



Particle emission from pulsars

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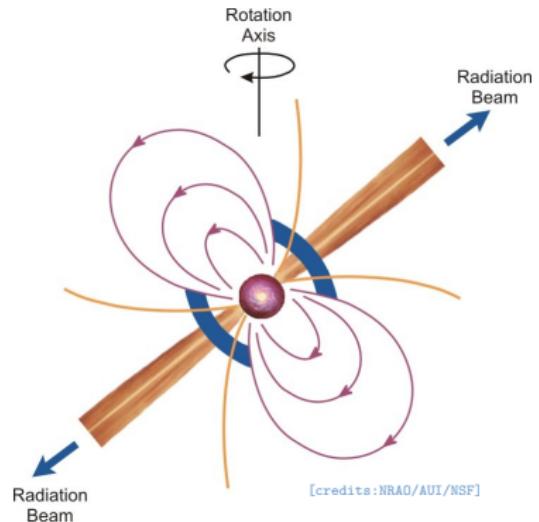
Pulsars

Fast rotating, magnetized $B \sim 10^{9-12}$ G
neutron star $> 8 M_\odot$

- Discovered in radio, then X and γ rays
- Pulsed + stable, extended emission
- Populate Galaxy & source catalogs

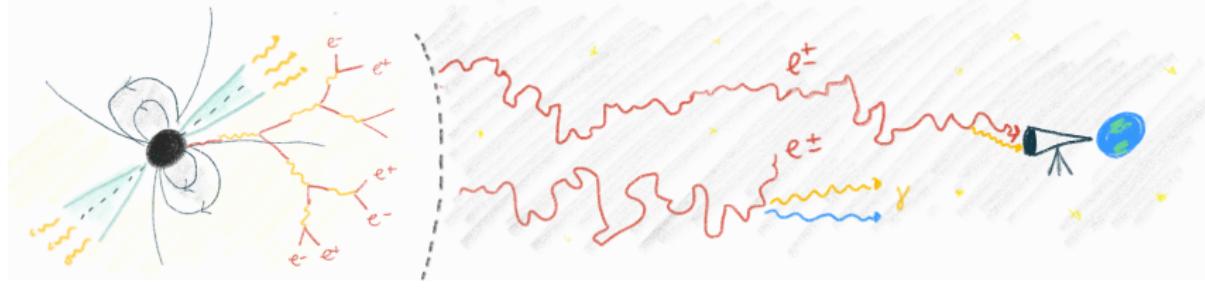
Spin-down luminosity \leftrightarrow particle +EM energy

$$\dot{E} = \frac{dE_{\text{rot}}}{dt} = \dot{E}_0 \left(1 + \frac{t}{\tau_{\text{sd}}}\right)^{-2} \propto \frac{\dot{P}}{P^3}$$



Photons at different energies and spatial scales: particles extracted from star surface
accelerated in pulsar & their surroundings

Outline: particle cosmic ray e^\pm from pulsars



1) Production, acceleration,
release

2) Galactic transport

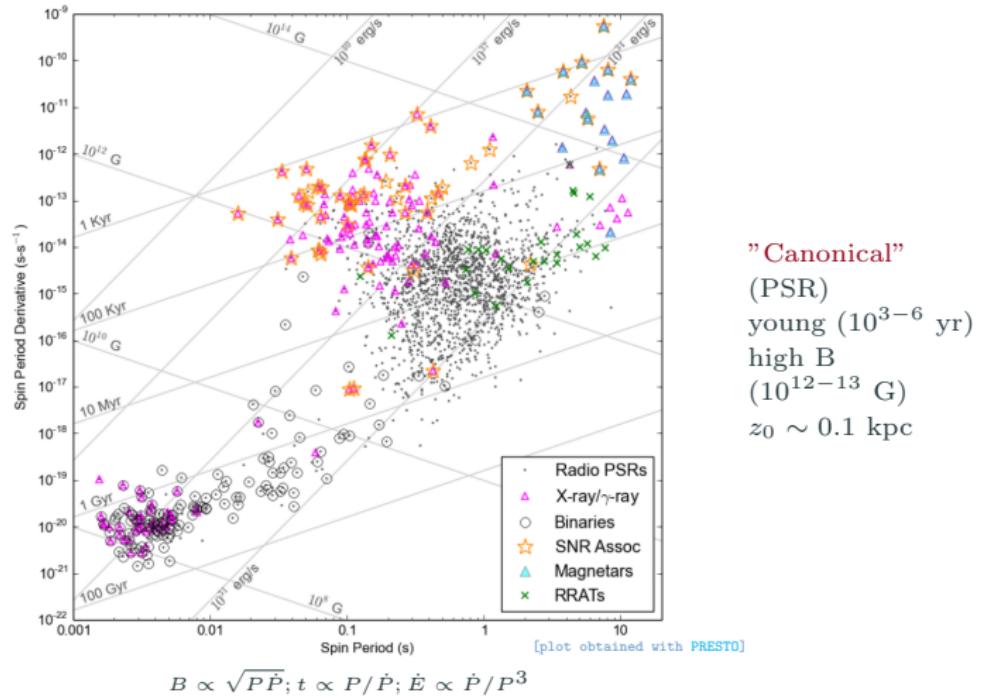
3) Local particle flux &
non-thermal emissions

Understanding e^\pm emission from pulsars is crucial for many hot topics:

- 4) Origin of e^+ excess in local cosmic rays
- 5) Interpretation of γ -ray Galactic center excess
- 6) Diffuse TeV γ -ray emission

Galactic population

Millisecond
pulsar (MSP)
old (10^{8-9} yr)
low B (10^{8-9} G)
 $z_0 \sim 0.7$ kpc
mostly binary

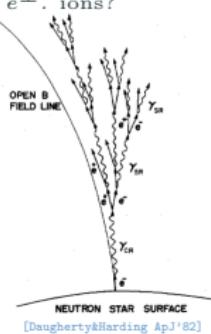


Spatial distribution: disk, $n(z, R) \propto \exp(-R/5 \text{ kpc}) \exp(-z/z_0 \text{ kpc})$

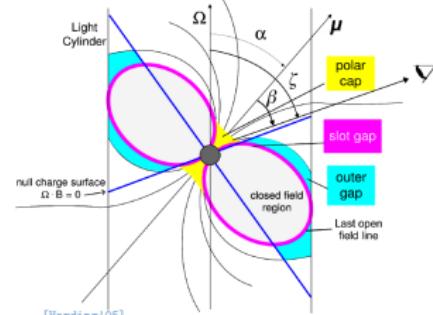
e^\pm creation and radiation mechanisms

Strong B,E:
pair production*

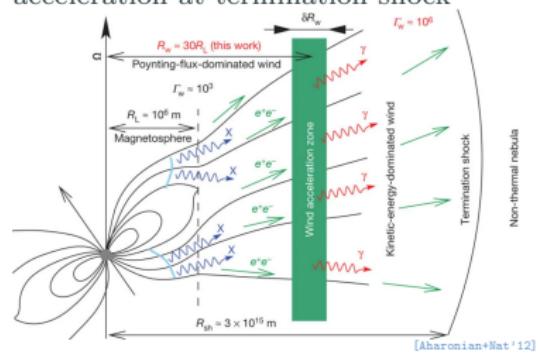
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Production zone: unclear



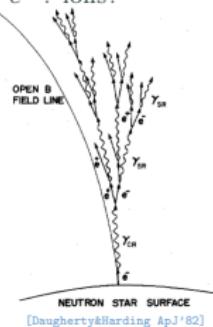
e^\pm wind fills magnetosphere
acceleration at termination shock



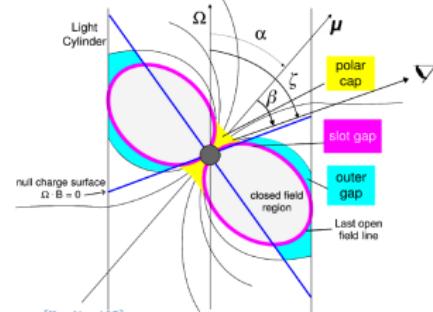
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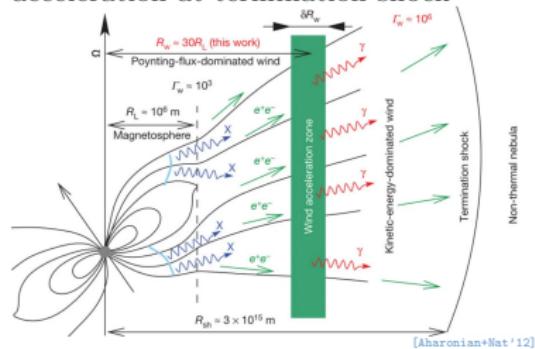
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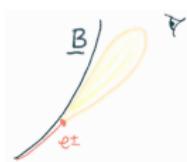
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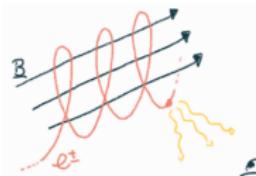
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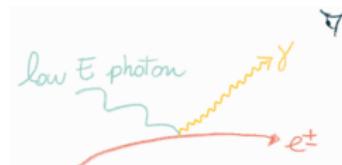
High energy radiation mechanism:



Curvature radiation



Synchrotron

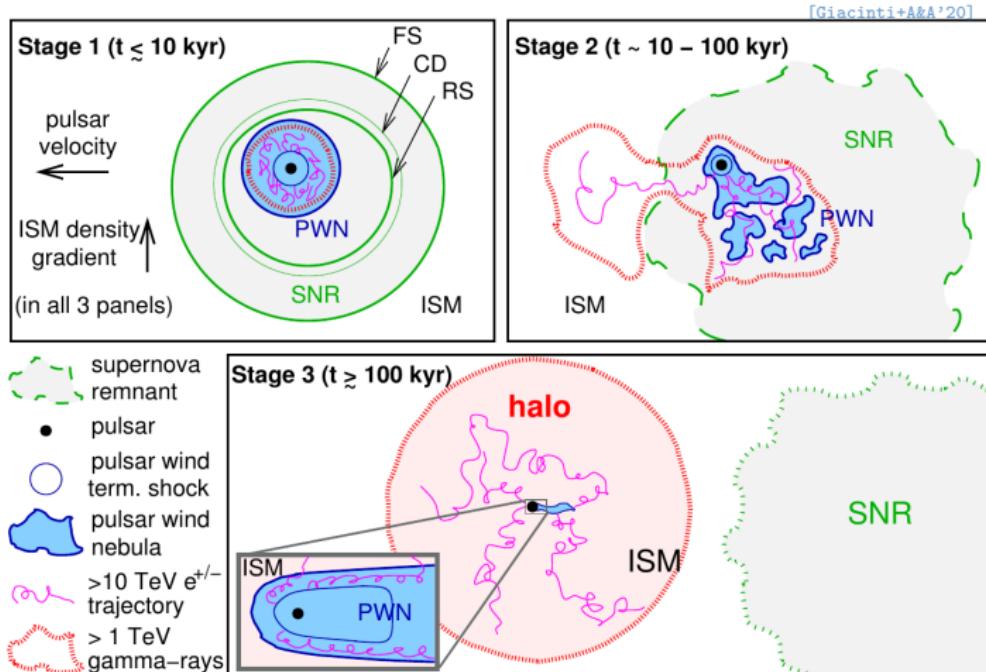


Inverse Compton

Open questions: production model, B structure, MSP pair production

[reviews: Grenier&Harding'15, Harding'21, ...]

Evolutionary stages



Not a rigid classification, but helps to label observations

Evolutionary stages

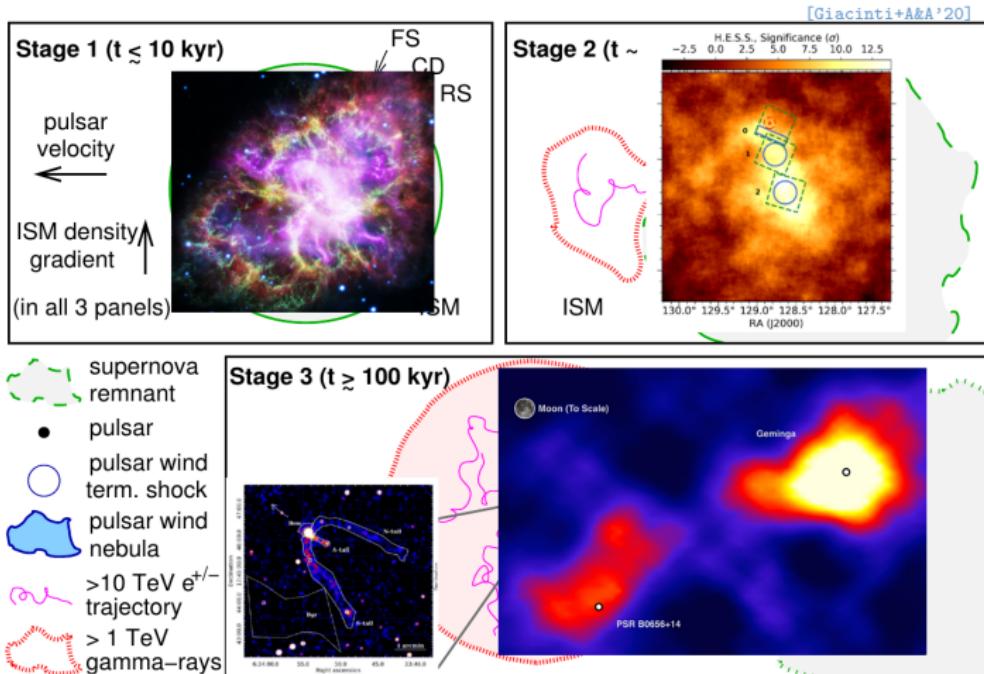
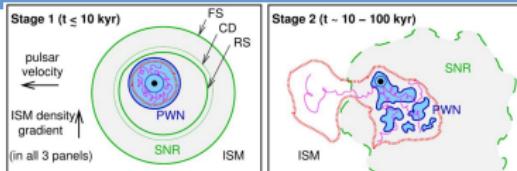


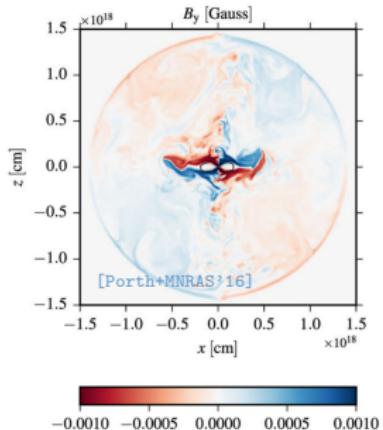
image credits: stage 1 Crab [JPL], stage 2 Vela X HESS Coll., stage 3, Geminga: Posselt+ApJ'17 & HAWC

e^\pm in pulsar winds

Particle production, acceleration, emission,
transport *within* the nebula (few pc)



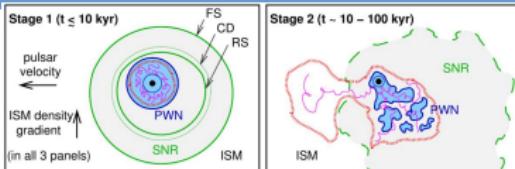
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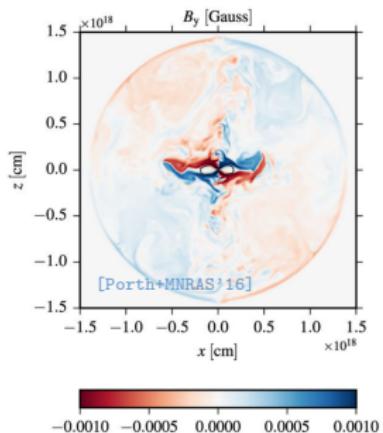
Morphology, B, particle density + emission

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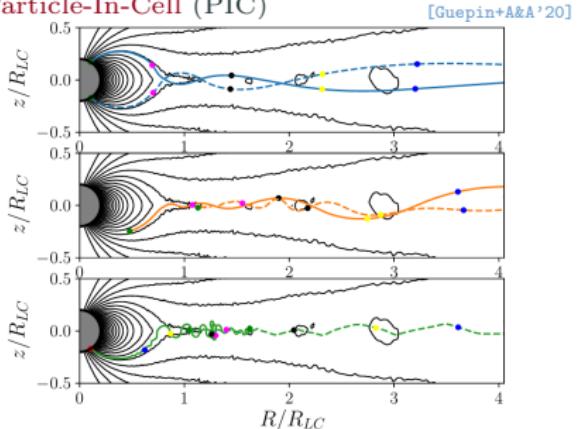


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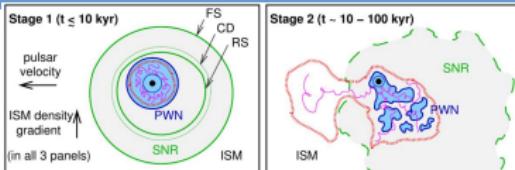
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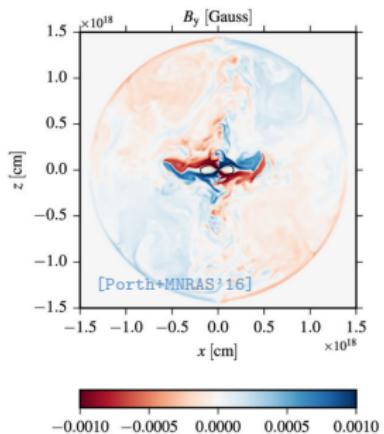
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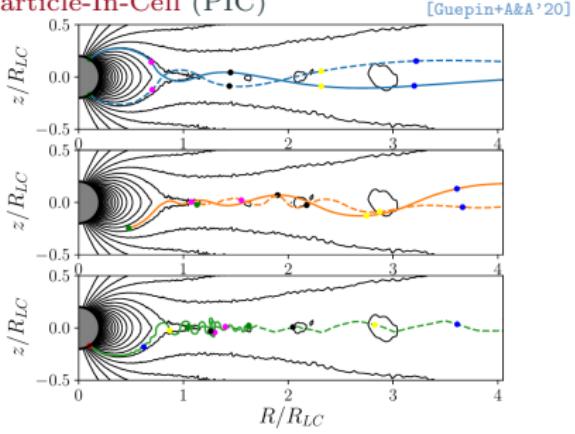


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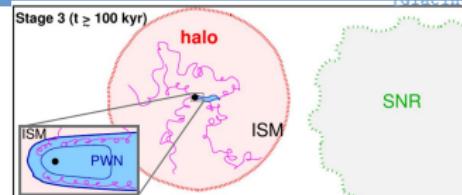
Challenges: multi-frequency spectra + morphology at large distances, time dependency, acceleration mechanism, PeV hadrons?

[recent reviews: Mitchell&Gelfand'22, Olmi&Bucciantini'23]

e^\pm becoming cosmic rays: Geminga halo

PSR J0633+1746, first radio-quiet pulsar
250 parsec, 340 kyr

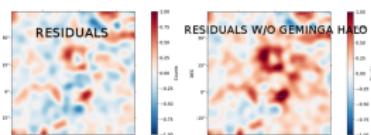
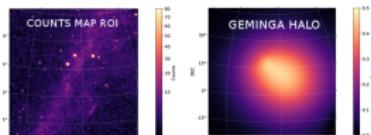
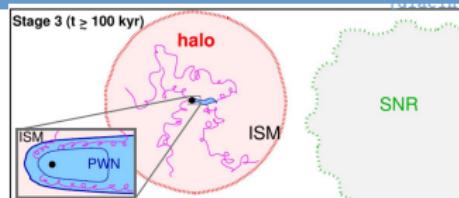
γ -ray halo from GeV to multi-TeV:



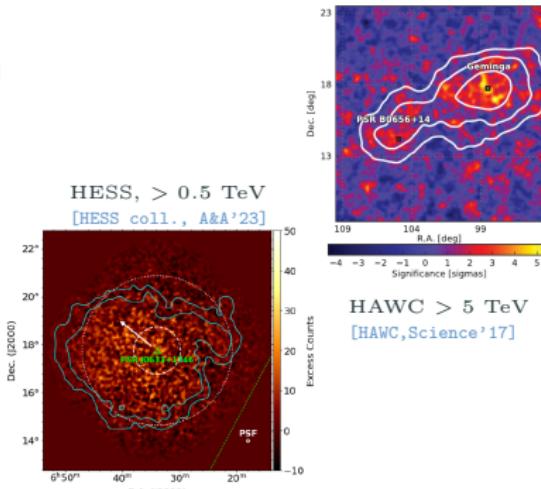
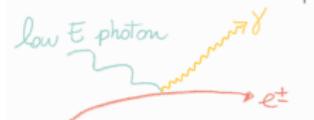
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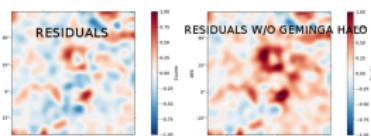
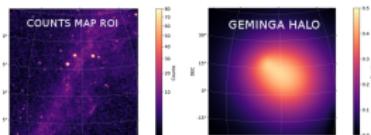
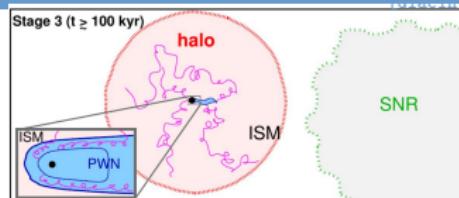
Fermi-LAT > 8 GeV
[DiMauro, SM+PRD '19]



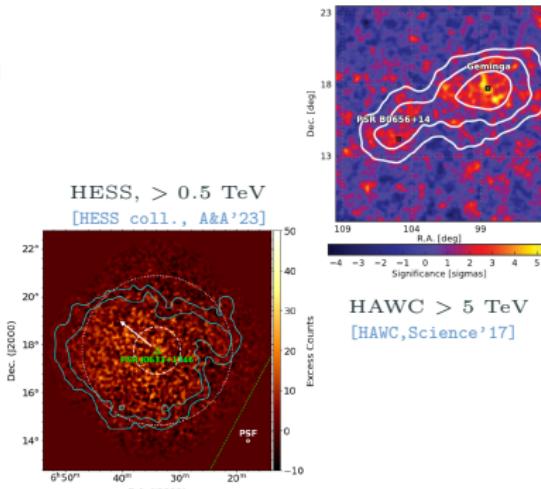
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e^\pm diffusing away from the nebula up-scatter background photons
by inverse Compton emission (tens pc)

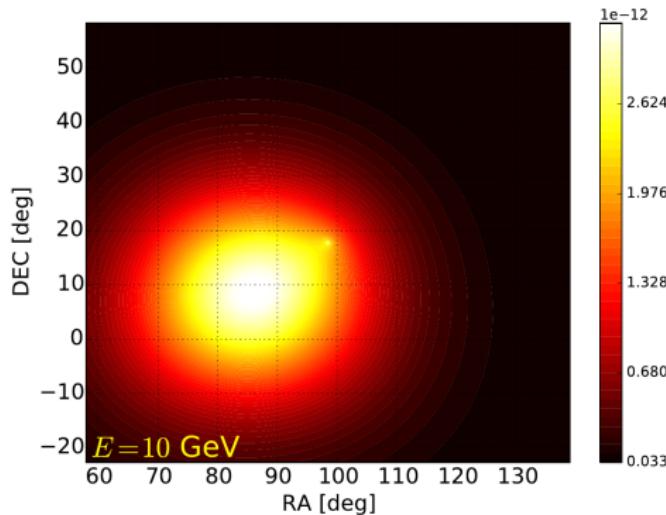
[recent reviews: Liu Int.J.Mod.P.A'22, Fang'22, LopezLoco+NA'22]

Geminga halo: interpretation

e^\pm propagated with diffusion-loss equation:

$$\frac{\partial \mathcal{N}_e}{\partial t} - \nabla \cdot \{ D(E) \nabla \mathcal{N}_e \} + \frac{\partial}{\partial E} \left\{ \frac{dE}{dt} \mathcal{N}_e \right\} = Q(E, \mathbf{x}, t)$$

$$\Phi_\gamma(E_\gamma, \Delta\Omega) = \frac{1}{4\pi} \int_{m_e c^2}^{\infty} dE \int_{\Delta\Omega} d\Omega \int_0^{\infty} ds \mathcal{N}_e(E, s, t) \mathcal{P}_{1C}(E, E_\gamma)$$



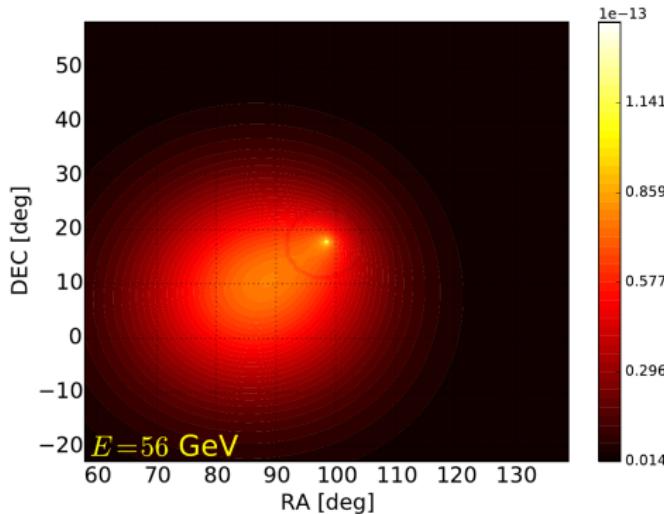
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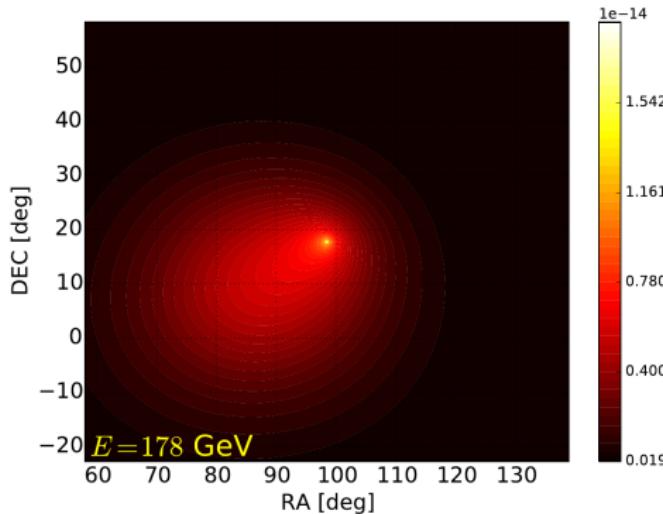
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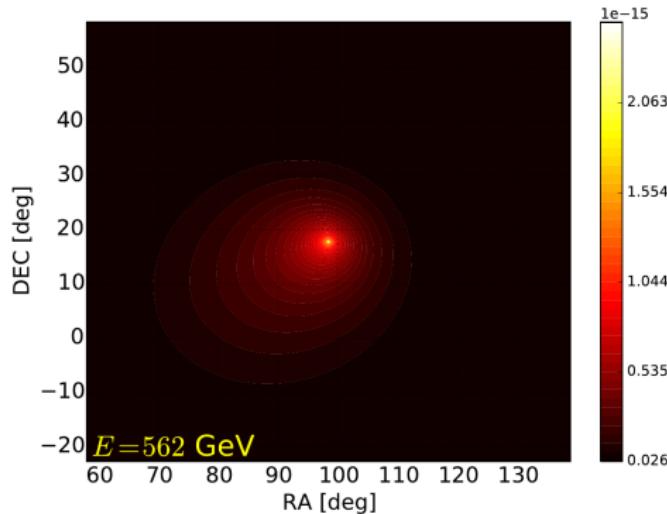
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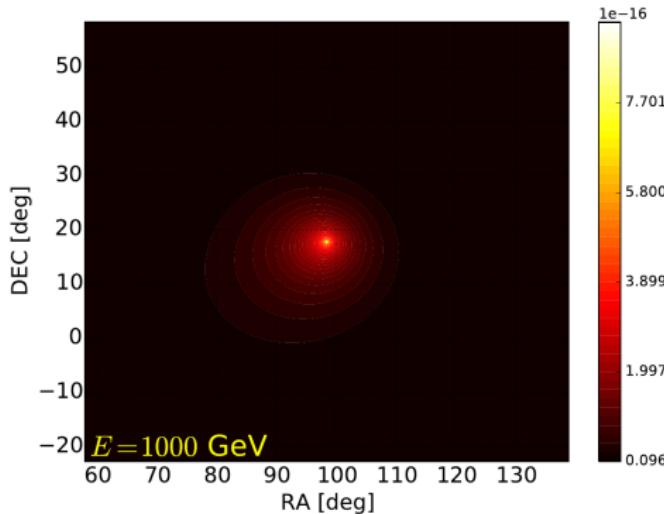
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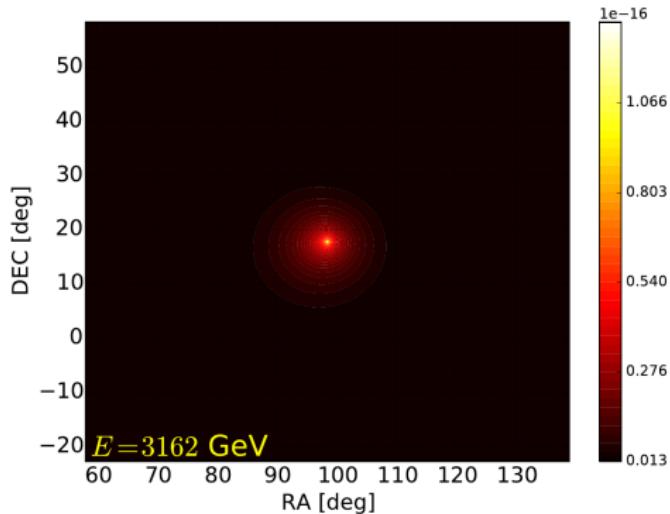
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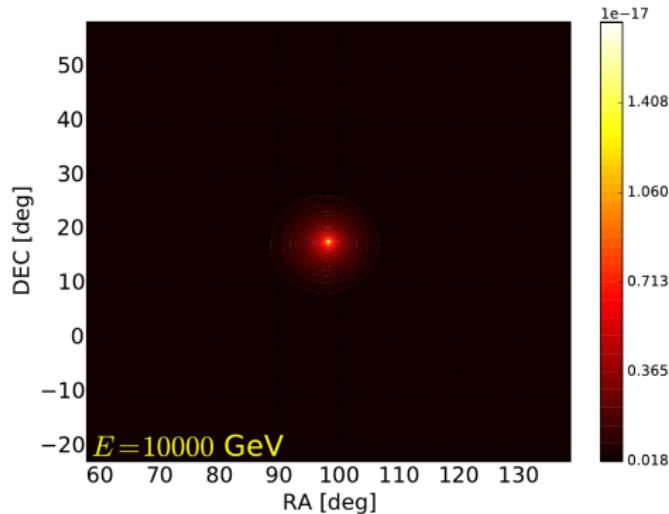
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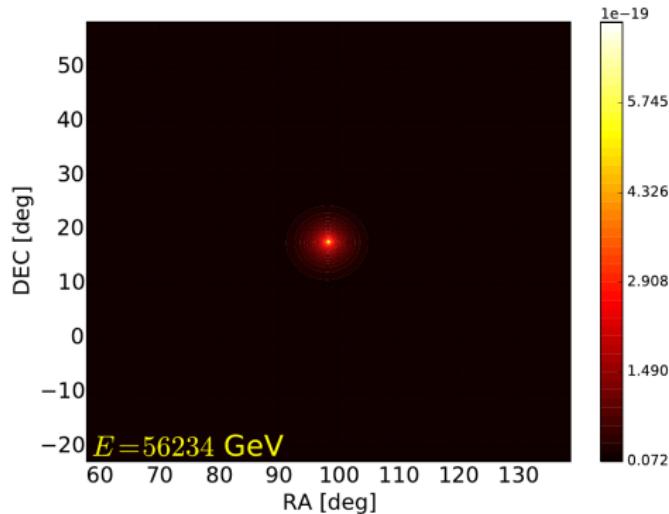
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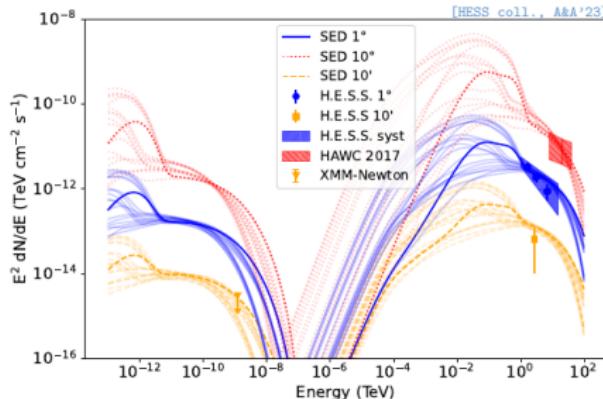


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Geminga halo: interpretation

Spectral energy distribution

→ integrated at different angular distances

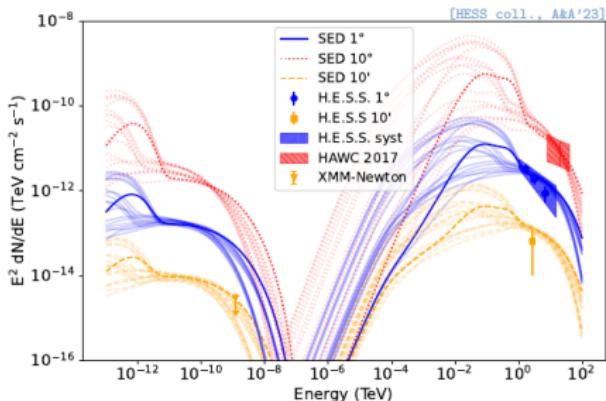


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- X-ray: upper limits
- γ -ray flux matched if
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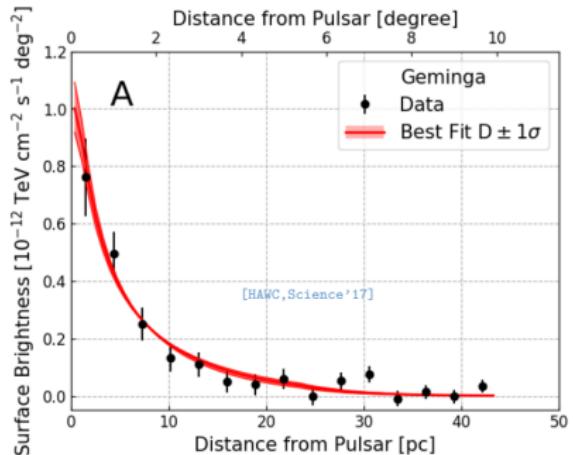


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Emission angular profile

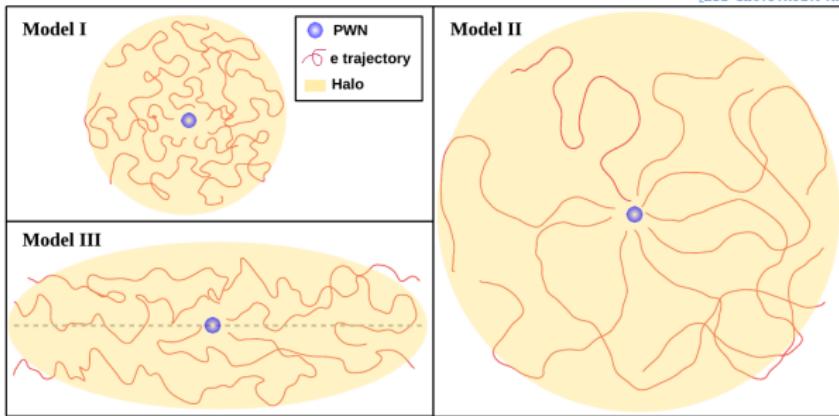
→ integrated in energy



- Energy-dependent extension
- Diffusion appears suppressed (500x) wrt average Galactic transport inferred from other cosmic rays

Halo interpretation: current challenges

[Liu Int.J.Mod.P.A'22]

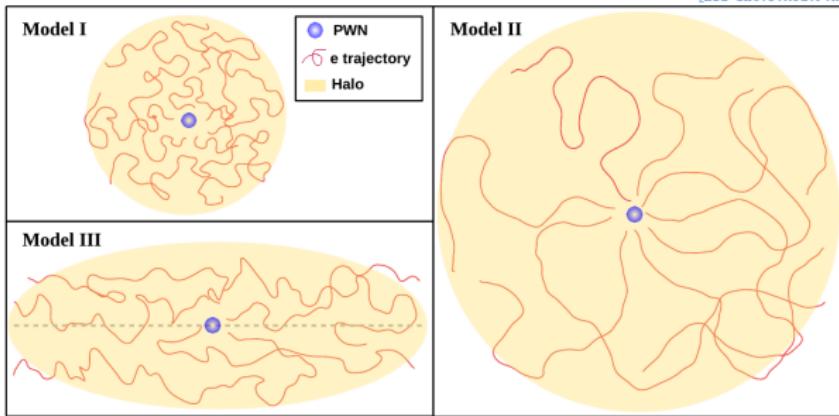


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Angular profile & energetic ok. Origin? e^\pm self-generated turbulence not enough
Galactic cosmic ray propagation: two-zone? swiss-cheese? [Johannesson+ApJ'19, Jacobs+23]

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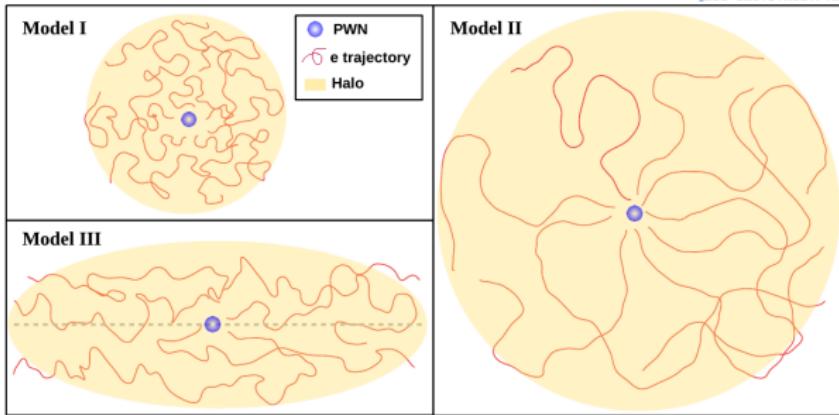
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Small radius: quasi-ballistic, then isotropized. No need for suppressed diffusion
 e^\pm more diluted: higher conversion efficiency

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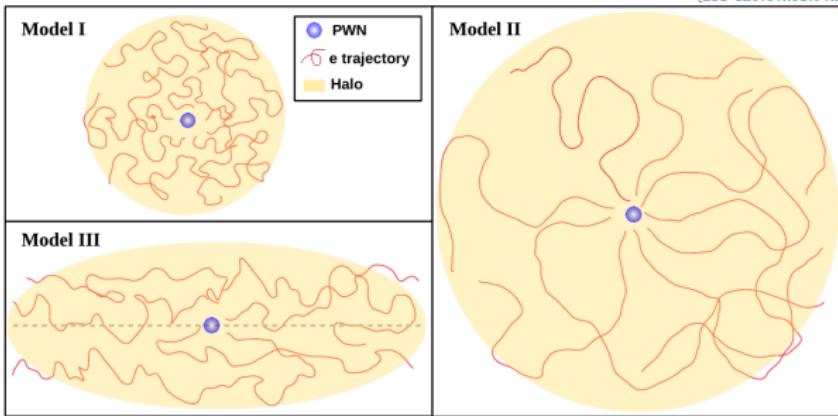
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e^\pm follow mean B line direction
spherical only if small inclination B-observer; many more asymmetric

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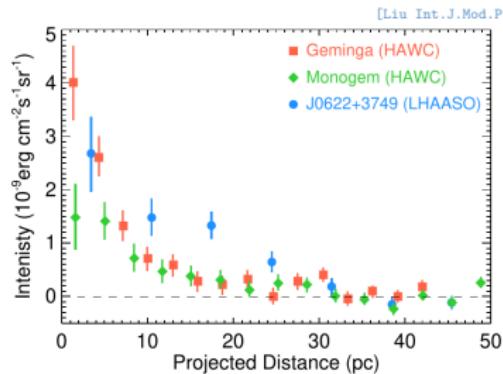
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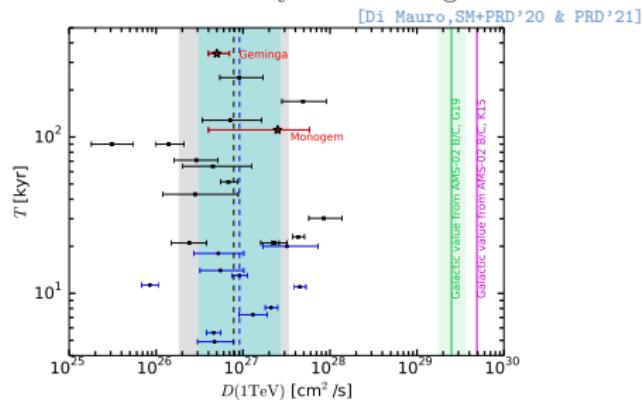
Test: Angular & energy dependent size, B field structure

Observation: bright future

3 confirmed halos

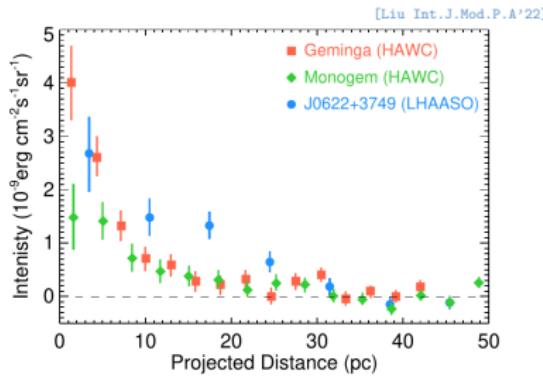


More "PWN" already in halo stage?

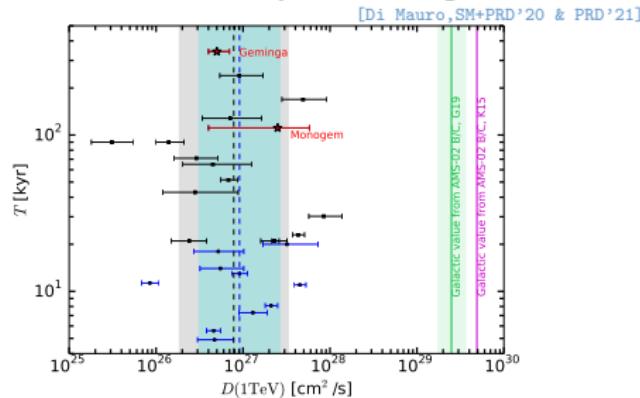


Observation: bright future

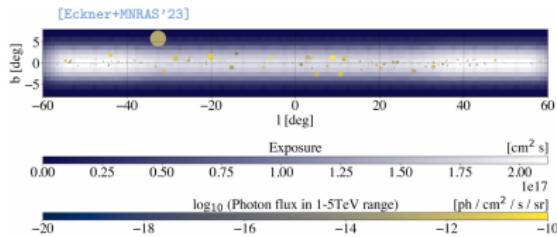
3 confirmed halos



More "PWN" already in halo stage?



→ Population study needed

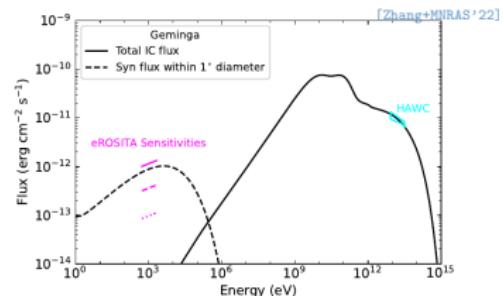


γ rays, CTA: 100+ depending on spin-down + efficiency

[Sudoh+PRD'19, DiMauro, SM+PRD'20&PRD'21, Martin+A&A'22]

S. Manconi (LAPTh,CNRS)

| e^\pm emission from pulsars

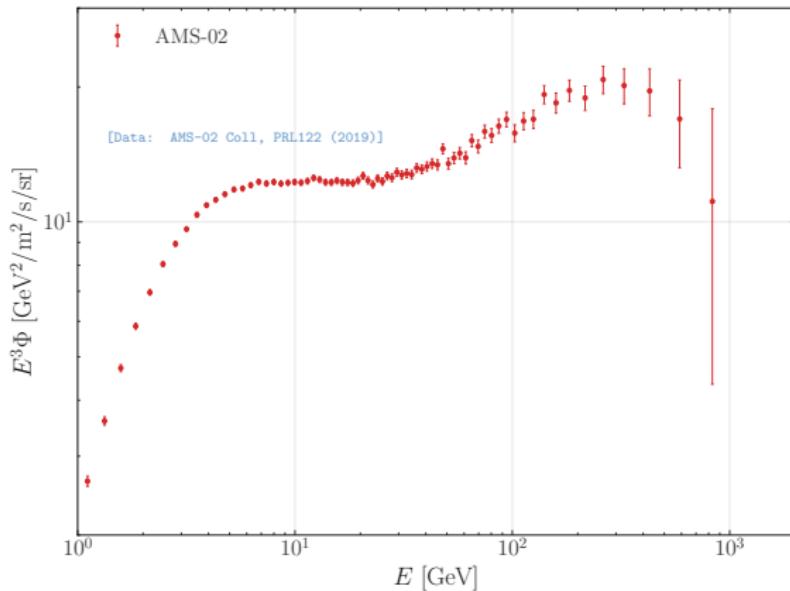


X-ray: FoV challenging
eROSITA + far objects [SM+in prep]

| 3rd EuCAPT Symposium 31.5.23

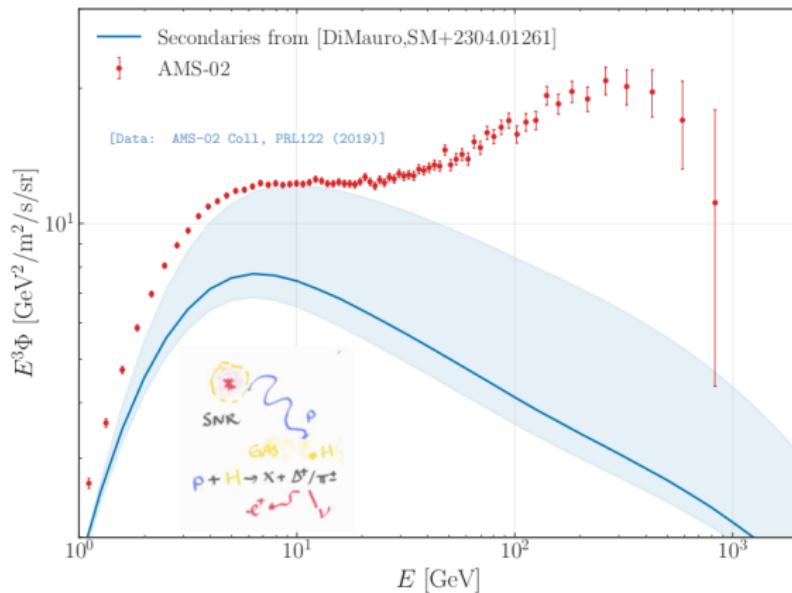
Positron excess

Since 2008, rise in the positron flux measured by PAMELA,
Fermi-LAT, and AMS-02 experiments



Positron excess

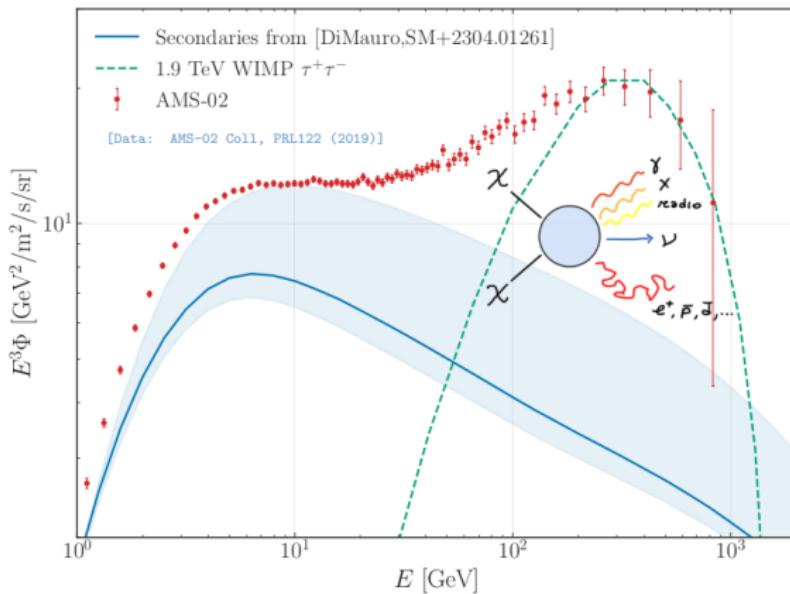
Since 2008, rise in the positron flux measured by PAMELA,
Fermi-LAT, and AMS-02 experiments



- Exceeds secondaries from spallation of hadronic cosmic rays
(updated computation with propagation, cross section uncertainties [DiMauro,SM+'23])

Positron excess

Since 2008, rise in the positron flux measured by PAMELA,
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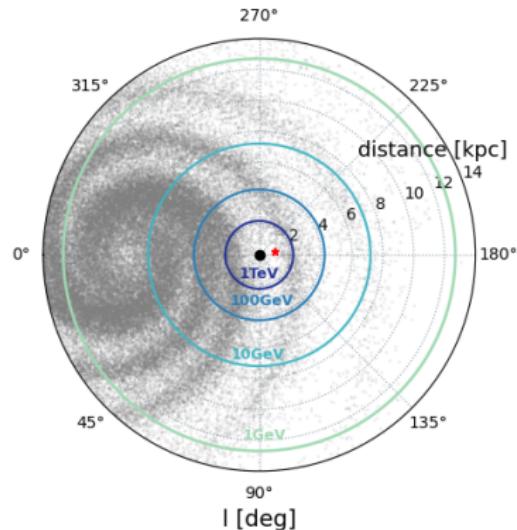


- Exceeds secondaries from spallation of hadronic cosmic rays
- Dark matter annihilation: $\langle \sigma v \rangle$, m_{DM} excluded by indirect searches
e.g. Planck CMB (leptonic) gamma-rays (hadronic)

Pulsars, winds, halos: natural e^+ sources

e^\pm at GeV-TeV are local (few kpc)

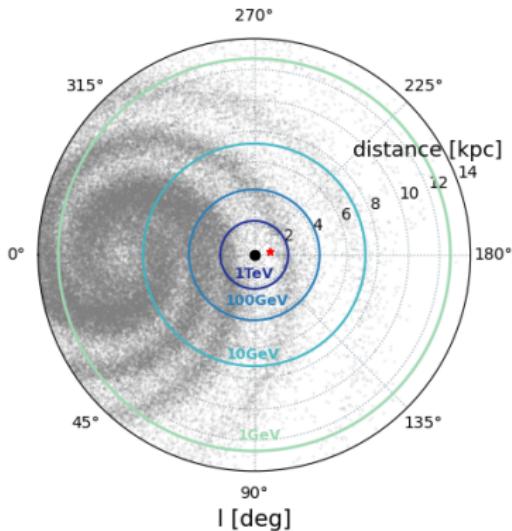
→ sync, inverse Compton losses



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

Pulsars, winds, halos: natural e^+ sources

e^\pm at GeV-TeV are local (few kpc)
 → sync, inverse Compton losses

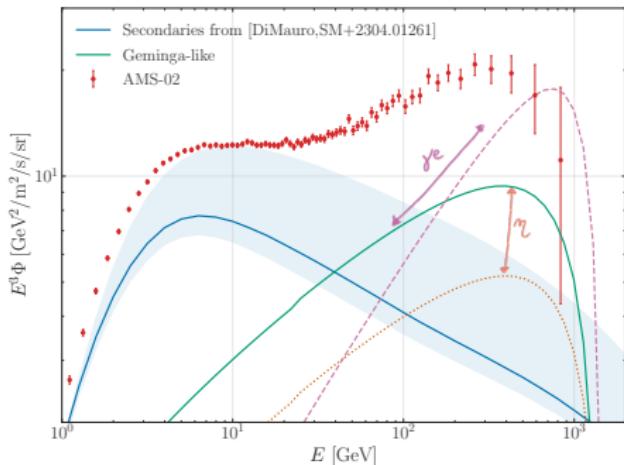


$$\chi^2(E, E_S) = 4 \int_E^{E_S} dE' \frac{D(E')}{b_{\text{loss}}(E')}$$

e^\pm injection \leftrightarrow local flux

$$Q(E, t) \propto L(t) E^{-\gamma_e} \exp(-E/E_c),$$

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



Halos: evidence & test of properties of cosmic-ray e^\pm emitted

Geminga contribution constrained by Fermi-LAT

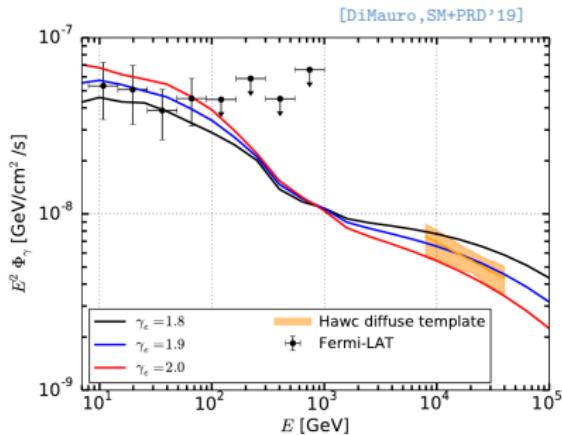
AMS-02 e^+ excess $\sim 1 - 100$ GeV \rightarrow inverse Compton of this population is at GeV

\rightarrow Fermi-LAT, challenging: halo is 5+deg, distorted by proper motion

Geminga contribution constrained by Fermi-LAT

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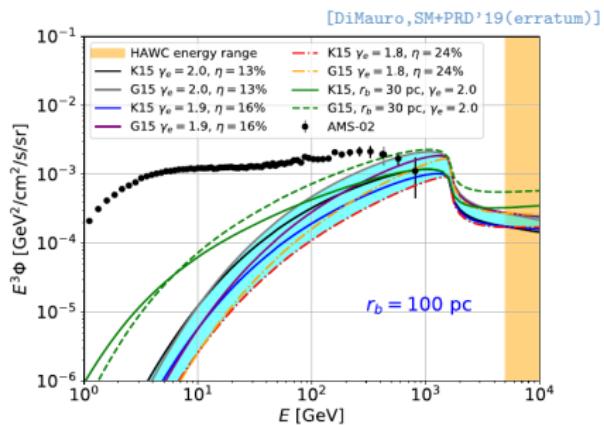
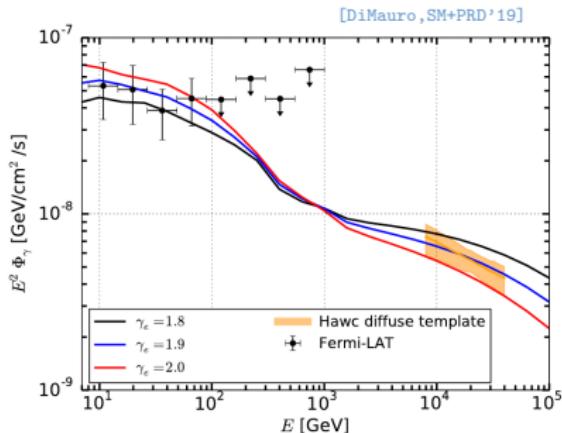
\rightarrow Fermi-LAT, challenging: halo is 5+deg, distorted by proper motion



Geminga contribution constrained by Fermi-LAT

AMS-02 e^+ excess $\sim 1 - 100$ GeV \rightarrow inverse Compton of this population is at GeV

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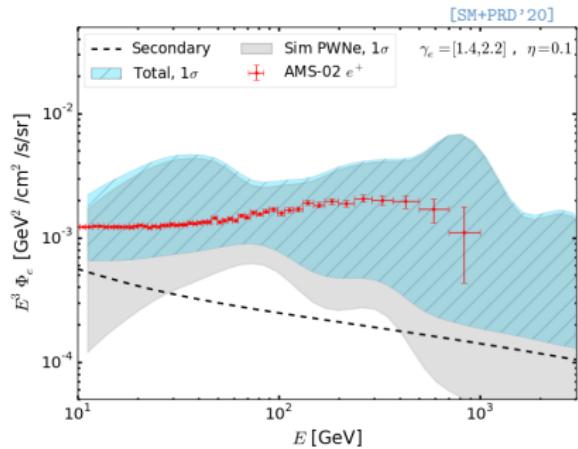


- Inverse Compton GeV-TeV spectrum: constrain spectral shape $\gamma_e < 2$, $\eta \sim 10\%$
- Geminga contributes to local AMS-02 e^+ at \sim TeV
- Uncertainties: size (r_b) of suppressed diffusion

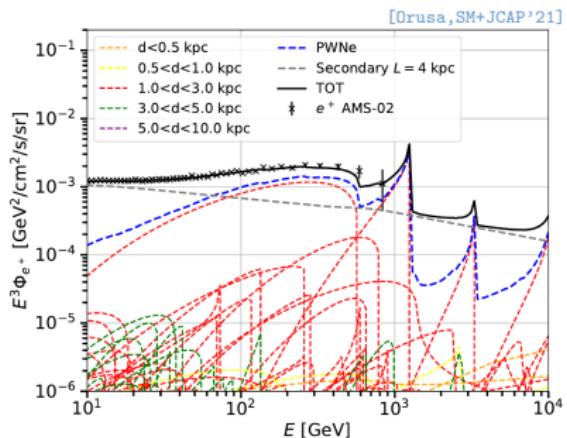
Geminga pulsar not alone in the Galaxy ...

Galactic pulsar population explains e^+ excess

Galactic pulsars with properties of emitted $e^+ \sim$ Geminga



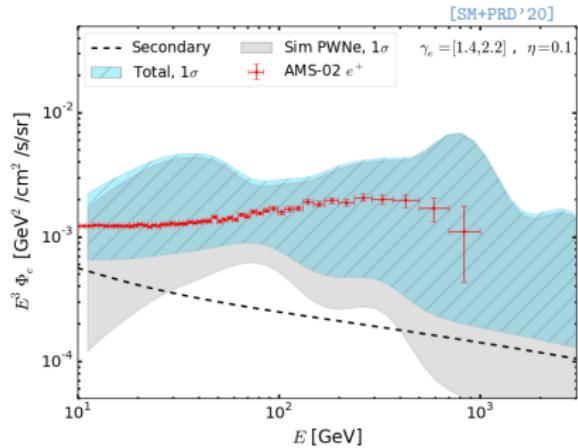
→ including suppressed diffusion



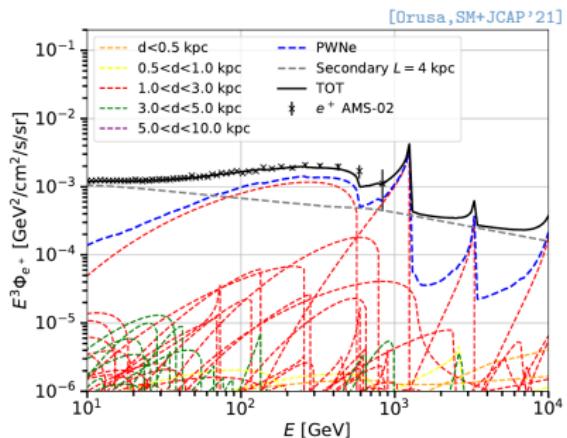
→ fit prefers few nearby, bright sources

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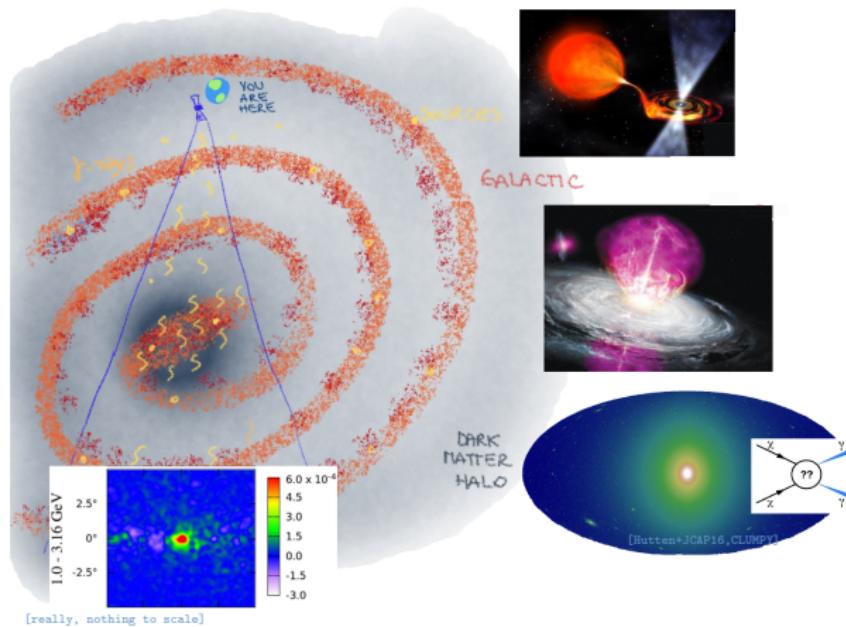
→ fit prefers few nearby, bright sources

- Few dominant sources: e^+ anisotropy, depending on local B structure [SM+JCAP'17]
- Detailed background models needed to derive robust constraints on exotic e^+ injection, e.g. WIMP annihilation [Krommydas+PRD'23]

See also [Evoli+PRD'21, Asano+ApJ'22, Cholis+PRD'22, ...]

Galactic center excess: dark matter or MSP?

Statistically significant excess in Fermi-LAT data few % of 2-20 GeV inner Galaxy flux



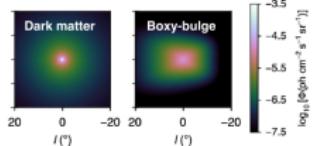
- + **MSP**: New population of (yet) unresolved millisecond pulsar (MSP)-like sources
- + **Dark Matter**: WIMP annihilation in Galactic halo

[Goodenough+'09, Vitale+'09, Abazajian+PRD'12, Hooper+PDU'13, Daylan+PDU'16, Calore+JCAP'15, Cholis+JCAP'15, Calore+PRD'15, Ajello+2015, Linden+PRD'16, Ackermann+ApJ'17, ... 500+ papers, review: S. Murgia ARNPS'20]

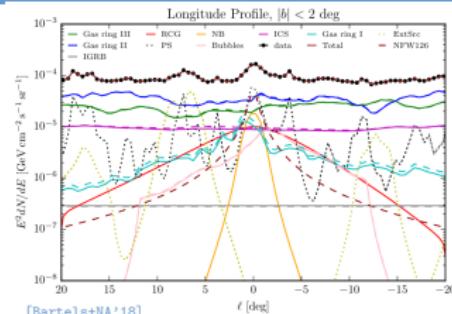
MSP in the Milky Way's bulge: evidence

Morphology: Stellar bulge-like morphology preferred over dark matter-like when reducing residuals

[Bartels+NA'18; Macias+NA'18; Calore, SM+PRL'21; Pohl+ApJ22]



Debated: [DiMauroPRD'21, Cholis+PRD'22, McDermott+'22]

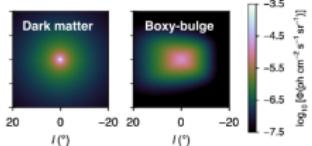


Longitudinal asymmetry at ~ 10 deg

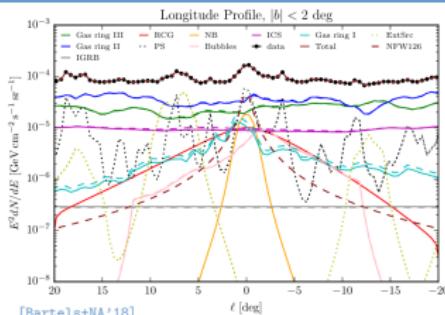
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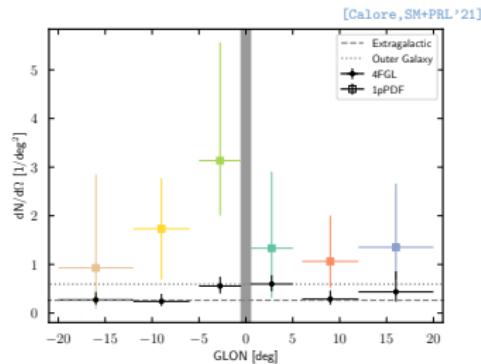
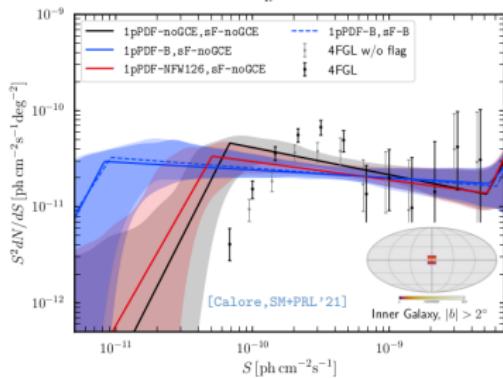


Debated: [DiMauroPRD'21, Cholis+PRD'22, McDermott+'22]



Longitudinal asymmetry at ~ 10 deg

Photon-count statistics: Faint, non-isotropic point sources measured by several methods [recent: Calore,SM+PRL'21, List+PRD'21, Mishra-Sharma+PRD'22]



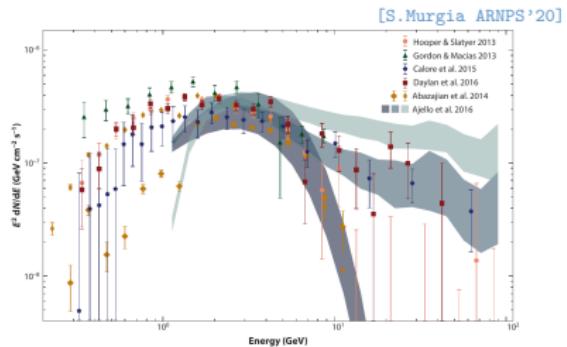
High energy tail: e^\pm by MSP?

e^\pm in MSP: prompt magnetosphere γ rays
+ inverse Compton of emitted e^\pm ?

[Petrovic+JCAP'15, Horiuchi+JCAP'16, Linden+PRD'16, Macias+MNRAS'22]

→ similar hints in globular clusters

[Song+MNRAS'21]



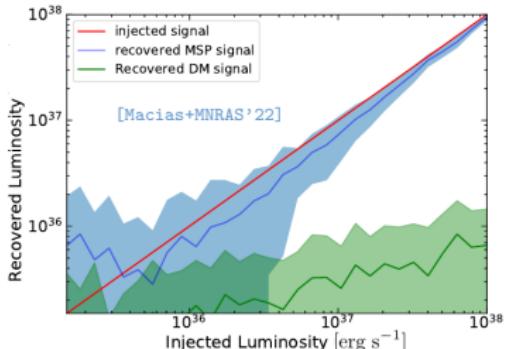
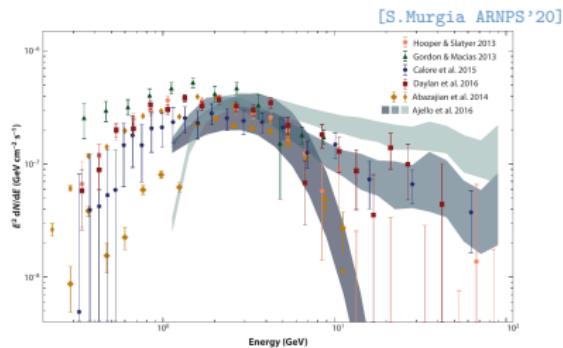
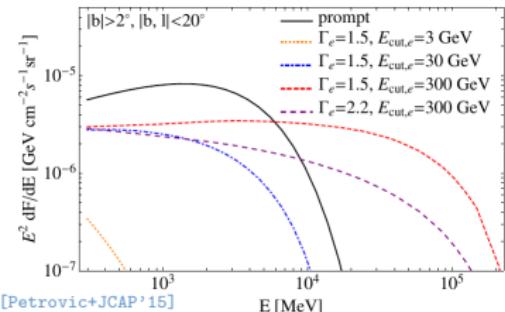
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→ similar hints in globular clusters

[Song+MNRAS'21]



CTA could detect this signature and discover bulge MSP population
depends on luminosity function + spectral properties

→ understanding MSP e^\pm emission decisive

Galactic Diffuse TeV γ ray emission

Measured from MeV to TeV (Tibet AS γ : sub-PeV [\[Amenomori+PRL'21\]](#))

Main expected component: π^0 from cosmic ray hadrons. *Leptonic contribution?*

LHAASO TeV catalog: $\sim 1/2$ sources connected to pulsars/nebulae [\[LHAASO Coll.2305.17030\]](#)

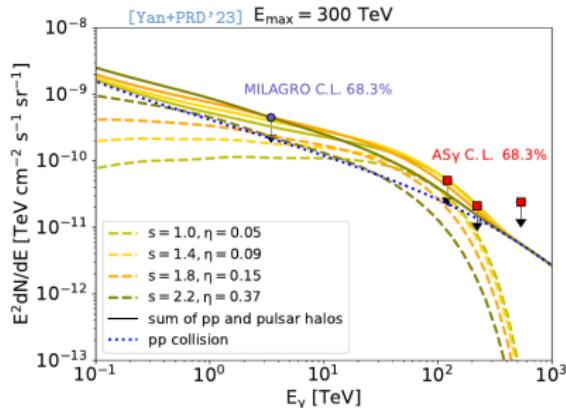
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LHAASO TeV catalog: $\sim 1/2$ sources connected to pulsars/nebulae [LHAASO Coll.2305.17030]

Unresolved pulsar-powered sources could contribute significantly to GeV [Vecchiotti+'21] and saturate TeV diffuse in the Galactic plane [Linden+PRL'18, Vecchiotti+ApJ'22, Yan+PRD'23]



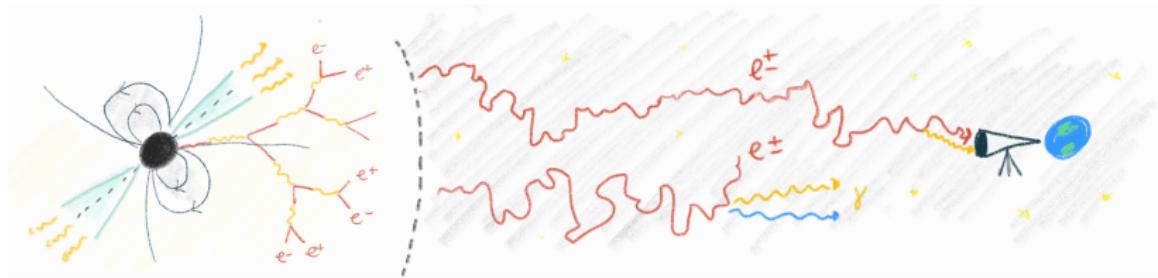
Could test pulsar halo models I-III (efficiency, transport)

Consequences also for Galactic neutrino emission models [Liu+ApJL'21]

Summary & Outlook

Pulsars and their halos as laboratories to investigate e^\pm acceleration, cosmic rays and their non-thermal emissions in the Galaxy

Crucial to clarify positron excess, Galactic Center excess, and interpretation of TeV γ -ray diffuse emissions



Moving forward:

- *Microphysics*: e^\pm , ions? acceleration mechanism & efficiency
- *Transport/non thermal emissions*: consequences for Galactic cosmic-ray propagation & diffuse backgrounds
- *Observations*: population studies with CTA (γ rays), eRosita (X rays)

Credits

My collaborators:



Fiorenza Donato (*University of Turin & INFN Turin*); Mattia Di Mauro (*INFN Turin*); Francesca Calore (*LAPTh, CNRS*); Luca Orusa, Sarah Recchia (*University of Turin & INFN Turin*); Michael Korsmeier (*OKC, Stockholm University*)

Bibliography with links to the references mentioned during the talk:

<https://doi.org/10.5281/zenodo.7984914>

Thank you for your attention!



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<https://silviamanconi.wordpress.com/>

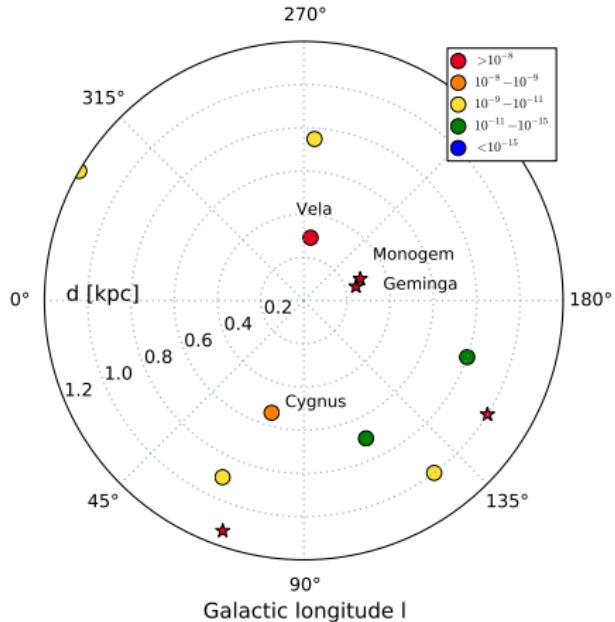
I acknowledge the European Union's Horizon Europe research and innovation programme for support under the Marie Skłodowska-Curie Action PF2021, grant agreement No.10106280, project VerSi.

Backup

Galactic pulsars (catalogs)

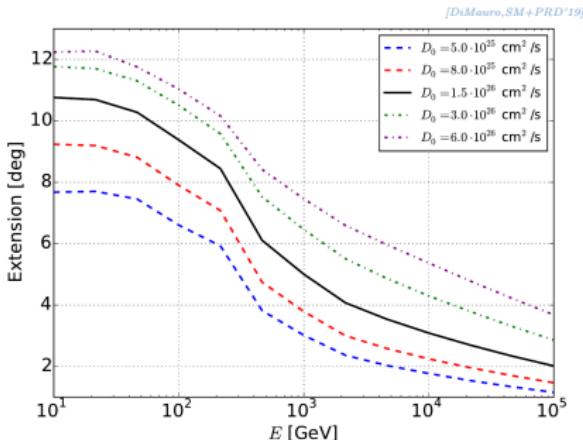
- ★ ATNF catalog ($\sim 1k$ sources) (distance, age, W_0)

Color coding: integrated e^\pm flux $E > 50$ GeV [SM, PhD thesis, 2019]



Extension depends on energy + diffusion

Expected angular extension of Geminga as a function on energy:

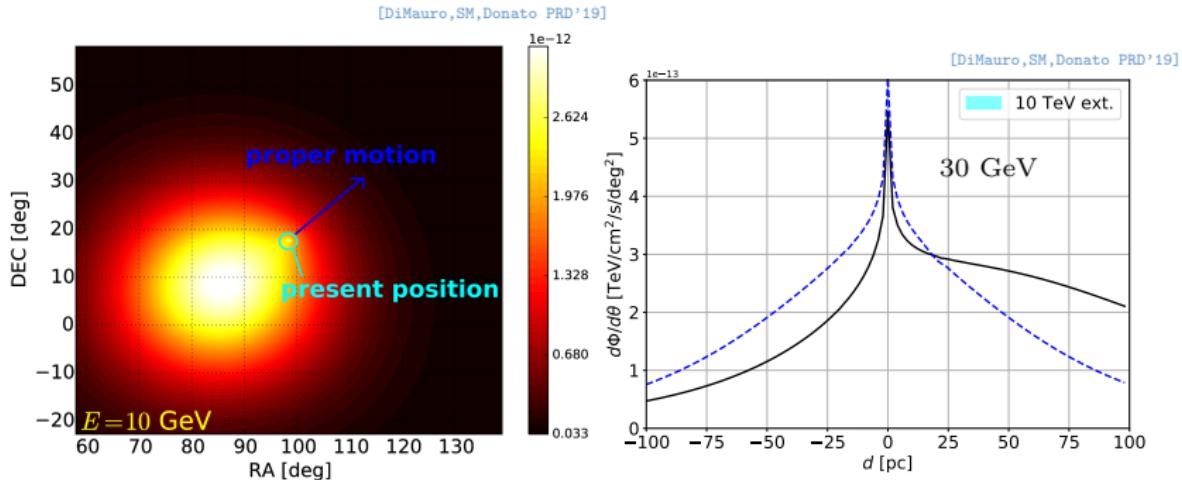


- TeV: Geminga halo < 5 deg; GeV: > 8 deg
- $D_0 \sim 10^{28} \text{ cm}^2/\text{s}$: Geminga halo spread out in the interstellar medium
- Region of Interest of 70deg x 70deg

*extension = angle containing 68% of the ICS flux

Pulsar proper motion: consequences for GeV halo

As first pointed out by [Tang&Piran MNRAS19], transverse velocity affects significantly morphology of Geminga halo γ -ray emission at $E < 100$ GeV:

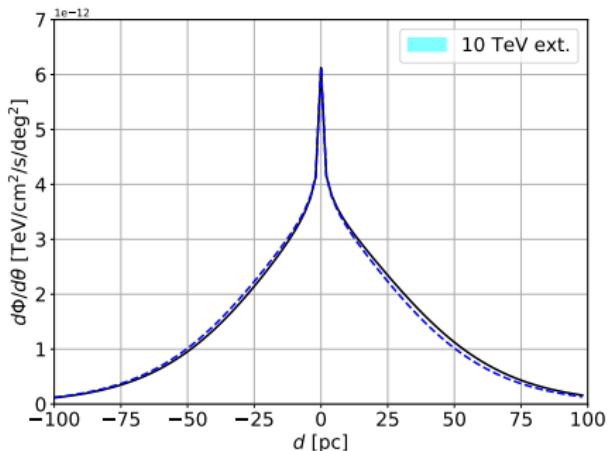
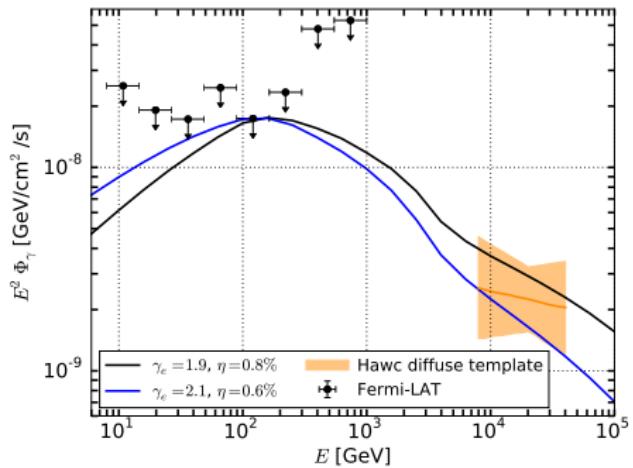


- Geminga pulsar proper motion: transverse velocity of $v_t \sim 211$ km/s [Faherty+AS07]: ~ 70 pc across its age (342 kyr)
- Expected distortion of about 10 deg in opposite direction wrt proper motion at tens of GeV

See also [Johannesson+ApJ19], [Zhang+ApJ21]

Monogem in Fermi-LAT: upper limits

- Lower limits on $D_0 > 1 - 10 \cdot 10^{26} \text{ cm}^2/\text{s}$, compatible with HAWC
- Upper limits on spectral energy distribution in all GeV range
- Proper motion **not affecting gamma-ray morphology**



Angular size: key parameter for detectability

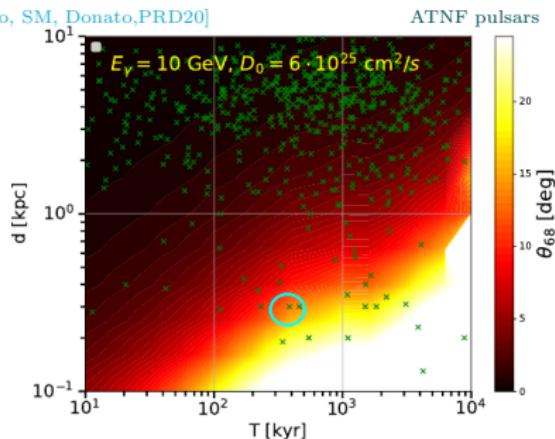
Assuming suppressed diffusion \sim Geminga:

Fermi-LAT: challenging detection for > 10 degrees

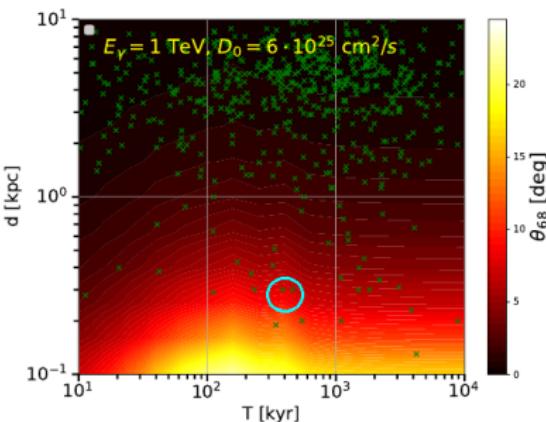
VHE experiments: few degrees instantaneous field of view

$$\Phi_{\gamma}^{68\%}(E_{\gamma}) = 2\pi \int_0^{\theta_{68}} \frac{d\Phi_{\gamma}}{d\theta}(E_{\gamma}) \sin \theta d\theta$$

[Di Mauro, SM, Donato, PRD20]



ATNF pulsars



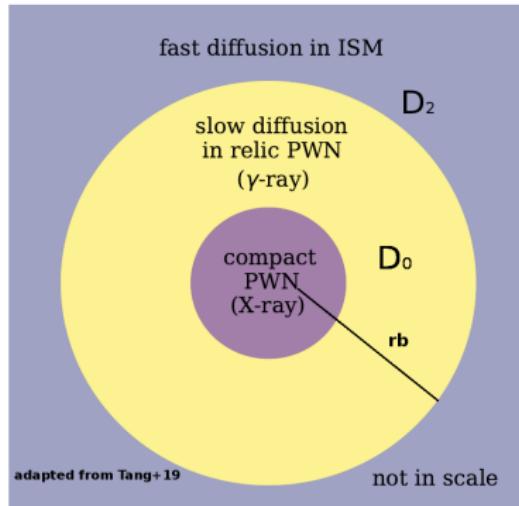
- **10 GeV**: a source of 100 kyr should be far at least 0.9 kpc to be detected with extension smaller than 2 deg
- **1 TeV**: D_0 is similar to Geminga value: most ATNF pulsars would be good targets for inverse Compton gamma-ray halo

Two-zone diffusion model

Effective way to solve propagation equation for e^\pm diffusing from source to Earth:

two-zone diffusion model: [\[Tang&Piran MNRAS19\]](#)

$$D(r) = \begin{cases} D_0(E/1\text{ GeV})^\delta & \text{for } 0 < r < r_b, \\ D_2(E/1\text{ GeV})^\delta & \text{for } r \geq r_b, \end{cases}$$

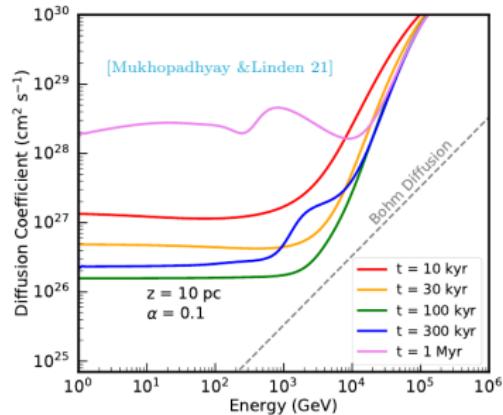
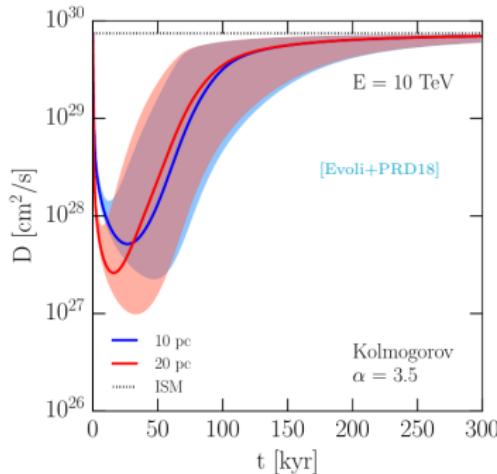


Controversial solutions: [\[Osipov+J. Phys.: Conf. Ser. 1697 \]](#), [\[S.Wagner, RWTH Bachelor thesis\]](#)

Cosmic ray self-confinement

Cosmic-ray gradient produced by pulsar (Alfven waves, resonant) induces streaming instability self-confining cosmic-ray population, similar to supernova remnants

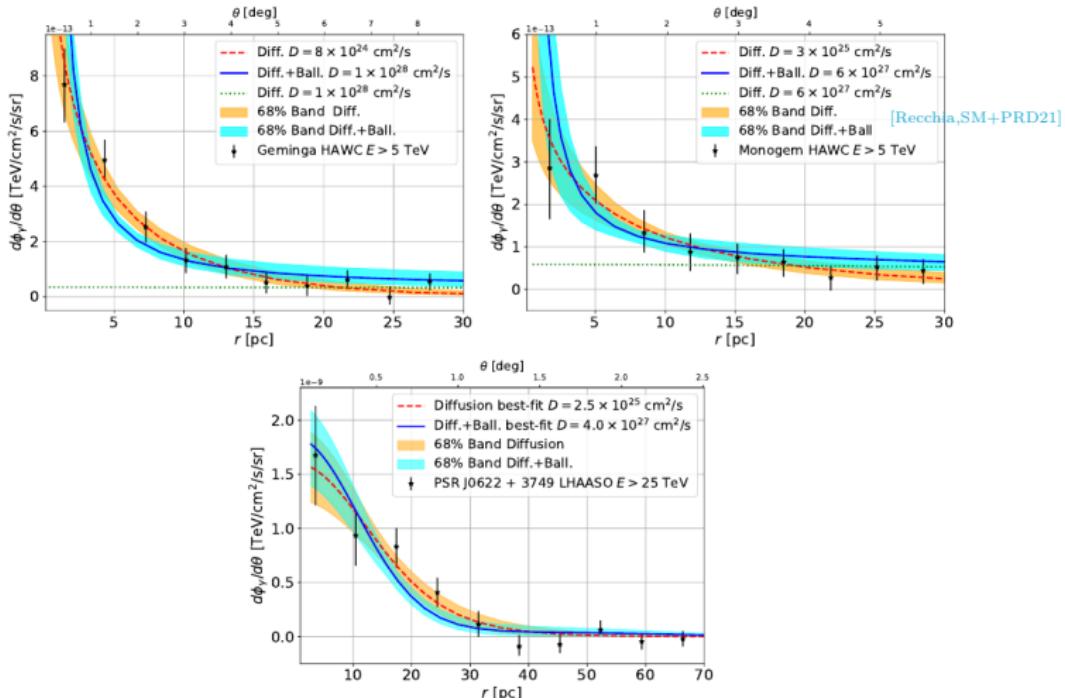
[D'Angelo+MNRAS18]



- Mechanism works
- Not enough to suppress diffusion Geminga angular+temporal scales
- Error in damping term?

- Correct error in [Evoli+PRD18]
- 1D: enough to explain Geminga?
- 3D: additional contribution from supernova remnant needed...

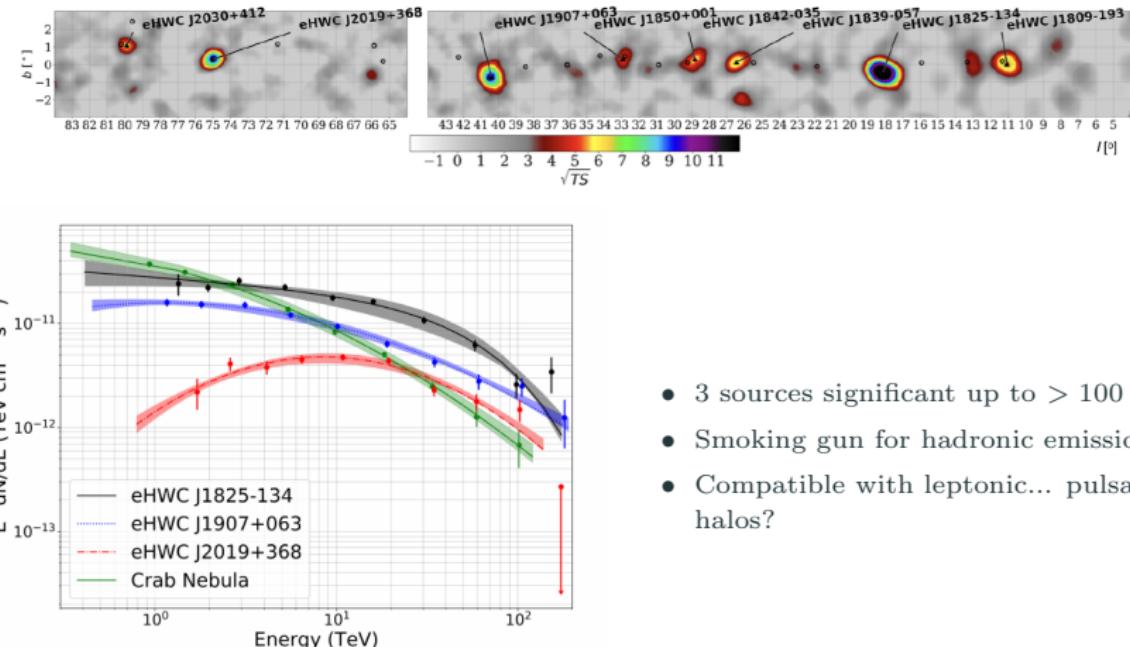
Surface brightness fit with model II



- Conversion efficiencies are higher, but $< 100\%$ for 2/3 sources [Recchia,SM+PRD21,Bao+21]
- Compact halo does not necessarily imply suppressed diffusion**

Highest gamma-ray sky: HAWC at $E > 56 - 100$ TeV

[HAWC PRL 20]

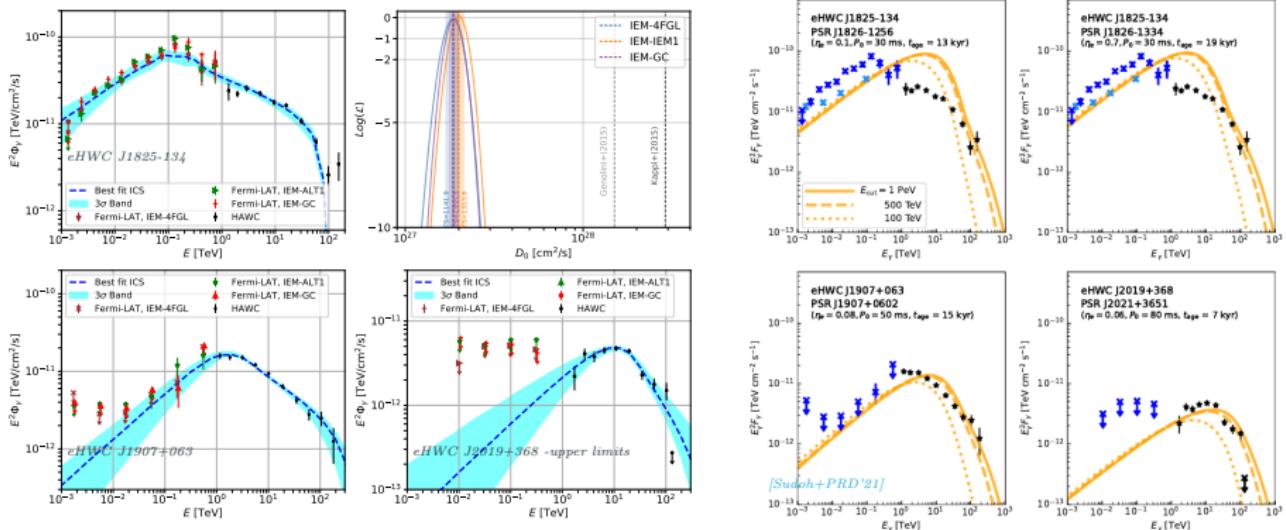


- 3 sources significant up to > 100 TeV
- Smoking gun for hadronic emission?
- Compatible with leptonic... pulsar halos?

Counterparts in Fermi-LAT

Search performed using suppressed-diffusion templates [DiMauro,SM+PRD21]

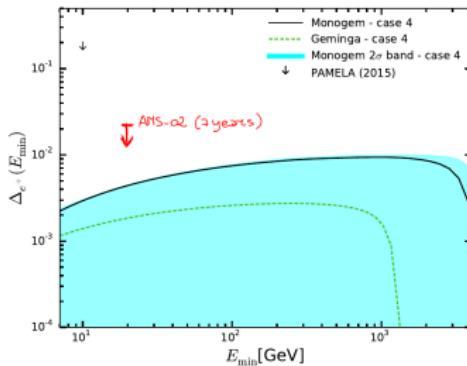
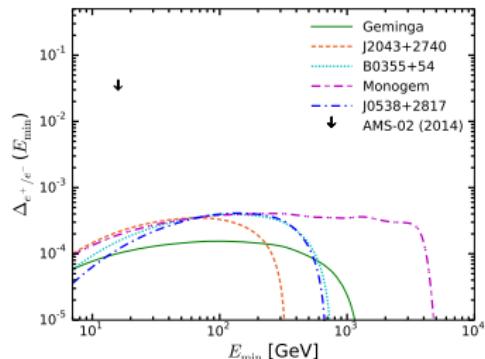
PSR name	l	b	d	T	\dot{E}	HAWC source	θ_{68} at $E > 56$ TeV	θ_{68} at $E = 10$ GeV
	[deg]	[deg]	[kpc]	[kyr]	[erg / s]		[deg]	[deg]
J1826-1334	18.00	0.69	3.61	21.4	$2.8 \cdot 10^{36}$	eHWC J1825-134	0.36 ± 0.05	0.50
J1907+0602	40.18	-0.89	2.37	19.5	$2.8 \cdot 10^{36}$	eHWC J1907+063	0.52 ± 0.09	0.65
J2021+3651	75.22	0.11	1.8	17	$3.4 \cdot 10^{36}$	eHWC J2019+368	0.20 ± 0.05	0.23



GeV-TeV compatible with leptonic emission from halos, but young pulsars

Dipole anisotropy: e^+ upper limits vs. pulsar models

Using fit to AMS-02 data from [Manconi et al., JCAP (2017)]



- Maximum e^+ dipole from five most powerful (W_0) pulsars is largely below upper limits
- Similar results also if Monogem, Geminga are considered as only pulsars to account for e^+ data