Lectures on selected topics in Astroparticle Physics:

Lecture 3:

Indirect Detection of Particle (WIMP) Dark Matter

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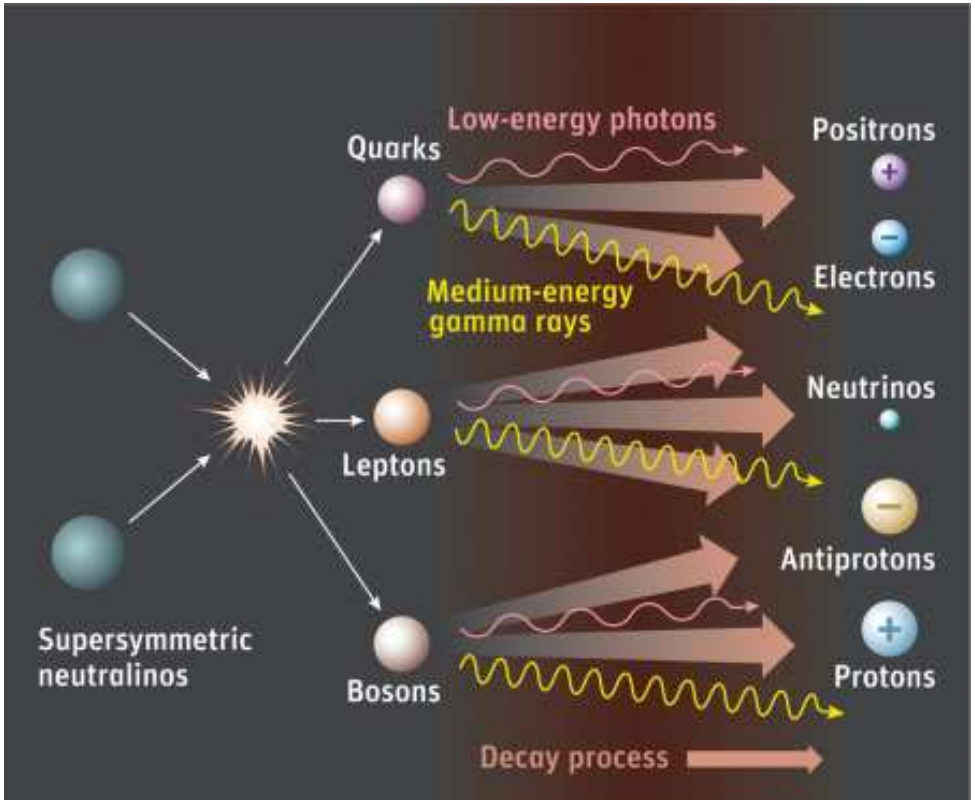
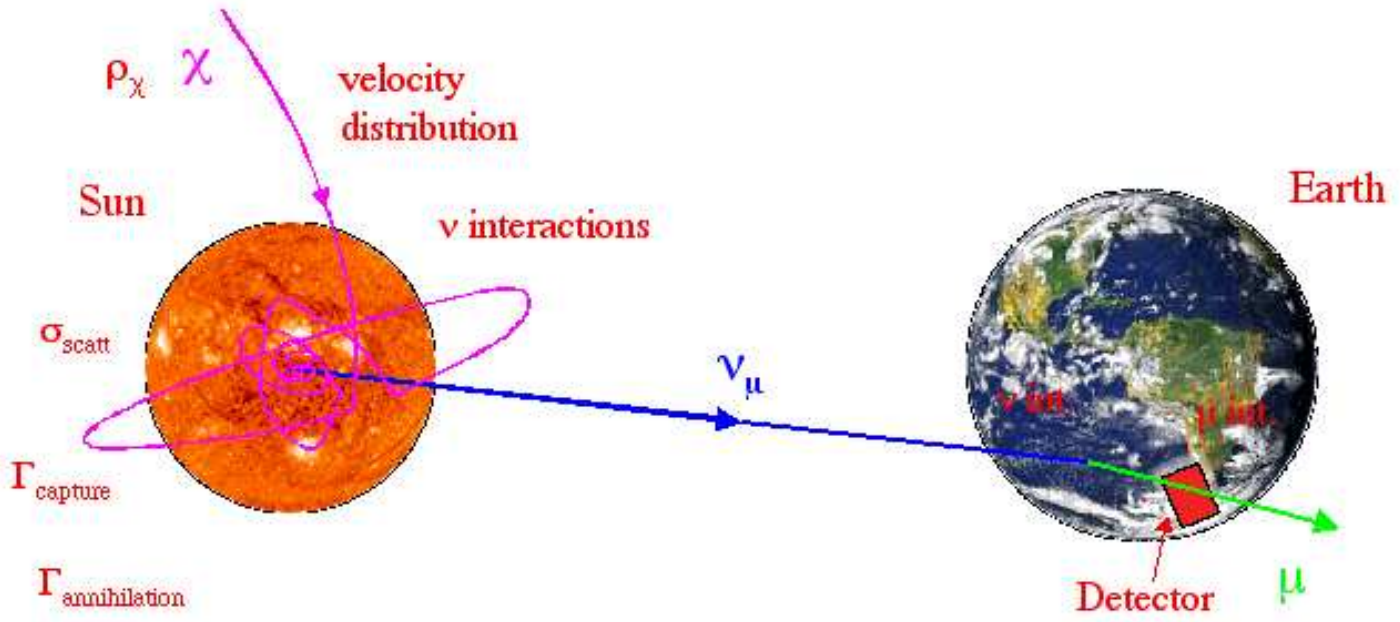
Indirect Detection: WIMP annihilation



AMS-2 positron excess, Fermi γ rays from dwSph, Galactic center, ...

Indirect Detection: WIMP Capture and Annihilation



WIMP Capture and Annihilation Rates: Order-of-magnitude Estimates

Capture rate by Sun:

$$C^{\odot} \sim \left(\frac{\rho_\chi}{m_\chi} v_\chi\right) \left(\frac{\mathrm{M}_\odot}{m_p}\right) \sigma_{\chi p} \Rightarrow$$

$$C^{\odot} \approx 10^{20}\,\mathrm{sec}^{-1} \left(\frac{\rho_{\mathrm{local}}}{0.3\ \mathrm{GeV/\,cm^3}}\right) \left(\frac{300\,\mathrm{km\,s^{-1}}}{v_\chi}\right) \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right) \left(\frac{\sigma_{\chi p}}{10^{-6}\,\mathrm{pb}}\right)$$

Proper calculations should include (1) Gravitational focussing of WIMPs towards Sun; (2) not every scattered WIMP will be captured; (3) WIMPs have a velocity distribution; (4) sun has other elements (He, O, . . .), . . . $\Rightarrow$

$$C^{\odot} \approx 3.4 \times 10^{20}\ \mathrm{sec}^{-1} \left(\frac{\rho_{\mathrm{local}}}{0.3\ \mathrm{GeV/\,cm^3}}\right) \left(\frac{270\,\mathrm{km\,s^{-1}}}{\bar{v}_{\mathrm{local}}}\right)^3 \times \left(\frac{100\,\mathrm{GeV}}{m_\chi}\right)^2 \left(\frac{\sigma_{\chi\mathrm{H,SD}} + \sigma_{\chi\mathrm{H,SI}} + 0.07\sigma_{\chi\mathrm{He,SI}}}{10^{-6}\,\mathrm{pb}}\right)$$

Annihilation rate ($\Gamma^{\odot}_{\mathrm{ann}}$) :

$$\frac{dN_\chi}{dt} \approx C^{\odot} - 2\Gamma^{\odot}_{\mathrm{ann}}$$

In equilibrium, $\frac{dN_\chi}{dt} = 0 \quad \Rightarrow \Gamma^{\odot}_{\mathrm{ann}} = \frac{1}{2} C^{\odot}$

Is WIMP Annihilation Already Detected in Cosmic Rays?

Excess positrons in cosmic rays:

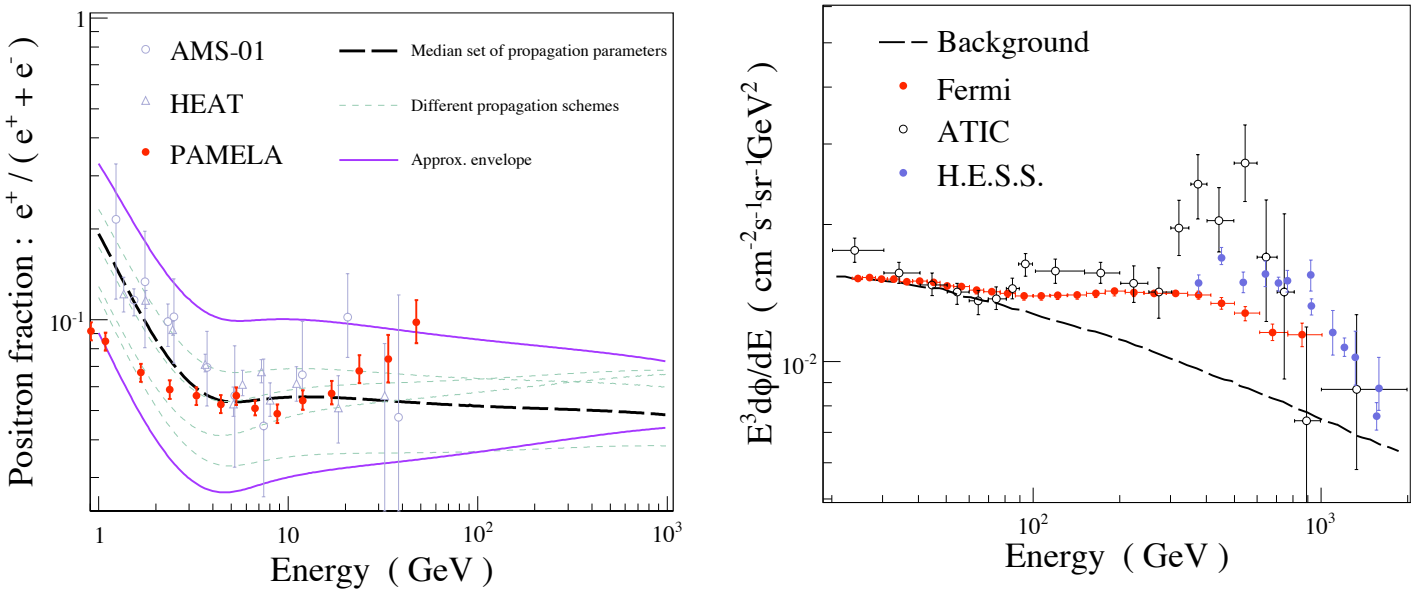


FIG. 1: Cosmic ray positron fraction (left) and electrons+positrons fluxes (right) (figure from P. Brun & T. Delahaye, CERN Courier Sep. 2009 issue).

But no excess is seen in antiprotons!

Fitting the excess positron data with WIMP annihilations or decay :

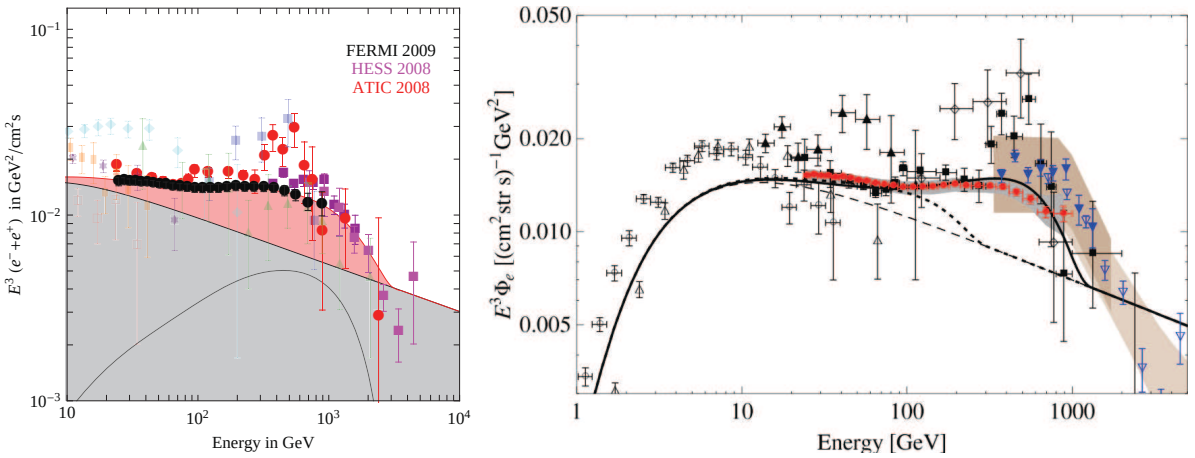


FIG. 3: Fit of the electron data with annihilating dark matter (M.Cirelli), decaying dark matter (A.Ibarra).

To avoid $\bar{p}$-excess, can allow only “leptophilic" (and “hadrophobic") WIMP coupling to SM particles.

Also need a “boost" in the annihilation x-section

Also, there are conventional, astrophysical explanations! The e^+-excess without $\bar{p}$-excess can be well-explained in terms of pulsars as sources and/or a few nearby sources of cosmic rays

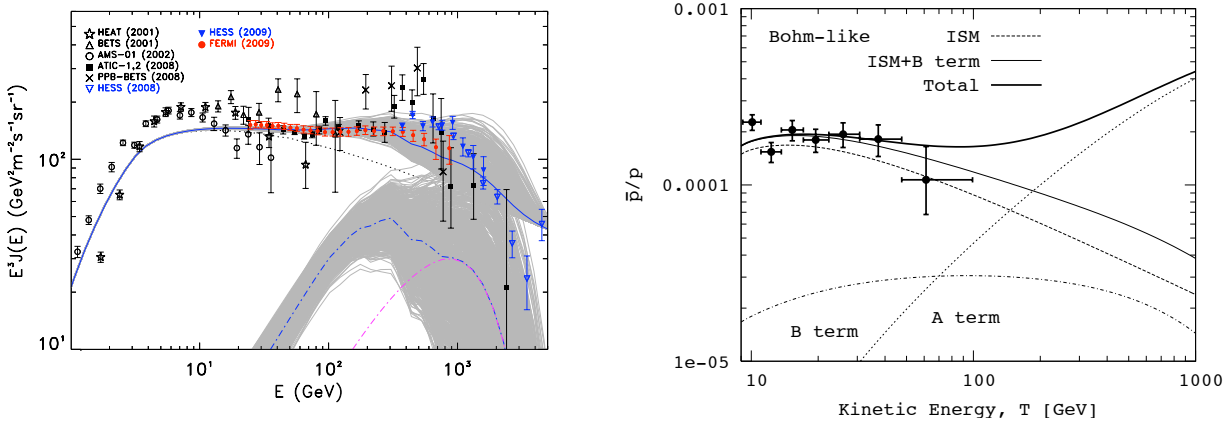


FIG. 2: Fit of the electron data with pulsars (J.Bregeon) and $\bar{p}$ predictions in case of secondary production within a supernovae remnant (P. Blasi).

Gamma Ray Flux from WIMP Annihilation

$$\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{8\pi} \underbrace{\frac{\langle\sigma v\rangle}{m_{DM}^2} \frac{dN_\gamma}{dE_\gamma}}_{\text{Particle Physics}} \times \underbrace{\bar{J}(\Delta\Omega)\Delta\Omega}_{\text{Astrophysics}} \tag{1}$$

An extra factor of $1/2$ if WIMP $\neq$ anti-WIMP

$$J = \int_{l.o.s} \rho^2(r[\ell])d\ell \qquad \bar{J}(\Delta\Omega) = \frac{1}{\Delta\Omega} \int_{\Delta\Omega} PSF \times J \, d\Omega \tag{2}$$

where PSF stands for the point spread function of the instrument.

$$r(\ell, \theta) = \sqrt{r_\odot^2 + \ell^2 - 2\, r_\odot\, \ell \cos\theta}\,, \tag{3}$$

where $r_\odot \approx 8.33 \pm 0.35$ kpc, and $\cos\theta = \cos b \cos l$.

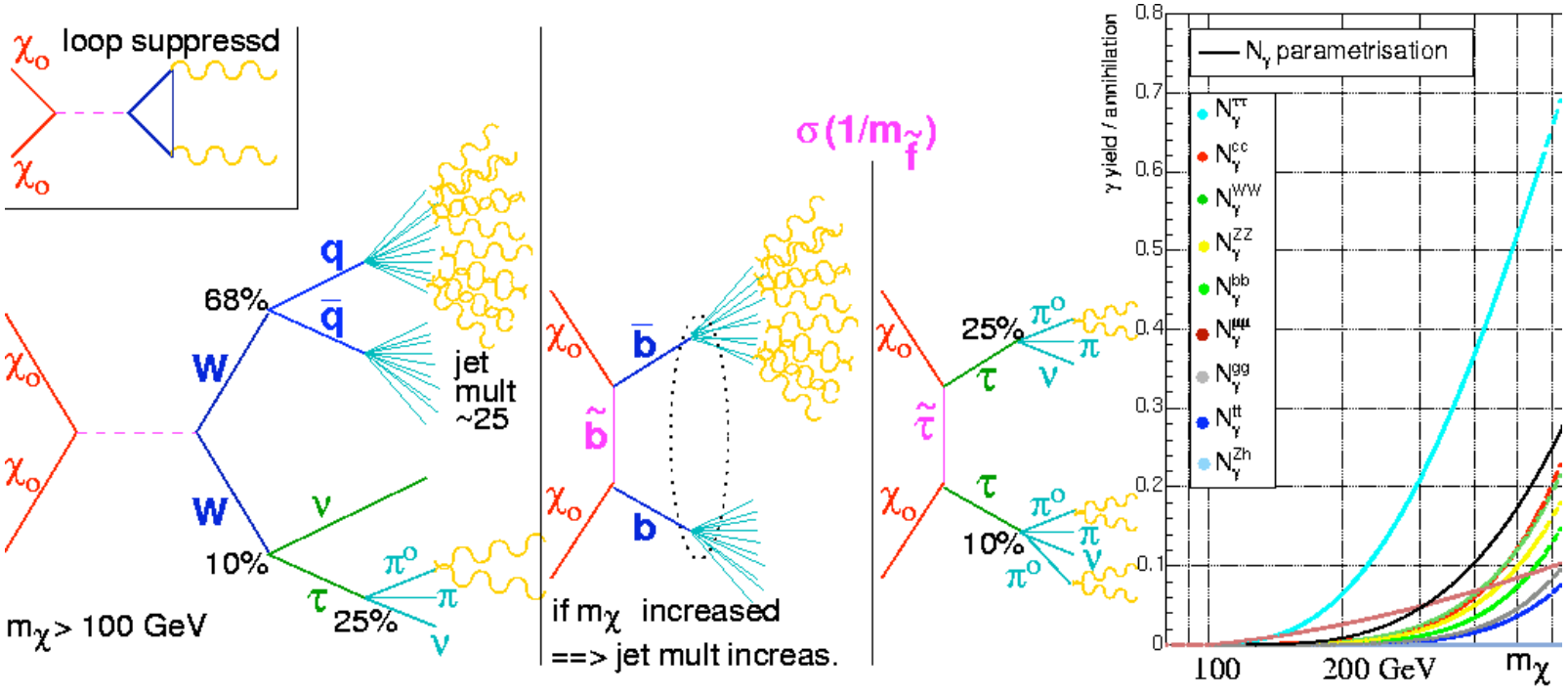
In convenient units:

$$\frac{\Phi_\gamma(E_\gamma, \Omega)}{\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{sr}^{-1}} \approx 2.8 \times 10^{-10}\, J(\Omega)\, \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma}(E_\gamma) \frac{\langle\sigma v\rangle}{\mathrm{pb}} \left(\frac{100\,\mathrm{GeV}}{m_\mathrm{X}}\right)^2. \tag{4}$$

$$J(\Omega) = \frac{1}{8.5\,\mathrm{kpc}} \left(\frac{1}{0.3\,\mathrm{GeV/cm}^3}\right)^2 \int_{\mathrm{los}} \rho^2(\ell, \Omega)\mathrm{d}\ell\,. \tag{5}$$

Gamma rays from WIMP Annihilation

WIMP doesn't couple directly to γ (else it won't be 'dark'!)



Energy Spectrum of Gamma Rays from WIMP Annihilation

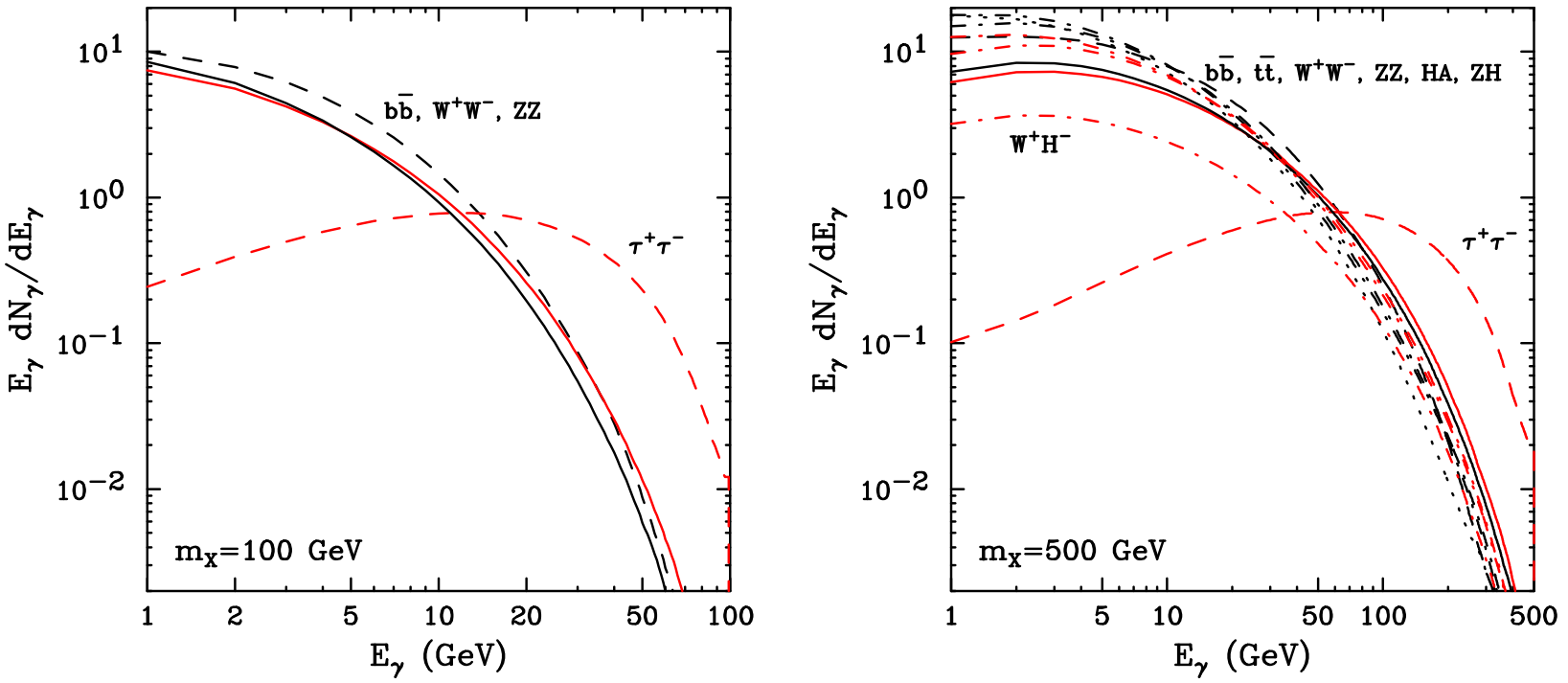


Figure 1: The gamma-ray spectrum per annihilation for a 100 GeV (left) and 500 GeV (right) WIMP. Each curve denotes the result for a different dominant annihilation mode. (From Dodelson).

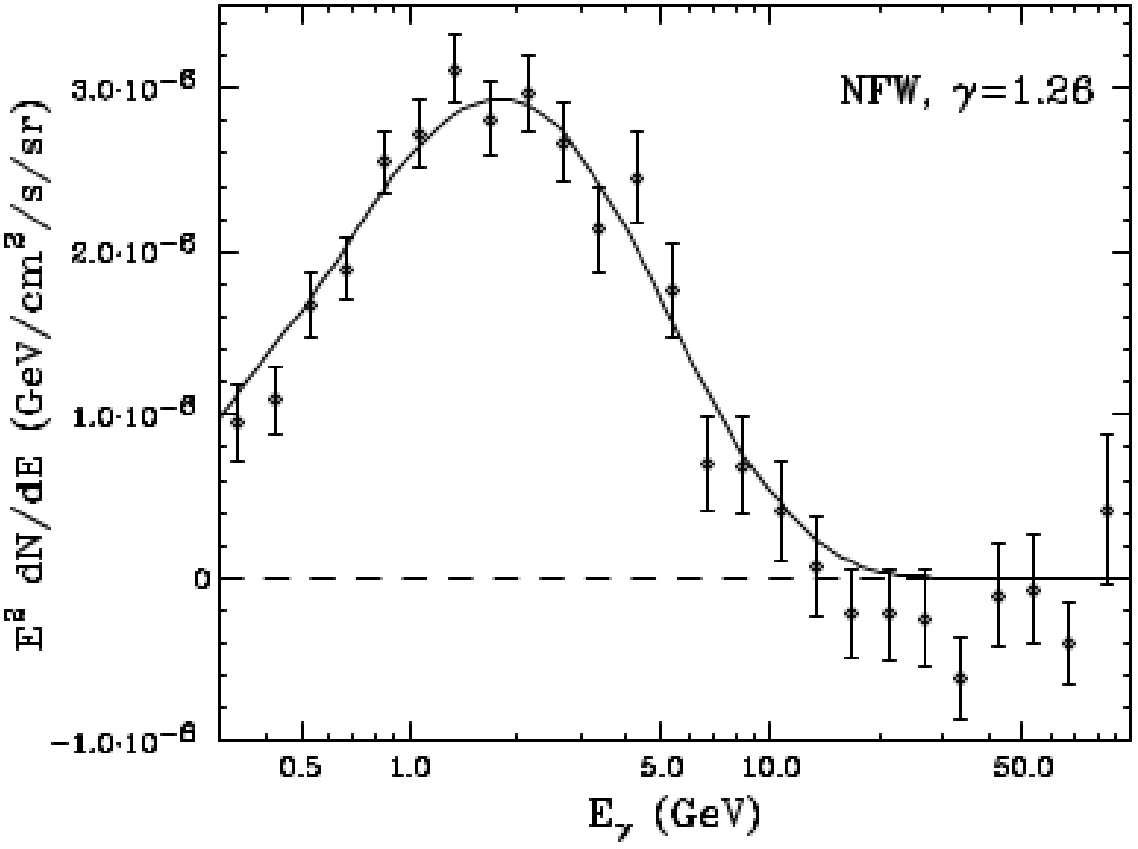
DM density profile

$$\rho(r) = \left(\frac{r_s}{r}\right)^{\gamma} \frac{\rho_0}{[1 + (r/r_s)^{\alpha}]^{(\beta-\gamma)/\alpha}}, \qquad (6)$$

Model	α	β	γ	$\rho_\odot$ [GeV cm^{-3}]	r_s [kpc]
Moore *et al.*	1.5	3	1.5	0.27	28
NFW	1.0	3	1.0	0.30	20
Kravtsov	2.0	3	0.4	0.37	10

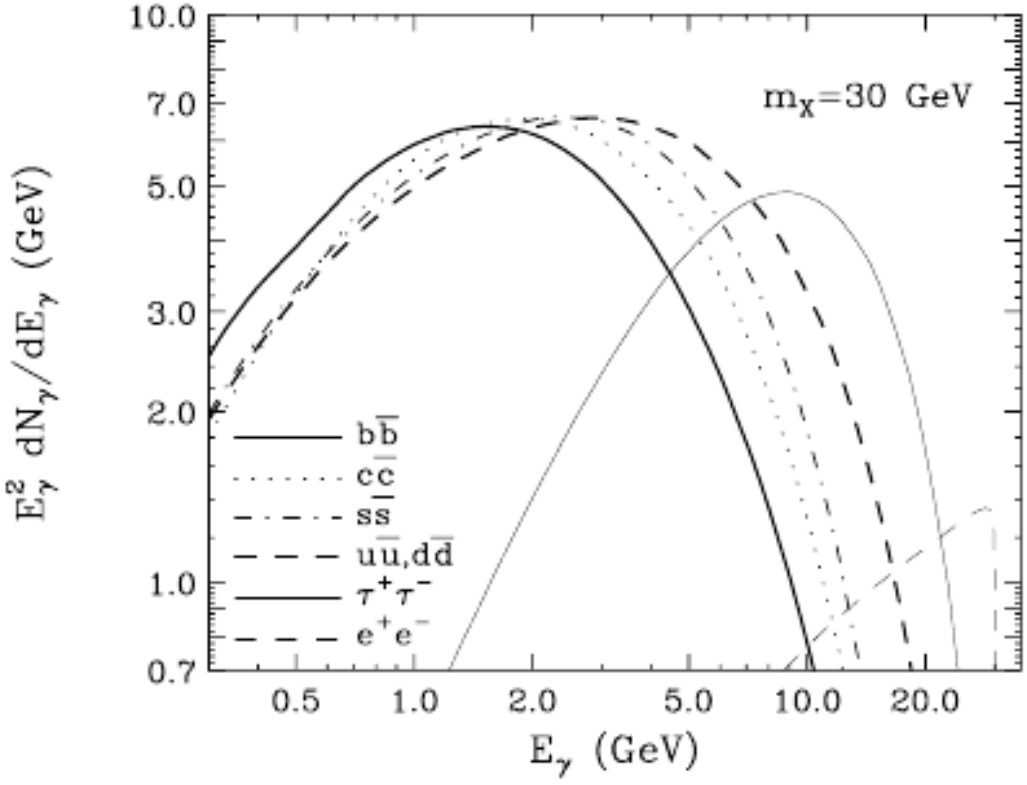
Table 1: Parameters describing some common halo profiles of the form described by Eq. (6), where $\rho_\odot$ is the DM density at the Solar distance from the GC.

Fitting the Galactic Center excess γ-rays with WIMP annihilations :



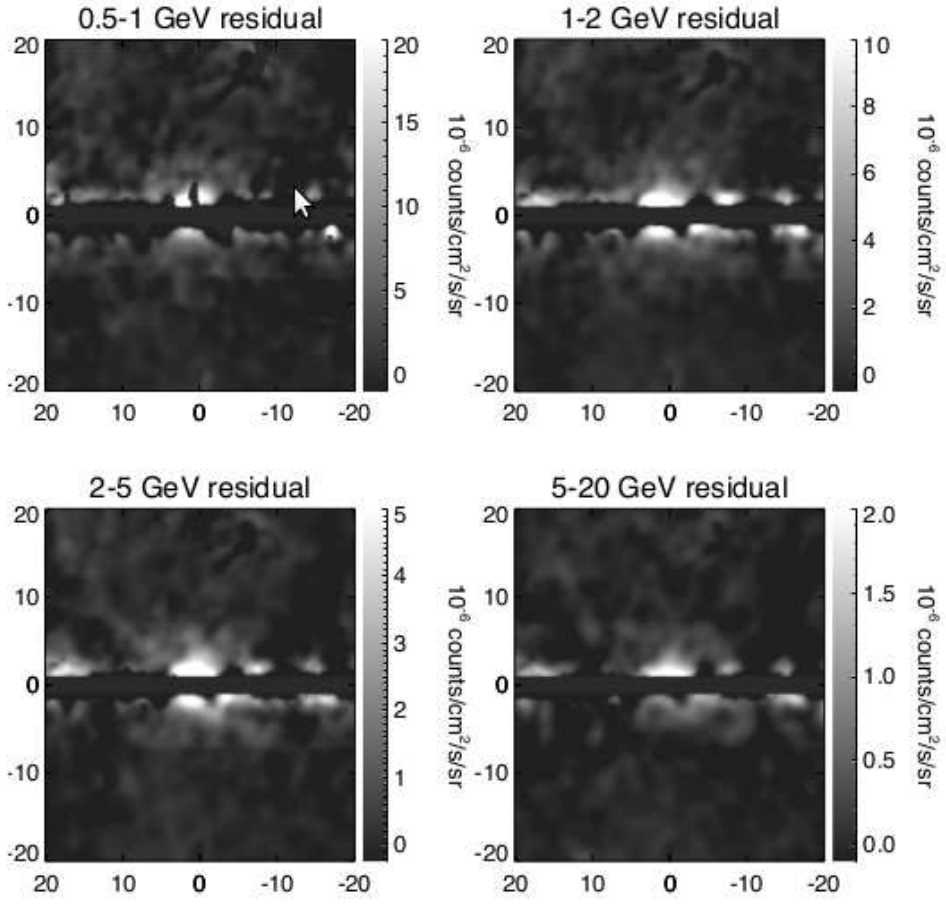
Daylan et al, arXiv:1402.6703

γ-ray spectrum from 30 GeV WIMP annihilation:



Daylan et al, arXiv:1402.6703

Residuals after subtracting known backgrounds:



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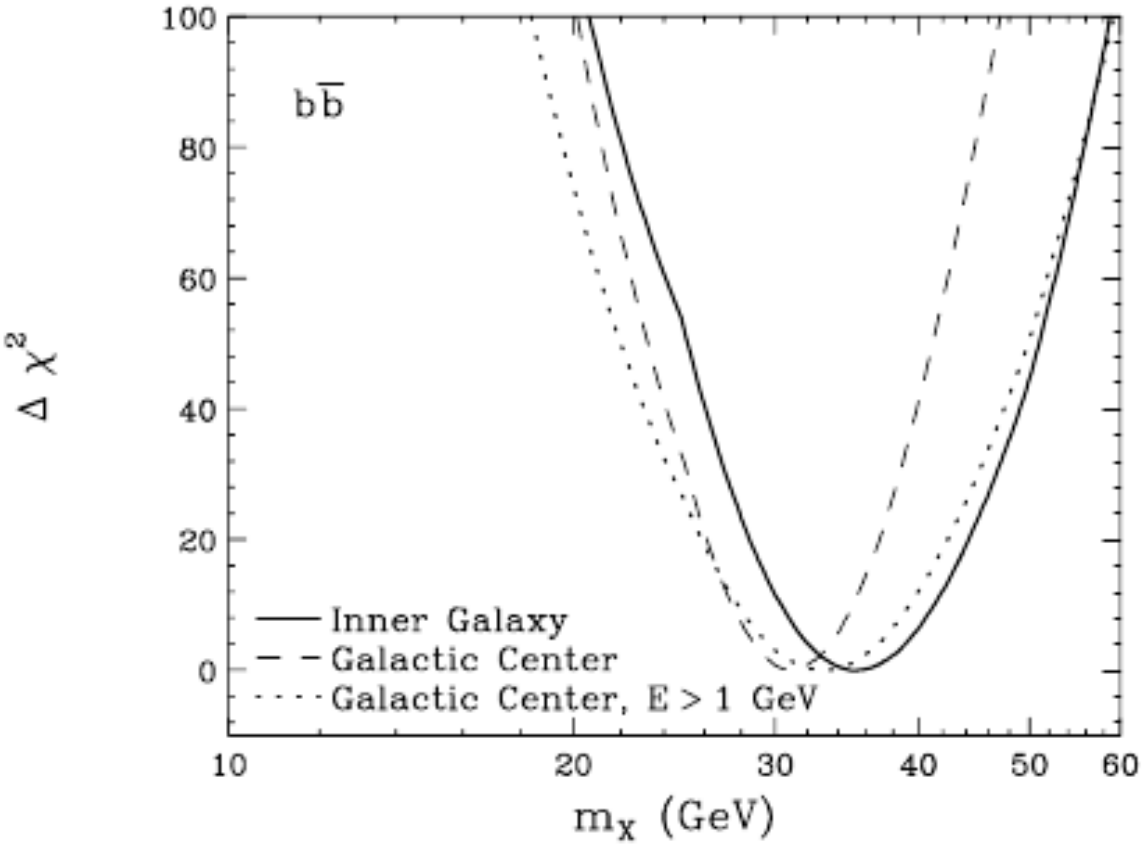
γ-ray spectrum from 30 GeV WIMP annihilation:



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