Testing dark matter interactions through cosmic history

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New Physics from Galaxy Clustering
ICTP Trieste
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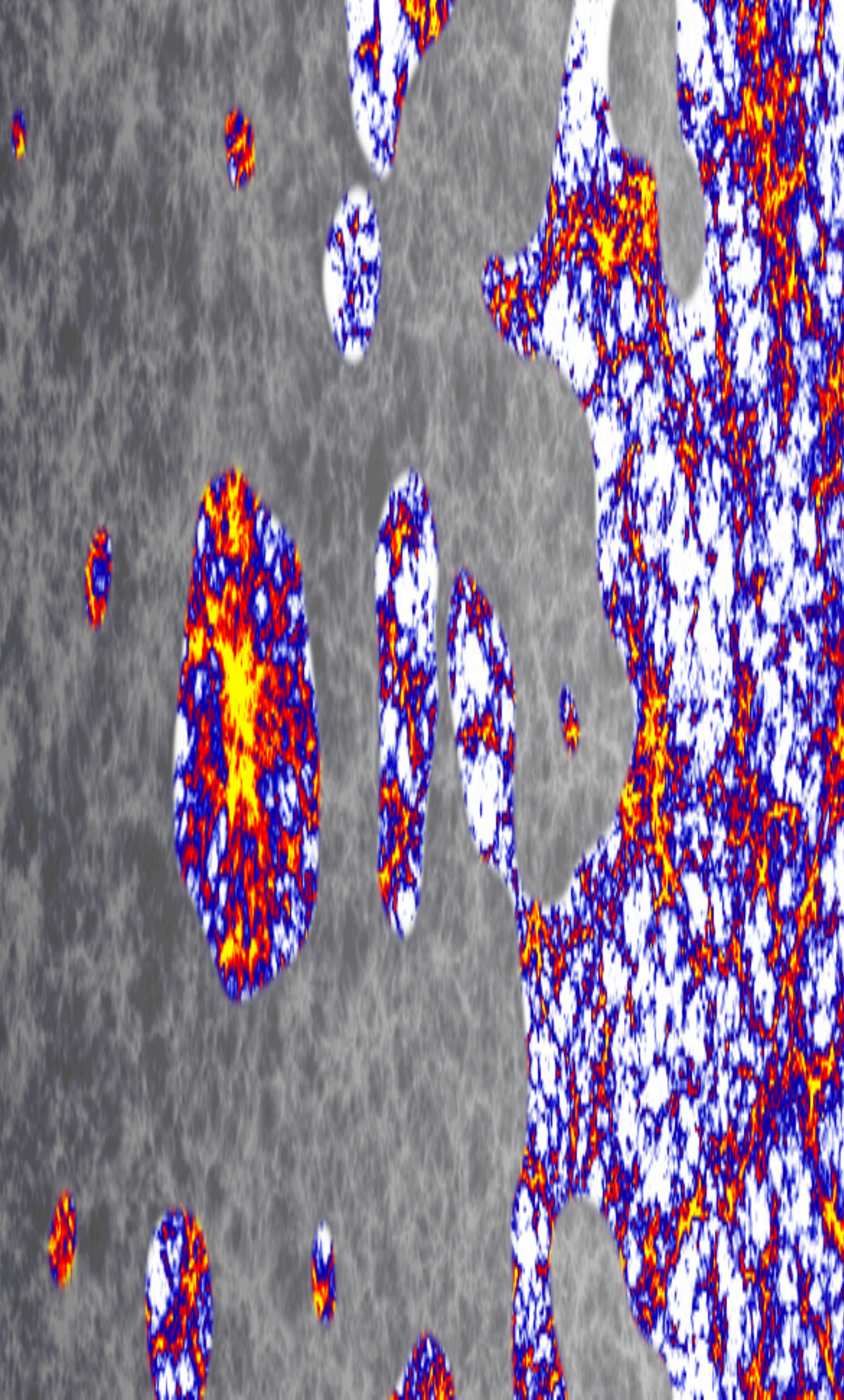

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What does cosmology teach us about DM?

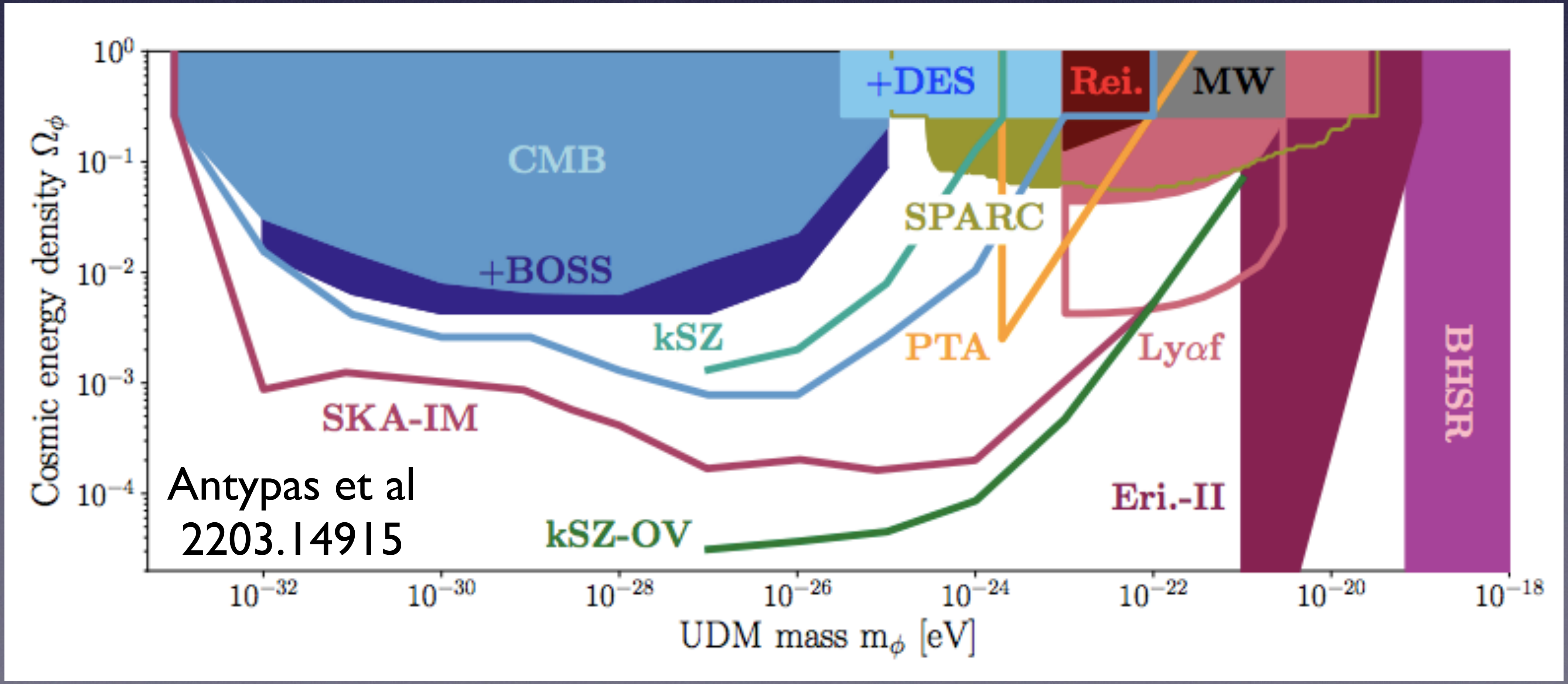
- Baseline assumptions of "standard" ΛCDM (works pretty well):
  - DM has only gravitational interactions
  - DM has equation of state of matter over all observable redshifts
  - DM has no (observable) characteristic mass/distance scale associated with its fundamental nature
- Variations on these assumptions (for some or all of the DM):
  - Non-gravitational interactions (with itself, other "dark" particles including dark radiation, or visible particles)
  - New characteristic scale (e.g. set by wavelength for fuzzy DM, or velocity for warm DM)
  - DM evolution with redshift is modified (e.g. due to decays)

The scale of new DM physics

- One generic modification (occurs in many model classes) is to suppress power below some characteristic scale:
  - Fuzzy DM: $\lambda_{\rm DB} = 2\pi/mv \approx \left(10^{-3}/v\right)\left(10^{-25}\text{eV}/m\right) 0.4\text{Mpc}$
  - Warm DM: $\lambda_{\rm fs}^{\rm eff} \approx (m/1\text{keV})^{-1.11} 0.07\text{Mpc}$
  - DM interacting with SM: $k_{\rm cutoff}$ set by modes entering horizon when momentum transfer rate is ~H
- In all these cases, suppression is most dramatic in smallest-scale structures we can observe (see e.g. Bechtol et al 2203.07354 for a review)
  - probed by stellar streams, Ly-alpha, strong lensing, MW satellites
- But if only a fraction of the DM interacts in this way (or if effects have a non-trivial scale dependence), best tests may involve precision measurements of larger scales

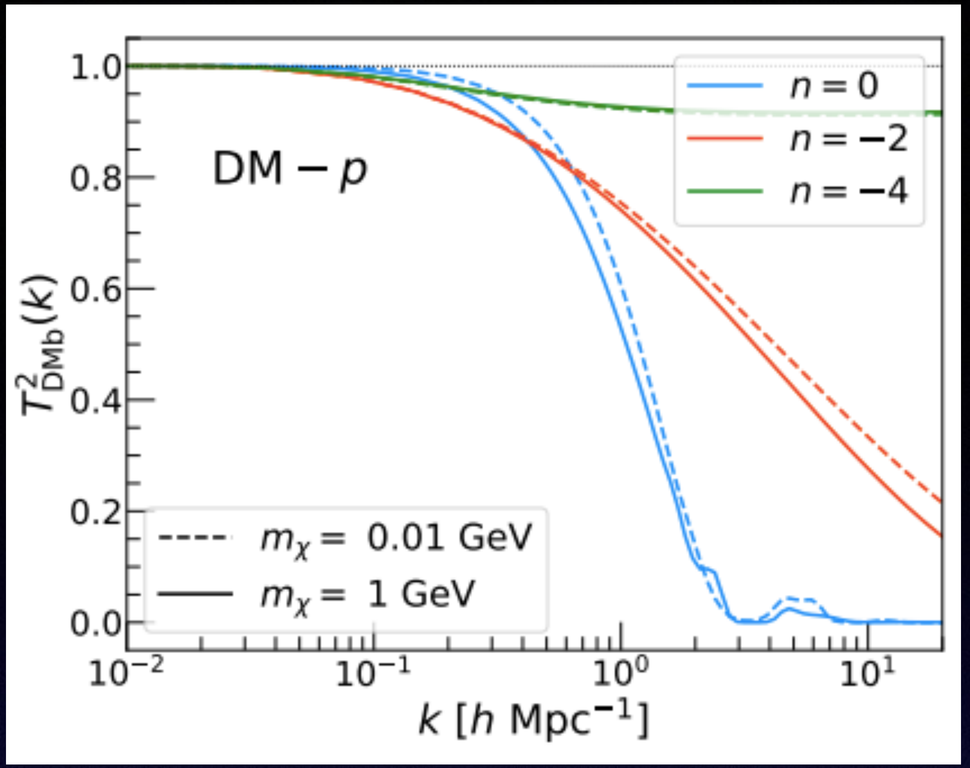
Example: fuzzy DM

- Highest-mass constraints for 100% of DM come from observations of dwarf galaxy Eridanus II + black hole superradiance limits
- At low mass with a subdominant fraction, strongest bounds arise from large-scale structure (see also Shevchuk et al 2308.14640 for new limits from galaxy-galaxy strong lensing)

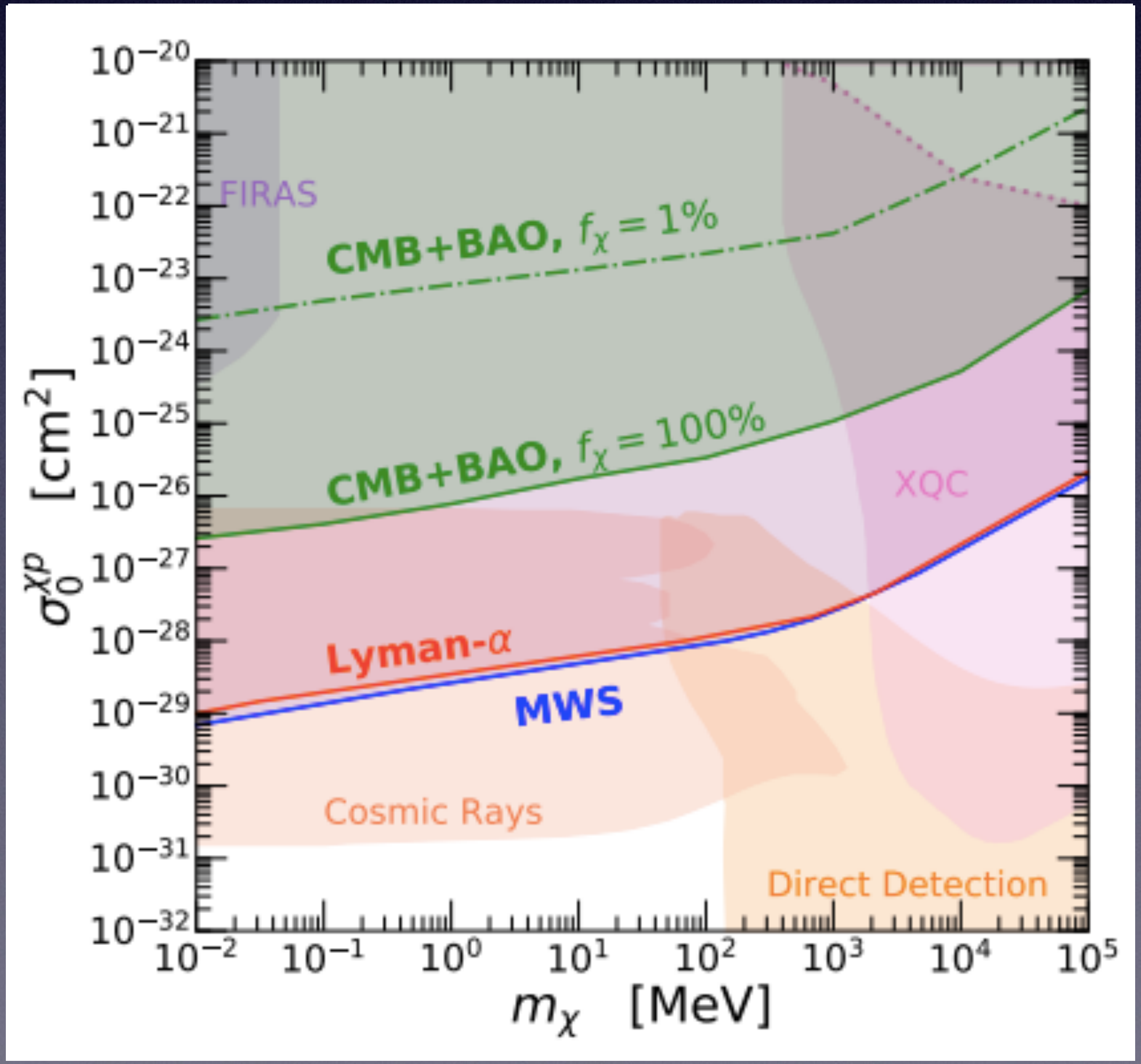


DM-SM scattering (perturbations)

- Coupling DM to SM in the early universe collisionally damps structure growth for small-scale modes (up to horizon scale)
- Damping is most pronounced for modes that were inside horizon when momentum transfer rate exceeds H
- Larger interaction = later decoupling, damping extends to larger scales
- Enhancement of scattering at low velocities = signal weighted toward lower redshift / lower k
- Probes with sensitivity to smaller scales do better than the CMB, if low-velocity enhancement is not too strong



Buen-Abad et al 2107.12377



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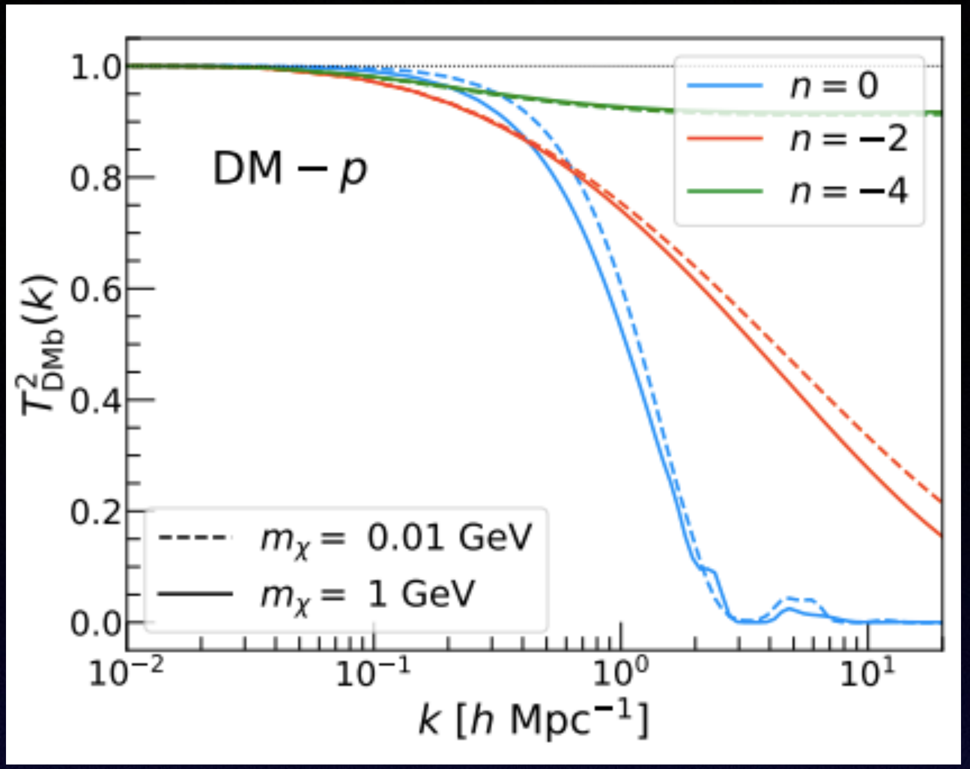

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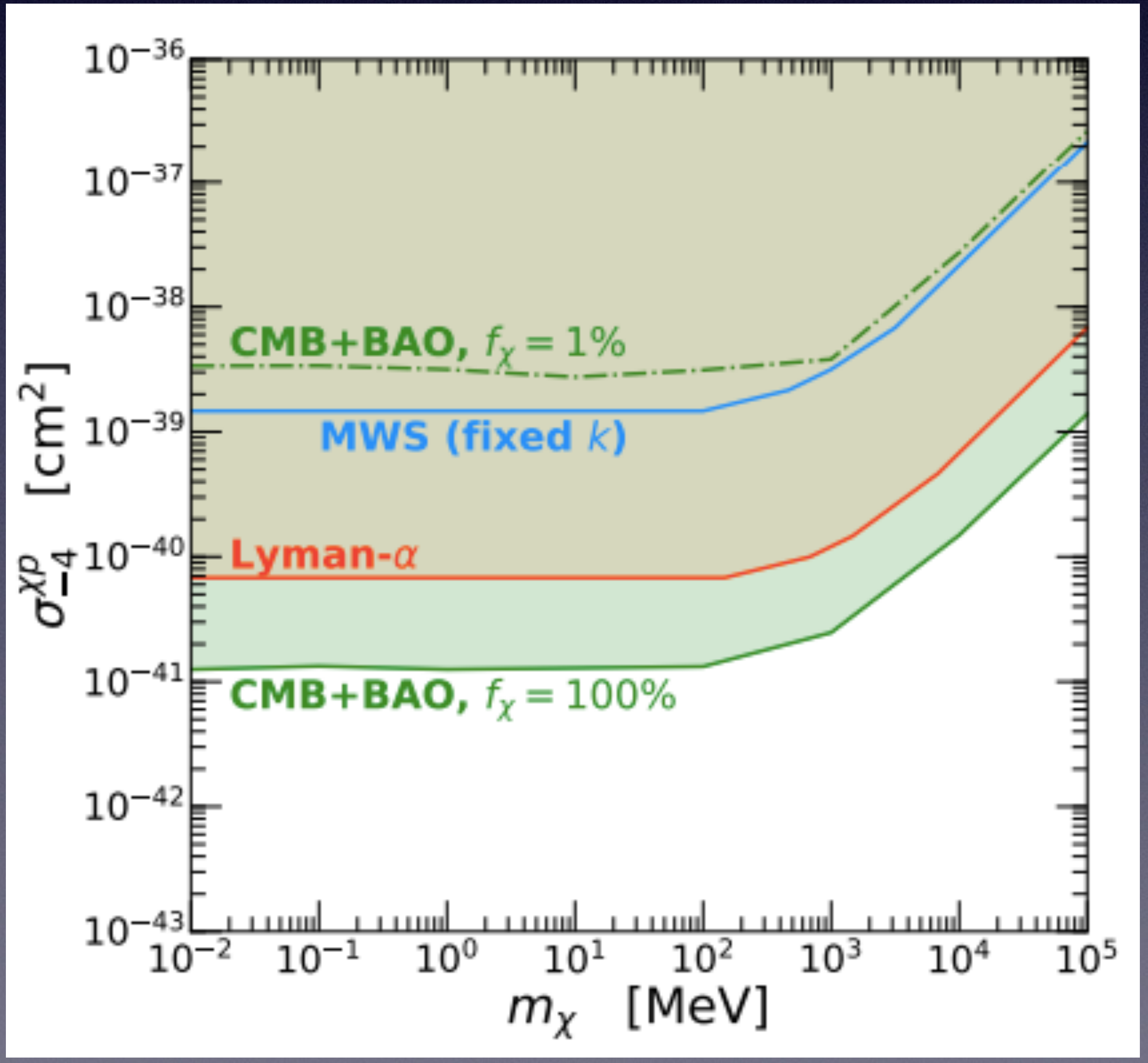
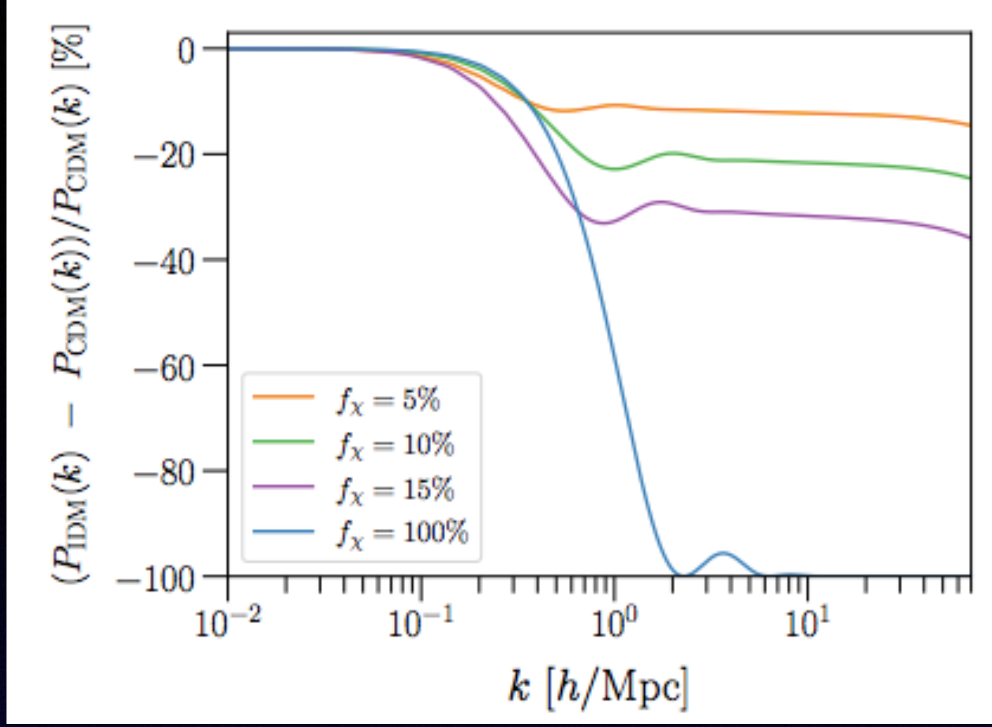
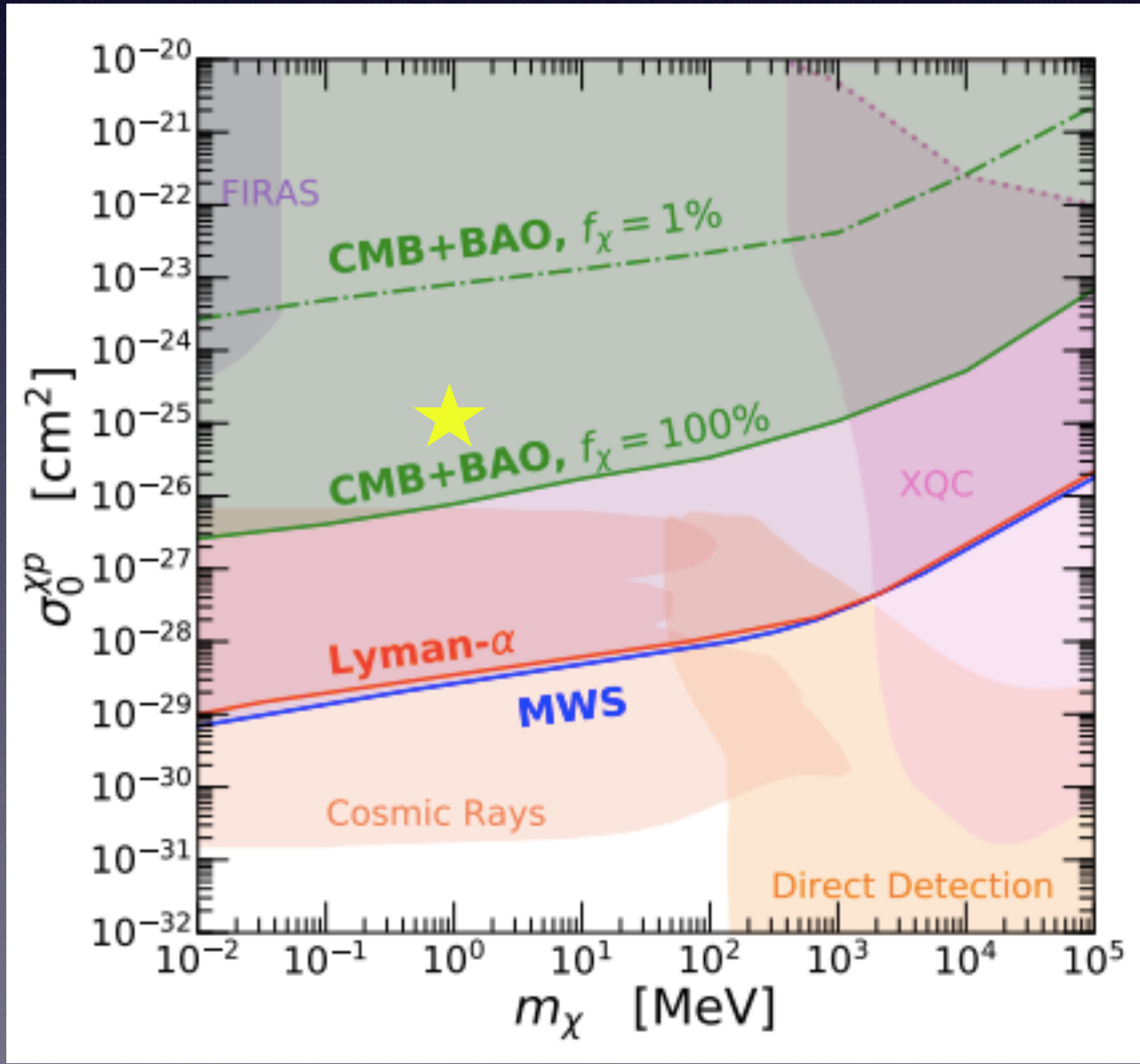


BOSS data for DM-SM scattering

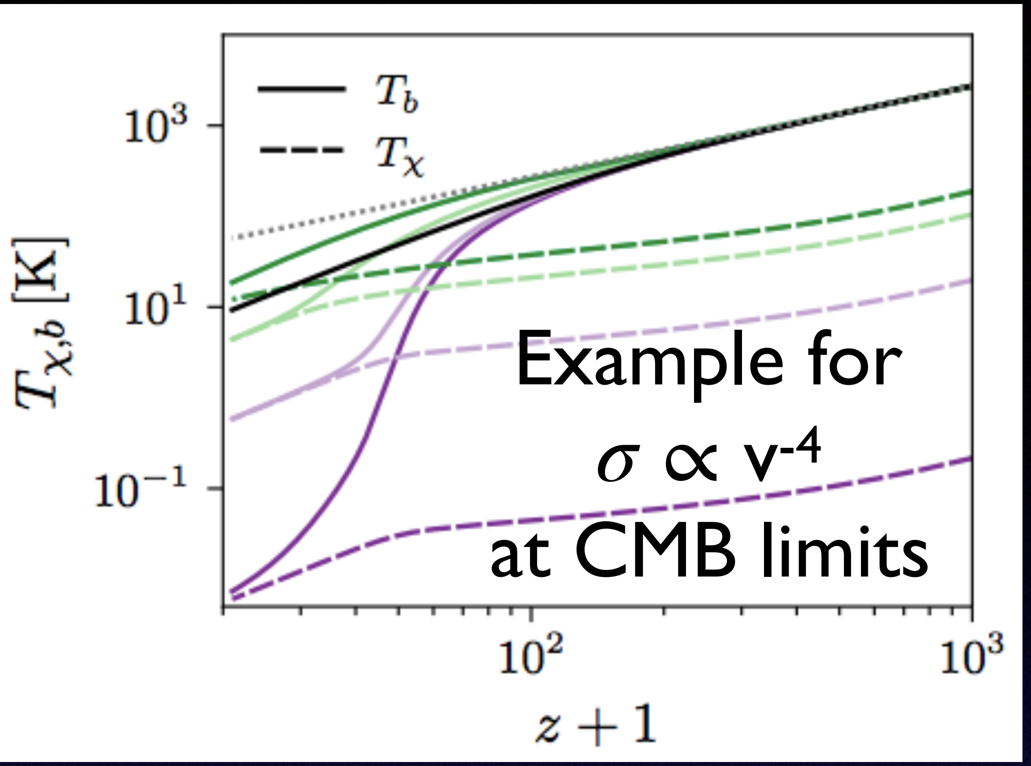
- As discussed in talk by Misha Ivanov, recent analysis includes CMB+BAO+full-shape BOSS analysis
- Focuses on case of only 10% of DM scattering (avoiding small-scale bounds) - corresponds to plateau in transfer function
- Constrains $\sigma \approx 3\text{x}10^{-25}$ cm^2 for 1 MeV DM, slight preference for non-zero value (associated with S_8)



He et al 2301.08260



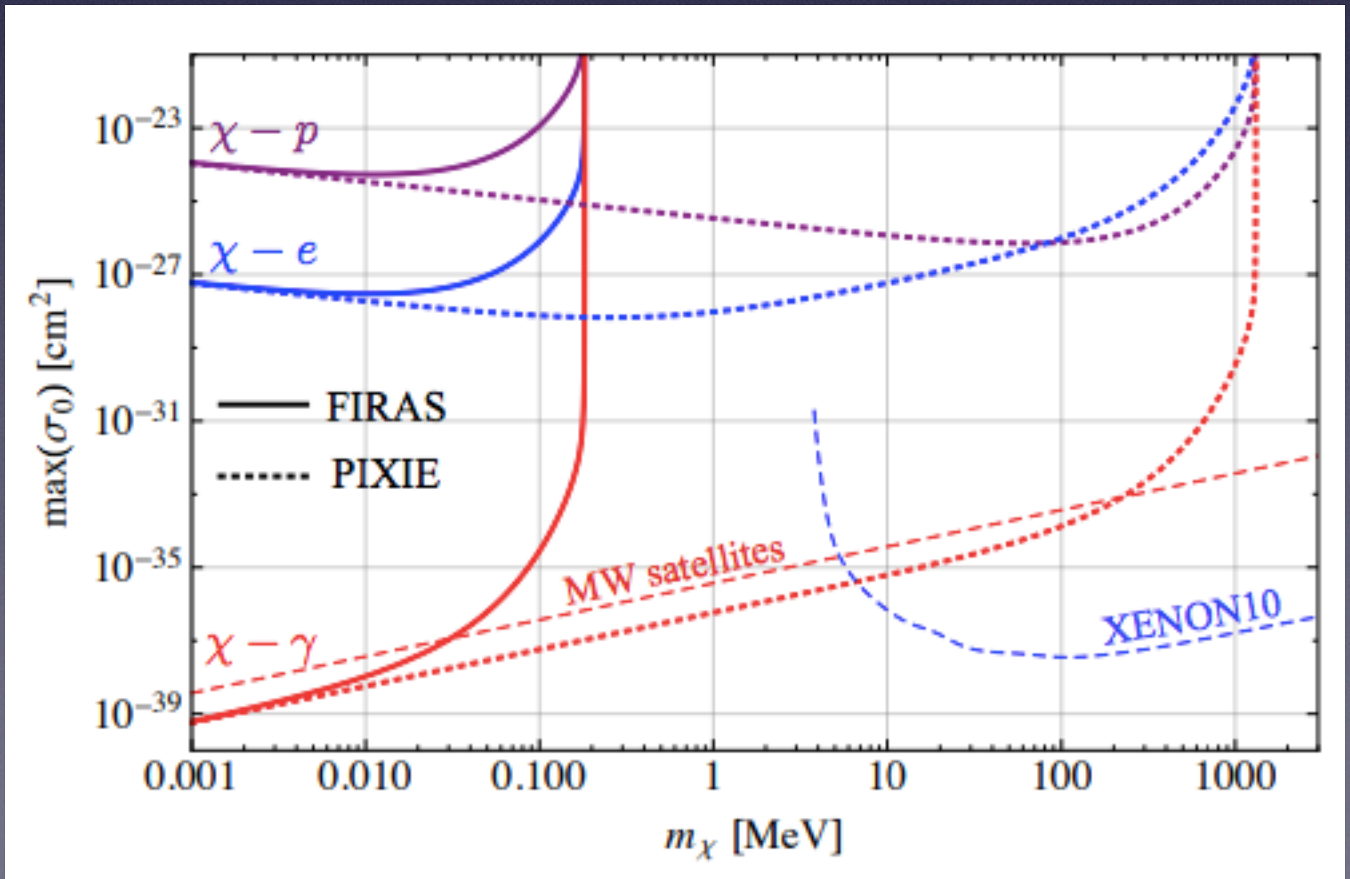
DM-SM scattering (heating effects)



Short et al 2203.16524 (includes analysis of temperature perturbations)

- DM can act as a heat sink for SM (especially if DM number density > baryon number density)
- Frictional effects can also heat both fluids
- Effect is enhanced once baryons decouple from CMB at z~200
- Induces distortions in CMB blackbody spectrum, changes to temperature during cosmic dawn (affecting 21cm signal), and heating of gas-rich dwarf galaxies [Wadekar et al 1903.12190].

Ali-Haimoud et al 1506.04745



Testing DM-SM interactions

- More generally, DM-SM interactions provide a channel for energy/momentum transfer between visible and dark sectors
- Can change the distribution of DM, but can also leave traces in visible cosmos directly

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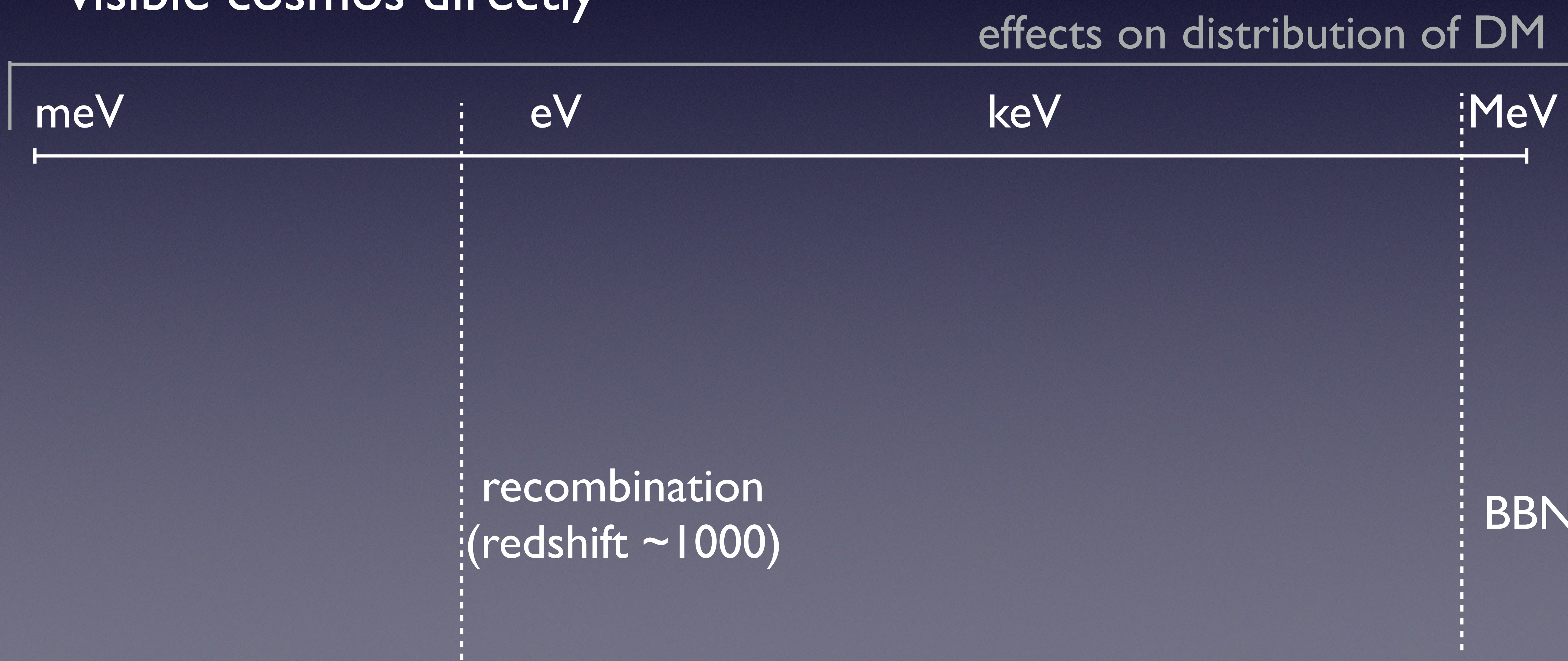

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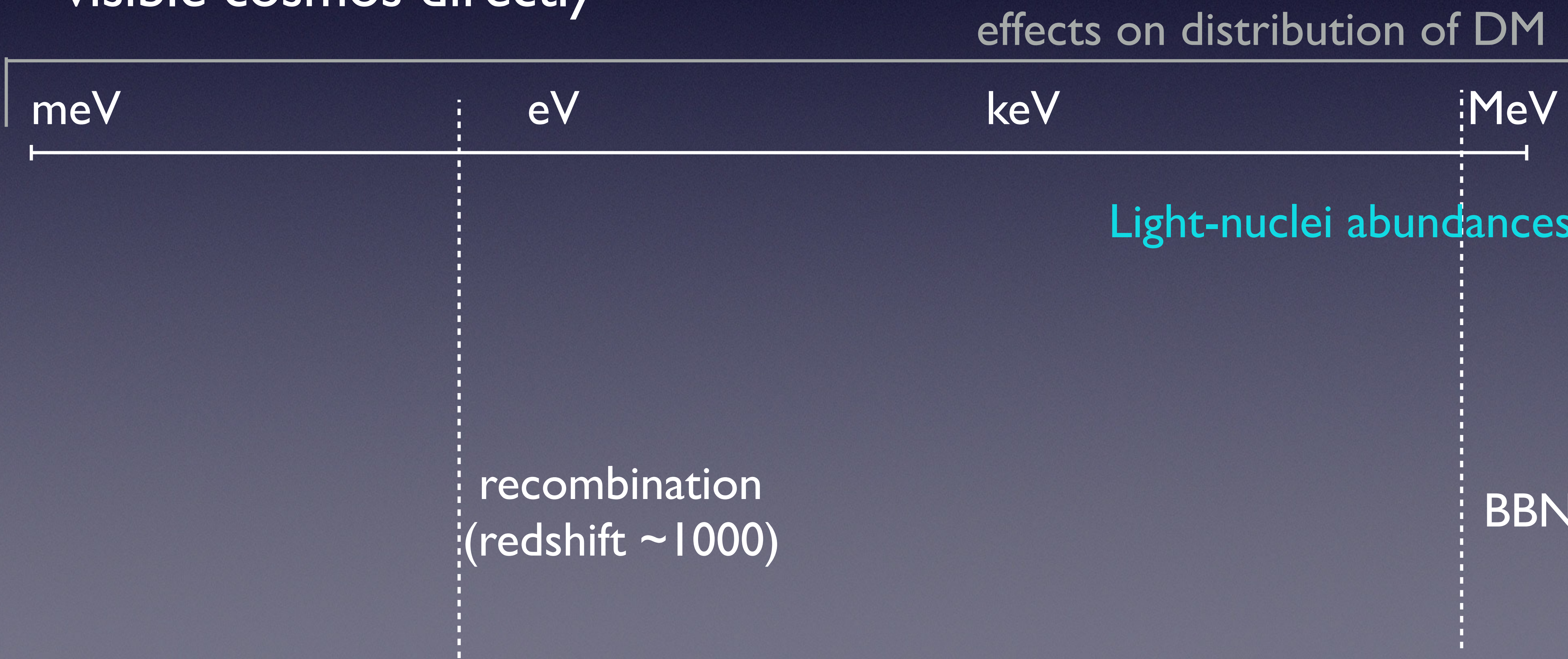

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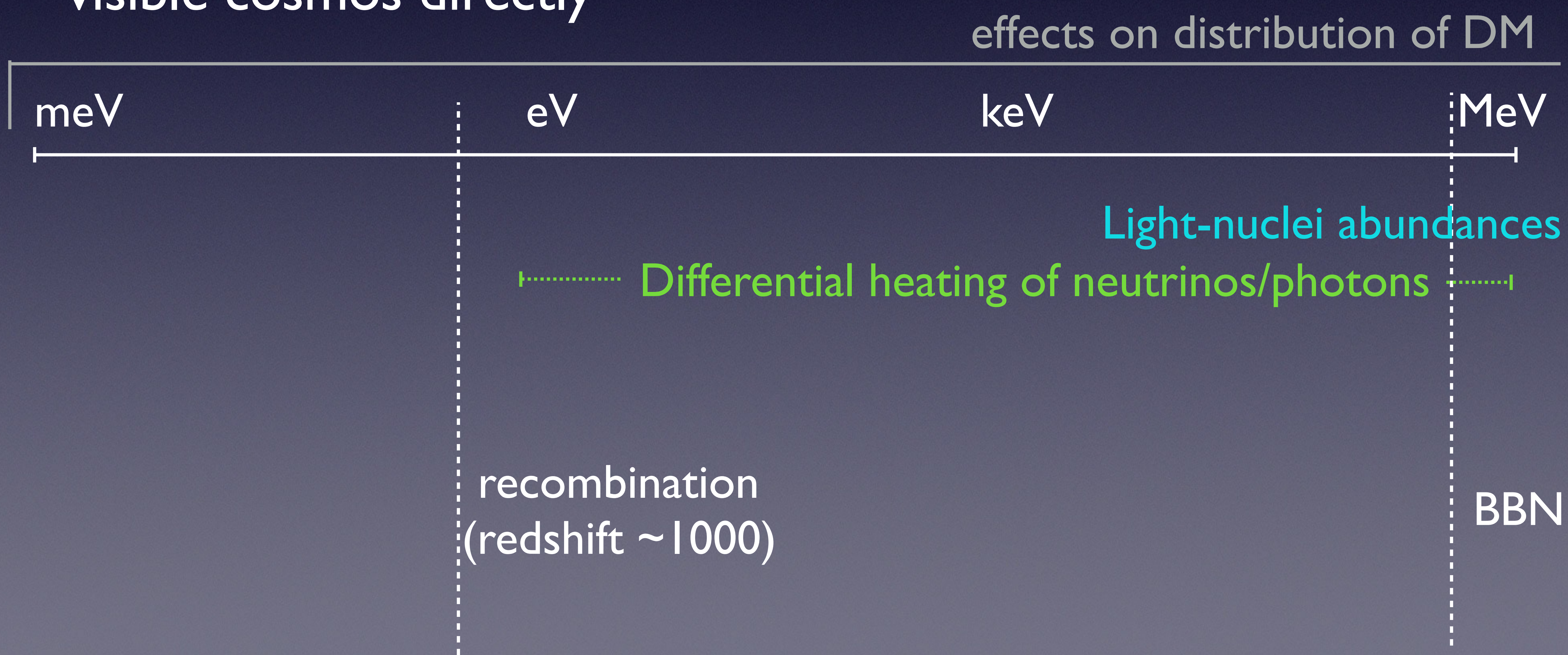

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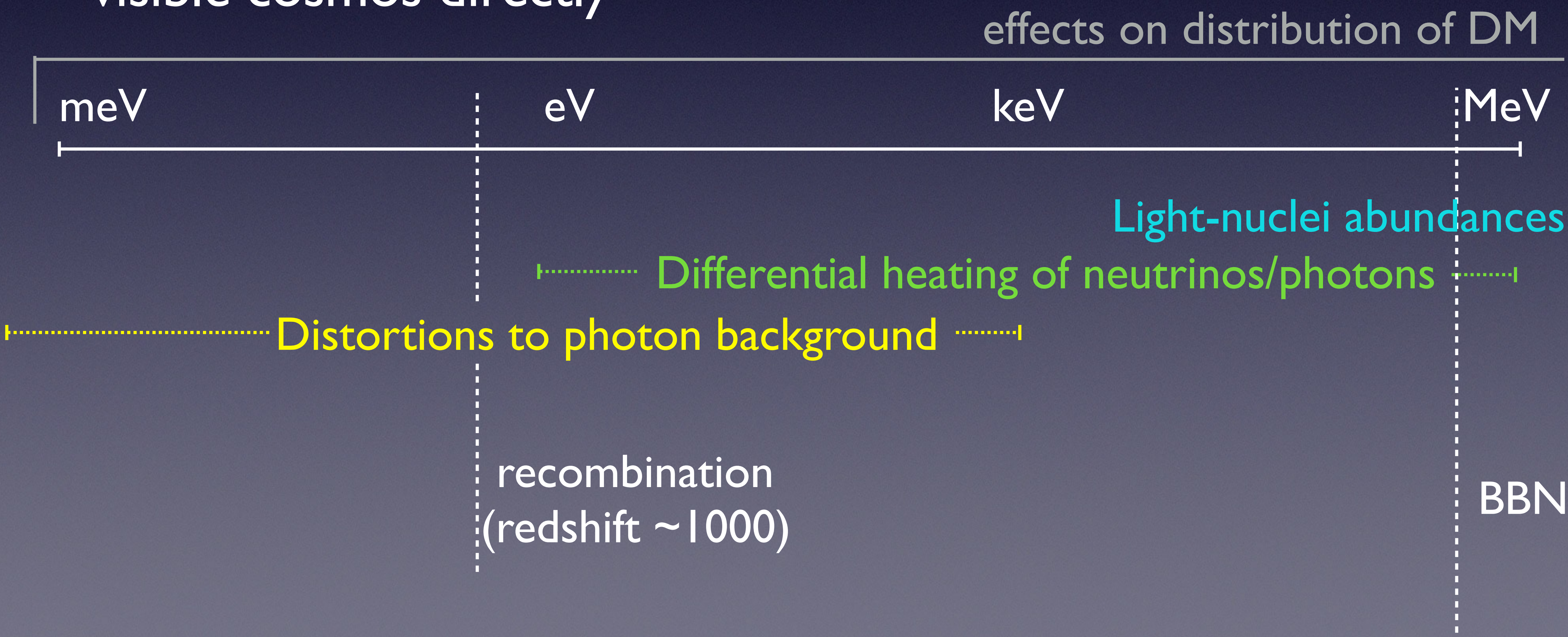

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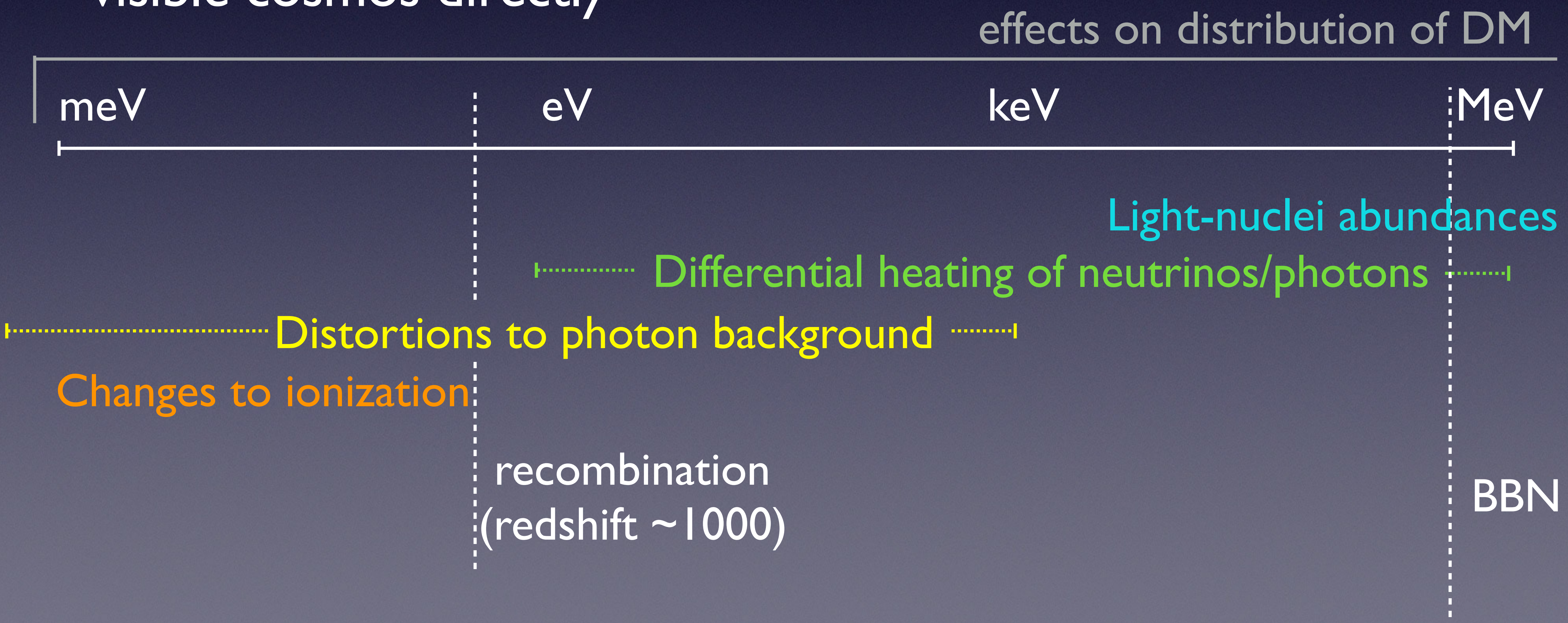

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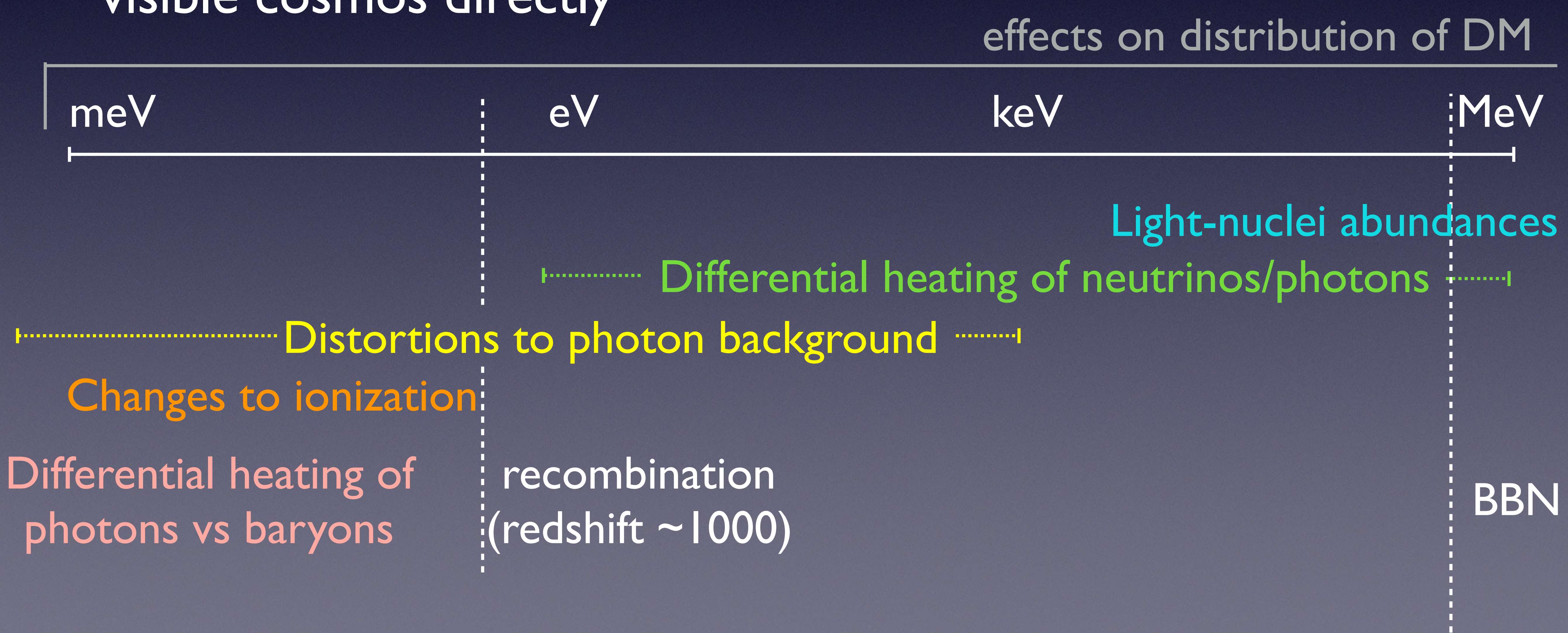

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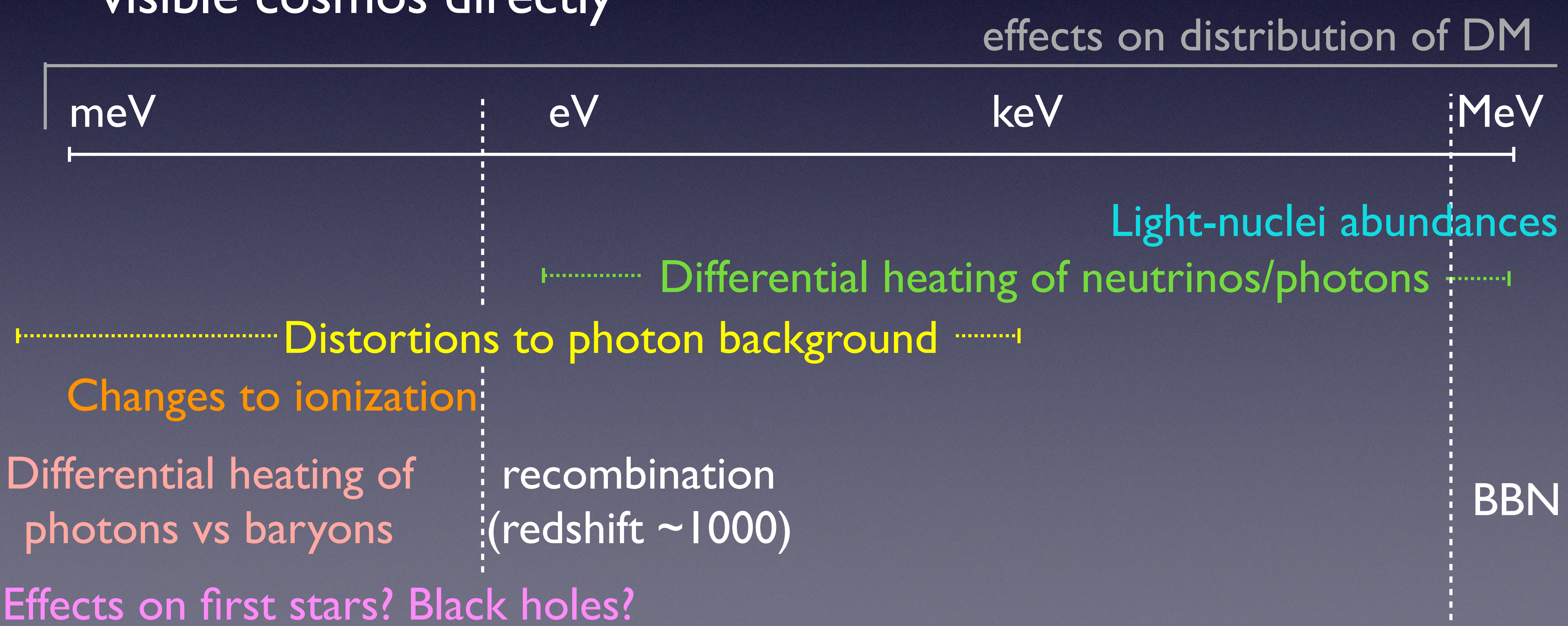

How do these effects compare?

- Galaxy clustering is most obviously a probe of the matter distribution (although it could be used to inform other observables, e.g. by cross-correlation; see talk by Junwu Huang)
- Modifying DM distribution = will usually need non-negligible fractions of the DM to participate (at some point in cosmic history)
- DM-SM elastic scattering example: currently signatures in photon backgrounds, gas temperature, etc give comparable/ weaker constraints to changes to the DM distribution
- This is not the case for all signals from DM interactions

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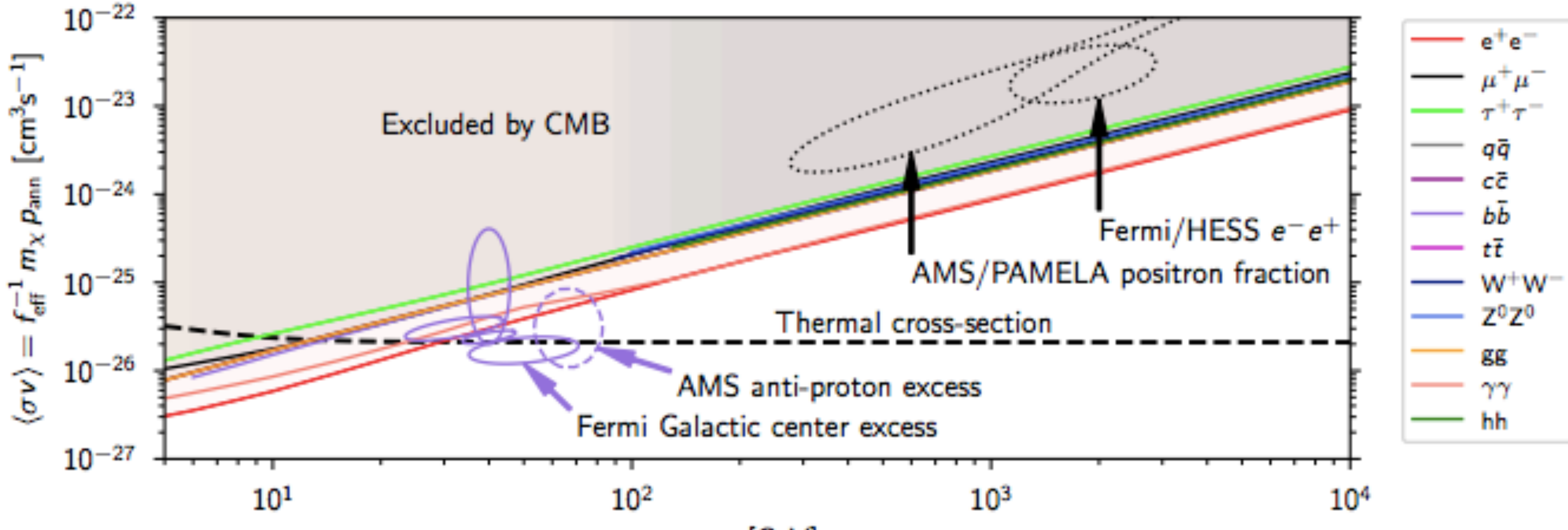
- Only tiny fraction of DM needs to convert its energy for large signals! In this case expect ~no impact on DM distribution from viable parameter space
- Difference from elastic scattering case is there we only have access to momentum/kinetic energy, not mass energy - energy budget is much smaller

Example: decaying DM

- For decay to electromagnetically interacting SM particles, from energy injection budget:
  - rough estimate: if temperature increase from DM decay is less than 10^4 K at epoch of reionization ($t \sim 10^9$ years),
    $\Rightarrow$ lifetime $\gtrsim 10^9$ years/$(2 \times 10^{-10}) \sim 5 \times 10^9$ Gyr $\sim 10^{26}$ s.
    (If a 21cm observation establishes the temperature at the end of the cosmic dark ages was <100 K, expect to improve limit by 2 orders of magnitude.)
- CMB+LSS allow placing lifetime limits on decays that modify DM evolution (e.g. to dark radiation, or dark radiation + warm DM) but do not produce visible particles [e.g. Simon et al 2203.07440]
- These limits are sensitive to cases where a percent-level fraction of DM decays by the present day
- e.g. for 100% of DM decaying to dark radiation, Simon et al find lower lifetime limit of 250 Gyr from a CMB+EFTofLSS analysis (currently dominated by CMB)

What are the (detailed) effects of energy injection?

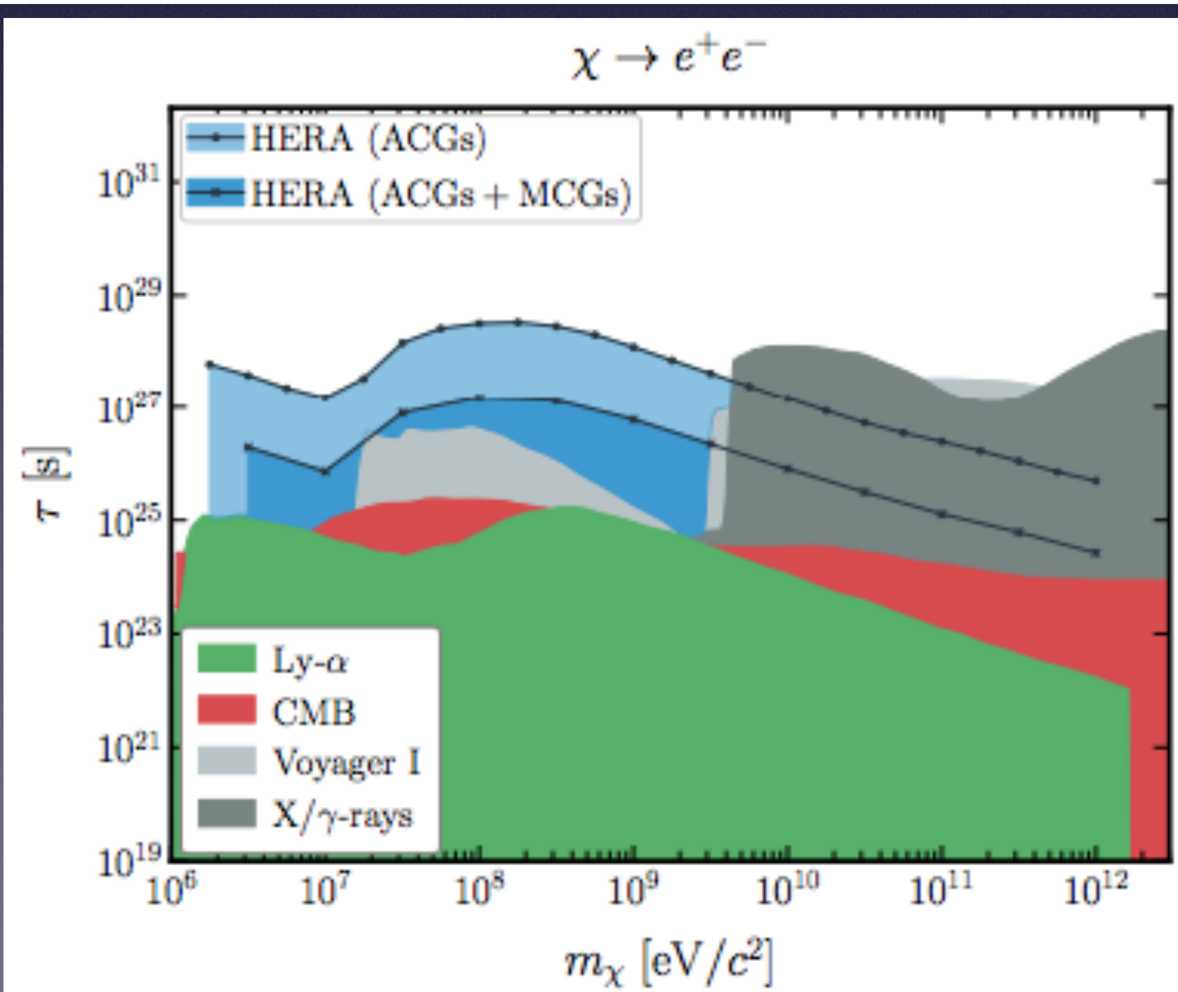
- If energy transfer is in the form of highly energetic SM particles (much more energetic than thermal bath):
  - generically have cascade of interactions producing (many) non-thermal secondary particles (can model with DARKHISTORY public code, Liu et al 1904.09296, Sun & TRS 2207.06425, Liu et al arXiv:2303.07366, 2303.07370)
  - produce extra ionization (if injection energy > ionization threshold) + heating + distortions to photon background
  - many details of initial model washed out by cascade; gives ~model-independent limits set mostly by total injected energy, potentially extending to very high mass
- If energy transfer is in lower-energy particles (or solely pre-recombination), suppresses ionization contribution, but can retain large spectral distortions and/or heating, e.g. through photon absorption [see e.g. Acharya et al 2303.17311]



CMB bounds from changes to ionization history

Planck Collaboration '18

Facchinetti et al 2308.16656

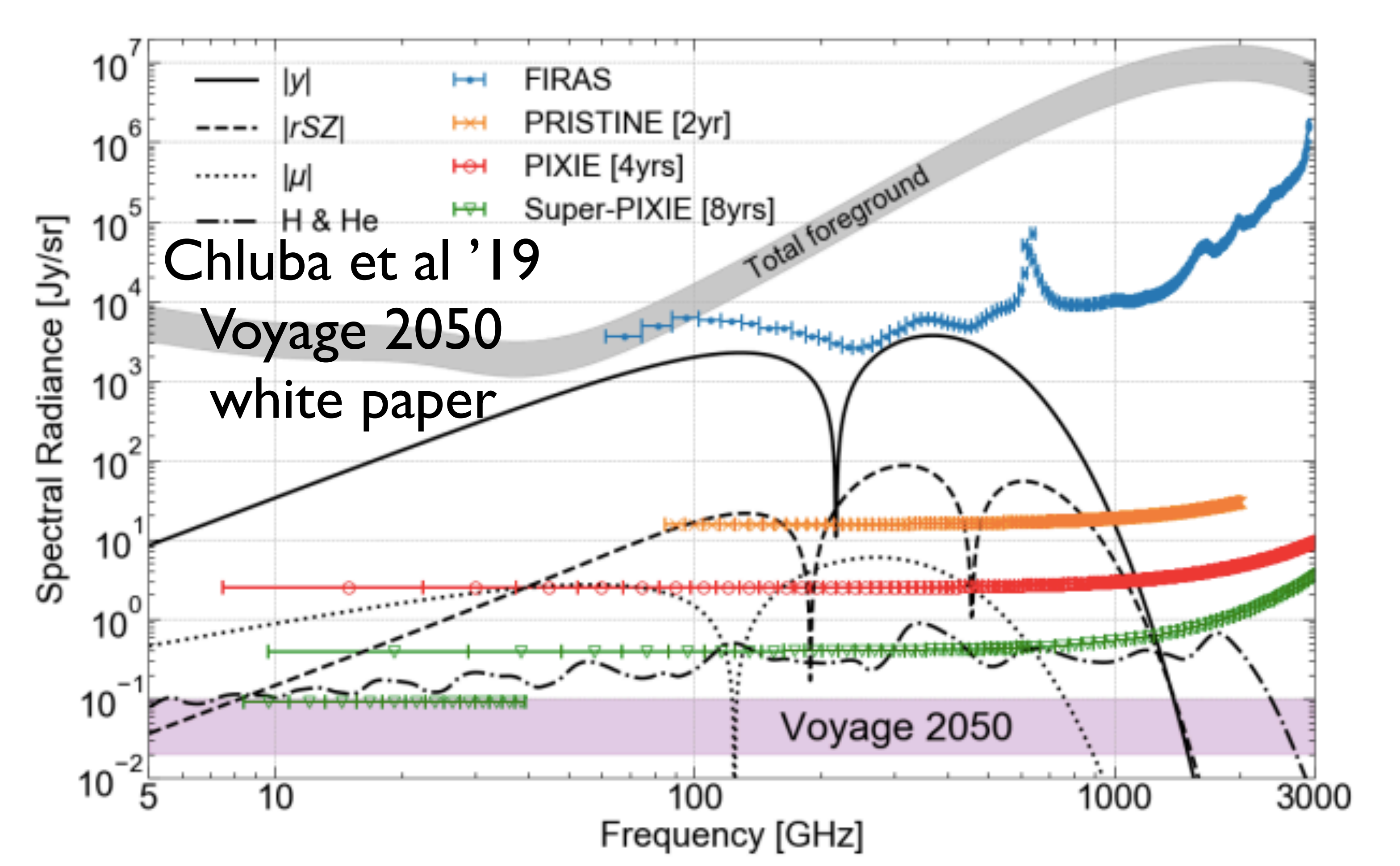


Bounds on light DM decaying to leptons

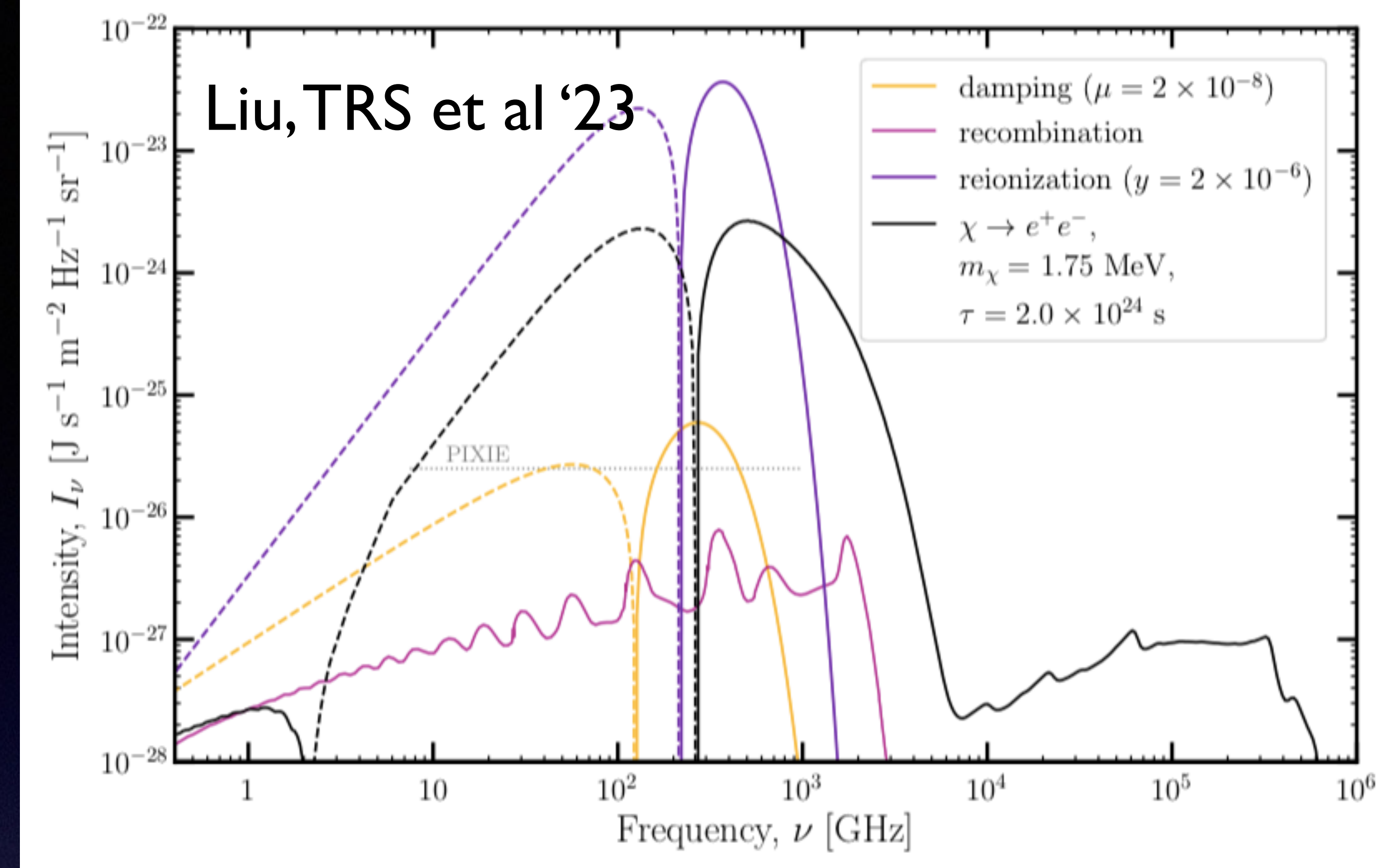
- Changes to the ionization history modify the CMB anisotropies
- Planck observations set stringent constraints on DM annihilation and decay
- Lyman-alpha forest observations bound the amount of heating from decaying DM (with potential for better future bounds from 21cm)

Prospects for improved limits on energy injection

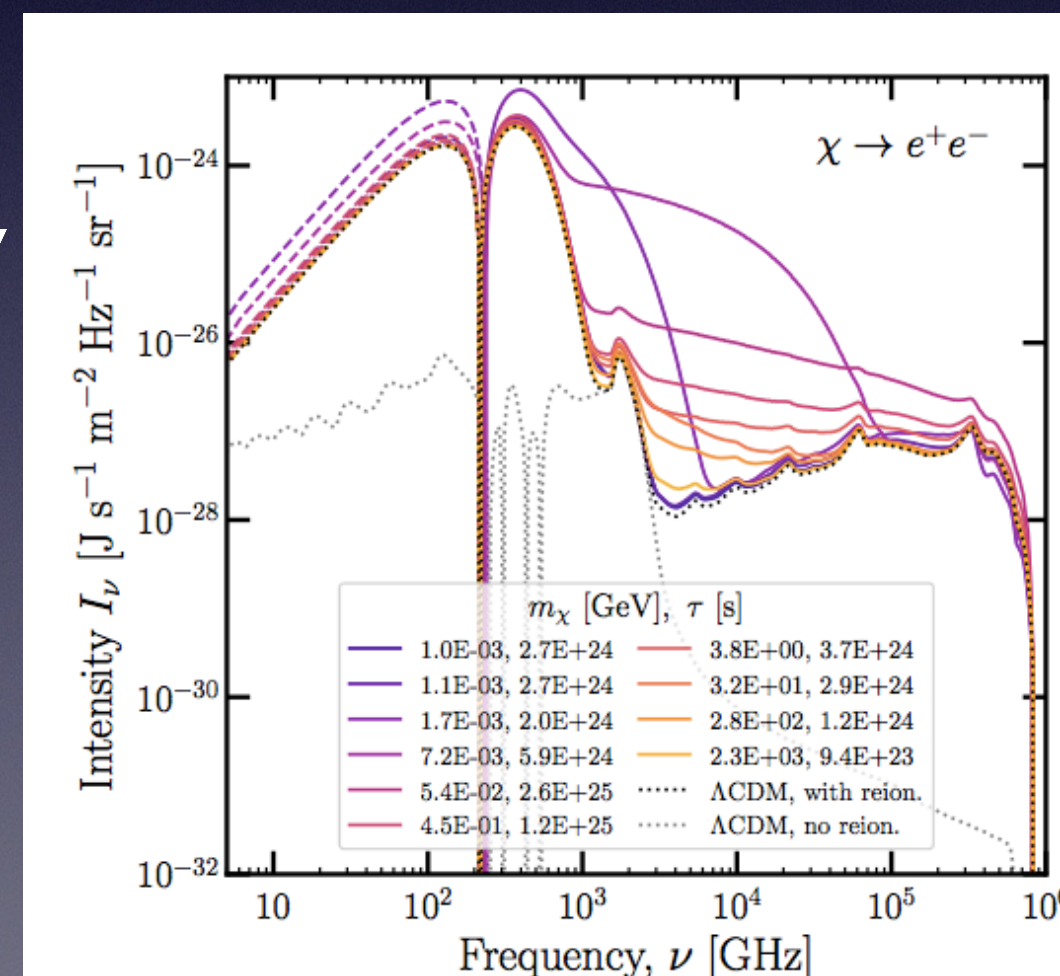
- Expect CMB-S4 to improve decay/annihilation bounds from CMB anisotropies by a factor of 2-3
- Ongoing effort to measure 21cm radiation - can be viewed as a measurement of LSS but also has sensitivity to temperature/ionization perturbations
- Distortions to CMB blackbody spectrum last measured with COBE/ FIRAS in 1990, sensitivity could be improved by 4+ orders of magnitude with future experiments (e.g. Chluba et al 1909.01593)



Spectral distortions from DM



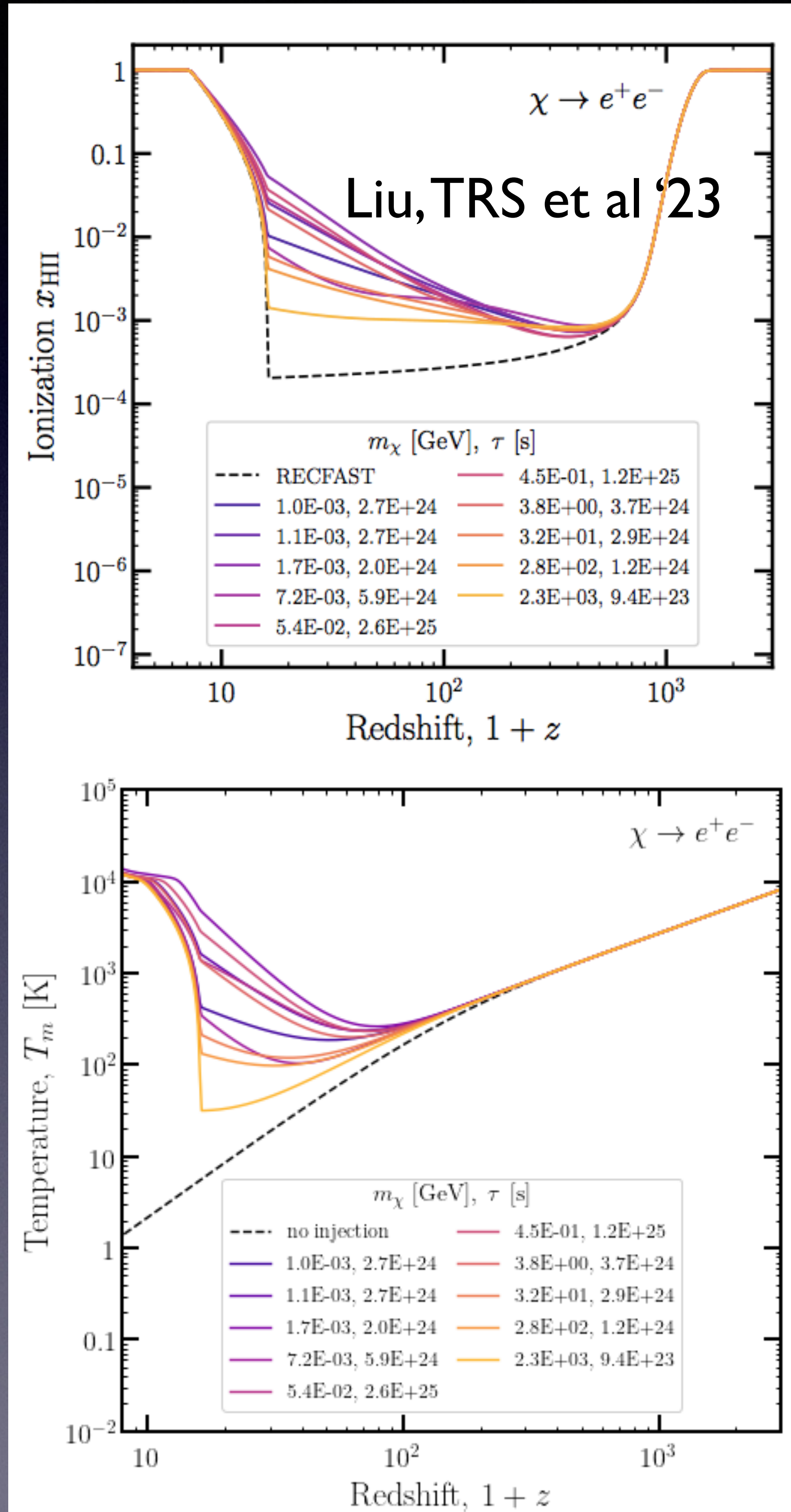
- Recent upgrades to DARKHISTORY (Liu et al 2303.07366,2303.07370): for the first time, we can compute the full spectral distortion from arbitrary injections of high-energy (ionizing) particles
- Builds on previous work on pre-recombination signals (e.g. Acharya & Khatri 1808.02897)
- Sub-GeV decaying DM models that are not already excluded could have interesting signals in next-generation experiments
- Distinctive spectral shapes with some variation between different DM models



Liu, TRS et al '23

Formation of the first stars

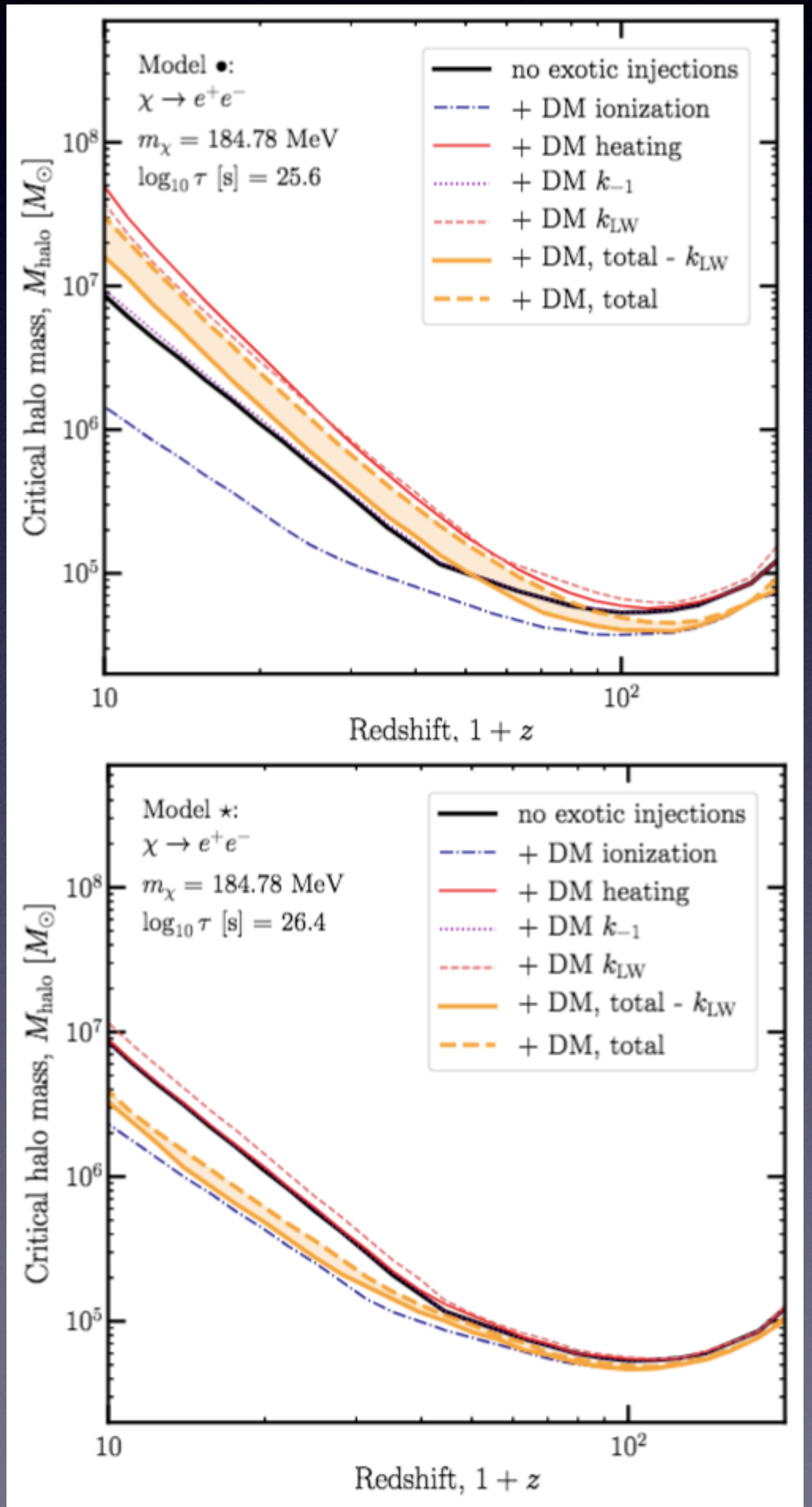
- Gas needs to cool to collapse into stars
- For the first stars, there are no heavy elements - very limited ways for low-temperature gas to radiate energy
- Expectation is that molecular hydrogen H_2 acts as the main coolant
- The reactions that form and destroy H_2 depend sensitively on the ionization, temperature, and background of Lyman-Werner photons (11.1-13.6 eV, can dissociate H_2)
- These can all look quite different in a universe with non-thermal energy injection from a dark sector!
- DM annihilation or primordial black hole decay may influence the formation of high-redshift black holes through similar effects [e.g. Pandey et al 1801.06649, Friedlander et al 2212.11100].



Effects of energy injection

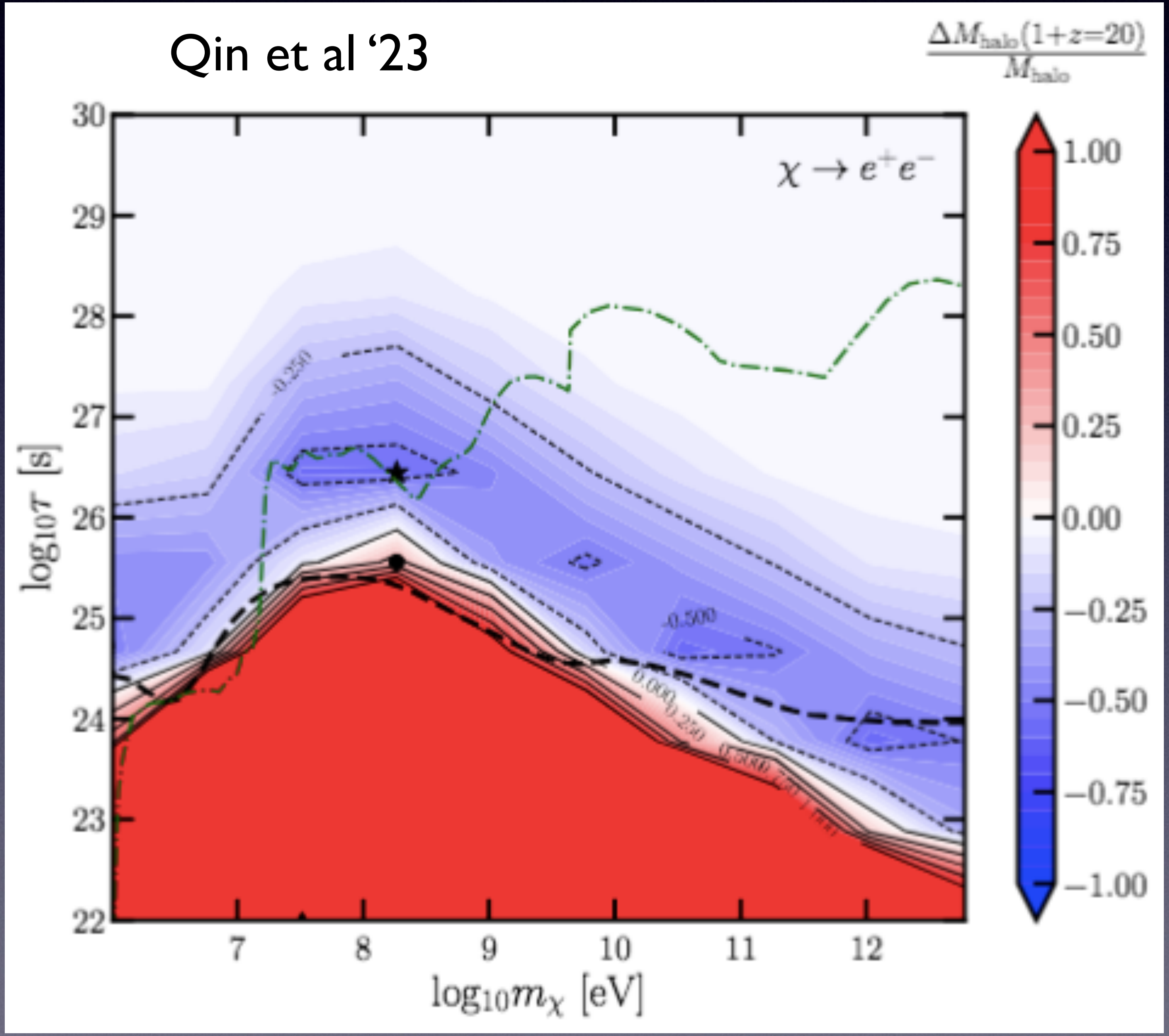
- Initial analytic study in Qin, TRS et al 2308.12992
- Extra free electrons catalyze H_2 formation, accelerating cooling
- Extra Lyman-Werner photons (if not shielded in halos) can dissociate H_2, slowing cooling
- Extra heating counteracts cooling directly, making it harder for gas to collapse
- We can express these effects in terms of the minimum halo mass for the gas in the halo to collapse
- We find the (direction of the) net effect can vary between different DM models

Qin, TRS et al '23



Accelerating or delaying star formation?

- In most of the unconstrained region for keV+ DM, ionization wins out - easier to form stars in a universe with decaying DM
- However, there is a small allowed region where star formation is delayed (this region becomes larger with less LW self-shielding)
- Either effect could shift the redshift dependence of the primordial 21cm signal



Summary

- Cosmological datasets can provide powerful probes of the non-gravitational interactions of dark matter, as well as assorted other properties
- Galaxy clustering seems to be especially good (right now) for testing DM scenarios where (a) a small but non-negligible fraction of DM is involved, (b) it is helpful to access smaller scales than those probed by the CMB, (c) the primary signal involves changes to the DM distribution rather than direct energy injection into the SM
- In the case of DM that annihilates/decays to SM particles, there are powerful and broadly applicable limits from cosmology (CMB, Lyman-alpha); they primarily rely on modifying the temperature/ionization history or photon backgrounds
- Energy injections that are not currently excluded could change the ionization/temperature evolution of the early universe, impact the formation of the first stars, and imprint potentially detectable signals in the CMB blackbody spectrum and primordial 21cm radiation