UNIVERSITÀ DEGLI STUDI DI TORINO

Physics Torino Department of Excellence

INFN Istituto Nazionale di Fisica Nucleare

Constraining Galactic dark matter with γ -ray pixel counts statistics

&

Geminga γ -ray halo with Fermi-LAT

Silvia Manconi

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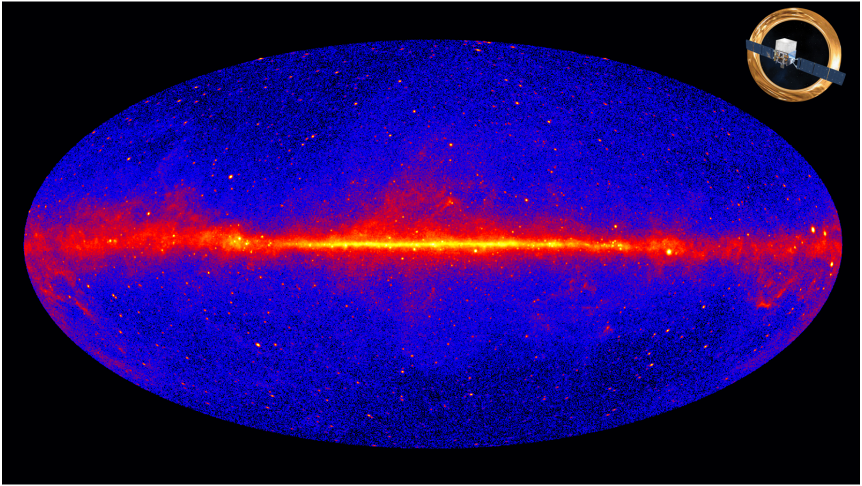
Gamma-ray Workshop, LapTh Annecy

Constraints to Galactic dark matter with γ -ray pixel counts statistics

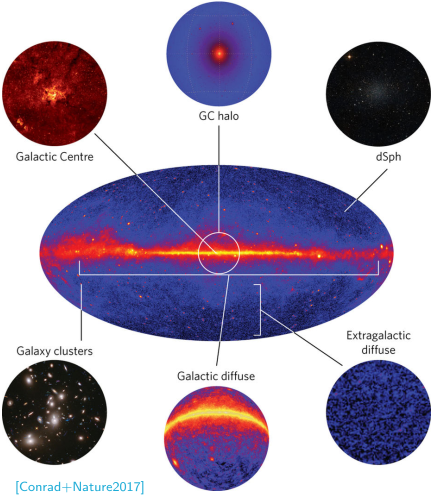
The γ-ray sky seen from Fermi-LAT

[Fermi-LAT 5 years, energy $>$ 1 GeV]



Fermi-**L**arge **A**rea **T**elescope: high-energy γ -ray telescope,
data from $E = 20$ MeV to more than 300 GeV, 10 years of operation

Targets for indirect dark matter searches with γ rays



[Conrad+Nature2017]

This talk:

Galactic DM halo, high latitudes

see also: [Fermi-Lat Coll., Apj11] (1 year of data)

[Chang+PRD18] (template fitting)

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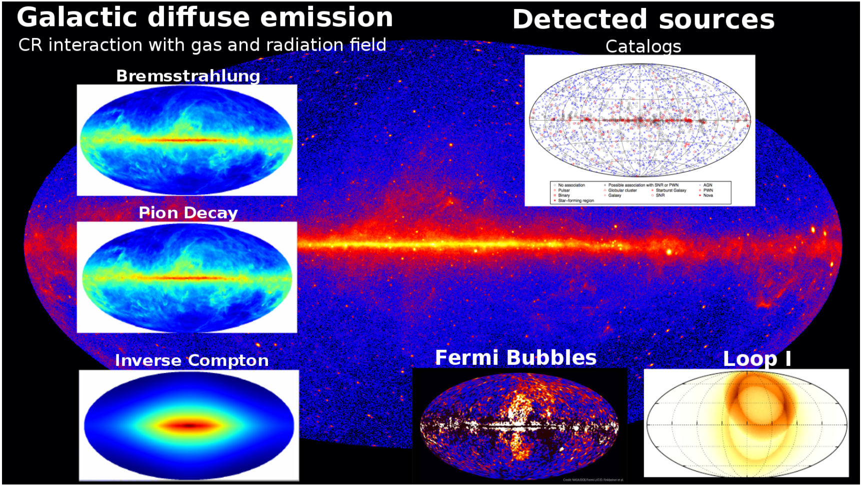

+ **isotropic emission** from unresolved sources and truly diffuse processes

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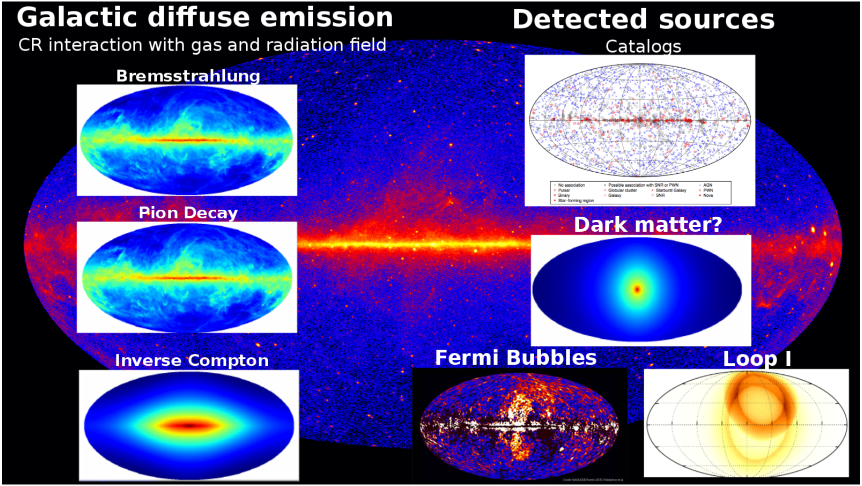
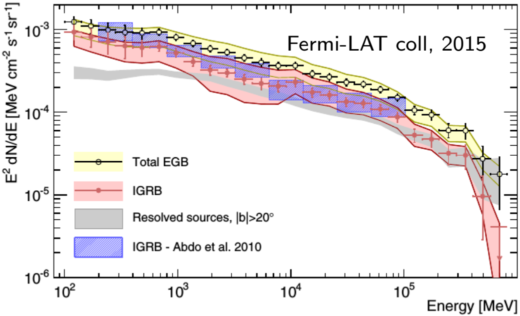


+ **isotropic emission** from unresolved sources and truly diffuse processes... Dark Matter?

γ-ray sky = Galactic diffuse + **E**xtragalactic γ-ray **B**ackground (**EGB**) emissions.

EGB= **point sources** + **isotropic γ ray background** (IGRB)



Dissecting the γ ray sky at high Galactic Latitudes

γ-ray sky = Galactic diffuse + **E**xtragalactic γ-ray **B**ackground (**EGB**) emissions.

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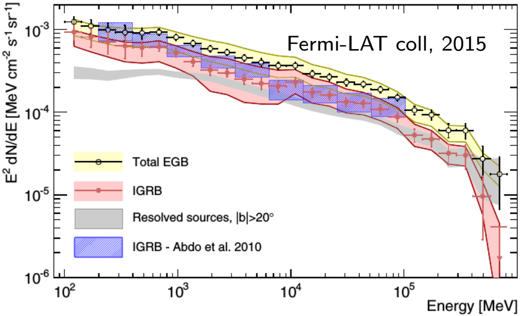

IGRB: **global contribution of unresolved** (too faint to be detected) sources: extragalactic sources (blazars) + more exotic, e.g. dark matter

Investigation of IGRB composition: unique tool to search for dark matter signals and to characterize unresolved γ-ray source populations

The source count distribution of γ-ray sources

Source count distribution dN/dS: # of sources N per $d\Omega$ with integral flux in $(S, S + dS)$.

Contribution to EGB from γ-ray sources is quantified by:

1. Source catalogs: limited by detection threshold (efficiency) of the instrument
2. Extrapolation/correlation with other wavelength: significant uncertainties
3. This talk: **Statistical properties of photon counts**

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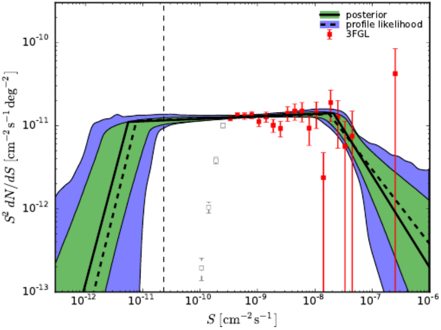
Catalog (3FGL) →
Detection efficiency < 1
Statistical analysis results

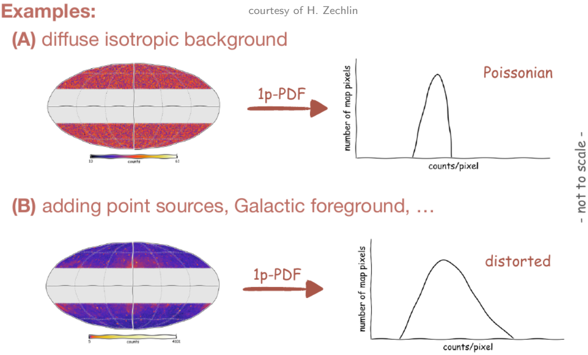


[Zechlin+ApjS2016, 1-10 GeV]

Pixel count statistics with the 1-point Probability Distribution Function (1pPDF)

Statistical analysis of intensity to decompose the γ-ray sky [Malyshev+ApJ2011]

courtesy of H. Zechlin



- Applied to measure dNdS at high latitudes [Zechlin+ApjS2016], [Zechlin+ApjL2016], [Lisanti+Apj2016]
- **This talk**: *extend this framework* to account for dark matter Galactic halo

The 1pPDF analysis - (technical)

Separate sources based on statistical properties of their photon counts

Modeling: *probability generating functions* $\mathcal{P}^{(p)}(t)$*:*

$$p_k^{(p)} = \frac{1}{k!} \left. \frac{\mathrm{d}^k \mathcal{P}^{(p)}(t)}{\mathrm{d}t^k} \right|_{t=0}$$

$p_k^{(p)}$ = probability to find k photons in pixel (p)

OBSERVED
Probability distribution of photon counts in pixels $p_k^{(p)}$

$\Longleftrightarrow$

WANTED
Decompose γ-ray sky in:
-Point sources dN/dS
-Diffuse contributions

$$\mathcal{P}^{(p)}(t) = \sum_{k=0}^{\infty} p_k^{(p)} t^k = \exp\left(\sum_{m=1}^{\infty} x_m^{(p)} (t^m - 1)\right)$$

$x_m^{(p)}$ = **expected number of sources contributing m photons per pixel p:**

- point sources (dN/dS)
- Galactic diffuse emission
- Diffuse isotropic background
- **Dark matter**

1pPDF applied to Galactic Dark Matter searches

Analysis from Zechlin, Manconi, Donato, PRD 2018.

Investigate sensitivity reach of 1-point statistics for constraining a diffuse Dark Matter component at *high latitudes*

⇒ Unresolved point sources: *subdominant BUT comparable* to DM component

⇒ 1pPDF is *independent* from source catalogs

⇒ First time 1pPDF is tested for constraining Milky Way DM halo

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Overview: (see also backup slides)

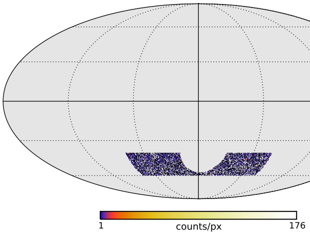
1. **Data**: Fermi-LAT 8yrs, 3 energy bins from 1 GeV to 10 GeV
2. **Dark Matter profile**: Einasto, $\rho_\odot = 0.4$ GeV cm^{-3} [Catena+JCAP2010]
3. **Dark Matter spectra**: dN_f/dE from [Cirelli+JCAP2010], $b\bar{b}$, $\tau^+\tau^-$ final states
4. **Main systematics**: Galactic diffuse emission
   - ⇒ high latitudes $|b| > 30$ deg
   - ⇒ different benchmark templates
   - ⇒ ROI optimization
5. **Simulations**: to validate analysis framework

Region Of Interest (ROI) optimization

Zechlin, Manconi, Donato, PRD 2018

- Mask galactic plane: $|b| > 30 - 40$ deg
- Mask stuctures: Fermi Bubbles, Loop I
- Simulations w/o DM, expected sensitivity

$\Rightarrow$ **DM_ROI at high latitudes where real sky results consistent with simulations in all bins:**



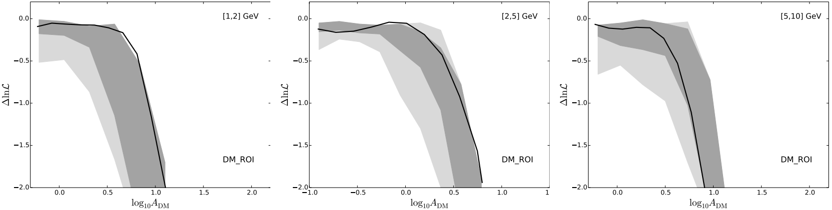
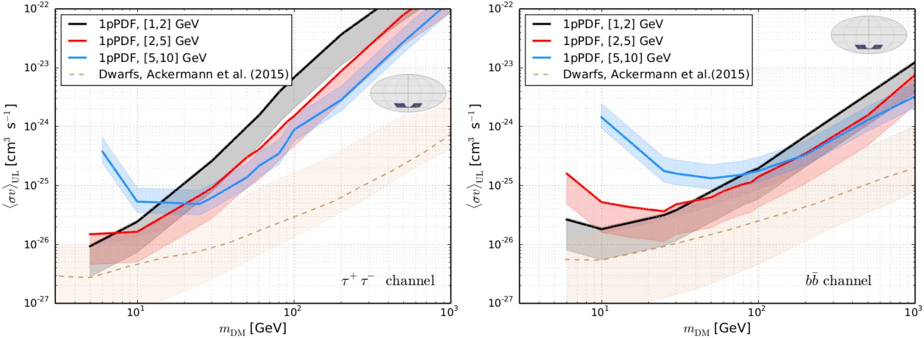


figure: Profile likelihood for $A_{\rm DM}$, rescaling parameter for $\langle \sigma v \rangle_0 = 10^{-26}$ cm^3 s^{-1} for $m_{\rm dm} = 15$ GeV.
Colors: 95% CL from simulations Real sky

Zechlin, Manconi, Donato, PRD 2018

Upper limits on $\langle \sigma v \rangle$ for two benchmark dark matter annihilation channels:



- Sensitivity of 1pPDF for dark matter searches at high latitudes is comparable with Dwarfs for $m_{\rm DM} < 50$ GeV for τ channel and $m_{\rm DM} < 100$ GeV for b channel
- The [1,2] GeV ([5,10] GeV) bin is more sensitive to low (high) dark matter masses

Main systematics: Galactic Diffuse Emission

Complex modeling, e.g. possible degeneracy Inverse Compton $\Longleftrightarrow$ DM halo

Different benchmark templates:

1. *Official* released with pass8 Fermi-LAT data
2. *models A,B,C* from [Ackermann+ApJ2015]

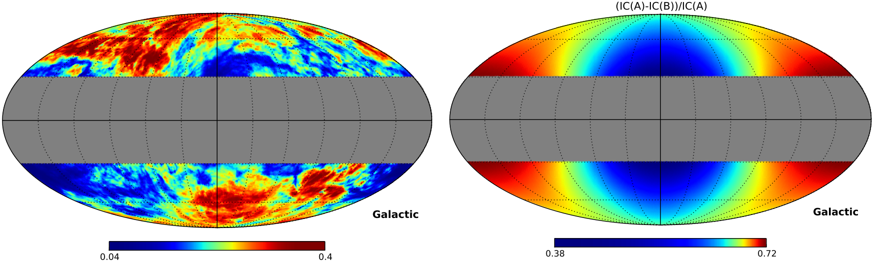


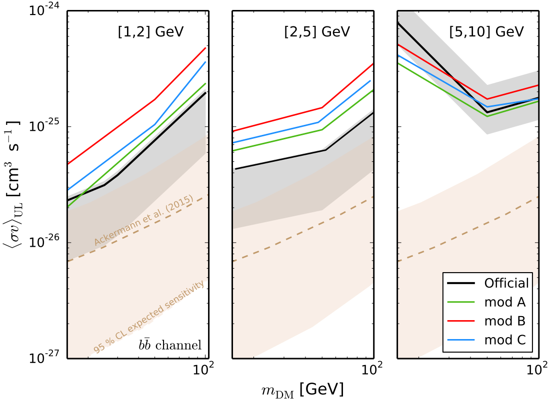
figure: Relative difference between Galactic diffuse emission (left) and Inverse Compton components only (right) from **mod A** and **mod B** **integrated in the energy bin [2,5] GeV** for $|b| > 30$ **deg**

$\Rightarrow$ **Region of interest search depends from the galactic diffuse emission**

Better modeling: ongoing effort, e.g. SkyFact [Storm+17], [Porter+17,Gaggero+15, Selig+15]

Systematics on Galactic Diffuse Emission

Zechlin, Manconi, Donato, PRD 2018

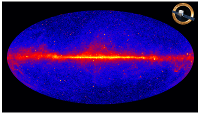


$\Rightarrow$ **Scatter between models: factor** $\sim 2-5$ in $\langle \sigma v\rangle$

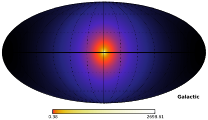
model B from [Ackermann+2015] has lower inverse Compton for $|b| > 30$ deg

Summary - DM searches with γ -ray pixel count statistics

- The **1-point Probability Distribution Function** is a **powerful statistical method** to:
    - ⋆ resolve faint point sources
    - ⋆ dissect γ-ray sky components

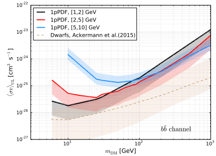


- **1pPDF sensitivity for Galactic DM halo signals at high latitudes was explored in simulated and real data**
    - ⋆ 8 yrs of Fermi-LAT data
    - ⋆ 3 energy bins in from 1 GeV to 10 GeV
    - ⋆ optimazed region of interest



Results:

1. **Sensitivity is comparable with other searches and methods**
2. Limited by systematics from background Galactic emission modeling

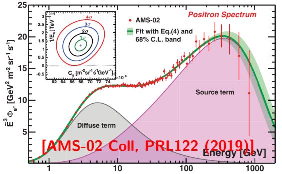


Perspectives: extend to lower latitudes, dark matter subhalos

Geminga γ -ray halo with Fermi-LAT

Cosmic-ray e^+: main facts (One-slide challenge)

1. e^+ **excess** PAMELA, AMS-02 data:
   flux above 10 GeV exceeds secondary component



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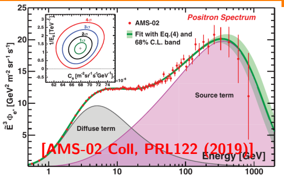

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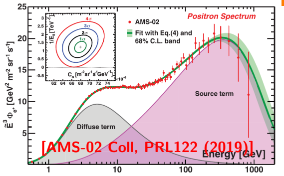

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3. **Pulsars and their nebulae (PWNe)**:
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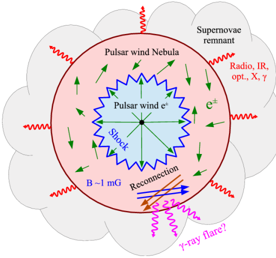

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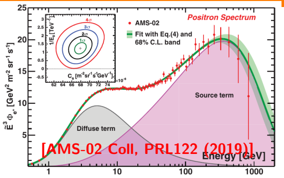

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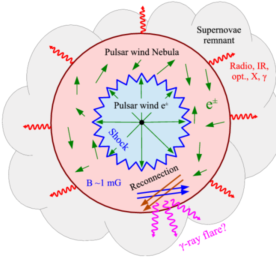

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   main candidates to explain e^+ excess

4. **Nearby PWNe**: Geminga, Monogem, $d < 500$ pc
   Uncertainties: $e^\pm$ acceleration, release, energy spectrum... **Multimessenger constraints!**

Multi-wavelenght emission in PWNe

⇒ $e^{\pm}$ pairs accelerated by PWNe loose energy by Inverse Compton scattering, synchrotron emission:

cascade of photons in a broad range of frequency

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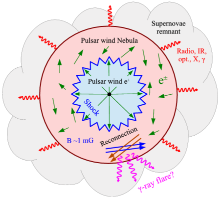
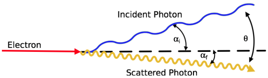
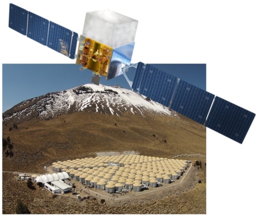
Modeling intensity, distribution of photon emission in PWNe: properties of accelerated $e^{\pm}$





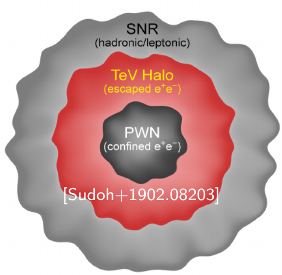


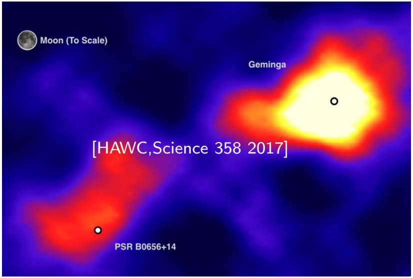
- GeV-TeV Inverse Compton emission in HAWC, Fermi-LAT data

Extended Gamma-ray halo of Geminga and Monogem

The HAWC recently detected a **few-degrees extended γ-ray emission** at $E > 5$ TeV around **Geminga** and **Monogem** pulsars [HAWC Collaboration, Science 358 2017]
main candidates ($d < 500$ pc) to explain e^+ flux

- First evidence of $e^\pm$ diffusing away from the pulsar and up-scatter CMB photons, **inverse Compton emission**



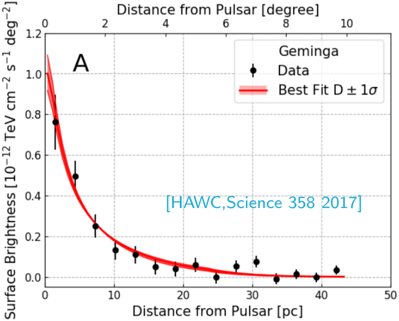


Interpreted as $e^\pm$ accelerated, and then released in the interstellar medium, from the PWNe.

Strong support to PWNe as e^+ sources.

What we learn from HAWC discovery?

1. **Efficiency of conversion of pulsar spin-down energy in high-energy $e^{\pm}$** is $\eta = 40(4)\%$ for Geminga (Monogem) for $\gamma_{e^{\pm}} = 2.3$
2. **Diffusion in the vicinity of Geminga and Monogem is inhibited**
   - HAWC finds $K(1\ \mathrm{GeV}) \sim 7 \times 10^{25}\mathrm{cm}^2/\mathrm{s}$
     $\sim$ 500 times smaller than the average value in the Galaxy



←Gamma-ray emission intensity profile (surface brightness): how $e^{\pm}$ diffuse away from the pulsar

Beyond HAWC: the role of Fermi-LAT

HAWC: 5-40 TeV γ -rays $\Rightarrow$ Inverse Compton of $e^{\pm}$ of at least tens of TeV
$\Rightarrow$ **using HAWC to predict e^{+} at AMS-02 energies is an extrapolation**

Beyond HAWC: the role of Fermi-LAT

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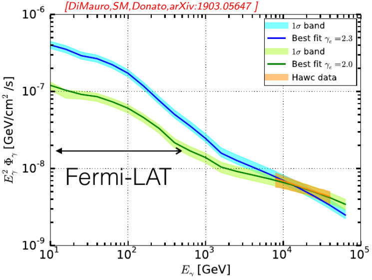
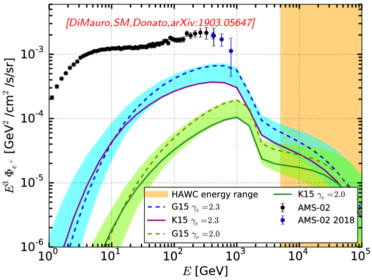
Spectral energy distribution
of Inverse Compton emission



e^{+} flux at Earth



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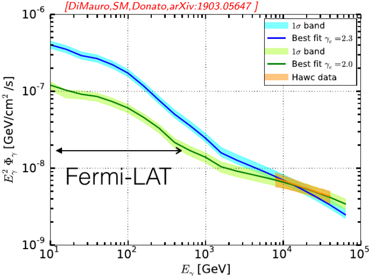
Spectral energy distribution of Inverse Compton emission



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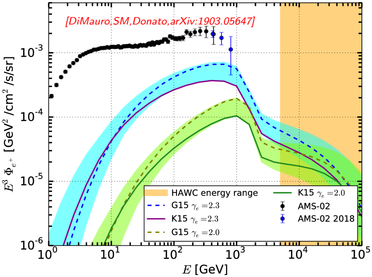


Fermi-LAT data:

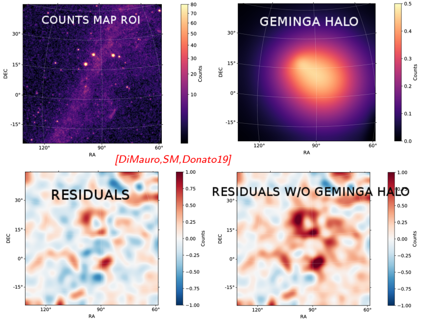
1. **test the extrapolation of HAWC results** to lower γ -ray energies
2. **discriminate between different spectral index γ_e** of the e^+ distribution

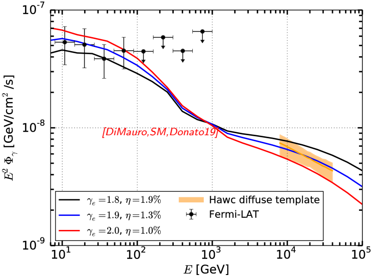
Geminga extended halo in Fermi-LAT data

Di Mauro, SM, Donato, arXiv:1903.05647:
Geminga extended emission detected in Fermi-LAT data

- **7.8-11.8σ significance** depending on background emission model
- Diffusion $K(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s, compatible within 2σ with HAWC
- Size of ~ 60 **pc at 100 GeV**, $\gamma_{PWN} = 1.8 - 2$

Inverse Compton emission from $e^{\pm}$ accelerated and escaped from PWN.

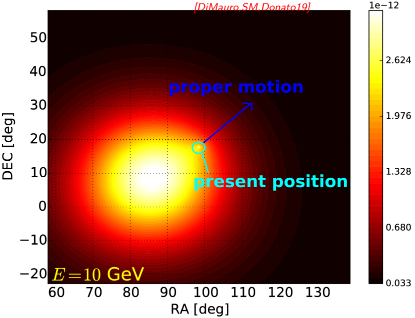




Monogem halo is not significantly detected: upper limits.

Proper motion of Geminga pulsar

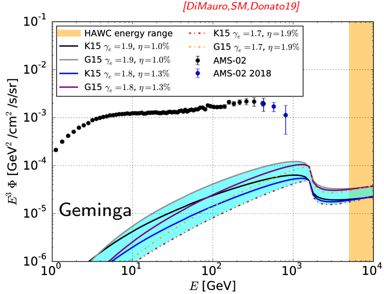
- Geminga pulsar has a proper motion, with transverse velocity of $v_t \sim 211$km/s [Faherty+AS07]: ~ 70 pc across its age
- Transverse velocity affects significantly morphology of Geminga halo γ -ray emission at $E < 100$ GeV

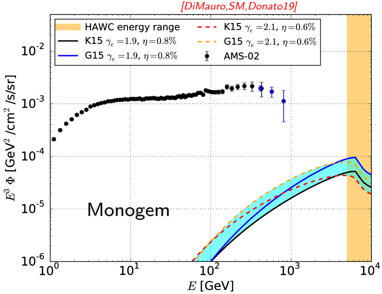


Model fit with proper motion preferred at least at 4σ: our analysis is unique in γ -ray astronomy, we detected a source moving across the sky

Consequences for the cosmic e^+ flux at Earth (I)

We compute Geminga and Monogem e^+ flux using results of Fermi-LAT (η, γ_e) within **two-zone diffusion model**: inhibited diffusion $r_b < 60$ pc, $\sim$ angular size of Geminga at 100 GeV





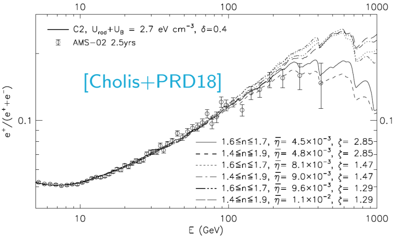
- Geminga contributes 1% (10%) to e^+ at 100 GeV (800 GeV); Monogem at most 3%

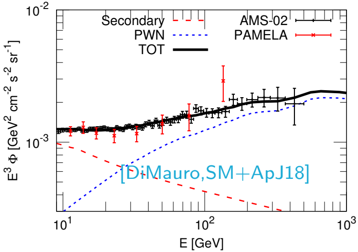
Geminga and Monogem alone, as constrained by Fermi-LAT, cannot be major contributors to e^+ excess

Consequences for the cosmic e^+ flux at Earth (II)

Geminga and Monogem are not the only PWNe in our Galaxy.

- An efficiency of 1-3% for the conversion of pulsar spin down in $e^\pm$ pairs considering a smooth Galactic distribution of PWN can explain the e^+ excess
  [Cholis+PRD18], [DiMauro+19, in preparation]
- Previous studies considering PWNe in the ATNF catalog [DiMauro+JCAP14,Manconi+JCAP17,DiMauro,SM+ApJ18] also find similar values





The cumulative e^+ emission from Galactic PWNe remains a viable interpretation for the e^+ excess

Summary - Geminga γ-ray halo

- Local PWNe are the most promising candidates to explain the e^+ excess
- Multi-messenger analysis of cosmic-ray fluxes, radio and γ -ray emission is used to reduce the uncertainties for cosmic-ray emission

Summary - Geminga γ-ray halo

- Local PWNe are the most promising candidates to explain the e^+ excess
- Multi-messenger analysis of cosmic-ray fluxes, radio and γ -ray emission is used to reduce the uncertainties for cosmic-ray emission

- Extended γ -ray halo from Geminga and Monogem in HAWC: evidence for γ -rays from Inverse Compton scattering from $e^\pm$
- A counterpart of the Geminga halo is detected in Fermi-LAT data

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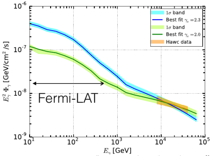
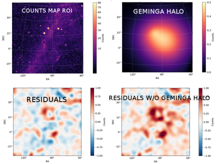
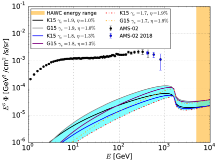
- A counterpart of the Geminga halo is detected in Fermi-LAT data

- Diffusion is inhibited around pulsars; diffusion coefficient around Geminga is $K(1GeV) = 1.6 - 3.5 \times 10^{26}$ cm^2/s
- Geminga and Monogem, as constrained from Fermi-LAT, contribute at most 10% to the flux of e^+ at 800 GeV



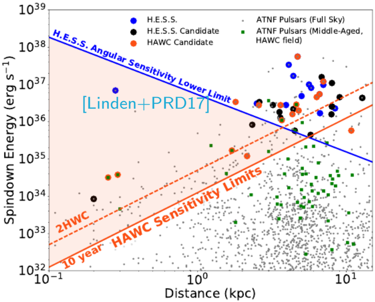




Multi-wavelength/messenger for cosmic ray $e^{\pm}$ sources

Application of multi-wavelength and multi-messenger approach to constrain the origin of e^{+} flux and cosmic ray emission models from PWNe.

PWNe γ -ray halos are a **new and promising** source class: New halos discovered by HAWC, more (O(30) [Linden+PRD17]) expected in the next years!

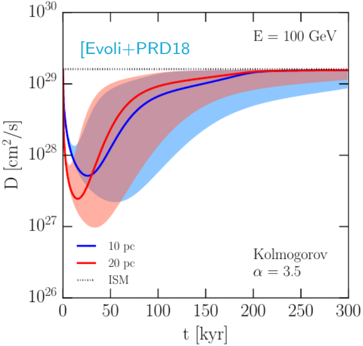


Bright future in γ -rays (CTA, AMEEGO), cosmic rays (DAMPE, CALET)

Multi-wavelength/messenger for cosmic ray $e^{\pm}$ sources

PWNe γ -ray halos many interesting roads ahead:

- Search for counterpart in other wavelengths: radio, X-rays
- Constrain and refine production and emission models of cosmic $e^{\pm}$ from PWNe
- Study propagation of cosmic rays around sources
- Other evidence of inhomogenous diffusion in the Galaxy (H,He breaks)



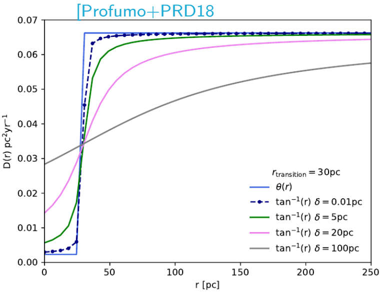


figure: Diffusion coefficient around PWNe as a function of source age and distance

BACKUP

Simulations of the Fermi-LAT sky

Components simulated with Fermi Science Tool *gtobbsim*:

1. **Point sources** following same dNdS of real sky
2. **Galactic diffuse** background (gll_iem_v06)
3. **Isotropic** background (iso_P8R2_ULTRACLEANVETO_V6_PSF3_v06)

Each simulation contains a list of point sources from a different Monte Carlo realization of the dN/dS:

- Power law, $\Gamma_{\rm mean} = 2.4$, $\sigma_\Gamma = 0.4$
- $S_{\rm min} = 10^{-12} {\rm cm}^{-2} {\rm s}^{-1}$
- random positions across the sky

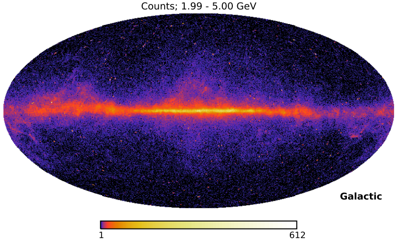


figure: Counts map for a simulation w/o DM, [2,5] GeV

Galactic DM halo modeling

Flux per unit energy and solid angle:

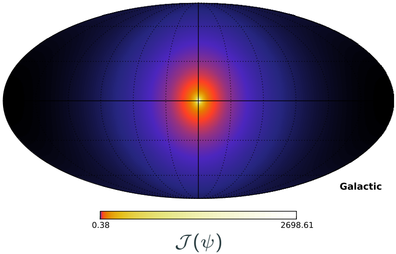
$$\frac{\mathrm{d}\phi_{\mathrm{DM}}}{\mathrm{d}E\mathrm{d}\Omega} = \frac{1}{4\pi}\frac{\langle\sigma v\rangle}{2} r_{\odot}\frac{\rho_{\odot}^{2}}{m_{\mathrm{DM}}^{2}}\sum_{f}\left(\frac{\mathrm{d}N_f}{\mathrm{d}E}B_f\right)\mathcal{J}(\psi)\,.$$

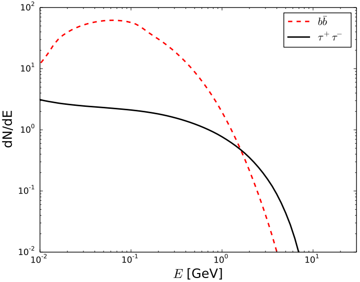
Spatial :

- Smooth DM halo: Einasto, $\rho_{\odot} = 0.4$ GeV cm^{-3} [Catena+JCAP2010]
- Extragalactic: subdominant
- possible DM suhalos absorbed by dN/dS

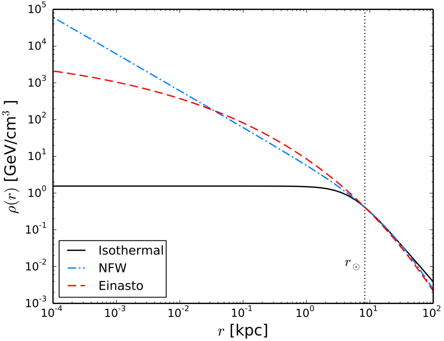
Energy:

- WIMP self-annihilations into pure $b\bar{b}$, $\tau^{+}\tau^{-}$ final states
- dN_f/dE from [Cirelli+JCAP2010]

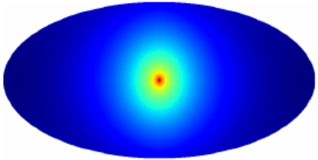




Dark matter density profile



Astrophysical J-factor:



where:

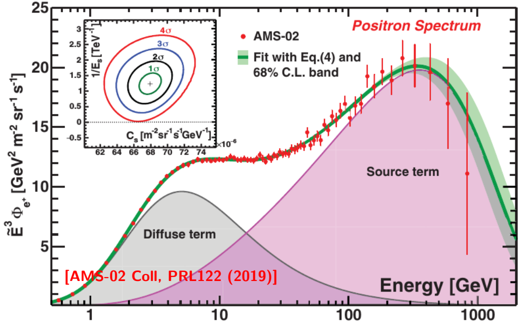
$$\rho(r)_{Ein} = \rho_\odot \exp\left[-\frac{2}{\alpha}\frac{r^{\alpha_E} - r_\odot^{\alpha_E}}{r_s^{\alpha_E}}\right]$$

Fermi-LAT Data selection

- 8 years of Pass8 data [239557417, 492018220] s MET
- `DATA_QUAL==1` and `LAT_CONFIG==1`
- evclass=ULTRACLEANVETO, evtype=PSF3
- Energy bins: [1, 2] GeV, [2,5] GeV, [5,10] GeV as in [Zechlin+ApjS2016, ApjL2016]
- Derived PSF widths: 0.31 deg, 0.18 deg, 0.10 deg
- HEALPix order 7

The rise (and fall?) of the cosmic-ray positron flux

- 2008: PAMELA measures a rise in the positron fraction $e^+/(e^+ + e^-)$, lately confirmed by Fermi-LAT, AMS-02.
- The e^+ flux above about 10 GeV exceeds the predicted secondary component
- AMS-02 recently reported a sharp fall above about 300 GeV.

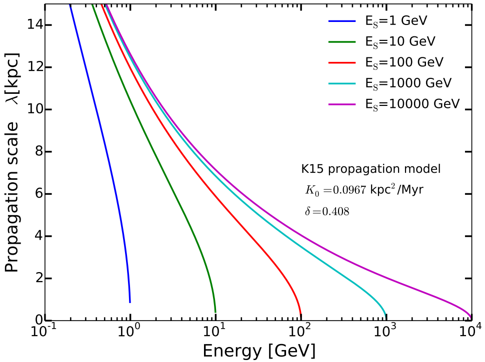


A new, primary source of e^+ in addition to secondaries is needed to explain data.

Typical propagation scale for cosmic electrons and positrons

For GeV-TeV $e^{\pm}$ the **energy loss timescale is smaller than the diffusion one.**

$$\lambda^2(E, E_S) = 4 \int_E^{E_S} dE' \, \frac{K(E')}{b_{\rm loss}(E')}$$

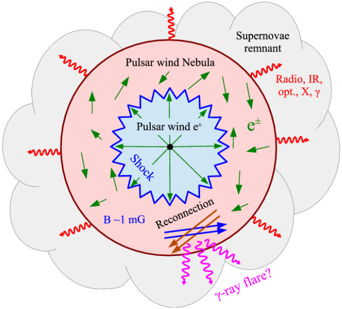


- $E_{e^\pm} \gtrsim 10$ GeV: typical propagation scale $\lambda < 5$ kpc
- 80% of flux at 1 TeV is produced at less than 1kpc
- GeV-TeV $e^{\pm}$ probe the few kpc near the Earth: modeling of **local sources**

Pulsar Wind Nebulae as cosmic-ray $e^{\pm}$ sources

Engine of Pulsar Wind Nebula (PWN): pulsar, fast rotating magnetized neutron star from collapse of $> 8\ M_{\odot}$ star

- High magnetic fields $\sim 10^9 - 10^{12}$ G: wind of particles extracted from the surface, $e^{\pm}$ **pairs produced** in EM cascades
- **Pulsar Spin-down energy (W_0) transfered to $e^{\pm}$ pairs** accelerated up to very high-energies, $Q(E) \propto E^{-\gamma}$
- After few kyrs: $e^{\pm}$ **pairs possibly released** in interstellar medium
- Relativistic $e^{\pm}$ pairs in PWNe shines from radio to γ rays



Normalization $Q_{0,\mathrm{PWN}}$ connected to the spin-down energy W_0 with η (conversion efficiency):

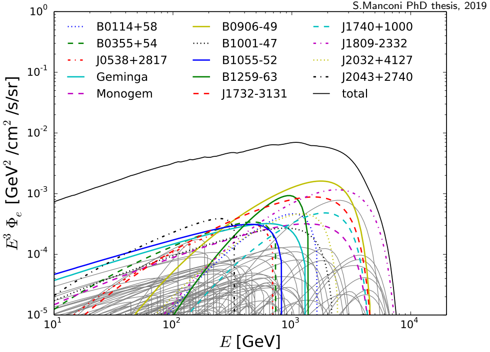
$$E_{e^{\pm}} = \int dE\ E\ Q(E) = \eta W_0$$

Important parameters for $e^{\pm}$:
Spectral index of $e^{\pm}$ distribution (γ), conversion efficiency of W_0 in $e^{\pm}$ pairs (η)

Cosmic ray $e^{\pm}$ flux from pulsars in source catalogs

Assume that each pulsar has powered a PWN in the past, and produced $e^{\pm}$

1. Pulsars are numerous in our Galaxy: 1000+ sources in the catalogs (ATNF)
2. Few nearby candidates: e.g. Geminga and Monogem at $d < 500$ pc



Uncertainties: acceleration, release in the interstellar medium, energy spectrum of $e^{\pm}$...

Multimessenger constraints!

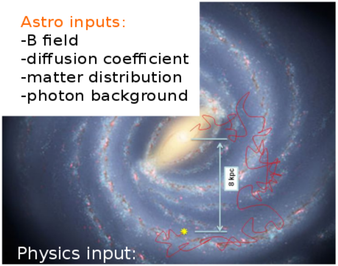
Modeling cosmic ray electrons and positrons

Cosmic ray sources

-acceleration mechanism
-source distribution
-source spectrum

Propagation

Astro inputs:
-B field
-diffusion coefficient
-matter distribution
-photon background



Physics input:
-cross sections
-EM interactions

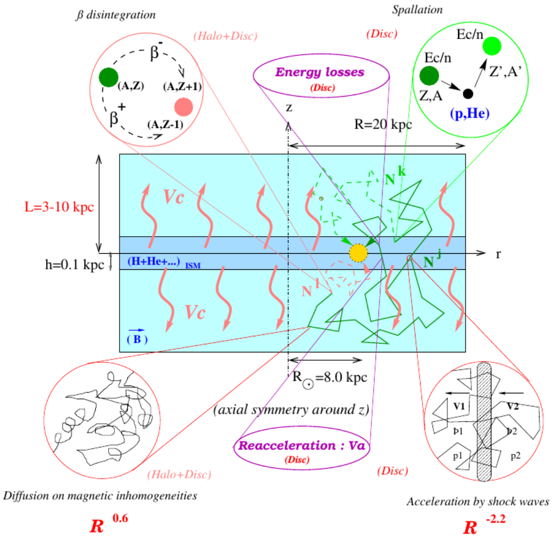
Earth

-propagated spectrum

$$Q(E, \mathbf{x}, t) = \hat{D}\psi$$

$$\text{source term} = (\text{Propagation})(\text{Flux at Earth})$$

The Galaxy: view from a cosmic ray physicist



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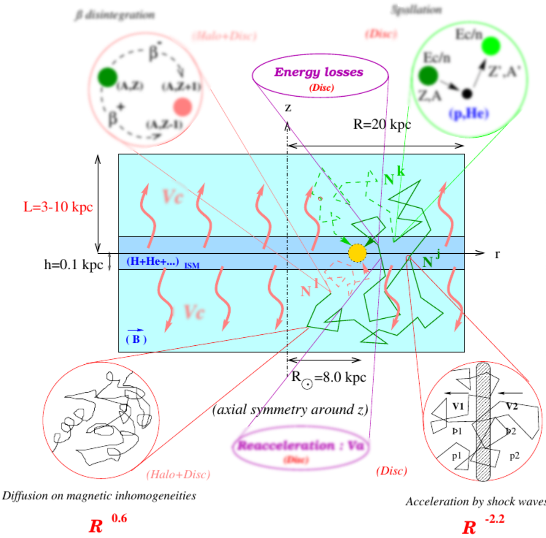

Figure adapted from arXiv:0212111

Dominant effects for $E_{e^\pm} > 10$ GeV:

-**Energy losses**: Synchrotron; Inverse Compton on Interstellar Radiation Fields

-**Diffusion (space)**: [Fermi'49, Chandrasekhar'43, Jones'90]
random scattering in B_{gal} irregularities $\Leftrightarrow$ spatial diffusion

-**Solar modulation**: [Strauss+2014]
sub-dominant for $E_{e^\pm} > 10 - 20$ GeV

Propagation of cosmic-ray $e^{\pm}$ in the Galaxy

Diffusion-loss equation for $e^{\pm}$

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{K(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

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Diffusion

$K(\mathbf{x}, \mathcal{R})$ in general $K_{//}, K_{\perp}$, but:
B inhomogeneities difficult to model
$\Rightarrow$ **isotropic** (see later...)

$$K(E) = K_0 E^{\delta}$$

-K_0, δ constrained by Sec/Primary ratio, e.g. Boron/Carbon [Kappl+15,Genolini+15] (K15)

Energy losses

$$\frac{dE}{dt} = b_{\mathrm{loss}}(E)$$

-Synchrotron on $B_{\mathrm{gal}} = 3.6\mu$G [Sun+06]
-Full relativistic treatment of Inverse Compton losses on: CMB, Stellar, UV, IR

Propagation of cosmic-ray $e^{\pm}$ in the Galaxy

Diffusion-loss equation for $e^{\pm}$

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Energy losses

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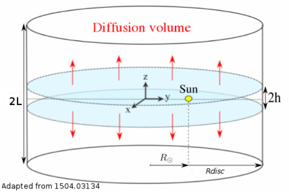
-Full relativistic treatment of Inverse Compton losses on: CMB, Stellar, UV, IR

Semi analytical solutions, vertical and radial border conditions at $L \sim 1 - 15$ kpc and $R_{disc} = 20$ kpc [Baltz+98, Maurin+2001, Donato+2004, DiMauro+2014, ...] or

Numerical codes GALPROP, DRAGON, USINE



Adapted from 1504.03134

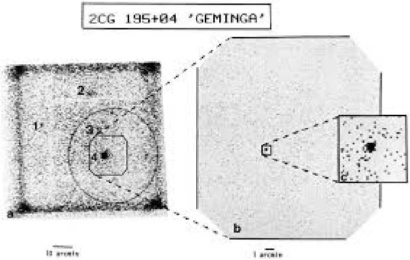
Focus: Geminga and Monogem

GEMINGA, **Gemini gamma**-ray source (B0633+17)

- Distance: 250 parsec
  (∼ 800 light years)
- Age: 340 kyr

MONOGEM (B056+14)

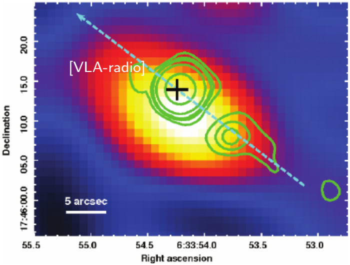
- Distance: 288 parsec
- Age: 110 kyr

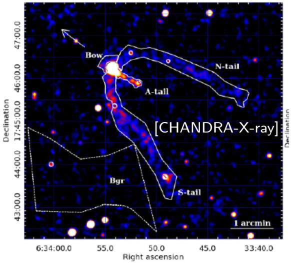


[Bignami+96]

Geminga: one of the most studied nearby pulsars

- Pulsar**(point-like)**: first radio quiet discovered [Bignami+A&A96], Very bright in γ-rays in Fermi-LAT, MAGIC data
- Pulsar Wind Nebula **(arcsec-arcmin angular scale)**:
  - X-rays : complicated morphology, time variation [Posselt+ApJ 2017]
  - Radio: radio feature consistent with cooling of X-ray leptons



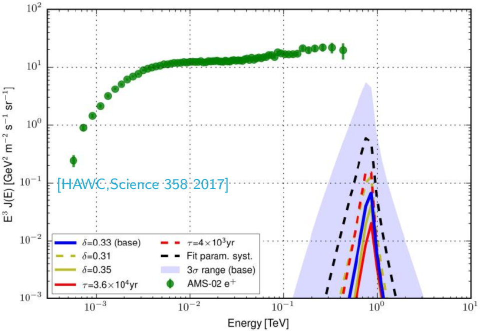


Bow-shock PWNe: pulsar proper motion $v_T \sim 211$ (d/250pc) km s^{-1} this has consequences in the X-ray and GeV morphology!

What we learn from HAWC discovery?

3. *"We demonstrate that the lepton emitted by Geminga and Monogem are therefore unlikely to be the origin of the excess of positrons, which may have a more exotic origin"* [HAWC,Science17]

Assuming the same diffusion coefficient found around the sources to diffuse e^+ to the Earth:



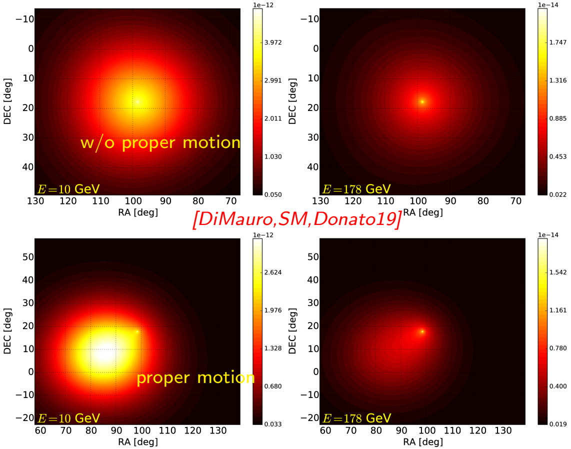
However:

- extension of γ -ray emission is $\sim$ 1% of the propagation volume. Using the mean value of $K(1\ \mathrm{GeV})$ in the Galaxy, [Hooper+PRD17, Profumo+PRD18] extimate the contribution of Geminga to more than $\sim$ 10% of AMS-02 e^+ data!
- Geminga and Monogem are not the only pulsars in our Galaxy...

Setup for Fermi-LAT data analysis

- 115 months of Fermi-LAT data in the energy range [8,1000] GeV
- Region of Interest of 70deg x 70deg: extension is predicted to increase at GeV

We account for the energy dependence of the spatial morphology of Inverse Compton emission by creating templates for $K(1\ \mathrm{GeV})$ in the range $10^{25} - 10^{29}\mathrm{cm}^2/\mathrm{s}$:



[DiMauro,SM,Donato19]

The quest for the interpretation of the e^+ flux

Different sources have been invoked in the literature.
A (not at all exhaustive) view of the main proposals:

Dark matter annihilation /decay: interpretations and constraints:

[Baltz+PRD98],[Hooper+JCAP09], [Ibarra+JCAP09], [Bertone+JCAP09], [Cirelli+NPB09],[Kopp,PRD13] [Cirelli+PRD14],[Lin+,PRD15],[Cheng+,JCAP17]....

Production in Supernova Remnants:

[Blasi+PRL09], [Ahlers+PRD09], [Mertsch+PRD14], [Cholis+PRD14] , ...

Production and acceleration in Pulsars and their nebulae:

[Chi+ApJL96], [Boulars+ApJ89], [Malyshev+,PRD09] [Pato+JCAP10],[Profumo,CEJP11] [Serpico2012], [Linden+ApJ13], [Cholis+PRD13], [Boudad+A&A15],[DiMauro+JCAP14,JCAP16], ...

Modification of secondary production mechanism:

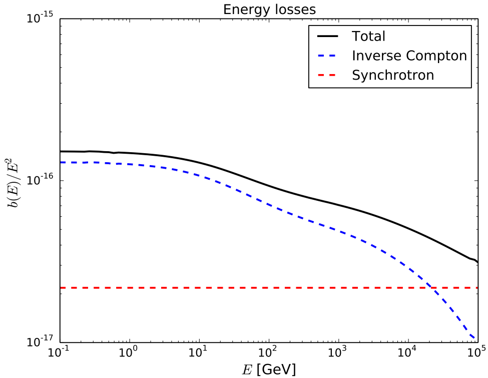
[Mertsch+,PRL09], [Cholis+PRD14], [Tomassetti+ApJ15], ...

Reviews: [Serpico 2012,2018], [Bykov+,SSR17] (PWN)

Energy losses

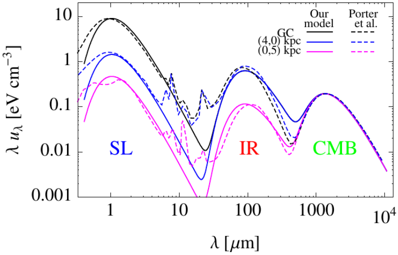
Above a few GeV Synchrotron + Inverse Compton dominate over ionization, adiabatic and bremsstrahlung. [Delahaye+2008]

- Full relativistic treatment from [Delahaye+2010]
- IC scattering off the interstellar radiation field (ISR)
- ISR from [Delahaye+2010] M2
- Synchrotron emission on galactic magnetic field $B = 3.6\mu G$ [Sun+2007]



Interstellar radiation field, inverse Compton emission

Gamma rays are produced through inverse Compton scattering on the interstellar radiation fields: emission of starts, and subsequent scattering, absorption and re-emission of the absorbed light by the dust in the interstellar medium.



Model from Cirelli+2014

Inverse Compton flux from a distribution of electrons ψ_e:

$$\phi^{\mathrm{IC},Sync}(E_\gamma,\theta) = \int_{m_e c^2}^{\infty} dE \mathcal{M}(E,\theta)\mathcal{P}^{\mathrm{IC},Sync}(E,E_\gamma)$$

$$\mathcal{M}(E,\theta) = \int_{\Delta\Omega} d\Omega \int_0^\infty dr\, \psi_e(E,r).$$

where:

$$\mathcal{P}^{IC(E,E_\gamma)} = \frac{3\sigma_T c\, m_e^2 c^4}{4E^2} \int_{\frac{m_e c^2}{4E}}^{1} dq \frac{d\mathcal{N}}{d\epsilon}(\epsilon(q)) \left(1 - \frac{m_e^2 c^4}{4qE_e^2(1-\tilde{\epsilon})}\right) \left[2q\log q + q + 1 - 2q^2 + \frac{\tilde{\epsilon}(1-q)}{2-2\tilde{\epsilon}}\right],$$

$$q = \frac{\tilde{\epsilon}}{\Gamma_\epsilon(1-\tilde{\epsilon})}\ ,\ \Gamma_\epsilon = \frac{4\epsilon E}{m_e^2 c^4}\ ,\ \tilde{\epsilon} = \frac{E_\gamma}{E}\,.$$

What we learn from HAWC discovery (I)

(I) Estimate efficiency of conversion of pulsar spin-down energy in high-energy $e^{\pm}$

Assuming that all the observed γ -ray luminosity of Geminga and Monogem ([8,40] TeV $\sim 10^{32}$ ergs per second) is produced by relativistic $e^{\pm}$ emitted by the PWNe, they infer $e^{\pm}$ properties.

Total energy emitted in $e^{\pm}$ from the PWNe, continous injection:

$$E_{e^{\pm}} = \int dt\, dE\, E\, Q(E,t) = \eta W_0$$

We know pulsar spin-down W_0, $\Rightarrow$ we infer efficiency η!

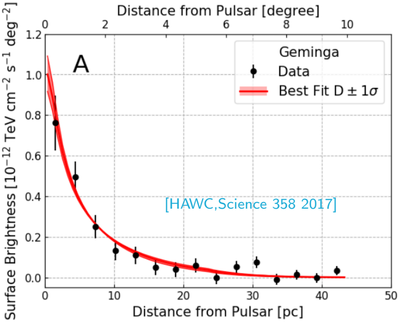
HAWC finds $\eta = 40(4)\%$ for Geminga (Monogem) and using $\gamma_{PWN} = 2.3$

[HAWC Collaboration, Science 358 2017]

What we learn from HAWC discovery (II)

(II) Diffusion in the vicinity of Geminga and Monogem is inhibited.

Gamma-ray emission intensity profile (= surface brightness): how $e^{\pm}$ diffuse away from the pulsar



HAWC finds $K(1\ \mathrm{GeV}) \sim 710^{25}$cm^2/s ($K(E) = K_0(E/1\ \mathrm{GeV})^{-0.33}$)): $\sim$ 500 times smaller than the average value in the Galaxy (inferred e.g. from cosmic-ray B/C)

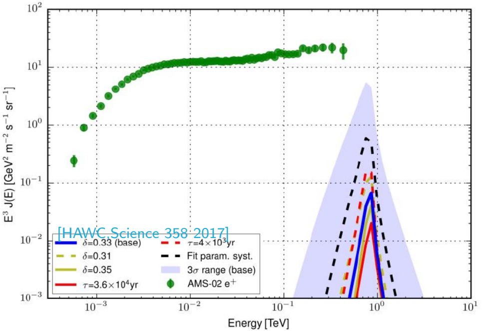
For average Galactic value of $K(E)$: angular extent of γ -ray halo would be 10 times larger: 20deg, undetectable by HAWC [Hooper+PRD17]

Evidence for inhomogeneos diffusion in the Galaxy, see [Evoli+PRD18] for theoretical models

What we learn from HAWC discovery (III)

(III) *"We demonstrate that the lepton emitted by Geminga and Monogem are therefore unlikely to be the origin of the excess of positrons, which may have a more exotic origin"* [HAWC,Science17]

Assuming the same diffusion coefficient found around the sources to diffuse e^+ to the Earth:



However, the extension of γ -ray emission is $\sim 1\%$ of the propagation volume.
Using the mean value of $K(1\ \mathrm{GeV})$ in the Galaxy, [Hooper+PRD17, Profumo+PRD18] extimate the contribution of Geminga to more than $\sim 10\%$ of AMS-02 e^+ data.

A Code for multi-wavelenght emission from PWNe and SNRs

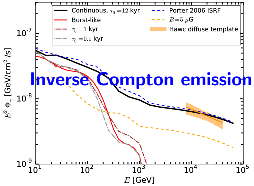
We developed a code which implements [DiMauro,SM,Donato, to be submitted]:

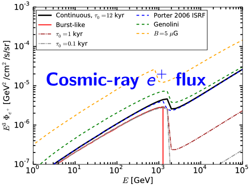
- computation of the cosmic-ray $e^{\pm}$ and photon emission (e.g. synchrotron and Inverse Compton) from PWNe and SNRs in a broad range of energies
- most updated models for the interstellar radiation fields [Vernetto+PRD16,Porter+05]
- two-zone diffusion model [Tang&Piran18]:

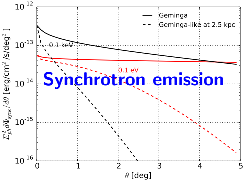
$$K(r) = \begin{cases} K_0(E/1\,\mathrm{GeV})^{\delta} & \text{for } 0 < r < r_b, \\ K_2(E/1\,\mathrm{GeV})^{\delta} & \text{for } r \geq r_b, \end{cases}$$

- effects of the proper motion of sources

Python-based code, we plan to release it in the future.

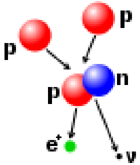




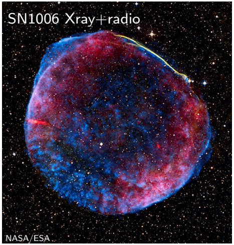


Sources of cosmic ray $e^{\pm}$ in the Galaxy

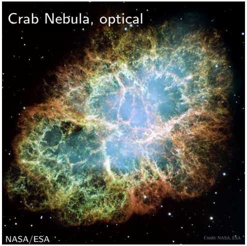
Spallation of primary cosmic rays in the interstellar medium



Supernova Remnants (SNRs)



Pulsar Wind Nebulae (PWNe)



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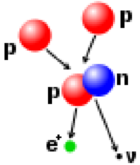

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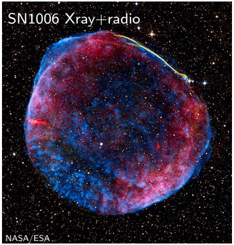

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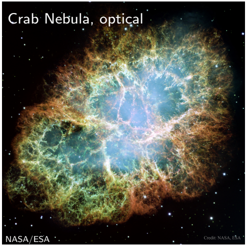


$$Q(E, \mathbf{x}, t) = Q(E)\rho(\mathbf{x})f(t)$$

Energy

- Acceleration mechanism: Diffusive Shock Acceleration (DSA)

Spatial distribution

- Single source at distance d: $\delta(d)$
- Continous source distribution: $\rho(\mathbf{x}) = \rho(r, z)$

Time dependency

- Burst like: $\delta(t)$ e.g. SNR
- Continuous for a typical time τ: e.g. PWNe
- Stationary: rate $1/\Gamma$ e.g. far SNRs

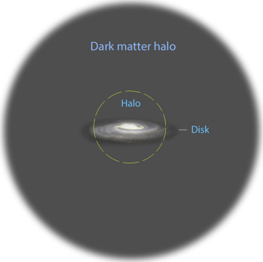
What about Galactic dark matter?

$$\chi + \chi \rightarrow q\bar{q}, \tau^+\tau^-, ... \rightarrow \gamma, e^{\pm}, \nu, \bar{p}...$$

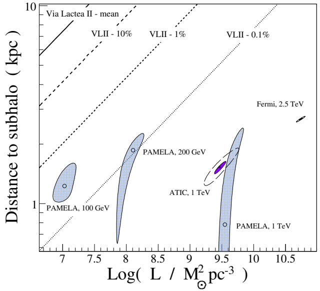
Galactic dark matter halo:

$$Q_{\mathrm{DMhalo}}(\mathbf{x}, E) = \frac{1}{2} < \sigma v > \left(\frac{\rho_{\mathrm{DM}}(\mathbf{x})}{m_{DM}}\right)^2 \frac{dN_{e^{\pm}}}{dE}$$

Subhalos: predicted by N-body simulations.
Nearby and dense substructures may led to signatures...



Milky Way model



However...

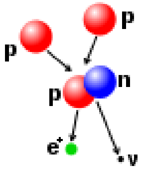
- Subhalos explaining all e^+ data are disfavored according to cosmological simulation [Brun+2009]
- Tipycal $< \sigma v >$, m_{DM} required to explain all $e^{\pm}$ data tested by other indirect searches, e.g. gamma-rays
- Exotic mechanism required, ex. [Cai+JHEP2018], [Demir+PRD10], [Cholis+PRD09]
- **Background from other astrophysical sources**

Spallation of hadronic cosmic-rays in the interstellar medium

Interstellar medium: gas (mainly H and He, 10:1), 0.5-1% of dust

- Cosmic-ray nuclei (p, He) spallation on the H, He
- Dominant mechanism for $e^{\pm}$ production above few GeV:

$$\mathrm{p_{CR}} + \mathrm{H_{ISM}} \rightarrow X + \pi^{\pm} \rightarrow ...$$



Source term: [Delahaye+A&A 2009]

$$Q_{\mathrm{sec}}(\mathbf{x}, E_e) = 4\pi\, n_{\mathrm{ISM}}(\mathbf{x}) \int dE_{\mathrm{CR}} \Phi_{\mathrm{CR}}(\mathbf{x}, E_{\mathrm{CR}}) \frac{d\sigma}{dE_e}(E_{\mathrm{CR}}, E_e)$$

interstellar gas density
$n_{\mathrm{ISM}} \sim 1\ \mathrm{cm}^{-3}$

primary flux
Φ_{CR} (p, He) from AMS-02 data

inclusive cross section parametrization, ex.
[Kamae+2006]

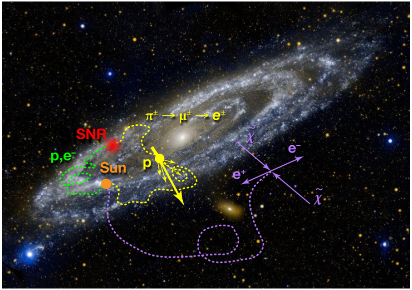
$\Rightarrow$ Uncertainties coming from cross section parametrization, [Delahaye+A&A08,Reinert+JCAP18]

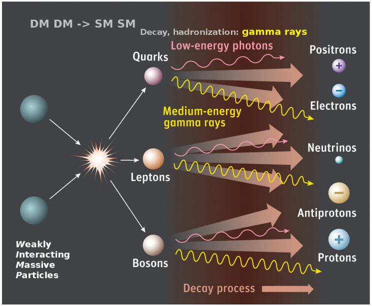
Galactic dark matter

Overwhelming evidence that dark matter is required to explain distribution and amount of structures, from Galactic to cosmological scales.
It accounts for the $\sim 85\%$ of matter content of the universe.

Indirect detection of dark matter signals: spectral distortions, anomalous components in cosmic-rays:

$$\chi + \chi \to q\bar{q}, \tau^+\tau^-, ... \to \gamma, e^+, \nu, \bar{p}...$$





Weakly Interacting Massive Particles with $m_{\rm DM} \sim$ GeV-TeV as benchmark, but also MeV [Boudaud+PRL17]

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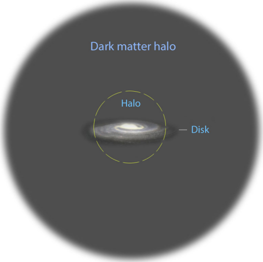

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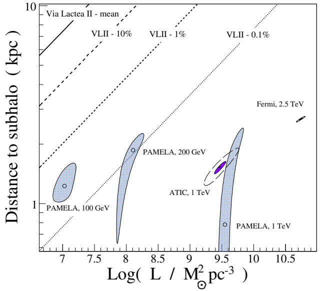

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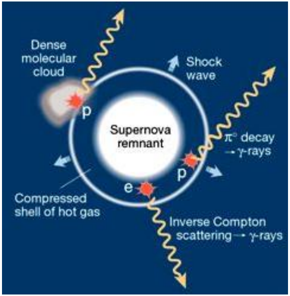
Supernova Remnants

Supernova remnants are considered as main sources of cosmic-rays (p, e^-) in the Galaxy.

- **Fermi diffusive shock acceleration**
  see particle-in-cell simulations [Crumley+ApJ 2017]
- *Evidence*: γ from π_0,"pion bump" [FermiLAT+2010], radio from e^-
- *Injection spectrum*:

$$Q(E) = Q_{0,\mathrm{SNR}} \left(\frac{E}{E_0}\right)^{-\gamma_{\mathrm{SNR}}} \exp\left(-\frac{E}{E_c}\right)$$



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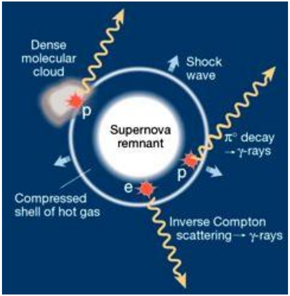

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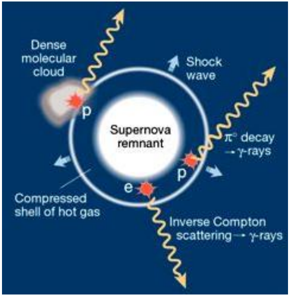

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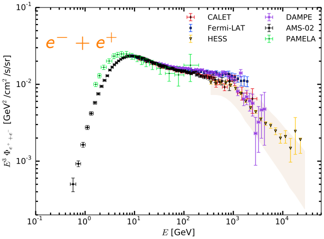
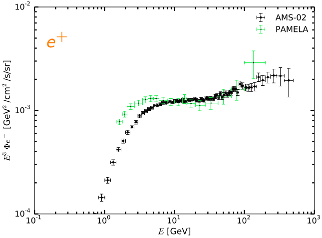
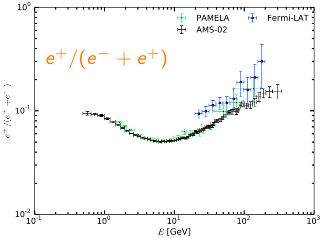
- Antimatter production ($\bar{p}$, e^+): particles accelerated at SN shock produce secondary particles through (mainly) hadronic interactions [Blasi PRL09]
  This effect should produce also a rise of secondary over primary ratios, ex. B/C [Cholis+PRD14]

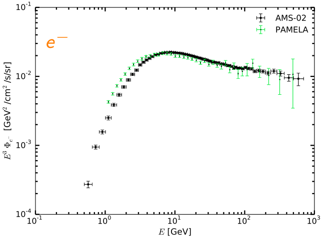
Cosmic-ray electron and positron data: present status

Unprecented energy coverage, high statistical accuracy







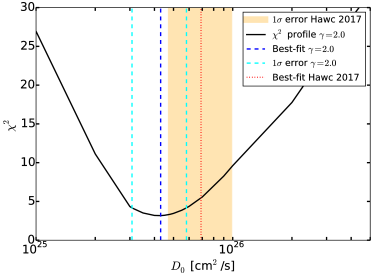


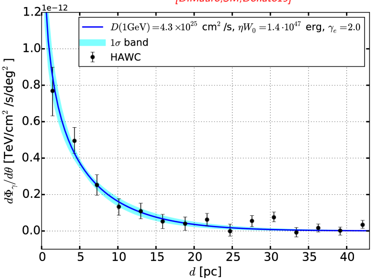
Spectral characteristics are the result of different mechanisms and source classes

Analysis of HAWC data: fit to surface brightness

- We fit HAWC surface brightness for Geminga and Monogem

Geminga:





- Results are compatible with [HAWC Collaboration, Science 358 2017]
- Similar results using spectral index for $e^{\pm}$ $\gamma_{PWN} = 2.3$