Dark Matter Constraints from the Cosmic Microwave Background

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References
Original analysis (DM decay): Chen & Kamionkowski, astro-ph/0310473.
DM annihilation: Finkbeiner & Padmanabhan, astro-ph/0503486.
My papers (in collaboration with, at various times, Finkbeiner, Iocco, Lin, Galli, Madhavacheril, Padmanabhan, Sehgal & Valdes): 0906.1197, 1109.6322, 1211.0283, 1306.0563, 1310.3815, 1503.XXXX.

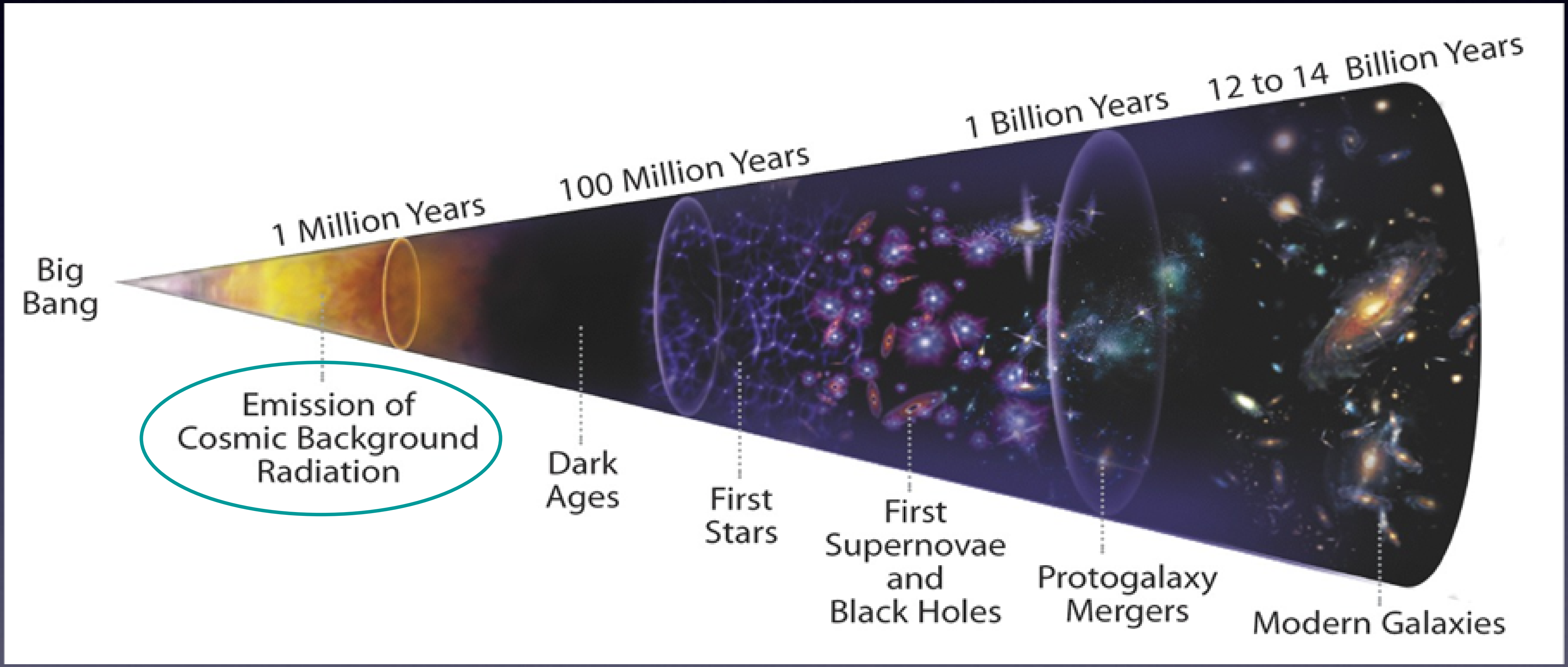
Outline

- The cosmic microwave background as a probe of DM annihilation
  - Why? (do we look in this channel)
  - How? (does DM annihilation imprint an observable signal on the CMB)
  - How sensitive? (are the current bounds)
- Beyond the basics: how to constrain your favorite DM model
  - Improvements to the calculation
  - The signatures of arbitrary energy injections
  - Calculating the Planck limit on arbitrary DM models

DM annihilation signatures

- Many possible signatures from DM annihilation:
  - Photons (esp. gamma rays, radio) - Galactic center, dwarf galaxies, galaxy clusters, small DM clumps, high-latitude Galactic emission, extragalactic isotropic background.
  - Cosmic rays (positrons, antiprotons, antideuterons etc) at the Earth's location.
  - Neutrinos - Earth, Sun, Galactic center, DM halo.
- However, many uncertainties associated with DM distribution and astrophysics!
  - Large uncertainties in cosmic ray propagation (also relevant to photon signals from upscattered photons or synchrotron).
  - Potentially large astrophysical backgrounds in many search channels, cannot always be well-characterized.
  - Signals often depend strongly on DM distribution in the inner parts of halos, or the DM mass function at small scales - not well known.
- How can we evade these uncertainties?

The cosmic microwave background



- Cosmic microwave background radiation carries information from around z~1000, the epoch of hydrogen recombination. No messy Galactic astrophysics, DM density perturbations are small and linear.
- Want to investigate the effect of high energy SM particles injected by DM annihilation (or other new physics) – NOT the usual gravitational effects of DM.

The cosmic dark ages

- Roughly z~30-1000, age of the universe ~400 000 years - 100 million years.
- For most of this period, matter fluctuations are small and perturbative; non-linear structure formation does not begin until $z < 100$.
- Residual ionization fraction ~ few x 10^{-4}.
- Any ionization acts as a screen to the cosmic microwave background radiation - can be sensitively measured.
- Consider the power from a single annihilation of 5 GeV DM - how many hydrogen ionizations?
  - 10 GeV / 13.6 eV ~ 10^{9}
  - For every hydrogen atom there is ~1 DM particle (so DM mass density is ~5x baryonic).
  - If one in a billion DM particles annihilates, enough power to ionize all the hydrogen in the universe…

But what fraction of the energy is absorbed?

(5 GeV photons are terrible ionizers)

From energy injection to the CMB

Annihilation injects high-energy particles

↓ Decay with Pythia or similar program

High-energy photons + e^+e^- (others largely escape)

↓ Cooling processes

Absorbed energy (ionization+excitation+heating)

↓ Modify public recombination calculator (RECFAST, CosmoRec)

Cosmic ionization history

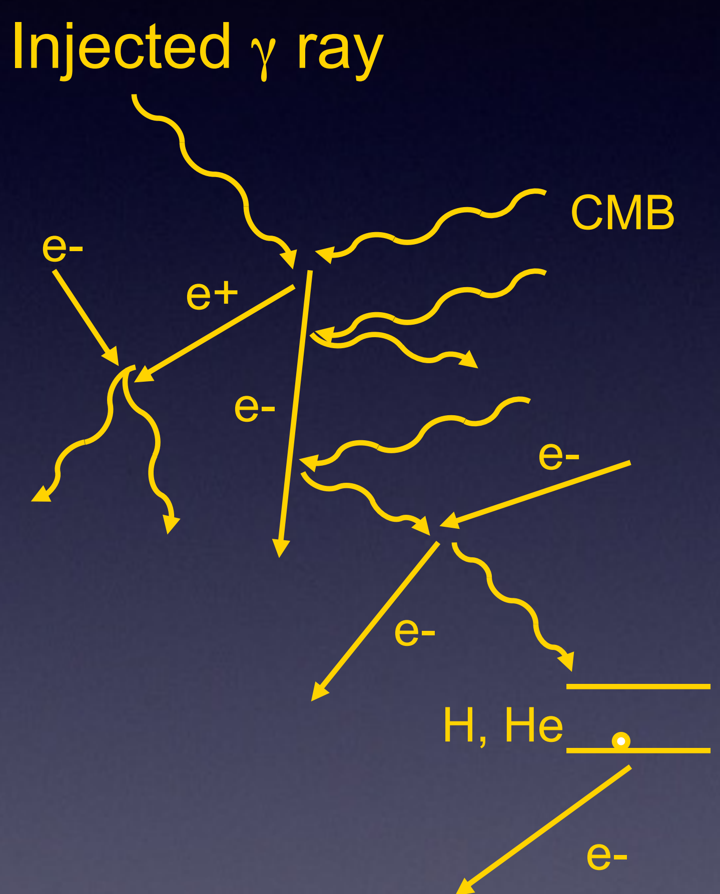
↓ Public CAMB code

Perturbations to CMB anisotropies

The photon-electron cascade

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

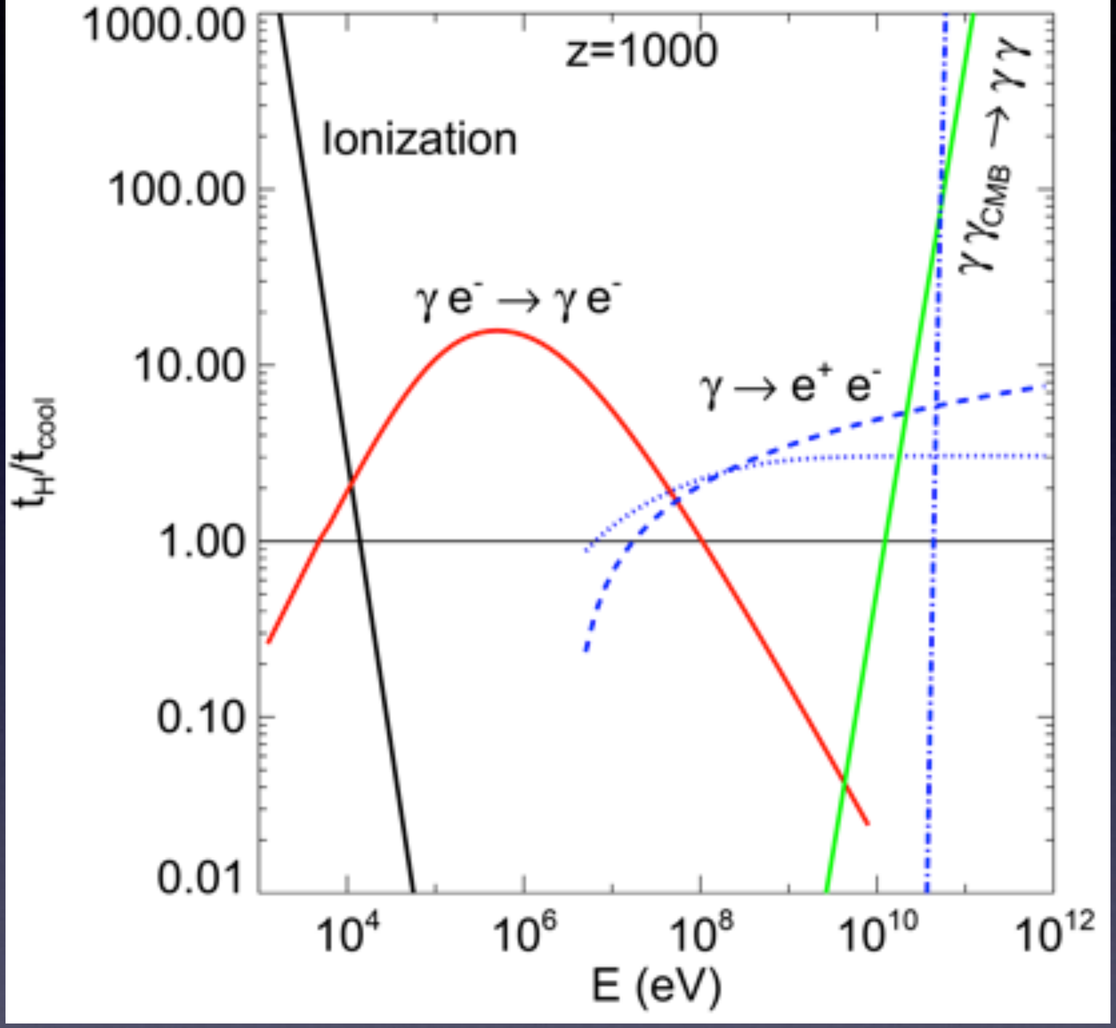
-> pair production
-> ICS producing a new γ

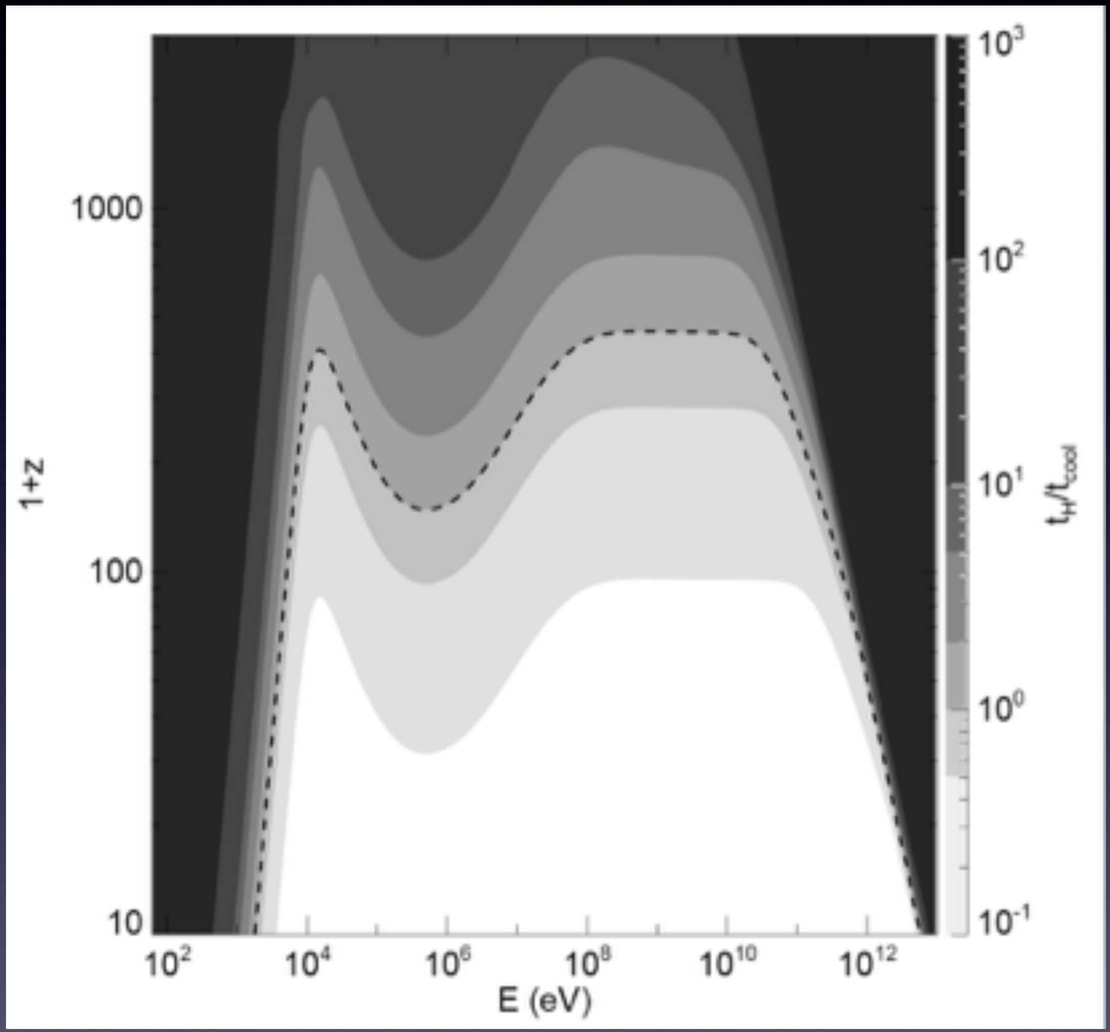
-> inelastic Compton scattering
-> photoionization

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.

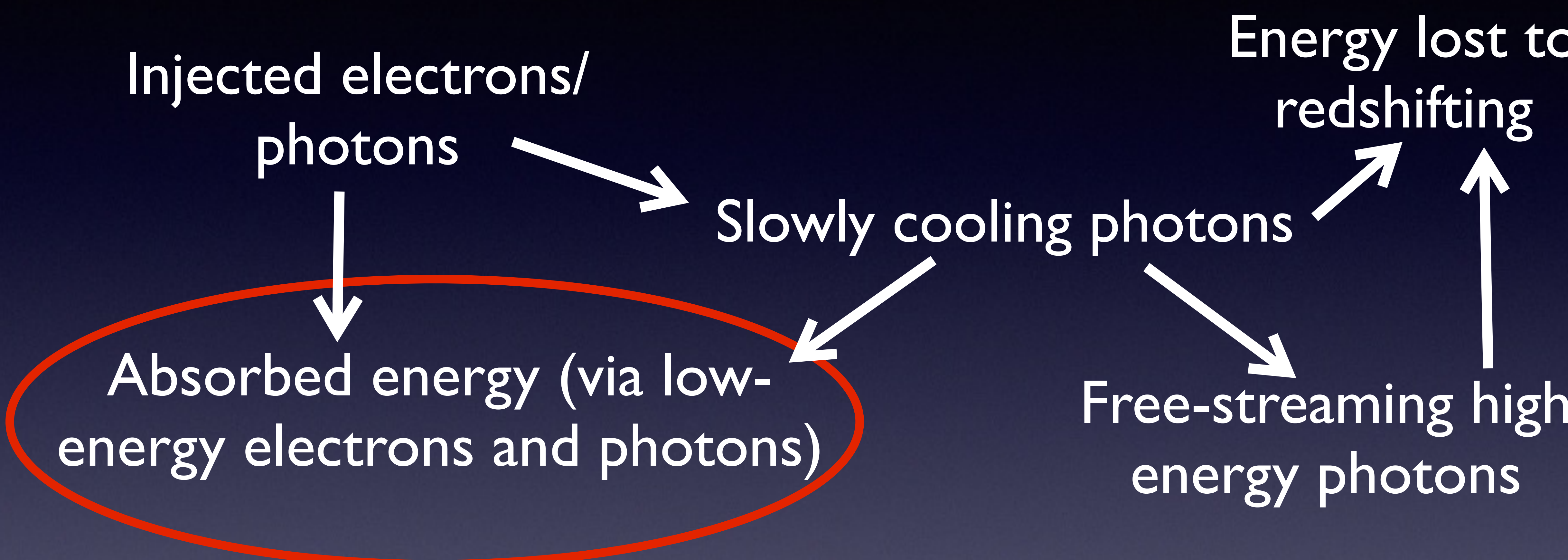
Photon cooling





- At redshift 1000, cooling time is much shorter than a Hubble time at low (< 1 keV) and high (> 100 GeV) energies, where photoionization and pair-production are fast. Intermediate-energy photons lie in a semi-transparent window.
- At lower redshifts, the universe becomes more transparent, and more gamma-rays contribute to present-day gamma backgrounds rather than ionization/heating.

From injection to absorption



- Any given energy injection history (spectrum and redshift dependence) has a corresponding energy absorption history.
- "On-the-spot" approximation assumes proportionality, described by a constant factor f. Breaks down to the extent that absorption is not instantaneous, and its efficiency is redshift-dependent.
- More generally, map injection to deposition by "effective efficiency" f(z).

f(z) curves

- For DM annihilation, we write the energy deposition history as:

$$\epsilon(z) = f(z)\frac{m_\chi \langle \sigma v \rangle (1+z)^3 n_{\mathrm{DM},0}^2}{n_{\mathrm{baryon},0}}$$

power per baryon deposited to the photon-baryon fluid

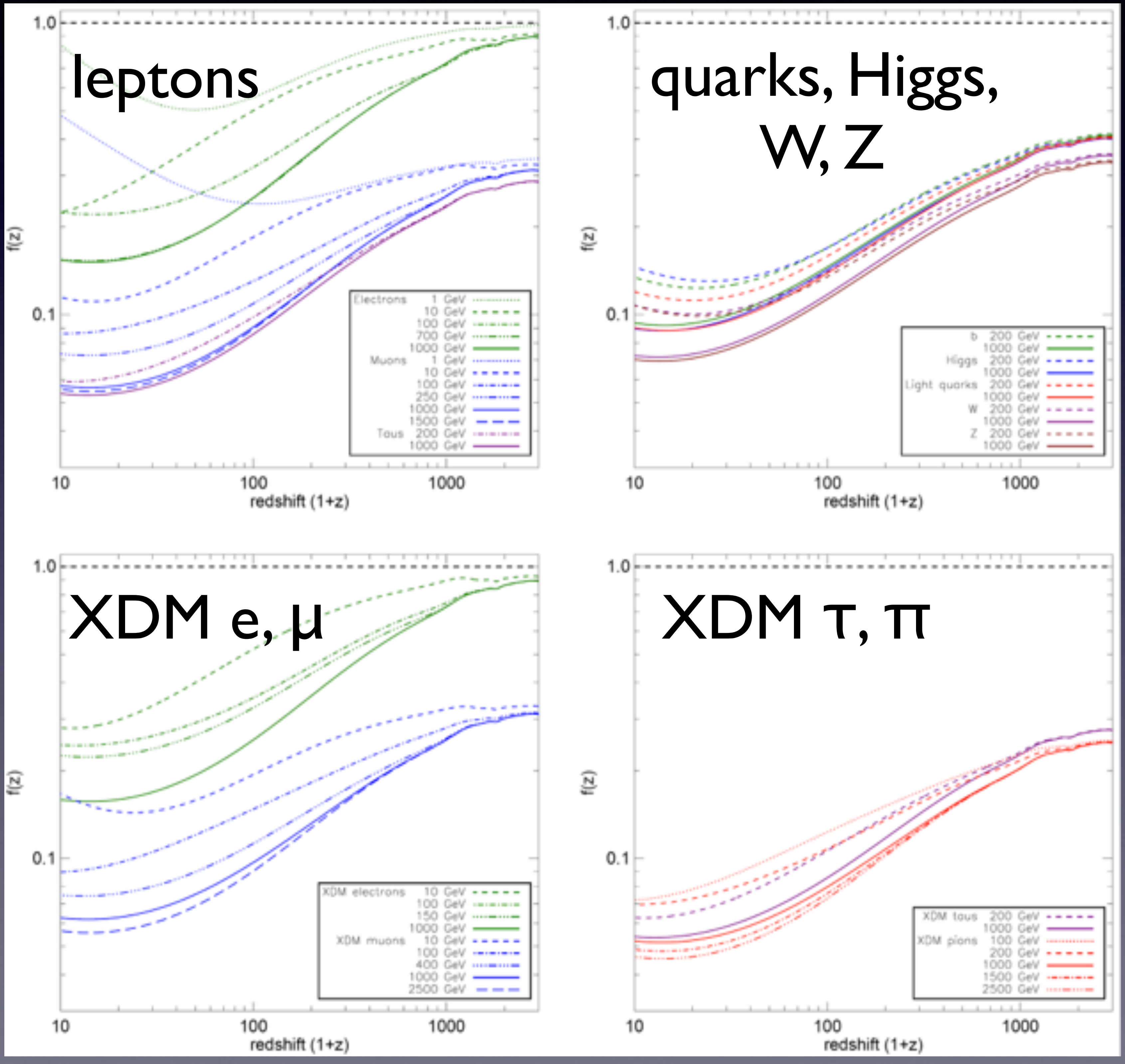
efficiency factor from particle + astrophysics

power per baryon injected at redshift of interest

- f(z) curves were computed for 41 combinations of DM mass and final state in TRS, Finkbeiner & Padmanabhan 0906.1197.

Sample models

- Numerical calculation performed for WIMP masses ranging from 1 GeV to 2.5 TeV, wide range of SM final states.
- Most energy is lost to neutrinos at high redshift, f(z) falls at lower redshifts due to increasing transparency.
- f(z) generally O(1).



Q: But what fraction of the energy is absorbed?

(5 GeV photons are terrible ionizers)

A: Much of it!

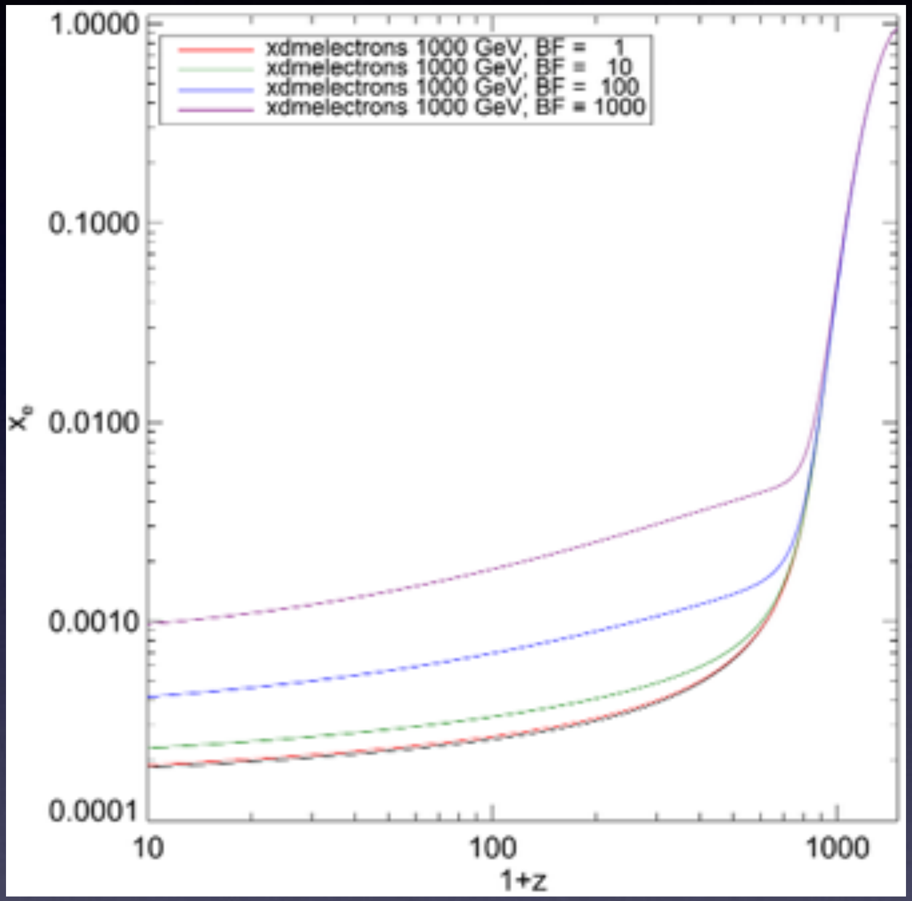
What are the consequences for the CMB?

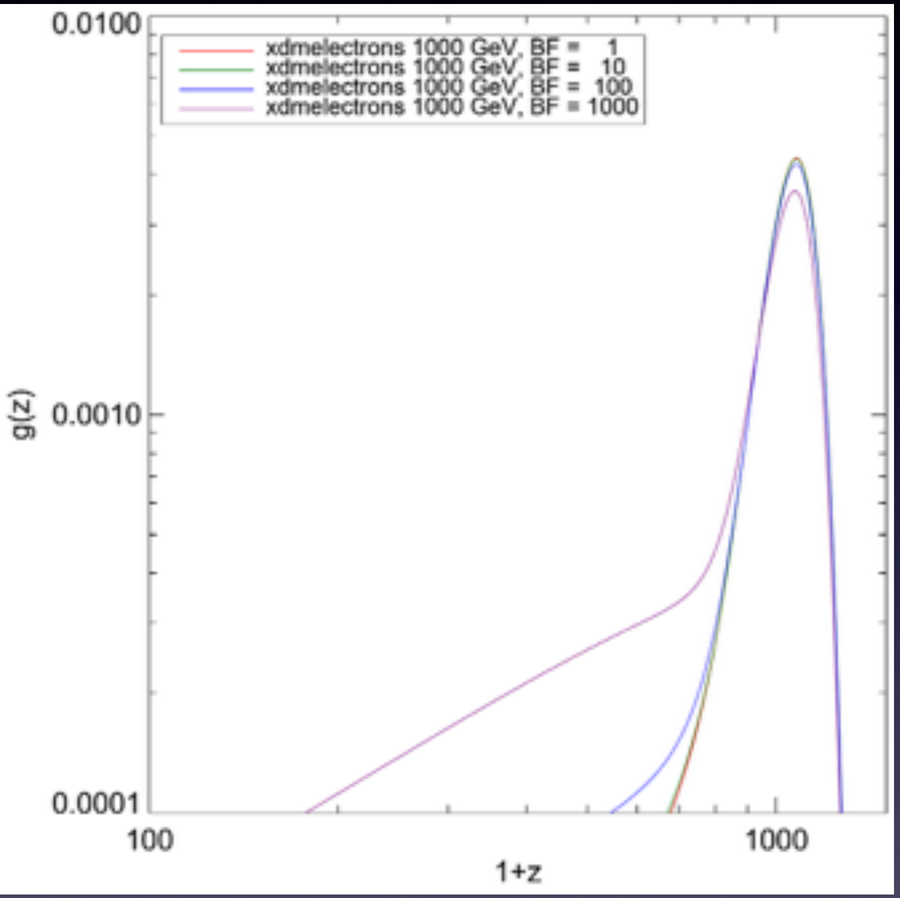
The ionization history

- Given an energy deposition history, how does it affect the ionization history?
- Recombination physics treated in great detail by RECFAST and successor codes. Add extra terms for additional ionization/excitation/heating.
- We follow (for now) the prescription of Chen & Kamionkowski 2003, Finkbeiner & Padmanabhan 2005:
  - Ionization ~ excitation ~ $\dfrac{1-x}{3}$ $\quad x = \text{ionization fraction}$
  - Heating ~ $\dfrac{1+2x}{3}$

$$-\delta\left(\frac{dx[\mathrm{H},\mathrm{He}]}{dz}\right) = \frac{\epsilon(z)}{H(z)(1+z)}\frac{1}{E_{\mathrm{ion}}}\frac{1-x[\mathrm{H},\mathrm{He}]}{3\,(1+f_{\mathrm{He}})}$$

Example ionization history





- Example DM model, 1 TeV DM annihilating to electrons.
- Use public codes RECFAST (Seager, Sasselov & Scott 1999) / CosmoRec (Chluba & Thomas 2010) / HyRec (Ali-Haimoud & Hirata 2010) to solve for ionization history.
- At redshifts before recombination, many free electrons => the extra energy injection has little effect.
- After recombination, secondary ionization induced by DM annihilation products => higher-than-usual residual free electron fraction.
- Surface of last scattering develops a tail extending to lower redshift.

CMB perturbations

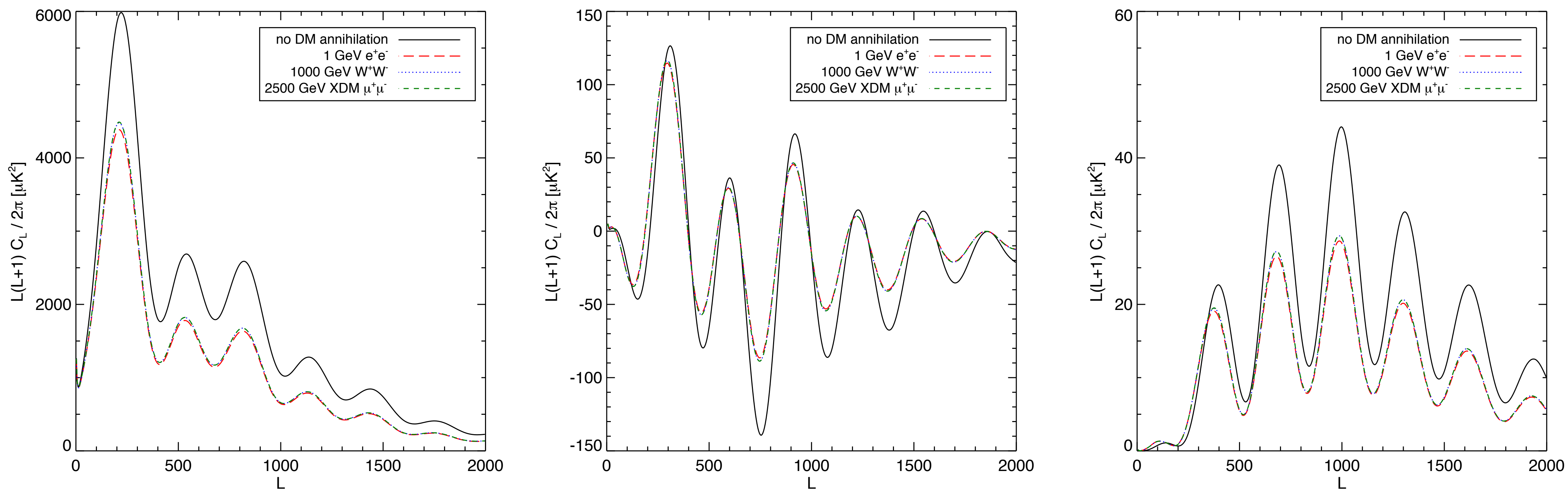
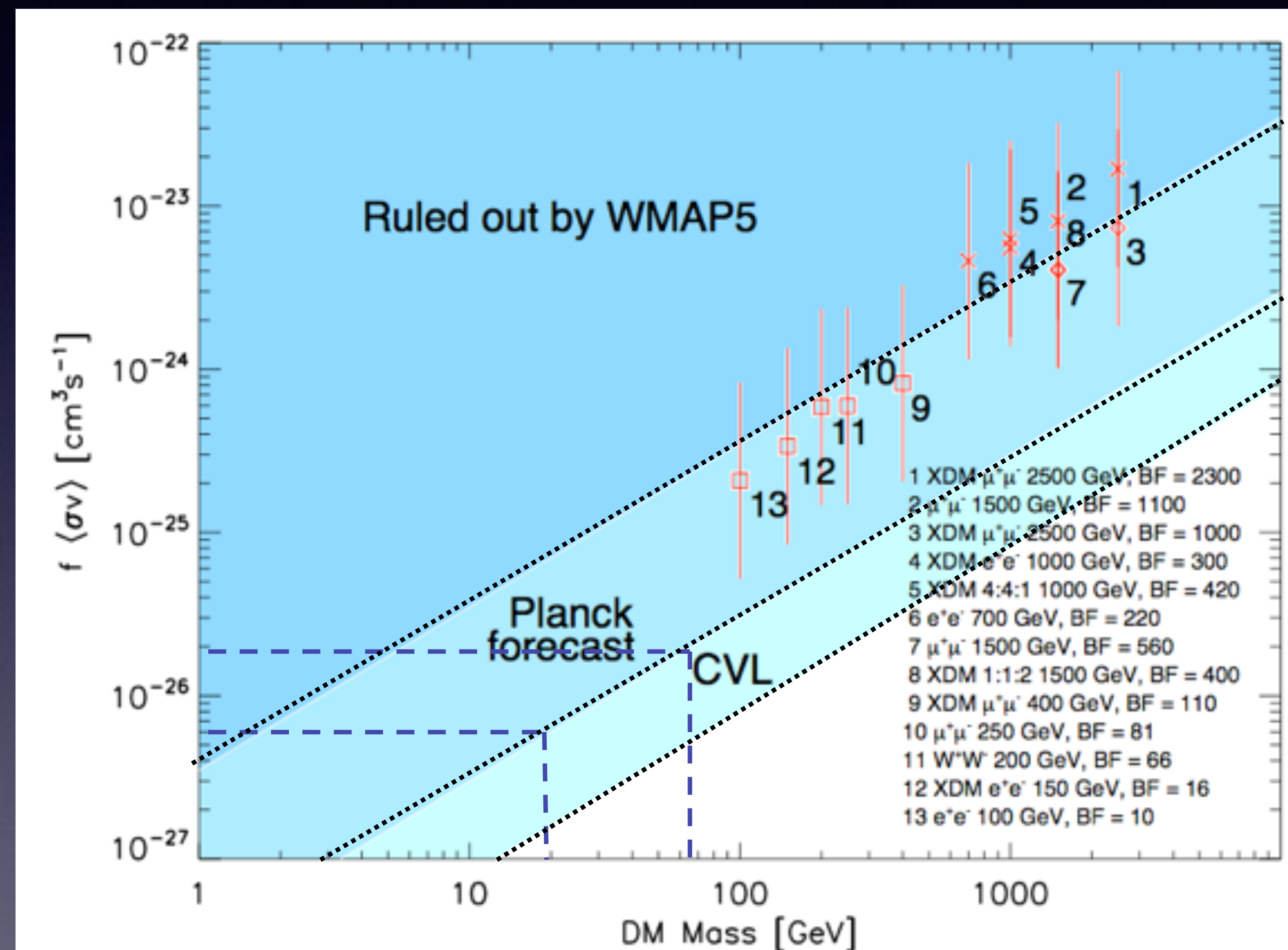


FIG. 5: CMB power spectra for three different DM annihilation models, with power injection normalized to that of a 1 GeV WIMP with thermal relic cross section and $f = 1$, compared to a baseline model with no DM annihilation. The models give similar results for the TT (*left*), TE (*middle*), and EE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

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

Constraints on DM annihilation

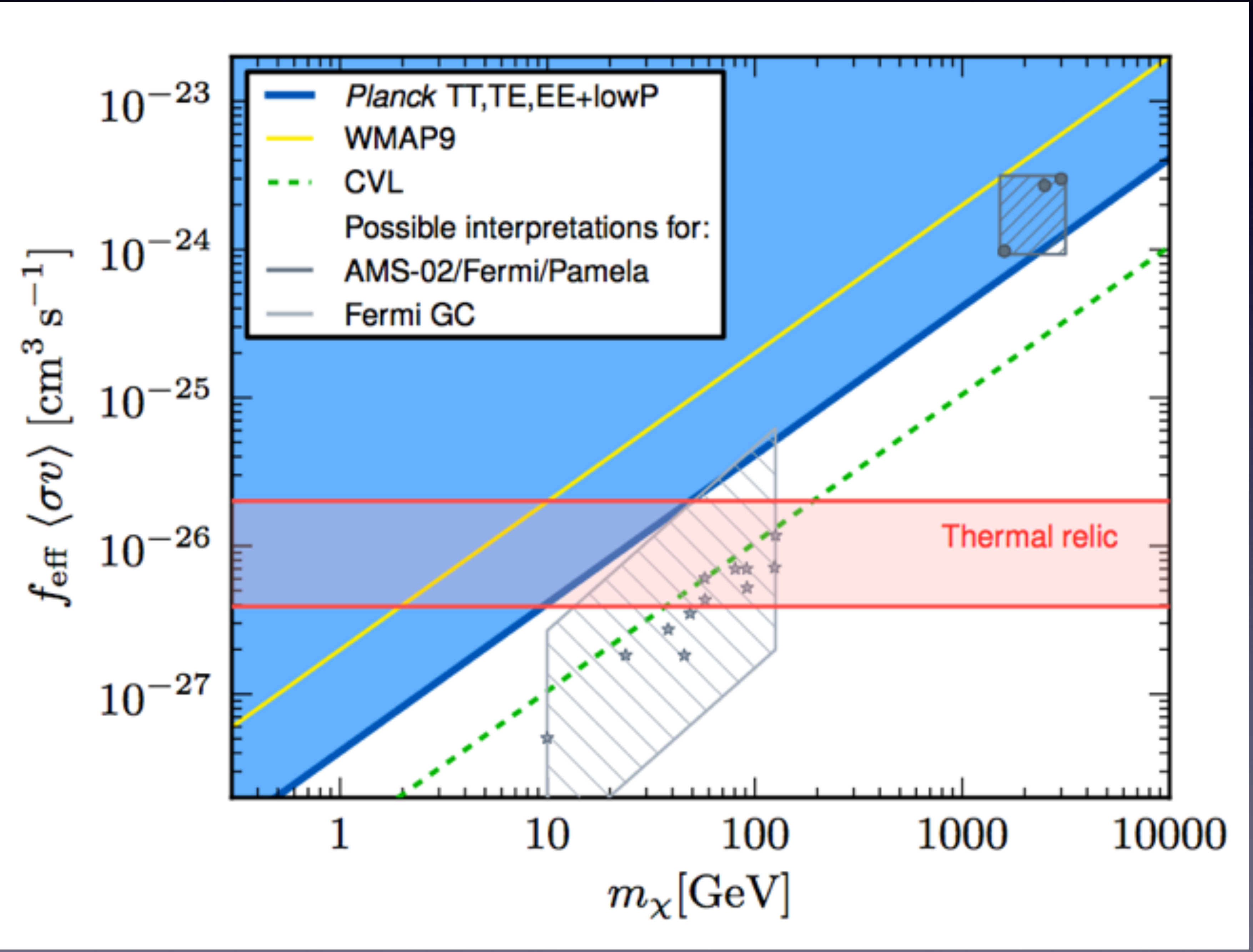
- First approach: f(z) slowly varying, average over z=800-1000 (for specific DM model) to estimate effective constant f.
- Constraint for constant f worked out by Finkbeiner & Padmanabhan 05, Galli et al 09.
- Models fitting PAMELA/Fermi/ATIC (red squares/diamonds/crosses) within a factor of a few of WMAP5 limit.
- Conclusion: Planck will probe thermal relic DM at 20-70 GeV.



Note: all the model points lie roughly parallel to the constraint line because the power injected in electrons/photons is also roughly what the cosmic-ray experiments measure.

Bounds from Planck

- Early this year, Planck Collaboration released polarization results
- (Technical note: these results use a slightly different ionization prescription, to be discussed shortly.)
- 1502.01589 (cosmological parameters paper) provides constraints for constant f_{eff}



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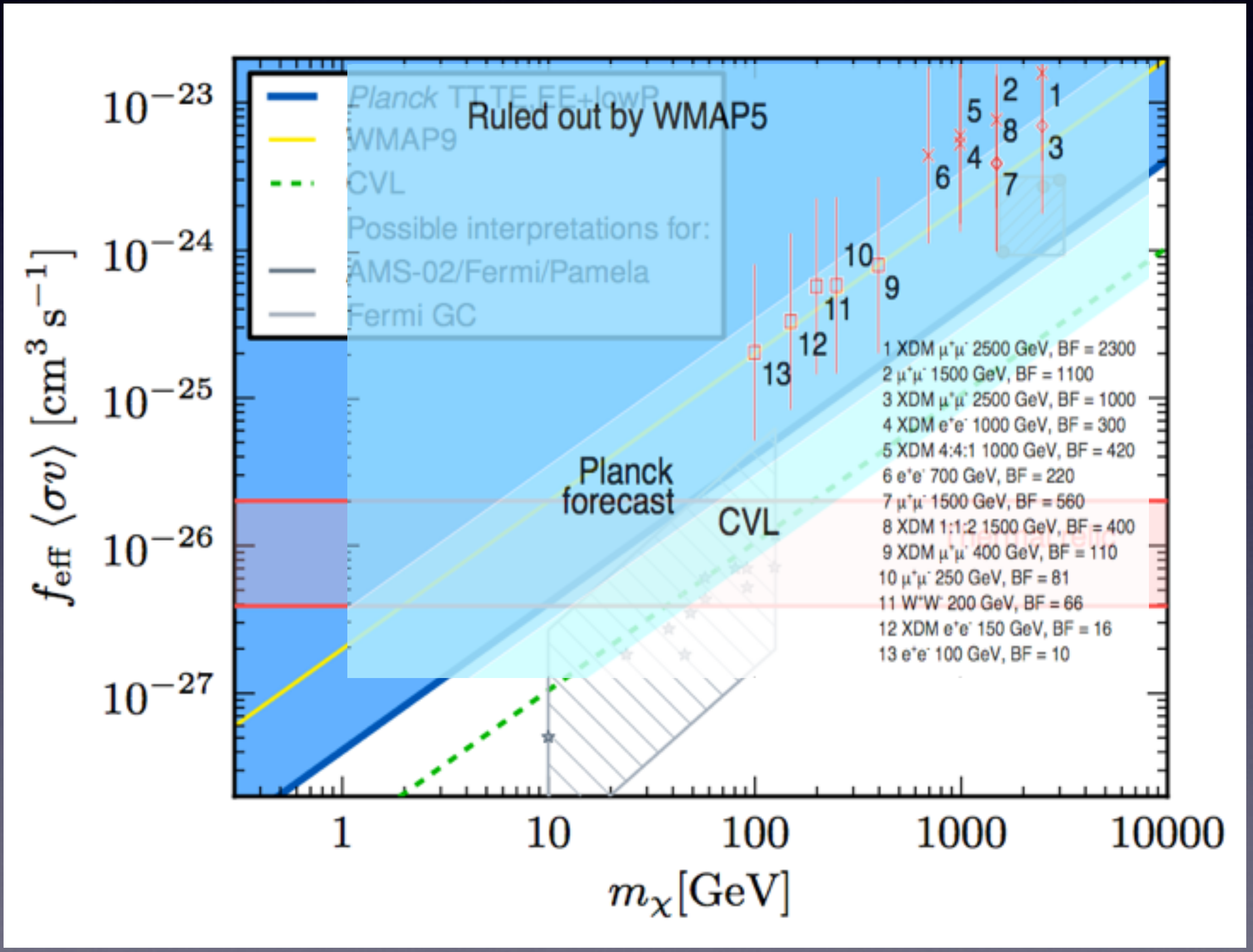

Beyond the basics

- Improvements to the basic analysis since 2009:
  - Better estimate for energy losses into ionization/excitation/heating (original version was based on a simple linear fit to a numerical calculation in a 1980s paper)
  - Rigorously derived weighting function to determine effective f-value, given f(z) for any DM model
- New tools:
  - Understand CMB constraints/sensitivity for energy injections with arbitrary photon/electron spectra and arbitrary redshift dependence
  - As a subtopic of this, allow easy calculation of f(z) (and hence the CMB bound) for any arbitrary DM model

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An improved estimate for energy loss into ionization/excitation/heating

Improving the energy fractions

- Previous results all used simplified partition of low-energy “absorbed” particles into ionization/excitation/heating, based on results for 3 keV electrons.
- Calculation can be improved: Monte Carlo codes study the detailed energy losses of electrons/photons.
    - Include improved cross-section estimates and careful treatment of secondaries.
    - Compute detailed dependence on background ionization fraction and initial energy of the electron/photon.
    - Since the signal depends primarily on power into ionization, can use results derived using simplified partition by rescaling f(z) by new/old power into ionization.
- Such codes do not take into account the delay between injection and absorption of energy (during which the universe expands).
- Composite method: use code from TRS et al 09 to compute cooling of high-energy particles, match onto Monte-Carlo-based low-energy code at energies where all processes are fast relative to Hubble time.

Composite method

ELECTRONS

PHOTONS

HIGH ENERGY CODE

energy > 3 keV
ICS dominates electron cooling

redshifting relevant

redshifting irrelevant (photoionization dominates), energy > 3 keV

LOW ENERGY CODE

energy < 3 keV
atomic processes dominate electron cooling

redshifting irrelevant (photoionization/excitation dominates), energy < 3 keV

DETAILED MC CALCULATION

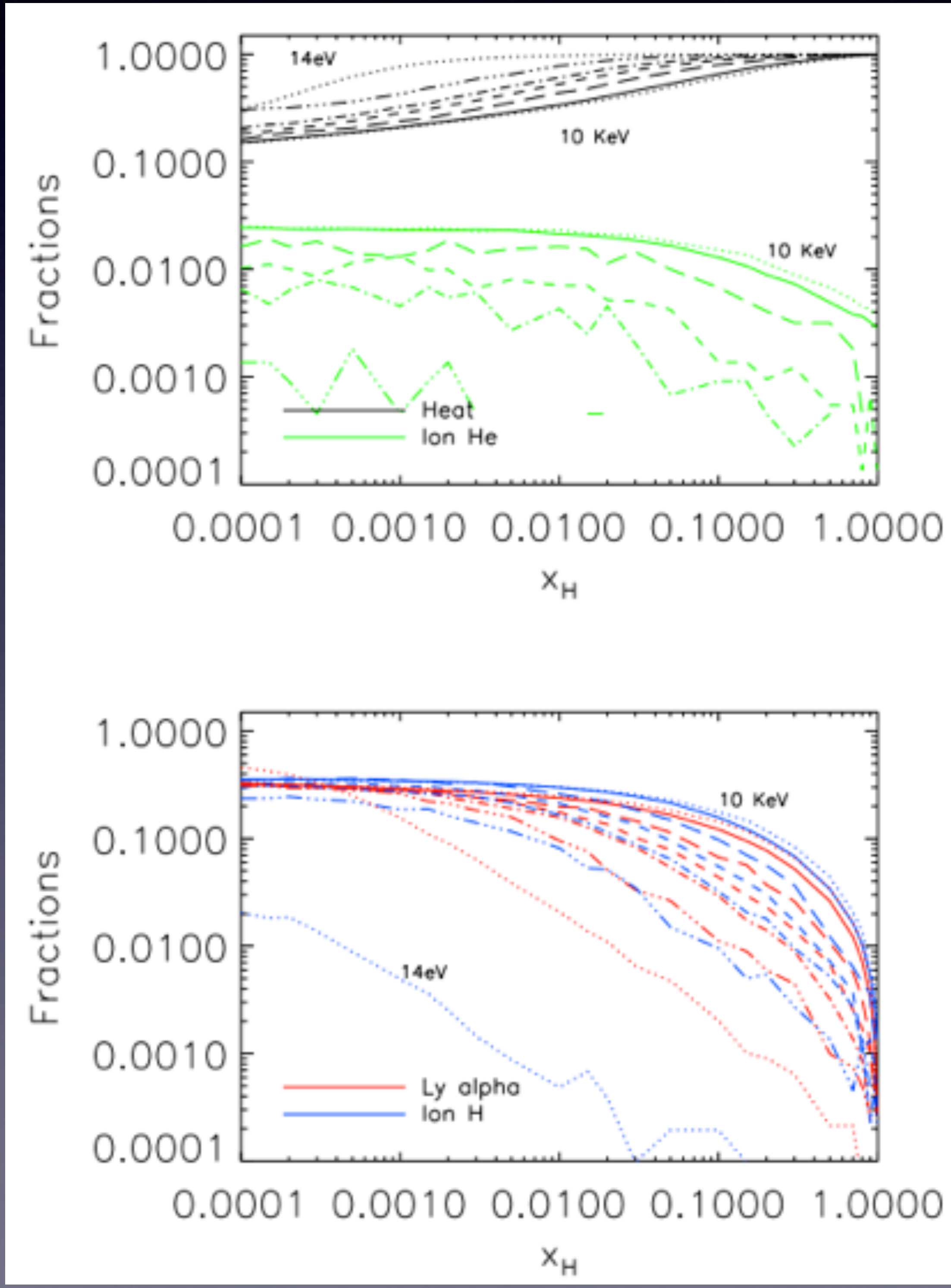
heating

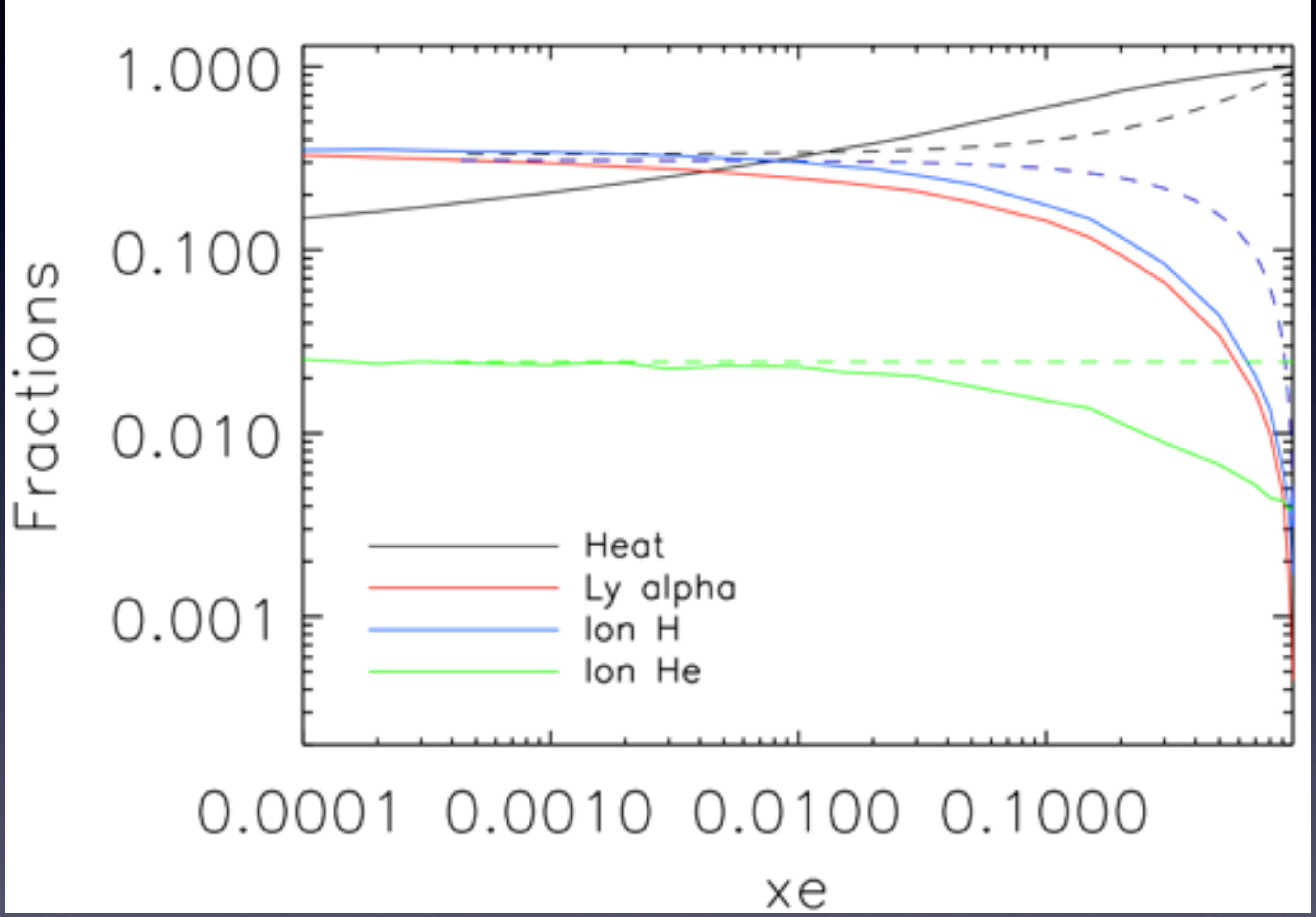
excitation

ionization

energy < 10.2 eV, "continuum photons"

Updated low-energy fractions





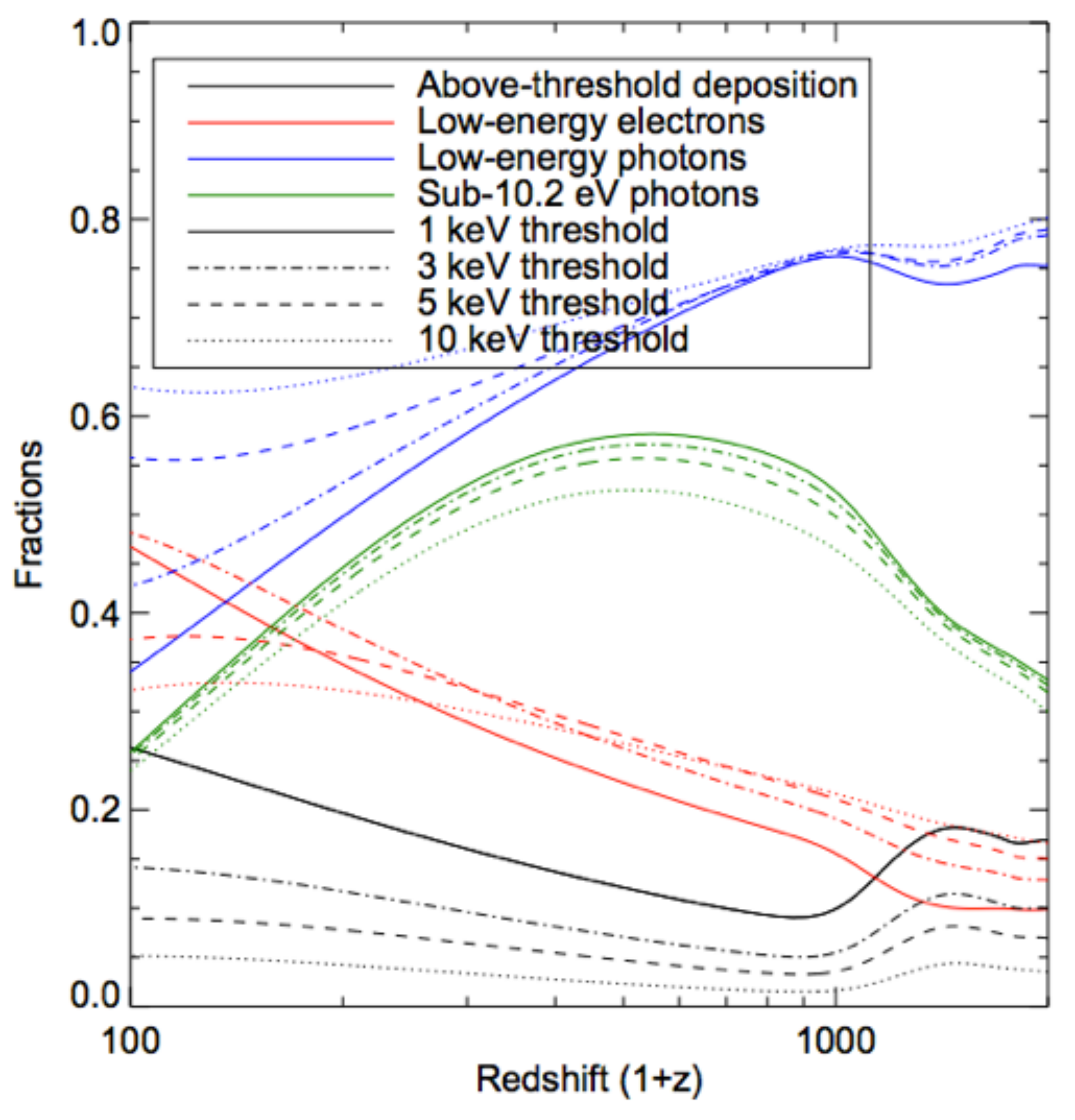
- Above: energy fractions for a 10 keV electron as a function of ionization, dashed lines = older approximation.
- Left: variation with electron energy.
- Plots from Galli, TRS, Valdes & Iocco 1306.0563.
- Planck collaboration uses a simplified ionization prescription based on these results at 3 keV.

“Continuum” photons

- Scattering of CMB photons by non-relativistic or mildly relativistic electrons produces only a very small increase in the photon energy (like Sunyaev-Zel’dovich effect).
- Resulting “continuum” photons are not energetic enough to excite/ ionize hydrogen.
- However, these inverse Compton scattering (ICS) losses can be the most efficient cooling process for electrons - dominate over atomic processes for electrons with energies down to a few keV, at redshift ~600. (There are some incorrect statements in the earlier literature on this point.)
- Earlier studies which neglected these losses for keV-MeV electrons underestimate CMB spectral distortions, overestimate ionization/ excitation/heating.

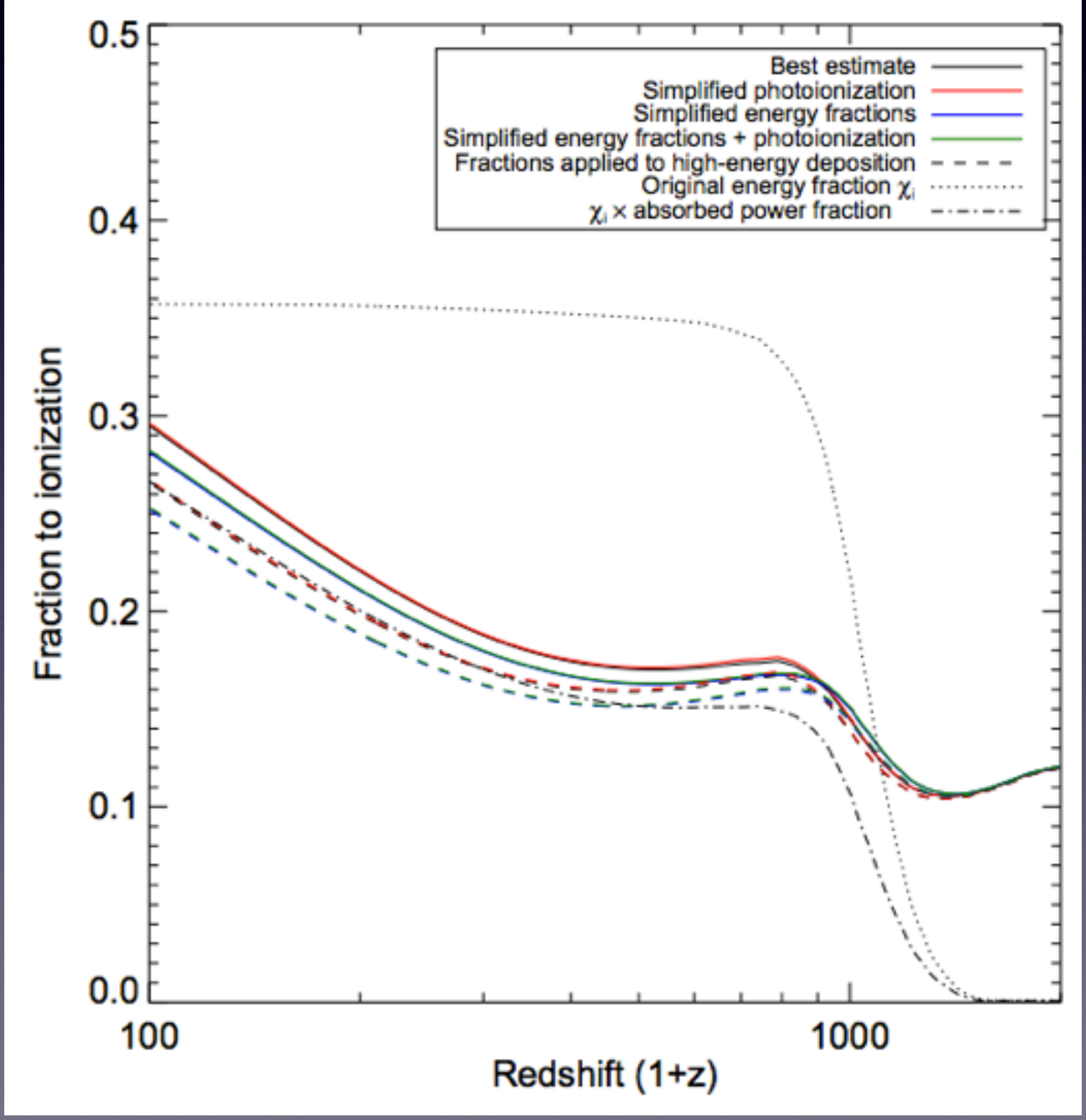
Energy losses from high-energy code

- Example for 1 GeV DM annihilating to electrons/ positrons.
- Green line = photons too low-energy to interact with the gas - up to half total "deposited" energy at some redshifts.
- Red = electrons piped to low-energy code (well modeled by previous studies), blue = total low-energy photons, black = deposition by atomic processes in high-energy code.



Effect on power into ionization

- Fraction of "absorbed" power proceeding into ionization with different prescriptions, again for example of 1 GeV DM annihilating to e^+e^-.
- Dotted line = treatment in previous works.
- Other lines = treatment in 1306.0563, with various simplifications/approximations.
- Relative to previous work, can be a ~factor of 2 suppression.



Effect on constraints

DM mass [GeV]	channel	$\langle\sigma v\rangle$ $\{f_{\mathrm{previous}}(z)\}$ [cm^3/s]	$\langle\sigma v\rangle$ $\{f_{\mathrm{approx}}(z)\}$ [cm^3/s]	Ratio approx./prev.	$\langle\sigma v\rangle$ $\{f_{\mathrm{best}}(z)\}$ [cm^3/s]	Ratio best/prev.	Ratio best/approx.
1	electrons	$< 3.1 \times 10^{-28}$	$< 7.2 \times 10^{-28}$	2.31	$< 6.2 \times 10^{-28}$	1.96	0.85
2	electrons	$< 6.1 \times 10^{-28}$	$< 1.2 \times 10^{-27}$	2.01	$< 1.0 \times 10^{-27}$	1.68	0.84
5	electrons	$< 1.6 \times 10^{-27}$	$< 2.3 \times 10^{-27}$	1.39	$< 2.2 \times 10^{-27}$	1.31	0.94
10	electrons	$< 3.4 \times 10^{-27}$	$< 4.6 \times 10^{-27}$	1.35	$< 4.2 \times 10^{-27}$	1.25	0.93
20	electrons	$< 7.5 \times 10^{-27}$	$< 1.0 \times 10^{-26}$	1.39	$< 9.5 \times 10^{-27}$	1.27	0.91
100	electrons	$< 4.3 \times 10^{-26}$	$< 6.4 \times 10^{-26}$	1.48	$< 6.0 \times 10^{-26}$	1.38	0.94
1000	electrons	$< 4.5 \times 10^{-25}$	$< 6.6 \times 10^{-25}$	1.48	$< 6.1 \times 10^{-25}$	1.37	0.93
1	muons	$< 8.8 \times 10^{-28}$	$< 1.5 \times 10^{-27}$	1.72	$< 1.3 \times 10^{-27}$	1.51	0.87
2	muons	$< 1.8 \times 10^{-27}$	$< 3.6 \times 10^{-27}$	2.02	$< 3.2 \times 10^{-27}$	1.75	0.87
5	muons	$< 4.4 \times 10^{-27}$	$< 7.9 \times 10^{-27}$	1.77	$< 6.7 \times 10^{-27}$	1.51	0.85
10	muons	$< 9.0 \times 10^{-27}$	$< 1.4 \times 10^{-26}$	1.55	$< 1.2 \times 10^{-26}$	1.36	0.88
20	muons	$< 2.0 \times 10^{-26}$	$< 2.8 \times 10^{-26}$	1.39	$< 2.4 \times 10^{-26}$	1.23	0.88
100	muons	$< 1.2 \times 10^{-25}$	$< 1.7 \times 10^{-25}$	1.41	$< 1.5 \times 10^{-25}$	1.30	0.92
1000	muons	$< 1.3 \times 10^{-24}$	$< 1.9 \times 10^{-24}$	1.48	$< 1.8 \times 10^{-24}$	1.37	0.93

- Weakens previously claimed constraints by a factor of 1.2-2.
- Note the most-affected cases (in this parameter space) are already ruled out for thermal relic cross sections.

Probing general energy injections with the CMB

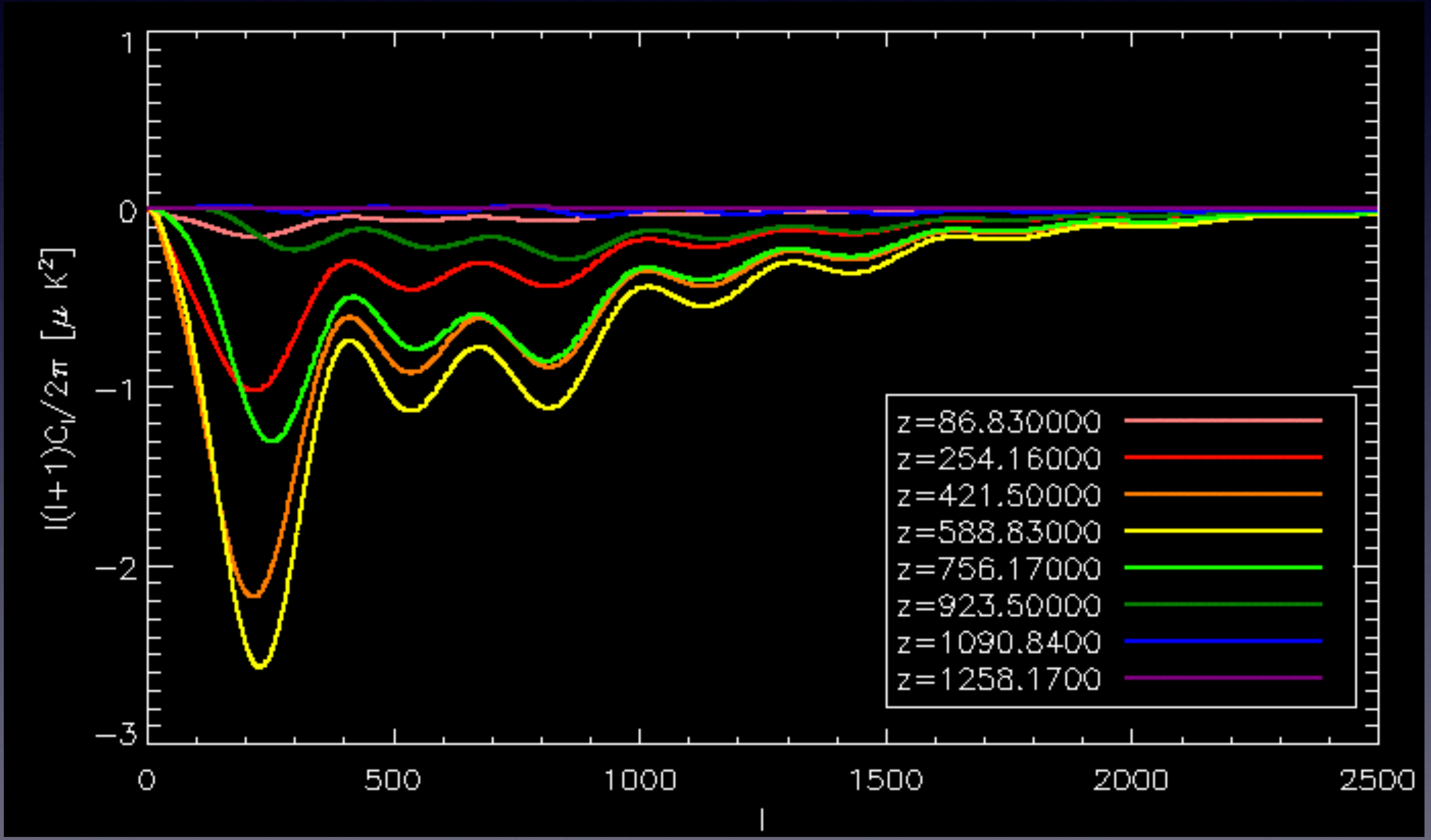
Generalized energy absorption histories

- Starting from the energy absorption history, want to ask: what are the possible effects of energy absorption on the CMB, and how best to parameterize them?
- Allows a more model-independent study of DM annihilation compared to working out the effects of specific models - gives rigorous weighting function as a byproduct (as we understand which redshifts are most important).
- Also allows constraints on non-standard models, e.g.
  - Late-decaying / metastable species.
  - Asymmetric DM models where annihilation "turns on" at a late time.
  - Models of dark matter with excited states, where the excited state decays at some time after recombination.

The imprint on the CMB

Finkbeiner, Galli, Lin & TRS 2011

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



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

Principal components

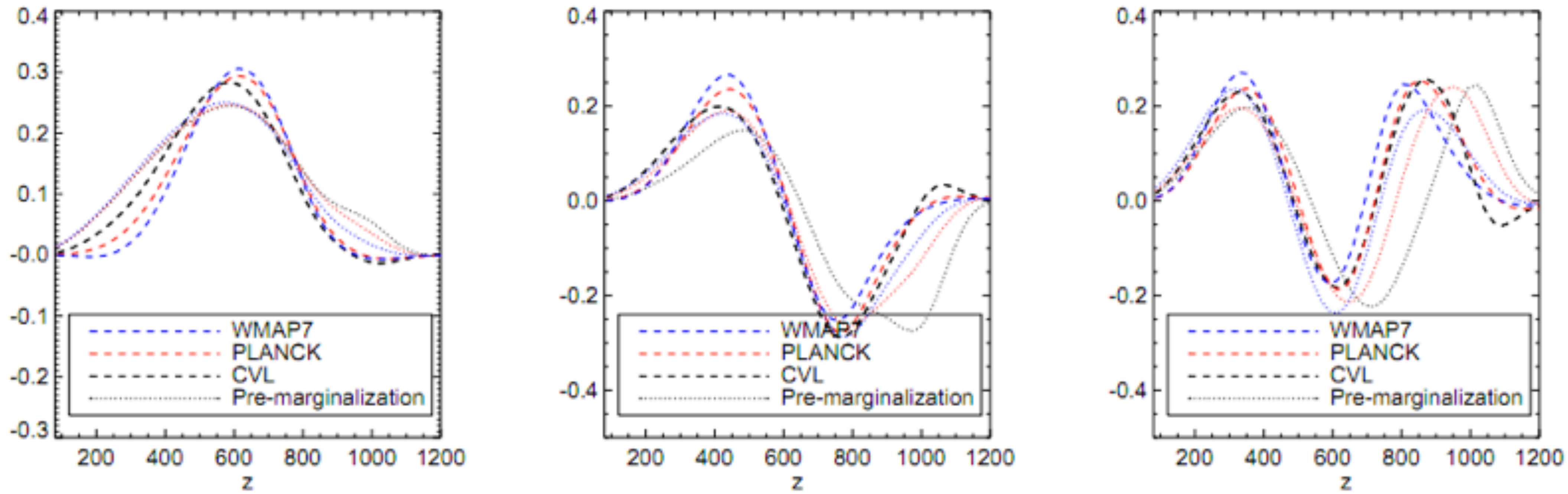


FIG. 4: The first three principal components for *WMAP* 7, *Planck* and a CVL experiment, both before and after marginalization over the cosmological parameters.

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

... and in the CMB

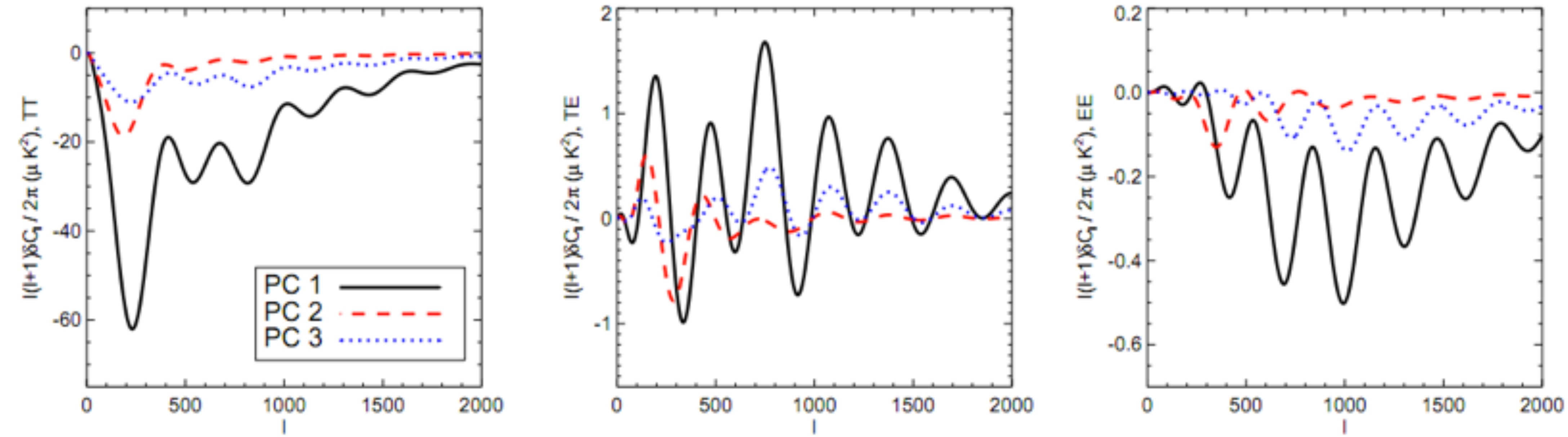


FIG. 7: The mapping of the first three principal components for *Planck*, after marginalization, into δC_ℓ space. The PCs are multiplied by $\varepsilon_i(z) = 2 \times 10^{-27}$ cm^3/s/GeV for all i, to fix the normalization of the δC_ℓ's.

h_i

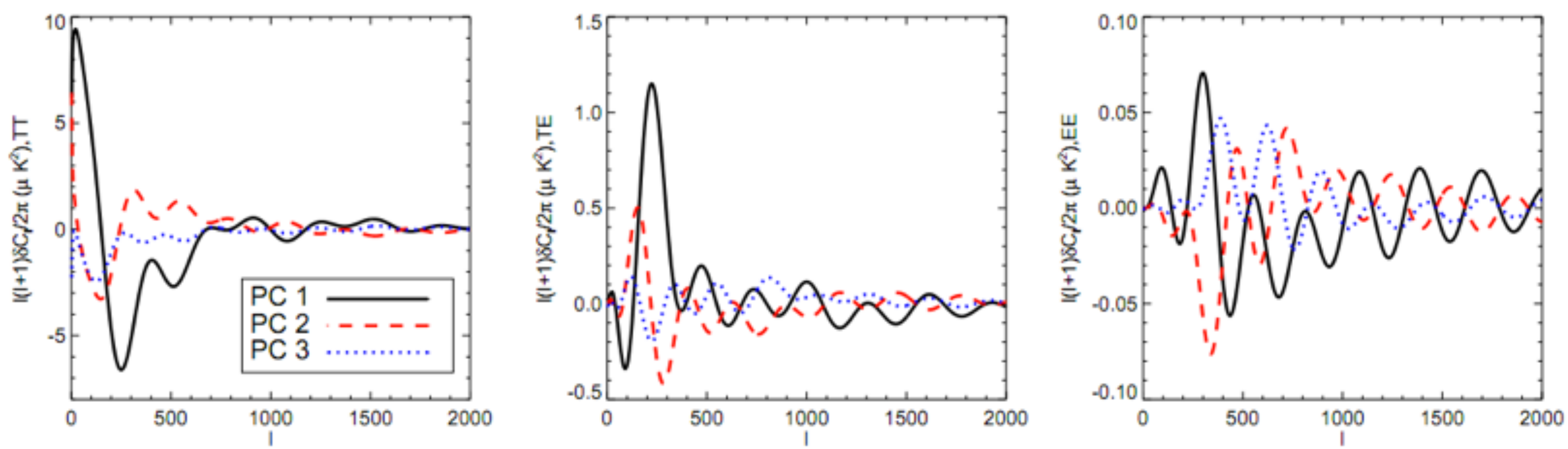


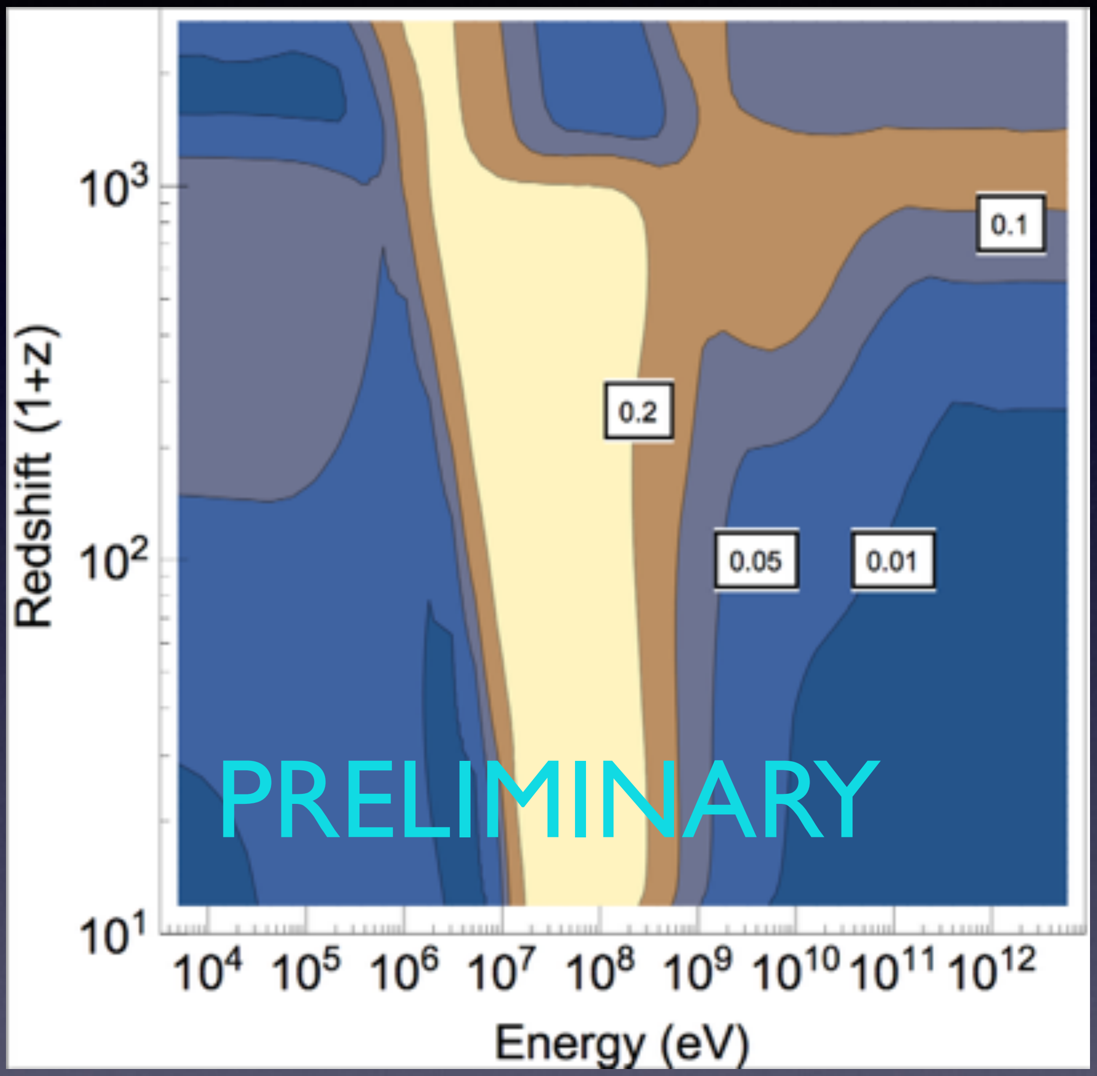
FIG. 8: The $\perp$ components of the first three principal components for *Planck*, after marginalization, mapped into δC_ℓ space. The normalization is the same as for Figure 7.

$h_i^\perp$

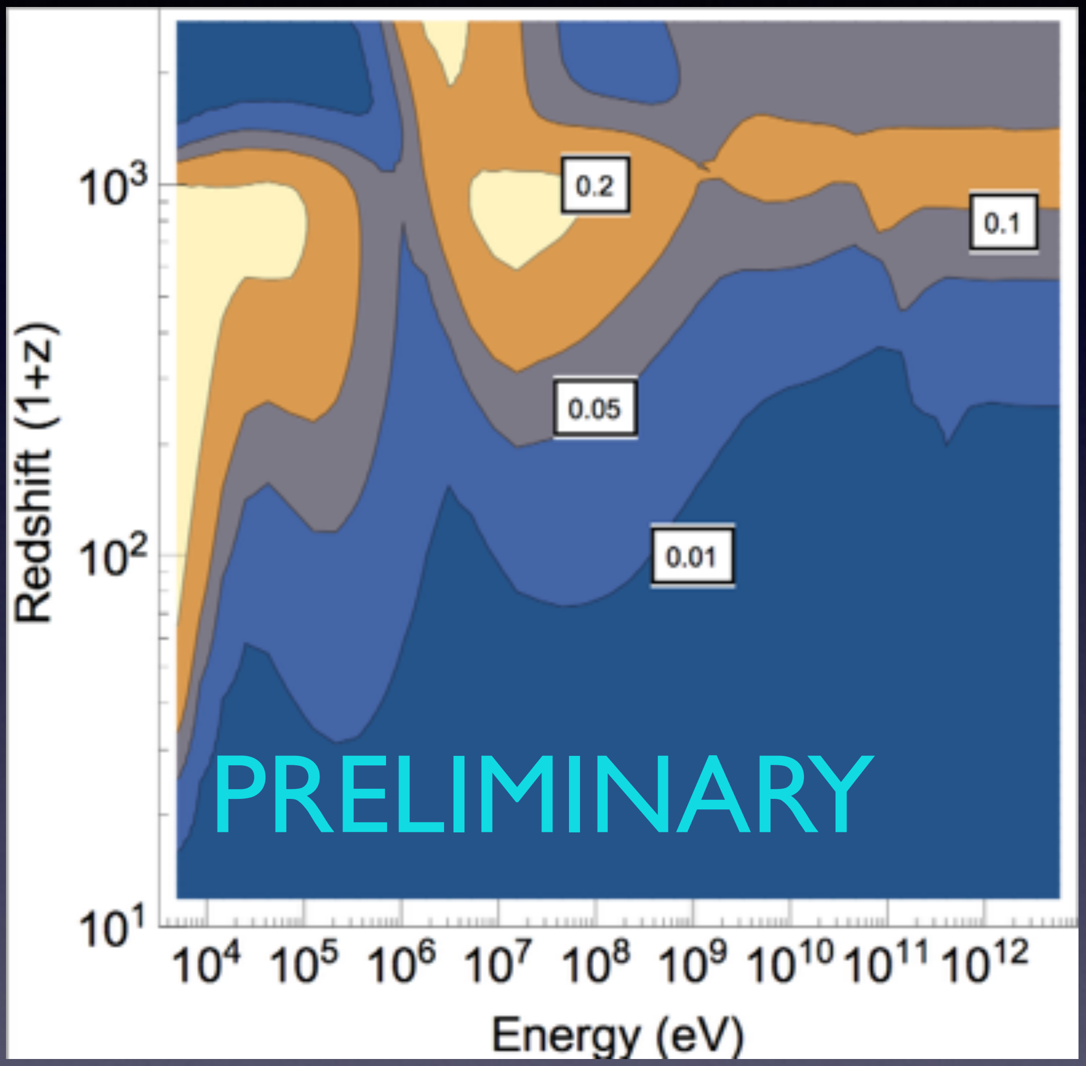
From injection to absorption

- Result: first <u>3</u> PCs describe vast bulk of variance - 3 numbers sufficient to characterize effect of arbitrary absorption histories (result of Finkbeiner et al 2011).
- For arbitrary energy <u>injection</u> history, need the transfer function from injection to absorption, for electrons and photons injected at arbitrary energy and redshift.
- This transfer function has been fully mapped out, using the techniques described earlier. First version provided in TRS 1211.0283; new analysis (to appear soon) incorporates the composite method discussed earlier and provides a detailed breakdown of "absorbed" energy.

The transfer function



Electron+positron pairs



Photons

- An example: what fraction of energy is eventually deposited into ionization, for a particle injected at some redshift z and energy E?
- Full transfer function has this information differential by output redshift.

Prescription for general energy injections

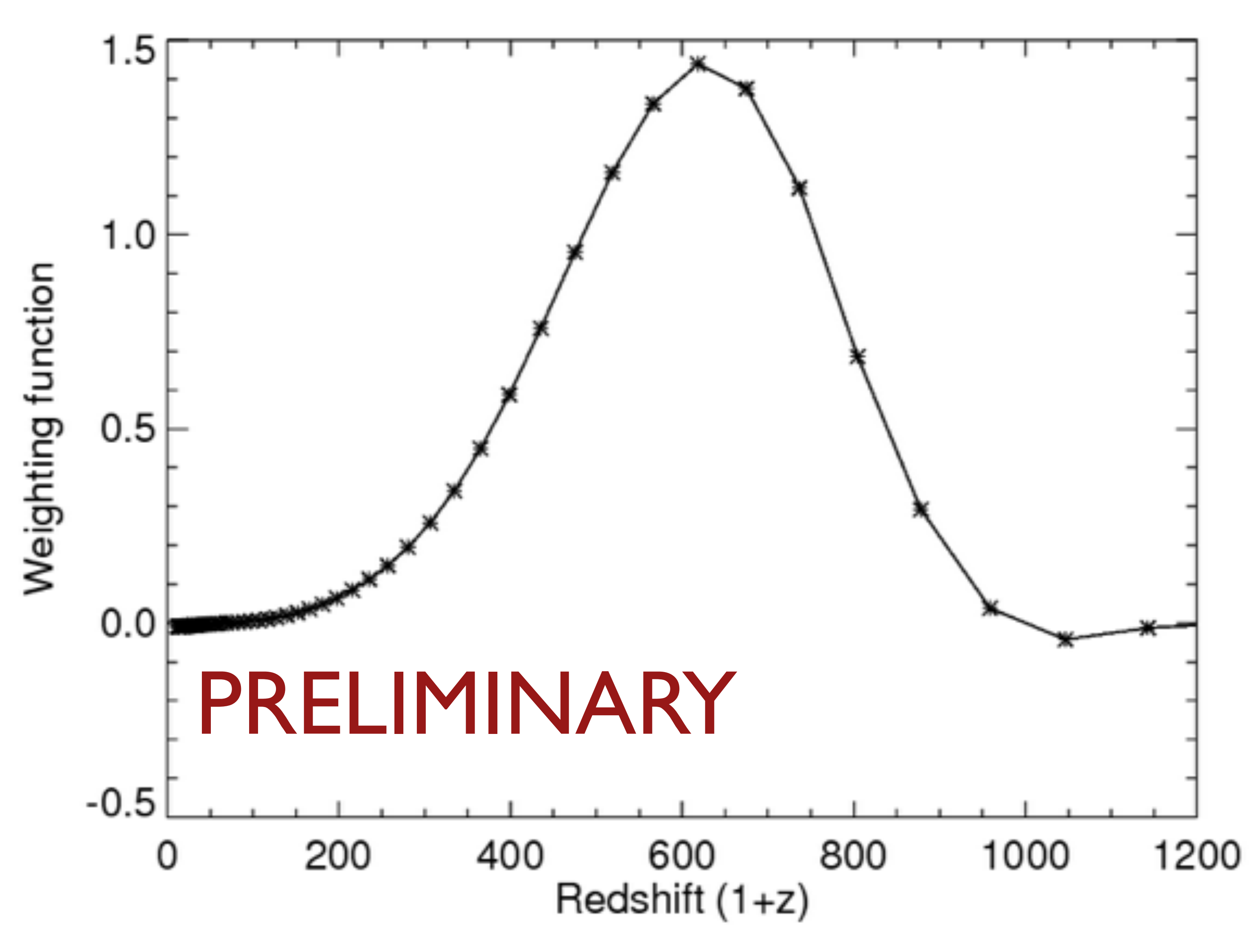
- Work out your spectrum of injected photons/electrons (e.g. with Pythia).
- Work out the time dependence of your photon/electron injection.
- Convolve with the transfer function to compute the power absorbed into ionization as a function of redshift; calculate an equivalent "f(z)" curve by dividing by the fraction of power into ionization using the simplified partition with f=1. (This allows you to use results derived using the simplified partition.)
- Compute the coefficients of each of the principal components, for this f(z) curve.
- Compare result to constraints on the PC coefficients.
- Full PCA has not yet been done with Planck data - for future work. But for DM annihilation specifically, we can already do better.

The DM case

- If we want to restrict to the case of DM annihilation (without unusual redshift dependence), the generality of the full PCA is <u>not required</u>.
- All models turn out to have quite similar energy absorption histories (based on the transfer function for electrons and photons with 1 keV - 10 TeV energy).
- To parameterize "standard" DM energy absorption history and deviations from it, apply same PCA approach to set of sample f(z) curves. Originally (1109.6322) done for the 41 energy deposition curves derived in 0906.1197. Now (new work) also done for 1 keV - 10 TeV DM producing arbitrary e^+e^-, photon spectra, using updated treatment of low-energy particles.
- Result: first principal component accounts for vast bulk (99.97%) of the variance, if PC coefficients are comparable.
- Restricting to WIMP models, different masses / final states are <u>not expected to be distinguishable</u>, even by a cosmic variance limited experiment.
- Good news: very model-independent limits!

The weighting function

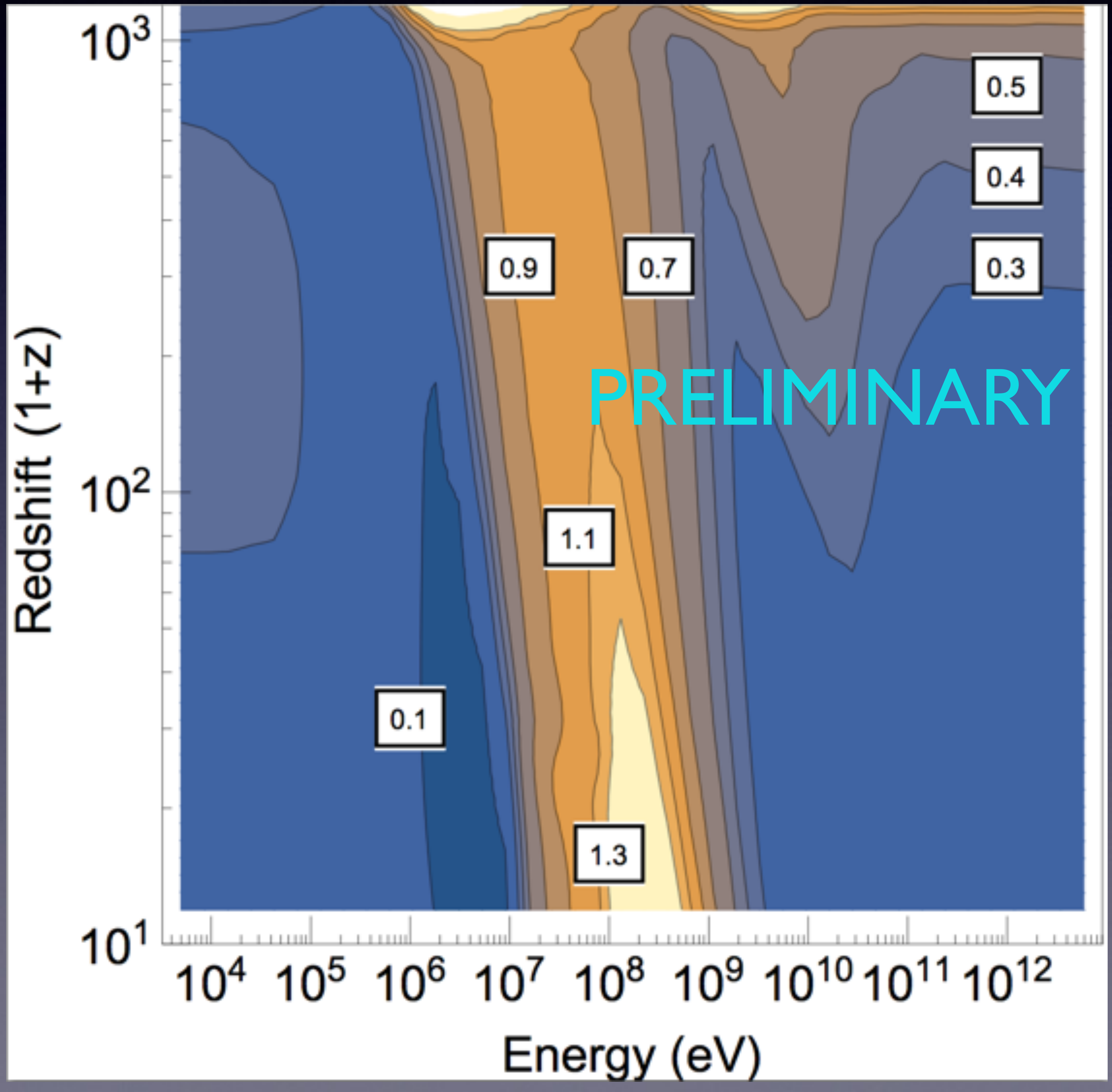
- Can write any f(z) as a linear combination of PCs: the coefficient of the first PC (for the DM-specialized analysis) then completely describes the effect on the CMB.



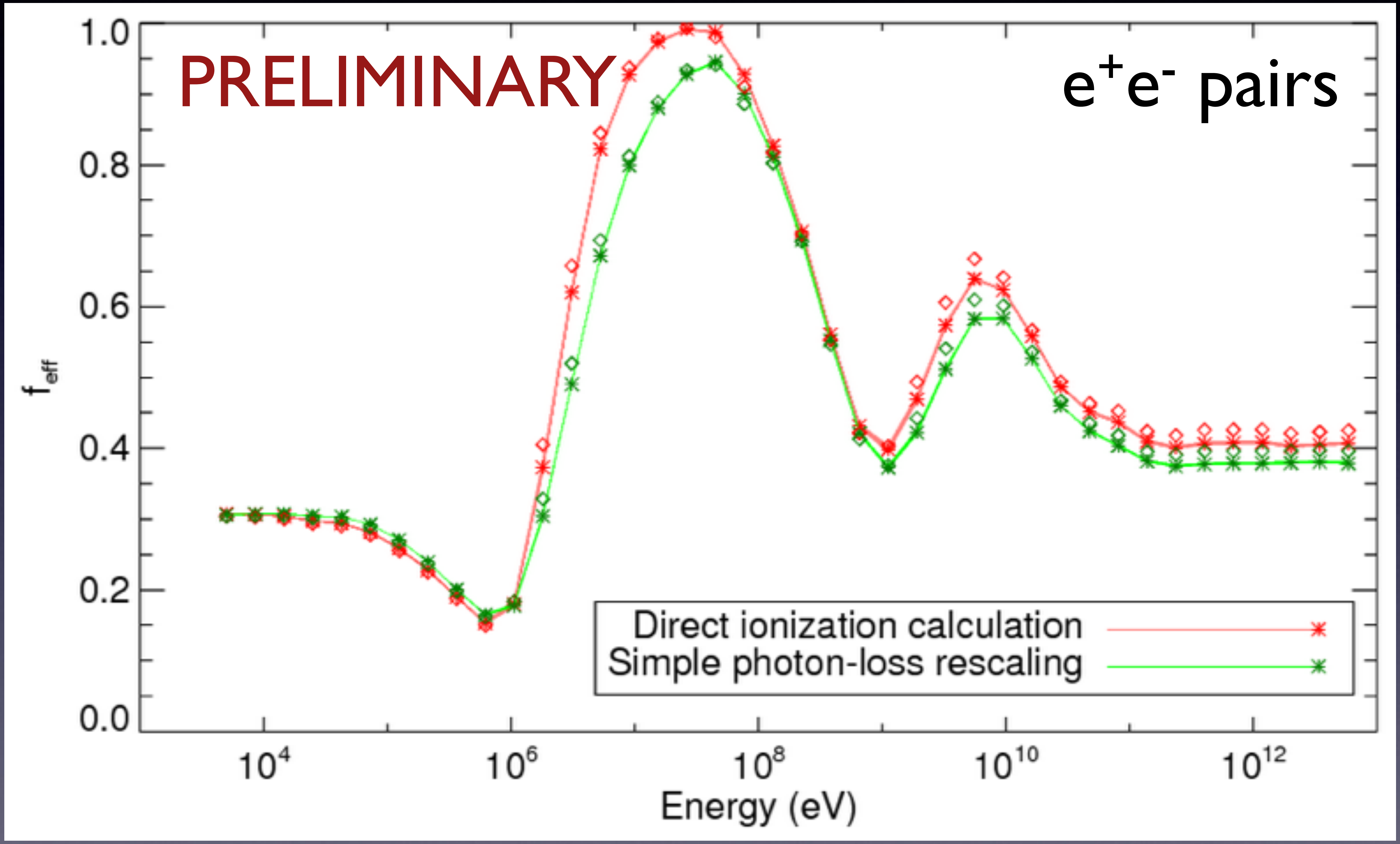
- Equivalently, we now have a unique weighting function that generates "effective f" when integrated with the f(z) curve. (Normalize by f(z)=1, to compare to constraints derived under that assumption.)
- Allows translation of constraints derived for constant f to arbitrary f(z).
- Valid for any annihilating DM model in the ~keV-10 TeV range.

The f(z) curve

- As previously, define f(z) as absorbed/injected energy, rescaled by the new partition into ionization. (Alternatively, rescale by power lost to continuum photons - similar results.)
- Obtain for all energies, z by integrating transfer function; assume annihilation rate scales as density^2.

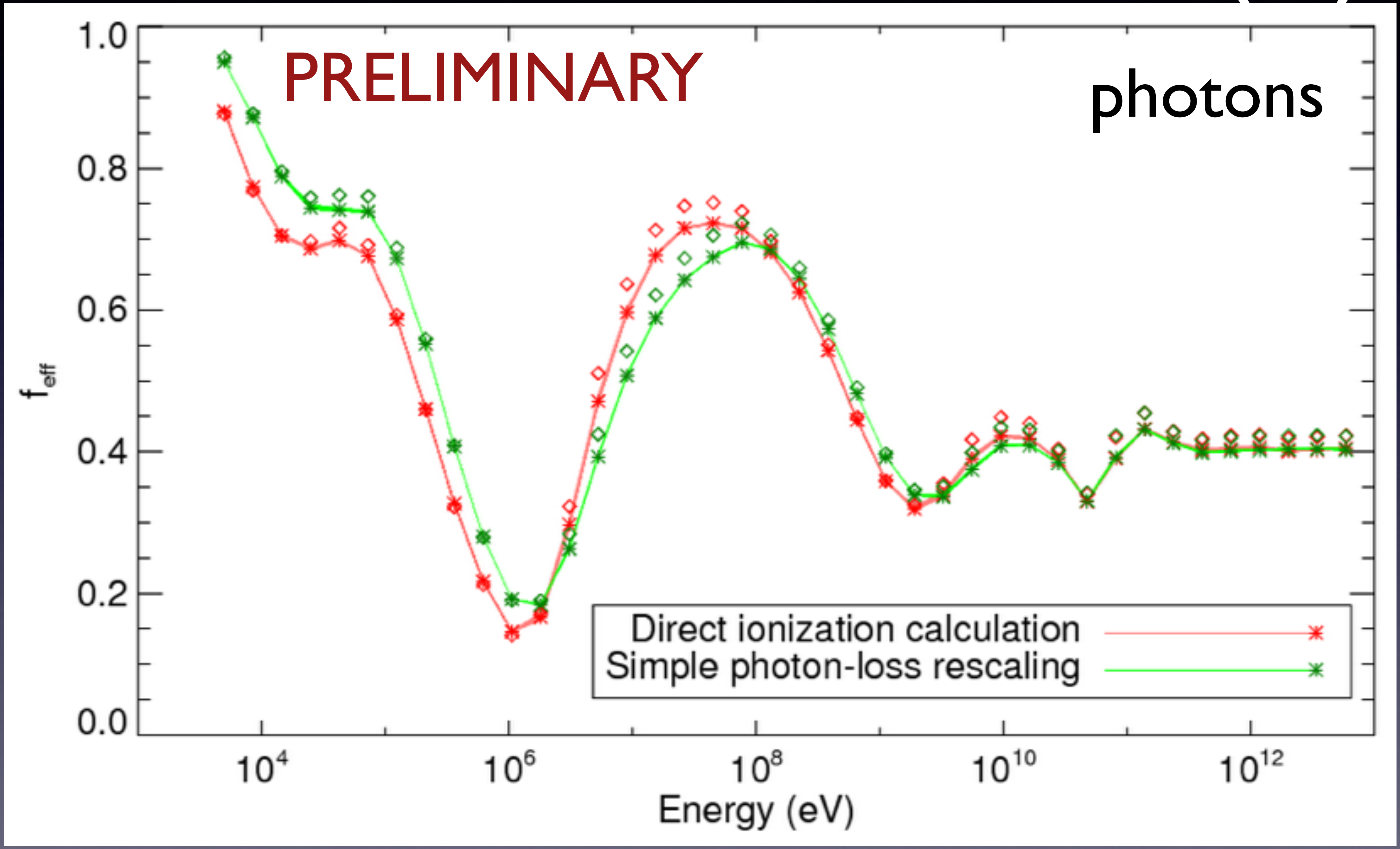


New f_{eff} calculations



- Result for electrons+positrons - f_{eff} is around 0.4 and stable at high injection energies, around 0.3 for electrons injected almost at rest, in between can rise as high as 1 and fall as low as ~0.15.

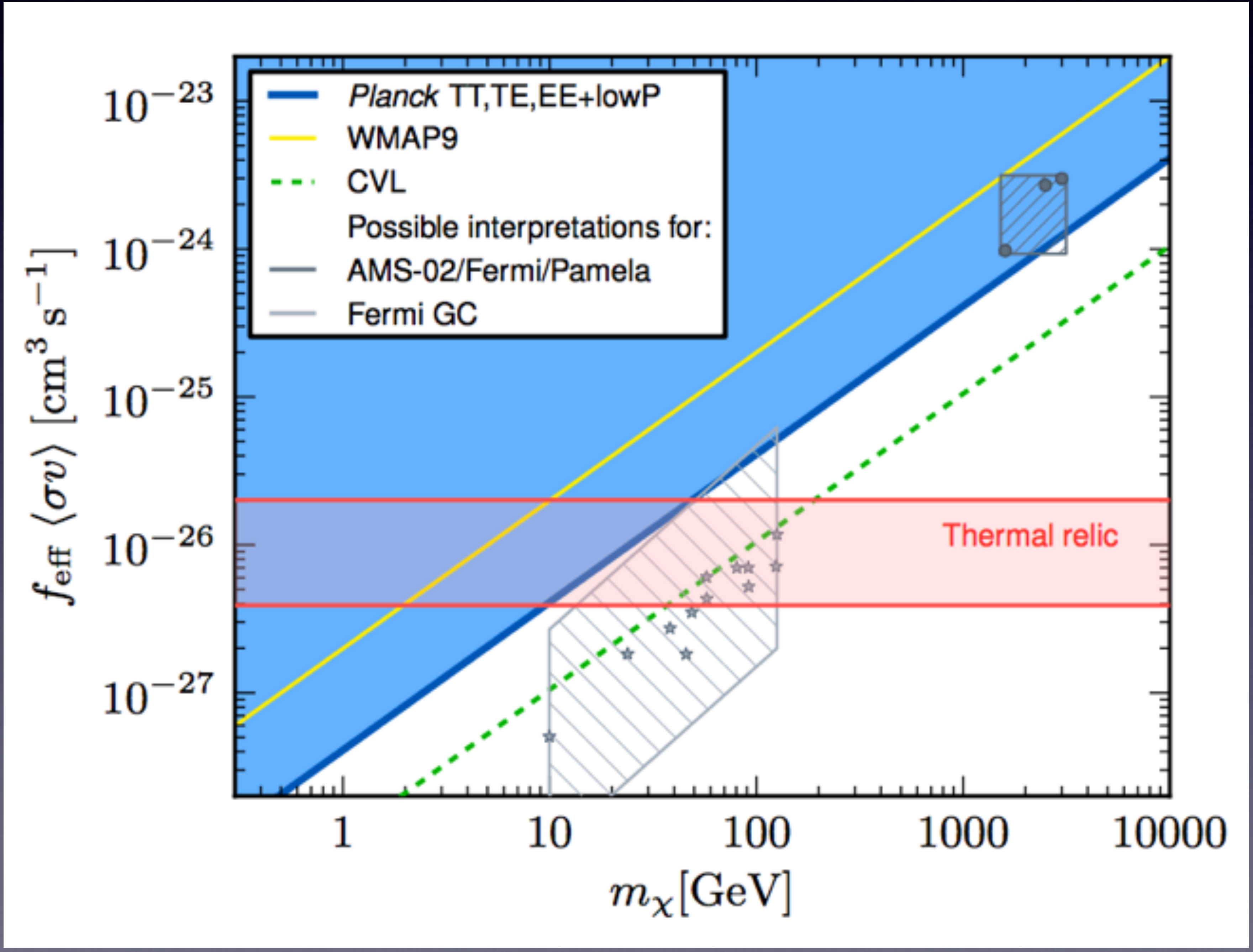
New f_{eff} calculations (II)



- Result for photons - f_{eff} is around 0.4 and stable at high injection energies, has a valley around 1 MeV, rises to ~0.7-0.9 at low energies and around 100 MeV.

Setting constraints

- Now for each energy, integrate f(z) W(z) dln(1+z) to obtain effective f (where W(z) = weighting function shown earlier).
- For an arbitrary DM model, can simply determine electron, positron, photon spectra and average over these curves to find total f_{eff}. Can then apply Planck bounds directly.



Conclusions

- Measurements of the cosmic microwave background provide a clean, robust and model-independent probe of dark matter annihilation, or any process that injects electromagnetic energy during/after recombination.
- Results from Planck rule out thermal relic dark matter (annihilating through the s-wave) with mass less than ~10-50 GeV, depending on the annihilation channel.
- The effects of DM annihilation on the CMB anisotropy spectra can be characterized in a model-independent way by a single parameter - the effects of different DM models on the CMB are very similar up to an overall normalization factor.
- The CMB limit on any DM model can now be calculated immediately once its photon and electron spectra are known.

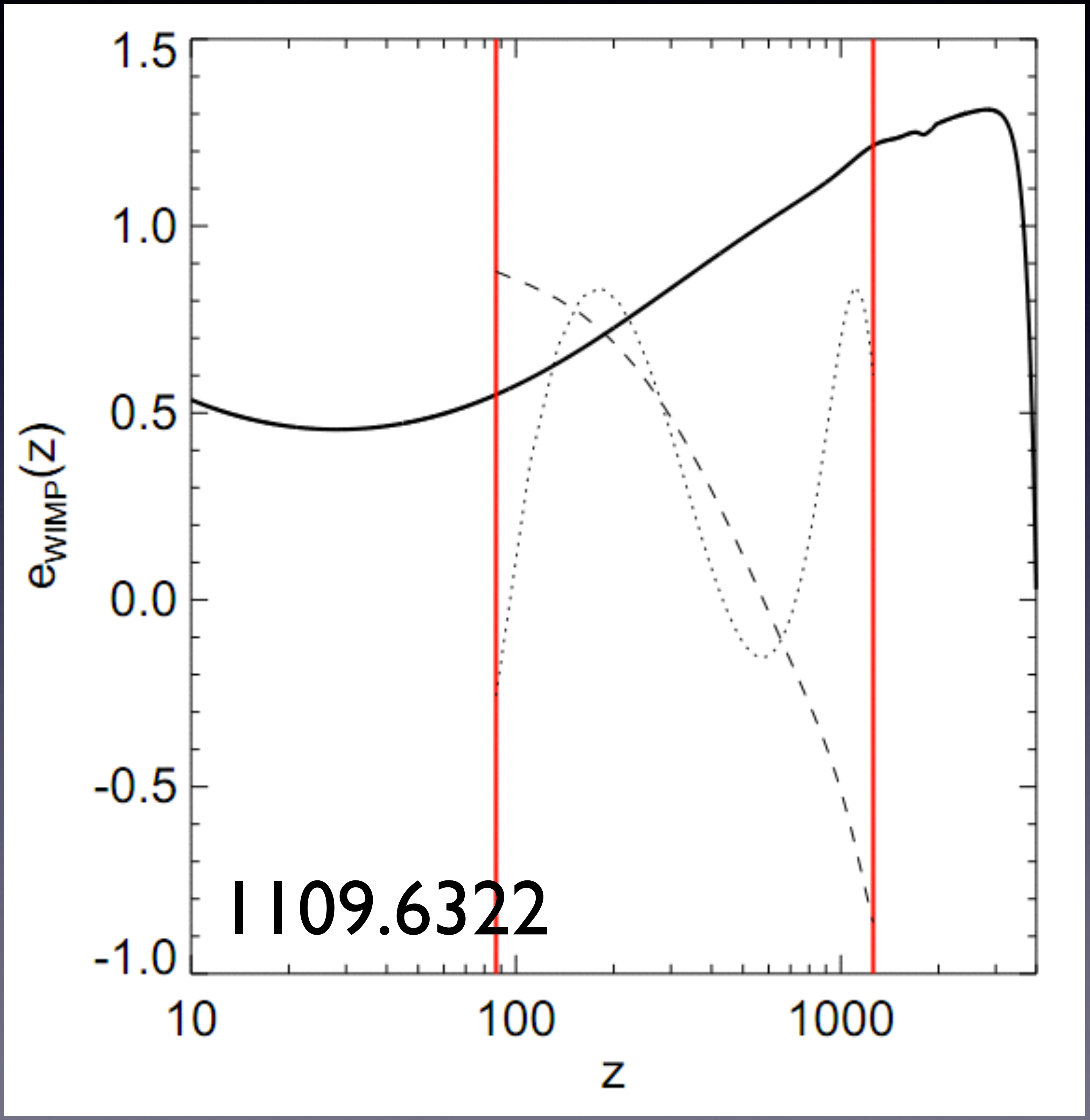
BONUS SLIDES

Updated "f" curves

- It is no longer precisely possible to characterize the energy deposition of a model by a single function f(z) - the partition into ionization/excitation/heating/continuum photons is also somewhat model-dependent.
- However, we can get close, in two ways:
  - Option 1: add up total power going into high-energy deposition + electrons + photons above 10.2 eV, apply energy fractions at 3 keV. Shown in 1306.0563 that this gives weaker constraints than "best estimate" by ~5-15%.
  - Option 2: if we are only interested in the effect on the CMB anisotropies, it is driven almost entirely by ionization - characterize models by the power into *ionization* as a function of redshift.
- For convenience, we can divide out by the original approximate fraction of power into ionization (i.e. $(1 - x_H)/3$), to obtain a new $f_{eff}(z)$ curve - can be plugged into code that multiplies the f(z) curve by this approximate expression to get the effect on the ionization history.

The universal DM curve

- Result: first principal component accounts for vast bulk (99.97%) of the variance, if PC coefficients are comparable.
- Restricting to WIMP models, different masses / final states are <u>not expected to be distinguishable</u>, even by a cosmic variance limited experiment.
- Good news: very model-independent limits!



General energy injections

- For each particle species (photons, electrons, positrons) there is a function g(z,z',E), such that g(z,z',E) dz' is the fraction of initial energy deposited during the redshift interval dz', by a particle injected at redshift z with energy E.
- Can map out these functions and provide data tables, allowing interpolation for arbitrary E, z, z'.
- Then given any energy injection history (spectrum and redshift dependence), we can immediately compute the effective efficiency function f(z):

Energy injection history

$$f(z') = \frac{\int \int g(z, z', E)\, E\, \frac{dN}{dE dz}(z, E)\, dE\, dz}{\int E\, \frac{dN}{dE dz}(z', E)\, dE}$$

Energy absorbed at z'

Energy injected at z'

Most up-to-date limits

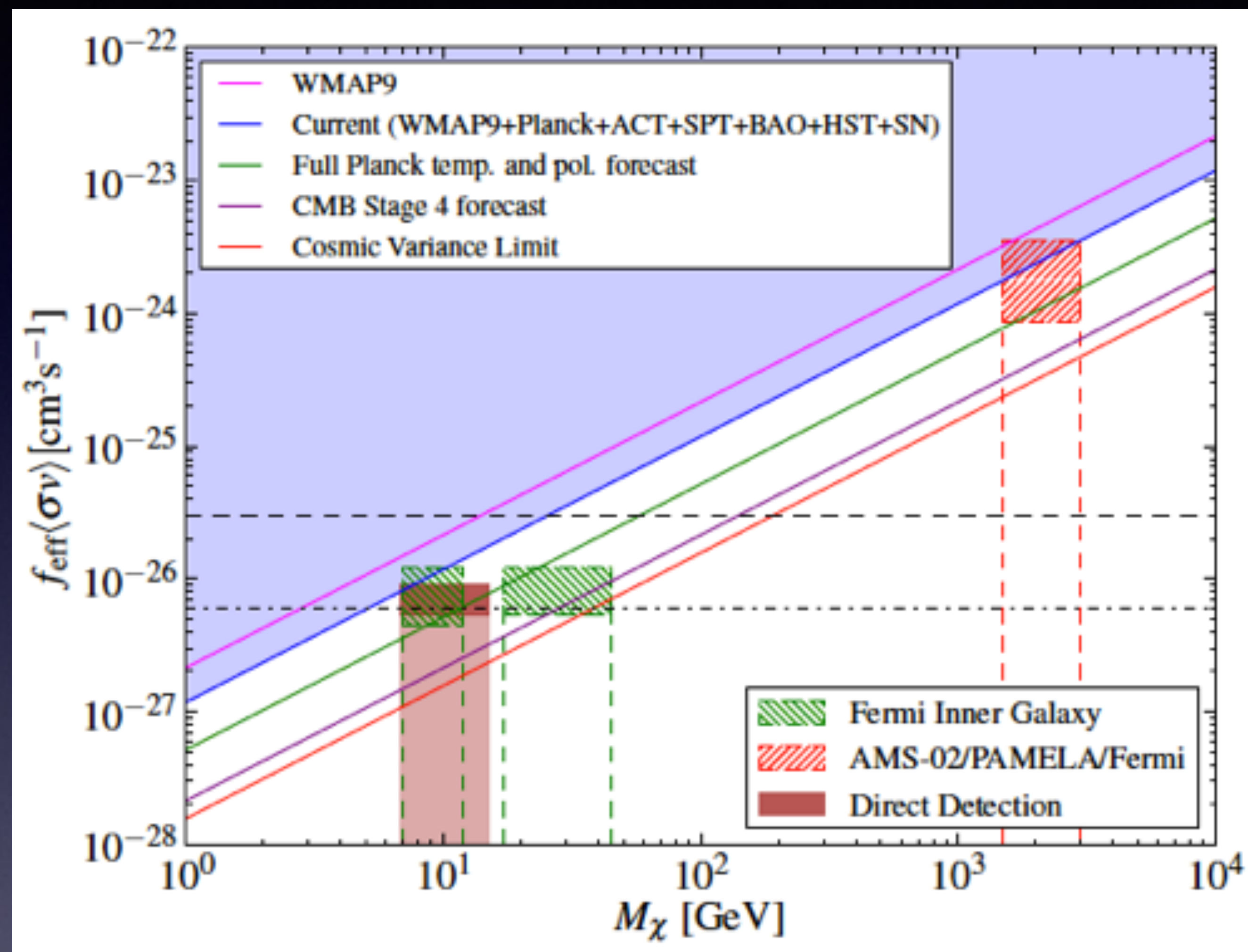
Madhavacheril, Sehgal & TRS 2013

Data Set	Const. Ann.	Non-Const. Ann.	Non-Const. w/ Sys. ($m^3s^{-1}kg^{-1}$)
WMAP9	$p_{\rm ann} < 1.20 \times 10^{-6}$	$p_{\rm ann} < 1.26 \times 10^{-6}$	$p_{\rm ann} < 1.21 \times 10^{-6}$
WMAP9 + Planck	$p_{\rm ann} < 0.87 \times 10^{-6}$	$p_{\rm ann} < 0.85 \times 10^{-6}$	$p_{\rm ann} < 0.80 \times 10^{-6}$
WMAP9 + Planck + Planck Lensing	$p_{\rm ann} < 0.85 \times 10^{-6}$	$p_{\rm ann} < 0.86 \times 10^{-6}$	$p_{\rm ann} < 0.79 \times 10^{-6}$
WMAP9 + Planck + Planck Lensing + ACT + SPT	$p_{\rm ann} < 0.75 \times 10^{-6}$	$p_{\rm ann} < 0.75 \times 10^{-6}$	$p_{\rm ann} < 0.73 \times 10^{-6}$
All CMB + BAO	$p_{\rm ann} < 0.70 \times 10^{-6}$	$p_{\rm ann} < 0.66 \times 10^{-6}$	$p_{\rm ann} < 0.67 \times 10^{-6}$
All CMB + BAO + HST	$p_{\rm ann} < 0.71 \times 10^{-6}$	$p_{\rm ann} < 0.74 \times 10^{-6}$	$p_{\rm ann} < 0.66 \times 10^{-6}$
All CMB + BAO + HST + Supernova	$p_{\rm ann} < 0.70 \times 10^{-6}$	$p_{\rm ann} < 0.71 \times 10^{-6}$	$p_{\rm ann} < 0.66 \times 10^{-6}$

- Uses data from Planck (temperature + lensing), WMAP9 (temperature + polarization), ACT, SPT, measurements of BAO+HST+supernovae.
- Nearly factor-of-two improvement over WMAP9 alone; most of the improvement comes from inclusion of Planck temperature data, and then from ACT/SPT and BAO data.
- Results are similar using constant f(z), the original universal curve or our updated universal curve - as expected, since by construction they are normalized to give the same bound in the Fisher matrix treatment. The difference enters in the $f_{\rm eff}$ values.

Constraints on DM models

- Current results constrain thermal relic DM in the 5-25 GeV (and lighter) mass range.



Channel	DM Mass (GeV)	$f_{\rm eff}$	$f_{\rm eff,\,sys}$
Electrons	1	0.85	0.45
$\chi\chi \to e^+e^-$	10	0.77	0.67
	100	0.60	0.46
	700	0.58	0.45
	1000	0.58	0.45
Muons	1	0.30	0.21
$\chi\chi \to \mu^+\mu^-$	10	0.29	0.23
	100	0.23	0.18
	250	0.21	0.16
	1000	0.20	0.16
	1500	0.20	0.16
Taus	200	0.19	0.15
$\chi\chi \to \tau^+\tau^-$	1000	0.19	0.15
XDM electrons	1	0.85	0.52
$\chi\chi \to \phi\phi$	10	0.81	0.67
followed by	100	0.64	0.49
$\phi \to e^+e^-$	150	0.61	0.47
	1000	0.58	0.45
XDM muons	10	0.30	0.21
$\chi\chi \to \phi\phi$	100	0.24	0.19
followed by	400	0.21	0.17
$\phi \to \mu^+\mu^-$	1000	0.20	0.16
	2500	0.20	0.16
XDM taus	200	0.19	0.15
$\chi\chi \to \phi\phi, \phi \to \tau^+\tau^-$	1000	0.18	0.14
XDM pions	100	0.20	0.16
$\chi\chi \to \phi\phi$	200	0.18	0.14
followed by	1000	0.16	0.13
$\phi \to \pi^+\pi^-$	1500	0.16	0.13
	2500	0.16	0.13
W bosons	200	0.26	0.19
$\chi\chi \to W^+W^-$	300	0.25	0.19
	1000	0.24	0.19
Z bosons	200	0.24	0.18
$\chi\chi \to ZZ$	1000	0.23	0.18
Higgs bosons	200	0.30	0.22
$\chi\chi \to h\bar{h}$	1000	0.28	0.22
b quarks	200	0.31	0.23
$\chi\chi \to b\bar{b}$	1000	0.28	0.22
Light quarks	200	0.29	0.22
$\chi\chi \to u\bar{u}, d\bar{d}$ (50% each)	1000	0.28	0.21

- Sensitive to DM models suggested to explain PAMELA/Fermi/AMS positron excess, inner Galaxy gamma-ray signal, and light DM hints from direct detection (if a thermal relic annihilating in s-wave) but cannot yet rule them out - looking forward to Planck polarization!

CosmoMC cross-checks

- Fisher matrix + principal component analysis assume:
  - Linearity (to write arbitrary history as linear combination of PCs, and to marginalize over cosmological parameters).
  - Likelihood function is approximately Gaussian in perturbations of all parameters.
  - For WMAP7 "constraints": we can use the best-fit cosmological model as a good proxy for the data.
- Cross-check by performing likelihood analysis using CosmoMC (Markov chain Monte Carlo), using actual WMAP7 data and forecast Planck sensitivity, adding PC coefficients as extra parameters in the analysis.

PC reconstruction

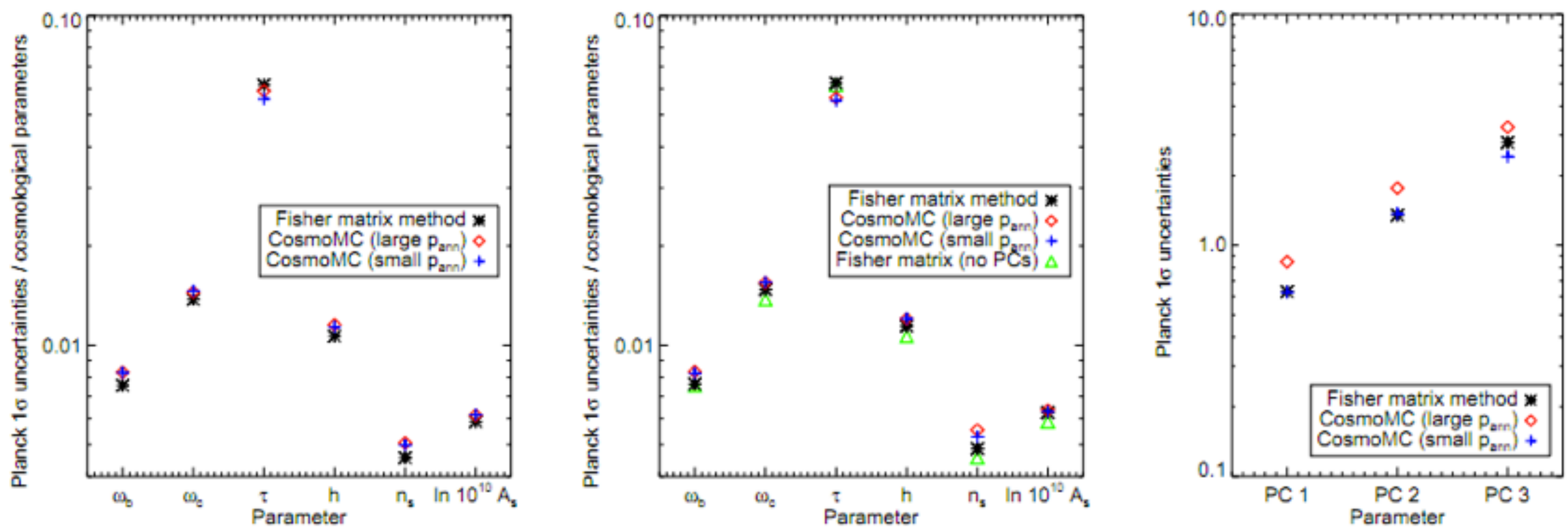


FIG. 20: Error bars for the cosmological parameters and coefficients of the principal components, in mock *Planck* data, simulated assuming a constant-$p_{\rm ann}(z)$ energy deposition history. The points marked "large $p_{\rm ann}$" have $p_{\rm ann} = 1 \times 10^{-6}\mathrm{m}^3/\mathrm{s/kg}$ $= 1.8 \times 10^{-27}$ $\mathrm{cm}^3/\mathrm{s/GeV}$, while for the points marked "small $p_{\rm ann}$" the value is a factor of 10 lower. In the *left panel* the fit to the data is performed using only the standard six cosmological parameters, whereas in the *center panel* and *right panel* three PCs are also included in the fit. For ease of comparison, the green triangles in the center panel reproduce the black asterisks in the left panel. For the PCs, the dimensionless uncertainties plotted here should be multiplied by $p_{\rm ann}$ to obtain the uncertainties on the ε_i coefficients. The uncertainties on the cosmological parameters have been divided by the central values of the respective parameters.

- Generally good agreement between Fisher matrix methods and CosmoMC, if energy deposition is in the linear regime (estimated errors accurate at ~5% for first two PCs, ~15% for third PC).

Removing cosmological parameter biases

- In Planck forecasting, adding a single PC removes most of the bias; 3 PCs are needed to fix the biases to n_s and A_s.
- Fisher matrix gets directions and approximate sizes of biases correct, but overestimates the A_s bias.

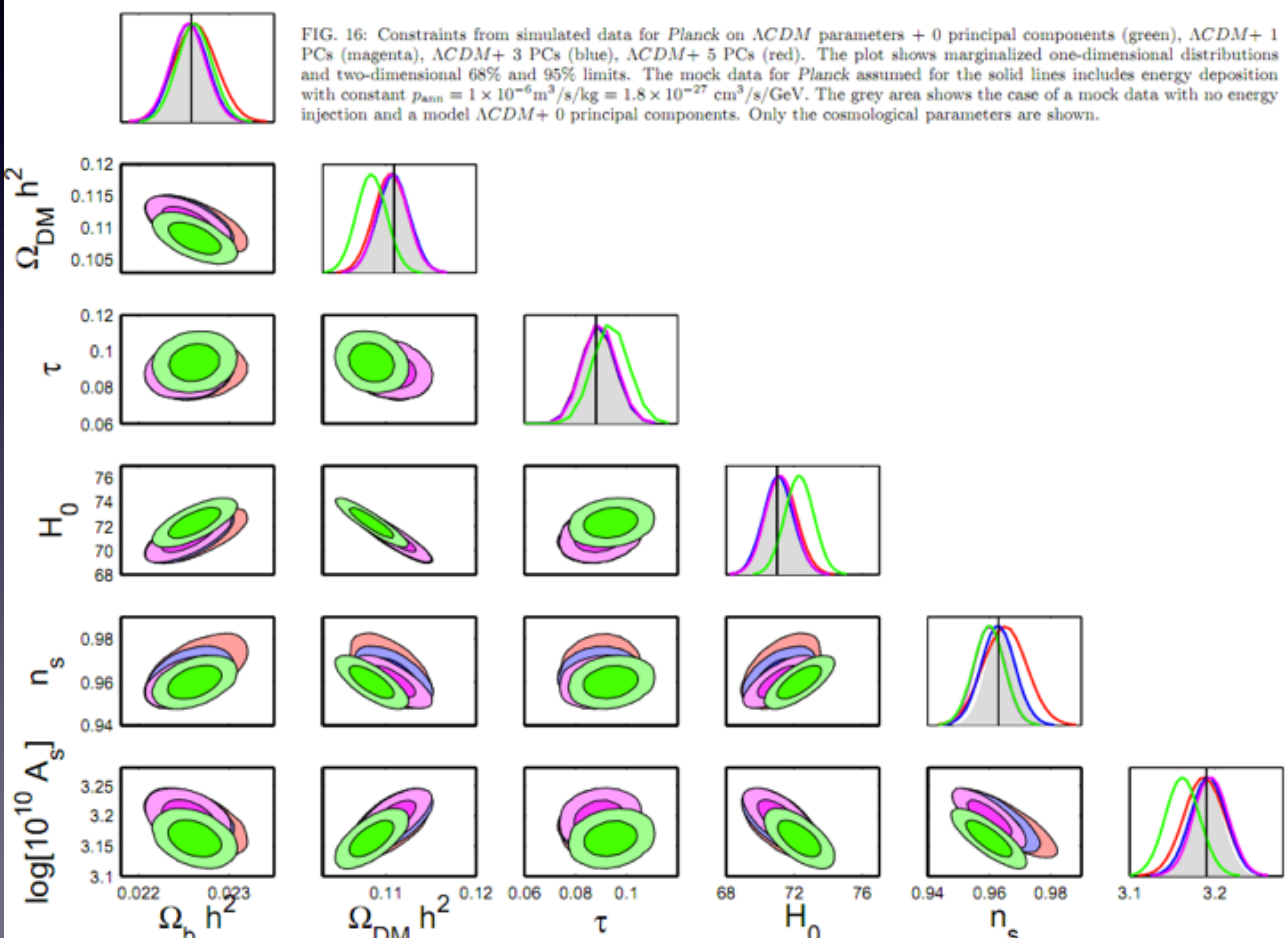


FIG. 16: Constraints from simulated data for *Planck* on ΛCDM parameters + 0 principal components (green), ΛCDM+ 1 PCs (magenta), ΛCDM+ 3 PCs (blue), ΛCDM+ 5 PCs (red). The plot shows marginalized one-dimensional distributions and two-dimensional 68% and 95% limits. The mock data for *Planck* assumed for the solid lines includes energy deposition with constant $p_{ann} = 1 \times 10^{-6} \mathrm{m}^3/\mathrm{s}/\mathrm{kg} = 1.8 \times 10^{-27}\ \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$. The grey area shows the case of a mock data with no energy injection and a model ΛCDM+ 0 principal components. Only the cosmological parameters are shown.

Linearity

- Can test for "linearity", e.g. whether the effect of two energy injections is the sum of their individual effects.
- Example: the predicted S/N curve for constant p_{ann}.
- Bottom line: linearity approximation can be invalid at the ~30% level for energy injections allowed by WMAP. Good at the few-percent level for energy injections at the expected limit that will be set by Planck.

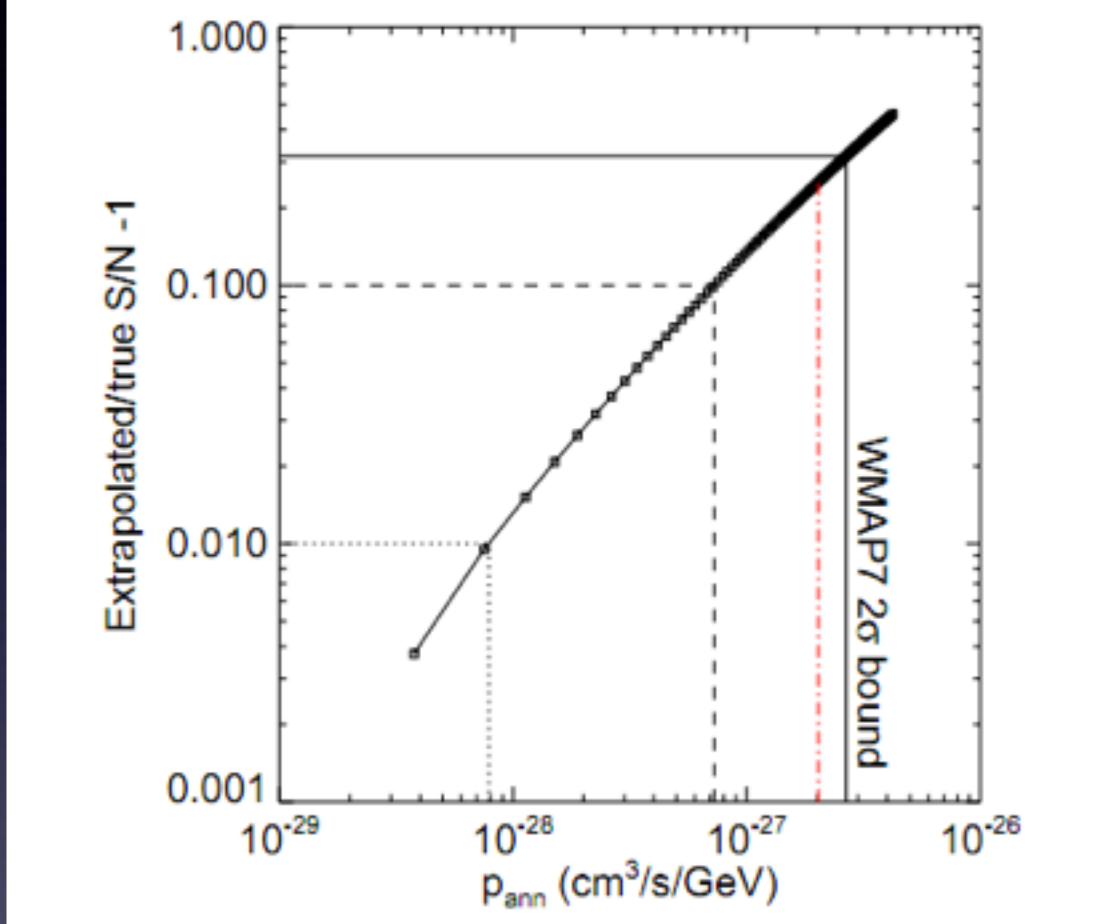


FIG. 3: The degree of nonlinearity in the computed significance of a sample energy deposition history, for p_{ann} constant, using *WMAP* 7 noise parameters. We show the ratio of (1) the S/N estimated by a linear extrapolation from small energy deposition to (2) the "true" S/N (estimated as in §II C), as a function of p_{ann}. The solid, dashed and dotted lines indicate the *WMAP* 7 2σ upper limit on p_{ann}, the value of p_{ann} for which the nonlinearity is 10%, and the value for which the nonlinearity is 1%, respectively. The red dot-dashed line indicates the 2σ upper limit on p_{ann} that would be obtained by linearly extrapolating the significance from small energy deposition, which overestimates the significance and hence leads to a too-strong constraint.

Degeneracy and linearity

- For WMAP7 generally, and for higher PCs for Planck, the allowed energy deposition probes regions of parameter space where the effect on the CMB is nonlinear.
- Leads to oddly shaped favored regions due to nonphysical large negative energy deposition.
- Also can lead to non-orthogonality between PCs and cosmological parameters.
- There is an optimal number of PCs to include: 1 for WMAP7, ~3 for Planck, ~5 for CVL.

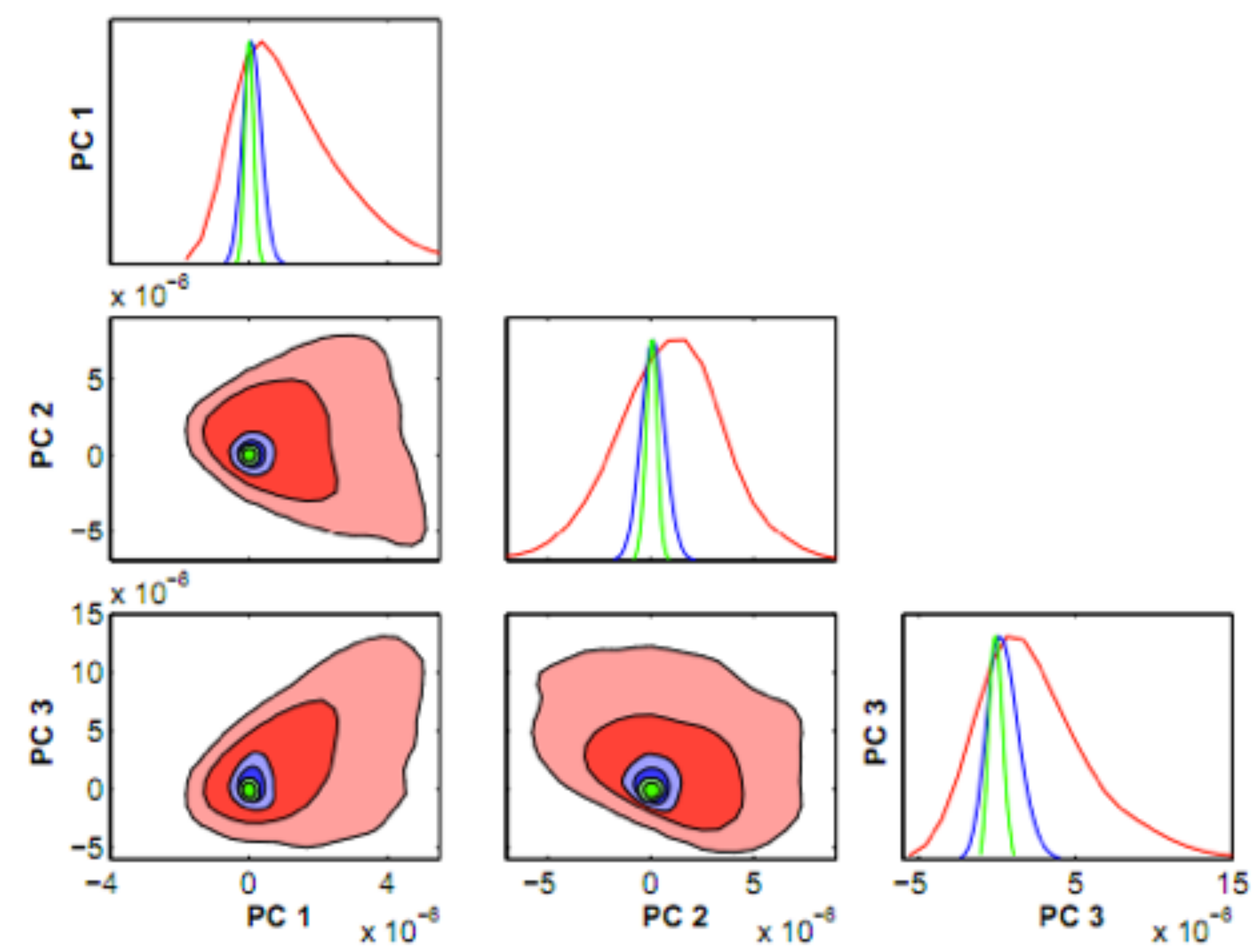


FIG. 14: Constraints from the seven-year *WMAP* data (red), and from simulated data for Planck (blue) and a cosmic variance limited experiment (green). The plot shows marginalized one-dimensional distributions and two-dimensional 68% and 95% limits. The mock data for Planck and the CVL experiment assumed no dark matter annihilation. Three Principal Components were used in each run to model the energy deposition from dark matter annihilation. The units of the PC coefficients here are in $m^3/s/kg$, with $1 \times 10^{-6} m^3/s/kg = 1.8 \times 10^{-27}\ cm^3/s/GeV$.

Validation checks

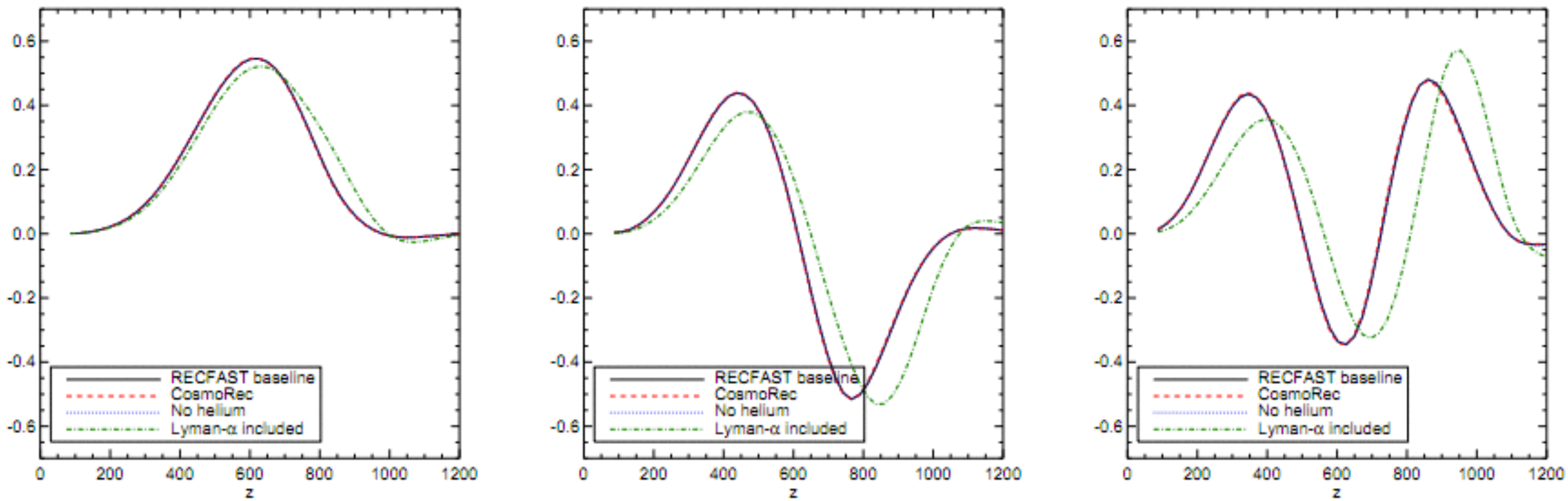
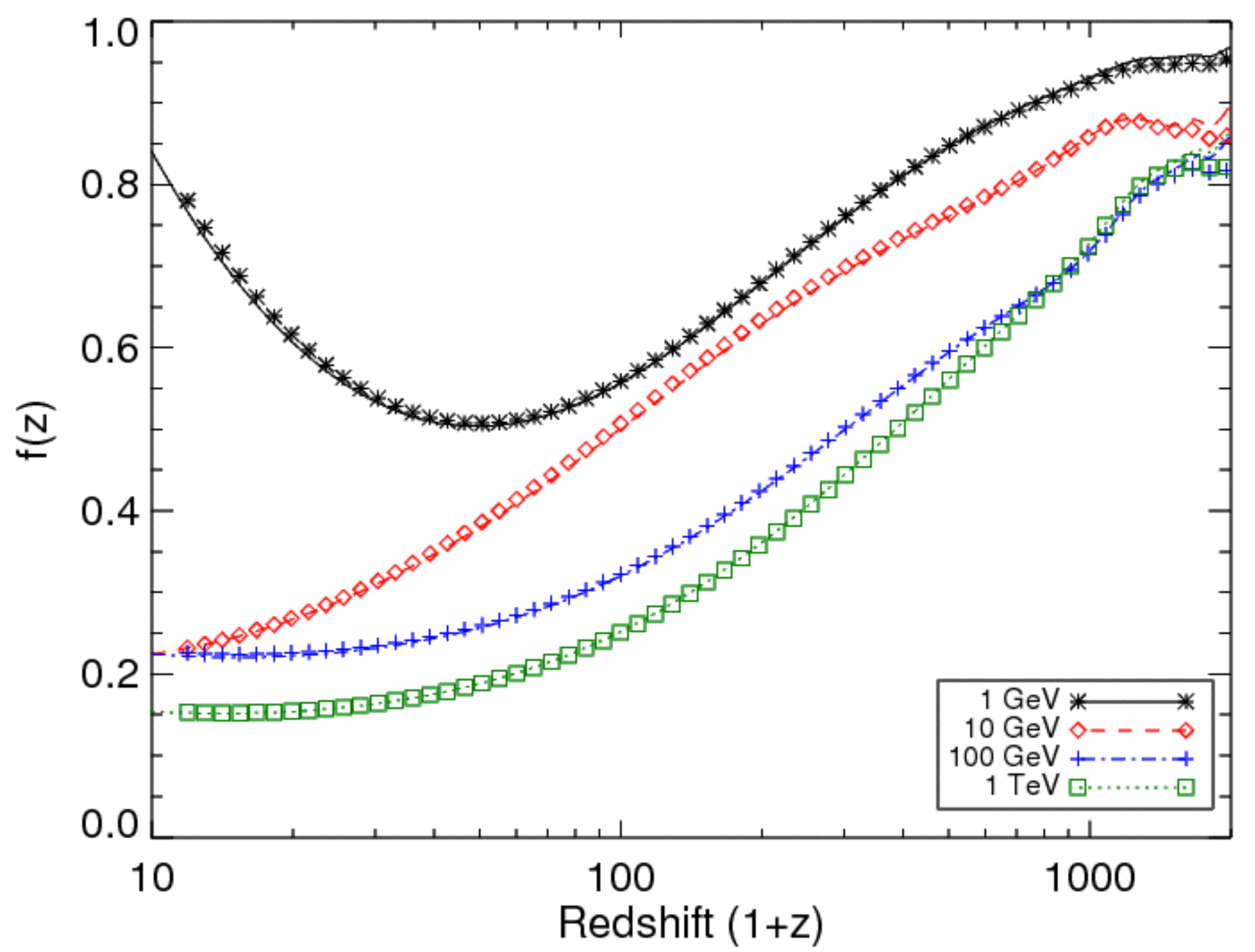


FIG. 24: The first three principal components for *Planck*, after marginalization, computed using `RECFAST 1.5` and `CosmoRec`. In the baseline case (as in `CosmoRec`), ionization of helium is included but injection of Lyman-α photons is not. We also show the effects of including a contribution to Lyman-α photons, and neglecting helium. The effect of helium ionization on the PCs is negligible because it is approximately a redshift-independent effect.

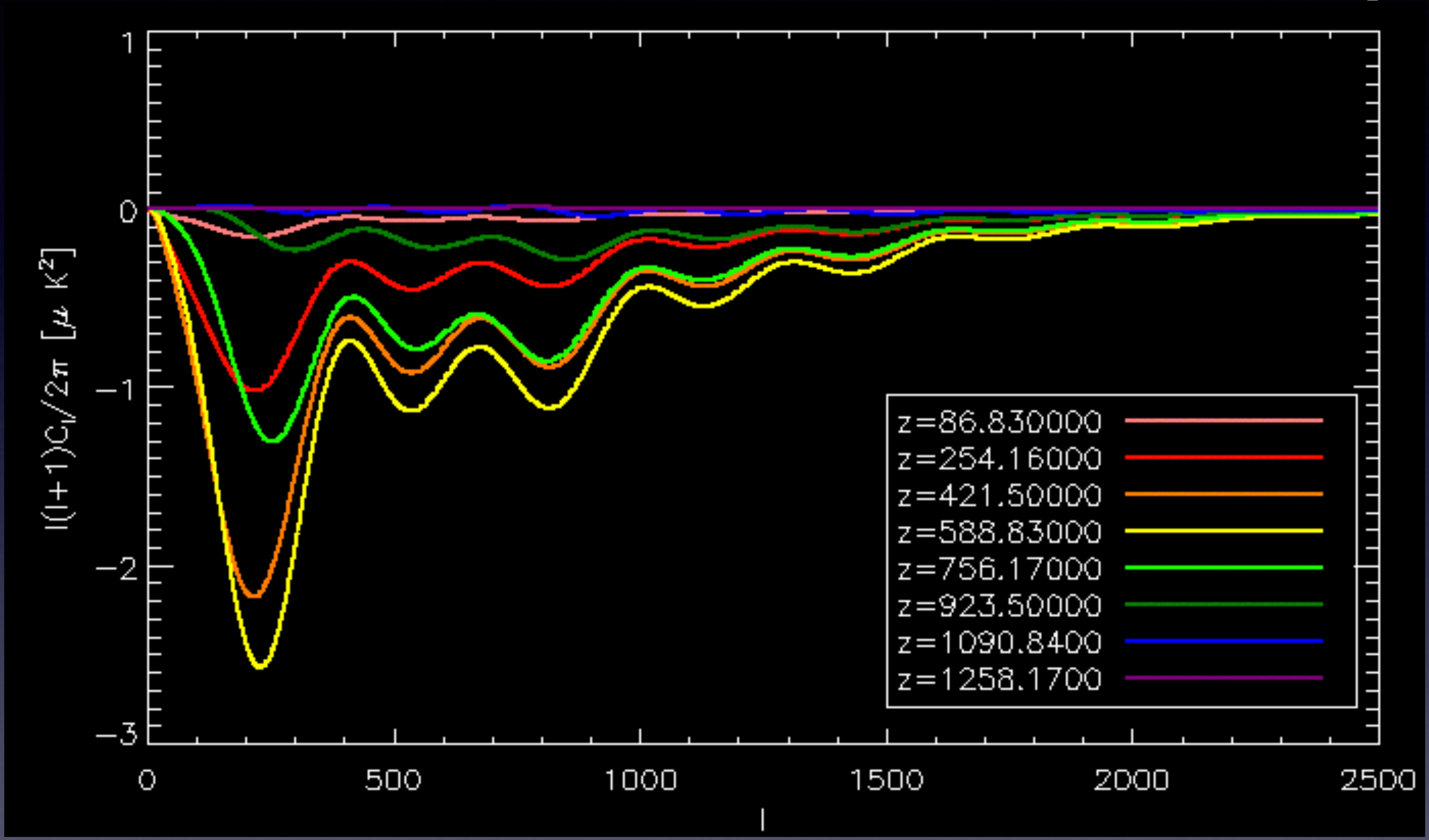
- Have tested effects of neglecting excitation/ionization on He, including extra cosmological parameters, changing binning of energy injections, changing maximum l, going from RECFAST to CosmoRec.
- NO noticeable changes to PCs (except if e.g. taking low l_{max} for high PCs in Planck).
- The one significant change comes from the treatment of Lyman-alpha photons. Needs further study. Even in this case, changes to PCs are modest.

Checks on the energy deposition function

- Lines are computed by direct time evolution of the spectrum (and include photons from FSR).
- Points are computed using a grid of 65 delta-function (in redshift) e^+e^- energy injections.



Derivatives of the C_l's



- Using RECFAST/CosmoRec and CAMB as described earlier, we can compute derivatives of the C_l's (i.e. the CMB anisotropy spectrum) with respect to the coefficients of the delta-functions.
- Defines an n_l x N transfer matrix T, if there are N basis delta-functions and we include n_l multipoles.

The Fisher matrix

- The Fisher matrix describes the covariance of the signals due to energy injection at different redshifts.
- Can be used to estimate detectability in the Gaussian approximation.
- Obtained by contracting the transfer matrix T with the appropriate covariance matrix.

$$(F_e)_{ij} = \sum_l T_{li}^T \cdot \Sigma_l^{-1} \cdot T_{lj}$$

- The covariance matrix depends on the temperature sensitivity and beam width of the experiment.

Marginalization

- Need to take into account degeneracies between energy injection and ordinary cosmological parameters.
- Can be done in Fisher-matrix formalism by projecting out the part of the transfer matrix parallel to the cosmological parameters.
- The effect of perturbing the cosmological parameters on the CMB is computed just as for the energy injections.

PCs in ionization history...

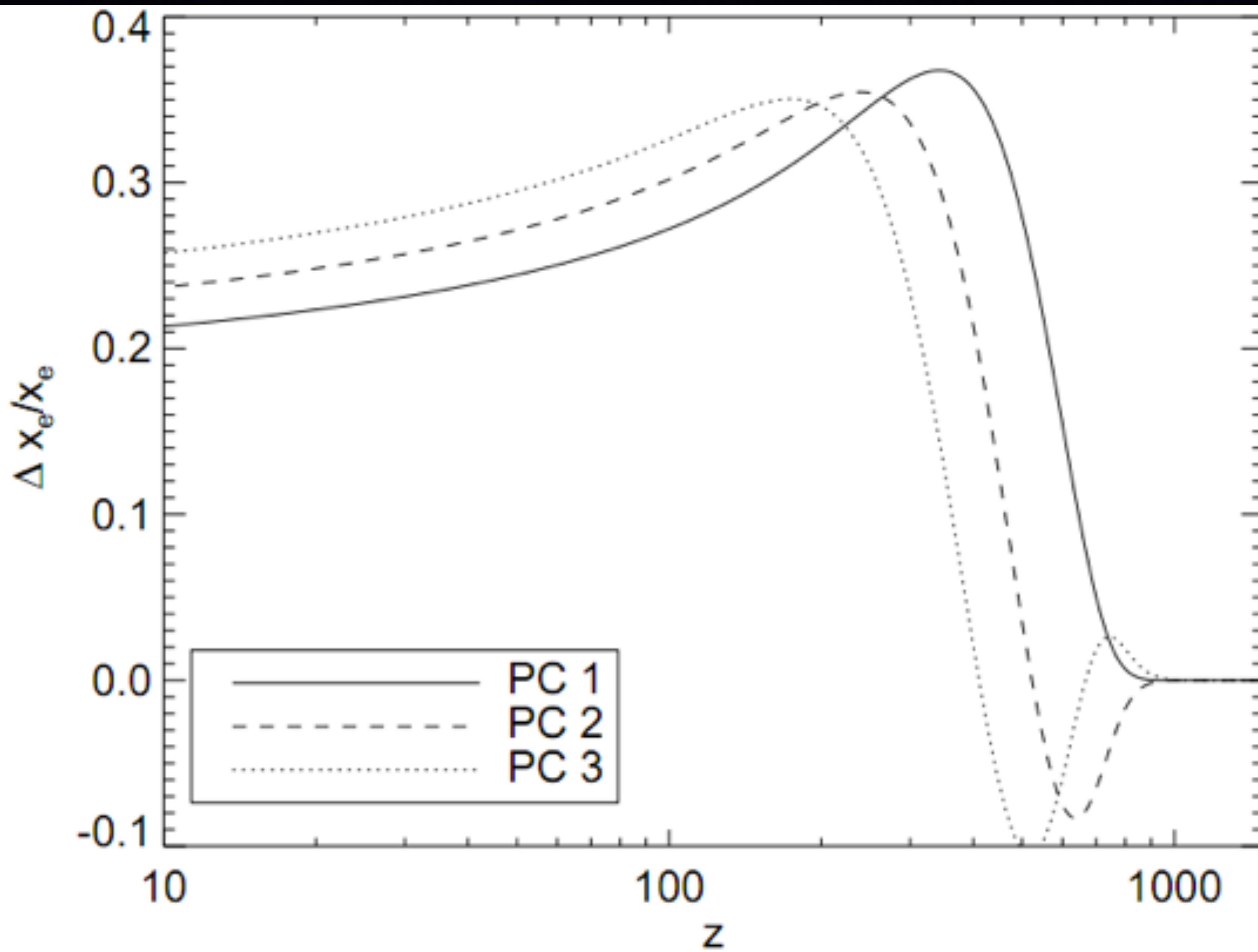
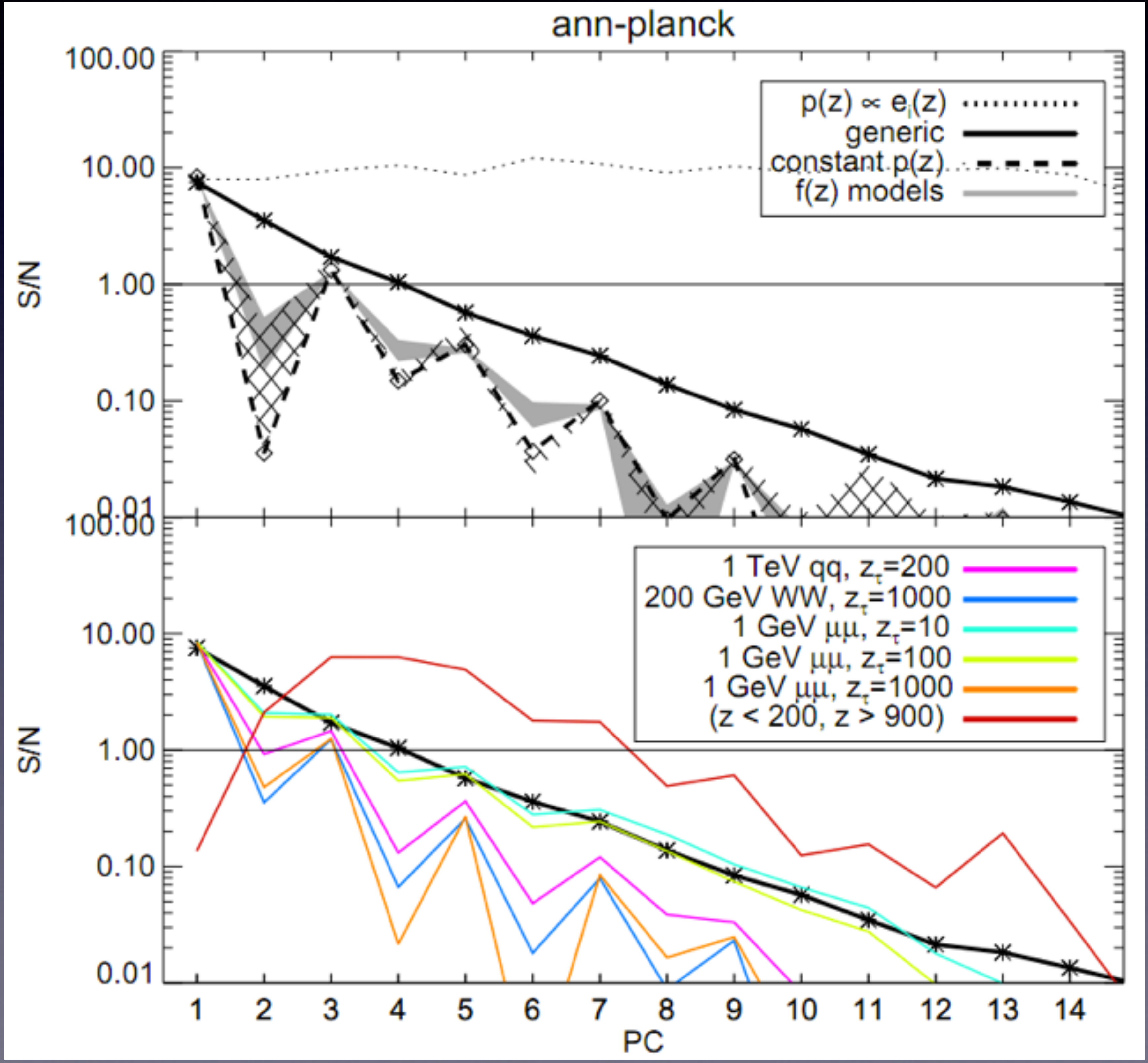


FIG. 6: Fractional change to the ionization fraction x_e in the presence of energy deposition, for the first three (marginalized) principal components in *Planck*. The curve shown is extrapolated from the linear (small energy deposition) regime, with normalization factor $\varepsilon_{1,2,3} = 2 \times 10^{-27}$ cm^3/s/GeV.

Detectability

- For any given energy deposition history, estimate 95% confidence limit on energy injection from WMAP7.
- Plot S/N expected in Planck for each principal component.



Reconstructing the energy deposition

- Given a non-zero residual between the model and the data, can project it onto the orthogonal basis defined by the PCs (perpendicular to the cosmological parameters).
- Automatically determines how much of the "signal" can be attributed to energy injection, taking degeneracies with the standard parameters into account.
- Reconstructed PC coefficients:

Residual

Eigenvalues

$$p(z) = \sum \varepsilon_i e_i(z) \qquad \bar{\varepsilon}_i = \frac{R \cdot h_i^{\perp}}{\lambda_i} \pm \frac{1}{\sqrt{\lambda_i}}$$

Energy deposition PCs Reconstructed coefficient

Bias

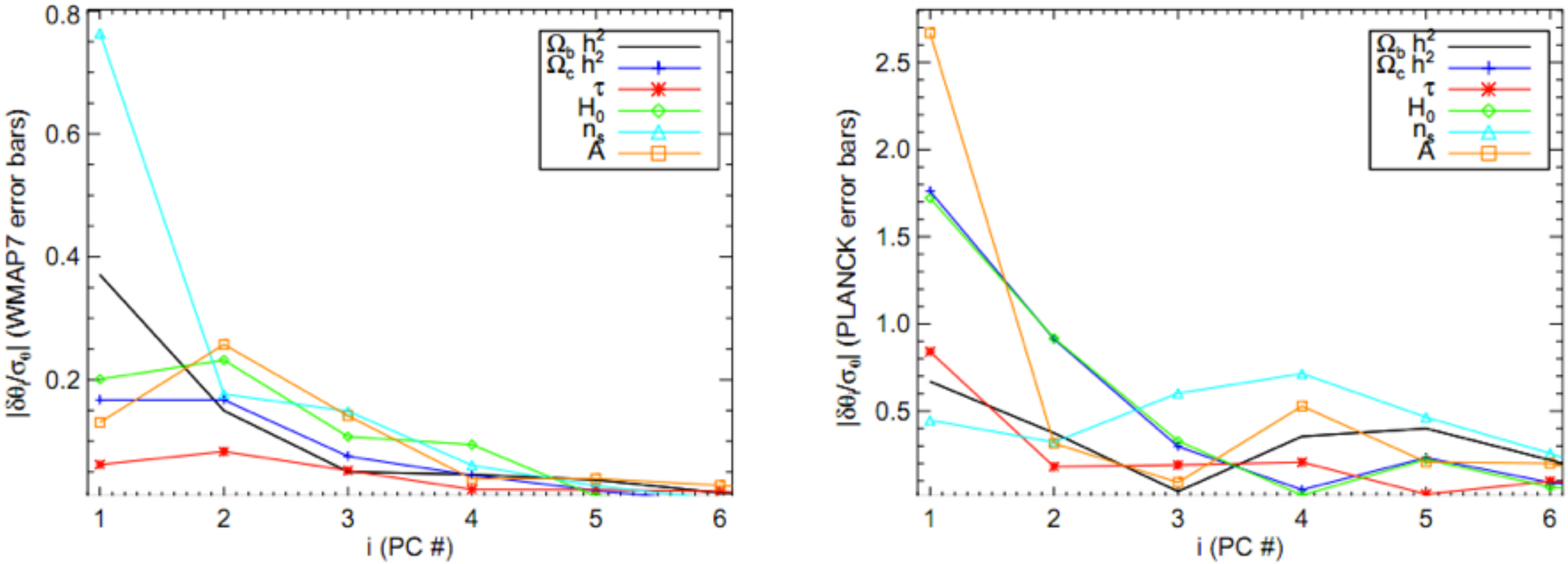


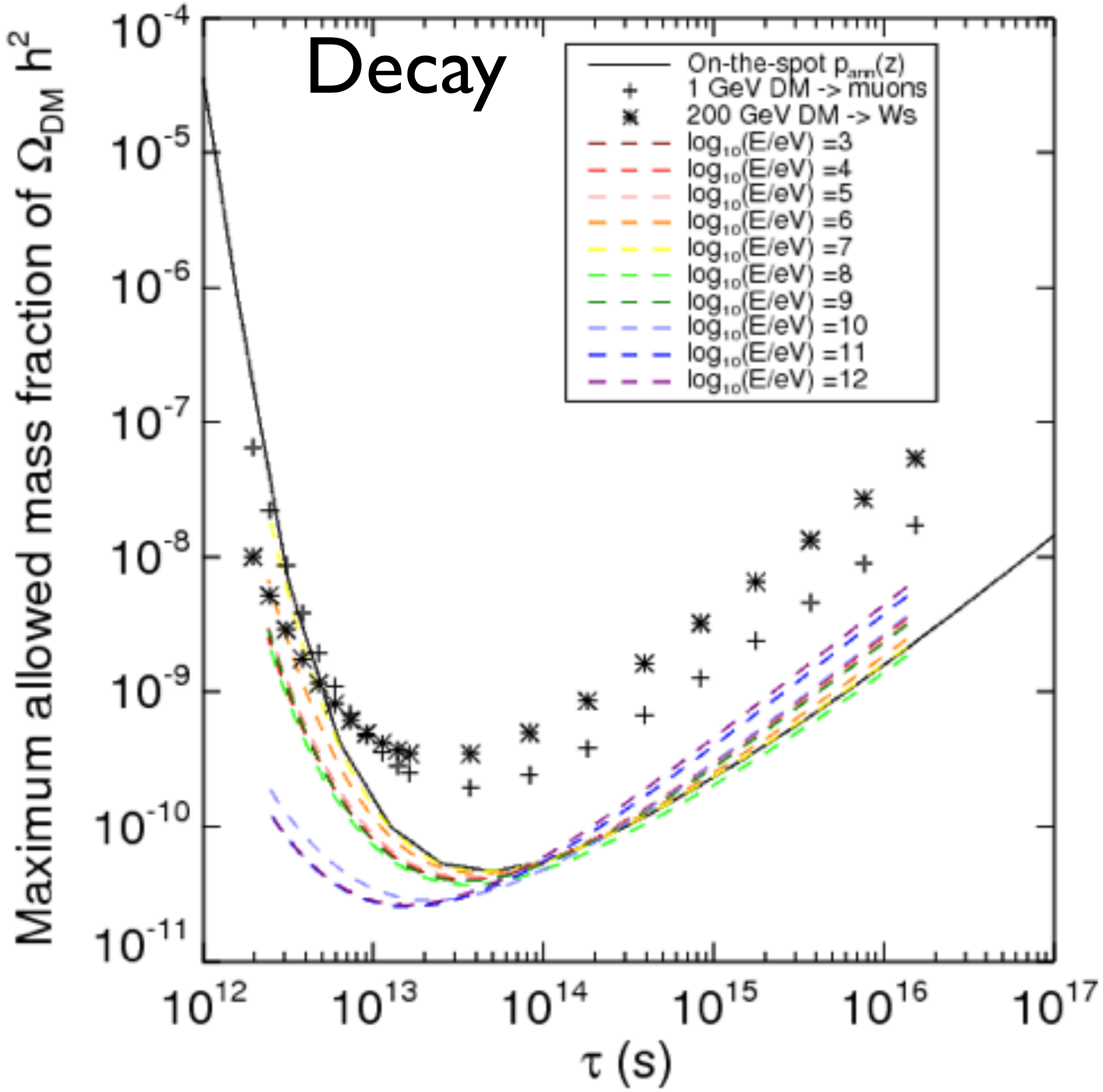
FIG. 11: For the ith PC, the contribution to the bias to cosmological parameters in *WMAP 7* (*left panel*) and *Planck* (*right panel*), relative to the error bars forecast from the Fisher matrix. The normalization is that of the "generic" case (see discussion in §IV B or Figure 10), where each PC coefficient has the same absolute value and the overall normalization is the maximum allowed by *WMAP 7* at 2σ. The total bias for the parameter θ is $\sum_i \delta\theta_i$.

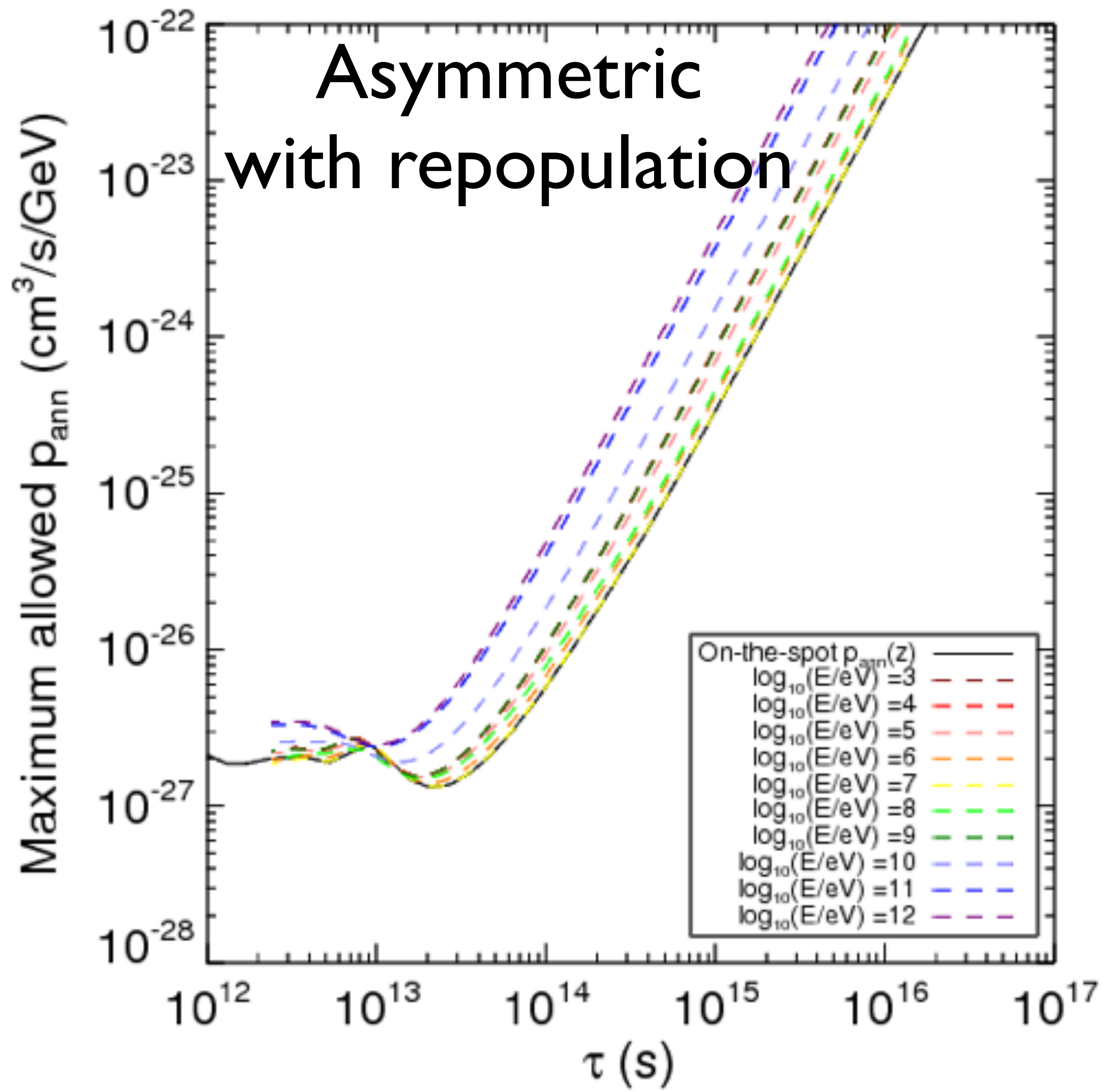
- The part of the h_i's parallel to the effect of shifting the cosmological parameters causes a bias in the standard parameters, if energy injection is not accounted for.
- For WMAP, bias is largest for n_s (up to ~1 sigma); true value of n_s closer to 1.

Exotic energy deposition histories

- Some example energy deposition histories that go beyond the "conventional annihilating WIMP" case:
  - A late-decaying species (mass density must be << DM); studied in e.g. Chen & Kamionkowski 03, so can use this as a cross-check.
  - DM with a nearly-degenerate excited state that decays producing electrons or photons, again with a long lifetime (but shorter than the present age of the universe).
  - Asymmetric dark matter models, where the symmetric component is repopulated at/after recombination, so annihilation "turns on" at some redshift.
  - More? (very happy to hear other ideas!)

Constraints on asymmetric and decaying DM





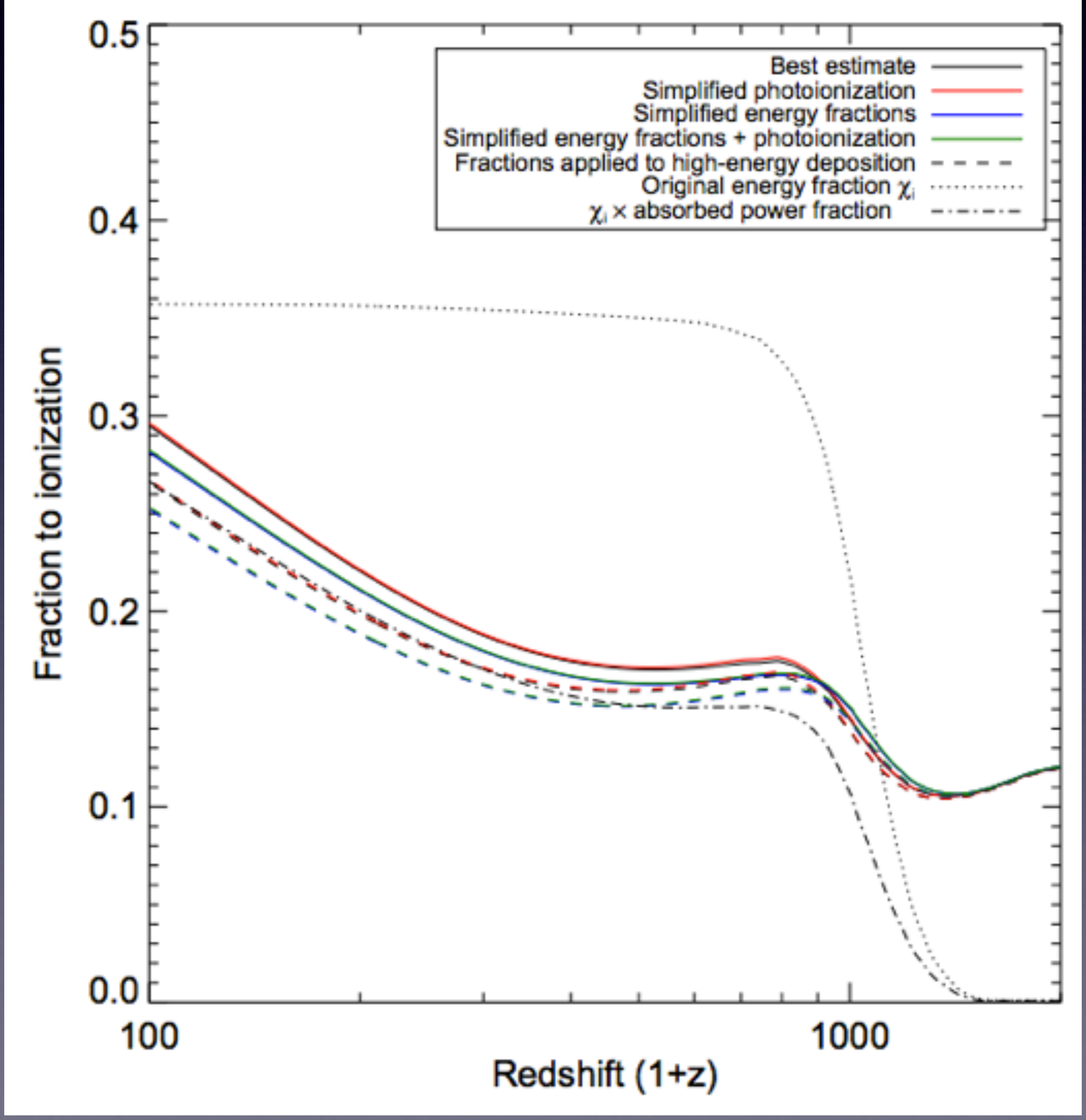
Constraints from WMAP7

Number of PCs used	PC	WMAP7 95%c.l.
1	PC	$< 1.2 \times 10^{-26} \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$
1	$e_{\mathrm{WIMP}}(z)$	$< 2.43 \times 10^{-27} \mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$

- When applied to constant-p(z) case, good agreement with previous results for WMAP7 (e.g. Hutsi et al 1103.2766, Galli et al 1106.1528).
- Constrains ~10 GeV DM annihilating to electrons, few GeV DM annihilating to other SM final states.
- For heavier DM, can put strong limits on models motivated by PAMELA/Fermi CR excesses.

Updated "f" curves

- Option 1: the updated $f_{eff}(z)$ curve would be the dot-dashed line divided by the dotted line, multiplied by the original f(z) curve.
- Option 2: the updated $f_{eff}(z)$ curve would be the solid black line divided by the dotted line, multiplied by the original f(z) curve.
- Note: these are normalized to *ionization* and should not be used to multiply Lyman-alpha and heating contributions, in cases where the effect of these contributions is non-negligible.



Recombination

- Before z~1000, the universe is almost completely ionized. Afterward (until reionization at $z \lesssim 30$) it is almost completely neutral.
- For photons below the ionization threshold of hydrogen, this transition makes the universe transparent.
- Photons of the cosmic microwave background radiation last scattered around recombination, at this epoch of last scattering. (After reionization, density has fallen enough that the universe is transparent even when ionized.)
- Planck, WMAP, ACT, SPT, BICEP etc measure the temperature and/or polarization fluctuations of these photons - sensitive probe of recombination and the intervening "dark ages".

Questions

- How good is our approximation for energy losses into ionization/excitation/heating? (what I've shown is based on a simple linear fit to a numerical calculation in a 1980s paper...)
- Can the effect of each individual DM model on the CMB really be captured by a single number? If so, is that number "the average of f between z=800-1000"? How can we estimate this number for arbitrary DM models?
- Likewise, to what degree are energy injections with different photon/electron spectra and redshift-dependences distinguishable by their effect on the CMB?