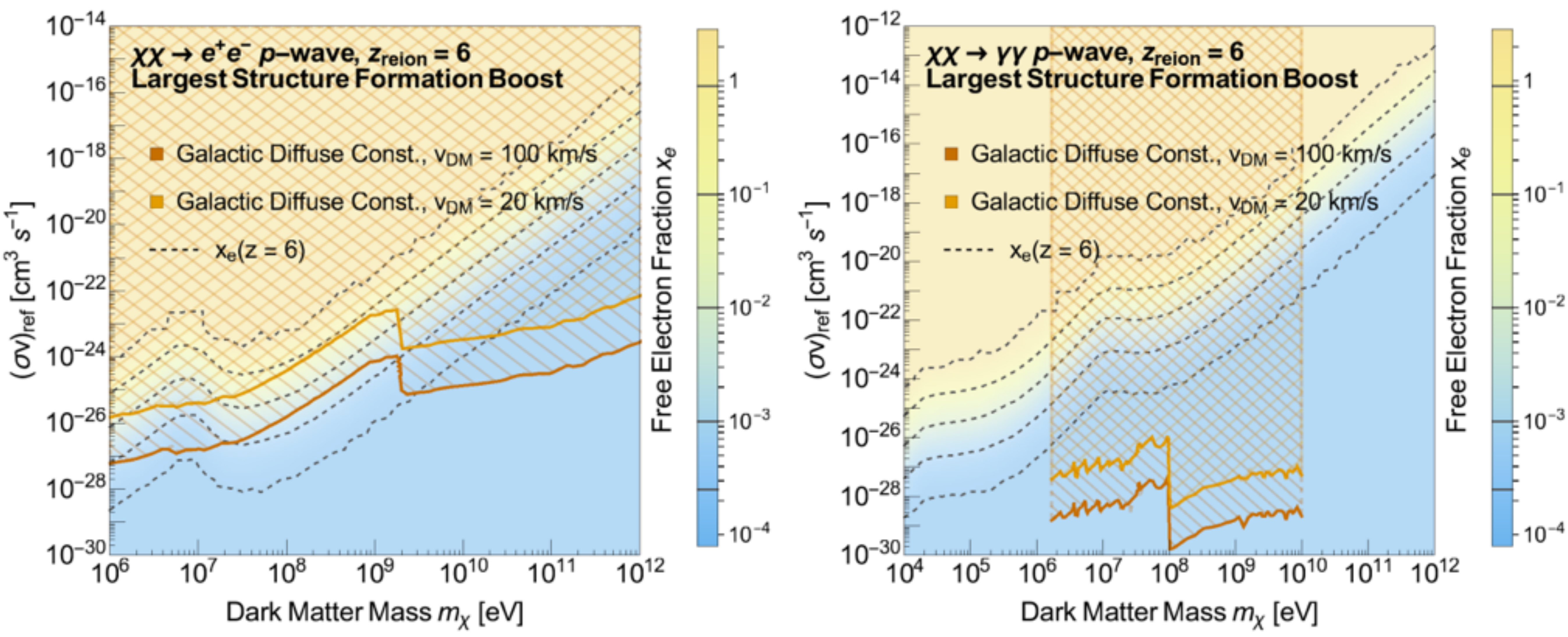
Cross-section limits

- For s-wave annihilation, CMB anisotropy bounds dominate those from optical depth and temperature.
- Black dotted lines give contribution to ionization fraction at reionization; from bottom to top they correspond to 0.025%, 0.1%, 1%, 10% and 90%.
- CMB anisotropy bounds force contribution to ionization fraction at reionization to be sub-percent.



Cross-section limits

- For p-wave annihilation, bounds from present-day searches (e.g. Galactic diffuse emission) provide strongest limits, in energy regions where telescopes have sensitivity (Essig et al '13, Albert et al '14, Boddy & Kumar '15).
- In other regions, temperature bounds can be important.
- Demanding thermal relic cross sections would set stronger limits, i.e. the relevant cross-sections are >> thermal.



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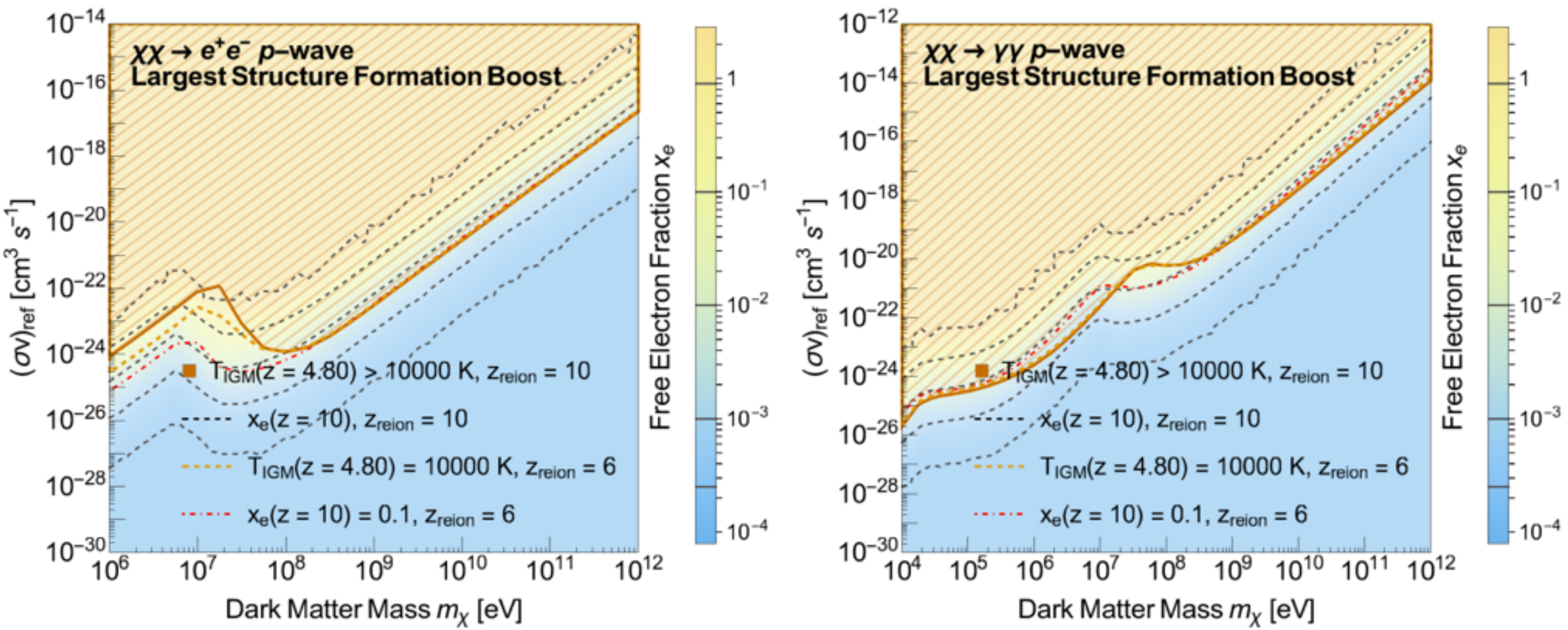
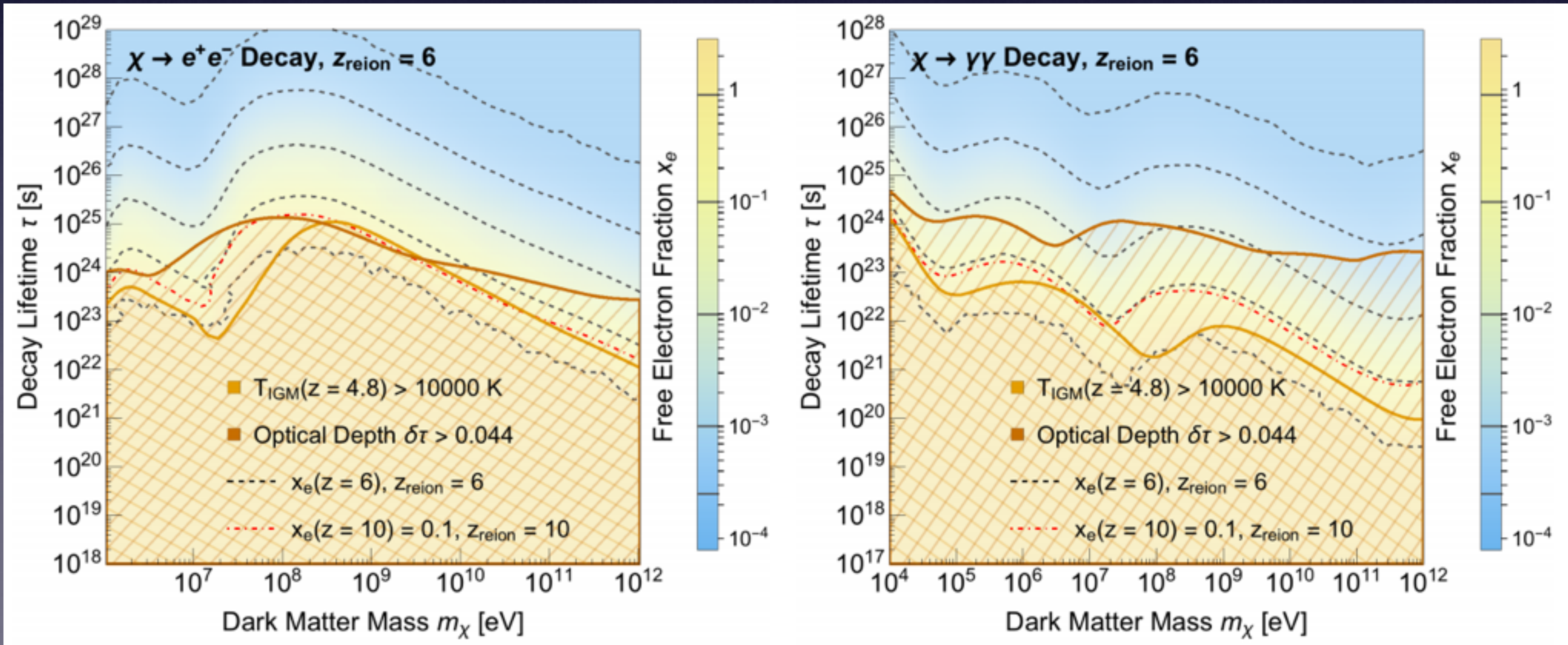


Lifetime limits

- For decay, bounds from optical depth, temperature and present-day diffuse photon searches are competitive (at least for light DM decaying to electrons).
- Photon-rich channels are more constrained generally (there are also present-day bounds not shown on this plot, but early-universe bounds are sufficient to rule out any large contribution to reionization).



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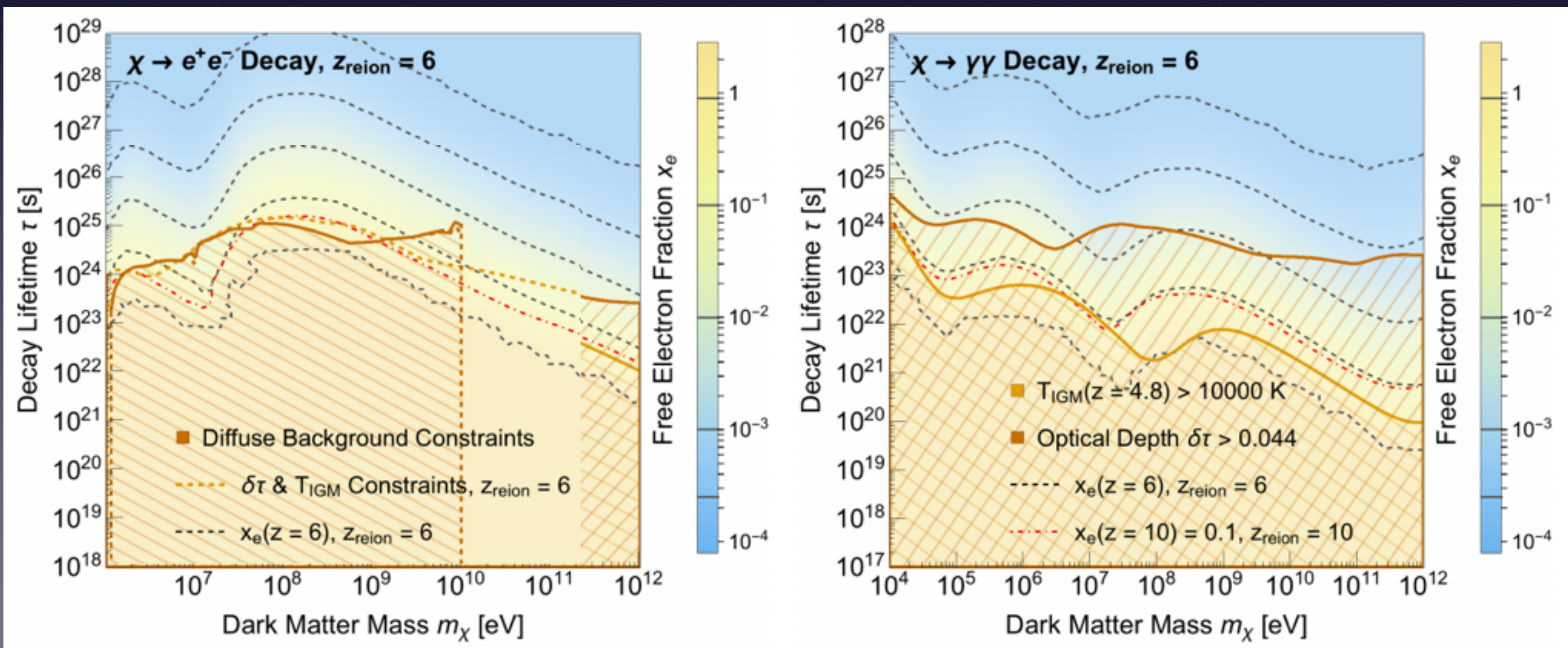

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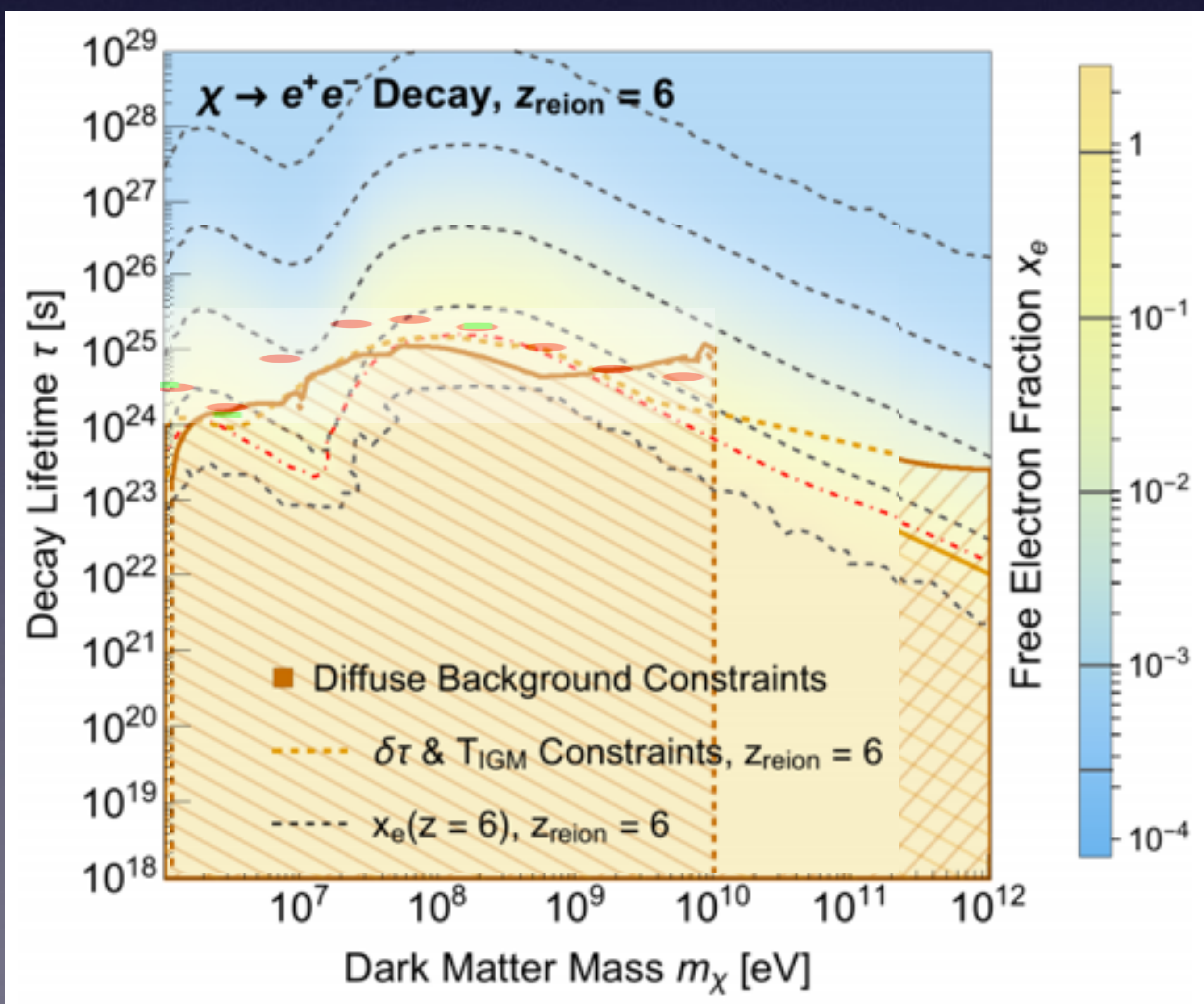
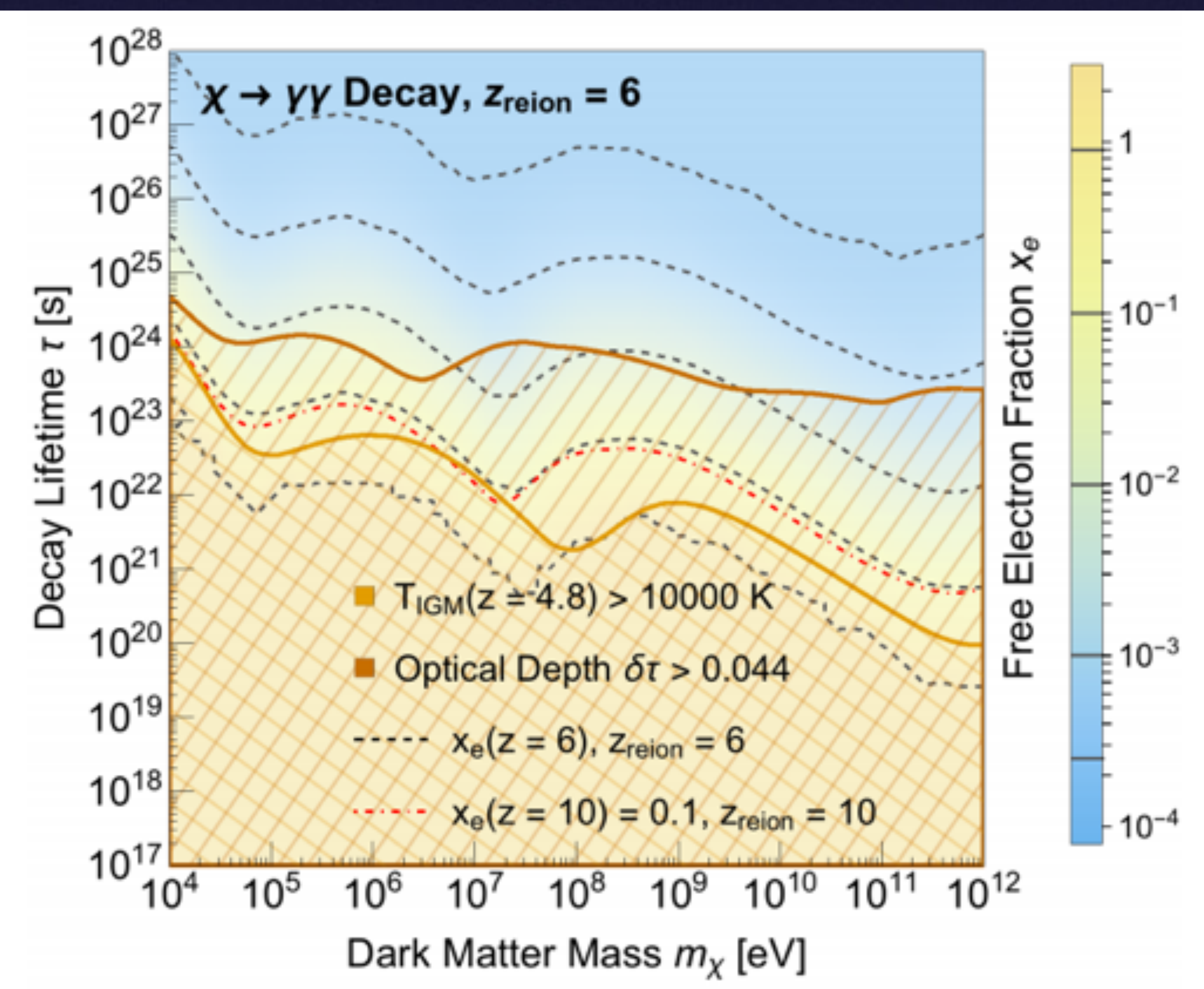
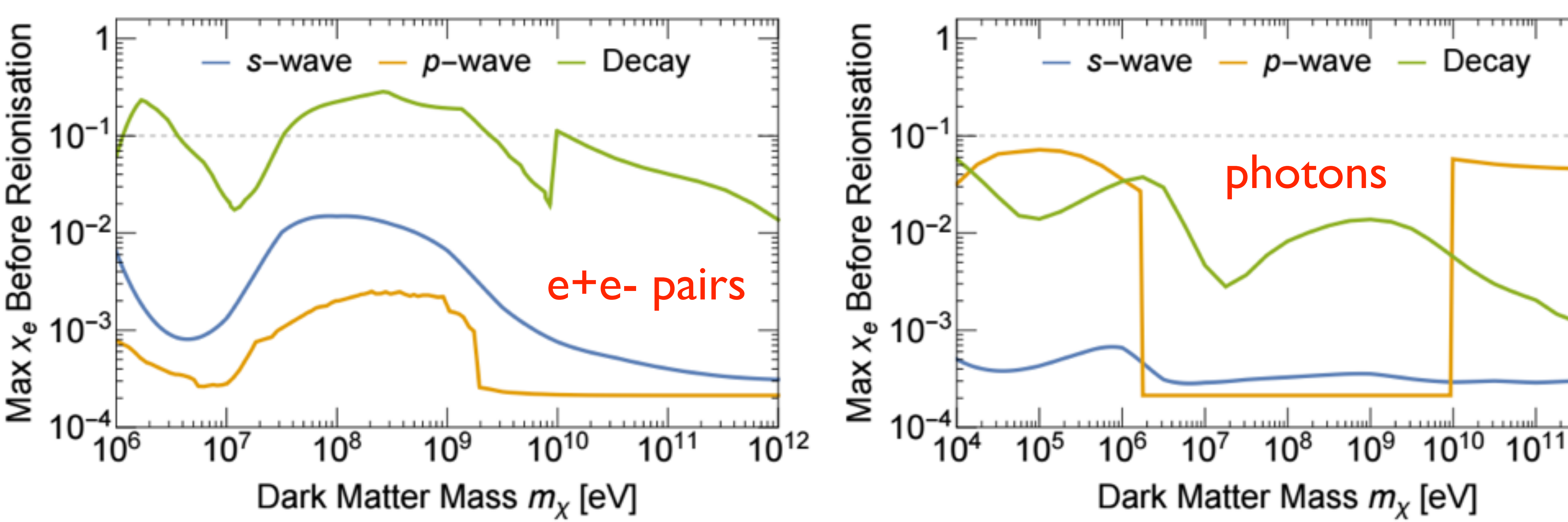


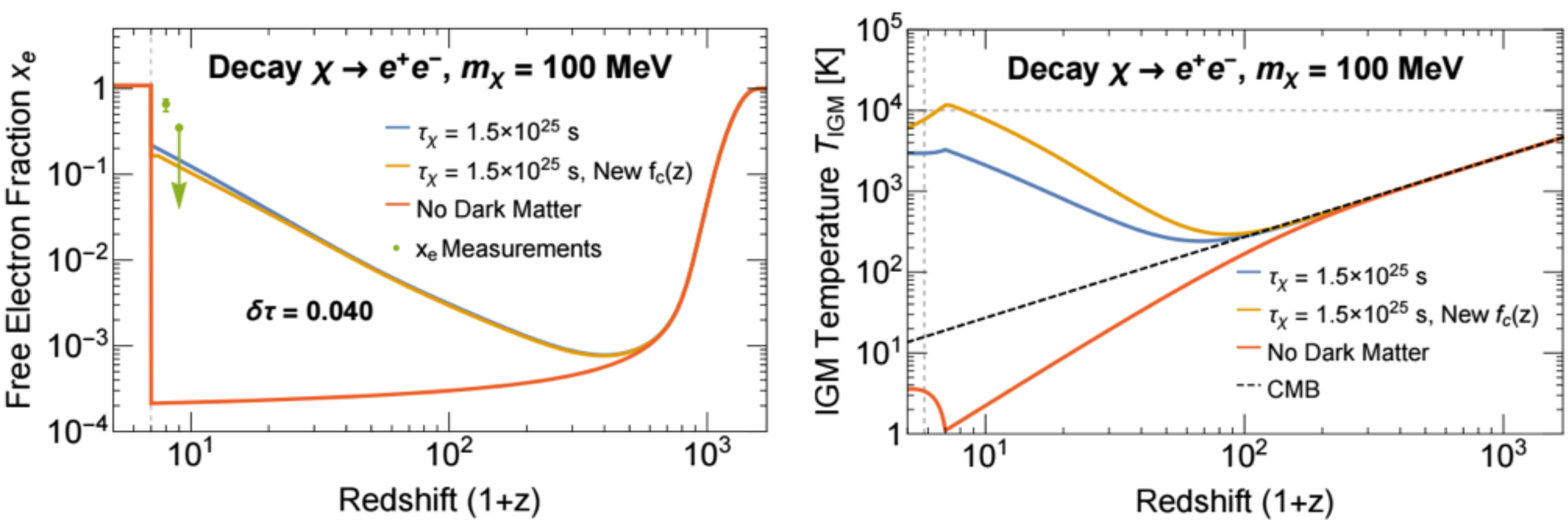


Can DM reionize the universe?



- Even with very conservative constraints we have taken, answer appears to be "no"
- Note: these figures do not always show the strongest possible bounds; for this figure, once we had established the DM contribution could not be above the few-percent level from the conservative bounds we had considered, we did not include other - potentially stronger - limits (e.g. light DM decaying to photons has strong bounds from Galactic observations)
- Light DM decaying to electron/positron pairs with lifetime $O(10^{25}$ s) could potentially give a significant contribution, at the O(10%) level - however, may be ruled out by updated CMB limits, or less conservative temperature bounds.

An example scenario



- Ex: 100 MeV DM decaying to e^+e^- pairs
- Marginally allowed by conservative constraints - likely ruled out by more realistic temperature bounds (and preliminarily, possibly by bounds from CMB anisotropy).