Dark Matter and the Cosmic Microwave Background

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Identification of Dark Matter 2018
Brown University
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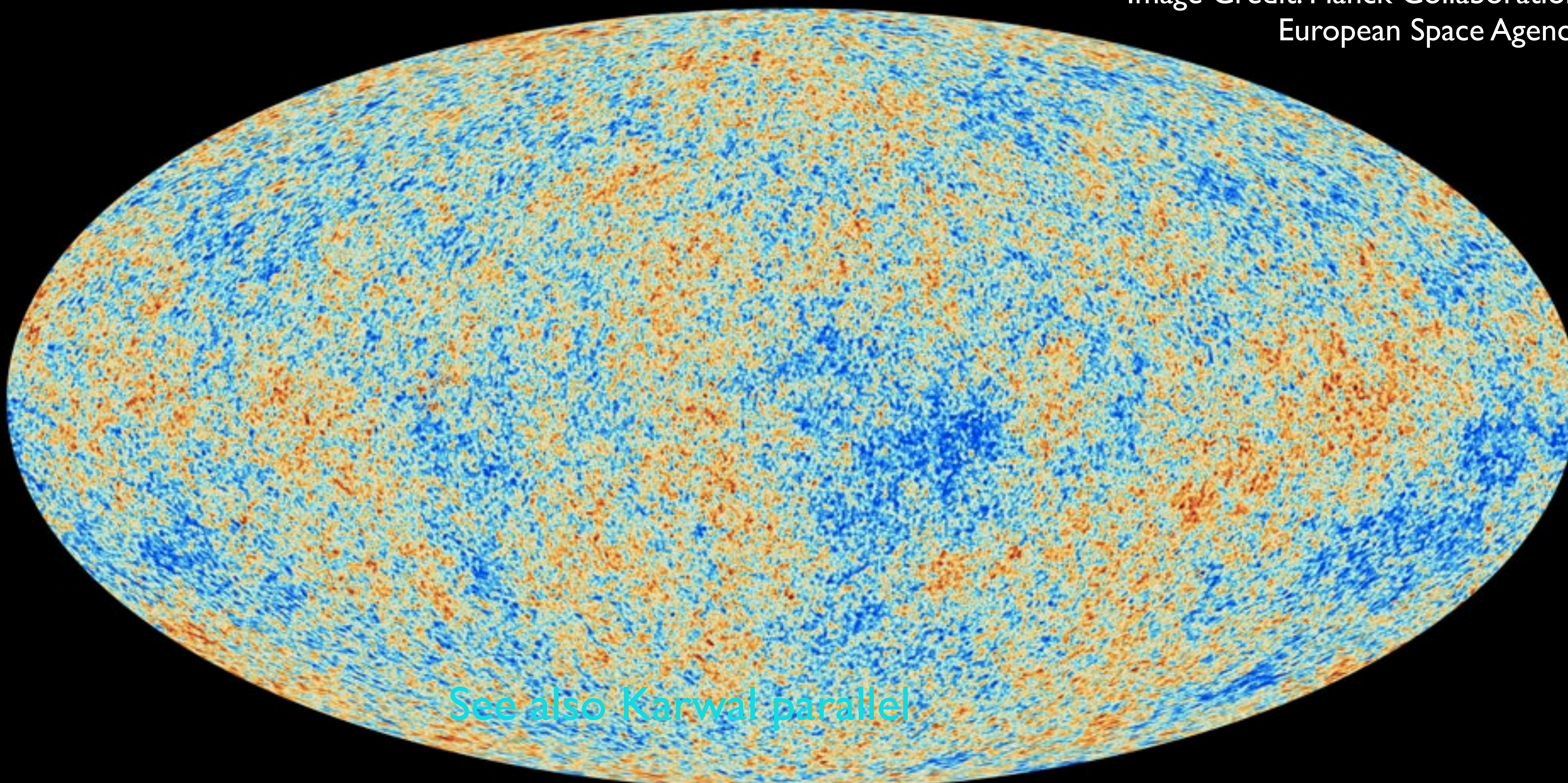
U.S. DEPARTMENT OF ENERGY | Office of Science

The cosmic microwave background radiation

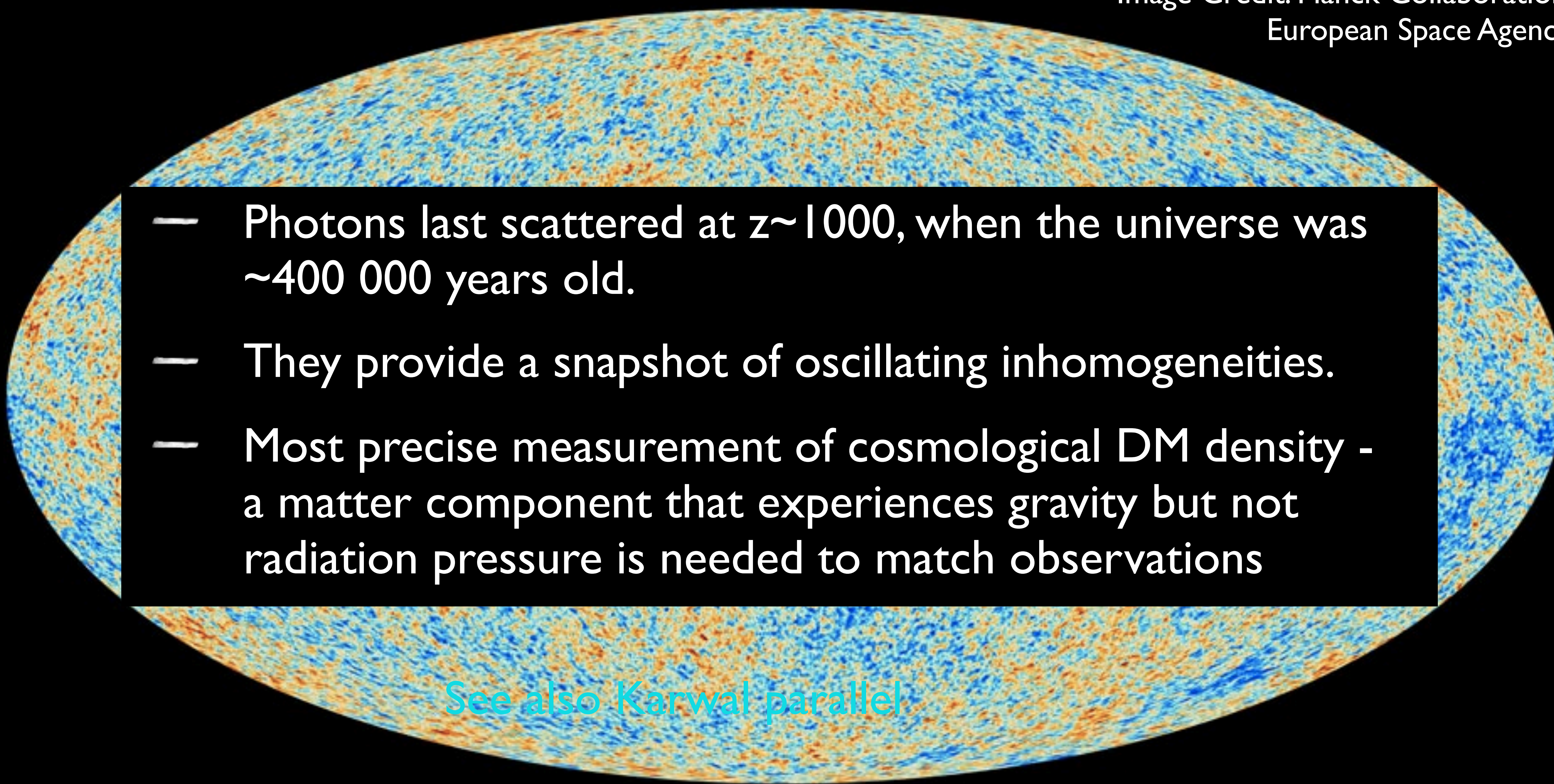
Image Credit: Planck Collaboration,
European Space Agency



See also Karwal parallel

The cosmic microwave background radiation

Image Credit: Planck Collaboration, European Space Agency



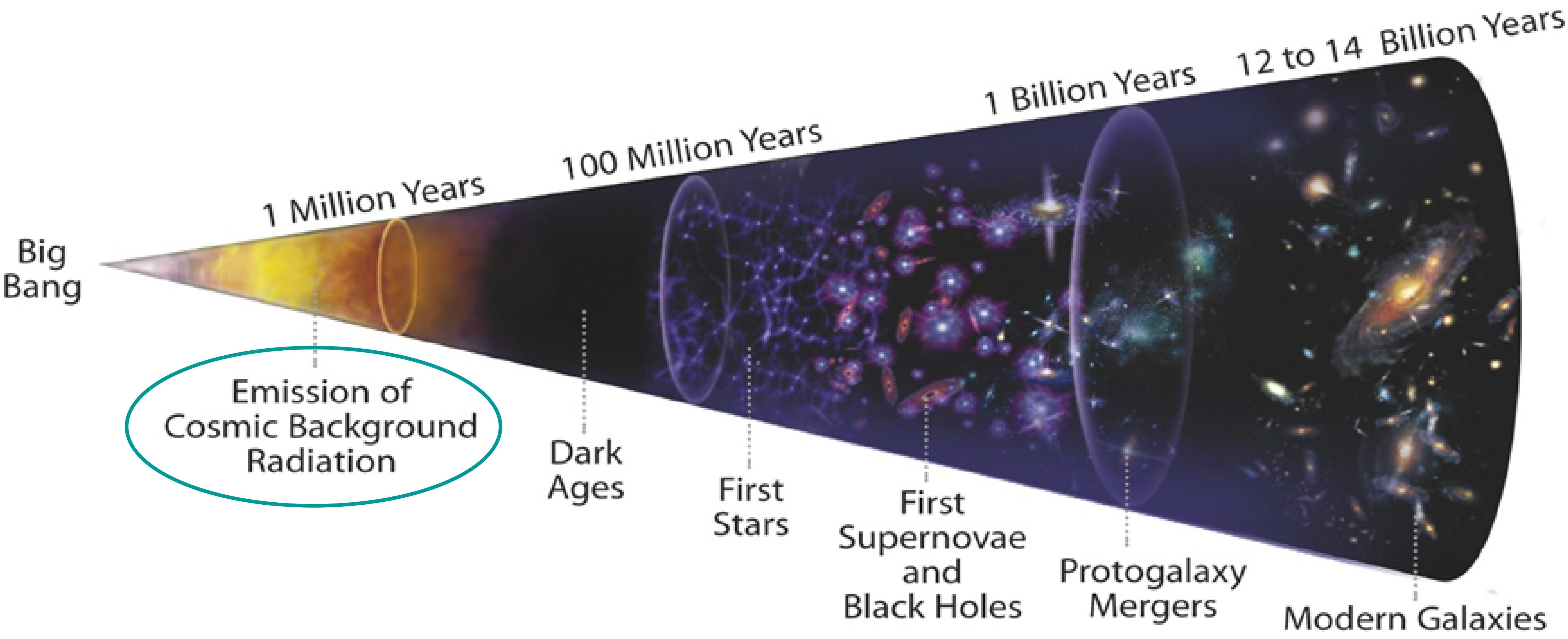
- Photons last scattered at z~1000, when the universe was ~400 000 years old.
- They provide a snapshot of oscillating inhomogeneities.
- Most precise measurement of cosmological DM density - a matter component that experiences gravity but not radiation pressure is needed to match observations

See also Karwal parallel

Non-gravitational interactions (?) of DM

- As yet no unambiguous detections.
- May not be detectable at all.
- But IF present would provide enormous insight into DM nature and properties - motivation behind direct, indirect, collider searches.
- Observations of the CMB provide precision data on the early universe - spatial anisotropies + blackbody spectrum.
- Physics is relatively simple and well-understood, no uncertainties due to e.g. complex Galactic astrophysics.
- Density at high redshift is greatly enhanced - high interaction rates.
- Generic interactions between dark and visible matter would lead to energy transfer between the two. How would this change early cosmic history?

How can dark matter change the early universe?



affects CMB   affects 21cm

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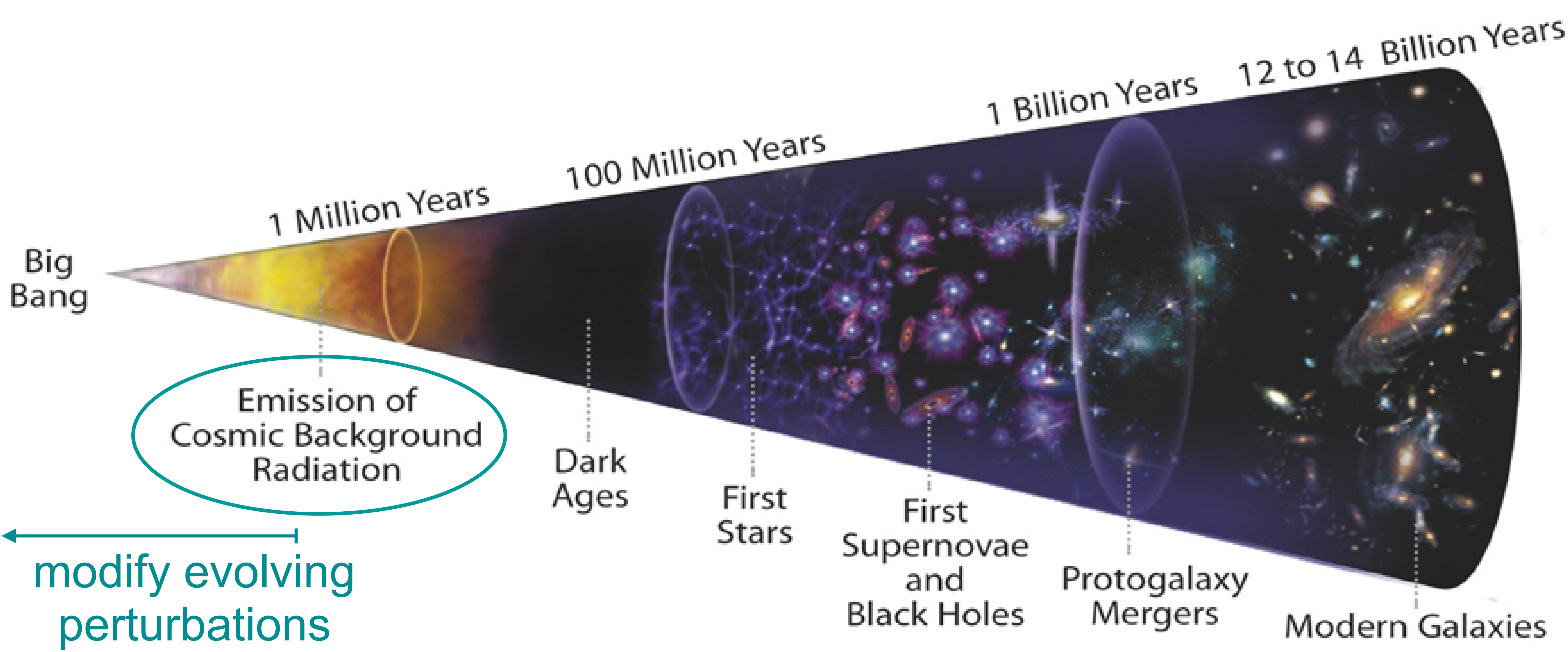

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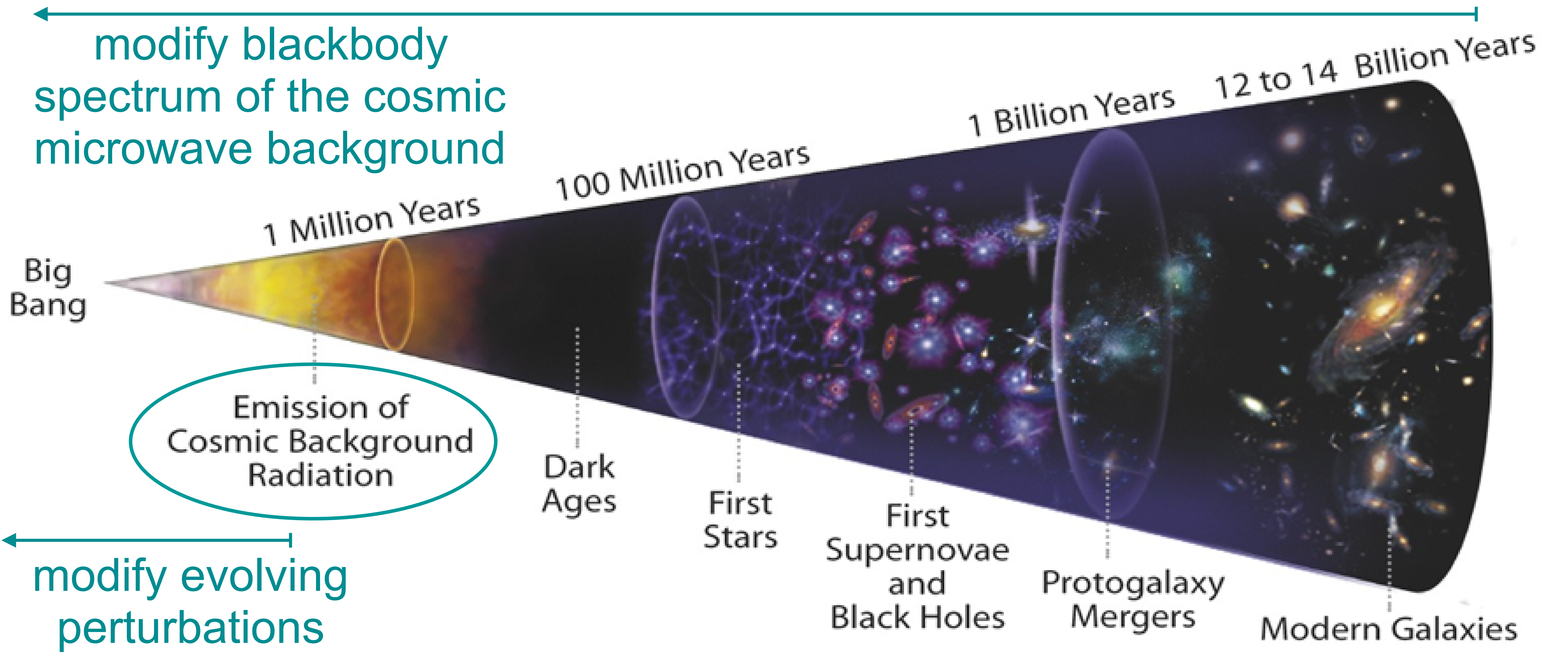

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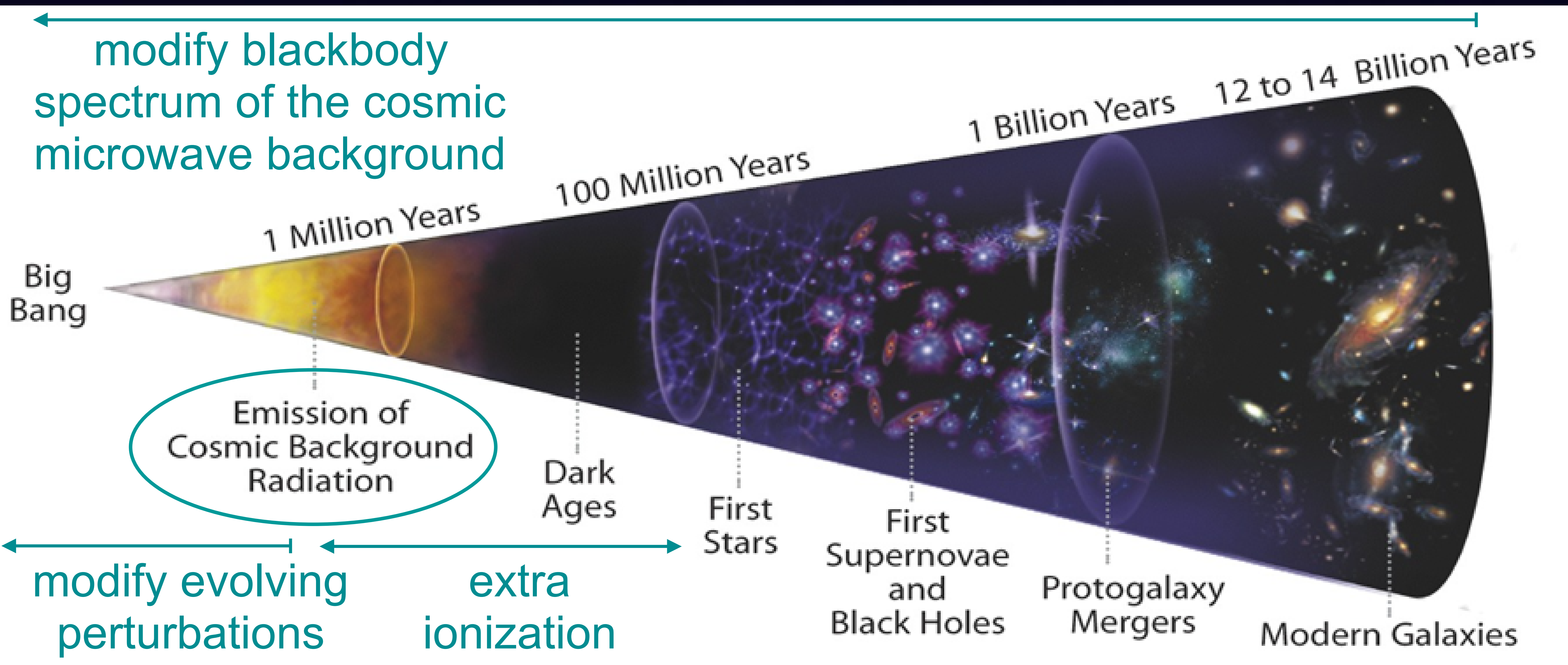

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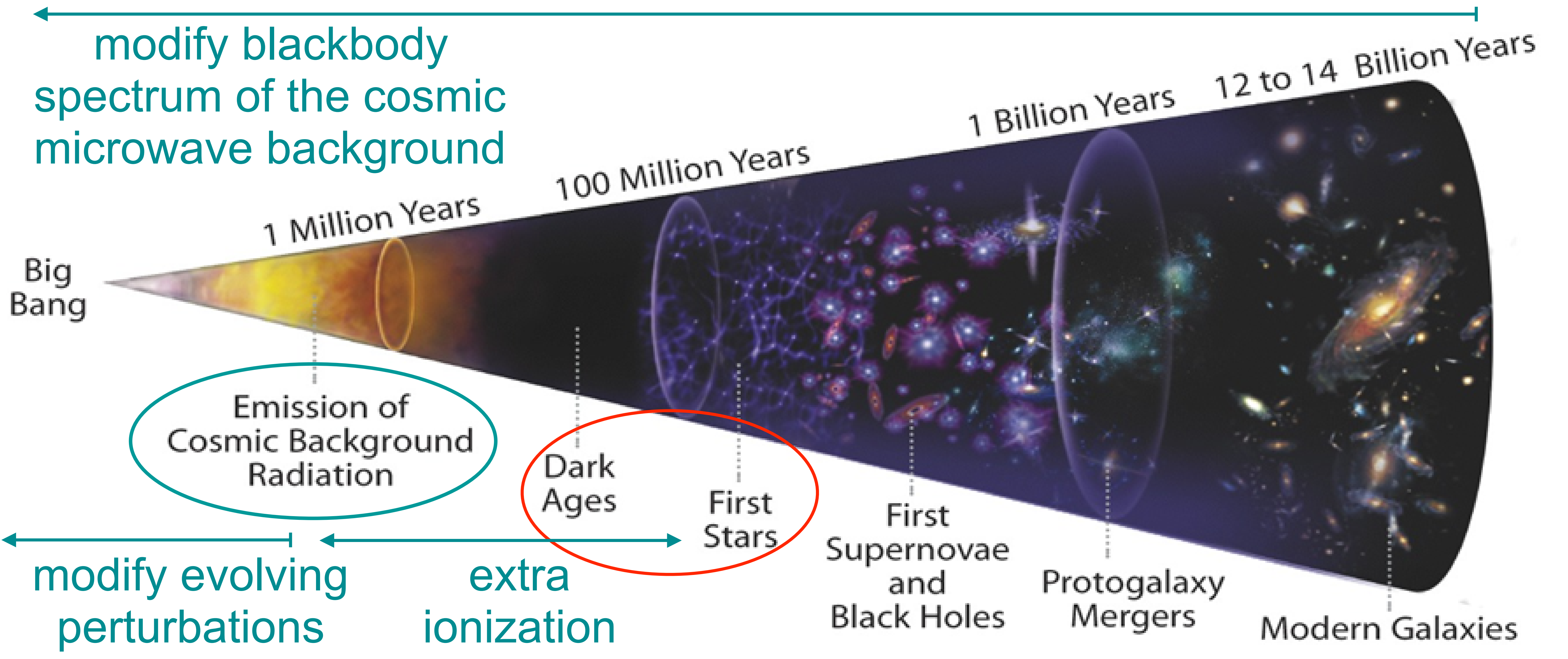

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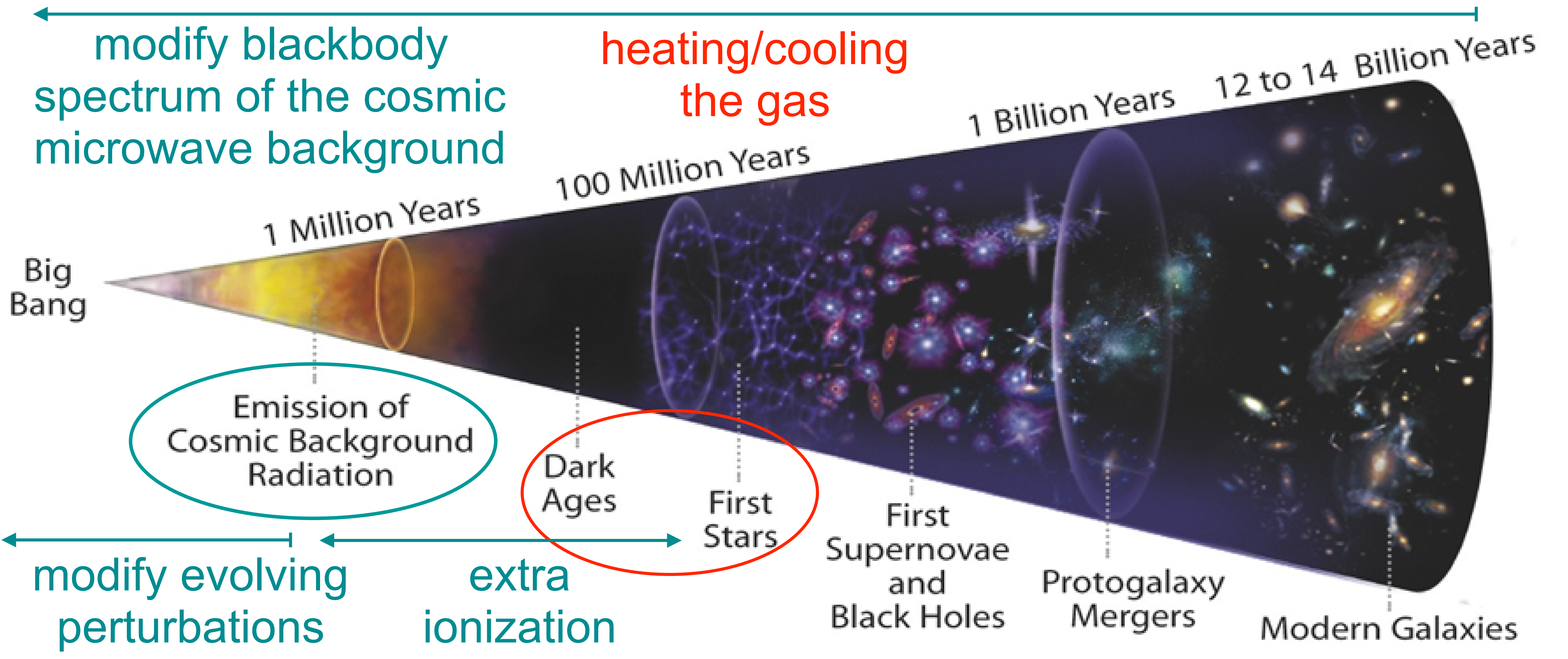

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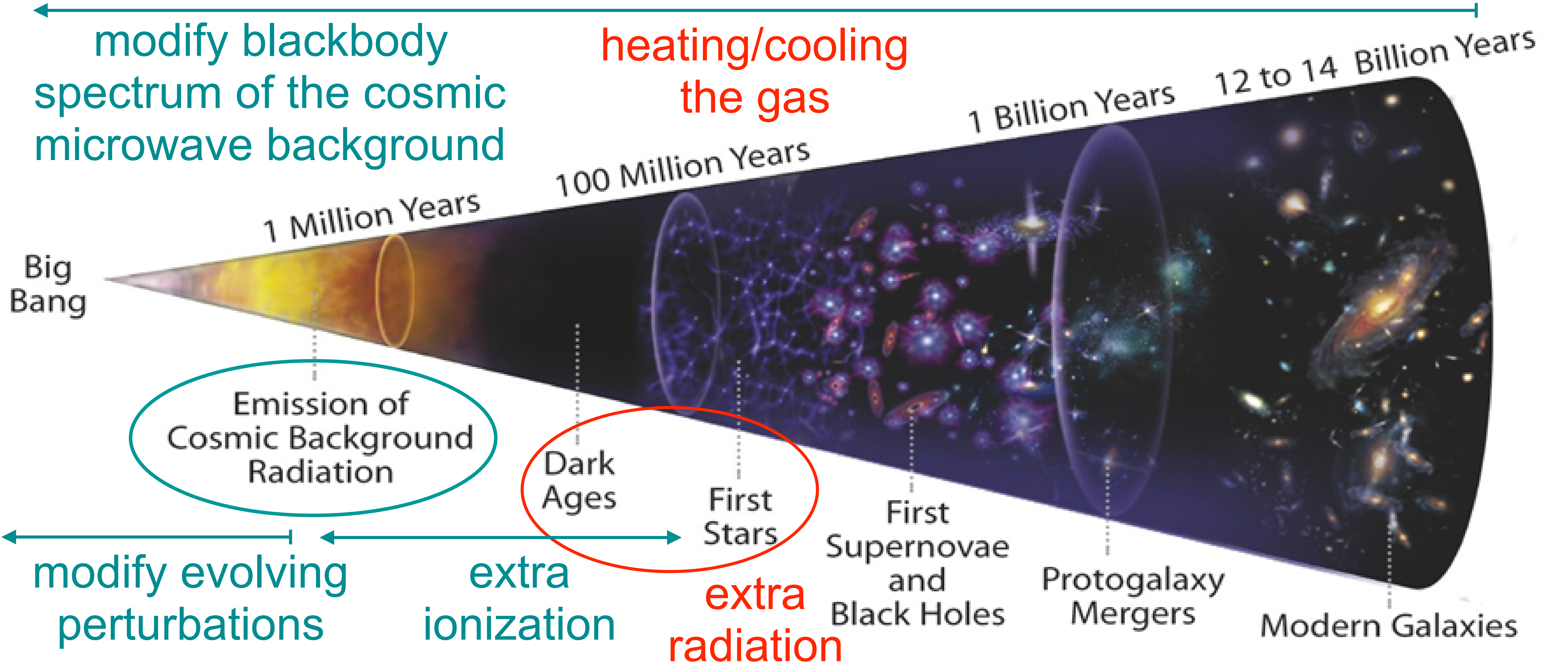
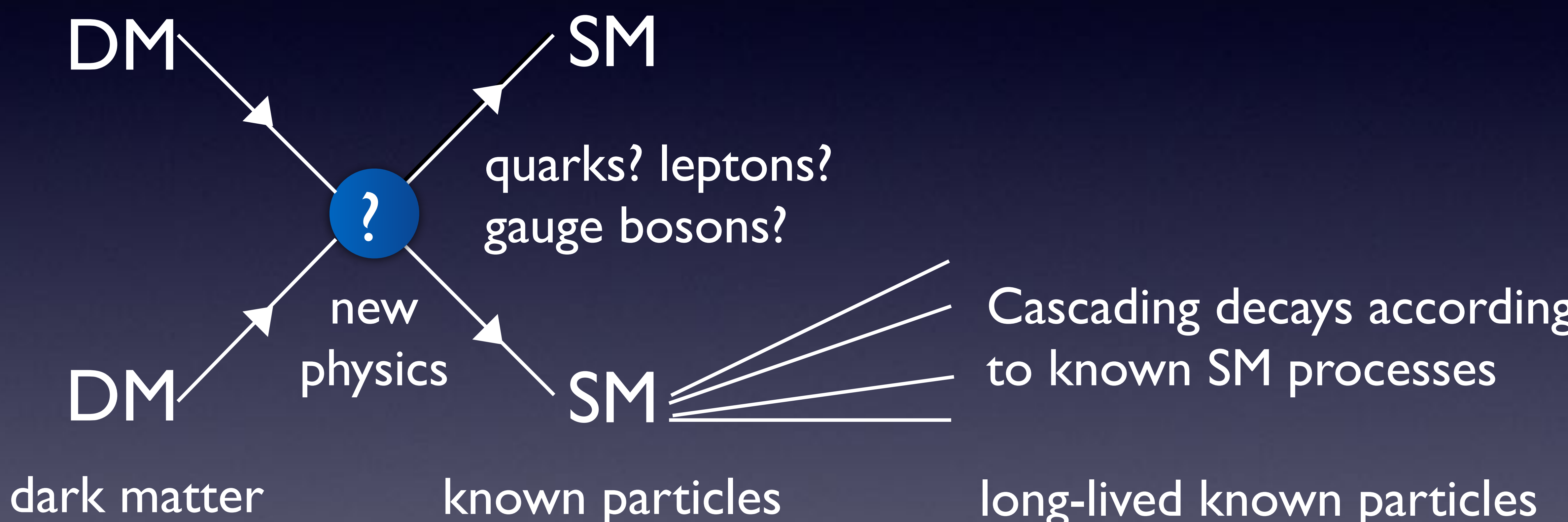


affects CMB affects 21cm

Annihilation

tested by
present-day
indirect
searches

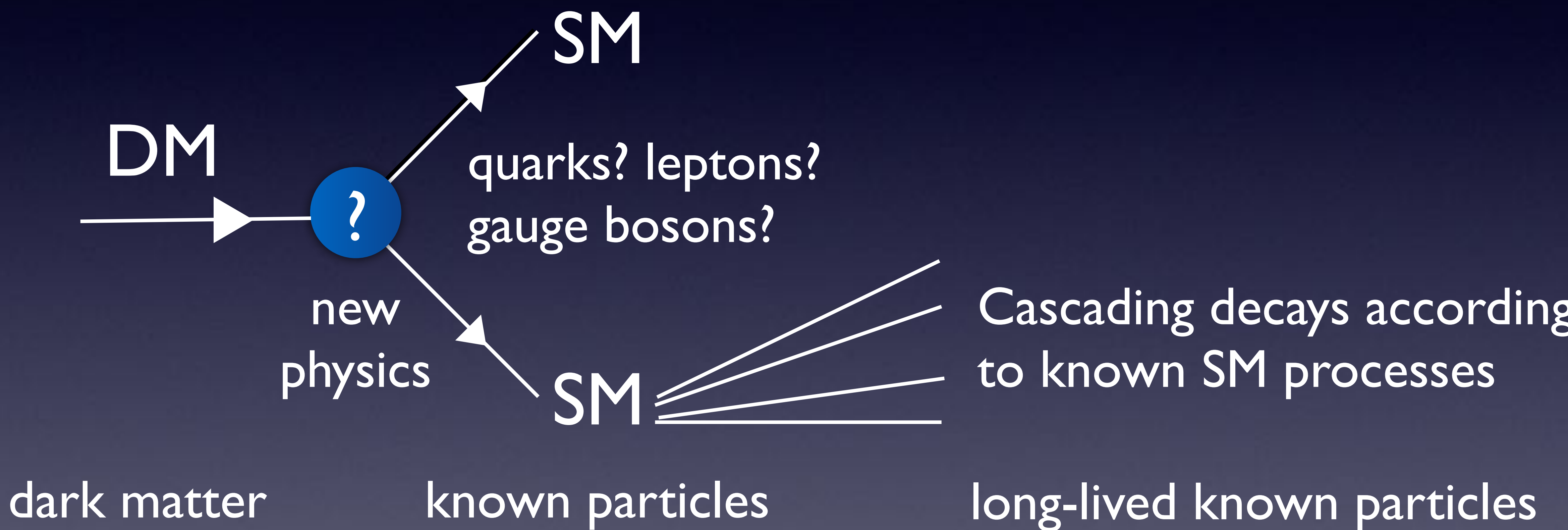


– "Thermal relic" benchmark - annihilation at this level would deplete early-universe abundance of DM to observed value:

$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{s} \sim \pi \alpha^2 / (100\,\mathrm{GeV})^2$$

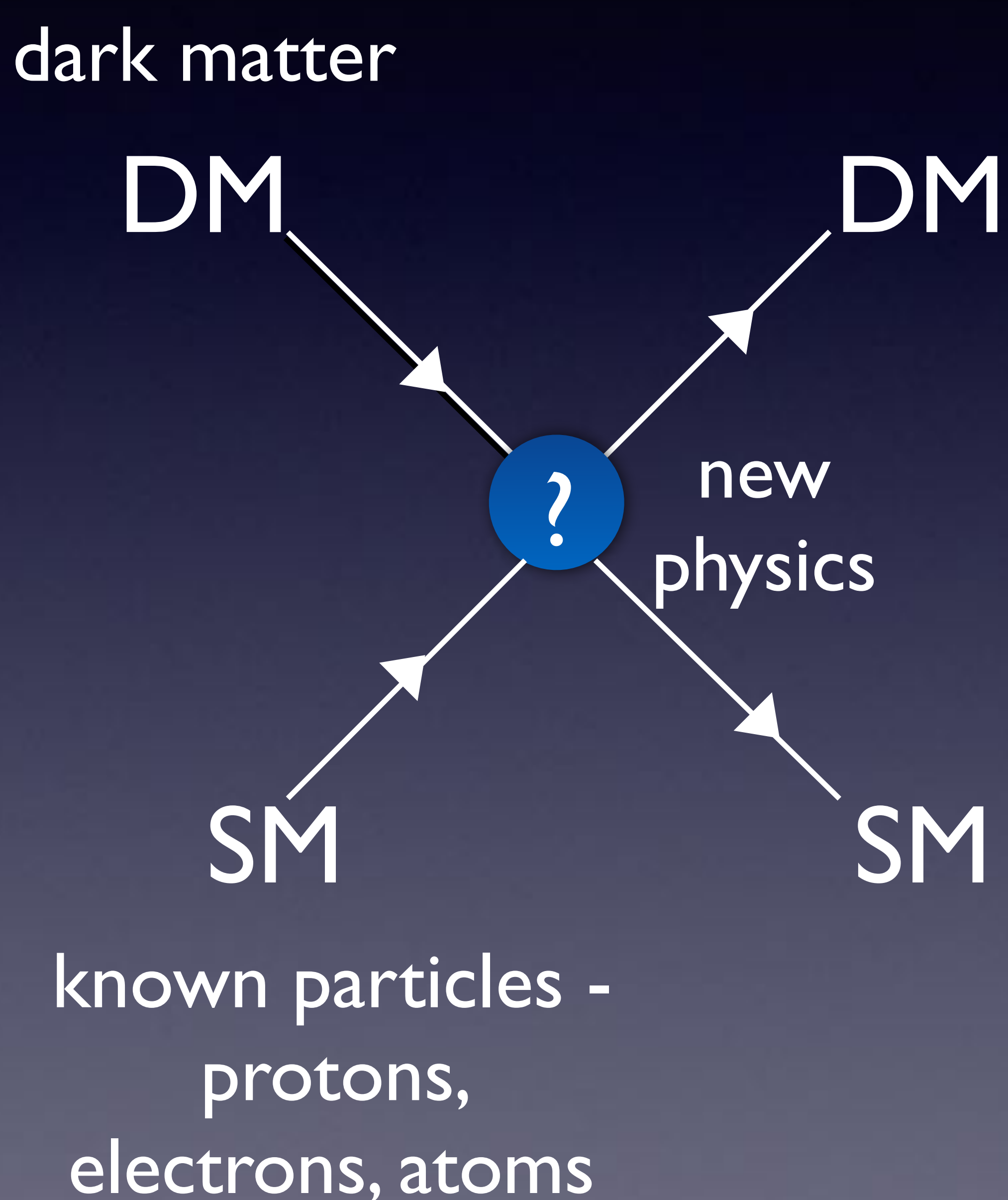
Decay

tested by
present-day
indirect
searches



Scattering

tested in direct-detection experiments



Look for effects of energy transfer to/from DM on visible matter

Related talks @IDM18

	Monday	Tuesday	Thursday	Friday
Exotic energy injection (e.g. from decay or annihilation)	Poulin (plenary) Liu Ridgway			
DM-baryon scattering	McDermott	Pfeffer Boddy	Burns (plenary) Fialkov (plenary) Ewall-Wice (plenary) Wu	Bermejo (plenary) Ali-Haimoud (plenary)
Gravitational effects		Poulin Karwal		

Cyan = primarily CMB observations
Yellow = primarily 21cm observations

Case study: from annihilation to ionization

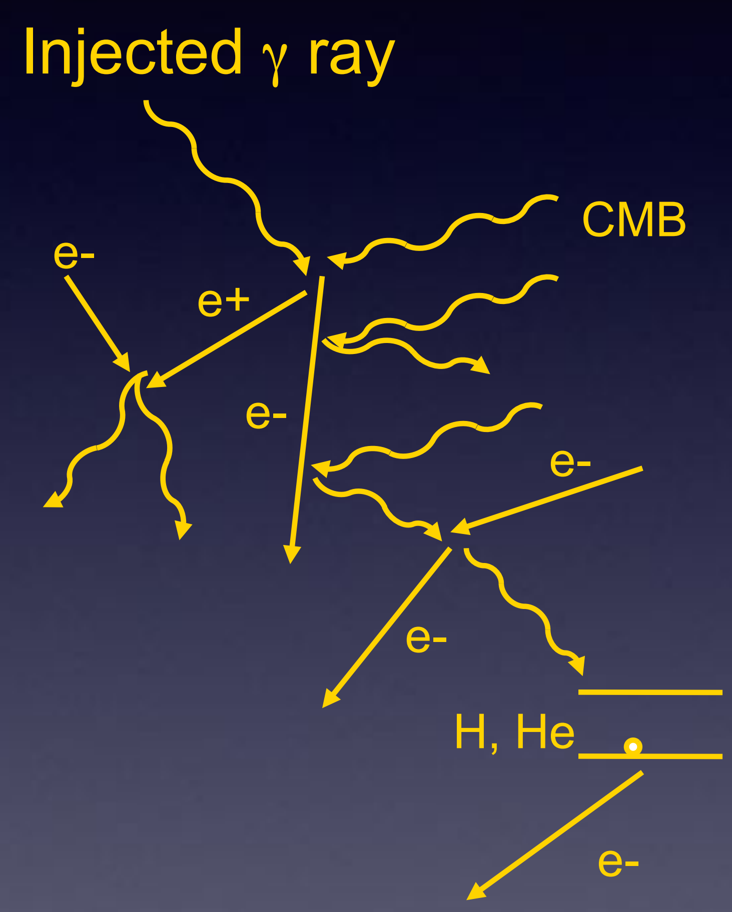
- Consider the power from DM annihilation - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates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

The photon-electron cascade

TRS, Padmanabhan & Finkbeiner 2009; TRS 2016

ELECTRONS

- Inverse Compton scattering 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

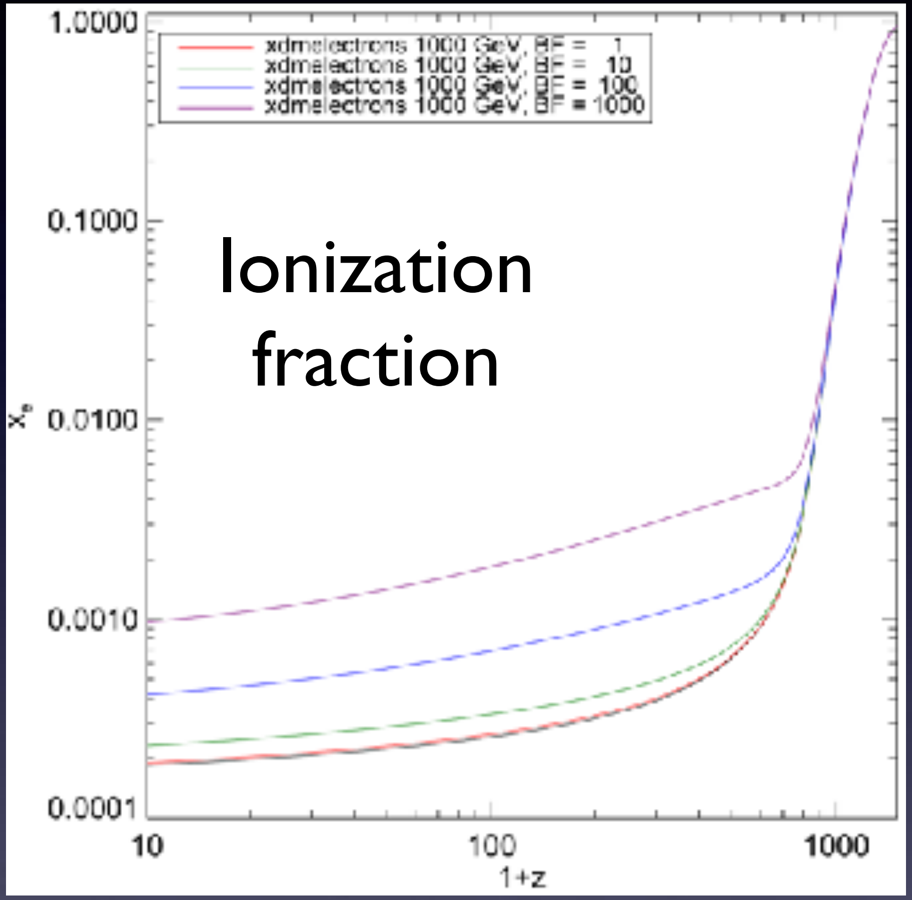
PHOTONS

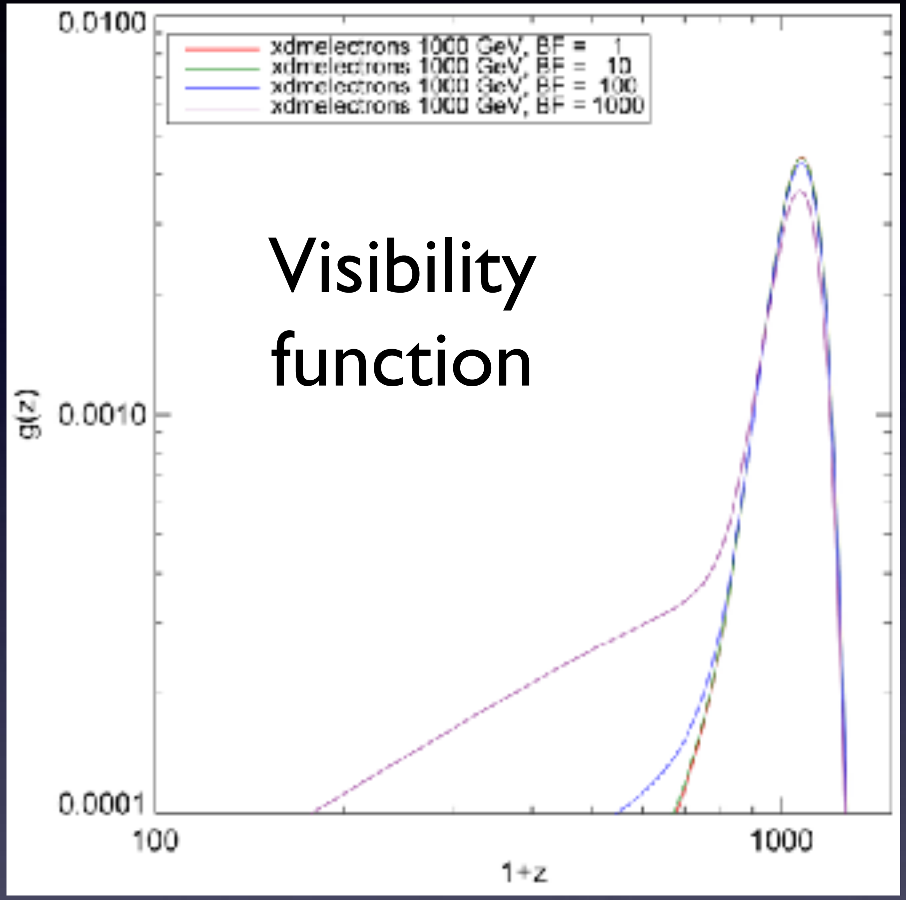
- Pair production on the CMB.
- Photon-photon scattering.
- Pair production on the H/He gas.
- Compton scattering.
- Photoionization.
- Redshifting is important, energy can be deposited long after it was injected.

Building transfer functions

- For all observables - heating, ionization, modifications to late-time photon spectra - need to understand how injected particles cool down and deposit their energy.
- Transfer function tables produced in TRS '16 are publicly available (https://faun.rc.fas.harvard.edu/epsilon/) - map out heating/ionization/excitation/free-streaming photons produced as a function of redshift, by injections of keV-TeV electrons, positrons, photons at arbitrary redshift.
- Limitations: assumes a fixed baseline ionization history + uniform cosmological density
  - becomes a problem for modeling end of dark ages, where reionization is not well understood/constrained.
  - also cannot include backreaction, which can be important at late times.

Example ionization history

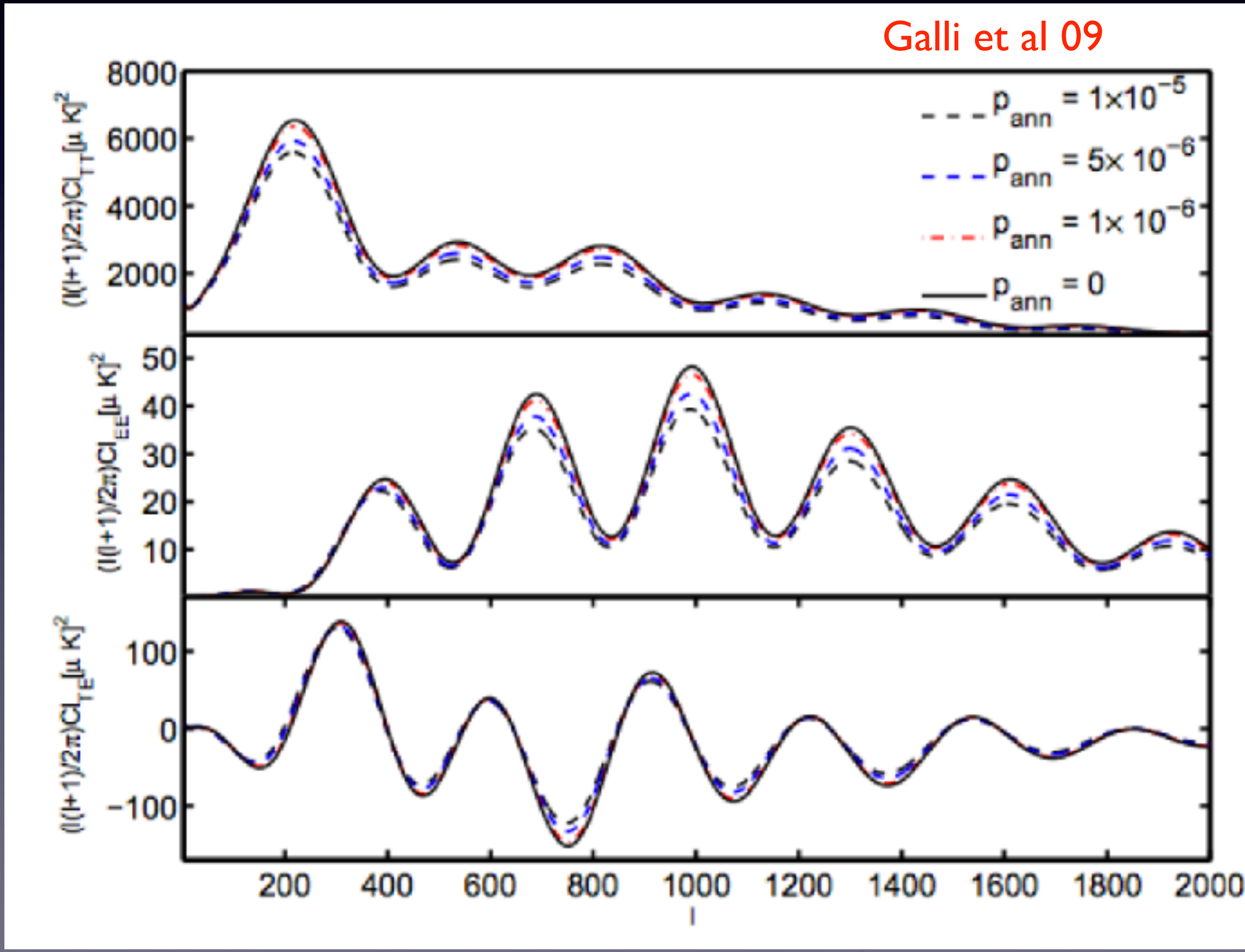




- Use public codes RECFAST (Seager, Sasselov & Scott 1999) / CosmoRec (Chluba & Thomas 2010) / HyRec (Ali-Haimoud & Hirata 2010) to solve for ionization history given extra ionization+heating+excitation. Interface with CLASS now available as ExoCLASS (Stocker et al '18).
- At redshifts before recombination, 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.

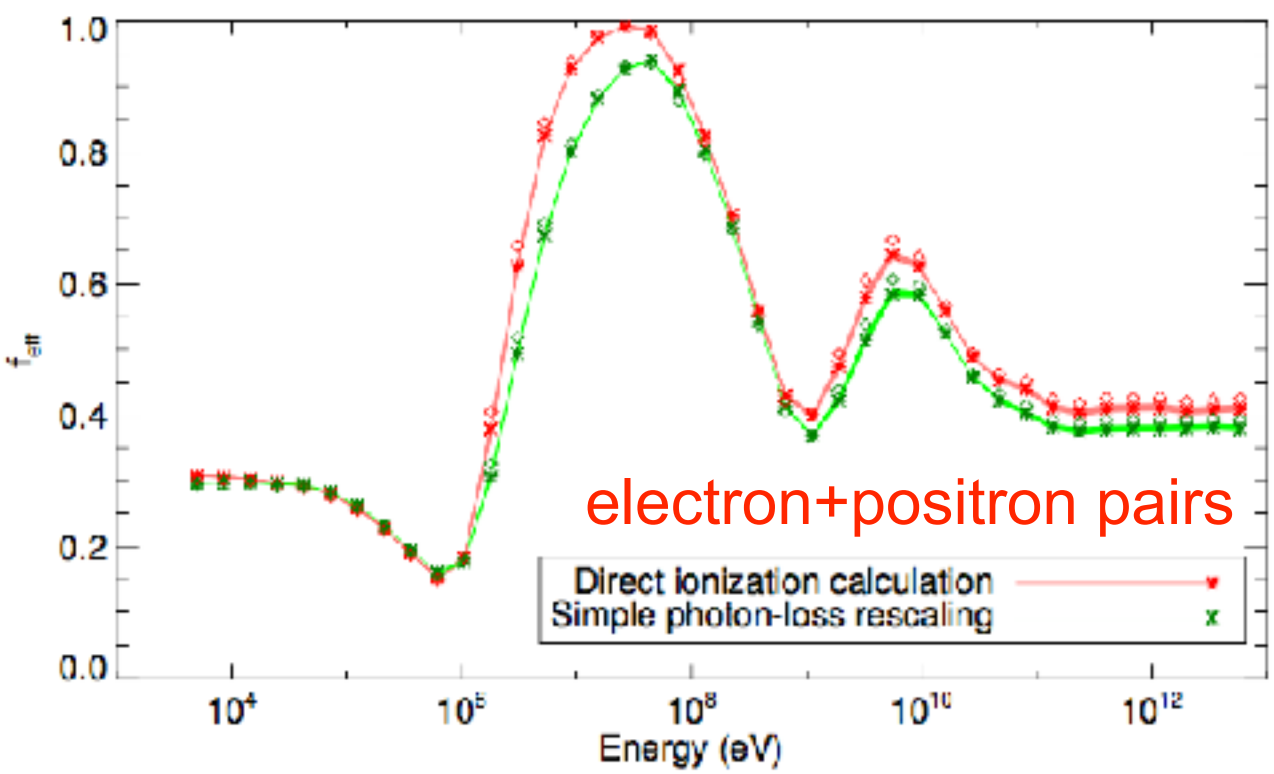
DM annihilation and the CMB

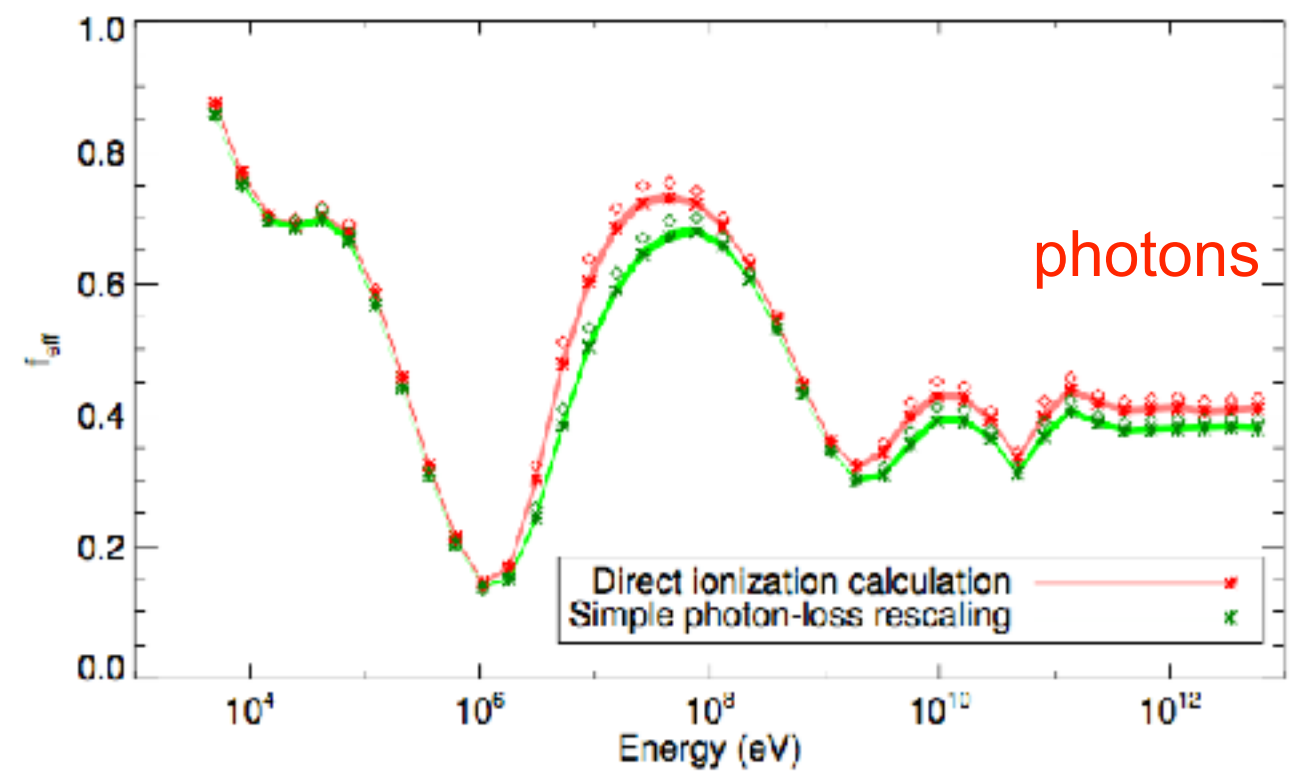
- Use public codes (CLASS, CAMB) to calculate effect on CMB anisotropies.
- In the case of DM annihilation, can test the effects of a range of different DM masses (keV-TeV) and all possible Standard Model final states.
- We find the <u>shape</u> of the imprint on the CMB is ~universal (first principal component >99% of variance).
- For each model, only need to calculate normalization factor.



Efficiency factors (annihilation)

TRS 2016

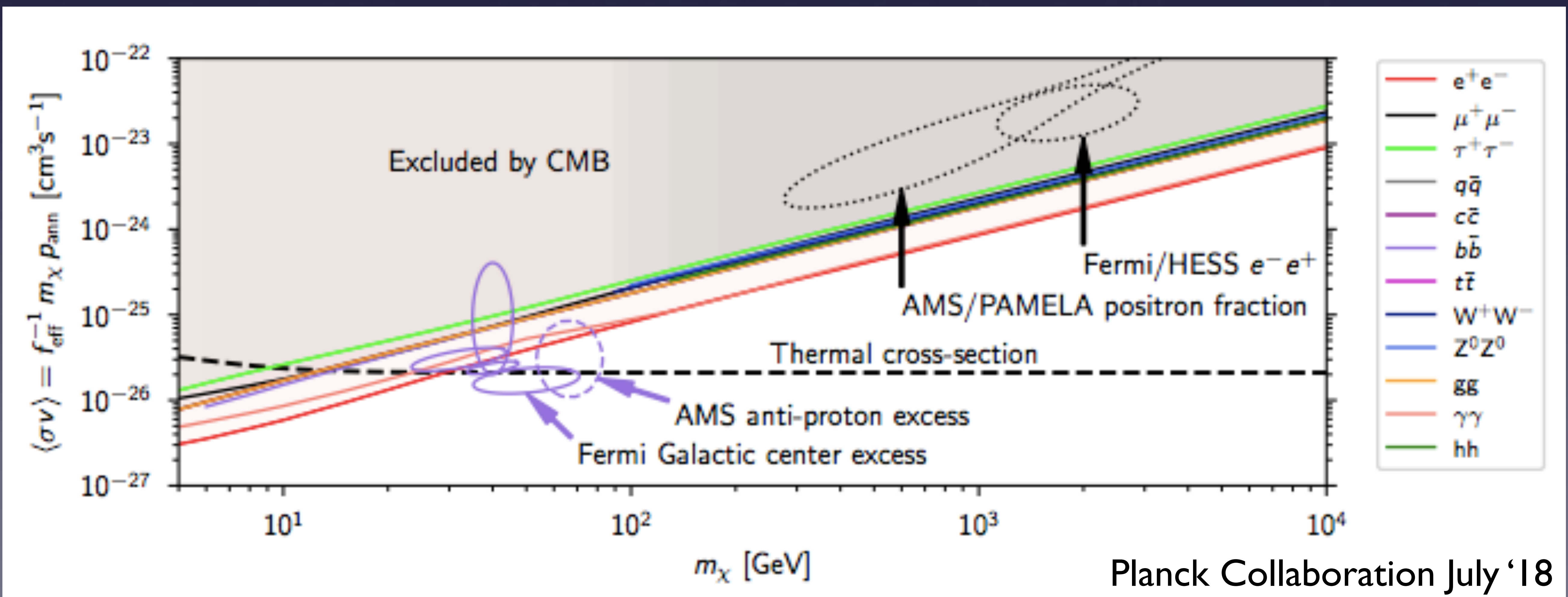




- We can compute this normalization/efficiency factor for electrons, positrons, photons at all injection energies.
- Integrate over this curve to determine strength of CMB signal for arbitrary spectra of annihilation products.
- These curves are also available online, https://faun.rc.fas.harvard.edu/epsilon/
- Signal dominated by annihilation around z~600, independent of late-time structure formation.

Annihilation limits from Planck

- Latest results from Planck Collaboration '18 (1807.06209) improve previous bounds on DM annihilation by ~20%.
- Thermal benchmark excluded below ~10 GeV DM mass (for visible final states).
- Limits continue to improve down to ~keV masses - often the strongest bounds on light annihilating DM.



Planck Collaboration July '18

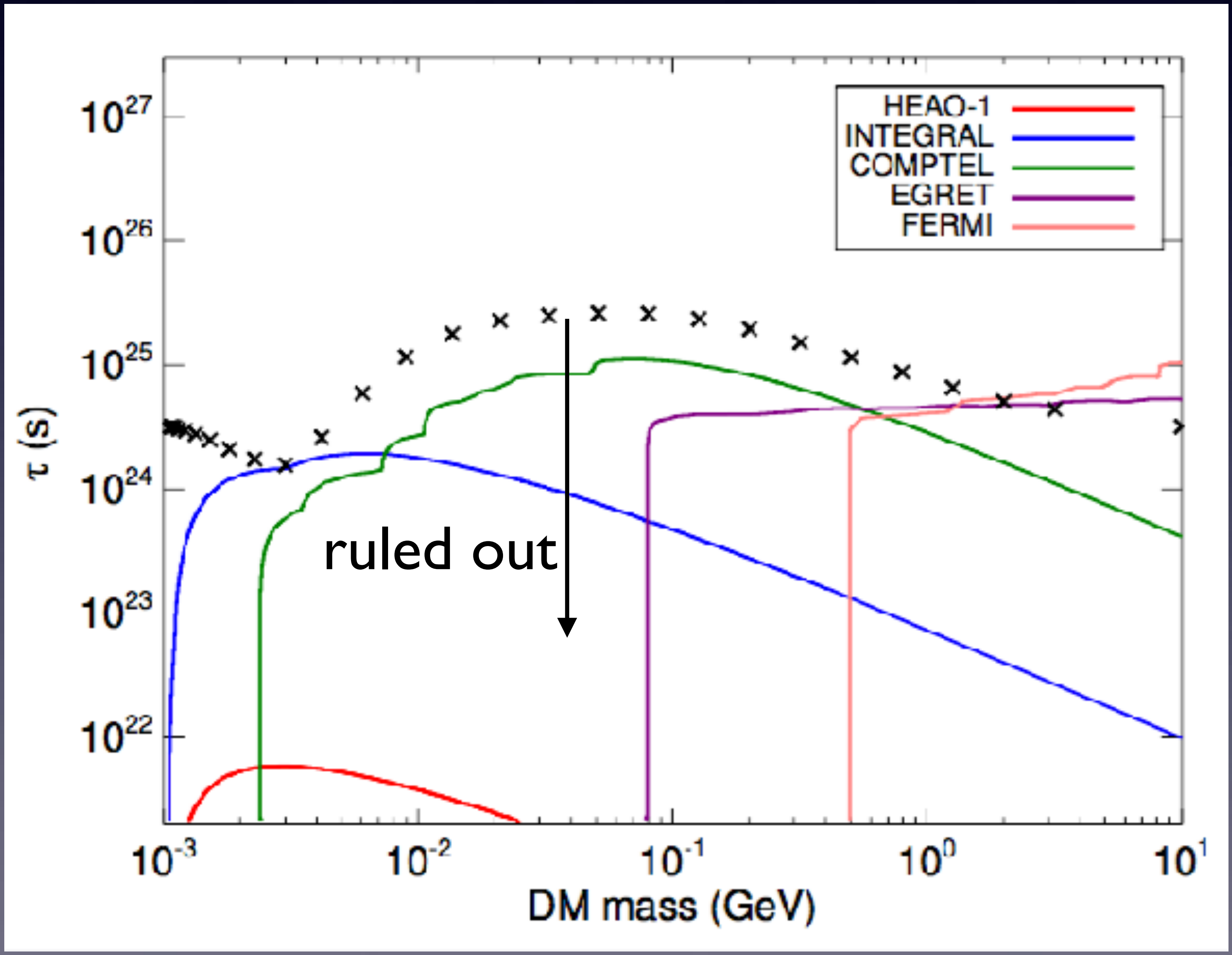
Constraints on decay from Planck

– For decaying dark matter, can use same approach (see plenary talk by Poulin for more details).

– 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 and Wu, PRD95, 023010 (2017)

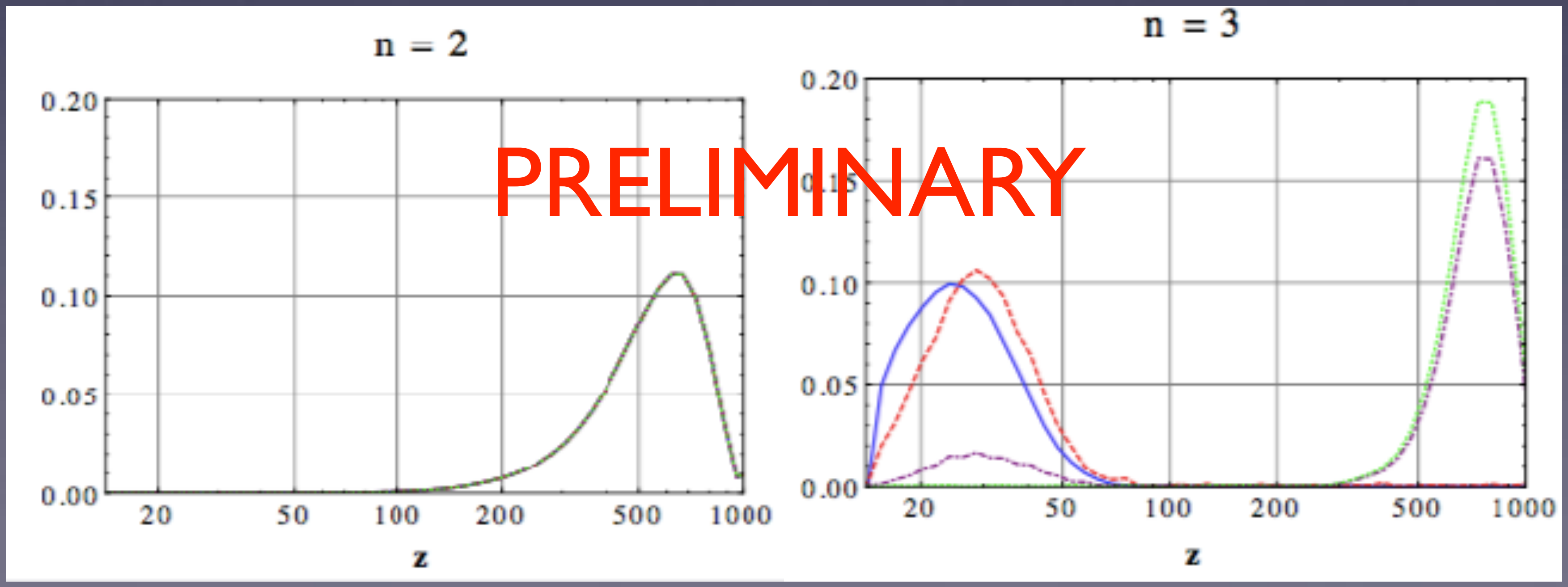


Other constraints from Essig et al '13

More general energy injections

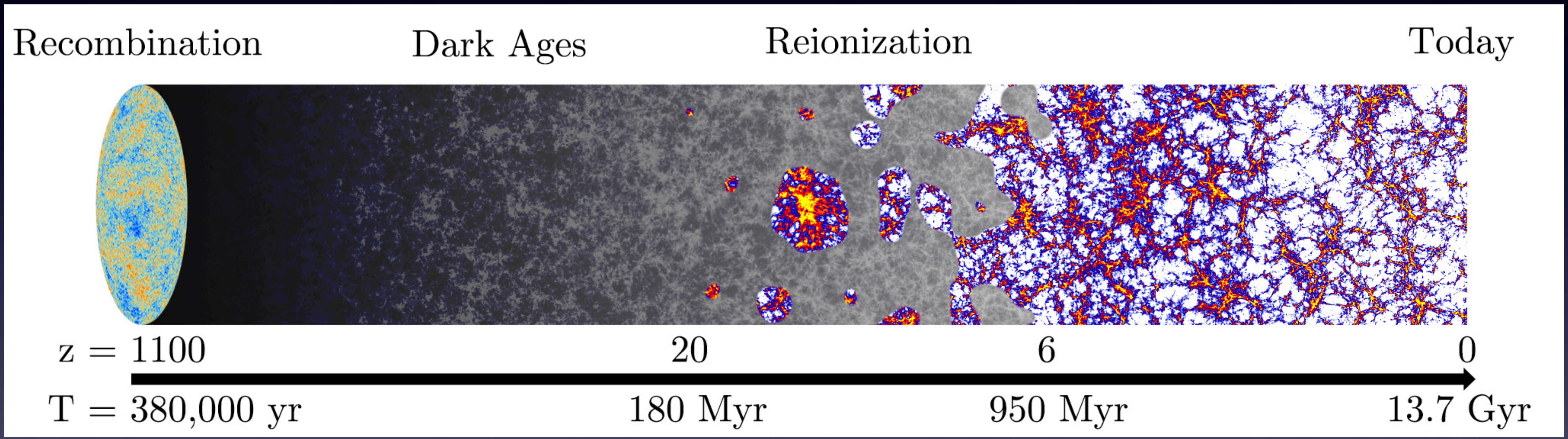
work in progress with M. Namjoo & C.-L. Wu

- Similar limits apply to essentially any injection of ionizing energy during the cosmic dark ages - same transfer functions can be used to compute ionization/heating/CMB signals.
- As one example, we can consider processes with a higher scaling with the local density - e.g. 3- and 4-body DM annihilation, which can dominate freezeout in some models, and could be strongly enhanced at low velocities.
- In this case we can again set robust limits from annihilation at high redshifts, but (in contrast to 2-body annihilation) the signal can be easily dominated by low redshifts where structure formation is important.
- Example: dominance of different redshifts in the CMB signal for 2- and 3-body annihilation, for different structure formation models.



The epoch of reionization

Liu, TRS & Zavala 2016, PRD 94, 063507



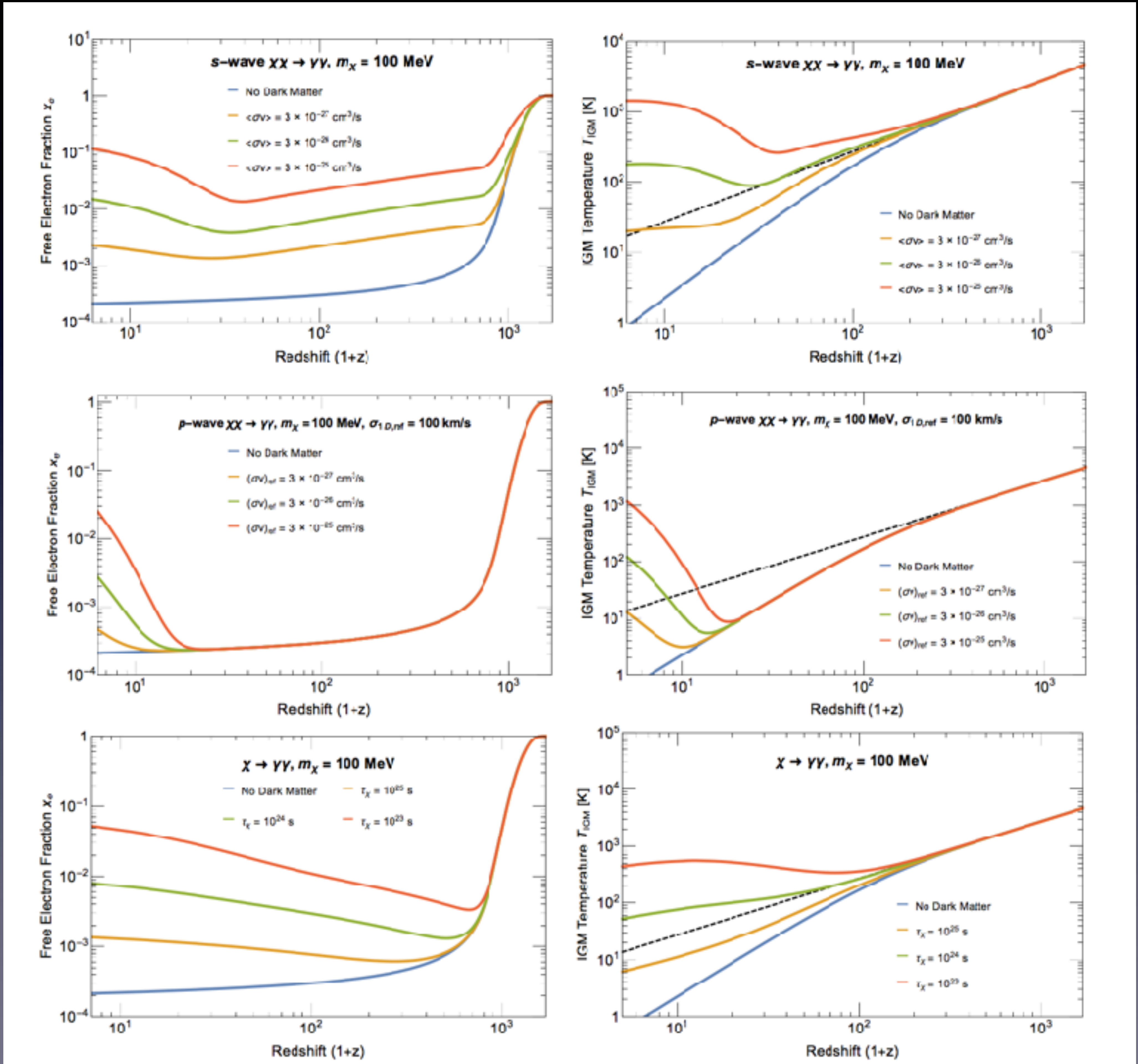
- Around z~6-10, the universe became ~fully ionized again.
- Can DM annihilation or decay affect <u>re</u>ionization?
- Can it affect the thermal history of our cosmos? Could DM annihilation/decay overheat the universe?

ionization temperature

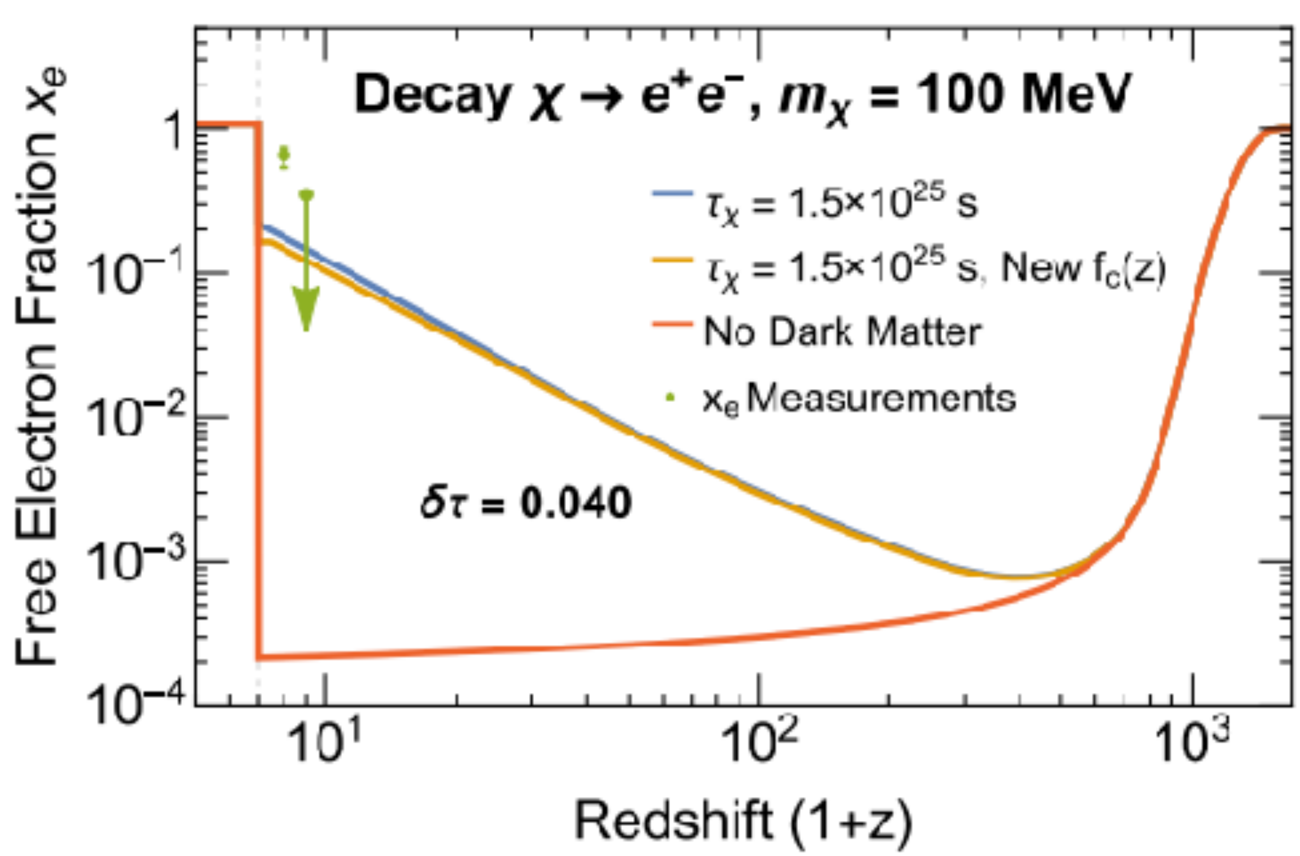
s-wave annihilation

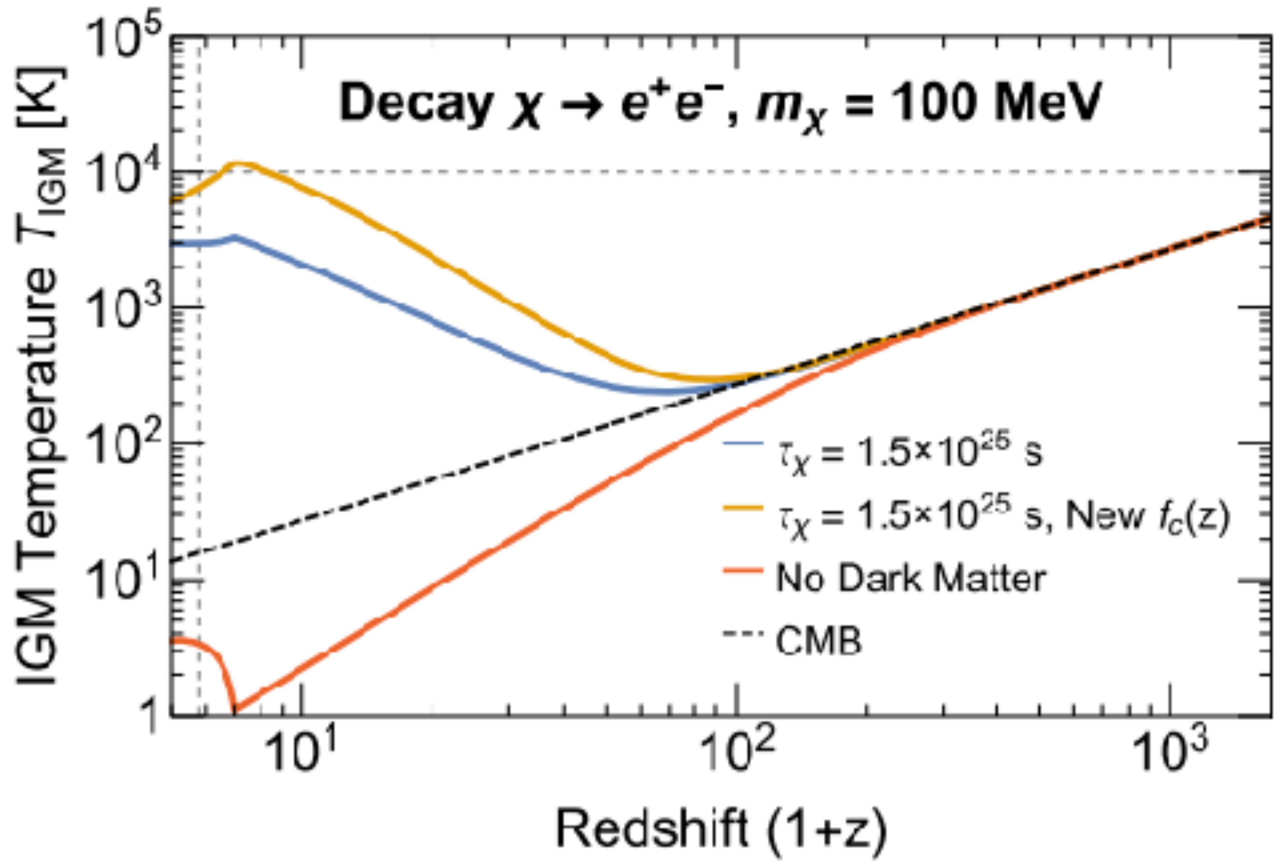
p-wave annihilation (v^2 scaling of injection)

decay



An (optimistic) example scenario



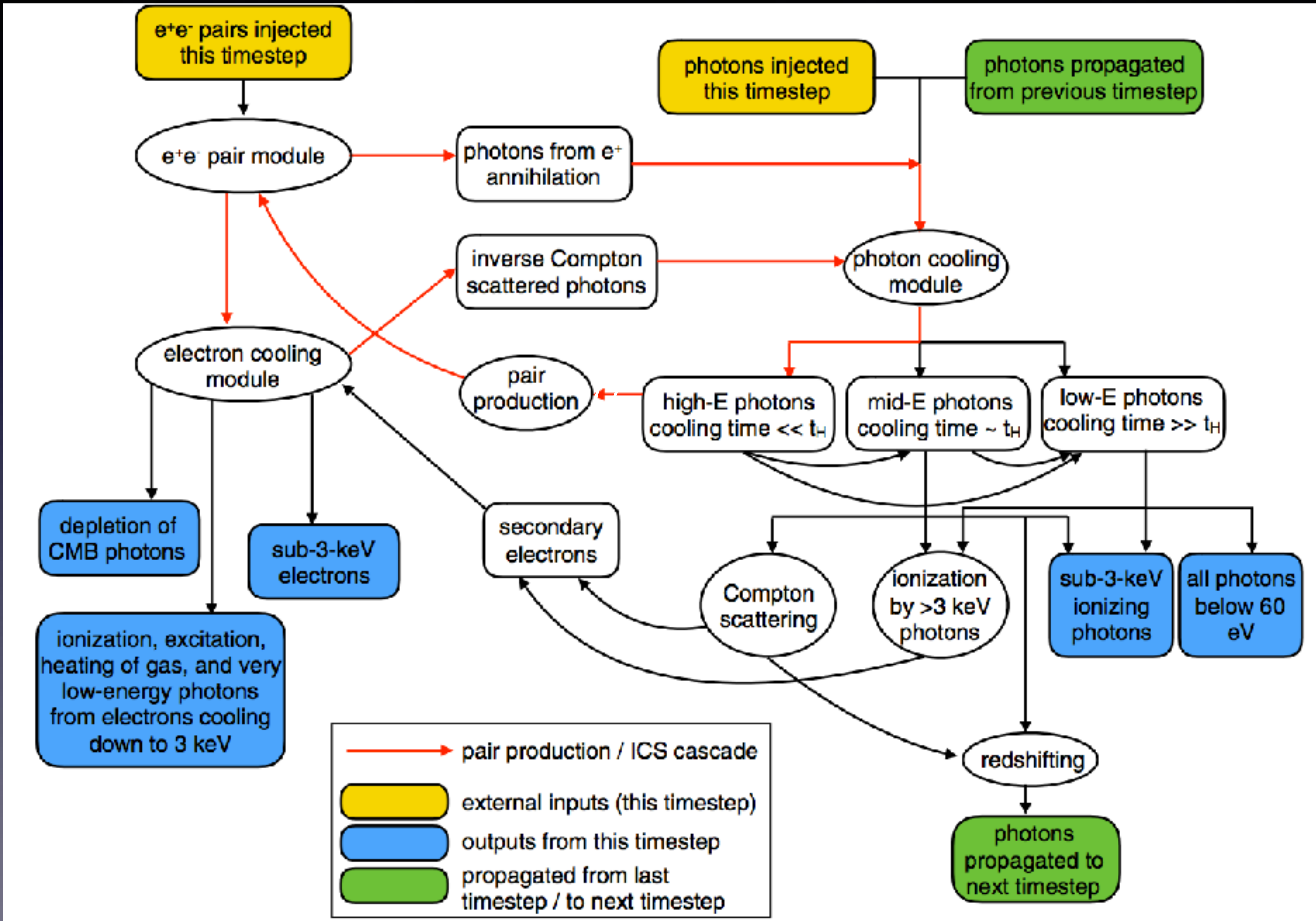


- Ex: 100 MeV DM decaying to e^+e^- pairs
- Marginally consistent with constraints from CMB at higher redshift (albeit likely now in conflict with Voyager observations, Boudaud et al '16).
- Could be ruled out conclusively by stronger bounds on late-time temperature - which can be obtained through 21cm observations (see Liu, Ridgway talks later today!)

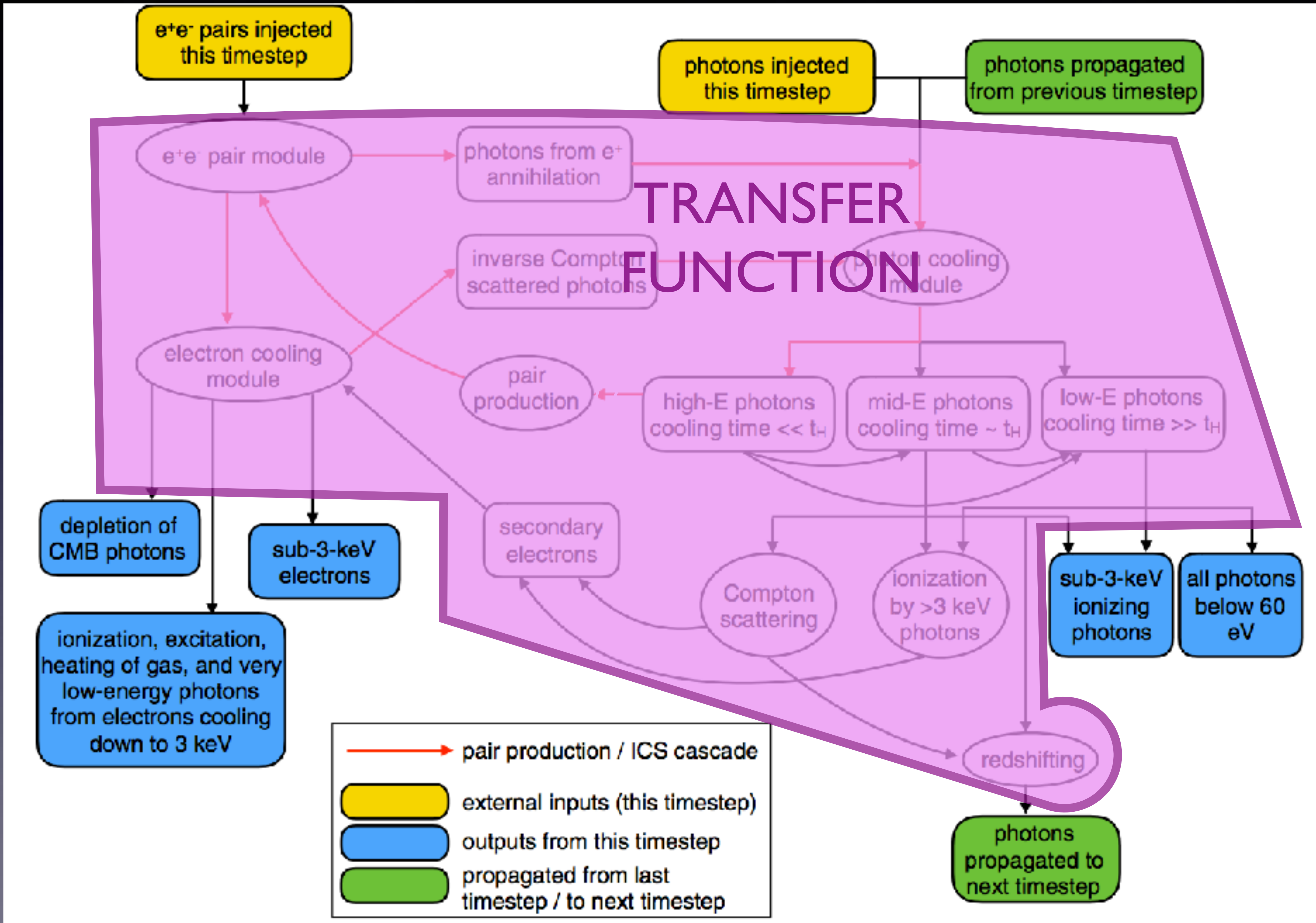
Ongoing work

- Many other questions we can address using a similar toolbox.
- Work in progress:
  - adapt modeling of secondary-particle cascade to self-consistently include changes to ionization history, allow testing of many ionization scenarios rapidly - hope to use as input for codes modeling the reionization epoch, and 21cm signals.
  - improve treatment of low-energy particles to get precise predictions for distortion of CMB blackbody spectrum, + constraints for light (sub-keV) dark matter.
- Goal: comprehensive understanding of the possible effects of DM annihilation/decay/scattering in the early universe.

Modeling energy loss



Modeling energy loss



DarkHistory

work in progress with H. Liu, G. Ridgway, C. Vogel & S. Chen

- Recast code to store <u>transfer function</u> for arbitrary input spectra at <u>every</u> redshift separately - as well as ionization/heating/etc, outputs now also include photons to be passed forward to next timestep.
- Previous code effectively calculated and integrated over transfer functions at each timestep, & recalculated them anew for each injection model - highly redundant.
- Store results for a range of different ionization levels (or e.g. gas density levels) at each redshift.
- Given a desired ionization history, code can simply interpolate to get appropriate transfer functions for each timestep - string together these transfer functions to get complete result.
- Backreaction is easy to include, via an interface to any code solving for the modified ionization history; at each timestep, read in ionization level from previous timestep and choose transfer functions accordingly.
- Code will be public, written in Python, and include detailed example notebooks.

Summary

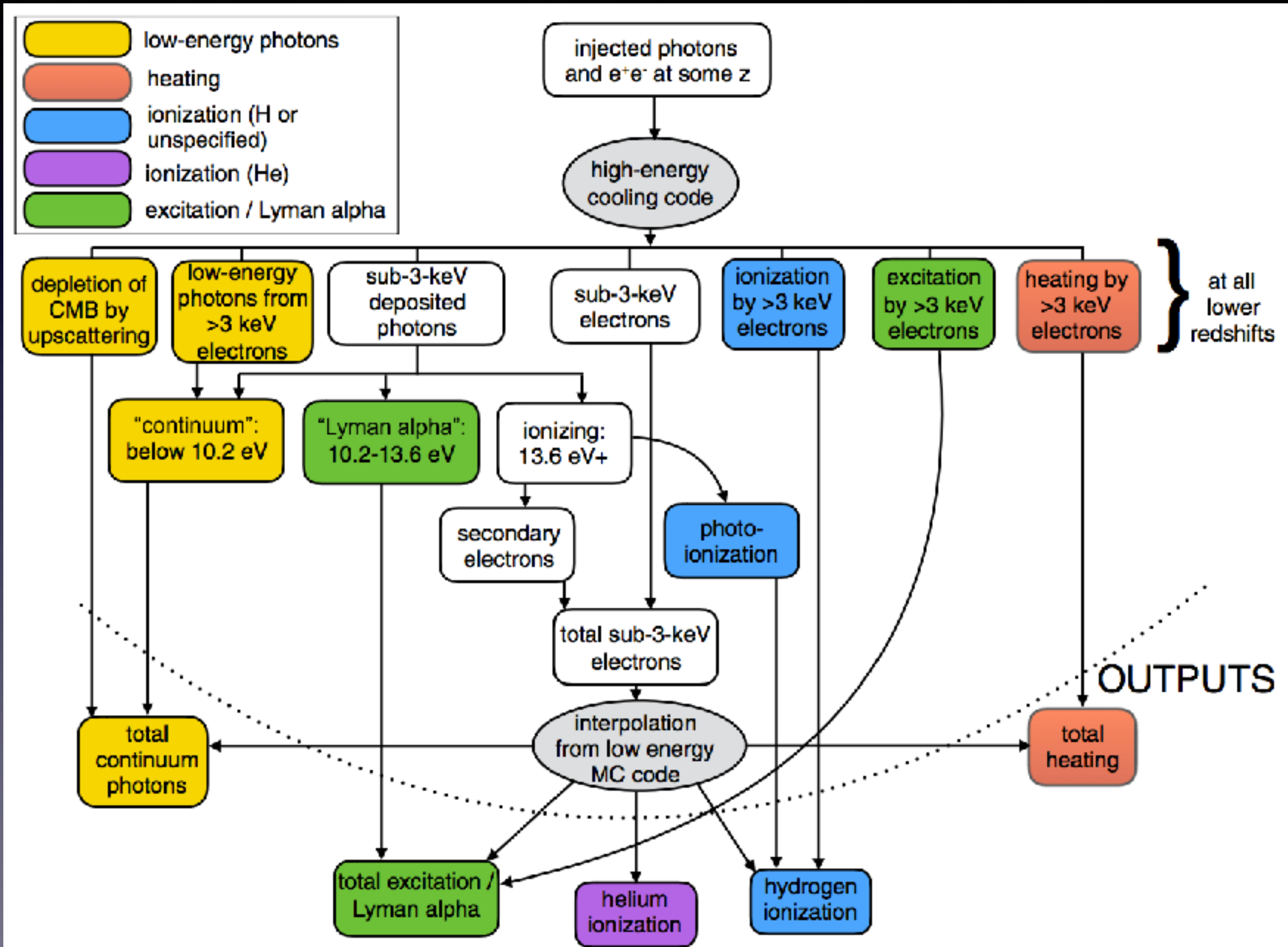
- Measurements of the ionization and temperature history of the early universe, in particular via CMB and 21cm observations, can set stringent and robust constraints on the properties of dark matter and its interactions with visible matter - many talks to come at IDM2018!

- Recent Planck 2018 papers have strengthened previous limit on DM annihilation by ~20%; excludes thermal cross-section into visible channels for DM below 10 GeV, and sets stringent limits on lighter DM.

- Active work in progress to build better tools for predicting the impact of DM annihilation and decay on the late dark ages, the 21cm line, and the blackbody spectrum of the CMB.

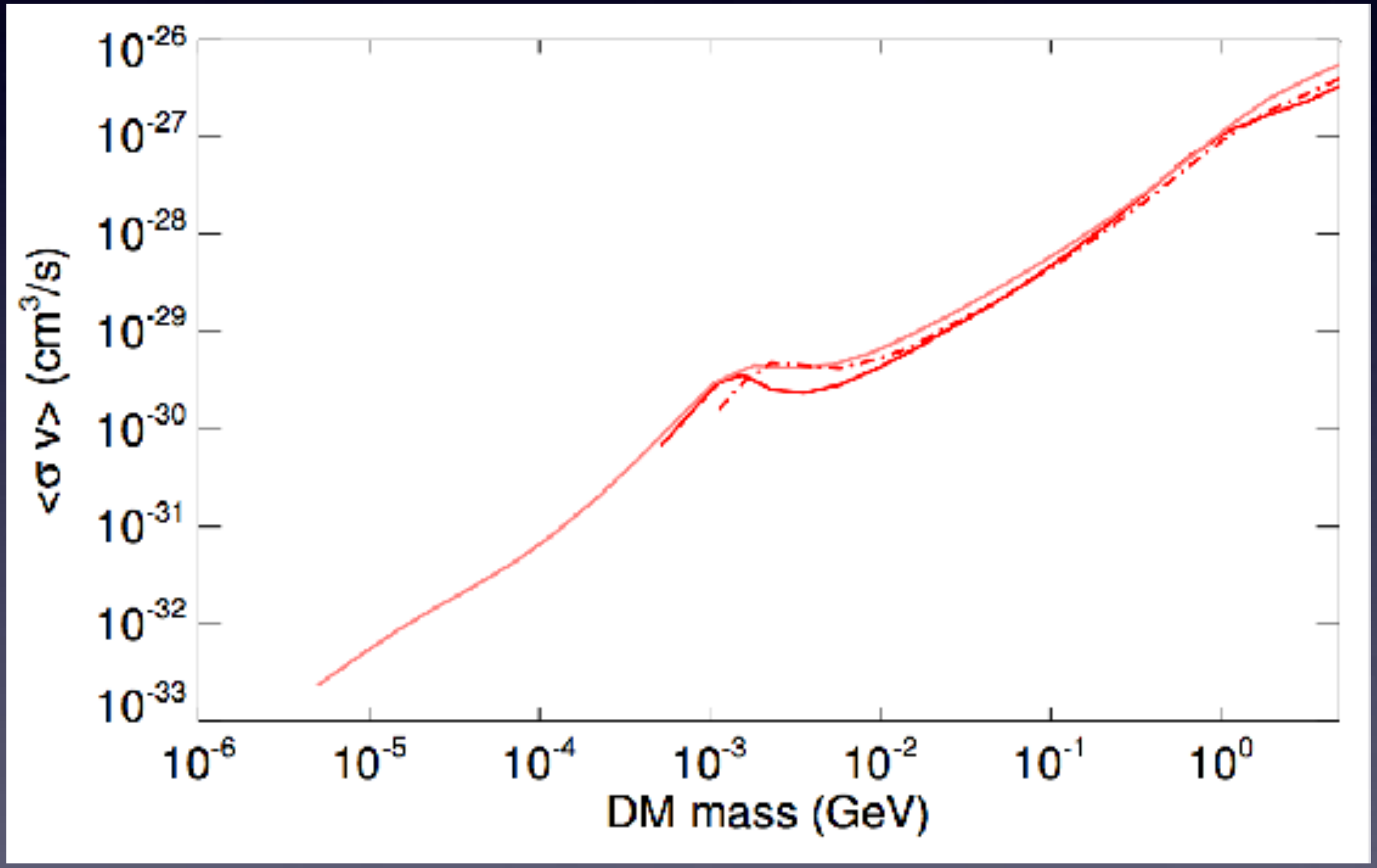
BONUS SLIDES

Modeling energy loss (low)



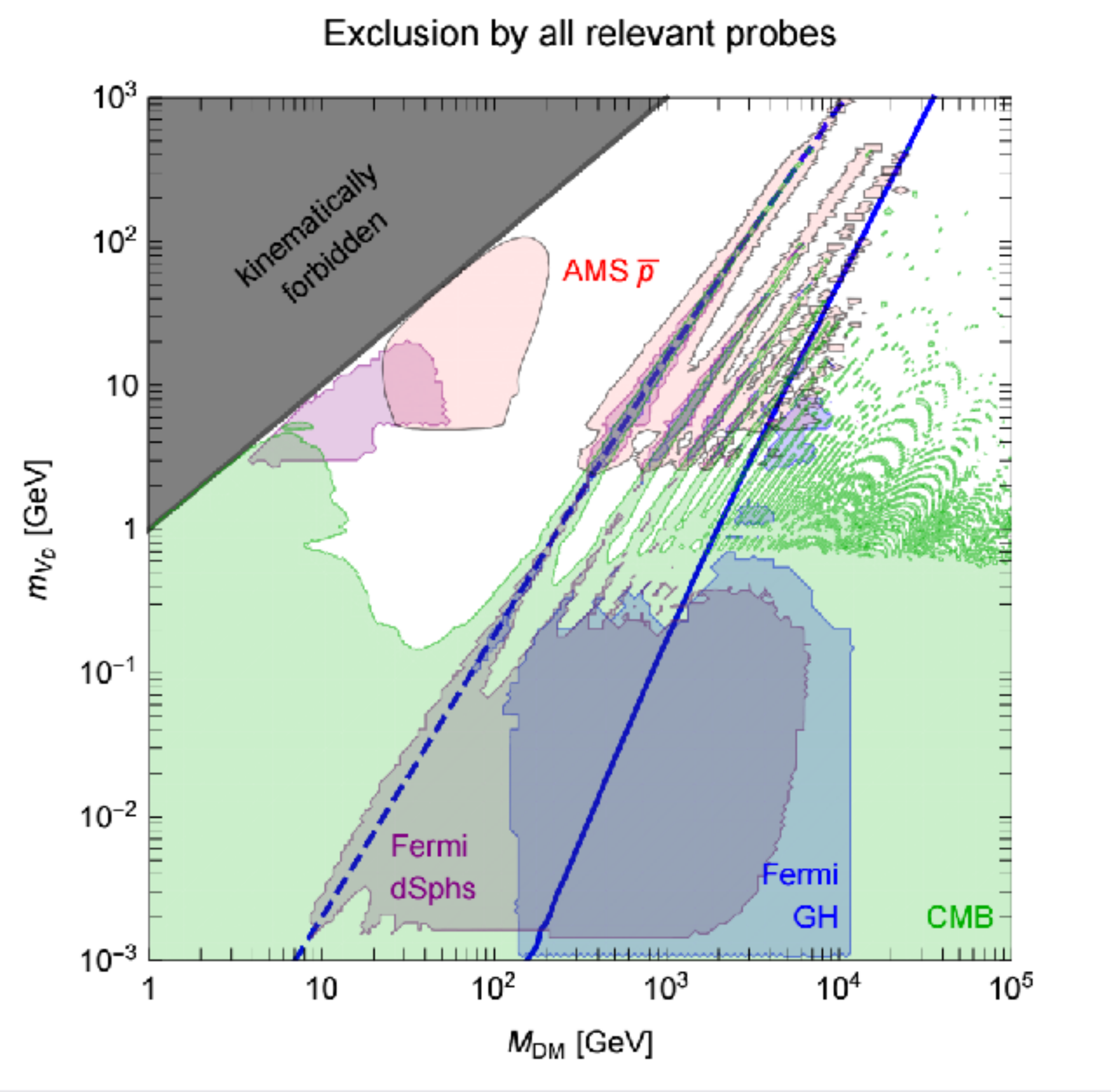
Limits on light dark matter

- These are often the strongest existing bounds on light (sub-GeV) dark matter.
- Often other constraints are limited by lack of observations or large backgrounds at relevant energies.
- Such models are also less constrained by direct detection - have garnered much recent interest.



CMB constraints on dark photons

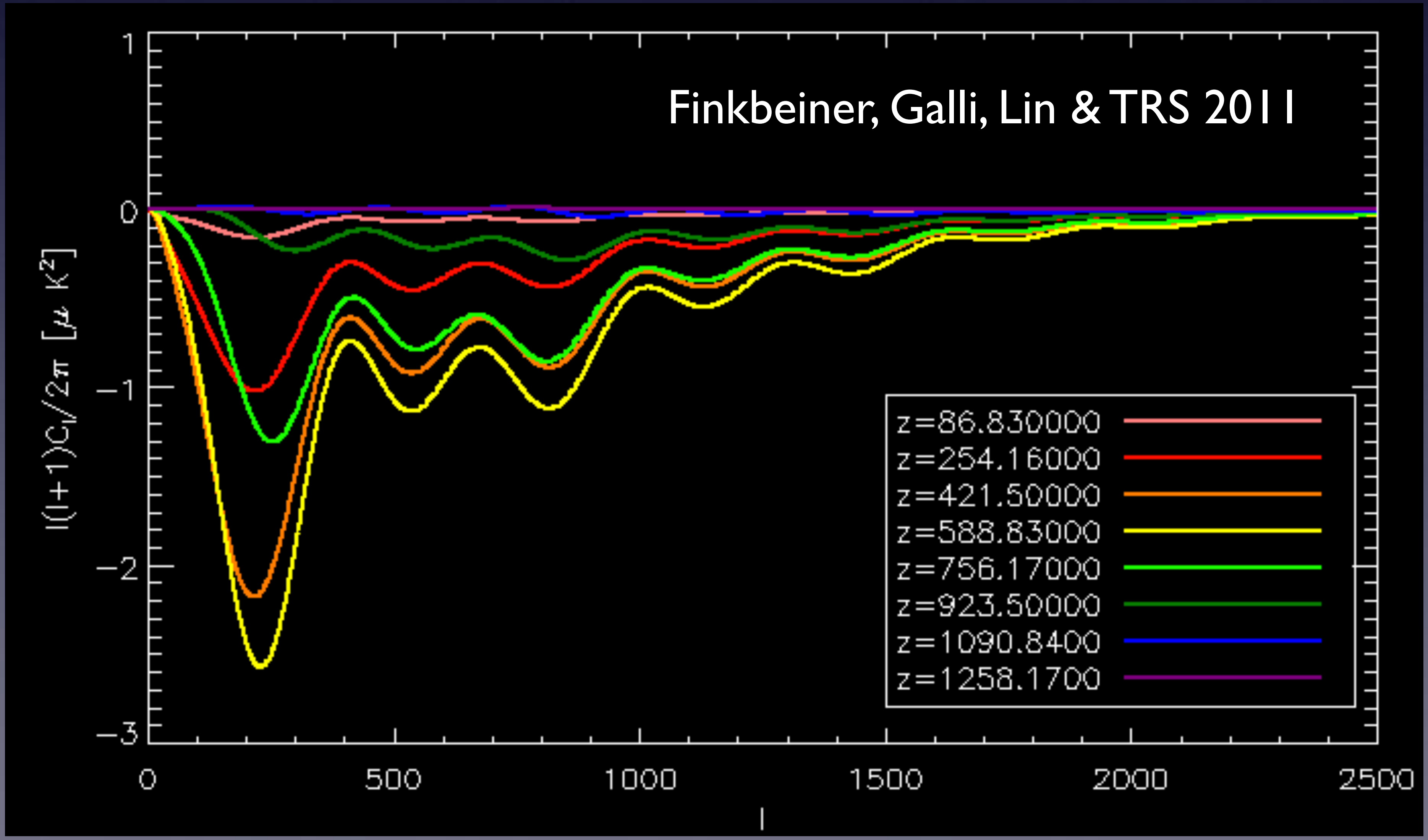
Cirelli et al 1612.07295



- Model of dark matter coupled to new “dark photons”, mediating dark matter self-interaction.
- Green region ruled out by CMB, assuming DM is a thermal relic and main annihilation channel is to dark photons (sets DM-dark photon coupling).

Energy injection & the CMB

- Extra ionization from DM annihilation would suppress & distort temperature and polarization anisotropies in the CMB. Different DM models lead to different amount of ionizing energy, + slightly different redshift dependence (due to cooling times of annihilation products).
- We can numerically calculate the CMB imprint of a generic source of extra ionization at early times (model-independent), then combine with calculation of ionization from a given DM model.



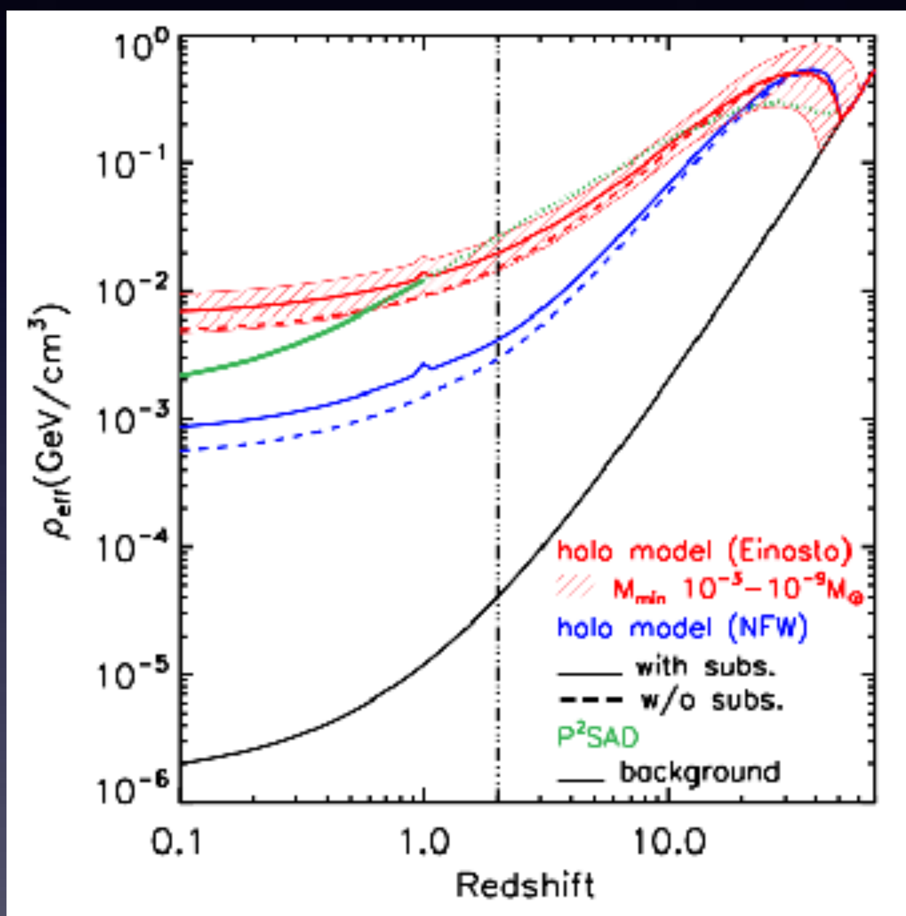
- Note: ionization at different redshifts has similar (albeit not identical) effects - can be described by low-dimensional parameter space.
- Codify with principal component analysis.

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.

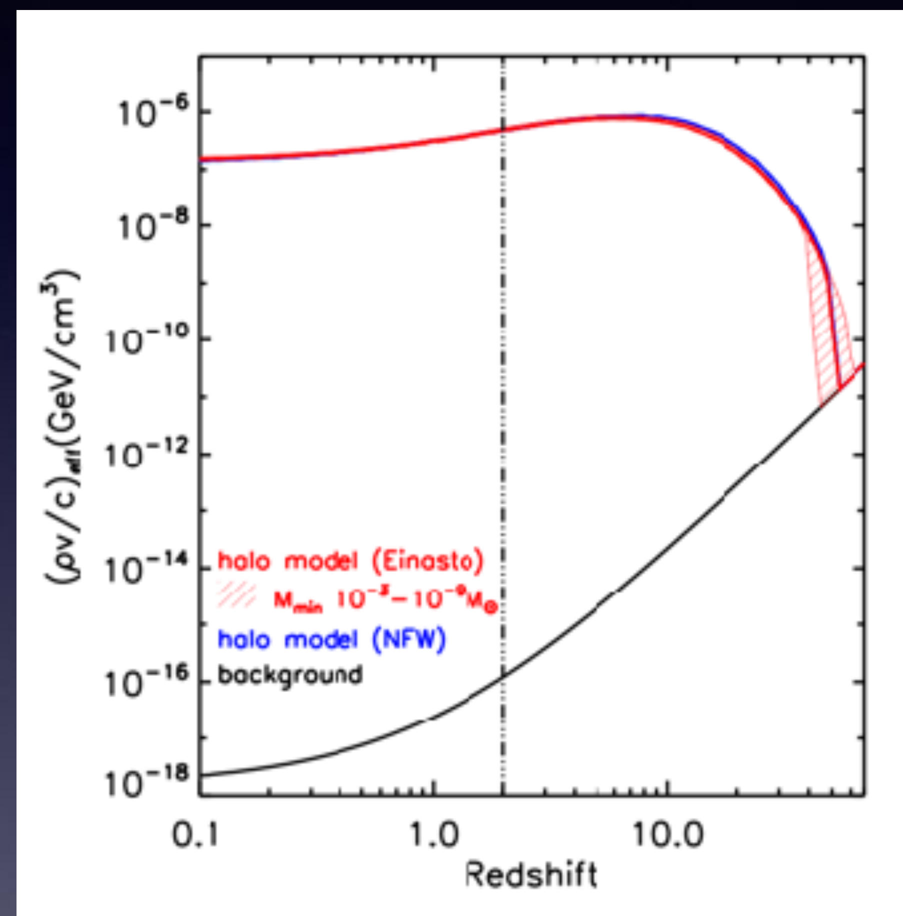
s-wave annihilation

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



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

- 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?

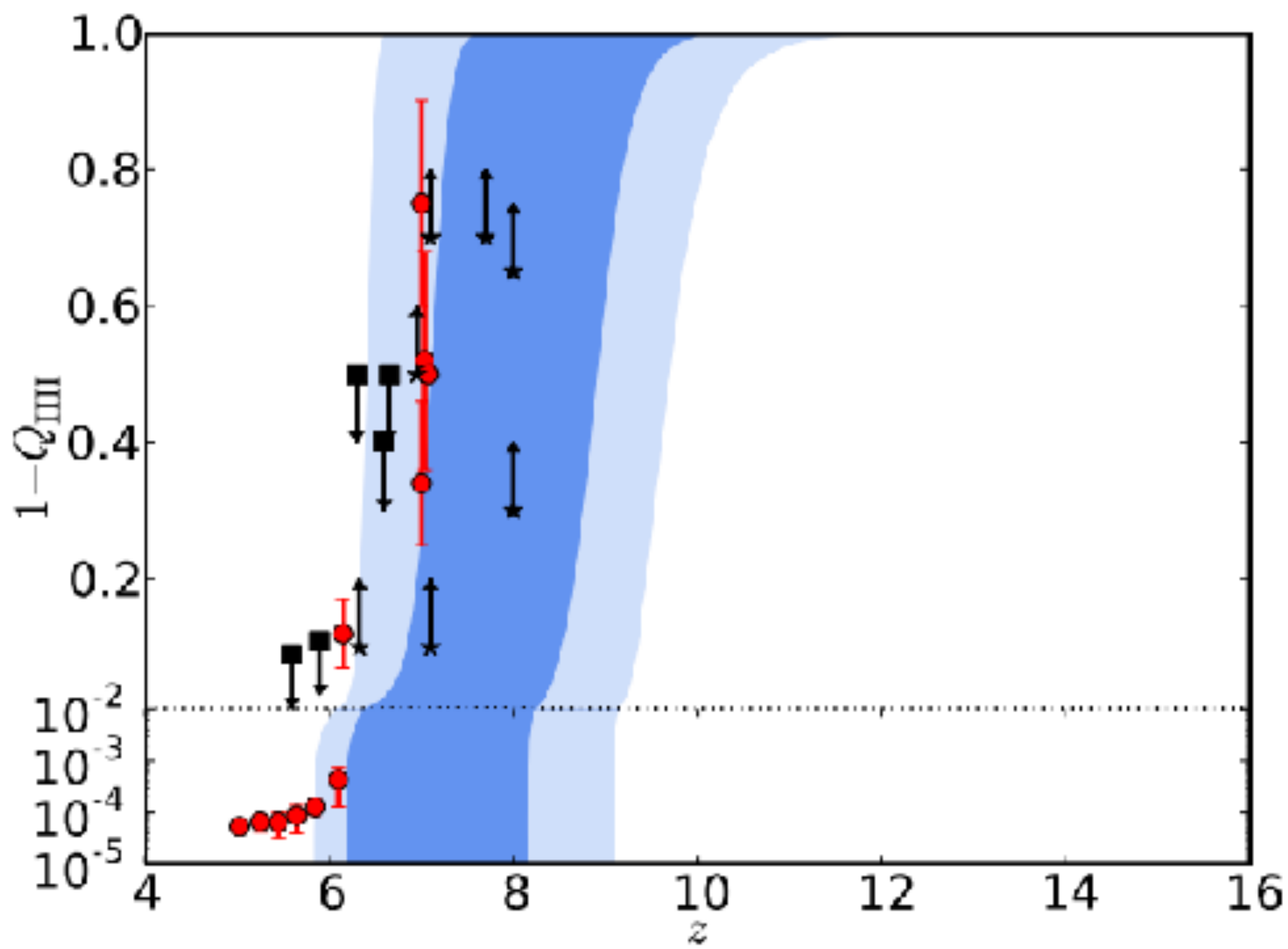


Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints compiled by Bouwens et al. (2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the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

CMB constraints on short-lifetime decays

- Long-lived particles could decay completely during cosmic dark ages
- Alternatively, decays from a metastable state to the final DM state could liberate some fraction of the DM mass energy
- CMB constrains the amount of power converted to SM particles in this way; width of band reflects variation with energy of SM products

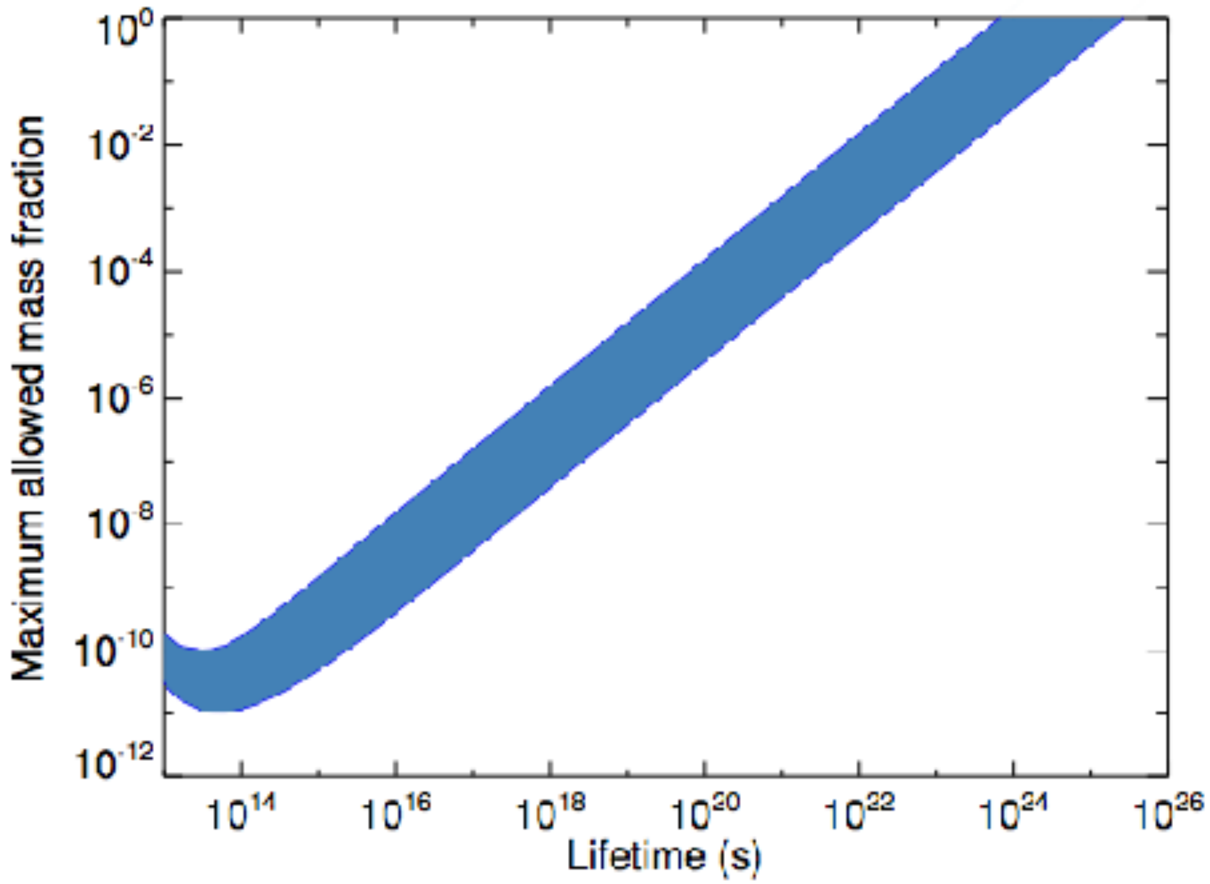


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime τ, for injections of 10 keV – 10 TeV photons and e^+e^- pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the MCMC bound for our reference model.