APEC seminar, Kavli IPMU Oct 13th 2021

Particle Astrophysics of the Galactic Center

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VIRGINIA TECH

The Center for Neutrino Physics

KAVLI IPMU

WPI

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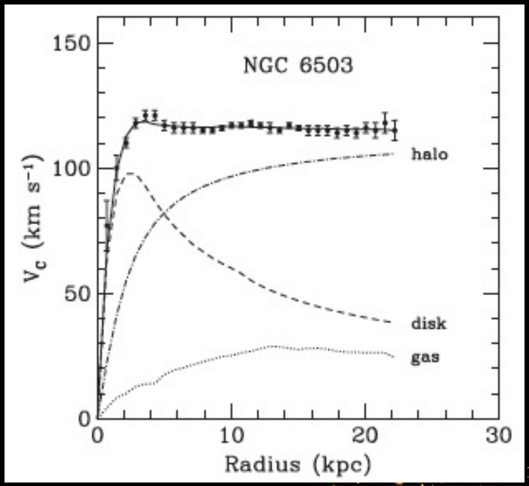
Today's contents

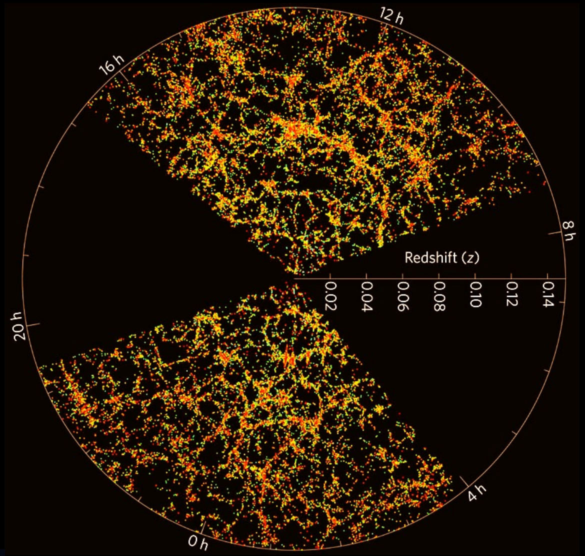
1. Intro to dark matter and the gamma-ray excess
2. Pulsars as alternative explanation
3. Spatial tests
4. Implications
5. Future directions

Evidence for dark matter

From astronomical data on many scales

Galaxies (~kpc = 10^{19} m)

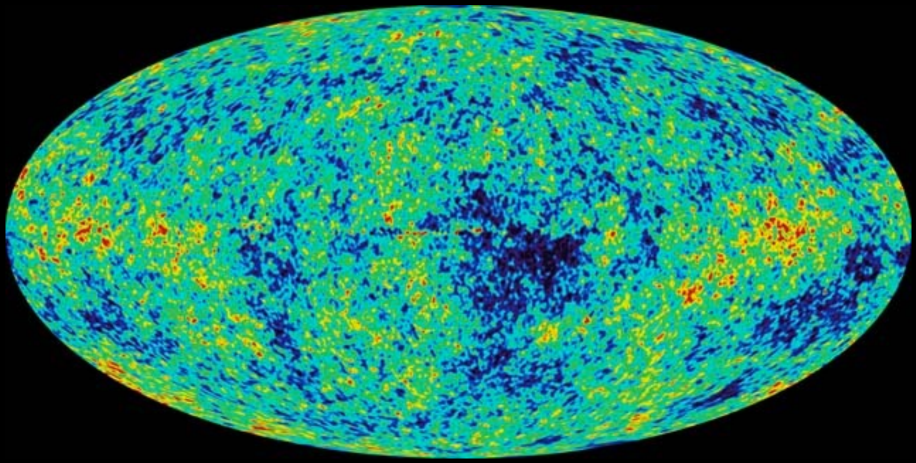




Large-scale Structure (~100Mpc)

Galaxy clusters (~Mpc)

Cosmological (~Gpc)



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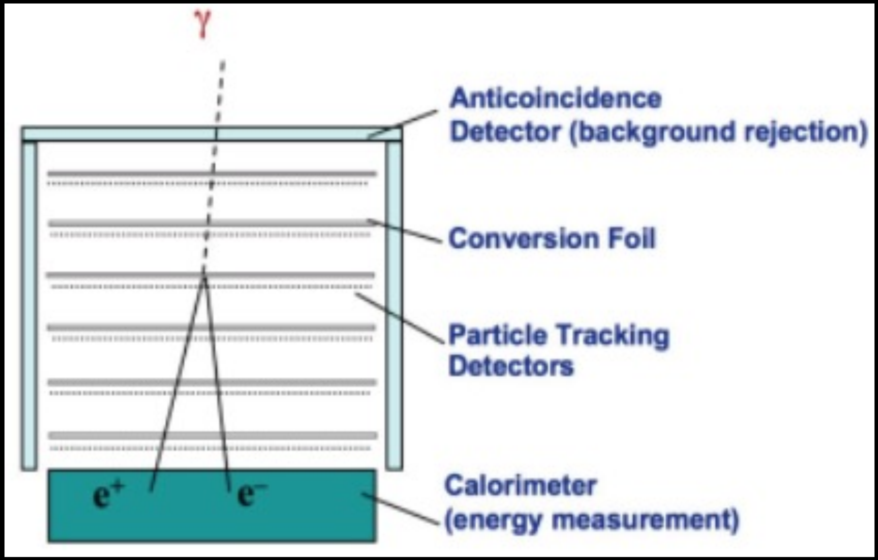
Gamma-ray search

Fermi satellite
Launched in June 2008

Large area telescope (LAT)

- Particle detector in space
  - 50 MeV – 500 GeV
- Excellent survey instrument
  - Field of view 2.4 sr at 1 GeV
  - PSF < 1 deg above 1 GeV
- Data and analysis tools are public:

http://fermi.gsfc.nasa.gov/ssc/data/

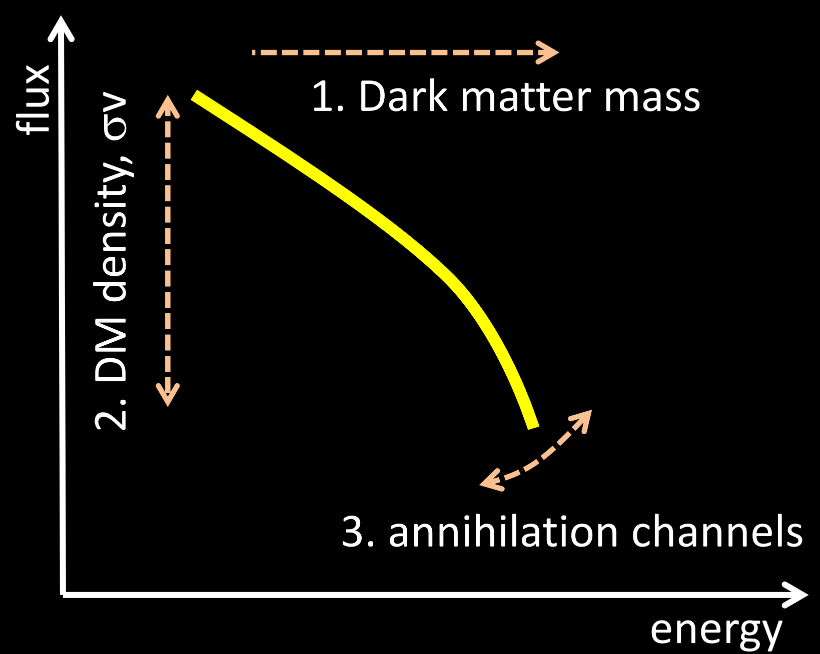


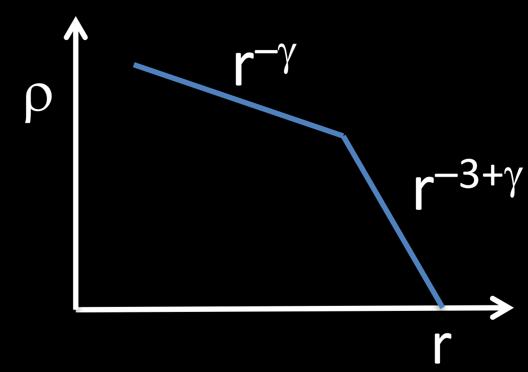
Dark matter signal

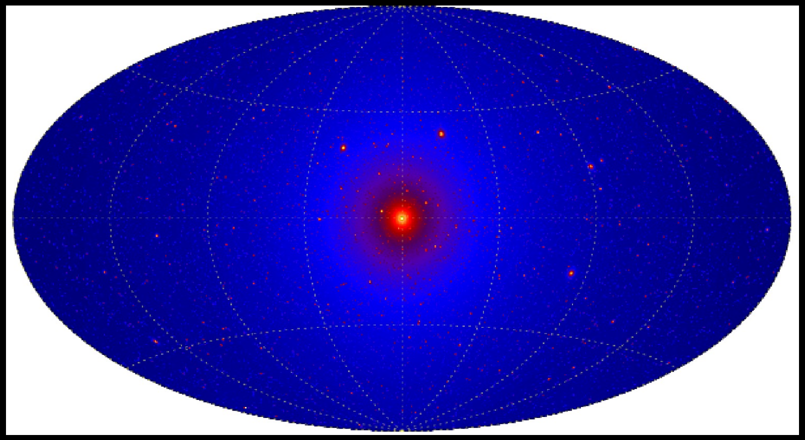
Annihilation of thermally produced DM (via hadronic decays)

$$\Phi(E,\psi) = \frac{\sigma_A v}{8\pi m_\chi^2} \frac{dN_\gamma}{dE} \int d\ell \, \rho\left[r(\ell,\psi)\right]^2$$

DM + DM → standard model
(photons, leptons, quarks, …)







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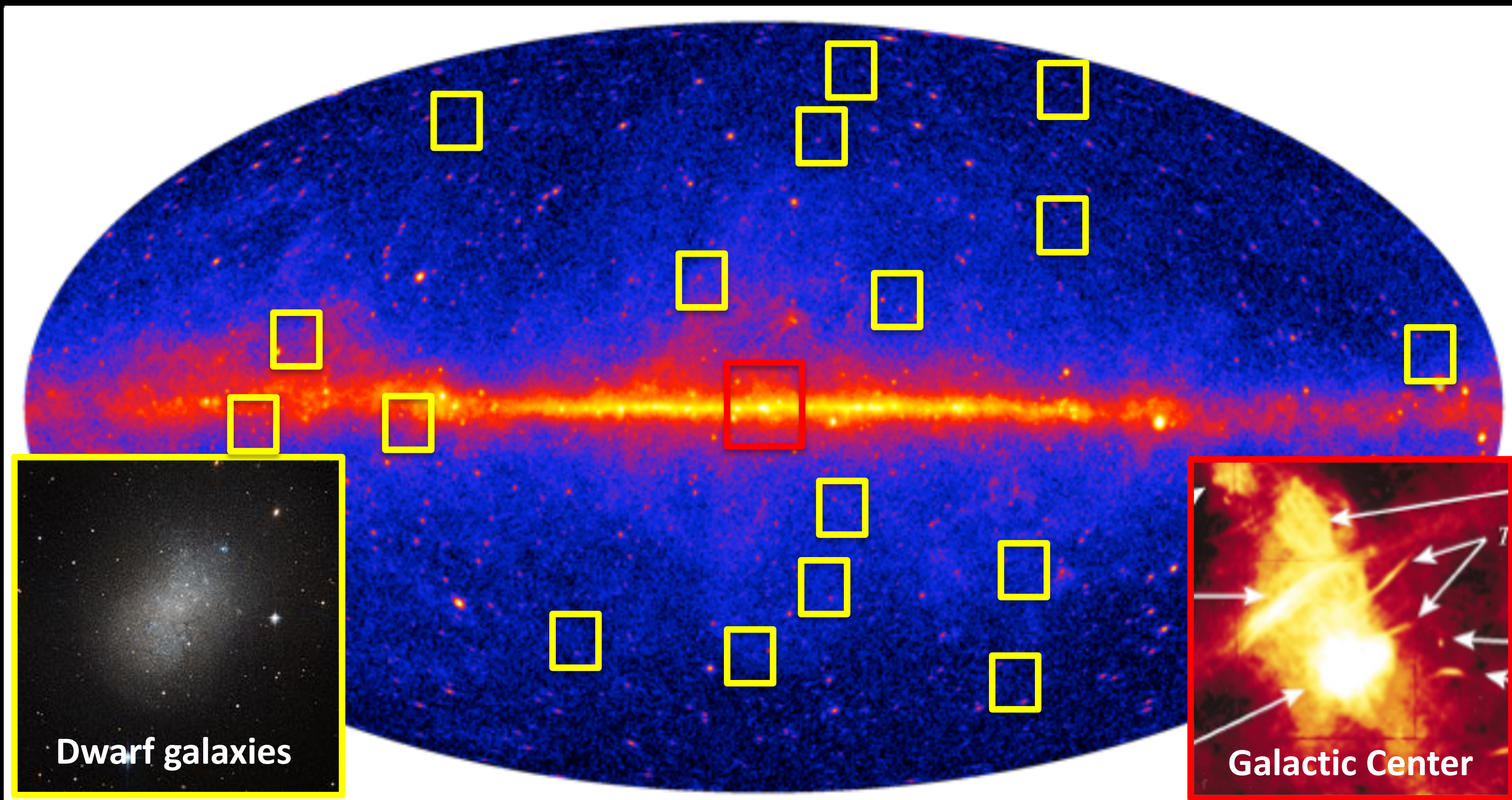
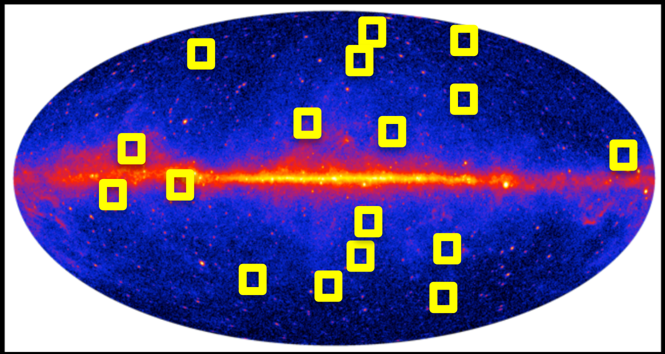
The strategy

This is the predicted dark matter squared distribution

And this is the gamma-ray sky, as observed by the *Fermi* satellite.



Searches in dwarf galaxies

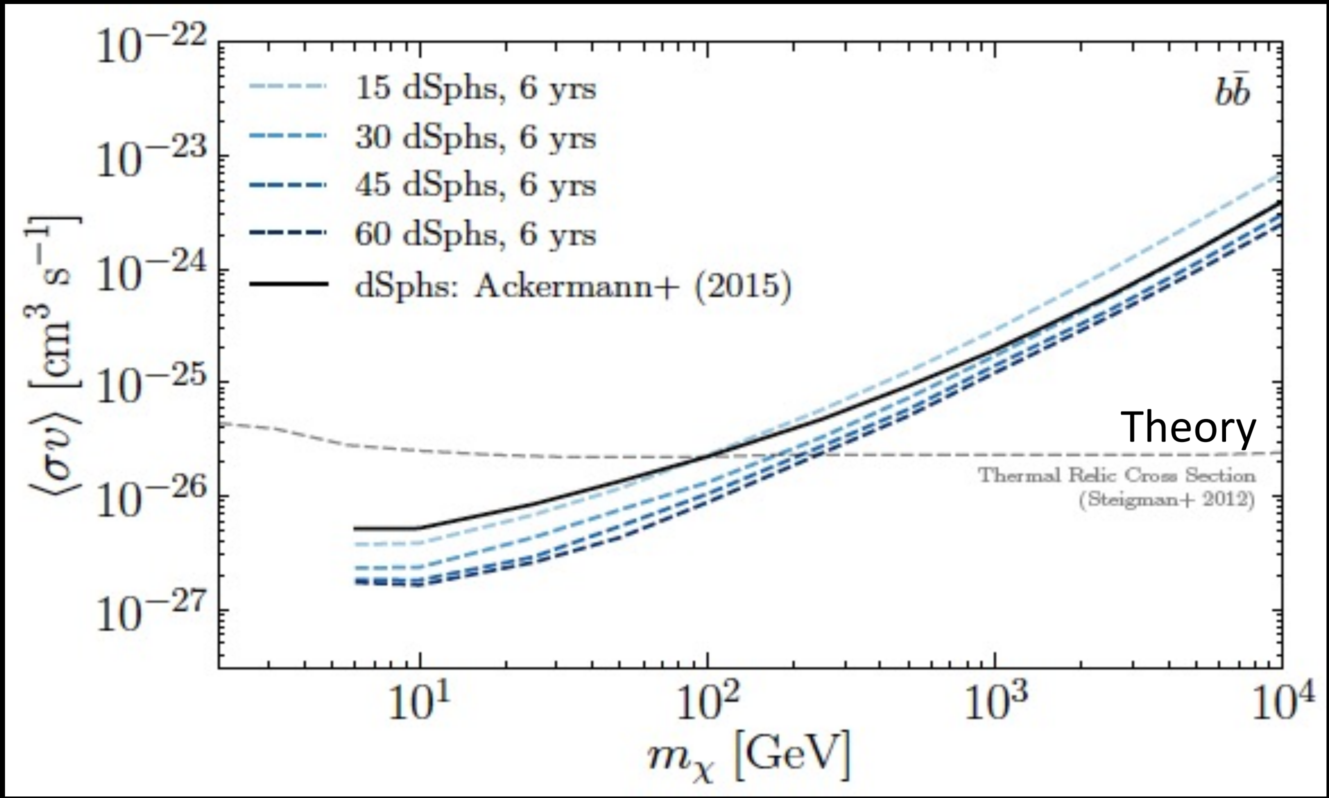


Advantages:
- Dark matter dominated
- Clean search regions

Disadvantages:
- Faint dark matter signal
- Uncertain dark matter amount

Status:
- 16-27 dwarf objects stacked
- No excess signal found

→ **constraints in mass & cross section space**



Fermi collab. (2012)
Charles et al (2016)
Hoof et al (2020)
Ando et al (2020)

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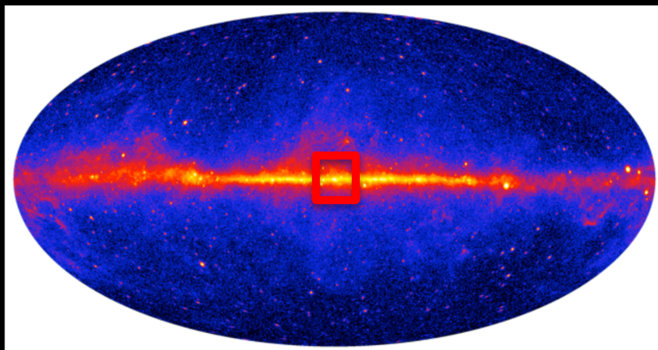
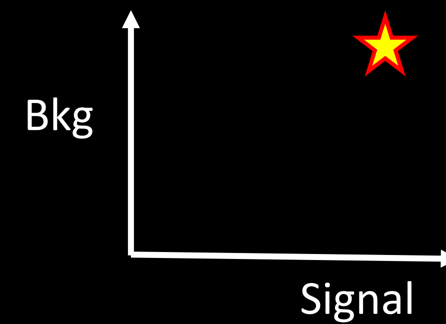
Searches in the Galactic Center



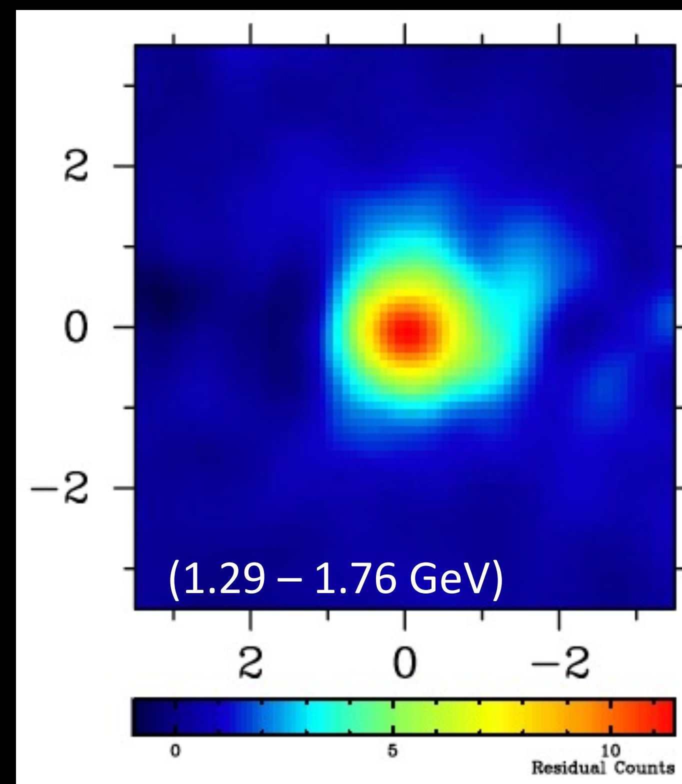
Advantages:
- Strong dark matter signal
- Multi-wavelength data

Disadvantages:
- Complex region
- Intense backgrounds



An unexplained excess found:
- Peaked spectra, $L_\gamma \sim 10^{37\text{-}38}$ erg/s
- Significance $\sim$20–60σ [!]
- Many systematics checks

  → **The Galactic Center Excess**



Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Daylan et al (2014)
Hooper & Slatyer (2013)
Huang et al (2013)
Zhou et al (2014)
Daylan et al (2014)
Calore 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)
Abazajian et al (2018, 2020)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Horiuchi et al (2016)
Linden et al (2016)
Ackermann et al (2017)
Macias et al (2019)
Bartels et al (2018)
Balaji et al (2018)
Zhong et al (2019)
Chang et al (2020)
Buschmann et al (2020)
Leane & Slatyer (2020)
List et L (2020)
Di Mauro (2020)
Burns et al (2020)
…

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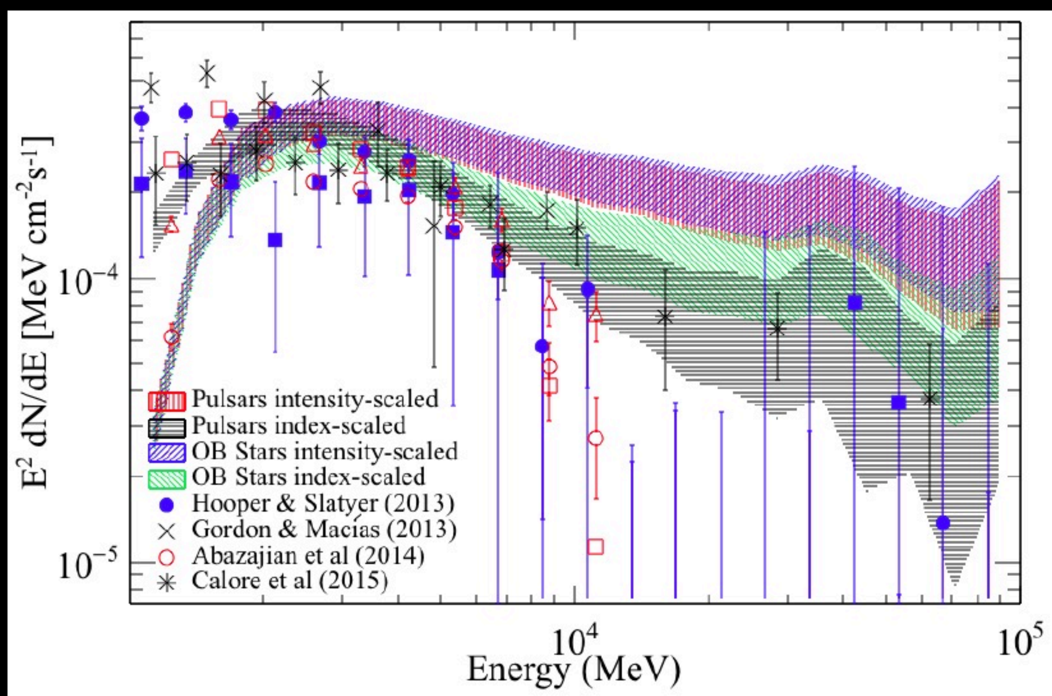
THE ASTROPHYSICAL JOURNAL, 819:44 (30pp), 2016 March 1 doi:10.3847/0004-637X/819/1/44

CrossMark

FERMI-LAT OBSERVATIONS OF HIGH-ENERGY γ-RAY EMISSION TOWARD THE GALACTIC CENTER

of the interstellar emission and energy ranges used by the respective analyses. Three 1FIG sources are found to spatially overlap with supernova remnants (SNRs) listed in Green's SNR catalog; these SNRs have not previously been associated with high-energy γ-ray sources. Most 3FGL sources with known multi-wavelength counterparts are also found. However, the majority of 1FIG point sources are unassociated. After subtracting the interstellar emission and point-source contributions from the data a residual is found that is a sub-dominant fraction of the total flux. But, it is brighter than the γ-ray emission associated with interstellar gas in the inner $\sim$ 1 kpc derived for the IEMs used in this paper, and comparable to the integrated brightness of the point sources in the region for energies $\gtrsim$ 3 GeV. If spatial templates that peak toward the GC are used to model the positive residual and included in the total model for the $15° \times 15°$ region, the agreement with the data improves, but they do not account for all the residual structure. The spectrum of the positive residual modelled with these



➔ **The data contains a centrally peaked spherical excess (beyond dedicated background models)**

Fermi collaboration (2016)

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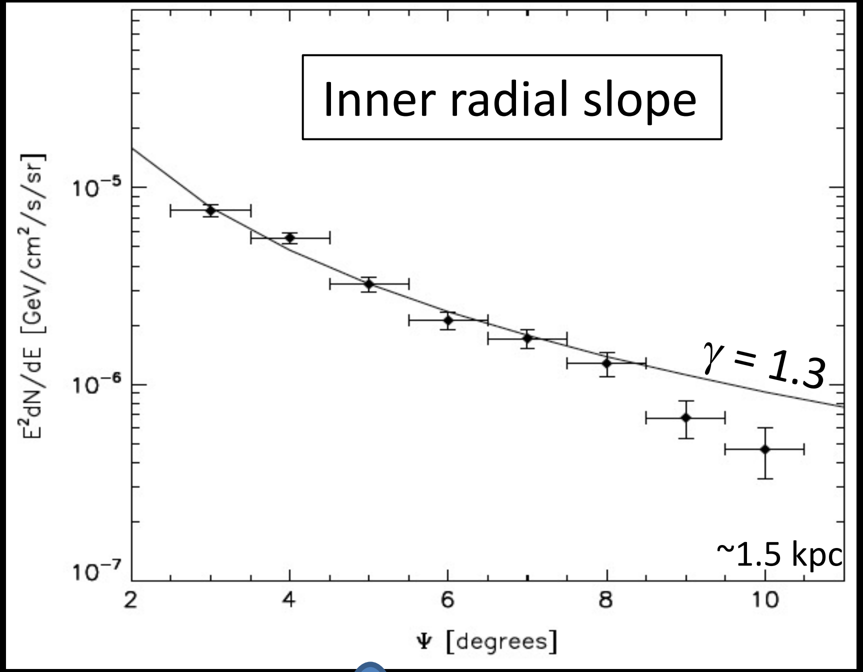
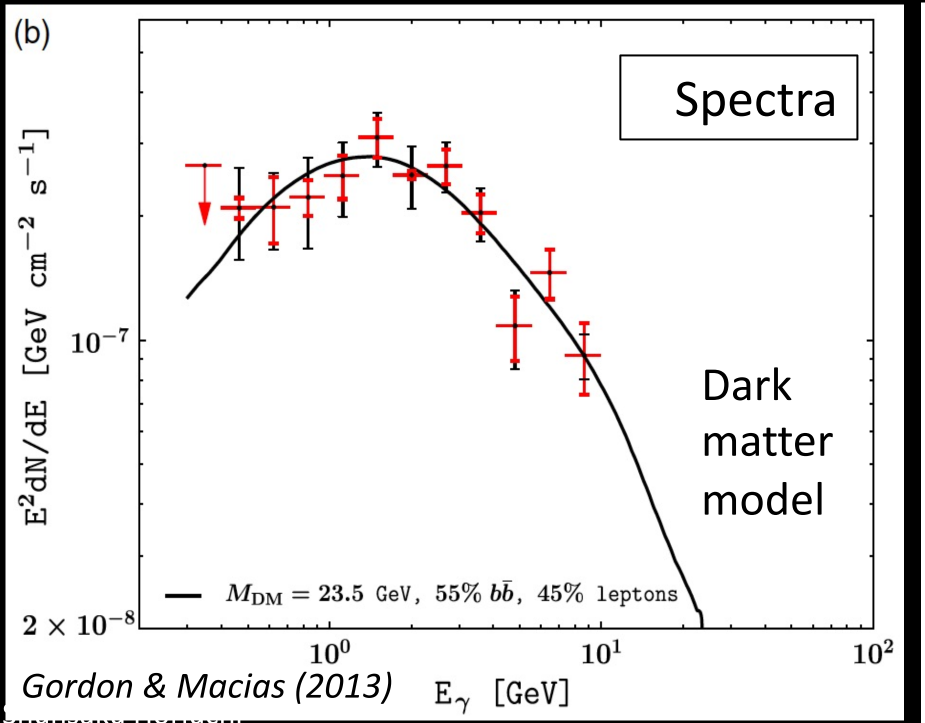
Is it dark matter?

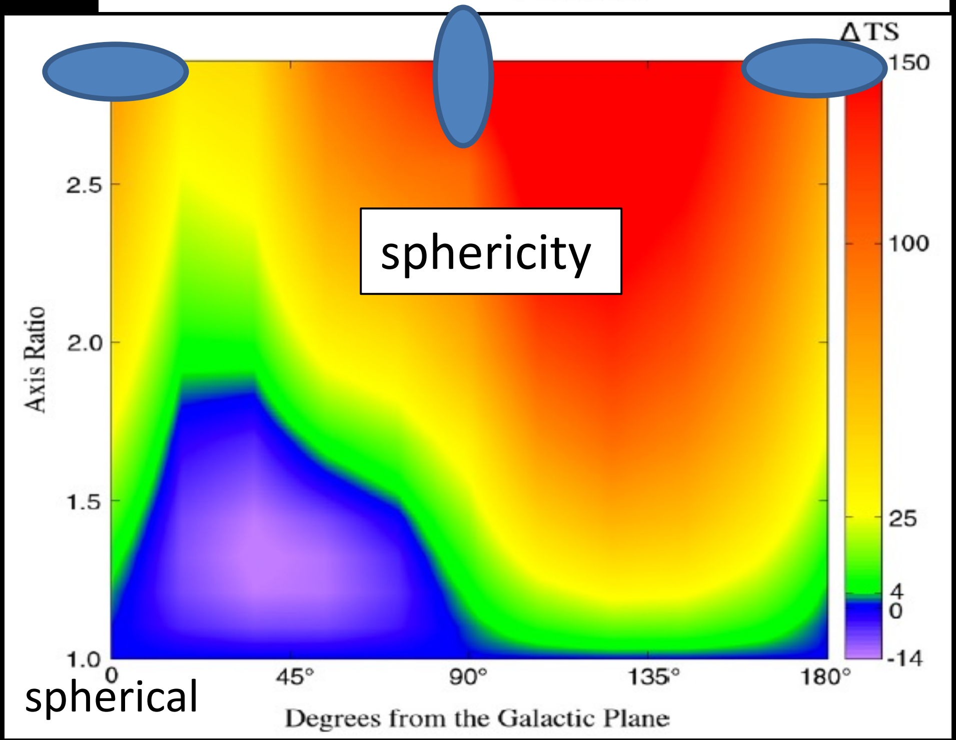
Certainly looks intriguing

- Spectrum consistent with thermally produced dark matter annihilations
- Spatial morphology consistent with dark matter

➔ **All consistent with dark matter**



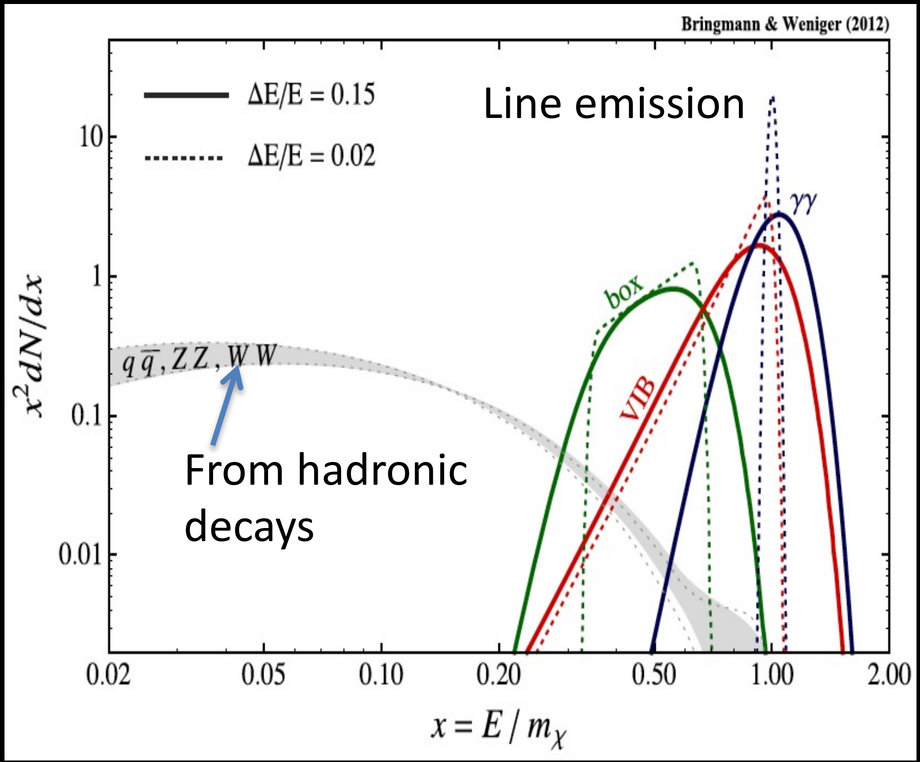




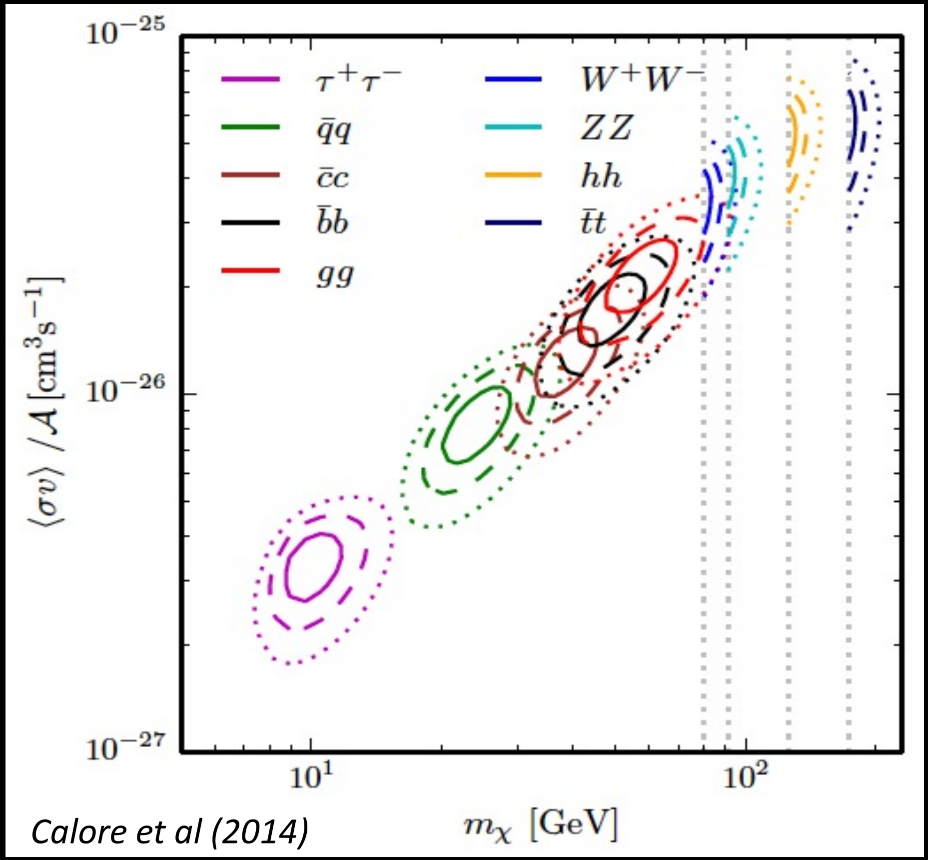
Implications

Annihilation of thermally produced DM (via hadronic decays) explains the spectrum

$$\Phi(E,\psi) = \frac{\sigma_{\rm A} v}{8\pi m_\chi^2}\frac{dN_\gamma}{dE}\int d\ell\,\rho\left[r(\ell,\psi)\right]^2$$



Spectral energy distribution per annihilation



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But wait!

The similarity with a dark matter signal is tantalizing!

→ Hundreds of papers on this possibility

But are there other explanations?

- Nature is often creative and we need to scrutinize this

THE PULSAR HYPOTHESIS & SPATIAL TESTING

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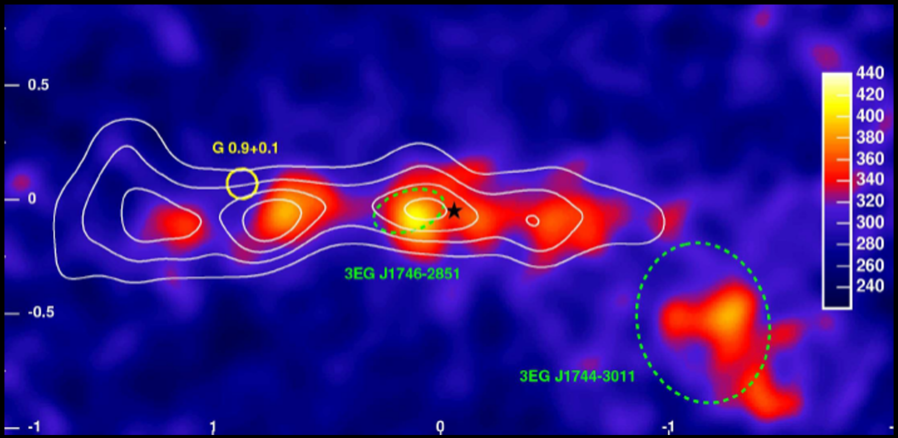
Galactic high-energy sources

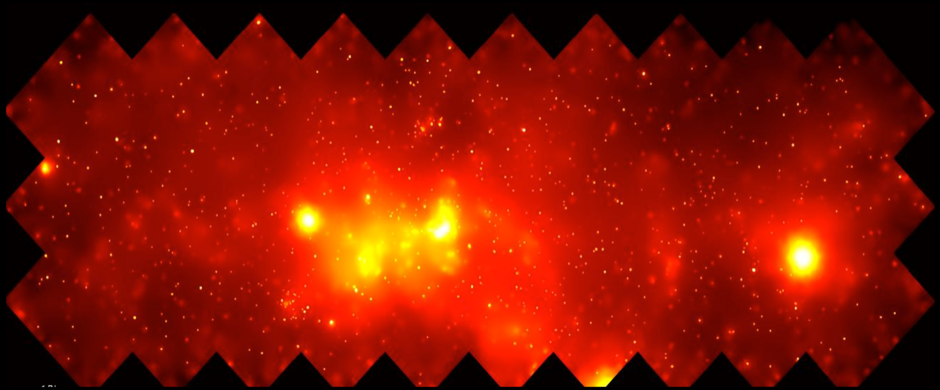
Supernova remnants

SMBH

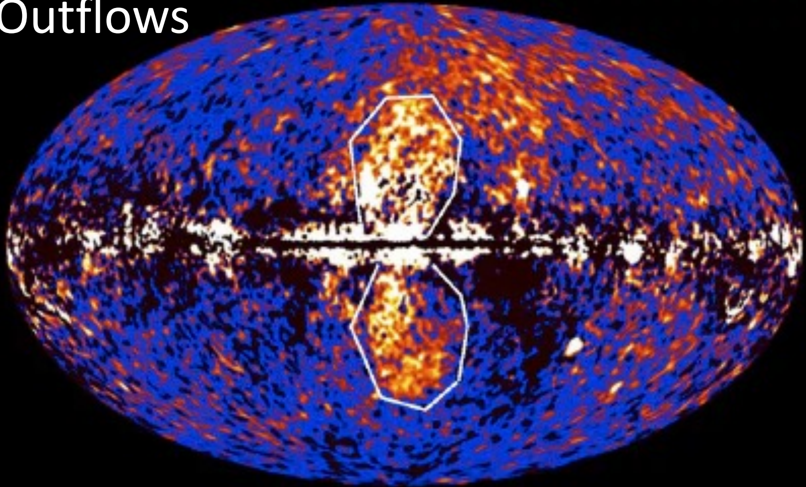


➔ Multiple source classes injecting $\sim 10^{38}$ erg/s

Pulsars



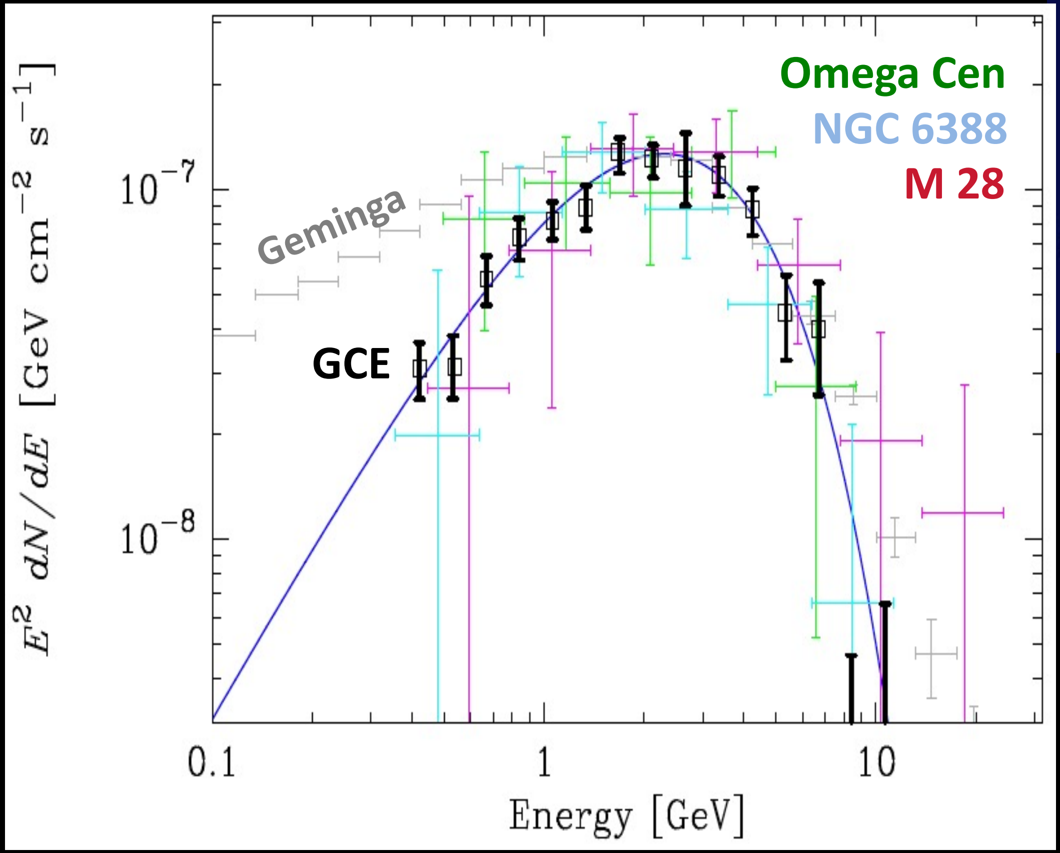
Outflows



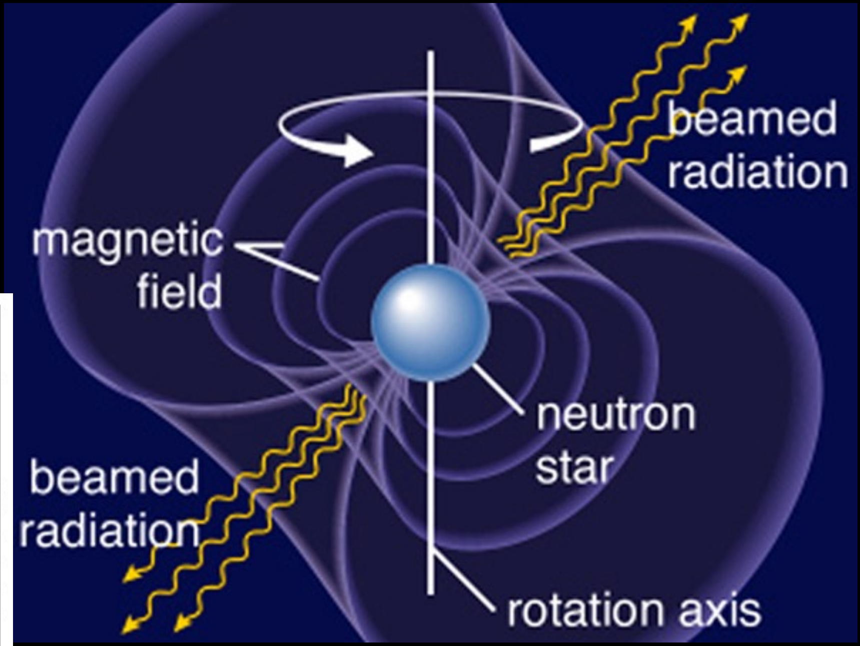
Millisecond pulsars

Millisecond pulsars

- Millisecond pulsars are γ-ray sources with similar spectra to the excess
- $O(10^4)$ needed in the Galactic Center

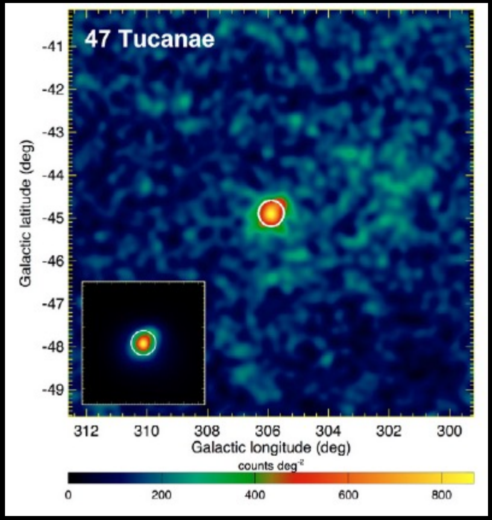


Abazajian (2011)



Gamma-ray observations of globular clusters

e.g., Fermi (2010)



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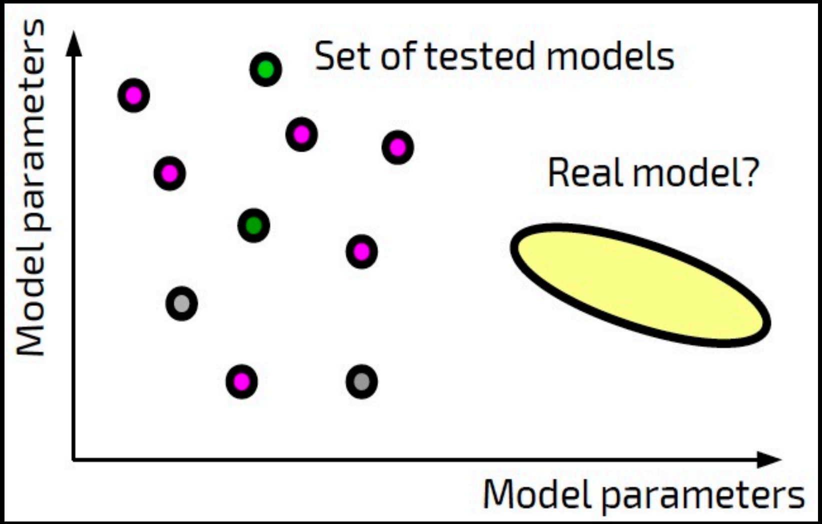
New approaches

Are millisecond pulsars causing the gamma-ray excess?

Mindful to implement something different

Studies have shared similarities (e.g., background modeling)

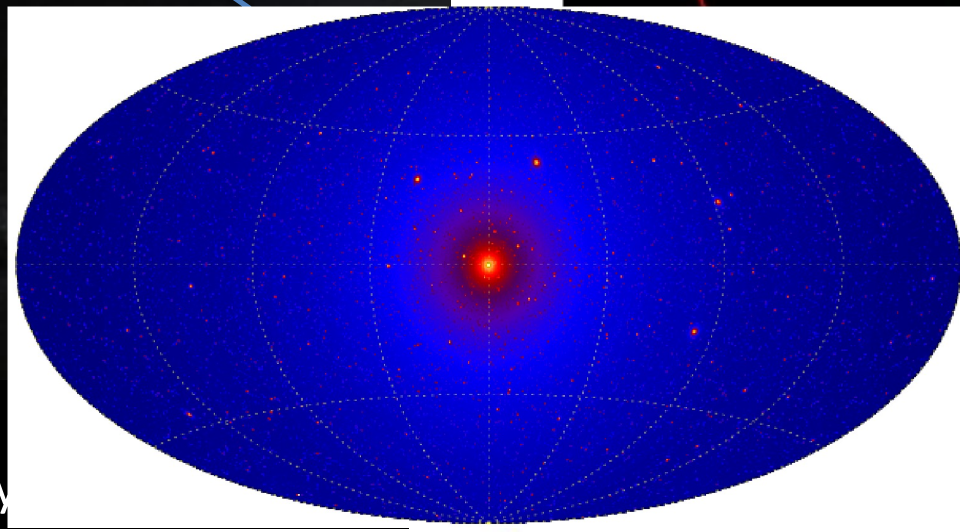


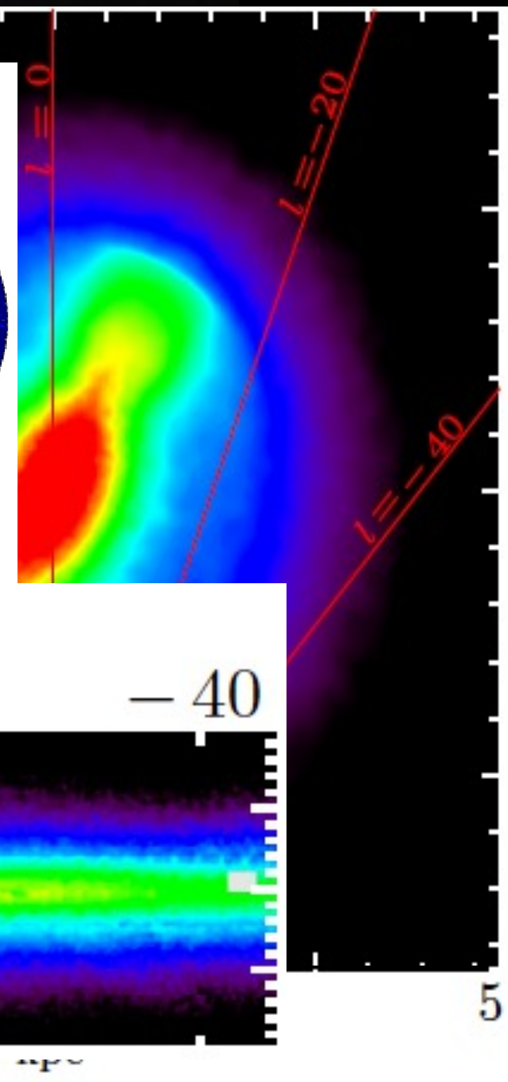
New focus:

1. New hypothesis test
2. Background modeling: better physics-driven models

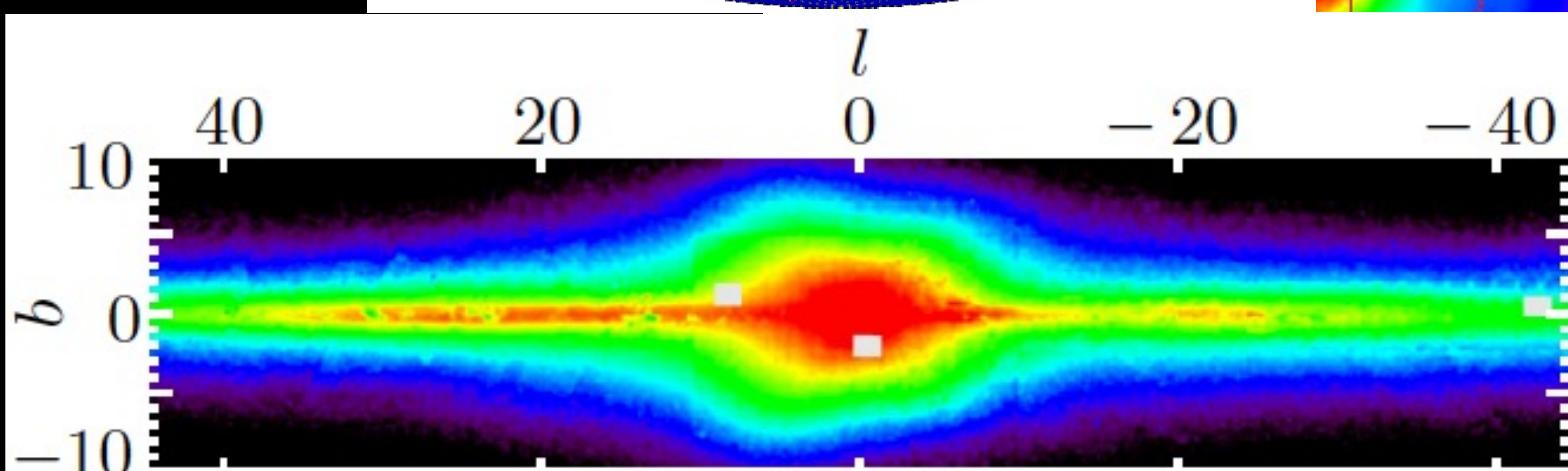
Millisecond pulsar morphology

Bulge: ~1/3 mass of the Galaxy and very old (> 8 Gyrs)





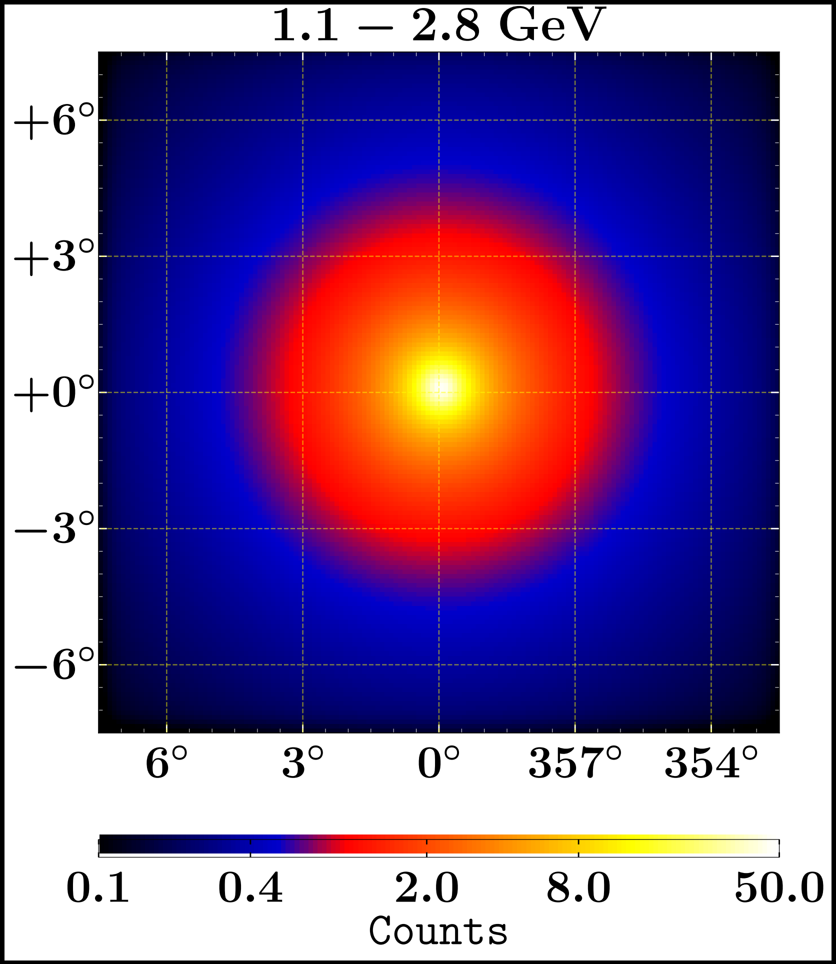
The boxy bulge:
rectangle, not sy



Bland-Hawthorn & Gerhard (2017)

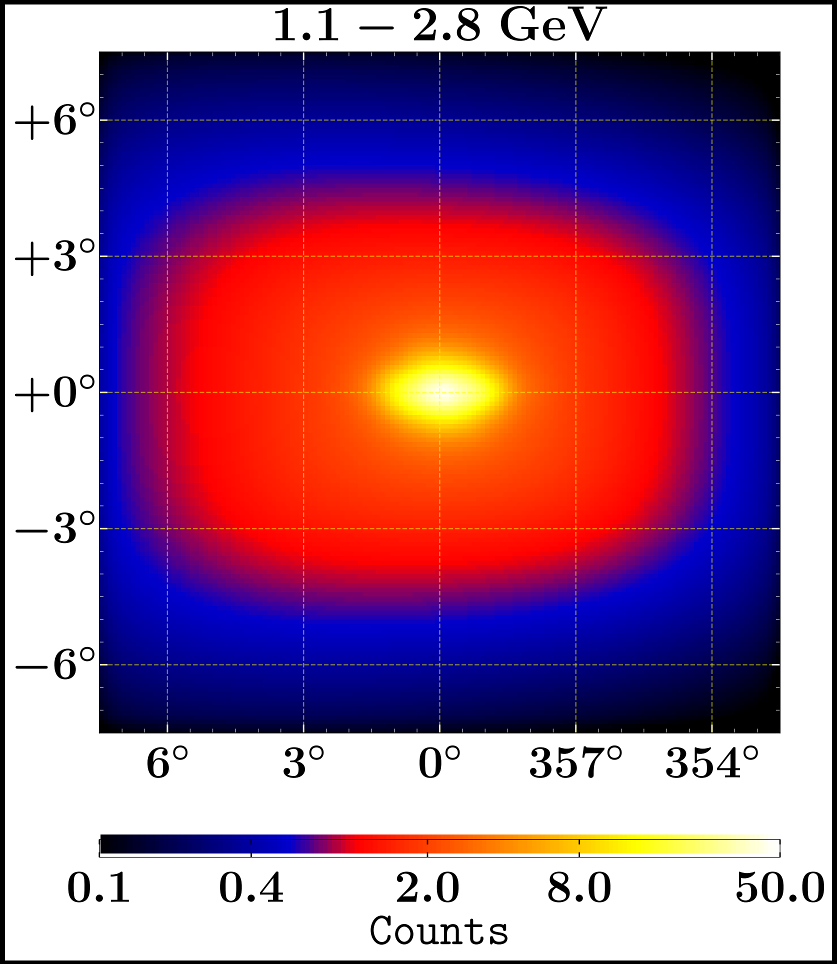
The hypothesis

Dark matter annihilation



VS

Astrophysics (pulsar)



(Use Freudenreich 1998)

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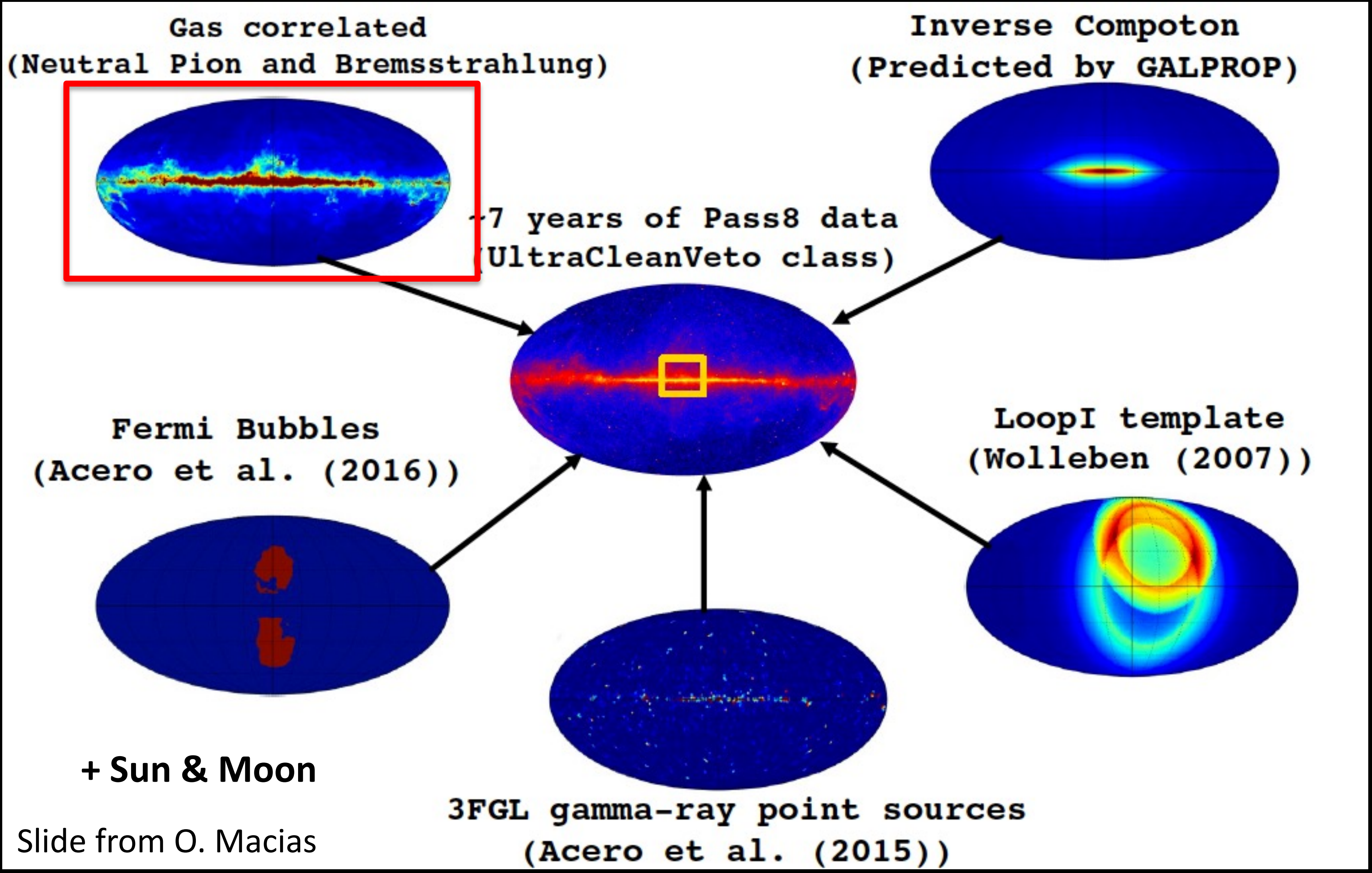
Baseline background model

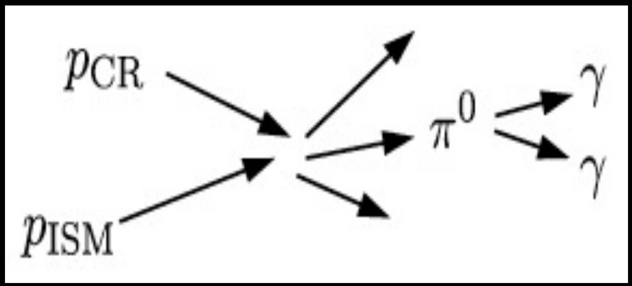


+ Sun & Moon

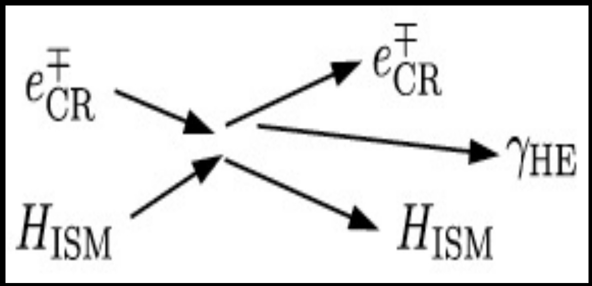
Slide from O. Macias

Background I

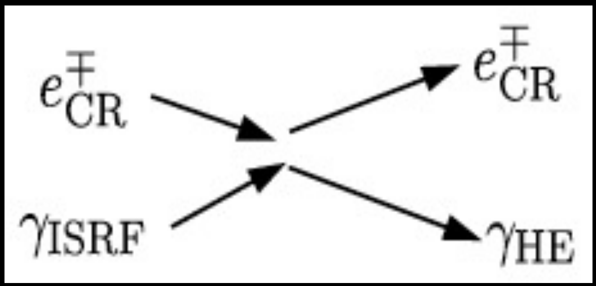
Decay of neutron pions



Bremsstrahlung



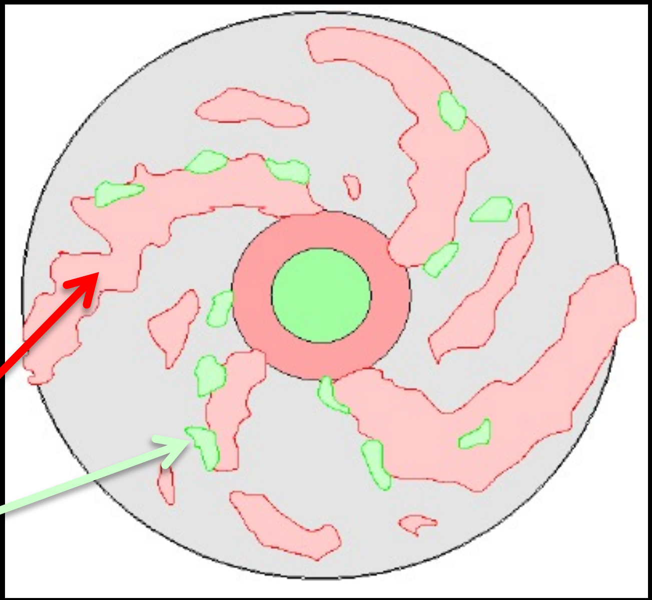
Inverse Compton



Strategies

1. Minimalist: use multi-wavelength e.g. gas maps

- ✓ Empirical
- ✓ Most of gamma is gas-dependent
- ✗ Does not capture salient variations of cosmic-ray injection and propagation

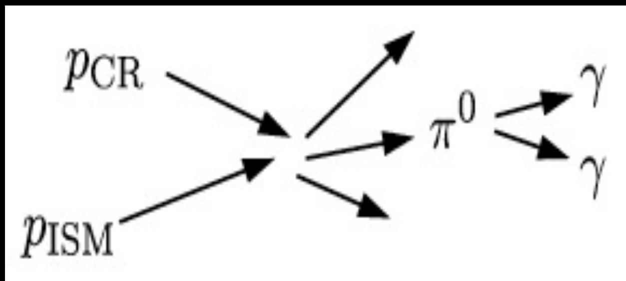


Atomic HI is measured by 21-cm emission

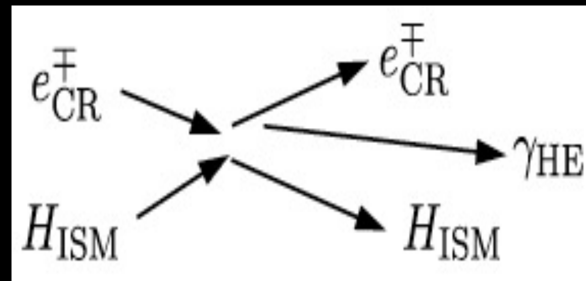
Molecular H2 is traced by the 2.6mm line of CO

Background II

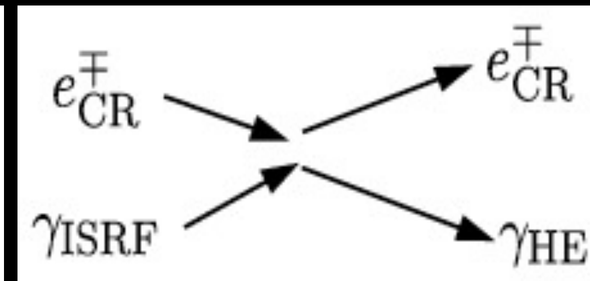
Decay of neutron pions



Bremsstrahlung



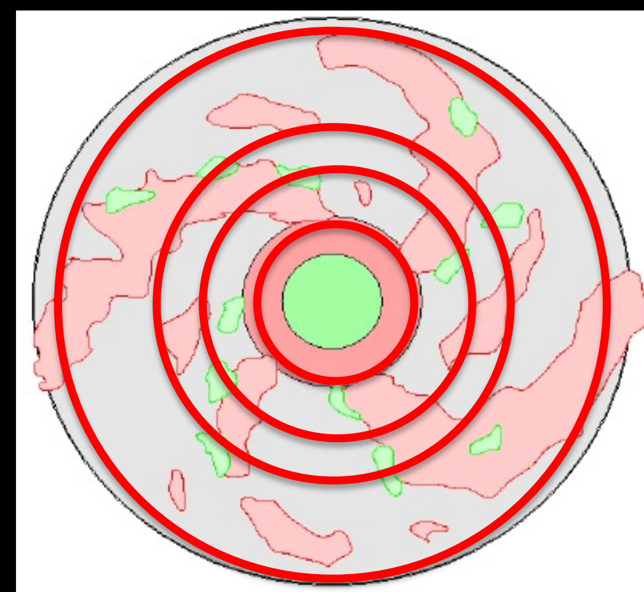
Inverse Compton



Strategies

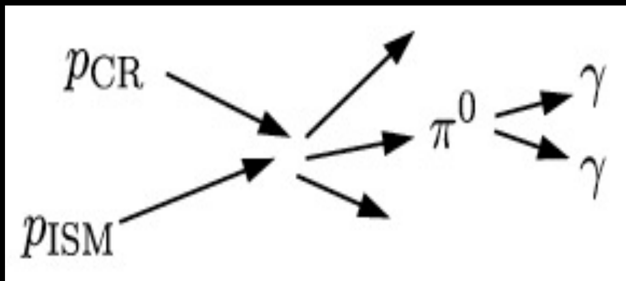
1. Minimalist: use multi-wavelength e.g. gas maps
2. Empirical model: data-driven and annuli to account for desired flexibility

- ✓ Empirical
- ✓ Accounts for some cosmic-ray injection and propagation variations (annuli)
- ✓ Can be tuned to the Galactic Center
- ✗ Time consuming

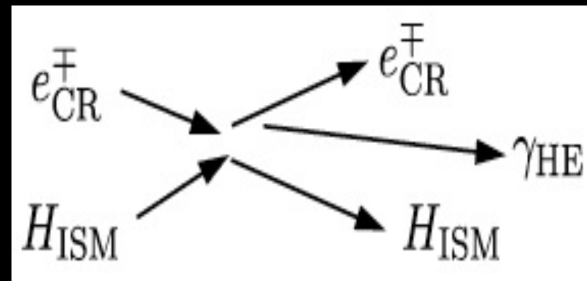


Background III

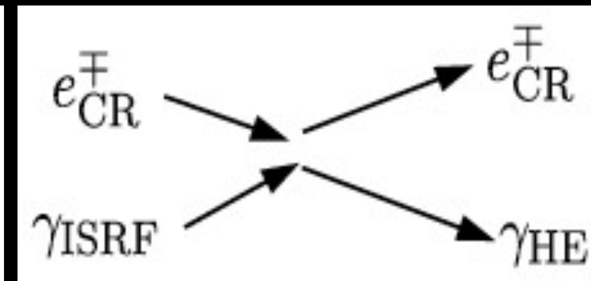
Decay of neutron pions



Bremsstrahlung



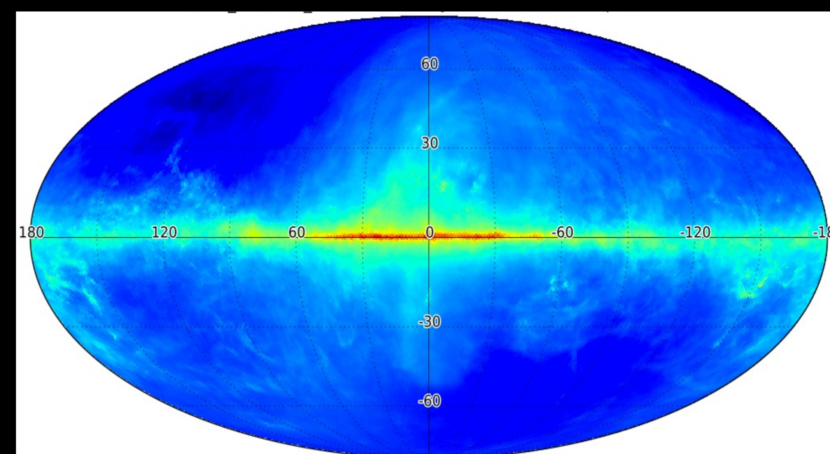
Inverse Compton



Strategies

1. Minimalist: use multi-wavelength e.g. gas maps
2. Empirical model: data-driven and annuli to account for desired flexibility
3. Fermi diffuse map: built for all-sky starting with many templates and annuli

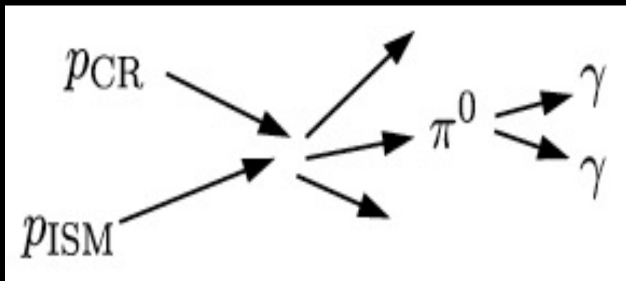
✓ Simple (hard work done!)
✓ Accounts for some cosmic-ray injection and propagation variations (via annuli)
✗ Somewhat of a black box for user
✗ Fixed to (usually) older data
✗ Constructed not dedicated for the Galactic Center



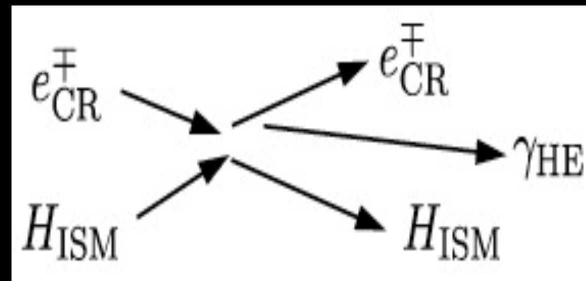
Acero et al (2016)

Background IV

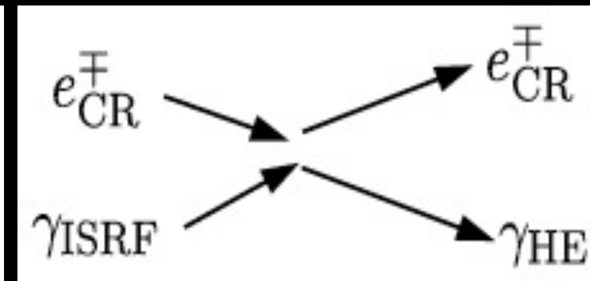
Decay of neutron pions



Bremsstrahlung



Inverse Compton

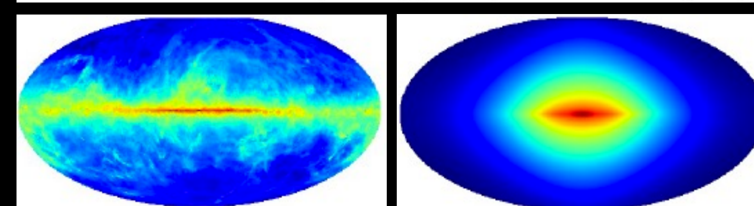


Strategies

1. <u>Minimalist</u>: use multi-wavelength e.g. gas maps
2. <u>Empirical model</u>: data-driven and annuli to account for desired flexibility
3. <u>Fermi diffuse map</u>: built for all-sky starting with many templates and annuli
4. <u>Model builder</u>: numerically solve the diffusion equation

✓ Allows physical parameter choices
✓ Can be tuned to the Galactic Center
✗ Many parameters not well known
✗ Still poor resolution

$$\frac{\partial\psi}{\partial t} = q(\vec{r},p) + \vec{\nabla}\cdot(D_{xx}\vec{\nabla}\psi - \vec{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left[\dot{p}\psi - \frac{p}{3}(\vec{\nabla}\cdot\vec{V})\psi\right] - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

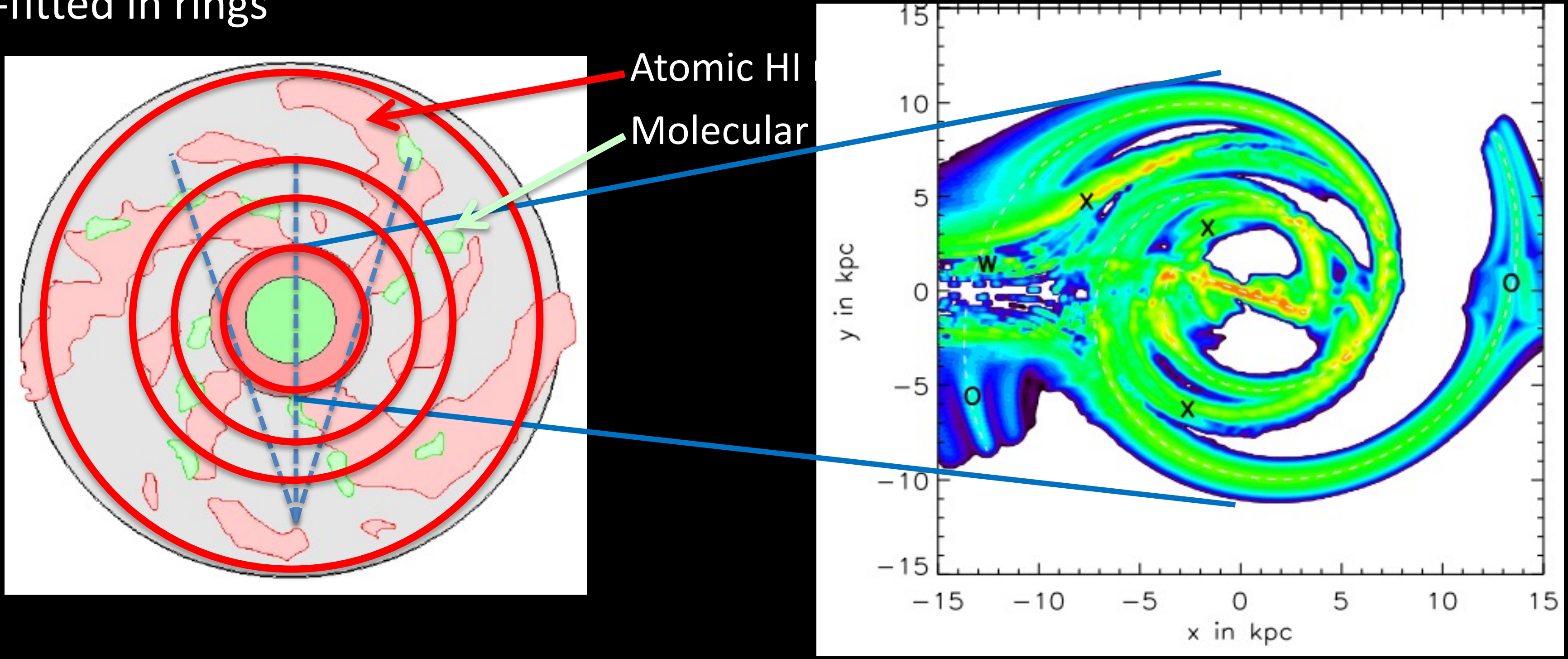


e.g., Galprop; Moskalenko & Strong (1998)

Improve background modeling

Previous approach

Single gas-map model assuming circular motion and interpolation between edges, pre-fitted in rings



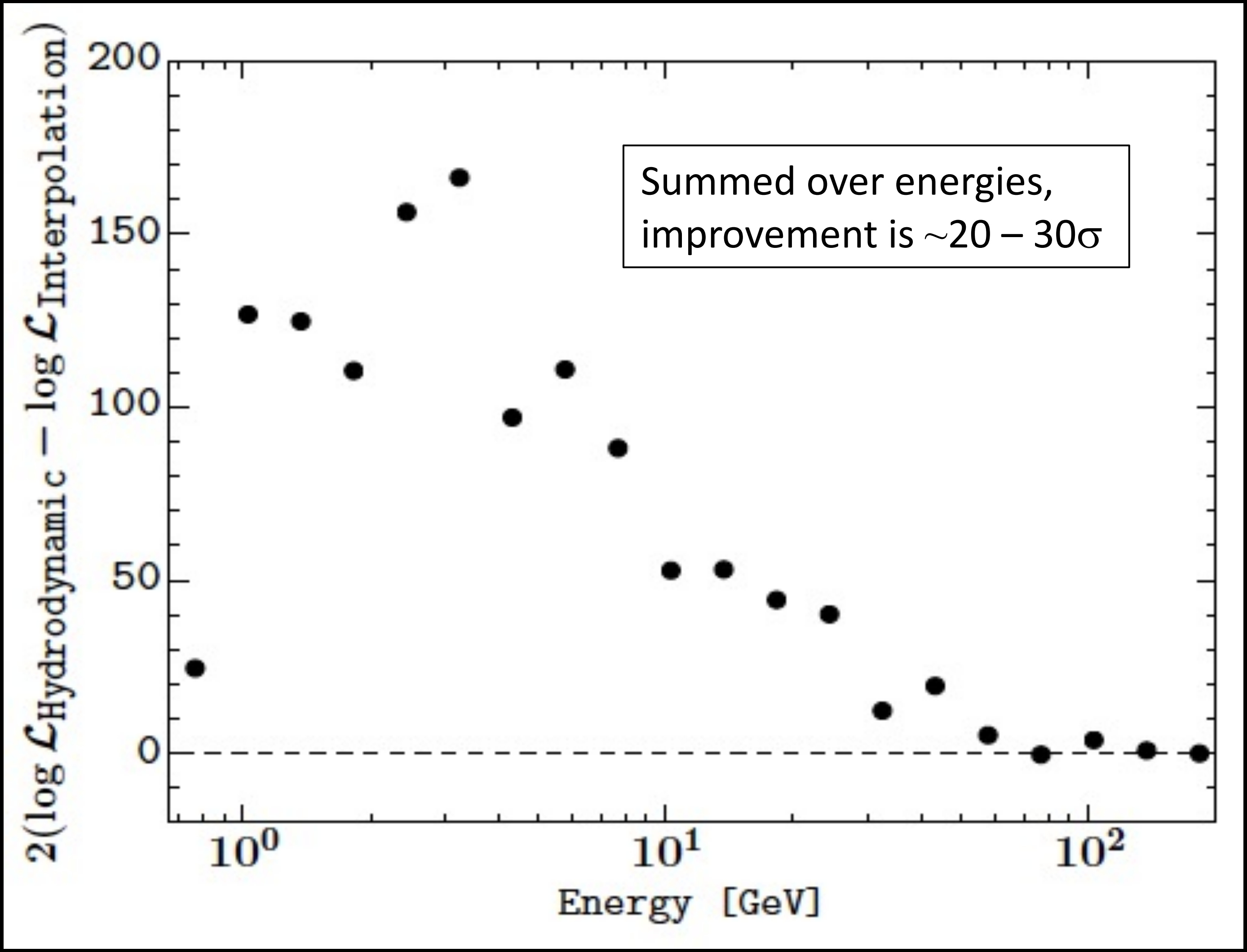
Pohl et al (2009)

New approach

- Gas-flow model from SPH simulations which include the bulge + disk potential
- Split gas-map model into rings

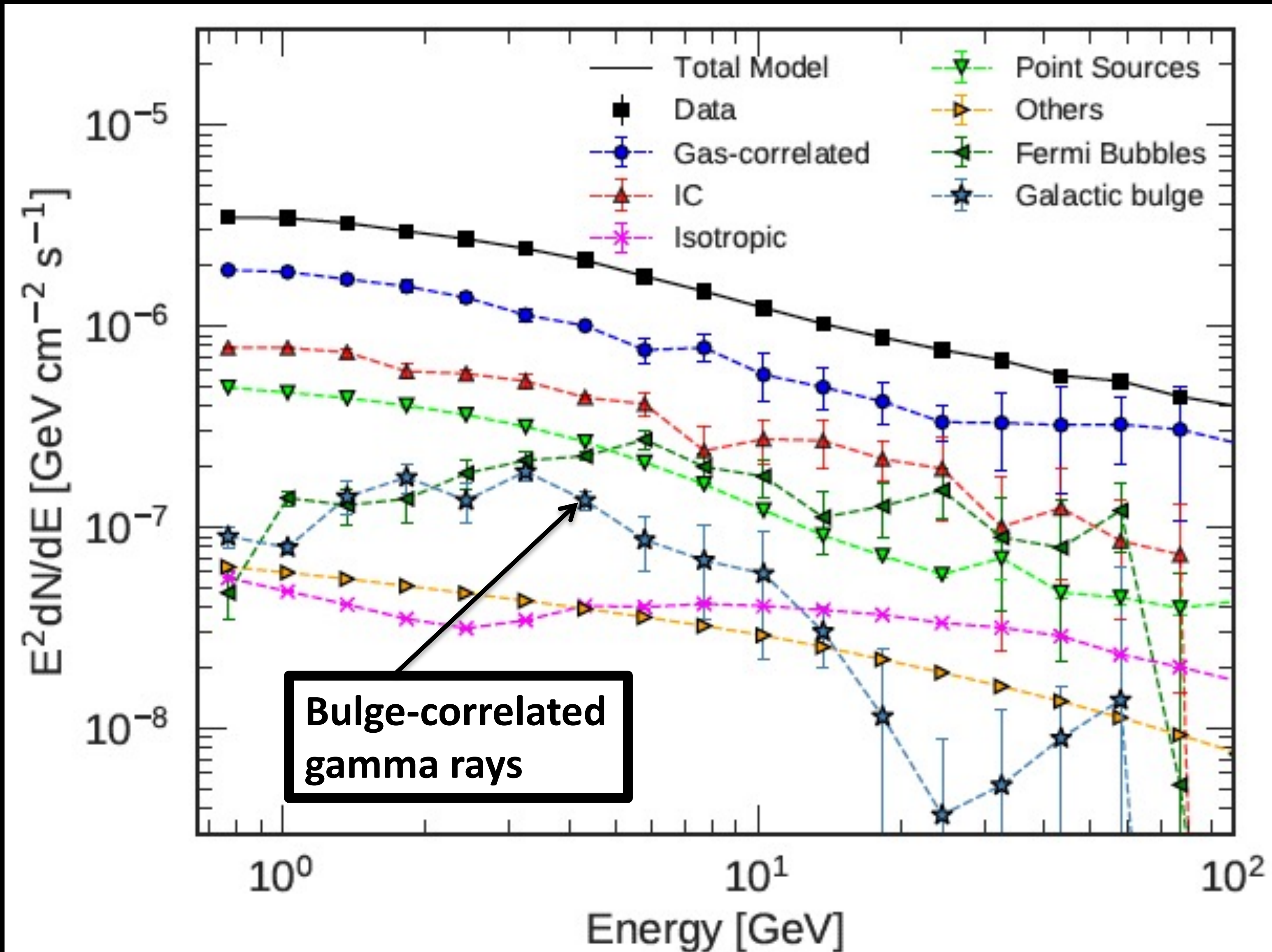
New background model much better

Significant improvement observed by hydrodynamical templates



Macias et al (2018)

Detection!!!



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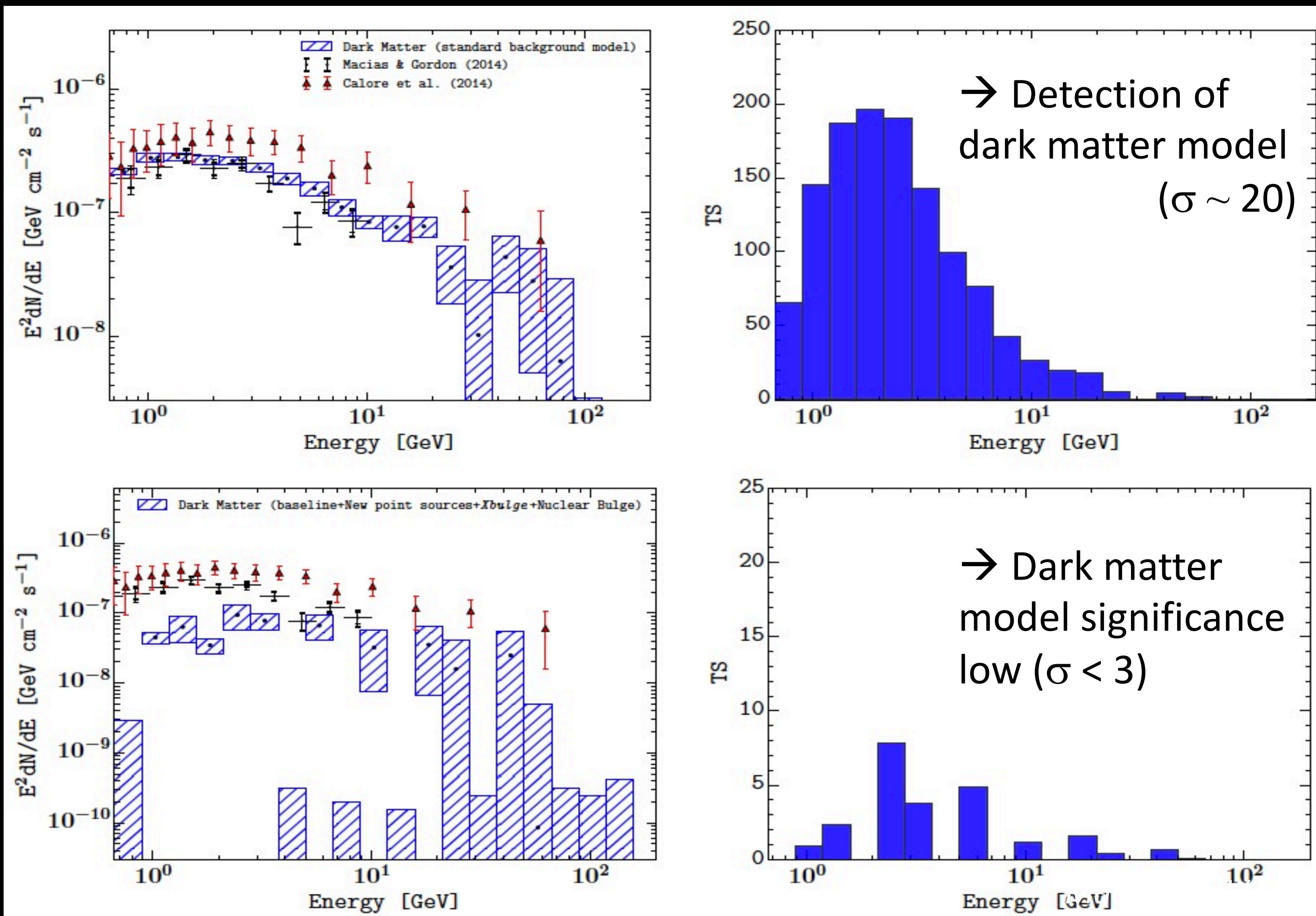
Macias et al (2018)

No dark matter correlated gamma rays!

Evidence for dark matter now gone



← WITHOUT bulge
(representative of previous studies)

← WITH bulge
Including our new extended bulge, the **data no longer needs a dark matter component**

Macias et al (2018)

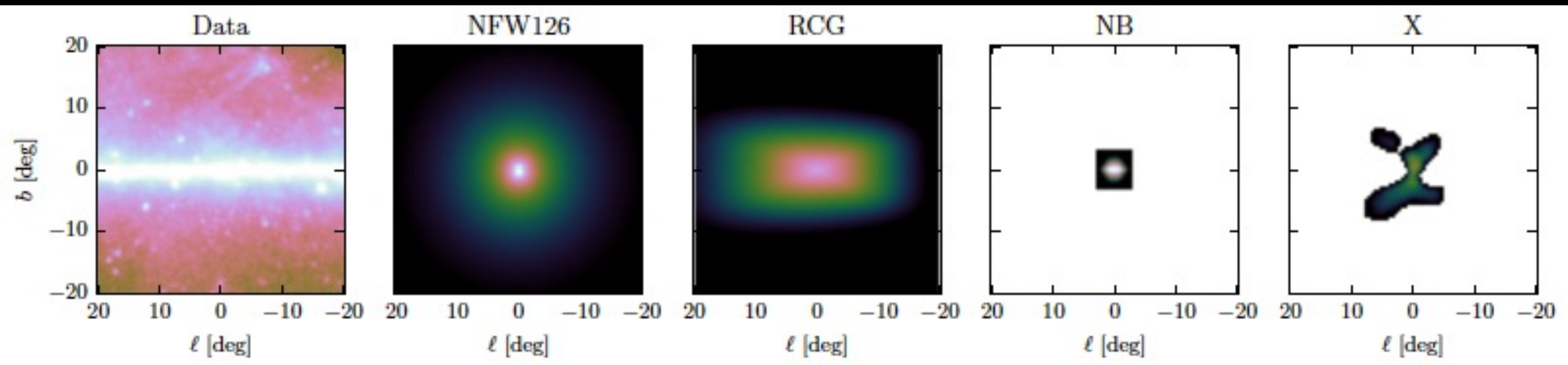
Shunsaku Horiuchi

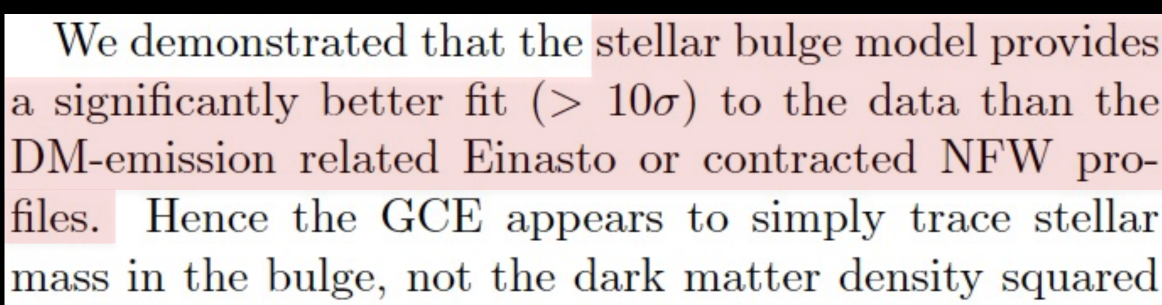
SkyFACT : a hybrid approach

SkyFACT = **Sky F**actorization with **A**daptive **C**onstrained **T**emplates

Hybrid method to study diffuse gamma rays that combines adaptive spatial-spectral template regression and image reconstruction to account for small-scale model inaccuracies.

Storm et al (2017)




We demonstrated that the stellar bulge model provides a significantly better fit ($> 10\sigma$) to the data than the DM-emission related Einasto or contracted NFW profiles. Hence the GCE appears to simply trace stellar mass in the bulge, not the dark matter density squared

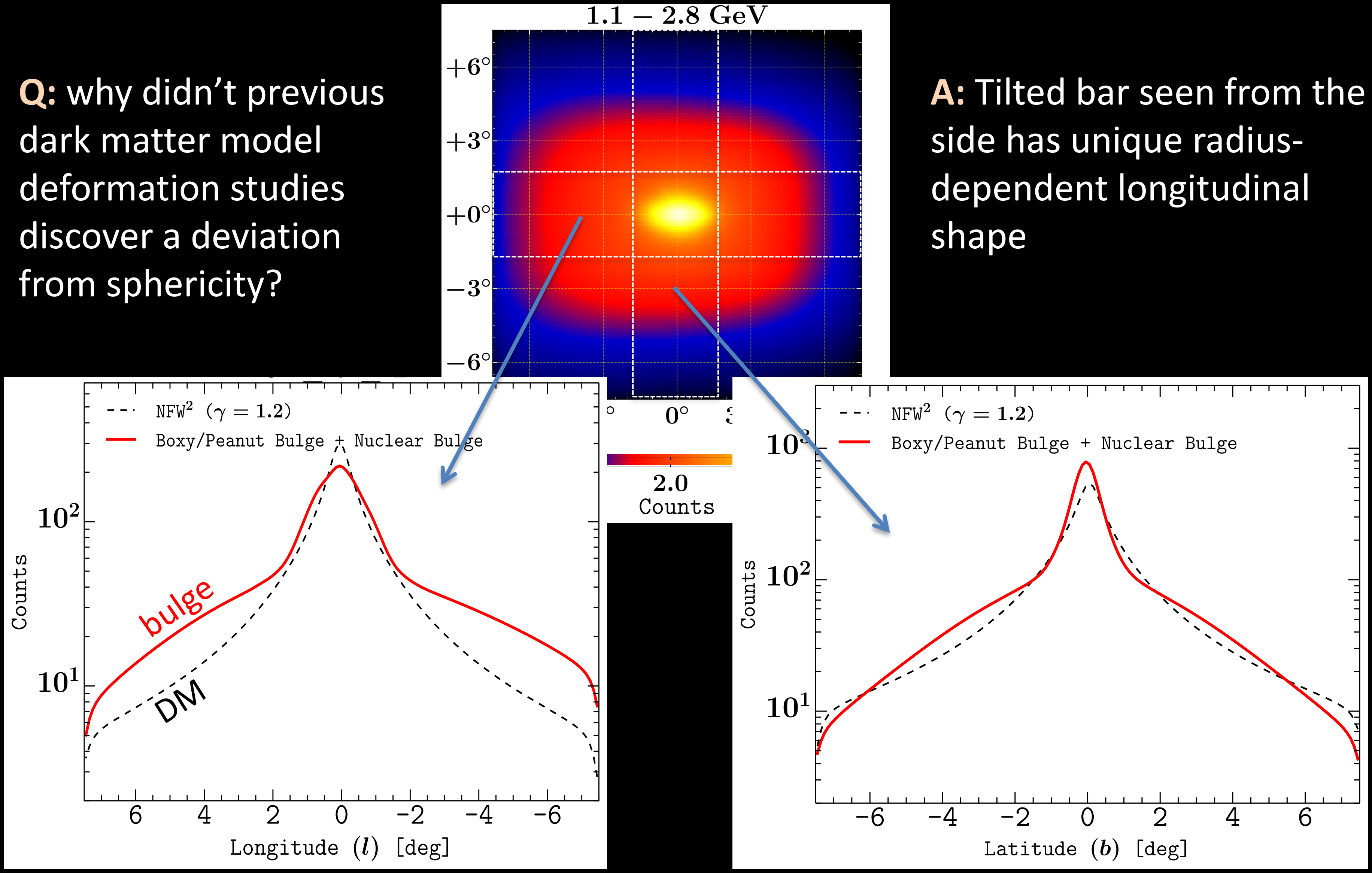
Fit in central 40x180 degrees, which facilitates the fitting of gas template rings (x3) and provides leverage to disentangle components.

Bartels et al (2018)

How are the two distinguished?

Q: why didn't previous dark matter model deformation studies discover a deviation from sphericity?

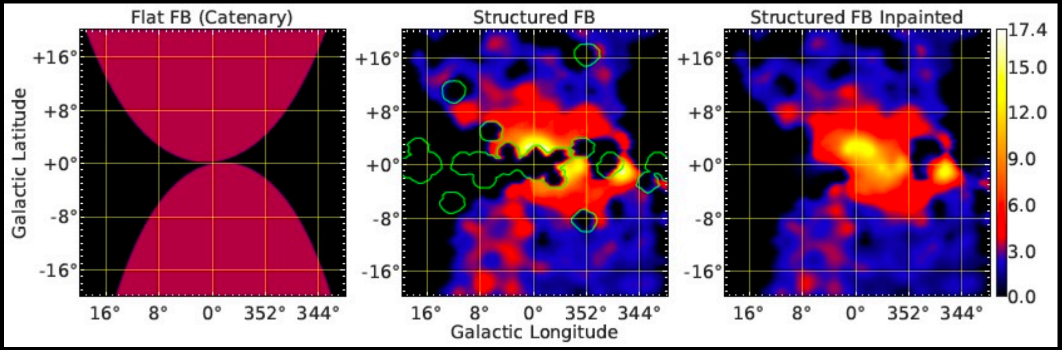
A: Tilted bar seen from the side has unique radius-dependent longitudinal shape



Systematics

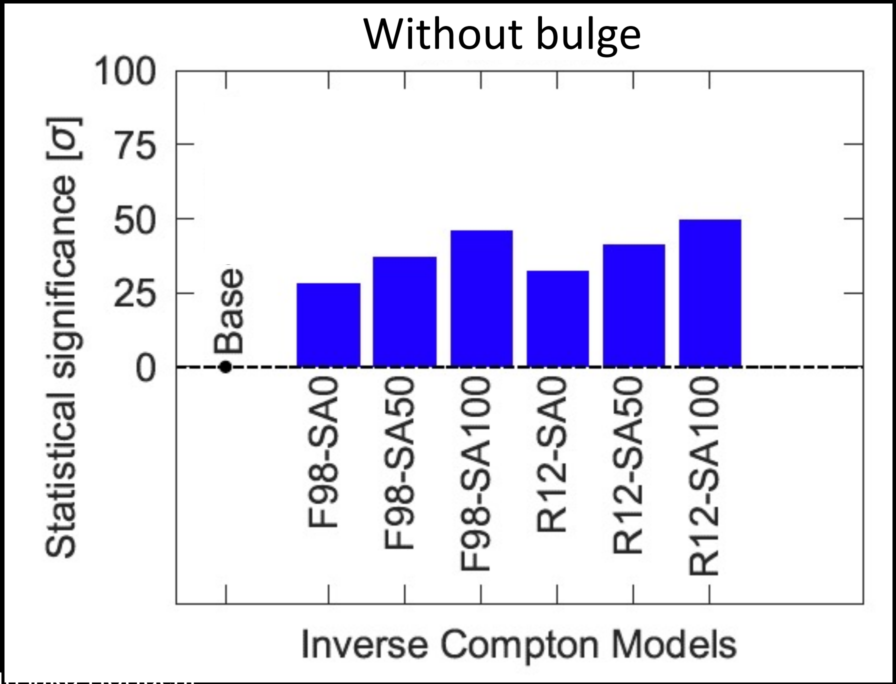
Many astrophysical systematics

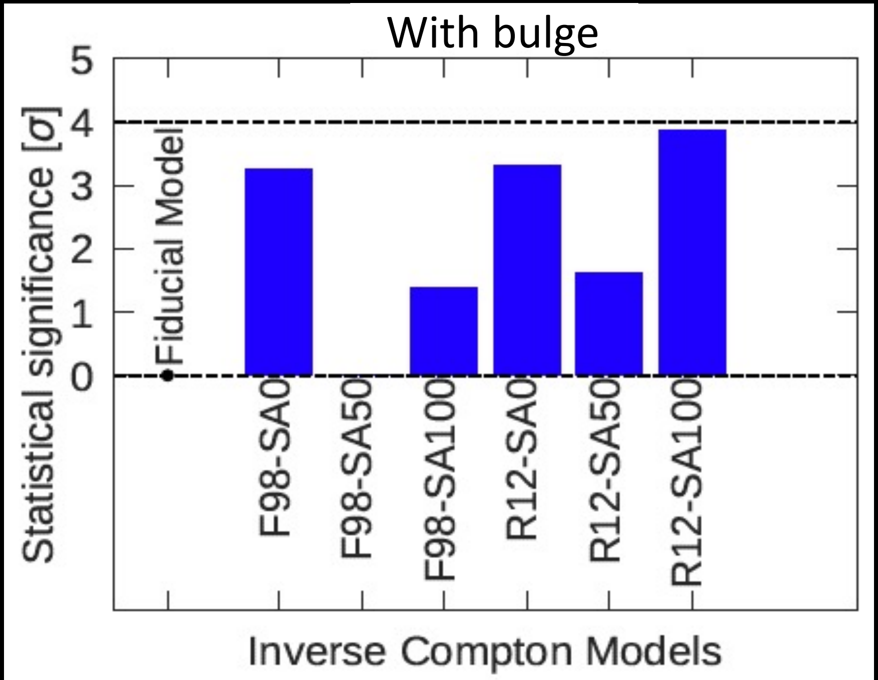
1. Bulge model
2. Fermi bubble model
3. Background (IC models)
4. Background (gas maps)
5. Point source catalogs
6. Galactic disk masks



Significance of NFW^2 for bulge and IC model combinations

Macias et al (2018, 2019)





Systematics

Gas maps: using the gas maps used by the Fermi Diffuse models yield the same conclusions

Base	Source	$\log(\mathcal{L}_{\text{Base}})$	$\log(\mathcal{L}_{\text{Base+Source}})$	$\text{TS}_{\text{Source}}$	σ	Number of source parameters
baseline+$\boxed{\text{NB+Boxy}}$	$\boxed{\text{NFW}}$	-172005.9	-171999.0	13.8	$\boxed{1.4}$	19
baseline+NFW	NB+Boxy	-172167.9	-171999.0	337.8	18.3	2×19
baseline*	NFW	-173565.0	-172929.2	1272	34.6	19
baseline*+NFW	NB+Boxy	-172929.2	-172533.0	792.4	28.2	2×19
baseline*+$\boxed{\text{NB+Boxy}}$	$\boxed{\text{NFW}}$	-172547.4	-172533.0	28.8	$\boxed{3.0}$	19

Point sources: using none or the 2FIG point source catalog yield the same conclusions

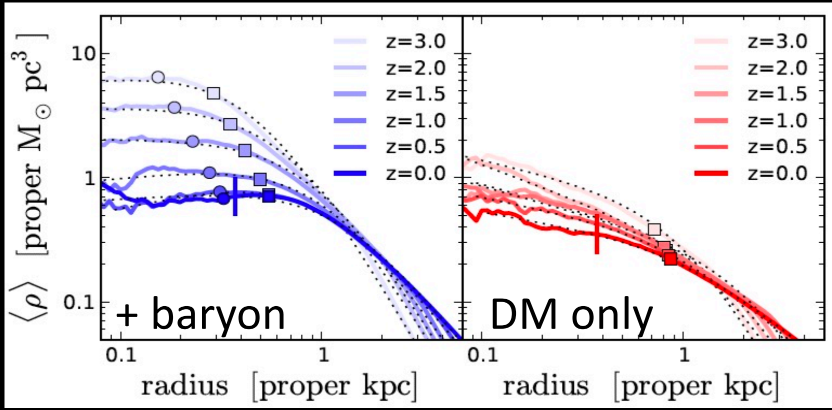
baseline	2FIG	-172461.4	-170710.5	3501	37.3	81×19
baseline+2FIG	Boxy	-170710.5	-170536.3	348.4	18.7	19
baseline+2FIG	NFW	-170710.5	-170484.6	452	19.9	19
baseline+2FIG	NB	-170710.5	-170470.5	480	20.6	19
baseline+2FIG+NB	NFW	-170470.5	-170387.8	165	11.1	19
baseline+2FIG+NB	Boxy	-170470.5	-170317.2	306.6	17.5	19
baseline+$\boxed{\text{2FIG+NB+Boxy}}$	$\boxed{\text{NFW}}$	-170317.2	-170313.5	7.4	$\boxed{0.5}$	19

Galactic plane mask: using a $|b| < 1$ deg mask yields the same conclusions

baseline	NFW	-430824.6	-430696.9	255	14.4	19
baseline	Boxy	-430824.6	-430626.1	397	18.5	19
baseline	NP	-430824.6	-430189.9	1269	35.6	22×19
baseline+NP	NFW	-430189.9	-430097.0	186	12.0	19
baseline+NP	Boxy	-430189.9	-430035.8	308	16.1	19
baseline+NP+$\boxed{\text{Boxy}}$	$\boxed{\text{NFW}}$	-430035.8	-430026.3	19	$\boxed{2.0}$	19

Dark matter systematics

Kuhlen et al (2012)

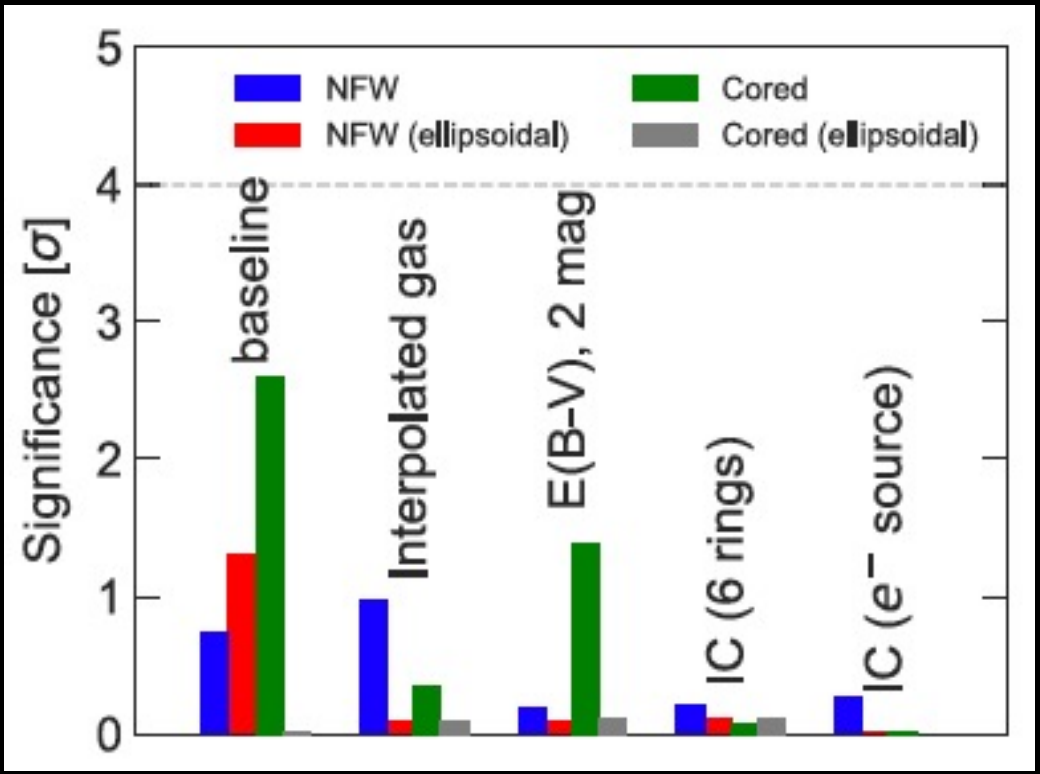


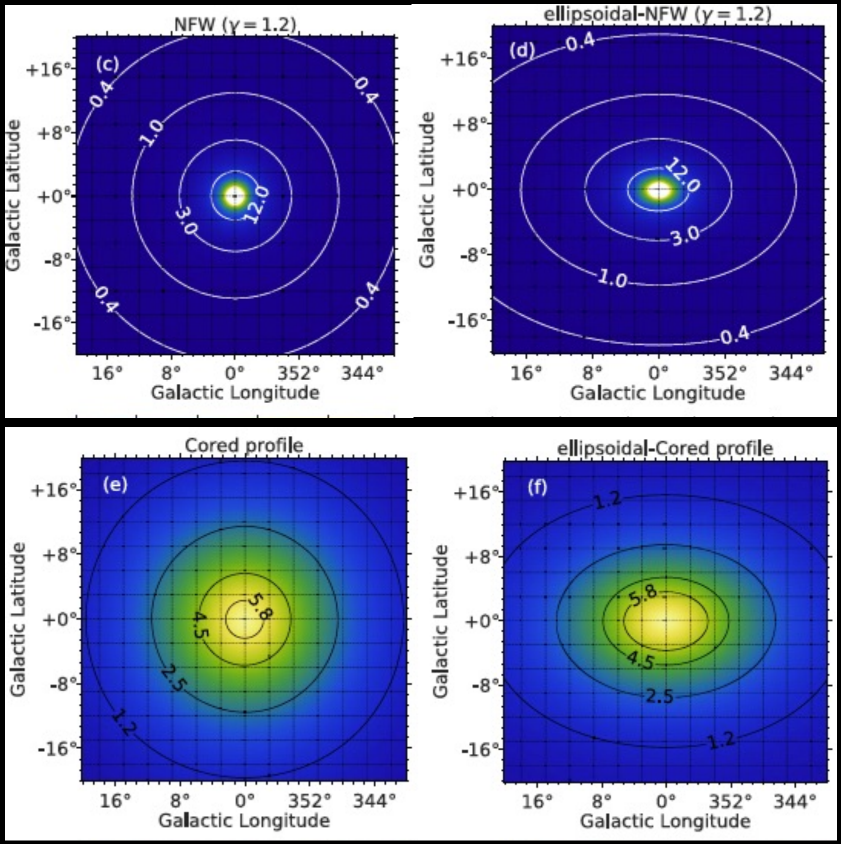
1. Inner slope, including cores
2. Asymmetry

➔ Try γ [0.5,1.5], 1kpc core, axis ratio 0.7

Eg, bulge kinematics, Eris, FIRE simulations

➔ Again dark matter model not detected

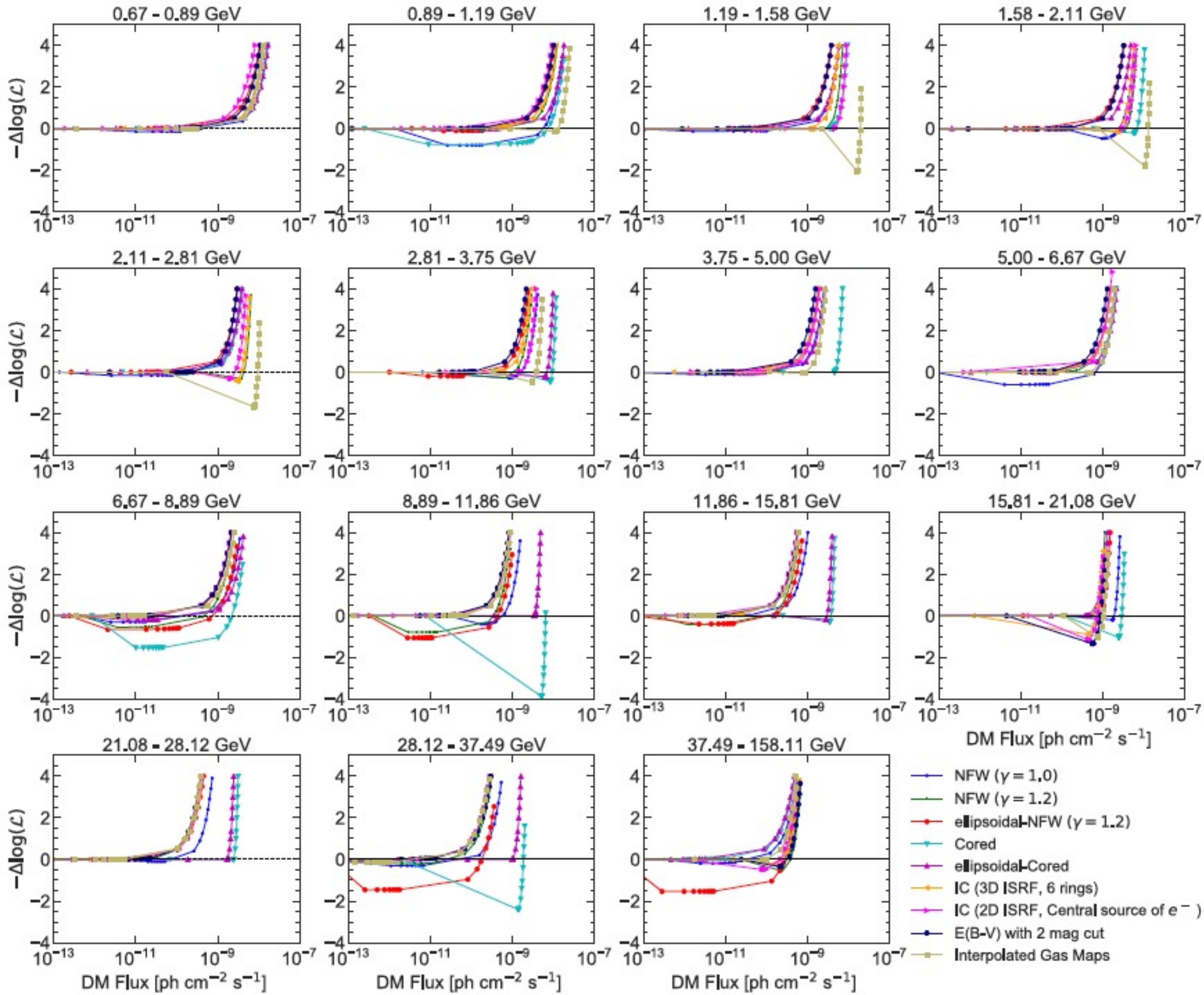




Abazajian, Horiuchi, et al (2020)

Shunsaku Horiuchi

IMPLICATIONS

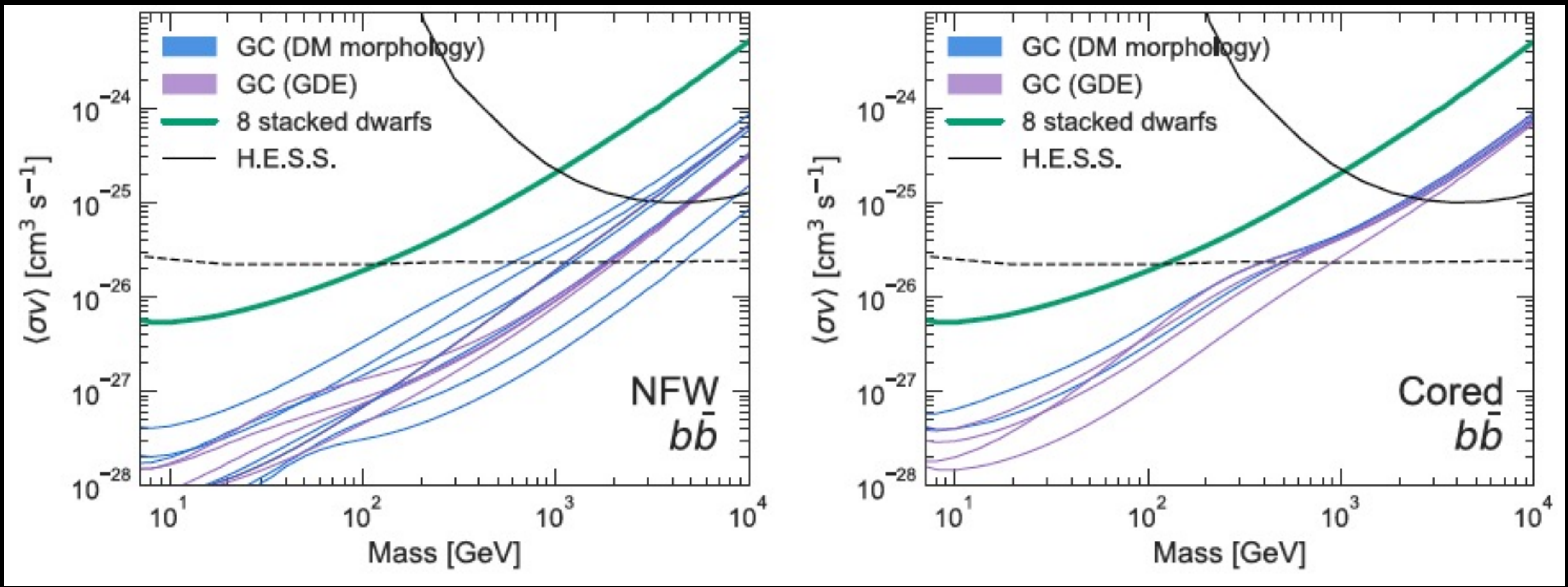

0.67 - 0.89 GeV
0.89 - 1.19 GeV
1.19 - 1.58 GeV
1.58 - 2.11 GeV
2.11 - 2.81 GeV
2.81 - 3.75 GeV
3.75 - 5.00 GeV
5.00 - 6.67 GeV
6.67 - 8.89 GeV
8.89 - 11.86 GeV
11.86 - 15.81 GeV
15.81 - 21.08 GeV
21.08 - 28.12 GeV
28.12 - 37.49 GeV
37.49 - 158.11 GeV
$-\Delta\log(\mathcal{L})$
DM Flux [ph cm^{-2} s^{-1}]
NFW ($\gamma = 1.0$)
NFW ($\gamma = 1.2$)
ellipsoidal-NFW ($\gamma = 1.2$)
Cored
ellipsoidal-Cored
IC (3D ISRF, 6 rings)
IC (2D ISRF, Central source of e^-)
E(B-V) with 2 mag cut
Interpolated Gas Maps

Shunsaku

Improved sensitivity to dark matter

We addressed a major systematic, which allowed us to realize the potential of the Galactic Center to constrain dark matter

Abazajian, Horiuchi, et al (2020)



- Impacts of NFW slope [0.5,1.5] & sphericity
- Impacts of background modeling

- Impacts of core (1 kpc) & sphericity
- Impacts of background modeling

➔ Tests thermal dark matter out to ~500 GeV

Millisecond pulsar insights

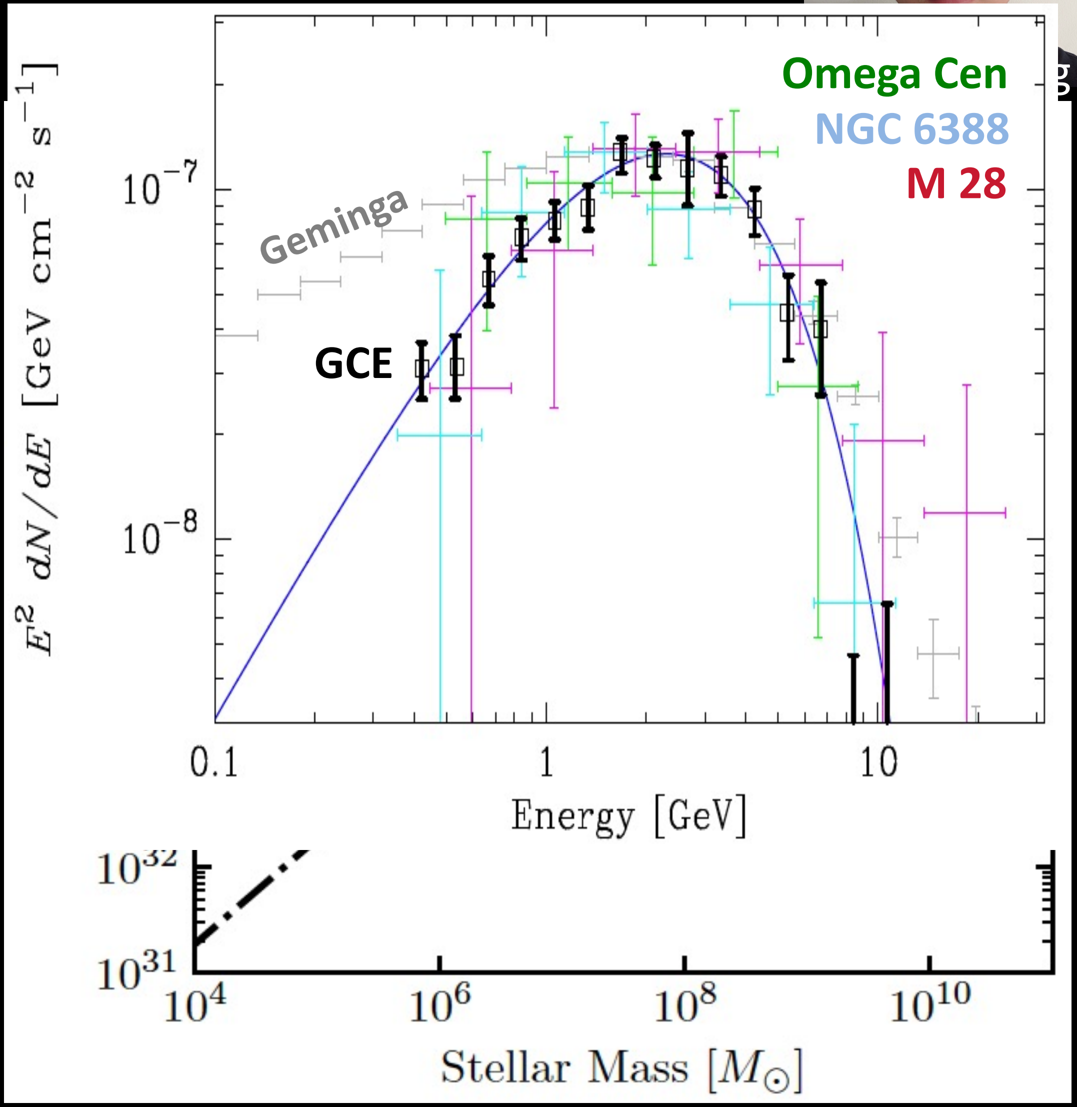
Some insights:

1. Spectrum similar to pulsars
2. Of order $O(10^{4\text{-}5})$ needed
3. Gamma-ray luminosity seems to scale with mass

Bulge

Both nuclear and boxy

$$\sim 3 \times 10^{27}\,\mathrm{erg/s/M_\odot}$$



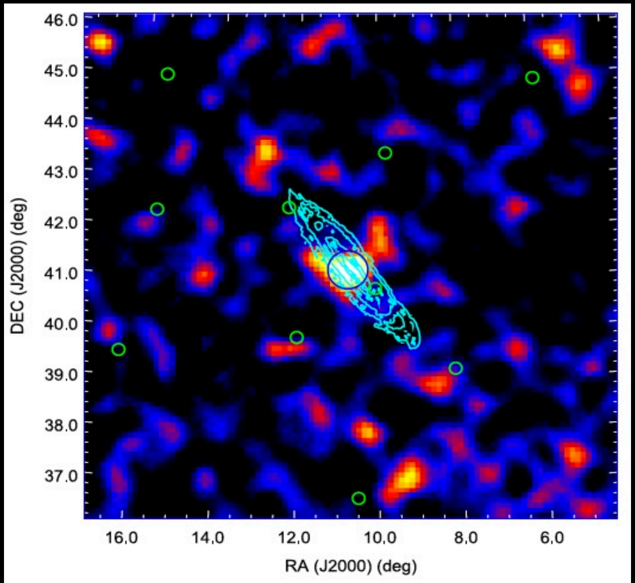
Song et al (2021), Also Macias et al (2018), Bartels et al (2018)

Gamma / mass ratio

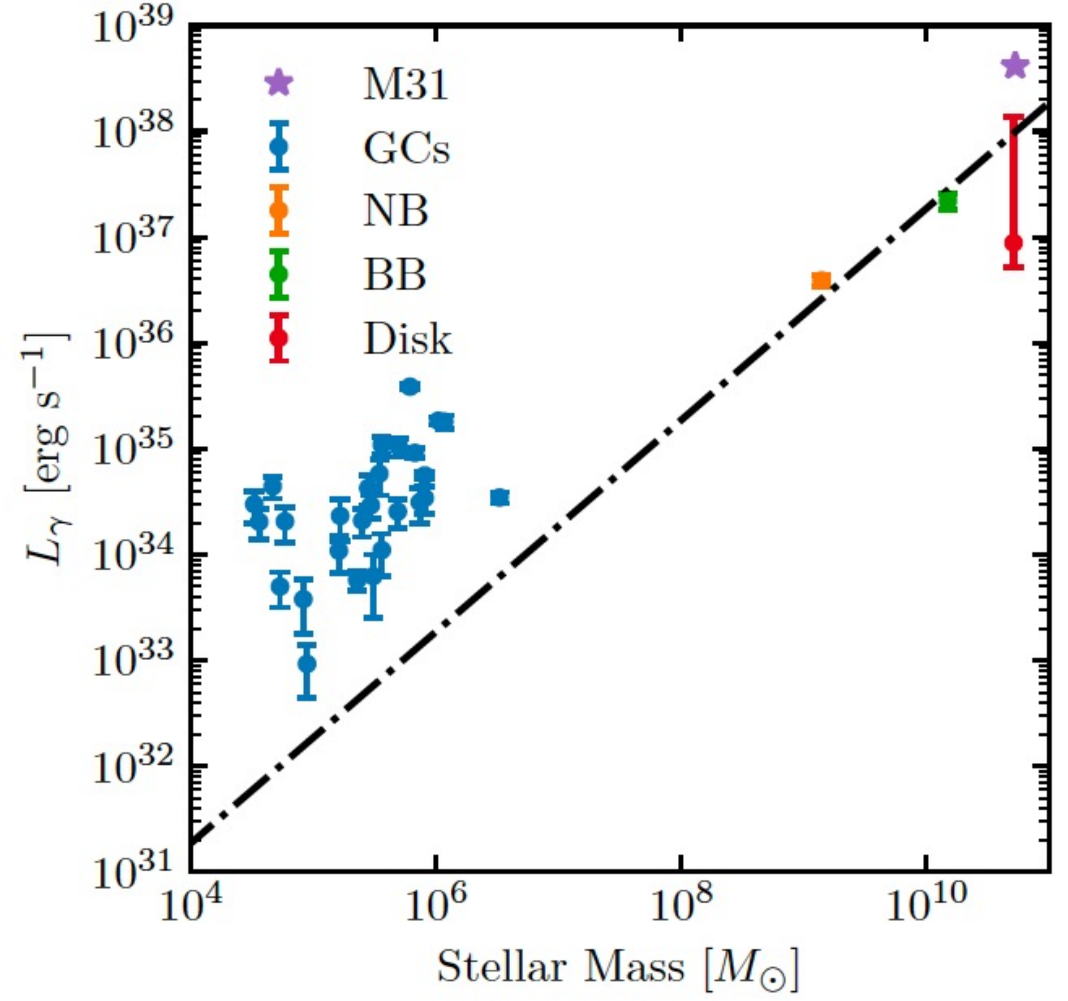

Deheng Song

M31

Extended (at 4σ) and does not obviously correlate with gas density. Ratio high (may include some disk emission and sources)



Fermi (2017)



Song et al (2021), Also Macias et al (2018), Bartels et al (2018)

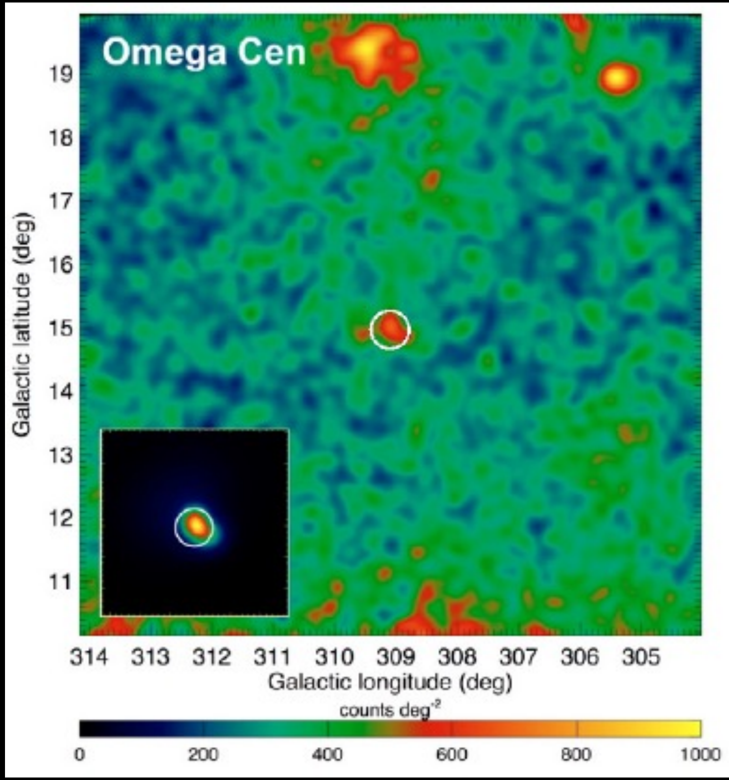
Shunsaku Horiuchi

Gamma / mass ratio

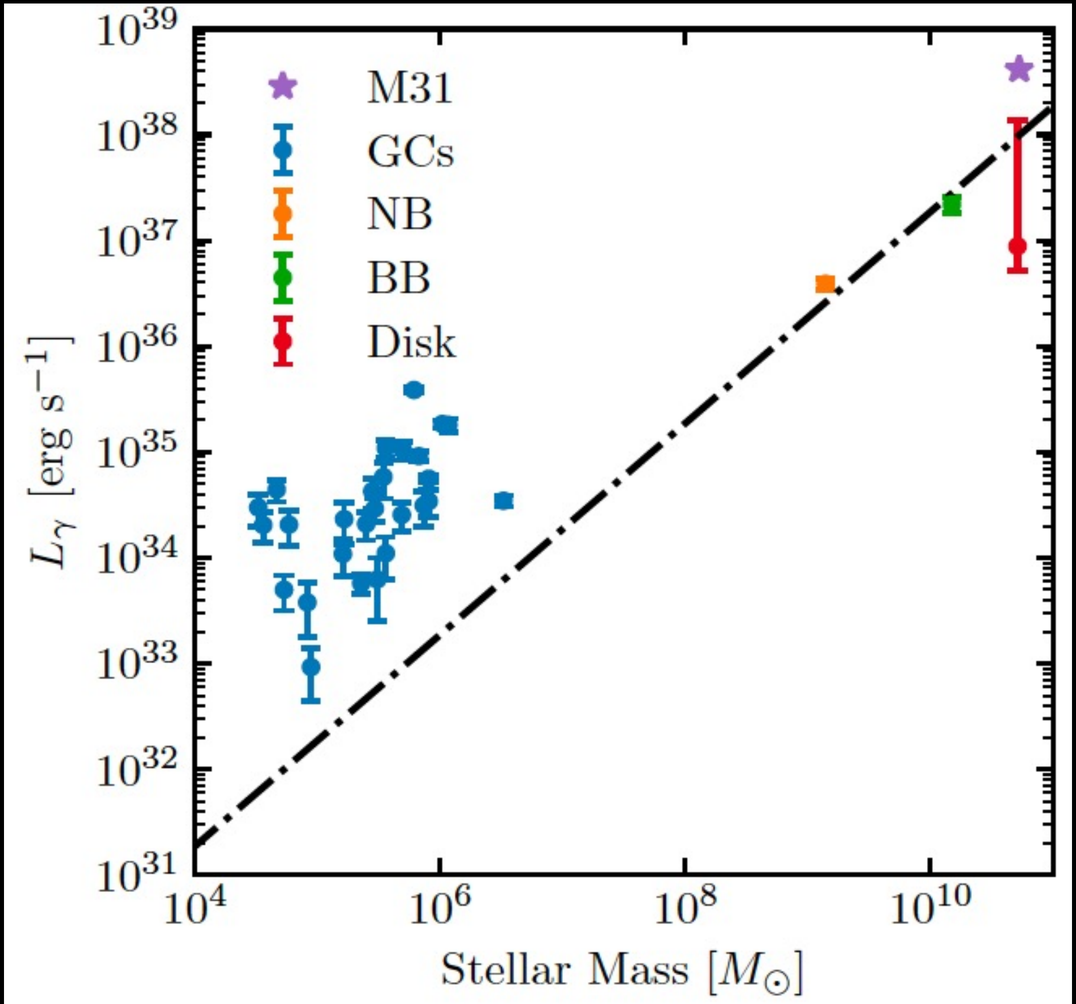

Deheng Song

Globular clusters

30 detections so far, shows higher γ-ray efficiency given their mass



Fermi (2010); see also Song et al (2021)



Song et al (2021), Also Macias et al (2018), Bartels et al (2018)

Shunsaku Horiuchi

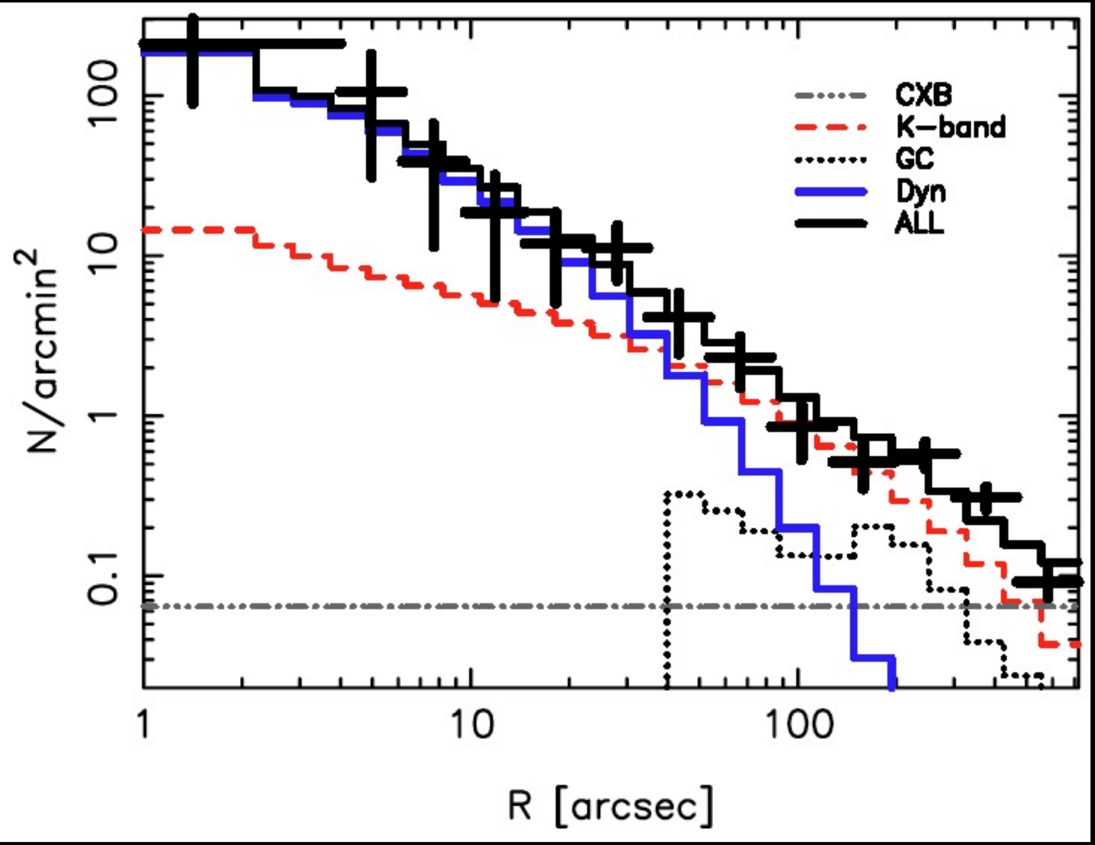
Millisecond formation scenarios

Importance of binaries

Millisecond pulsars form in binaries, going through a X-ray binary phase (recycling scenario), and this binary can be:

- Primordial: scales ~ stellar mass
- Dynamically captured: scales ~ encounter rate

$$\Gamma \propto \rho_*^2/\sigma$$



c.f. X-ray binaries

Departure from linear scaling:

- 10-100 times more common in globular cluster than in the disk

Verbunt & Lewin (2006)

- In M31, ~25% show dynamic origin

Voss & Gilfanov (2007)

Shunsaku Horiuchi

Millisecond formation scenarios

Importance of binaries

Millisecond pulsars form in binaries, going through a X-ray binary phase (recycling scenario), and this binary can be:

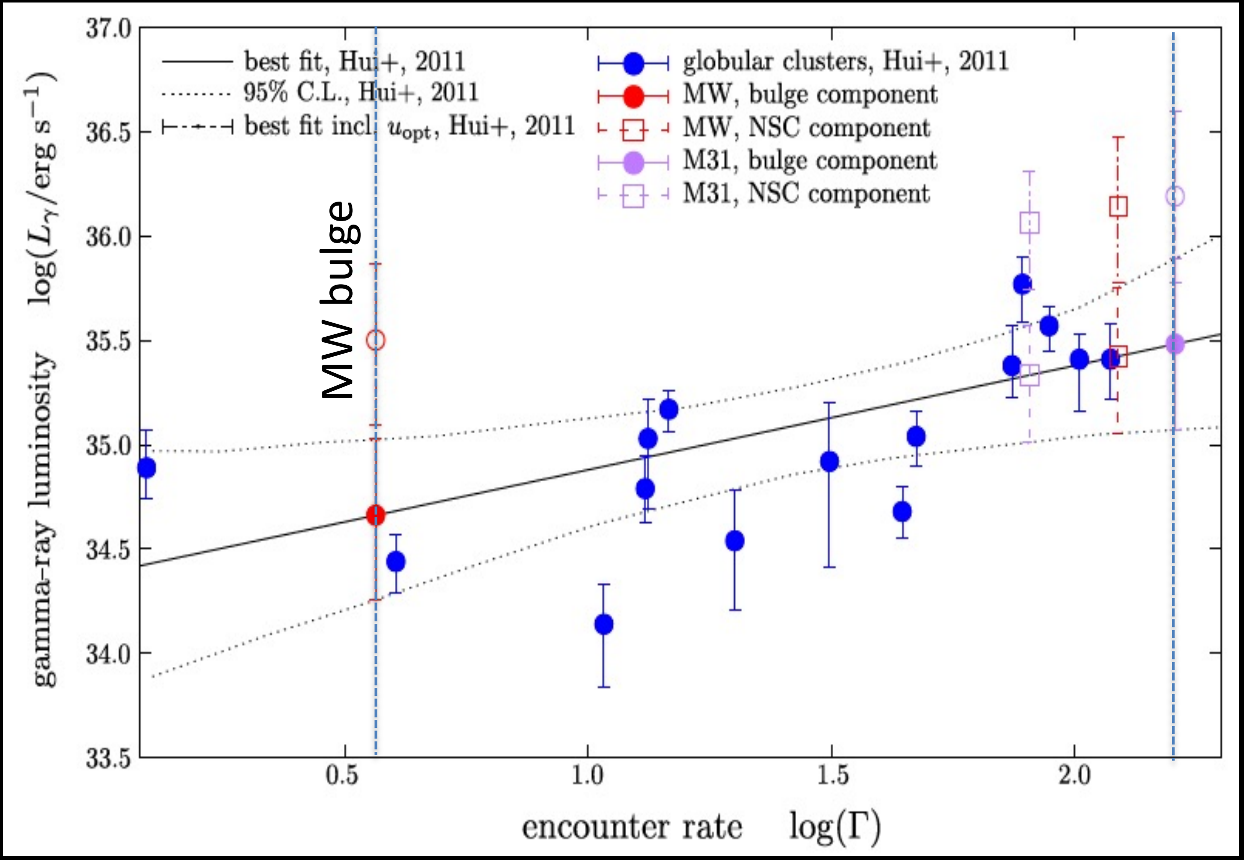
- Primordial: scales ~ stellar mass
- Dynamically captured: scales ~ encounter rate

$$\Gamma \propto \rho_*^2/\sigma$$

Milky Way bulge has low Γ

Globular clusters and M31 bulge have larger Γ

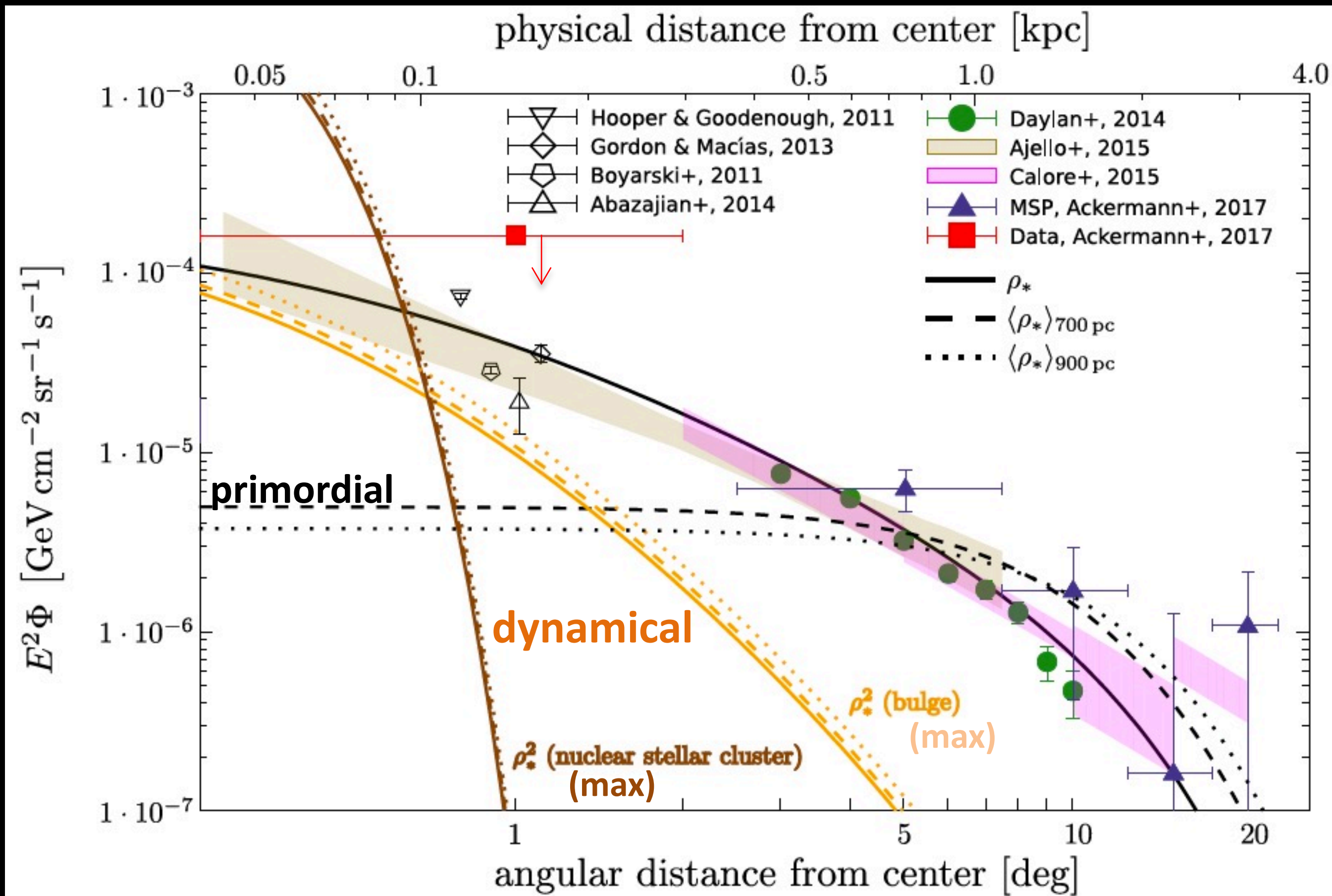
➔ Gamma-ray correlates with encounter rate



Eckner et al (2017); also Hui et al (2011)

Implementation to Milky Way

Millisecond pulsars in the bulge
= primordial + dynamical (modeled after globular clusters)



Eckner et al (2017)

Using similar morphological modeling, the primordial powers 30-70% of bulge γ rays

Macias et al (2019)

Backed by population synthesis studies

e.g., Gonthier et al (2018)

➔ **Millisecond pulsars consistent with bulge-correlated γ-rays**

FUTURE DIRECTIONS

How to further test between pulsar vs dark matter origins?

Find the pulsars

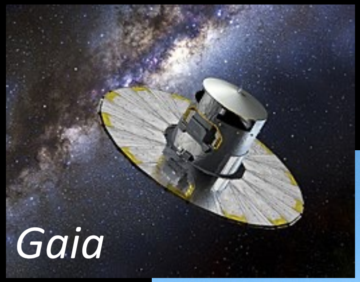
To directly confirm the source

→ *Multiwavelength search campaign*

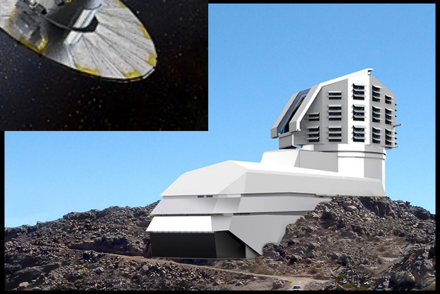
Dark matter distribution

To rule in/out the dark matter hypothesis

→ *Improved dark matter distribution, compare to other regions & messengers & limits*



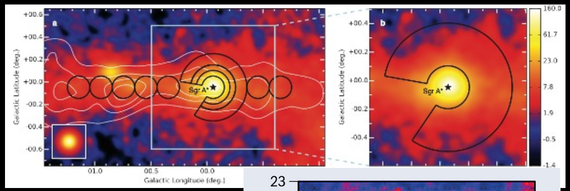
VRO



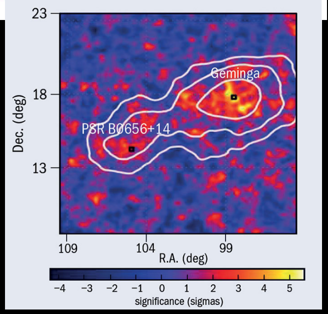
Understand transport

Of cosmic rays in the Galactic Center

→ *Improved background, pulsar behavior, leptonic predictions*



HESS

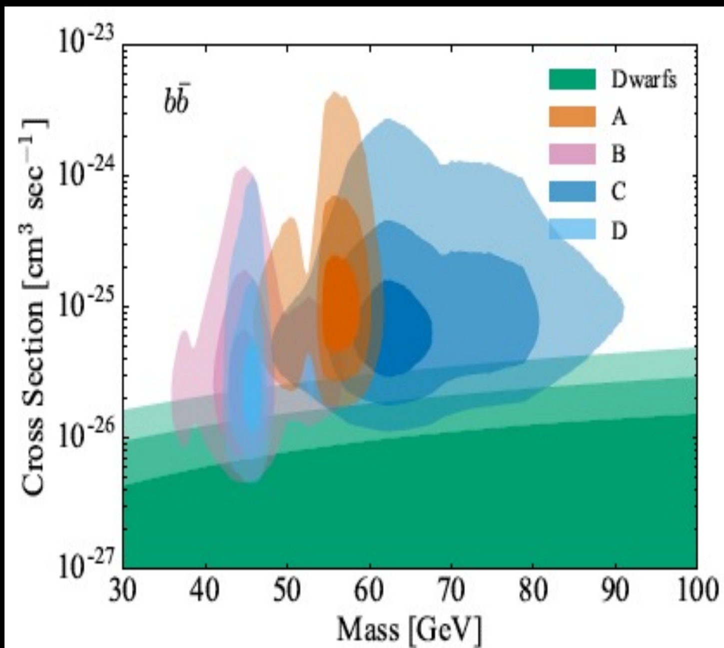


HAWC

Comparison with dwarf galaxies

simple* dark matter is already cornered by dwarf galaxies
(*prompt two-body annihilating DM)

Posteriors for GCE-DM varying the MW J-factors, for 4 Galactic diffuse models



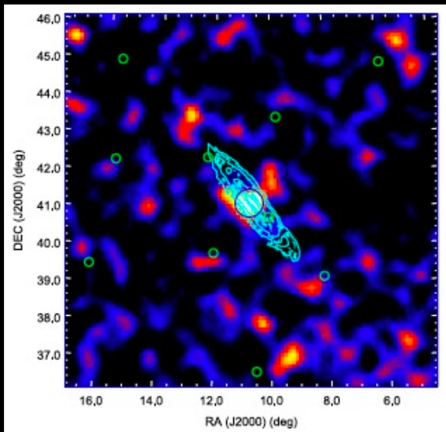
The parameter that the J-factor is most sensitive to is the local density of DM. As stated in a previous section, we use a value of 0.28±0.08 GeV/cm^3 taken from Zhang et al. (2012) [59]. Other groups including Pato et al. (2015) [65] and McKee et al. (2015) [66] tend to find higher values for the local density. To fully resolve the tension between the GCE and the dwarfs, the GCE J-factor needs to increase between 1 and 1.5 orders of magnitude, which translates into a local density of 3 to 6 times greater. As we show, none of these determinations of the local density relieve the GCE-dwarf evidence ratio to be unity.

Keeley et al (2017)

➔ Important to address systematic assumptions of both dwarf & Milky Way J-factors

e.g., Ando et al (2020), Horigome et al (2019, 2020)

Comparison with Andromeda

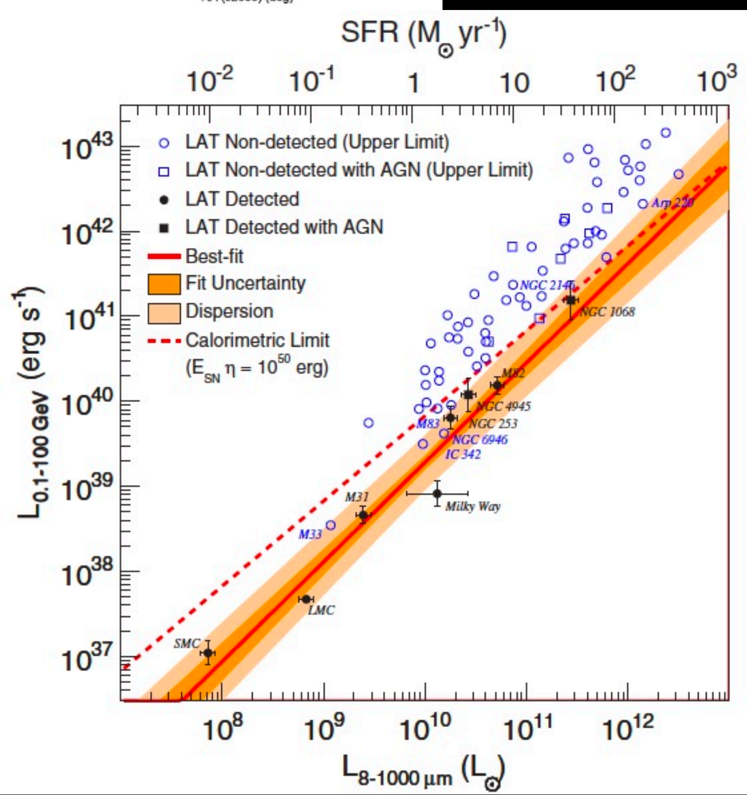


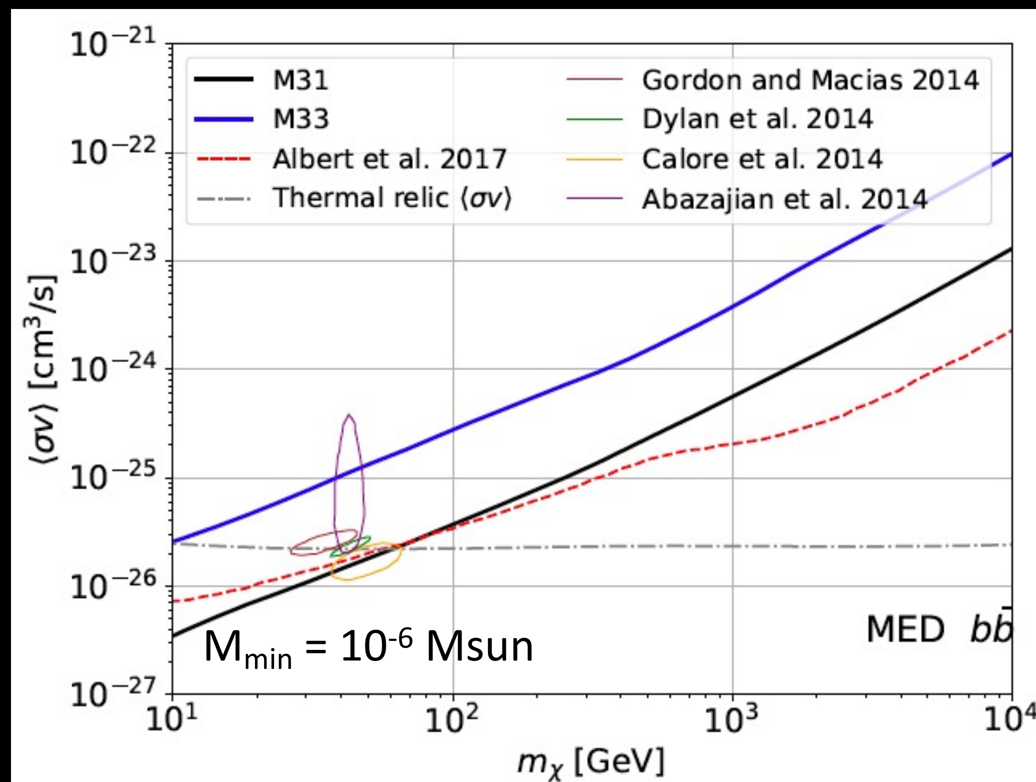
Gamma-ray excess in M31

- Doesn't correlate with gas distribution
- But sits on gamma-SFR correlation
- Emission out to virial radius
- If DM, matches Galactic Center (with $M_{min} = 10^{-6}$ Msun)
- Adding astro model negates the need for DM

Eg Karwin et al 2020, Burns et al 2021

Eg Di Mauro et al 2020

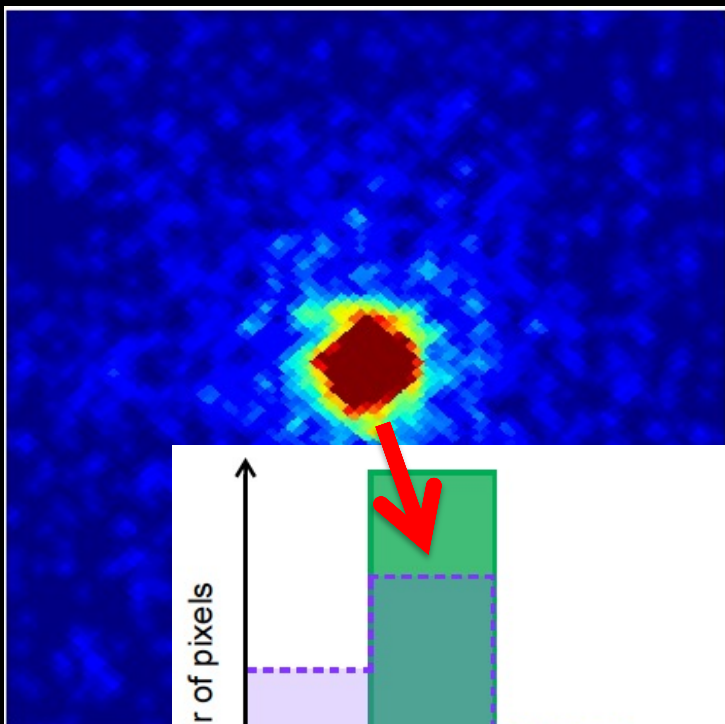




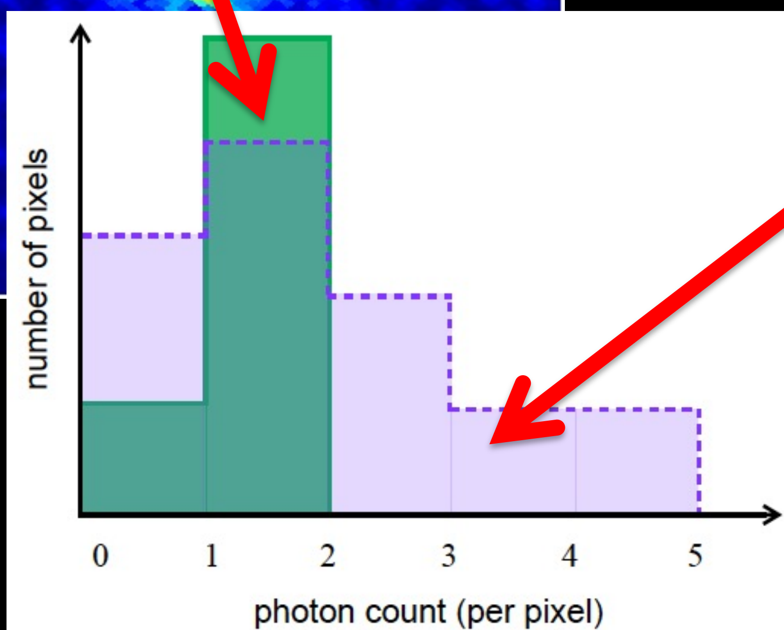
Sh

point source vs diffuse source

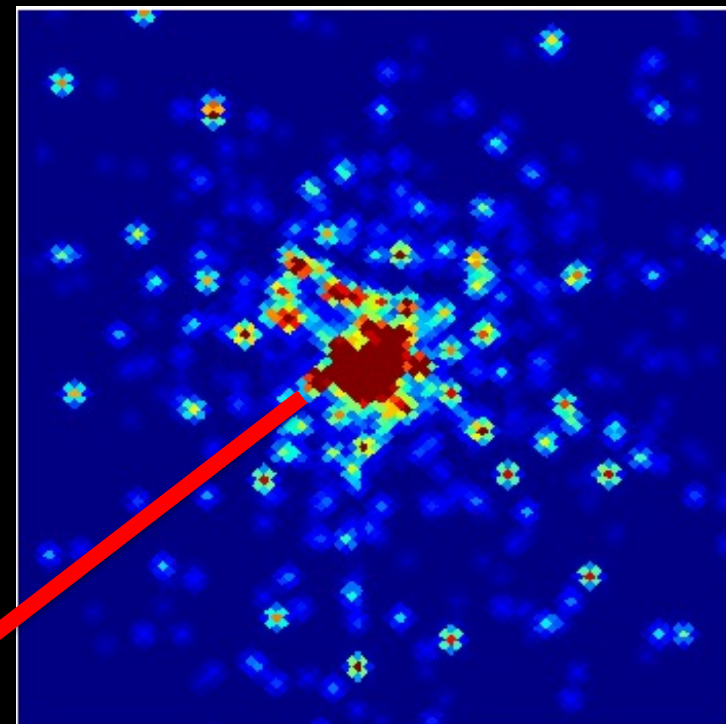
Dark matter annihilation



VS



Astrophysics (eg pulsar)



Photon count distribution look different

Lee et al (2016)
also Malyshev & Hogg (2011), *Bartels et al (2016) , Zechlin et al (2016)*

Shunsaku Horiuchi

Photon count distribution fit result

- Smooth should absorb dark matter
- Point-source should absorb astrophysical objects

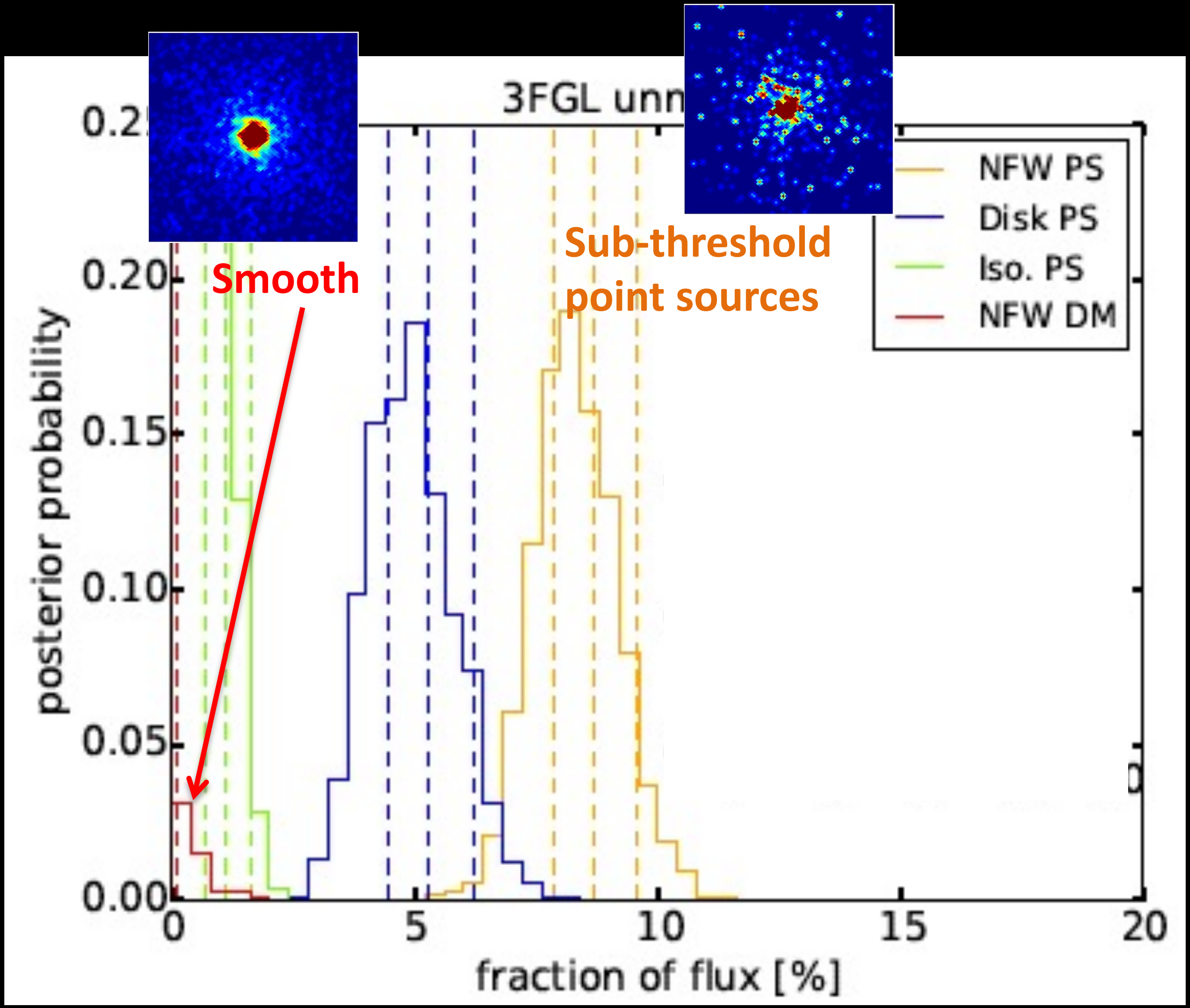
But…
- Smooth: ~0% !
- Point sources: ~8.7% !

Also, if point sources are not added, smooth becomes ~8%

➔ Preference for sub-threshold point sources over smooth dark matter

➔ Could be faint pulsars

Lee et al (2016)
See also Bartels et al (2016)



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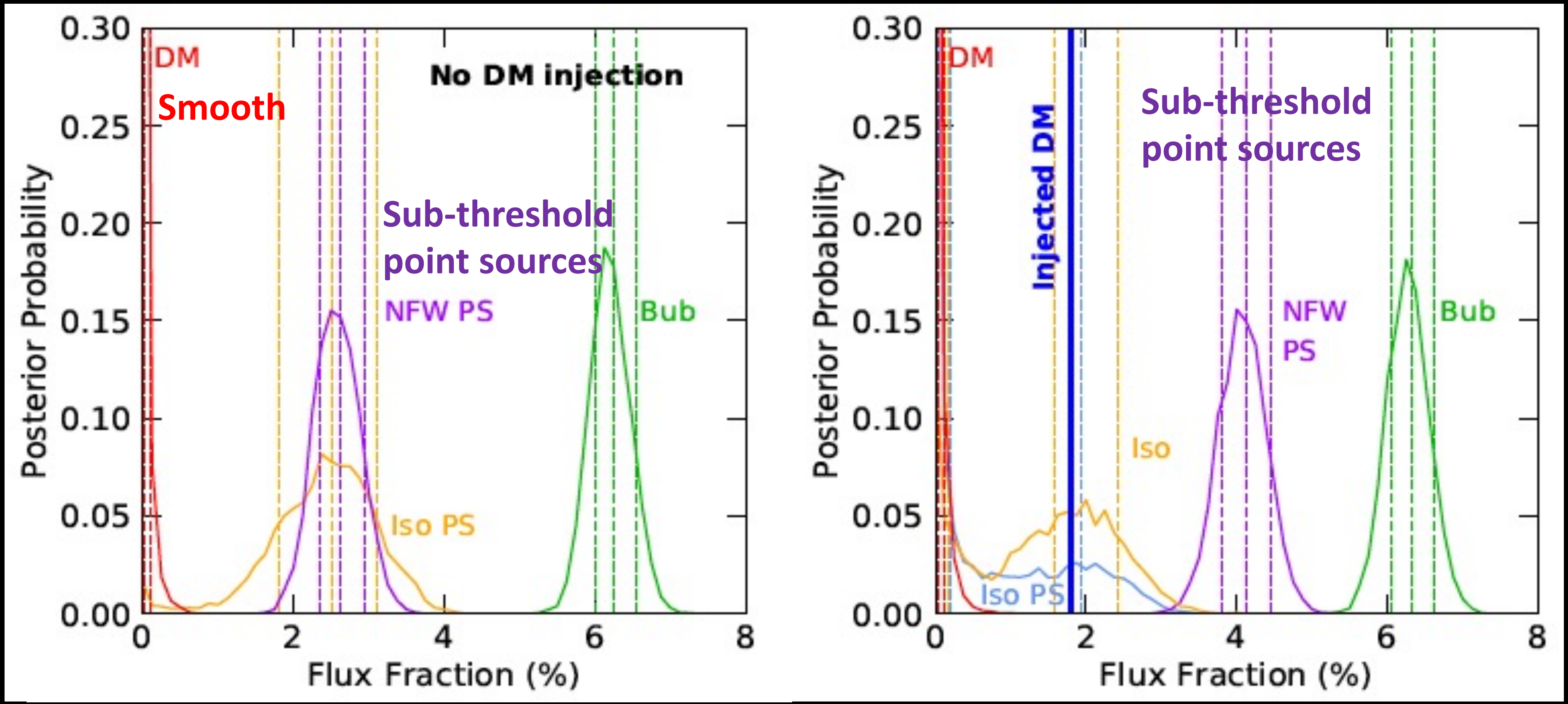
But…challenges

- Ultra-faint point population is degenerate with a smooth diffuse source
- Injected dark matter erroneously absorbed by sub-threshold point-source model
- Impacts of mismodeling diffuse model appears problematic



Leane & Slatyer (2019, 2020)
Also Chang et al (2019), Zhong et al (2019), Buschmann et al (2020),

➔ **Can be confident there's substantial point sources**
➔ **Still allow DM signal (more work needed)**

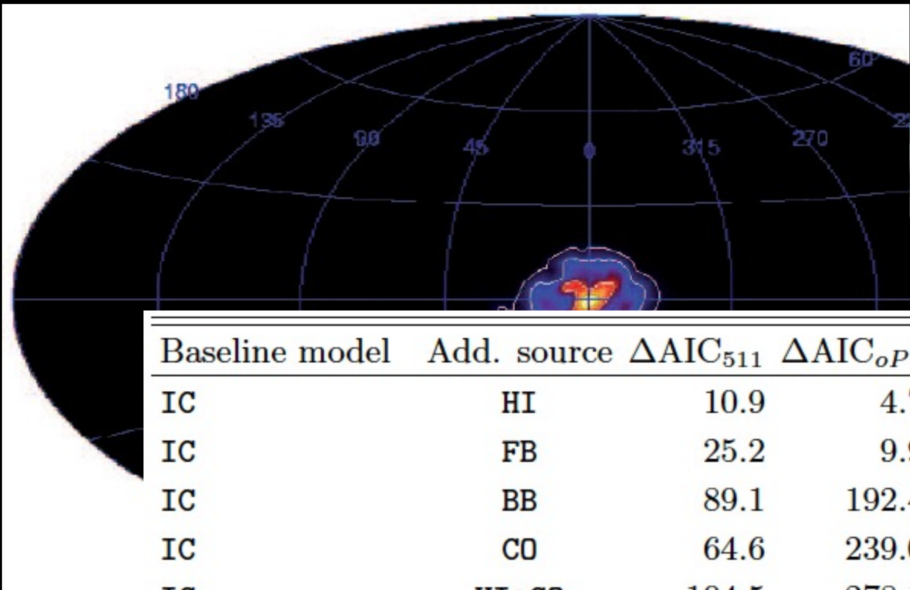
Low-energy counterparts

The 511 keV excess

There are striking parallels:

- Large, tens of degrees
- Strongly centrally peaked

Knodlseder et al 2005
Siegert et al 2016



INTEGRAL

Spatial morphology

We see very strong parallels

- When mutually exclusive, dark matter and bulge are both detected
- When simultaneously added, the dark matter significance become negligible

Siegert et al (2021)

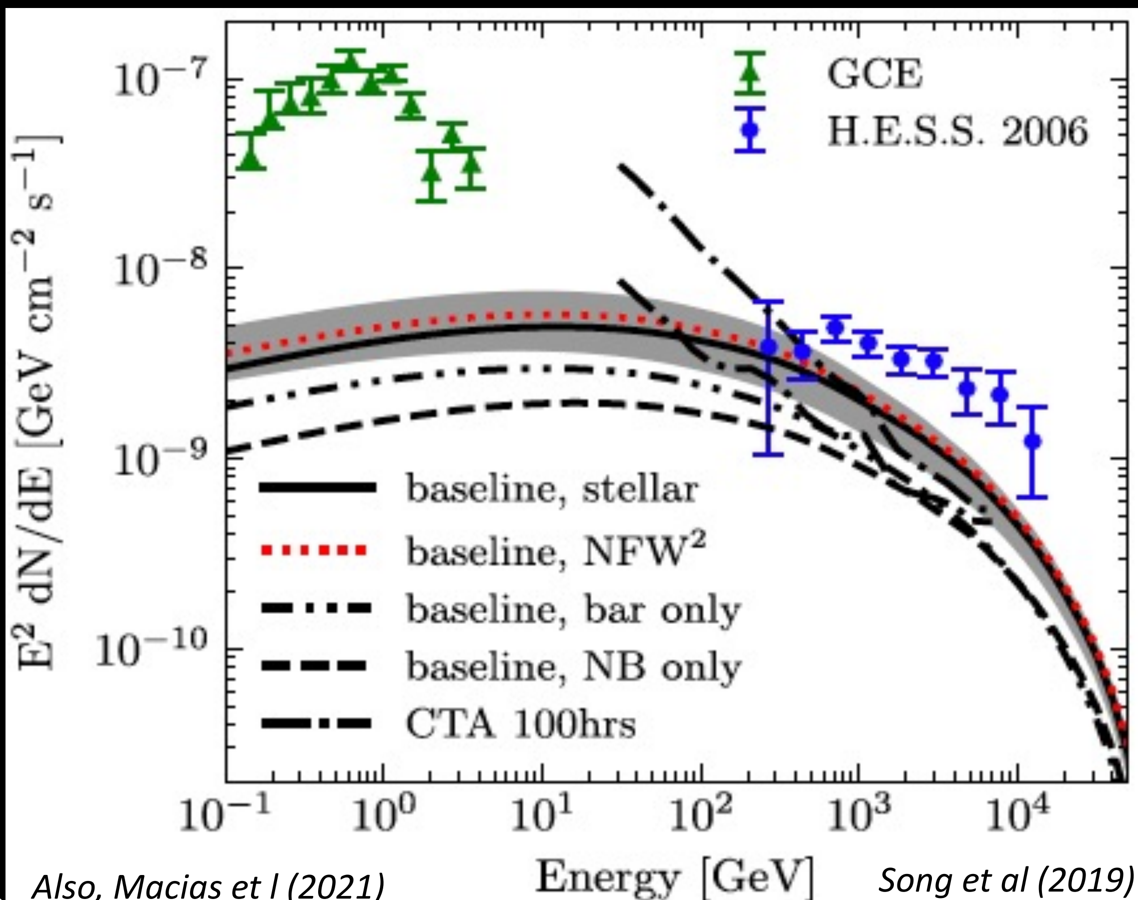
Baseline model	Add. source	$\Delta\mathrm{AIC}_{511}$	$\Delta\mathrm{AIC}_{oPs}$	$\Delta\mathrm{AIC}_{\pm}$
IC	HI	10.9	4.7	15.6
IC	FB	25.2	9.9	35.1
IC	BB	89.1	192.4	281.5
IC	CO	64.6	239.0	303.6
IC	HI+CO	104.5	278.1	382.6
IC	NB	123.8	383.8	507.6
IC	DM2	134.8	375.8	510.6
IC	DM0	164.3	433.3	597.6
IC	BB+NB	**162.0**	**456.2**	**618.2**
IC+BB+NB	CO	-2.0	-1.7	-3.7
IC+BB+NB	DM2	-0.5	-0.8	-1.3
IC+BB+NB	DM0	3.6	-1.1	2.5
IC+BB+NB	CO+HI	-1.4	16.8	15.4
IC+BB+NB	HI	**-0.3**	**16.3**	**16.0**
IC+BB+NB+HI	DM0	4.8	0.8	5.6
IC+BB+NB+HI+CO	DM0	4.6	1.3	5.9

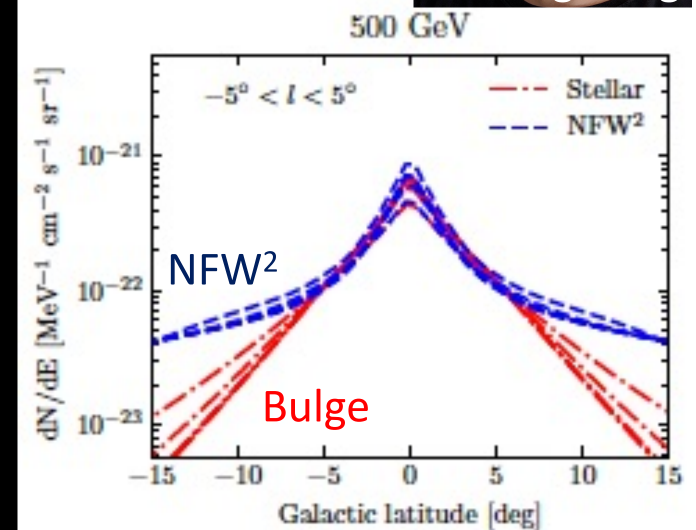
➔ Could be seeing leptonic side of millisecond pulsar population?

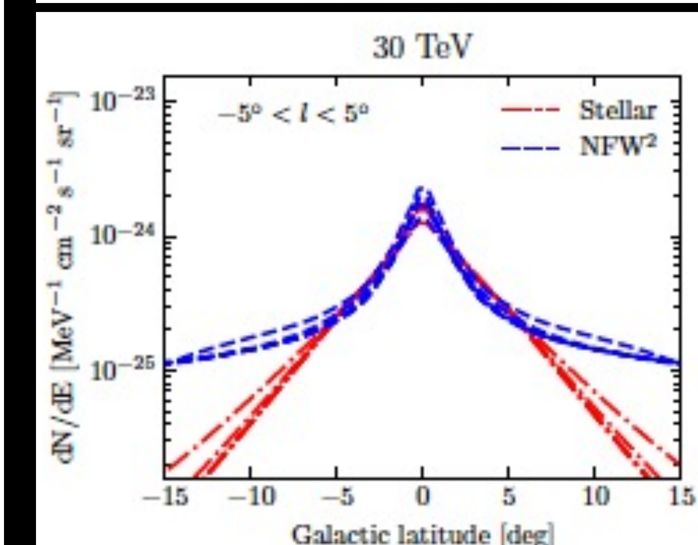
TeV counterparts

Pulsars can emit relativistic e+e- up to TeV energies (dark matter models typically have *O*(100) GeV mass so do not)

➔ **Testable with up-coming gamma-ray telescopes e.g., Cherenkov Telescope Array**





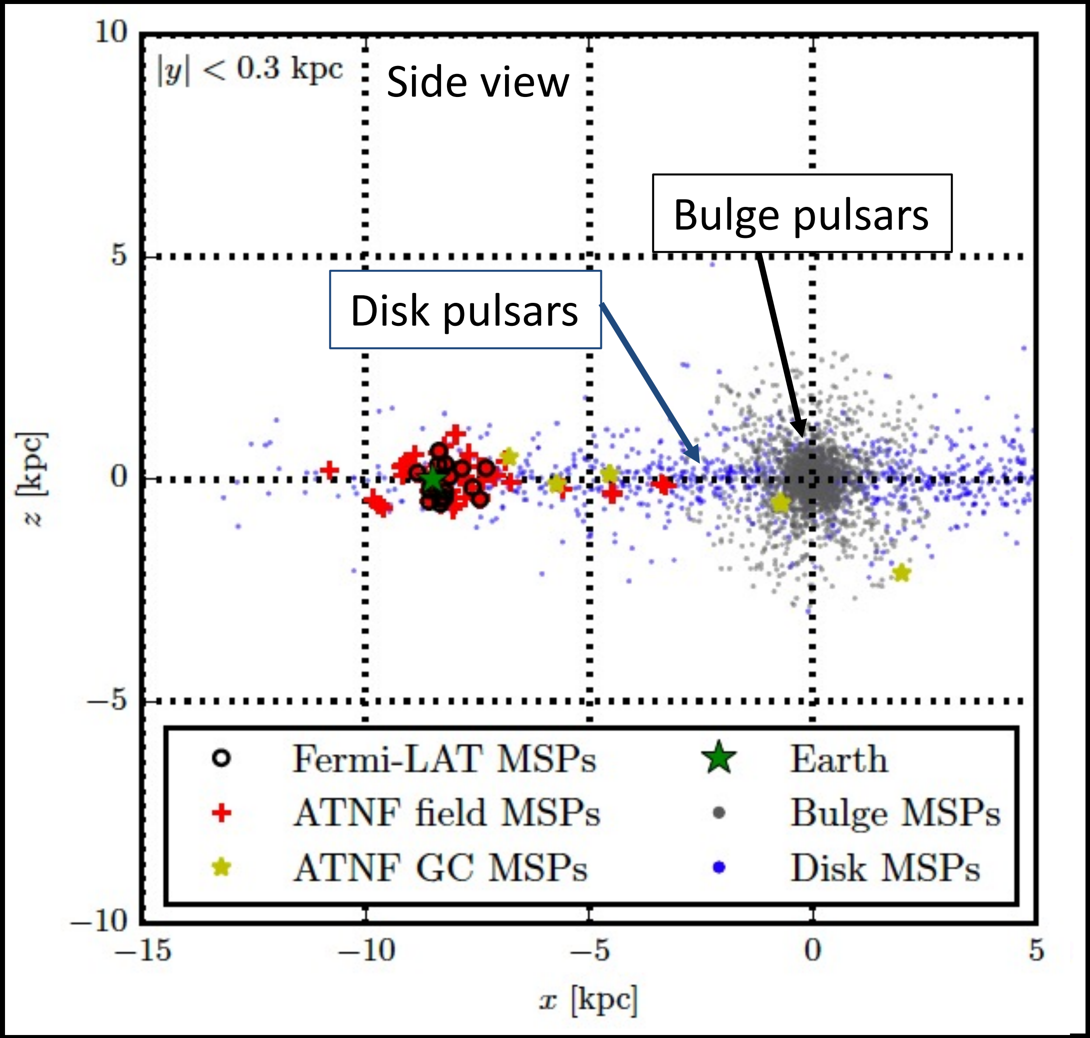


Radio counterparts

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



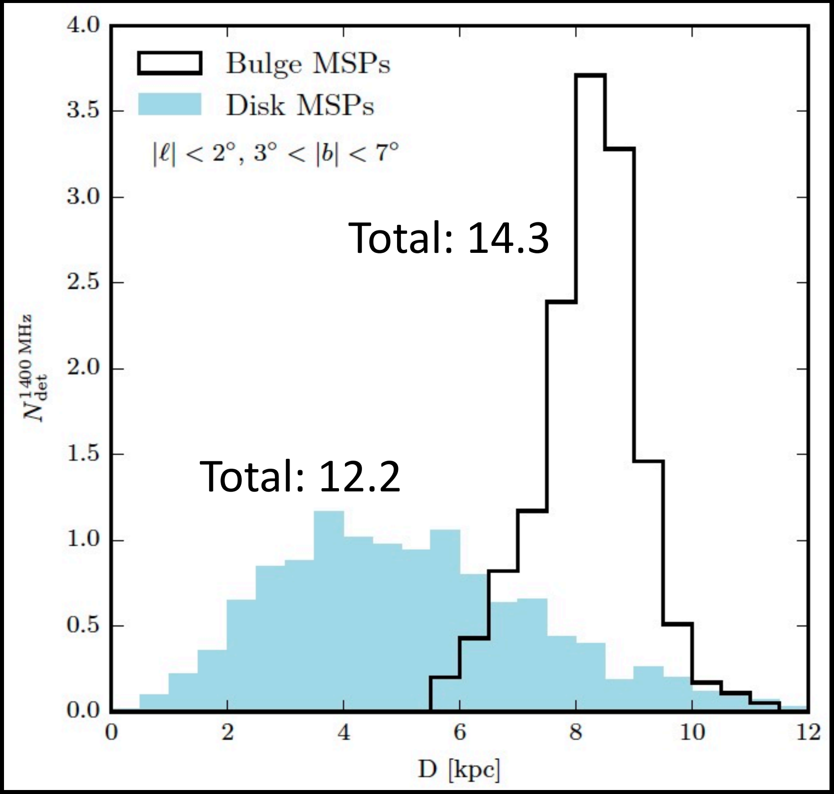
So…the target
Enhanced millisecond pulsar density in the Galactic bulge (out to ~10 deg)

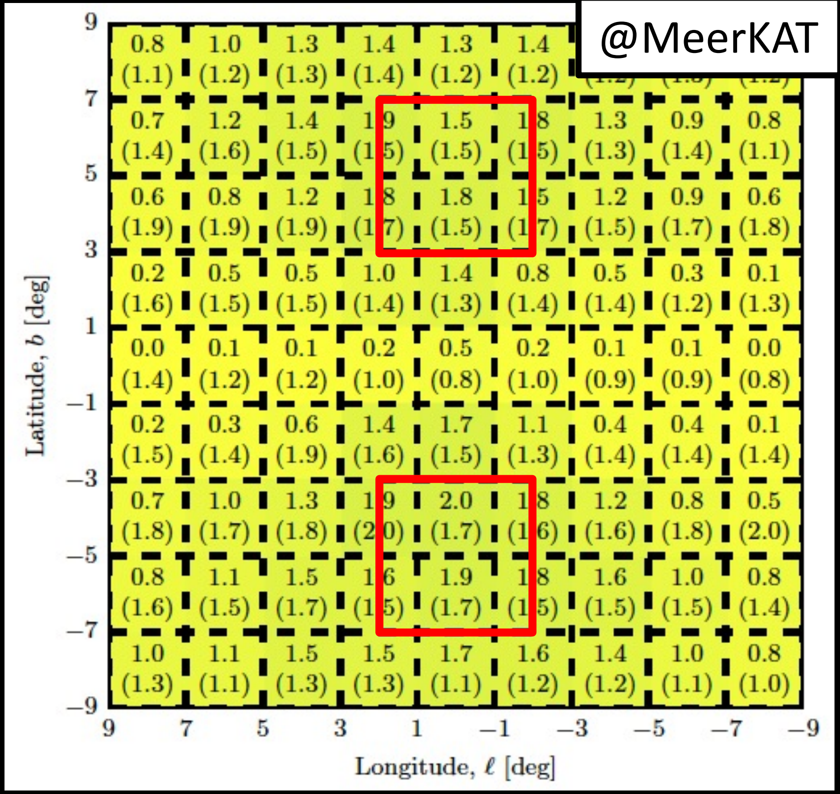
Calore et al (2015)

Radio detection prospects

- Model the radio-gamma relation using globular clusters
- Bulge MSP population is just below Parkes High Time Resolution Universe (HTRU) mid-latitude survey, but can be reached by future searches, e.g.,
  - ➢ MeerKAT @1.4GHz: ~2.5h per 2x2 region →1-2 bulge MPSs

Calore et al (2016)





→ Multi-wavelength window to identify the millisecond pulsars

Concluding remarks

The nature of dark matter remains an open question

There's a mysterious gamma-ray flux from the Galactic Center direction that has persisted 10+ years of scrutiny

We've found evidence that this excess correlates with the stellar bulge

- **Supports in-situ pulsars over dark matter origin**
- **Checked many systematics**
- **Strong constraints in GeV mass range**
- **Multi-messenger connections**

We're actively cornering dark matter candidates and discovering new insights along the way…the Galactic Center will continue to play an important role in the **multi-messenger era**