Pulsars: The Missing Piece of the Puzzle in Explaining various outstanding Astrophysical Excesses

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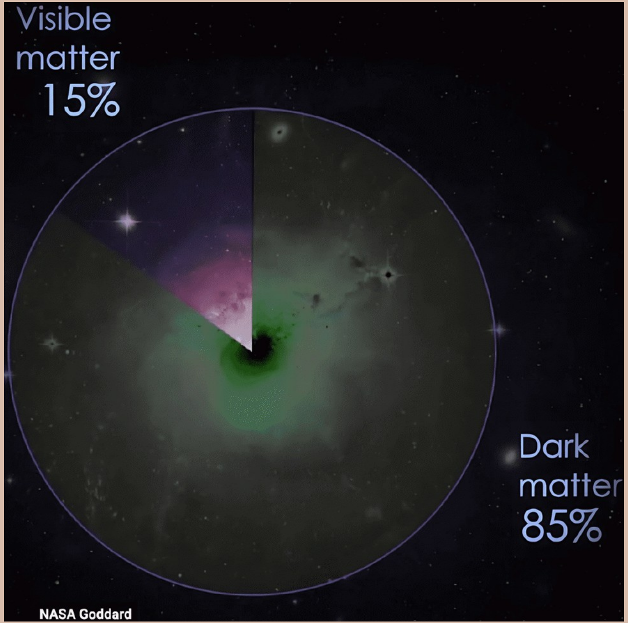
CEA - Saclay

April 3, 2023

GRAPPA

GRavitation AstroParticle Physics Amsterdam

What is the nature of dark matter?



- **What is it made of?** e.g a new particle? Ancient black holes?
- Does it **interact** with ordinary particles? If so how?

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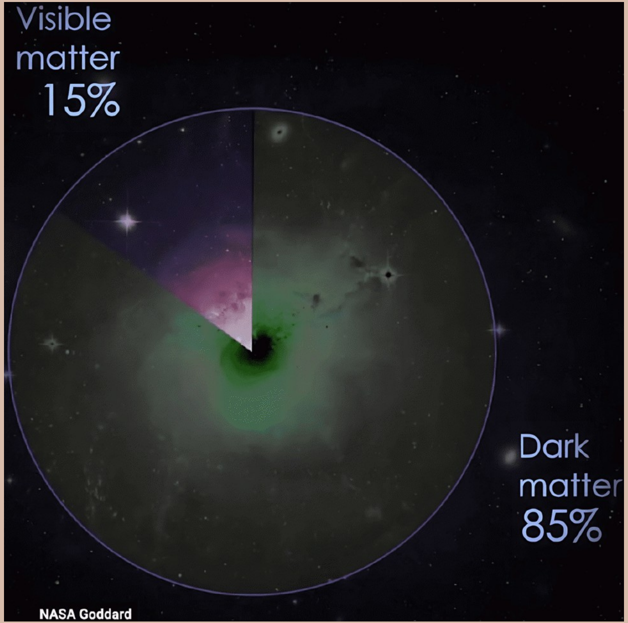

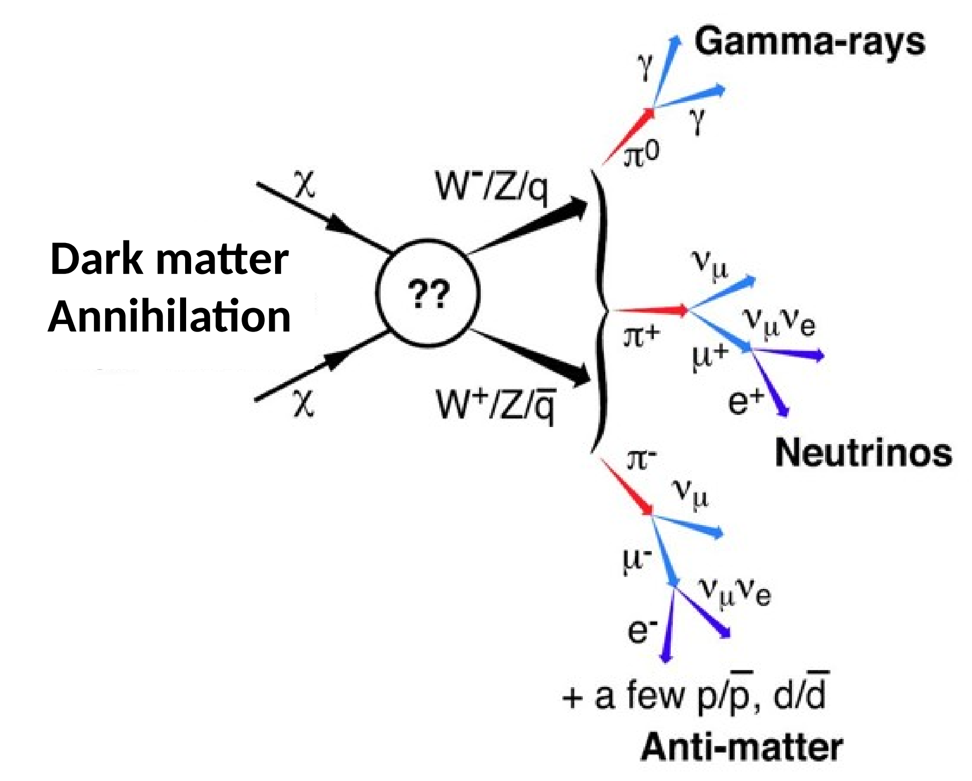

Credit: NASA

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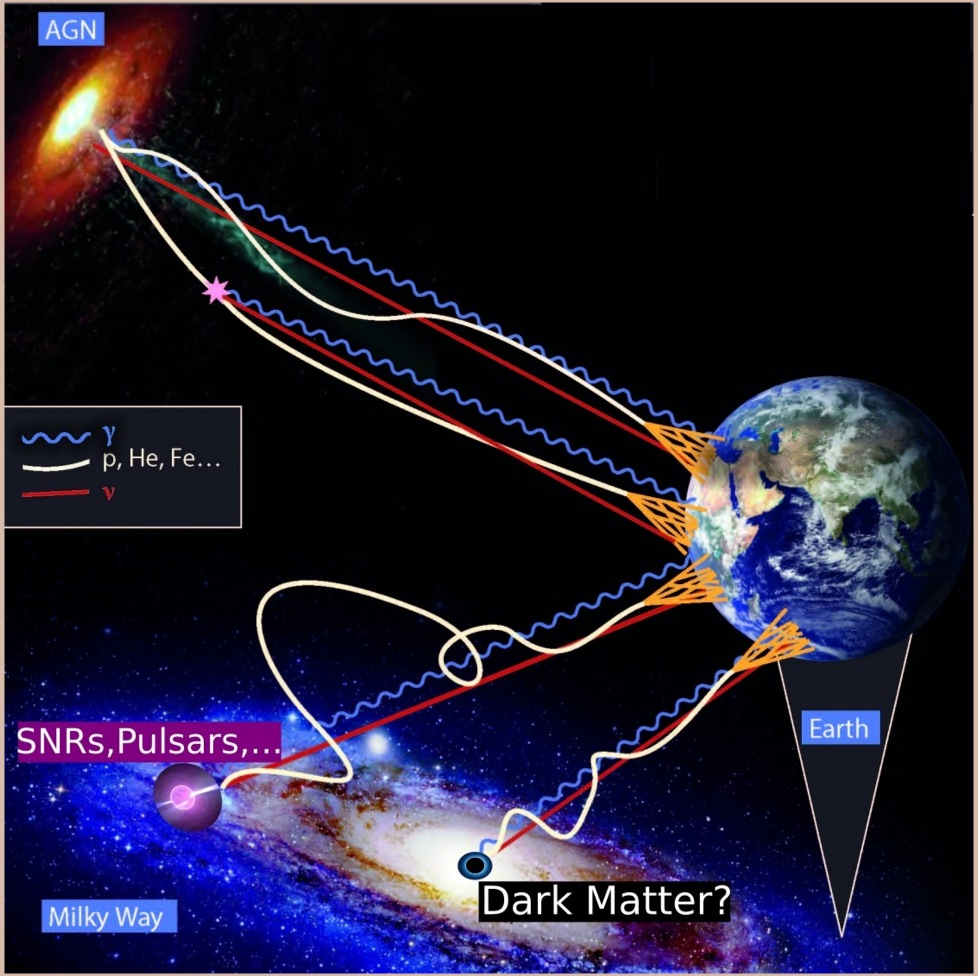
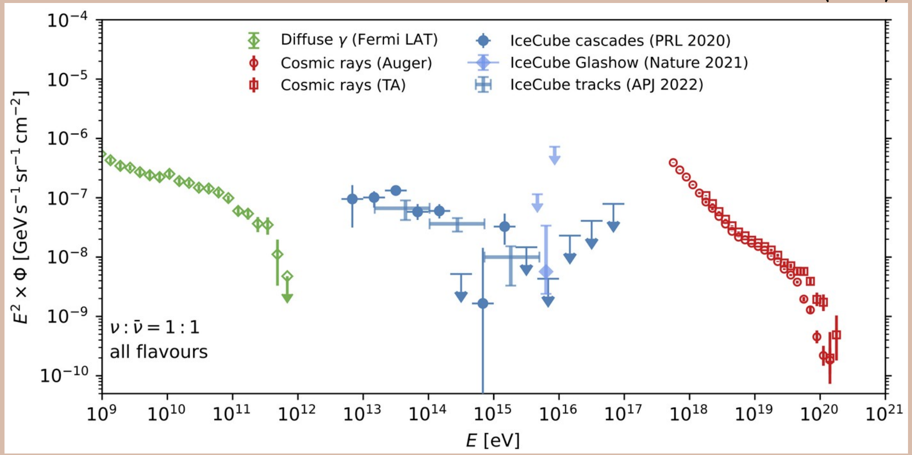
- Does it **interact** with ordinary particles? If so how?

Hidden signals of dark matter in multi-messenger data?



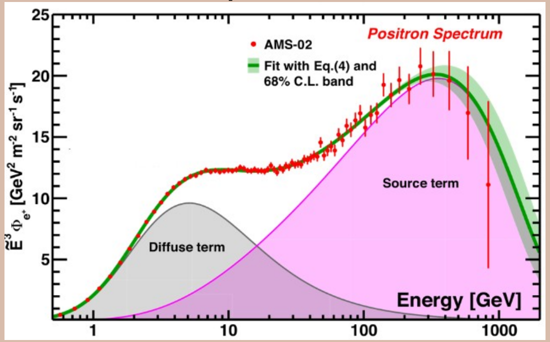
Ackermann et al. (2022)



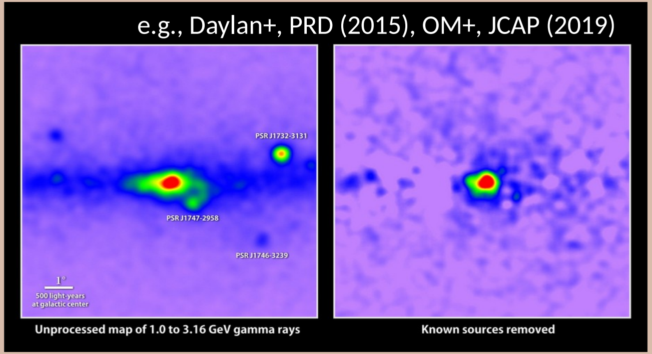
- Study gamma rays, neutrinos, cosmic rays to understand the nature of astrophysical particle accelerators (AGN, SNRs, pulsars, GRBs, ...)

Many Unsolved Astrophysical Puzzles

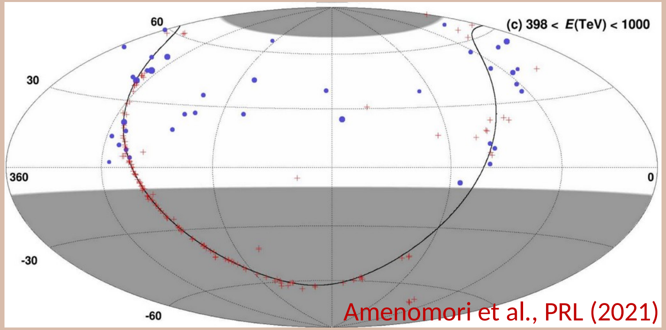
AMS-02 positron excess



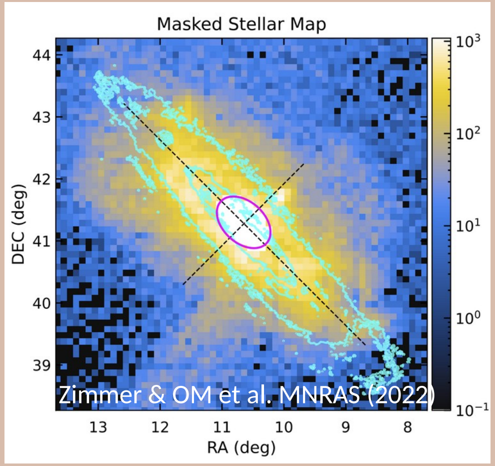
Fermi GeV excess in the Galactic center



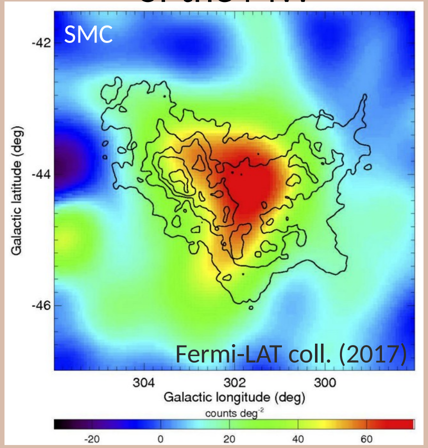
Tibet AS-gamma sub-PeV gamma-ray excess



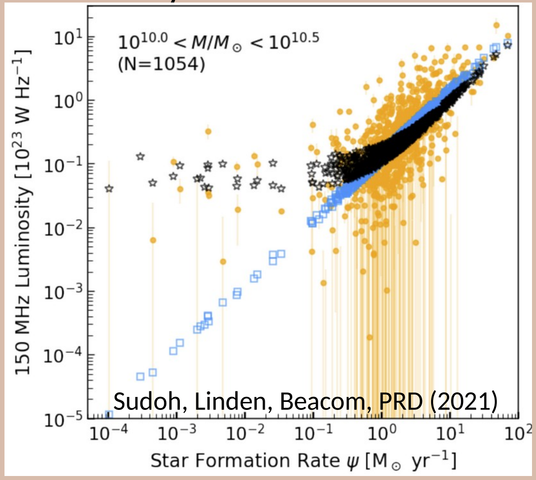
Gamma-ray excess in Andromeda



Excess gamma rays in satellites of the MW



Synchrotron excess



Pulsars: Extreme and Mysterious Particle Accelerators

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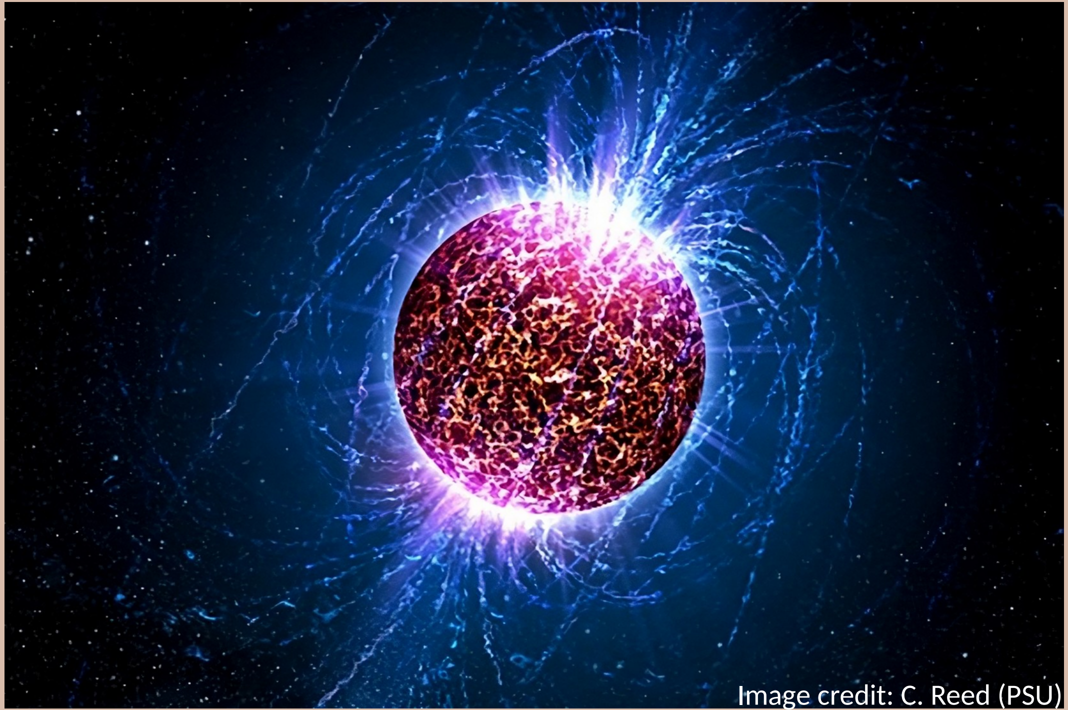


Image credit: C. Reed (PSU)

★ Mass $\approx 1.4\ M_\odot$

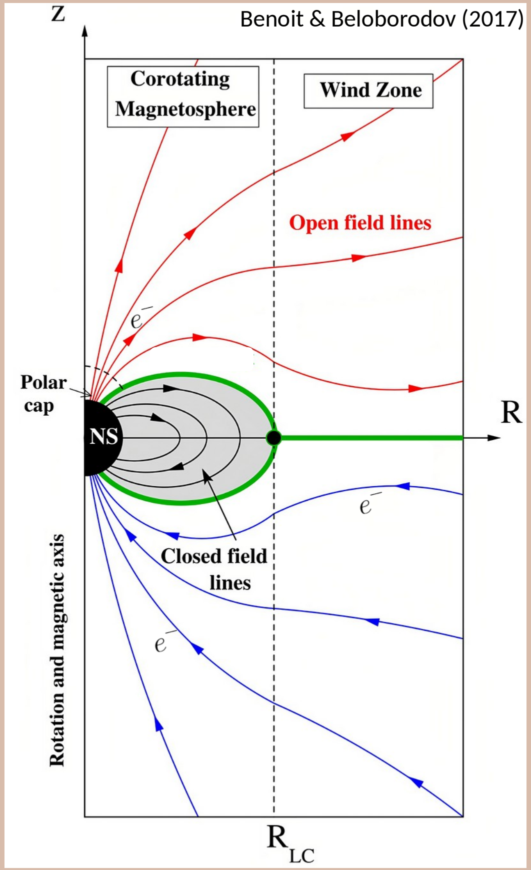
★ Magnetic field $\approx 10^8 - 10^{15}$ G

★ Size $\approx 10 - 13$ km

★ Rotational Periods: from a few milliseconds to seconds

➡ Pulsars convert their spin-down power to high-energy radiation, making them efficient particle accelerators.

Acceleration of Electrons and Positrons by Pulsars



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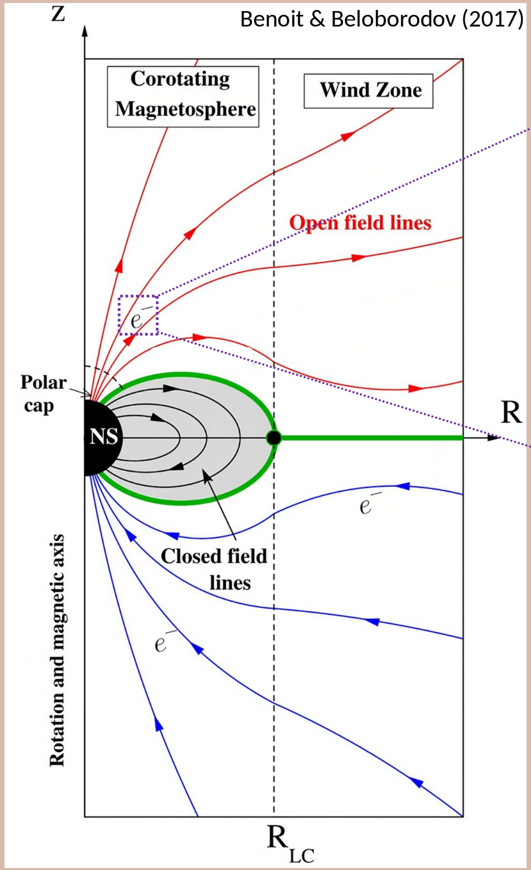
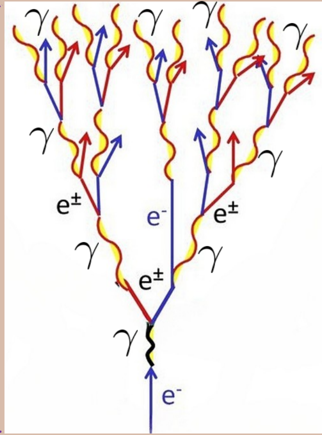


Prompt gamma radiation



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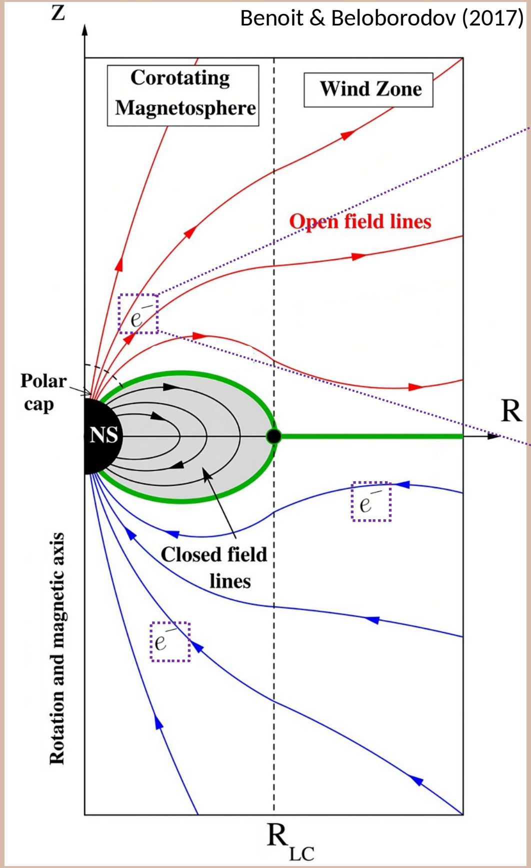

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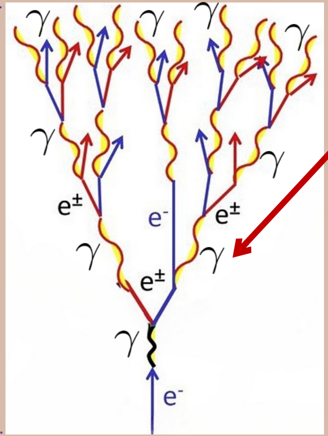

electron/positron pair creation

$$\mathbf{B} + \gamma \longrightarrow e^- + e^+$$

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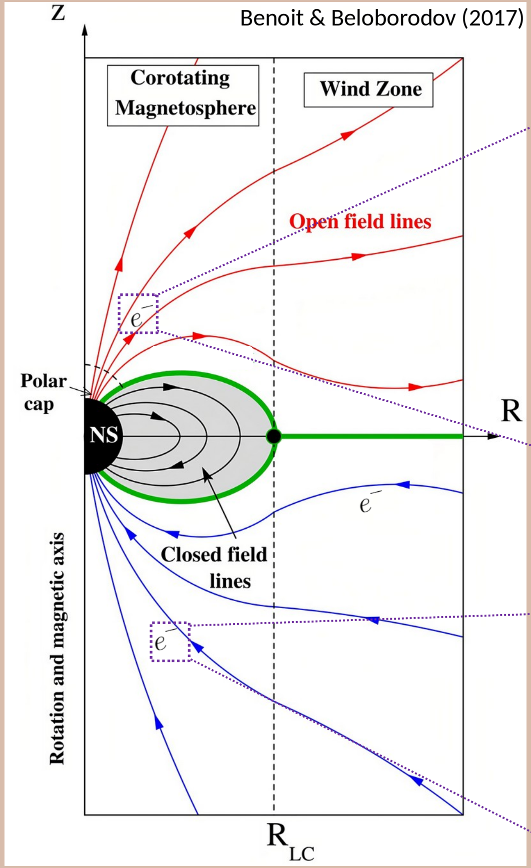
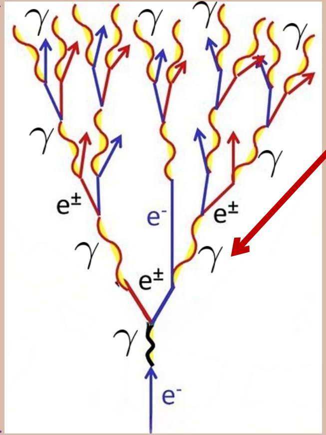


Benoit & Beloborodov (2017)

Prompt gamma radiation



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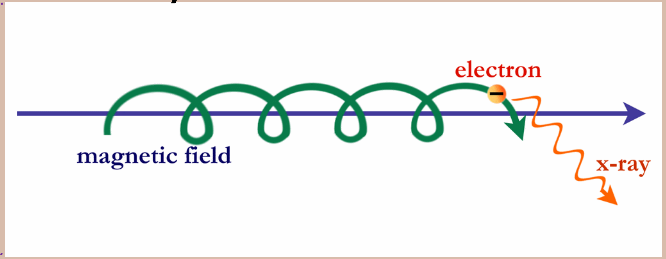

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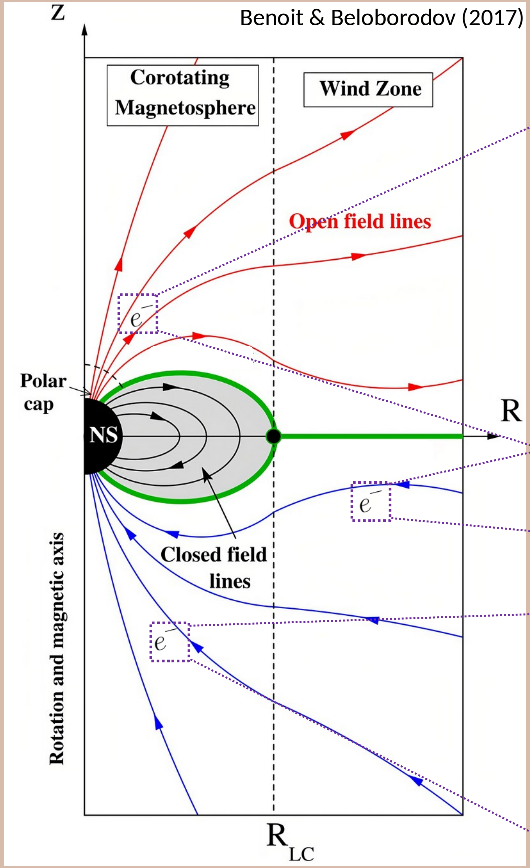

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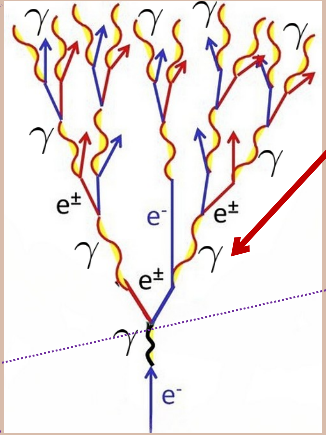

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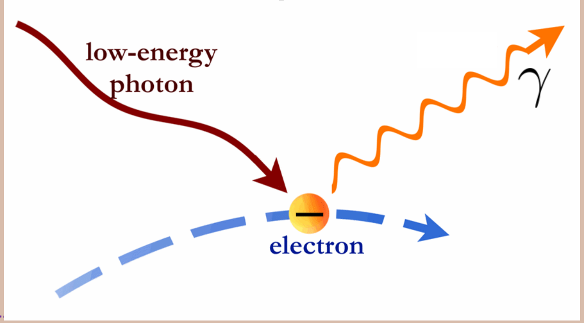
Inverse Compton radiation



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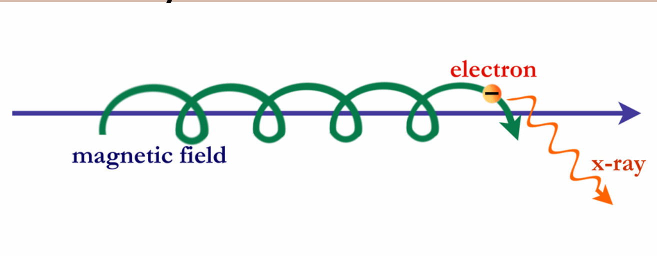
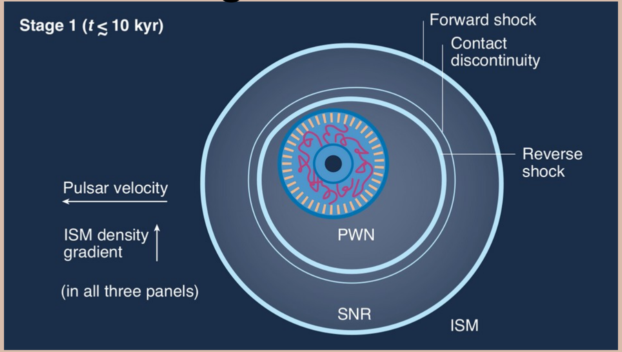


Copious production of electron/positron pairs and multi-wavelength radiation

Pulsar Evolution

Stage 1 $(t \lesssim 10 \text{ kyr})$



- Free expansion of the Pulsar Wind Nebula (PWN).
- PWNe are the most abundant class of candidates in the Galactic plane.
- Strong gamma-ray emission expected.

Lopez-Coto et al. Nature Astr. (2022)

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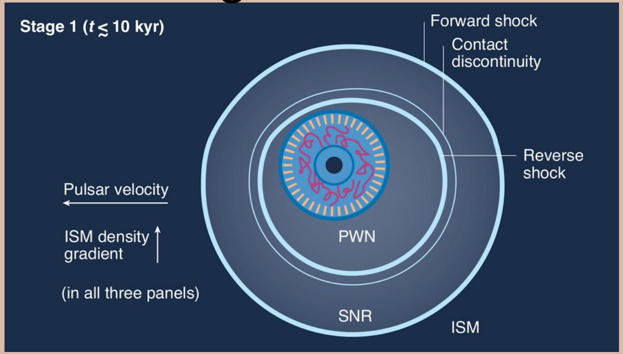
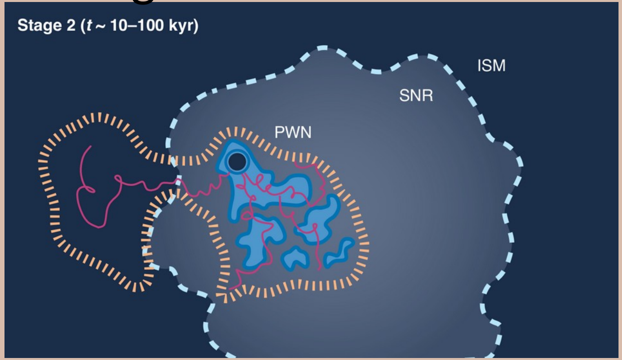


Stage 2 $(t \sim 10 - 100\ \mathrm{kyr})$



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- PWN interacts with the turbulent plasma left behind by SN explosion.
- Observed relic bubbles dim in X rays and bright in gamma rays.
- Expected emission of high-energy protons, neutrinos, electrons, positrons, and photons.

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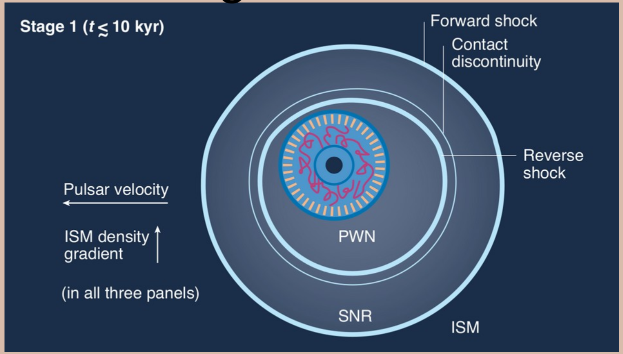

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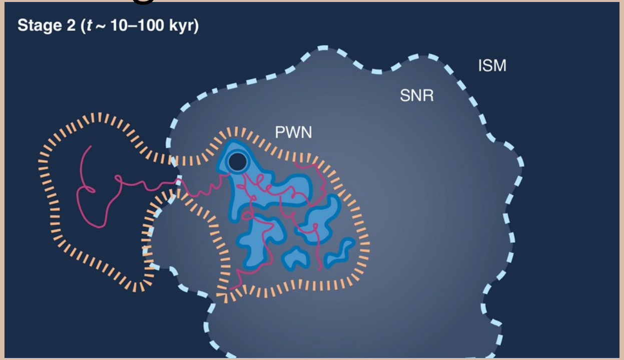

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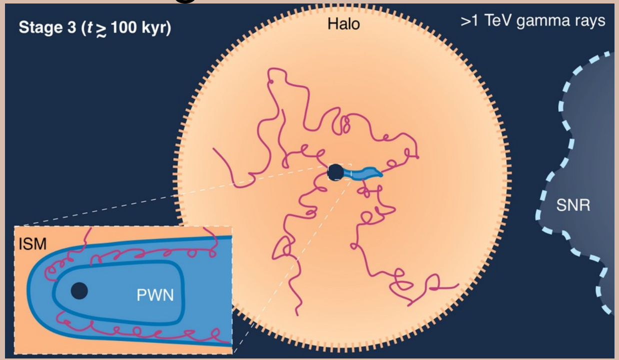
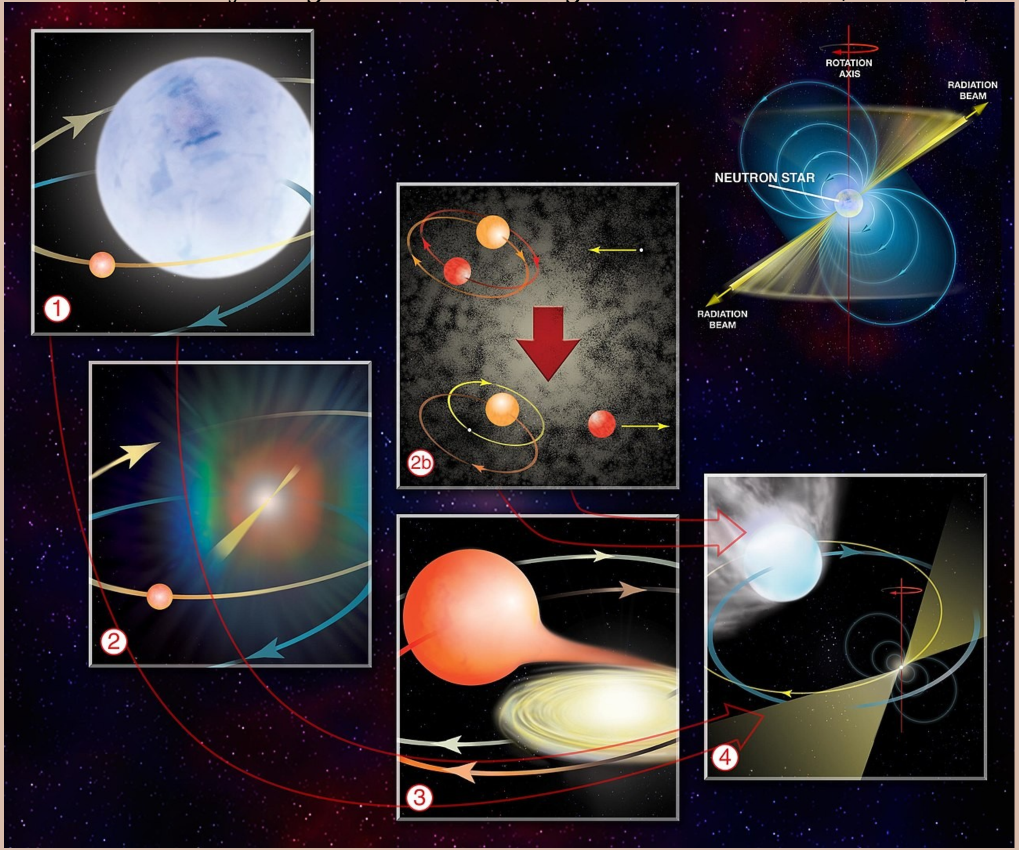


- Pulsar leaves its parent supernova.
- Powerful sources of electrons and positrons.
- Observed large energetic gamma-ray halos.

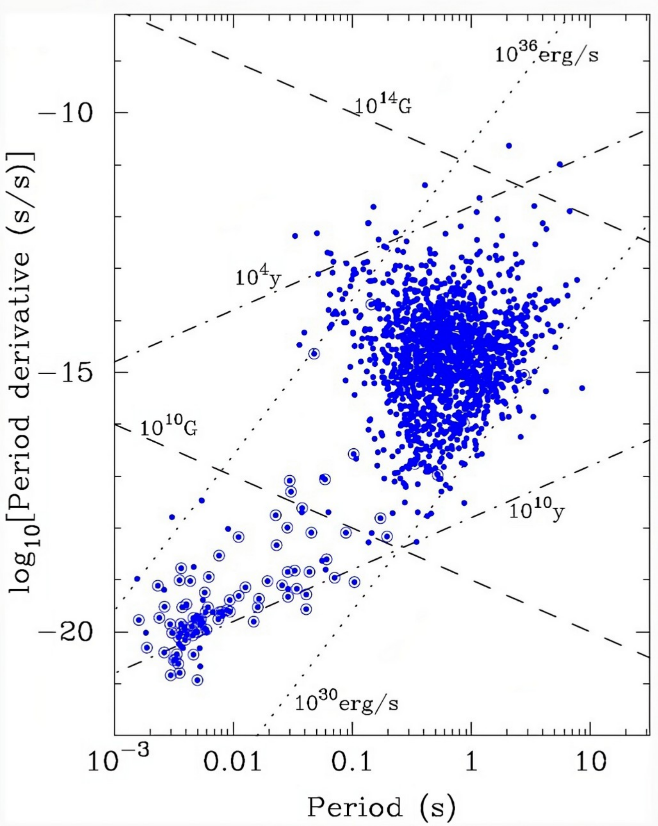
opez-Coto et al. Nature Astr. (2022)

Millisecond Pulsars

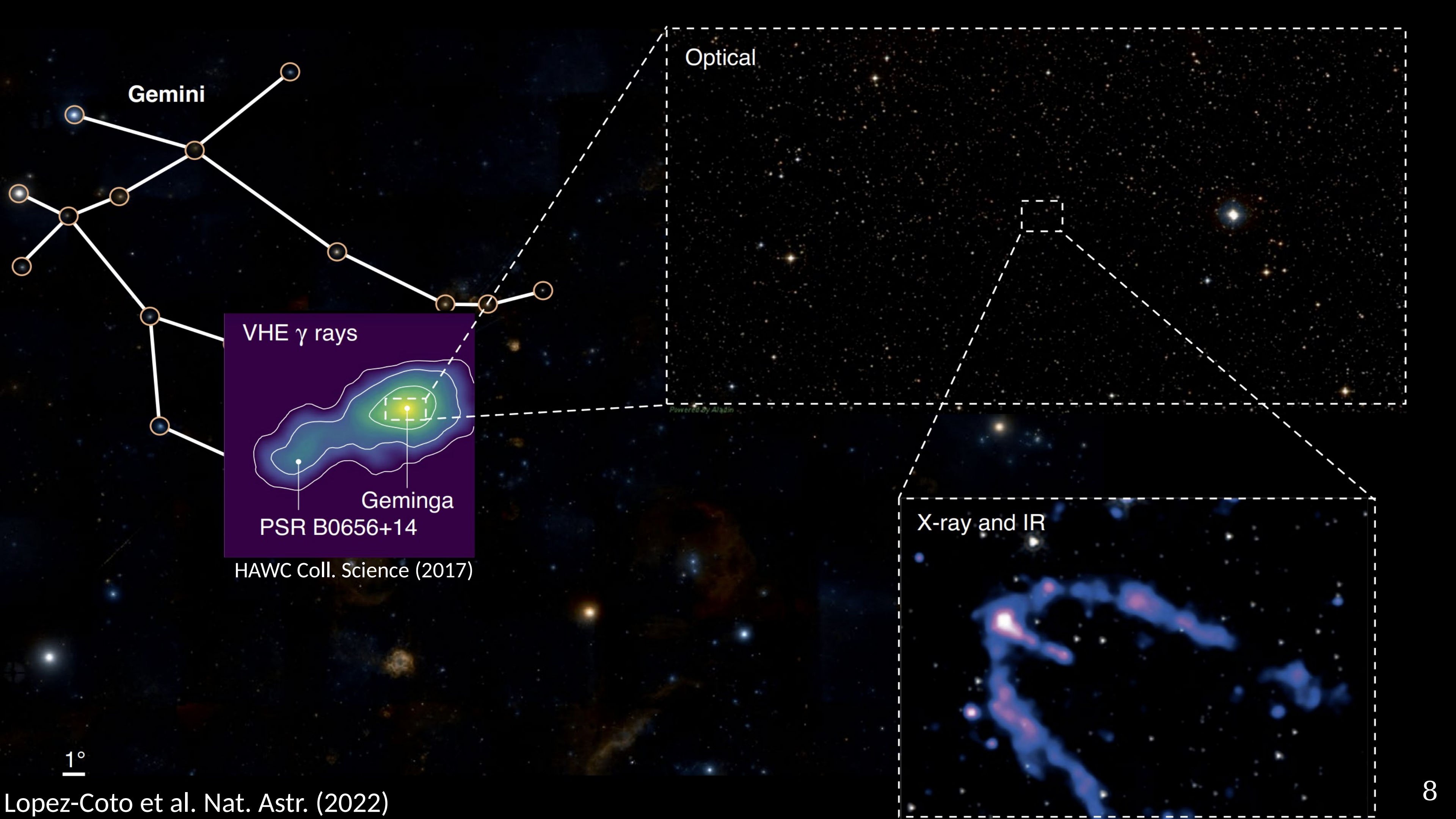
Pulsar Recycling Scenario (Image credit: Saxton, NRAO)



Lorimer (2008)

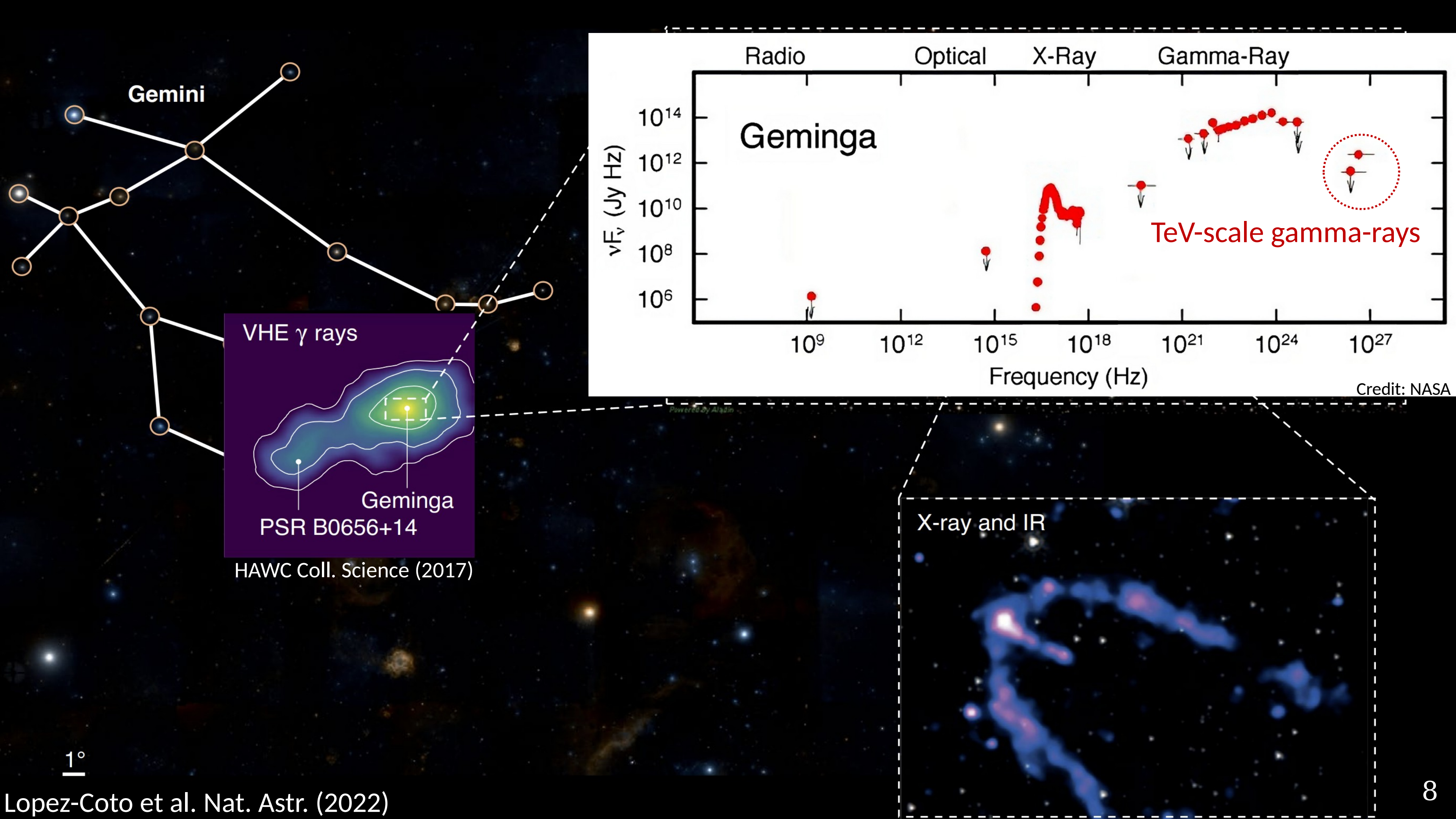


MSPs have low magnetic fields, but high and stable spin-down power



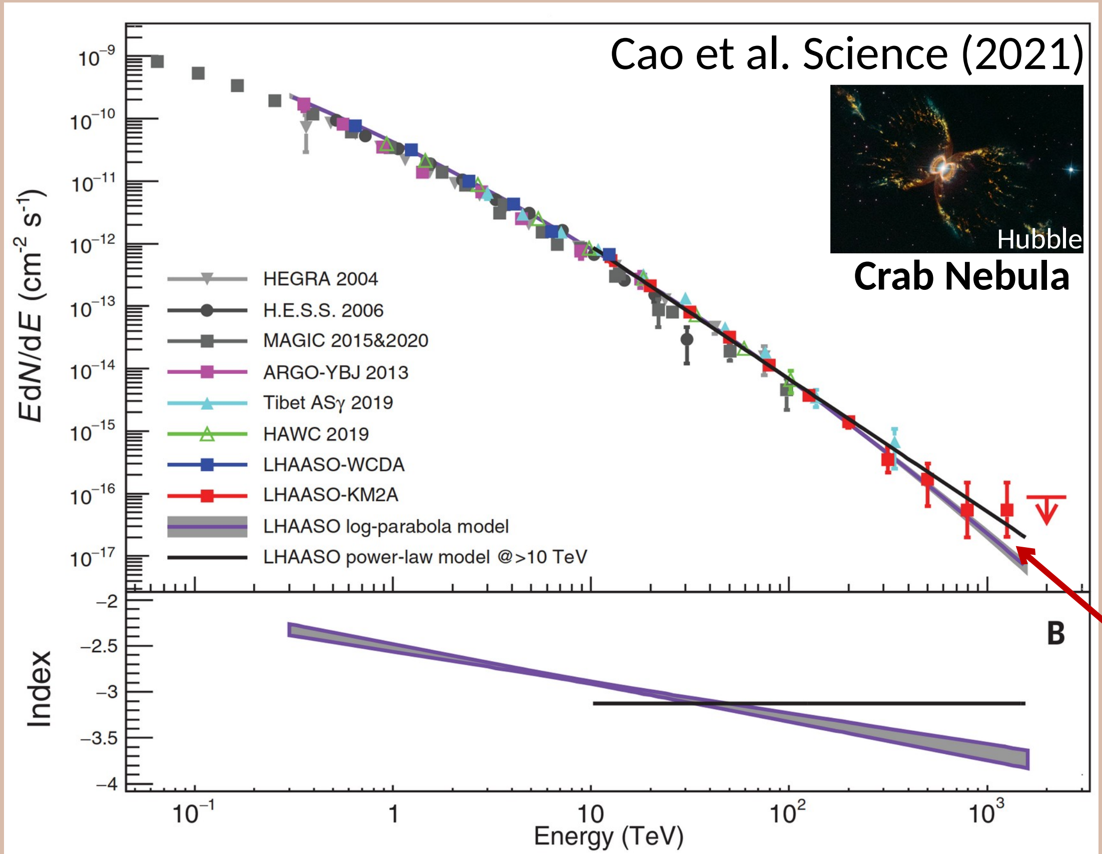
HAWC Coll. Science (2017)

Lopez-Coto et al. Nat. Astr. (2022)

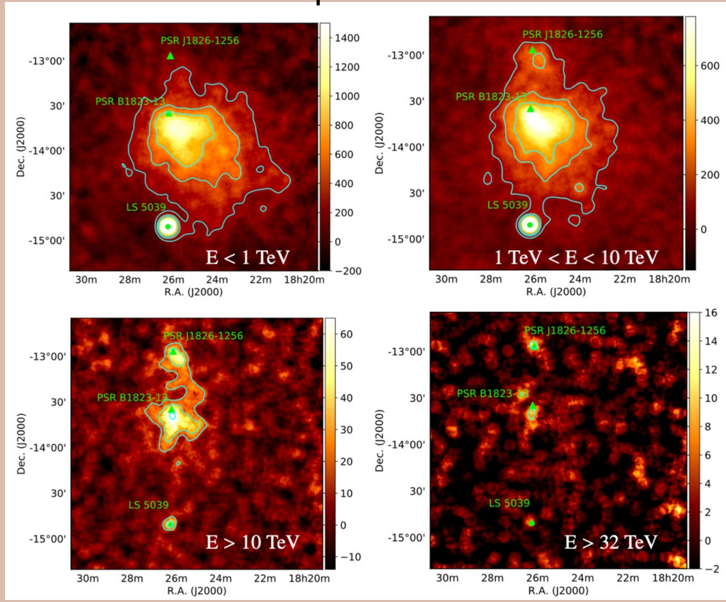


Lopez-Coto et al. Nat. Astr. (2022)

Pulsars: Confirmed **PeVatrons** of the Milky Way



Spatial Morphology of the Crab Pulsar is energy dependent

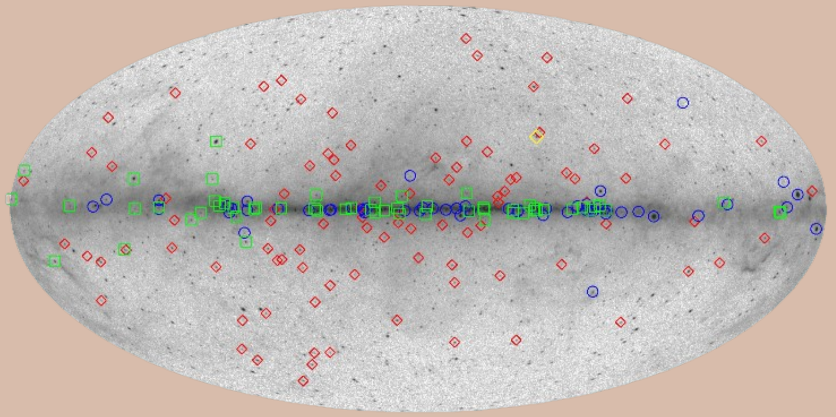


H.E.S.S. 2006

Measurement of photons with
$\approx 1\,\mathrm{PeV} = 10^{15}\,\mathrm{eV}$
of energy

Mechanism: Inverse Compton on 2.7 K CMB photons. **Direct relation** $\mathrm{E_e} \simeq 2.15\,(\mathrm{E}_\gamma/1\mathrm{PeV})^{0.77}\,\mathrm{PeV}$

Pulsars: An Abundant Class of Astrophysical Accelerators

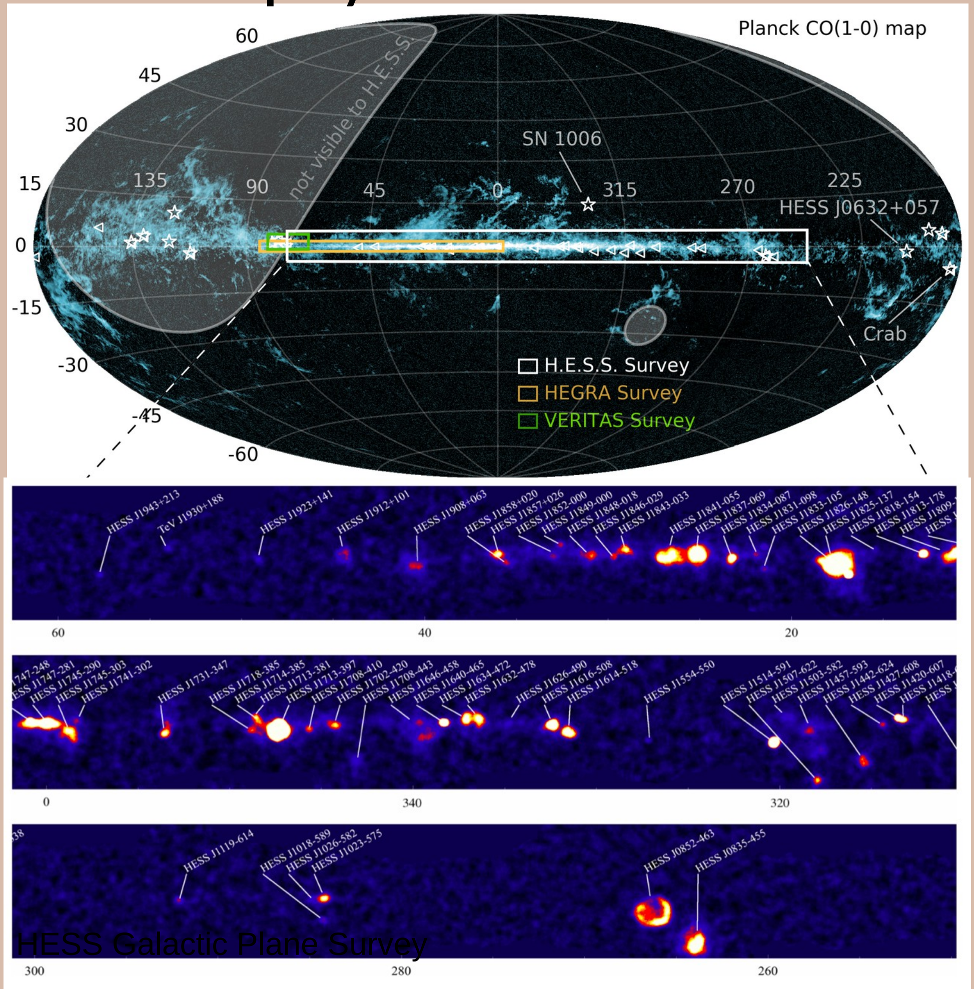


Fermi-LAT Third Pulsar Catalog (2021)

★ 144 young/middle-aged pulsars (29% radio-loud and 25% radio-quiet). 126 millisecond pulsars.

★ Pulsar Wind Nebulae are the most abundant class of sources for E>100 GeV.

★ Pulsars are a very important source of background for dark matter searches.



HESS Galactic Plane Survey

Puzzling Astrophysical Excesses

The Fermi GeV Excess

Goodenough & Hooper (2009)
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Abazajian & Kaplinghat (2012)
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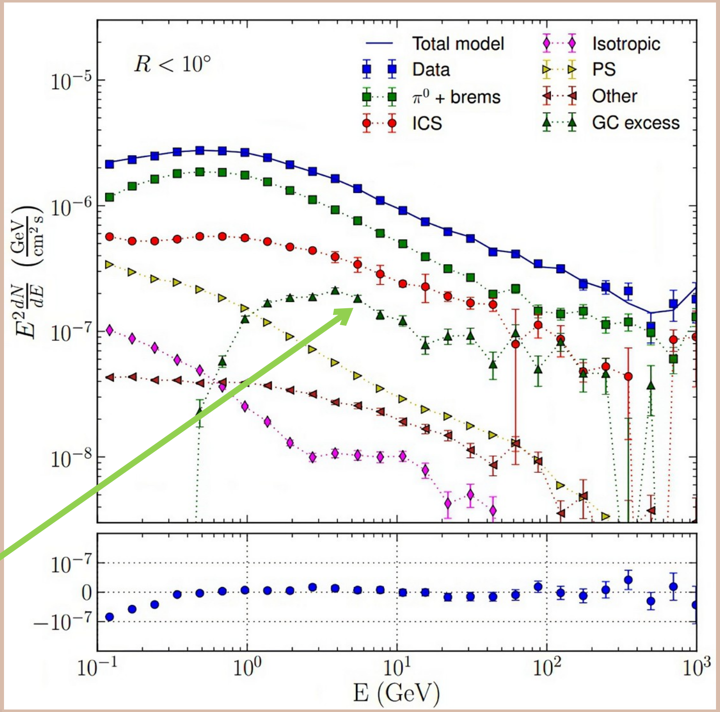
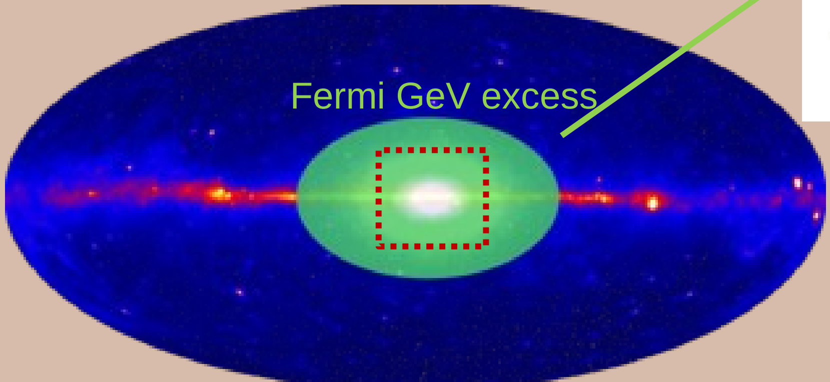
Daylan et al (2014)
Selig et al (2015)
Huang et al (2015)
Gaggero et al (2015)
Carlson et al (2015, 2016)
de Boer et al (2016)
Yang & Aharonian (2016)
Fermi Coll. (2016)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Macias et al (2018)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
Macias et al (2019)
Buschmann et al (2020)
Leane & Slatyer (2020)
Abazajian et al (2020)
List et L (2020)
Di Mauro (2020)
Burns et al (2020)
Cholis et al (2022)
Pohl, Macias+(2022)



Ackermann et al. (2017)



The Fermi GeV Excess

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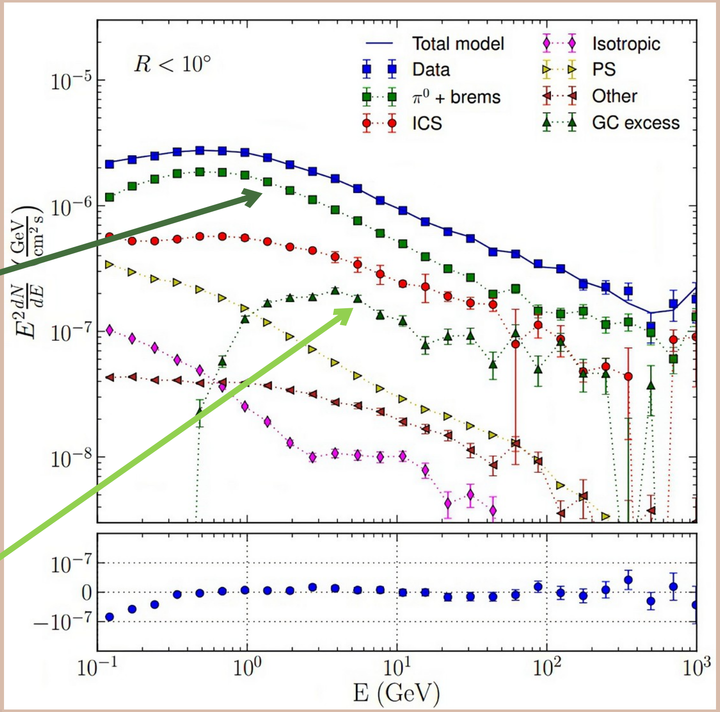
Gas-correlated gamma rays dominate in this sky region



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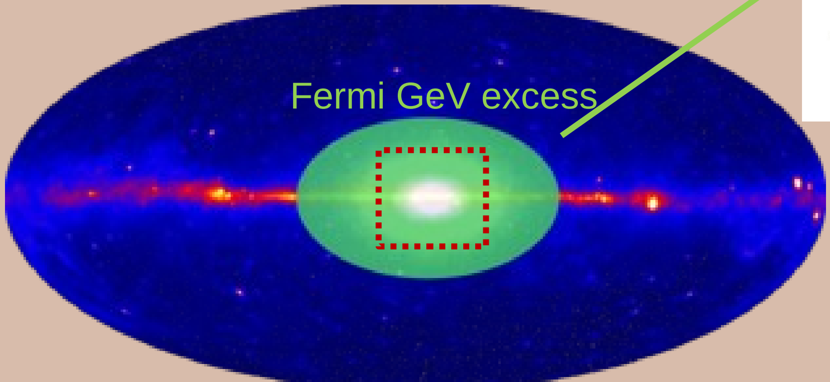
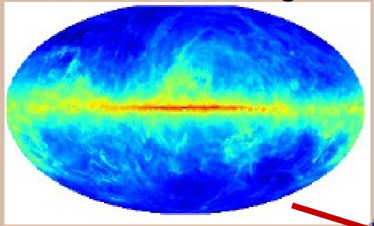
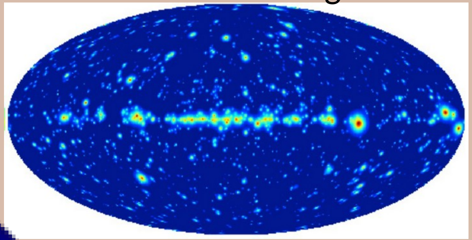


Maximum Likelihood Analysis Method Applied to Fermi Gamma Ray Data

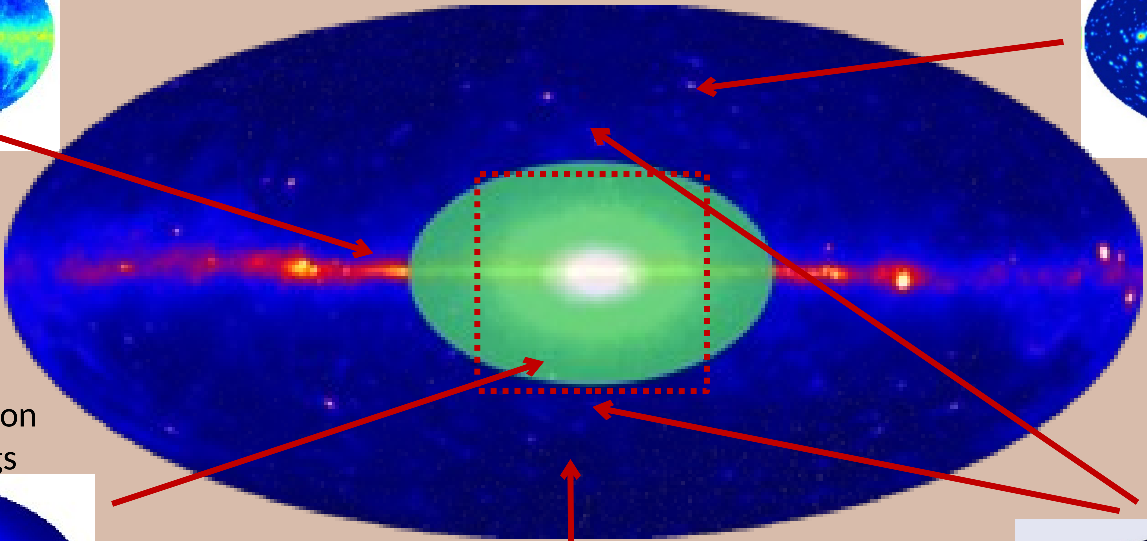
New hydrogen maps
divided in 4 rings



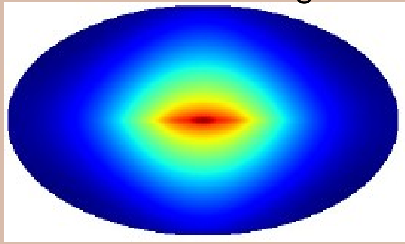
4FGL Catalog



Fermi-LAT data (inner 40x40 deg region)

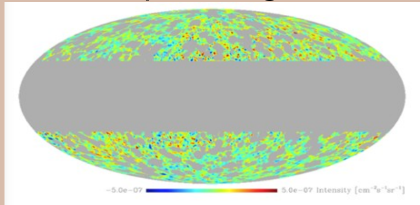


3D Inverse Compton
divided in 6 rings

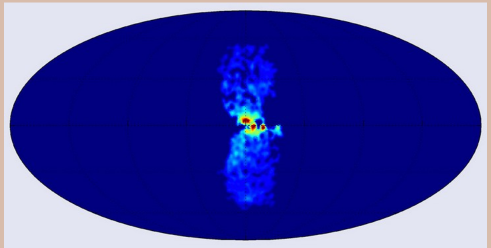


Porter et al. (2017)

Isotropic background

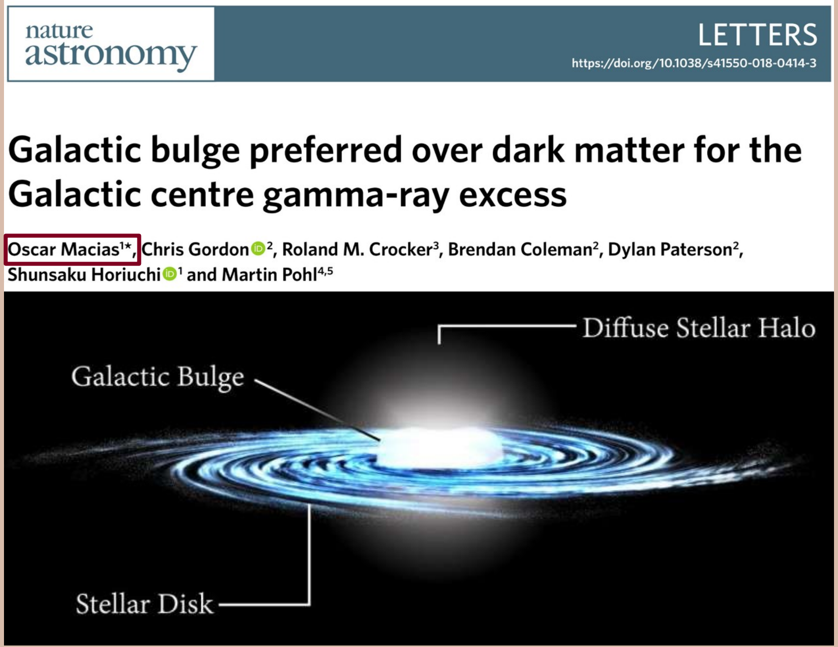


Fermi Bubbles



Result 1. Strong evidence for thousands of new Millisecond Pulsars in the Galactic bulge

(2018)


nature astronomy

LETTERS

https://doi.org/10.1038/s41550-018-0414-3

Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess

Oscar Macias[1*], Chris Gordon[2], Roland M. Crocker[3], Brendan Coleman[2], Dylan Paterson[2], Shunsaku Horiuchi[1] and Martin Pohl[4,5]

★ Statistically significant <u>correlation</u> between stellar mass and gamma rays in the Galactic bulge.

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nature astronomy
LETTERS
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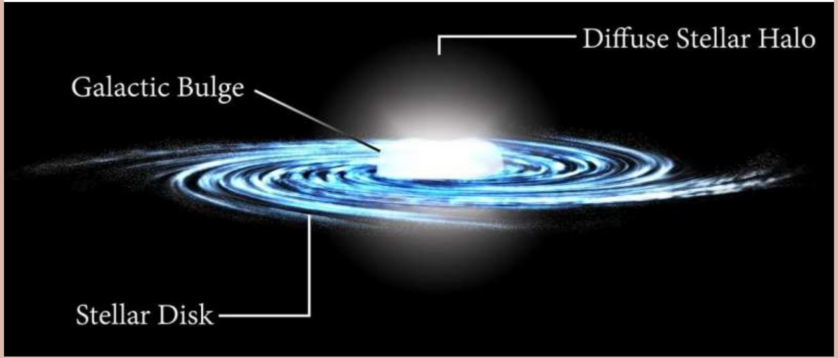
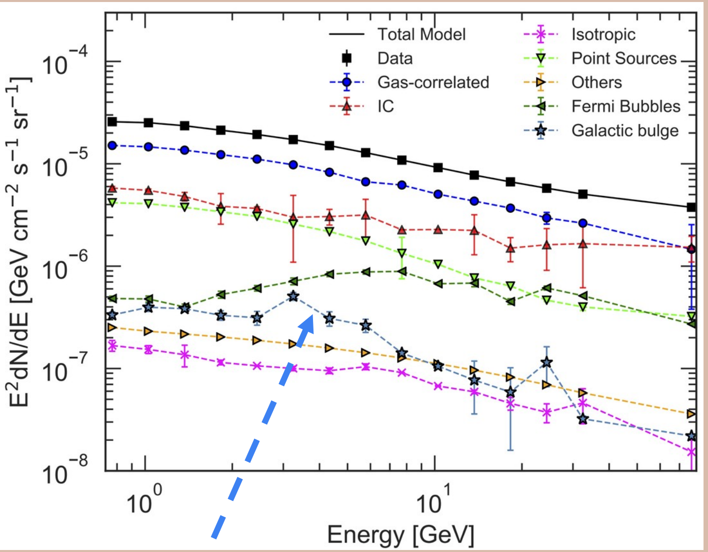
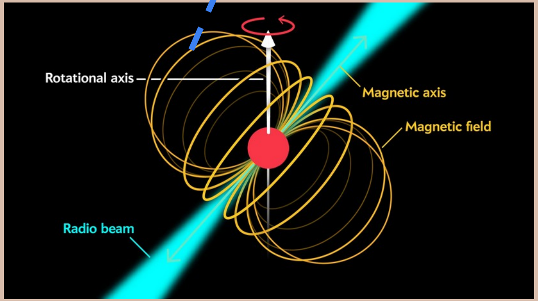






Magnetospheric MSPs emission

- ★ Statistically significant correlation between stellar mass and gamma rays in the Galactic bulge.
- ★ Spectrum consistent with magnetospheric gamma ray emission from millisecond pulsars.

Result 2. Simulated Millisecond Pulsars in the Galactic bulge consistent with all available data

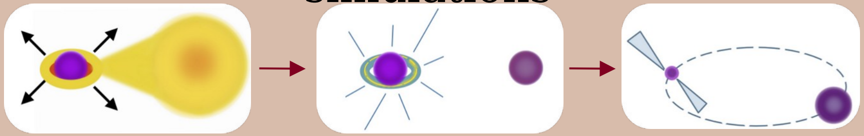
(2022)

nature astronomy
LETTERS
https://doi.org/10.1038/s41550-022-01658-3
Check for updates

Millisecond pulsars from accretion-induced collapse as the origin of the Galactic Centre gamma-ray excess signal

Anuj Gautam[1], Roland M. Crocker[1] ✉, Lilia Ferrario[2], Ashley J. Ruiter[3], Harrison Ploeg[4], Chris Gordon[4] and Oscar Macias[5,6]

Binary Population synthesis simulations



MSPs from Accretion-induced collapse naturally explain the Fermi GeV excess

Result 2. Simulated Millisecond Pulsars in the Galactic bulge consistent with all available data

(2022)

nature astronomy

LETTERS

https://doi.org/10.1038/s41550-022-01658-3

Check for updates

Millisecond pulsars from accretion-induced collapse as the origin of the Galactic Centre gamma-ray excess signal

Anuj Gautam[1], Roland M. Crocker[1]✉, Lilia Ferrario[2], Ashley J. Ruiter[3], Harrison Ploeg[4], Chris Gordon[4] and Oscar Macias[5,6]

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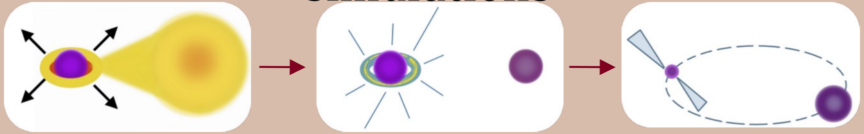

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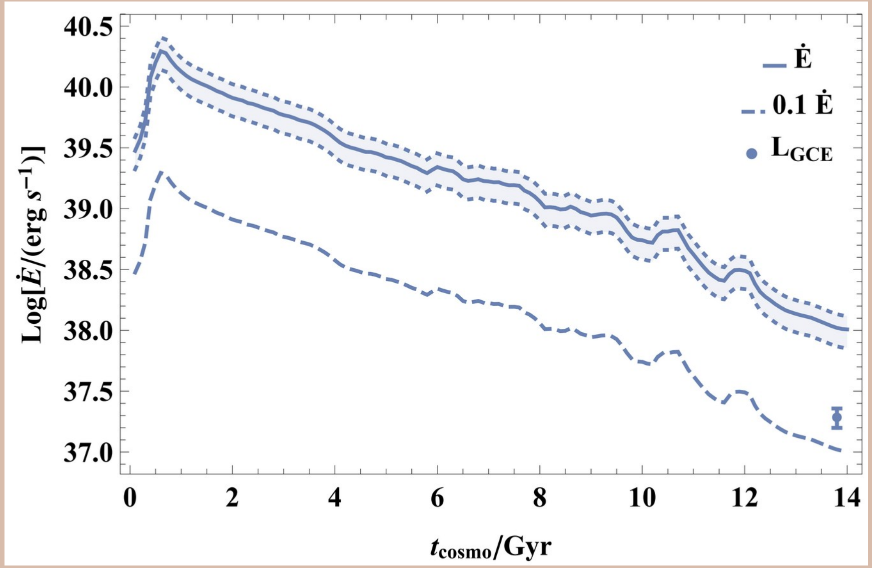
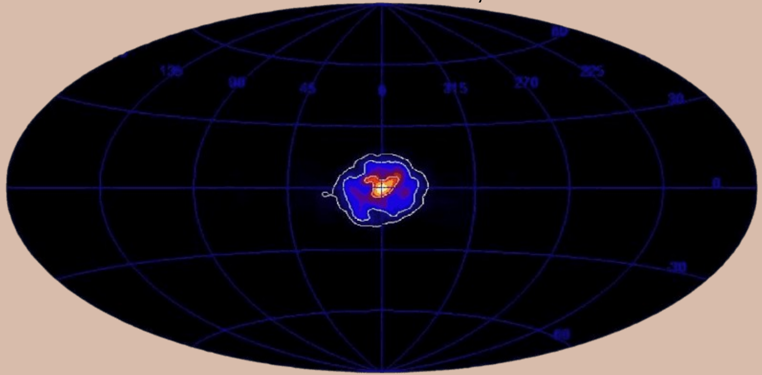


Spin-down power liberated by Galactic bulge **MSPs** over cosmological history

Result 3. 511 keV positron line excess in the Galactic center

Knodlseder et al., 2005



- ★ $\text{Bulge/Disk} \approx 1$ [Siegert+2016]
- ★ Injection of 2×10^{42} positrons/s
- ★ Guaranteed contribution from **Al** and **Ti** in core-collapse SN.

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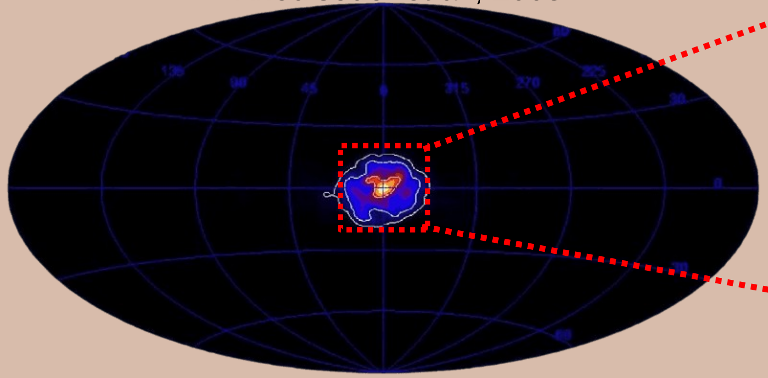
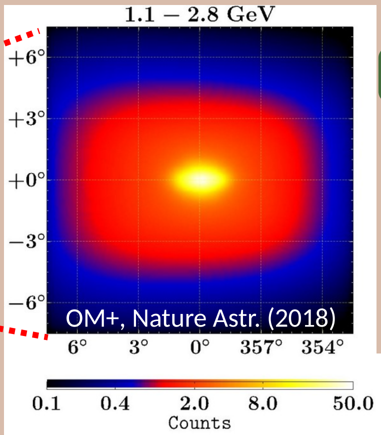
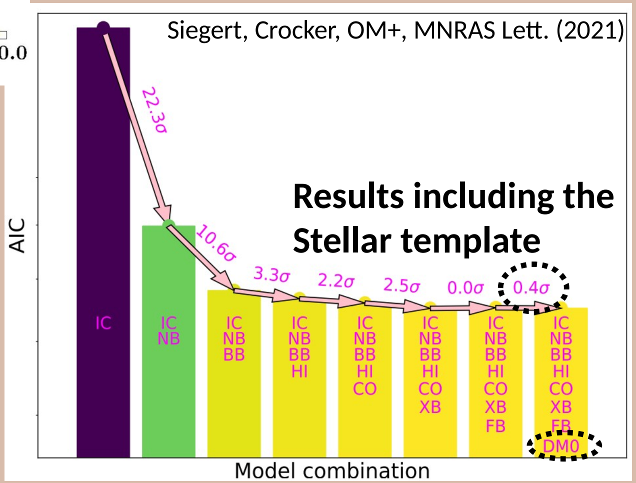




Stellar template for the Galactic bulge



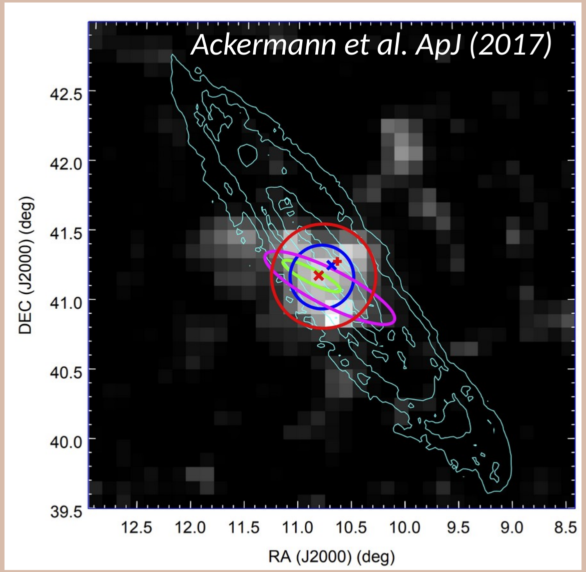
★ $\mathrm{Bulge/Disk} \approx 1$ [Siegert+2016]

★ Injection of 2×10^{42} positrons/s

★ Guaranteed contribution from **Al** and **Ti** in core-collapse SN.

Once models for the stellar bulge are included in the fits no evidence is found of dark matter emission in the Galactic center

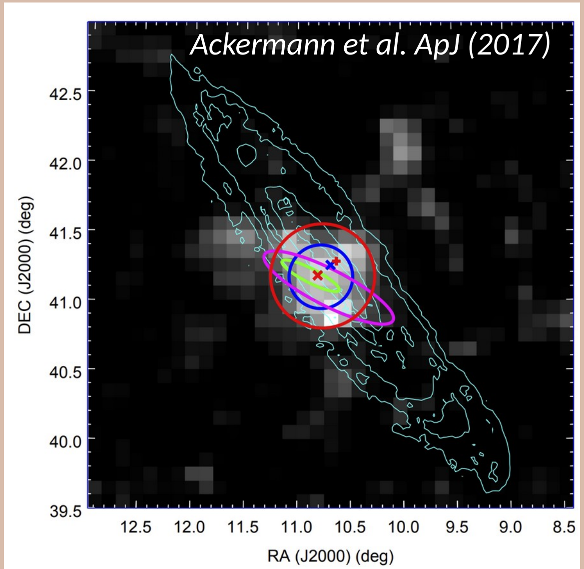
Result 4. Gamma-ray evidence for dark matter annihilations in Andromeda?

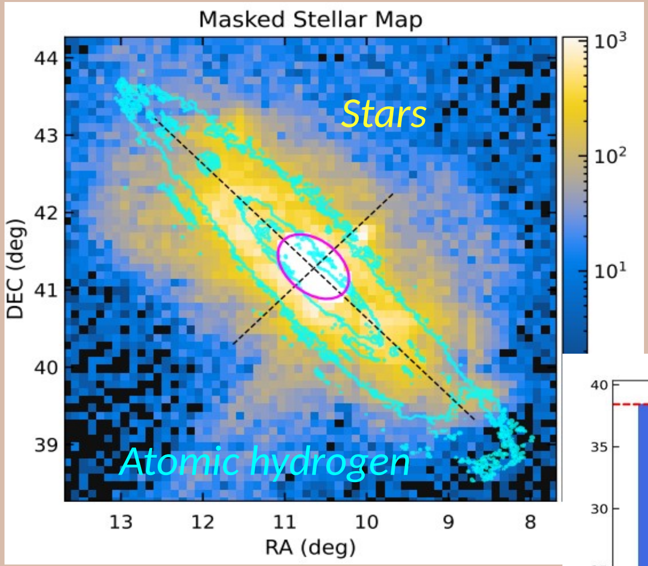


★ Detection of extended gamma-ray emission in Andromeda

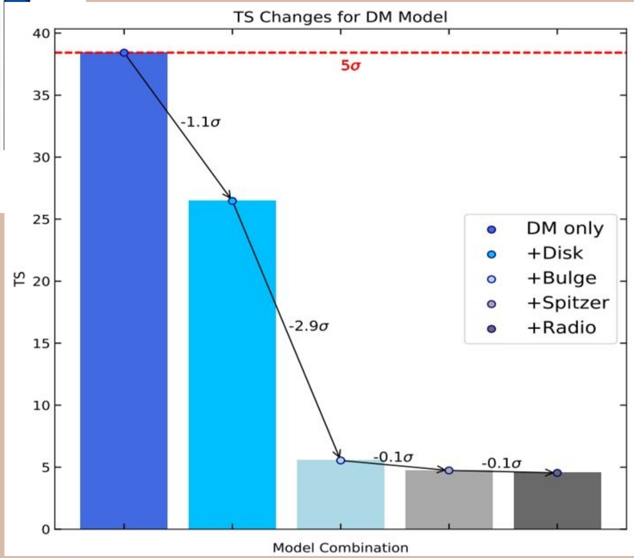
★ Excess is consistent with dark matter annihilation [Ackermann et al 2017].

Result 4. Gamma-ray evidence for dark matter annihilations in Andromeda?





*Zimmer, **OM**+, MNRAS (2022)*



★ Detection of extended gamma-ray emission in Andromeda

★ Excess is consistent with dark matter annihilation [Ackermann et al 2017].

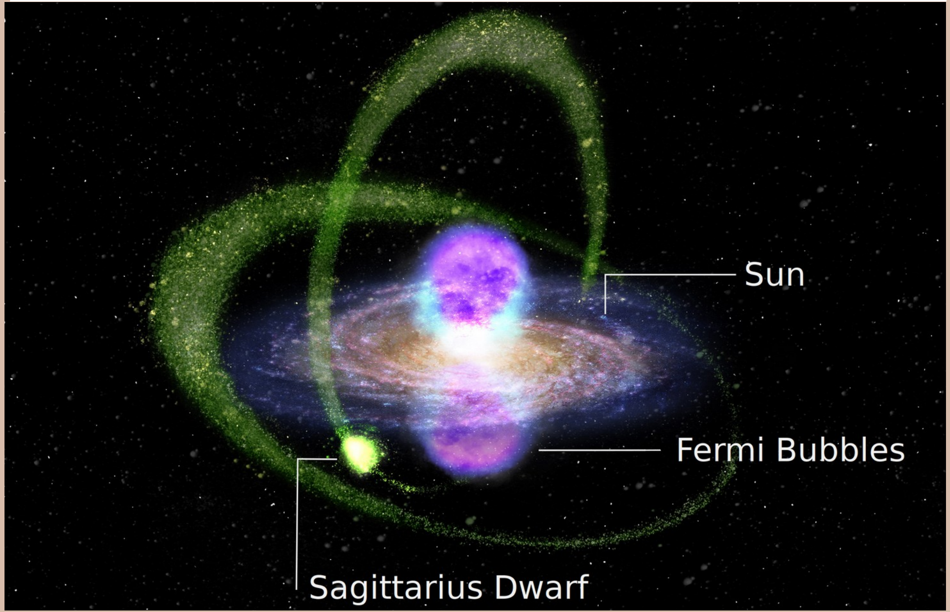
➡ No evidence for **dark matter** found once the stellar disk+bulge are included in the fit

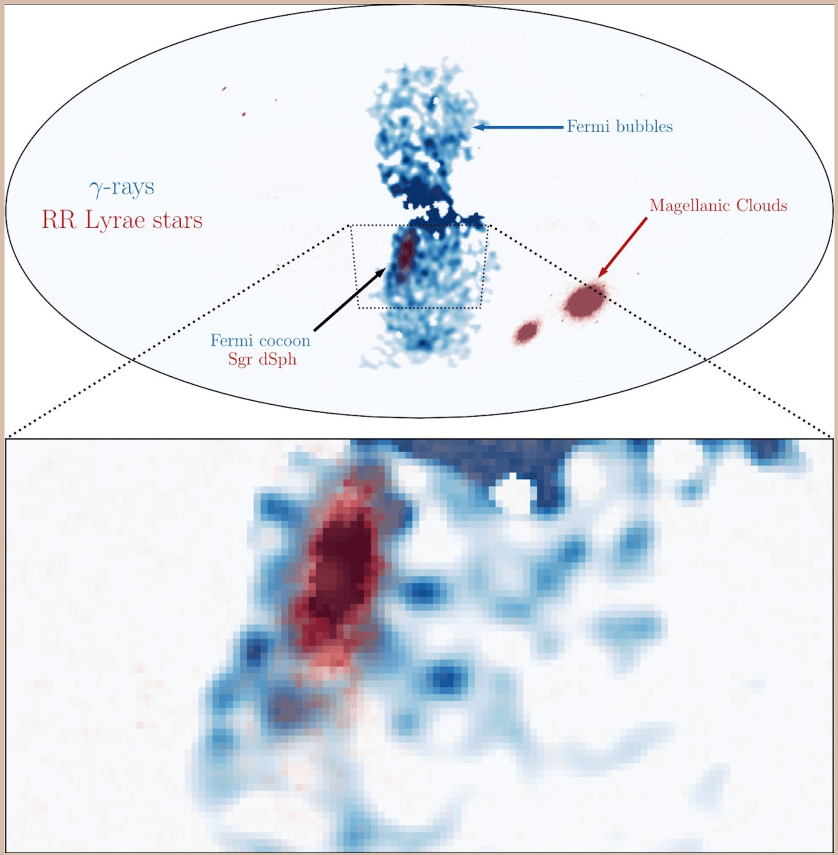
Result 5. Discovery of Extended Gamma Rays from the Sagittarius Dwarf Spheroidal

nature astronomy
ARTICLES
https://doi.org/10.1038/s41550-022-01777-x
Check for updates

Gamma-ray emission from the Sagittarius dwarf spheroidal galaxy due to millisecond pulsars

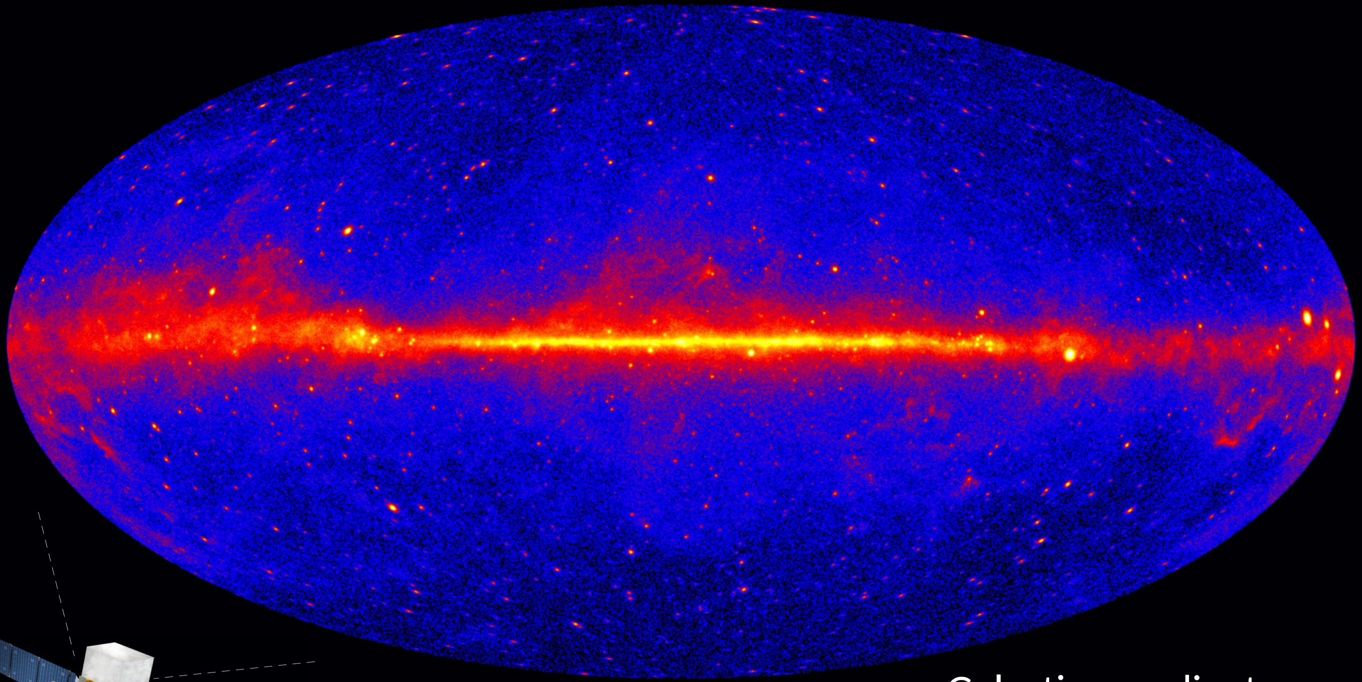
Roland M. Crocker[1,2,15] ✉, Oscar Macias[3,4,15] ✉, Dougal Mackey[1], Mark R. Krumholz[1], Shin'ichiro Ando[3,4], Shunsaku Horiuchi[4,5], Matthew G. Baring[6], Chris Gordon[7], Thomas Venville[8], Alan R. Duffy[8], Rui-Zhi Yang[9,10,11], Felix Aharonian[2,12], J. A. Hinton[2], Deheng Song[5], Ashley J. Ruiter[13] and Miroslav D. Filipović[14]



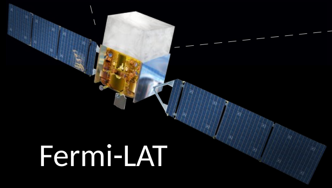


★ Fermi cocoon due to gamma rays from the Sgr dSph galaxy.

Fermi Gamma Ray Telescope All-Sky Image



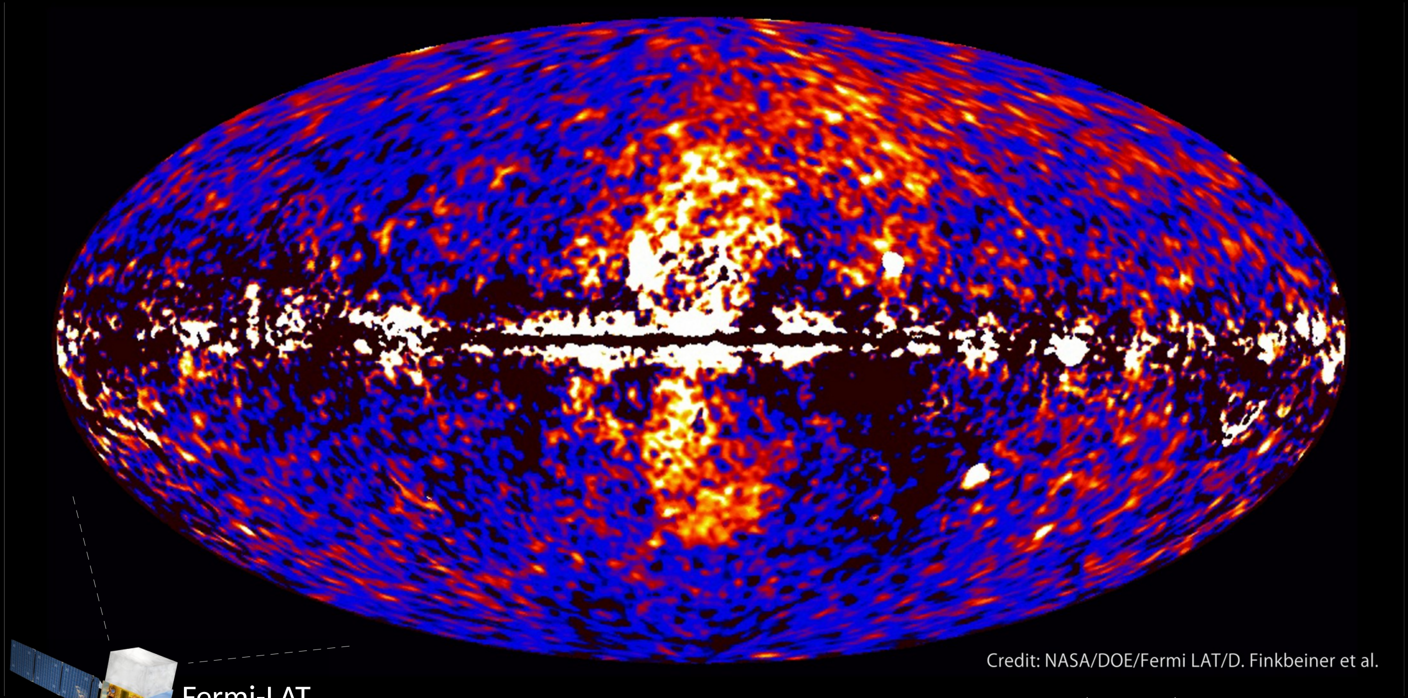
Galactic coordinates



Fermi-LAT

Image Credit: Fermi Coll.

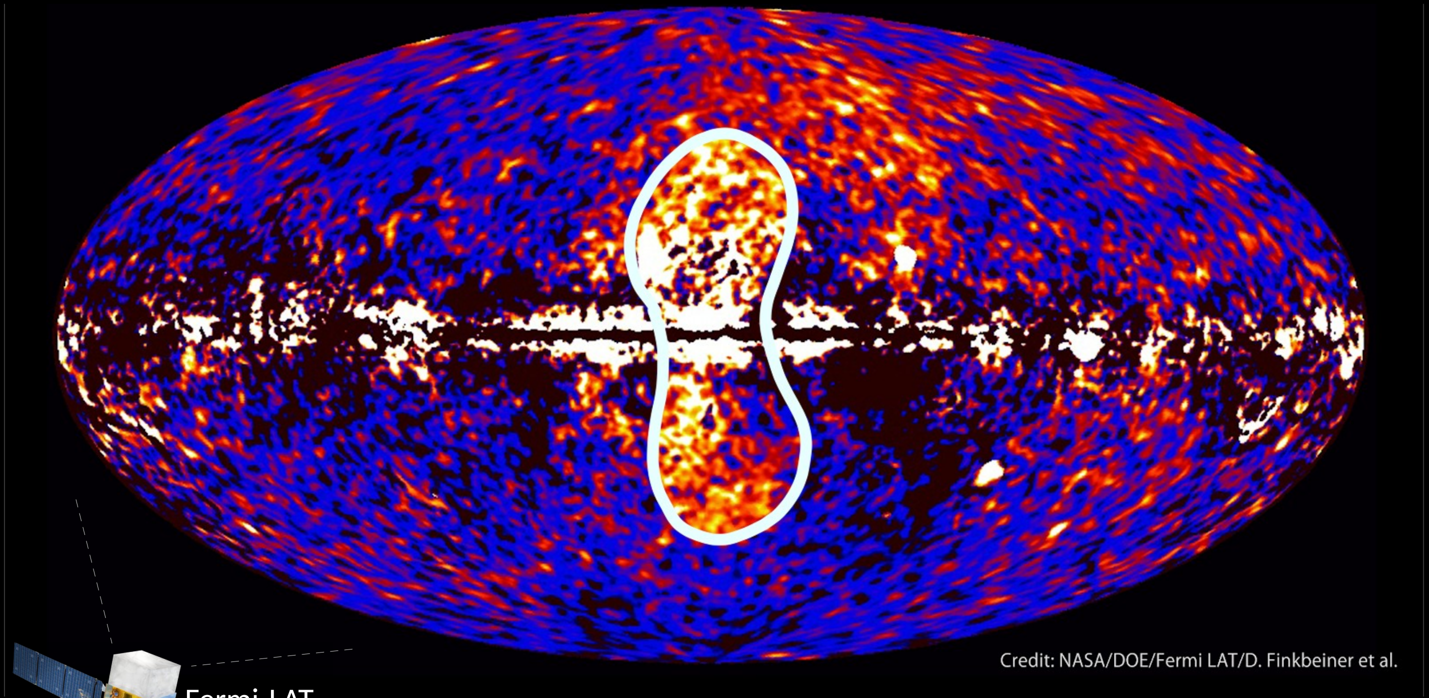
Fermi Gamma Ray Telescope reveals giant lobes of radiation



Su, Slatyer, Finkbeiner, ApJ (2010)

Image Credit: Fermi Coll.

Fermi Gamma Ray Telescope reveals giant lobes of radiation

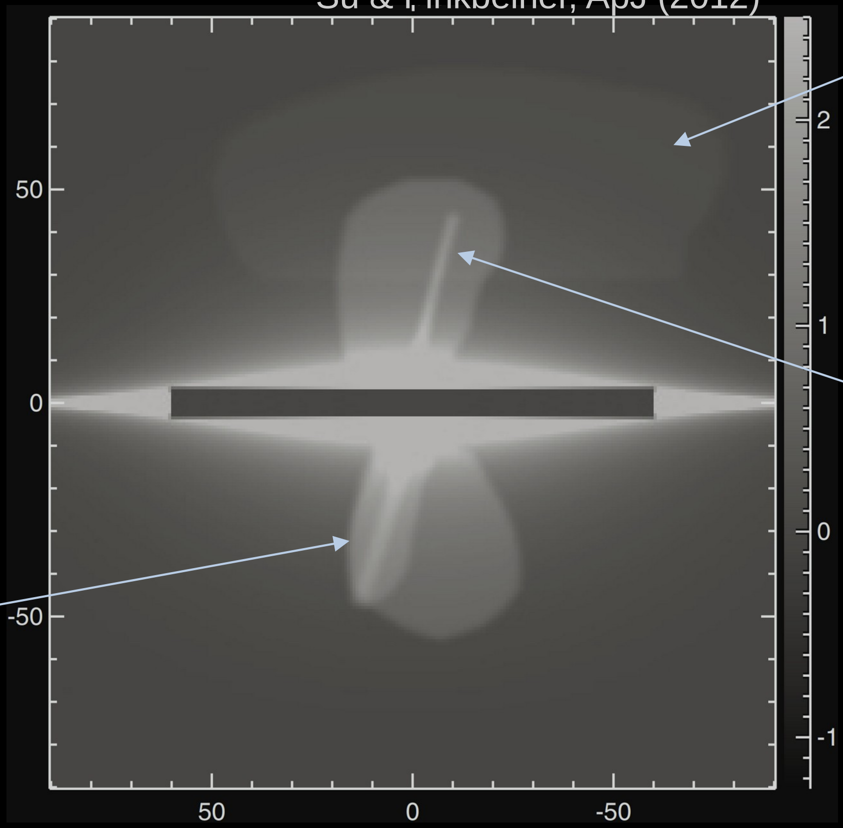


Su, Slatyer, Finkbeiner, ApJ (2010)

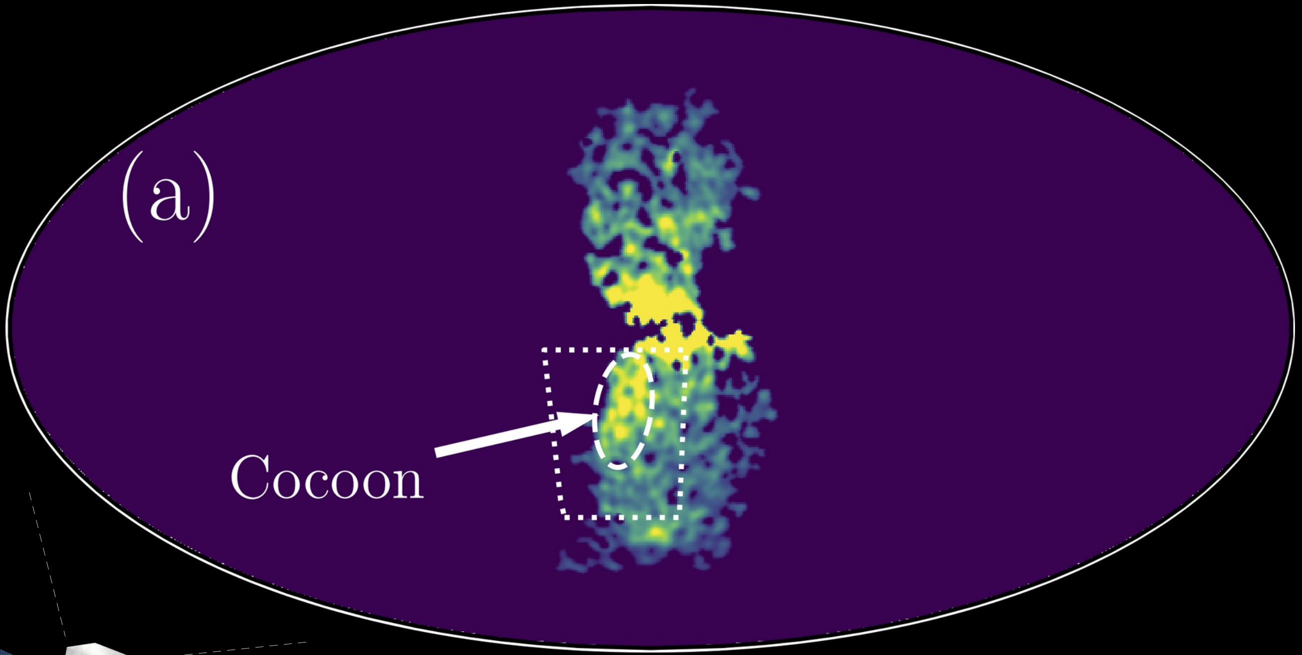
Credit: Adapted from Fermi Coll.

Evidence for an AGN-like jet in our Galaxy?

Su & Finkbeiner, ApJ (2012)



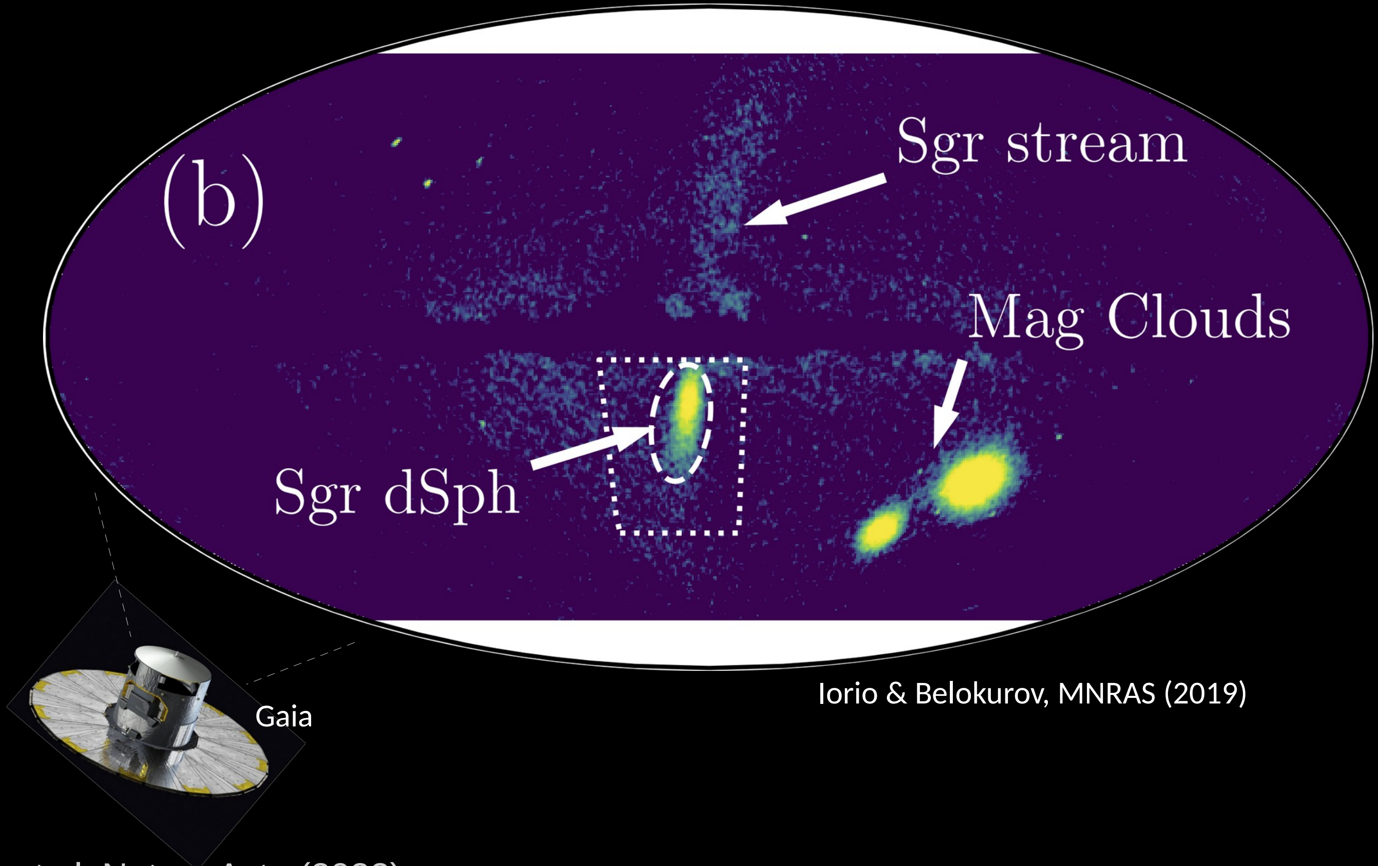
Brightest substructure in the Fermi bubbles: The Cocoon



Ackermann et al. ApJ (2014)

Crocker & OM, et al. Nature Astr. (2022)

The Sagittarius dwarf Spheroidal Galaxy as observed by Gaia



Iorio & Belokurov, MNRAS (2019)

Crocker & OM, et al. Nature Astr. (2022)

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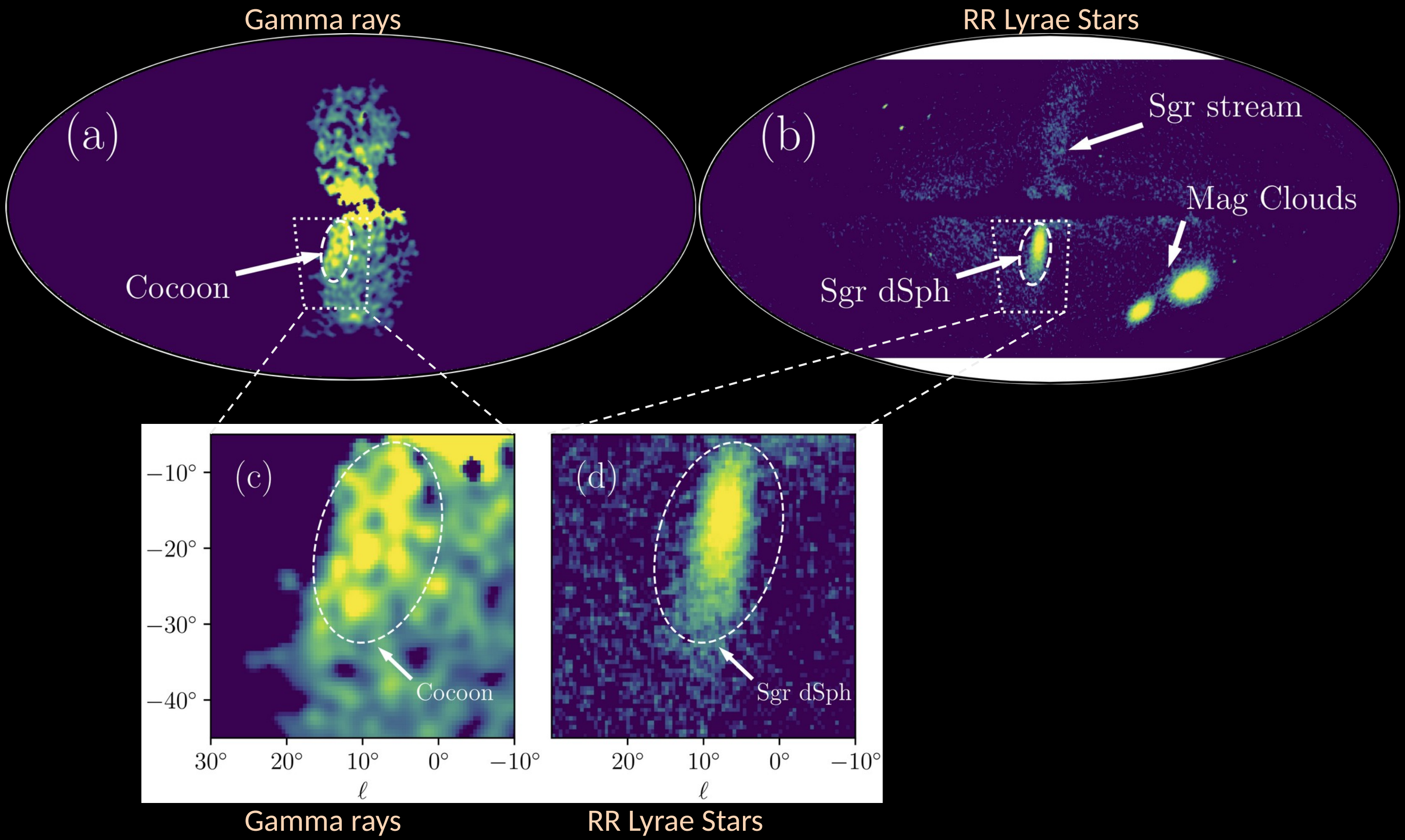
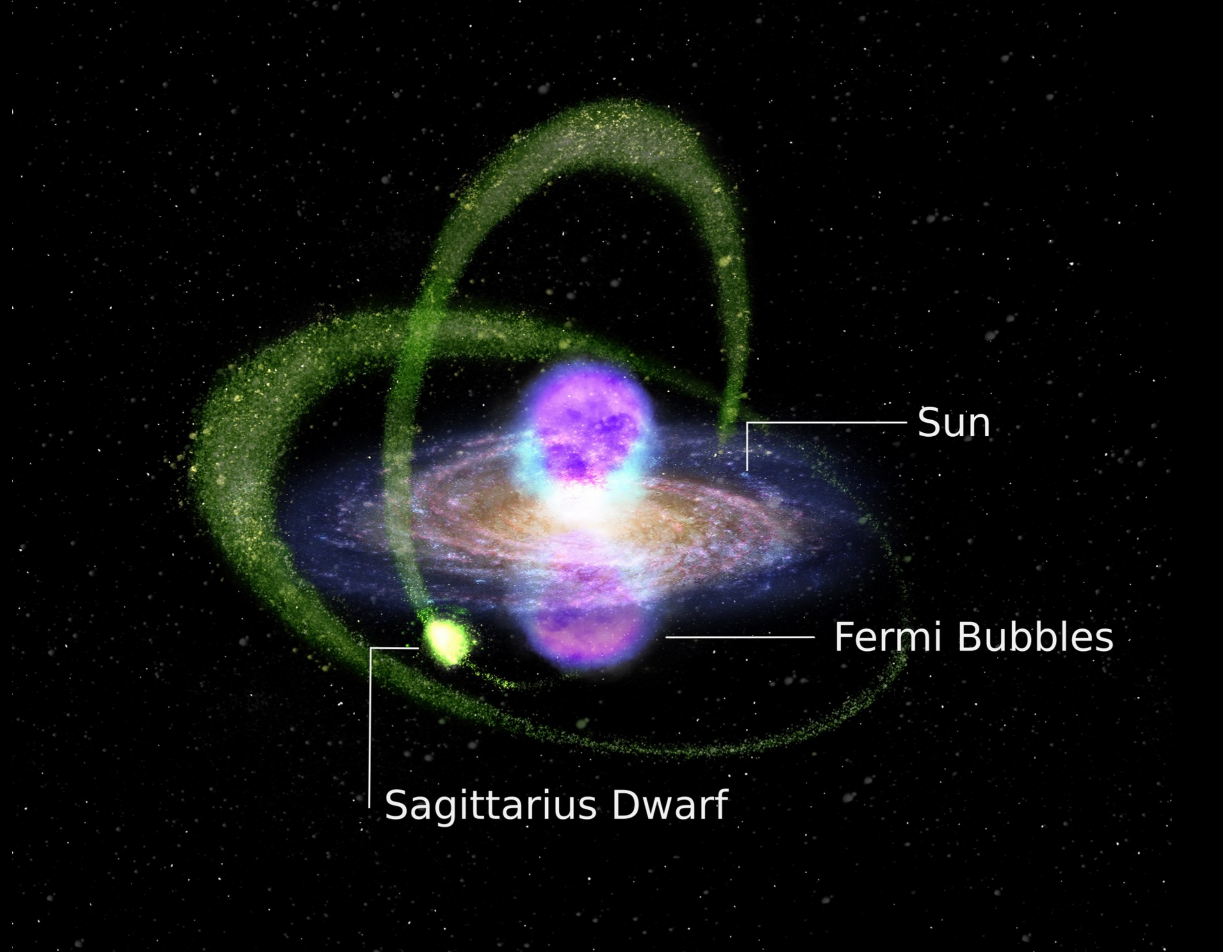


Crocker & OM, et al. Nature Astr. (2022)

Sgr dSph is located behind the Fermi bubbles



Artist Illustration: GRAPPA/Kavli IPMU

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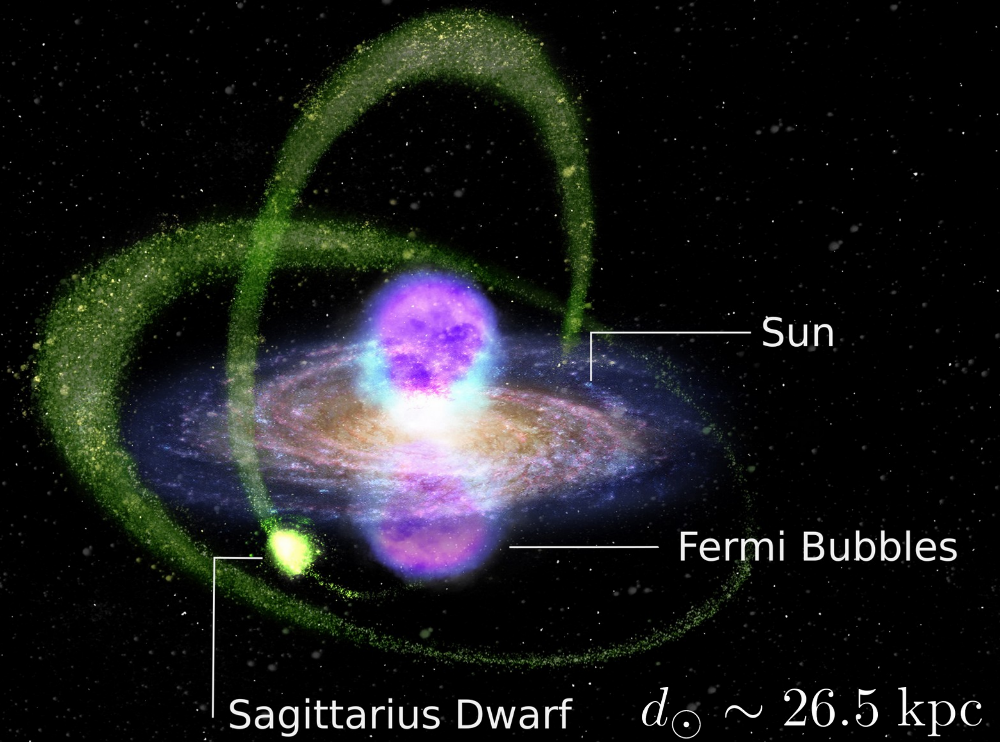
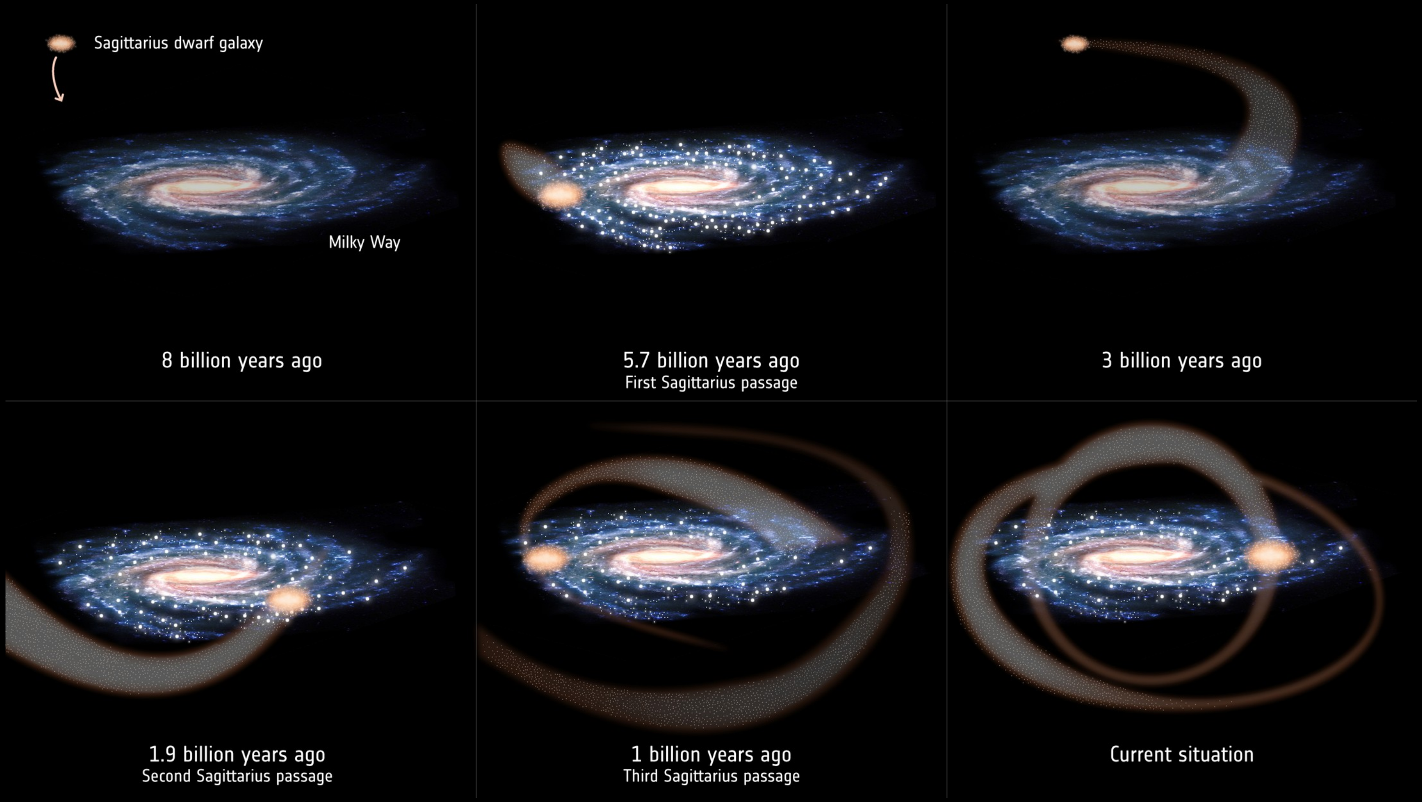


$d_\odot \sim 26.5\ \mathrm{kpc}$

$\mathrm{Mass} \sim 10^8\ M_\odot$

Artist Illustration: GRAPPA/Kavli IPMU

Dynamical history of the Sagittarius dSph



Ruiz-Lara et. al., Nature Astr. (2020)

Satellite galaxies of the Milky Way

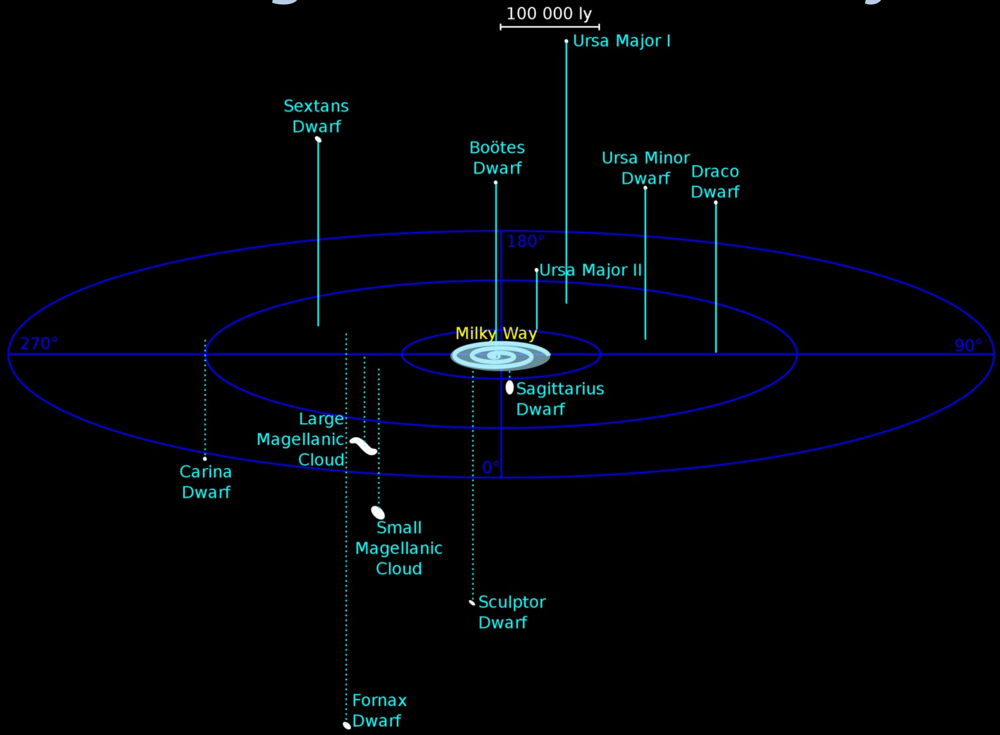


Image credit: Andrew RT

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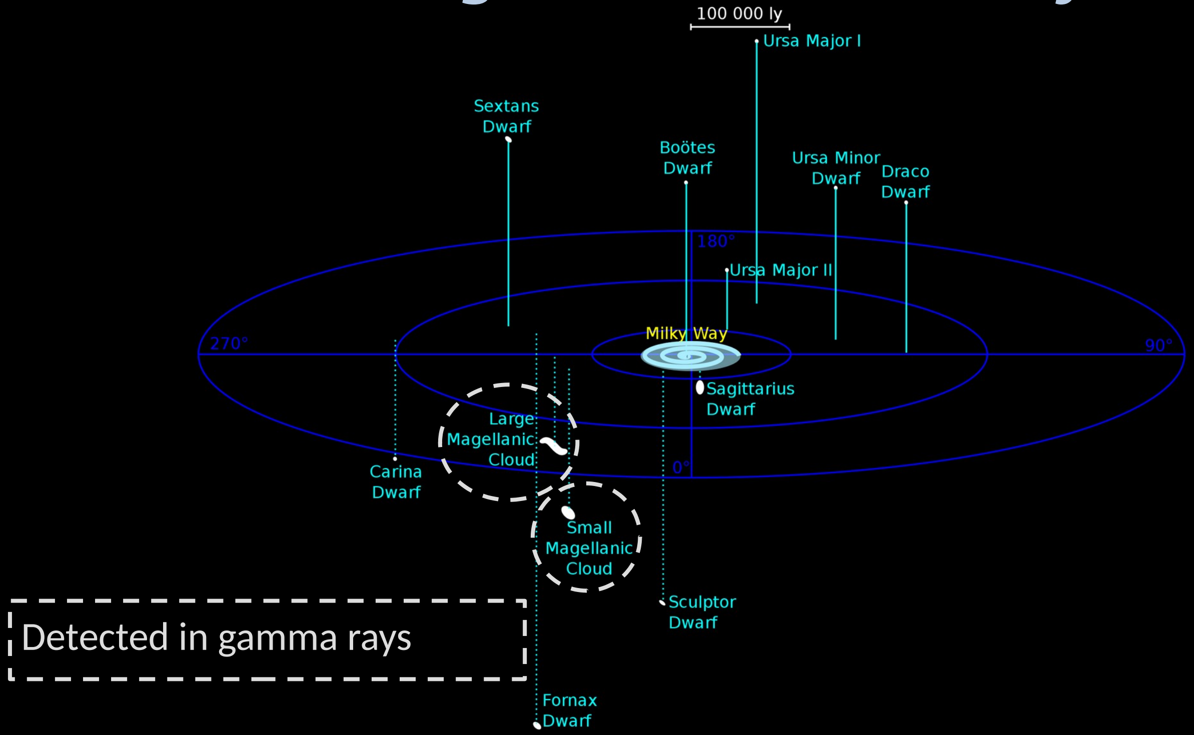

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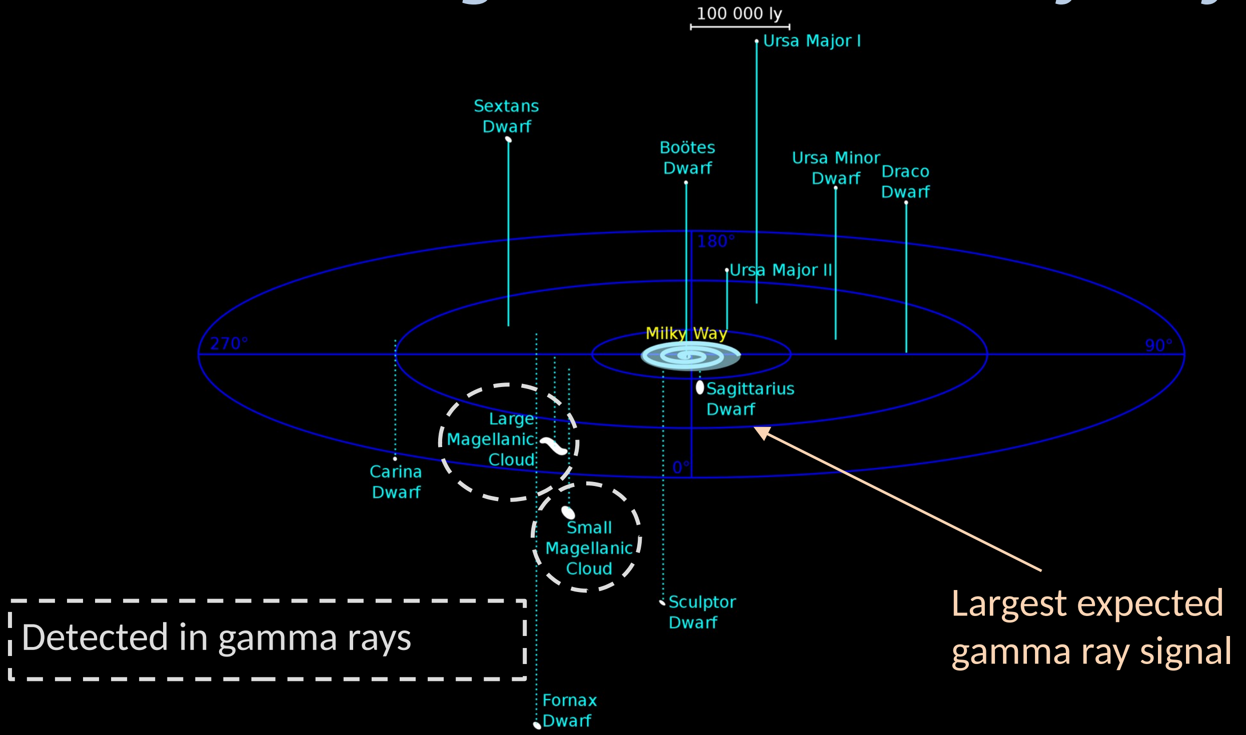
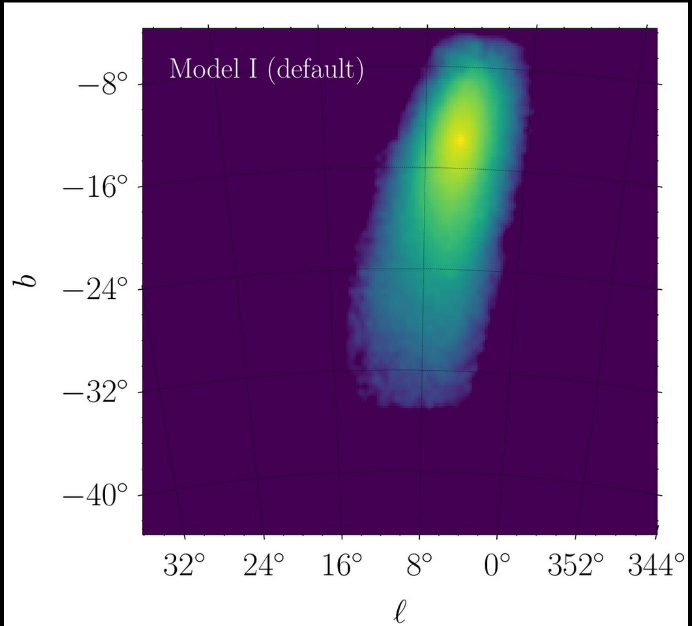


The Sagittarius dSph has the largest $M_{\odot}/d^2$ of any astronomical object not yet detected in gamma rays.

Image credit: Andrew RT

Stellar Population of the Sagittarius dSph



- More than 200,000 stars from *Gaia* DR2
- Extinction-corrected G-band >18 mag
- More than 50% are red clump stars

Crocker & OM, et al. Nature Astr. (2022)

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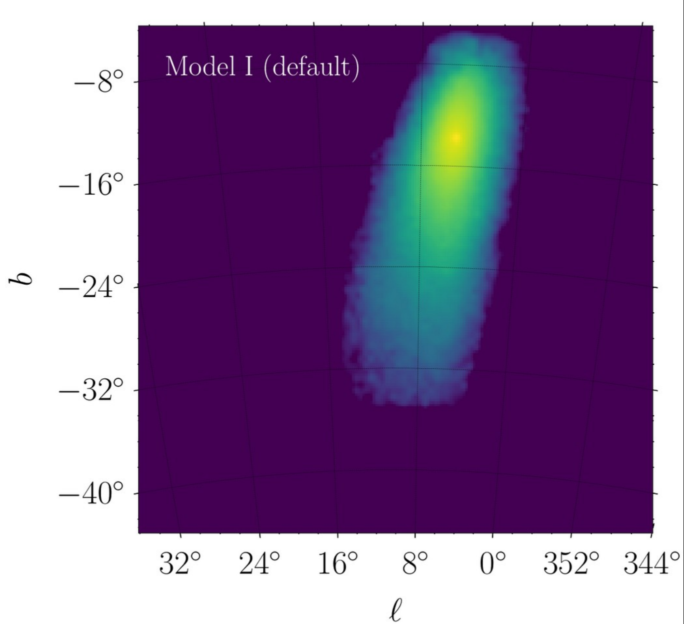

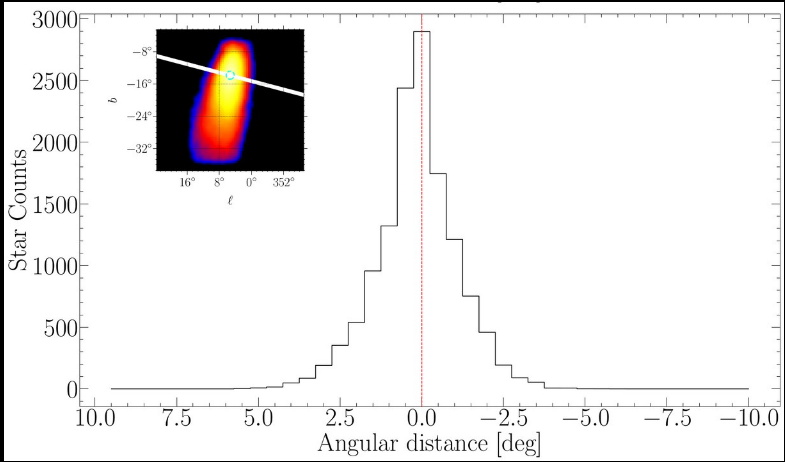

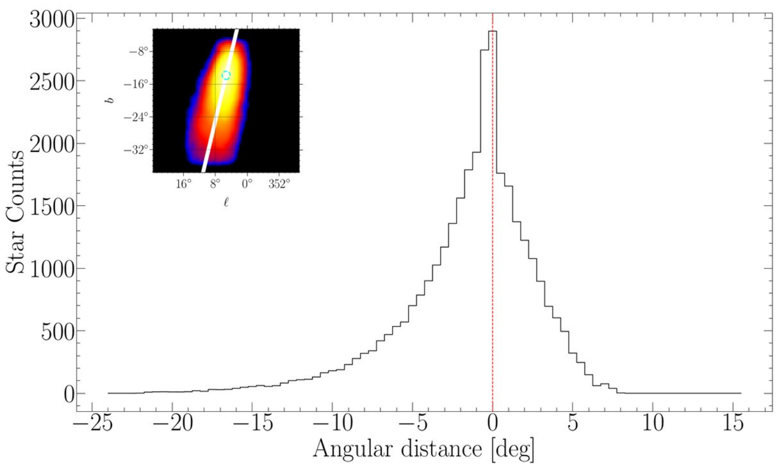

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Statistical Tests

Template choices				Results			
Hadr. / Bremss.	IC	FB	Sgr dSph	$-\log(\mathscr{L}_{\text{Base}})$	$-\log(\mathscr{L}_{\text{Base+Sgr}})$	$\text{TS}_{\text{Source}}$	Significance
			Default model				
HD	3D	S	Model I	866680.6	866633.0	95.2	8.1 σ
			Alternative background templates				
HD	2D A	S	Model I	866847.1	866810.9	72.3	6.9 σ
HD	2D B	S	Model I	867234.9	867192.1	85.8	7.8 σ
HD	2D C	S	Model I	866909.4	866868.5	81.7	7.4 σ
Interpolated	3D	S	Model I	867595.4	867567.4	56.0	5.8 σ
GALPROP	3D	S	Model I	866690.5	866640.8	99.5	8.3 σ
			Flat FB template				
HD	3D	U	Model I	867271.7	867060.1	423.2	19.1 σ
HD	2D A	U	Model I	867284.2	867122.9	322.5	16.5 σ
HD	2D B	U	Model I	867624.3	867464.0	320.7	16.4 σ
HD	2D C	U	Model I	867322.7	867158.2	329.0	16.6 σ
Interpolated	3D	U	Model I	867287.4	867081.2	412.4	18.9 σ
GALPROP	3D	U	Model I	868214.6	868040.9	347.6	17.2 σ

HD:= Hydrodynamic gas model
Interpolated:= Standard gas model
Model I:= baseline Gaia map

Crocker & OM, et al. Nature Astr. (2022)

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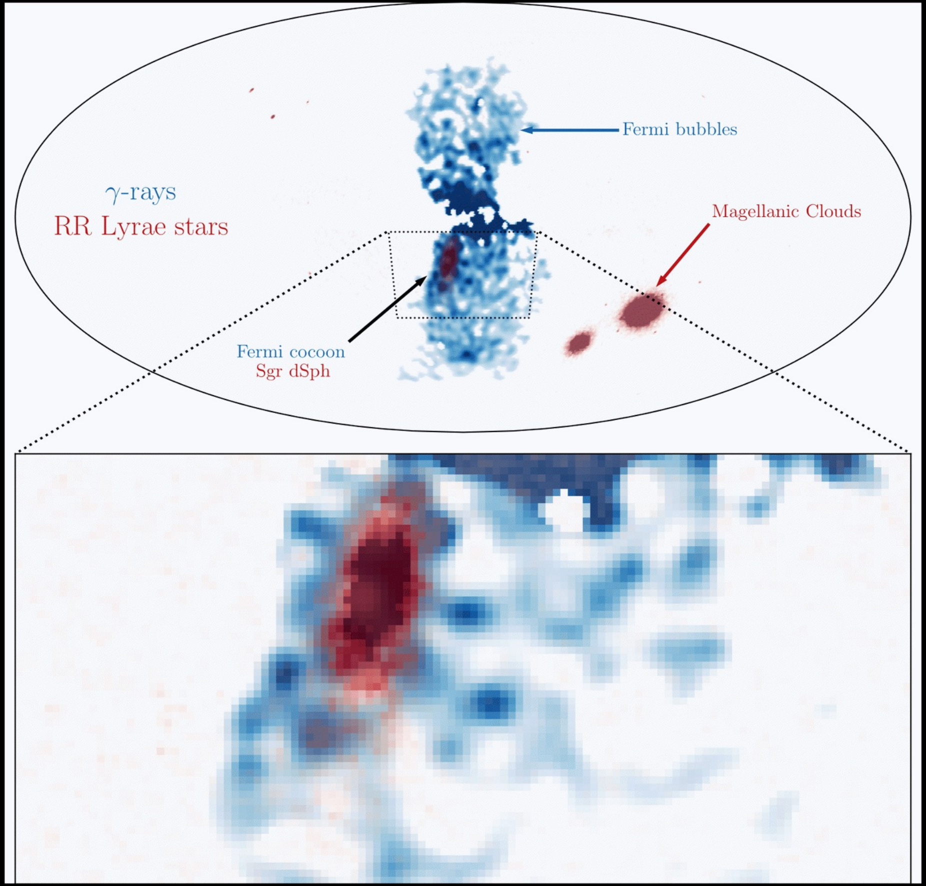
Crocker & OM, et al. Nature Astr. (2022)

What is producing the signal?



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Crocker & OM, et al. Nature Astr. (2022)

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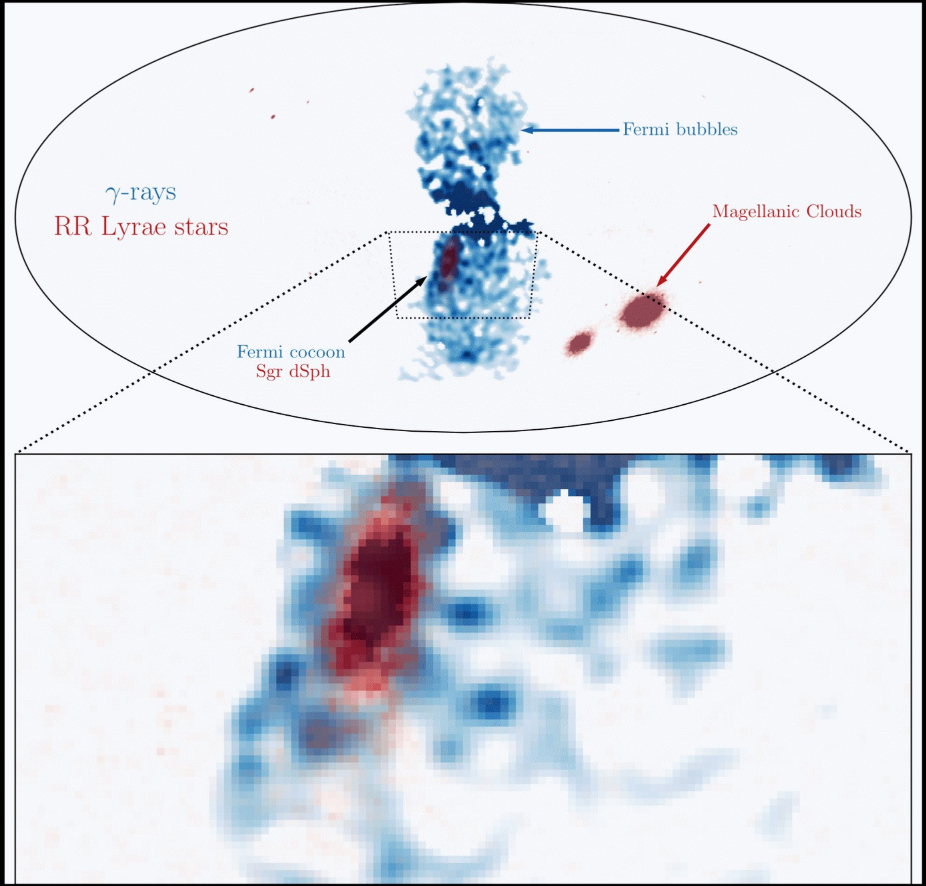

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Crocker & OM, et al. Nature Astr. (2022)

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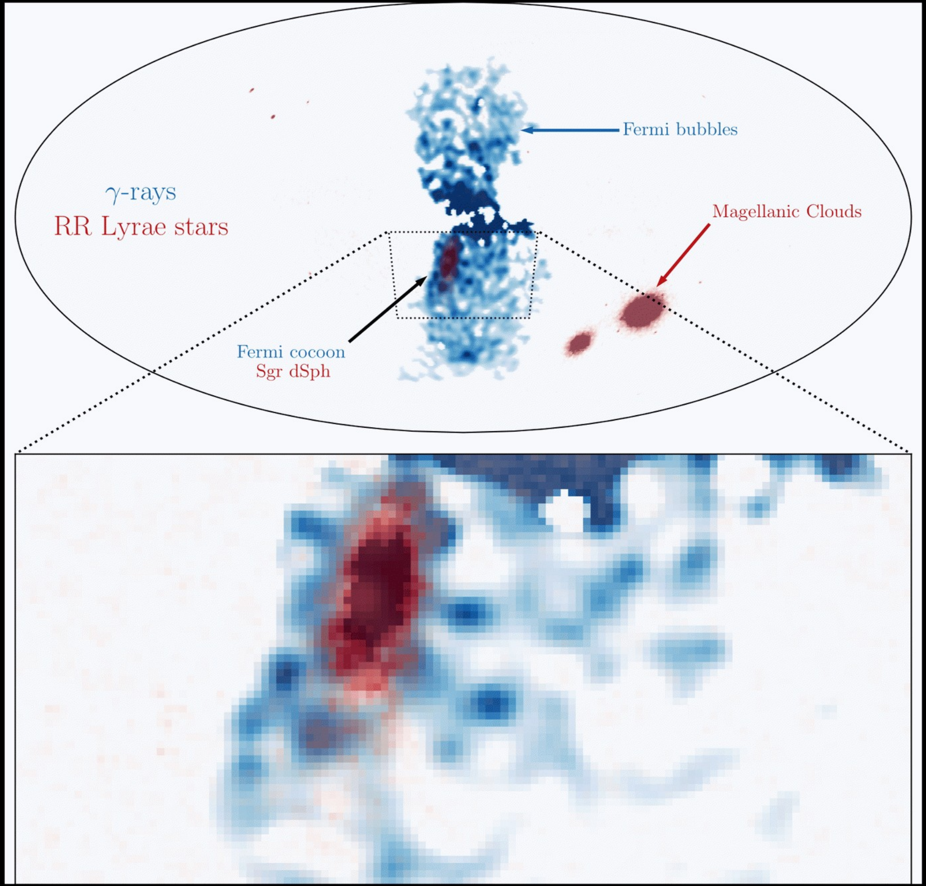

- NO Gas: Lost to tidal and ram pressure stripping (Tepper-Garcia & Bland-Hawthorn 2018)

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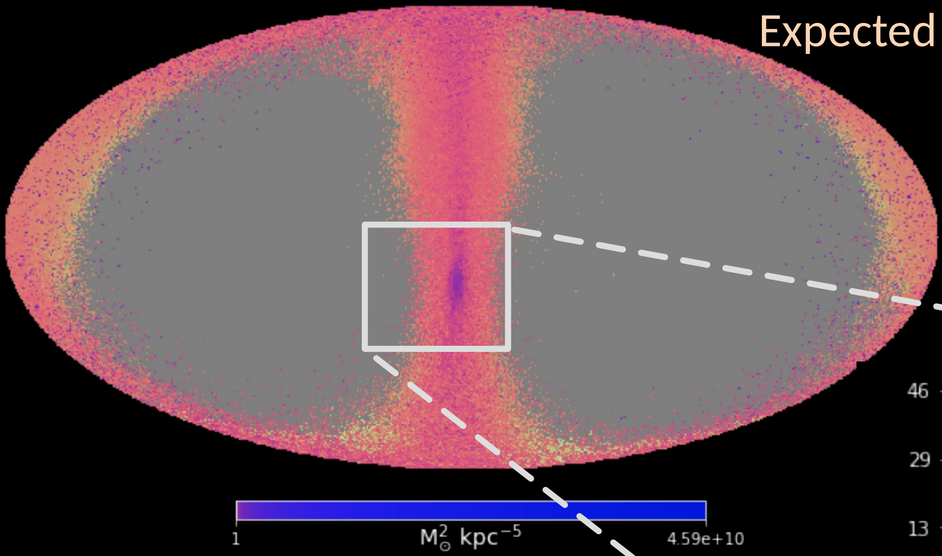
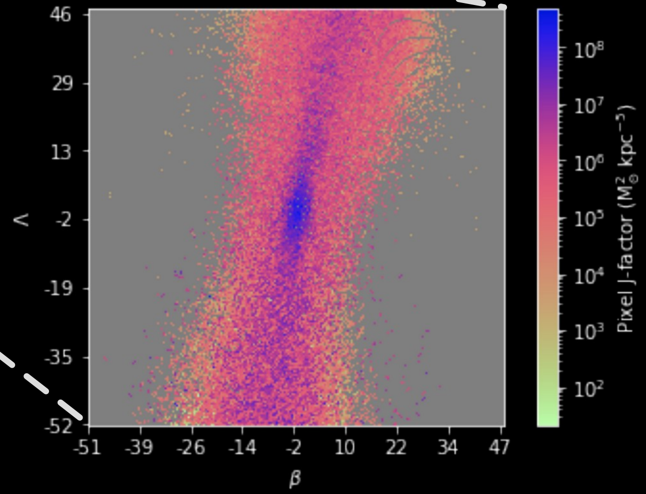
  - *Not* hadronic emission:

Crocker & OM, et al. Nature Astr. (2022)

Is the Cocoon due to dark matter annihilation?

Expected dark matter intensity (simulated J-factor)



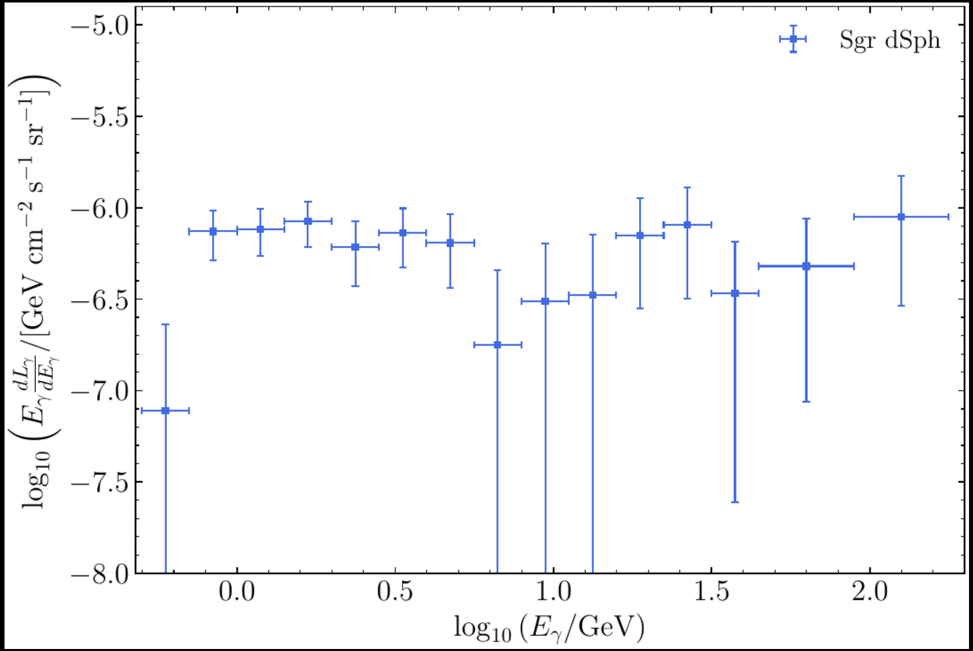


Venville, Duffy, Crocker, **OM**, Tepper-Garcia, (2023)

Is the signal due to Millisecond pulsars (MSPs)?

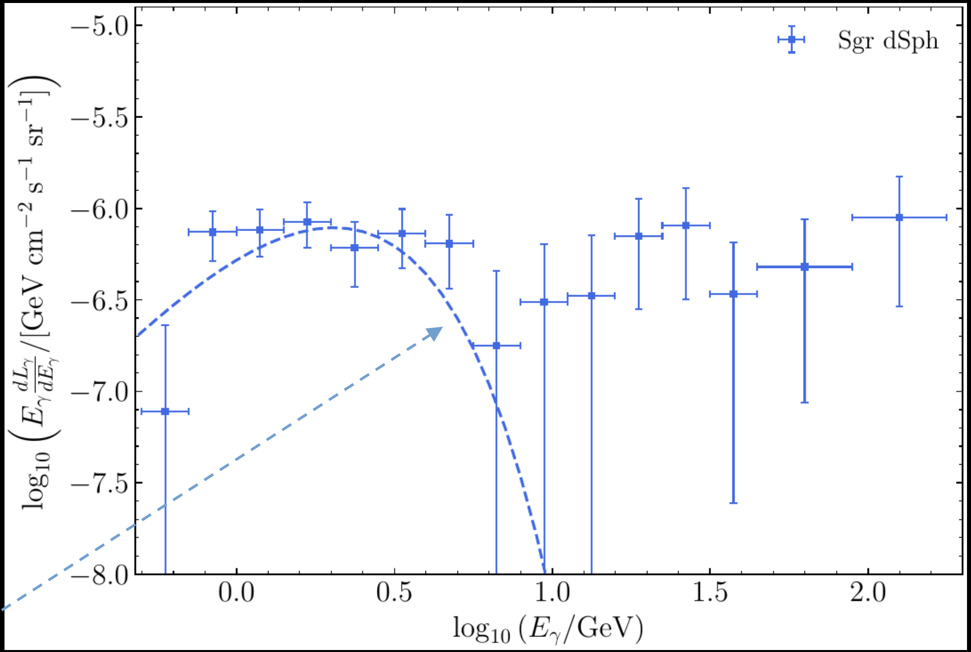
- ✓ Very likely:
  - MSPs generate GeV gamma rays amongst old stellar populations (e.g., globular clusters)
  - Signal expected to trace the stars

Spectrum of the Sagittarius dSph

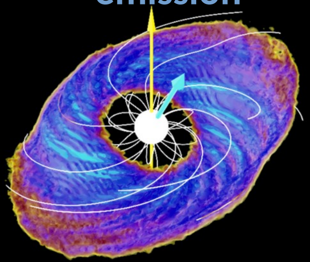


Crocker & OM, et al. Nature Astr. (2022)

Spectrum of the Sagittarius dSph



Magnetospheric MSPs emission



Crocker & OM, et al. Nature Astr. (2022)

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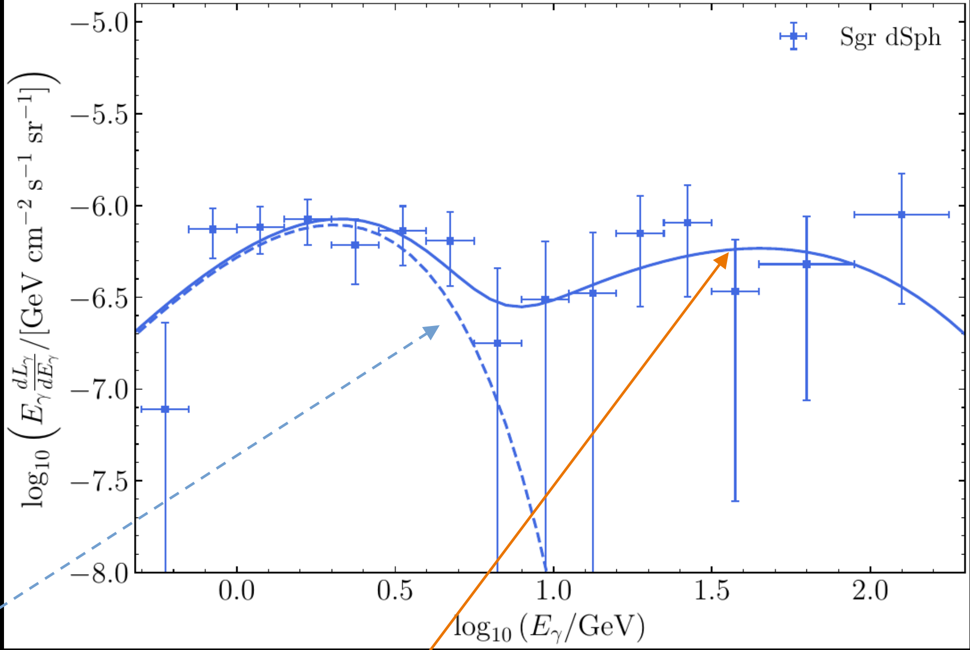

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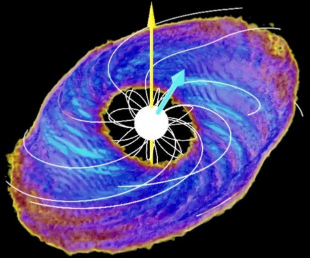
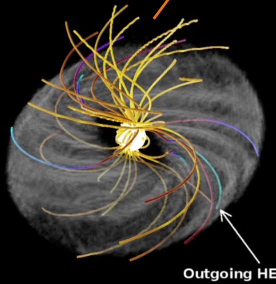


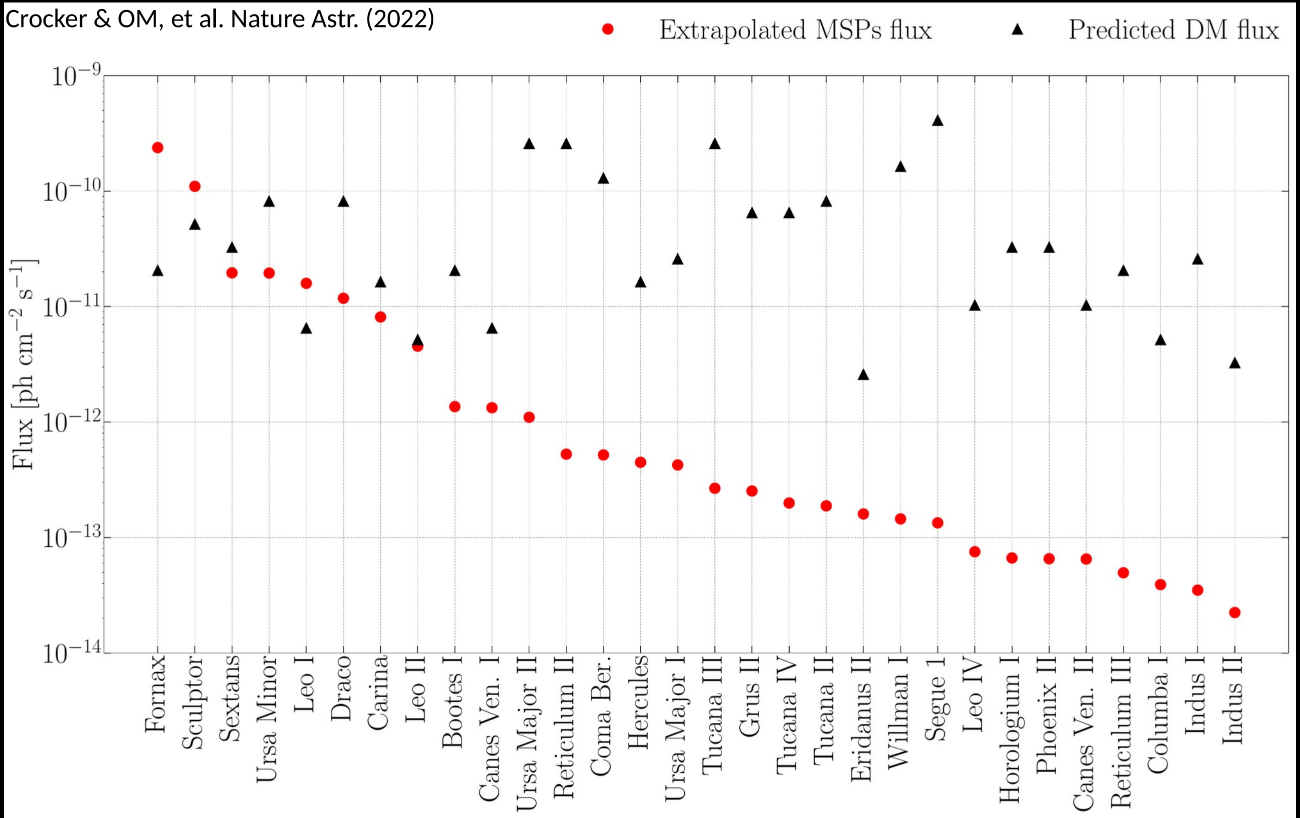


Inverse Compton from outgoing e-/e+

$$u_{\mathrm{ISRF}} = u_{\mathrm{CMB}} \gg u_{\mathrm{B}}$$

Crocker & OM, et al. Nature Astr. (2022)

Dark Matter implications



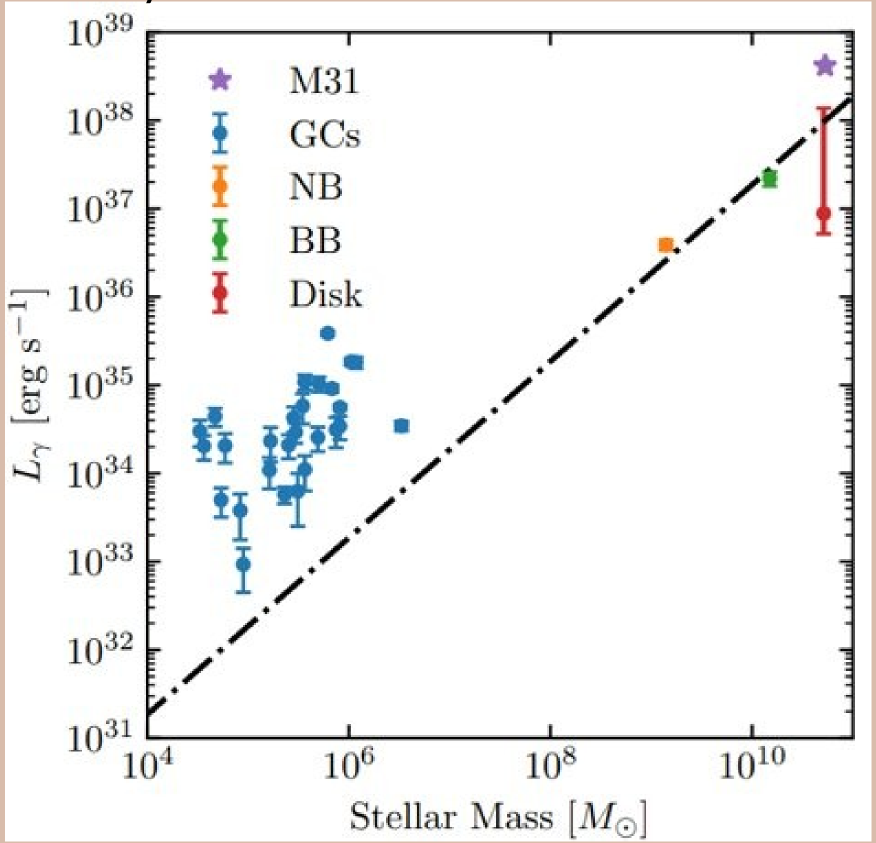
- Extrapolation of our results suggests that the stellar gamma-ray background could be stronger than previous estim

Comparison of Regions

Gamma-ray to mass ratios

Shows environmental dependence of MSP gamma rays

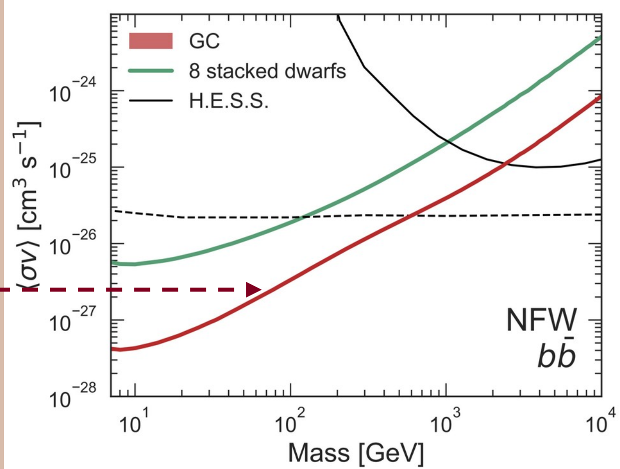
Song, OM, Horiuchi, Crocker, Nataf (2021)



- Boxy bulge, nuclear bulge, Milky Way disk (from MSPs) consistent with each other.
- Globular clusters higher by factor ~10-40, explained by large dynamical channel
- M31 also higher, consistent with its higher encounter rate.

Leading constraints on GeV-scale WIMP dark matter

Abazajian, OM et al. PRD (2020)



Gamma rays from Galactic center

P.A. Zyla et al. (Particle Data Group), Prog. Theor. Exp. Phys. 2020, 083C01 update 2021

X^0 Annihilation Cross Section

Limits are on σv for X^0 pair annihilation at threshold.

VALUE (cm^{3}s^{-1})	CL%	DOCUMENT ID		TECN	COMMENT
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<2.5 \times 10^{-27}$	95	[1] ABAZAJIAN	20	FLAT	γ from galactic center
		[2] ABDALLAH	20	HESS	WIMP annihilation in dwarf satellite galaxies
$<1.2 \times 10^{-24}$	90	[3] ABE	20G	SKAM	WIMP annihilation to neutrinos
$<2.2 \times 10^{-24}$	95	[4] ALBERT	20	HAWC	WIMP annihilation to γ
$<5 \times 10^{-24}$	90	[5] ALBERT	20A	ANTR	WIMP annihilation to νs in galactic center

- One of the strongest constraints on GeV-scale WIMP dark matter in the literature.
- Limits are robust to uncertainties in the astrophysical background.
- Thermal Dark Matter particles with masses less than ~400 GeV ruled out

Resolving the GCE with multi-wavelength measurements

Radio Counterparts

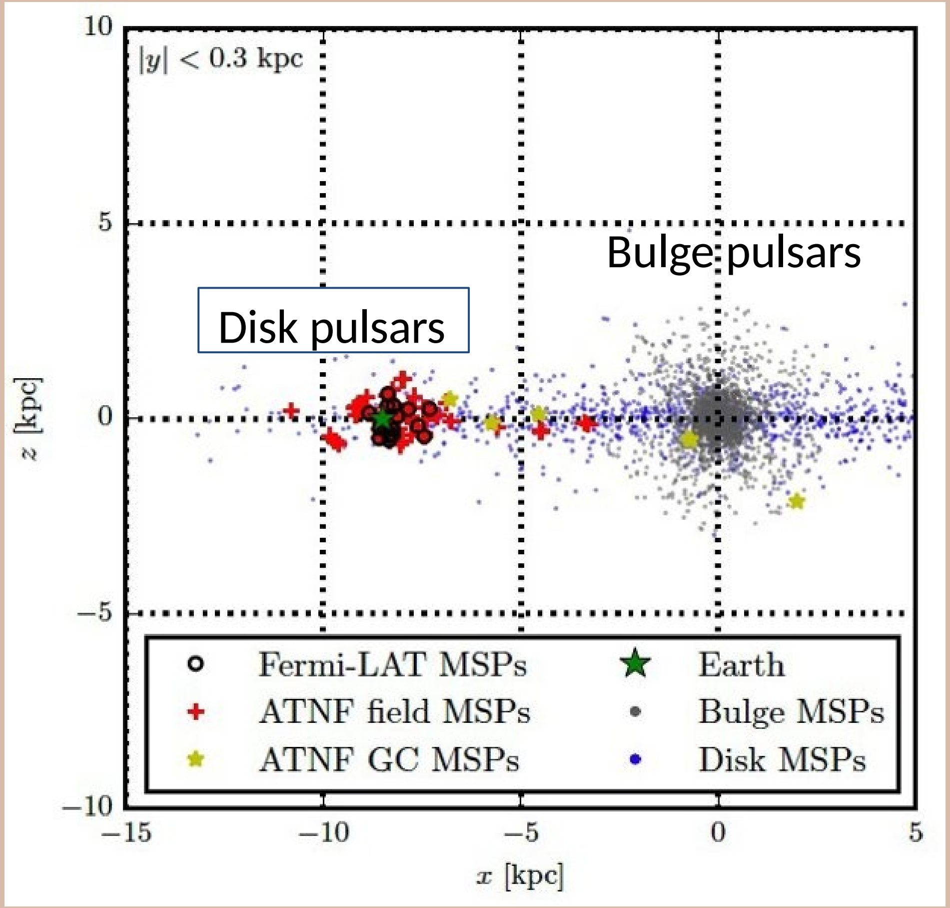
Calore et al. (2016)

The present

There are strong selection effects in millisecond pulsar catalogue

- Most are < a few kpc
- GC pulsars all associated with globular clusters

e.g., Bagchi et al 2011



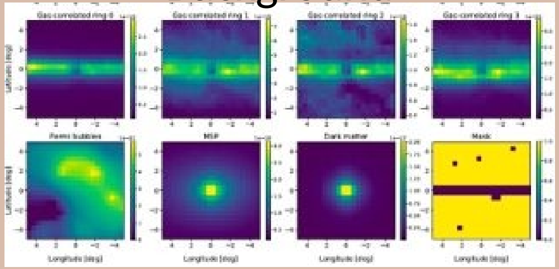
So…the target

Expected large millisecond pulsar population in the bulge

TeV Counterparts

Forecast with ctools

Background



- ROI 10x10 deg^2
- Resolution 0.5 deg
- Mask galactic plane & sources
- Exposure 500 hours
- 16 GeV – 158 TeV

source

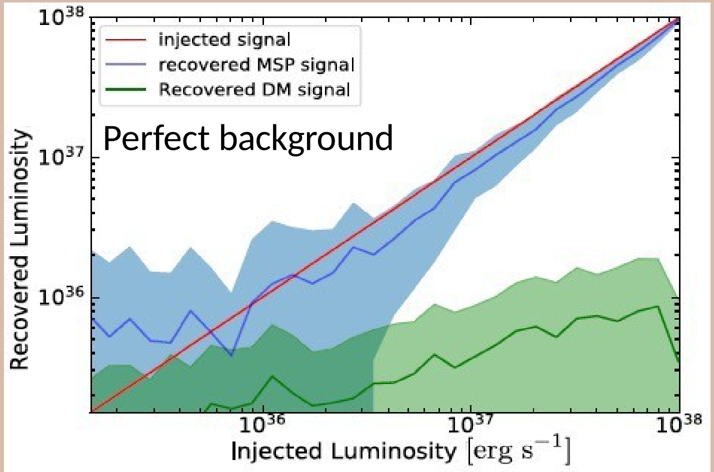
$$\frac{d^2N}{dE\,dt} \propto E^{-\Gamma} \exp(-E/E_{\mathrm{cut}})$$

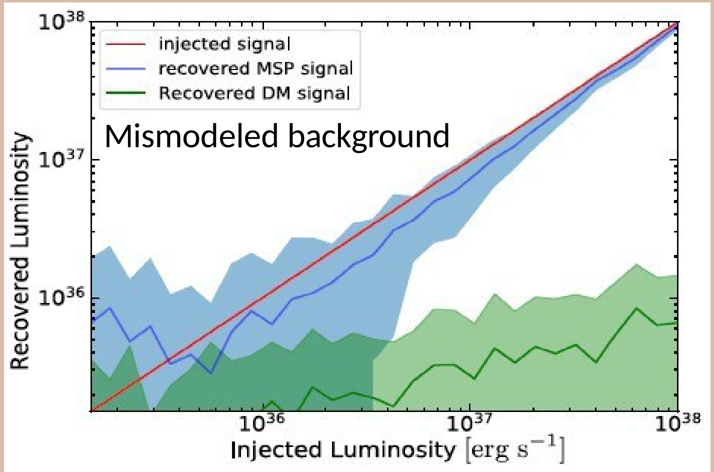
Model Name	Γ	E_{cut} (TeV)
Baseline	2.0	50
Inj1	1.5	50
Inj2	2.5	50
Inj3	2.0	10
Inj4	2.0	100

- Spherical
- Bulge-like

Two analyses: background mismodeling

Minimum $f_{e^\pm}$ for detection (per cent)				
Baseline	Inj1	Inj2	Inj3	Inj4
FB$_{\mathrm{min}}$, perfect GDE.				
10.5 per cent	2.9 per cent	158.4 per cent	24.3 per cent	8.2 per cent
FB$_{\mathrm{min}}$, mismodelling of the GDE.				
14.5 per cent	3.8 per cent	163.4 per cent	25.3 per cent	10.8 per cent





OM+, MNRAS (2021)

Conclusions

★ Various astrophysical excesses (GeV excess, Sgr dSph excess, Andromeda excess) cast new light on MSPs as sources of cosmic rays and non-thermal radiation in the Galaxy.

★ Pulsars and millisecond pulsars are an important source of astrophysical background for dark matter searches. It is crucial to understand them to increase our sensitivity to dark matter.

★ Bright future ahead. New observational and modeling techniques will allow us to understand the role of pulsars in the high-energy Universe.