CMB dark matter constraints

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Outline

Introduction

- CMB power spectrum well-known
- Use this precision to constrain dark matter parameters
- Add a dark matter annihilation to reionization and compare

Cosmic Microwave Background

- Big Bang
- Recombination and decoupling
- Dark Ages
- Reionization

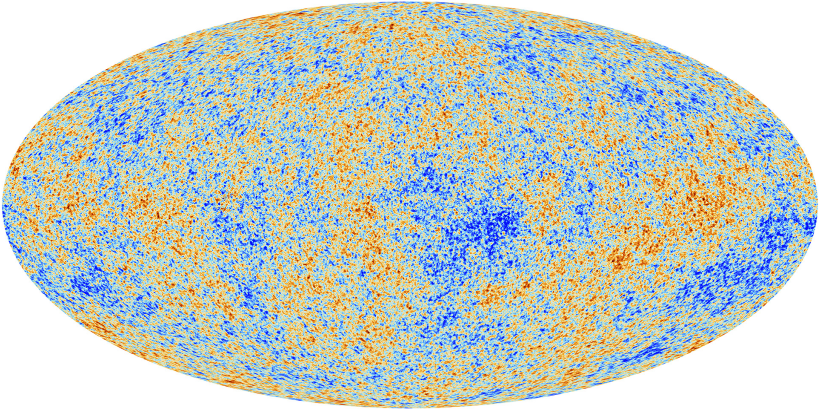


Figure: Copyright ESA and the Planck Collaboration

CMB power spectrum - ESA Movie

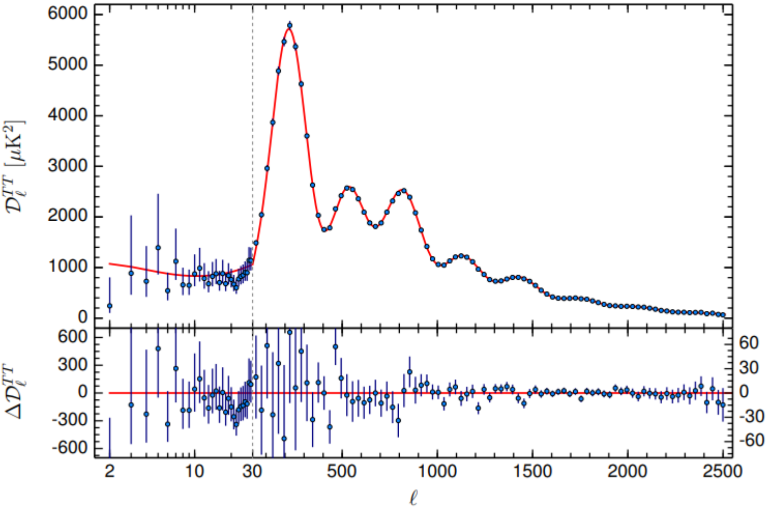


Figure: Planck collaboration 2015

Dark matter annihilation

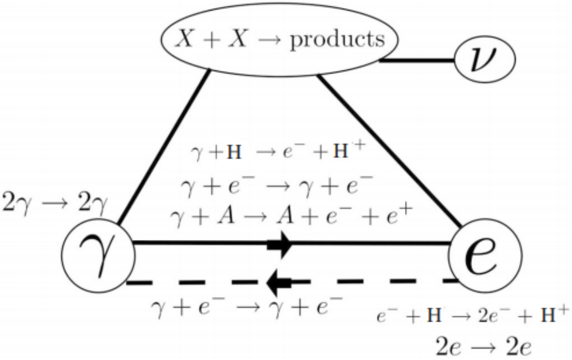


Figure: N. Padmanabhan and D. P. Finkbeiner 2005

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)} \left[R_s(z) - I_s(z) - I_\chi(z)\right] \quad (1)$$

Relation to dark matter parameters

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

$$\frac{dx_e}{dz} \propto I_\chi(z) \propto \frac{dE(z)}{dVdt} \tag{3}$$

We have related the interesting DM properties $< \sigma v >$ and m_χ to $\frac{dx_e}{dz}$ that we can compare to our measurements of the CMB power spectrum.

Outline

The DM annihilation parameter

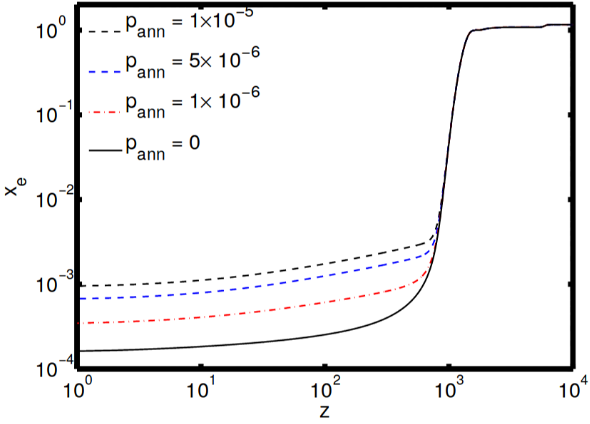
- Potential footprints of DM annihiliation?
- A crucial parameter:

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

- The *RECFAST* package[1]
  - Compute recombination of H, HeI and HeII
  - Analyze ionization history for arbitrary cosmology

[1] See Seager et al. (2011)

The free electron fraction



Galli et al. (2009)

The angular power spectrum

- What can we expect?
-
-

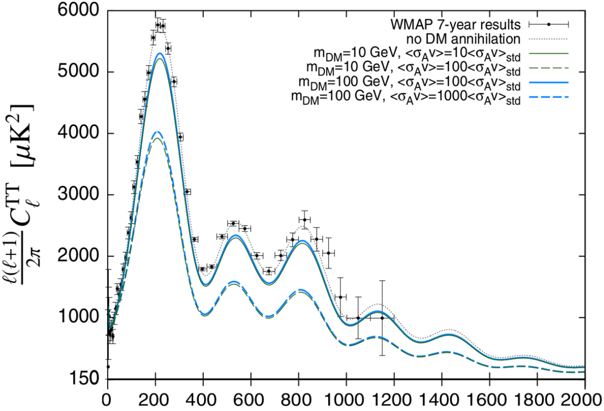
The angular power spectrum

- What can we expect?
- x_e has increased, so optical depth goes up
- Important consequences:

  - Amplitudes go down
  - Small-scale anisotropies are seemingly erased
  - Enhanced Thomson scattering

    $\longrightarrow$ Induces polarization anisotropies on large scales

The angular power spectrum



Hütsi et al. (2011)

Outline

Including data

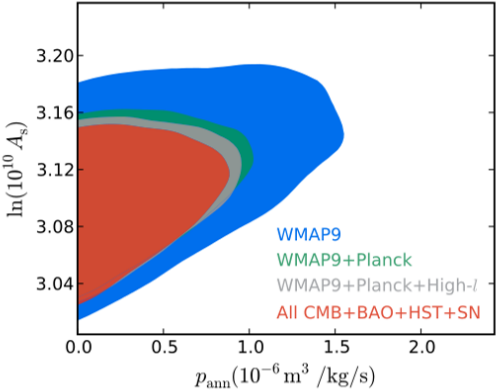
- So which DM model (which p_{ann}) holds the most merit?
- Confer with observational data (WMAP, PLANCK, etc.)
- Parameters of interest:

$$\{\Omega_{b,0}h^2, \Omega_{DM,0}h^2, \Theta_s, z_{reio}, n_s, \ln\left[10^{10}A_s\right], < \sigma v >, m_\chi\}$$

- The *CosmoMC* package[2]
  - MCMC exploration of cosmological parameter space
- Maximum likelihood fits

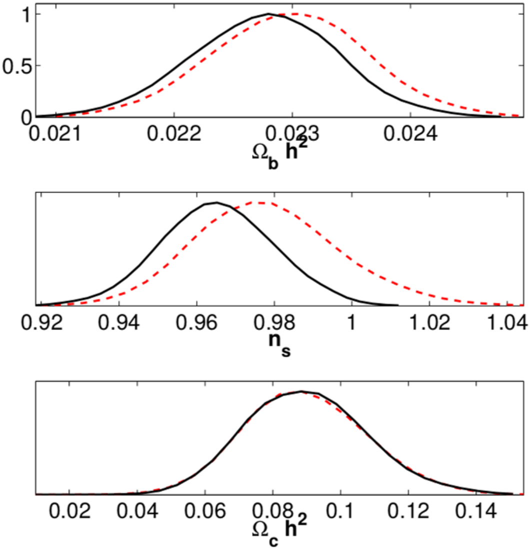
[2] See Lewis et al. (2011) and Hu et al. (2014)

Primordial density fluctations spectrum amplitude



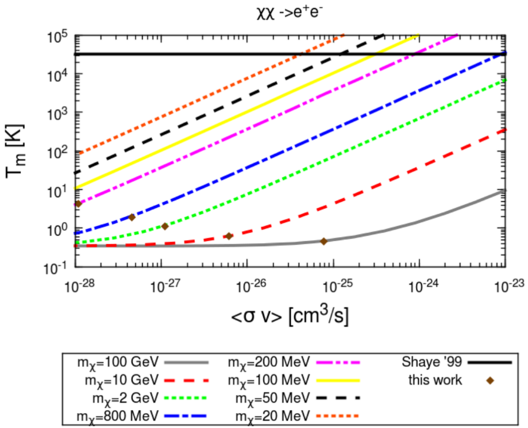
Madhavacheril et al. (2013)

Matter densities and scalar spectral index



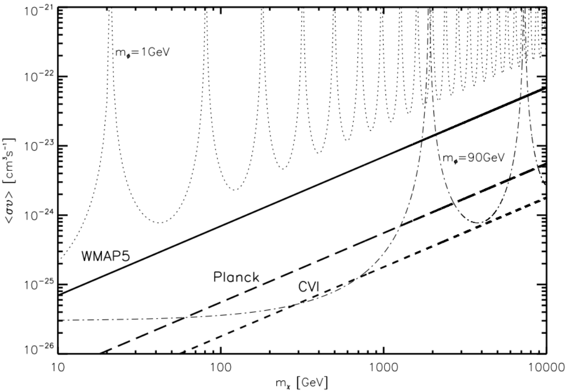
Galli et al. (2009)

IGM temperature



Laura Lopez-Honorez (2013)

Annihilation cross-section



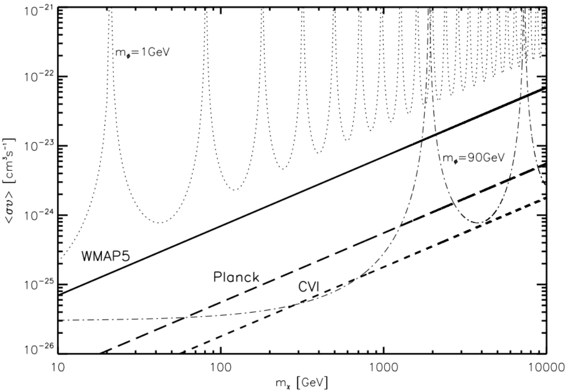
Silvia Gali et al. (2009)

Sommerfeld enhancement solution

$$SE(\beta) = \frac{\alpha\pi}{\beta}\left(1 - e^{-\alpha\pi/\beta}\right) \tag{4}$$

Solution to Schrodinger equation.
Saturated for low velocity at $\beta \sim \frac{m_\phi}{m_\chi}$.
Implies resonating form.

Annihilation cross-section



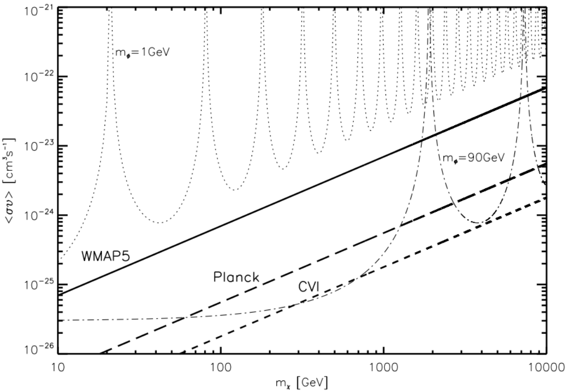
Silvia Gali et al. (2009)

WMAP5

$$\sigma v_{z_r}^{max} = 71.2 \cdot 10^{-26} \left(\frac{p_{ann}^{max}}{2.0 \cdot 10^{-6} m^3 s^{-1} kg^{-1}} \right) \left(\frac{m_\chi}{100 GeV} \right) \left(\frac{0.5}{f} \right) \tag{5}$$

Upper limit self annihilating corss-section.
In terms of $p_{ann} = f \frac{<\sigma v>}{m_\chi}$.
Dark matter mass m_χ.
Coupling factor f.

Annihilation cross-section



Silvia Gali et al. (2009)

WMAP

Successor of COBE.
Launched in 2001 into L2 orbit by NASA.
Frequency range: $23 - 94 GHz$ over 5 bands.
Amplitude power spectrum $A_{ps} = 0.0011 \pm 0.001 \mu K^2 sr$

SUMMARY OF THE COSMOLOGICAL PARAMETERS OF ΛCDM MODEL AND THE CORRESPONDING 68% INTERVALS

Class	Parameter	*WMAP* 5-year ML[a]	*WMAP*+BAO+SN ML	*WMAP* 5-year Mean[b]	*WMAP*+BAO+SN Mean
Primary	$100\Omega_b h^2$	2.268	2.262	2.273 ± 0.062	$2.267^{+0.058}_{-0.059}$
	$\Omega_c h^2$	0.1081	0.1138	0.1099 ± 0.0062	0.1131 ± 0.0034
	Ω_Λ	0.751	0.723	0.742 ± 0.030	0.726 ± 0.015
	n_s	0.961	0.962	$0.963^{+0.014}_{-0.015}$	0.960 ± 0.013
	τ	0.089	0.088	0.087 ± 0.017	0.084 ± 0.016
	$\Delta^2_{\mathcal{R}}(k_0{}^e)$	2.41×10^{-9}	2.46×10^{-9}	$(2.41 \pm 0.11) \times 10^{-9}$	$(2.445 \pm 0.096) \times 10^{-9}$
Derived	σ_8	0.787	0.817	0.796 ± 0.036	0.812 ± 0.026
	H_0	72.4 km/s/Mpc	70.2 km/s/Mpc	$71.9^{+2.6}_{-2.7}$ km/s/Mpc	70.5 ± 1.3 km/s/Mpc
	Ω_b	0.0432	0.0459	0.0441 ± 0.0030	0.0456 ± 0.0015
	Ω_c	0.206	0.231	0.214 ± 0.027	0.228 ± 0.013
	$\Omega_m h^2$	0.1308	0.1364	0.1326 ± 0.0063	$0.1358^{+0.0037}_{-0.0036}$
	$z_{\rm reion}{}^f$	11.2	11.3	11.0 ± 1.4	10.9 ± 1.4
	$t_0{}^g$	13.69 Gyr	13.72 Gyr	13.69 ± 0.13 Gyr	13.72 ± 0.12 Gyr

[a] Dunkley et al. (2008). "ML" refers to the Maximum Likelihood parameters
[b] Dunkley et al. (2008). "Mean" refers to the mean of the posterior distribution of each parameter
[c] Dunkley et al. (2008). "ML" refers to the Maximum Likelihood parameters
[d] Dunkley et al. (2008). "Mean" refers to the mean of the posterior distribution of each parameter
[e] $k_0 = 0.002$ Mpc^{-1}. $\Delta^2_{\mathcal{R}}(k) = k^3 P_{\mathcal{R}}(k)/(2\pi^2)$ (Eq. [15])
[f] "Redshift of reionization," if the universe was reionized instantaneously from the neutral state to the fully ionized state at $z_{\rm reion}$
[g] The present-day age of the universe

E. Komatsu et al. (2009)

Planck

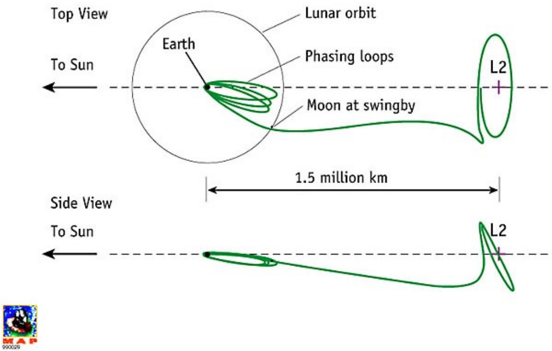
Successor of WMAP
Launched in 2009 into L2 orbit by ESA.
Frequency range: $30 - 857 GHz$ over 9 bands.
In agreement with WMAP. 2 - 3 Orders of magnitude improvement on uncertainties.

Parameter	PlanckTT+lowP 68% limits	PlanckTT, TE, EE+lowP 68% limits
$\Omega_b h^2$	0.02222 ± 0.00023	0.02225 ± 0.00016
$\Omega_c h^2$	0.1197 ± 0.0022	0.1198 ± 0.0015
$100\theta_{MC}$	1.04085 ± 0.00047	1.04077 ± 0.00032
τ	0.078 ± 0.019	0.079 ± 0.017
$\ln(10^{10} A_s)$	3.089 ± 0.036	3.094 ± 0.034
n_s	0.9655 ± 0.0062	0.9645 ± 0.0049
H_0	67.31 ± 0.96	67.27 ± 0.66
Ω_Λ	0.685 ± 0.013	0.6844 ± 0.0091
Ω_m	0.315 ± 0.013	0.3156 ± 0.0091

N. Aghanim et al. (2016)

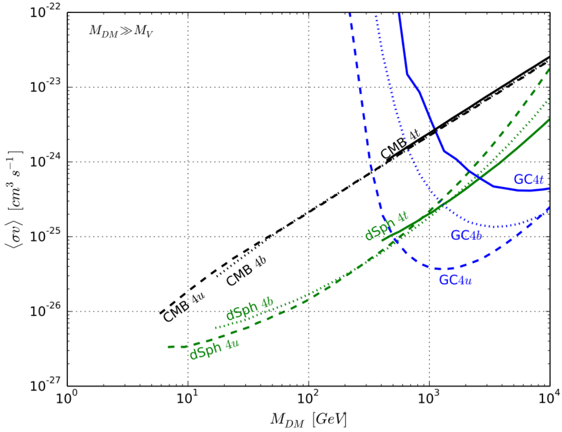
WMAP and Planck orbit

Lunar assisted trajectory to orbit around L2.



NASA website

annihilation cross-section by Planck



Stefano Profuma et al. (2017)