GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

NWO
Netherlands Organisation for Scientific Research

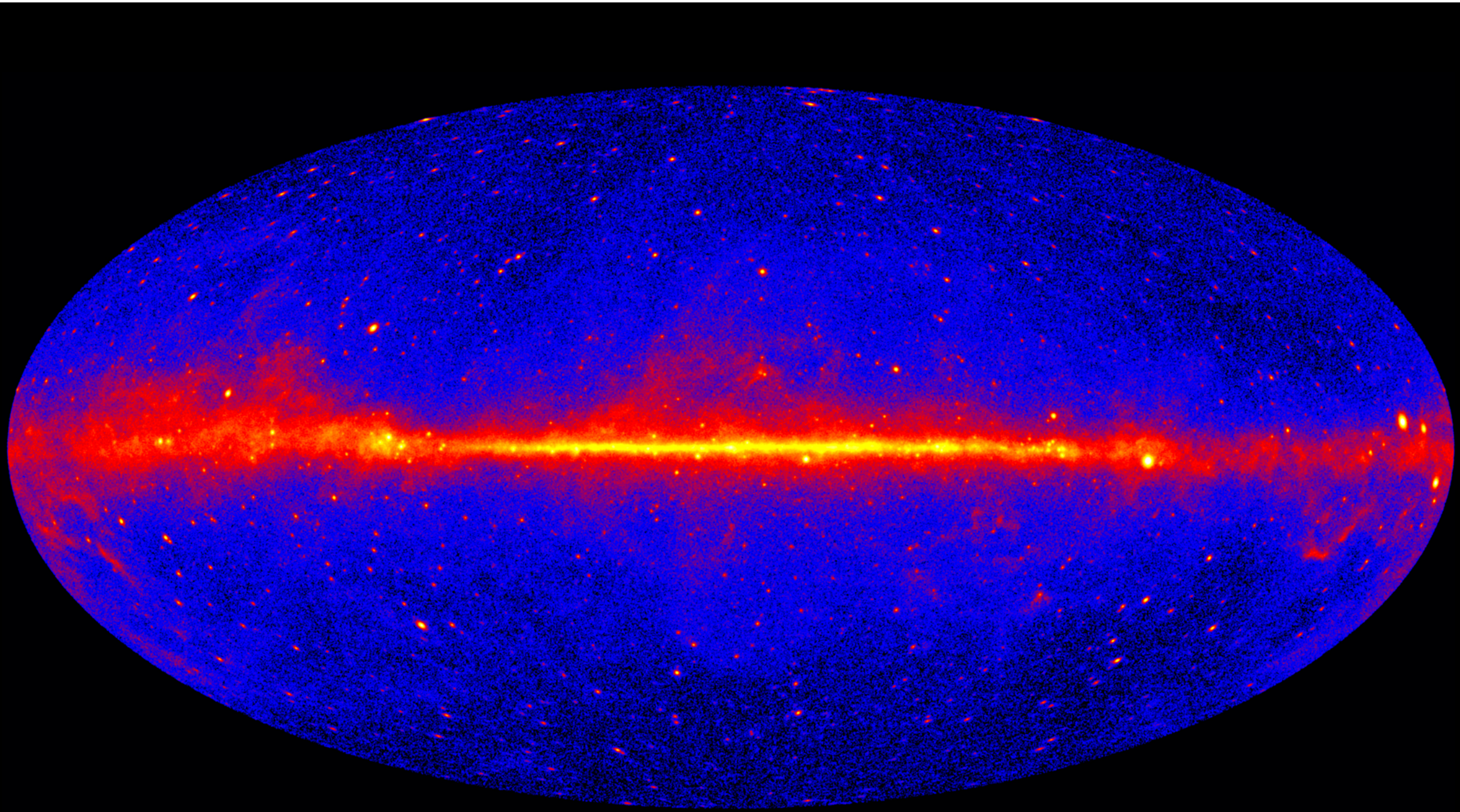
Francesca Calore

Status and interpretations of the Fermi GeV excess

Gamma Rays & Dark Matter 2015
8th December 2015, Obergurgl (Austria)

The low-latitude Fermi-LAT gamma-ray sky

D. Hooper (today)



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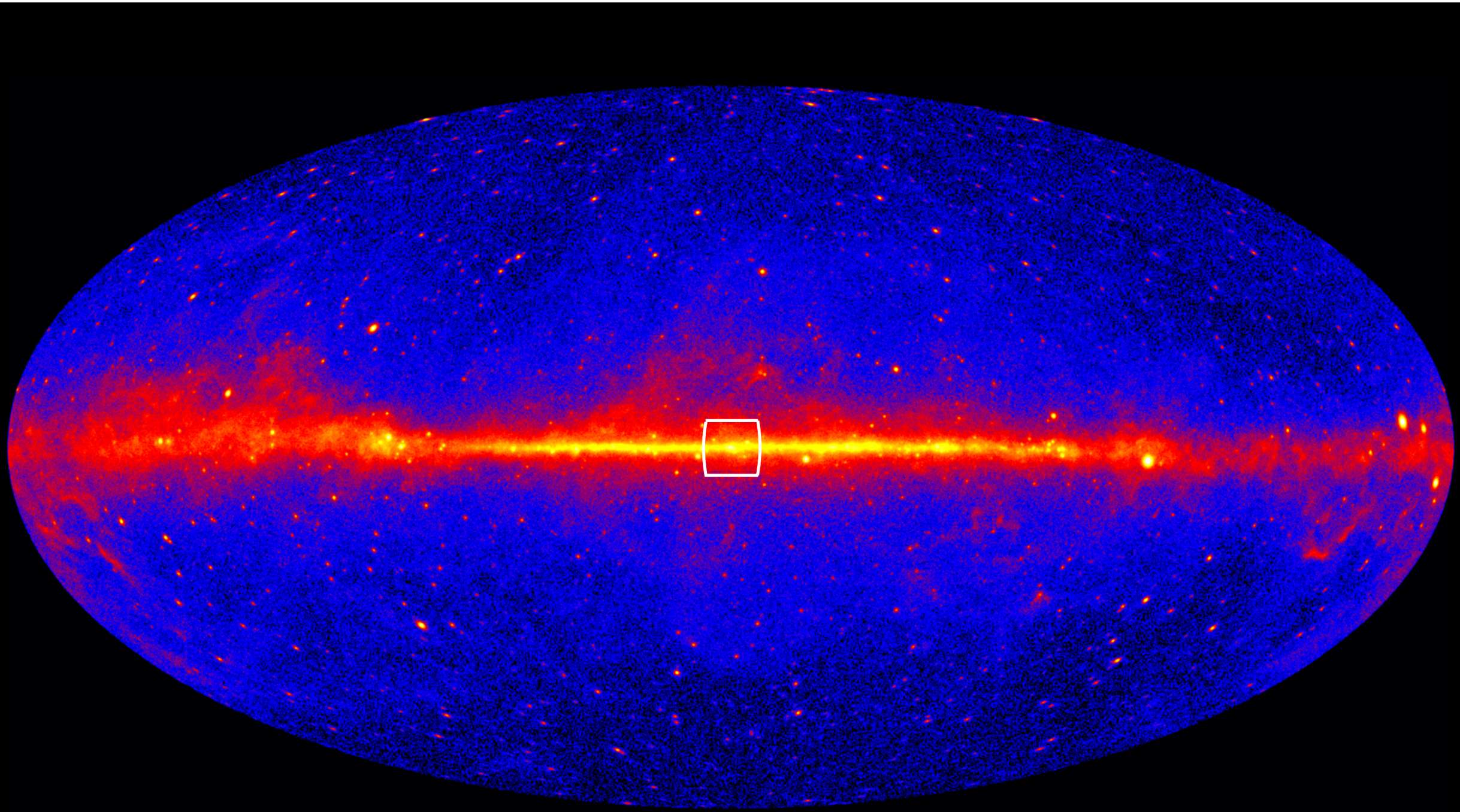

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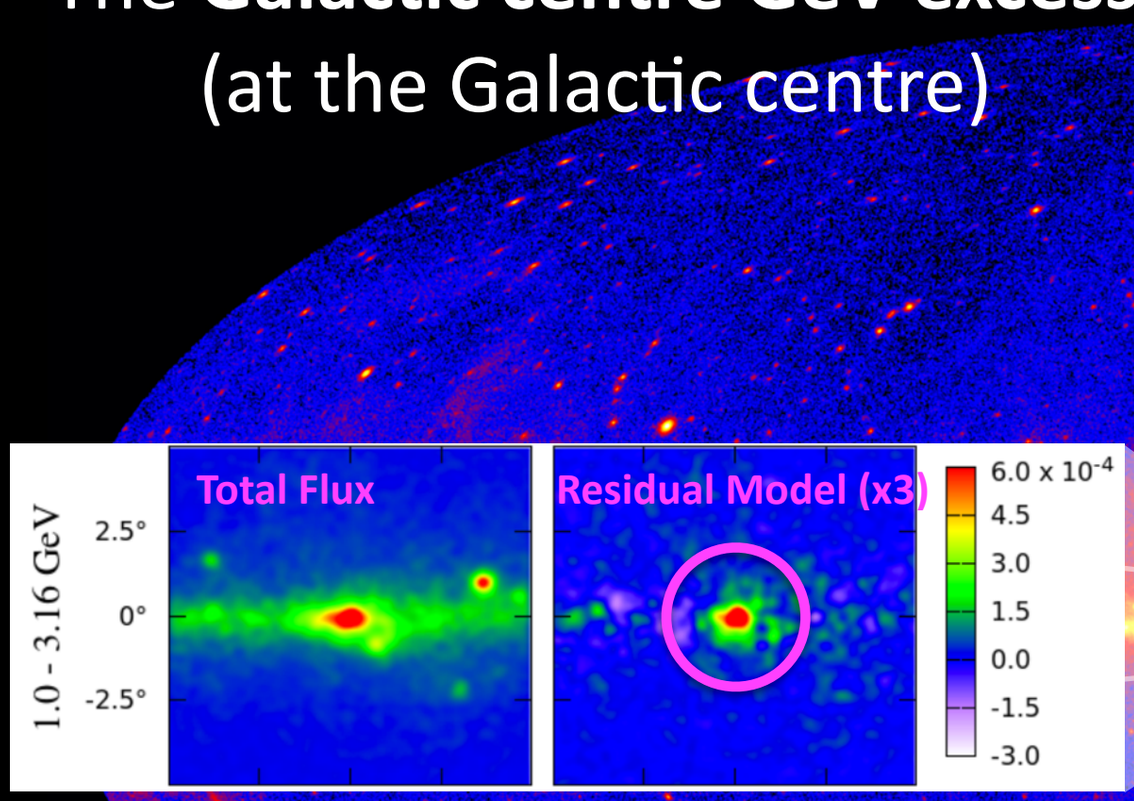
The **Galactic centre GeV excess** (at the Galactic centre)

Hooper&Goodenough '09; Vitale&Morselli '09;
Hooper&Linden PRD'11;
Hooper&Goodenough PLB'11;
Boyarsky+ PLB'11;
Abazajian&Kaplinghat PRD'12;
Macias&Gordon PRD'14;
Abazajian+ PRD'14; Daylan+ '14;
Huang+ '15; Carlson+ '15; Ajello+15;
Casandjian Fermi Symp.'14;
de Boer+ ICRC15; etc.



Daylan+ '14

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(in the inner Galaxy)

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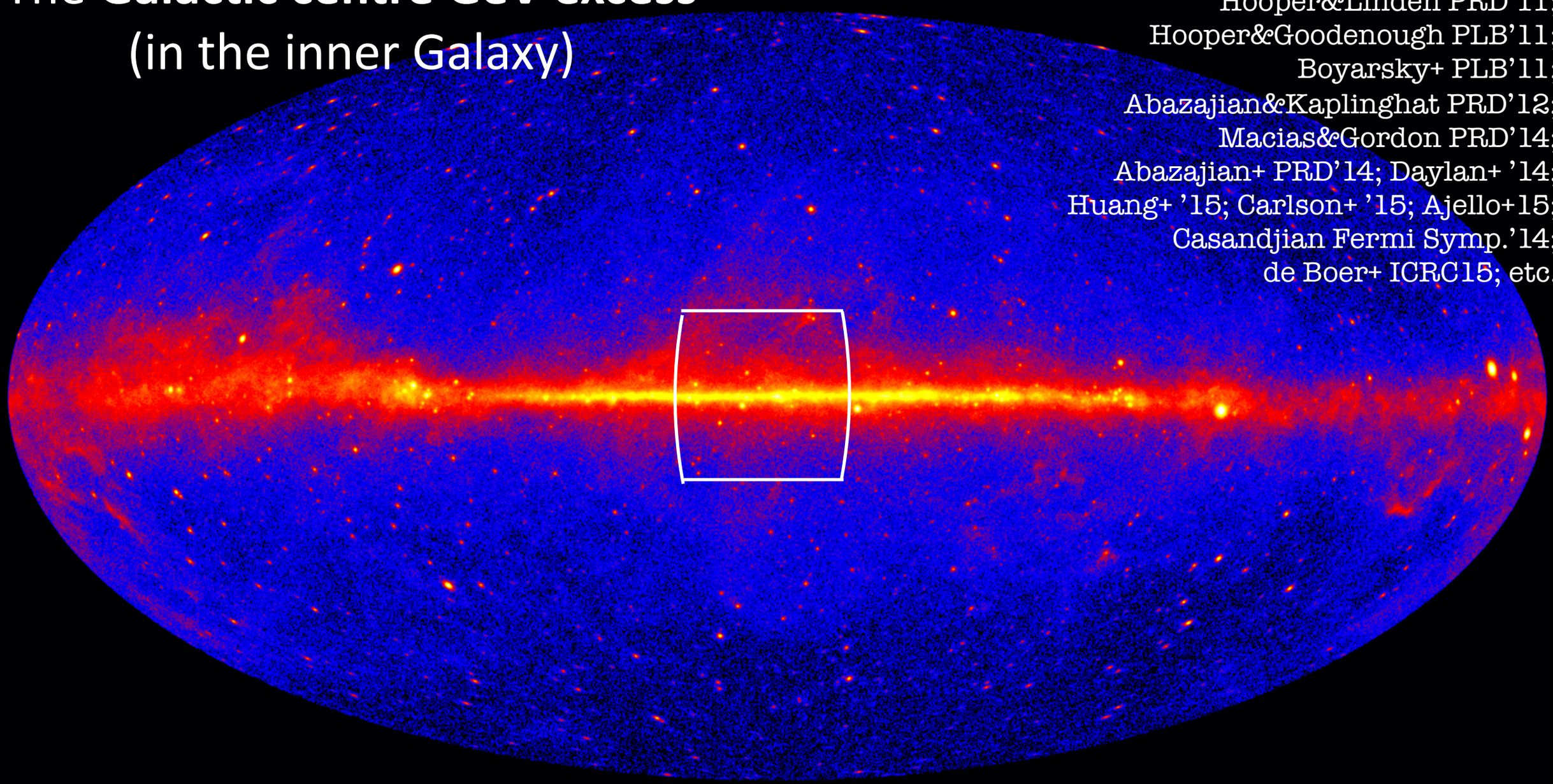

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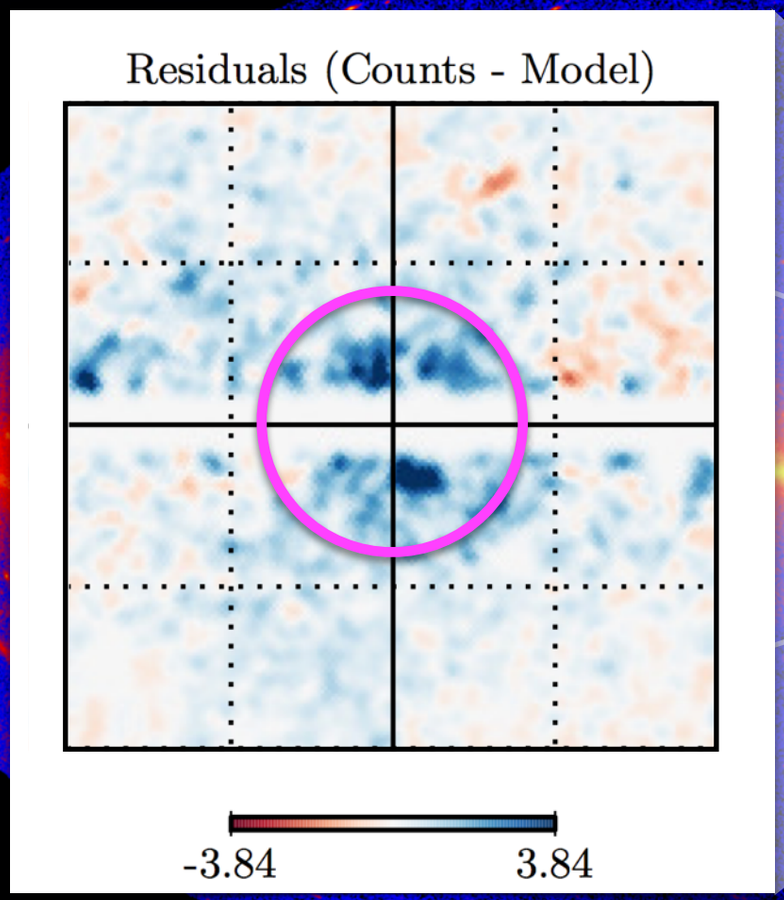
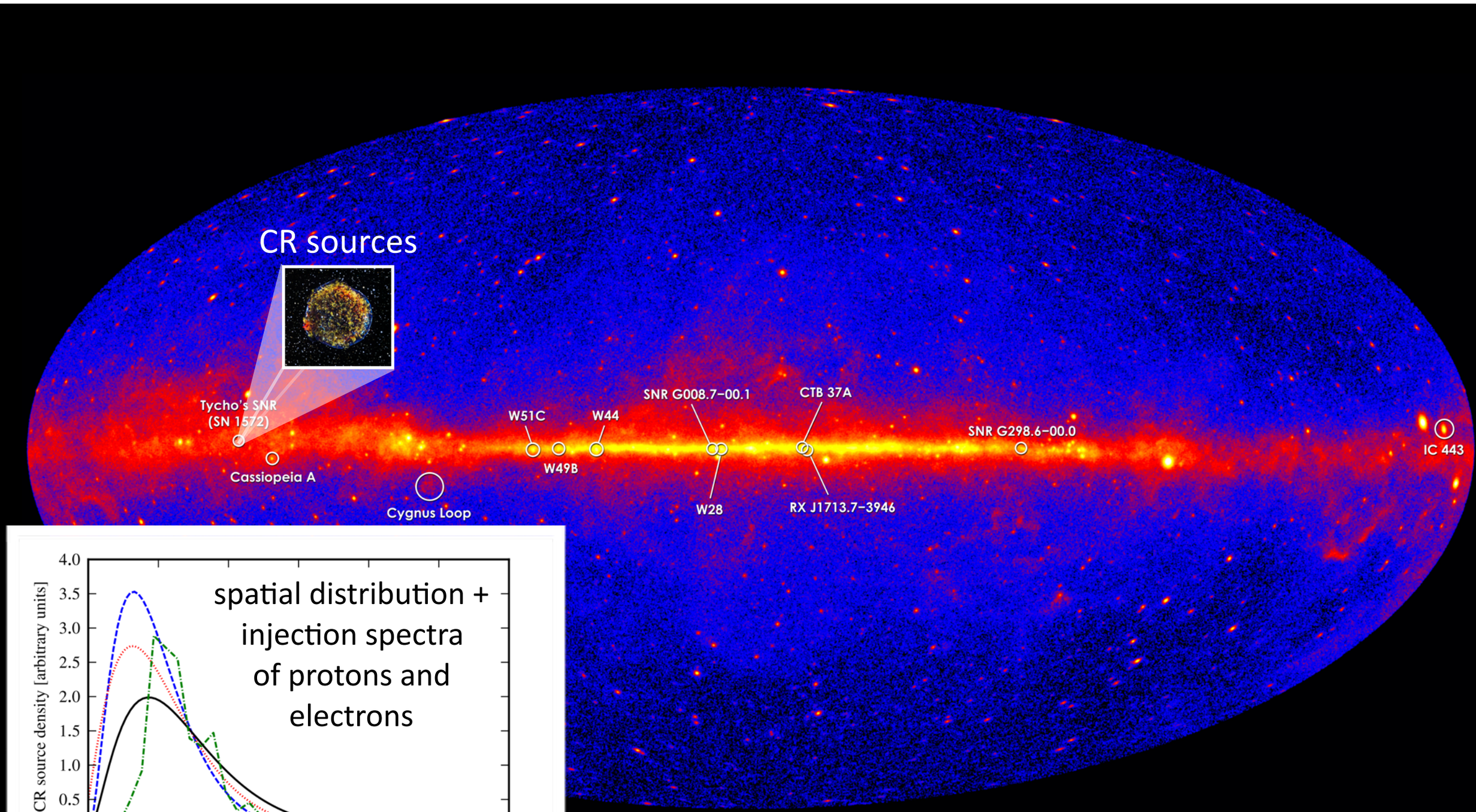


Calore+ JCAP'15

Hooper&Slatyer PDU'13; Huang+ JCAP'13;
Zhou+ PRD'15; Daylan+ '14; Calore+ JCAP'15;
Gaggero+ 2015; Ajello+ 2015; Huang+ '15

The low-latitude Fermi-LAT gamma-ray sky

The **standard** (artistic) view of cosmic-ray interactions in the Milky Way



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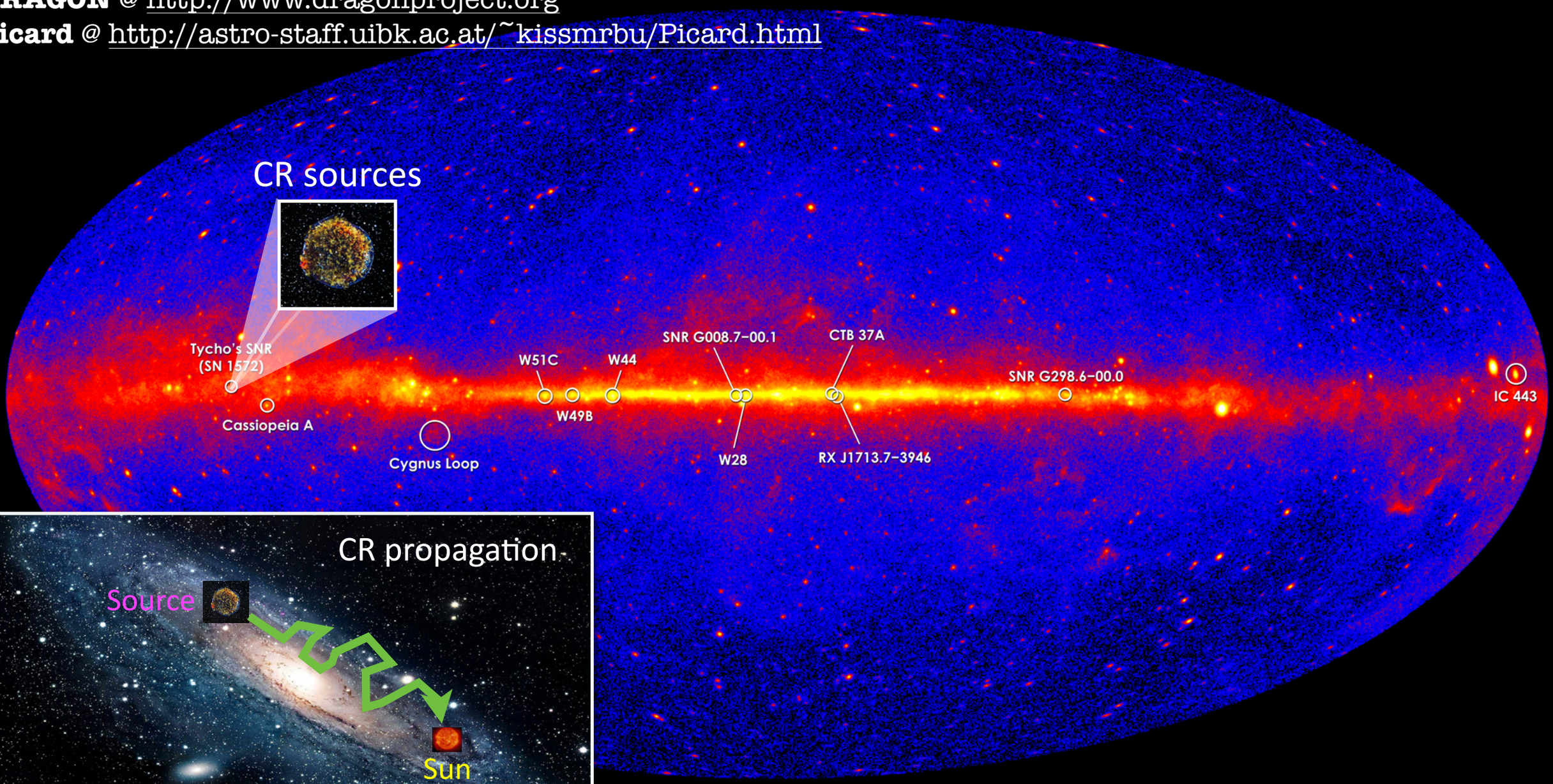
Galprop @ http://galprop.stanford.edu
DRAGON @ http://www.dragonproject.org
Picard @ http://astro-staff.uibk.ac.at/~kissmrbu/Picard.html



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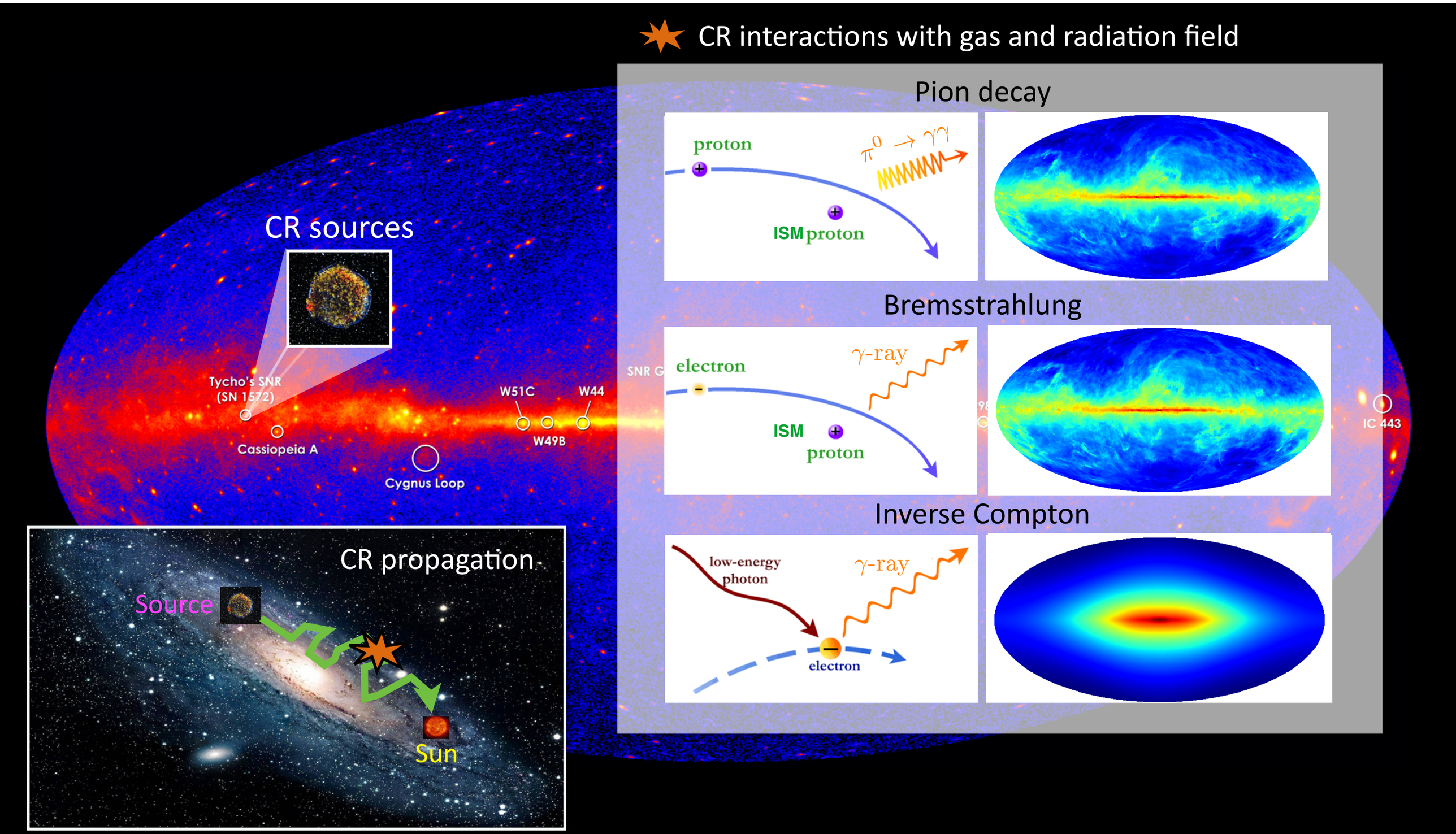

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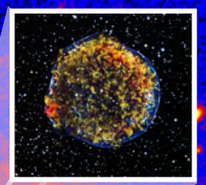
The **standard** (artist) view of cosmic-ray interactions in the Milky Way

CR interactions with gas and radiation field

CR sources



Tycho's SNR (SN 1572)

Cassiopeia A

Cygnus Loop

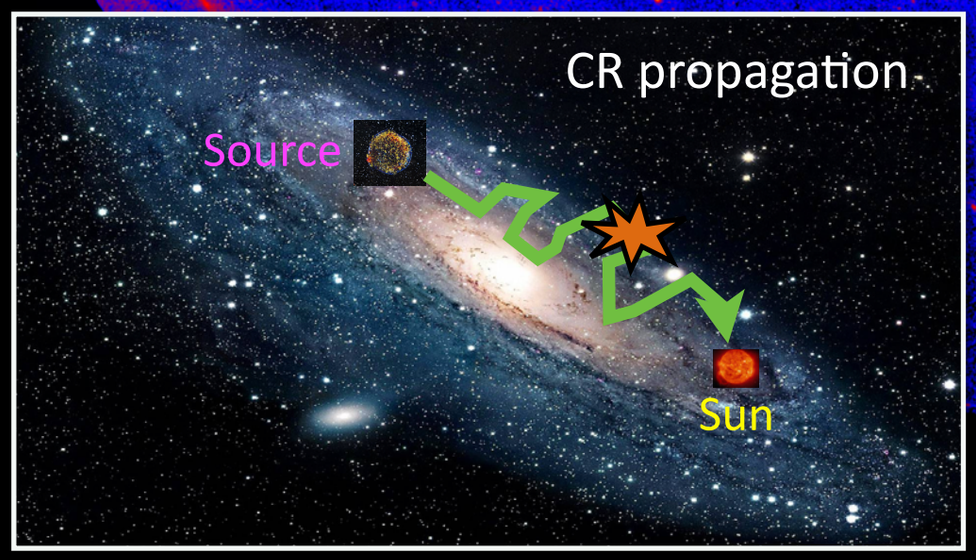
W51C

W44

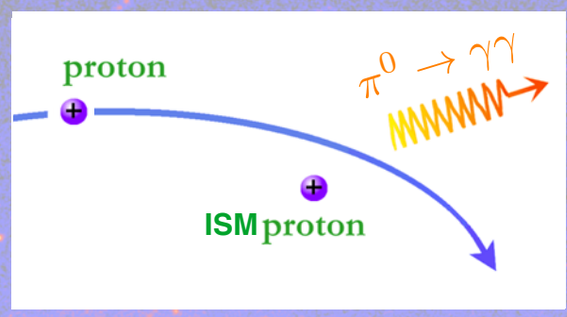
W49B

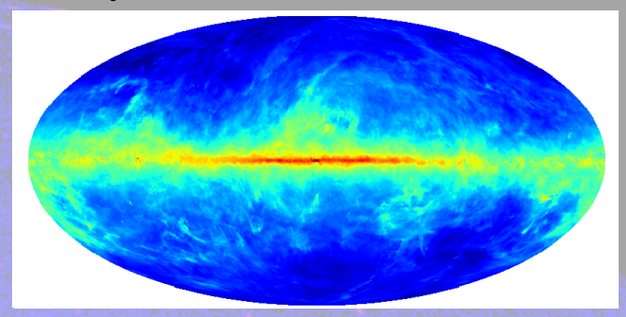
IC 443

CR propagation

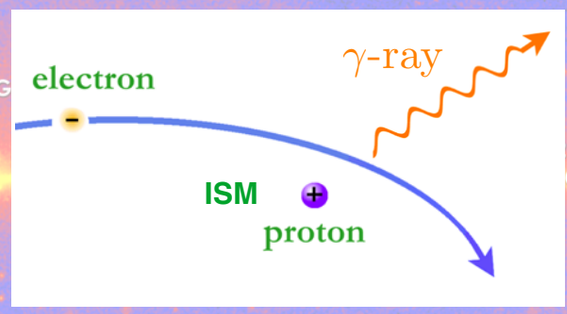


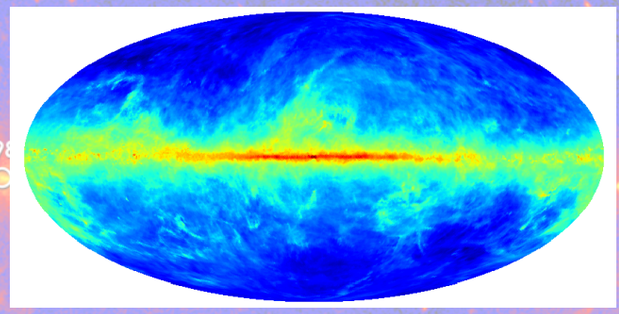
Pion decay



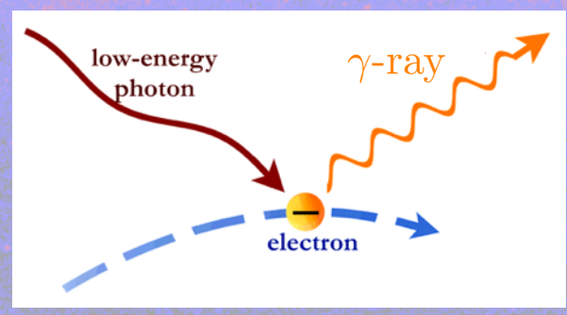


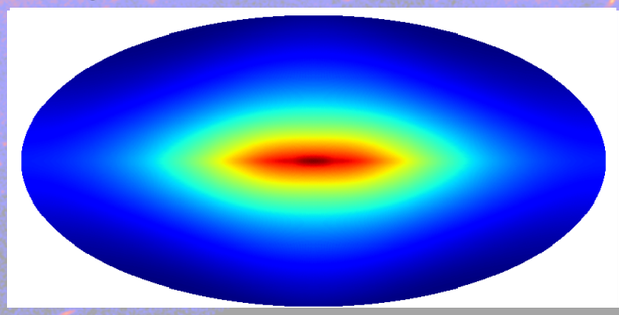
Bremsstrahlung





Inverse Compton

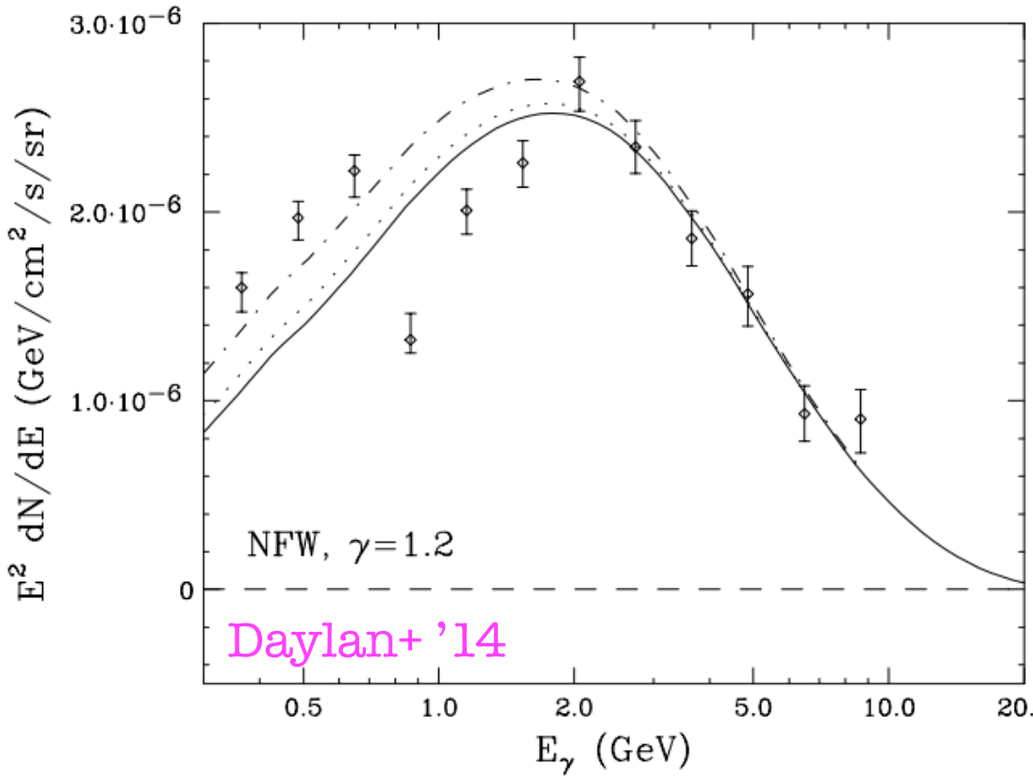




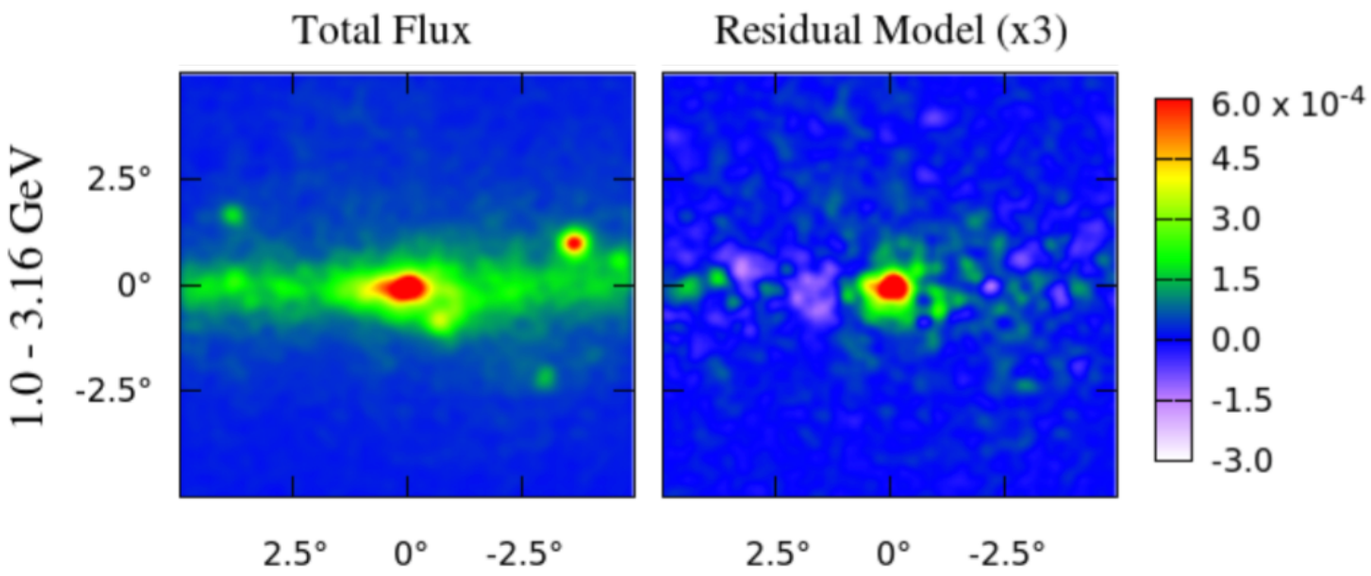
Galactic diffuse gamma-ray emission (GDE)

The GeV excess at the Galactic centre

Spectrum



Morphology



$$|\ell|, |b| \lesssim 2^\circ$$

- ✓ **Extended excess emission** above: model for diffuse emission, Sgr A* and other point sources.
- ✓ The **spectrum** might strongly suffer from **background modeling**.

Abazjian+ PRD'14

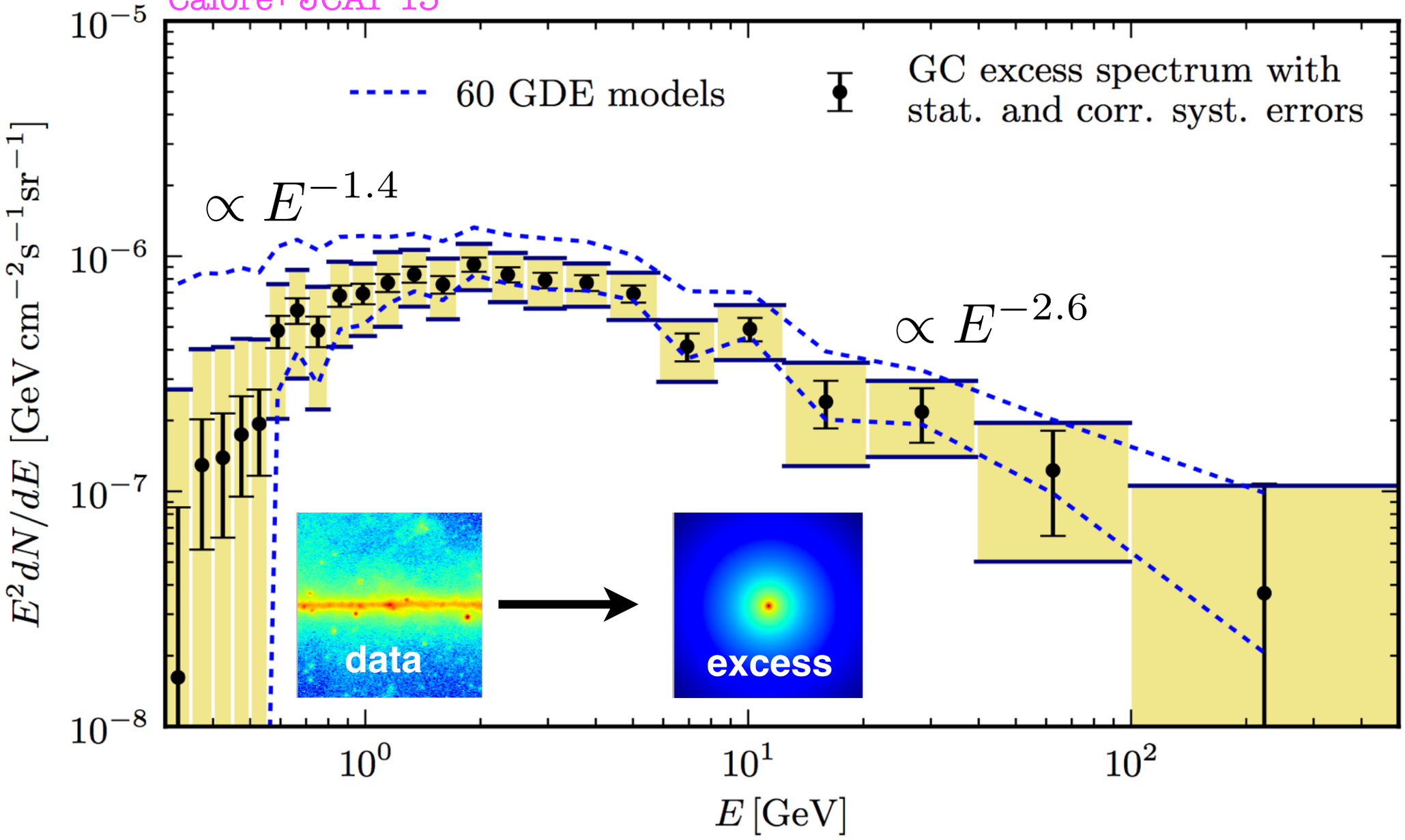
- ✓ Compatible to be **spherically symmetric** about the Galactic centre.
- ✓ Emission profile:

$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.6$$

The GeV excess in the inner Galaxy

$$|\ell| \lesssim 20^\circ, \quad 2^\circ \lesssim |b| \lesssim 20^\circ$$

Calore+ JCAP'15



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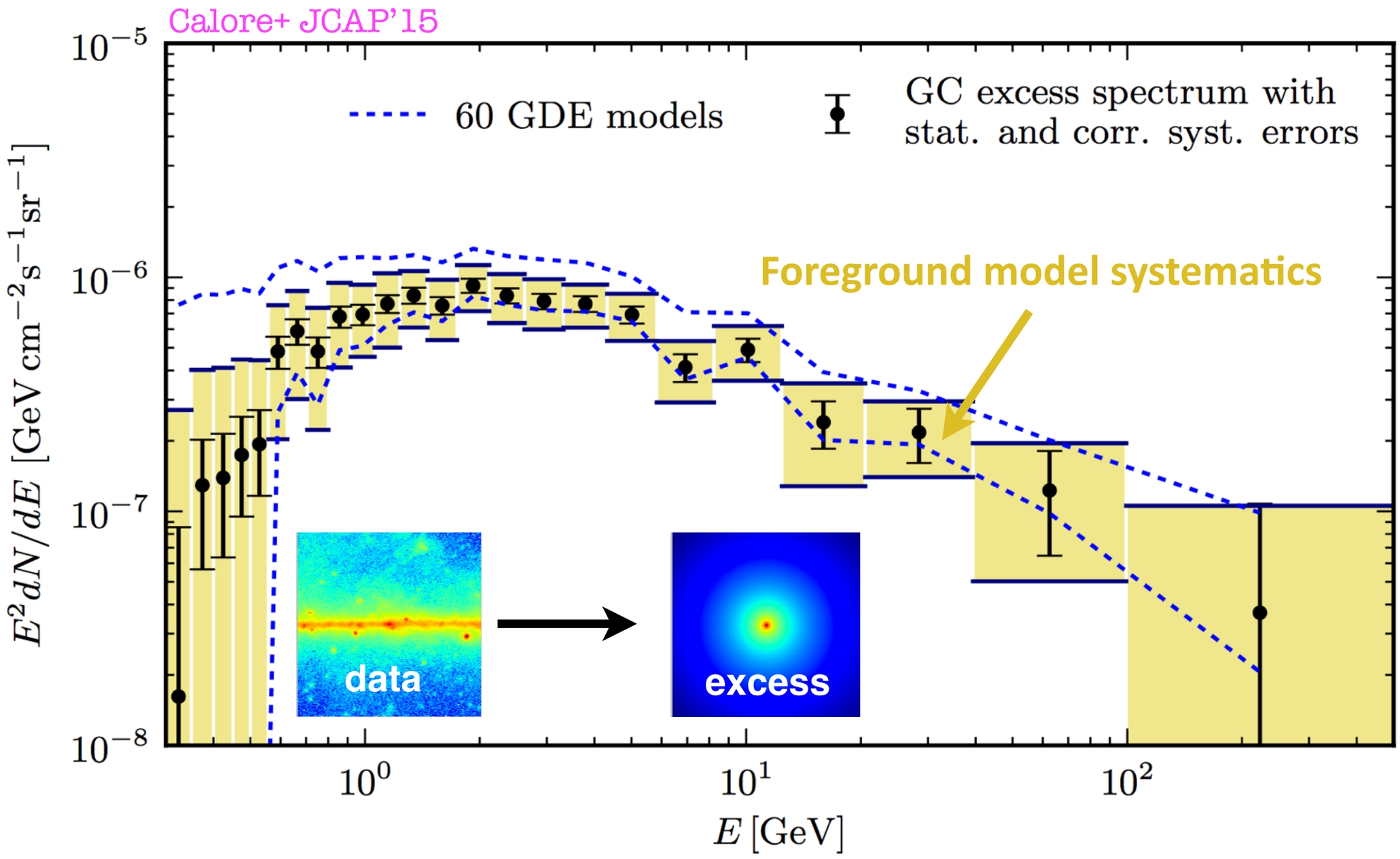

Foreground model systematics: uncertainty in the Galactic diffuse emission subtraction

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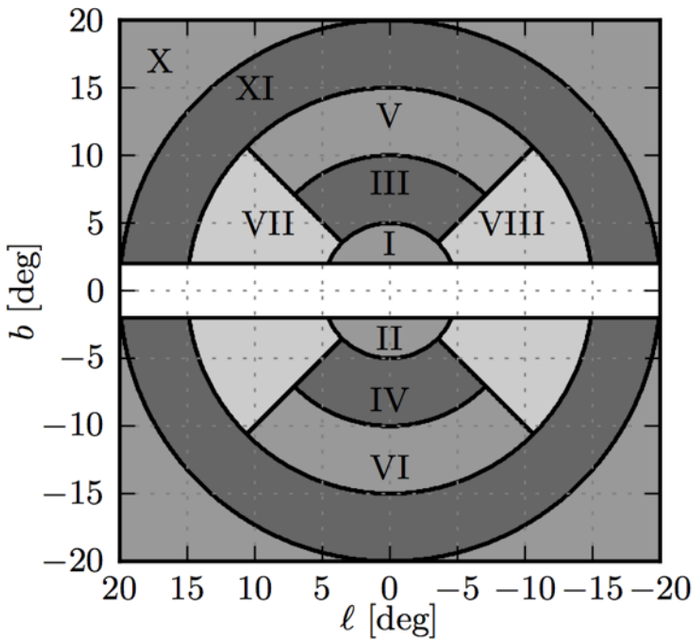

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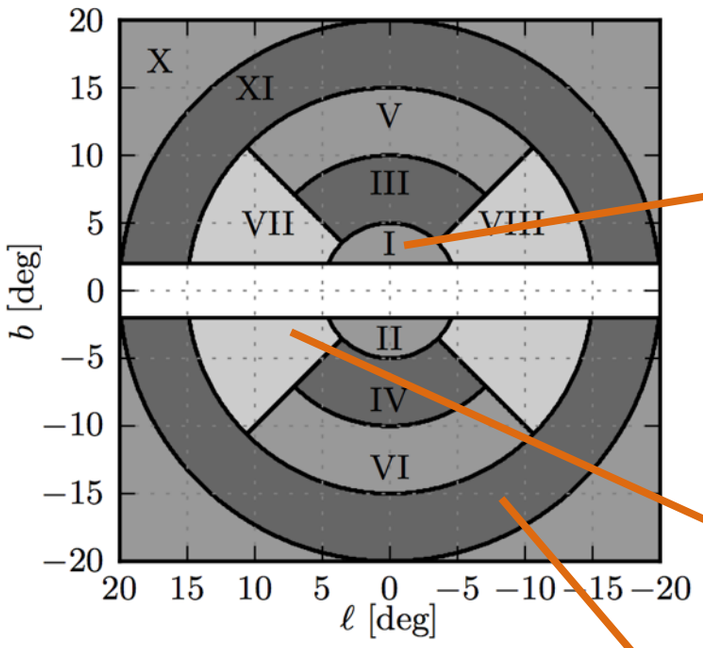

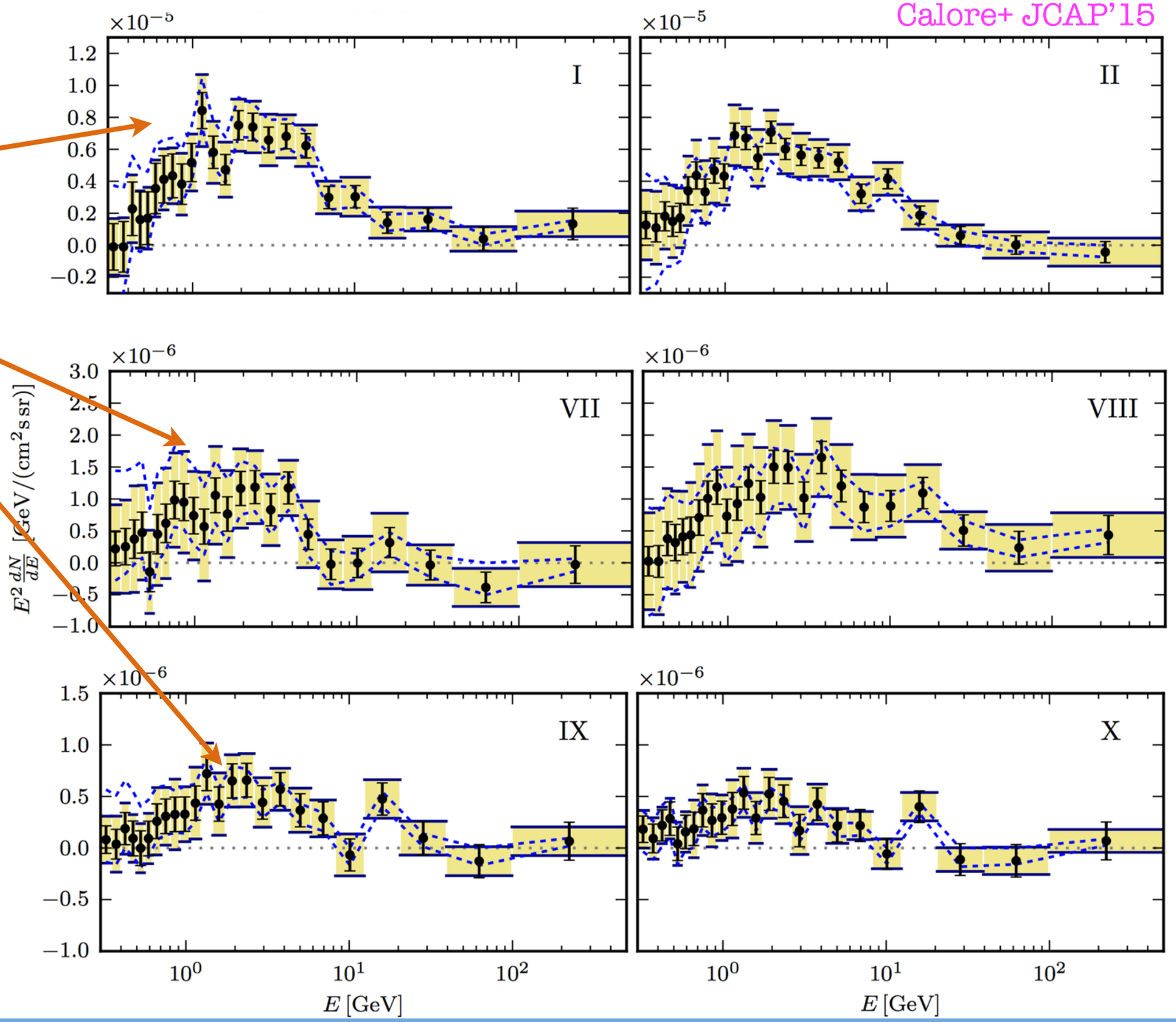

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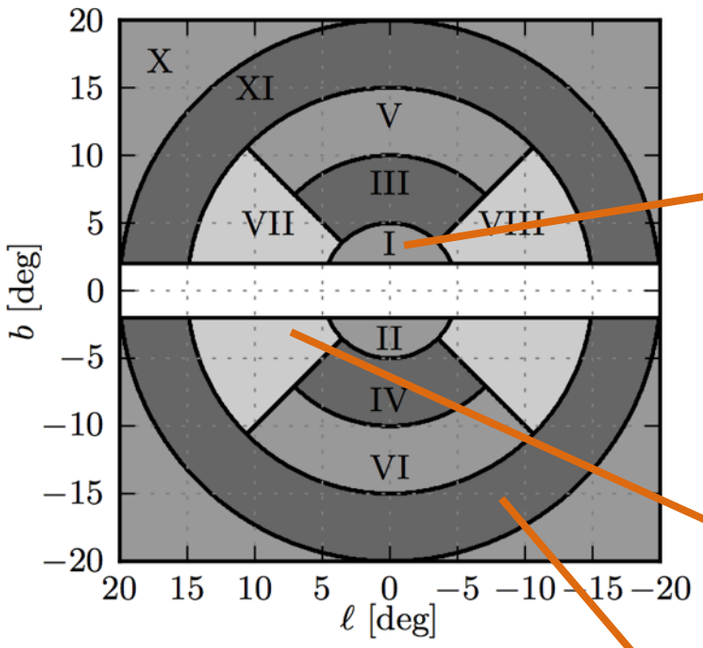
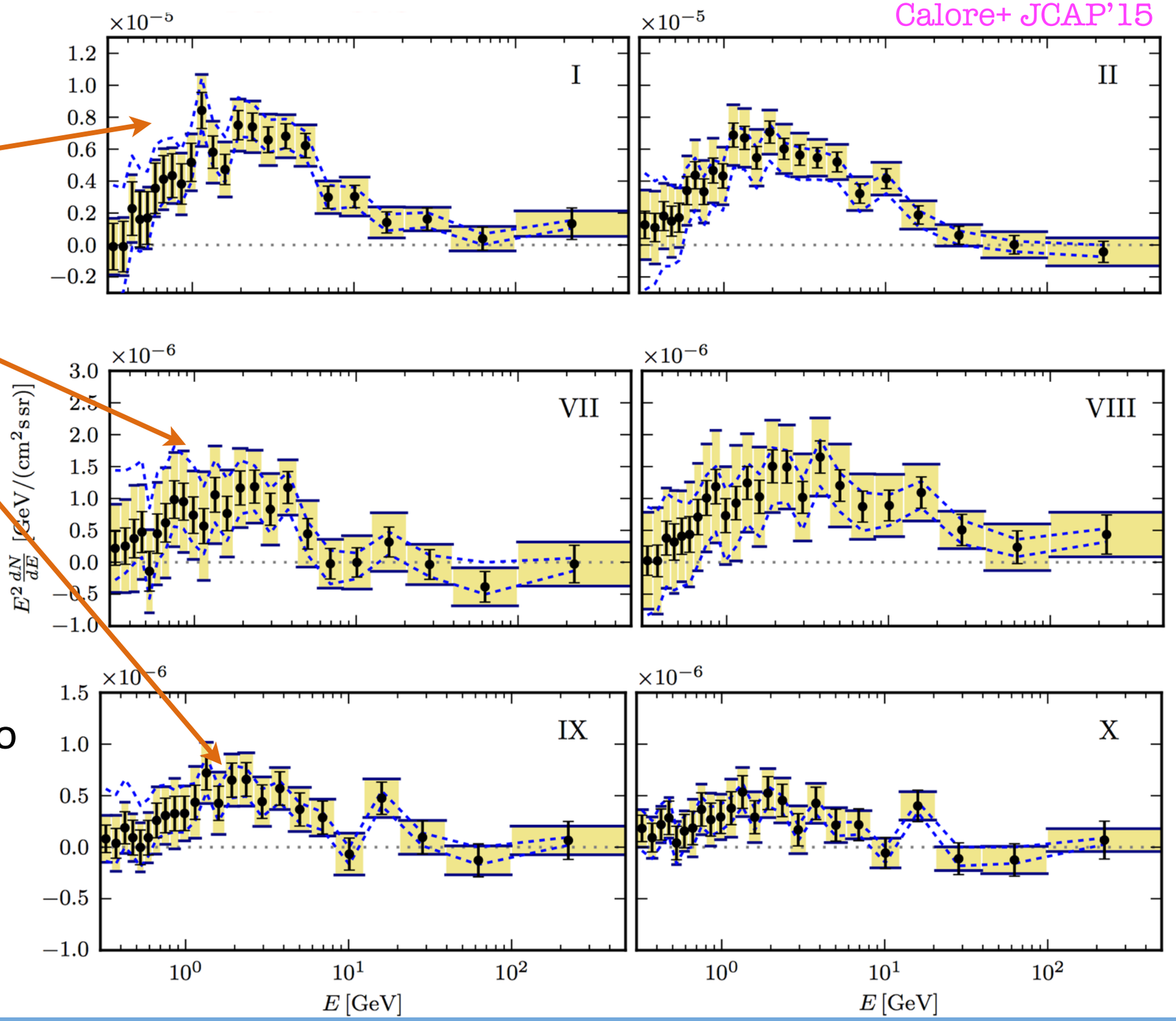


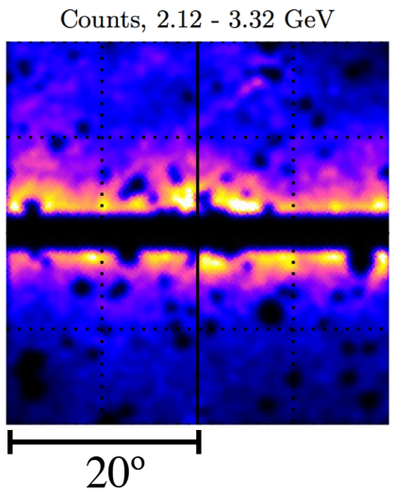


- ✓ Compatible with a spherically symmetric unique component.
- ✓ Uniform spectrum.
- ✓ Extended *at least* up to 10 degrees, 1.5 kpc.

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

$$\Gamma = 2.52 \pm 0.17$$

The (standard) analysis set up

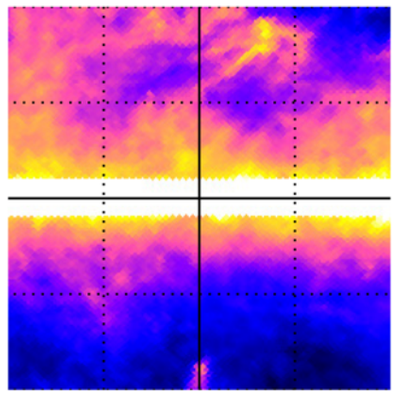


Data counts

$$k_{i,j}$$

Model counts

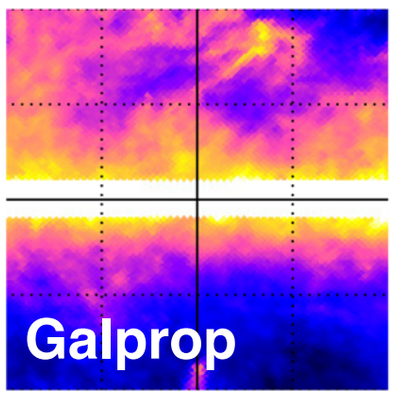
$$\mu_{i,j} = \sum_k \theta_{i,k} \mu_{i,j}^{(k)}$$



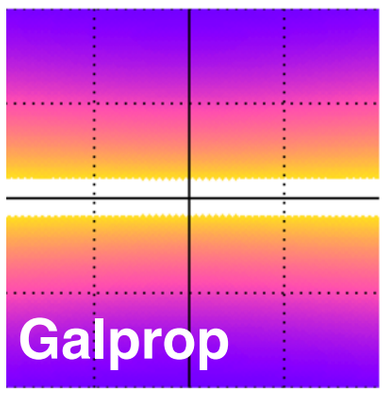
The (spatial) **template-fitting** method (maximum likelihood) → $\theta_{i,k}$

Hooper+ PDU'13; Huang+ JCAP'13; Daylan+ '14; Calore+ JCAP'15; Gaggero+ '15

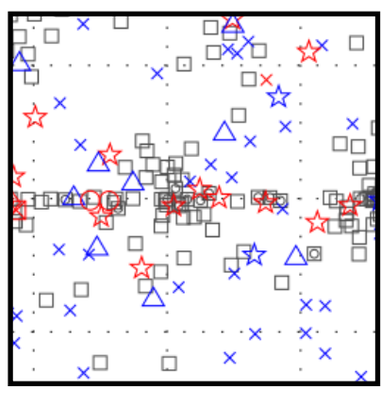
i^{th} energy



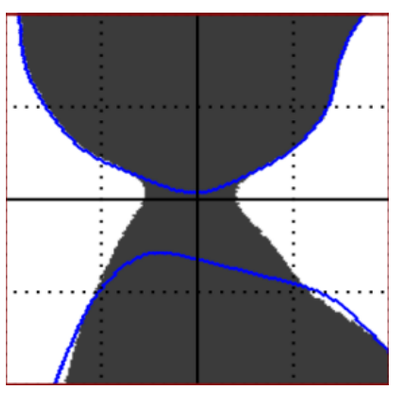
1. π^0 + Brems (free)



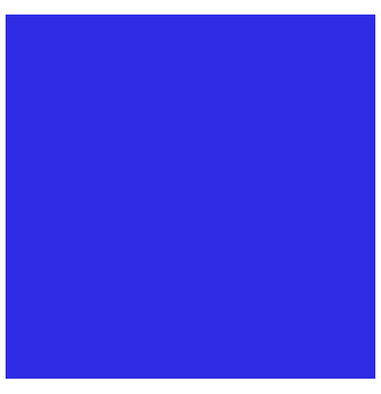
2. ICS (free)



3. 2FGL (fixed)

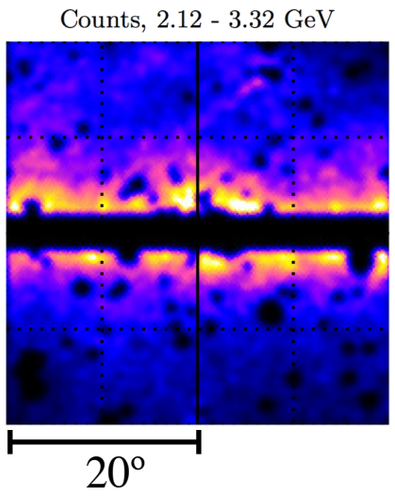


4. Fermi bubbles (constrained)



5. Isotropic diffuse bkg (constrained)

The (standard) analysis set up



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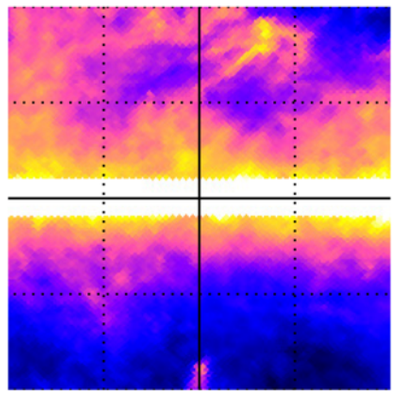

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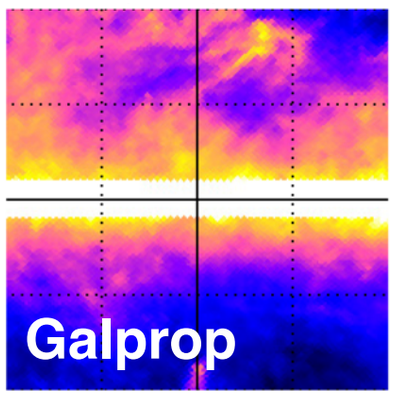

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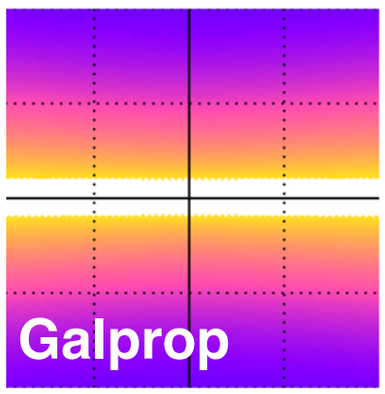
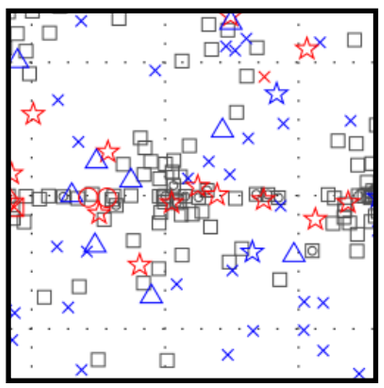
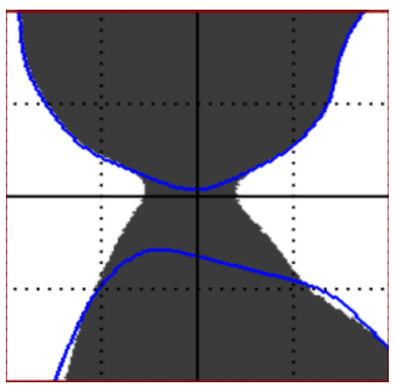


2. ICS (free)



3. 2FGL (fixed)



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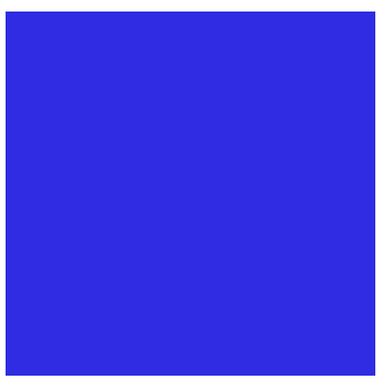

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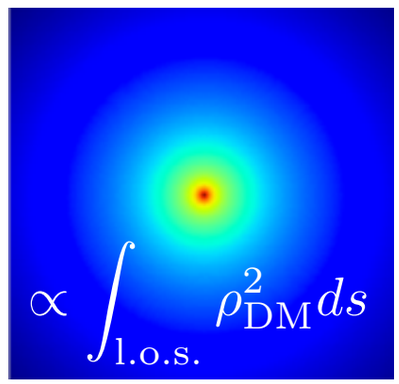


6. GeV excess template (free)

The Fermi-LAT Collaboration analysis

Ajello+ '15

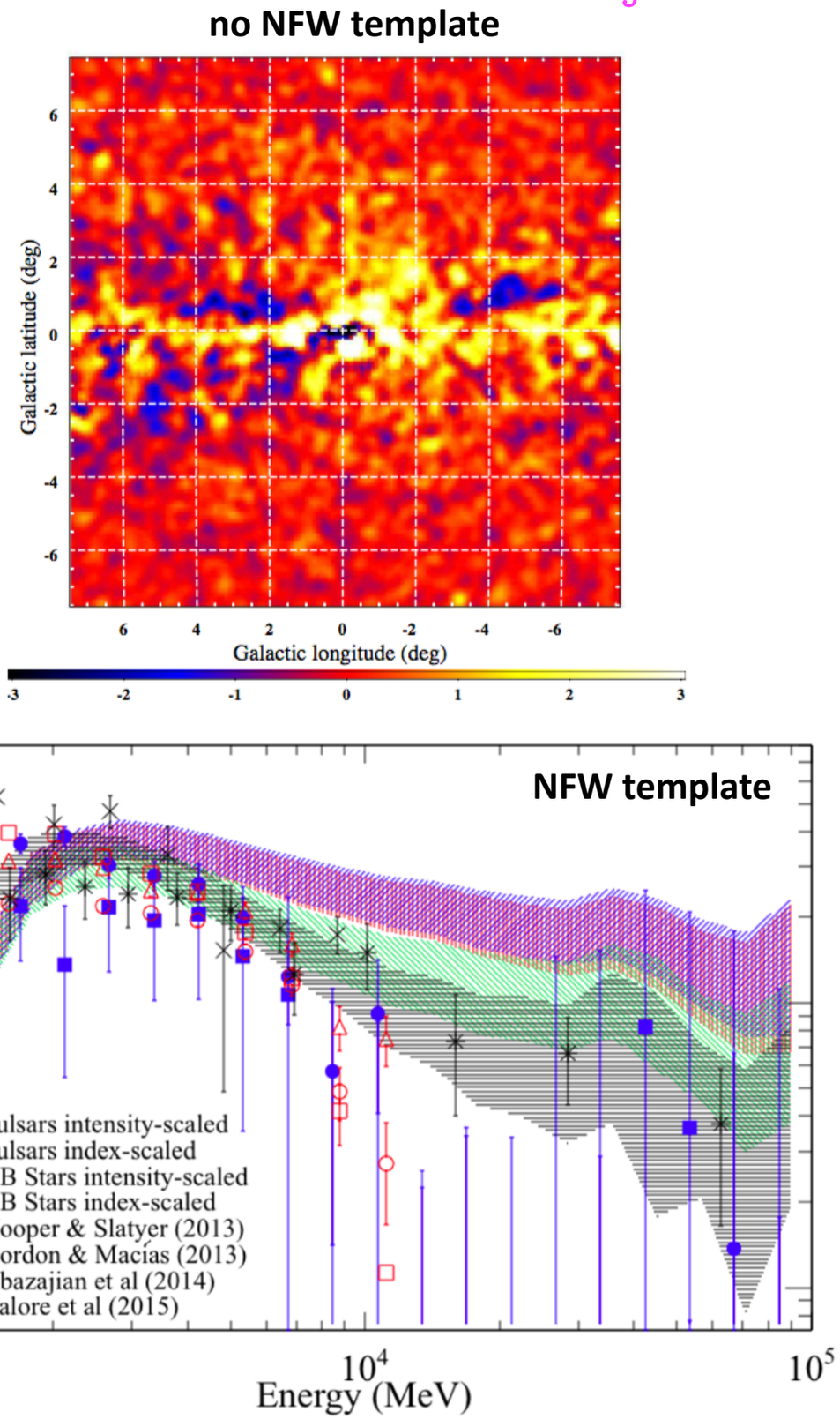
- 15° x 15° ROI; tuning of GDE outside → specialised interstellar emission models.
- Wavelet transform for source identification (1FIG catalog).

✓ **IC emission in inner 1 kpc enhanced** w.r.to baseline prediction (20% of the total GDE emission).

✓ Positive residuals are left and can be partially absorbed by an **additional centrally peaked spatial template**.

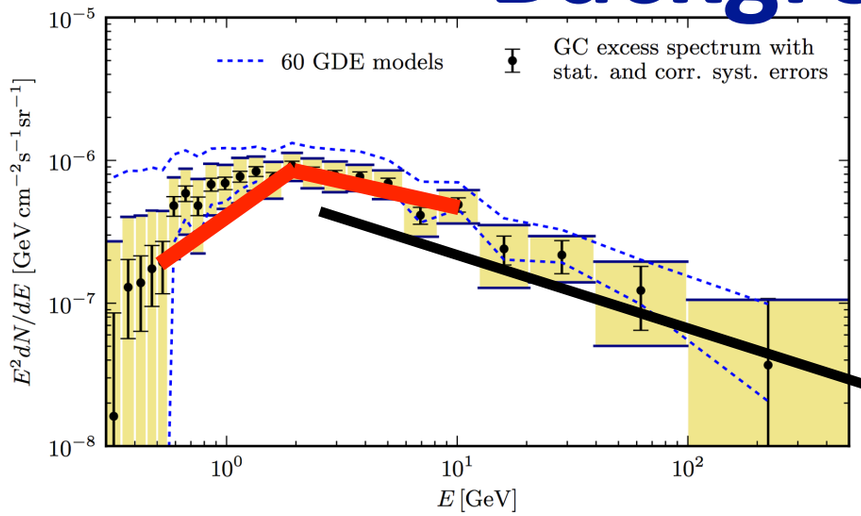
✓ **Not all positive residuals** are **accounted for** by such a model.

S. Murgia (Fri)



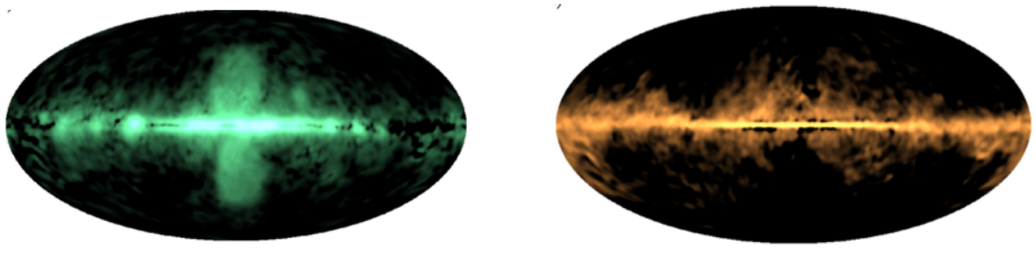
Background model systematics

Calore+ JCAP'15



An alternative method: the D^{3}PO algorithm

- GDE phenomenologically constructed 2-component model: **bubble-like** & **cloud-like** (90% emission).
- Faint point-sources accounted for.



Selig+ A&A'14

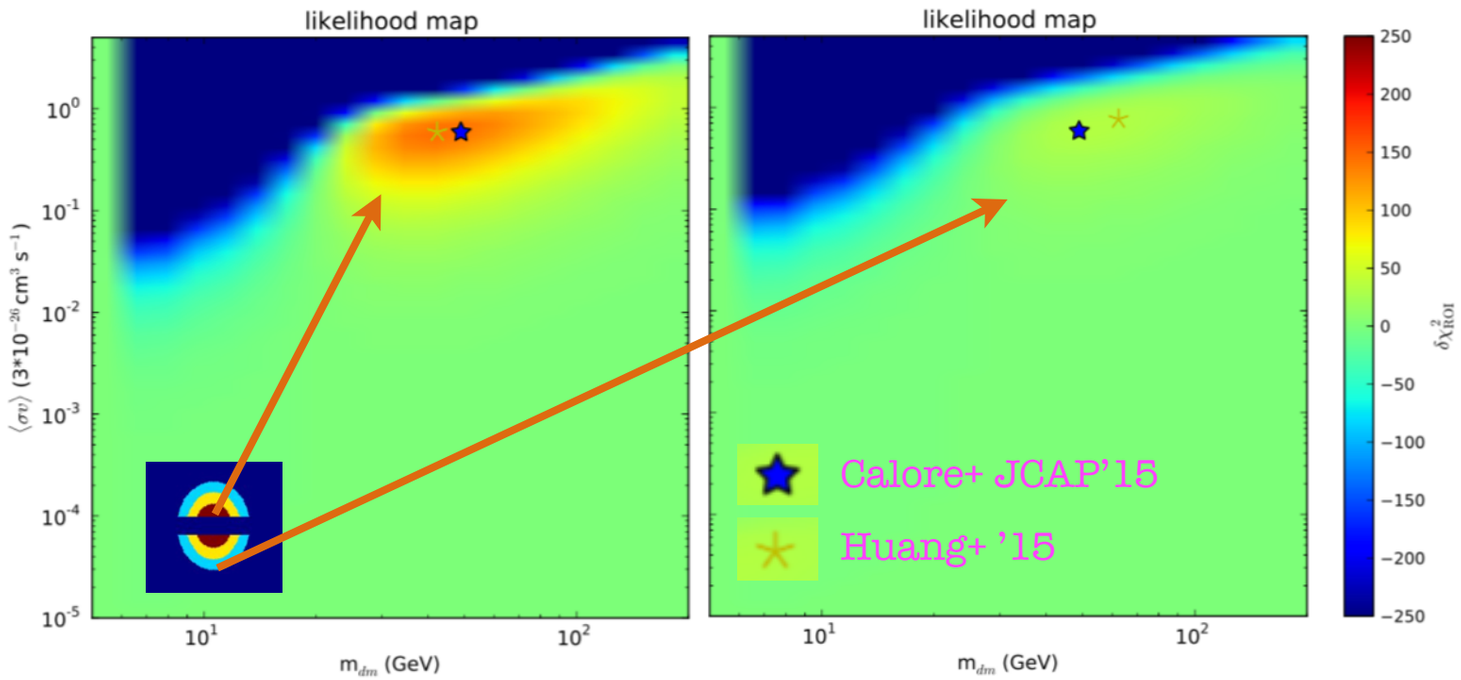
Pixel-wise maximum likelihood decomposition → $\theta_{i,k}$ (i^{th} pixel)

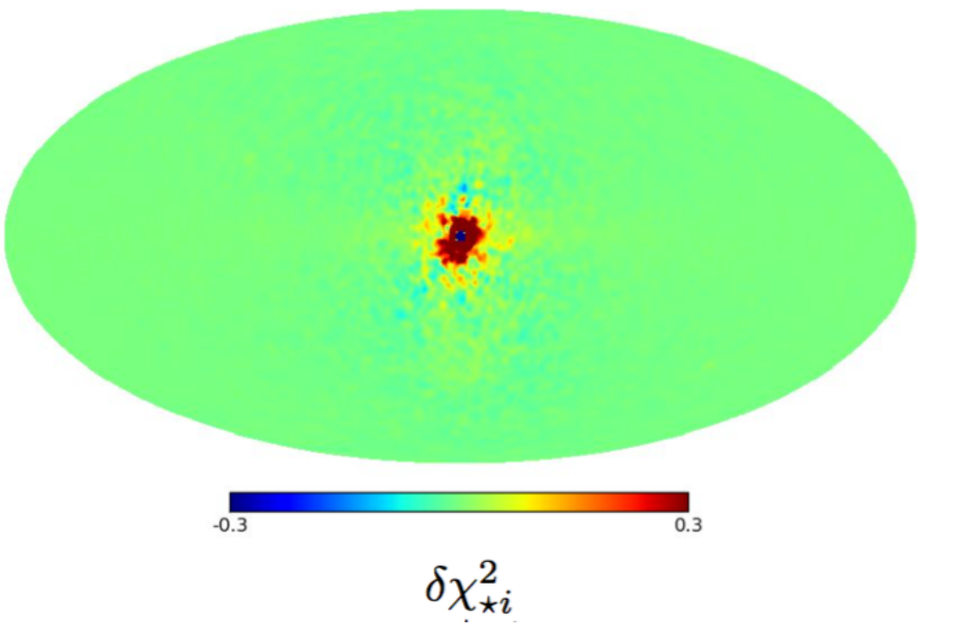
Huang+ '15

✓ Uniform and extended spectrum.

✓ Compatible with previous results.

✓ Spherically symmetric about the Galactic centre.

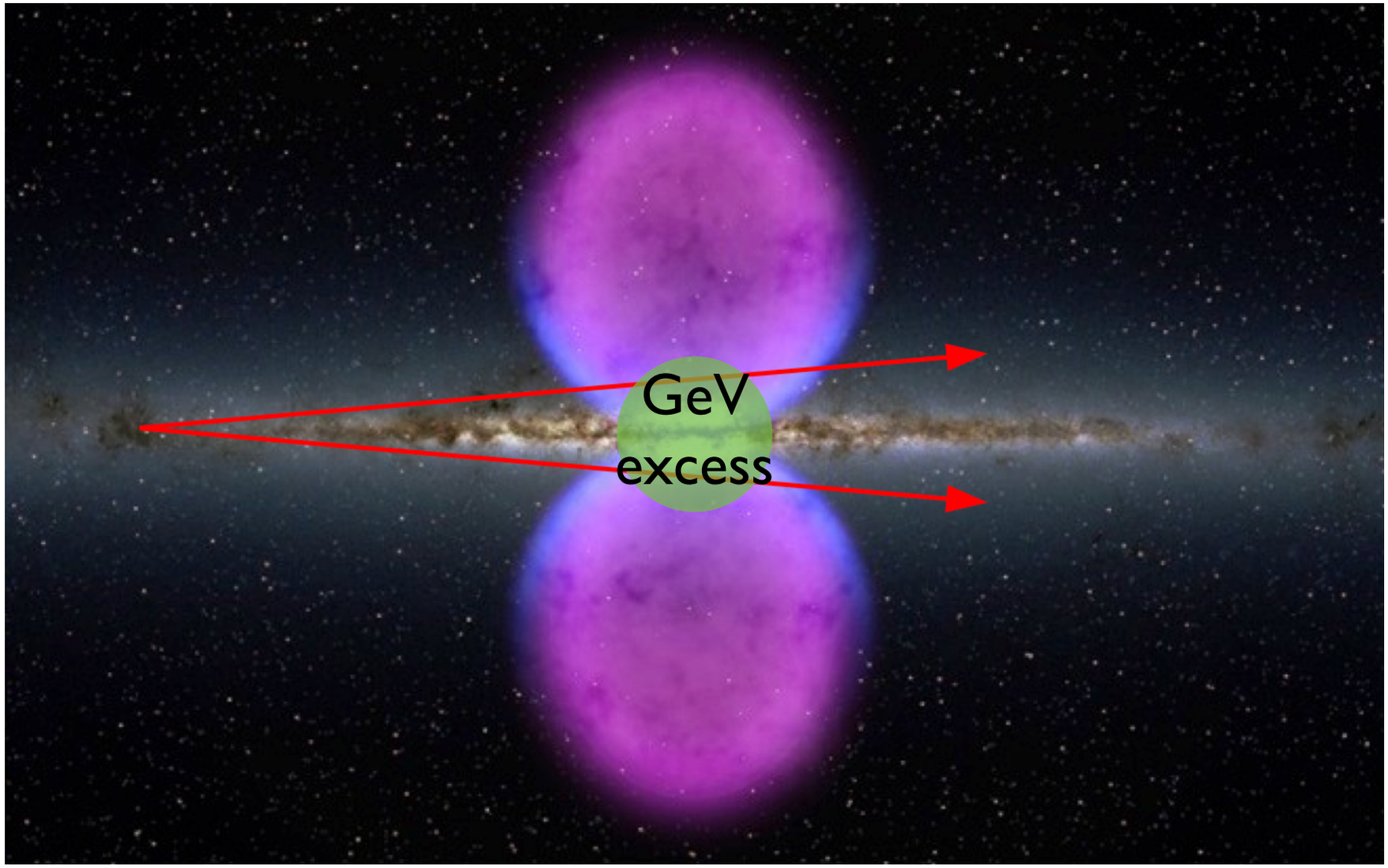




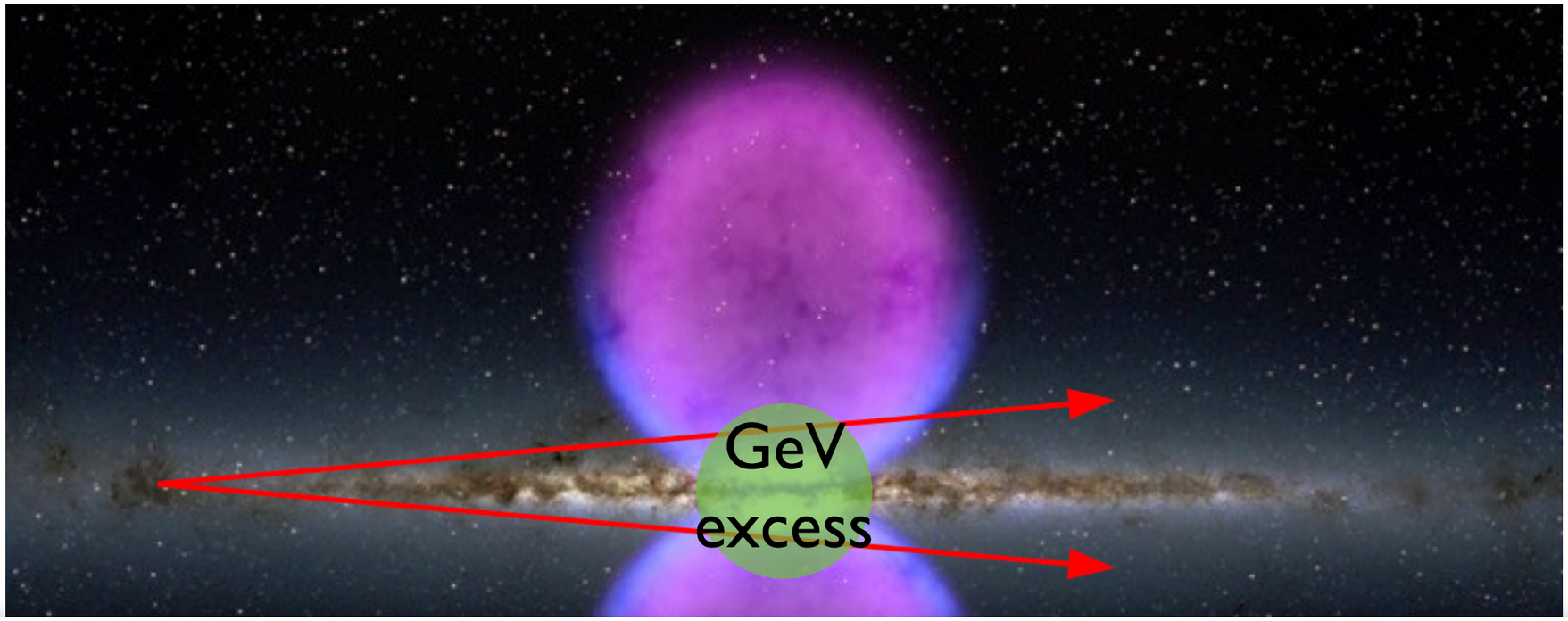
… but also the disk prefers a DM-like spectral component!

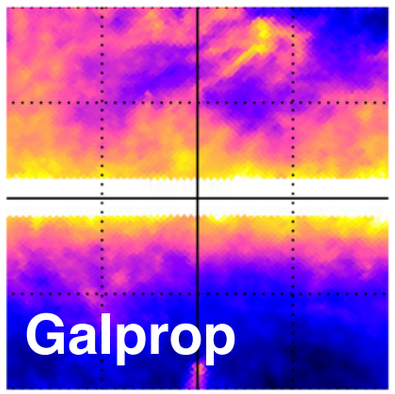
X. Huang (Fri)

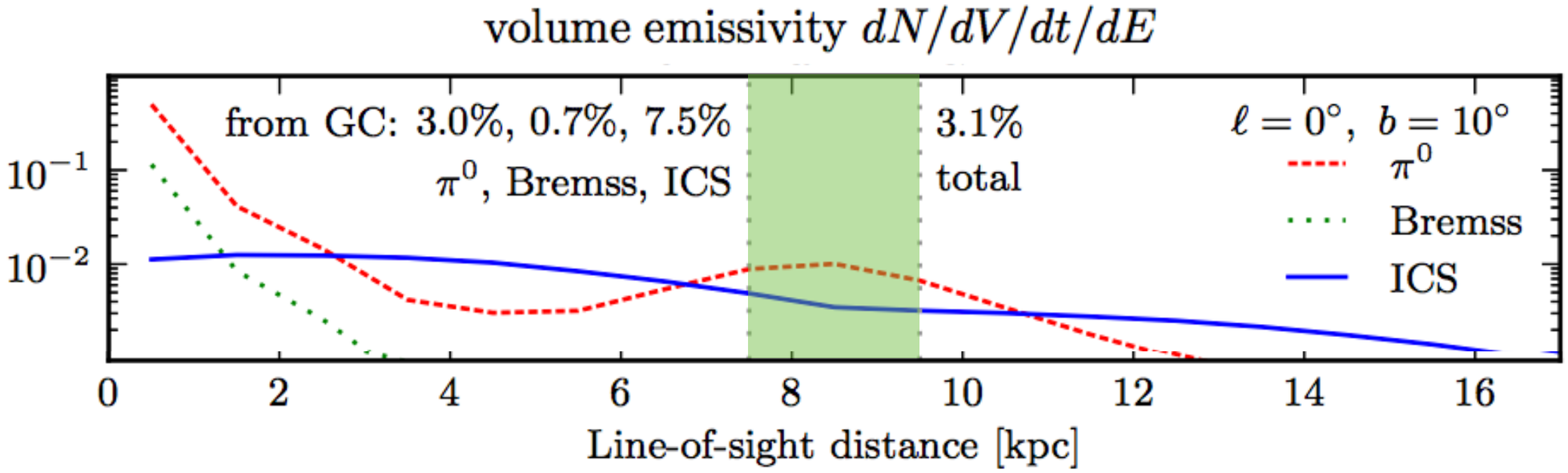
Possible interpretations



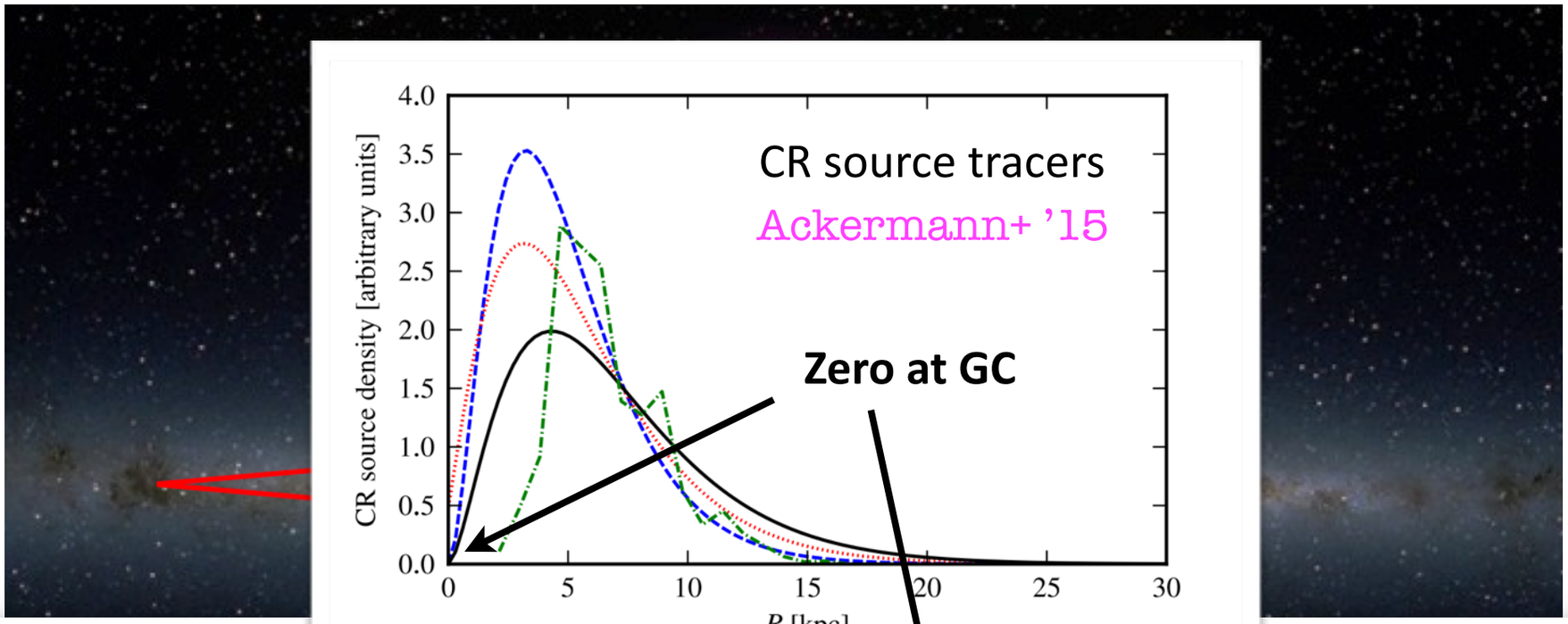
Possible interpretations

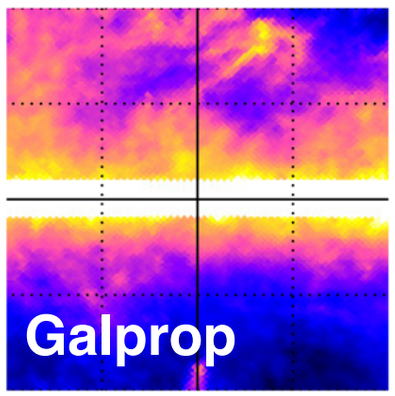


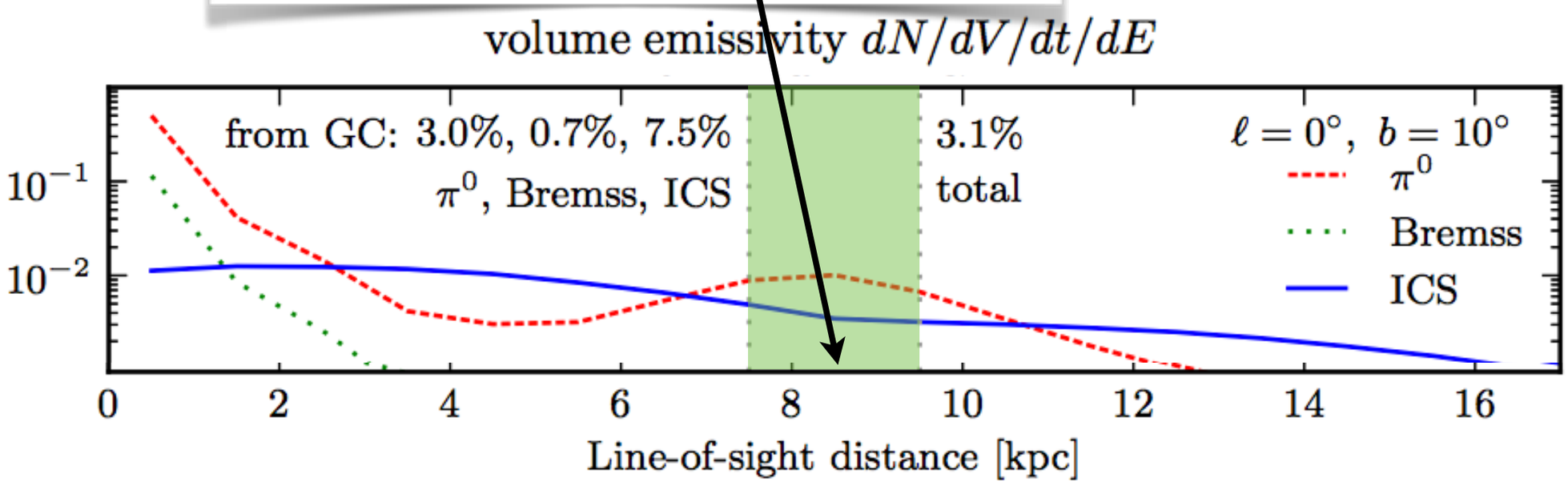




Possible interpretations



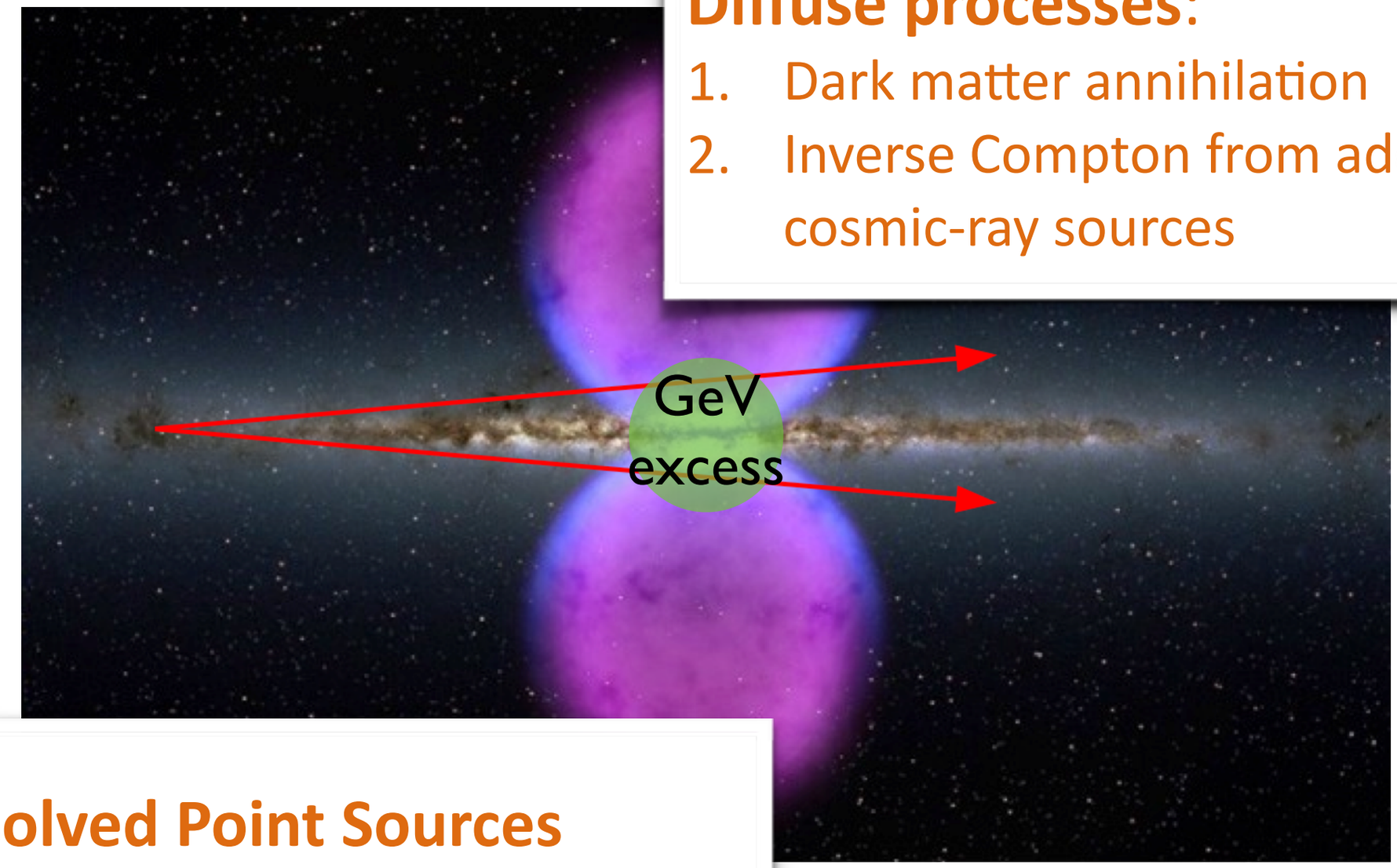




Possible interpretations

Diffuse processes:

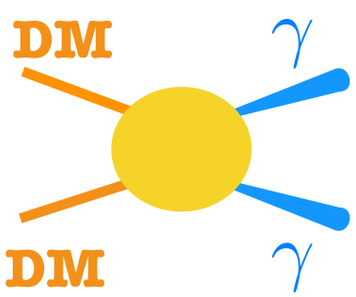
1. Dark matter annihilation
2. Inverse Compton from additional cosmic-ray sources



Unresolved Point Sources

Constraints:

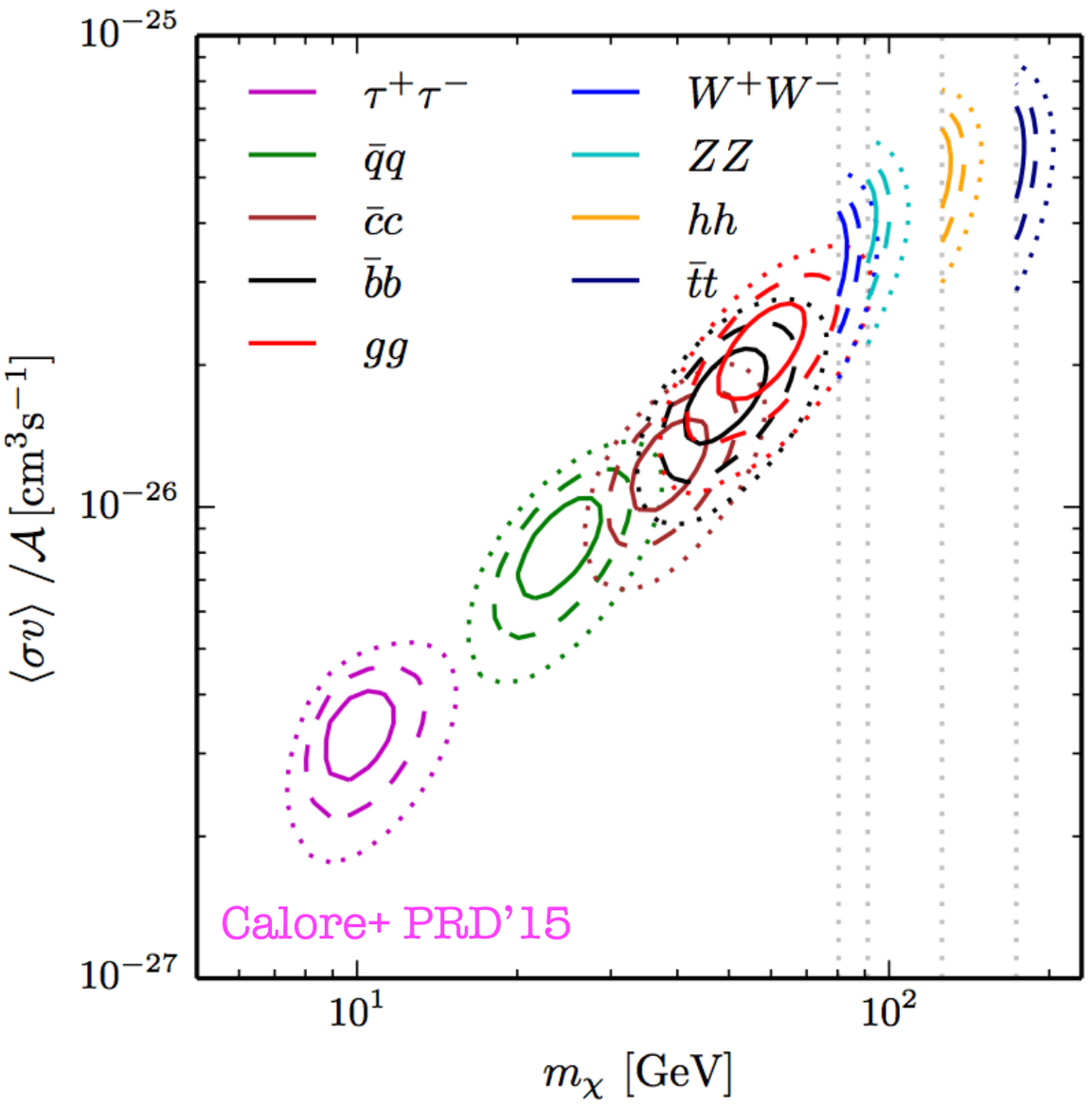
(a) Spectrum & Morphology of the excess? (b) Emission in other wavelengths?



Dark matter annihilation: spectrum

$$\frac{dN}{dE} = \sum_f \frac{\langle \sigma v \rangle_f}{8\pi\, m_\chi^2} \frac{dN_\gamma^f}{dE} \int_{\text{l.o.s}} ds\, \rho^2(r(s,\psi))$$

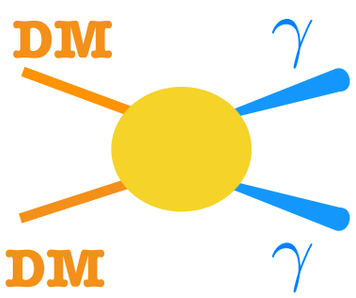
Prompt gamma-ray emission
Single annihilation channel



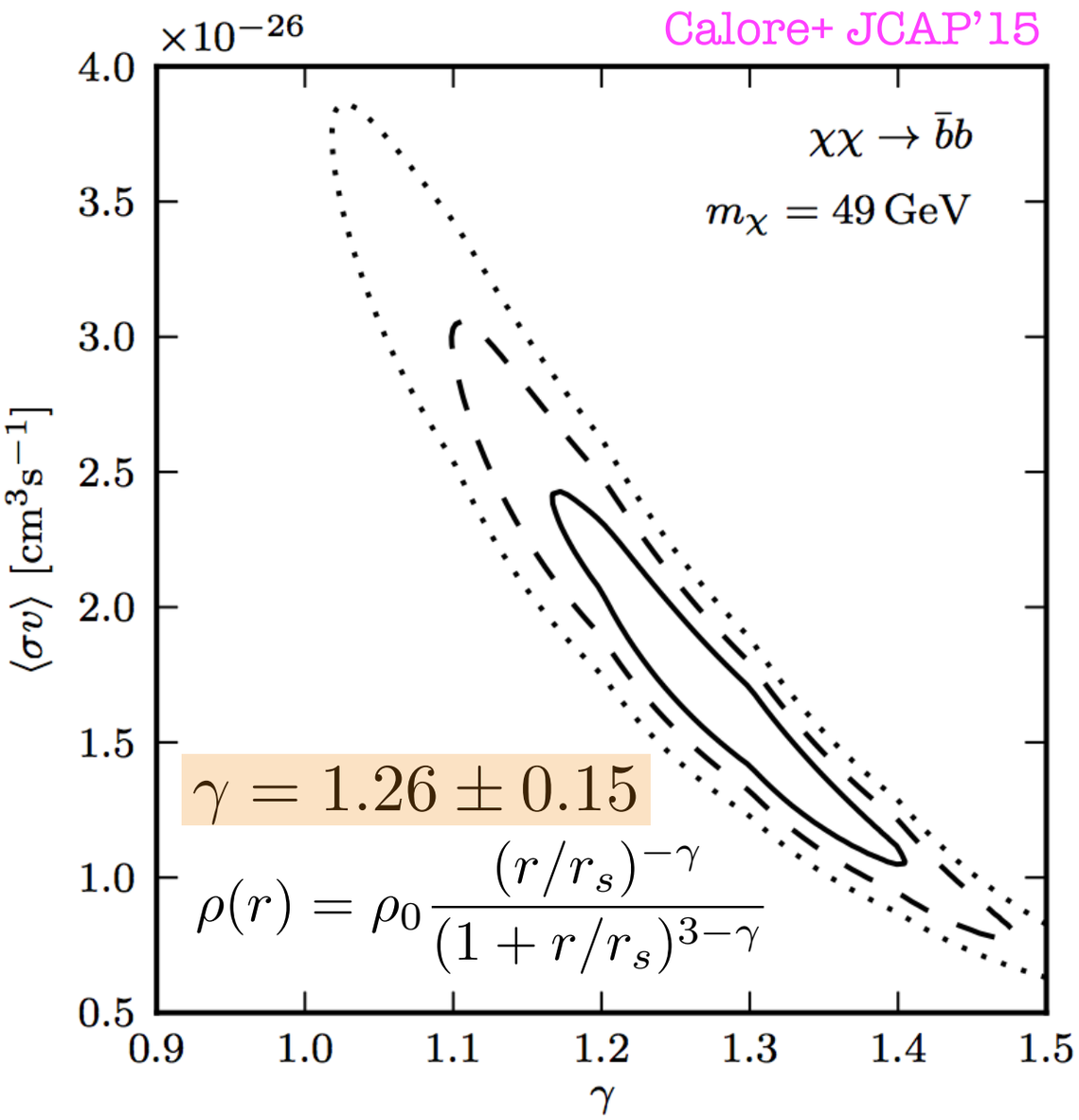
- ✓ Good fit owing to the correlated systematics.
- ✓ **More freedom**: also higher masses and other final states are allowed.
- ✓ Constraints from radio and antiproton data?

Bringmann+ PRD'14; Cholis+ PRD'15
Giesen+ JCAP'15; Evoli+ '15

D. Malyshev (today), C. Evoli (Thu)

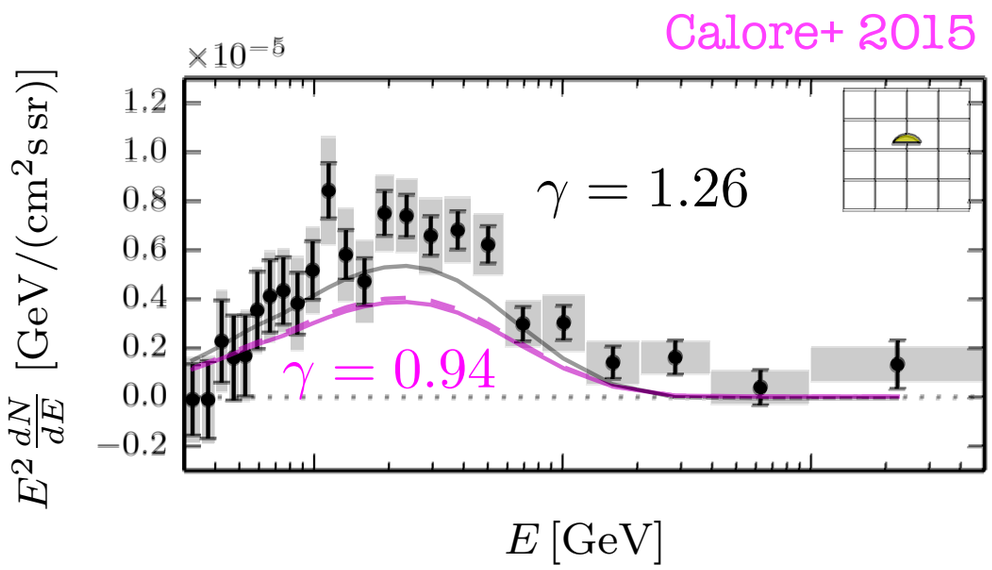


Dark matter annihilation: morphology



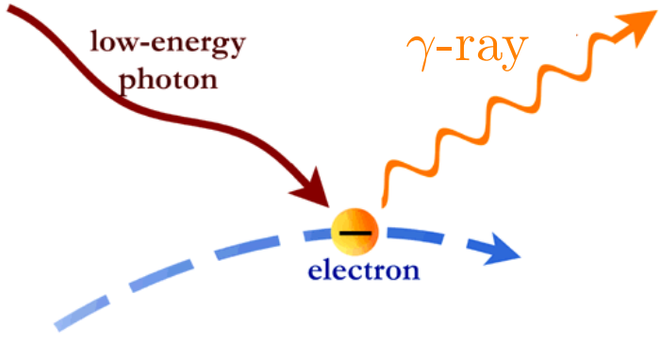
What do we expect from simulation of galaxy formation? What is the effect of baryons on the inner DM profile?

➡ For EAGLE* simulation: typically **shallower profiles** for Milky Way analogues.



*Evolution and Assembly of GaLaxies and their Environments

Inverse Compton scattering



Additional population of **leptonic cosmic rays** required at the Galactic centre:

a. Steady-state source term (from star forming CMZ)

T. Linden, D. Gaggero (today) Gaggero+15; Carlson+ '15

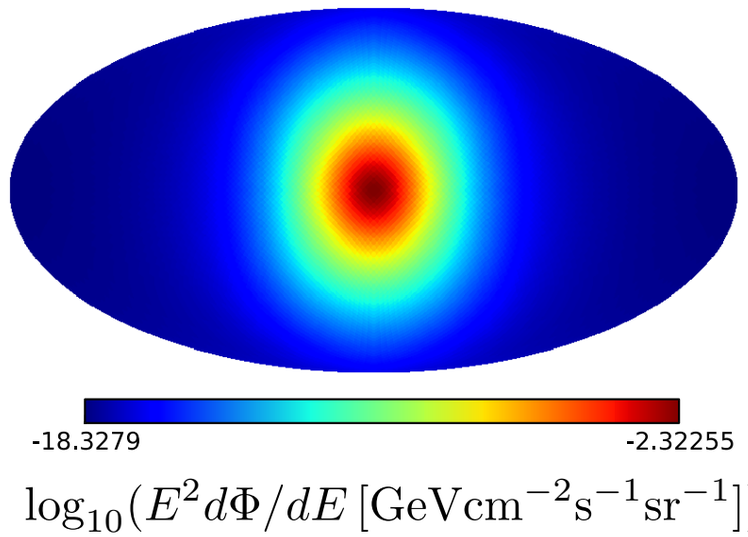
b. Time-dependent source term (from outburst event)

Petrovic+ JCAP'14

- Injection of high-energy CR in the past, at the GC (central black hole or starburst activity) ⟶ Outburst parameters.

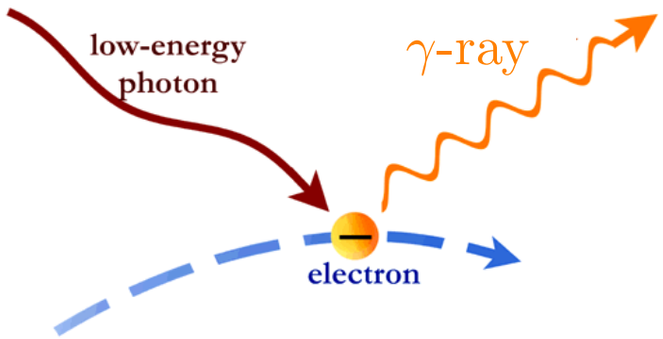
$$E_{\rm tot} \sim 10^{51}{\rm erg} \qquad \frac{dN_e}{dE_e} \propto E_e^{-\alpha} \exp(-E_e/E_{\rm cut})$$

- Inverse Compton and bremsstrahlung emission (no hadronic emission that is correlated with gas) ⟶ Propagation and energy losses parameters.



Cholis+ JCAP'15

Inverse Compton scattering



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Gaggero+15; Carlson+ '15

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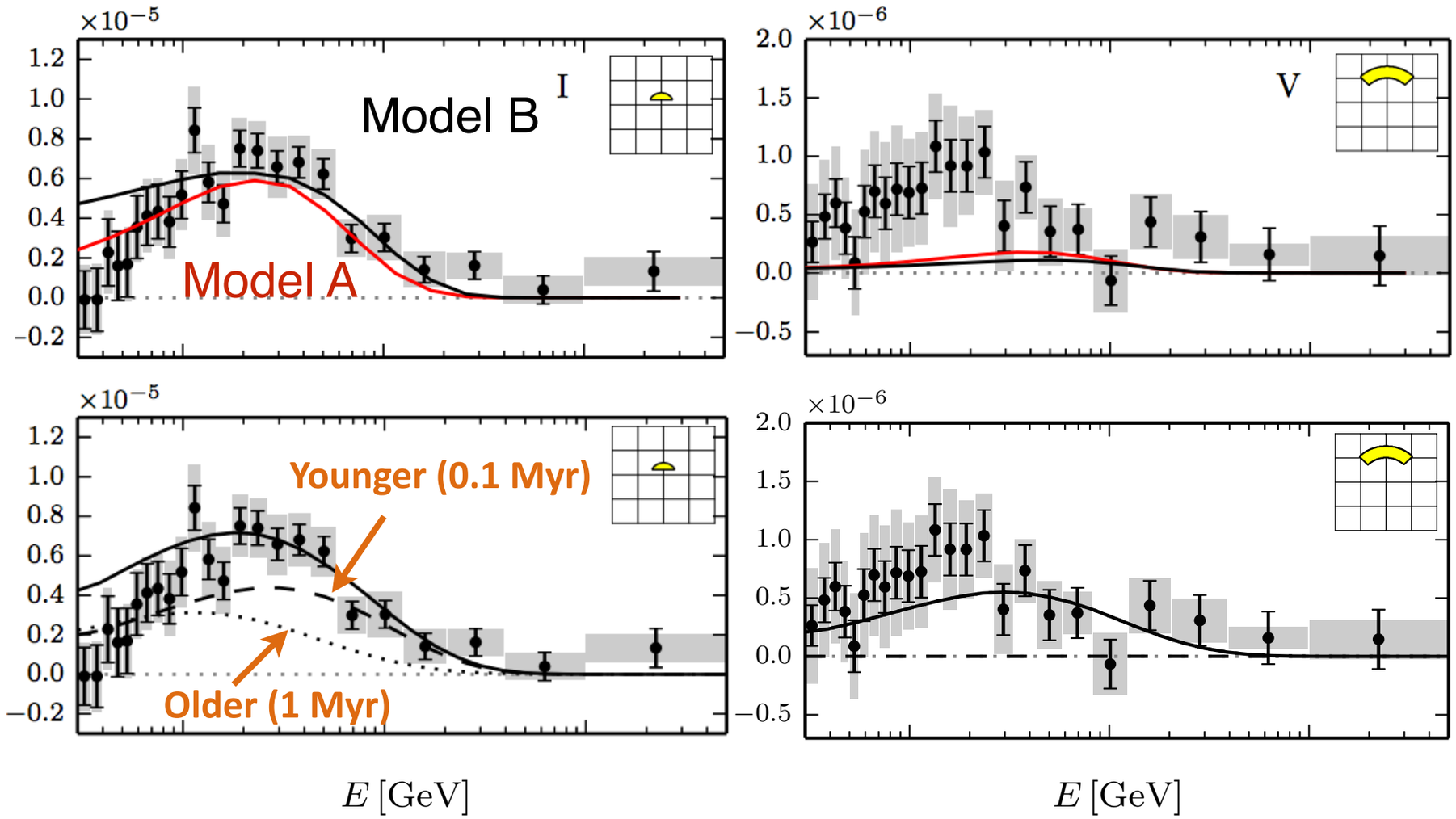


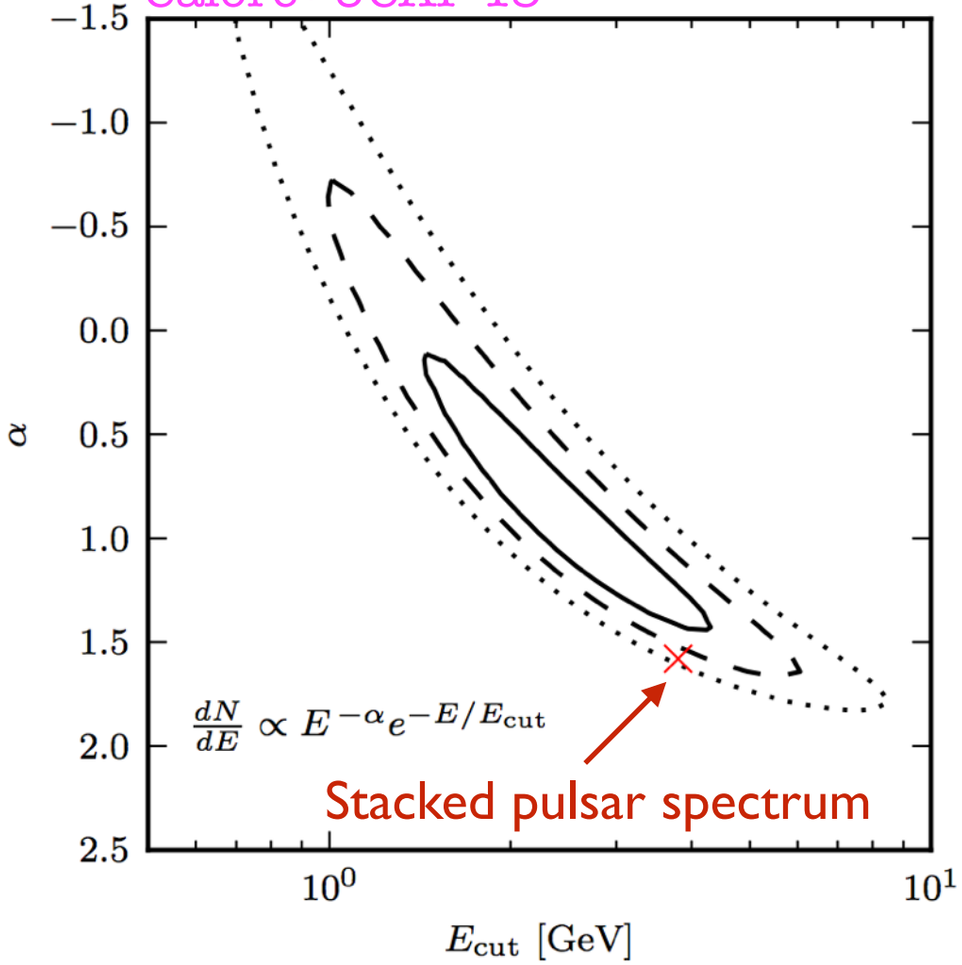
- ✓ Hard injection indices (<2).
- ✓ *At least* two bursts.
- ✓ No excess in the inner few degrees.
- ✓ Seems to be highly fine-tuned.

Cholis+ JCAP'15

Unresolved point sources

Spectrum

Calore+ JCAP'15

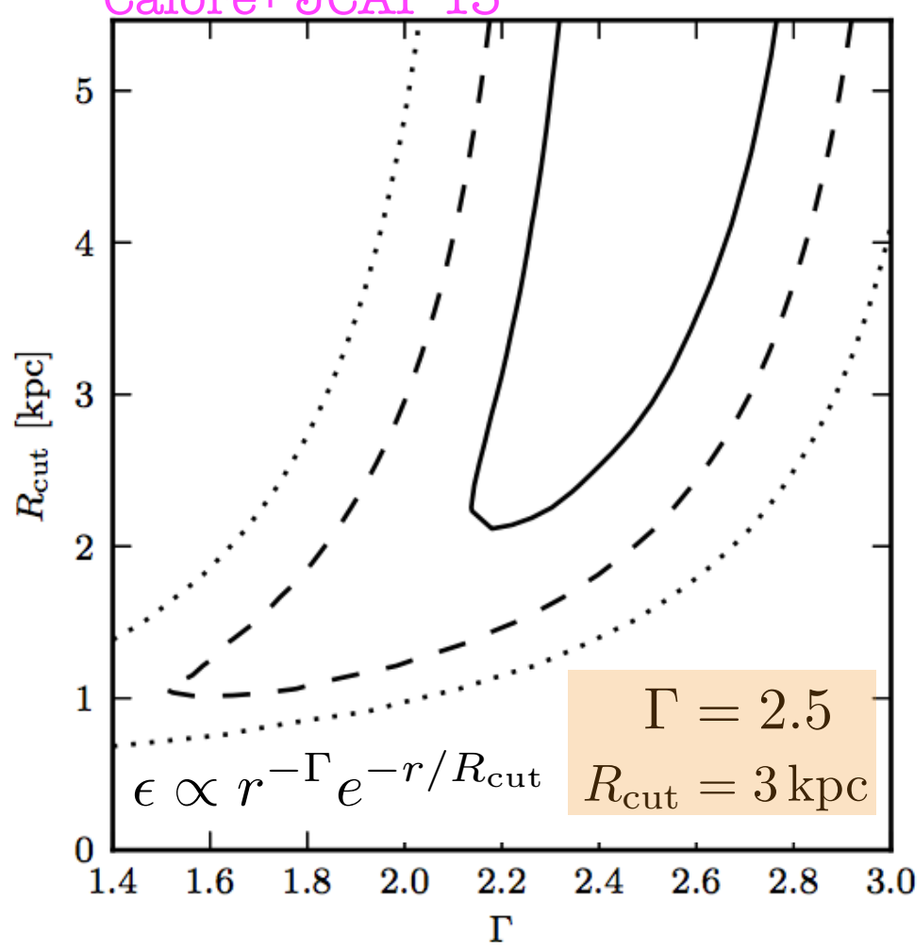


✓ Spectrum compatible with Fermi-LAT observed **millisecond pulsars** (and marginally **young pulsars**).

R. O'Leary (Wed), T. Brandt (Thu)

Morphology

Calore+ JCAP'15

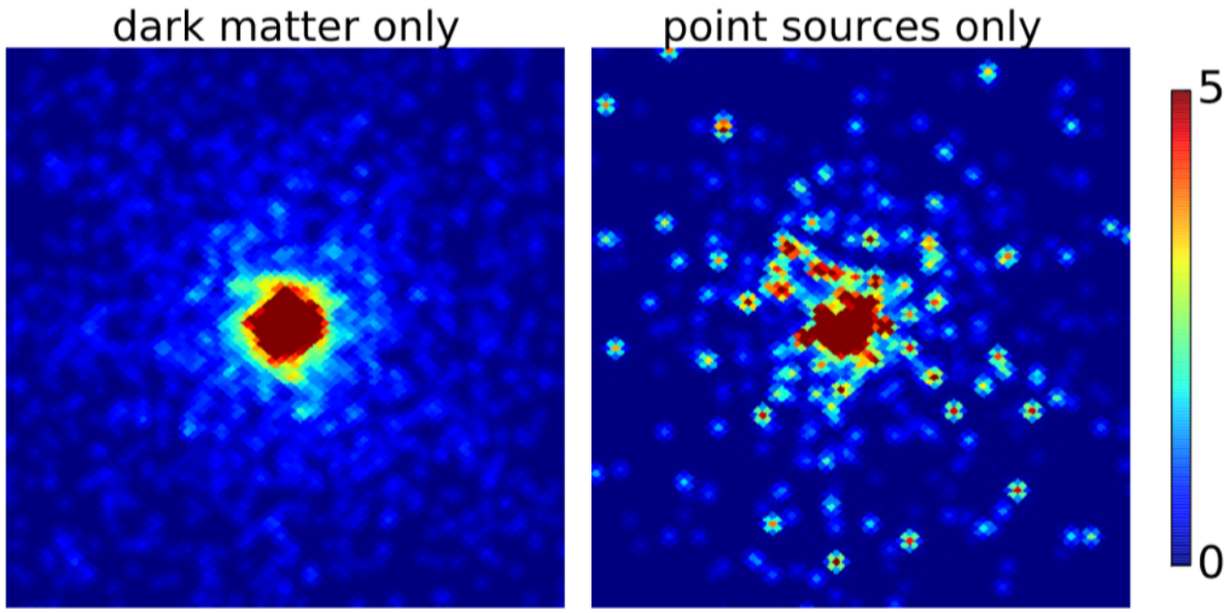


✓ Proposed population of MSPs in the bulge (vs disk). Cholis+'14; Petrovic+ JCAP'15; Yuang+ MNRAS'14;

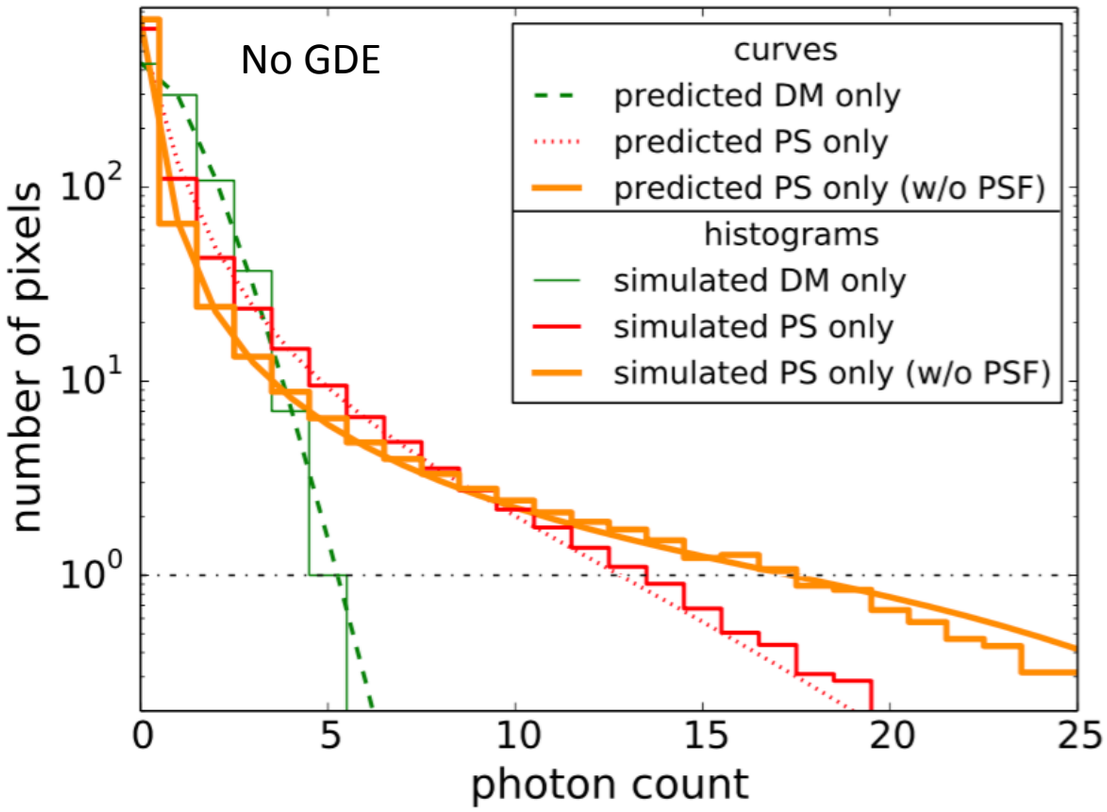
✓ Young pulsars from SF in the CMZ. O'Leary+ '15

✓ Bulge MSPs: from tidally disrupted globular clusters. Brandt&Kocsis'15

How to discriminate point sources from diffuse emission?



Lee+ JCAP'15

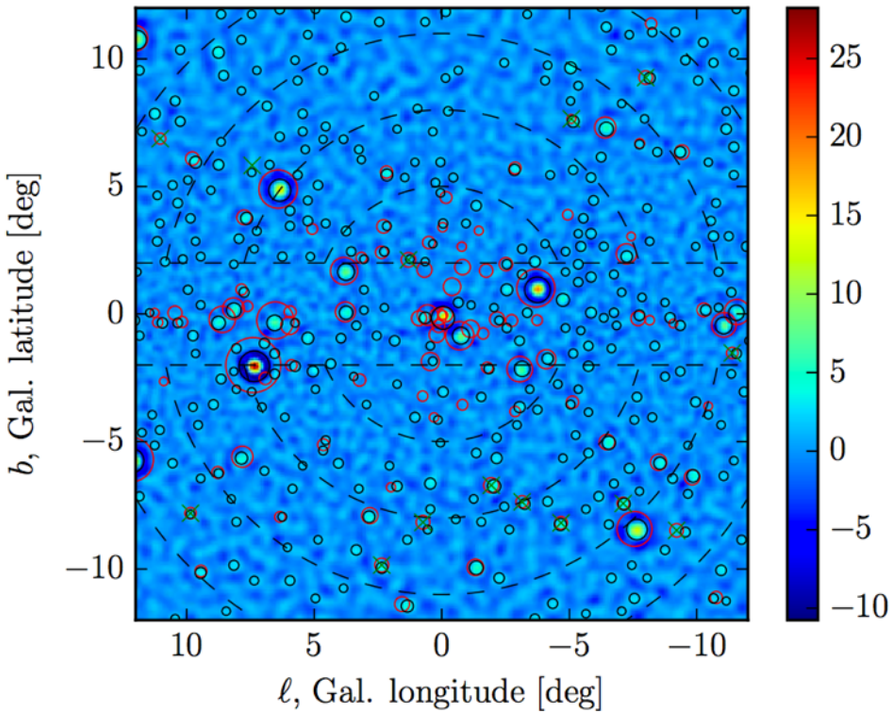


Differences in the statistics of the photon counts can be quantified and used for model comparison.

Caveat: Effect of Galactic diffuse emission.

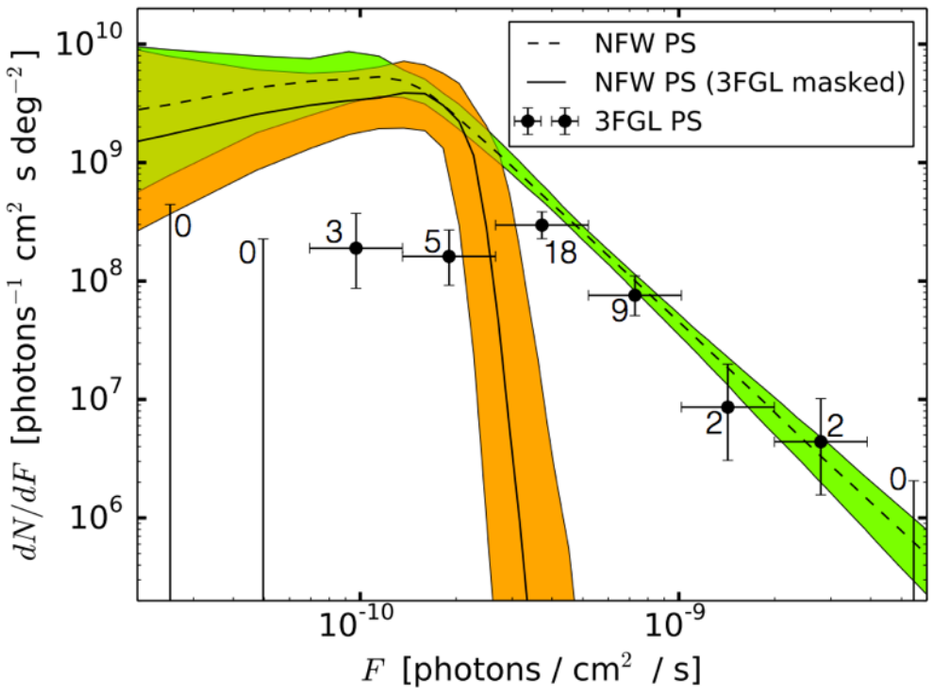
Support for MSPs interpretation

Bartels+ 15



Local maxima of normalised wavelet transform

Lee+'15

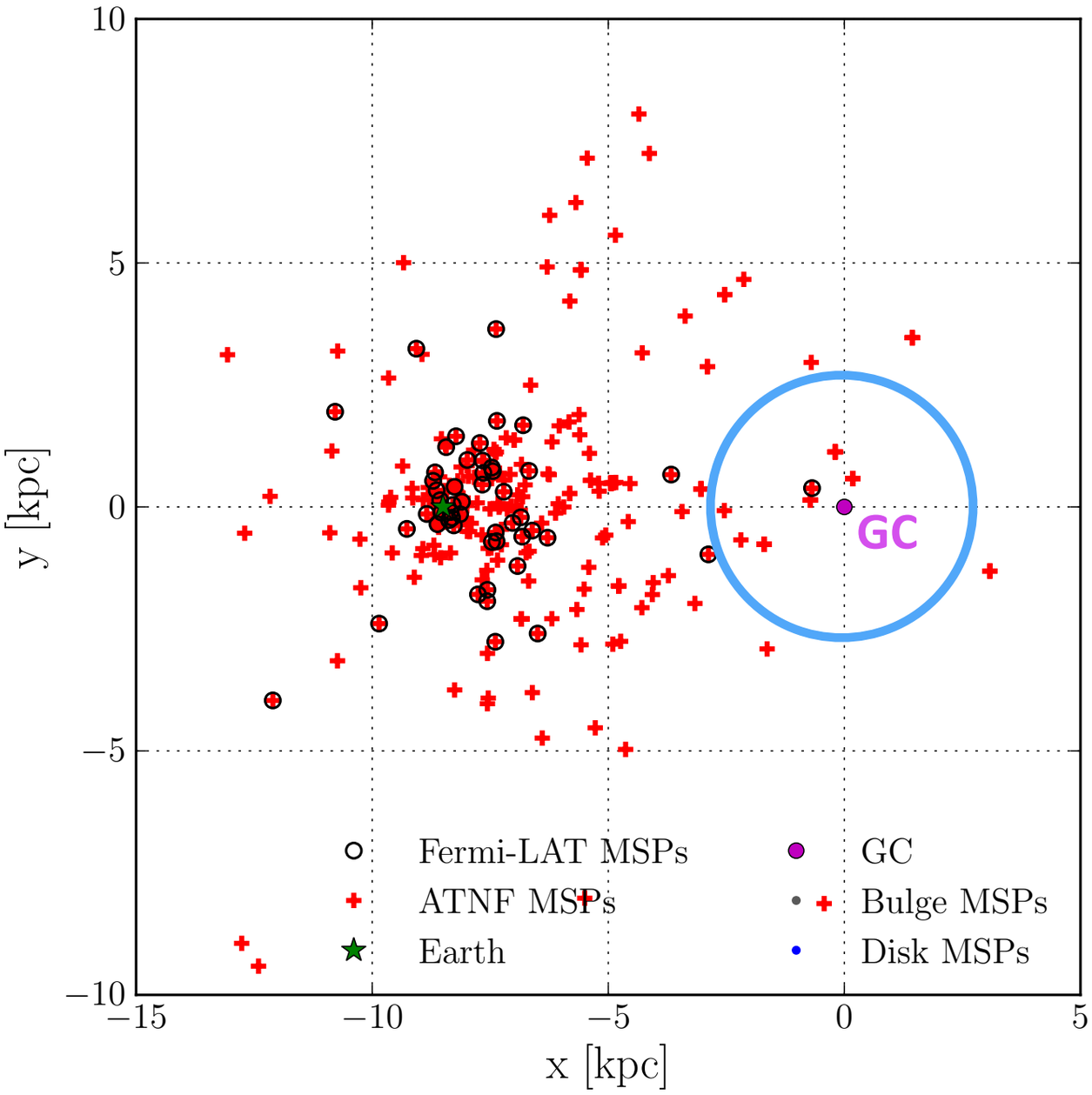


Non-Poissonian template fitting

- Two independent techniques reached similar conclusions: significant contribution from dim point sources (very mild dependence on GDE).
- Phenomenological description of sources (luminosity function and a NFW-squared spatial distribution).

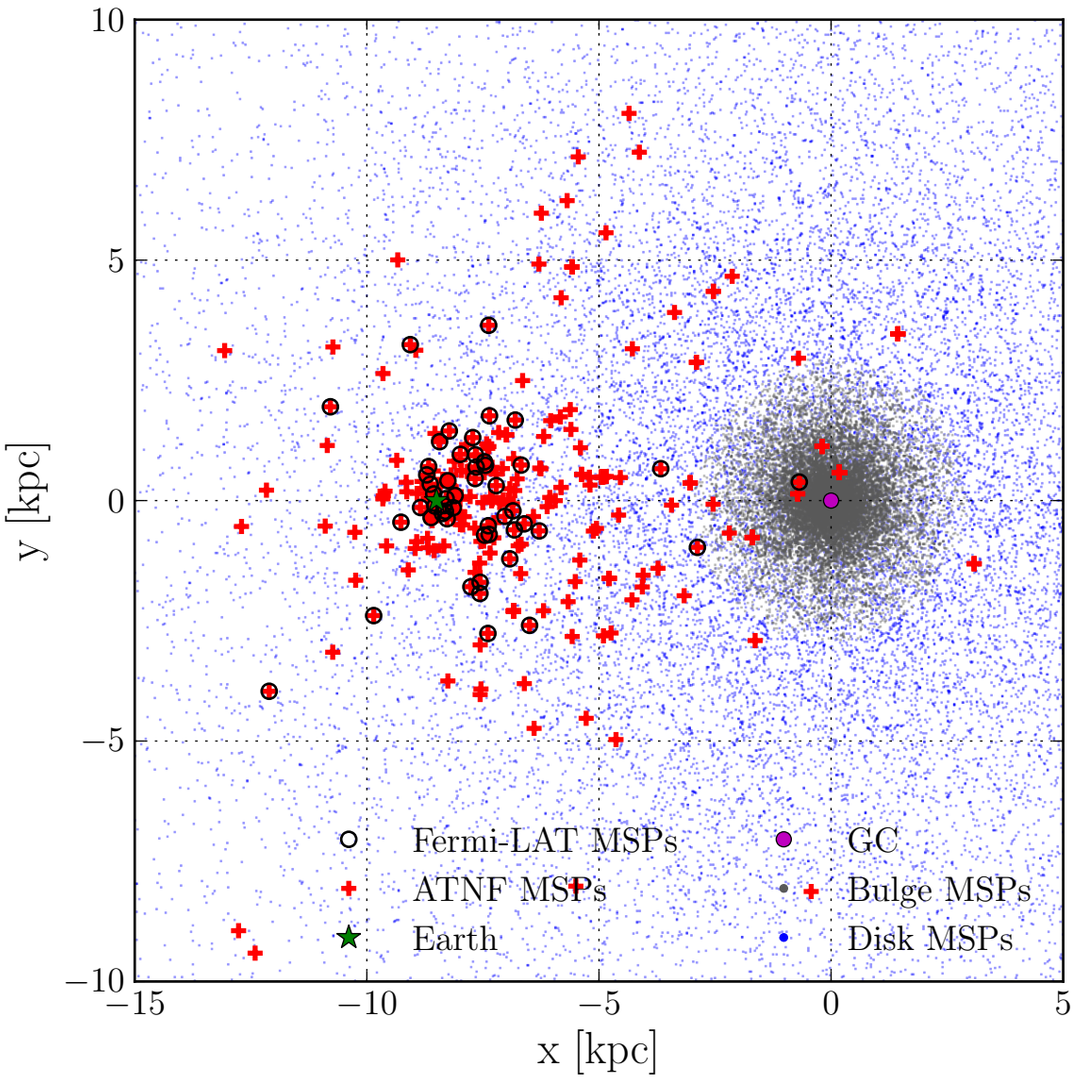
R. Bartels (Wed)

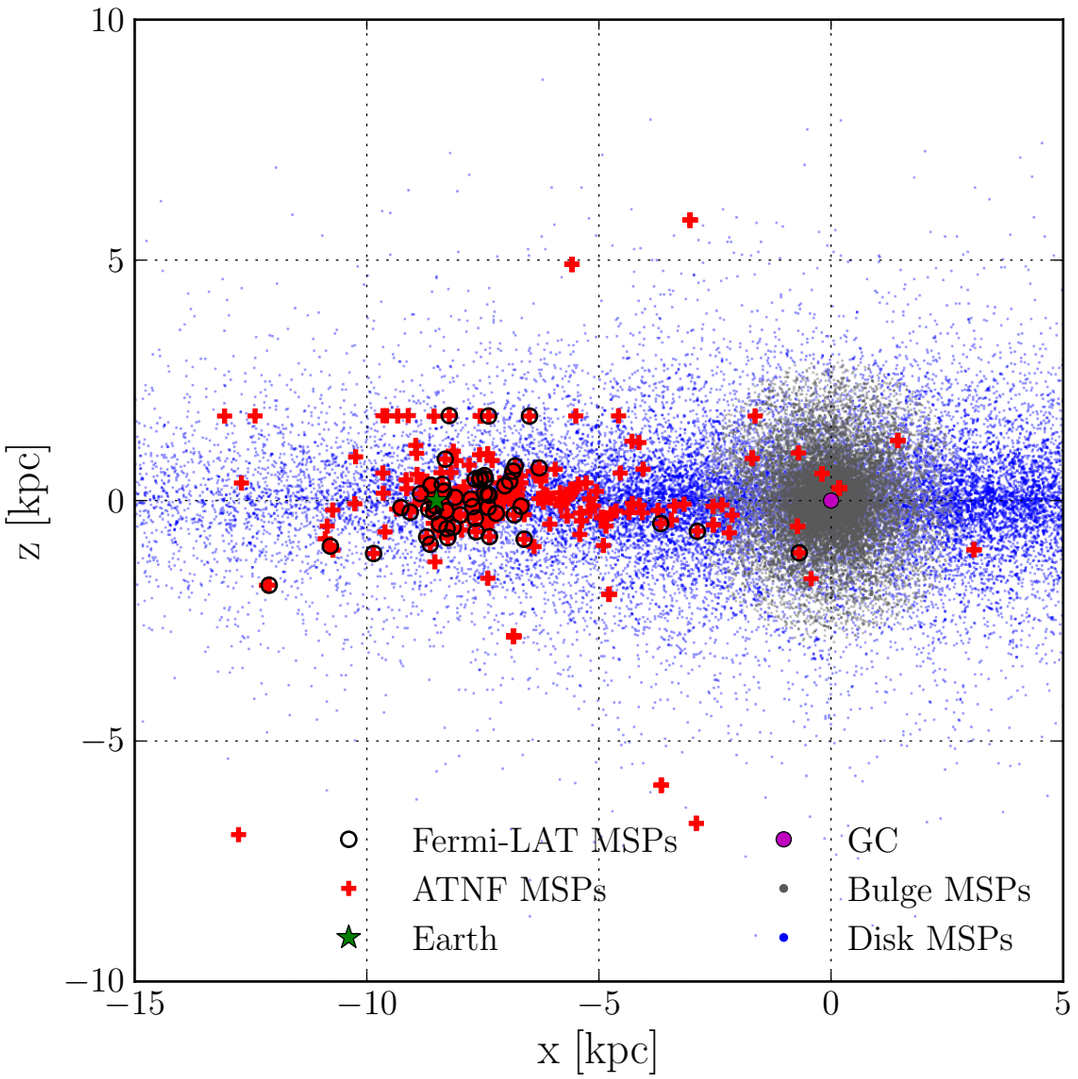
MSPs in the radio sky



- 328 MSPs in radio, P < 30 ms.
- Most sources are local, within 3-4 kpc from Earth.
- Among the sources in the GC l.o.s ($|b| < 10^{o}$ & $|l| < 10^{o}$), only a few in the inner 2 kpc.
- Only 7 MSPs — all associated with globular clusters, but one (isolated object).
- Young pulsars more abundant.

Looking for MSPs at radio frequency





- O(10000) MSPs in the **bulge**, such to account for gamma-ray observations.

$$\epsilon \propto r^{-\Gamma} e^{-r/R_{\rm cut}} \qquad \Gamma = 2.5 \qquad R_{\rm cut} = 3\,{\rm kpc}$$

- O(20000) MSPs in the **disc**, radio luminosity of observed local radio sources.

Looking for MSPs at radio frequency

Deep targeted searches

- ✓ Deep (a few hours) **follow-up observations** of gamma-ray "hot spots", like wavelet peaks.
- ✓ Caveats on instrumental systematics and source beaming modelling.
- ✓ Most promising strategy for the Green Bank Telescope (GBT).

Radio surveys

- ✓ Deep (100 hrs) **surveys** of deg^2 regions in the inner Galaxy.
- ✓ Most promising strategy for future radio telescopes, like MeerKAT and SKA.

Promising sensitivity predictions
at radio frequencies
→ Future dedicated observations can allow us to discover the bulge MSP population.

F. Donato (Wed)

Calore, Di Mauro, Donato, Hessels, Weniger '15, Very soon

What do we currently know about the excess?

- ✓ The existence of GeV excess above the standard astrophysical background is **well-established**.
- ✓ An **extended source in the inner part of Galaxy**, consistent with a spherically symmetric density profile, does exist.
- ✓ The excess extends up to at least **10º in latitude** and it is compatible with a **unique spherically symmetric component**.
- ✓ However, owing to the **background model systematics**, there is large freedom for models fitting the excess.
- ✓ Spectrum consistent with different models because of background model systematics.

Challenges and open questions

- What is the role of **CR sources distribution at the GC** and **non-standard CR propagation**?
- Can we **find a population of dim sources** that would be associated with the bulge in other wavelengths?
- Can we improve simulations of galaxy formation with baryons and robustly bracket the **uncertainty on the dark matter density profile** at sub-kiloparsec scales?
- Is the **spectrum** of the GeV excess **truly uniform** up to 10 degrees above and below the Galactic disc?
- Consistency with limits from dwarf spheroidal galaxies?

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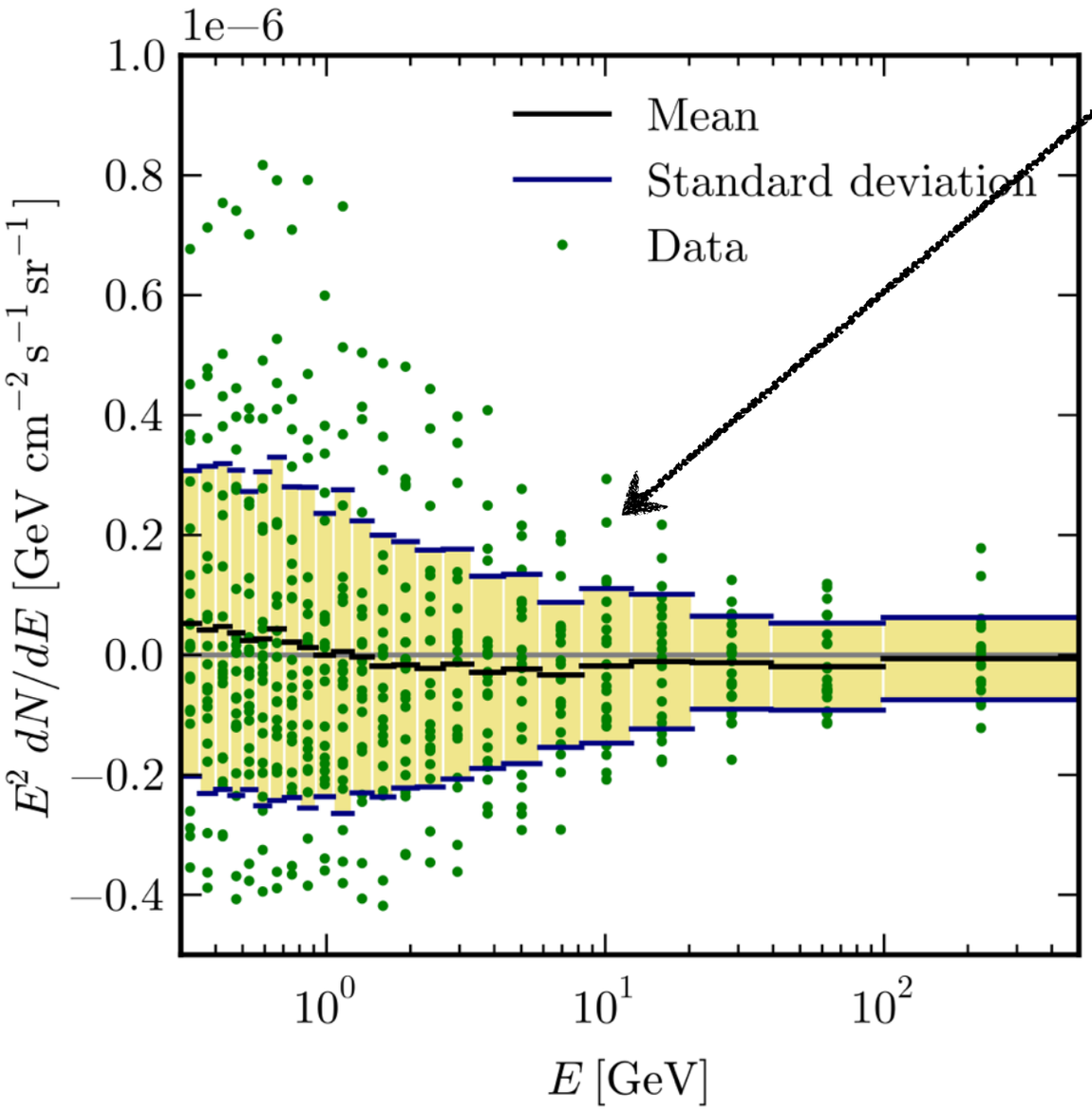
STAY TUNED!!

Backup slides

Background model systematics: covariance matrix



Flux absorbed by excess template in 22 test regions along the Galactic disk.

Standard deviation is a first estimate for how inaccuracies in the foreground modelling affect the excess template.

Observed variations along the disk are correlated in energy.

$\longrightarrow$ Define the **covariance matrix:**

$$\Sigma_{ij,\,\mathrm{mod}} = \left\langle \frac{dN}{dE_i}\frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$

i, j = 1, ..., 24; averaged over 22 test regions

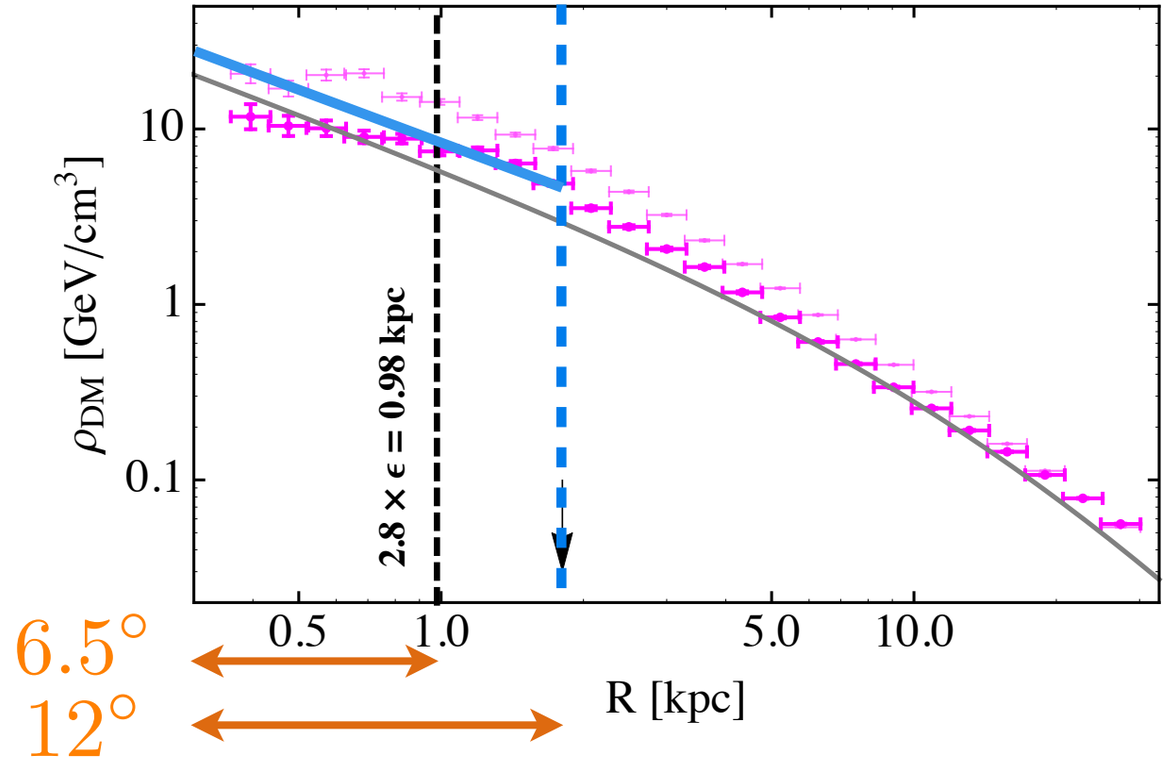
Dark matter density in EAGLE

Approach: Power-law extrapolation with maximal asymptotic slope at Power radius => Very conservative choice!

$$\text{EAGLE HR (2 haloes): } 0.94 < \gamma_{\rm max} < 0.98 \text{ at } R_{\rm P03} = 1.8 \text{ kpc}$$

$$\text{APOSTLE IR (2 haloes): } 0.50 < \gamma_{\rm max} < 0.62 \text{ at } R_{\rm P03} = 1.8 \text{ kpc.}$$

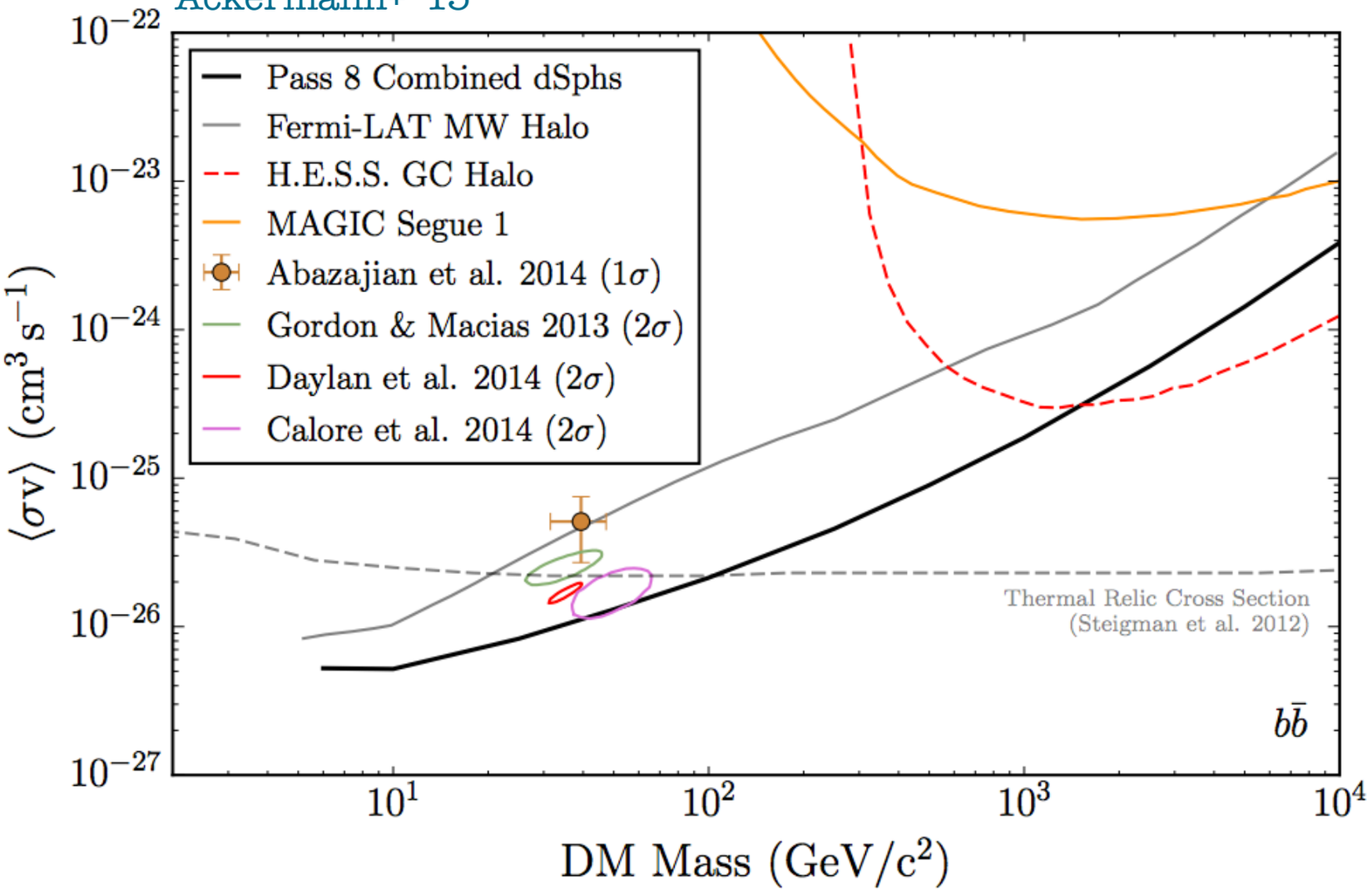
EAGLE Intermediate Resolution



arXiv: 1509.02164

Consistency with dSphs: present and future

Ackermann+ '15



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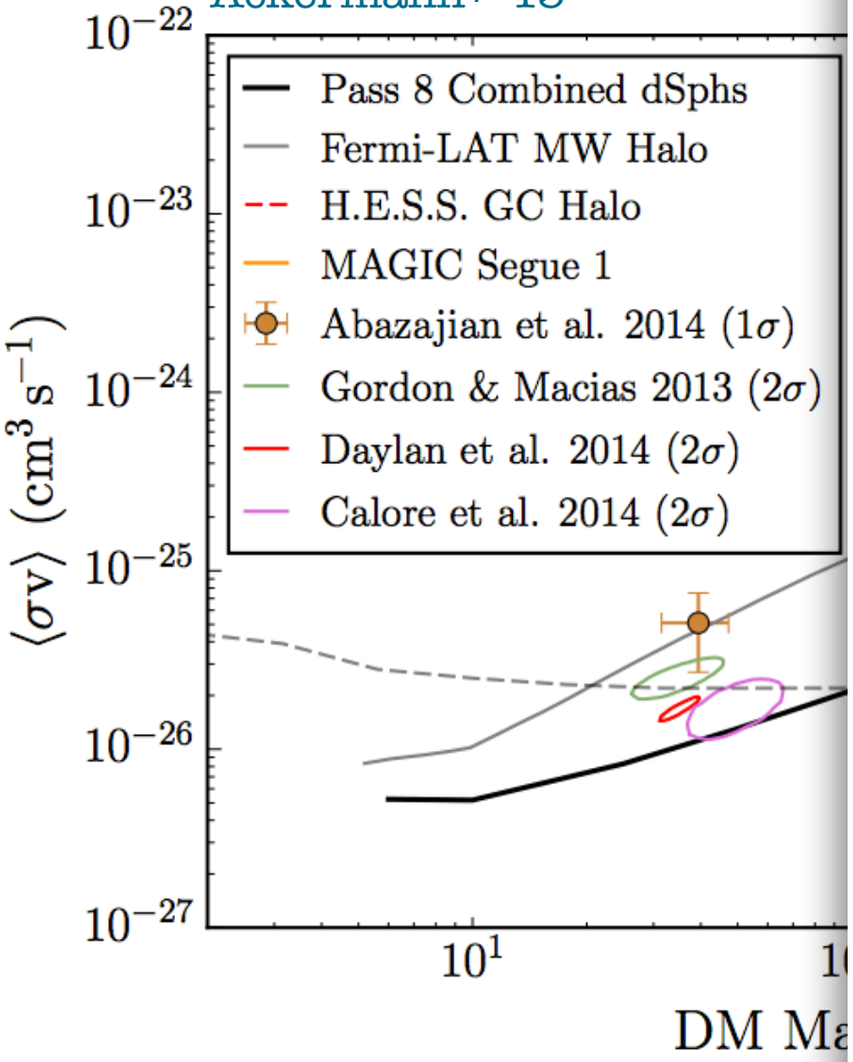

Calore+ PRD'15