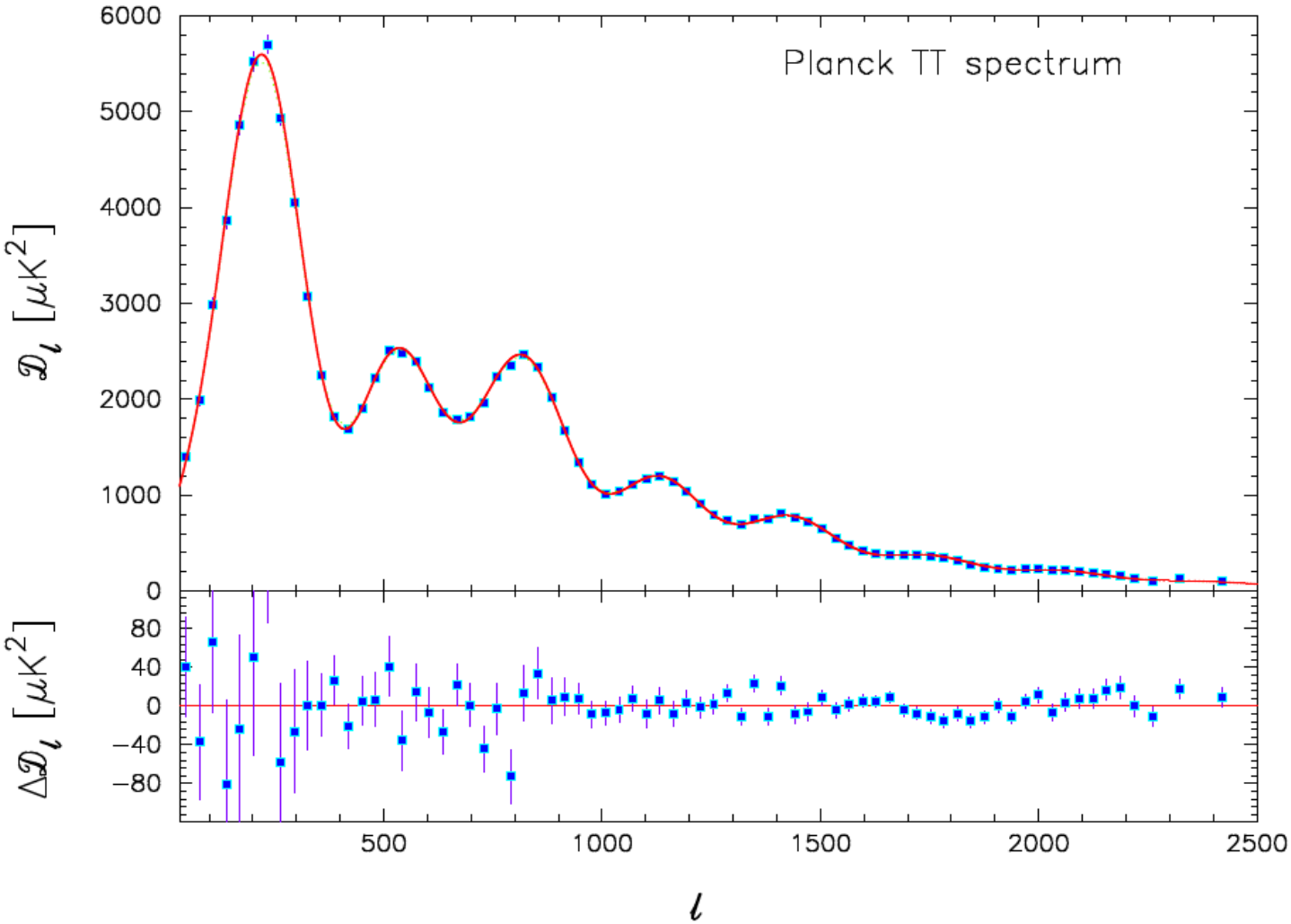
Shedding light on fundamental physics with Planck

Silvia Galli

IAP-Paris

Heidelberg 27/06/2013

ΛCDM: The most boring universe?



Outline

- Introduction

- What is the nature of Dark Matter?

  - Dark Matter Searches
  - Dark Matter Annihilation in the CMB
    - Simplified constraints
    - Refined constraints
    - Latest results on the study of energy propagation

- Is currently known physics sufficient to describe our universe?

  - Testing Variation of Fundamental Constants
    - CMB
    - Clusters of galaxies

Dark Matter Searches

- **Collider searches**: LHC.
- **Direct detection:** CoGeNT, DAMA/LIBRA, XMASS, CRESST-II, EDELWEISS, CDMSII, XENON, PICASSO, COUPP
- **Indirect detection**
  - High energy photons: Fermi-LAT, ACTs (HESS, Veritas, Magic)
  - Electrons/positrons: PAMELA,AMS02, ATIC, Fermi-LAT, HESS, MAGIC.
  - Antiprotons: PAMELA, AMS.
  - Neutrinos: ANTARES, IceCube.

  - CMB, 21 cm, BBN etc..

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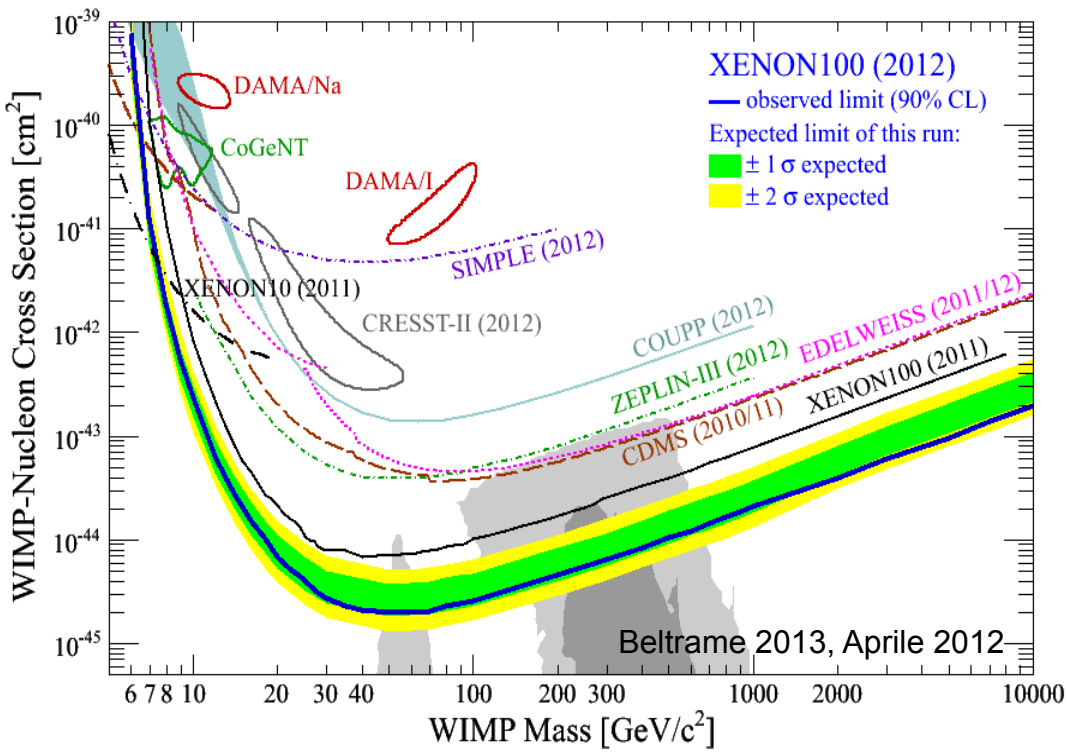

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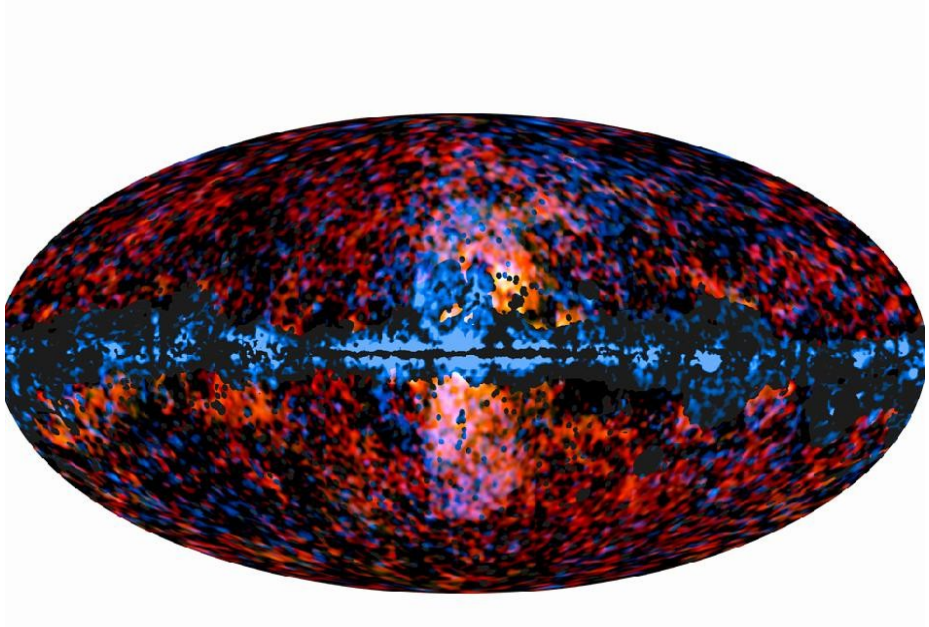

Planck Collaboration/ Su et al./Dobler et al./ Finkbeiner et al.

Dark Matter Searches

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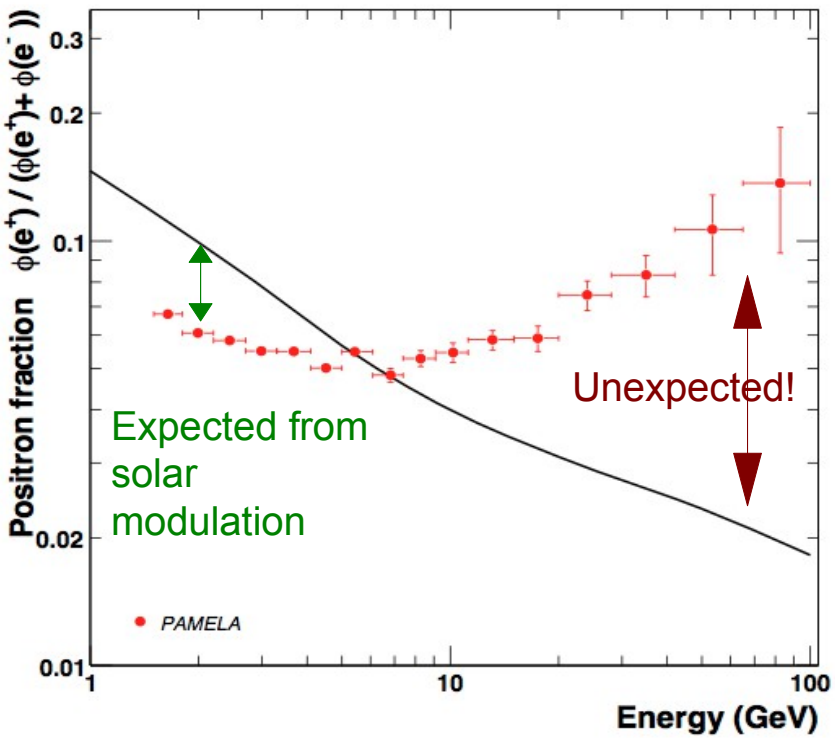
Anomalies in Cosmic Rays

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

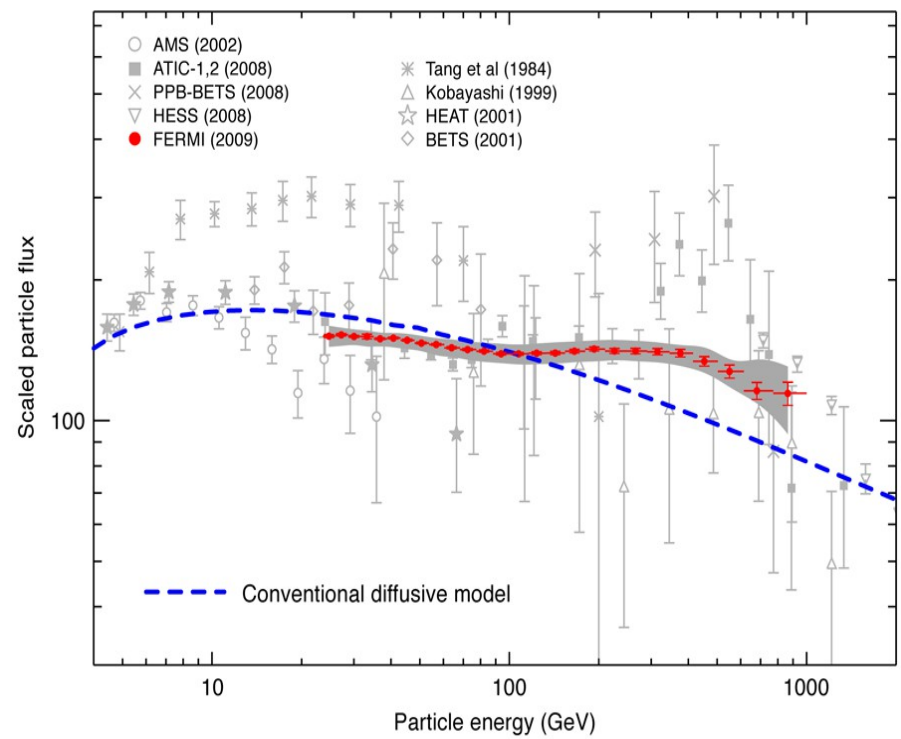
Positron Electron Fraction



Pamela

Adriani et al. 2009

Electron Spectrum



Fermi

Fermi Lat-collaboration 2010

Anomalies in Cosmic Rays

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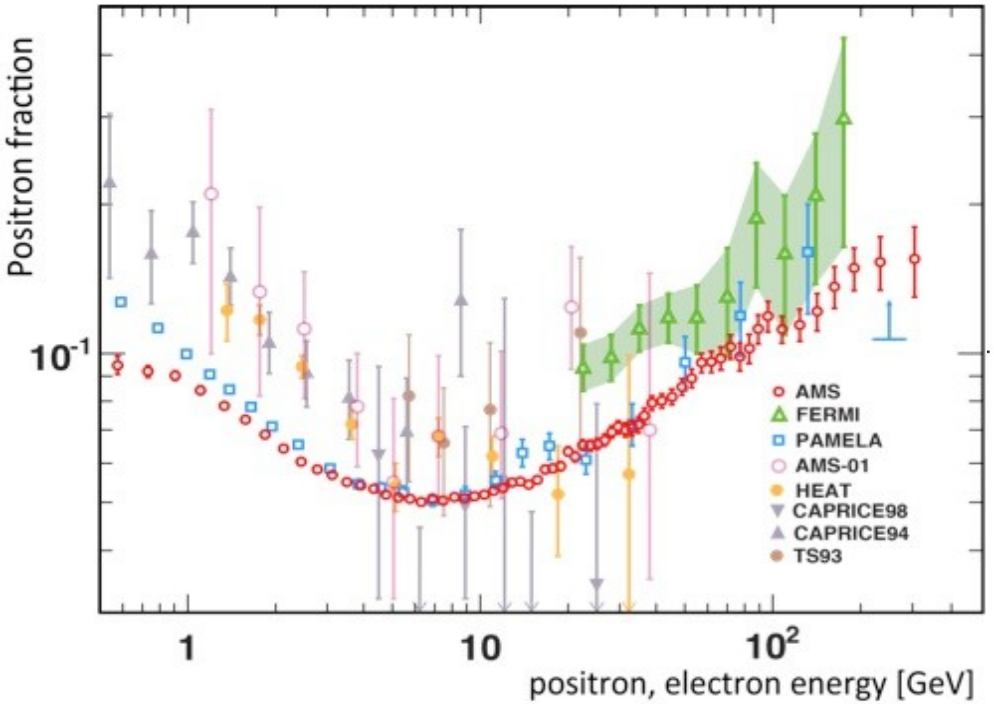
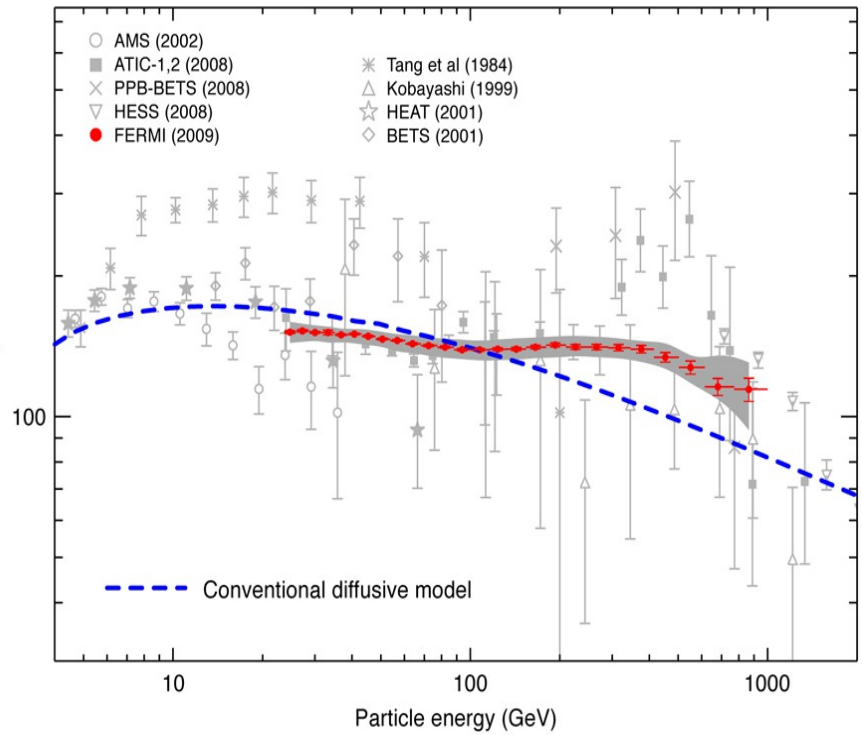
Positron Electron Fraction



Ams02 confirms Pamela!

Electron Spectrum



Fermi

Fermi Lat-collaboration 2010

Anomalies in Cosmic Rays

→ **Thermal production of DM:**

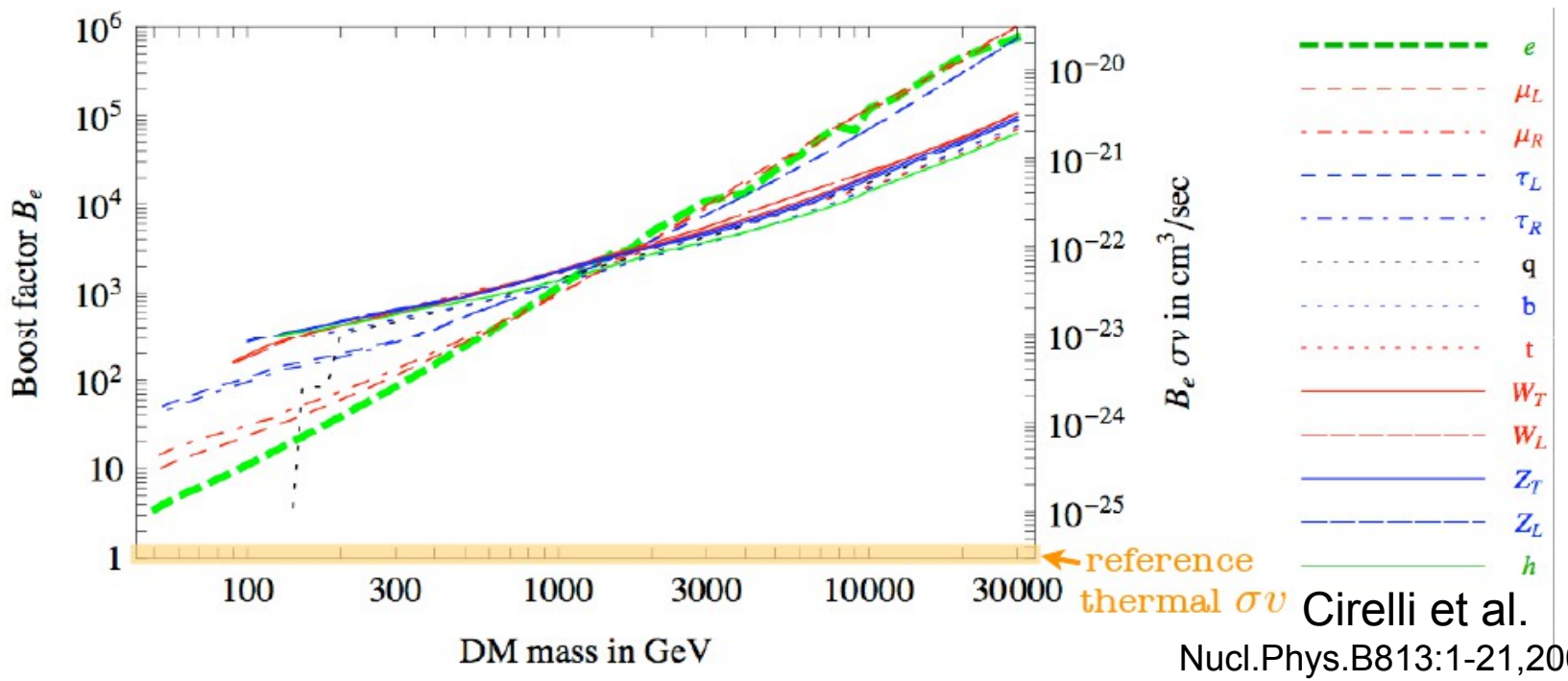
$\langle\sigma v\rangle \sim 3\times10^{-26}$ cm^3/s. **(WIMP)**

→ **Annihilation rate**:

$\Gamma \sim n^2 \langle\sigma v\rangle$. 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**:

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

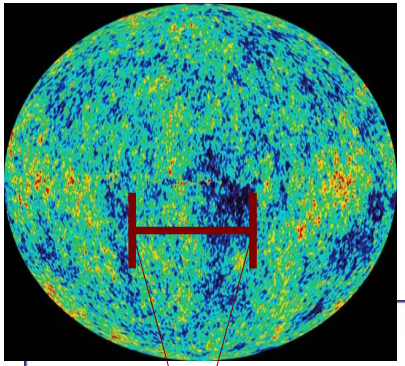
BOOST of the cross section to explain the data, depends on mass of DM and annihilation channel.

Dark Matter annihilation should leave a signature in CMB:

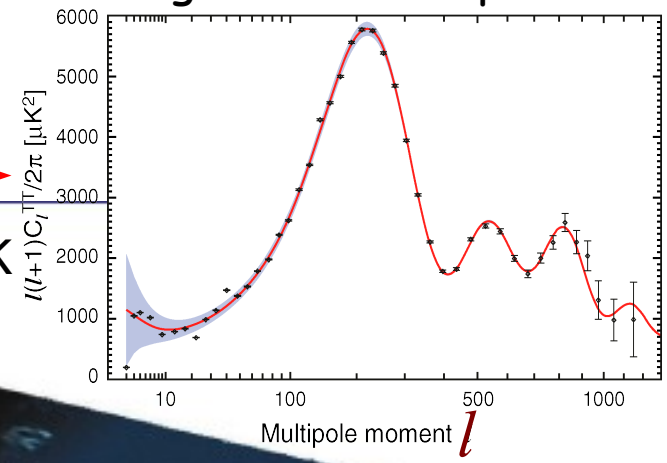
- At (z~1000), when CMB forms, the homogeneous dark matter density is $n(z=1000) = n_{today}\,(1+z)^3 \sim n_{today} \times 10^9$

- DM mean velocity **$\beta \sim 10^{-8}$**. Favours Sommerfeld Enhancement.

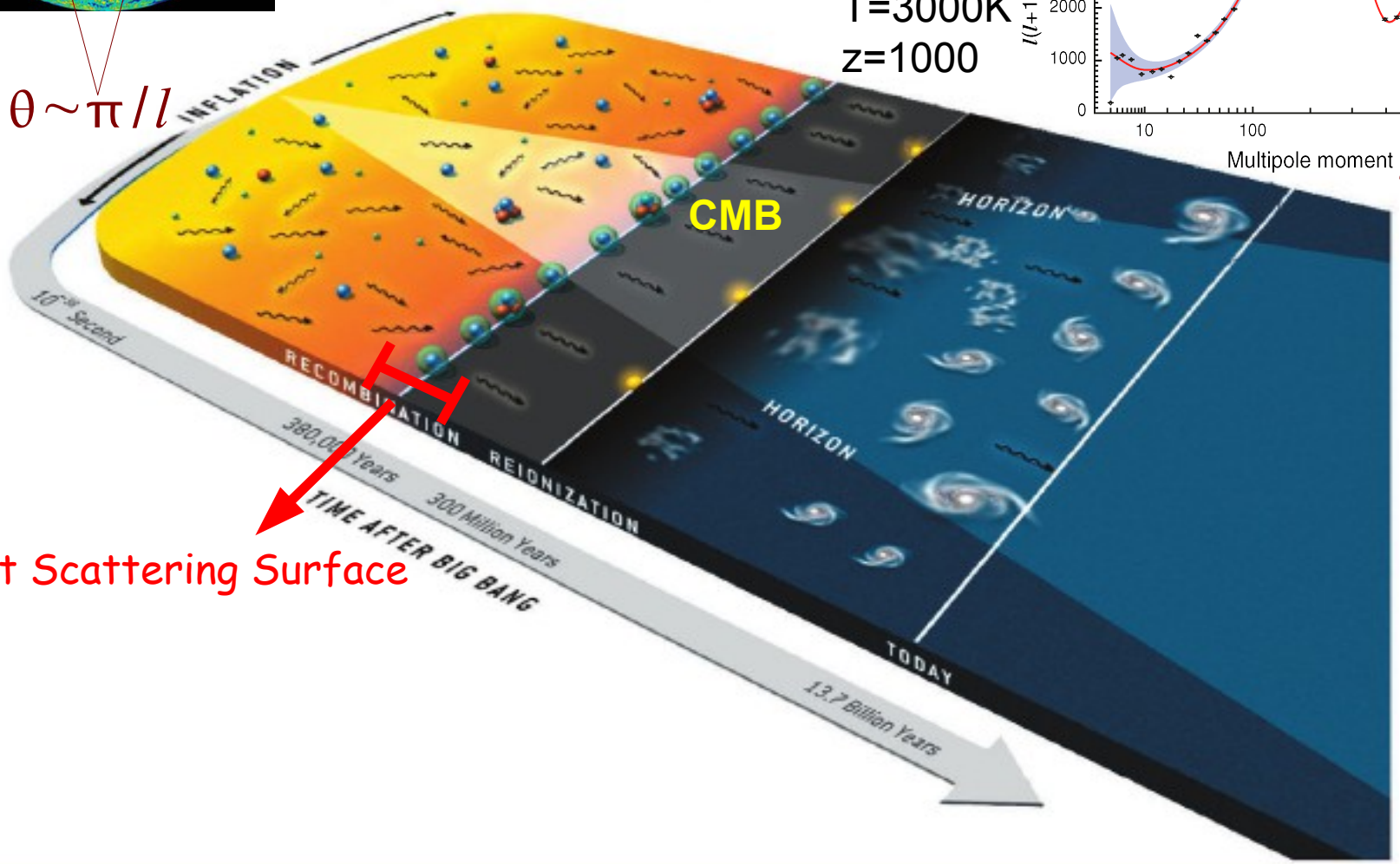
CMB



$\theta \sim \pi / l$



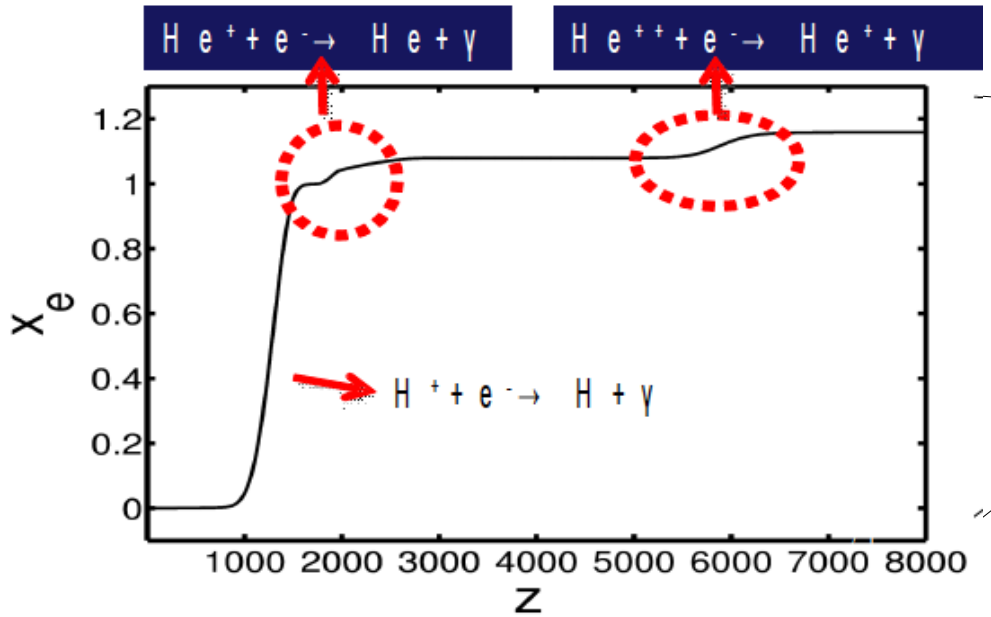
T=3000K
z=1000

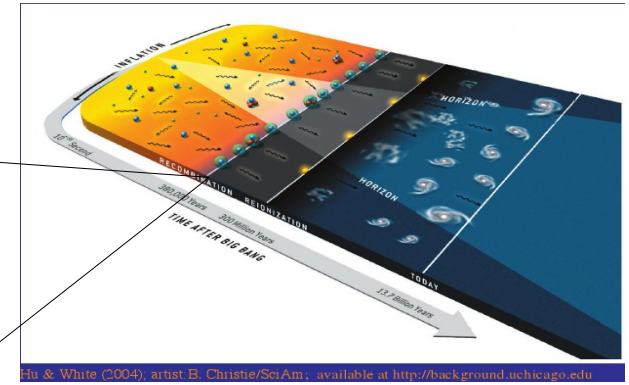


Last Scattering Surface

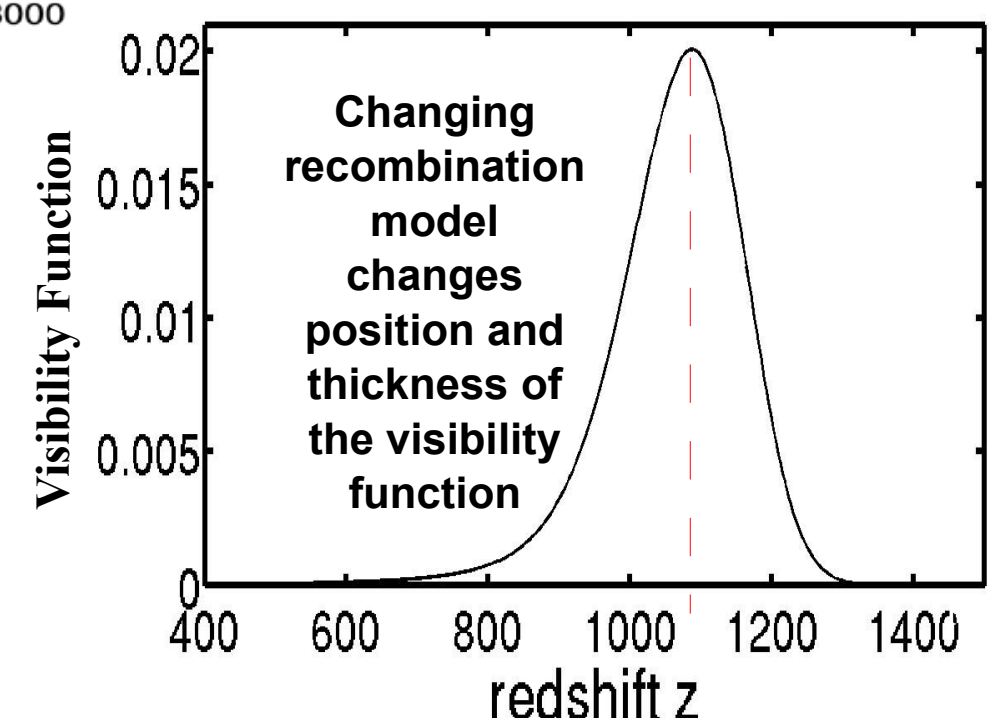
Hu & White (2004); artist: B. Christie/SciAm; available at http://background.uchicago.edu

Recombination and Visibility Function





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



DM annihilation in the recombination epoch

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

p_{ann}

$$\chi_i \frac{dE}{dt} \qquad \chi_\alpha \frac{dE}{dt} \qquad \chi_h \frac{dE}{dt}$$

IONIZATIONS LYMAN-α HEATING

DM annihilation in the recombination epoch

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$$\chi_i \frac{dE}{dt}$$

IONIZATIONS

$$\chi_\alpha \frac{dE}{dt}$$

LYMAN-α

$$\chi_h \frac{dE}{dt}$$

HEATING

- f(z) is the fraction of energy that from the annihilation is absorbed by the plasma at each z. Depends on DM mass and annihilation channel.

DM annihilation in the recombination epoch

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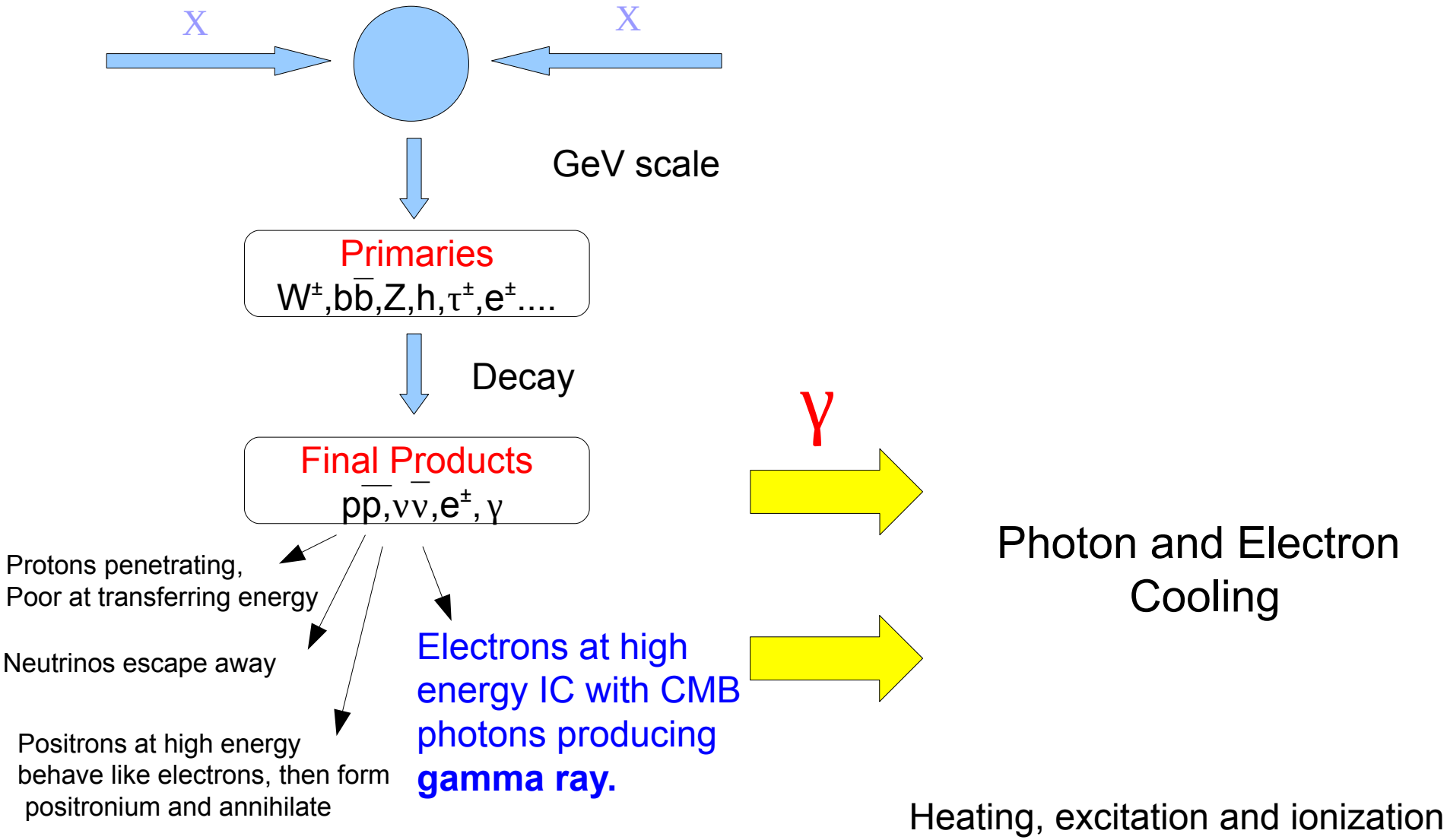
$$\chi_i \frac{dE}{dt} \qquad \chi_\alpha \frac{dE}{dt} \qquad \chi_h \frac{dE}{dt}$$

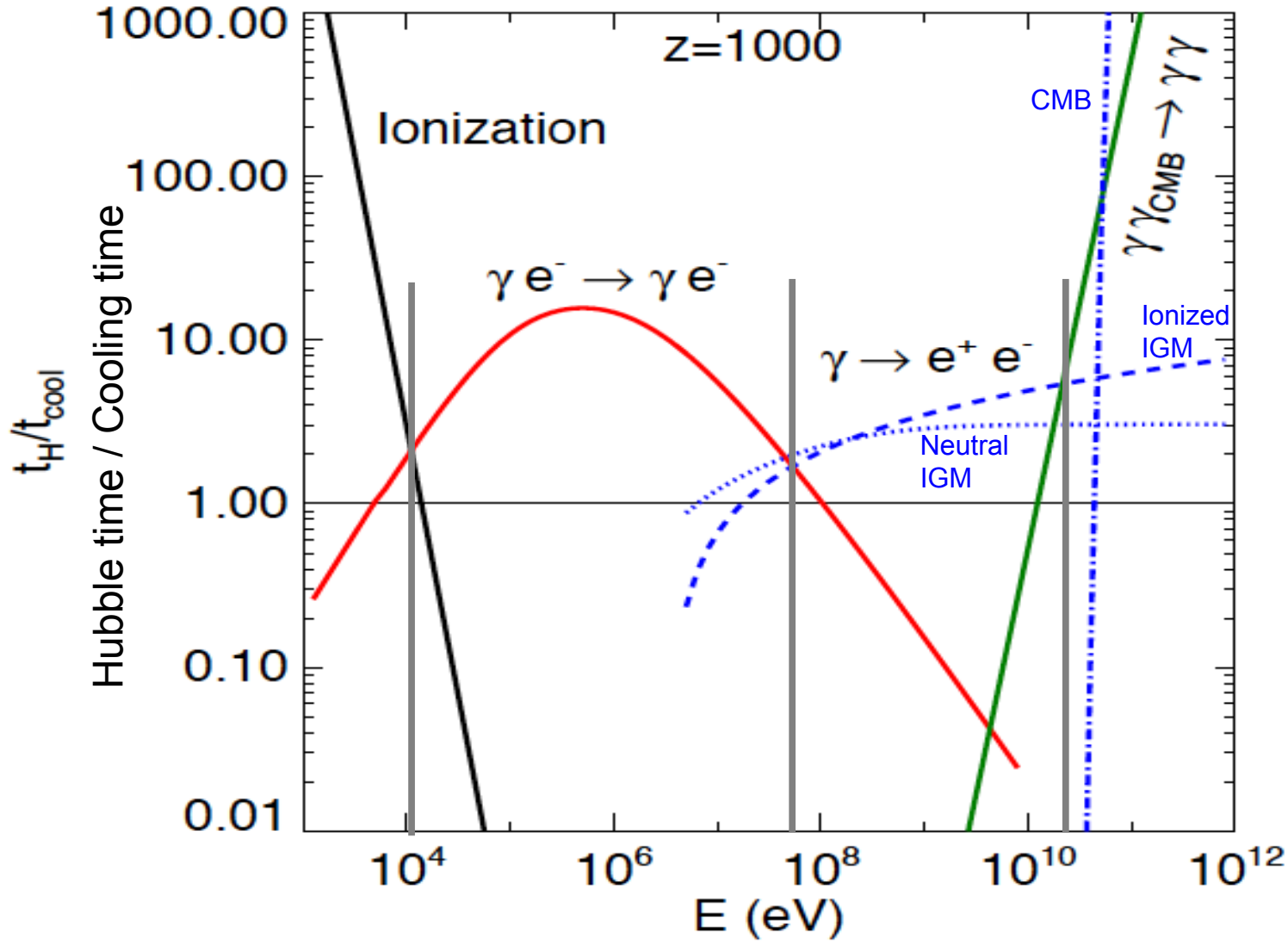
IONIZATIONS LYMAN-α HEATING

- χ_i are the fractions going into heating, ionization and excitation (Lyman alpha) of the medium!

Energy Deposition History



Photon cooling



z=1000

Slatyer 2009

~10 KeV ~100 MeV ~10 GeV

Ionization

Compton Scattering

Pair production

Photon Scattering

Propagation of the shower

DM

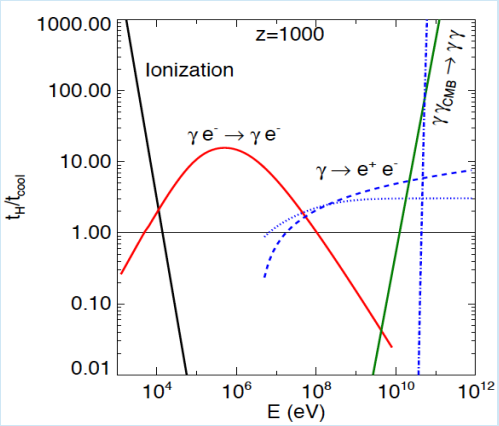
↓

Secondary shower

E~TeV/GeV

f(z)

►Photon cooling:



►Electron cooling:

-Through IC

-Trough absorption in plasma

t_cool ~ t_H → redshifting need to be taken into account, NO on the SPOT!

e⁻

E~KeV

$\chi_i(x\_e)$

- H, He, HeI ionization
- H, He excitation;
- collisions with thermal electrons;
- free-free interactions with ionized atoms;
- recombinations.

Many very rapid processes, t_cool<<t_H. OK on the SPOT OK. MCMC approach.

Propagation of the shower

DM

↓

Secondary shower

E~TeV/GeV

→

f(z)

High energy Code
(Slatyer et al.)

- Analytical
- $t_{cool} \sim t_H$, redshifting need to be taken into account
- Electron and photon spectra calculated at each time step.

- NO on the SPOT!

e^- →

E~KeV

$\chi_i(x\_e)$

Low energy Code
(Valdes et al.)

- MCMC from 1 injected electron at energy ~KeV.
- $t_{cool} << t_H$, no redshifting taken into account

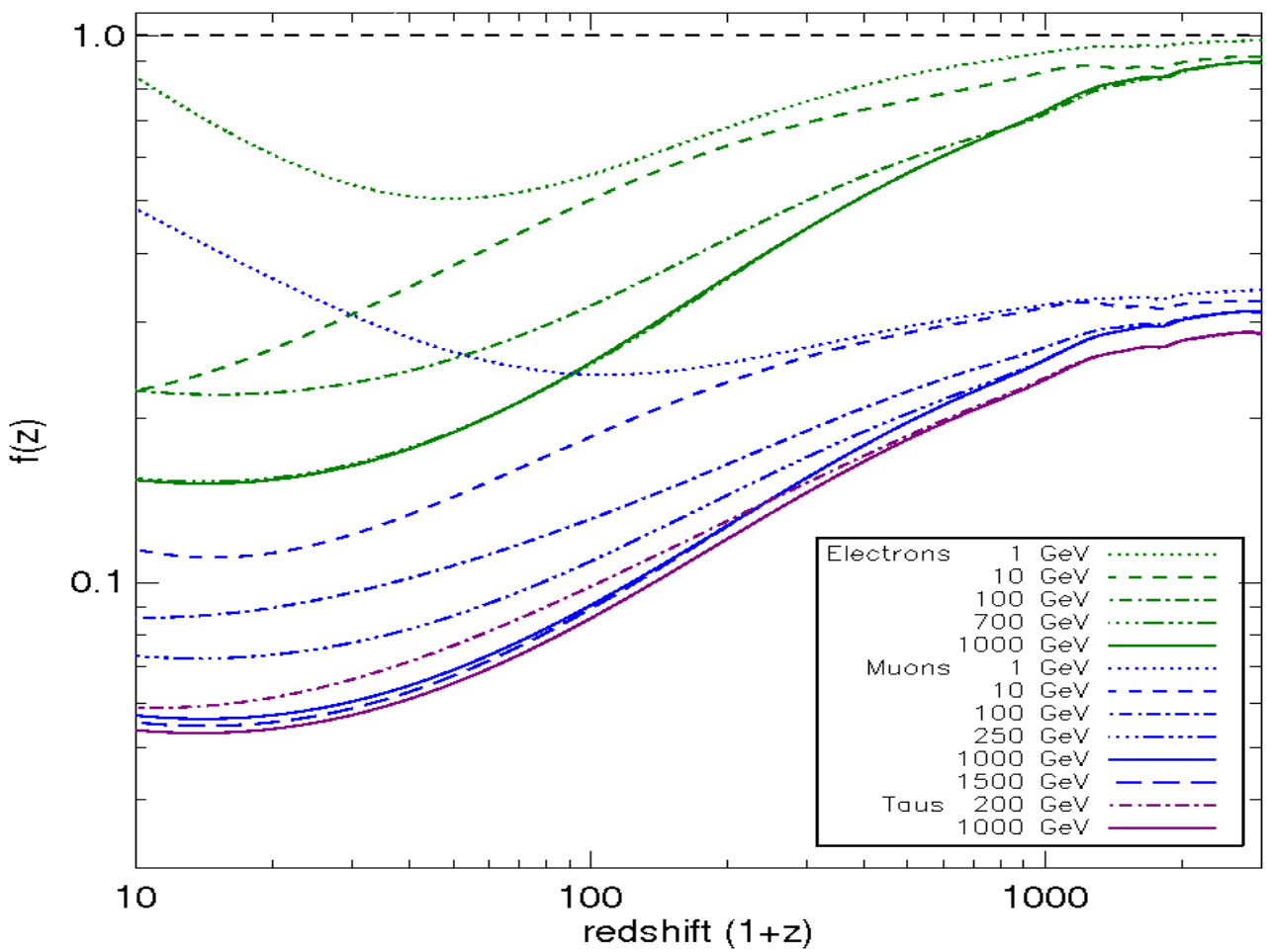
- ON THE SPOT.

Galli, Slatyer, Valdes, Iocco 2013

f(z) fractions

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

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



Slatyer et al. 2009

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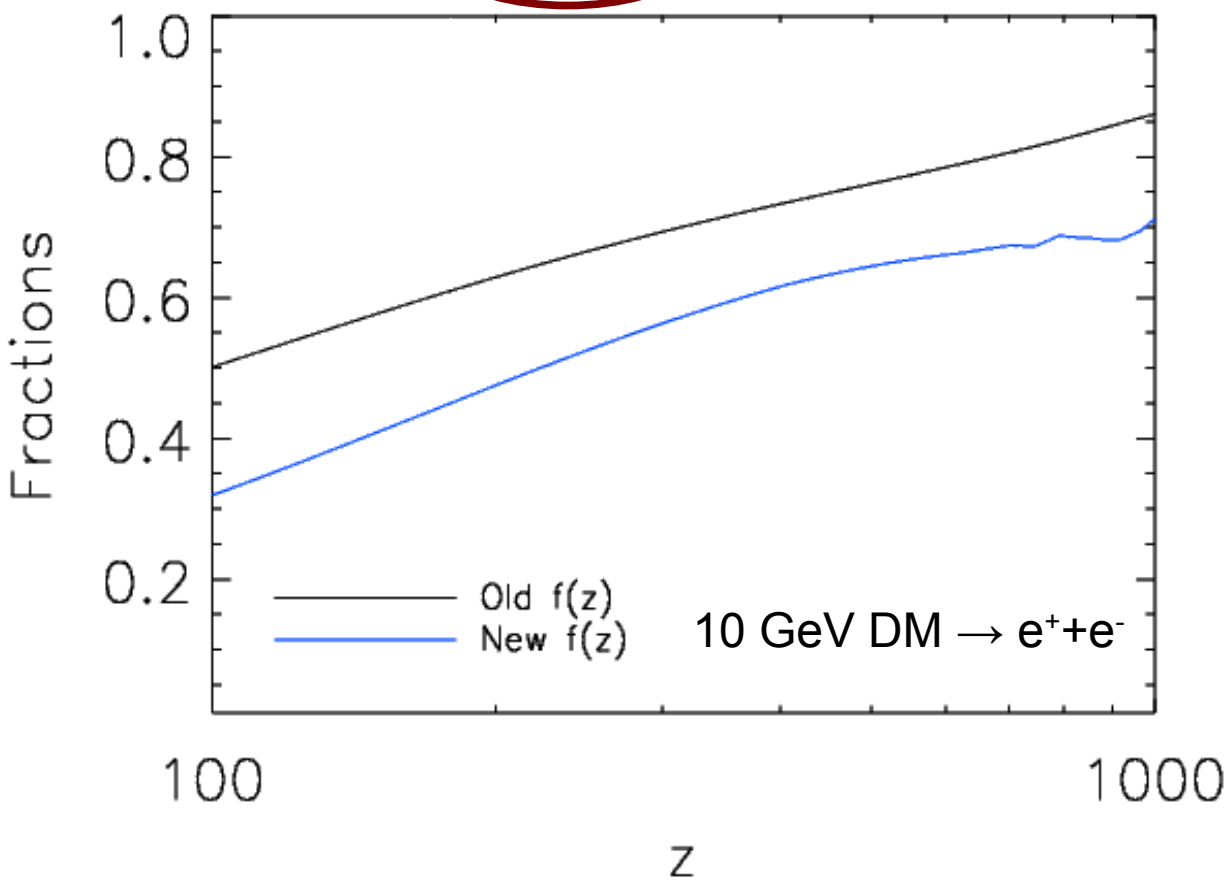
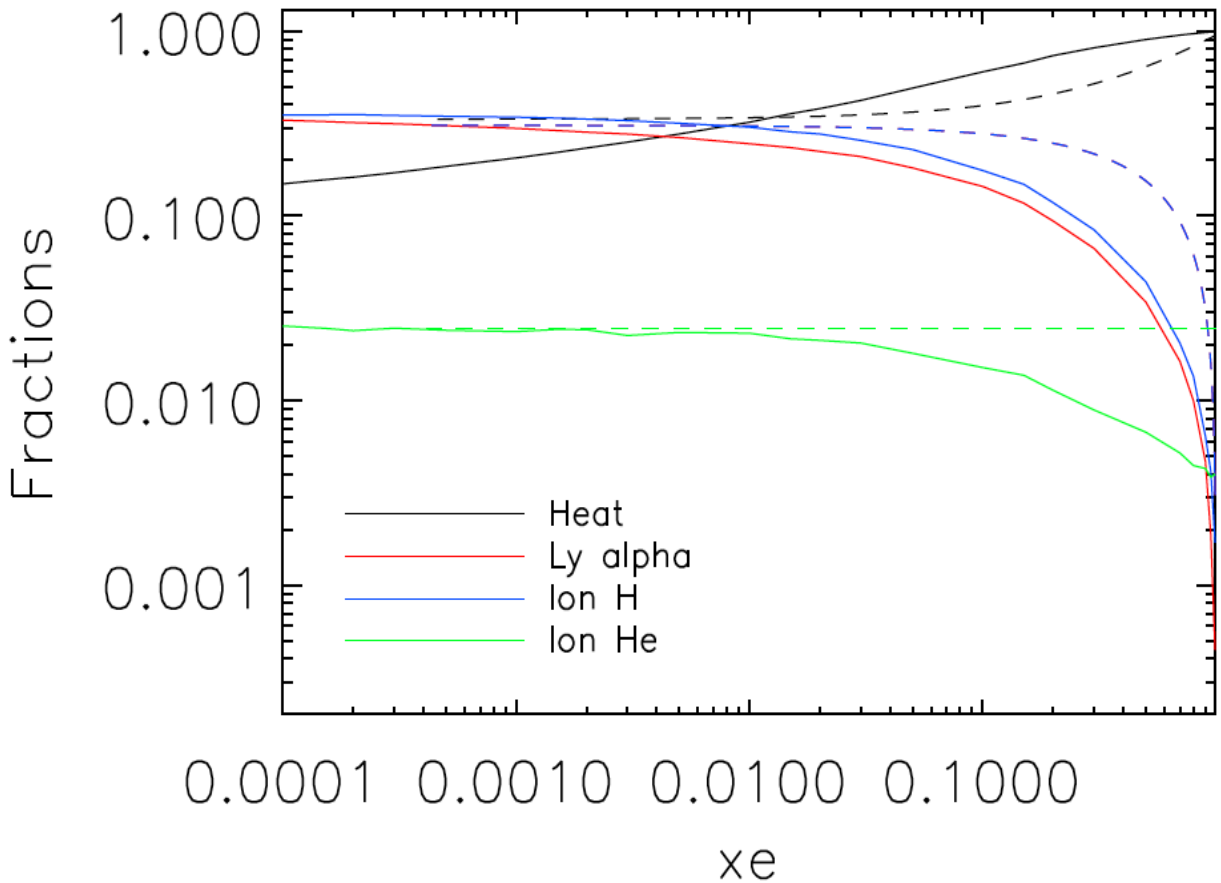


Galli, Slatyer, Valdes, Iocco 2013

Correct vs Approximate χ fractions



Dashed: Approximate fractions used in the literature.

Solid: our accurate new fractions. We calculate for the first time the correct amount of energy going into Lyman α radiation.

We checked our fractions again a very large number of possible systematics, none of them affects the constraints.

Galli, Slatyer, Valdes, Iocco, 2013

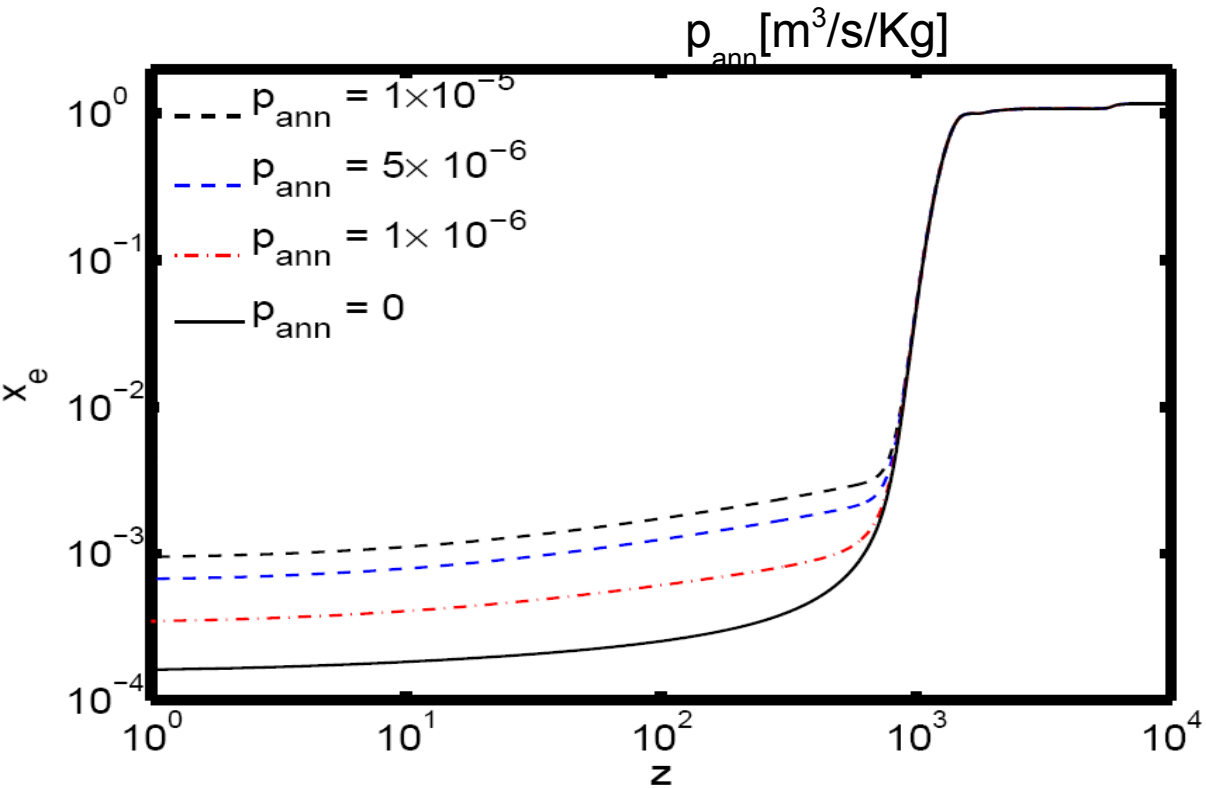
EFFECT ON THE CMB

DM annihilation in the recombination epoch

p_{ann}

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

•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.

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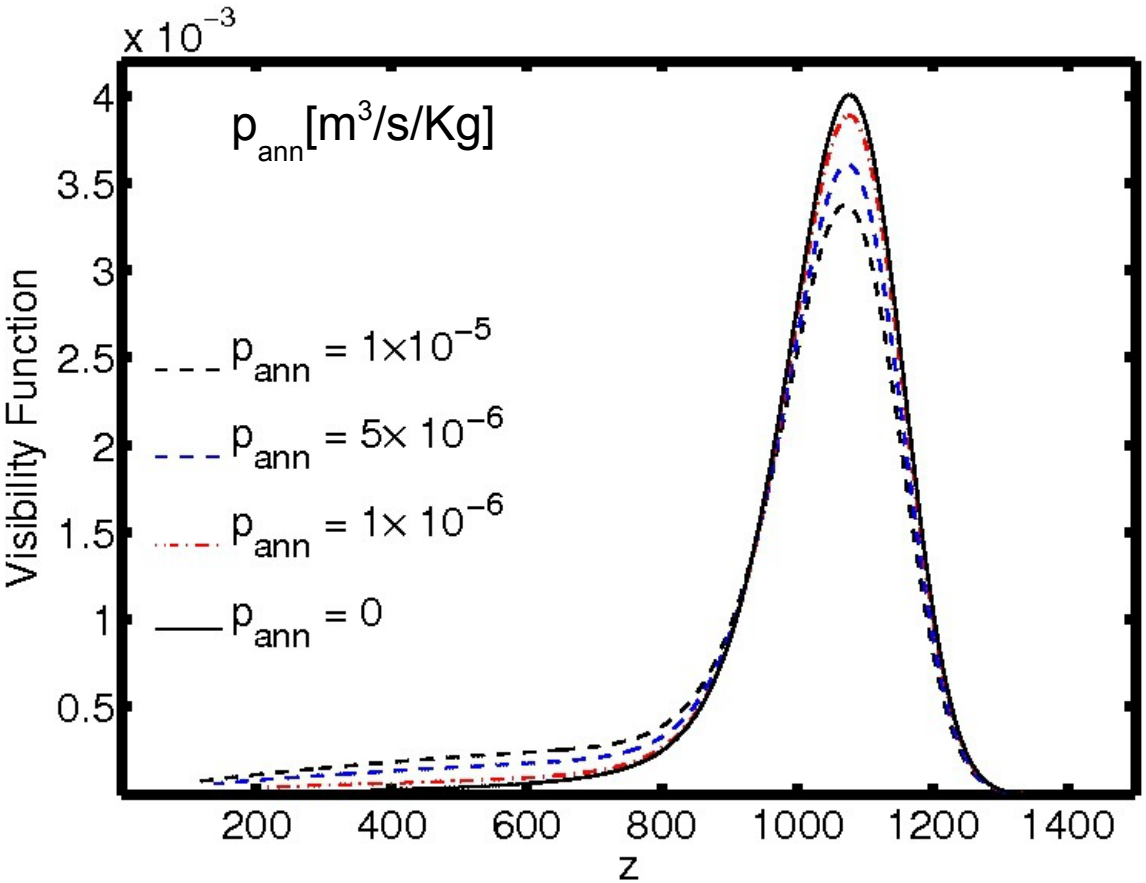
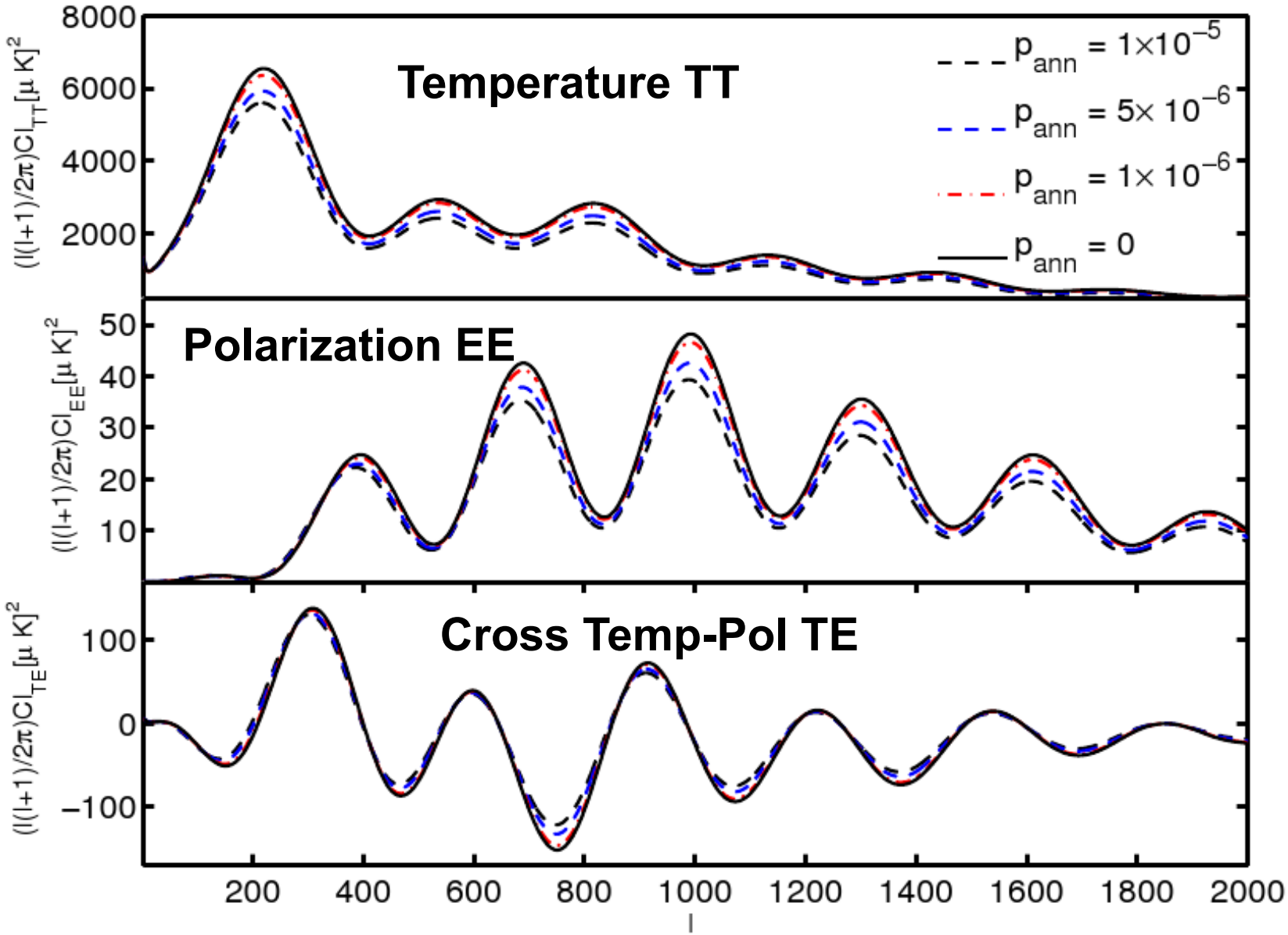


•A larger amount of free electrons after recombination makes the width of the visibility function larger.

CMB Angular Power Spectra



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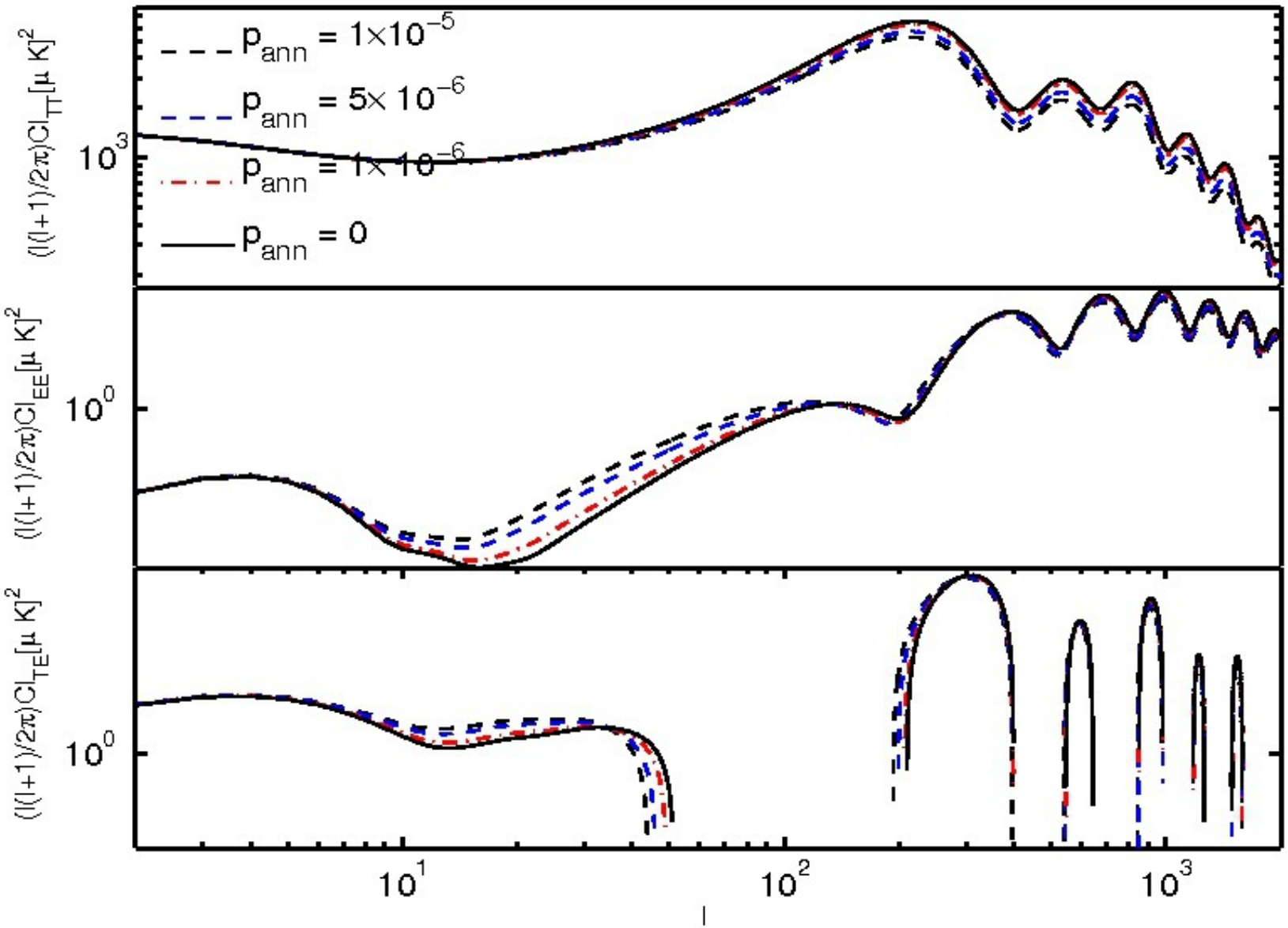


Constraints....

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, mm 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)

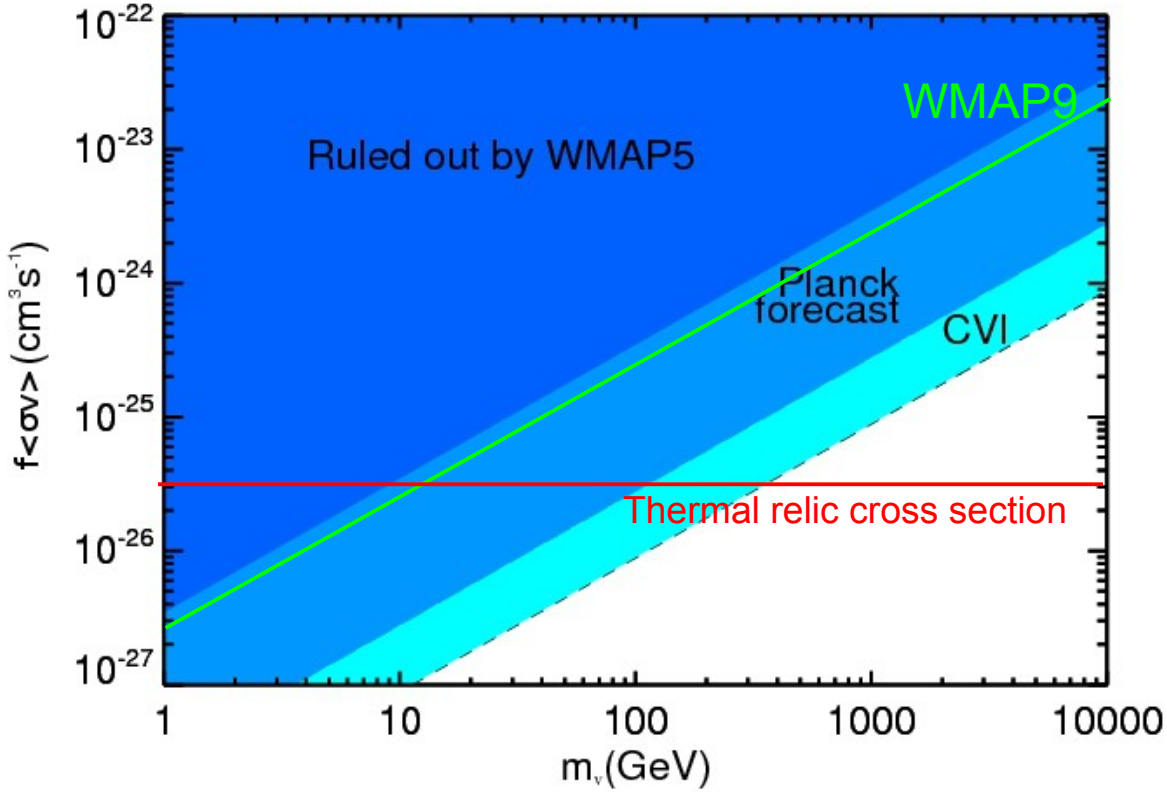
Giesen et al. 2012 (WMAP7+SPT, f constant and variable)

Lopez-Honorez, L. et al 2013 (WMAP9+ACT2013/SPT2013.)

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.

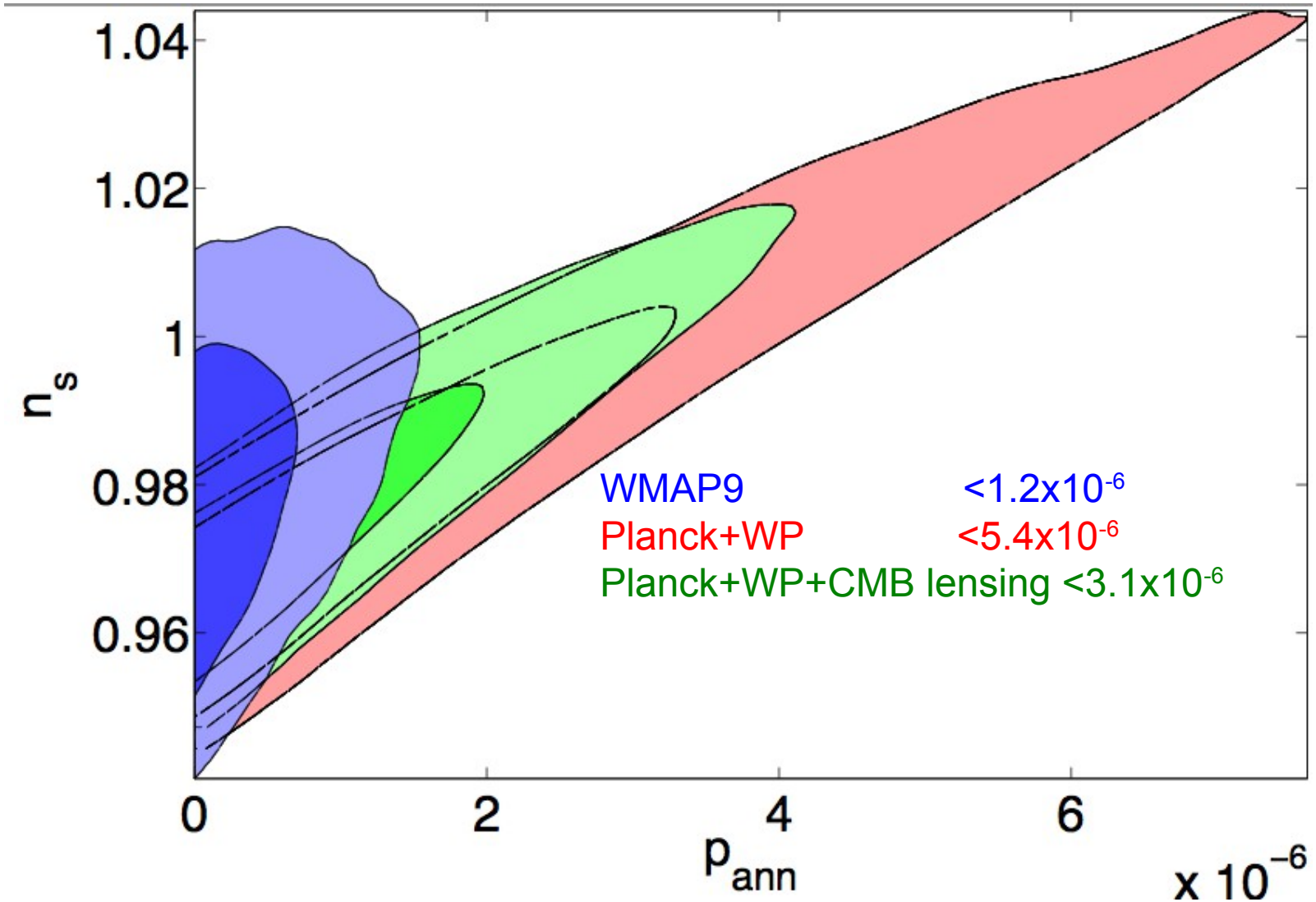


$p_{ann}[m^3/s/Kg]$ at 95% c.l.	
WMAP5	$< 2.0 \times 10^{-6}$
WMAP7	$< 1.4 \times 10^{-6}$
WMAP7+ACT	$< 1.2 \times 10^{-6}$
Planck	$< 1.7 \times 10^{-7}$
CVl	$< 5.9 \times 10^{-8}$

Forecasts!

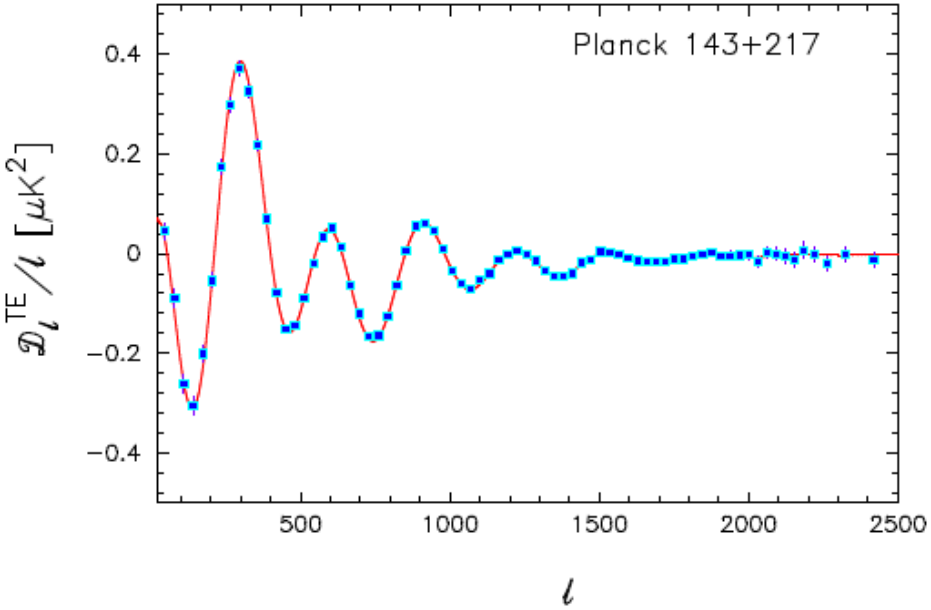
SG, F. Iocco, G. Bertone, A. Melchiorri, Phys. Rev. D, vol. 80, Issue 2, 2009.
SG, F. Iocco, G. Bertone, A. Melchiorri, 2011, Phys. Rev. D, 84, 02730.

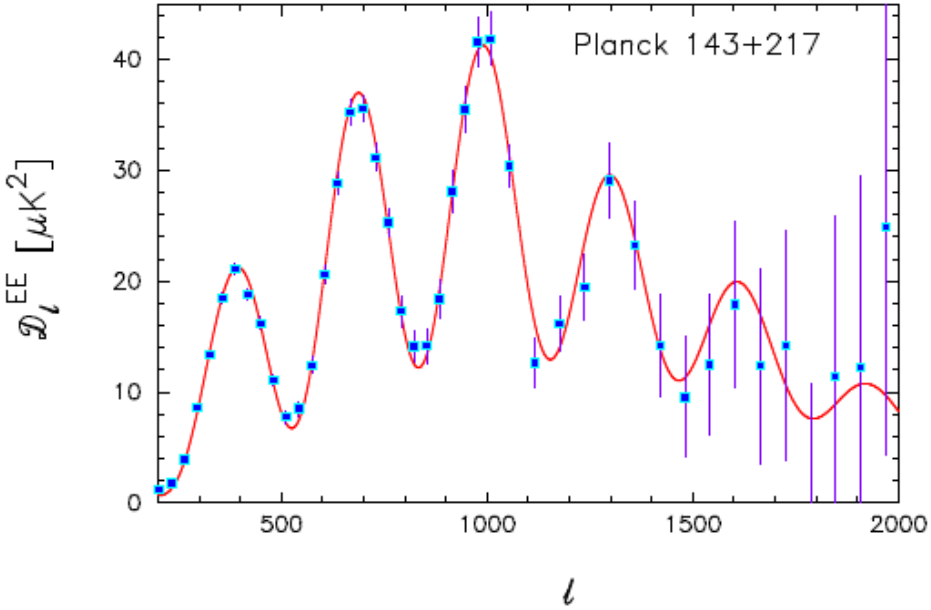
Planck constraints (from TT only)

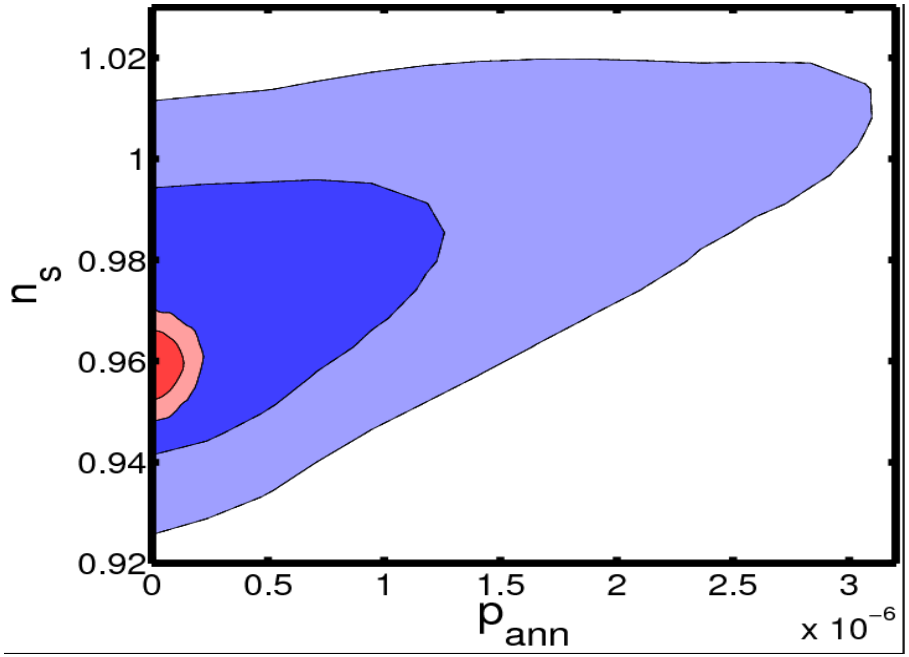


[m^3/s/kg]

Polarization (not used in this release)







FORECAST!

Wmap (Blue)

Planck simulated (Red)

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^-	$< 2.41 \times 10^{-27}$	$< 2.41 \times 10^{-27}$	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

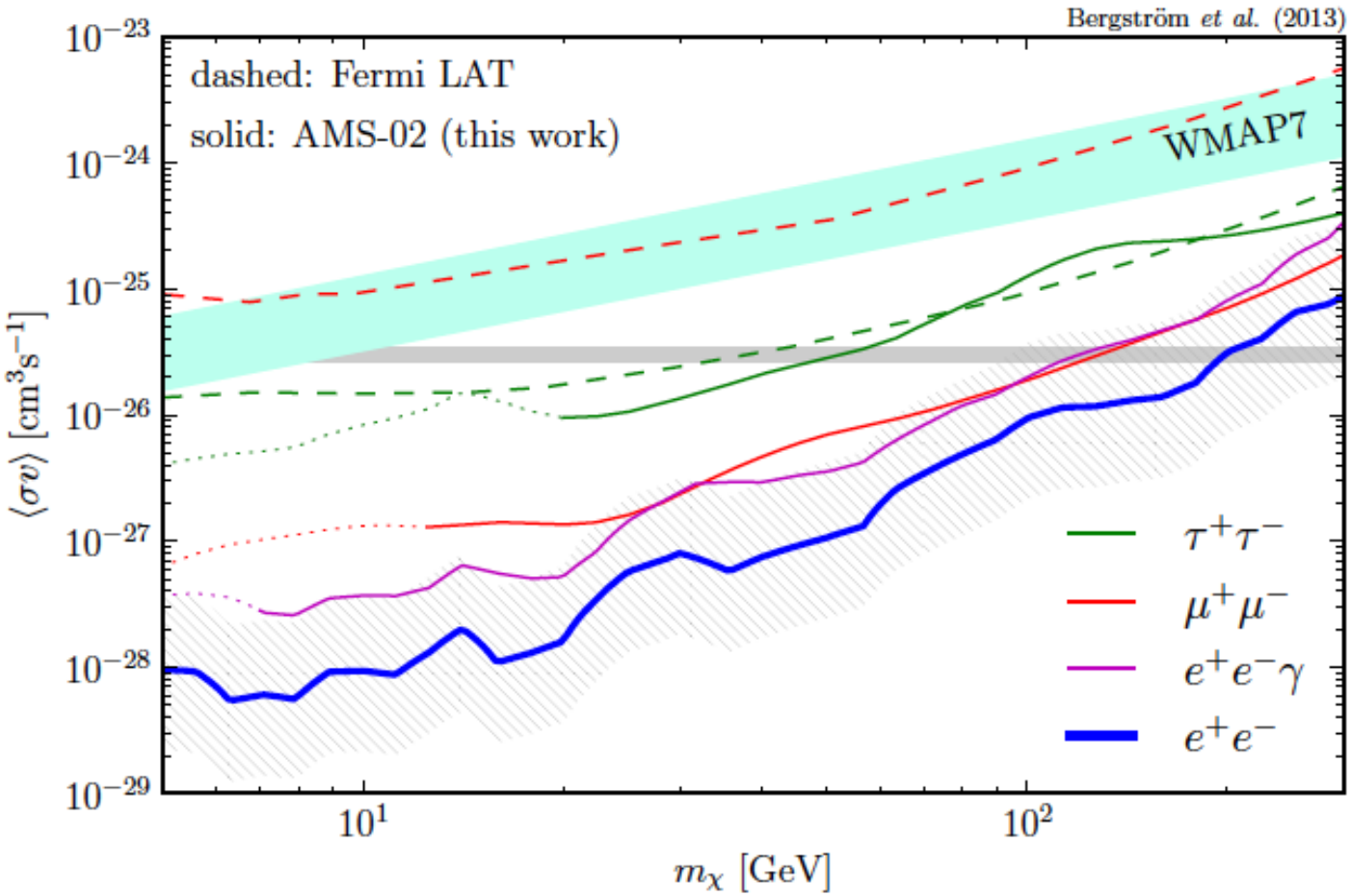
$$\frac{dE}{dt} = \rho_c^2 c^2 \Omega_{dm} (1+z)^6 f(z) \frac{<\sigma v>}{m_\chi}$$

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

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.

Comparison of constraints



CMB constraints from Galli et al. 2011

Fermi constraints from dwarf spheroidal galaxies (Fermi-LAT Collaboration 2011).

AMS constraints from feature searches in positron spectrum.(Bergstrom 2013)

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.

Variation of the fine structure constant

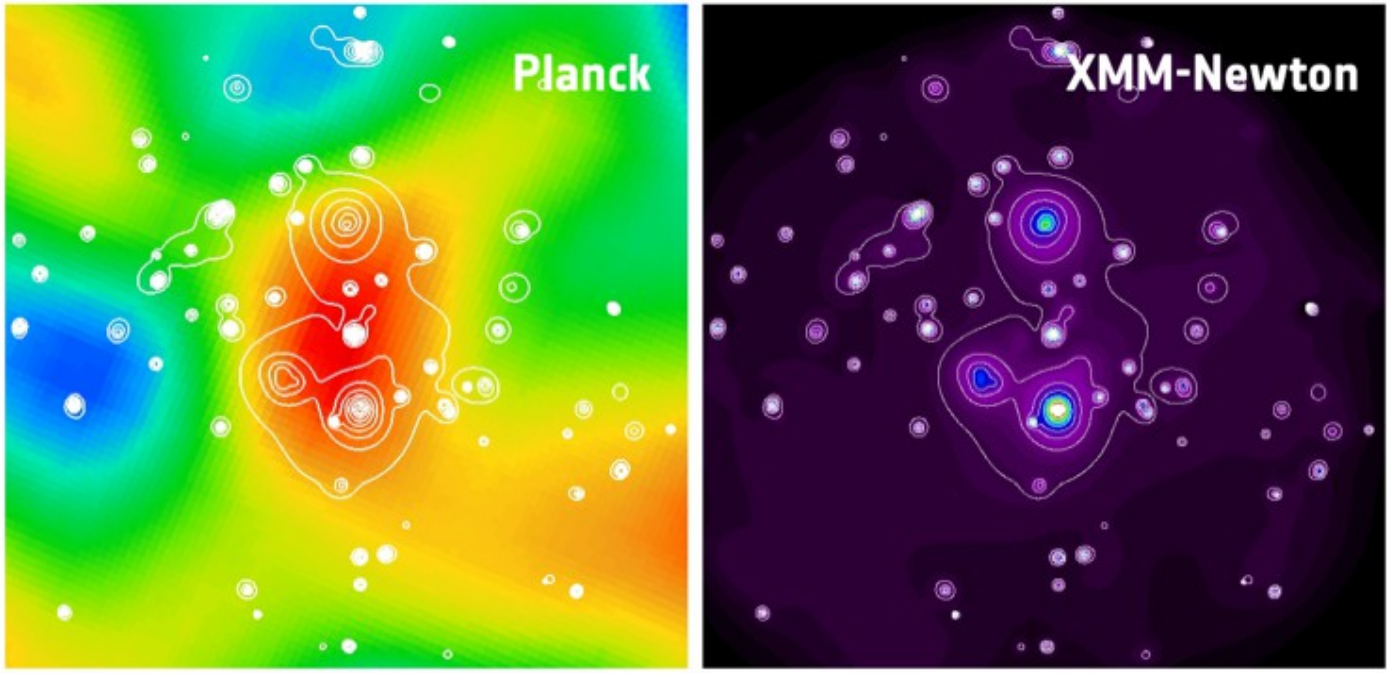
The short version

New probe of variation of fine structure constant

Clusters can be observed through:

SZ effect:Clusters leave an imprint in the CMB spectrum as the hot gas inverse Compton scatter CMB photons.
X-rays: Clusters at T>2 KeV mainly emit through Bremsstrahlung effect.

From both, one can estimate quantities proportional to the thermal energy of the cluster.



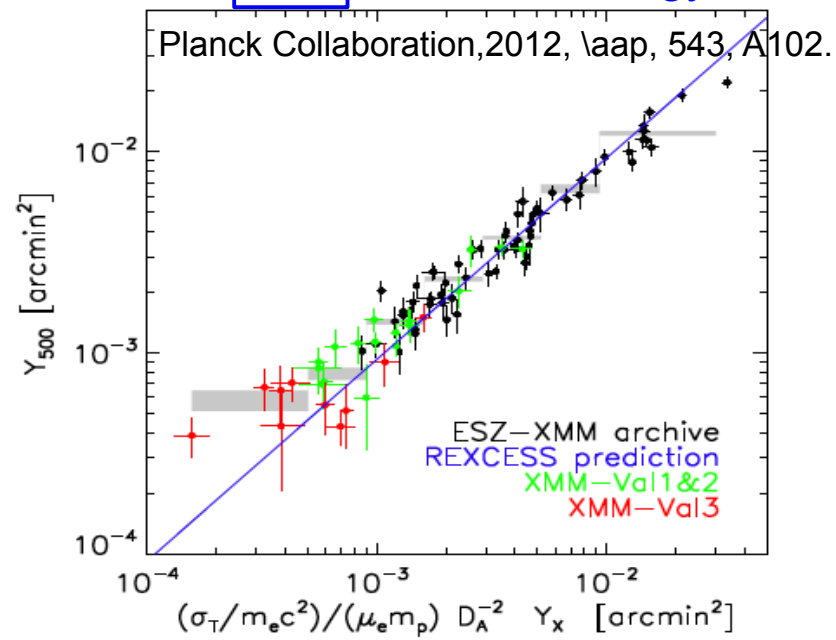
New probe of variation of fine structure constant

SZ effect → Inverse Compton scattering → Y_{SZ} α^2

X-ray emission → Bremsstrahlung effect → Y_X $\alpha^{-1.5}$

Estimates of cluster thermal energy

$$\left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_i = \left(\frac{\alpha_i}{\alpha_0}\right)^{3.5} \left(\frac{Y_{SZ} D_A^2}{Y_X}\right)_0$$



With 62 clusters observed by Planck in SZ and XMM-Newton in Xrays,

0.8% constraint on α

Comparable to CMB constraints today (but completely different redshift range) and are robust!

S. Galli, PRD 2013, accepted for publication

The long version

Testing the validity of known physics

•Fundamental Constants characterize theories, only measured and not theoretically predictable.

•Testing for variation of constants corresponds to testing validity of known physics.

•Fine Structure Constant (strength e.m. force)

- Claim of a space-time variation of α in quasars. (Webb et al. 2004, 2011)
- From Pre-Planck CMB constraints at 2% (0.5% in combination) (Menegoni, SG, et al 2009, 2010 2012; Galli et al 2009, Martins, SG et al 2010)
  - Planck alone CMB constraint at 0.4%!

CMB constraints test physics at redshift ~1000.
Time-space scales different from laboratory constraints.

The Fine Structure Constant ?

Evidence for spatial variation of the fine structure constant

J. K. Webb[1], J. A. King[1], M. T. Murphy[2], V. V. Flambaum[1], R. F. Carswell[3], and M. B. Bainbridge[1]
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(Dated: August 25, 2010)

We previously reported observations of quasar spectra from the Keck telescope suggesting a smaller value of the fine structure constant, α, at high redshift. A new sample of 153 measurements from the ESO Very Large Telescope (VLT), probing a different direction in the universe, also depends on redshift, but in the opposite sense, that is, α appears on average to be larger in the past. The combined dataset is well represented by a spatial dipole, significant at the 4.1σ level, in the direction right ascension 17.3 ± 0.6 hours, declination -61 ± 9 degrees. A detailed analysis for systematics, using observations duplicated at both telescopes, reveals none which are likely to emulate this result.

PACS numbers: 06.20.Jr, 95.30.Dr, 95.30.Sf, 98.62.Ra, 98.80.-k, 98.80.Es, 98.80.Jk

Webb, J. K., King, J. A., Murphy, M. T., Flambaum, et al. 2011, PRL, 107, 191101, arXiv:1008.3907

The Fine Structure Constant ?

The UVES Large Program for Testing Fundamental Physics: I Bounds on a change in α towards quasar HE 2217−2818 ★

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ABSTRACT

Context. Absorption-line systems detected in quasar spectra can be used to compare the value of the fine-structure constant, α, measured today on Earth with its value in distant galaxies. In recent years, some evidence has emerged of small temporal and also spatial variations of α on cosmological scales which may reach a fractional level of ≈10 ppm (parts per million).

Aims. To test these claims we are conducting a "Large Program" of observations with the Very Large Telescope's Ultraviolet and Visual Echelle Spectrograph (UVES). We are obtaining high-resolution ($R \approx 60000$) and high signal-to-noise ratio (S/N ≈ 100) UVES spectra calibrated specifically for this purpose. Here we analyse the first complete quasar spectrum from this Program, that of HE 2217−2818.

Methods. We apply the Many Multiplet method to measure α in 5 absorption systems towards this quasar: z_{abs} = 0.7866, 0.9424, 1.5558, 1.6279 and 1.6919.

Results. The most precise result is obtained for the absorber at $z_{abs} = 1.6919$ where 3 Fe II transitions and Al II λ1670 have high S/N and provide a wide range of sensitivities to α. The absorption profile is complex, with several very narrow features, and requires 32 velocity components to be fitted to the data. We also conducted a range of tests to estimate the systematic error budget. Our final result for the relative variation in α in this system is $\Delta\alpha/\alpha = +1.3 \pm 2.4_{stat} \pm 1.0_{sys}$ ppm. This is one of the tightest current bounds on α-variation from an individual absorber. A second, separate approach to the data-reduction, calibration and analysis of this system yielded a slightly different result of $-3.8 \pm 2.1_{stat}$ ppm, possibly suggesting a larger systematic error component than our tests indicated. This approach used an additional 3 Fe II transitions, parts of which were masked due to contamination by telluric features. Restricting this analysis to the Fe II transitions only and using a modified absorption profile model, gave a result consistent with the first approach, $\Delta\alpha/\alpha = +1.1 \pm 2.6_{stat}$ ppm. The other 4 absorbers have simpler absorption profiles, with fewer and broader features, and offer transitions with a smaller range of sensitivities to α. Therefore, they provide looser bounds on $\Delta\alpha/\alpha$ at the ≳10 ppm precision level.

Conclusions. The absorbers towards quasar HE 2217−2818 reveal no evidence for variation in α at the 3-ppm precision level (1-σ confidence). If the recently-reported 10-ppm dipolar variation of α across the sky were correct, the expectation at this sky position is (3.2–5.4) ± 1.7 ppm depending on dipole model used. Our constraint of $\Delta\alpha/\alpha = +1.3 \pm 2.4_{stat} \pm 1.0_{sys}$ ppm is not inconsistent with this expectation.

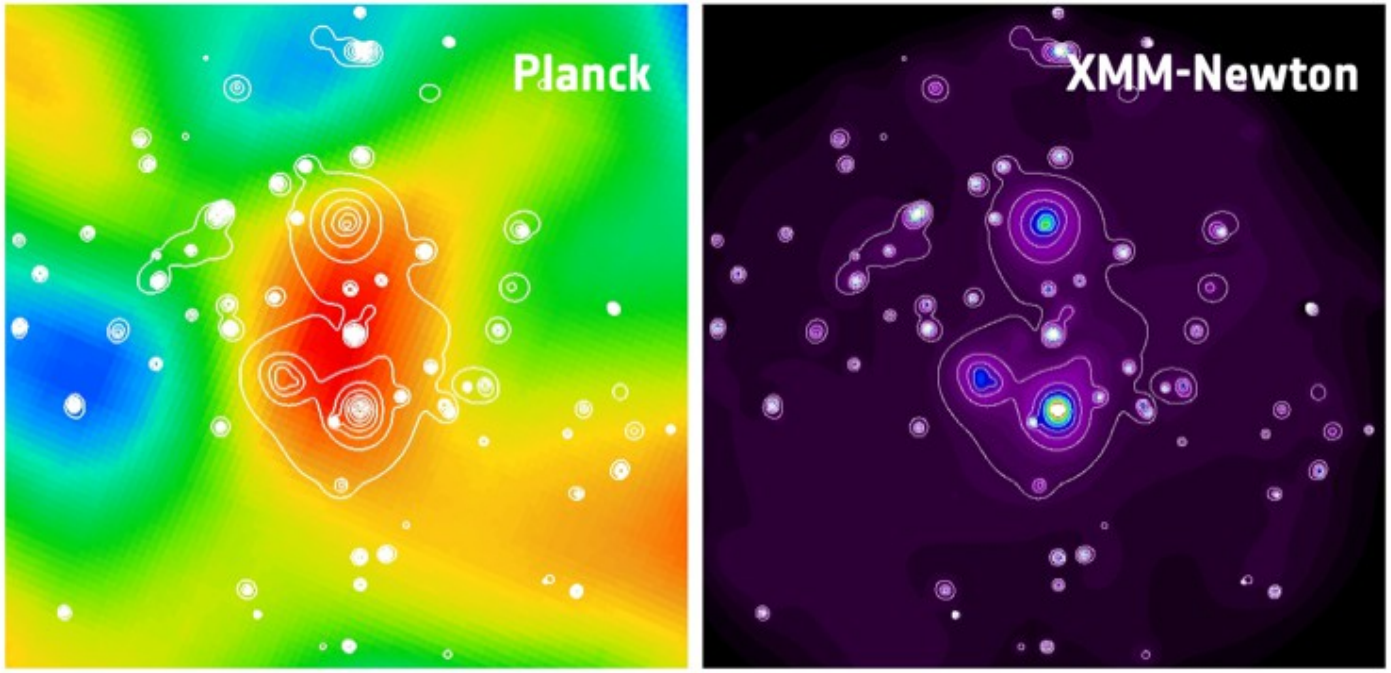
New probe of variation of fine structure constant

Clusters can be observed through:

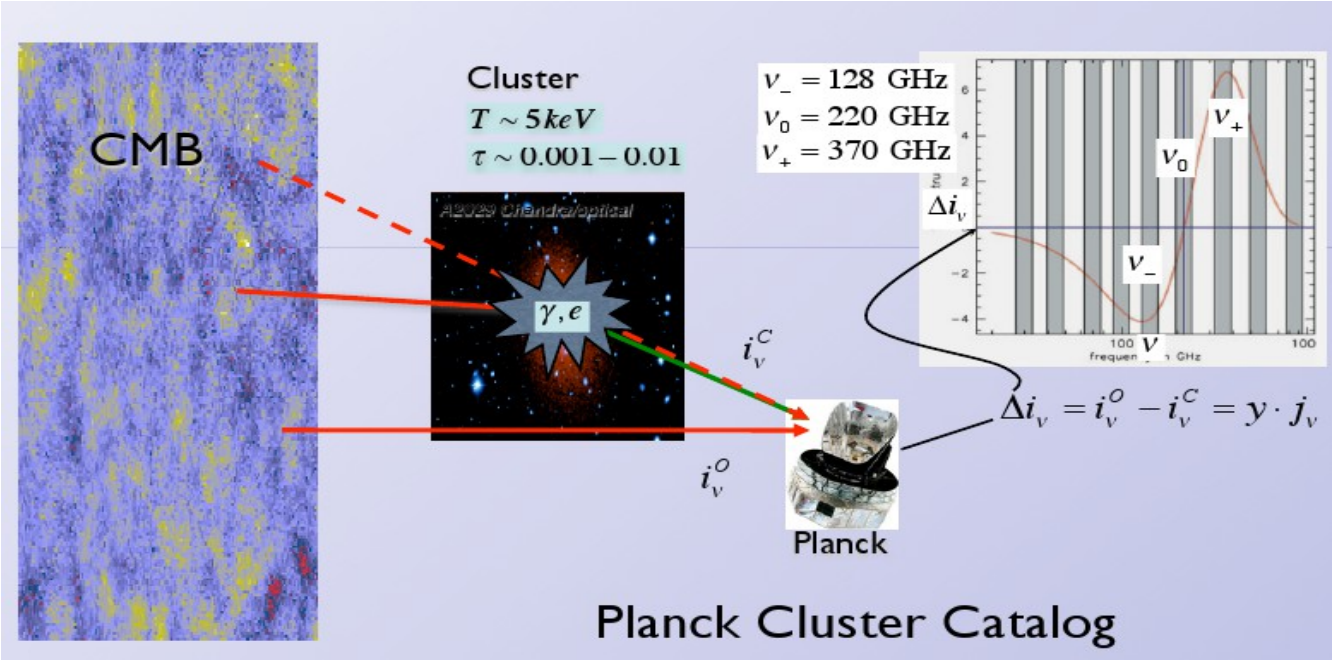
SZ effect: Clusters leave an imprint in the CMB spectrum as the hot gas inverse Compton scatter CMB photons.

X-rays: Clusters at T>2 KeV mainly emit through Bremsstrahlung effect.

From both, one can estimate quantities proportional to the thermal energy of the cluster.



Ysz and the fine structure constant



The spectral distortion due to the SZ effect is proportional to the y parameter. This is proportional to the thermal pressure integrated along the line of sight.

$$y = \frac{\sigma_T}{m_e c^2} \int n_e(r) T(r) dl$$

Thomson scattering cross section

SZ and the fine structure constant

The spherical $Y_{sz}D_A^2$ is the estimate of the thermal energy of the cluster from SZ.

$$Y_{SZ}^{sp}(R)D_A^2 = \frac{\sigma_T}{m_e c^2}\int_0^R n(r)T(r)4\pi r^2 dr$$

$$\sigma_T = \frac{8\pi}{3}\frac{\hbar^2}{m_e^2 c^2}\alpha^2$$

$$\boxed{Y_{SZ} \propto \alpha^2}$$

X-ray and the fine structure constant

Y_X is the estimate of the thermal energy from X-rays.

$$Y_X = M_g(R)T_X$$

Gas mass determined from density profile, which is inferred from observed surface brightness of the galaxy. Surface brightness depends on the Bremsstrahlung emissivity, the DEPENDS ON α.

$$\epsilon_\nu = \alpha^3 \frac{2^5 \pi \hbar^3}{3 m_e} \left(\frac{2\pi}{3 m_e k} \right)^{1/2} Z^2 g_{ff} n_e n_i T^{-1/2} e^{-h\nu/kT}$$

X-ray and the fine structure constant

Y_X is the estimate of the thermal energy from X-rays.

$$Y_X = M_g(R)T_X$$

Gas mass determined from density profile, which is inferred from observed surface brightness of the galaxy. Surface brightness depends on the Bremsstrahlung emissivity, the DEPENDS ON α.

$$M_g(R) \propto \sqrt{\alpha^{-3} I_\nu} D_A^{5/2}$$

$$\boxed{Y_X \propto \alpha^{-1.5}}$$

Ysz/Yx and the fine structure constant

SZ effect → Inverse Compton scattering → Y_{sz} α^2

X-ray emission → Bremsstrahlung effect → Y_X $\alpha^{-1.5}$

$$\left(\frac{Y_{SZ}D_A^2}{Y_X}\right)_i = \left(\frac{\alpha_i}{\alpha_0}\right)^{3.5}\left(\frac{Y_{SZ}D_A^2}{Y_X}\right)_0$$

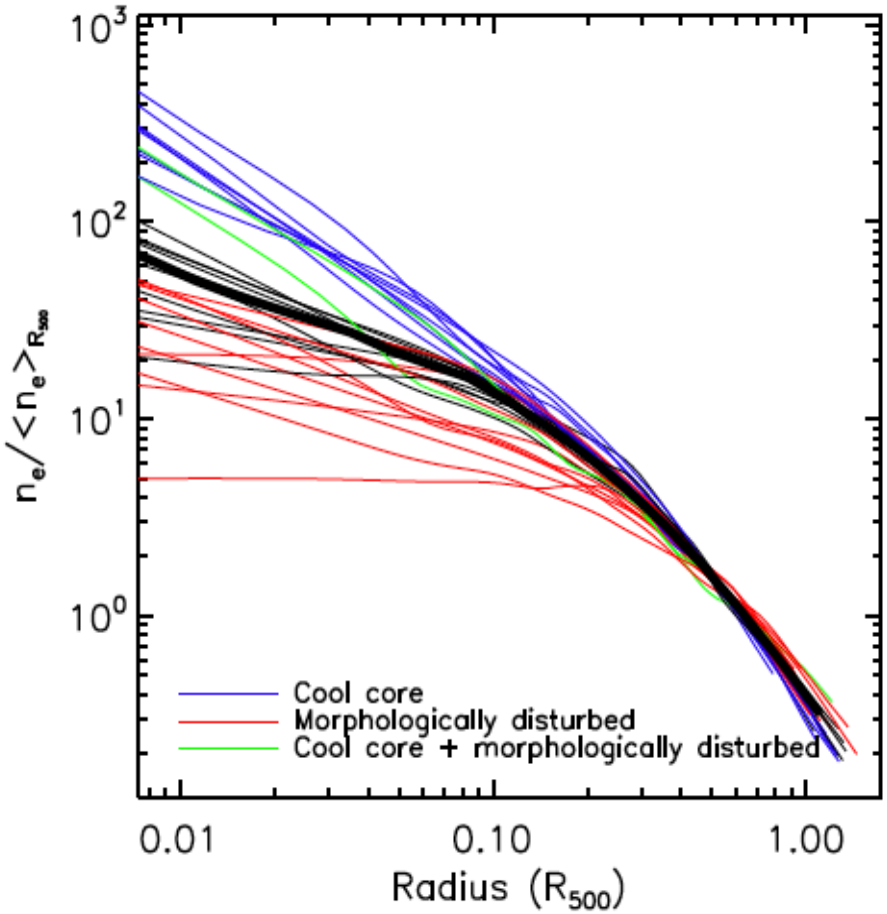
If thermal profile of clusters is universal, because scaling relation are self-similar (evolution of the cluster only determined by gravitational physics-mass), then the ratio is expected to be CONSTANT.

$$\frac{Y_{SZ}D_A^2}{Y_X} = C_{XSZ}\frac{\int n_e(r)T(r)dV}{T_X(R)\int n_e(r)dV} \sim const$$

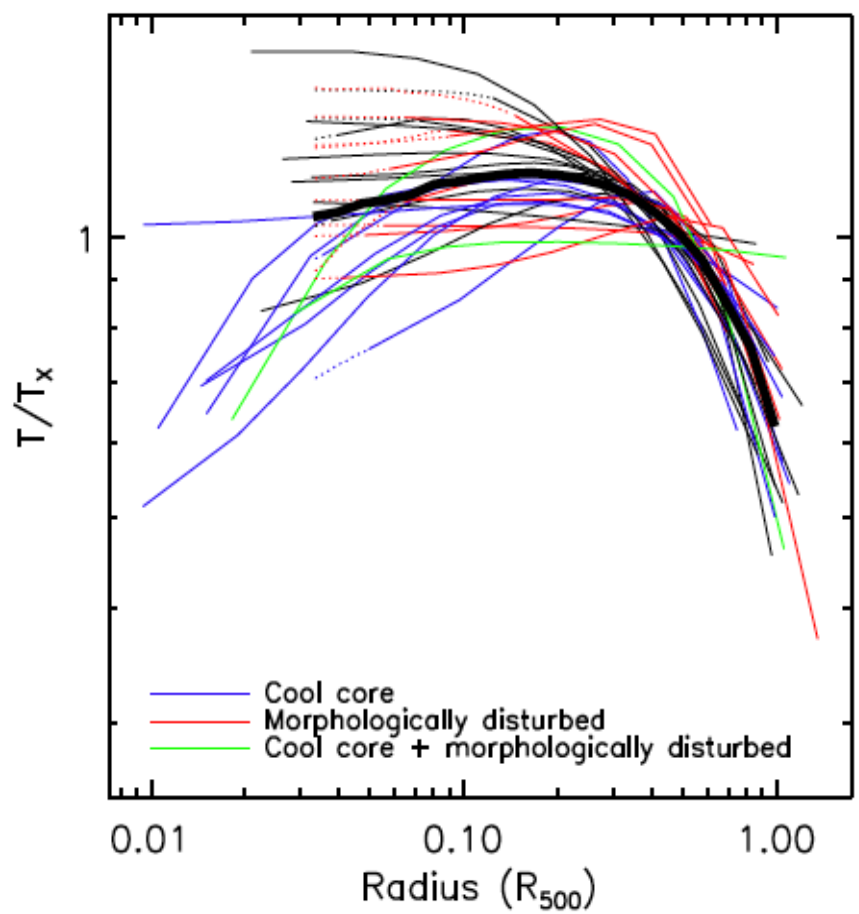
S. Galli, PRD 2013

Universal Profiles

Rescaled density profile



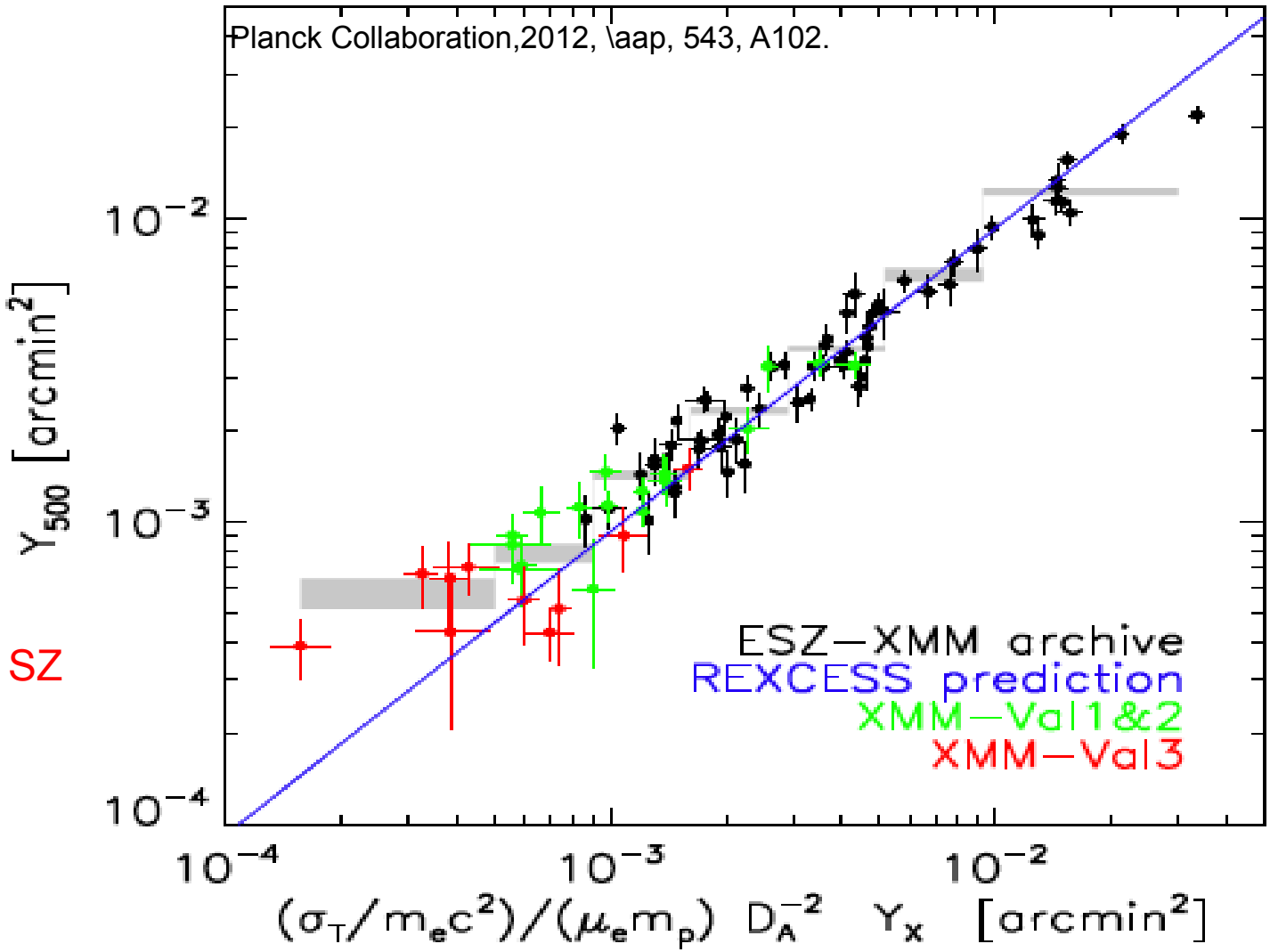
Rescaled temperature profile



Arnaud et al. 2010

A new probe for the variation of the fine structure constant

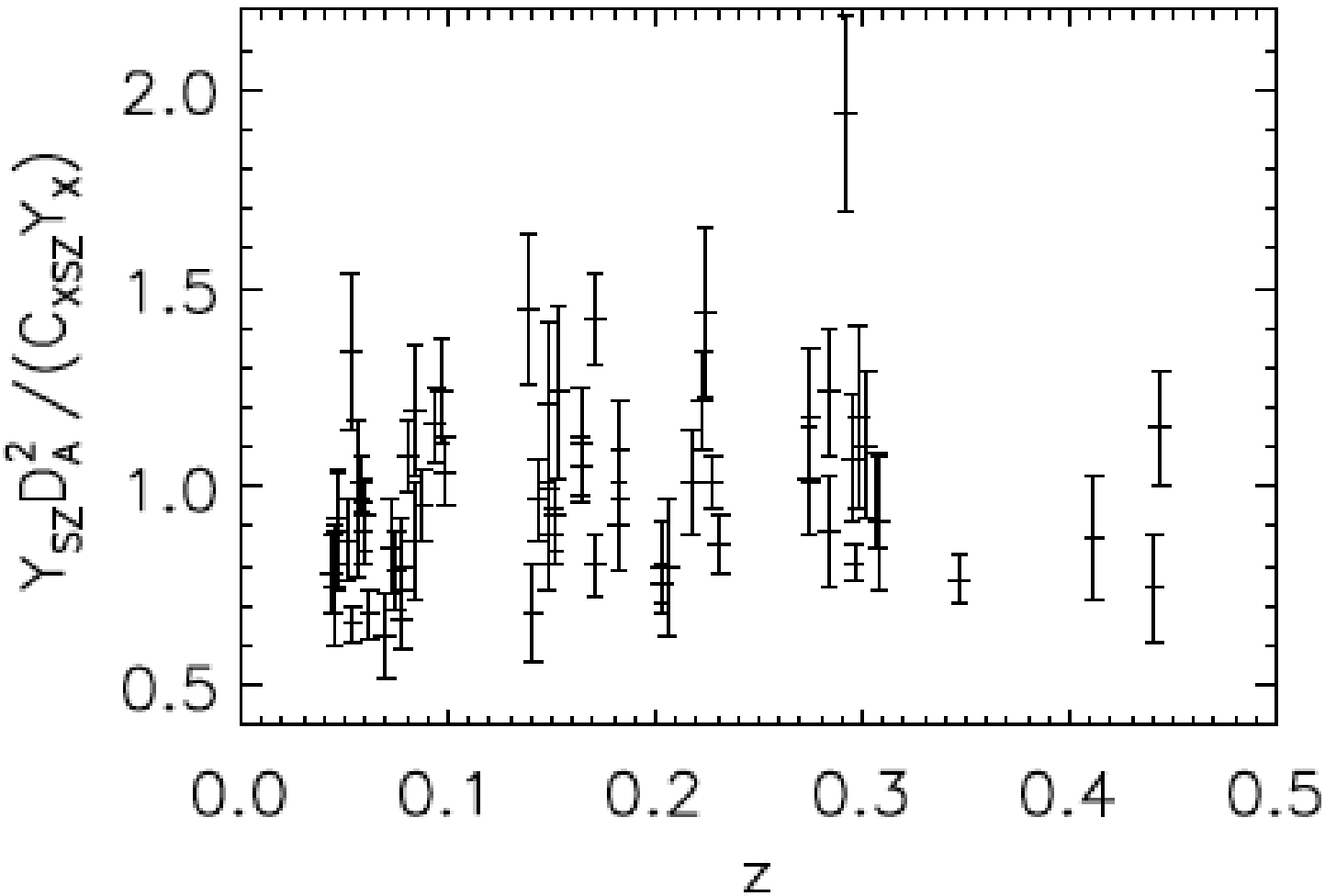
Clusters Thermal Energy



SZ

X-ray

New probe of variation of fine structure constant



To the error budget, we quadratically add a constant term representative of the unaccounted intrinsic scatter. This scattering term is estimated directly from the data, imposing that the reduced χ^2 of the fit must be 1.

New probe of variation of fine structure constant

With 62 clusters observed by Planck in SZ and XMM-Newton in Xrays,

$$\sigma(\alpha/\alpha_0) = 0.8\%$$

Comparable to CMB constraints today (but at completely different redshift range)

Galli 2013

Future improvements

Current constraints are not limited by the uncertainty on cosmological parameters. However, with an arbitrarily large sample of clusters, the constraint on α attainable would be (assuming cosmology constrained by pre-Planck data):

$$\sigma(\alpha/\alpha_0) = 0.3\%$$

Using future Planck+Euclid data, a constraint using **2000** cluster could be:

$$\sigma(\alpha/\alpha_0) = 0.34\%$$

Galli 2013