DM21cm: modeling inhomogeneous energy injection for 21cm

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Based (primarily) on arXiv:2312.11608, with Yitian Sun, Josh Foster, Hongwan Liu & Julian Muñoz

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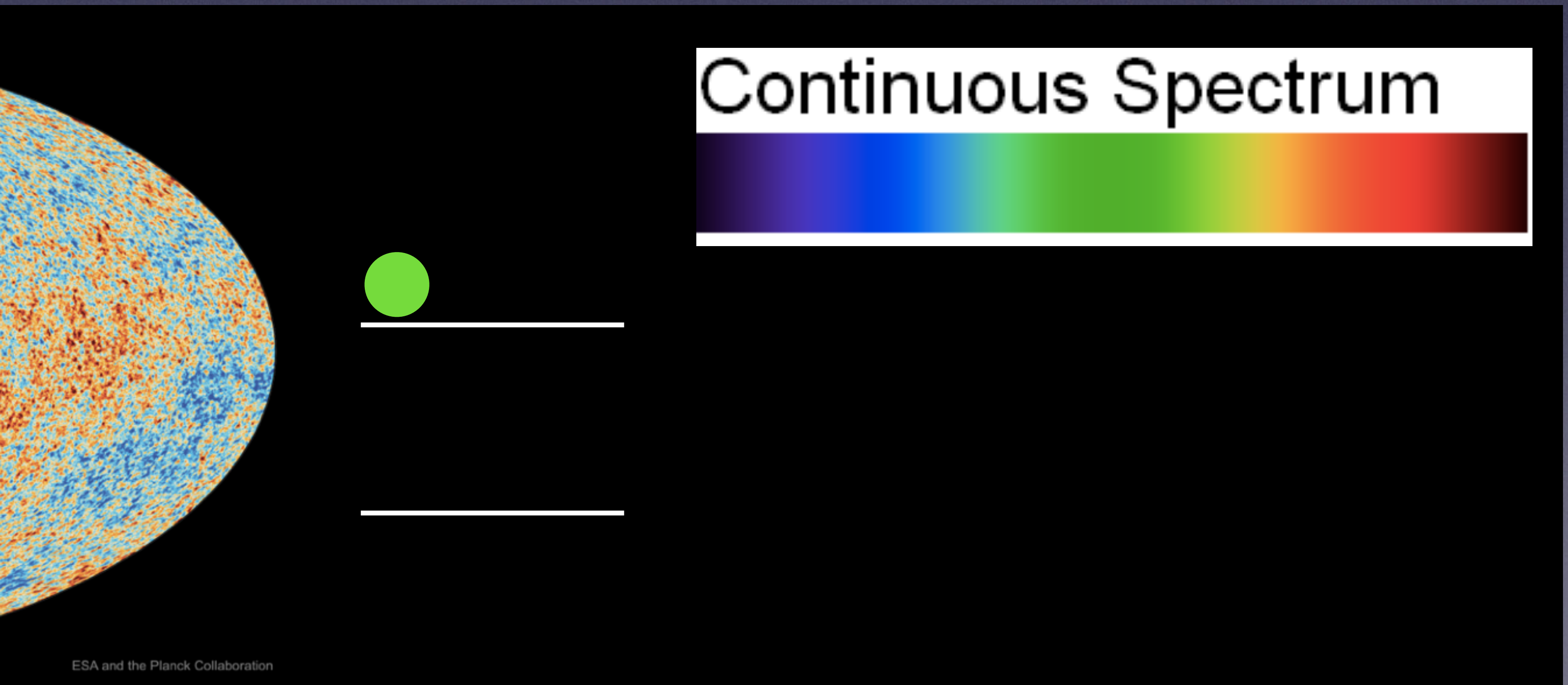
Outline

- Intro: expected behavior of redshifted 21cm line + current observational status
- How dark matter decay could affect this signal (back-of-the-envelope)
- DM21cm: capturing inhomogeneity of the cosmos and upgrading the treatment of energy injection in 21cmFAST
- Forecasts for DM decay sensitivity with HERA Phase II

Primordial 21cm

- Long-standing effort to measure primordial redshifted 21cm radiation from spin-flip transition of neutral hydrogen
- Global average brightness: $T_{21}(z) \approx x_{\mathrm{HI}}(z)\left(\frac{0.15}{\Omega_m}\right)^{1/2}\left(\frac{\Omega_b h}{0.02}\right)\left(\frac{1+z}{10}\right)^{1/2}\left[1-\frac{T_R(z)}{T_S(z)}\right]$ 23mK
- "Spin temperature" T_S characterizes relative abundance of ground (electron/proton spins antiparallel) and excited (electron/proton spins parallel) states: $n_{\mathrm{exc}}/n_{\mathrm{gr}} = 3e^{-h\nu_0/k_B T_S}$
- Local brightness (relevant for fluctuations) also depends on local hydrogen density + peculiar velocity of gas clouds
- Would be a powerful new 3D probe of the end of the cosmic dark ages and "cosmic dawn"



- If T_S exceeds the ambient radiation temperature T_R, there is net emission; otherwise, net absorption.
- If T_S greatly exceeds T_R we lose all sensitivity to T_S - null results set lower bounds on T_S/T_R.

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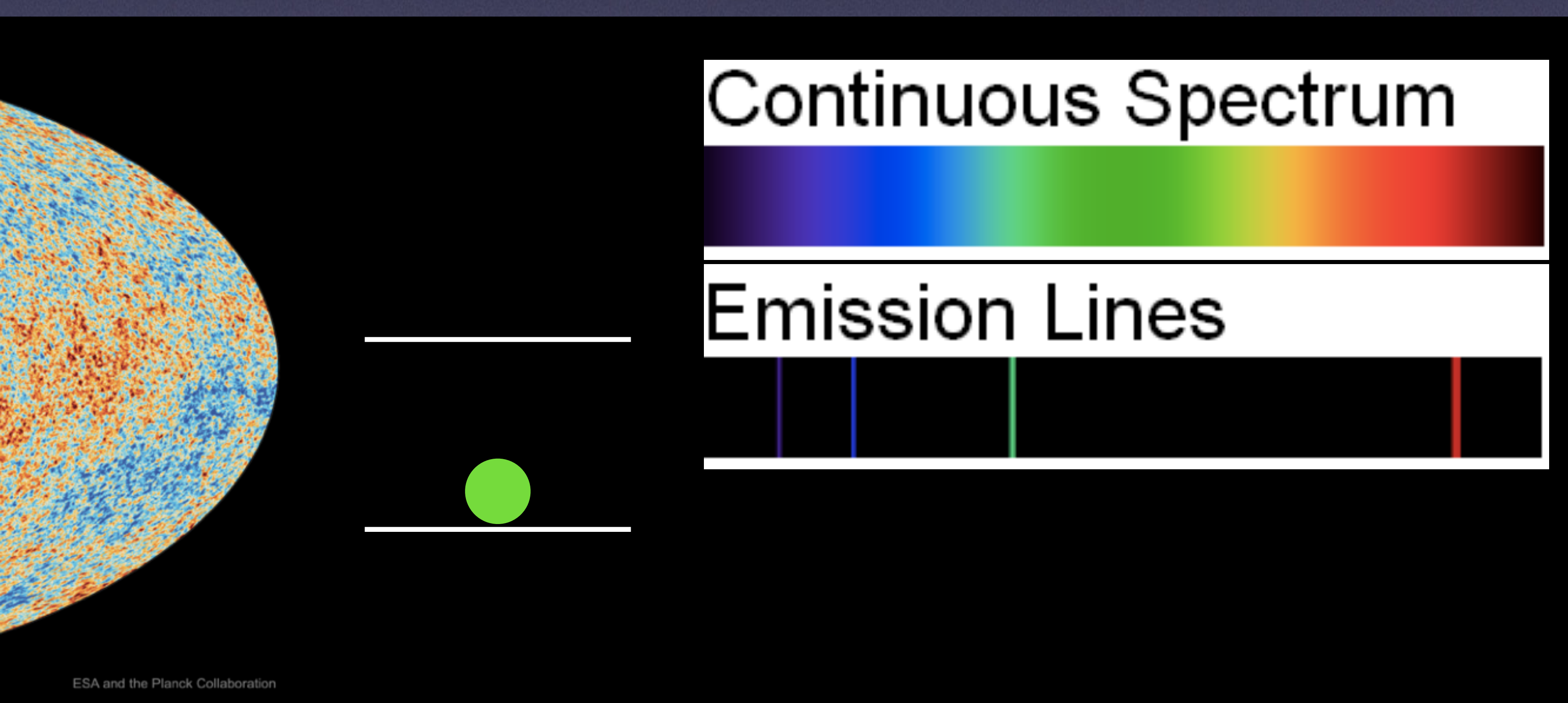

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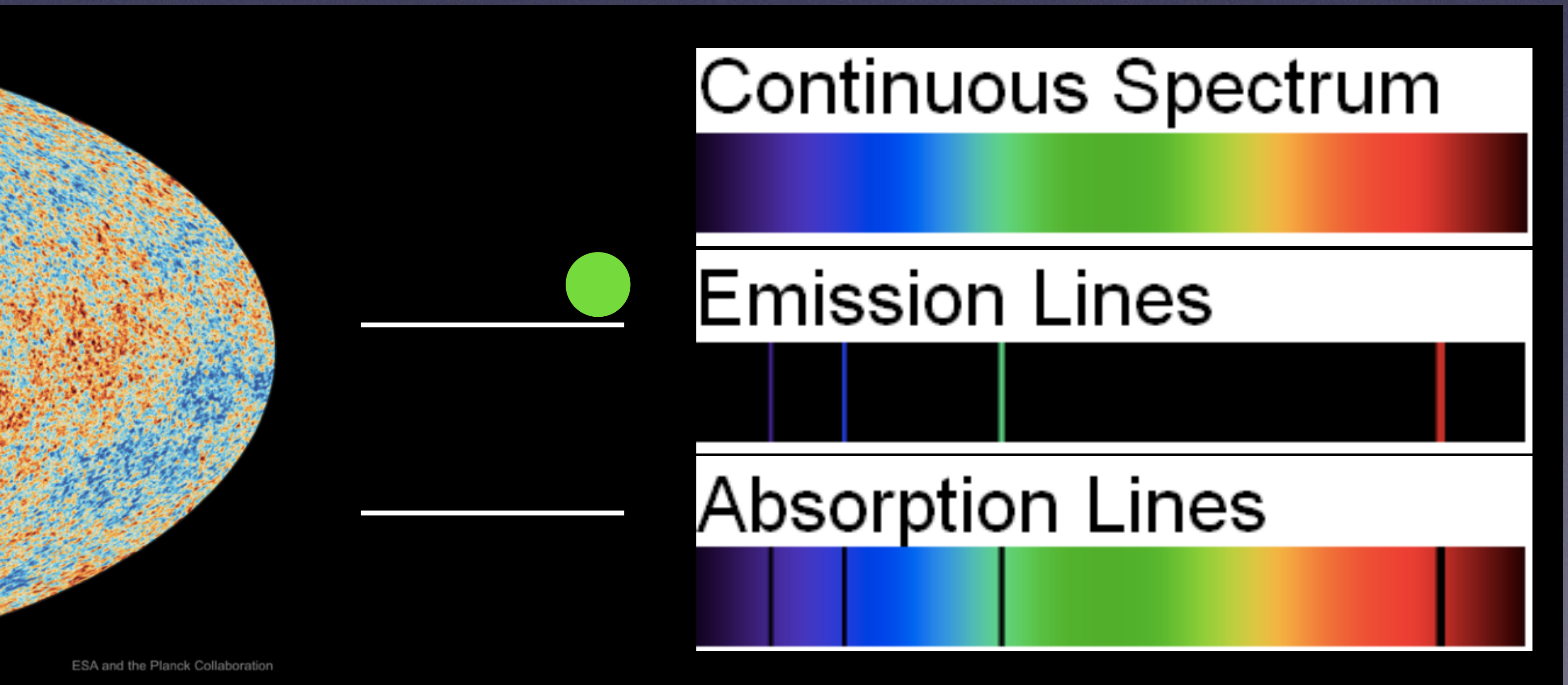

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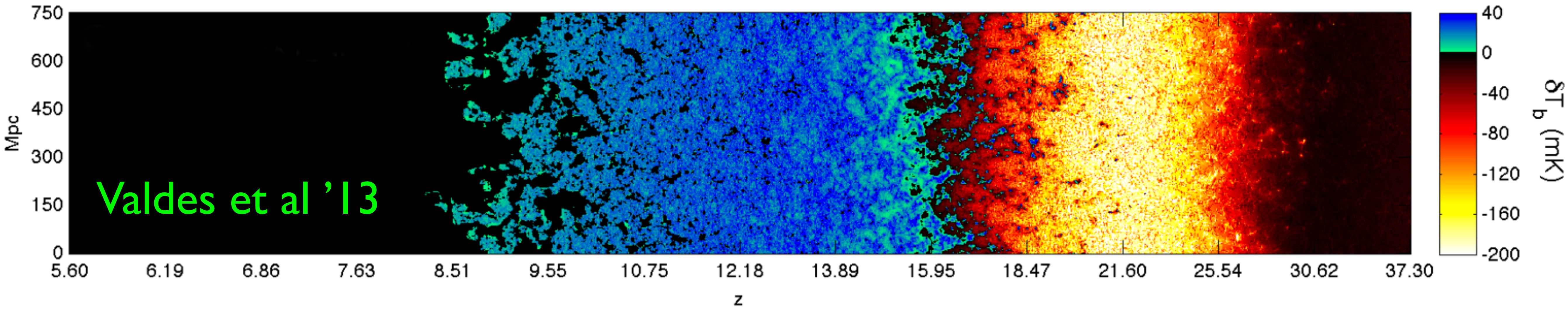
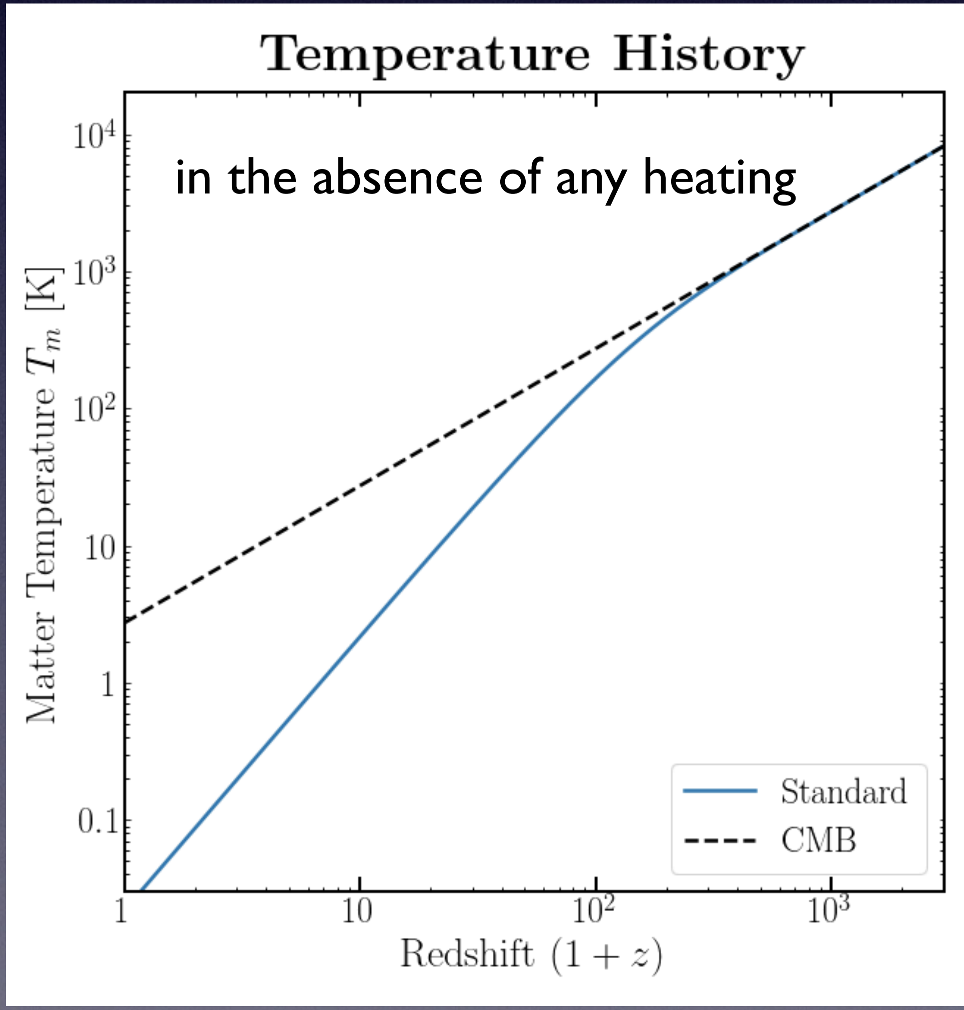
Expectations for a 21cm signal

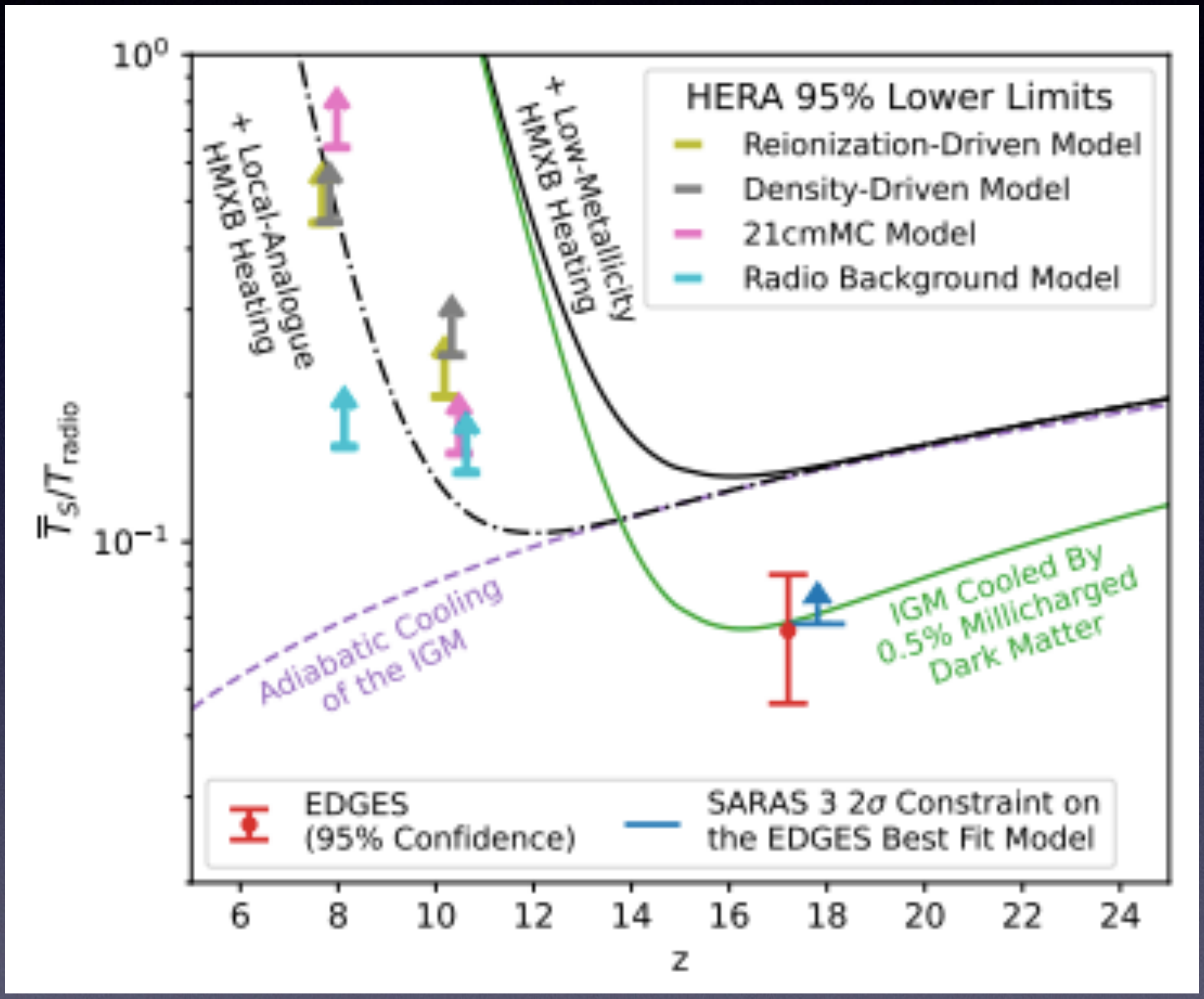


- T_S may be coupled to T_{gas}, T_R, T_α by various processes, but expect $T_S \sim T_{gas}$ after first stars turn on.
- Expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature (unless there is exotic/unexpected early heating).
- Later, stars heat $T_{gas} > T_R$, expect an overall emission signal with fluctuations from inhomogeneity of heating.
- As we approach reionization, 21cm fluctuations are mainly set by density+ionization fluctuations. Lose sensitivity to $T_S >> T_R$, but can probe distribution of neutral hydrogen.
- Multiple 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 - can aim to measure either global signal or power spectrum.



Current status of the search for 21cm

- Claimed global signal detection by EDGES [Bowman et al 1810.05912]; in mild tension with SARAS 3 non-detection [Singh et al 2112.06778]
- The HERA telescope 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], see also limits from MWA, LOFAR [Trott et al 2002.02575, Mertens et al 2002.07196]
- Focus so far is on reionization, z < 12
- Null observations exclude low temperatures in this epoch (which would give a deep absorption signal inconsistent with observations)



- "Deployment of the phase II system is nearing completion" [Berkhout et al 2401.04304]: 350 antennas, frequency range 50–250 MHz, 4.7 < z < 27.4.

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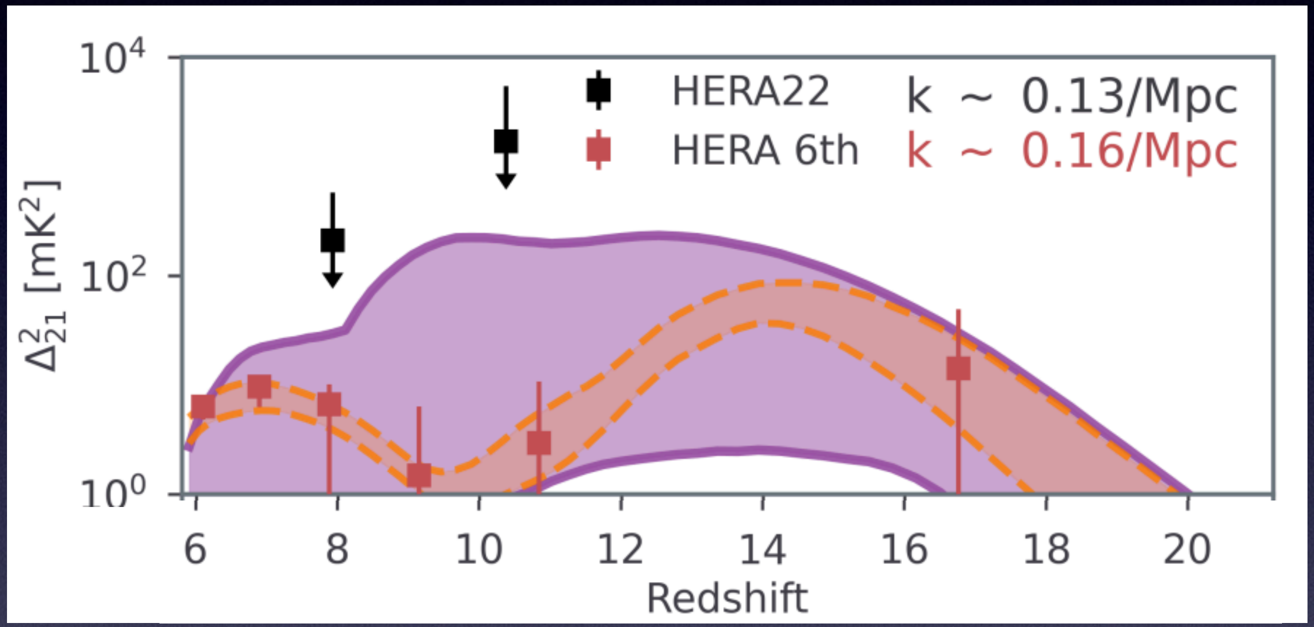

Forecast sensitivity for HERA season 6, data taken 2022-2023, ~150 nights (1300 hours) x 150 antennas, 50-230 MHz [Breitman et al 2309.05697]

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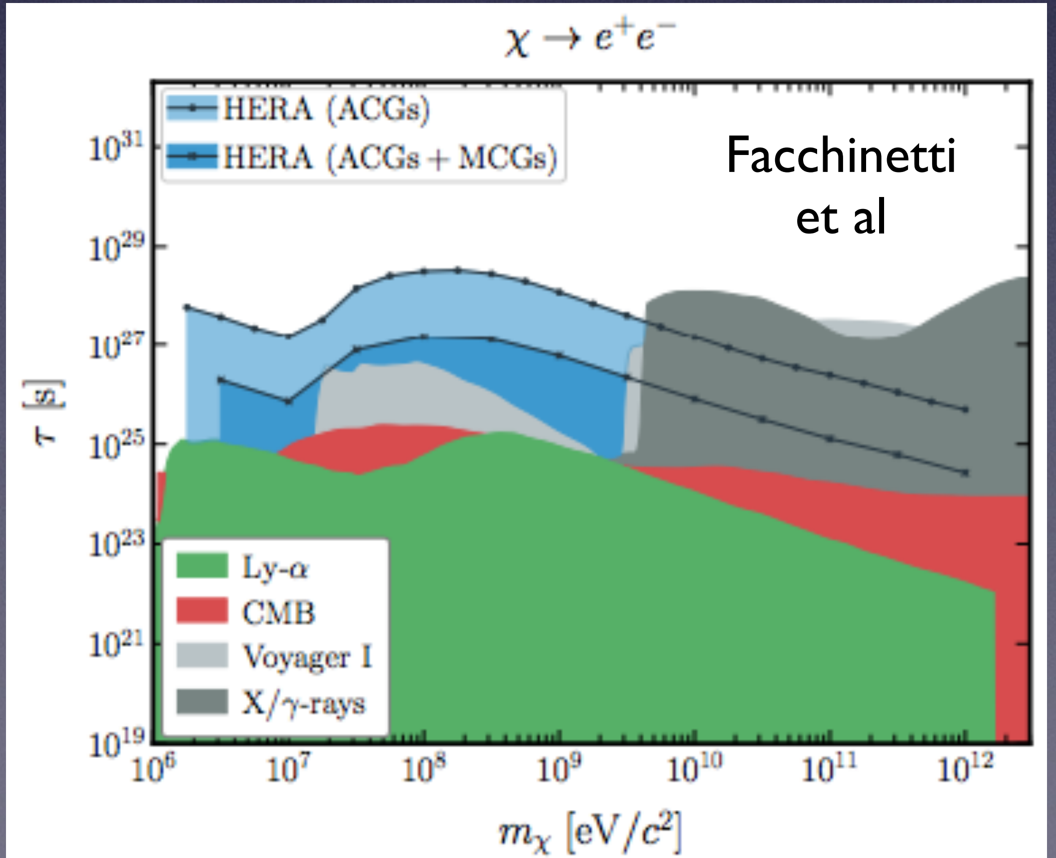
Applications for DM physics

- Can be used as a 3D probe of large scale structure extending to high redshifts (see next talk by Ely Kovetz) - relevant for fuzzy DM, warm DM, etc
- Can also be used as a sensitive probe of extra heating/ionization, e.g. from DM decay, annihilation, oscillations, axion star explosions, evaporation/accretion of PBHs, etc (or extra cooling, a la EDGES…)
- Limits on heating/ionization compete with indirect detection + other cosmological bounds - advantage of 21cm for heating-based signals is that it will probe an epoch when the universe is expected to be quite cold

Estimating 21cm sensitivity to decaying DM

- Fraction of DM decaying per e-fold in a given epoch ~ lifetime of cosmos / lifetime of DM
- Suppose primordial 21cm radiation is detected and implies a gas temperature at z~20 of ~10 Kelvin (rough expectation from standard astrophysics) with an O(1) error bar
- 10 K heating costs ~10^{-3} eV/baryon, DM is 5 GeV/baryon, hence can constrain ~10^{-13} of the DM decaying if mass energy is converted efficiently into heating
- Age of the universe at z~20 ~ 1% of present age ⇒ DM lifetime exceeding 10^{11} x present age of universe ~ few x 10^{28} s
- This is comparable to the best current indirect detection bounds and about three orders of magnitude stronger than cosmological bounds from CMB/Lyman-alpha, consistent with results of Facchinetti et al 2308.16656



DarkHistory

- To study energy injection via high-energy particles in detail, we need to know how the primary particles 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 compute the modified ionization/temperature history by:
  - modeling energy-loss processes and production of secondary particles,
  - accounting for cosmic expansion / redshifting,
  - with self-consistent treatment of exotic and conventional (astrophysical) sources of energy injection.
- Publicly available at https://github.com/hongwanliu/DarkHistory
- Compact version using neural networks led by Yitian Sun (2207.06425); version with in-depth treatment of low-energy particles + spectral distortions of photon background led by Wenzer Qin & Greg Ridgway (2303.07366, 2303.07370).
- Assumes a spatially homogeneous universe (all quantities = cosmic average values)

Can we assume homogeneity for 21cm?

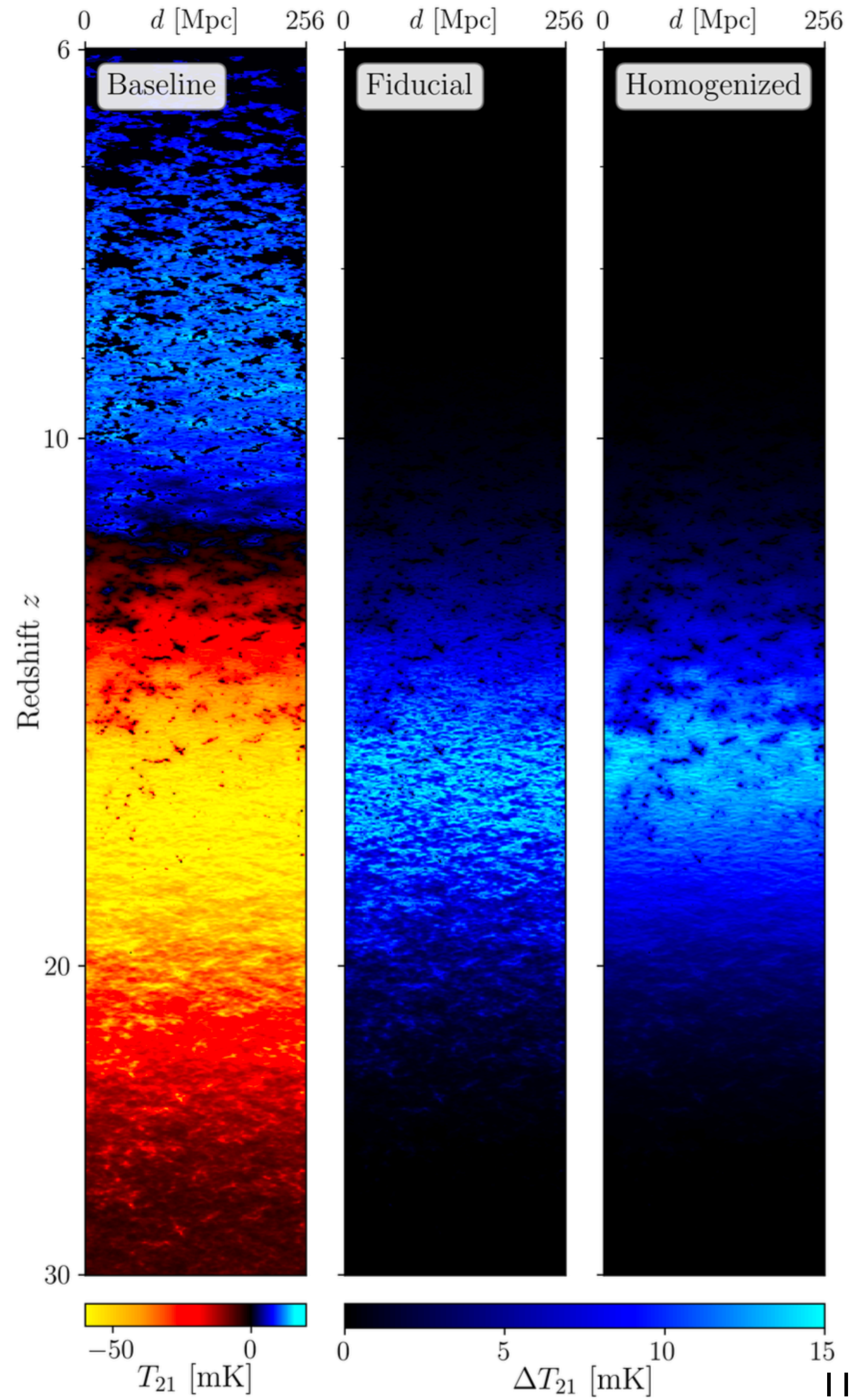
- Previous studies of DM-induced heating in 21cm assume signal is ~homogeneous in space [e.g. Evoli et al 1408.1109, Lopez-Honorez et al 1603.06795, Poulin et al 1610.10051, Facchinetti et al 2308.16656], but this is an approximation: neither the "beam" (dark matter distribution) nor "target" (gas to be heated) are homogeneous over the relevant redshifts
- However, an inhomogeneous source distribution may be smeared out by long path lengths for injected particles
- If we assume homogeneity, how should we assess the correct ionization/temperature level to use for computing the secondary particle cascade?
- Can average, but regions with very high ionization have no/suppressed 21cm emission; what is the right weighting function?
- Spatial distribution of DM-sourced energy injection will differ from astrophysics - does homogeneity assumption exaggerate the difference / hide degeneracies?
- Validity of homogeneity assumption is likely to be strongly dependent on the spectrum of particles injected (path lengths differ strongly by photon energy) - could conceal differences between models

21cmFAST

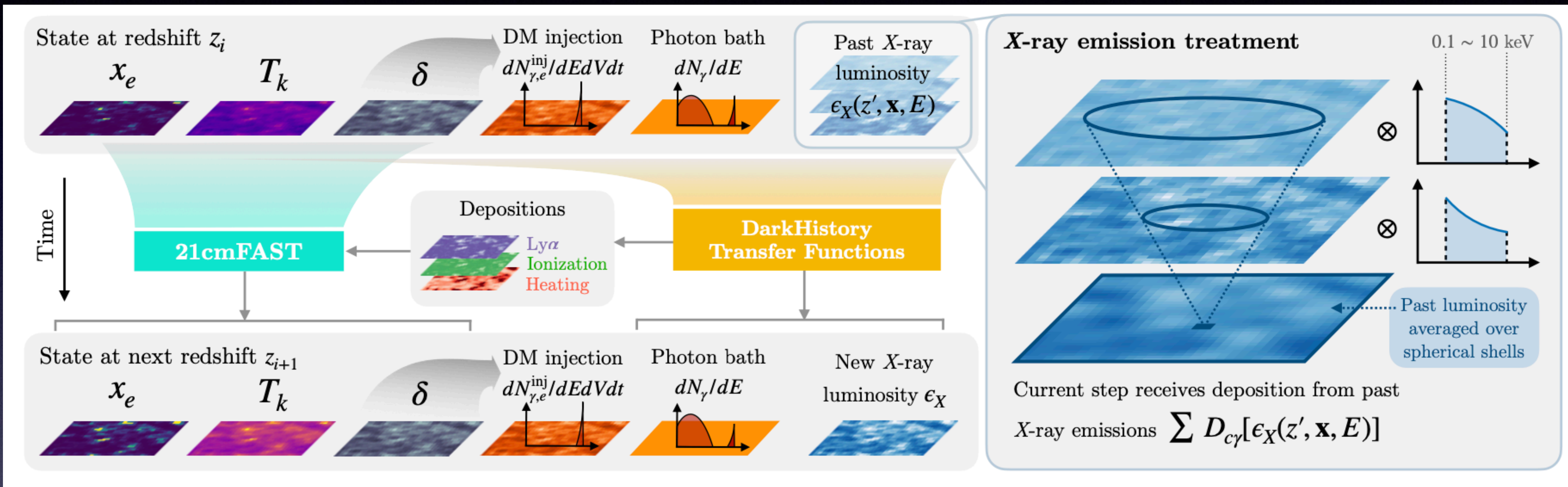
- We started from a widely-used public code for estimating the 21cm power spectrum (without exotic energy injection), 21cmFAST [Mesinger et al 1003.3878]
- Semi-numerical simulation that generates realizations of the (inhomogeneous) density, ionization, peculiar velocity, and spin temperature, and consequently the 21cm brightness temperature
- Checked against hydrodynamic simulations, agrees at 10s of percent level
- Models both prompt energy deposition from ionizing photons and longer-range energy deposition from X-rays (expected to dominate heating prior to reionization) - requires integrating signal from earlier X-ray sources
- What we need: particle injection model not tied to star formation history, ability to handle general photon spectra extending to higher energies, and injection of other particles

DM21cm

- We developed a new public code (https://github.com/yitiansun/DM21cm) built off existing public 21cmFAST code + DarkHistory
- Extends 21cmFAST with flexible, general treatment of energy injection (from DM or astrophysics)
- Accounts for inhomogeneous injection (arbitrary function of density) + propagation effects + inhomogeneous cooling
- Code is written in JAX, takes advantage of GPU acceleration for computationally expensive steps; only O(1) time increase vs 21cmFAST in our configuration (32 CPUs and one A100 GPU)
- Example: changes to 21cm brightness temperature for 1 keV DM decaying to monochromatic photons



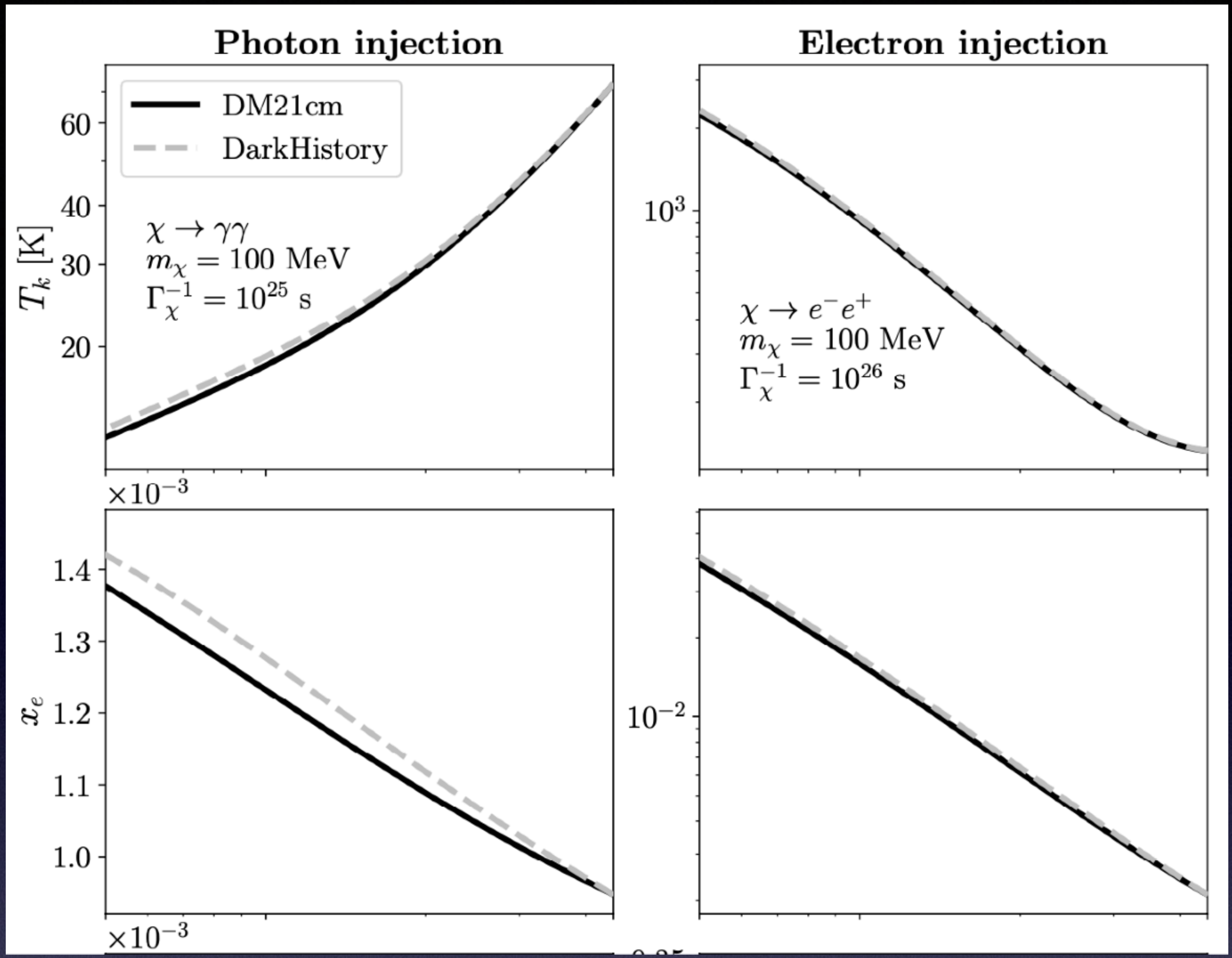
DM21cm approach

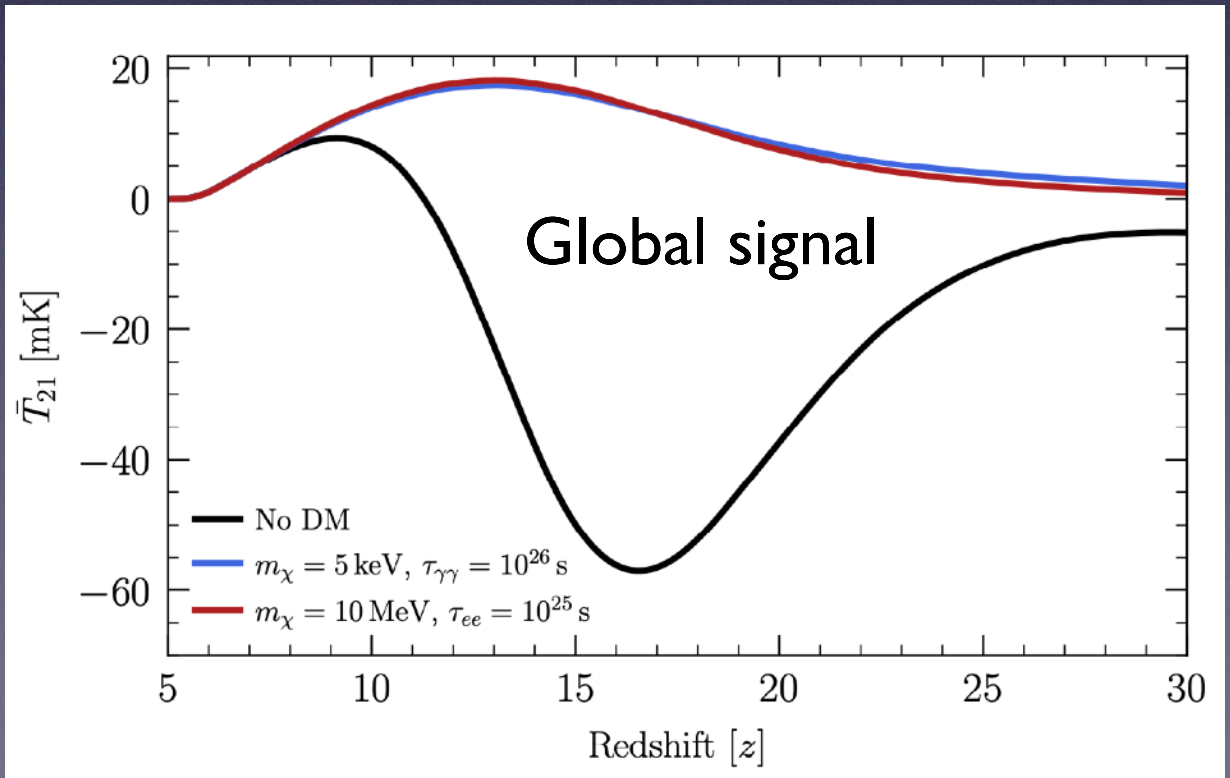


- Subdivide additional high-energy particles into free-streaming bath + X-rays (finite propagation length) + promptly deposited particles
- Treat free-streaming bath as homogenized source, but compute absorption/cooling in each cell independently based on gas density/ionization (using extended transfer functions adapted from DarkHistory, but accounting for gas density)
- Lightcone integral to account for X-rays incident on each cell (checked against existing 21cmFAST treatment for astrophysical X-rays, but removes simplifying assumptions)

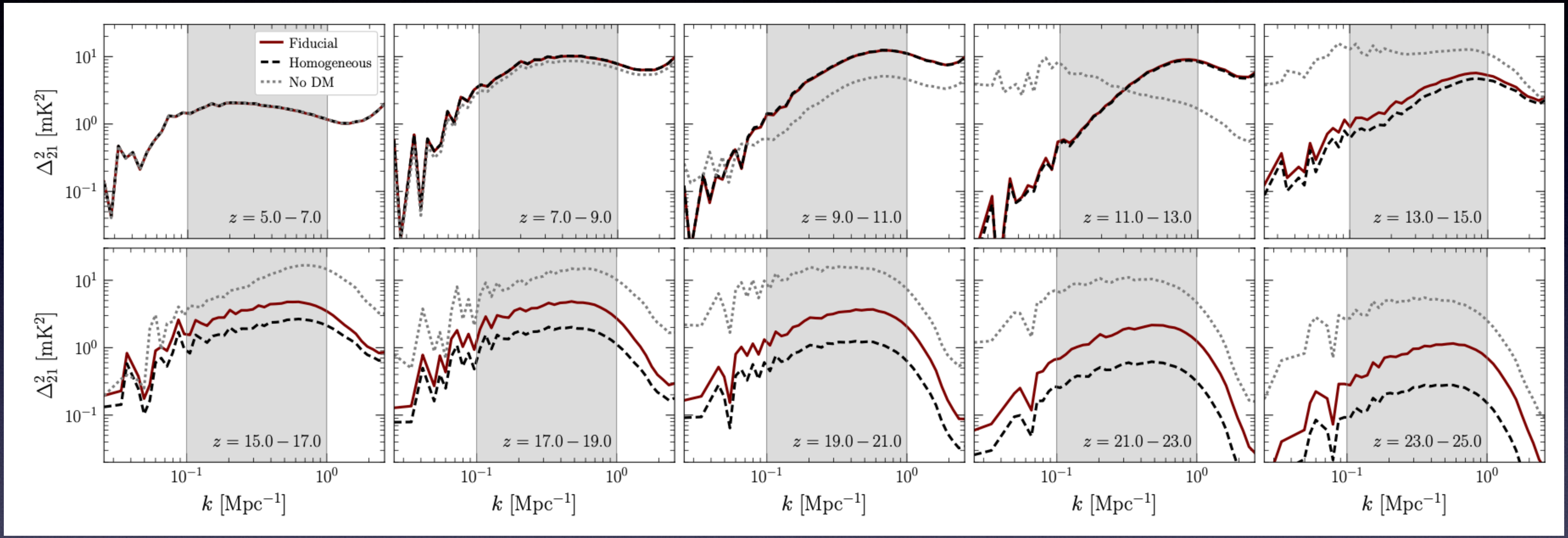
The global signal

- One question we might ask is whether previous global signal calculations are valid?
- Many such calculations were motivated by 2018 EDGES claimed detection; based on homogeneity assumption similar to DarkHistory
- We compared global temperature/ ionization evolution with DarkHistory (homogeneous) vs DM21cm (inhomogeneous)
- Within the decaying-DM scenarios we tested, we find agreement at the level of several percent
- This in turn implies similar evolution of global signal with redshift for different DM models



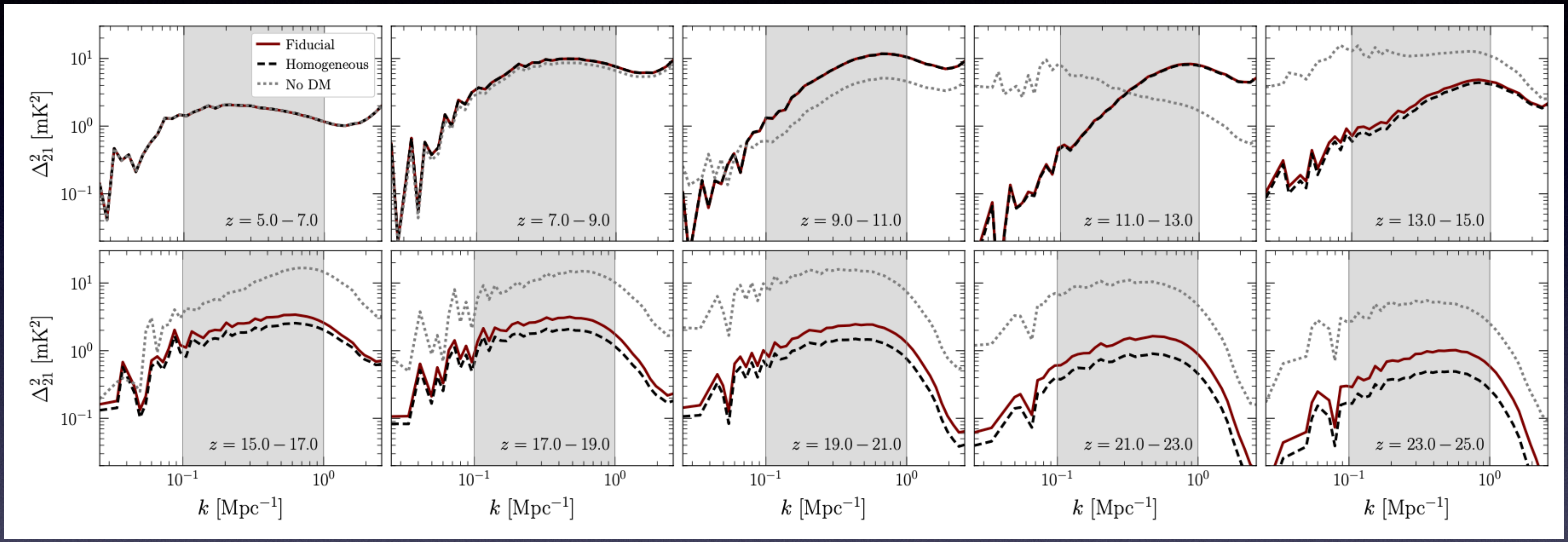


The power spectrum



- We obtain the power spectrum as a function of redshift bin
- Example above is for 10 MeV DM decaying to e^+e^- (with relatively short lifetime, 10^{25} s, to demonstrate the effects clearly); fairly local deposition where inhomogeneity is relatively important
- Gray band indicates wavenumbers used in our detectability analysis
- Effects of inhomogeneity are very small below z=13 (main effect is modest acceleration of reionization)
- O(1) differences in signal between homogeneous/inhomogeneous treatments emerge at higher redshift

The power spectrum (II)



- As previously, but for 5 keV DM decaying to photons, i.e. injection into X-ray band
- Inhomogeneity effects are still visible at higher redshift, but are washed out due to relatively long path length of X-rays

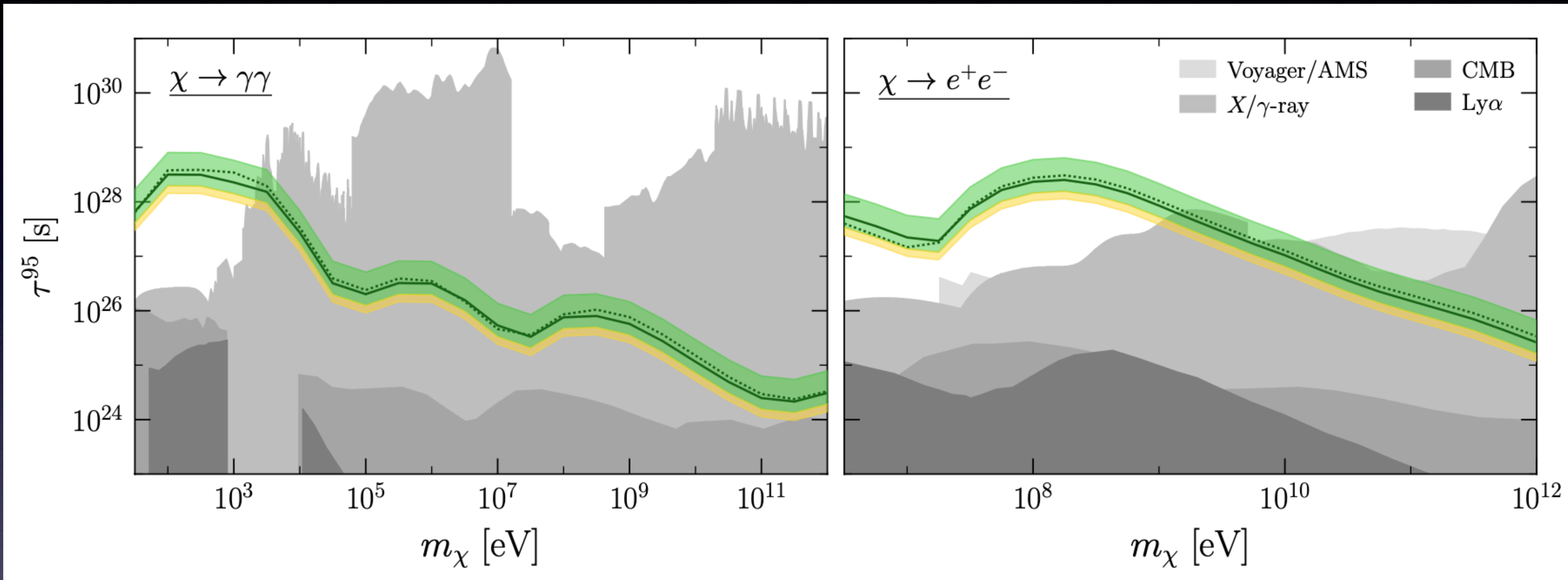
Projecting sensitivity

- We performed a Fisher analysis using the public 21cmfish framework [Mason et al 2212.09797]
- Considered sensitivity for HERA Phase II configuration
  - 331 antennae
  - 8MHz frequency bandwidths between 50 and 250MHz
  - total exposure 1080 hours
- Include “moderate” foreground model from 21cmSense, HERA system temperature estimate, 20% systematic error budget

PopII parameters	$f_{\star,10}^{\mathrm{II}}$	$\alpha_\star^{\mathrm{II}}$	$f_{\mathrm{esc},10}^{\mathrm{II}}$	L_X^{II}
Fiducial value	-1.25	0.5	-1.35	40.5
PopIII parameters	$f_{\star,7}^{\mathrm{III}}$	$\alpha_\star^{\mathrm{III}}$	$f_{\mathrm{esc},7}^{\mathrm{III}}$	L_X^{III}
Fiducial value	-2.5	0.0	-1.35	40.5
Shared parameters	$t_\star$	α_{esc}	E_0	A_{LW}
Fiducial value	0.5	-0.3	500	2.0

- Fiducial model contains two stellar populations, PopII and PopIII stars, residing respectively in atomic-cooling galaxies and (earlier) molecular-cooling galaxies
- Astrophysical nuisance parameters capture the star formation rate in these galaxies, the efficiency with which UV (ionizing) radiation escapes into the surrounding medium, the X-ray luminosity, and the minimum X-ray energy

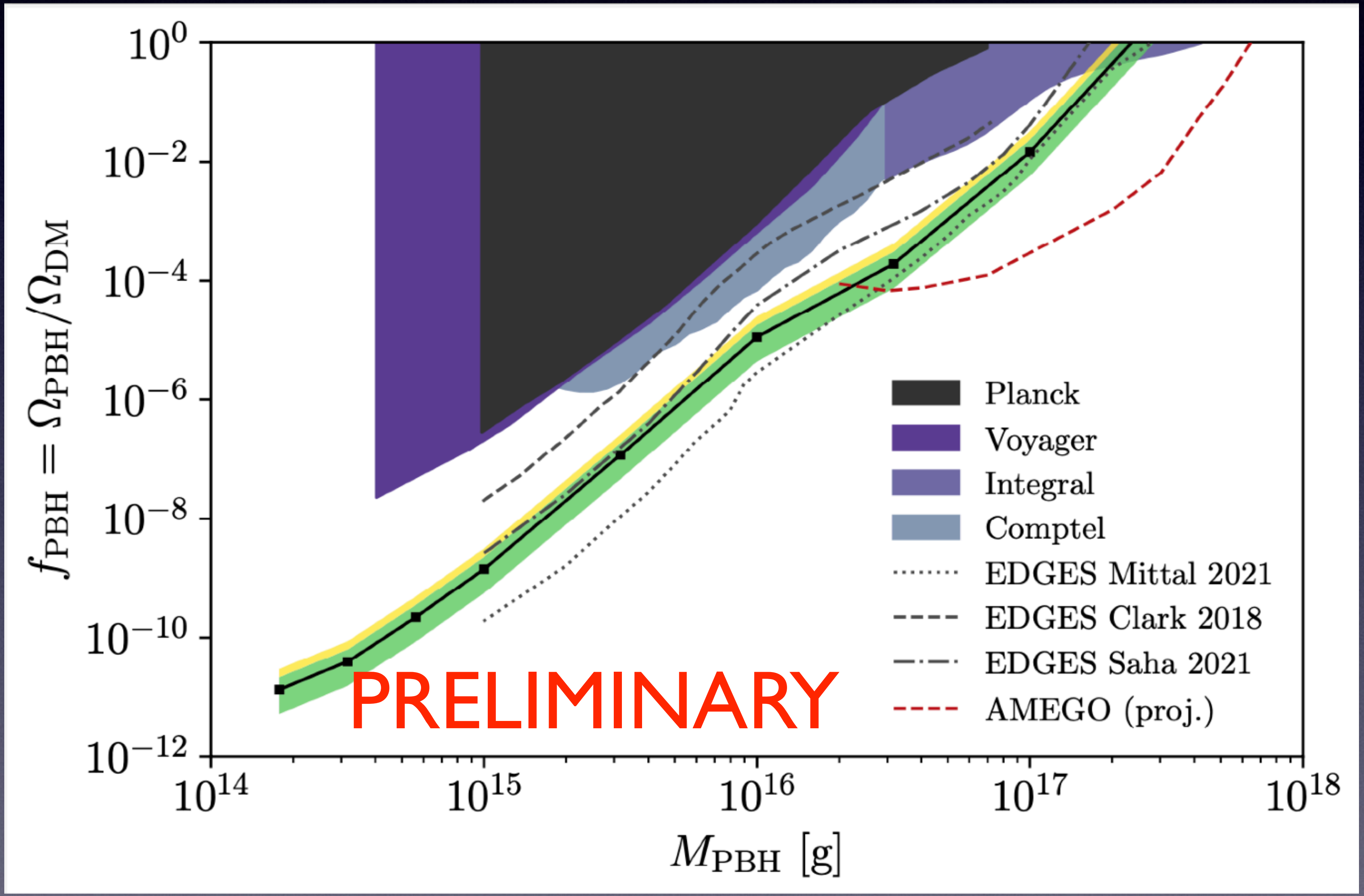
Sensitivity forecast



- Forecast constraints would exceed current limits for leptonic decays for masses below ~1 GeV, for decays to photons below ~1 keV
- Constraints on photon channel do not rely on measuring spectral shape; likely to remain similarly strong for photon-rich final states with a broader spectrum, vs indirect detection bounds which are much stronger for lines than for other channels
- Homogeneity approximation (dotted line) is also quite good in this case - likely because HERA sensitivity is dominated by lower redshifts

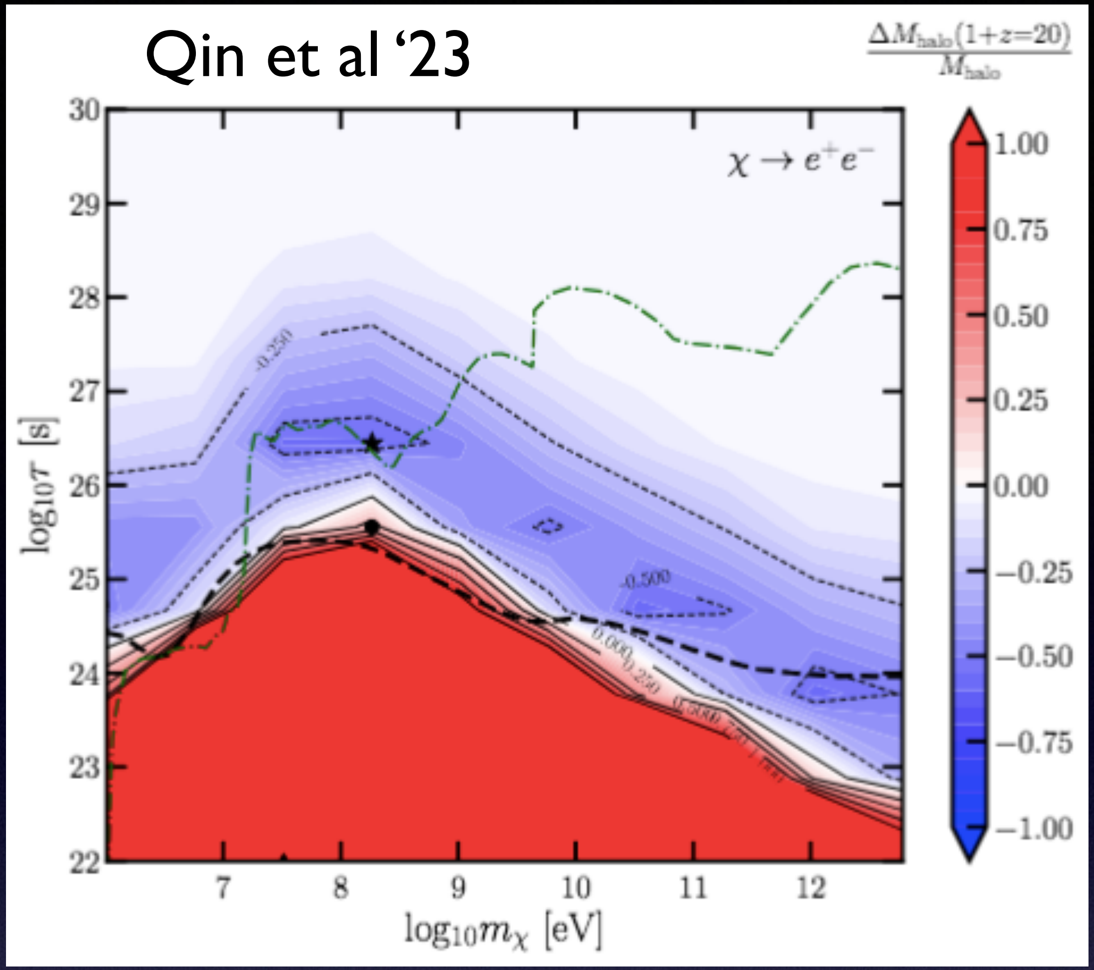
PBH evaporation forecast (PRELIMINARY)

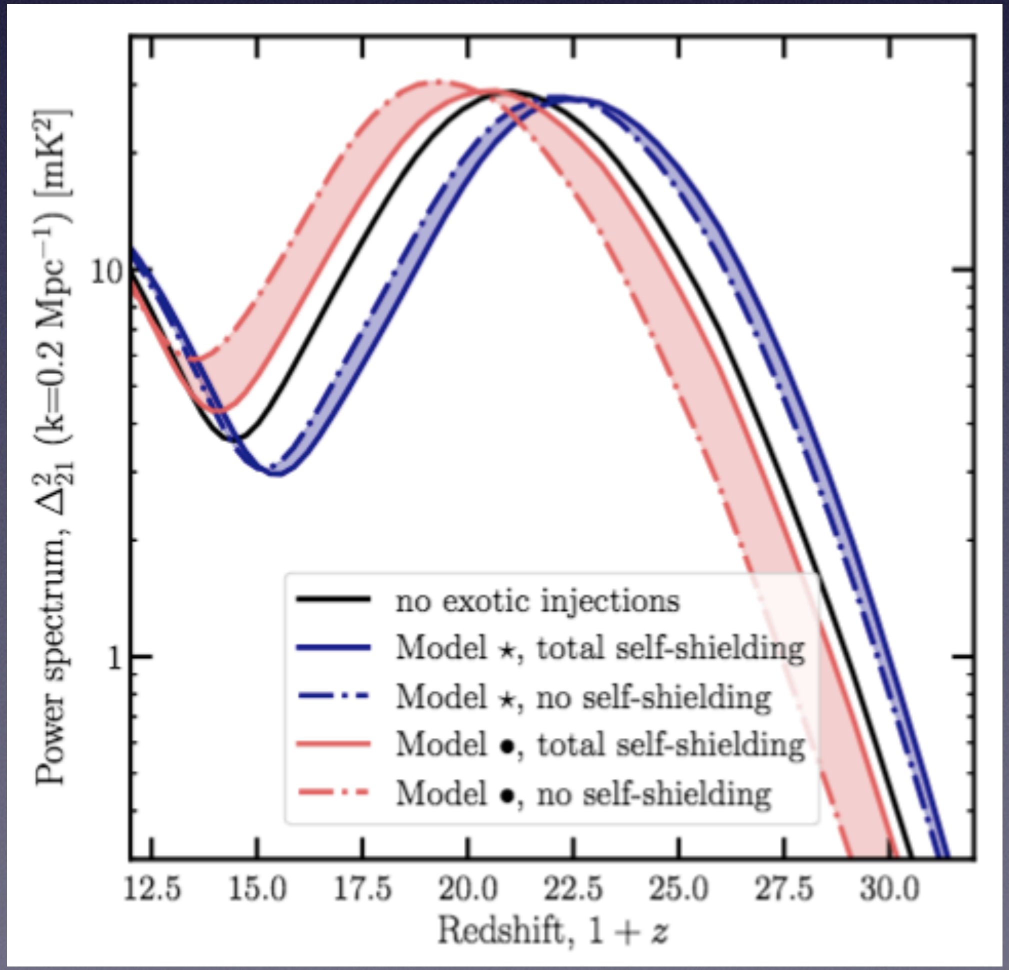
- Primordial black holes would decay via Hawking radiation
- Lifetime proportional to mass^3; temperature proportional to mass^{-1}
- For lifetimes longer than the age of the universe, behave similarly to decaying dark matter, with photon spectrum set by the temperature (+other particles at sufficiently low PBH masses / high temperature)



Other energy injection effects on 21cm

- The analysis in this paper considered only the direct effects of ionization/heating from DM decay
- It is also possible that energy injection could change the evolution of astrophysical objects, and hence indirectly affect the primordial 21cm signal
- e.g. in Qin, TRS et al 2308.12992 (following older work by Ripamonti et al '06, Stasielak et al '06) we argued that energy injection from decaying DM could accelerate the formation of the first stars, shifting the timescale for injection of X-rays and ionizing radiation



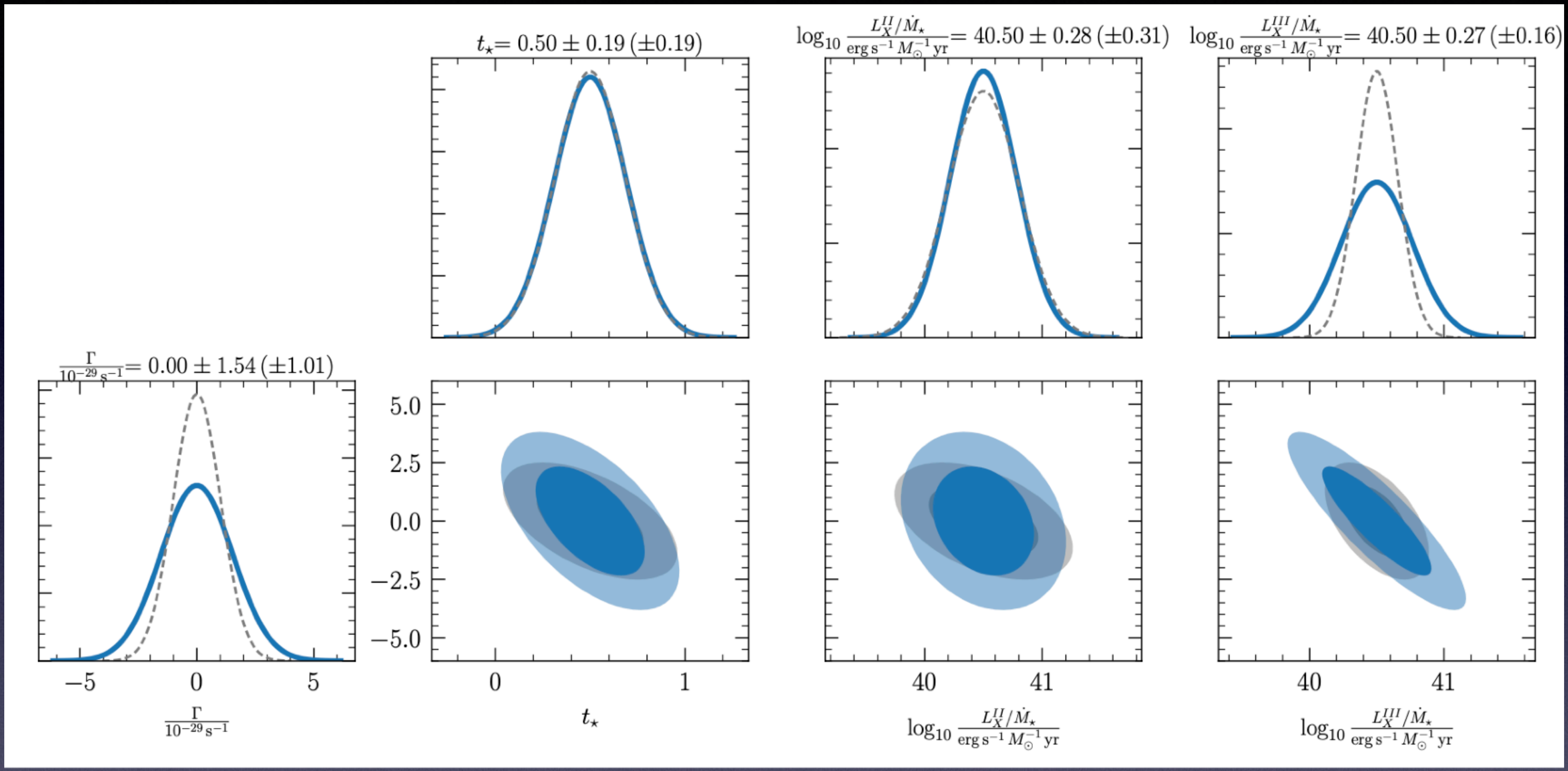


Summary

- Experiments are getting close to being able to detect primordial 21cm radiation under plausible astrophysical assumptions
- A confirmed detection of primordial 21cm radiation would provide a new window on the ionization and/or temperature history of cosmic dawn and the end of the cosmic dark ages
- Both back-of-the-envelope estimates and more detailed calculations suggest the potential to establish lifetime limits on decaying DM as long as a few x 10^{28} s
- We have presented a new publicly available code, DM21cm, to compute the effect of additional energy injection on the 21cm global signal and power spectrum
- DM21cm upgrades the energy injection treatment in the public code 21cmFAST and allows for flexible models of energy injection with user-specified spatial inhomogeneity, redshift dependence, and spectrum of injected particles

BACKUP SLIDES

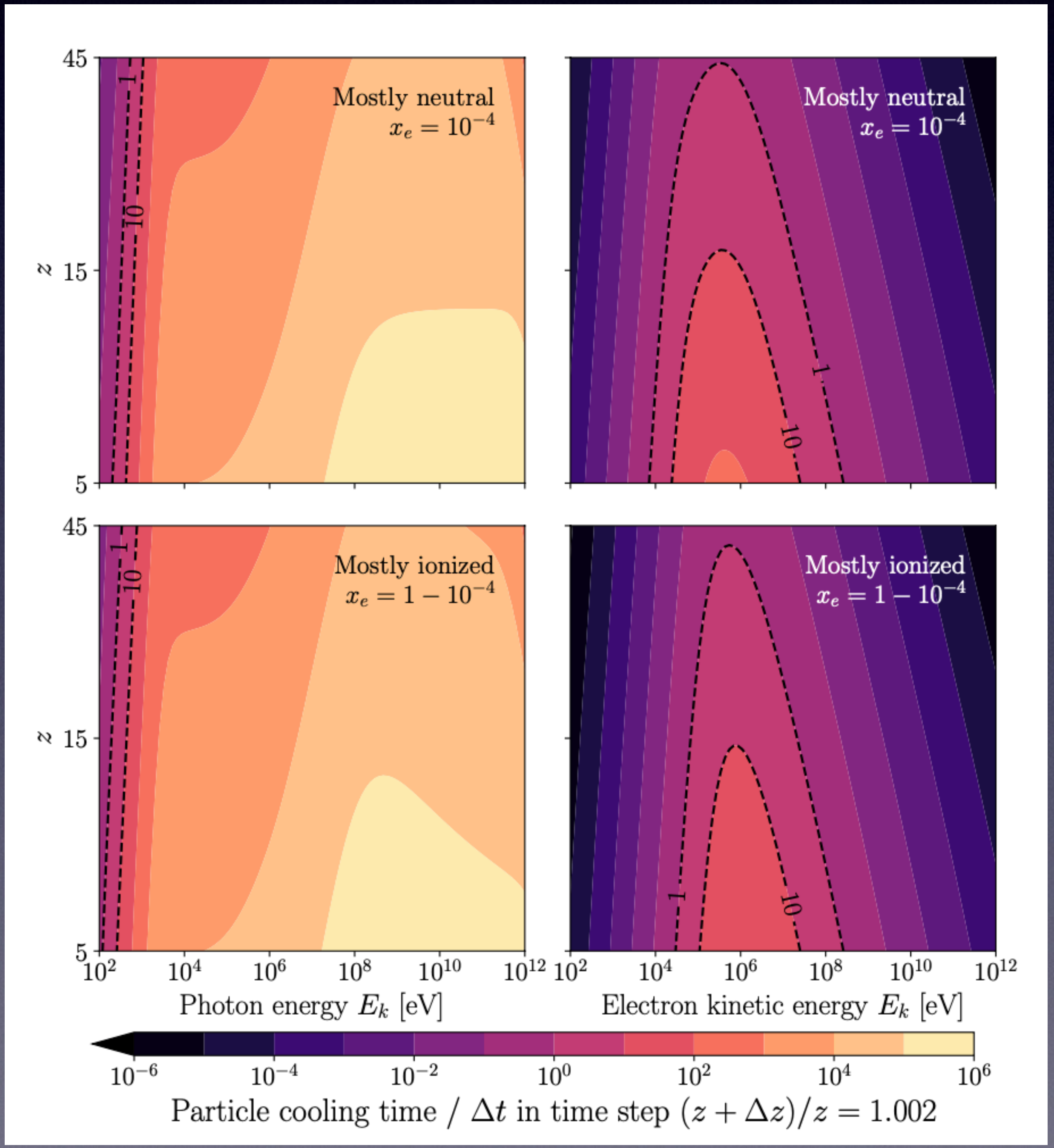
Degeneracies



- The astrophysical parameters most degenerate with the decay lifetime control the star formation rate (t_*) and the X-ray luminosities of the two stellar populations
- This example is for 100 MeV DM decaying to e^+e^-, where deposition is fairly prompt. Gray contours show the effect of making an approximation of homogeneity, which reduces the apparent degeneracy from its true value (leading to slightly tighter constraints).

Incorporating inhomogeneity

- Context: path lengths / cooling times of injected particles differ by orders of magnitude depending on species/energy
- Already incorporated in traditional 21cm modeling, e.g. 21cmFAST separates out X-rays (0.1-10 keV) from lower-energy photons, estimates effect of long path length
- We need to consider even higher-energy photons - but to a good approximation these do homogenize



Improvements over 21cmFAST baseline

- Beyond DM annihilation and decay, DM21cm can be used to study generic energy injections (from exotic and/or astrophysical sources) and their impact on 21cm
- Allows for a user-defined injection of photons or electrons with custom spatial and spectral morphology, does not assume a particular redshift/spatial dependence for the energy injection (i.e. associated with the linear growth of structure)
- Incorporates up-to-date cross sections and treatment of energy deposition into different channels
- Takes into account that X-ray attenuation depends on gas density and is not all-or-nothing (21cmFAST uses top-hat attenuation approximation)
- Code is written in JAX, takes advantage of GPU acceleration for computationally expensive steps; only O(1) time increase vs 21cmFAST in our configuration (32 CPUs and 1 A100 GPU)

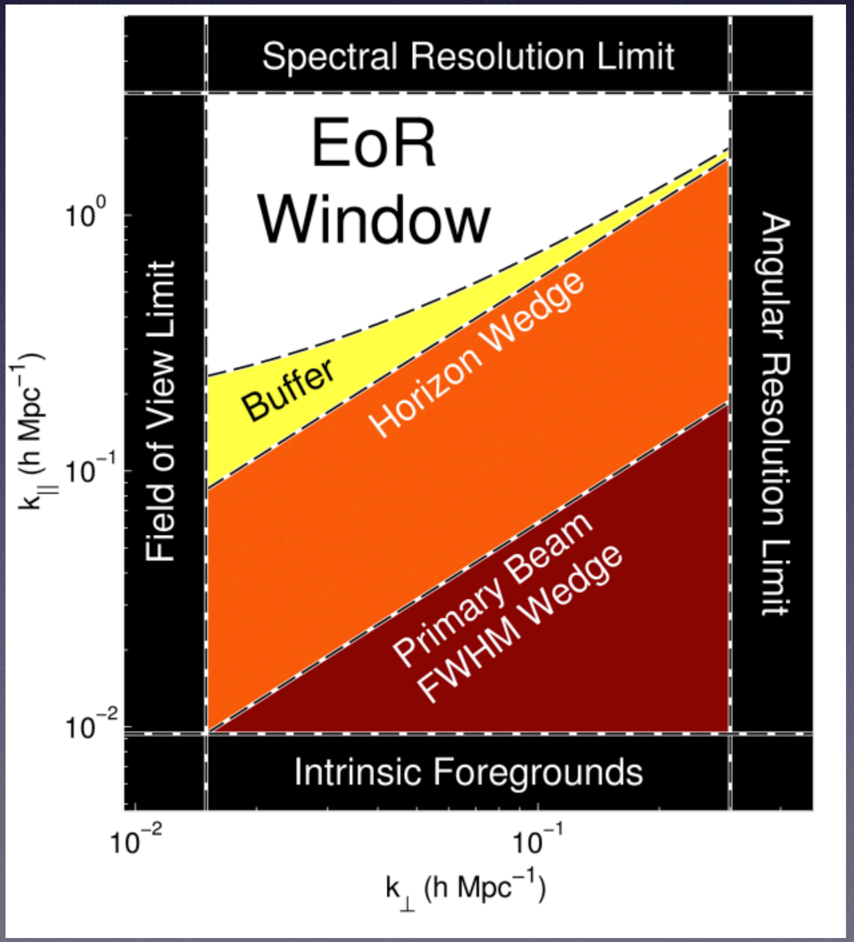
Global signal & power spectrum measurements

- Experiments can aim to measure either global signal (monopole) or power spectrum (fluctuations)
- Power spectrum generally requires more investment (interferometer vs simple antenna) but holds more information:

$$\langle \widetilde{\delta T}_b^*(\mathbf{k}) \widetilde{\delta T}_b(\mathbf{k}') \rangle \equiv (2\pi)^3 \delta(\mathbf{k} - \mathbf{k}') P(\mathbf{k})$$

$$\Delta^2_{21}(k) \equiv \frac{k^3}{2\pi^2} P(k).$$

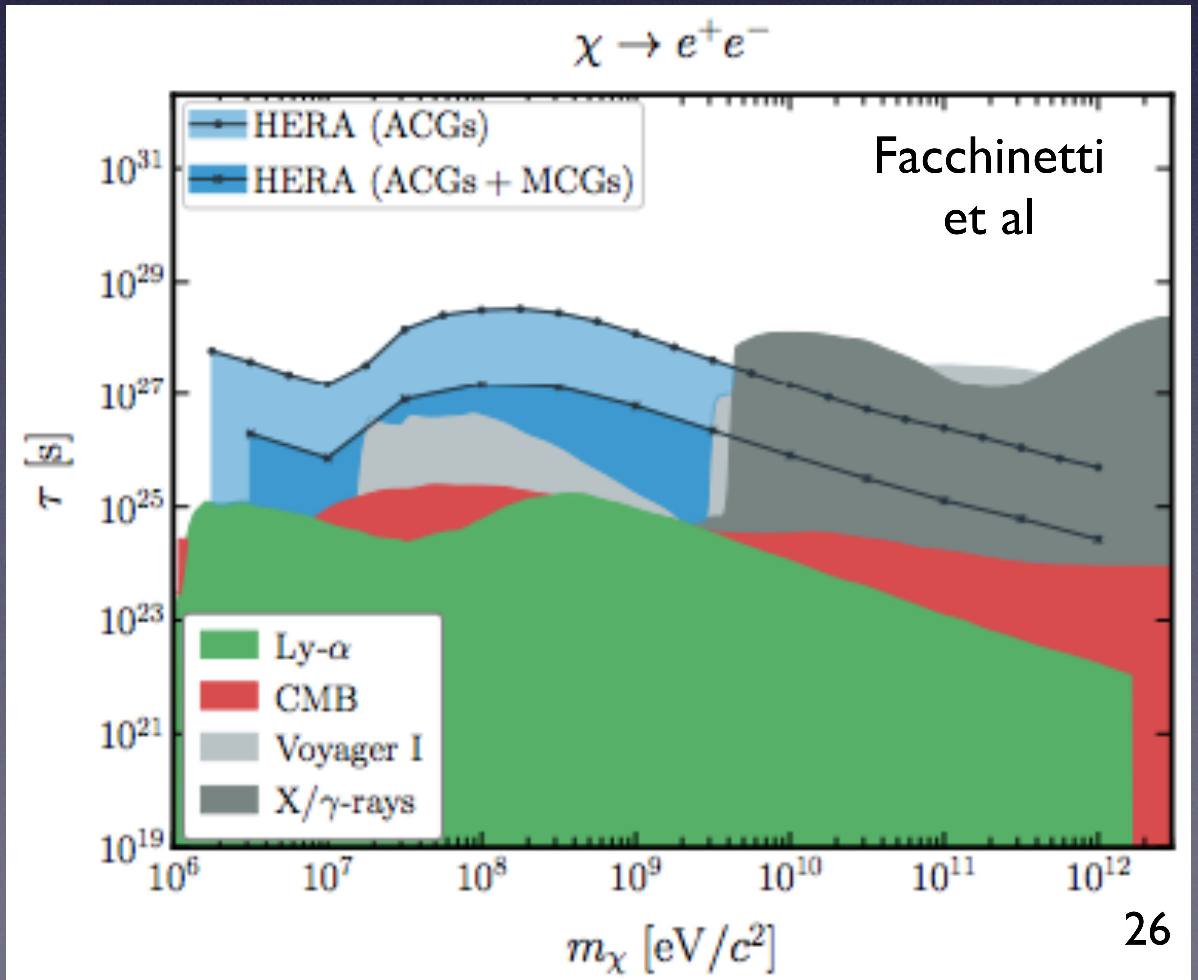
- 21cm is not Gaussian random field so power spectrum does not hold <u>all</u> information, but still a useful summary statistic
- Foregrounds are hard: lots of radio sources between us and cosmic dawn - but hope they are spectrally smooth
- In power spectrum, can characterize foregrounds with just a few maps at different frequencies (while experiments will measure at 100s of frequencies)
- However, instrumental effects can impose a non-trivial frequency dependence - can cause foregrounds to leak into signal



Josh Dillon PhD thesis, 1506.03024

Past 21cm constraints on DM decay/annihilation

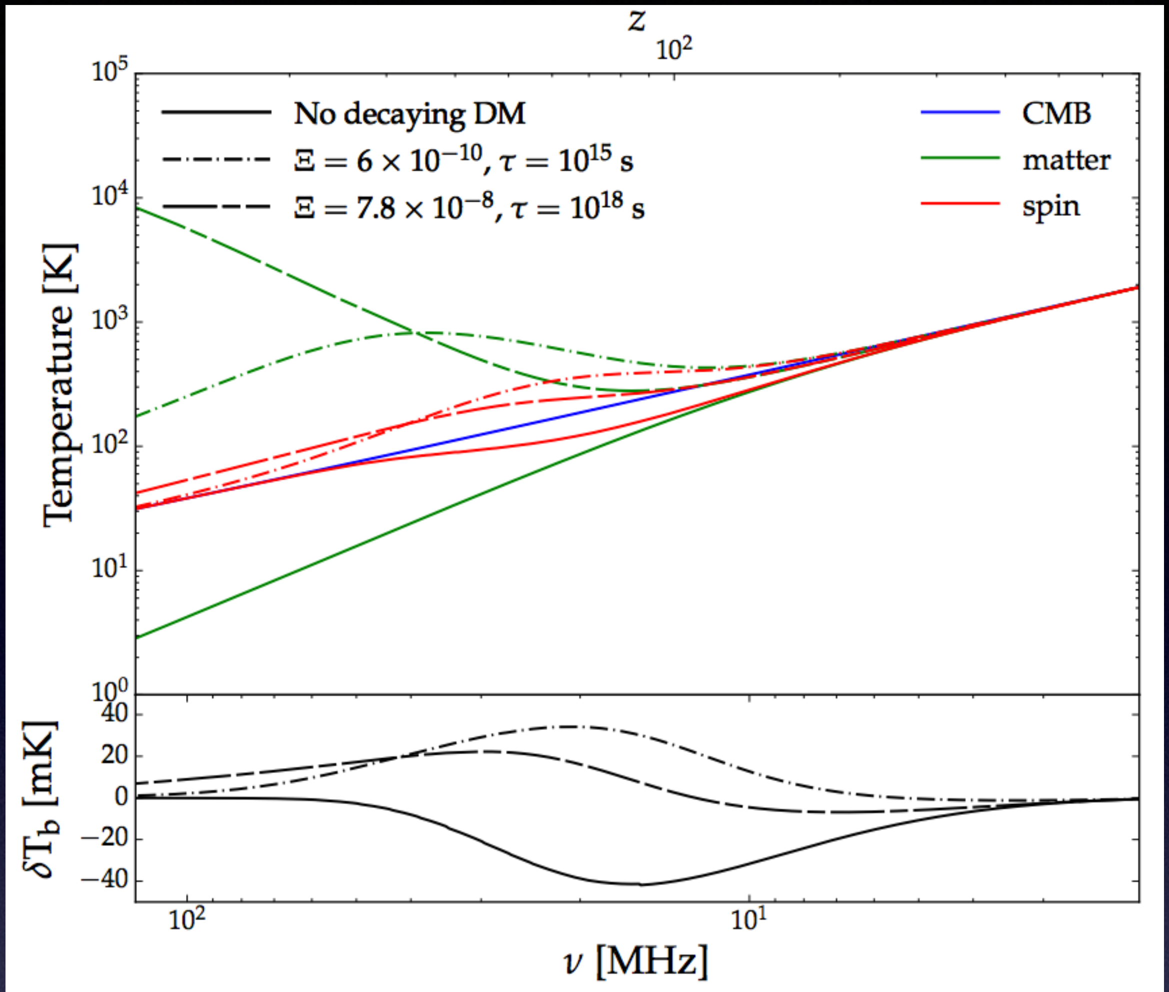
- Evoli et al 1408.1109: consider DM annihilation, assume signal dominated by small abundant haloes and is ~homogeneous, + instantaneous energy deposition - early homogeneous heating leads to distinct behavior vs astrophysics
- Lopez-Honorez et al 1603.06795: account for delayed energy deposition, still assume spatial homogeneity, focus on DM annihilation - find that given current limits it will be difficult to distinguish from astrophysics
- Poulin et al 1610.10051: considers DM decay (as homogeneous heating), identifies z~15-30 emission signal as promising channel
- Facchinetti et al 2308.16656: detailed analysis of HERA sensitivity for decaying DM, using updated deposition efficiency results from DARKHISTORY, still assumes homogeneity



Predictions for 21cm signals

- Heating from decays before reionization leads to “spin temperature” exceeding CMB temperature - i.e. 21cm line in emission at z~20-25 (generally expected to be in absorption).
- Annihilation case more challenging, but (at least for some DM masses) could potentially leave unique signatures.

Poulin et al JCAP03(2017)043



Lopez-Honorez et al JCAP08(2016)004