Deciphering the Universe's Dark History

Tracy Slatyer

MIT

Georges Lemaitre Lecture Series
Lecture 4, 19 May 2022

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- A cosmic timeline + early-universe probes
- Intro to DarkHistory: a self-consistent calculation of perturbed ionization and temperature histories
  - Review of previous approaches
  - CMB constraints on annihilation and decay
  - Calculating the size of backreaction effects
  - Corrected sensitivity to 21cm signals
  - Combining exotic energy injections with reionization

The cosmic microwave background radiation

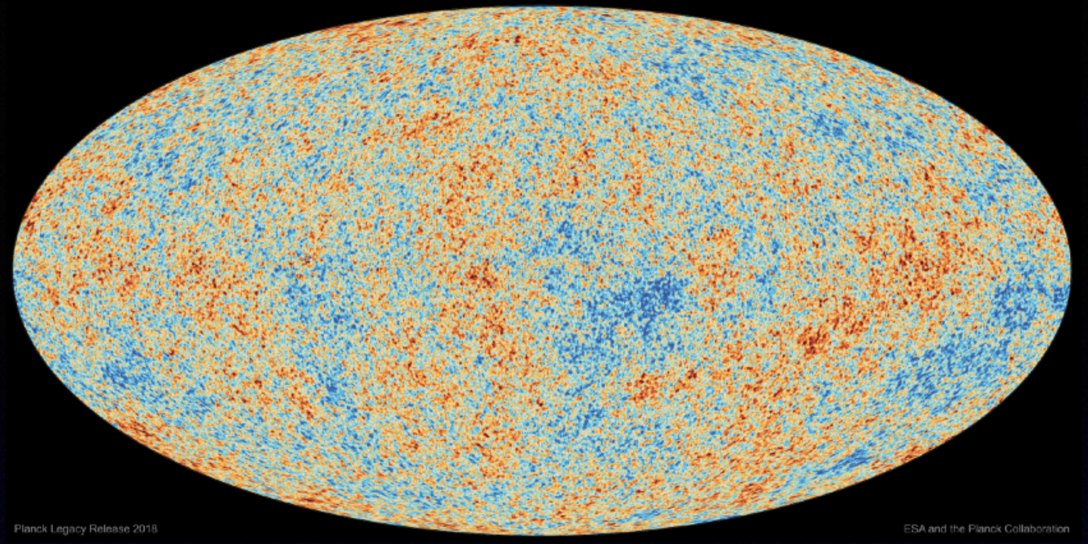
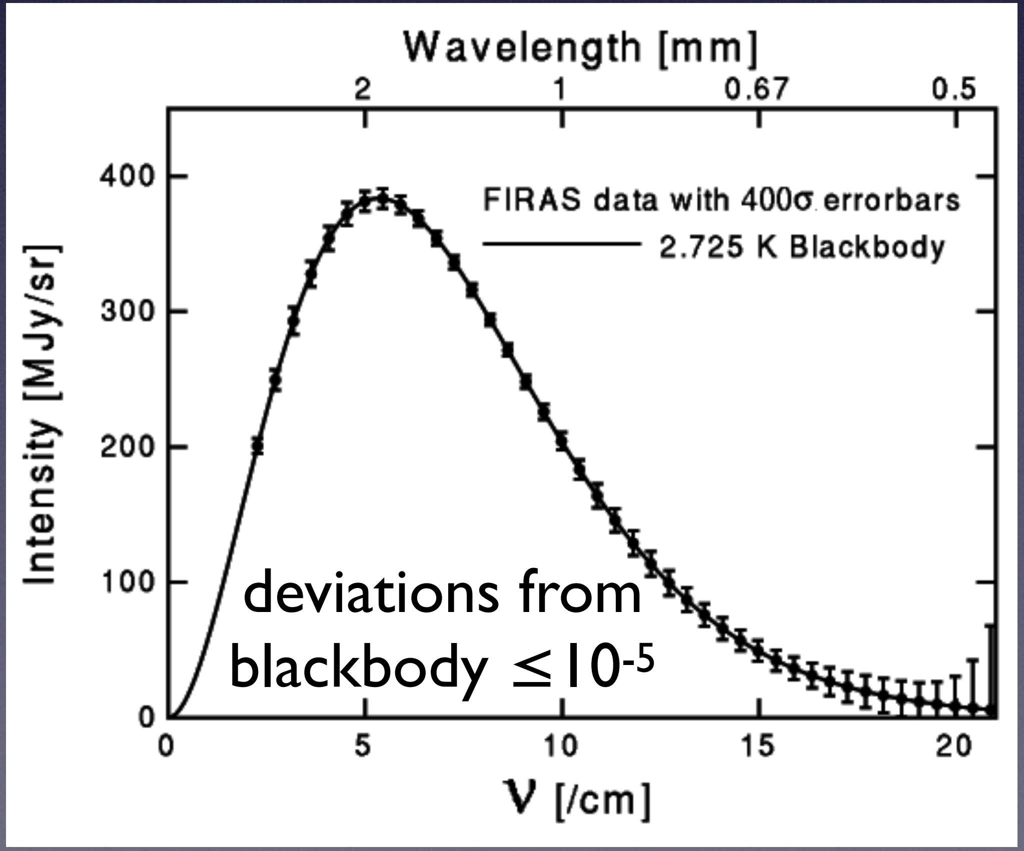


Image credit: European Space Agency / Planck Collaboration

- Redshift z > 1000 - universe is filled with a tightly-coupled plasma of electrons, protons and photons, + dark matter and neutrinos. Almost 100% ionized.
- Redshift z ~ 1000 - ionization level drops abruptly, cosmic microwave background (CMB) photons begin to stream free of the electrons/protons.
- The cosmic microwave background provides a snapshot of the z~1000 universe - oldest light we measure, earliest direct observations of our cosmos.

spatial information: describes pattern of oscillations in density and temperature

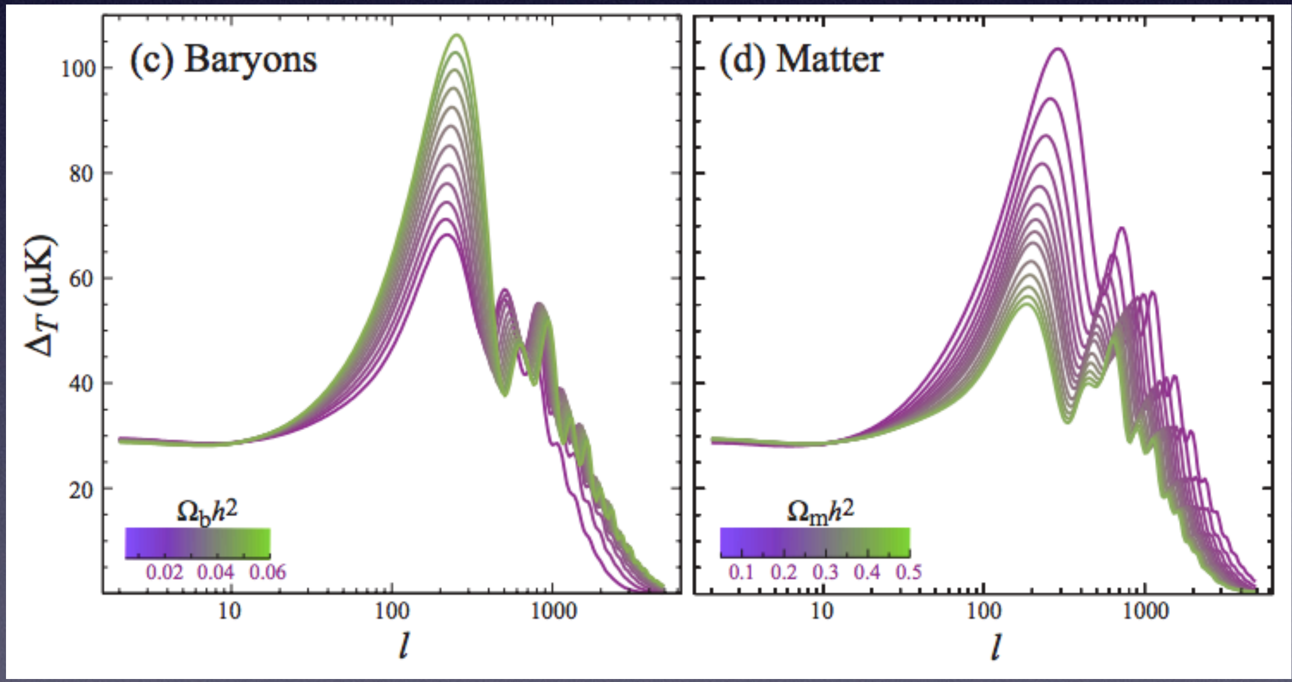
spectral information: near-perfect blackbody



Signatures in the CMB (I)

- We can change the observed CMB either by:
  - z > 1000: Modifying the target of the "snapshot" - change the plasma to which the photons couple before emission
  - z < 1000: Changing the photons on their way to us - modifying the "picture" after it is taken

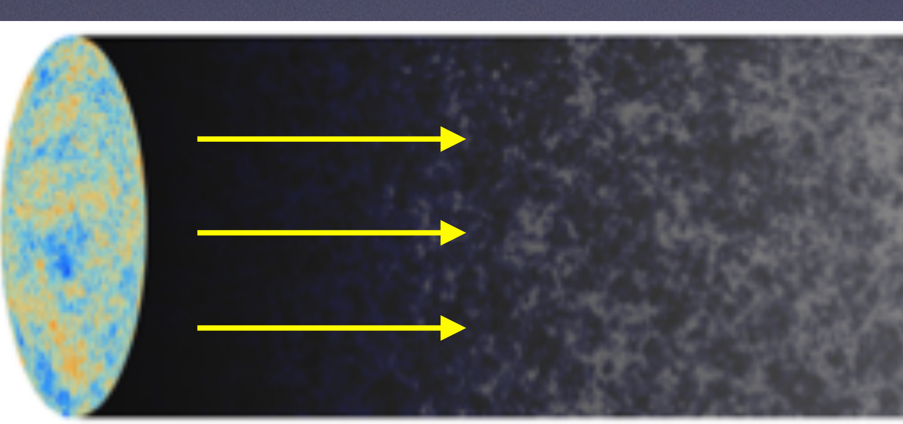
Hu & Dodelson '02

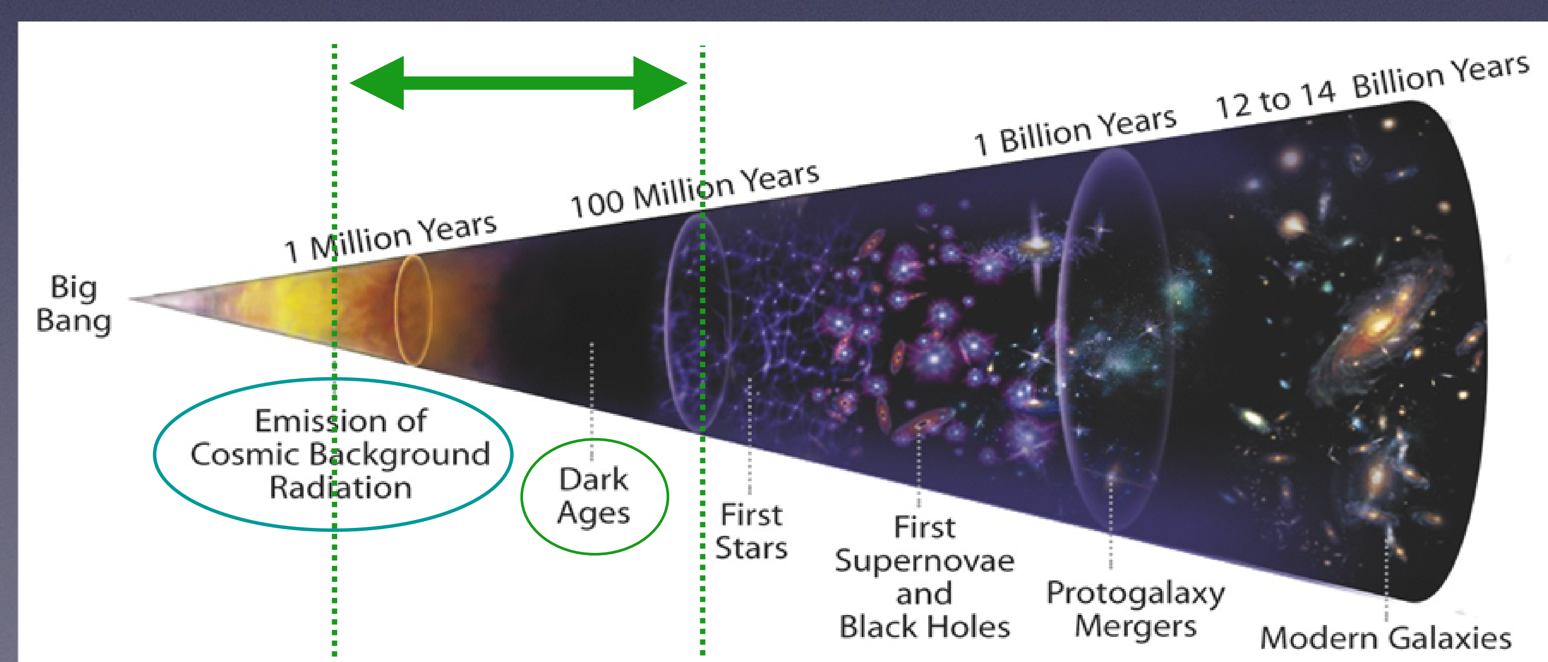


- Classic example of first case: temperature/density oscillations in plasma are driven by competition between gravity and radiation pressure.
- Presence of matter that feels gravity but not radiation ("dark") changes properties of oscillations - used to measure DM abundance.
- Scattering between DM and ordinary matter would make DM not-quite-dark, and likewise modify the oscillation pattern
- Heating of the ordinary matter by DM annihilation/decay can also modify the photon/baryon plasma, changing the energy spectrum of the CMB.

Signatures in the CMB (II)

- Second case (modification after emission): "cosmic dark ages" span redshift z ~ 30-1000, ionization level expected to be very low.
- Increasing ionization would provide a screen between CMB photons and our telescopes - can be sensitively measured.
- Annihilation/decay could also produce extra low-energy photons, again modifying CMB energy spectrum.





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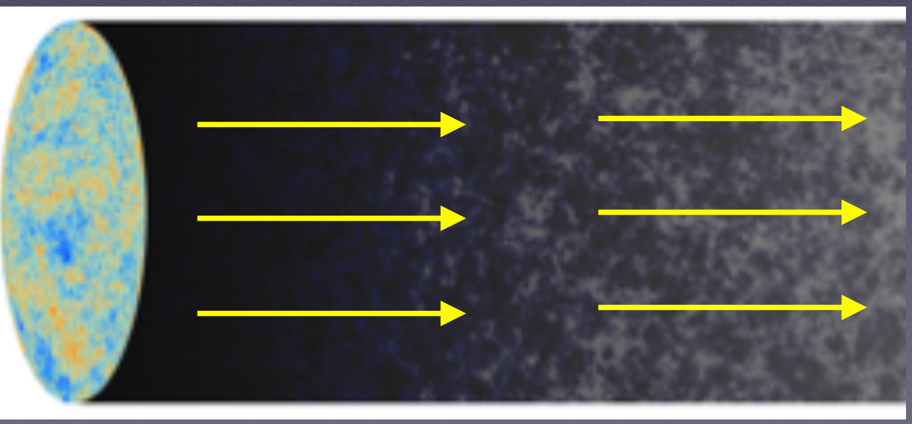
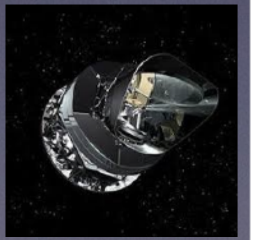
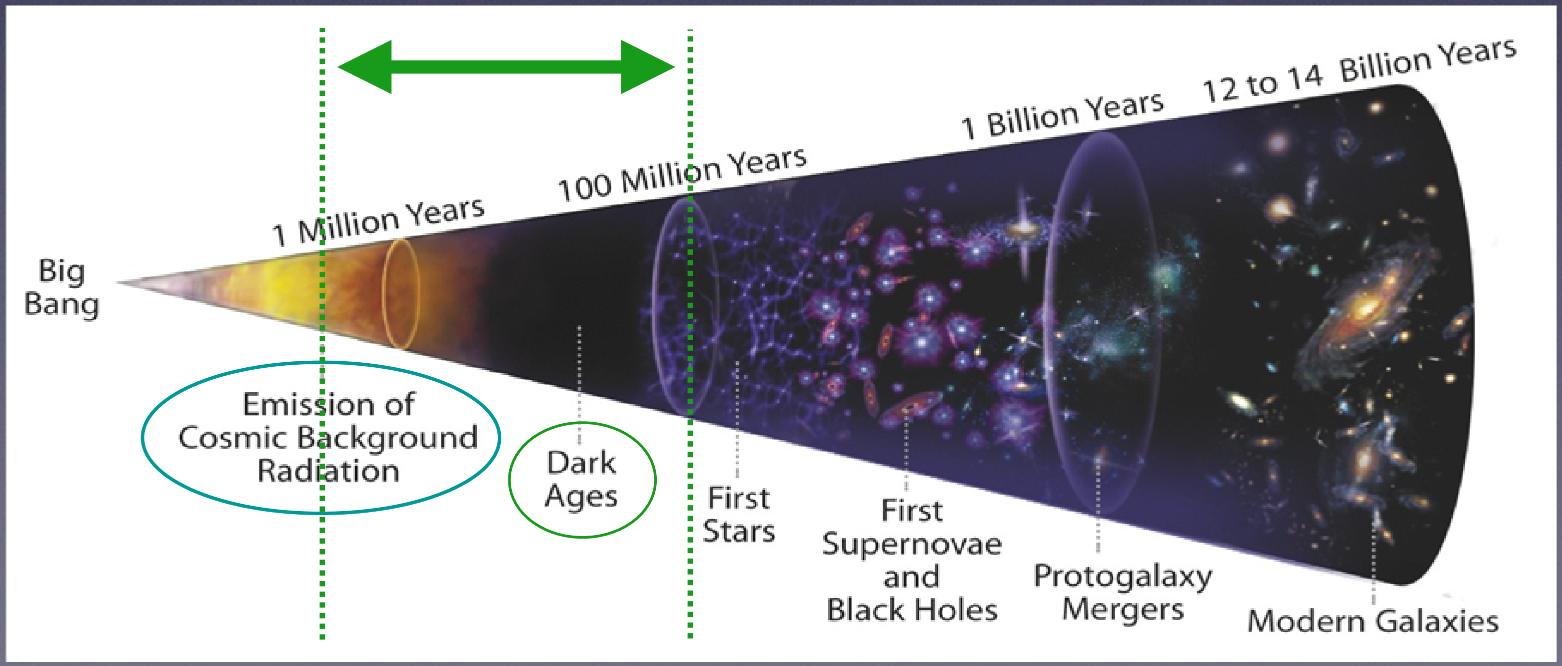




Planck



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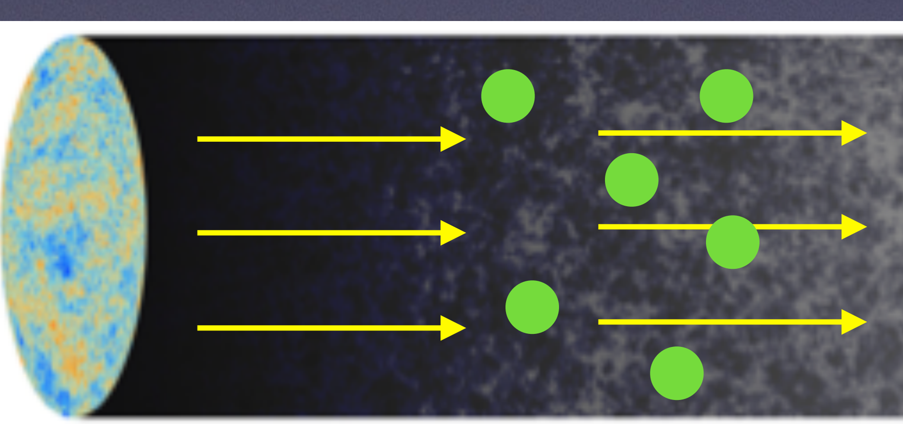

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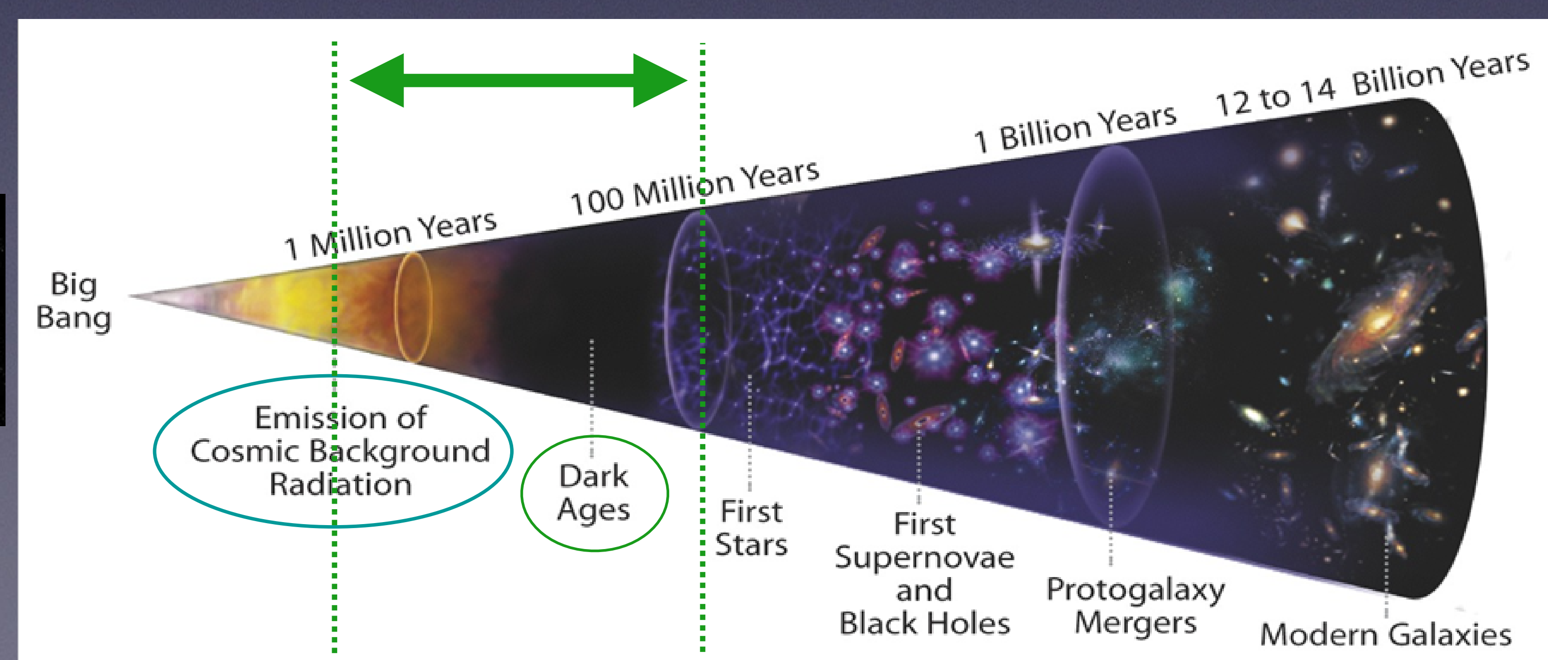

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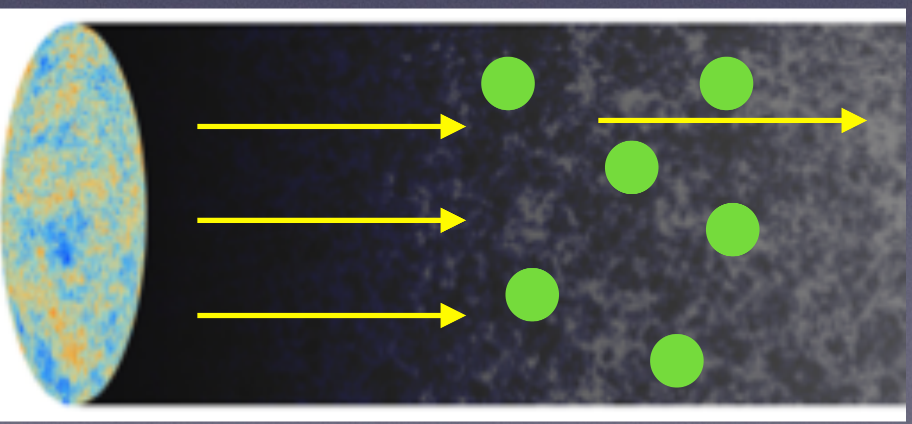

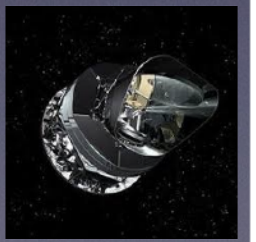

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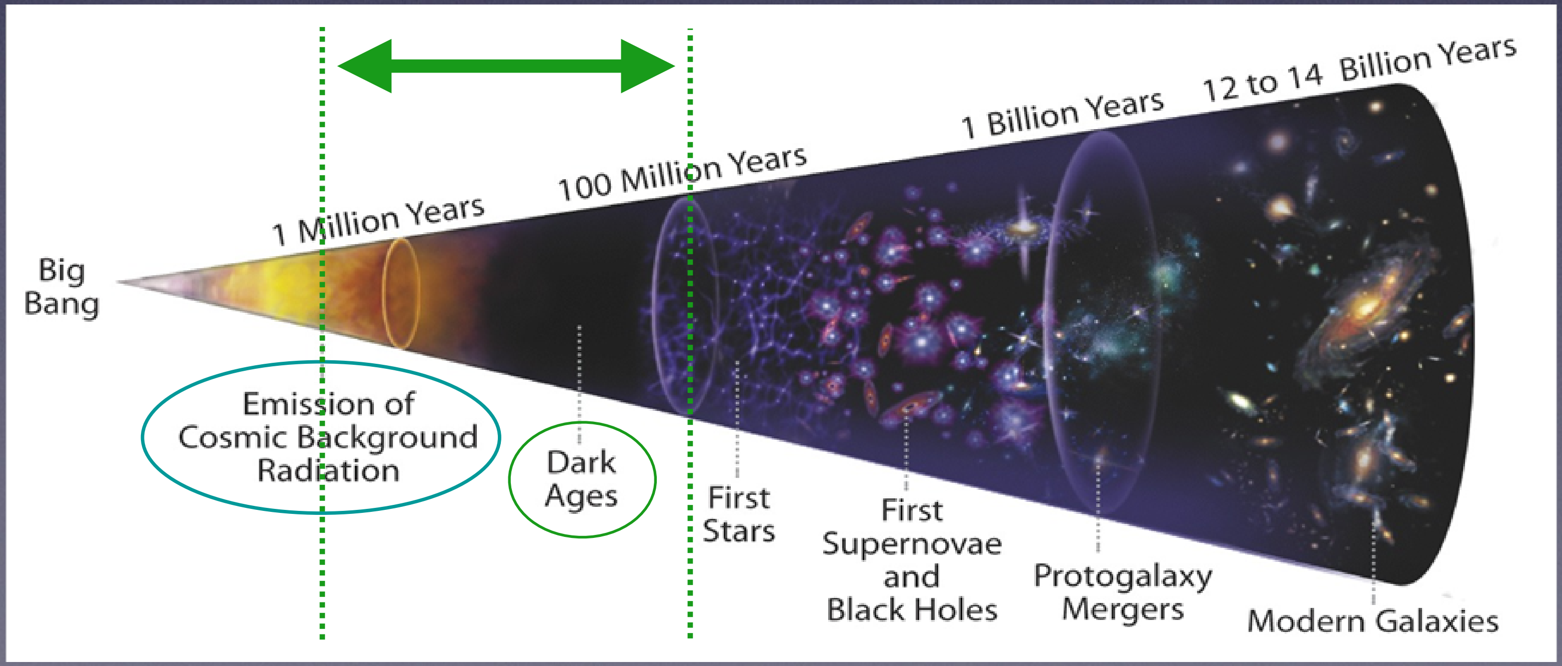
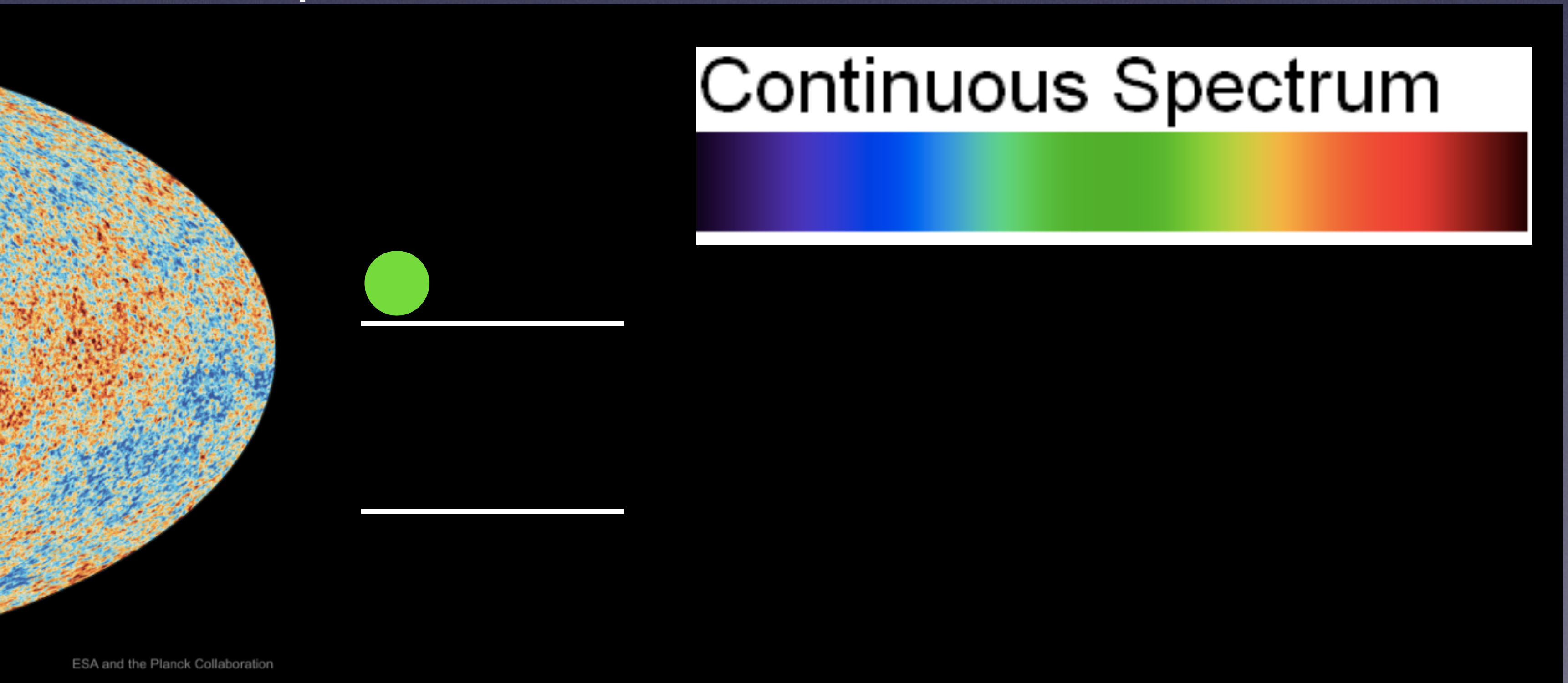


Taking the universe's temperature with 21cm

- 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.
- As the universe expands, the energy of these photons decreases - lines get smeared out into a broad structure.
- "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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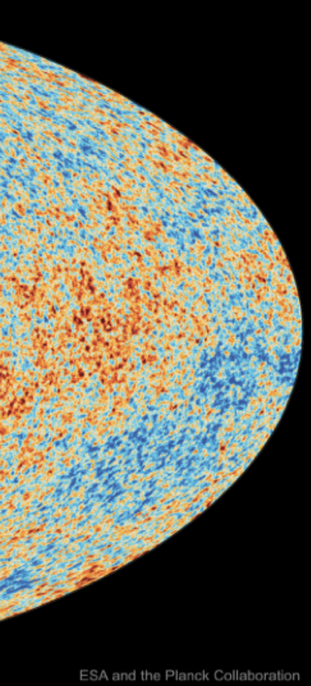

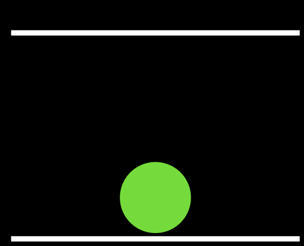

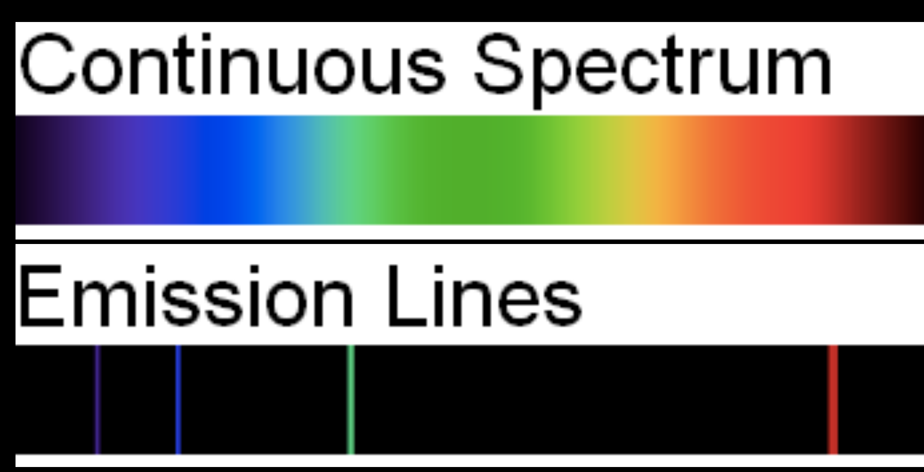

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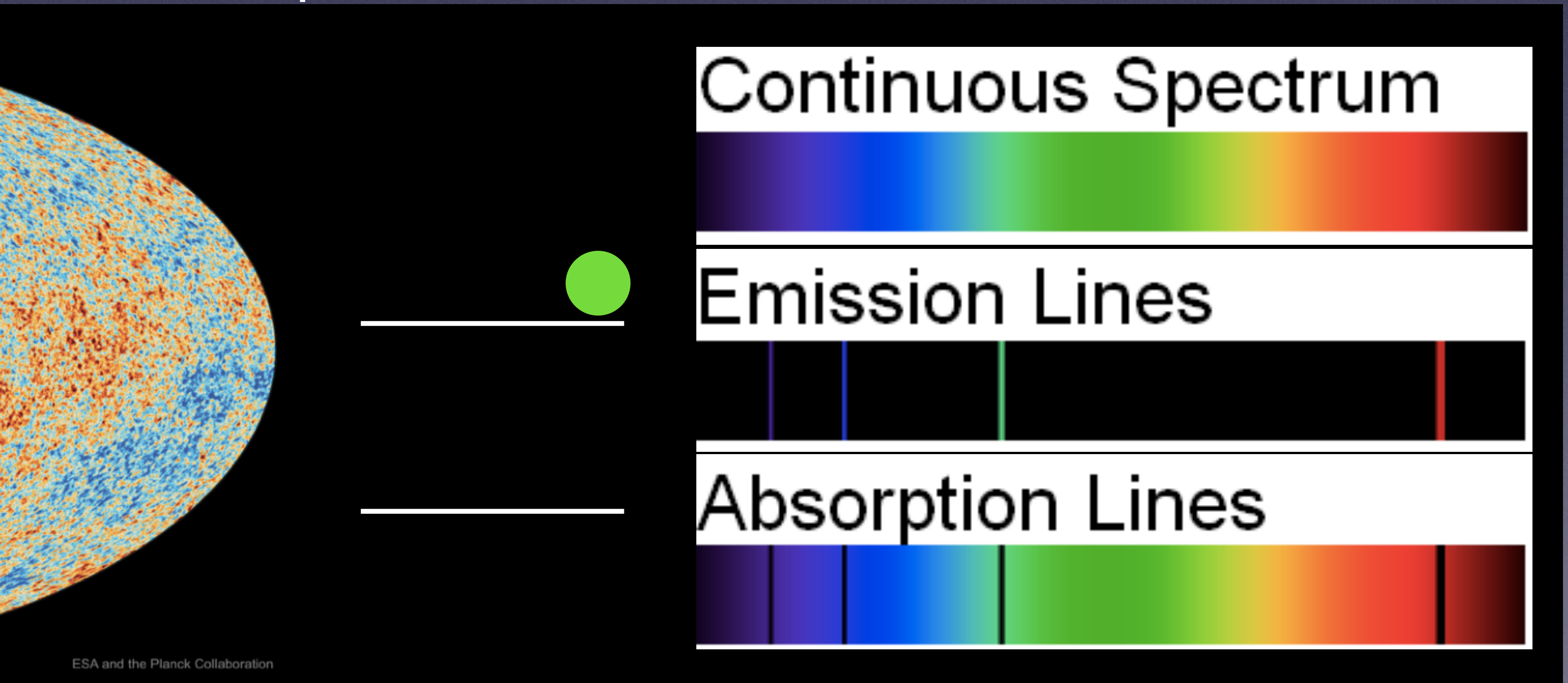

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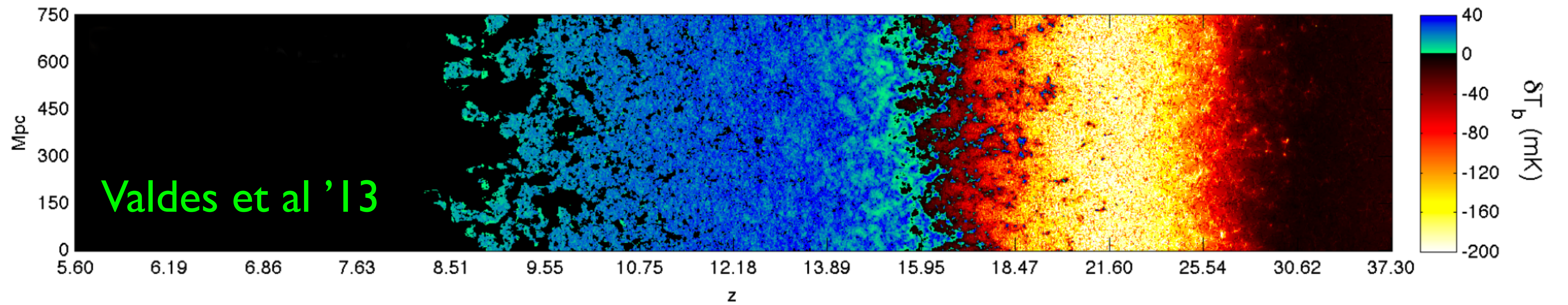
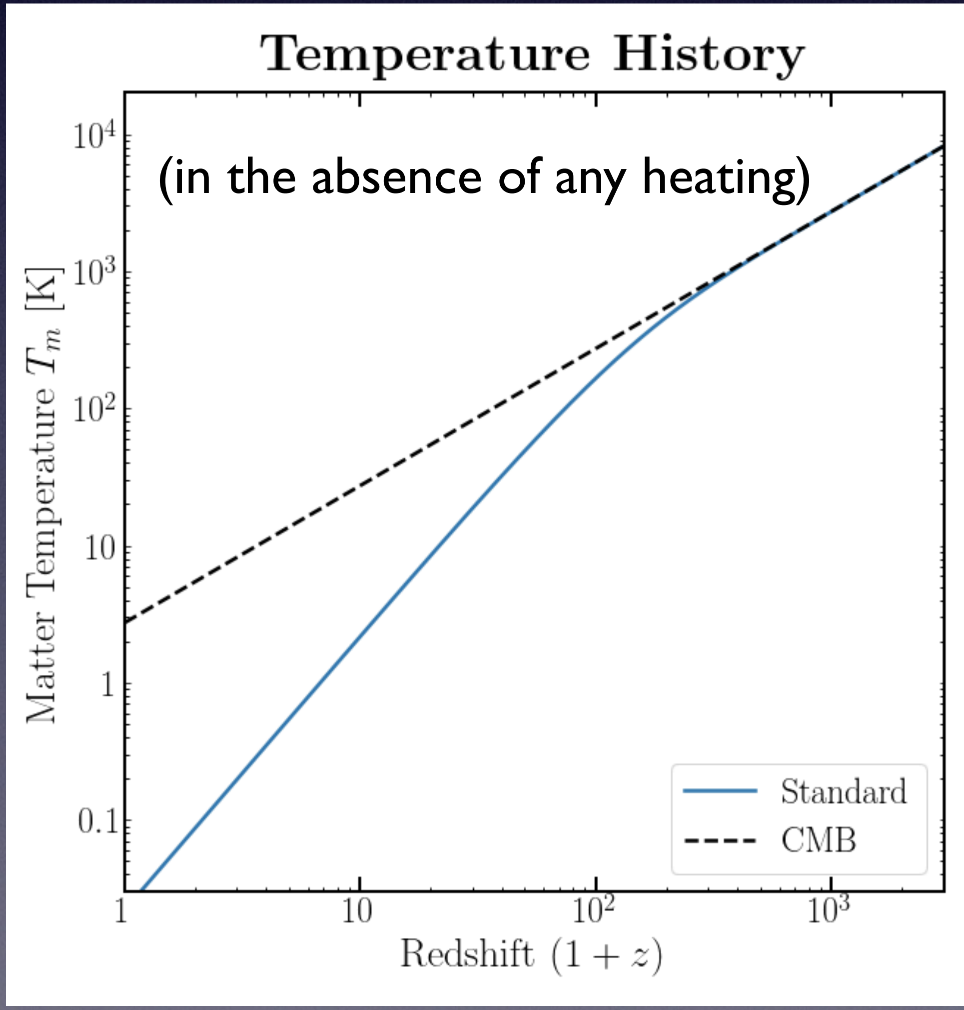
Expectations for a 21cm signal

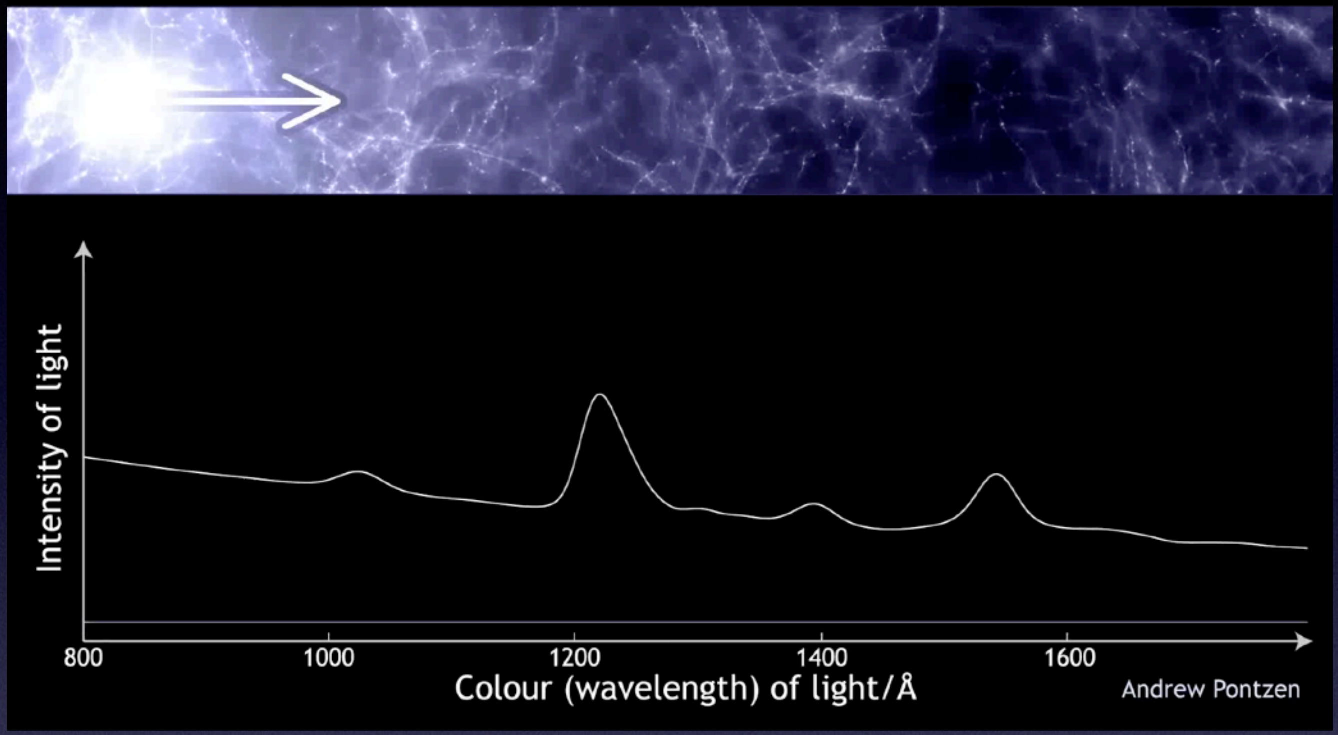


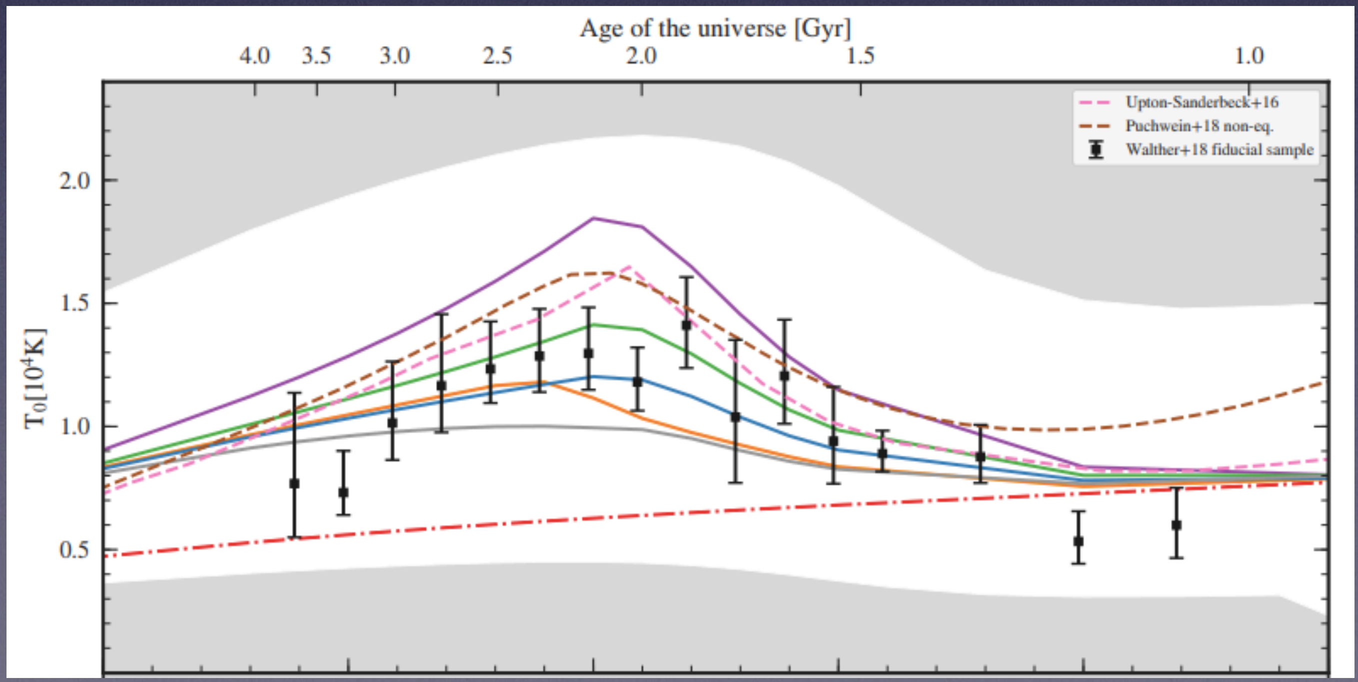
- First stars turn on = flux of Lyman-alpha photons - couples T_S to the hydrogen gas temperature T_{gas}.
- We expect $T_{gas} < T_R$ initially - gas cools faster than the CMB after they decouple - leading to absorption signature.
- Exotic heating could lead to an early emission signal [e.g. Poulin et al '17].
- Later, stars heat $T_{gas} > T_R$, expect an emission signal.
- There are a number of current (e.g. EDGES, LOFAR, MWA, PAPER, SARAS, SCI-HI) and future (e.g. DARE, HERA, LEDA, PRIZM, SKA) telescopes designed to search for a 21cm signal, potentially probing the cosmic dark ages & epoch of reionization.
- Any measurement would set a bound on T_{gas}.



The Lyman-alpha forest

- After the universe mostly reionizes, there are still clouds of neutral hydrogen in the universe - light passing through these clouds produces the "Lyman-alpha forest" of absorption features in the spectrum.
- T_{gas} affects the width of the absorption features via Doppler broadening.
- Temperature also affects the distribution of the hydrogen gas - smoothed out by the gas pressure on small scales.
- Several recent studies [Walther et al '18, Gaikwad et al '20] have compared measurements of the Ly-α forest with simulations, to extract the gas temperature for z~2-6.





Gaikwad et al '20

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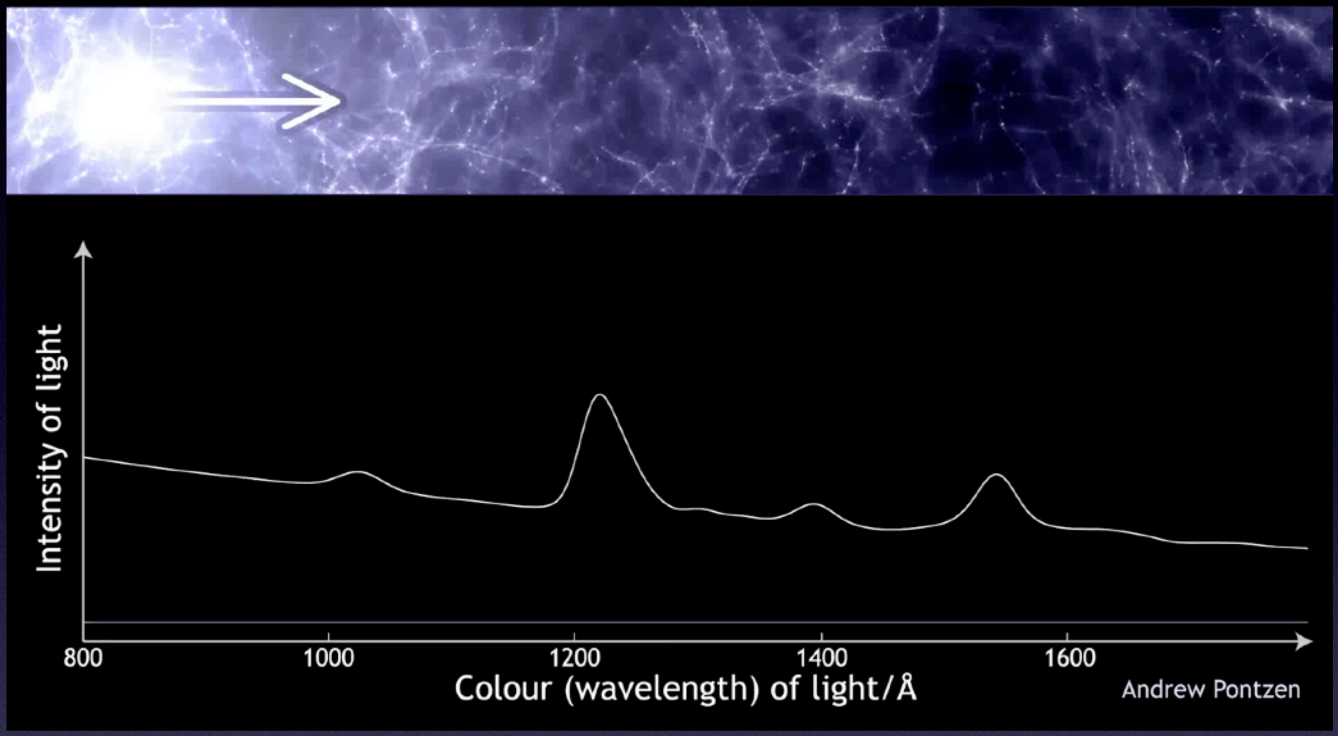

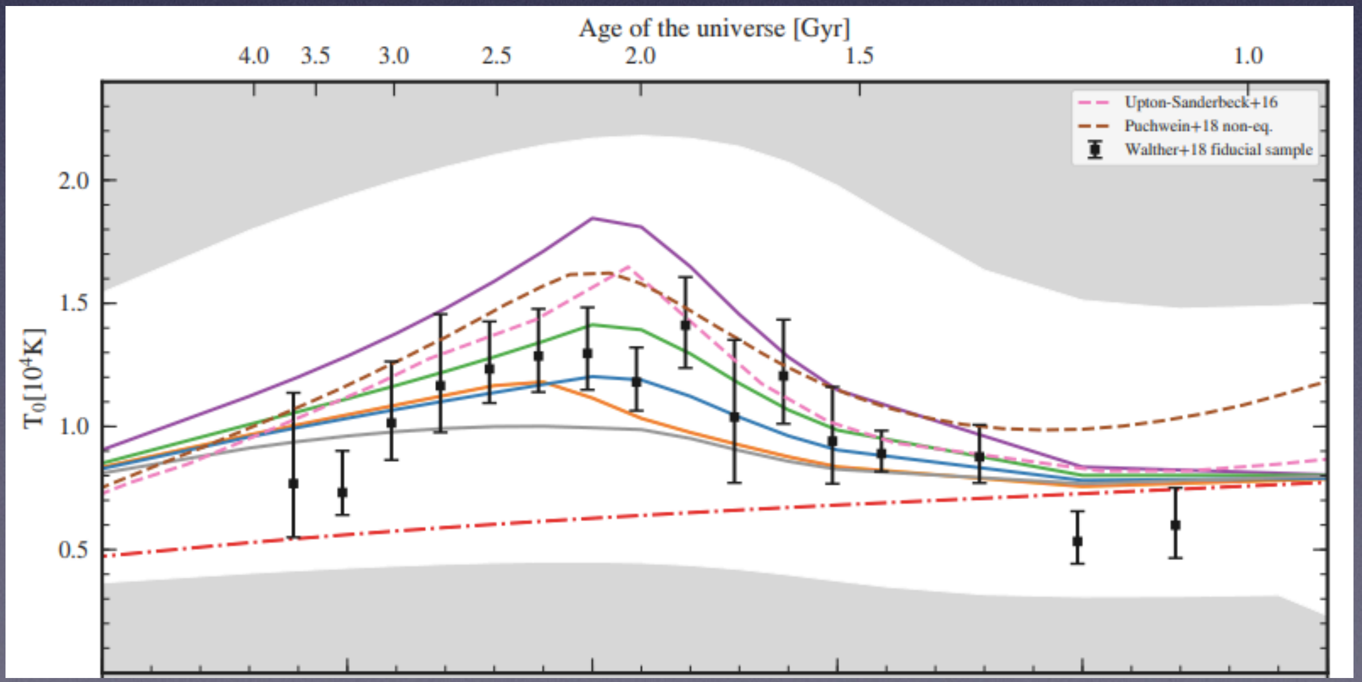

Gaikwad et al '20

Now to the blackboard for some estimates…

DarkHistory

computing modified ionization/thermal histories

- To study any of these effects, we need to know how particles injected by annihilation/decay transfer their energy into heating, ionization, and/or photons.
- My collaborators and I have written a Python package 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

Predicting a signal

Annihilation/decay/etc injects high-energy particles

↓ Decay with Pythia or similar program

Time-dependent injection of high-energy photons + e^+e^-
(others largely escape or are subdominant; neglect)

↓ Cooling processes

Absorbed energy (ionization+excitation+heating)

↓ Modify evolution equations, e.g. with public recombination calculator (RECFAST, CosmoRec)

Cosmic ionization and thermal histories

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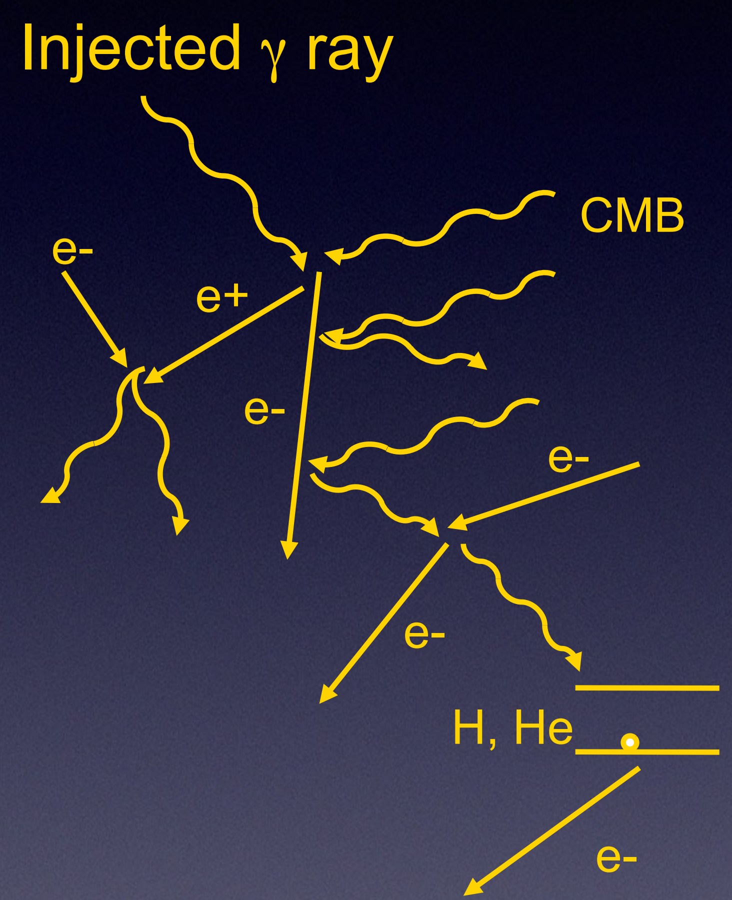
Cosmic ionization and thermal histories

The photon-electron cascade

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

From energy deposition to modified histories

- Coupled equations govern evolution of the temperature and ionization history
- Energy deposition to ionization/heating provides extra source terms in these equations
- Simplest treatment uses three-level atom (TLA) approximation - basis of RECFAST code
- More advanced codes (CosmoRec, HyRec) include more levels of hydrogen

$$\dot{T}_m = \dot{T}_m^{(0)} + \dot{T}_m^{\mathrm{inj}} + \dot{T}_m^{\mathrm{re}} ,$$
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$$\dot{T}_m^{\mathrm{inj}} = \frac{2 f_{\mathrm{heat}}(z, \mathbf{x})}{3(1 + \mathcal{F}_{\mathrm{He}} + x_e) n_{\mathrm{H}}} \left(\frac{dE}{dV\, dt} \right)^{\mathrm{inj}} ,$$
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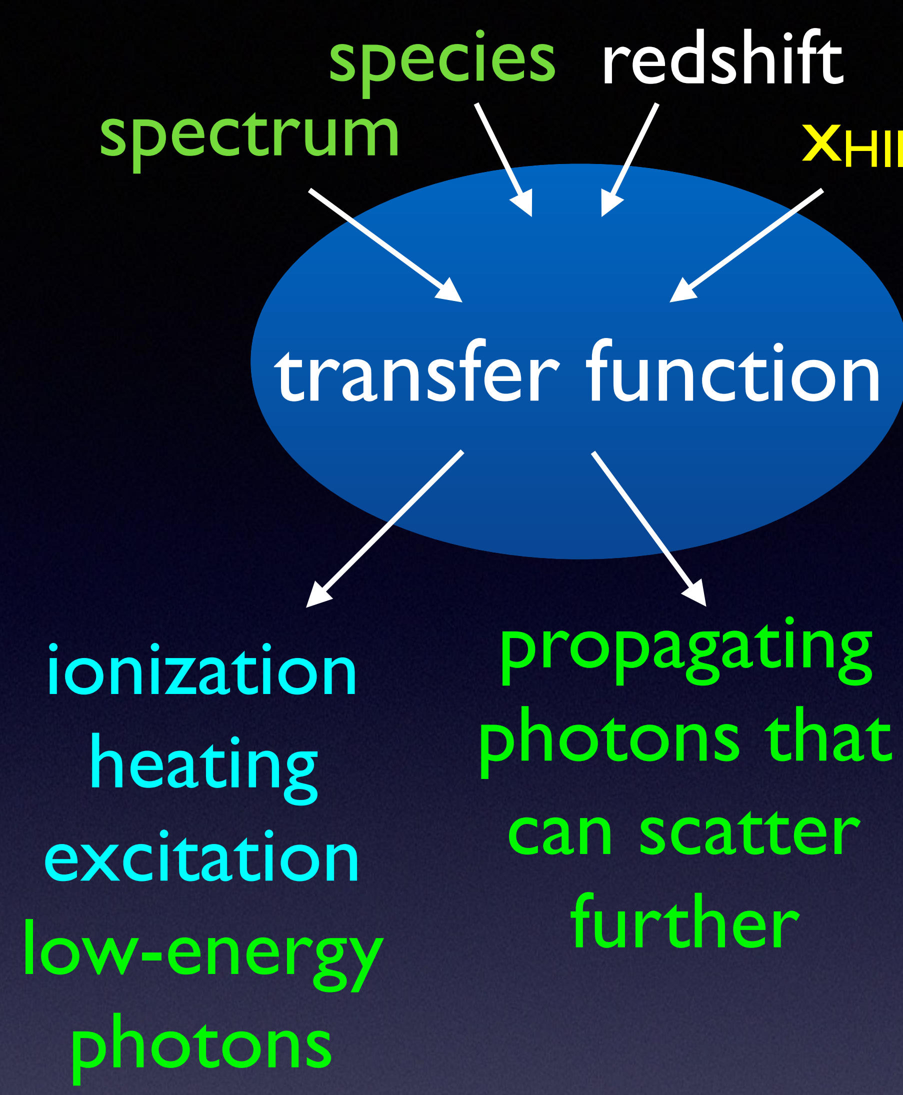
Ingredients of DarkHistory



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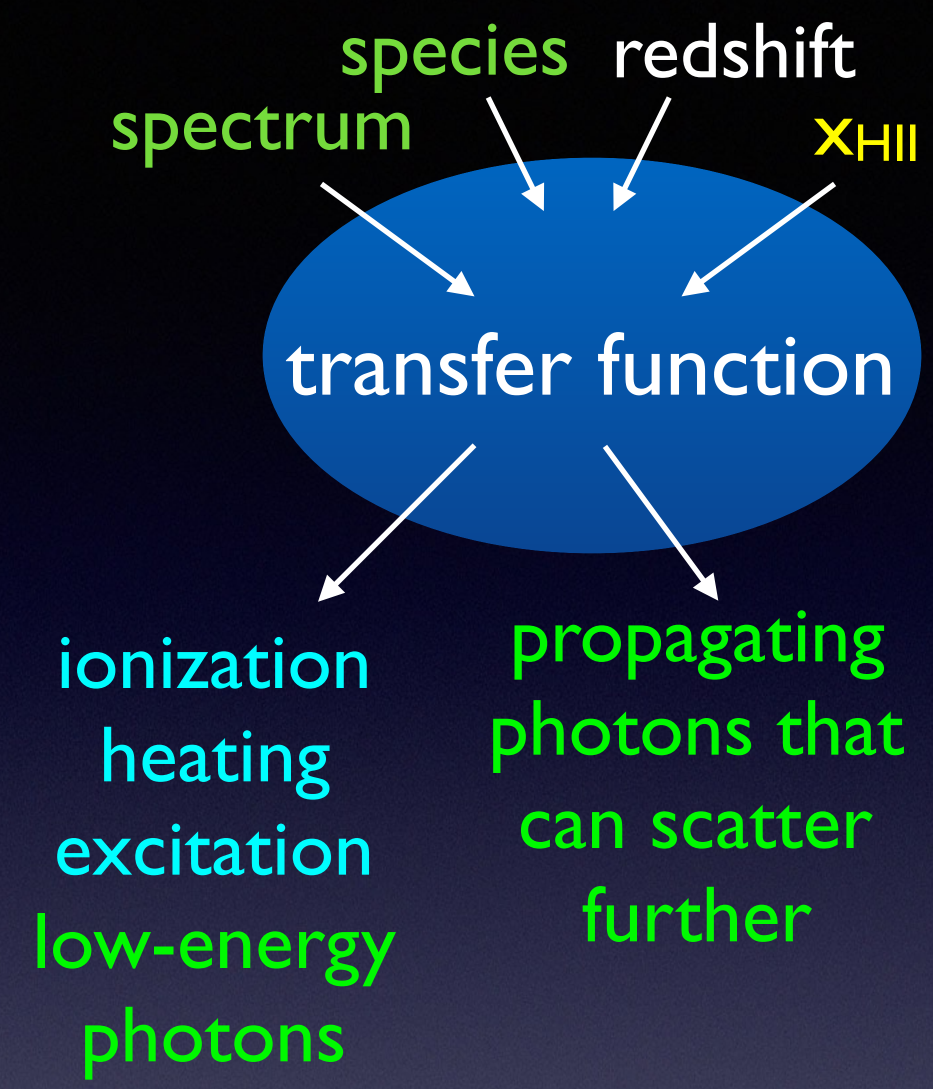

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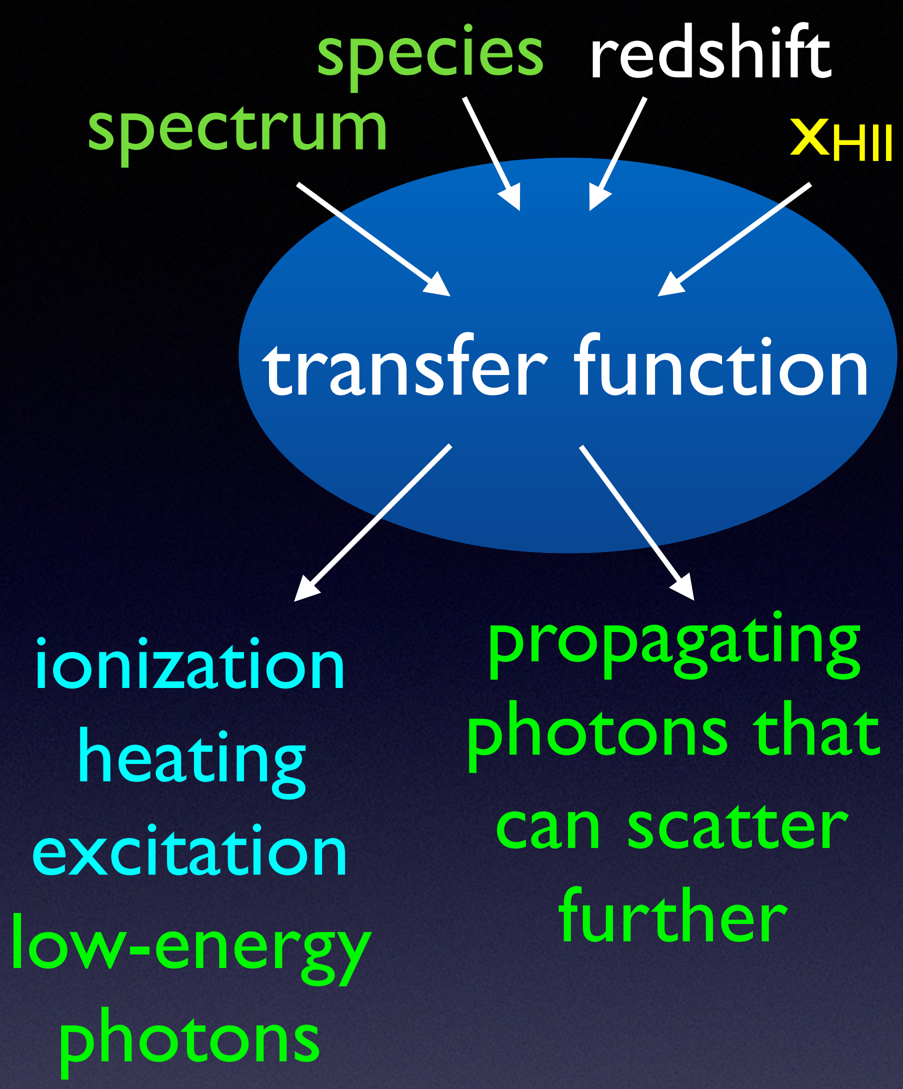

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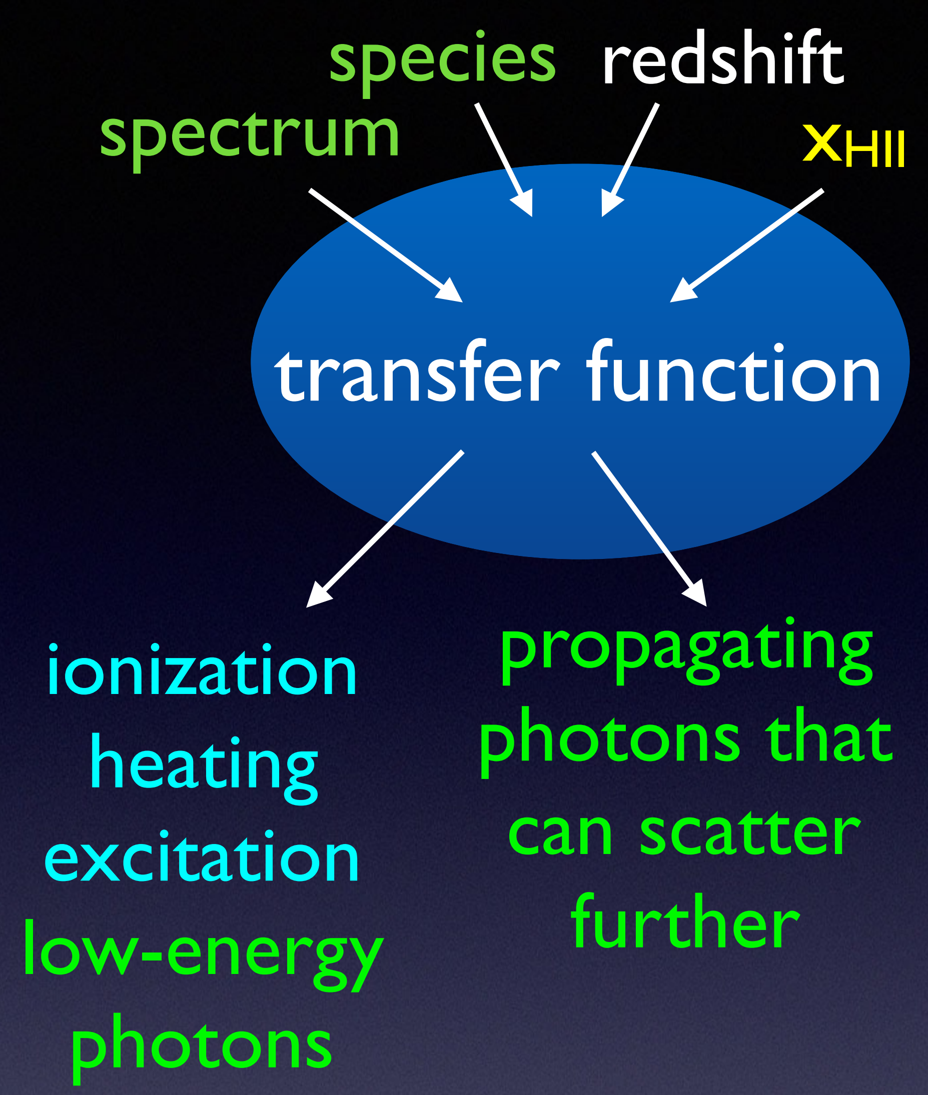

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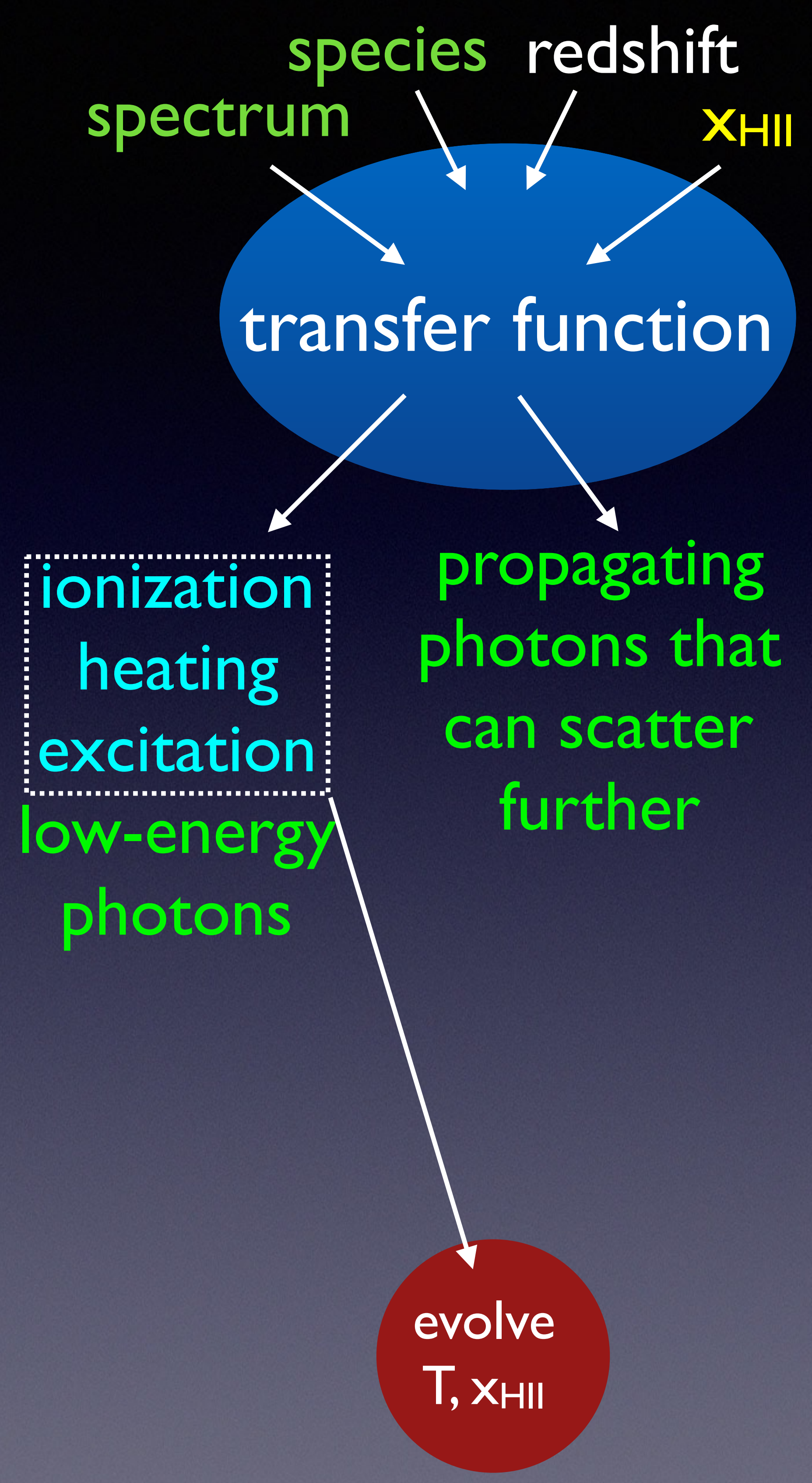
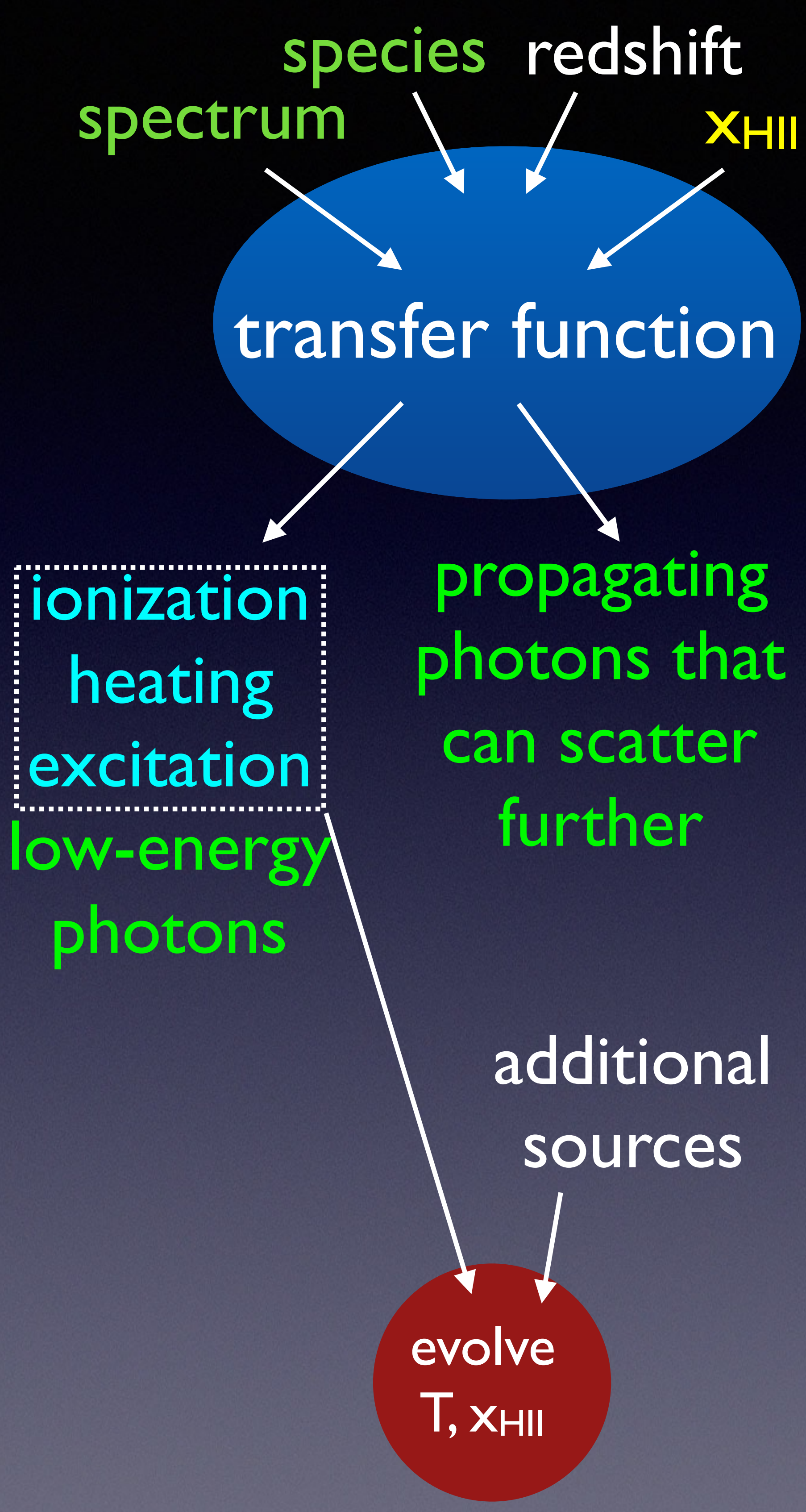
- Feed ionization/heating/excitation into evolution equations - obtain modified thermal+ionization history.



Ingredients of DarkHistory

- Cooling cascade calculation is slow, so precompute how individual electrons/positrons/photons deposit energy over a timestep, at a given energy/redshift/x_{HII}, producing a transfer function that acts on an input spectrum of particles.
- Transfer function depends on redshift + ionization level - pre-compute over a grid of these parameters, interpolate to desired x_{HII} & redshift in each timestep.
- Outputs of transfer function include secondary photons (propagate to next timestep, add to injection) and ionization/heating/etc.
- Feed ionization/heating/excitation into evolution equations - obtain modified thermal+ionization history.



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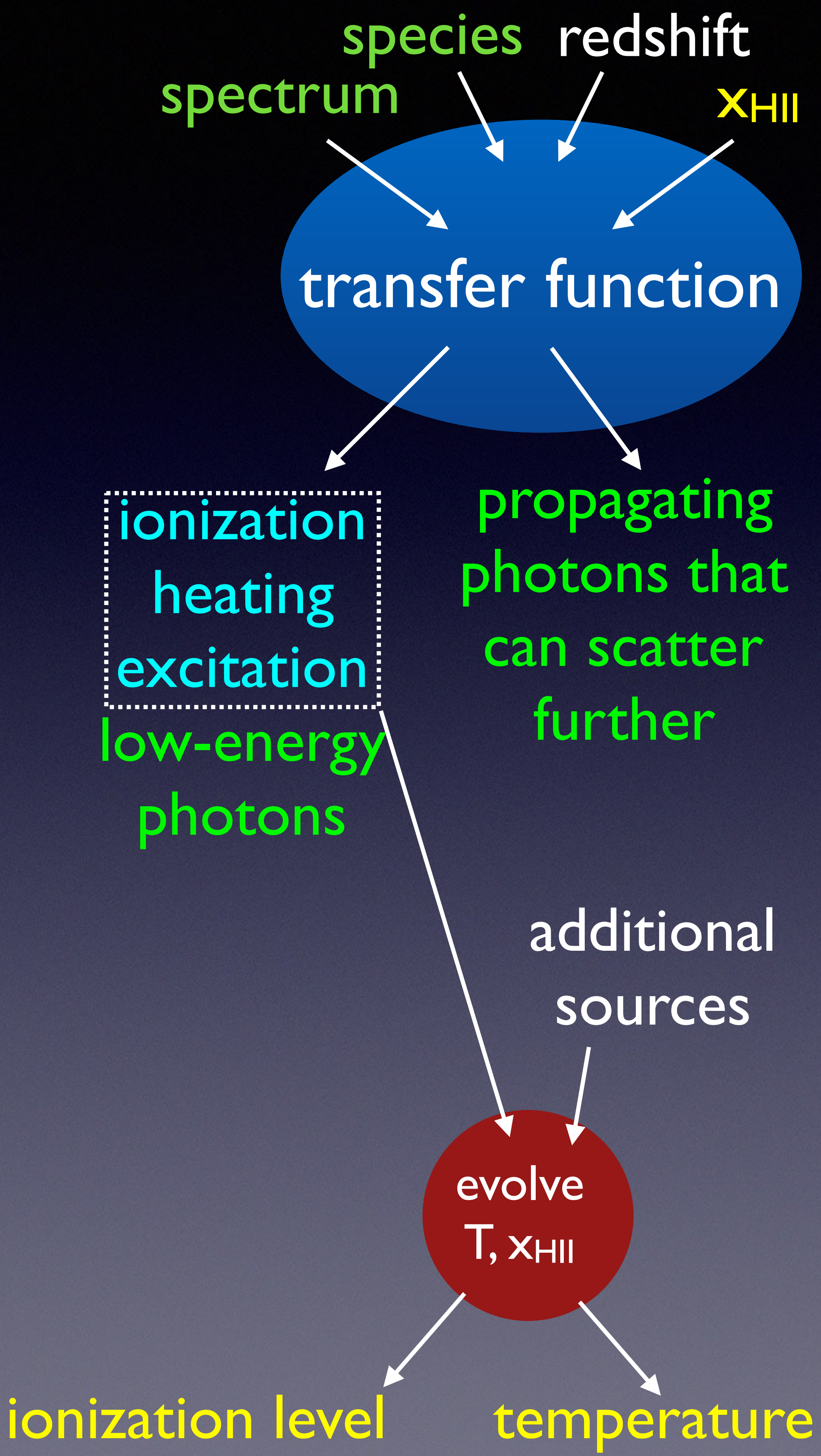

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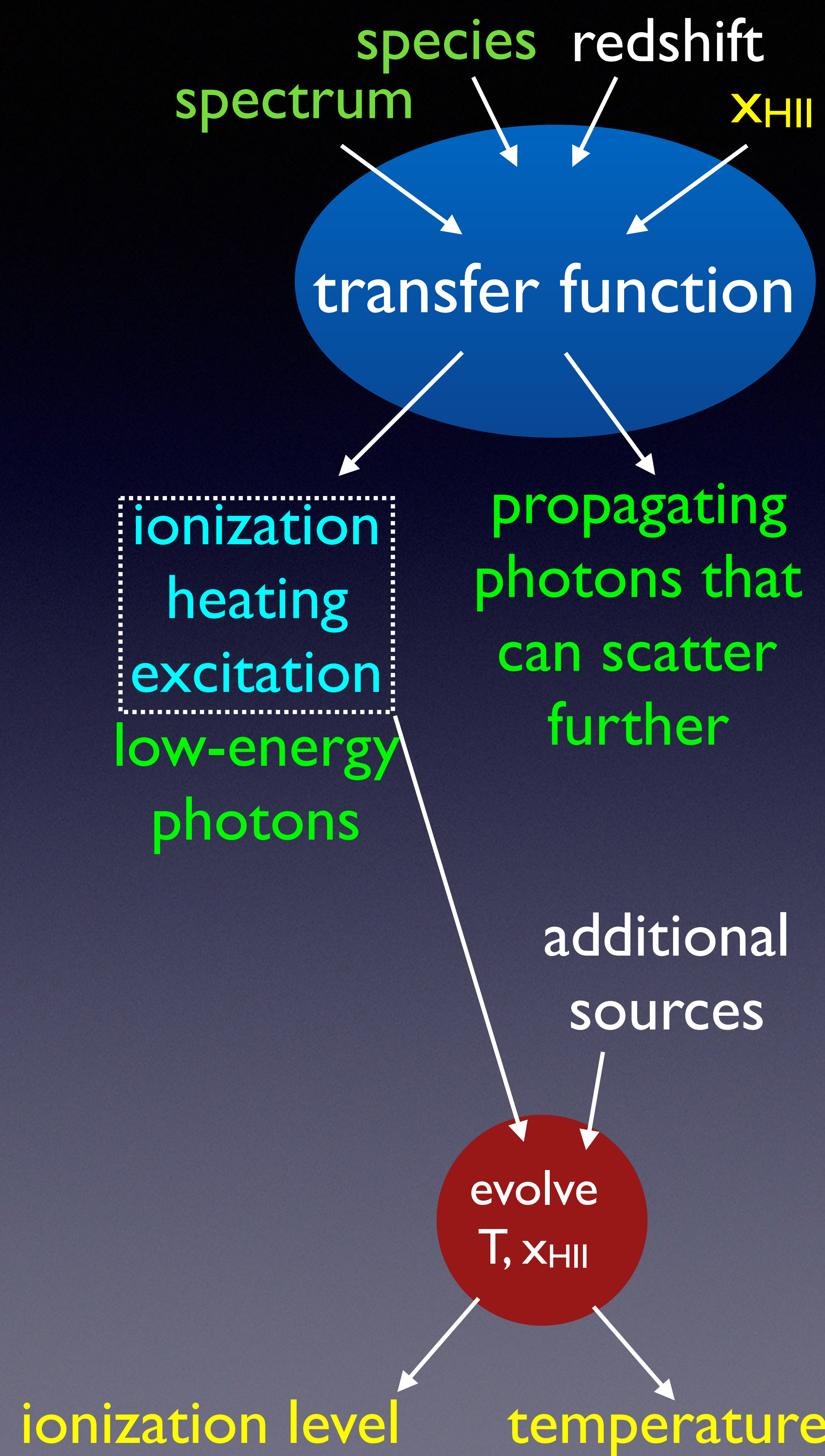
- Feed ionization/heating/excitation into evolution equations - obtain modified thermal+ionization history.
- Pass propagating particles + new ionization level as inputs to next timestep. Add newly injected particles to spectrum. Iterate.



An earlier/simplified treatment

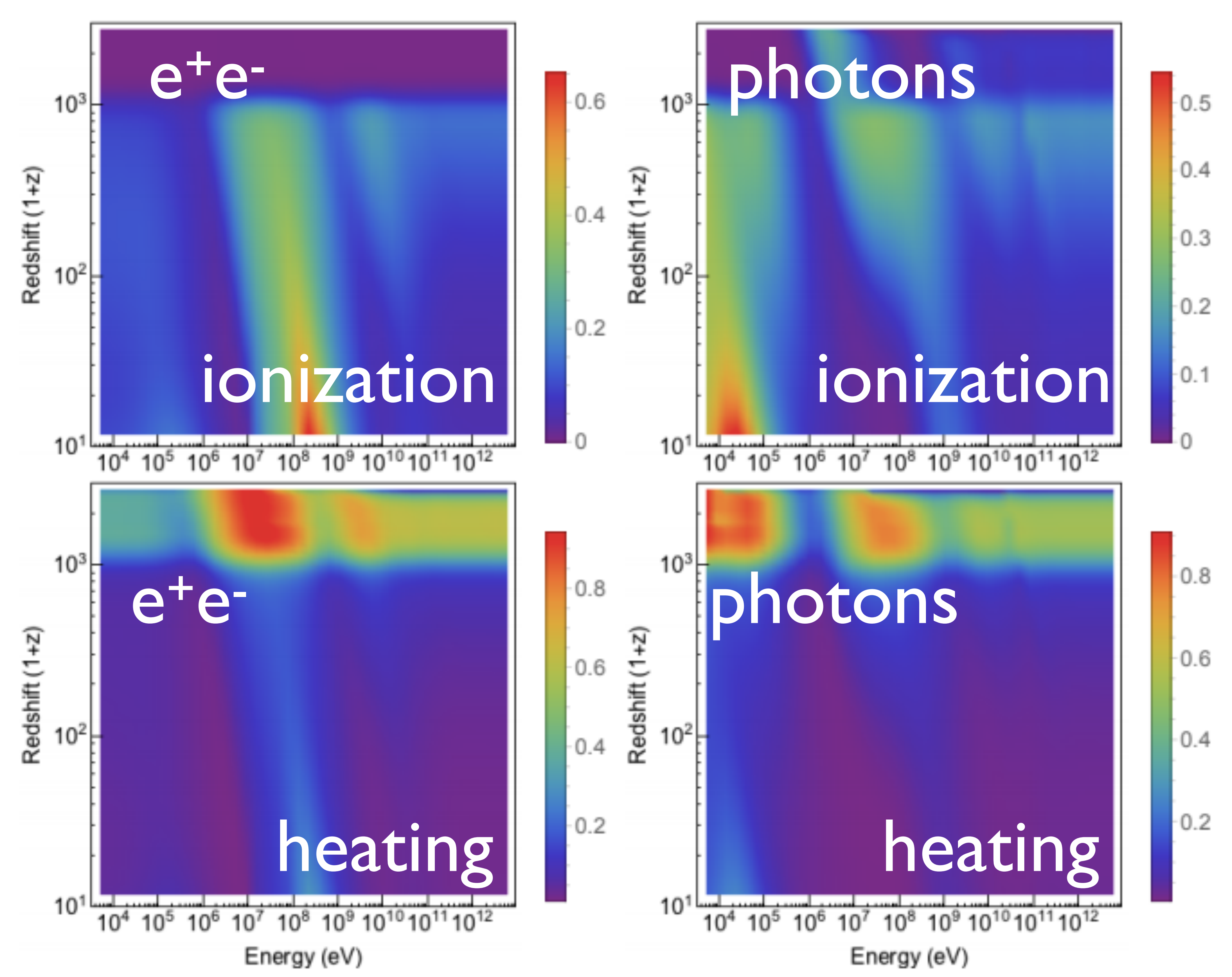
- Suppose that modifications to the ionization history from exotic injections are negligible + ionization history is well-known.
- Can then compute transfer functions at unperturbed $x_{HII}(z)$ values - transfer function determined by z only.
- Energy deposition into ionization/heating/excitation is then linear in the spectrum of injected particles - does not depend on injection history.
- Can pre-compute this deposition as a function of redshift for particles injected at different energies/redshifts, then take linear combinations.
- Having obtained exotic heating/ionization rate for a given model, can solve evolution equations for T/x_{HII}.
- This approach ("no backreaction") is significantly faster than running the full coupled evolution, once the pre-computation steps are done, and corresponds to tabulated results in use prior to DarkHistory (e.g. TRS '16).

Example application: CMB limits on DM physics

- This approach is thus well-suited for situations where:
  - the ionization history in the redshift range of interest is well-known
  - modifications to the ionization history from the energy injection itself are likely to be small
  - we want to scan over many different injection histories/spectra
- These conditions turn out to apply to constraints on DM annihilation/decay from CMB anisotropies.

Deposition basis for DM annihilation

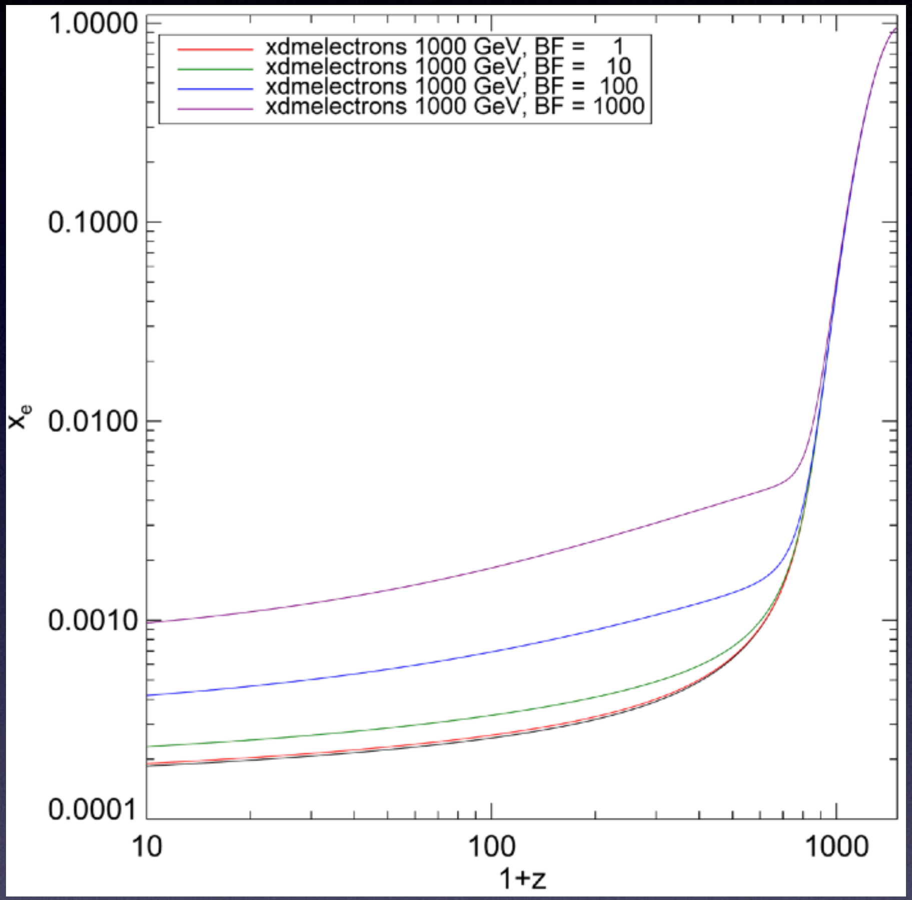
- Example $f_c(z)$ results for ionization, heating channels [TRS '16]
- Can be used to obtain heating/ ionization from arbitrary keV-TeV DM models

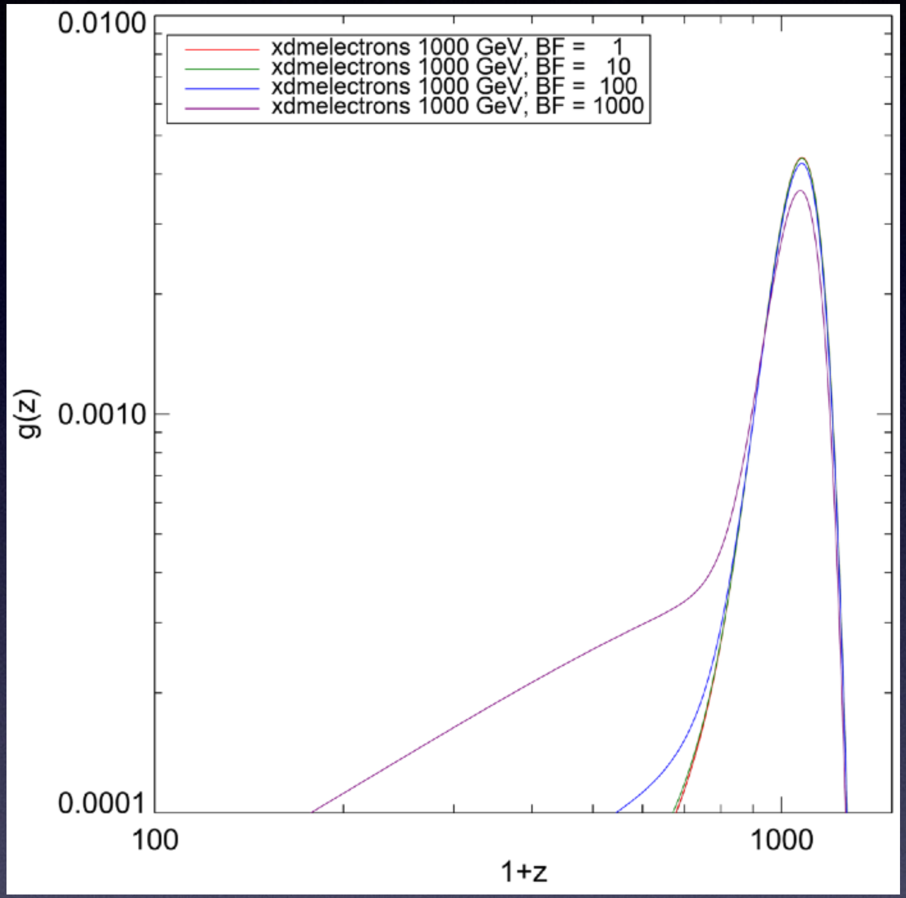


From deposition to CMB bounds

- We can now use public code packages (RECFAST/CosmoRec) to solve for the ionization history.
- Public codes CAMB/CLASS can compute the resulting CMB perturbations.
- We find that:
  - Signal is dominated by redshifts of several hundred, ~no impact from reionization uncertainties.
  - Injections are constrained to be small enough that CMB perturbations are ~linear in energy injection.
  - Shape of CMB perturbations doesn't depend on energy/species of injected particles - signal normalization is set by an appropriately-weighted integral over $f_{ionization}(z)$.

Example ionization history





- Example DM model, 1 TeV DM annihilating to electrons.
- At redshifts before recombination, many free electrons => the extra energy injection has little effect.
- After recombination, secondary ionization induced by DM annihilation products => higher-than-usual residual free electron fraction.
- Surface of last scattering develops a tail extending to lower redshift.

CMB perturbations

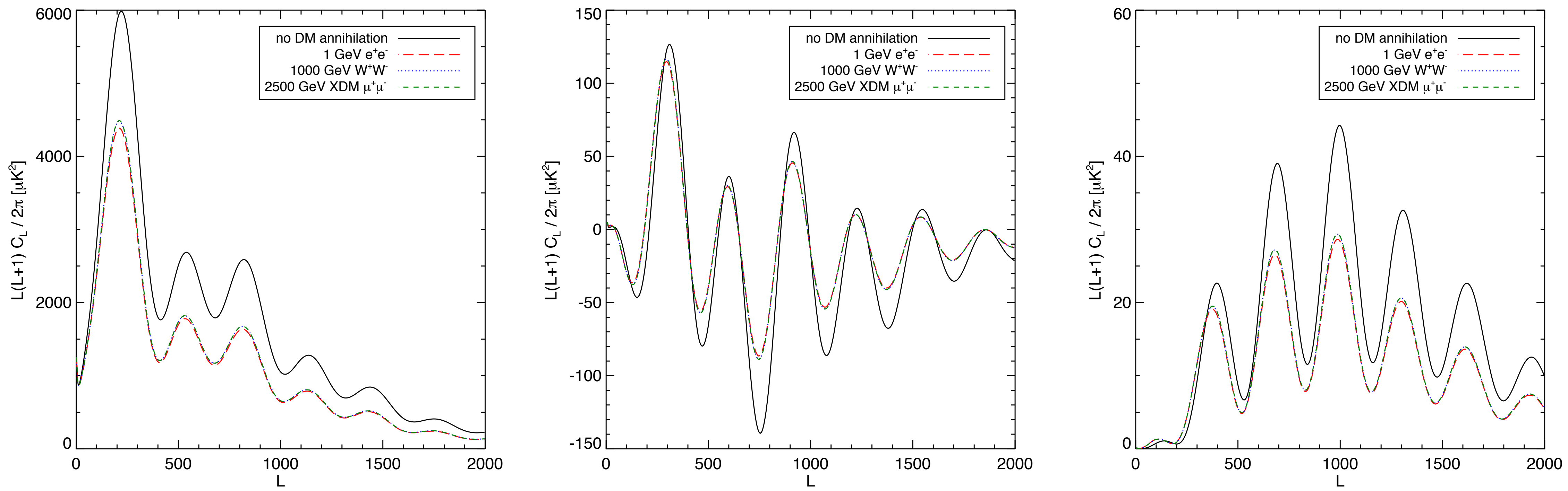


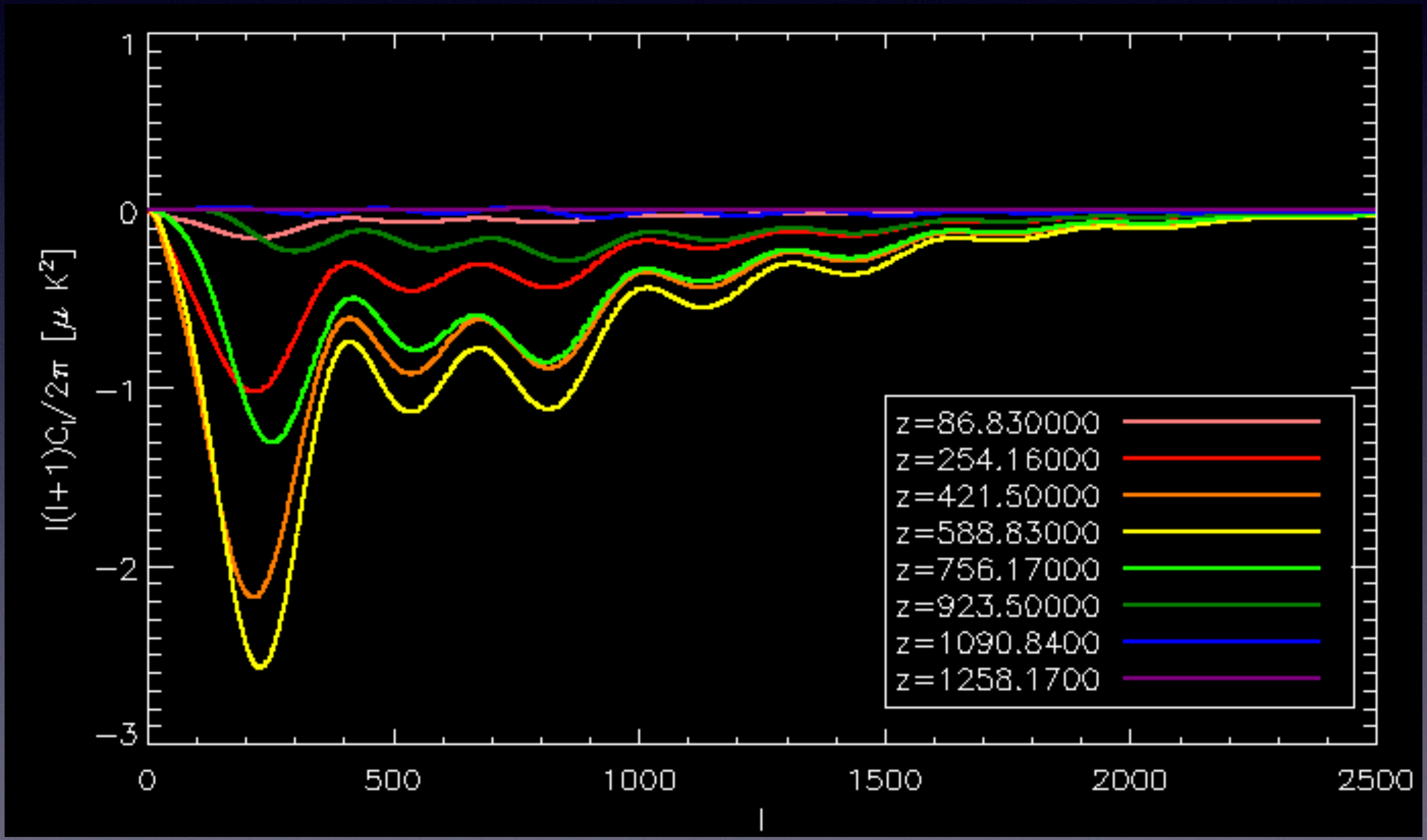
FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and $f = 1$, compared to a baseline model with no DM annihilation. The models give similar results for the TT (*left*), TE (*middle*), and EE (*right*) power spectra. This suggests that the CMB is sensitive to only one parameter, the average power injected around recombination. All curves employ the WMAP5 fiducial cosmology: the effects of DM annihilation can be compensated to a large degree by adjusting n_s and σ_8 [4].

- Run CAMB (or CLASS, or other similar package) with modified ionization history, compute shifts to the temperature and polarization anisotropies.
- Broader last scattering surface => enhanced damping of mid-l temperature fluctuations. Strong degeneracy with shifting n_s (primordial scalar spectral index), in temperature. Polarization breaks this degeneracy.
- Note: all curves (1) use extreme cases to make the effect clear, and (2) use the fiducial cosmology, without shifting the cosmological parameters to compensate for DM annihilation.

The range of CMB signals

- Consider energy absorption sharply peaked around a particular redshift, study its imprint in the CMB.
- Can build up any arbitrary energy deposition history from these “delta functions”.
- Perform a principal component analysis to pick out the main directions in which the anisotropy spectrum can be altered.

Finkbeiner, Galli, Lin & TRS 2011



Note: results shown here make outdated assumptions for the partition into excitation/ionization/heating. Since the signal is driven almost entirely by ionization, errors in the ionization prescription can be absorbed as differences in the energy absorption history.

Principal components

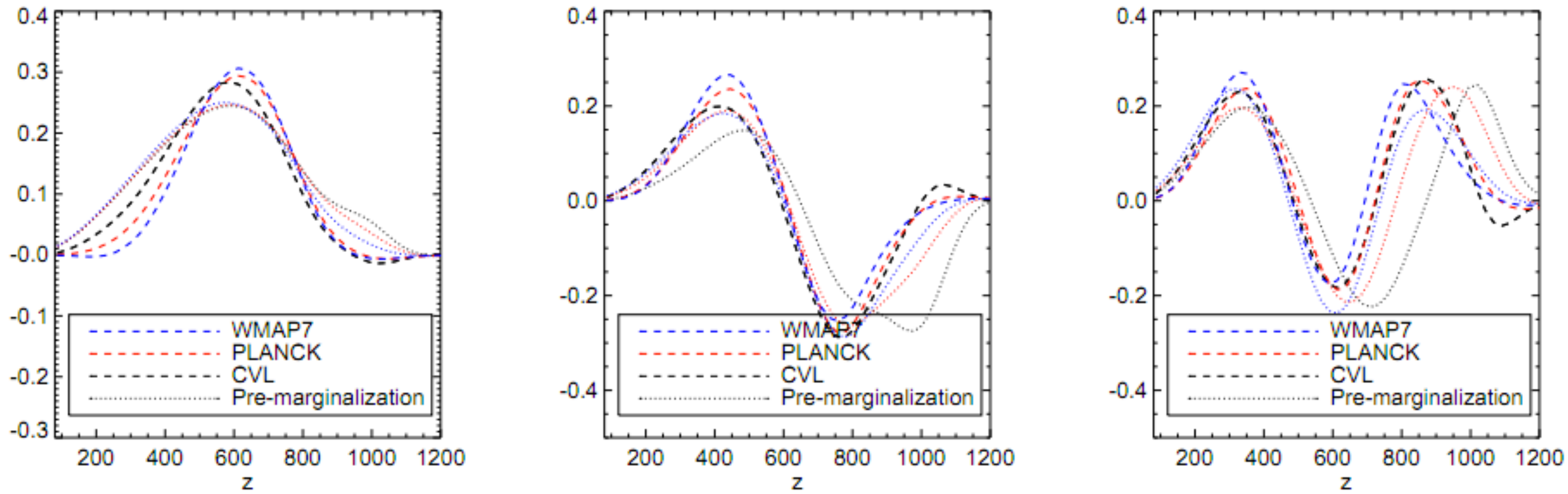


FIG. 4: The first three principal components for *WMAP* 7, *Planck* and a CVL experiment, both before and after marginalization over the cosmological parameters.

- Principal components characterize orthogonal shifts to the C_l's, after marginalization over the other cosmological parameters.
- First PC describes properly weighted average over redshifts (peak represents where signal is strongest).
- Second PC describes effect of having more power at low vs high redshifts.
- Third PC describes effect of power at low + high redshifts vs intermediate redshifts.
- … etc
- Any energy deposition history can be written uniquely as a linear combination of these principal components; the first few PCs capture the vast majority of the effect on the CMB.

... and in the CMB

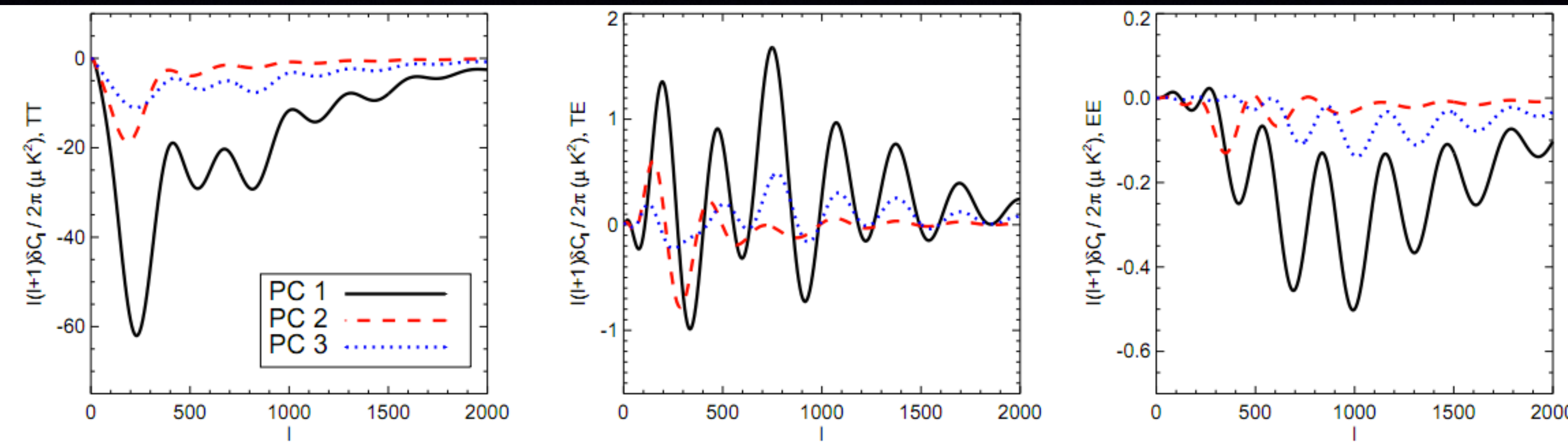


FIG. 7: The mapping of the first three principal components for *Planck*, after marginalization, into δC_ℓ space. The PCs are multiplied by $\varepsilon_i(z) = 2 \times 10^{-27}$ cm^3/s/GeV for all i, to fix the normalization of the δC_ℓ's.

h_i

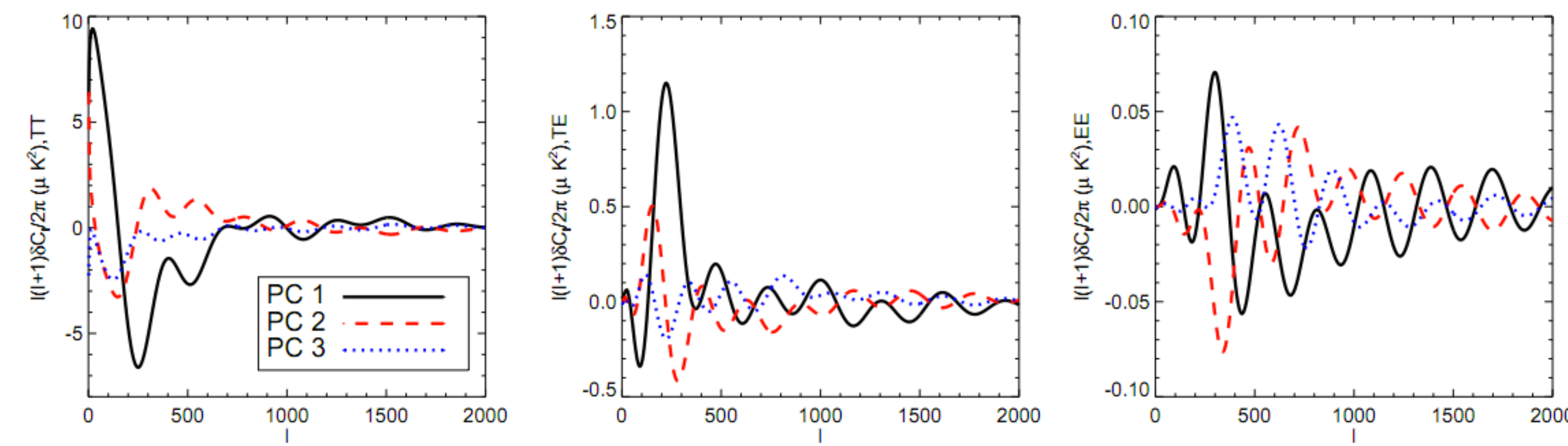


FIG. 8: The $\perp$ components of the first three principal components for *Planck*, after marginalization, mapped into δC_ℓ space. The normalization is the same as for Figure 7.

$h_i^\perp$

CMB signals for annihilation

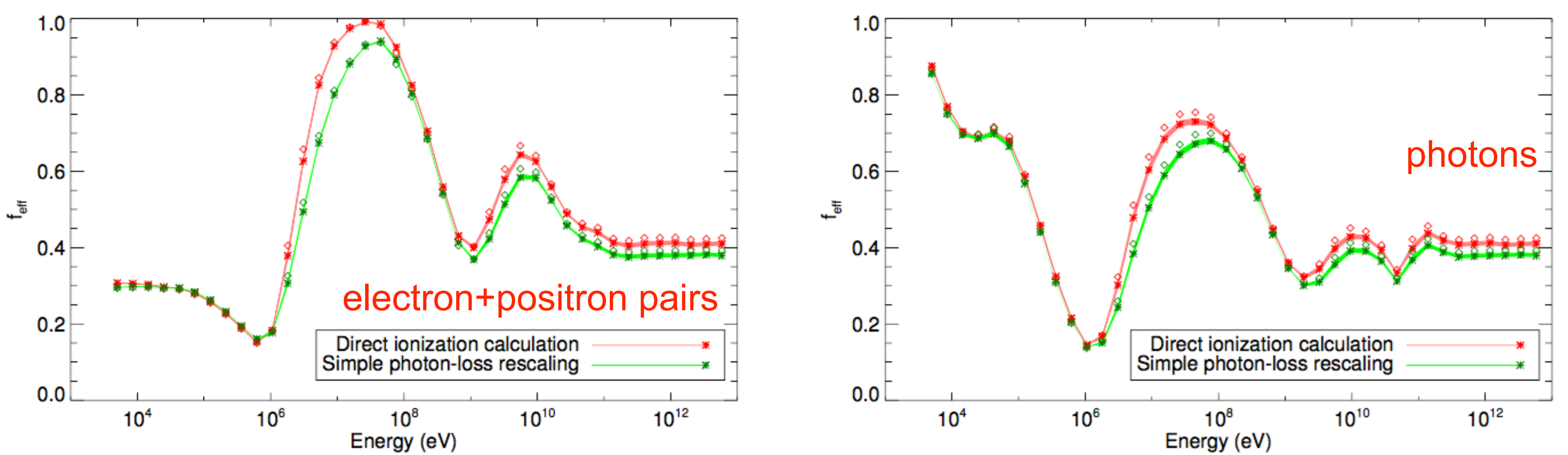
- s-wave annihilation defines a subspace of this general space - can be lower dimension
- Repeat PCA using energy deposition histories for keV-TeV electron/photon injections, with redshift dependence appropriate to DM annihilation
- First principal component captures >99% of variance - imprint on CMB is essentially a one-parameter family of curves
- Normalization of signal determined by parameter

$$f_{\rm eff} \langle \sigma v \rangle / m_\chi$$

- Given the bound on a specific DM model, the bound on any other DM model can be determined just from $f_{\rm eff}$.

Efficiency factors (annihilation)

TRS 2016



- We can then quickly compute this normalization/ efficiency factor $f_{eff}(E)$ for all injection energies for injected electrons/photons/positrons.
- Integrate over $f_{eff}(E)$ to determine strength of CMB signal for arbitrary spectra of annihilation products.

Recipe for generic DM model

(with s-wave annihilation)

- Given DM mass and couplings, determine spectra of e+e- pairs and photons produced per annihilation:

$$\left(\frac{dN}{dE}\right)_\gamma, \left(\frac{dN}{dE}\right)_{e^+}$$

- Determine f_{eff} by average over photon and electron spectra:

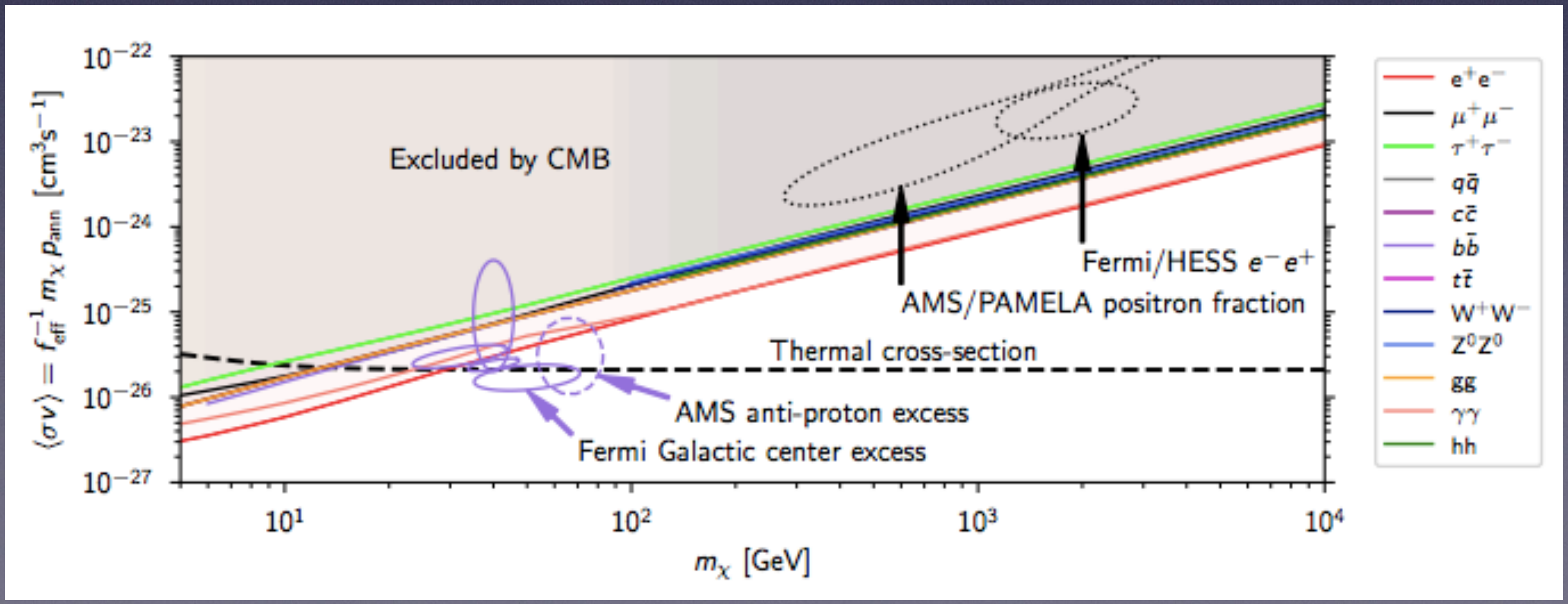
$$f_{\rm eff}(m_\chi) = \frac{\int_0^{m_\chi} E dE \left[2 f_{\rm eff}^{e^+e^-}(E) \left(\frac{dN}{dE}\right)_{e^+} + f_{\rm eff}^{\gamma}(E) \left(\frac{dN}{dE}\right)_\gamma\right]}{2 m_\chi}$$

- Impose constraint derived by Planck team on annihilation parameter, via likelihood analysis:

$$f_{\rm eff} \frac{\langle \sigma v \rangle}{m_\chi} < 3.2 \times 10^{-28} {\rm cm}^3/{\rm s}/{\rm GeV}$$

Annihilation limits from Planck

- A single analysis of CMB data simultaneously tests all annihilation channels, over a huge mass range.
- Excludes full thermal relic cross section below ~10 GeV, often sets the strongest indirect limits for sub-GeV DM.

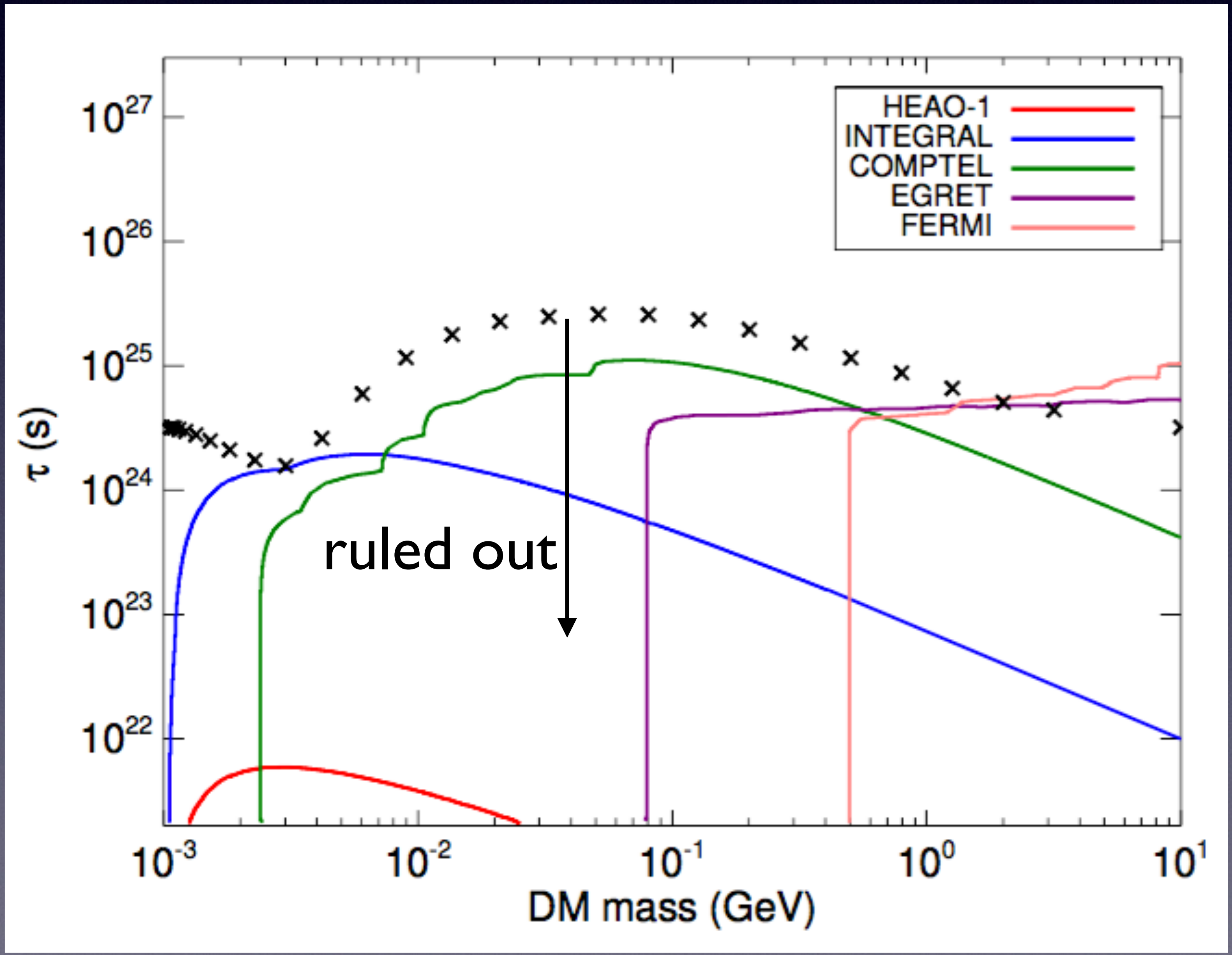


Planck Collaboration '18 1807.06209

Constraints on decay from Planck

- For decaying dark matter, can use the same approach.
- Sets some of the strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even 10^{-11} of the DM decaying (for lifetimes $\sim 10^{14}$ s)

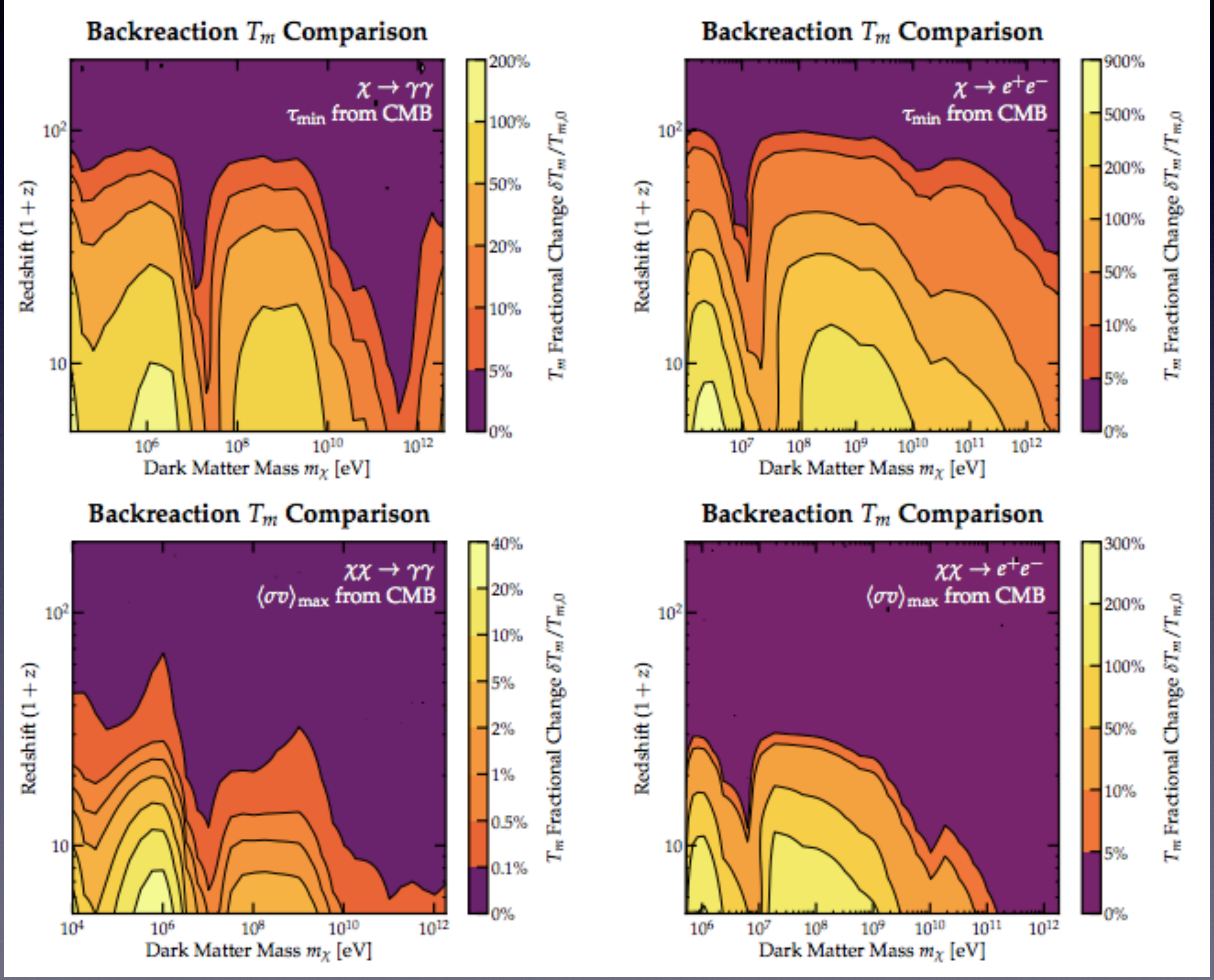
TRS & Wu, PRD '17



Other constraints (colored lines) from Essig et al '13

When does backreaction matter?

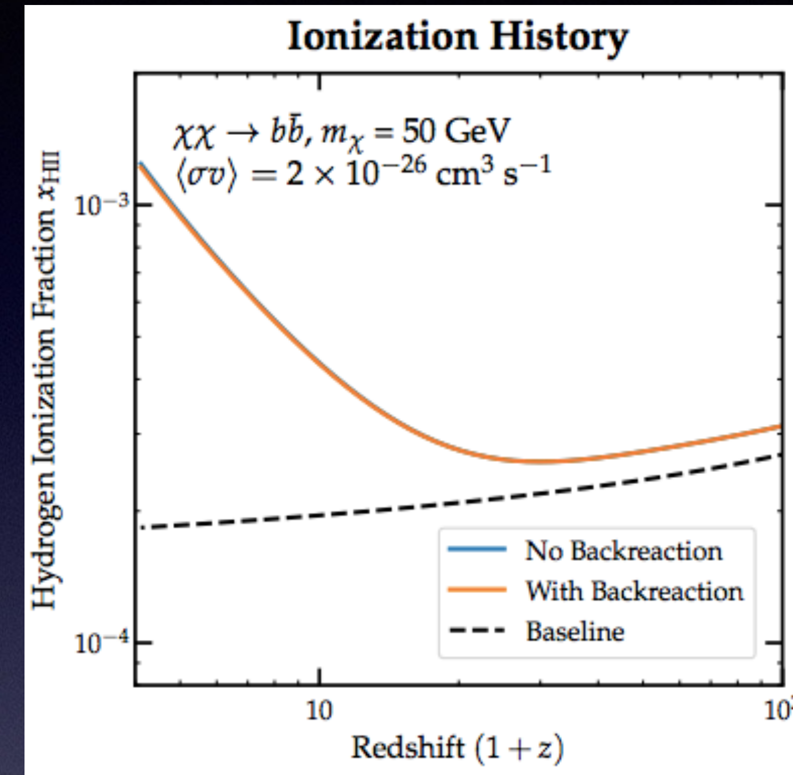
- In this scan we take models on the verge of exclusion by CMB bounds and compute the effect of backreaction on the change in the matter temperature, using DARKHISTORY.
- Effects are tiny above z~100, but can be large during cosmic dawn, especially for DM decay.

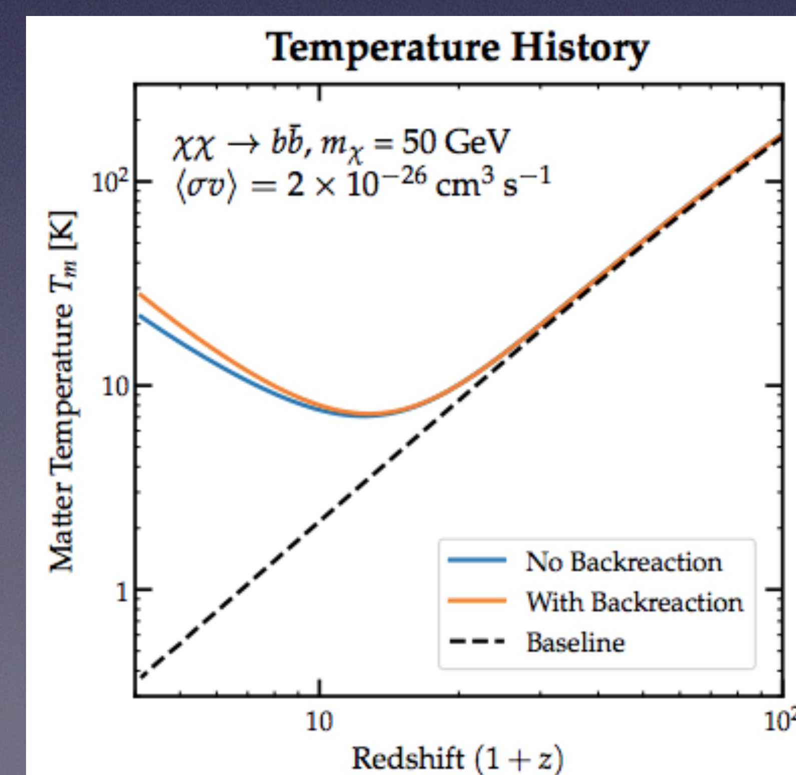


Running DarkHistory

```
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
- Turning backreaction on or off is a matter of a single keyword.
- Example: ionization/temperature histories for a 50 GeV thermal relic annihilating to b quarks, with and without backreaction.

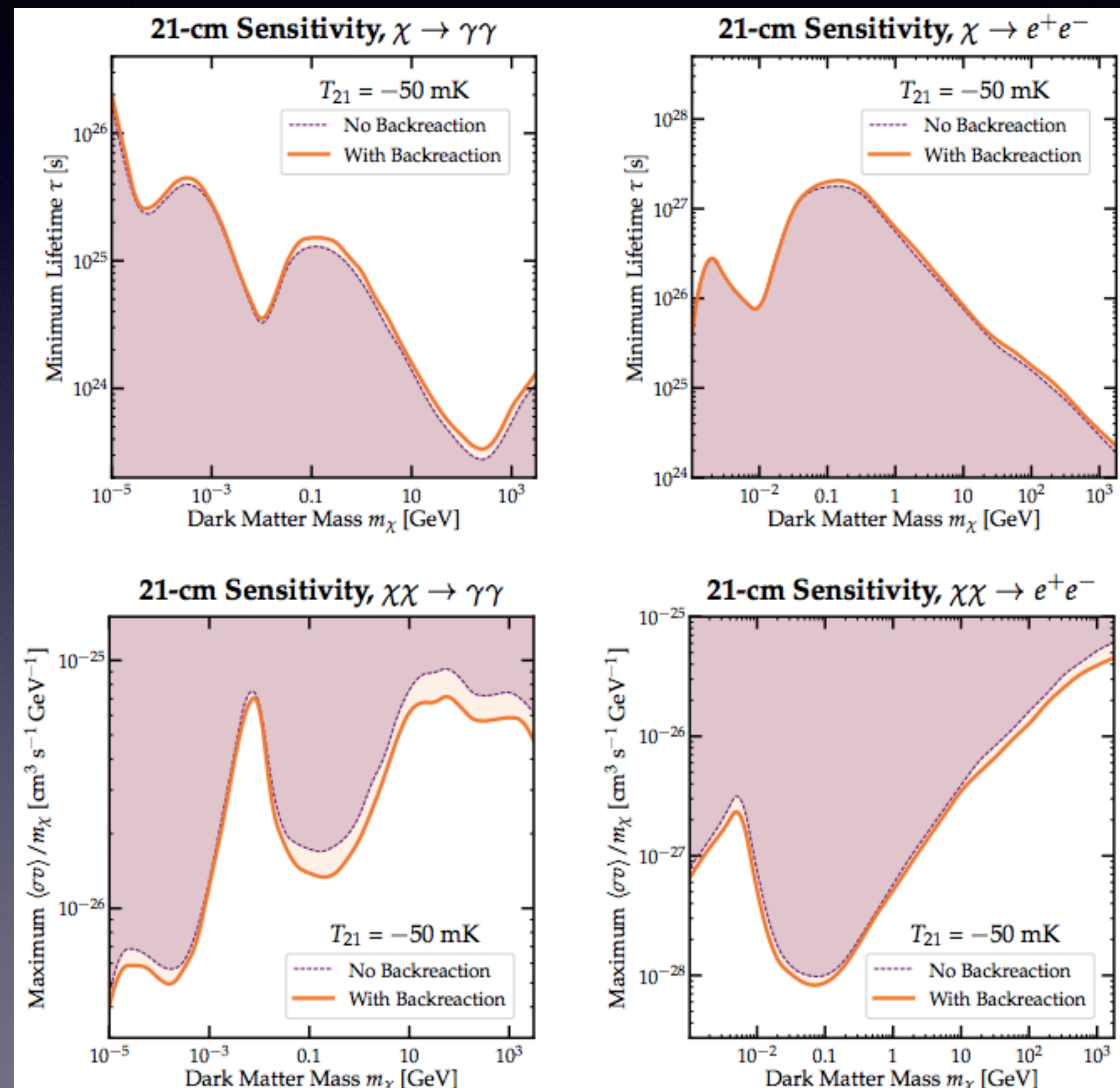




21cm sensitivity

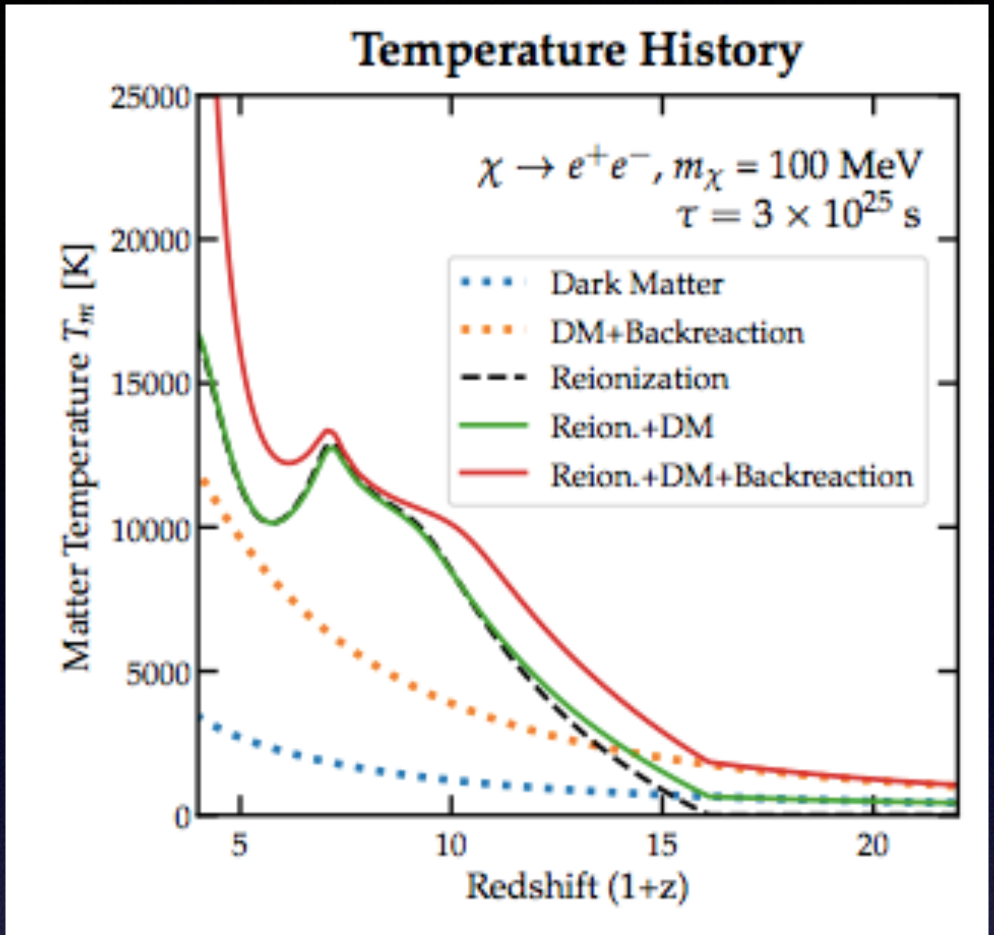
$$T_{21}(z) \approx x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

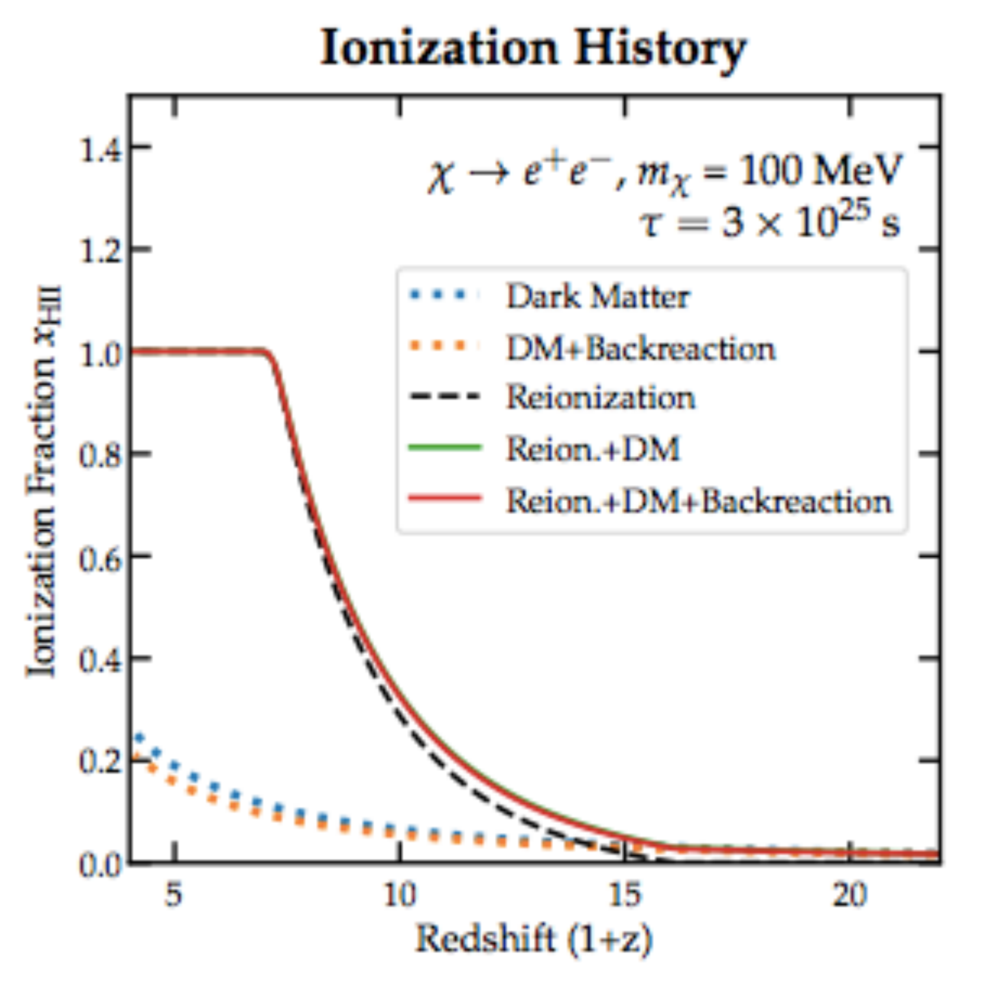
- Consider a hypothetical 21cm measurement of T_{21} < -50 mK at z~17.
- If $T_R = T_{CMB}$, this corresponds to an upper limit on the gas temperature of T_m~20 K.
- With DARKHISTORY, it is easy to compute the resulting limits with and without backreaction.
- Note particular sensitivity to decay to electrons.



Including reionization

- Here we include a model for reionization [Puchwein et al ’18], as photoionization/photoheating contributions in the evolution equations.
- Example: DM decay, at the minimum lifetime allowed by the CMB.
- We see that backreaction significantly enhances the DM-induced heating during reionization.

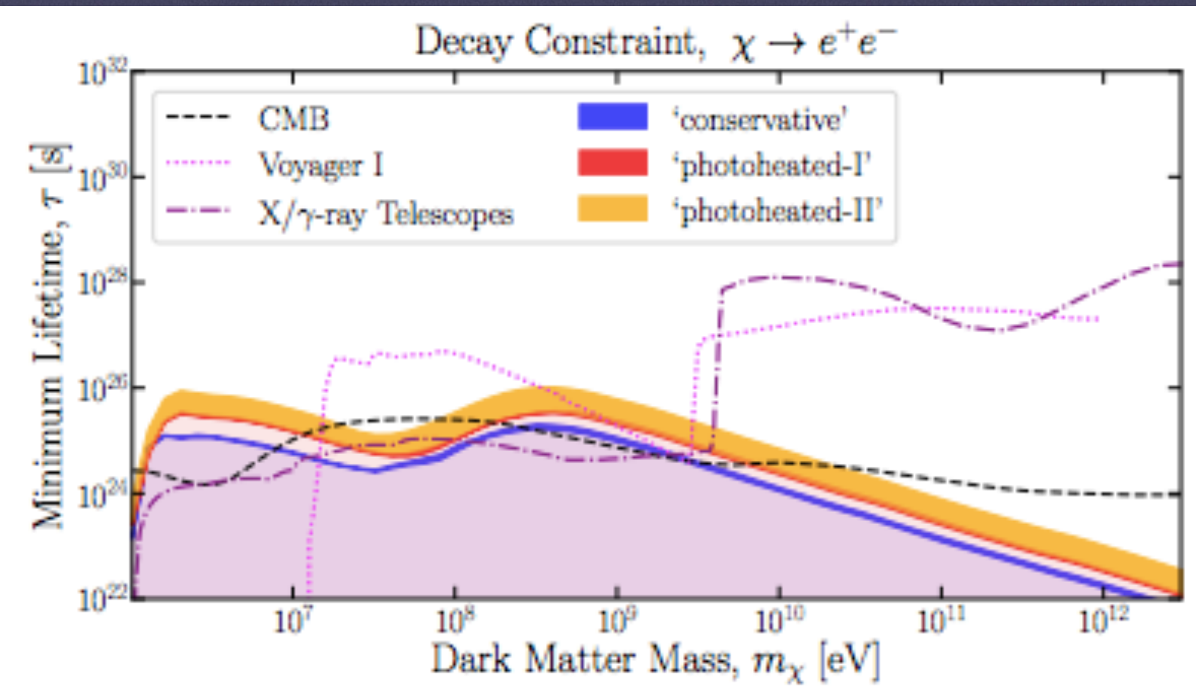




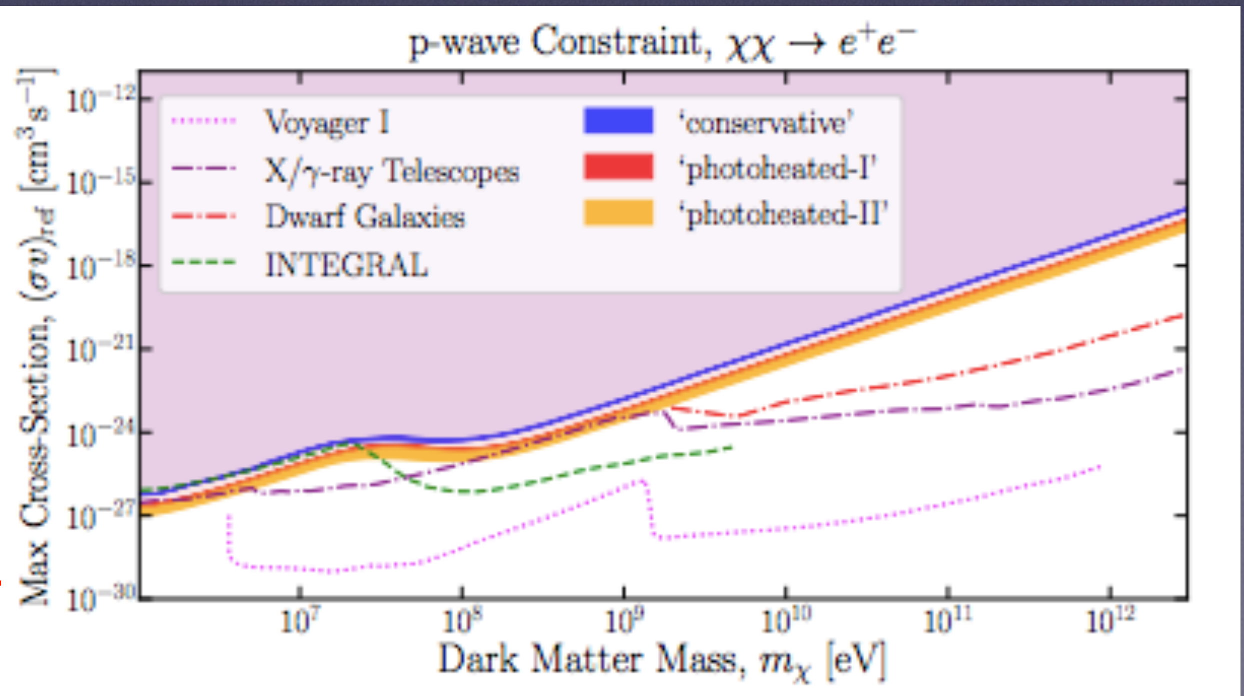
Heating constraints from Lyman-alpha

Liu, Qin, Ridgway & TRS '20

- Example limits on DM decaying or annihilating to electrons and positrons.
- Width of bands denotes uncertainty in reionization history. Conservative vs photoheated limits differ by a factor of a few, up to 1 order of magnitude.
- Limits are broadly competitive with other constraints for light DM that decays or annihilates through p-wave processes (suppressed at low velocities). For s-wave annihilation CMB bounds are stronger.



Liu et al '20



Tools in DarkHistory

- DarkHistory contains self-contained modules/functions for:
  - quick, accurate numerical calculation of inverse Compton scattering spectra over very broad energy ranges (including non-relativistic and ultra-relativistic electrons).
  - fast calculation of the cooling of electrons due to inverse Compton scattering and atomic processes, for arbitrary gas density / ionization level / CMB temperature.
- These tools are applicable in contexts beyond early-universe cosmology.
- Also note DarkHistory fixes some bugs in previous calculations - largest changes for decay/annihilation to e^+e^- at low energies & low redshifts (no effect on CMB bounds).

Ongoing work/questions

- Short term:
  - Improving module for cooling of low-energy electrons - in current public version, for electrons below 3 keV, we interpolate results from the MEDEA code [Evoli et al '12].
  - A consequence of the improved electron module will be an improved prediction for the low-energy photon spectrum = distortion to the CMB blackbody
  - Developing (via neural network) efficient fitting functions to replace the large interpolation tables currently included with DARKHISTORY.
  - Factoring out the dependence of the cascade calculation on H_0 and Ω_b, to allow easy variation of the cosmological parameters.
- Longer term:
  - Possible integration with other public codes - CosmoRec/HyRec, CLASS, codes modeling 21cm power spectrum.
  - DARKHISTORY still assumes homogeneity of deposition - not true in general at low redshift.
  - DARKHISTORY assumes the only radiation field is the CMB - stars turning on could modify the cooling cascade.

Summary

- Cosmological datasets are enormously rich and can provide powerful probes of the non-gravitational properties of dark matter, over a huge range of possible scenarios.
- The cosmic microwave background provides stringent limits on both annihilating and decaying DM.
- Scenarios that are not yet ruled out could have large effects on the matter temperature at the end of the cosmic dark ages. Equivalently, 21cm measurements could set robust, stringent new constraints on DM annihilation/decay (especially light DM decaying to electrons).
- We have developed a new public numerical toolbox, DARKHISTORY, to self-consistently compute the effects of exotic energy injections on the cosmic thermal and ionization histories. A self-consistent approach is needed to accurately compute changes to the matter temperature at the end of the dark ages and during reionization.