Sterile Neutrinos and the 130 GeV Gamma Signal

Daniel Schmidt

Outline:

INTRODUCTION

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references:

arXiV: 1202.4039
1204.2797
1205.2739
1204.6047
1206.1616
1205.6811
1208.6082

hep-ph: 9706232

Fermi: http://fermi.gsfc.nasa.gov

talks: Torsten Bringmann @ MPIK on April 30th 2012

I) Shedding Light on (Particle) Dark Matter χ

We know: i) There must be an additional source of gravity in the Universe (→ galaxy rotation curves, Bullet Cluster, etc.).

ii) If this additional component of gravity is made up of particles χ, these particles are:

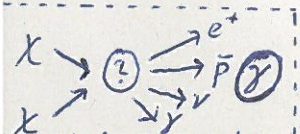
→ massive;
→ (quasi) stable, but pair annihilations;
→ electrically neutral, i.e., dark;
→ weakly interacting: spin-independent elastic χ-nucleon scattering cross section $< 2 \cdot 10^{-45}\,cm^2$ at $m_\chi = 55\,GeV$ (arXiV: 1207.5988).

iii) contribution to energy density of the Universe:

$\Omega_{DM} h^2 = 0{,}1109 \pm 0{,}0056$ (WMAP 7 data)

If Dark Matter is made up of weakly interacting massive (WIMP) particles χ, the thermal freeze out of χ yields:

$$\Omega_\chi h^2 \simeq \frac{3 \cdot 10^{-27} \frac{cm^3}{s}}{\langle \sigma v \rangle_{th}} \overset{!}{=} \Omega_{DM} h^2 \Rightarrow \langle \sigma v \rangle_{th} \simeq 3 \cdot 10^{-26} \frac{cm^3}{s}.$$



We want: "See" χ indirectly by annihilation products present in Cosmic Rays!
↳ Gamma γ-Rays

II) The Diffuse Galactic Gamma-Ray Emission: Where is χ?

(Known) sources of DGE:

(i) Cosmic Ray nucleons interacting with interstellar gas (atomic, molecular and ionized hydrogen)

ii) Bremsstrahlung by Cosmic Ray electrons

iii) Inverse Compton scattering of Cosmic Ray electrons with low energy interstellar photons

iv) π^0-decay: $\pi^0 \to 2\gamma$ with $\frac{\Gamma_{2\gamma}}{\Gamma_{tot}} = 98{,}8\%$

v) point sources, e.g., pulsars (pulsars are sources of Cosmic Rays, too, as supernovae remnants)

vi) ? unknown sources ?

(see The Astrophysical Journal, 494: 523–534 and references therein)

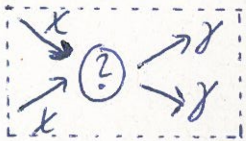
↓

Large amount in Galactic Center

↓

Fig. 15 from arXiv: 1202.4039

Where is χ: 2 body annihilation of χ into photons yields monochromatic gamma-rays



→ gamma-rays point directly to source: clear spatial signature

→ gamma-rays are monochromatic: $E_\gamma = m_\chi$ clear spectral signature of a line

⇒ Smoking gun signal: no astrophysical known process that gives line at $E \gtrsim 1\,\text{GeV}$

(see talk "Dark Matter Searches with Gamma Rays" by Torsten Bringmann held at MPIK on April 30th 2012)

III) Gamma-Ray Flux J_γ from $\chi\chi \to \gamma\gamma$

$$\frac{dJ_\gamma}{dE}(b,l) = \frac{\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}}{8\pi m_\chi^2}\, 2\,\delta(E-E_\gamma)\, r_\odot \rho_\odot^2 \int db \int dl \int \frac{ds}{r_\odot} \cos b \left(\frac{\rho(r)}{\rho_\odot}\right)^2$$

$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$: partial annihilation cross section for $\chi\chi\to\gamma\gamma$, loop suppressed $\sim\mathcal{O}(\alpha_e^2)$

$2\delta(E-E_\gamma)$: photon energy spectrum with $E_\gamma = m_\chi$

$\rho_\odot = 0{,}4\ \frac{GeV}{cm^3}$ Dark Matter density at position of the Sun

$\rho(r)$: Dark Matter profile

→ Einasto profile

$$\rho_E(r) \propto \exp\left(-\frac{2}{\alpha_E}\frac{r^{\alpha_E}}{r_s^{\alpha_E}}\right)$$

with $\alpha_E = 0{,}17$ and $r_s = 20\ Kpc$

→ Navarro-Frenk-White profile

$$\rho_{NFW}(r) \propto \frac{1}{(r/r_s)^\alpha (1+r/r_s)^{3-\alpha}}$$

with α parametrizing inner slope

Galactic coordinates:

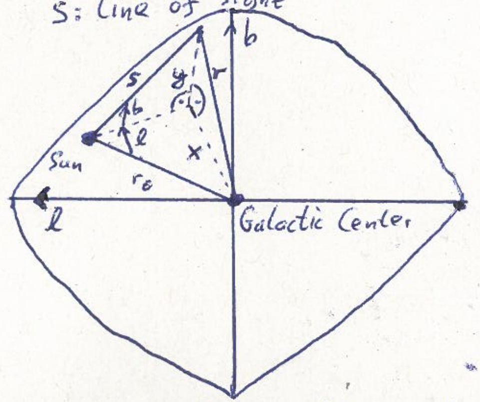
$r_\odot = 8{,}5\ Kpc$ (|Sun-Galactic Center|)

r: Galactocentric distance

b: Galactic lattitude

l: Galactic longitude

s: Line of sight



$x^2 = r_\odot^2 + (s\cdot\cos b)^2 - 2 r_\odot s \cdot \cos b \cdot \cos l$

$y = s\cdot \sin b$

$r^2 = x^2 + y^2 = r_\odot^2 + s^2 - 2 r_\odot s \cos b \cdot \cos l$

IV) "Tentative" 130 GeV Gamma-Ray Line (arXiV:1204.2797)

i) data: Fermi Large Area Telescope data collected between 4 Aug 2008 – 8 Mar 2012

ii) consider 5 reference Dark Matter profiles

iii) Optimization algorithm automatically selects target region with largest signal to noise ratio for a given Dark Matter profile → 5 optimal target regions

iv) For each region LAT data give gamma-ray flux → energy spectra

→ Figure 1 from arXiv: 1204.2797

v) Fit energy spectra with 3 parameter model: $\frac{dJ}{dE} = S\,\delta(E-E_\gamma) + \beta\left(\frac{E}{E_\gamma}\right)^{-\gamma}$ E_γ fixed during fit

↑ normalization of line; $S \sim \langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ ↑ background flux with spectral index γ and normalization β

→ best-fit $S_{best}, \beta_{best}, \gamma_{best}$

vi) significance of line signal for given E_γ by maximal test statistic → TS value

(fit with Dark Matter contribution vs. fit without Dark Matter signal)

→ Figure 3 from arXiv: 1204.2797 (filter: Pass 7 Version 6)

⇒ result: largest TS value for SOURCE events for $\rho^{(r)}_{NFW}$ with $\alpha = 1{,}15$: TS = 21,4; E_γ = 129,8 GeV; Significance: 4,65

Fit with highest significance for line contribution

→ Figure 4 from arXiV: 1204.2797 (signal evidence based on 57 photons → low number of events so far)

⇒ $m_\chi = E_\gamma = (129{,}8 \pm 2{,}4^{+7}_{-13})\,\text{GeV}$

$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1{,}27 \pm 0{,}32^{+0{,}18}_{-0{,}28}) \cdot 10^{-27}\,\frac{cm^3}{s}$ (for Einasto profile)

V (Why not) "definitive" Gamma-Ray Line?

→ Low number of events

→ instrumental artifact?! (see arXiv: 1209.4562)
so far, no instrumental systematics found that could plausibly explain the excess Galactic Center emission at 130 GeV.

A. Is the line really due to Dark Matter annihilations?!

B. How to get the enhancement for $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ in a particle model?

→ $\frac{\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}}{\langle\sigma v\rangle_{th}} \approx 4{,}2\,\% \Rightarrow$ large

expectation for neutralino χ Dark Matter:

$$\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} \sim 10^{-29}\ \frac{cm^3}{s}\ !$$

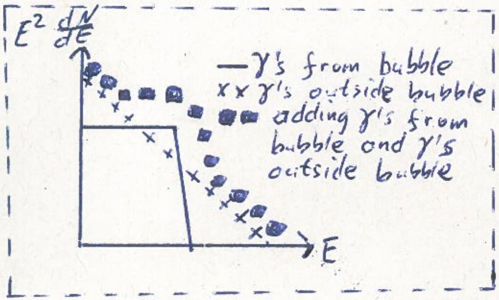
(see hep-ph/9706232; Bergström and Ullio)

VI A. Is the line really due to Dark Matter annihilations?

i) FERMI-LAT collaboration: → only two years of Fermi LAT data
→ only Pass6 photon selection
→ FIG. 6 of arXiv: 1205.2739

⇒ result: "We find no detection of spectral lines from 7 to 200 GeV (...). implications for indirect dark matter searches of the absence of significant gamma-ray spectral lines:
for $E_\gamma = 130\,\text{GeV}$ and Einasto profile → $\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \lesssim 1.0\cdot 10^{-27}\,\frac{cm^3}{s}$

ii) "Is it a Bubble?" (arXiv: 1204.6047)
→ target regions of arXiv: 1204.2797 overlap with regions where intense gamma-ray emission has been discovered → gamma-ray bubbles (arXiv: 1005.5480)
→ spectrum of bubbles $\frac{dN}{dE} \sim E^2$ harder than inverse Compton emission and gamma-rays from π^0 decay
FIG. 10 and FIG. 12 of arXiv: 1005.5480
→ spectral break of these Fermi bubbles at $E \gtrsim 150\,\text{GeV}$:



⇒ result: spectral break of bubbles adds up with background photons yielding a spectrum which can easily be misinterpreted as a line.
(arXiv: 1204.6047)

VI A. Is the line really due to Dark Matter annihilations

iii) "Strong Evidence for Gamma-Ray Lines (arXiv: 1206.1616)

→ gamma-ray excess at Galactic Center at $E \sim (120-140)$ GeV

→ cusp has different shape from bubbles → no obvious connection to bubbles

→ FIG. 4, 5 of arXiv: 1206.1616)

→ For given template (for Galactic disk, Fermi bubbles, uniform background), the spectral energy distribution is determined.
Compute likelihood that gamma-ray excess is given by a linear combination of the templates and fit the coefficient for each emission component.

→ FIG. 10 of arXiv: 1206.1616

⇒ result: "Except for unexpected instrumental systematics or (...) statistical fluke, a dark matter annihilation signal (...) is the most likely explanation."

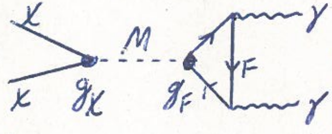
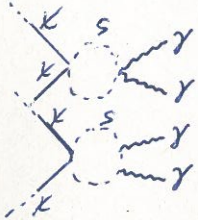
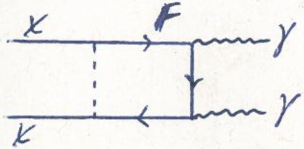
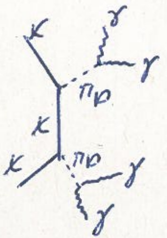
- best fit: pair of lines at $E_\gamma^1 = (110{,}8 \pm 4{,}4)$ GeV and $E_\gamma^2 = (128{,}8 \pm 2{,}7)$ GeV
  for $m_\chi = 142$ GeV:  
  and $m_h \approx 130$ GeV

We take up the position that there is a gamma-ray line in the Fermi data and that it is due to dark matter annihilations.

→ consequences for particle model building?

VII B. How to get the enhancement for $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma}$ in a particle model

i) General Considerations (arXiv: 1205.6811)

$\chi\chi \to \gamma\gamma$	description	features/conditions	→ cross section
• 	s-channel annihilation of Majorana fermion χ via scalar mediator M over loop of charged particle F into photon γ	$m_F \gtrsim m_\chi$; g_F and $g_\chi \sim 1$ (large); resonance within 5 GeV of $2m_\chi$ ($m_M = 2m_\chi$)	$\langle\sigma v\rangle^{max}_{\chi\chi\to\gamma\gamma} = \frac{\alpha^2 g_F^2 g_\chi^2}{4096\pi\Gamma_M^2} \approx 2\cdot 10^{-27}\frac{cm^3}{s}$
• 	$\frac{\lambda_\chi}{2}\chi^2\lvert S\rvert^2$ coupling ⇒ χ and S not fermionic, S charged	$m_S \gtrsim m_\chi$; $\lambda_\chi \sim 10$ (very large)	$\langle\sigma v\rangle^{max}_{\chi\chi\to\gamma\gamma} = \frac{\alpha^2\lambda_\chi^2}{128\pi^3 m_\chi^2}\left(\frac{\pi^2}{4}-1\right)^2 \approx 2.0\cdot 10^{-29}\frac{cm^3}{s}\cdot\left(\frac{\lambda_\chi}{1}\right)^2\left(\frac{130\,GeV}{m_\chi}\right)^2$
• 	box-type diagramm ↓ as in arXiv: 1208.6082	$m_F \gtrsim m_\chi$; $g_\chi \gtrsim 1{,}4$ (very large)	$\langle\sigma v\rangle^{max}_{\chi\chi\to\gamma\gamma} = \frac{\alpha^2 g_\chi^2}{4\pi^3 m_\chi^2}\left(\frac{\pi^2}{4}-1\right)^2 \approx 6{,}4\cdot 10^{-28}\frac{cm^3}{s}\left(\frac{g_\chi}{1}\right)^4\left(\frac{130\,GeV}{m_\chi}\right)^2$
• 	• π_D intermediate state	$m_{\pi_D} \simeq m_\chi$ → $E_\gamma \sim \frac{m_\chi}{2}$	$\langle\sigma v\rangle^{max}_{\chi\chi\to\gamma\gamma} \approx 4\cdot 10^{-27}\frac{cm^3}{s}$ for $m_{\pi_D} \approx 250$ GeV, $m_\chi \simeq 260$ GeV, $g_\chi = 0{,}25$

ii) constraints:

Fermi's observation of Galactic center (NFW profile, $m_\chi = 130$ GeV)

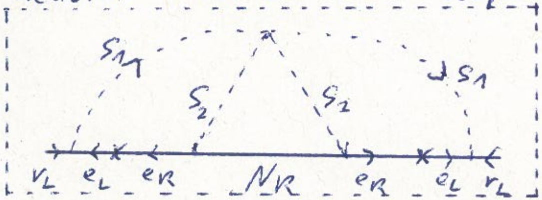
→ $\langle\sigma v\rangle_{\chi\chi\to W^+W^-/ZZ} < 1\cdot 10^{-26}\frac{cm^3}{s}$ (for $b\bar{b}$ [illegible] $< 8\cdot 10^{-27}\frac{cm^3}{s}$) ≪ $\langle\sigma v\rangle_{th}$!!!

VIII Getting the Line(s) with Right-handed Neutrino N_R as Dark Matter

The model: → Standard model particles + charged scalar singlets S_1 and S_2 + one right-handed neutrino N_R + $\mathbb{Z}_2$: $\{S_2, N_R\} \xrightarrow{\mathbb{Z}_2} \{-S_2, -N_R\}$

→ $\mathcal{L}_{new} = f_{\alpha\beta} L_\alpha^T C i\tau_2 L_\beta S_1 + g_\alpha N_R S_2^+ l_{\alpha R} + M_R N_R^T C N_R + V(S_1, S_2) + h.c.$

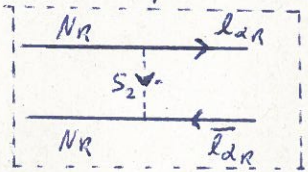
→ Majorana neutrino mass at three loop level



$M_{N_R} < M_{S_1} < M_{S_2} \propto 100\ GeV - 1\ TeV$

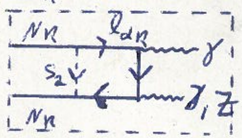
Dark Matter: → N_R leptophilic interacting massive particle LIMP

→ thermal relic density:



→ contribution to gamma-rays: ($m_{N_R} = 135\ GeV$) → FIG. 1 of arXiv: 1208.6082

- $N_R N_R \to l_{\alpha R}^+ l_{\alpha R}^- \gamma$ (Bremsstrahlung from diagram above)
- $N_R N_R \to \gamma\gamma$



- $N_R N_R \to \gamma Z$

→ FIG. 2 of arXiv: 1208.6082