Signatures of Dark Matter Annihilation in the Cosmic Microwave Background

ICHEP 2012
Melbourne, Australia
7 July 2012

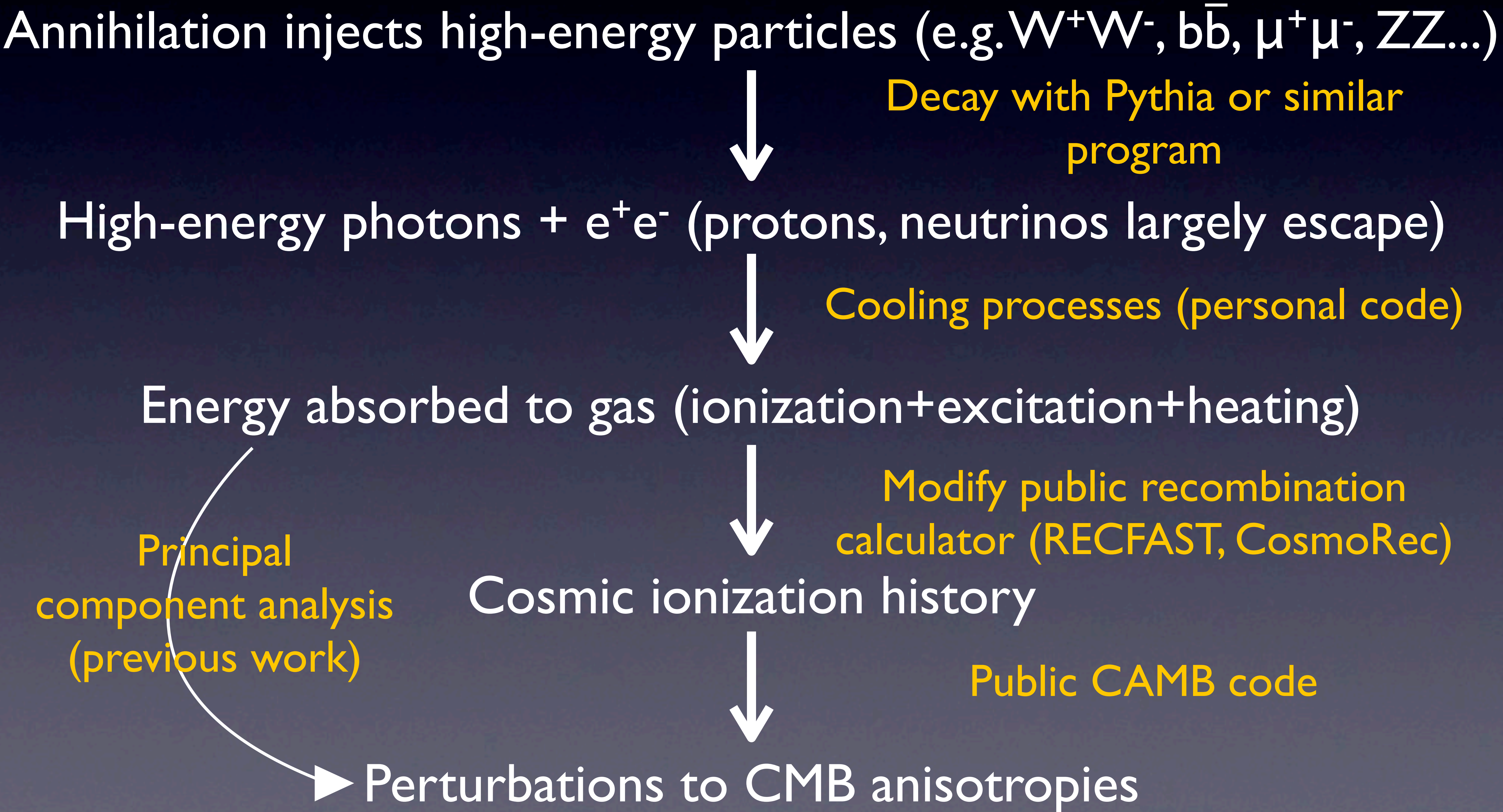
Tracy Slatyer
Institute for Advanced Study, USA

based on work with Douglas Finkbeiner, Silvia Galli, Tongyan Lin, and Nikhil Padmanabhan
0906.1197, 1109.6322, upcoming work

Outline

- During the cosmic dark ages (between reionization and recombination, z~30-1000) the universe is:
  - Almost completely neutral: ionization fraction ~10^{-4}.
  - Almost homogeneous and isotropic, density fluctuations are small and perturbative.
- CMB photons come to us from the surface of last scattering at z~1000: temperature/polarization anisotropies sensitive to small changes in ionization during the dark ages.
- Even long after freezeout, weak-scale dark matter annihilation can change the redshift-dependent ionization fraction by O(1), predicting a signal close to current sensitivity.
- WMAP7 rules out few-GeV-and-lighter DM with thermal relic cross sections, and Planck will do much better.

From energy injection to the CMB



Annihilation injects high-energy particles (e.g. W^+W^-, $b\bar{b}$, $\mu^+\mu^-$, ZZ...)

Decay with Pythia or similar program

High-energy photons + e^+e^- (protons, neutrinos largely escape)

Cooling processes (personal code)

Energy absorbed to gas (ionization+excitation+heating)

Modify public recombination calculator (RECFAST, CosmoRec)

Principal component analysis (previous work)

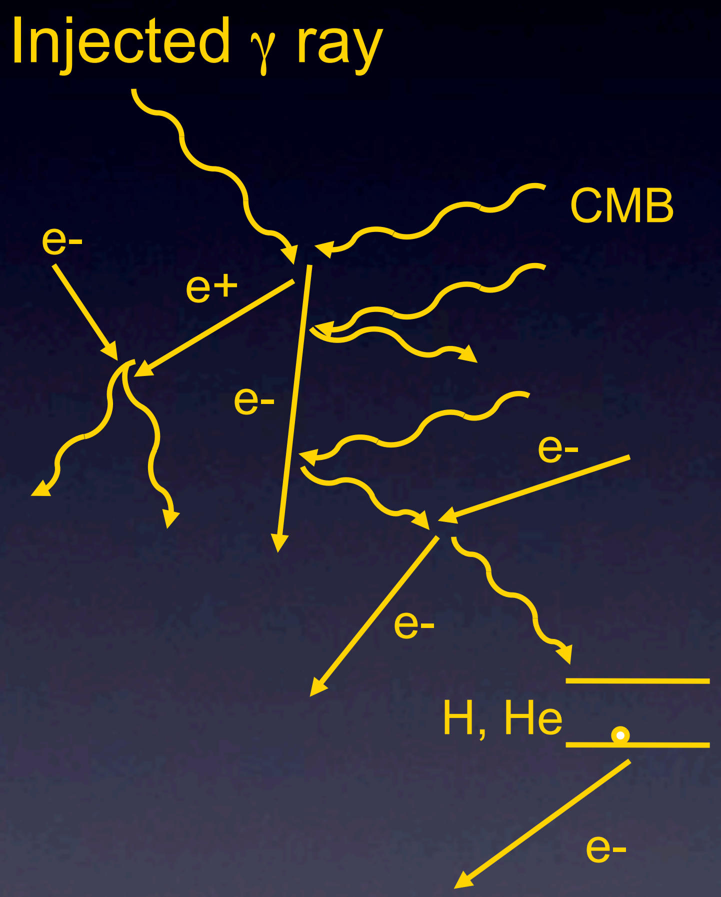
Cosmic ionization history

Public CAMB code

Perturbations to CMB anisotropies

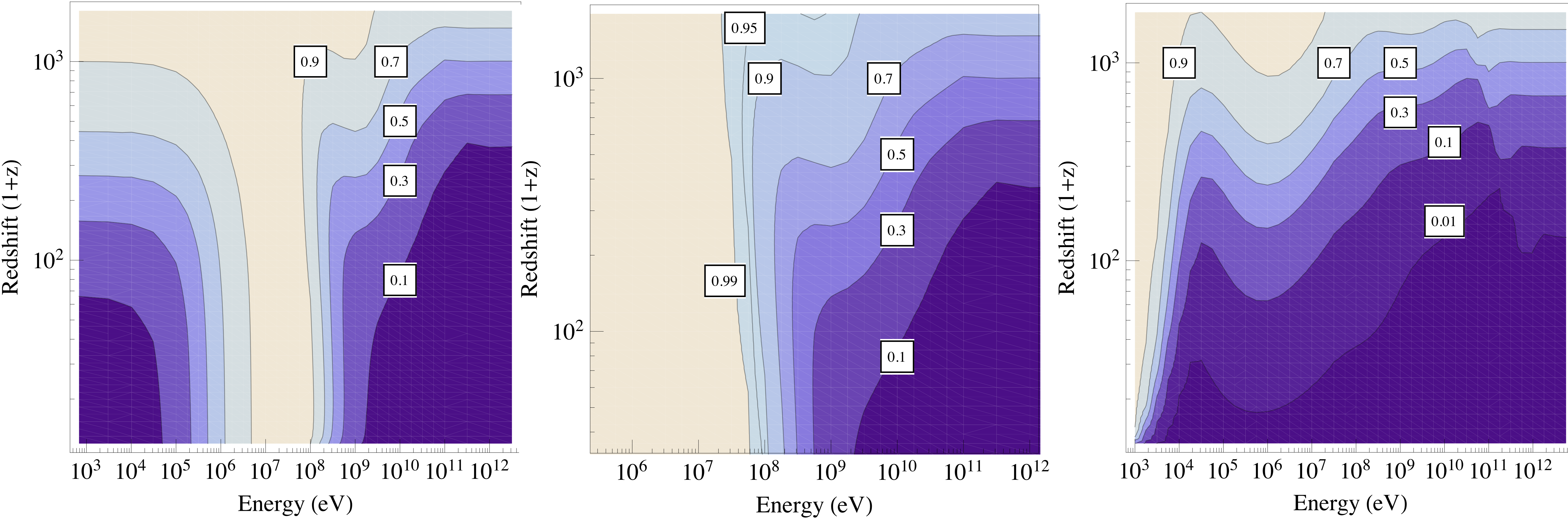
From injection to absorption

- High-energy photons = very poor ionizers.
- However, can cool via pair production, photon-photon scattering, Compton scattering, redshifting.
- Much of energy partitioned into sub-keV photons, which ionize gas efficiently.
- Numerically map out this transfer function from injection to absorption (using code developed for TRS, Finkbeiner & Padmanabhan 0906.1197).
- For each initial redshift and energy at which particle is injected, and for each species (photons, electrons, positrons), compute absorption history as a function of redshift.



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

Total absorbed energy



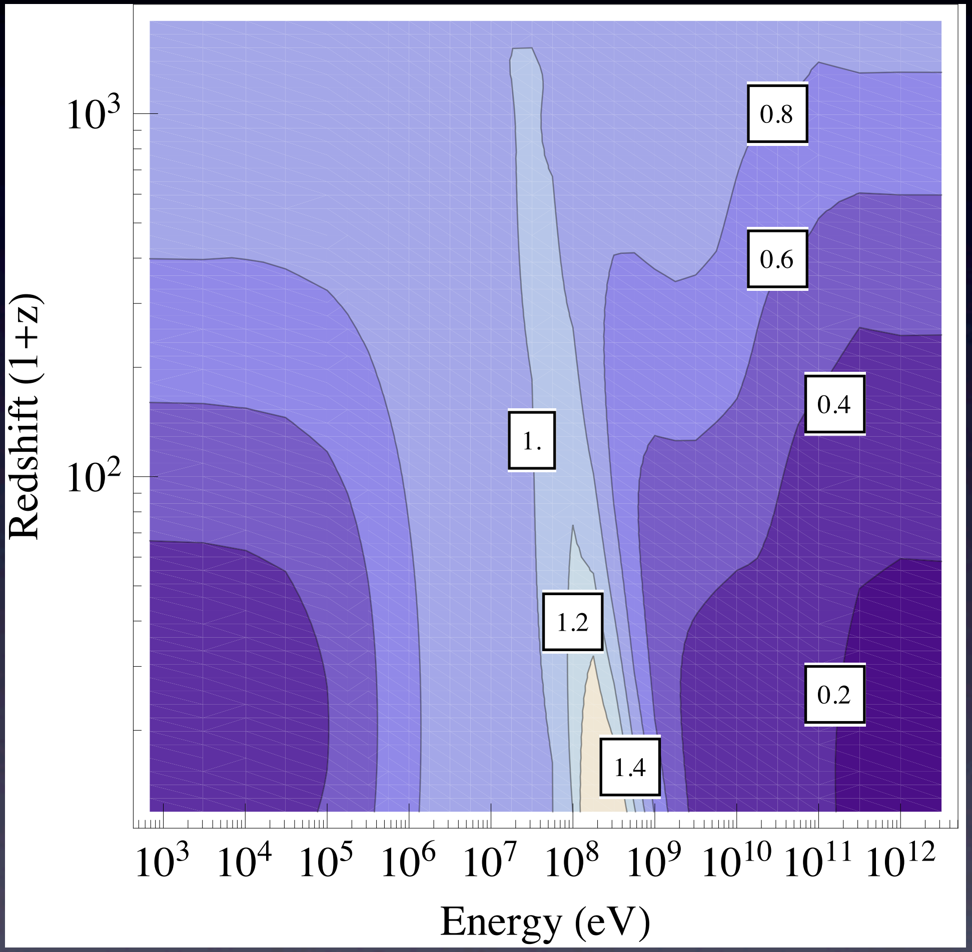
Electron+positron pairs

Electrons only

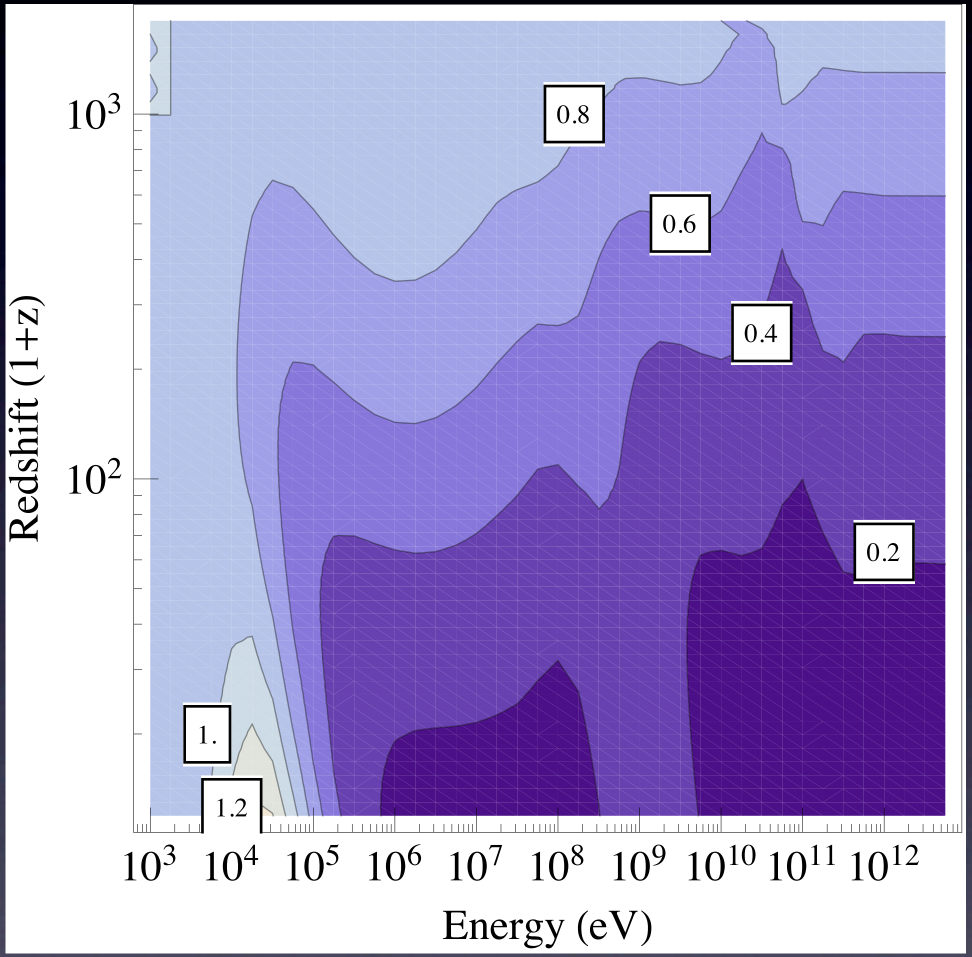
Photons

- What fraction of energy is eventually absorbed (as opposed to lost to redshifting/free-streaming) by a particle injected at some redshift z and energy E?
- Integrate the transfer function with respect to the output redshift.

The case of DM annihilation



Electron+positron pairs

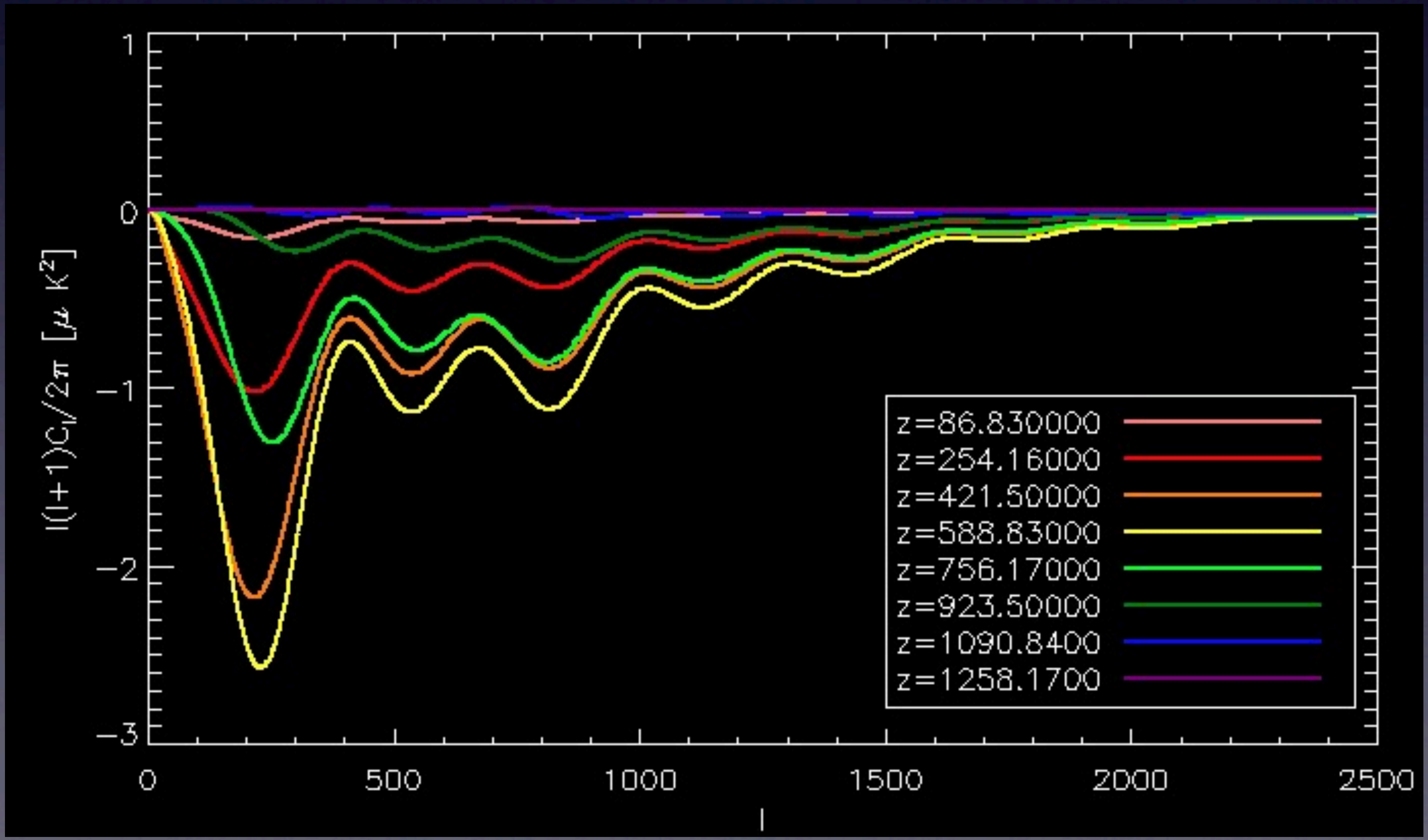


Photons

- Given redshift dependence of the energy injection, integrate over input redshift.
- Get the total energy-absorption rate as a function of initial photon/electron energy and redshift.
- In these plots, divide out by the energy-injection rate as a function of redshift, for convenience.

From energy absorption to constraints

- Studied in detail in Finkbeiner, Galli, Lin & TRS 1109.6322; consider energy absorption at different redshifts and computed the effect on the anisotropy spectra (using RECFAST/CosmoRec modified for additional ionizing energy).



Example: effect on the TT anisotropy spectrum for different redshifts - greatest effect is around z~600

How many parameters?

- Effect of energy absorption at different redshifts is somewhat but not perfectly degenerate.
- Can characterize arbitrary 10<z<1000 energy absorption history by three parameters in Planck, given limits from WMAP + ACT.
- For conventional DM annihilation, redshift dependence of injection is fixed (density squared), and consequently redshift dependence of absorption is nearly fixed - effect on CMB can be described by one (normalization) parameter.

From model to constraint

- Take your model of energy injection, map it to an energy absorption curve using the results shown earlier.
- Take this curve, decompose it into linear combination of first three principal components (which are orthogonal by construction):

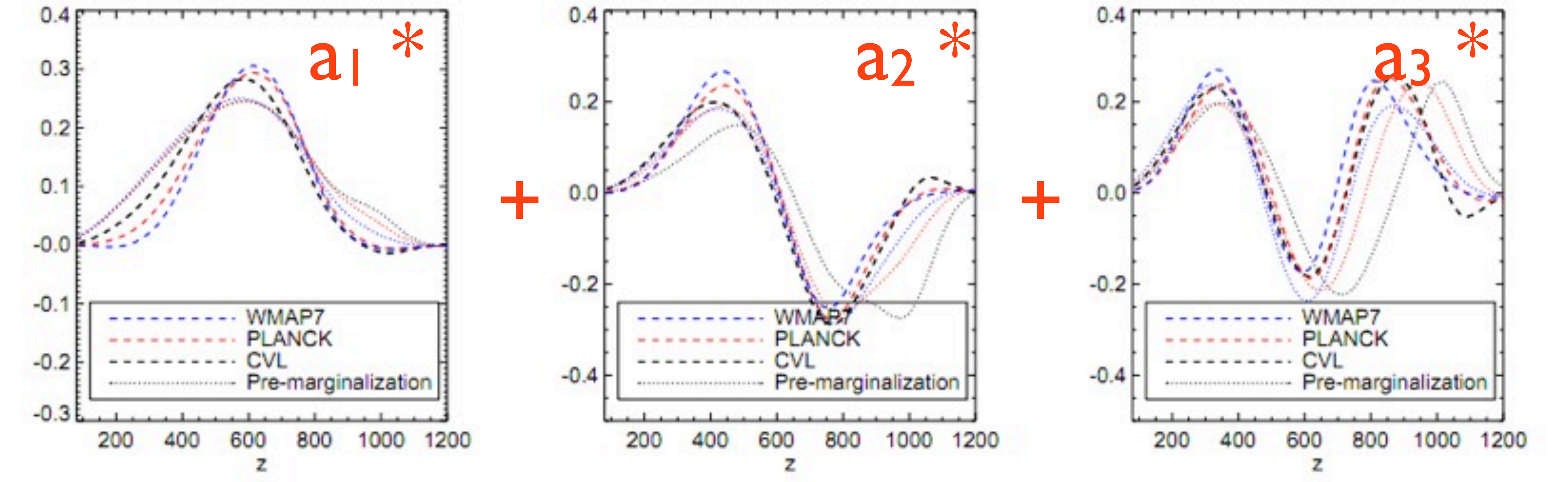


FIG. 4: The first three principal components for *WMAP* 7, *Planck* and a CVL experiment, both before and after marginalization over the cosmological parameters.

Significance $\approx \sqrt{\sum a_i^2 \lambda_i}$

Effect on the CMB

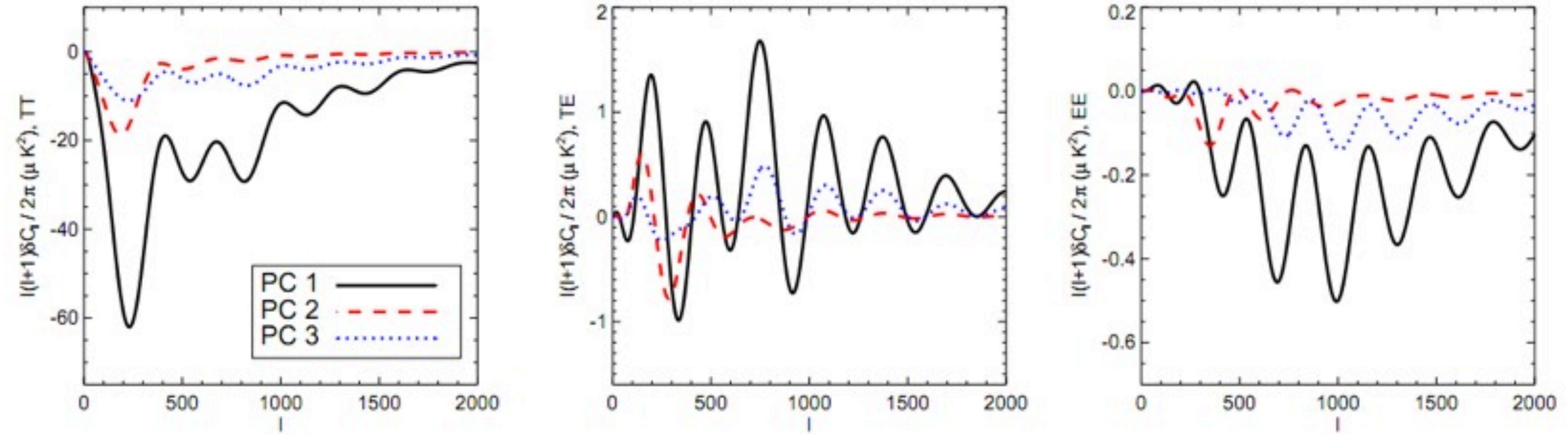


FIG. 7: The mapping of the first three principal components for *Planck*, after marginalization, into δC_ℓ space. The PCs are multiplied by $\varepsilon_i(z) = 2 \times 10^{-27}$ cm^3/s/GeV for all i, to fix the normalization of the δC_ℓ's.

h_i

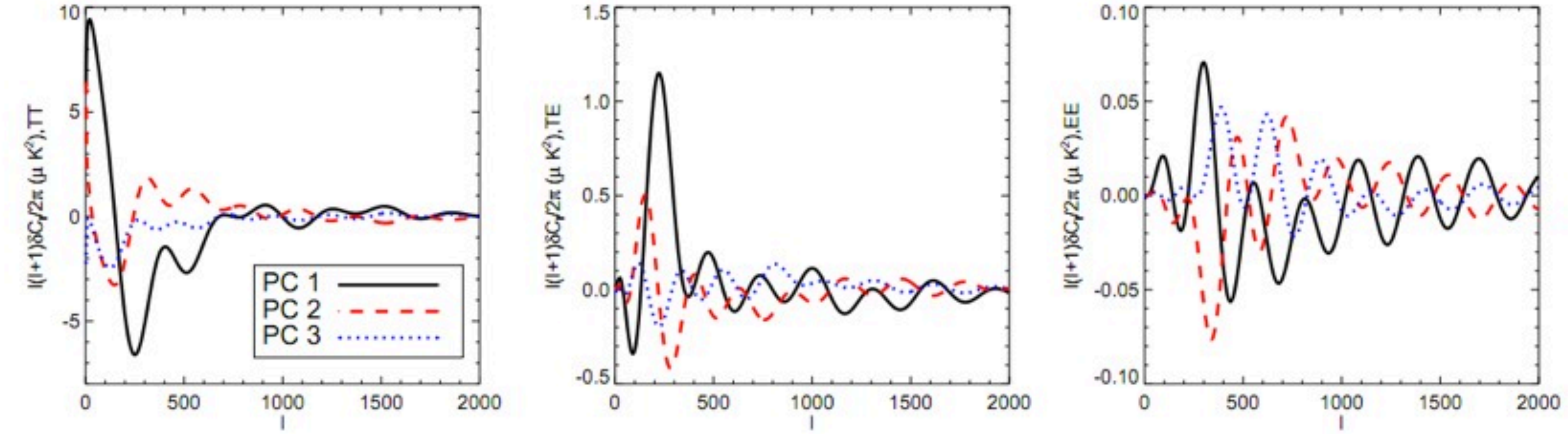
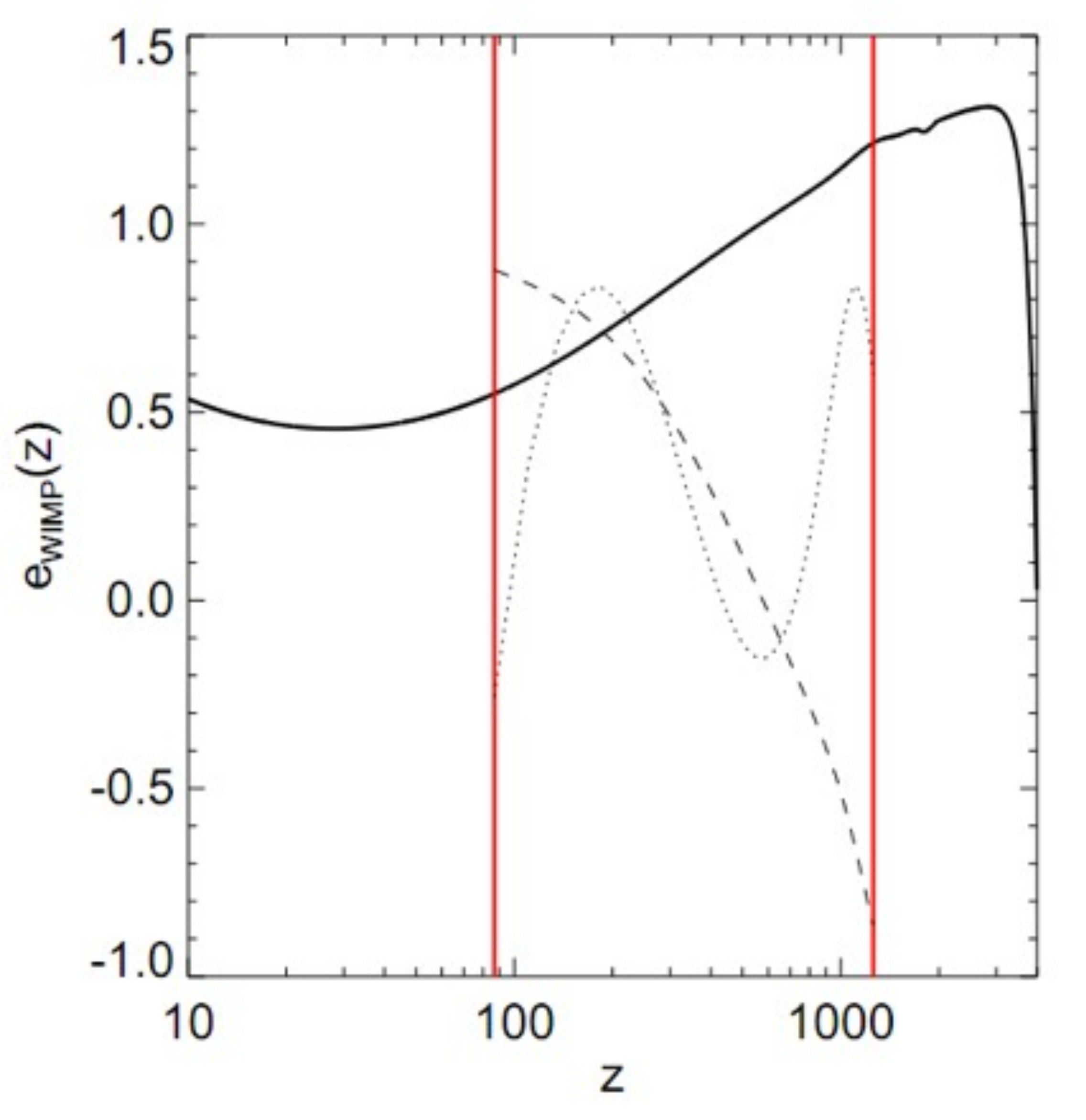


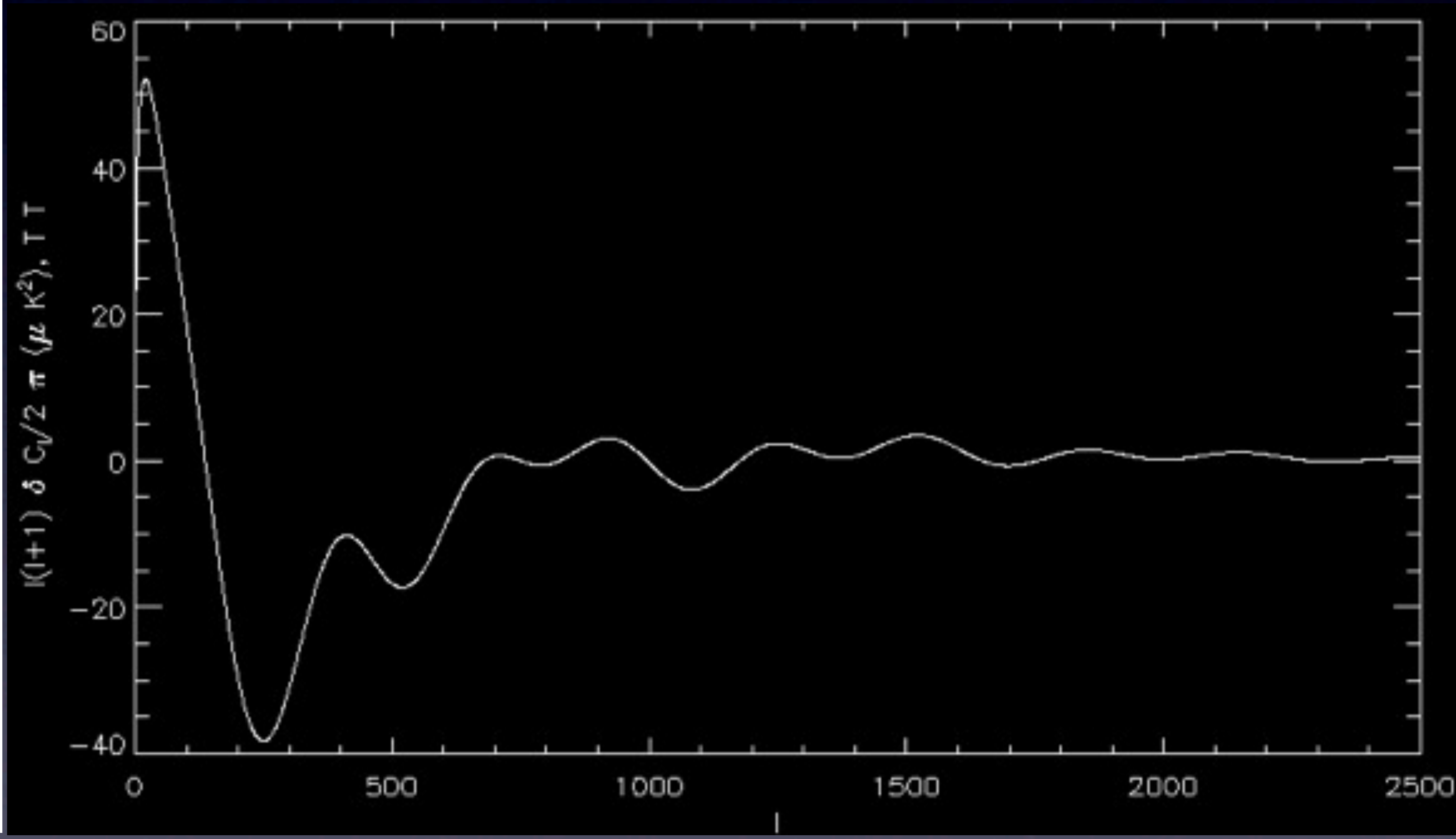
FIG. 8: The $\perp$ components of the first three principal components for *Planck*, after marginalization, mapped into δC_ℓ space. The normalization is the same as for Figure 7.

$h_i^{\perp}$

The WIMP case



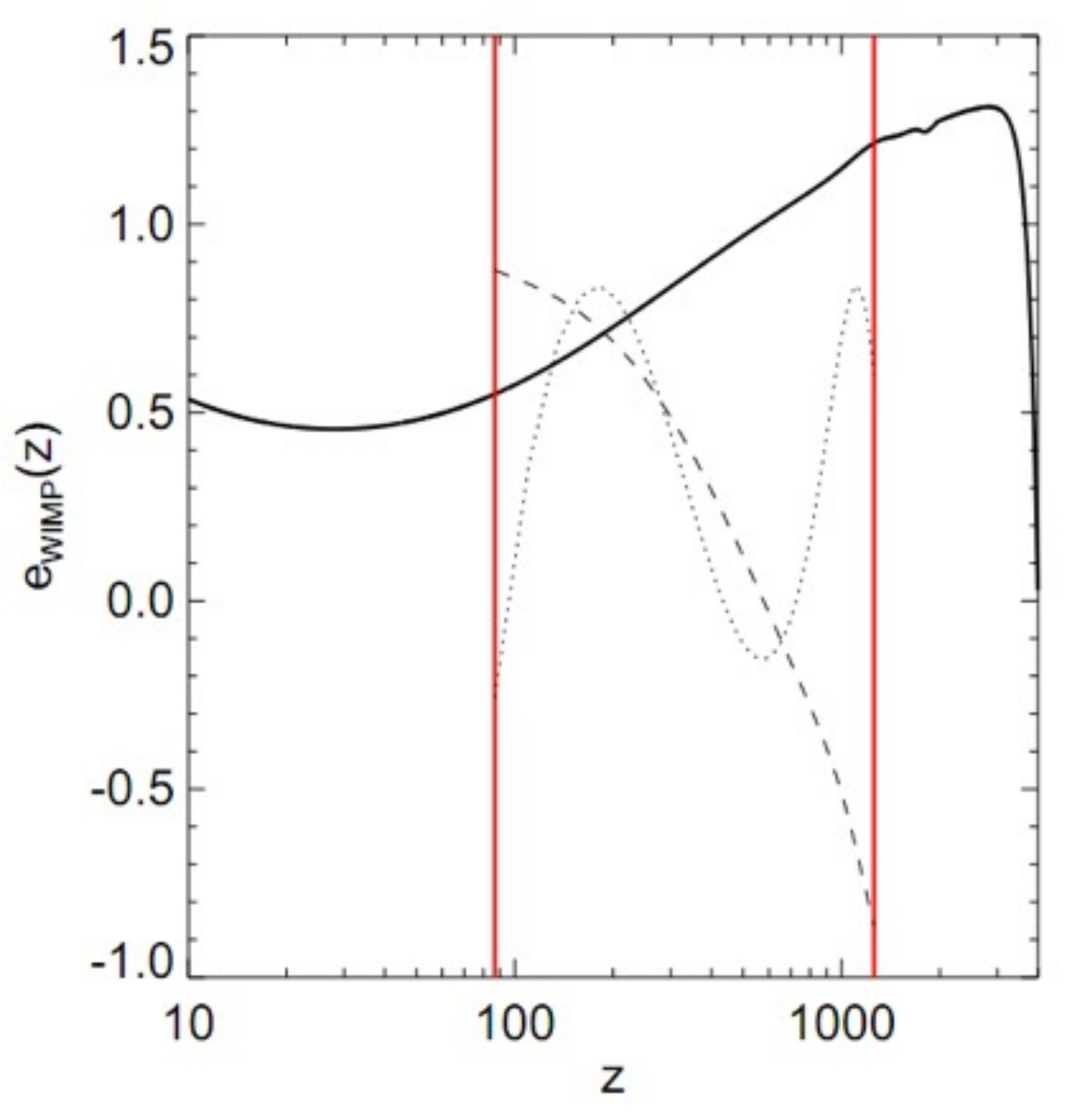
- Conventional DM case is much simpler, needs only one parameter.



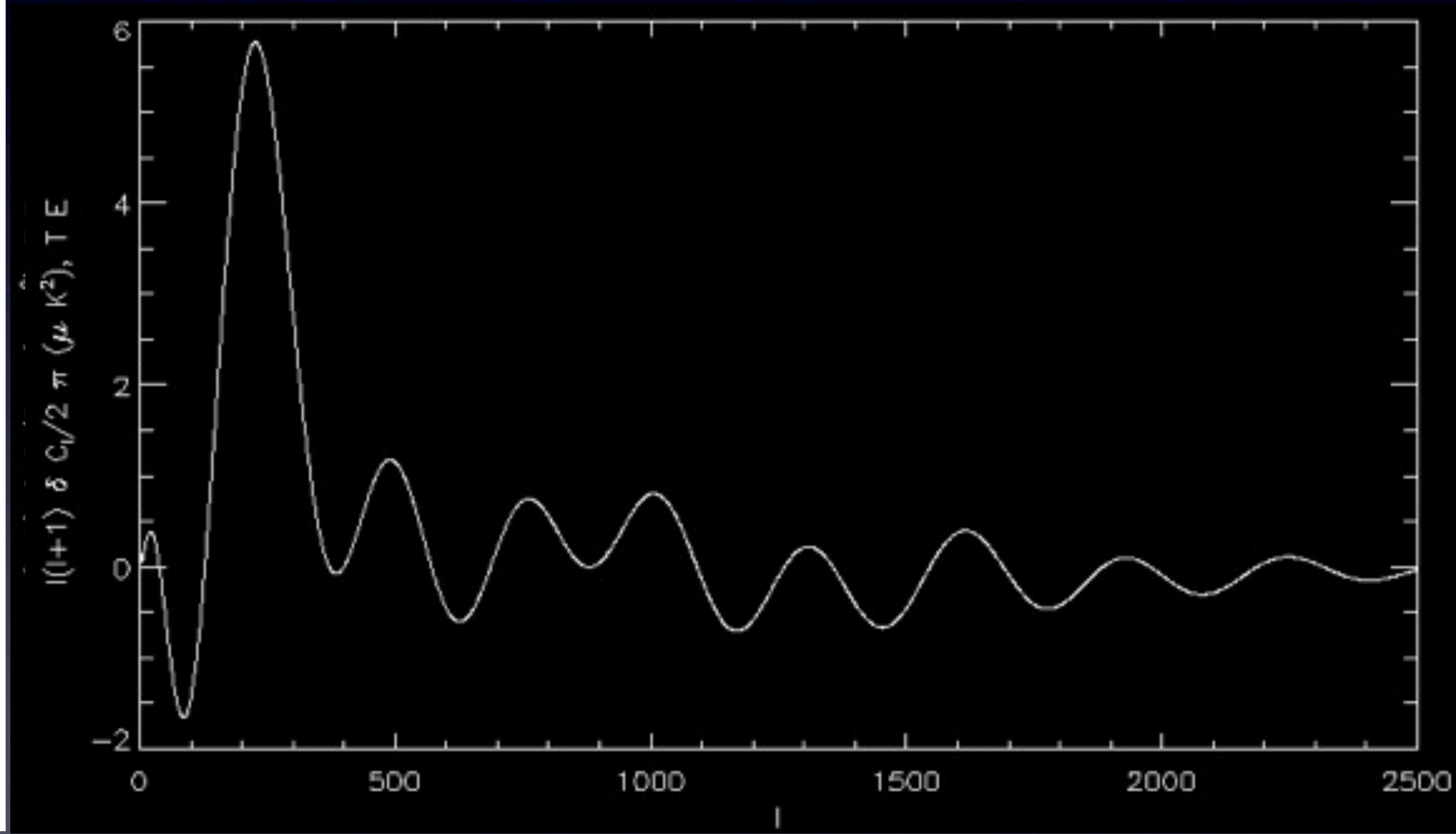
- Get energy absorption history, take dot product with black line: sets coefficient *f* of template for DM annihilation in CMB (*f* is generally 0.2-0.9).

$$f\,\frac{\langle\sigma v\rangle}{m_{\rm DM}} < 2.43\times10^{-27}{\rm cm}^3/{\rm s}/{\rm GeV}$$

The WIMP case



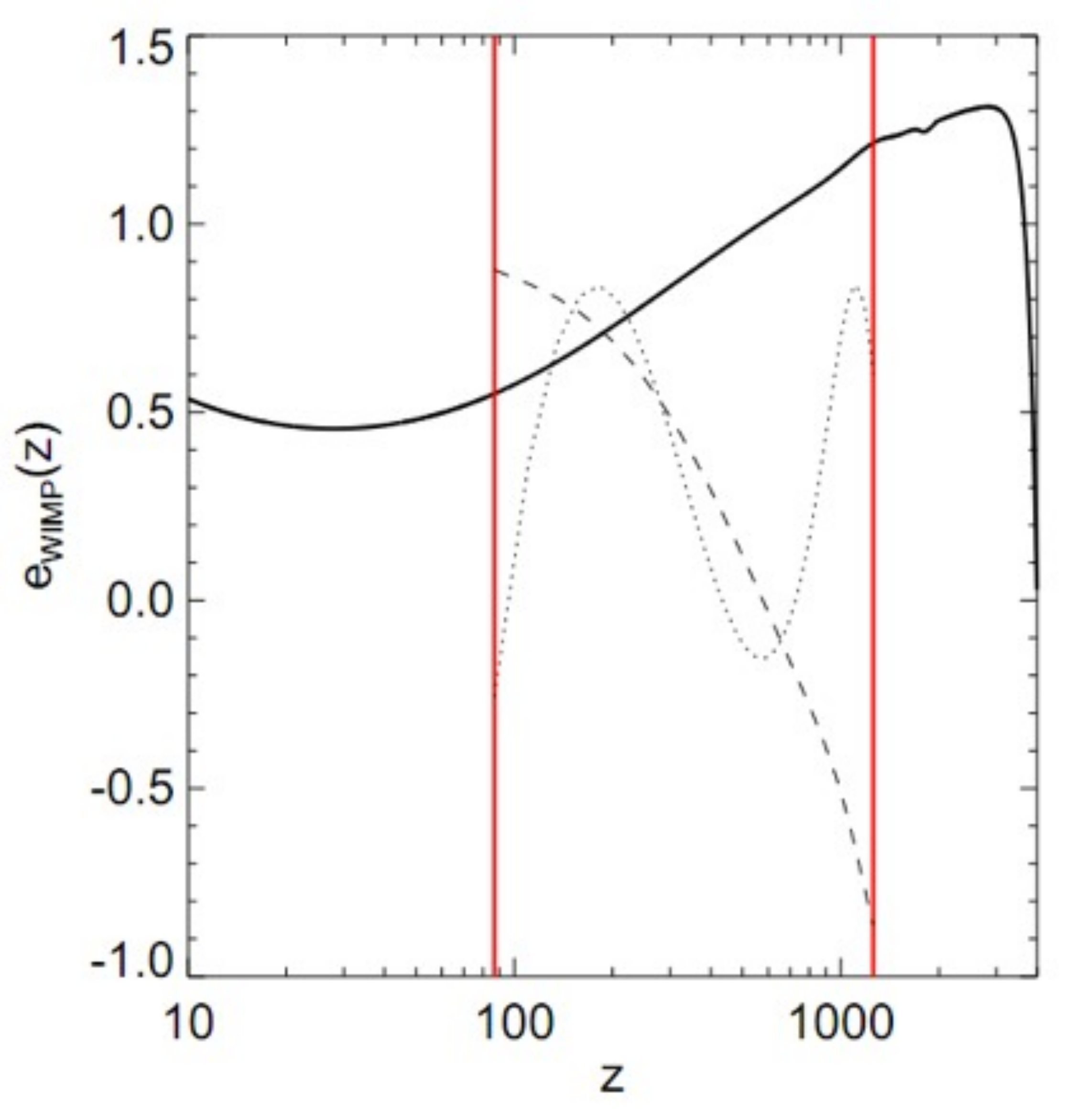
- Conventional DM case is much simpler, needs only one parameter.



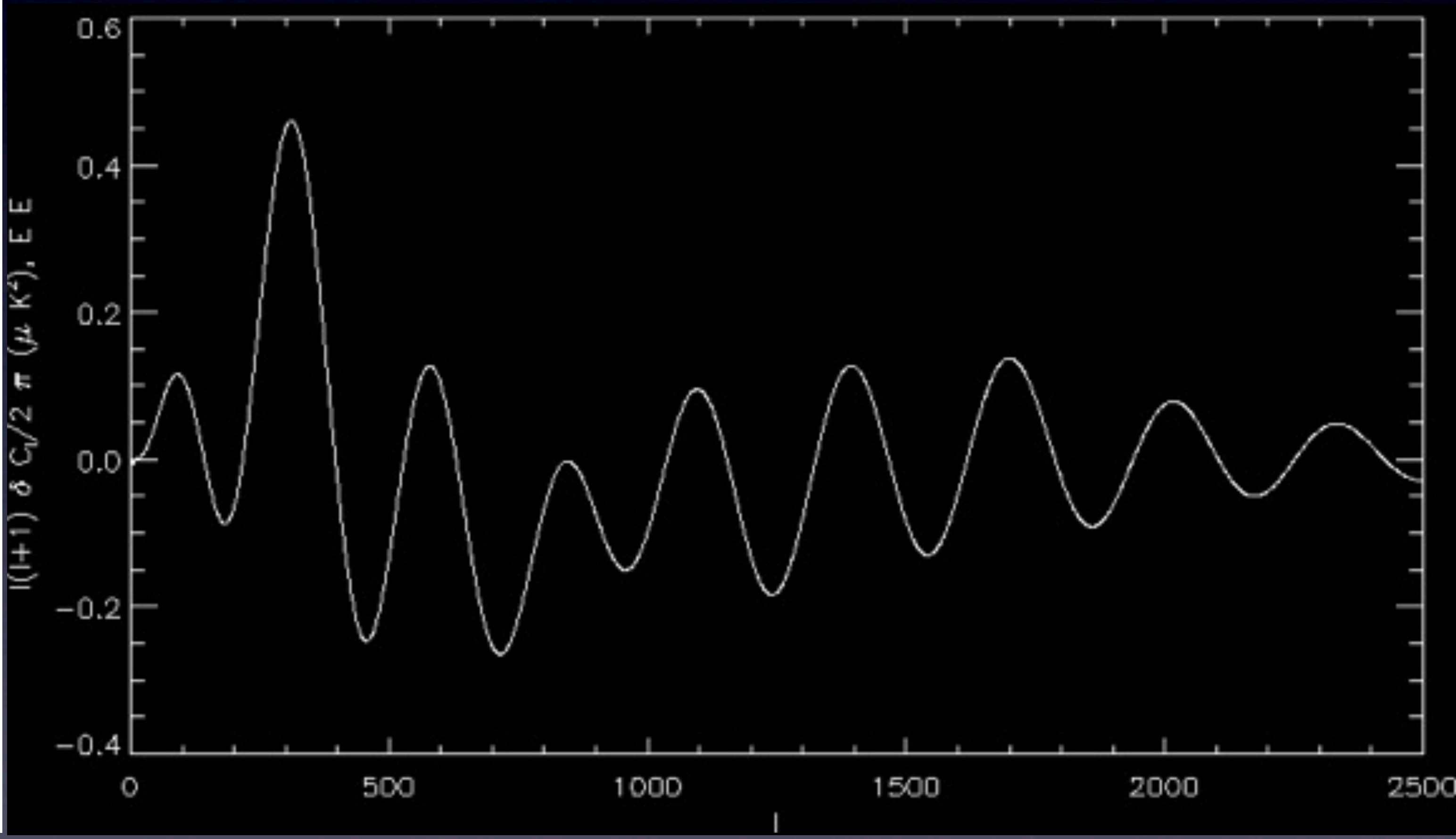
- Get energy absorption history, take dot product with black line: sets coefficient *f* of template for DM annihilation in CMB (*f* is generally 0.2-0.9).

$$f\,\frac{\langle \sigma v \rangle}{m_{\rm DM}} < 2.43 \times 10^{-27} {\rm cm}^3/{\rm s}/{\rm GeV}$$

The WIMP case



- Conventional DM case is much simpler, needs only one parameter.

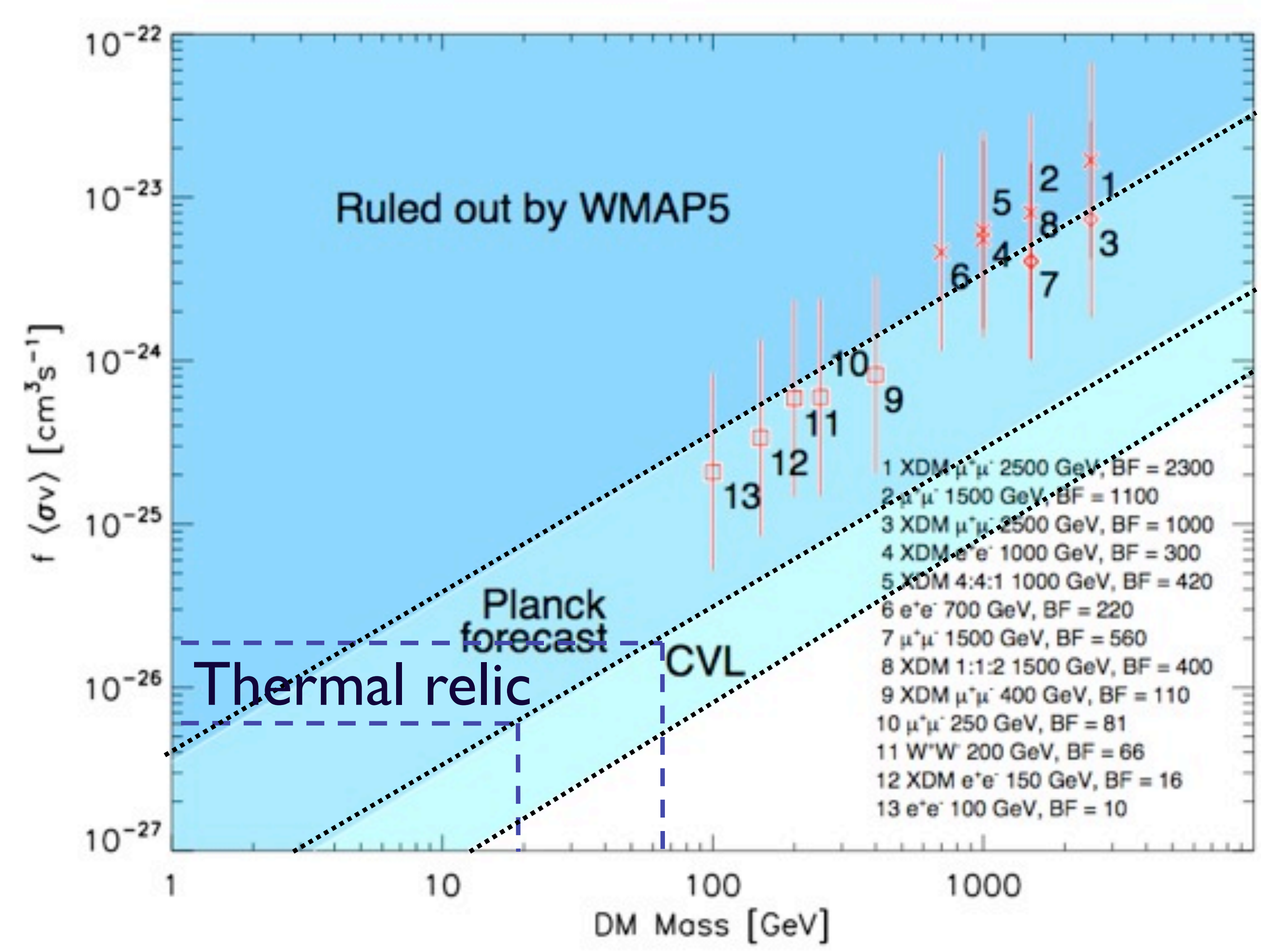


- Get energy absorption history, take dot product with black line: sets coefficient *f* of template for DM annihilation in CMB (*f* is generally 0.2-0.9).

$$f\,\frac{\langle \sigma v\rangle}{m_{\rm DM}} < 2.43\times 10^{-27}{\rm cm}^3/{\rm s}/{\rm GeV}$$

Constraints on DM annihilation

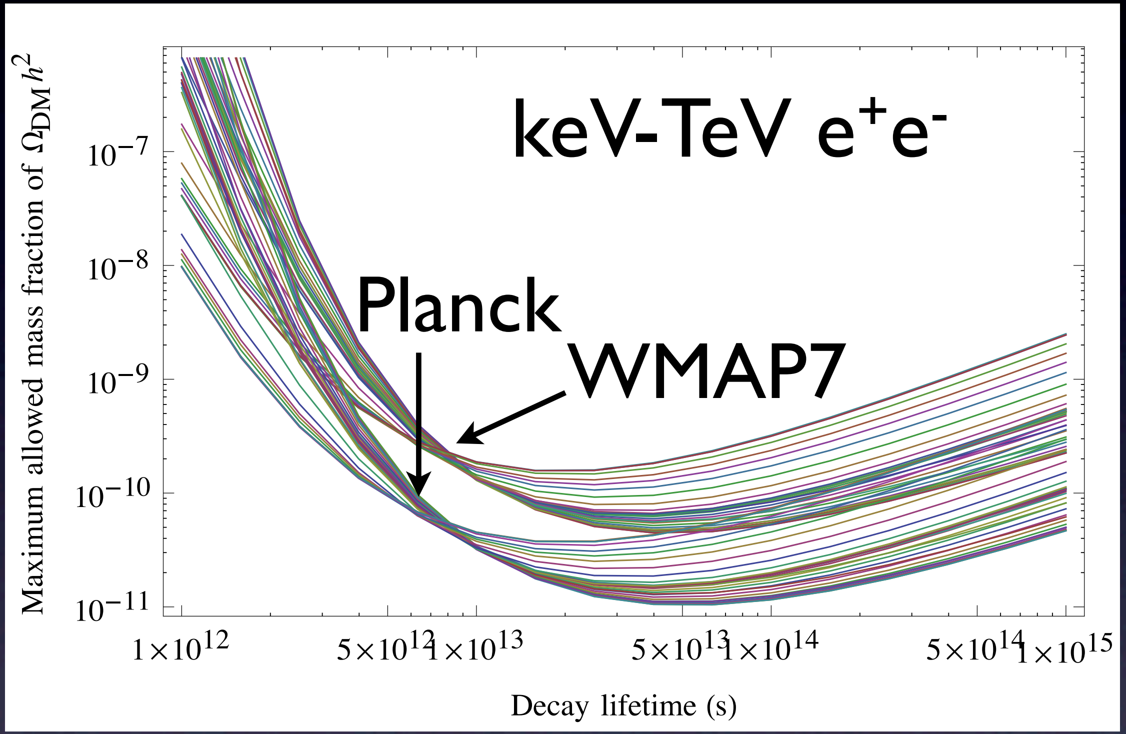
- Models fitting PAMELA/Fermi/ATIC (red squares/diamonds/crosses) within a factor of a few of WMAP5 limit.
- WMAP5 constraints (current limits are about 40% better) rule out thermal relic DM with s-wave annihilation below ~2-7 GeV (depending on final state).
- Planck will probe thermal relic DM at 20-70 GeV.

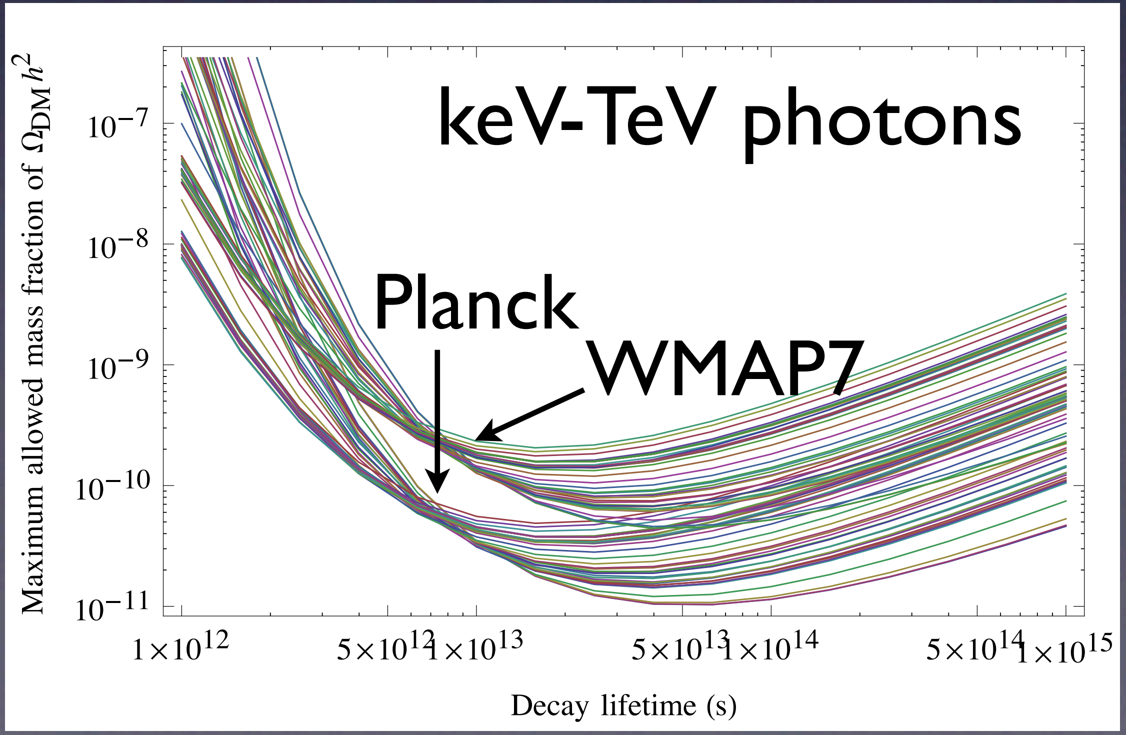


Note: all the model points lie roughly parallel to the constraint line because the power injected in electrons/photons is also roughly what the cosmic-ray experiments measure.

Constraints on late-decaying species

- If DM or some other metastable particle decays during the cosmic dark ages to electromagnetic channels, can constrain the allowed mass fraction in this species.
- Also applicable to excited state of DM that decays during this period.
- For dark matter decay, limits comparable to those from galactic and extragalactic diffuse emission (few x 10^{25} s), weaker than cluster constraints for high masses.





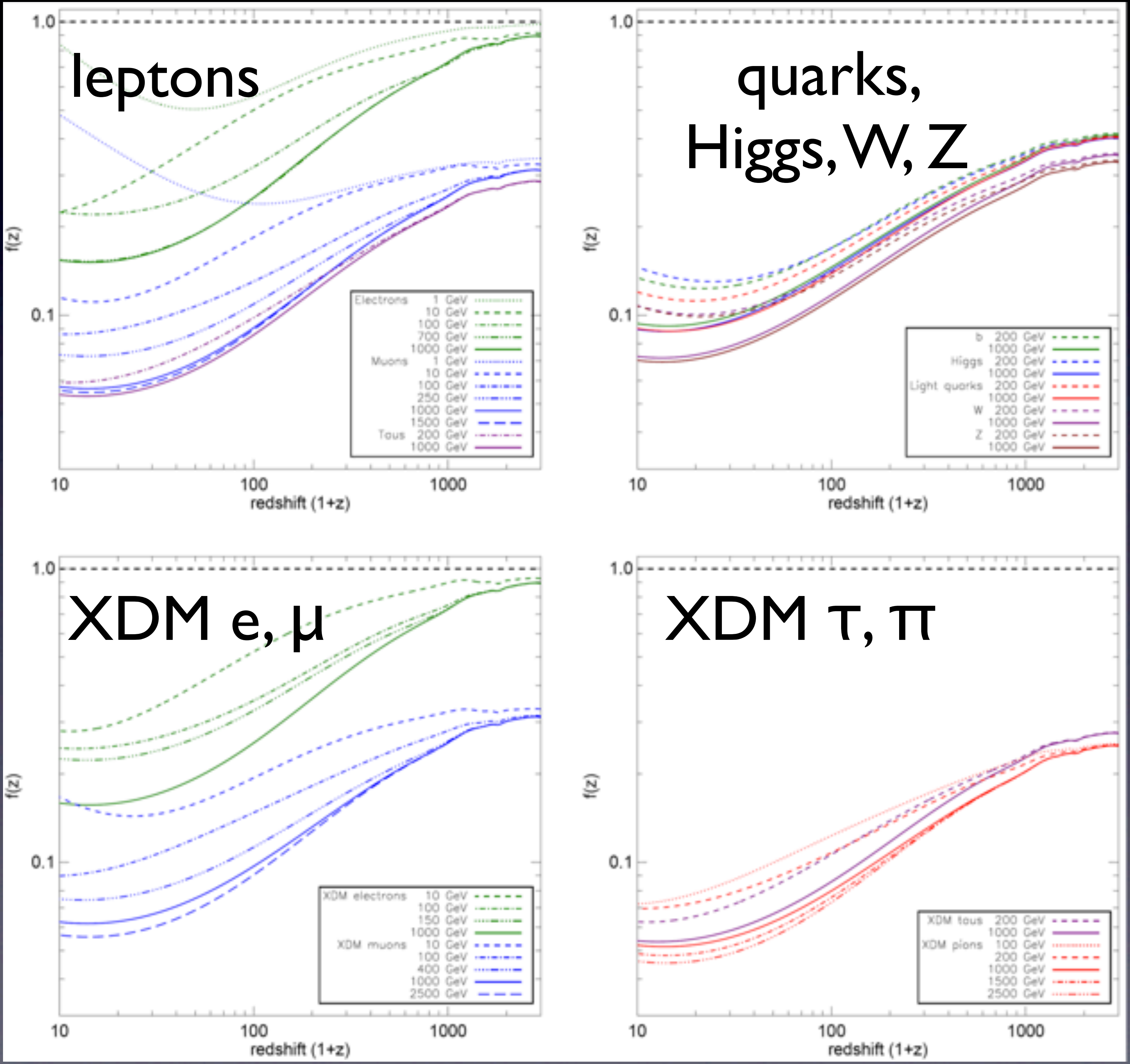
Conclusions

- Any model that injects electrons or photons during the cosmic dark ages can potentially be constrained by the CMB anisotropy spectra.
- We now have the tools to instantly map any model of energy injection (spectrum + redshift dependence) into a constraint from the CMB: can constrain late-decaying species, exotic dark matter models in addition to conventional WIMPs.
- For conventional DM, WMAP7 + ACT currently rules out up-to-several-GeV DM annihilating (through s-wave) to most SM final states and up to 10 GeV DM annihilating to electrons. Planck should do roughly a factor of six better in mass reach.
- This is a robust limit independent of present-day astrophysics or the phase-space distribution of DM.

BONUS SLIDES

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).



Bias

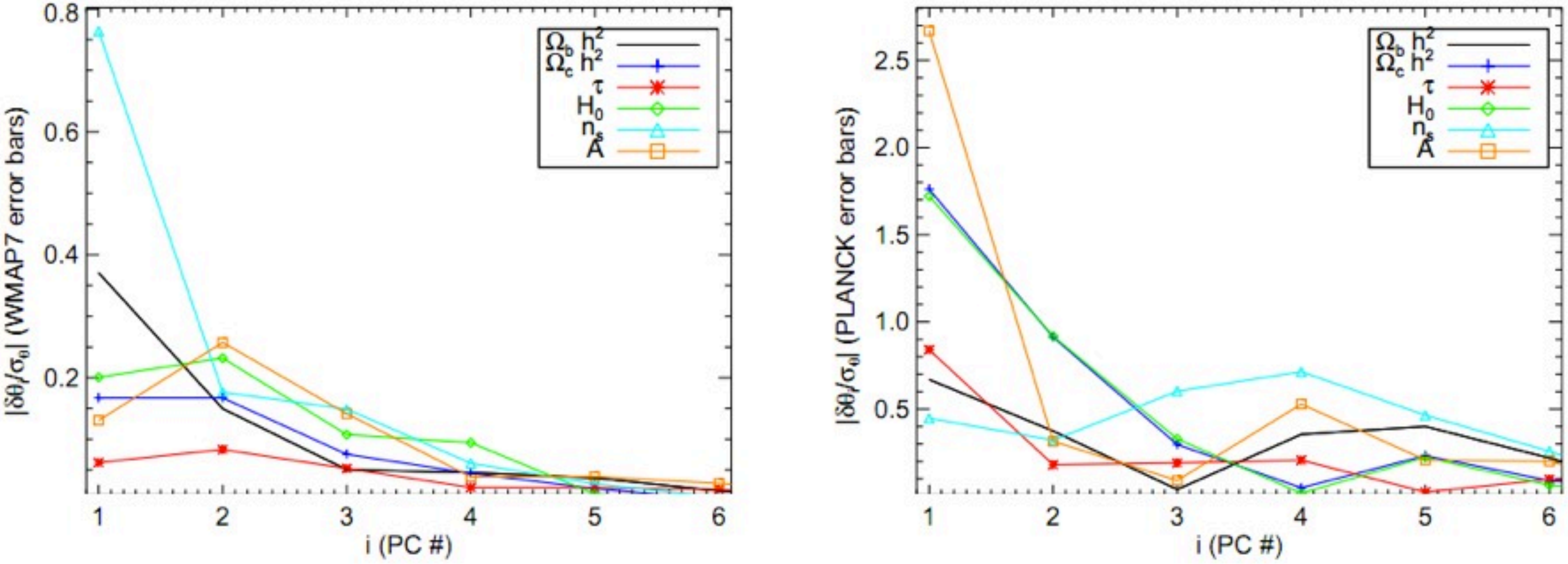


FIG. 11: For the *i*th PC, the contribution to the bias to cosmological parameters in *WMAP 7* (*left panel*) and *Planck* (*right panel*), relative to the error bars forecast from the Fisher matrix. The normalization is that of the "generic" case (see discussion in §IV B or Figure 10), where each PC 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.

PC reconstruction

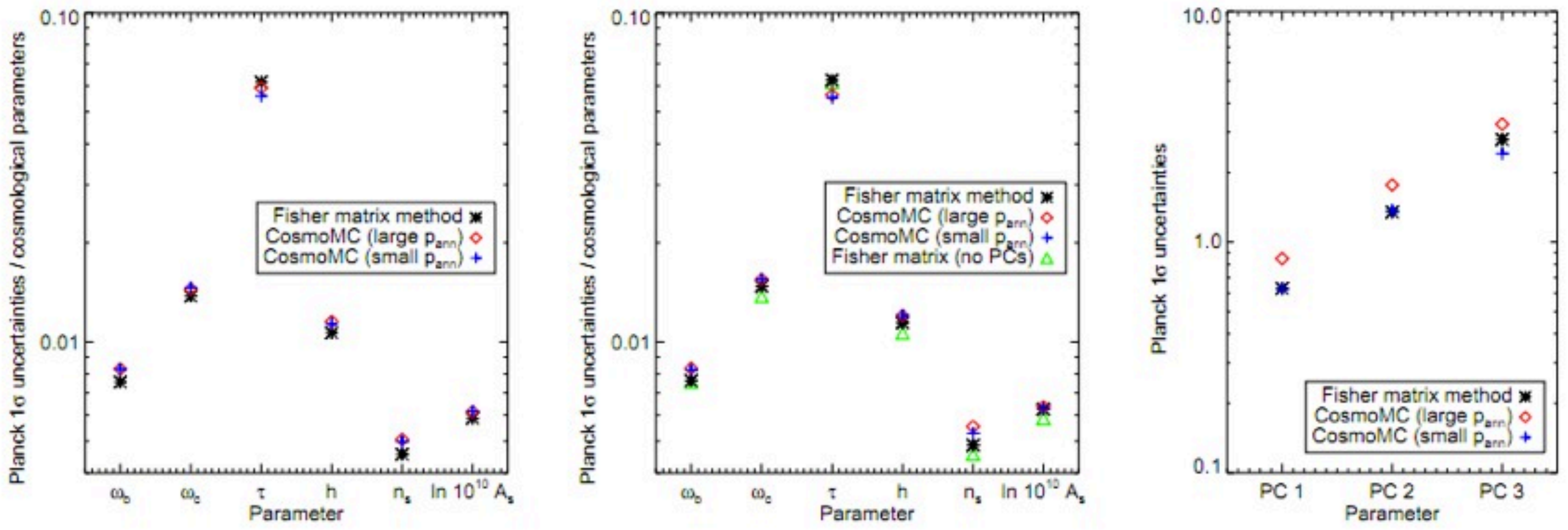


FIG. 20: Error bars for the cosmological parameters and coefficients of the principal components, in mock *Planck* data, simulated assuming a constant-$p_{\mathrm{ann}}(z)$ energy deposition history. The points marked "large p_{ann}" have $p_{\mathrm{ann}} = 1 \times 10^{-6}\mathrm{m}^3/\mathrm{s}/\mathrm{kg}$ $= 1.8 \times 10^{-27}$ $\mathrm{cm}^3/\mathrm{s}/\mathrm{GeV}$, while for the points marked "small p_{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_{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.

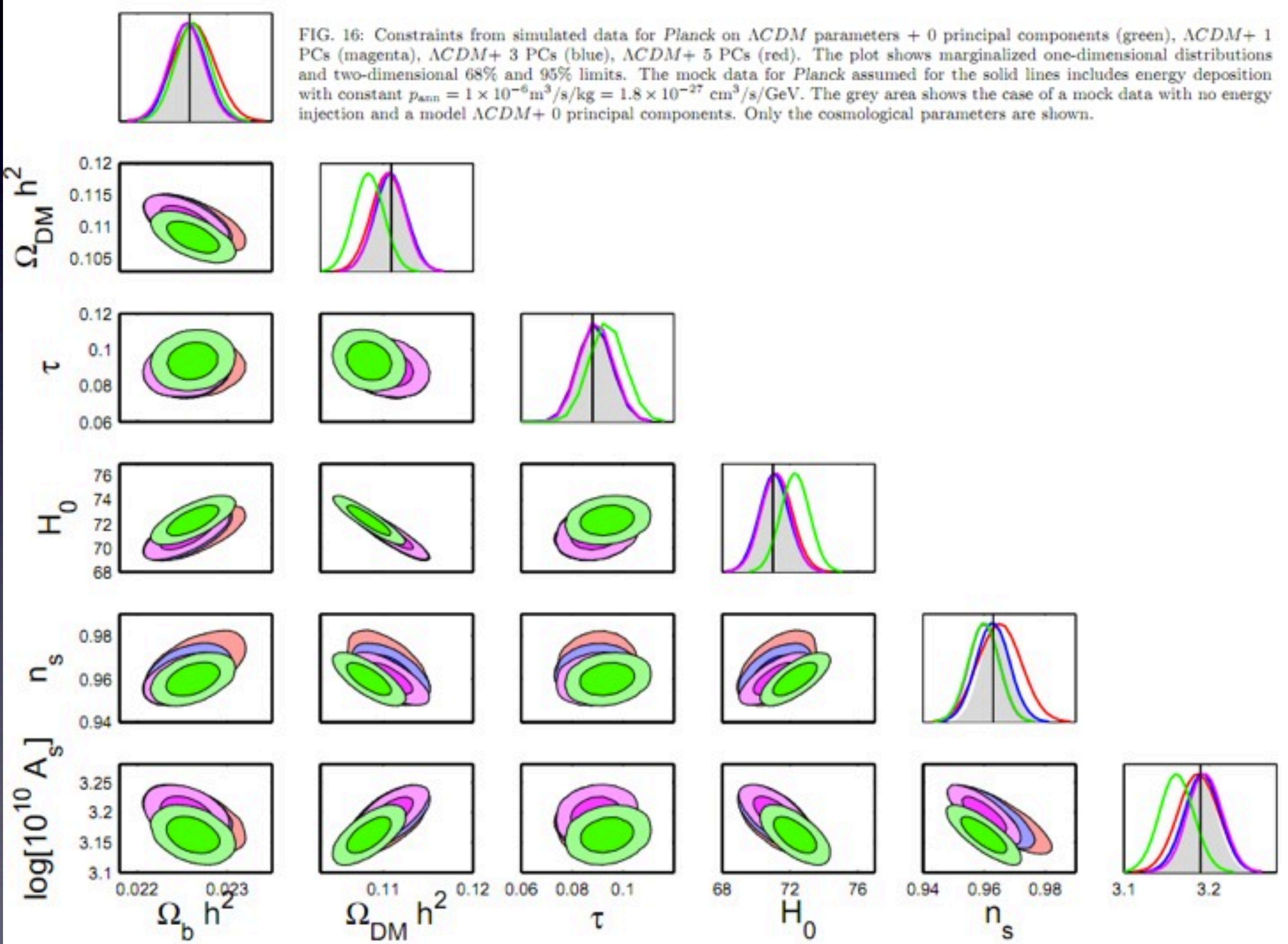
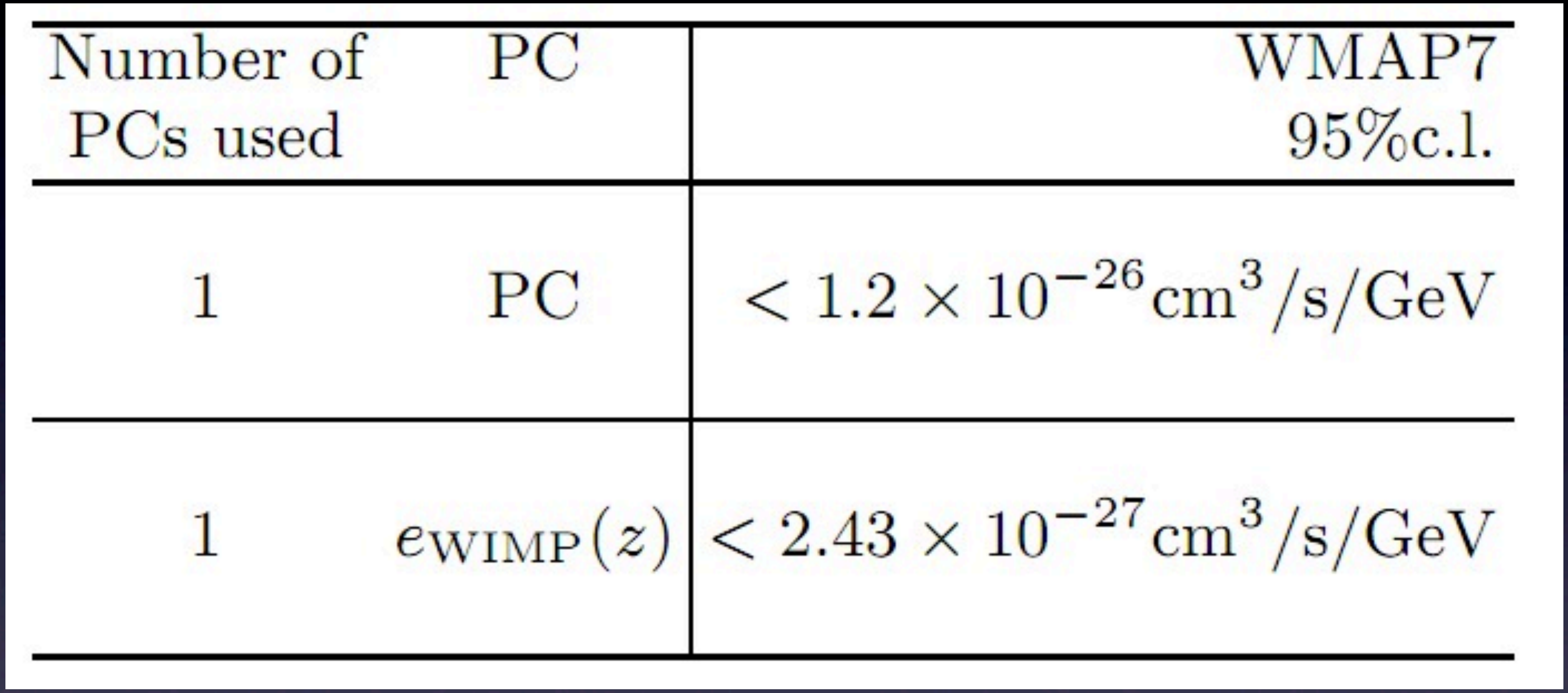


FIG. 16: Constraints from simulated data for *Planck* on ΛCDM parameters + 0 principal components (green), ΛCDM+ 1 PCs (magenta), ΛCDM+ 3 PCs (blue), ΛCDM+ 5 PCs (red). The plot shows marginalized one-dimensional distributions and two-dimensional 68% and 95% limits. The mock data for *Planck* assumed for the solid lines includes energy deposition with constant $p_{\rm ann} = 1 \times 10^{-6}\rm m^3/s/kg = 1.8 \times 10^{-27}\ cm^3/s/GeV$. 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.

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.

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.

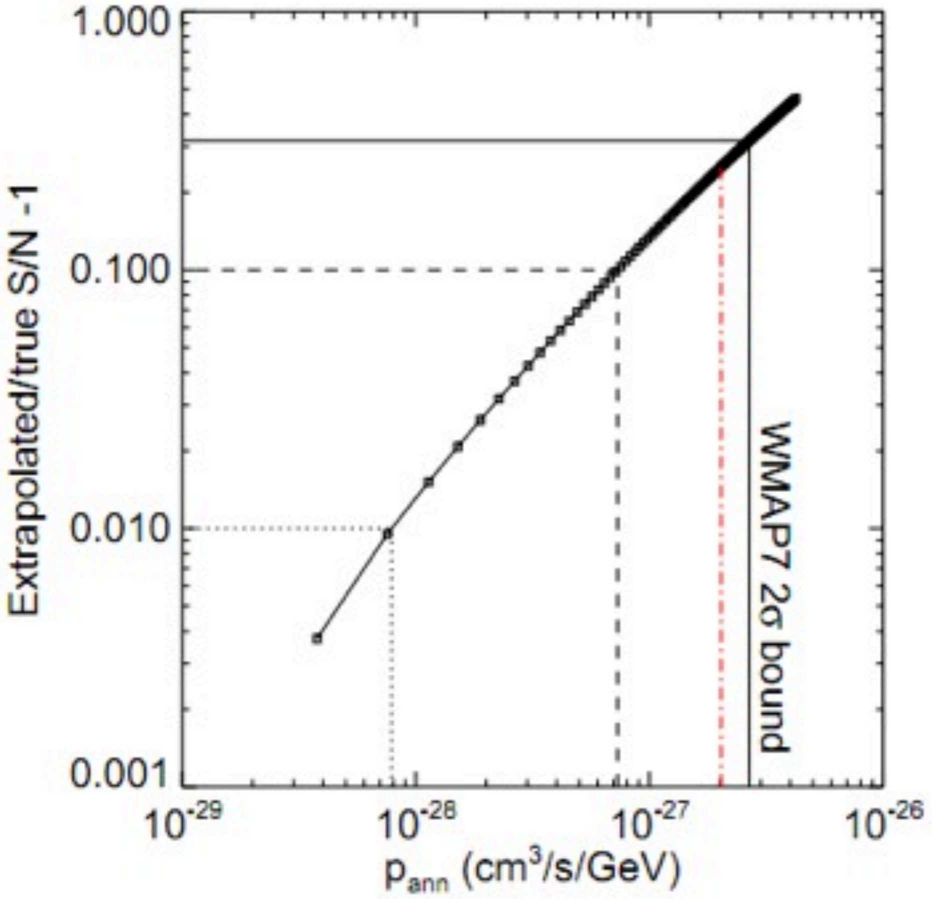


FIG. 3: The degree of nonlinearity in the computed significance of a sample energy deposition history, for p_{ann} constant, using *WMAP* 7 noise parameters. We show the ratio of (1) the S/N estimated by a linear extrapolation from small energy deposition to (2) the “true” S/N (estimated as in §II C), 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.

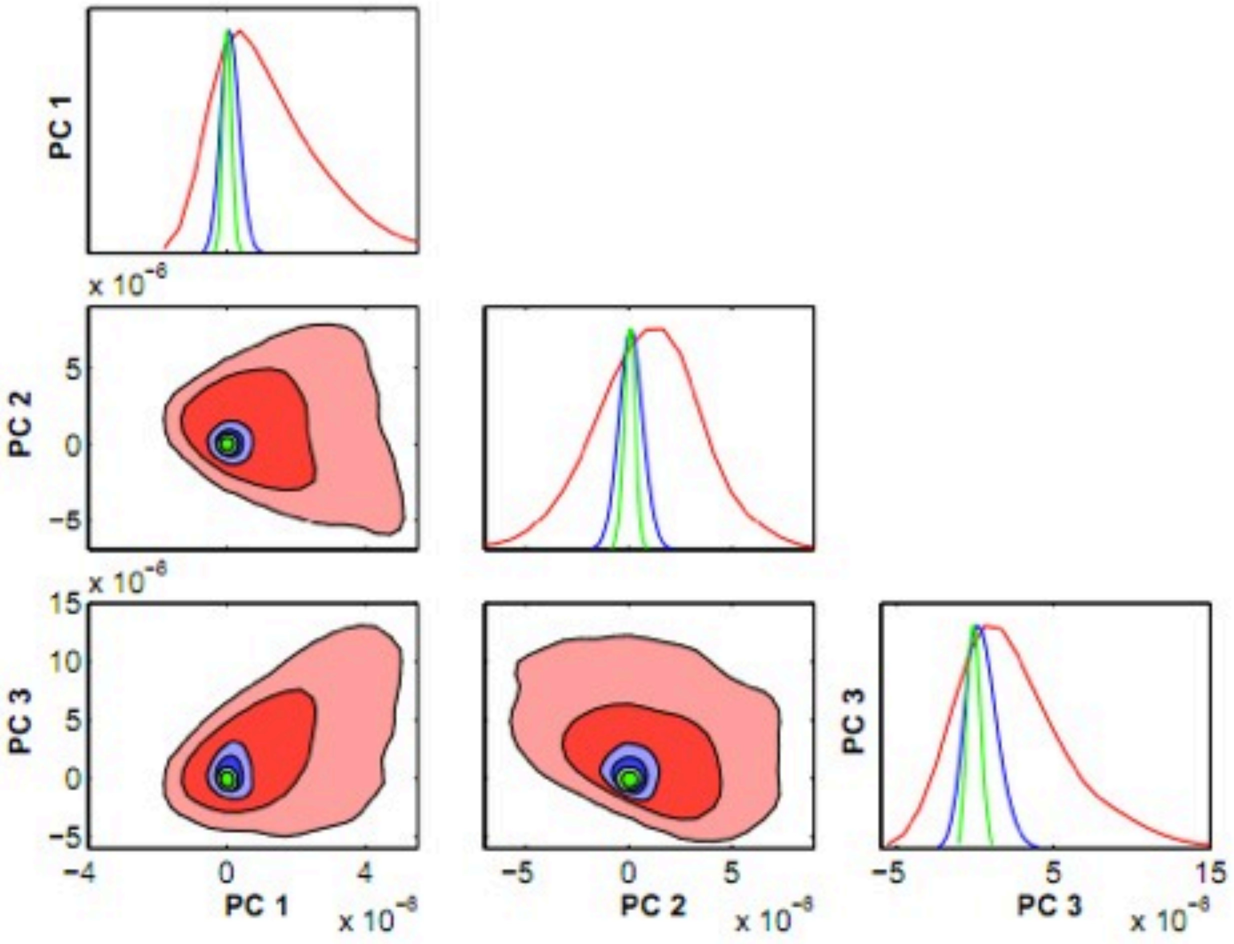


FIG. 14: Constraints from the seven-year *WMAP* data (red), and from simulated data for Planck (blue) and a cosmic variance limited experiment (green). The plot shows marginalized one-dimensional distributions and two-dimensional 68% and 95% limits. The mock data for Planck and the CVL experiment assumed 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 1×10^{-6}m^3/s/kg = 1.8×10^{-27} cm^3/s/GeV.

Validation checks

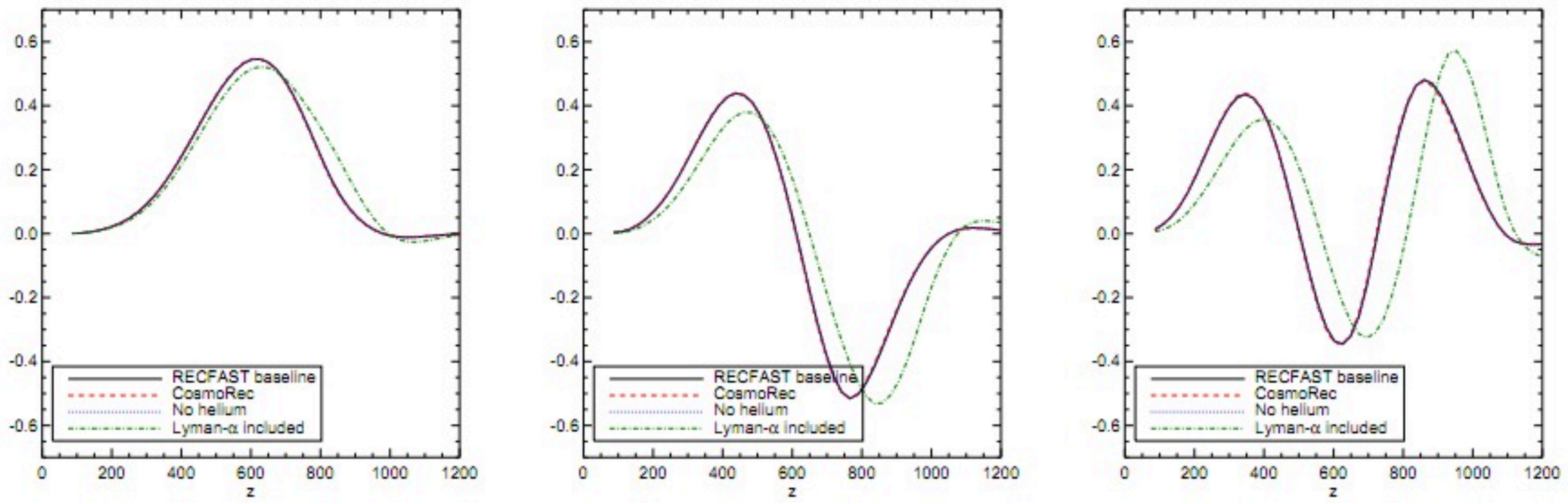


FIG. 24: The first three principal components for *Planck*, after marginalization, computed using `RECFAST 1.5` and `CosmoRec`. In the baseline case (as in `CosmoRec`), ionization of helium is included but injection of Lyman-α photons is not. We also show the effects of including a contribution to Lyman-α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