

21-cm Implications for Dark Matter Part II: Results

Hongwan Liu

HL, Tracy R. Slatyer, Phys. Rev. **D98** No. 2, 023501 (2018), 1803.09739

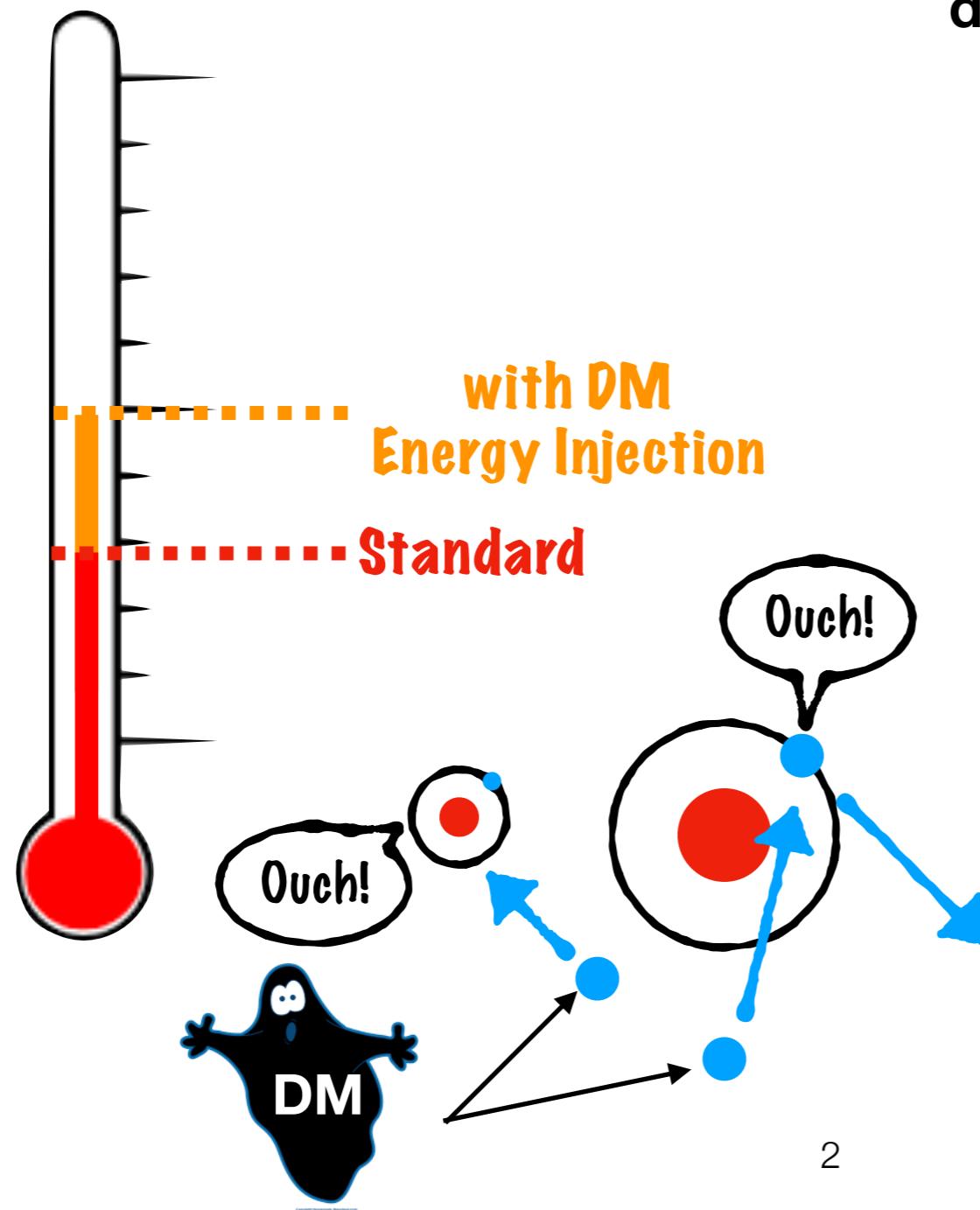
HL, Gregory W. Ridgway, in preparation



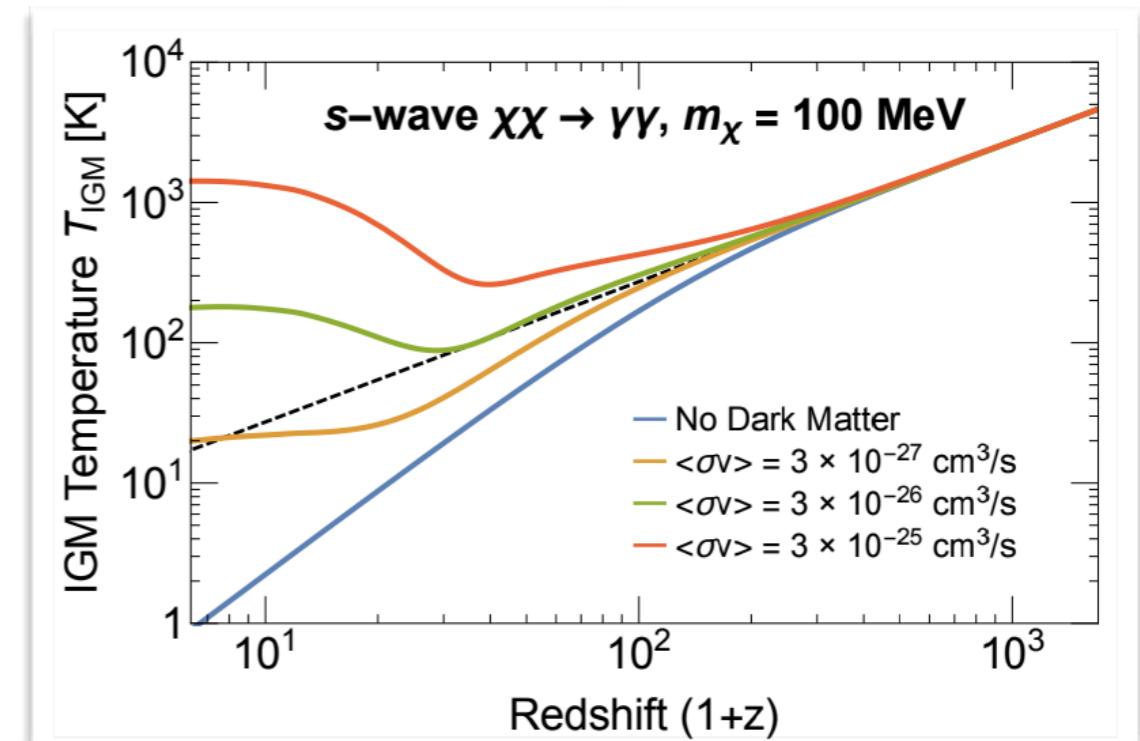
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Punchline

$T_m(z = 17.2)$



Dark matter decay or annihilation
increases the matter temperature and
decreases the 21-cm absorption
during the cosmic dark ages.



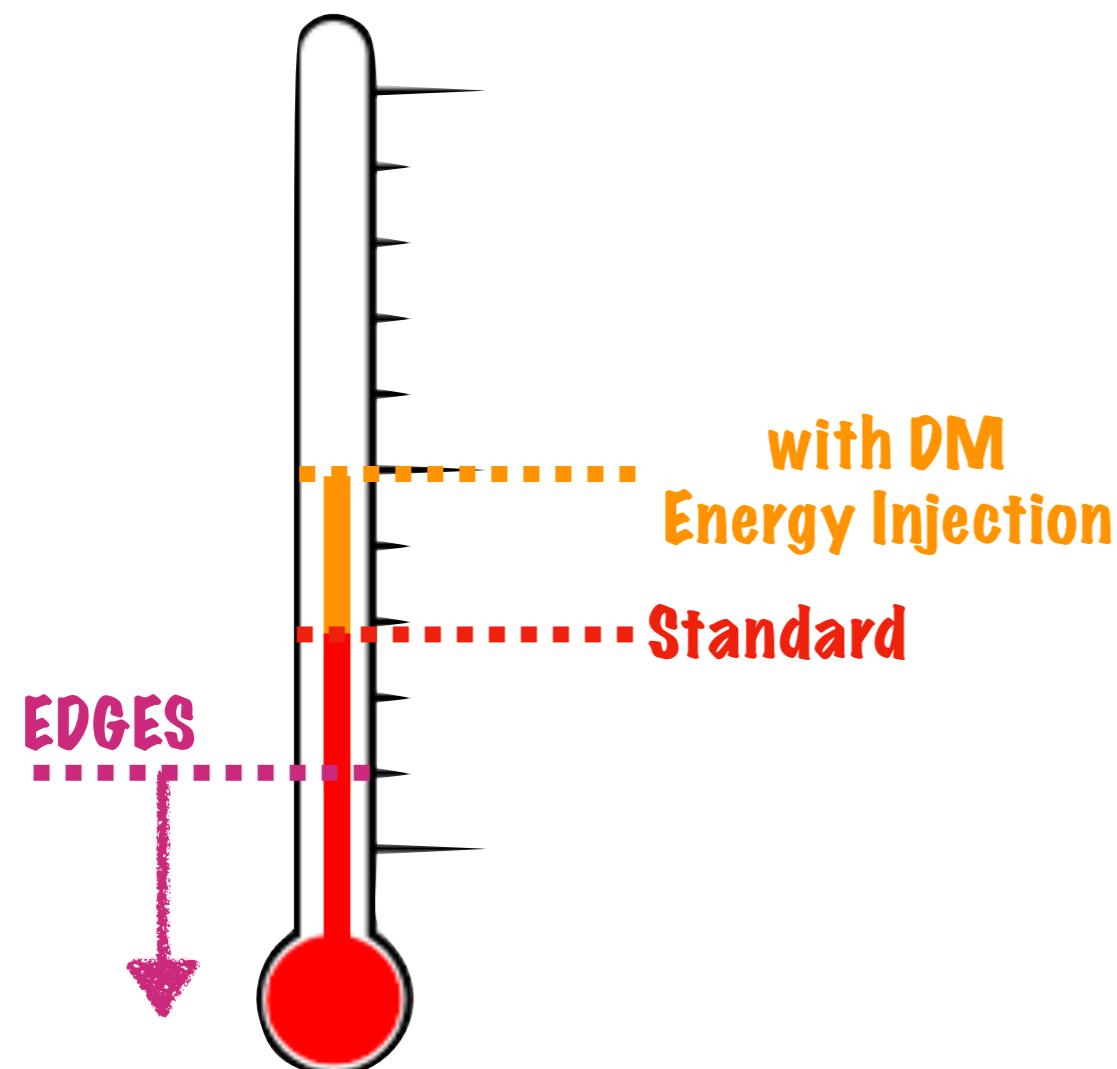
HL, Slatyer and Zavala, 1604.02457



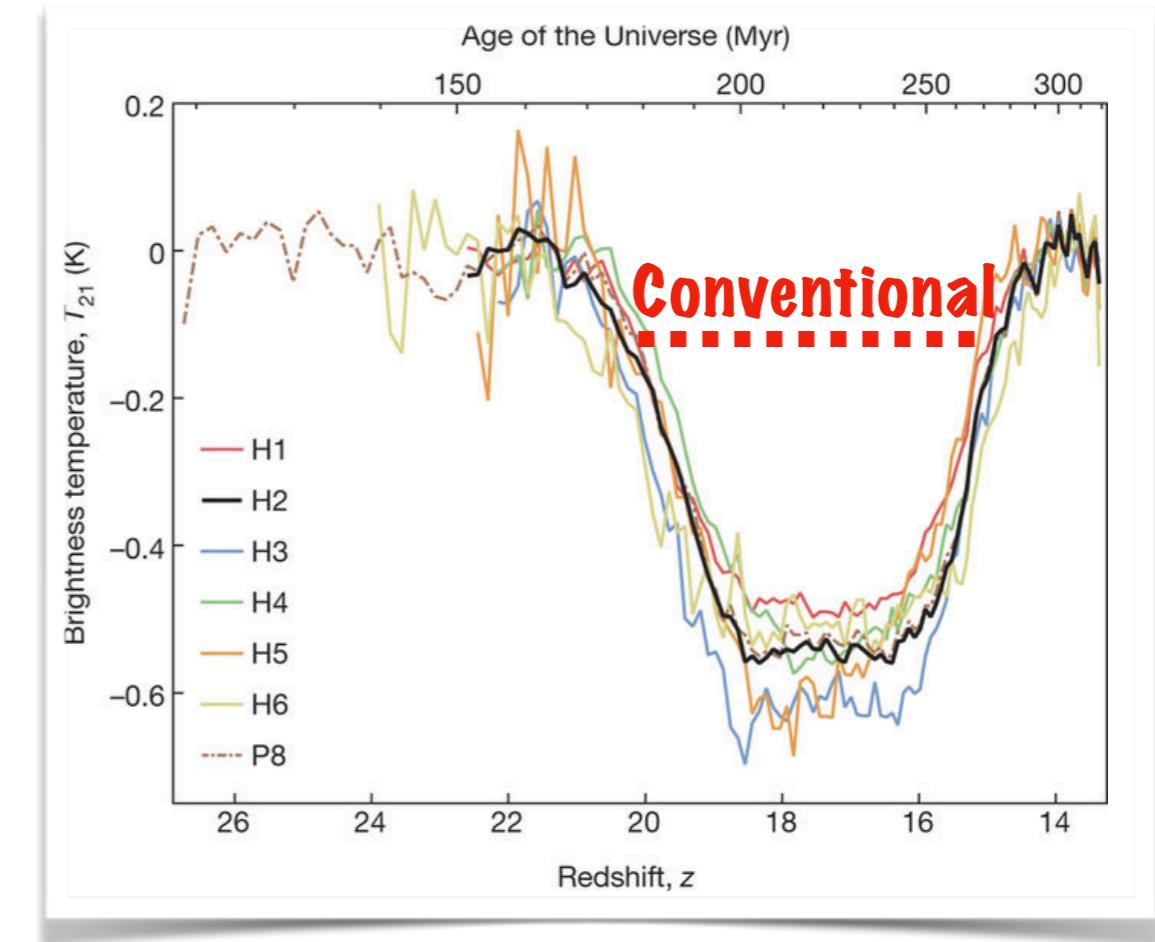
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Punchline

$T_m(z = 17.2)$



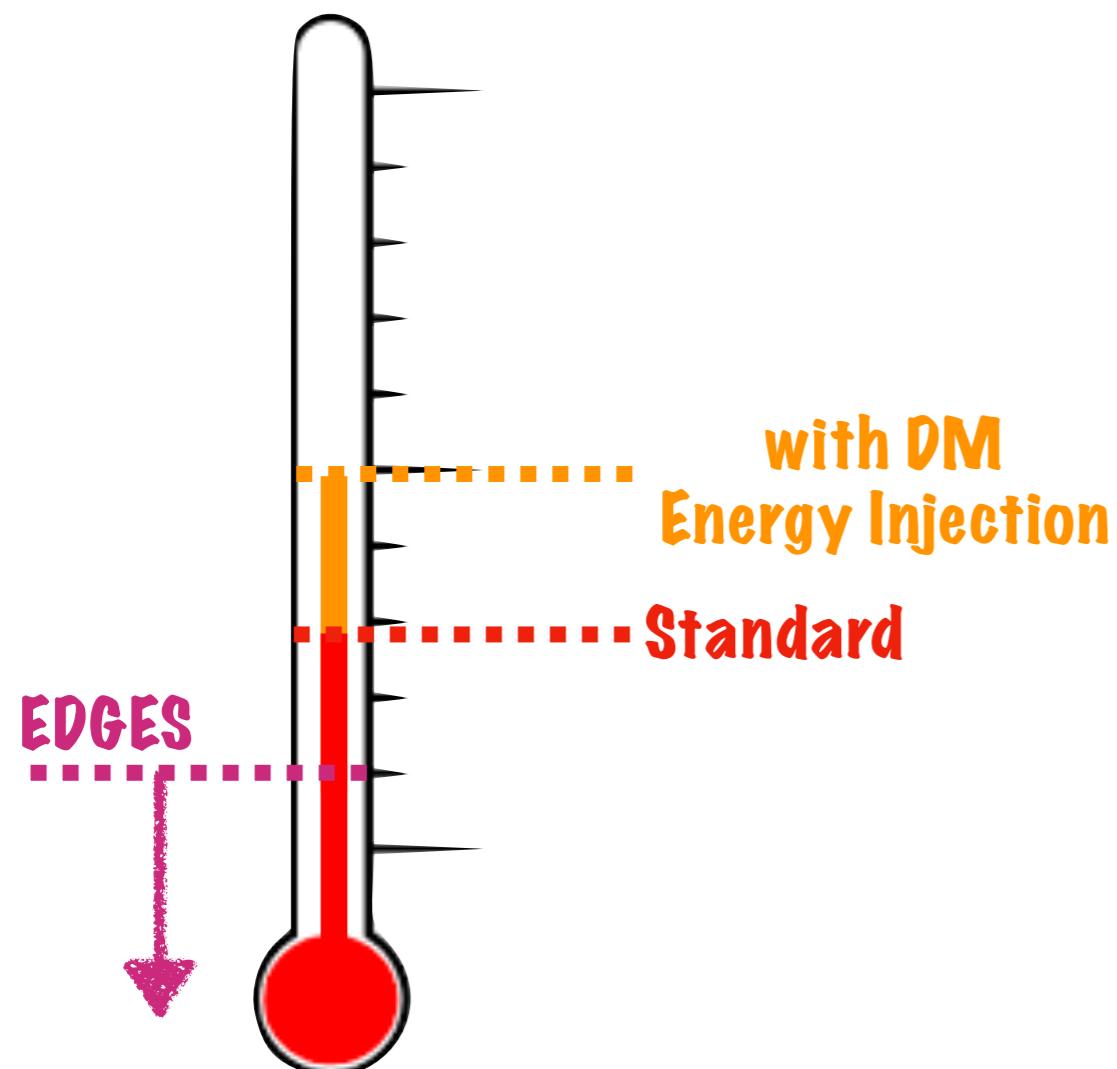
The EDGES measurement found that 21-cm radiation was **absorbed much more strongly than expected** between $z \sim 14$ and 20.



Bowman et al. Nature 555, 67 (2018)

Punchline

$$T_m(z = 17.2)$$

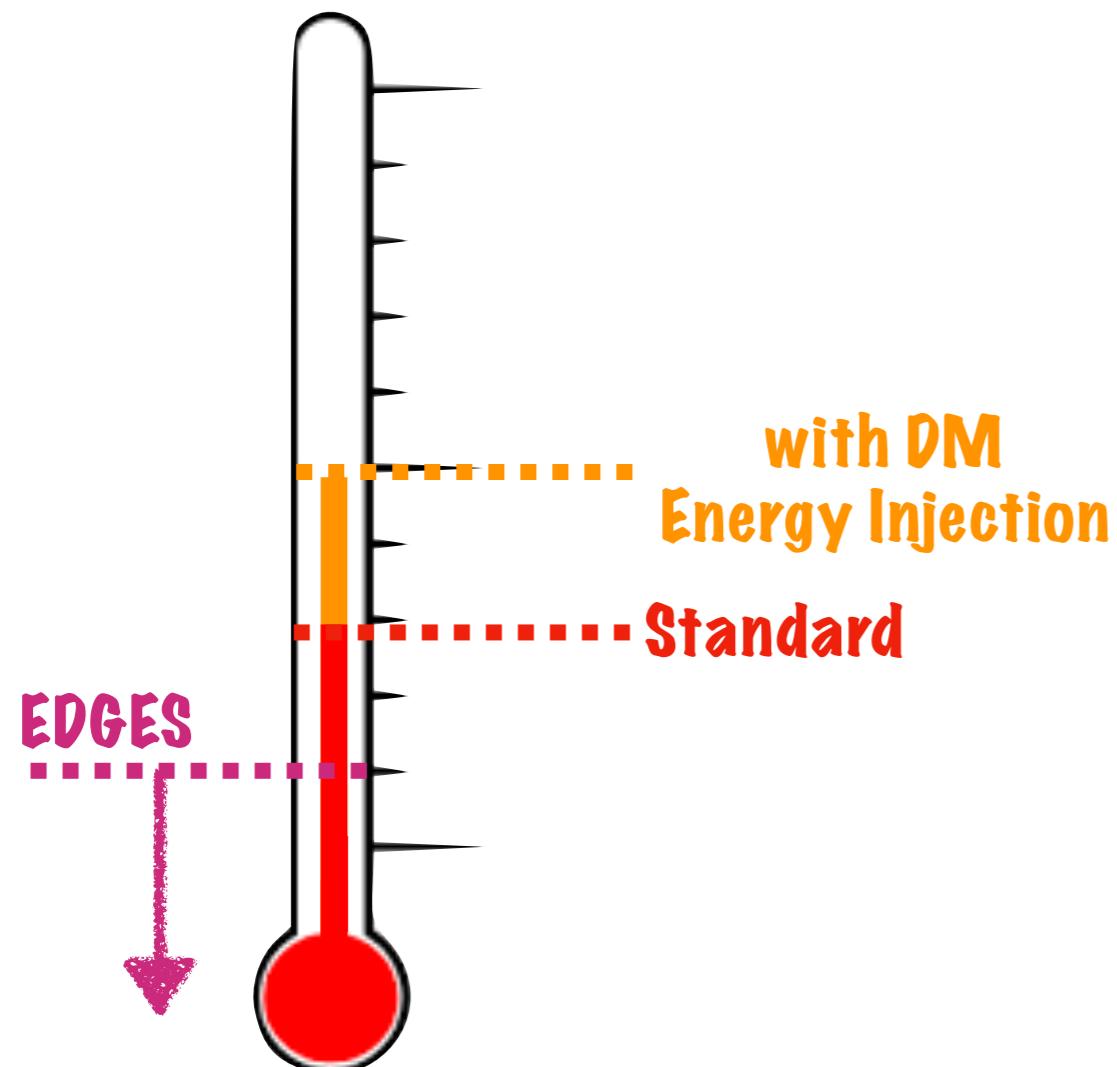


This suggests that **novel effects** were present **during the cosmic dark ages**, affecting 21-cm absorption.

We study **three broad classes of possible effects**, covering many of the models proposed so far to explain the EDGES result.

Punchline

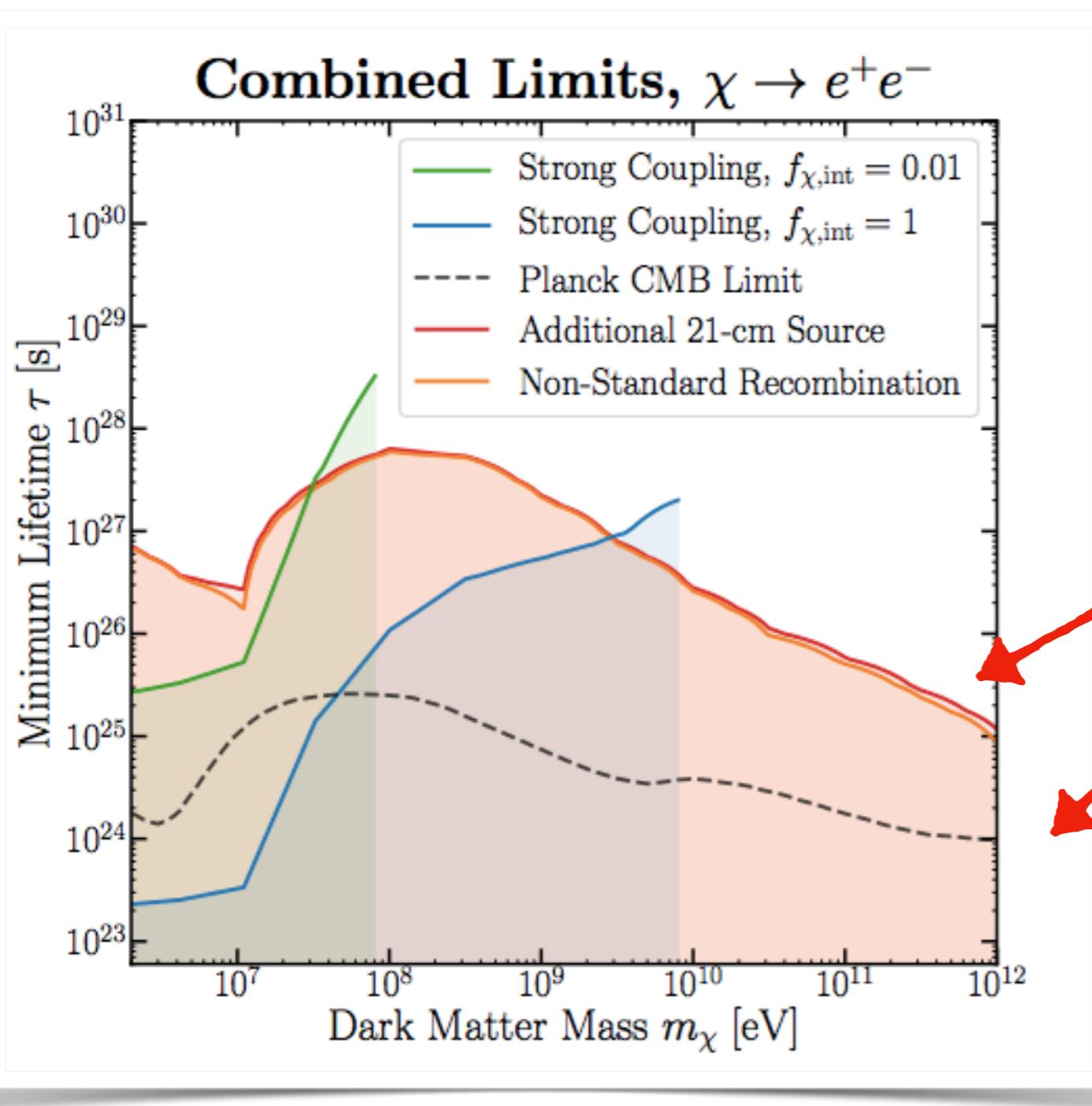
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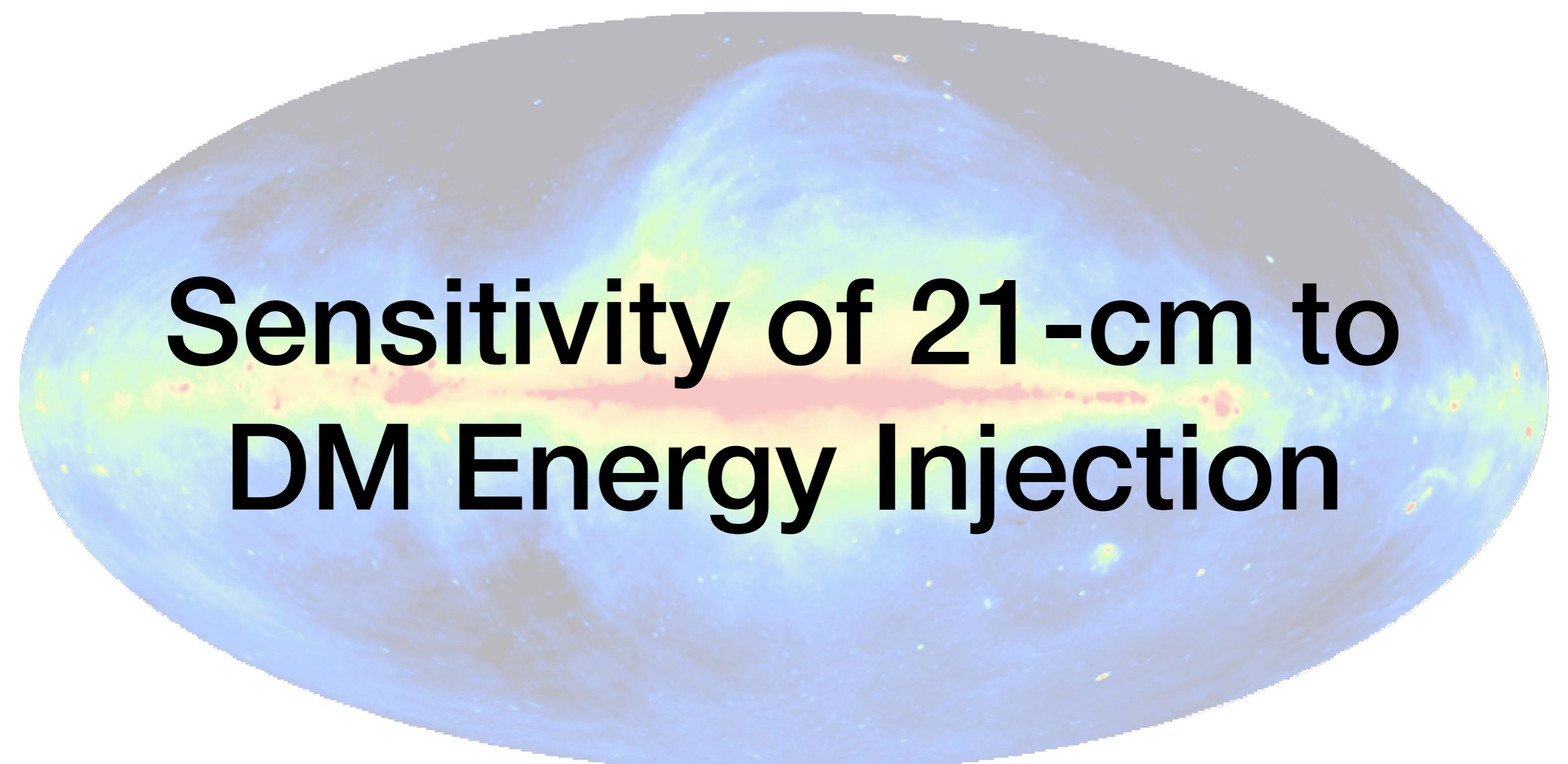
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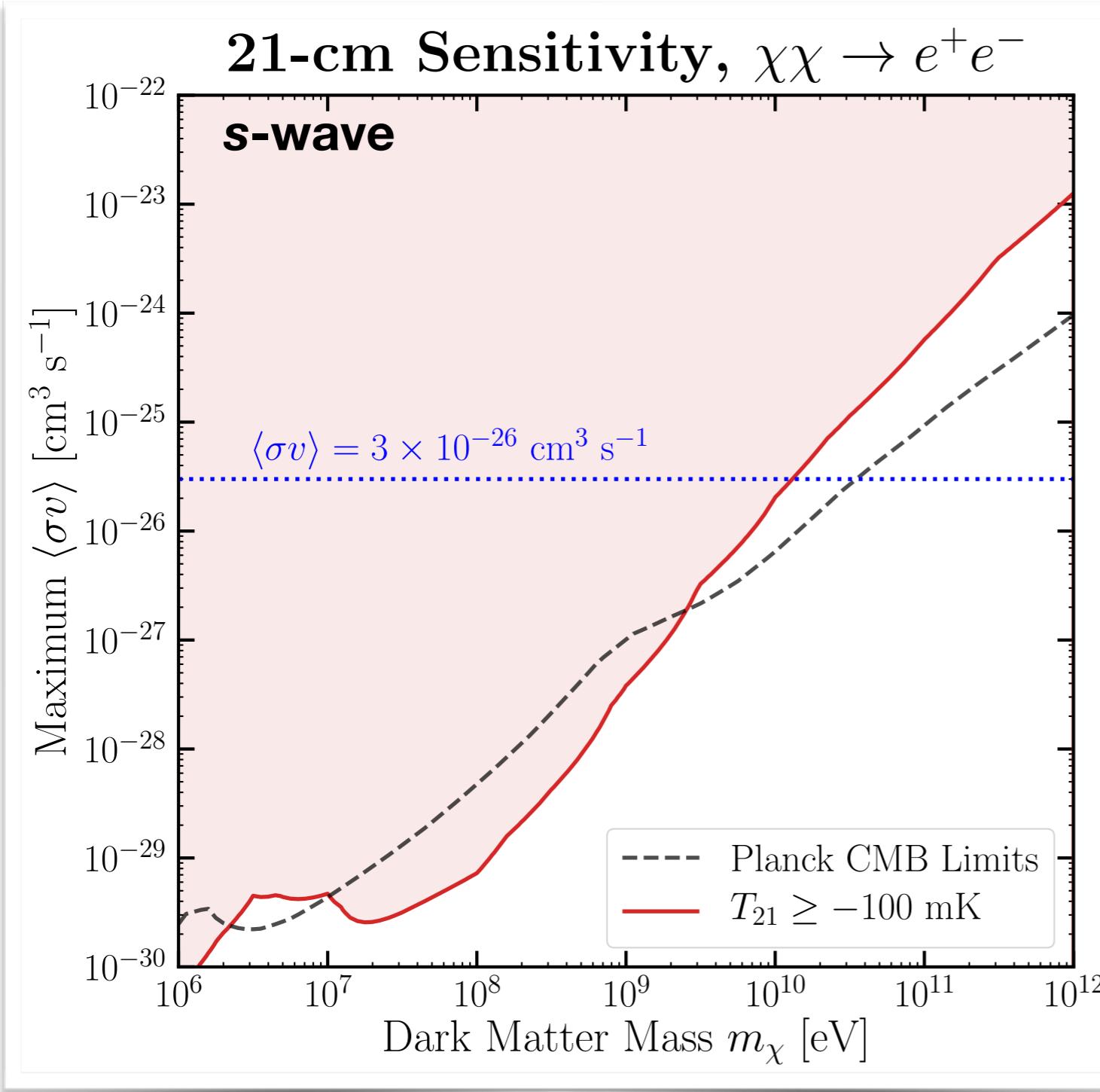
Accounting for **possible novel scenarios** affecting 21-cm absorption, we can set **strong constraints** on **DM annihilation and decay**.

HL & Slatyer 1803.09739

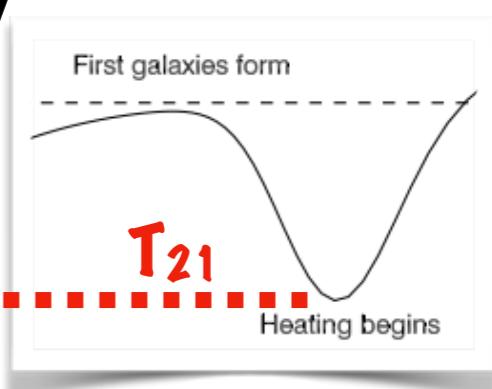


Sensitivity of 21-cm to DM Energy Injection

21-cm Sensitivity



Conventional, no DM:
 $\approx -200 \text{ mK}$

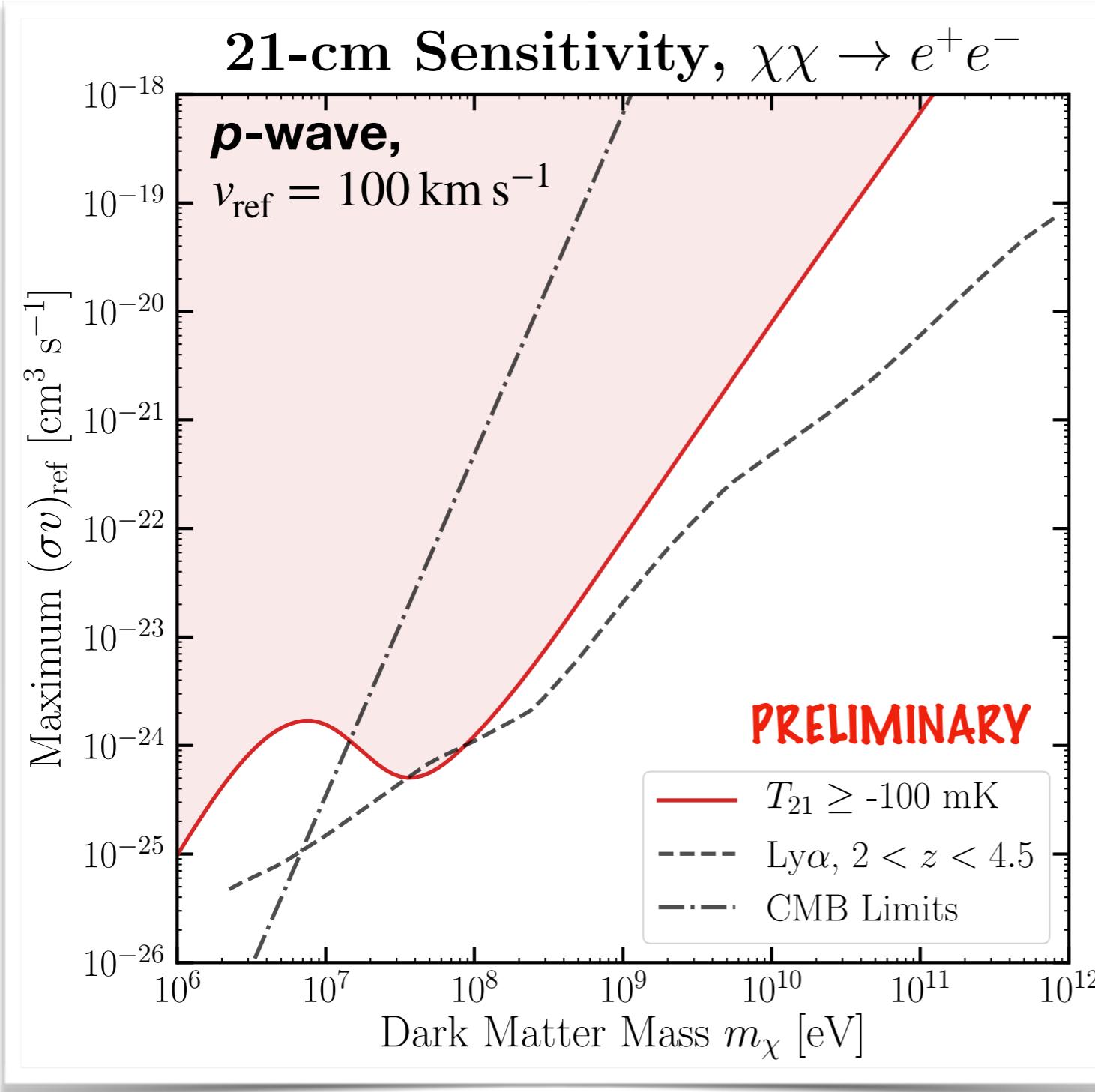


21-cm sensitivity estimated by assuming a measured brightness temperature of $T_{21}(z = 17.2) \geq -100 \text{ mK}$.

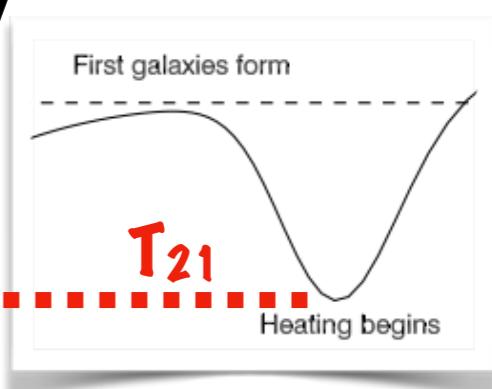
Sets an **upper bound** on T_m , with $T_R = T_{\text{CMB}}$.

Comparable s-wave limits to Planck CMB depending on measured value of T_{21} .

21-cm Sensitivity



Conventional, no DM:
 $\approx -200 \text{ mK}$



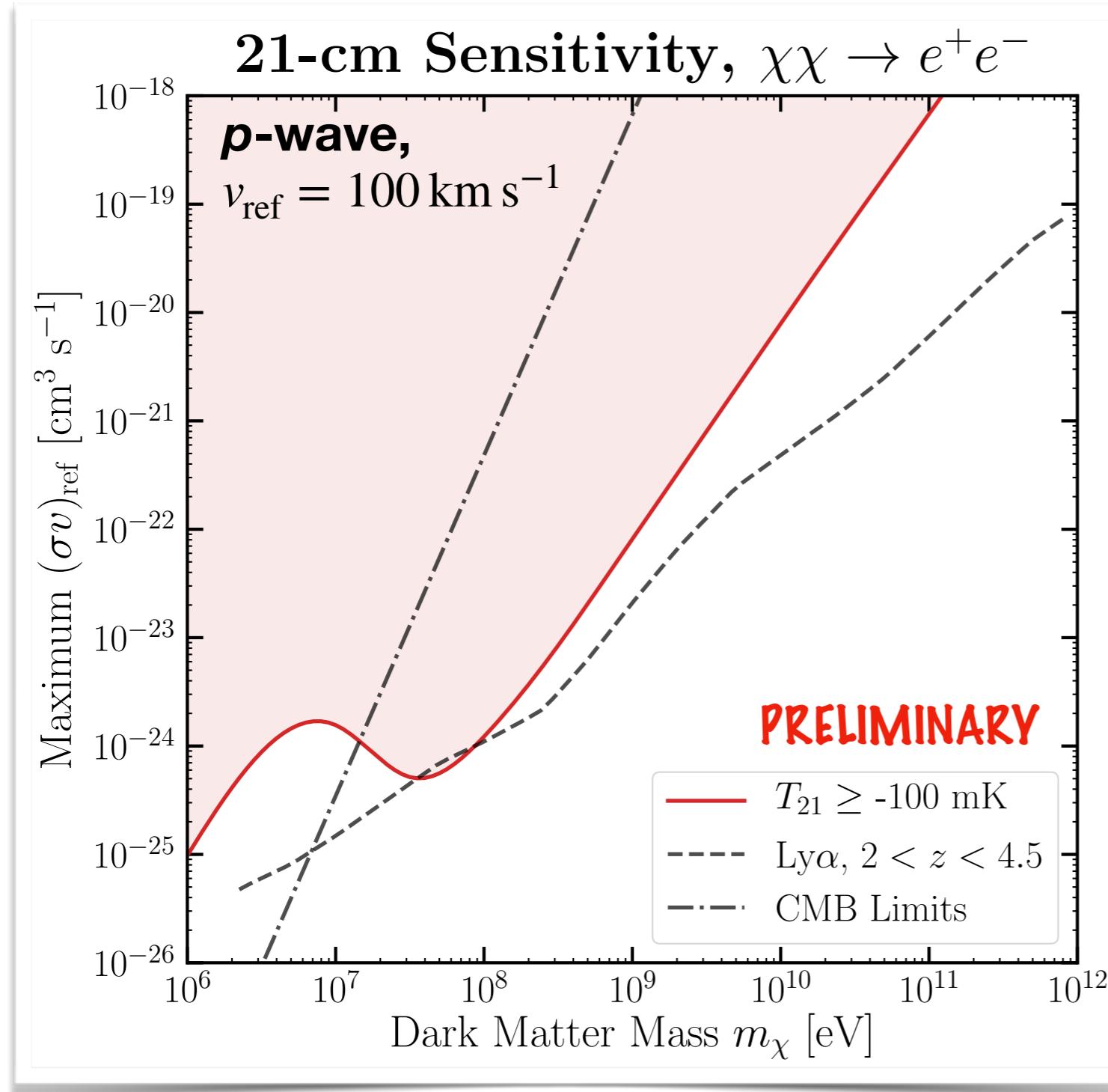
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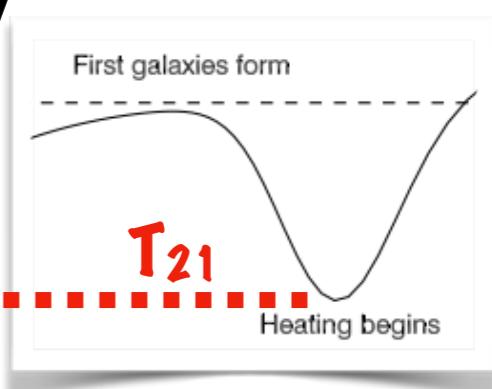
Strong p-wave limits due to enhanced annihilation rate and **heating from structure formation**.

see Essig+ 1309.4091 for present-day indirect detection.

21-cm Sensitivity



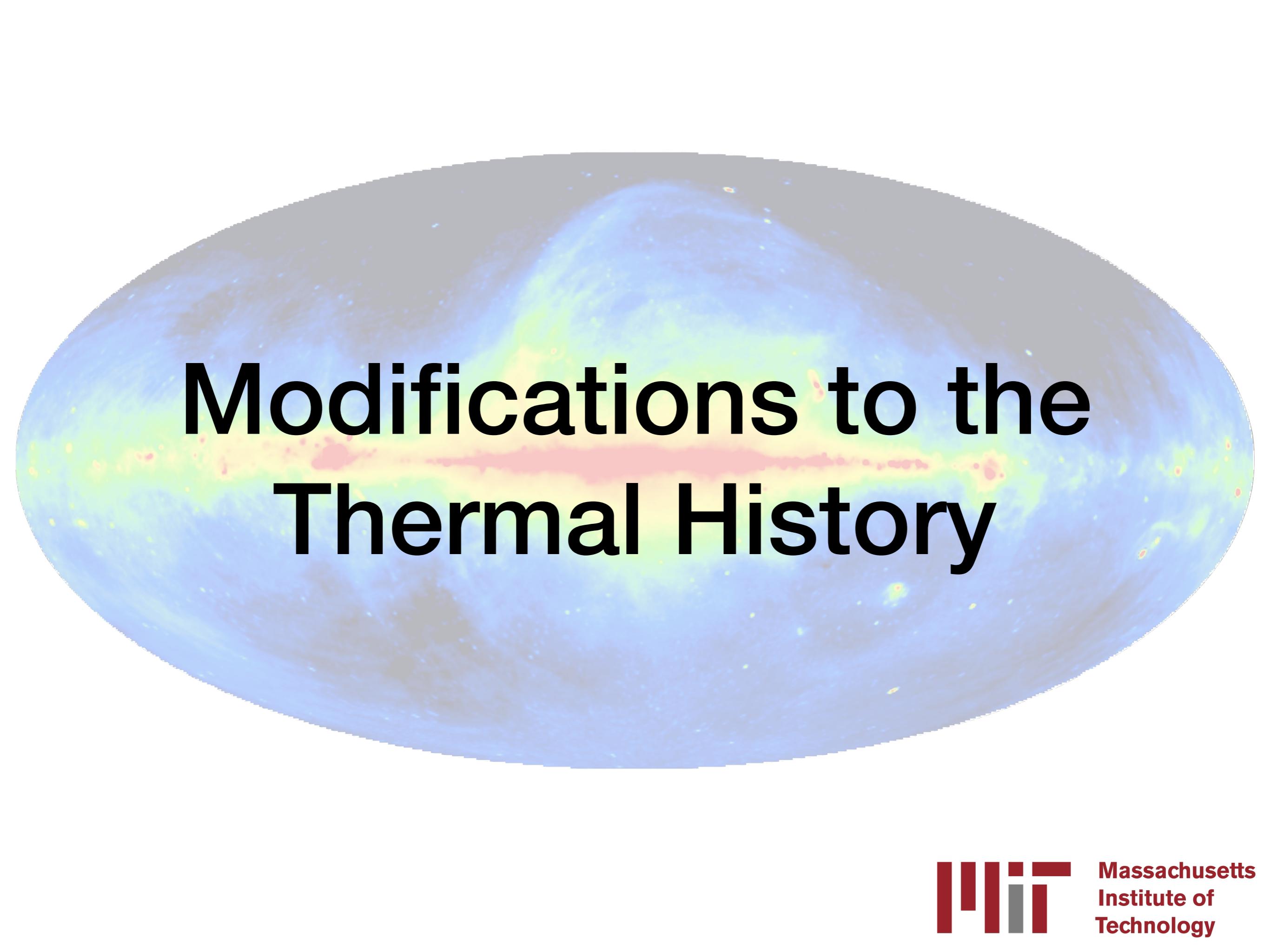
Conventional, no DM:
 $\approx -200 \text{ mK}$



Sensitivity study completely ignores **EDGES measurement**,
 $T_{21}(z = 17.2) \lesssim -300 \text{ mK}$
 at 99% confidence.

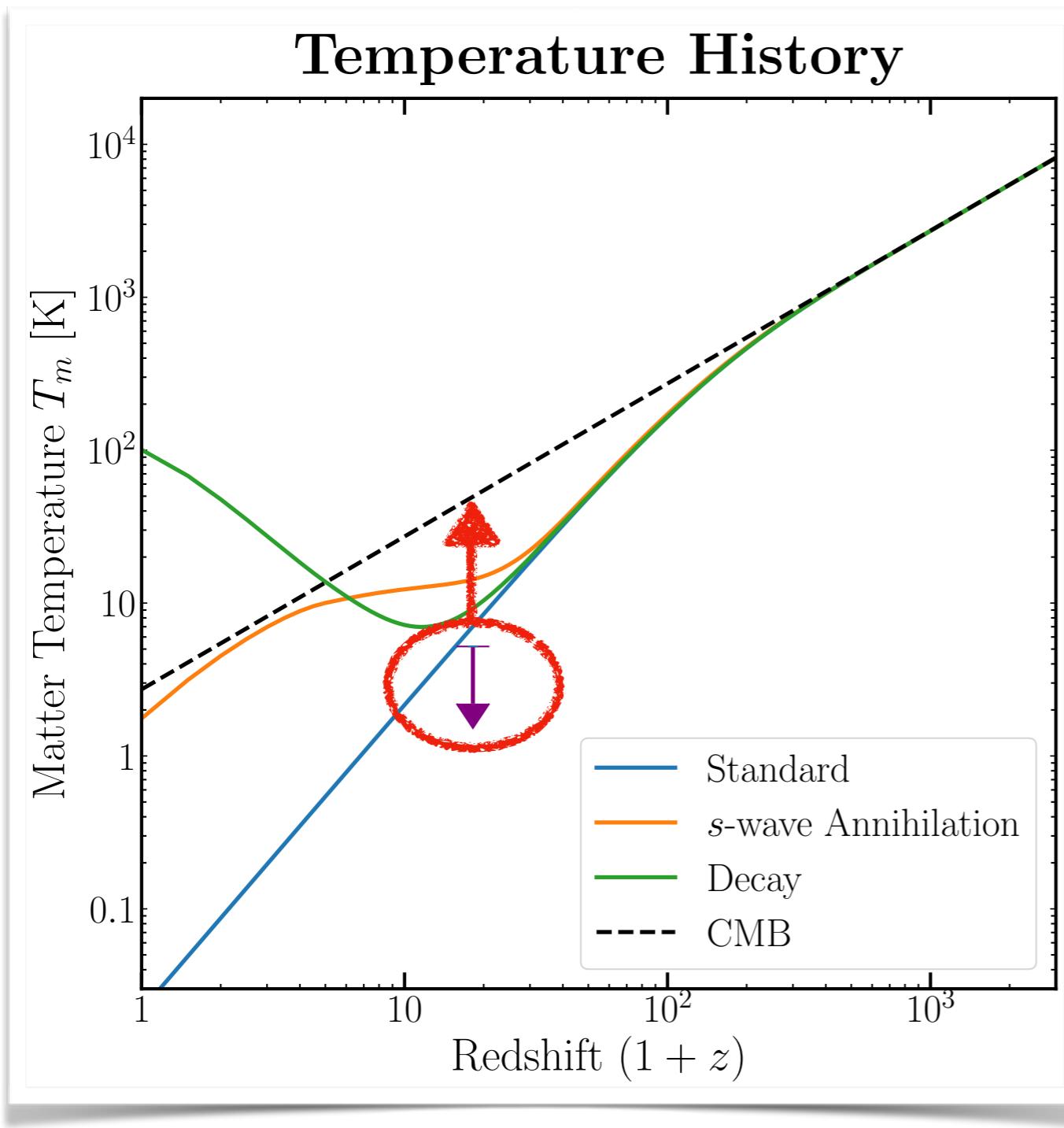
To explain the EDGES result, we must introduce **modifications to the thermal history**.

see Essig+ 1309.4091 for present-day indirect detection.



Modifications to the Thermal History

Additional 21-cm Source



DM decays to 21-cm photons
 Fraser+ 1803.03245

Dark photon/ALP interaction with 21-cm photons
 Pospelov+ 1803.07048
 Moroi+ 1804.10378
 Lambiase and Mohanty 1804.05318

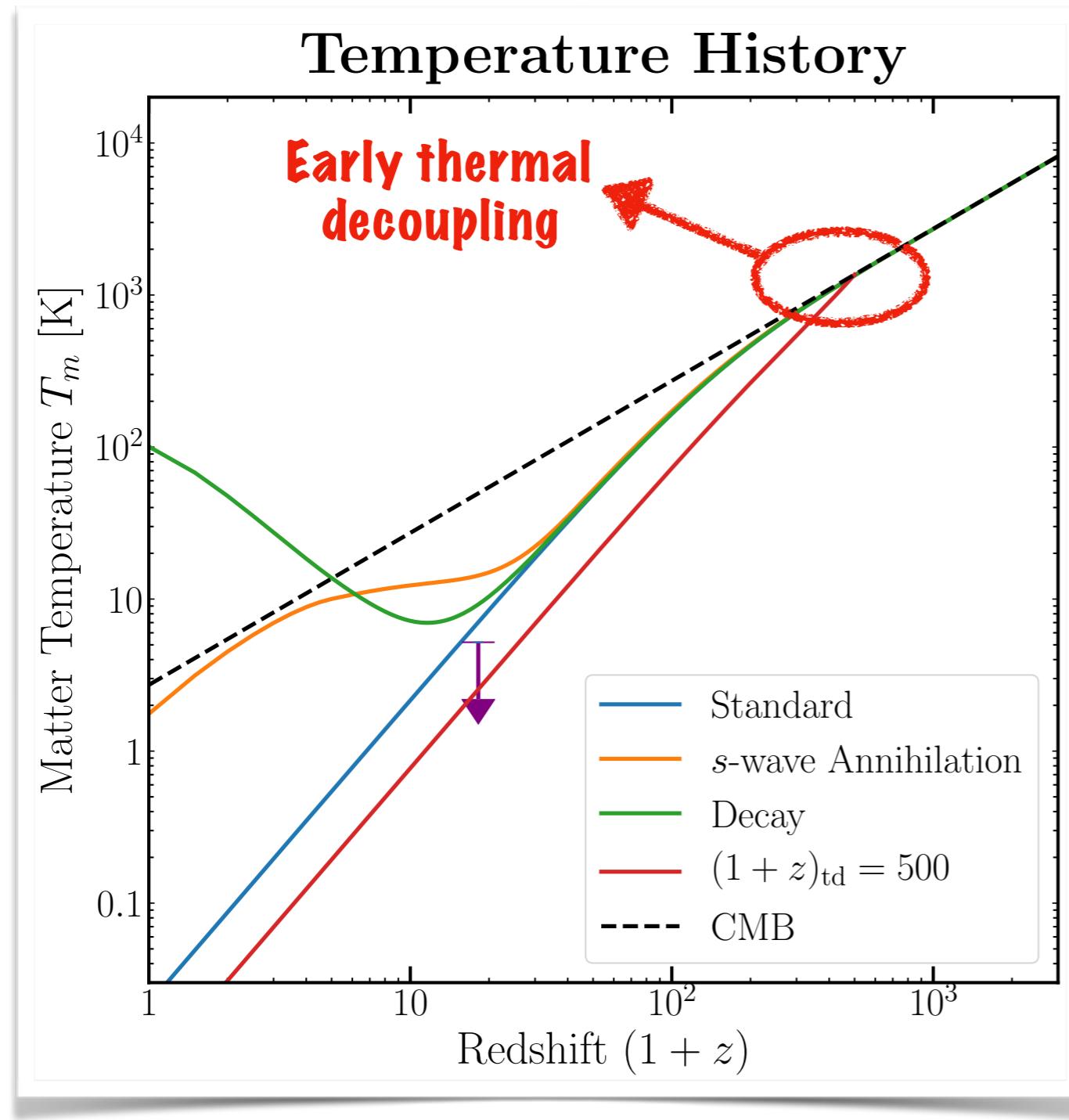
Emission from black holes
 Ewall-Wice+ 1803.01815,
 Gong+ 1803.02745

$$\frac{T_m}{T_R}(z = 17.2) \lesssim 0.105$$

$T_R > T_{\text{CMB}}$



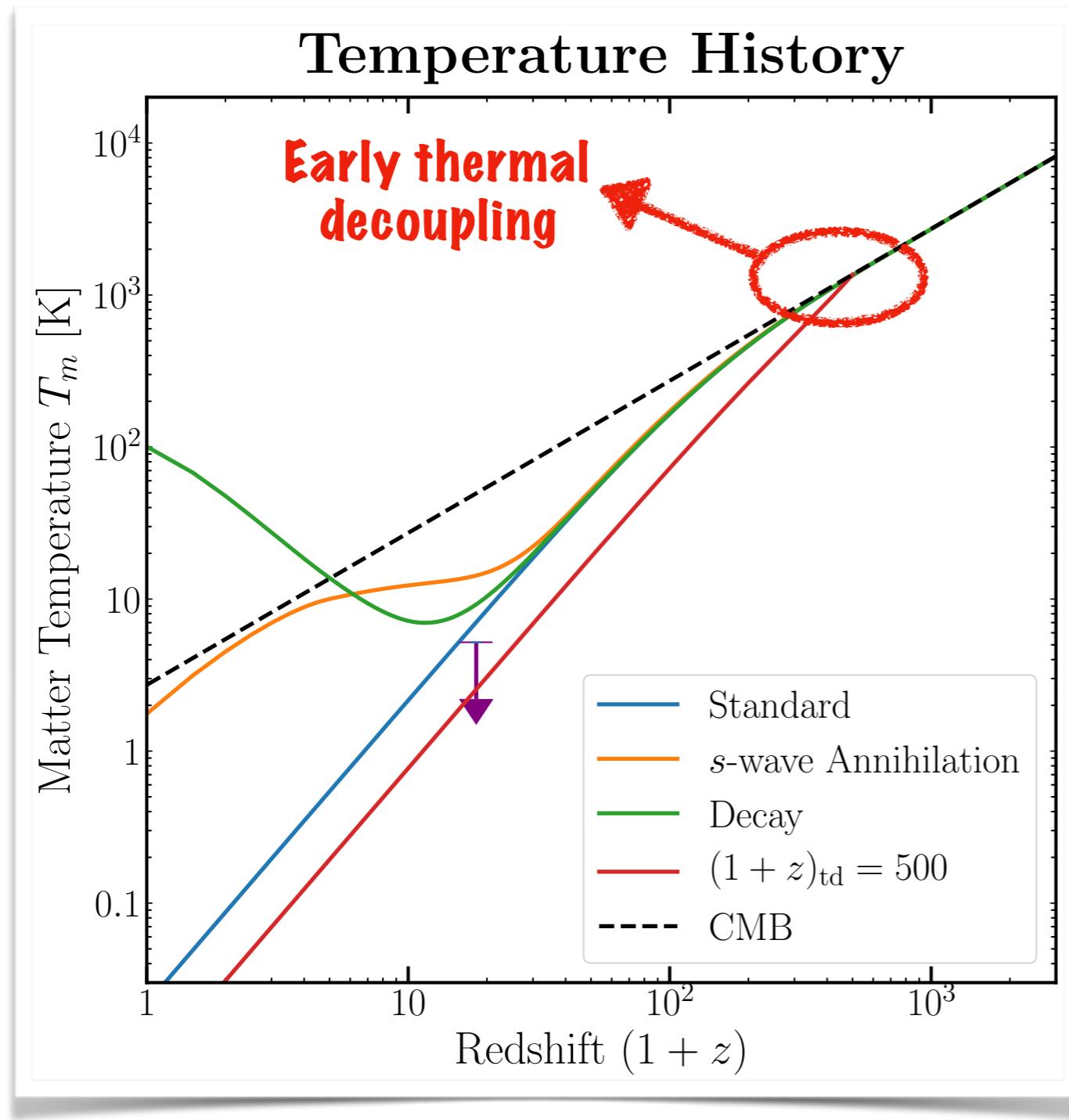
Modified Recombination



Thermal decoupling set by when **Compton heating** becomes less important than **adiabatic cooling**:

$$(1 + z)_{\text{td},0} \approx \left[\frac{45m_e H_0 \sqrt{\Omega_m}}{4\pi^2 \sigma_T x_e T_{\gamma,0}^4} \right]^{2/5}$$

Modified Recombination



Additional component that interacts with baryons
Limiting case of cooling models

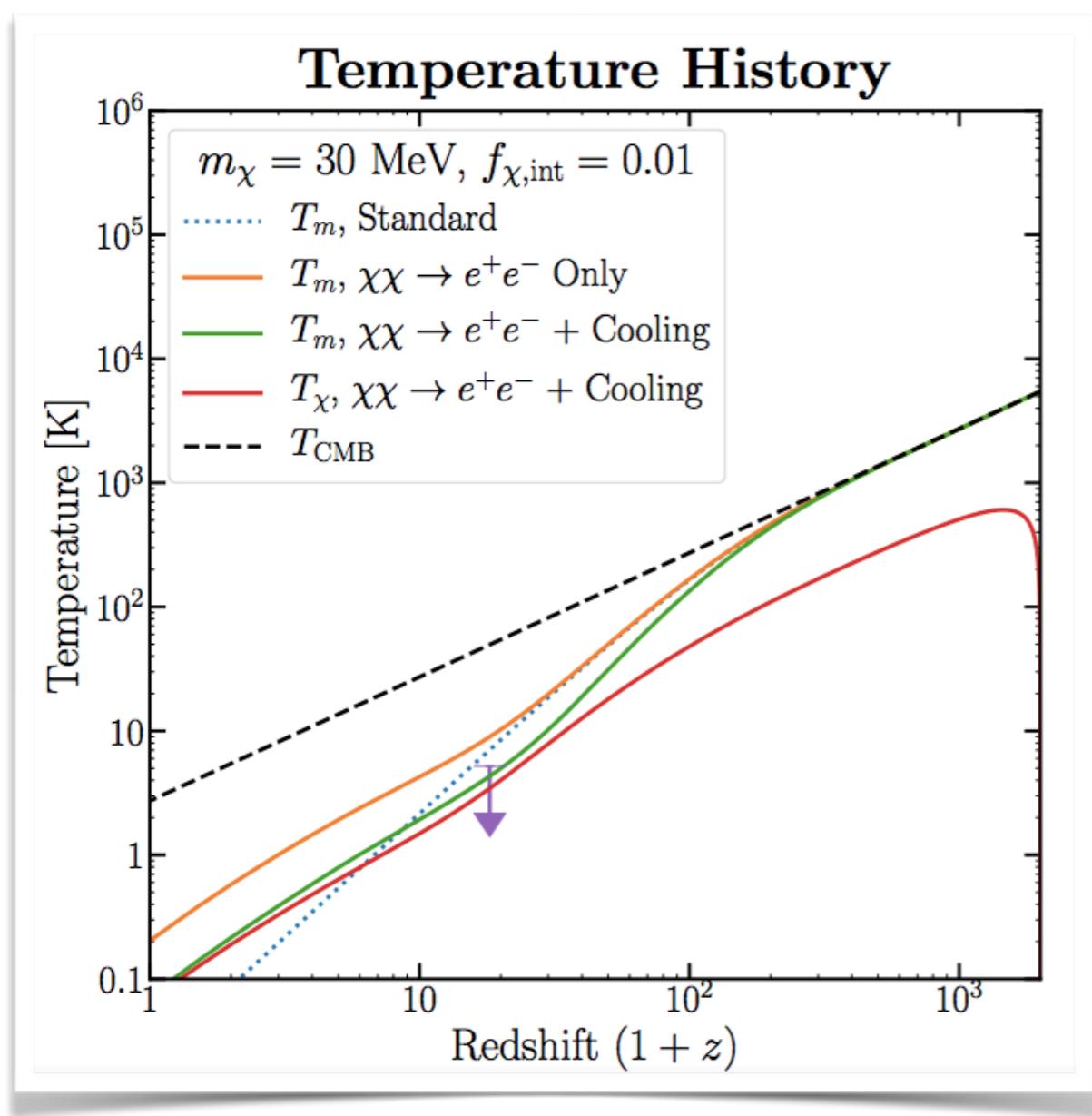
Unequal proton and electron density
Falkowski and Petraki 1803.10096

Early dark energy
Hill and Baxter 1803.07555

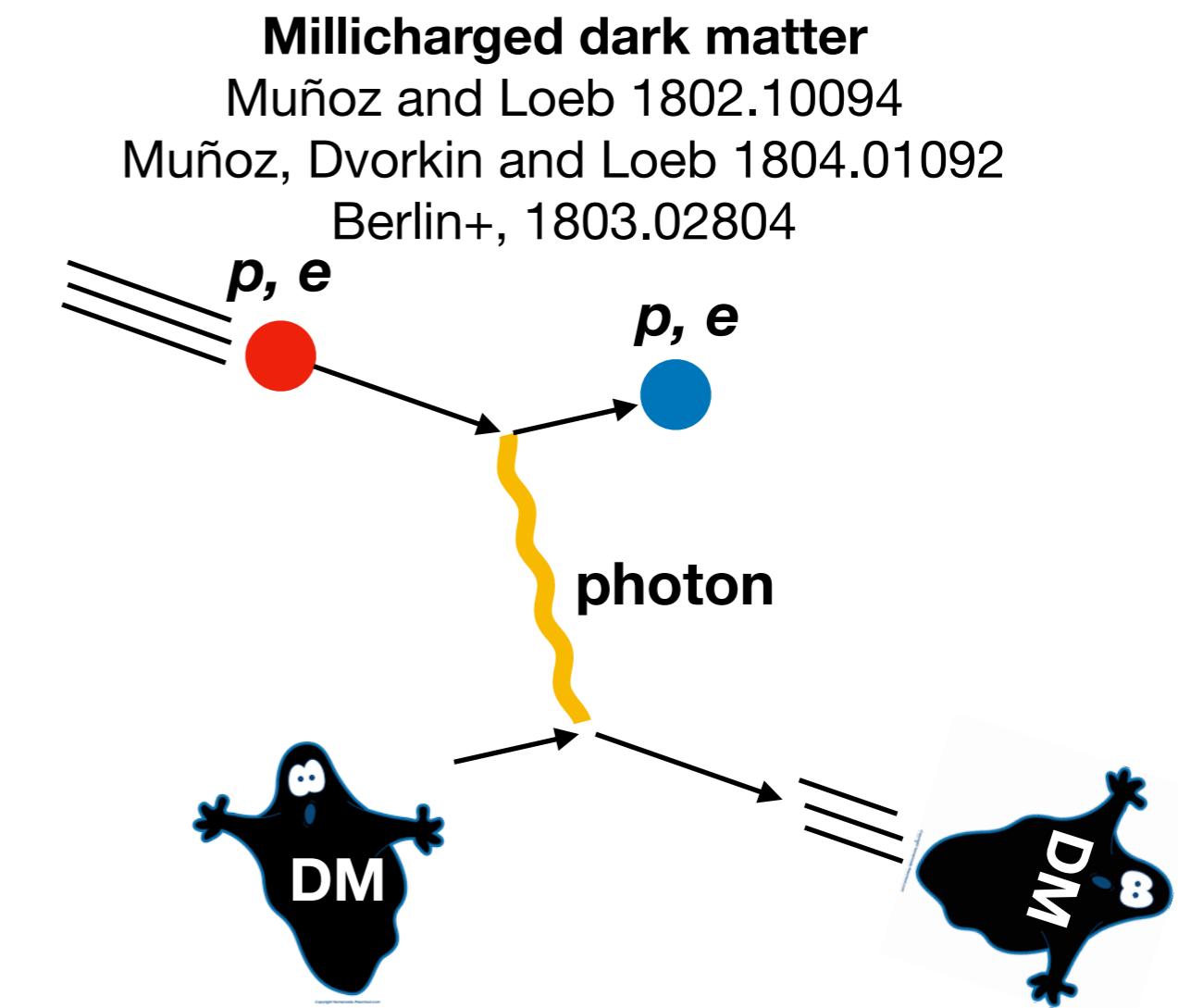


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Cooling - Millicharged DM



HL and Slatyer 1803.09739

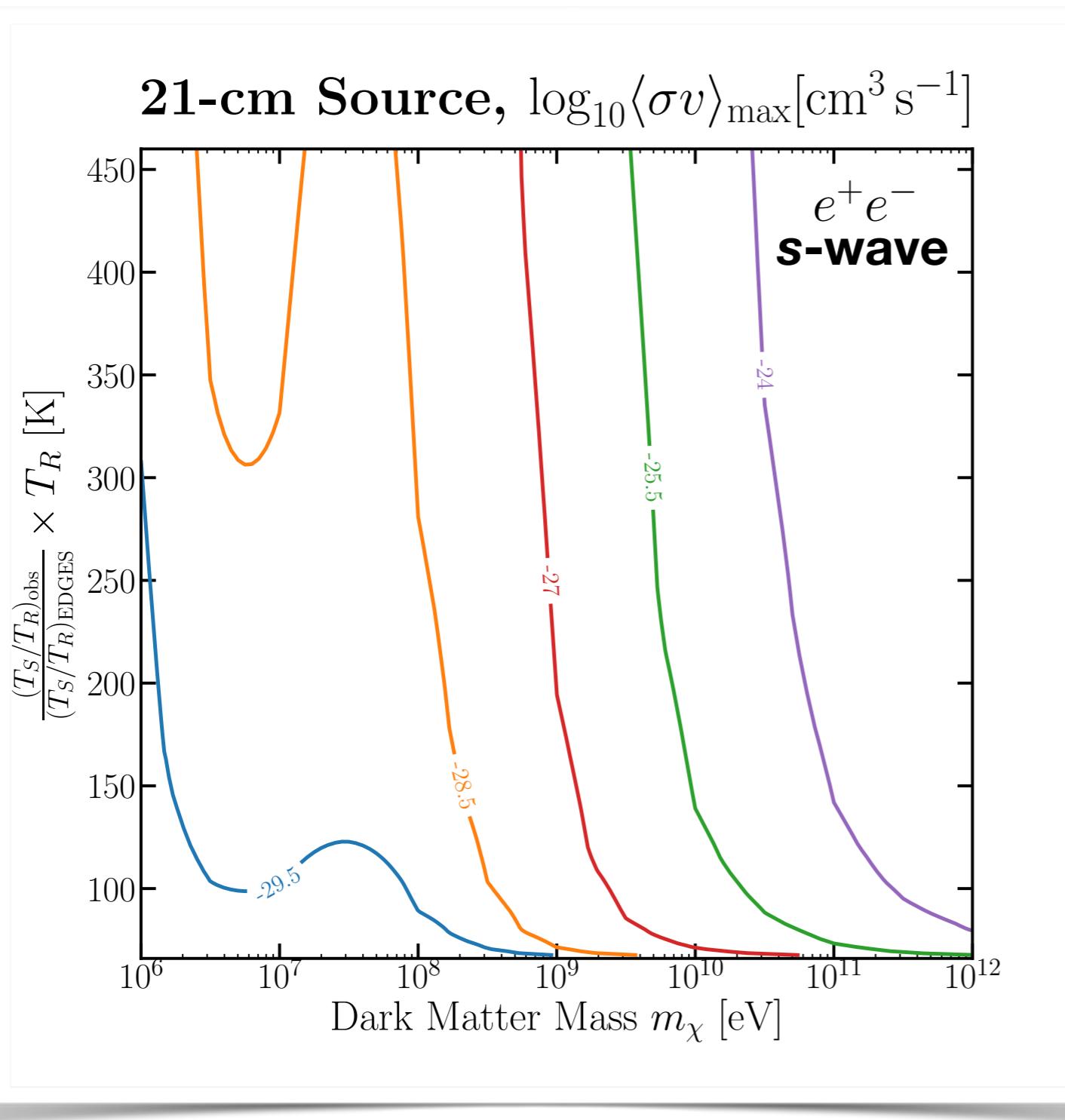


Focus on case where **1% of DM is millicharged**: higher percentages ruled out by **CMB power spectrum**.
 e.g. Slatyer and Wu 1803.09734, de Putter+ 1805.11616

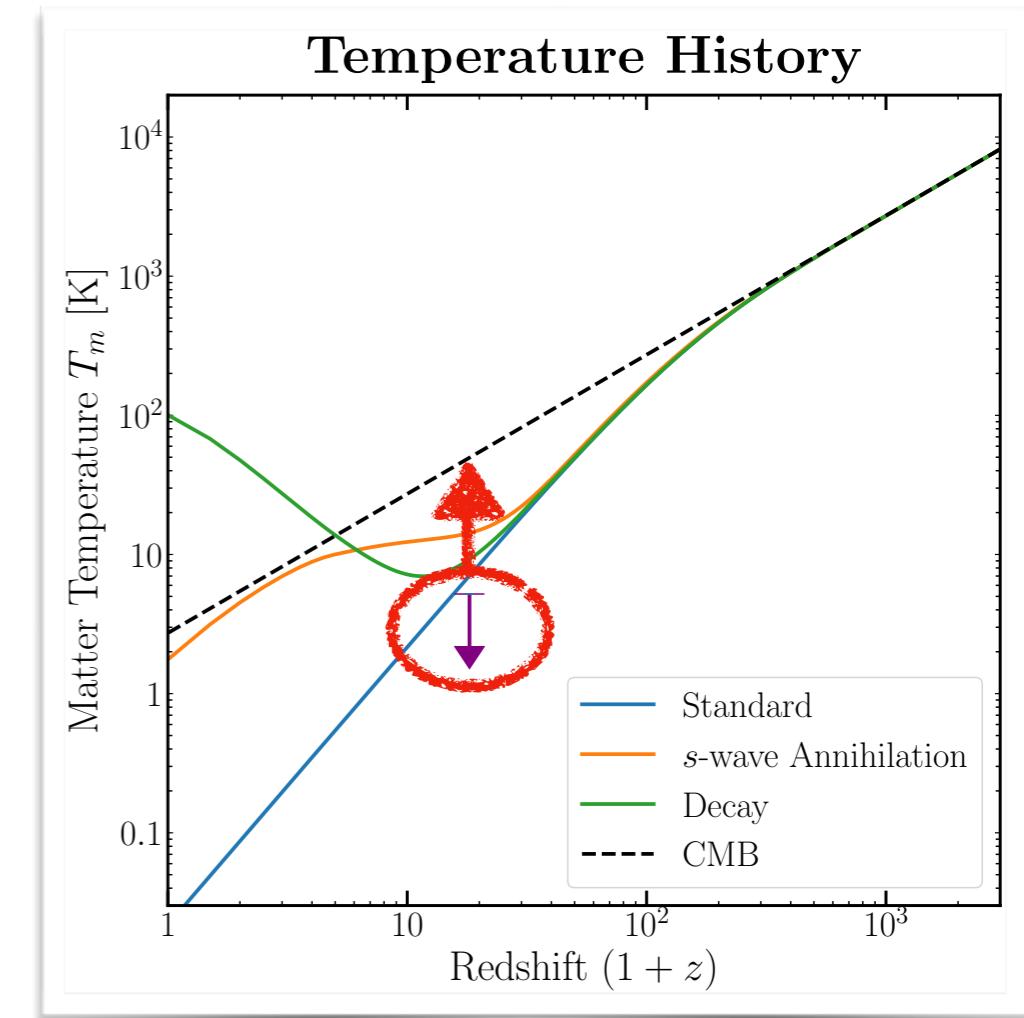


21-cm Constraints on Dark Matter

Additional 21-cm Source



HL and Slatyer 1803.09739



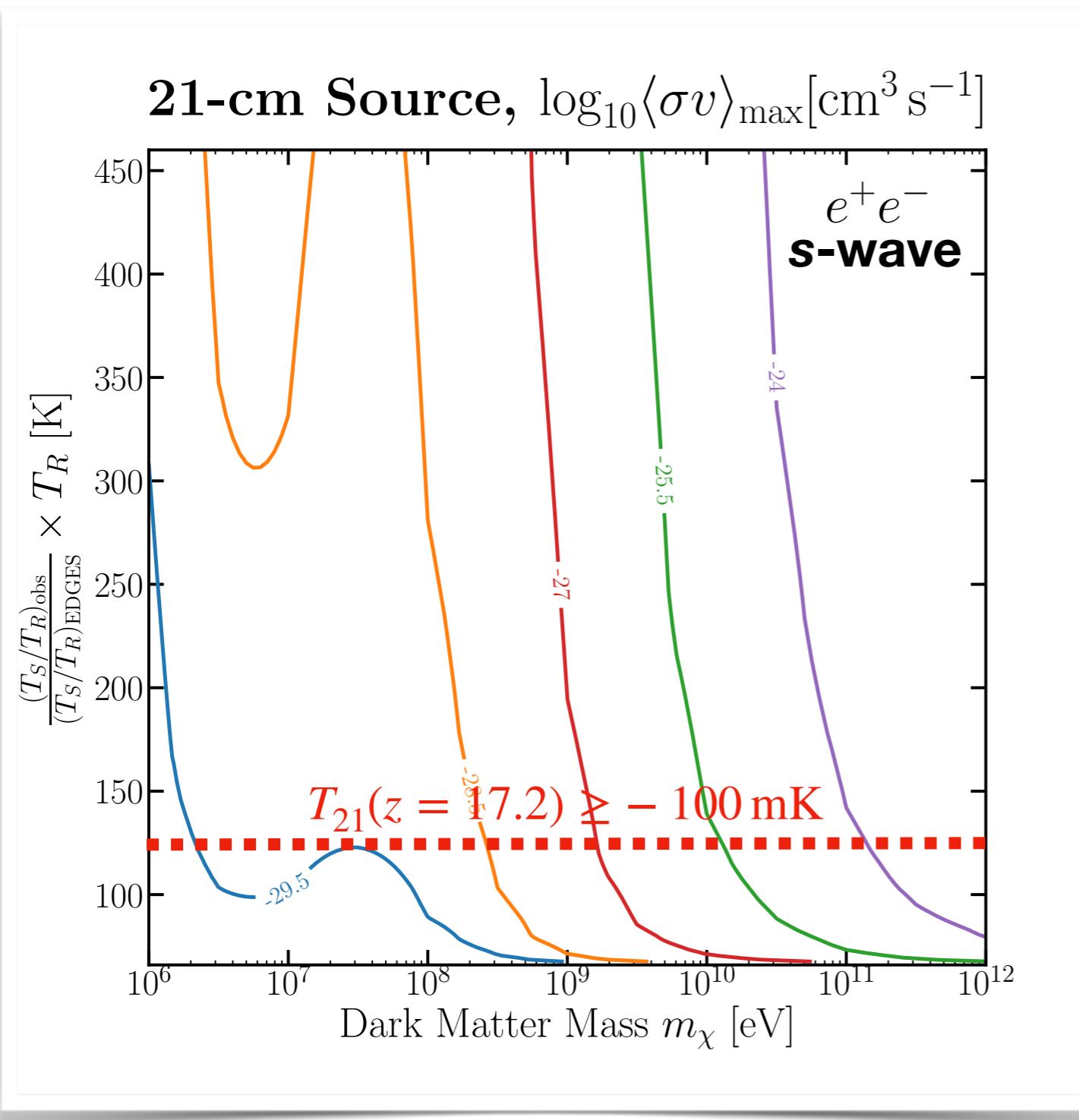
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$T_R > T_{\text{CMB}}$



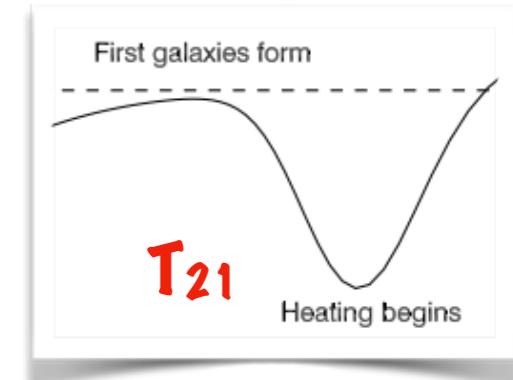
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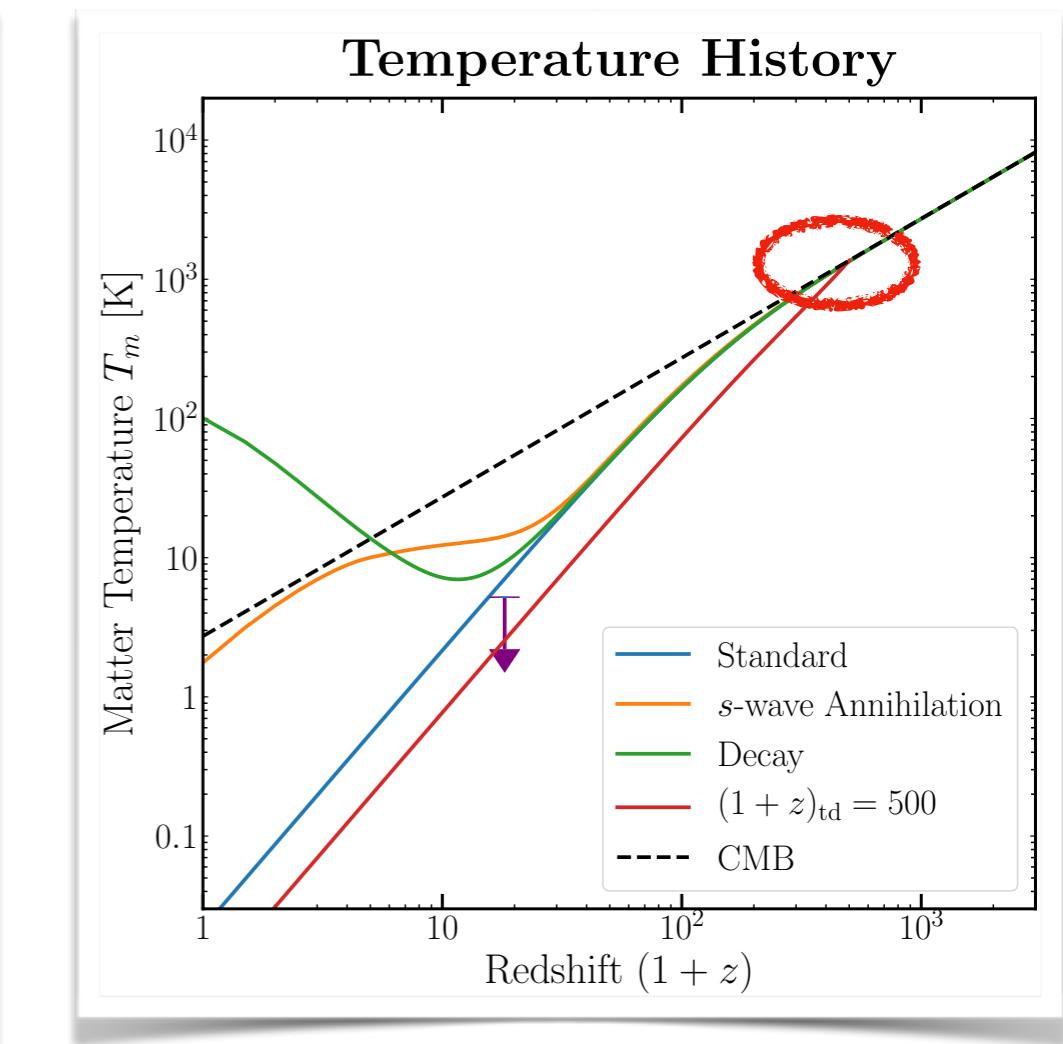
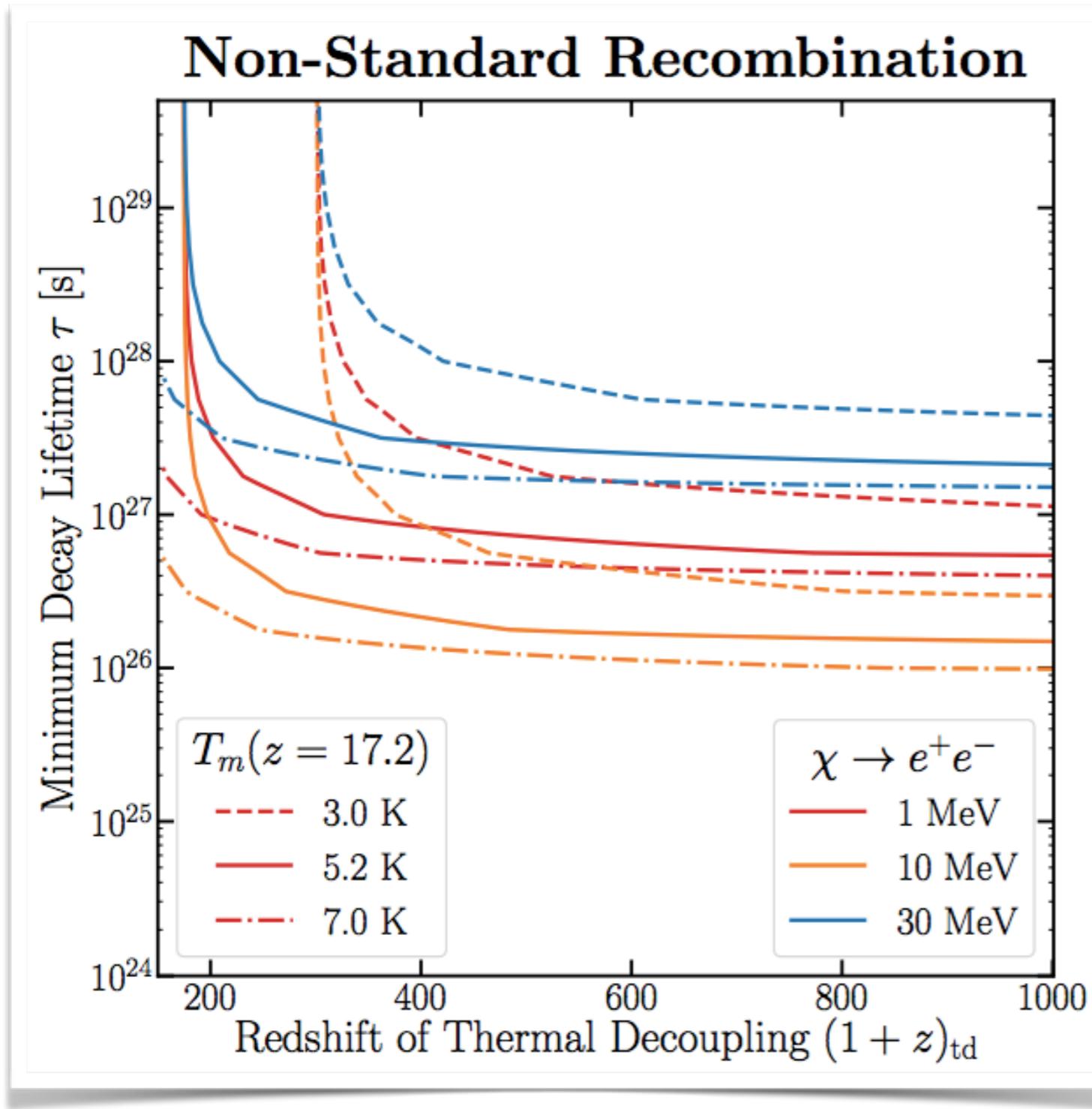


Horizontal slices of this plot can be reinterpreted as limits from sensitivity study.

Constraints can be obtained for any **future T_{21} measurement.**

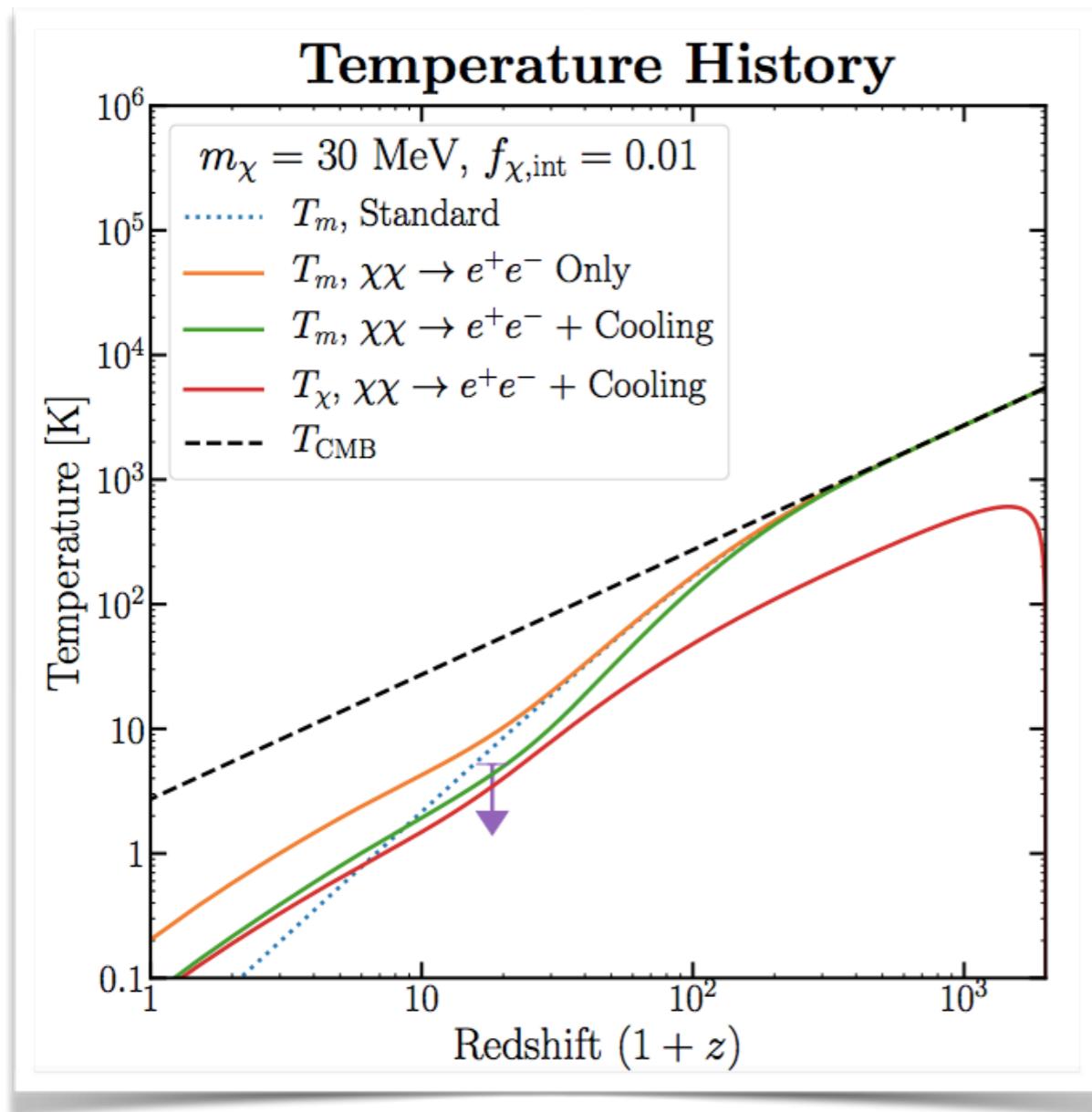


Modified Recombination



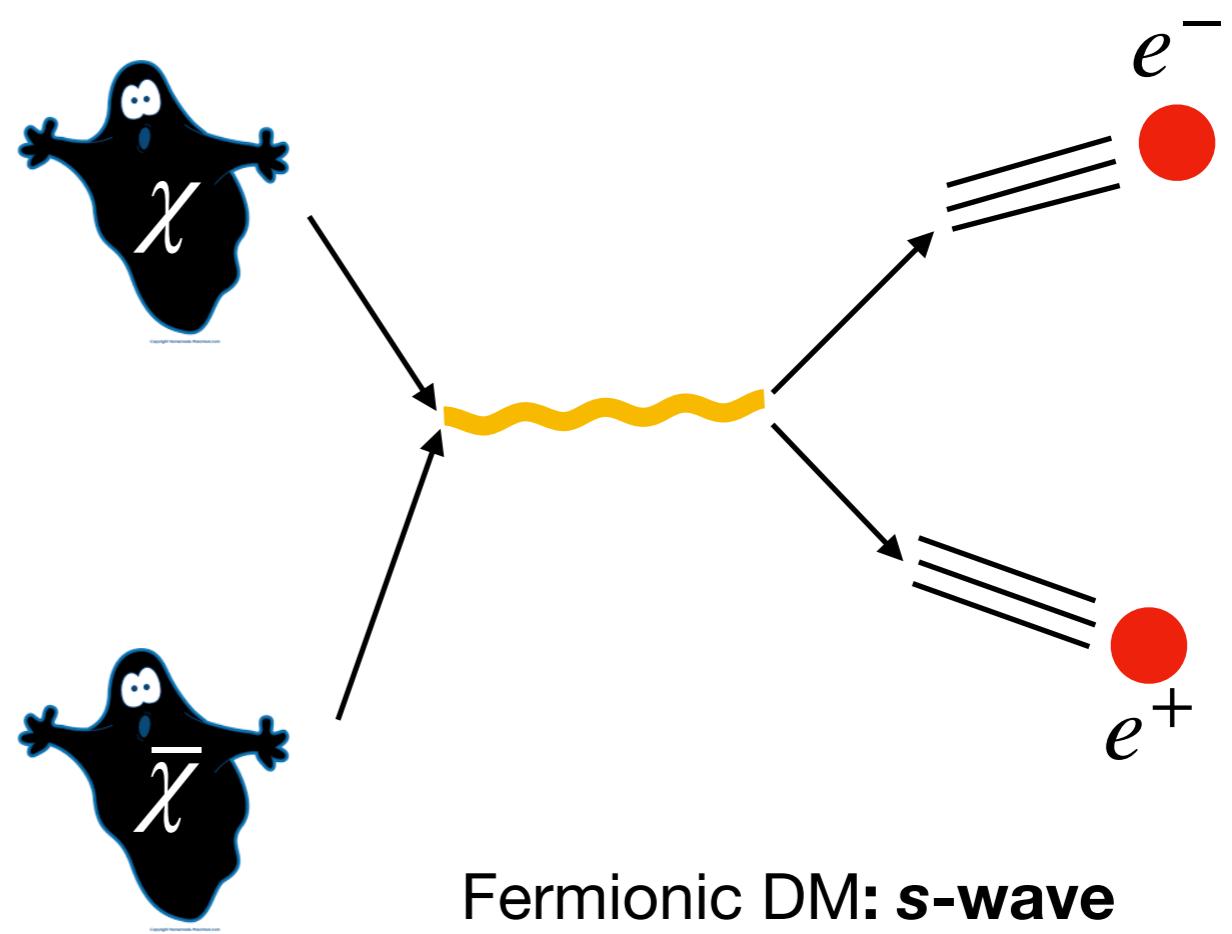
Limits are relatively **independent** of **redshift of thermal decoupling**: set by rate required to raise the temperature by ~ 10 K.

Millicharged DM



HL and Slatyer 1803.09739

Millicharged, symmetric DM has **irreducible annihilation channel** into electrons:
 Additional heating sets constraints.

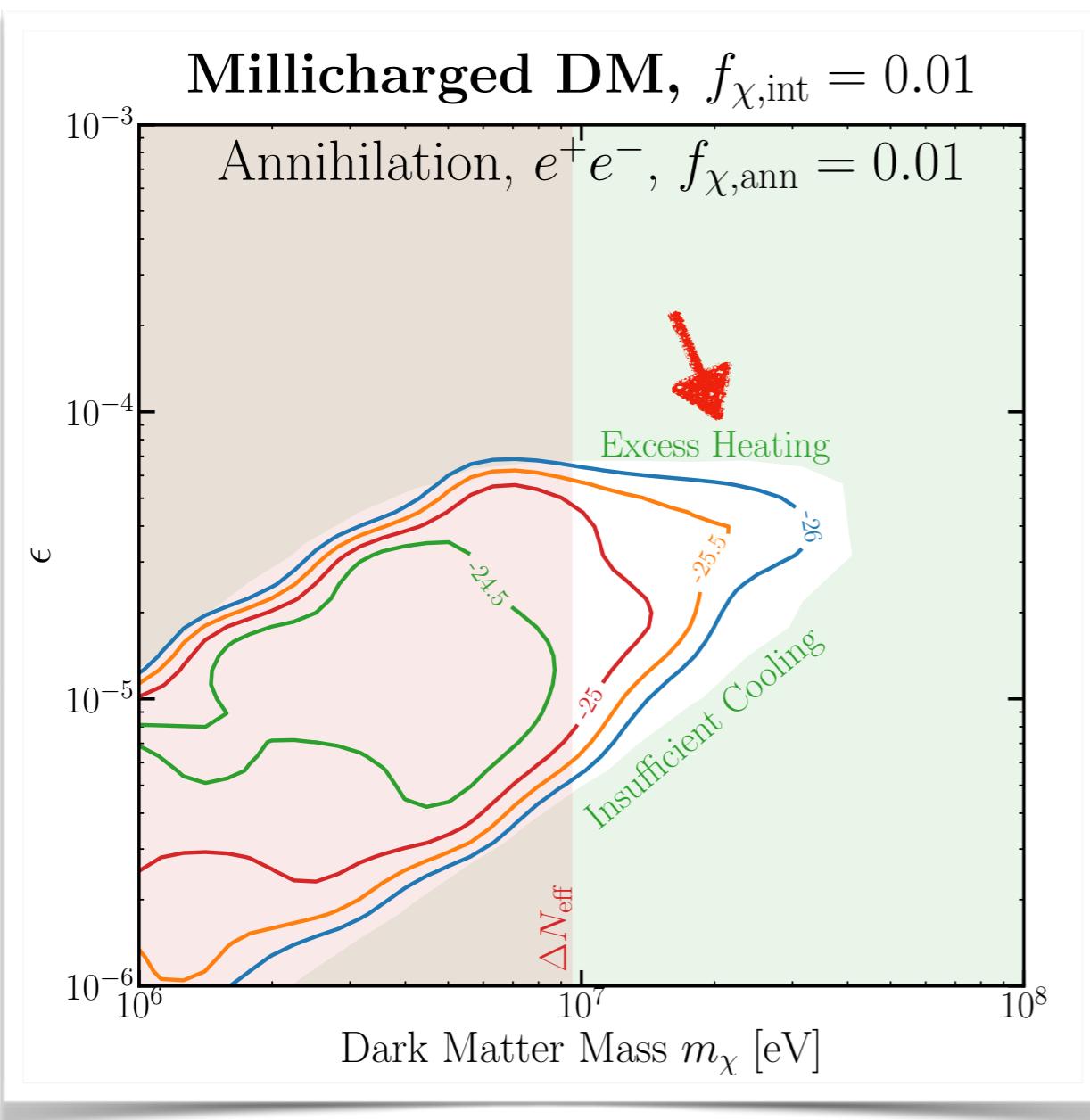


Fermionic DM: **s-wave**
 Complex Scalar DM: **p-wave**



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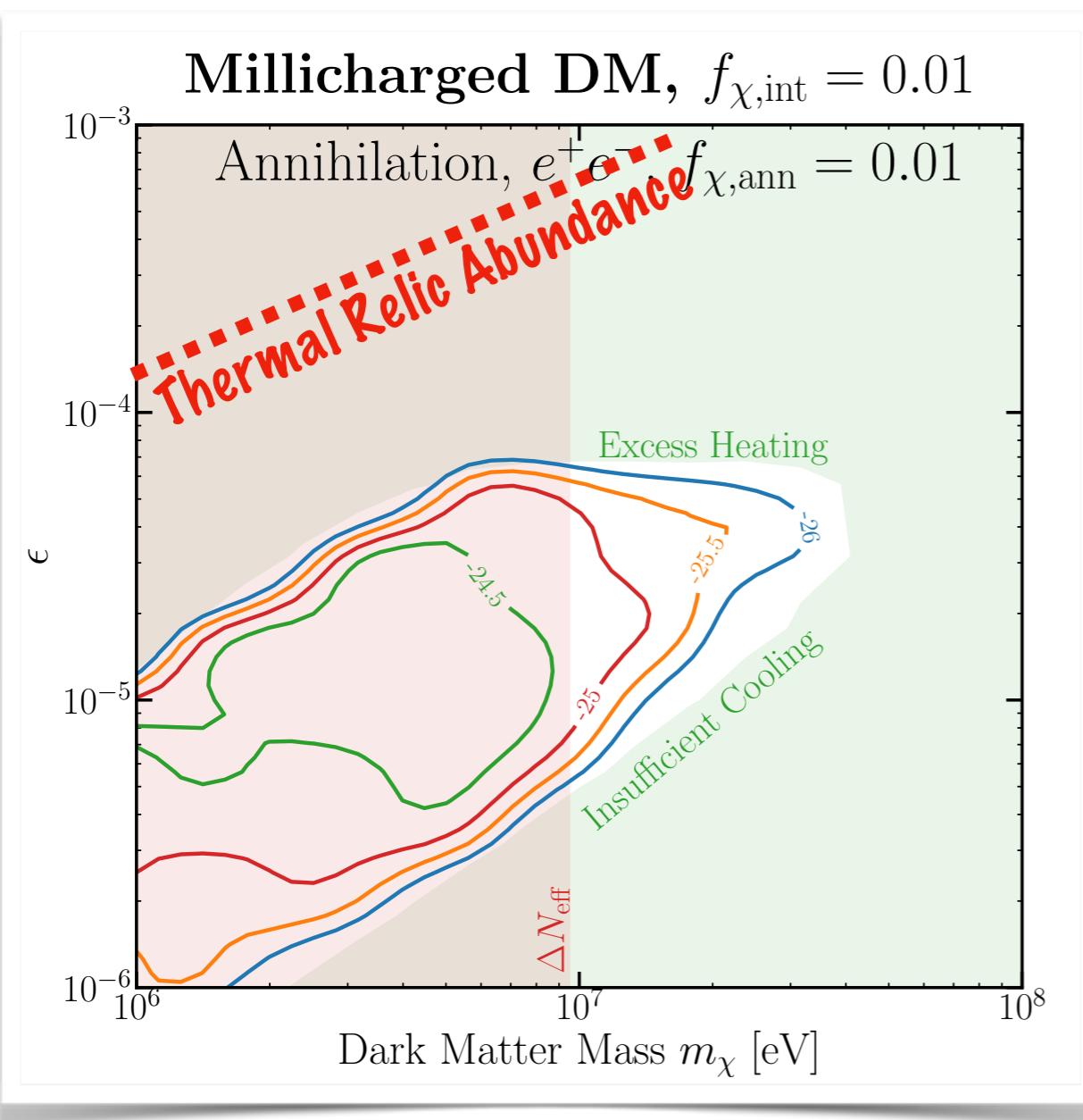
Millicharged Fermionic DM



HL and Slatyer 1803.09739

Irreducible **s-wave annihilation** to electron pairs: large couplings constrained due to **heating** from these annihilations.

Millicharged Fermionic DM



HL and Slatyer 1803.09739

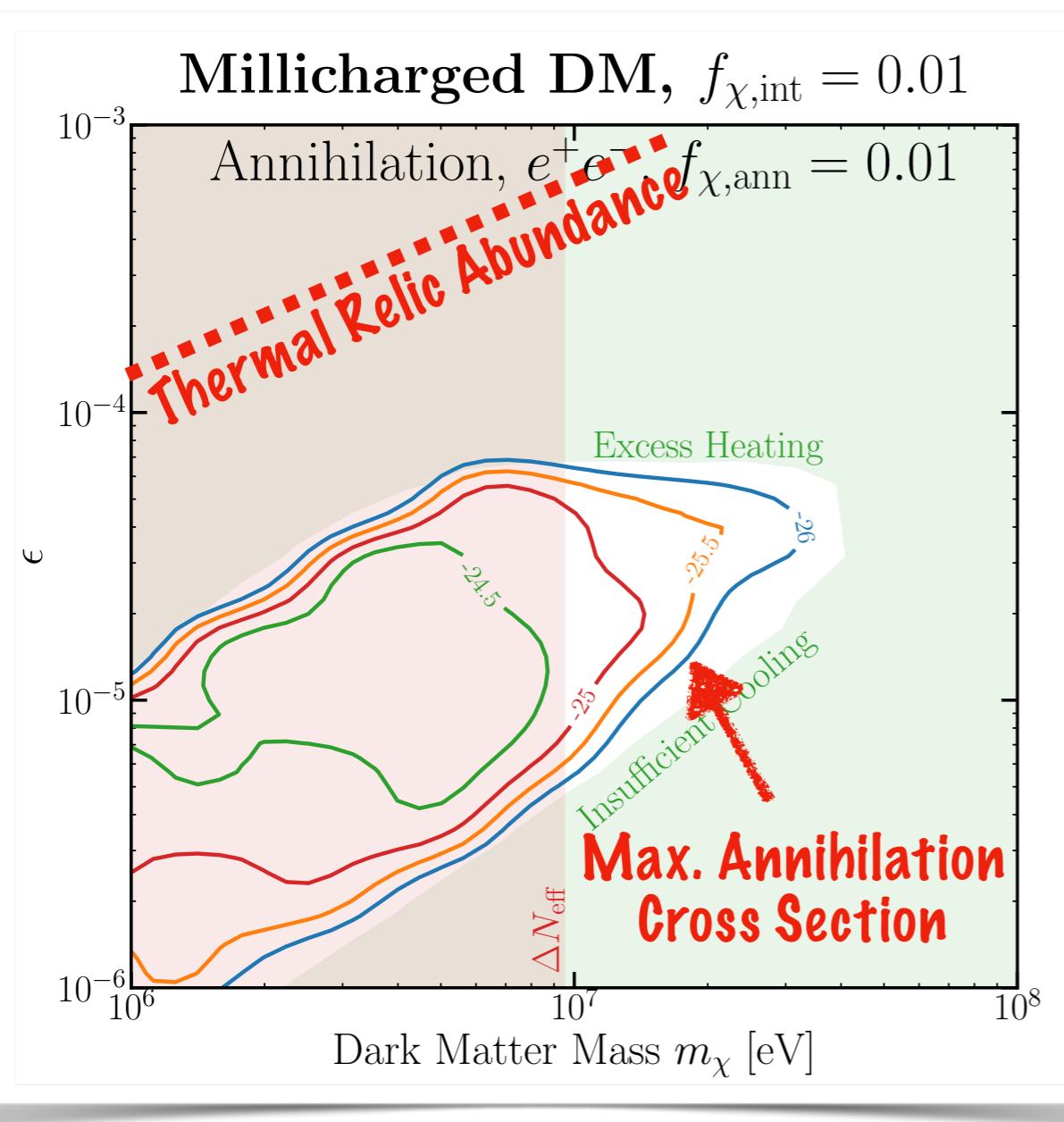
Irreducible **s-wave annihilation** to electron pairs: large couplings constrained due to **heating** from these annihilations.

Thermal relic abundance from $\chi\bar{\chi} \rightarrow \gamma^* \rightarrow e^+e^-$ is **ruled out**.

Additional annihilation channel to electrons in the allowed region required to achieve correct relic abundance.

see Berlin+ 1803.02804

Millicharged Fermionic DM



HL and Slatyer 1803.09739

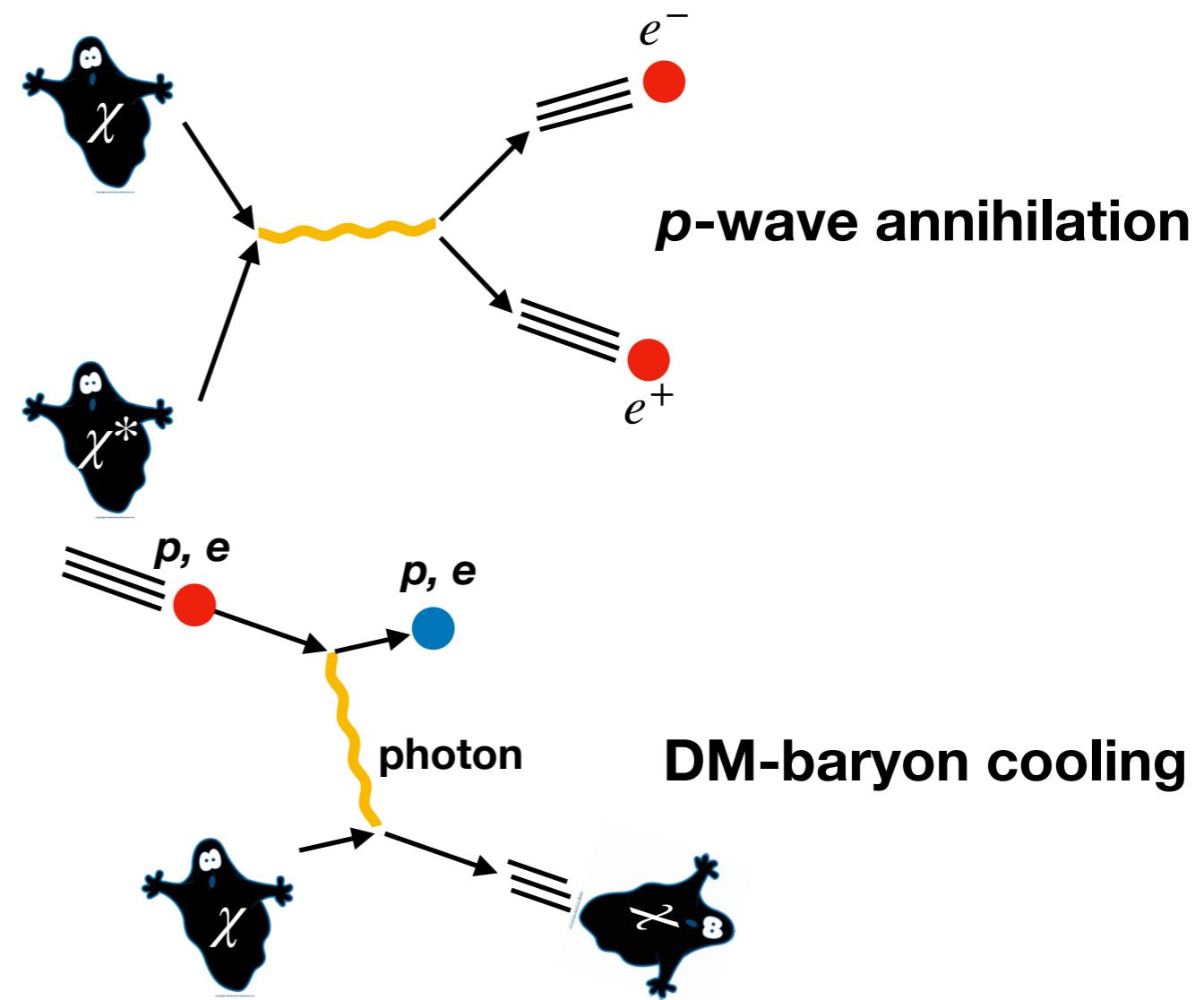
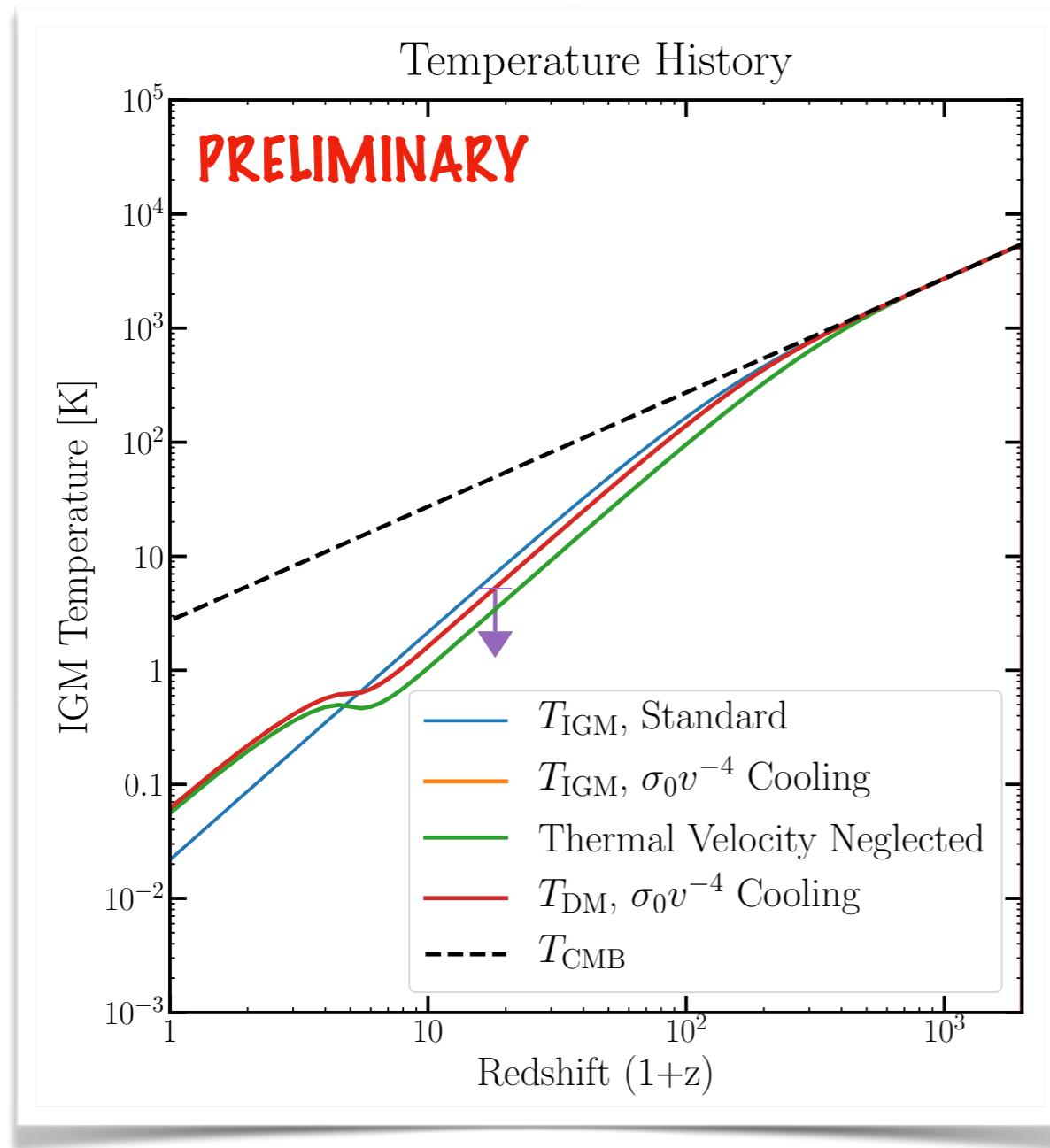
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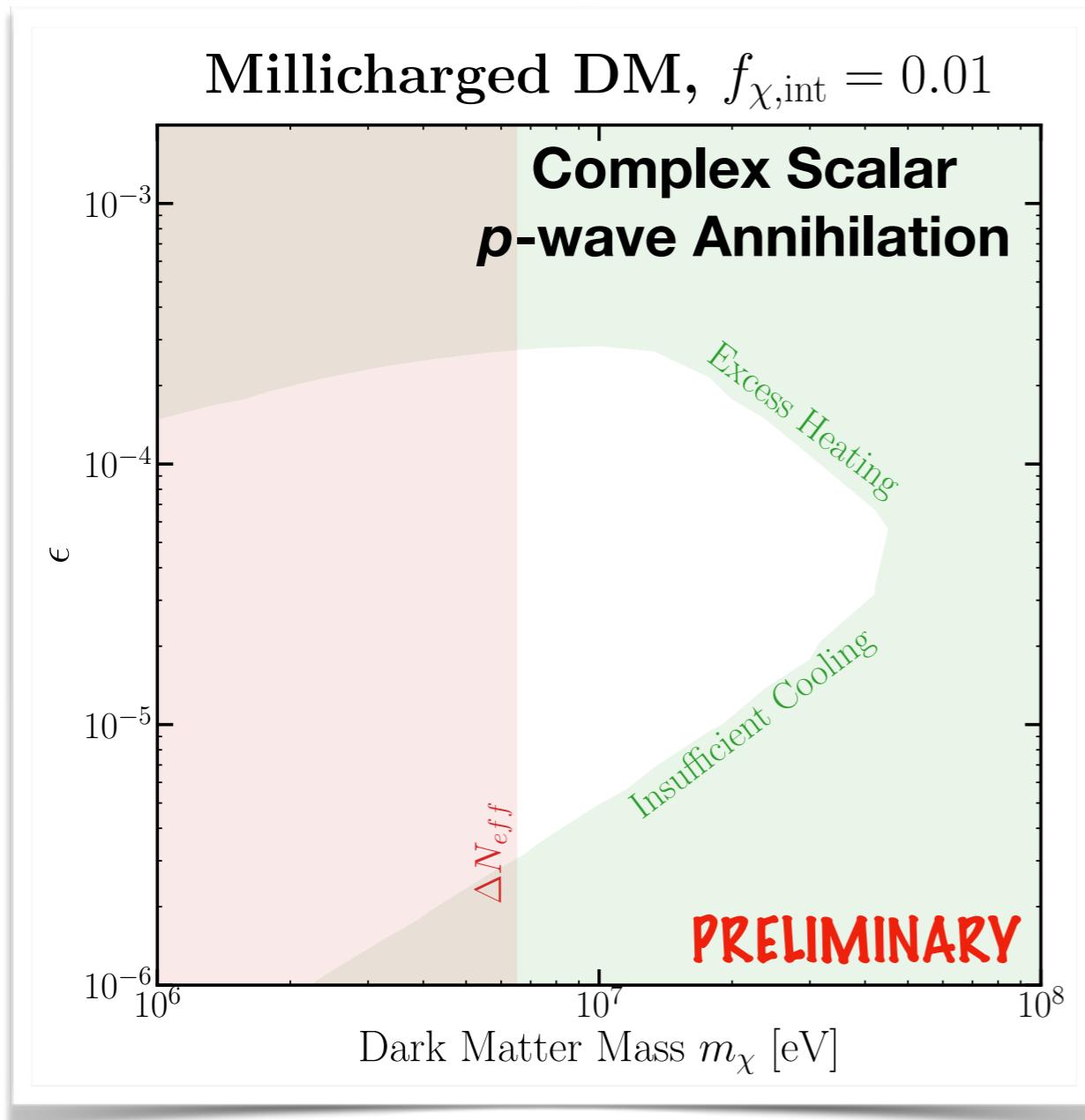
Additional annihilation channel to electrons in the allowed region required to achieve correct relic abundance.

Even in this case, **heating constraints** on this additional annihilation channel **prevents the relic abundance from being achieved**.

Millicharged Scalar DM



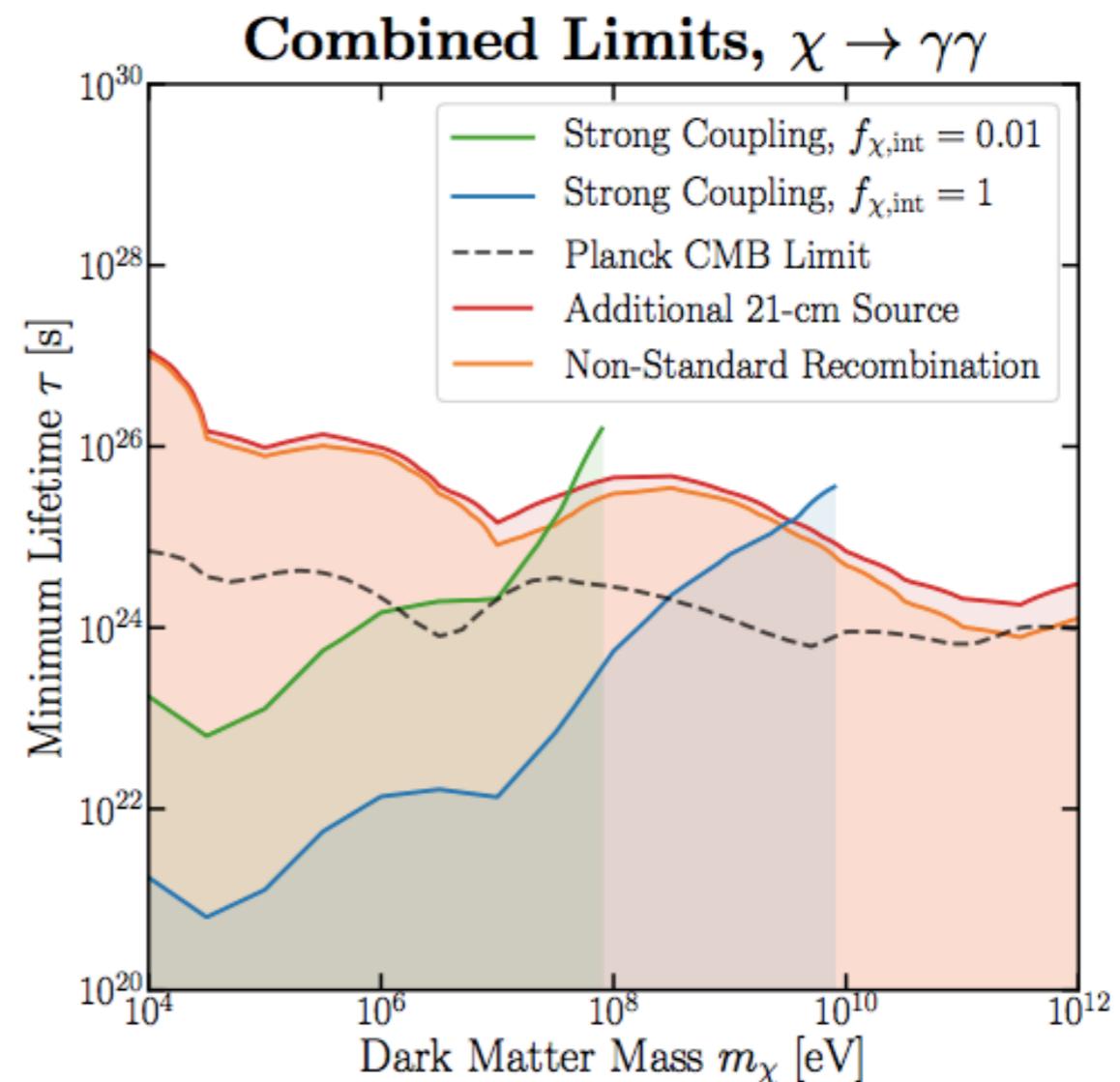
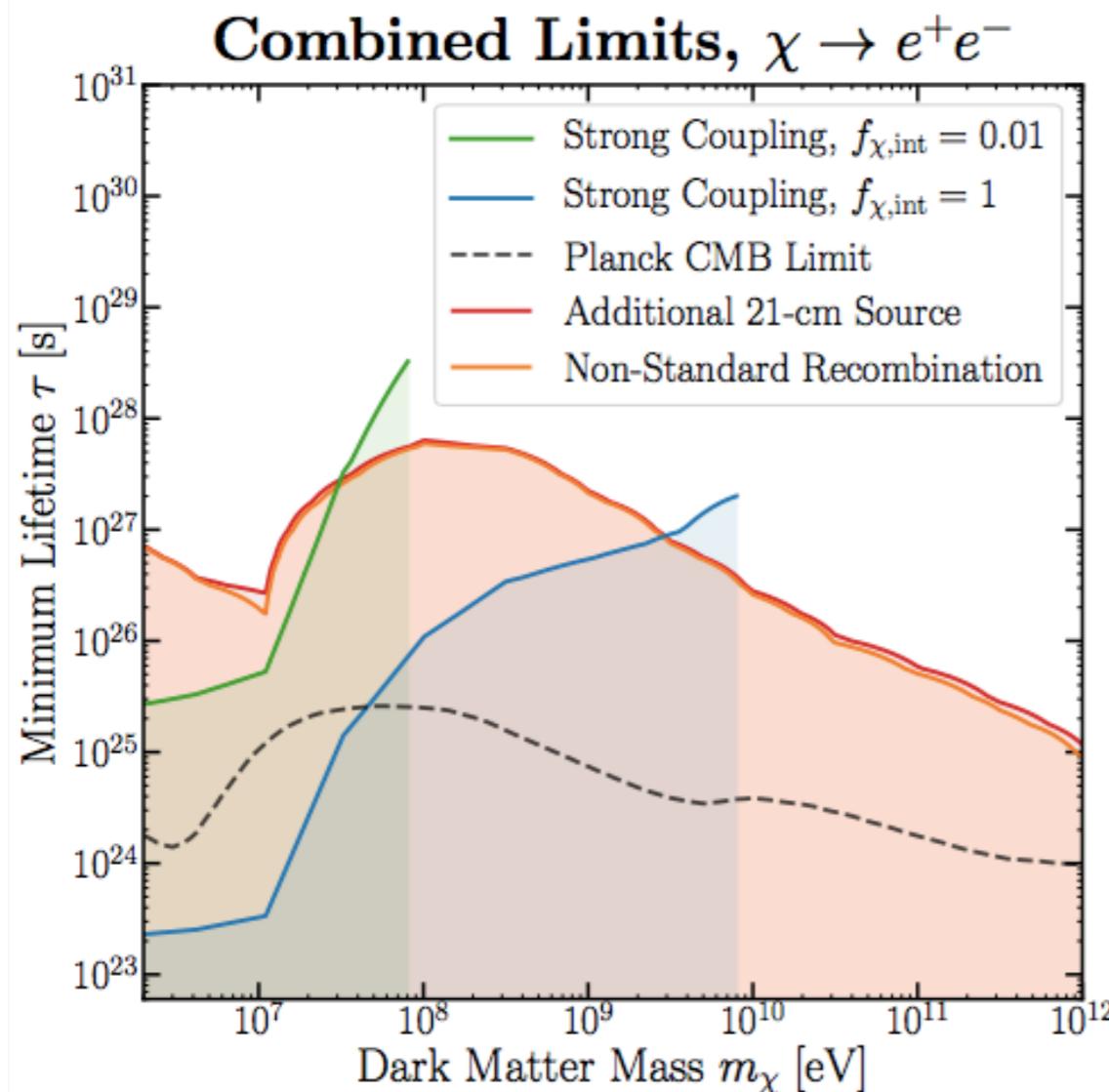
Millicharged Scalar DM



p -wave annihilation enhanced by non-zero thermal velocity of DM: heating counteracts cooling from DM.

Proper accounting of this **thermal velocity** and **structure formation** are important.

Summary Plots

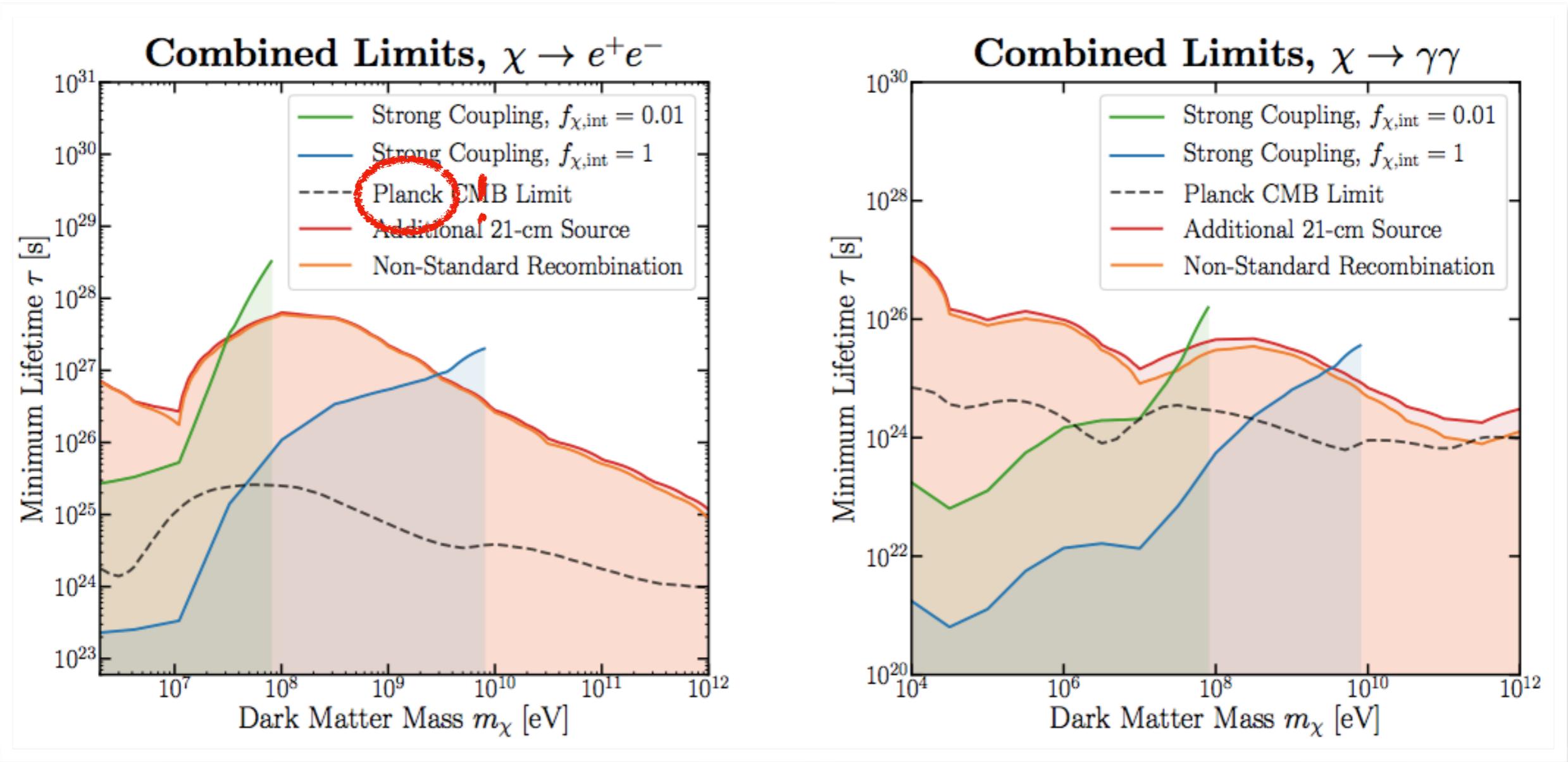


HL and Slatyer 1803.09739



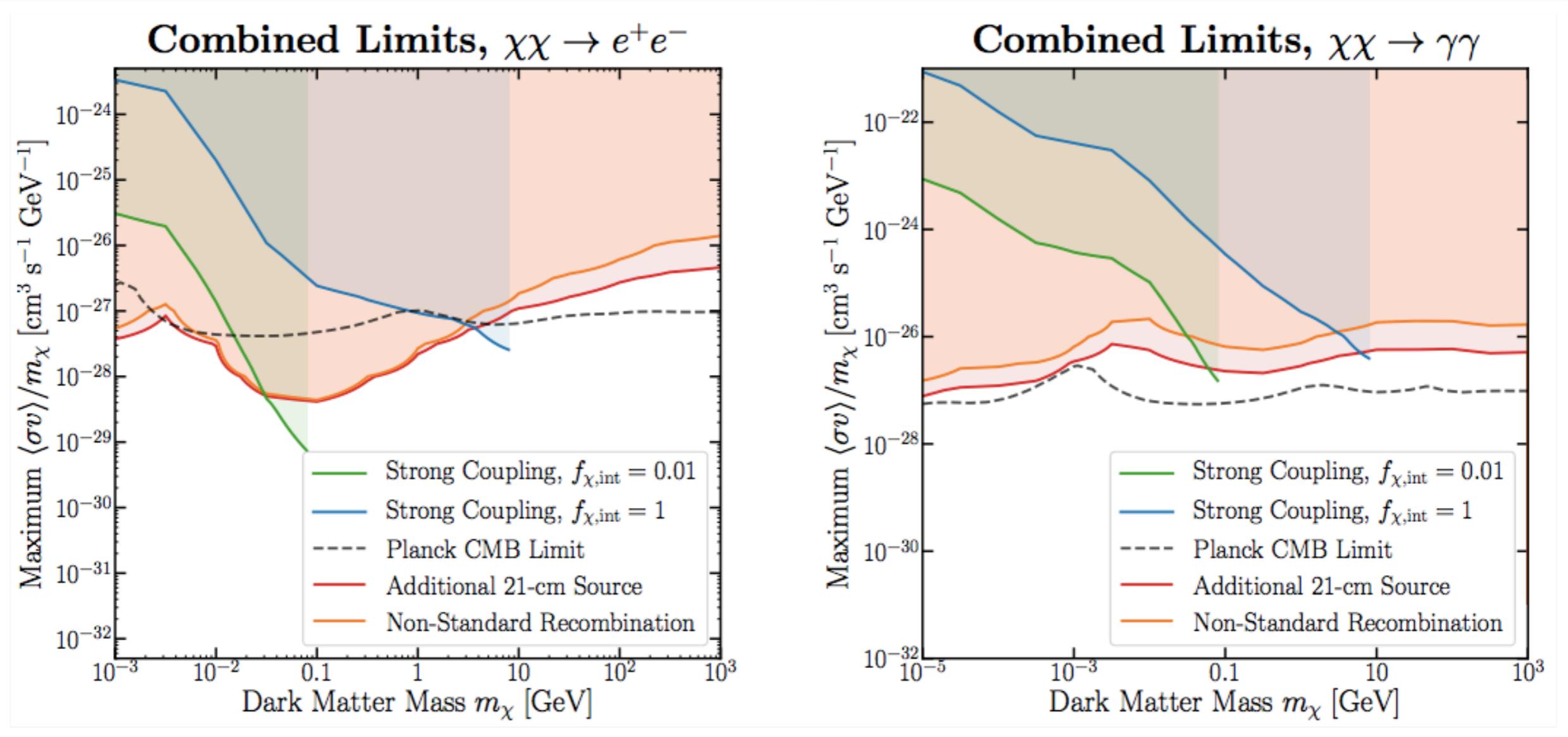
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Summary Plots



HL and Slatyer 1803.09739

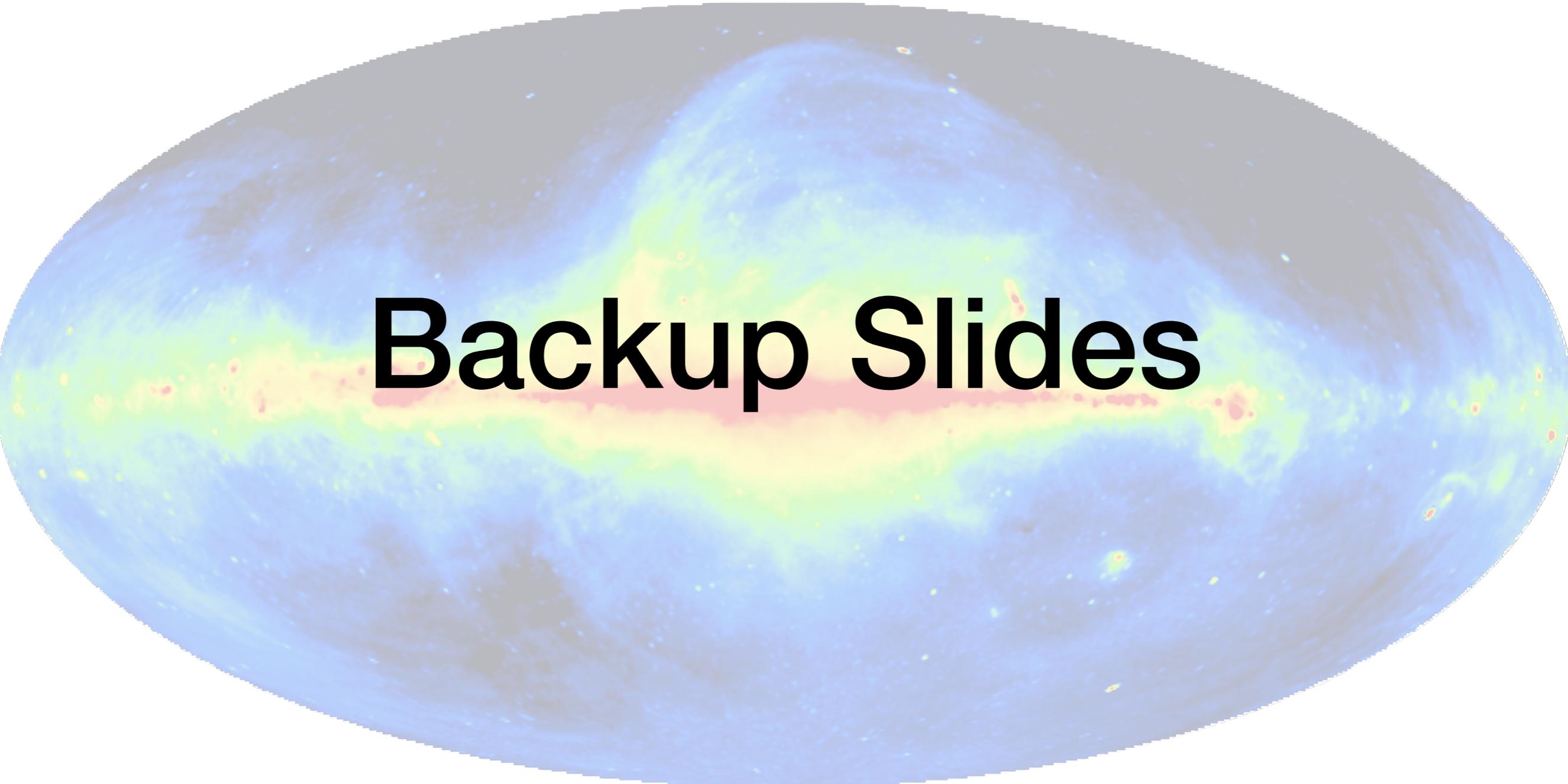
Summary Plots



HL and Slatyer 1803.09739

Conclusion

1. A **deeper-than-expected** 21-cm absorption feature suggests that the standard thermal/ionization history is not the complete story.
2. **Additional 21-cm sources, non-standard recombination or additional cooling** can explain this measurement.
3. **Dark matter annihilation and decay constraints** have been set including these effects: constraints from 21-cm can be a **powerful indirect probe** of the dark sector.



Backup Slides

Ionization/Temperature Evolution

Muñoz and Loeb 1802.10094

$$\dot{T}_b = -2HT_b + 2\dot{Q}_b/3 + \Gamma_C(T_\gamma - T_b)$$

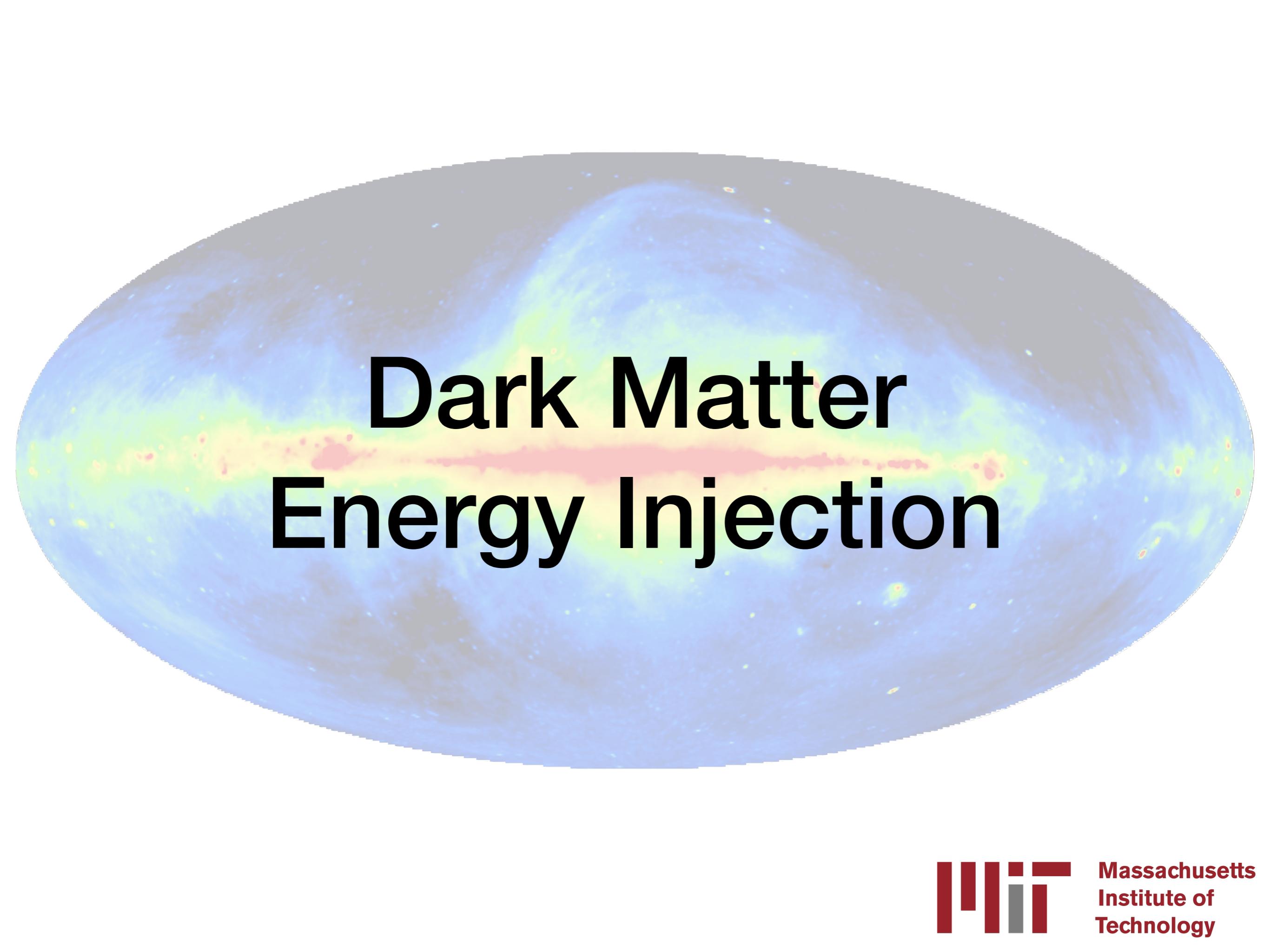
$$\dot{T}_\chi = -2HT_\chi + 2\dot{Q}_\chi/3$$

$$\dot{x}_e = -C \left[n_H \mathcal{A}_B x_e^2 - 4(1-x_e) \mathcal{B}_B e^{3E_0/(4T_\gamma)} \right]$$

$$\dot{v}_{\chi,b} = -Hv_{\chi,b} - D(v_{\chi,b}),$$

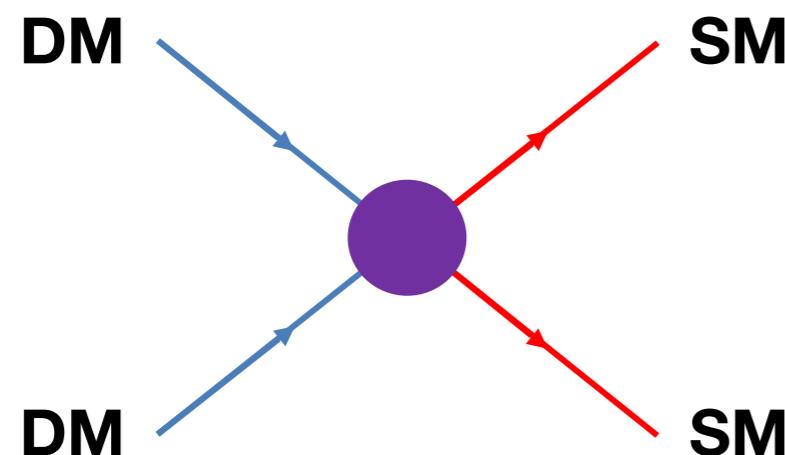
$$\dot{Q}_b = n_\chi \frac{x_e}{1+f_{\text{He}}} \sum_{t=e,p} \frac{m_\chi m_t}{(m_\chi + m_t)^2} \frac{\bar{\sigma}_t}{u_{\text{th},t}} \times$$

$$\times \left[\sqrt{\frac{2}{\pi}} \frac{e^{-r_t^2/2}}{u_{\text{th},t}^2} (T_\chi - T_b) + m_\chi \frac{F(r_t)}{r_t} \right]$$

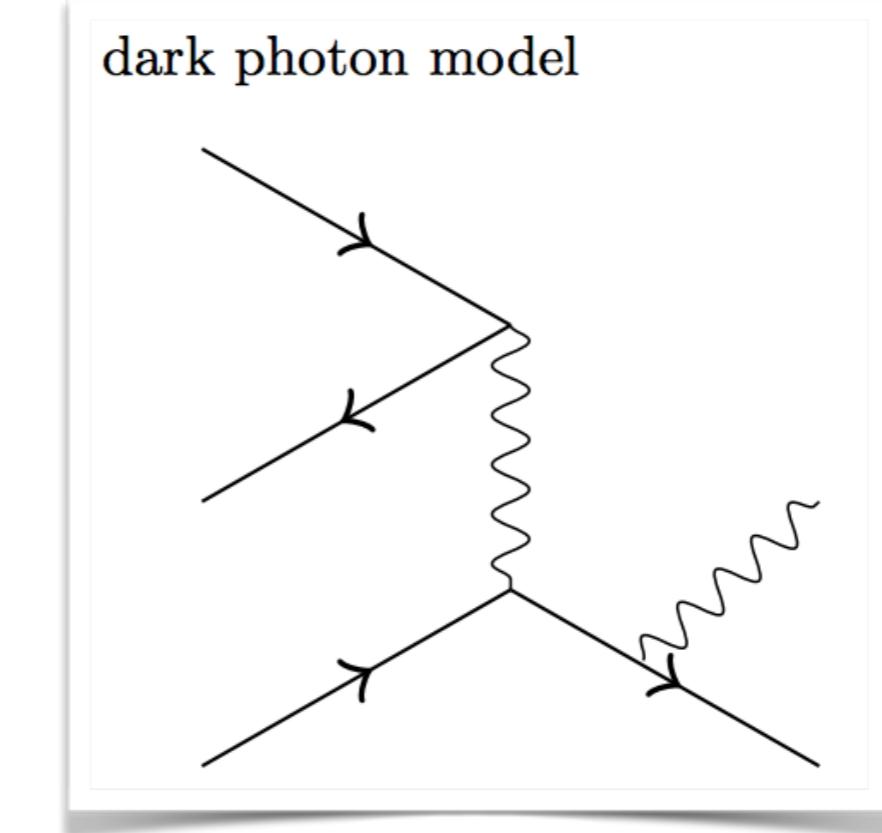
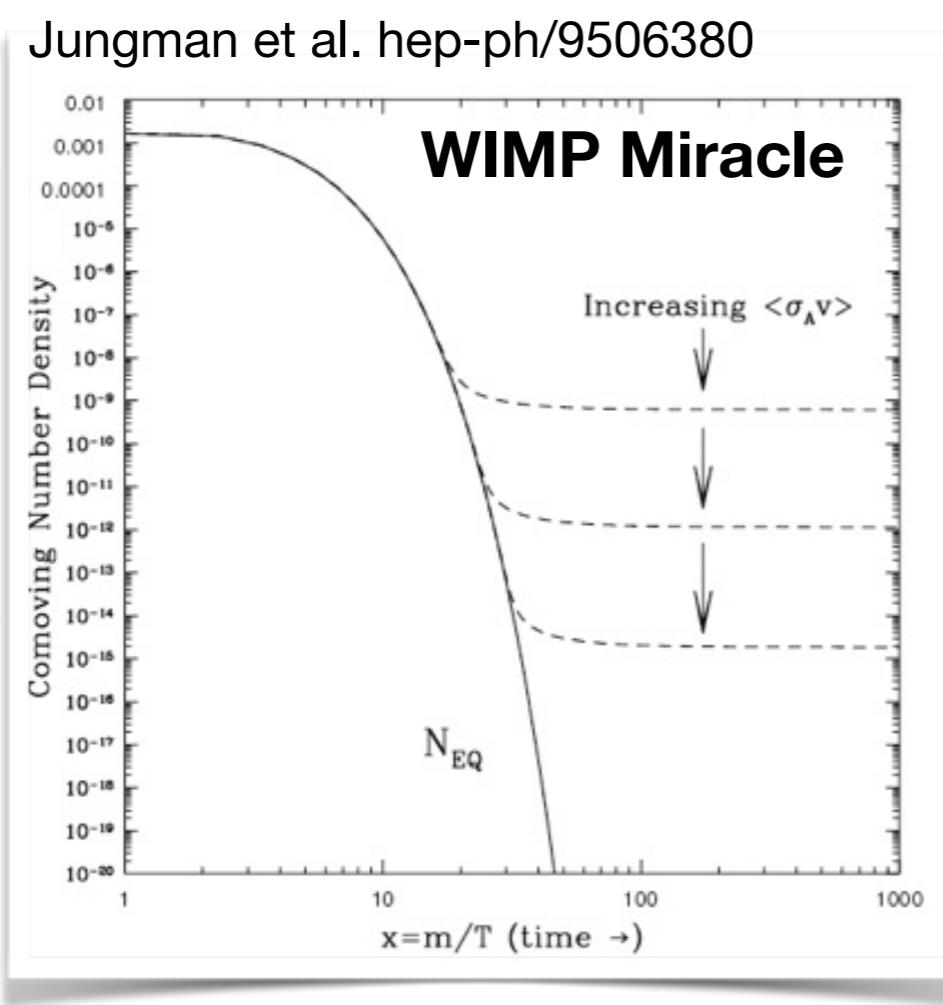


Dark Matter Energy Injection

Why Annihilation?



Dark matter can be **thermal**:
many well-motivated mechanisms to
get **correct relic abundance**.

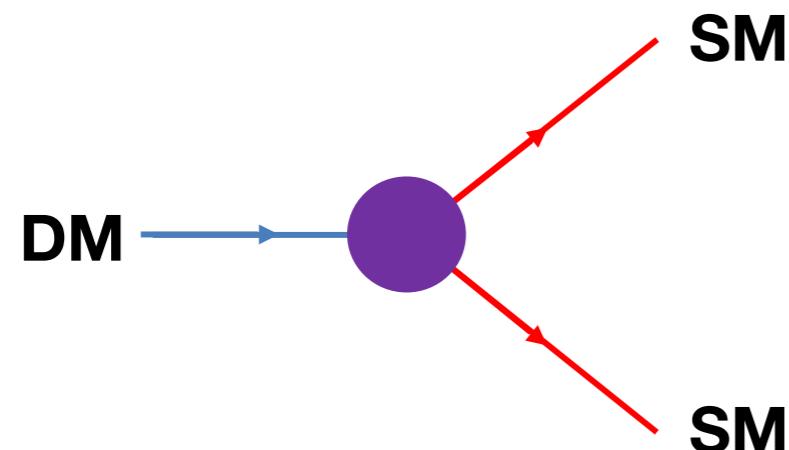


Cline, HL, Slatyer and Xue 1702.07716



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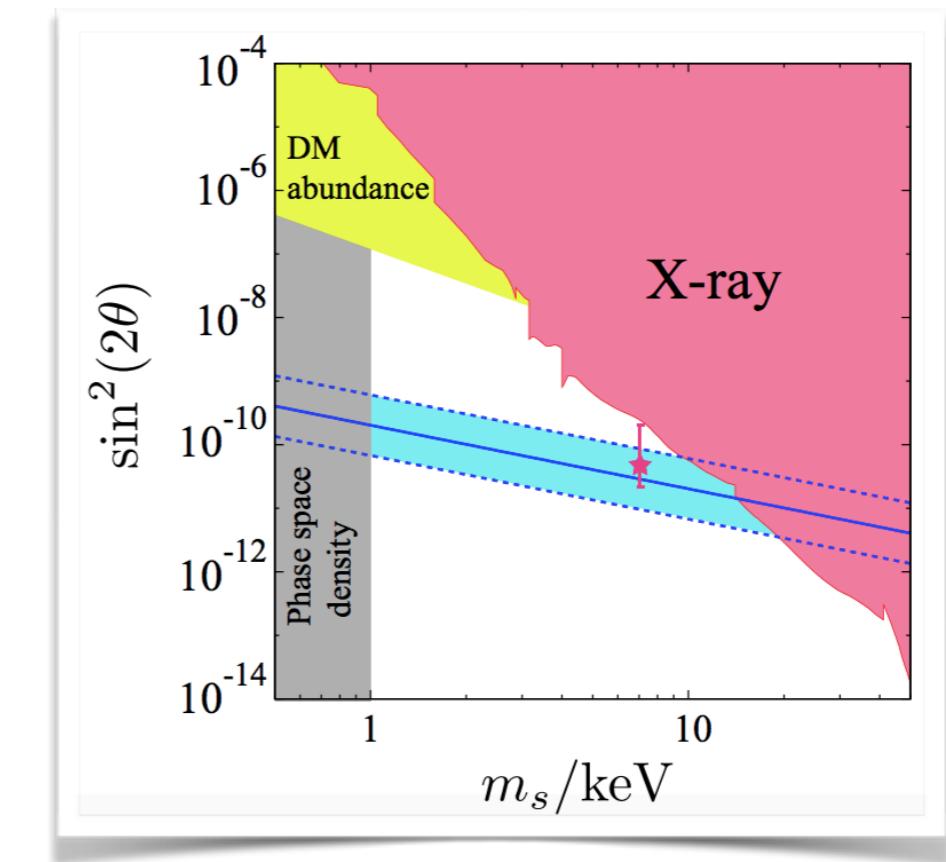
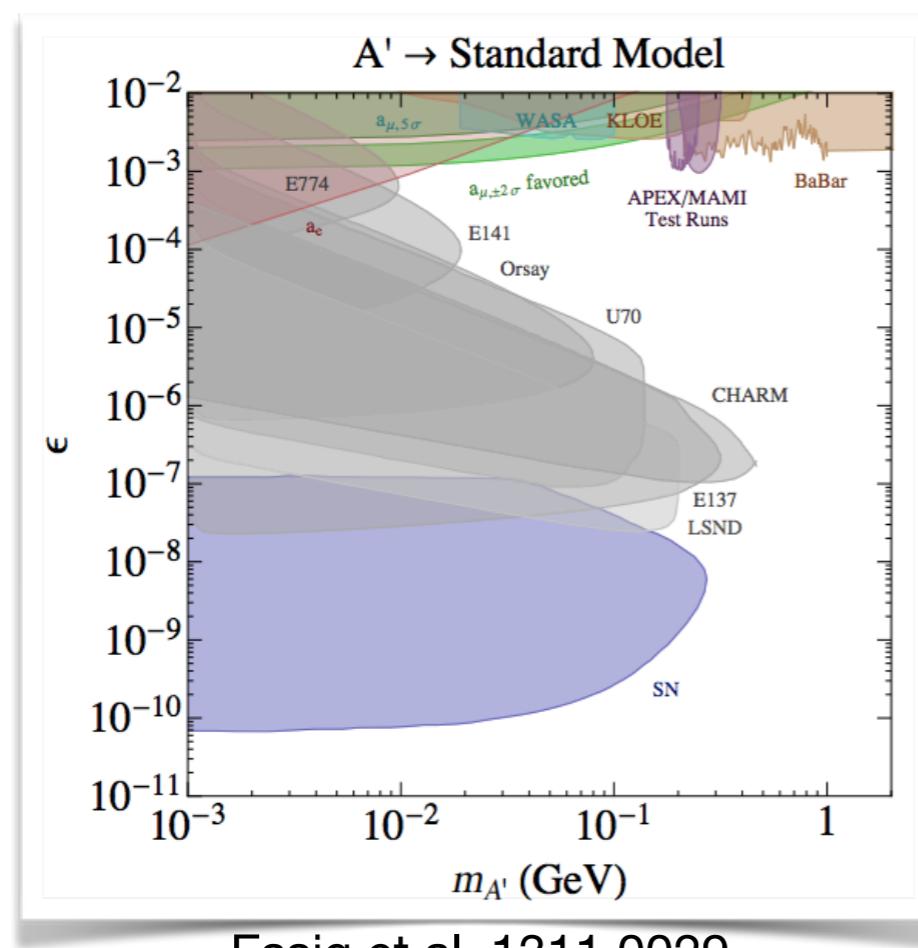
Why Decay?



Dark matter should be stable for timescales \gtrsim the age of the universe.

But any small interaction between the SM and dark sector can lead to **decay**.

Portal models, sterile neutrinos, ALPs...

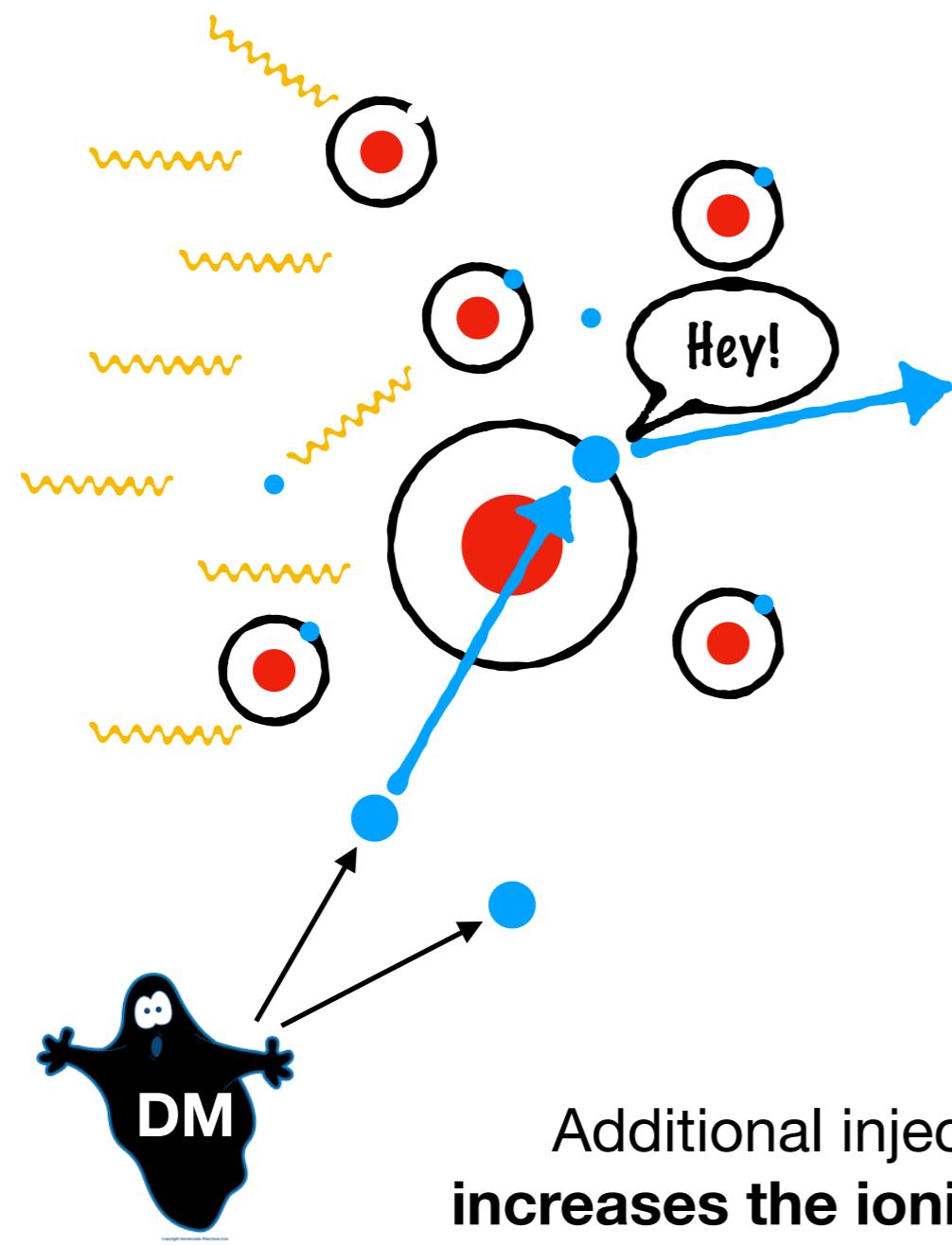


Ishida et al. 1402.5837

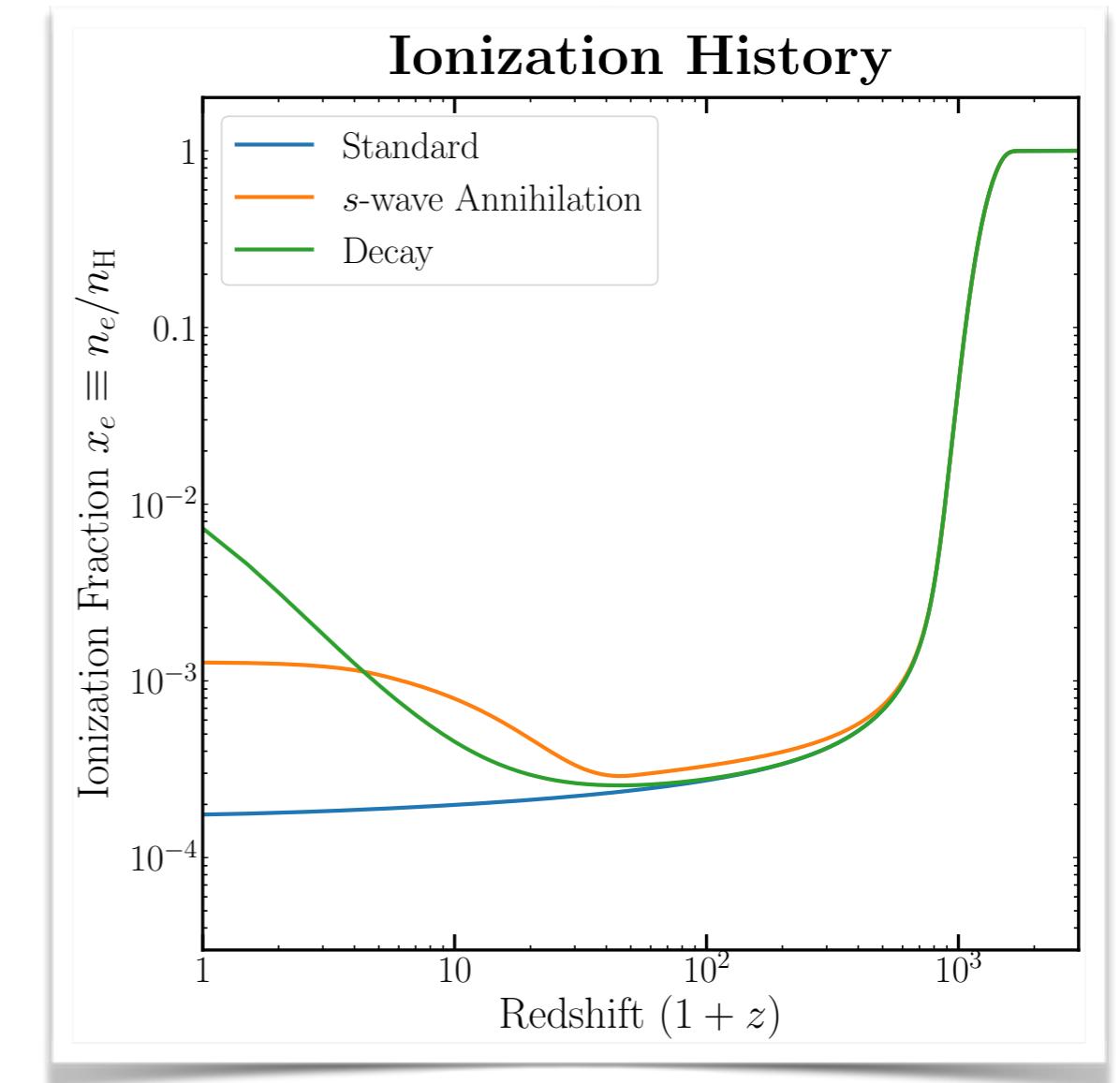


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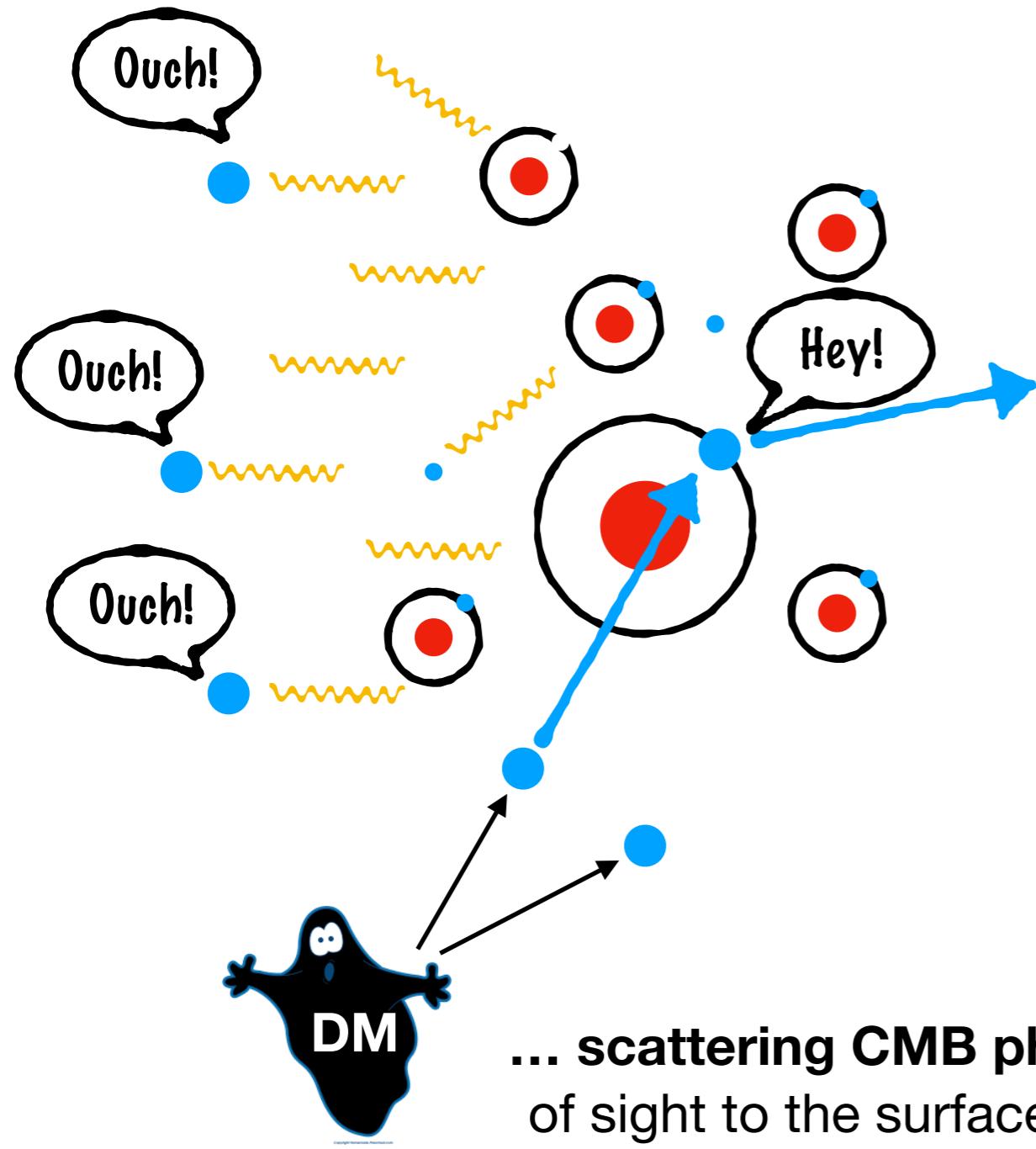
Dark Ages, Dark Matter



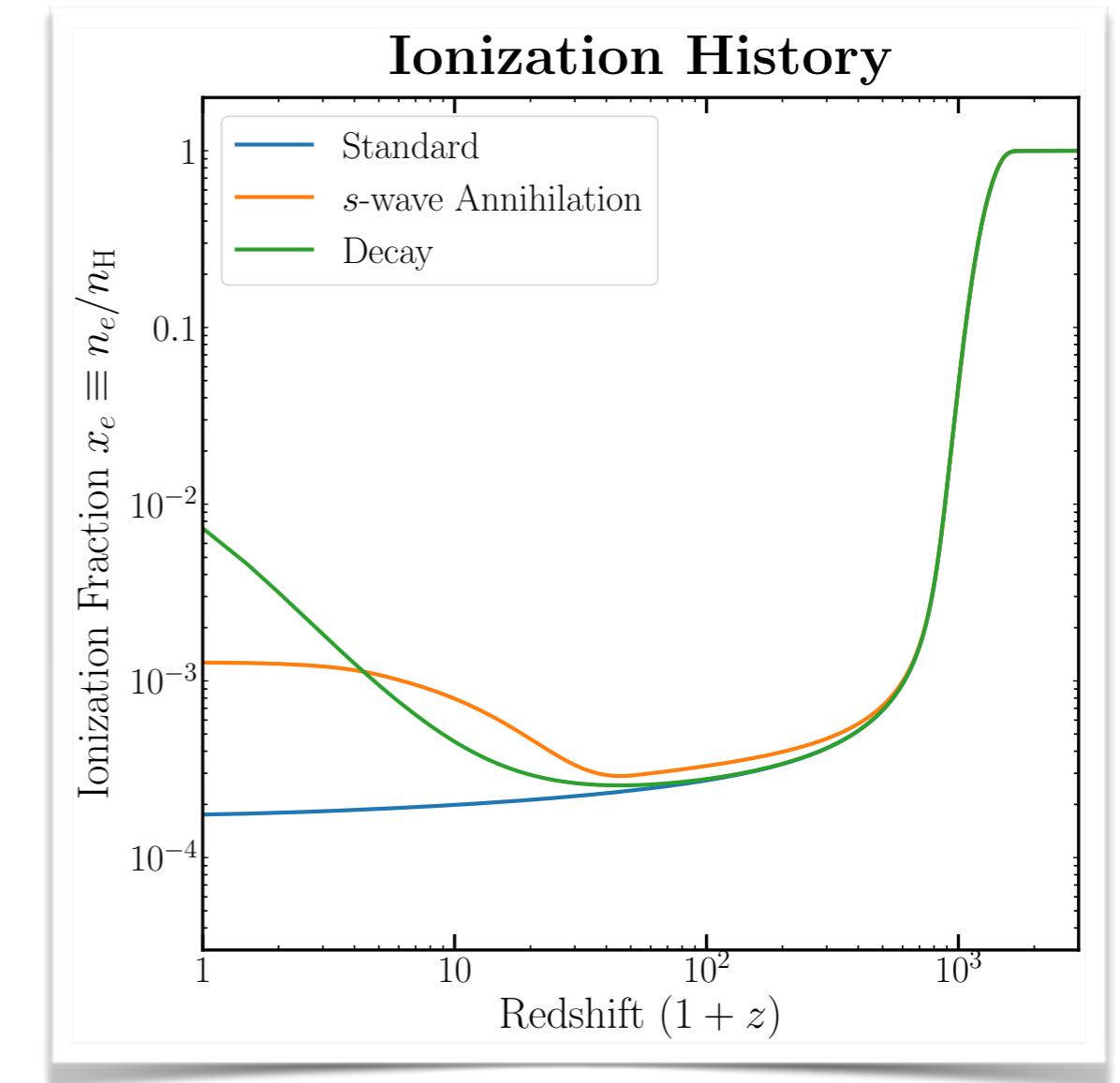
Additional injection of energy
increases the ionization fraction...



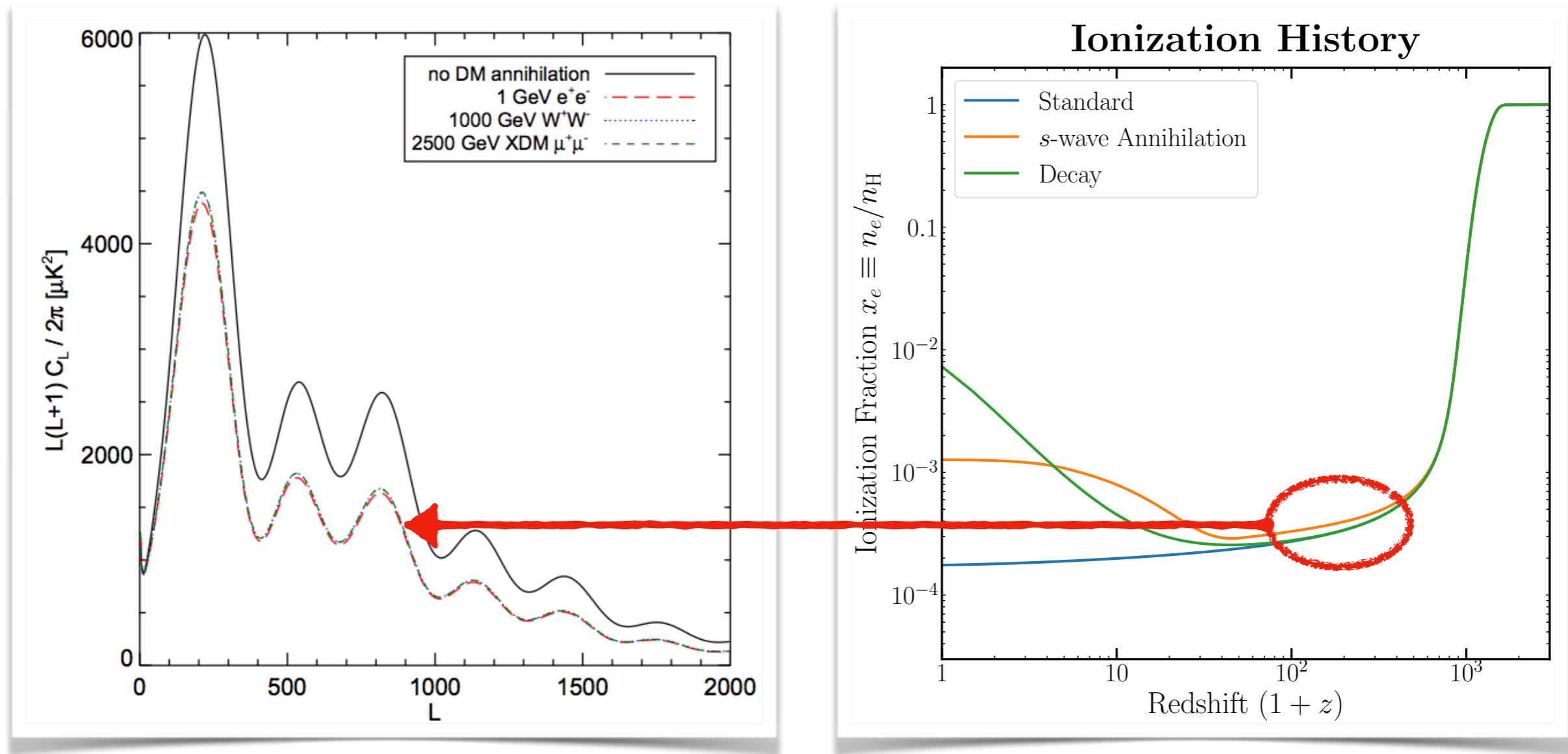
Dark Ages, Dark Matter



... scattering CMB photons along our line
of sight to the surface of last scattering...



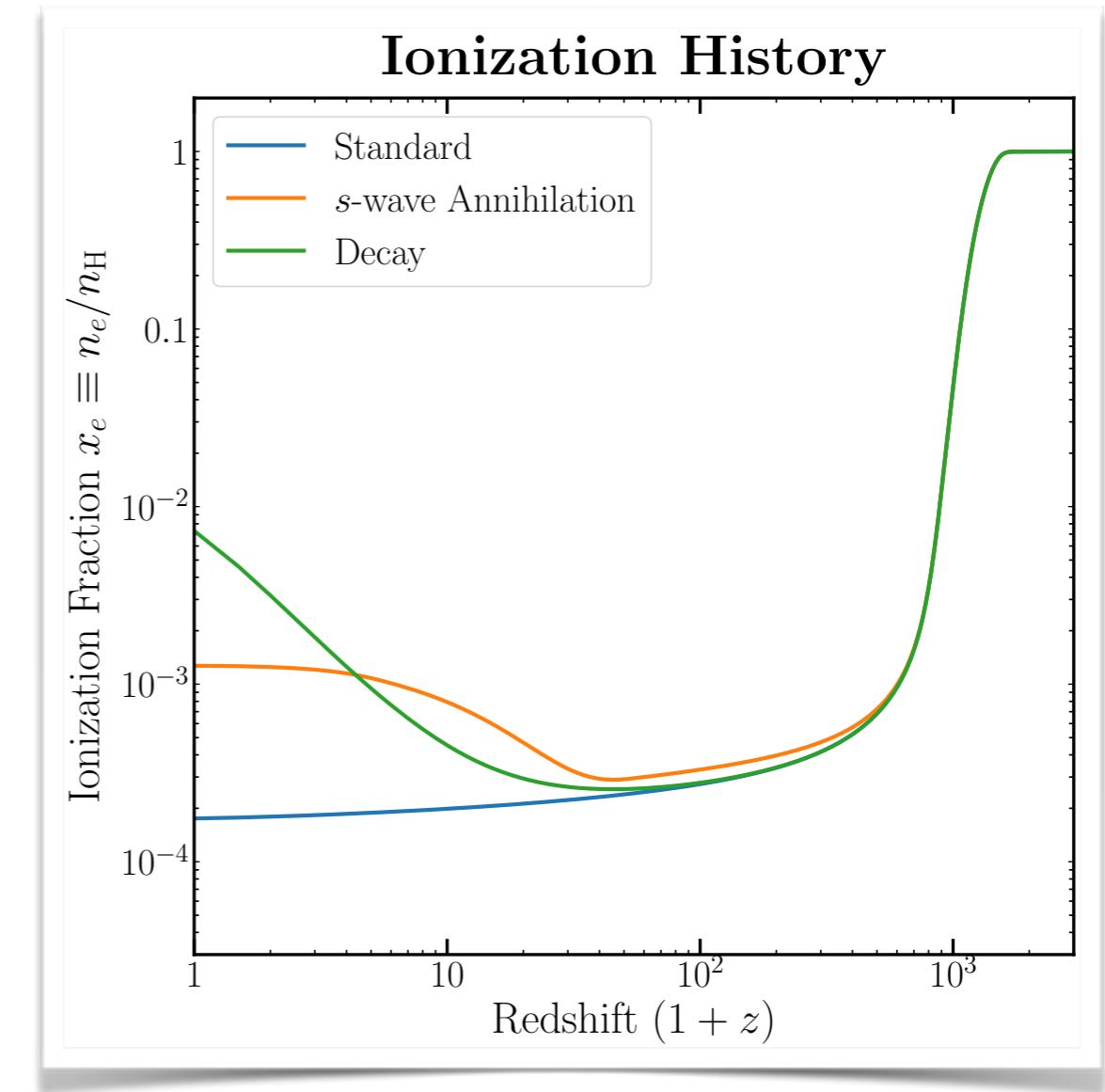
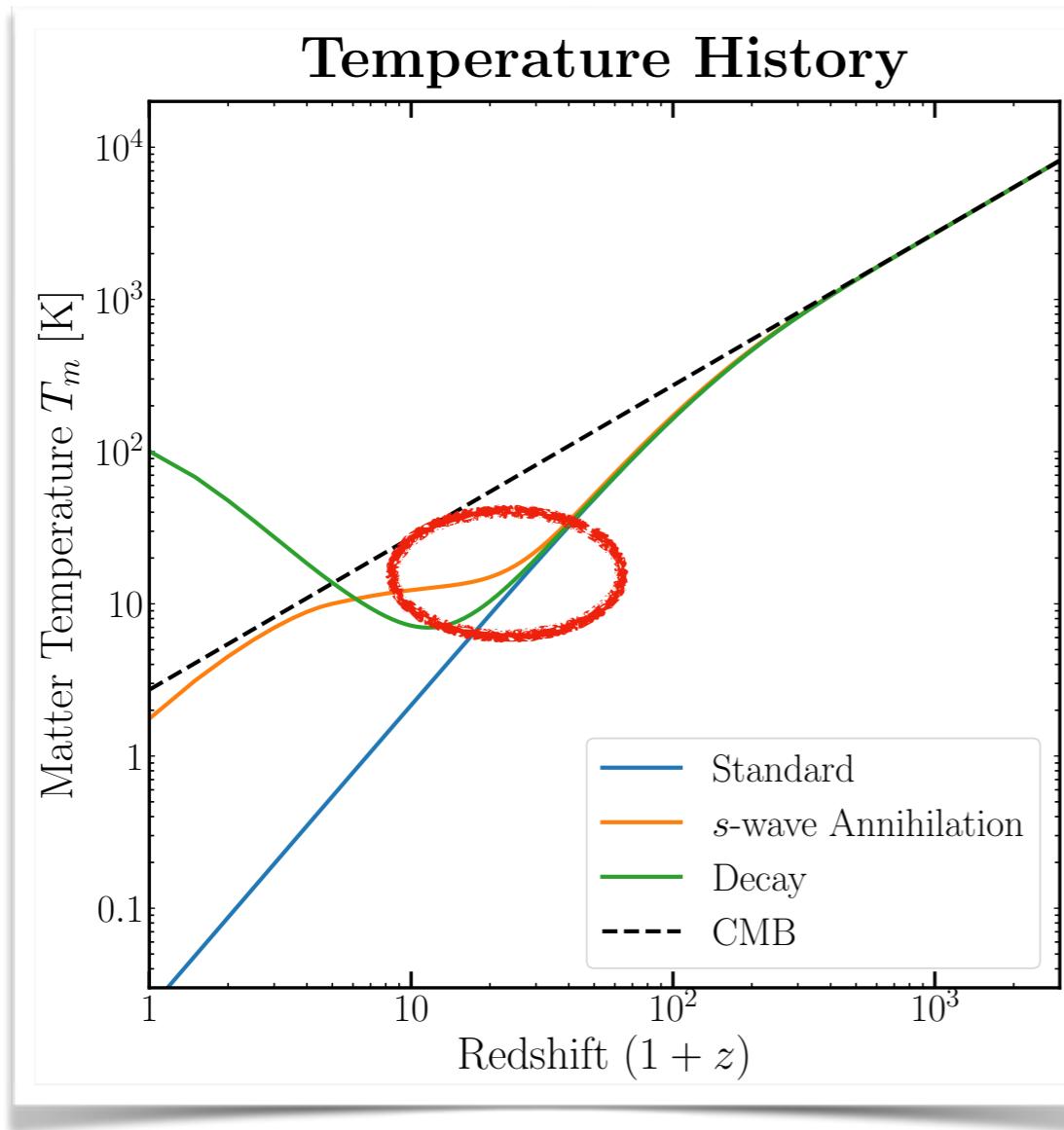
Dark Ages, Dark Matter



Slatyer et al., 0906.1197

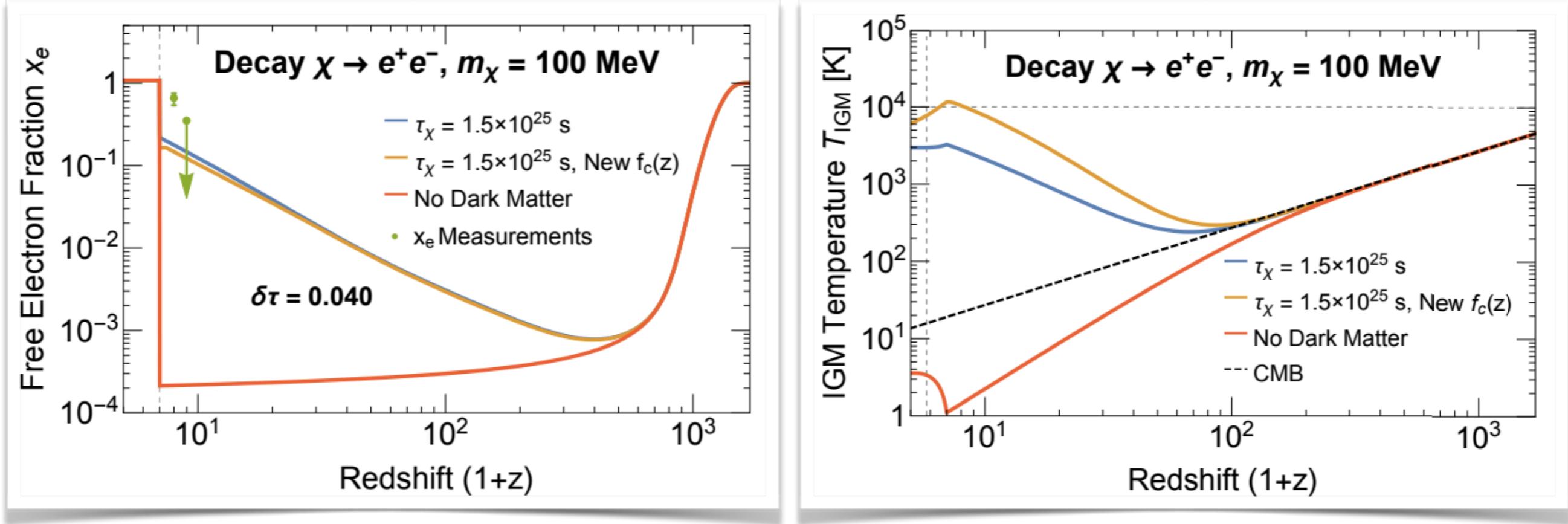
... leading to a **suppression of the TT** and
enhancement of the EE power spectrum.

Thermal History and DM



Additional energy injection also **heats the intergalactic medium:**
thermal history can be a powerful probe of energy injection.

Dark Matter and Reionization

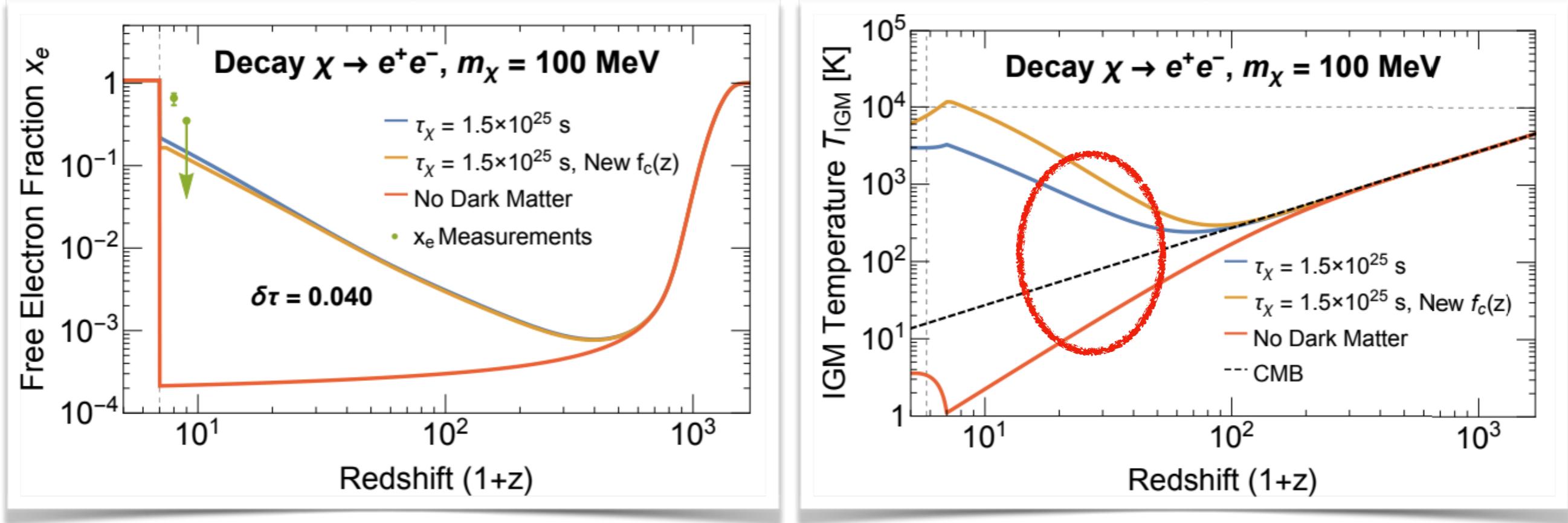


HL, Slatyer and Zavala 1604.02457

Energy injection from dark matter may contribute to **reionization**.

Maximum contribution to the free electron fraction is likely only
~10 - 20% prior to complete reionization at $z \sim 6$.

Dark Matter and Reionization

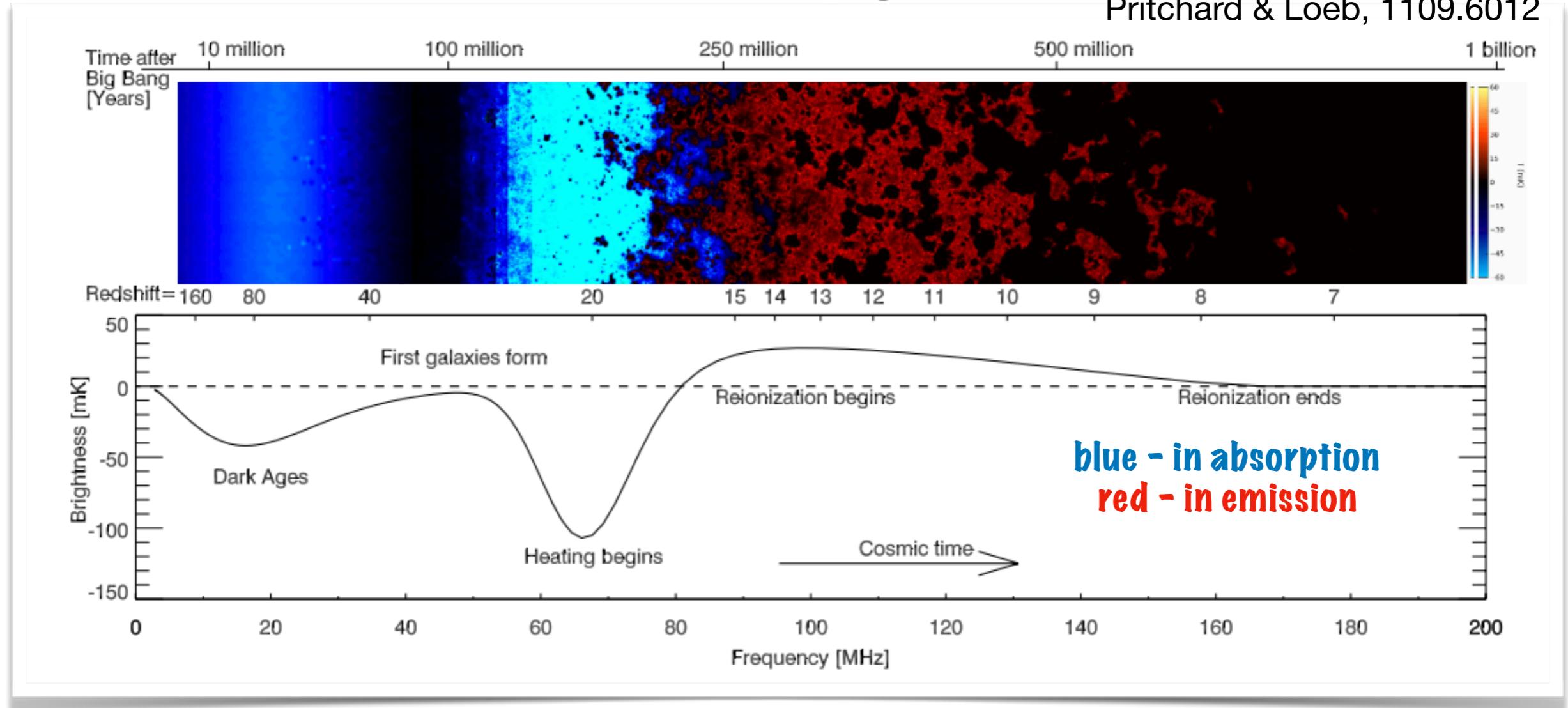


HL, Slatyer and Zavala 1604.02457

But getting a handle on the gas temperature during the dark ages can place very powerful limits on energy injection processes!

21-cm Brightness

Pritchard & Loeb, 1109.6012



We measure the brightness of the sky in the MHz range,
relative to the CMB temperature.

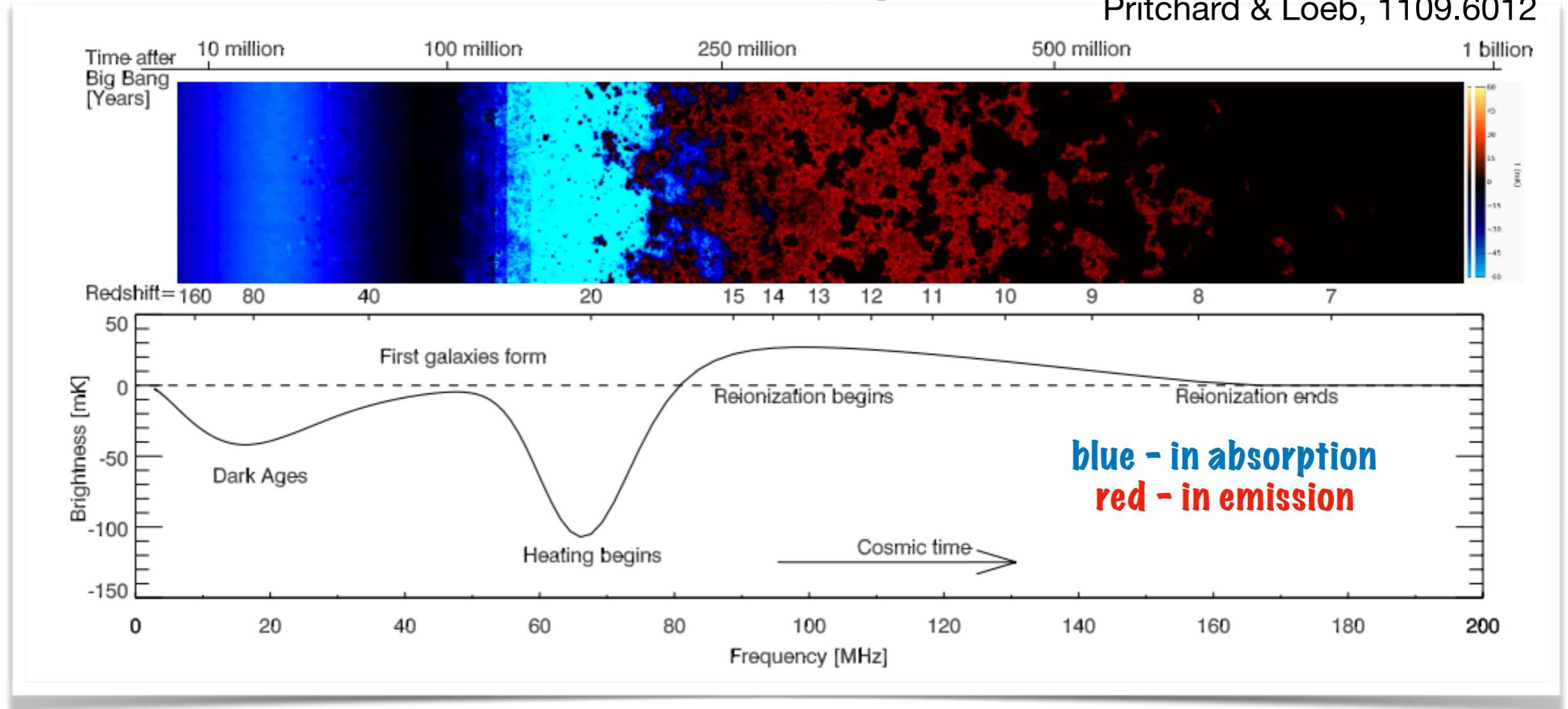
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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21-cm Brightness

Pritchard & Loeb, 1109.6012



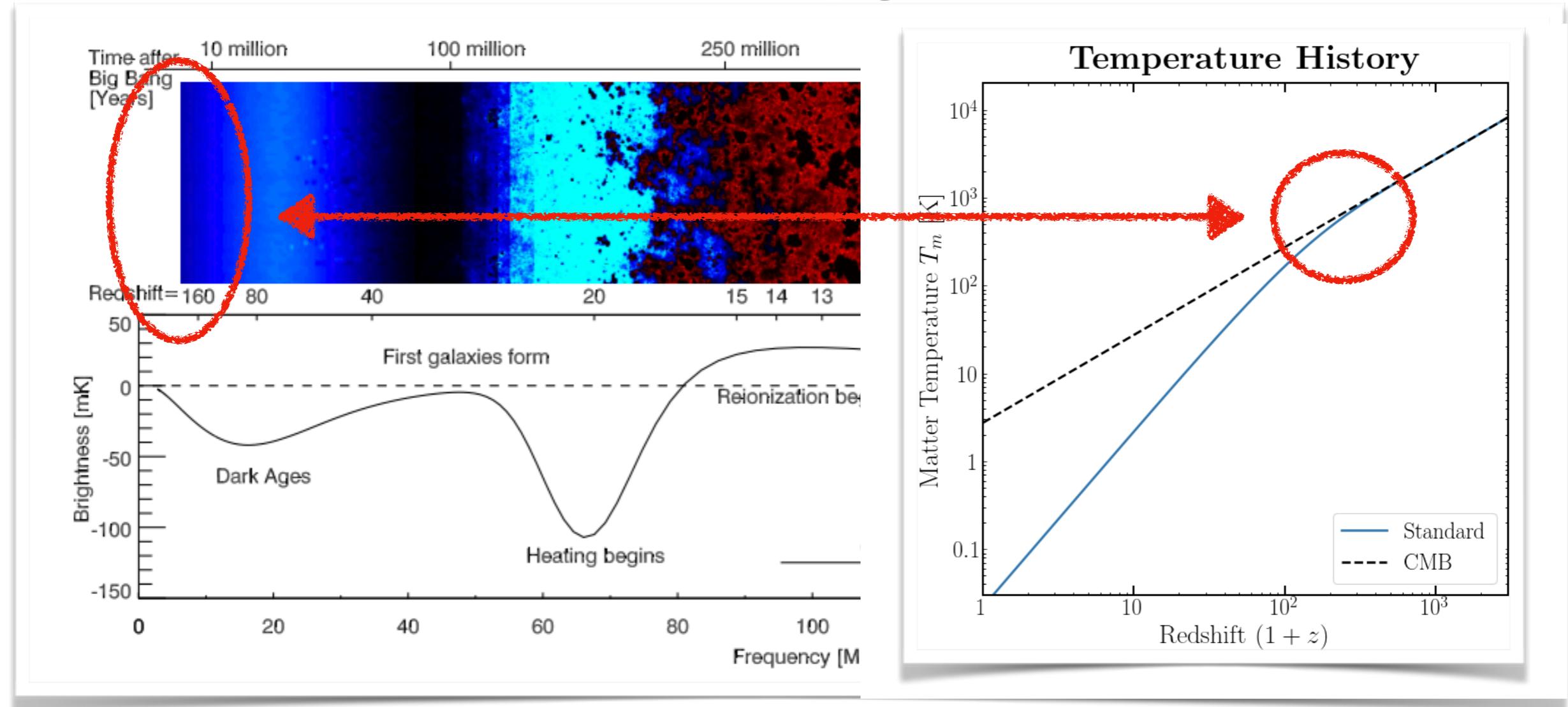
Lower frequencies probe earlier times due to redshift.

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



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21-cm Brightness

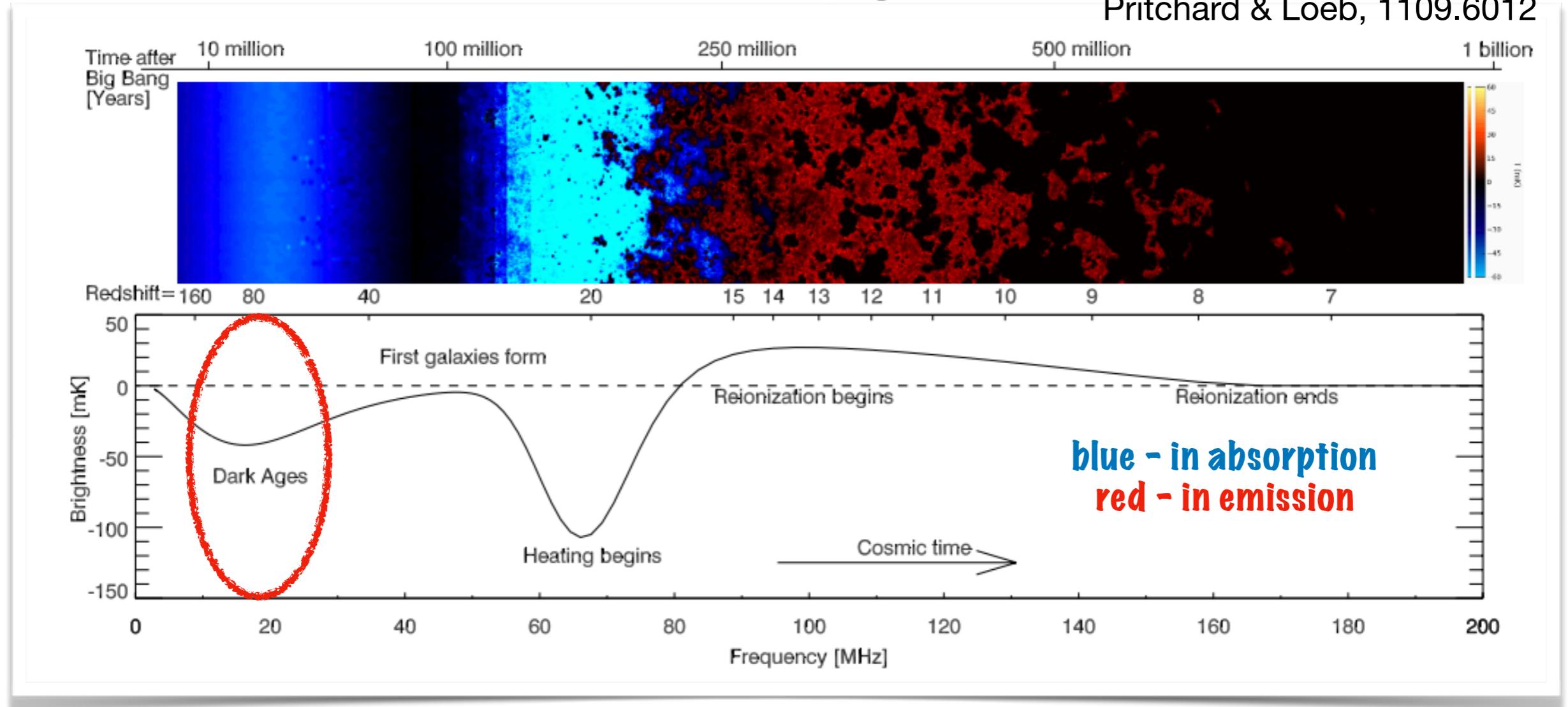


Prior to thermal decoupling,
matter temperature = CMB temperature.

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

21-cm Brightness

Pritchard & Loeb, 1109.6012



After decoupling, **collisions bring the spin temperature down to T_m** , and the gas is in **absorption**.

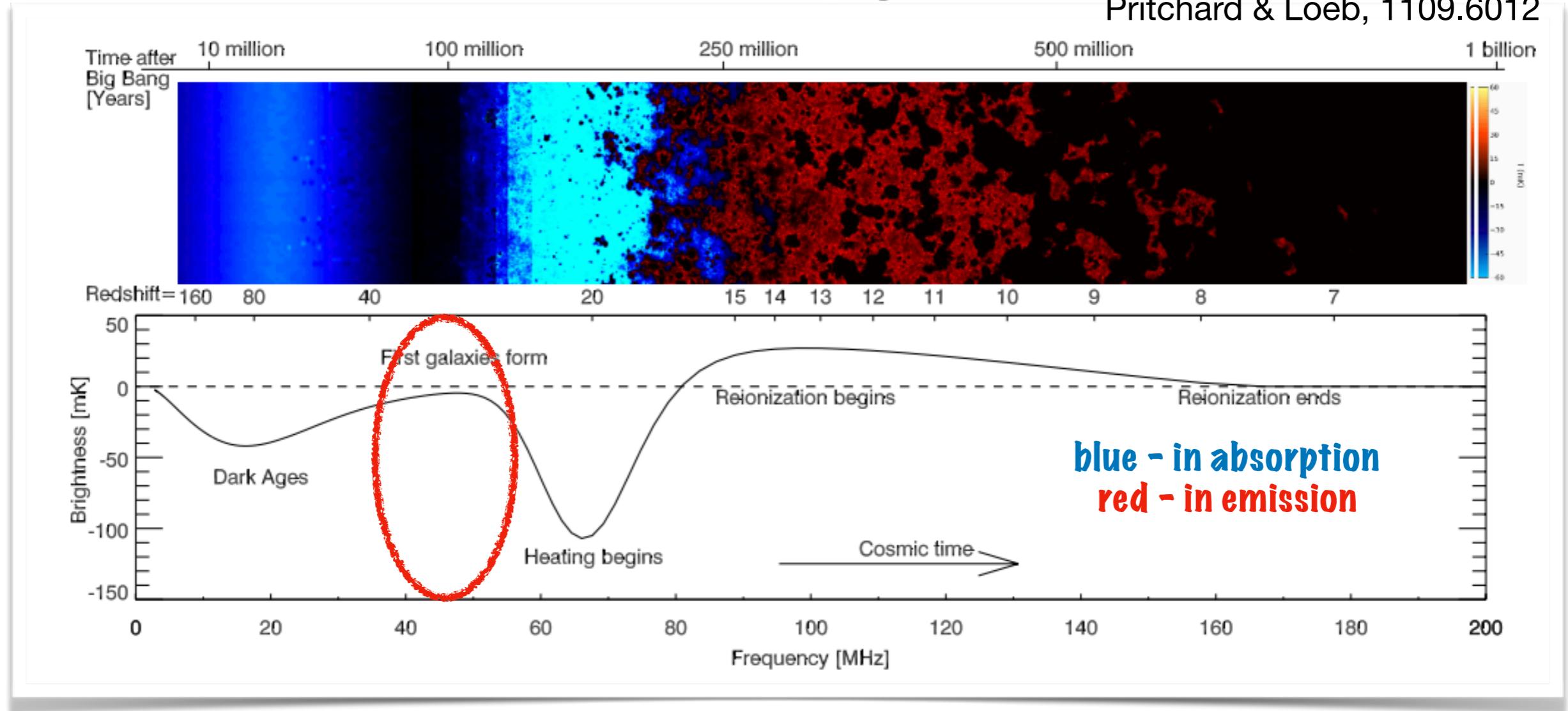
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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Pritchard & Loeb, 1109.6012



Matter gets less dense as the universe expands, collisions become highly inefficient, T_s goes back up to T_{CMB} .

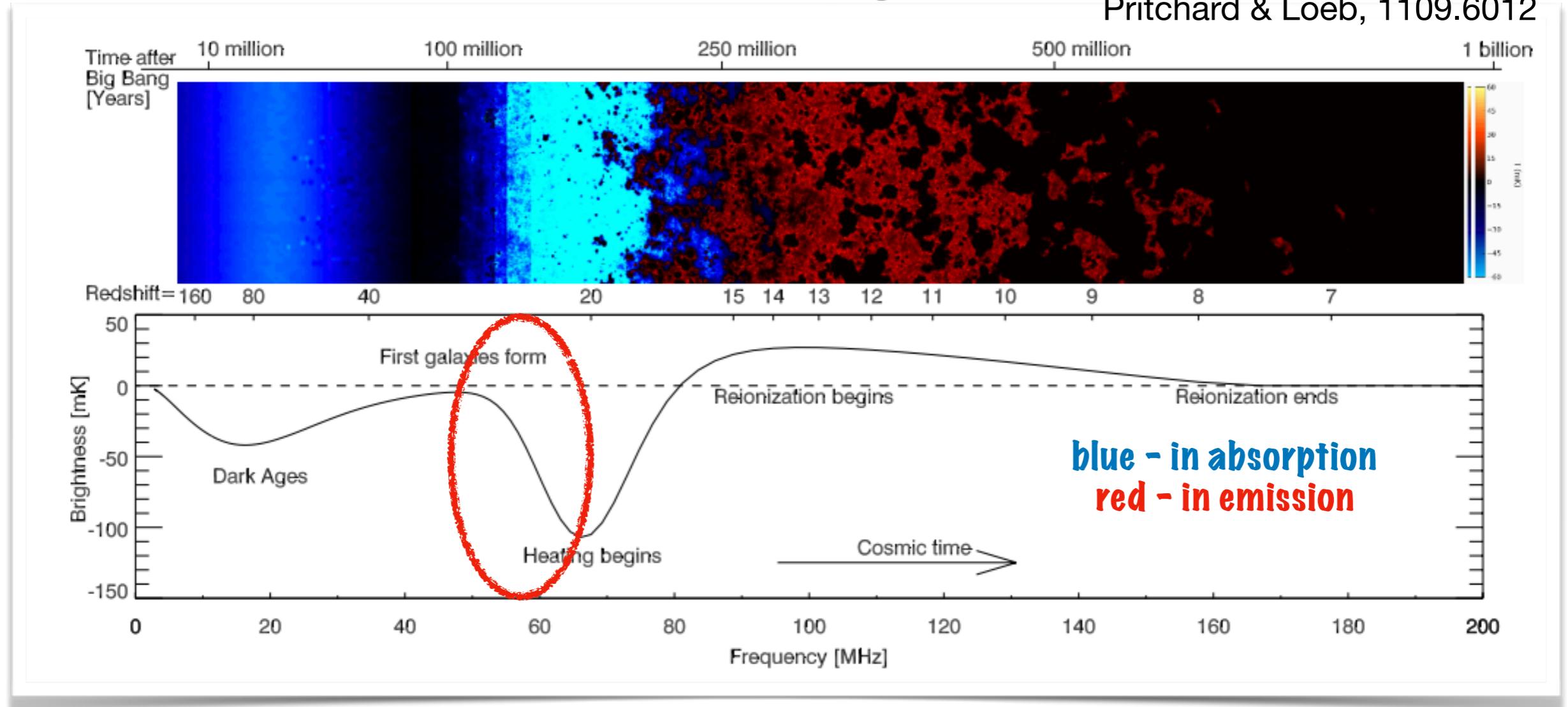
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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Stars start emitting UV radiation. T_s goes to T_m .

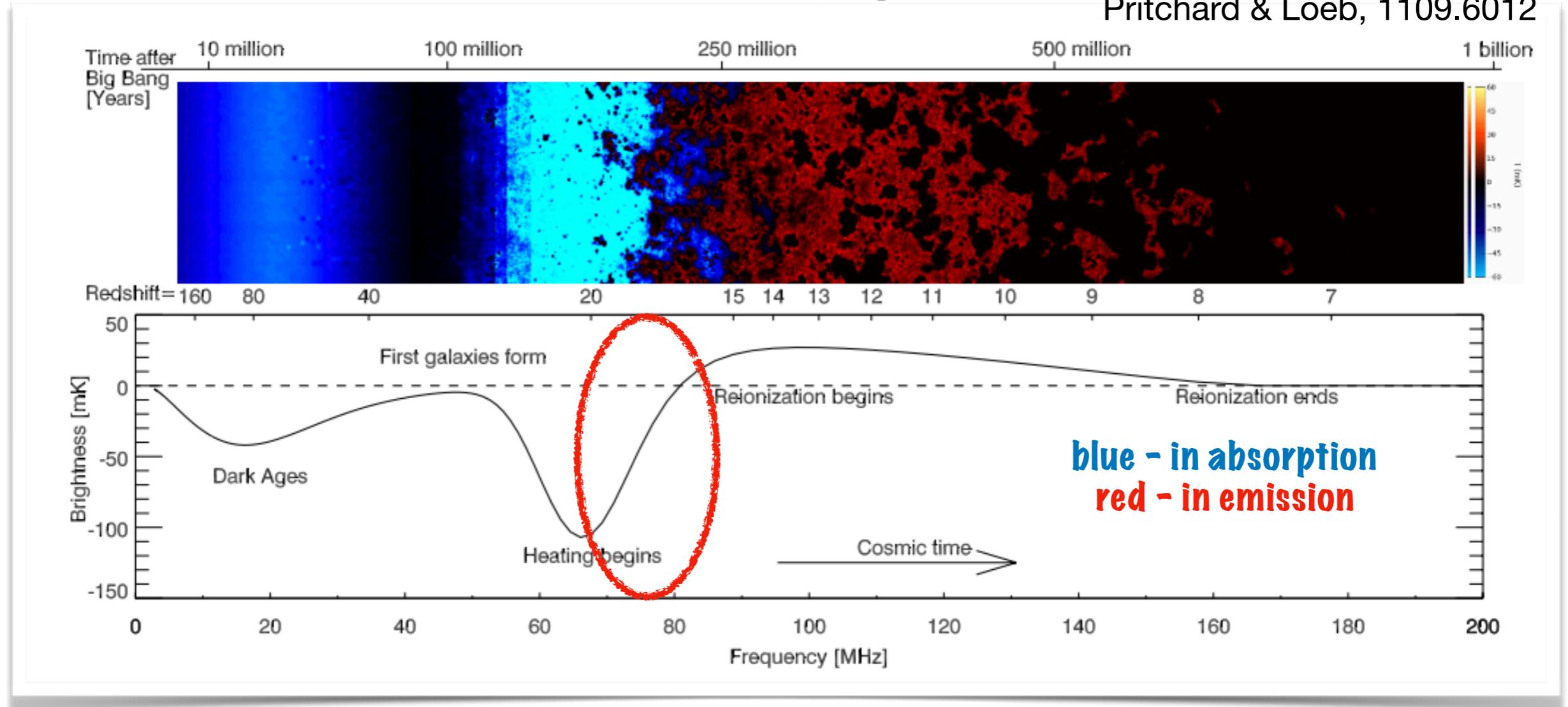
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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Matter starts to heat up due to **starlight...**

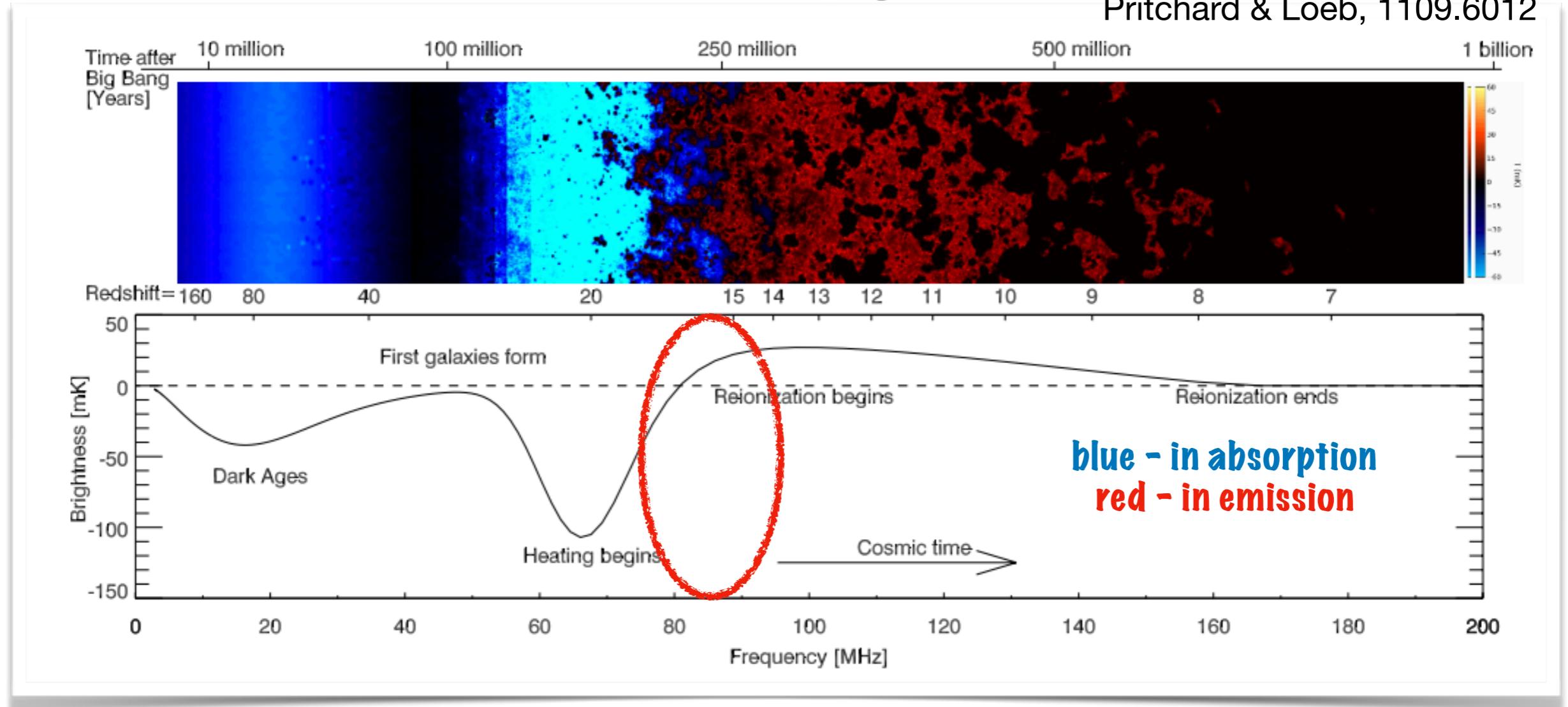
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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Pritchard & Loeb, 1109.6012



... and eventually matter becomes hotter than the CMB.
Now in **emission!**

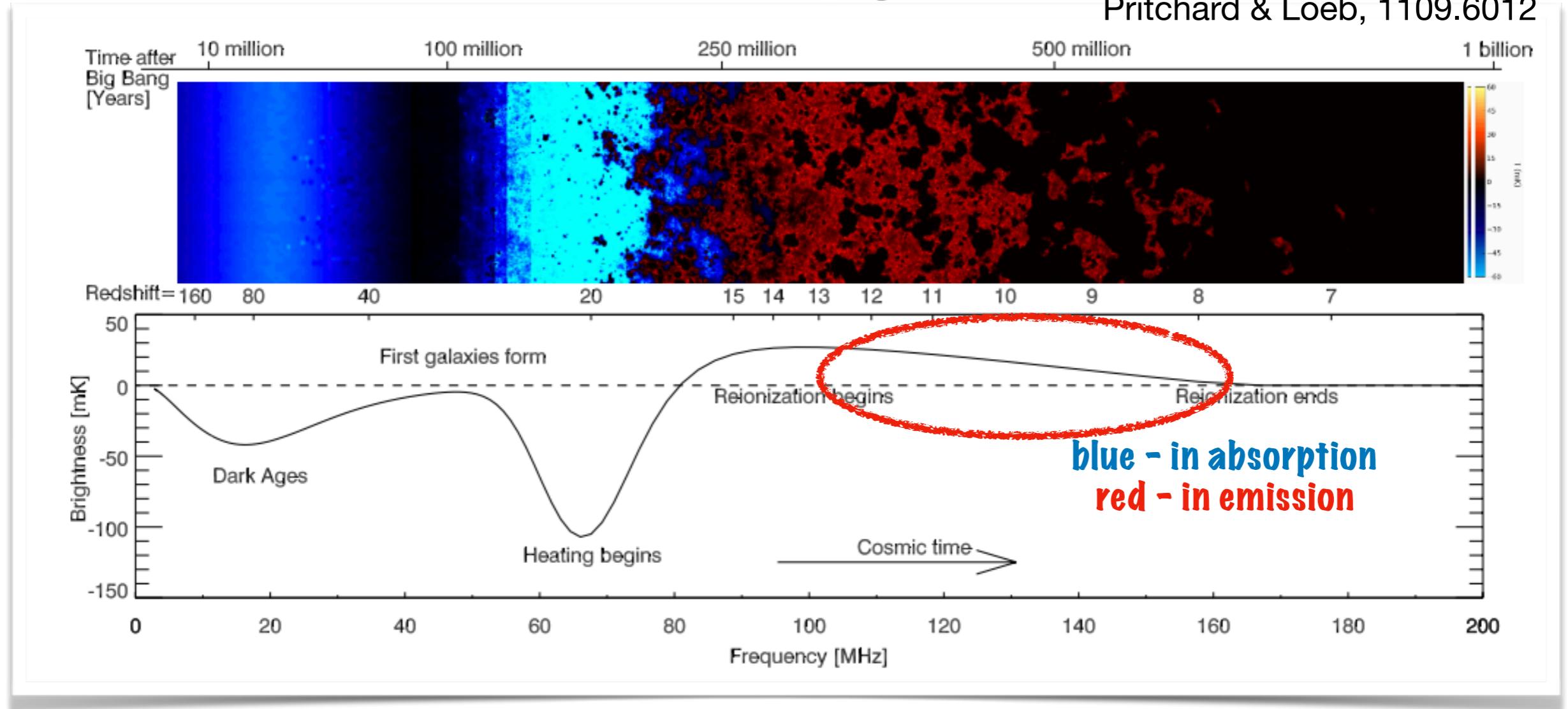
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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21-cm Brightness

Pritchard & Loeb, 1109.6012



Reionization quickly depletes neutral hydrogen.

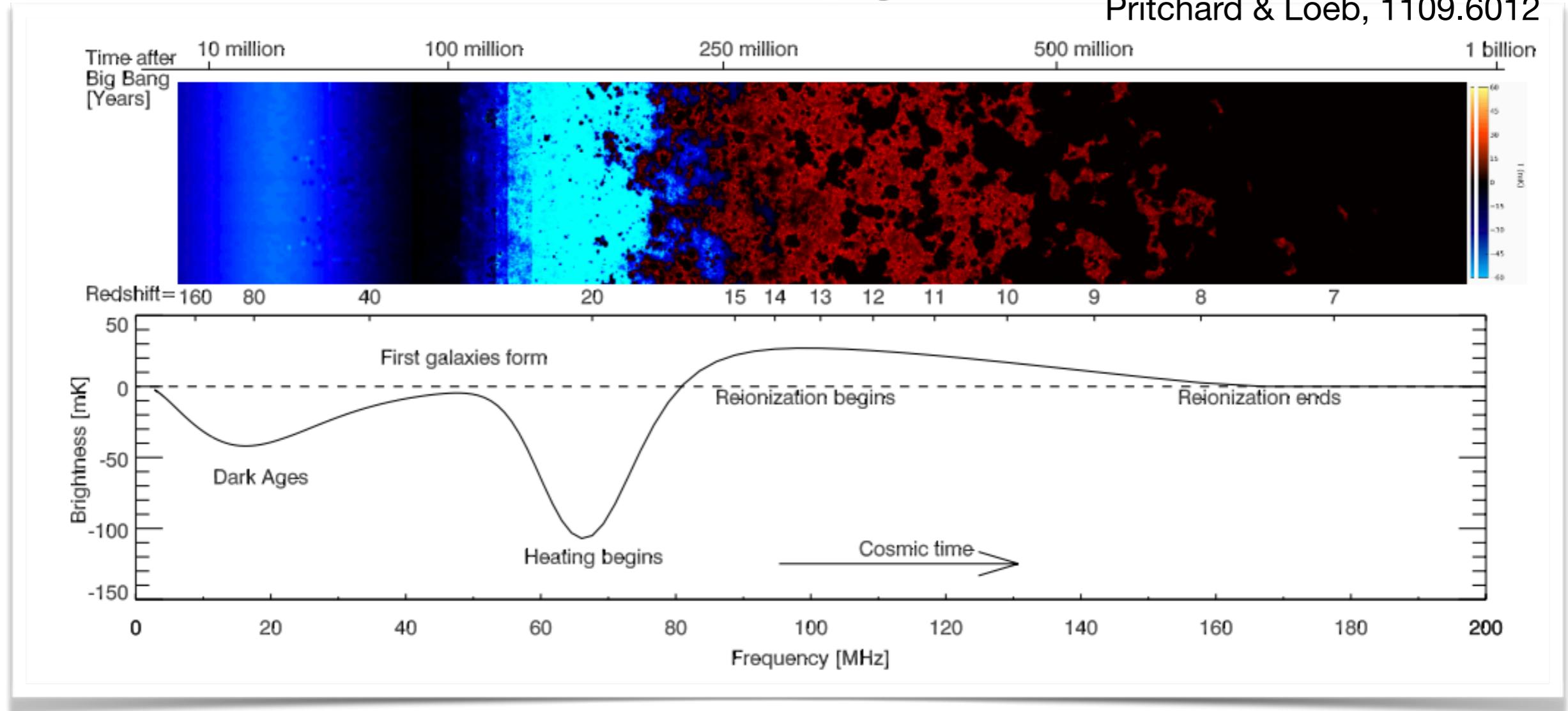
$$T_{21}(z) \approx x_{\text{HI}}(z) \left(\frac{0.15}{\Omega_m} \right)^{1/2} \left(\frac{\Omega_b h}{0.02} \right) \left(\frac{1+z}{10} \right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)} \right] \times 23 \text{ mK}$$



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Pritchard & Loeb, 1109.6012



Measuring the brightness temperature at different frequencies
 sets an **upper limit** on T_m/T_R :

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

assumed = T_{CMB}

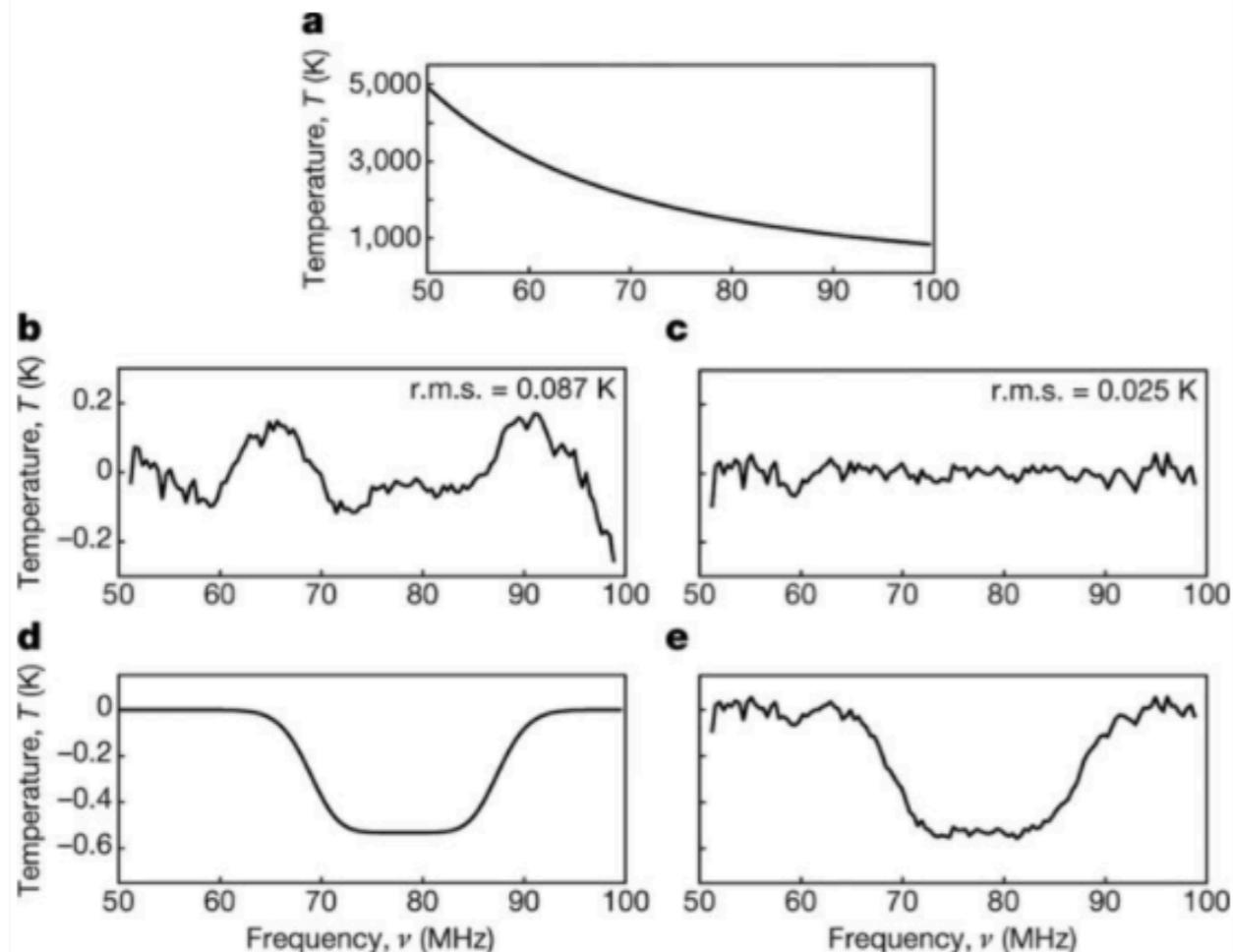
T_m < T_S



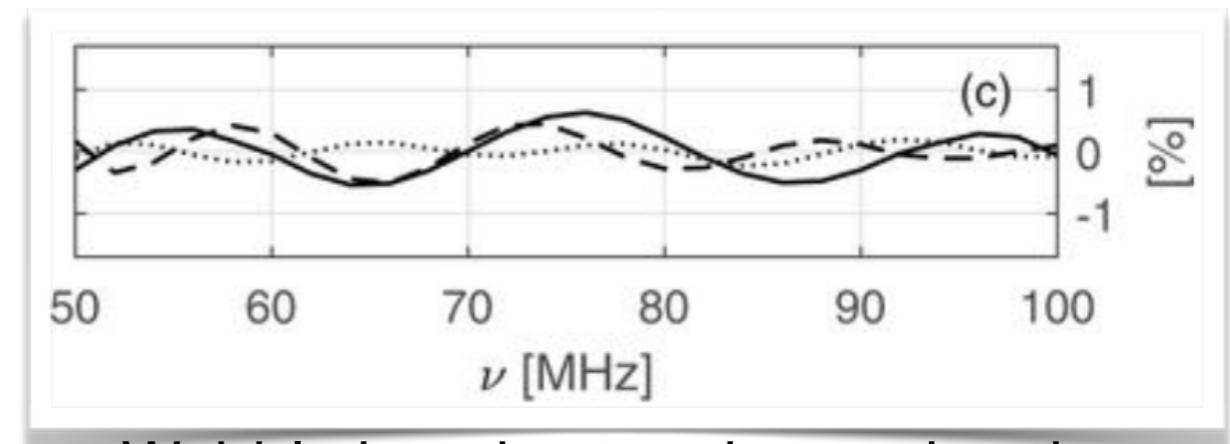
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EDGES Systematics

Figure 1: Summary of detection.



a, Measured spectrum for the reference dataset after filtering for data quality and radio-frequency interference. The spectrum is dominated by Galactic synchrotron emission. **b, c**, Residuals after fitting and removing only the foreground model (**b**) or the foreground and 21-cm models (**c**). **d**, Recovered model profile of the 21-cm absorption, with a signal-to-noise ratio of 37, amplitude of 0.53 K, centre frequency of 78.1 MHz and width of 18.7 MHz. **e**, Sum of the 21-cm model (**d**) and its residuals (**c**).



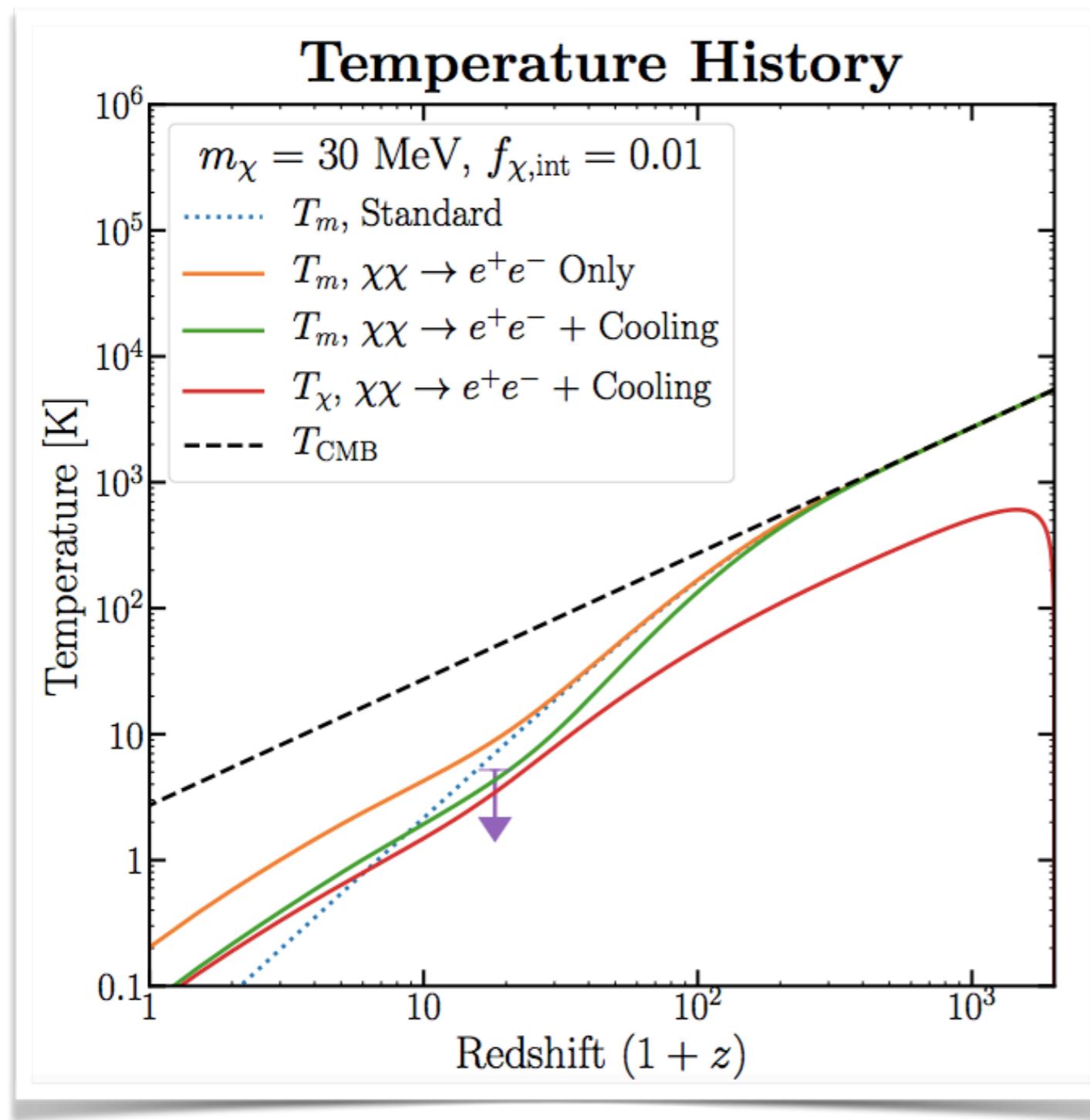
Wobble in gain at various azimuths.

Bowman et al. Nature 555, 67 (2018)



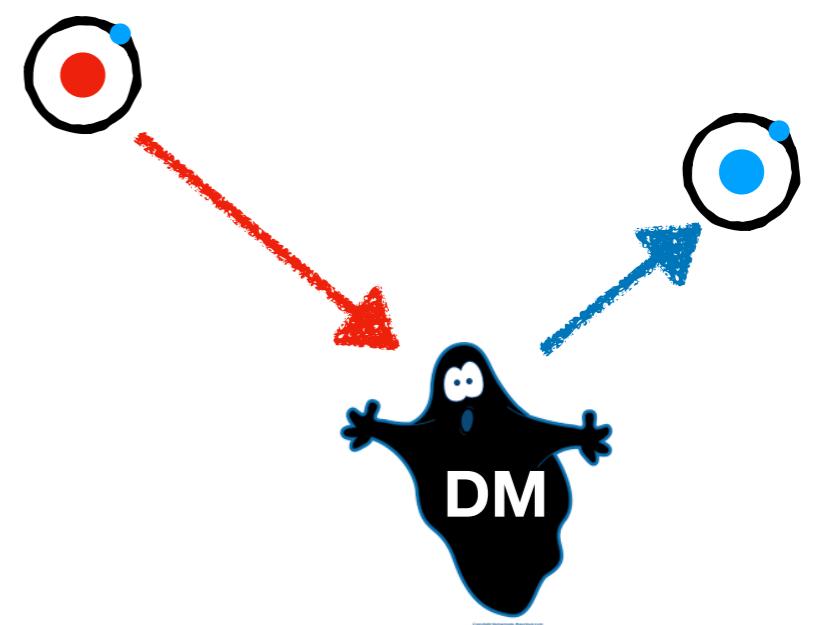
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Cooling

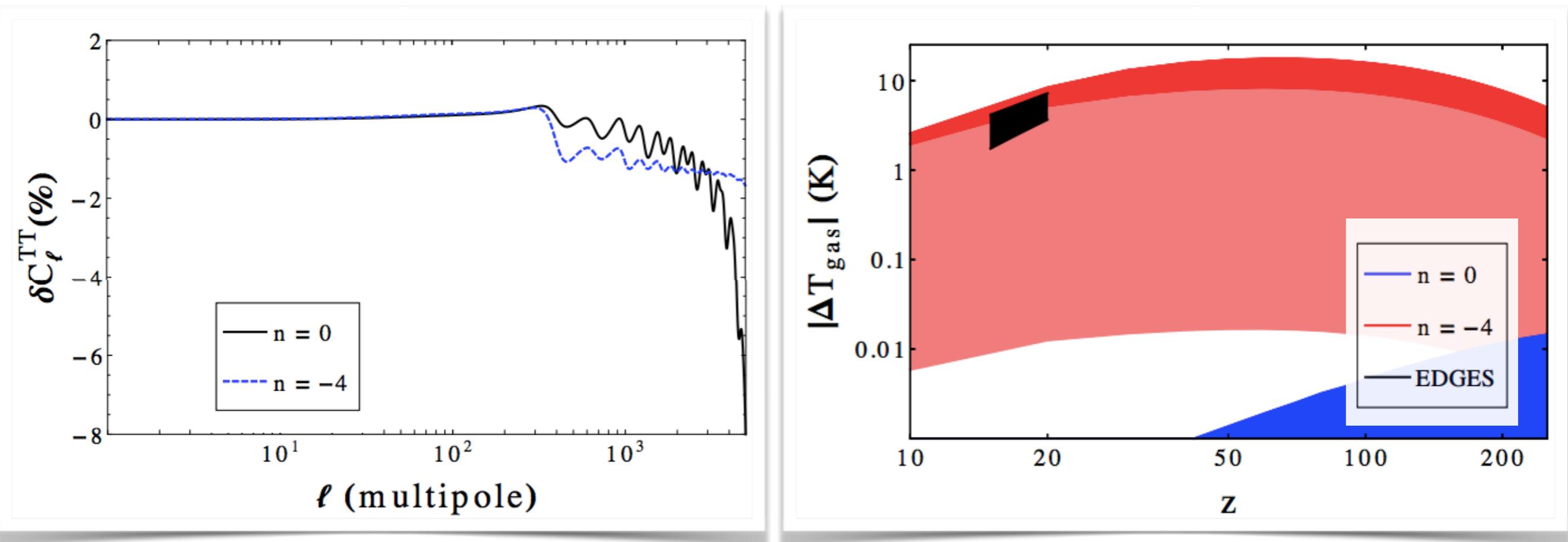


Dark matter is **cold**.

Scattering between baryons and dark matter can decrease the matter temperature.



Cooling

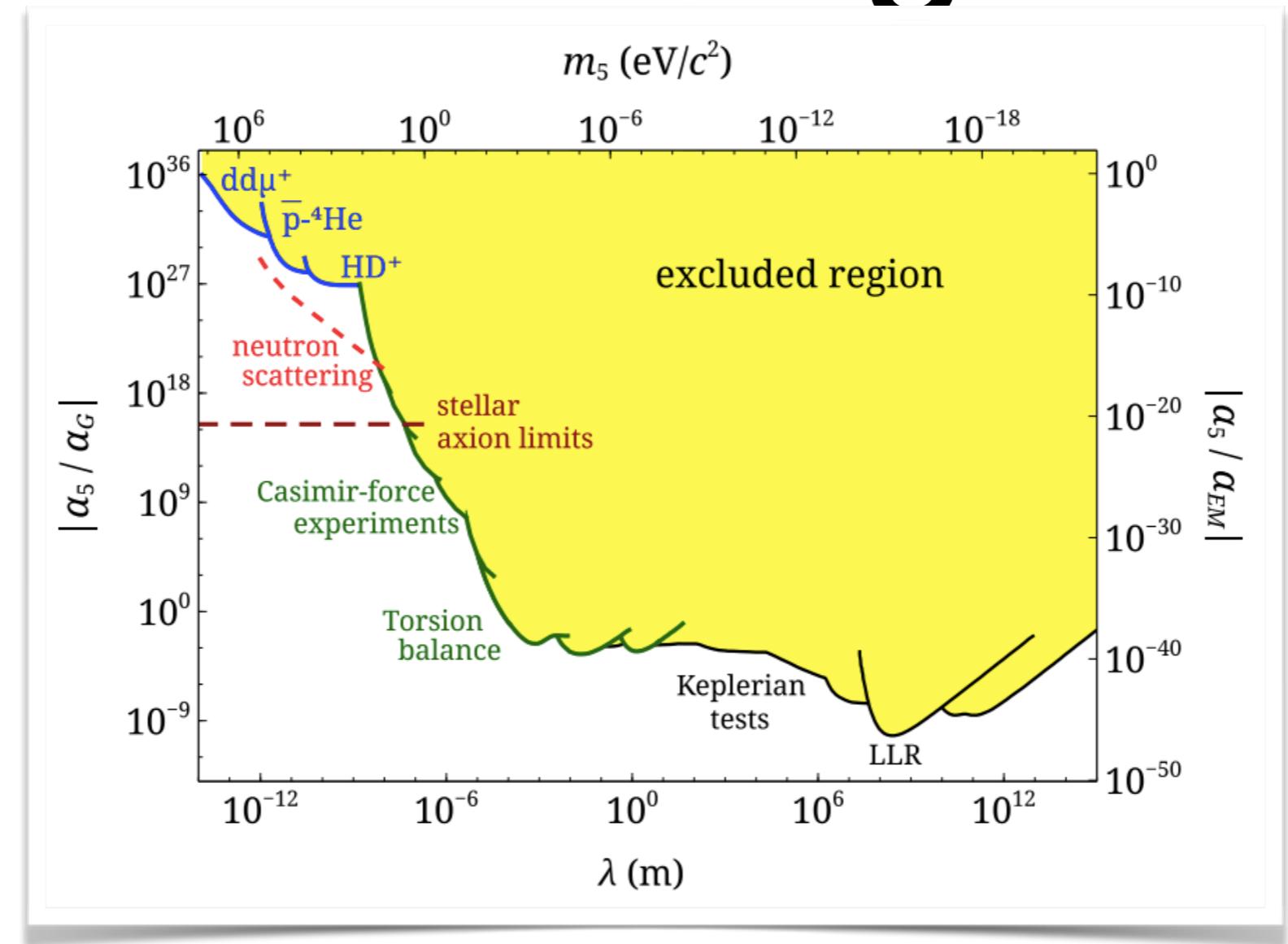


Slatyer and Wu, 1803.09734, also Xu, Dvorkin and Chael 1802.06788

Significant cooling required: **Sub-GeV DM** for a large number of degrees of freedom.
 Large scattering cross section.

Severely constrained by the **CMB power spectrum**, with only $\sigma \propto v^{-4}$ allowed: **light mediator** required, relativistic at sub-eV scales. New mediators **highly constrained**.

Cooling



Salumbides et al., 1308.1711

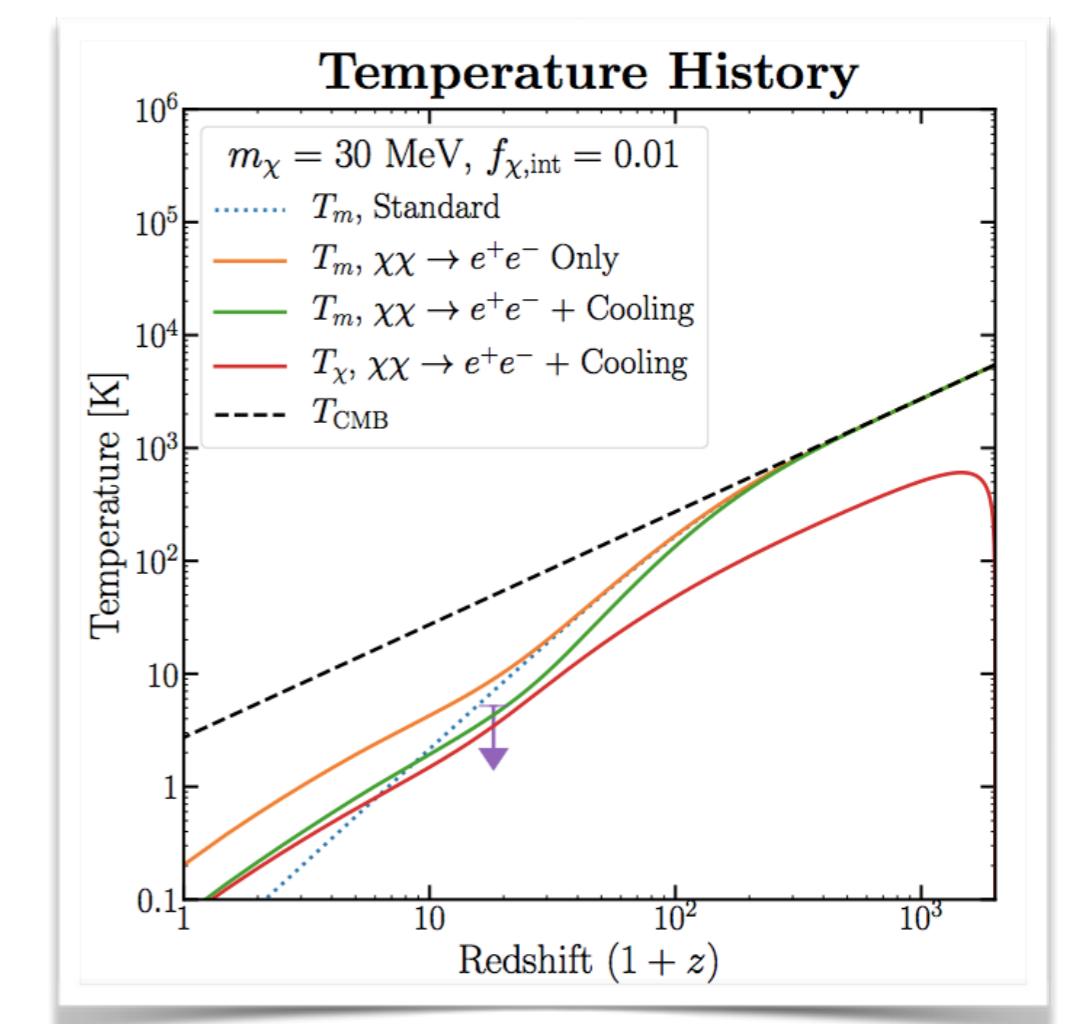
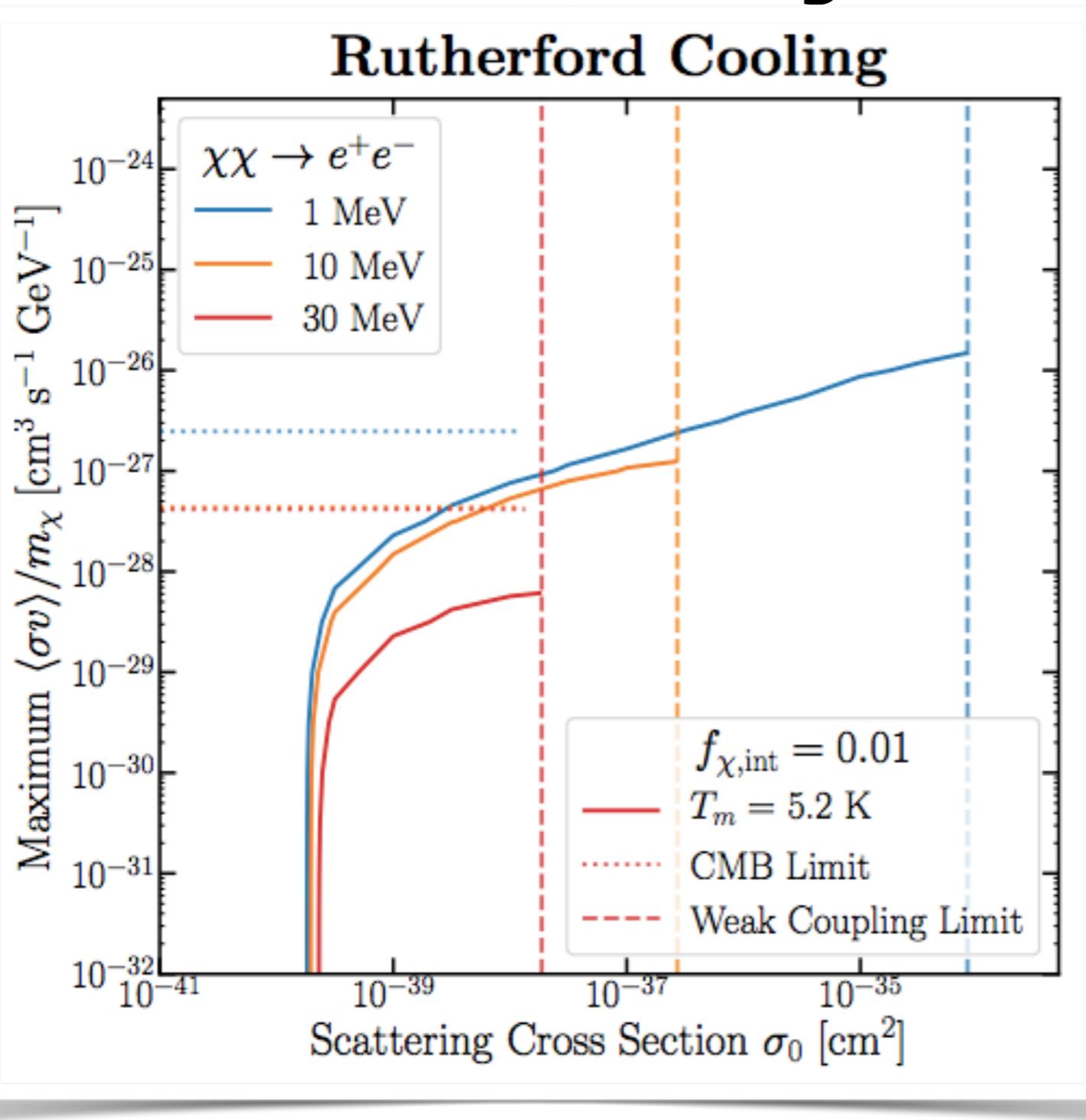
New light mediators are severely constrained.



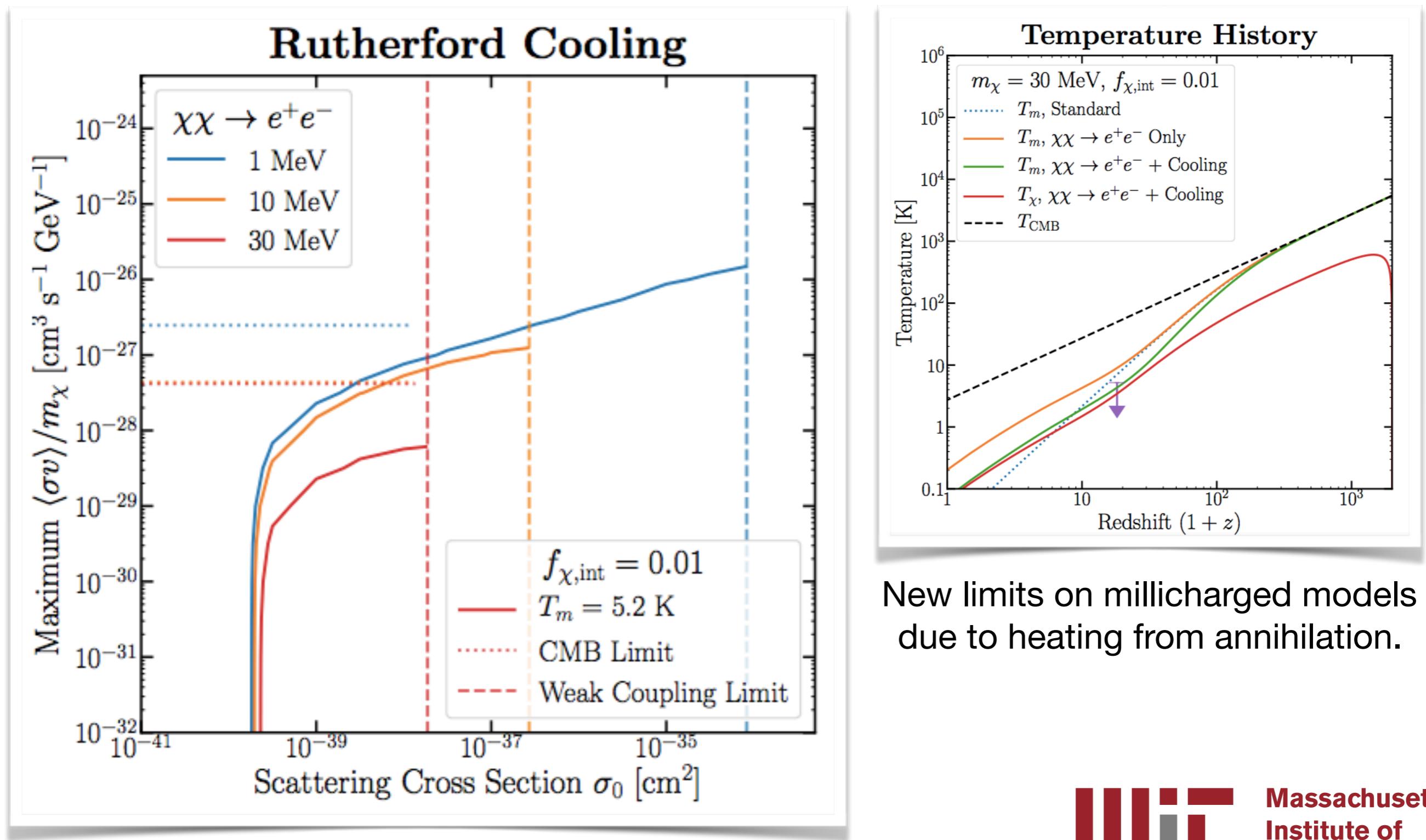
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DM-Baryon Cooling

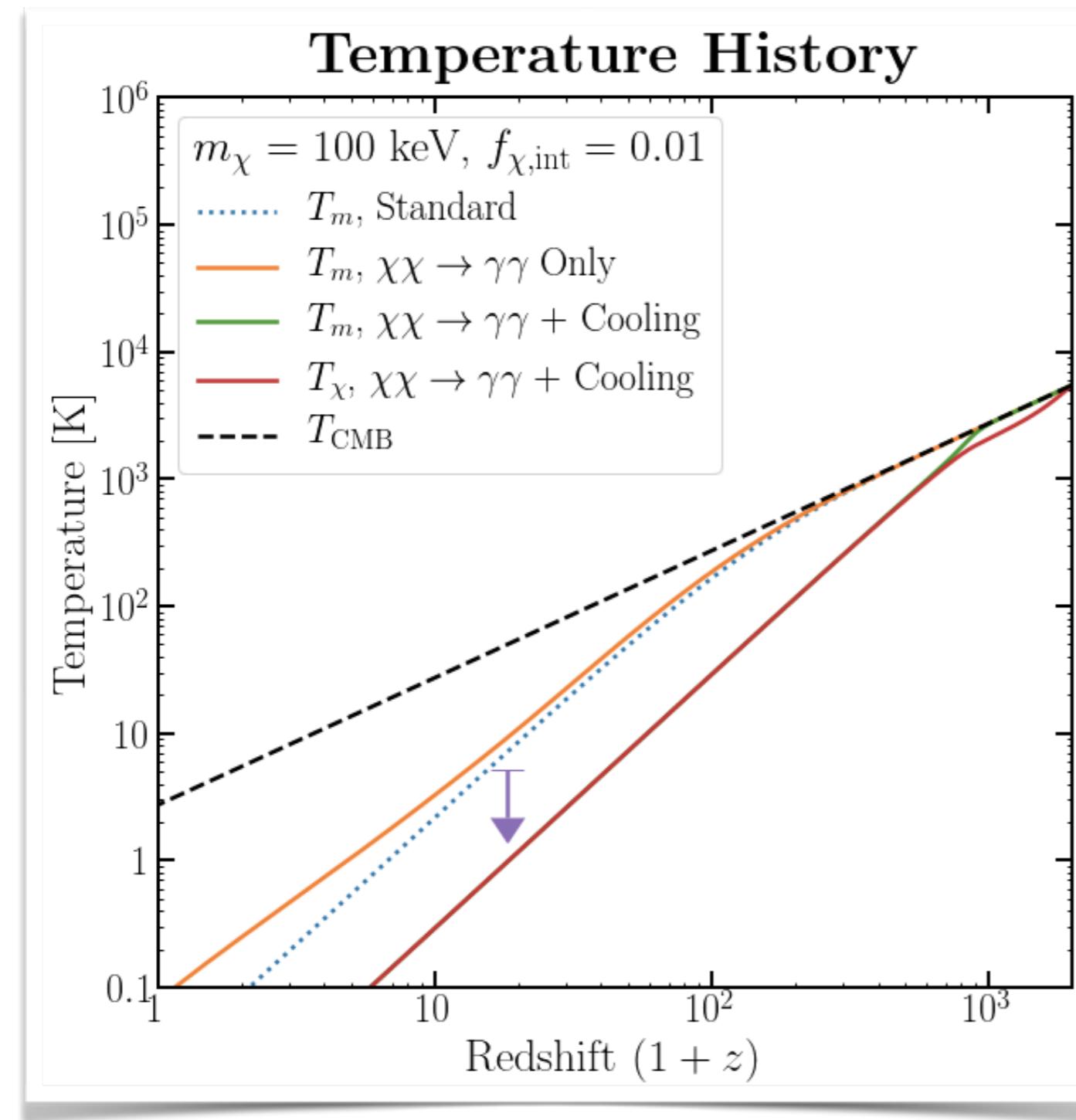
Rutherford Cooling



Cooling



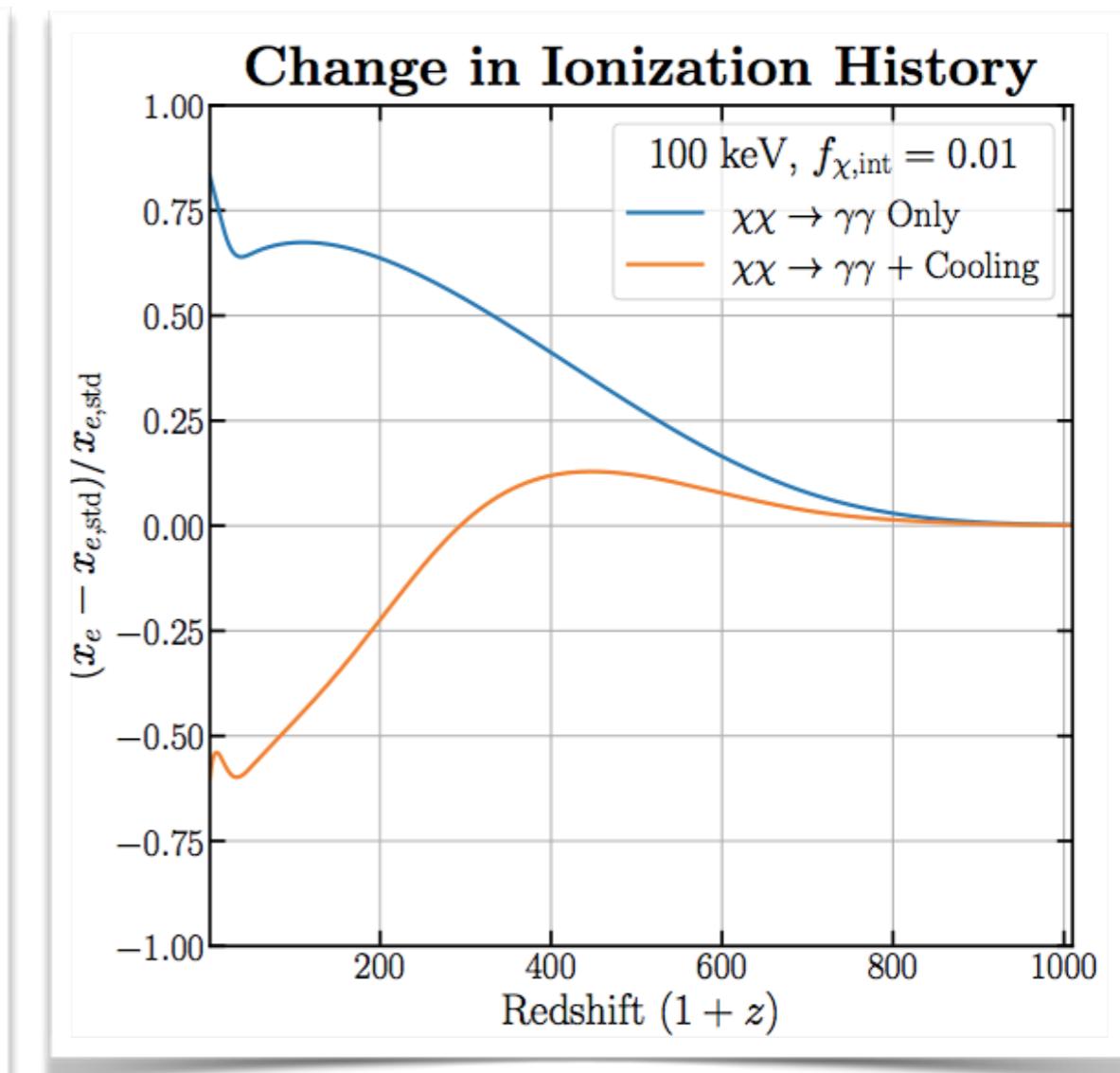
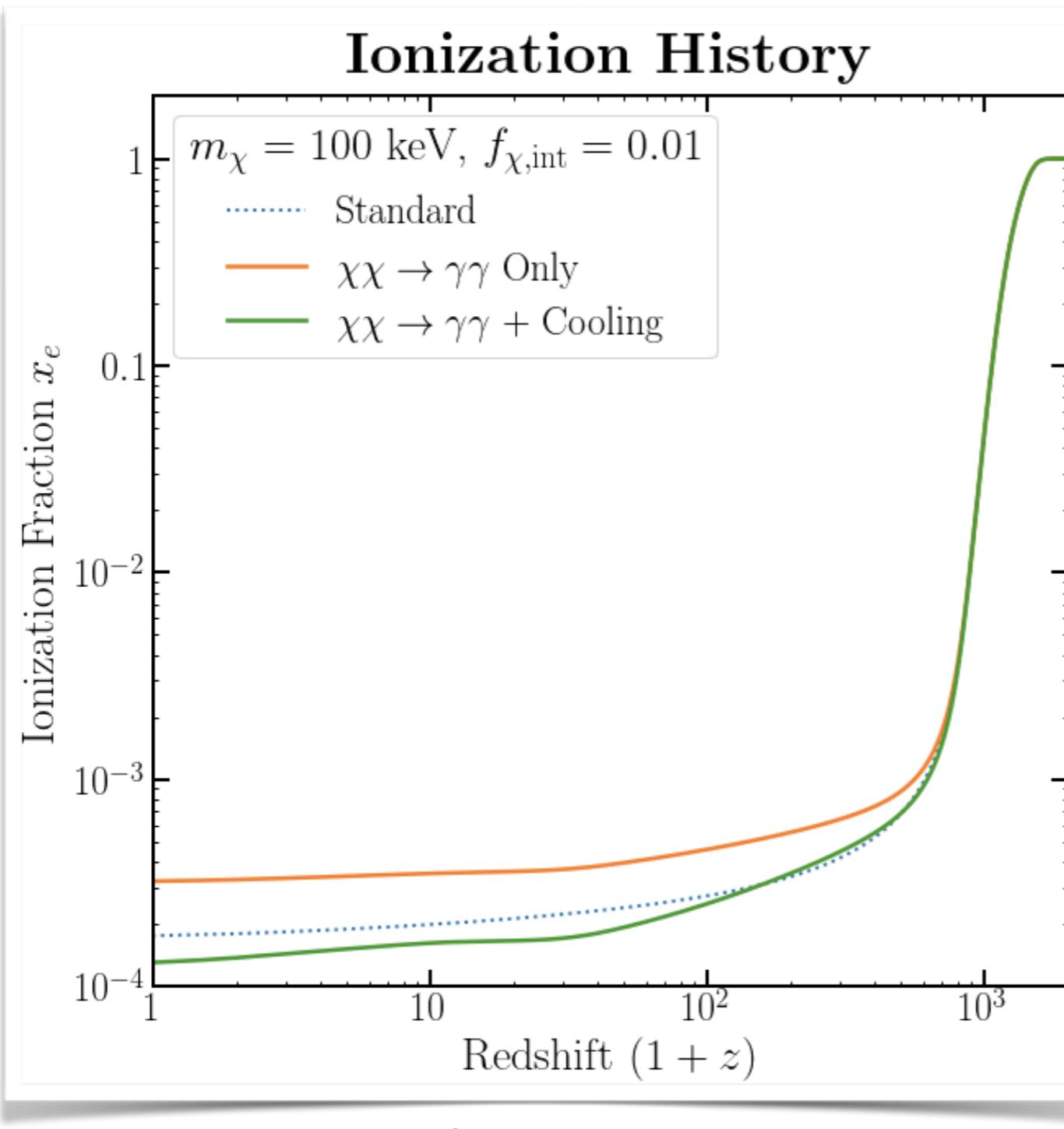
Cooling - Strong Coupling



Strong coupling between sub-component of DM and baryons leads to interesting effects.

Equivalent to early decoupling:
the DM sub-component acts like
additional baryons, Compton
heating becomes ineffective earlier.

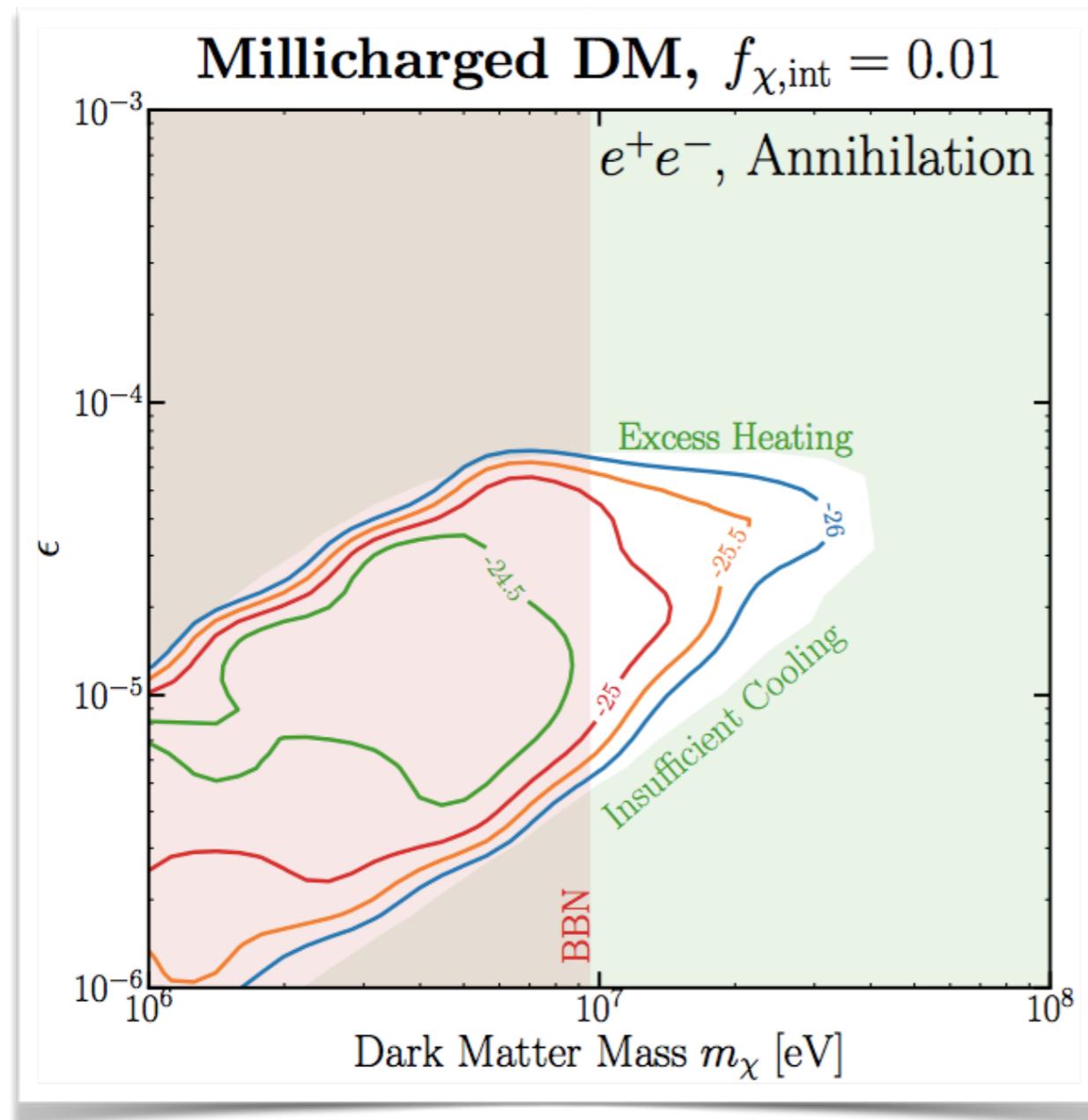
Cooling - Strong Coupling



Significant modification
to the ionization history:
CMB limits may not apply!

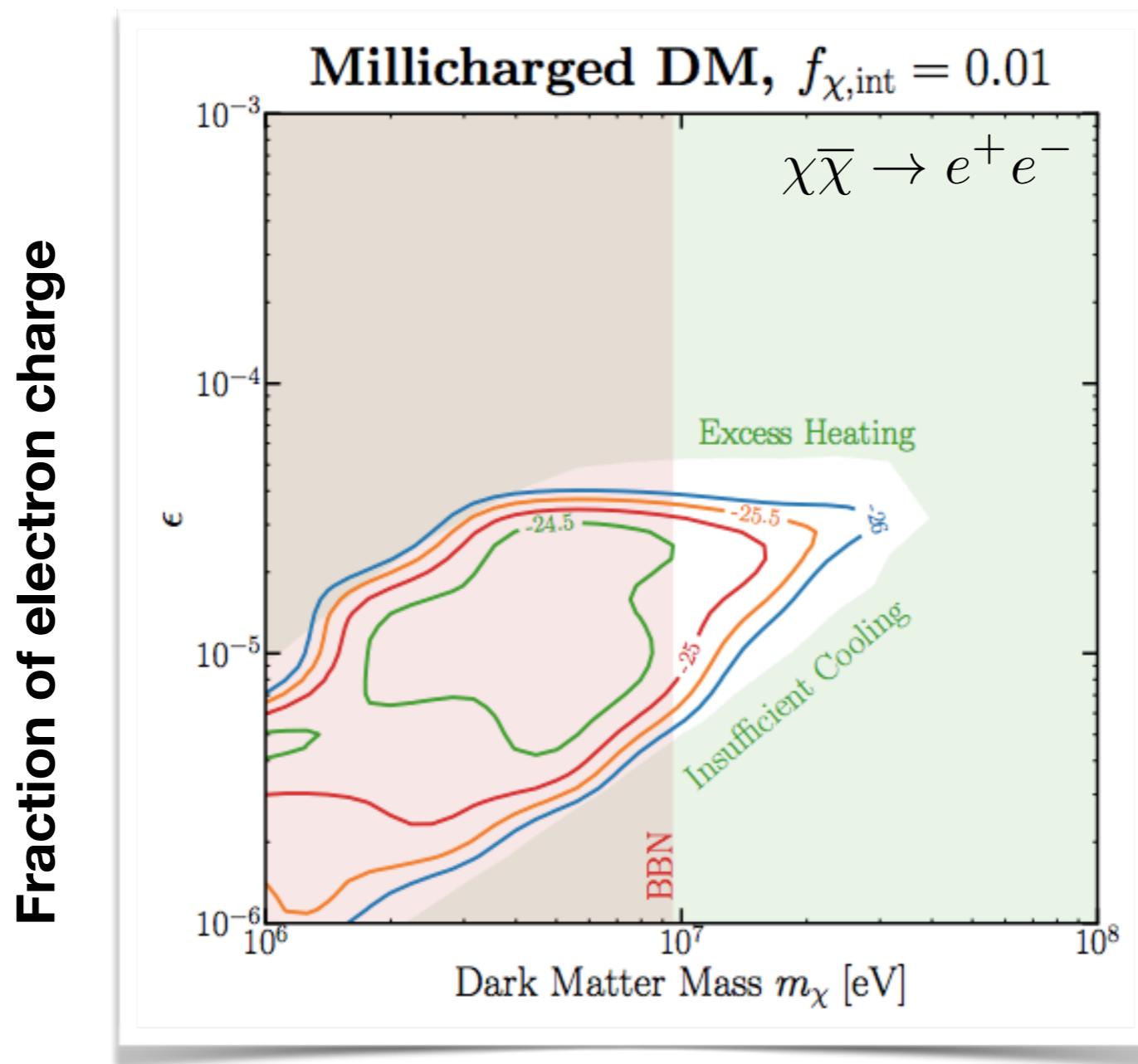
HL and Slatyer 1803.09739

Millicharged Dark Matter



Baryons scatter off millicharged DM, exchanging a photon and transferring energy to the dark sector.

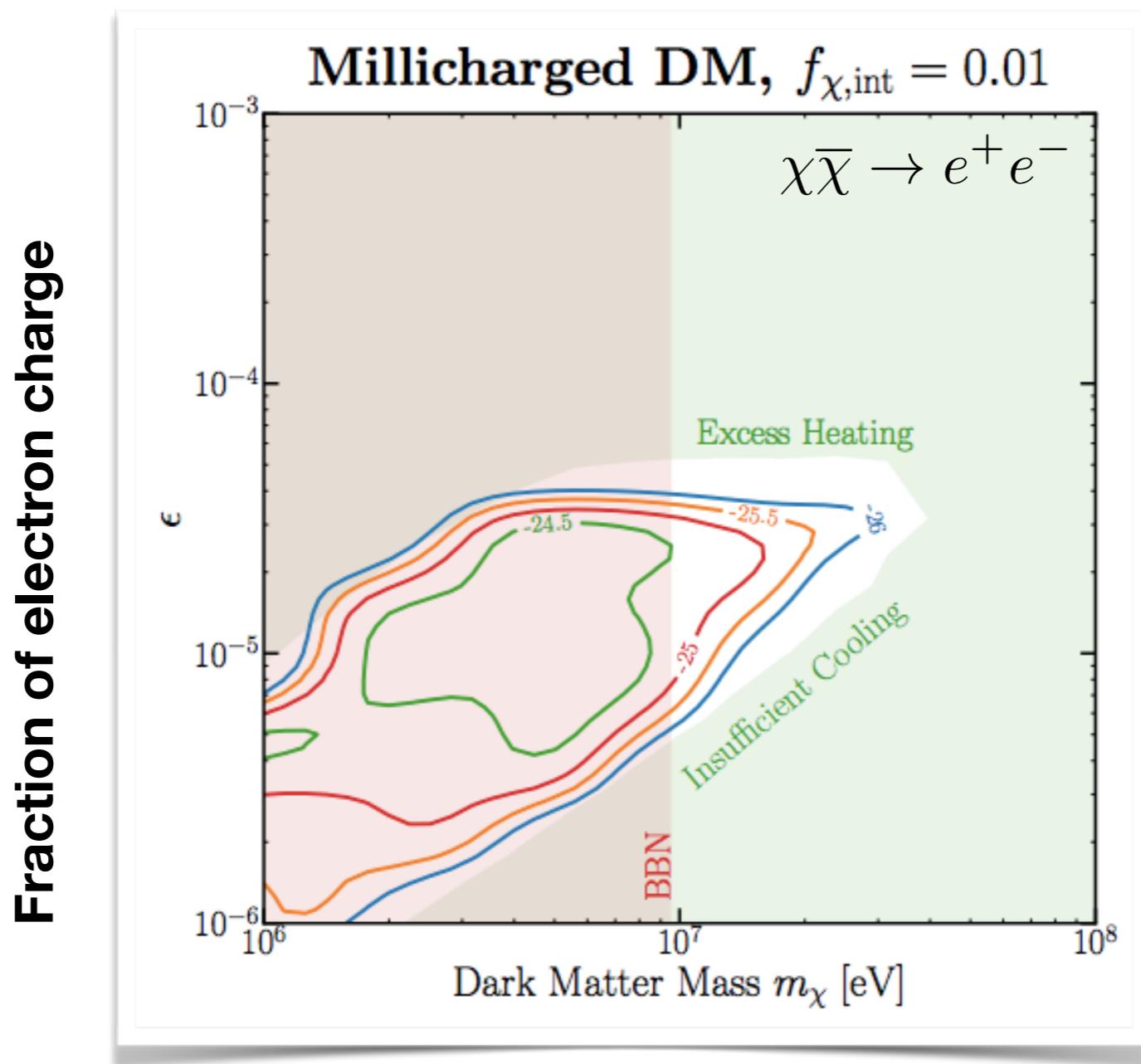
Millicharged Dark Matter



Charge too small - insufficient cooling.

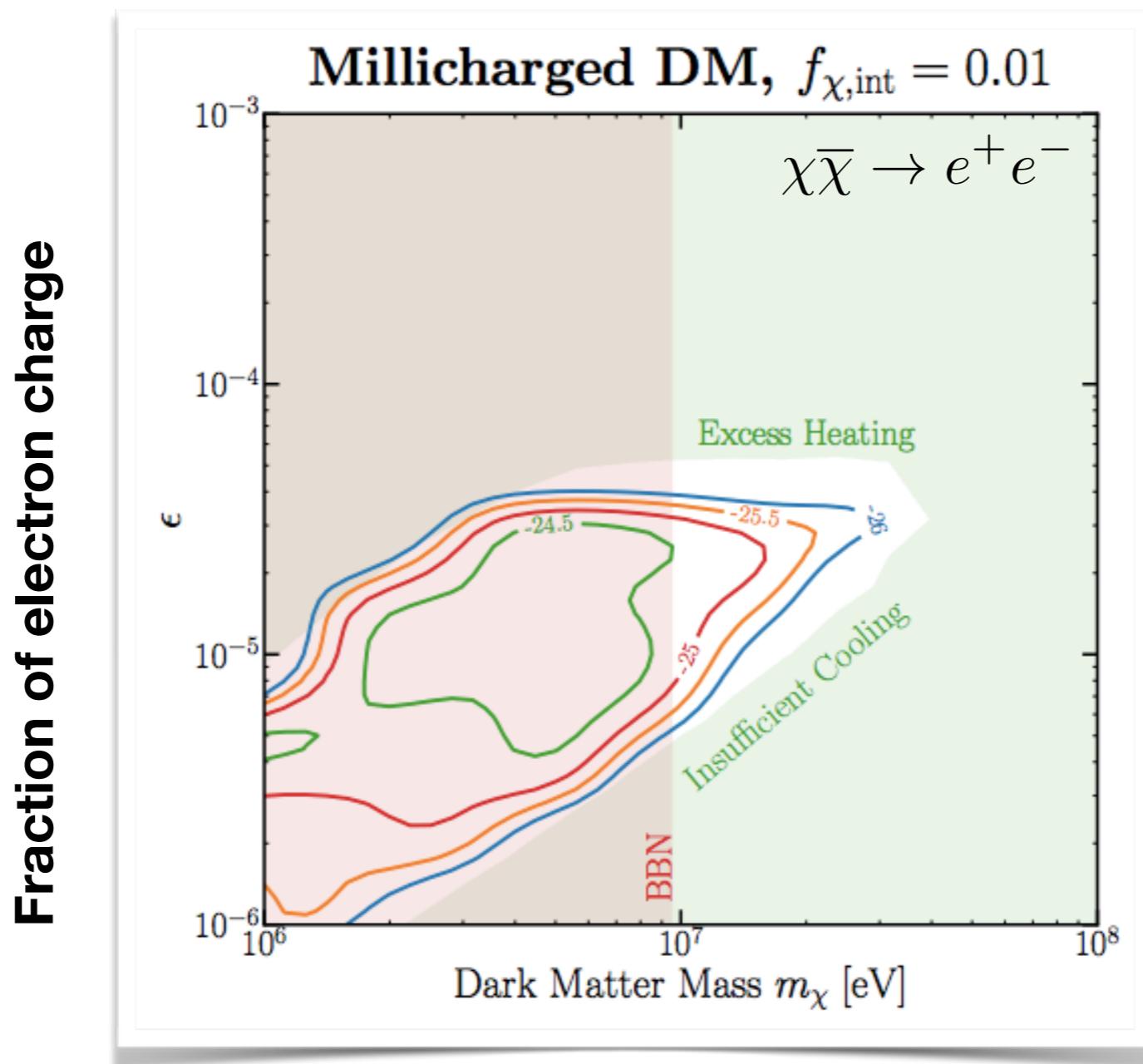
Charge too big - $\chi\bar{\chi} \rightarrow e^+e^-$ heats the baryons too much.

Millicharged Dark Matter



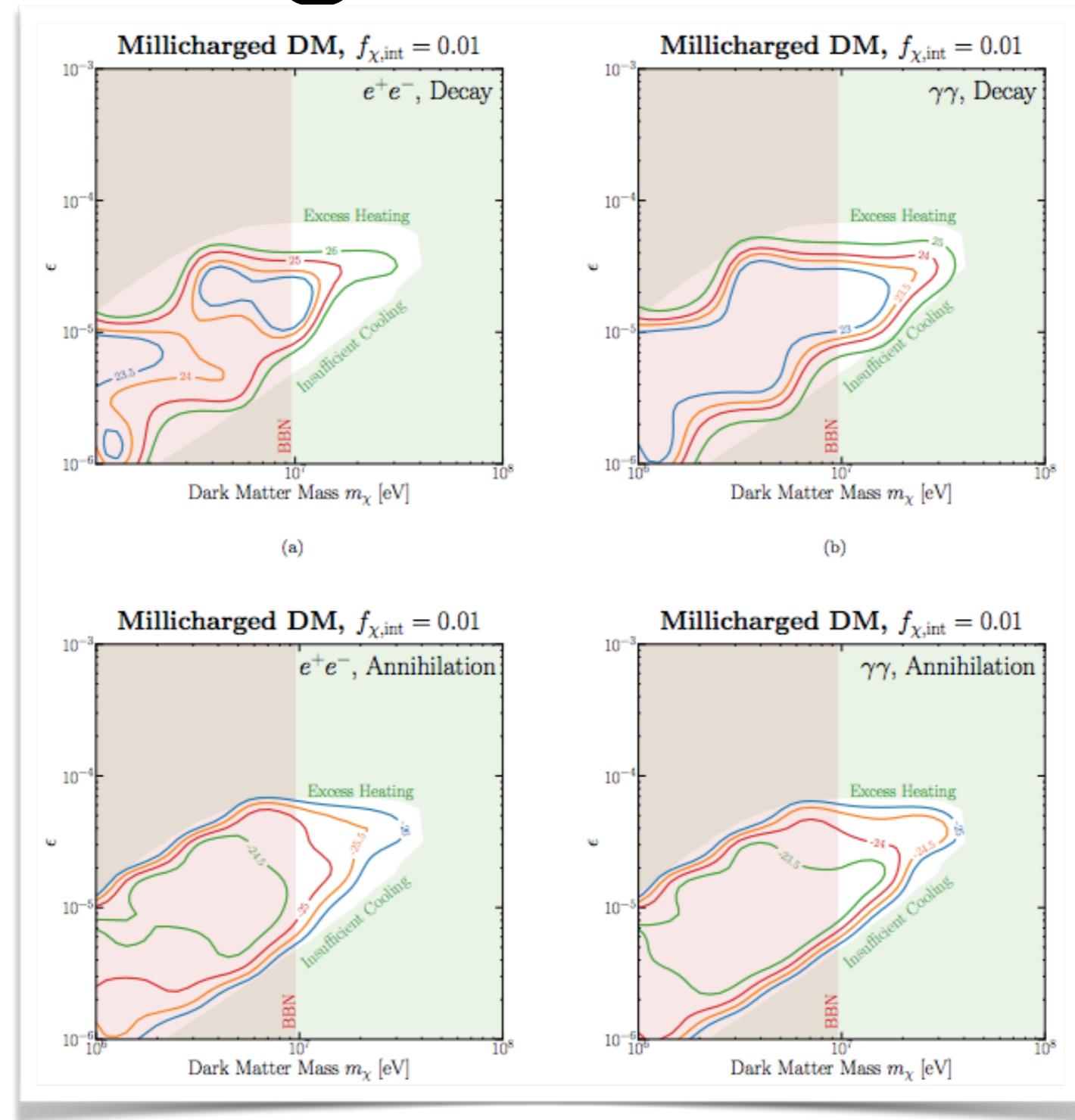
Annihilation cross section of $\chi\bar{\chi} \rightarrow e^+e^-$ through photons too small to achieve relic abundance in allowed region...

Millicharged Dark Matter

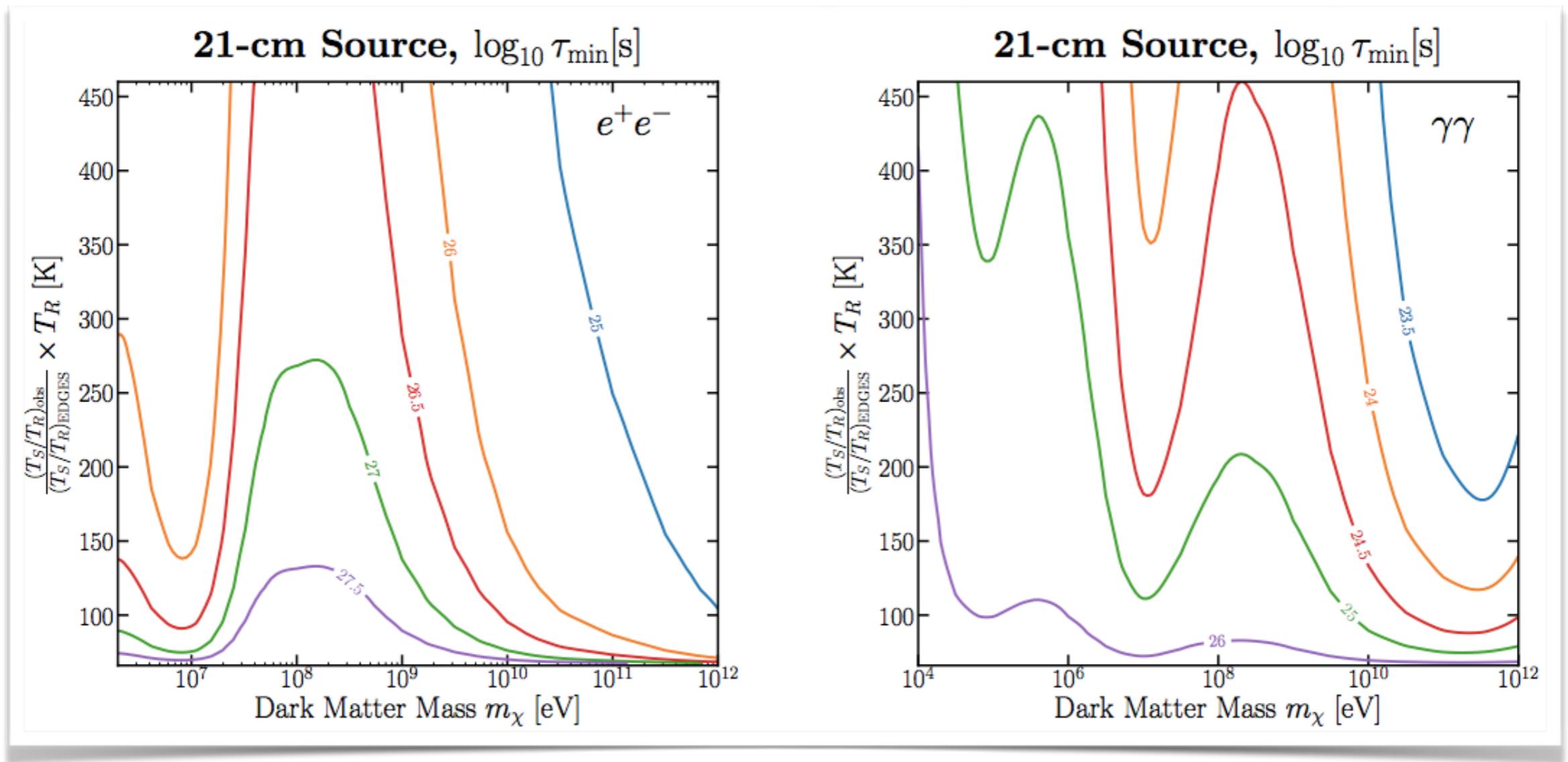


... but an *additional* source of annihilation to electrons that could lead to the correct relic abundance is ruled out by BBN.

Millicharged Dark Matter

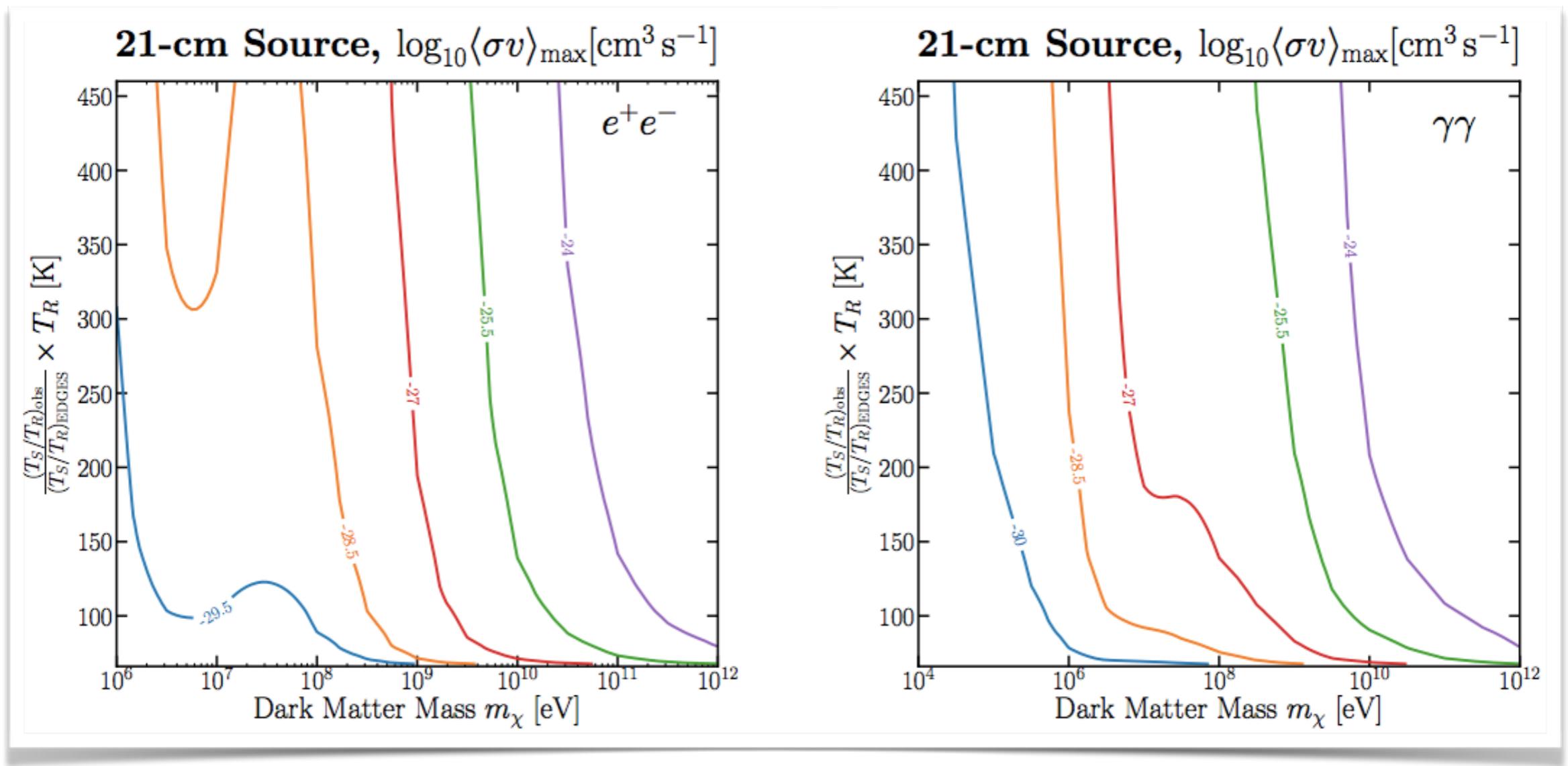


Additional 21-cm Source



HL and Slatyer 1803.09739

Additional 21-cm Source

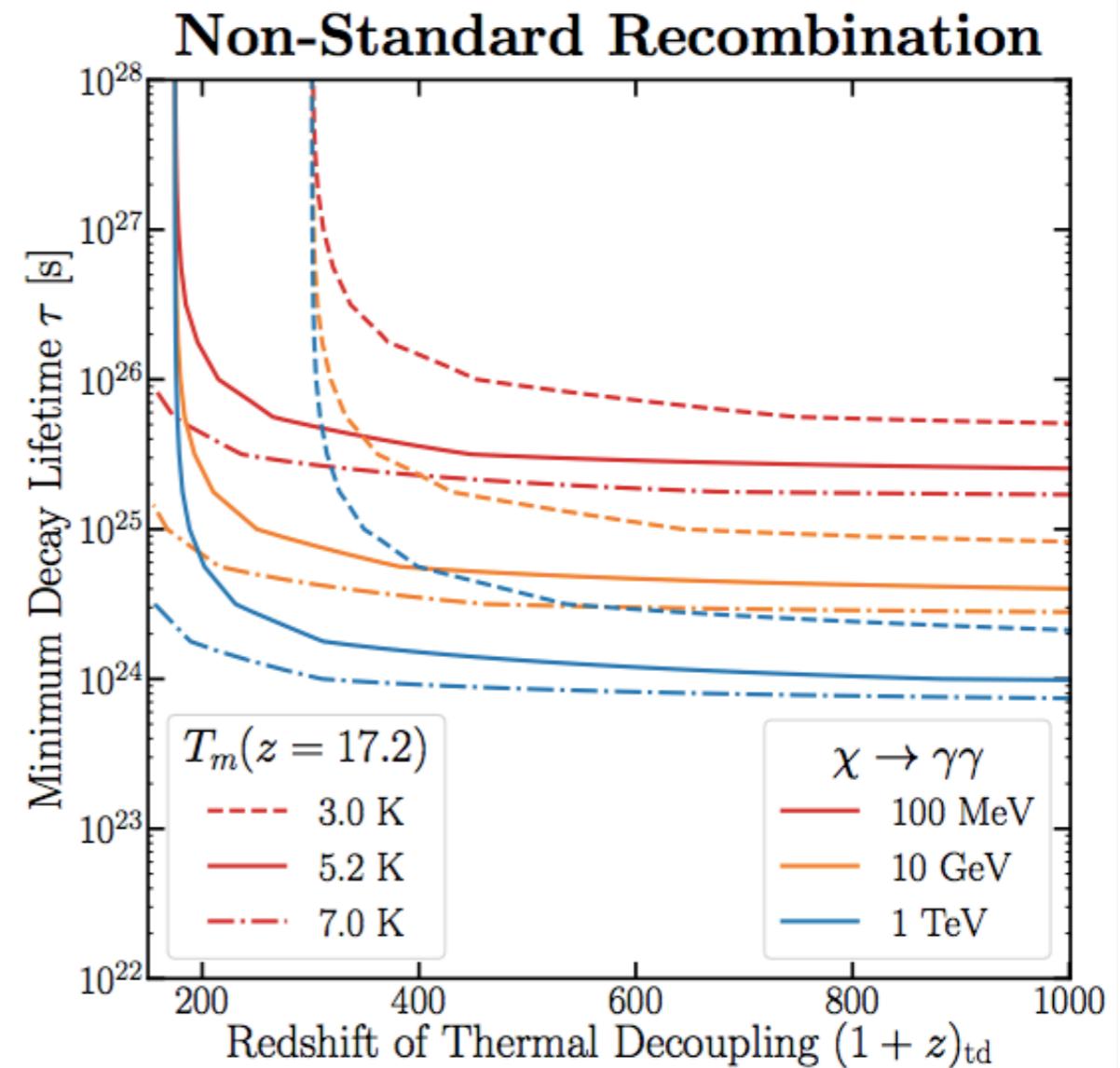
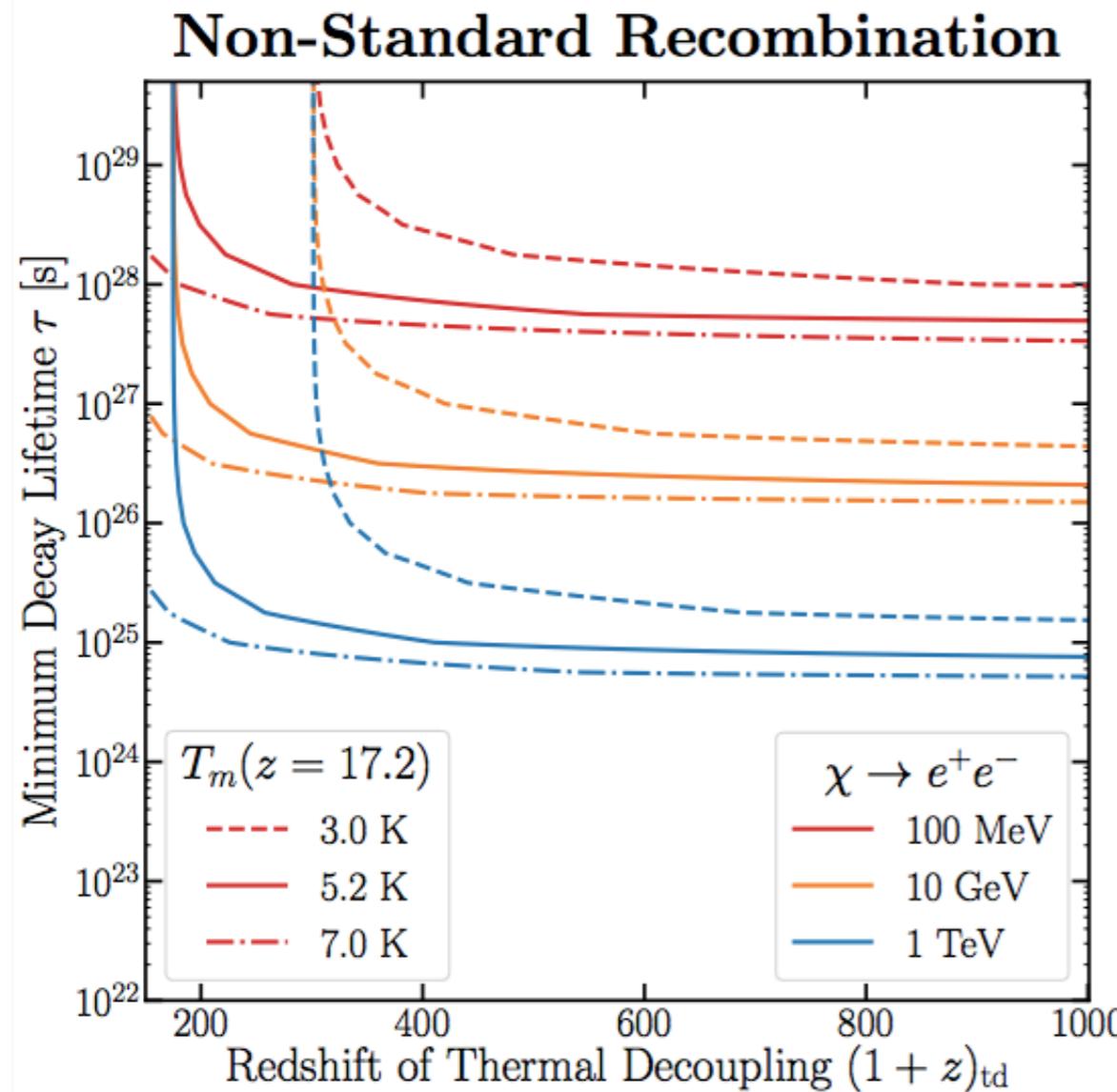


HL and Slatyer 1803.09739



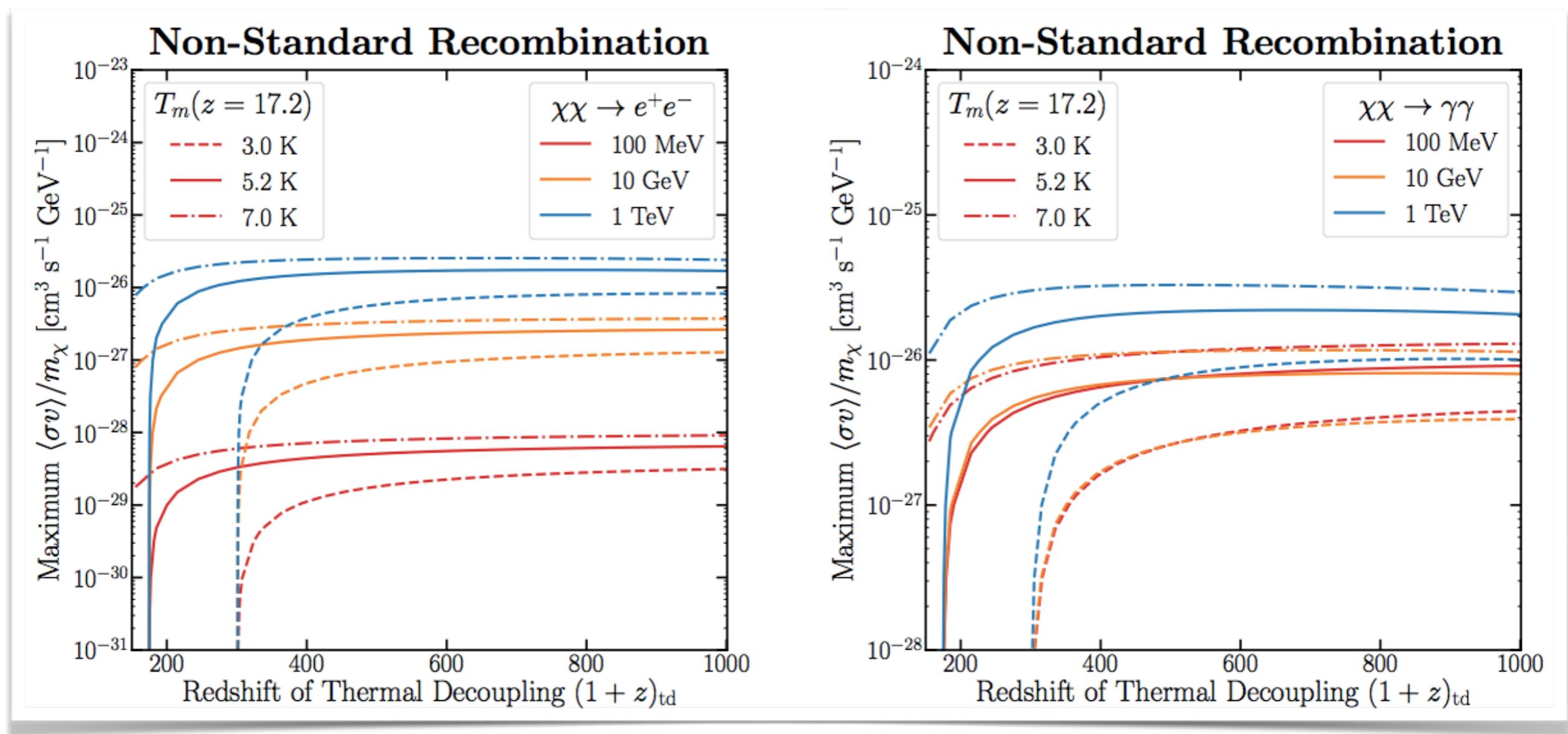
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Non-Standard Recombination

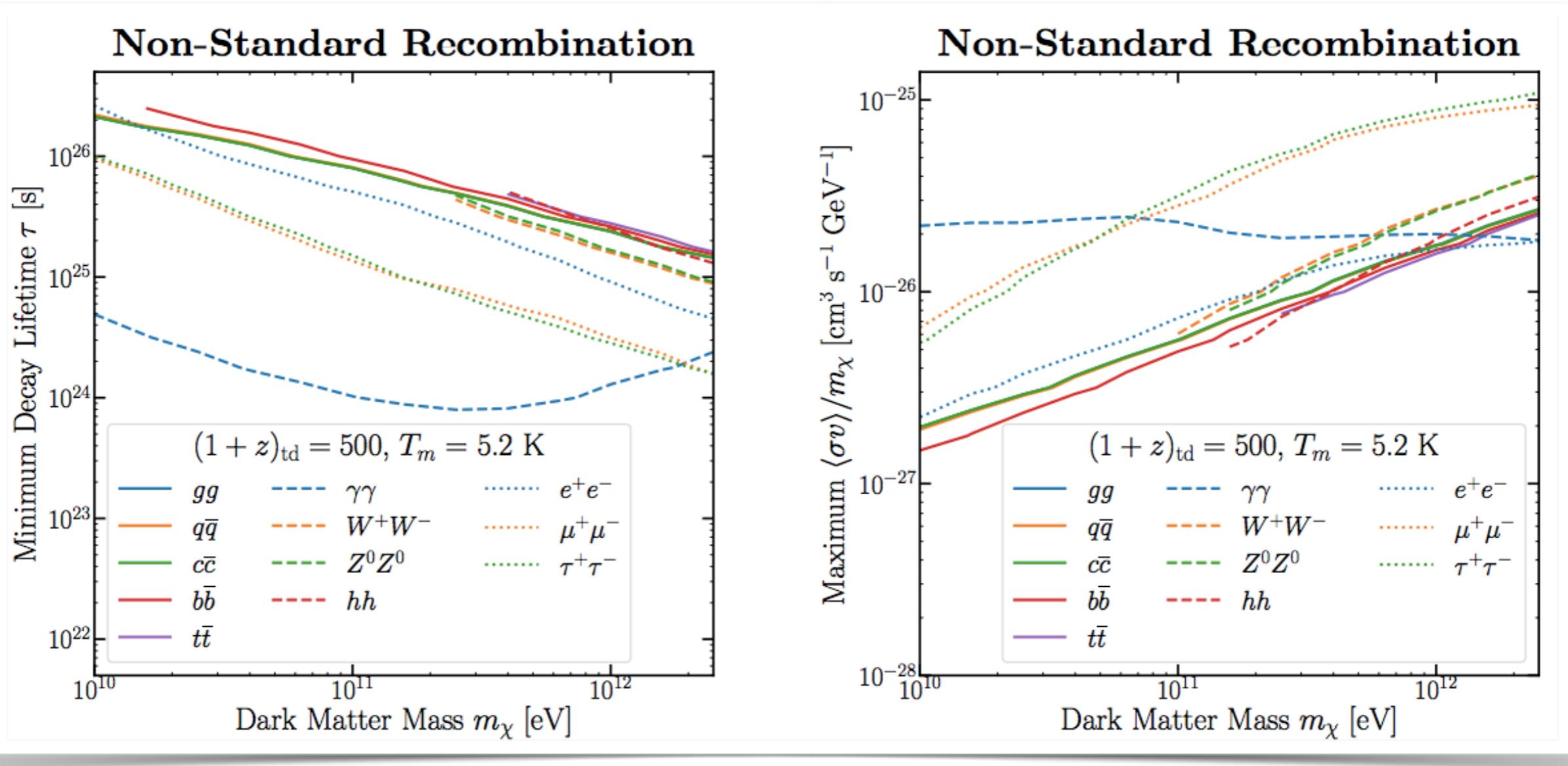


HL and Slatyer 1803.09739

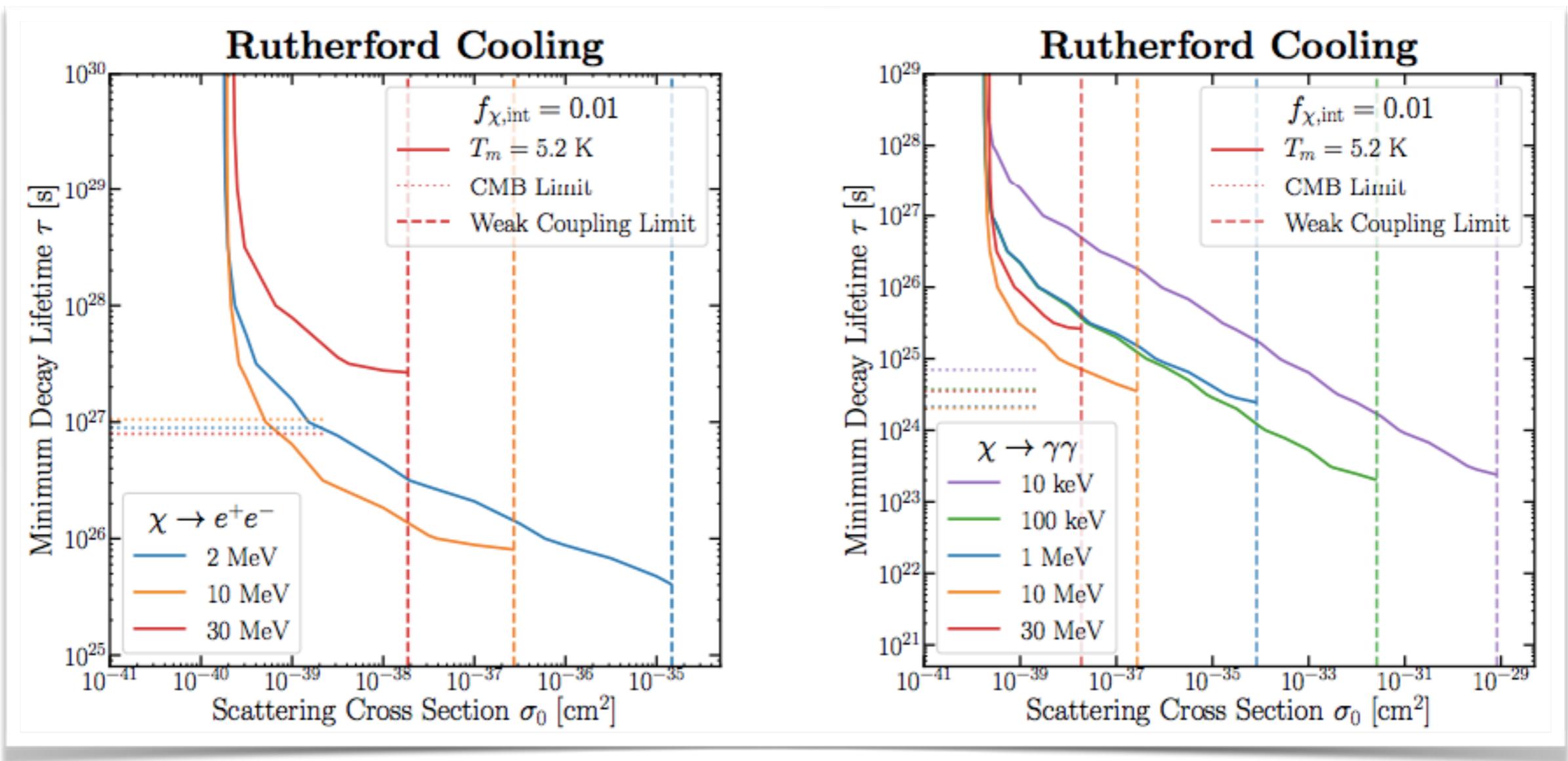
Non-Standard Recombination



Non-Standard Recombination



Rutherford Cooling



Rutherford Cooling

