Title: Dark Matter Annihilation: From High Redshift to the Galactic Center

Date: Sep 22, 2011 09:40 AM

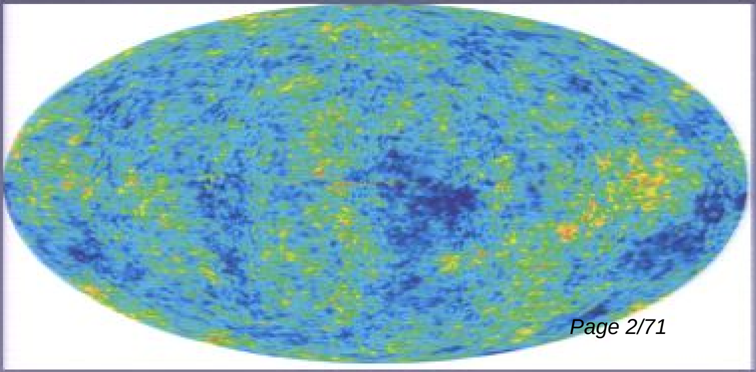
URL: http://pirsa.org/11090108

Abstract: The existence of dark matter is hardly in doubt, yet astrophysicists continue to search in vain for any non-gravitational signals of it. In the case of weakly interacting massive particle (WIMP) models, ongoing annihilation or decay of WIMPs to Standard Model particles could provide observable signals, e.g. as excess gamma rays in the center of the Milky Way or as excess ionization at high redshift.
I will present our latest results on the most rigorous constraint from astrophysics: the effect of WIMP annihilation on the ionization history of the Universe, as recorded in the CMB.

Searching for Dark Matter in the CMB:
A Compact Parameterization of Energy Injection from New Physics

Doug Finkbeiner, Silvia Galli, Tongyan Lin, &
Tracy Slatyer

arXiv:1109.????



What astronomical / cosmological signals might come from dark matter?

- PAMELA positrons
- Fermi e+e-
- INTEGRAL 511 keV line(?)
- Excess microwaves/gammas in GC, dwarf galaxies, diffuse background...
- Effects on the CMB?

Motivation for looking at the CMB

- The CMB, together with LSS and SNe Ia, provides persuasive evidence of the existence of dark matter.

- This evidence comes from things like $H(z)$, d_A, and the growth of structure. This can tell us about CDM/HDM, but little about the particle nature of the DM.

- If the DM is a WIMP and if the WIMP annihilates appreciably, then there is more to be learned from the CMB!

The CMB originates at the time of "last scattering," when the Universe first becomes transparent.
($z \approx 1100$ $t \approx 380{,}000$ yr)

•WIMP annihilation (or decay) can inject high-energy particles and photons into the gas at $z \sim 100$-1000.

•This energy modifies the "recombination" history of the Universe (really, *ionization fraction* as a function of time).

•The CMB power spectrum is sensitive to this change in the ionization history.

By measuring the CMB we can:

- Search for departures from the "standard recombination" scenario,

- Place limits on energy injection at z=100-1000,

- Translate these limits to exclusions in WIMP parameter space (e.g. the cross-section / mass plane, etc.)

Note that these results are quite robust -- we understand recombination and the CMB *quite well*, and the measurements are good and rapidly improving!

There is less "wiggle room" in CMB constraints at z=100-1000 than constraints based on e.g. annihilation in late-time halos.

Selected key papers:

2004: Chen & Kamionkowski - calculated effect of DM decay on recombination history. (to explain high tau in WMAP 1)

2005: Padmanabhan & Finkbeiner - repeated calculation for WIMP annihilation, obtained limits from WMAP.

2009: Galli, Iocco, Bertone, & Melchiorri - computed limits from WMAP 5 on Sommerfeld-enhanced DM.

2009: Slatyer, Padmanabhan, & Finkbeiner - careful calculation of deposition efficiency of WIMP annihilation energy as a function of z, *f(z)*. Computed actual limits for 42 benchmark WIMP masses / annihilation channels.

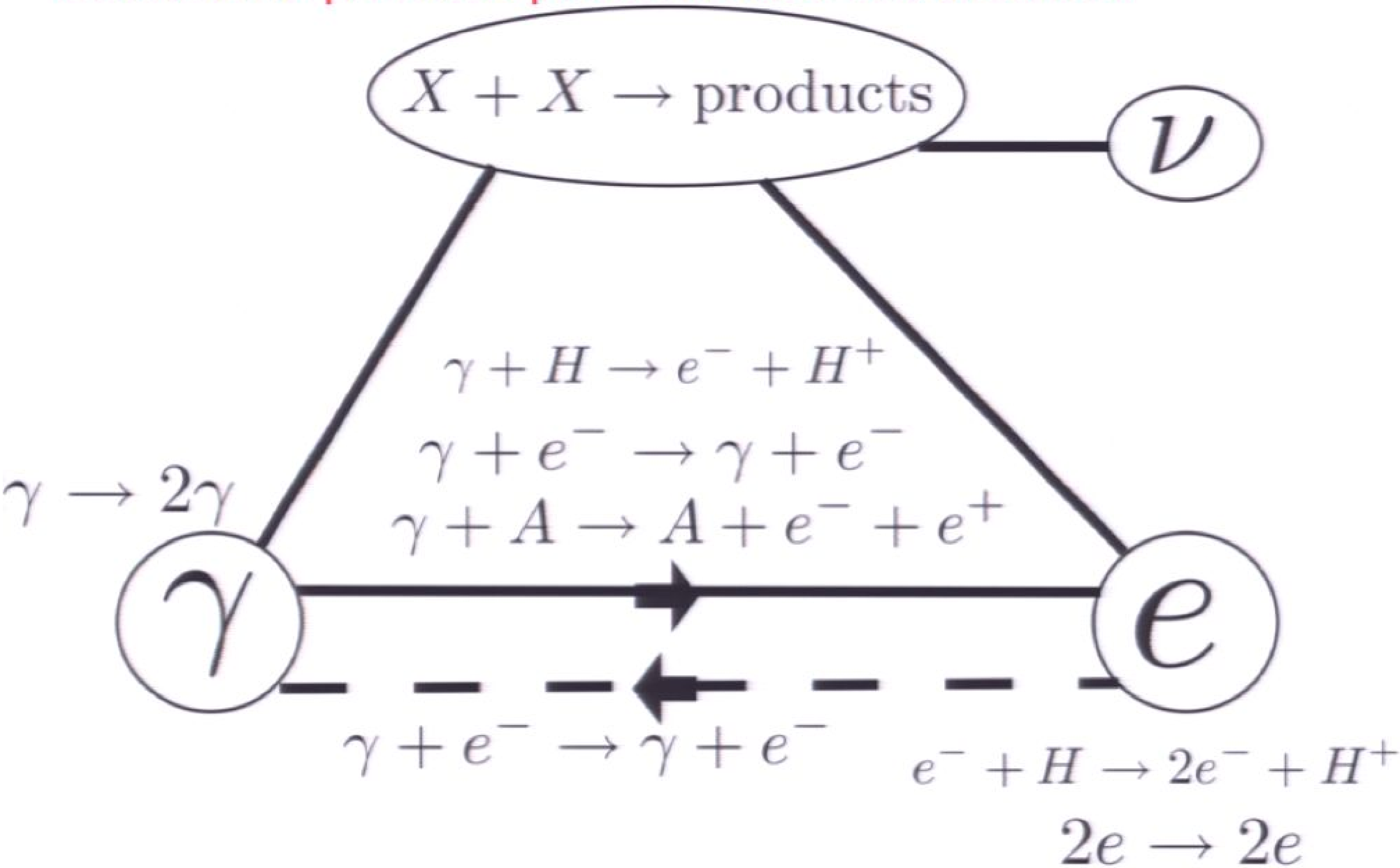
Recent papers:

2011: Hütsi, Chluba, Hektor, & Raidal - Focus on light DM case, generate *f(z)* curve appropriate for light WIMPs, use WMAP 7.

2011: Galli, Iocco, Bertone, & Melchiorri - derive latest limits from WMAP 7 and ACT, use *f(z)* from Slatyer et al.

2011: Finkbeiner, Galli, Lin, & Slatyer - introduce PCA formalism for robust model-independent constraints.

Annihilation produces photons, electrons, neutrinos



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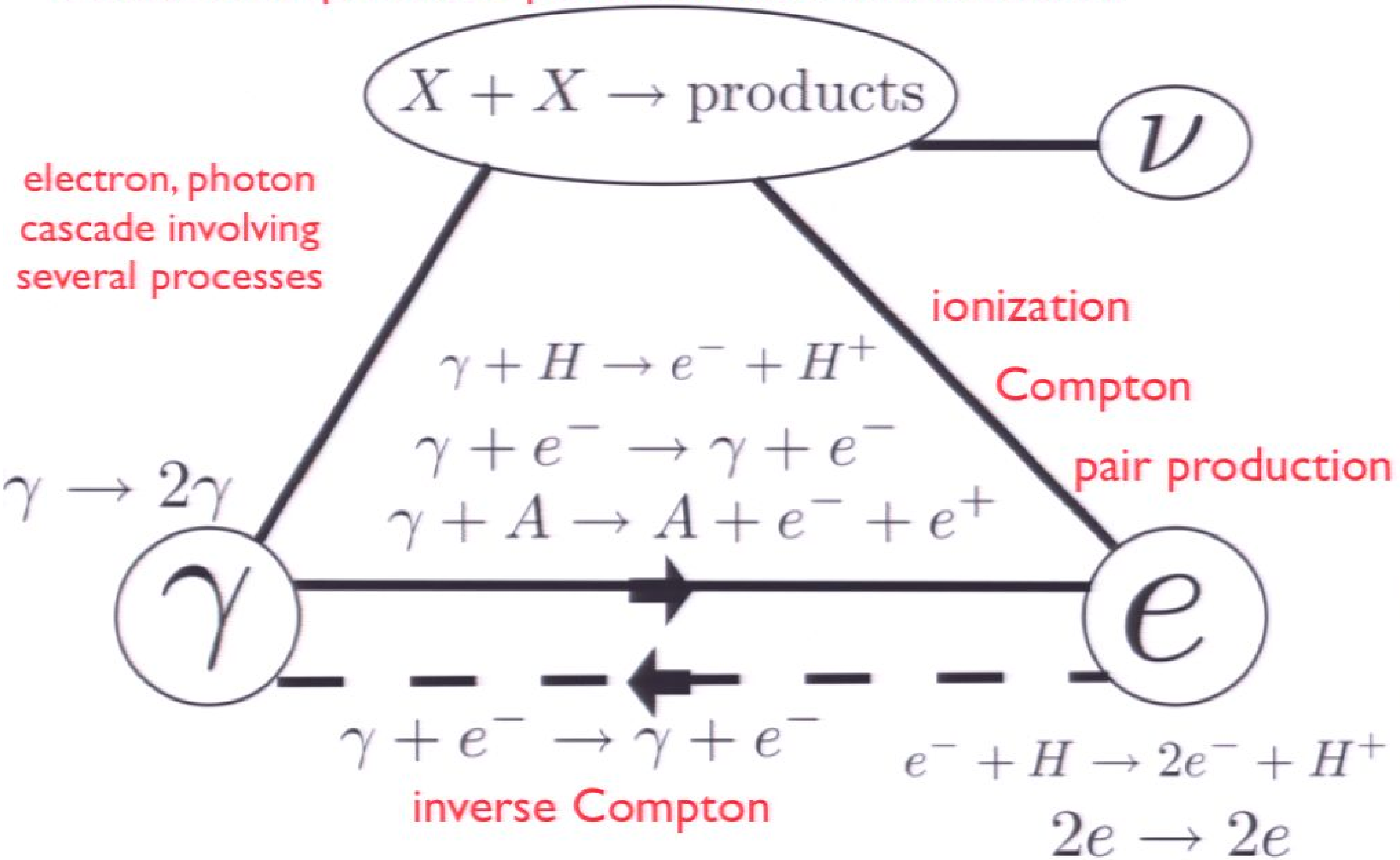
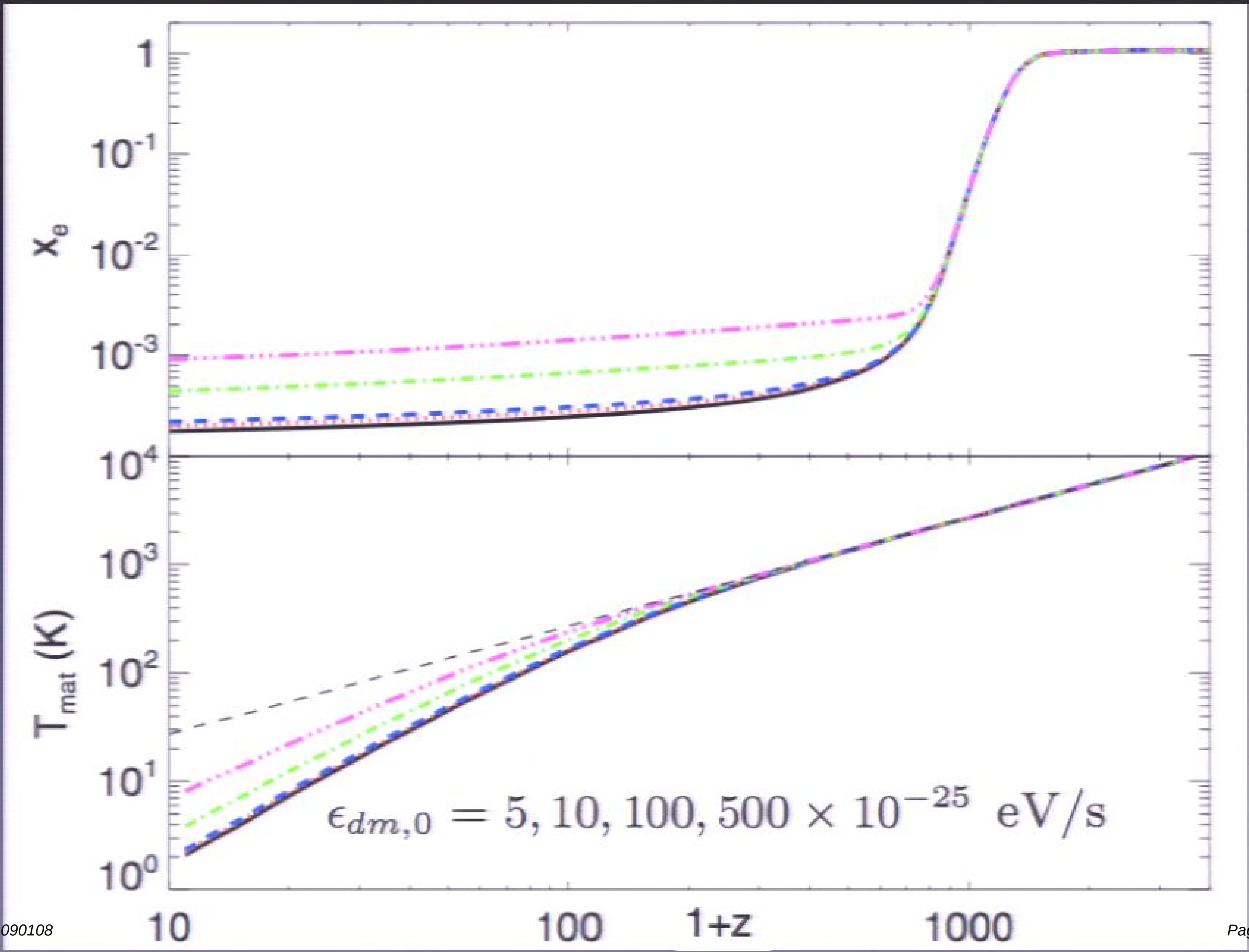
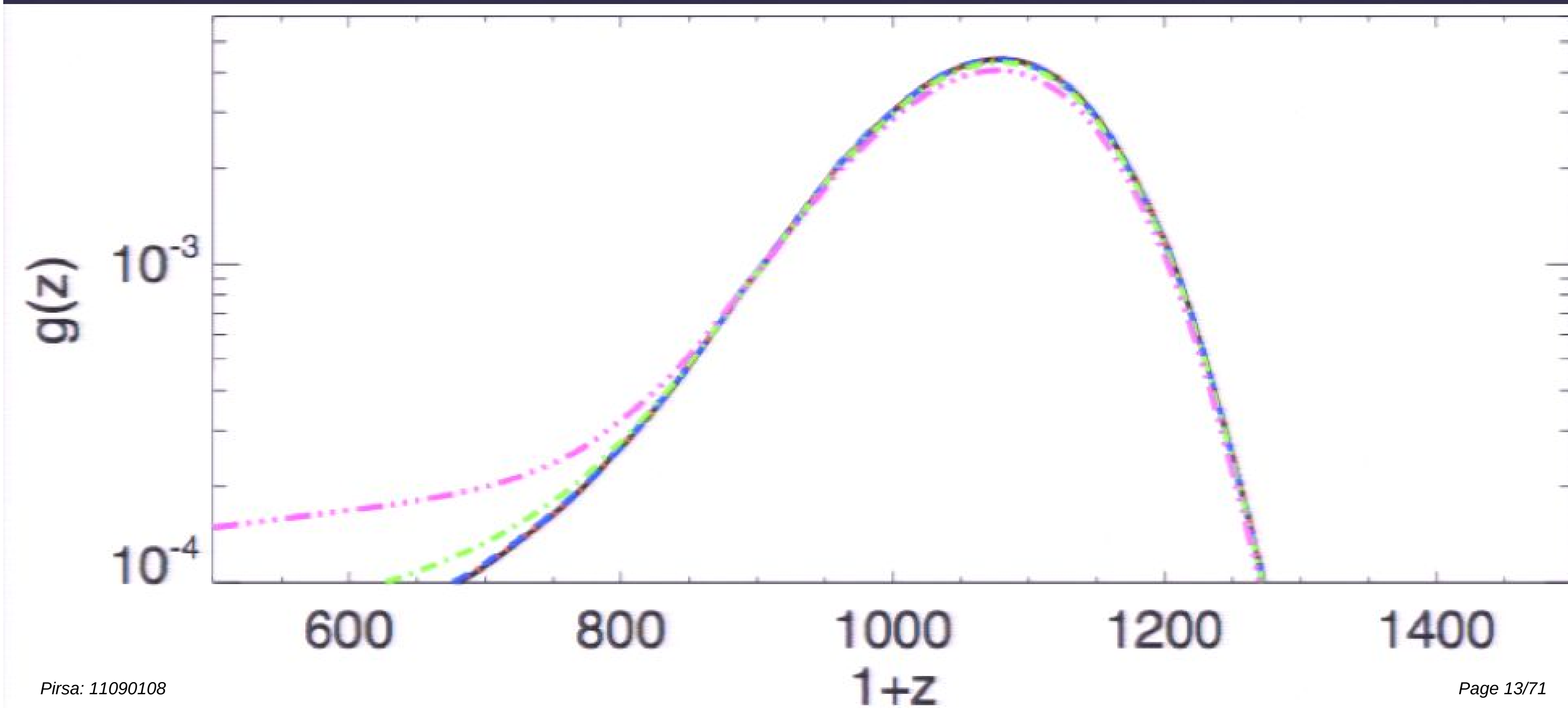


Ionization fraction (x_e) and gas temperature change...



... and this changes the visibility function ...
(= the distribution function of the last scattering redshift of CMB photons)

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



What effect does this change in g(z) have?

$$C_l = 4\pi A \int_0^\infty d(\ln k)\, k^{n_s} D^2(k) T^2(k)$$

T(k) ~ constant, D(k) = damping function, k = wavenumber

$$D(k) = \int dz\, g(z) \exp\left(-\frac{k^2}{k_D^2(z)}\right)$$

$$\frac{1}{k_D^2} = \int_z^\infty dz\, \frac{c}{H^2(z)} \frac{1}{6(1+R)\tau'(z)} \left[\frac{R^2}{(1+R)} + \frac{16}{15}\right]$$

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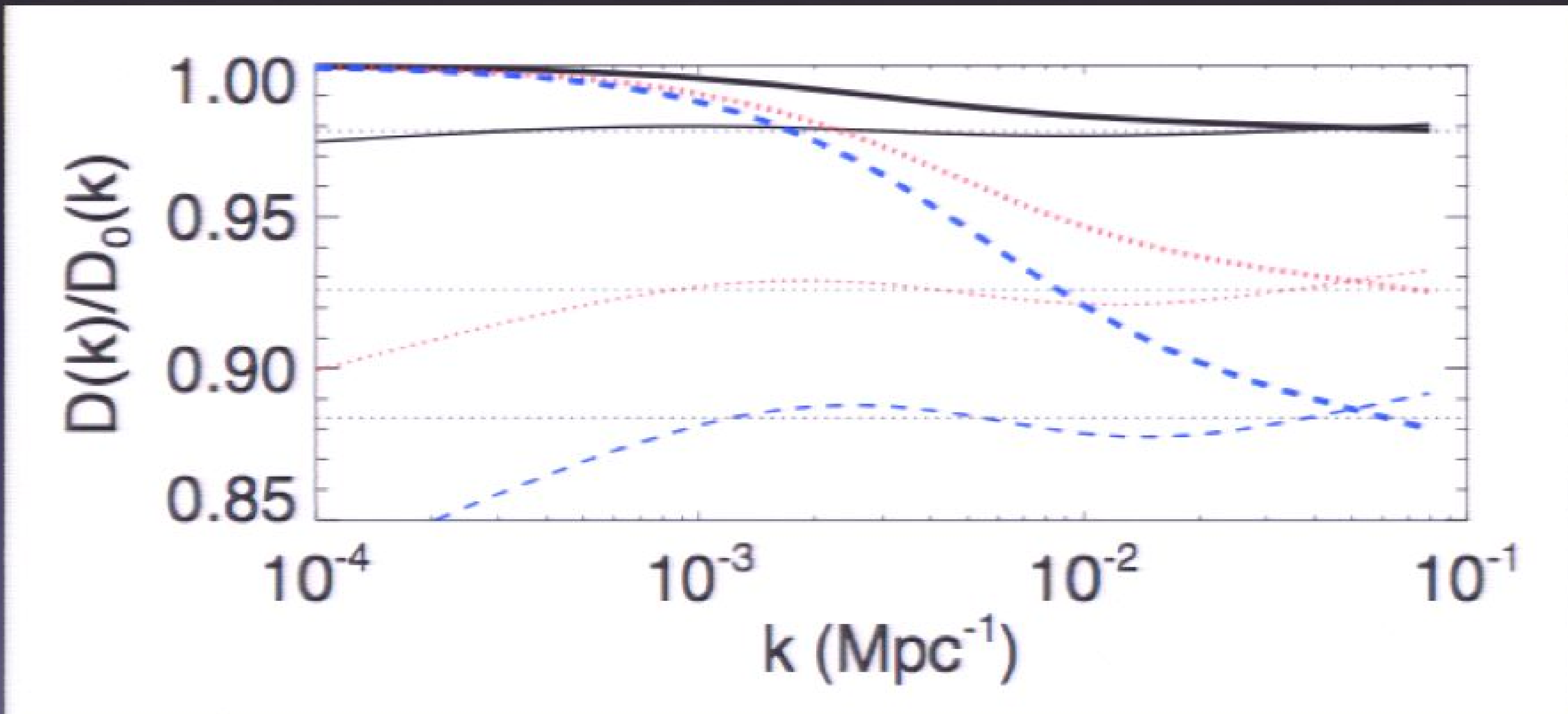

Changing g(z) mostly changes D(k)/D0(k).
The CMB gets damped like $k^{-\alpha}$

$n_s \rightarrow n_s + 2\alpha$

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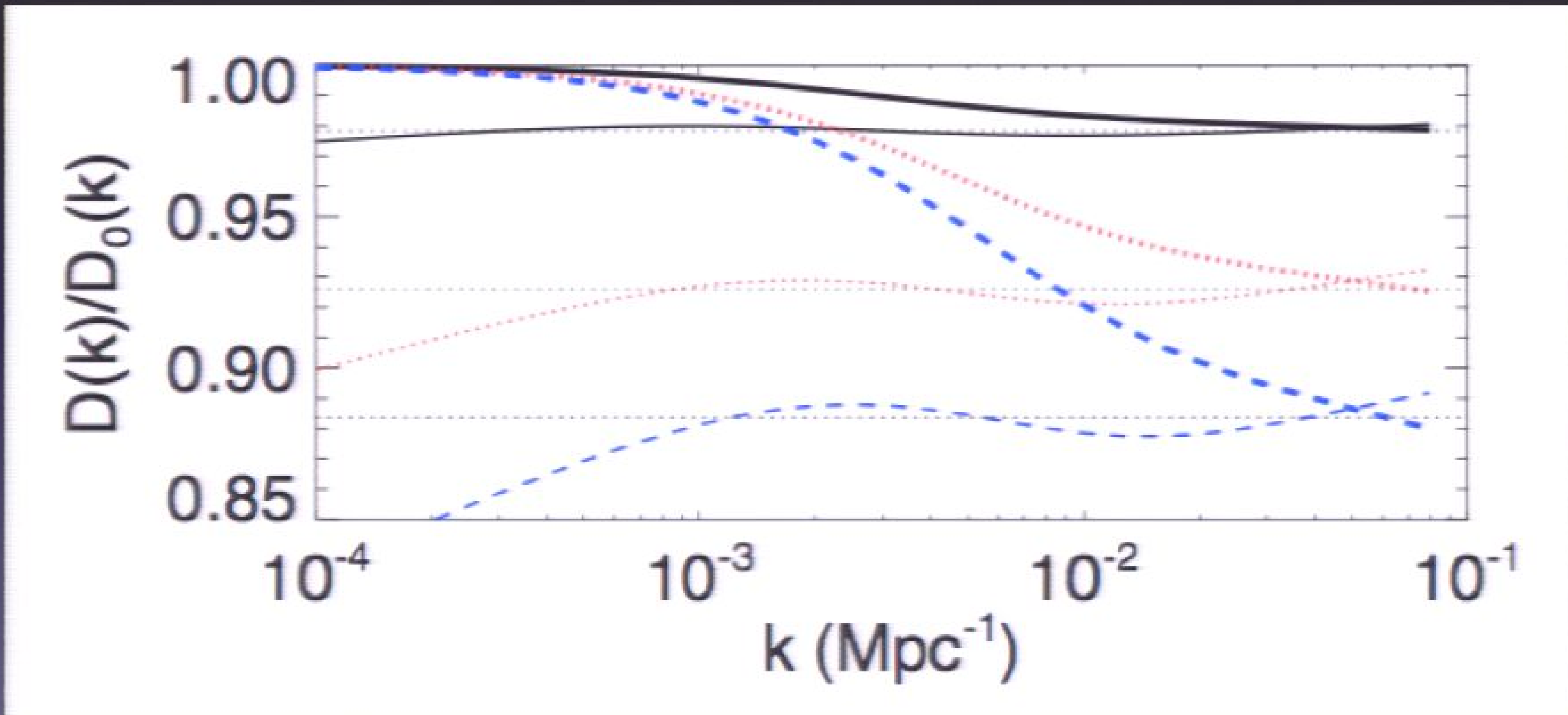

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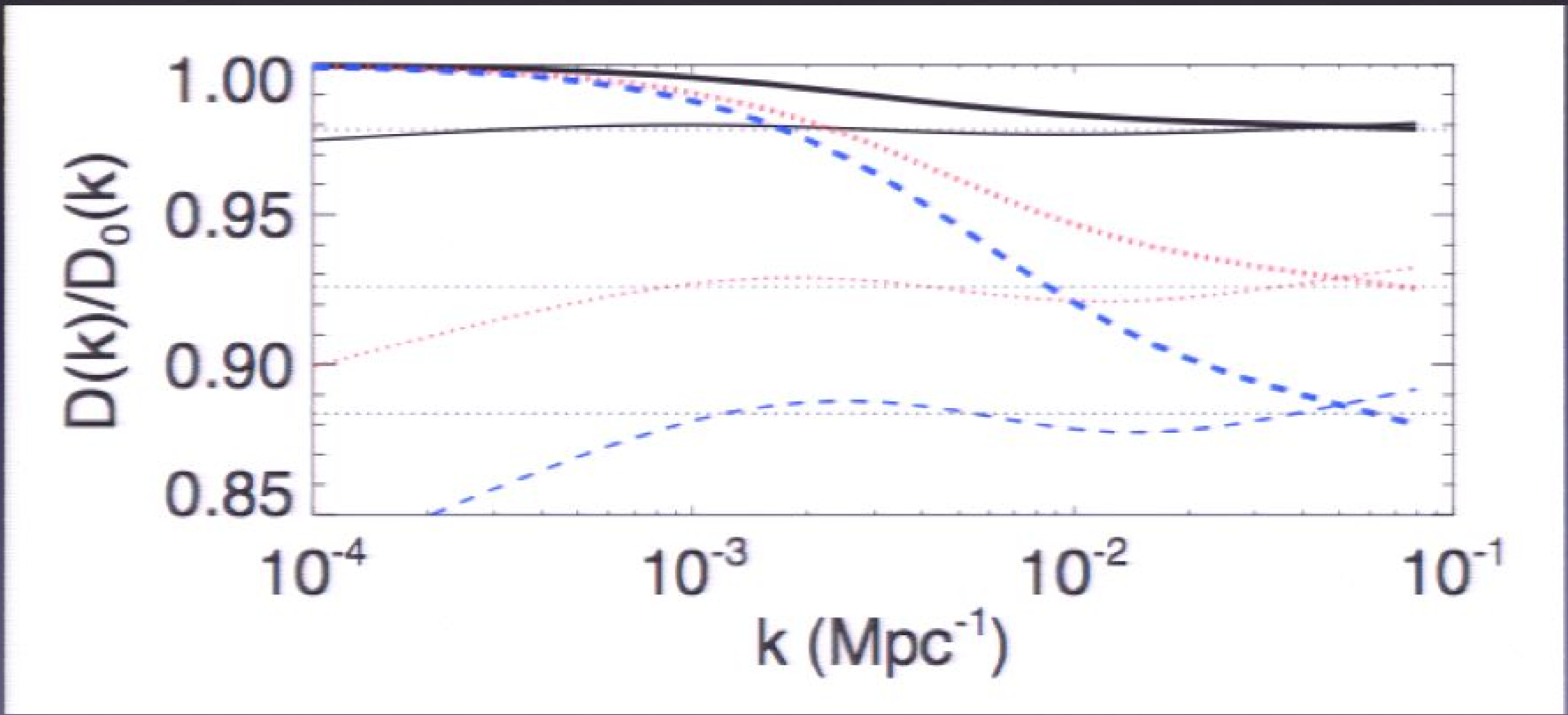

Changing g(z) mostly changes $D(k)/D_0(k)$.
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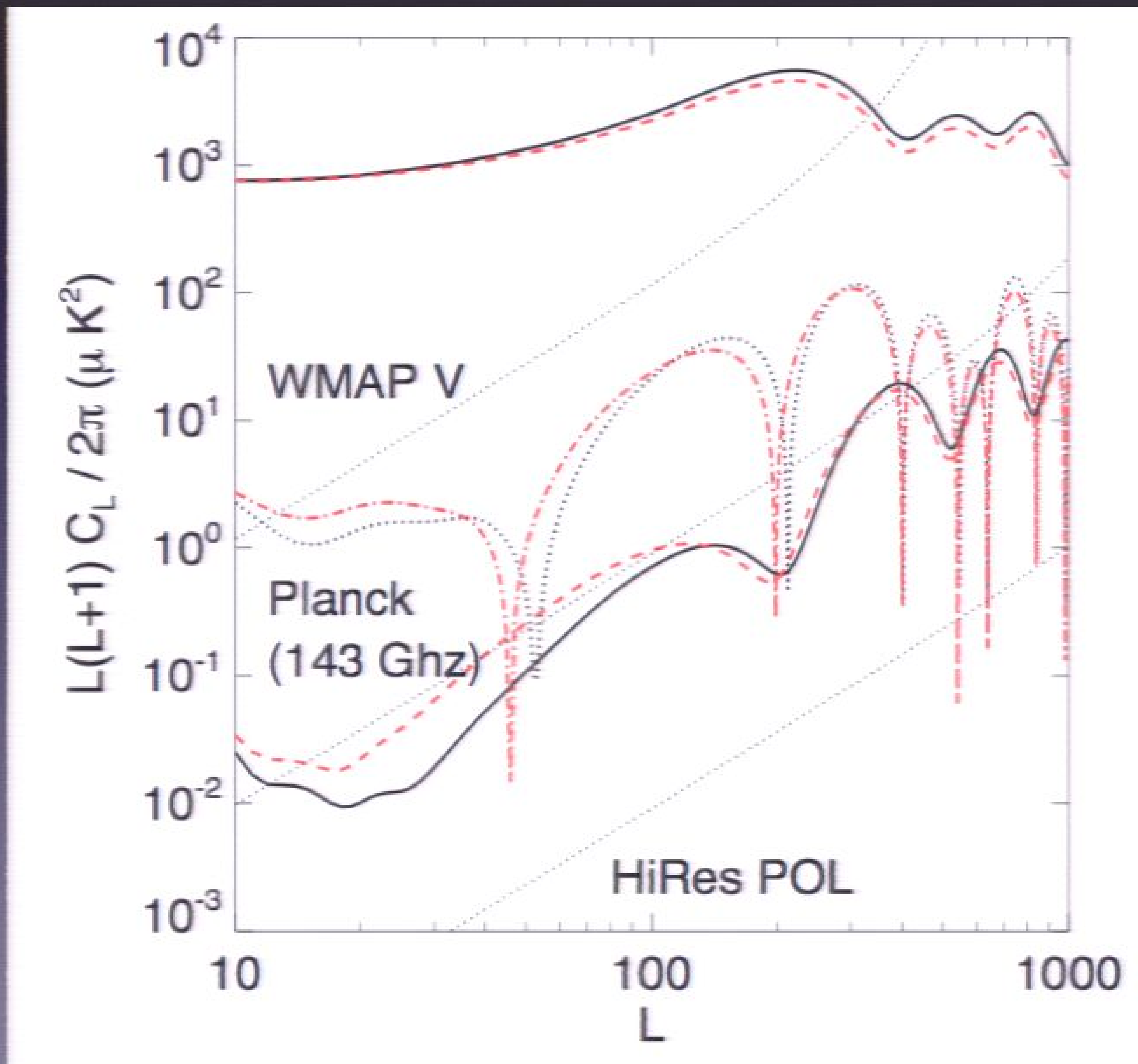
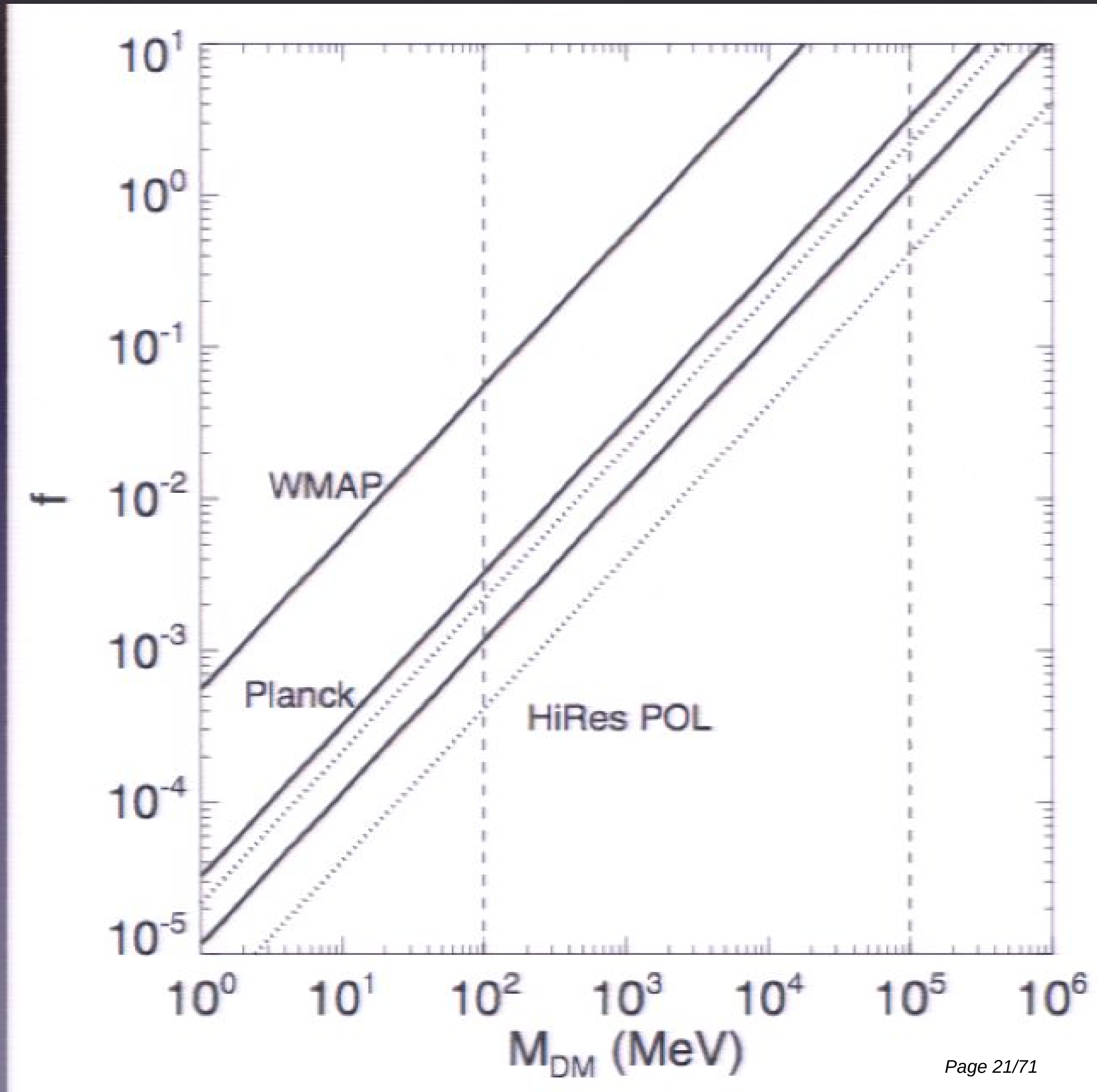
... and increased scattering at z ~ 600 modifies the power spectrum.



Constraints in f / M plane. (for thermal relic Xsec)

f is a "fudge factor" parameterizing energy deposition efficiency.

f=1 is "on the spot" approximation



Cosmology

$$\left(\frac{dE}{dt\,dV}\right)_{\text{ann}} = p_{\text{ann}}(z)c^2\Omega^2_{\text{DM}}\rho_c^2(1+z)^6$$

$$p_{\text{ann}} = f(z)\langle\sigma v\rangle/m_{\text{DM}}$$

Dark matter model

But what value does f have?

f depends on WIMP mass, annihilation channels, etc.

If all energy is immediately deposited in the gas, $f = 1$.

Any energy to neutrinos, gamma-ray background, etc., $f < 1$.

Values from $0.2 < f < 0.7$ are typical.

PAMELA positrons (Adriani+ 2010):

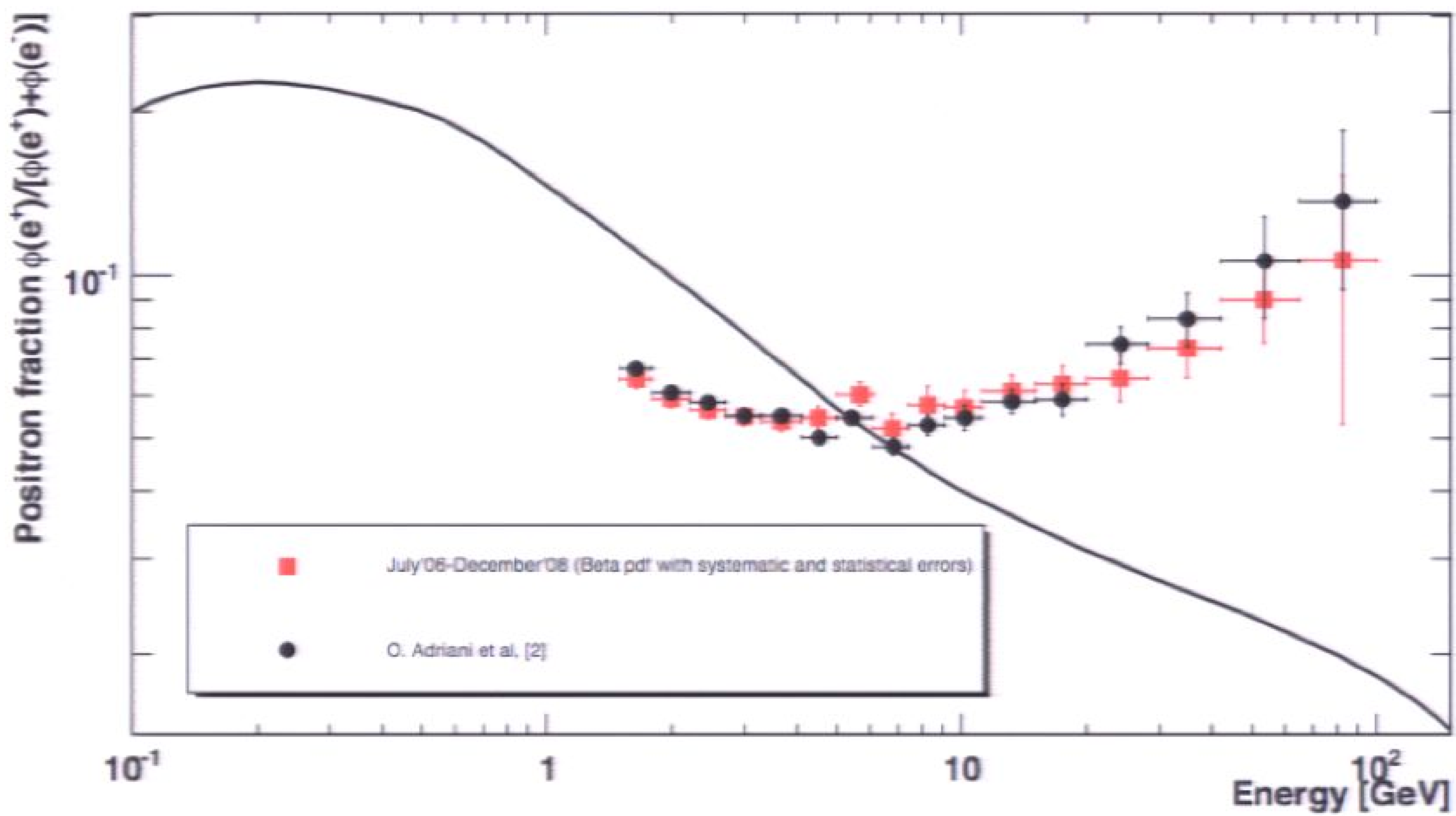


Figure 11: The positron fraction R obtained using a beta-fit with statistical and systematic errors summed in quadrature (red), compared with the positron fraction reported in [2] (black). The solid line shows a calculation by Moskalenko & Strong [40] for pure secondary production of positrons during the propagation of cosmic-rays in the galaxy.

Also built into f is any enhancement to the annihilation cross section.

For example, Sommerfeld-enhanced models motivated by the PAMELA positron spectrum can have $f >> 1$.

Can these models be ruled out with WMAP?

Accurate calculations of f for benchmark models:
The "SPF factor" paper...

CMB Constraints on WIMP Annihilation: Energy Absorption During the Recombination Epoch

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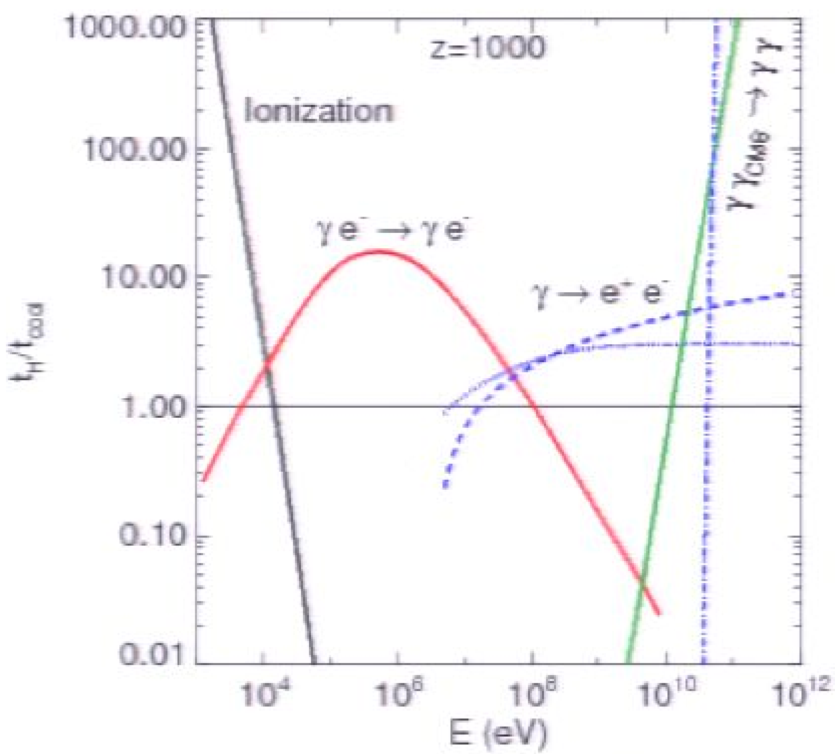
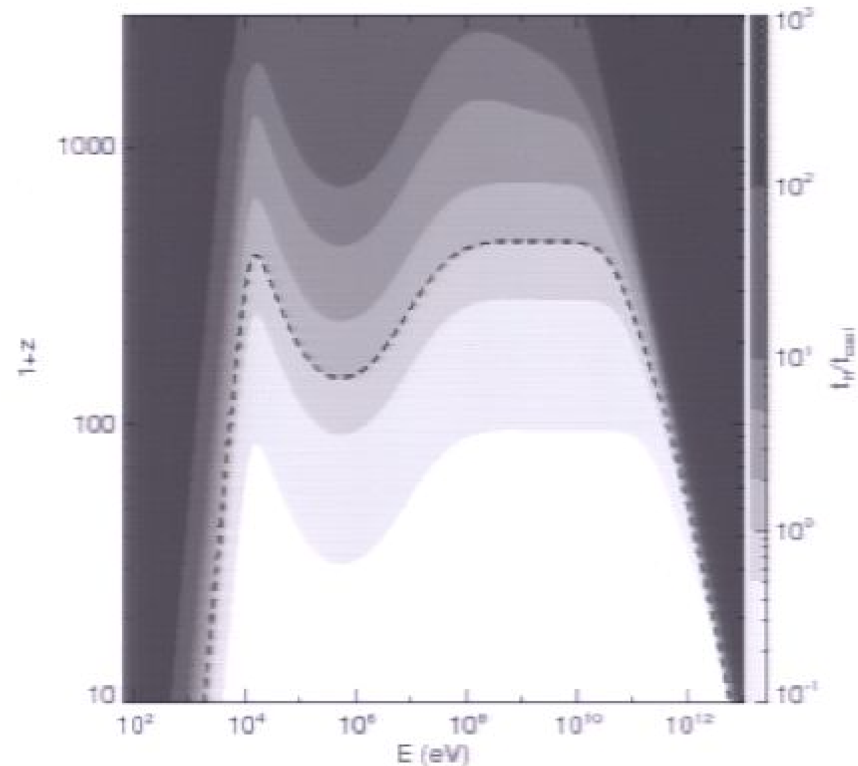
[3] *Harvard-Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA*

We compute in detail the rate at which energy injected by dark matter annihilation heats and ionizes the photon-baryon plasma at $z \sim 1000$, and provide accurate fitting functions over the relevant redshift range for a broad array of annihilation channels and DM masses. The resulting perturbations to the ionization history can be constrained by measurements of the CMB temperature and polarization angular power spectra. We show that models which fit recently measured excesses in 10-1000 GeV electron and positron cosmic rays are already close to the 95% confidence limits from WMAP. The recently launched Planck satellite will be capable of ruling out a wide range of DM explanations for these excesses. In models of dark matter with Sommerfeld-enhanced annihilation, where $\langle \sigma v \rangle$ rises with decreasing WIMP velocity until some saturation point, the WMAP5 constraints imply that the enhancement must be close to saturation in the neighborhood of the Earth.

Energy transfer from electrons to photons is efficient.
(i.e. essentially instantaneous)
We are mainly concerned with the fate of high energy photons.

There is a z-dependent transparency window:

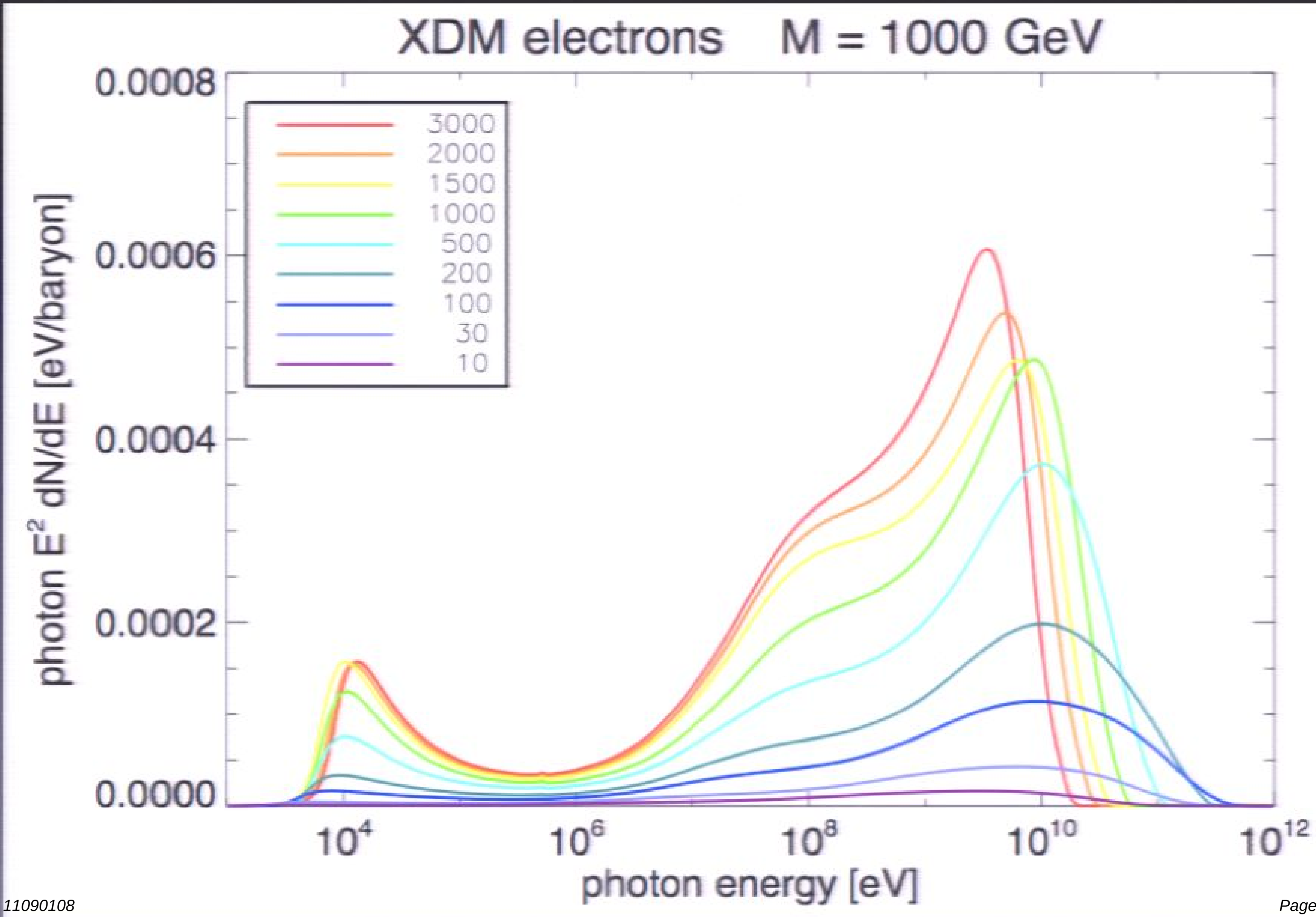




Note difference to P&F (2005) and Chen & Kamionkowski (2004)

Slatyer+ (2009)

Annihilation photons not yet thermalized



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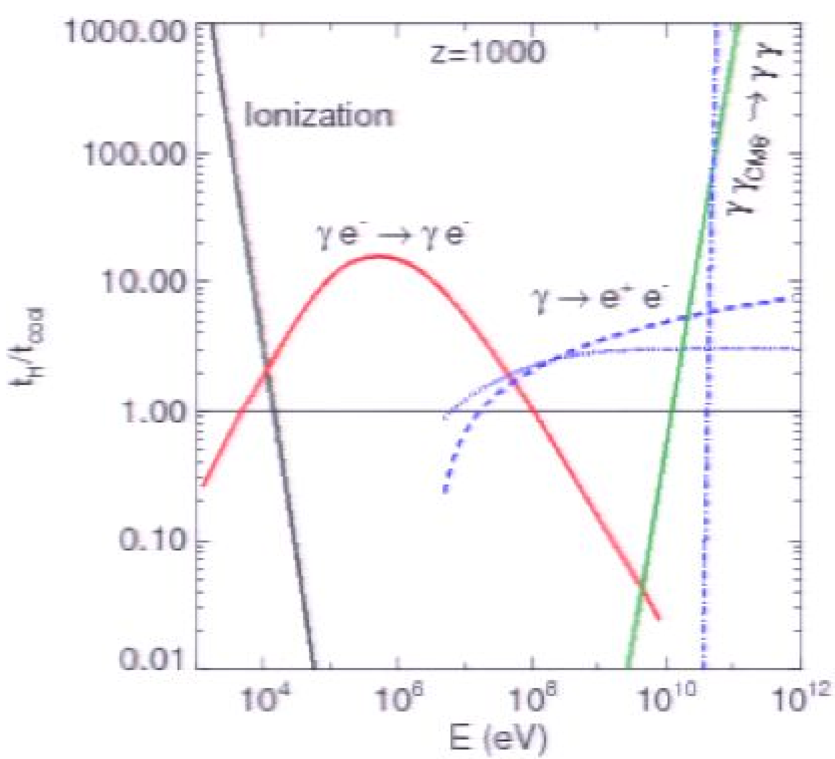

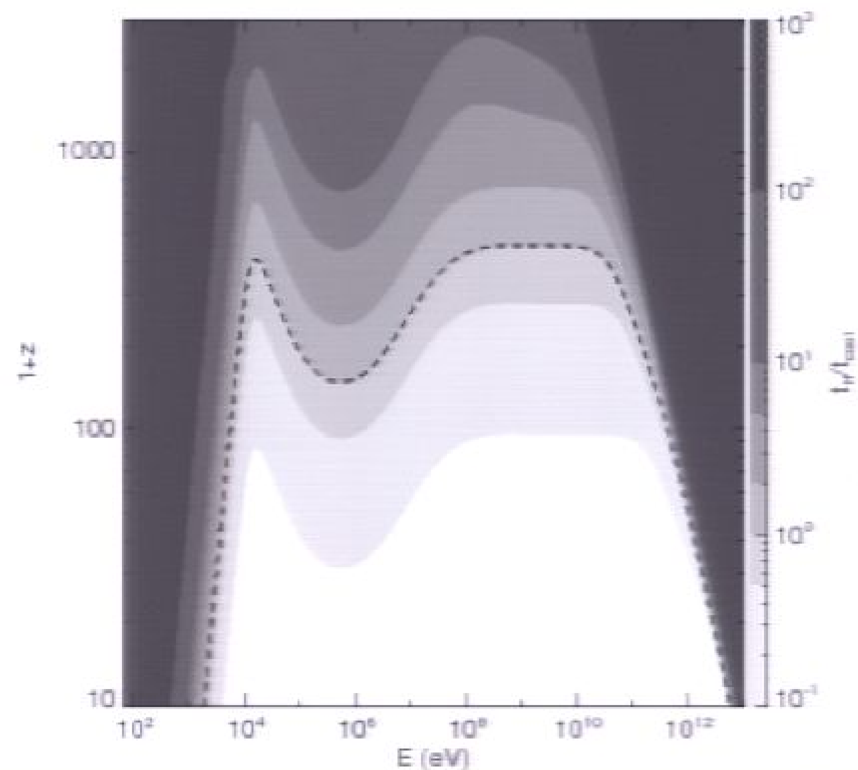

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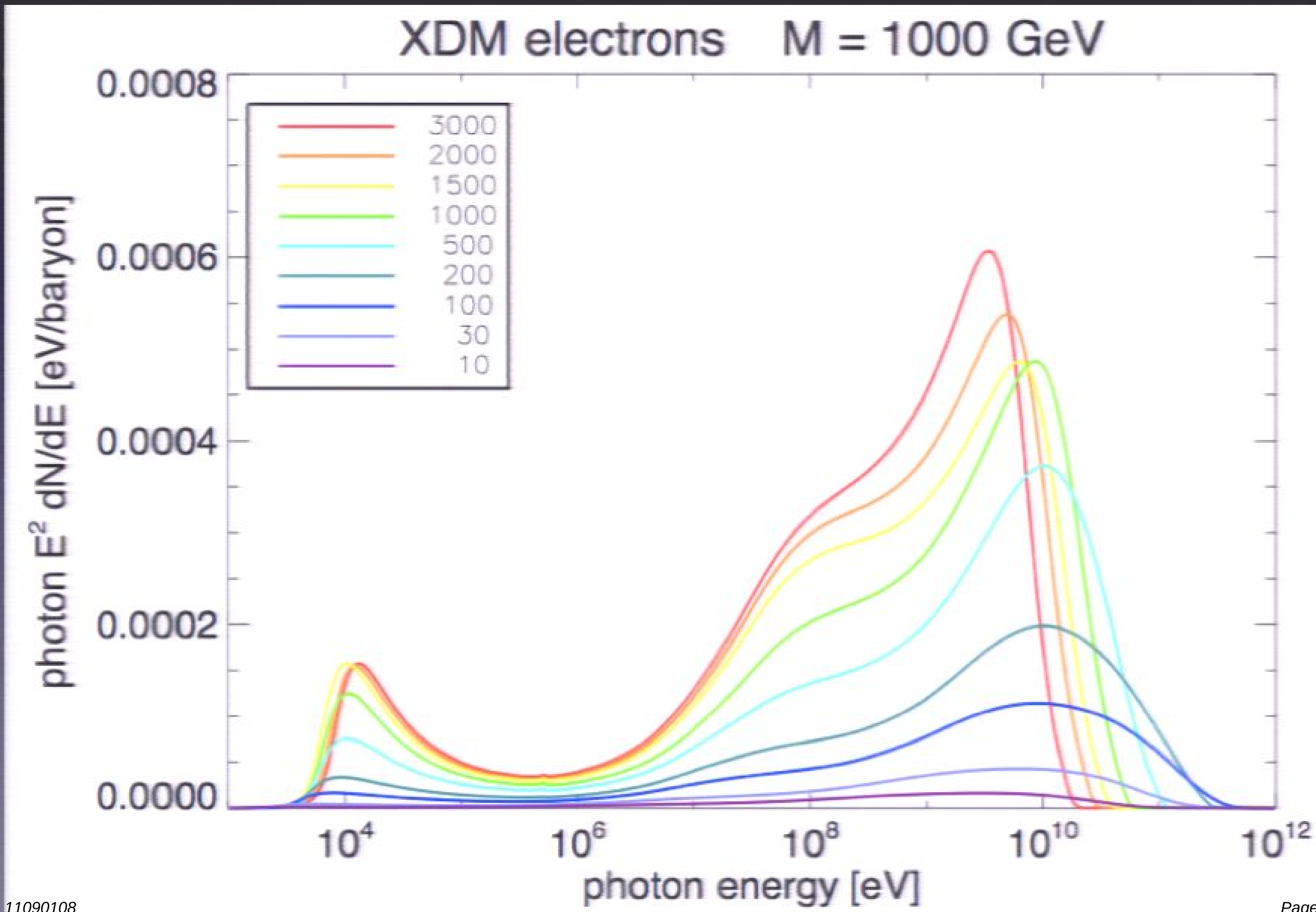

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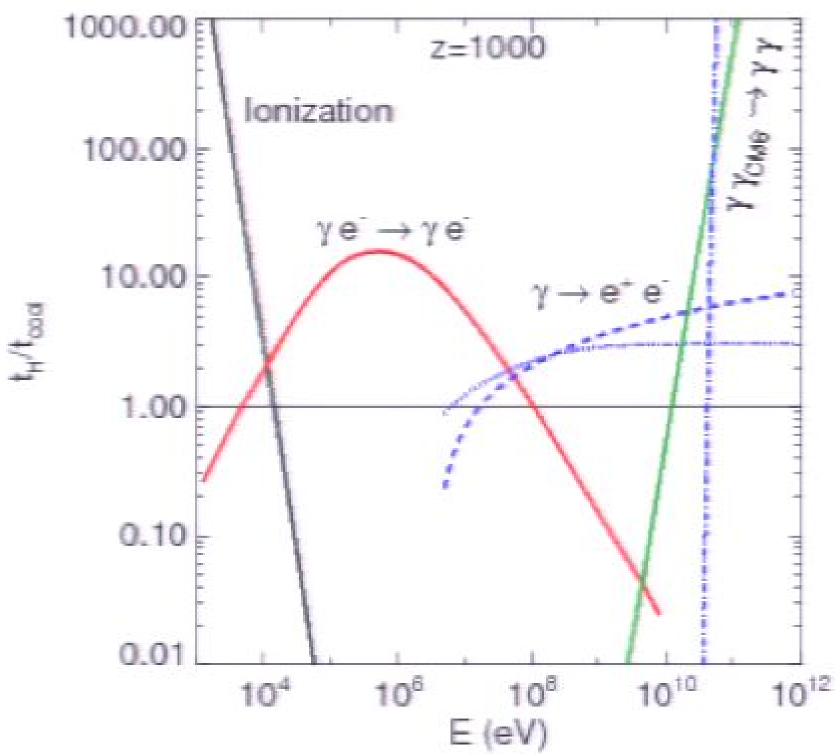

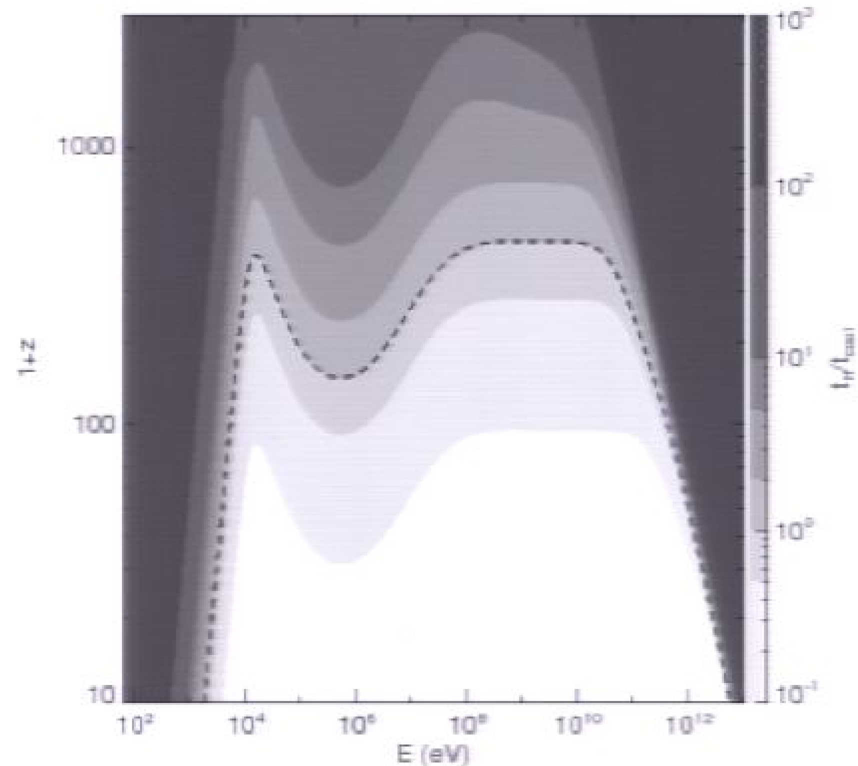

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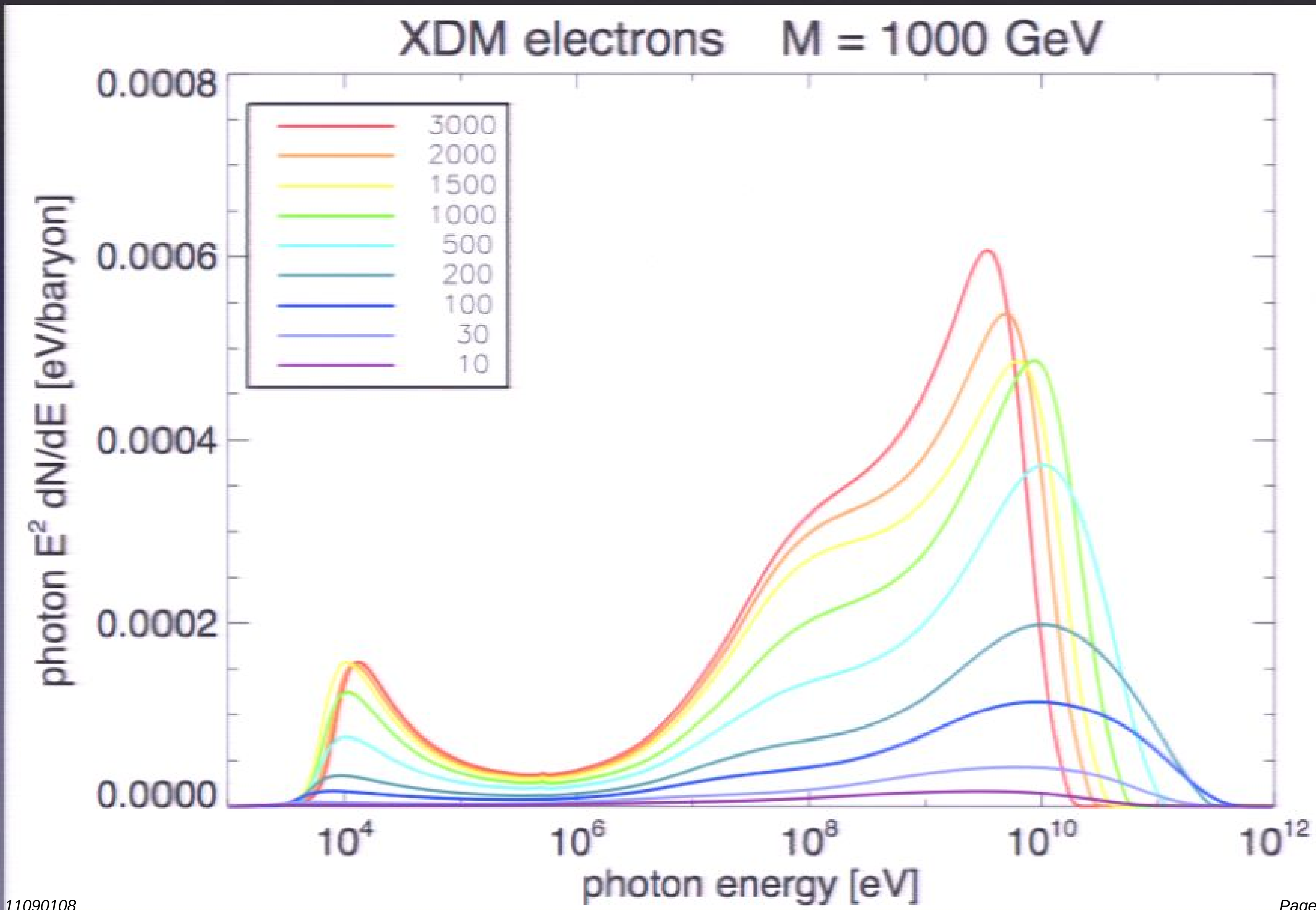
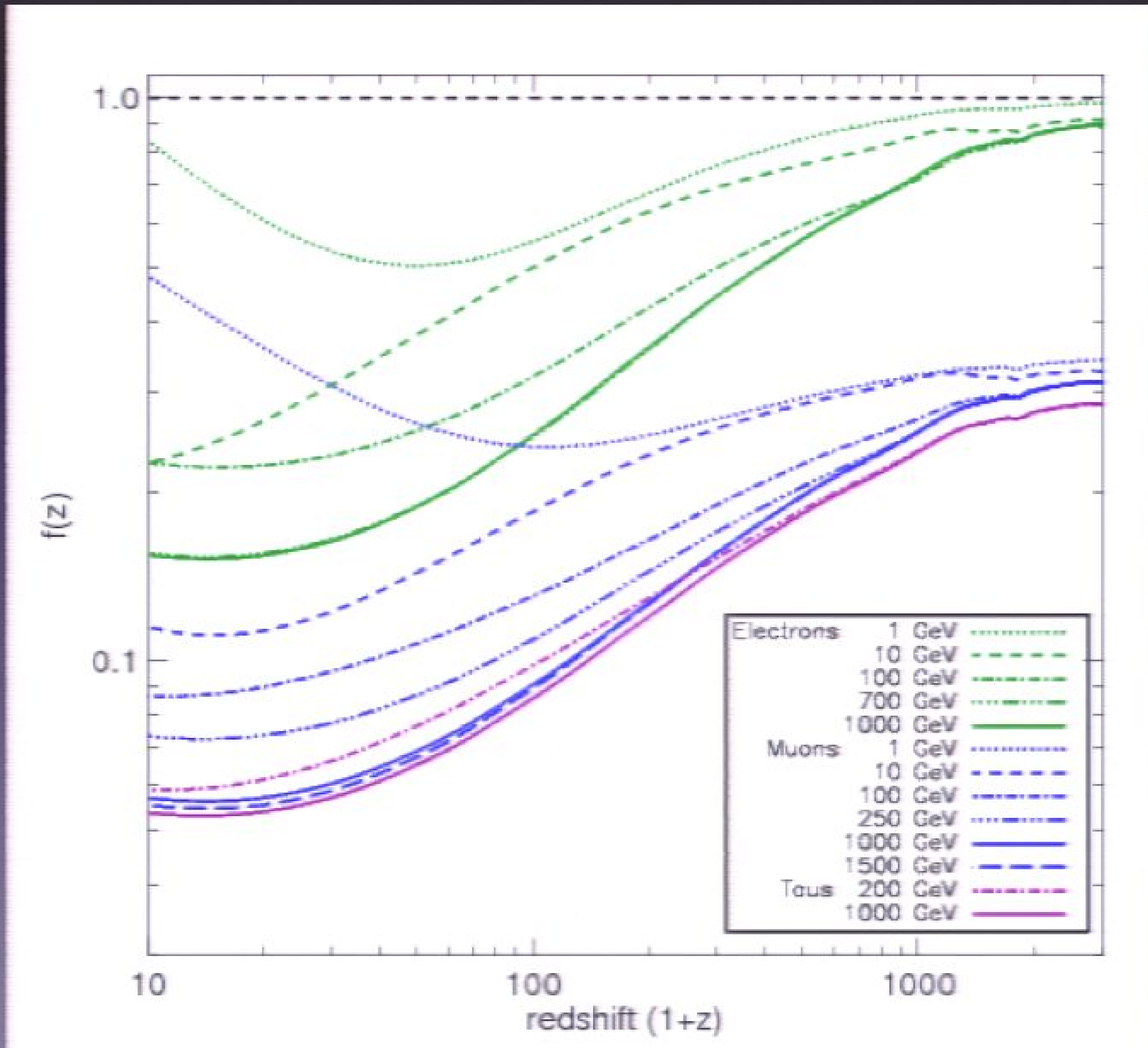


The Slatyer-Padmanabhan-Finkbeiner (SPF) factor, f :



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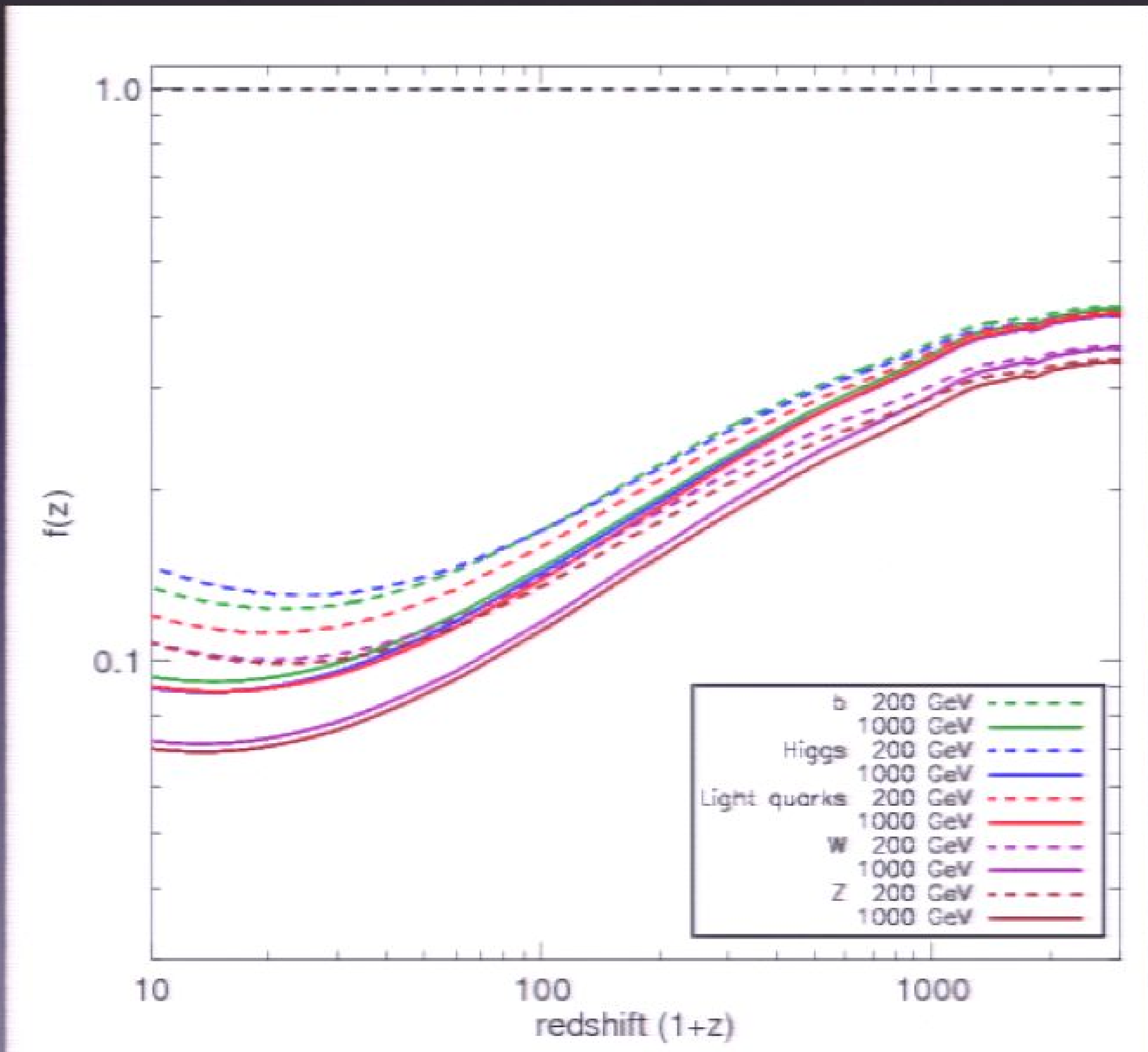

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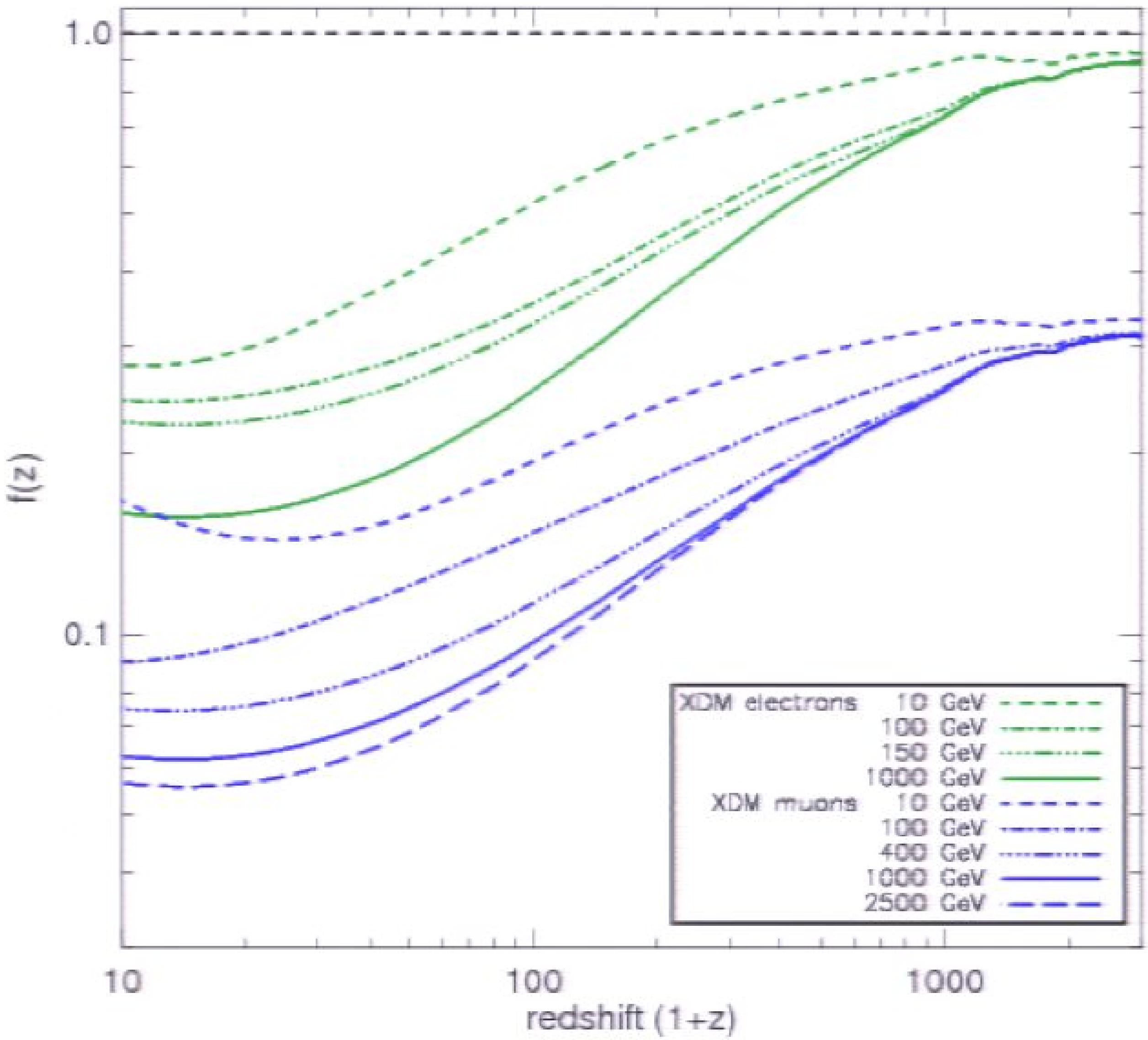

Here, "XDM" just means annihilates through a new light state, which then decays.

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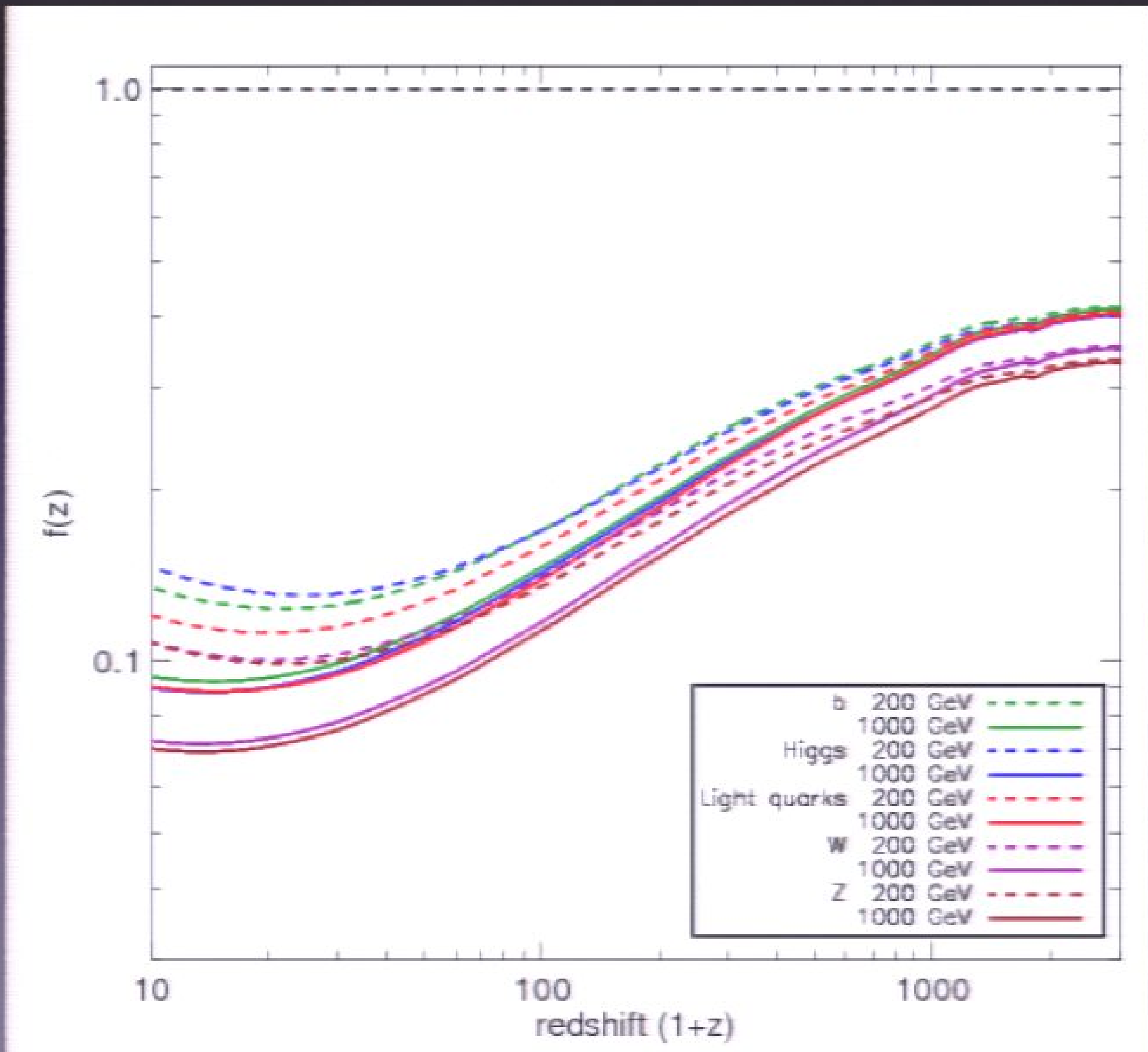

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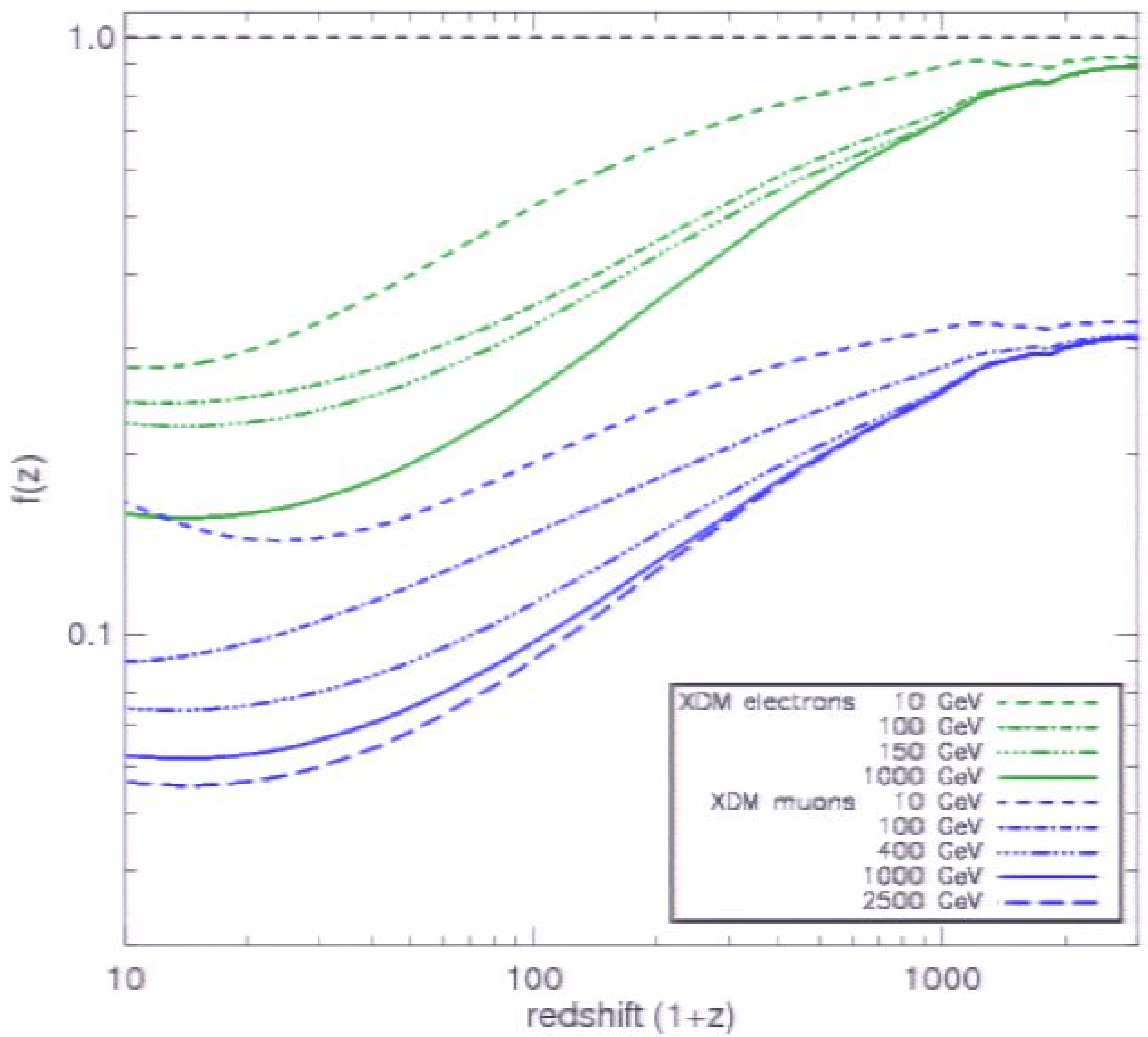

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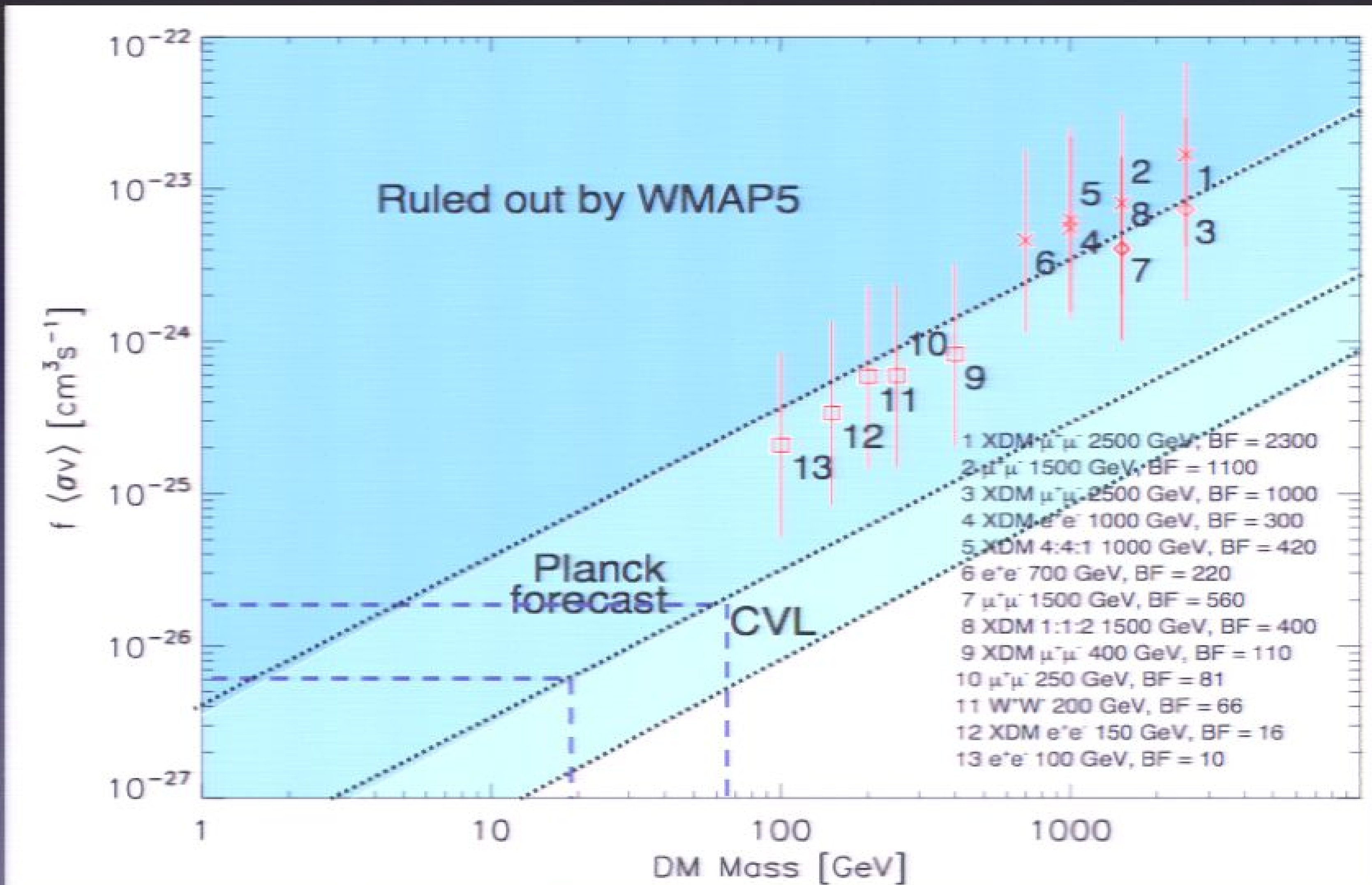
$$f(z) = F(1+z)^{\alpha}\left(\left(\frac{1+z}{z_0}\right)^{\gamma} + \left(\frac{1+z}{z_0}\right)^{-\gamma}\right)^{\beta} \exp\left(\frac{\delta}{1+((1+z)/1100)^{\eta}}\right). \quad \text{(A1)}$$

These fits are accurate to within 1% between $z = 300 - 1200$ for all channels. These fits remain accurate to $< 5\%$ between $z = 170$ and $z = 1470$, but outside this range they may perform very poorly.

Channel	DM mass (GeV)	f_{mean}	$f(z = 2500)$	a	b	c	F	α	β	γ	δ	η	z_0
Electrons	1	0.92	0.98	0.5069	51.8802	2.2828	0.1140	0.4099	−0.5634	0.6445	0.0043	−5.1992	150.3970
$\chi\chi \to e^+e^-$	10	0.84	0.91	0.0715	0.0078	6.7966	0.0864	0.4028	−0.2453	1.1481	0.0488	−4.1911	166.4426
	100	0.69	0.89	0.2207	14.6754	3.1748	0.0676	0.3746	−0.1973	0.9746	0.0682	−13.0681	322.3401
	700	0.70	0.89	0.1527	13.3066	2.8822	0.0841	0.3698	−0.5719	0.5410	0.0528	−12.3998	663.9780
	1000	0.70	0.89	0.1515	13.3421	2.8416	0.0701	0.3696	−0.3077	0.7263	0.0469	−12.9124	678.7171
Muons	1	0.32	0.34	0.2396	133.1554	3.0272	0.0602	0.3284	−0.4350	0.5484	−0.0094	−4.7619	97.2662
$\chi\chi \to \mu^+\mu^-$	10	0.31	0.33	0.1092	8.7012	3.4240	0.0550	0.3256	−0.3532	0.7324	−0.0429	4.5242	179.1546
	100	0.26	0.31	0.0844	6.8923	4.0683	0.0441	0.2986	−0.3359	0.6027	0.0303	−14.5100	465.1301
	250	0.25	0.31	0.0726	12.4318	3.2776	0.0557	0.2950	−0.7418	0.3300	0.0546	−10.3133	823.4443
	1000	0.24	0.31	0.0662	12.9596	2.9742	0.0514	0.2925	−0.6312	0.5611	0.0575	−10.5586	947.3654
	1500	0.24	0.31	0.0546	13.0970	2.9112	0.0553	0.2926	−0.7359	0.5133	0.0573	−10.5603	952.6785
Taus	200	0.23	0.28	0.0577	7.5935	3.5566	0.0341	0.2860	−0.0818	1.4385	0.0573	−8.8065	935.1002
$\chi\chi \to \tau^+\tau^-$	1000	0.23	0.29	0.0529	12.7237	2.9838	0.0565	0.2866	−0.8266	0.4640	0.0562	−10.5471	934.1133
XDM electrons	10	0.88	0.92	0.2419	2.7143	4.1521	0.0906	0.4080	−0.2529	1.1047	0.0081	−0.9440	149.6370
$\chi\chi \to \phi\phi$	100	0.73	0.89	0.2427	10.4821	3.6656	0.0792	0.3787	−0.3787	0.6703	0.0418	−13.7399	296.5718
followed by	150	0.70	0.89	0.2226	12.5182	3.3474	0.0686	0.3748	−0.2138	0.7970	0.0603	−11.9976	292.5551
$\phi \to e^+e^-$	1000	0.70	0.89	0.1565	13.1537	2.9202	0.0727	0.3697	−0.3598	0.6831	0.0486	−12.7614	675.8390
XDM muons	10	0.32	0.33	0.1464	25.7835	2.7962	0.0569	0.3250	−0.4137	0.6546	0.0370	−3.1624	173.1706
$\chi\chi \to \phi\phi$	100	0.27	0.31	0.0809	2.5357	4.7587	0.0457	0.3035	−0.3322	0.5392	0.0179	−13.3422	321.8945
followed by	400	0.25	0.31	0.0741	11.3064	3.3949	0.0402	0.2937	−0.2579	0.5965	0.0505	−10.3800	774.7615
$\phi \to \mu^+\mu^-$	1000	0.25	0.31	0.0617	12.5196	3.1133	0.0418	0.2925	−0.3294	0.7487	0.0541	−10.6936	939.3080
	2500	0.24	0.31	0.0556	13.0389	2.9543	0.0522	0.2926	−0.6537	0.5413	0.0566	−10.5987	952.4342
XDM taus	200	0.22	0.27	0.0604	6.6206	3.6373	0.0333	0.2861	−0.0610	1.0364	0.0548	−8.7336	638.6944
$\chi\chi \to \phi\phi, \phi \to \tau^+\tau^-$	1000	0.22	0.27	0.0534	11.2208	3.1569	0.0424	0.2841	−0.4351	0.6734	0.0542	−10.5137	911.3169
XDM pions	100	0.22	0.25	0.0607	1.4655	5.0403	0.0394	0.2881	−0.2700	0.5445	0.0137	−12.6965	304.5202
$\chi\chi \to \phi\phi$	200	0.21	0.25	0.0674	6.0060	4.1253	0.0363	0.2826	−0.1722	0.7910	0.0323	−13.6146	477.7644
followed by	1000	0.20	0.25	0.0515	12.5319	3.1745	0.0382	0.2762	−0.3601	0.6781	0.0517	−10.8809	1030.3075
$\phi \to \pi^+\pi^-$	1500	0.20	0.25	0.0481	12.6927	3.0715	0.0428	0.2760	−0.5297	0.5865	0.0547	−10.7564	1026.1082
	2500	0.20	0.25	0.0463	12.9871	2.9688	0.0460	0.2762	−0.6968	0.5217	0.0566	−10.6509	1025.4334
W bosons	200	0.29	0.35	0.1015	19.1565	2.9322	0.0396	0.3076	−0.0895	1.1093	0.0377	−13.2287	446.3091
$\chi\chi \to W^+W^-$	300	0.29	0.35	0.0906	15.7615	3.0067	0.0388	0.3053	−0.0855	1.0554	0.0389	−13.1812	528.0655
	1000	0.28	0.35	0.0711	10.6406	3.1935	0.0415	0.3025	−0.2181	0.8366	0.0516	−10.0586	782.1619
Z bosons	200	0.28	0.34	0.0998	20.7336	2.8932	0.0392	0.3043	−0.1088	1.0375	0.0359	−13.3227	447.9354
$\chi\chi \to ZZ$	1000	0.27	0.33	0.0689	10.6396	3.2027	0.0407	0.2988	−0.2263	0.7934	0.0514	−9.9893	773.0394
Higgs bosons	200	0.34	0.40	0.1313	24.2160	2.8491	0.0479	0.3206	−0.2349	0.7599	0.0297	−13.5576	388.8721
$\chi\chi \to hh$	1000	0.32	0.40	0.0877	10.9586	3.1982	0.0430	0.3133	−0.1570	0.8487	0.0490	−9.8120	616.1287
b quarks	200	0.35	0.41	0.1244	20.6286	2.8789	0.0467	0.3217	−0.1873	0.8494	0.0345	−13.3583	383.5586
$\chi\chi \to b\bar{b}$	1000	0.33	0.41	0.0917	11.6611	3.1846	0.0425	0.3149	−0.1246	0.9724	0.0467	−9.8366	635.3690
Light quarks	200	0.34	0.40	0.1129	18.5996	2.9221	0.0432	0.3174	−0.1218	0.9244	0.0361	−13.1747	430.2257
$\chi\chi \to u\bar{u}, d\bar{d}$ (50 % each)	1000	0.32	0.40	0.0882	12.3648	3.1280	0.0434	0.3135	−0.1700	0.9101	0.0490	−9.8915	674.5797

Benchmark models that fit PAMELA and/or Fermi

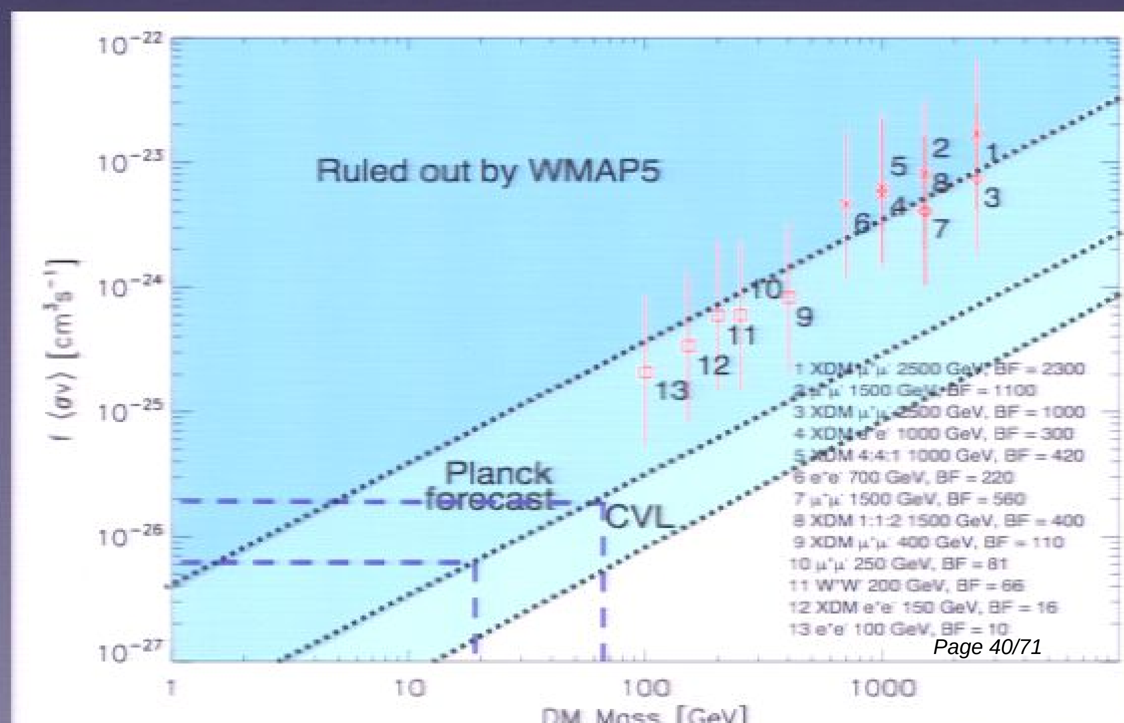


from SPE modeled on Galli+ (2009)

Note that the PAMELA - constrained models fall along the edge of the ruled-out region.

They all have ~ the same injection power. The CMB is approximately sensitive to injection power.

>> There must be a more general way to do this!



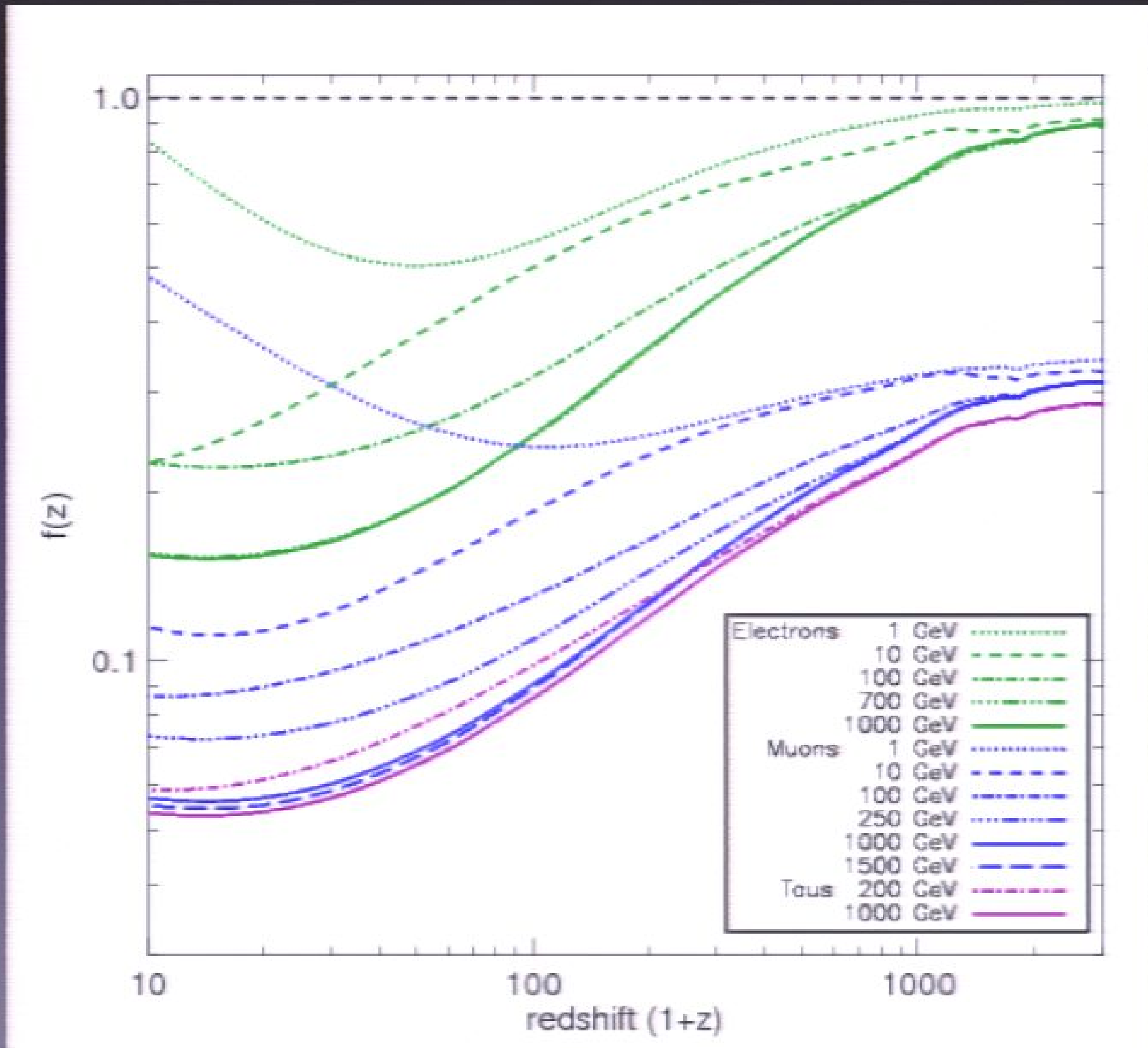
Recent work with Galli, Lin, & Slatyer (2011)

Idea: The energy injection is already constrained to be small, so we can linearize the problem and perturb about a fiducial model, i.e. the standard cosmology with no extra energy injection.

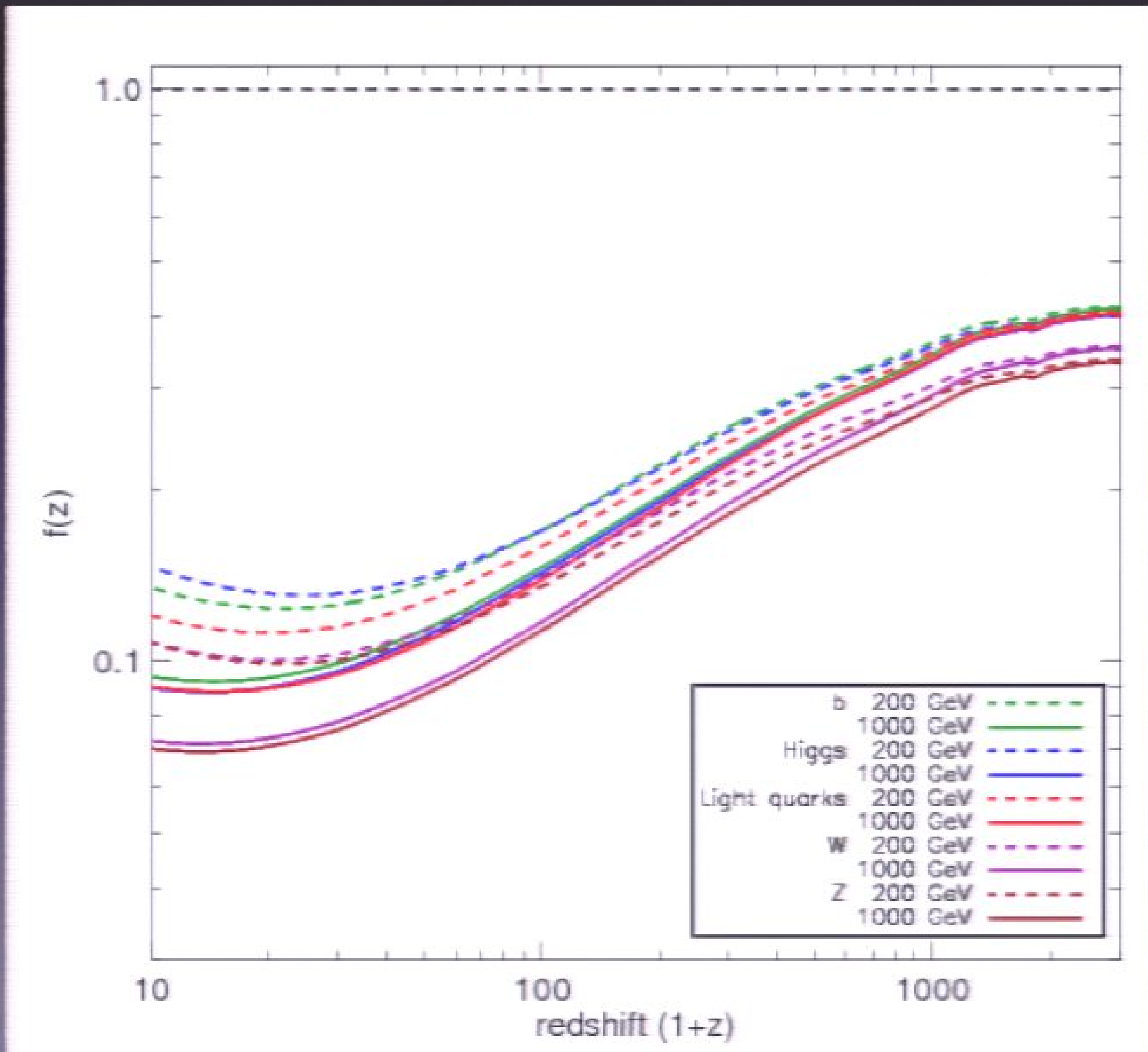
Various energy injection functions, *f(z)*, perturb the C_l spectrum in a small dimension subspace, allowing us to describe arbitrary (smooth, non-negative) energy injection with only a few numbers.

We can work out degeneracies, detectability, etc., by considering a few generic parameters.

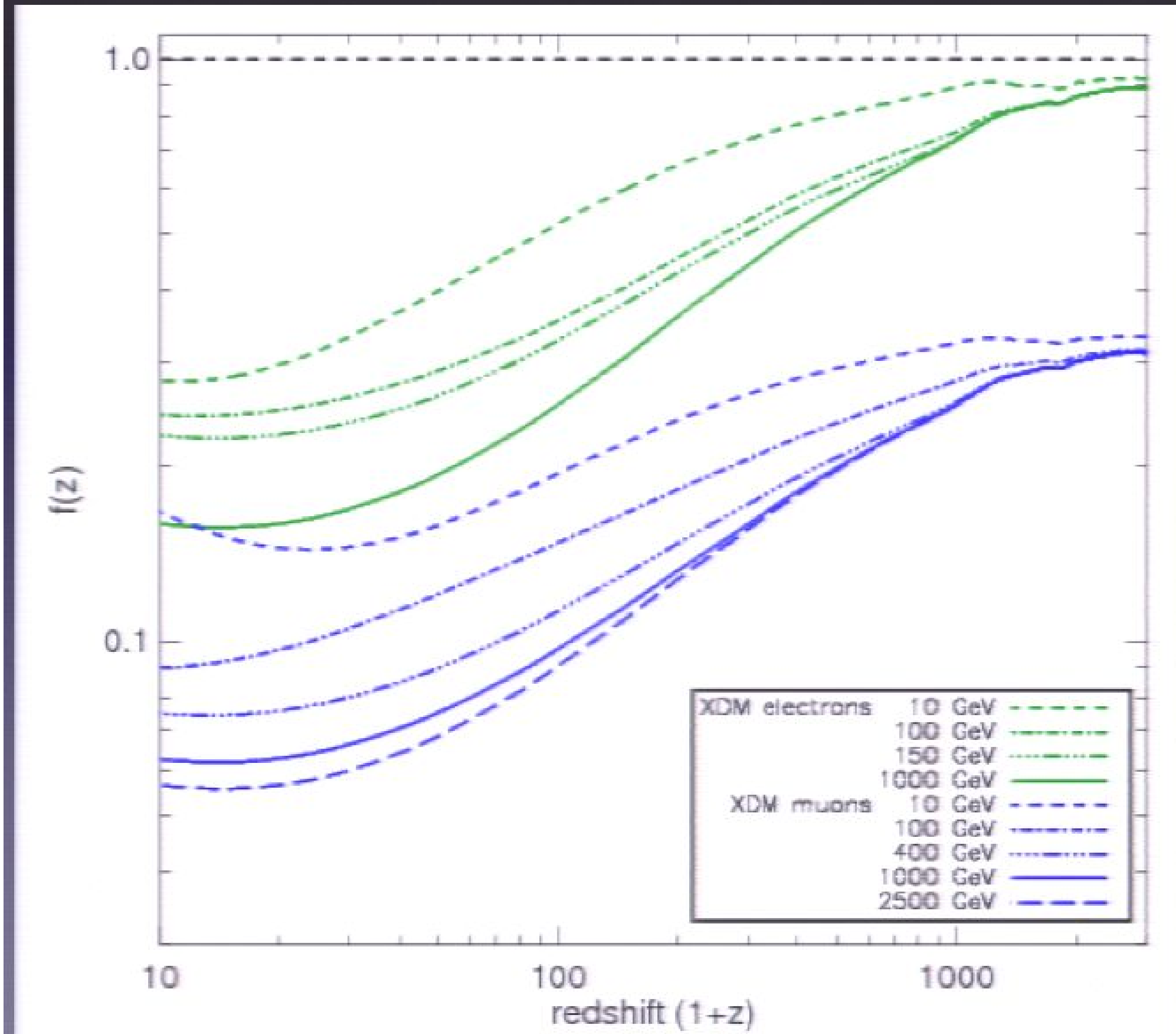
The Slatyer-Padmanabhan-Finkbeiner (SPF) factor, *f* :



The Slatyer-Padmanabhan-Finkbeiner (SPF) factor.



The Slatyer-Padmanabhan-Finkbeiner (SPF) factor.



Here, "XDM" just means annihilates through a new light state, which then decays.

Recent work with Galli, Lin, & Slatyer (2011)

Idea: The energy injection is already constrained to be small, so we can linearize the problem and perturb about a fiducial model, i.e. the standard cosmology with no extra energy injection.

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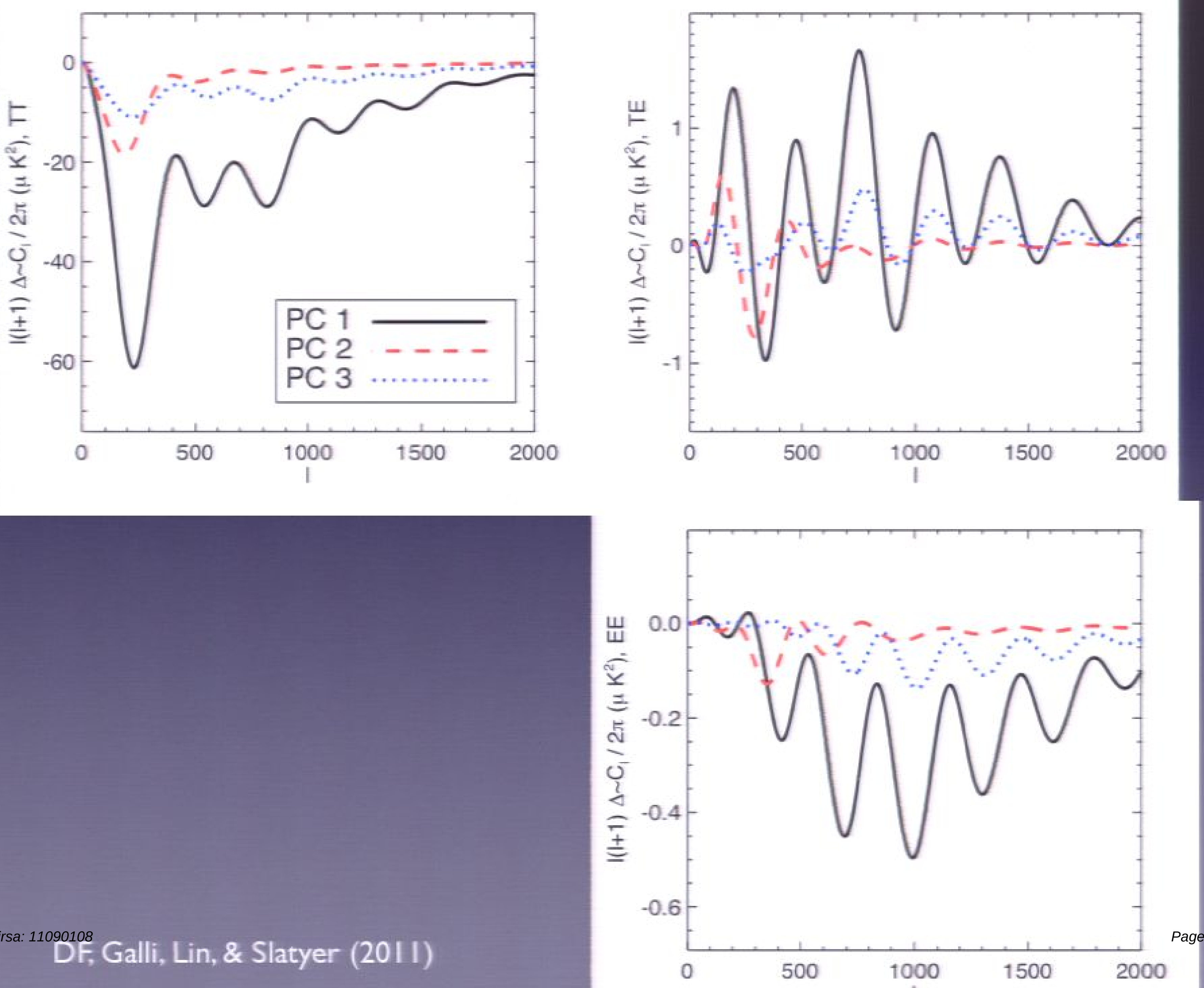
What basis to use in Delta C_l ("delta power spectrum") space?
Or equivalently, *f(z)* space?

We can consider the effect of a delta function energy injection at some redshift. This maps to a vector in ΔC_l space.

Now find Principle Components, map back to *f(z)* space.

This gives you the components that provide most of the variance in ΔC_l.



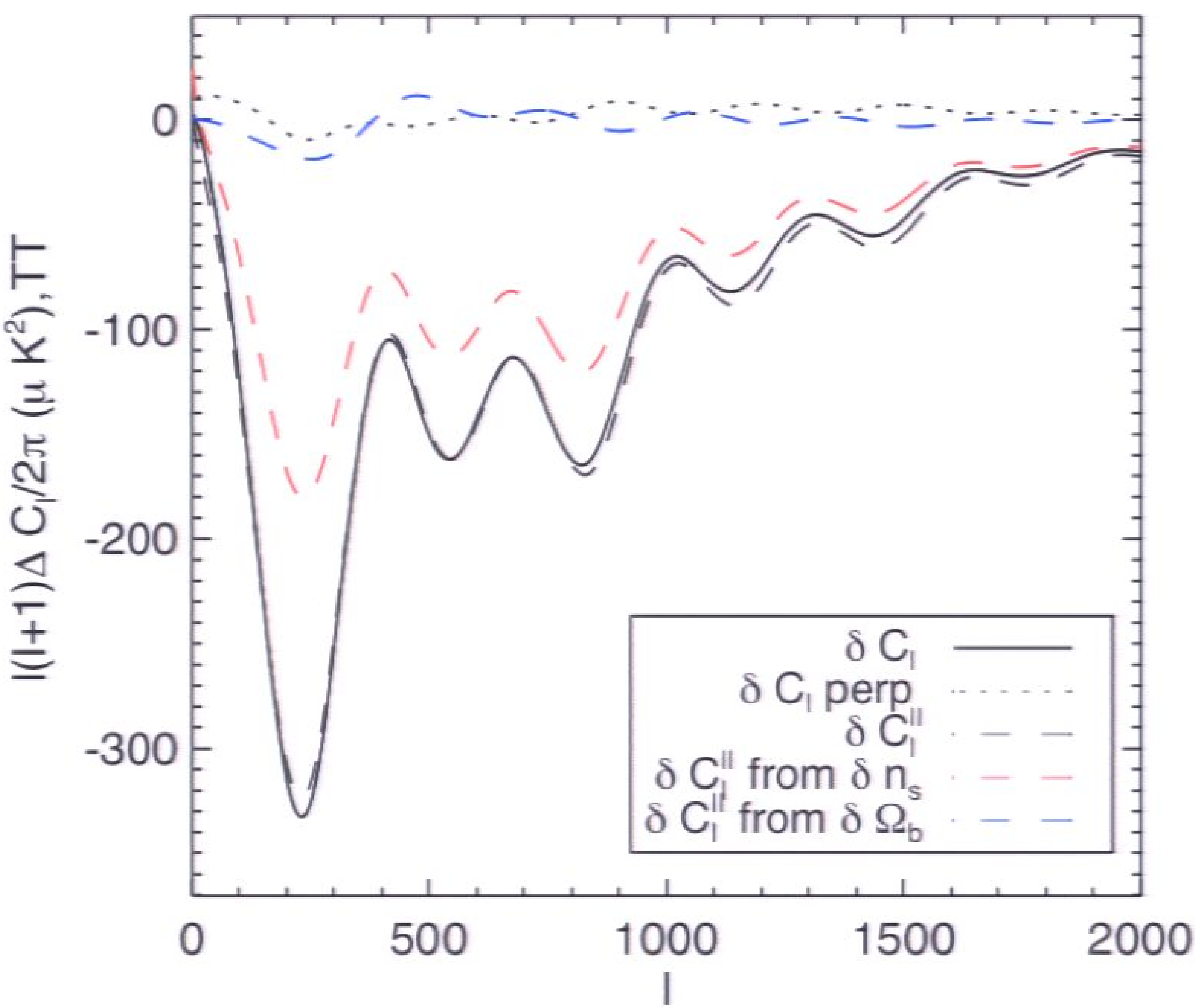
DF, Galli, Lin, & Slatyer (2011)

However -- we care about *detectability*, not variance.

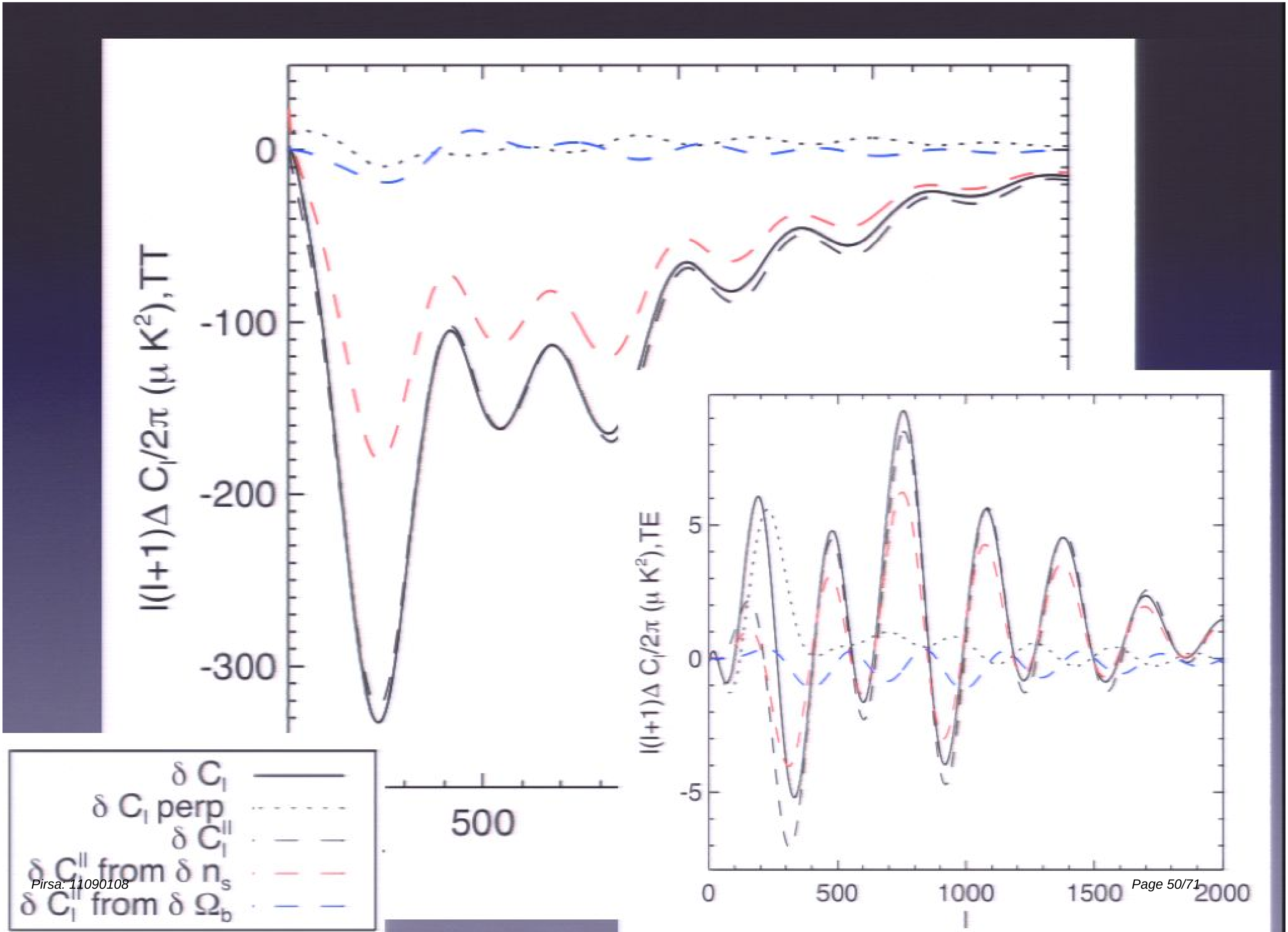
Given the expected uncertainties (both cosmic variance and measurement noise), how detectable are each of these components?

Also -- what about degeneracies with cosmological parameter variations? (especially n_s)

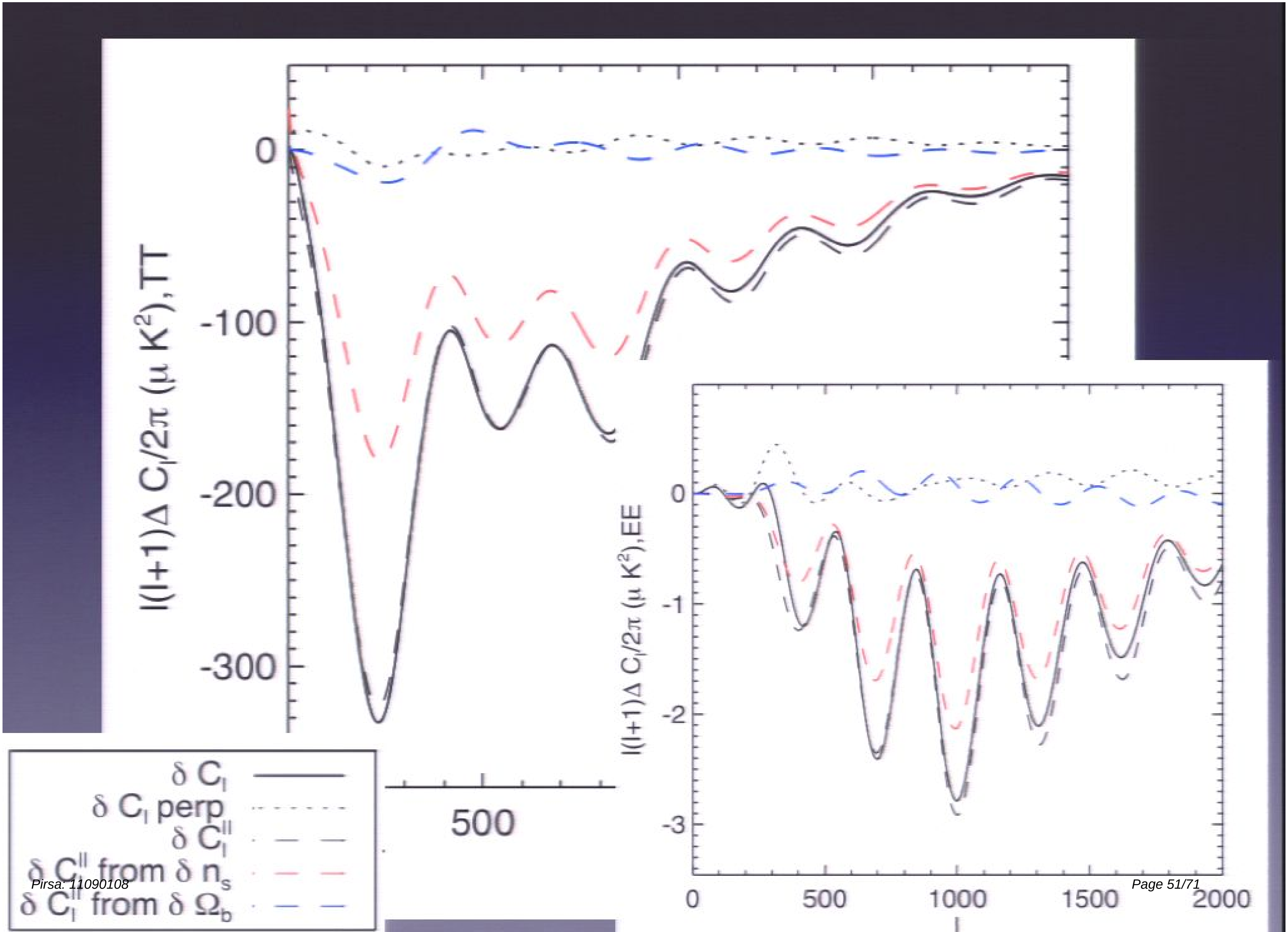
To illustrate this problem, we take a toy (constant *f*) model, and project out the directions in ΔC_l space corresponding to the cosmological parameters.



$l(l+1)\Delta C_l/2\pi\ (\mu K^2)$, TT
0
-100
-200
-300
0
500
1000
1500
2000
l
δC_l
δC_l perp
$\delta C_l^{||}$
$\delta C_l^{||}$ from δn_s
$\delta C_l^{||}$ from $\delta \Omega_b$



0
-100
-200
-300
500
l(l+1)Δ C_l/2π (μ K²),TT
δ C_l
δ C_l perp
δ C_l^∥
δ C_l^∥ from δ n_s
δ C_l^∥ from δ Ω_b
5
0
-5
0
500
1000
1500
2000
l
l(l+1)Δ C_l/2π (μ K²),TE

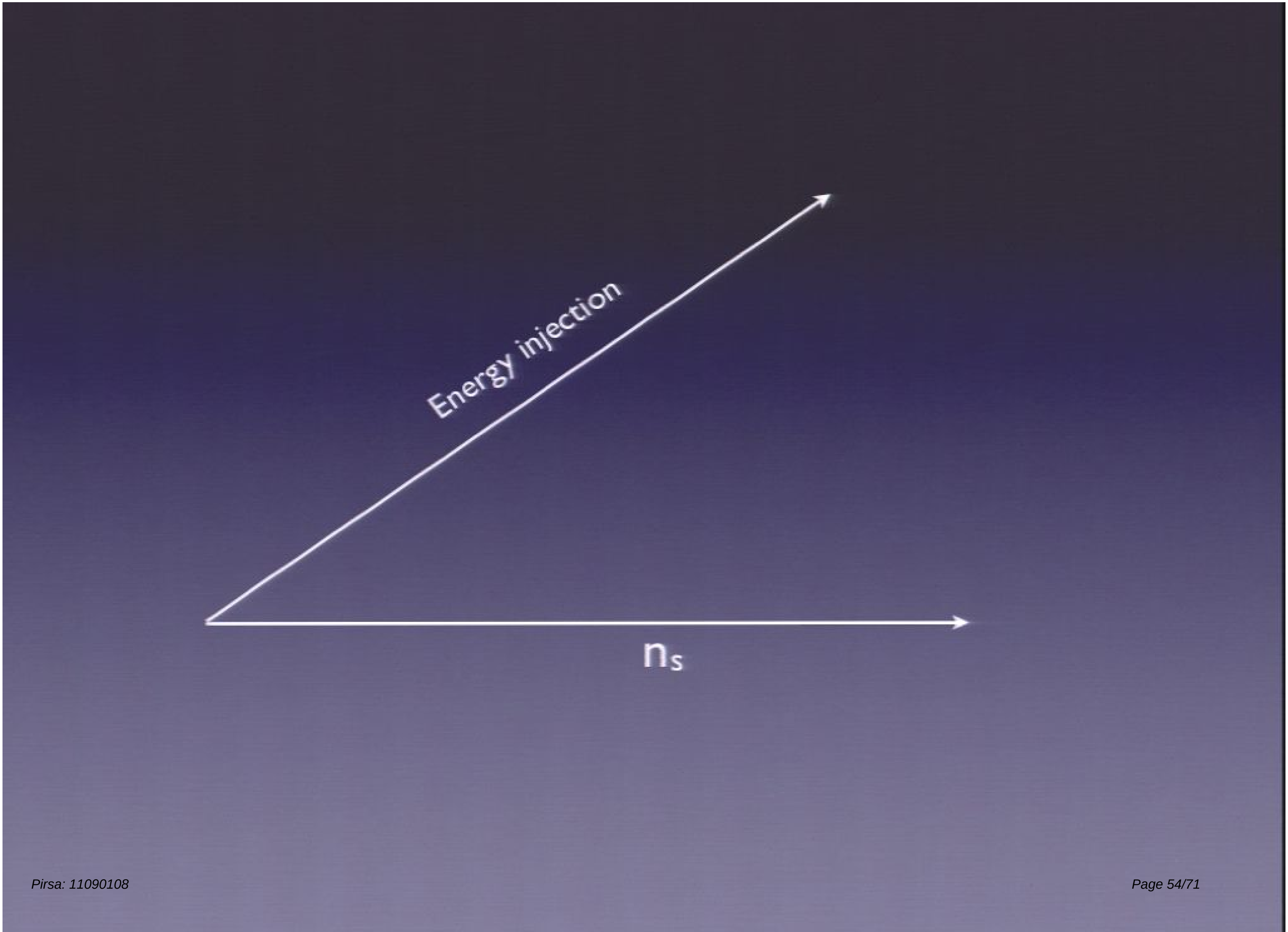


0
-100
-200
-300
500
l(l+1)Δ C_l/2π (μ K²),TT
δ C_l
δ C_l perp
δ C_l^∥
δ C_l^∥ from δ n_s
δ C_l^∥ from δ Ω_b
0
-1
-2
-3
0
500
1000
1500
2000
l
l(l+1)Δ C_l/2π (μ K²),EE

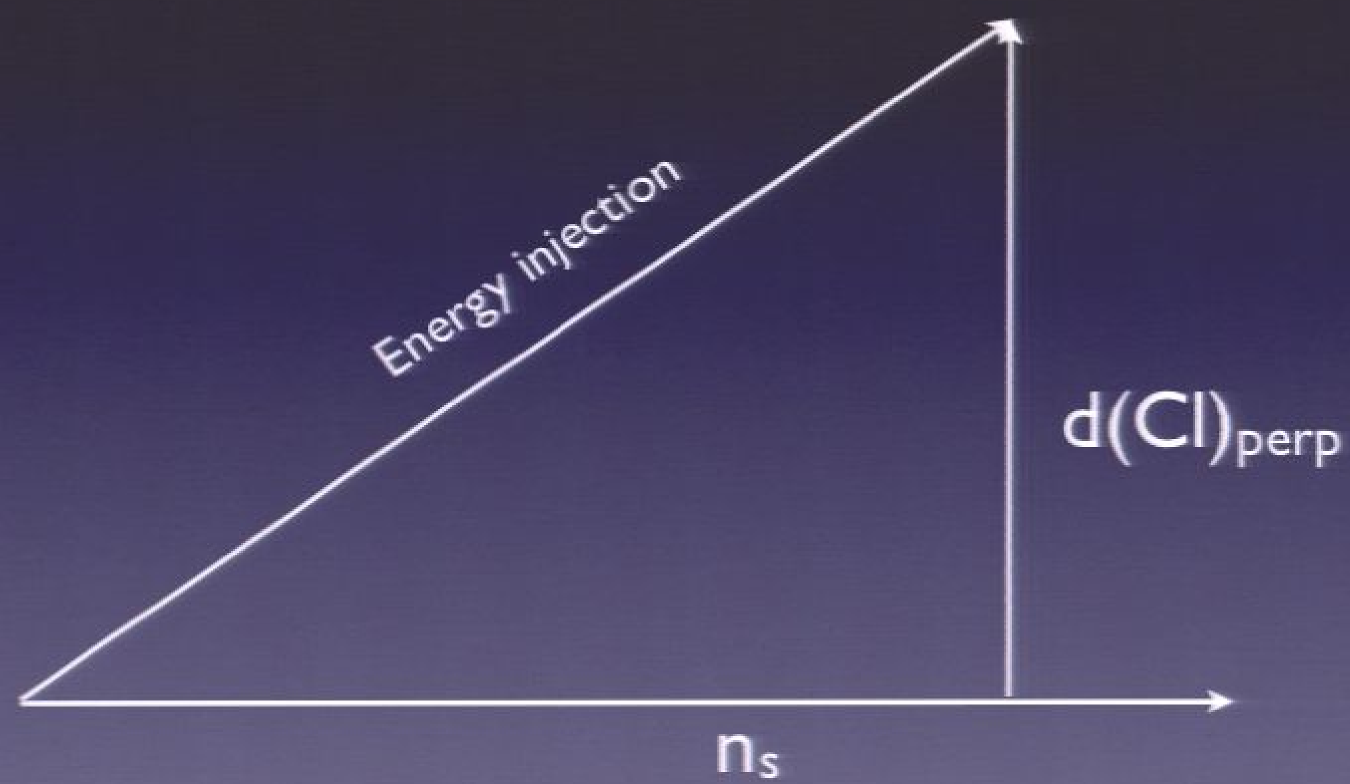
It is not correct to simply project in ΔC_l space.

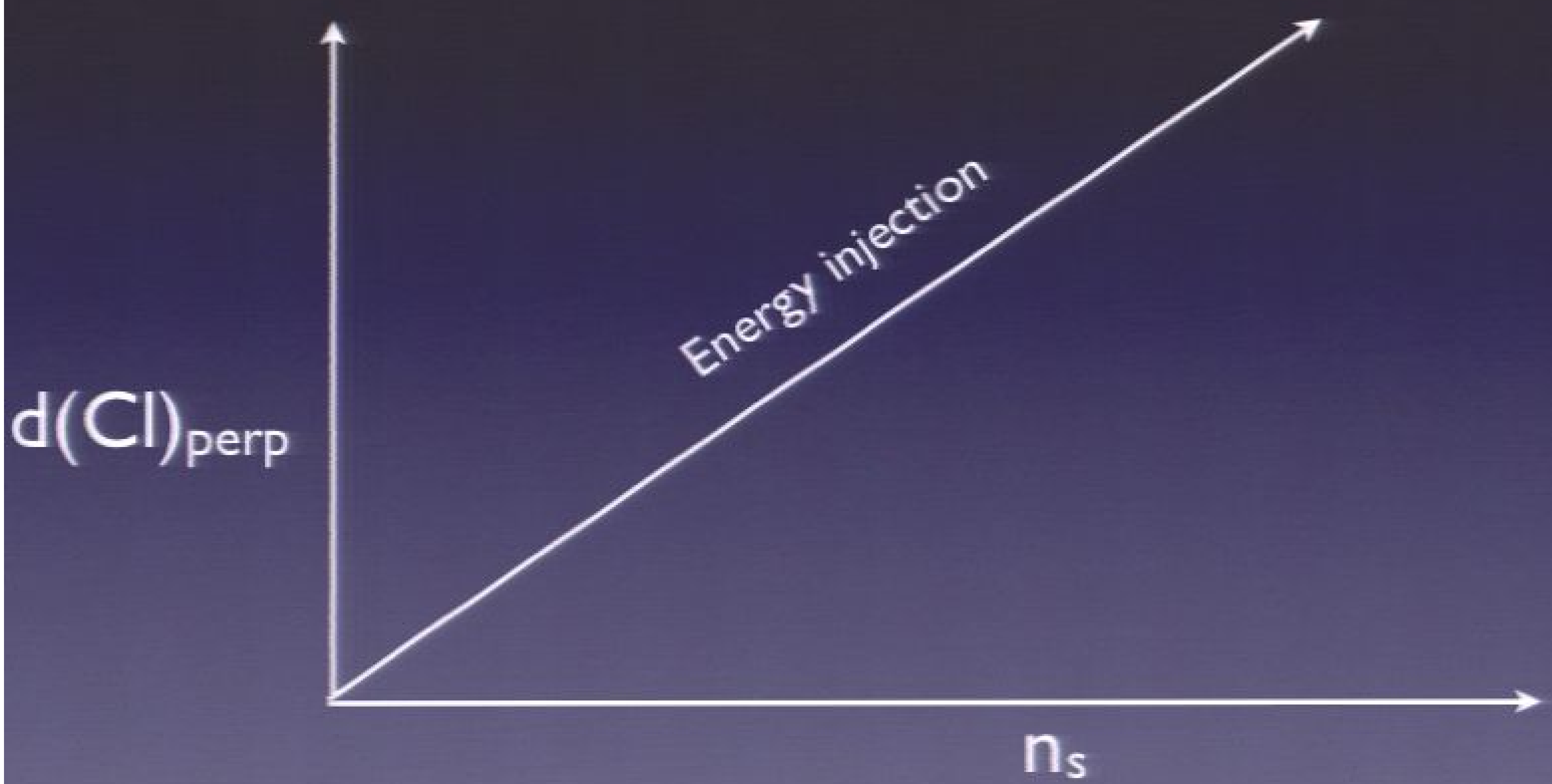
We must *marginalize* over the cosmological parameters ("nuisance parameters!") taking account of the uncertainty at each l. Doing this, we find a basis for perturbations in ΔC_l corresponding to injection histories *f(z)*.

Think of perturbations as vectors in power-spectrum space.

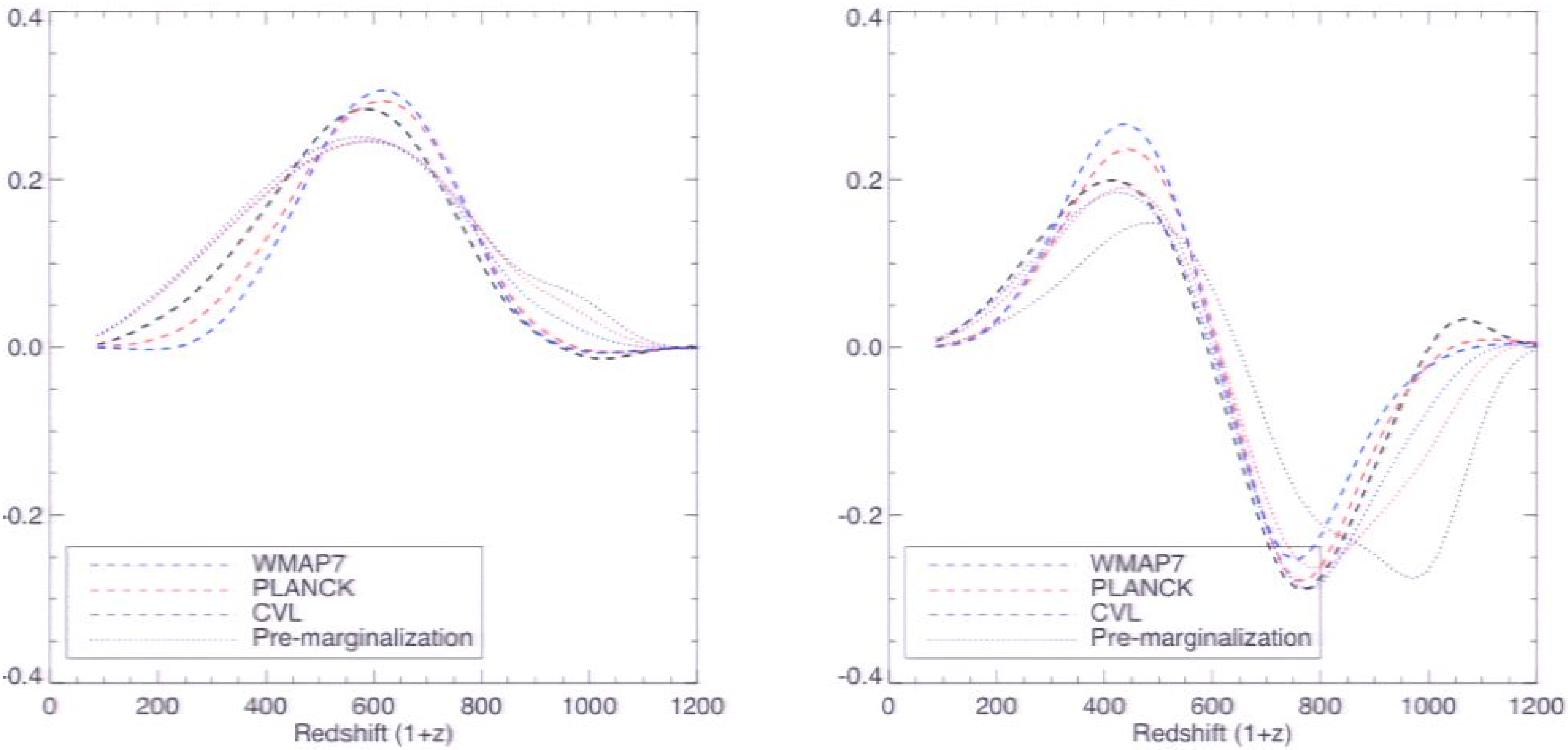


Energy injection
n_s

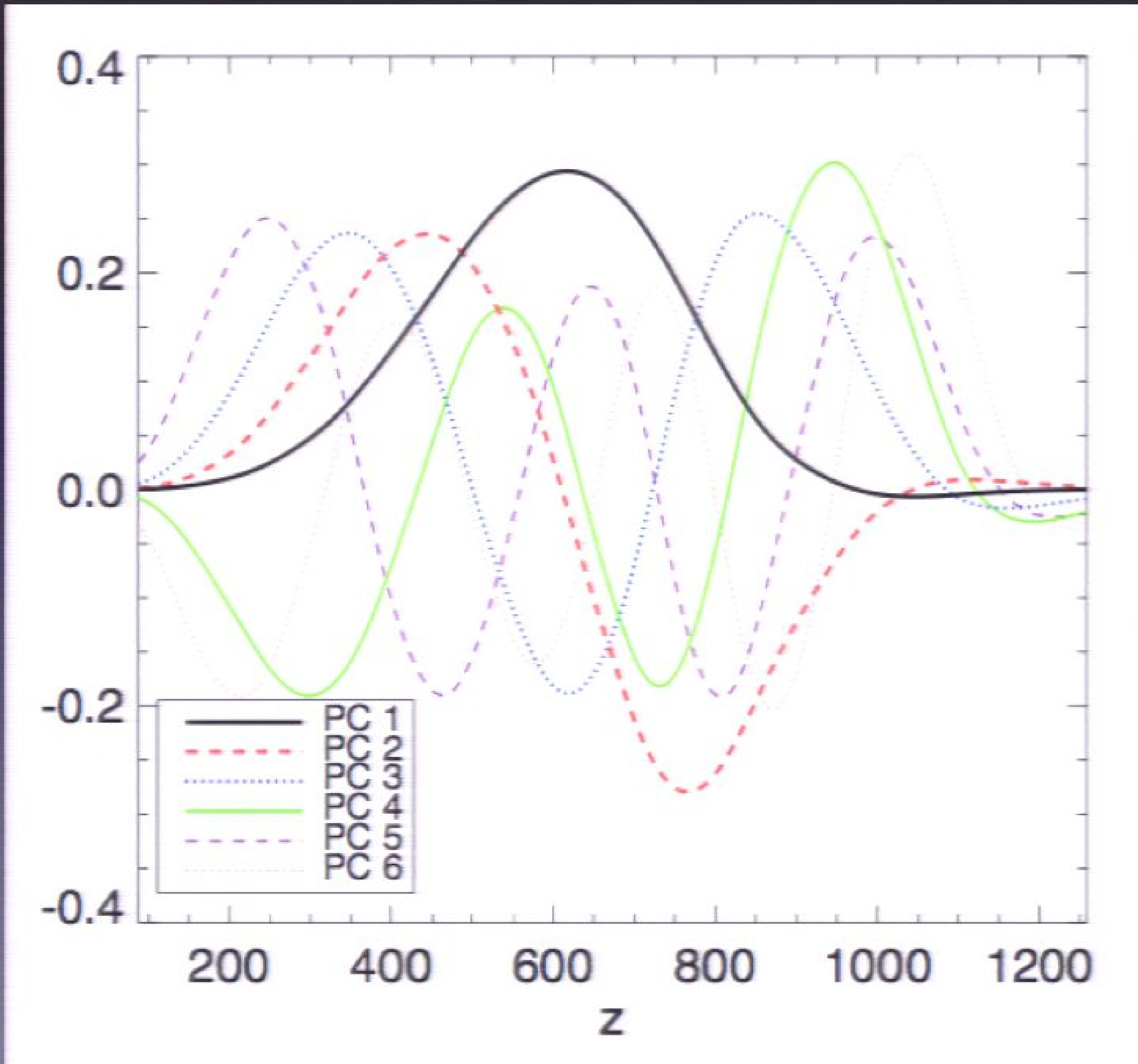

Energy injection
d(Cl)perp
ns



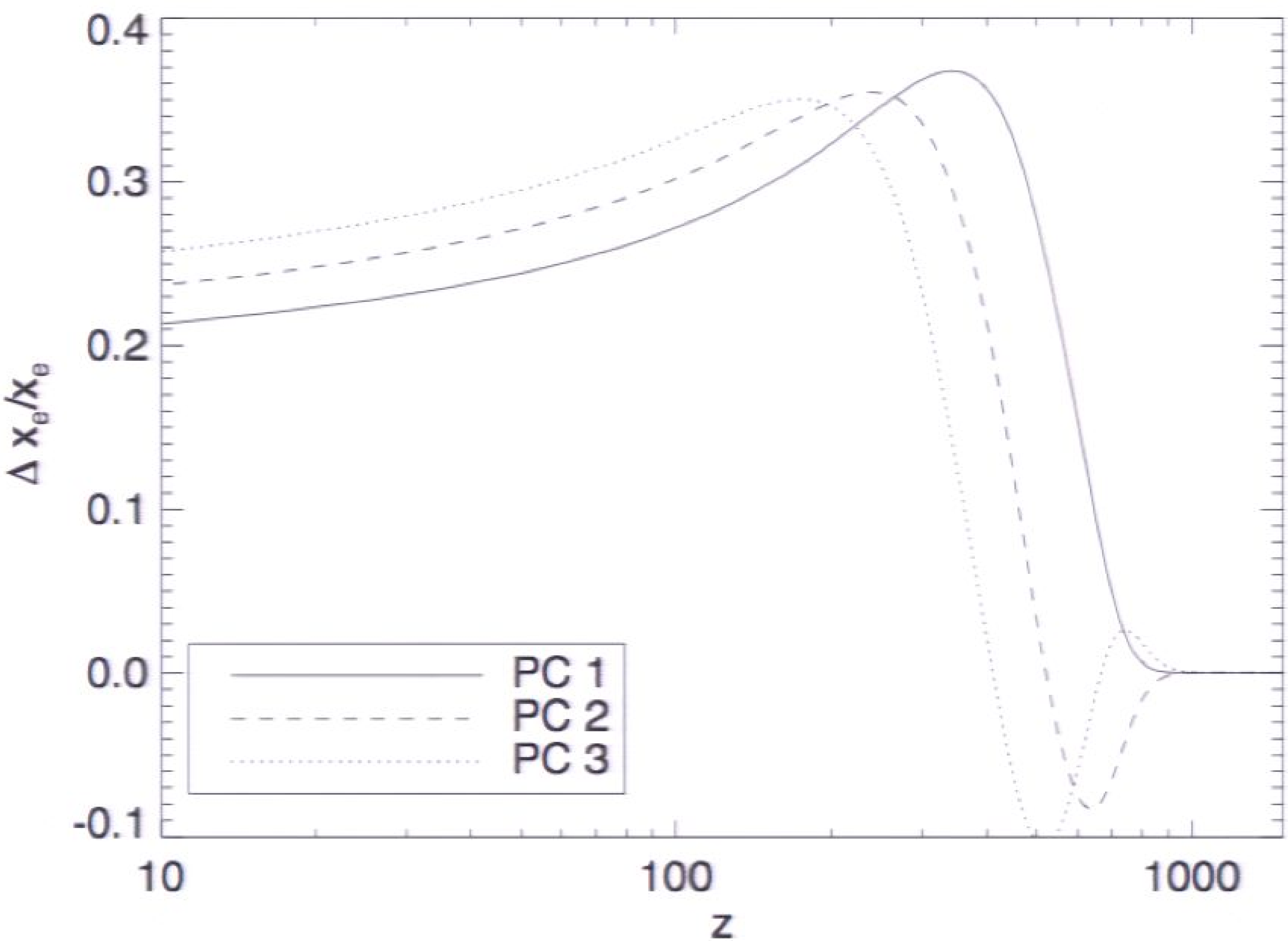
Energy injection
d(Cl)perp
ns



DF, Galli, Lin, & Slatyer (2011)


0.4
0.2
0.0
-0.2
-0.4
PC 1
PC 2
PC 3
PC 4
PC 5
PC 6
200
400
600
800
1000
1200
z

…F Galli, Lin, & Slatyer (2011)



DF Galli, Lin, & Slatyer (2011)

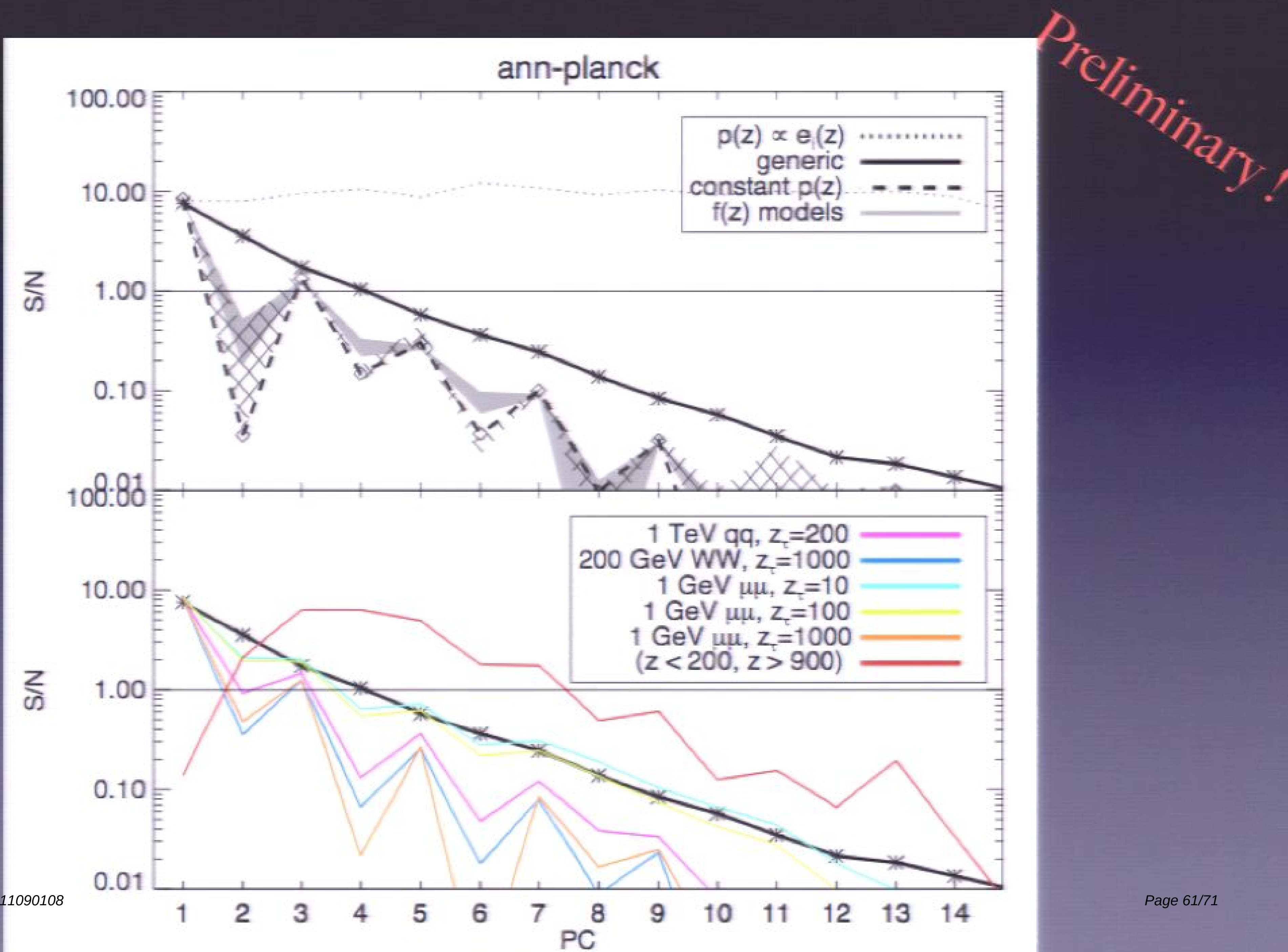
Detectability:

The most optimistic assumption is that WMAP5 barely missed detecting this signal at 2 sigma.

So assume $f(z)$ = constant at the maximum annihilation power allowed by WMAP5.

Prospects for *Planck*: (annihilation)

DF, Galli, Lin, & Slatyer (2011)



Bottom line:

- Planck may detect *one* PC at high confidence, worth trying first 3. Let's call these ε_1, ε_2, ε_3...

- CV - limited mission could go for ~ 5.

- These parameters are *simple* to measure. Just take dot product (including covariance matrix) of measured ΔC_l with ΔC_l principle components; this measures ε_1, ε_2, ε_3.

- Predict ε_1, ε_2, ε_3 for your favorite DM model. Compare.

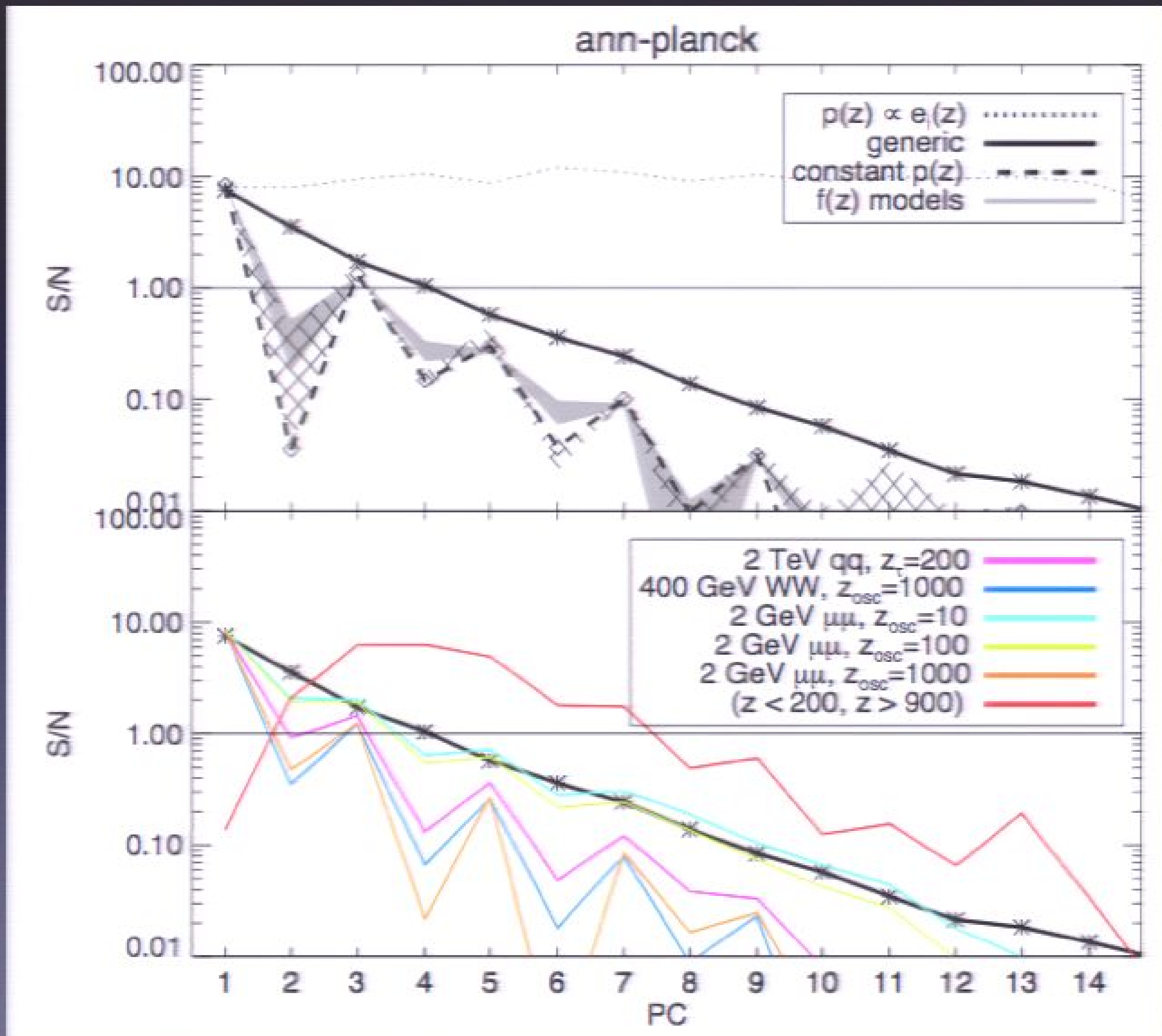
This works for decay also

Assume appropriate redshift dependence

Marginalize, etc... to get PCs for decay.

Prospects for *Planck*: (decay)

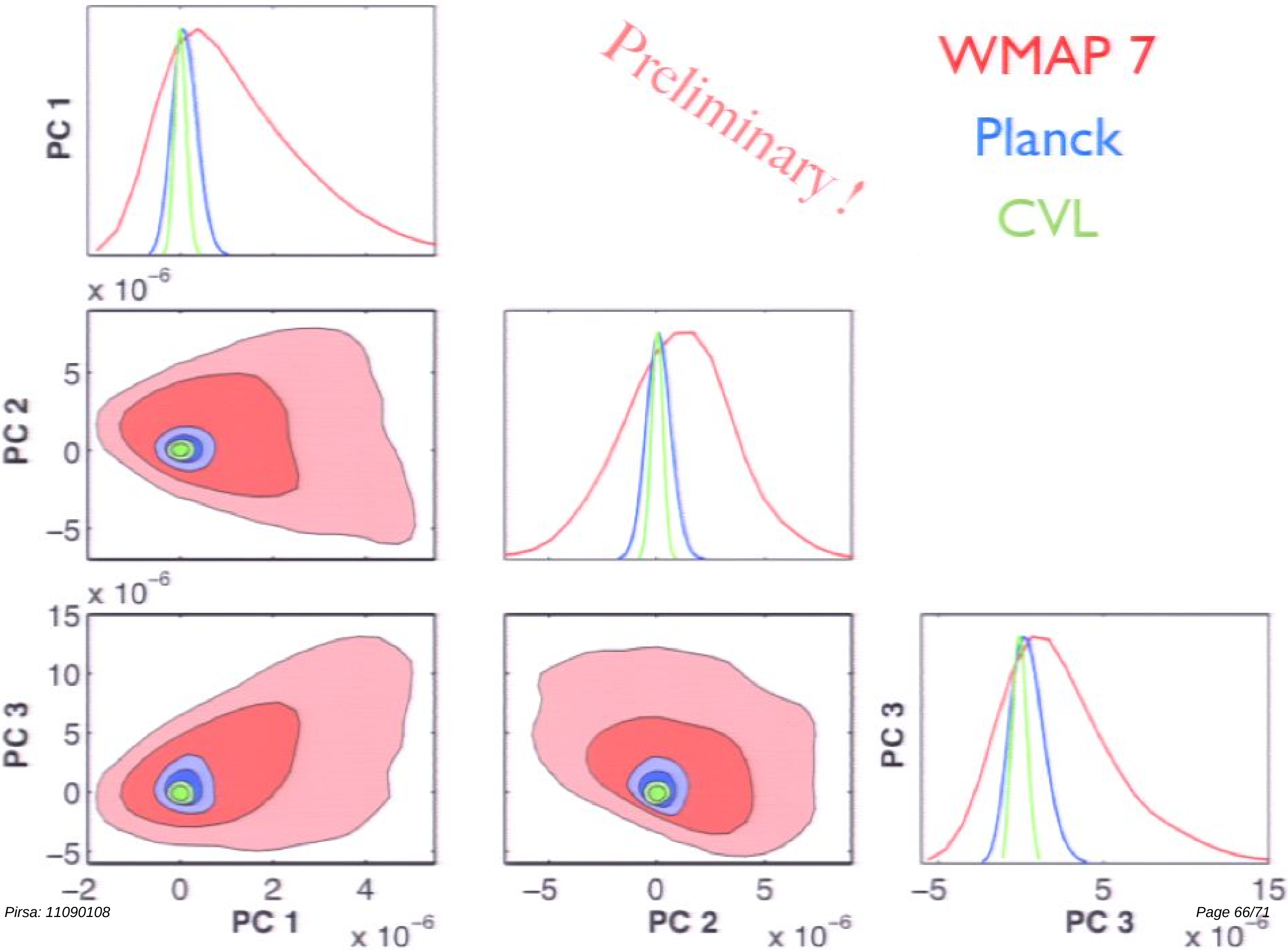
DF, Galli, Lin, & Slatyer (2011)



Preliminary !

Markov chain Monte Carlo (MCMC)

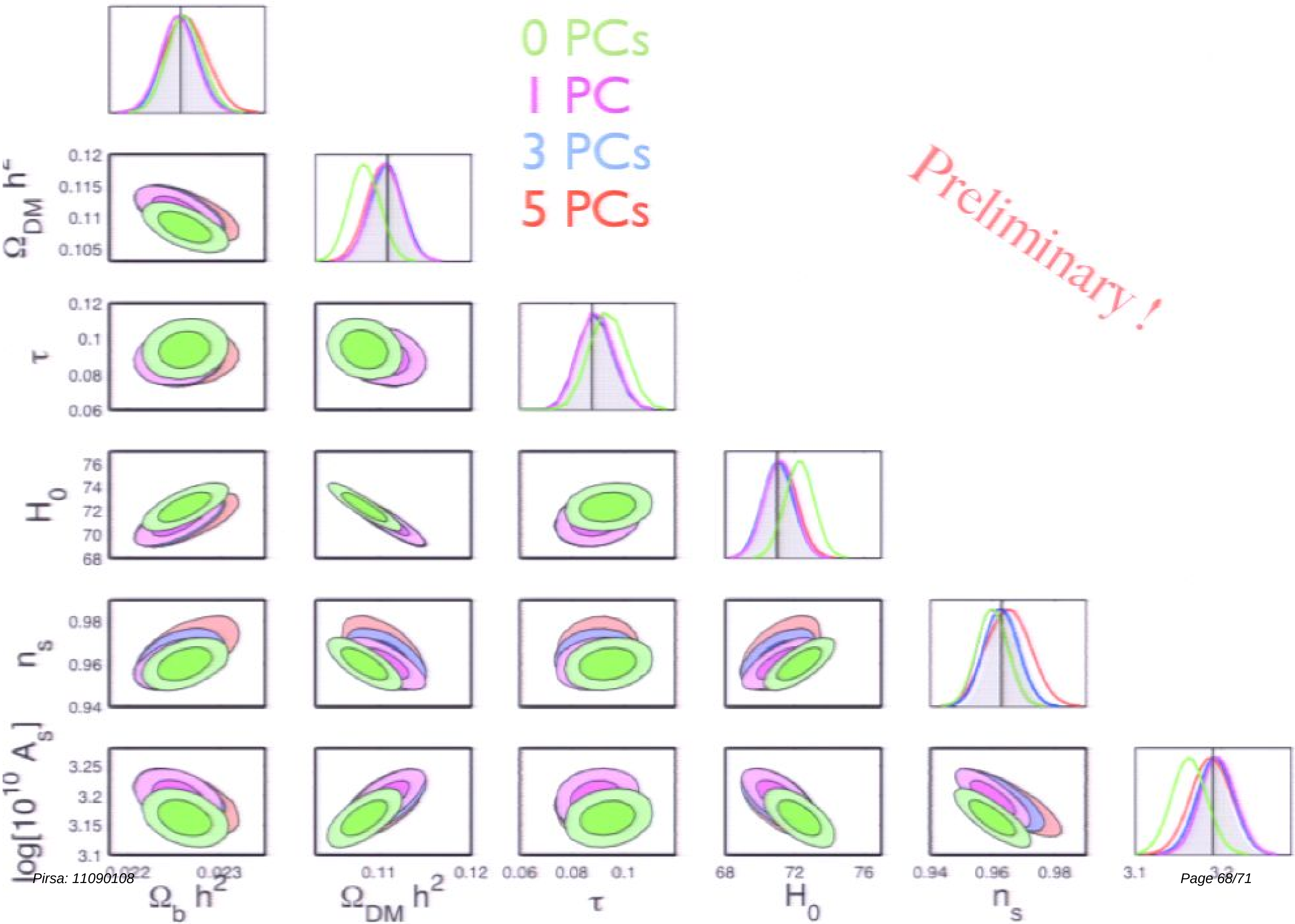
The Fisher matrix analysis assumes linearity and Gaussian likelihood. These are good approximations, but a we can compute the likelihood numerically with a Markov chain.

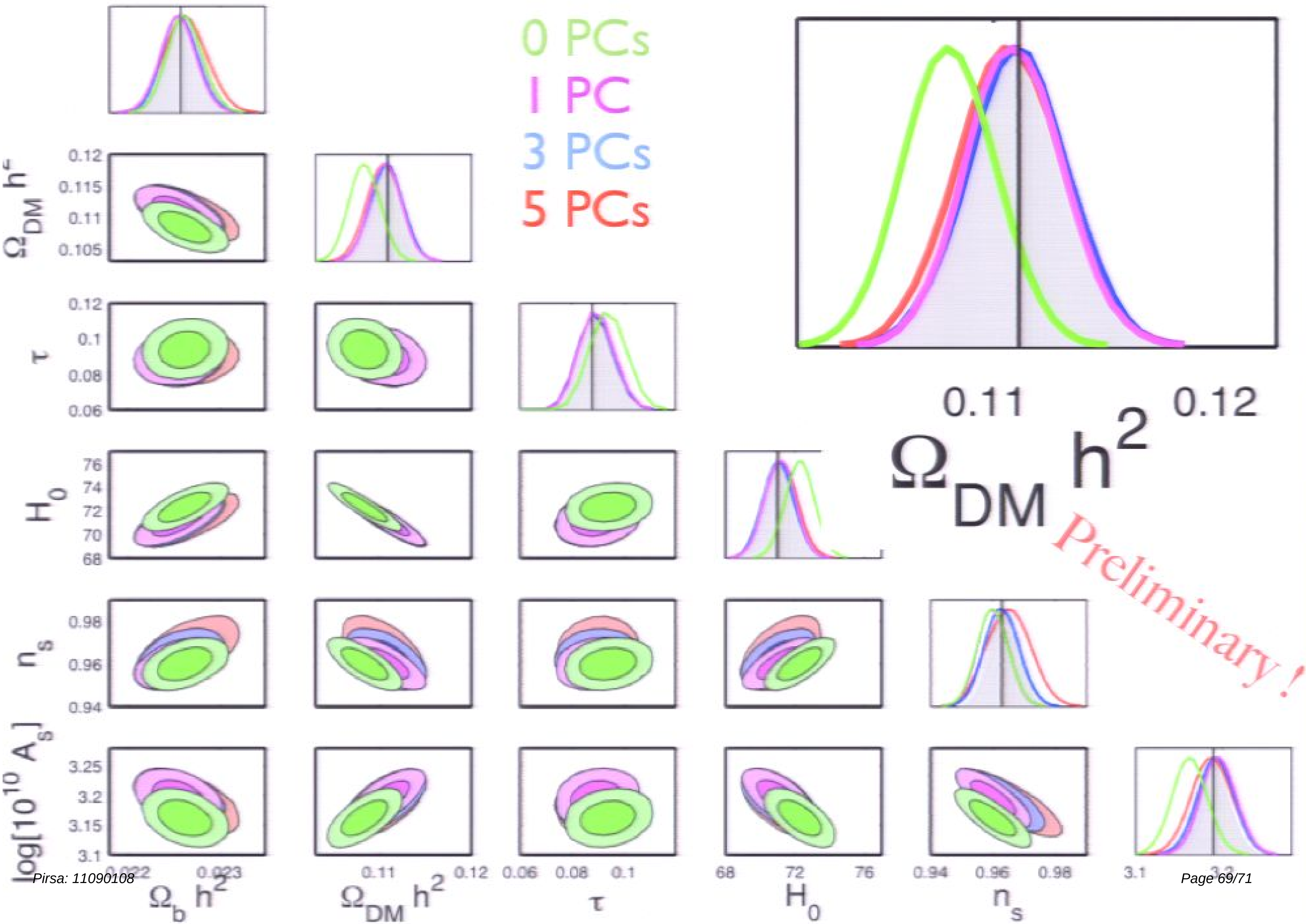

Preliminary !
WMAP 7
Planck
CVL
PC 1
x 10^-6
PC 2
PC 3
5
0
−5
15
10
−2
2
4
x 10^-6

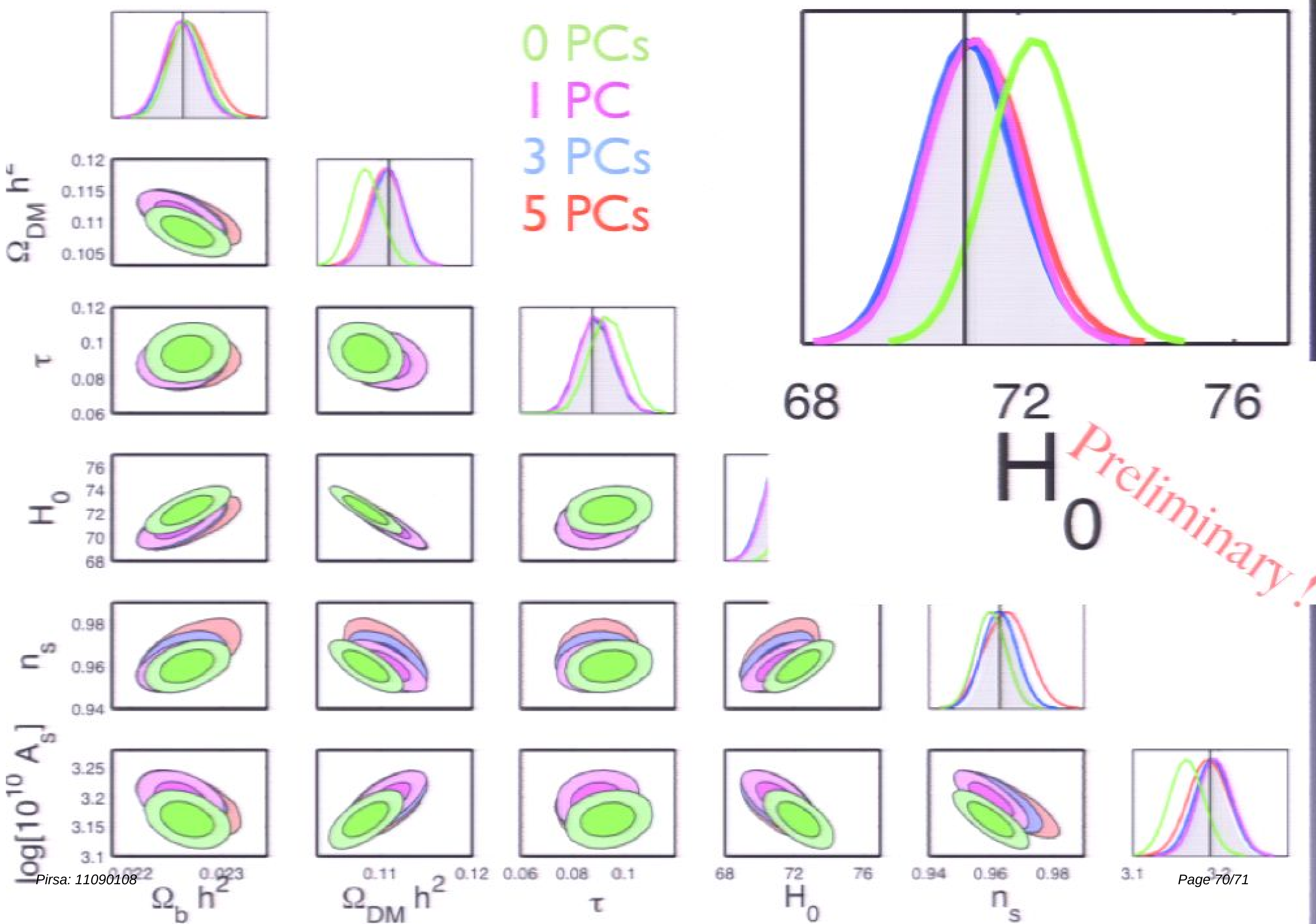
Markov chain Monte Carlo (MCMC)

We can also use MCMC to compute the bias in the cosmological parameters caused by neglect of energy injection.

We find the Fisher matrix-based estimates were good to ~ 10%.


0 PCs
1 PC
3 PCs
5 PCs
Preliminary !
$\Omega_{DM}\,h^2$
τ
H_0
n_s
$\log[10^{10} A_s]$
$\Omega_b\,h^2$
$\Omega_{DM}\,h^2$
τ
H_0
n_s


0 PCs
1 PC
3 PCs
5 PCs
0.11
0.12
$\Omega_{DM}\, h^2$
Preliminary !
$\Omega_b\, h^2$
$\Omega_{DM}\, h^2$
τ
H_0
n_s
$\log[10^{10} A_s]$


0 PCs
1 PC
3 PCs
5 PCs
Preliminary !
68
72
76
H_0
$\Omega_{DM}\, h^2$
τ
H_0
n_s
$\log[10^{10} A_s]$
$\Omega_b\, h^2$
$\Omega_{DM}\, h^2$
τ
H_0
n_s

Conclusions:

- A general energy injection at $z \sim 100$-1000 can be parameterized in a general way, yielding only 1 (or maybe 3 or 5) parameters to measure, after accounting for degeneracies with cosmological parameters.

- Neglect of these parameters (assuming $\varepsilon_1, \varepsilon_2, \varepsilon_3 = 0$) will bias the cosmological parameter fits -- often by > 1 sigma.

- If you want to know n_s (with correct error bars) you should make sure to marginalize over $\varepsilon_1, \varepsilon_2, \varepsilon_3$..