Constraining Dark Matter annihilation with the CMB

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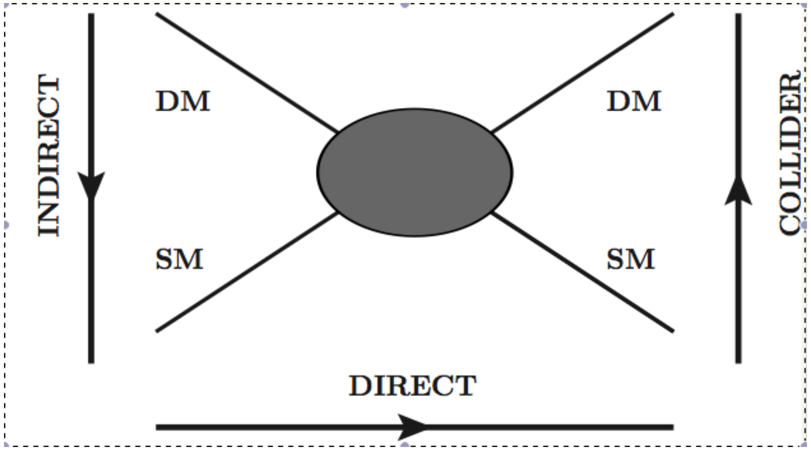
Frascati 19/10/2012

Dark Matter Searches



- **Collider searches**: LHC.
- **Direct detection:** CoGeNT, DAMA/LIBRA, XMASS, CRESST-II, EDELWEISS, CDMS, XENON10/100, PICASSO, COUPP
- **Indirect detection**
  - High energy photons: Fermi-LAT, ACTs (HESS, Veritas, Magic)
  - Electrons/positrons: PAMELA, ATIC, Fermi-LAT, HESS, MAGIC.
  - Antiprotons: PAMELA, AMS.
  - Neutrinos: ANTARES, IceCube.

  - CMB, 21 cm, BBN etc..

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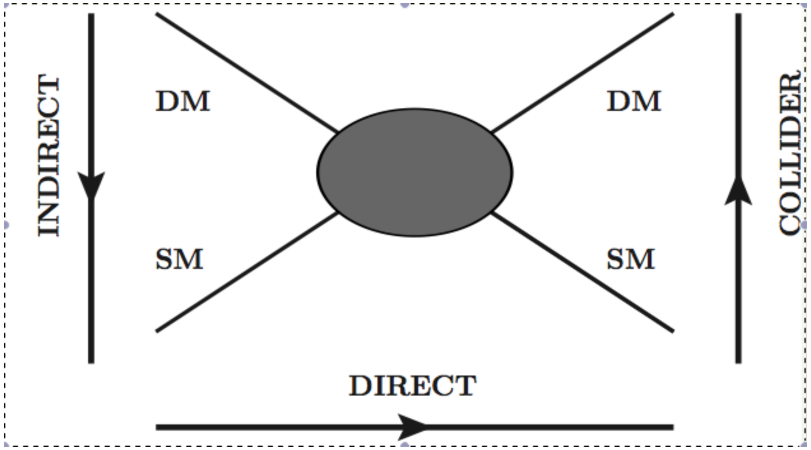

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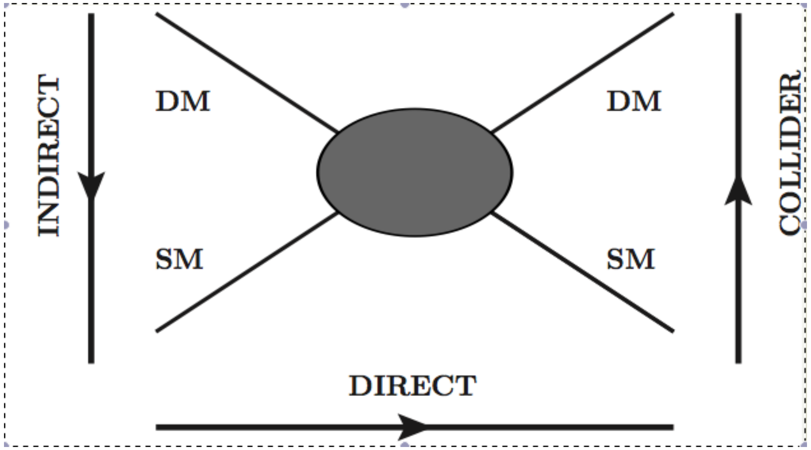

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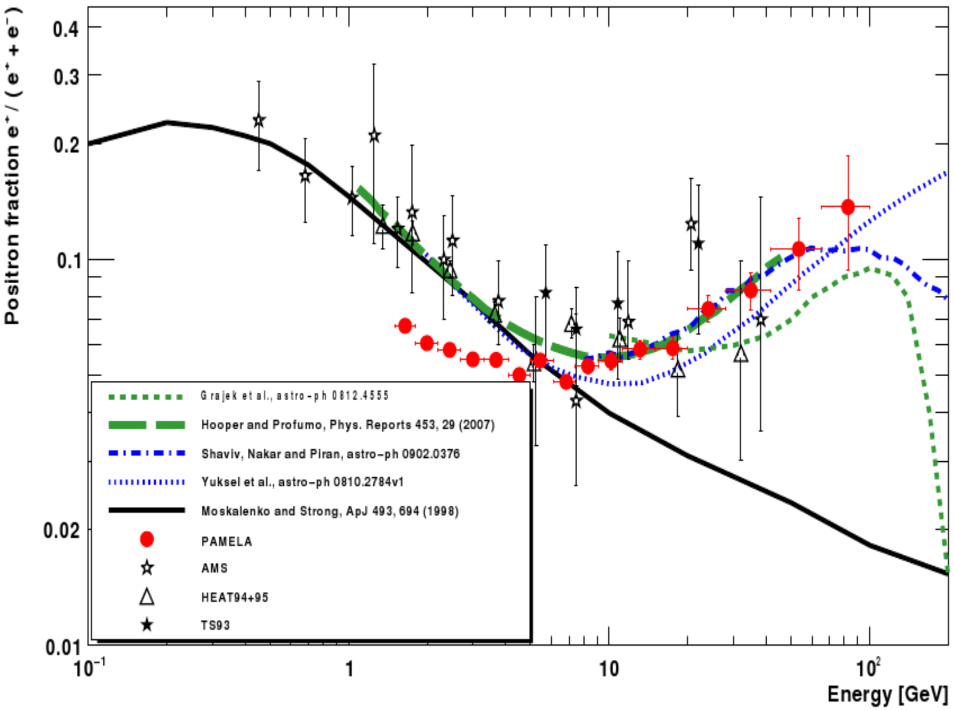
Anomalies

- **Anomalies:** excess in the positron electron fraction and in the energy spectrum of electrons.
- Several explanations: pulsar emission, dark matter decay, **dark matter annihilation** etc...

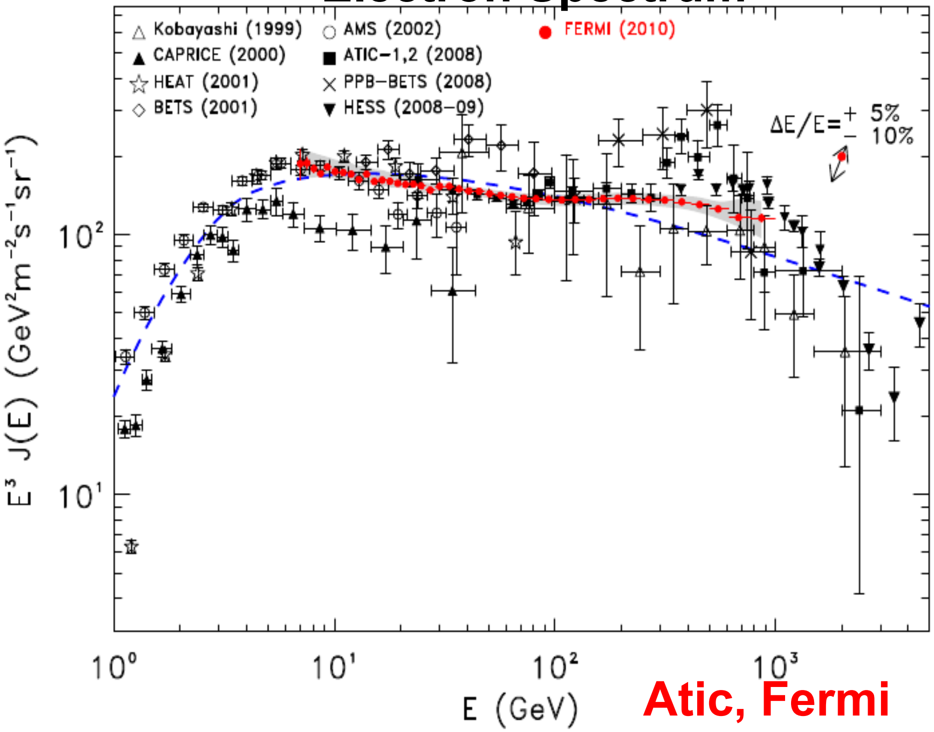
Positron Electron Fraction



Adriani et al. 2009
Mocchiutti et al. 2009

Pamela

Electron Spectrum



Atic, Fermi

Fermi Lat-collaboration arXiv:1008.3999

Anomalies

→ **Thermal production of DM:**

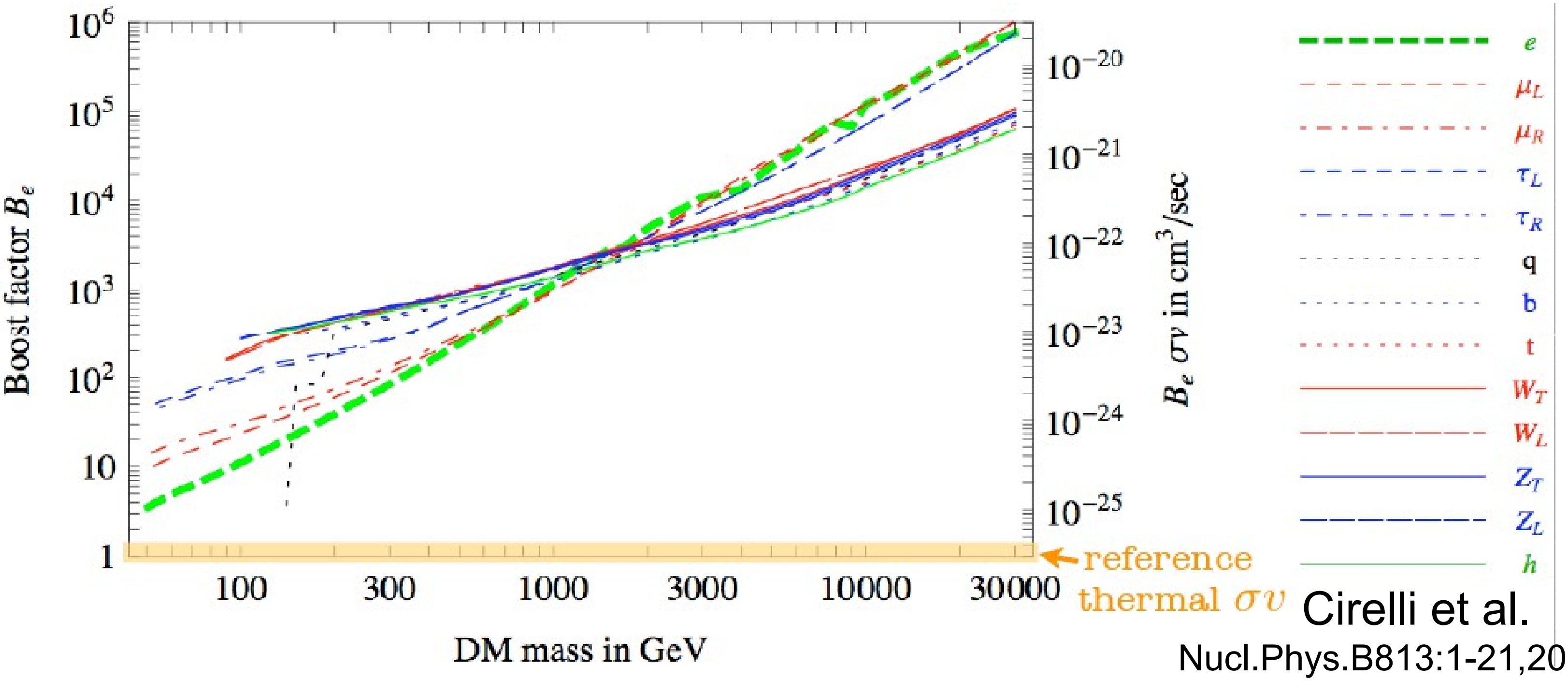
$\langle\sigma v\rangle \sim 10^{-26}$ cm^3/s. **(WIMP)**

→ **Annihilation rate:**

$\Gamma \propto n^2 \langle\sigma v\rangle$. n from dm simulations, models, observations

Astrophysical or Particle Physics **BOOST** to explain the data.

Profumo, S. 2005, PRD, 72, 103521



Cirelli et al.
Nucl.Phys.B813:1-21,2009

Motivations

→ **Thermal production of DM:**

$<\sigma v> \sim 10^{-26}$ cm^3/s. **(WIMP)**

→ **Annihilation rate:**

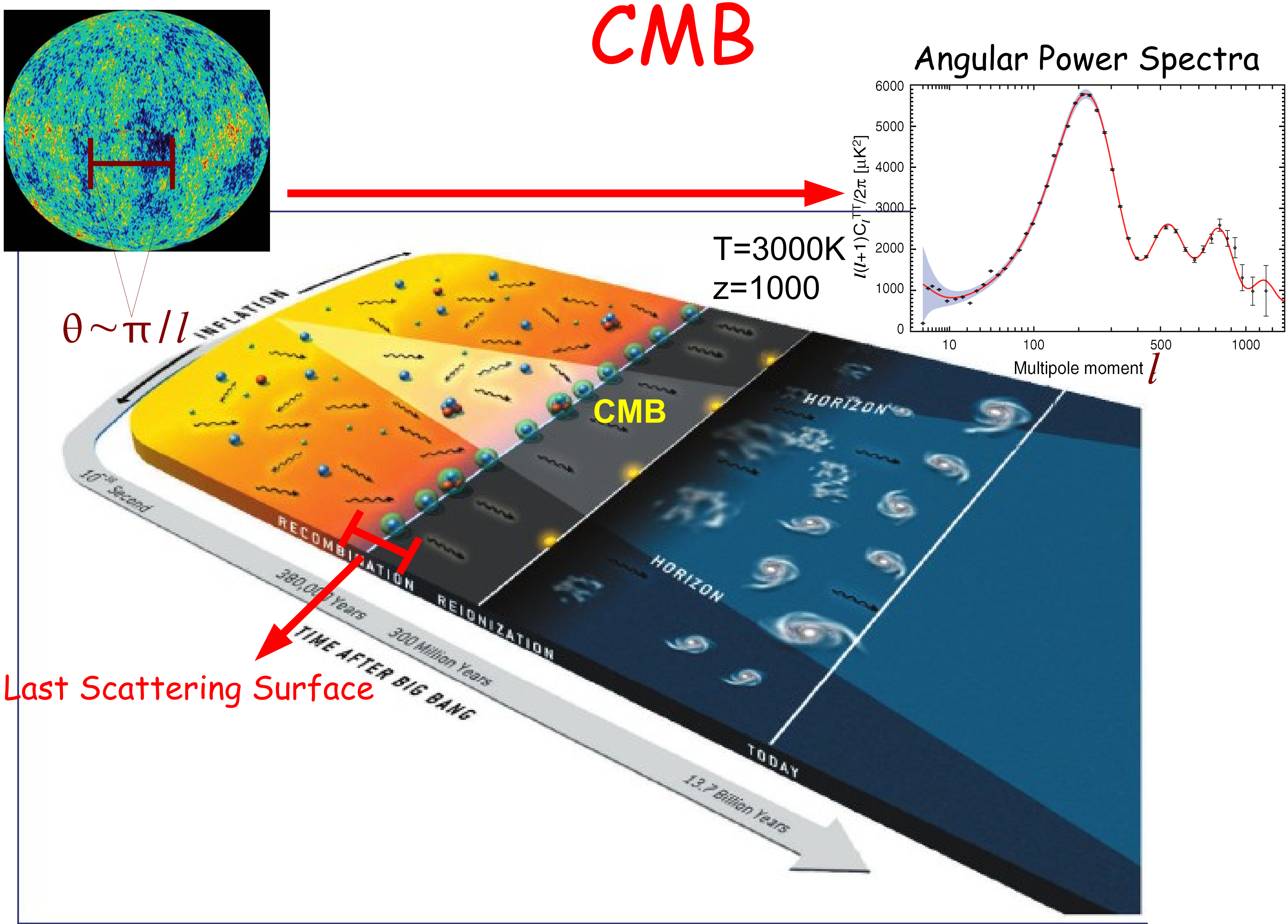
$\Gamma \propto n^2 <\sigma v>$. n from dm simulations, models, observations

BOOST of the cross section to explain the data, depends on mass of DM and annihilation channel.

Dark Matter annihilation should leave a signature in CMB:

- At (z~1000), when CMB forms, the homogeneous dark matter density is $n(z=1000) = n_{today} (1+z)^3 \sim n_{today} \times 10^9$
- DM mean velocity $\beta \sim 10^{-8}$. Favours Sommerfeld Enhancement.

CMB



θ ~ π / l

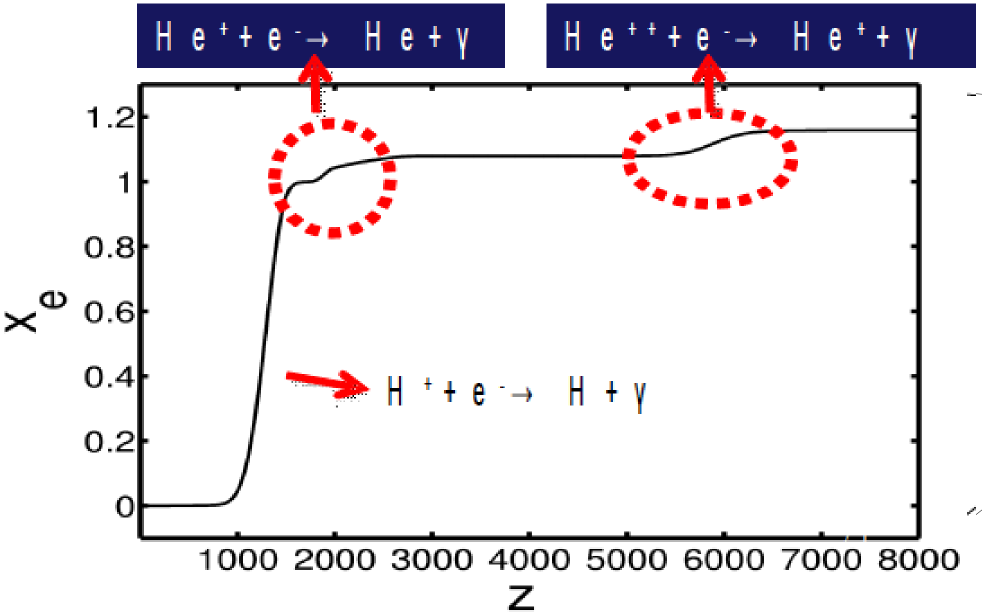
T=3000K
z=1000

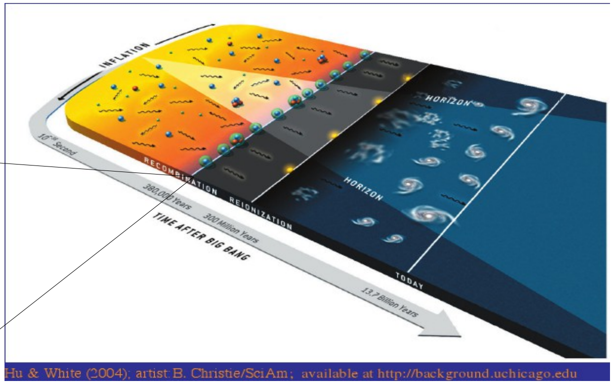
Angular Power Spectra

Last Scattering Surface

Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

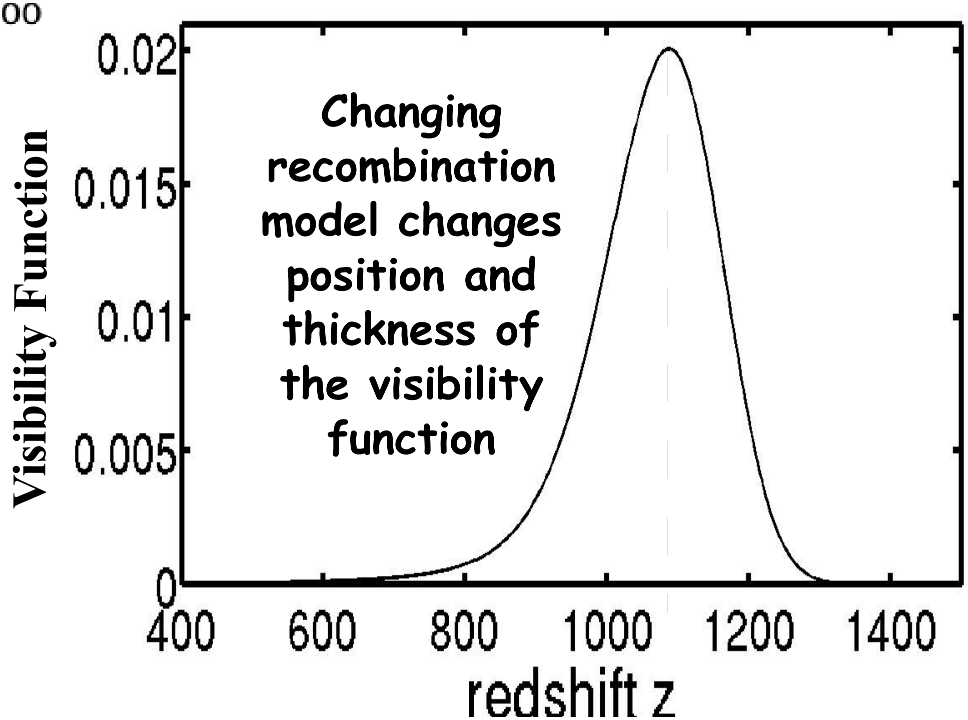
Recombination and Visibility Function





Hu & White (2004); artist B. Christie/SciAm; available at http://background.uchicago.edu

The visibility function represents the probability density that a photon is last scattered at redshift z.



Changing recombination model changes position and thickness of the visibility function

DM annihilation in the recombination epoch

$$\boxed{\frac{dE}{dt}=\rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \left[\overset{\mathbf{p}_{\mathbf{ann}}}{\boxed{f(z)\frac{<\sigma v>}{m_\chi}}}\right]}$$

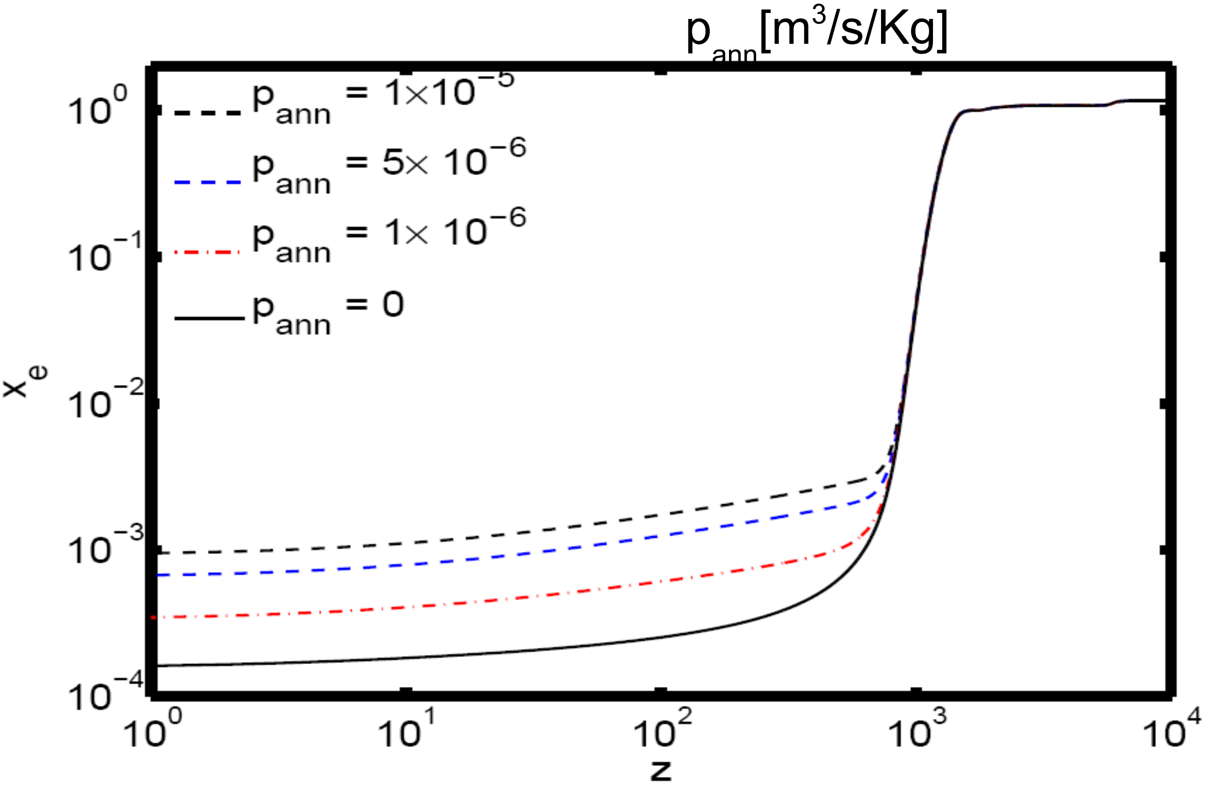
- f(z) is the fraction of energy that from the annihilation is absorbed by the plasma.

- This fraction of energy then goes into:
  - Heating
  - Ionization of H, HeI and HeII
  - Excitation ofH, HeI and HeII

DM annihilation in the recombination epoch

$$\boxed{\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \left[\overset{\mathbf{p_{ann}}}{\boxed{f(z)\frac{<\sigma v>}{m_\chi}}} \right]}$$

- The CMB can only constrain **p_{ann},** which is the combination of f(z), i.e. the fraction of DM annihilation energy that goes into the plasma, of the cross section and of the mass.

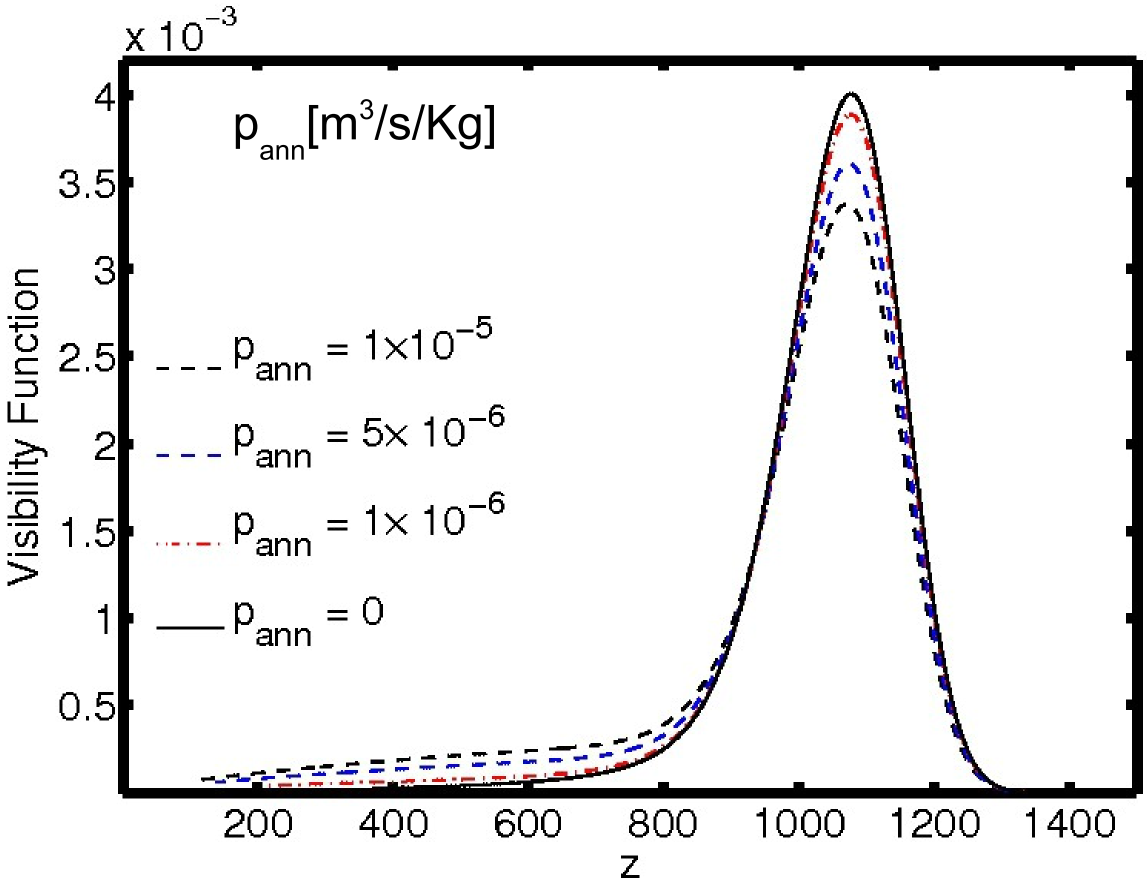


- At first, we assume **f(z) = CONSTANT**

- The energy injected **ionizes, excites and heats** the medium. This affects the evolution of the free electron fraction.

DM annihilation in the recombination epoch

$$\boxed{\frac{dE}{dt}=\rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 \overset{\mathbf{p_{ann}}}{\left[\boxed{f(z)\frac{<\sigma v>}{m_\chi}}\right]}}$$

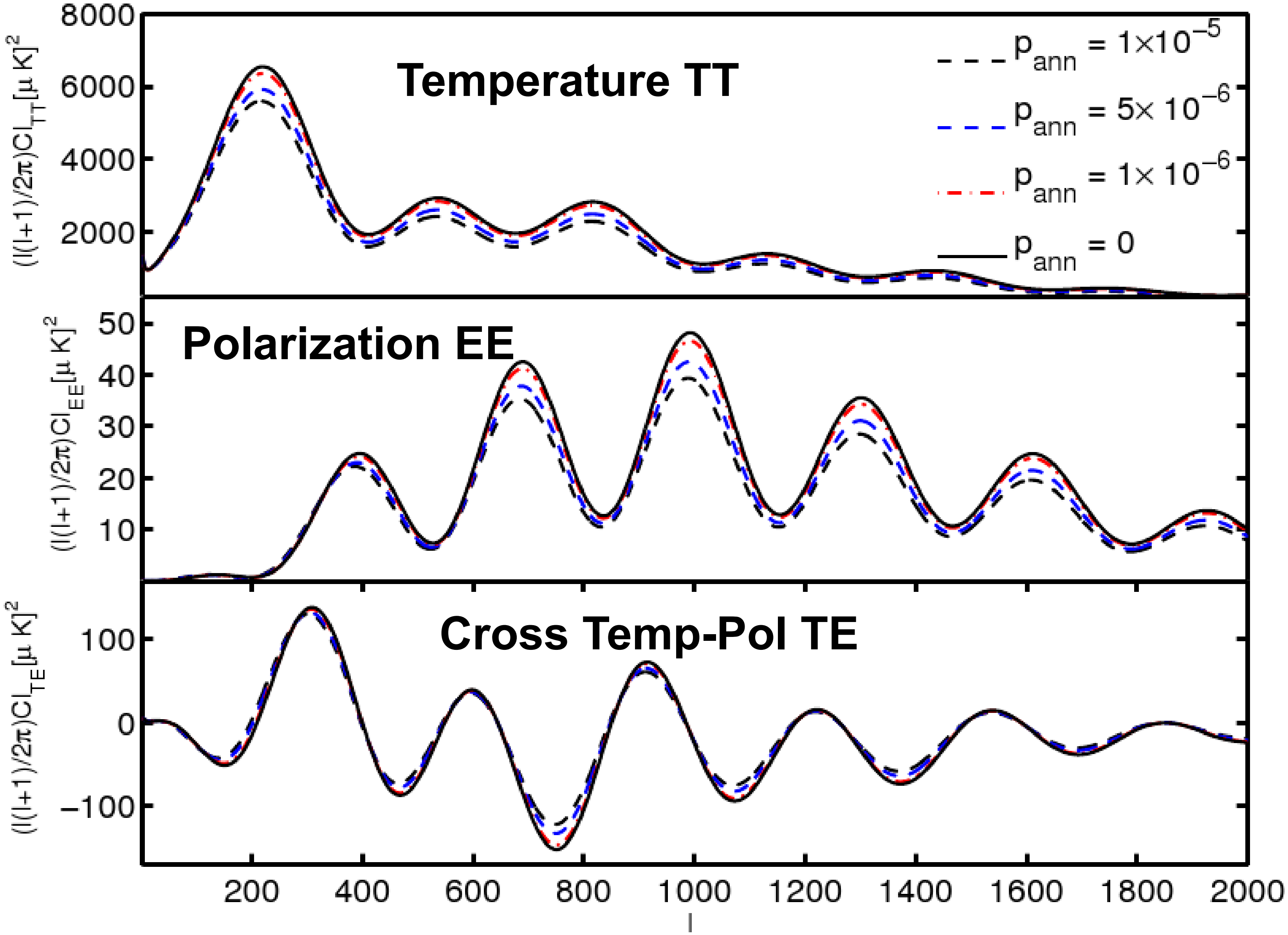


- The CMB can only constrain **p_{ann}**, which is the combination of f(z), i.e. the fraction of DM annihilation energy that goes into the plasma, of the cross section and of the mass.

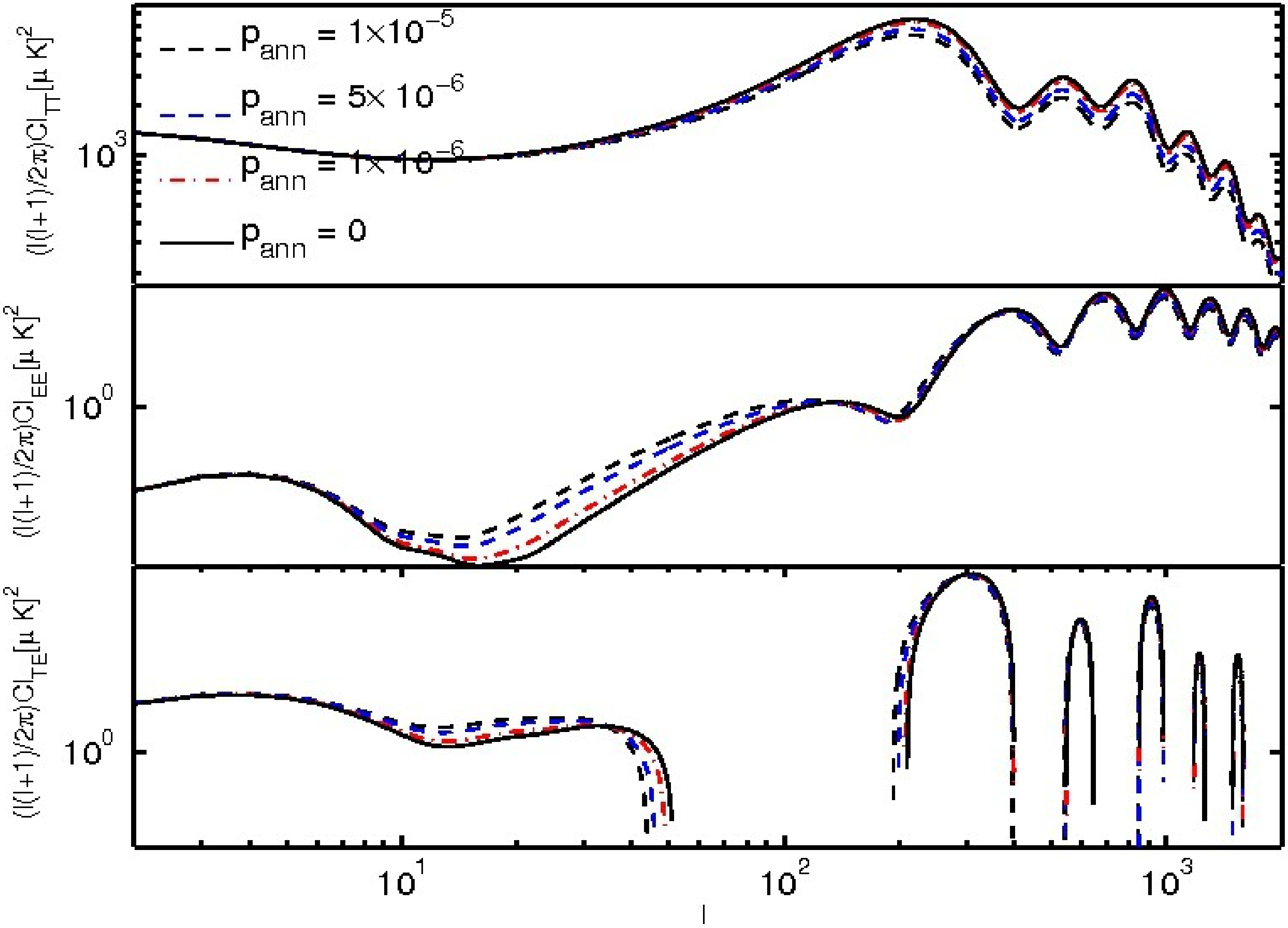
- At first, we assume **f(z) = CONSTANT**

- A larger amount of free electrons after recombination makes the width of the visibility function larger.

CMB Angular Power Spectra



CMB Angular Power Spectra



Constraints….

Chen & Kamionkowski 2004 (decay)

Padmanabhan & Finkbeiner 2005;

Zhang et al. 2006 (WMAP3+others, constant f)

Galli et al. 2009 (WMAP5+others, constant f)

Kim & Naselsky (WMAP5+others, constant f)

Galli et al 2011 (Future constraints, constant f)

Galli et al. 2011 (WMAP7+ACT, constant f and f for ee, μμ channels)

Huetsi et al. 2011 (WMAP7, empirical parametrization of f)

Natarajan 2012 (WMAP7+SPT+other, f for bbar)

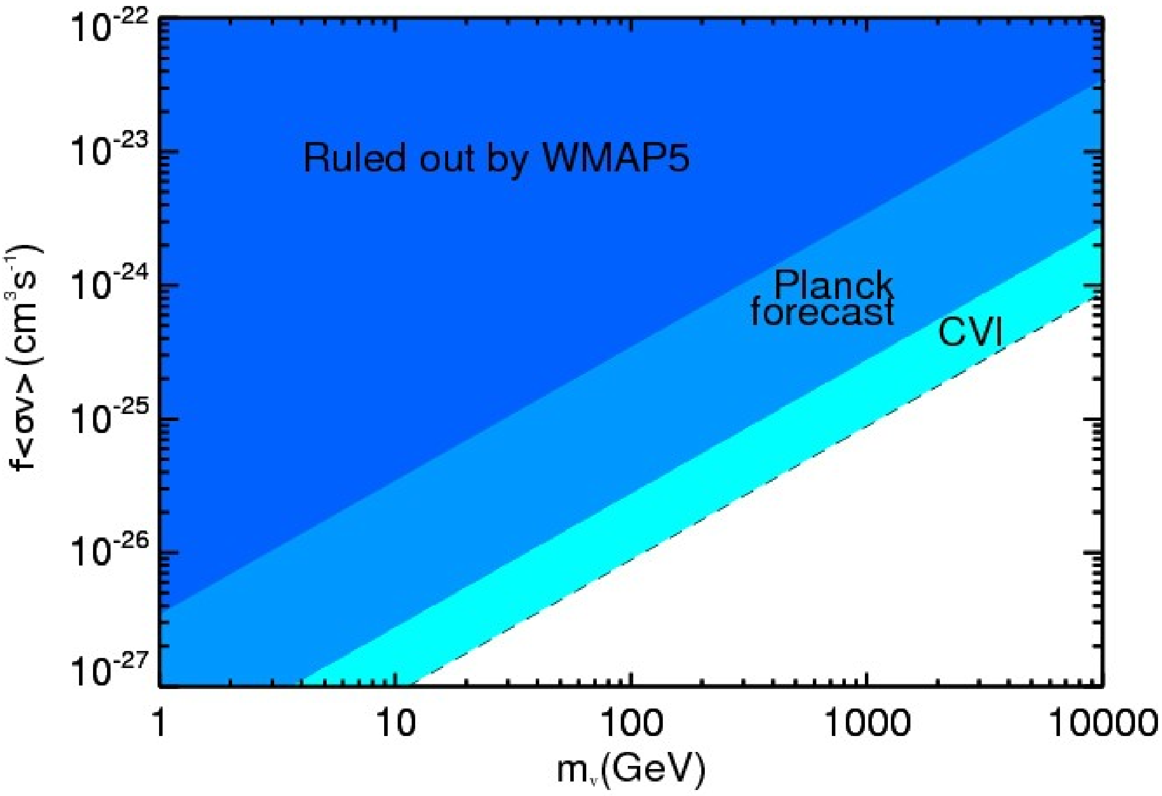
Finkbeiner, SG, et al. (Principal components approach for f)

Giesen et al. 2012 (WMAP7+SPT, f constant and variable)

Results on DM annihilation with constant f

$$p_{ann} = \frac{f < \sigma v >}{m_\chi}$$

- Wmap5 data already puts stringent constraints on the cross section/mass, i.e. on the properties of dark matter particles.
- WMAP7 improves of a factor 1.4, thanks to better measurements at higher l in TT, TE.
- Dark Matter models favoured by Pamela almost excluded by WMAP.
- Planck will improve results thanks to polarization data.



$p_{ann}[m^3/s/Kg]$ at 95% c.l.	
WMAP5	$< 2.0 \times 10^{-6}$
WMAP7	$< 1.4 \times 10^{-6}$
WMAP7+ACT	$< 1.2 \times 10^{-6}$
Planck	$< 1.7 \times 10^{-7}$
CVl	$< 5.9 \times 10^{-8}$

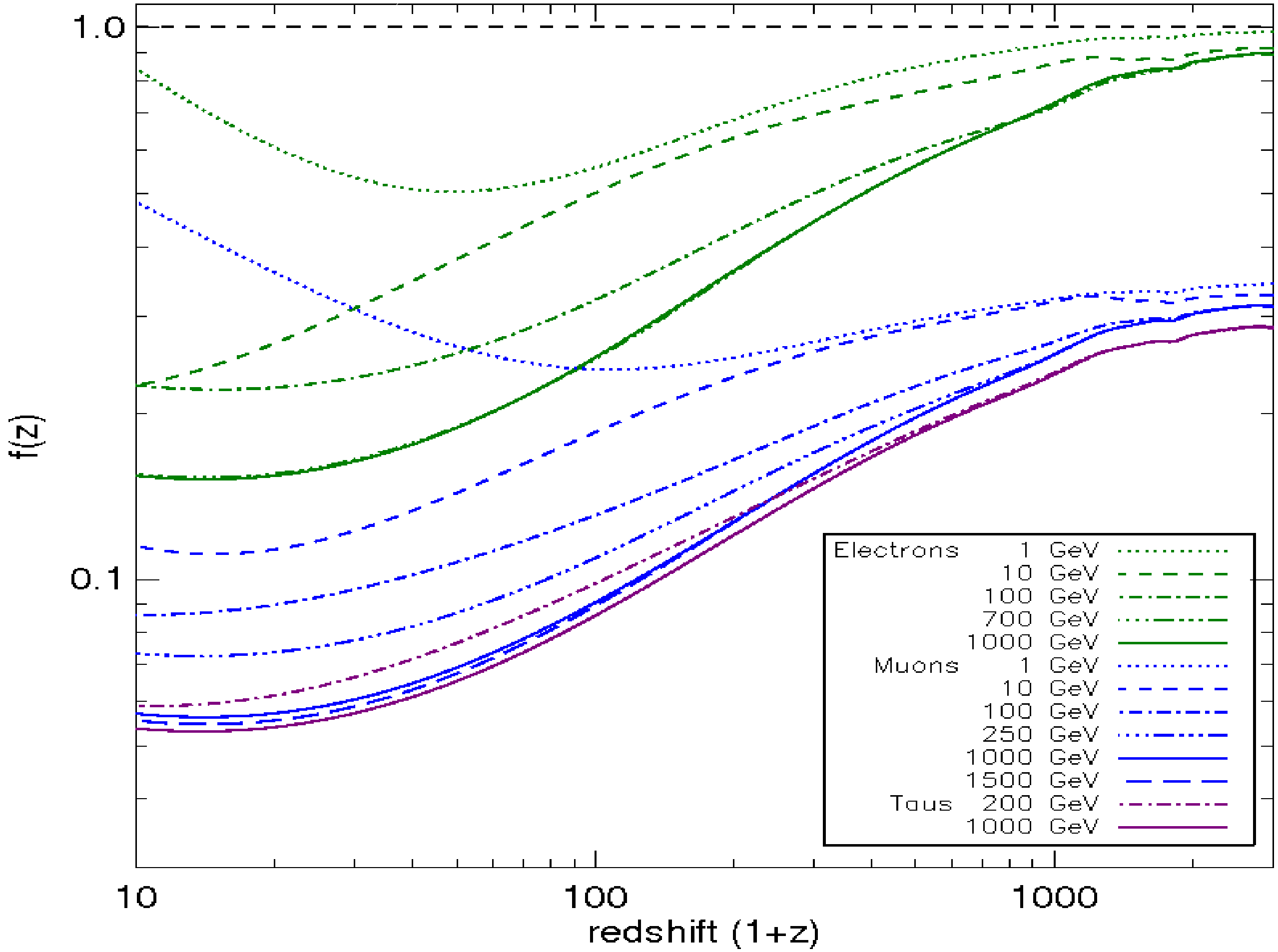
Forecasts!

SG, F. Iocco, G. Bertone, A. Melchiorri, Phys. Rev. D, vol. 80, Issue 2, 2009.
SG, F. Iocco, G. Bertone, A. Melchiorri, 2011, Phys. Rev. D, 84, 02730.

Improving the constraints: f(z)

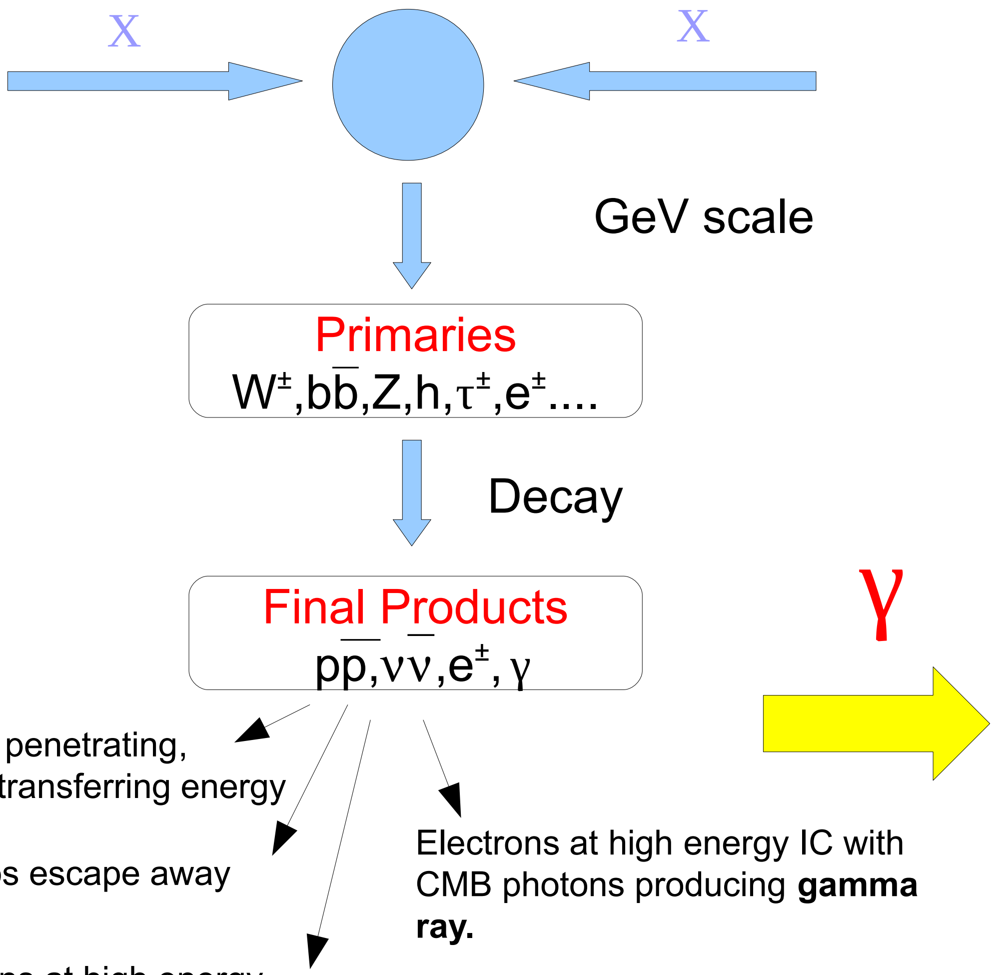
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{dm} (1+z)^6 f(z) \frac{<\sigma v>}{m_\chi}$$

f(z) depends on the mass, model and annihilation channel of the DM particle considered.



Slatyer et al. 2009

Energy Deposition History



X

X

GeV scale

Primaries

$W^{\pm}, b\bar{b}, Z, h, \tau^{\pm}, e^{\pm}$....

Decay

Final Products

$p\bar{p}, \nu\bar{\nu}, e^{\pm}, \gamma$

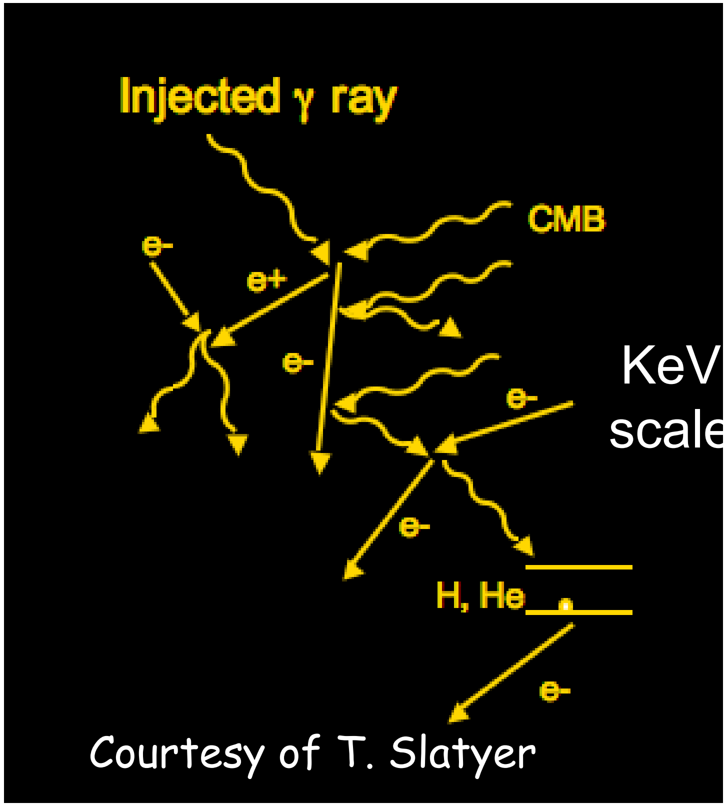
γ

Protons penetrating,
Poor at transferring energy

Neutrinos escape away

Positrons at high energy
behave like electrons, then form
positronium and annihilate

Electrons at high energy IC with CMB photons producing **gamma ray.**



Courtesy of T. Slatyer

Heating, excitation and ionization

A second approach: constraints with variable f(z)

For each specific f(z) one can set constraints on the cross-section.

Constraints on $< \sigma v >$ [cm^3/s] using WMAP7+ACT

m_χ	channel	Variable $f(z)$	Constant f	$f(z = 600)$
1 GeV	e^+e^-	$< \boxed{2.41 \times 10^{-27}}$	$< \boxed{2.41 \times 10^{-27}}$	0.87
100 GeV	e^+e^-	$< 3.55 \times 10^{-25}$	$< 3.35 \times 10^{-25}$	0.63
1TeV	e^+e^-	$< 3.80 \times 10^{-24}$	$< 3.48 \times 10^{-24}$	0.60

$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{dm} (1+z)^6 f(z) \frac{\boxed{<\sigma v>}}{m_\chi}$$

$$<\sigma v> = \frac{p_{ann}^{const} m_\chi}{f(z=600)}$$

For WMAP7 and WMAP7+ACT, knowing the overall normalization f(z=600) is sufficient. This might not be the case for Planck!.

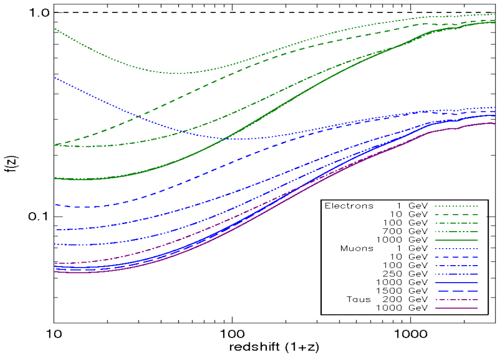
SG, F. Iocco, G. Bertone, A. Melchiorri, 2011, Phys. Rev. D, 84, 02730.

A General Approach to f(z)

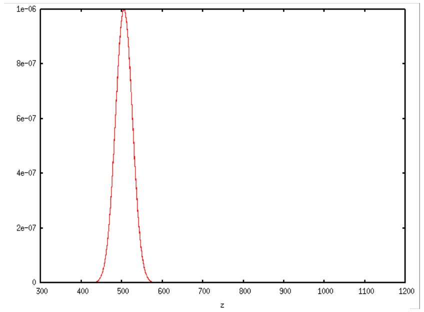
D. Finkbeiner, SG, T. Slatyer, T. Lin, 2012, PRD, 85, 043522 .

A general approach to f(z)

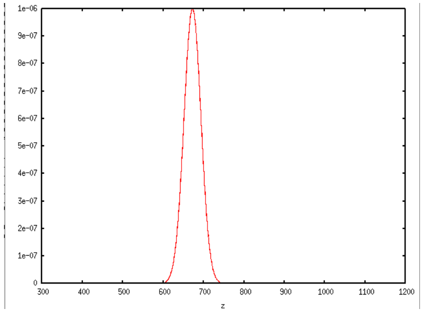
1) Parametrize injection histories with N gaussians in redshift bins. End up with N correlated.



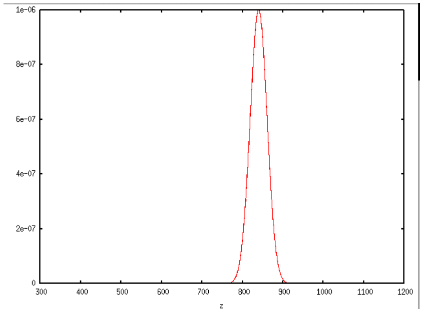
α_1



$+\alpha_2$



$+\alpha_3$



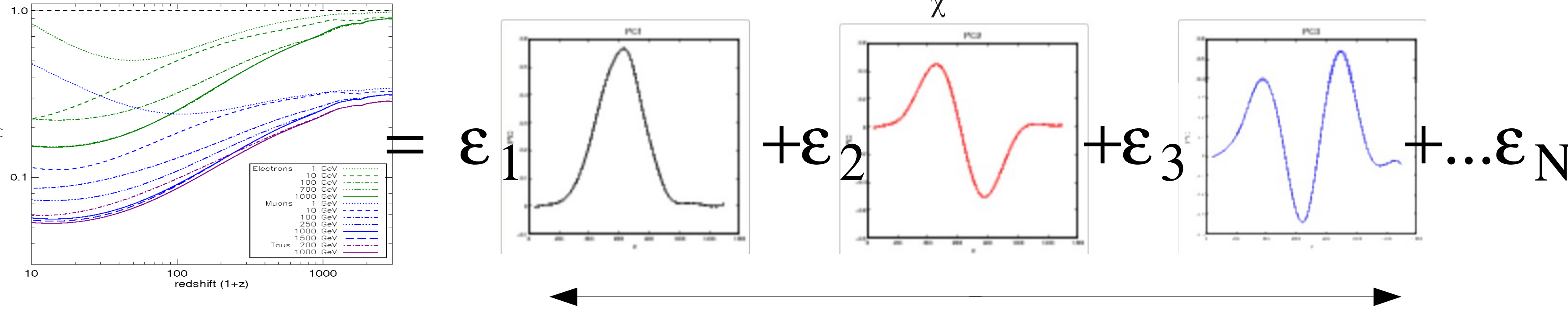
$\ldots\alpha_N$

$$p_{ann}(z) = f(z)\frac{<\sigma v>}{m_\chi} = \Sigma_{i=1}^{N} \alpha_i g_i(z)$$

A general approach to f(z)

2) Calculate the Fisher Matrix for these parameters for a specific experiment (e.g. Planck).
3)Calculate the eigenvectors and eigenvalues by diagonalizing the Fisher Matrix.

$$p_{ann}(z) = f(z)\frac{<\sigma v>}{m_\chi} = \Sigma_{i=1}^{N} \varepsilon_i e_i(z)$$

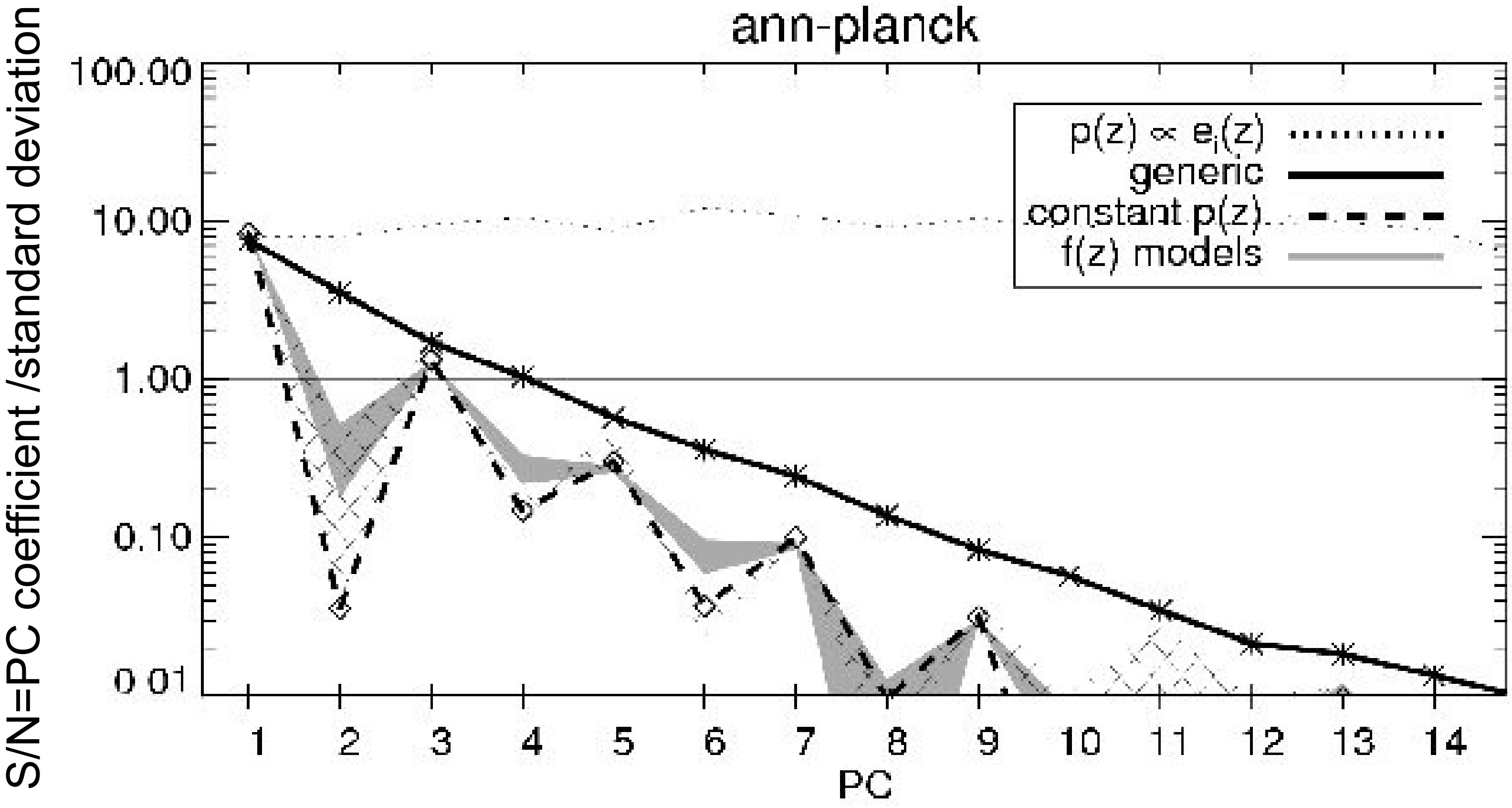


$$= \varepsilon_1 \quad + \varepsilon_2 \quad + \varepsilon_3 \quad + \dots \varepsilon_N$$

Advantages:

- Parameters e1, e2....eN uncorrelated (Diagonal Fisher Matrix)
- Errors are known from the FM.
- It is possible to identify the best measured components with a S/N criterion. An experiment will be able to measure only few PC's.

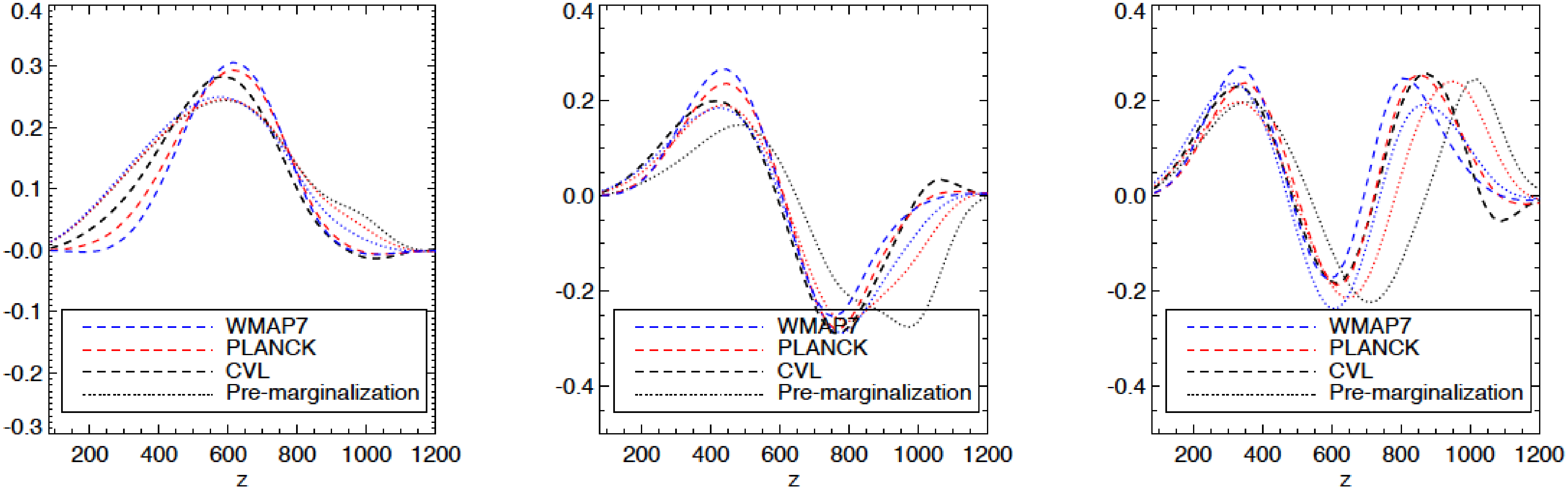
S/N detectability criterion for Planck



4)Assuming a dark matter annihilation signal at the 2-sigma current WMAP7 bound,
Planck could detect up to 3 PC's.
A CVL experiment would detect~6 PC's

D. Finkbeiner, SG, T. Slatyer, T. Lin, 2012, PRD, 85, 043522 .

Principal components for WMAP, Planck, CVL

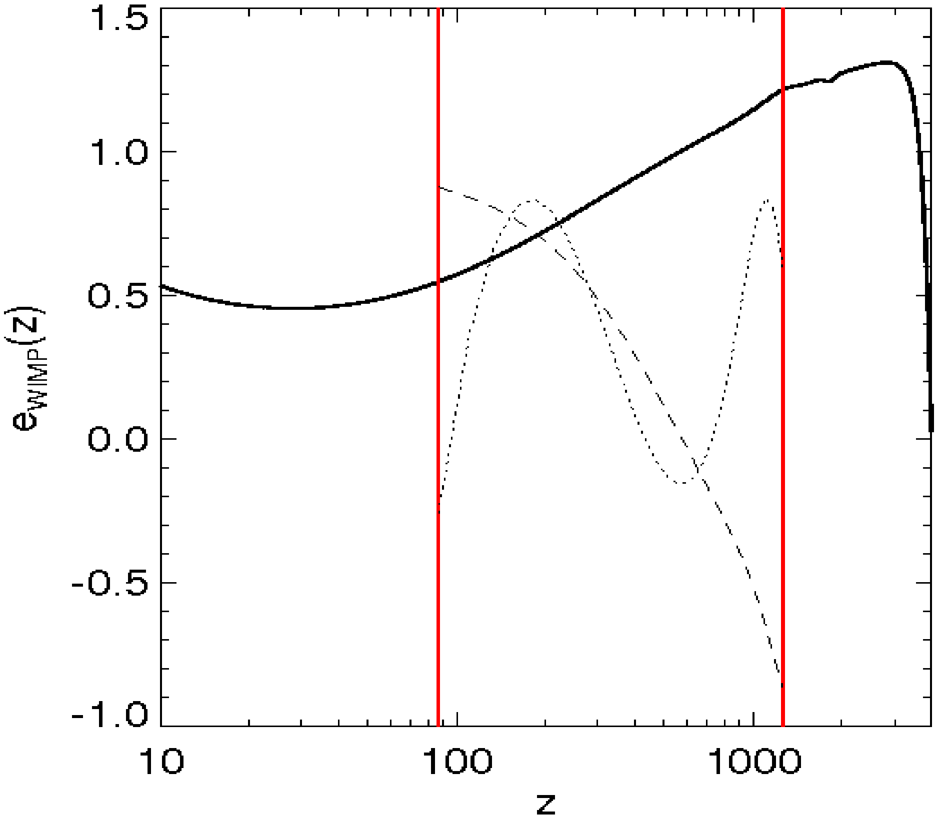


Marginalization over cosmological parameters is needed and makes the PC's slightly correlated

D. Finkbeiner, SG, T. Slatyer, T. Lin, 2012, PRD, 85, 043522 .

A universal WIMP curve

- The same procedure can be executed using as initial basis all the possible known f(z) instead of generic gaussians in redshift bins.
- In this case **ONLY 1 PC CONTAINS ALL THE INFORMATION ABOUT ANNIHILATION.**



Heating, Excitation and Ionization

$$\left[f(z) \frac{<\sigma v>}{m_\chi} \right] \longrightarrow$$

- Heating
- ionization of H, HeI and HeII
- excitation ofH, HeI and HeII

Fractions computed through MCMC by Shull and Van Steenberg (1985) (see also Valdes & Ferrara 2008, Furlanetto & Stoever 2010,).

- 1000 MCMC for 18 values of electron fractions, for 3 KeV electron.

- At each step, electron can collisionally ionize, excite HI,HeI,HeII or heat the medium via Coulomb interaction with thermal e^-. Probabilities depend on number densities of e^-, H, HeI, and HeII and on cross sections.

- Assumes that $n(H^+)/n(H)=n(He^+)/n(He)$.

$$\begin{aligned}
\chi_i(H) &= \chi_\alpha(H) = \frac{1-x_H}{3(1+f_{He})} \\
\chi_i(He) &= \chi_\alpha(He) = \frac{(1-x_{He})f_{He}}{3(1+f_{He})} \\
\chi_h &= \frac{1+f_{He}(1+2x_{he})+2x_H}{3(1+f_{He})}
\end{aligned}$$

All in heating when medium is completely ionized.
1/3 heating, 1/3 excitation, 1/3 ionization when medium is neutral

Heating, Excitation and Ionization: Possible Improvements

$$[f(z)\frac{<\sigma v>}{m_\chi}] \longrightarrow$$

- Heating
- ionization of H, HeI and HeII
- excitation ofH, HeI and HeII

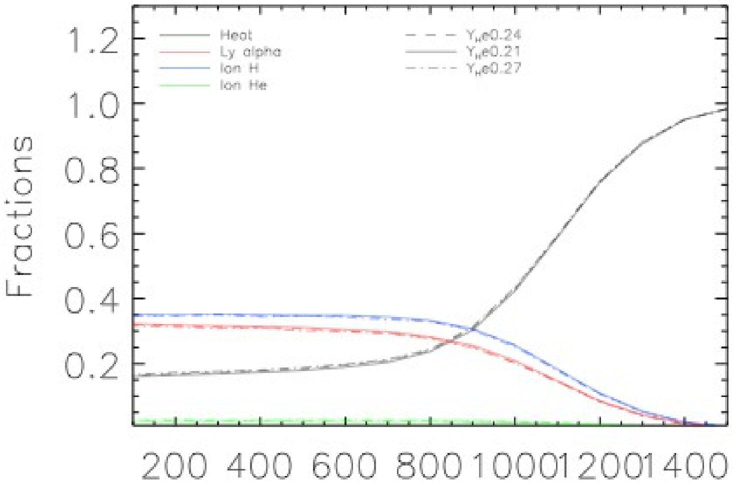
- Estimate how much uncertainties in the heating/ionization/excitation fractions affect final constraints

- Need a more accurate calculation of fractions. Simulations assume $n(H^+)/n(H)=n(He^+)/n(He)$.

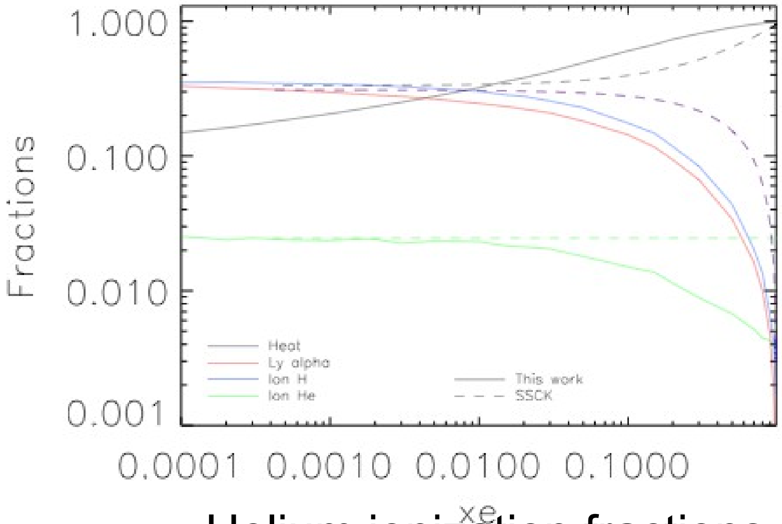
- Need to calculate how much excitation goes to Ly-alpha. Constraints calculated by assuming that all excitation is Ly-alpha are **~10%** stronger than the ones calculated without.

Galli, Iocco, Valdes (In preparation)

Effect of systematics

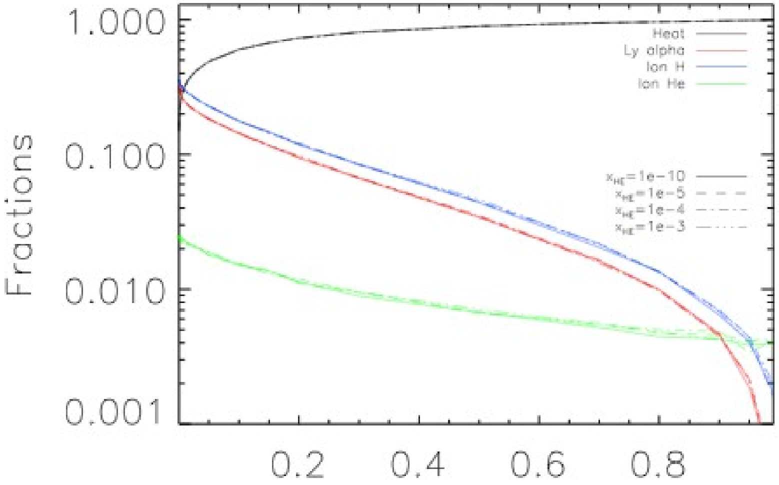


Helium Abundance



Helium ionization fractions

Accurate vs approximate fractions



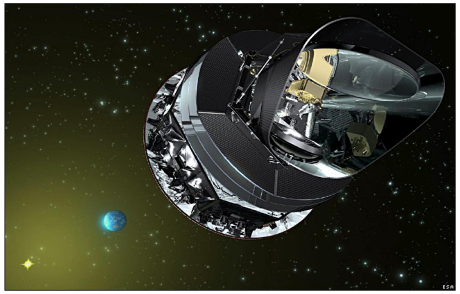
Galli, Valdes, Iocco, in preparation

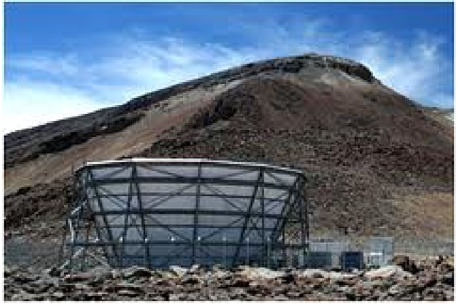
Conclusions

- CMB is a very good DM annihilation probe, independent from the knowledge of DM distribution.
- WMAP already puts strong constraints, that are already used to rule out DM models that fit Pamela data.
- We provided a general accurate approach to model different injection histories.
- Planck will need this accurate approach. Polarization is essential to have improvements.

Future constraints with constant f

- Constraints improvable by extracting the lensing signal with the Hu and Okamoto quadratic estimator. (Okamoto, T., & Hu, W. 2003, Phys. Rev. D, 67)





Adding lensing extraction will improve Planck data by 10%.

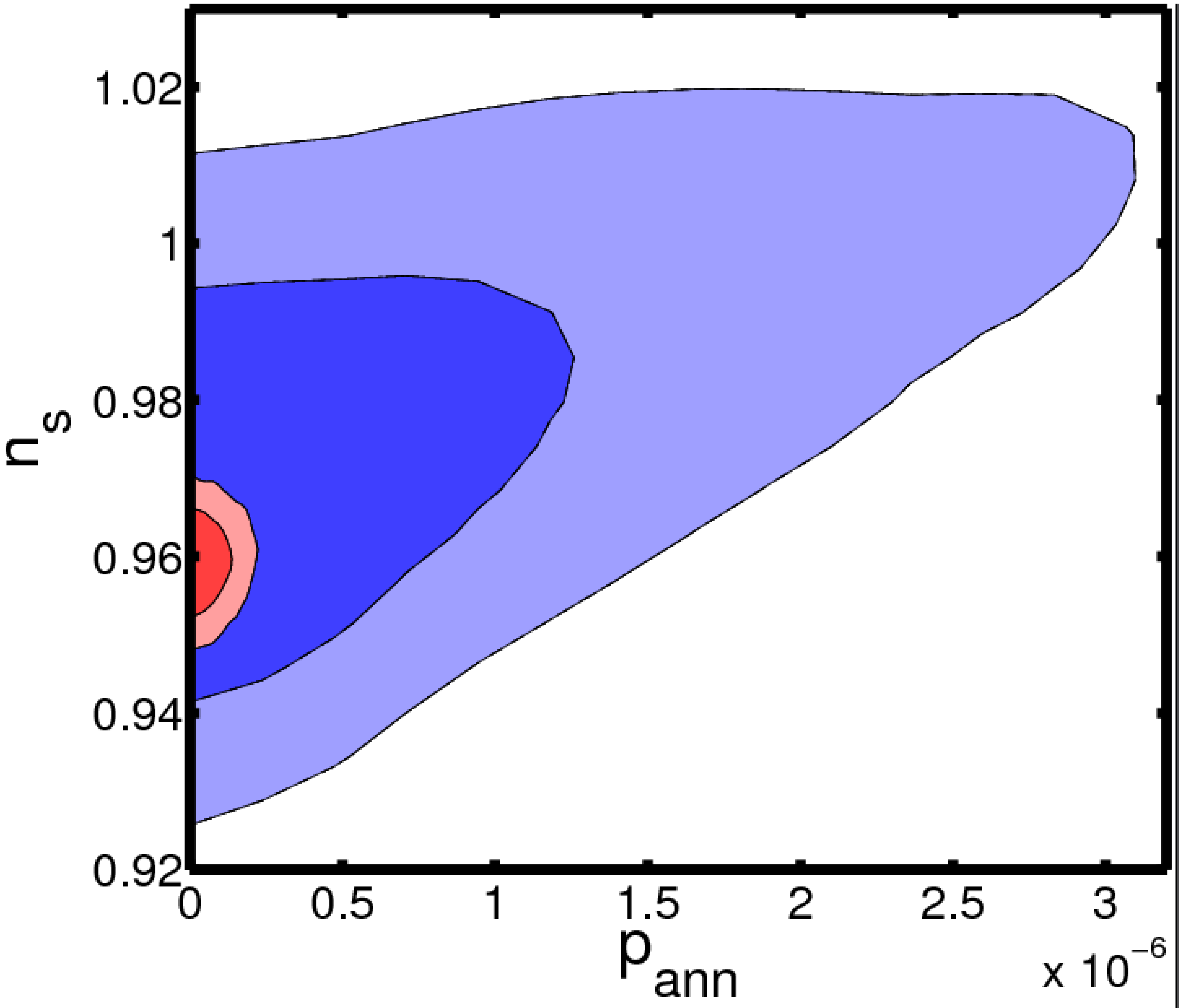
ACTpol will provide info useful for CMB science till **TT lmax~2500** and **EE lmax~3500** (foregrounds limited). ACT will improve Planck Data by 20%.

Experiment	p_{ann} 95% c.l.
Planck	$< 1.5 \times 10^{-7} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
Planck+ACT	$< 1.2 \times 10^{-7} \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$
CMBpol	$< 6.3 \times 10^{-8}\ \mathrm{m}^3/\mathrm{s}/\mathrm{kg}$

CMBpol with lensing extraction will constrain DM annihilation to a level comparable to the CVI case.

SG, M. Martinelli, A. Melchiorri, L. Pagano, B. Sherwin, D. Spergel, 2010, Phys. Rev. D, 82, 123504

Degeneracy pann-ns



Wmap (Blue)
Planck
simulated
(Red)