Cosmological Probes of Dark Matter

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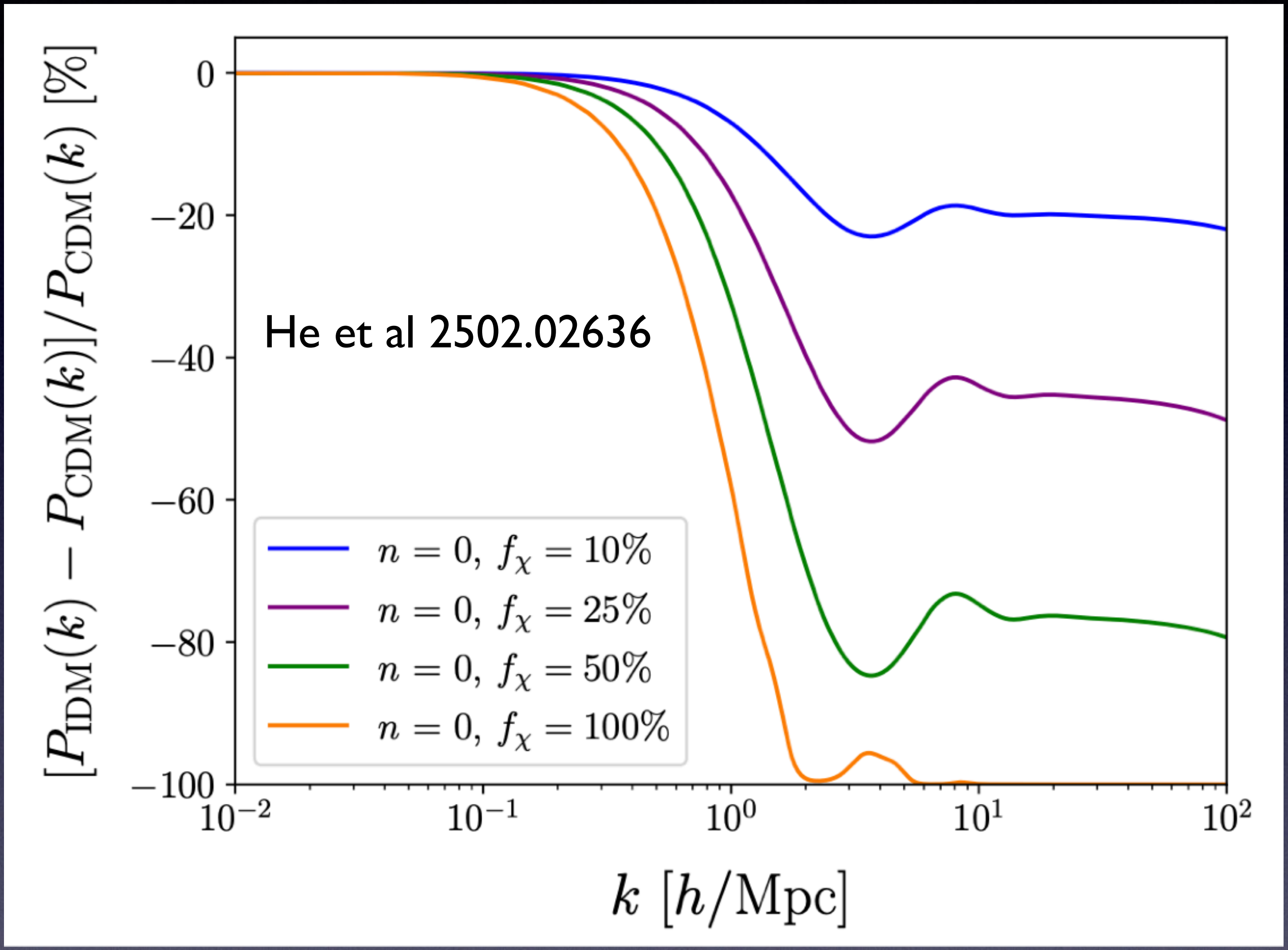
U.S. DEPARTMENT OF ENERGY | Office of Science

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)

Scales from DM physics?

- One generic modification (occurs in many model classes) is to suppress power below some characteristic scale:
  - Fuzzy DM: $\lambda_{\text{DB}} = 2\pi/mv \approx \left(10^{-3}/v\right)\left(10^{-25}\text{eV}/m\right) 0.4\text{Mpc}$
  - Warm DM: $\lambda_{\text{fs}}^{\text{eff}} \approx (m/1\text{keV})^{-1.11} 0.07\text{Mpc}$
  - DM interacting with SM: k_{cutoff} set by modes entering horizon when momentum transfer rate is ~H



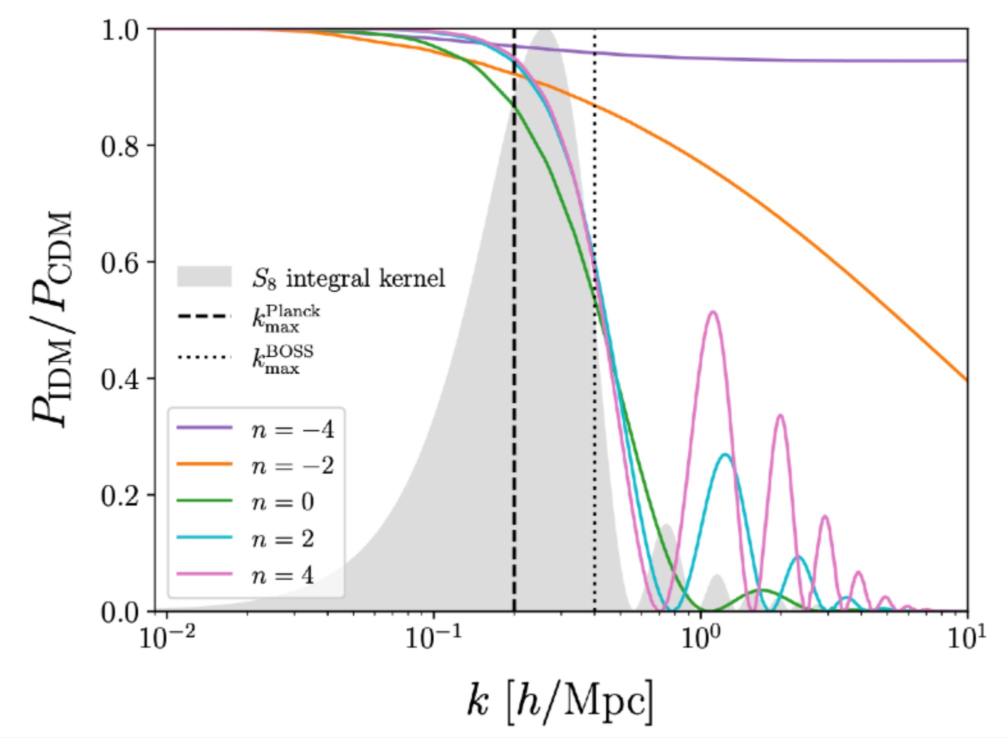
- In all these cases, suppression is most dramatic in smallest-scale structures we can observe (see e.g. Bechtol et al 2203.07354 for a review)
  - probed by stellar streams, Ly-alpha, strong lensing, MW satellites
- But if only a fraction of the DM interacts in this way (or if effects have a non-trivial scale dependence), best tests may involve precision measurements of larger scales

Tools for cosmological perturbation theory

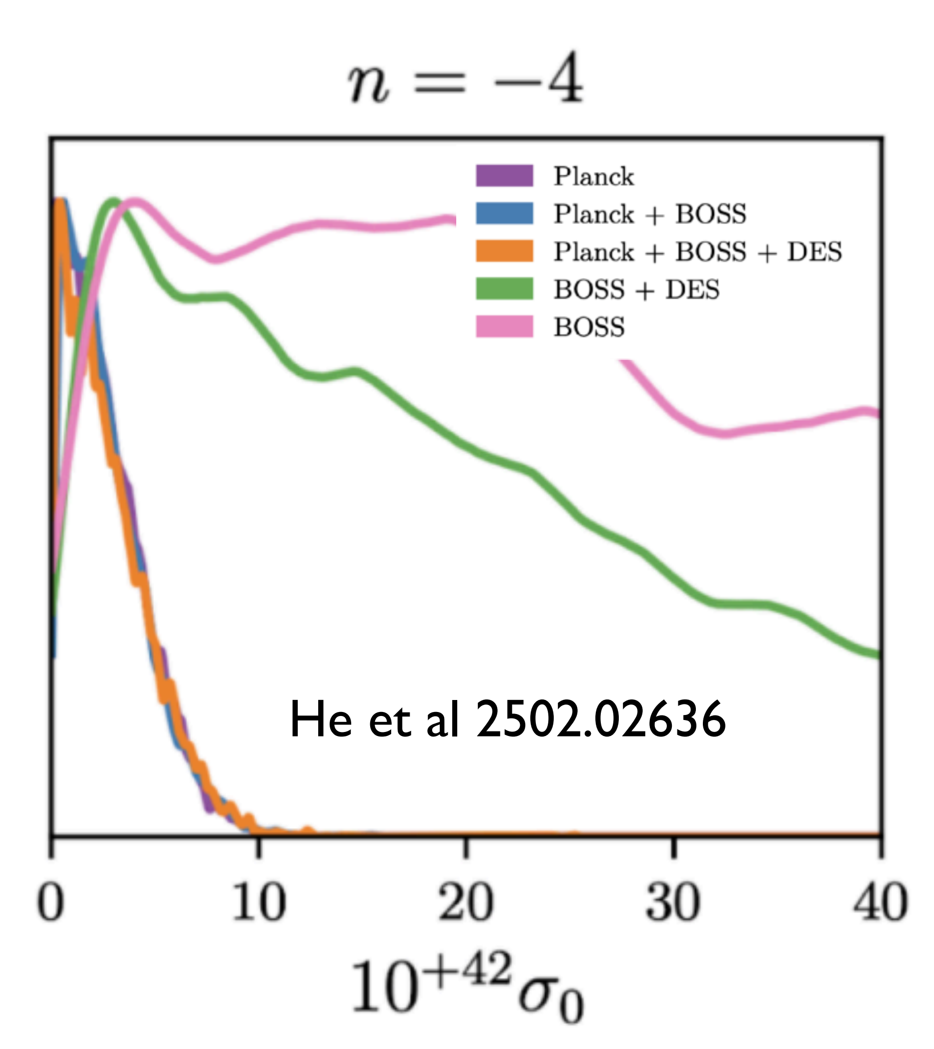
- On large scales, density fluctuations are small
- Classic approach is cosmological perturbation theory, expand fluctuations around FLRW background
- Observationally, rely on precise measurements of cosmic microwave background (CMB) and large-scale structure (LSS)
- Long-standing public Boltzmann codes: CAMB (https://camb.readthedocs.io/en/latest/), CLASS (http://class-code.net/) - solve for (global) ionization/thermal history, forecast CMB and LSS observables
- Very fast, can be coupled to Markov chain Monte Carlo codes (e.g. CosmoMC, MontePython) for scans over parameters
- Large literature on how to implement new physics (e.g. warm dark matter, DM-baryon scattering, etc) into these codes
- To go to higher order / into mildly non-linear regime, use effective field theory to develop a systematically improvable perturbative expansion: public codes include CLASS-PT (https://github.com/Michalychforever/CLASS-PT), PyBird (https://github.com/pierrexyz/pybird)

Example: DM-SM scattering

- Coupling DM to SM in the early universe 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
- CMB+LSS dominates models with steeply growing cross-section at low v; for flat or falling cross-sections, probes with sensitivity to smaller scales do better



He et al 2502.02636 (CLASS+CLASS-PT analysis)



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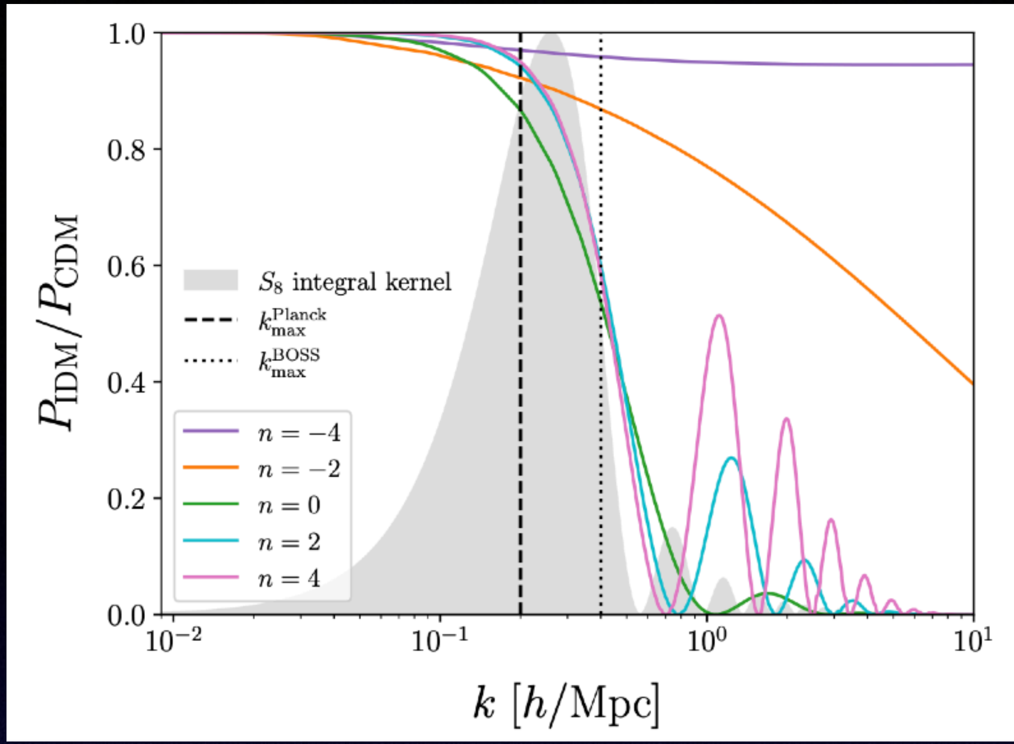

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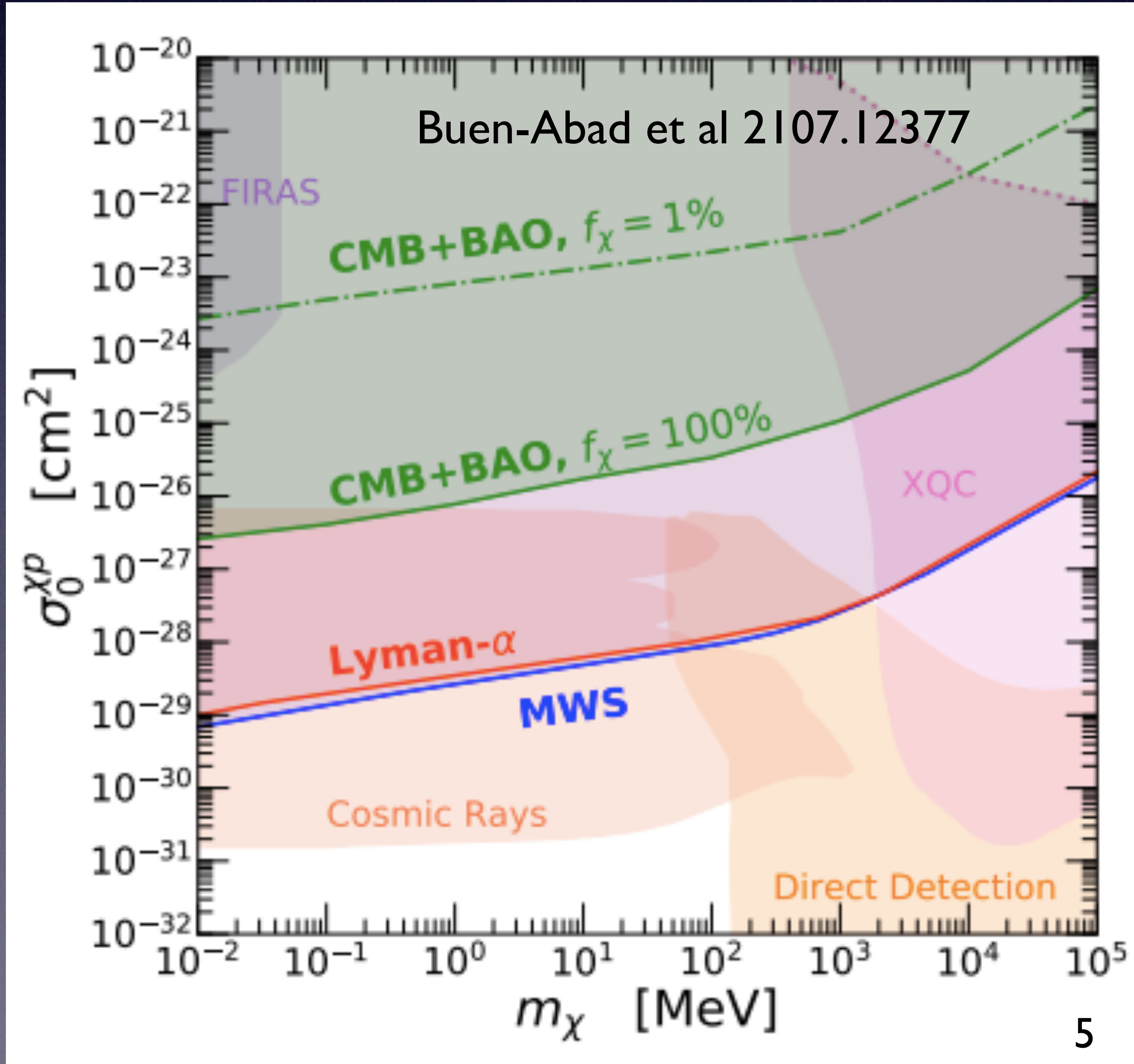

Testing DM-SM interactions

- 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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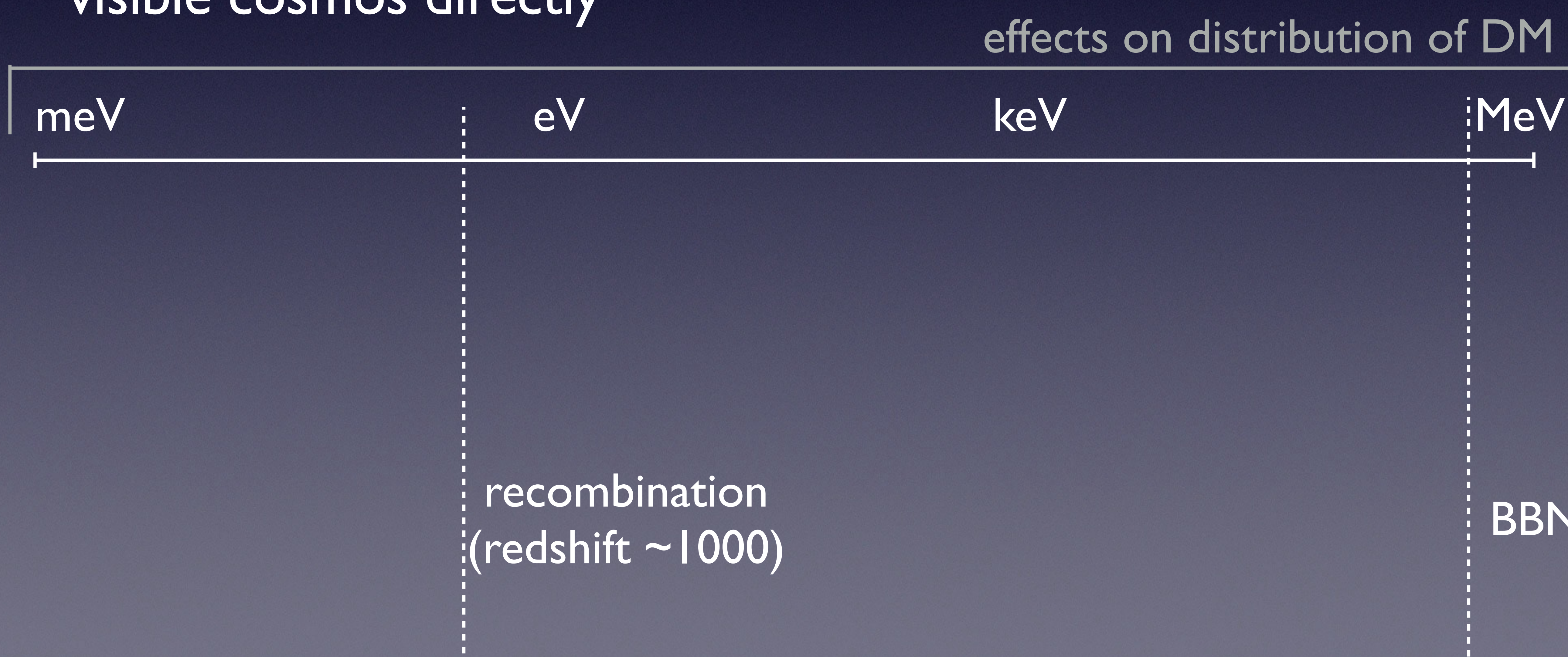

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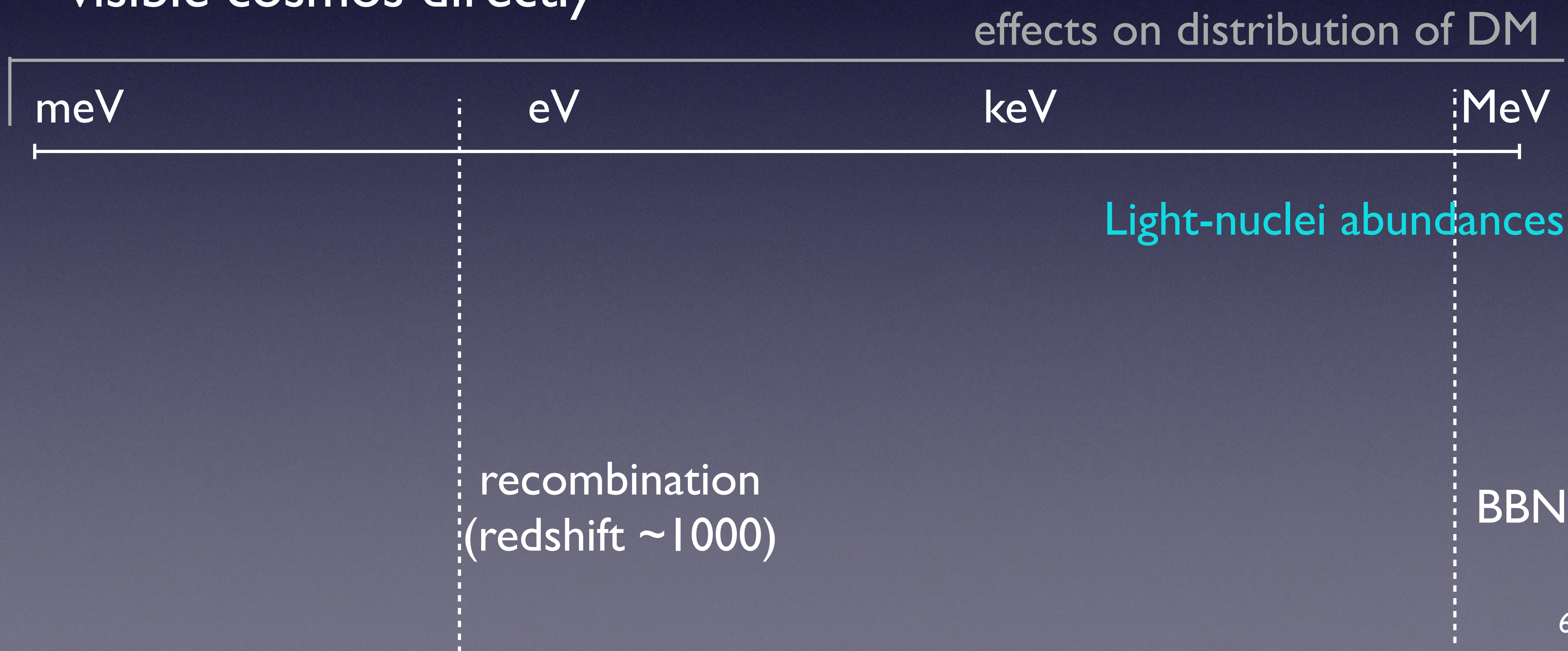

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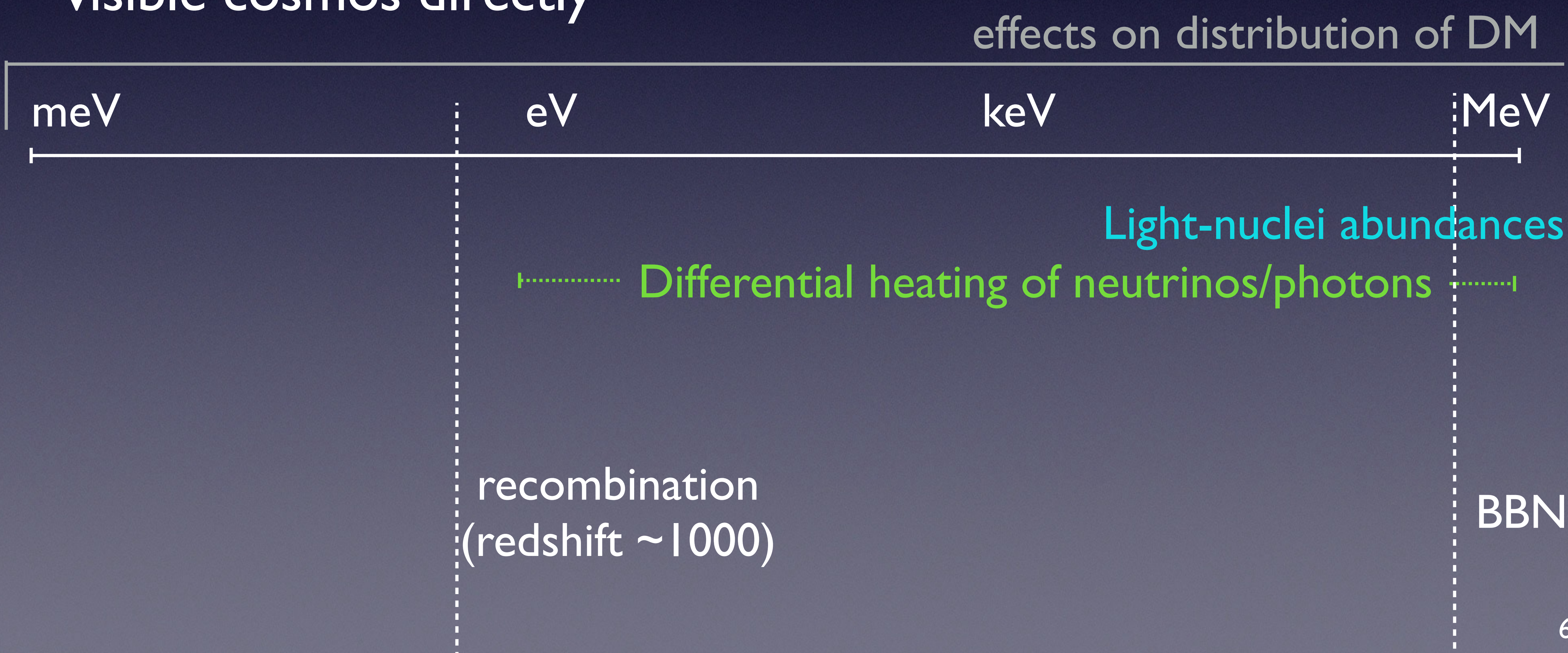

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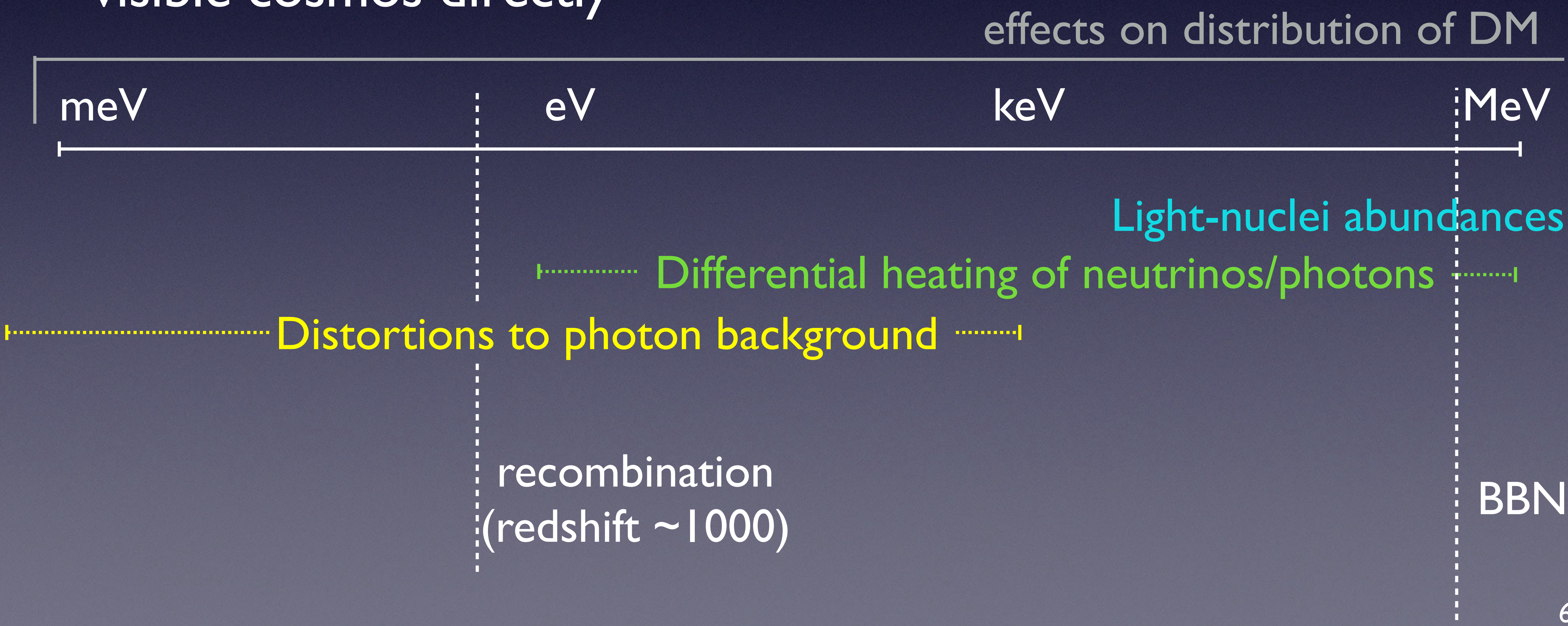

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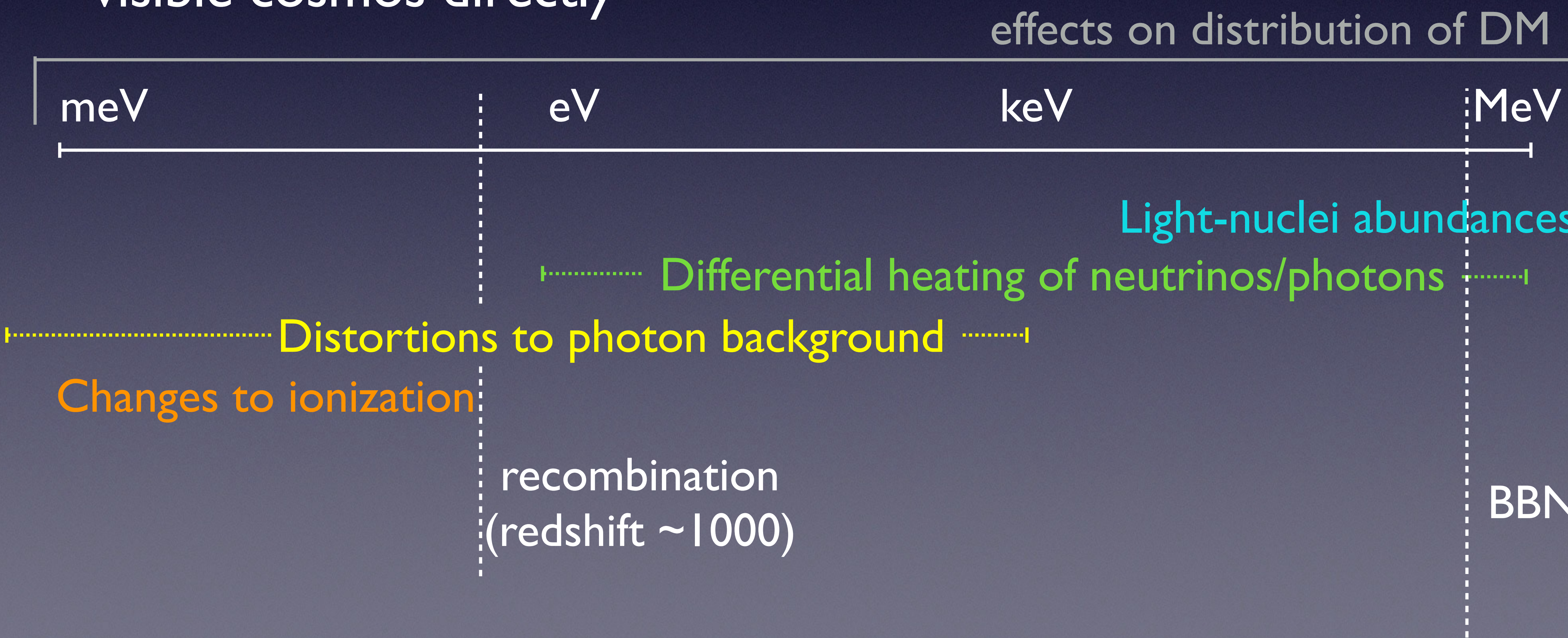

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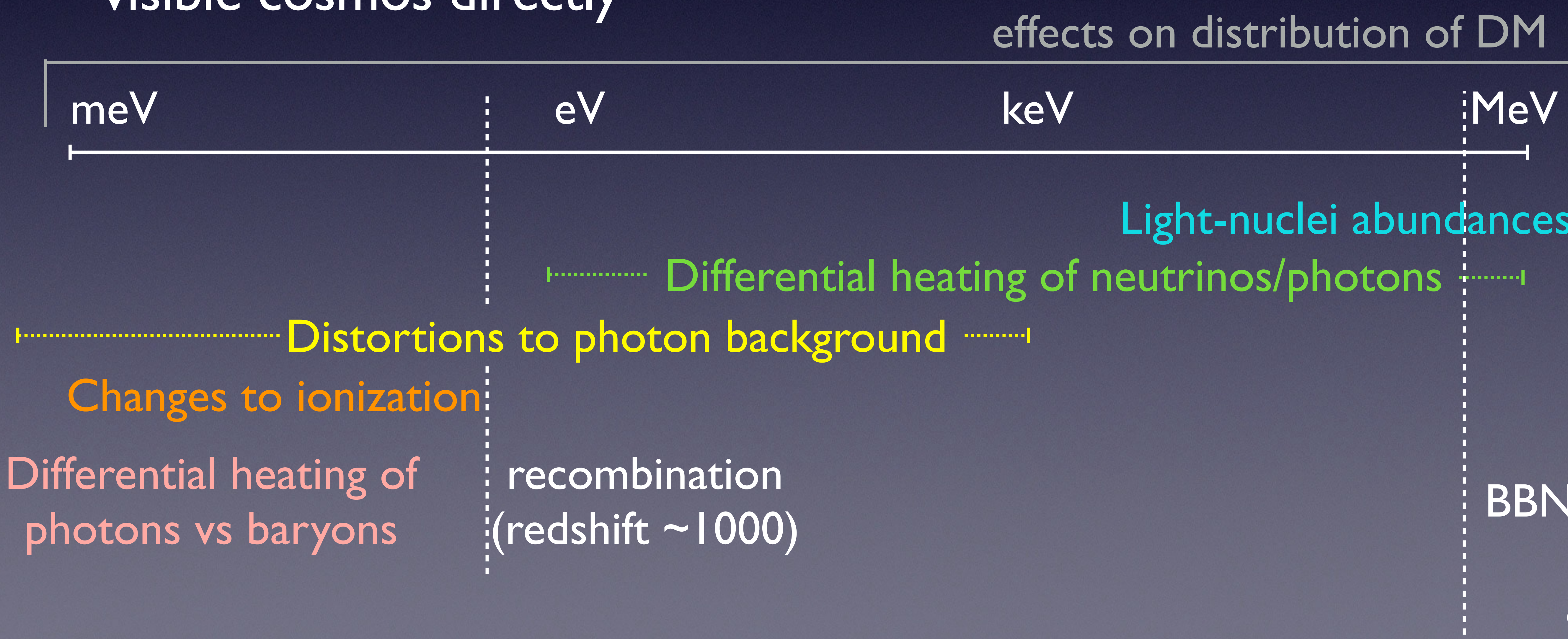

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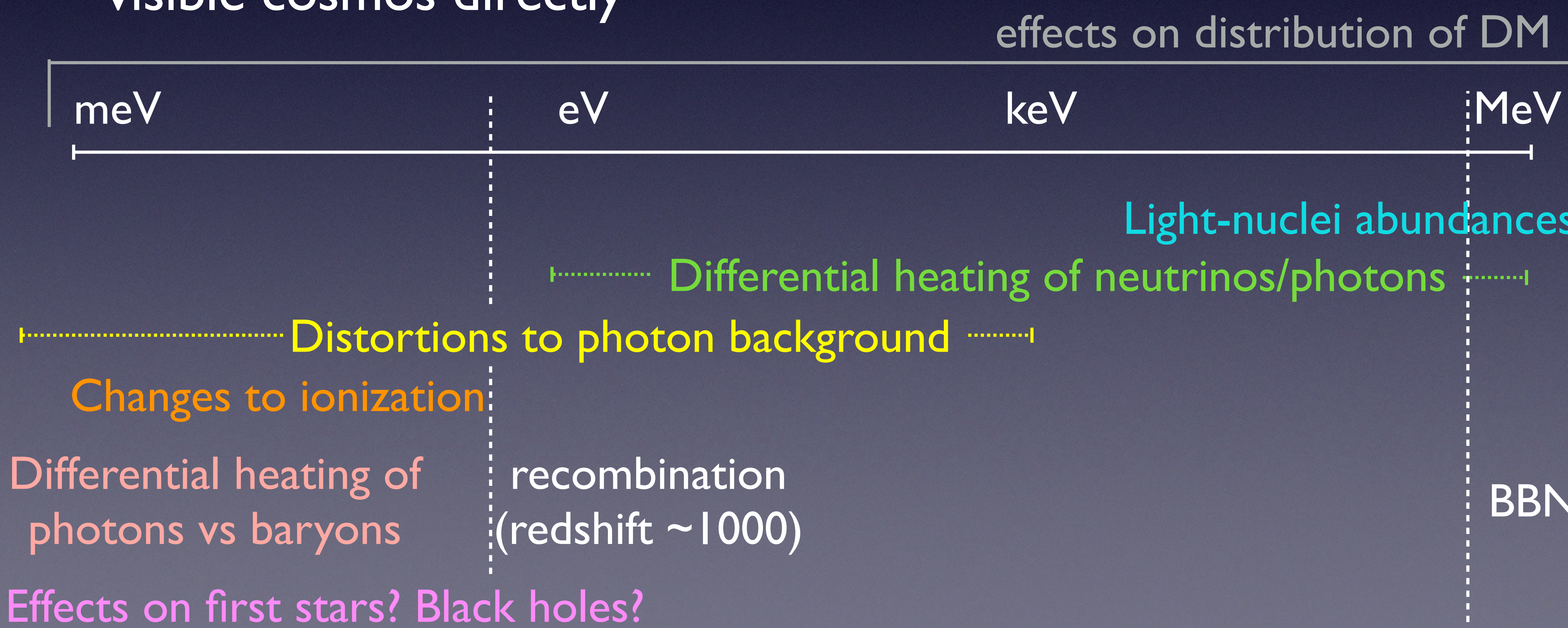


Big Bang nucleosynthesis

- Big Bang nucleosynthesis is currently the earliest point in the universe's history for which we have detailed observational tests
- Powerful in particular for testing light/ultralight dark matter
    - energy density can modify the expansion rate during BBN
    - annihilation/decay from dark sector into SM particles can modify the relative temperature of photons and neutrinos
- Several new public codes in recent years: e.g. LINX (Giovanetti et al 2408.14538), PRyMordial (Burns et al 2307.07061), PRIMAT (Pitrou et al 1801.08023)
- For example, can largely exclude thermal dark matter (i.e. reaches full thermal equilibrium with the Standard Model) below a few MeV in mass [e.g. Giovanetti et al 2109.03246]

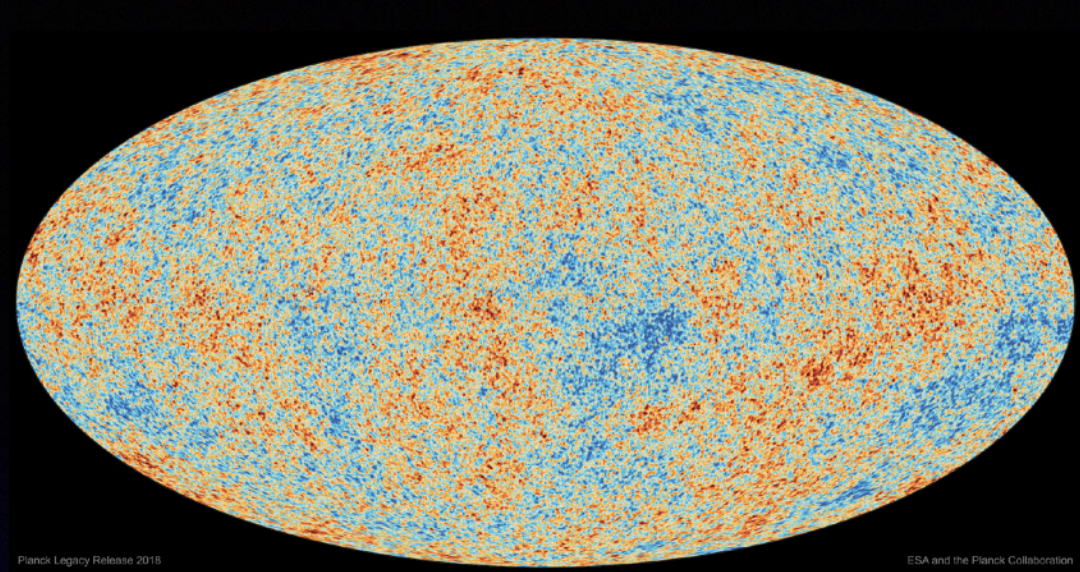
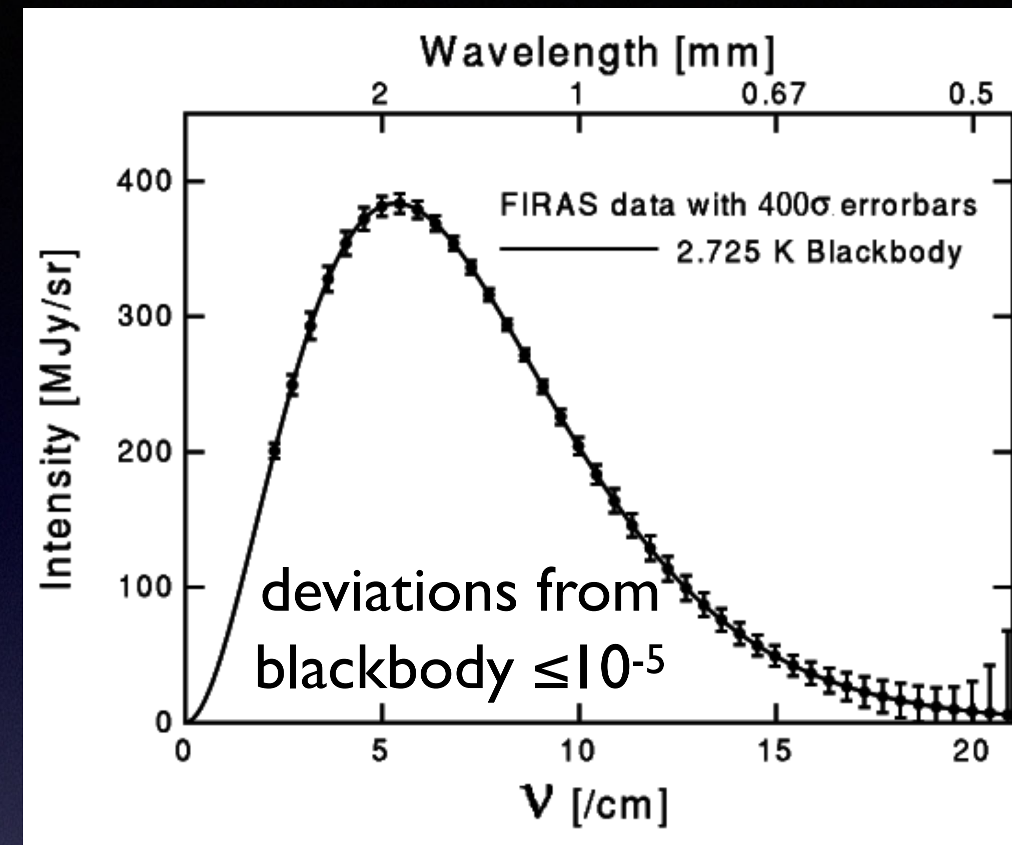


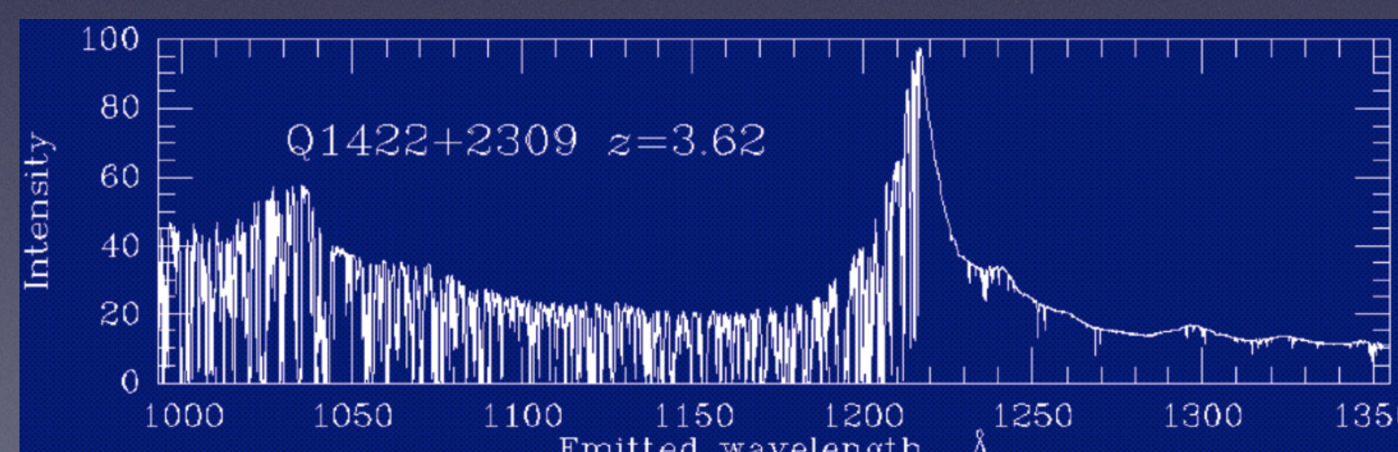
Image credit: European Space Agency / Planck Collaboration

spatial information: describes pattern of oscillations in density and temperature in the primordial plasma, + post-recombination corrections from scattering

spectral information: near-perfect blackbody, but distortions hold information on primordial plasma + injected photons



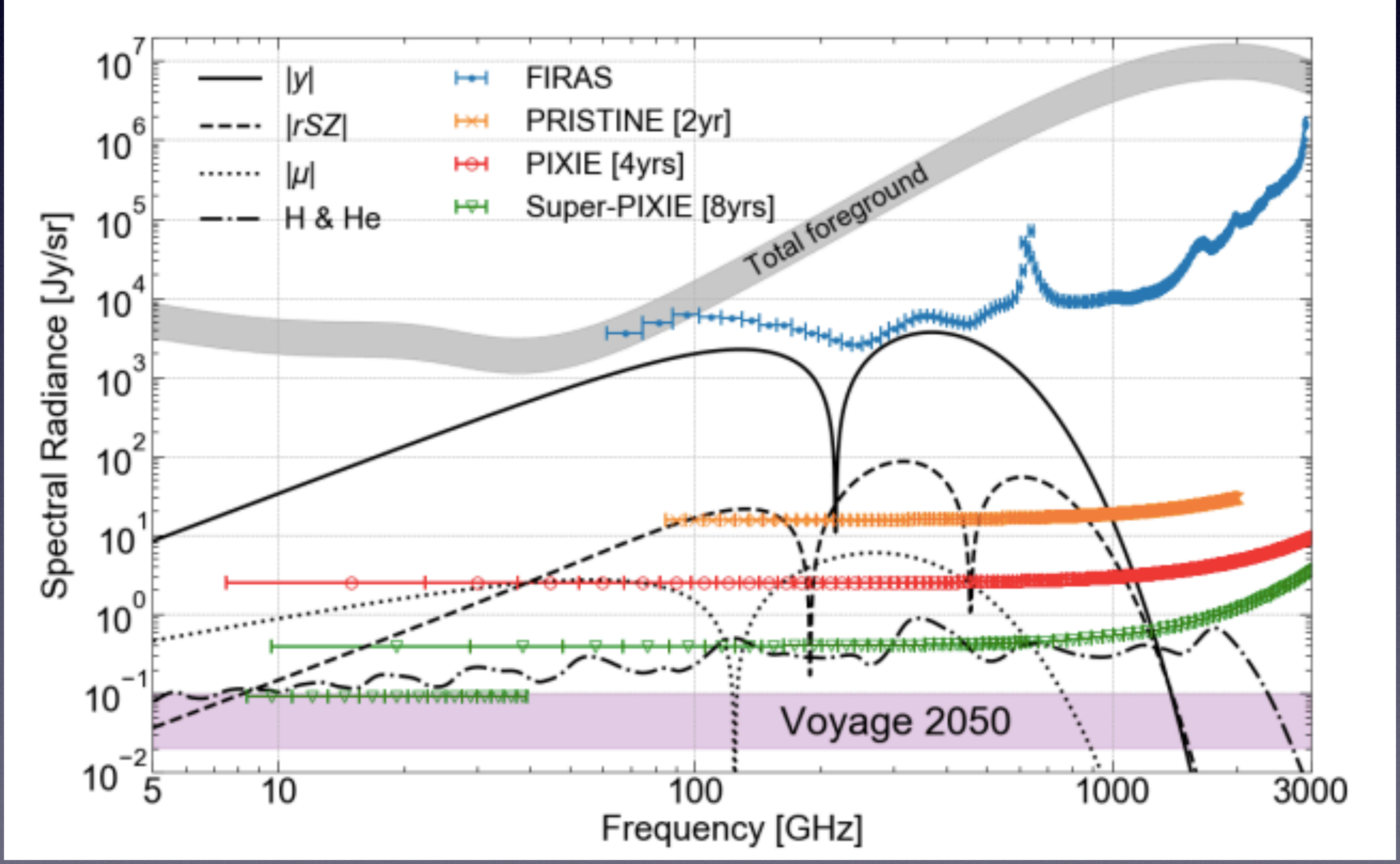
atomic transition lines: probe gas temperature, ionization level, 3D distribution. Currently we have constraints from the Lyman-alpha forest, z~2-6



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

Photon background distortions

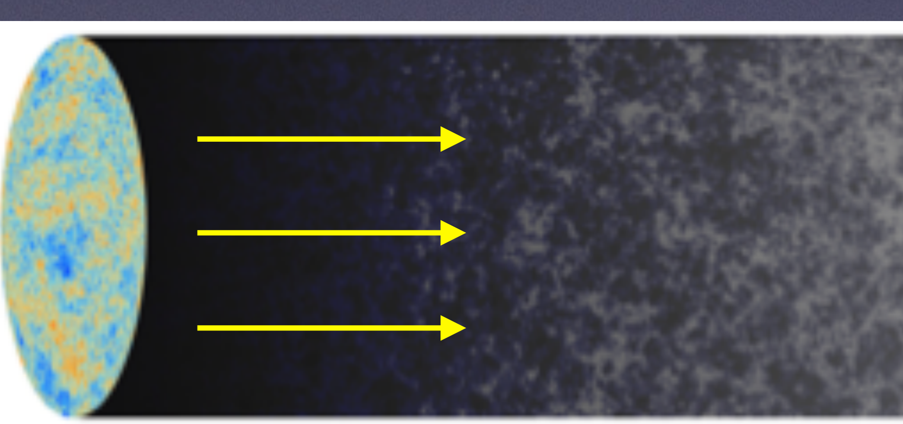
- Energy injections from $z \lesssim 10^6$ ($T \lesssim$ keV) generically leave imprints in the CMB blackbody spectrum
- We last measured the CMB blackbody with COBE/FIRAS in 1990
- Advances in detector technology and cryogenics have opened up the possibility of improving limits by 4+ orders of magnitude [e.g. Chluba et al 1909.01593]

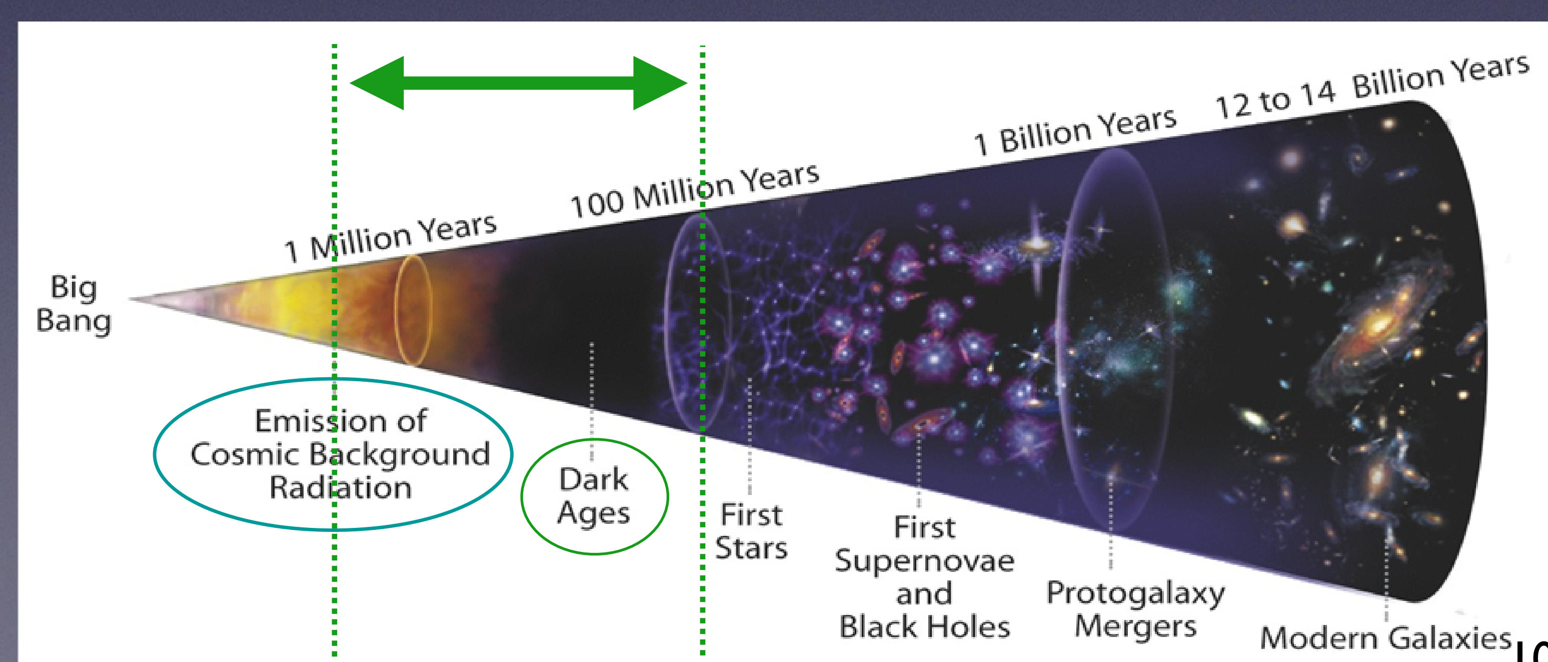


Chluba et al '19
Voyage 2050 white paper

Photon anisotropy distortions

- The CMB anisotropies have been beautifully measured by a range of experiments (WMAP, Planck, ACT, SPT, etc)
- Often used as a probe of (very) large-scale structure
- "Cosmic dark ages" span redshift z ~ 30-1000, ionization level expected to be very low (as low as few x 10^{-4}).
- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured (at the level of 10^{-3}-10^{-4} ionization fraction).
  - This channel is a primary source of current robust constraints





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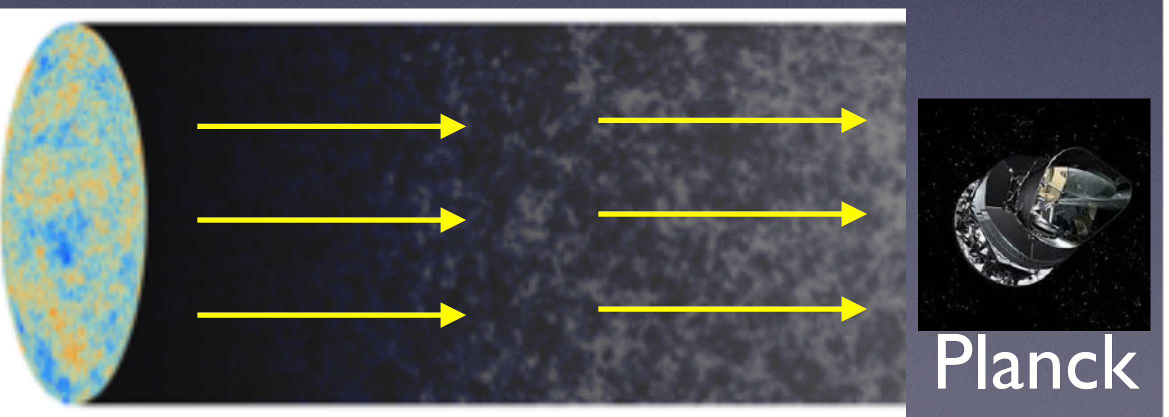

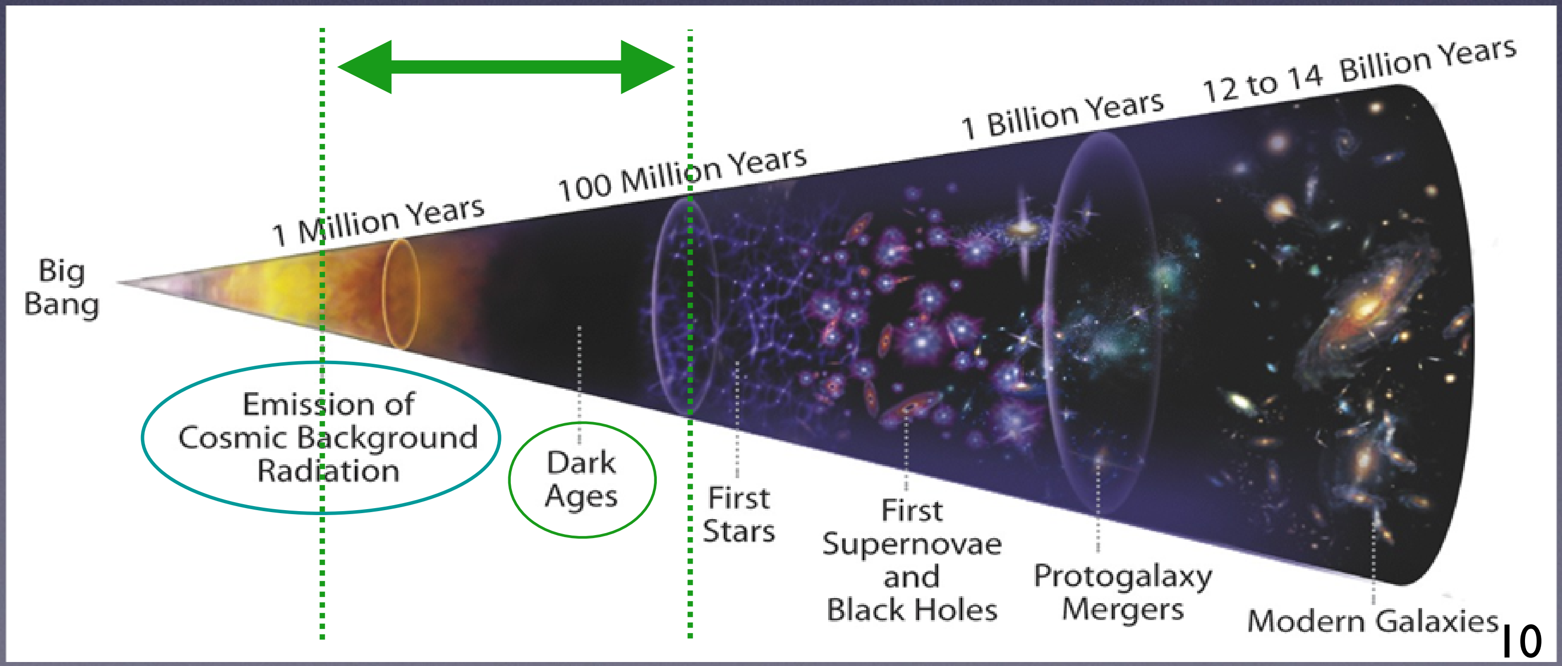

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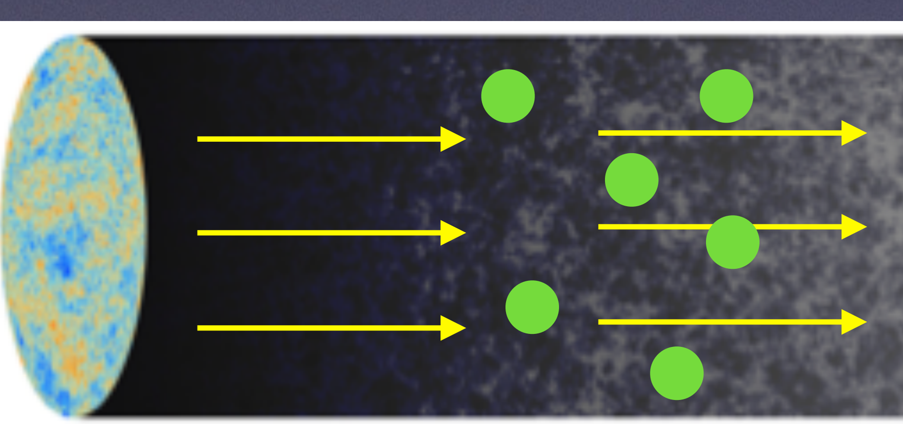
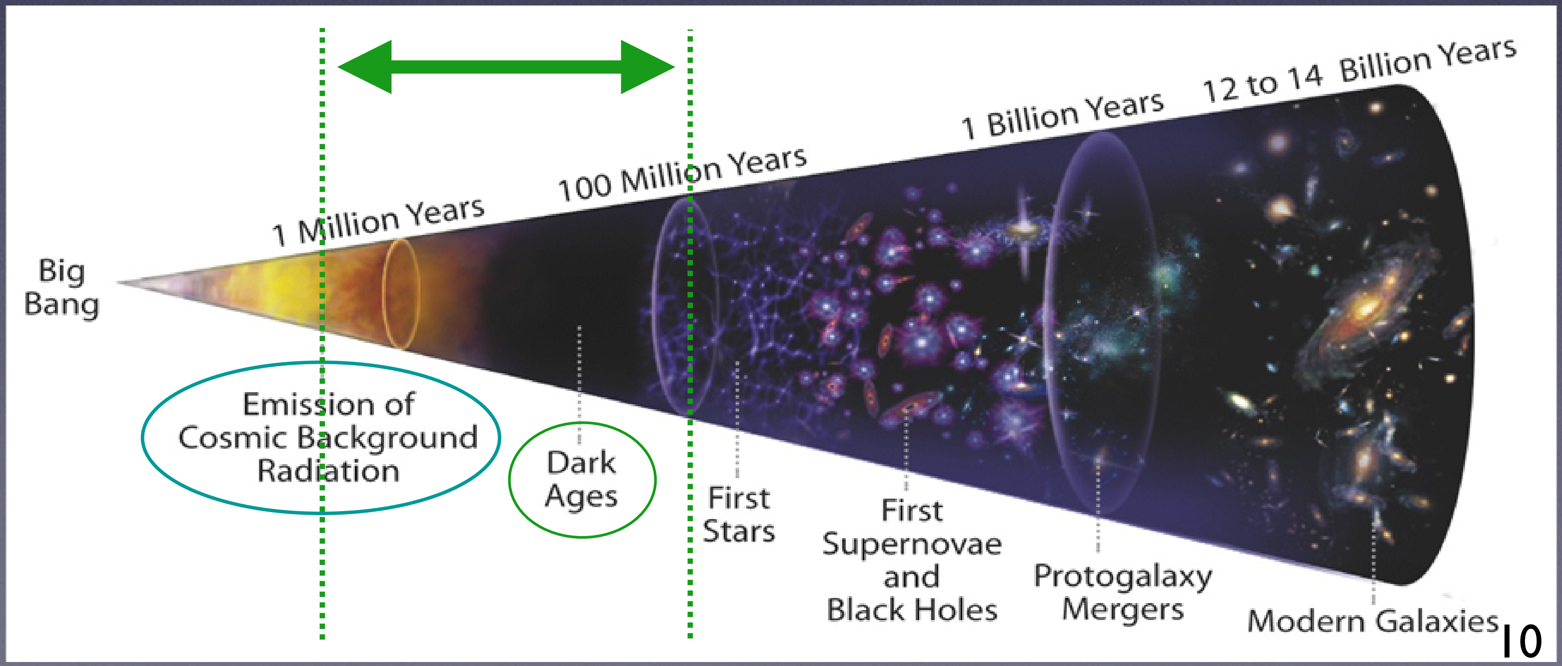


Planck



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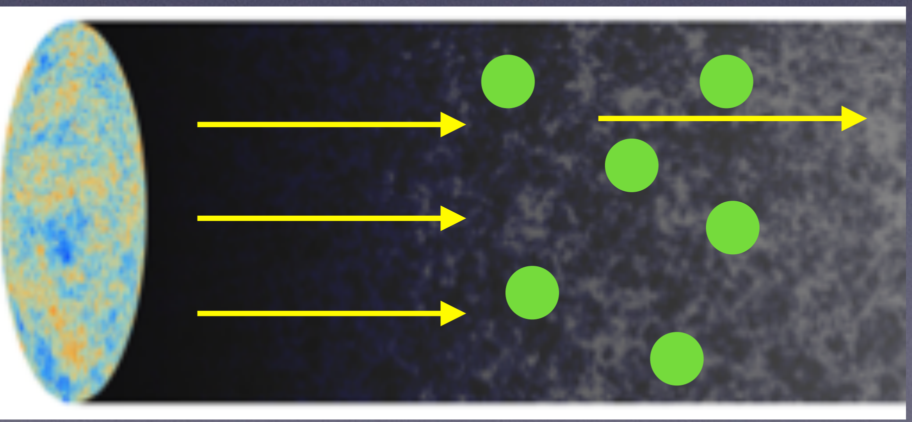

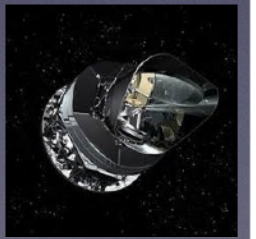

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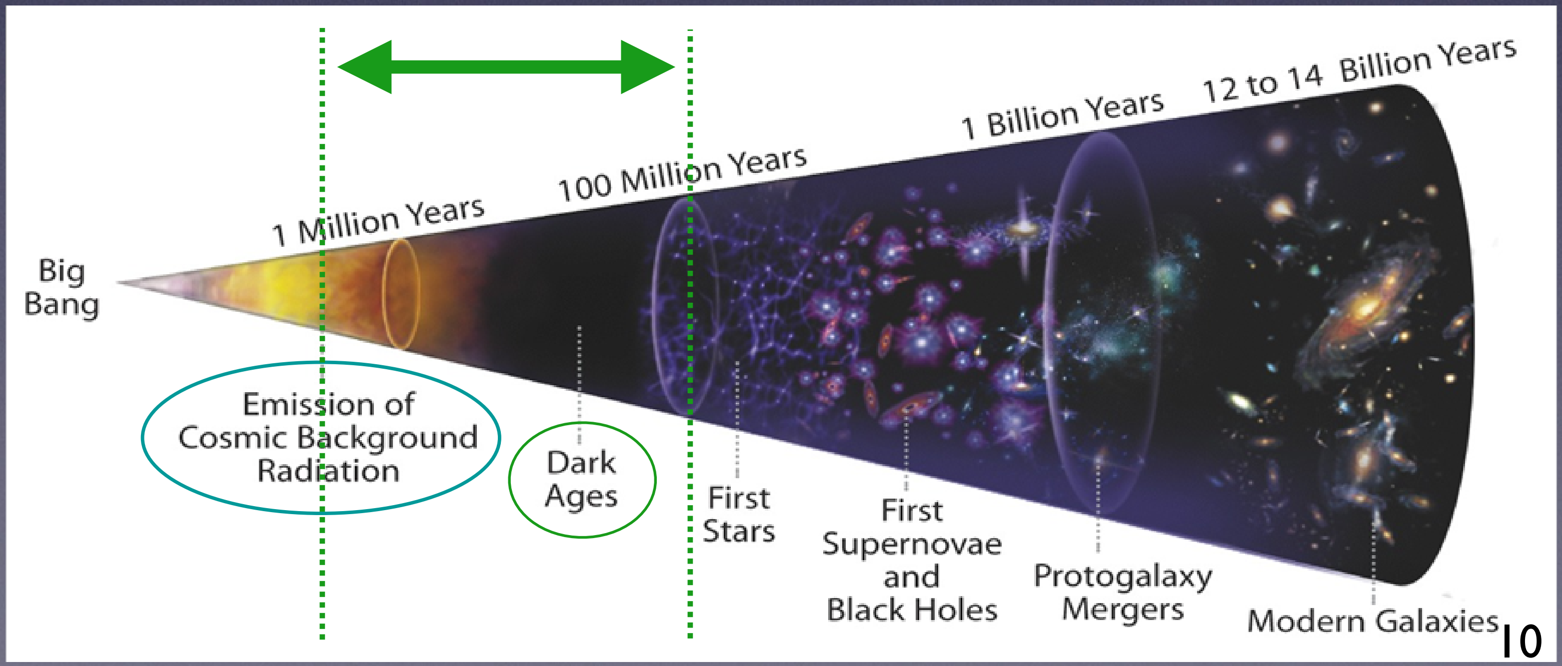
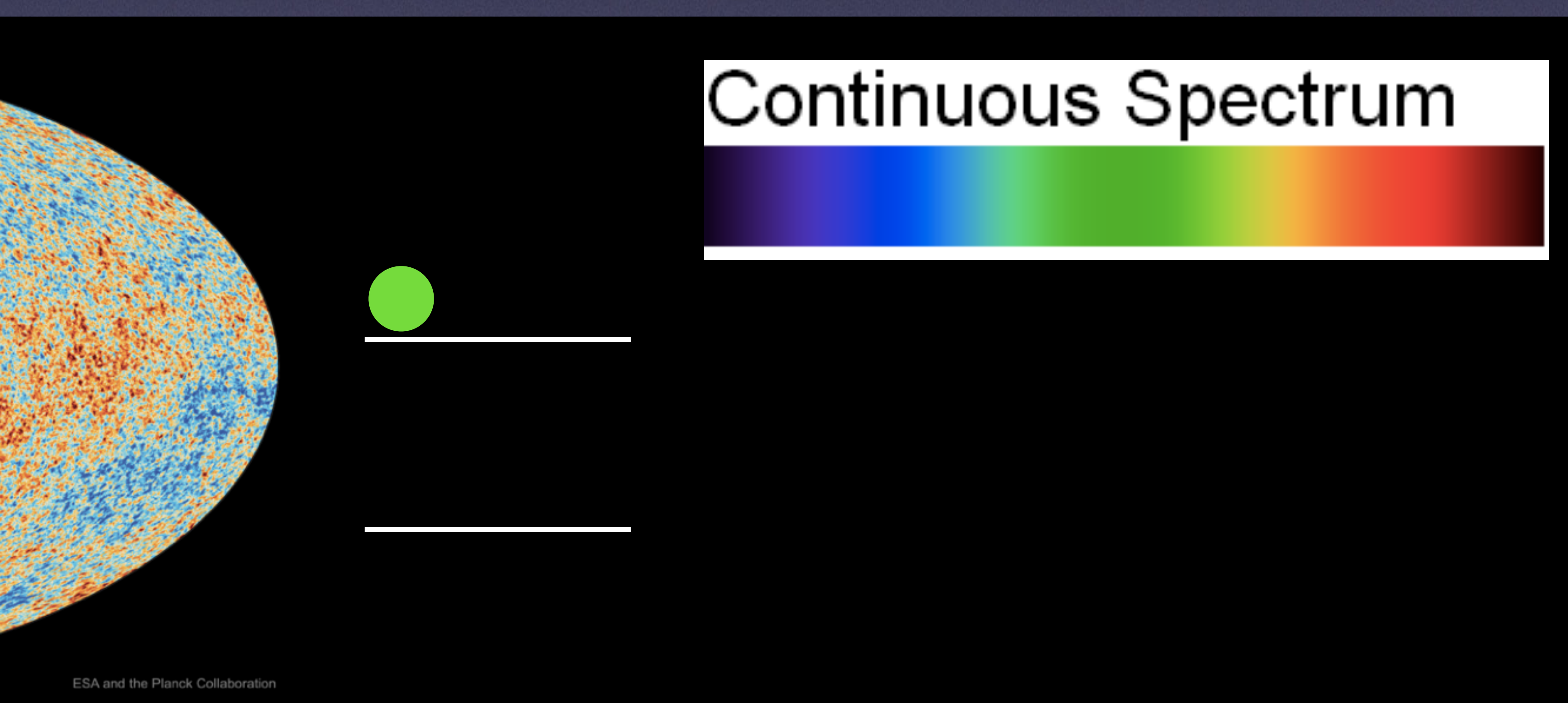


21cm and the cosmic thermal history

- To measure the gas temperature at late times, we can search for atomic transition lines, in particular the 21cm spin-flip transition of neutral hydrogen.
- "Spin temperature" T_S characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states - T_S gives the temperature at which the equilibrium abundances would match the observed ratio.
- If T_S exceeds the ambient radiation temperature T_R, there is net emission; otherwise, net absorption.



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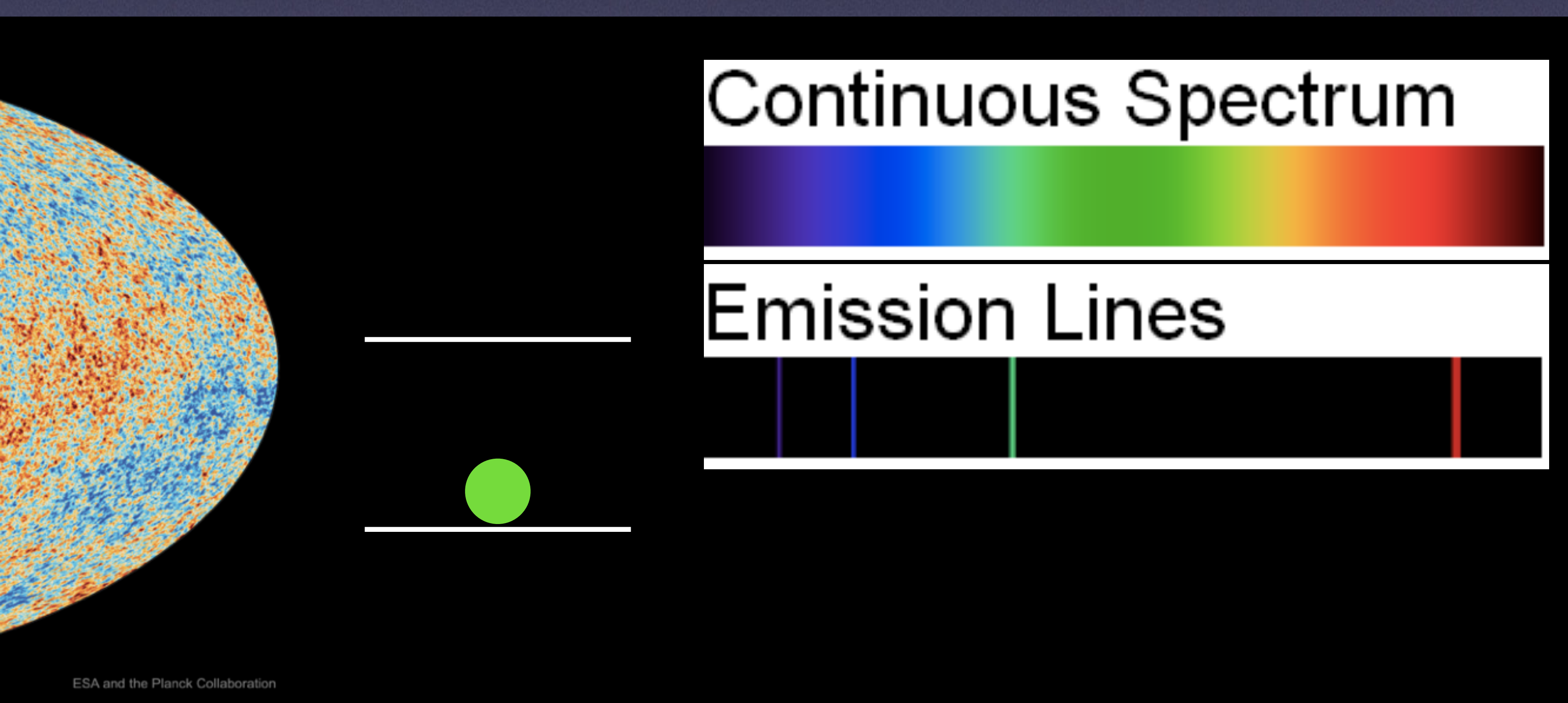

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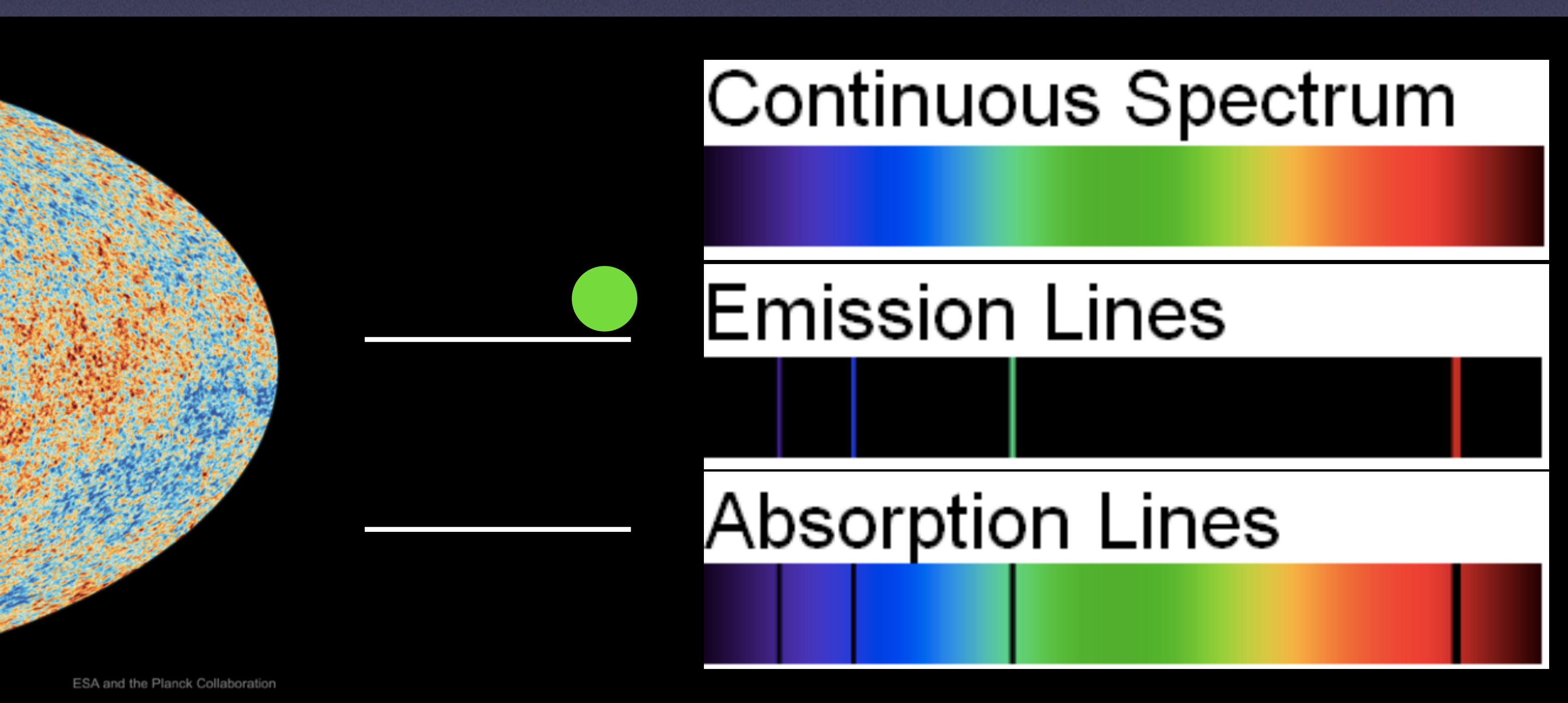

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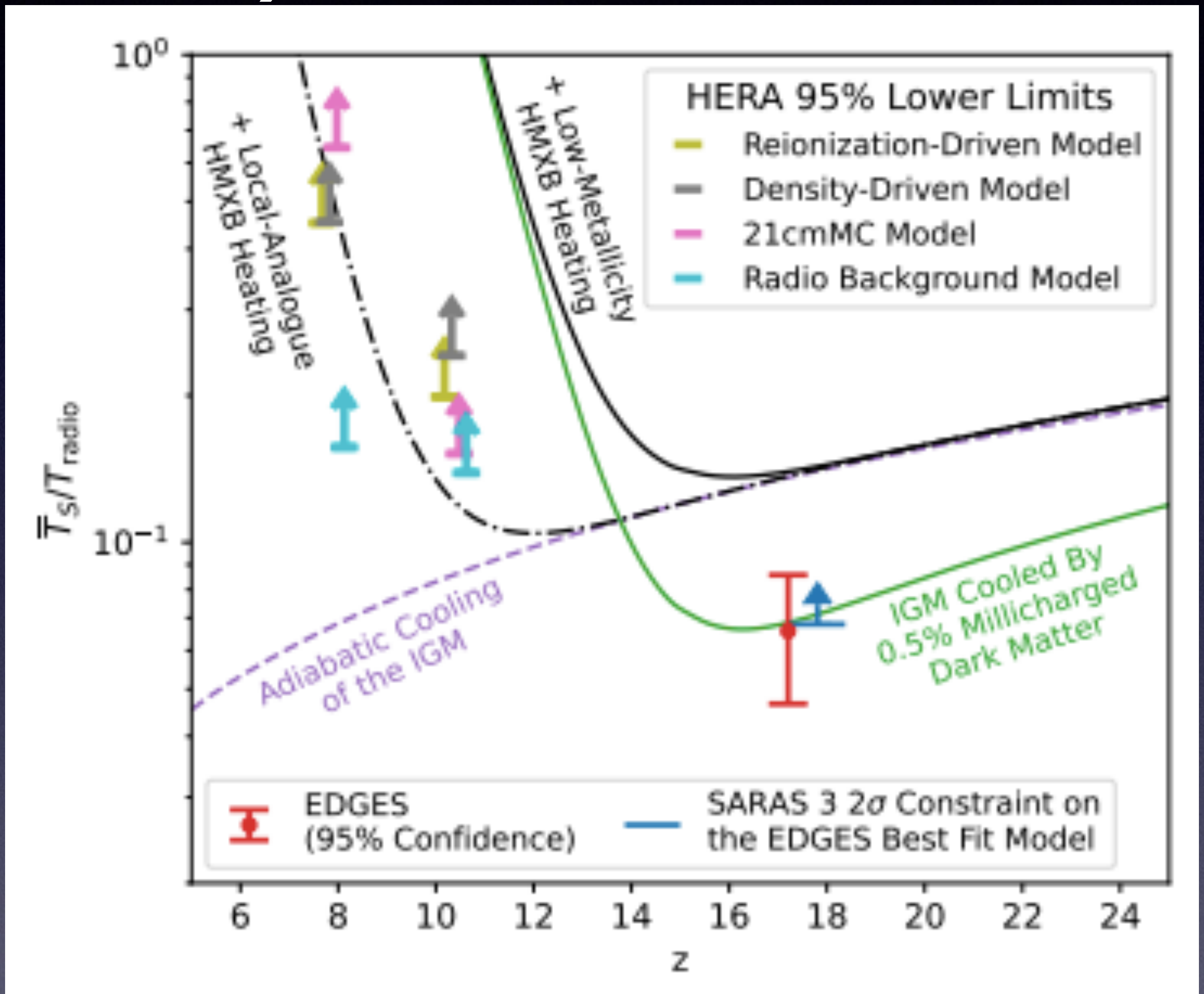
The search for (cosmological) 21cm

- Measurements of the 21cm power spectrum can constrain temperature, ionization history, matter distribution
- Forecasts typically use public codes 21cmFAST (Mesinger et al 1003.3878), Zeus21 (Munoz 2302.08506).
- There are a number of current (e.g. HERA, EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Claimed global signal detection by EDGES [Bowman et al 1810.05912]; in mild tension with SARAS 3 non-detection [Singh et al 2112.06778]



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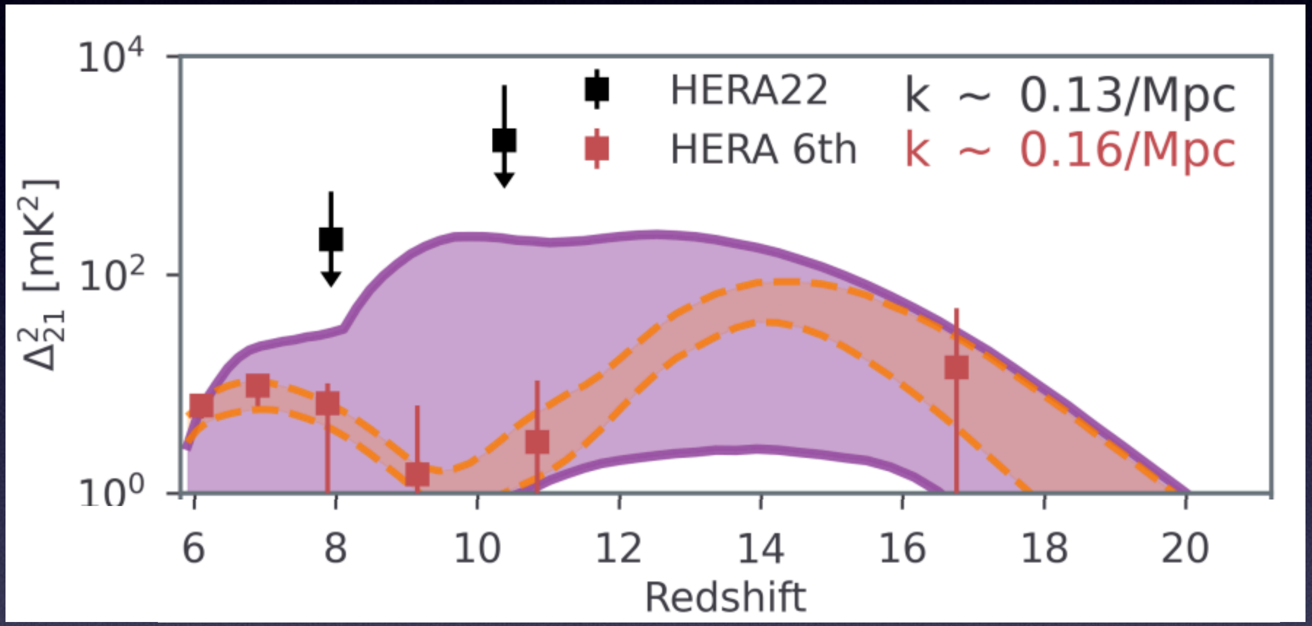

Forecast sensitivity for HERA season 6, data taken 2022-2023, ~150 nights (1300 hours) x 150 antennas, 50-230 MHz [Breitman et al 2309.05697]

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Distribution effects vs energy transfer

- 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, as measured e.g. by galaxy clustering
- 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

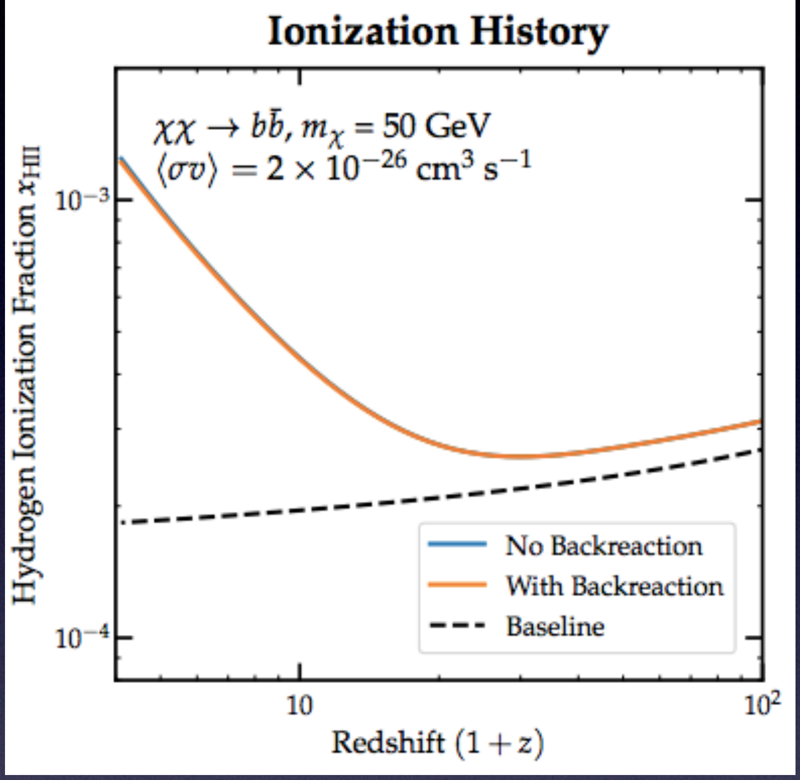
What are the (detailed) effects of energy injection?

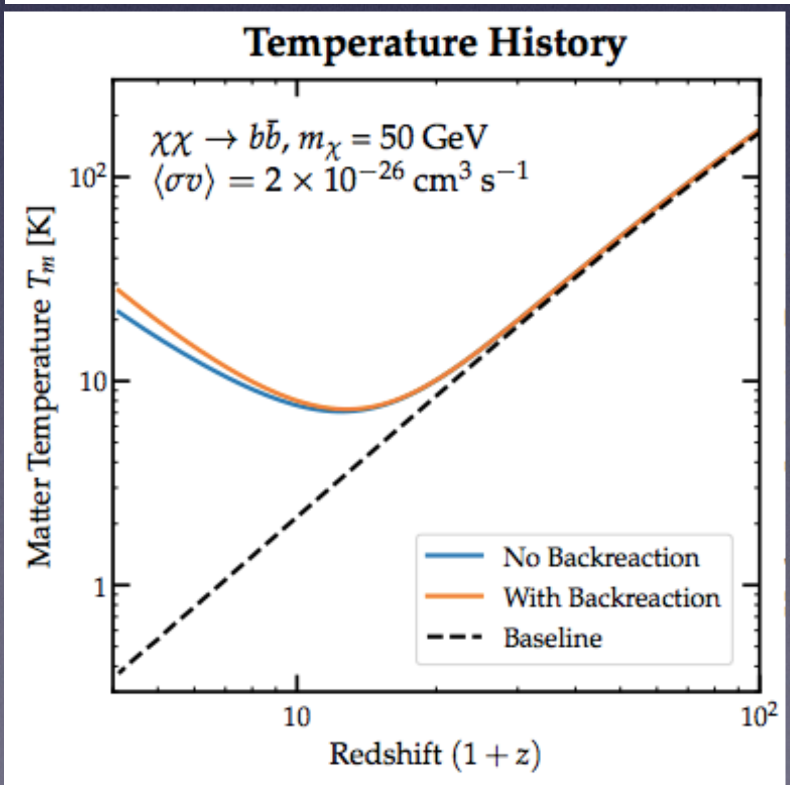
- If energy transfer is in the form of highly energetic SM particles (much more energetic than thermal bath):
  - generically have cascade of interactions producing (many) non-thermal secondary particles
  - produce extra ionization (if injection energy > ionization threshold) + heating + distortions to photon background
  - model with DarkHistory public code (https://github.com/hongwanliu/DarkHistory)
    - Thermal/ionization history: Liu et al 1904.09296, Sun & TRS 2207.06425
    - Spectral distortion: Liu et al arXiv:2303.07366, 2303.07370
- 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]

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()
)
```

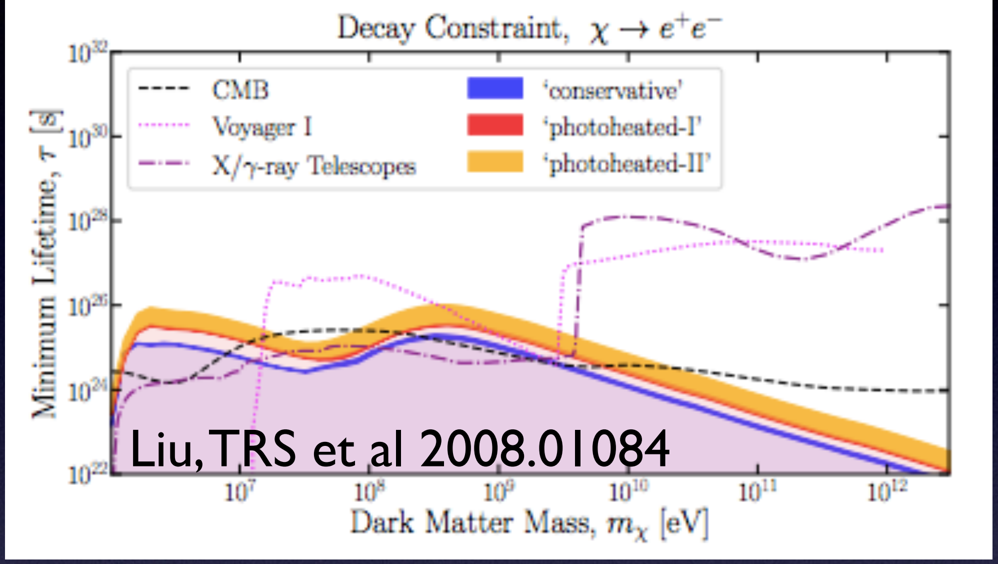
- DarkHistory is provided with extensive example notebooks.
- It contains built-in functions for:
  - redshift dependence corresponding to DM decay or s-wave annihilation
  - injection spectra of electrons/positrons/photons corresponding to all SM final states
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks.
- DarkHistory can include "backreaction" effects, where changes to the ionization level from earlier energy injection modify the particle production cascade - can be important for heating.





Changes to the ionization/ thermal history

- Modified temperature history can be compared directly to temperature limits from Lyman-alpha forest (T~10^4 K), or global 21cm measurements
- Heating/ionization/excess photons can also modify formation of stars / black holes [e.g. Qin, TRS et al 2308.12992]
- Baseline DARKHISTORY is slow - not compatible with MCMC



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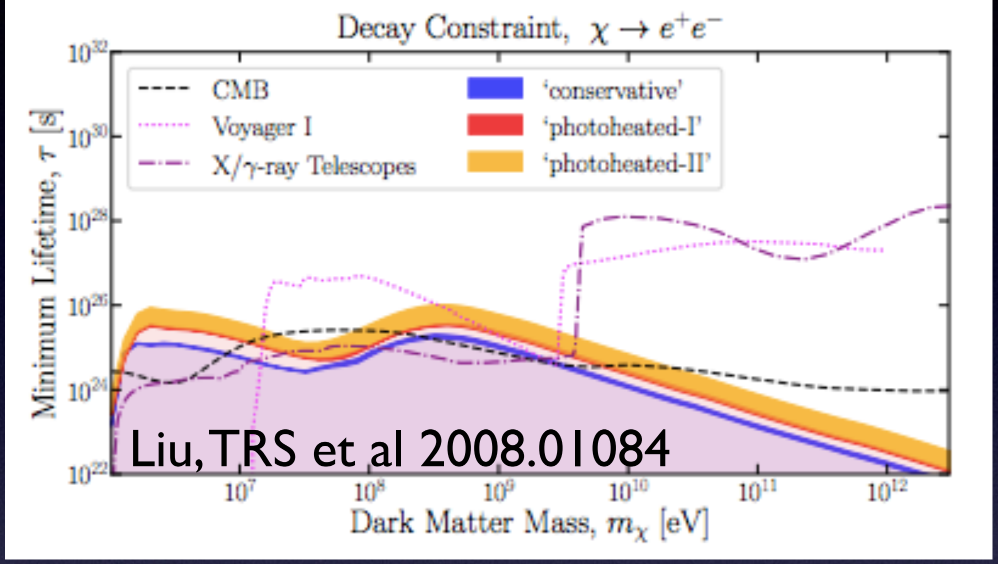

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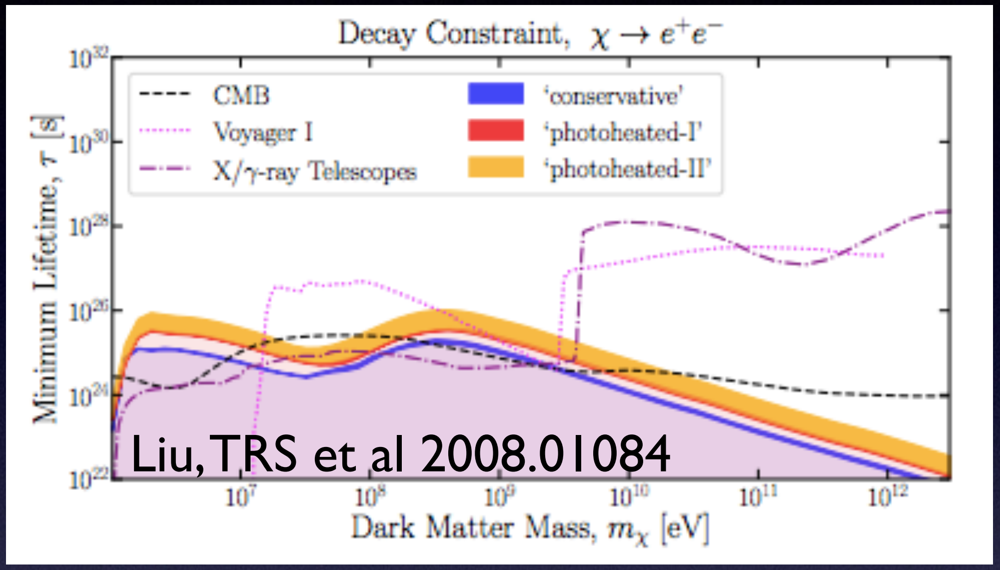

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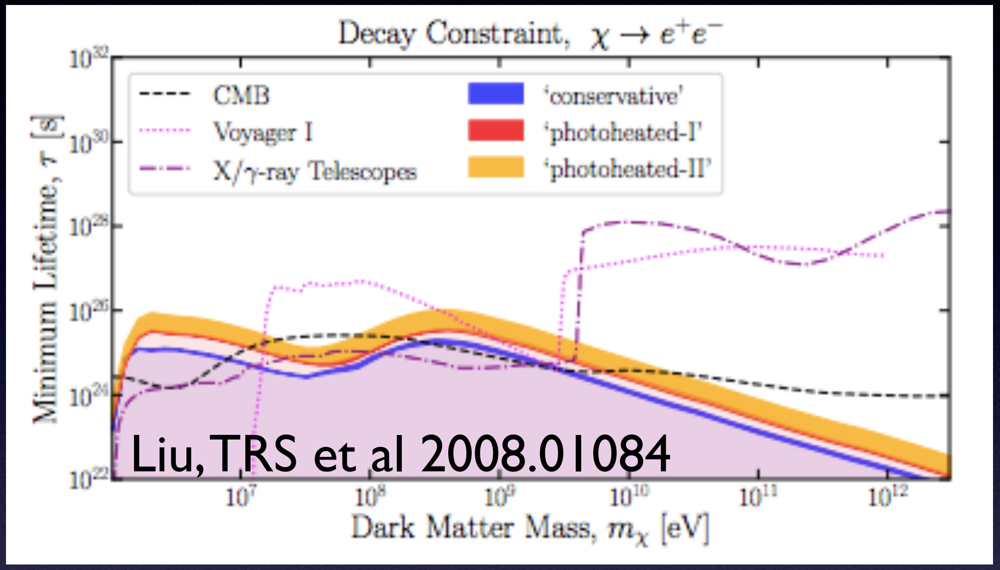

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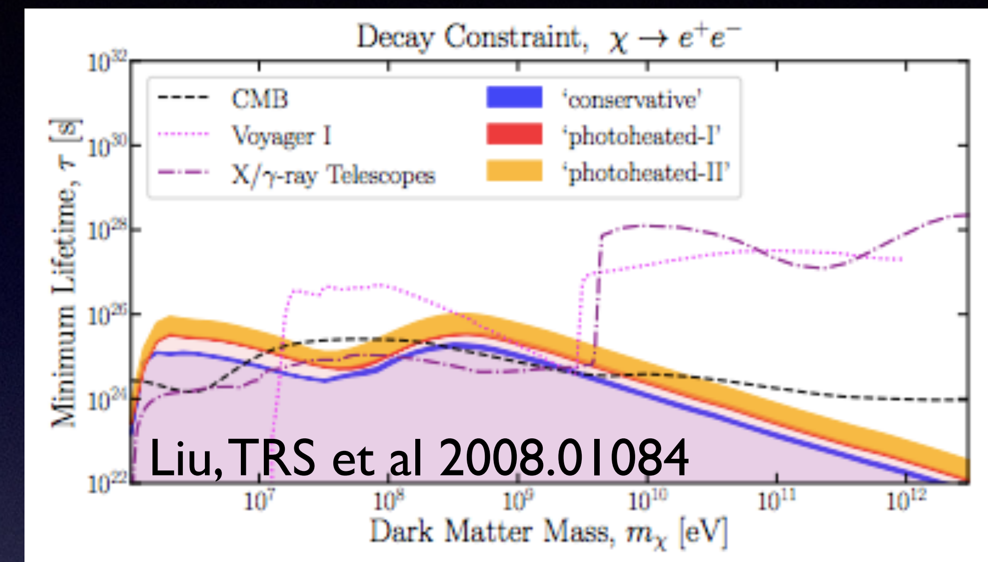

Liu, TRS et al 2008.01084

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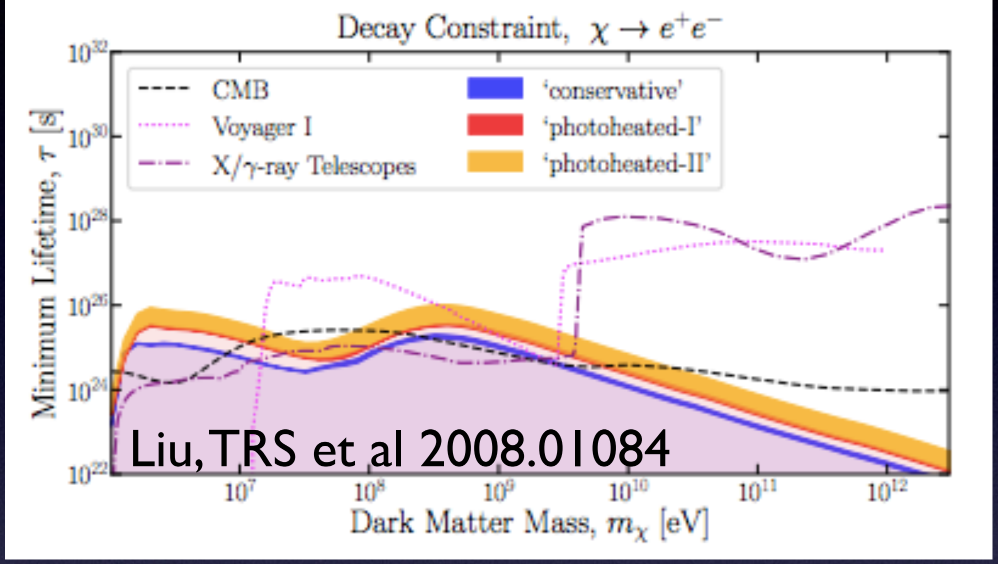

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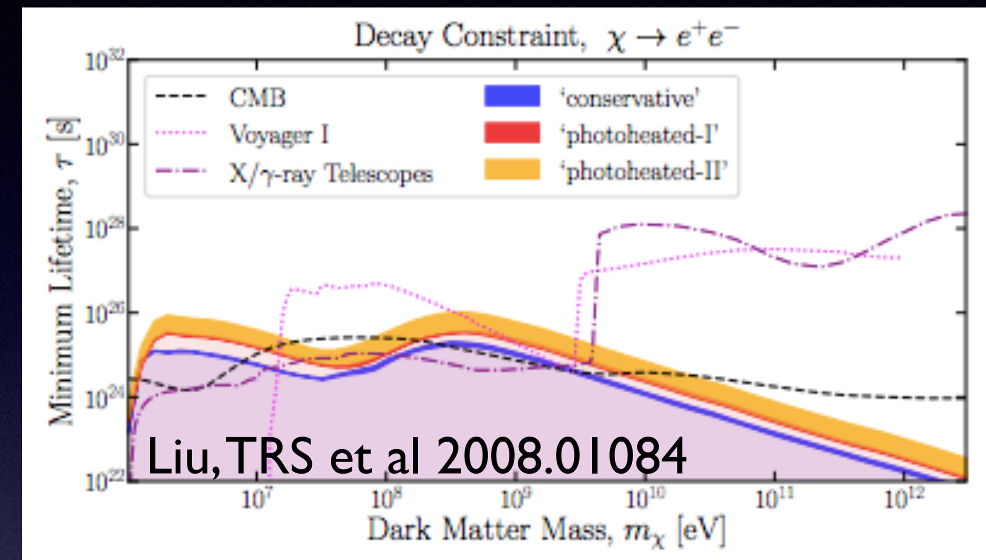

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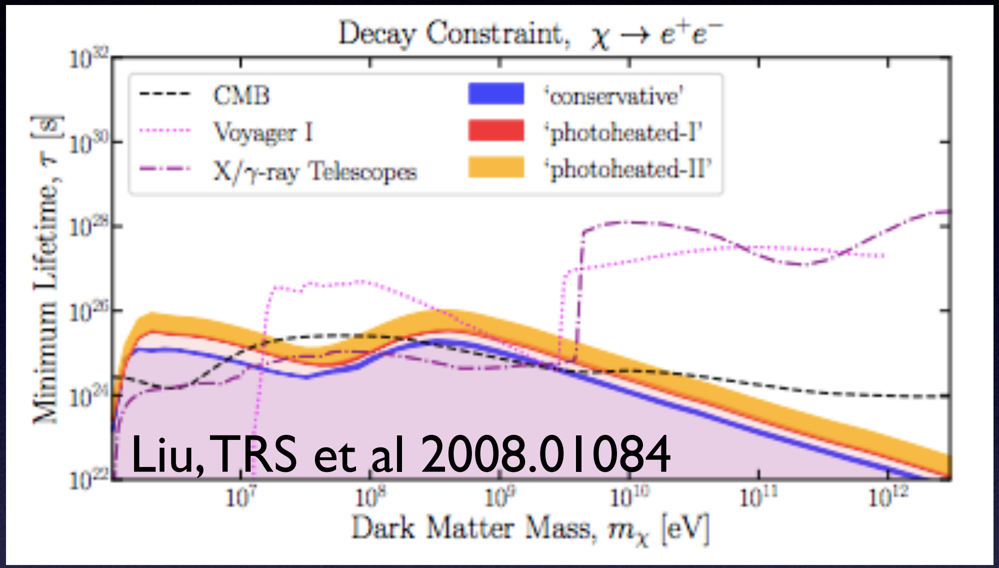

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SLOW

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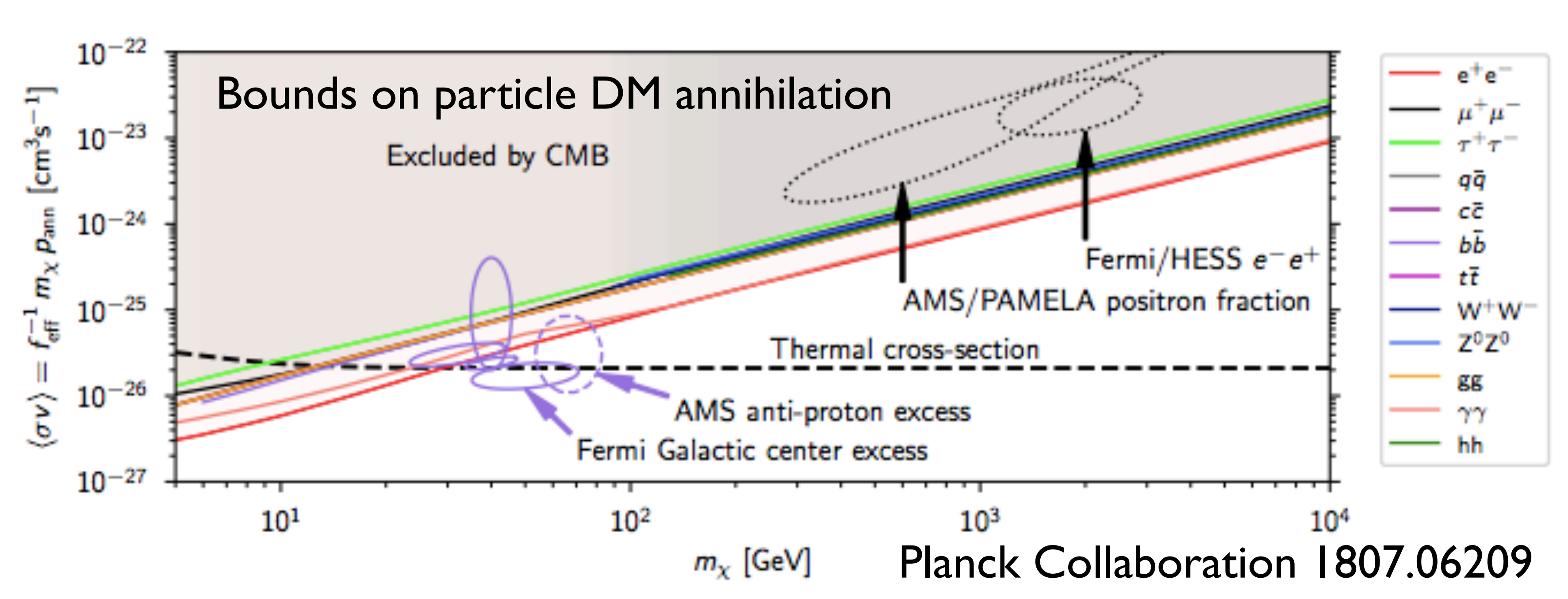
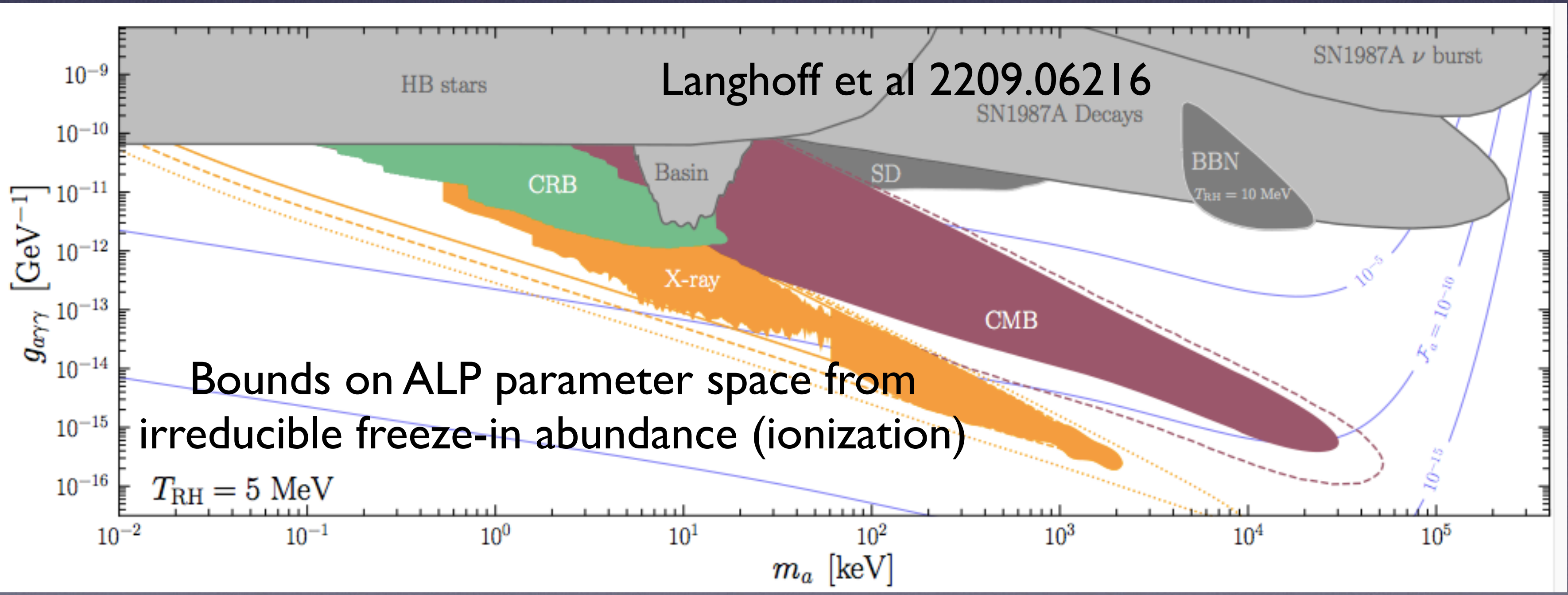
FAST

Limits from CMB anisotropies

- For scenarios not yet excluded, the backreaction effect on ionization is known to be small
- This approach has been used to set stringent constraints on dark matter annihilation and decay, primordial black holes, etc
- Note: for injection energies below 13.6 eV (no direct ionization), need full DARKHISTORY, see e.g. Xu, TRS et al 2408.13305



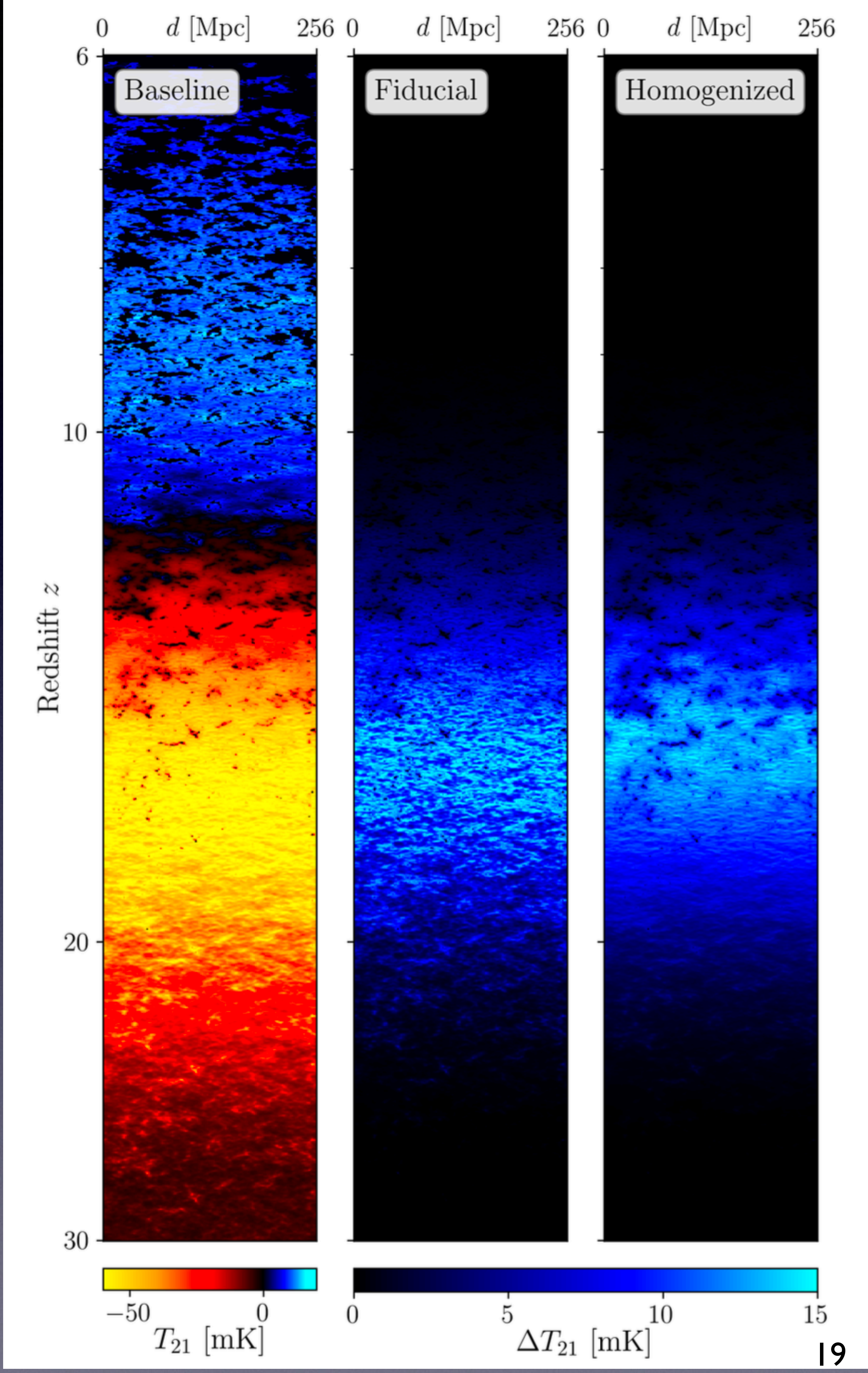
Planck Collaboration 1807.06209



Langhoff et al 2209.06216

Applications to 21cm

- 21cmFAST: widely-used public code for modeling 21cm radiation
- exo21cmFAST: combine DarkHistory+21cmFAST to model effects of energy injection [Facchinetti et al 2308.16656]
- DM21cm: same combination of codes, but add gas-density dependence for DarkHistory to capture inhomogeneous energy injection [Sun, TRS et al 2312.11608]
- Speed similar to baseline 21cmFAST



Projected DM decay limits

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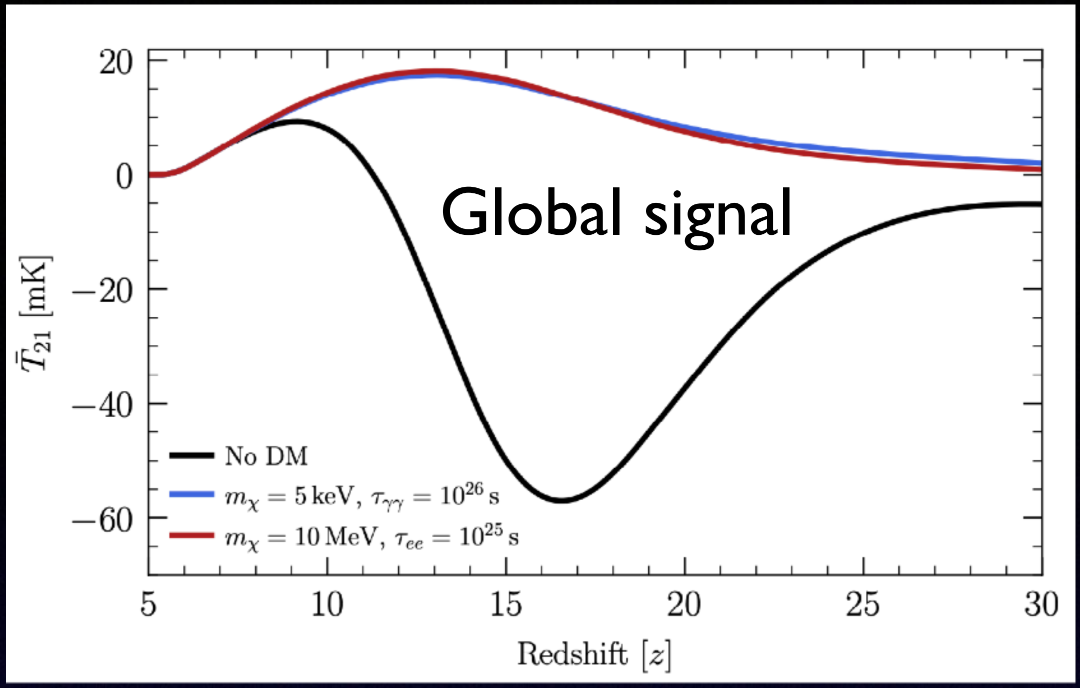

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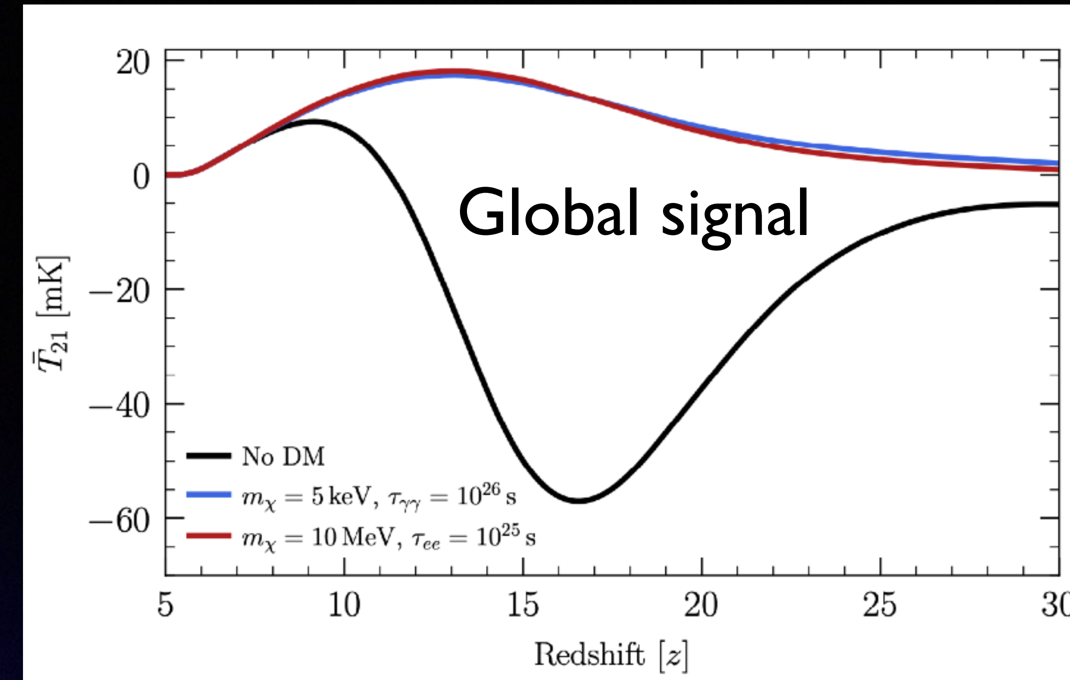

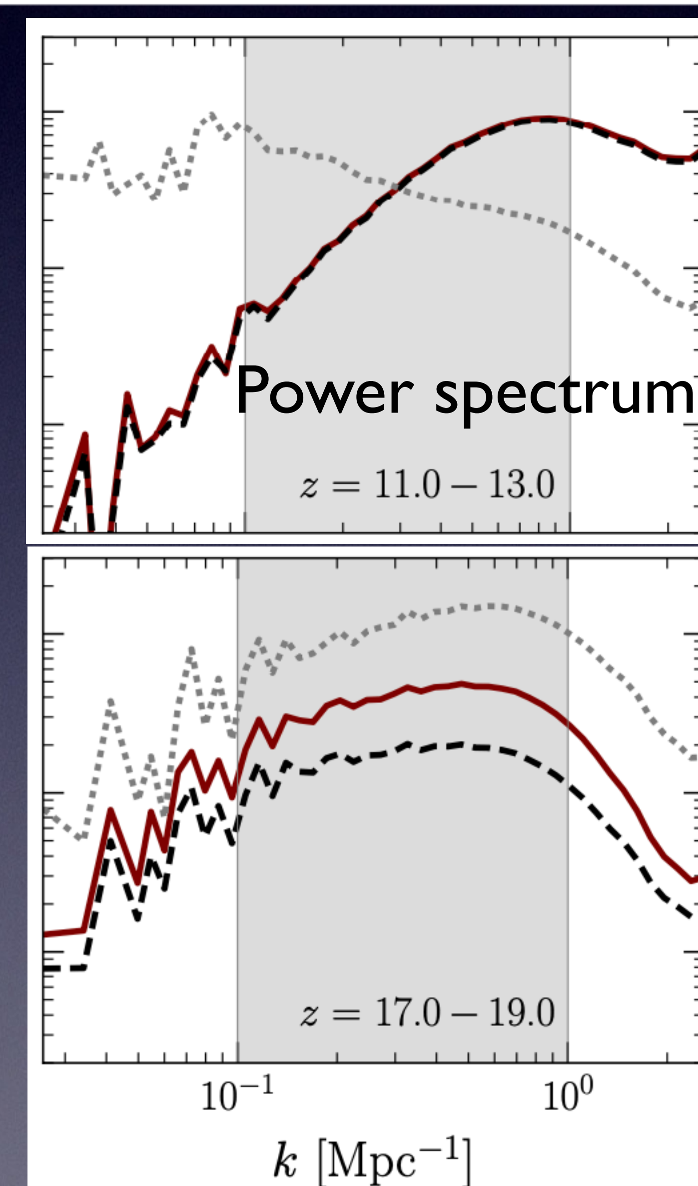

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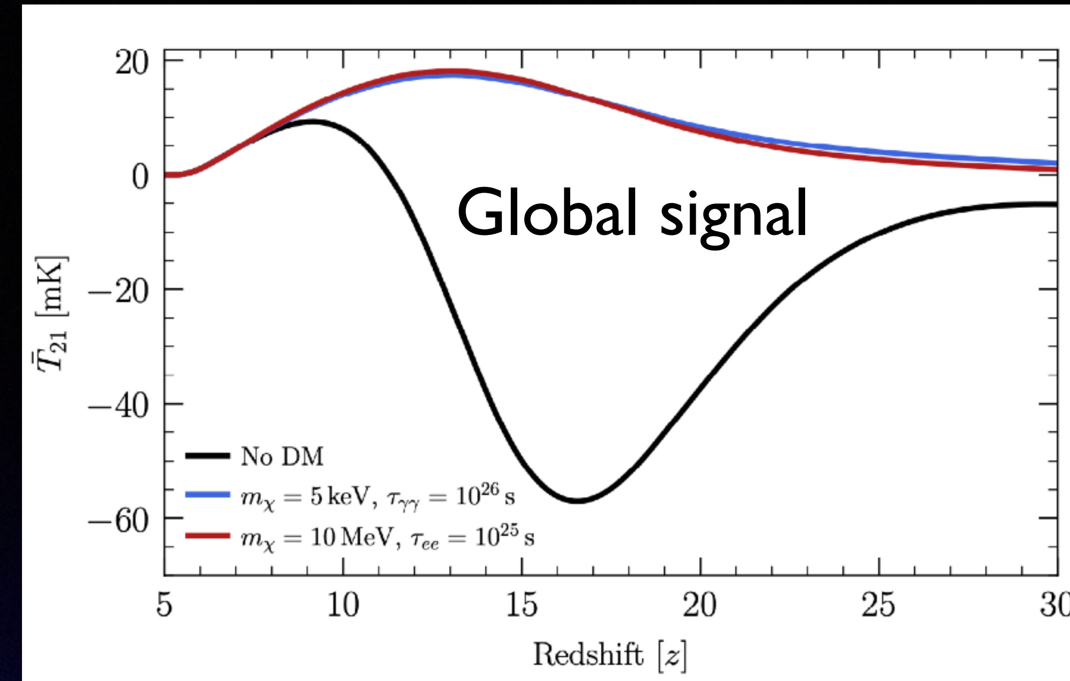

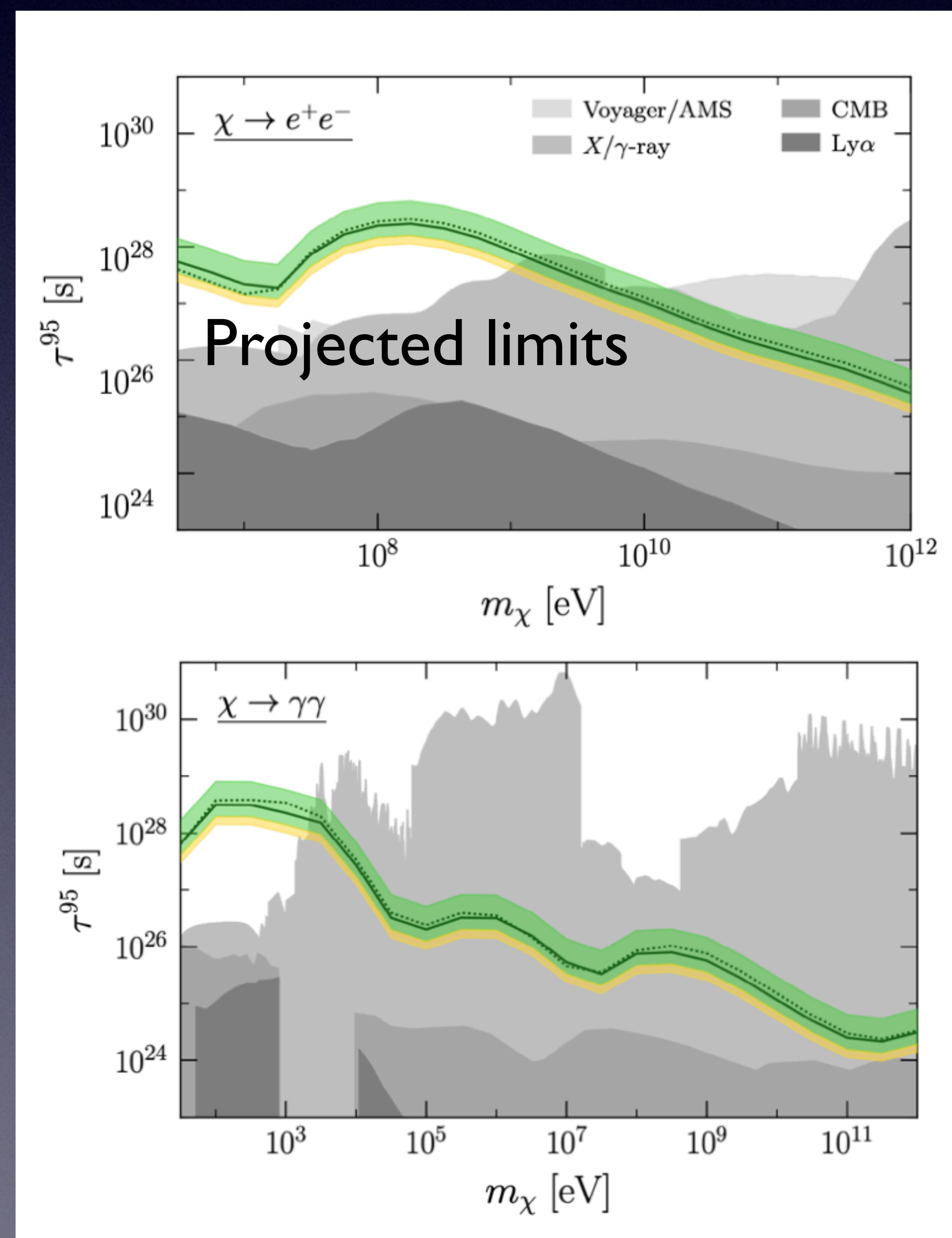

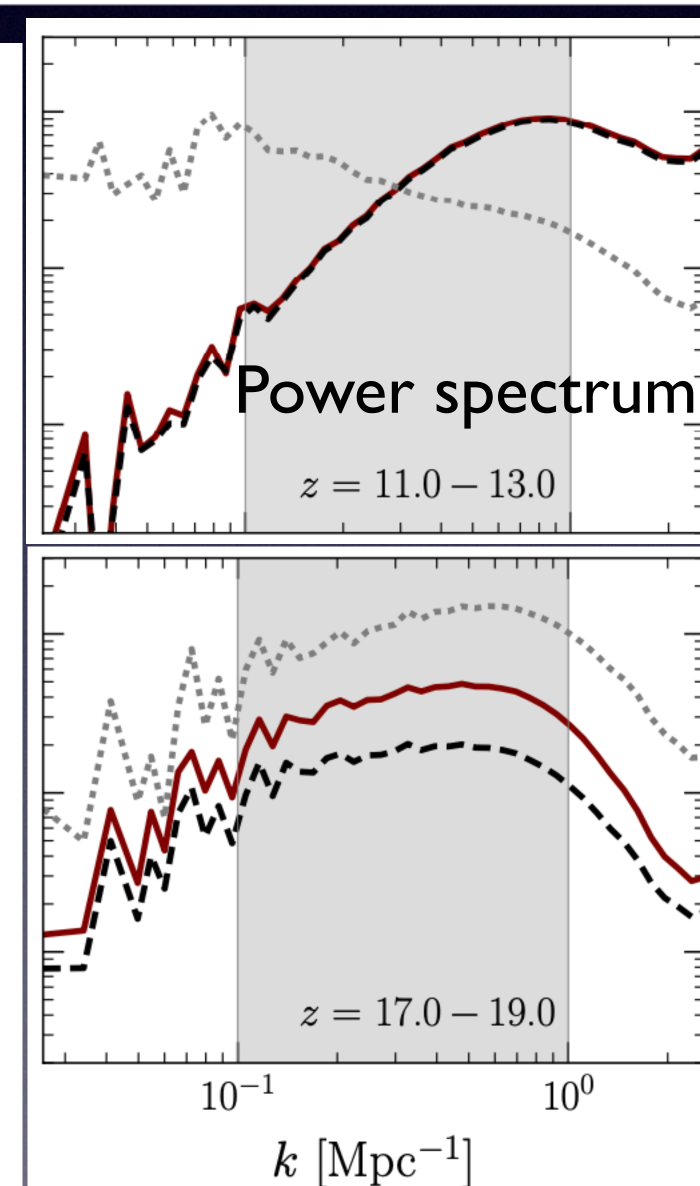

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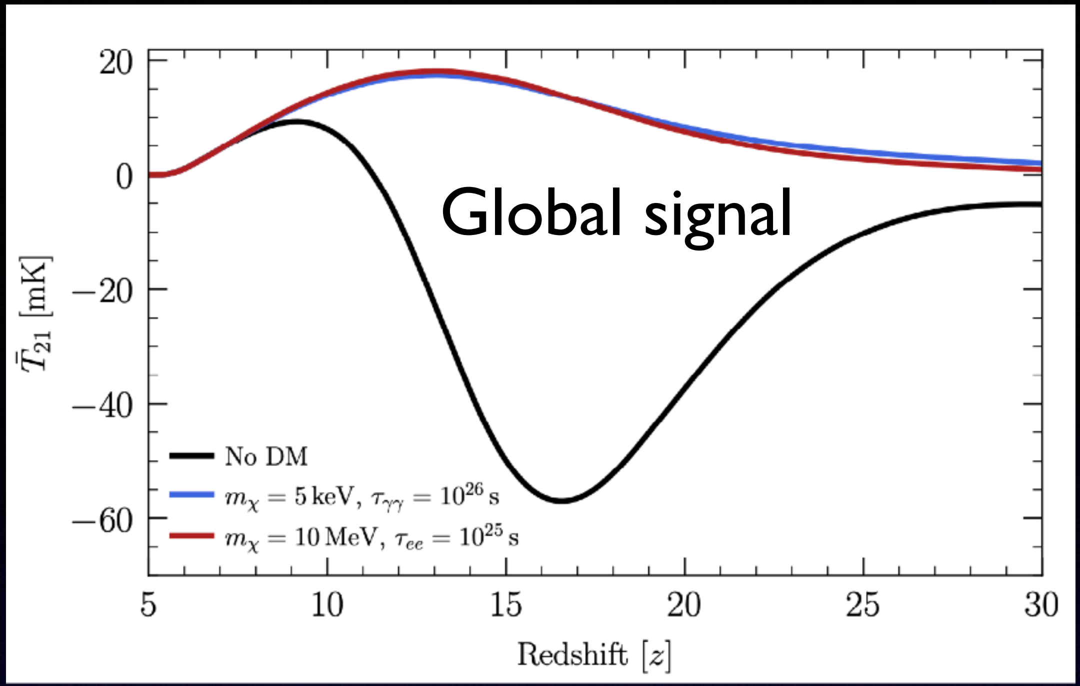

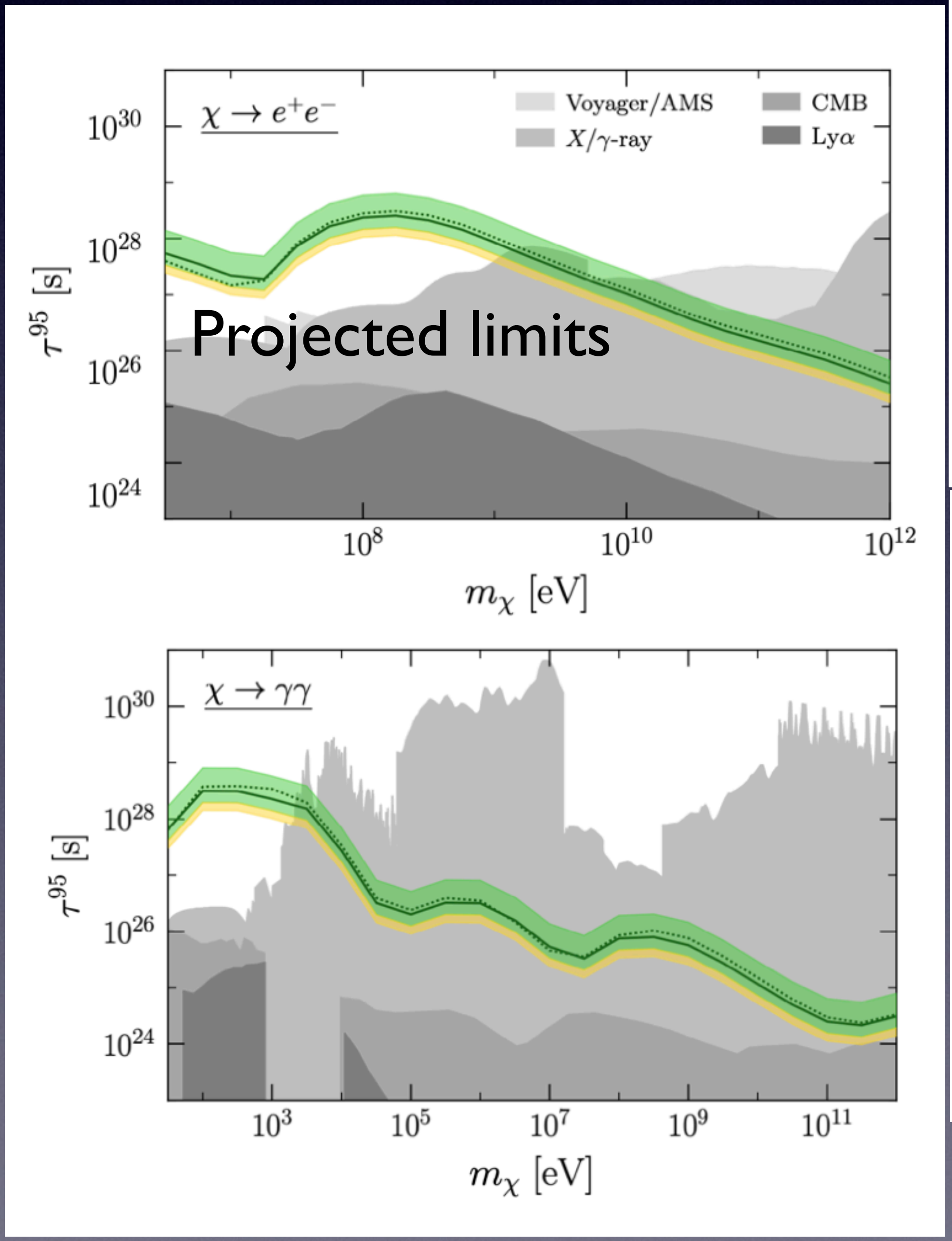

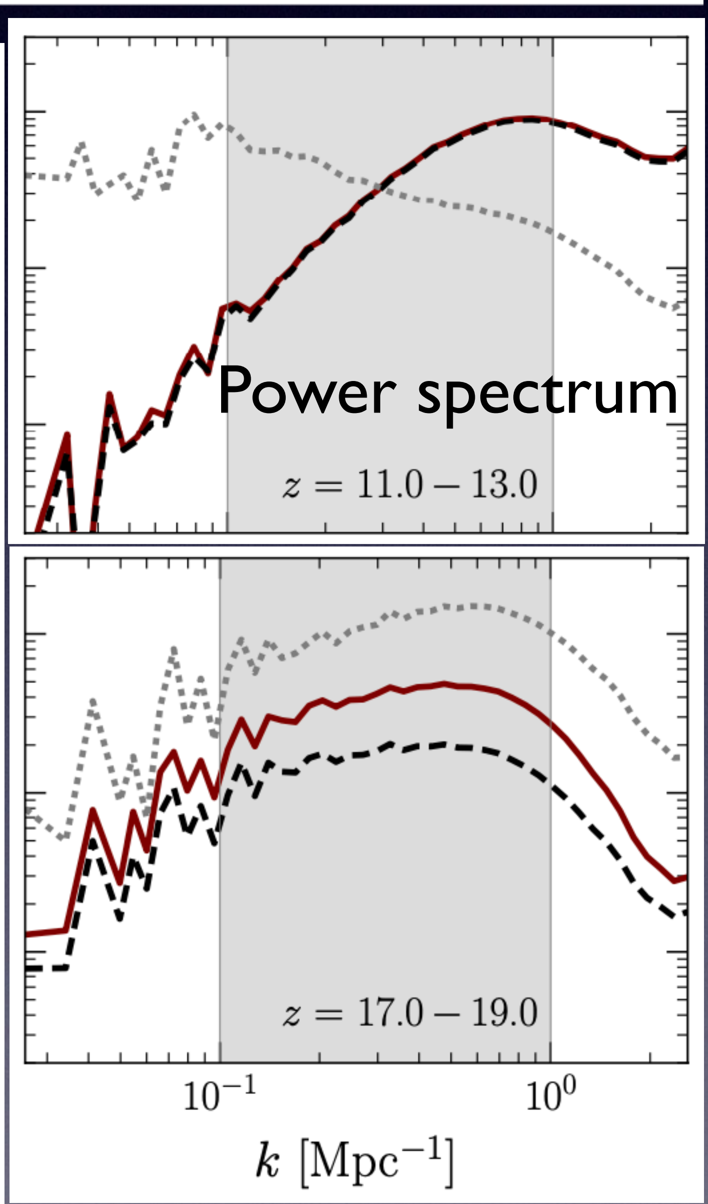

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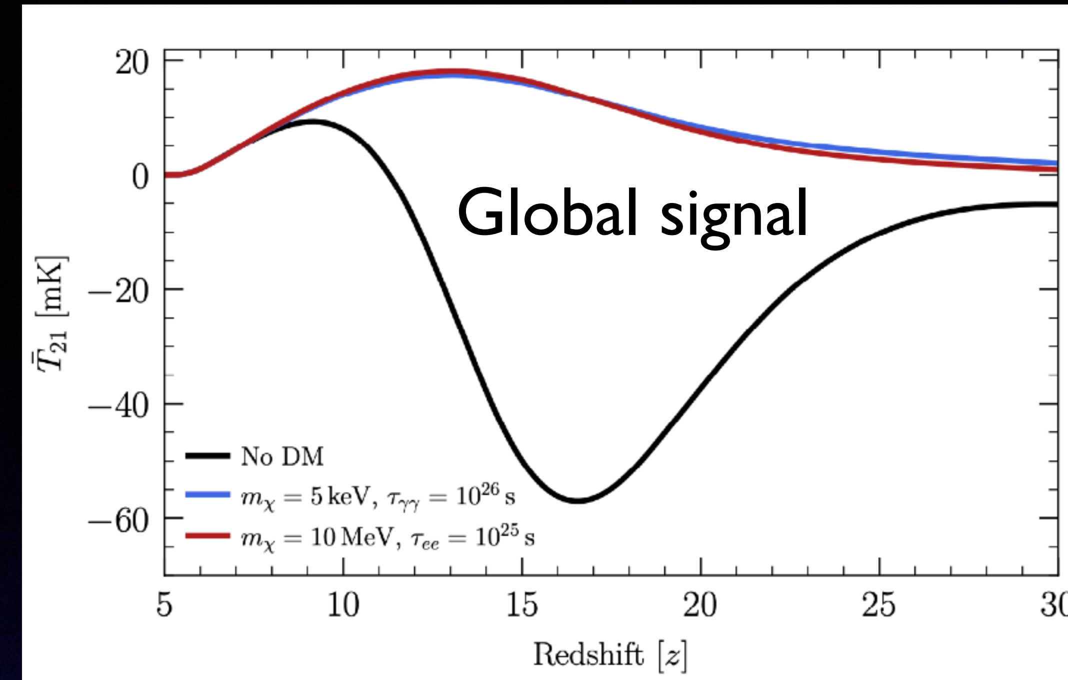
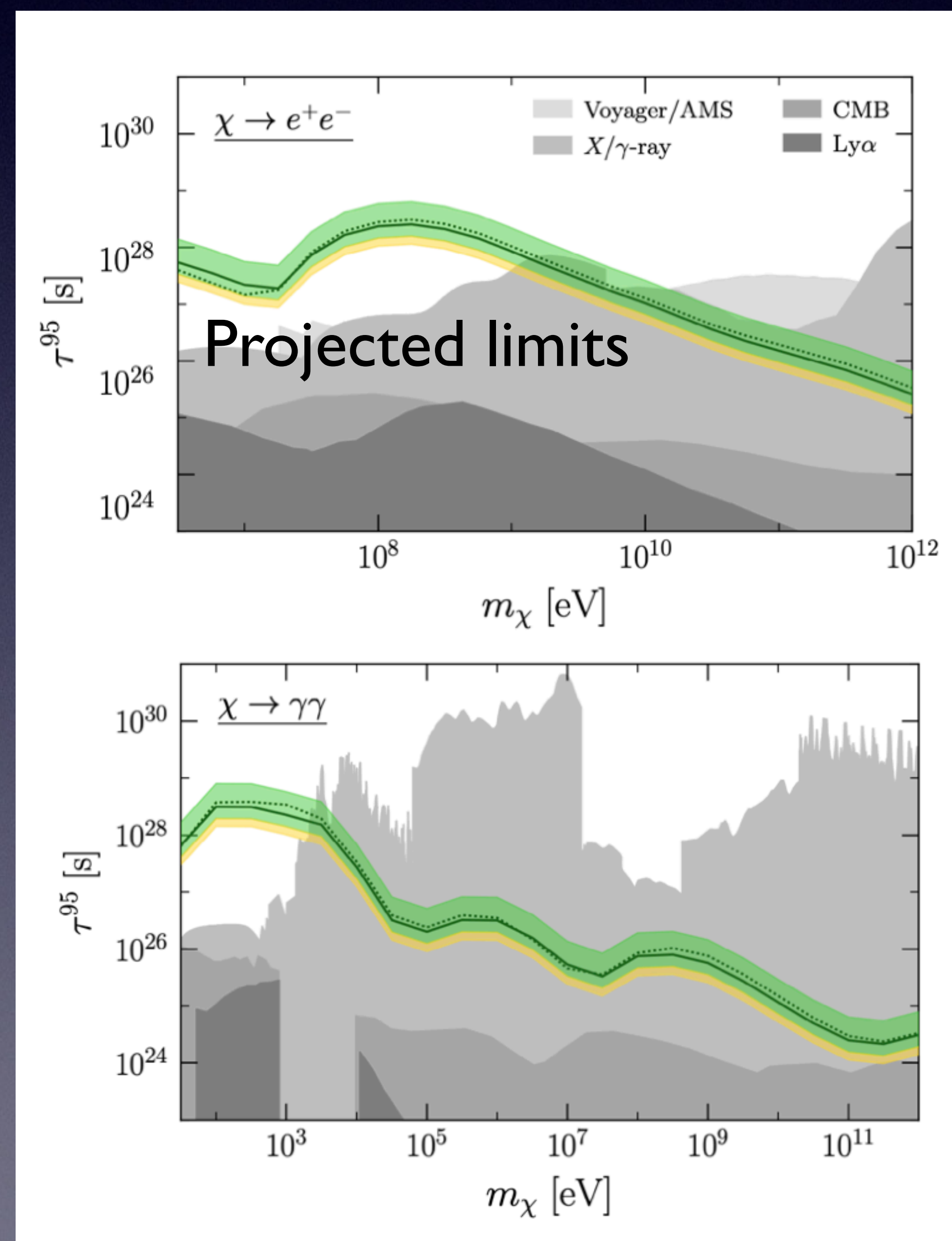
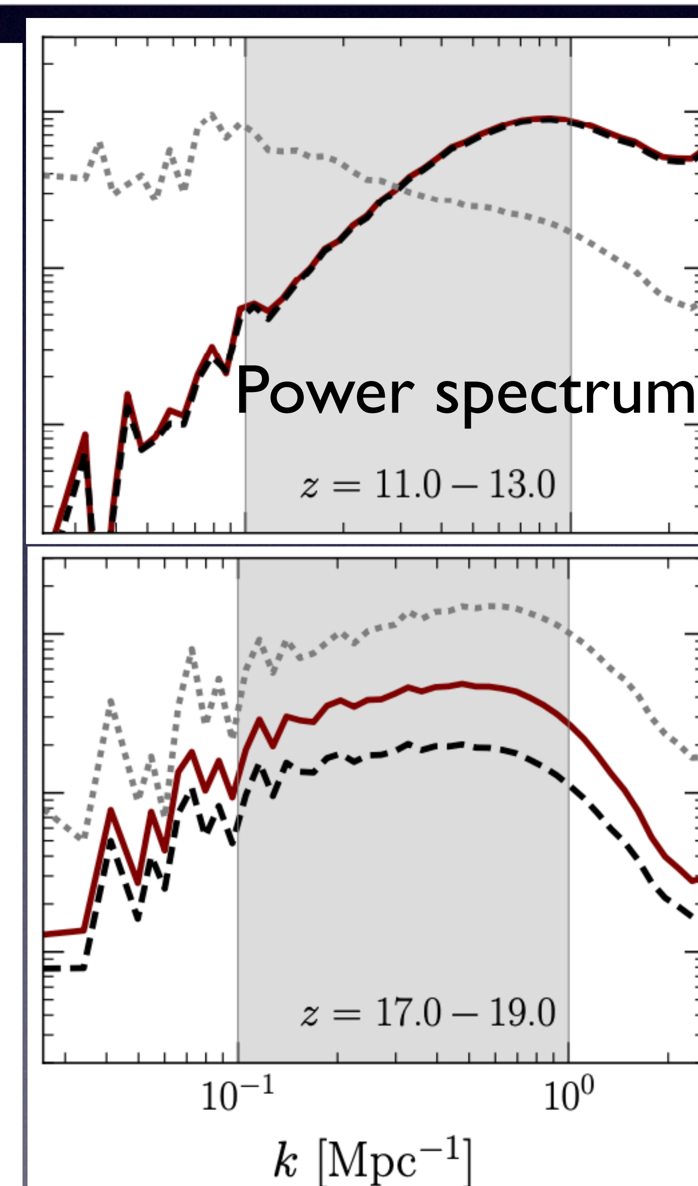
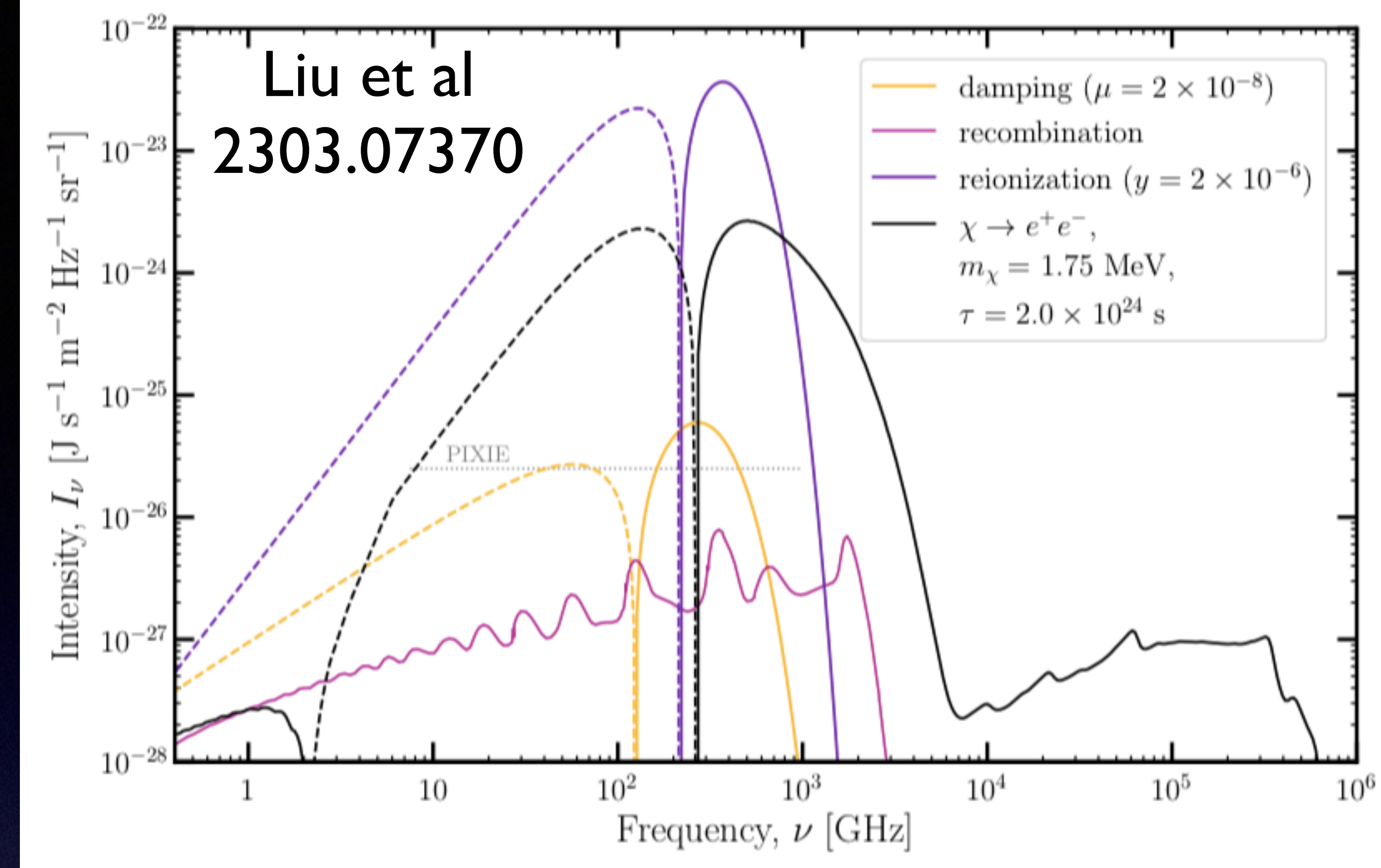
- HERA Phase II limit would be dominated by low redshifts - if a signal is seen, higher redshifts might help distinguish scenarios



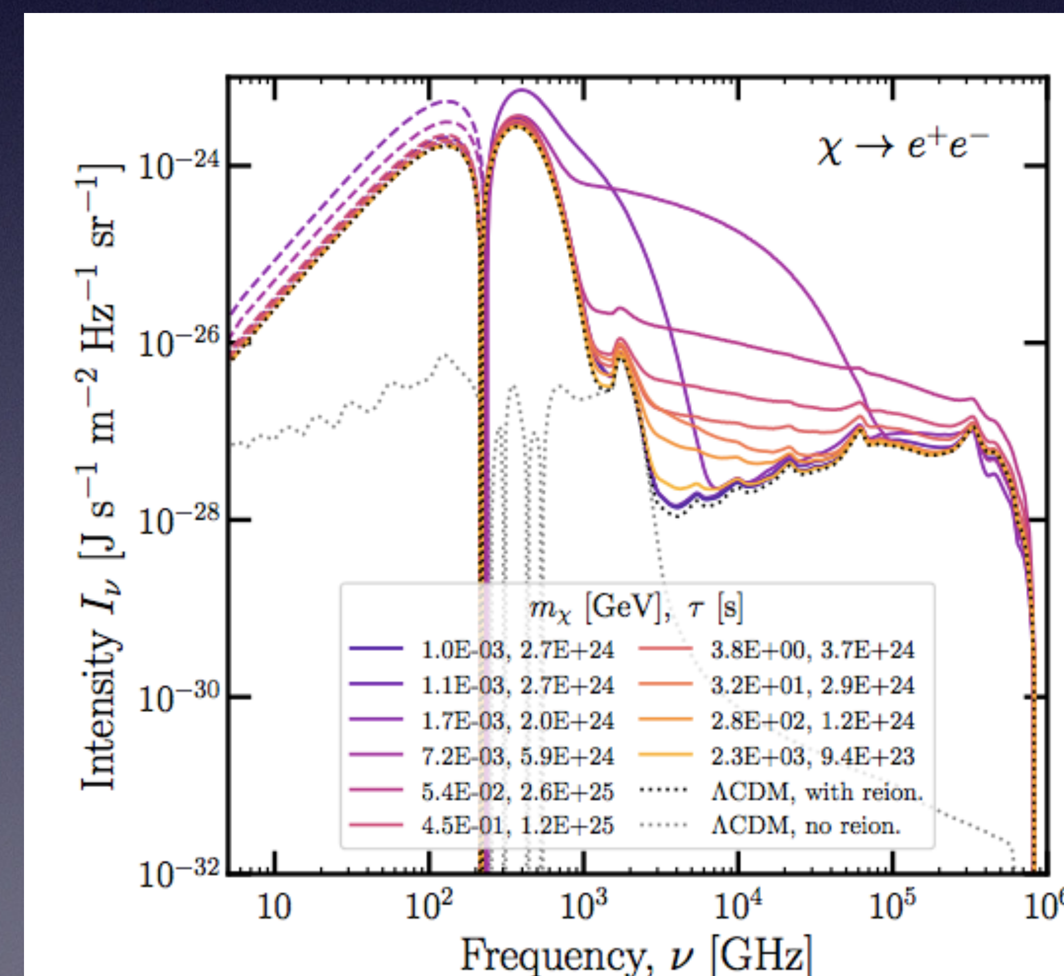




Spectral distortions from DM



- DarkHistory (Liu et al 2303.07366,2303.07370): allows computation of the full spectral distortion from arbitrary injections of high-energy (ionizing) particles
- Tracks all secondary particles produced by cascade
- 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 et al 2303.07370

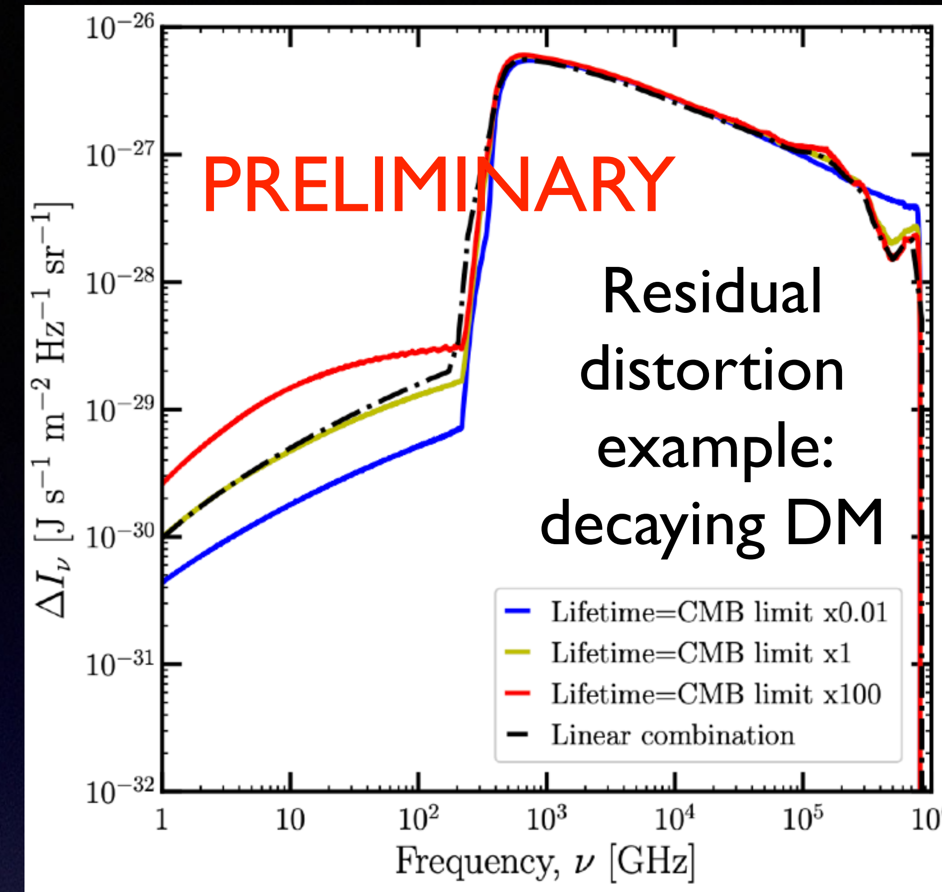
ExoCLASS for spectral distortions?

- DarkHistory for spectral distortions is *very* slow (can be hours for final production runs)
- Would like to combine with CLASS (already has technology for pre-recombination spectral distortions)
- Can we take inspiration from ExoCLASS?
- i.e. pre-compute a table of spectral distortions sourced by individual particle injections at different redshifts/energies, then integrate over desired distribution of injections
- Works for ionization history because backreaction is small - is it small in this case?

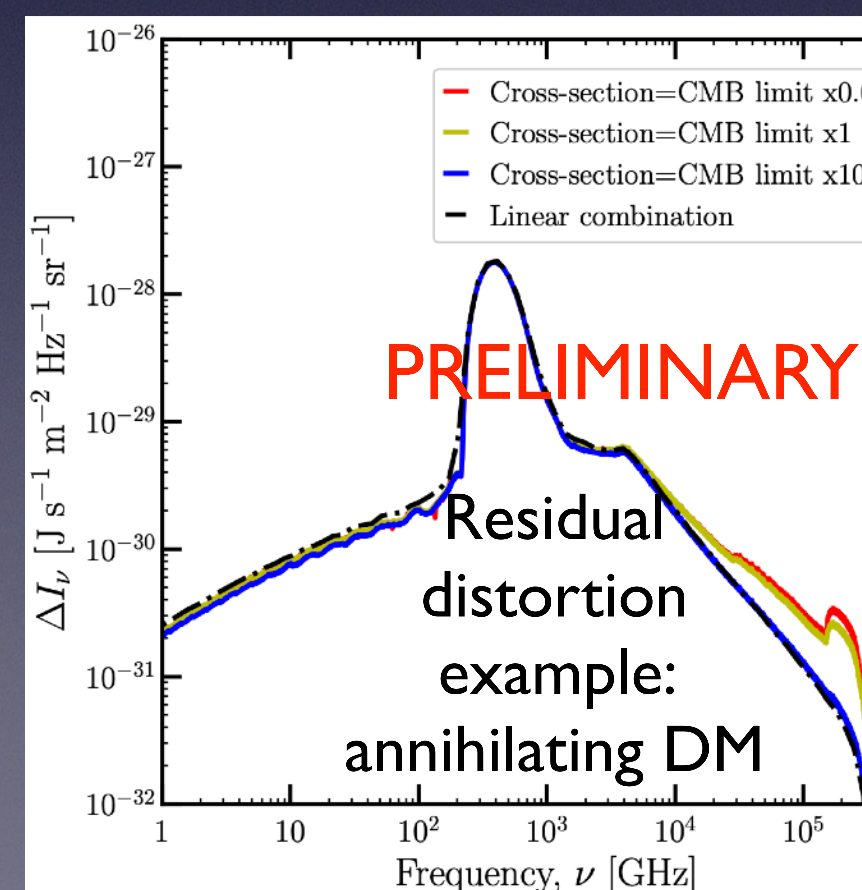
A single code for spectral distortions?

Work in progress with Julien Lavalle, Vivian Poulin, Wenzer Qin

- Separate spectral distortion into y-distortion (sourced by heating of the gas) + residual part
- y-distortion piece is affected by backreaction (similarly to temperature history) - but also likely to be degenerate with Standard Model sources of y-distortion (i.e. reionization)
- Residual part is more distinctive - and seems (preliminarily) to be quite linear
- We have implemented a full (but slow) CLASS + DarkHistory integration - will use for testing fast+approximate approach



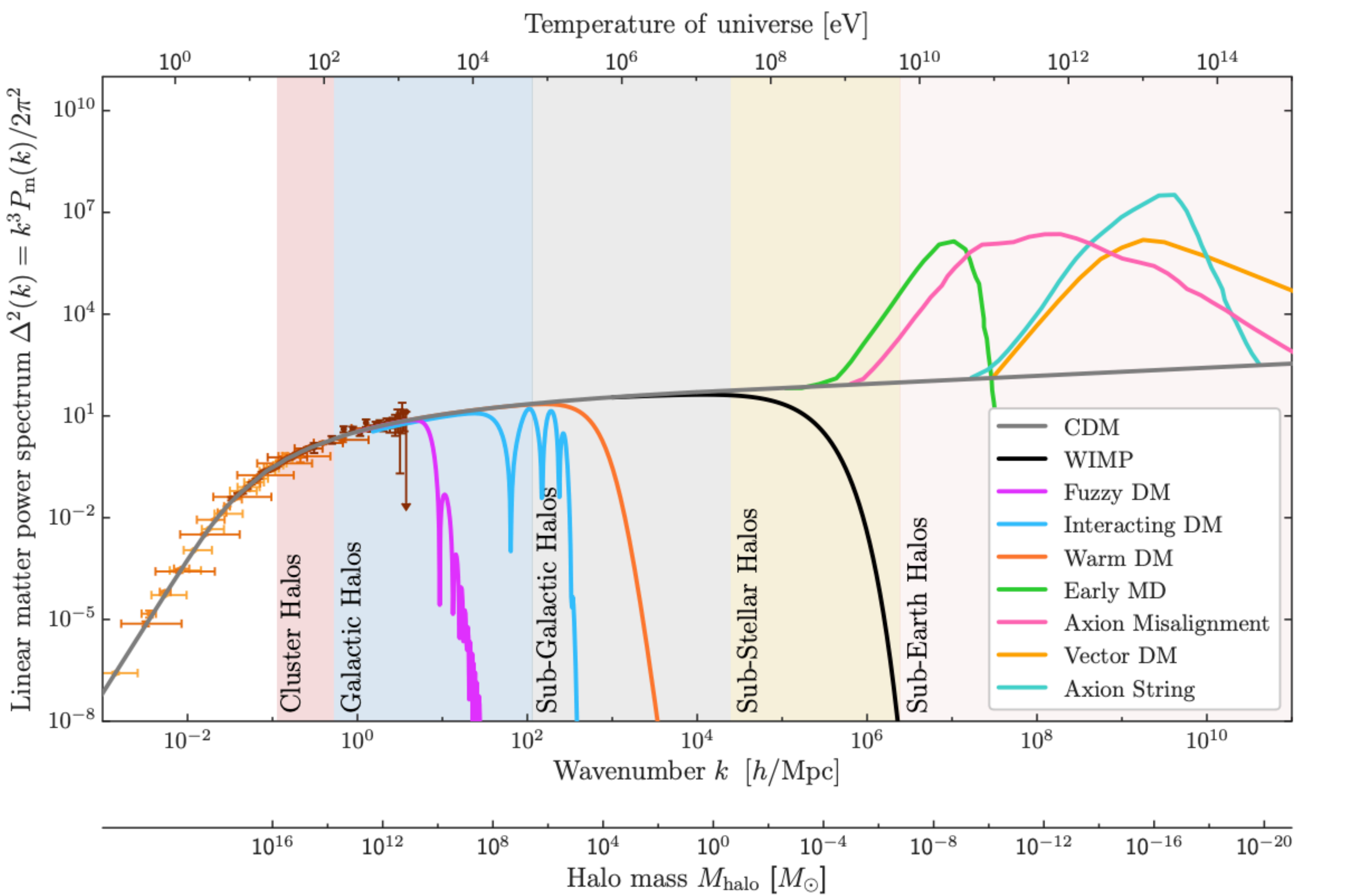
All lines rescaled to match total energy injection



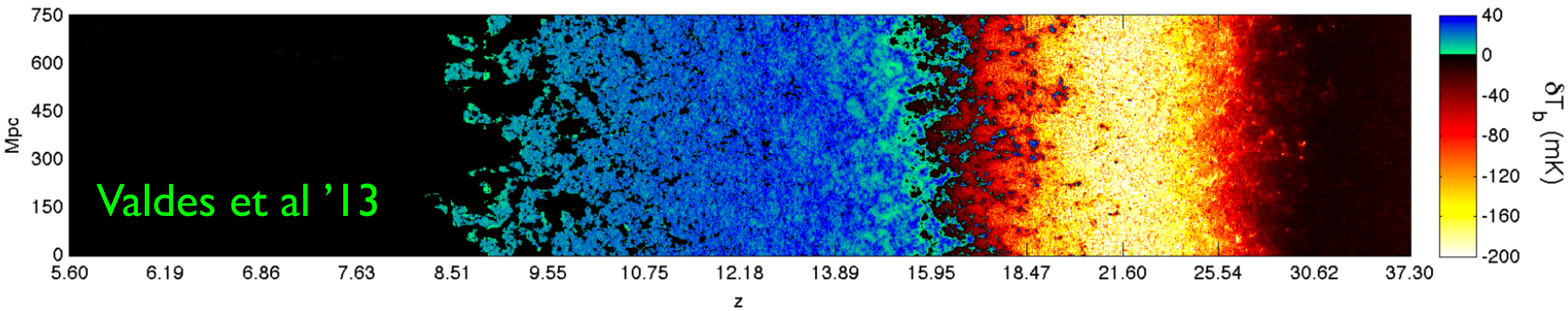
Summary

- Cosmological datasets can provide powerful probes of the non-gravitational interactions of dark matter, the presence of new scales controlled by dark matter microphysics, and the evolution of dark matter over cosmic history
- For CMB and large-scale structure constraints, perturbative approaches (traditional perturbation theory + more recent effective-field-theory methods) are powerful and have been implemented in longstanding public codes
- Beyond modifications to the dark matter distribution, energy transfer from the dark→visible sector (or vice versa) could have striking observable effects
- The DarkHistory public code and its variations/extensions aim to model one class of such effects — the impact of injecting non-thermal Standard Model particles into the early universe (primarily around/after recombination, and at energies > 13.6 eV):
    - changes to the ionization history and thence the CMB anisotropies
    - changes to the temperature history, affecting the Lyman-alpha forest and the 21cm signal
    - changes to the blackbody spectrum of the CMB
- We have already set powerful bounds on such energy injections and consequently on the properties of dark matter; scenarios that are not currently excluded could have striking effects in upcoming observations (in particular 21cm)

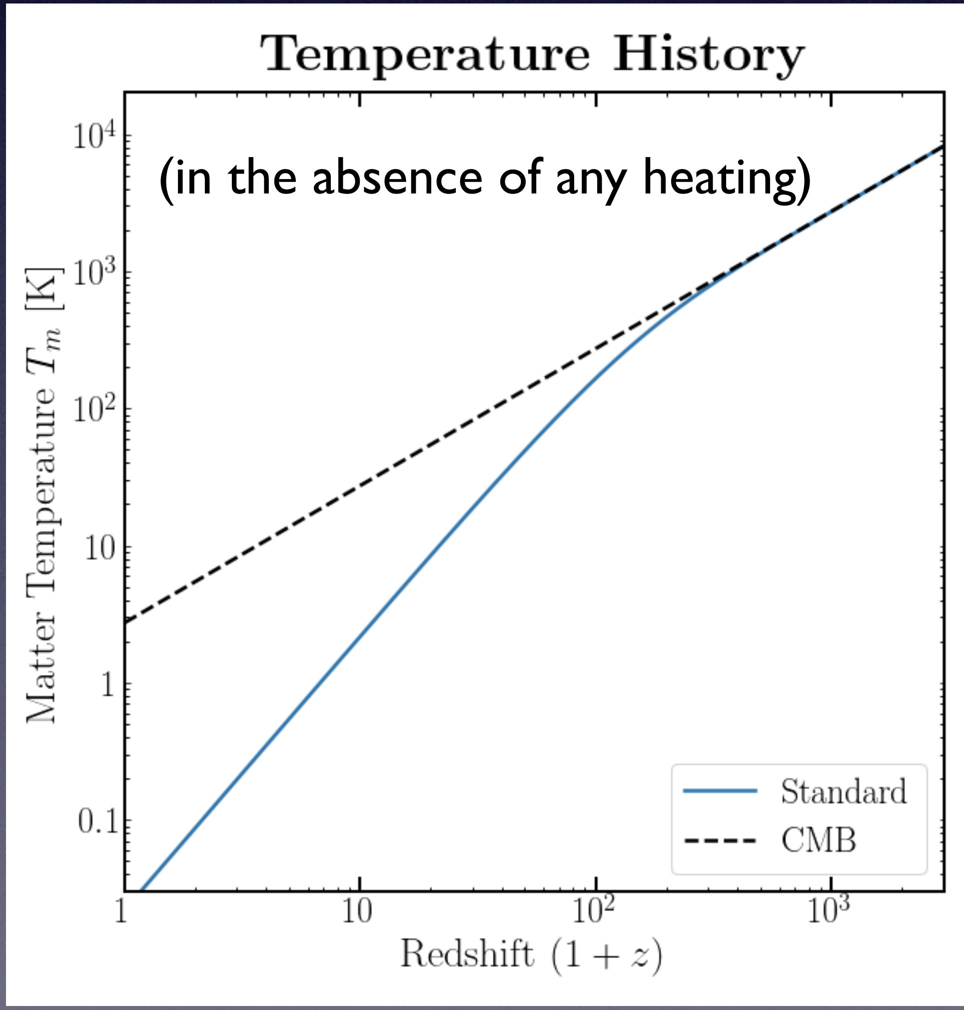
Backup slides


Temperature of universe [eV]
10^0
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
Linear matter power spectrum $\Delta^2(k) = k^3 P_m(k)/2\pi^2$
10^{10}
10^7
10^4
10^1
10^{-2}
10^{-5}
10^{-8}
Cluster Halos
Galactic Halos
Sub-Galactic Halos
Sub-Stellar Halos
Sub-Earth Halos
CDM
WIMP
Fuzzy DM
Interacting DM
Warm DM
Early MD
Axion Misalignment
Vector DM
Axion String
10^{-2}
10^0
10^2
10^4
10^6
10^8
10^{10}
Wavenumber k [h/Mpc]
10^{16}
10^{12}
10^8
10^4
10^0
10^{-4}
10^{-8}
10^{-12}
10^{-16}
10^{-20}
Halo mass M_{halo} [$M_\odot$]

Predicting the 21cm signal

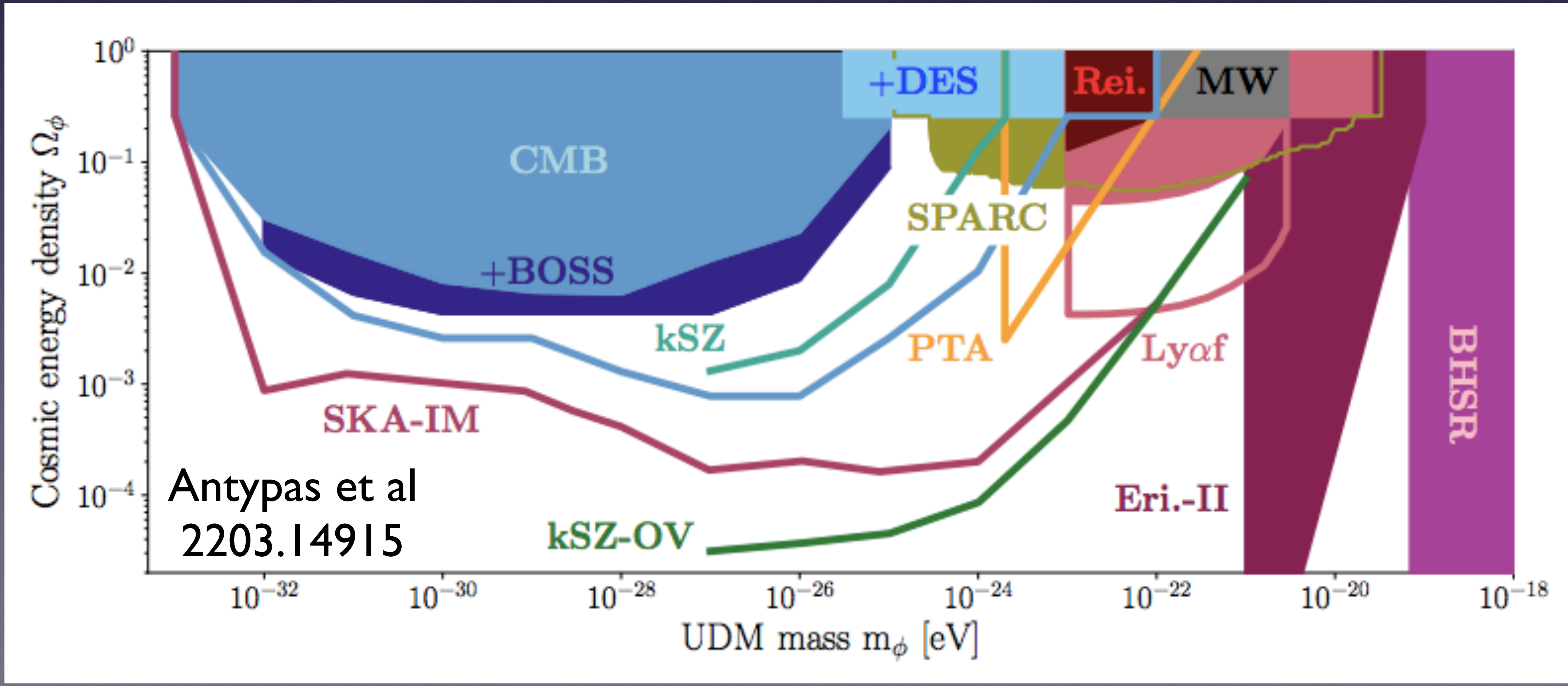


- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature. Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- There are a number of current (e.g. HERA, EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Measurements of power spectrum can constrain temperature, ionization history, matter distribution
- Forecasts typically use public codes 21cmFAST (Mesinger et al 1003.3878), Zeus21 (Munoz 2302.08506).



Example of a new scale: 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)

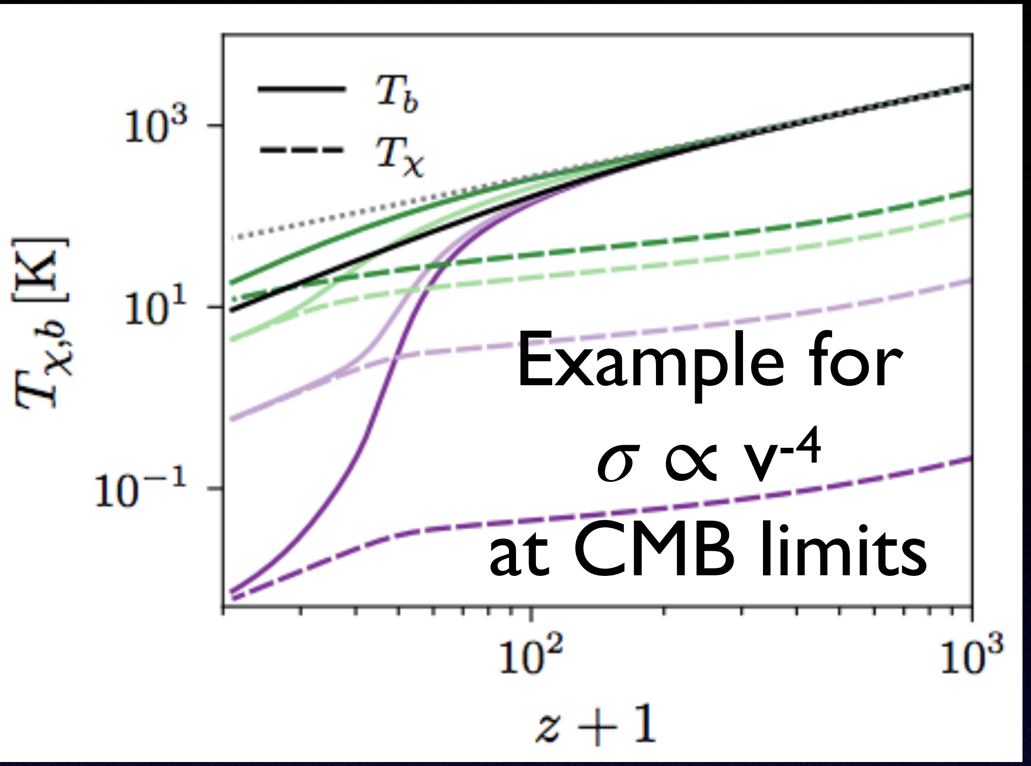


Example: decaying DM

- 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 ~ 10^9 years),
    $\Rightarrow$ lifetime $\gtrsim 10^9$ years/(2 x 10^{-10}) ~ 5 x 10^9 Gyr ~ 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 <u>not</u> 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)

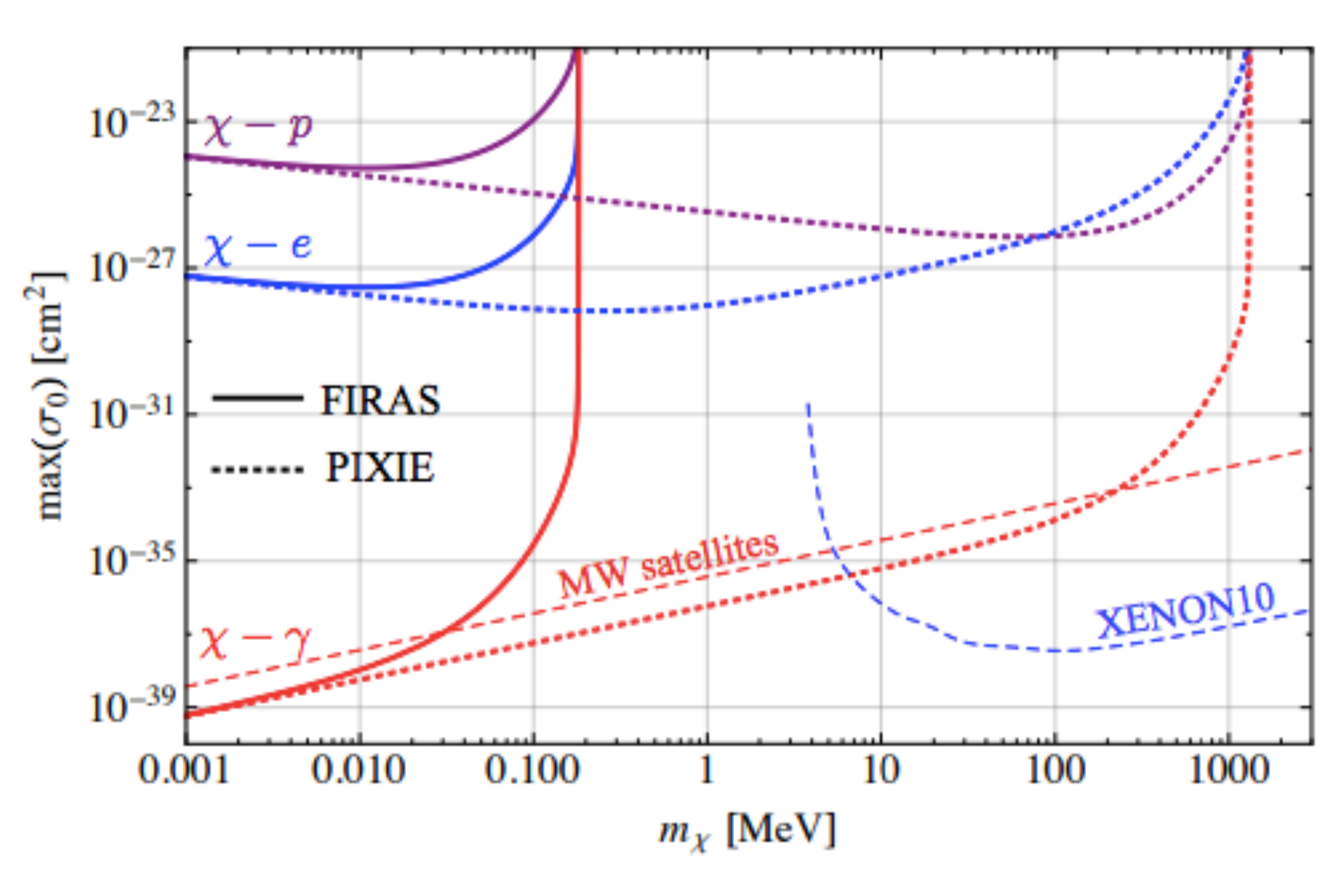
DM-SM scattering (heating effects)

- 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].



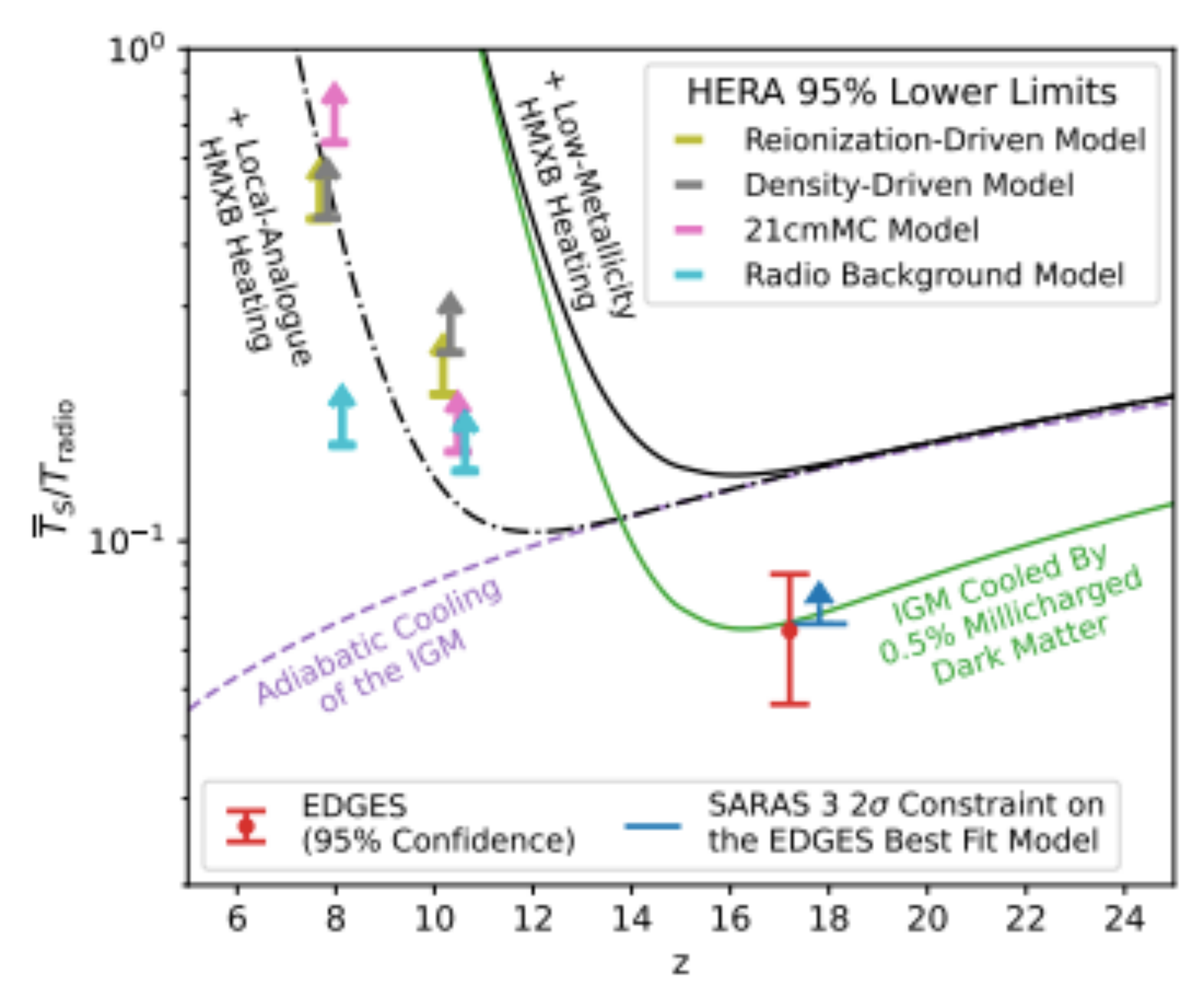
Short et al 2203.16524
(includes analysis of temperature perturbations)

Ali-Haimoud et al 1506.04745



The search for primordial 21cm

- In addition to global limits (see talk by Tomer Volansky), HERA has released upper limits on the power spectrum based on 94 nights of Phase I data, with 35-41 antennas (HERA Collaboration 2210.04912)
- Data collected in 2017-18
- 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."