‘We have no idea…’ - status of a search for dark matter signals in astrophysical data

Gabrijela Zaharijas
University of Nova Gorica, Slovenia and INFN, Trieste
on behalf of the Fermi LAT Collaboration
Dark matter is out there!
an essential building block of the Standard Model of Cosmology

large scale structures

clusters of galaxies

Milky Way-sized galaxies
dwarf galaxies

10s Mpc

Mpc

10s kpc

<~ kpc

Orsi et al. (2009)

Rubin et al. (1980)

Rotation Curves

Zwicky (1937)

Missing mass on Galaxy Cluster scale

Clowe et al. (2006)
Bullet Cluster

Almost collisionless majority

Evidence for / Salient Features of Dark Matter of mass in Galaxies

WMAP (2010), Planck (2015)

CMB Acoustic Oscillations

Big-Bang

Non-Baryonic correlation length depend upon the choice of evolutionary $m$ (Groth & Peebles 1977). In this case, the results obtained for the correlation function made from small fields. The models are in reasonable agreement with the estimate by Geach et al. (2008) at low redshift measurements. The agreement with the estimate by Geach et al. (2008) at low redshift measurements is sometimes assumed for the correlation function whereas others report in comoving units. Lastly, how sampling variance can affect measurements of the correlation length (see Orsi et al. 2008 for an illustration).

First, a form must be adopted for the distribution of sources. Second, some papers quote results in terms of projection. First, a form must be adopted for the distribution of sources. Second, some papers quote results in terms of projection. First, a form must be adopted for the distribution of sources. Second, some papers quote results in terms of projection. First, a form must be adopted for the distribution of sources. Second, some papers quote results in terms of projection. First, a form must be adopted for the distribution of sources. Second, some papers quote results in terms of projection.
Dark matter is out there!
an essential building block of the Standard Model of Cosmology

large scale structures

clusters of galaxies

Milky Way

All evidence is astrophysical through gravity

dwarf galaxies
The challenge

- How does it couple to the Standard Model?
- Why so abundant? Note $\Omega_{DM} \sim \text{few} \times \Omega_b$.
- Why ‘stable’?
- Composite or elementary?
- ‘Maverick’ or dark ‘sector’?
What can it be? — the WIMP miracle

Thermal decoupling from primordial plasma singles out the Weak Scale - WIMP miracle suggestive & predictive!

\[ \Omega_{\text{DM}} \approx \frac{2 \times 10^{-37} \text{cm}^2}{\langle \sigma_{\text{annih}} v \rangle} \approx 0.23 \]
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How to find it?

For thermal dark matter:
— indirect searches provide insight into the early Universe decoupling
— we know ‘where’ to look

@ $\mathcal{O}(M_2)$ for standard WIMPs

in astrophysical systems - remotely
How to find it?

thermal freeze-out (early Univ.)
indirect detection (now)

For thermal dark matter:
— indirect searches provide insight into the early Universe decoupling
— we know ‘where’ to look

@ $\mathcal{O}(M_Z)$ for standard WIMPs

Through cosmological clustering probes:
we know DM interacts gravitationally...
look at small scales — could probe dark matter self-interactions, its de-Broglie wave length (fuzzy DM) etc

[see e.g. Murgia+ 1704.07838]
'The Golden Age'

\[ \Theta(M_Z) \]

\[ \gamma \rightarrow e^\pm, p^\pm, D^- \]

\[ V \]

Ground based, ACTs

Fermi LAT, AGILE

HESS, VERITAS, MAGIC

HAWC Observatory

ANTARES

CREAM, TIGER

PAMELA, AMS02

Ice Cube

Tracker Entry

Tracker Exit

0.33 X

Tracker Total

0.50 X

TRD

TOF

RICH

ECAL
‘The Golden Age’

\[ @ \mathcal{O}(M_\gamma) \]

\[ \gamma \rightarrow e^\pm, p^\pm, D^- \]

\[ \nu \rightarrow \nu \]

Interact with the interstellar medium (magnetic field) — only local spectra

Ground based, ACTs

Source emits \( \gamma \)-ray

\( \gamma \)-ray interacts in atmosphere
Producing electromagnetic shower and Cherenkov Light
Large Optical Reflector
Images Cherenkov light onto PMT camera

Fermi LAT, AGILE

HAWC Observatory

ANTARES

PAMELA, AMS02

Ice Cube

\( \nu \) ray interacts in atmosphere
Producing electromagnetic shower and Cherenkov Light
Source emits \( \gamma \)-ray

\( \frac{4}{3} \pi r^2 \times \text{Distance} \)

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Astrophysical experiments: multipurpose experiments w rich scientific program --> discovering the sky @>>~Mz energies

charged cosmic rays
AMS results:

First detection of astrophysical neutrinos!

~3000 point sources (Galactic and extraGal):
Astrophysical experiments: multipurpose experiments w rich scientific program --> discovering the sky @>~Mz energies

charged cosmic rays

New AMS results:

Strategy — in case of a signal ‘hint’
look at different targets within a single experiment
confirm w different experiments/messengers

~3000 points of astrophysical neutrinos!

Galactic and extraGal

Fermi bubbles

diffuse emission from our Galaxy:

ASTROPHYSICAL EXPERIMENTS: multipurpose experiments w rich scientific program --> discovering the sky @>~Mz energies

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Galactic and extraGal

Fermi bubbles

diffuse emission from our Galaxy:
Strategy 01: cross-check with different targets

**Gamma rays:**

\[
\frac{d\Phi(\Delta\Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi} \frac{(\sigma_{\text{ann}} v)}{2 m_\chi^2} \times \sum_i B R_i \frac{dN^i_\gamma}{dE_\gamma} \times \int_{\Delta\Omega} d\Omega \int_{\text{los}} ds \rho^2(s, \Omega)
\]

**Gamma ray spectrum per interaction**

**Probability of interaction**

**Cumulative extragalactic signal**

**GC**

**GC halo**

**Dwarf satellites**

**Clusters of galaxies**

**Spectral line**

[adapted from: H.-S. Zechlin]
DM search in the inner Galaxy with Fermi LAT

**Prime example of a search strategy in practice:**
- Look in high-signal/high background region
- In case of a detection hint — cross check the signal with different targets and experiments

![Diagram showing LAT data, model(s) of the diffuse emission, and point sources from the catalog.](image)

**Model(s) of the diffuse emission**
- LAT data
- Uniform-brightness template for the Fermi Bubbles
- 1-3 GeV residual
- Galactic centre excess

**Point sources from the catalog**
- Fermi LAT data
- Masked pixels are indicated in black
- All maps have been smoothed to a common PSF of $y$
Pass 8 Fermi LAT analysis


DM spectral fits

DM morphology

Many works reaching similar results:

Vitale & Morselli (2009), Goodenough & Hooper (2009), Hooper & Goodenough (2011, PLB 697 412), Hooper & Linden (2011, PRD 84 12), Abazajian & Kaplinghat (2012, PRD 86 8),
1207.6047, Hooper & Slatyer (2013, PDU 2 118),
1302.6589 Gordon & Macias (2013, PRD 88 8)
1306.5725 Macias & Gordon (2014, PRD 89 6)
1312.6671, Abazajian et al. (2014, PRD 90 2)
1402.4090, Daylan et al. (2014) 1402.6703,
1407.5583 1407.5625 1410.1527
Could it be dark matter?

Right on the spot where WIMP DM is supposed to be!

Thermal cross section & \(<\sim 100 \text{ GeV}\) & at the Galactic center
Spatial distribution close to the predicted NFW profiles.
Or…

Spectral twins: Pulsar/DM Annihilation (30 GeV bb channel)

But, only a handful gamma-ray pulsars known pre-Fermi LAT.

Baltz et al. (2007)
Or...

Spectral twins: Pulsar/DM Arm (30 GeV bb channel)

Since, >100 pulsars and milli-second pulsars observed in the MW, most of them local — possible that many faint ones contribute to the Galactic centre excess

[Caraveo, 2014]
Bulge MSP population?

Individual pulsars hard to detect at the distance of the GC. What if we account for unassociated sources (1/3 of all sources)?
— Identify candidate pulsar sources among the unassociated ones,
— use the ‘local’ γ-ray pulsar luminosity function from known pulsars to estimated efficiency of the pulsar selection
— use maximum likelihood analysis to extract the morphology of the Galactic pulsar population

Preliminary

Consensus is building up that (milli-second) pulsar population in the Galactic bulge is responsible for the excess

[see also Bartels+ and Lee+, 2016]
How can we test the GCE origin?

For DM interpretation, **multi-target tests** are essential —> dwarf spheroidal galaxies!
DM search in dwarf galaxies with Fermi LAT

Using the joint likelihood to combine info from 15 dSphs, taking into account the uncertainties in their DM content —> one of the strongest DM limits to date

**annihilation cross section**

![Graph showing annihilation cross section vs DM mass]

GCE dark matter origin in tension with complementary gamma ray observations
LAT data coincident with four of the newly discovered targets show a ~2σ (local) γ-ray emission in excess of the background, weakening the limits by 1.5x at low masses.

[Bechtol+ 1503.02584, Belokurov+, 1403.3406, Laevens+, 1503.05554]
[Gerringer-Sameth et al. 2015, Hooper & Linden 2015, Li et al. 2016]
Strategy 02: cross-check with different messengers

-> charged cosmic rays:

anti-particles - golden channels

anti-matter & photons

matter

[Beischer et al., 2009]
FIG. 1: Comparison of the best fit of the \( \bar{p}/p \) ratio to the AMS-02 data [14], with a DM component (left panel) and without DM (right panel). The lower panels show the corresponding residuals. The fit is performed between the dotted lines, i.e., for rigidities 5 GV \( \lesssim R \lesssim 10 \) TV. The grey bands around the best fit indicate the 1 and 2 \( \sigma \) uncertainty, respectively. The dashed black line (labeled "\( \phi_\odot=0 \)MV") shows the best fit without correction for solar modulation. The solid red line shows the best fit DM contribution. We also show, for comparison, the contribution from astrophysical tertiary antiprotons denoted by the dot-dashed line.

not reduce the evidence for a DM matter component in the antiproton flux, and modifies only slightly the preferred ranges of DM mass and annihilation cross-section,

FIG. 2: Best fit regions (1, 2 and 3) for DM component of the antiproton flux, using the antiproton cross-section models of [40] (Tan&Ng), [41] (DiMauro et al.), and [42] (Kachelrieß et al.). For comparison, we also show the best fit region of the DM interpretation of the Galactic center gamma-ray excess [38], and the thermal value of the annihilation cross-section, \( h v = 3 \times 10^{-26} \text{cm}^3 \text{s}^{-1} \).

see FIG. 2. This represents an important test, since the cross-sections used are quite different in nature. While those of [40, 41] are based on a phenomenological parameterization of the available cross-section data, the cross-section of [42] is based on a physical model implemented through Monte Carlo generators. While this check does not exhaust the range of possible systematics related to the antiproton cross-section, a more robust assessment of this issue requires more accurate and comprehensive experimental antiproton cross-section measurements.

From TABLE I we note that including a DM component induces a shift in some of the propagation parameters. In particular the slope of the diffusion coefficient, changes by about 30% from a value of \( \phi_\odot=0 \) with- out DM to \( \phi_\odot=0 \) when DM is included. This stresses the importance of fitting at the same time DM and CR background. The changes induced by a DM component in the other CR propagation parameters are less than about 10%. More details are reported in the supplementary material.

As a further estimate of systematic uncertainties, we have extended the fit range down to a rigidity of \( R=1 \) GV. In this case, the fit excludes a significant DM component in the antiproton flux. This can be understood from the residuals for this case, which are very similar to the ones shown in the right panel of FIG. 1. Clearly, the excess feature at \( R=18 \) GV, responsible for the DM preference in the default case, still remains. The reason why...
Remember:

— propagation of charged cosmic rays determined by many free parameters

$\Rightarrow$ significant uncertainties!

— strong limits, in tension but not excluding the GCE

\[ \gamma_{1,p} = 1.54_{-0.18}^{+0.04}, \quad 1.41_{-0.01}^{+0.19}, \quad 1.2 - 1.8 \]
\[ \gamma_{2,p} = 2.425_{-0.002}^{+0.023}, \quad 2.531_{-0.010}^{+0.008}, \quad 2.3 - 2.6 \]
\[ \gamma_{1} = 1.56_{-0.18}^{+0.03}, \quad 1.21_{-0.02}^{+0.22}, \quad 1.2 - 1.8 \]
\[ \gamma_{2} = 2.388_{-0.003}^{+0.021}, \quad 2.480_{-0.005}^{+0.005}, \quad 2.3 - 2.6 \]
\[ R_{0} [\text{GV}] = 8.43_{-0.13}^{+0.27}, \quad 5.01_{-0.12}^{+1.30}, \quad 1.0 - 10 \]
\[ s = 0.38_{-0.01}^{+0.11}, \quad 0.46_{-0.06}^{+0.01}, \quad 0.05 - 0.9 \]
\[ \delta = 0.361_{-0.004}^{+0.005}, \quad 0.245_{-0.007}^{+0.015}, \quad 0.2 - 0.5 \]
\[ D_{0} [10^{28} \text{ cm}^2/\text{s}] = 7.48_{-1.88}^{+1.52}, \quad 9.84_{-2.85}^{+0.36}, \quad 0.5 - 10.0 \]
\[ v_{A} [\text{km/s}] = 23.8_{-0.91}^{+3.09}, \quad 28.5_{-0.64}^{+1.7}, \quad 0 - 30 \]
\[ v_{0,c} [\text{km/s}] = 26.9_{-3.3}^{+34.7}, \quad 45.3_{-19.2}^{+5.69}, \quad 0 - 100 \]
\[ z_{h} [\text{kpc}] = 6.78_{-2.7}^{+0.22}, \quad 5.35_{-1.27}^{+1.65}, \quad 2 - 7 \]
\[ \phi_{\text{AMS}} [\text{GV}] = 580_{-50}^{+65}, \quad 520_{-35}^{+35}, \quad 0 - 1.8 \]
Remember:

propagation of charged cosmic rays determined by many free parameters

→ significant uncertainties!

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### Table

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<th>Standard fit with DM</th>
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→ Several probes are reaching the thermal cross section limits and are in tension with the GCE DM interpretation.
Things are getting more interesting…

The gamma-ray emission from M31

- Main facts
  - Emission confined to inner regions (R<5kpc)
  - Not correlated with interstellar gas and star formation sites
  - Galactic disk not detected

C. Eckner’s talk

Outlook: gamma ray limits come from many targets!

Many interesting analysis approaches, increasingly competitive constraints

Representative Results for Different Search Targets for the b-quark Channel

\[ \langle \sigma v \rangle \text{ [cm}^3 \text{s}^{-1}] \]

- MW Halo: Ackermann+ (2013)
- MW Center: Gomez-Vargas+ (2013)
- dSphs: Ackermann+ (2015)
- Isotropic: Ajello+ (2015)
- X-Correl.: Cuoco+ (2015)
- APS: Gomez-Vargas+ (2013)

Thermal Relic Cross Section (Steigman+ 2012)

\[ m_\chi \text{ [GeV]} \]

[Charles+, Phys.Rept. 636 (2016)]

Outlook

- Many interesting analysis approaches, increasingly competitive constraints

Outlook - gamma ray limits come from many targets!

M. Regis's talk

- gamma ray limits come from many targets!
- Many interesting analysis approaches, increasingly competitive constraints

Outlook

- gamma ray limits come from many targets!
- Many interesting analysis approaches, increasingly competitive constraints
Outlook - many experiments contribute to the effort!

![Graph showing the limits on WIMP self-annihilation for different channels and profiles.](image)

**Fig. 7** The final limits without systematic uncertainties (solid line), compared to the sensitivity (dashed line). Showing the 1σ (green band) and 2σ (yellow band) statistical uncertainty for dark matter self-annihilating through the $\tau^+\tau^-$ channel assuming a NFW (Burkert) halo profile on the left (right) plot.

**Fig. 8** Comparison of upper limits on $\langle \sigma_A v \rangle$ versus WIMP mass, for dark matter self-annihilating through $\tau^+\tau^-$ to neutrinos, assuming the NFW profile. This work (IC86 (2012-14)) is compared to other published searches from IceCube [28, 38–40] and ANTARES [41]. Also shown are upper limits from gamma-ray searches from the dwarf galaxy Segue 1 (Seg1) by Fermi+MAGIC [42] and from the galactic center by H.E.S.S. [43]. The 'natural scale' refers to the value of $\langle \sigma_A v \rangle$ that is needed for WIMPs to be a thermal relic [44].

**9 Conclusions**

This analysis demonstrates the continued improvements in dark matter searches with neutrinos, providing a valuable complement to the bounds from Cherenkov telescopes and gamma-ray satellites. A more inclusive event selection and the use of an improved event reconstruction algorithm have increased the sensitivity of IceCube to the signal of dark matter self-annihilation. However, no significant excess above the expected background has been observed in 3 years of IceCube/DeepCore data. Upper limits have been put on $\langle \sigma_A v \rangle$ providing the leading limits on WIMPs with a mass between 10–100 GeV for a neutrino observatory.
Outlook - future WIMP searches

Figure 28: Comparison of projected dSph stacking limits with current and future IACT limits from CTA for the $b\bar{b}$ (left) and $\tau^+\tau^-$ (right) channels. The dashed black curve shows the expected limit from the analysis of the artificially expanded target described in §4.5.2 for the 15-year data set. IACT limits are in red and taken from [281, 282]. The limits derived from the Planck data [13] are in gray. Finally, favored contours for several Galactic-center analyses are included for comparison.

Figure 29: Combined total uncertainty on the predicted secondary $\bar{p}/p$ ratio, superimposed on the PAMELA [283] and AMS-02 [284, 285] data. This figure appeared as Fig. 2 of Ref. [286]; additional details about the uncertainty bands may be found in that work; reproduced under the Creative Commons attribution license.

Similarly, the ratio of positron to electron fluxes has been measured by the LAT [28], AMS-02 [289, 290] and PAMELA [291] and is potentially sensitive to DM interactions. The observed positron to electron flux ratio rises steadily from $\sim 5\%$ at 1 GeV to $\sim 15\%$ above 100 GeV, suggesting the injection of high-energy positrons into the interstellar medium. Similarly to the situation with anti-protons, the interpretation of the rising positron fraction and implied constraints on DM annihilation are dominated by systematic modeling uncertainties, see, e.g., Refs [292–295] for discussion of the interpretation of the positron excess.

In summary, the LAT data, and in particular the analysis of the dSphs provide the best current constraints on the WIMP annihilation cross-section for light WIMPs.
Outlook—cornering the WIMPs

**Comparison of Projected Limits with Direct-Detection and Collider Limits**

**Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B**

**Caution: model dependent! EFT assumed here.**

Charles+ [Fermi-LAT Clb] 2016PhR...636....1C
Outlook—cornering the WIMPs

Comparison of Projected Limits with Direct-Detection

Conversion of direct detection and collider limits following EFT methodology of Bauer+ 2015PDU.....7...16B

Caution: model dependent! EFT assumed here.

Charles+ [Fermi-LAT Clb] 2016PhR...636....1C
Outlook— cornering the WIMPs

The community (theorists & experimentalists from many fields) came together over the past ~40 years and executed a complex strategy to test the WIMP models.

By ~2025+ n-ton scale direct detection + upgraded LHC + indirect detection should have delivered (bulk of) the message.
Not ‘only’ WIMPs…

DETECTING AXIONS/ALPs WITH PHOTONS

\[ \mathcal{L}_{a\gamma} = -\frac{1}{4} g_{a\gamma} F_{\mu\nu} \tilde{F}^{\mu\nu} a = g_{a\gamma} E B a \]

PRIMAKOFF EFFECT

DECAY

\[ \tau_{a\gamma\gamma} \sim 10^{25} \text{s} \left( \frac{g_{a\gamma}}{10^{-10} \text{ GeV}^{-1}} \right)^{-2} \left( \frac{m_a}{\text{eV}} \right)^{-3} \]

QCD Axion: \[ m_a \approx 0.3 \text{ eV} \frac{g_{a\gamma}}{10^{-10} \text{ GeV}^{-1}} = 0.3 \text{ eV} g_{10} \]

[slide credit: M. Meyer]

[Birenji, Gaskins, Meyer 2016]
1st Observable: axions/ALPs do not get absorbed during propagation, might lead to a boost in photon flux

\[ P_a \ll (g a B_l)^2 \]

\[ \exp(-\tau(E, z)) \]

Absorption on extragalactic background light

E\text{\textasciicircum 2}dN / dE

\[ \text{Energy} \]

\[ \text{Energy} \]

\[ \text{Energy} \]

\[ \text{Energy} \]

[slide credit: M. Meyer]

2nd Observable: irregularities in energy spectrum around $E_{\text{crit}}$ and $E_{\text{max}}$


[slide credit: M. Meyer]
SEARCH FOR IRREGULARITIES WITH FERMI LAT FROM NGC 1275

- Radio galaxy NGC 1275, bright *Fermi* source [e.g. Abdo et al. 2009]
- In the center of **cool-core** Perseus cluster

**ALP HYPOTHESIS:**
\[ P_{\gamma\gamma}(E, m_a, g_{\alpha\gamma}, B)F(E) \]
- Photon. surv. prob.; incl. EBL
- Intrinsic spectrum

**NO-ALP HYPOTHESIS:**
\[ \exp(-\tau)F(E) \]
- EBL attenuation only
- Intrinsic spectrum

[slide credit: M. Meyer]

[Ajello et al. (Fermi-LAT Collaboration) 2016]
AXIONLIKE PARTICLES FROM CORE COLLAPSE SUPERNOVAE

- ALPs would be produced in a core-collapse SN explosion via Primakoff process
- Could convert into gamma-rays in Galactic magnetic field
- Gamma rays would arrive co-incident with SN neutrinos (provides time tag)

EXPECTED ALP SIGNAL
- ALPs produced in SN core within ~10 s after explosion and escape core ➜ short burst
- Spectrum has thermal-like shape, peaks at ~50 MeV
- Gamma rays would arrive co-incident with SN neutrinos (provides time tag)

EXPECTED COUNTS FROM ALP MODEL
- Integrated over explosion time (~20s)
- Integrated over energy, 50-500 MeV
- Folded with Fermi-LAT instrumental response function
- Expected number of counts $\sim g\alpha^4$
- Little dependence on progenitor mass

Assuming 4 background counts in one 20s time bin:
Exclude ALP models predicting more than 6.4 counts at 95% confidence

[slide credit: M. Meyer]
CONSTRANITS & SENSITIVITIES

Preliminary

- TeV transparency
- CTA opacity
- CTA NGC1275 irreg.

[slide credit: M. Meyer]

[MM; M. Giannotti; A. Mirizzi; J. Conrad; M. Sanchez-Conde, PRL. ArXiv:1609.02350]
Summary

The ERA of data!
Extra Slides
the DM signal:

\[
\frac{d\Phi(\Delta \Omega, E_\gamma)}{dE_\gamma} = \frac{1}{4\pi} \frac{(\sigma_{\text{ann}} v)}{2 m_\chi^2} \times \sum_i BR_i \frac{dN_i}{dE_\gamma} \times \int_{\Delta \Omega} d\Omega \int_{\text{los}} ds \rho^2(s, \Omega)
\]

\text{this is what we are after!}

\text{genuinely multi-disciplinary field!}

**flux of SM particles per DM annihilation**

Bringmann & Weniger (2012)

\[x^2 \frac{dN}{dx} \]

\(x = E / m_\chi\)

\[\text{quasi-universal spectra} \]

\(\text{model dependent features} \)

**integrated DM density squared along the line of sight**

\(\Omega^2 = \frac{1}{M_\odot} \frac{d\rho^2}{ds} \int_{\text{los}} ds \rho^2(s, \Omega)\)

\(\Delta \Omega = 0.05 \text{ sr} \)

\(\rho^2(s, \Omega) \approx (10^{-10} - 10^{-13}) \text{ M}_\odot \text{ kpc}^{-3} \)

\(s = 0.2 \text{ kpc} \)

\(s = 100 \text{ kpc} \)

\(s = 1.3 \times 10^5 \text{ kpc} \)

\(\text{GC} \)

\(\text{Sun} \)

\(\text{NFW} \)

\(\text{GC} \)

\(\text{Sun} \)

\(\text{NFW} \)

**significant, target dependent uncertainties**
Many works reaching similar results: 

- Vitale & Morselli (2009),
- Goodenough & Hooper (2009),
- Hooper & Goodenough (2011, PLB 697 412),
- Hooper & Linden (2011, PRD 84 12),
- Abazajian & Kaplinghat (2012, PRD 86 8),
- Abazajian et al. (2014, PRD 90 2) 1402.4090,
- Daylan et al. (2014) 1402.6703, 1407.5583 1407.5625 1410.1527

**DM spectral fits**

- NFW, $\gamma=1.26$
- $r^{-2.4}$

**DM morphology**

- Excess emission at $E = 2$ GeV
- $r_0 = 8.5$ kpc
- $\rho_{DM}(r_0) = 0.4$ GeV·cm\(^{-3}\)
- EAGLE profiles normalised
- EAGLE power – law extrapolation
- gNFW with $\gamma = 1.26$
- Fermi Bubbles extrapolated from $|b| > 10^\circ$

**Spatial extent**

- Galactic latitude $b$ [deg] at $l = 0^\circ$
- 1-3 GeV residual

**GCE spectrum**

- Broken PL
- PL with exp. cutoff
- DM $\bar{b}\bar{b}$

**GC excess spectrum with stat. and corr. syst. errors**

- Broken PL
- PL with exp. cutoff
- DM $\bar{b}\bar{b}$

**Calore et al. (2015)**
- Fermi coll. (preliminary)
- EAGLE profiles normalised
- EAGLE power – law extrapolation
- gNFW with $\gamma = 1.26$

**Hooper & Goodenough (2011)**
- Boyarsky et al. (2011)
- Gordon & Macias (2013)
- Hooper & Slatyer (2013)
- Daylan et al. (2014)
- Abazajian et al. (2014)
Pass 8 Fermi LAT analysis

- uses more data (**80m**)
- uses improved event selection: **pass 8** (improved angular and energy resolution, increased effective area at the high- and low-energy ends)
- checks additional systematic uncertainties:
  - GALPROP model parameters variations
  - Alternative gas maps (softer GCE spectrum < 1GeV)
  - Include additional sources of **CR electrons near the GC** (Gaggero+2015, Carlson+2015; GCE reduced)
- add **data driven template of the Fermi Bubbles** (excess >10 GeV gone)

**GC excess, all cases**

**New emission component in the Galactic centre appears robust to various checks of the systematic uncertainty its exact spectral features are model dependent**

**The Fermi sky**

**Diffuse emission from our Galaxy**

![Diffuse emission from our Galaxy](image)

**Point sources**

![Point sources](image)

**Isotropie emission**

![Isotropie emission](image)

90% of the LAT photons!

*cosmic rays + interstellar medium* → *gamma rays parameters*: distribution of sources, magnetic fields, gas, injection spectra...

![Gamma rays parameters](image)

**Galactic Gamma-Ray Interstellar Emission**

- **Inverse Compton**
- **Bremsstrahlung**
- **π⁰ decay**
- **Bremsstrahlung**
- **Inverse Compton scattering**
- **Synchrotron radiation**

All of these mechanisms create also non*-ray radiation*

*S. Murgia, ICRC15*
The Fermi sky

Diffuse emission from our Galaxy

Point sources

Isotropic emission

The Fermi bubbles

8 kpc tall structures entered at the Galactic Centre
revealed after subtraction of the diffuse emission
apparent uniform brightness
hard power law spectrum

Significance of integrated residuals for $E = 6.4 - 289.6$ GeV

The Fermi sky

Diffuse emission from our Galaxy

Point sources

Isotropic emission

High-energy (ground-based observations)

Fermi catalog 3000 sources!

3FGL [Fermi LAT coll. 1501.02003]

PSR 7%

Other galactic 5%

Galactic 31%

Unassoc

AGN extragalactic 57%
The Fermi sky

Diffuse emission from our Galaxy

Point sources

Isotropic emission

dominates at high latitudes

origin not yet fully understood

guaranteed contribution: faint (not individually resolved) extragalactic sources

CTA - Cherenkov Telescope Array

Three types of telescopes:

A few large telescopes to cover the range 20 - 200 GeV

~km² array of medium-sized telescopes for the 100 GeV to 10 TeV domain

~4km² array of small-size telescopes, sensitive above a few TeV up to 300 TeV

4 LSTs [N & S]

15 MSTs [N]
25 MSTs [S] (+ 24 SCTs)

70 SSTs [S]