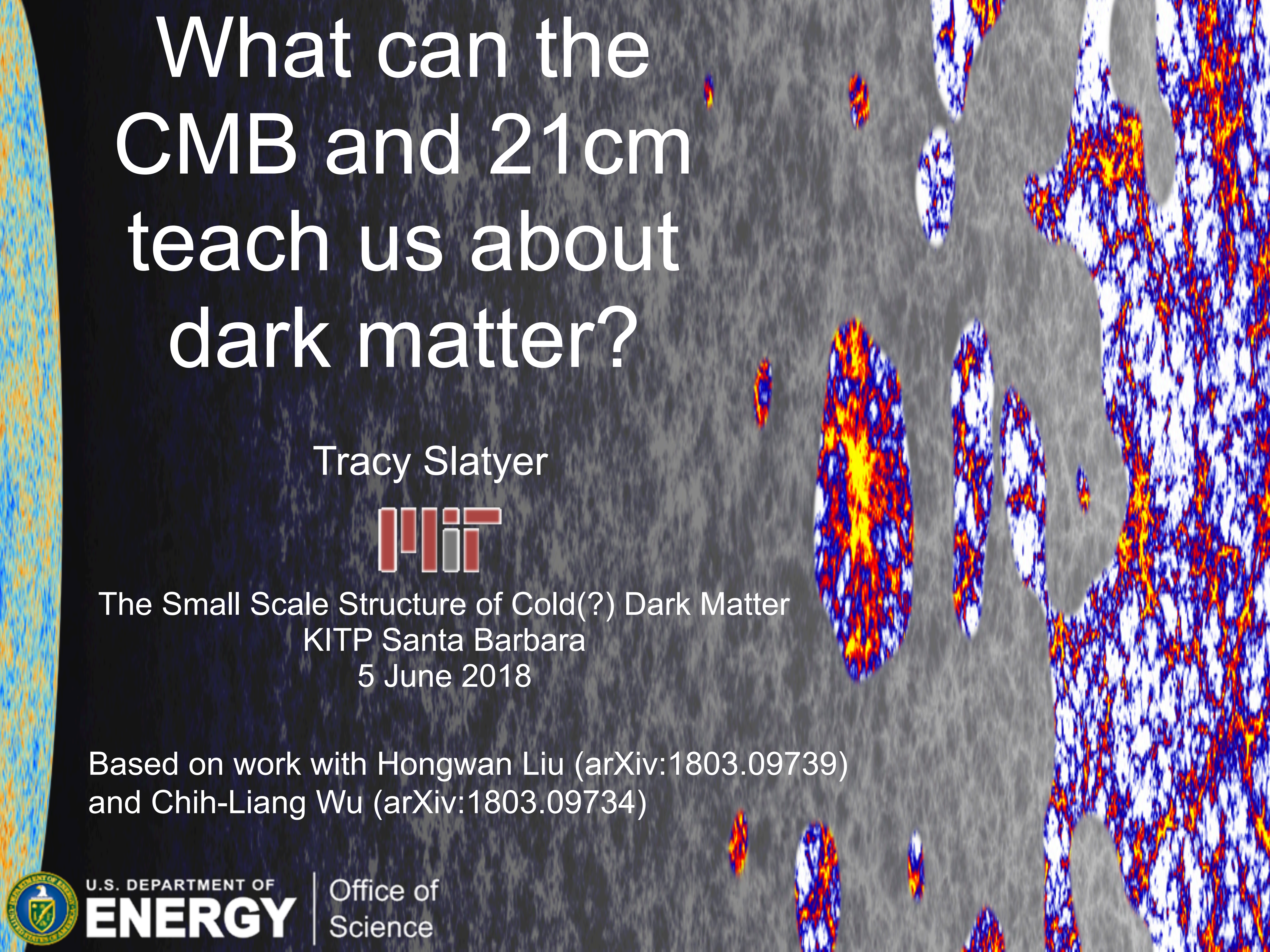


What can the CMB and 21cm teach us about dark matter?

Tracy Slatyer

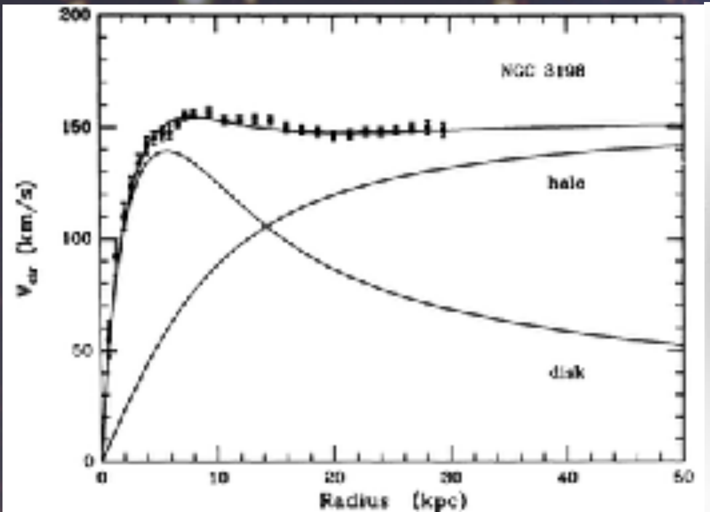
The Small Scale Structure of Cold(?) Dark Matter
KITP Santa Barbara
5 June 2018

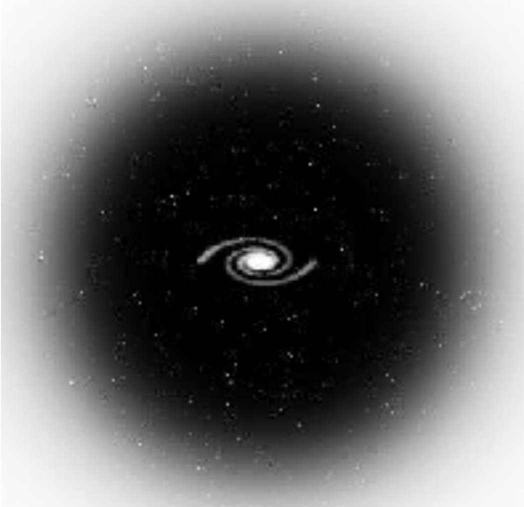
Based on work with Hongwan Liu (arXiv:1803.09739) and Chih-Liang Wu (arXiv:1803.09734)

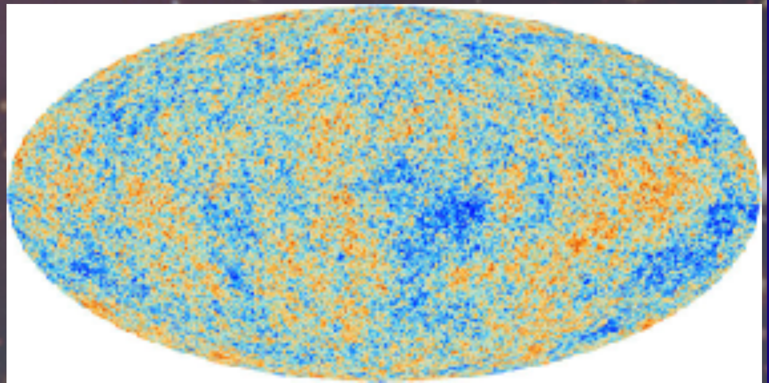
U.S. DEPARTMENT OF ENERGY | Office of Science

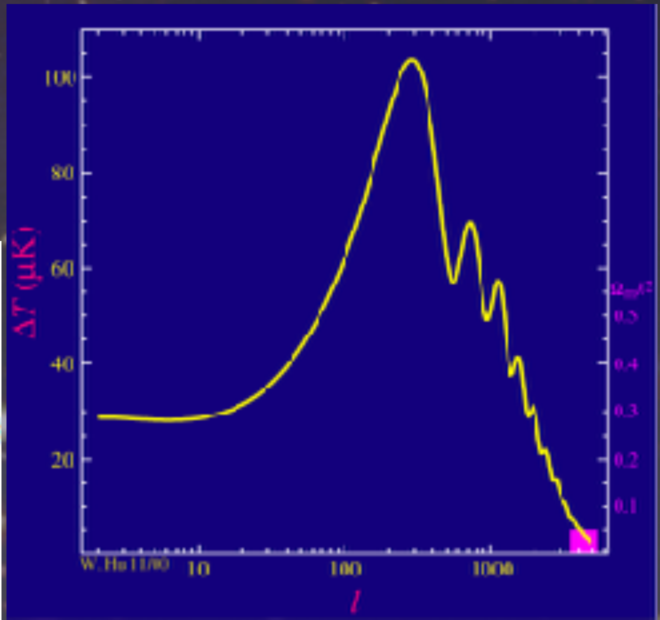
Gravitational probes of DM

- 100% of our current evidence for DM
- Tell us that (bulk of) DM is not too hot or too collisional
- Future probes in this category can map out DM distribution, test scenarios where DM is warm/self-interacting/etc - will give us useful information in any case!
- But also many models where DM will look cold+collisionless to all near-future gravitational probes







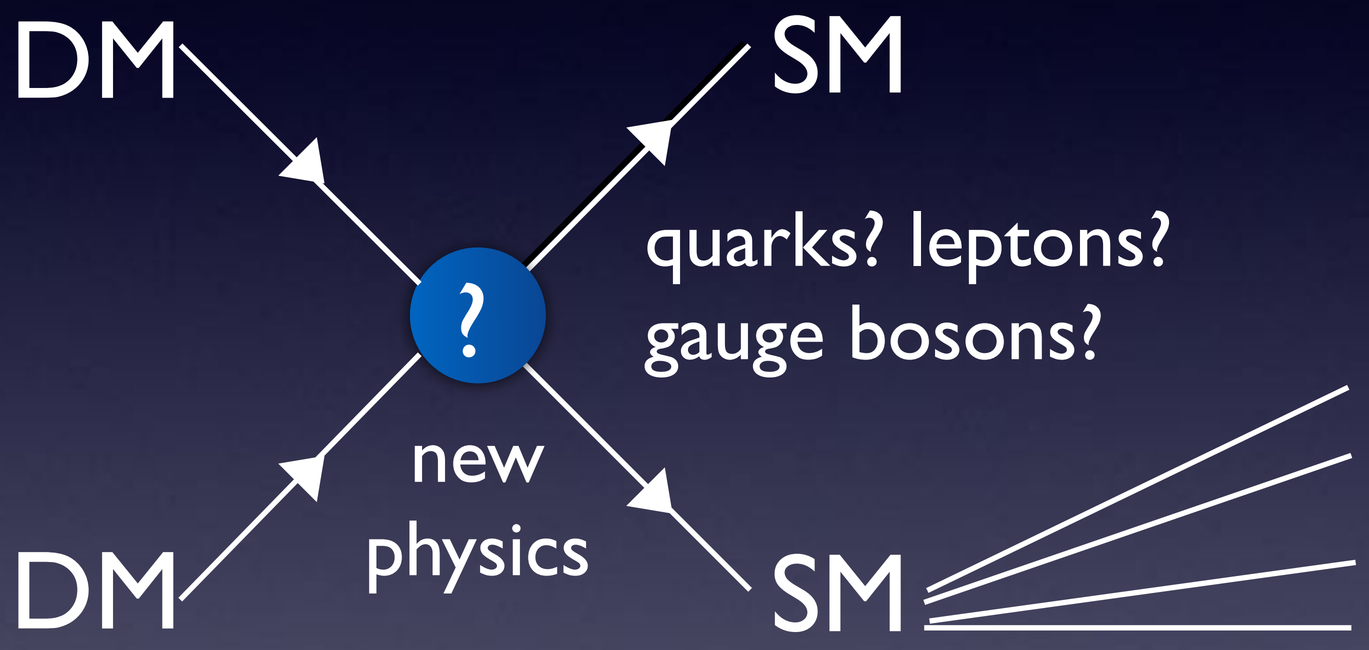


Non-gravitational interactions (?) of DM

- 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
- We have fantastic cosmological observations that provide precision data on the early universe - relatively well-understood baseline, allows us to avoid complex Galactic astrophysics
- Consider generic interactions that would lead to energy transfer between dark and visible matter - how would they change early cosmic history?

Annihilation

tested by
present-day
indirect
searches



DM

SM

?

quarks? leptons?
gauge bosons?

new
physics

DM

SM

Cascading decays according
to known SM processes

dark matter

known particles

long-lived known particles

Annihilation and abundance

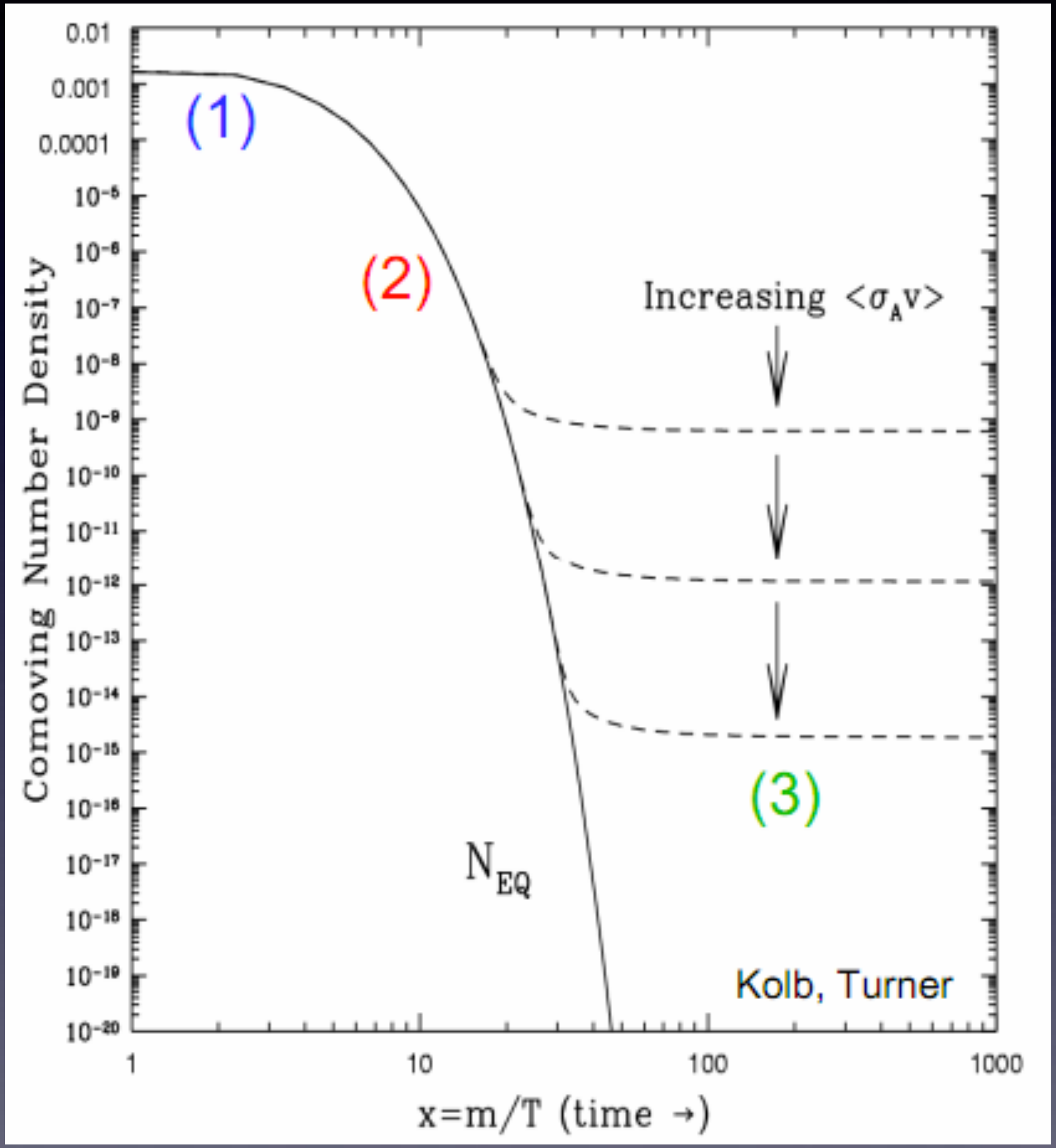
- In the early universe, suppose DM & visible matter (SM) in thermal equilbrium.
- DM can annihilate to SM particles, or SM particles can collide and produce it.

$$\chi\chi \leftrightarrow \mathrm{SM}\,\mathrm{SM} \quad (1)$$

- Temperature(universe) < particle mass => can still annihilate, but can't be produced.

$$\begin{aligned} \chi\chi &\rightarrow \mathrm{SM}\,\mathrm{SM} \\ \chi\chi &\not\leftarrow \mathrm{SM}\,\mathrm{SM} \end{aligned} \quad (2)$$

- Abundance falls exponentially, cut off when timescale for annihilation ~ Hubble time. The *comoving* dark matter density then freezes out.

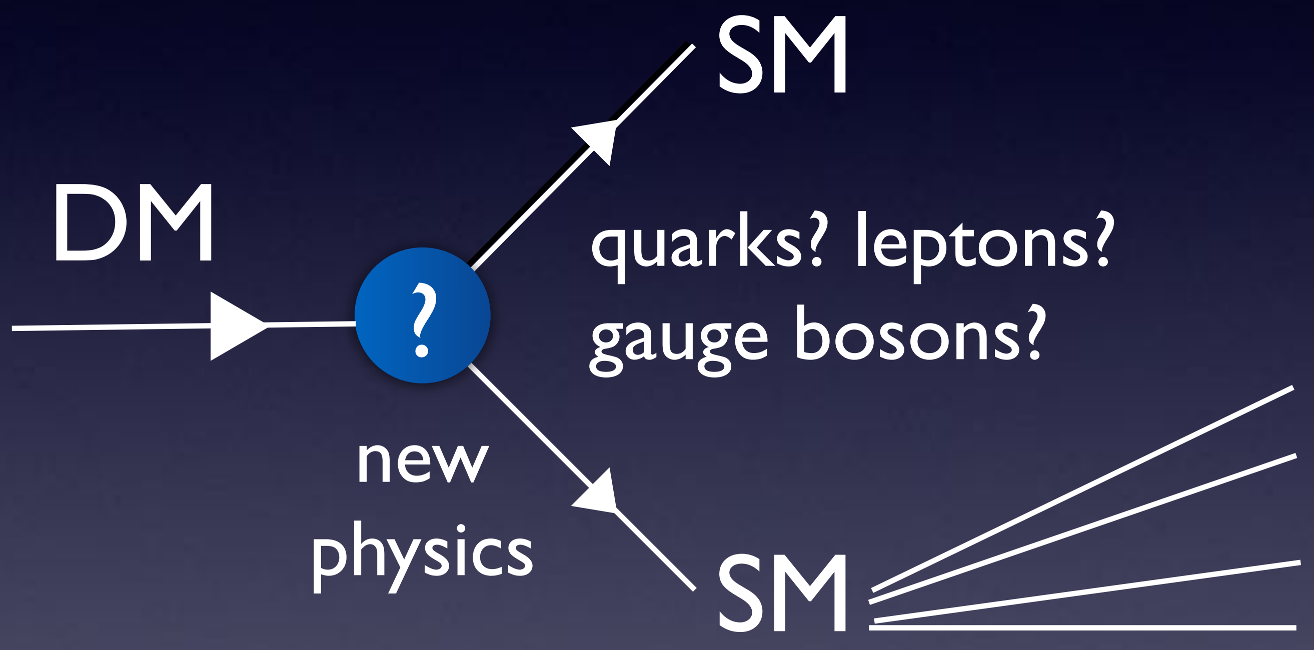


So (known) late-time density is set by annihilation rate.

$$\langle\sigma v\rangle \sim 3\times10^{-26}\,\mathrm{cm}^3/\mathrm{s} \sim \pi\alpha^2/(100\,\mathrm{GeV})^2 \quad (3)$$

Decay

tested by
present-day
indirect
searches



quarks? leptons?
gauge bosons?

new
physics

Cascading decays according to known SM processes

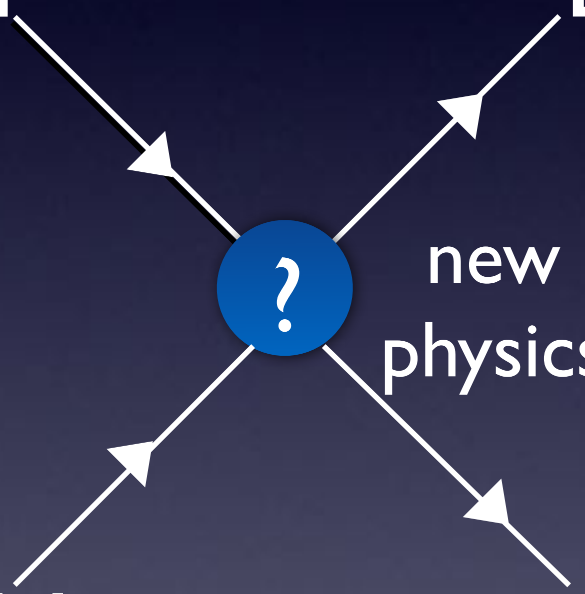
dark matter

known particles

long-lived known particles

Scattering

tested in direct-detection experiments



dark matter

DM

DM

new physics

SM

SM

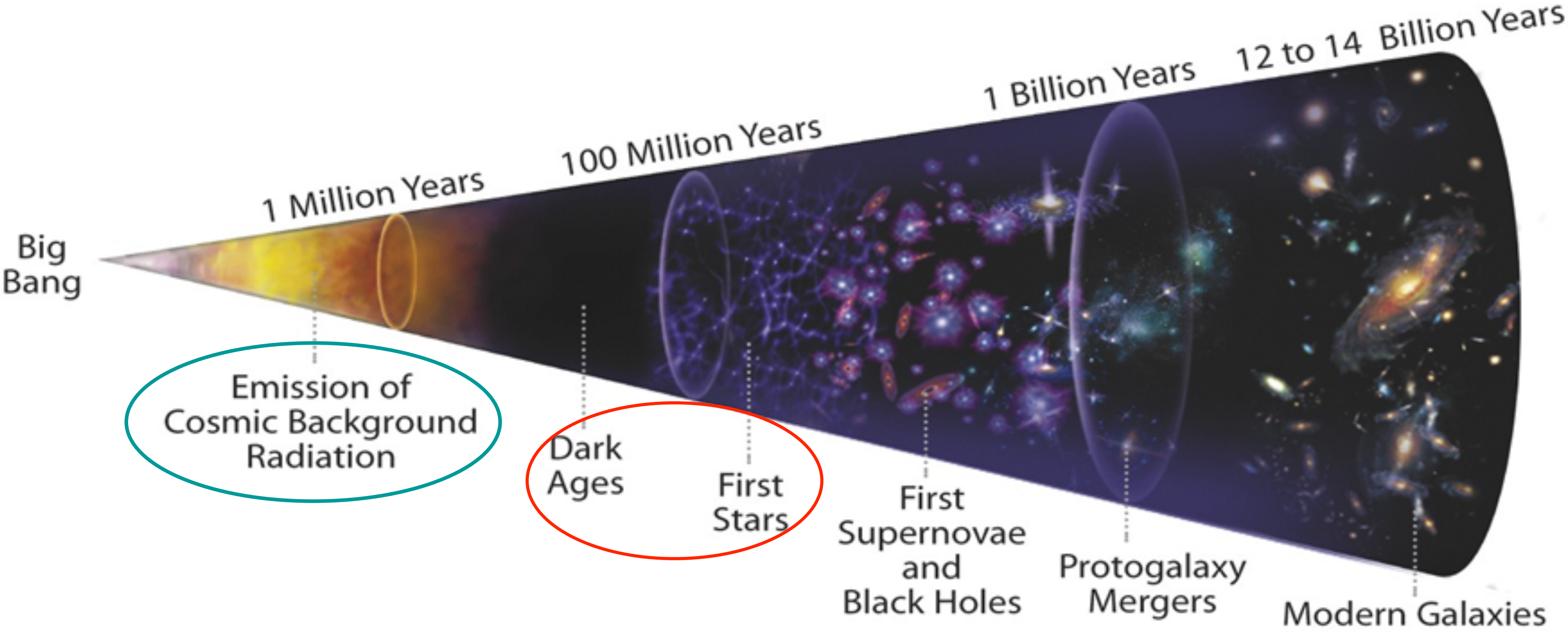
known particles - protons, electrons, atoms

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

A cosmic timeline

- Convenient to measure epochs by redshift - describes factor by which the universe has expanded since that time
- Redshift $z > 10^3$ - universe is filled with a plasma of electrons, protons and photons, + dark matter and neutrinos. Almost 100% ionized.
  - Small density/temperature perturbations in the plasma are oscillating and evolving.
  - Photon bath is a near-perfect blackbody - heating or cooling the matter can lead to distortions in the blackbody energy spectrum.
- Redshift $z \sim 10^3$ - ionization level drops abruptly, CMB photons begin to stream free of the electrons/protons. Provides "snapshot" of perturbations at this time.
- Redshift $z \sim 30\text{-}10^3$ - "cosmic dark ages", ionization level very low. Increasing ionization would provide a screen to CMB photons - can be sensitively measured.
- Redshift $z < 30$ - end of dark ages, start of reionization. Can be studied with 21cm observations. First claim of a measurement in February!

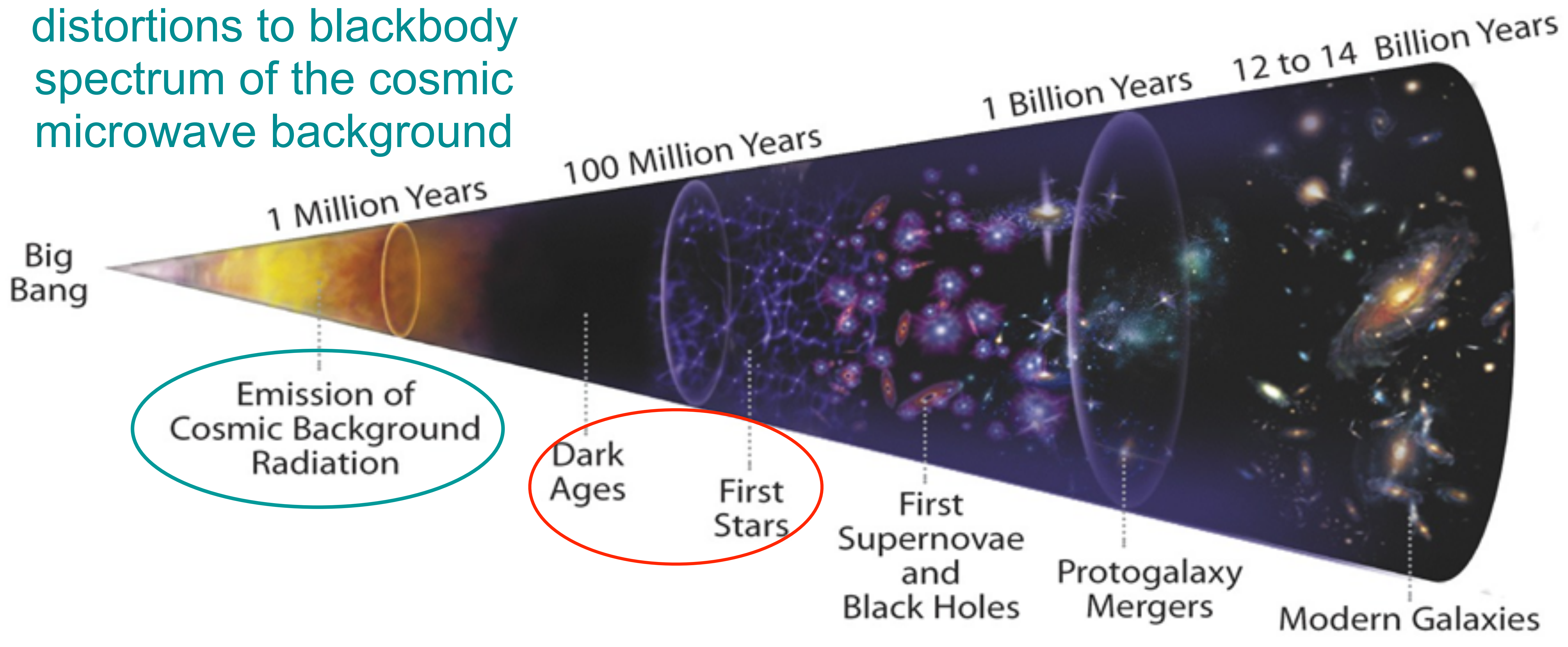
How can dark matter change the early universe?



affects CMB affects 21cm

How can dark matter change the early universe?

distortions to blackbody spectrum of the cosmic microwave background



affects CMB

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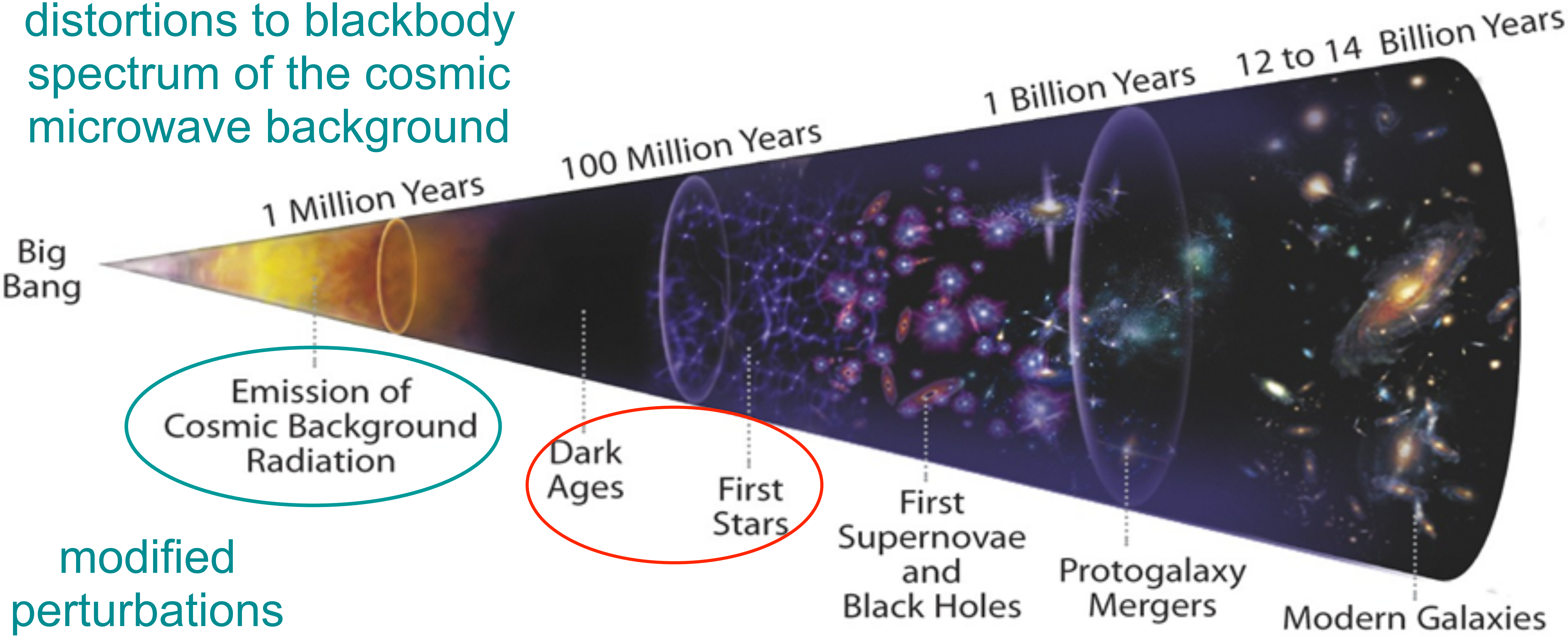
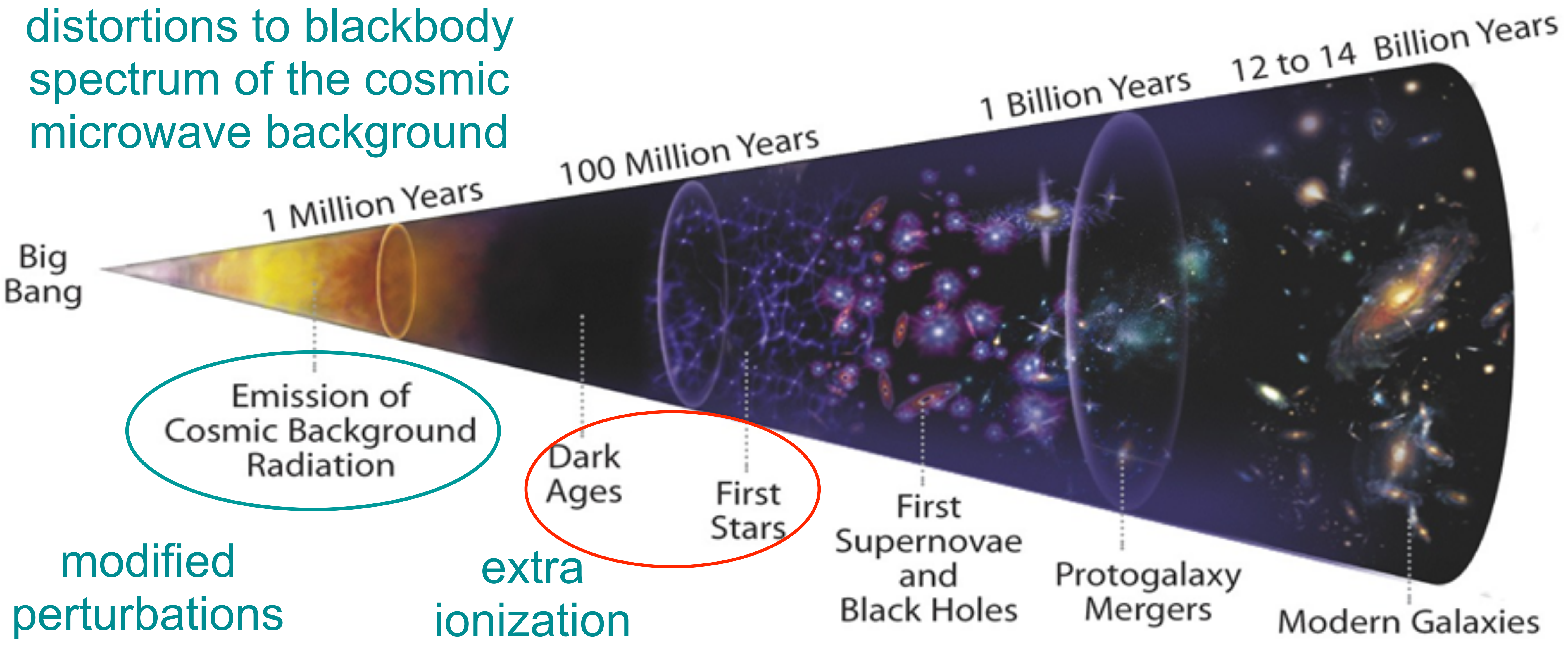


modified perturbations

affects CMB affects 21cm

How can dark matter change the early universe?



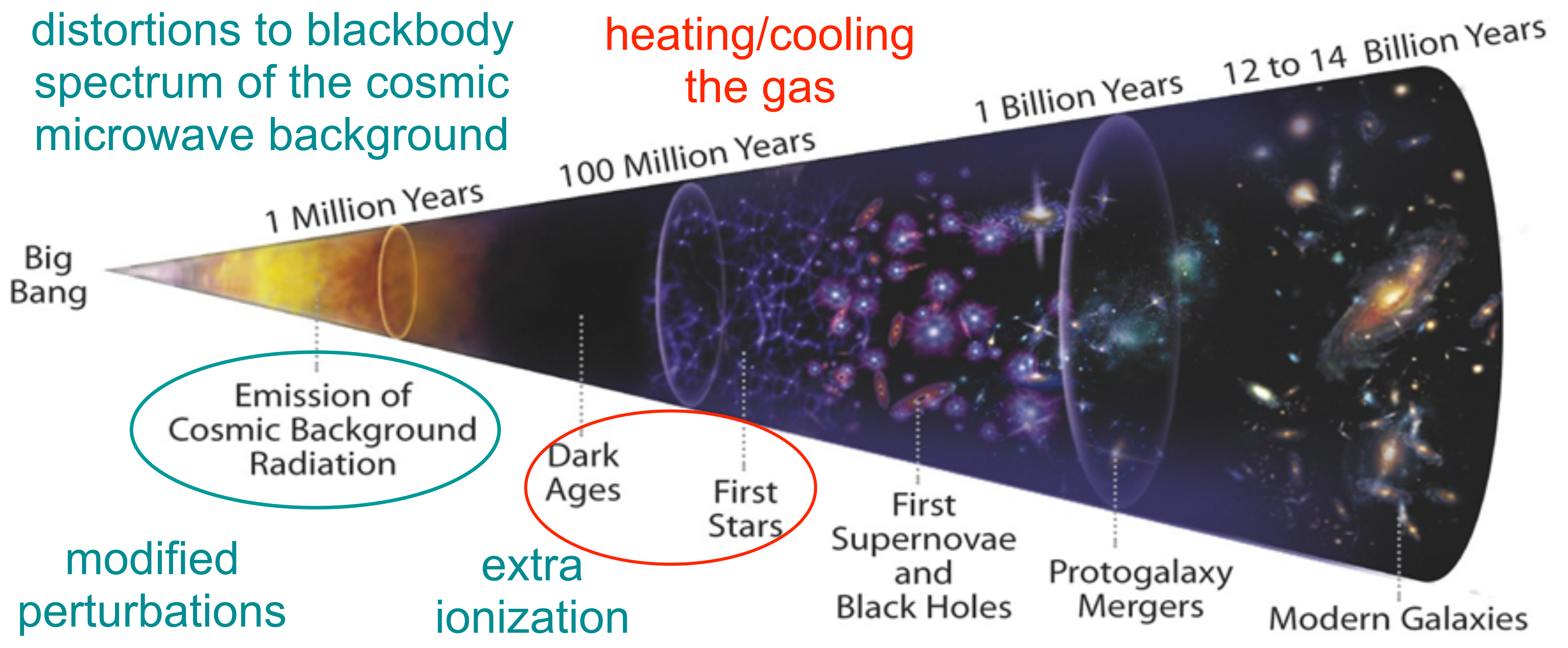
distortions to blackbody spectrum of the cosmic microwave background

modified perturbations

extra ionization

affects CMB   affects 21cm

How can dark matter change the early universe?



distortions to blackbody spectrum of the cosmic microwave background

heating/cooling the gas

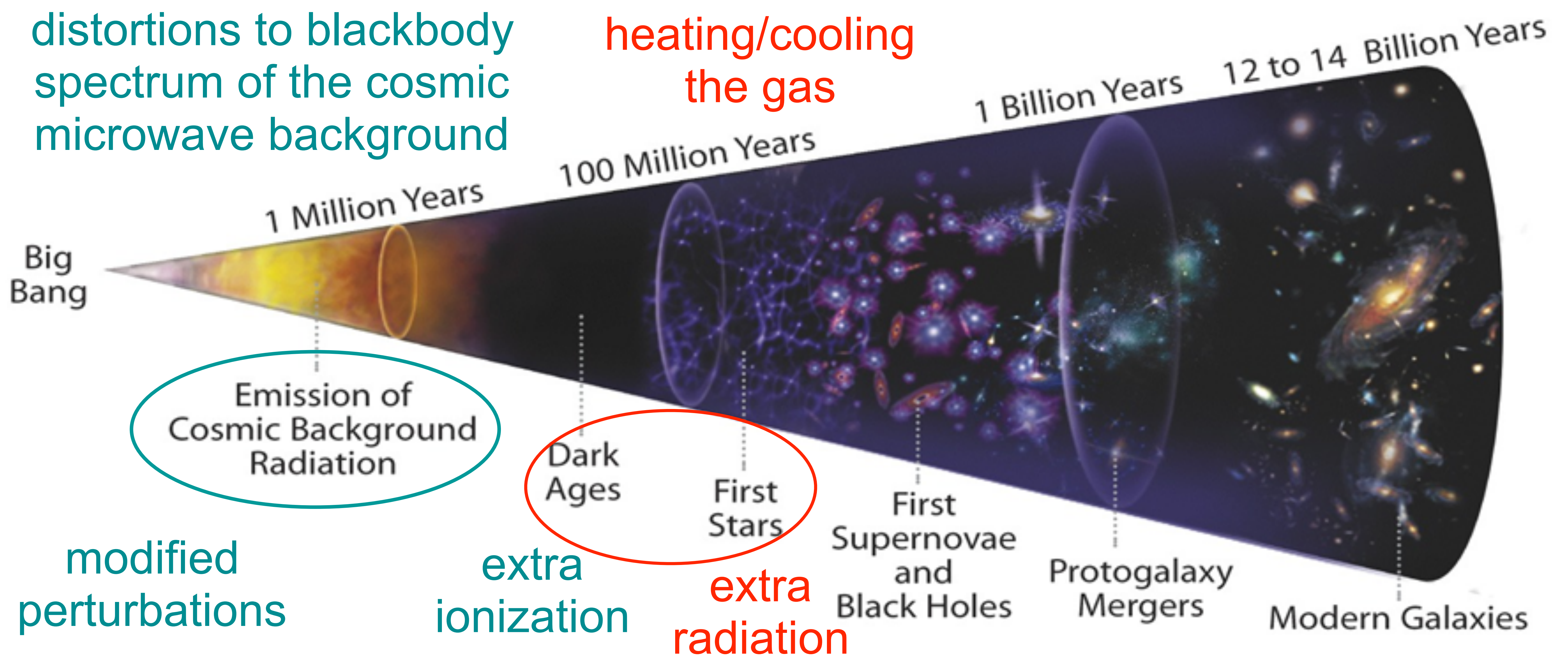
modified perturbations

extra ionization

affects CMB

affects 21cm

How can dark matter change the early universe?



distortions to blackbody spectrum of the cosmic microwave background

heating/cooling the gas

modified perturbations

extra ionization

extra radiation

affects CMB affects 21cm

Case study: from annihilation to ionization

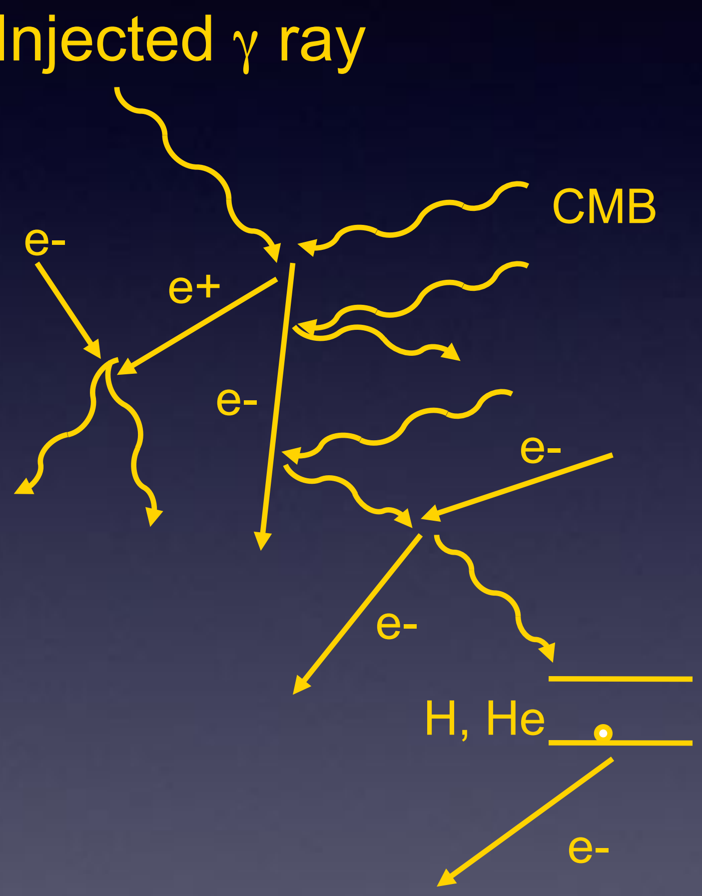
- Consider the power from DM annihilation - how many hydrogen ionizations?
  - 1 GeV / 13.6 eV ~ 10^8
  - If 10^{-8} of baryonic matter were converted to energy, would be sufficient to ionize entire universe. There is ~5x as much DM mass as baryonic mass.
  - If one in a billion DM particles annihilates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

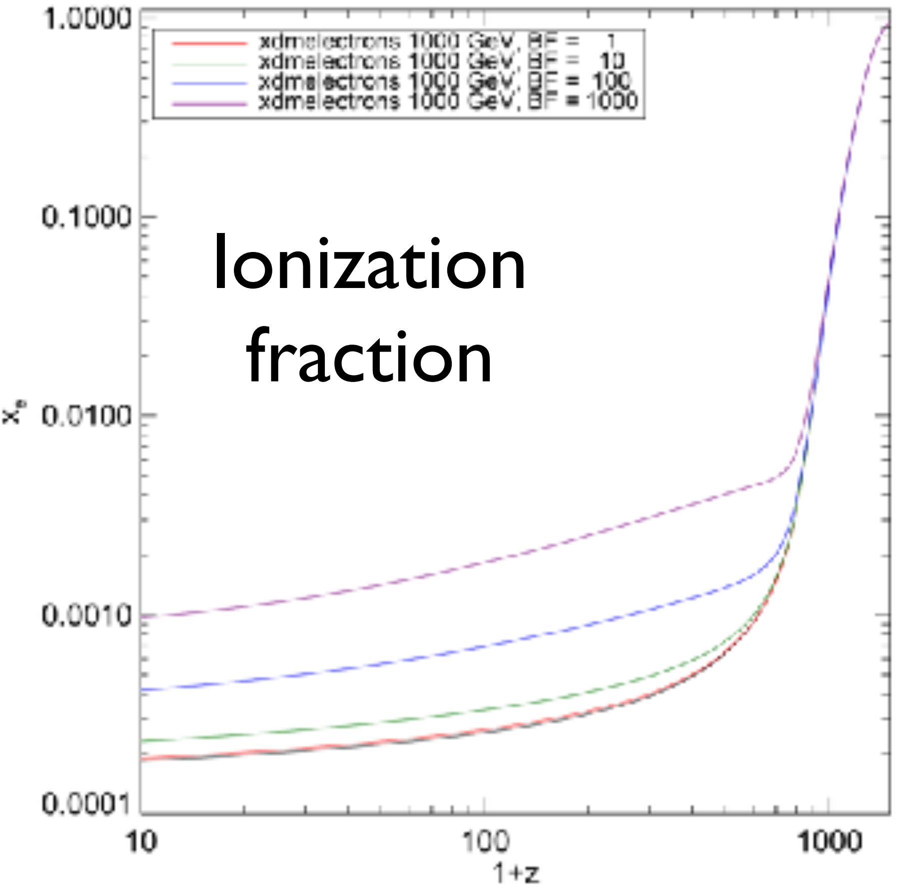


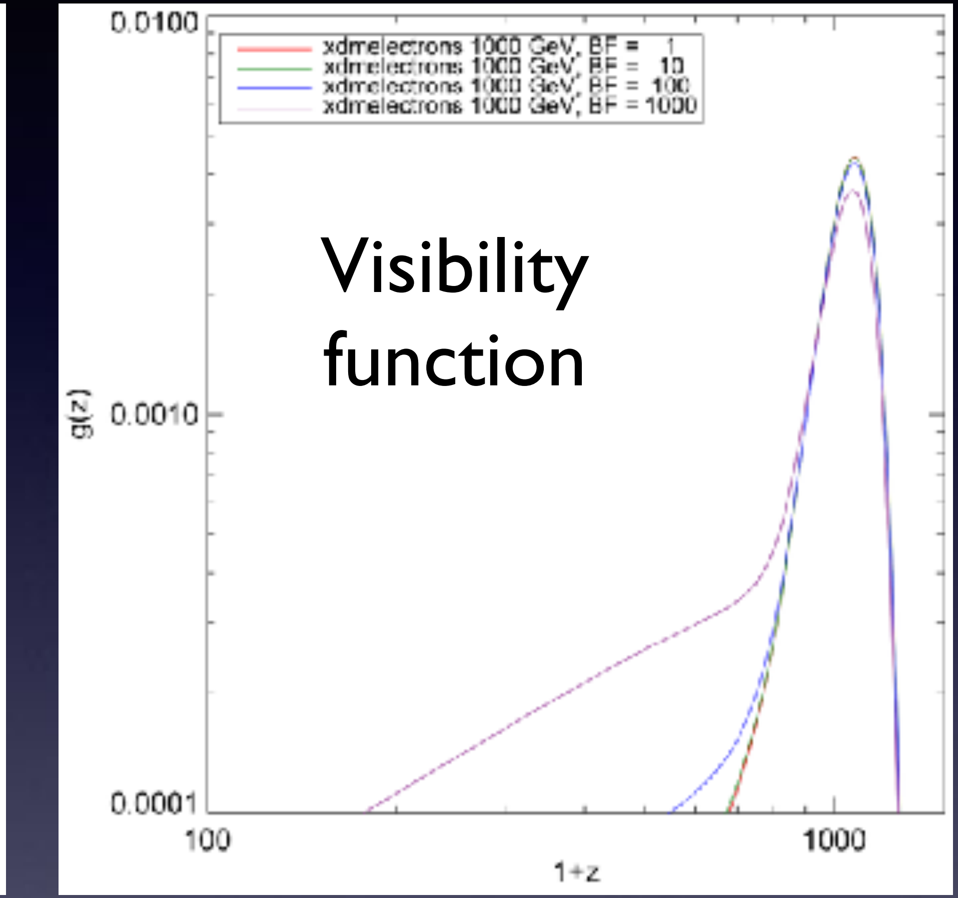
Schematic of a typical cascade:
initial γ-ray
-> pair production
-> ICS producing a new γ
-> inelastic Compton scattering
-> photoionization

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.

Example ionization history

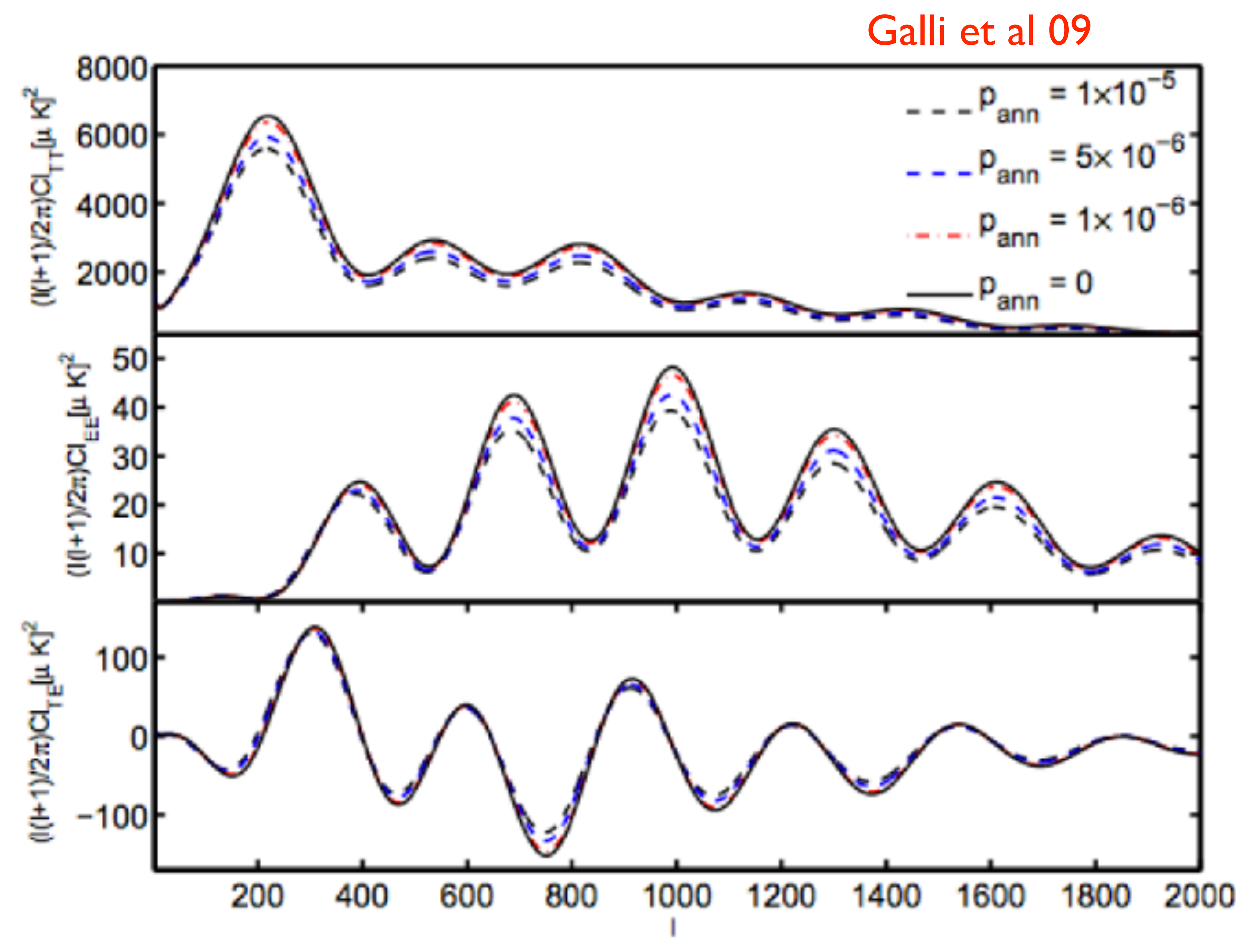




- Use public codes RECFAST (Seager, Sasselov & Scott 1999) / CosmoRec (Chluba & Thomas 2010) / HyRec (Ali-Haimoud & Hirata 2010) to solve for ionization history given extra ionization+heating+excitation.
- At redshifts before recombination, many free electrons => the extra energy injection has little 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

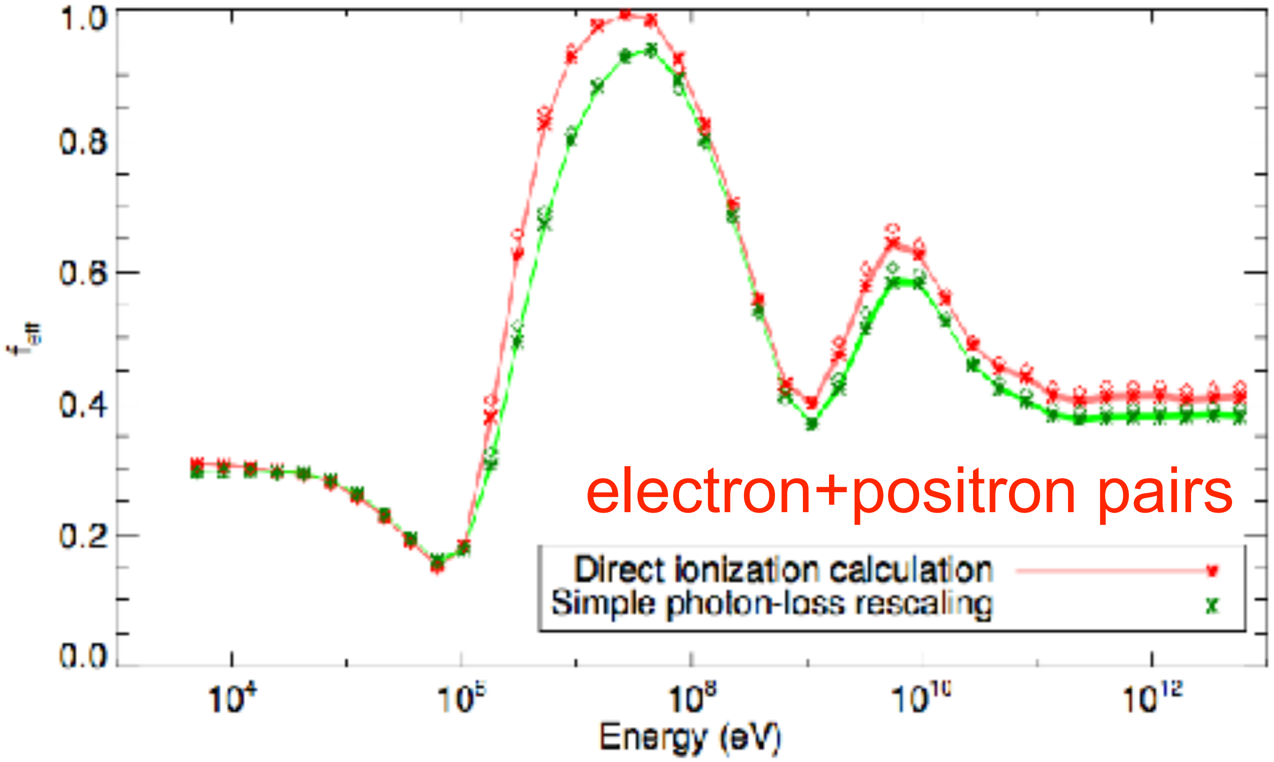
- In the case of DM annihilation, can test the effects of a range of different DM masses (keV-TeV) and all possible Standard Model final states.
- We find the shape of the imprint on the CMB is ~universal (first principal component >99% of variance).
- For each model, only need to calculate normalization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

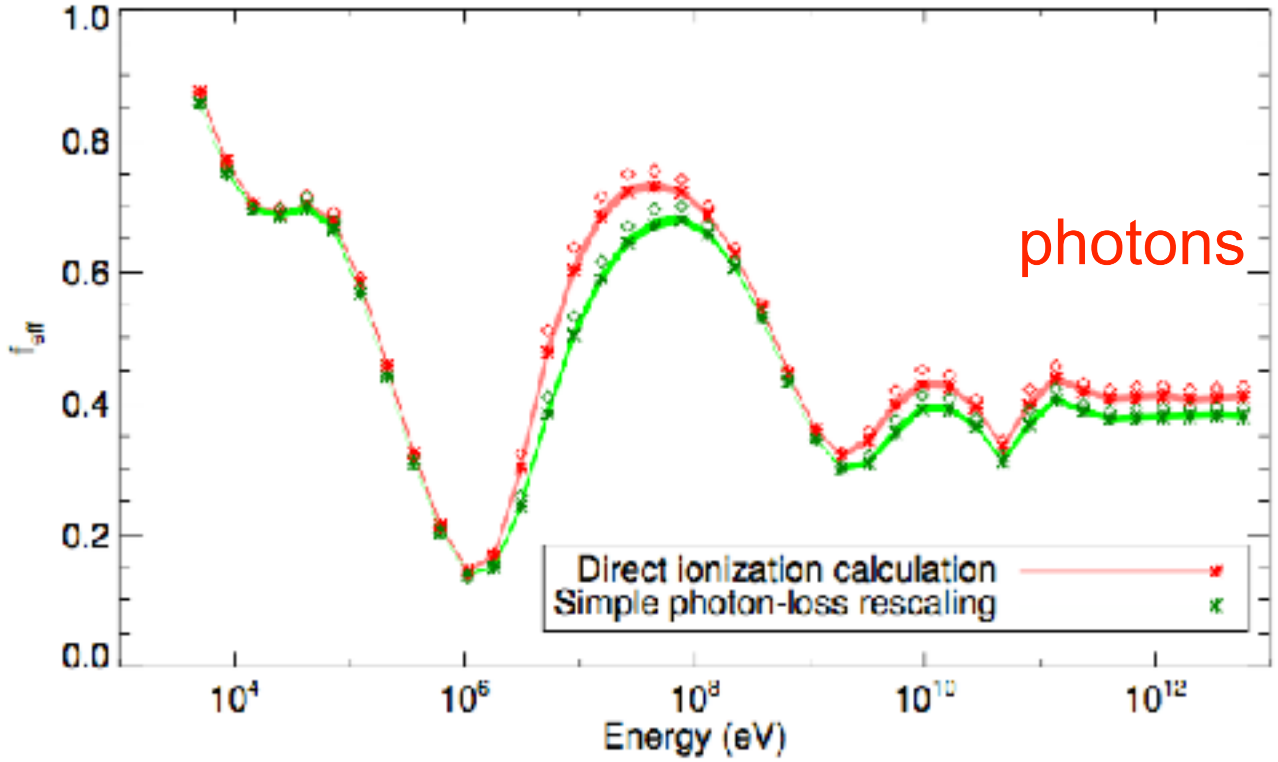


Galli et al 09

Efficiency factors (annihilation)

TRS 2016

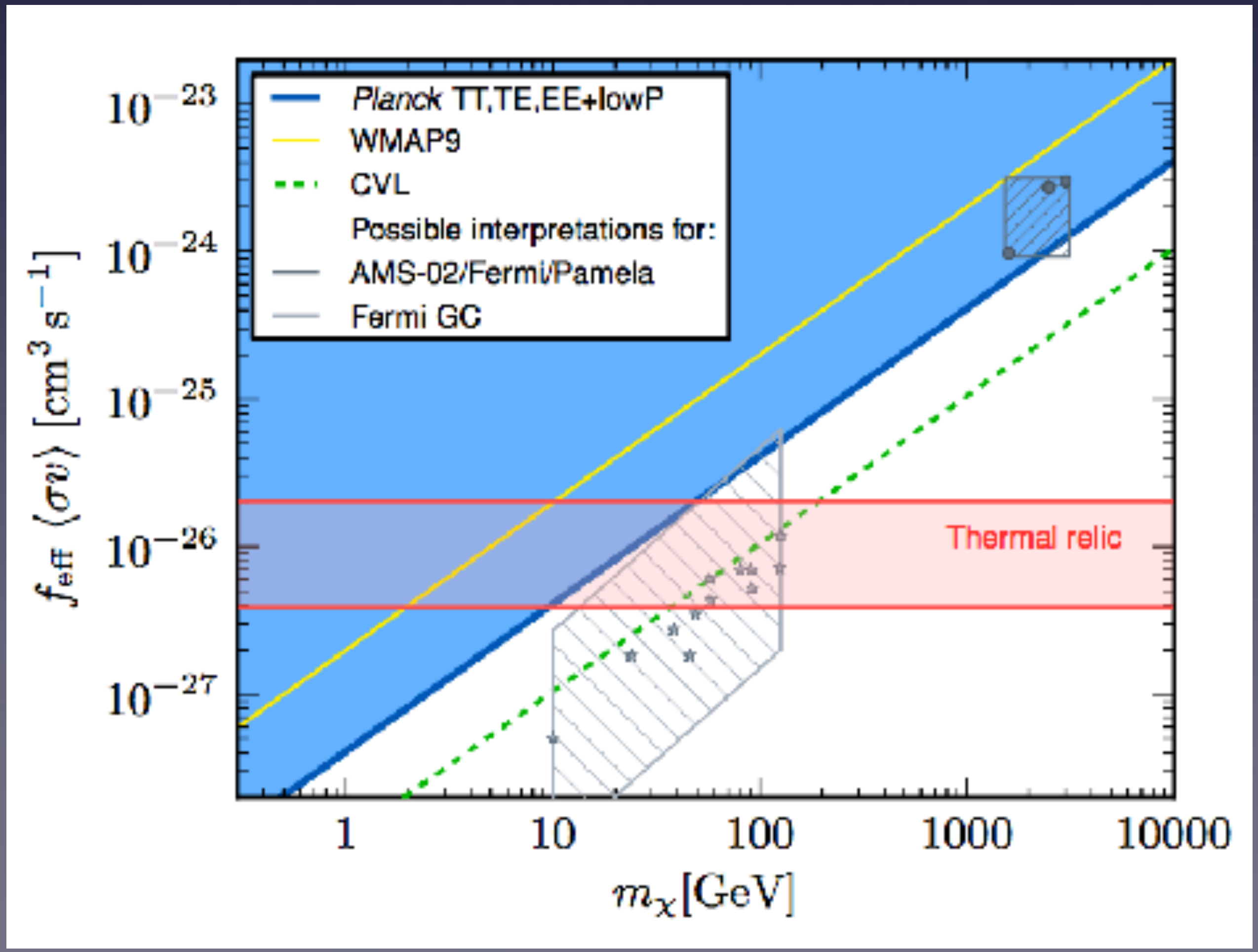


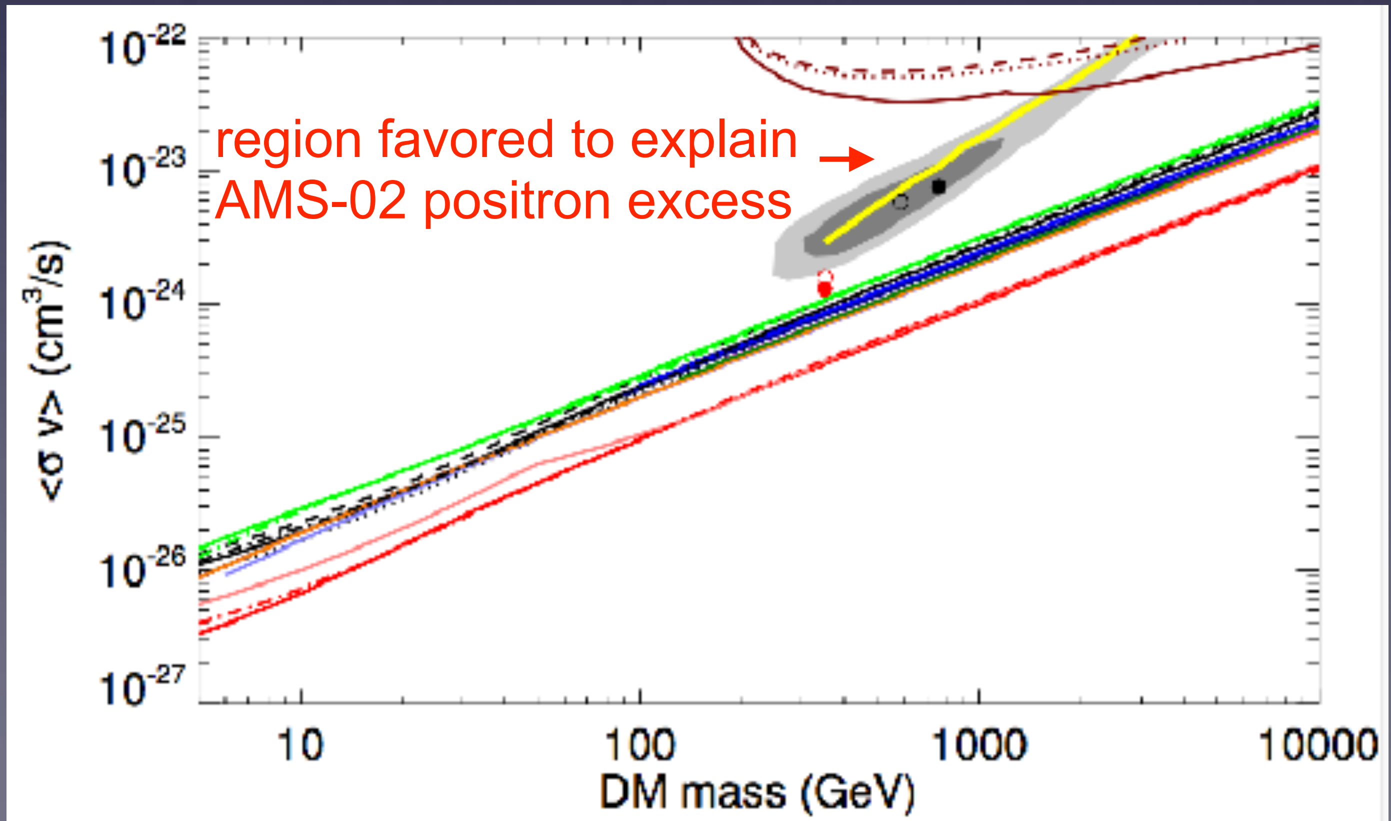


- Result: all (s-wave, velocity-independent) annihilation, of keV-TeV DM, has the same effect on the CMB up to a normalization factor.
- We can compute this normalization/efficiency factor for electrons, positrons, photons at all injection energies.
- Integrate over this curve to determine strength of CMB signal for arbitrary spectra of annihilation products.
- These curves (and the transfer functions used to calculate them) are available online, https://faun.rc.fas.harvard.edu/epsilon/

Annihilation limits from Planck

- Planck Collaboration '15 set bounds on DM annihilation; consistent with sensitivity predictions from TRS et al, Galli et al 09.
- Left plot shows Planck bound, right plot shows resulting cross-section limits for a range of channels from TRS '16.

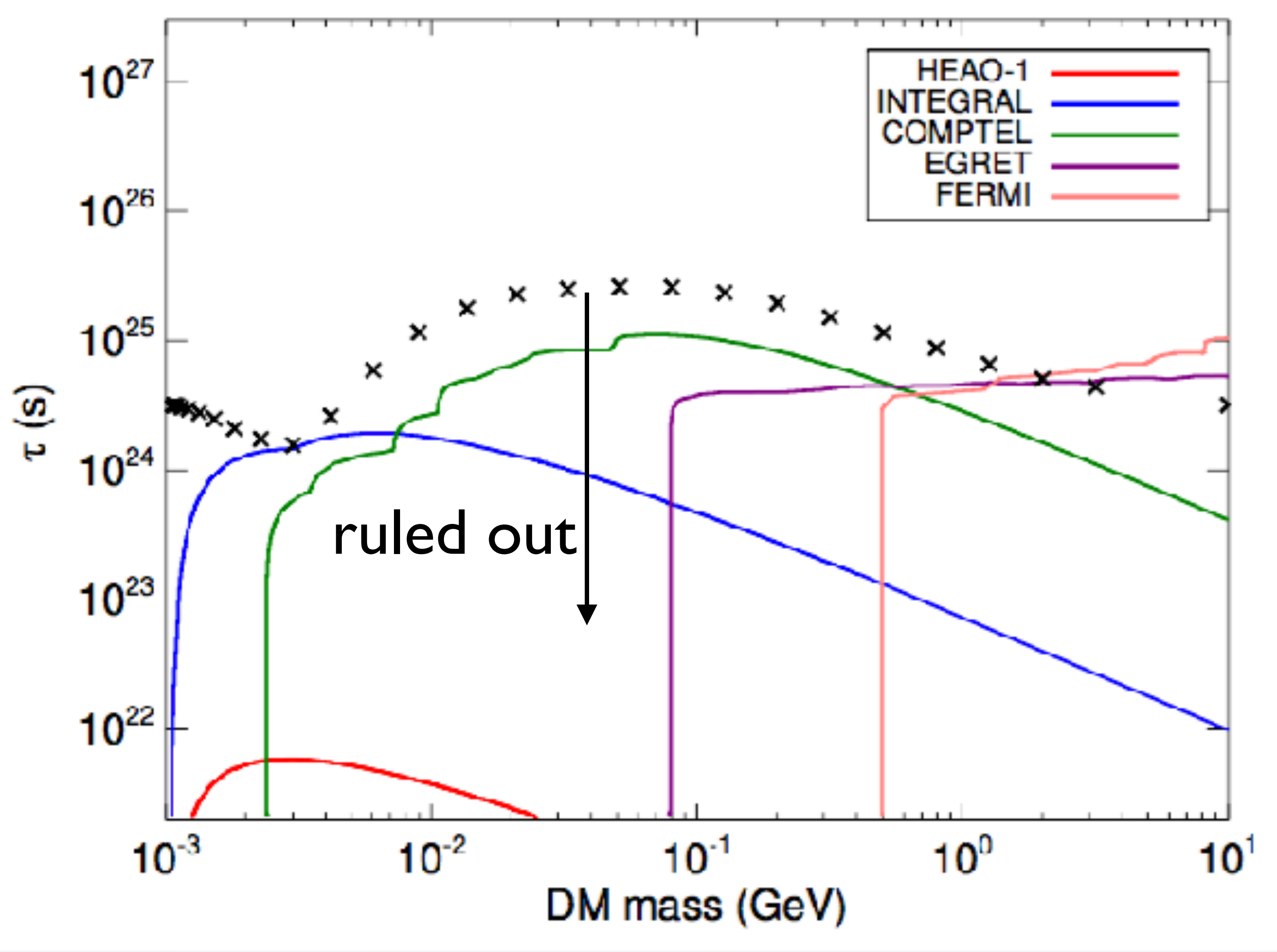



region favored to explain AMS-02 positron excess →

Constraints on decay from Planck

- For decaying dark matter, can use 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)

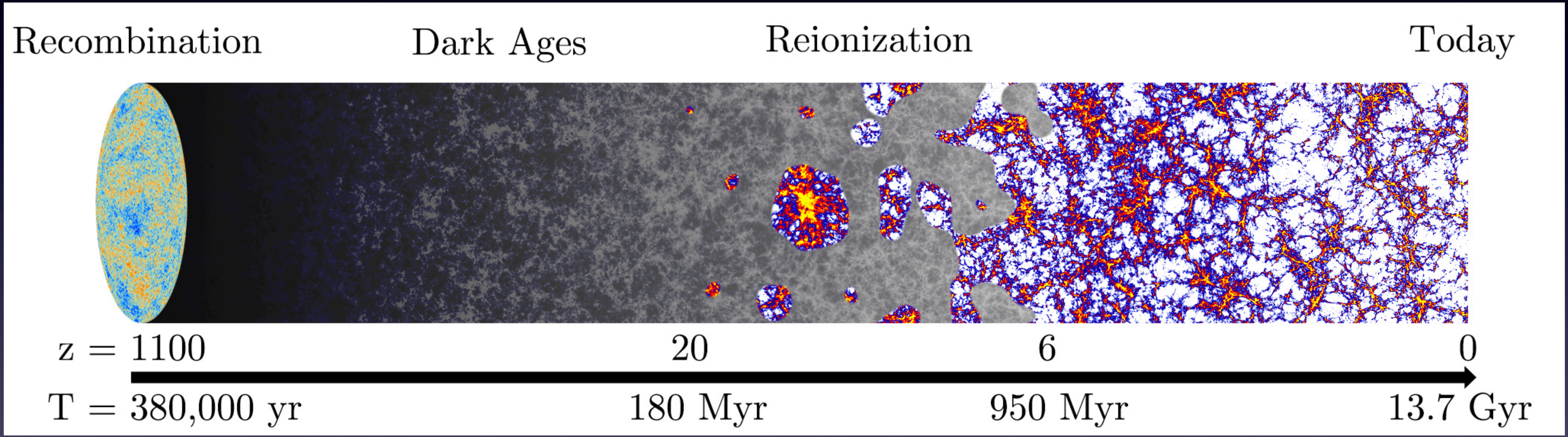
TRS and Wu, PRD95, 023010 (2017)



Other constraints from Essig et al '13

The epoch of reionization

Liu, TRS & Zavala 2016, PRD 94, 063507



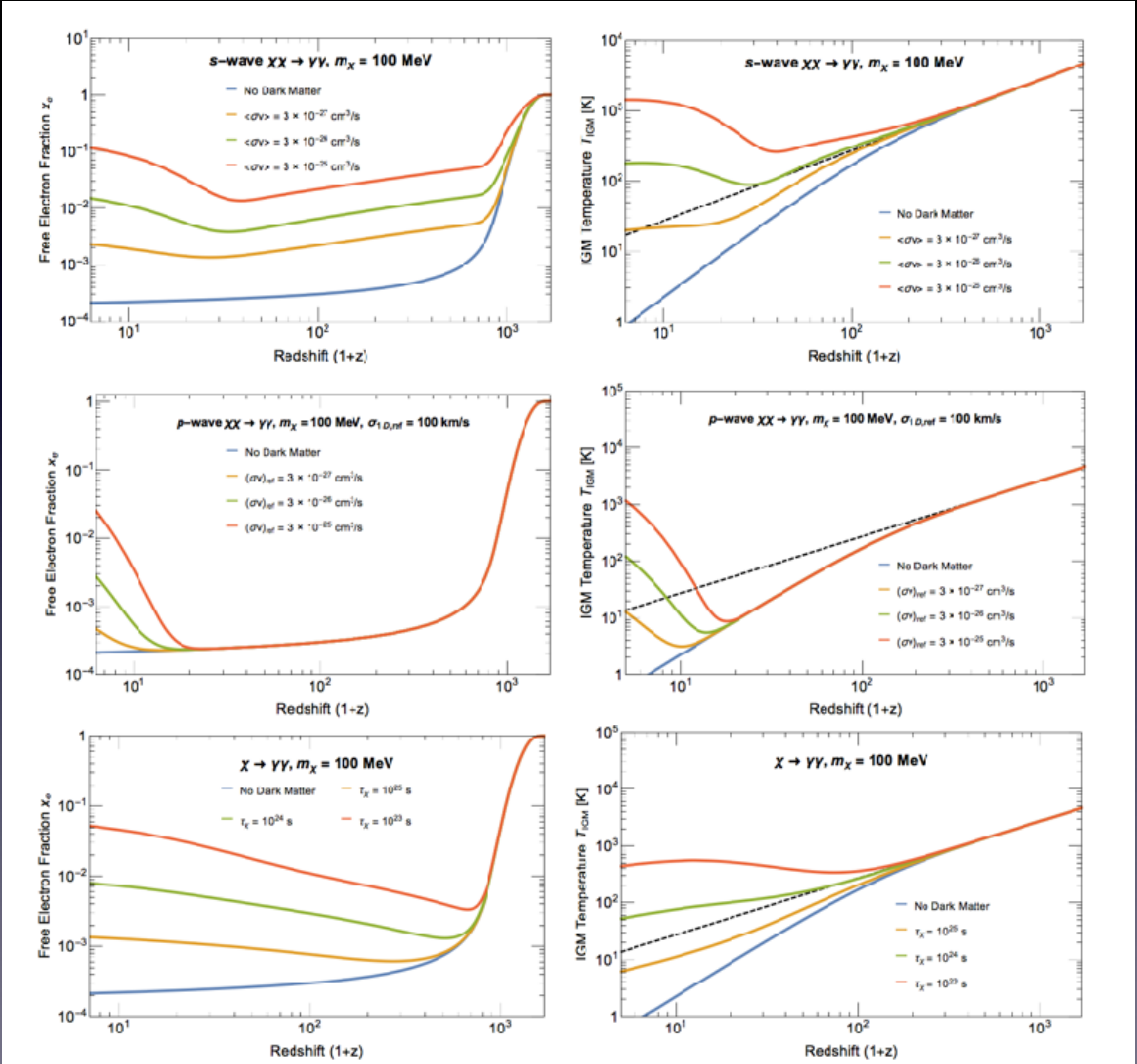
- Around z~6-10, the universe became ~fully ionized again.
- Can DM annihilation or decay affect reionization?
- Can it affect the thermal history of our cosmos? Could DM annihilation/decay overheat the universe?

ionization temperature

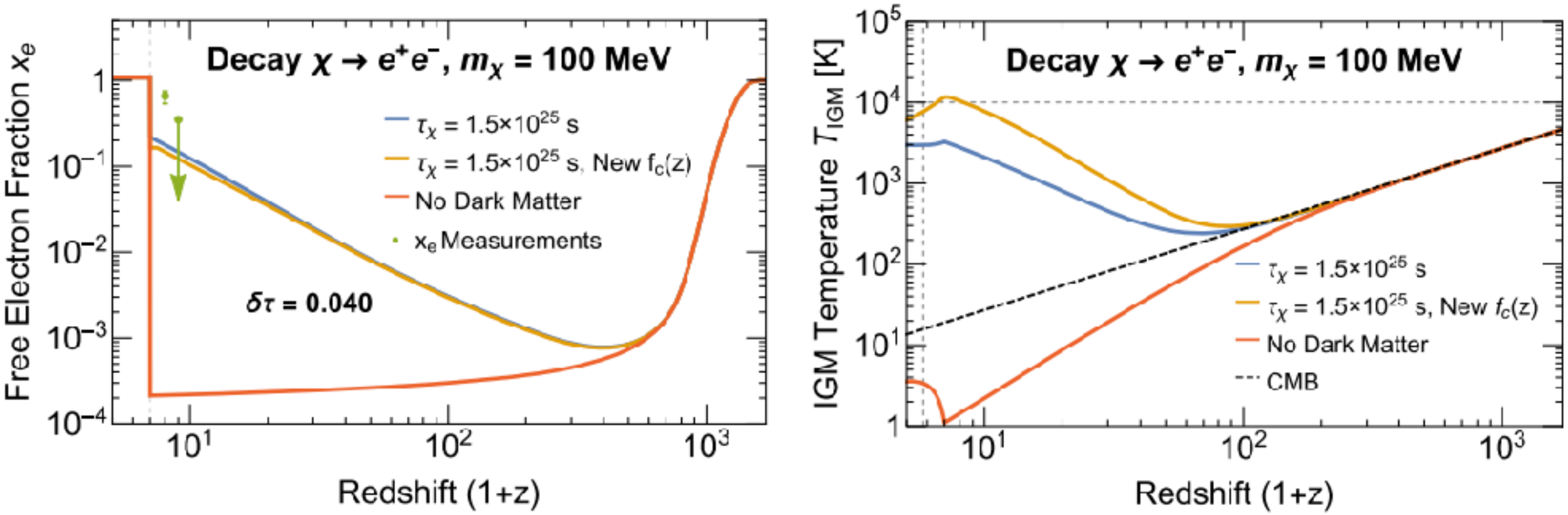
s-wave annihilation

p-wave annihilation

decay



An (optimistic) example scenario

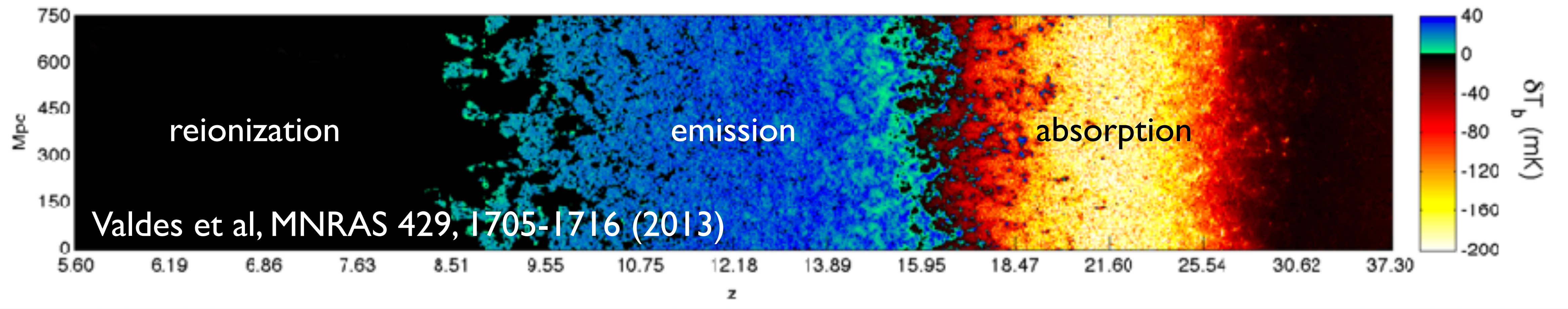


- Ex: 100 MeV DM decaying to e^+e^- pairs
- Marginally allowed by conservative constraints - could be ruled out by stronger bounds on late-time temperature

Parametrics of a 21cm signal

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

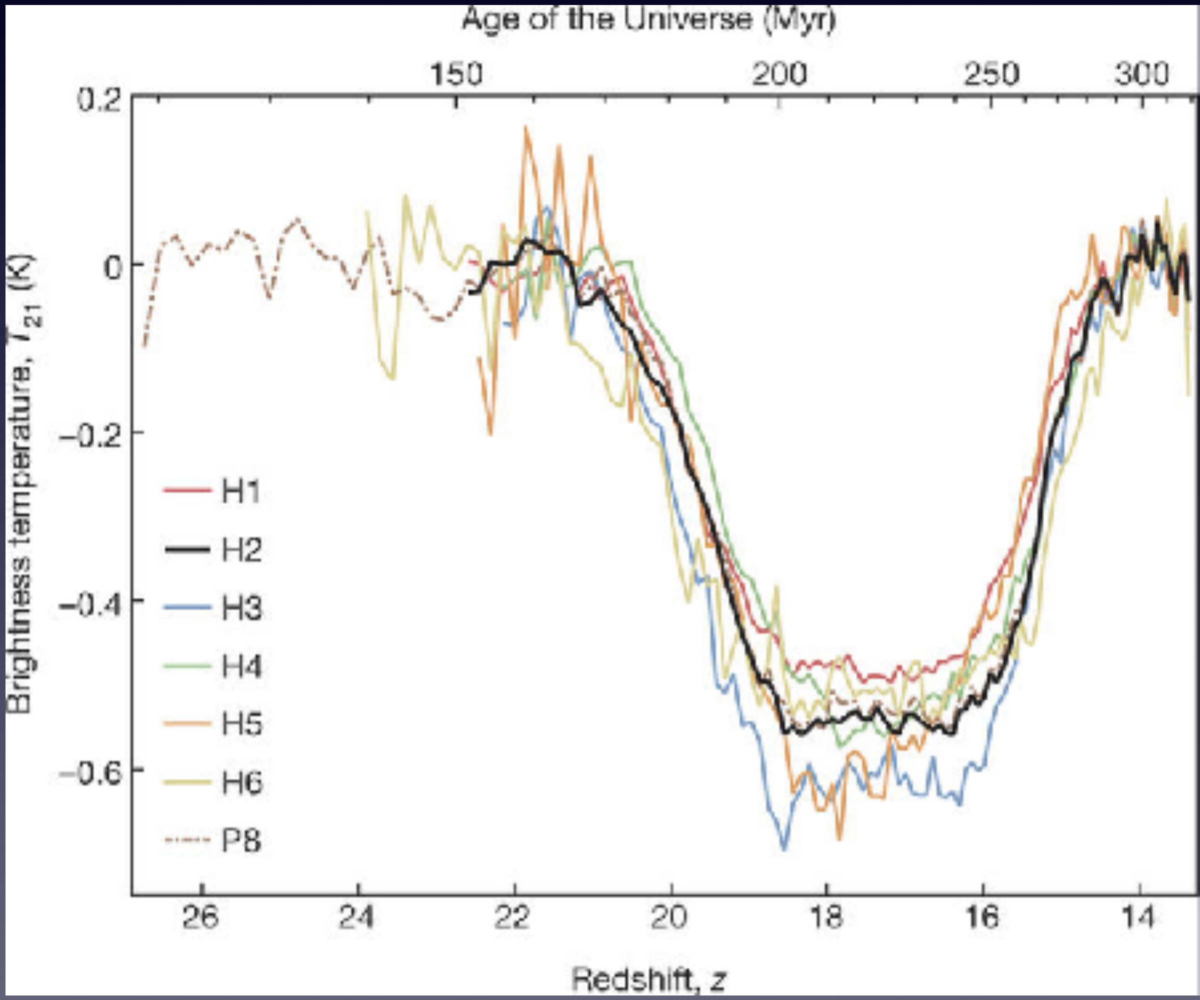
- Spin-flip transition of neutral hydrogen can be used to probe temperature and distribution of the neutral gas in the early universe prior to reionization ($z > 7$ or so).
- 21cm absorption/emission signal strength depends on “spin temperature” T_S, measure of #H in ground vs excited state - expected to lie between gas temperature T_{gas} and CMB temperature T_{CMB}.
- Absorption signal when $T_S < T_R$ (radiation temperature), emission signal if $T_S > T_R$.
- T_R here describes # photons at 21cm wavelength - not necessarily thermally distributed.
- Expected behavior: T_{gas} decouples from T_{CMB} around redshift $z \sim 150$, subsequently satisfies $T_{gas} \sim T_{CMB}\,(1+z)/(1+z)_{dec}$. Gas is later heated by the stars, and eventually T_{gas} increases above T_{CMB}. Thus expect early absorption, later emission.



Valdes et al, MNRAS 429, 1705-1716 (2013)

A measurement of 21cm absorption in the dark ages?

- 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 deep absorption trough corresponding to z~15-20 - implies spin temperature < CMB temperature.

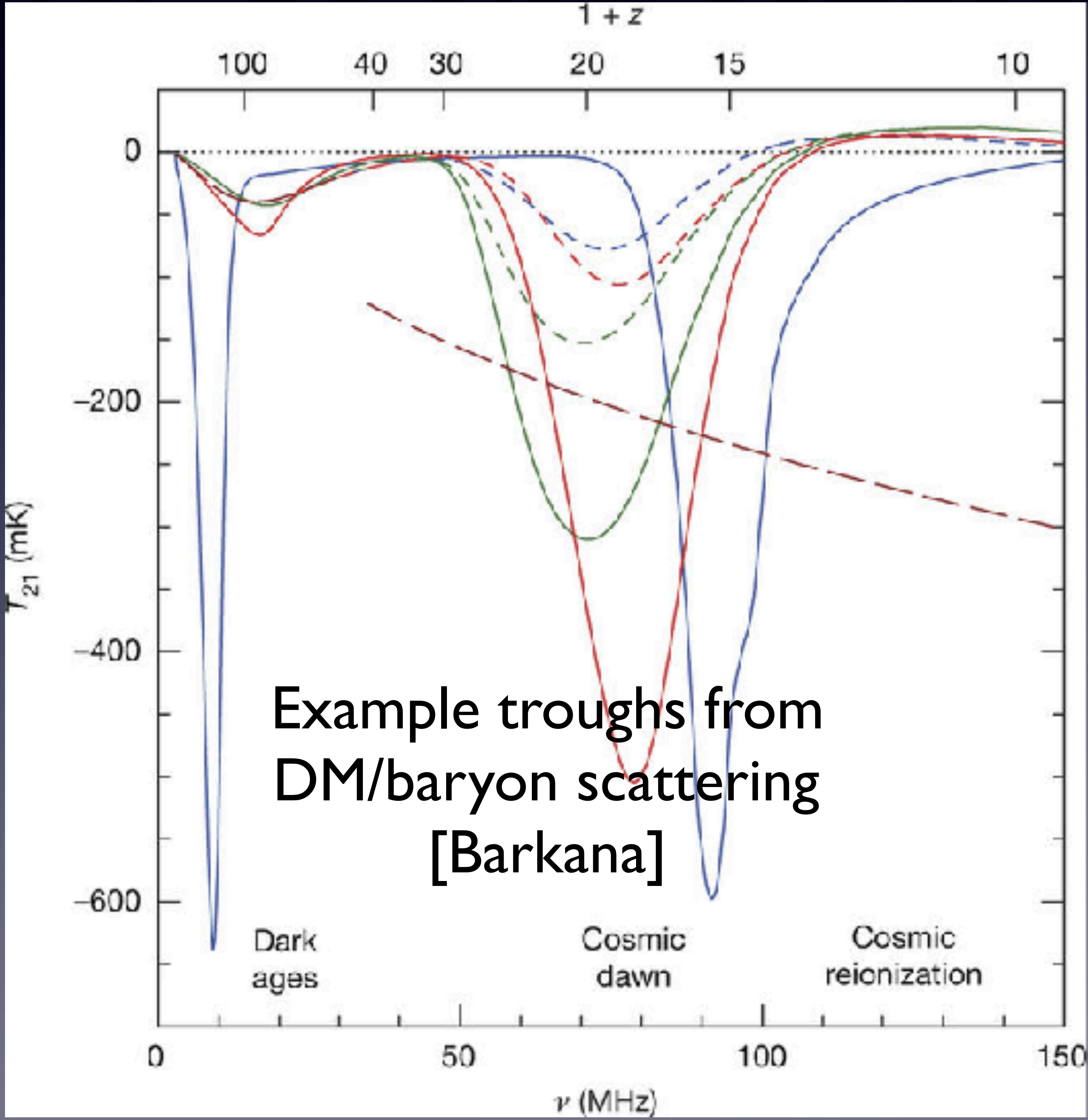
- Measurement of $T_{gas}/T_R(z=17.2) < T_S/T_R < 0.105$ (99% confidence).

Interpreting EDGES

- If T_R is taken to be the CMB temperature, this gives $T_{gas} < 5.2$ K.
- But assuming standard decoupling and <u>no</u> 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], 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].

DM scattering as an explanation for EDGES

- DM-baryon scattering can cool down the ordinary matter [e.g. Munoz et al '15]
- But strong DM-baryon interactions also disrupt CMB perturbations! [Dvorkin et al '13, Gluscevic et al '17, Boddy et al '18, Xu et al '18].
- If an O(1) fraction of DM scatters with baryons, need scattering to be enhanced at late times to avoid CMB limits.
- Late times = low thermal velocities - consider models where cross section scales like v^{-4} (Rutherford scattering)

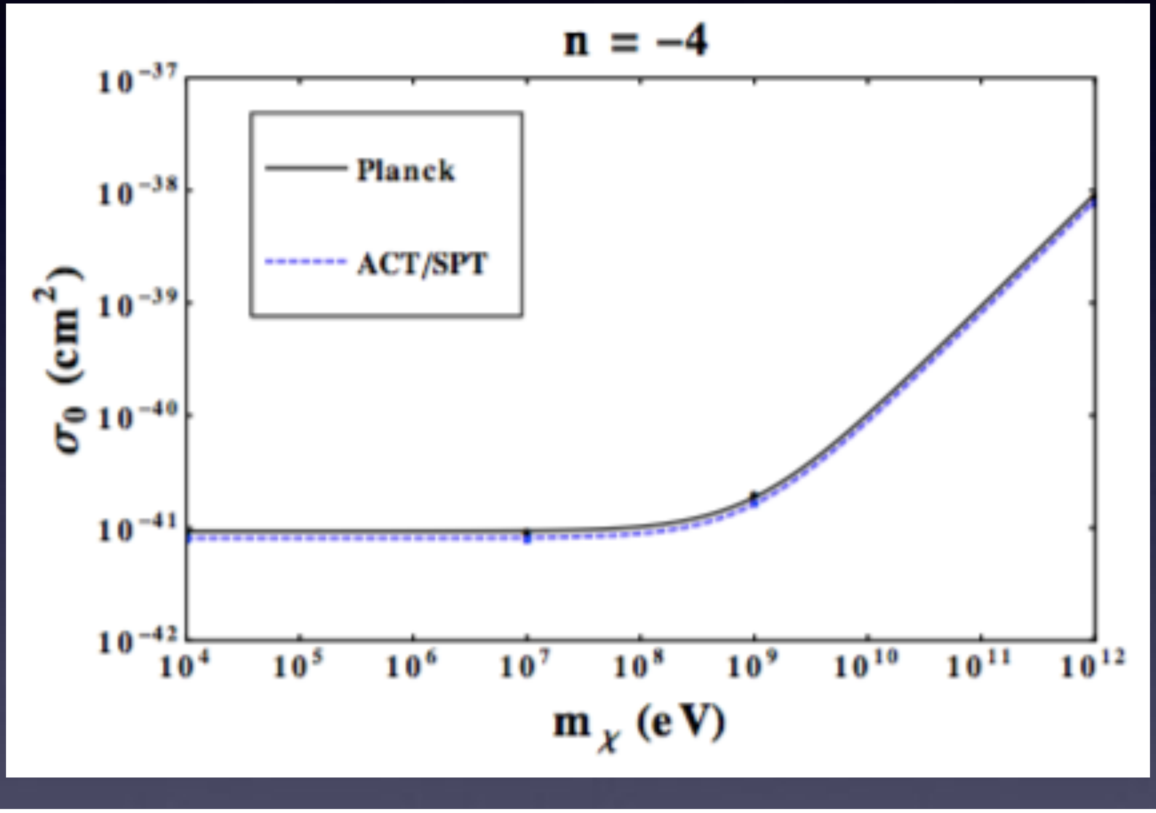


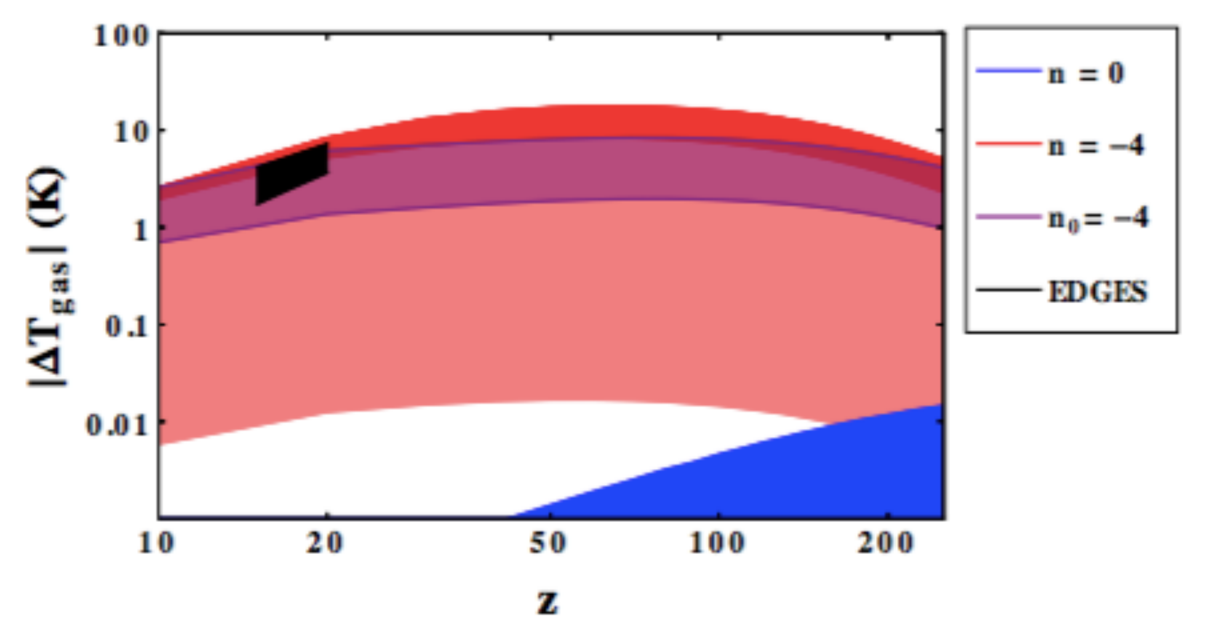
Example troughs from DM/baryon scattering [Barkana]

DM-baryon scattering in the early universe

TRS & Wu 1803.09734

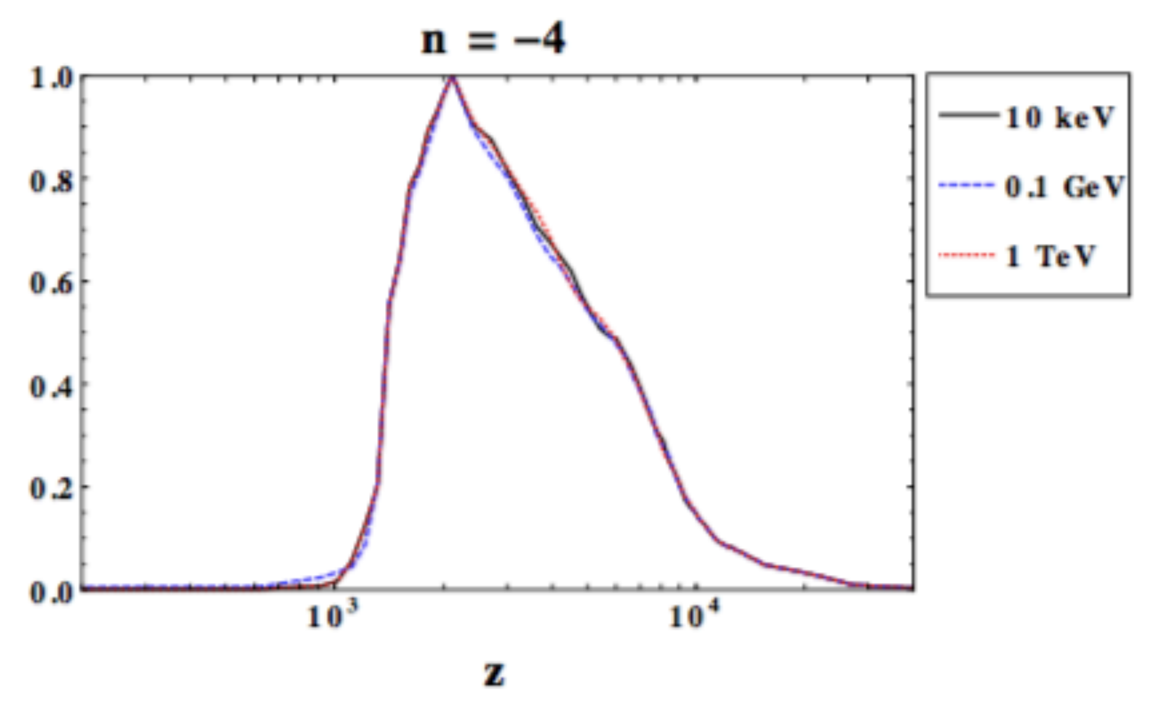
- Modify perturbation-evolution equations, temperature-evolution equations, solve using public CLASS code.
- $\sigma \sim v^{-4}$ scaling can cool the gas enough to accommodate the EDGES observation for sub-GeV DM masses, without violating CMB bounds.
- Substantially weaker velocity scalings (in particular, $\sigma \sim v^{-2}$ and $\sigma \sim v^{0}$) are not sufficient under standard assumptions.
- Likely requires very light mediator - in general, quite strongly constrained.

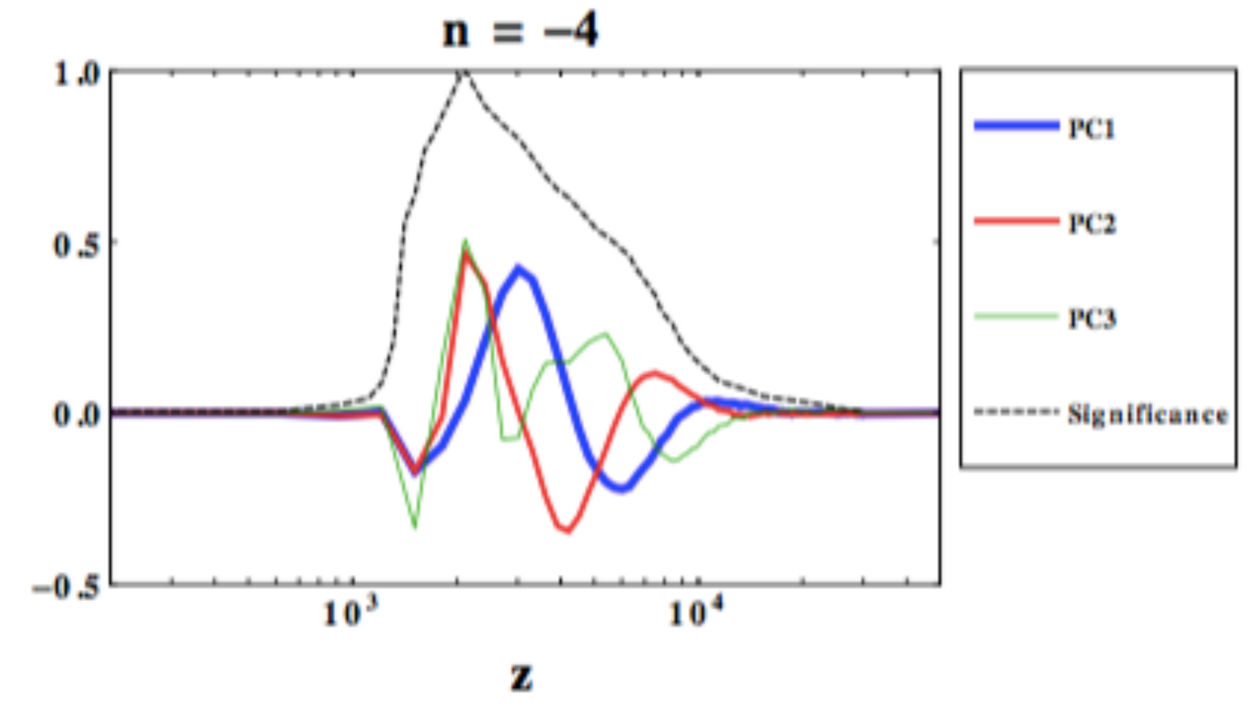




Understanding the CMB constraints on scattering

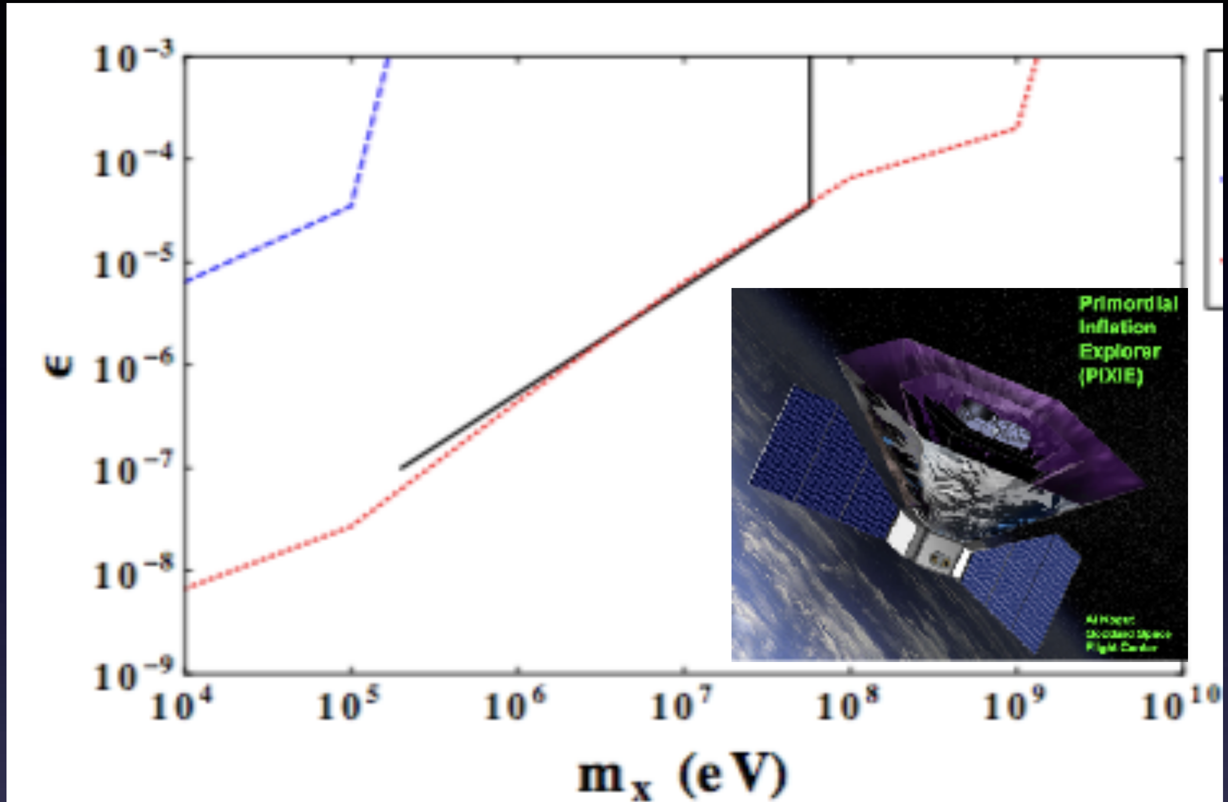
- If problem is linear (valid if DM remains sufficiently cold), final result can be decomposed into contributions from different redshifts.
- To probe impact of different redshifts, consider the effects of turning on scattering for short periods.
- We see the constraint dominantly comes from $z\sim10^3$-few x 10^4 - suppressing signal at these redshifts would evade CMB limits.
- We have developed a principal component basis for arbitrary redshift-dependent scattering histories - allows quick estimation of constraints for a wide range of redshift-dependent scattering histories.





Probing millicharged dark matter

- Several authors [e.g. Munoz et al '18, Berlin et al '18, Barkana et al '18] have suggested that if ~1% of (10-100 MeV) DM carries a tiny electric charge, this could explain the signal.
- Evade CMB-anisotropy constraints because bulk of DM is not interacting (although in strongly-coupled case, constrained to <0.6% [1805.11616])



TRS & Wu, 1803.09734

- But early DM-baryon interactions (cooling the gas) could distort CMB blackbody spectrum [Ali-Haimoud et al '2015, Choi et al '17] - depends on energy flow from baryons to DM, like EDGES, not on gravitational effects.

$$\rho_\gamma \frac{d\Delta}{dt} = \frac{3}{2} n_b \frac{2\mu_b}{m_e} R_\gamma \left(T_b - T_\gamma\right)$$

- We find that extending these limits to fractional abundance with millicharge, next-gen experiment PIXIE could test this parameter space.

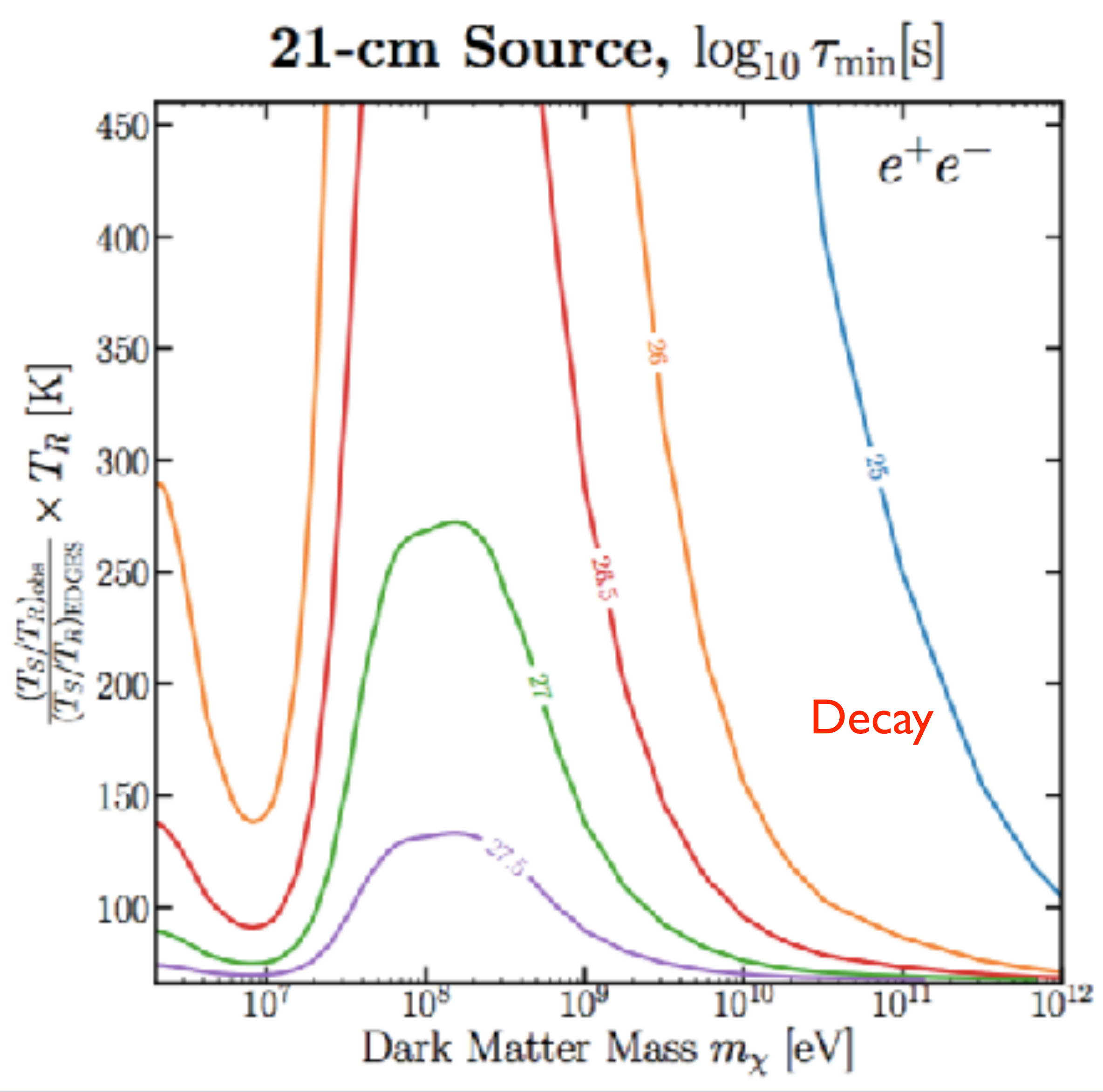
Constraining DM annihilation/ decay with 21cm

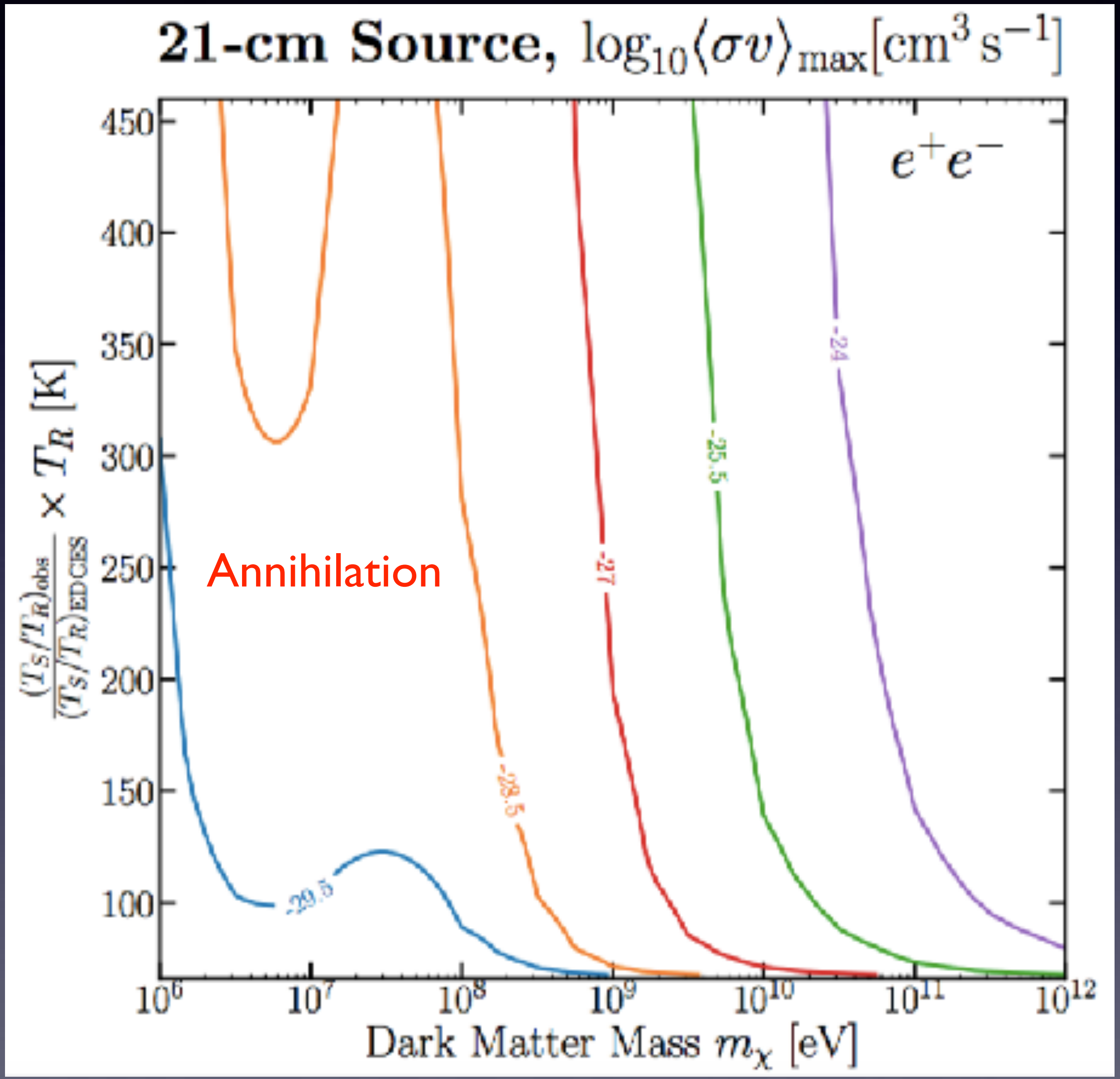
Liu & TRS 1803.09739

- If we can constrain the gas temperature at z~17 at a similar level of precision to the EDGES claim (T~5 K), what can we learn about DM annihilation/decay?
- Some previous studies [Lopez-Honorez et al '16, Poulin et al '17], but if we want to use EDGES result, need to account for whatever process is causing the deep absorption trough (else limits are unrealistically strong).
- Simplest case: extra radiation backgrounds, limit on gas temperature increases, but otherwise keep standard scenario.
- More complex cases: new gas-cooling processes (need to account for these when computing heating from decay/annihilation).
- We study the heating from annihilation and decay in the presence of:
  - DM-baryon scattering (all DM or sub-component)
  - Early baryon-photon decoupling
  - Extra radiation backgrounds

- We carefully model the cooling of annihilation products, and include a conservative model for dark matter structure formation (increasing annihilation rate).

Annihilation/decay heating + extra photons

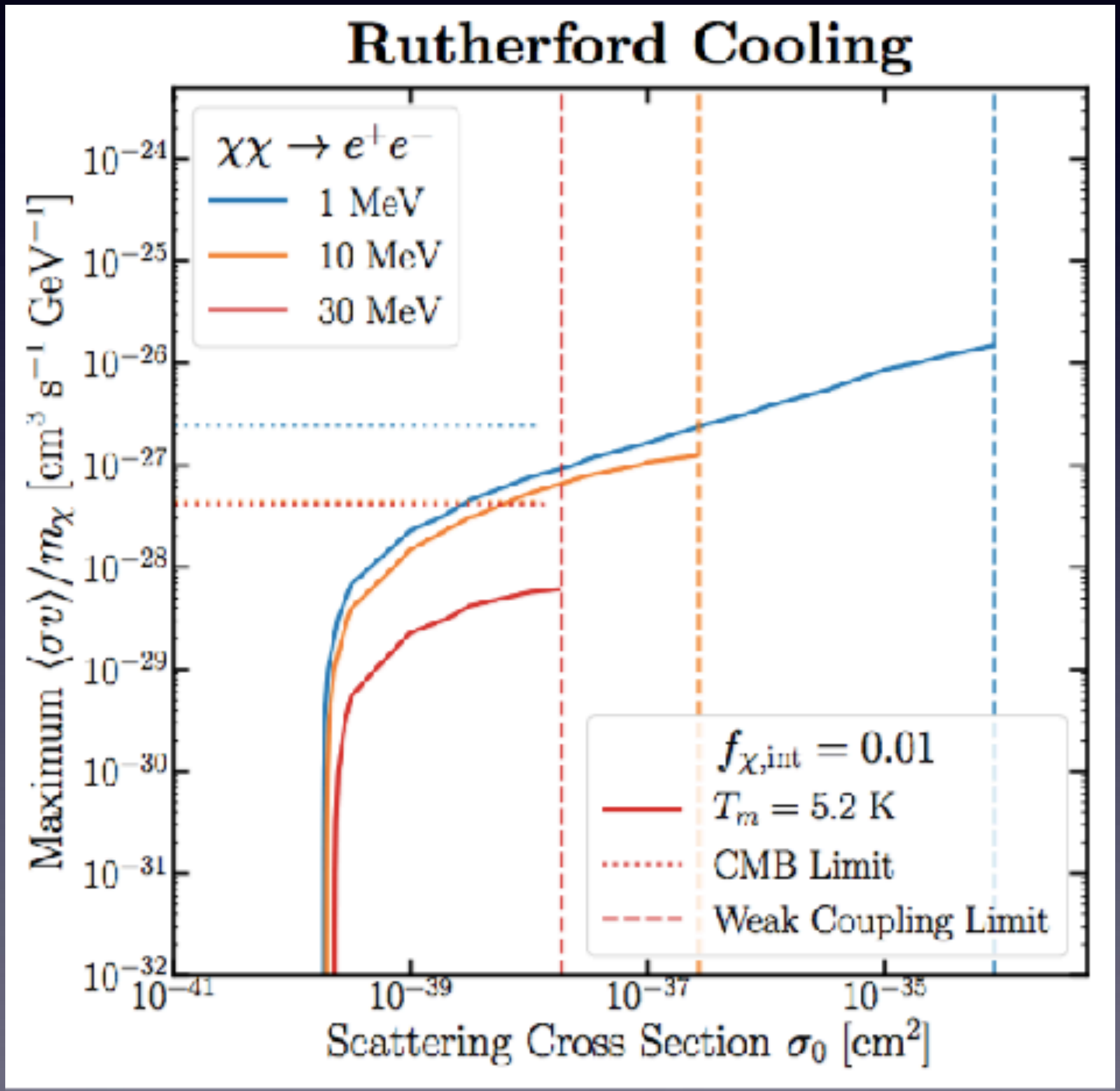




- Example for decay/annihilation to electrons - if extra radiation backgrounds are of same order as the CMB (at 21cm frequency), probe lifetimes of a few x 10^{27} s for 100 MeV DM, annihilation cross sections of order few x 10^{-30} cm^3/s - four orders of magnitude below thermal relic. [See also d'Amico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

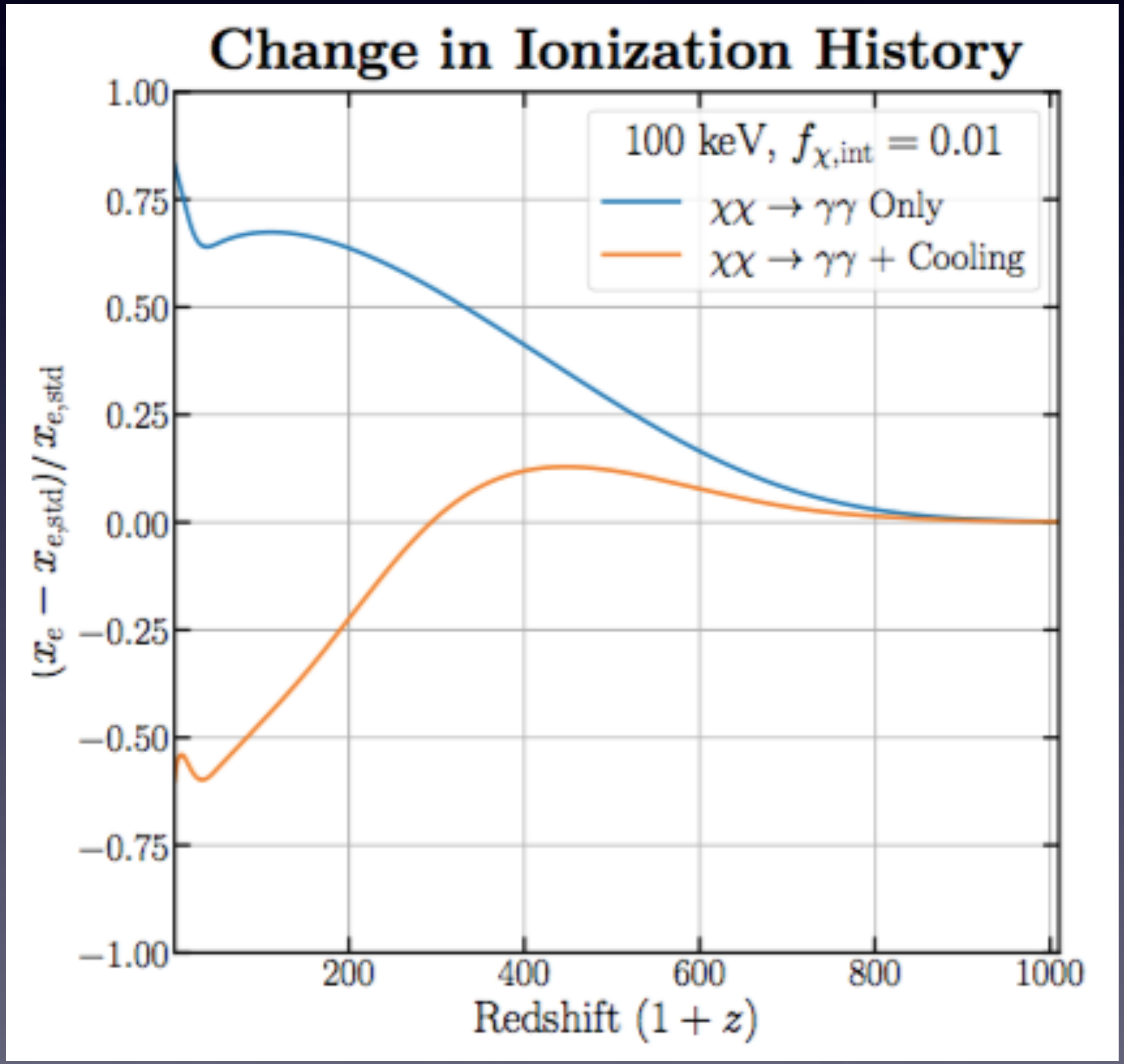
Annihilation/decay + weak scattering

- When we turn on DM-baryon scattering, the gas is cooled - counteracts heating from annihilation/decay
- Limits relax as cross section gets larger
- But for strong enough scattering, DM temperature = baryon temperature - increasing scattering further has no effect.
- Heating from exotic sources is divided between baryons and interacting DM - limit depends on #density of interacting DM, but not on xsec



Annihilation/decay + strong scattering

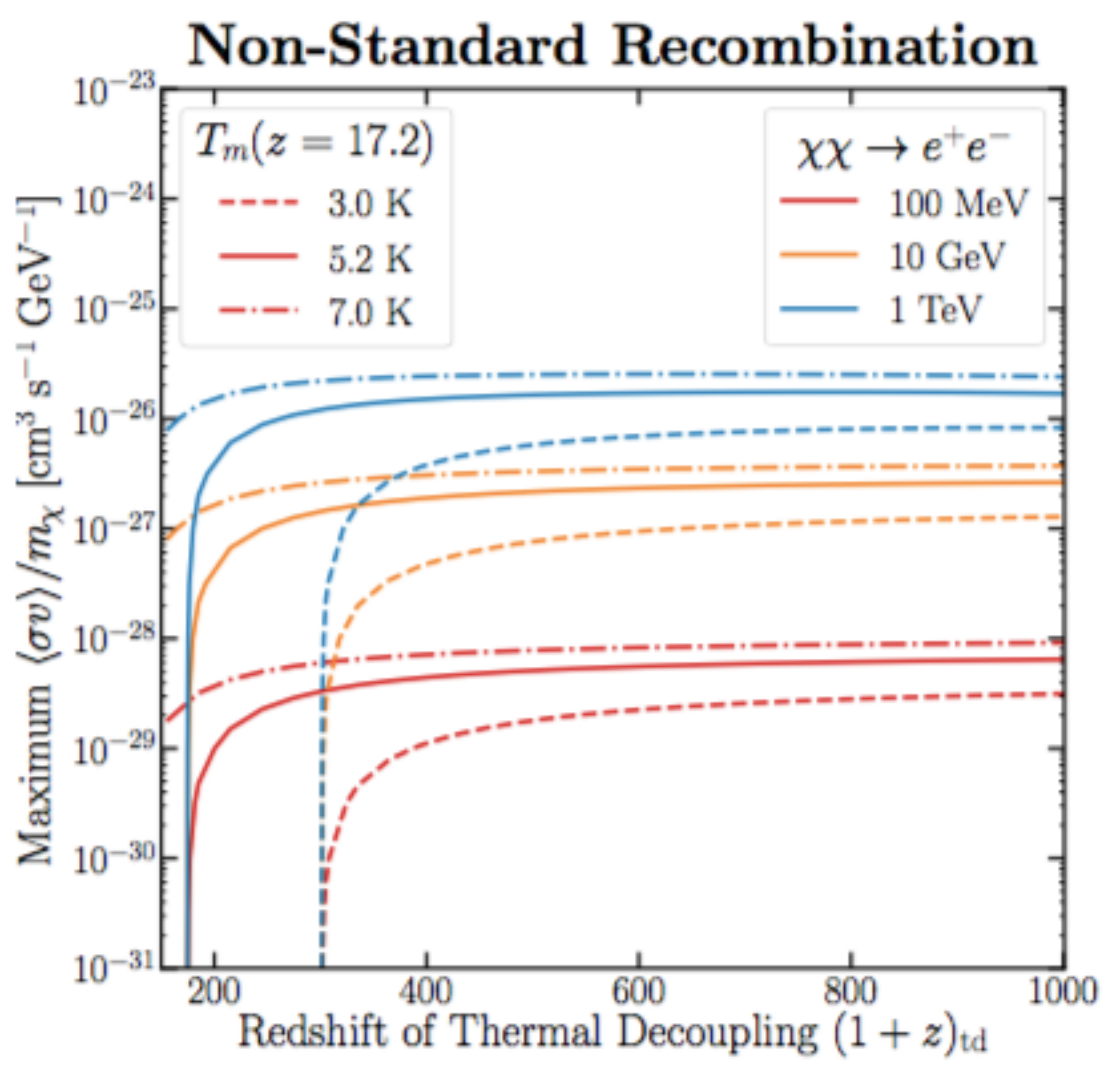
- Case where baryons and (some subcomponent of) DM are strongly coupled - DM acts as heat sink for all effects heating baryons
- Causes early photon-gas decoupling, gas has longer to cool due to expansion.
- Effect is independent of scattering xsec, once xsec is large enough.
- Net effect is delayed 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

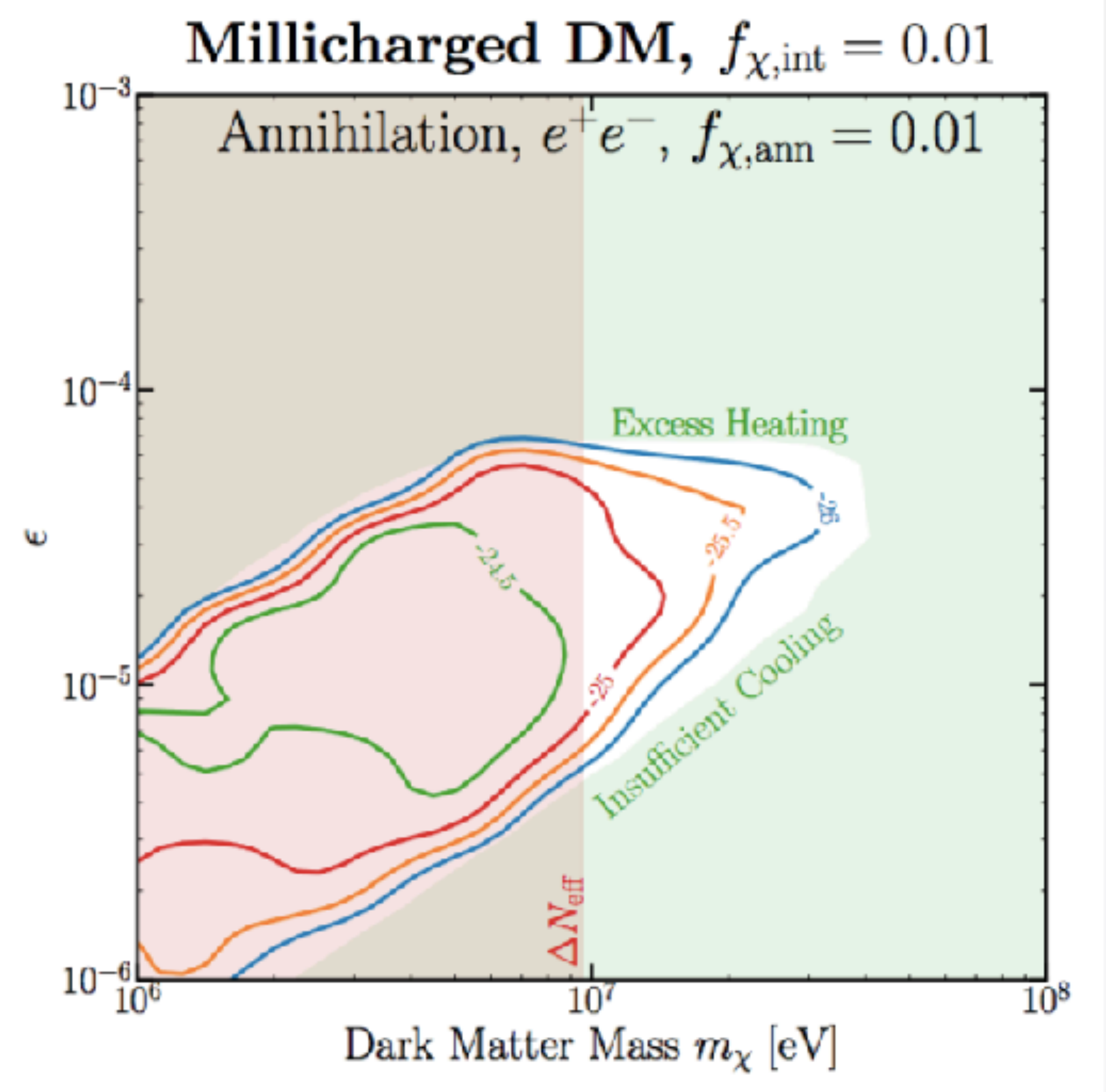
- Suppose baryons decouple from photons earlier than expected (can be due to a small scattering DM component, or for other reasons).
- If decoupling is early enough, gas temperature before heating at z~17 is very small - set constraint by requiring DM heating not overproduce total observed T_{gas}, starting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



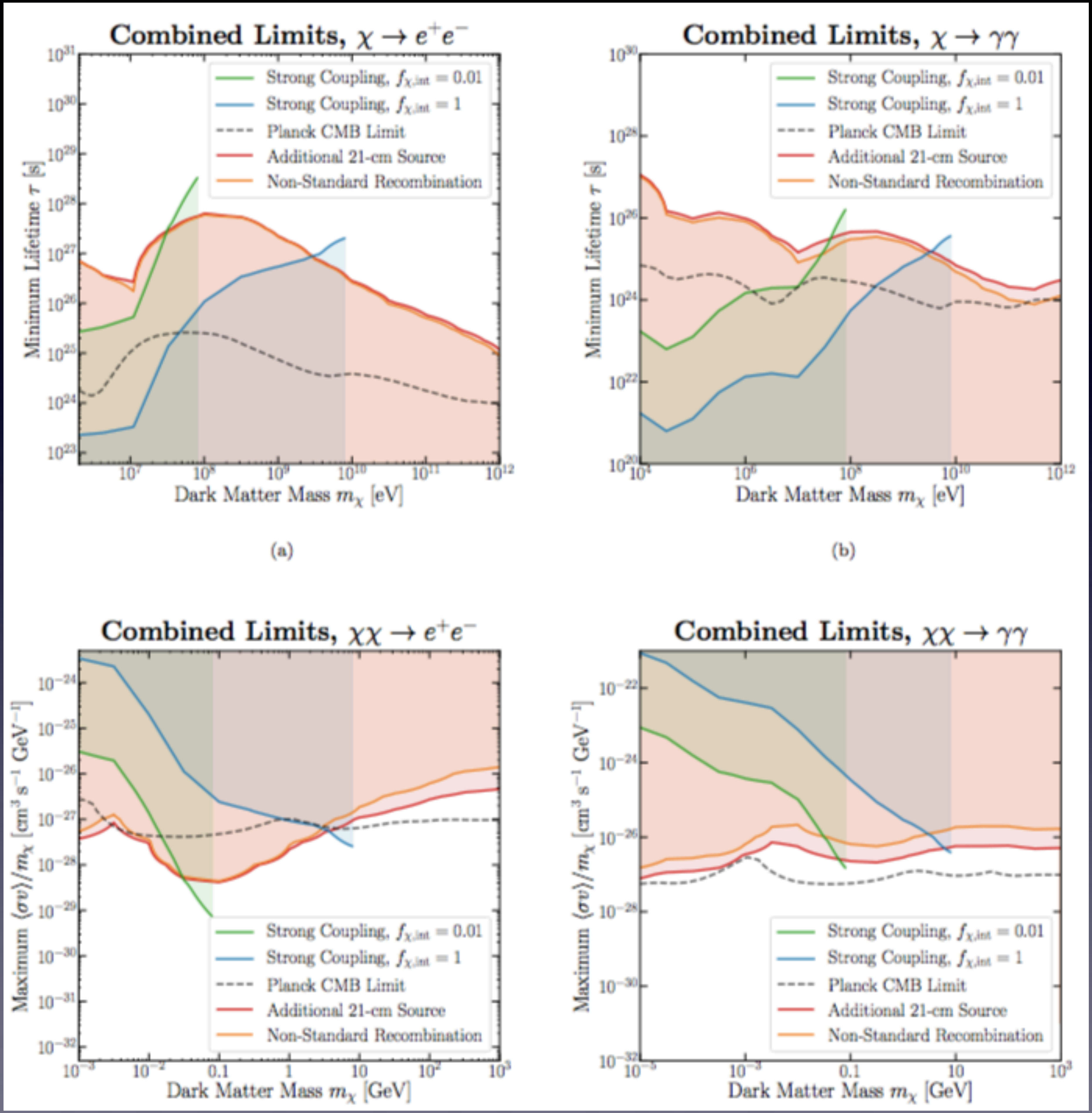
Example of DM annihilation to e^+e^- pairs; constraints as a function of decoupling redshift

Millicharged DM

- 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.



- 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-)



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.

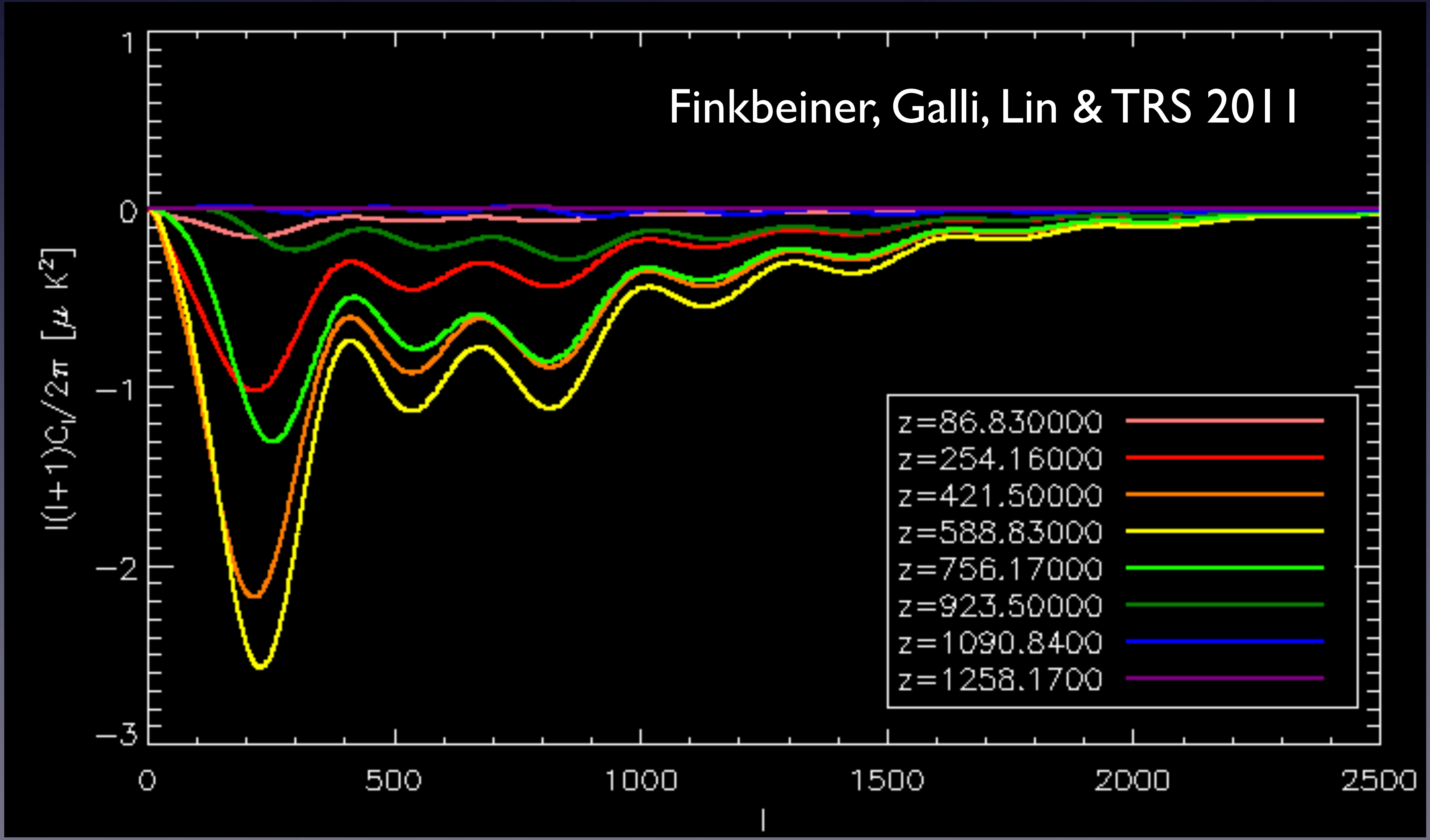
Summary

- Measurements of the ionization and temperature history of the early universe, via CMB and 21cm observations, can set stringent constraints on the properties of dark matter.
- Scattering between baryons and the bulk of the DM during the pre-recombination epoch $z \sim 10^3$-few x 10^4 is tightly constrained by the CMB. We have developed a framework for estimating CMB constraints on general scattering histories for cold DM.
- Scattering between baryons and a small sub-component of the DM is likely difficult to constrain with CMB anisotropies, but could be tested by future observations of CMB blackbody spectral distortions.
- Confirmed measurement of a global 21cm signal could set robust and stringent new constraints on DM annihilation/decay (especially light DM decaying to electrons), even in the presence of deviations from the standard scenario.
- Modifications to standard recombination, e.g. by having a small fraction of the DM coupling strongly to the baryons, could weaken standard limits on annihilating/decaying light dark matter from the CMB.

BONUS SLIDES

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.


Finkbeiner, Galli, Lin & TRS 2011

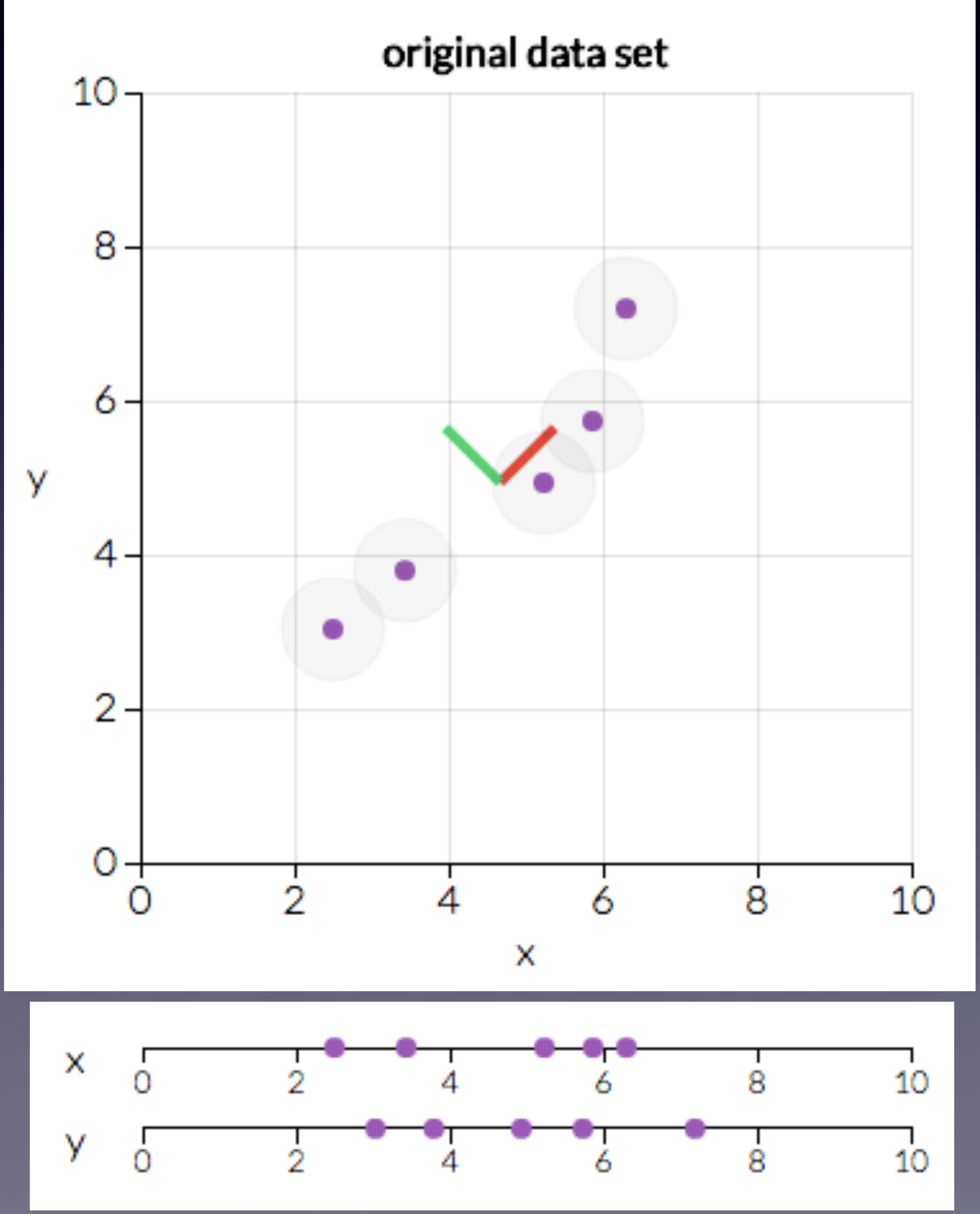
- Note: ionization at different redshifts has similar (albeit not identical) effects - can be described by low-dimensional parameter space.
- Codify with principal component analysis.

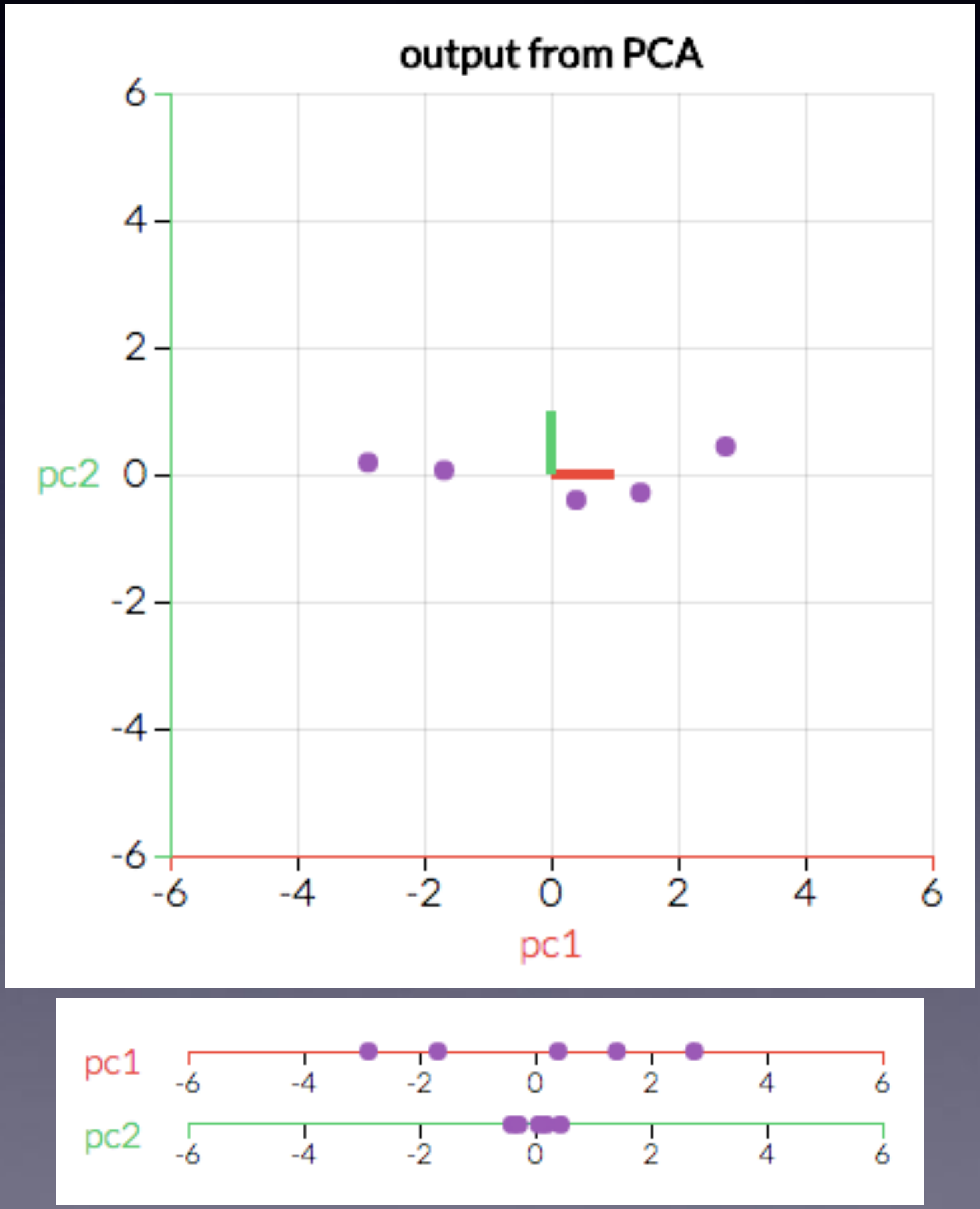
Principal component analysis

- Consider a space of models that span some interesting "model space" and predict signals in some dataset.
- Model space can generally be very high-dimensional, but signal space may be approximated by a low-dimensional space.
- Goal: find orthogonal basis for signal space, where first few basis vectors capture most of the significance of signals (with respect to some null hypothesis).
- Can then expand any model (within space spanned by initial set) in terms of corresponding model-space basis, and the first few terms in the expansion should largely describe the signal significance.

Toy example

Image credit: http://setosa.io/ev/principal-component-analysis/





Principal component analysis details

- Calculate Fisher matrix (describes significance) for signals as a function of model parameters $\{\alpha_i\}$

$$(F_e)_{ij} = \sum_{\ell} \left(\frac{\partial C_\ell}{\partial \alpha_i} \right)^T \cdot \Sigma_\ell^{-1} \cdot \frac{\partial C_\ell}{\partial \alpha_j}.$$

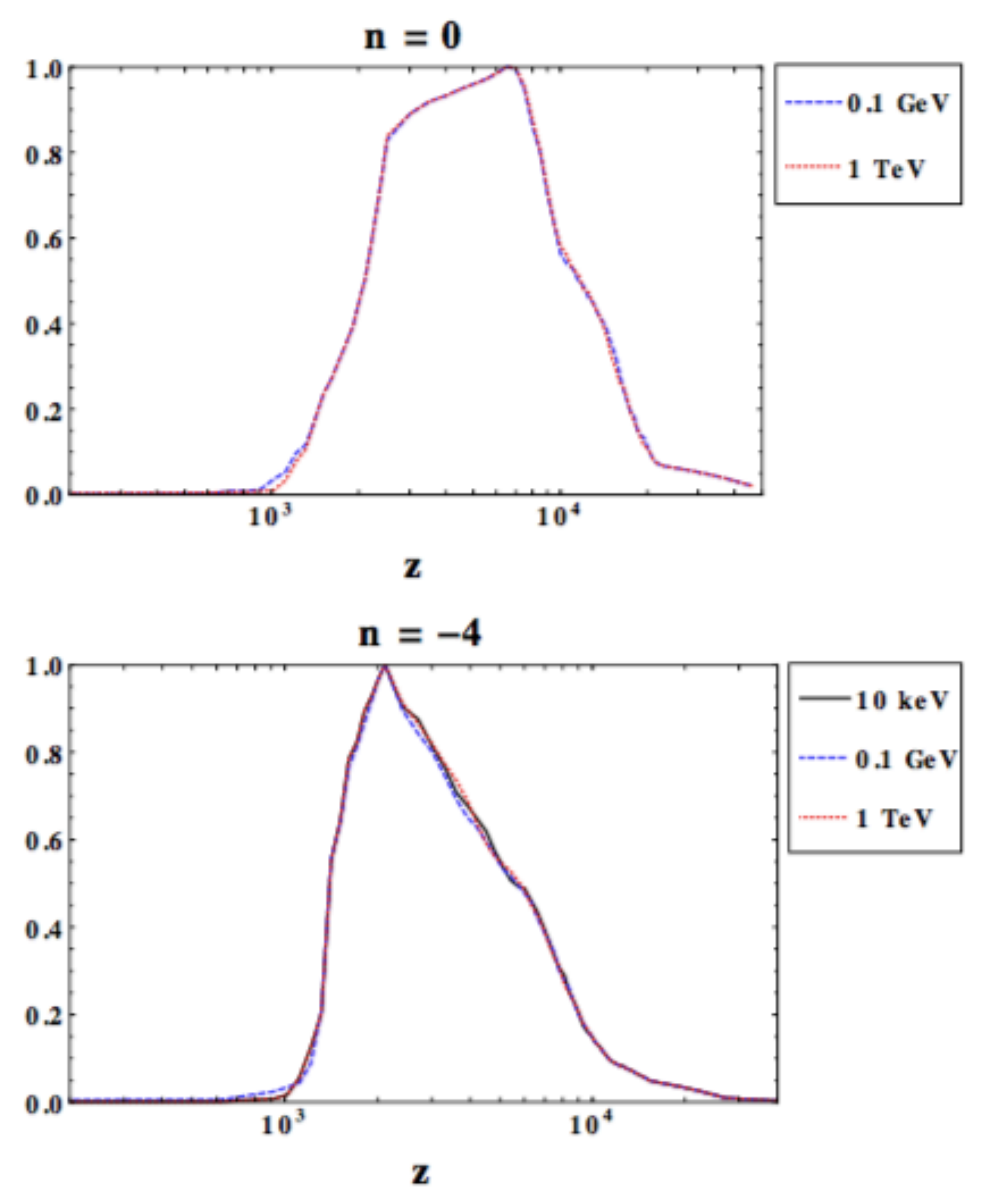
$$\Sigma_\ell = \frac{2}{2l+1} \times \begin{pmatrix} (C_\ell^{TT})^2 & (C_\ell^{TE})^2 & C_\ell^{TT} C_\ell^{TE} \\ (C_\ell^{TE})^2 & (C_\ell^{EE})^2 & C_\ell^{EE} C_\ell^{TE} \\ C_\ell^{TT} C_\ell^{TE} & C_\ell^{EE} C_\ell^{TE} & \frac{1}{2}\left[(C_\ell^{TE})^2 + C_\ell^{TT} C_\ell^{EE}\right] \end{pmatrix}$$

- Marginalize over cosmological parameters by including them in Fisher matrix, then inverting + truncating Fisher matrix.
- Diagonalize this matrix to obtain principal components (eigenvectors) PC_i.
- Eigenvalues λ_i describe the contribution of the corresponding eigenvectors to the variance. Suppose the null hypothesis is the best-fit result, then if a model to be tested can be written in the form $\sum \alpha_i \mathrm{PC}_i$

we estimate it will be excluded with approximately, $\Delta\chi^2 \approx \sum \lambda_i \alpha_i^2$

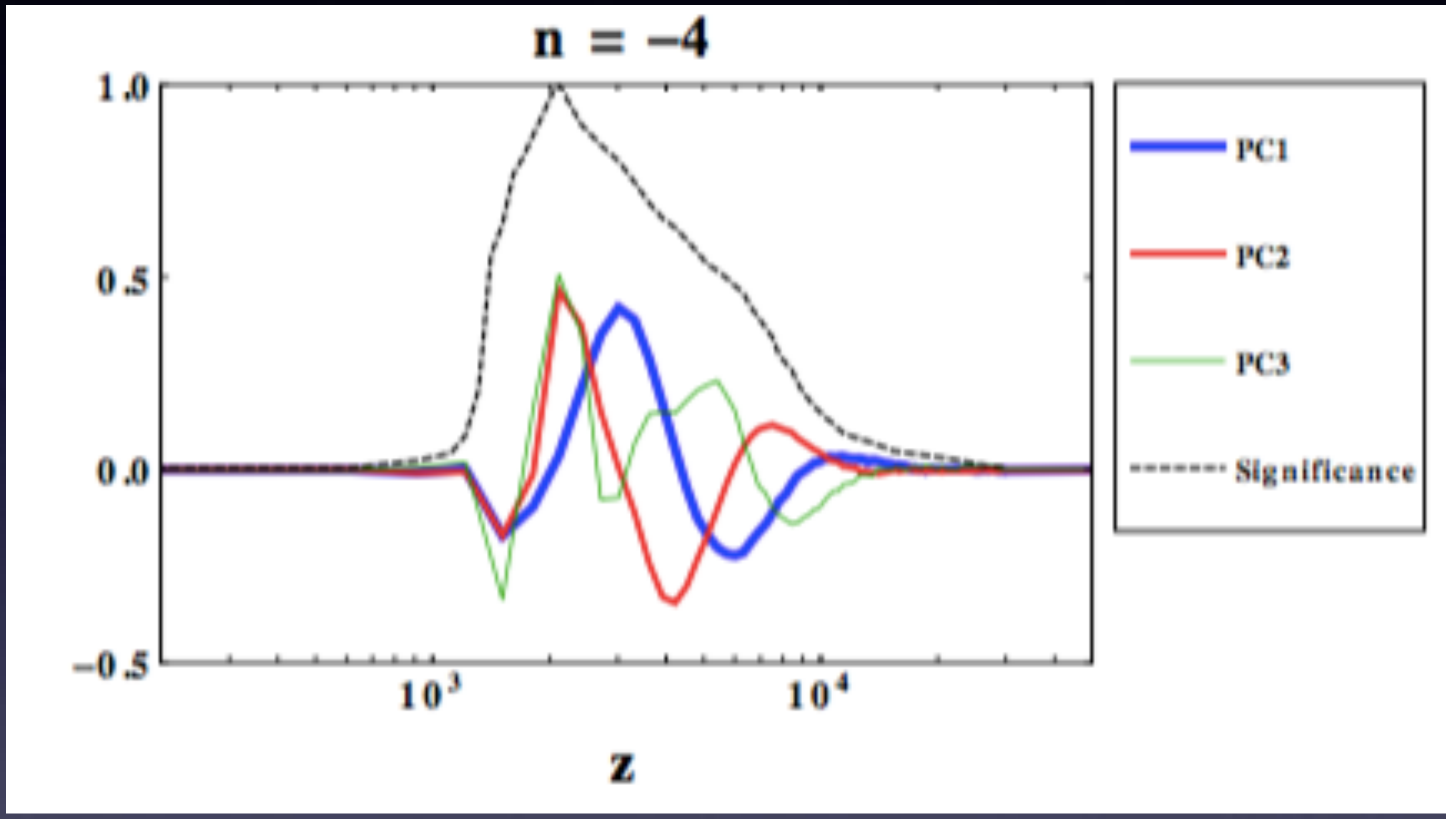
Understanding the CMB constraints on scattering

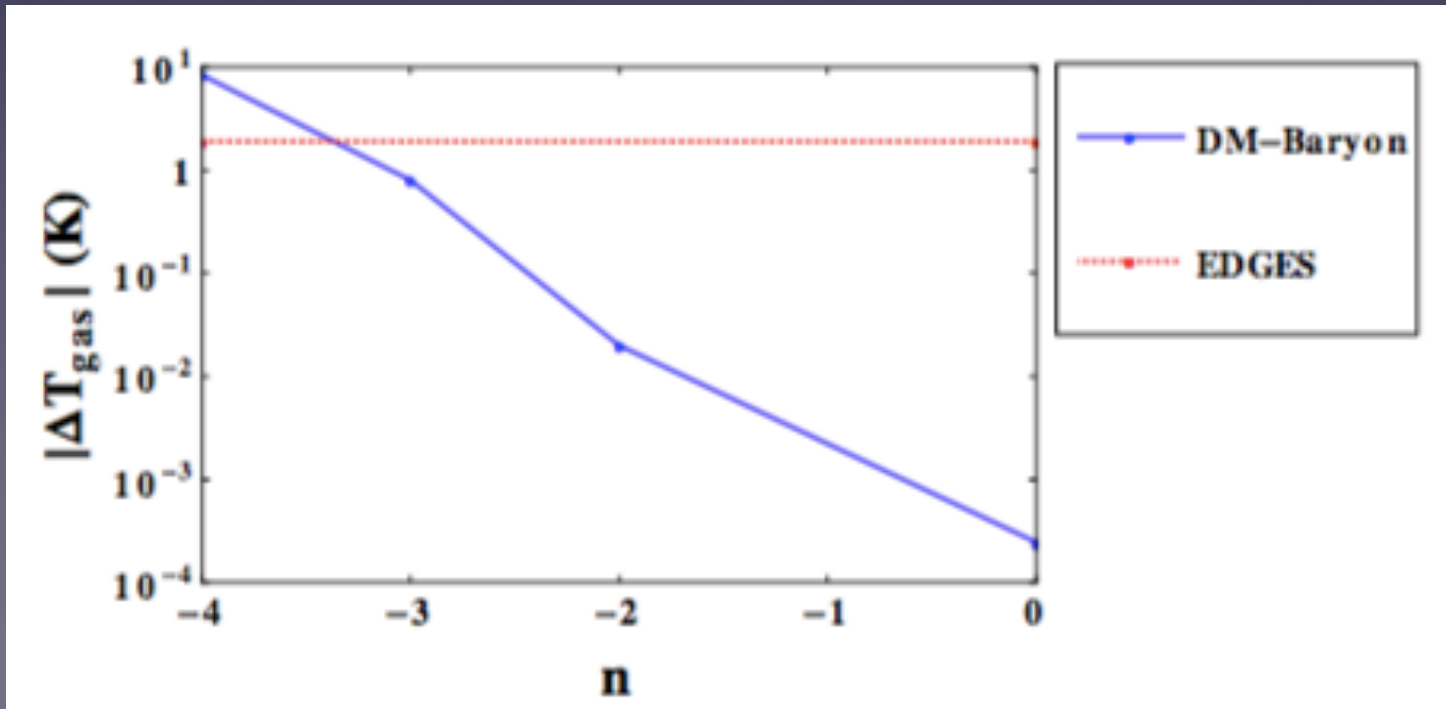
- If problem is linear (valid if DM remains sufficiently cold), final result can be decomposed into contributions from different redshifts.
- To probe impact of different redshifts, consider the effects of turning on scattering for short periods.
- Can generate a Fisher matrix F based on N such basis models, with scattering turned on around redshift z_i, i=1..N.
- Plot F_{ii} to estimate which redshifts have a large signal in the CMB.
- We see the constraint dominantly comes from z~10^3-few x 10^4 - suppressing signal at these redshifts would evade CMB limits.



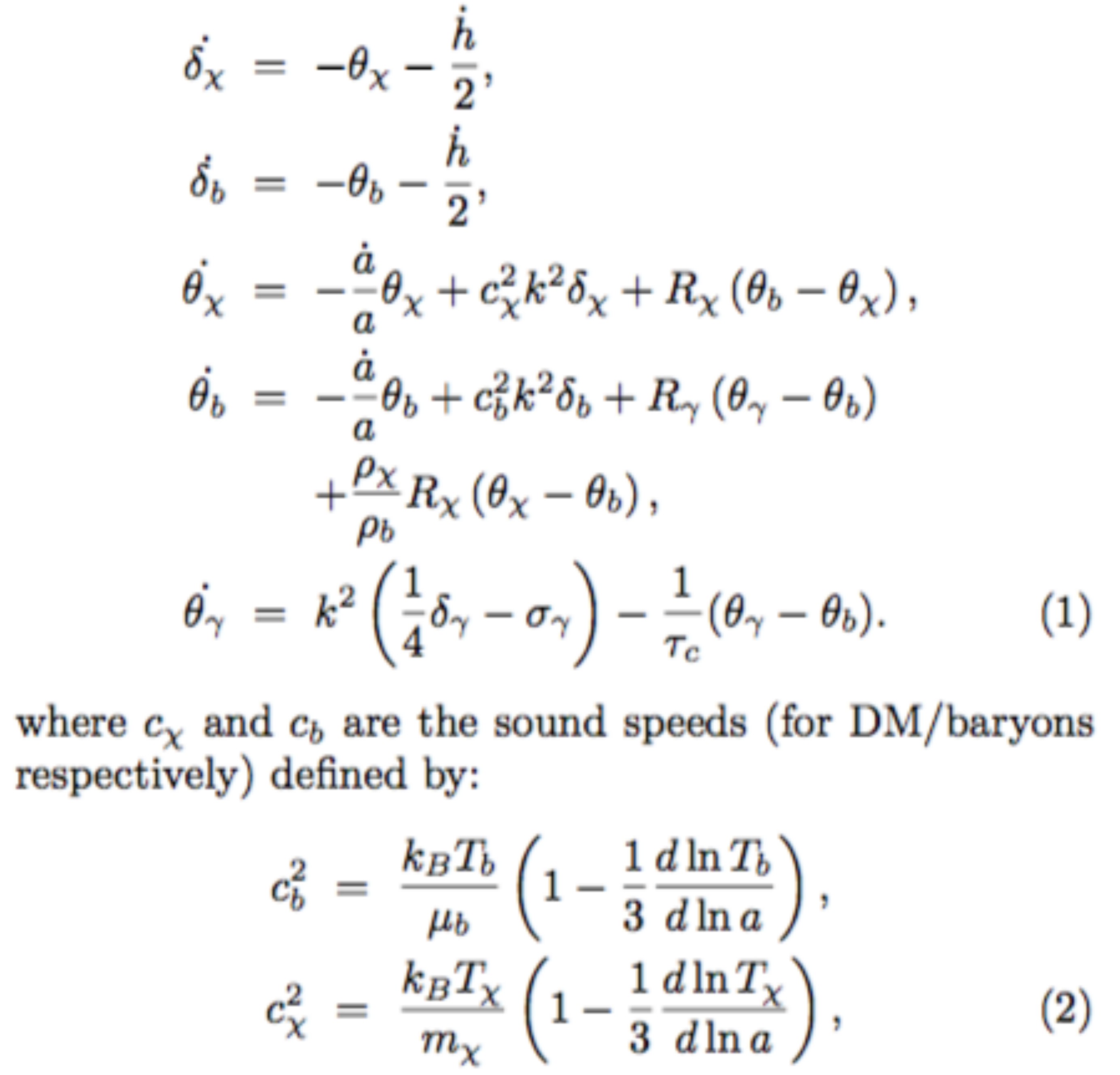
A principal component analysis for DM-baryon scattering

- Using the same Fisher matrix, we can perform a principal component analysis as previously.
- Find that first four PCs account for 90-95% of the variance.
- Allows quick estimate of constraints for a wide range of redshift-dependent scattering histories.
- For example, if 100% of DM scatters on baryons, cooling to match EDGES results requires n < -3.
- Caveat: will fail (linearity breaks down) if the DM thermal velocity from scattering becomes comparable to baryon thermal velocity.





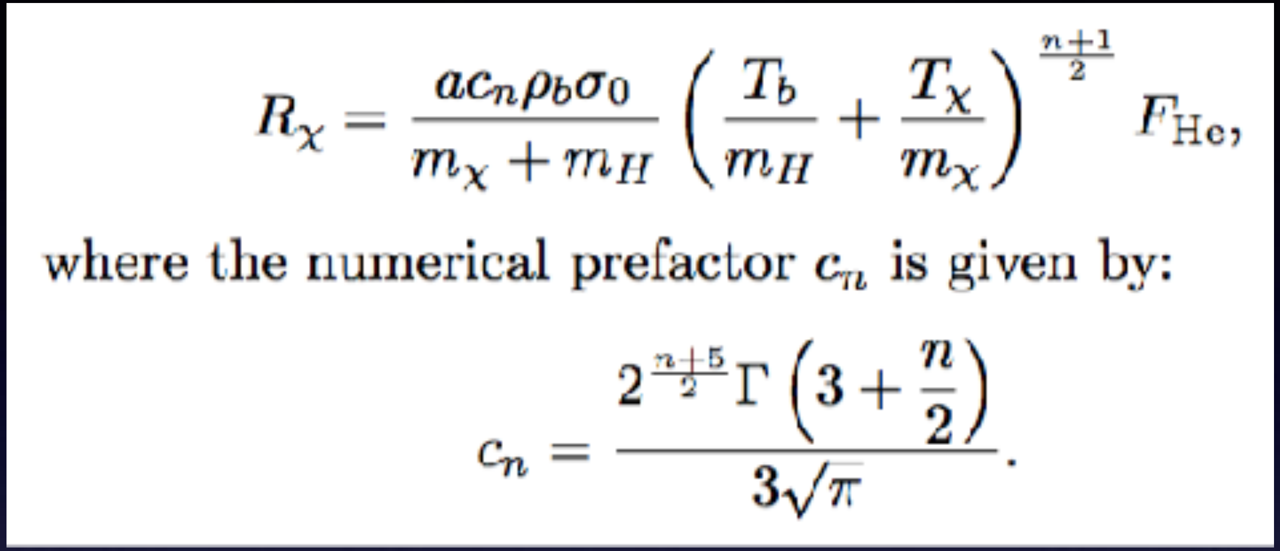
Modifications to evolution equations



$$
\begin{aligned}
\dot{\delta}_\chi &= -\theta_\chi - \frac{\dot{h}}{2}, \\
\dot{\delta}_b &= -\theta_b - \frac{\dot{h}}{2}, \\
\dot{\theta}_\chi &= -\frac{\dot{a}}{a}\theta_\chi + c_\chi^2 k^2 \delta_\chi + R_\chi \left(\theta_b - \theta_\chi\right), \\
\dot{\theta}_b &= -\frac{\dot{a}}{a}\theta_b + c_b^2 k^2 \delta_b + R_\gamma \left(\theta_\gamma - \theta_b\right) \\
&\quad + \frac{\rho_\chi}{\rho_b} R_\chi \left(\theta_\chi - \theta_b\right), \\
\dot{\theta}_\gamma &= k^2 \left(\frac{1}{4}\delta_\gamma - \sigma_\gamma\right) - \frac{1}{\tau_c}(\theta_\gamma - \theta_b).
\end{aligned} \tag{1}
$$

where c_χ and c_b are the sound speeds (for DM/baryons respectively) defined by:

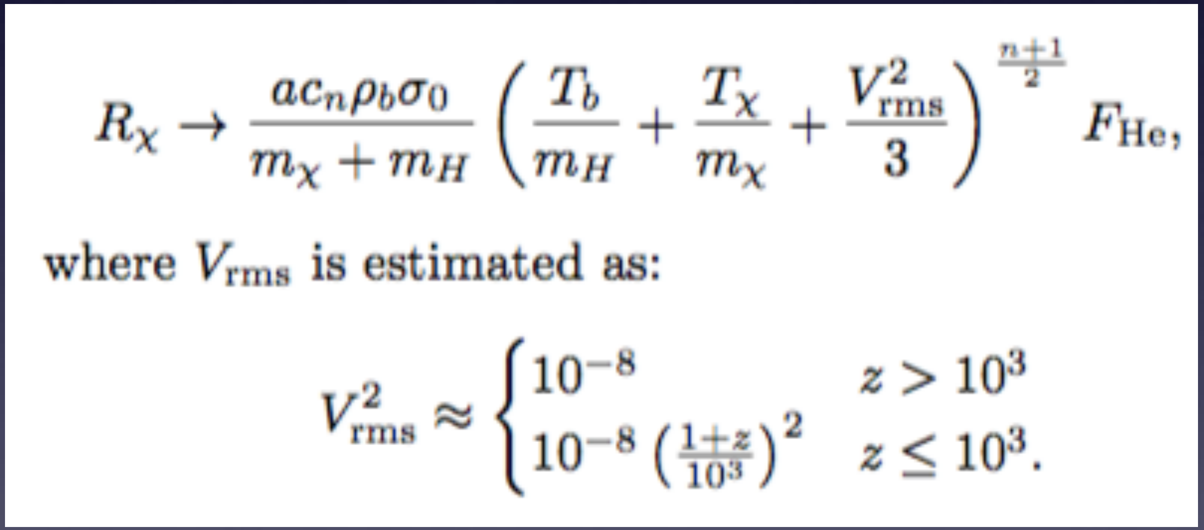
$$
\begin{aligned}
c_b^2 &= \frac{k_B T_b}{\mu_b}\left(1 - \frac{1}{3}\frac{d \ln T_b}{d \ln a}\right), \\
c_\chi^2 &= \frac{k_B T_\chi}{m_\chi}\left(1 - \frac{1}{3}\frac{d \ln T_\chi}{d \ln a}\right),
\end{aligned} \tag{2}
$$



$$
R_\chi = \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H}\left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi}\right)^{\frac{n+1}{2}} F_{\mathrm{He}},
$$

where the numerical prefactor c_n is given by:

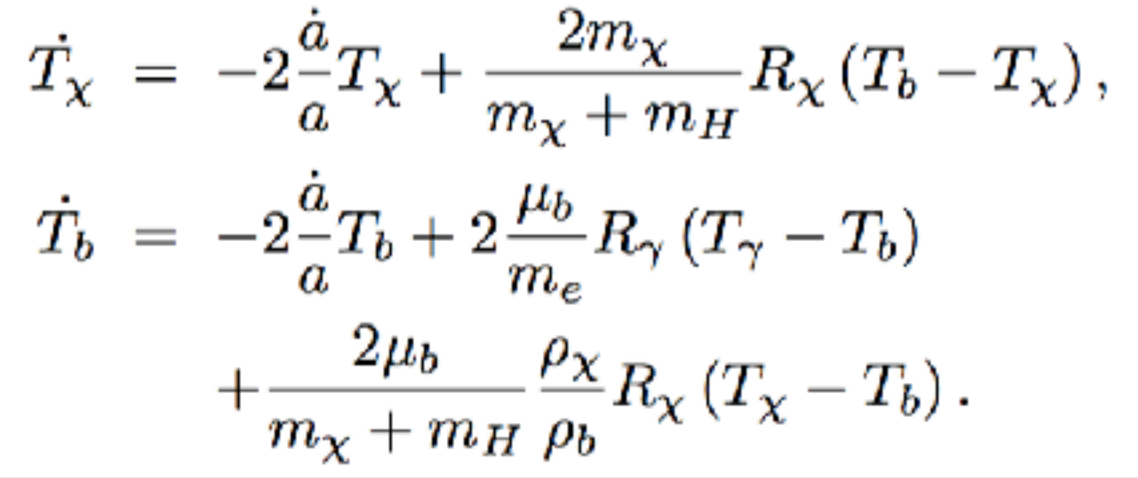
$$
c_n = \frac{2^{\frac{n+5}{2}}\Gamma\left(3 + \frac{n}{2}\right)}{3\sqrt{\pi}}.
$$



$$
R_\chi \to \frac{a c_n \rho_b \sigma_0}{m_\chi + m_H}\left(\frac{T_b}{m_H} + \frac{T_\chi}{m_\chi} + \frac{V_{\mathrm{rms}}^2}{3}\right)^{\frac{n+1}{2}} F_{\mathrm{He}},
$$

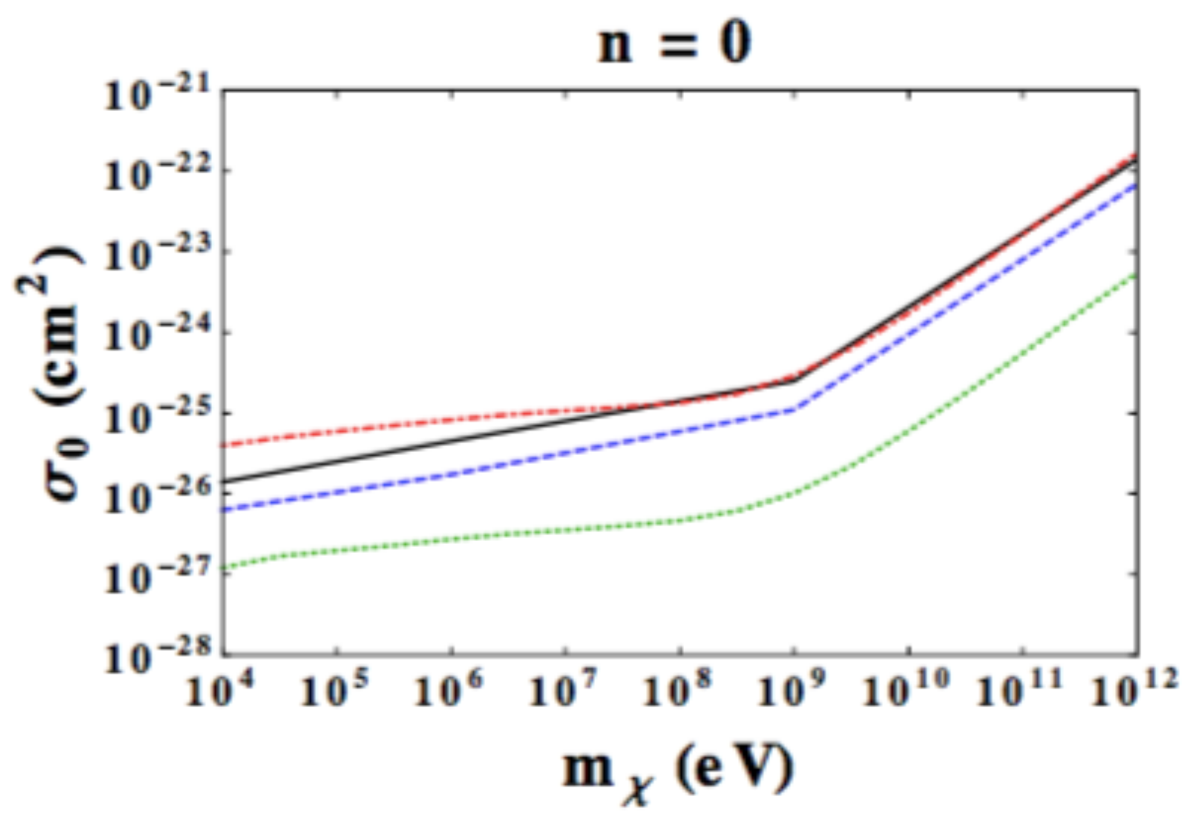
where V_{rms} is estimated as:

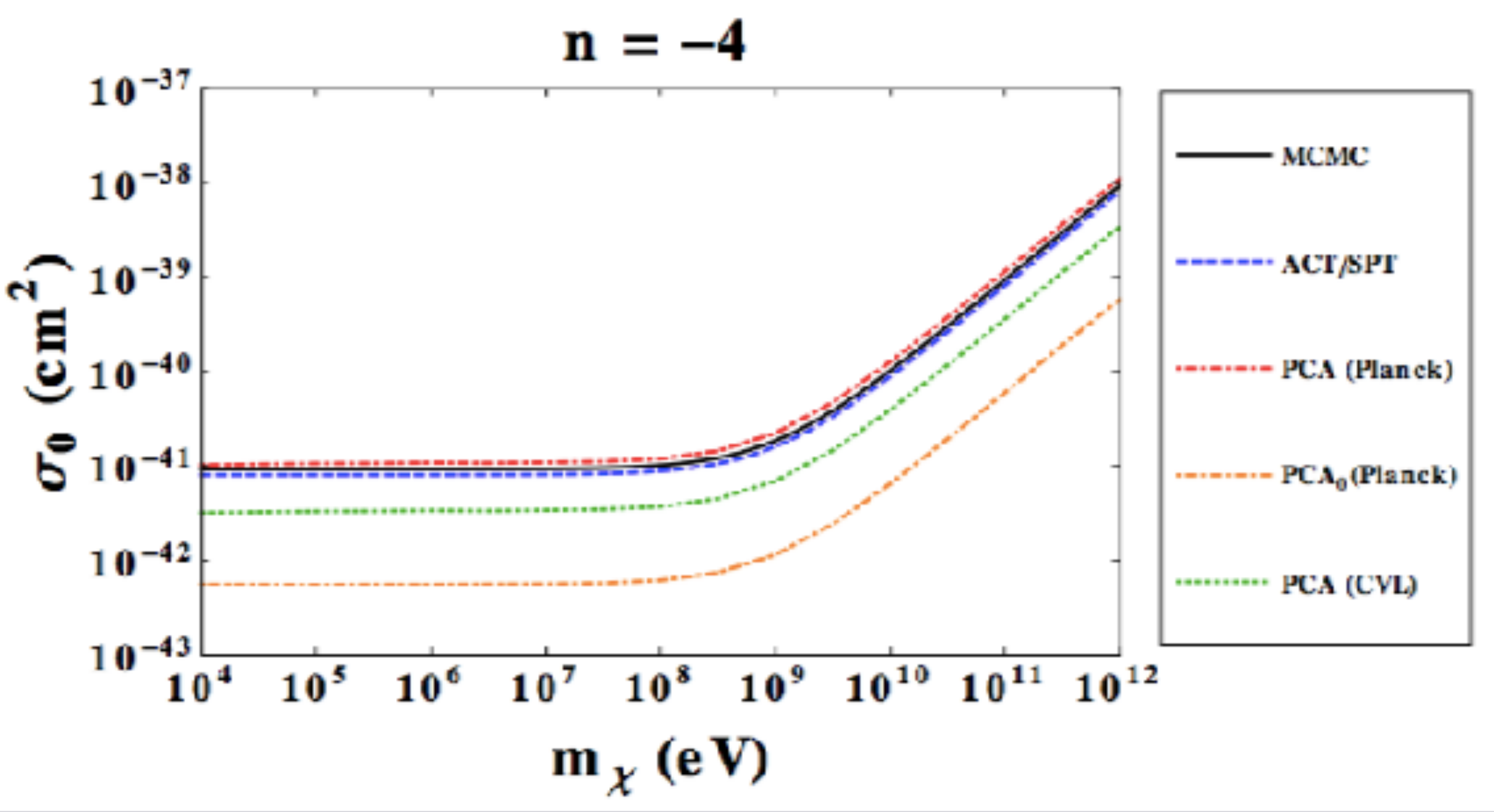
$$
V_{\mathrm{rms}}^2 \approx \begin{cases} 10^{-8} & z > 10^3 \\ 10^{-8}\left(\frac{1+z}{10^3}\right)^2 & z \leq 10^3. \end{cases}
$$



$$
\begin{aligned}
\dot{T}_\chi &= -2\frac{\dot{a}}{a}T_\chi + \frac{2m_\chi}{m_\chi + m_H} R_\chi \left(T_b - T_\chi\right), \\
\dot{T}_b &= -2\frac{\dot{a}}{a}T_b + 2\frac{\mu_b}{m_e} R_\gamma \left(T_\gamma - T_b\right) \\
&\quad + \frac{2\mu_b}{m_\chi + m_H}\frac{\rho_\chi}{\rho_b} R_\chi \left(T_\chi - T_b\right).
\end{aligned}
$$

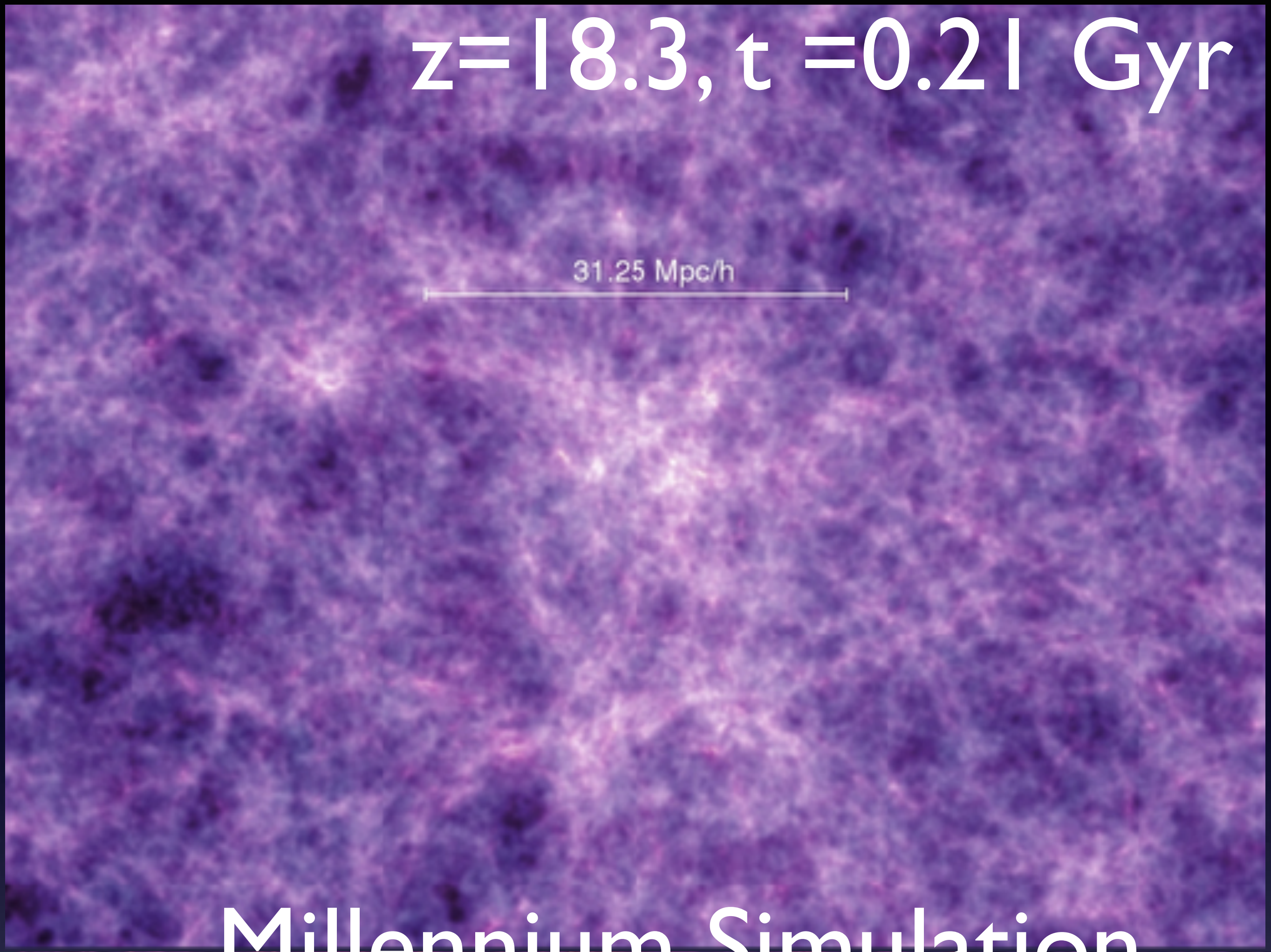
Validation of PCA vs MCMC





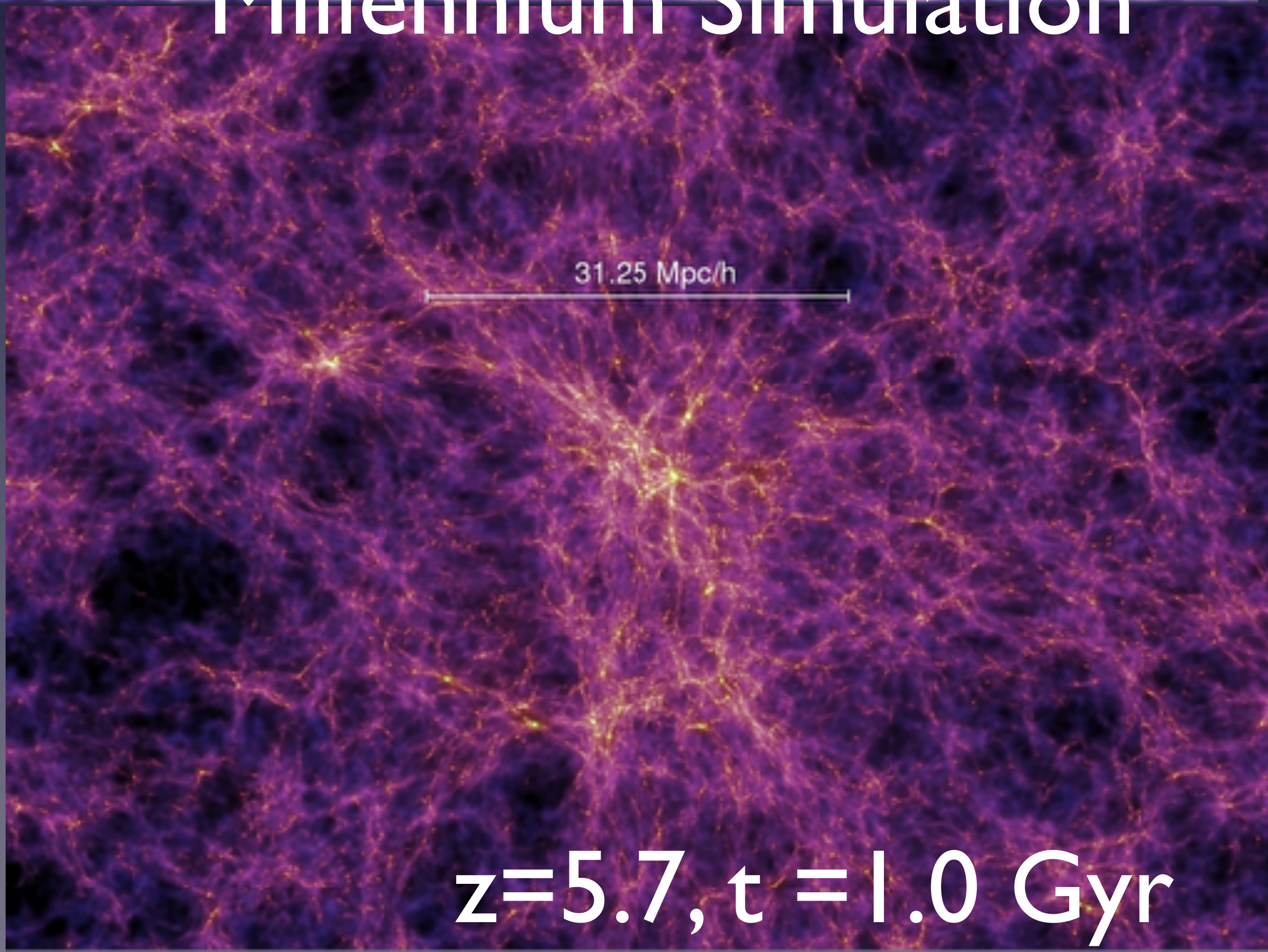
Dark matter in the reionization epoch

- 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.



z=18.3, t =0.21 Gyr

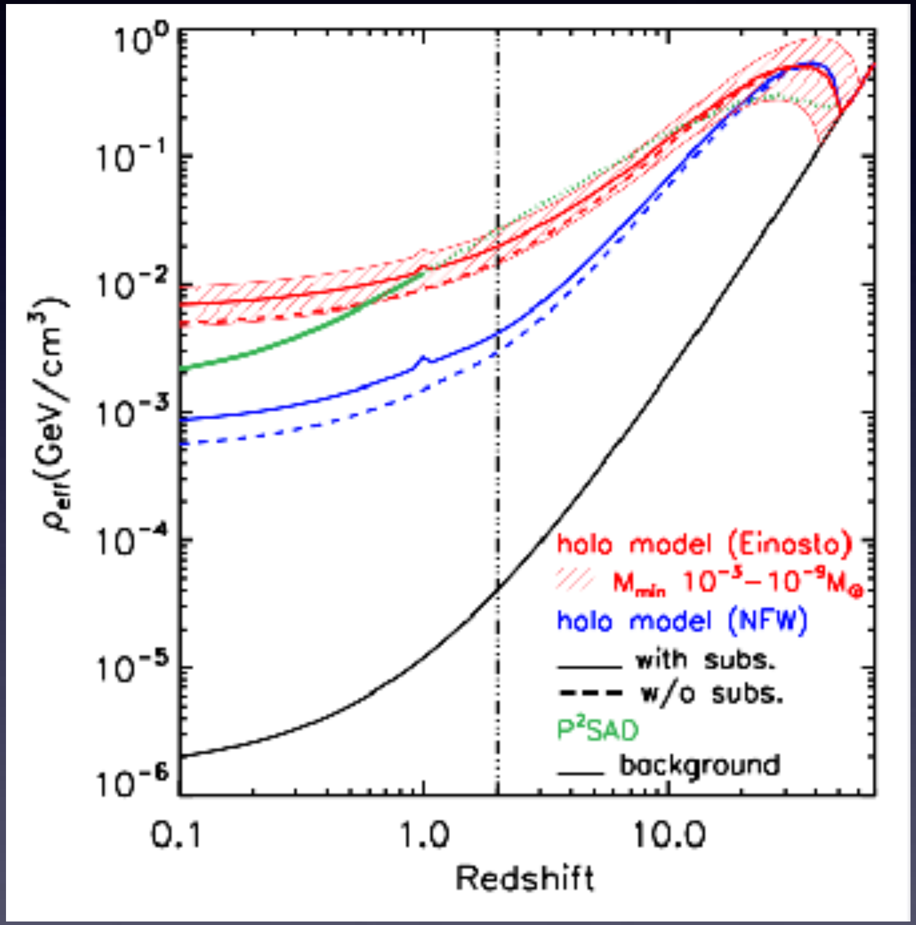
Millennium Simulation



z=5.7, t =1.0 Gyr

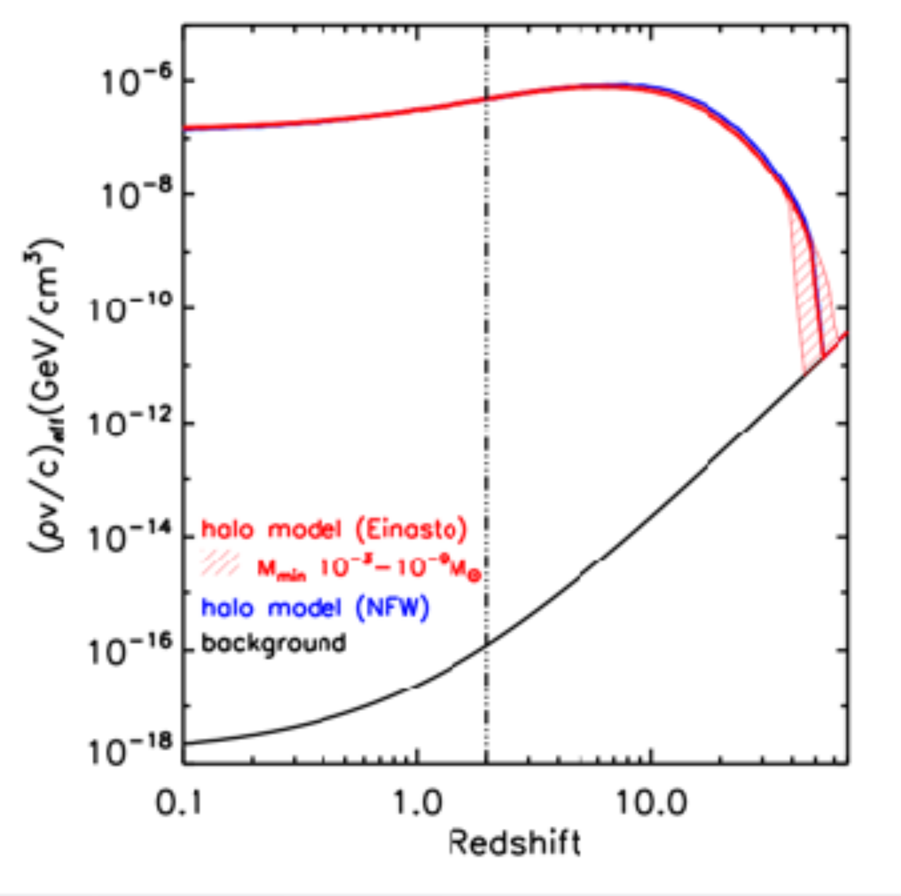
s-wave annihilation

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



p-wave annihilation

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



decay

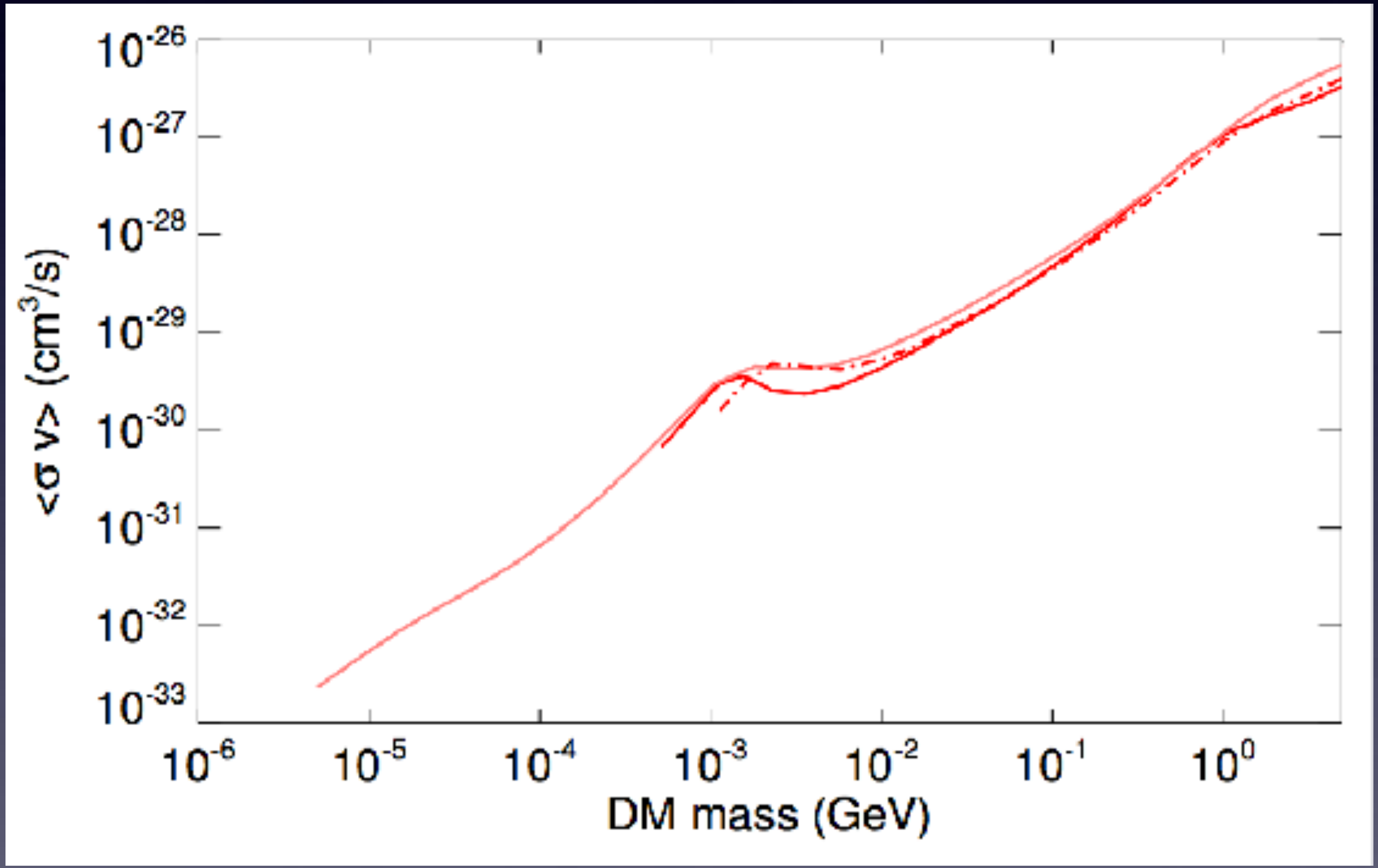
$$\text{rate} \propto \frac{\rho}{\tau} e^{-t/\tau}$$

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

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

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 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

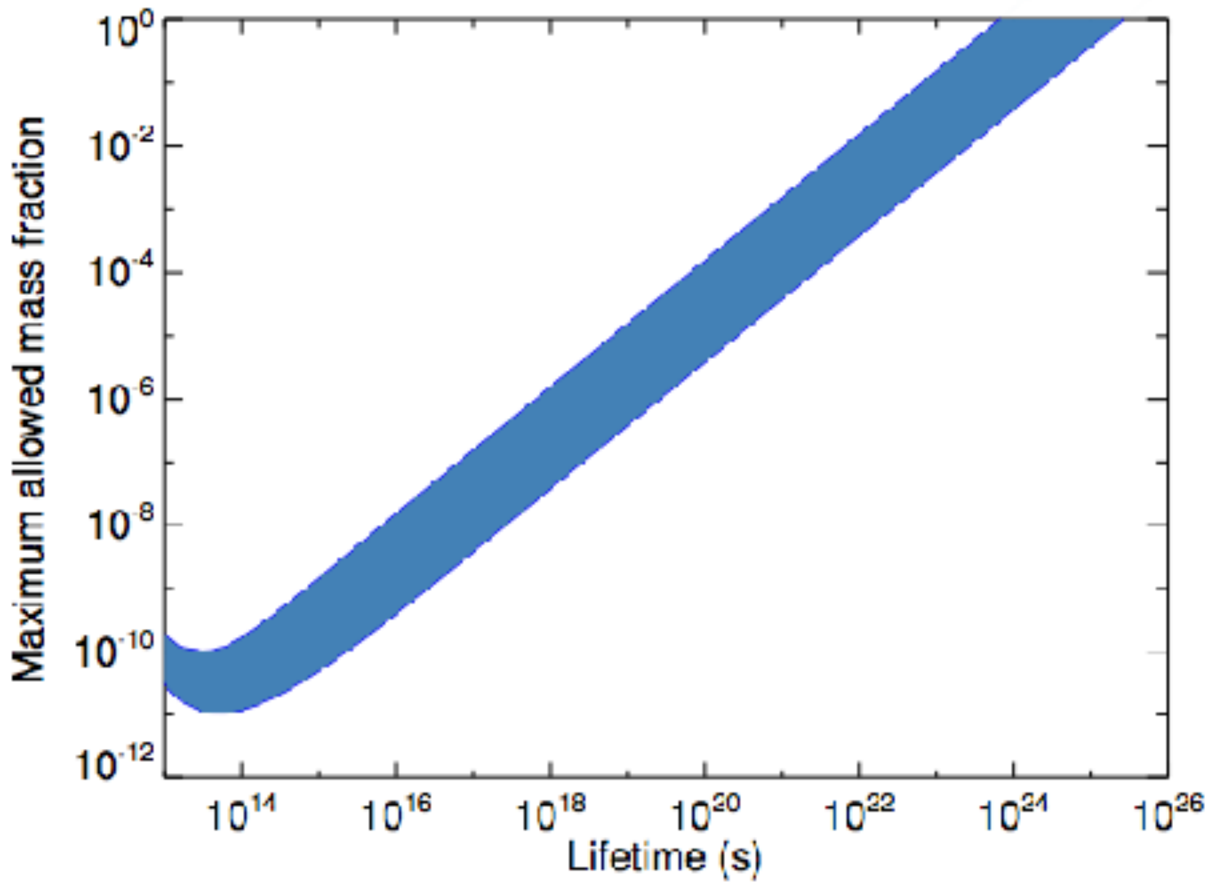
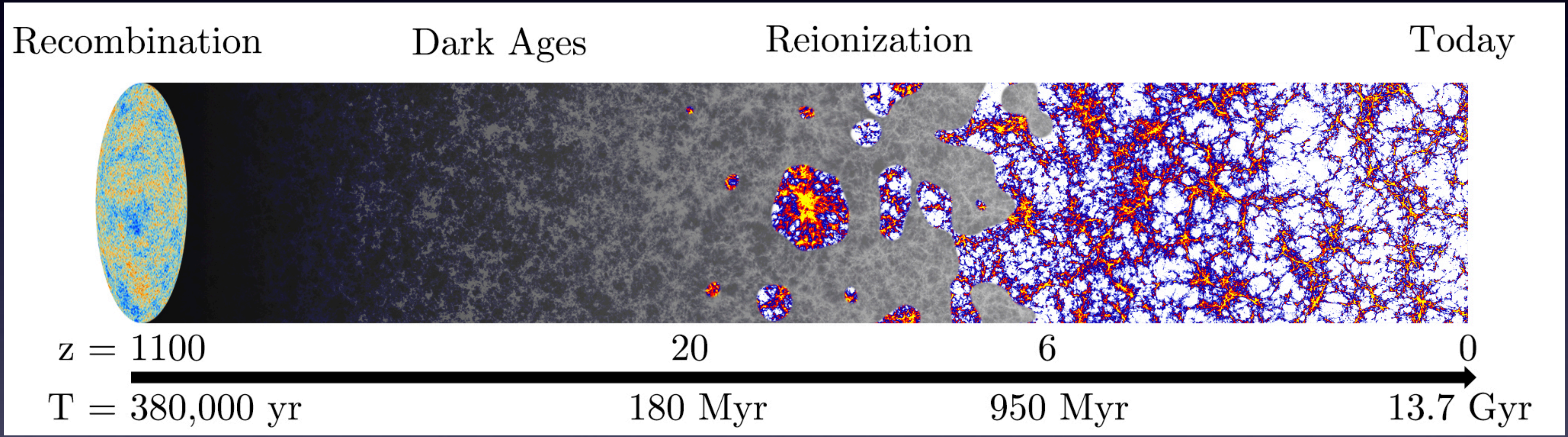


FIG. 11: Range of upper bounds on the mass fraction of DM that can decay with a lifetime τ, for injections of 10 keV – 10 TeV photons and e^+e^- pairs; the width of the band represents a scan over injection species and energy. The constraint is based on the PCA (first PC only) calibrated to the MCMC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

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?

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?

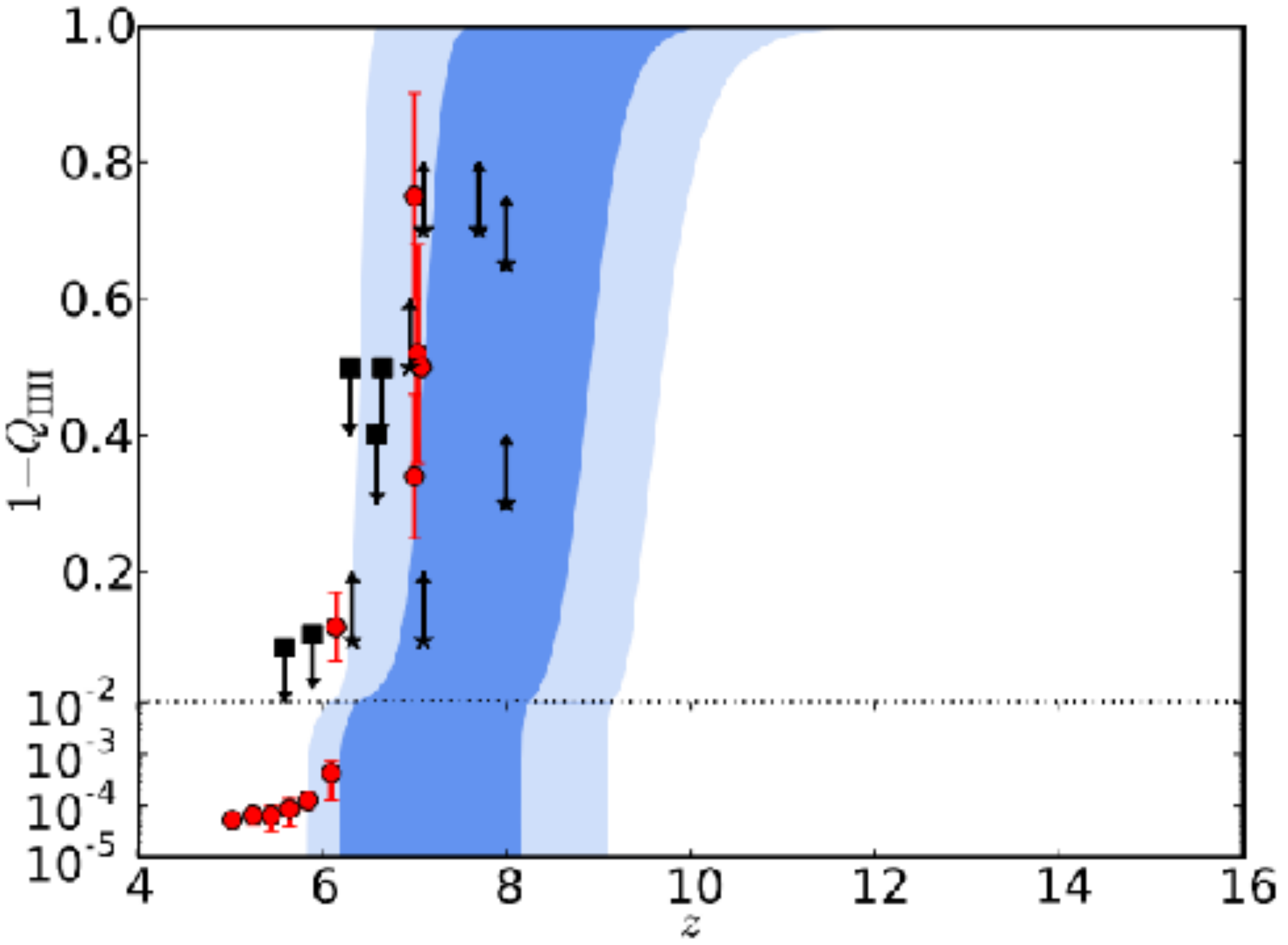


Fig. 17. Reionization history for the redshift-symmetric parameterization compared with other observational constraints compiled by Bouwens et al. (2015). The red points are measurements of ionized fraction, while black arrows mark upper and lower limits. The dark and light blue shaded areas show the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

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