Detecting Dark Matter Annihilation with CMB Polarization

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G. Jungman et al./Physics Reports 267 (1996) 195–373 247

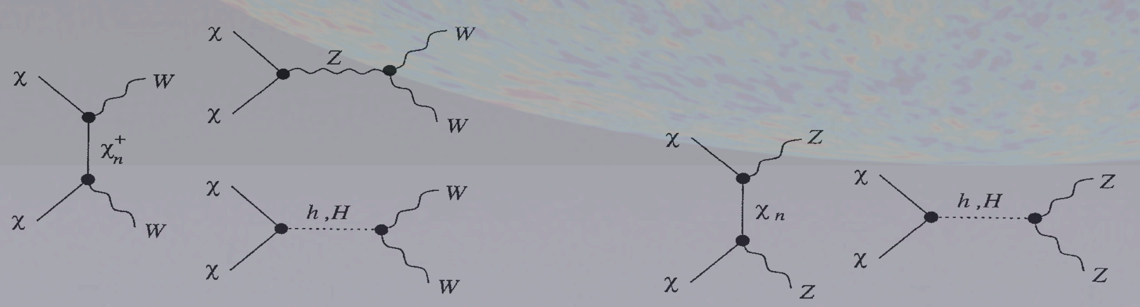

Fig. 9. Diagrams contributing to neutralino annihilation to W^+W^- pairs.

Fig. 10. Diagrams contributing to neutralino annihilation to Z^0Z^0 pairs.

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- ***Z > 1100***
  - H ionized, photons coupled to baryons, density perturbations don't grow, fluid undergoes acoustic oscillations
- ***900 < z < 1100***
  - Temperature falls ~ eV, hydrogen recombines, freezing out due to the expansion of the Universe.
  - Photons decouple from baryons, carrying imprint of density fluctuations.
  - Photons polarized by Thomson scattering
  - Details sensitive to exact recombination history; **effect of DM**

Outline

- The effect of DM annihilation on the CMB
  - The effect on the recombination history : the “on the spot” approximation
  - The effect on the CMB temperature fluctuations
  - The effect on the CMB polarization fluctuations
  - The detectability of these effects
- Detecting DM in the CMB
- Constraining the abundance of a DM species

- DM annihilations produce quarks, gauge bosons, Higgs, leptons, photons
- Unstable primary products decay via jets
- Assume energy is partitioned into high energy electrons, photons, neutrinos (***Generic!***)
- Need to understand how these interact with IGM (ionizations, excitations, heating)

Photons

Energy Loss :

Ionizations
Compton Scattering
Pair production (atoms)
Photon scattering
Pair production (CMB)

$$t_H/t_{cool} > 1$$

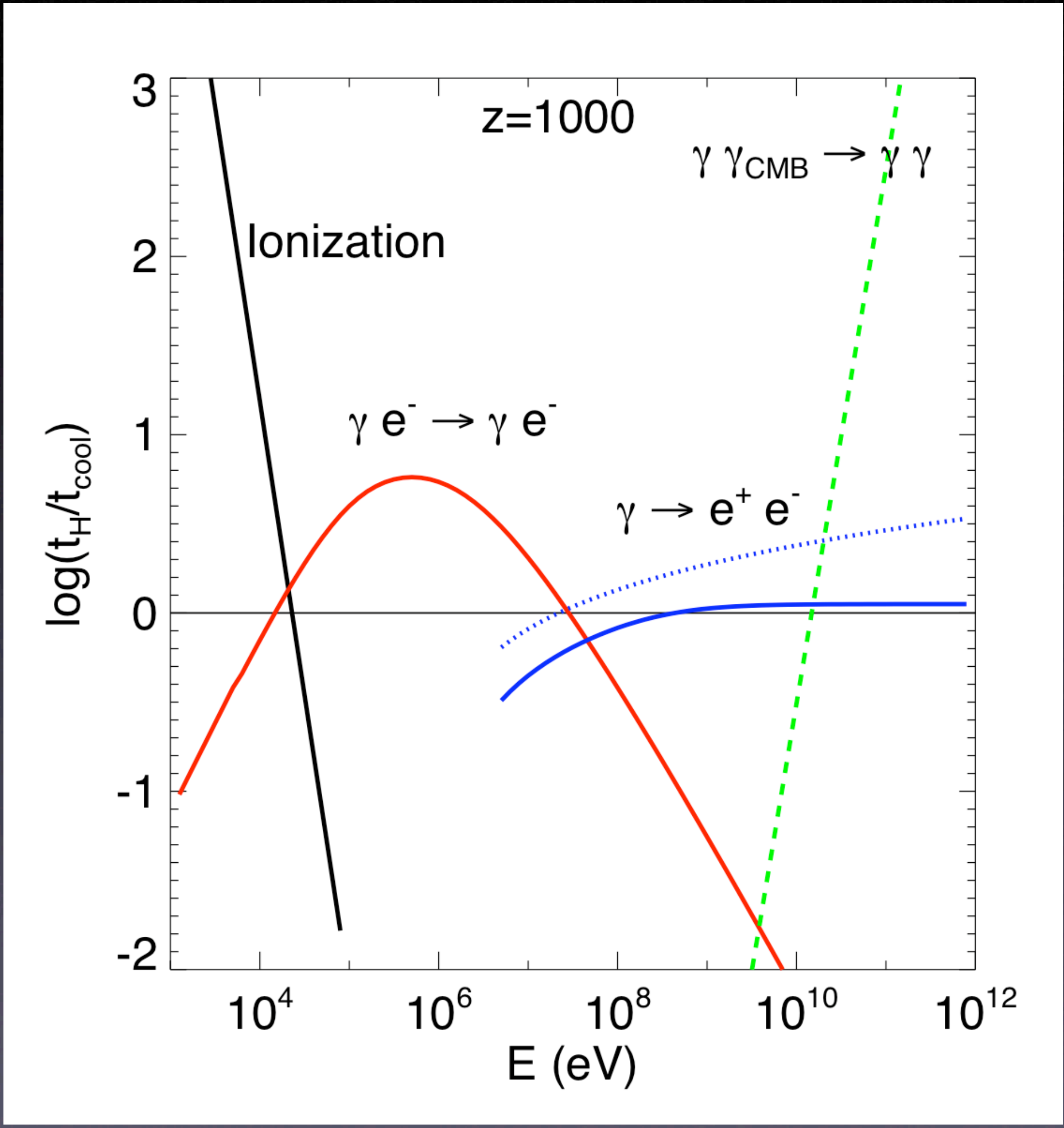
Energy loss virtually instantaneous

Secondary electrons can trigger EM cascades

Curves shift $\propto (1+z)^{3/2}$

(9/2 for photon scattering)

Photons in transparency region escape

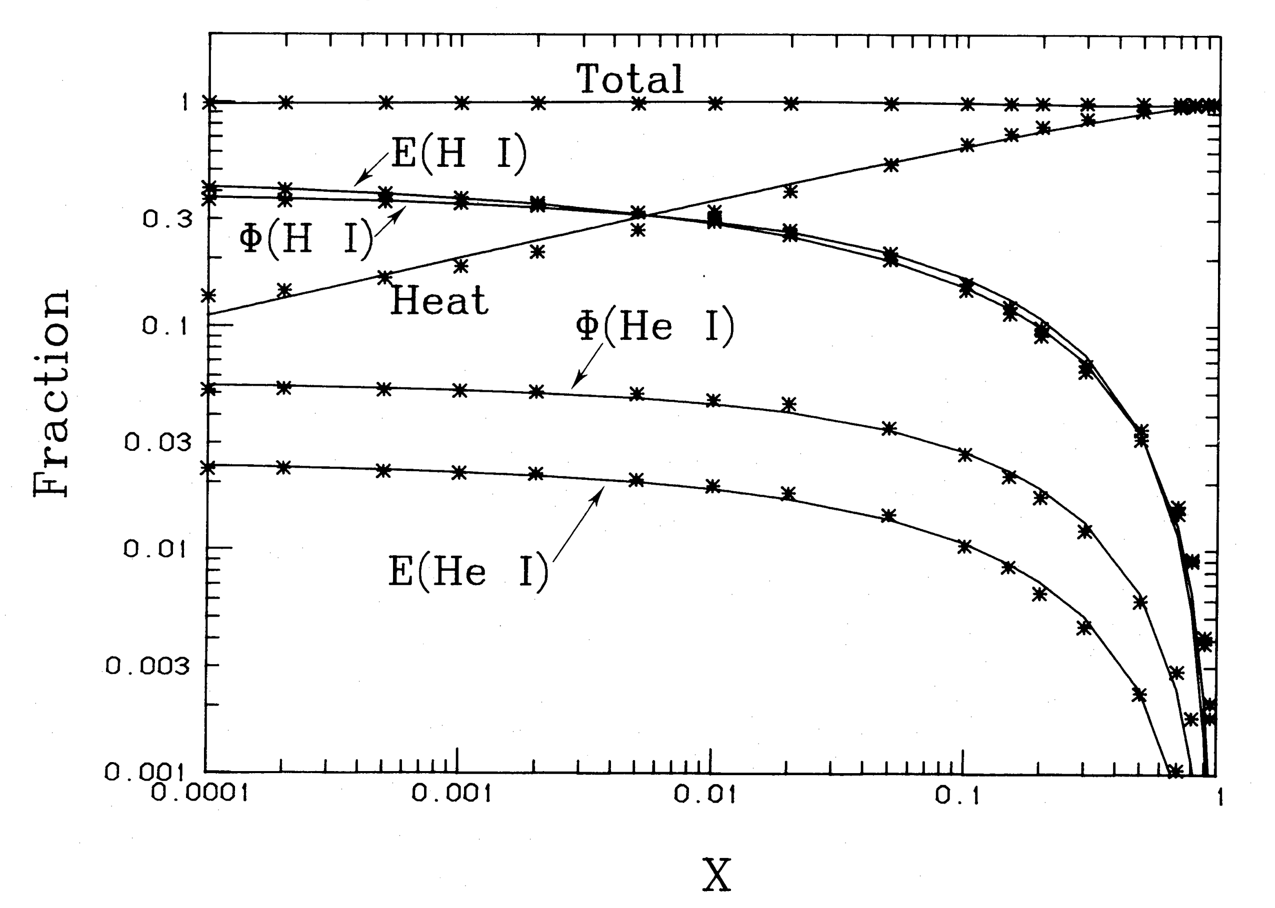


At low energies:

Collisional ionization,
excitation,
heating

Rapid process

Partitioning depends on ionization



Shull, van Steenberg 1985

At high energies:

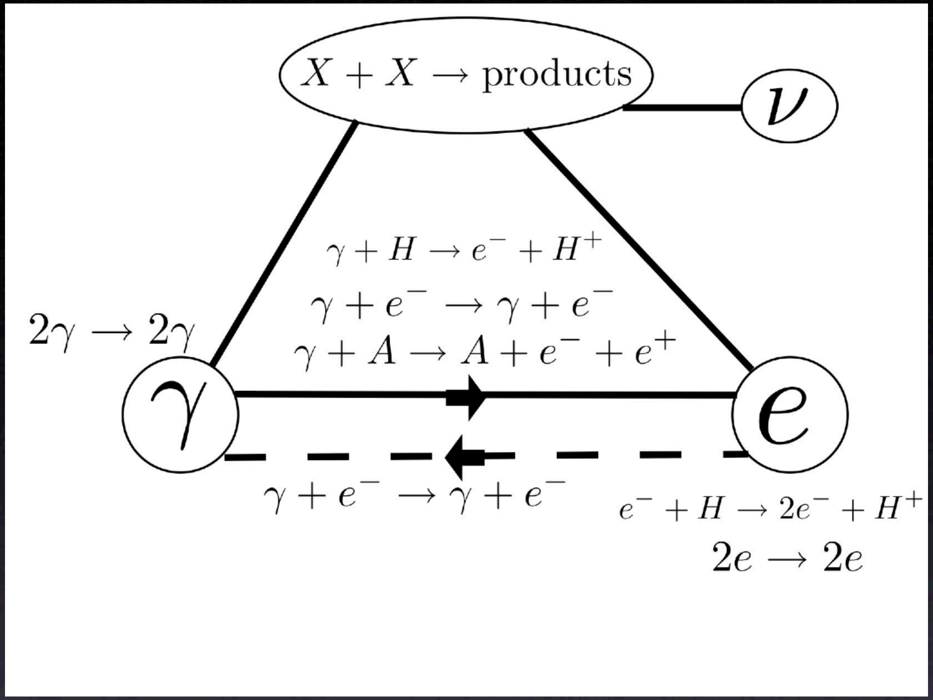
Inverse Compton
scattering - EM cascade

Rapid process

$$E_\gamma \sim 5 \left(\frac{1+z}{1000}\right) \left(\frac{E_e}{1\mathrm{GeV}}\right)^2 \mathrm{MeV}$$

Neutrinos escape!!!!

- DM annihilates (ultimately) into electrons, photons, neutrinos
- Neutrinos escape! Electrons/photons trigger EM cascades until they either escape or deposit their energy into IGM
- Energy deposition is rapid



Parametrization:

Energy injected per hydrogen atom per second : $\epsilon_{dm,0}(1+z)^3$

$$\epsilon_{dm} \sim f 10^{-24} (1+z)^3 \,\mathrm{eV s^{-1}} \times \left[\left(\frac{100\mathrm{GeV}}{M_{dm}} \right) \left(\frac{\langle \sigma v \rangle}{2 \times 10^{-26} \mathrm{cm^3 s^{-1}}} \right) \right]$$

All these parameters can be calculated given a theoretical model.

Recombination

Modified RECFAST for H, He, T

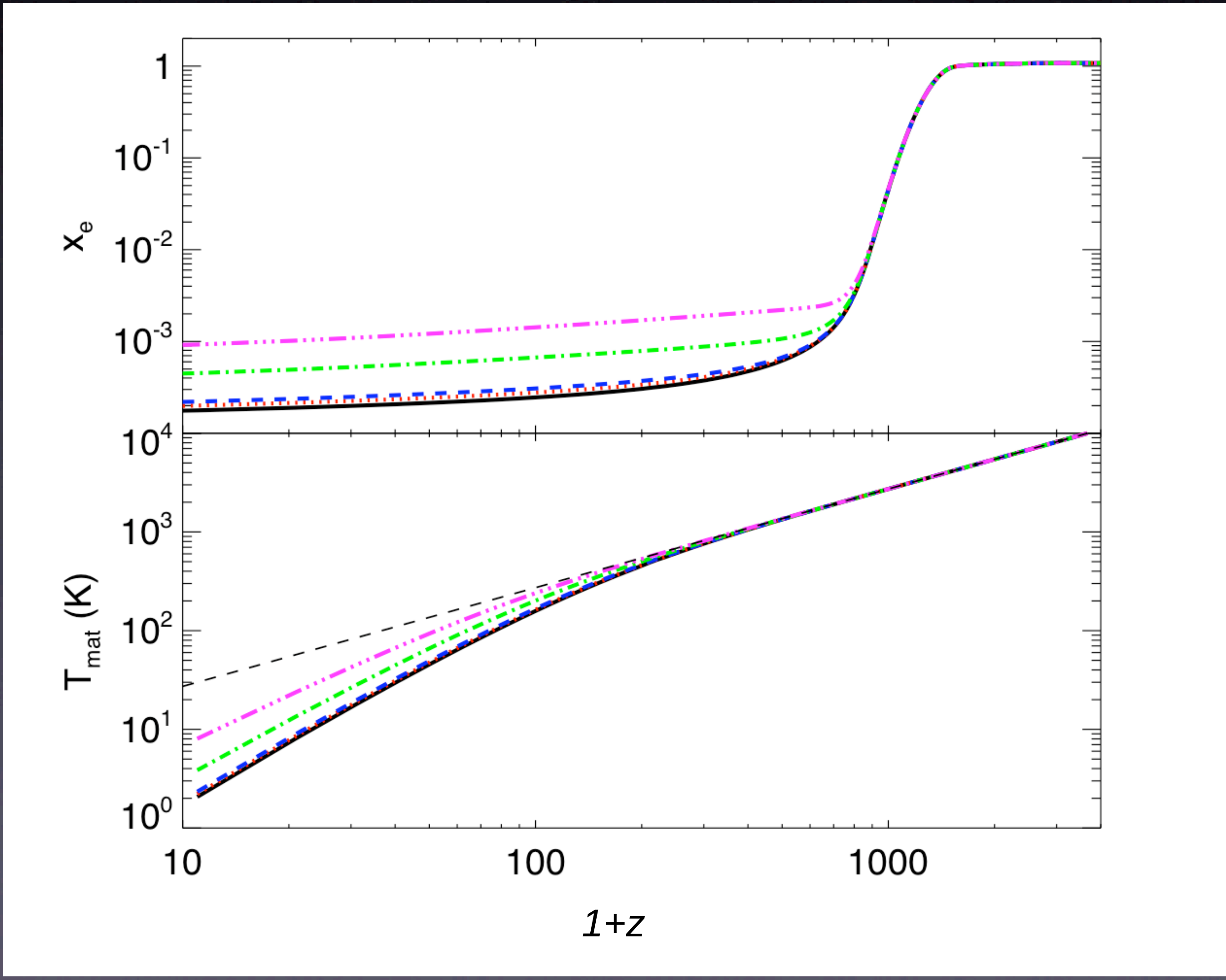
$$\delta\left(\frac{dx[H]}{dt}\right) = \frac{\epsilon_{dm,0}}{13.6}\frac{1-x[H]}{3(1+f_{He})}(1+z)^3$$

When recombination is rapid : energy injection has little effect.

Energy injection causes ionization freeze-out at higher residual ionization.

Useful to parametrize as an ionization floor.

Note that redshift of recombination unchanged

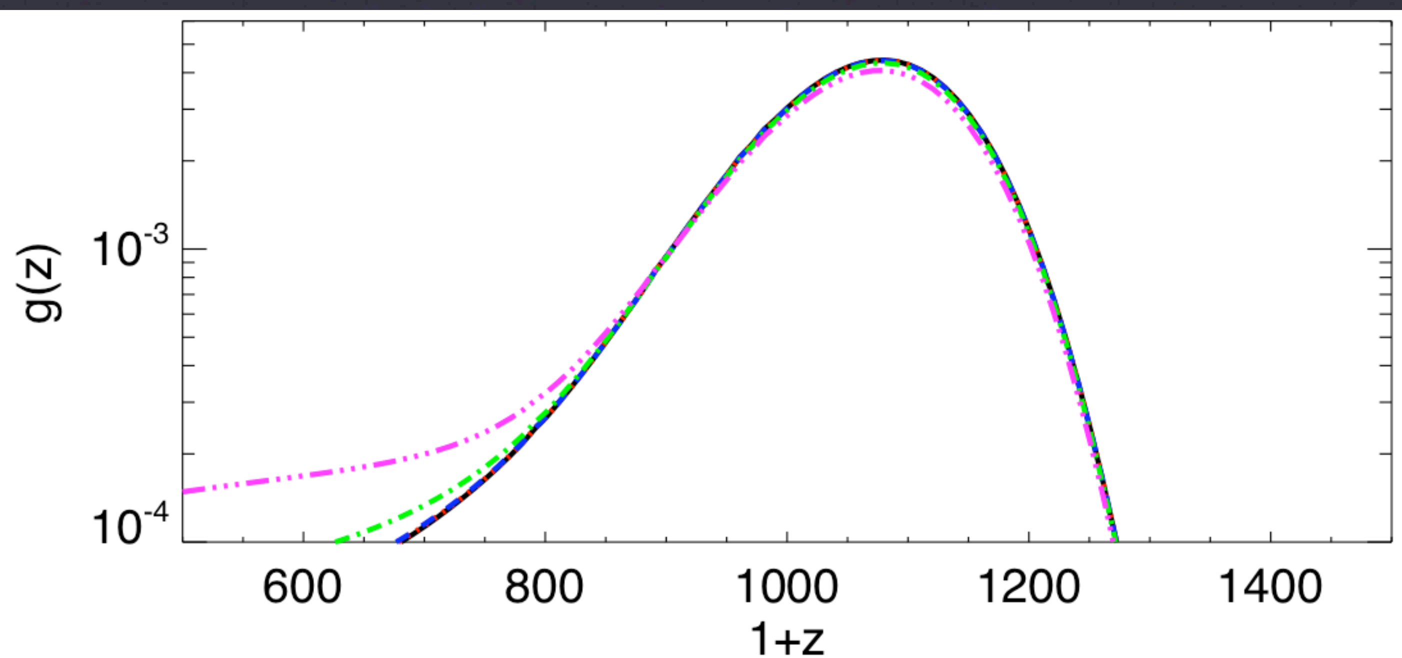


Temperature Correlations

- Effect on temperature fluctuations determined by the location, thickness of last scattering surface.
- For residual ionization << 0.01 (i.e. realistic DM models), position of last scattering surface unchanged.
- Thicker scattering surface washes out correlations on scales smaller than the thickness of the slice.

Visibility function : probability that photon last scattered at z

$$g(z) = \tau' e^{-\tau}$$



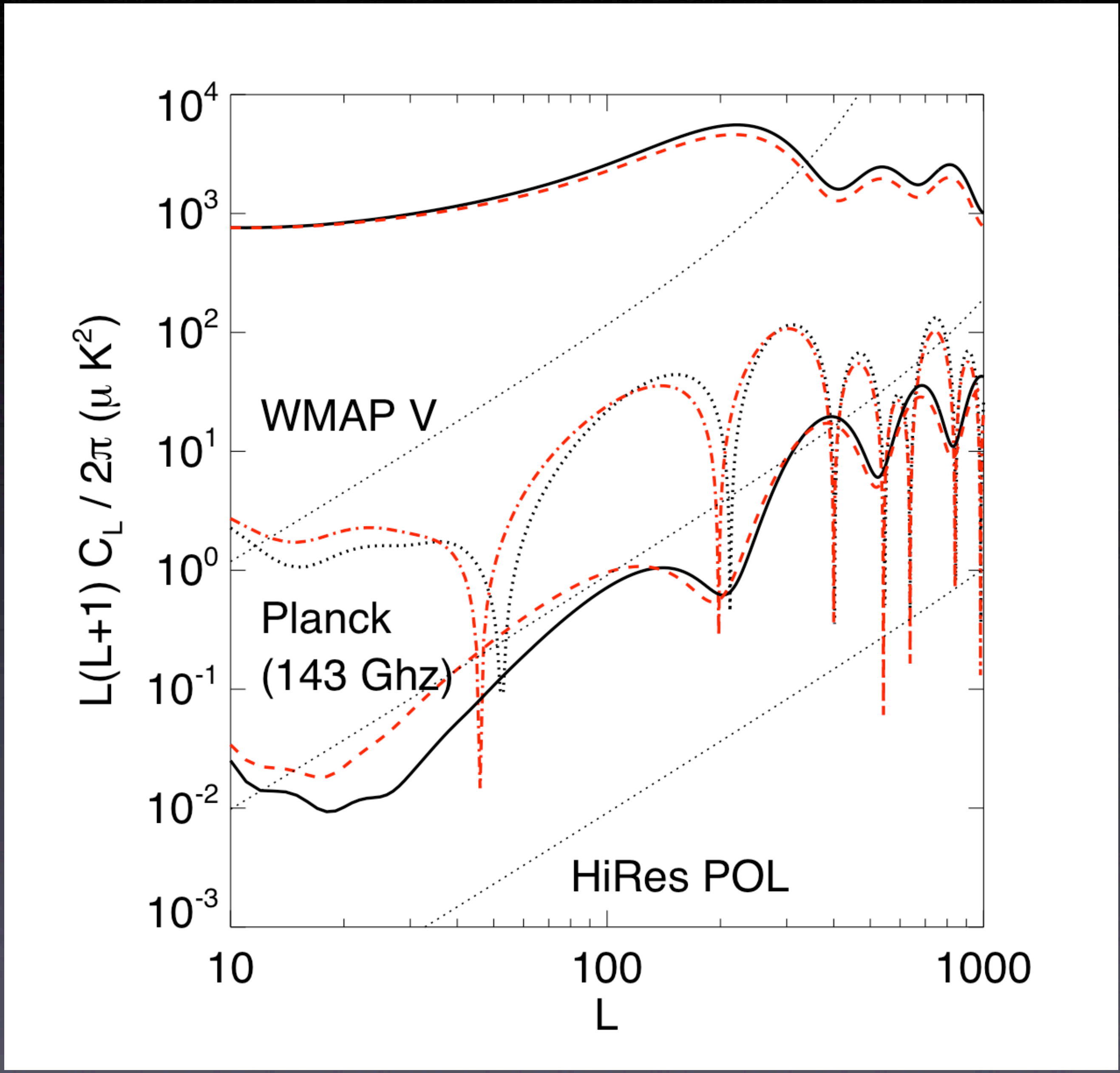
Peak positions unchanged

Power attenuation:

Scale dependent

Detectable?

- Degenerate with n,amplitude
- Broken on large scales, but cosmic variance
- Small scale limit due to secondary anisotropies



Note : HiRes POL ~ CMBpol

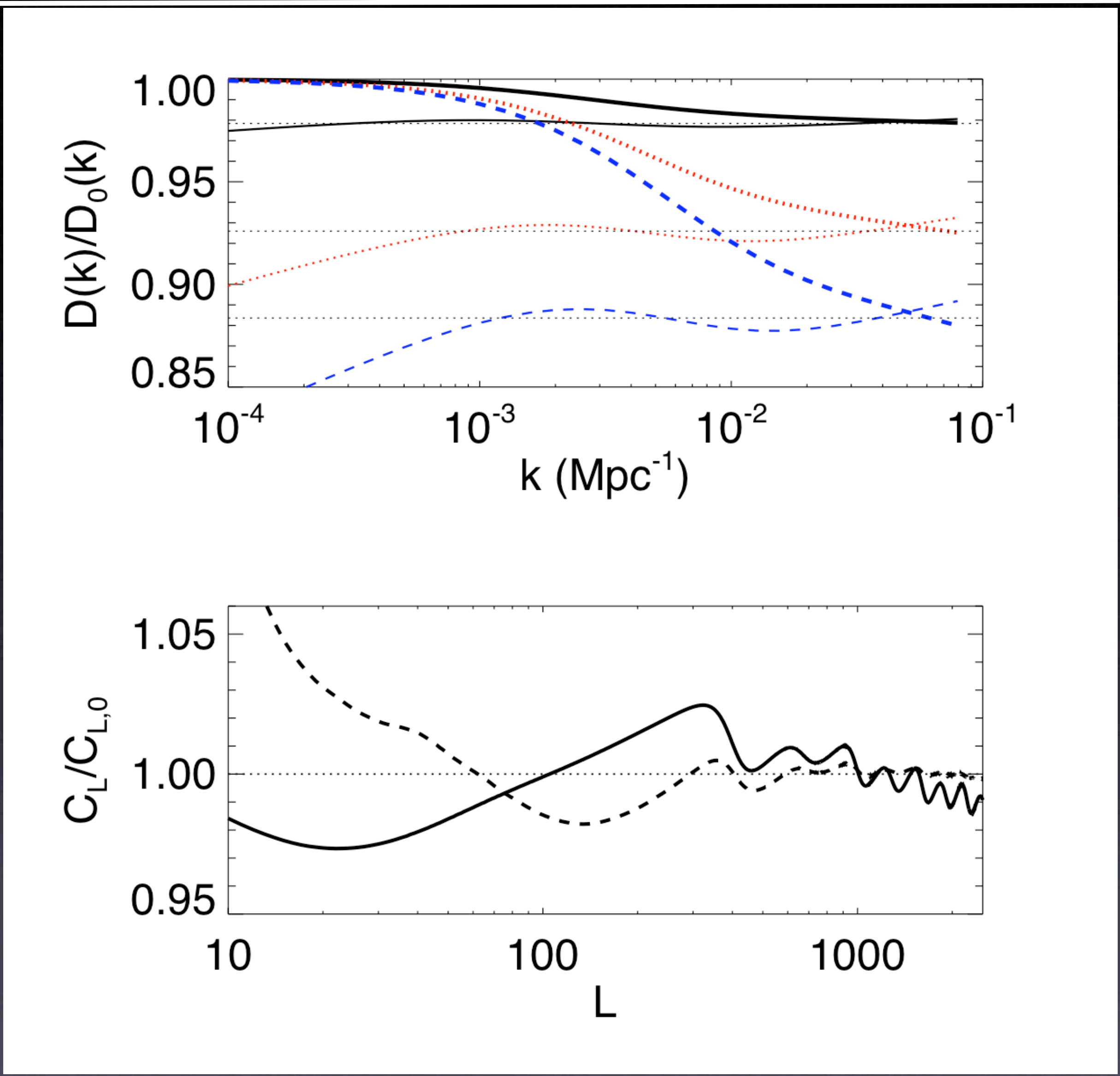
Degeneracy!!!

Damping on small scales:

Silk (diffusion) damping
Visibility function

$$D(k)/D_0(k) \sim k^{-\alpha}$$

$$P(k) \sim k^{n_s-1} \rightarrow k^{n_s-1+\alpha}$$



Accidental degeneracy:

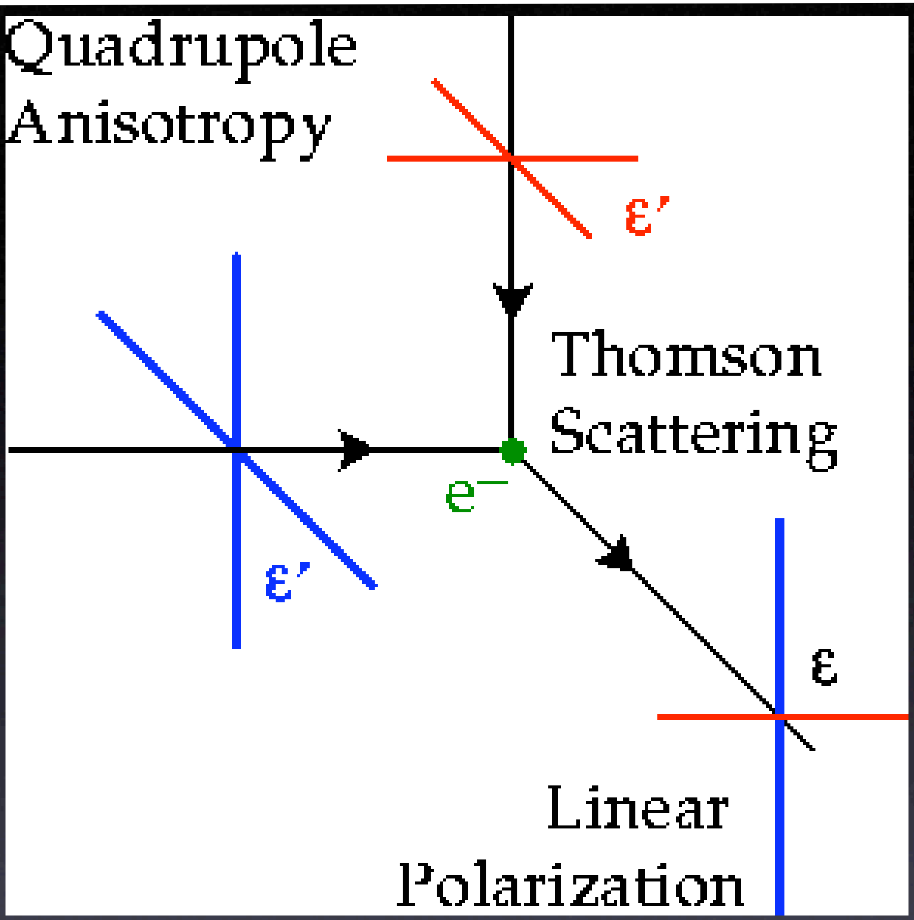
ISW
Vanishes for small/large k

Numerical fit : n_s, τ, A

Virtually undectable even with cosmic variance limited data

Polarization

- Polarization produced by Thomson scattering
- Requires a local quadrupole
- Quadrupole suppressed during tight-coupling epoch
- Quadrupole produced by free streaming monopole/dipole
- Altered admixture of monopole and dipole
- Monopole and dipole out of phase; modified phase structure of TT, TE, EE.



Hu & White, New Astron., 2 (1997) 323

$$\Theta_2(k) \sim \frac{\Theta_0(k)[k\Delta\eta]^2 + 6\Theta_1[k\Delta\eta]}{15} + \mathcal{O}(x^3)$$

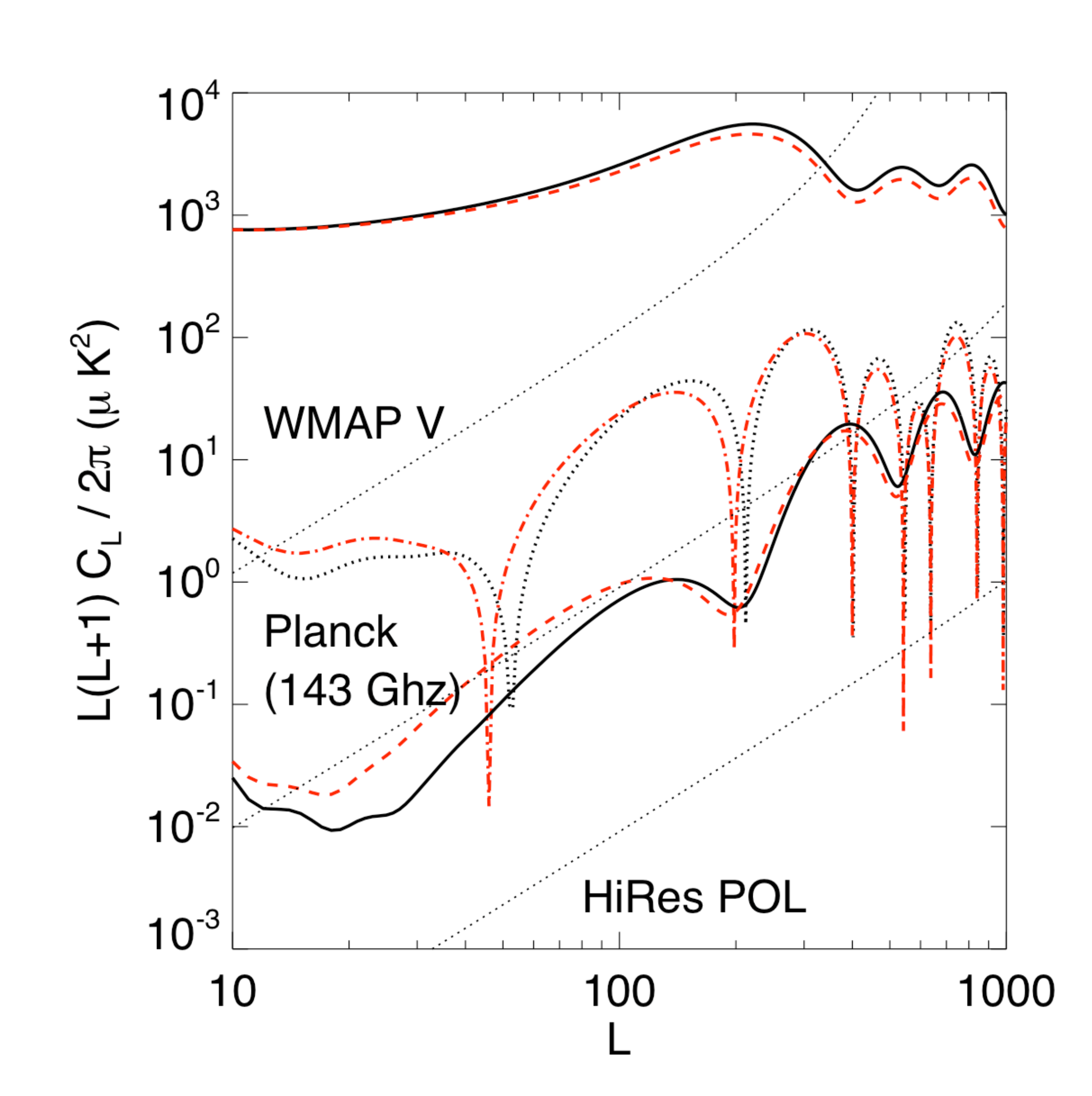
$$T \sim \Theta_0(k)$$

$$E \sim \Theta_2(k)$$

$$\Theta_1(k) \sim \sin(kr_s), \Theta_0(k) \sim \cos(kr_s)$$

Polarization

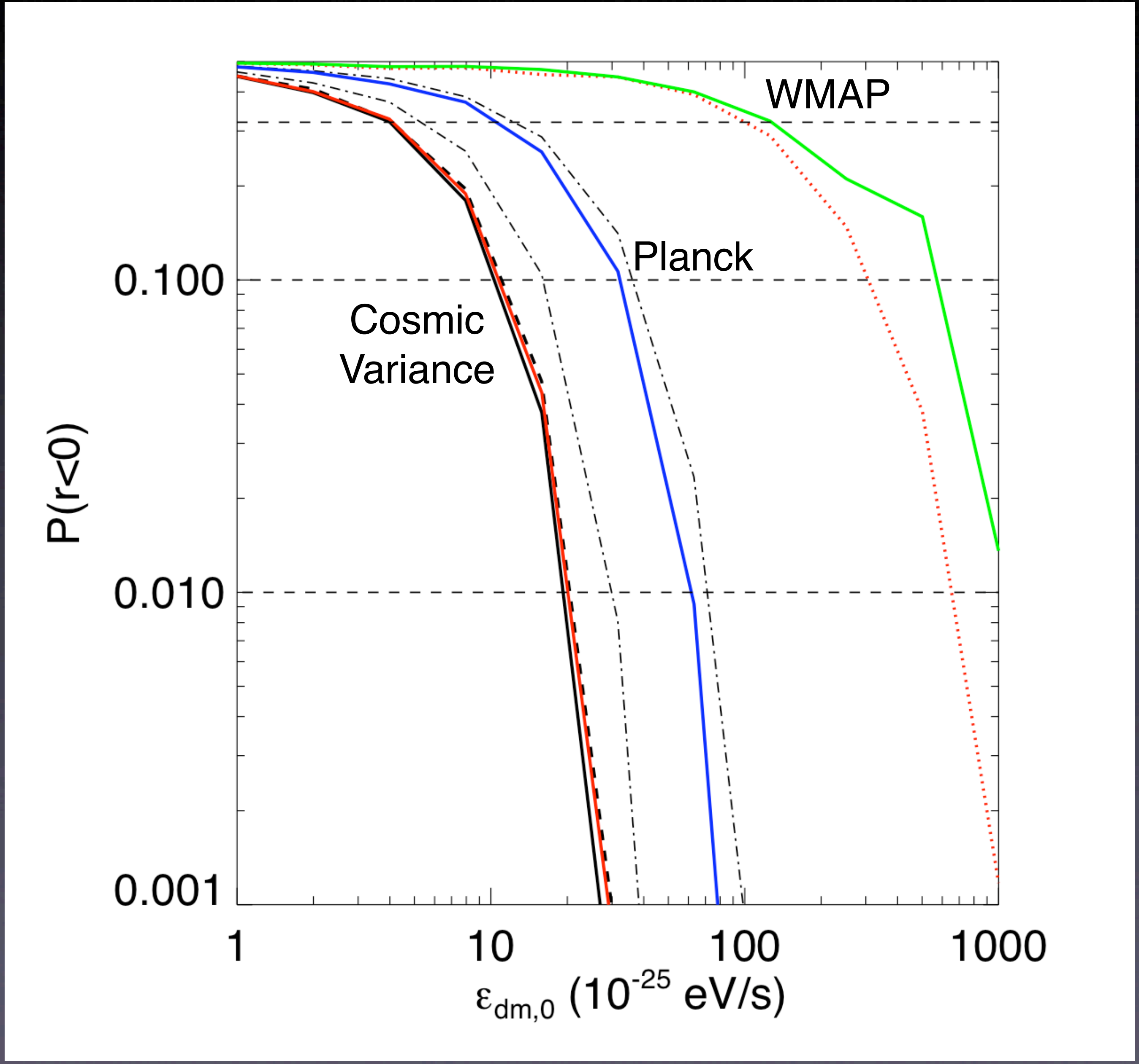
- Enhanced polarization signal on large scales (dip in EE power spectrum)
- Relative phase shift in TT, TE, EE power spectra
- Suppression on small scales
- Difficult to mimic these effects by altering cosmological parameters
- Polarization *can* potentially probe changes in recombination history (due to DM annihilation).



What is the probability that a model with DM annihilation will be mistaken for a universe with none?

$$r = \log\left(\frac{\mathcal{L}(\mathrm{true})}{\mathcal{L}(\mathrm{test})}\right)$$

- Gaussian likelihood
- Consider ensemble of universes
- Compute P(r < 0) = detectability level



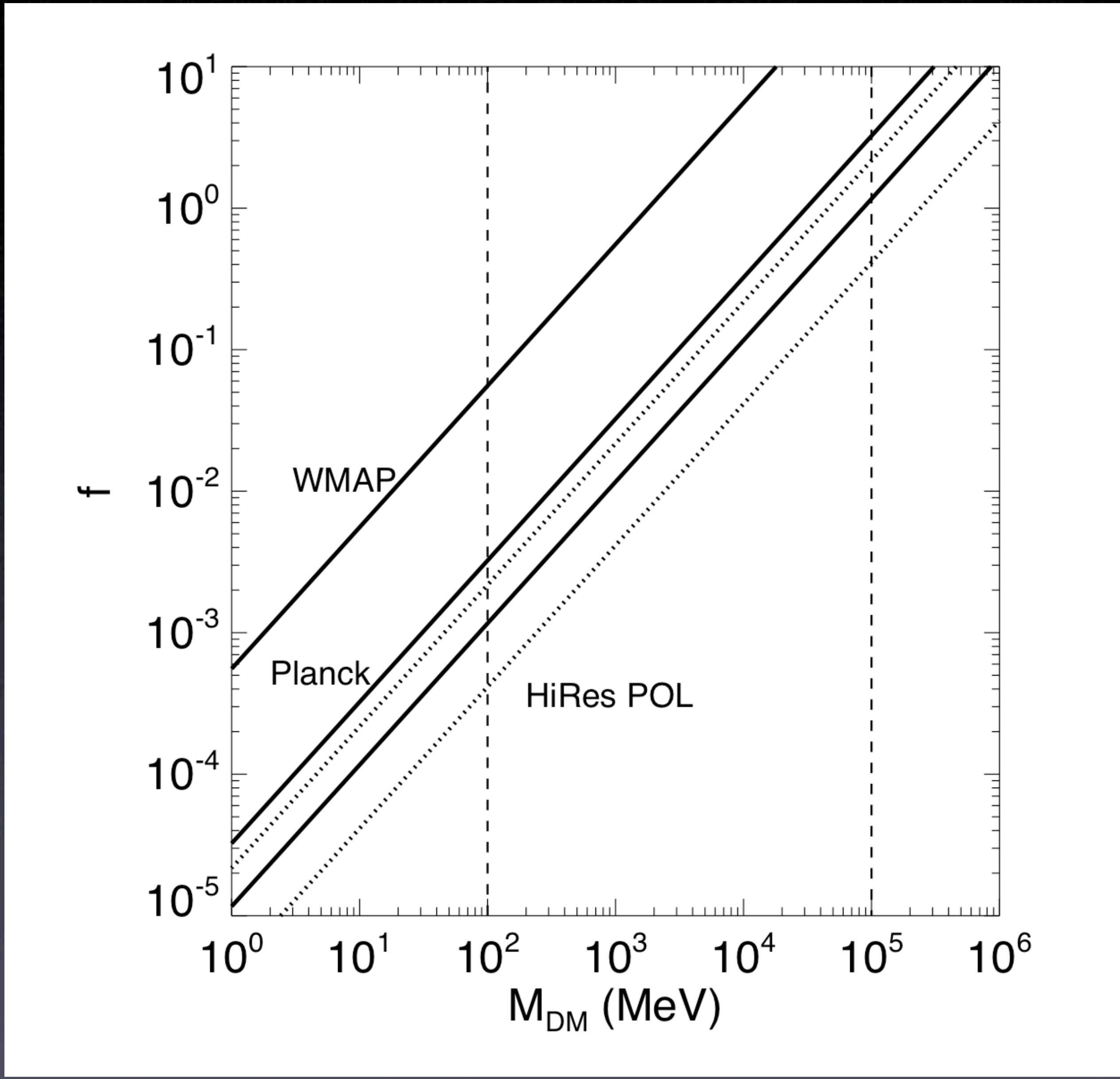
Constraints - I

CMB constrains: $\epsilon_{dm,0}$

$$\epsilon_{dm,0} \propto \frac{f\langle\sigma_A v\rangle}{M_{dm}}$$

- Translate into model dependent constraints

For a single DM species :
- WMAP ~ 1 GeV
- Planck ~ 10 GeV
- Cosmic Variance ~ 100 GeV



$$\langle\sigma_A v\rangle = 2 \times 10^{-26}\mathrm{cm}^3/\mathrm{s}$$

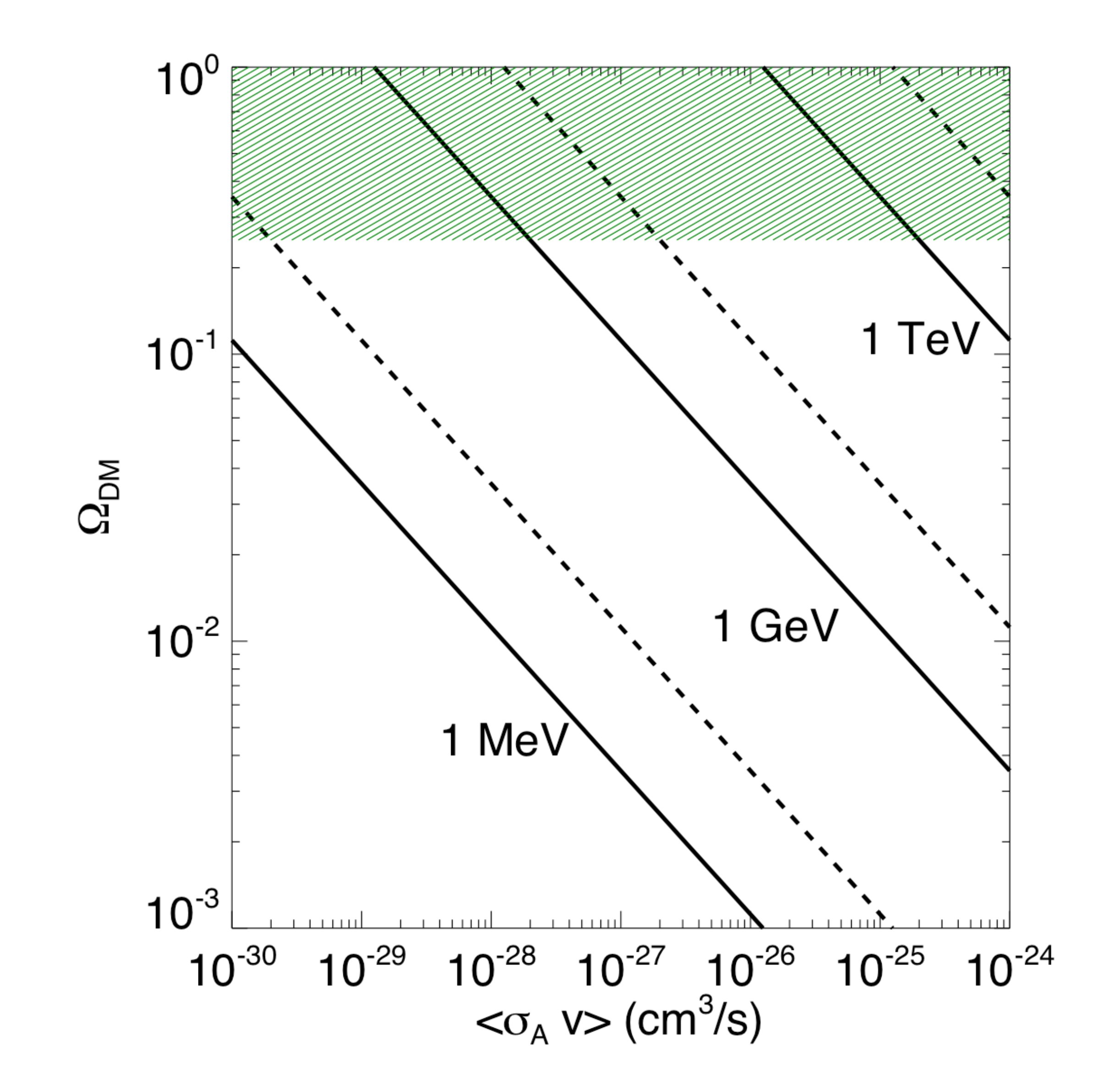
90% c.l.

Constraints - II

Cosmological abundance?

$$\epsilon_{dm,0} \propto \frac{f\Omega^2_{dm}\langle\sigma_A v\rangle}{M_{dm}}$$

Independent of assumptions about thermal relics



$$f = 1, \epsilon_{dm,0} = 10^{-24}\mathrm{eV/s}$$

Conclusions

- DM annihilation alters the recombination history
- This produces a detectable effect in the CMB temperature+polarization angular power spectra
  - Linear physics, avoids astrophysical complications
- WMAP will be sensitive to particles < ~1 GeV, a high resolution all sky polarization measurement < ~100 GeV
  - Assuming s-wave annihilation; lower for p-wave annihilation
- Probes the cosmological abundance independent of assumptions of being thermal relics