Indirect detection of dark matter

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Outline

Introduction

- Indirect detection via γ-rays
- Annihilation to standard model particles
- $\chi\chi \rightarrow b\bar{b} \rightarrow \gamma\gamma ...$
- $\chi\chi \rightarrow \tau^+\tau^- \rightarrow \gamma\gamma ...$
- DM map of the Universe

Outline

Theoretical *gamma*-ray flux

$$I_\gamma(E,\Theta) = \frac{1}{2}\frac{\langle \sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}\frac{1}{4\pi}\int dl \rho_{DM}^2(r[l,\Theta])$$

- Particle physics factor
- Astrophysics factor

Particle physics factor

$$\frac{1}{2}\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Relic abundance $\sim$ annihilation rate:

$$\Omega_{DM}h^2 \sim \frac{3\times 10^{-27}cm^3s^{-1}}{\langle\sigma v\rangle}$$

Which implies:

$$\langle\sigma v\rangle \sim 3\times 10^{-26}cm^3s^{-1}$$

Particle physics factor

$$\frac{1}{2}\frac{\langle \sigma v \rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Differential spectrum of emitted gamma-rays:

$$\frac{dN_{\gamma,ann}}{dE_\gamma}$$

Can be written as:

$$\frac{dN_{\gamma,ann}}{dE_\gamma} = \sum_i B_i \frac{dN^i_{\gamma,ann}}{dE_\gamma}$$

Particle physics factor

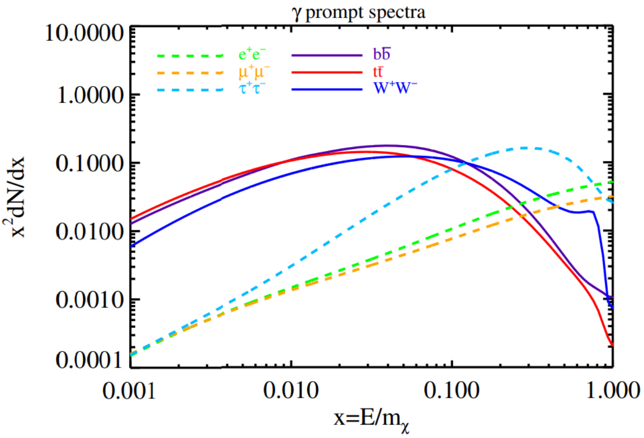


Figure: Figure from Gaskins et al. 2016: Gamma-ray spectrum from dark matter ($m_{DM} = 500 GeV$) annihilation to six different final states, calculated using PPPC4DMID.

Particle physics factor

$$\frac{1}{2}\frac{\langle\sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}$$

- Factor $\frac{1}{2}$ due to being its own anti particle.
- Factor $1/m_{DM}^2$ cancels the density squared integral.

Astrophysical factor

$$\frac{1}{4\pi}\int dl\rho_{DM}^2(r[l,\Theta])$$

J-factor definition:

$$J = \frac{1}{\Delta\Omega}\int\int_{\Delta\Omega}\rho_{DM}^2(l,\Omega)dld\Omega$$

Normalization factor:

$$\int d\Omega = \int_0^{2\pi}\int_0^{\pi}\sin\theta d\theta d\phi = 4\pi$$

Astrophysical factor

Simple density function:

$$\rho_{NFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1 + \left(\frac{r}{r_s}\right)\right]^2}$$

- R dependence
- Relate to line of sight integral

Astrophysical factor

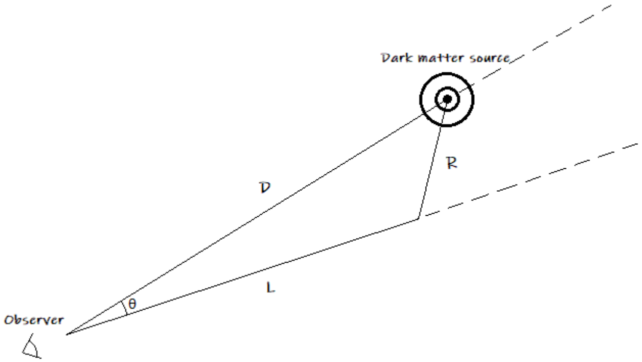


Figure: Top down view of observer looking down the line of sight with some angular separation Θ at a dark matter source.

- $R = \sqrt{L^2 + D^2 - 2L\cos\Theta}$

Theoretical *gamma*-ray flux - look back

$$I_\gamma(E,\Theta) = \frac{1}{2}\frac{\langle \sigma v\rangle}{m_{DM}^2}\frac{dN_{\gamma,ann}}{dE_\gamma}\frac{1}{4\pi}\int dl \rho_{DM}^2(r[l,\Theta])$$

- Rate of annihilation per volume: $\frac{1}{2}\frac{\langle \sigma v\rangle \rho_{DM}^2}{m_{DM}^2}$
- Differential spectrum of emitted gamma-rays: $\frac{dN_{\gamma,ann}}{dE_\gamma}$
- Volume: $\frac{1}{4\pi}\int dl$

Sagittarius dwarf galaxy

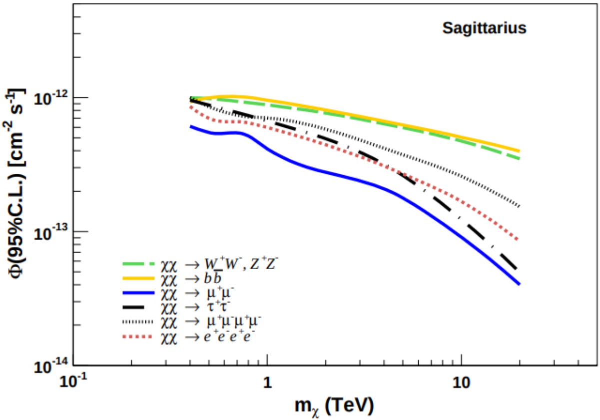


Figure: Figure from Abramowski et al. 2014: Gamma-ray flux as a function of dark matter mass (m_χ) under different annihilation channels.

Outline

DM density profiles and observations

- What would DM-induced gamma-ray signals look like?
- Highly dependent on DM density profiles!
- Hard to constrain observationally
- Usually given as model input

The NFW profile

- Navarro, Frenk White (1996)
- N-body simulation
- Showed that:

$$\rho_{NFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)\left[1 + \left(\frac{r}{r_s}\right)\right]^2} \tag{1}$$

can be used to fit DM haloes in arbitrary cosmology.

The GNFW profile

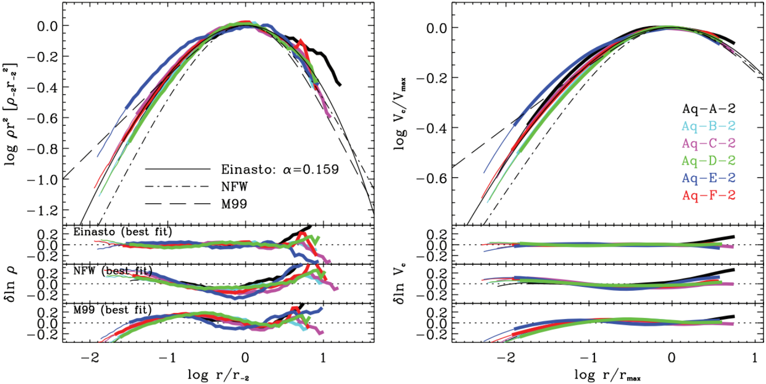
- Generalized version of the NFW profile
- Steeper slopes close to galactic center
  - Adiabatic compression
  - Supernovae and AGN feedback
- Arbitrary inner slope γ
- NFW for $\gamma = 1$

$$\rho_{GNFW} = \frac{\rho_0}{\left(\frac{r}{r_s}\right)^{\gamma}\left[1 + \left(\frac{r}{r_s}\right)\right]^{3-\gamma}} \qquad (2)$$

The Einasto profile

- Systematic discrepancy between NFW and N-body
- Radius-dependent slope

$$\rho_{Ein}(r) = \rho_0 \exp -\frac{2}{a}\left[\left(\frac{r}{r_s}\right)^a - 1\right] \quad (3)$$



Navarro et al. (2010)

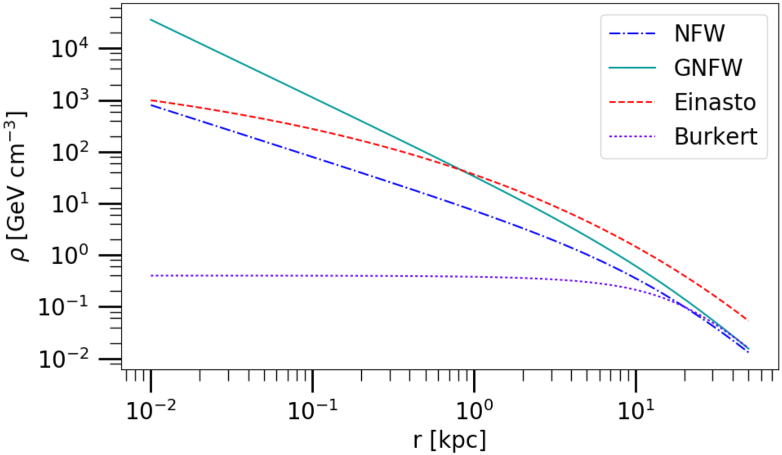
The Burkert profile

- Problem: spheroidal dwarf galaxies (dSphs)
  - Low density
  - Homogeneous
- Flattens towards the center

$$\rho_{Burk}(r) = \frac{\rho_0}{\left(1 + \frac{r}{r_s}\right)\left(1 + \left(\frac{r}{r_s}\right)^2\right)} \tag{4}$$

ESO/Digital Sky Survey 2

Comparison



NFW
GNFW
Einasto
Burkert
ρ [GeV cm^{-3}]
10^{4}
10^{3}
10^{2}
10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-2}
10^{-1}
10^{0}
10^{1}
r [kpc]

Some questions

- Do observed γ-rays accurately reflect the DM density?
- Scattering processes?
- Background sources?

Compton scattering

- Optical depth?
- Assuming $n_e \approx 10^0 \ \mathrm{cm}^{-3}$ (typical for ISM)
- Thomson approximation $\sigma_{K-N} \leq \sigma_{Th} \approx 10^{-24}$ cm
- Max distance d 20 kpc $\approx 10^{22}$ cm
- $\tau \approx n_e \sigma_{Th} d \approx 10^{-5}$
- $\longrightarrow$ **of little consequence**

Pair production

- annihilation of two photons into particle-antiparticle

$$\gamma\gamma \longrightarrow e^+ e^- \tag{5}$$

- Suppose a DM-induced photon annihilates with a CMB photon. What energy should the photon minimally have for pair production?

Pair production

- annihilation of two photons into particle-antiparticle

$$\gamma\gamma \longrightarrow e^{+}e^{-} \tag{6}$$

- Suppose a DM-induced photon annihilates with a CMB photon. What energy should the photon minimally have for pair production?
- $E_{\gamma} \geq 10^{14}$ eV
- Of litte consequence to Fermi-LAT
- Possibly important for CTA

Outline

Constraints from Fermi-LAT (2017)

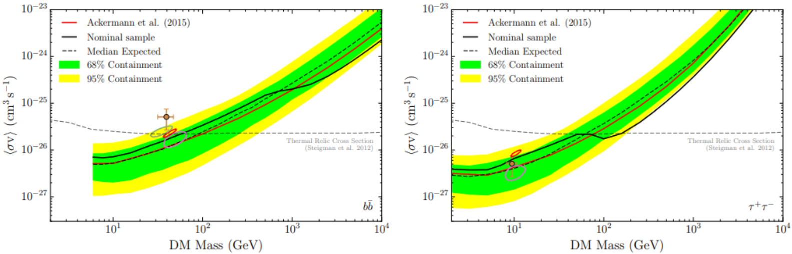


Figure: Albert et al. (2017)

Future telescopes - CTA

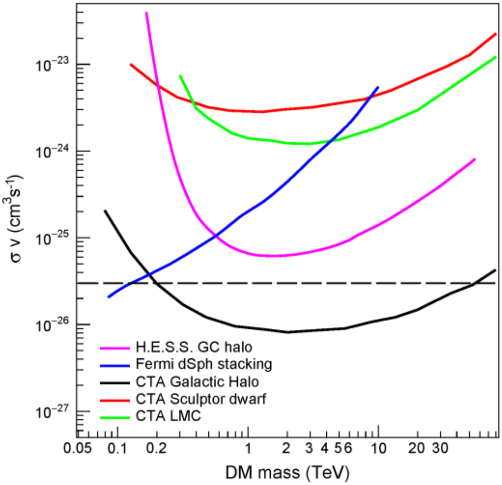


Figure: CTA consortium (2017)

Telescopes: summary

- Fermi at low mass range
- H.E.S.S at high mass range
- Future: CTA over broad mass range
  $\rightarrow$ below thermal relic cross section?

Outline

CMB constraints - Introduction

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

Outline

CMB power spectrum

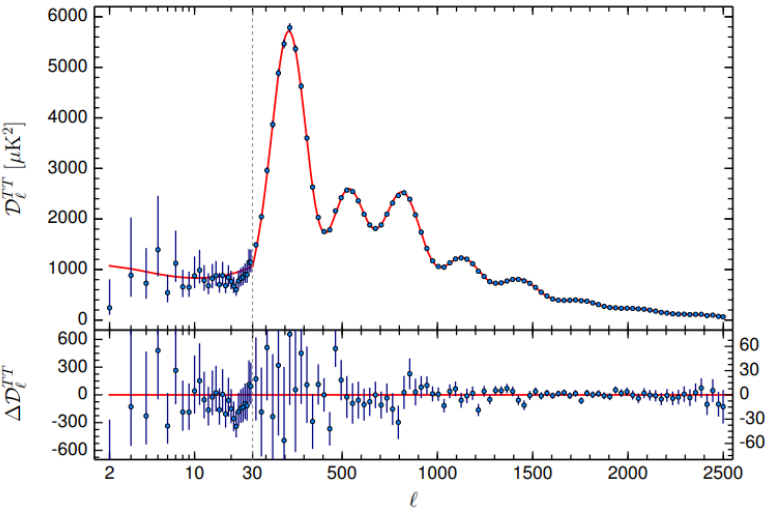


Figure: Planck collaboration 2015

Outline

Dark matter annihilation

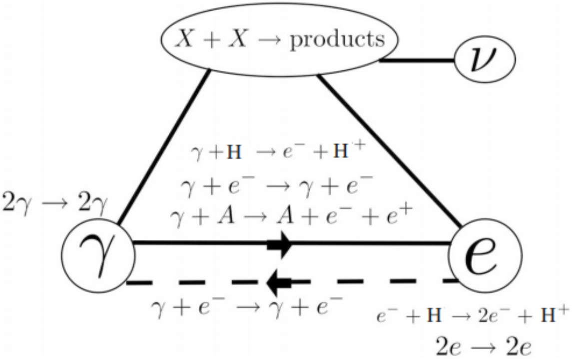


Figure: N. Padmanabhan and D. P. Finkbeiner 2005

$$\frac{dx_e}{dz} = \frac{1}{(1+z)H(z)}\left[R_s(z) - I_s(z) - I_\chi(z)\right] \tag{7}$$

Relation to dark matter parameters

$$\frac{dE(z)}{dVdt} = \rho_c^2 c^2 \Omega_{DM}^2 (1+z)^6 f \frac{<\sigma v>}{m_\chi} \tag{8}$$

$$\frac{dx_e}{dz} \propto I_\chi(z) \propto \frac{dE(z)}{dVdt} \tag{9}$$

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

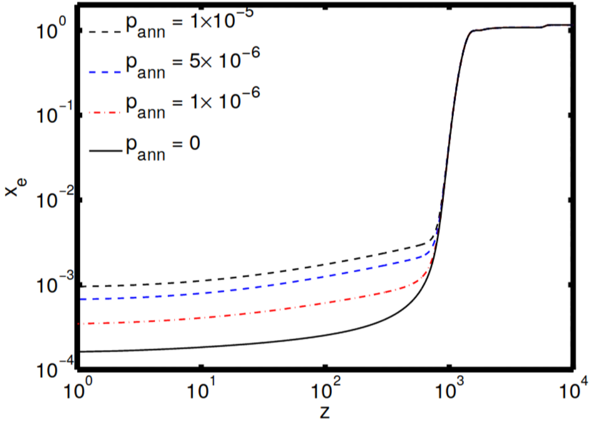
- Potential footprints of DM annihiliation?
- A crucial parameter:

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

- 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)

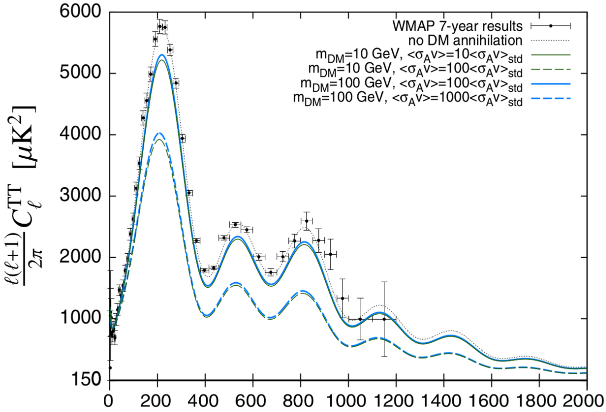
The angular power spectrum

- What can we expect?
- 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)

Including data

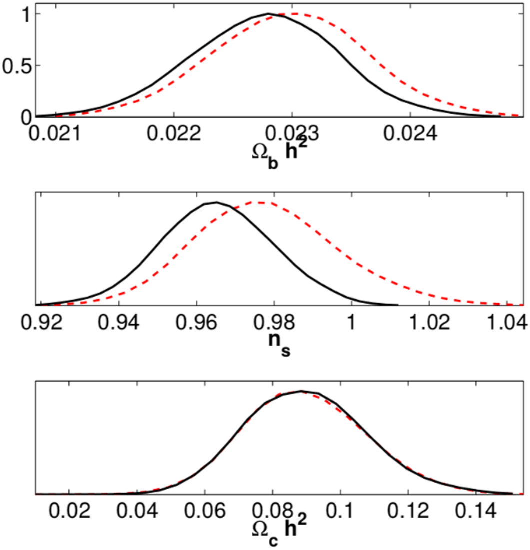
- So which DM model (which p_{ann}) holds the most merit?
- Confer with observational data (WMAP, PLANCK, etc.)
- Parameters of interest:

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

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

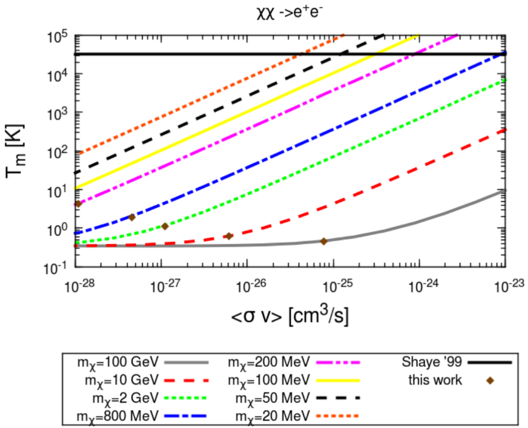
[2] See Lewis et al. (2011) and Hu et al. (2014)

Matter densities and scalar spectral index



Galli et al. (2009)

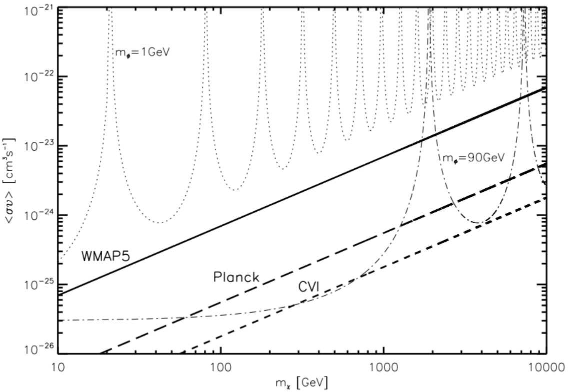
IGM temperature



Laura Lopez-Honorez (2013)

Outline

Annihilation cross-section



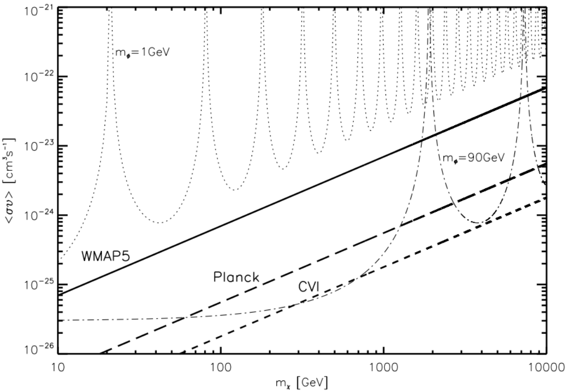
Silvia Gali et al. (2009)

Sommerfeld enhancement solution

$$SE(\beta) = \frac{\alpha\pi}{\beta}\left(1 - e^{-\alpha\pi/\beta}\right) \tag{10}$$

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

Annihilation cross-section



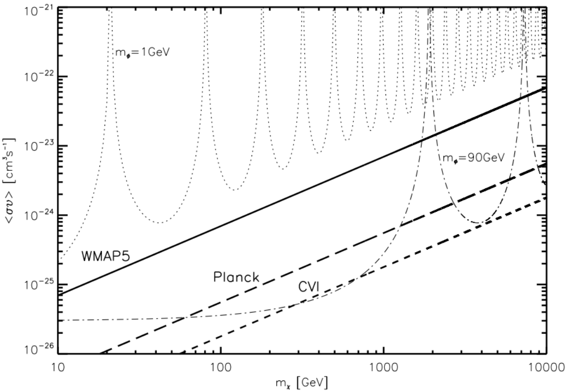
Silvia Gali et al. (2009)

WMAP5

$$\sigma v_{z_r}^{max} = 71.2 \cdot 10^{-26} \left(\frac{p_{ann}^{max}}{2.0 \cdot 10^{-6} m^3 s^{-1} kg^{-1}} \right) \left(\frac{m_\chi}{100 GeV} \right) \left(\frac{0.5}{f} \right) \quad (11)$$

Upper limit self annihilating cross-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)

Outline

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)

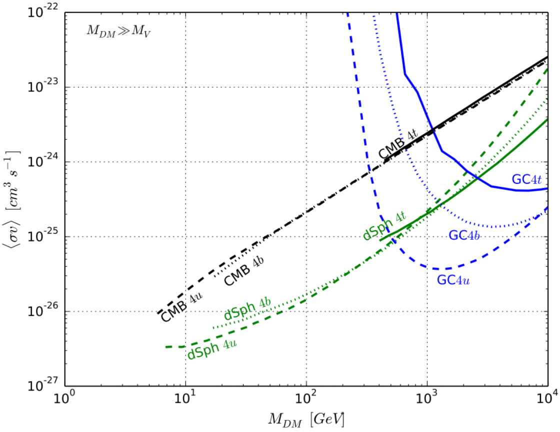
Planck

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)

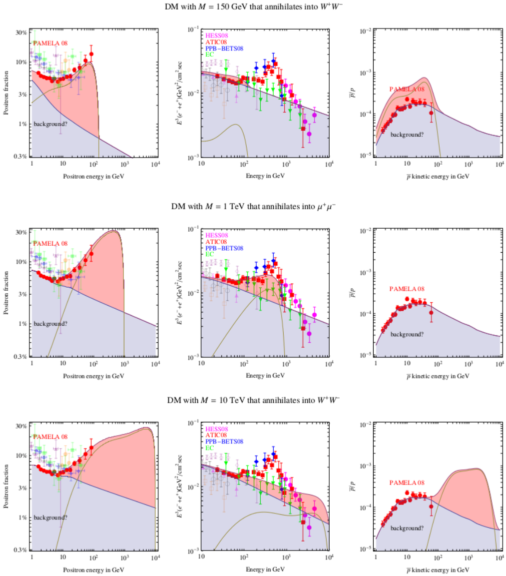
Annihilation cross-section by Planck



Stefano Profuma et al. (2017)

Cosmic Ray Excesses

Cosmic Ray Excesses



Cirelli et al. (2013)

Outline

Excess...with respect to what?

- Background flux of e^+ expected from HEA processes
- The positron fraction:

$$f(E) \equiv \frac{1}{1 + (\Phi_{e^-}/\Phi_{e^+})} \approx \frac{1}{1 + \kappa E_{GeV}^{\rho}}$$

- PAMELA data above 10 GeV:

$$\rho = -0.23 \pm 0.04$$

Excess...with respect to what?

- Fits to PAMELA electron data give:

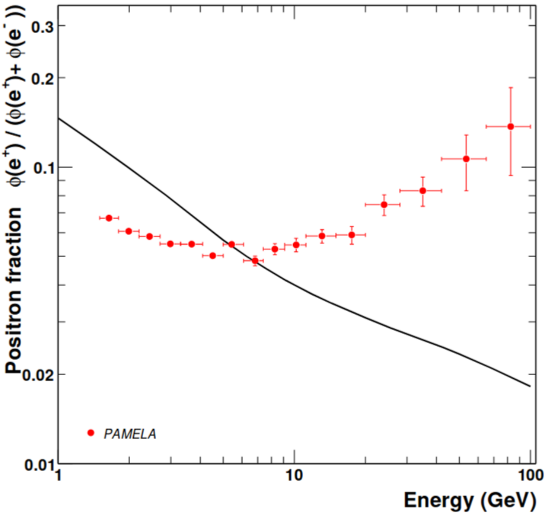
$$\Phi_{e^-} \propto E^{-3.23 \pm 0.02}$$
$$\implies \Phi_{e^+} \propto E^{-3.00 \pm 0.04}$$

- Violation with numerical analyses inferred from Φ_p:

$$\Phi_{e^+} \propto E^{-3.4}$$

- Current spectral steepening mechanisms insufficient

The PAMELA data



PAMELA collaboration (2008)

Excess...with respect to what?

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$$\implies \Phi_{e^+} \propto E^{-3.00\pm0.04}$$

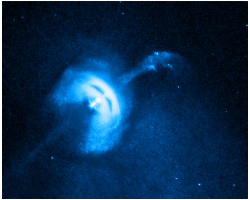
- Violation with numerical analyses inferred from Φ_p:

$$\Phi_{e^+} \propto E^{-3.4}$$

- Current spectral steepening mechanisms insufficient

A dark matter signature?

- Dark matter annihilation fits the positron excess
- E.g. in case of AMS-02 (2014):
  - $\chi^2/\mathrm{d.o.f.} = 52.2/82$ for
  - $m_\chi = 104.7 GeV$
  - $\langle \sigma v \rangle = 5.5e-27 cm^3 s^{-1}$
- Many caveats:
  - No spectral edge observed
  - $\langle \sigma v \rangle \gg \langle \sigma v \rangle_{\mathrm{th,S-wave}} \approx 1 pb$
  - No similar anomalies in other cosmic-ray channels



Fermi-LAT image of the Vela pulsar

Other explanations

- An uncomplete and inexhaustive overview:
  - Pulsar wind nebulae
  - Supernova remnants
  - Many more...

Outline

Astrophysical anti-proton background

CR high energy protons or helium nuclei + ISM $\rightarrow$ secondary anti-protons.

Uncertainties in:

- the injection of proton and helium fluxes from Galactic sources - AMS-02 data
- the collision cross sections for $\bar{p}$ production
- the propagation details
  - semi-analytical solution of the full transport equation
  - Solar modulation

Uncertainties in the $\bar{p}/p$ ratio

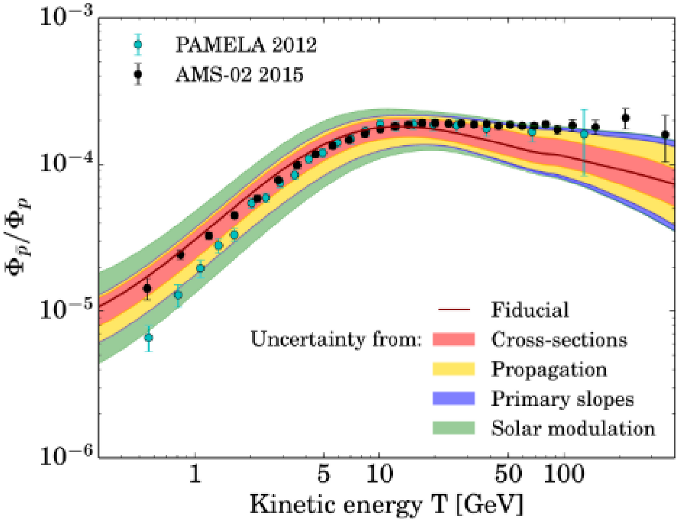


Figure: Giessen et al. (2017)

$\bar{p}$ constraints on dark matter parameters

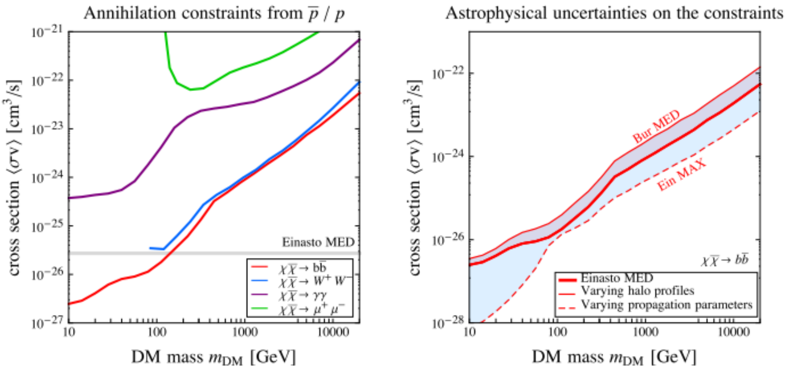


Figure: Giessen et al. (2017)

Outline

Anti-nuclei channel

- anti-anti-deuteron $\overline{d}$
- anti-helium $\overline{^{3}He}$

Anti-nuclei channel coalescence

$$\gamma \frac{d^3 N_{\bar{A}}}{d\vec{p}^3_{\bar{A}}} = (\frac{4\pi}{3} p_0^3)^{(A-1)} (\gamma \frac{d^3 N_{\bar{p}}}{d\vec{p}^3_{\bar{p}}})^A \tag{12}$$

Anti-nuclei channel

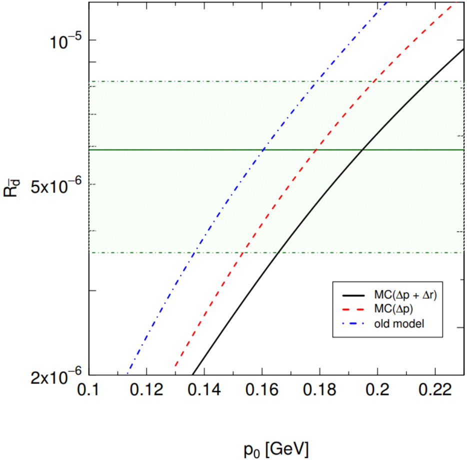
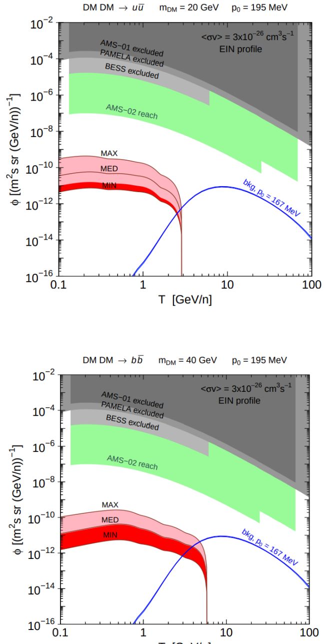


Figure: Production rate of anti-deuterons $\bar{d}$ from $e^+ + e^- \to \bar{d}$ at Z resonance as a function of coalescence momentum p_0 for three different models. The green line denotes the measurement by ALEPH.

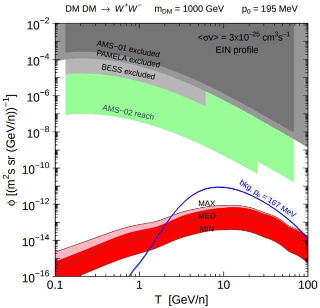
Propagation

$$\frac{\partial f}{\partial t} - K(T) \cdot \Lambda^2 f + \frac{\partial}{\partial z}(sign(z) f V_c) = Q - 2h\delta(z)\nabla f \qquad (13)$$

Results anti-deuteron $\overline{d}$

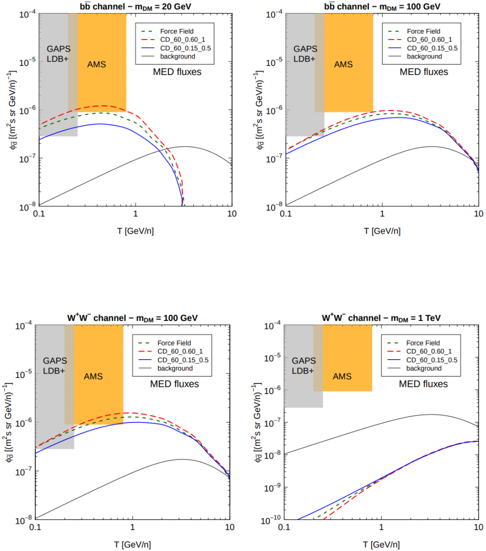


Results anti-deuteron $\overline{d}$



Model	Galactic charged CR propagation parameters			
	δ	$\mathcal{K}_0$ [kpc^2/Myr]	$V_{\rm conv}$ [km/s]	L [kpc]
MIN	0.85	0.0016	13.5	1
MED	0.70	0.0112	12	4
MAX	0.46	0.0765	5	15

Results anti-helium $\overline{{}^{3}He}$



A final word on indirect DM

- Gamma-rays:
  - Signal highly dependent on DM density profiles
  - Constraints by Fermi-LAT: $m_\chi \approx 10 GeV$

    $\langle \sigma v \rangle \approx 4 \cdot 10^{-26} cm^3 s^{-1}$
- CMB:
  - interpr. fluctuations as primordial footprint of DM annihilation
  - New constraints on cosmo parm. using numerical sim.
  - Upper limits on ratio $\langle \sigma v \rangle$ and m_χ

  $m_\chi \approx 10 GeV$

  $\langle \sigma v \rangle \approx 2 \cdot 10^{-26} cm^3 s^{-1}$
- Cosmic-rays:
  - Positron excess
  - Anti-protons

  $m_\chi \approx 10 GeV$

  $\langle \sigma v \rangle \approx 3 \cdot 10^{-27} cm^3 s^{-1}$

Let's combine our efforts!