ICRR seminar, Oct 20th 2021

Particle astrophysics of the Galactic Center

Shunsaku Horiuchi

Aim

Fermi-LAT data reveals an excess of gamma-ray photons arriving from the Galactic Center direction. What is its origin?

Various possibilities
- Backgrounds?
- New astrophysics?
- New physics (dark matter)?

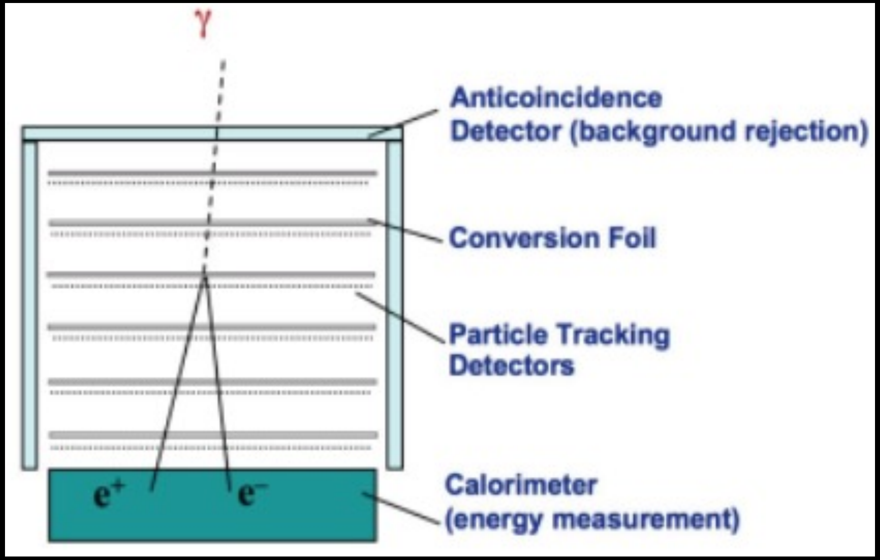
I will discuss
- What is the excess
- Studies of its spatial properties
- Implications for origins

Fermi-LAT

Launched in June 2008

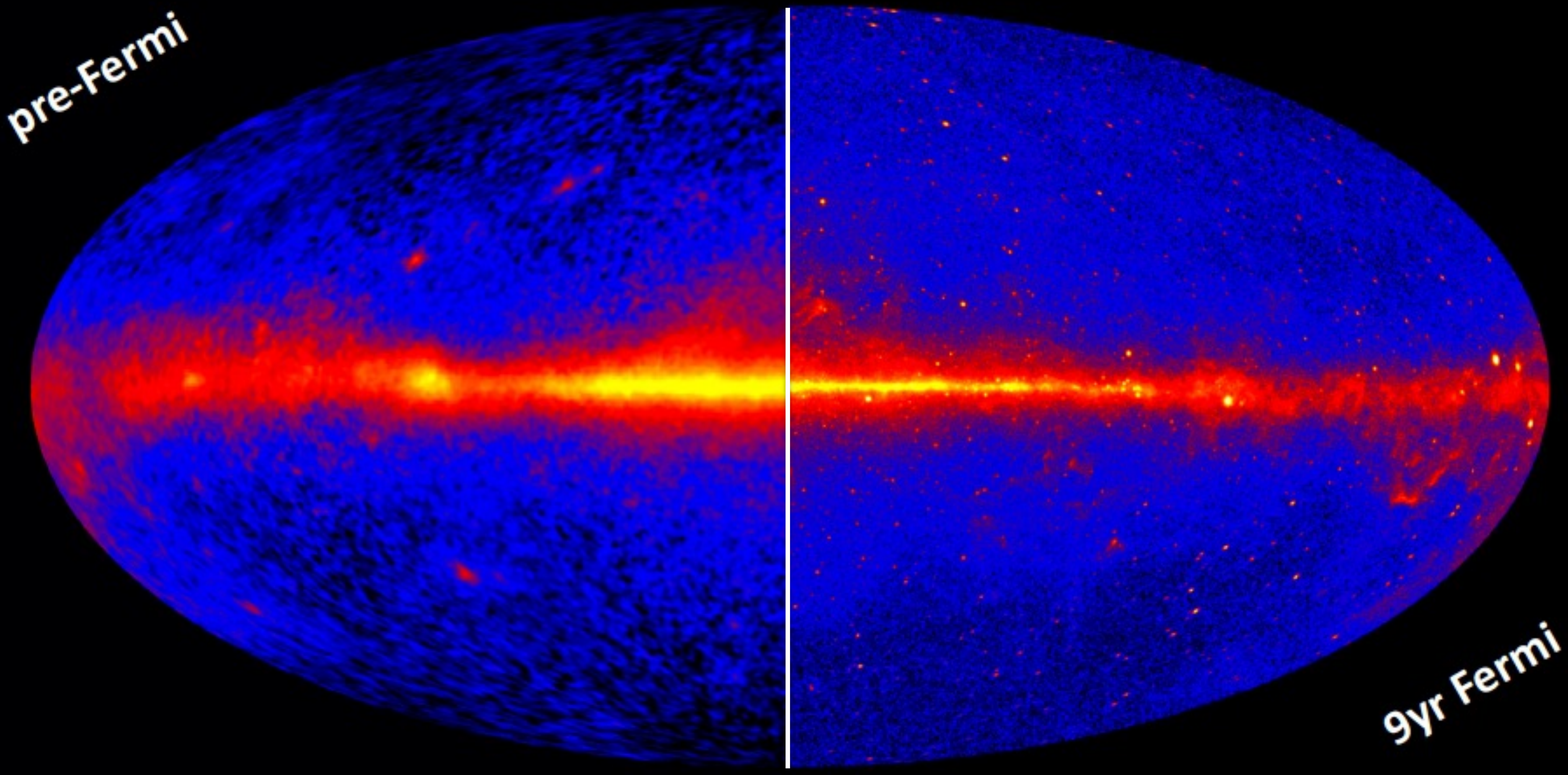
Large area telescope (LAT)

- Primary instrument of Fermi, consists of:
  - Anticoincidence
  - Pair conversion detector
  - Calorimeter
- 20 MeV – 500 GeV
- 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/

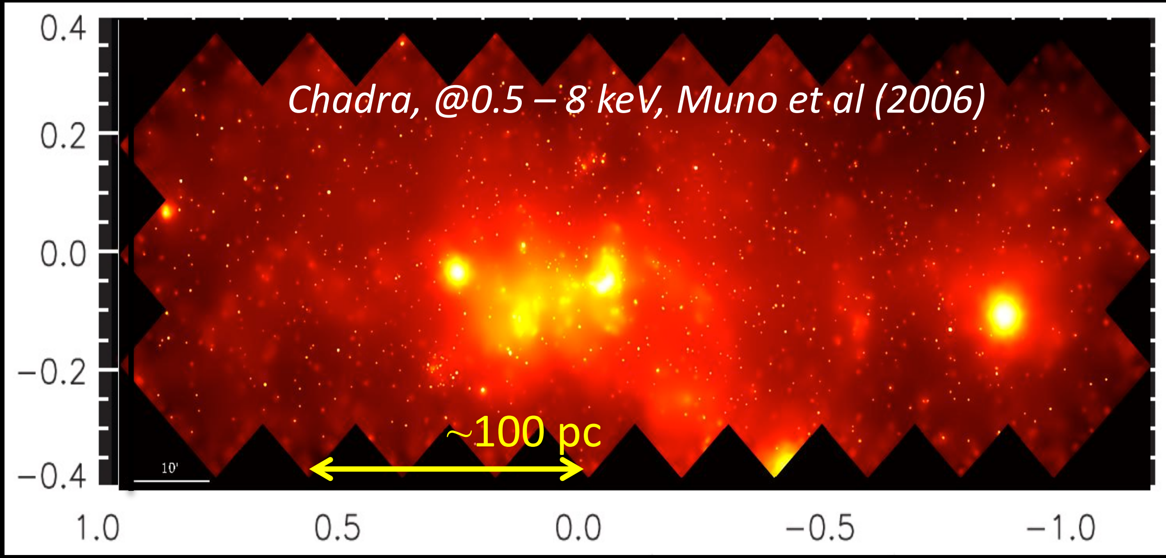
The Gamma-ray sky

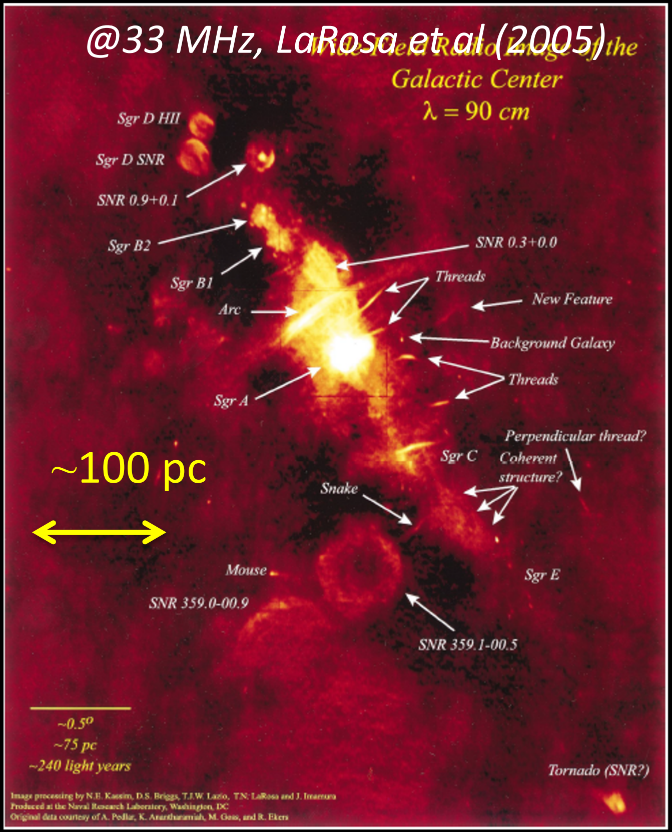


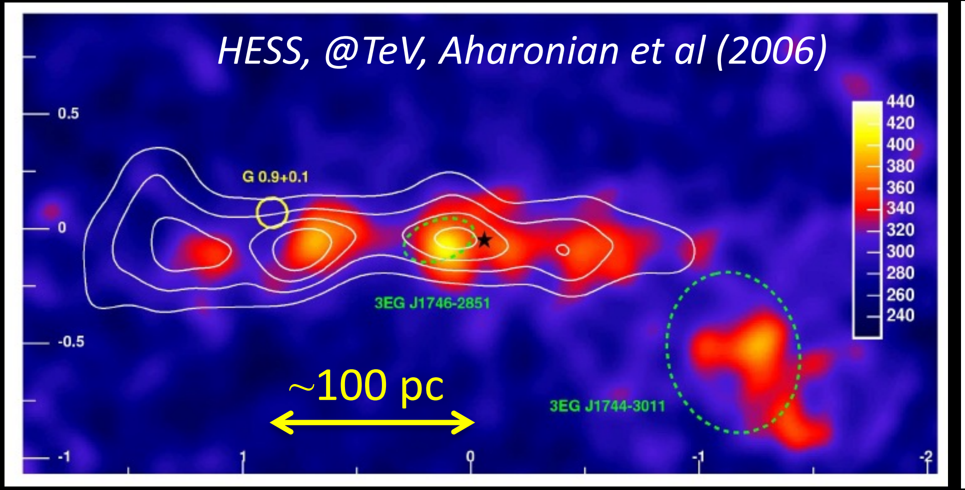
Galactic coordinates

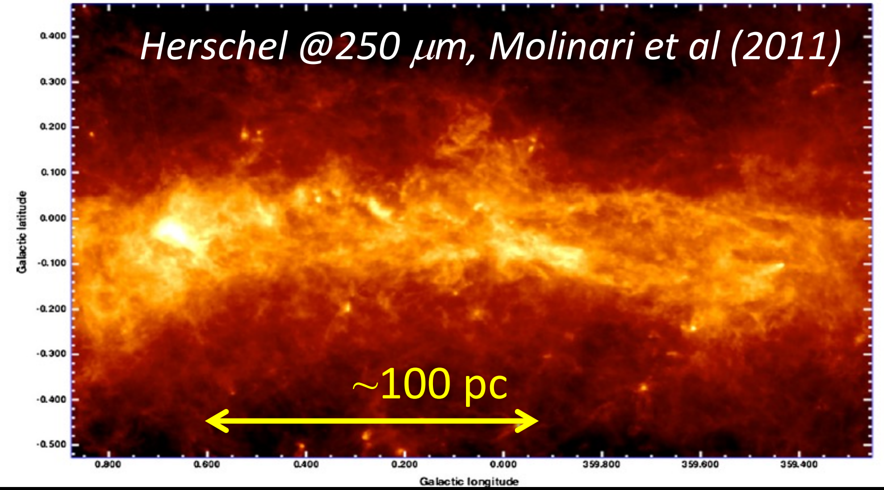
The Galactic Center

We have a wide spectral window view of the Galactic Center showing rich phenomenology









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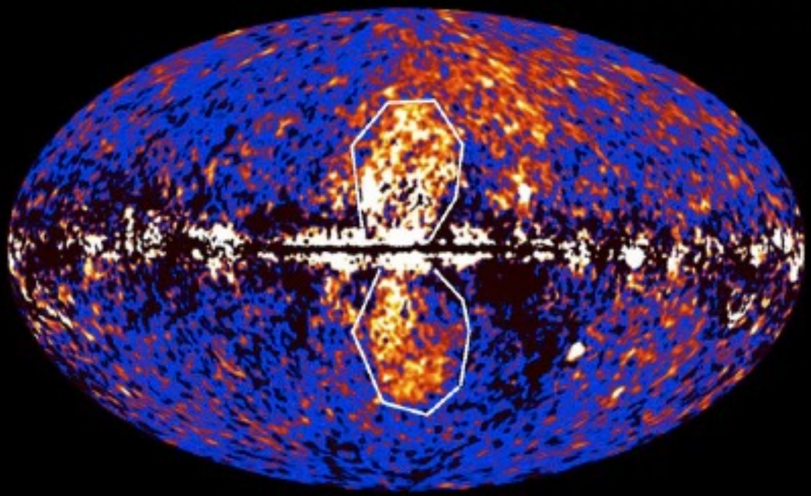
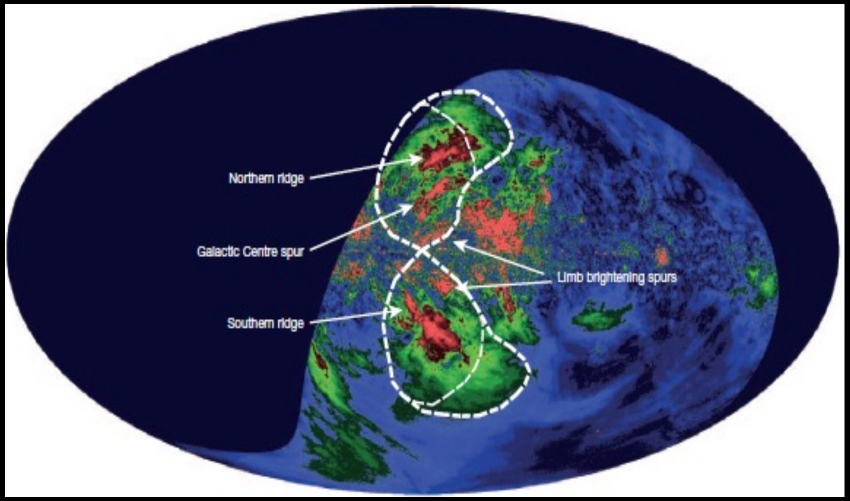
…and even on larger scales

Fermi bubbles



WMAP/Planck haze

Radio lobes



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Galactic Center Excess (GCE)

At the Galactic Center

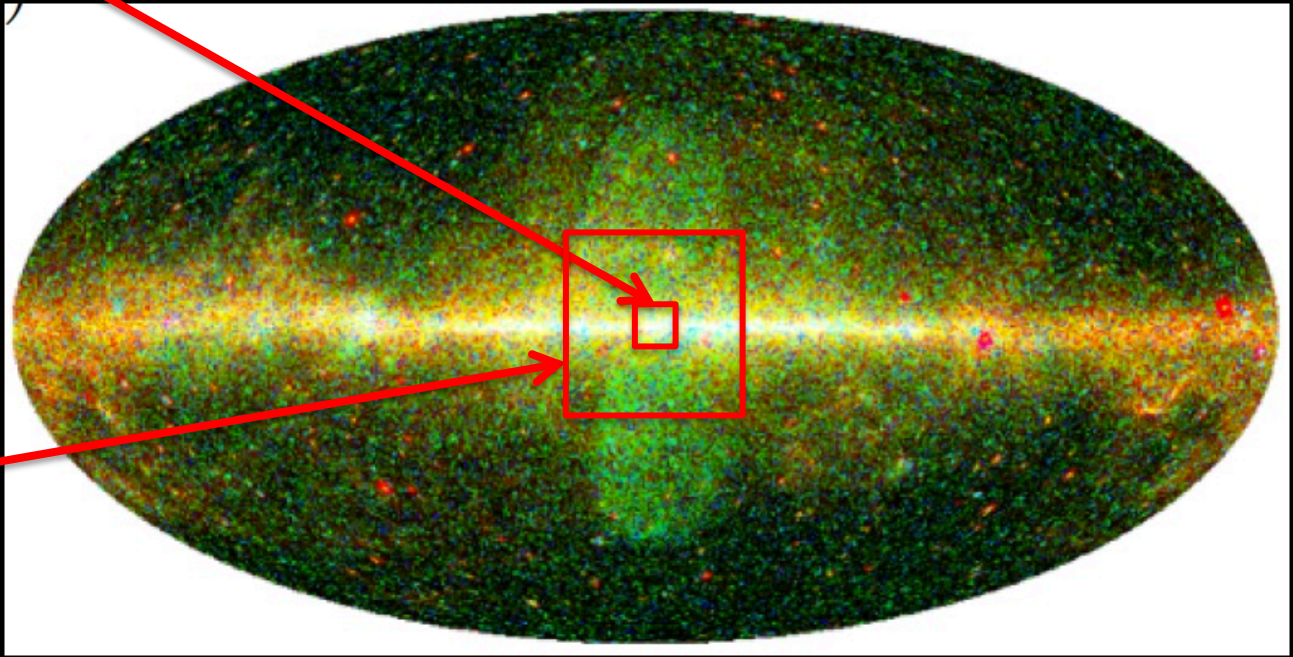
Goodenough & Hooper (2009)
Vitale & Morselli (2009)
Hooper & Goodenough (2011)
Hooper & Linden (2011)
Boyarsky et al (2011)
Abazajian & Kaplinghat (2012)
Gordon & Macias (2013)
Macias & Gordon (2014)
Abazajian et al (2014, 2015)
Calore et al (2014)
Daylan et al (2014)
Selig et al (2015)
Huang et al (2015)
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 (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)
…

An unexplained excess

- Found by morphological template fitting:

$$\mathrm{data}_i = \sum_j c_{ij}\,\mathrm{template}_{ij}$$

- New approaches, e.g., wavelets (*Balaji et al 2018*)



At mid-lat

Hooper & Slatyer (2013)
Huang et al (2013)
Zhou et al (2014)
Daylan et al (2014)
Calore et al (2014)
…

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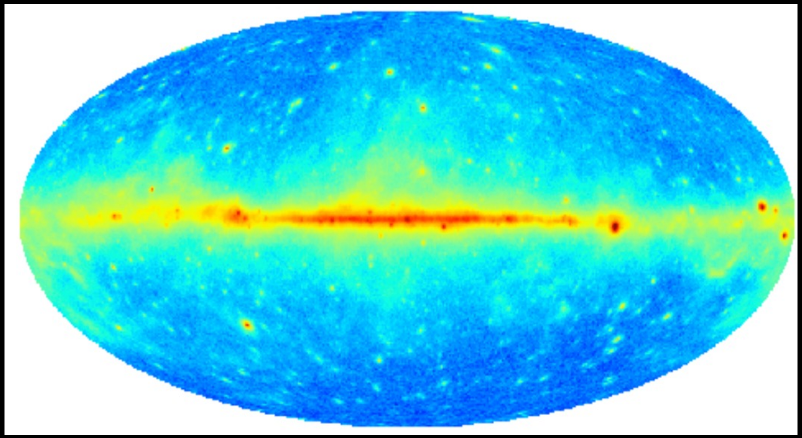
Modeling strategy: template fitting

Data



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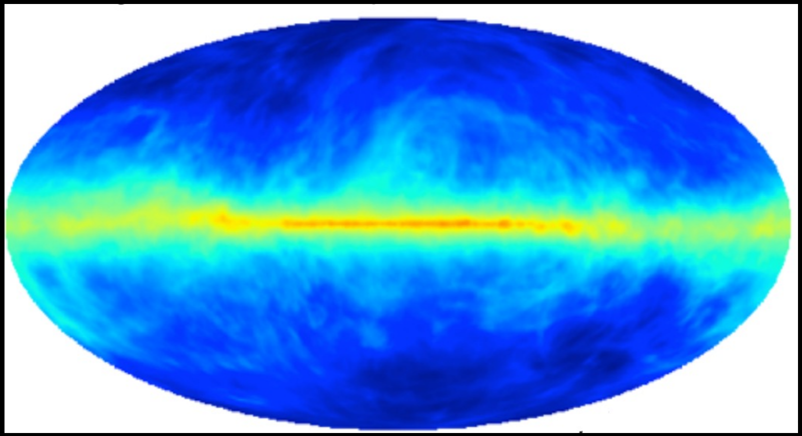
Galactic diffuse



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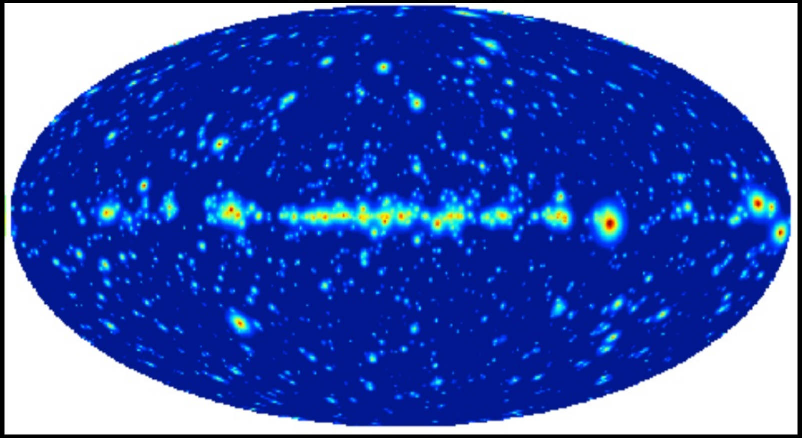
Known sources



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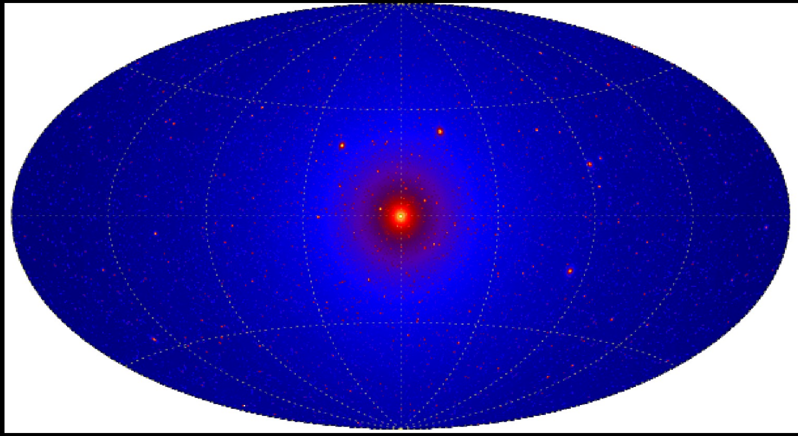
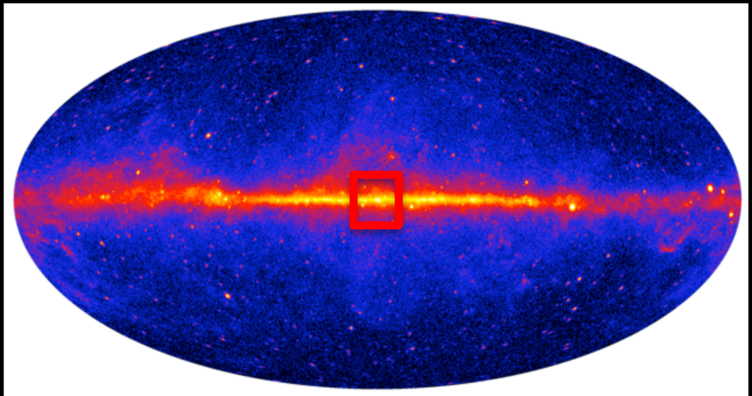
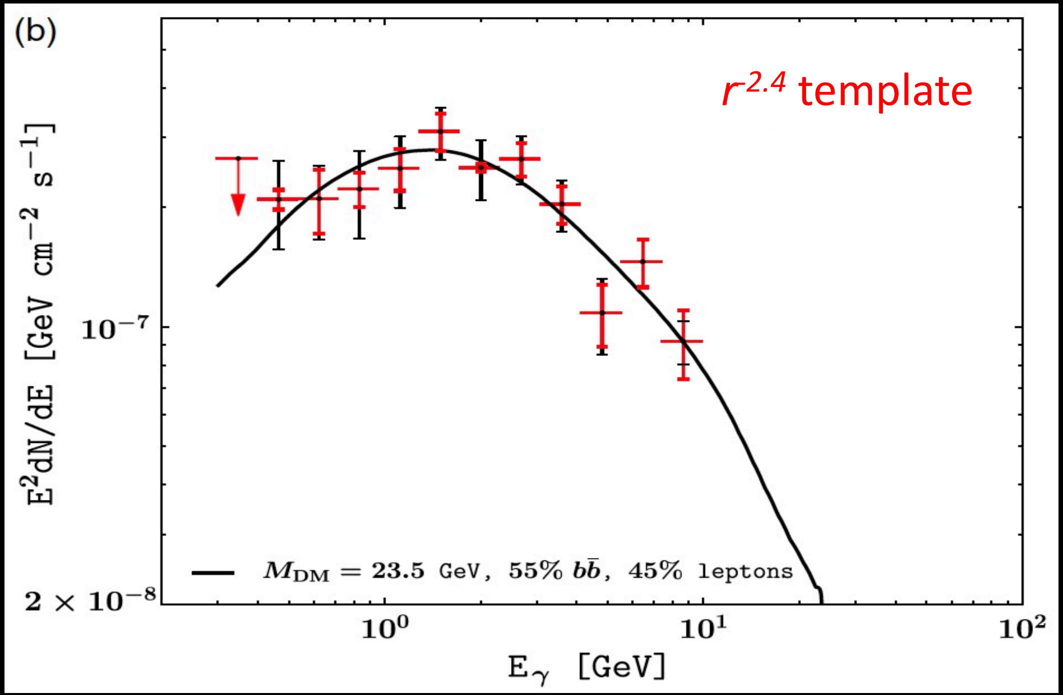
New sources, e.g., dark matter



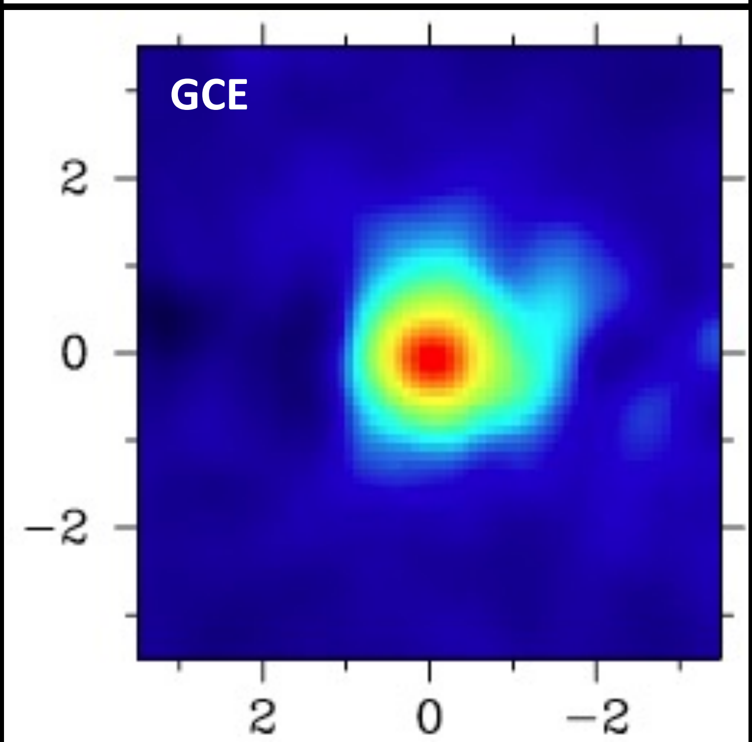
Properties of the GCE

Main features:
- Spectrum: peaks at a few GeV
- Peak flux: $\sim 10^{-(6\text{-}7)}$ GeV cm^{-2} s^{-1}
- Gamma-ray luminosity: $\sim 10^{37}$ erg/s
- Spatial morphology: $\sim r^{-2.4}$
- Statistical significance: $\sim 30\text{–}60\sigma$
- Many systematic checks





Gordon & Macias (2013)



Abazajian & Kaplinghat (2012)

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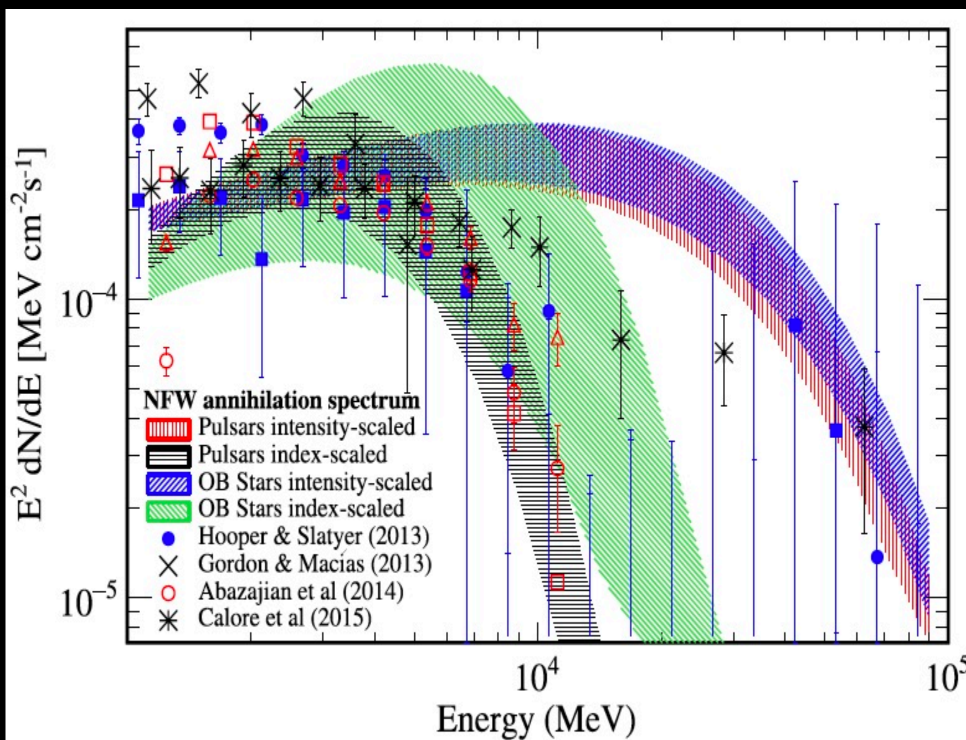
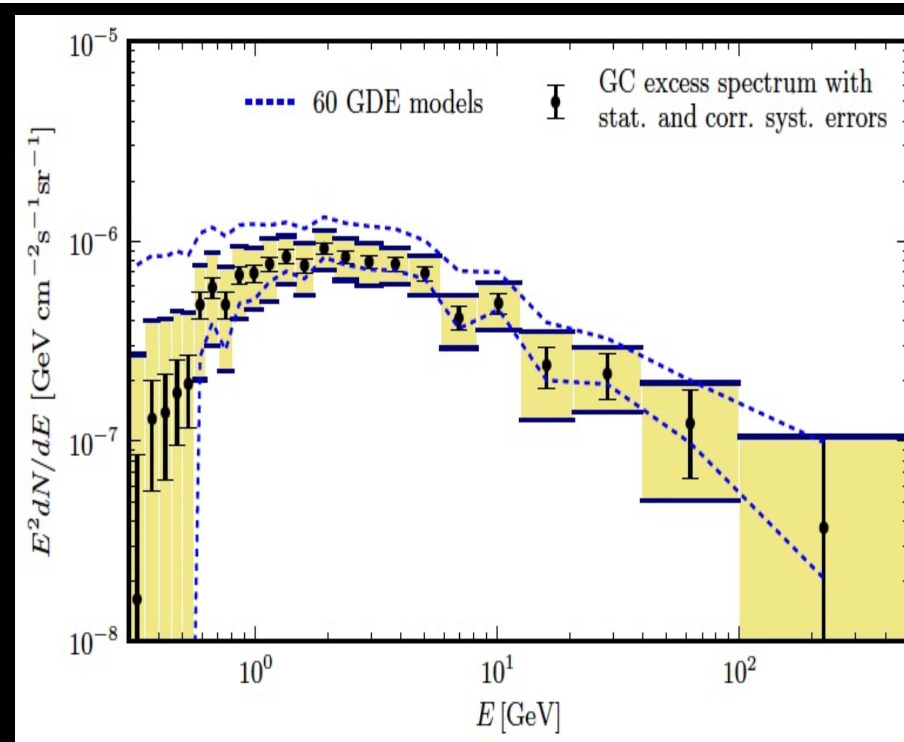
THE ASTROPHYSICAL JOURNAL, 819:44 (30pp), 2016 March 1 doi:10.3847/0004-637X/819/1/44

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

from the inner ~1 kpc surrounding the GC, and that from the rest of the Galaxy. A catalog of point sources for the 15° × 15° region is self-consistently constructed using these IEMs: the First *Fermi*-LAT Inner Galaxy Point Source Catalog (1FIG). The spatial locations, fluxes, and spectral properties of the 1FIG sources are presented, and compared with γ-ray point sources over the same region taken from existing catalogs. After subtracting the interstellar emission and point-source contributions a residual is found. If templates that peak toward the GC are used to model the positive residual the agreement with the data improves, but none of the additional templates tried account for all of its spatial structure. The spectrum of the positive residual modeled with these templates has a strong dependence on the choice of IEM.





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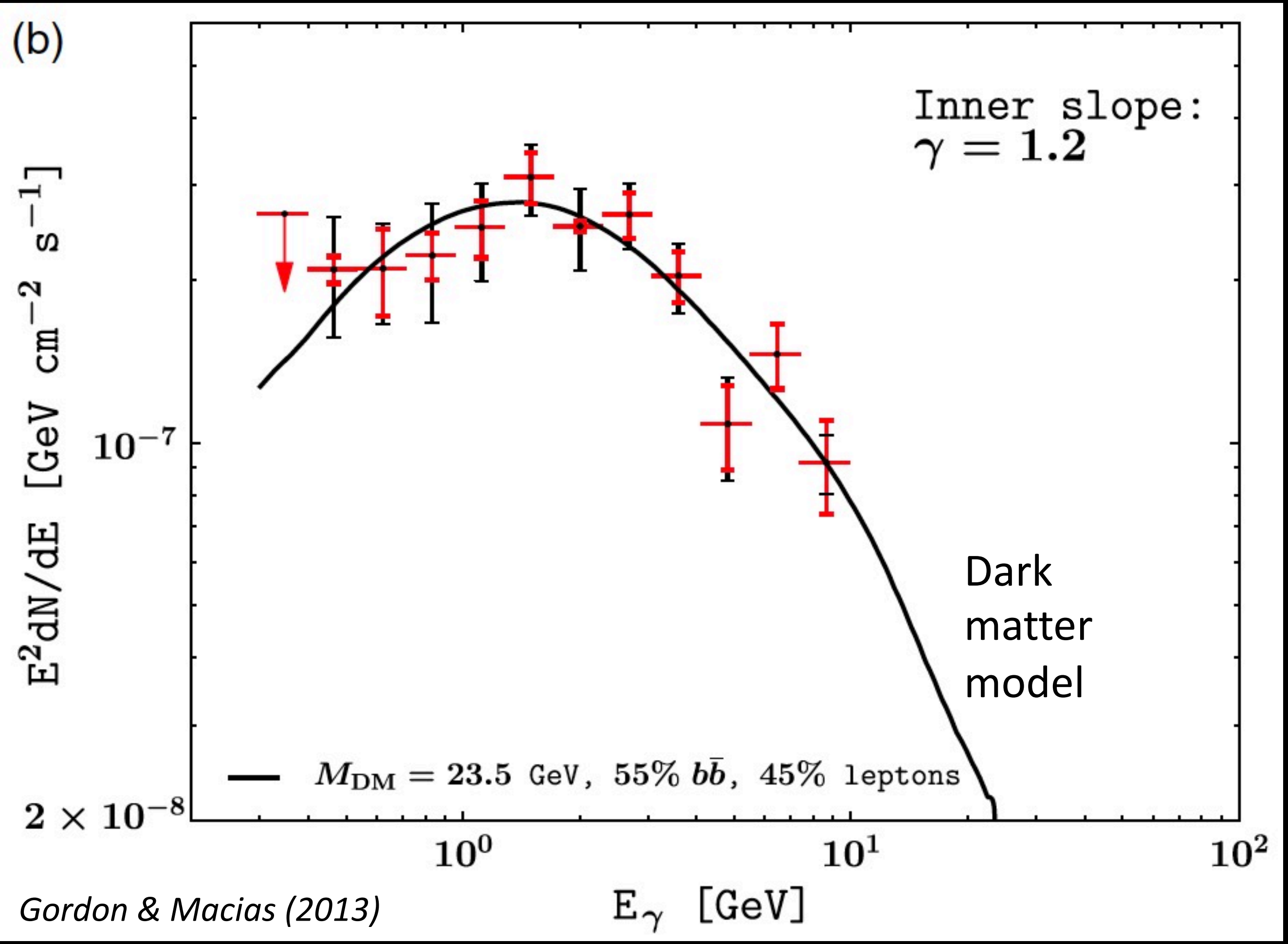
Fermi collaboration (2016)

Calore et al (2015)

Is it dark matter?

Spectral supporting evidence

Spectrum consistent with thermally produced WIMP annihilations

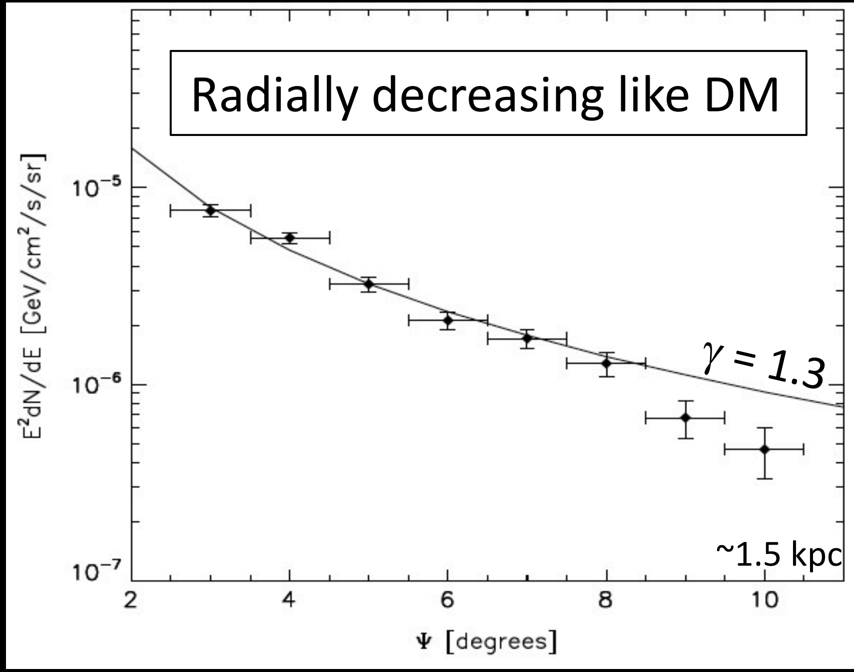


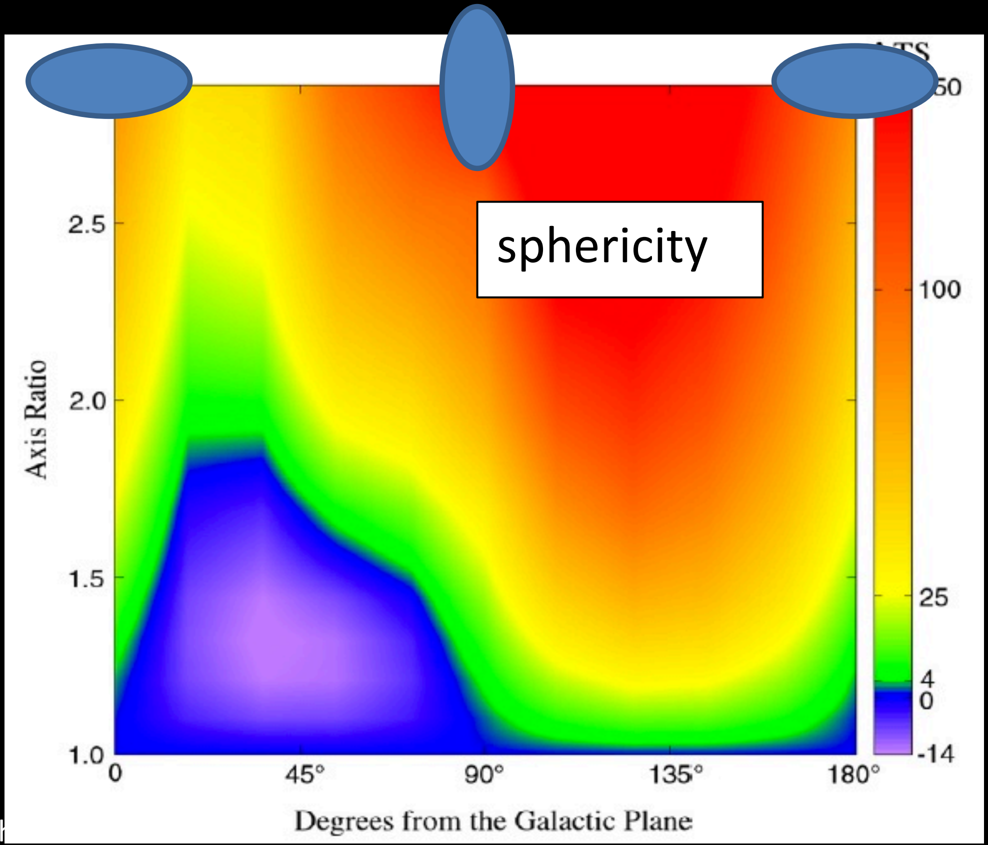
Is it dark matter?

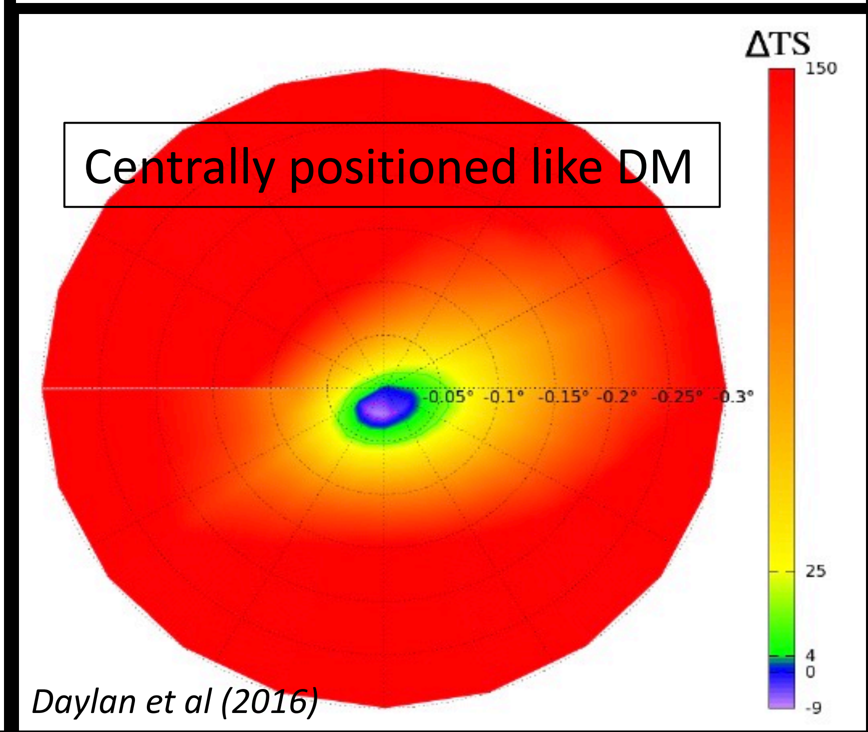
Spatial supporting evidence

Spatial morphology consistent with WIMP dark matter

➔ Consistent with dark matter







Daylan et al (2016)

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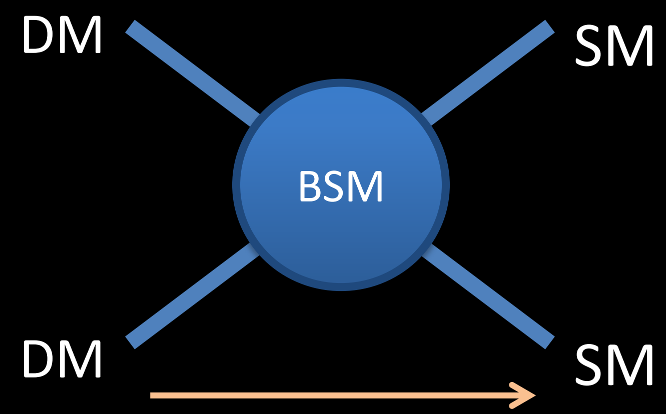
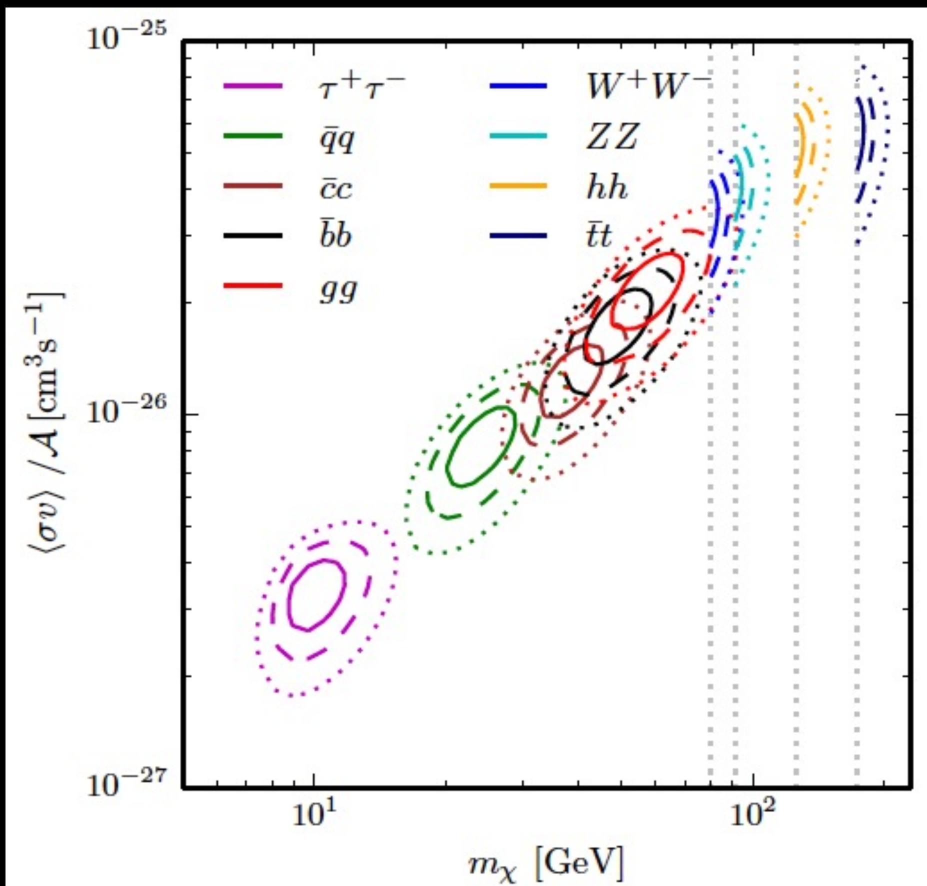
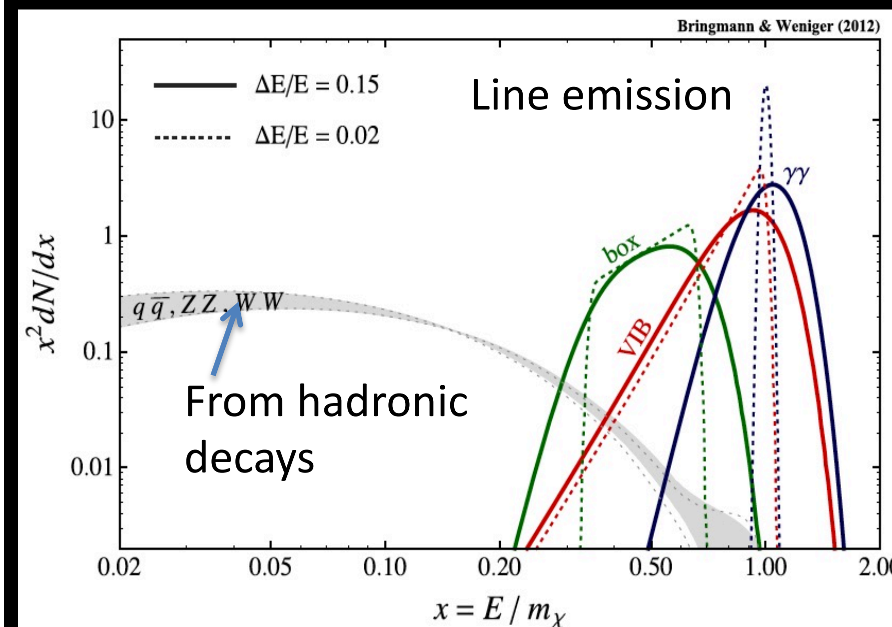
Dark matter interpretation

Dark matter
"Vanilla" dark matter works: annihilation of thermally produced WIMPs





Calore et al (2014)



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But wait!

Similarity with a "vanilla" 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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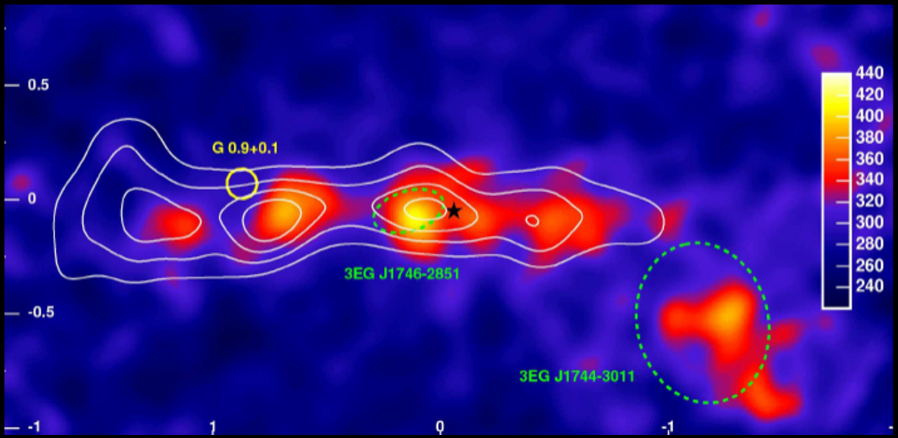
Galactic high-energy sources

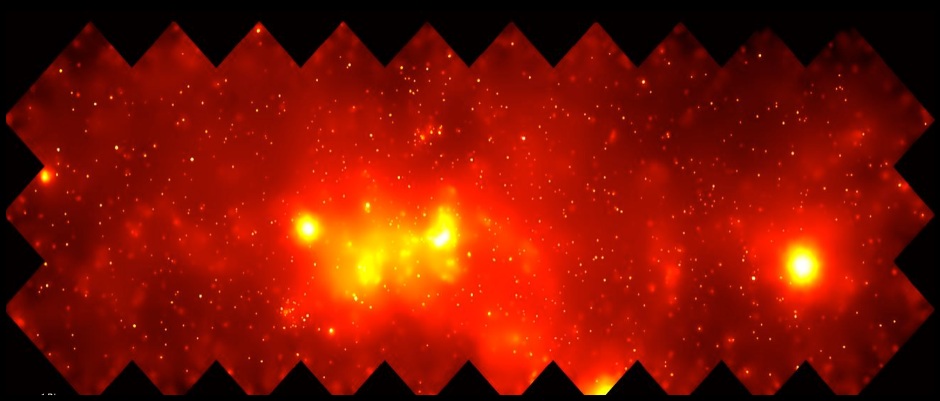
Supernova remnants

SMBH

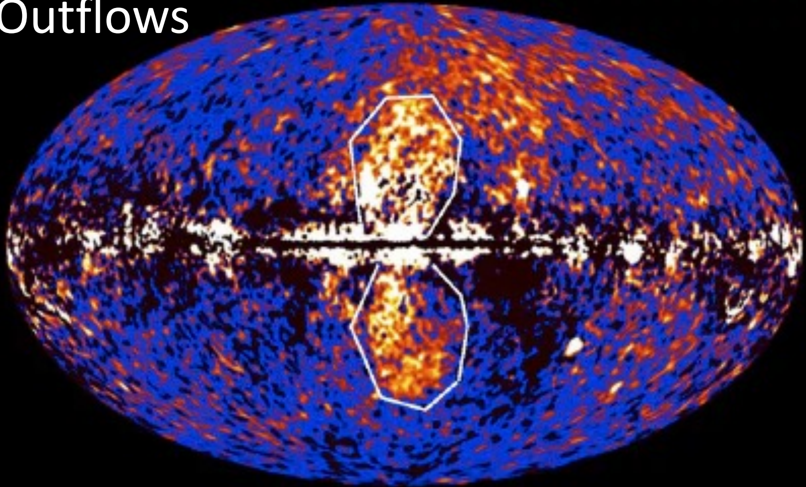


➔ Multiple source classes injecting $\sim 10^{38}$ erg/s

Pulsars



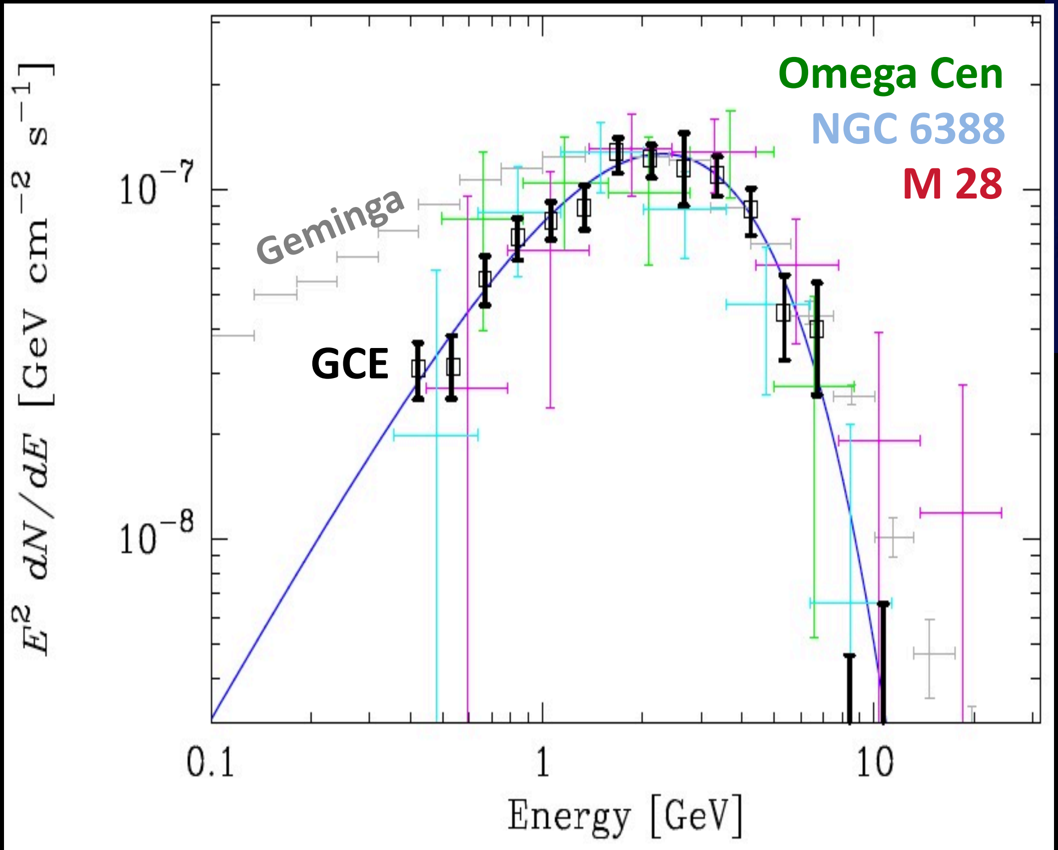
Outflows



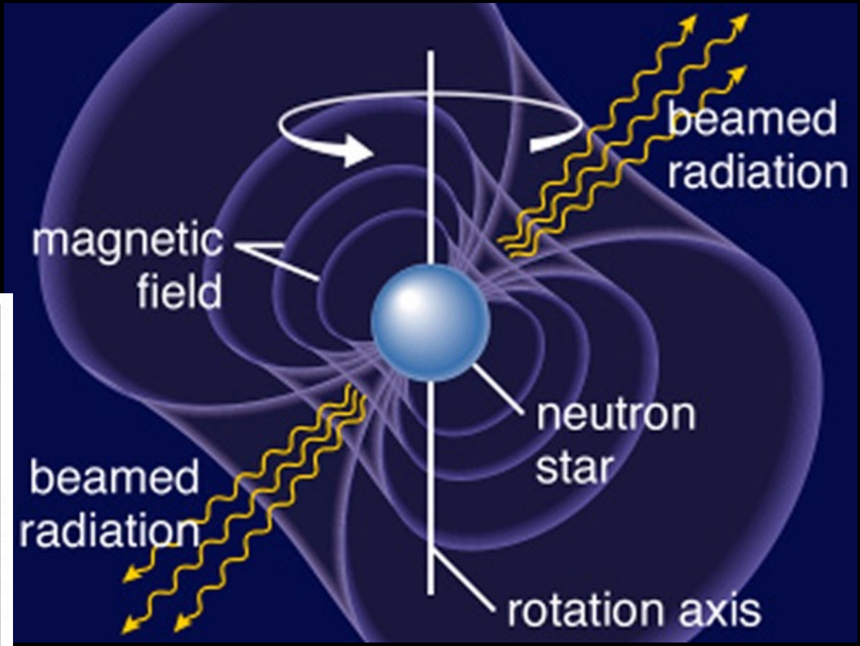
Millisecond pulsars

Millisecond pulsars

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

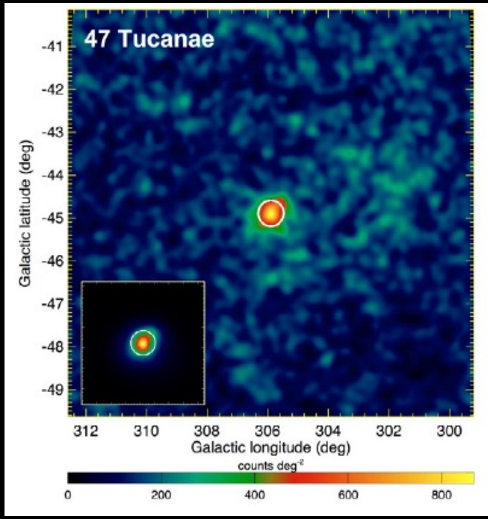


Abazajian (2011)



Gamma-ray observations of globular clusters

e.g., Fermi (2010)



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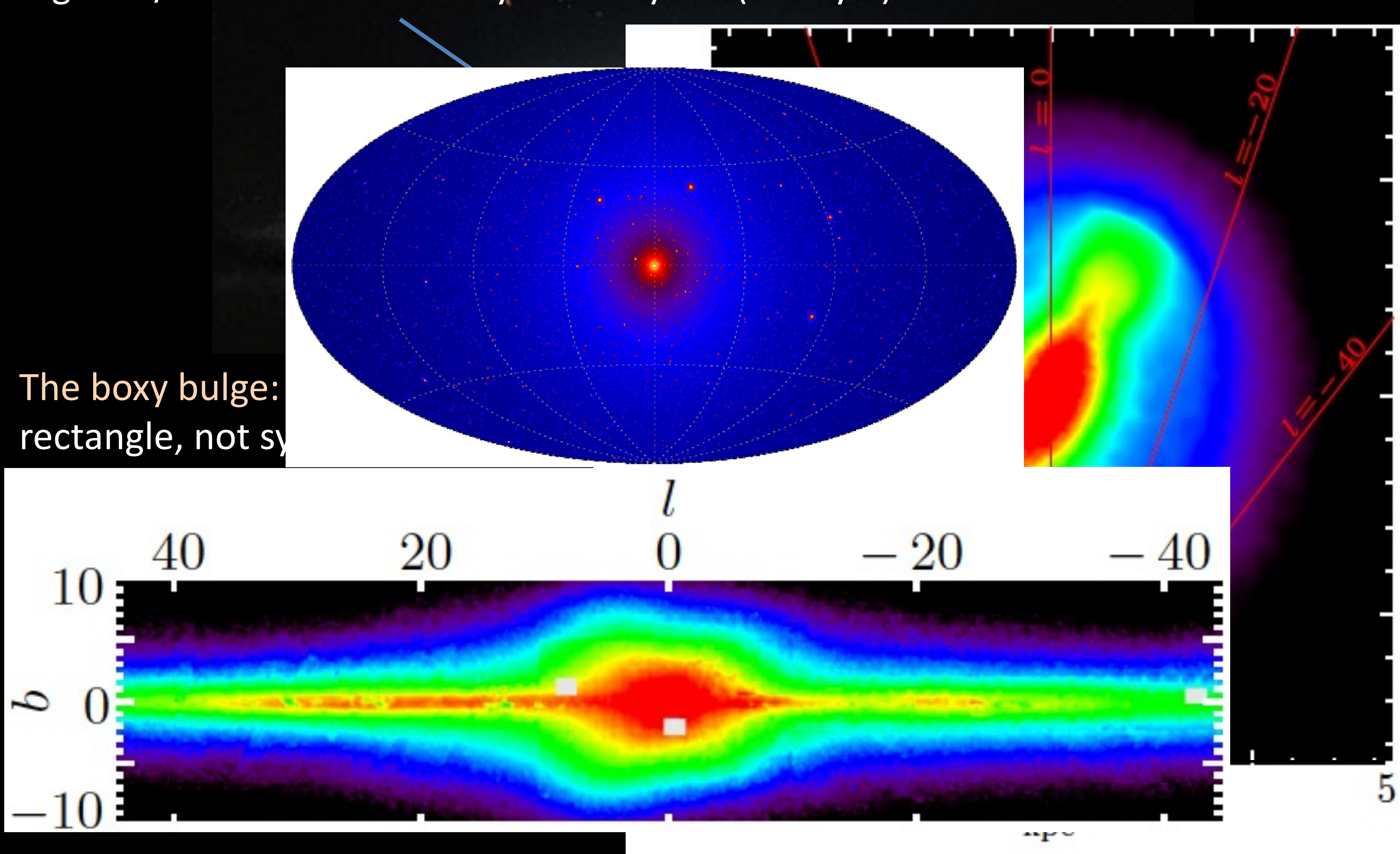
Millisecond pulsar morphology

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

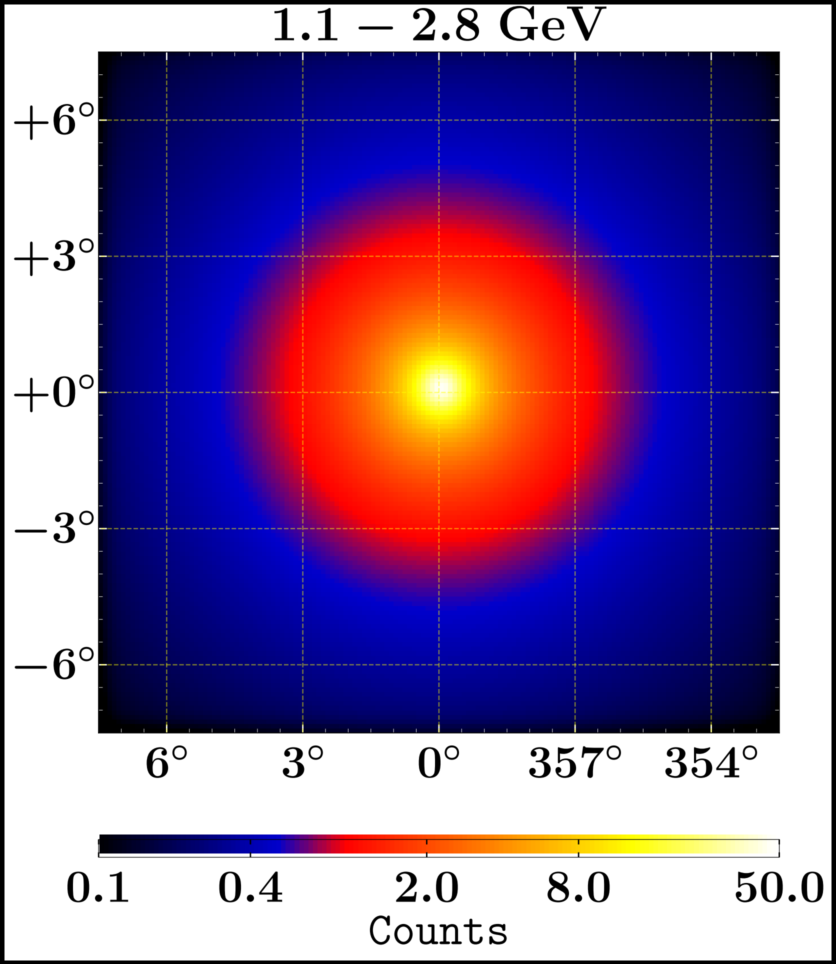
The boxy bulge:
rectangle, not sy



Bland-Hawthorn & Gerhard (2017)

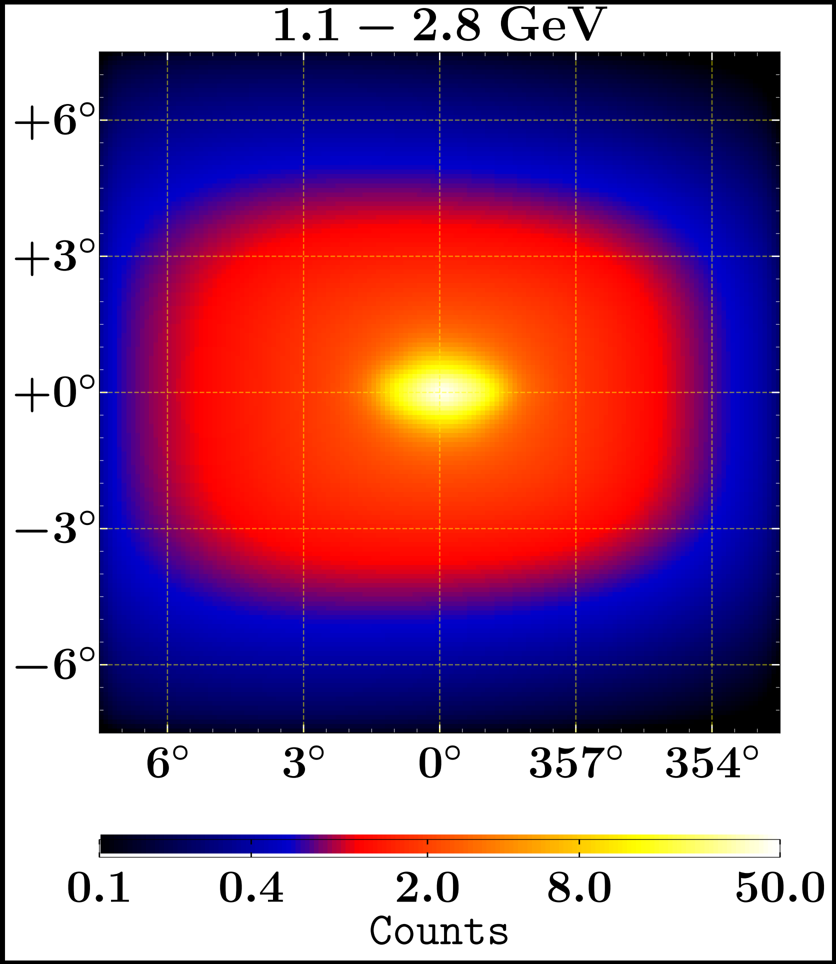
The hypothesis

Dark matter annihilation



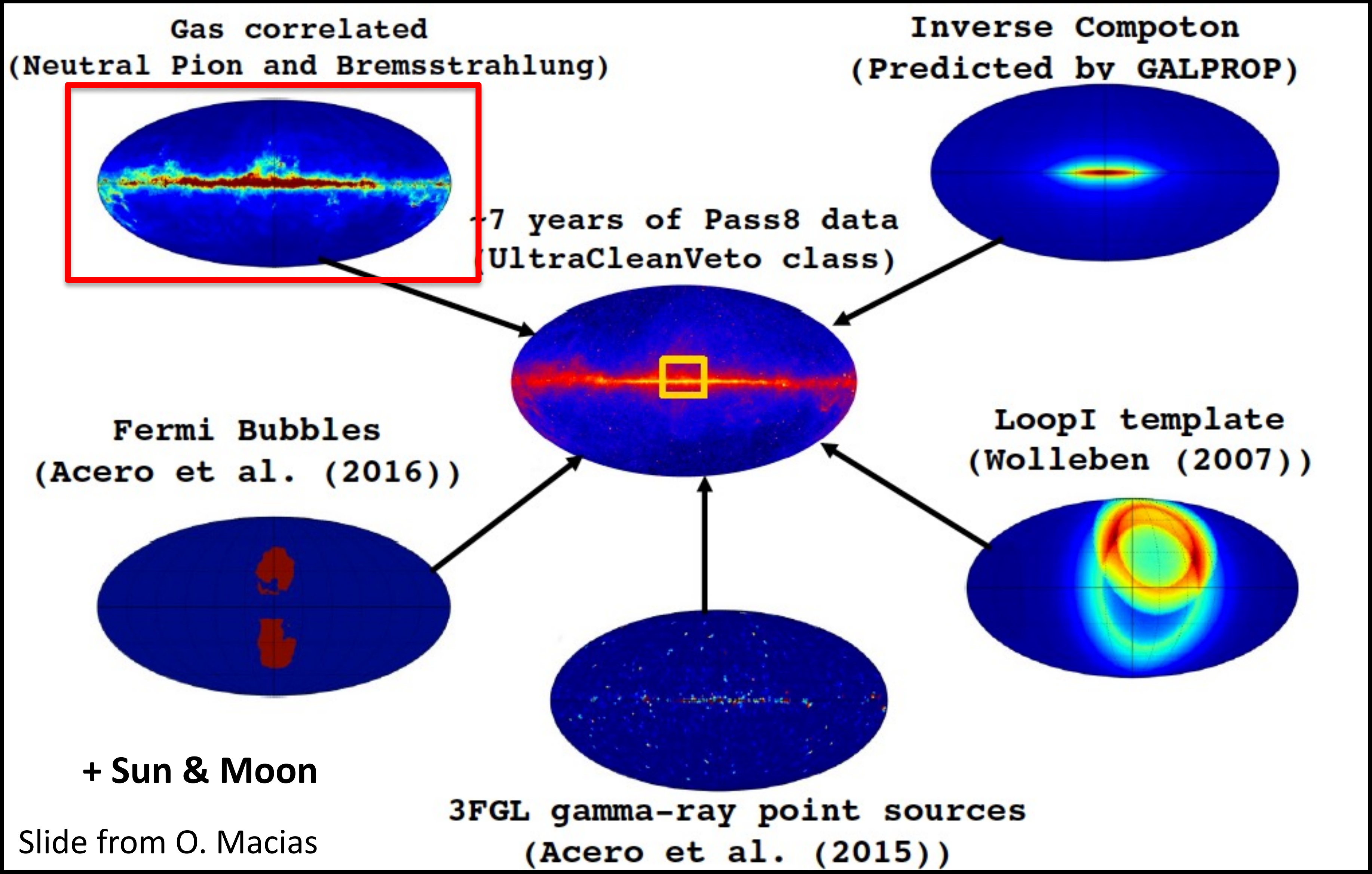
VS

Astrophysics (pulsar)



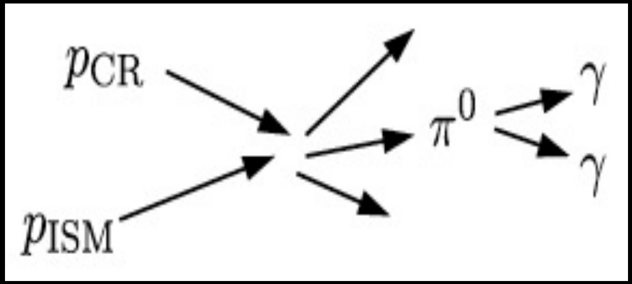
(Use Freudenreich 1998)

Baseline background model

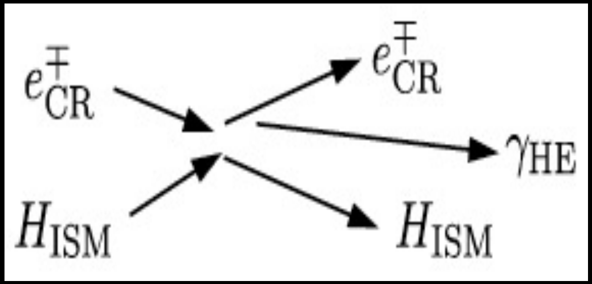


Background I

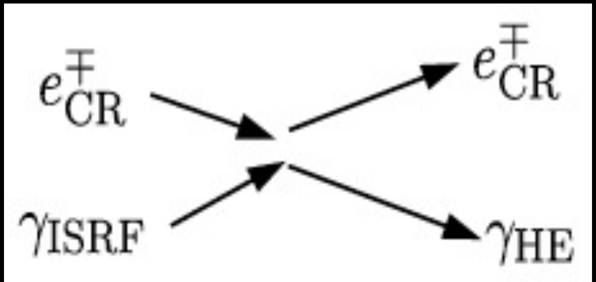
Decay of neutron pions



Bremsstrahlung



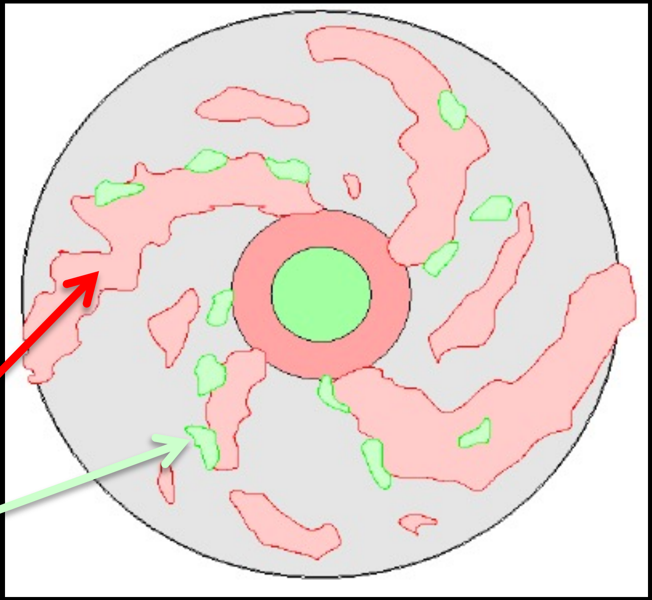
Inverse Compton



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

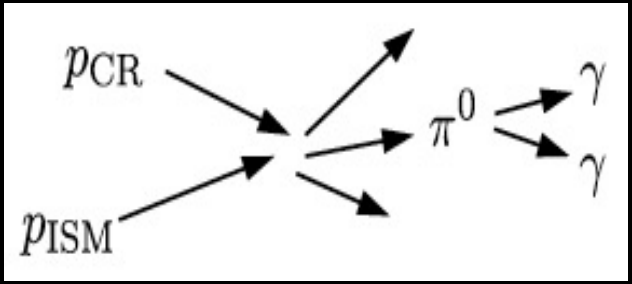


Atomic HI is measured by 21-cm emission

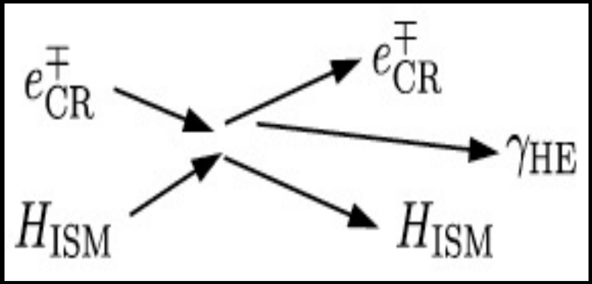
Molecular H2 is traced by the 2.6mm line of CO

Background II

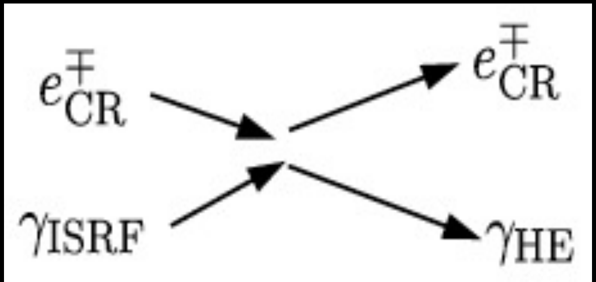
Decay of neutron pions



Bremsstrahlung



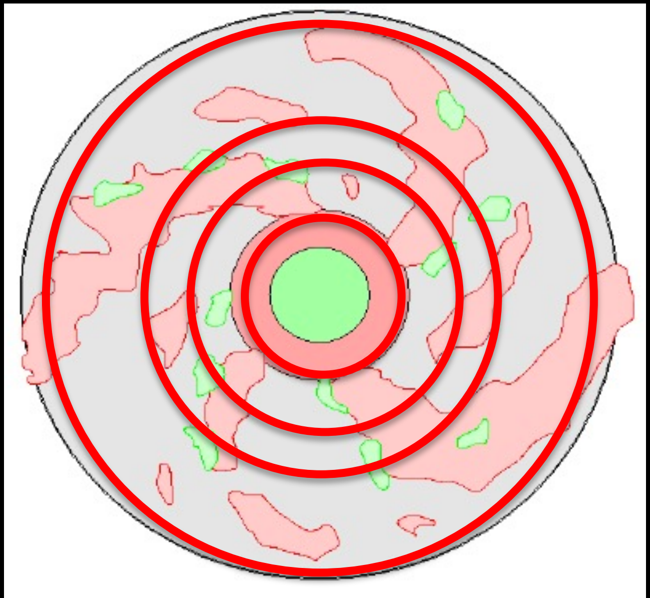
Inverse Compton



Strategies

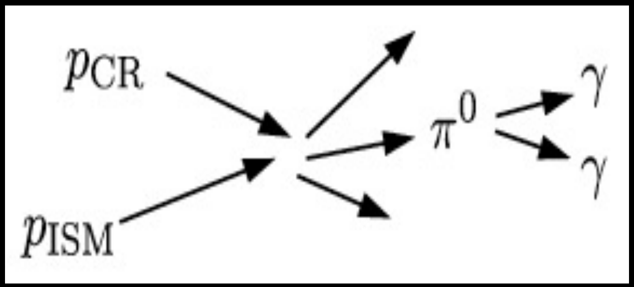
1. <u>Minimalist</u>: use multi-wavelength e.g. gas maps
2. <u>Empirical model</u>: data-driven and annuli to account for desired flexibility

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

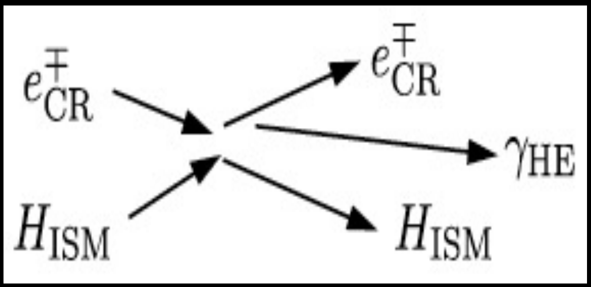


Background III

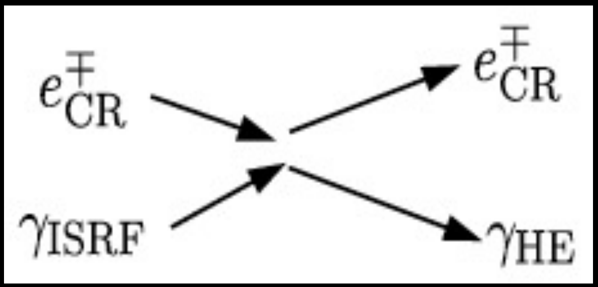
Decay of neutron pions



Bremsstrahlung



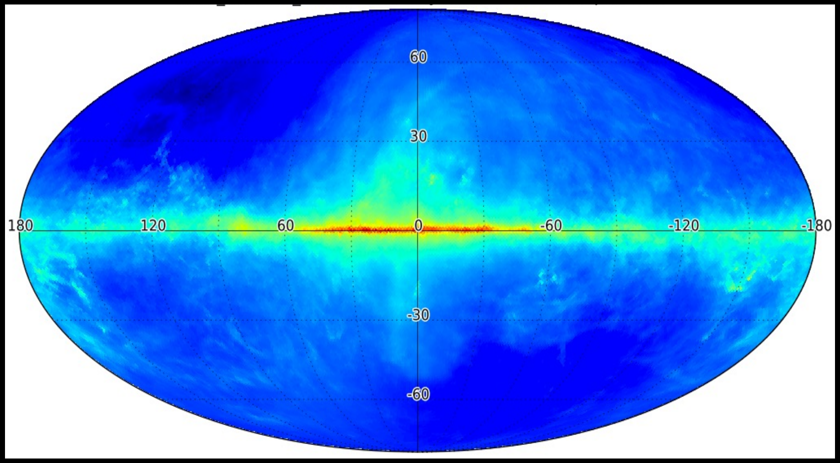
Inverse Compton



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

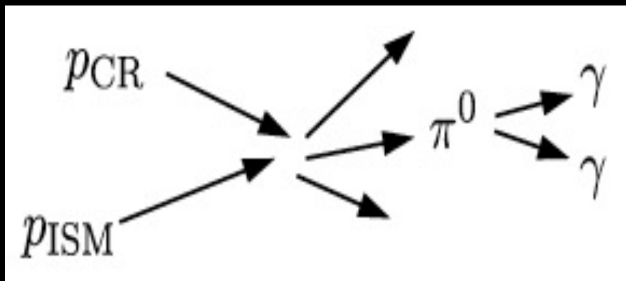
- ✓ Simple (hard work done!)
- ✓ Accounts for some cosmic-ray injection and propagation variations (via annuli)
- ✗ Somewhat of a black box for user
- ✗ Fixed to (usually) older data
- ✗ Constructed not dedicated for the Galactic Center



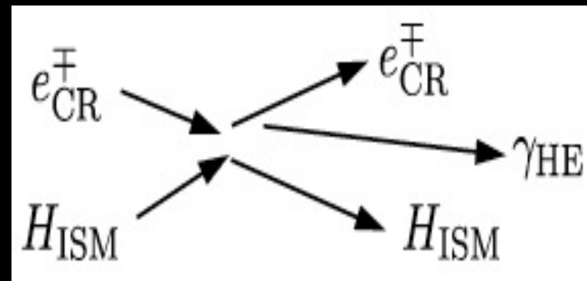
Acero et al (2016)

Background IV

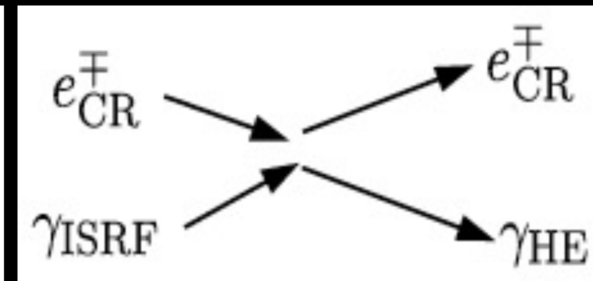
Decay of neutron pions



Bremsstrahlung



Inverse Compton

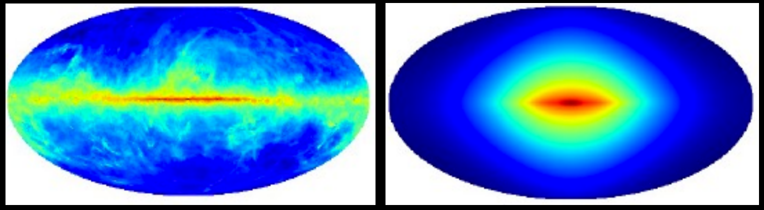


Strategies

1. 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
4. Model builder: numerically solve the diffusion equation

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

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

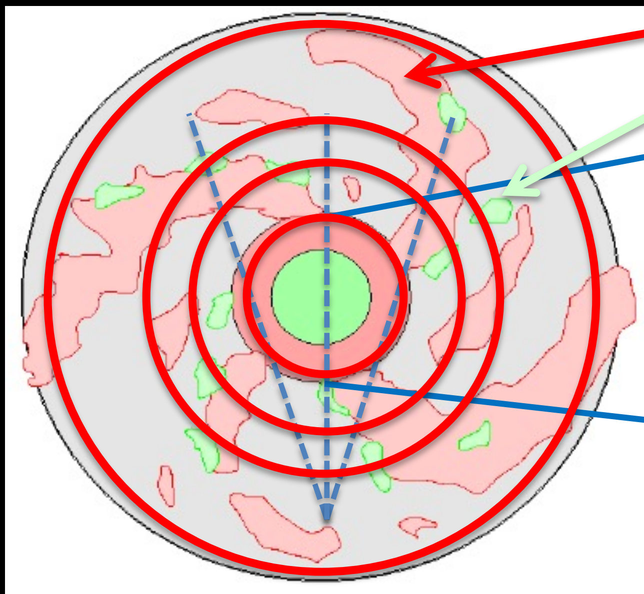


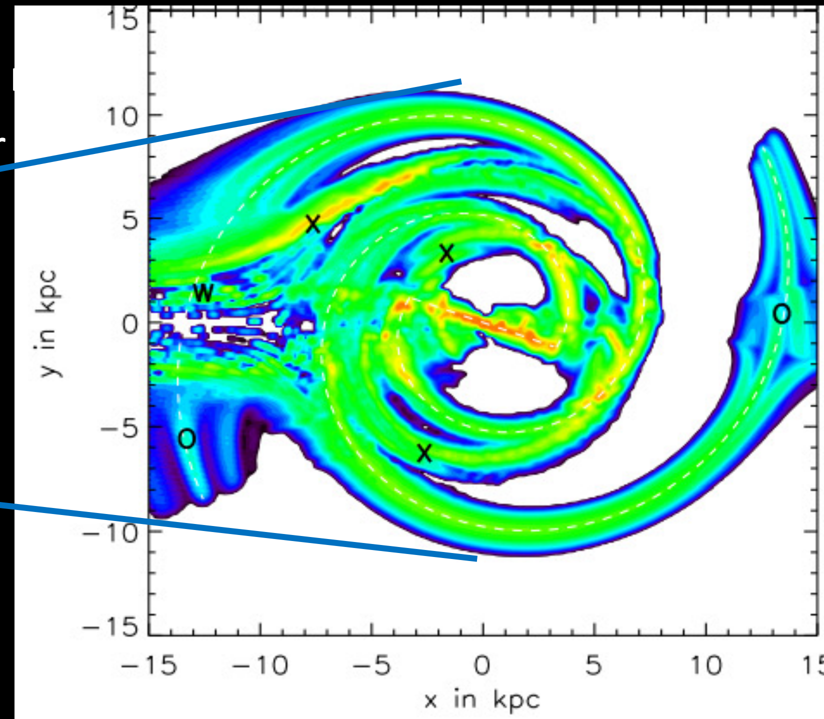
e.g., Galprop; Moskalenko & Strong (1998)

Improve background modeling

Previous approach

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





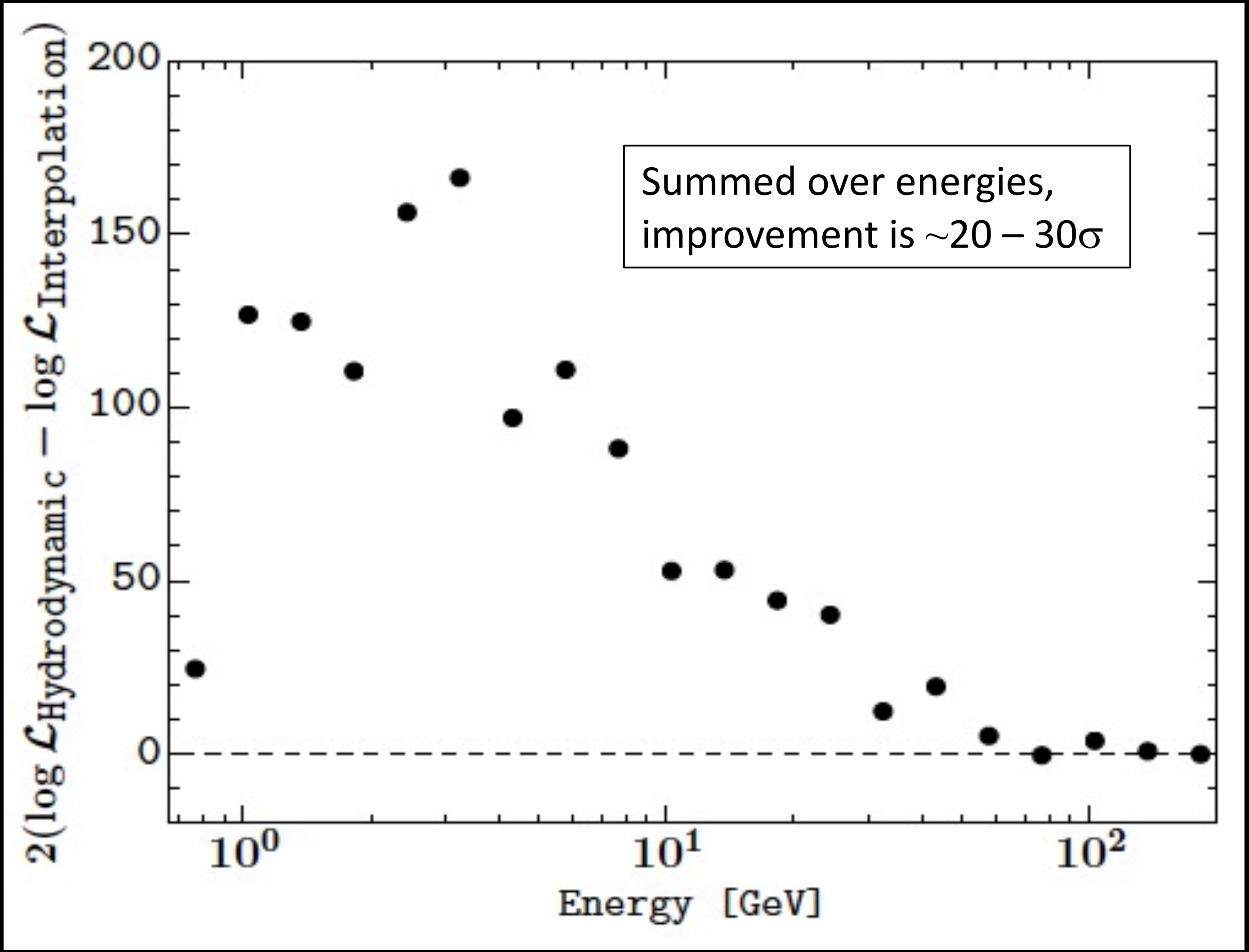
Pohl et al (2009)

New approach

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

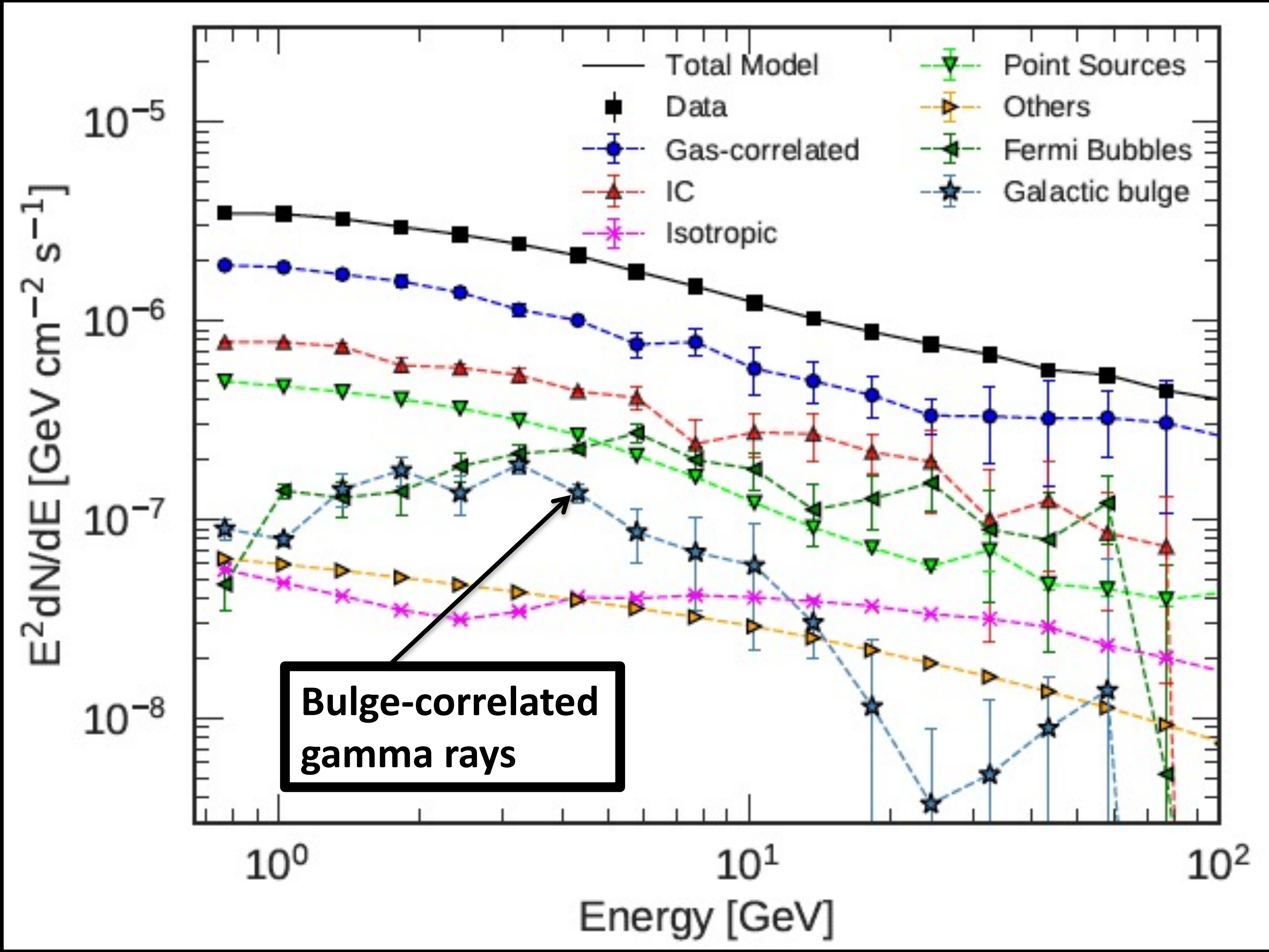
New background model much better

Significant improvement observed by hydrodynamical templates



Macias et al (2018)

Detection!!!



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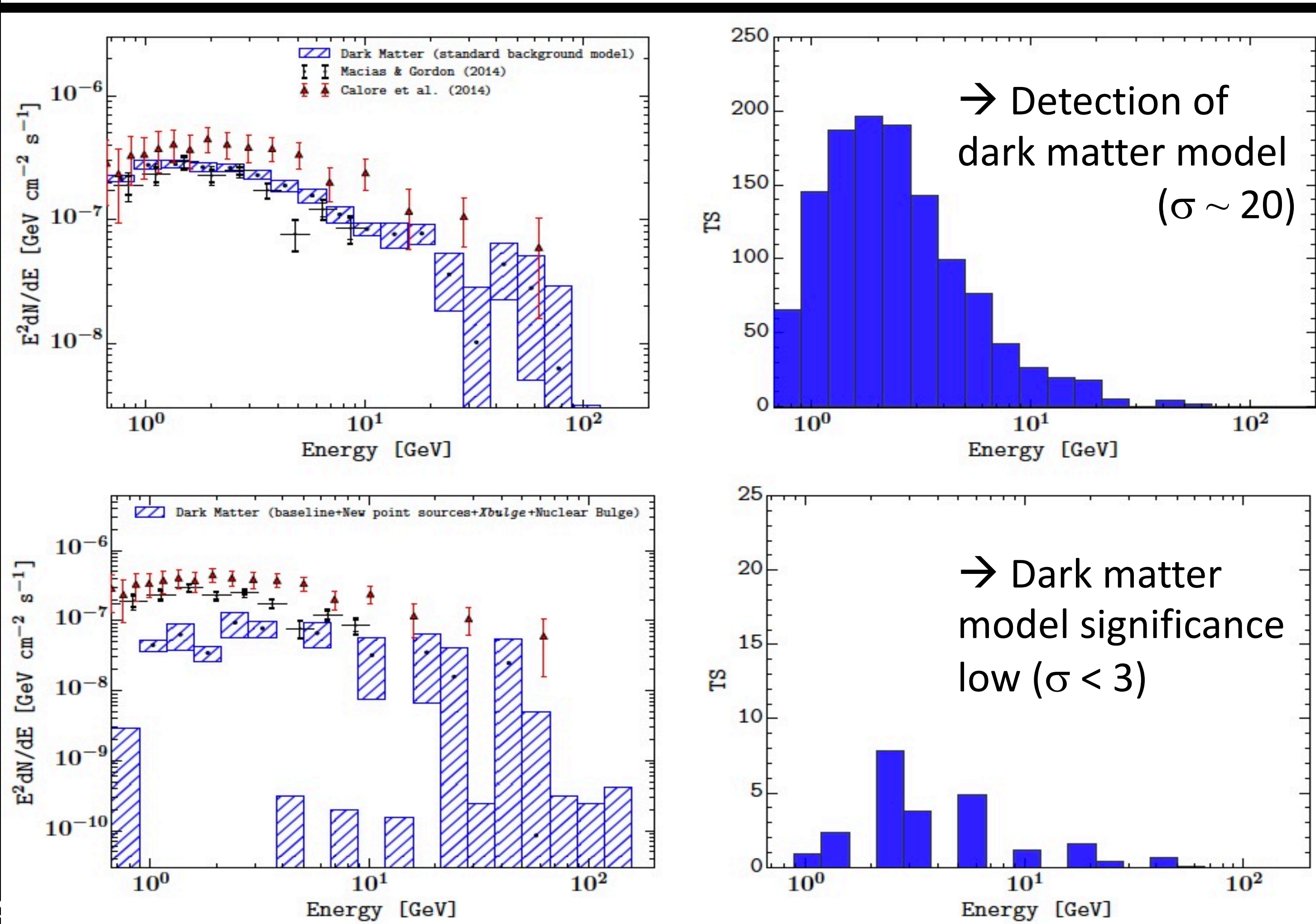
Macias et al (2018)

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



Macias et al (2018)

↖ WITHOUT bulge (representative of previous studies)

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

nature astronomy

ARTICLES

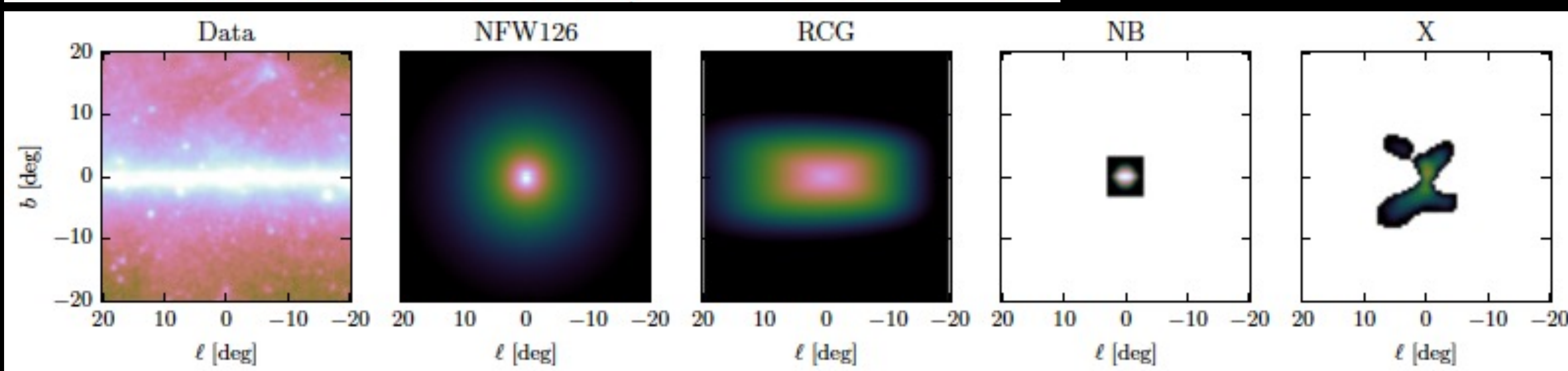
https://doi.org/10.1038/s41550-018-0531-z

The Fermi-LAT GeV excess as a tracer of stellar mass in the Galactic bulge

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 (although the actual DM profile is sufficiently uncertain that this possibility cannot be entirely excluded). What

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

Bartels et al (2018)



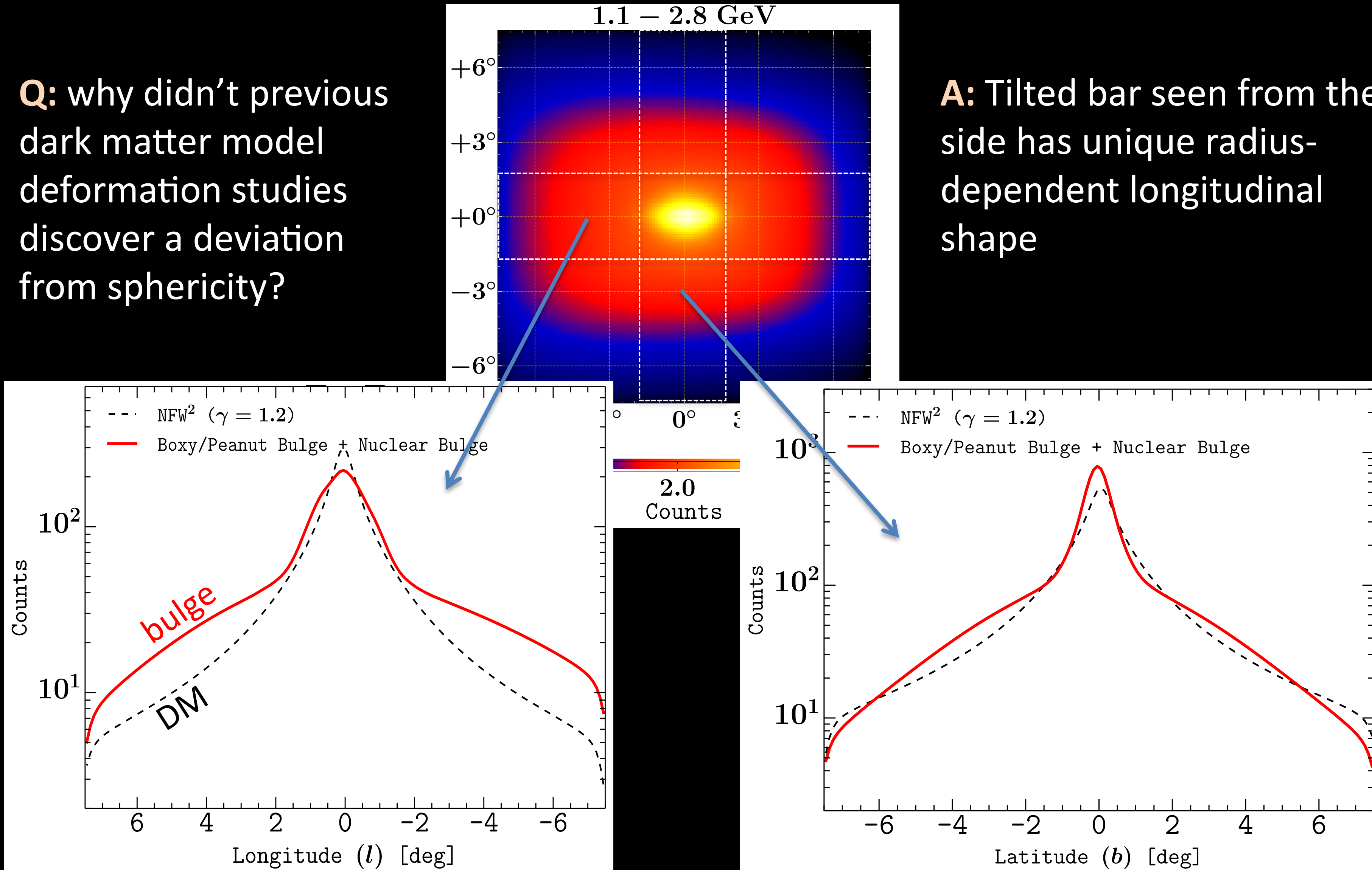
SkyFACT = **Sky F**actorization with **A**daptive **C**onstrained **T**emplates

Combines adaptive spatial-spectral template regression and image reconstruction to account for small-scale model inaccuracies. *Storm et al (2017)*

How are the two distinguished?

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

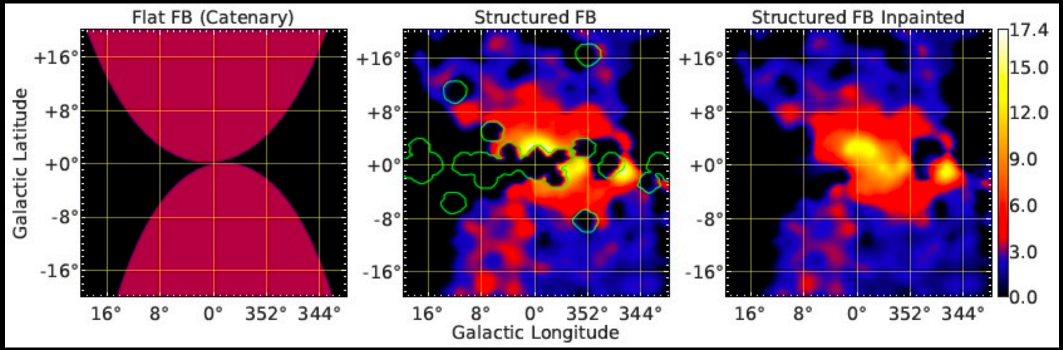
A: Tilted bar seen from the side has unique radius-dependent longitudinal shape



Systematics

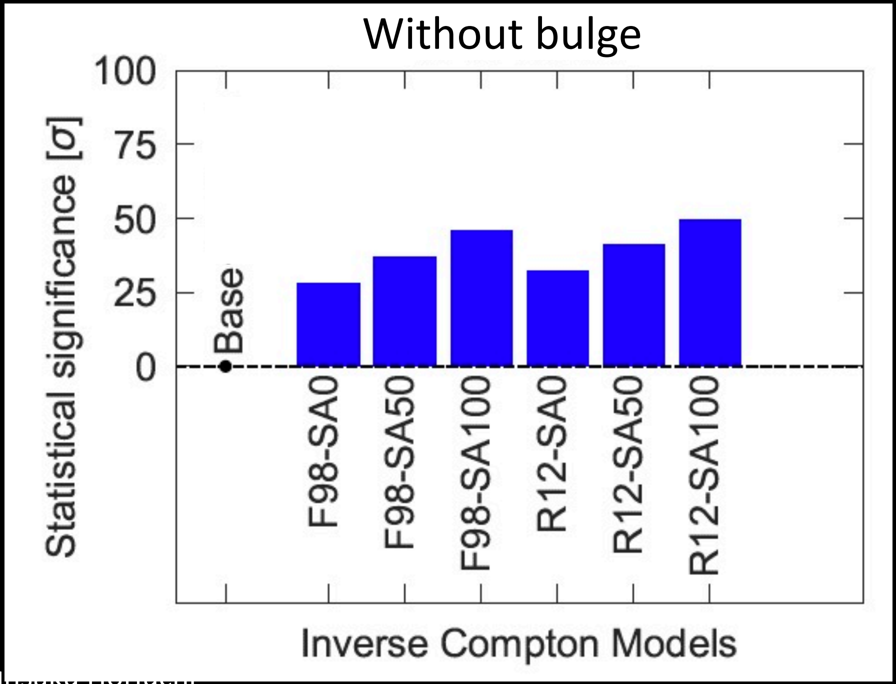
Many astrophysical systematics

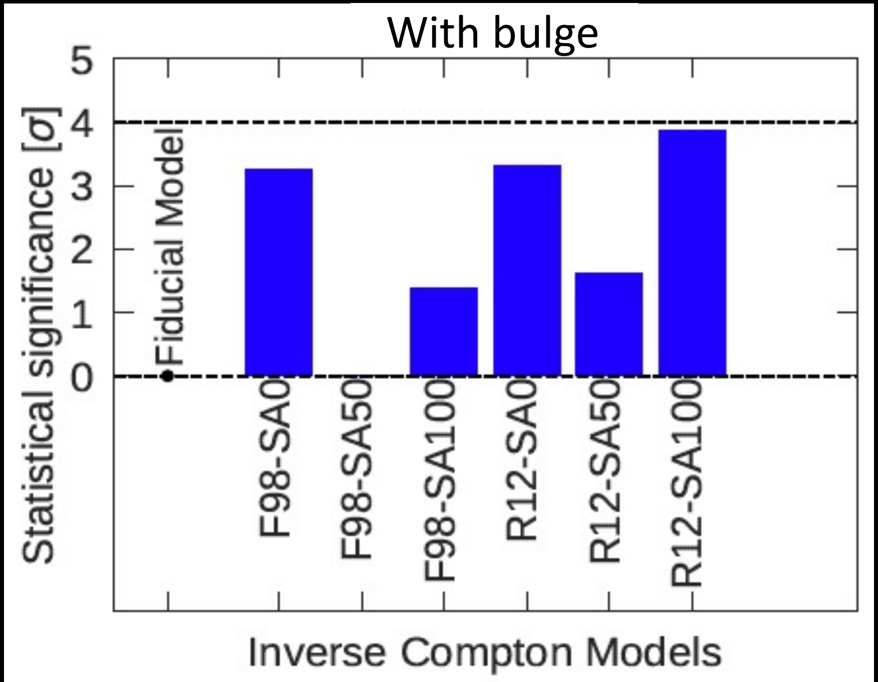
1. Bulge model
2. Fermi bubble model
3. Background (IC models)
4. Background (gas maps)
5. Point source catalogs
6. Galactic disk masks



Significance of NFW² 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	$\log(\mathcal{L}_{\rm Base})$	$\log(\mathcal{L}_{\rm Base+Source})$	$\rm TS_{Source}$	σ	Number of source parameters
baseline+NB+Boxy	NFW	-172005.9	-171999.0	13.8	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*+NB+Boxy	NFW	-172547.4	-172533.0	28.8	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+2FIG+NB+Boxy	NFW	-170317.2	-170313.5	7.4	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+Boxy	NFW	-430035.8	-430026.3	19	2.0	19

Dark matter systematics

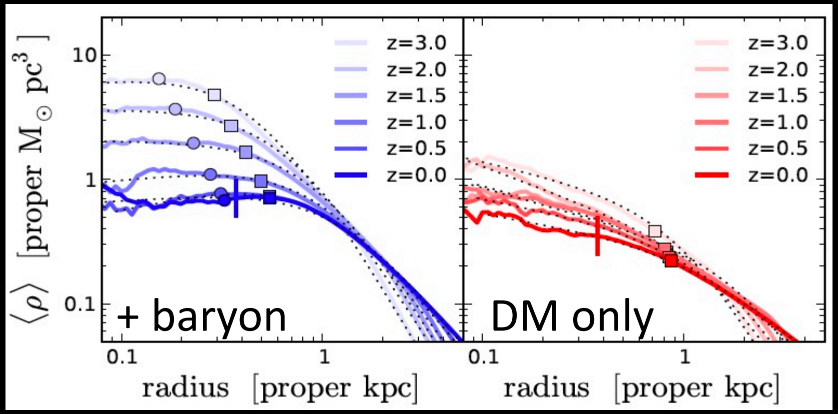
1. Inner slope, including cores
2. Asymmetry

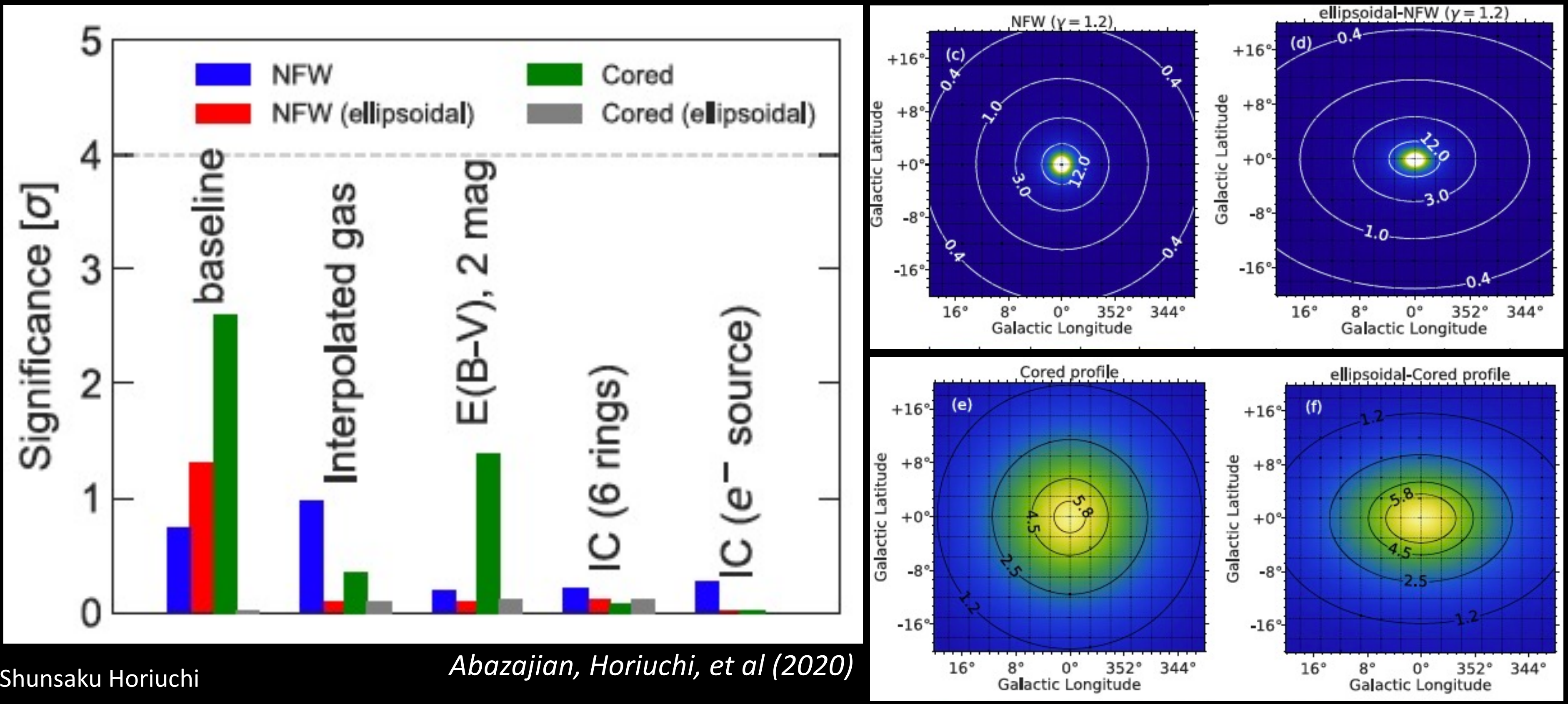
➔ Try γ [0.5,1.5], 1kpc core, axis ratio 0.7

Eg, bulge kinematics, Eris, FIRE simulations

➔ Again dark matter model not detected

Kuhlen et al (2012)

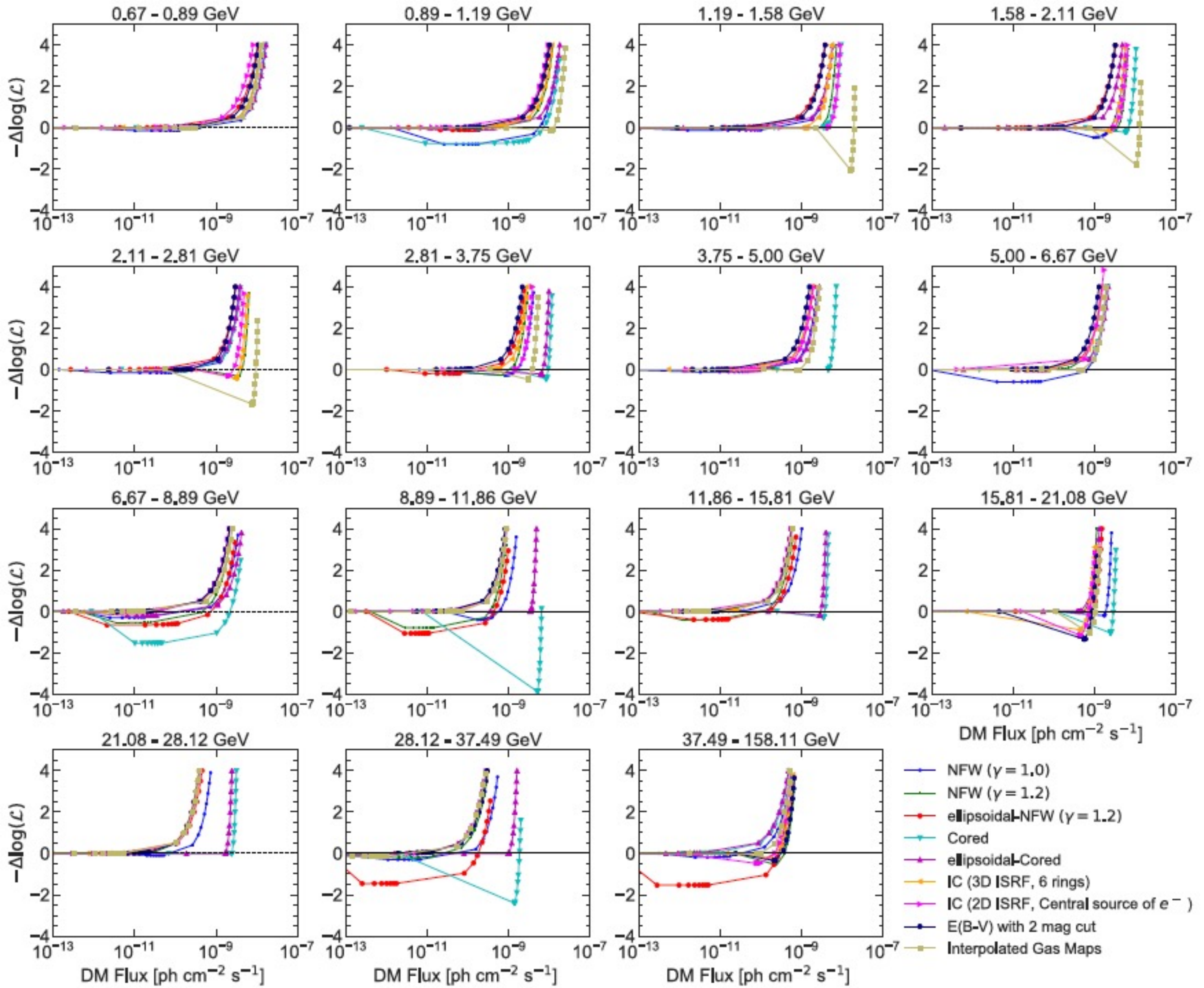




Abazajian, Horiuchi, et al (2020)

Shunsaku Horiuchi

IMPLICATIONS



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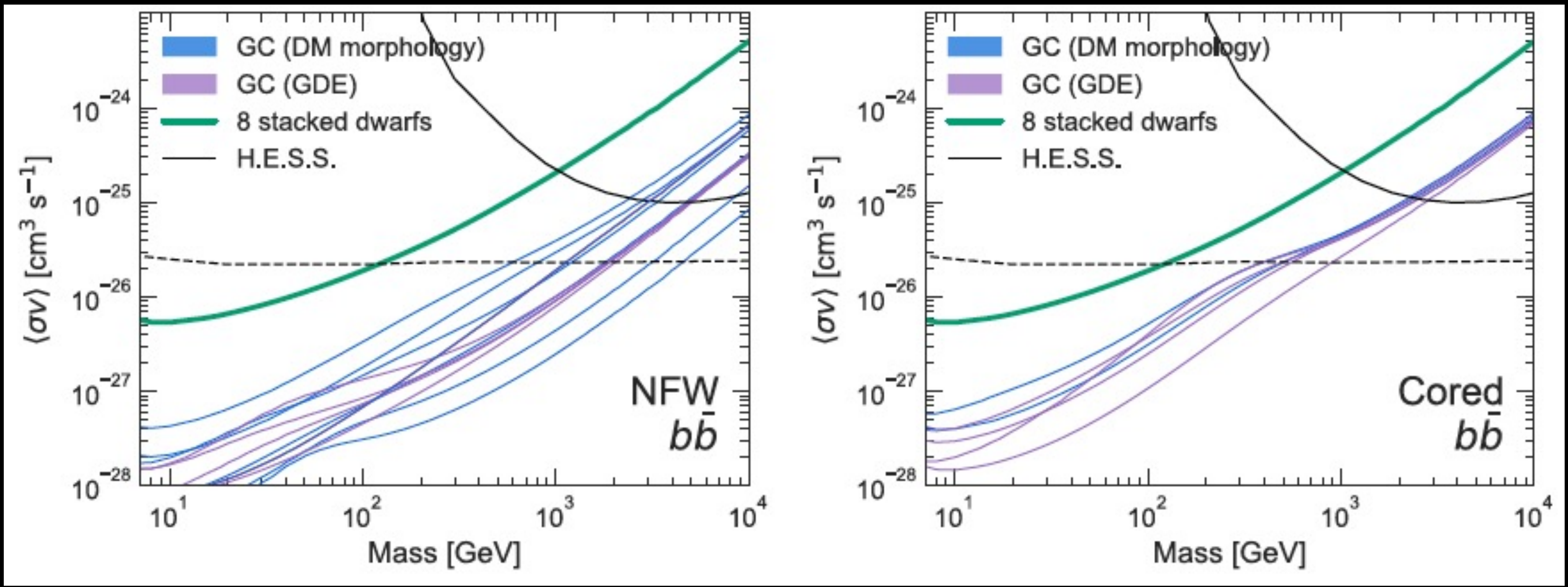
Improved sensitivity to dark matter

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


Deheng Song

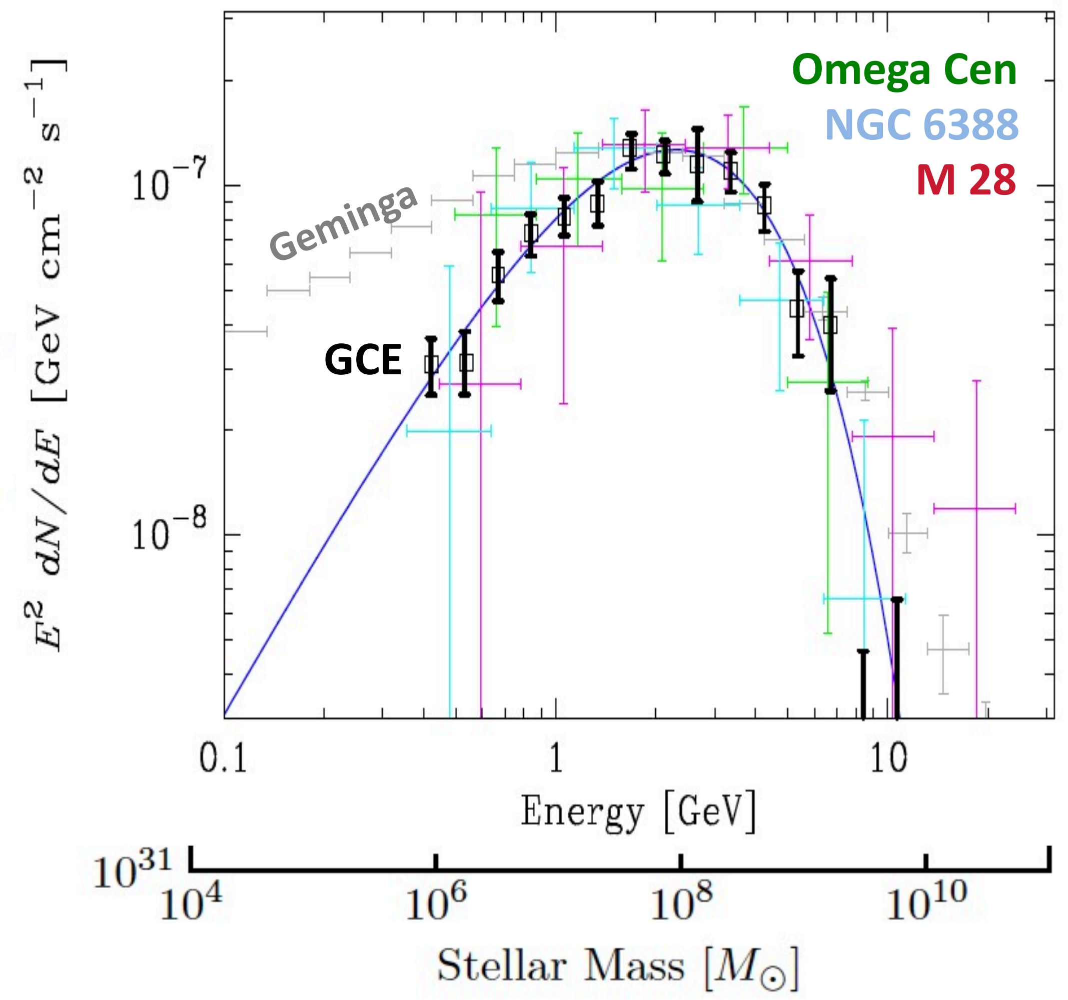
Some insights:

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)

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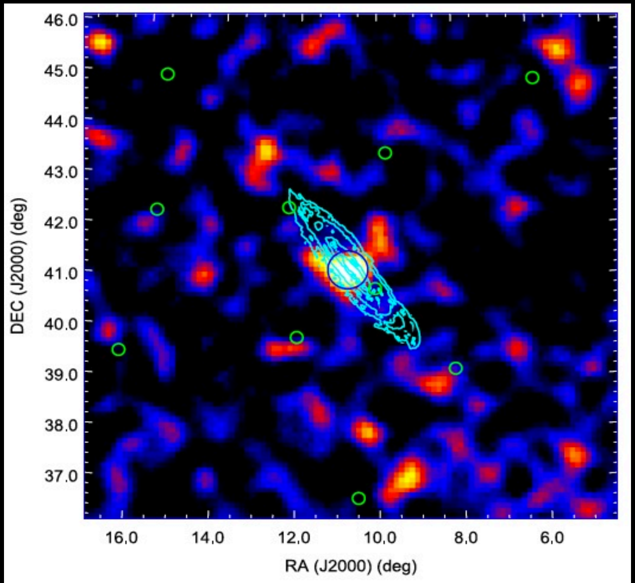
Gamma / mass ratio

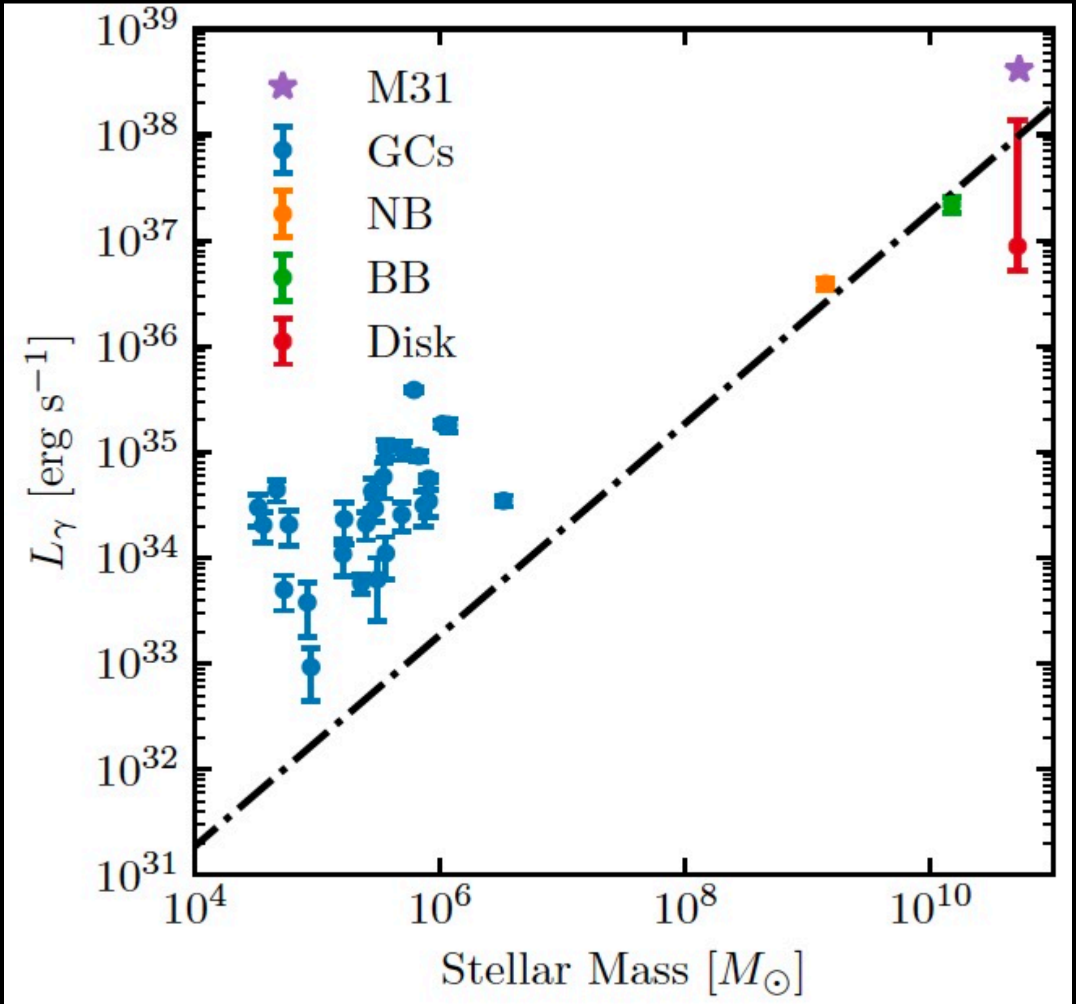

Deheng Song

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)

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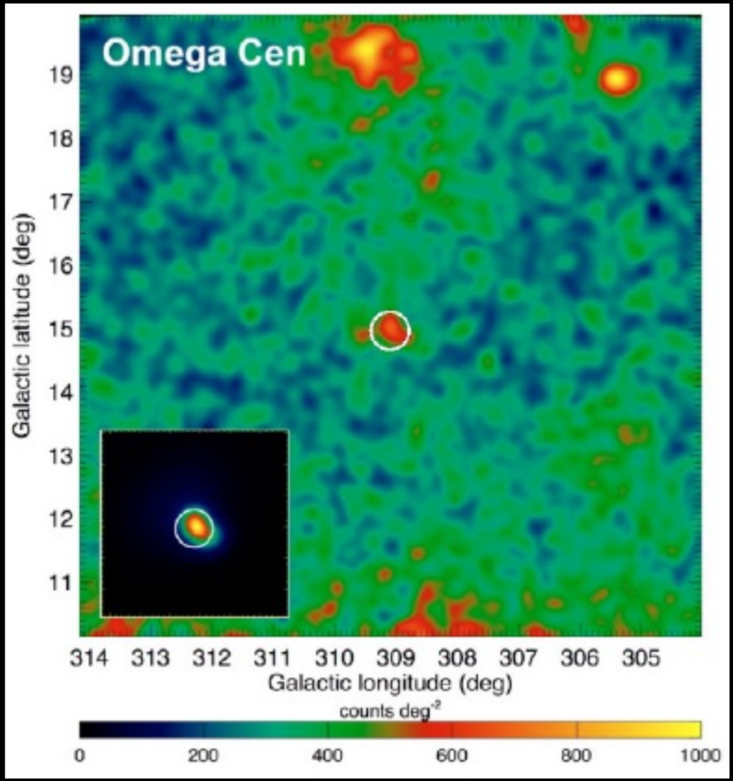
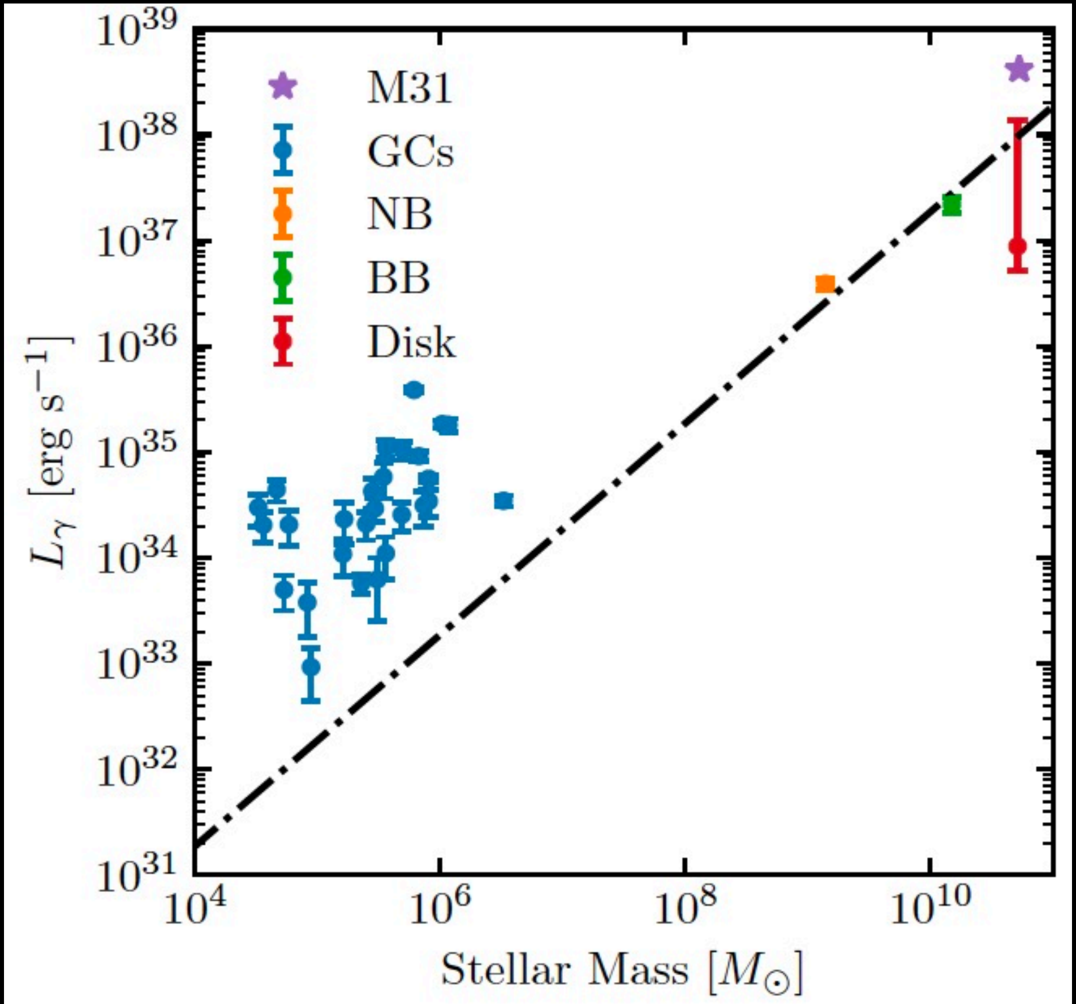
Gamma / mass ratio

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)

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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

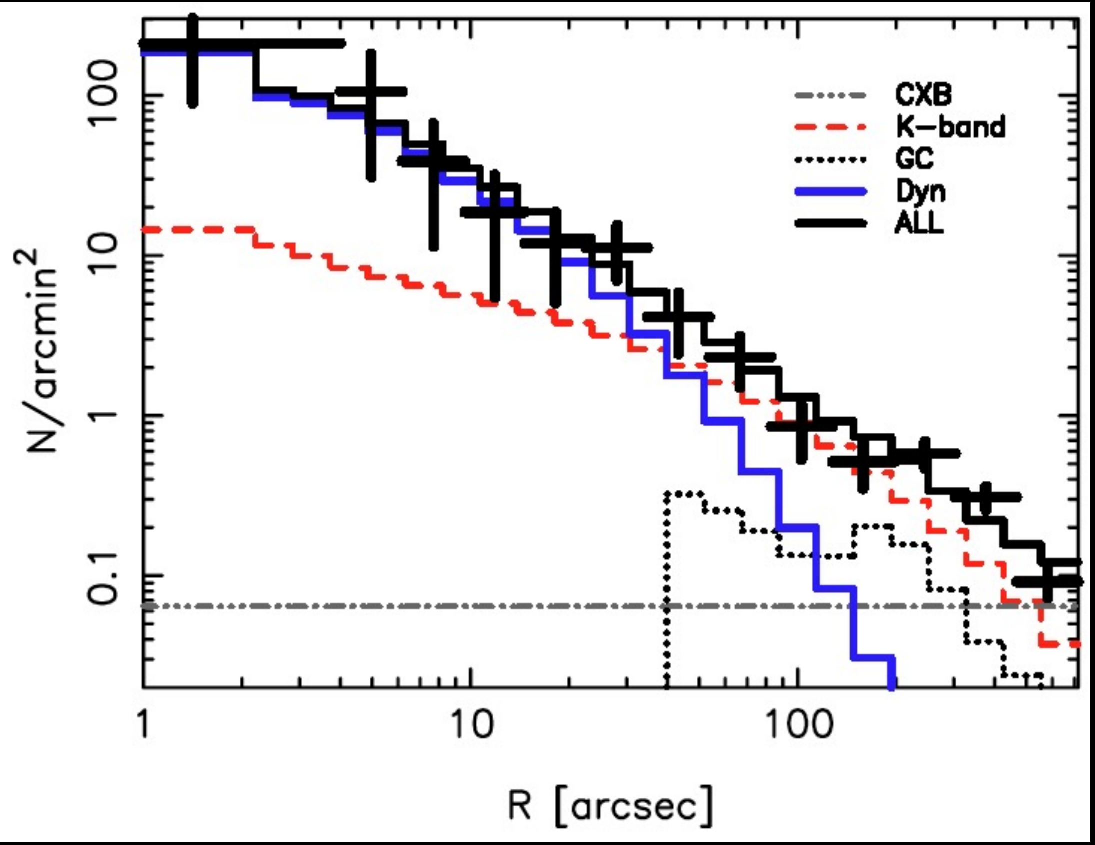
Departure from linear scaling:

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

Verbunt & Lewin (2006)

- In M31, ~25% show dynamic origin

Voss & Gilfanov (2007)



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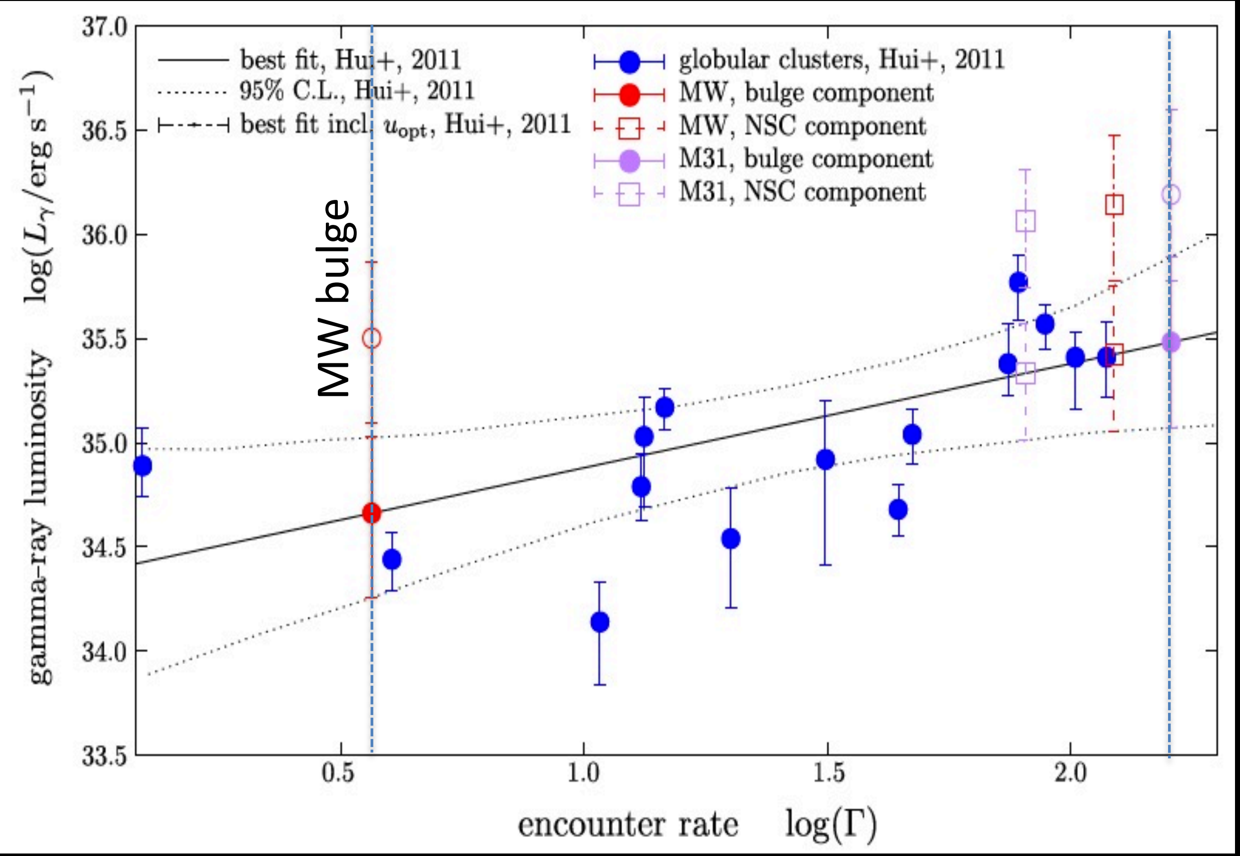
$$\Gamma \propto \rho_*^2/\sigma$$

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)

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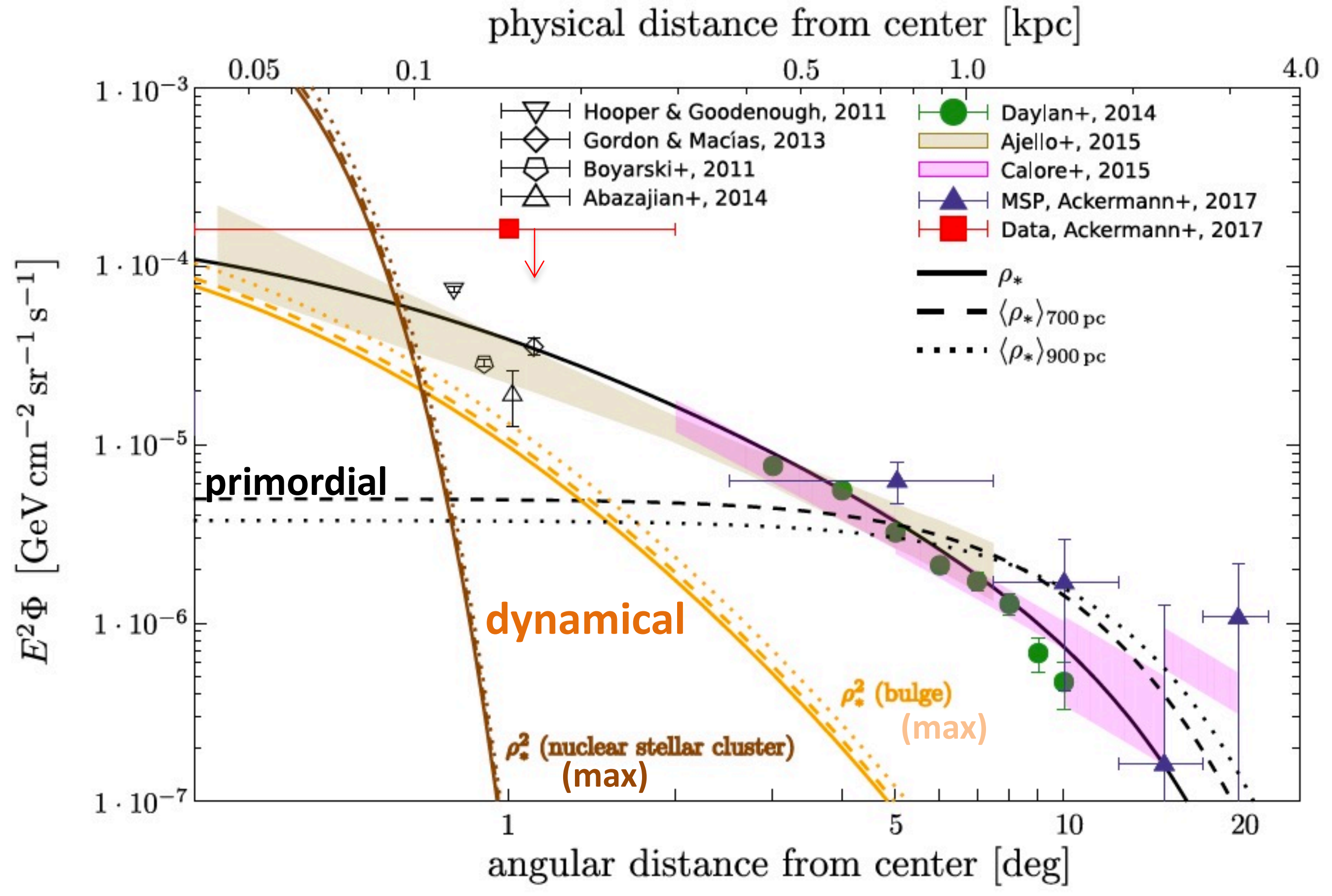
Implementation to Milky Way

Millisecond pulsars in the bulge

= primordial + dynamical (modeled after globular clusters)



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)

Eckner et al (2017)

➔ Millisecond pulsars consistent with bulge-correlated γ-rays

FUTURE THOUGHTS

How to further test between pulsar vs dark matter origins?

Find the pulsars

To directly confirm the source

→ *Multiwavelength search campaign*

Fermi

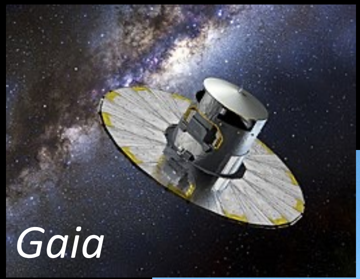
Radio

Compare other regions

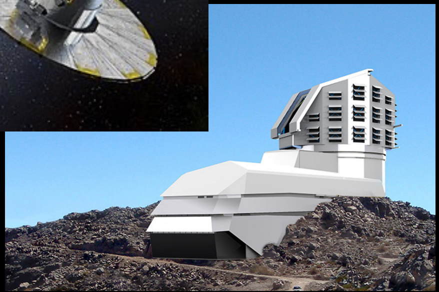
To rule in/out the hypotheses

→ *Improved dark matter distribution*

→ *Compare to other regions & limits*



Gaia

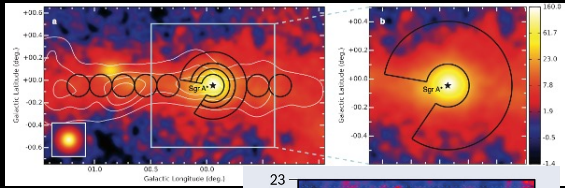


VRO

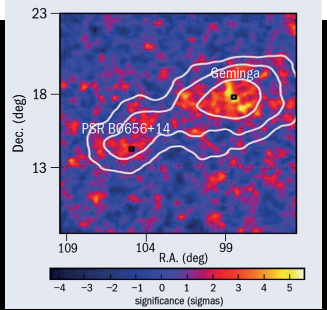
Understand transport

Of cosmic rays in the Galactic Center

→ *Improved background, pulsar behavior, leptonic predictions*



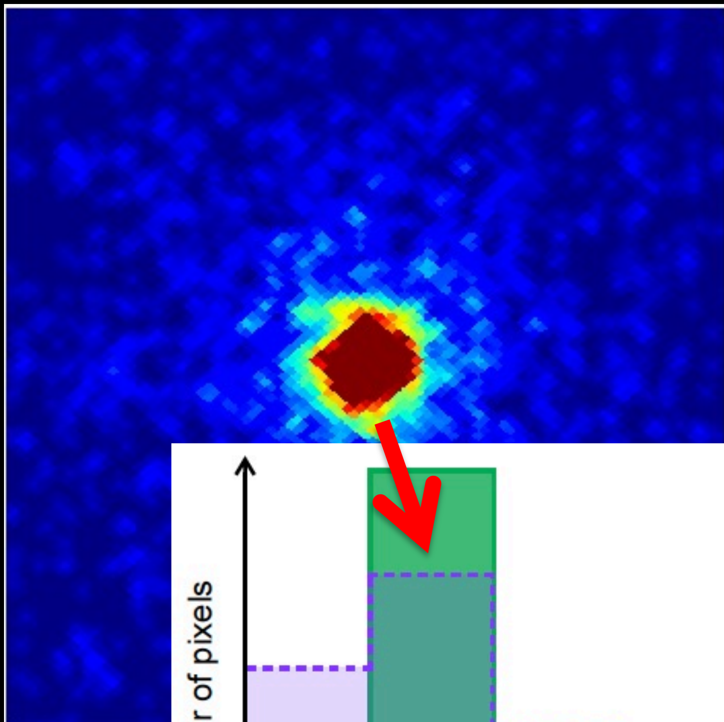
HESS



HAWC

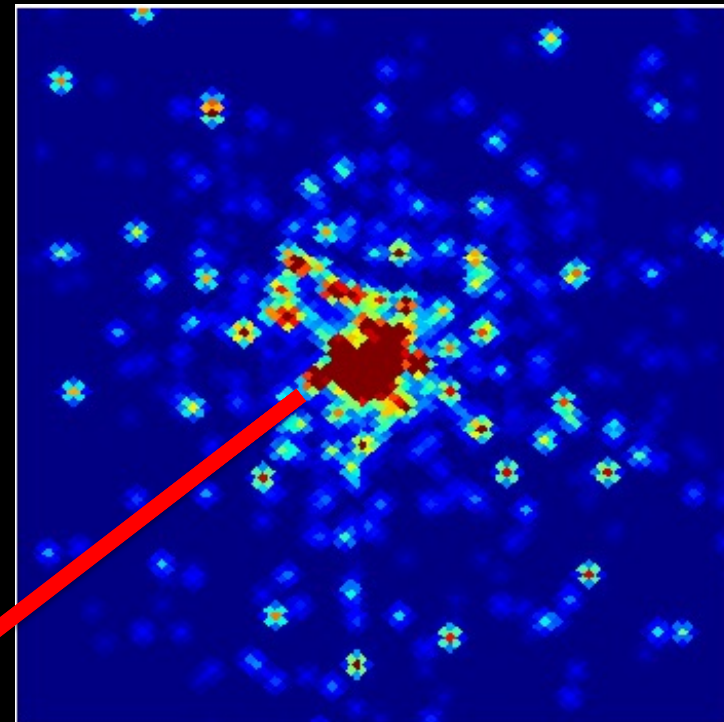
point source vs diffuse source

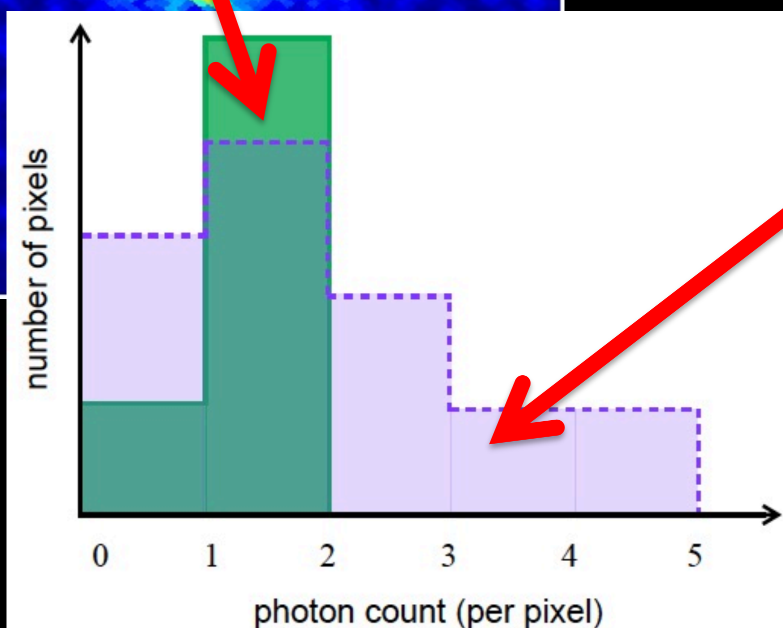
Dark matter annihilation



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)

Photon count distribution fit result

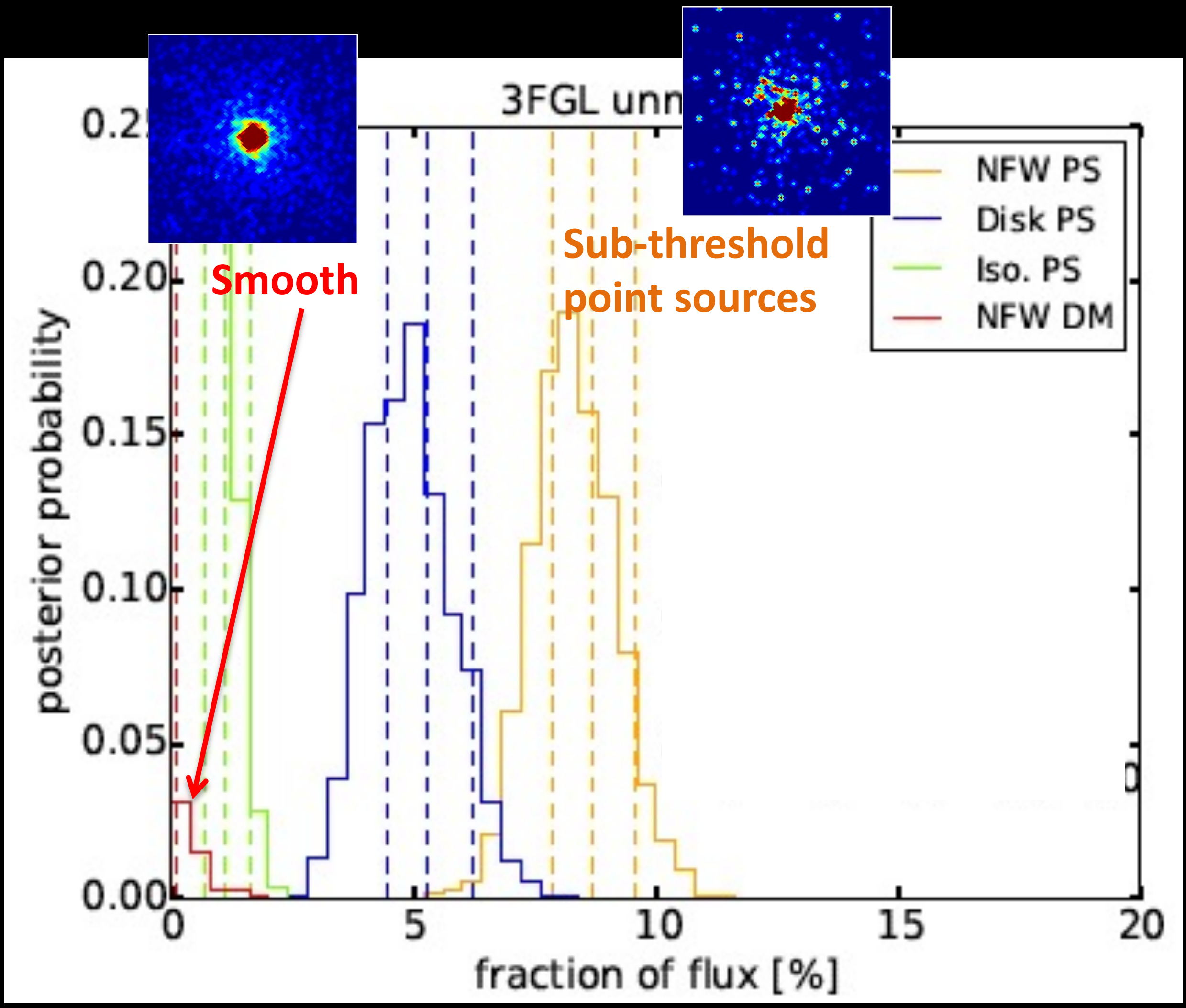
- Smooth should absorb dark matter
- Point-source should absorb astrophysical objects

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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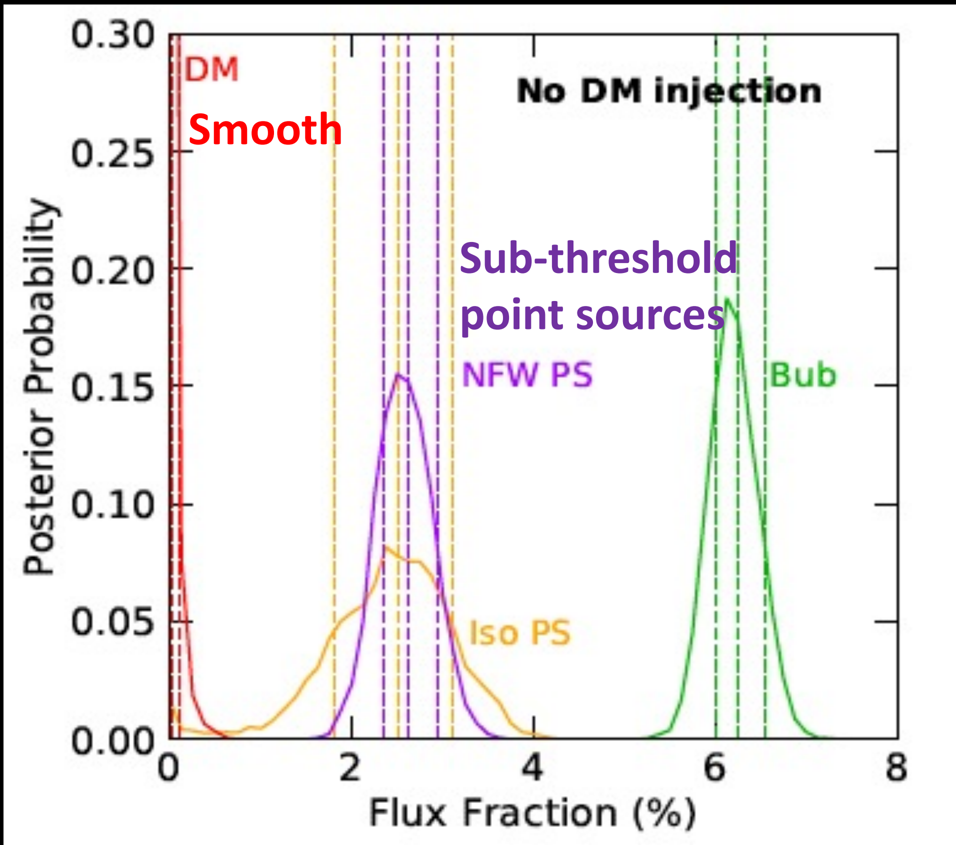
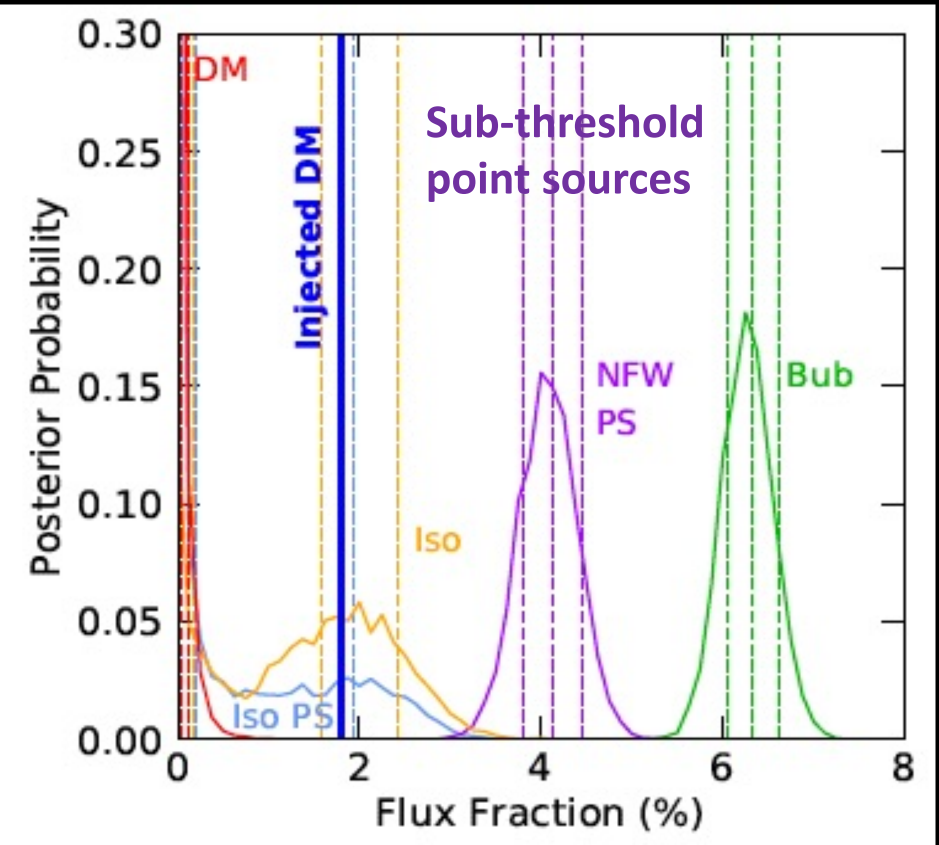
But…challenges

- 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





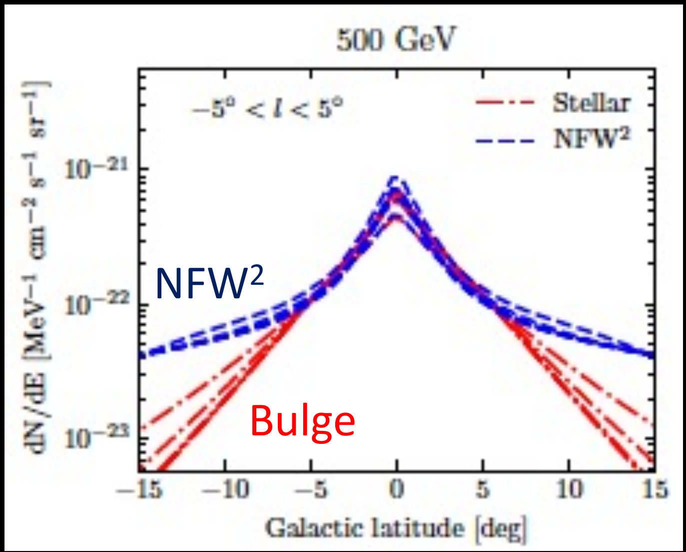
Leane & Slatyer (2019, 2020)
Also Chang et al (2019), Zhong et al (2019), Buschmann et al (2020),

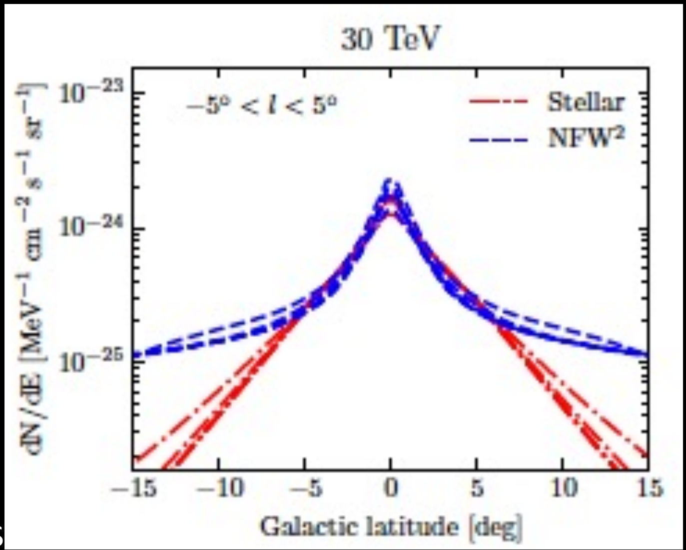
➔ **Can be confident there's substantial point sources**
➔ **Still allow DM signal (more work needed)**

TeV counterparts

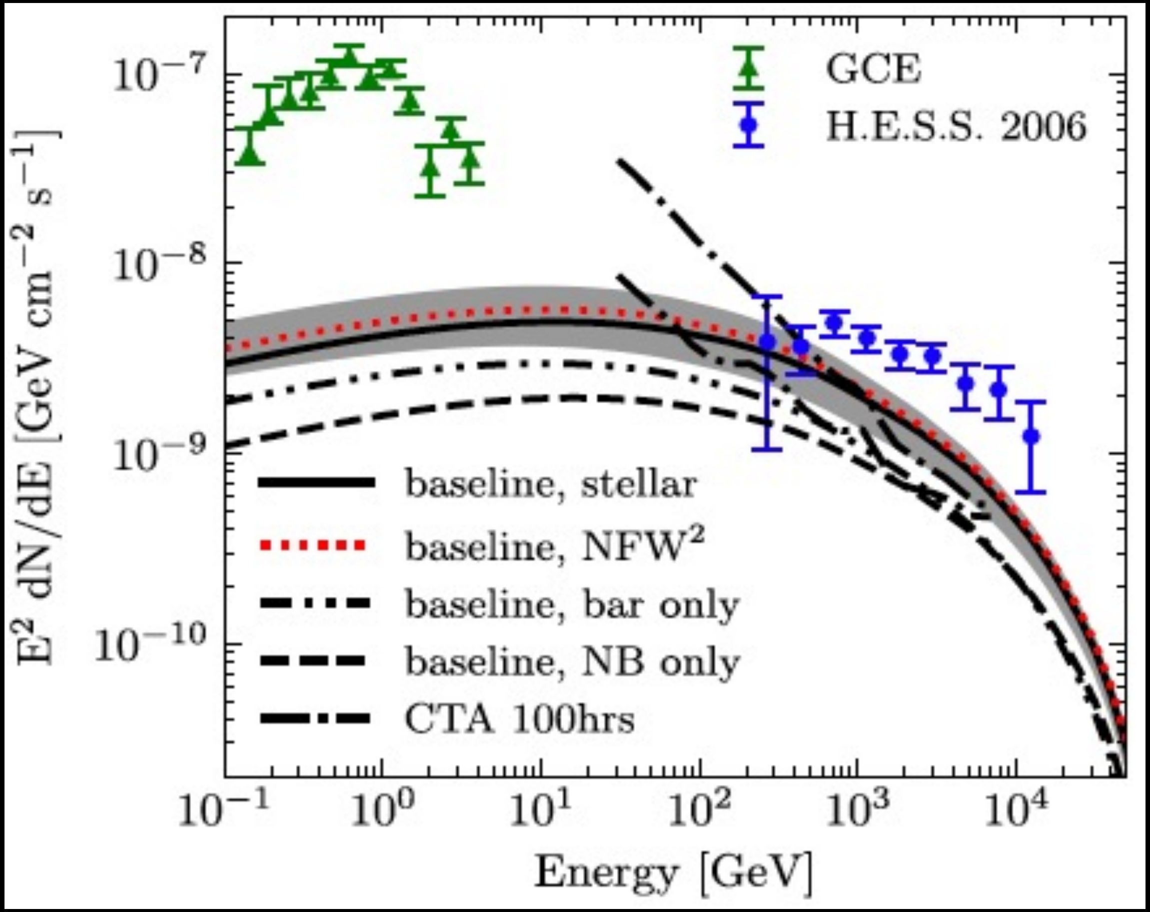
Deheng Song

- Consider IC due to relativistic e± generated by pulsars.
- Quantify that spatial morphology of IC reveals source distribution





→ **Interesting target for CTA**

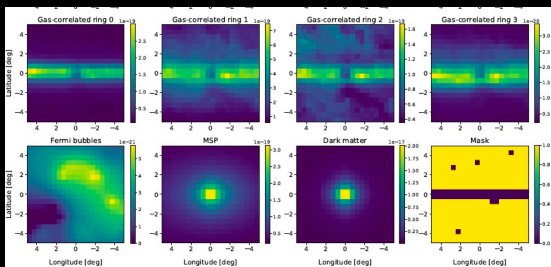


Song et al (2019), See also Yuan & Ioka (2014)

CTA sensitivity

Forecast with ctools

Background



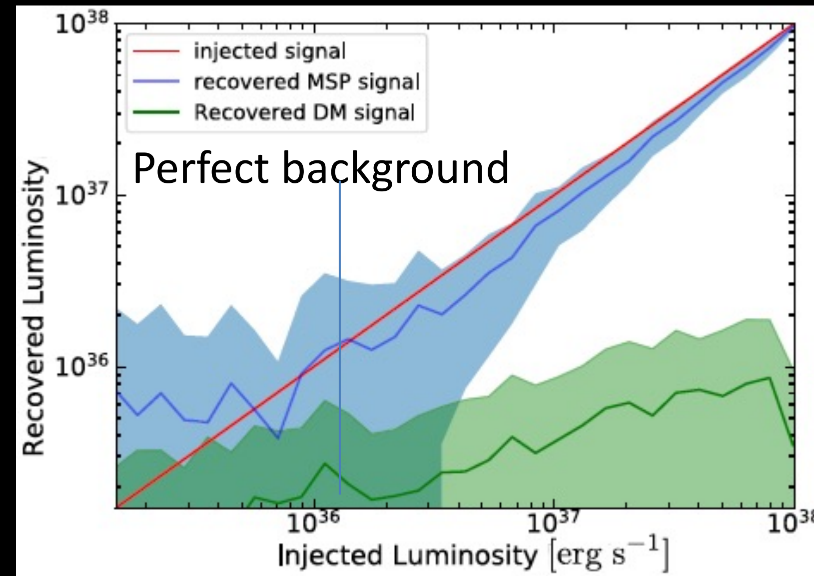
- ROI 10x10 deg^2
- Resolution 0.5 deg
- Mask galactic plane & sources
- Exposure 500 hours
- 16 GeV – 158 TeV

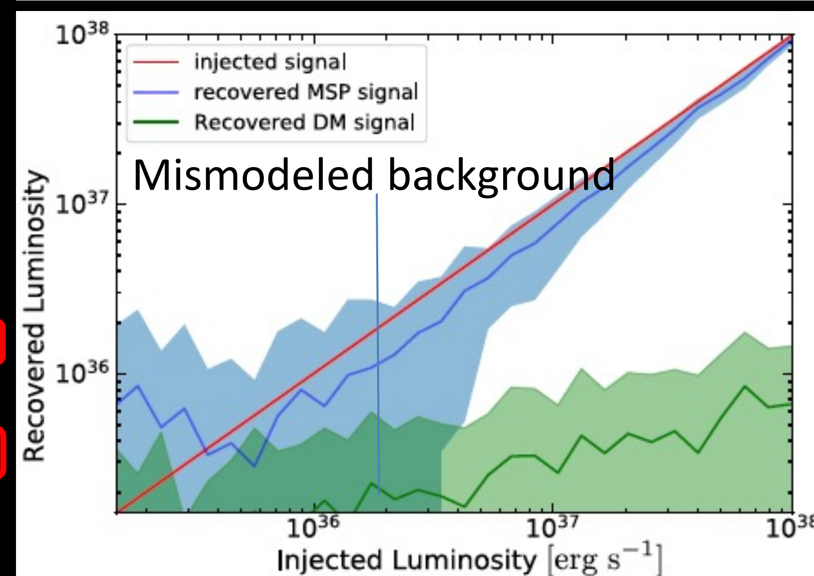
source

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

Model Name	Γ	$E_{\rm cut}$ (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$_{\rm min}$, perfect GDE.				
10.5 per cent	2.9 per cent	158.4 per cent	24.3 per cent	8.2 per cent
FB$_{\rm min}$, mismodelling of the GDE.				
14.5 per cent	3.8 per cent	163.4 per cent	25.3 per cent	10.8 per cent

➔ Within reach depending on e± spectrum

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Macias et al 2021

Low-energy counterparts

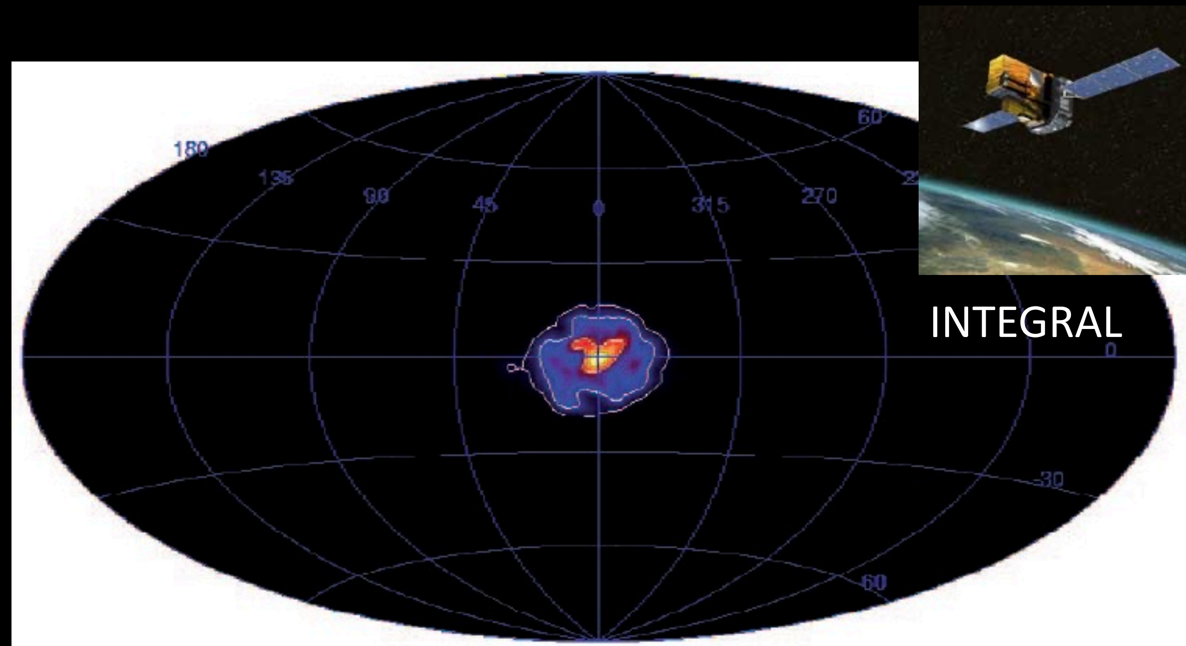
The 511 keV excess

There are striking parallels:

- Large, tens of degrees
- Strongly centrally peaked

Knodlseder et al 2005
Siegert et al 2016

- Can it be powered by positrons generated by millisecond population?



INTEGRAL

Low-energy counterparts

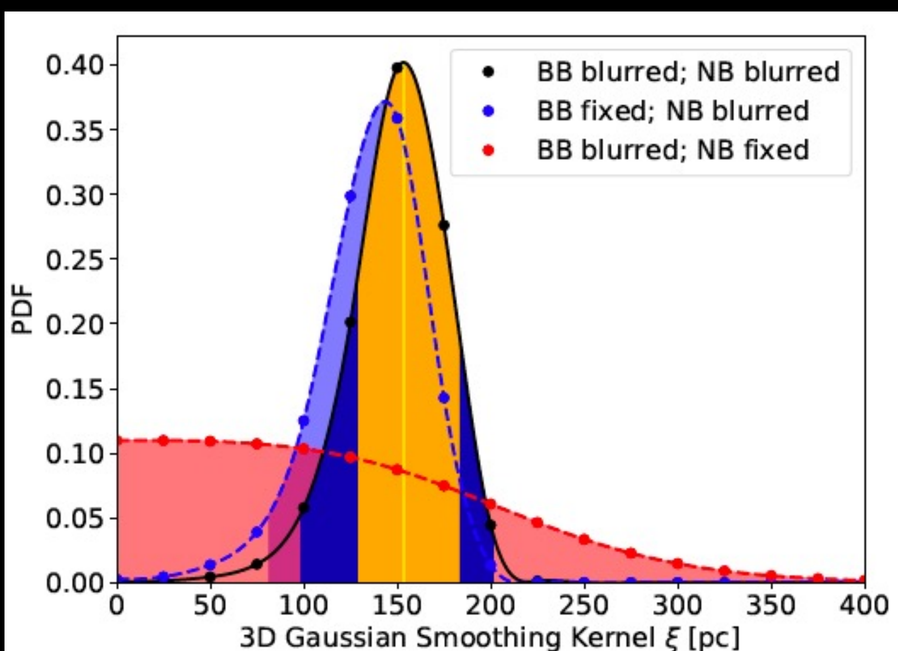
Spatial morphology

We see strong parallels with the GeV:

- When mutually exclusive, dark matter and bulge are both detected
- When simultaneously included, 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	DMO	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	DMO	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	DMO	4.8	0.8	5.6
IC+BB+NB+HI+CO	DMO	4.6	1.3	5.9



← However, we see a statistically significant smoothing of ~150pc

➔ **May be effect of pulsar kicks?**

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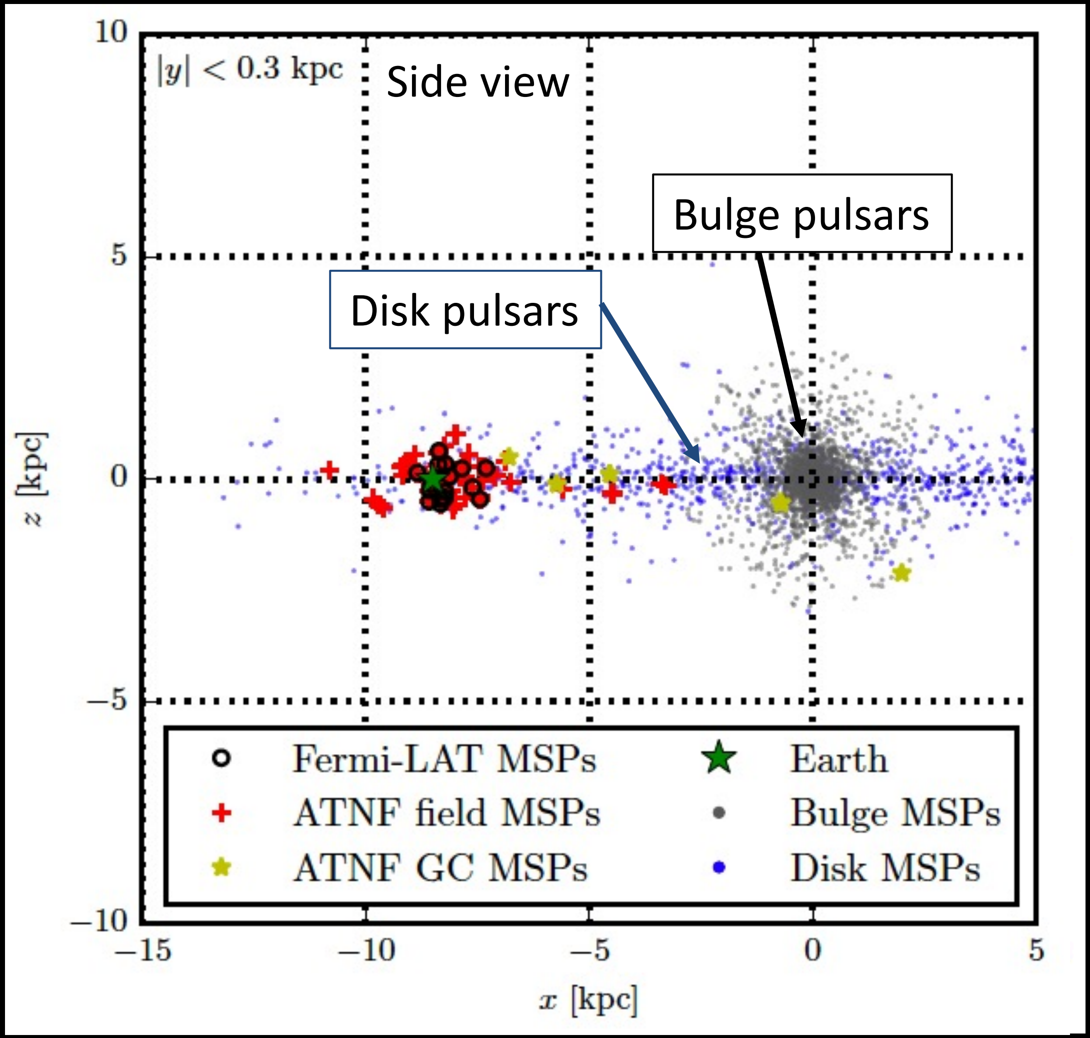
Radio counterparts

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



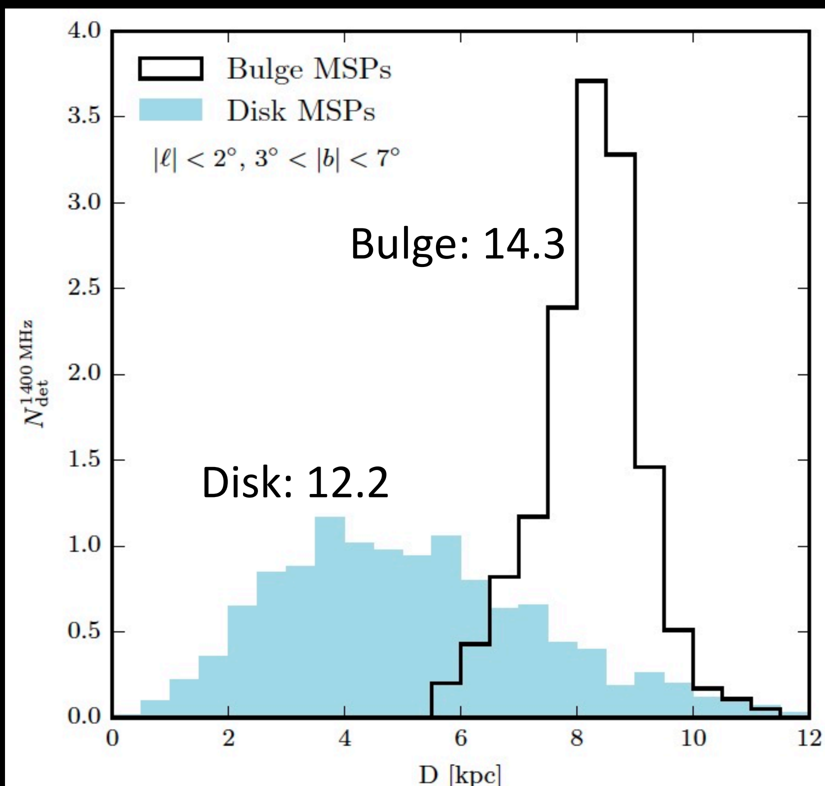
So…the target
Enhanced millisecond pulsar density in the Galactic bulge (out to ~10 deg)

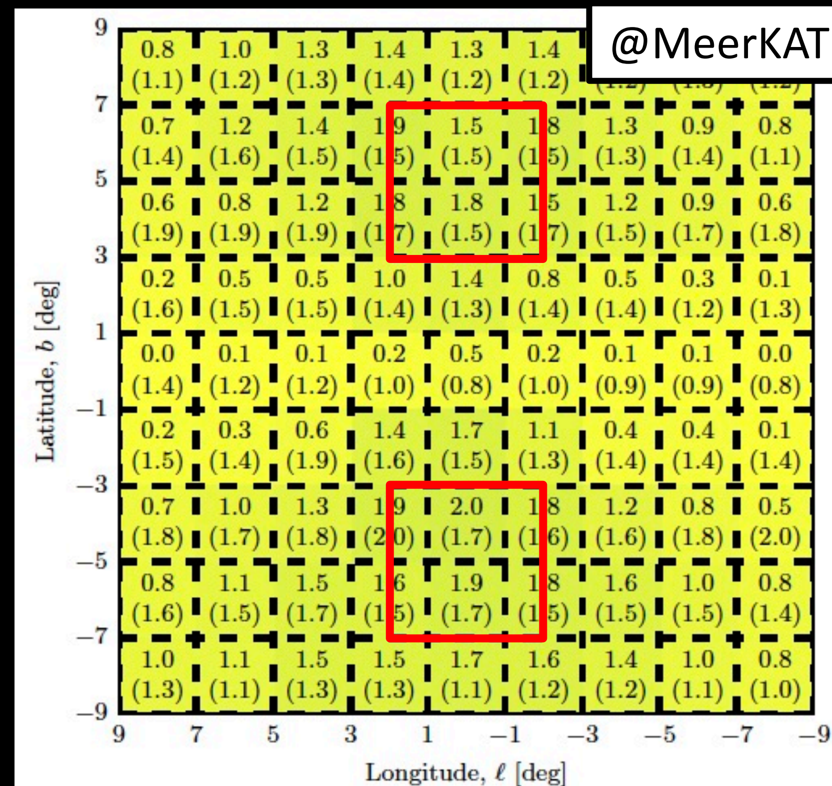
Calore et al (2015)

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

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 DM constraints in GeV mass range**
- **Interesting mlti-messenger connections**

The Galactic Center will continue to be an interesting region
in the **multi-messenger era**

Thank you!

BACKUP SLIDES

Parameters	HTRU (mid)	GBT	MeerKAT	SKA-mid
ν [GHz]	1.35	1.4	1.4	1.67
$\Delta\nu$ [MHz]	340	600	1000	770
t_{samp} [μs]	64	41	41	41
$\Delta\nu_{\mathrm{chan}}$ [kHz]	332	293	488	376
T_{rx} [K]	23	23	25	25
G [K/Jy]	0.74	2.0	2.9	15
Max. Base. Used [km]	–	–	1.0	0.95
Eff. G sub-array [K/Jy]	0.74	2.0	2.0	8.5
Ele. θ_{FWHM} [arcmin]	14	8.6	65	49
Ele. FoV [deg^2]	0.042	0.016	0.92	0.52
Beam θ_{FWHM} [arcmin]	14	8.6	0.88	0.77
Beam FoV [deg^2]	0.042	0.016	0.00017	0.00013
# Beams	13	1	3000	3000
Eff. FoV [deg^2]	0.55	0.016	0.51	0.39
T_{point} [min]	9	20	20	20
$T_{108\,\mathrm{deg}^2}$ [h]	29	2250	71	92
# Bulge(Foreground) MSPs	1(6)	34(37)	40(41)	207(112)

Calore et al (2016)

Bulge MSP origins

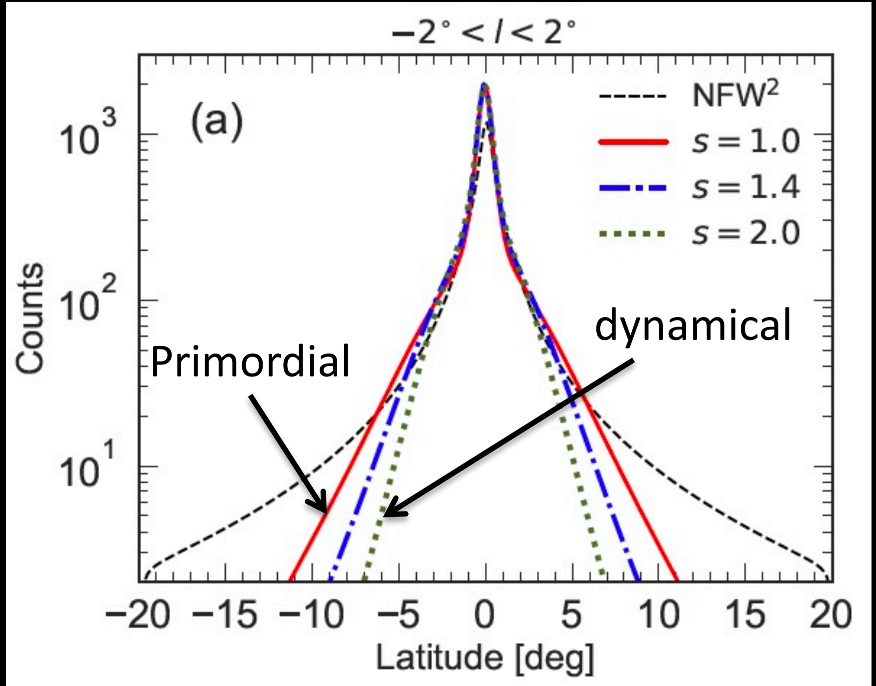
Primordial vs dynamical

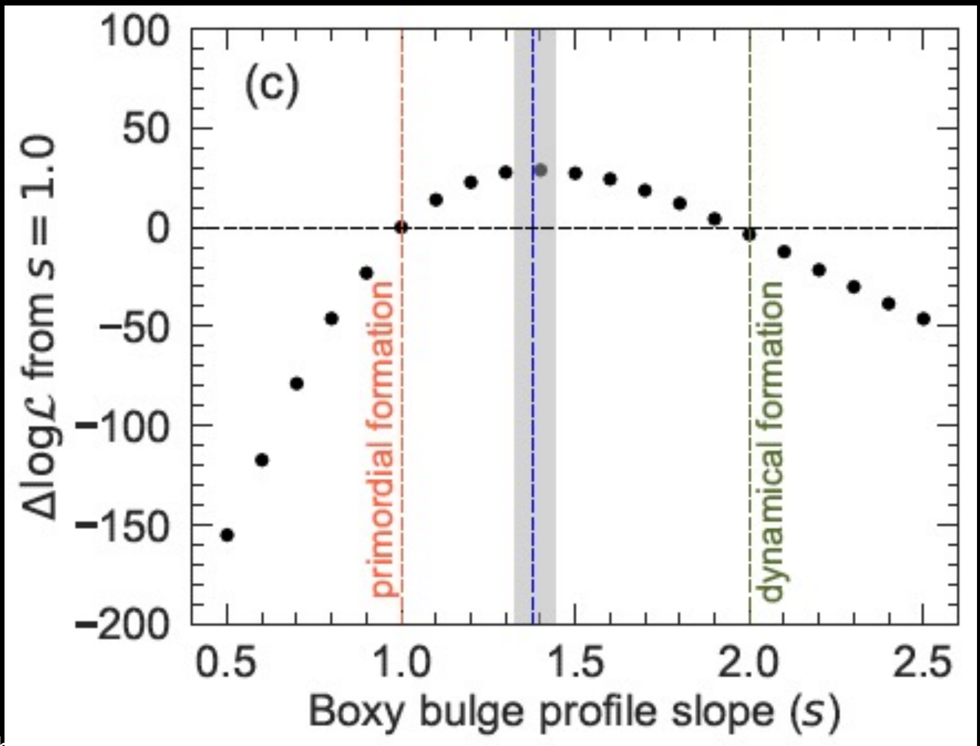
Simple search of primordial + dynamical formation channels in the boxy bulge

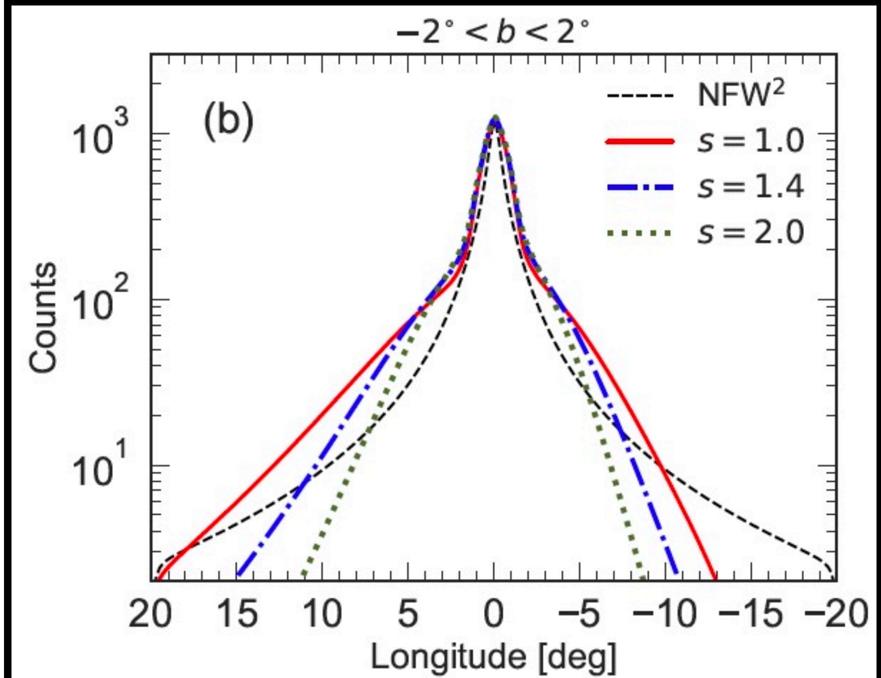
template = ρ_{boxy}^s

➔ **Primordial: 30 – 70% of gammas**

Macias et al (2019)





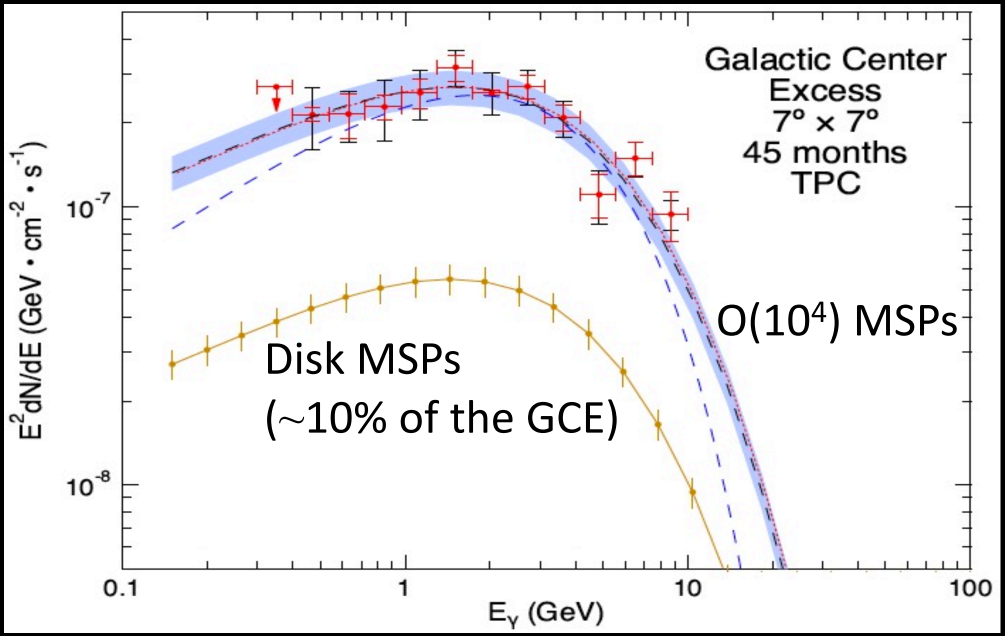


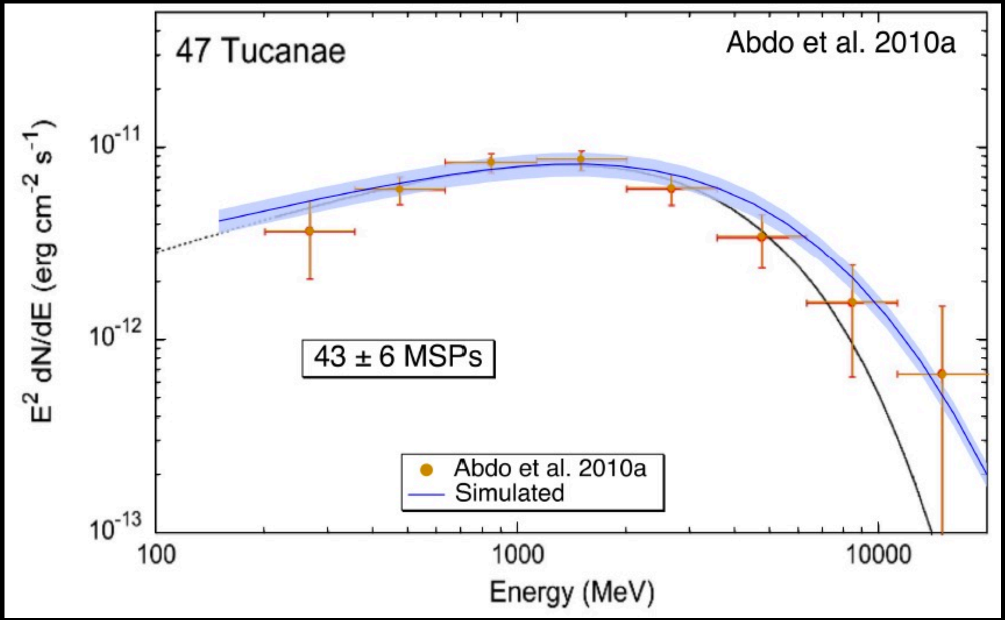
MSP population synthesis

MSP population synthesis
The bulge may host $O(10^4)$ MSPs below the Fermi detection threshold to explain the GCE, while maintaining consistency with disk MSPs and globular cluster gamma rays.

Gonthier et al (2018)

(Synthesis modeling of disk MSPs and their application to globular cluster & the bulge).





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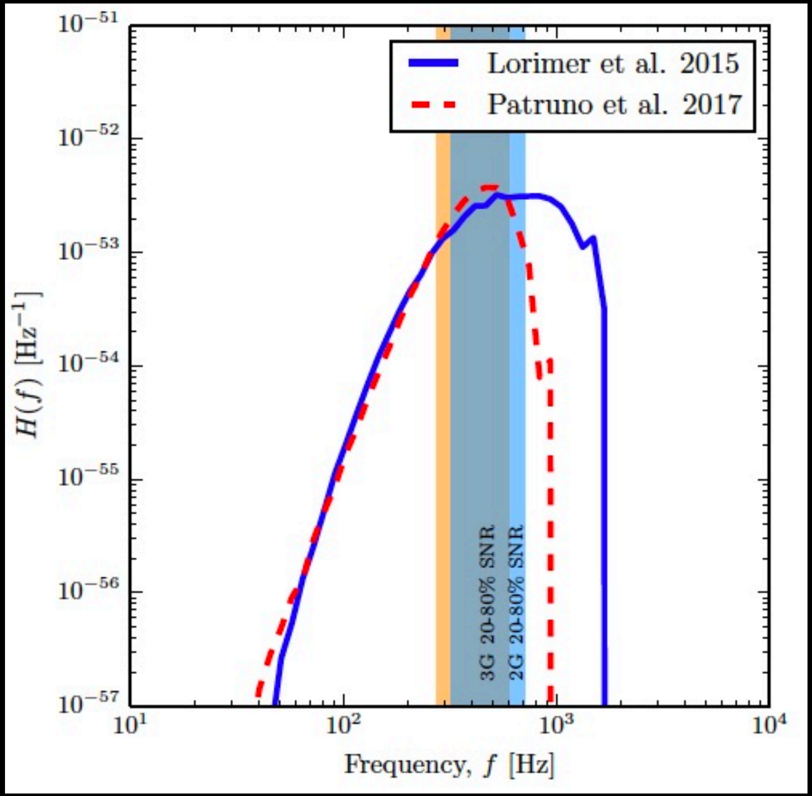
Gravitational wave counterparts

GW power spectral density



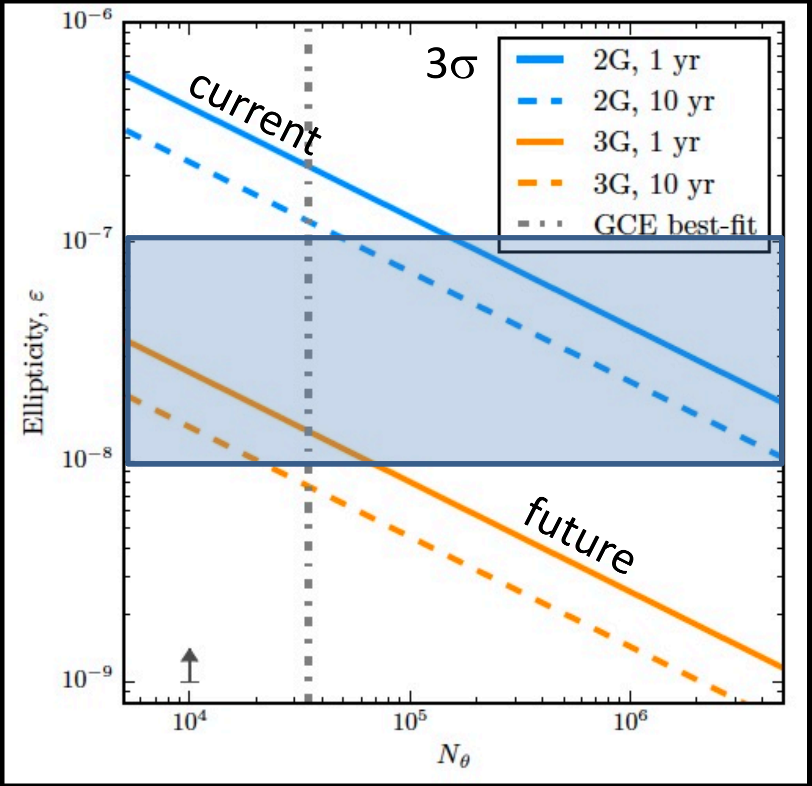
← Different models for MSP period distribution

GW emitted due to MSP not being perfectly spherical: e.g., crust elastic strains, B-field effects, instability in r-mode

→ Asphercitiy parameter: ellipticity

Sensitivity

Relies on cross-correlating data from multiple detectors searching for excess from GC



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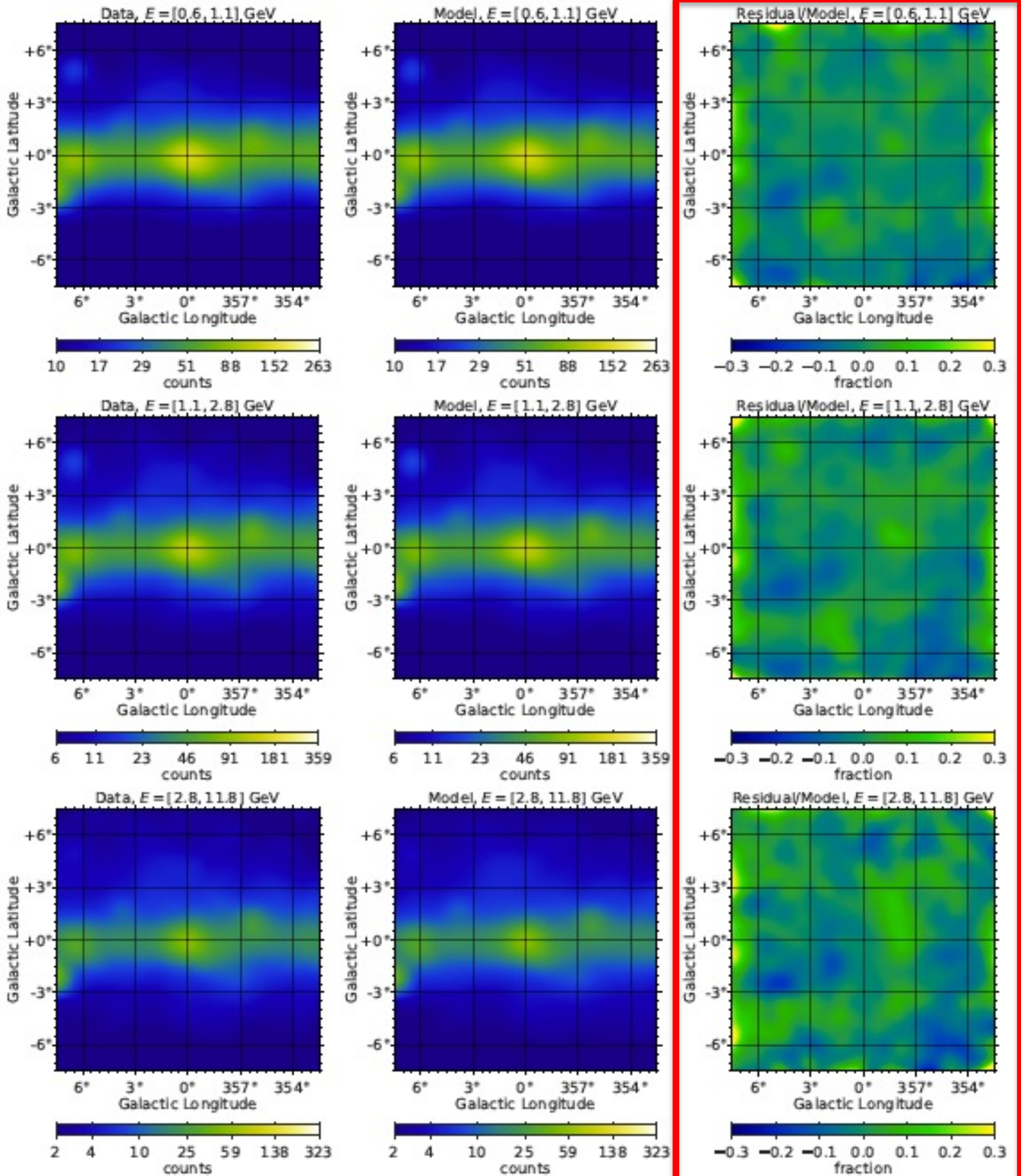
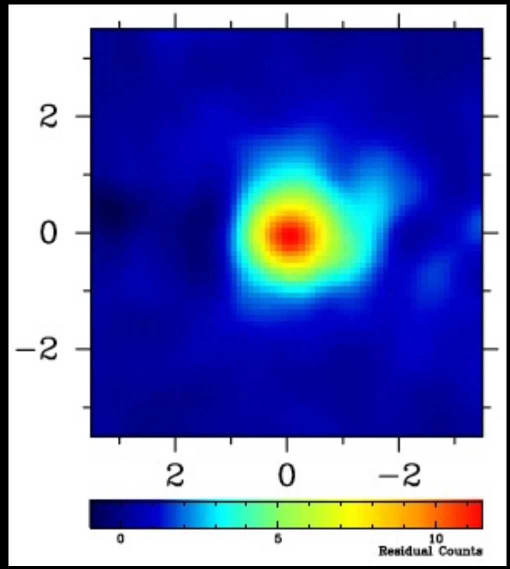
Residuals



Residuals look featureless

Including the bulge, the gamma-ray residuals do not show obvious spherically extended excess

≠



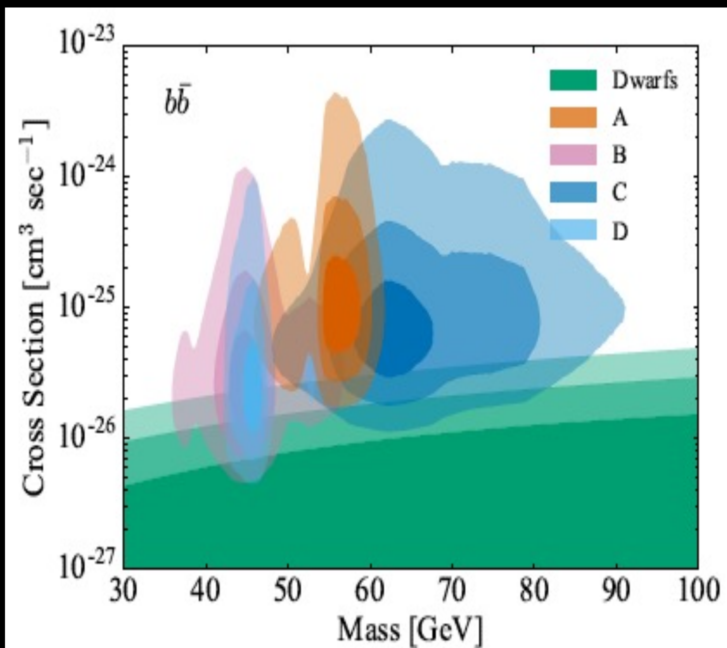
➔ No spherical excess

Macias et al (2019)

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)

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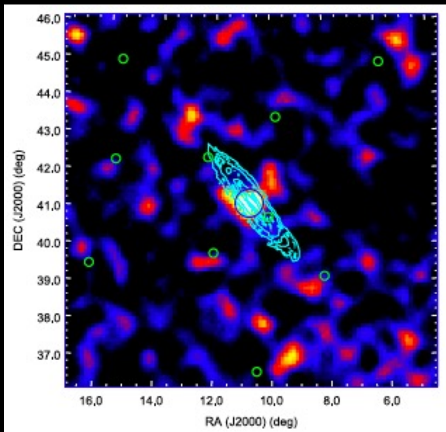
Comparison with Andromeda

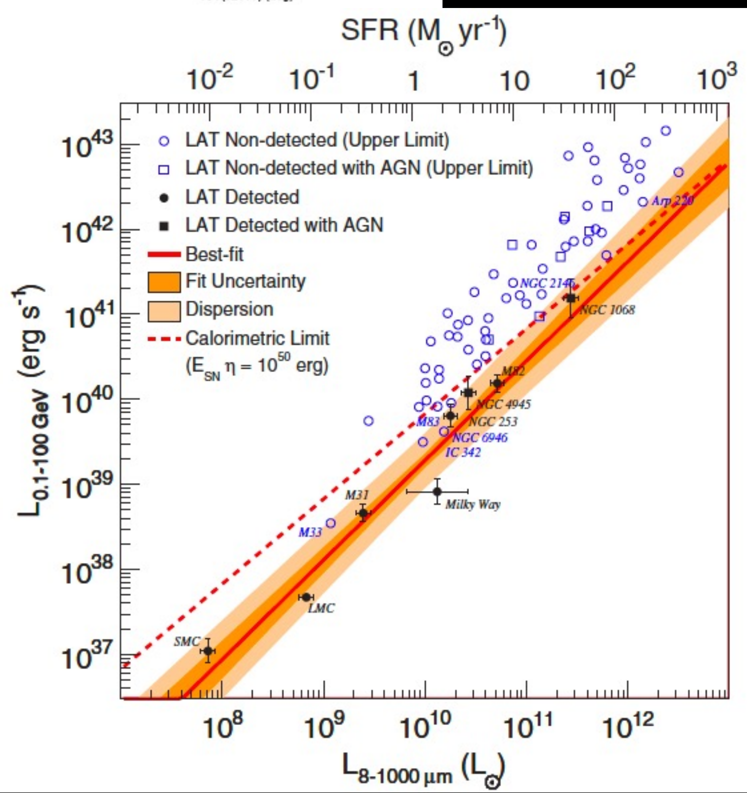


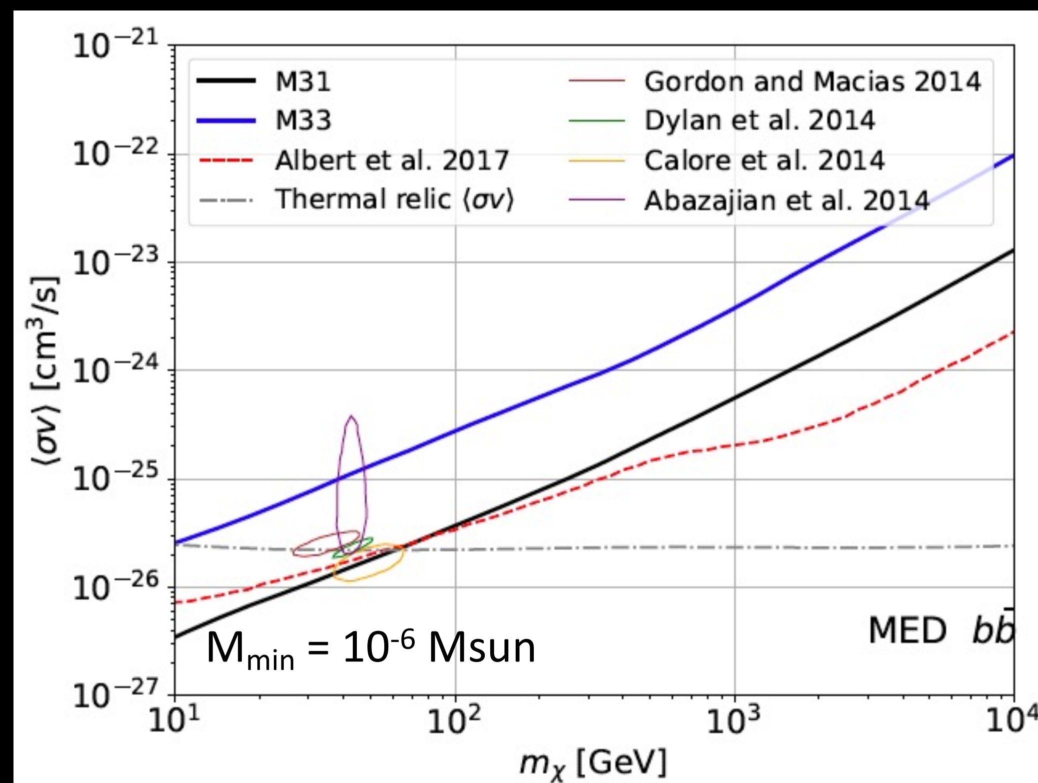
Gamma-ray excess in M31

- 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





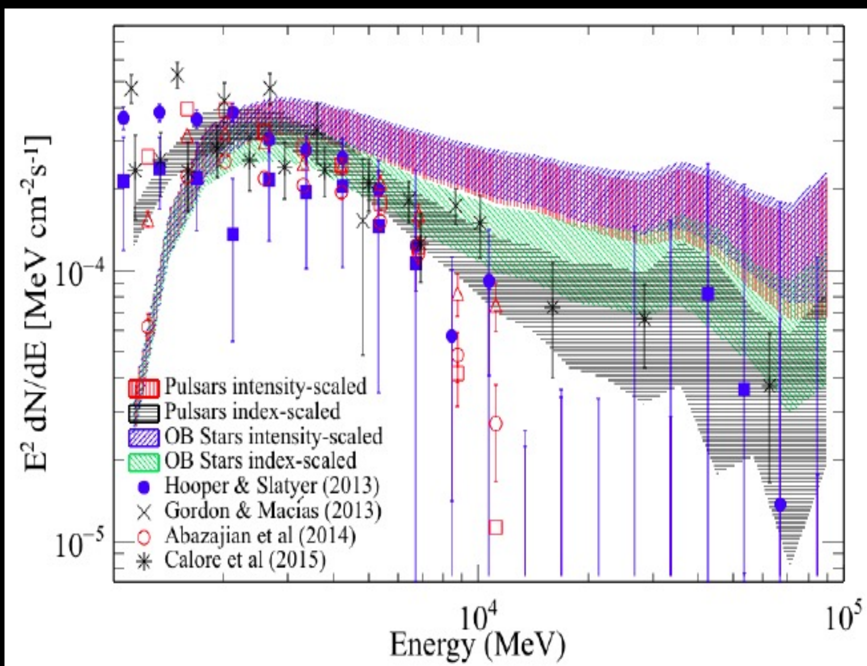
Sh

Background model uncertainties

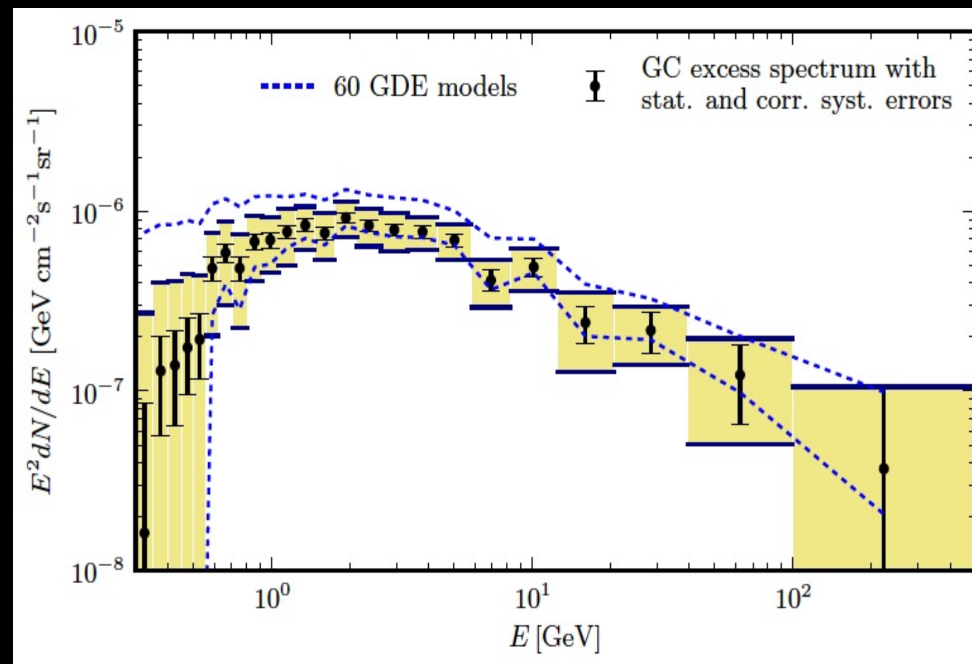
More relevant is systematic uncertainty.

Dedicated diffuse models
Calibrated by the Fermi collaboration to the Galactic Center region

Galprop models
Scan range of parameters of diffusion, B-fields, ISRF, cosmic-ray injection, etc…



Fermi collaboration (2016)



Calore et al (2015)

➔ **Despite efforts, the excess remains**

Add new components systematically

Gas + IC + 3FGL + Loop I + Sun & Moon

Base	Source	$\log(\mathcal{L}_{\mathrm{Base}})$	$\log(\mathcal{L}_{\mathrm{Base+Source}})$	$\mathrm{TS}_{\mathrm{Source}}$	σ	Number of source parameters
baseline	FB	-172461.4	-172422.3	78	6.9	19
baseline	NFW-s	-172461.4	-172265.3	392	18.4	19
baseline	Boxy bulge	-172461.4	-172238.7	445	19.7	19
baseline	X-bulge	-172461.4	-172224.1	475	20.5	19
baseline	NFW	-172461.4	-172167.9	587	23.0	19
baseline	NB	-172461.4	-171991.8	939	29.5	19
baseline	NP	-172461.4	-169804.1	5315	55.7	64×19
baseline+NP	FB	-169804.1	-169773.6	61	5.8	19
baseline+NP	NB	-169804.1	-169697.2	214	13.0	19
baseline+NP	Boxy bulge	-169804.1	-169663.7	281	15.3	19
baseline+NP	NFW	-169804.1	-169623.3	362	17.6	19
baseline+NP	X-bulge	-169804.1	-169616.2	376	18.0	19
baseline+NP+Boxy bulge	NFW	-169663.7	-169598.2	131	9.7	19
baseline+NP+Boxy bulge	NB	-169663.7	-169566.0	195	12.4	19
baseline+NP+Boxy bulge+NB	NFW	-169566.0	-169553.3	25	2.7	19
baseline+NP+Boxy bulge+NFW	NB	-169598.2	-169553.3	90	7.6	19
baseline+NP+NFW	Boxy bulge+NB	-169623.3	-169553.0	140	10.0	2×19
baseline+NP+NFW	X-bulge+NB	-169623.3	-169531.0	185	10.8	2×19
baseline+NP+NB	X-bulge	-169697.2	-169542.0	310	16.1	19
baseline+NP+NB	Boxy bulge	-169697.2	-169566.0	262	14.6	19
baseline+NP+NB	NFW	-169697.2	-169599.0	197	12.4	19
baseline+NP+NB+NFW	X-bulge	-169598.9	-169531.0	136	9.9	19
baseline+NP+X-bulge+NB	NFW	-169542.0	-169531.0	22	2.4	19

➔ NFW detected at low significance when bulge is included

Macias et al (2018)

Add new components systematically

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Gas + IC + 3FGL + Loop I + Sun & Moon

➔ **NFW detected at low significance when bulge is included**

Macias et al (2018)

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Add new components systematically

Gas + IC + 3FGL + Loop I + Sun & Moon

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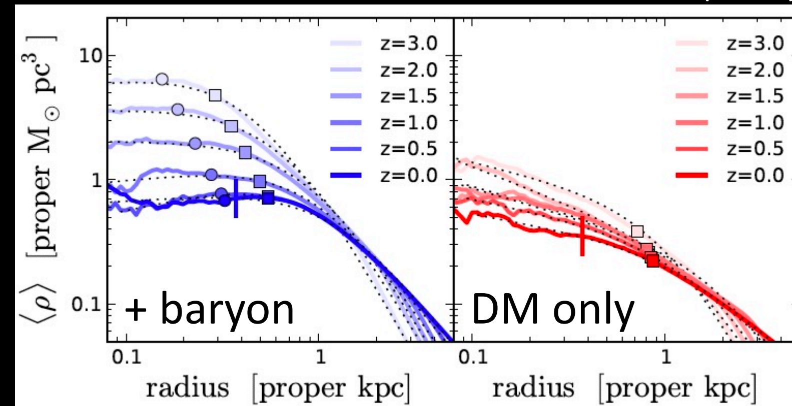
➔ **NFW detected at low significance when bulge is included**

Macias et al (2018)

Dark matter systematics

Kuhlen et al (2012)



Effects:

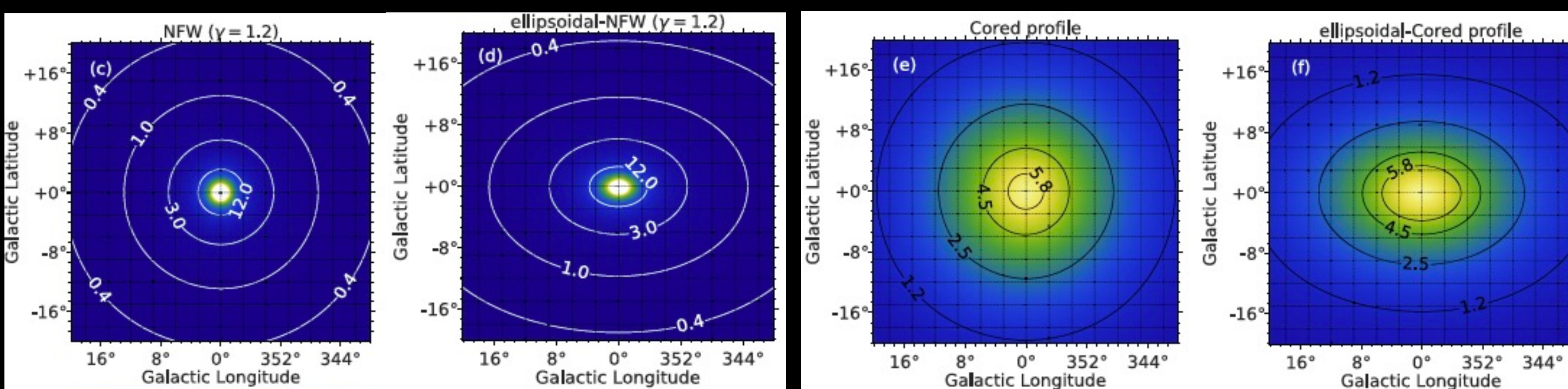
1. Inner slope, including cores
2. Asymmetry

➔ Use 0.5<γ<1.5, 1kpc core, and axis ratio 0.7

Eg, bulge kinematics, Eris, FIRE simulations

➔ **Again dark matter model not detected**

Base	Source	$-\log(\mathcal{L}_{\mathrm{Base}})$	$-\log(\mathcal{L}_{\mathrm{Base+Source}})$	$\mathrm{TS}_{\mathrm{Source}}$	Significance
Baseline + NB + BB	Cored ellipsoidal	−3259834.20	−3259834.45	0.5	0.0σ
Baseline + NB + BB	NFW	−3259834.20	−3259837.79	7.2	0.7σ
Baseline + NB + BB	NFW ellipsoidal	−3259834.20	−3259839.66	10.9	1.3σ
Baseline + NB + BB	Cored	−3259834.20	−3259844.40	20.4	2.6σ



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Abazajian, Horiuchi, et al (2020)