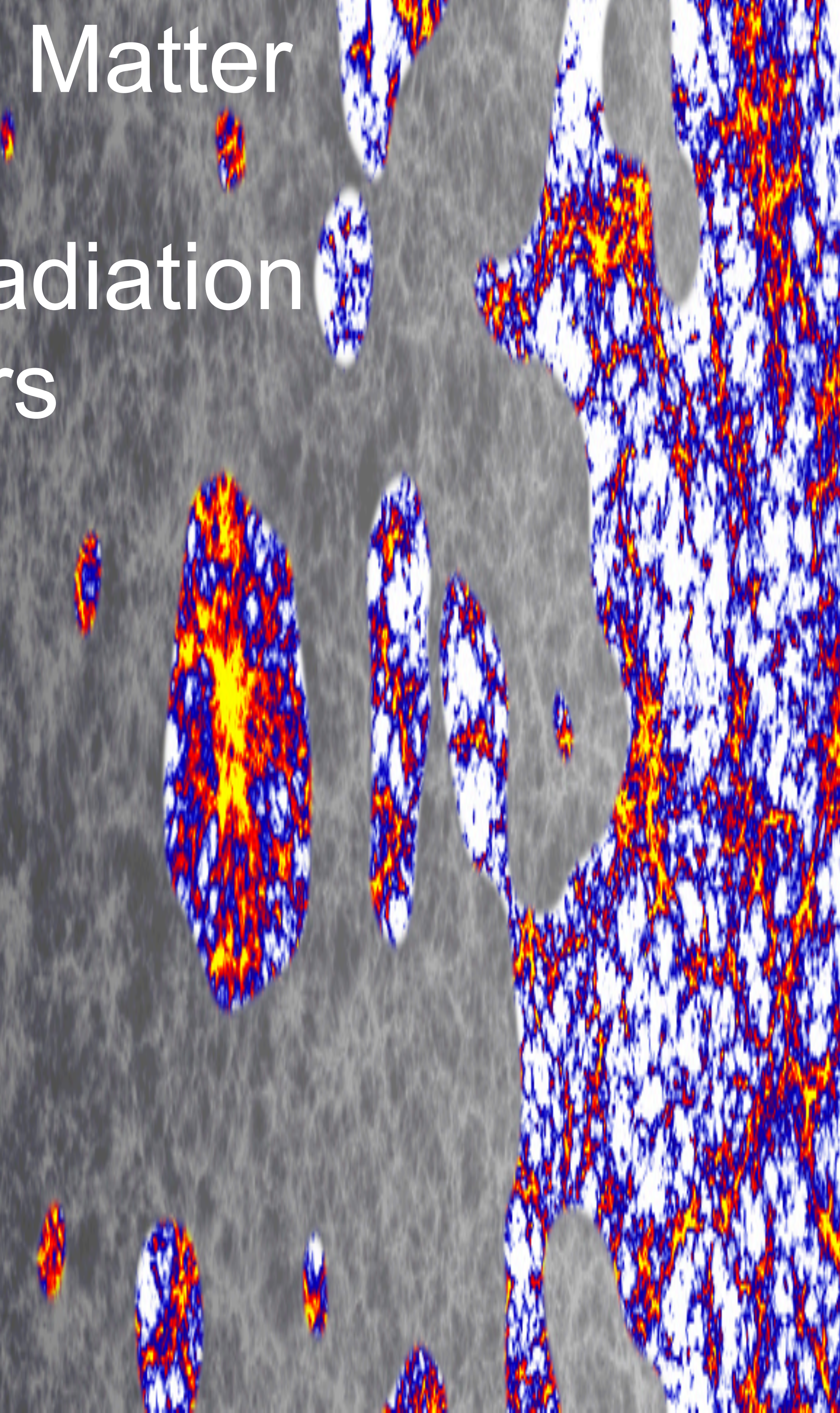
Testing Decaying Dark Matter with the Cosmic Background Radiation and the First Stars



Tracy Slatyer

IFT Colloquium
8th IBS-MultiDark-ICTP Workshop
16 November 2023

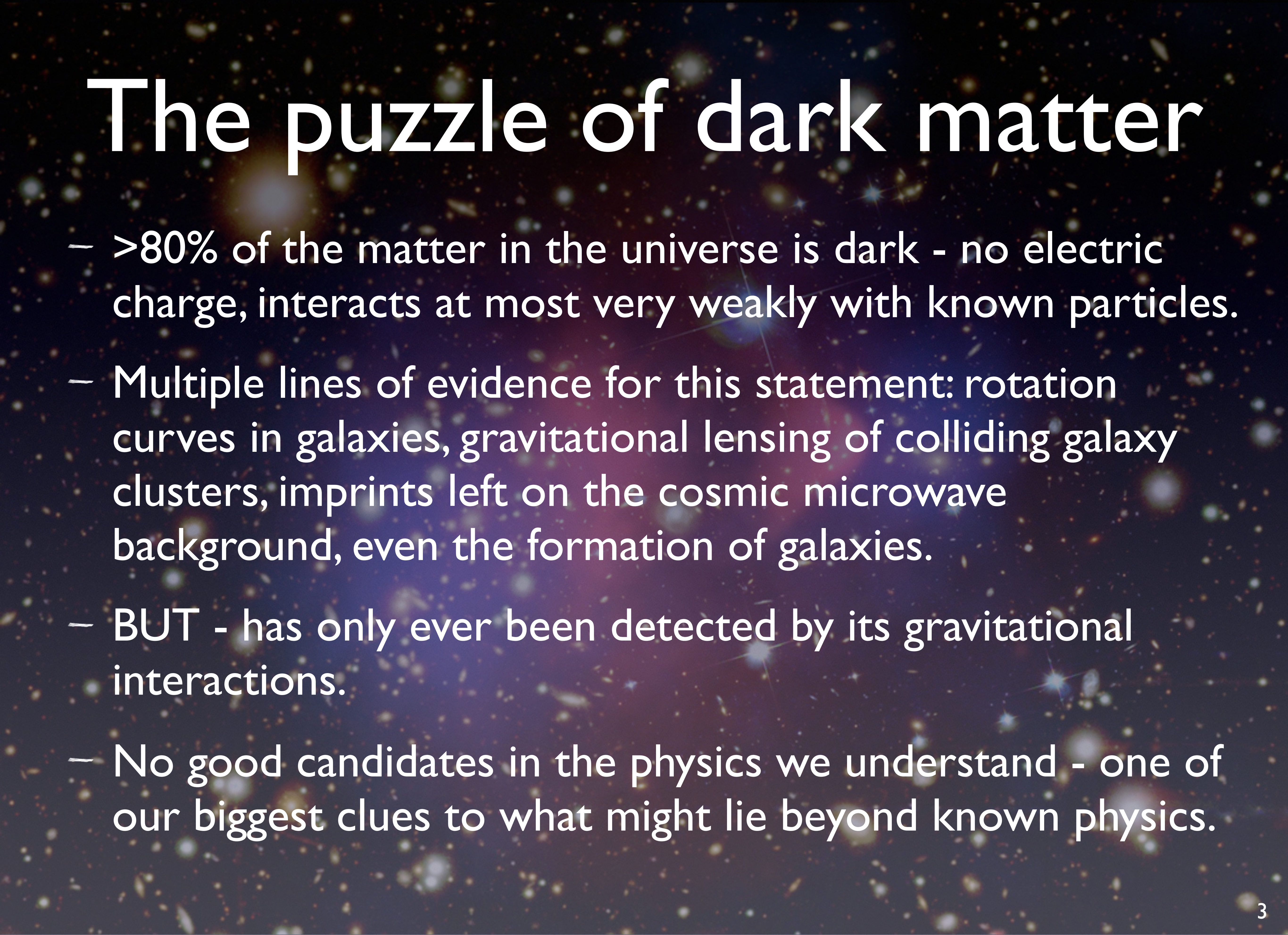
Based (primarily) on arXiv:2207.06425, 2303.07366, 2303.07370, 2308.12992, with Hongwan Liu, Julian Muñoz, Wenzer Qin, Greg Ridgway, & Yitian Sun

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- General introduction: how energy injection originating from (non-gravitational) interactions of dark matter with the Standard Model could change the early universe
- Summary of earlier constraints from this approach
- Some recent developments:
  - Using neural networks as efficient function approximators to improve the signal calculation
  - Treating low-energy photons/electrons in detail
  - Full prediction of the space of post-recombination CMB spectral distortions from exotic energy injections
  - Effects on the formation of the first stars

The puzzle of dark matter



- >80% of the matter in the universe is dark - no electric charge, interacts at most very weakly with known particles.
- Multiple lines of evidence for this statement: rotation curves in galaxies, gravitational lensing of colliding galaxy clusters, imprints left on the cosmic microwave background, even the formation of galaxies.
- BUT - has only ever been detected by its gravitational interactions.
- No good candidates in the physics we understand - one of our biggest clues to what might lie beyond known physics.

Identifying dark matter

- There is an enormous range of possible DM scenarios, spanning tens of orders of magnitude in mass.
- Many of these scenarios are ~equivalent from the perspective of gravitational effects
  - exceptions: DM is very light (fuzzy DM, $\sim 10^{-20}$ eV), very heavy (PBHs), warm/fast-moving, or strongly self-interacting (cross section/mass > 0.1 $\mathrm{cm^2/g}$)
- Non-gravitational interactions in principle provide much greater discriminating power (if they exist)
- Large ongoing experimental program to search for such interactions in accelerators, direct-detection searches, precision experiments, astrophysical observations
- But throughout the history of the universe, such interactions would also have allowed energy transfer between dark and visible sectors - could have observable effects on cosmology

Testing DM-SM interactions

- Cosmology provides a sensitive probe of DM-SM interactions throughout cosmic history, at least since Big Bang nucleosynthesis
- Redshift 1+z = expansion factor of the universe since that epoch ~ T/T_{today}

meV

eV

keV

MeV

recombination
(redshift ~1000)

BBN

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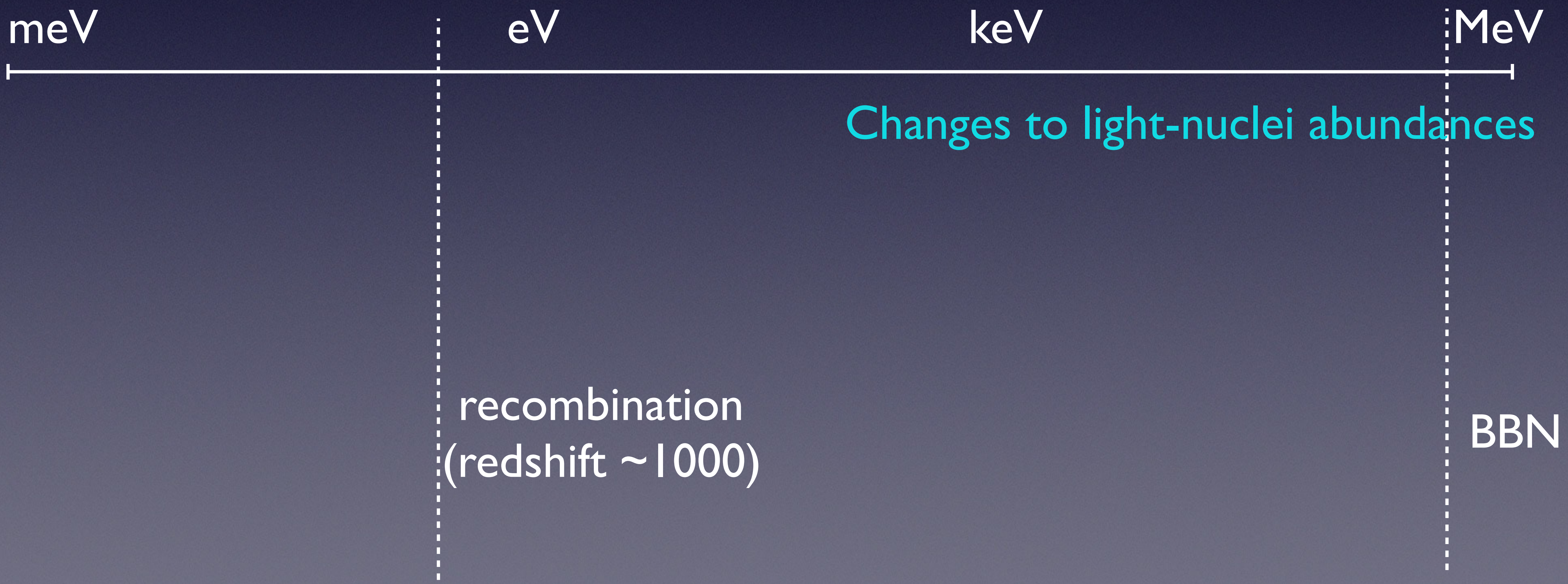

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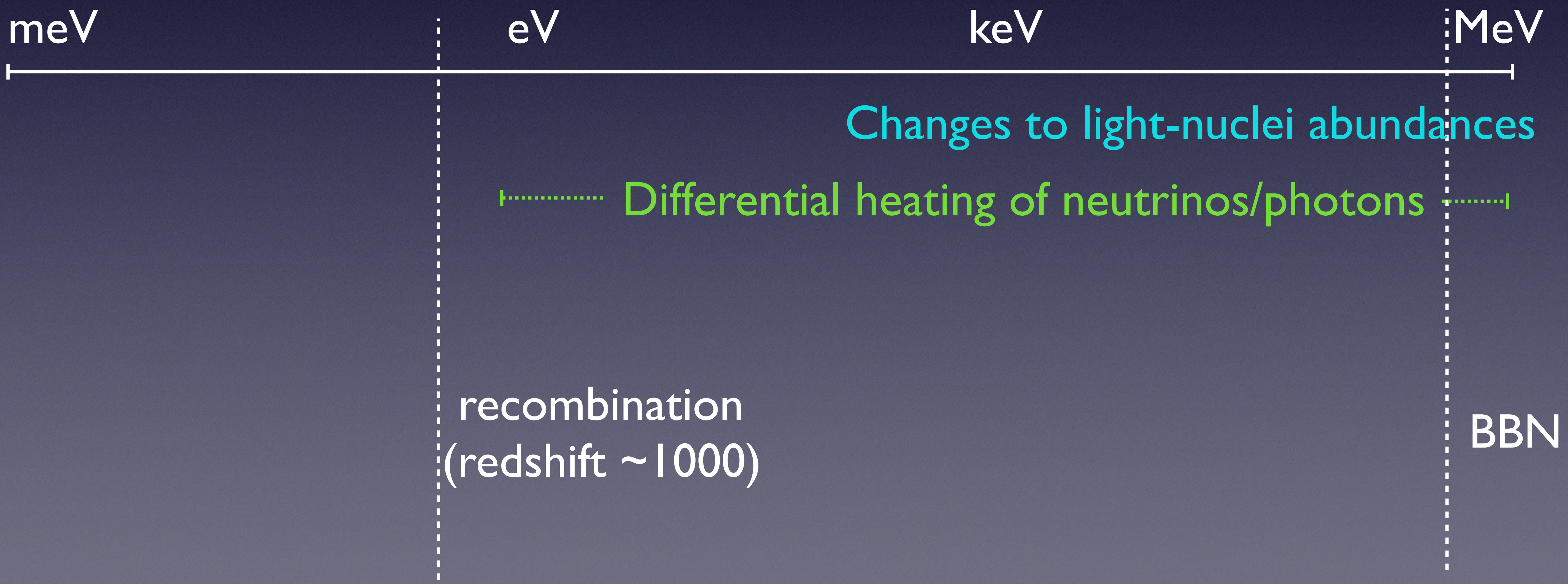

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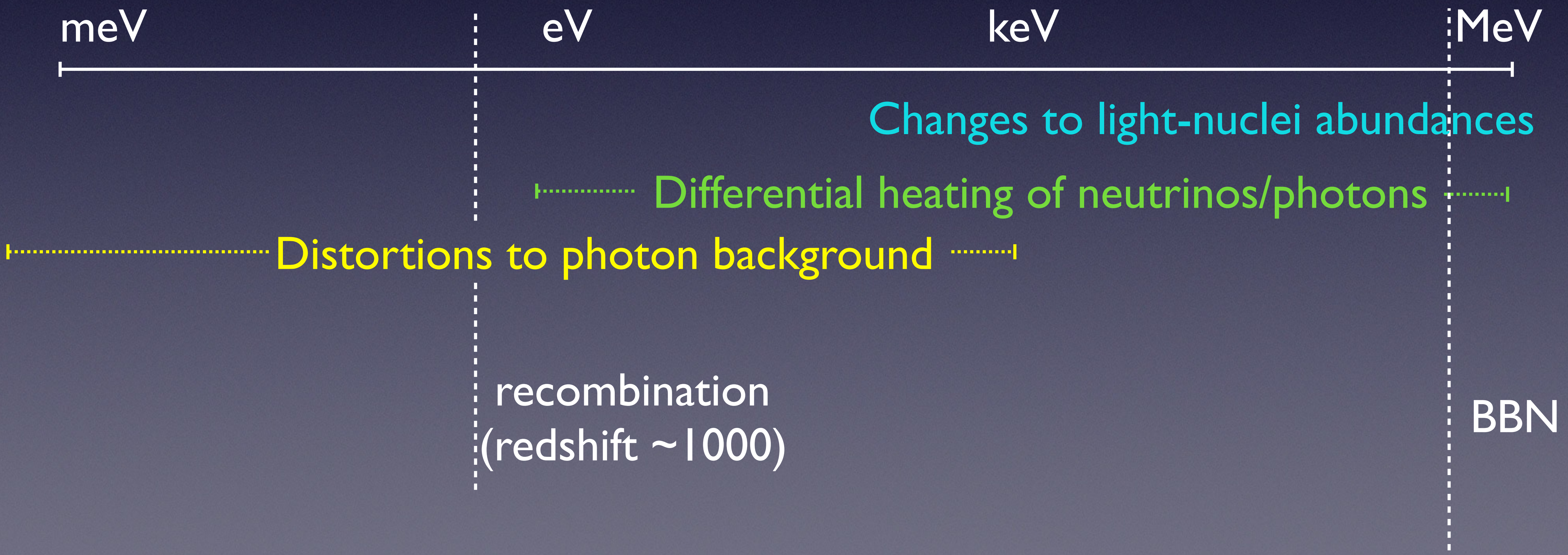

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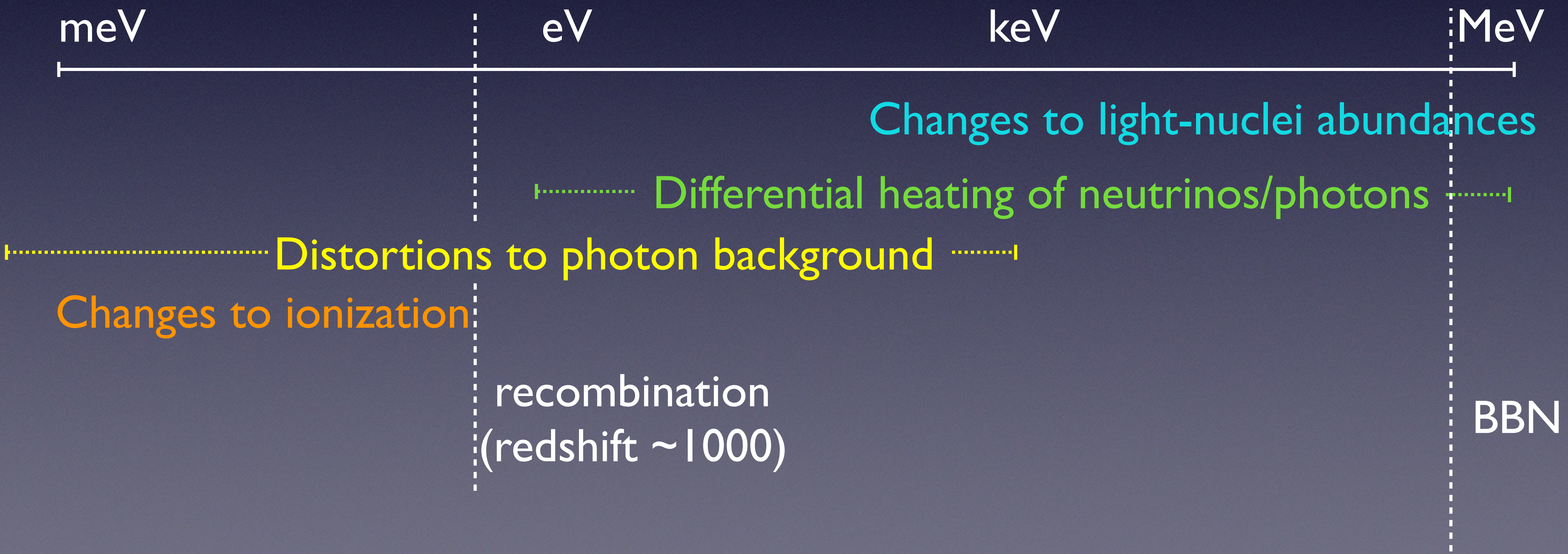

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Distortions to photon background

Changes to ionization

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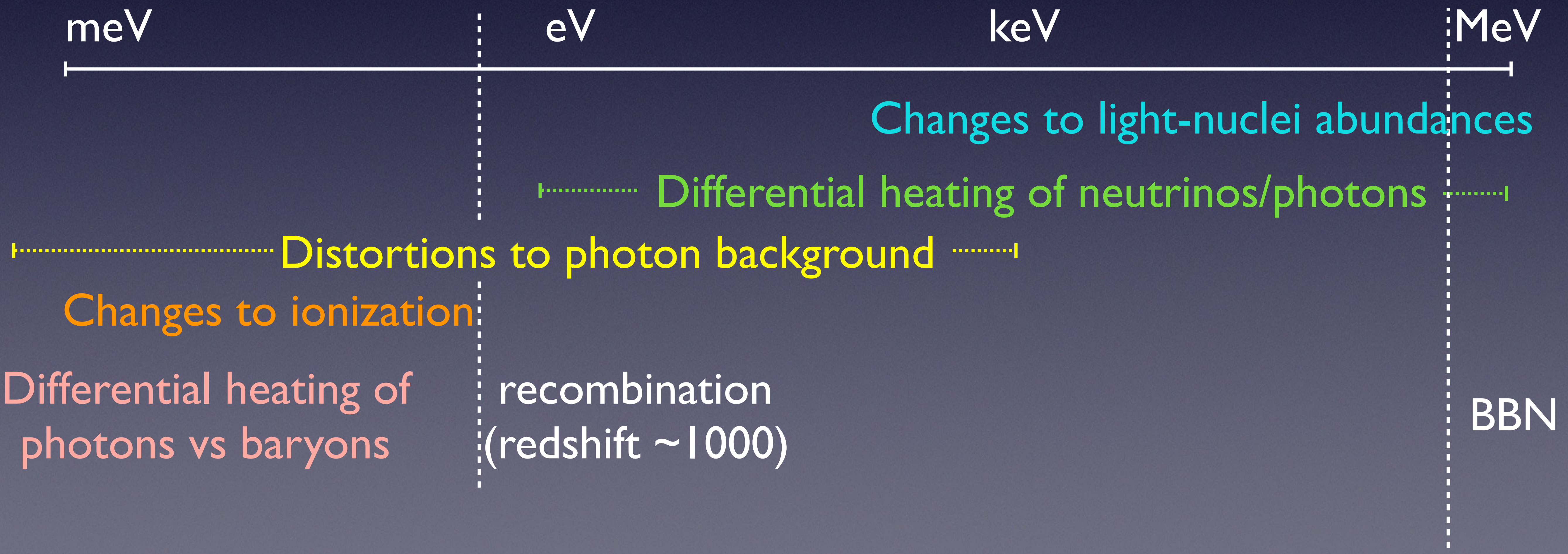

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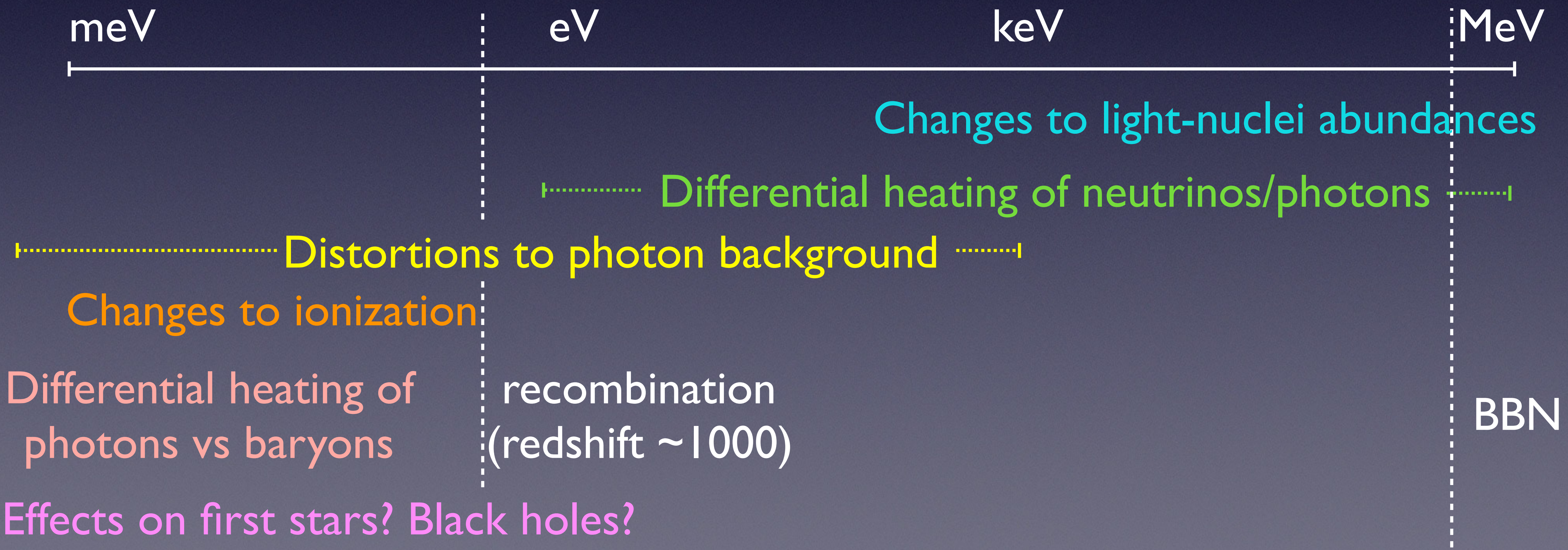

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Differential heating of photons vs baryons

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BBN

Effects on first stars? Black holes?

spectral information: near-perfect blackbody

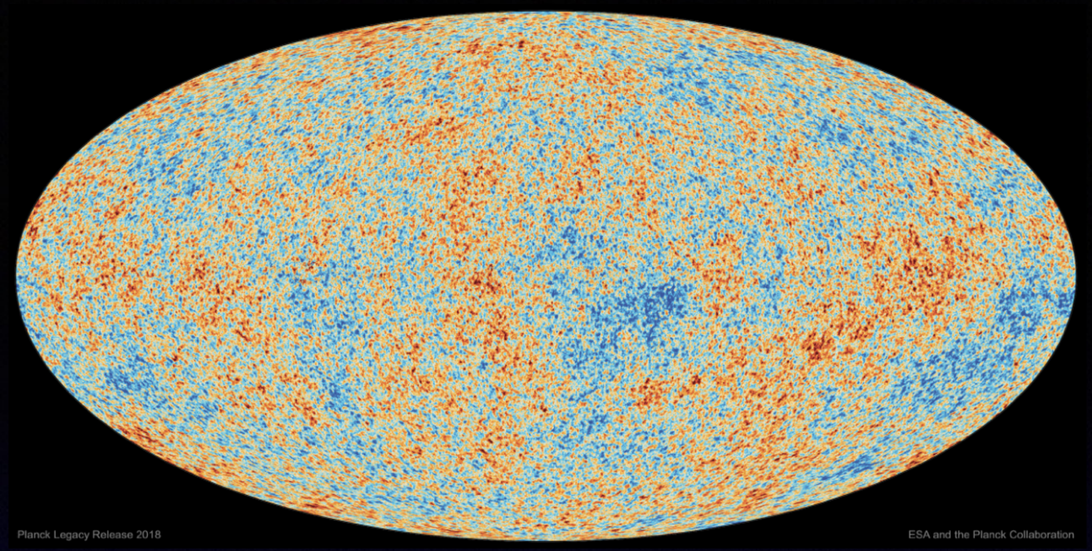
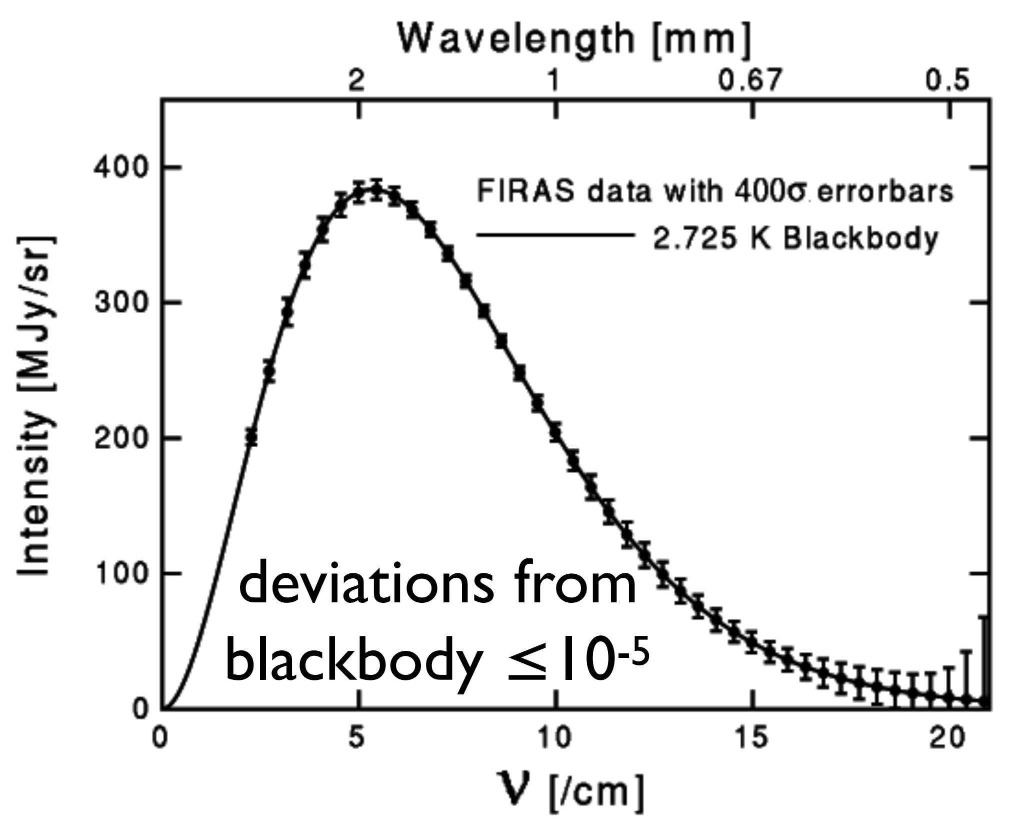


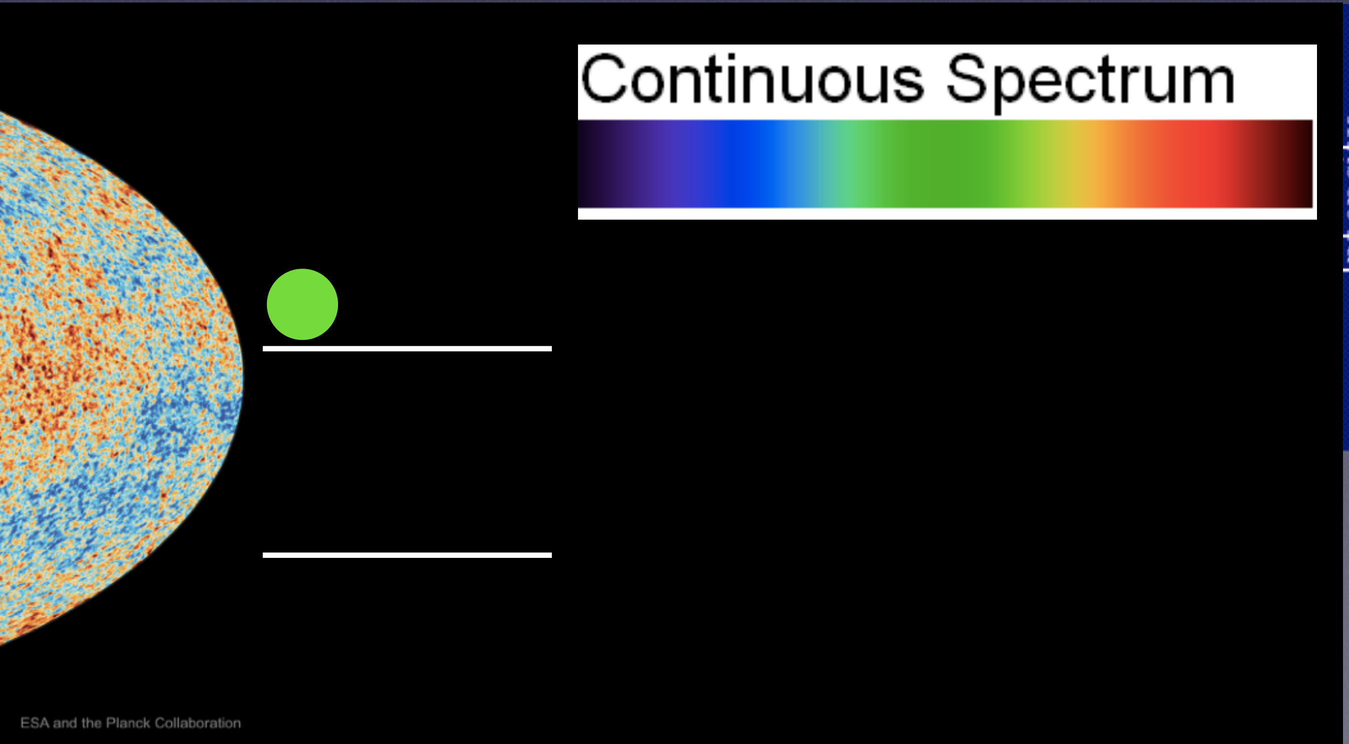
Image credit: European Space Agency / Planck Collaboration

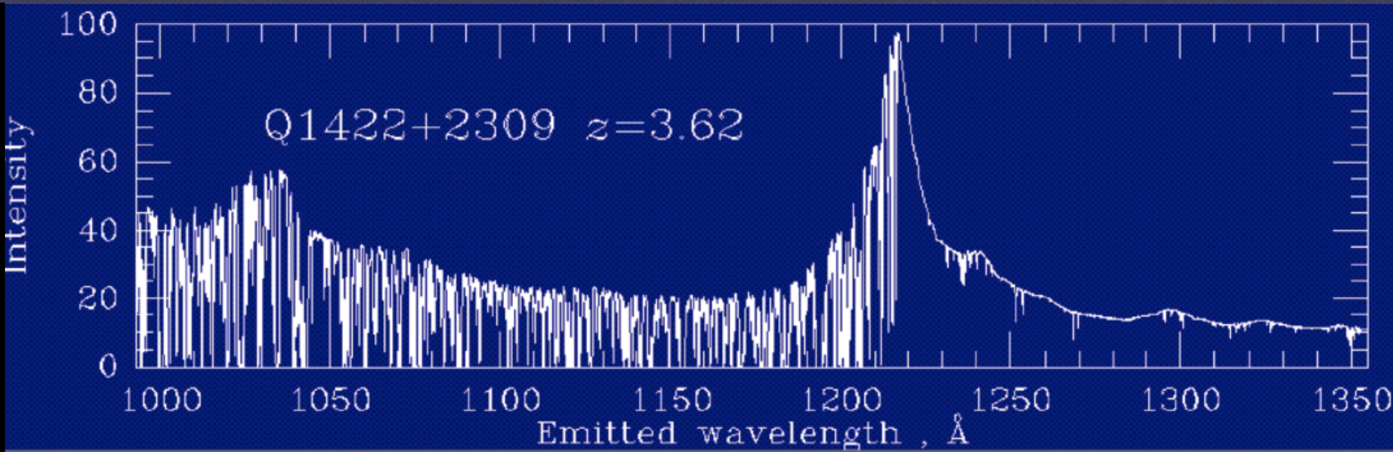
spatial information: describes pattern of oscillations in density and temperature in the pre-recombination plasma



deviations from blackbody $\lesssim 10^{-5}$

atomic transition lines: (e.g. Lyman-alpha at z~2-6, in future 21cm at higher redshift) probe gas temperature, ionization level, 3D distribution





Example Lyman-alpha absorption in quasar spectrum. Credit: Bill Keel, https://pages.astronomy.ua.edu/keel/agn/forest.html

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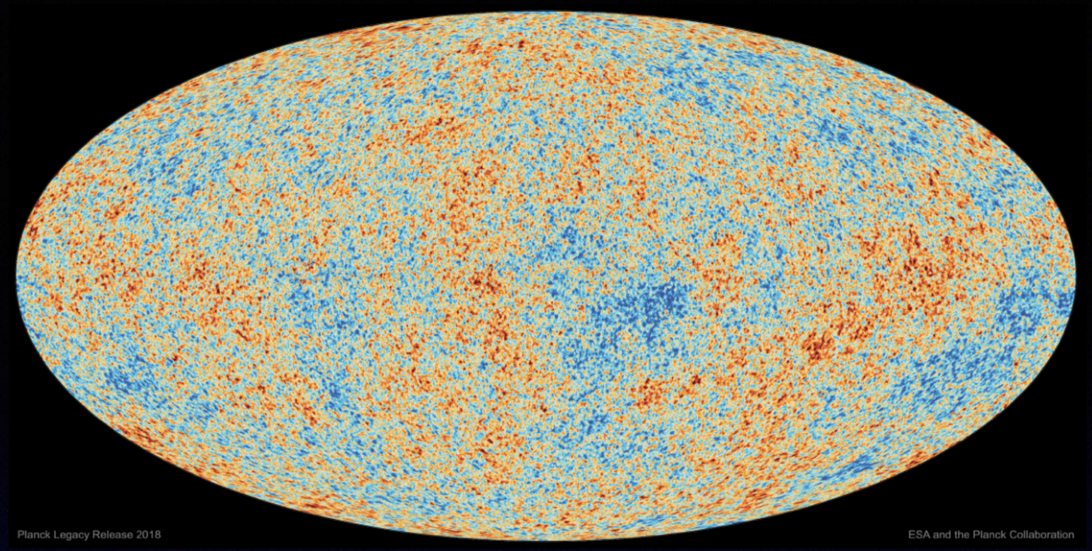

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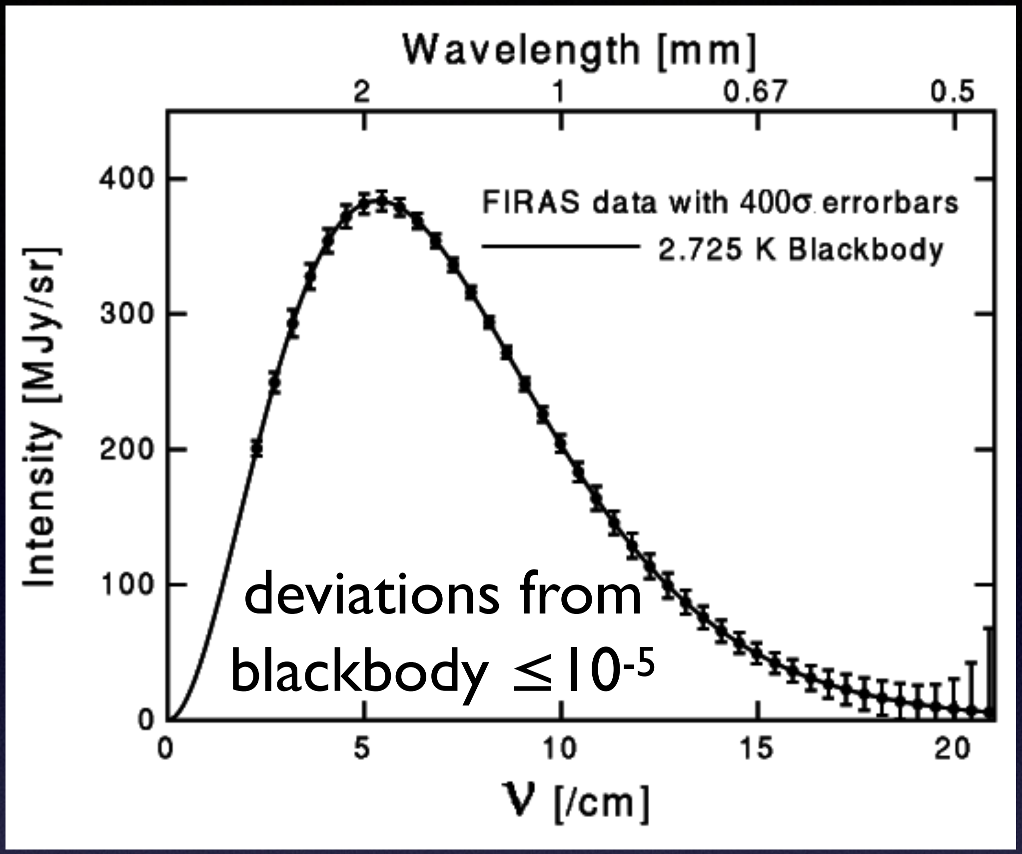

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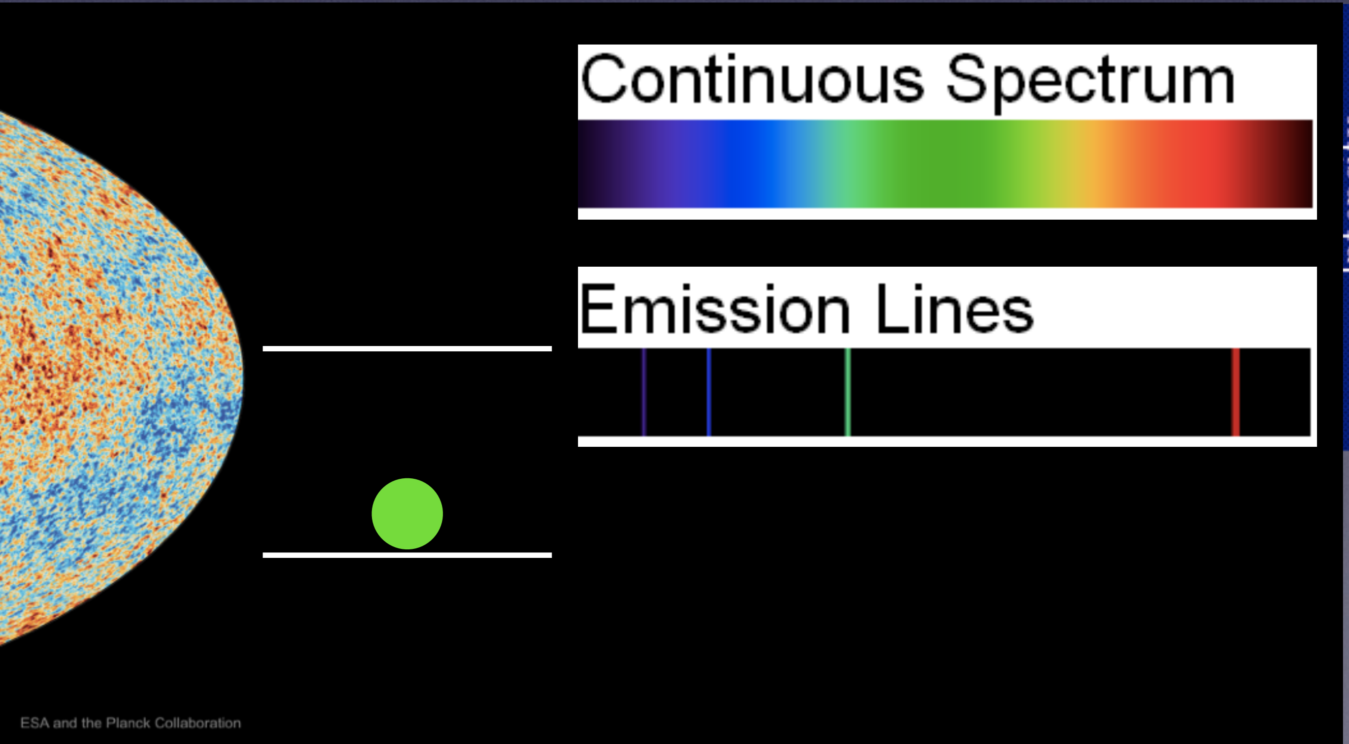

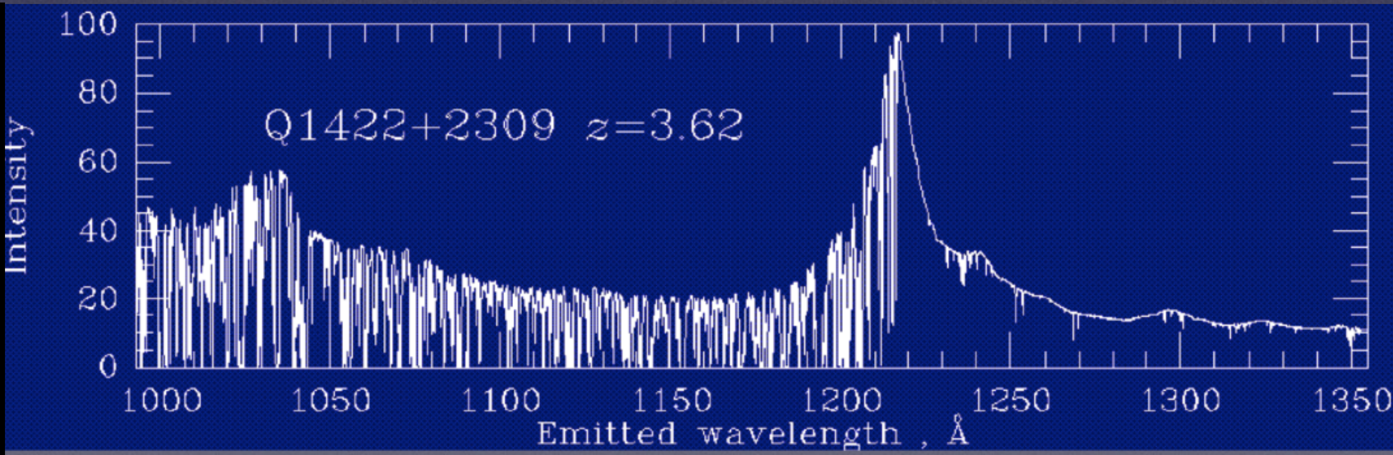

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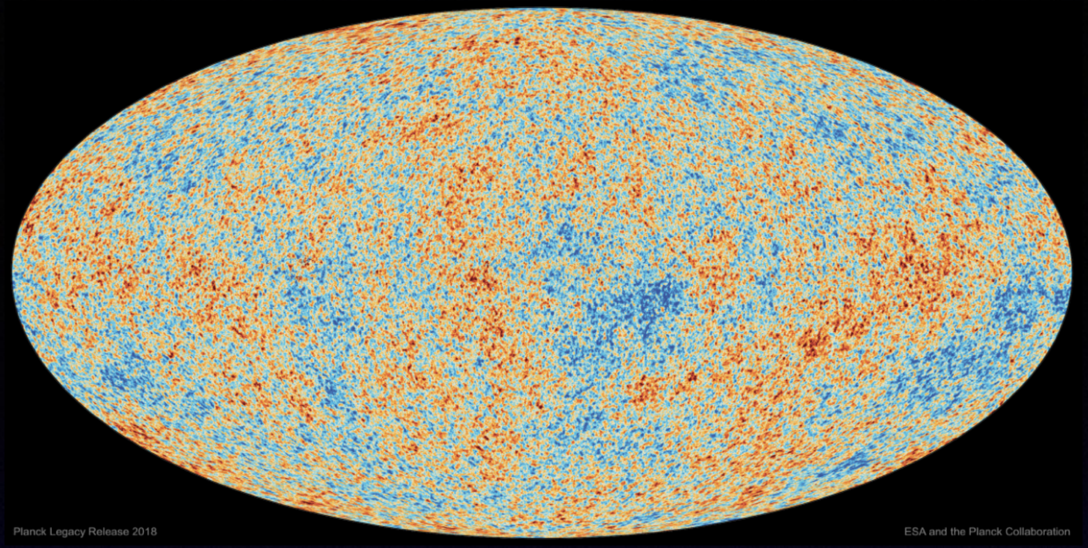

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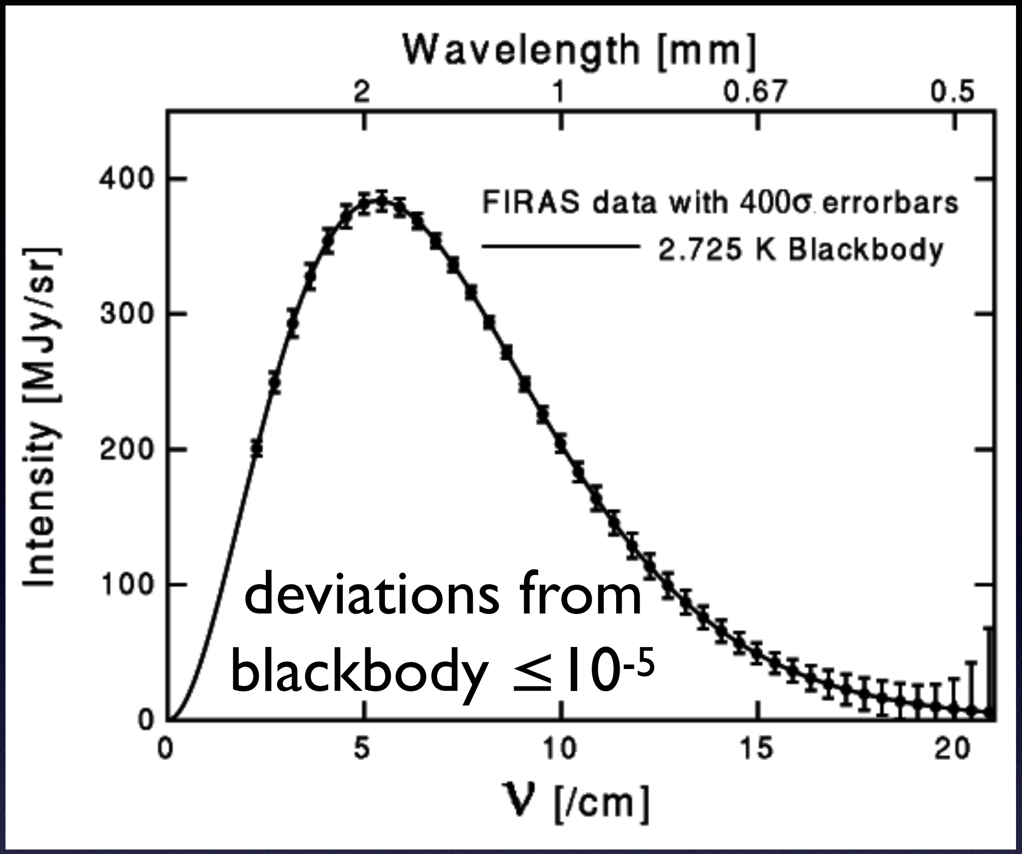

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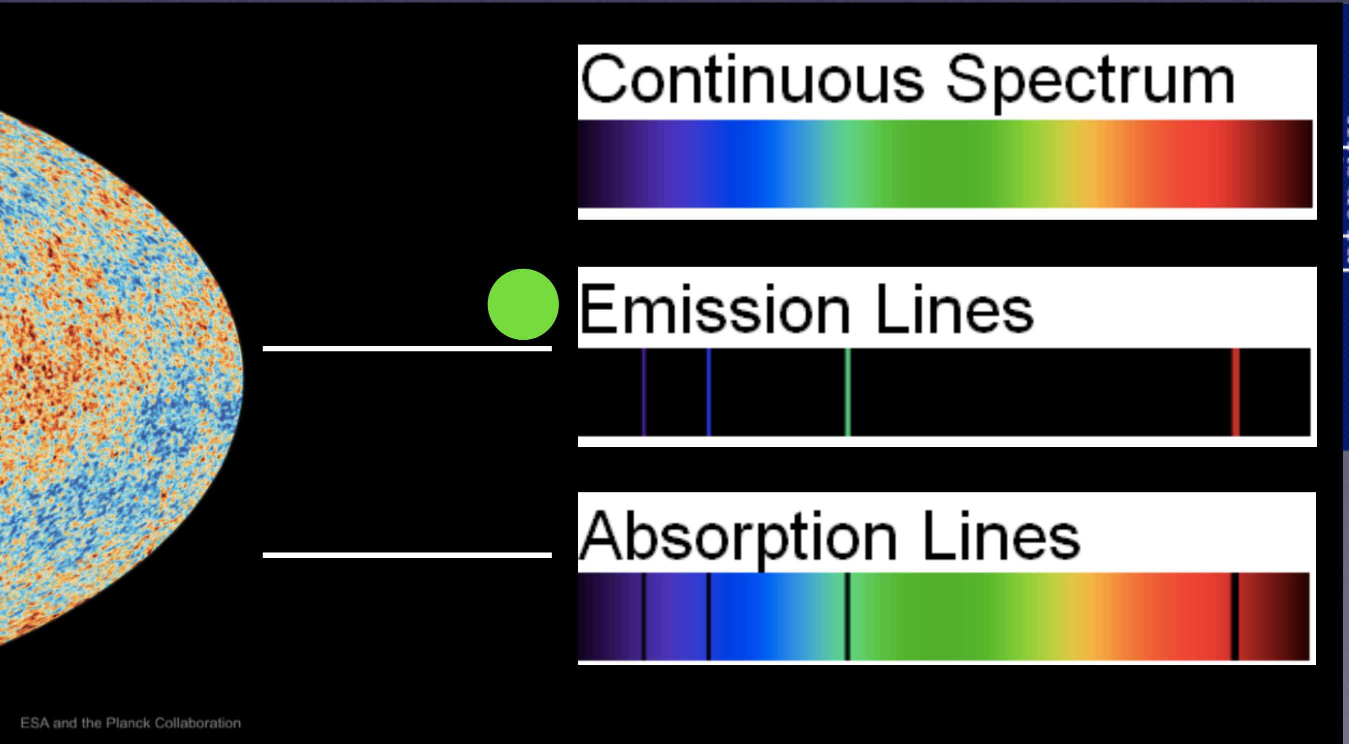

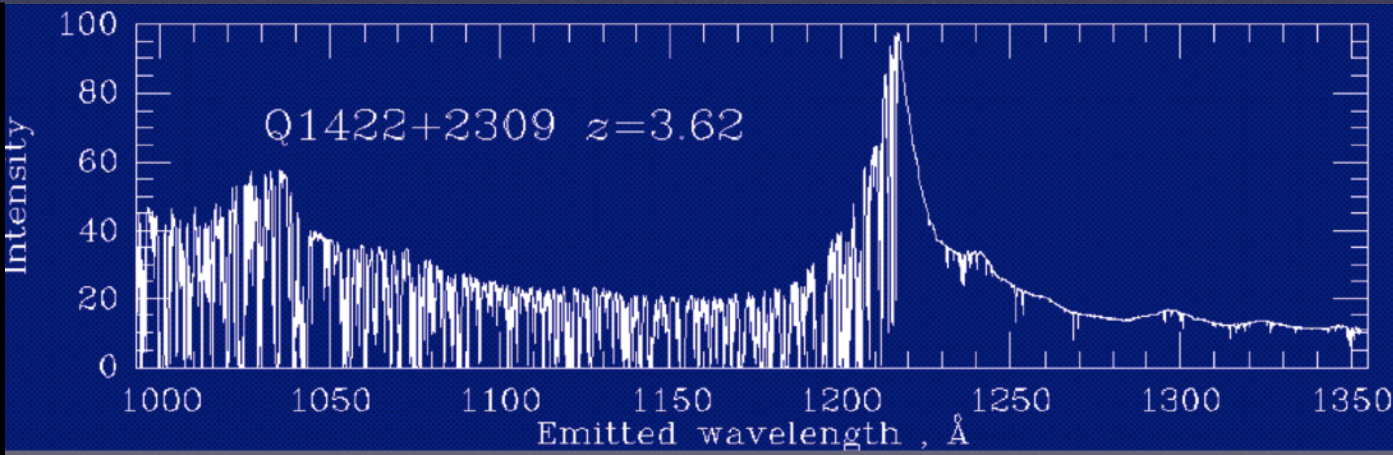

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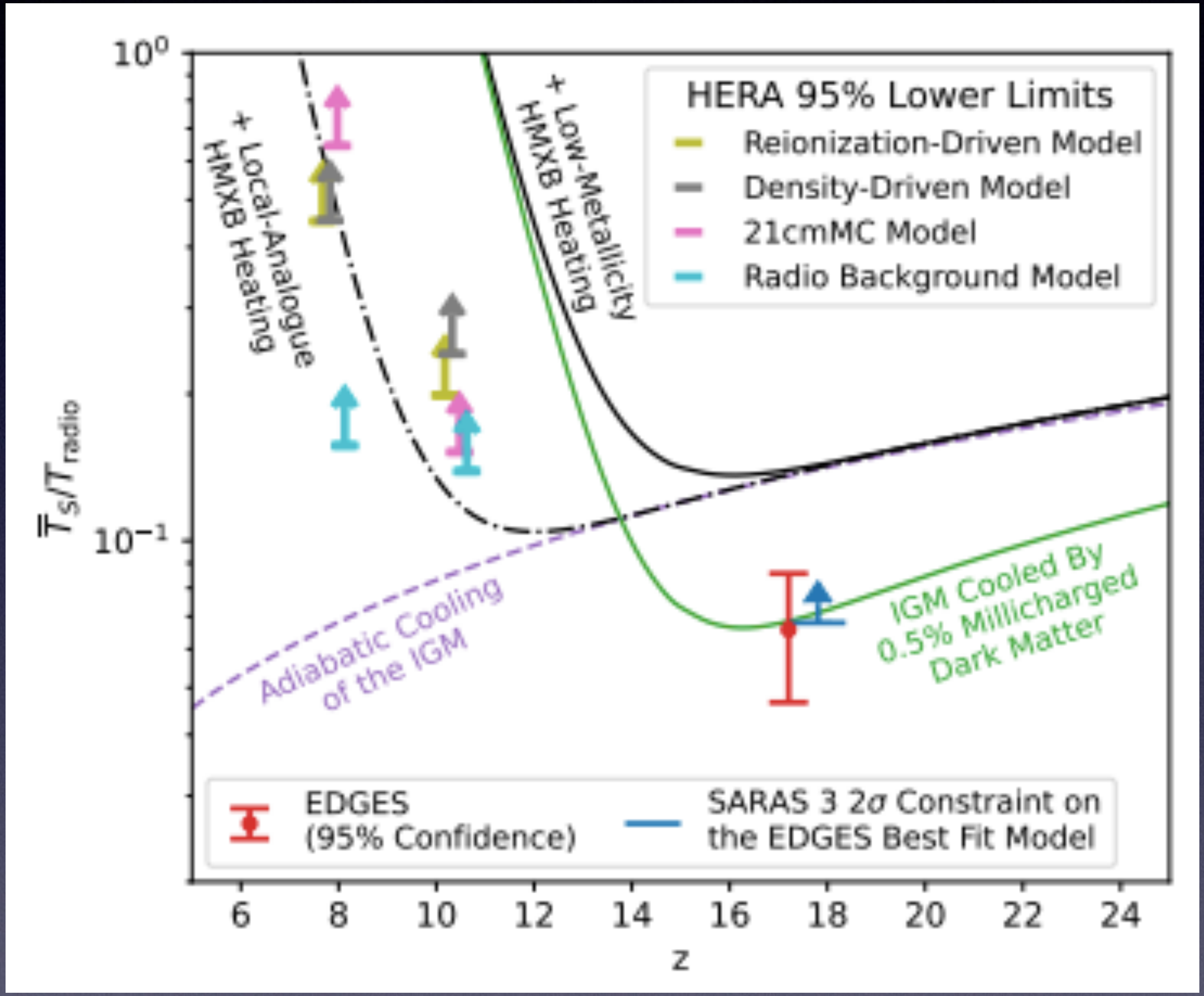
The search for primordial 21cm

- There is a large ongoing effort to measure primordial 21cm radiation
- HERA has recently released upper limits on the power spectrum based on 94 nights of Phase I data from 2017-18, with 35-41 antennas (HERA Collaboration 2210.04912)
- Focus is on epoch of reionization, z < 12
- Null observations exclude very low temperatures in this epoch (which would give rise to a deep absorption signal inconsistent with observations)



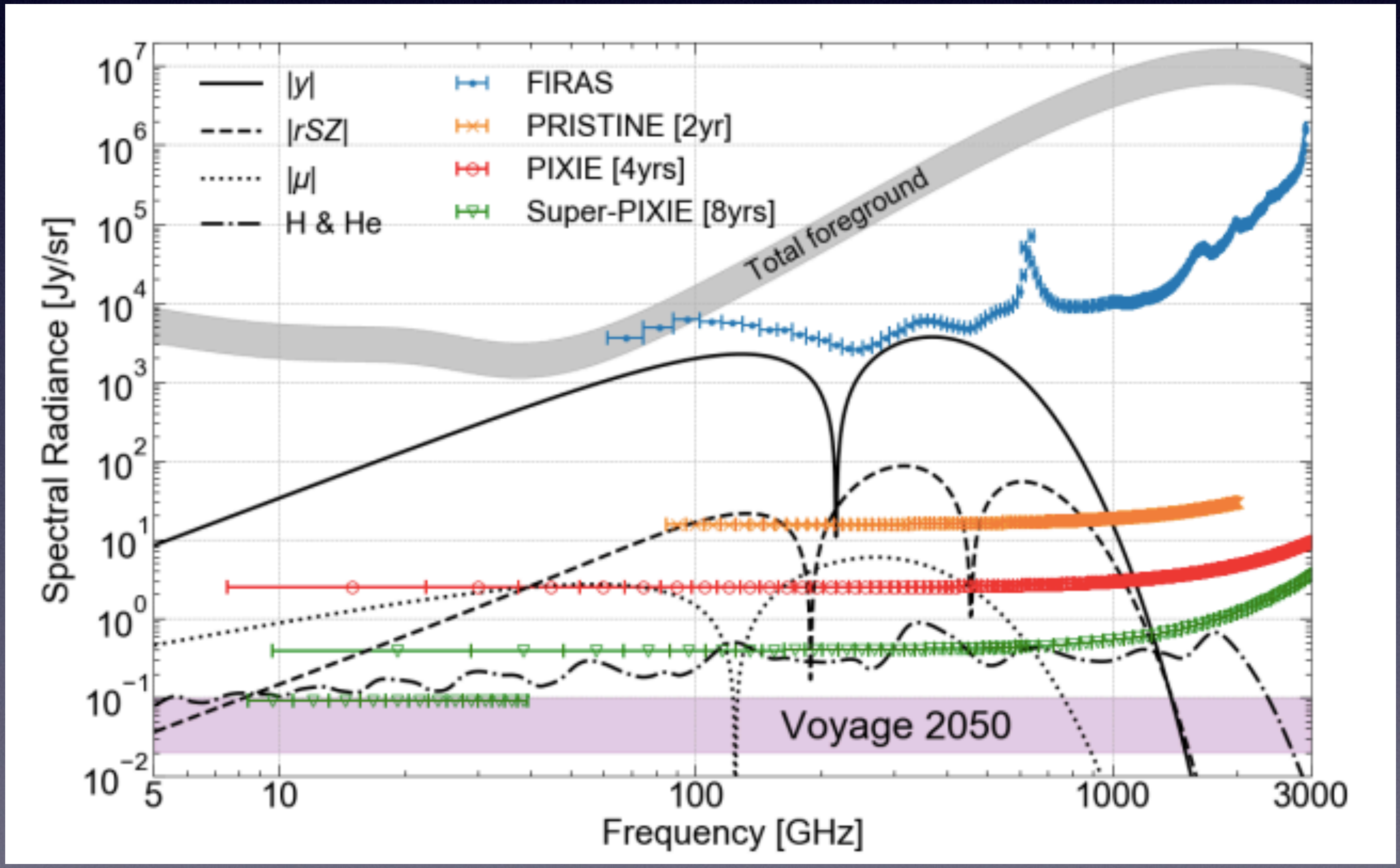
- "HERA Phase II, now being commissioned, will have 350 antennas observing from 50–250 MHz which corresponds to 4.7 < z < 27.4."

Photon background distortions

- Energy injections from $z \lesssim 10^6\,(T \lesssim \mathrm{keV})$ generically leave imprints in the CMB blackbody spectrum

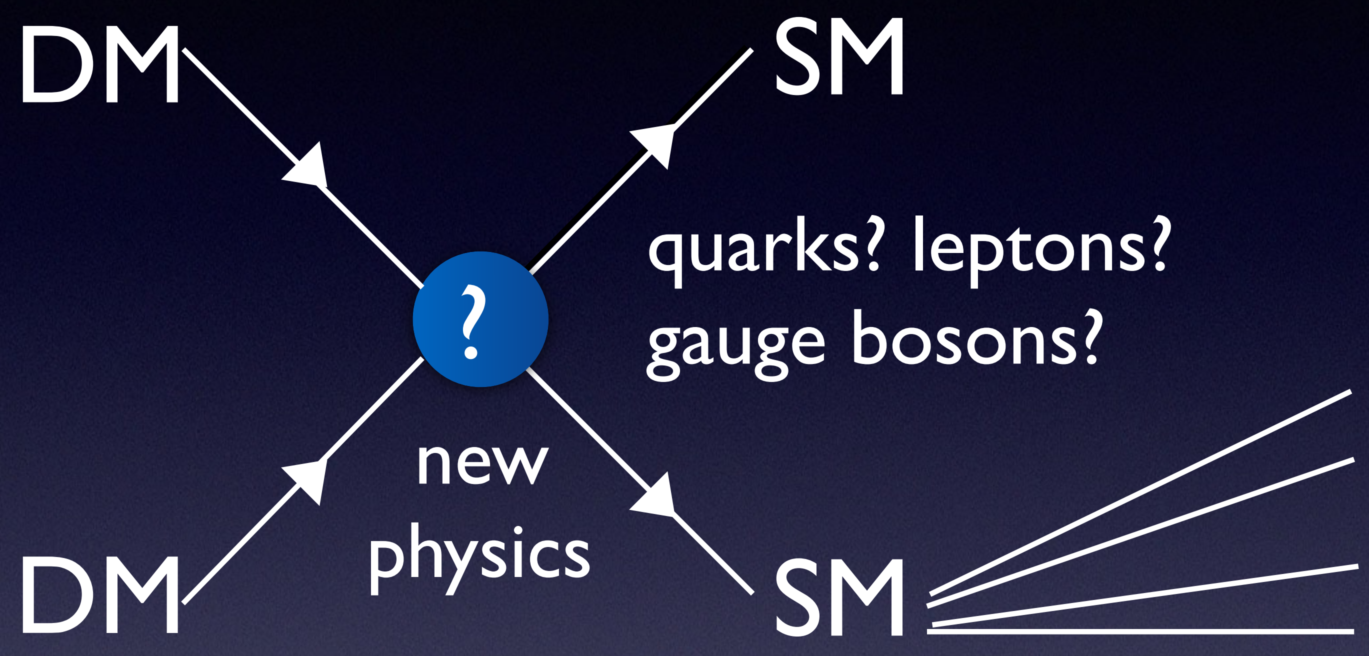
- We last measured the CMB blackbody with COBE/FIRAS in 1990

- Advances in detector technology and cryogenics have opened up the possibility of improving limits by 4+ orders of magnitude (e.g. Chluba et al 1909.01593)



Chluba et al ’19
Voyage 2050 white paper

Annihilation



DM

SM

quarks? leptons?
gauge bosons?

new
physics

DM

SM

Cascading decays according
to known SM processes

dark matter

known particles

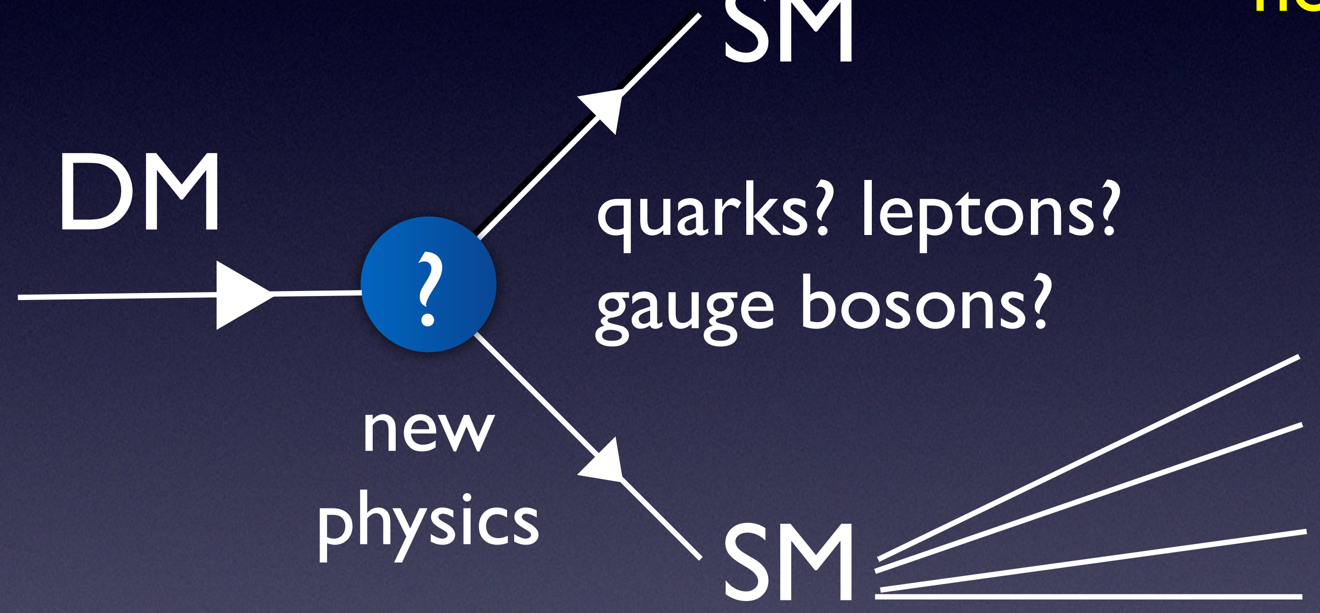
long-lived known particles

- Tightly linked to DM abundance in scenarios where (1) DM was in thermal equilibrium with SM in early universe, (2) annihilation depleted the initial abundance.
- Such scenarios favor a benchmark "thermal relic" cross section:

$$\boxed{\langle \sigma v \rangle \sim \frac{1}{m_{\mathrm{Planck}} T_{\mathrm{eq}}} \sim \frac{1}{(100\mathrm{TeV})^2} \approx 2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}}$$

Decay

also applicable to Hawking radiation from primordial black holes, decays from a metastable state to a lighter state, etc



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- These are not the only mechanisms for energy transfer - also scattering (but then transfer only kinetic energy, not mass energy), absorption, oscillation of light DM into photons or vice versa, etc

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- Similar arguments apply to indirect detection - possible to see striking effects from a very small fraction of the DM annihilating/decaying. Lets us test long lifetimes inaccessible in the lab.

Example: estimating limits on decaying DM

- Fraction of DM decaying per e-fold in a given epoch ~ lifetime of cosmos / lifetime of DM
- Thus constraining a 10^{-9} fraction of DM decaying (i.e. heating up to 5×10^{4} K per baryon) when the universe was 10% of its present age (O(1 billion years) old) leads to limits on lifetimes of 10^{8} x age of the universe ~ few x 10^{25} s
- Similar constraints for 10^{-12} decaying fraction when the universe was O(10^{6} years) old, i.e. the CMB epoch
- Can also probe tiny metastable components decaying with lifetimes > 10^{6} years but < 10^{10} years

DarkHistory

computing modified ionization/thermal histories

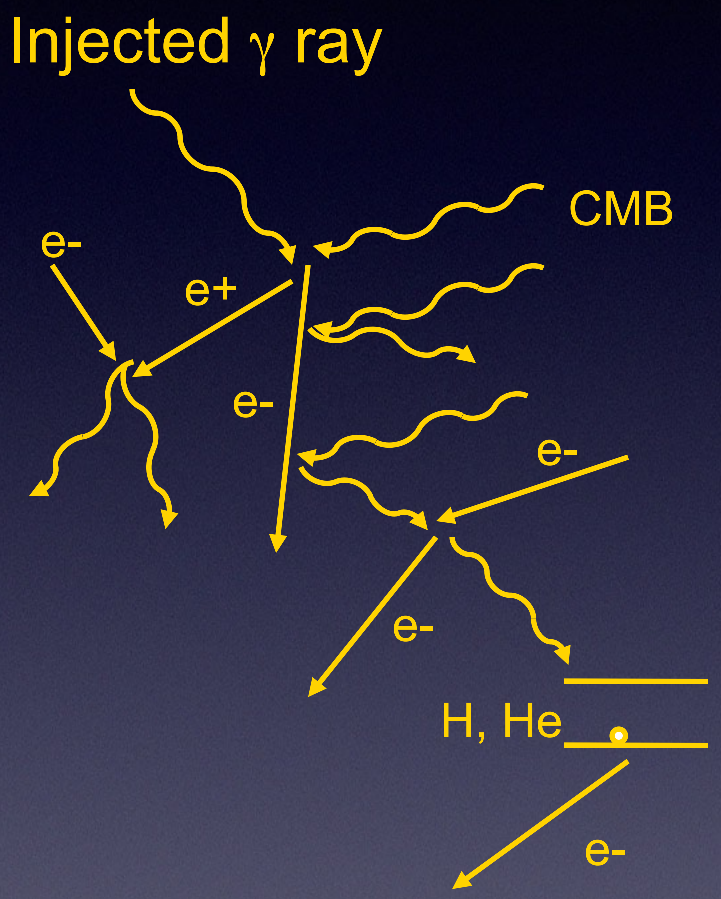
- To study any of these effects in detail, we need to know how particles injected by annihilation/decay transfer their energy into heating, ionization, and/or photons.
- My collaborators (Hongwan Liu, Greg Ridgway) and I wrote a Python package (building on my earlier papers TRS et al ’09, TRS ’16) to:
  - model energy-loss processes and production of secondary particles,
  - accounting for cosmic expansion / redshifting,
  - with self-consistent treatment of exotic and conventional sources of energy injection.
- Publicly available at https://github.com/hongwanliu/DarkHistory

The transfer functions

Based on code developed in TRS, Padmanabhan & Finkbeiner 2009; TRS 2016

ELECTRONS

- Inverse Compton scattering (ICS) on the CMB.
- Excitation, ionization, heating of electron/H/He gas.
- Positronium capture and annihilation.
- All processes fast relative to Hubble time: bulk of energy goes into photons via ICS.



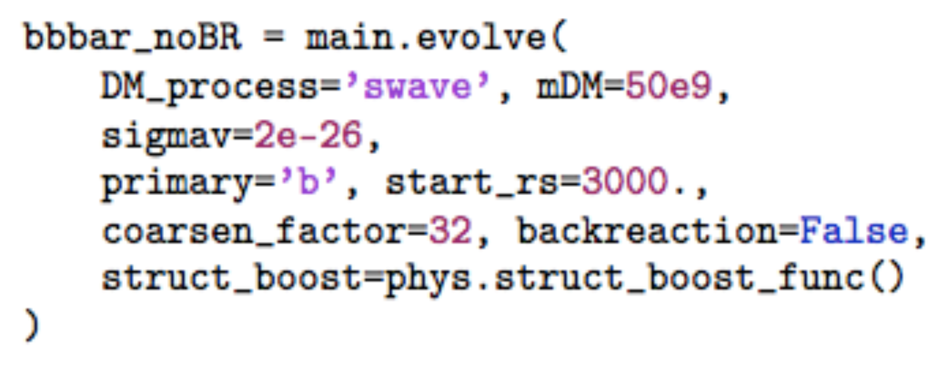
Schematic of a typical cascade:
initial γ-ray
-> pair production
-> ICS producing a new γ
-> inelastic Compton scattering
-> photoionization

PHOTONS

- Pair production on the CMB.
- Photon-photon scattering.
- Pair production on the H/He gas.
- Compton scattering.
- Photoionization.
- Redshifting is important, energy can be deposited long after it was injected.

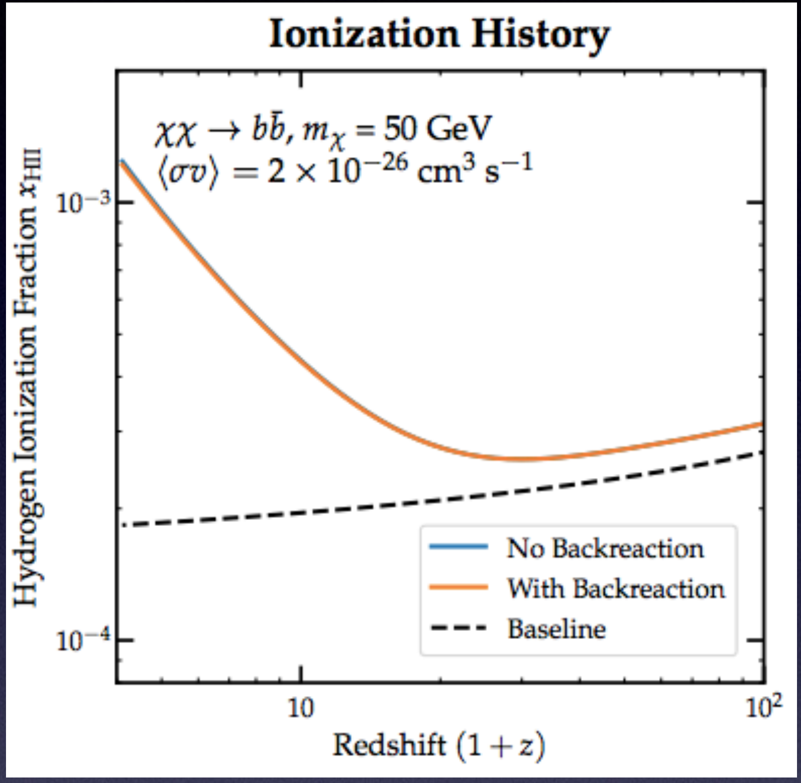
Note: rates depend on gas ionization level

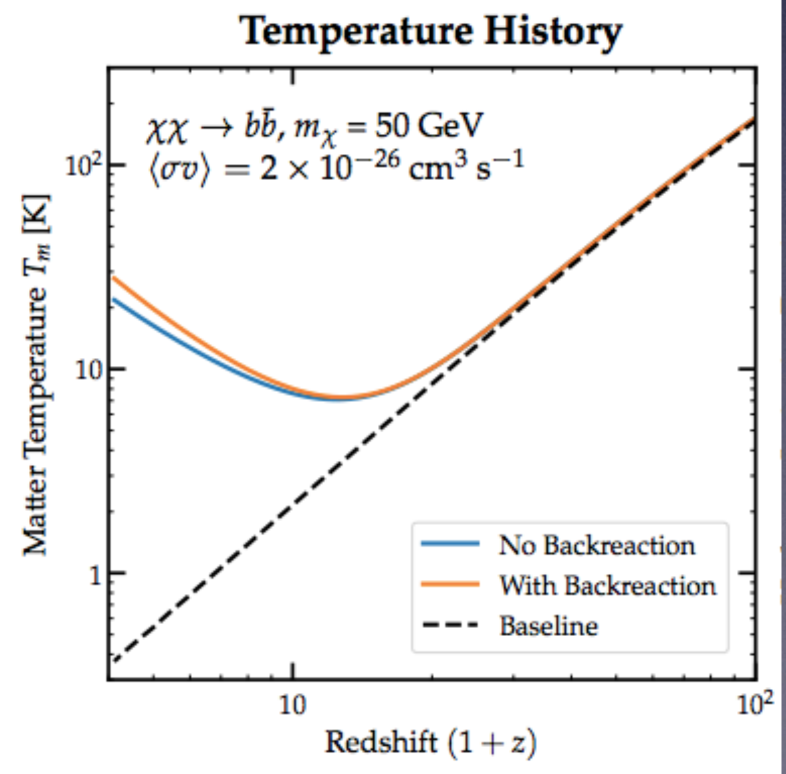
Running DarkHistory



```
bbbar_noBR = main.evolve(
    DM_process='swave', mDM=50e9,
    sigmav=2e-26,
    primary='b', start_rs=3000.,
    coarsen_factor=32, backreaction=False,
    struct_boost=phys.struct_boost_func()
)
```

- DarkHistory is provided with extensive example notebooks.
- It contains built-in functions for:
    - redshift dependence corresponding to DM decay or s-wave annihilation
    - injection spectra of electrons/positrons/photons corresponding to all SM final states
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks.
- Easy to turn on/off "backreaction" effects (changes to ionization level from earlier energy injection modifies particle production cascade).

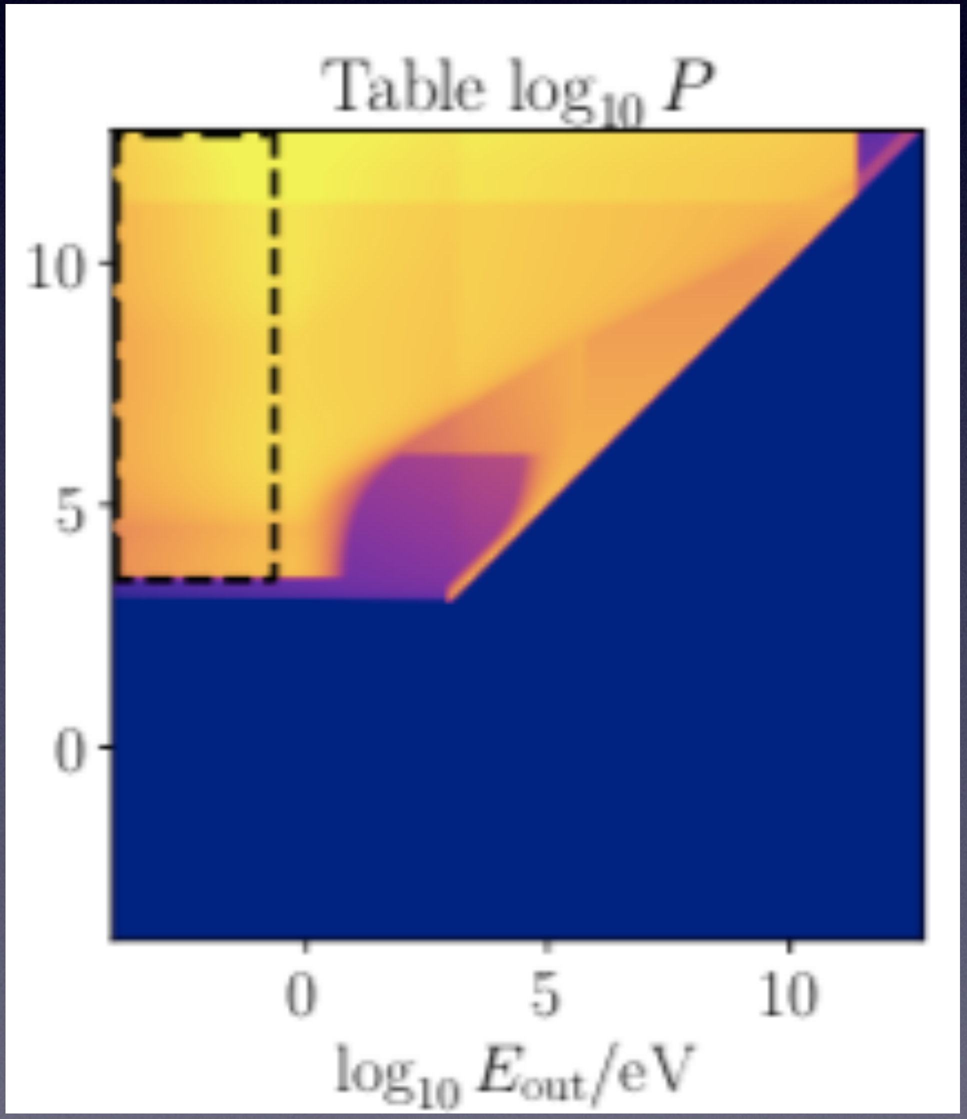




DarkHistory with neural networks

[Yitian Sun & TRS, 2207.06425]

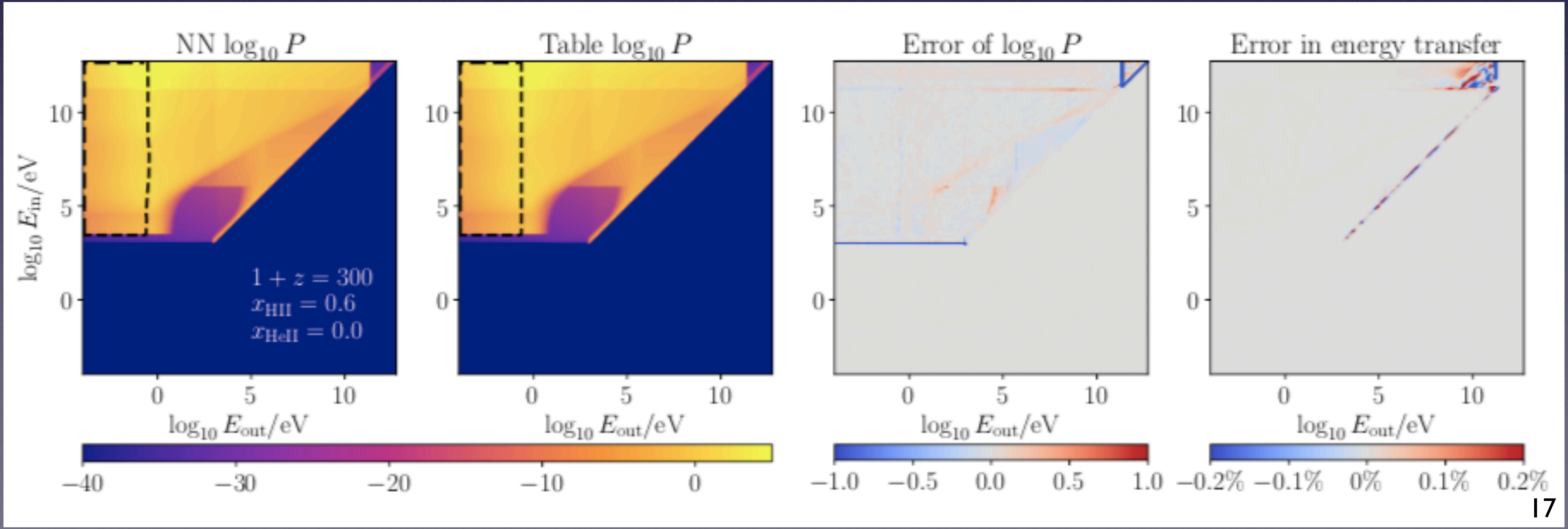
- Goal: store the transfer functions describing the particle cascade in a more efficient/compact way
  - improve usability
  - facilitate adding extra parameter dependences (e.g. on gas density, for future inhomogeneity studies + factorizing out Ω_b dependence)
- Observation:
  - neural networks can serve as general function approximators
  - the transfer functions have features and structure, but have significant regions where they are quite smooth - much less information than # of pixels



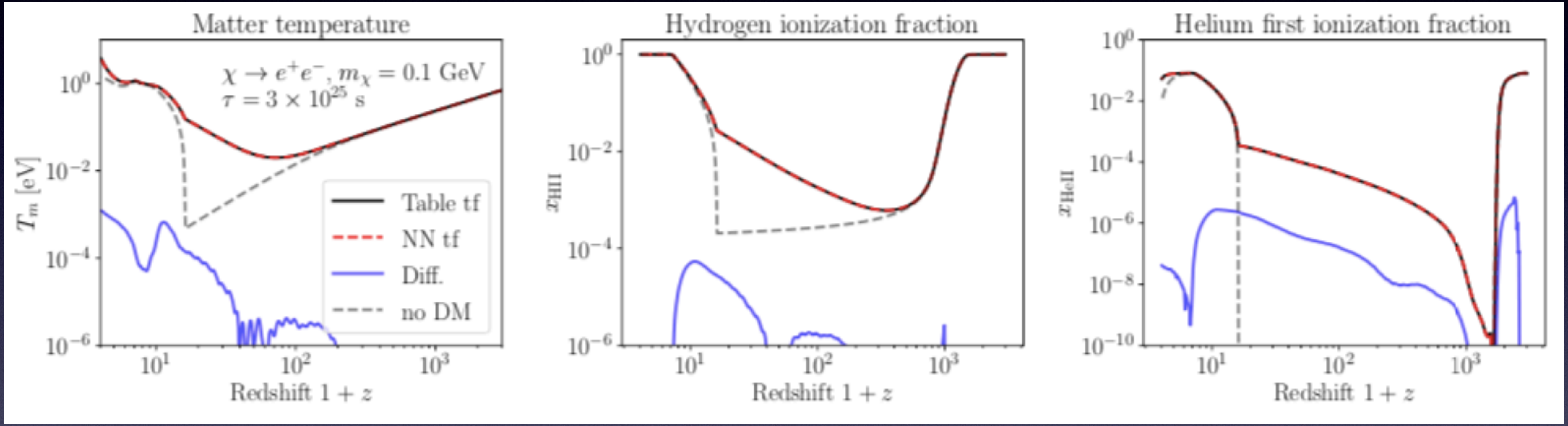
Example slice through a transfer function at 1+z=300, x_{HII}=0.6

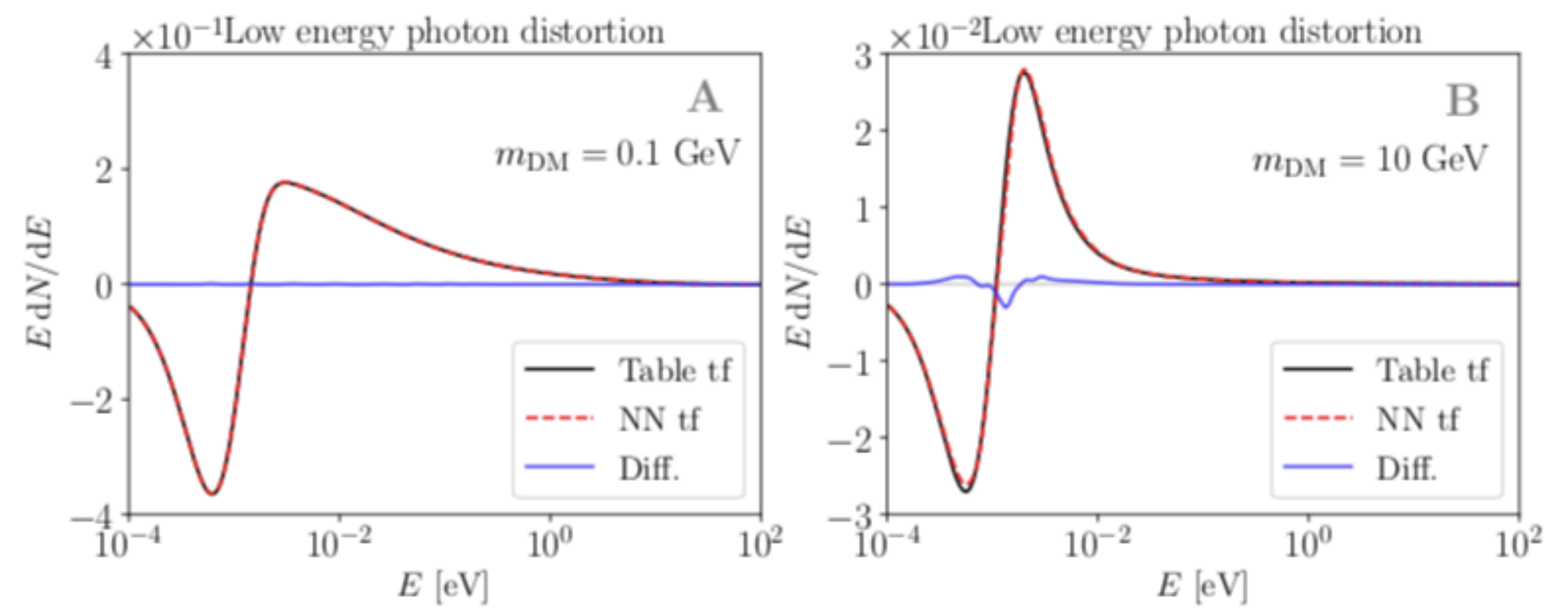
Results

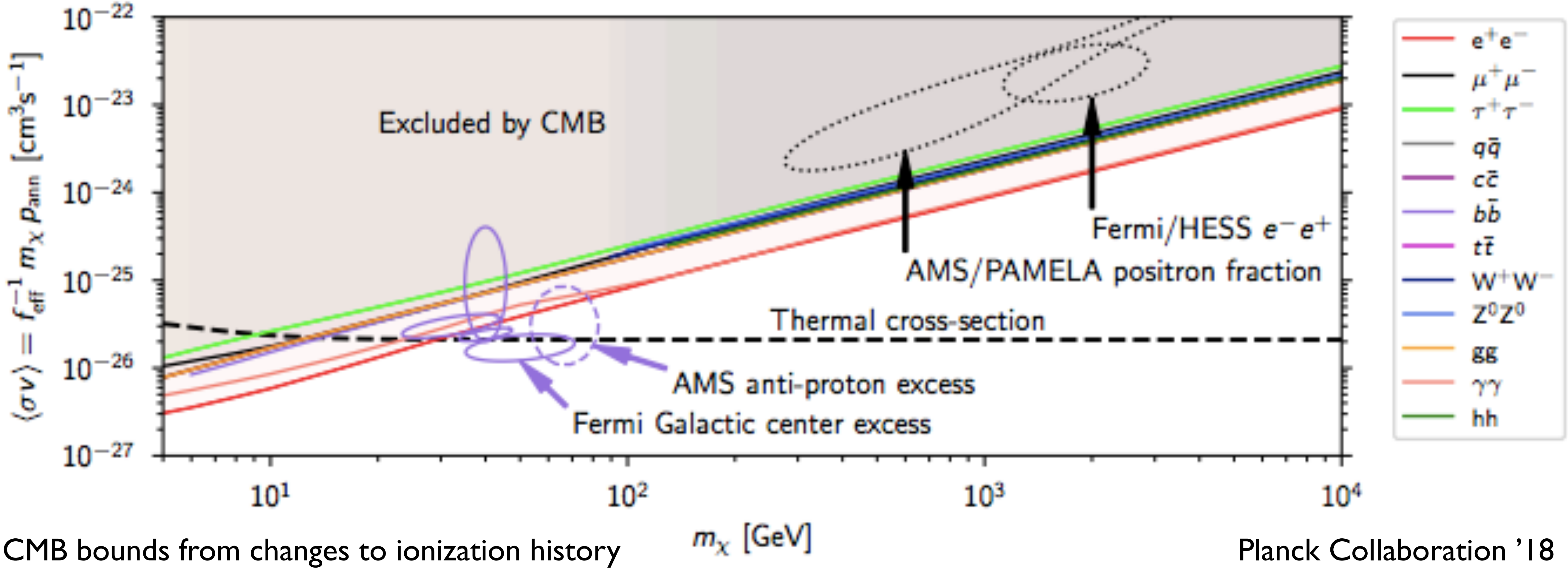
- Network is ~400x smaller than tables (may be possible to do even better)
- Speed of code with NN evaluation is comparable to that with table lookup
- Error in temperature/ionization histories is <2% (often much lower)
- This version of DARKHISTORY also predicts a component of the CMB spectral distortion - also well reproduced, although with larger errors (up to 10%)



Comparison of histories + spectral distortion



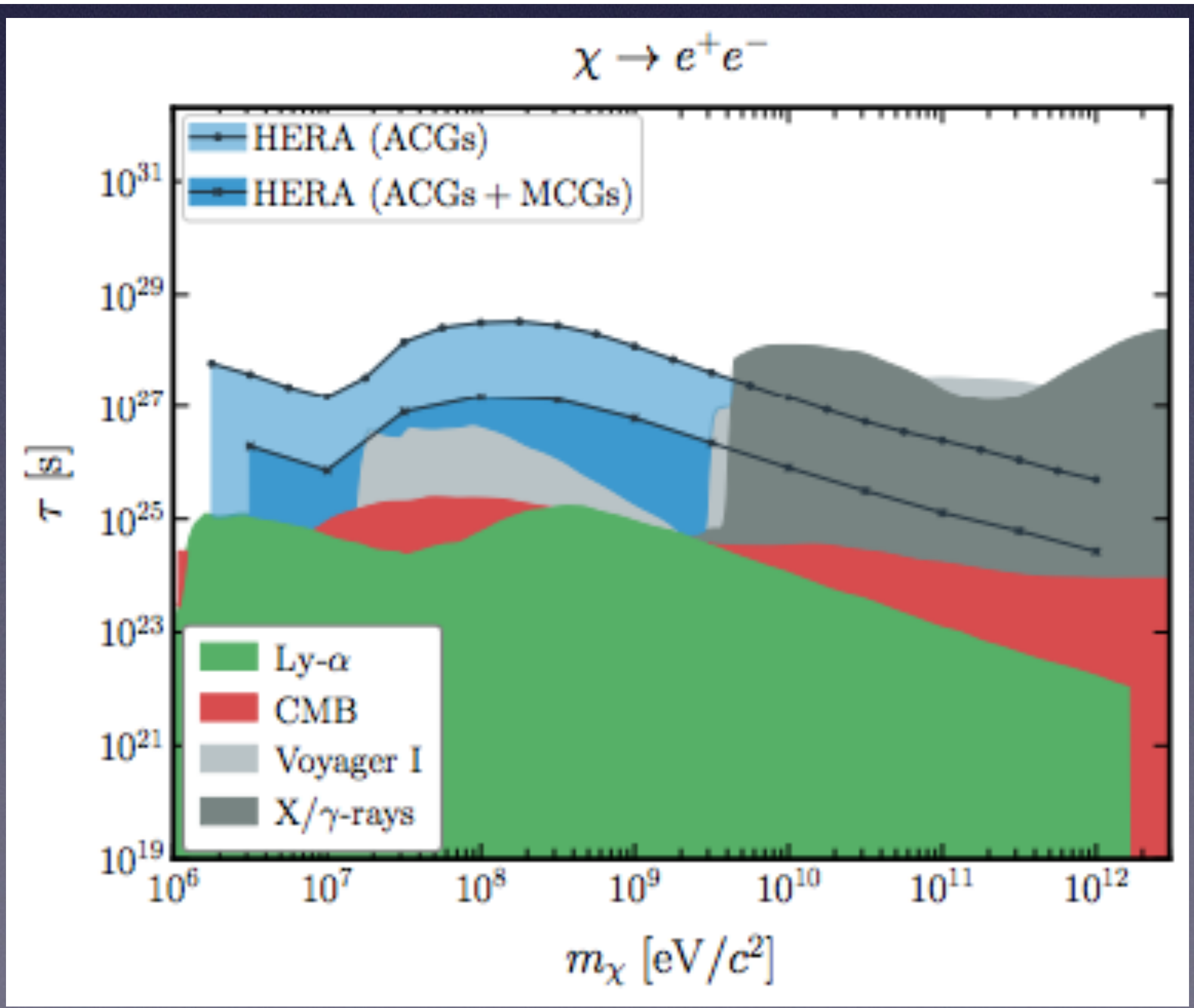




CMB bounds from changes to ionization history

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)

Eventual goal: a comprehensive map of the full space of possible early-universe signatures of exotic energy injections, allowing us to easily translate arbitrary energy injection models into observables and constraints

(We already have something very close to this for CMB anisotropy signals from DM annihilation/decay - I would like to extend it to other observables)

Detailed treatment of the low-energy cascade

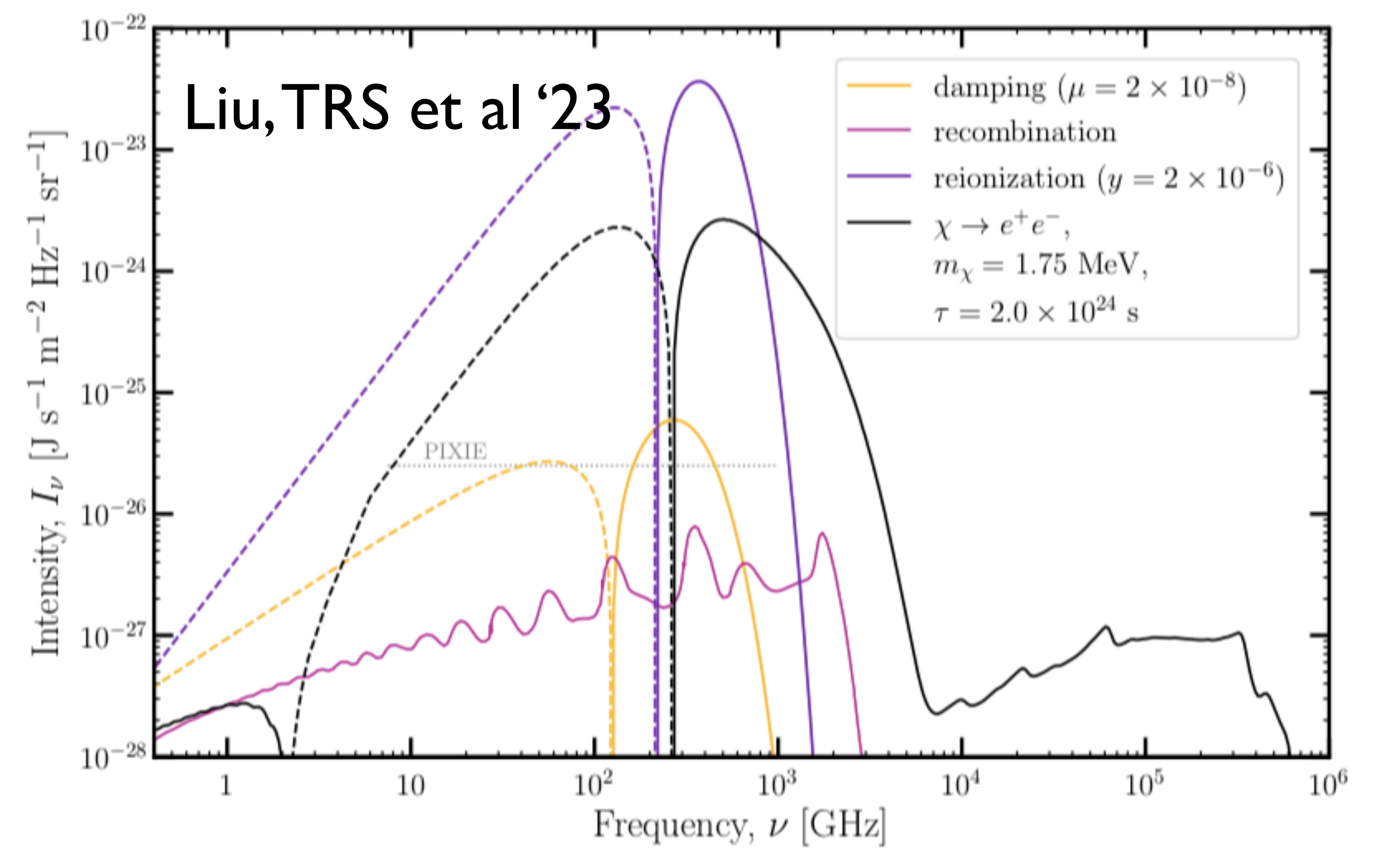
[Hongwan Liu, Wenzer Qin, Greg Ridgway, TRS, arXiv:2303.07366, 2303.07370]

- Original public version: once particles cool below 3 keV,
  - for electrons/positrons, we interpolate the published results of the MEDEA code over energy - but only 7 energies for interpolation + only evaluates integrated energy in spectral distortion, not spectrum
  - we track photons until they ionize or fall below 13.6 eV; we assign photons in the 10.2-13.6 eV range to hydrogen excitation and assume they free-stream below 10.2 eV
- We also used the "three-level atom approximation" (with fudge factors) for hydrogen + assumed a blackbody radiation field - may not be accurate in the presence of energy injection

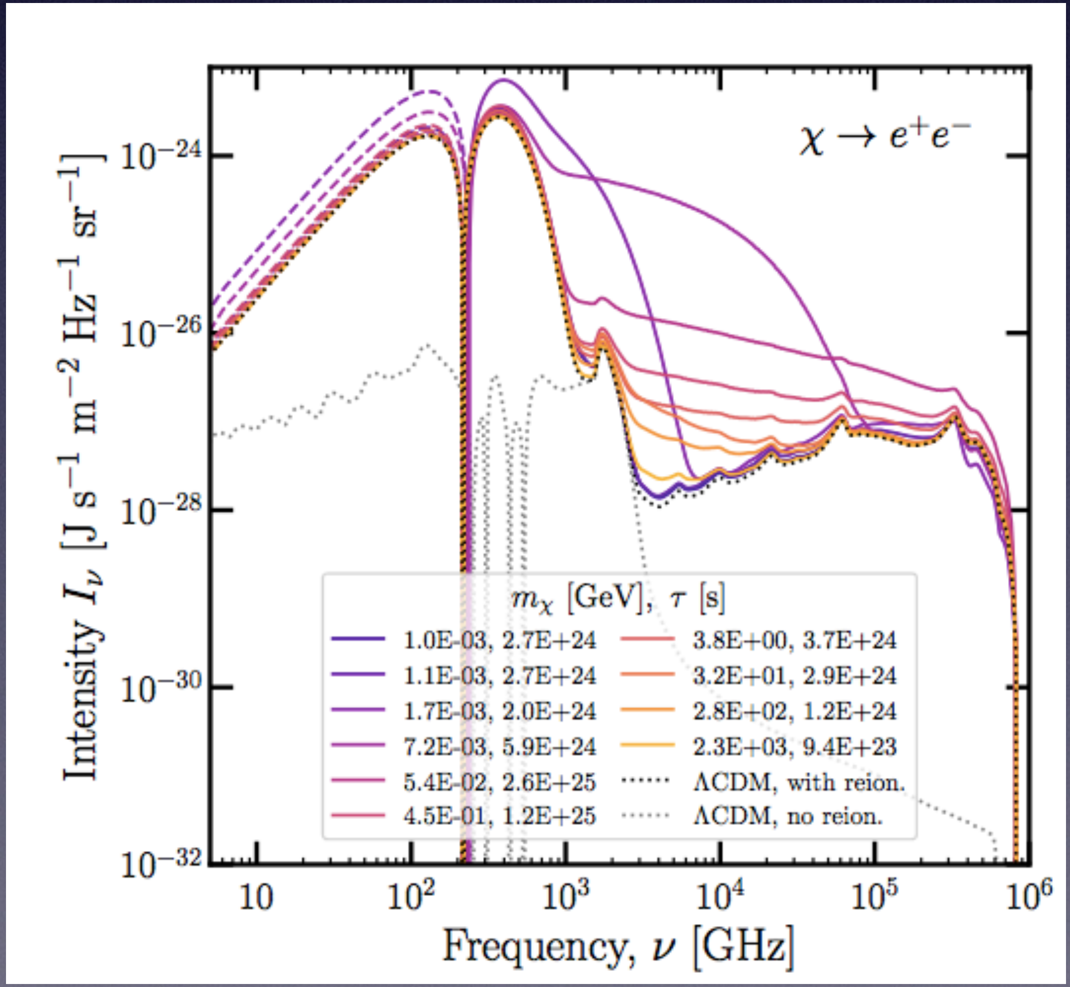
New capabilities

- Extend careful treatment of electron/positron energy losses down to energies where the electrons thermalize with the CMB (cross-checked against existing MEDEA code at sample points)
    - enables extension of previous constraints on DM decay from ionization down to arbitrarily low masses
    - enables tracking the detailed spectrum of photons produced by low-energy electrons
- Carefully track the joint evolution of the H/He atoms and the radiation field after recombination, taking into account a large number of atomic levels
- Take into account high-frequency distortions to the blackbody spectrum that can affect ionization/recombination/excitation rates
- Predict the final distortion to the CMB blackbody spectrum produced by arbitrary energy injection

Spectral distortions from DM



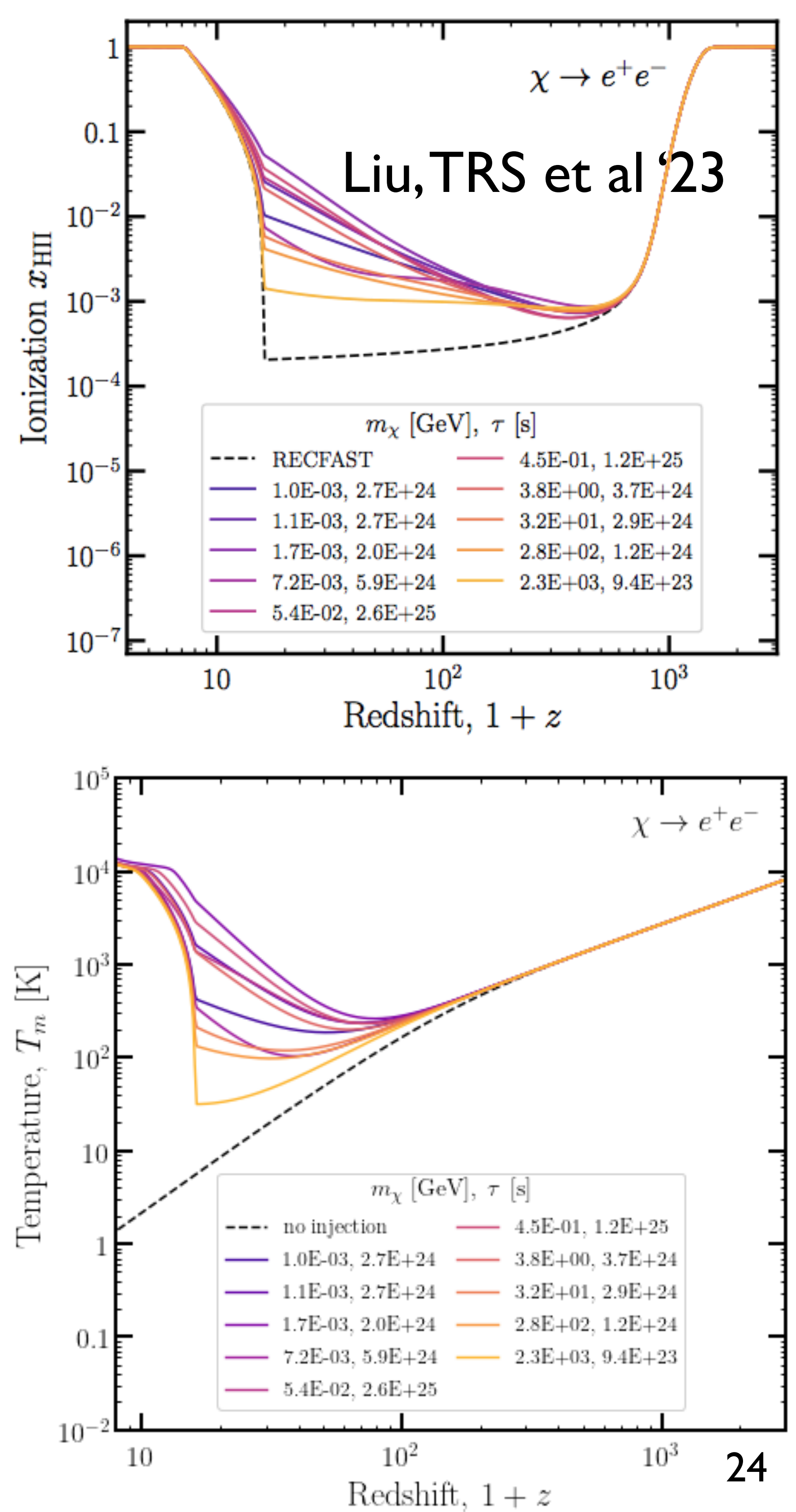
- Builds on previous work on pre-recombination signals (e.g. Acharya & Khatri 1808.02897)
- Sub-GeV decaying DM models that are not already excluded could have interesting signals in next-generation experiments (annihilation is harder)
- Distinctive spectral shapes with some variation between different 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].


Liu, TRS et al '23

Calculating the minimum halo mass for collapse

- Initial analytic study in Qin, TRS et al 2308.12992 - intention is to estimate possible effects and their directions/sizes, detailed study needs simulations
- Assume that up to virialization, halo grows as:

$$\rho(z) \approx \rho_0 (1+z)^3 \exp\left(\frac{1.9A}{1-0.75A^2}\right), \quad A = \frac{1+z_{\rm vir}}{1+z},$$

and hydrogen density scales in the same way

- Evolve temperature/ionization of gas inside halos accounting for atomic-line + molecular cooling, Compton scattering, adiabatic heating, exotic energy injection
- Consider halo virialized once density or temperature reach virial values; then hold gas density fixed, and continue evolving temperature for a short time
- Check for rapid cooling using criterion from literature,

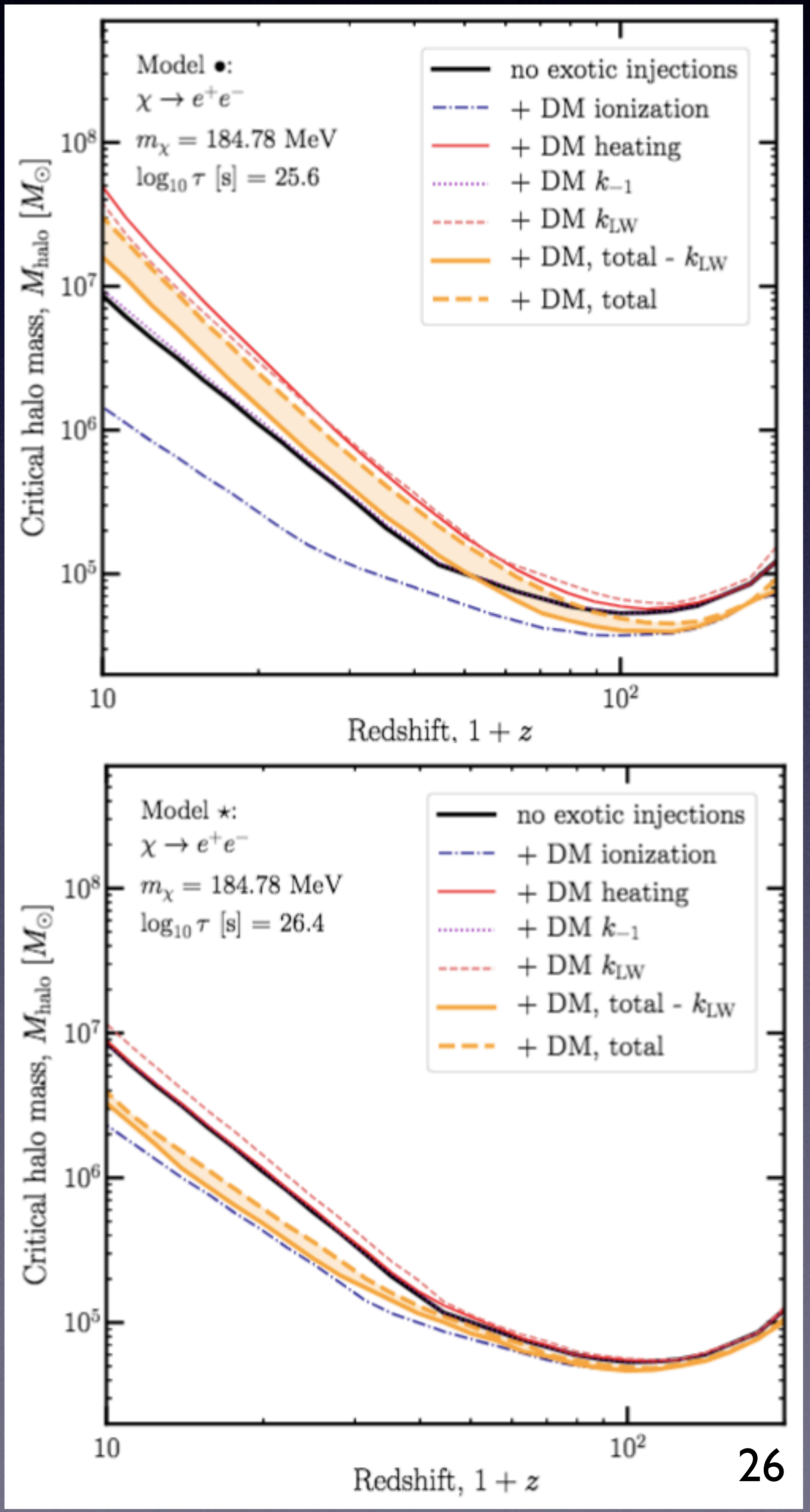
$$T_{\rm halo}(\eta z_{\rm vir}) \leq \eta T_{\rm halo}(z_{\rm vir})$$

(we set η=0.75 but have checked results are not very sensitive to this parameter)

Effects of energy injection

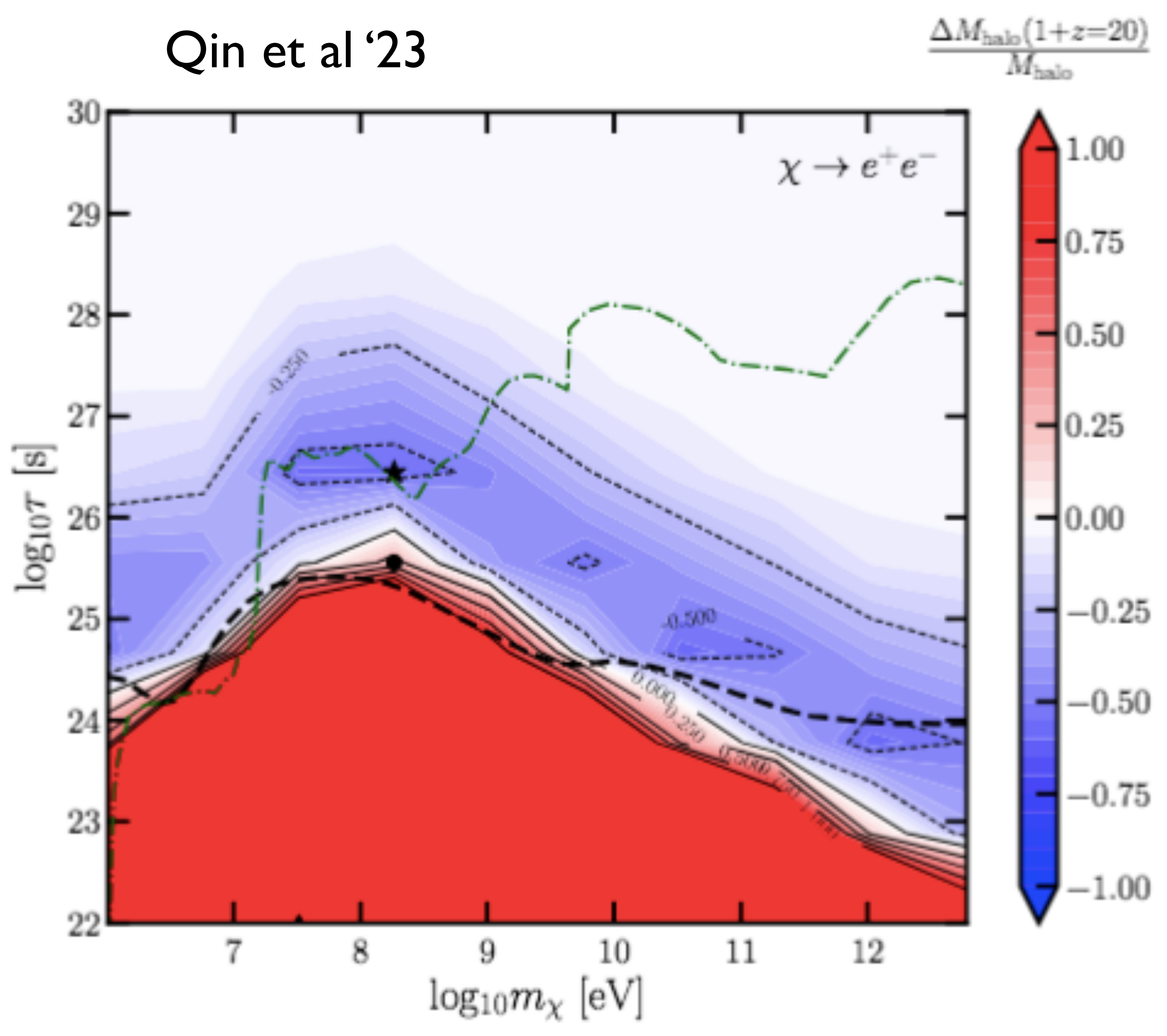
- Extra free electrons catalyze H_2 formation, accelerating cooling
- Extra Lyman-Werner photons (if not shielded in halos) can dissociate H_2, slowing cooling
- Extra heating counteracts cooling directly, making it harder for gas to collapse
- We can express the impact of these effects in terms of the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

Qin, TRS et al '23

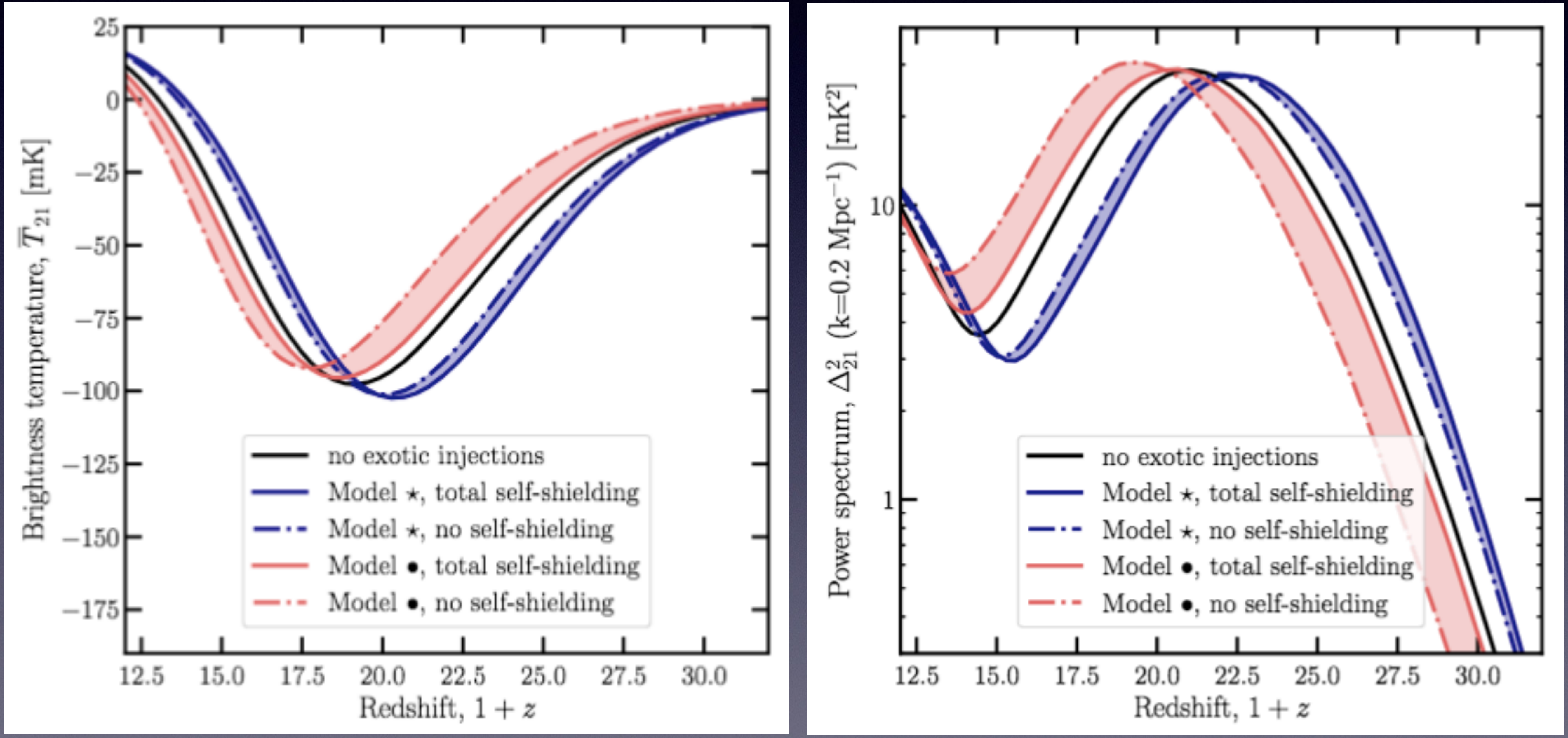


Accelerating or delaying star formation?

- 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


Qin et al '23

Direction of effect in 21cm



Where next?

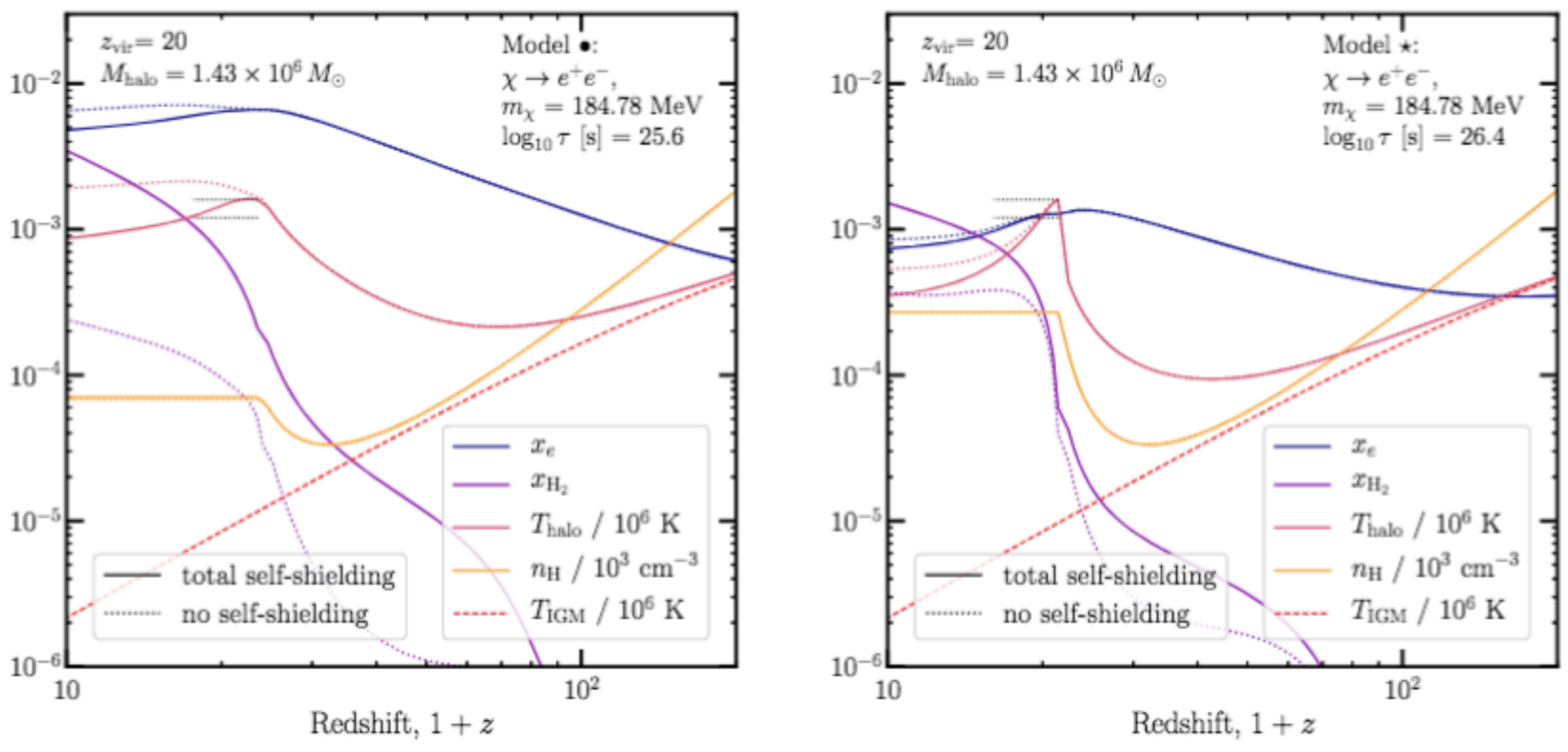
- Simulation follow-up on effects on early star formation
- Explore detectability/distinguishability of spectral distortions with realistic foreground+instrument models
- 21cm power spectrum predictions for decaying / annihilating DM (in progress, led by Josh Foster and Yitian Sun)
  - incorporate and measure the effects of <u>inhomogeneity</u> in gas density + ionization (currently treated as uniform for purposes of calculating the cascade)
- Understand how early black hole seeds could be affected by general non-thermal energy injections [see e.g. Pandey et al 1801.06649, Friedlander et al 2212.11100]
- Other applications - secondary effects of early cosmic rays? Relevance to excesses in photon backgrounds?

Summary

- Cosmological datasets can provide powerful probes of the non-gravitational properties of dark matter, and other exotic physics
- There are exciting prospects for significant experimental progress, especially on primordial 21cm and CMB energy spectrum measurements
- We already have stringent and broadly applicable limits on annihilating and decaying DM (especially at sub-GeV mass scales) from the cosmic microwave background, and complementary+competitive bounds from Ly-alpha for leptonically decaying light DM
- We have built public numerical tools to compute all these effects, including new results on the space of possible signals from exotic energy injection in cosmic photon backgrounds
- Energy injections that are not currently excluded could accelerate the formation of the first stars - we have identified interesting parameter space for follow-ups with simulations

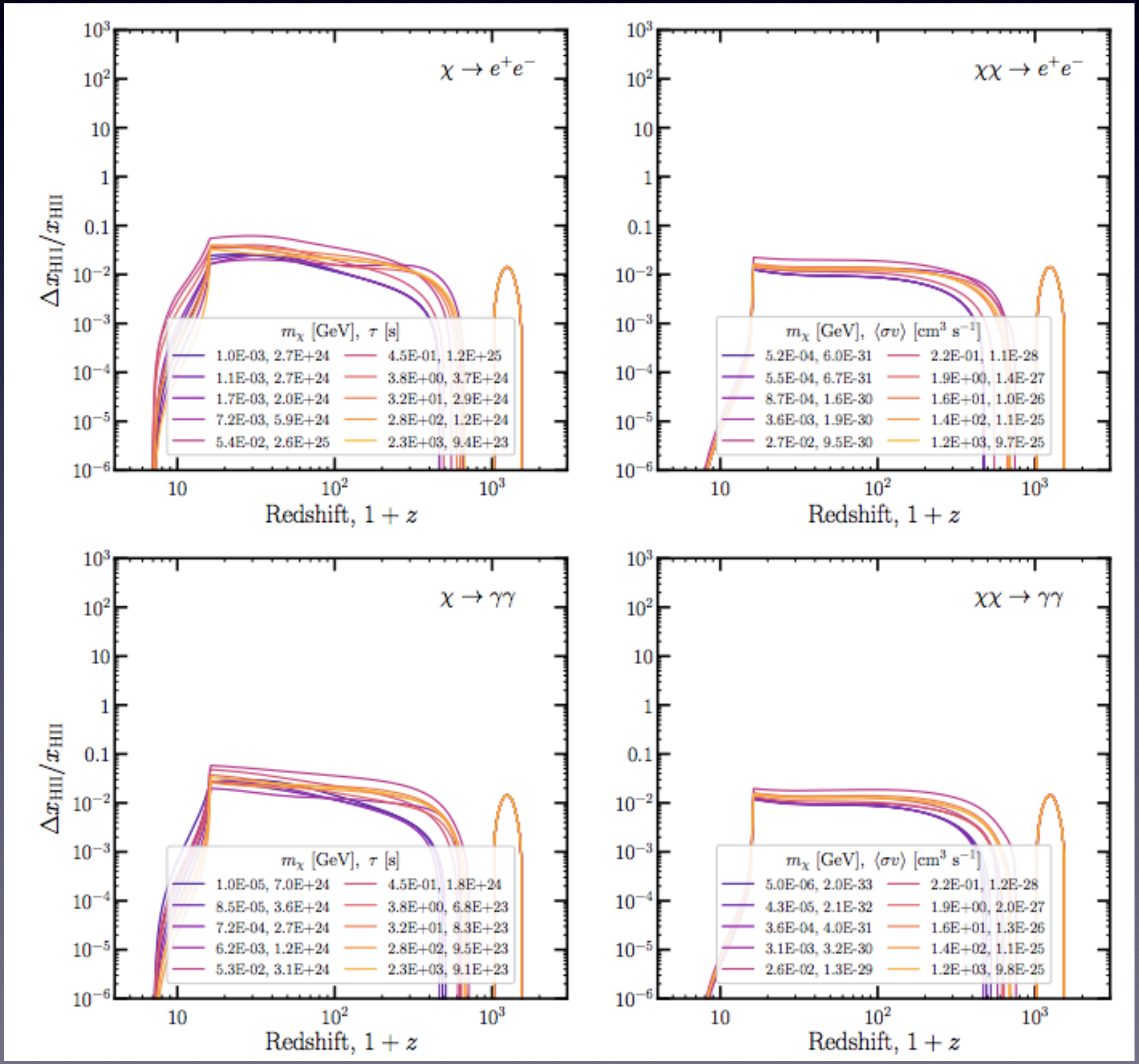
BACKUP SLIDES

Example halo histories



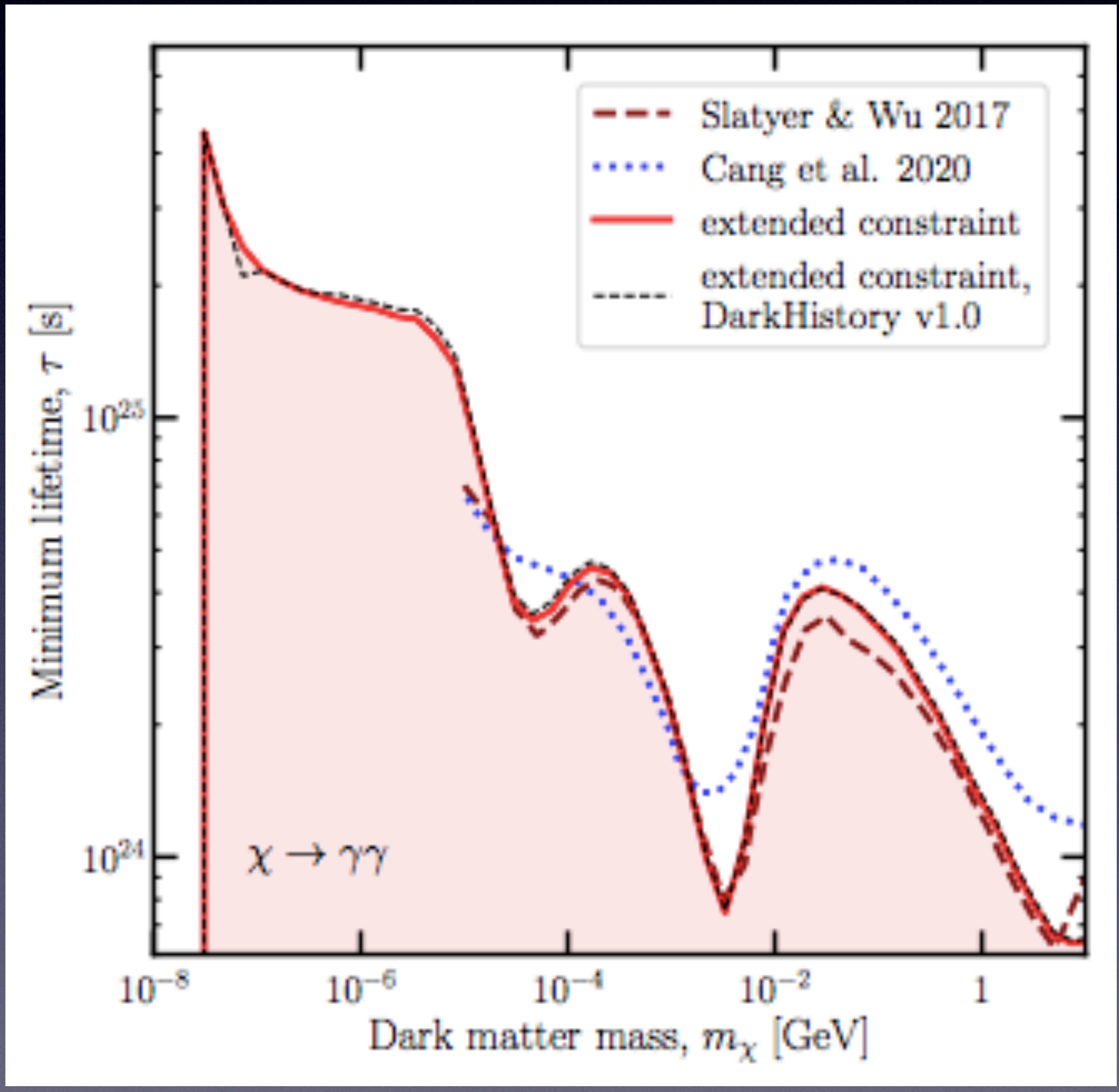
The ionization history, revisited

- Original treatment of low-energy particles was quite crude, many ~uncontrolled approximations
- What does the new and improved version say?
- It turns out we got lucky - errors often cancel/are small, ionization history perturbations are ~unchanged (at <10% level)
- Expect ~no significant changes to constraints based on ionization history+CMB
- Exception: now we can work out the ionization history perturbations for injected energies < 13.6 eV



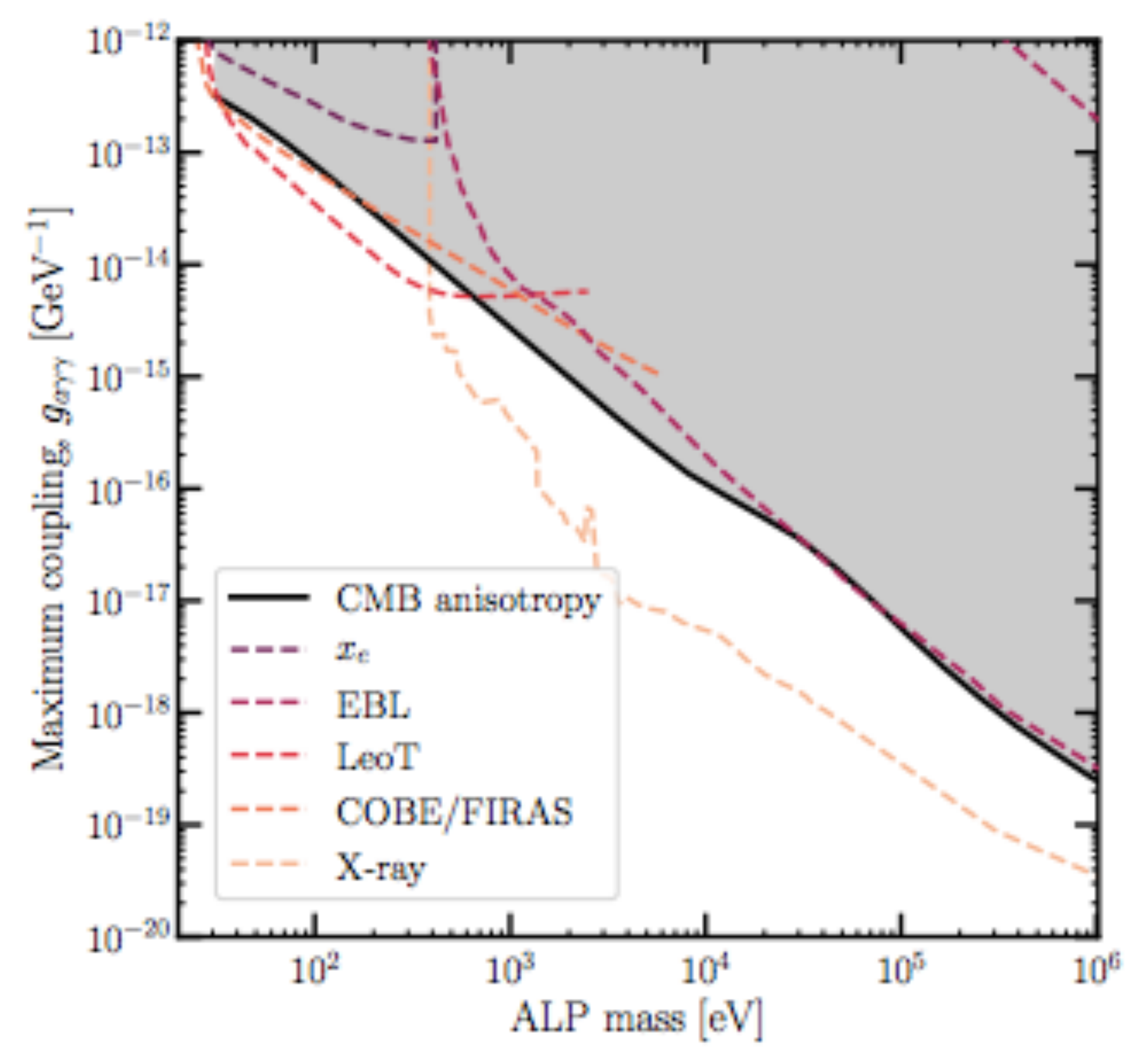
Estimated constraints on low-mass decaying DM

- We estimate the effect on the ionization history and hence the CMB by looking at the power into ionization at z~300 (previously validated for decaying DM)
- Allows extension of ionization limits down to O(30) eV (decaying) DM
- Approximation becomes invalid for energies < 13.6 eV - no power directly into ionization, but still a secondary effect from enhanced excitation (i.e. there is a cutoff, but still a limit)
- We check the change to the ionization level is small (albeit not negligible) from models that are not yet excluded



Estimated constraints on axion-like particles

- We can convert these estimated CMB bounds on light DM decaying to photons into limits on light axion-like particle (ALP) DM
- Bounds are competitive with other approaches - comparable to limits from gas heating in dwarf galaxies but with different systematics
- See also Capozzi et al 2303.07426; careful analysis using DarkHistory 1.0, obtains slightly stronger constraints than our estimate



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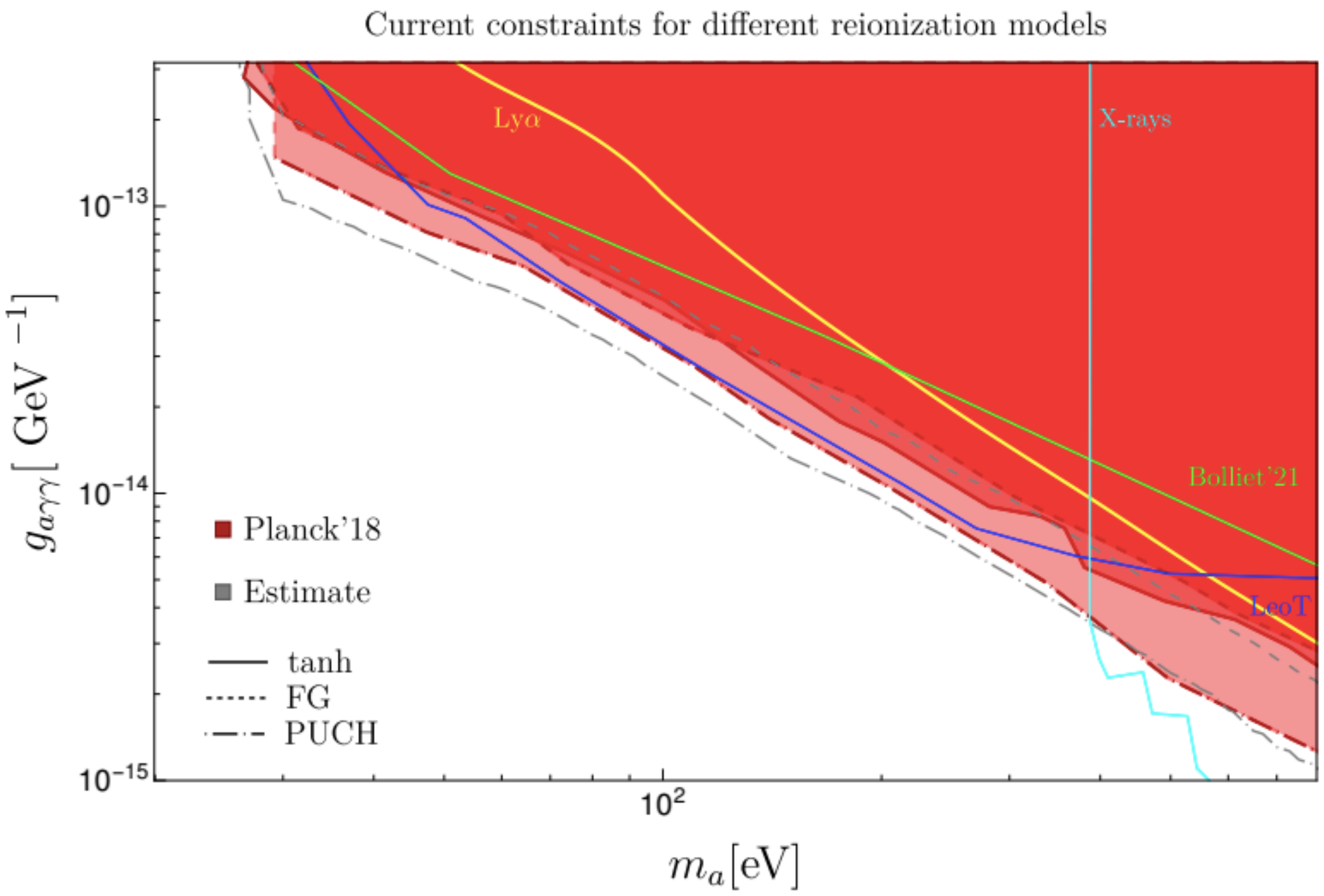
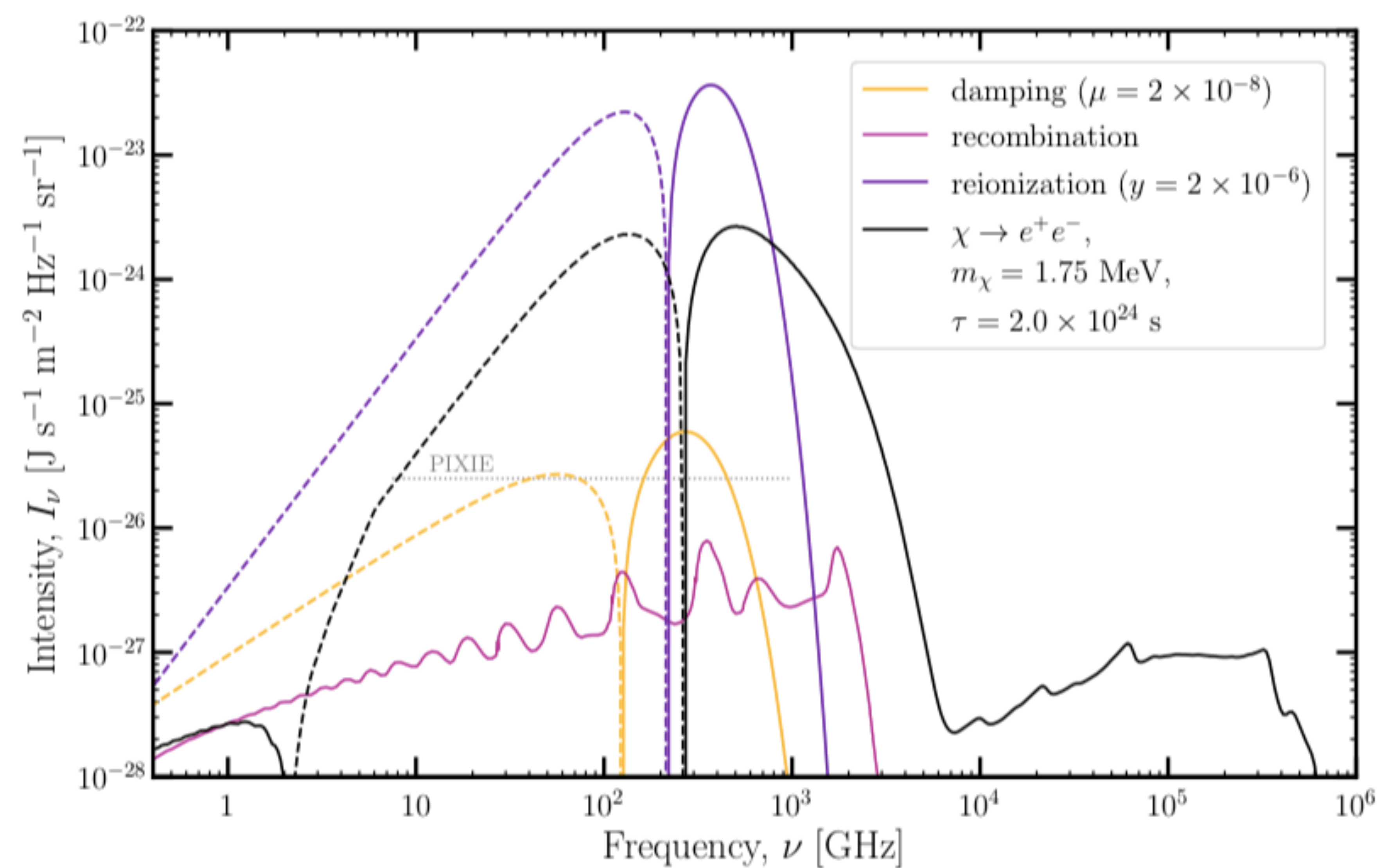


Capozzi et al '23

Spectral distortion results

- Cross-checked against previous studies that examined the spectral distortion from the high-redshift, fully ionized universe (e.g. Chluba et al '19, Acharya & Khatri '19)
- We have also confirmed we accurately reproduce the Standard Model spectral distortion from recombination
- We can now predict the full distortion including effects of arbitrary exotic energy injections



DM spectral distortions

- Sub-GeV decaying DM models that are not already excluded could have striking signals in next-generation experiments
- Distinctive high-frequency tail including structure from reionization
- Standard annihilation signals are subdominant to SM backgrounds and out of reach for next generation, although maybe still detectable in the future (distinct spectral shape)