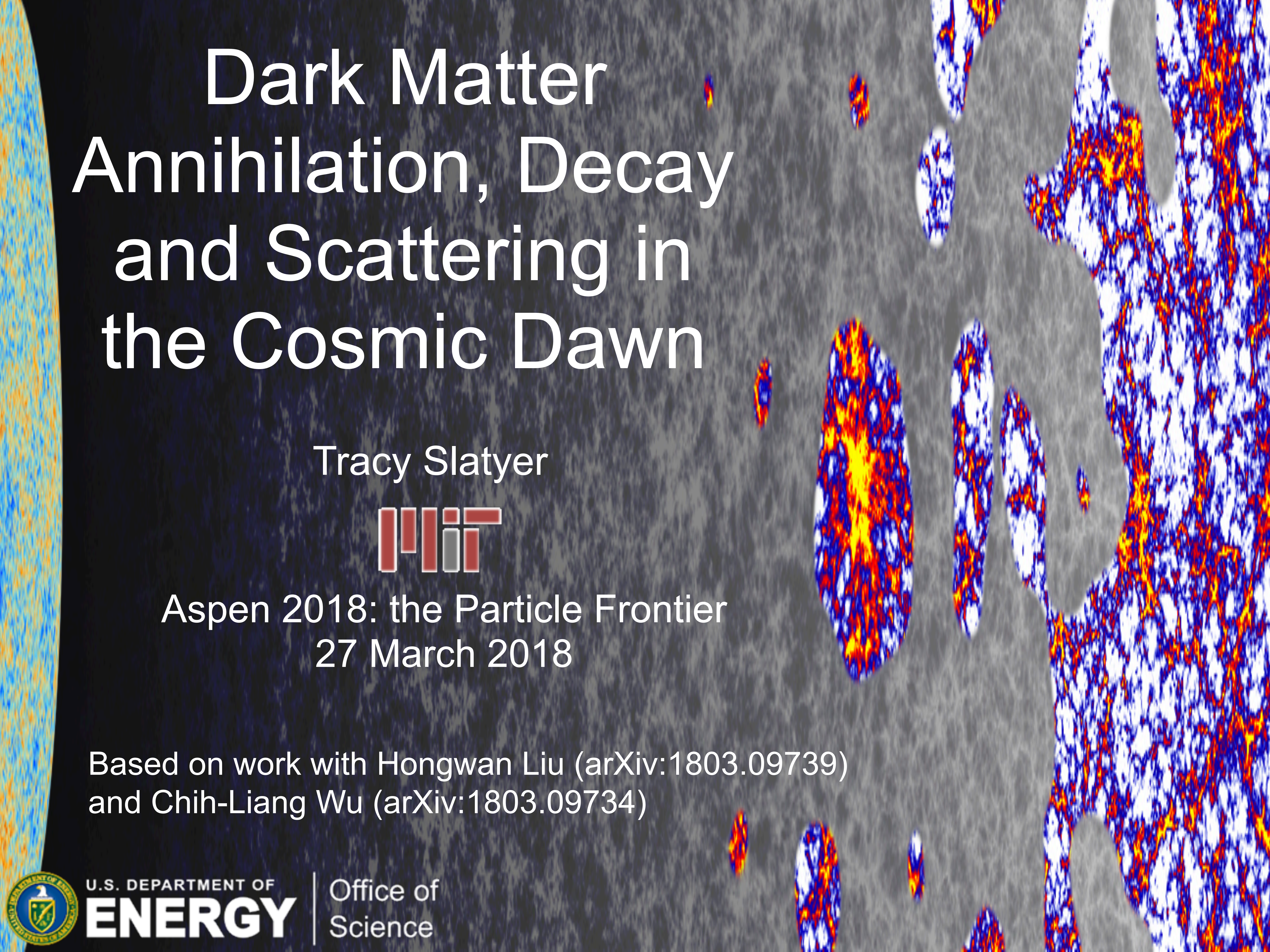


Dark Matter Annihilation, Decay and Scattering in the Cosmic Dawn

Tracy Slatyer

Aspen 2018: the Particle Frontier
27 March 2018

Based on work with Hongwan Liu (arXiv:1803.09739)
and Chih-Liang Wu (arXiv:1803.09734)

U.S. DEPARTMENT OF
ENERGY
Office of
Science

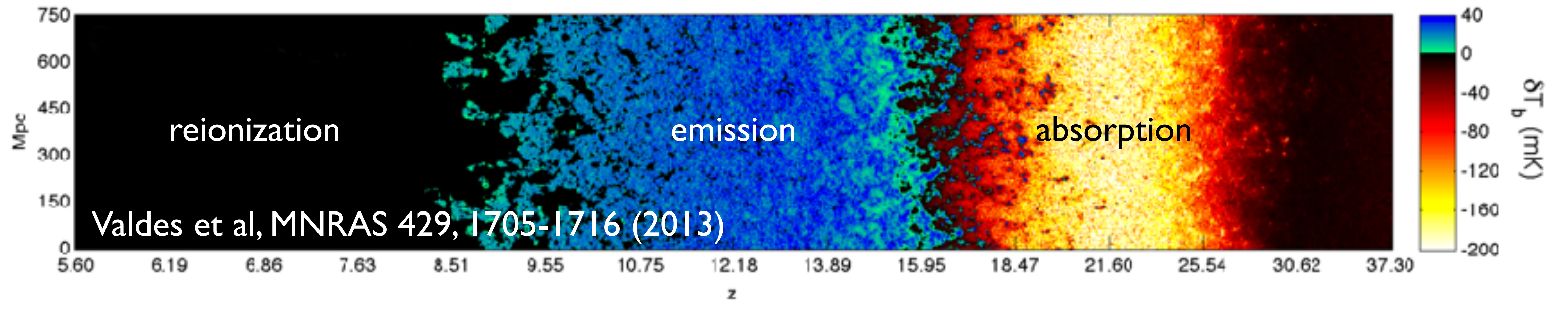
Outline

- Background: 21cm observations
- Claimed observation of an absorption trough by EDGES
- Possible interpretations
- Tests of DM-scattering interpretations
- What we can learn about DM annihilation/decay

Parametrics of a 21cm signal

$$T_{21}(z) \approx x_{\rm HI}(z)\left(\frac{0.15}{\Omega_m}\right)^{1/2}\left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2}\left[1-\frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

- Spin-flip transition of neutral hydrogen can be used to probe temperature and distribution of the neutral gas in the early universe prior to reionization ($z > 7$ or so).
- 21cm absorption/emission signal strength depends on “spin temperature” T_S, measure of #H in ground vs excited state - expected to lie between gas temperature T_{gas} and CMB temperature T_{CMB}.
- Absorption signal when $T_S < T_R$ (radiation temperature), emission signal if $T_S > T_R$.
- T_R here describes # photons at 21cm wavelength - not necessarily thermally distributed.
- Expected behavior: T_{gas} decouples from T_{CMB} around redshift $z \sim 150$, subsequently satisfies $T_{gas} \sim T_{CMB} (1+z)/(1+z)_{dec}$. Gas is later heated by the stars, and eventually T_{gas} increases above T_{CMB}. Thus expect early absorption, later emission.

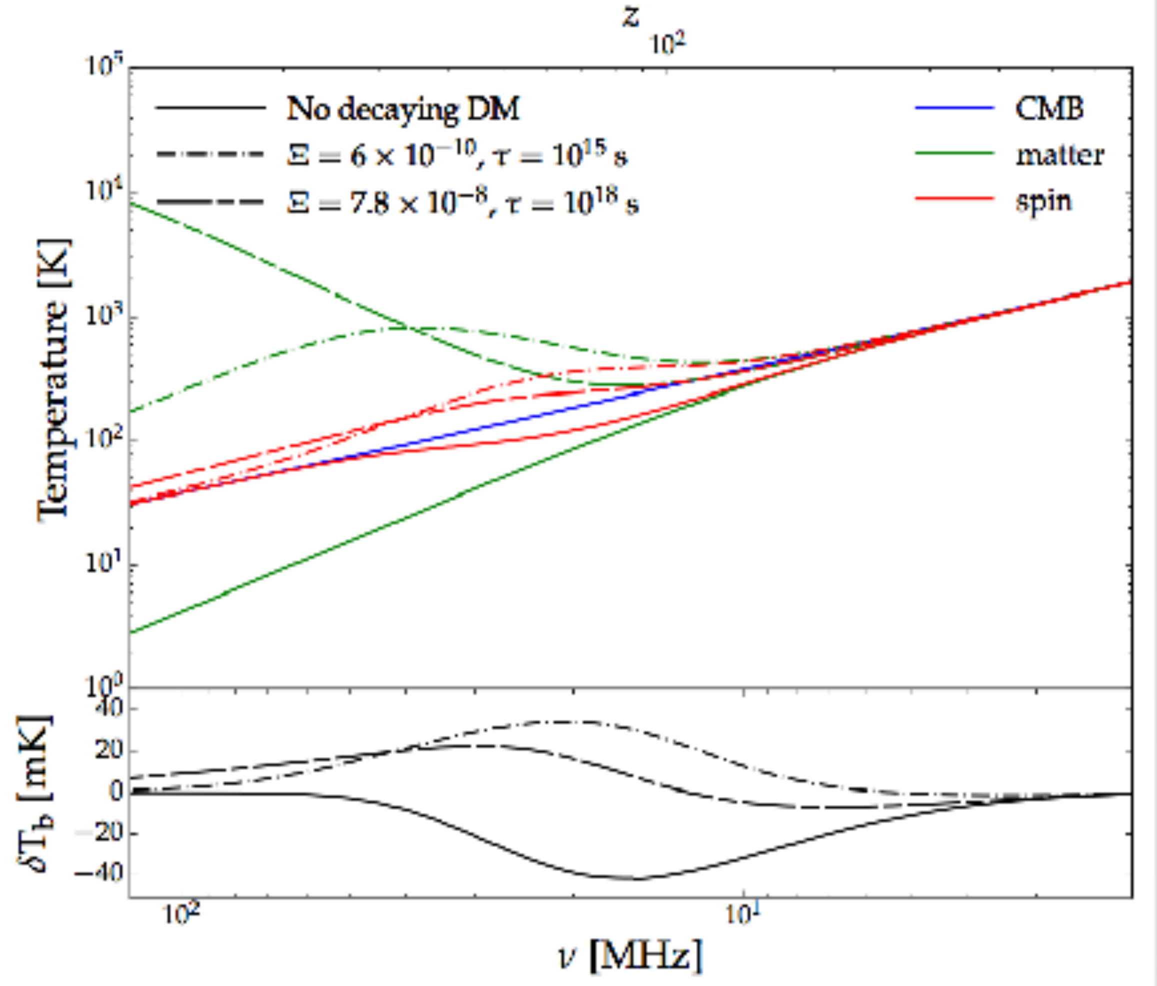


Valdes et al, MNRAS 429, 1705-1716 (2013)

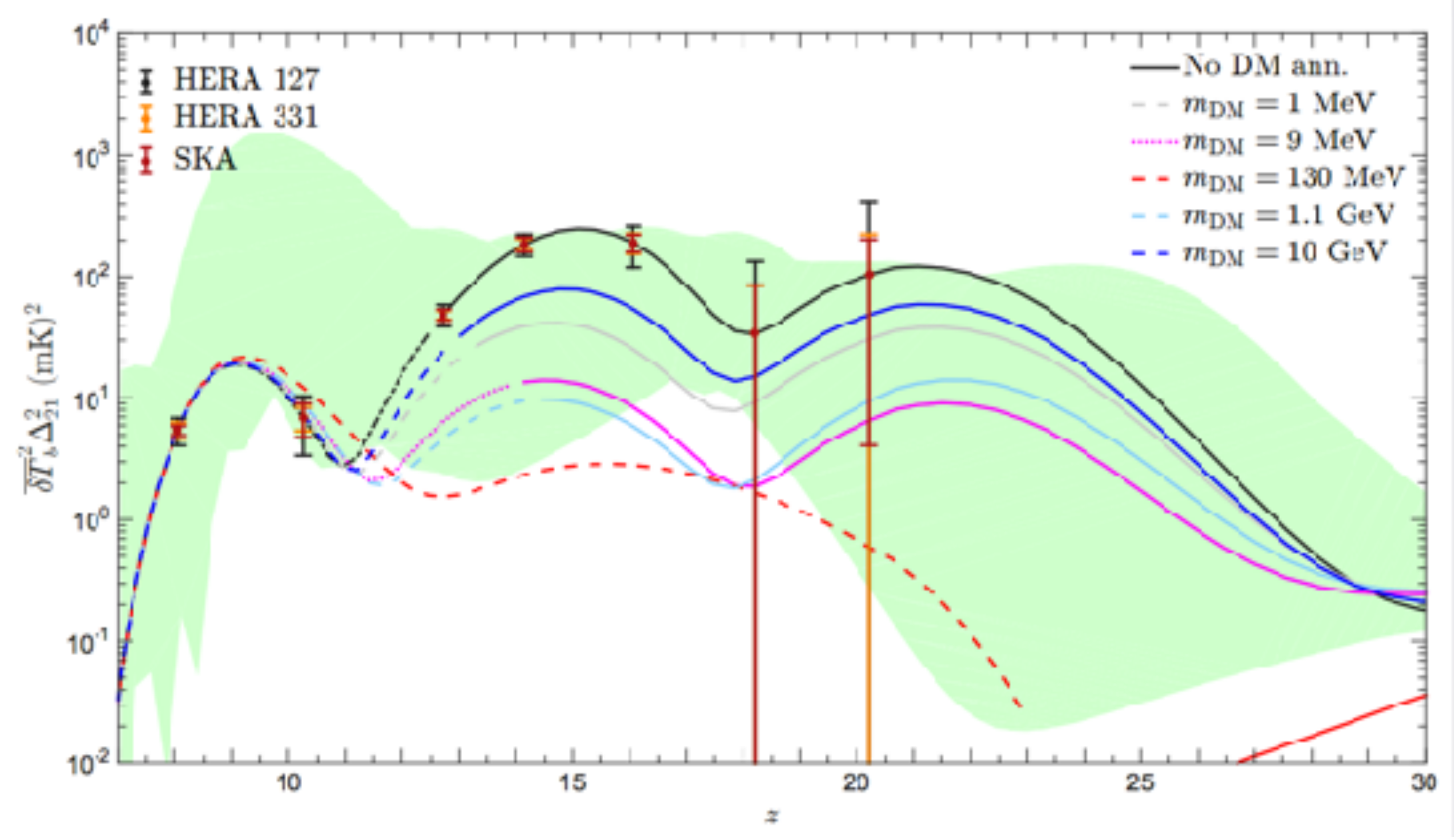
21cm signals from decay/annihilation

- Dark matter decay or annihilation can produce secondary particles that can heat the gas (also produce extra ionization, extra photons, etc).
- Can serve as an early source of heating, causing 21cm emission (not absorption) at unexpectedly early times (z~20-25 for decaying DM).
- Annihilation case more challenging, but (at least for some DM masses) could potentially leave unique signatures.

Poulin et al JCAP03(2017)043

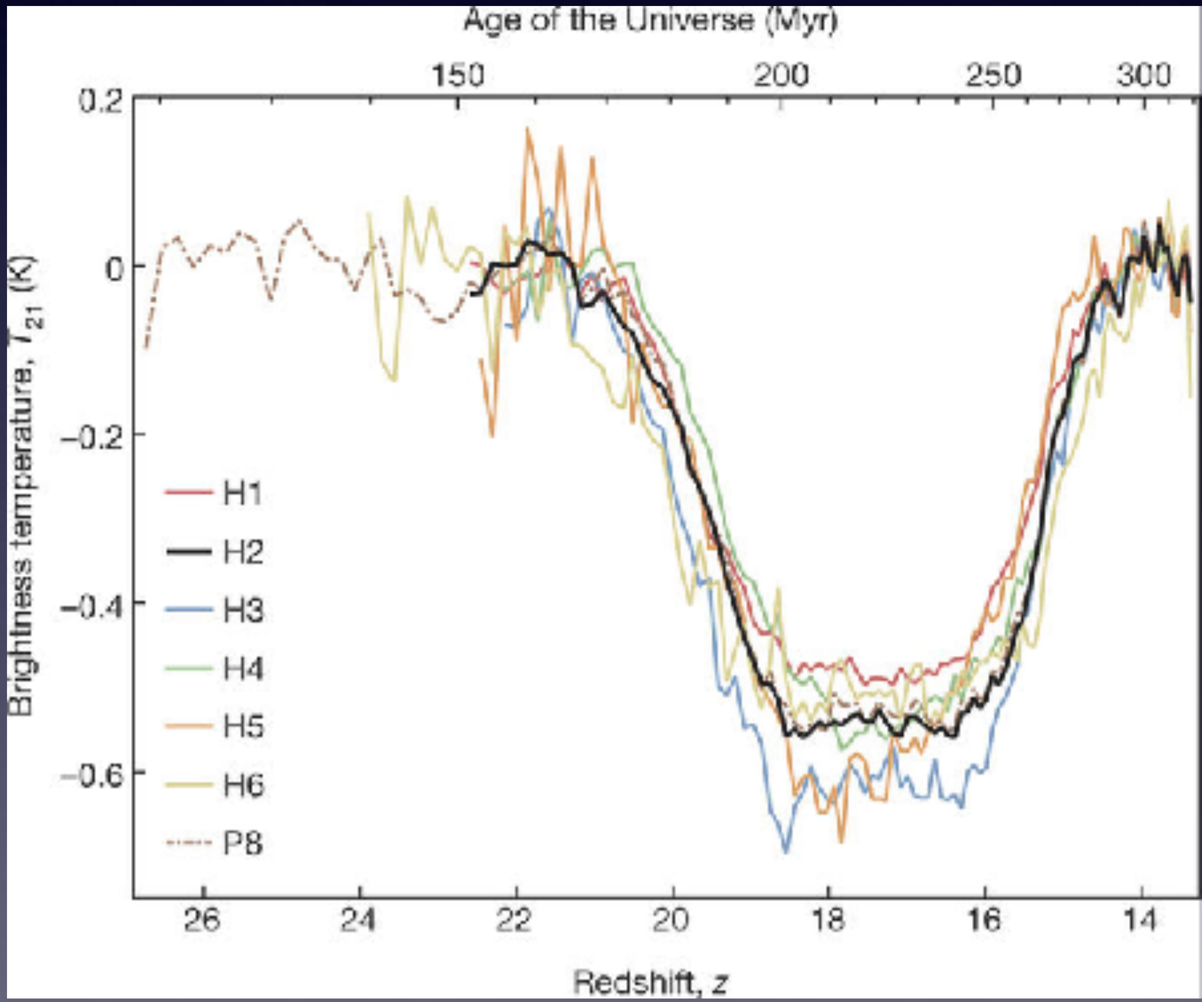


Lopez-Honorez et al JCAP08(2016)004



A measurement of 21cm absorption in the dark ages?

- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18]
- Claim is a deep absorption trough corresponding to z~15-20 - implies spin temperature < CMB temperature.
- Measurement of $T_{gas}/T_R(z=17.2) < T_S/T_R < 0.105$ (99% confidence).

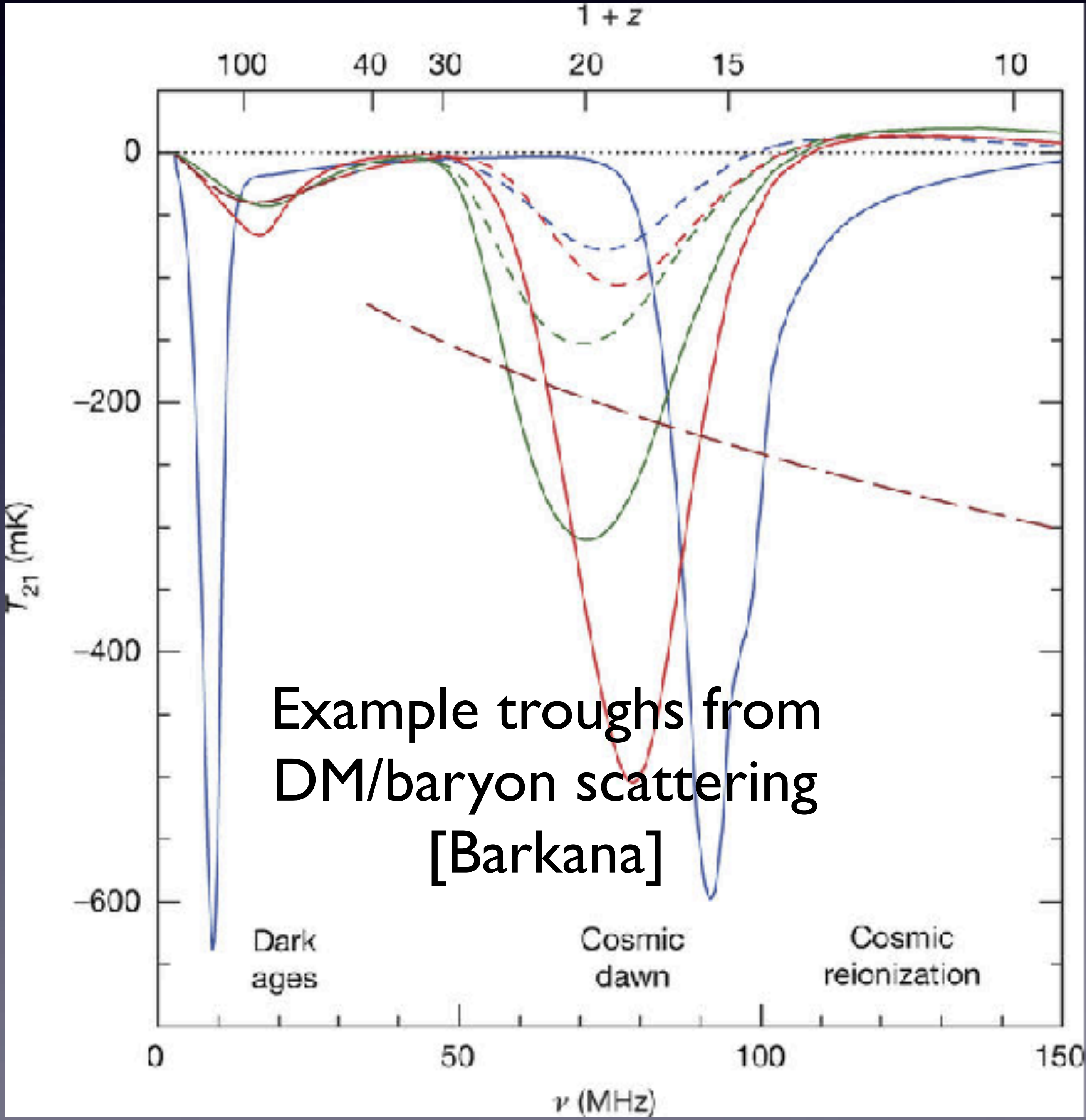


Interpreting EDGES

- If T_R is taken to be the CMB temperature, this gives $T_{gas} < 5.2$ K
- But assuming standard decoupling and no stellar heating, we can calculate $T_{gas} \sim 7$ K.
- It is quite possible this result is spurious - e.g. due to instrumental effects and/or foregrounds.
- But if it is confirmed, suggests either $T_R > T_{CMB}$ (new radiation backgrounds) [Feng & Holder 1802.07432], or some modification to the standard scenario that lowers T_{gas}.
- New radiation backgrounds could arise from either novel astrophysics, i.e. radio emission from early black holes [Ewall-Wice et al 1803.01815] or more exotic (DM-related?) sources [Fraser et al 1803.03245, Pospelov et al 1803.07048].
- Additional cooling of the gas could be due to modified recombination history (earlier decoupling from CMB), or scattering of the gas on a colder bath, e.g. (some fraction of) the dark matter [e.g. Barkana, Nature, March '18; Munoz & Loeb 1802.10094; Berlin et al 1803.02804; Barkana et al 1803.03091]

DM scattering as an explanation for EDGES

- DM-baryon scattering can cool down the ordinary matter [e.g. Munoz et al '15]
- But strong DM-baryon interactions also disrupt CMB perturbations! [Dvorkin et al '13, Gluscevic et al '17, Boddy et al '18, Xu et al '18].
- If an O(1) fraction of DM scatters with baryons, need scattering to be enhanced at late times to avoid CMB limits.
- Late times = low thermal velocities - consider models where cross section scales like v^{-4} (Rutherford scattering)

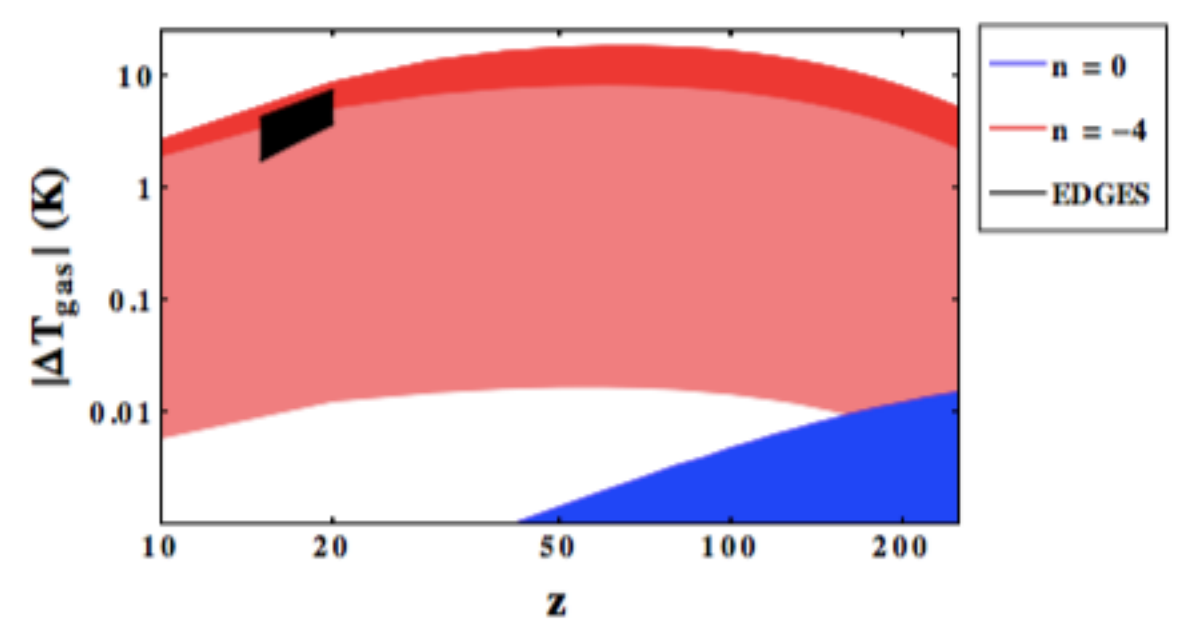


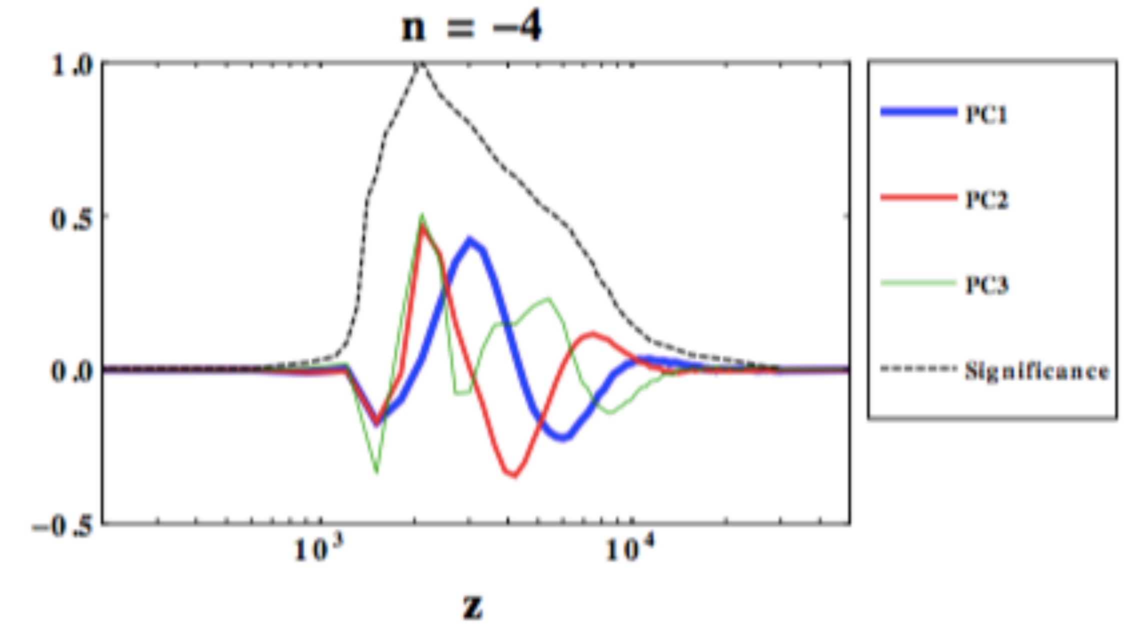
Example troughs from DM/baryon scattering [Barkana]

DM-baryon scattering in the early universe

[TRS & Wu 1803.09734]

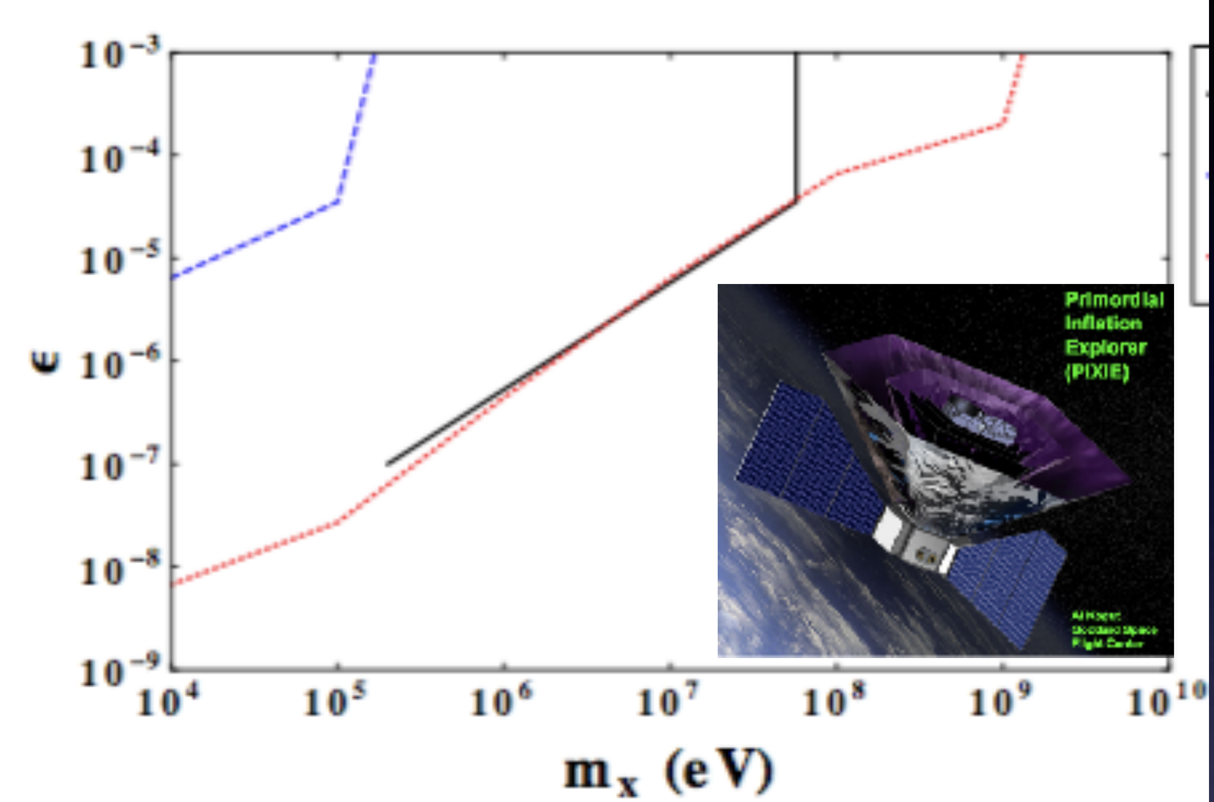
- $\sigma \sim v^{-4}$ scaling can cool the gas enough to accommodate the EDGES observation for sub-GeV DM masses, without violating CMB bounds [note: v1 of 1802.06788 suggested otherwise; v2 (to post tonight) revises the limit, now matches our result.]
- Substantially weaker velocity scalings (in particular, $\sigma \sim v^{-2}$) are not sufficient under standard assumptions.
- Constraint dominantly comes from z~10^3-few x 10^4 - suppressing signal at these redshifts would work as well as velocity dependence.
- If the DM is cold enough, problem is approximately linear - in this case, our paper provides a basis set of functions that can be used to estimate the *Planck* constraints on arbitrary redshift-dependent scattering within this period.





Probing millicharged dark matter

- Several authors [e.g. Munoz et al '18, Berlin et al '18, Barkana et al '18] have suggested that if ~1% of (10-100 MeV) DM carries a tiny electric charge, this could explain the signal.
- Evade CMB-anisotropy constraints because bulk of DM is not interacting - perturbations (probably) OK.

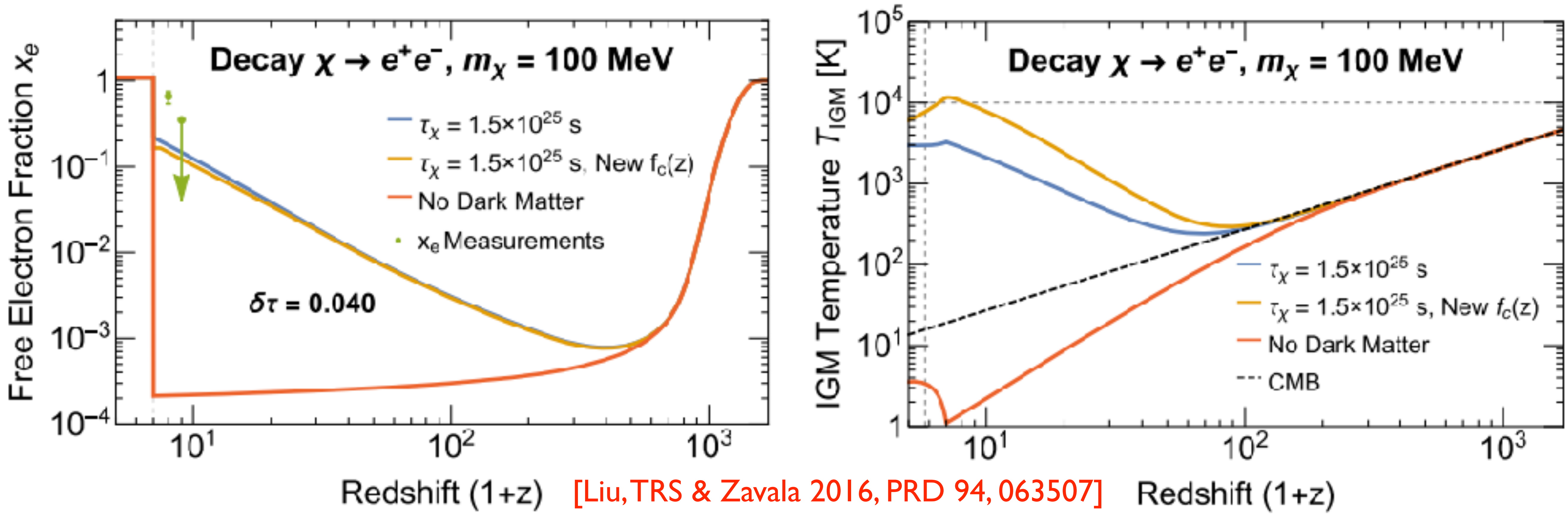


TRS & Wu, 1803.09734

- But early DM-baryon interactions (cooling the gas) could distort CMB blackbody spectrum [Ali-Haimoud et al '2015] - depends on energy flow from baryons to DM, like EDGES, not on gravitational effects.
- TRS & Wu 1803.09734: extending these limits to case with millicharge, next-gen experiment PIXIE could test this parameter space.

Testing DM annihilation/ decay with 21cm

- If we can constrain the gas temperature at z~17 at a similar level of precision to the EDGES claim, what can we learn about DM annihilation/decay?
- We said it predicts early emission - clearly not what is seen at the moment! What are the constraints?
- Calibration: for light DM decaying to electrons, competitive current constraints come from requiring that DM not overheat the universe - by 10,000K at redshift ~6!



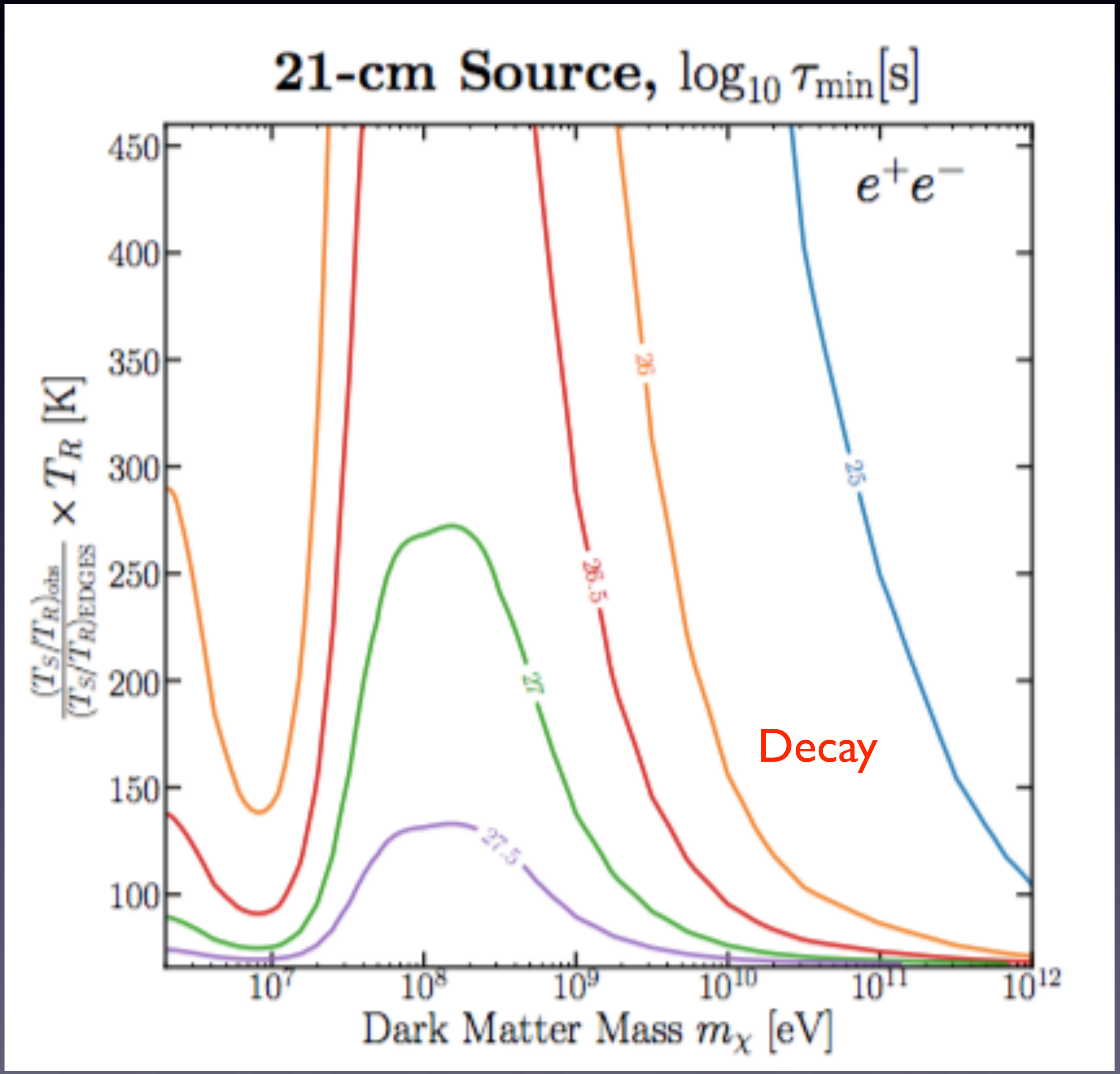
[Liu, TRS & Zavala 2016, PRD 94, 063507]

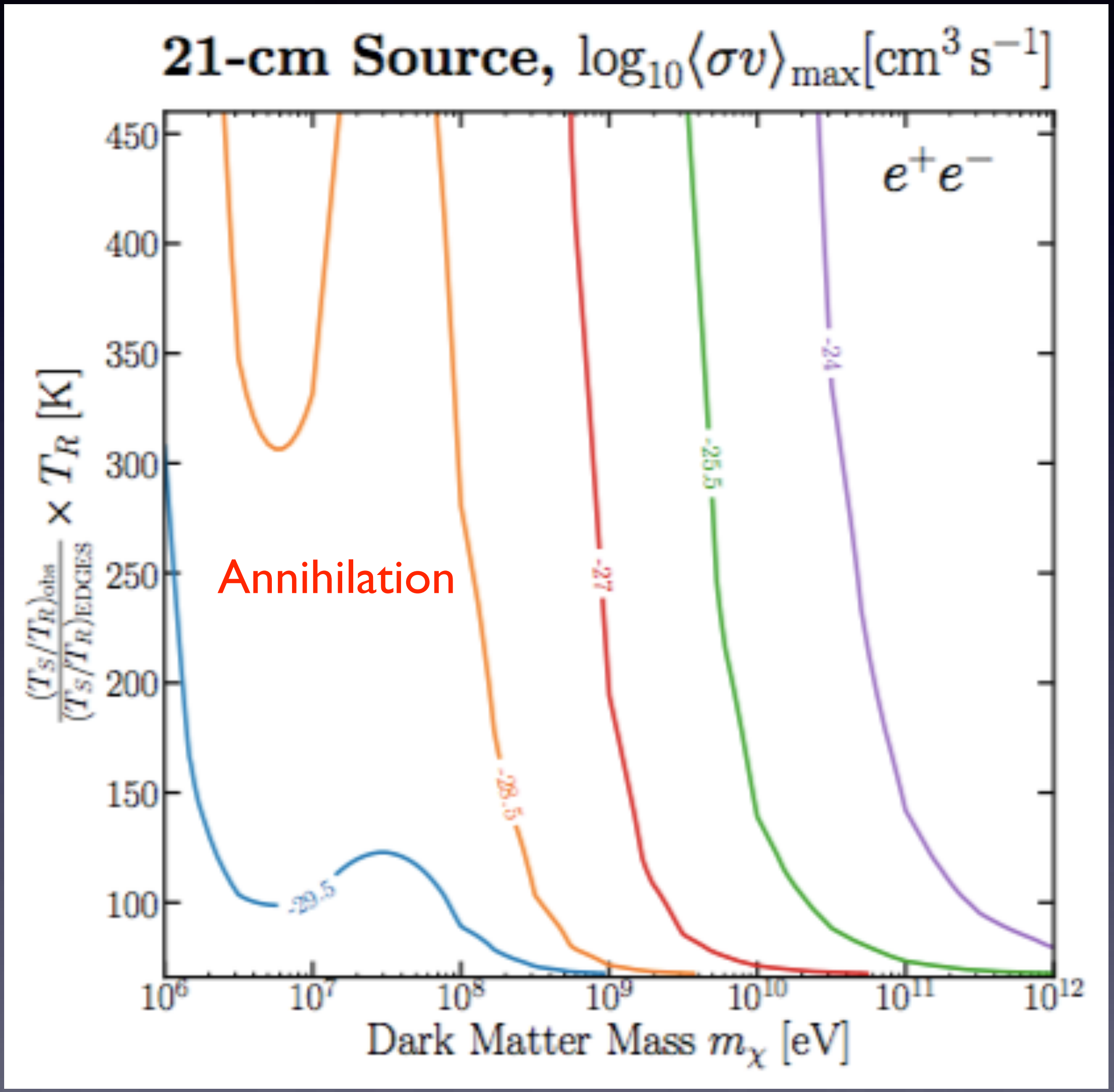
Too hot, too cold, or just right?

[Liu & TRS 1803.09739]

- Need to account for whatever process is causing the deep absorption trough (else limits are unrealistically strong).
- Simplest case: extra radiation backgrounds, limit on gas temperature increases, but otherwise keep standard scenario.
- More complex cases: new gas-cooling processes (need to account for these when computing heating from decay/annihilation).
- We study the heating from annihilation and decay in the presence of:
  - DM-baryon scattering (all DM or sub-component)
  - Early baryon-photon decoupling
  - Extra radiation backgrounds

Annihilation/decay heating + extra photons

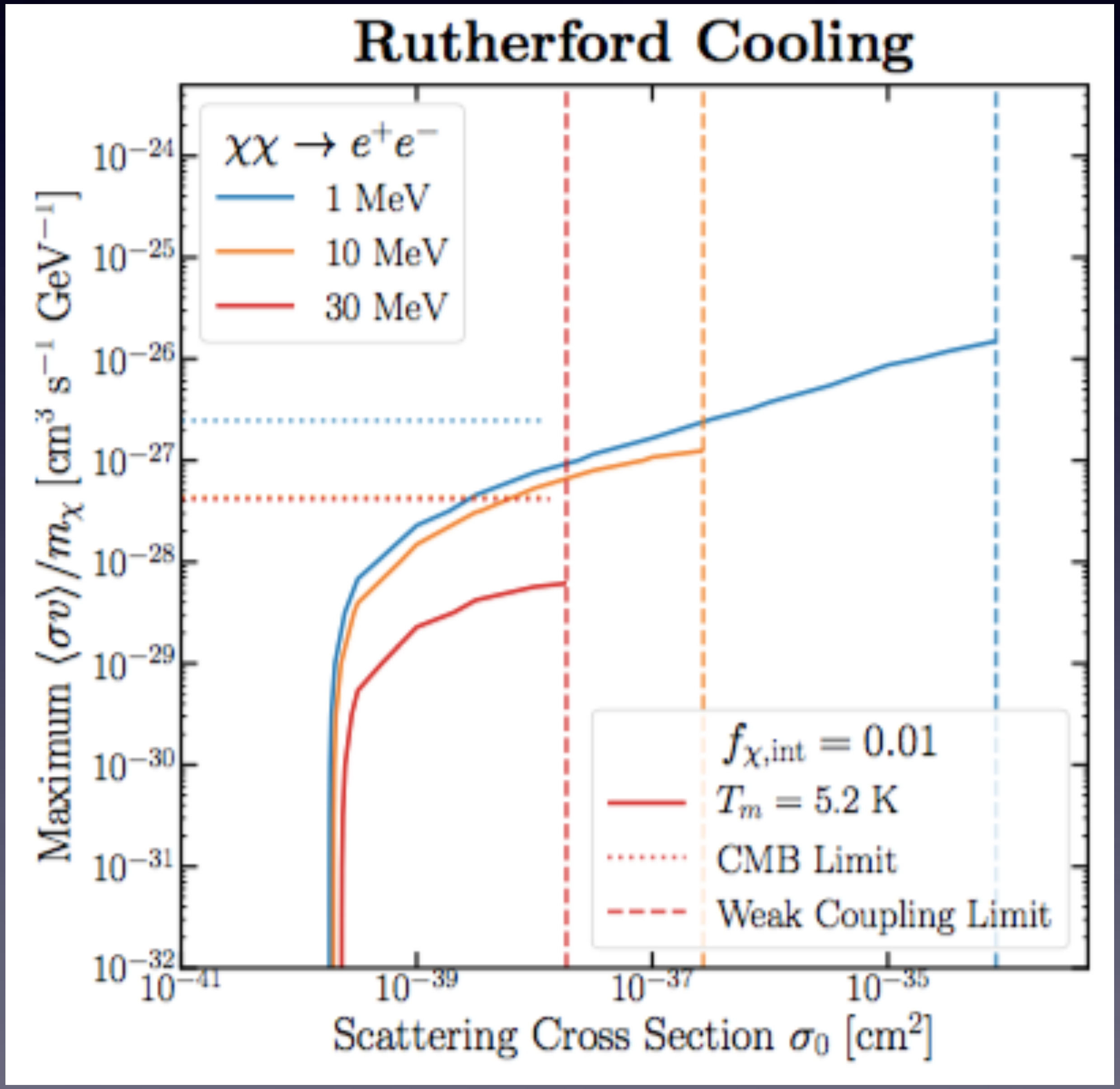




- Example for decay/annihilation to electrons - if extra radiation backgrounds are of same order as the CMB (at 21cm frequency), probe lifetimes of a few x 10^{27} s for 100 MeV DM, annihilation cross sections of order few x 10^{-30} cm^3/s - four orders of magnitude below thermal relic. (See also d'Amico et al 1803.03629.)

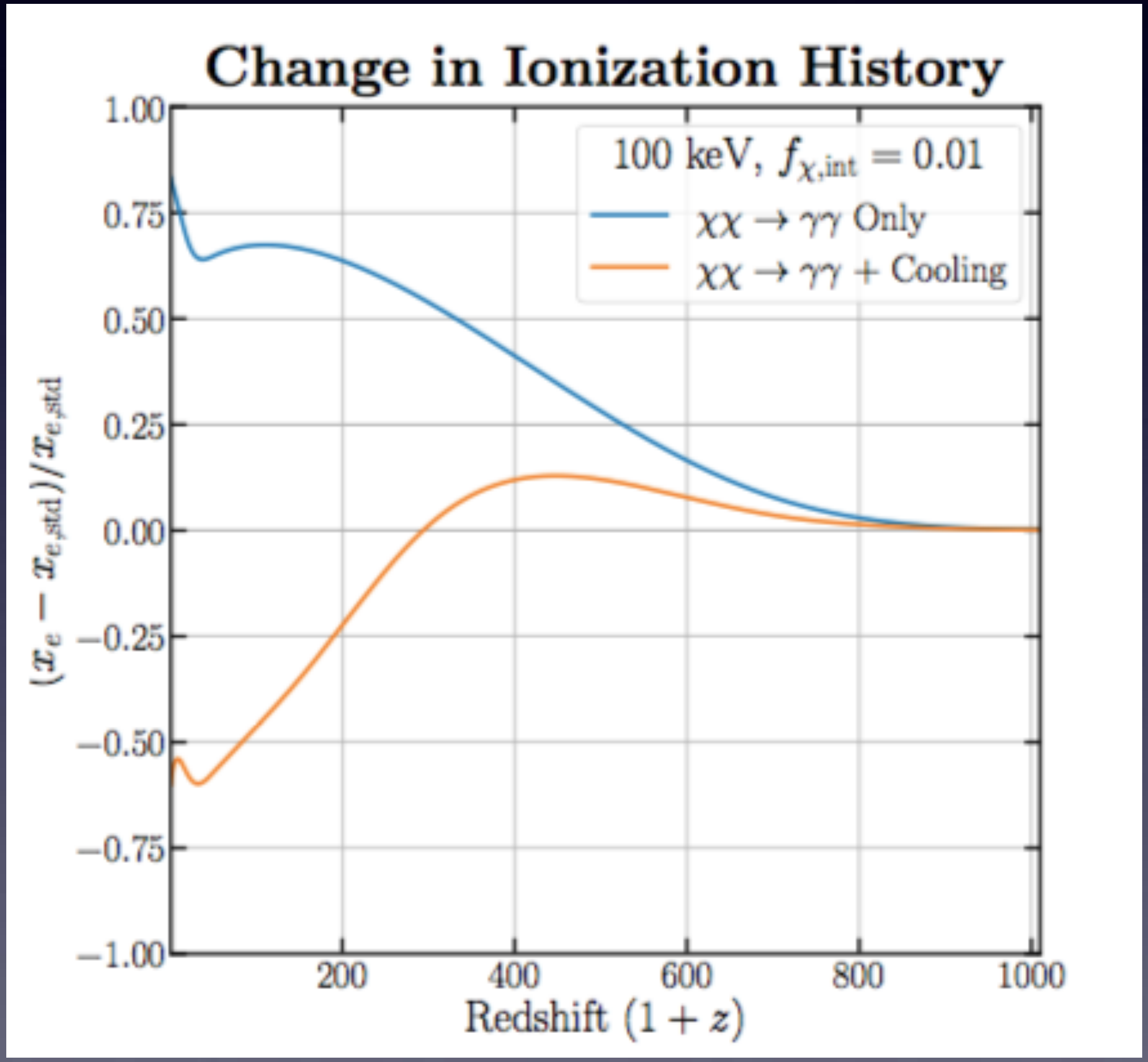
Annihilation/decay + weak scattering

- When we turn on DM-baryon scattering, the gas is cooled - counteracts heating from annihilation/decay
- Limits relax as cross section gets larger
- But for strong enough scattering, DM temperature = baryon temperature - increasing scattering further has no effect.
- Heating from exotic sources is divided between baryons and interacting DM - limit depends on #density of interacting DM, but not on xsec



Annihilation/decay + strong scattering

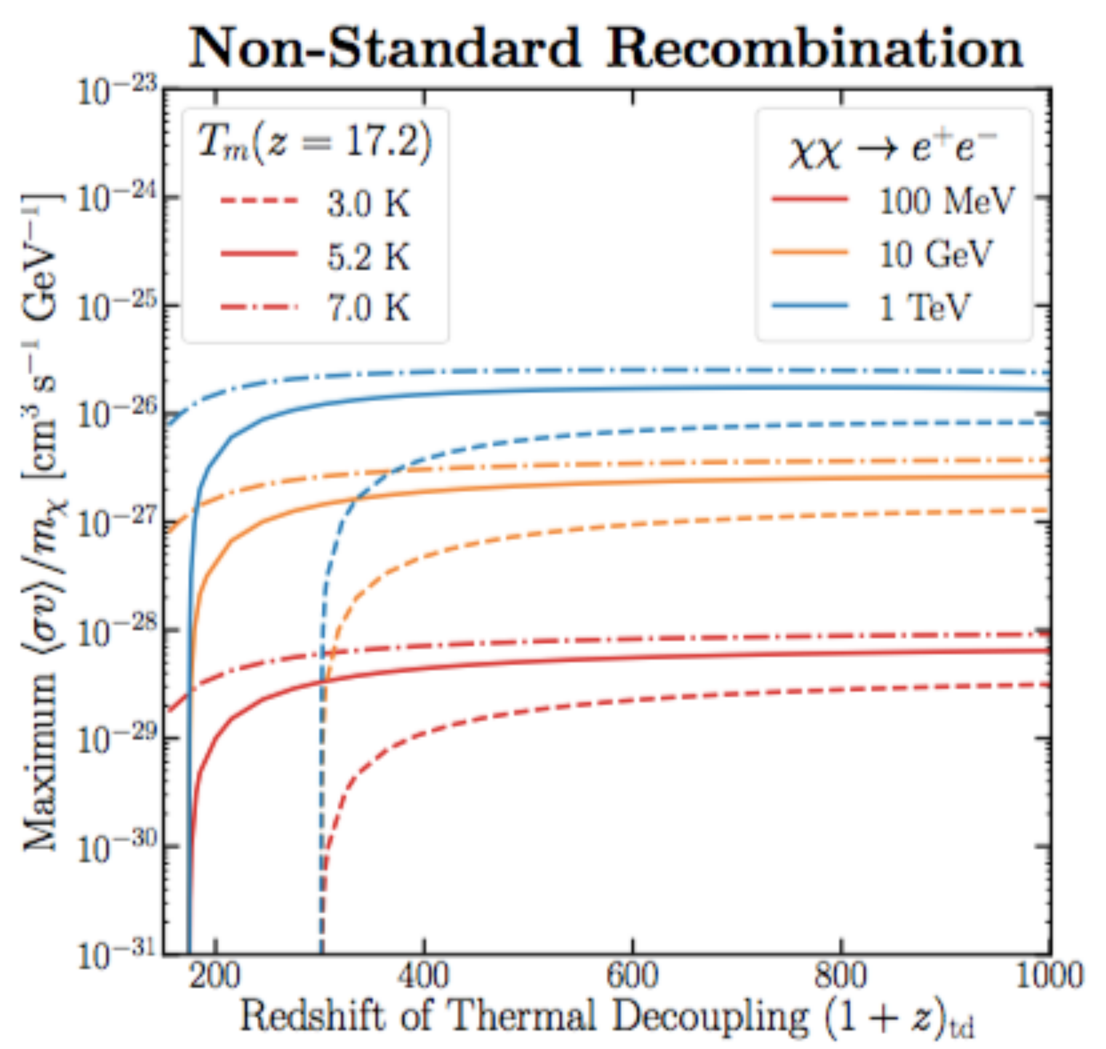
- Case where baryons and (some subcomponent of) DM are strongly coupled - DM acts as heat sink for all effects heating baryons
- Causes early photon-gas decoupling, gas has longer to cool due to expansion.
- Effect is independent of scattering xsec, once xsec is large enough.
- Net effect is delayed recombination + dilution of heating by needing to heat DM too.
- Cooler gas recombines better; can reduce ionization levels, also relaxes annihilation/decay constraints from CMB!



Example of a case nominally ruled out by CMB limits on extra ionization - turning on small scattering component reduces ionization signal.

Annihilation/decay + delayed recombination

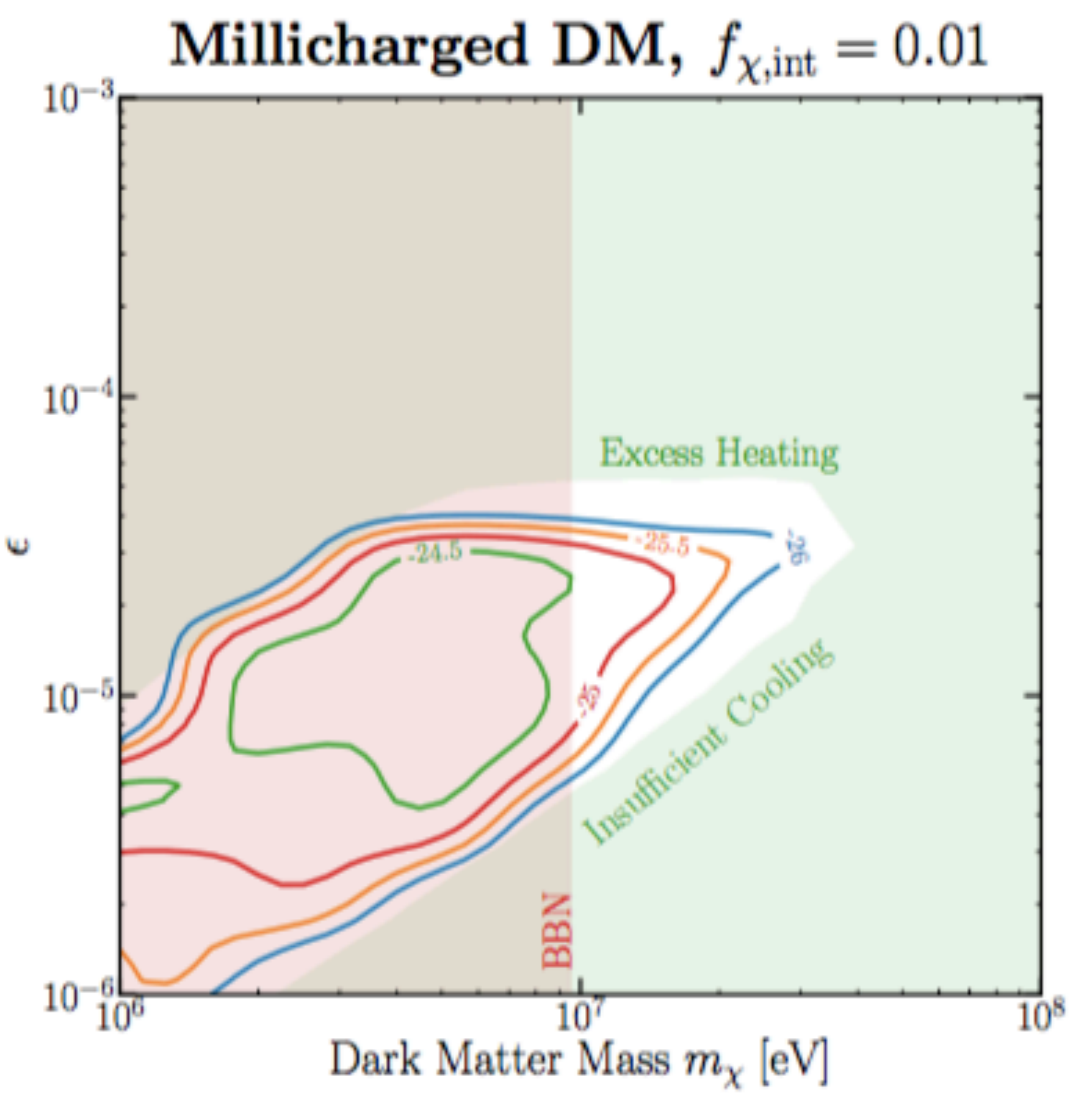
- Suppose baryons decouple from photons earlier than expected (can be due to a small scattering DM component, or for other reasons).
- If decoupling is early enough, gas temperature before heating at z~17 is very small - set constraint by requiring DM heating not overproduce total observed T_{gas}, starting from 0K.
- Thus as with scattering, there is an asymptotic constraint when decoupling is early enough.



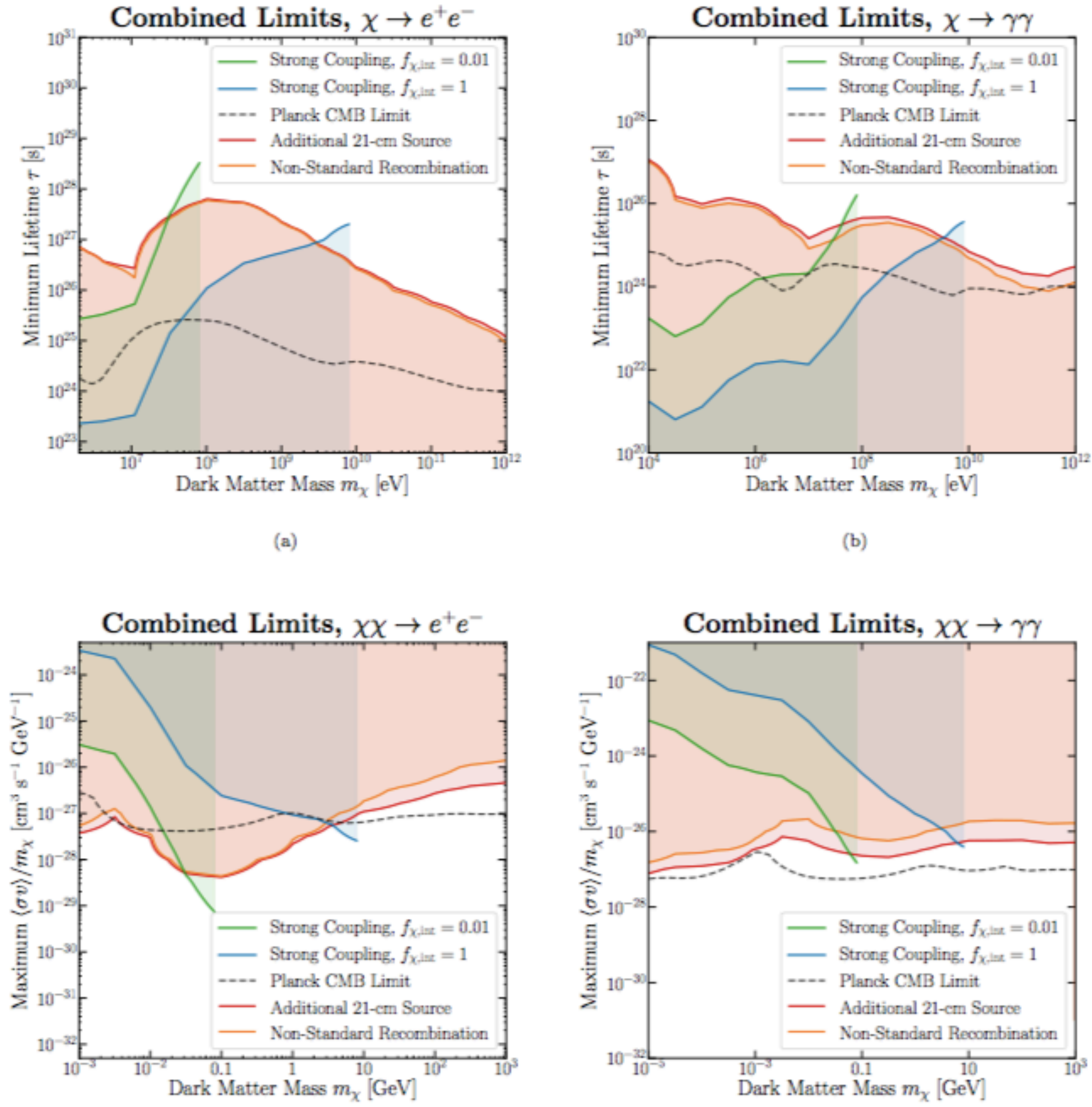
Example of DM annihilation to e^+e^- pairs; constraints as a function of decoupling redshift

Millicharged DM

- Consider millicharged DM comprising 1% of total DM, and assume EDGES observation is correct.
- If millicharge is too small, cannot scatter efficiently enough to cool the gas.
- If millicharge is too large, automatic annihilation (through s-channel photon) overheats the gas.
- In intermediate region, can set limits on extra (non-automatic) annihilation channels.
- Cannot get desired 1% density through thermal freezeout of such channels if branching ratio to electrons is appreciable & annihilation is unsuppressed at late times.



- Summary of limits assuming EDGES is correct
- Orange/red lines = limits in presence of early recombination (orange) or extra radiation up to same strength as CMB (red)
- Blue/green regions = allowed regions with 100%/1% of DM scattering, strong-coupling limit
- Dashed black lines = standard CMB bound
- Heating bounds are stronger than standard CMB limits for light DM in most cases (especially decay to e+e-)



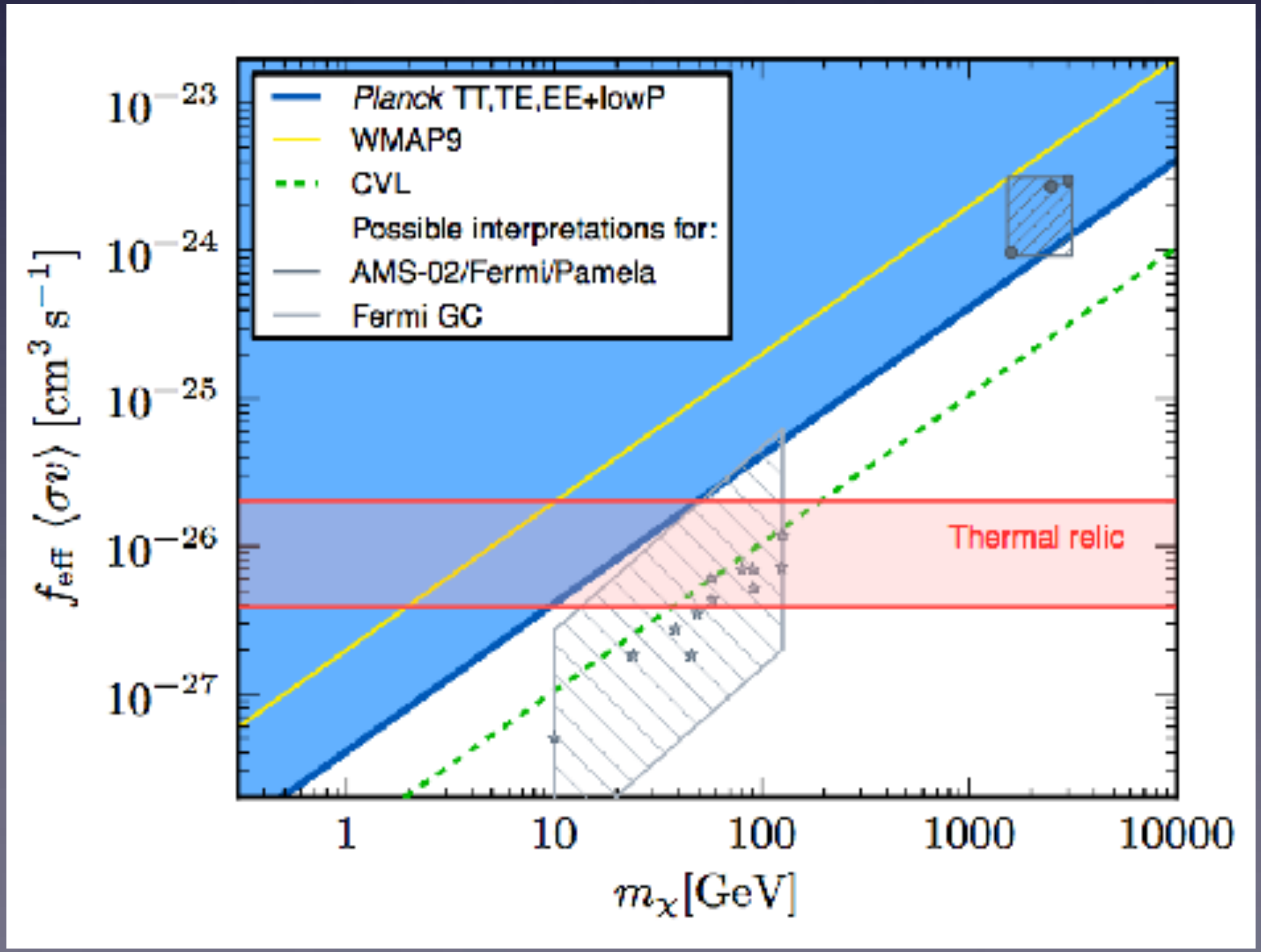
Summary

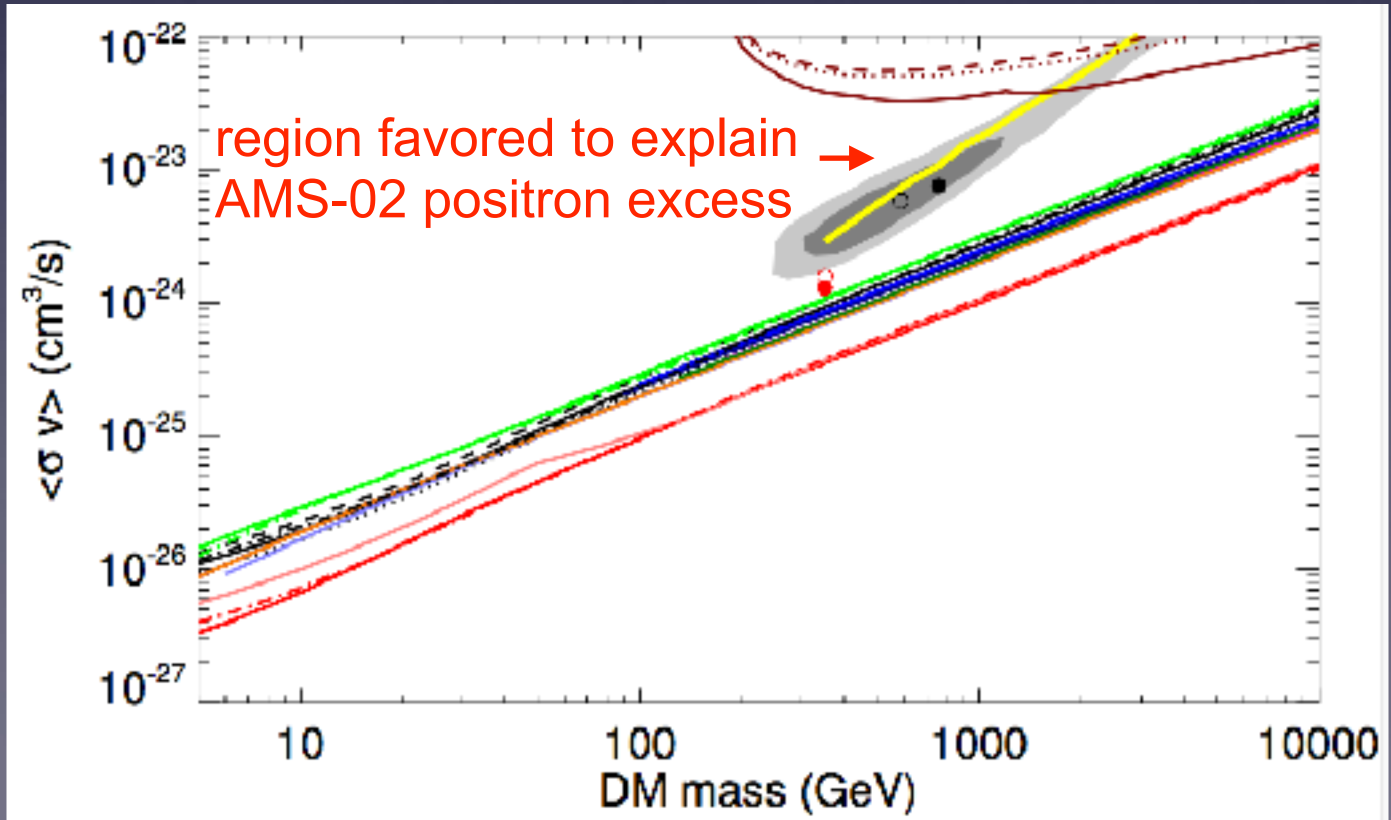
- Scattering between baryons and the bulk of the DM during the pre-recombination epoch $z \sim 10^3$-few x 10^4 is tightly constrained by the CMB. We have suggested a framework for estimating CMB constraints on general scattering histories for cold DM.
- Scattering between baryons and a small sub-component of the DM is likely difficult to constrain with CMB anisotropies, but could be tested by future observations of CMB blackbody spectral distortions.
- Confirmed measurement of a global 21cm signal could set robust and stringent new constraints on DM annihilation/decay (especially light DM decaying to electrons), even in the presence of deviations from the standard scenario.
- Modifications to standard recombination, e.g. by having a small fraction of the DM coupling strongly to the baryons, could weaken standard limits on annihilating/decaying light dark matter from the CMB.

BONUS SLIDES

Annihilation limits from Planck

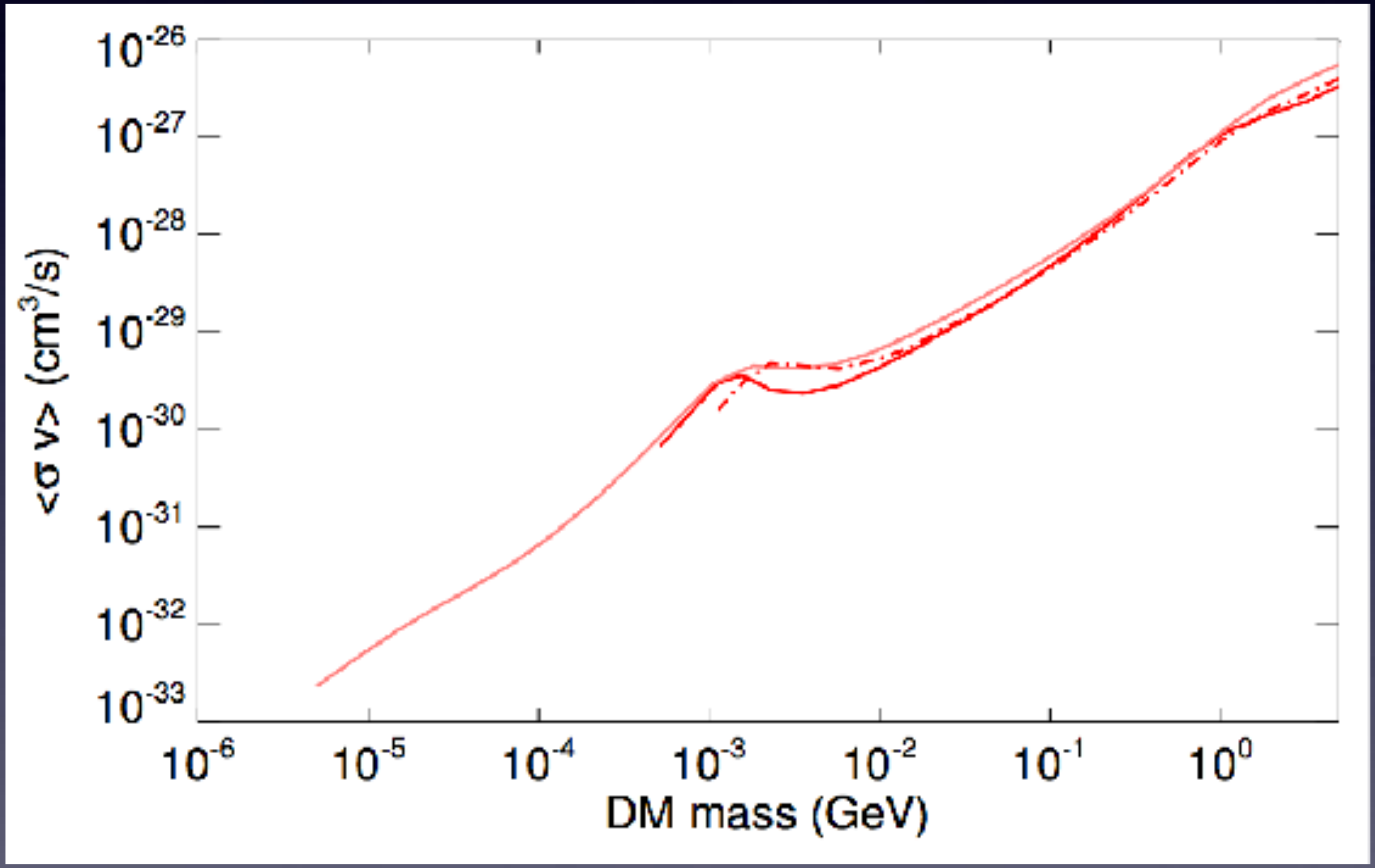
- Planck Collaboration ’15 set bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 09.
- Left plot shows Planck bound, right plot shows resulting cross-section limits for a range of channels from TRS ’16.





Limits on light dark matter

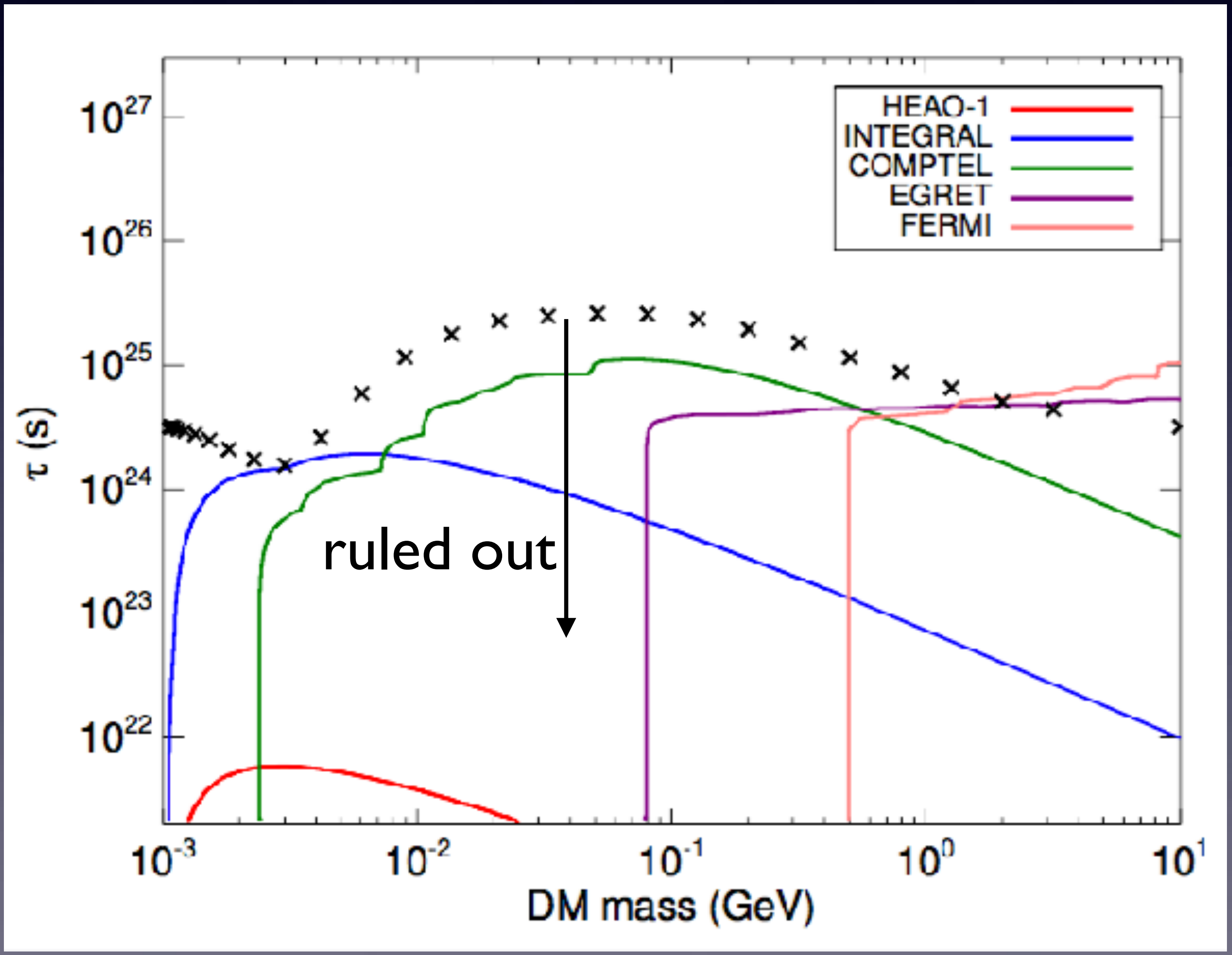
- These are often the strongest existing bounds on light (sub-GeV) dark matter.
- Often other constraints are limited by lack of observations or large backgrounds at relevant energies.
- Such models are also less constrained by direct detection - have garnered much recent interest.



Constraints on decay from Planck

- For decaying dark matter, can use same approach.
- Sets some of the 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 decaying! (for lifetimes $\sim 10^{14}$ s)

TRS and Wu, PRD95, 023010 (2017)



Other constraints from Essig et al '13

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

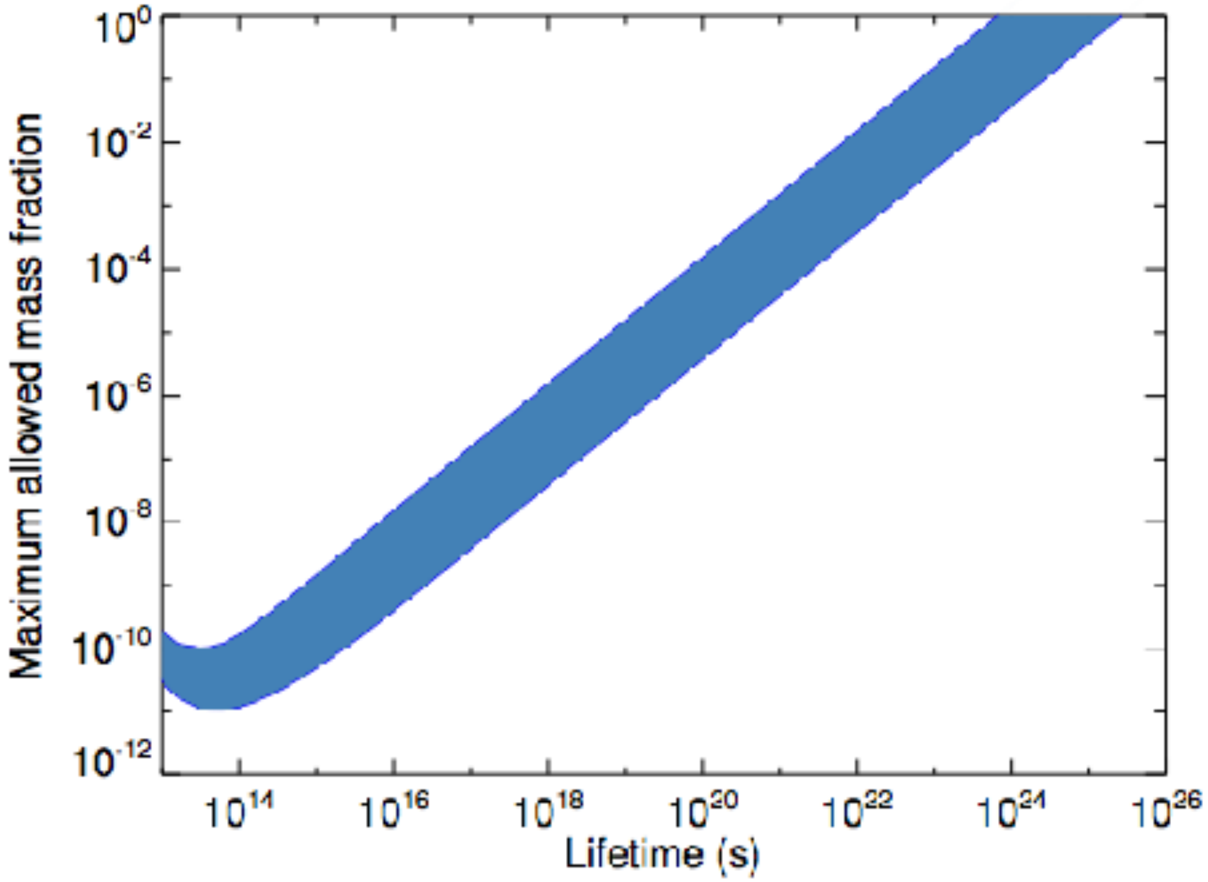
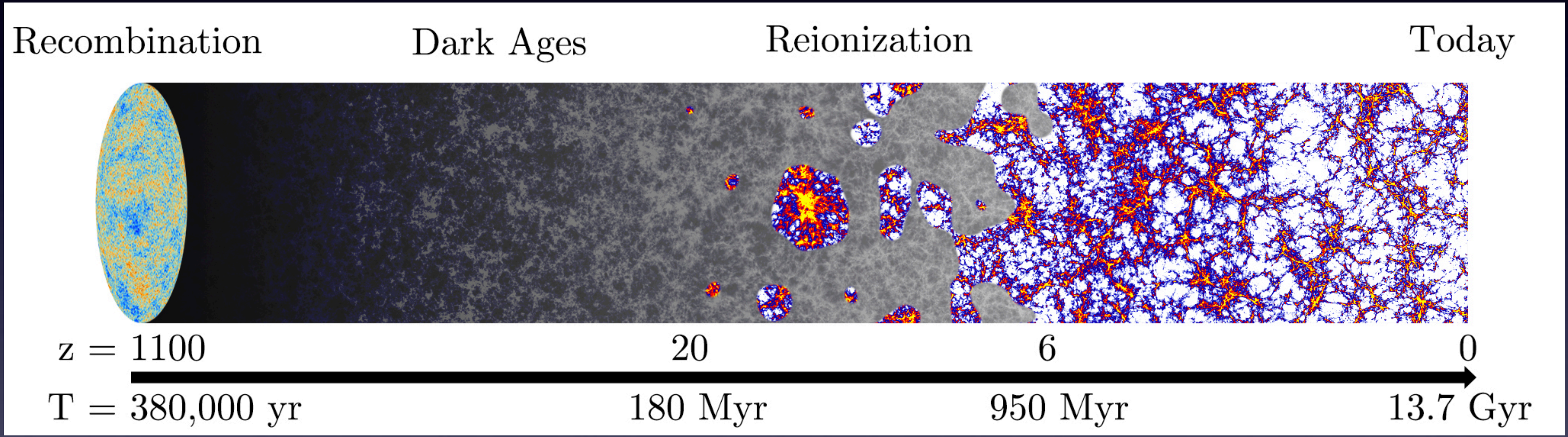


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime τ, for injections of 10 keV – 10 TeV photons and e^+e^- pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the MCMC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

The epoch of reionization

Liu, TRS & Zavala 2016, PRD 94, 063507



- 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 (paper XLVII), 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?

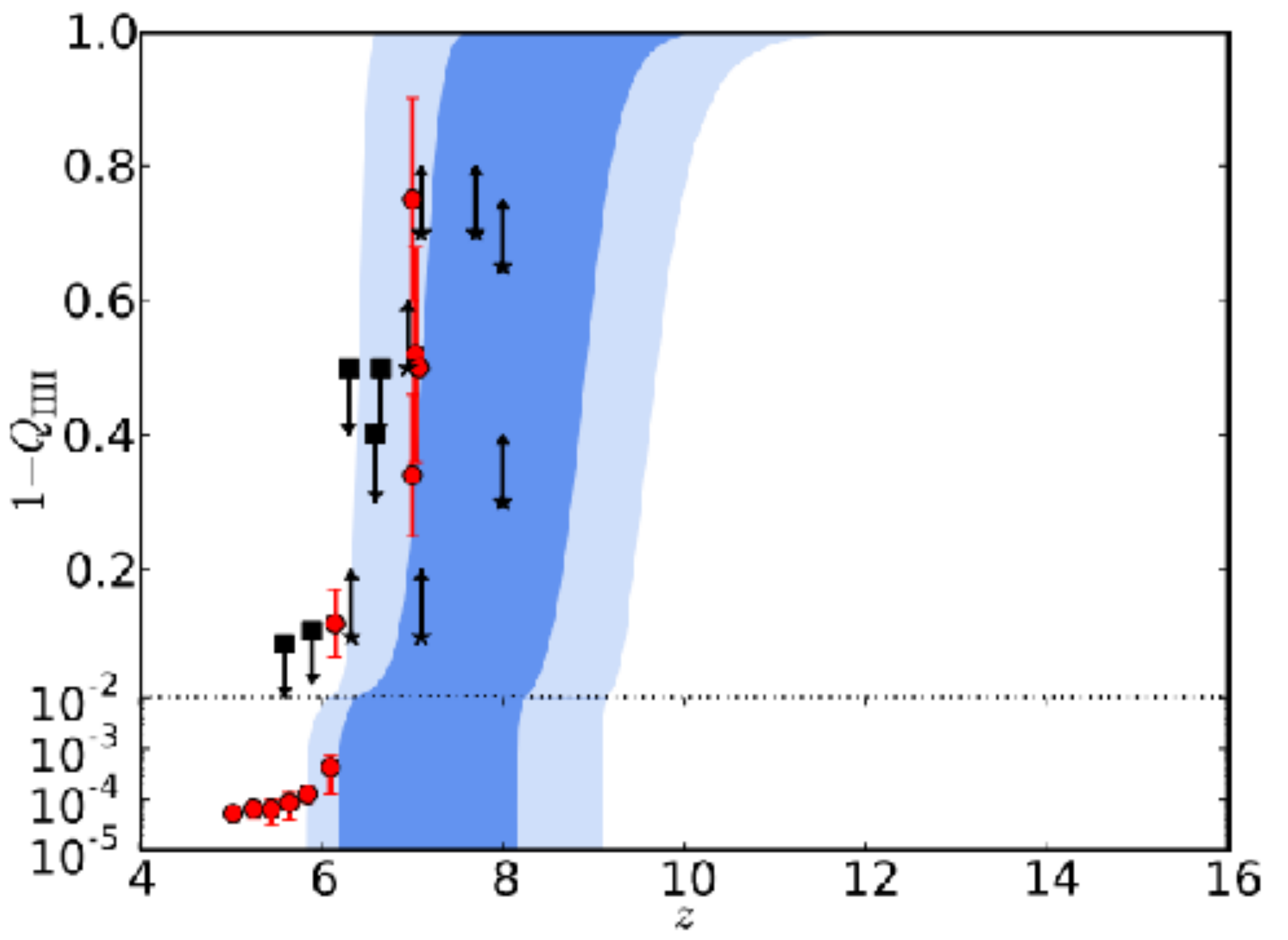
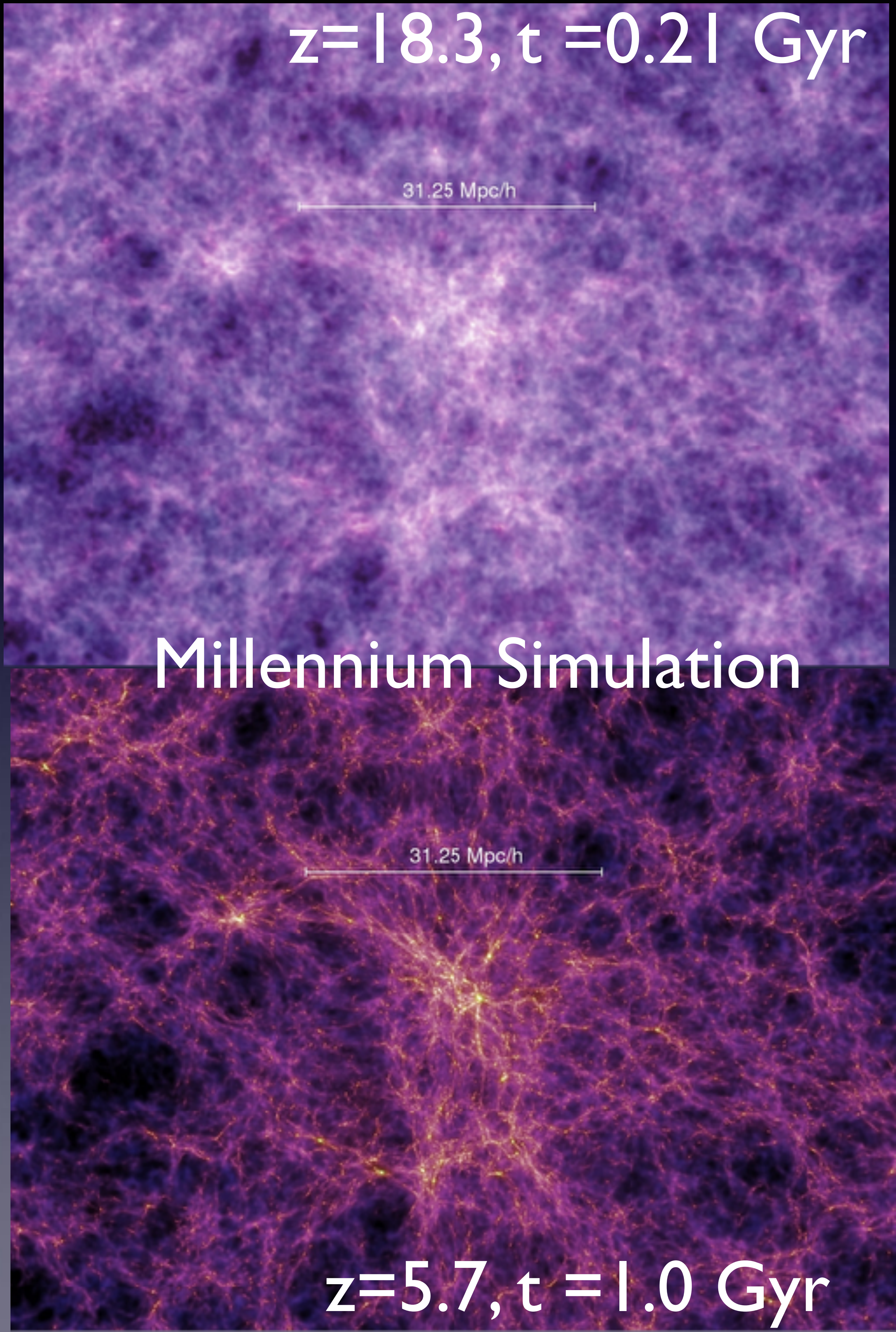


Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints compiled by Bouwens et al. (2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the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

Dark matter in the reionization epoch

- By this time, early galaxies have formed.
- Dark matter has clumped into halos and filaments at a wide range of scales.
- Need to account for the resulting higher densities - enhancement to annihilation.


z=18.3, t =0.21 Gyr

Millennium Simulation

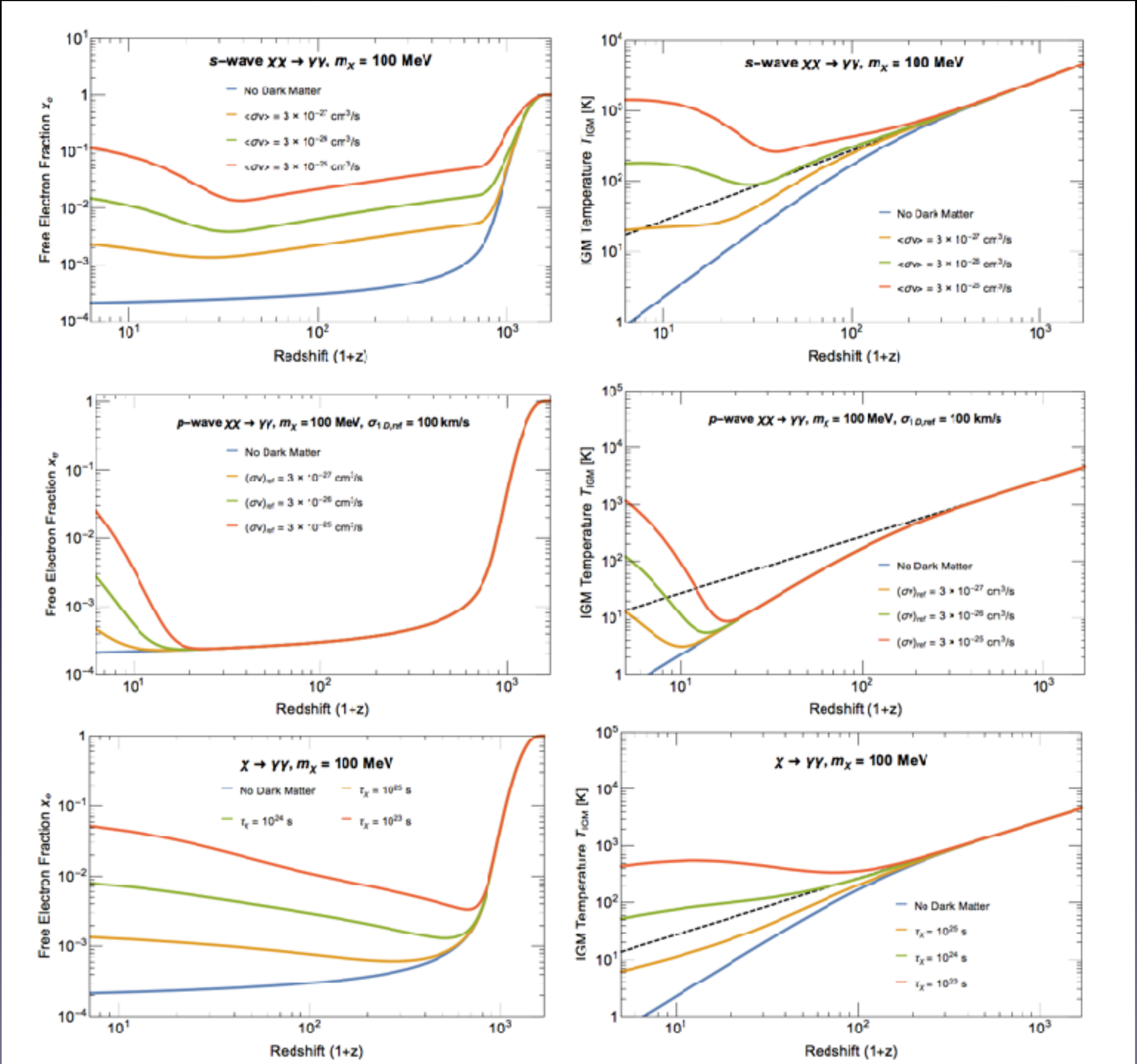
z=5.7, t =1.0 Gyr

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, as measured by Planck - limits integrated changes to ionization history.

$$\tau = 0.058 \pm 0.012$$

- 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

Can DM contribute to reionization?

- Answer appears to be “no”. Models that would give large contribution to reionization also produce:
  - late-time heating (potentially testable with 21cm observations?)
  - early ionization, leading to strong CMB bounds (for decay, s-wave annihilation)
  - diffuse photon backgrounds in present day
- Most optimistic scenario is for DM decay producing O(10-100) MeV electrons/positrons - could contribute at O(10%) level