Modeling dark matter signals in cosmic 21cm radiation

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What does cosmology teach us about dark matter (DM)?

- “Standard" ΛCDM works pretty well:
  - DM is ~5/6 of the matter in the universe
  - 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

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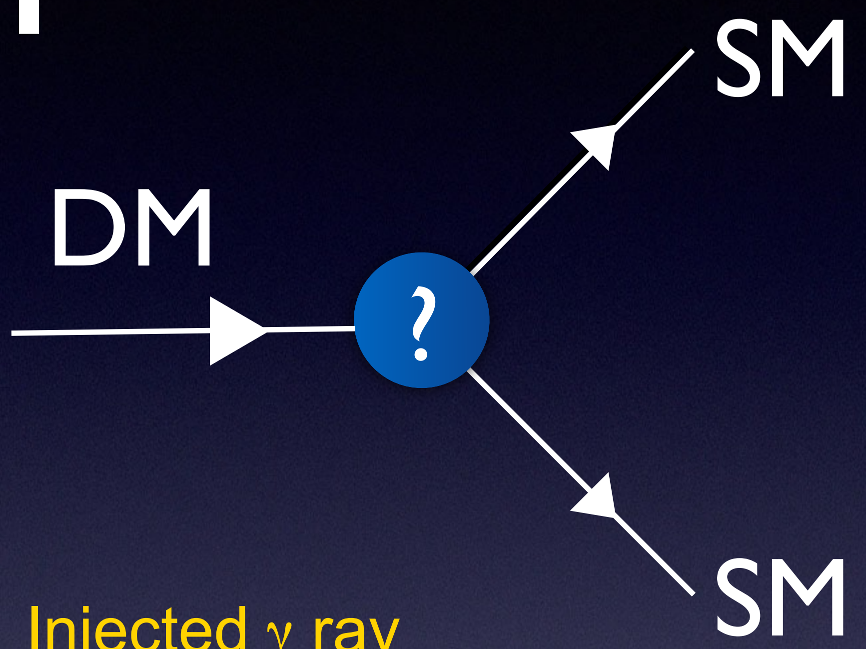
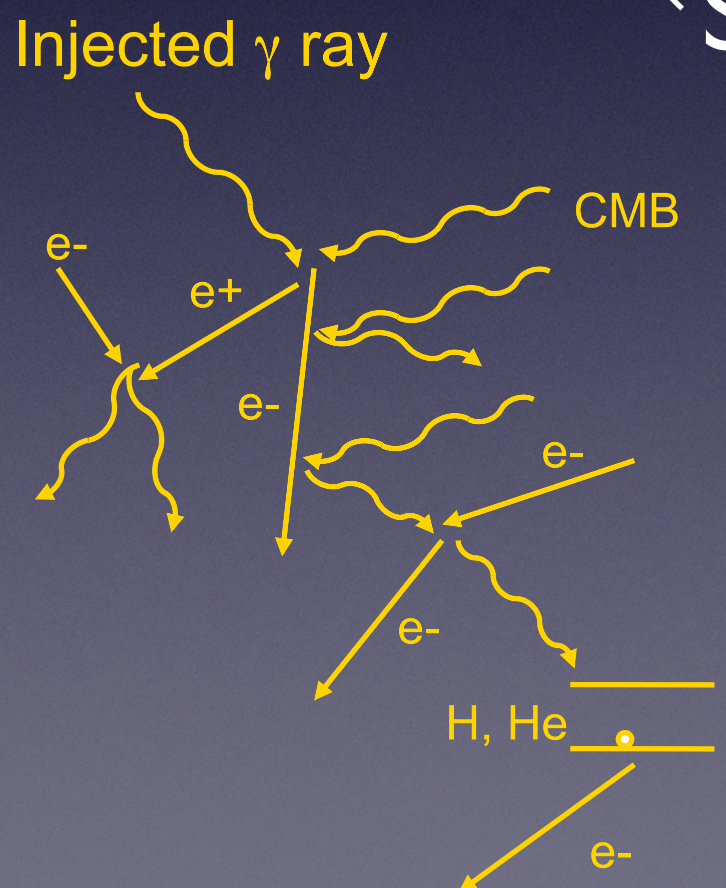
Energy injection from dark matter

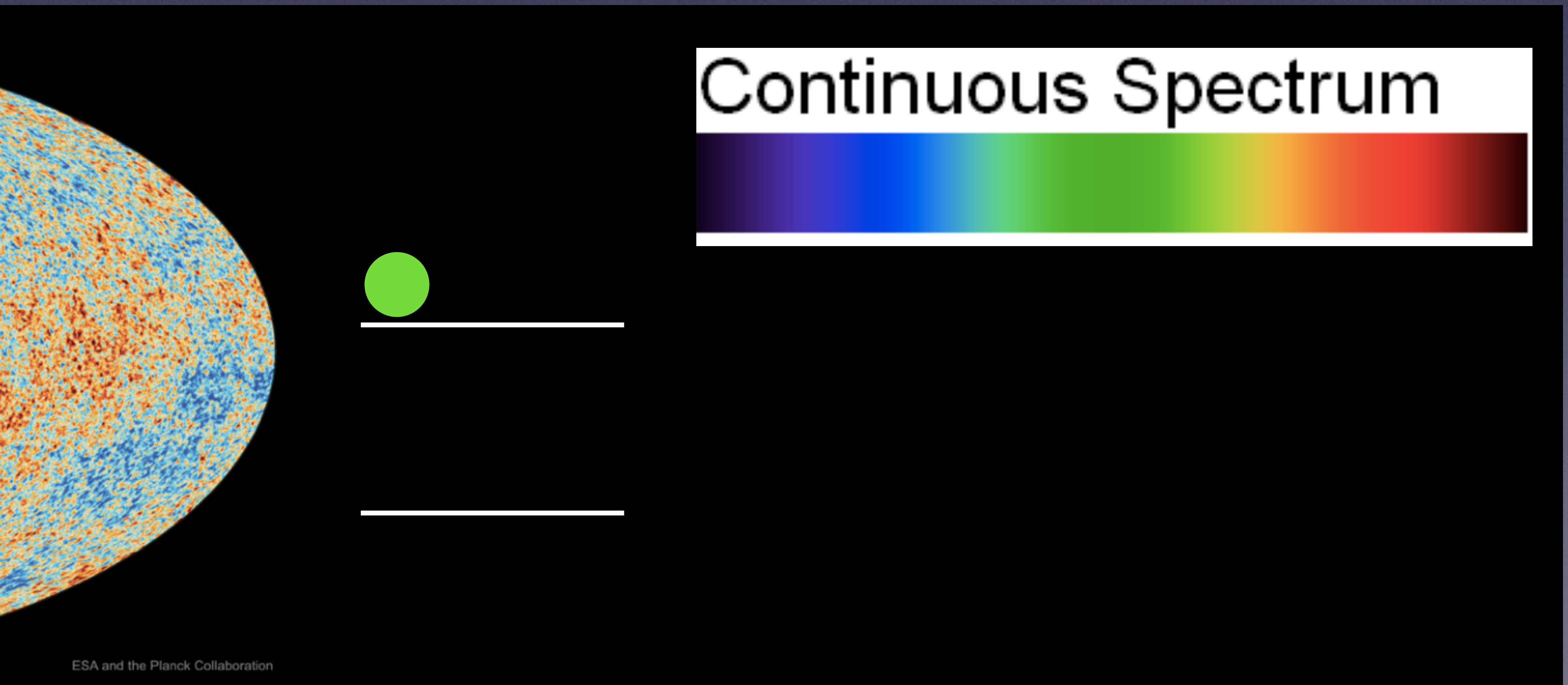
- A (meta)stable species that decays or annihilates could inject non-thermal Standard Model particles into the early universe.
- As these particles cool down, they could heat the intergalactic medium, ionize and excite atoms, and produce excess radiation.
- Plenty of energy: DM mass-energy is ~5 GeV/hydrogen atom (4×10^8 x ionization potential, 1 eV of heating ~10,000 K)





21cm and the cosmic thermal history

- To measure the gas temperature in the early universe, 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.



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

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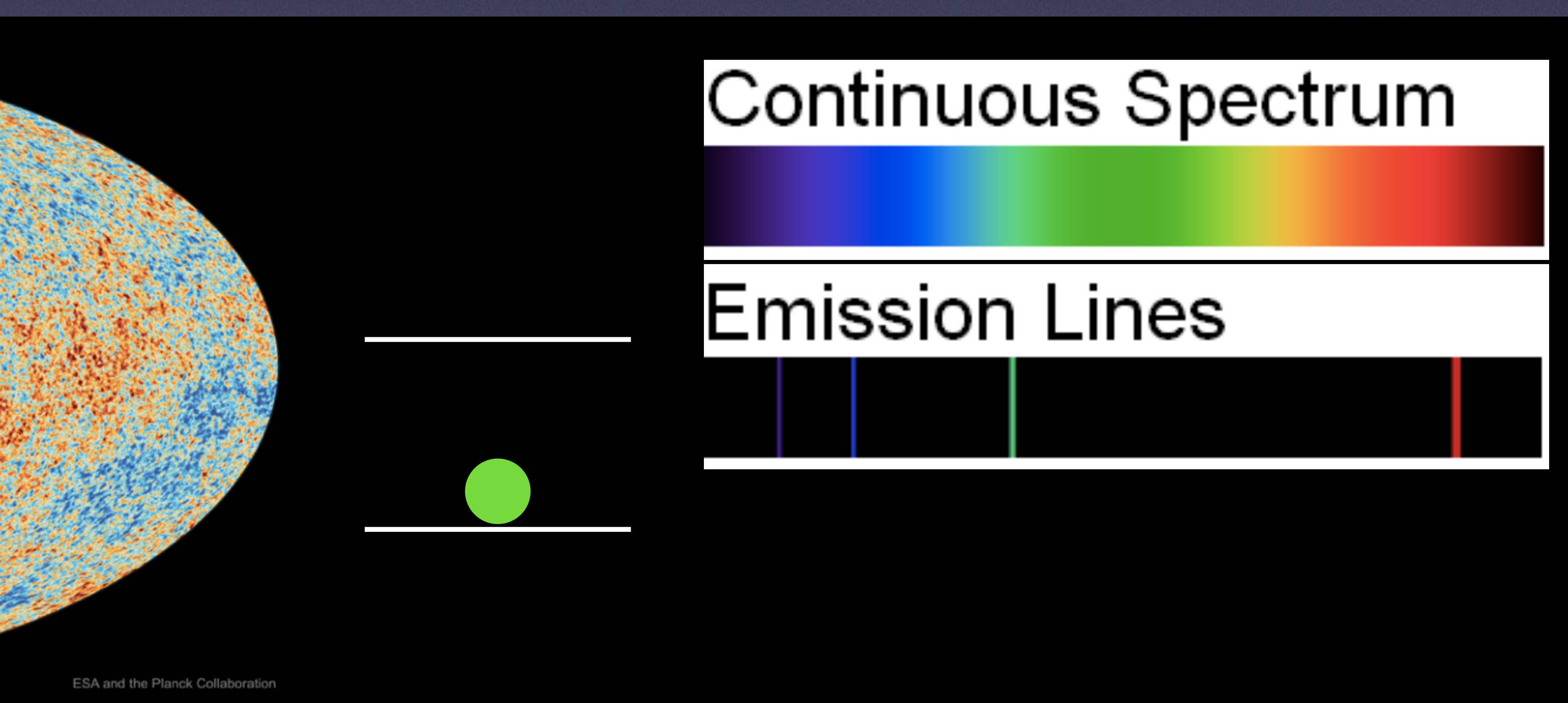

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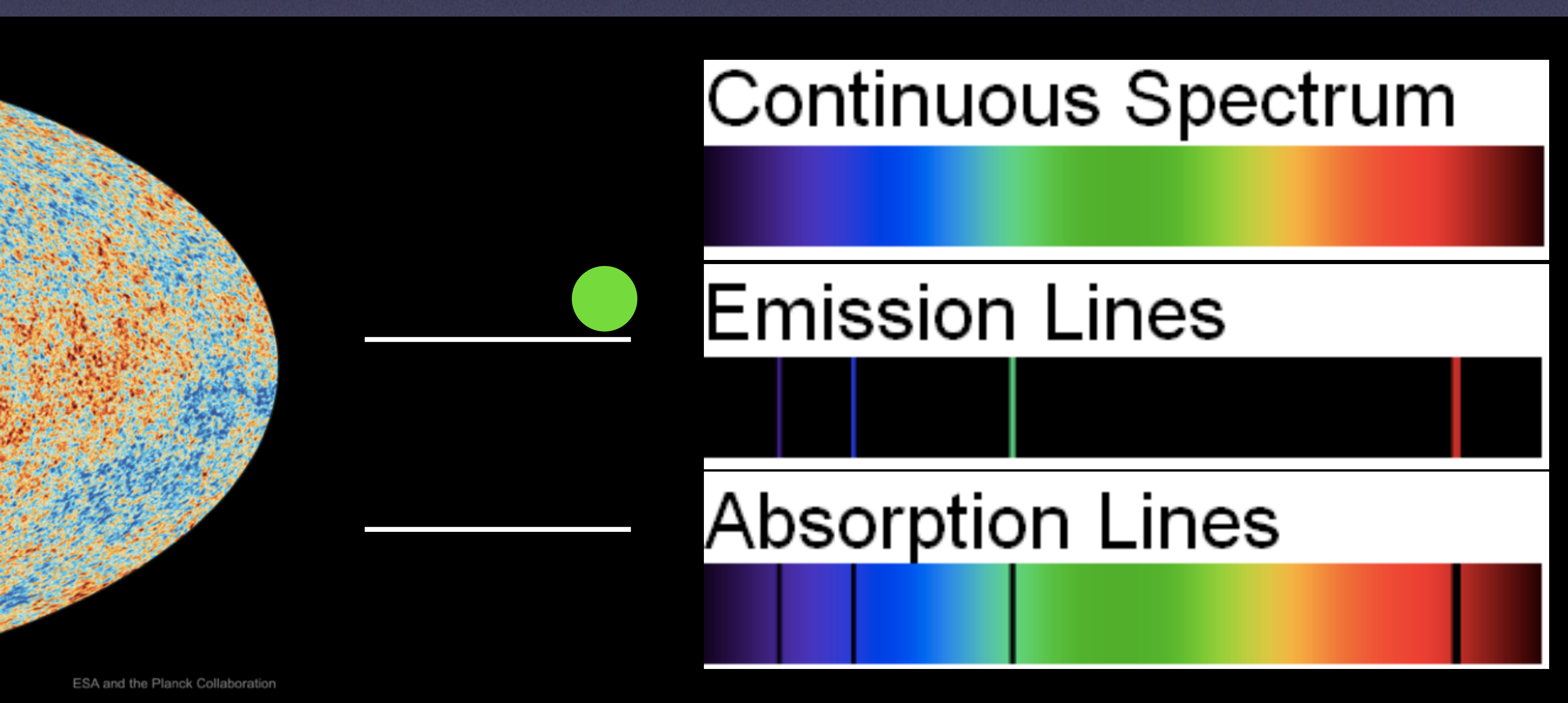

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The search for (cosmological) 21cm

- 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.
- Upper limits are reaching the point where they can exclude (some) realistic astrophysical scenarios
- Forecasts typically use public codes 21cmFAST (Mesinger et al 1003.3878), Zeus21 (Munoz 2302.08506)

What is the dominant effect of DM decay?

- In principle, energy injection affects 21cm signal in multiple ways:
  - Heating changes gas temperature
  - Ionization = less neutral hydrogen
  - Changes to radiation field — in particular, more photons in Lyman band (H excitation), enhances coupling between spin temperature and gas temperature
  - Also possible changes to formation of compact objects, such as first stars / black holes, with potential downstream effects
- Which of these matter most? Do multiple effects matter?
- 2023: we built a code DM21cm for incorporating inhomogeneous DM-induced heating, ionization, Lyman-alpha [Sun, TRS et al 2312.11608]

Heating and Lyman-band photons

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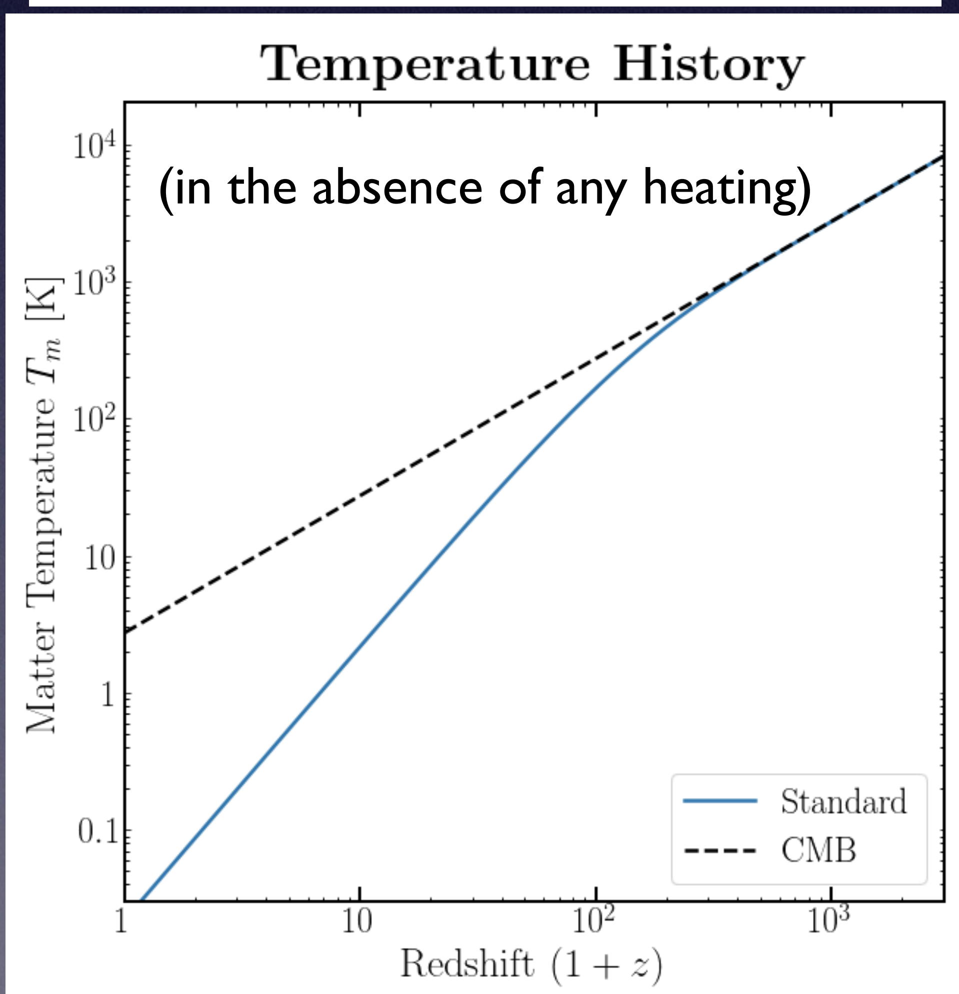
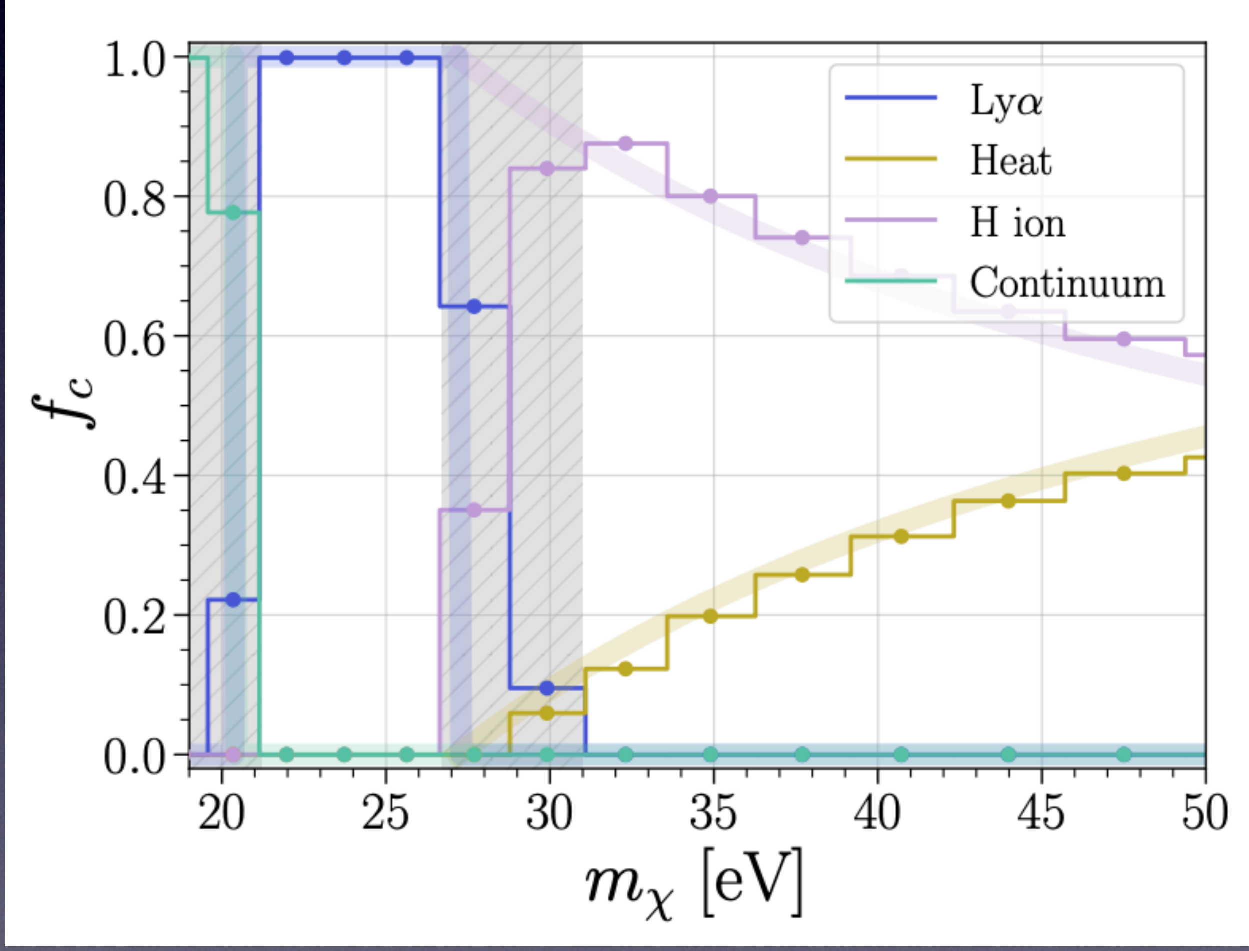


- Before stars turn on, gas cools below CMB temperature
- Lyman-alpha photons from the first stars affect 21cm through the Wouythusen-Field effect
- Lyman-alpha photons rapidly scatter in the resonance, couple the spin temperature (set by ratio of ground vs excited states) to the gas temperature
- This is essential in separating the spin temperature from the radiation temperature + sourcing a 21cm signal
- Secondary particle cascade from DM decay/annihilation will both heat the gas and strengthen Wouythusen-Field effect

Boosting the 21cm signal with Ly-α photons

Agius & TRS 2510.26791

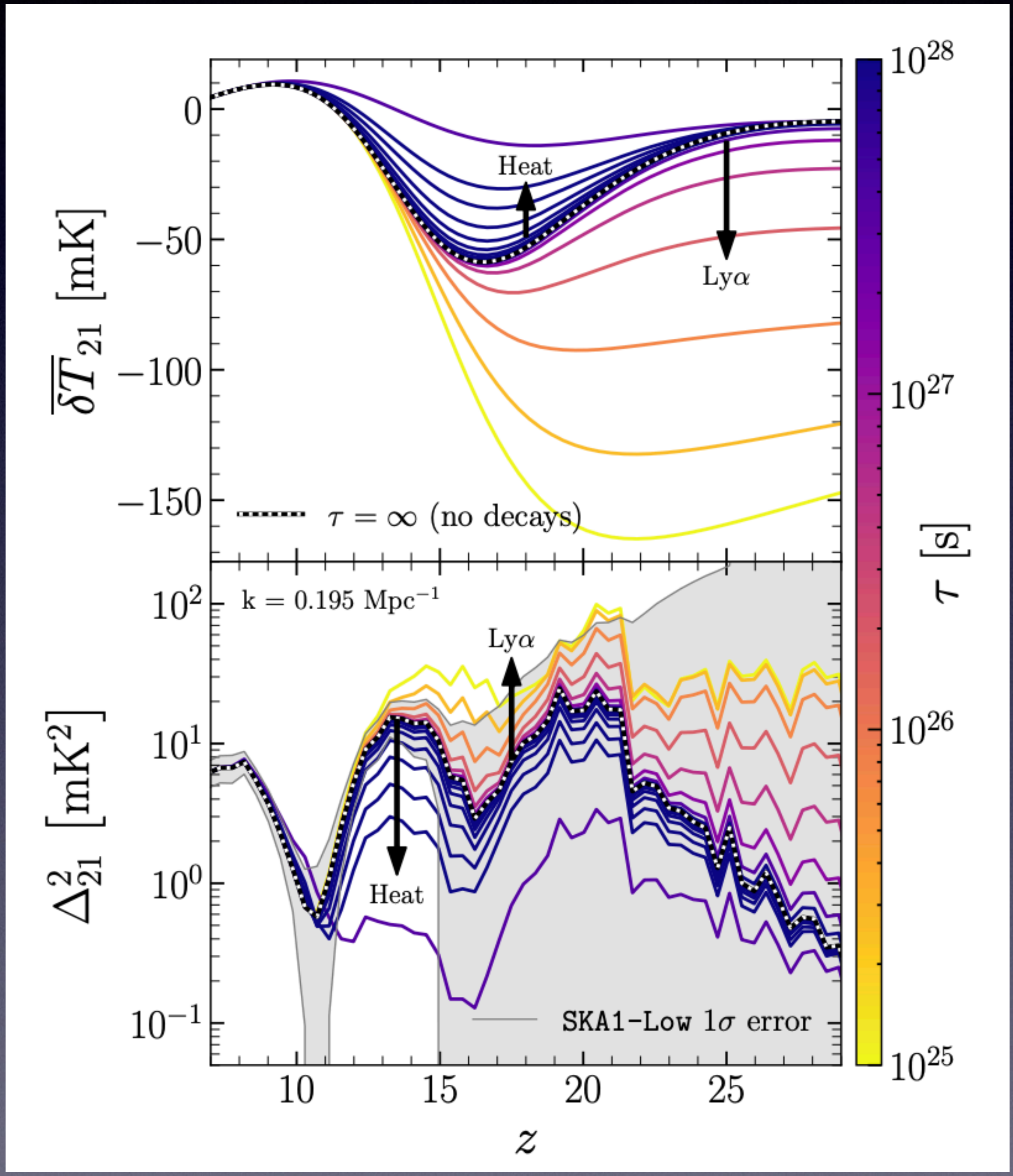
- We installed DM21cm on subMIT (taking advantage of GPU acceleration) and ran it to simulate the effects of DM decay for various scenarios
- Simple physical realization is DM in the ~20-50 eV band decaying to two photons:
  - Lower energies (~20-27 eV): DM decays directly into Lyman-band photons, no ionization/heating
  - Higher energies (~27-50 eV): DM decays into photons that promptly ionize the gas; ionization enhances gas heating by CMB, secondary electrons produce heating directly



- Allows us to study the effects of turning on heating/ionization vs Lyman-band photons independently

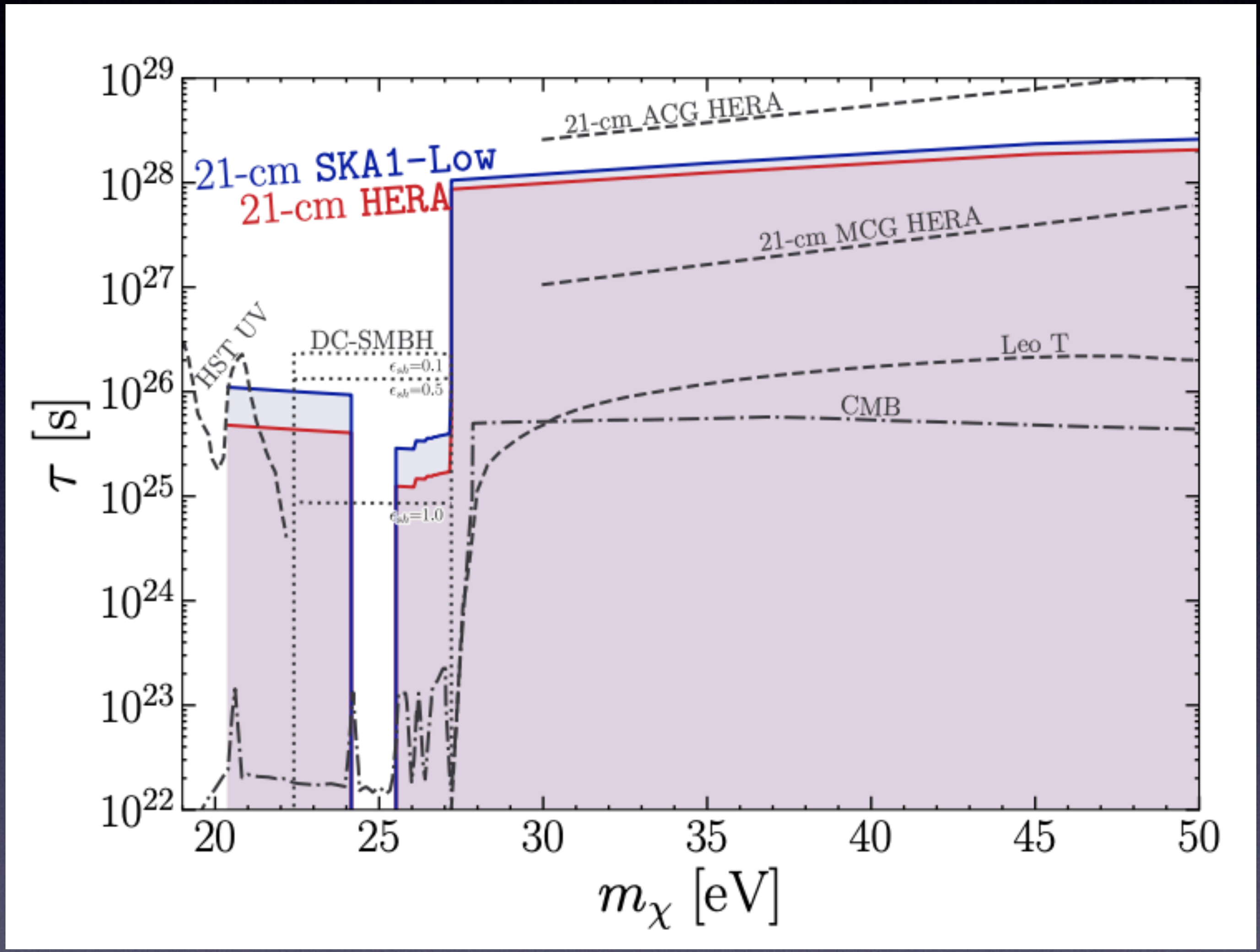
Effects of heating vs Ly-α

- We show the effect of decay of 20.4 eV DM (pure Ly-α injection) compared with 50 eV DM (~50-50 ionization/heating, no Ly-α)
- Ly-α injection leads to a larger (more negative) global signal at high redshifts; heating suppresses the signal at mid-redshifts
- Similar impact on power spectrum of fluctuations
- Relevant lifetimes for Ly-α are much shorter than for heating — suggests that if power into these channels is comparable, heating effect will dominate



Sensitivity to light DM

- For heavier DM (>50 eV), typically heating/Ly-α fractions are comparable (within 1 order of magnitude), so heating dominates
- But for 20.4 eV < m_{DM} < 27.2 eV, we can perform a novel sensitivity forecast based purely on the Ly-α effect
- Forecast limits are ~2 orders of magnitude weaker than heating-based sensitivity at higher mass, but could still set world-leading bounds in this mass range (which is hard to constrain)



- Forecast sensitivity covers a significant part of the parameter space where Lyman-Werner photons could enhance direct-collapse black hole formation [e.g. Friedlander et al 2212.11100, Lu et al 2404.03909.]

Summary

- Experiments seeking to measure the 21cm power spectrum have made great progress in improving sensitivity and are now getting close to the point where a signal is expected
- Decaying dark matter could leave signals in 21cm through its heating of the gas and/or its contributions to the Ly-α flux
- For DM with mass > 30 eV we generally expect the heating to dominate, but in a narrow mass range there is a potential signature of enhanced early Ly-α that would boost the 21cm signal
- For almost all DM masses above ~20 eV, 21cm constraints on decaying DM are expected to improve on current bounds by 2+ order of magnitudes