Probing Energy Injections from Dark Matter with Cosmology

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MIT

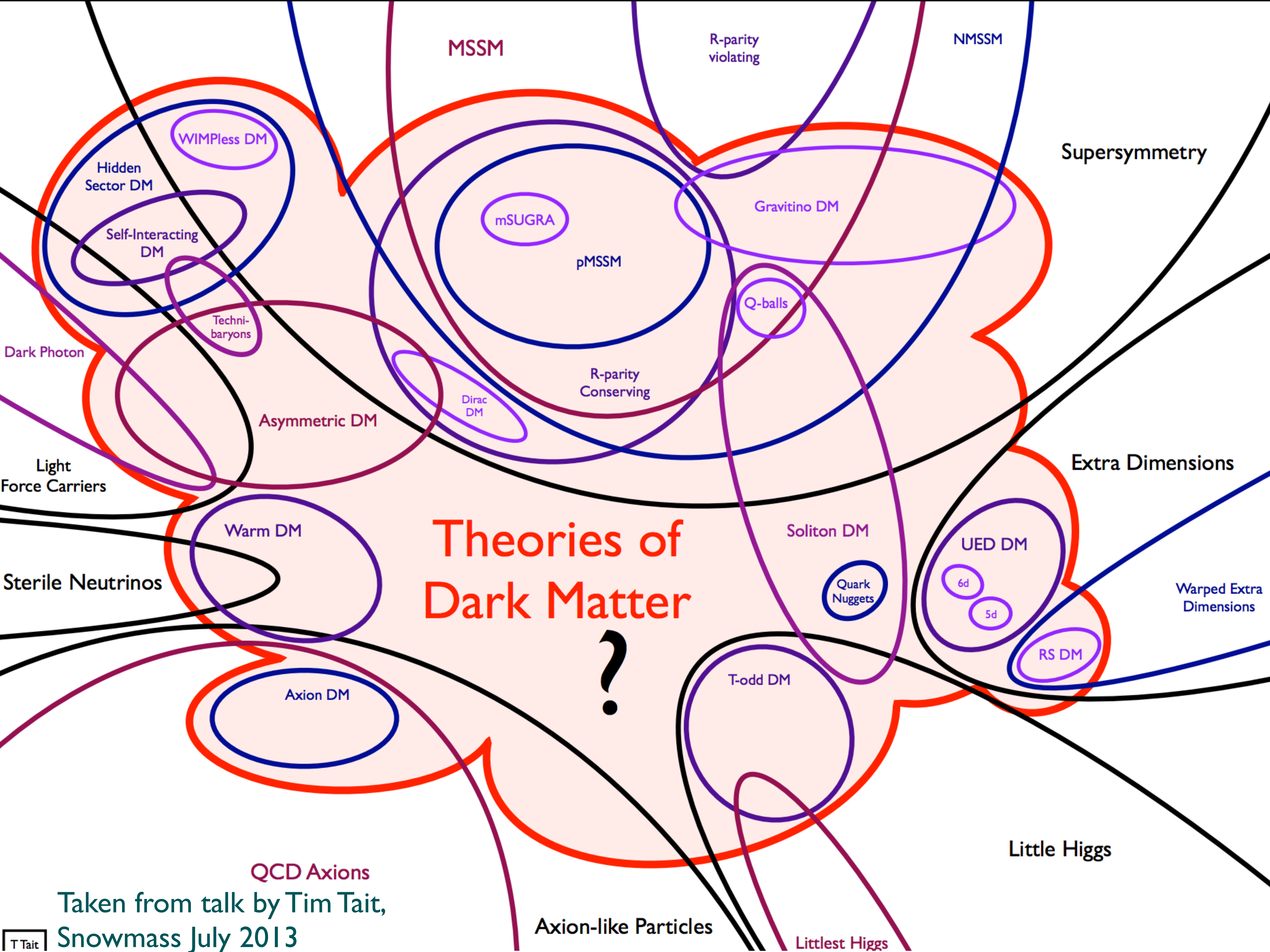
Understanding Cosmological Observations
Benasque, Spain
2 August 2019

Based on work with Hongwan Liu and Greg Ridgway
arXiv:1904.09296

U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

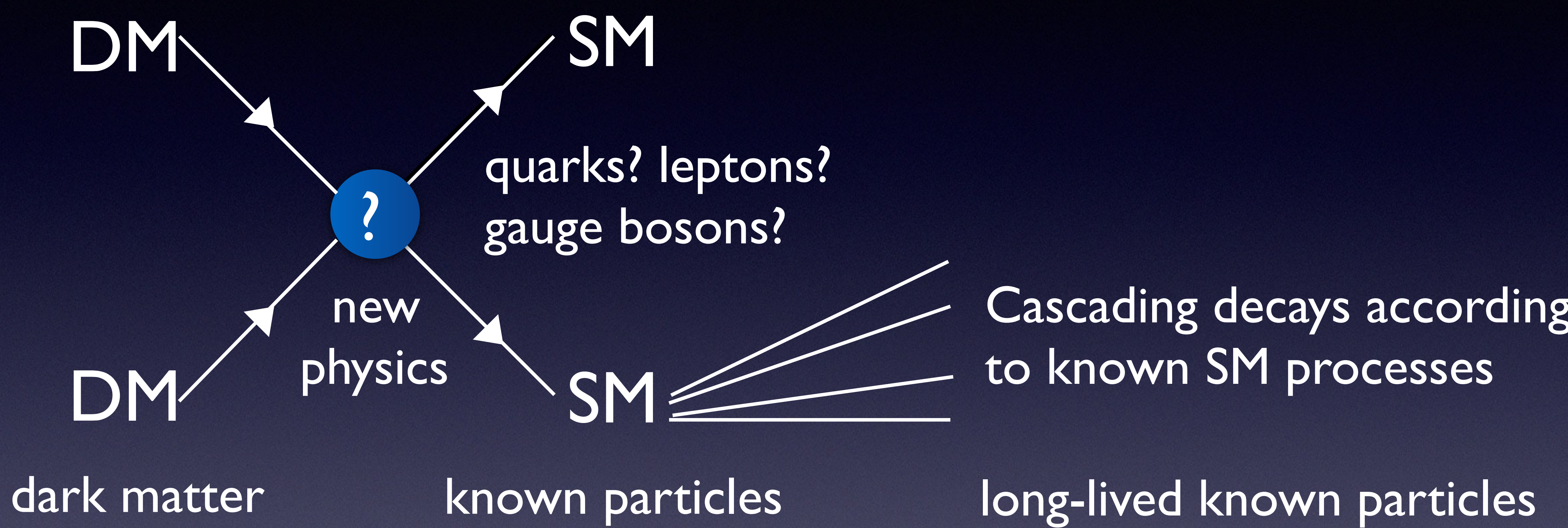
- How energy injection originating from (non-gravitational) dark matter interactions could change the early universe
- Intro to DarkHistory (https://darkhistory.readthedocs.io, code stored on github): a self-consistent calculation of perturbed ionization and temperature histories
- Applications
  - CMB constraints on DM annihilation and decay
  - Incorporating backreaction effects
  - Sensitivity of 21cm observations to DM signals
  - Combining exotic energy injections with reionization models



Taken from talk by Tim Tait, Snowmass July 2013

- Many of these scenarios are ~equivalent from the perspective of gravitational effects
  - exceptions: DM is very light (fuzzy DM, $\sim 10^{-21}$ eV) or very heavy (PBHs), warm/fast-moving, or strongly self-interacting (cross section/mass > 0.1 cm^2/g)
- Non-gravitational interactions in principle provide much greater discriminating power (if they exist)
- Large ongoing experimental program to search for such interactions in colliders, direct-detection searches, astrophysical observations
- Can regard such interactions as providing an energy transfer channel between dark and visible sectors - could have observable effects on cosmology
- Interactions can be elastic (see talk by Cora Dvorkin on Wednesday) or inelastic (focus of this talk, can constrain very tiny fractions of DM interacting)

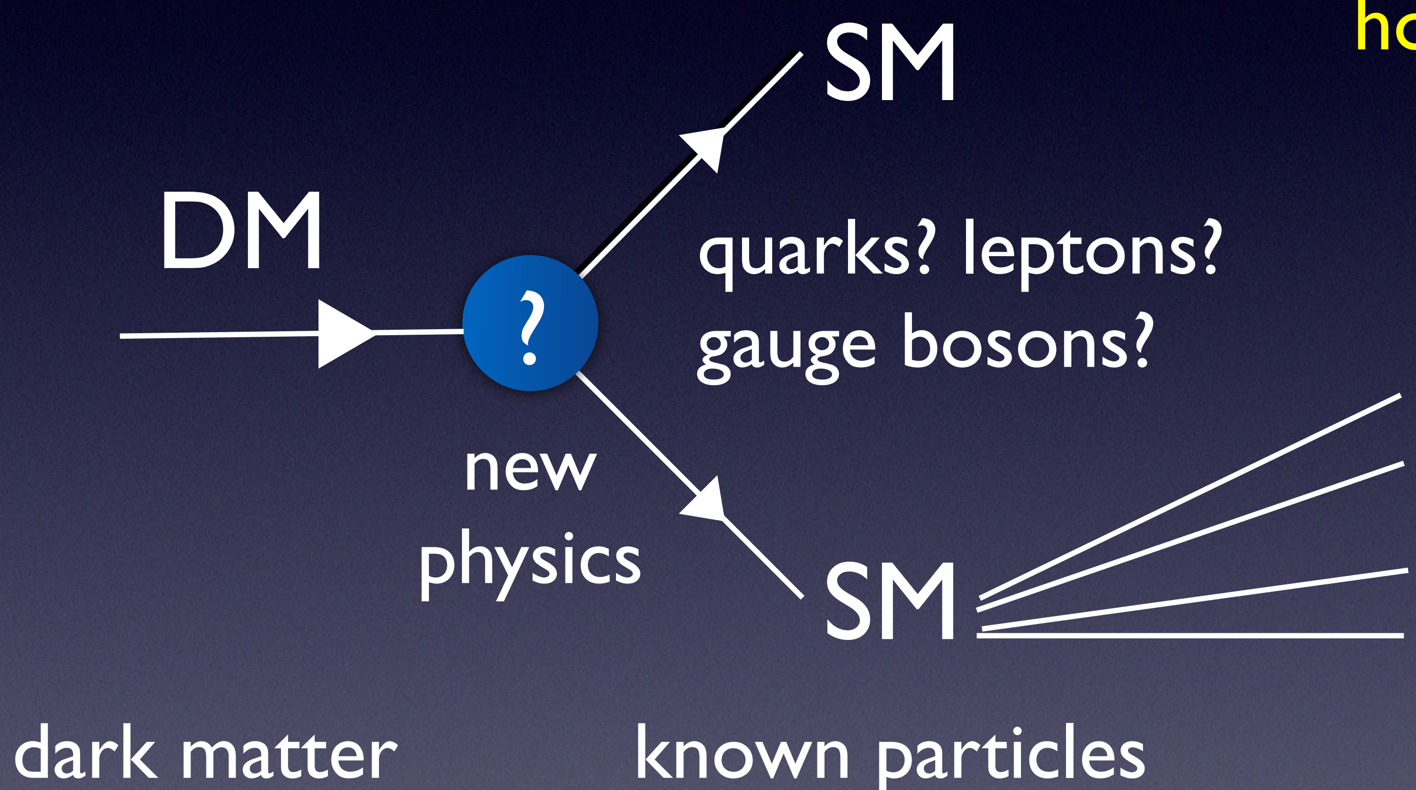
Annihilation



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

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

Decay



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

- Either annihilation or decay would lead to a slow trickle of energy into the visible sector over time.
- We can explore the effects of this energy transfer on the history of the universe.

Signatures in the CMB (I)

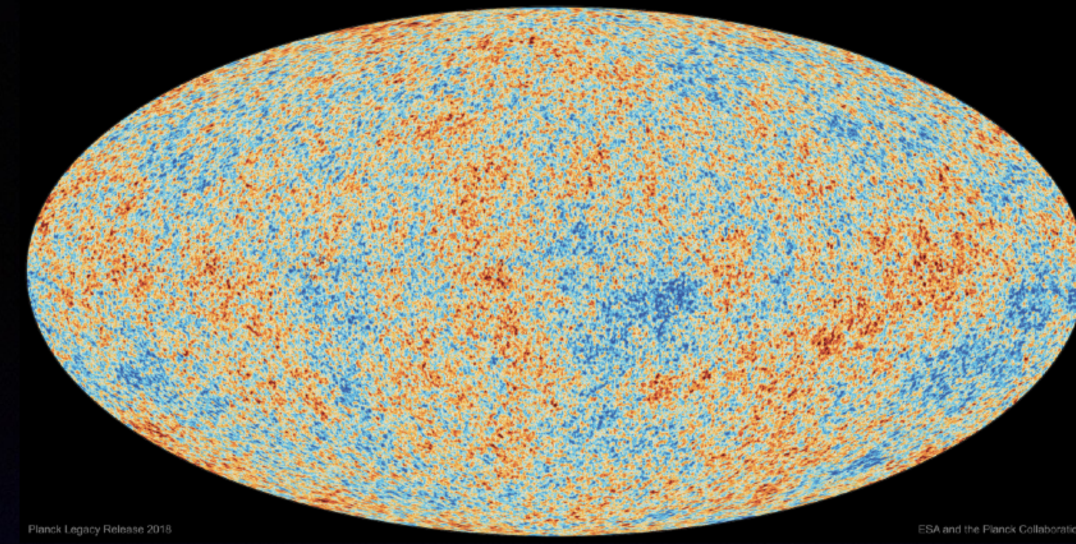
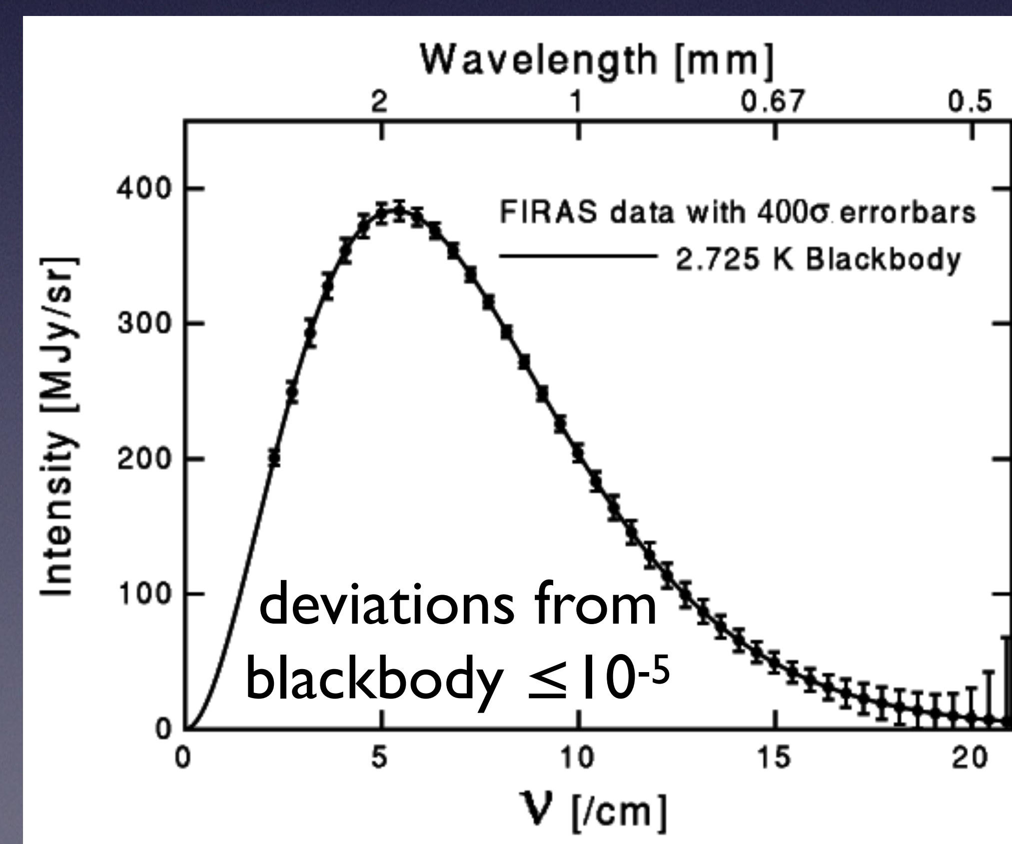


Image credit: European Space Agency / Planck Collaboration

- We can change the observed CMB by:
  - changing the plasma to which the photons couple (largest effects prior to recombination)
  - modifying the photon spectrum directly via scattering or injection
- Scattering between DM and ordinary matter would slightly couple DM and baryons, modifying the anisotropy pattern.
- Cooling (via scattering) or heating (via annihilation/decay) of the baryons would induce spectral distortions.

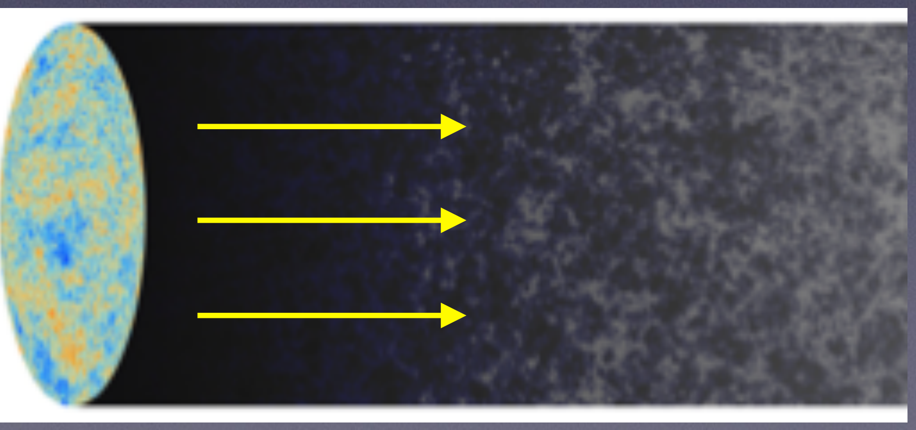
spatial information: describes pattern of oscillations in density and temperature

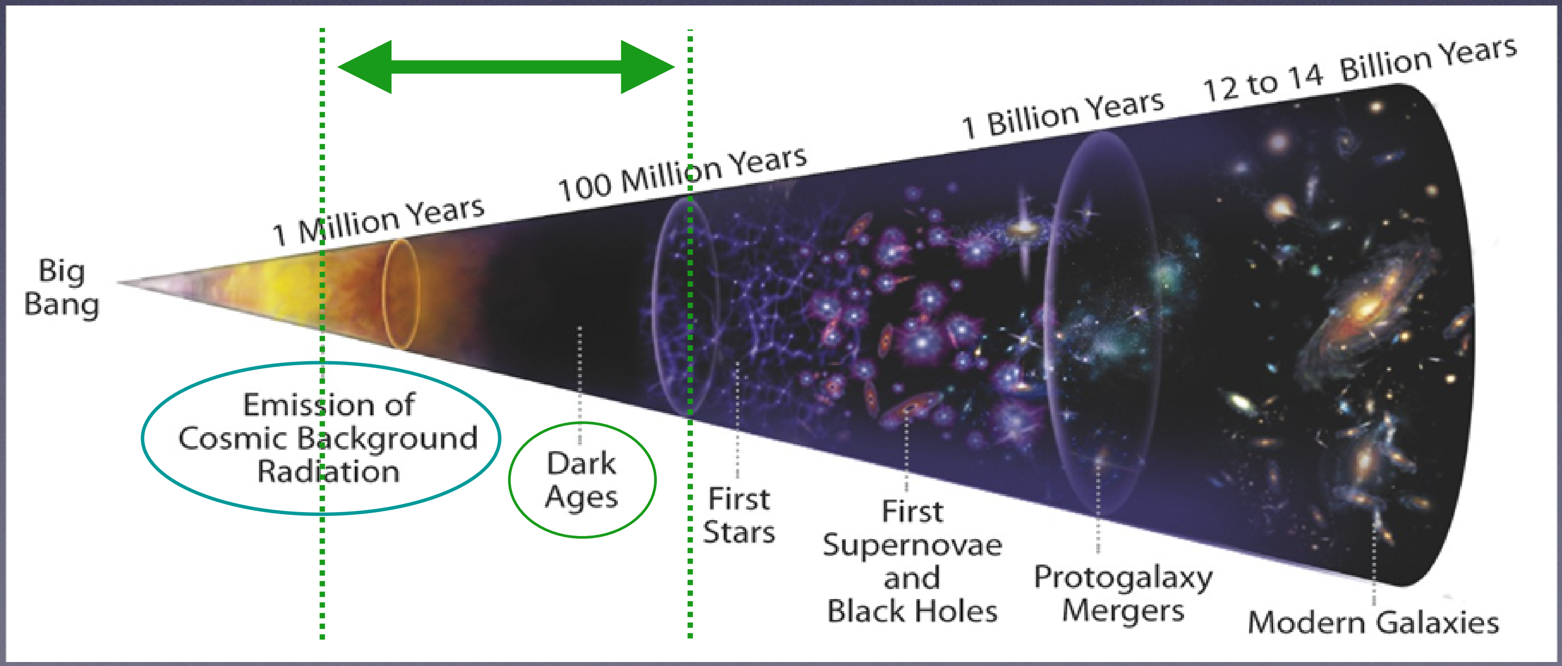
spectral information: near-perfect blackbody



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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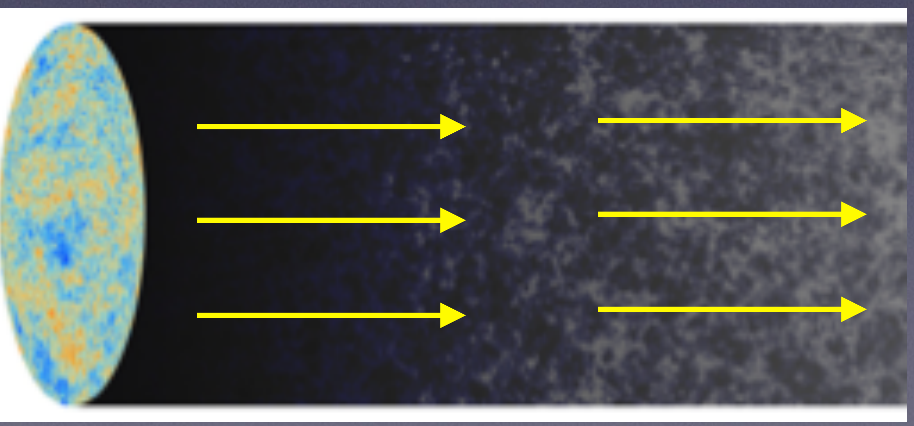
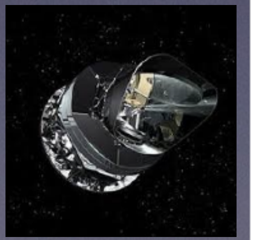
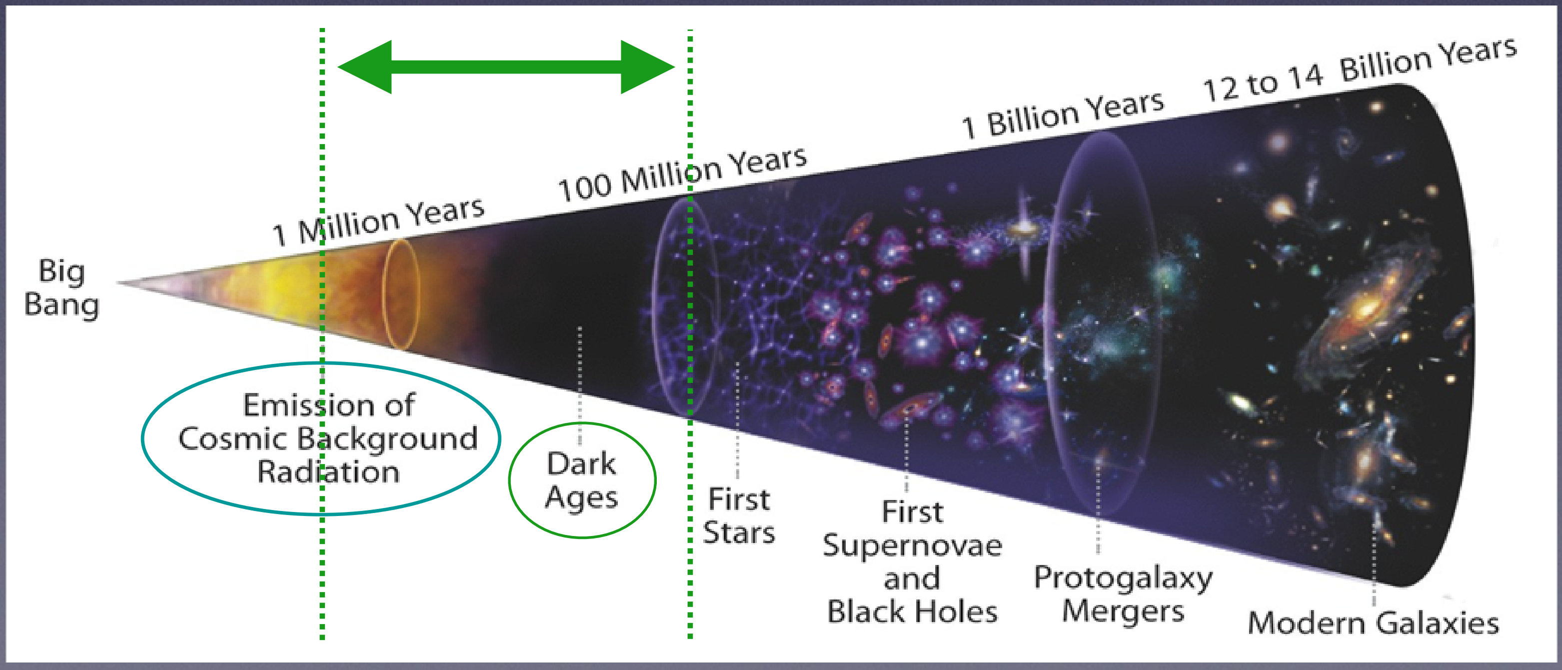




Planck



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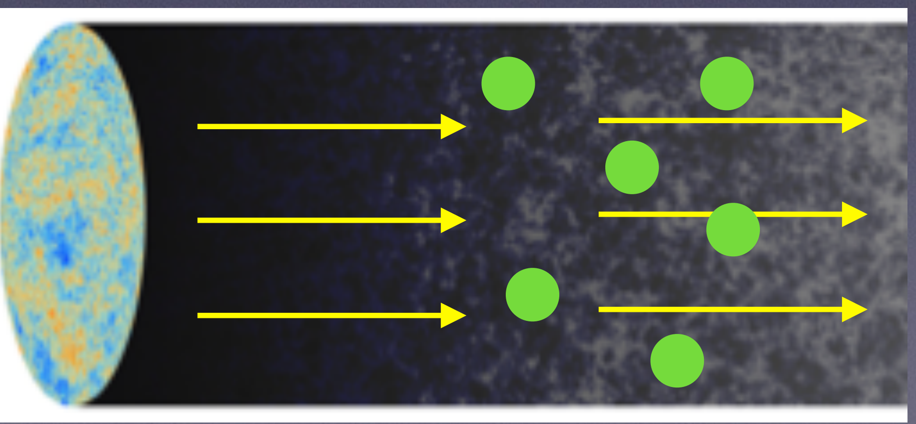

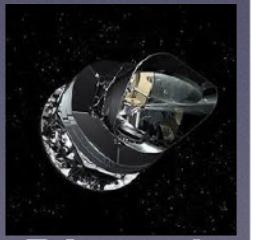

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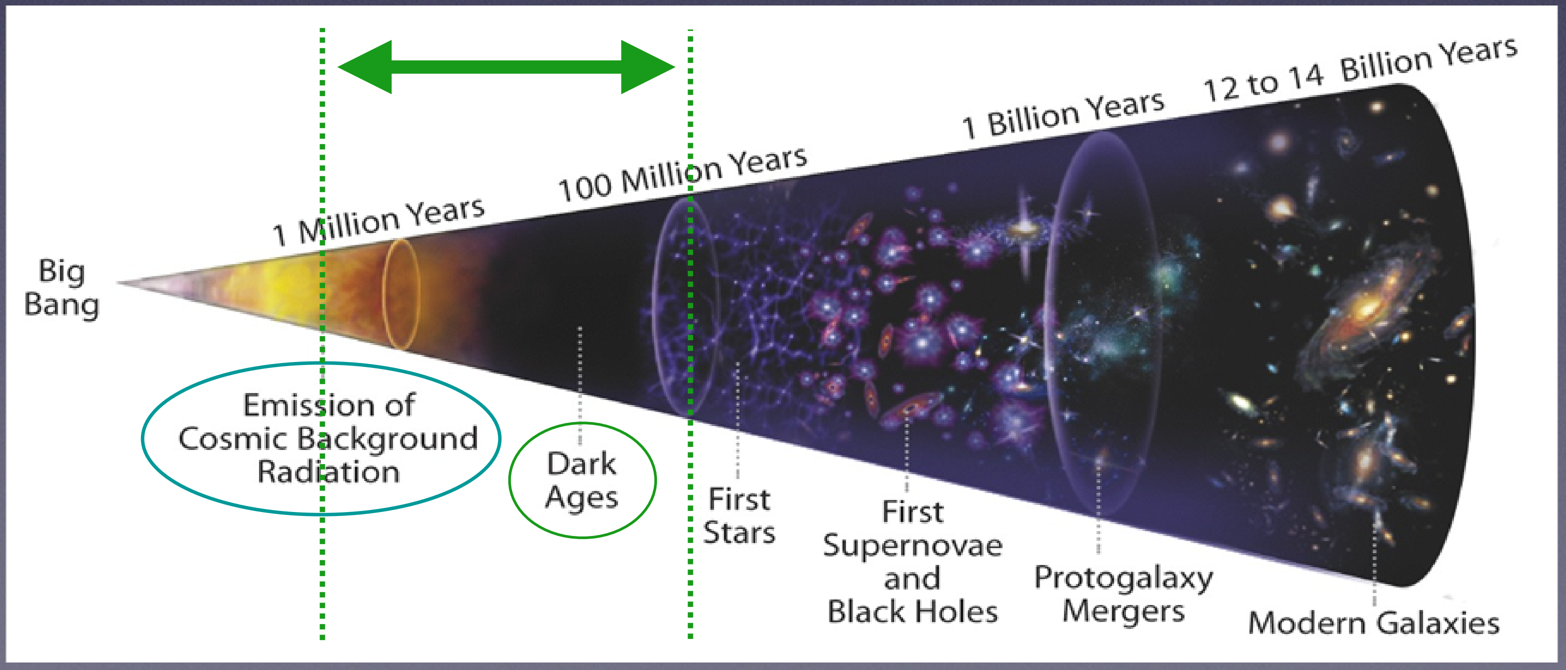

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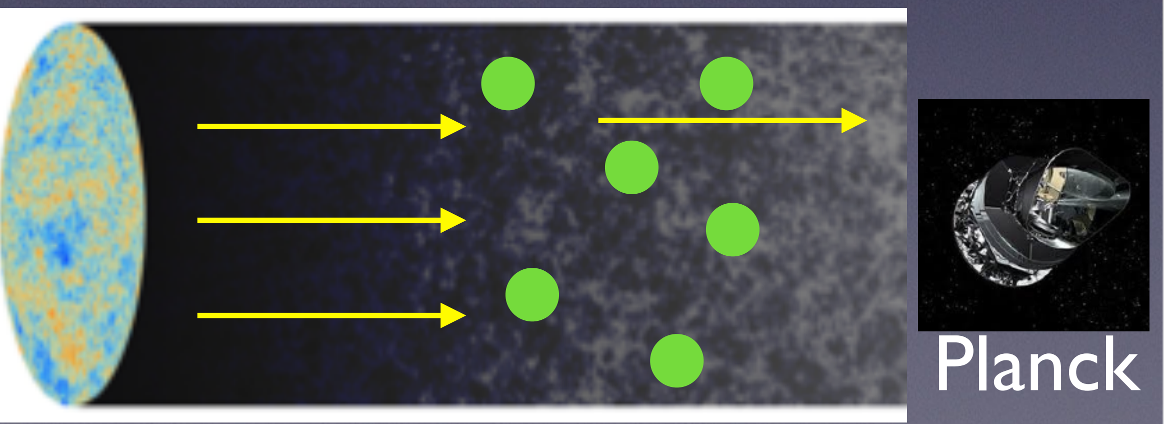
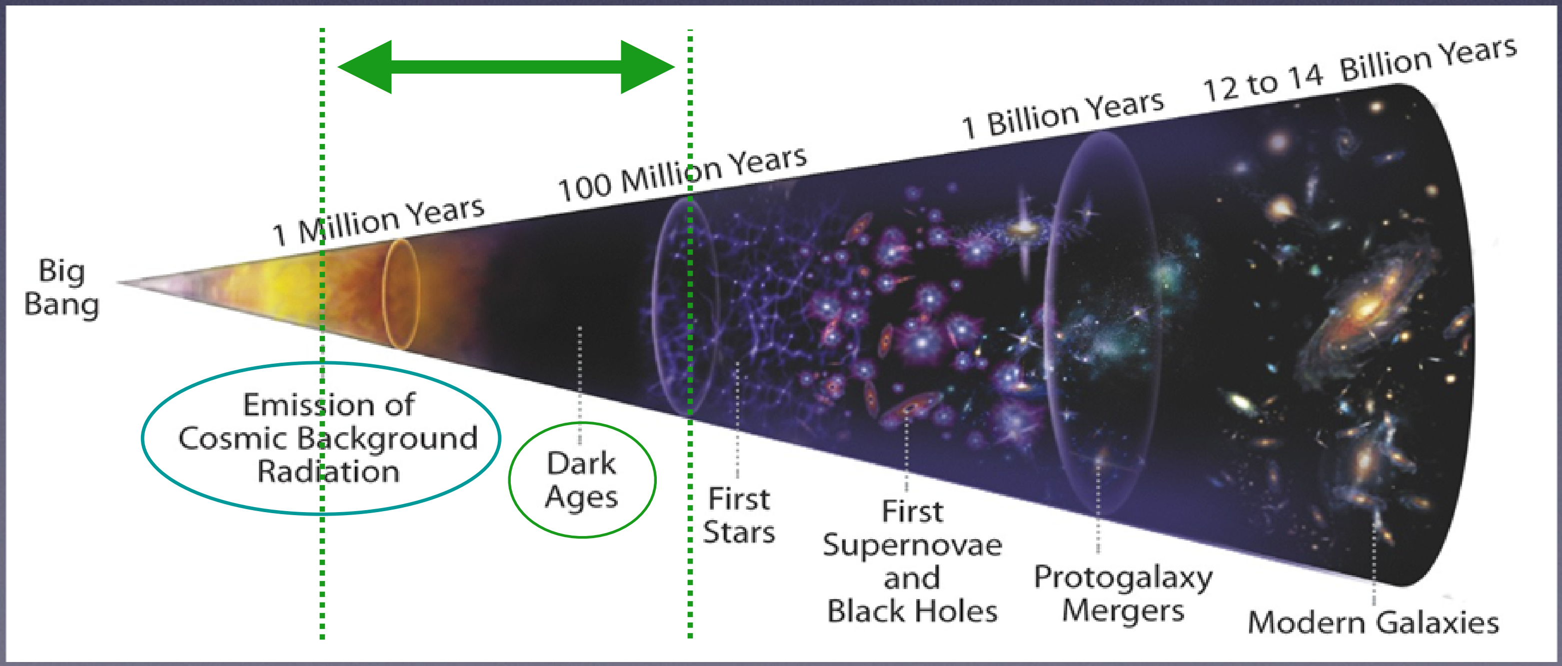
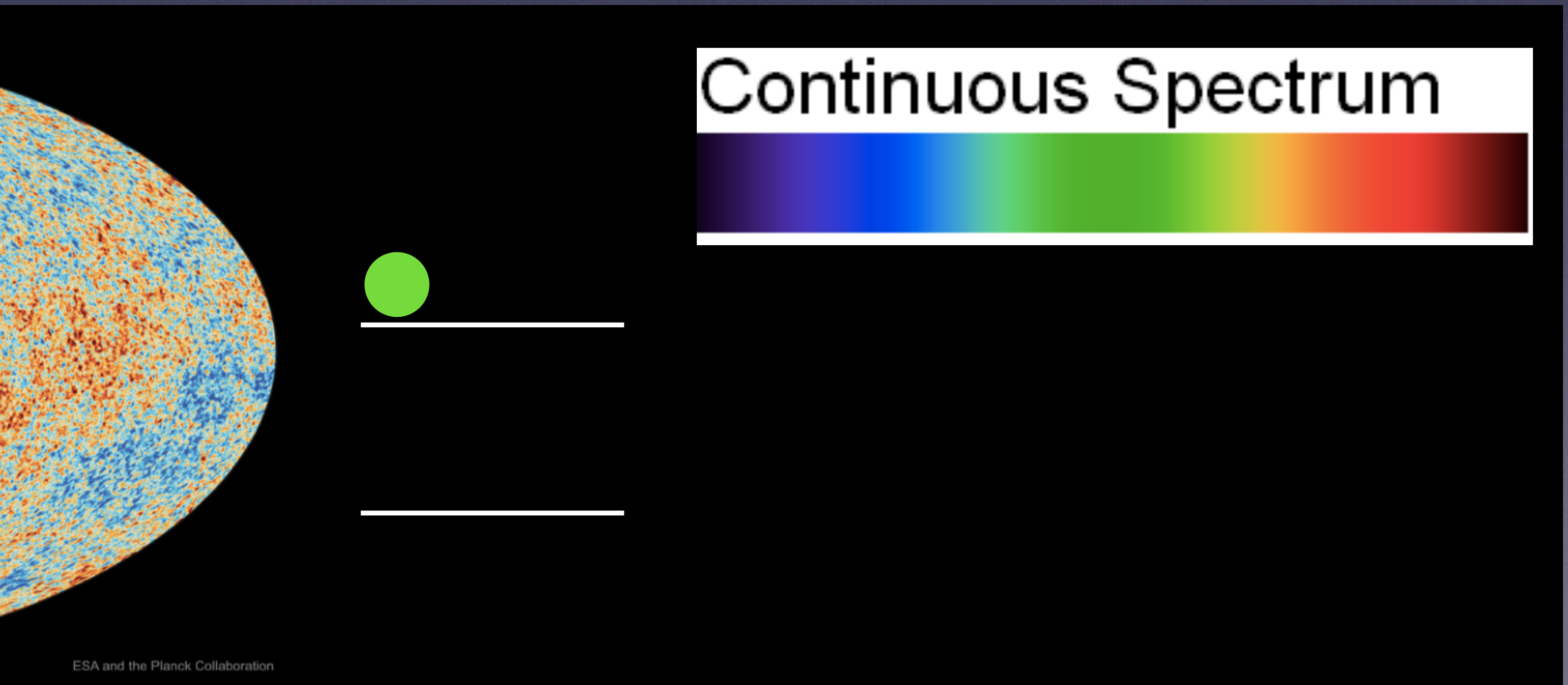




21cm and the cosmic thermal history

- 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.



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

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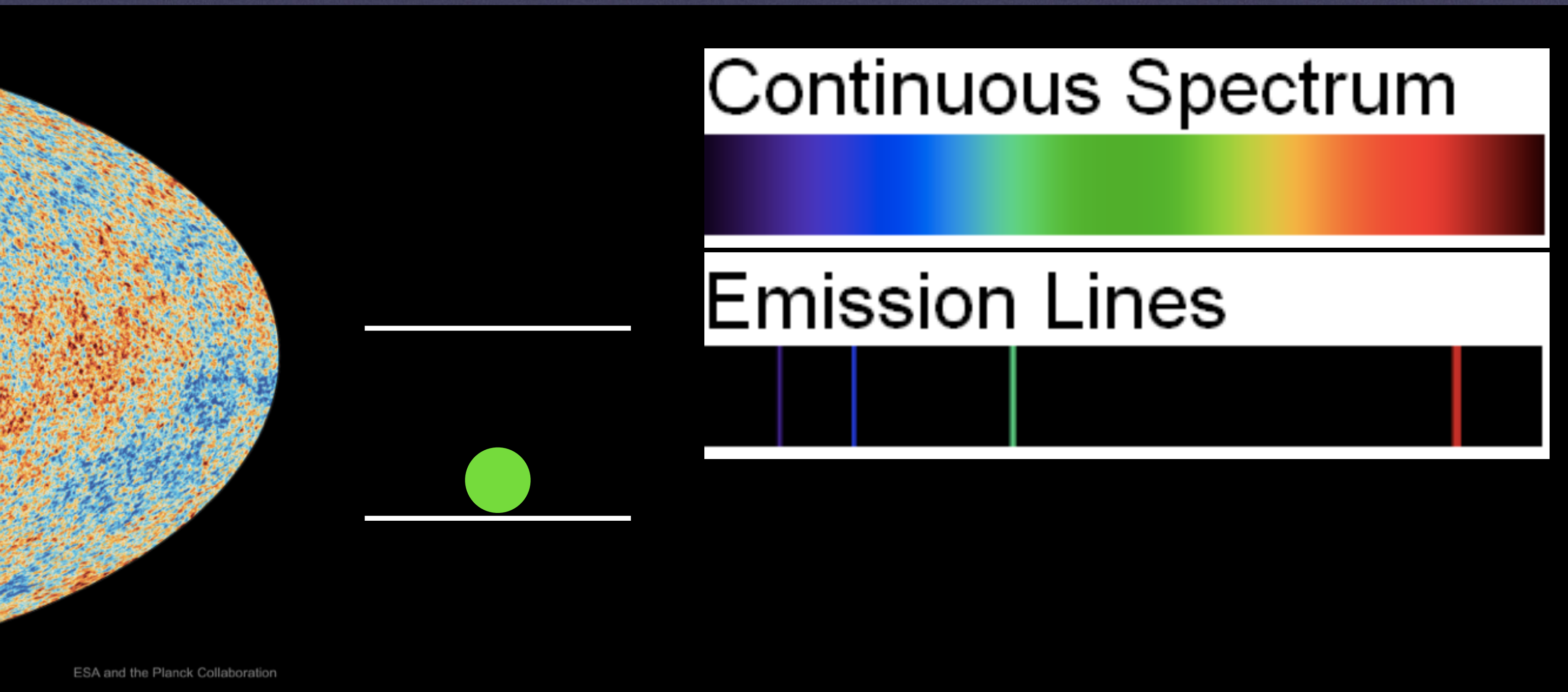

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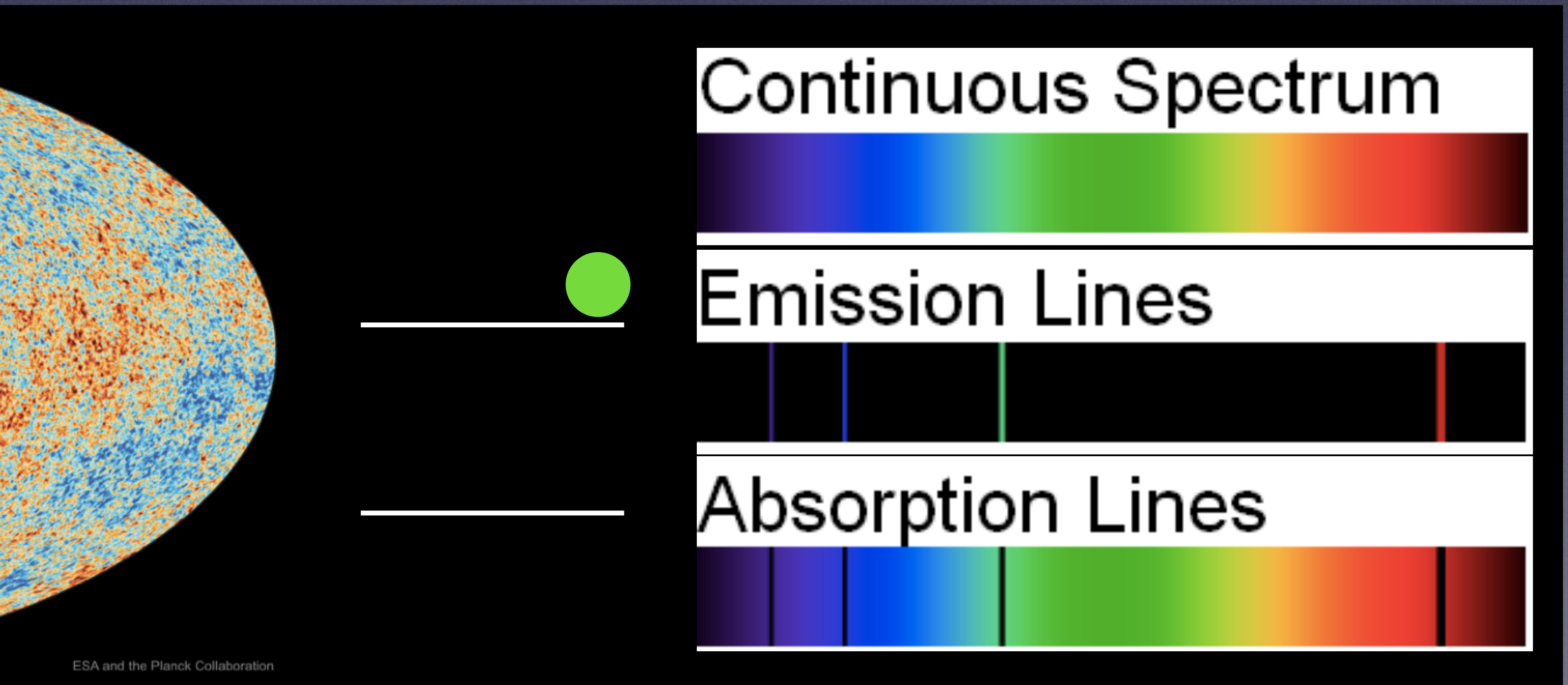

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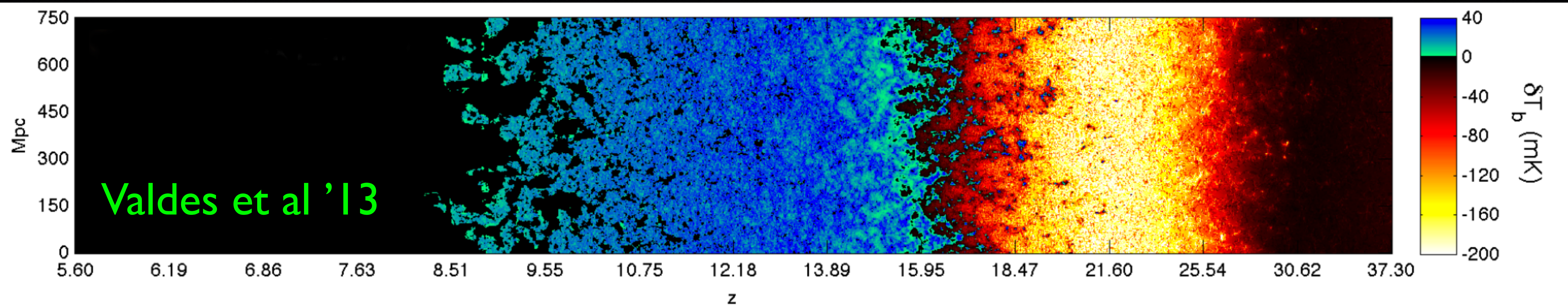
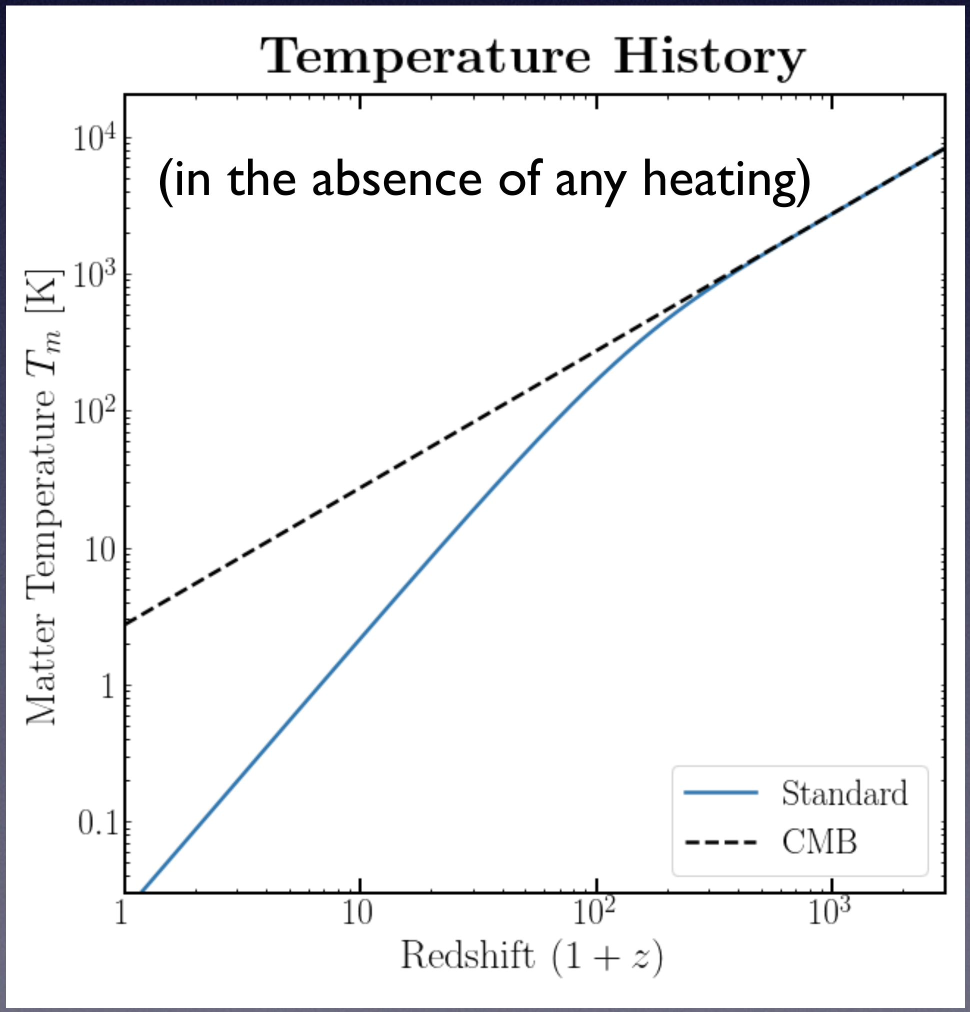
Expectations for a 21cm signal



- 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 of global T_{21} will set a bound on T_{gas}.



Ionization vs heating vs spectral distortions

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- Consider the power from DM annihilation - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates (or decays), enough power to ionize half the hydrogen in the universe…

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- How much spectral distortion to the CMB?
  - Radiation and matter energy densities were equal at z~3000, ratio scales as (1+z)
  - One-in-a-billion fraction of mass energy liberated = distortion of energy spectrum of CMB at level of one in 10^6 or less. Much less sensitive than ionization for $z < 1000$.

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  - Down to z~200, CMB and ordinary matter are coupled in temperature - need to heat whole CMB, not just matter. Same estimate as for spectral distortion.
  - Baryon number density is ~9 orders of magnitude smaller than CMB number density - heating divided between a much smaller number of particles for $z < 200$. One-in-a-billion fraction of mass energy liberated => increase baryon temperature by ~5 eV per particle ~ 50,000 K - two orders of magnitude higher than baseline temperature at decoupling.

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powerful probe of annihilation/ decay for z < 1000

probe of physics at z > 1000, or non-ionizing processes (e.g. scattering)

potentially a large effect for z < 200 - could be visible in 21cm

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

↓ If unstable, 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, HyRec)

Cosmic ionization and thermal histories

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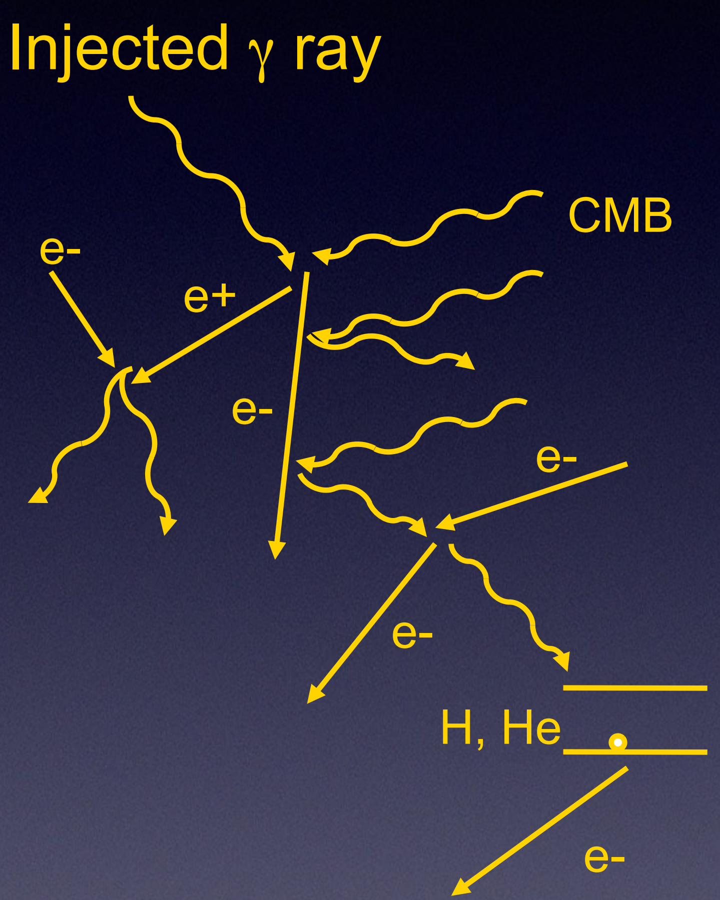
Cosmic ionization and thermal histories

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

$$\dot{T}_m = \dot{T}_m^{(0)} + \dot{T}_m^{\rm inj} + \dot{T}_m^{\rm re} \,,$$
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$$\dot{T}_m^{\rm inj} = \frac{2 f_{\rm heat}(z, \mathbf{x})}{3(1 + \mathcal{F}_{\rm He} + x_e) n_{\rm H}} \left(\frac{dE}{dV\,dt} \right)^{\rm inj} \,,$$
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baseline | exotic | reionization/astro

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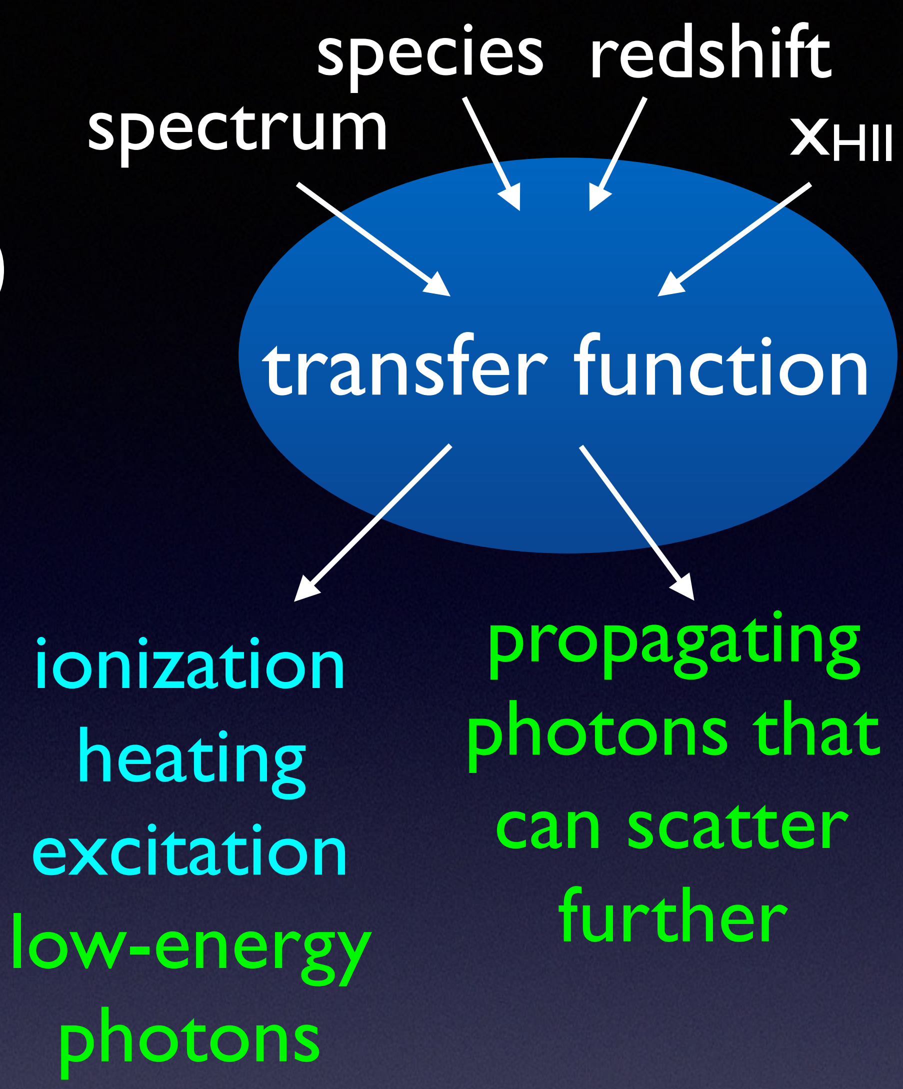
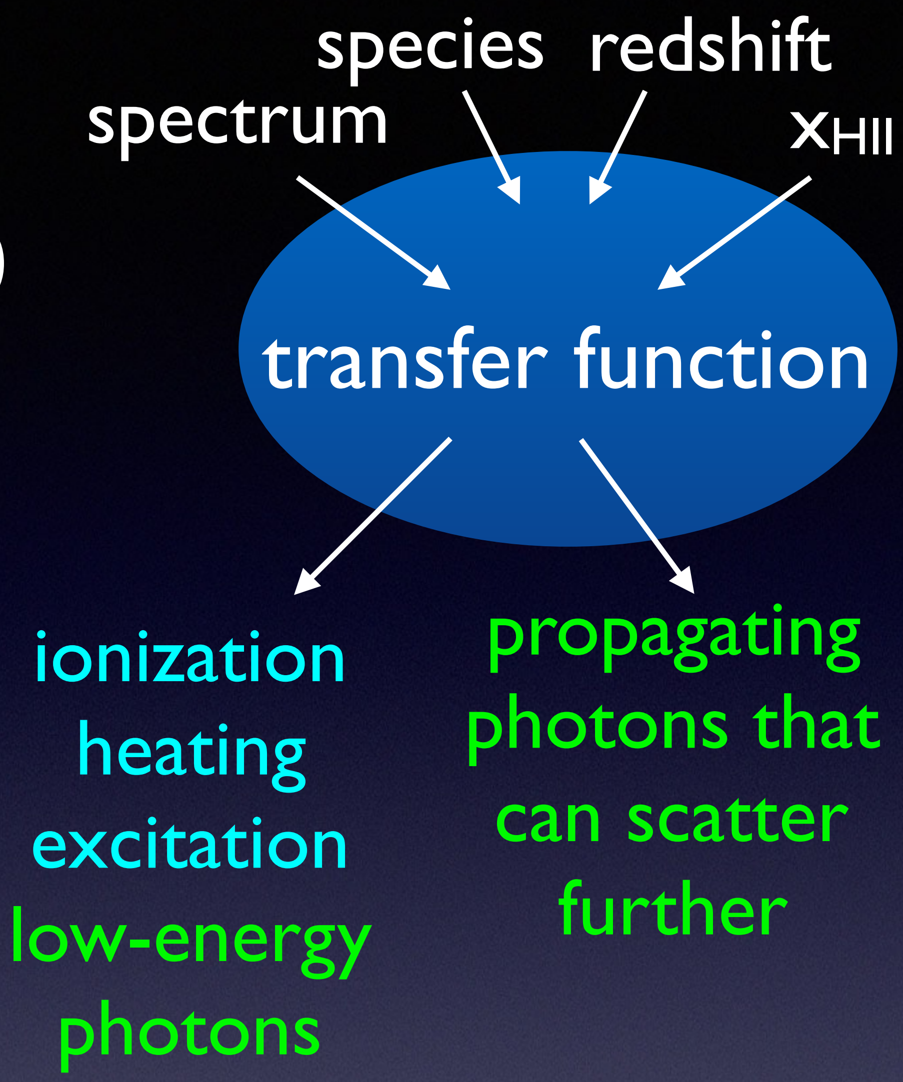
Ingredients of a DarkHistory step



Ingredients of a DarkHistory step

- Cooling cascade calculation is slow - precompute how individual electrons/positrons/photons deposit energy over a timestep, at a given energy/redshift/x_{HII}.



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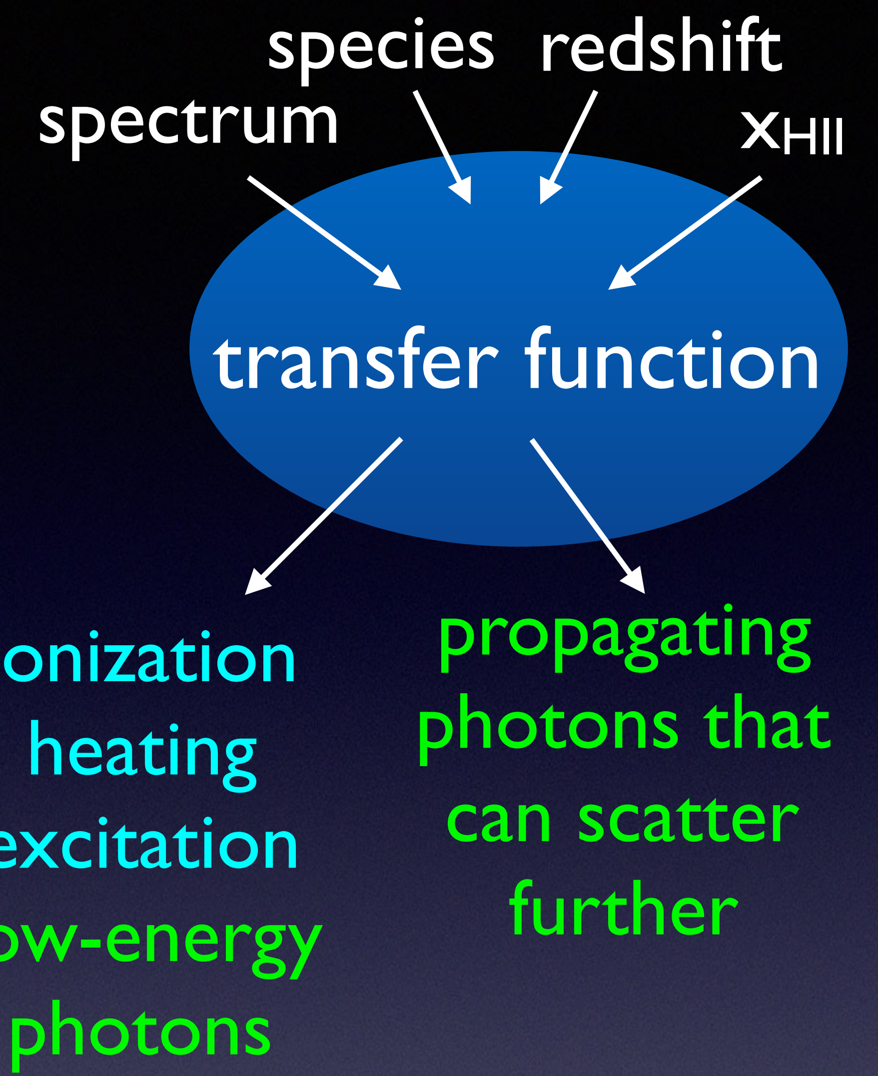

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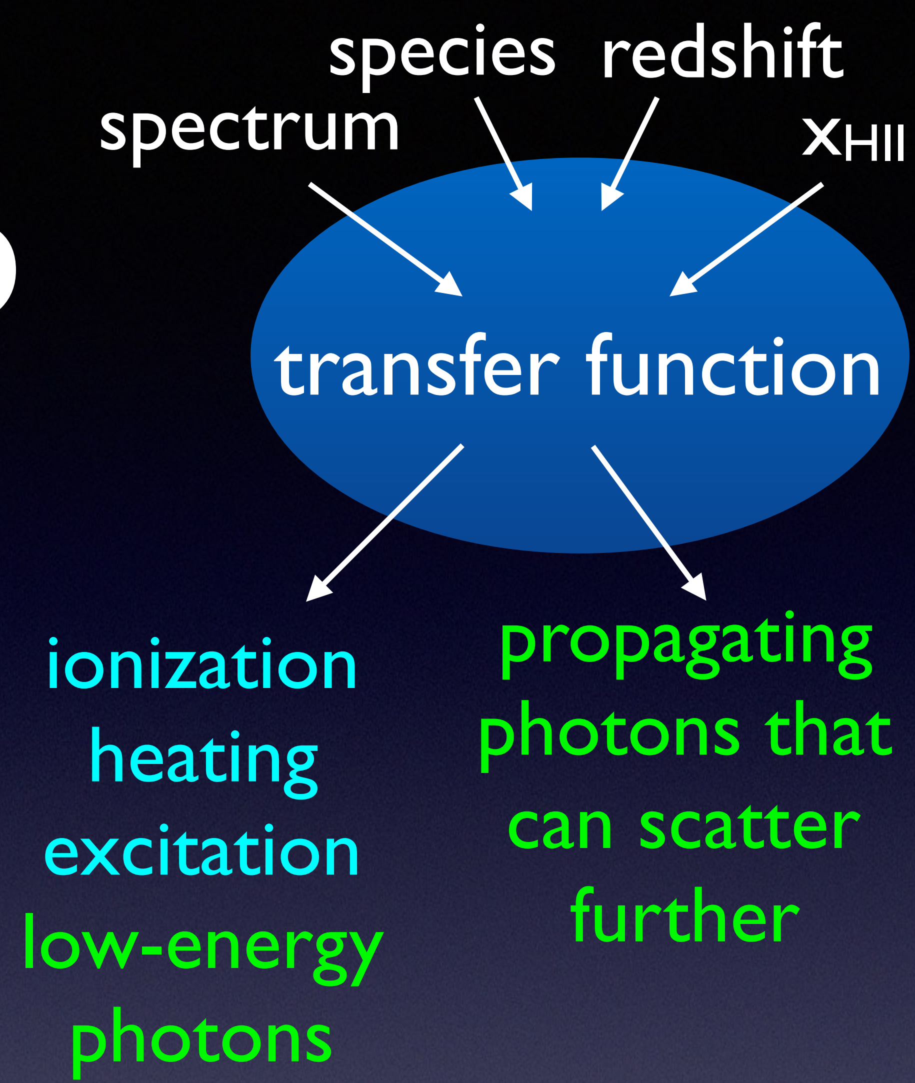

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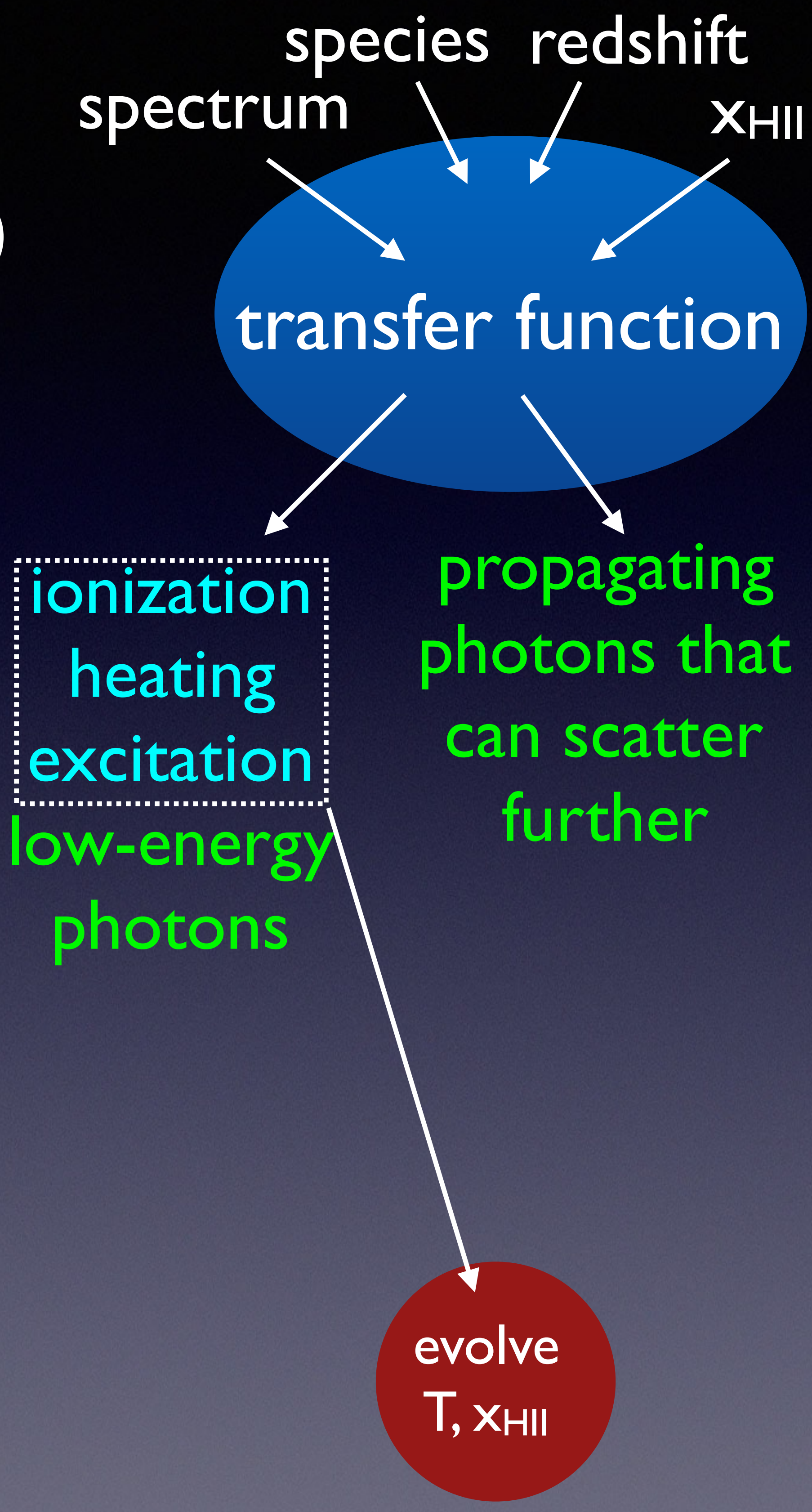

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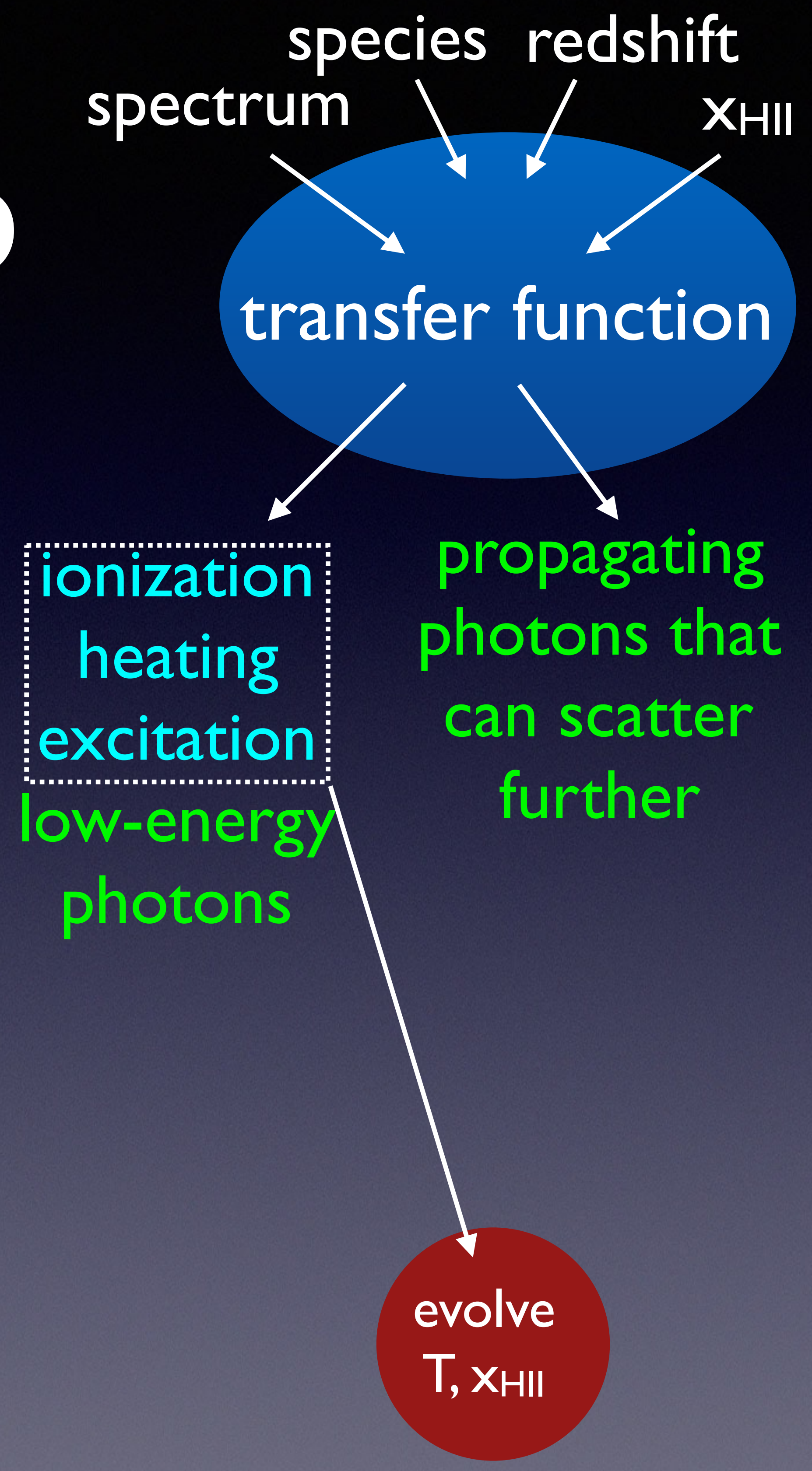

Ingredients of a DARKHISTORY step

- Cooling cascade calculation is slow - precompute how individual electrons/positrons/photons deposit energy over a timestep, at a given energy/redshift/x_{HII}.
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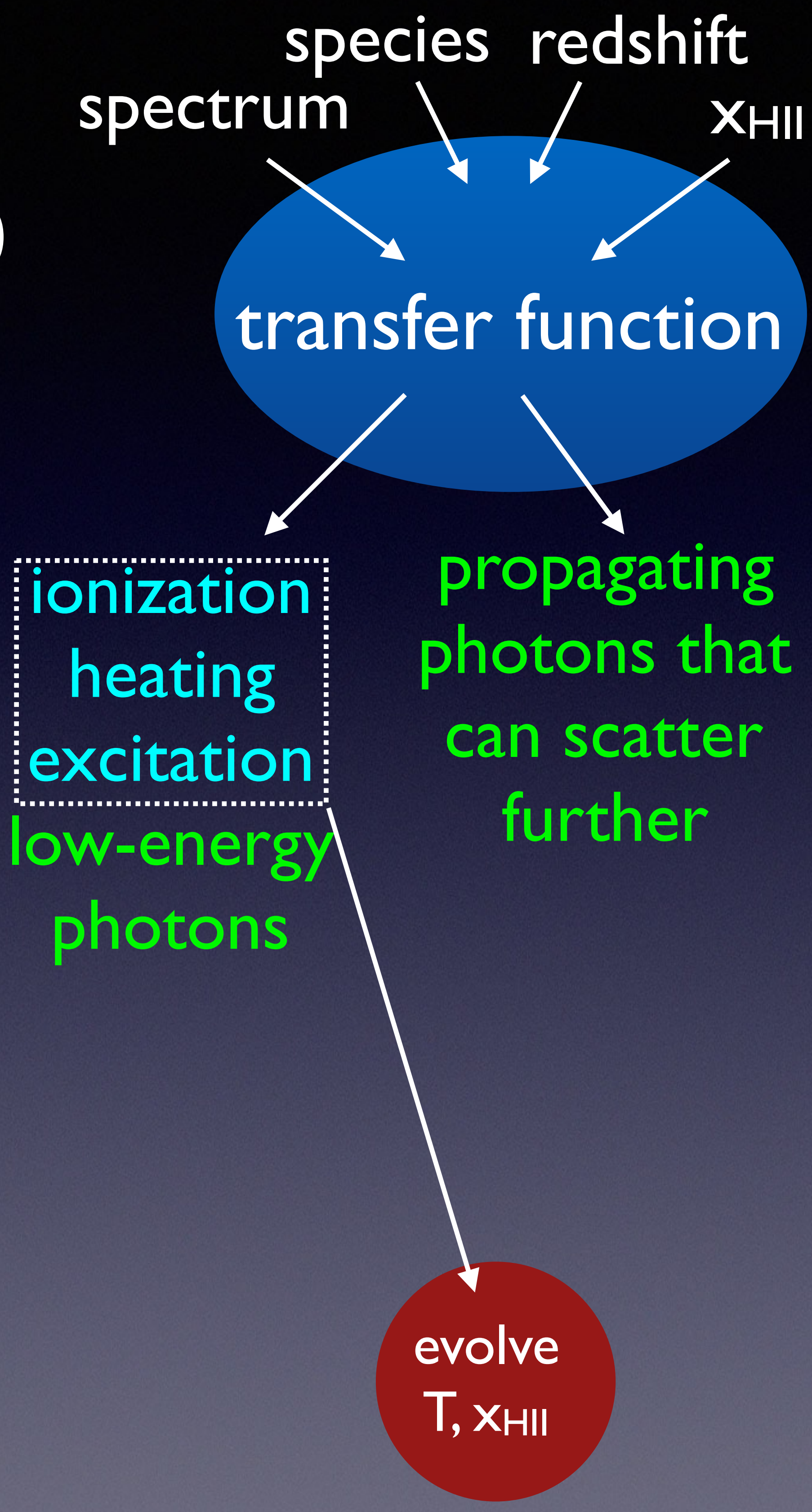
- Transfer function depends on redshift + ionization level + species - pre-compute over a grid of these parameters, interpolate to desired x_{HII} & redshift.
- Outputs of transfer function include secondary photons (propagate to next timestep, add to injection) and ionization/heating/etc.



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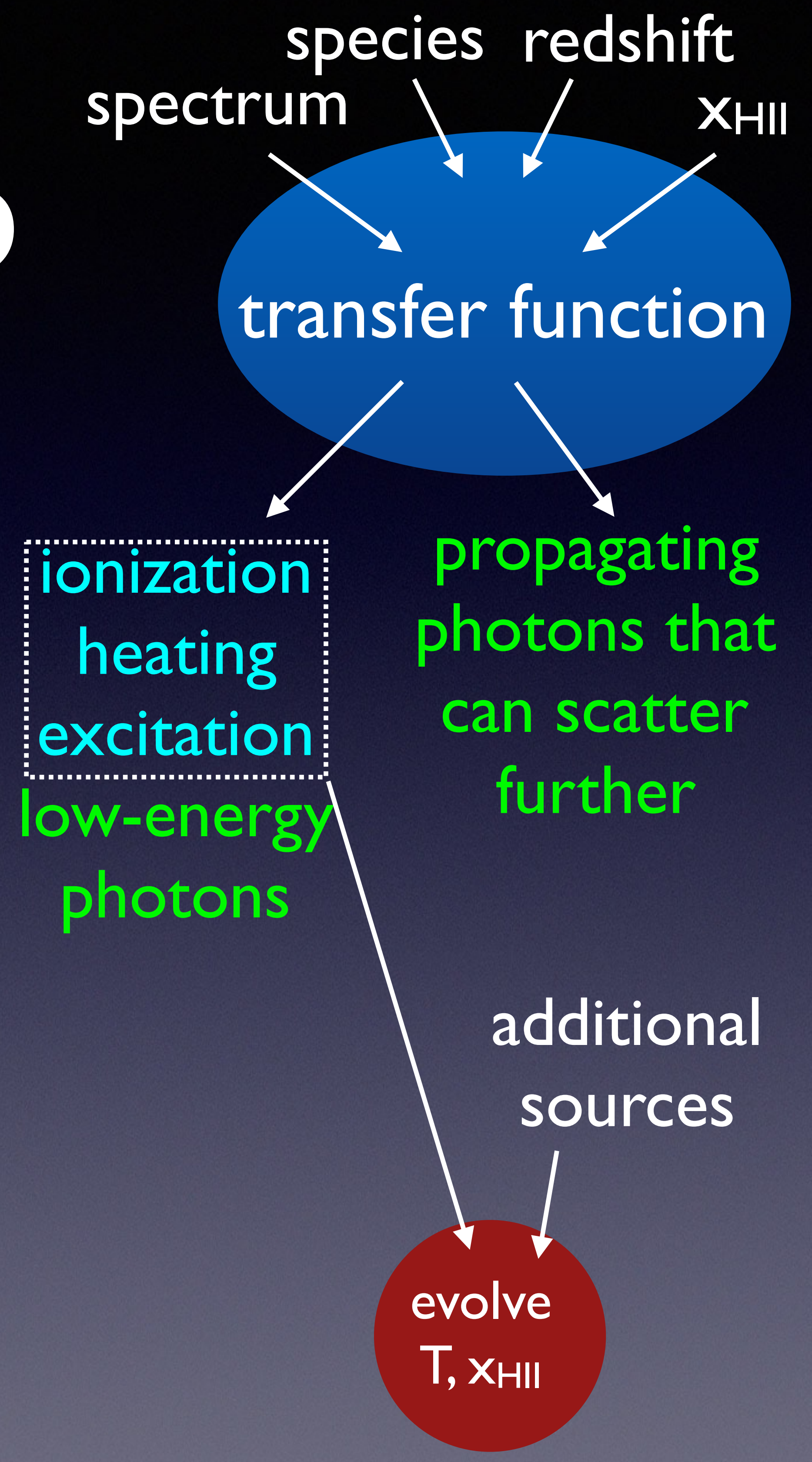

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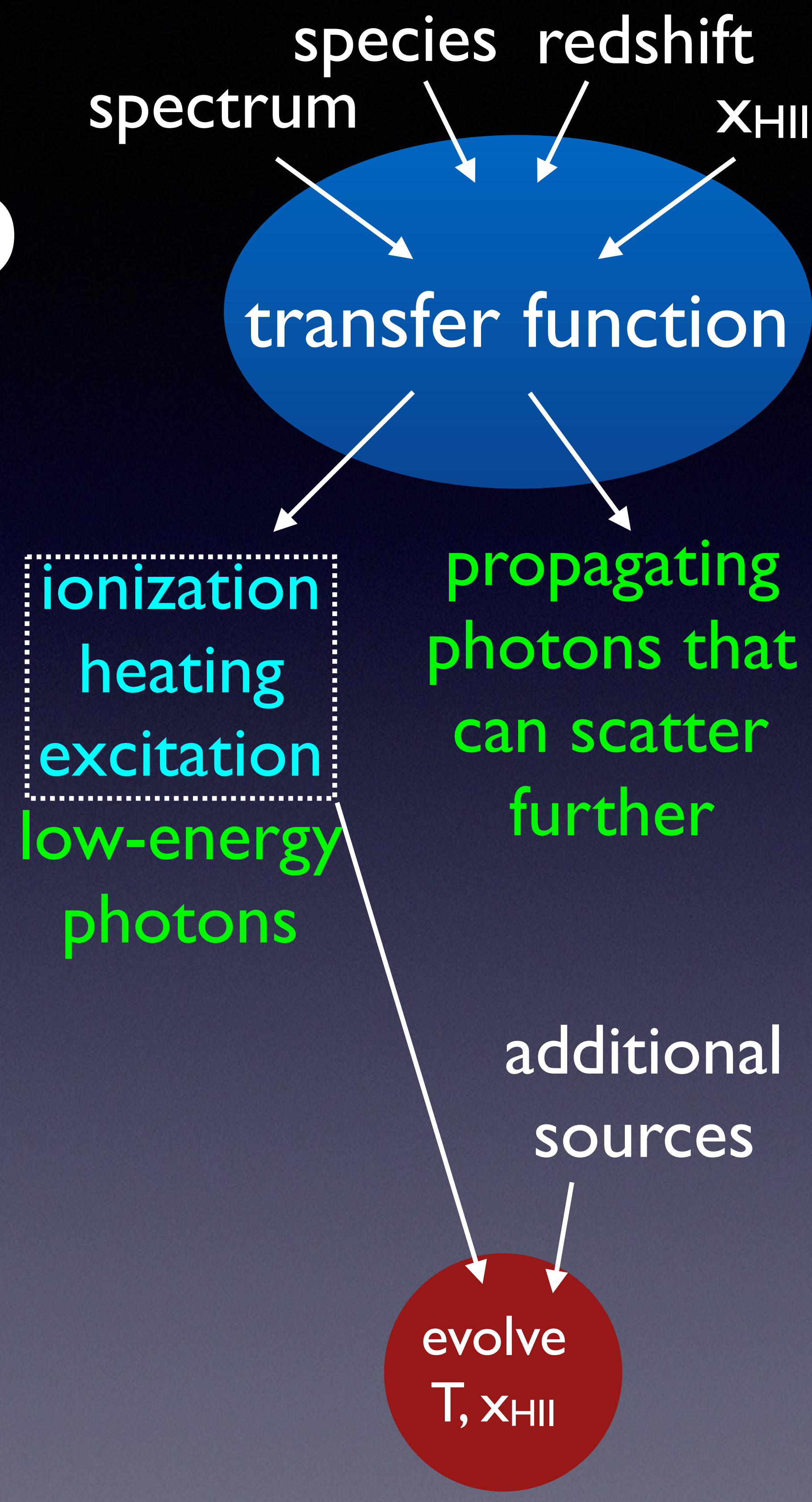
- Feed ionization/heating/excitation into evolution equations - obtain modified thermal+ionization history.



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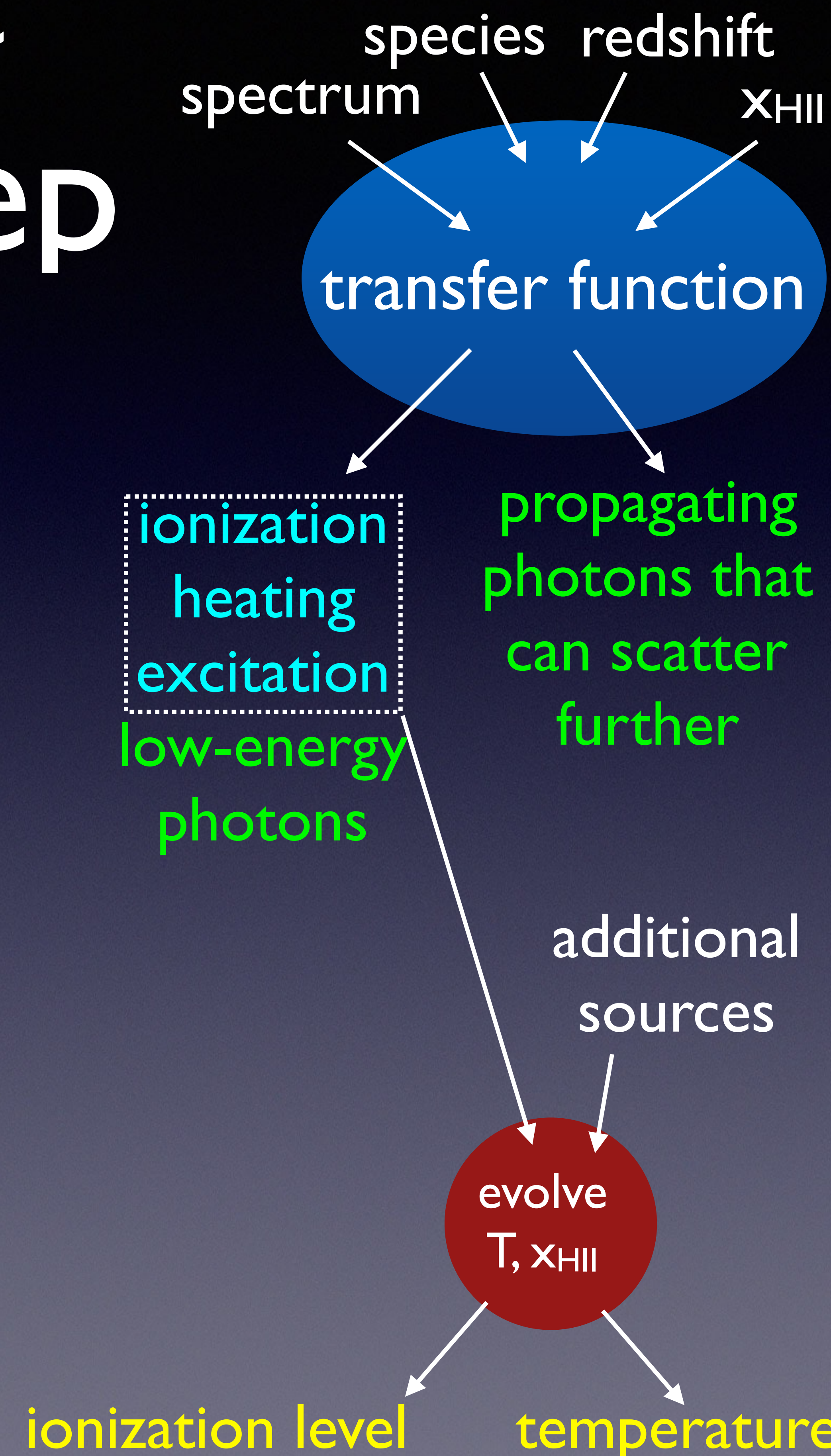
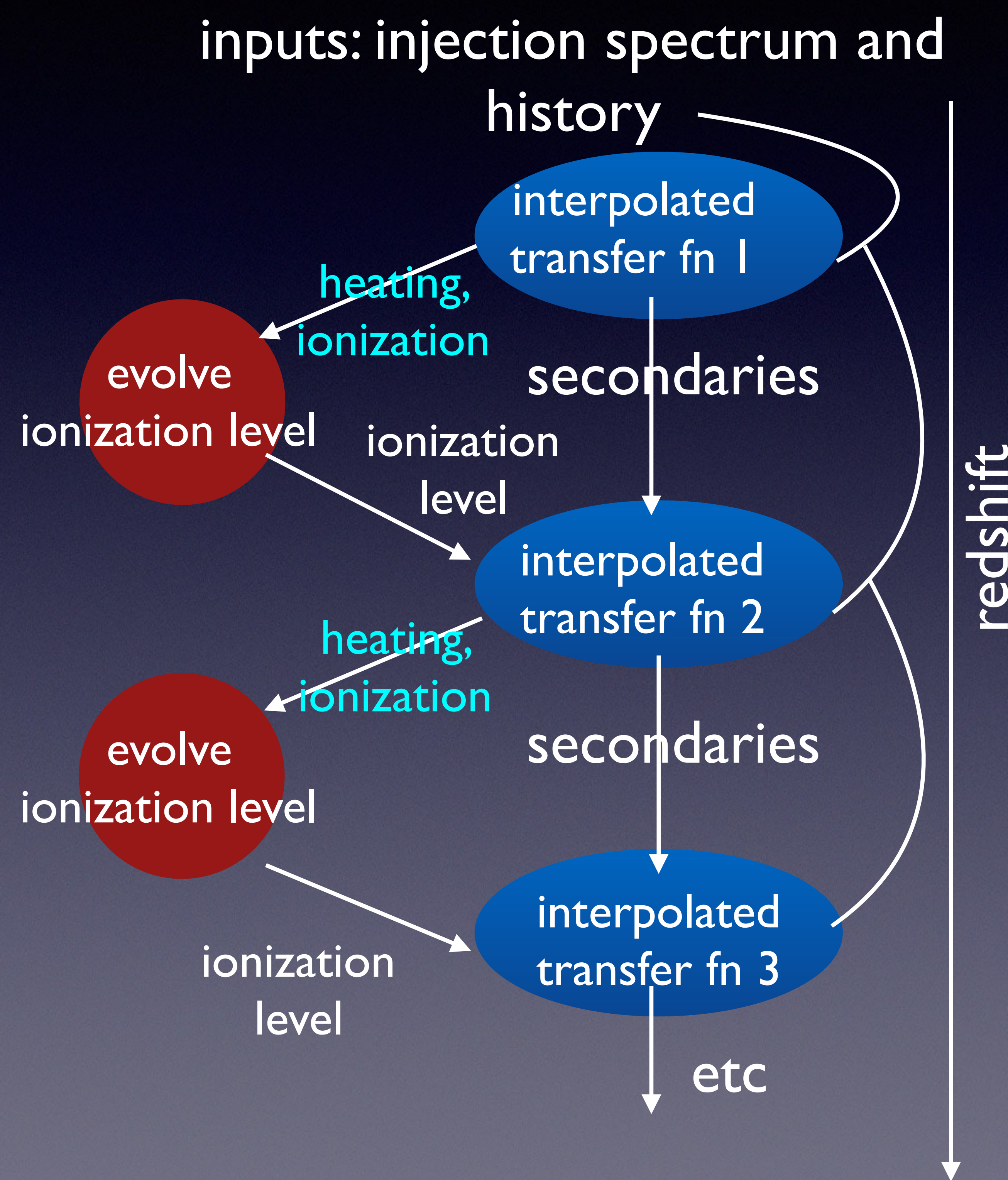


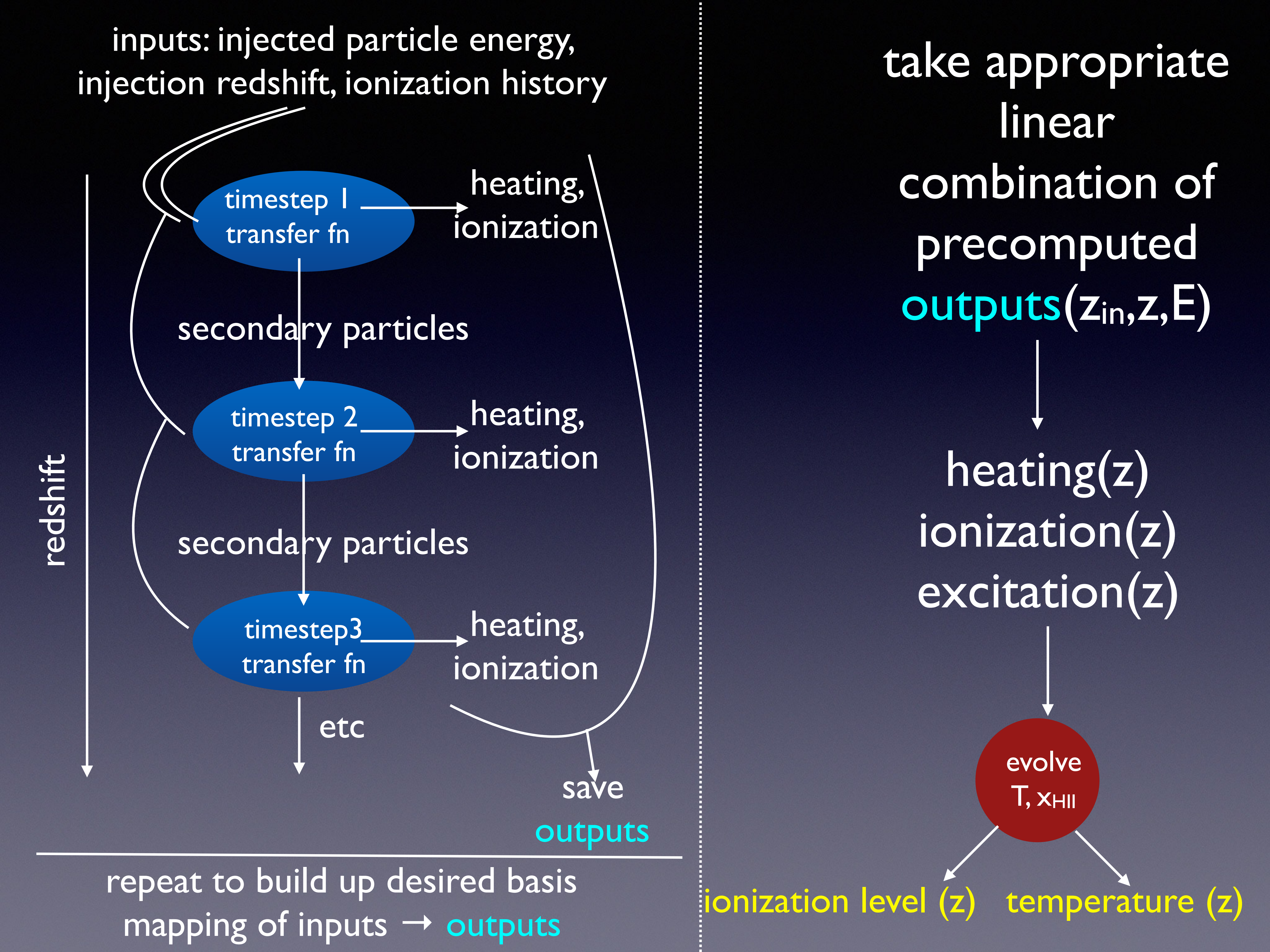
Time evolution

- At a given timestep, injection is specified by a redshift-dependent injected spectrum of particles (electrons, positrons, photons).
- Propagate injected particles through timestep (see last slide).
- At end of timestep, update ionization+temperature level, add propagating secondary photons to injected spectrum for next timestep.
- Iterate until desired end redshift is reached, read off computed T/ x_{HII} histories.



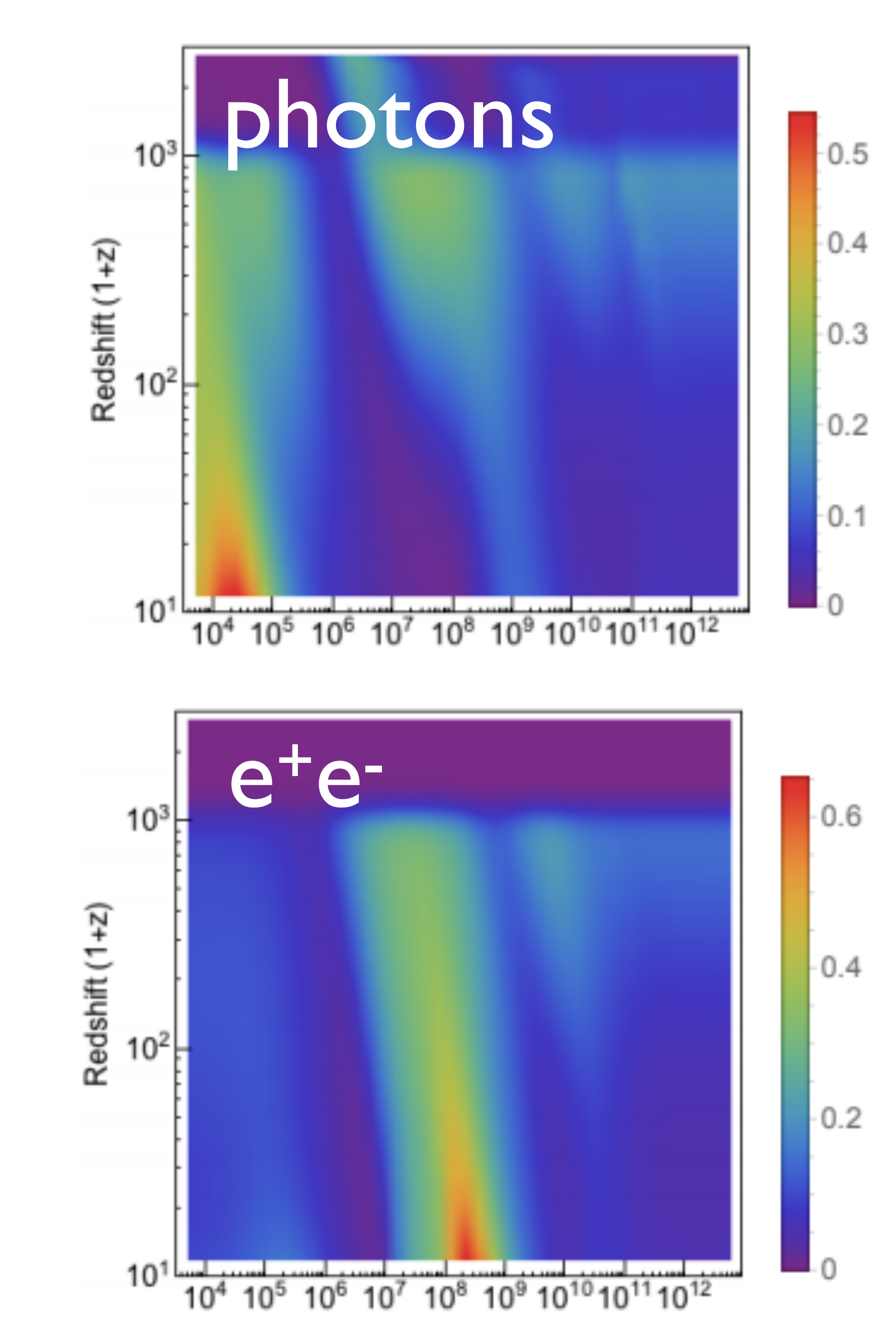
Omitting back-reaction

- Suppose: 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 is significantly faster than running the full coupled evolution, once the pre-computation steps are done.


inputs: injected particle energy,
injection redshift, ionization history
timestep 1
transfer fn
heating,
ionization
secondary particles
timestep 2
transfer fn
heating,
ionization
secondary particles
timestep3
transfer fn
heating,
ionization
etc
redshift
save
outputs
repeat to build up desired basis
mapping of inputs → outputs
take appropriate
linear
combination of
precomputed
outputs(zin,z,E)
heating(z)
ionization(z)
excitation(z)
evolve
T, xHII
ionization level (z)
temperature (z)

Example application: CMB limits on DM physics

- Backreaction is safe to omit for constraints on DM annihilation and decay from the CMB, which can be shown to be dominated by high redshifts ($z >> z_{reion}$).
- Example results for ionization power from DM annihilation [TRS '16] normalized to injected power at the same redshift.
- Can be used to obtain x_{HII} perturbation from arbitrary keV-TeV DM models.

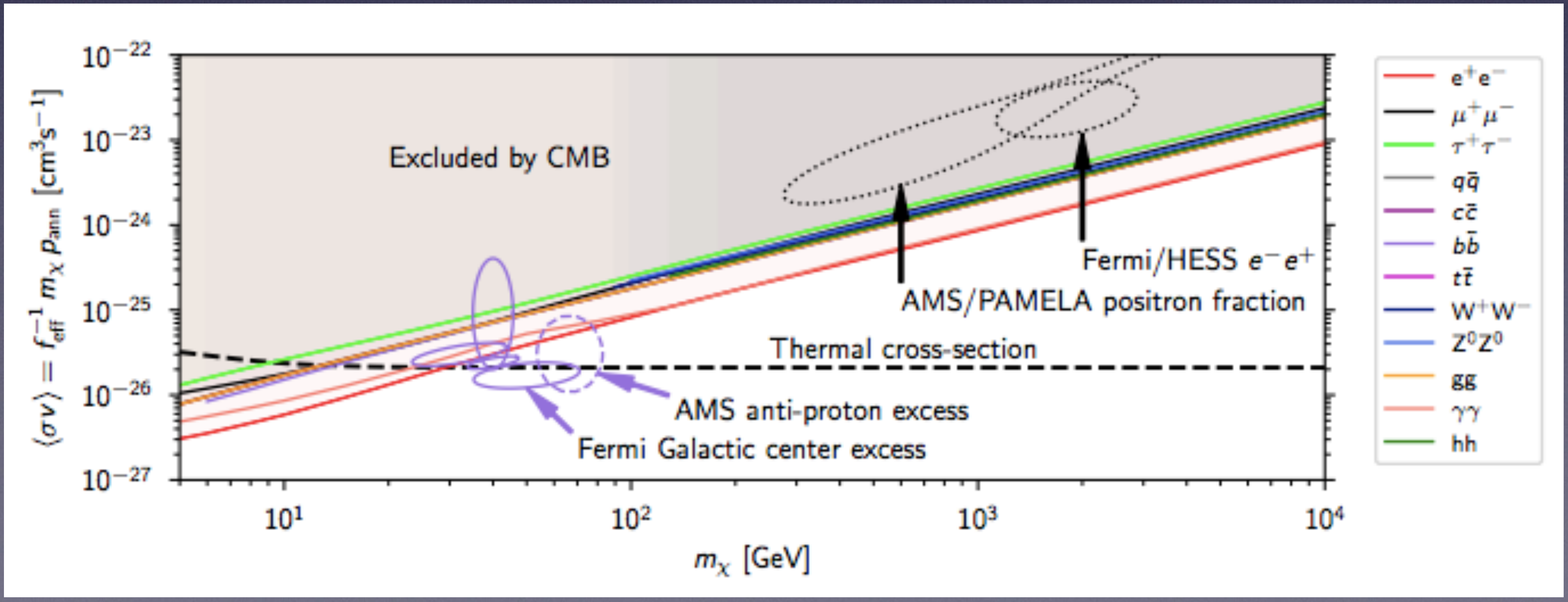


From deposition to CMB bounds

- We can now use public code packages (RECFAST/CosmoRec/HyRec) to solve for the ionization history.
- Public codes CAMB/CLASS can compute the resulting CMB perturbations (ExoCLASS, Stocker et al '18, can handle arbitrary energy injection histories using this no-backreaction formalism + pre-computed results from TRS '16).
- 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 the power deposited to ionization.

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.

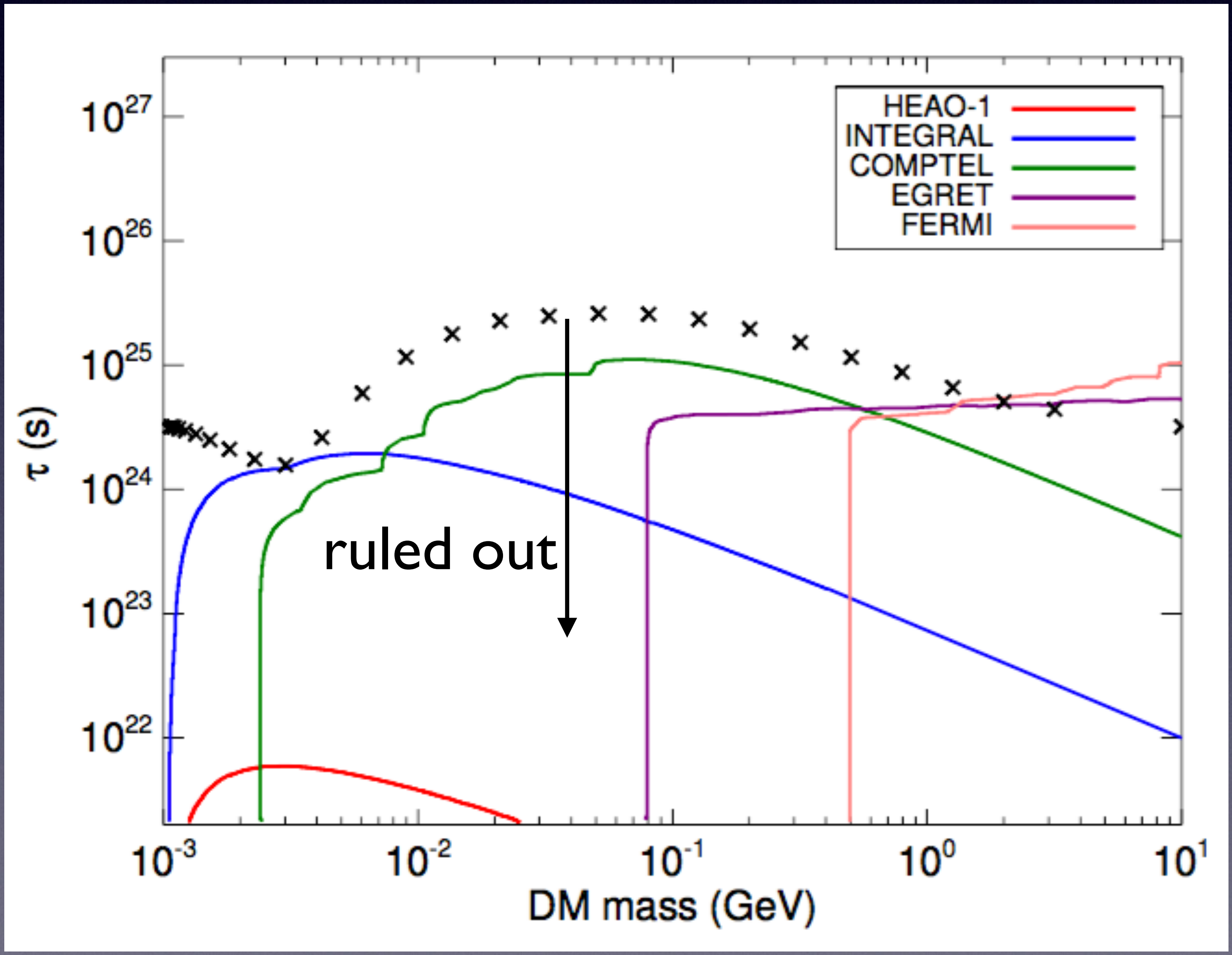


Planck Collaboration '18 1807.06209

Constraints on decay from Planck

TRS & Wu, PRD '17

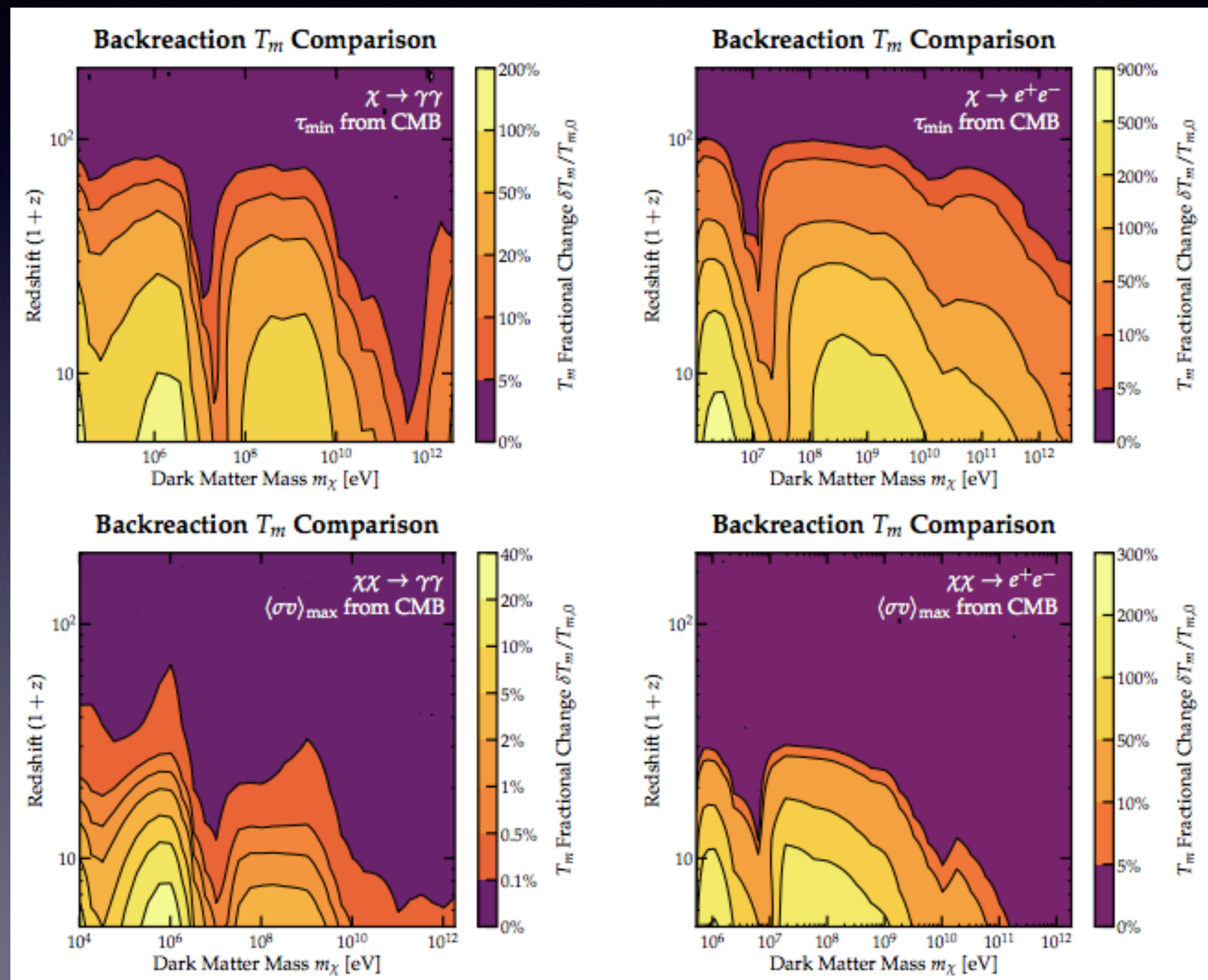
- For decaying dark matter, can use the same approach.
- Sets some of the strongest limits on relatively light (MeV-GeV) DM decaying to produce electrons and positrons.
- For short-lifetime decays, can rule out even 10^{-11} of the DM decaying (for lifetimes ~10^{14} s)



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

When does backreaction matter?

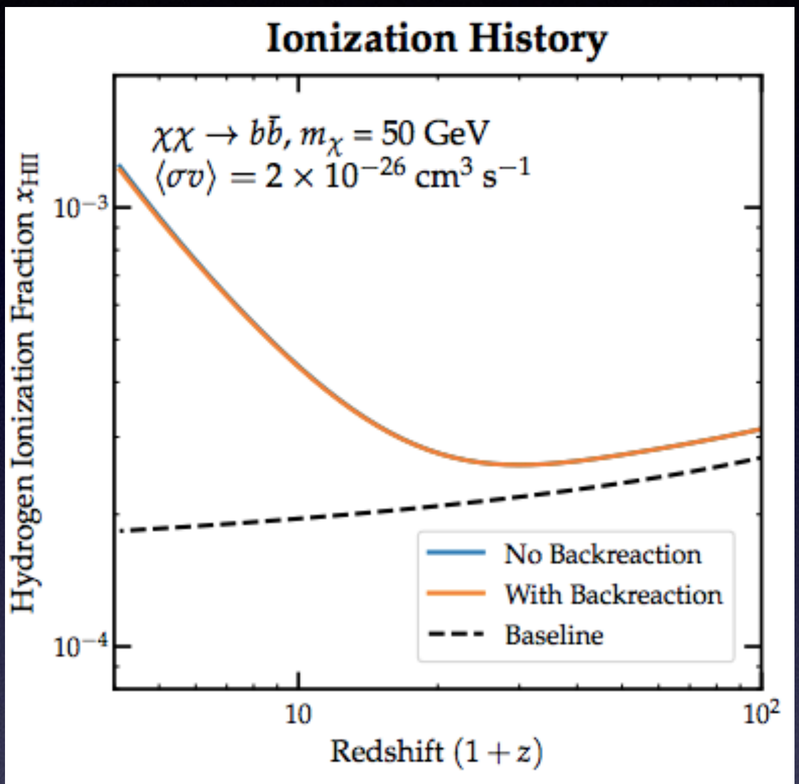
- In this scan we take models on the verge of exclusion by CMB bounds and compute the effect of backreaction on the change in the matter temperature, using DARKHISTORY.
- Effects are above z~100, but can be large during cosmic dawn, especially for DM decay.

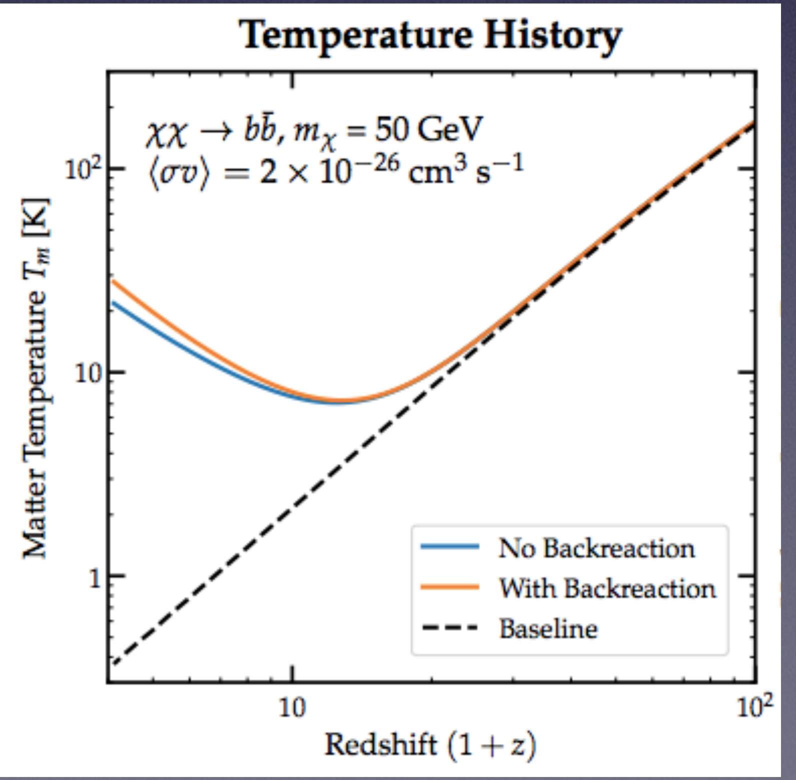


Running DarkHistory

```
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.

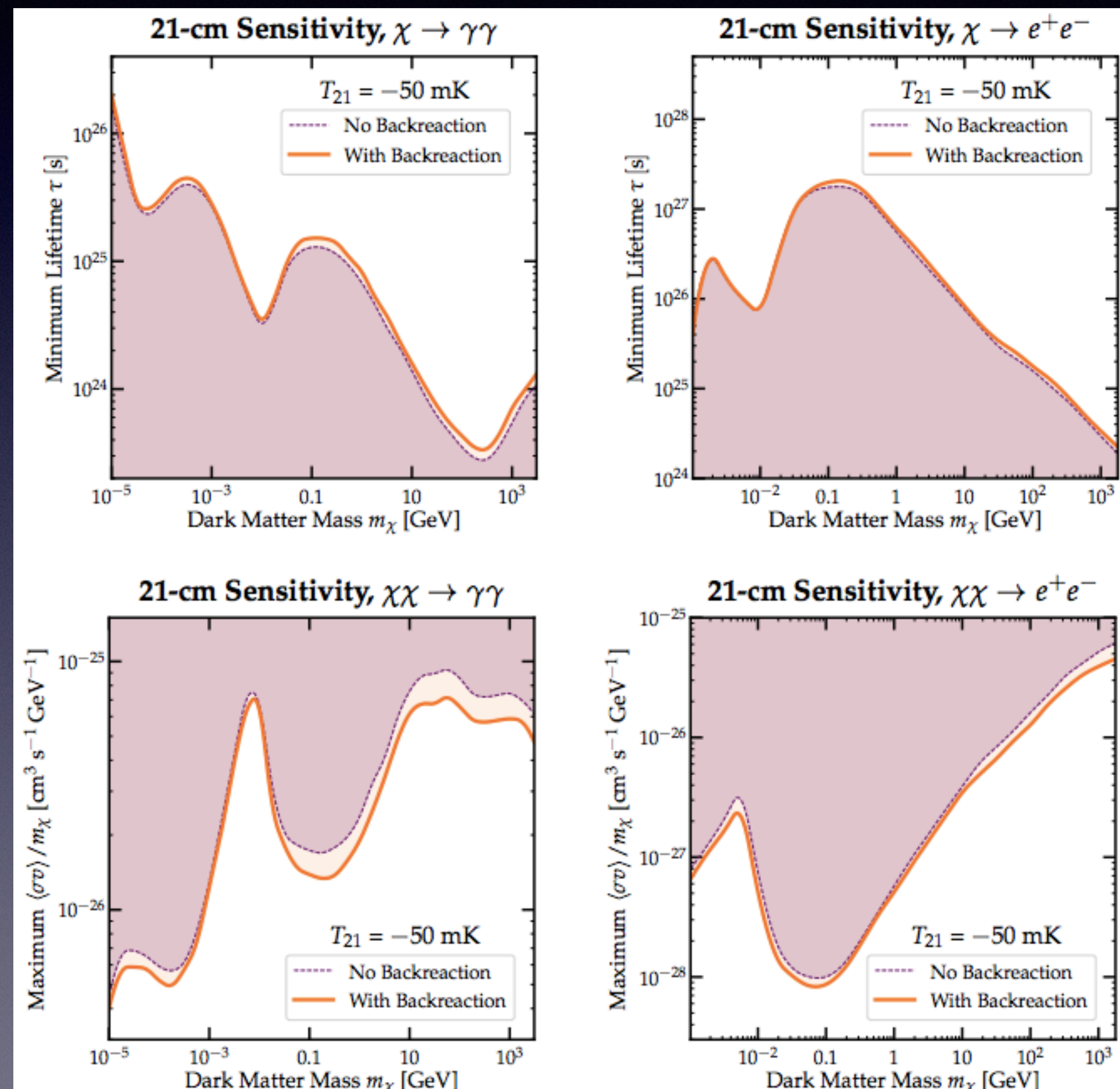




21cm sensitivity

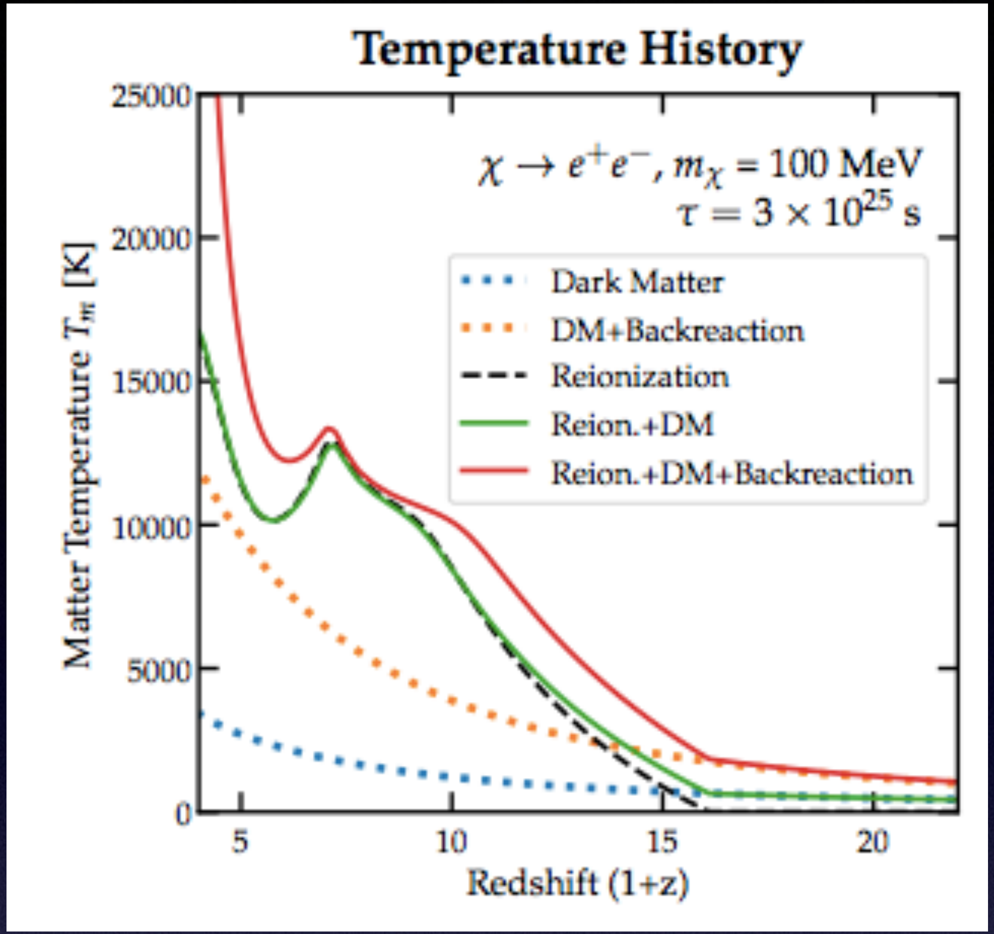
$$T_{21}(z) \approx x_{\rm HI}(z) \left(\frac{0.15}{\Omega_m}\right)^{1/2} \left(\frac{\Omega_b h}{0.02}\right) \times \left(\frac{1+z}{10}\right)^{1/2} \left[1 - \frac{T_R(z)}{T_S(z)}\right] 23\,\mathrm{mK},$$

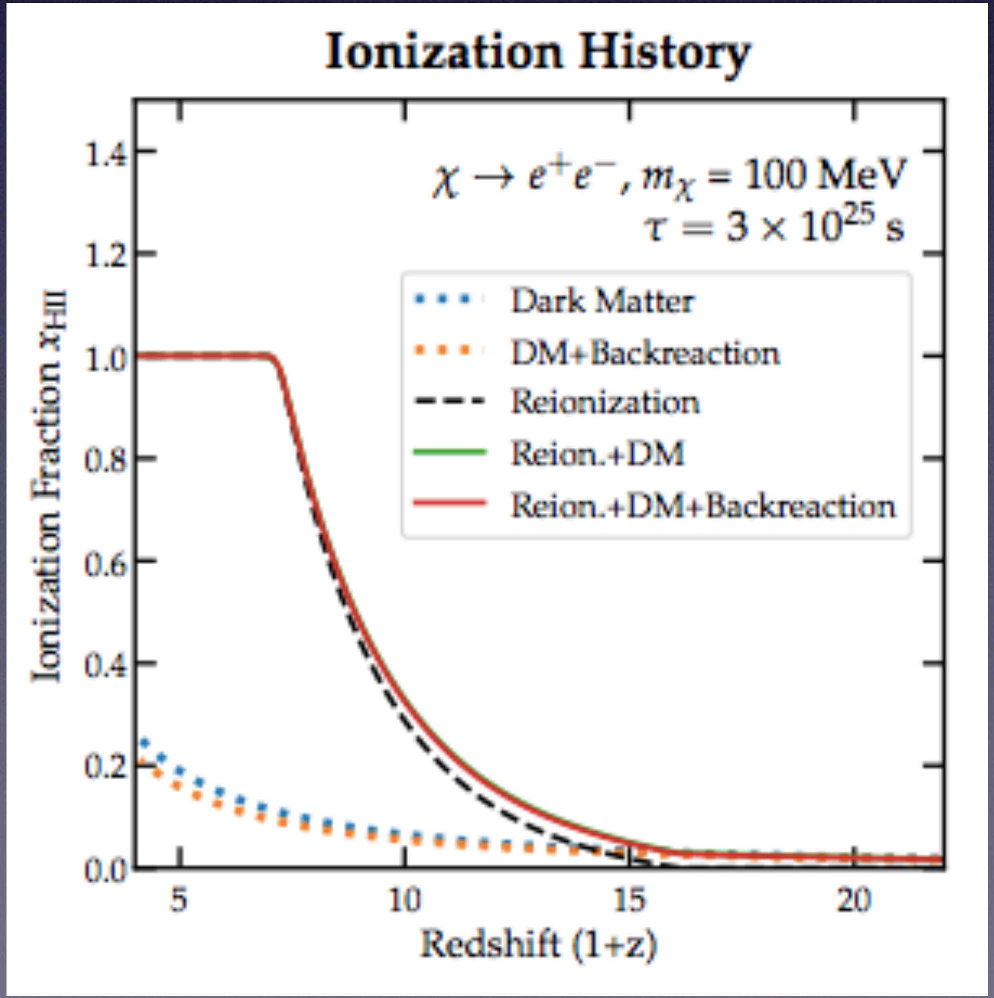
- Consider a hypothetical 21cm measurement of T_{21} < -50 mK at z~17.
- If T_R=T_{CMB}, this corresponds to an upper limit on the gas temperature of T_m~20 K.
- With DARKHISTORY, it is easy to compute the resulting limits with and without backreaction.
- Note particular sensitivity to decay to electrons.



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.





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:
  - Improve module for cooling of low-energy electrons - currently for electrons below 3 keV, we interpolate results calculated with the MEDEA code [Evoli et al '12]
  - A consequence of the improved electron module will be a full prediction for the low-energy photon spectrum = distortion to the CMB blackbody
- 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 detail at low redshift. Possible approaches include gas-density-dependent transfer functions, separate modeling of halos vs IGM.
  - DarkHistory assumes the only radiation field is the CMB - stars turning on could modify the cooling cascade.

Summary

https://darkhistory.readthedocs.io

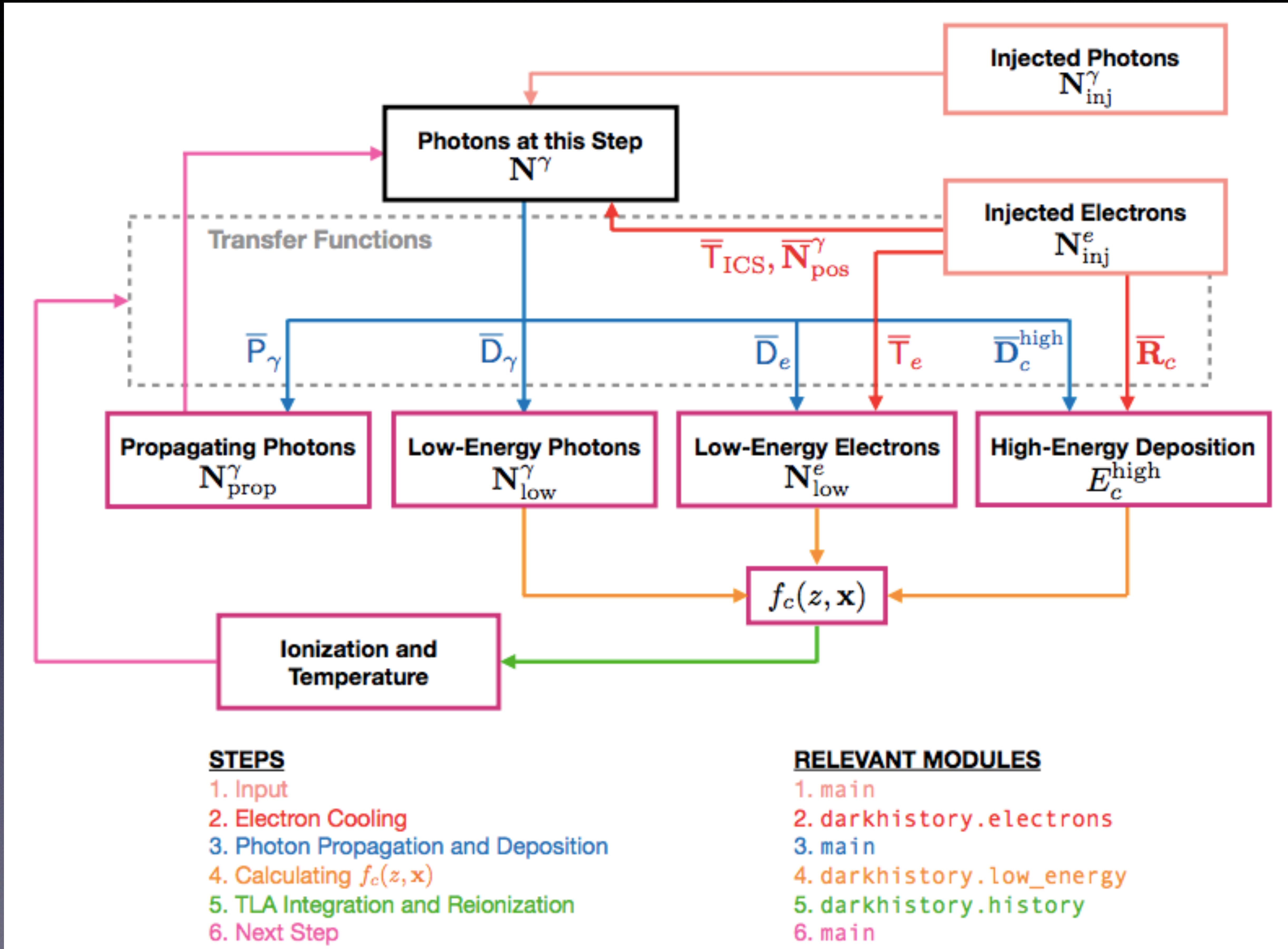
try it out!

Summary

- Cosmological datasets can provide powerful probes of the non-gravitational properties of dark matter.
- The cosmic microwave background provides stringent limits on both annihilating and decaying DM, especially at sub-GeV mass scales.
- Scenarios that are not yet ruled out could have large effects on the matter temperature at the end of the cosmic dark ages; thus 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.

BONUS SLIDES

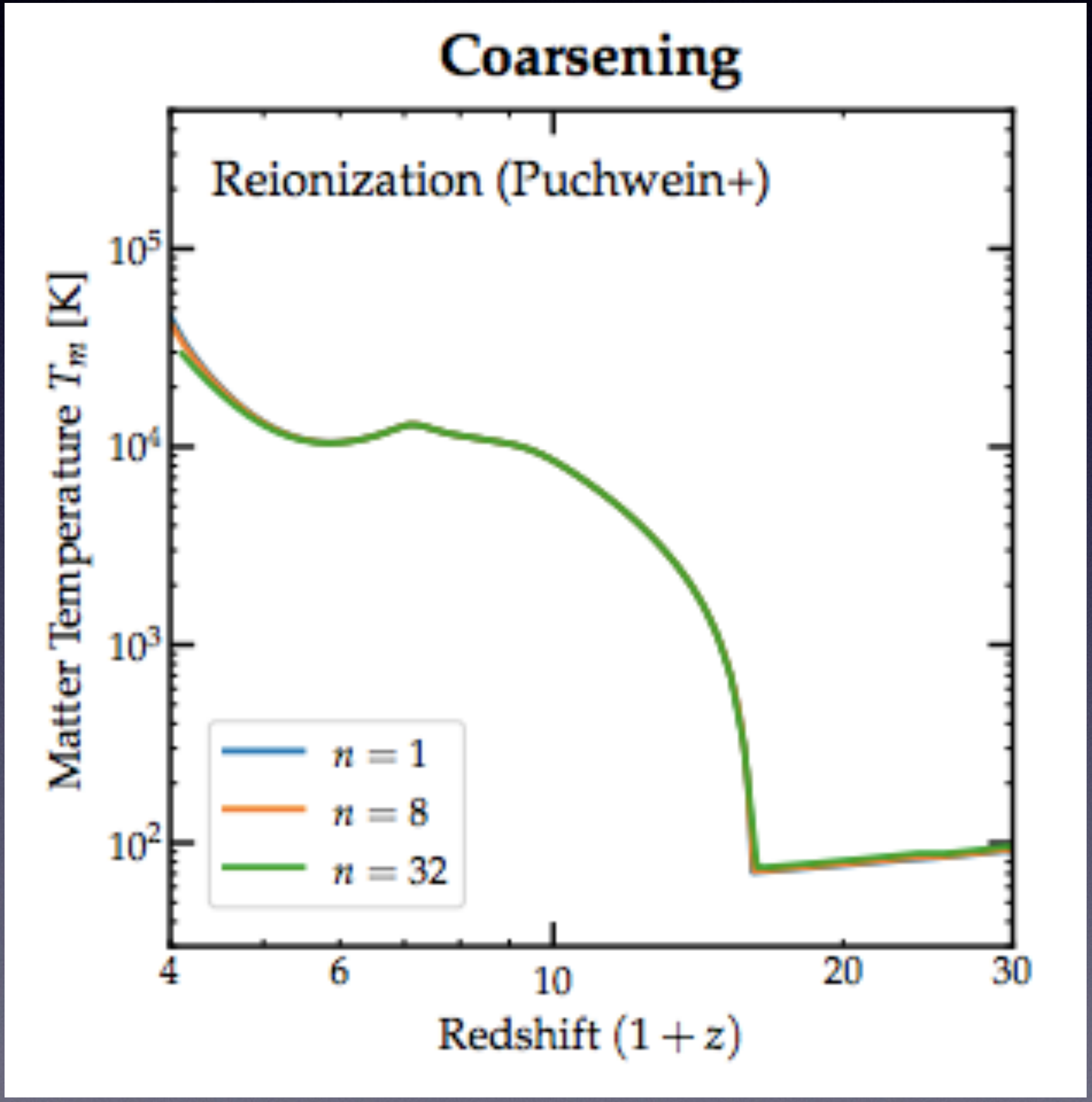
DarkHistory extras



Injected Photons
$\mathbf{N}^{\gamma}_{\rm inj}$
Photons at this Step
$\mathbf{N}^{\gamma}$
Injected Electrons
$\mathbf{N}^{e}_{\rm inj}$
Transfer Functions
$\overline{\mathsf{T}}_{\rm ICS}, \overline{\mathbf{N}}^{\gamma}_{\rm pos}$
$\overline{\mathsf{P}}_{\gamma}$
$\overline{\mathsf{D}}_{\gamma}$
$\overline{\mathsf{D}}_{e}$
$\overline{\mathsf{T}}_{e}$
$\overline{\mathbf{D}}^{\rm high}_{c}$
$\overline{\mathbf{R}}_{c}$
Propagating Photons
$\mathbf{N}^{\gamma}_{\rm prop}$
Low-Energy Photons
$\mathbf{N}^{\gamma}_{\rm low}$
Low-Energy Electrons
$\mathbf{N}^{e}_{\rm low}$
High-Energy Deposition
$E^{\rm high}_{c}$
$f_c(z, \mathbf{x})$
Ionization and Temperature
STEPS
1. Input
2. Electron Cooling
3. Photon Propagation and Deposition
4. Calculating $f_c(z, \mathbf{x})$
5. TLA Integration and Reionization
6. Next Step
RELEVANT MODULES
1. main
2. darkhistory.electrons
3. main
4. darkhistory.low_energy
5. darkhistory.history
6. main

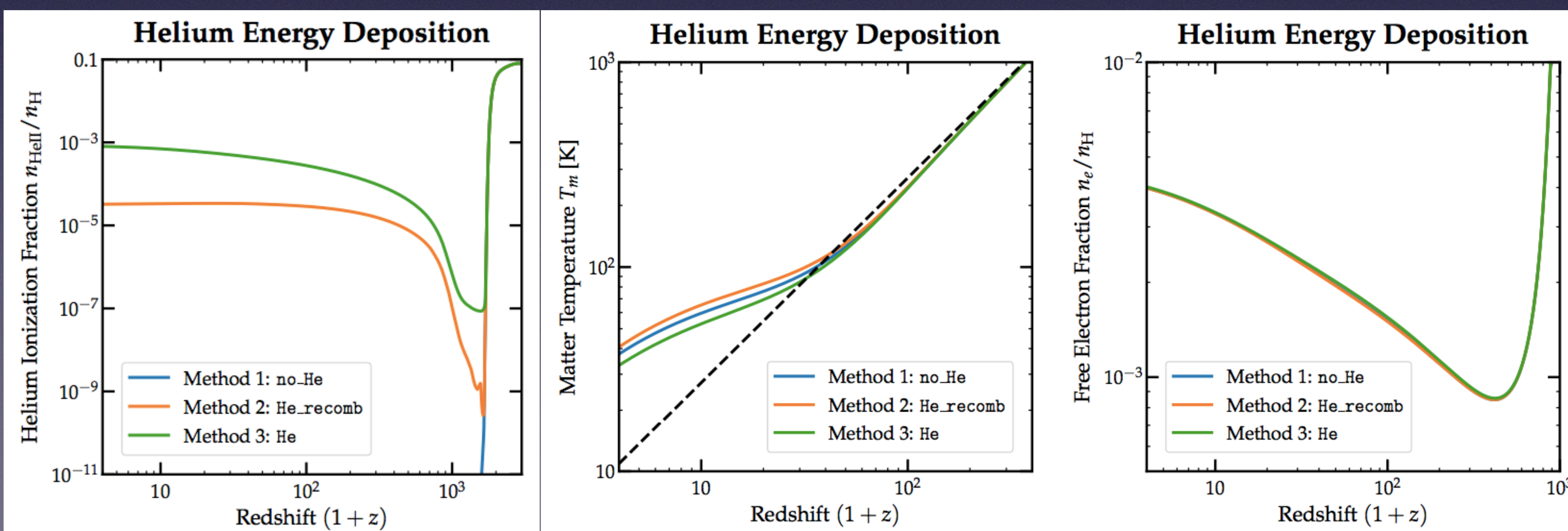
Coarsening

- We can speed up the code by using larger redshift steps
- Let n be the "coarsening ratio": (final bin width in log redshift)/(initial bin width in log redshift)
- Evaluate the transfer functions at the center of the new large redshift bin
- "Coarsen" by raising these transfer functions to power n

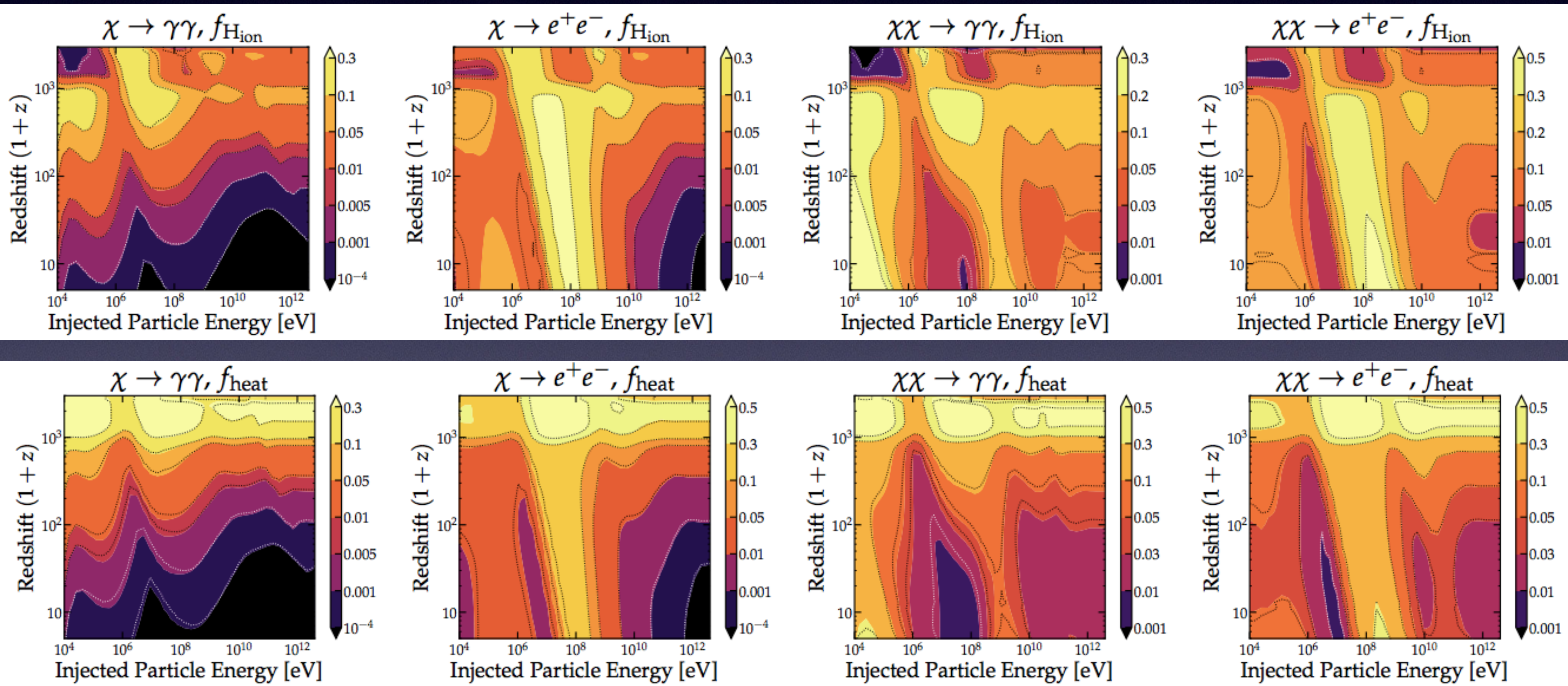


Treatment of helium

- We have the option to track helium ionization in our TLA evolution equations
- If tracking is turned on, low-energy electrons deposit some of their energy into helium ionization
- In addition, we have two simplified bracketing options for how to treat photoionization of helium:
  - assume prompt recombination, resulting in a recombination line photon that can then ionize hydrogen
  - treat it purely as a contribution to helium ionization

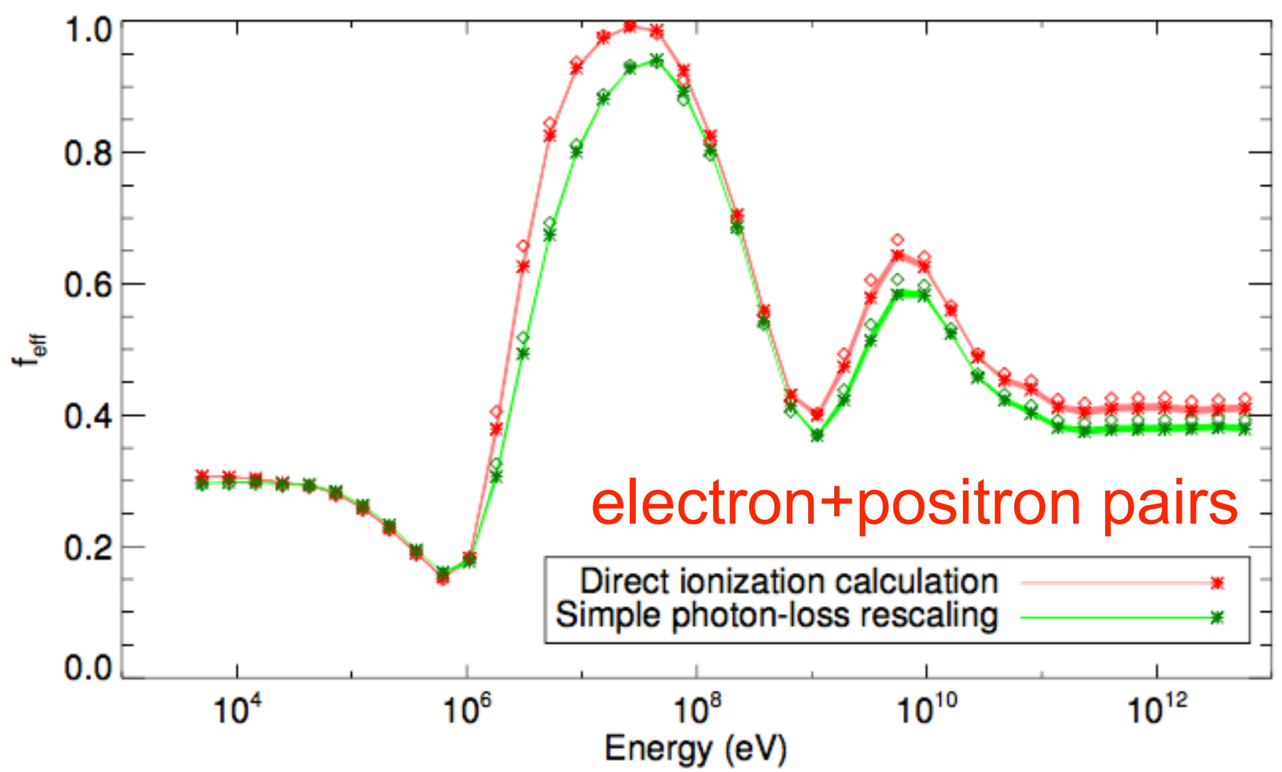


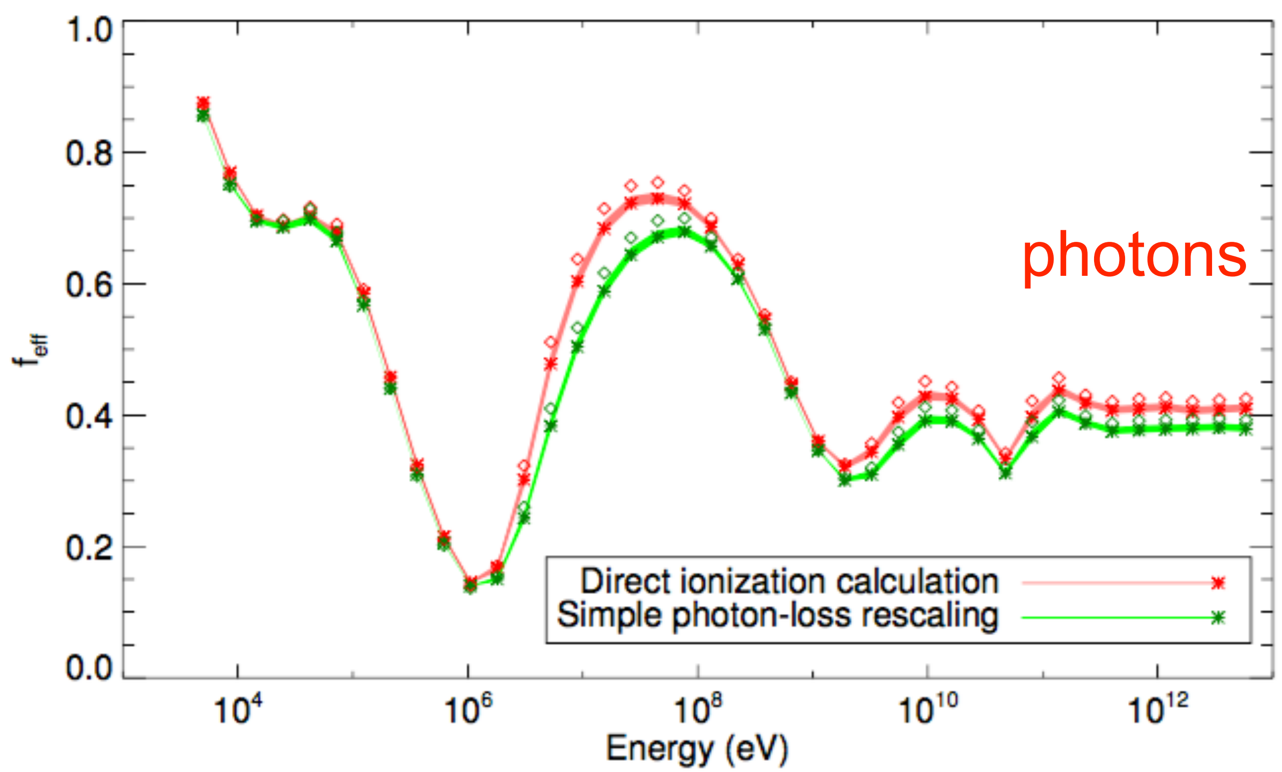
Comparison with earlier results



Efficiency factors (annihilation)

TRS 2016





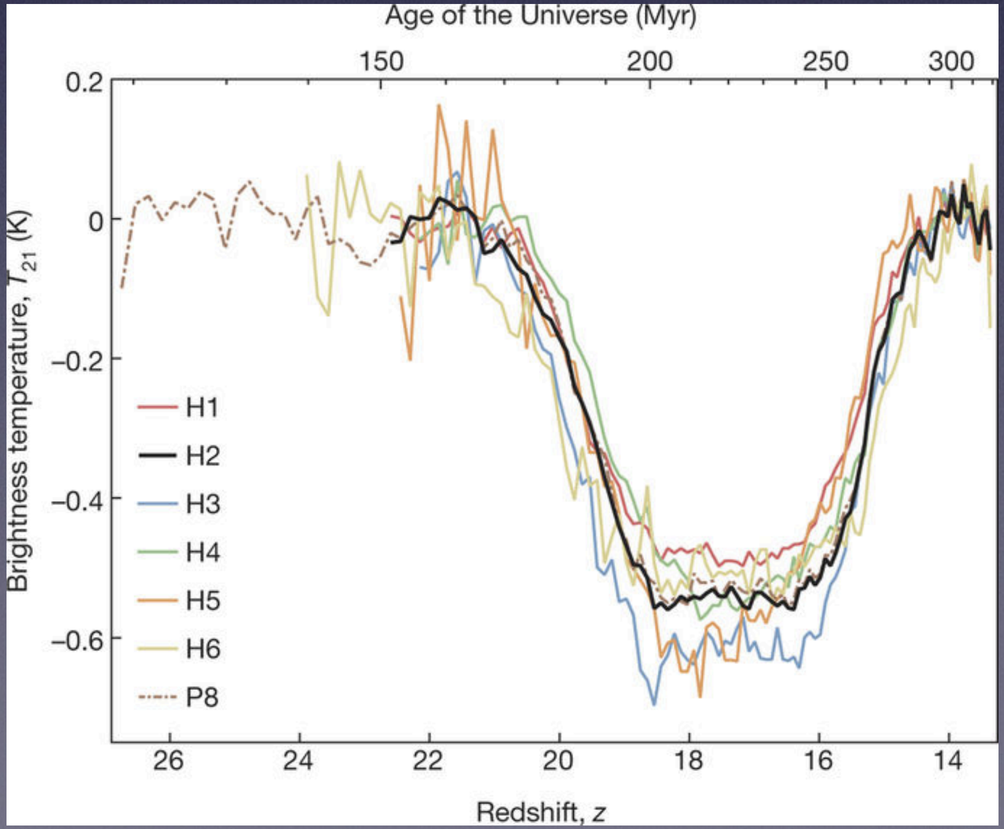
- We can then quickly compute this normalization/ efficiency factor for all injection energies - call it $f_{eff}(E)$ - for injected electrons/photons/positrons.
- Integrate over $f_{eff}(E)$ to determine strength of CMB signal for arbitrary spectra of annihilation products.

EDGES

Side note: have we already seen a signal?

- The Experiment to Detect the Global Epoch-of-reionization Signature (EDGES) has claimed a detection of the first 21cm signal from the cosmic dark ages [Bowman et al, Nature, March '18]
- Claim is a very deep absorption trough corresponding to z~15-20 - implies spin temperature < CMB temperature, $T_{gas}/T_R(z=17.2) < T_S/T_R < 0.105$ (99% confidence).


EDGES antenna in western Australia (photo credit: Judd Bowman/ASU)



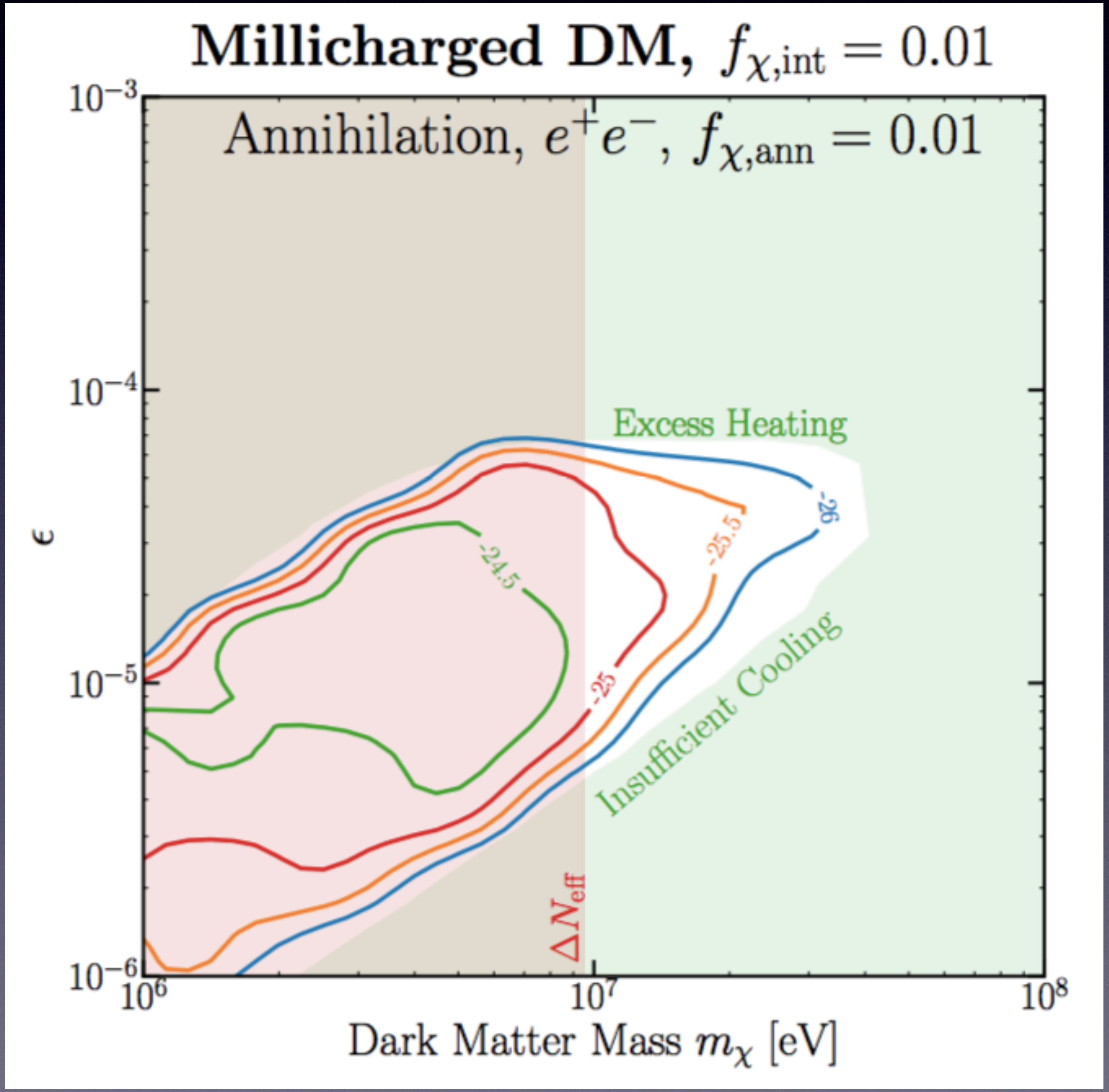
- Very surprising result - trough is much deeper than expected.
- Suggests either new physics of some form, or a systematic error [e.g. Hills et al '18, Bradley et al '19].

Interpreting EDGES

- If T_R is taken to be the CMB temperature, $T_{gas}/T_R < 0.105$ gives $T_{gas} < 5.2$ K.
- But assuming standard decoupling and no stellar heating, we can calculate $T_{gas} \sim 7$ K.
- It is quite possible this result is spurious - e.g. due to instrumental effects and/or foregrounds [e.g. Hills et al 1805.01421].
- But if it is confirmed, suggests either $T_R > T_{CMB}$ (new radiation backgrounds) [Feng & Holder 1802.07432], some significant change to the standard cosmological evolution, or some modification to the standard scenario that lowers T_{gas}.
- New radiation backgrounds could arise from either novel astrophysics, i.e. radio emission from early black holes [Ewall-Wice et al 1803.01815] or more exotic (DM-related?) sources [e.g. Fraser et al 1803.03245, Pospelov et al 1803.07048].
- Additional cooling of the gas could be due to modified recombination history (earlier decoupling from CMB), or thermal contact of the gas with a colder bath, e.g. (some fraction of) the dark matter [e.g. Barkana, Nature, March '18; Munoz & Loeb 1802.10094; Berlin et al 1803.02804; Barkana et al 1803.03091; Houston et al 1805.04426; Sikivie 1805.05577].
- Opposite effect to that expected from annihilation/decay - could set strong limits.
- Many possible explanations also imply large effects on 21cm power spectrum [e.g. Munoz et al 1804.01092, Kaurov et al 1805.03254].

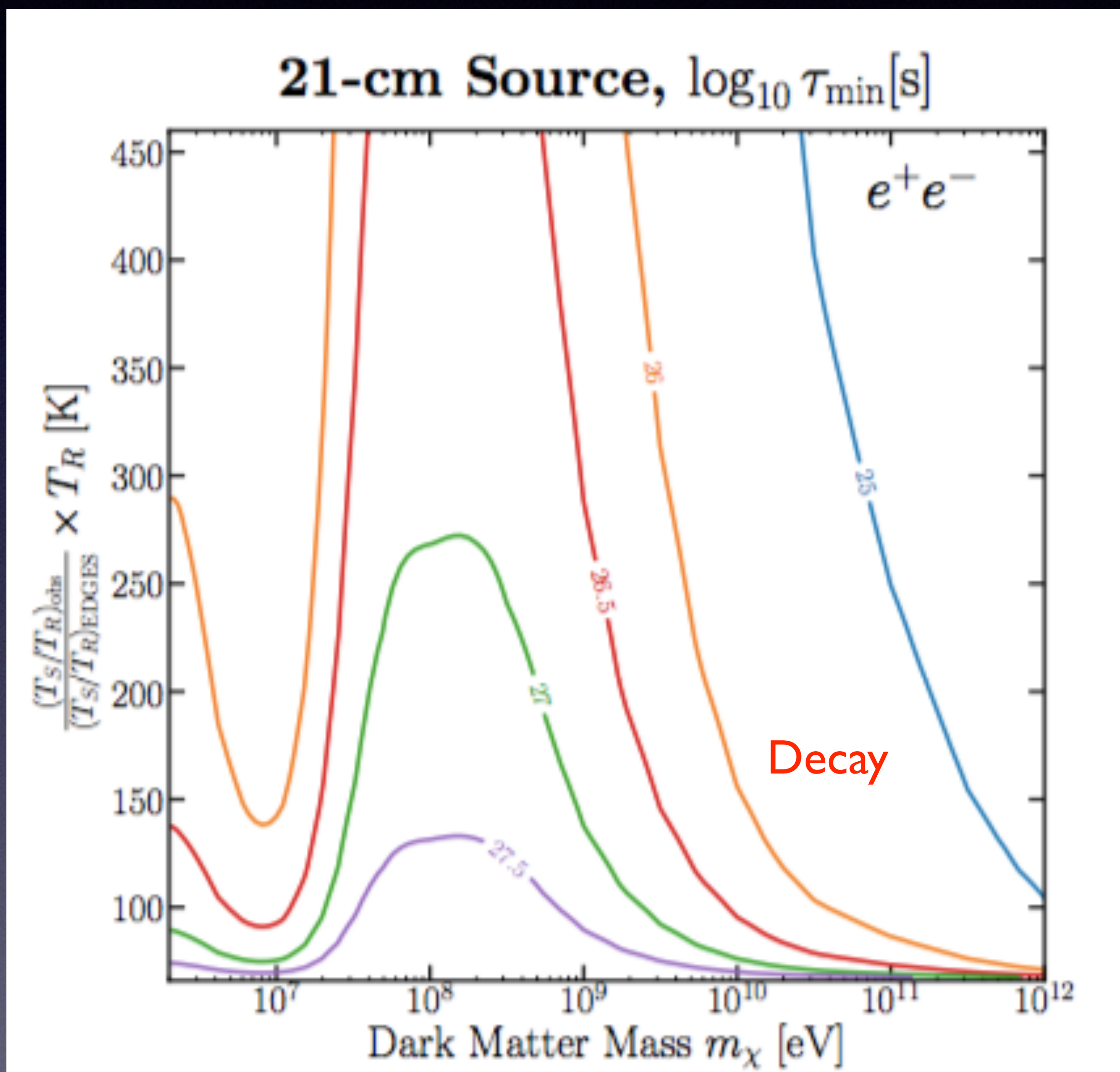
Millicharged DM and annihilation heating

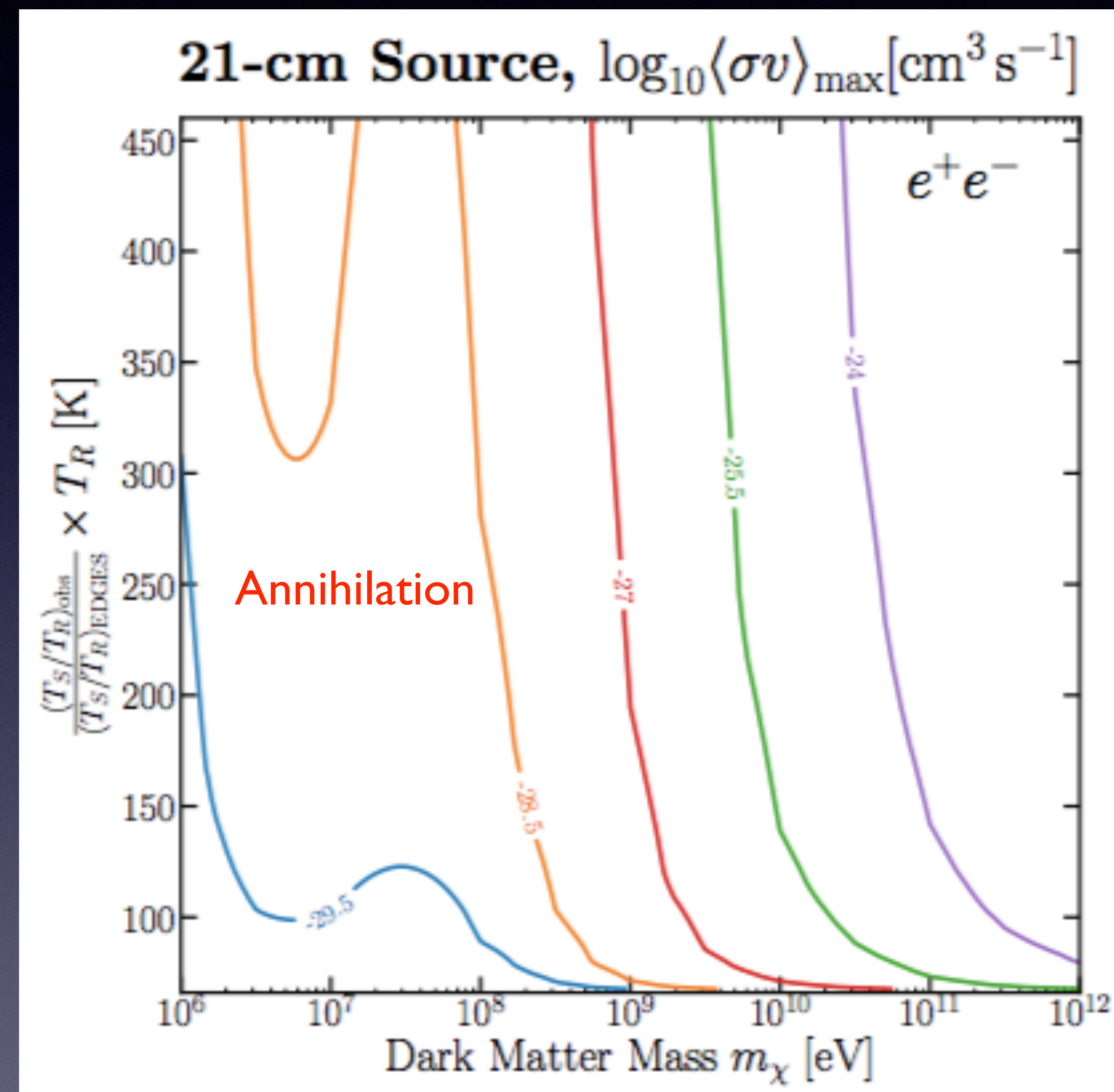
- Consider millicharged DM comprising 1% of total DM, and assume EDGES observation is correct.
- If millicharge is too small, cannot scatter efficiently enough to cool the gas.
- If millicharge is too large, automatic annihilation (through s-channel photon) overheats the gas.
- In intermediate region, can set limits on extra (non-automatic) annihilation channels.
- Cannot get desired 1% density through thermal freezeout of such channels if branching ratio to electrons is appreciable & annihilation is unsuppressed at late times.



Liu & TRS, PRD '18

Annihilation/decay heating + extra photons

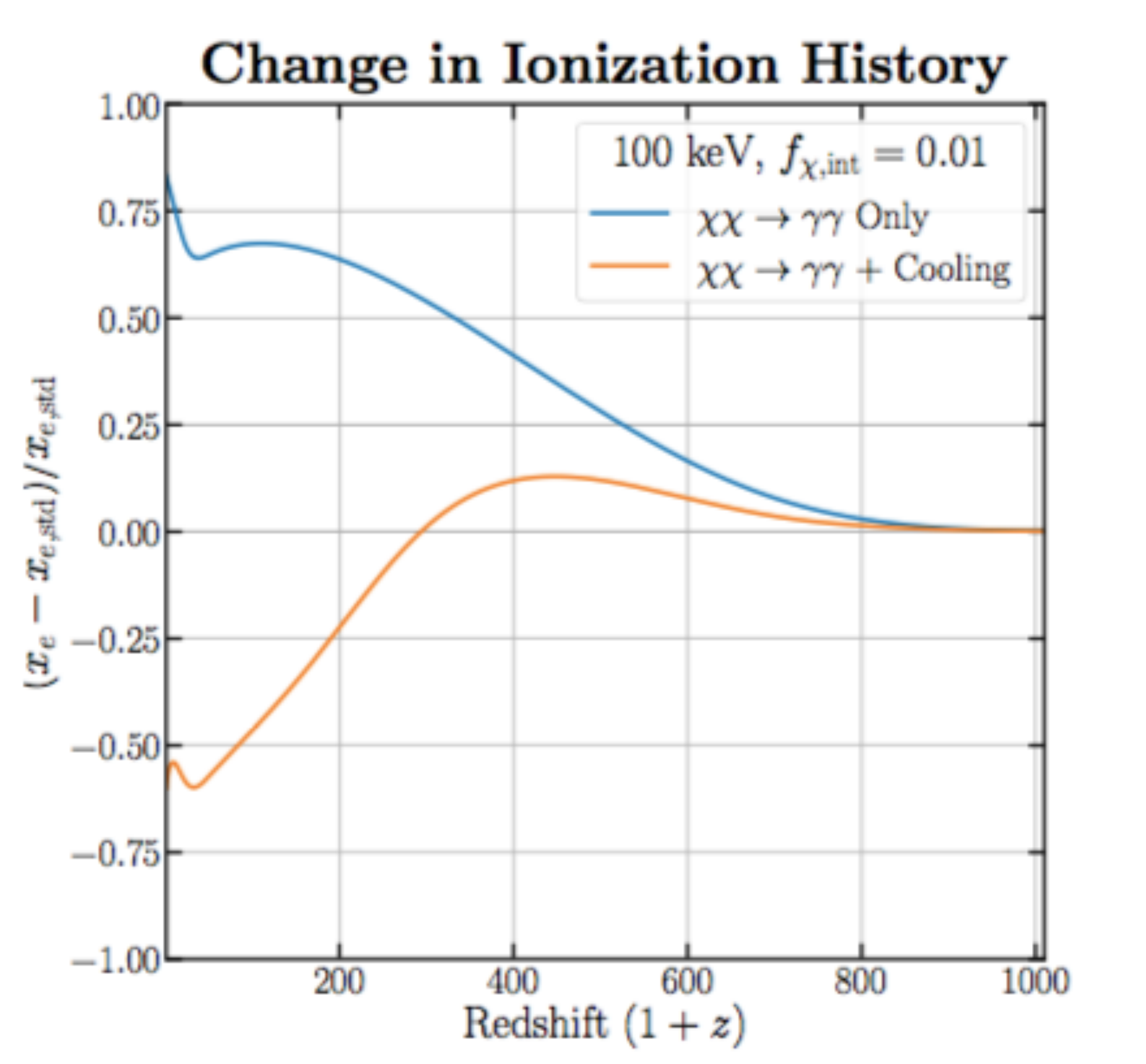




- Example for decay/annihilation to electrons - if extra radiation backgrounds are of same order as the CMB (at 21cm frequency), probe lifetimes of a few x 10^{27} s for 100 MeV DM, annihilation cross sections of order few x 10^{-30} cm^3/s - four orders of magnitude below thermal relic. (See also d'Amico et al 1803.03629.)

Annihilation/decay + strong scattering

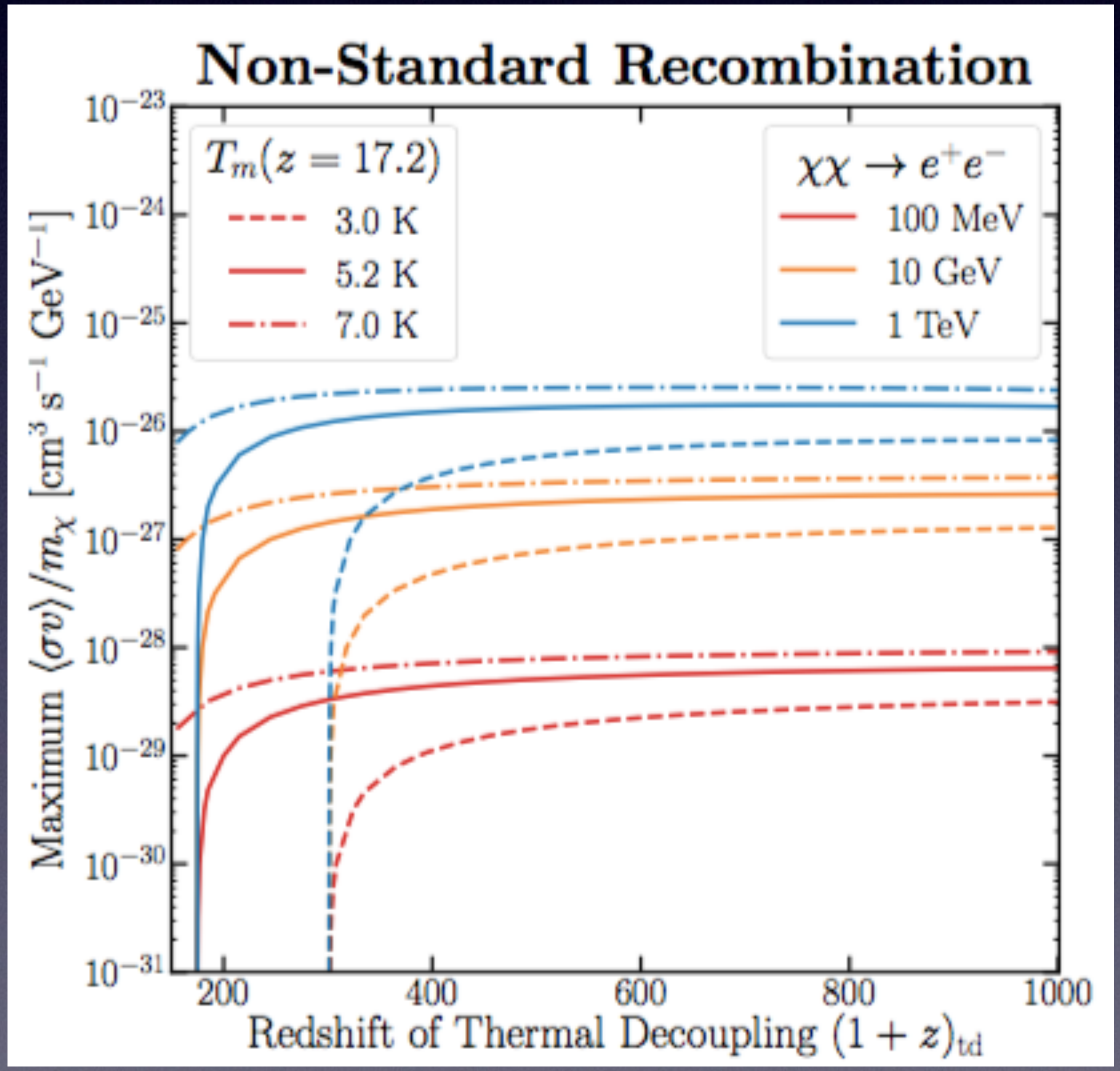
- Case where baryons and (some subcomponent of) DM are strongly coupled - DM acts as heat sink for all effects heating baryons
- Causes early photon-gas decoupling, gas has longer to cool due to expansion.
- Effect is independent of scattering xsec, once xsec is large enough.
- Net effect is delayed recombination + dilution of heating by needing to heat DM too.
- Cooler gas recombines better; can reduce ionization levels, also relaxes annihilation/decay constraints from CMB!



Example of a case nominally ruled out by CMB limits on extra ionization - turning on small scattering component reduces ionization signal.

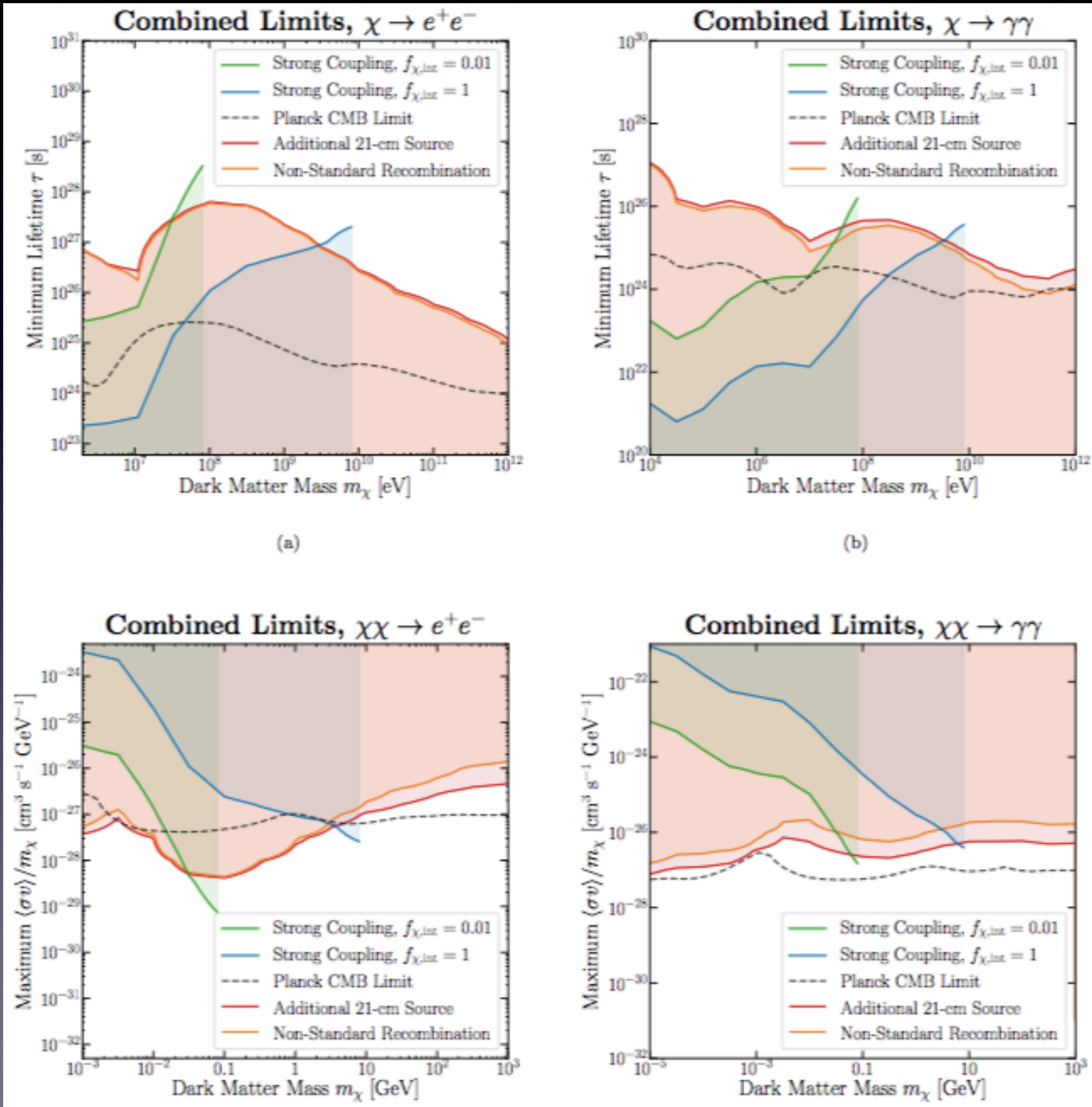
Annihilation/decay + delayed recombination

- Suppose baryons decouple from photons earlier than expected (can be due to a small scattering DM component, or for other reasons).
- If decoupling is early enough, gas temperature before heating at z~17 is very small - set constraint by requiring DM heating not overproduce total observed T_{gas}, starting from 0K.
- Thus as with scattering, there is an asymptotic constraint when decoupling is early enough.



Example of DM annihilation to e^+e^- pairs; constraints as a function of decoupling redshift

- Summary of limits assuming EDGES is correct
- Orange/red lines = limits in presence of early recombination (orange) or extra radiation up to same strength as CMB (red)
- Blue/green regions = allowed regions with 100%/1% of DM scattering, strong-coupling limit
- Dashed black lines = standard CMB bound
- Heating bounds are stronger than standard CMB limits for light DM in most cases (especially decay to e+e-)



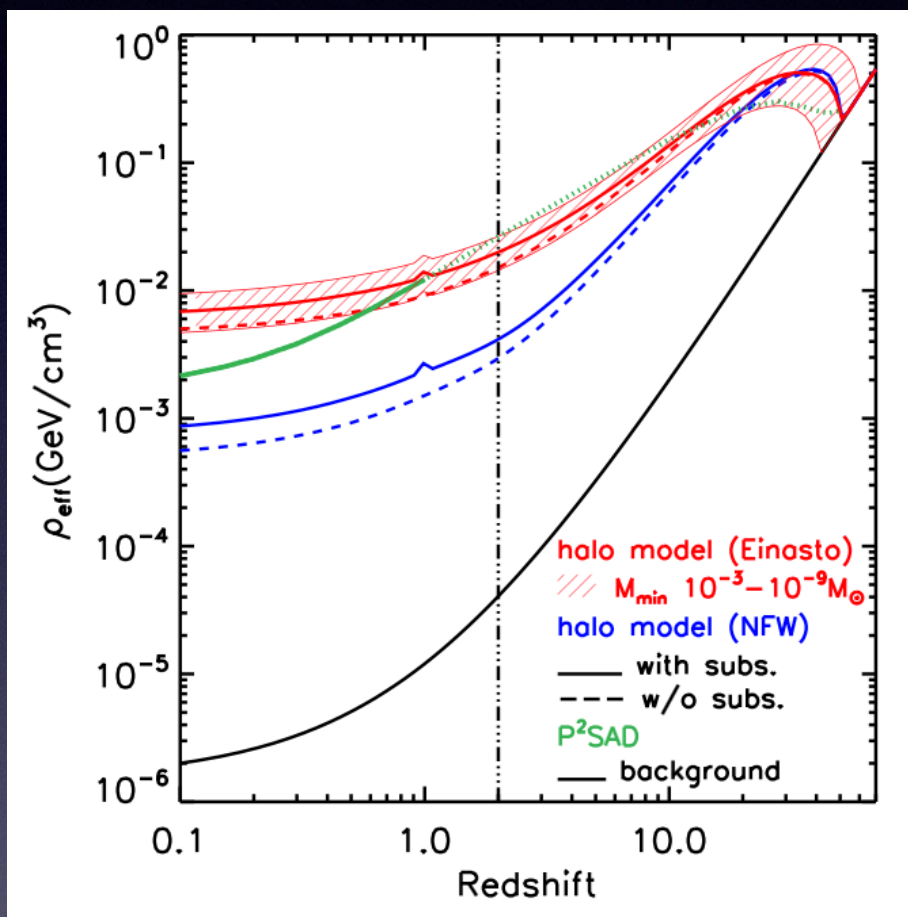
Reionization and boost factors

Dark matter in the reionization epoch

- By this time, early galaxies have formed.
- Dark matter has clumped into halos and filaments at a wide range of scales.
- Need to account for the resulting higher densities - enhancement to annihilation.

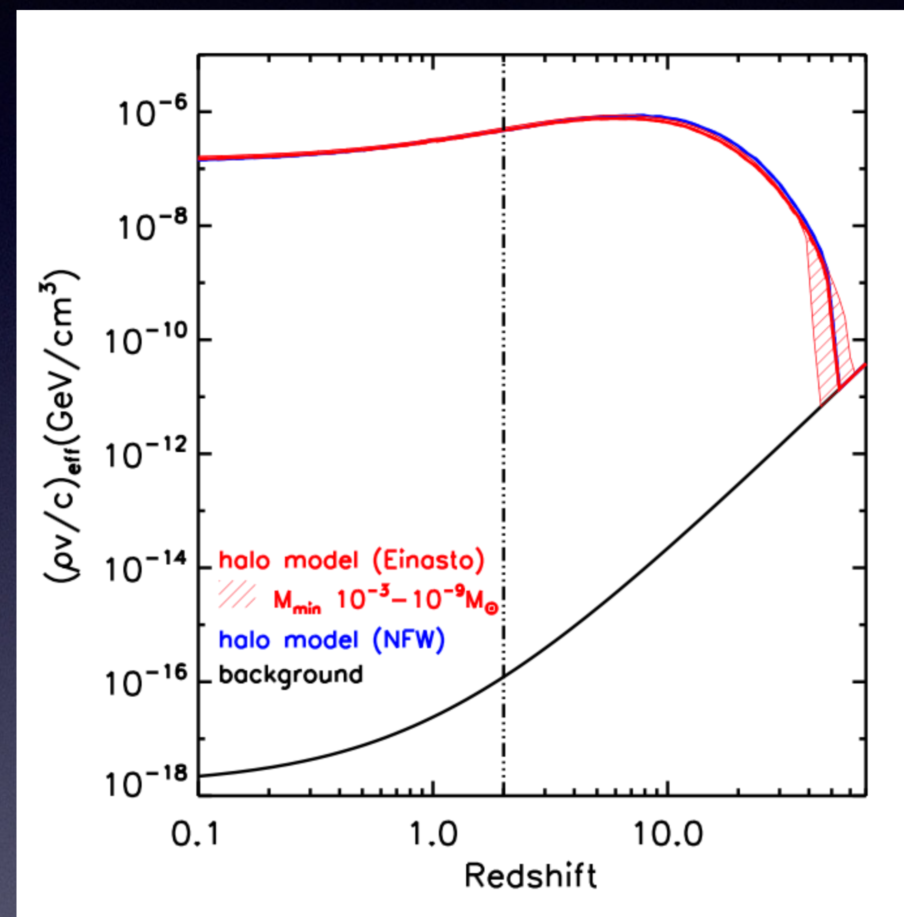
s-wave annihilation

$$\text{rate} \propto \rho^2$$



p-wave annihilation

$$\text{rate} \propto \rho^2 v^2$$



decay

$$\text{rate} \propto \frac{\rho}{\tau} e^{-t/\tau}$$

assume τ >> age of universe, rate follows DM density

colored curves show effective average ρ, ρv, accounting for structure formation

What we know about reionization

- Most recent results from Planck, May 2016 (paper XLVII), for cosmic reionization optical depth:

$$\tau = 0.058 \pm 0.012$$

- "The average redshift at which reionization occurs is found to lie between z = 7.8 and 8.8, depending on the model of reionization adopted… in all cases, we find that the Universe is ionized at less than the 10% level at redshifts above z =10."
- What limits does this set on DM annihilation? To what degree could DM contribute to the ionization history around reionization, consistent with these (and other) bounds?

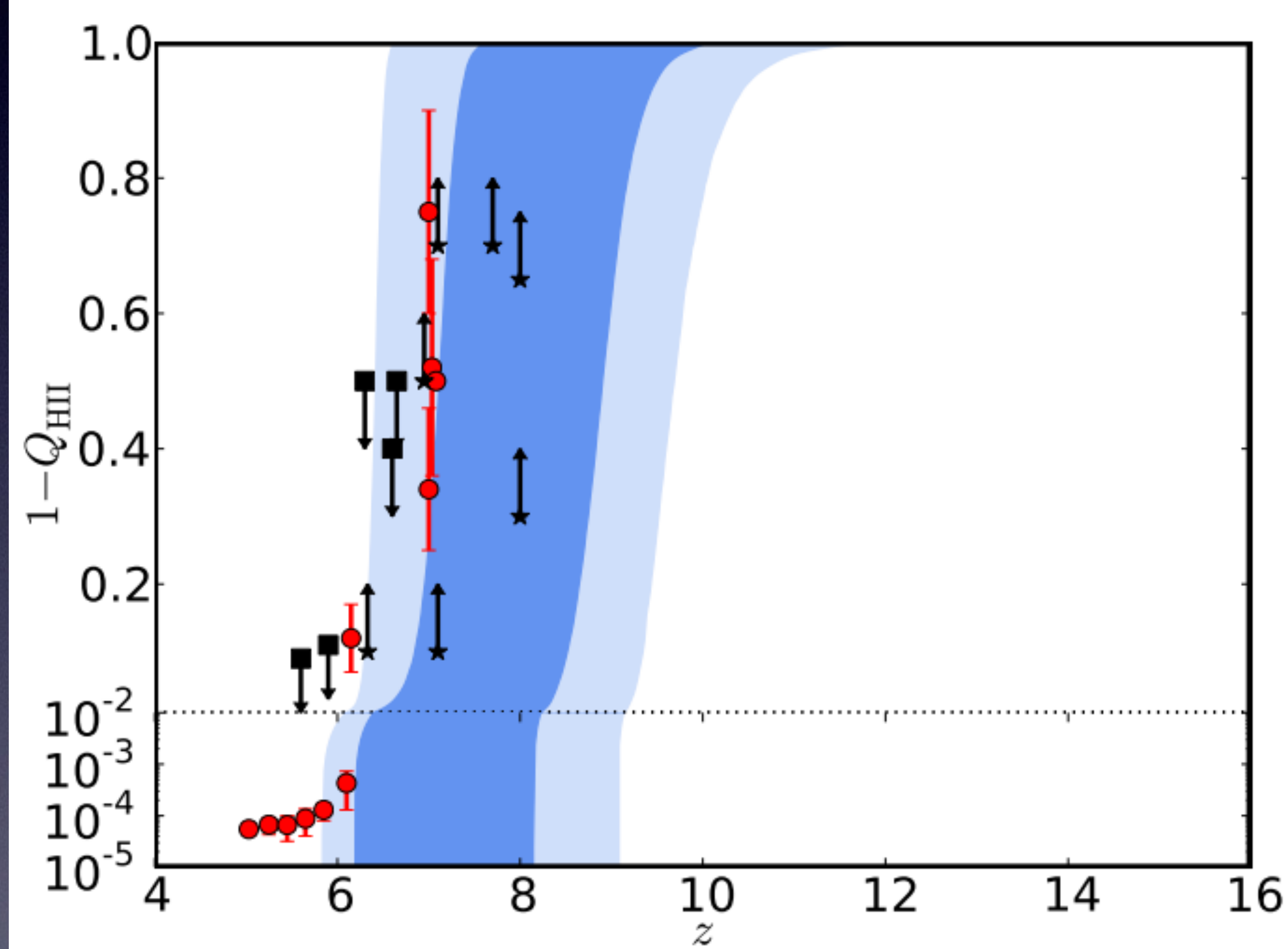
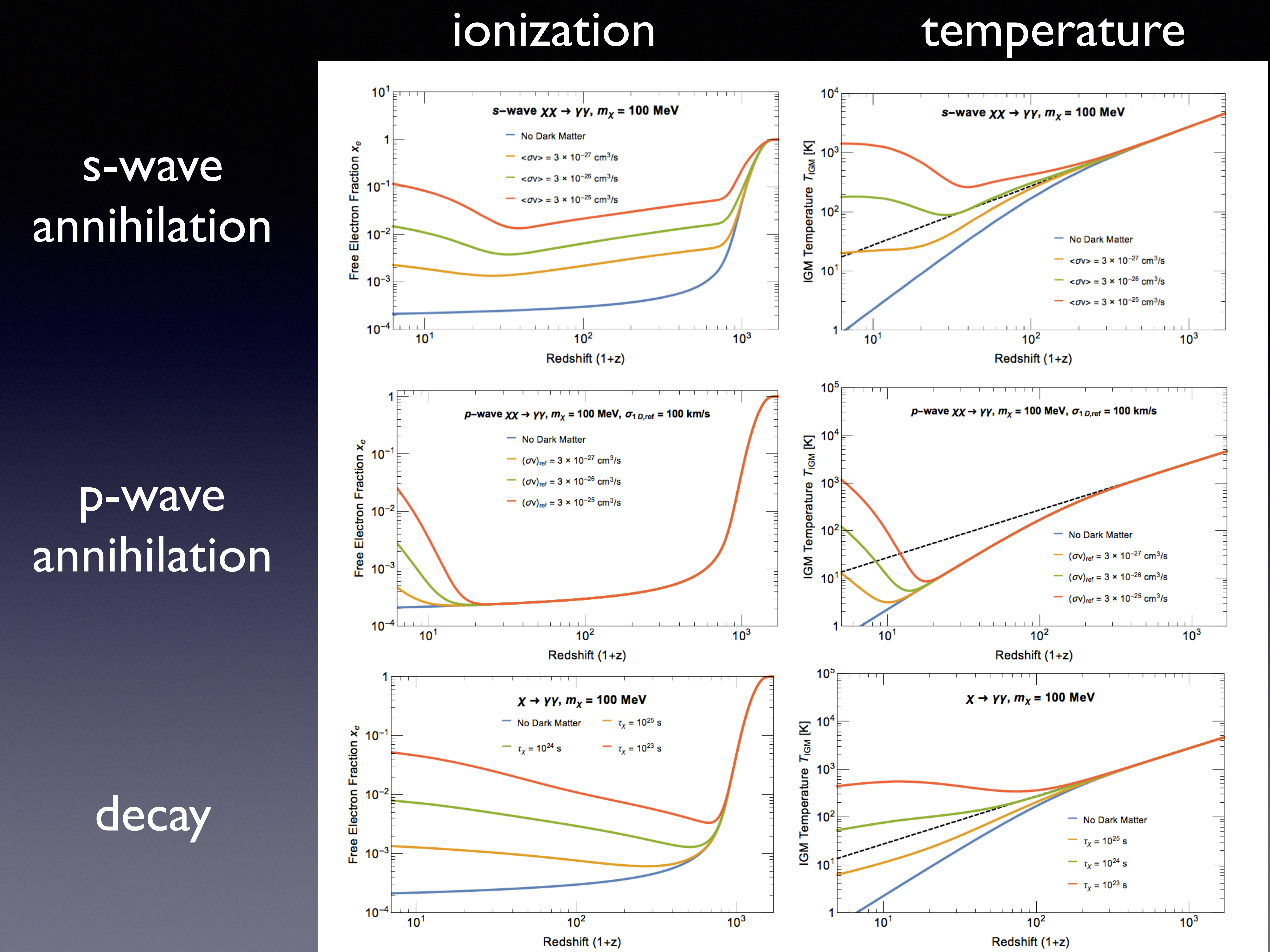


Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints compiled by Bouwens et al. (2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the 68 % and 95 % allowed intervals, respectively.


ionization
temperature
s-wave annihilation
p-wave annihilation
decay
s-wave χχ → γγ, m_χ = 100 MeV
No Dark Matter
<σv> = 3 × 10^-27 cm^3/s
<σv> = 3 × 10^-26 cm^3/s
<σv> = 3 × 10^-25 cm^3/s
Free Electron Fraction x_e
IGM Temperature T_IGM [K]
Redshift (1+z)
p-wave χχ → γγ, m_χ = 100 MeV, σ_1D,ref = 100 km/s
(σv)_ref = 3 × 10^-27 cm^3/s
(σv)_ref = 3 × 10^-26 cm^3/s
(σv)_ref = 3 × 10^-25 cm^3/s
χ → γγ, m_χ = 100 MeV
τ_χ = 10^25 s
τ_χ = 10^24 s
τ_χ = 10^23 s

Constraints

- CMB anisotropy bounds (discussed earlier) - limits changes to ionization history at high redshift. Strongly constrains s-wave annihilation, but less important for p-wave annihilation & decay.
- Total optical depth, as measured by Planck - limits integrated changes to ionization history.

$$\tau = 0.058 \pm 0.012$$

- Temperature after reionization (Becker et al '11, Bolton et al '11):

$$\log_{10}\left(\frac{T_{\mathrm{IGM}}(z=6.08)}{\mathrm{K}}\right) \leq 4.21^{+0.06}_{-0.07} \qquad \log_{10}\left(\frac{T_{\mathrm{IGM}}(z=4.8)}{\mathrm{K}}\right) \leq 3.9 \pm 0.1$$

+ bounds on decay and annihilation from present-day measurements of photon flux

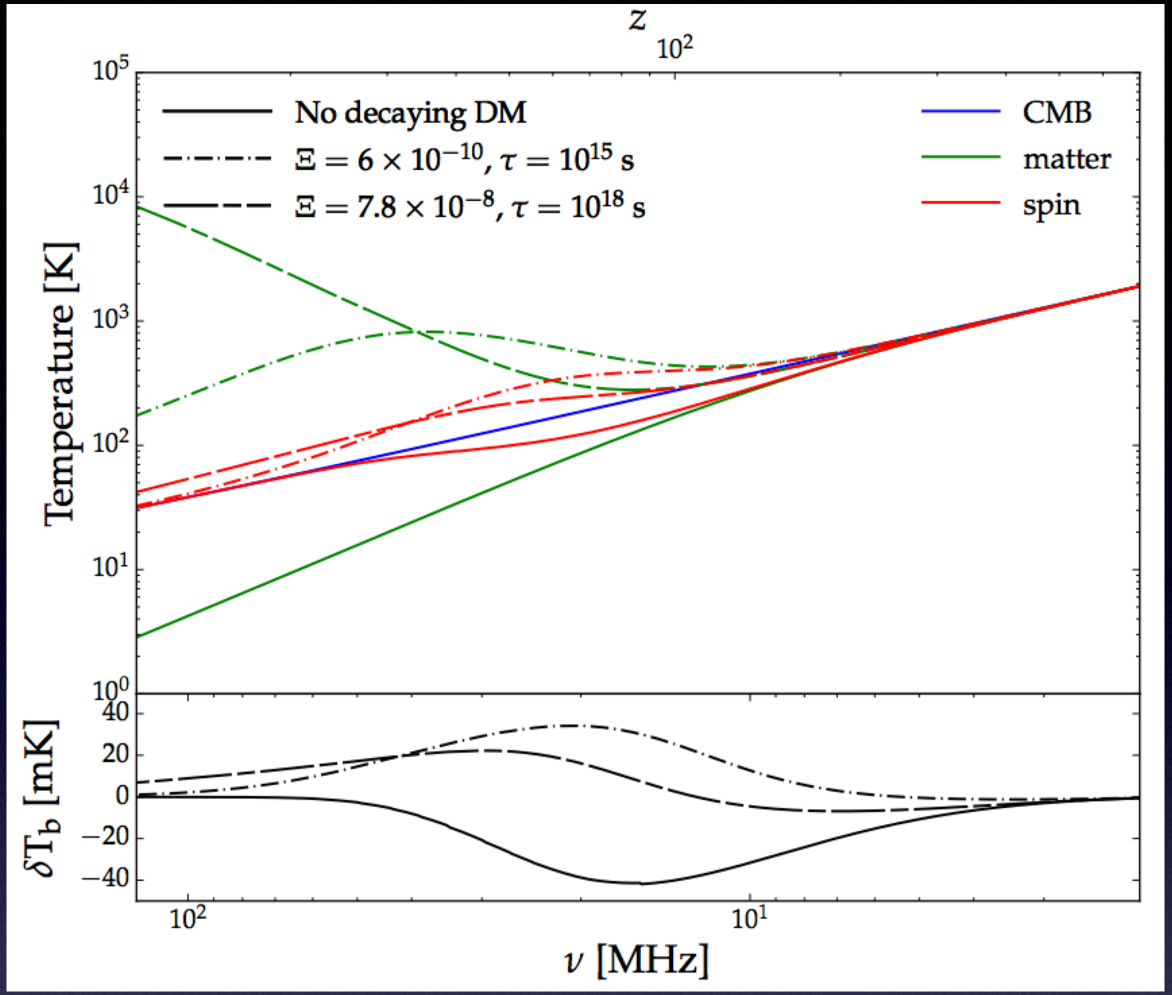
Can DM contribute to reionization?

- Answer appears to be "no". Models that would give large contribution to reionization also produce:
  - late-time heating (potentially testable with 21cm observations?)
  - early ionization, leading to strong CMB bounds (for decay, s-wave annihilation)
  - diffuse photon backgrounds in present day
- Most optimistic scenario is for DM decay producing O(10-100) MeV electrons/positrons - could contribute at O(10%) level

21cm

Predictions for 21cm signals

Poulin et al JCAP03(2017)043



- Heating from decays before reionization leads to "spin temperature" exceeding CMB temperature - i.e. 21cm line in <u>emission</u> 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.

Lopez-Honorez et al JCAP08(2016)004