GRAPPA
GRavitation AstroParticle Physics Amsterdam

UNIVERSITY OF AMSTERDAM

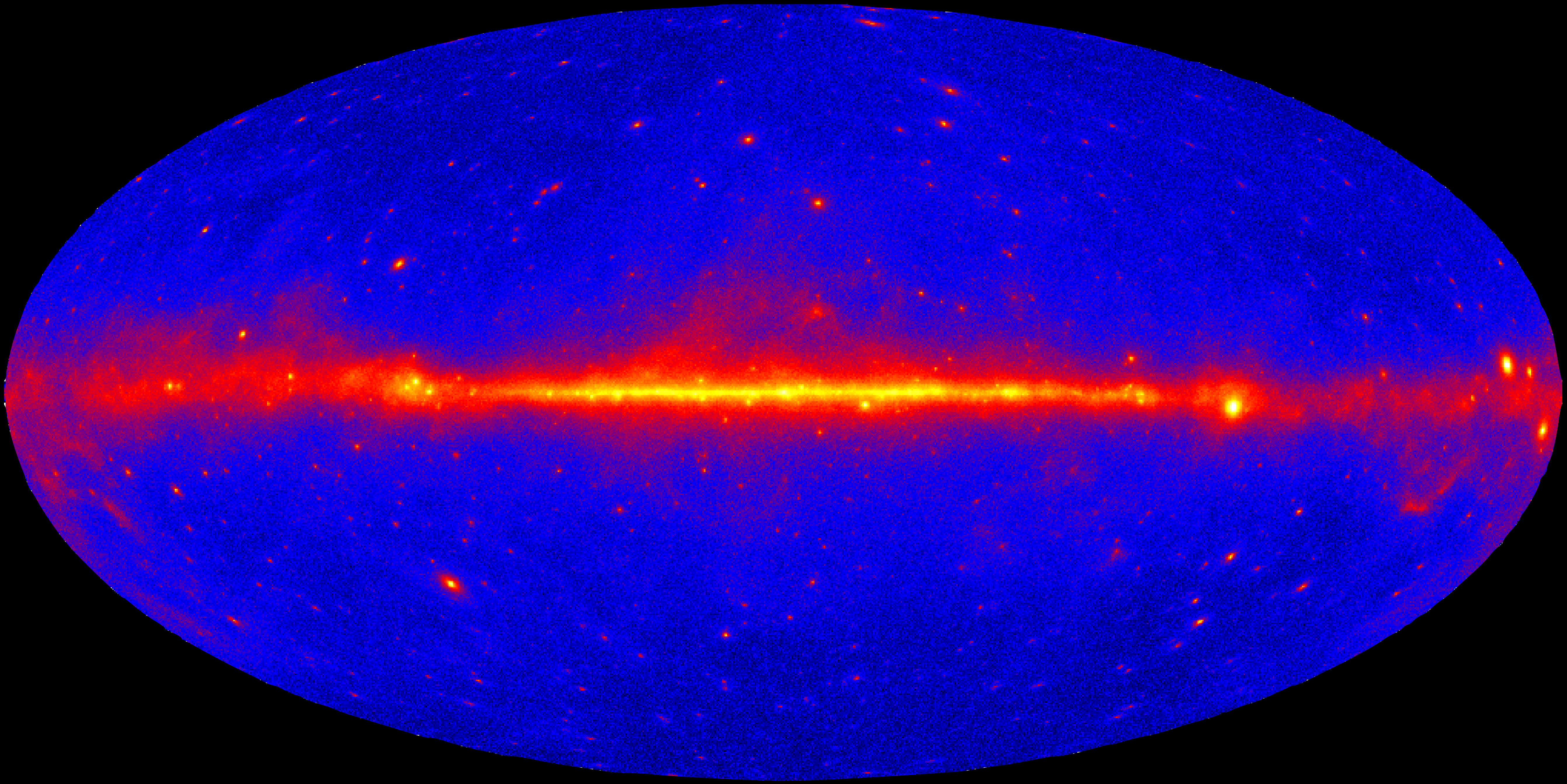
Francesca Calore

The case for a GeV excess in Fermi-LAT data from the Galactic centre

HAP Workshop Dark Matter
Karlsruhe, 23.09.2015

Mainly based on:
arXiv:1409.0042, 1411.4647, 1506.0511, 1509.02164

The GeV gamma-ray sky



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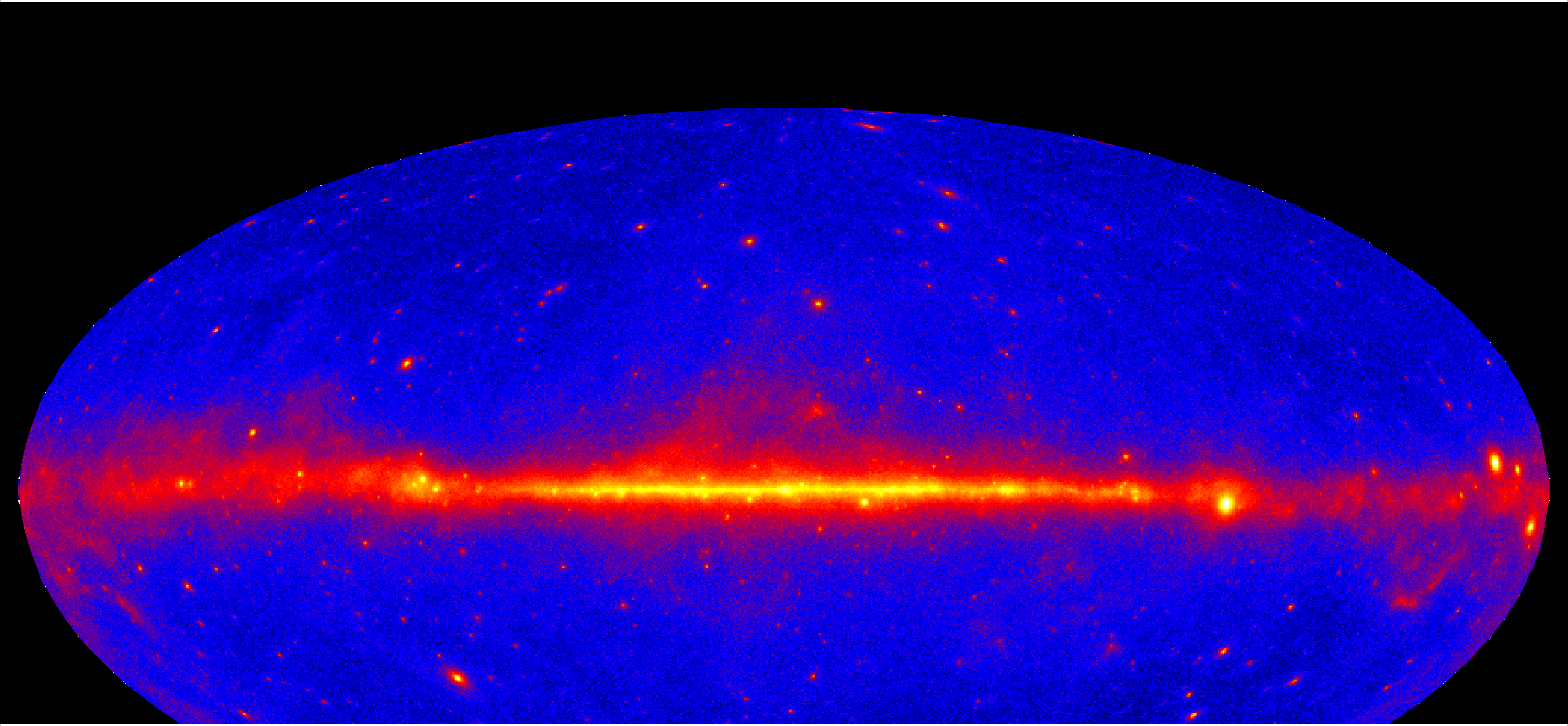
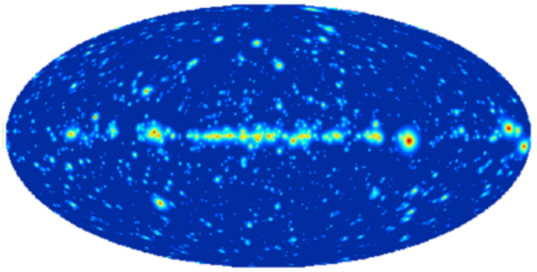
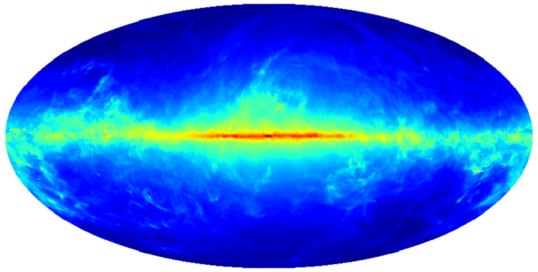


Detected sources



+

Galactic emission



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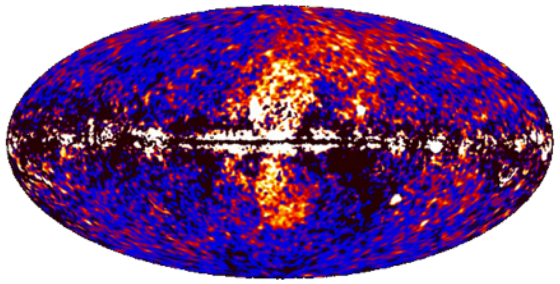
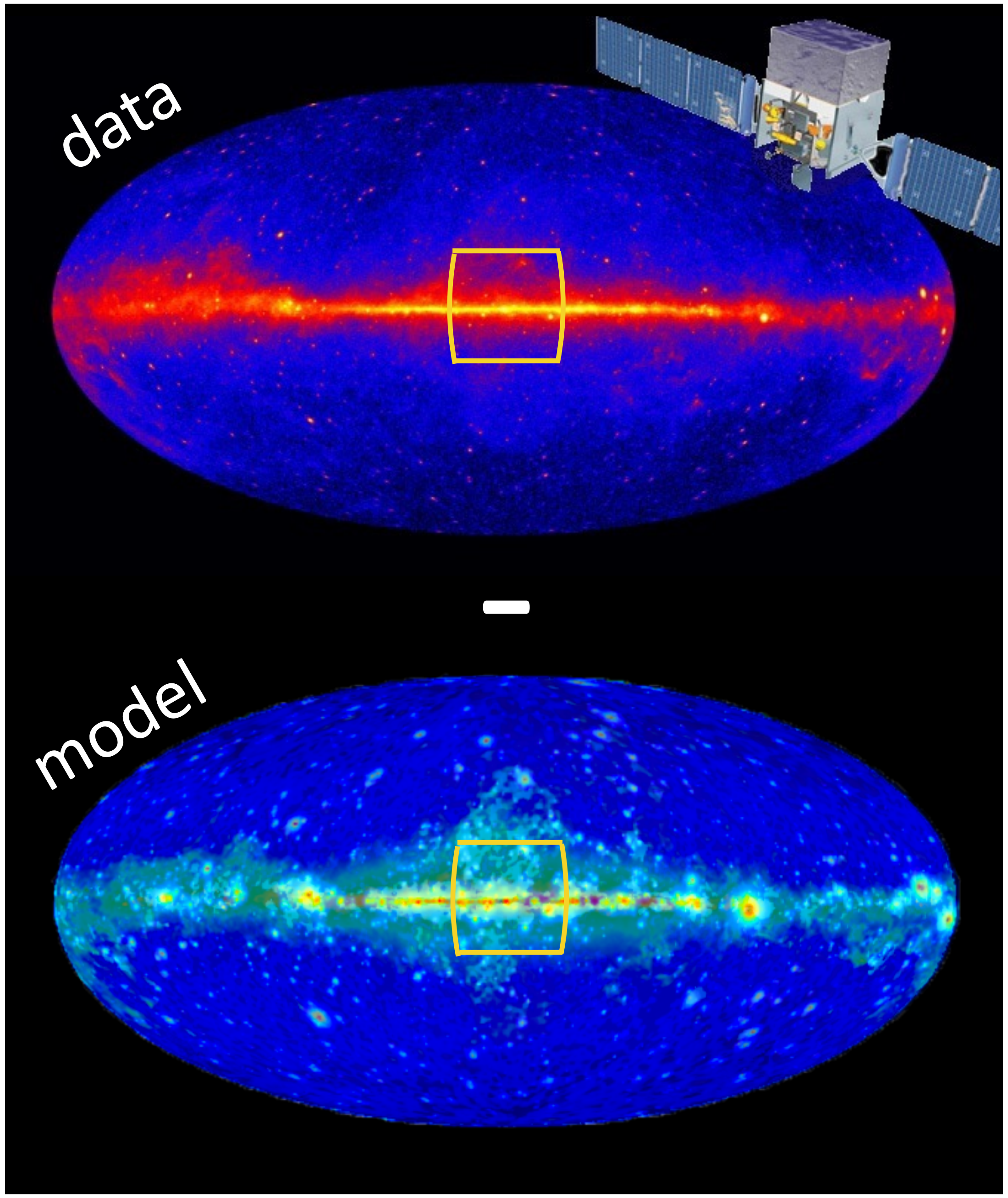
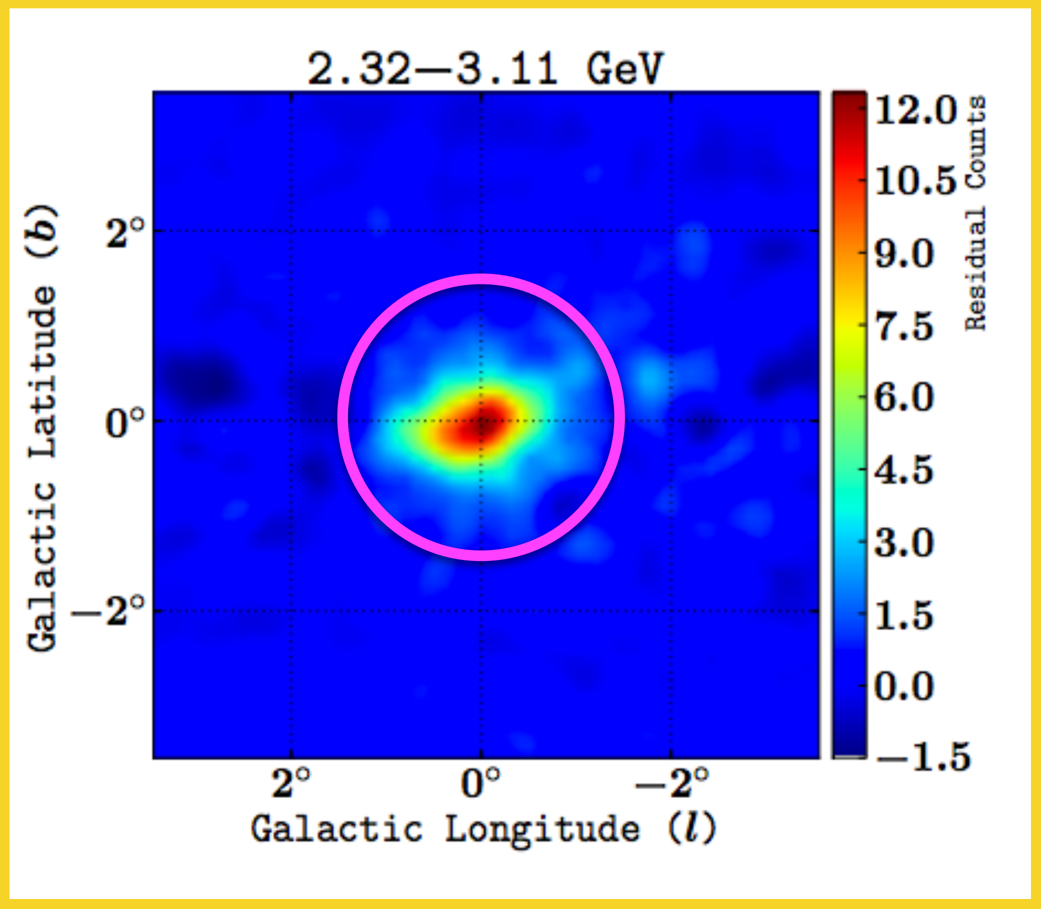
Fermi bubbles



An excess in gamma rays



The **Galactic centre GeV excess**

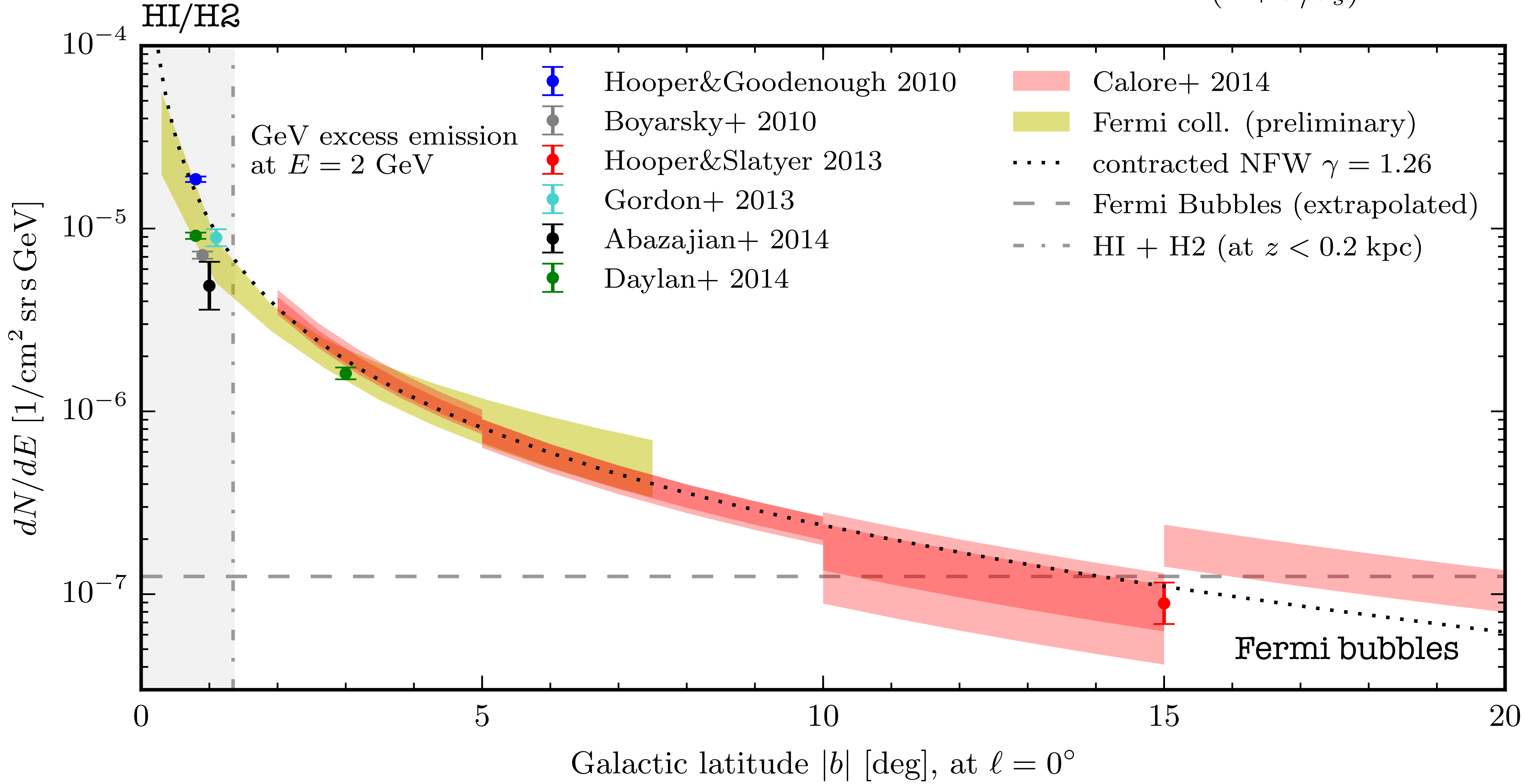


Macias & Gordon (2013)

Excess emission **above the astrophysical foregrounds and backgrounds**, i.e. Galactic diffuse emission (standard cosmic-ray propagation), point sources and Fermi bubbles.

The Fermi GeV excess today: a summary

$$\rho(r) = \rho_s \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$



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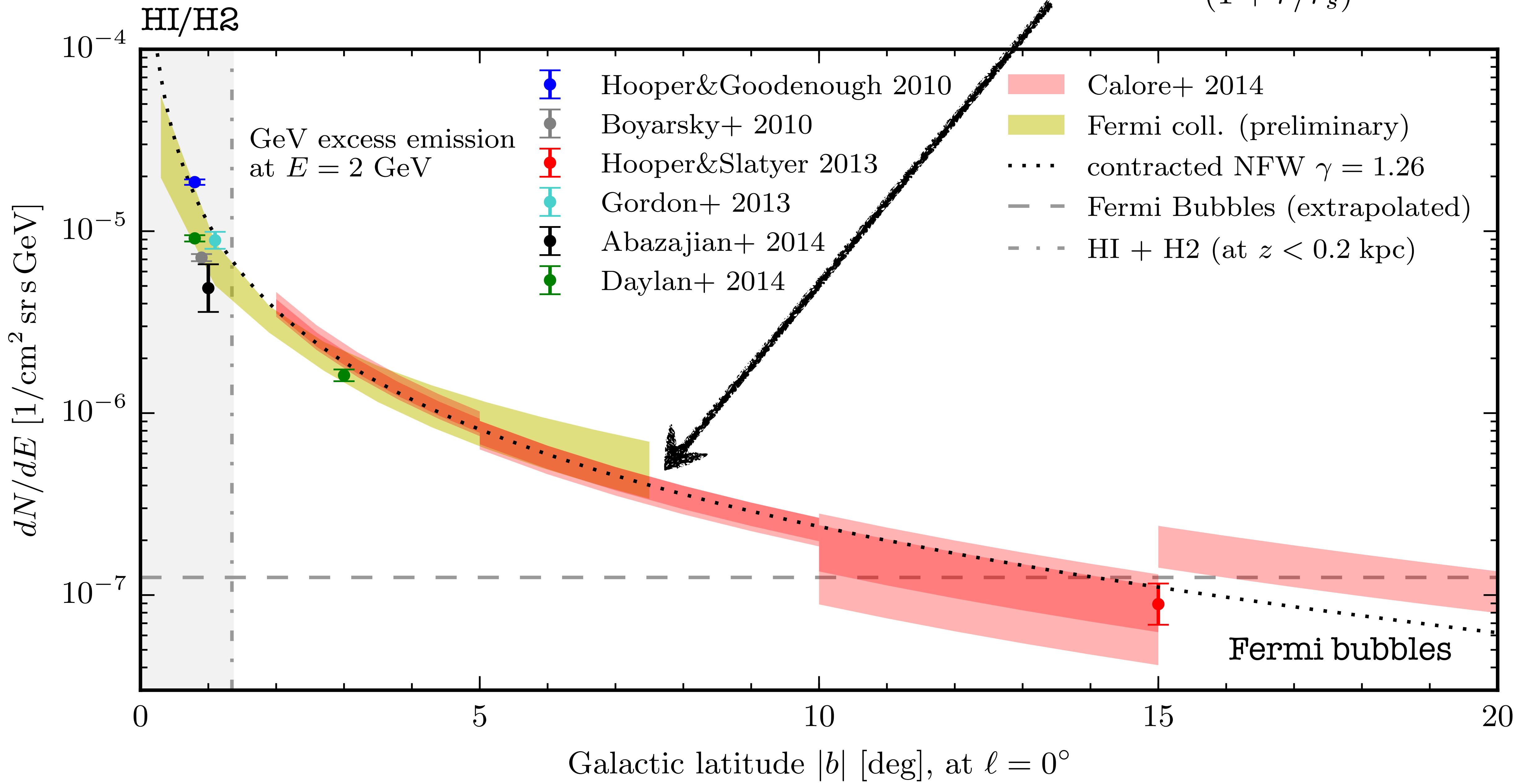

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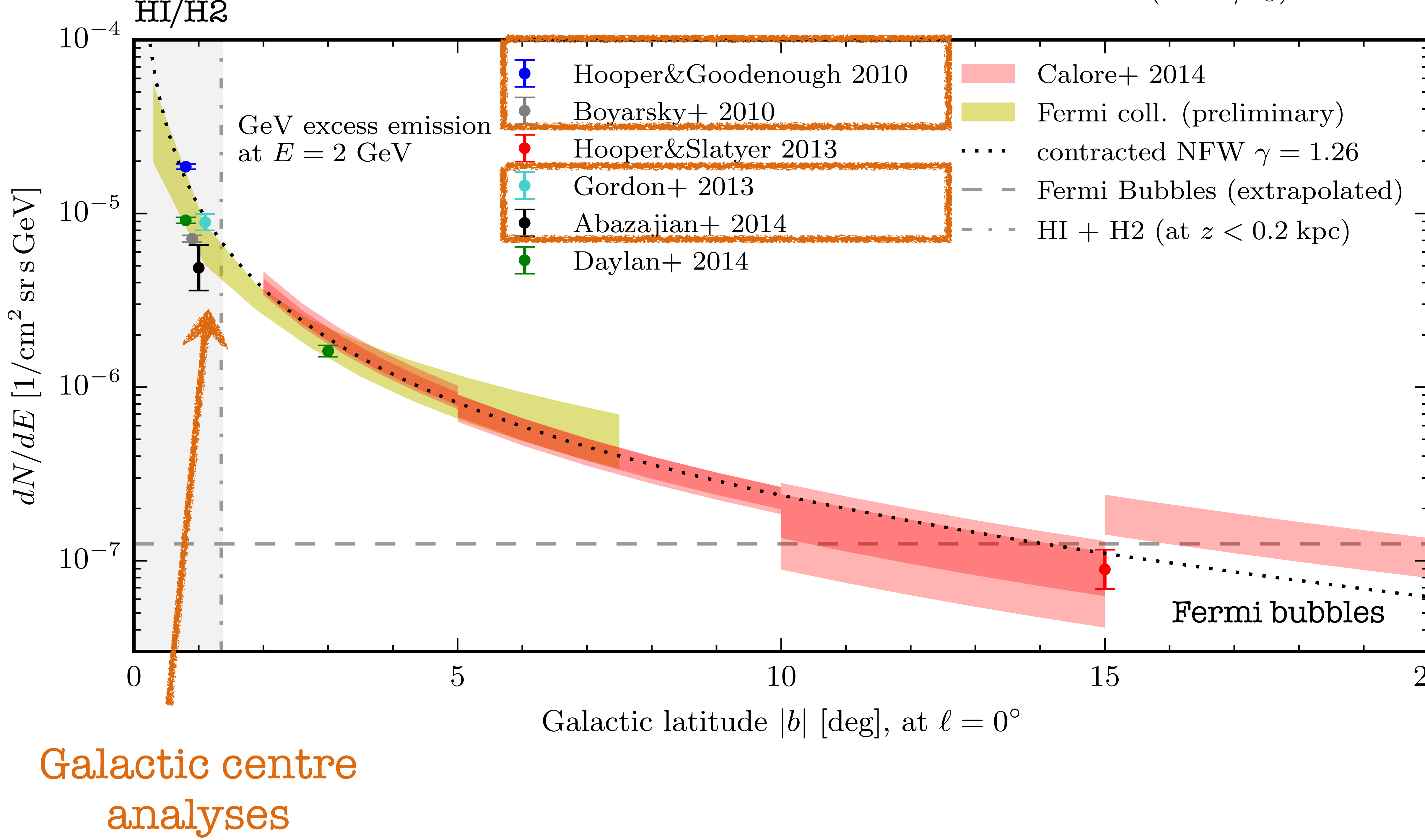

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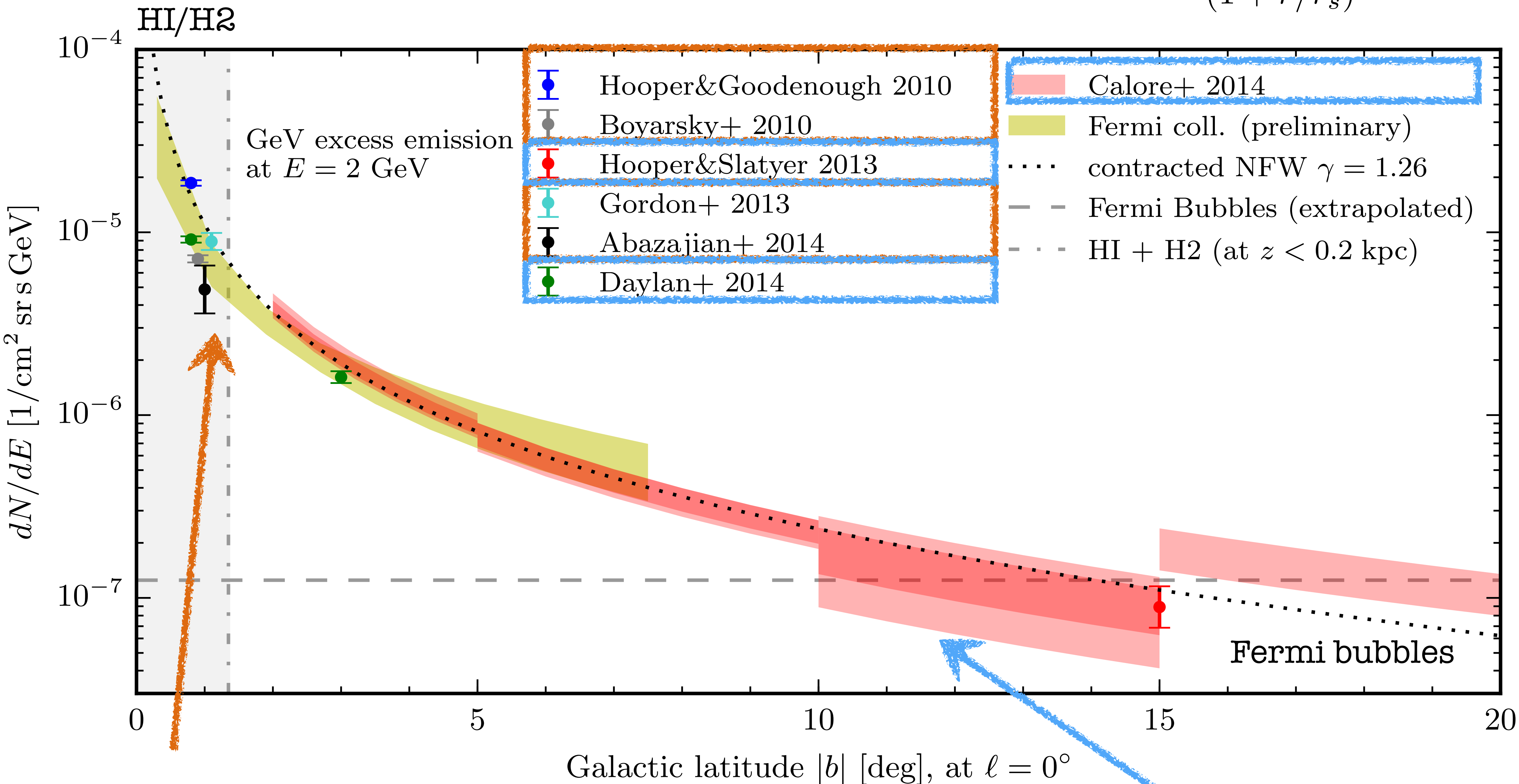

Galactic centre analyses

“Inner” Galaxy analyses

The Fermi GeV excess today: a summary

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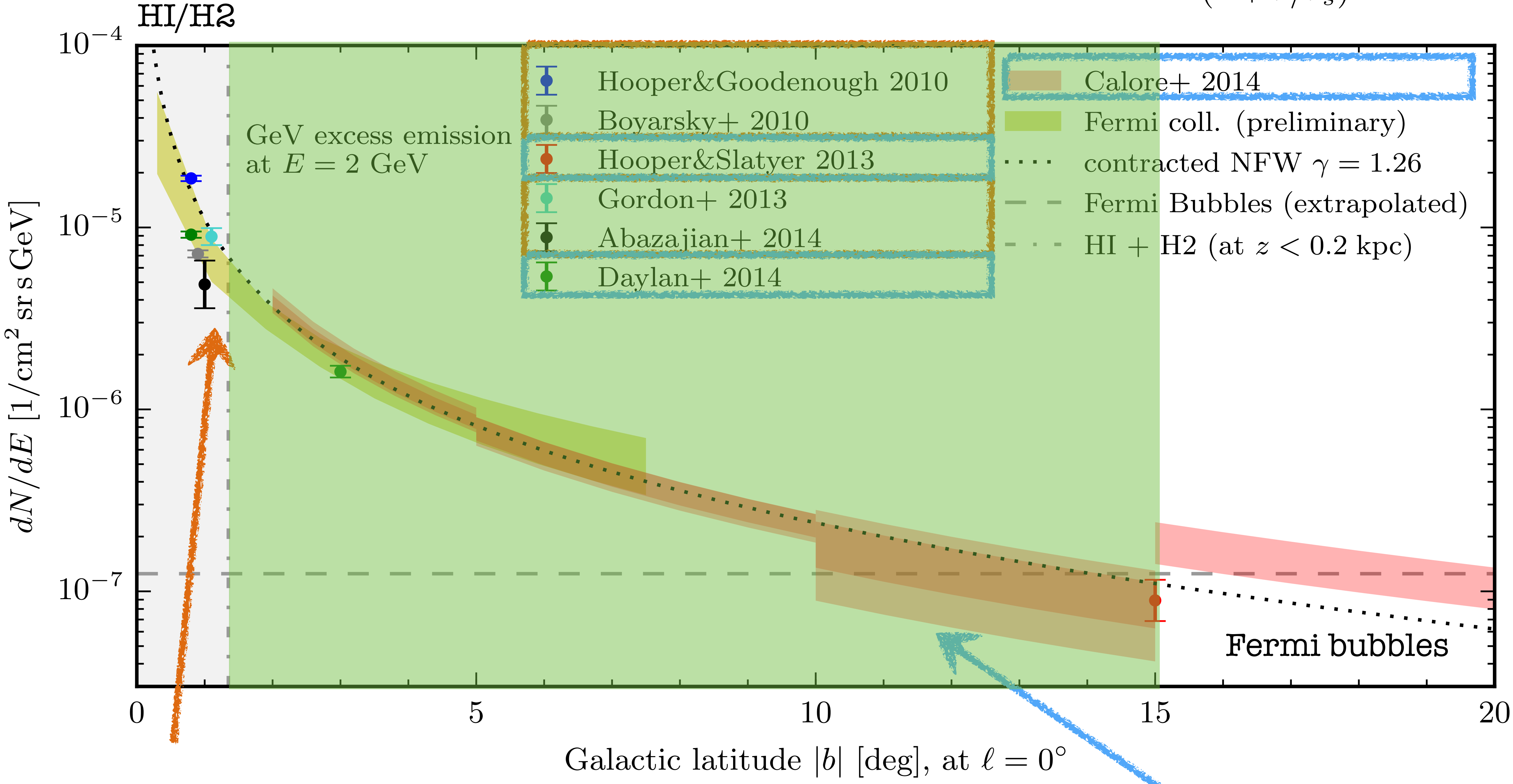
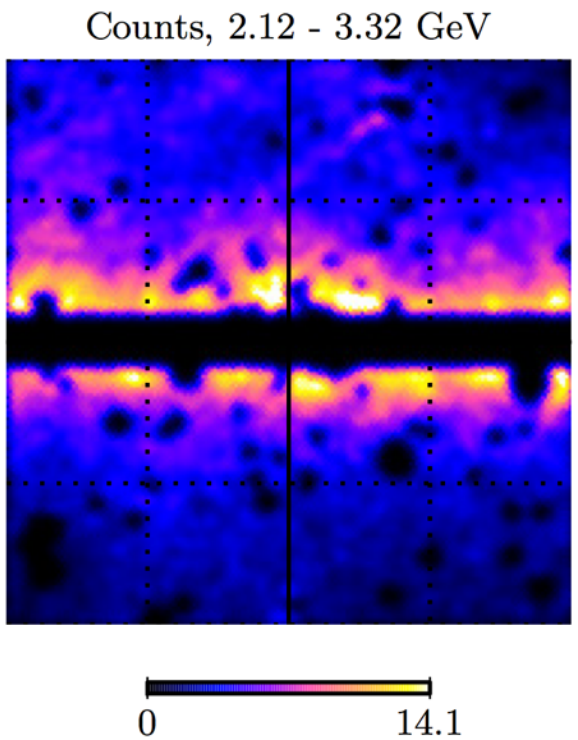


Galactic centre analyses

"Inner" Galaxy analyses

The (standard) analysis set-up



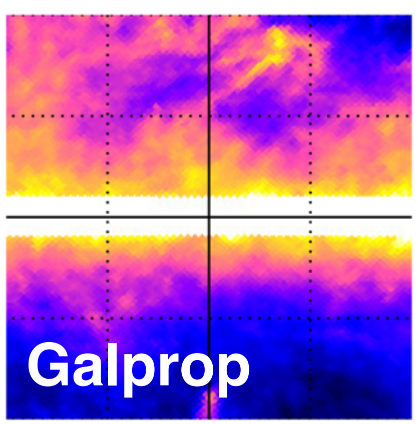
Data selection and standard preparation (P7REP)

284 weeks; 300 MeV—500 GeV

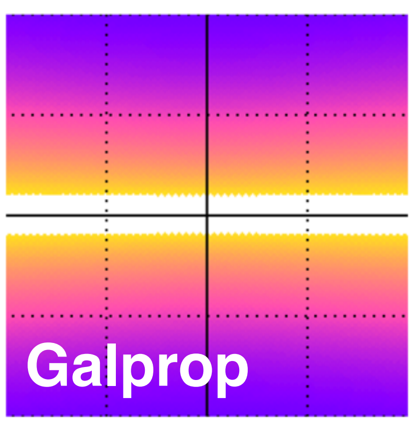
ROI: $2^\circ \leq |b| \leq 20^\circ \;\&\; |l| \leq 20^\circ$

Point sources (2FGL) weighted adaptive mask.

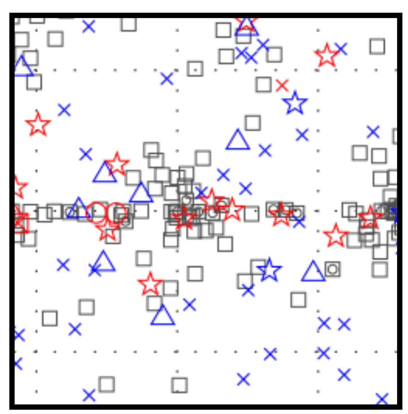
The (spatial) template-fitting method (maximum likelihood)



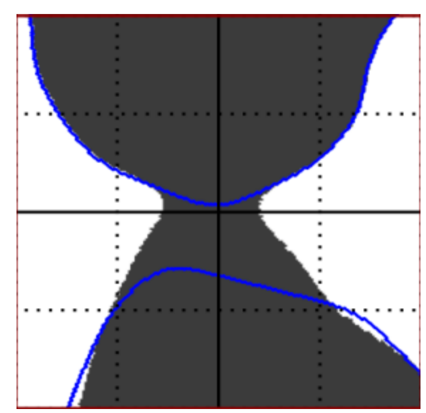
1. π^0+ Brems (free)



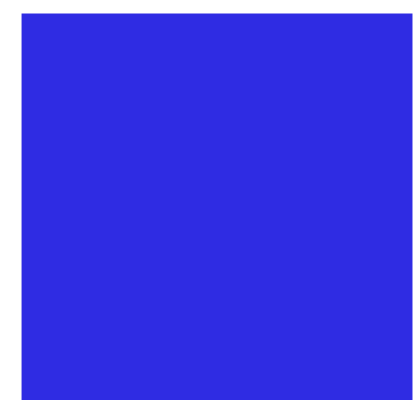
2. ICS (free)



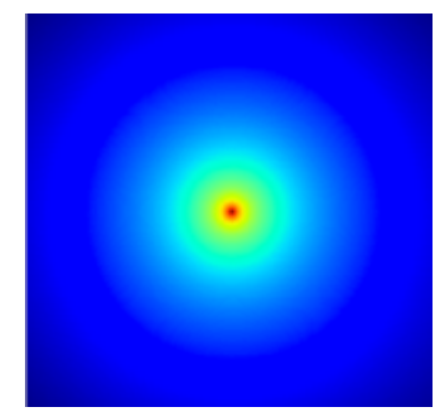
3. 2FGL (fixed)



4. Fermi bubbles (constrained)



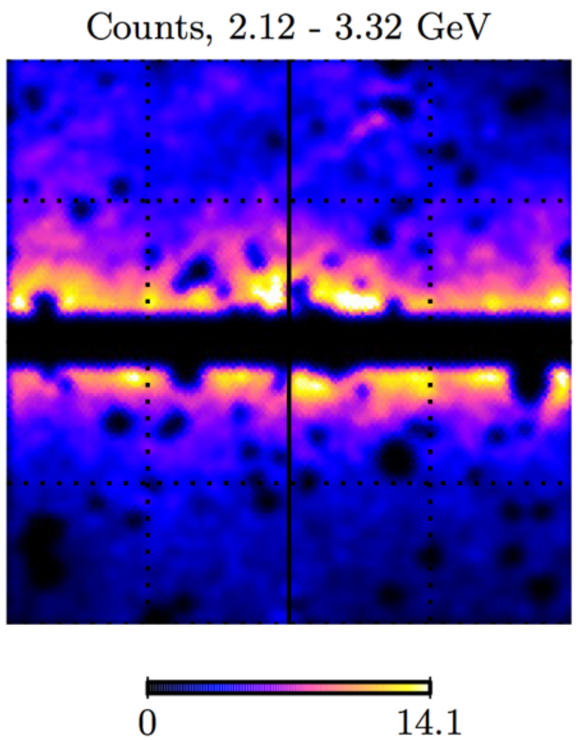
5. Isotropic diffuse bkg (constrained)



6. GeV excess template (free)

Calore+ 2014

The (standard) analysis set-up



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284 weeks; 300 MeV—500 GeV

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Point sources (2FGL) weighted adaptive mask.

The (spatial) template-fitting method (maximum likelihood)

Model counts

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

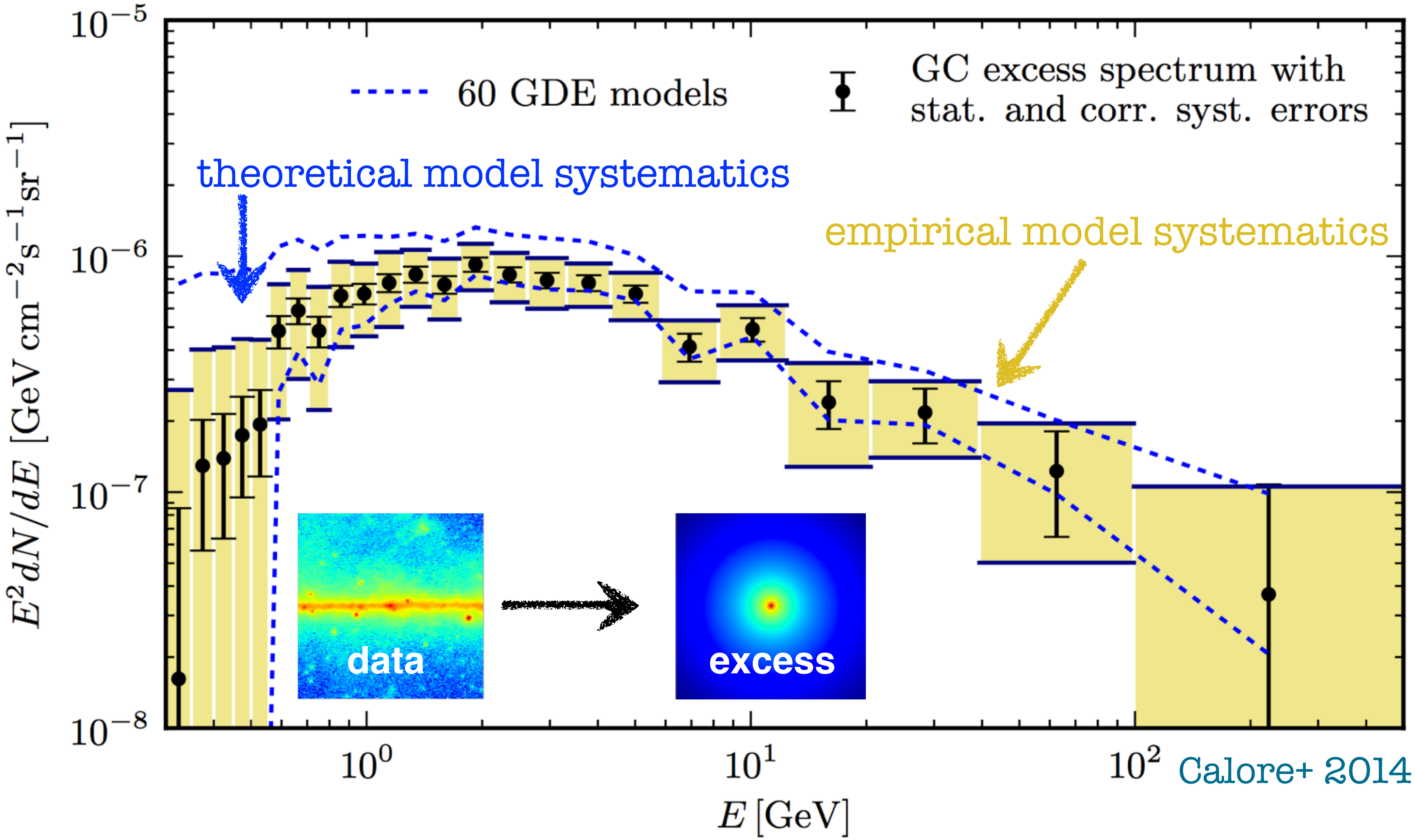
Data counts

$$k_{i,j}$$

$$-2 \ln \mathcal{L} = 2 \sum_{i,j} w_{i,j} (\mu_{i,j} - k_{i,j} \ln \mu_{i,j}) + \chi^2_{\rm ext} \rightarrow \theta_{i,k}$$

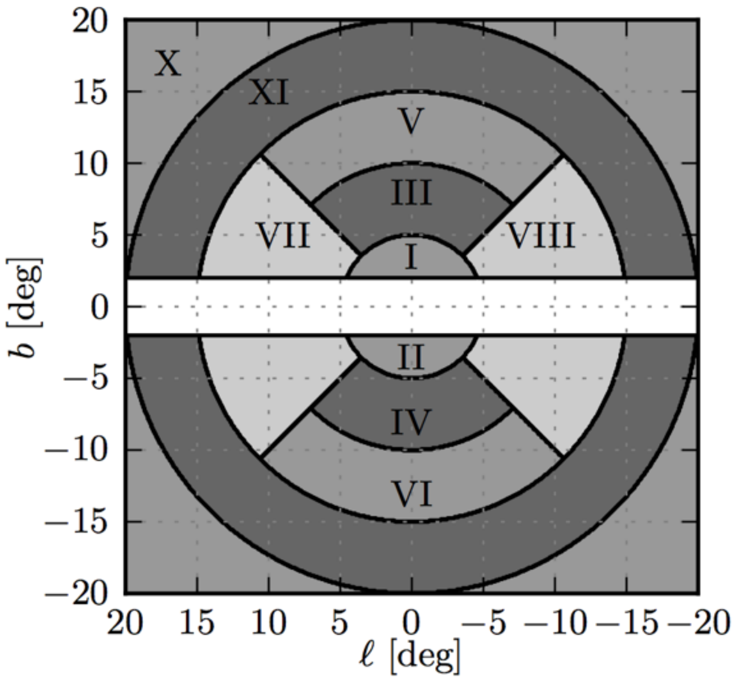
Calore+ 2014

The excess spectrum

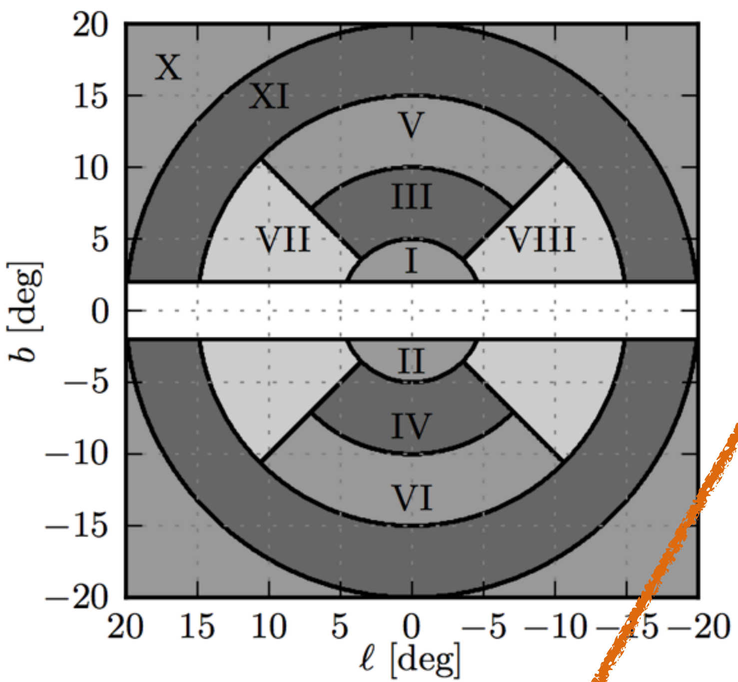


- ✓ **Theoretical systematics** from the variation of Galactic diffuse models (standard assumptions).
- ✓ **Empirical systematics** from a scan along the Galactic disc (only diagonal part of covariance matrix shown).

The excess morphology

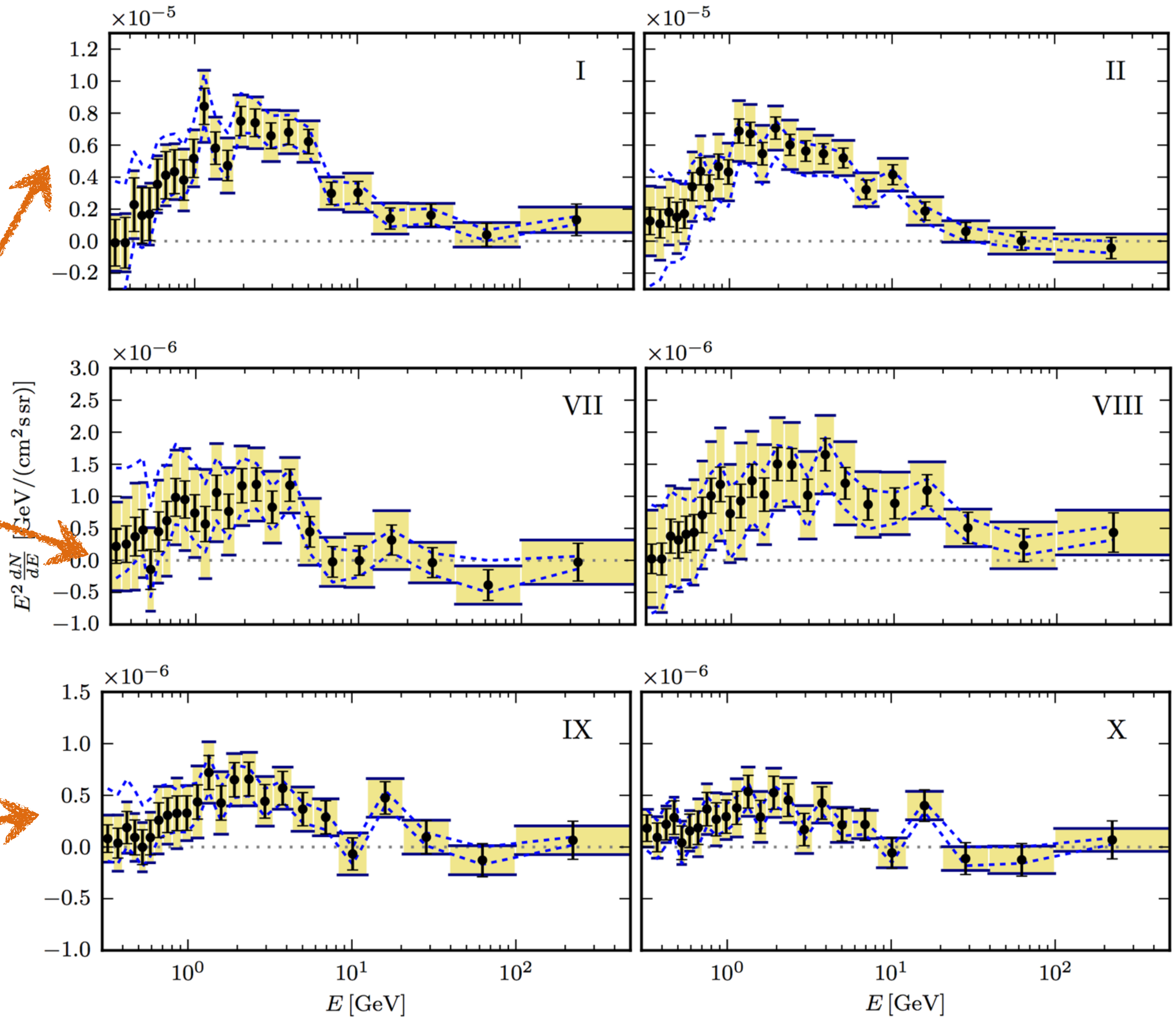


The excess morphology

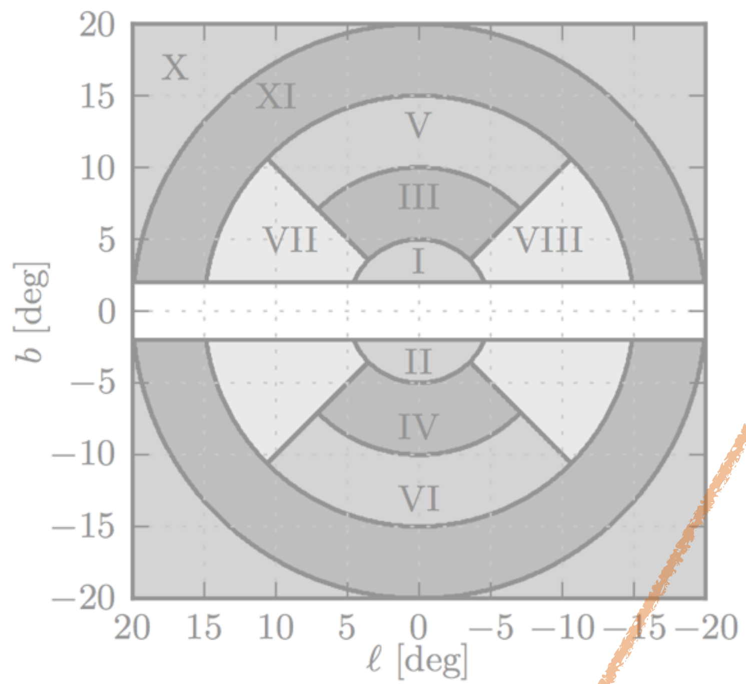


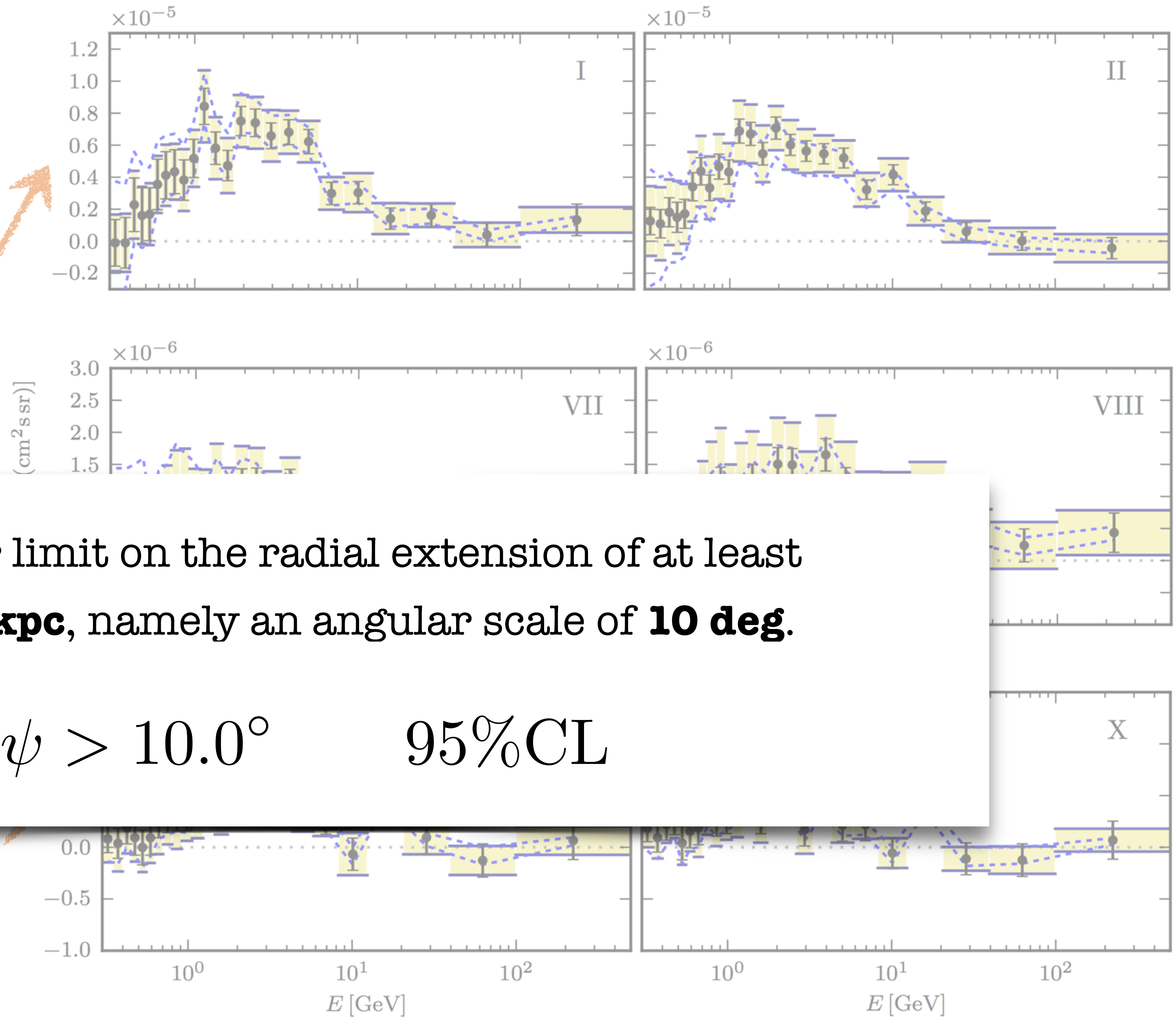
Symmetry properties

Latitude extension



The excess morphology





Sy
pro

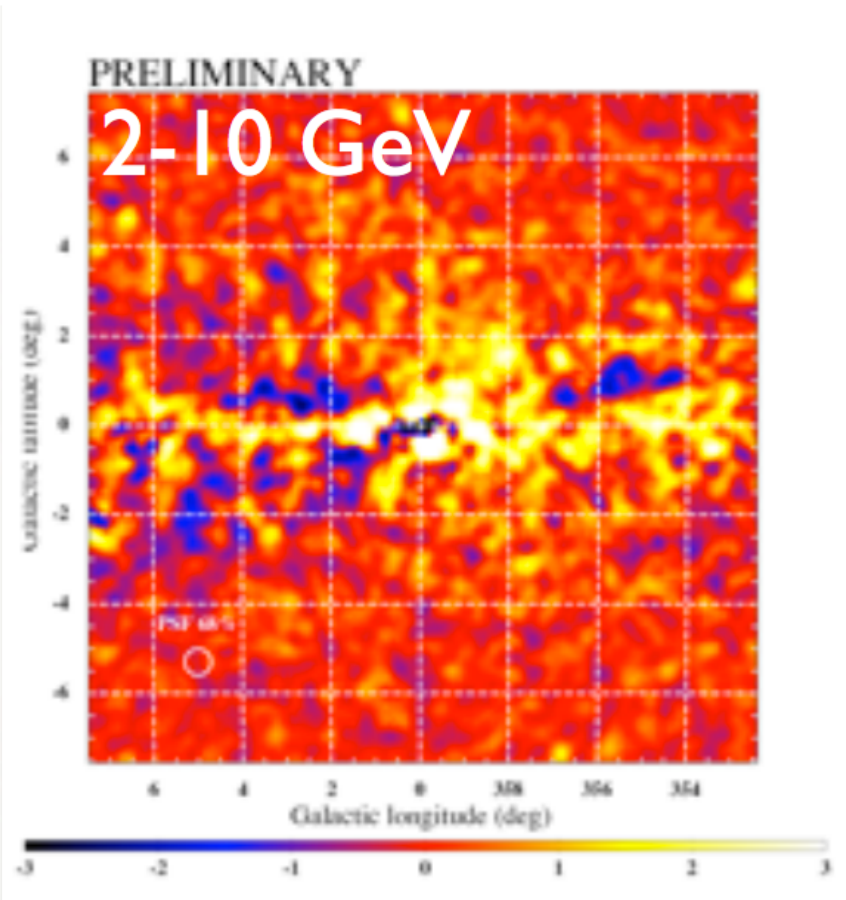
La
extension

Lower limit on the radial extension of at least **1.48 kpc**, namely an angular scale of **10 deg**.

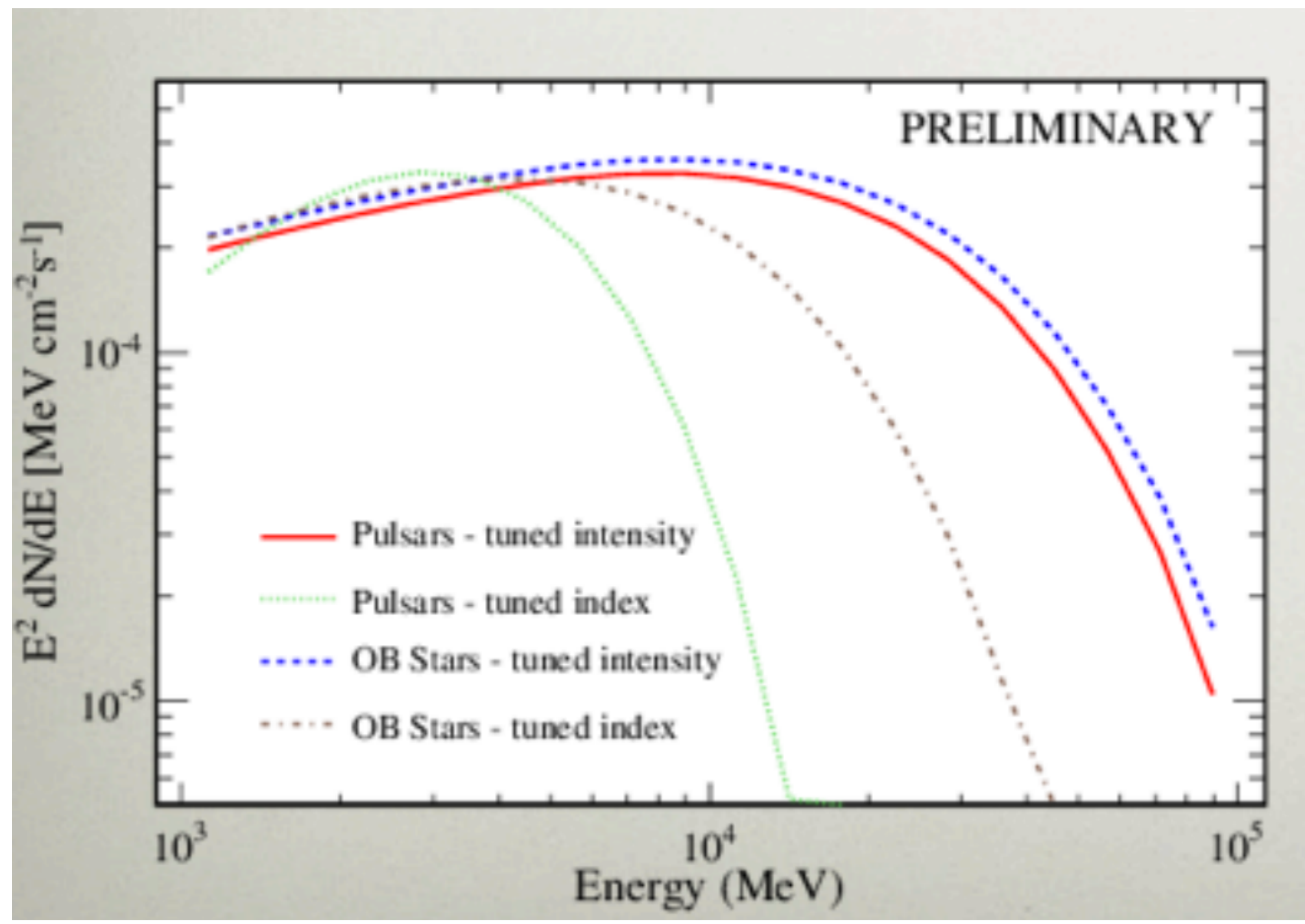
$$\psi > 10.0^\circ \qquad 95\%\mathrm{CL}$$

The Fermi-LAT analysis

- 15x15 region but tuning of Galactic diffuse emission outside
- Wavelet transform applied to subtract dim point sources
- Residuals (data-model) can improve (to some extent and at some energies) when introducing a spherical template



S. Murgia, Fermi Symposium 2014

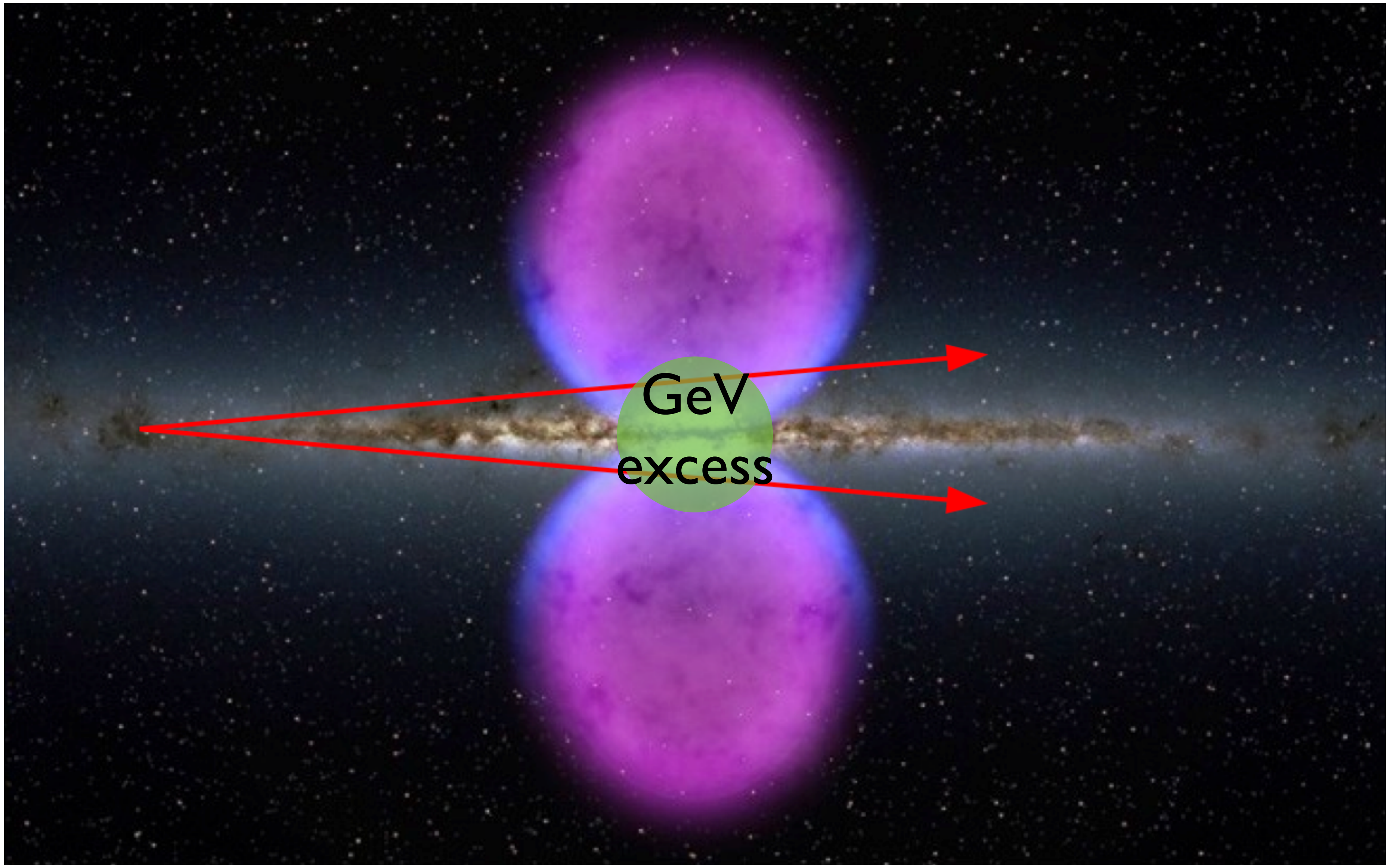


+ Gaggero et al. 2015, de Boer et al 2015

What do we 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 **10 deg 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.

Possible interpretations



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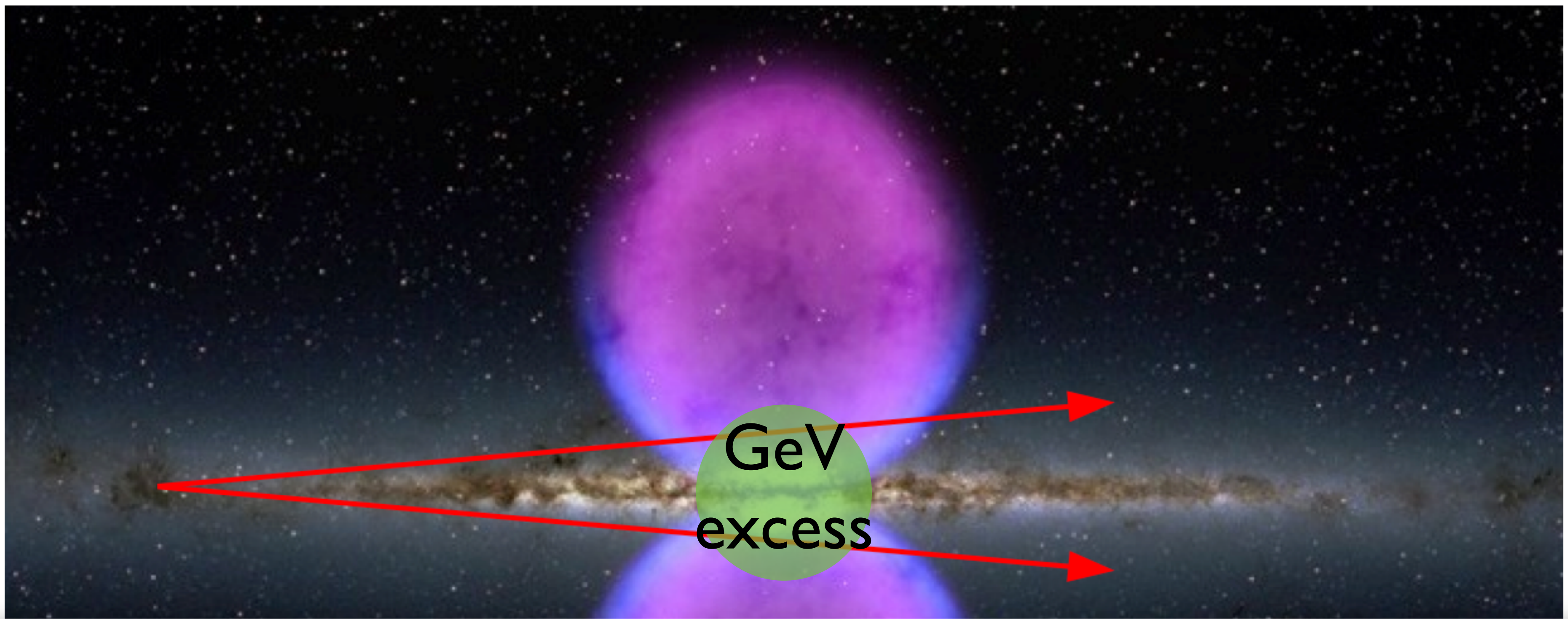

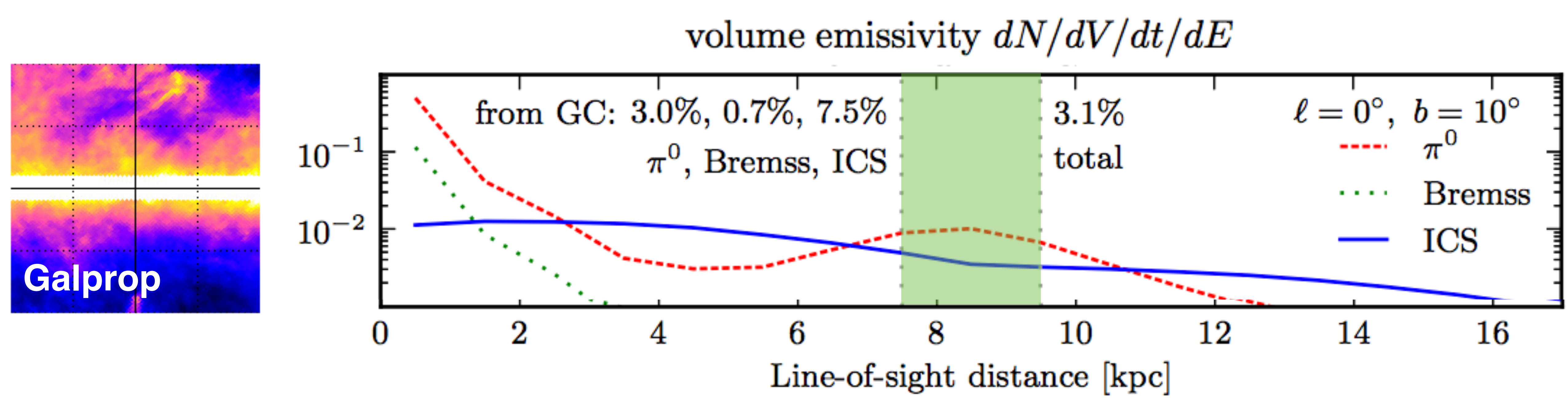

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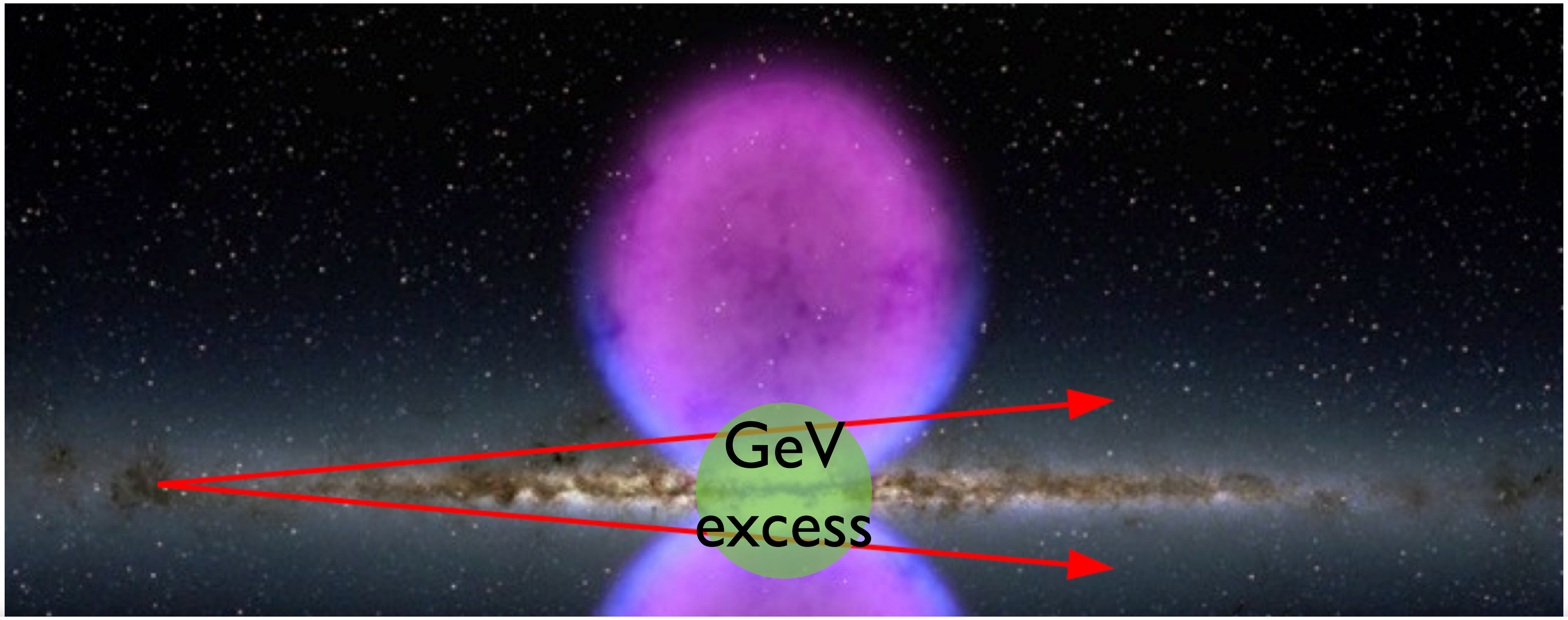
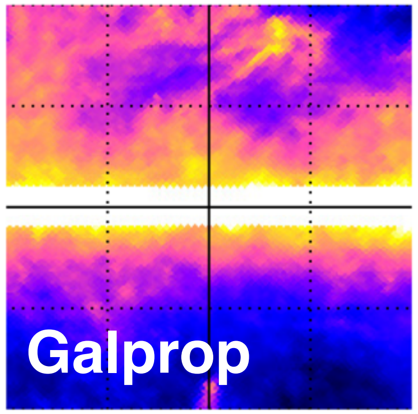
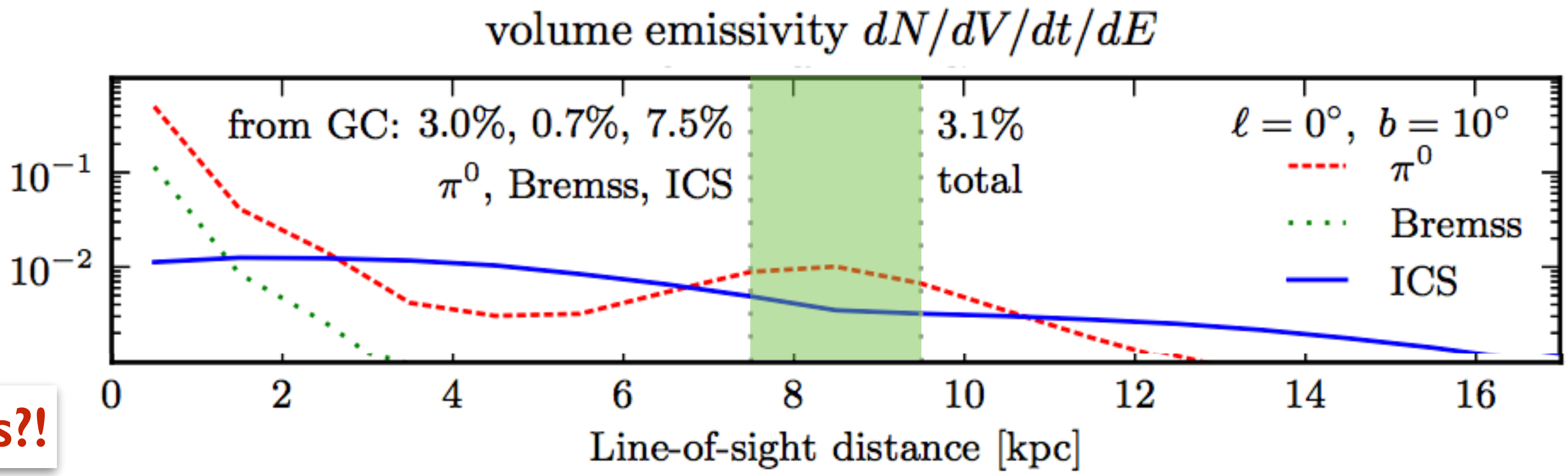


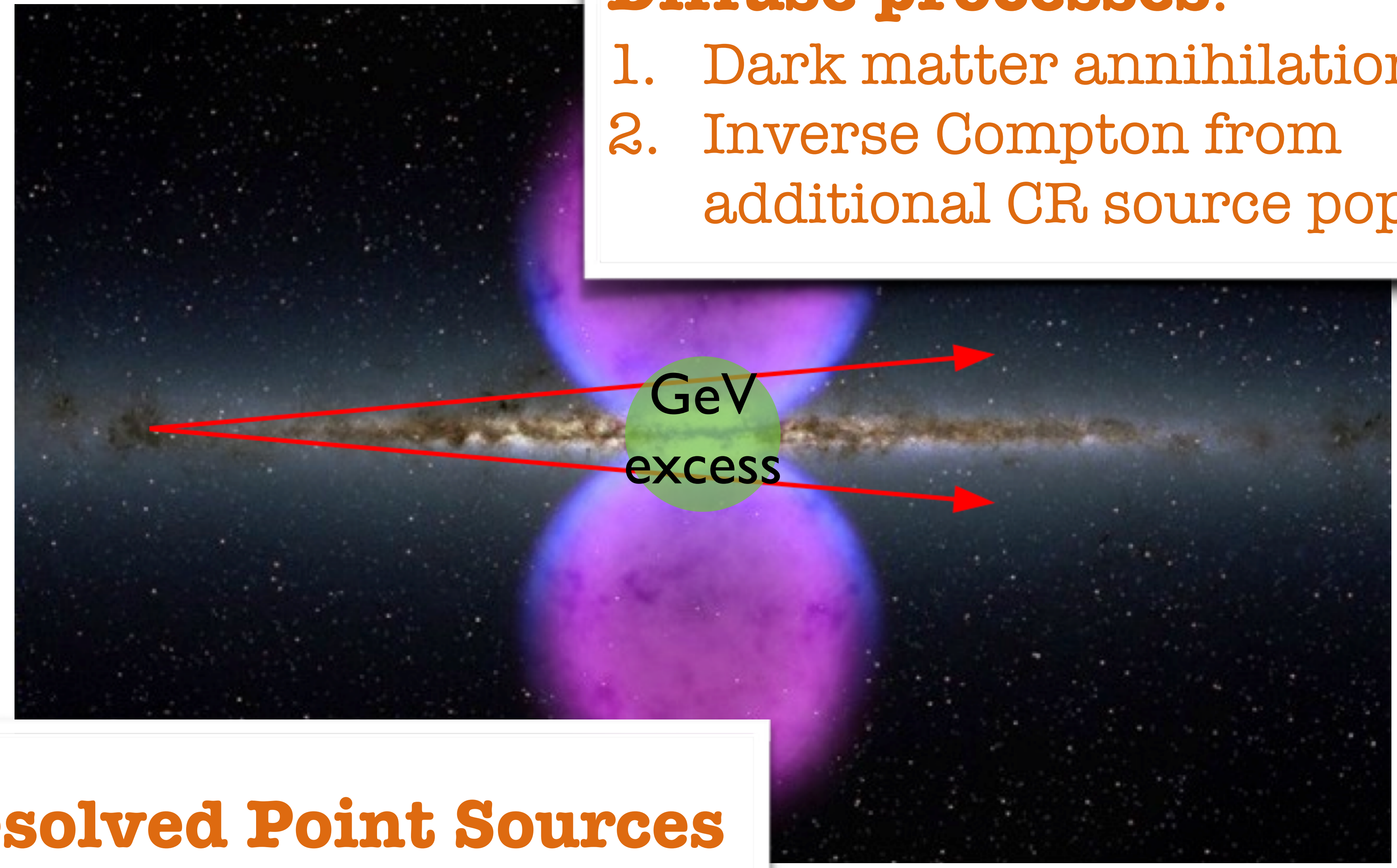


Standard codes?!



Possible interpretations

Diffuse processes:
1. Dark matter annihilation
2. Inverse Compton from additional CR source population

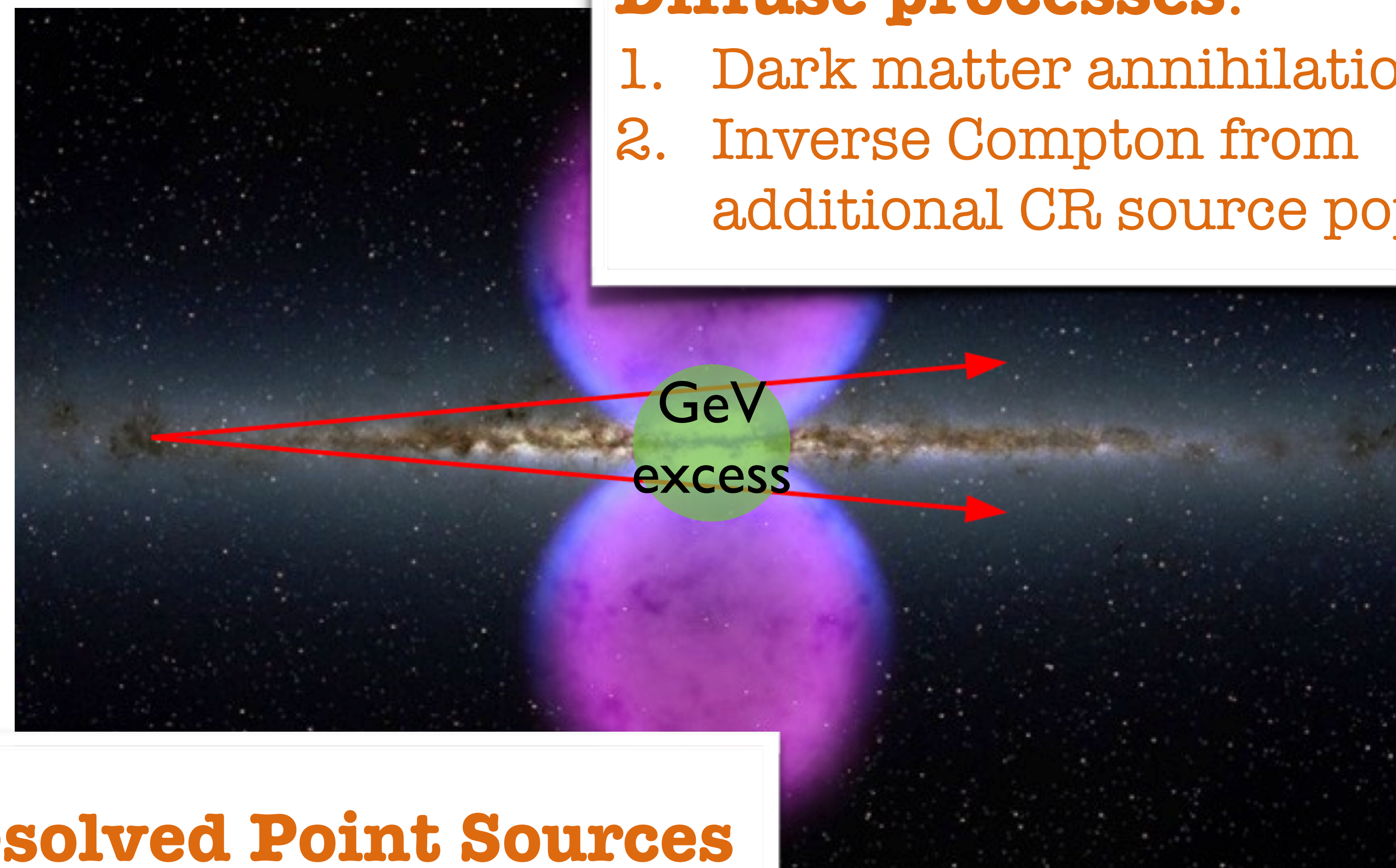


Unresolved Point Sources

Possible interpretations

Diffuse processes:

1. Dark matter annihilation
2. Inverse Compton from additional CR source population

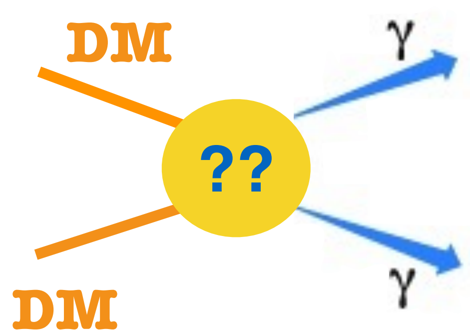


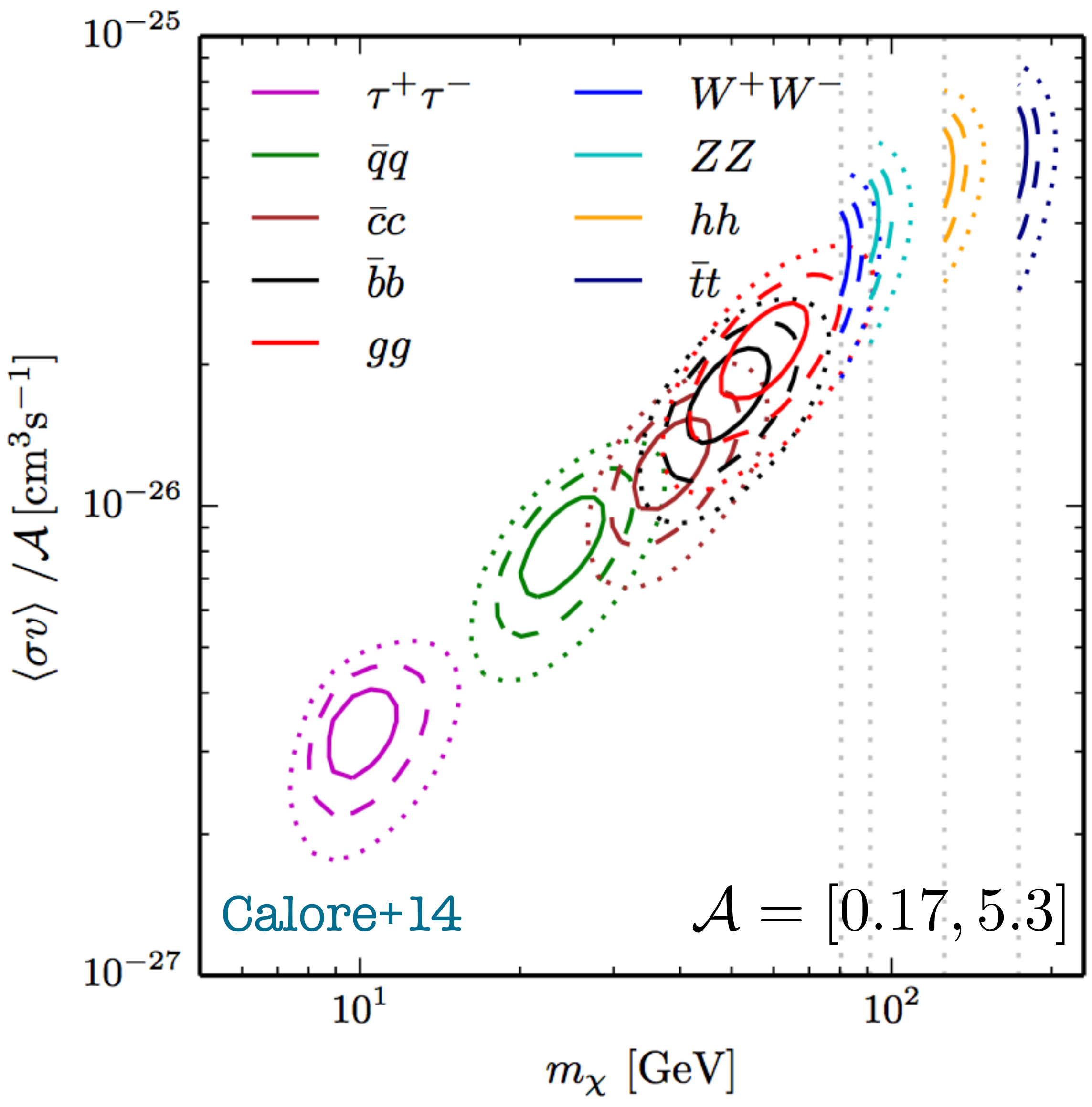
Unresolved Point Sources

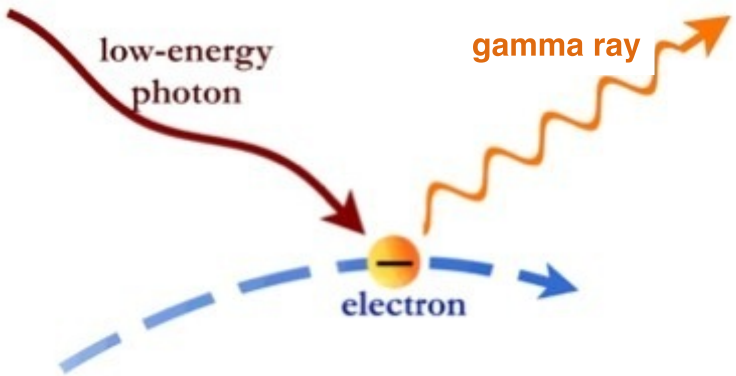
Constraints:

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

Diffuse processes







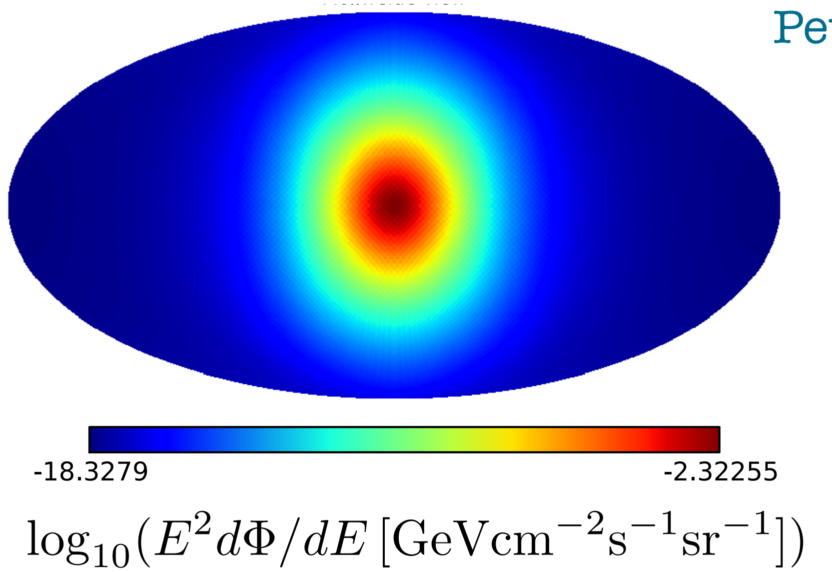
Additional population of **leptonic cosmic rays** required at the Galactic centre

a. Steady-state source term (from e.g. SN population)

Gaggero+15

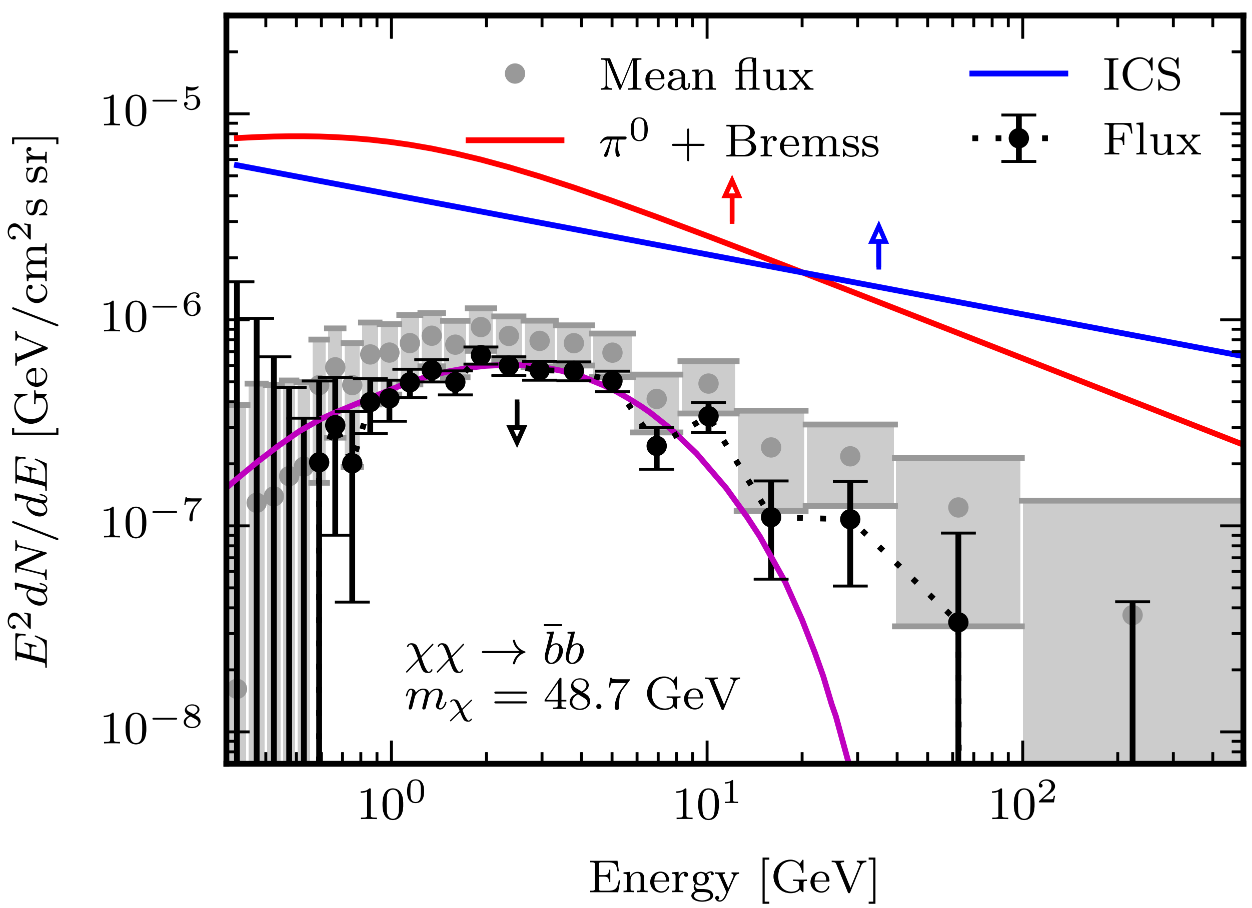
b. Time-dependent source term (from e.g. outburst event)

Petrovic+2014
Cholis+15



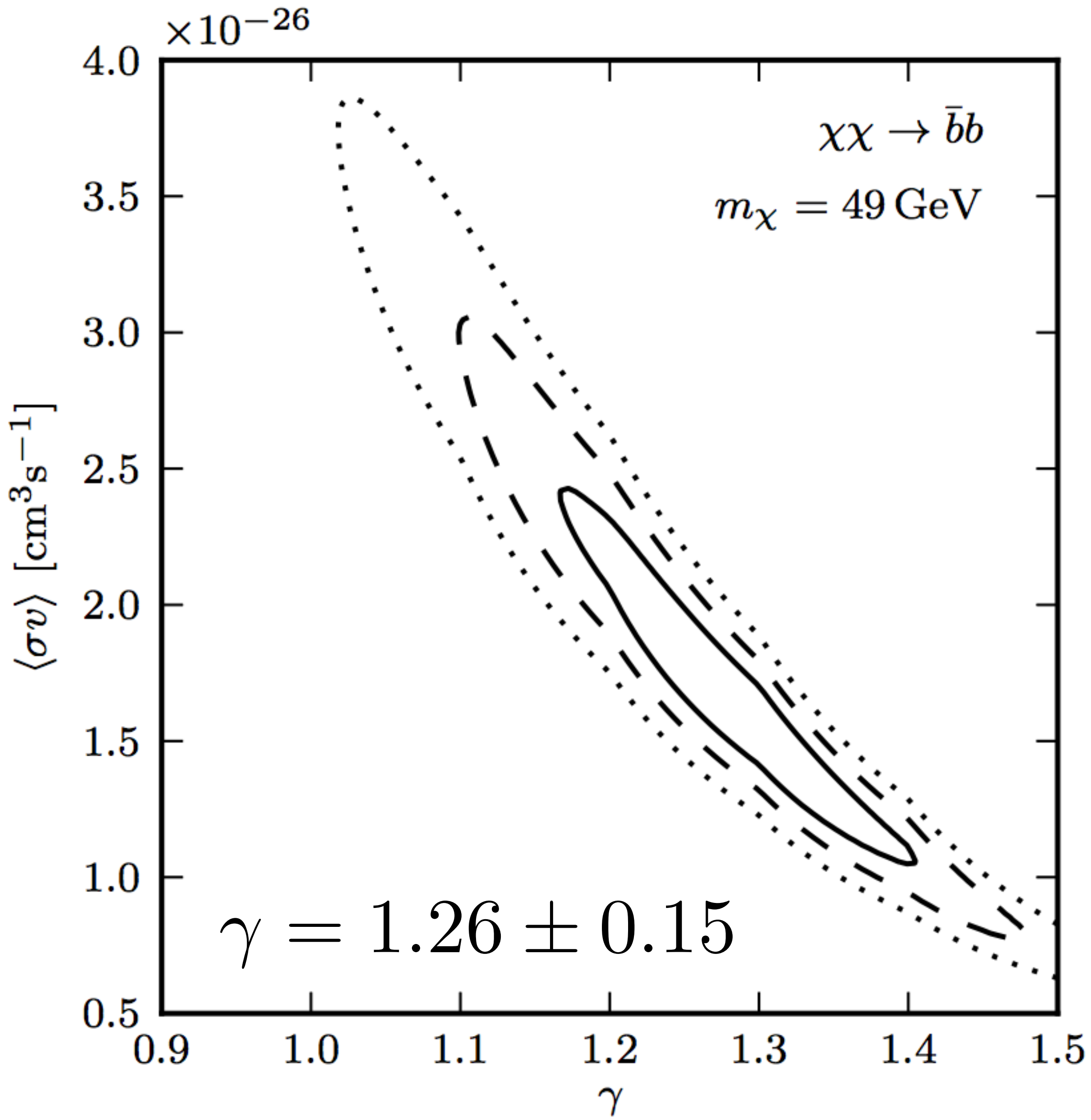
Dark matter annihilation

Spectrum?



Correlated errors can be reduced to variations of the slope and normalisation of the main galactic diffuse emission components.

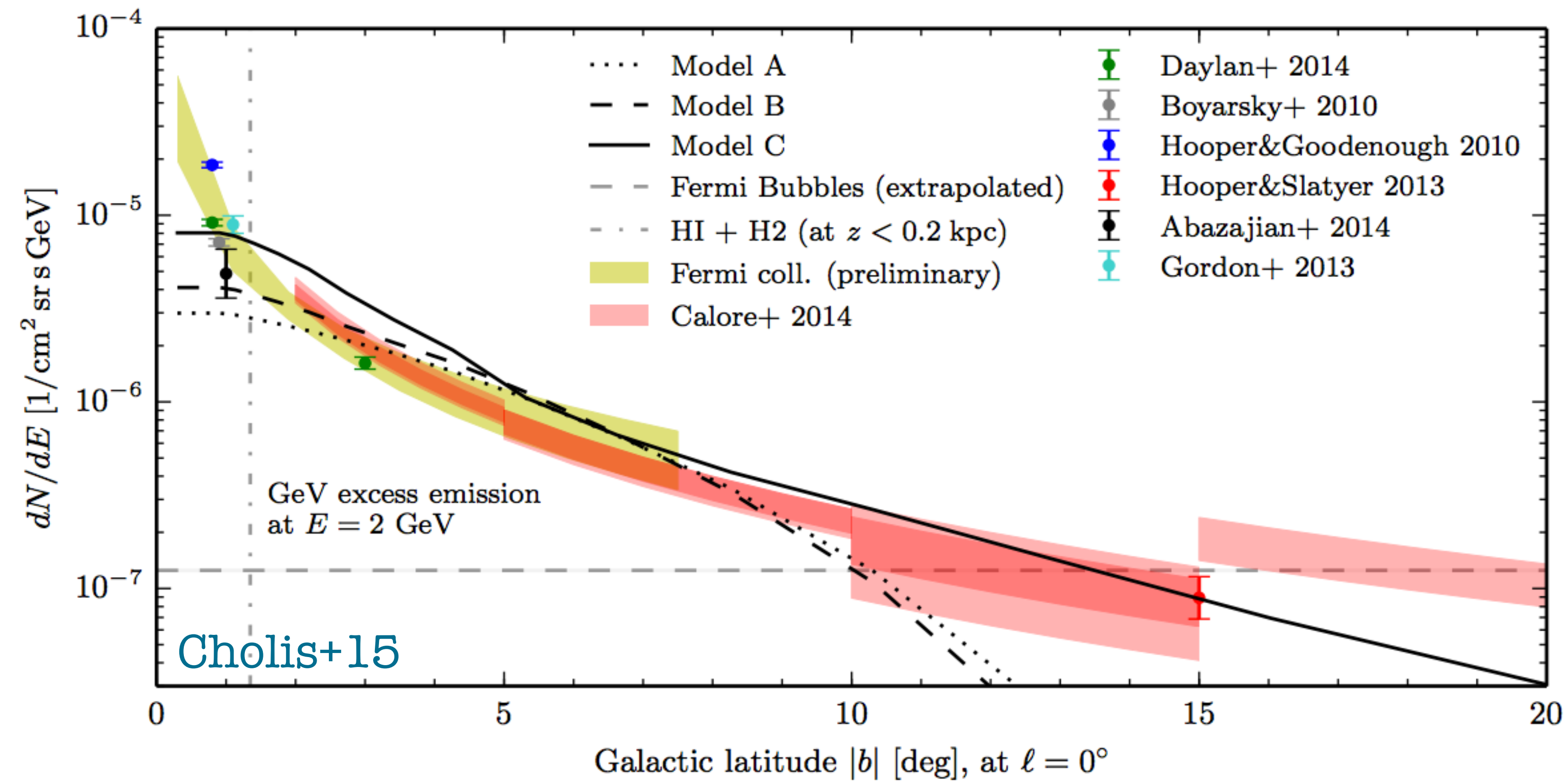
Morphology?



$$\rho(r) = \rho_0 \frac{(r/r_s)^{-\gamma}}{(1 + r/r_s)^{3-\gamma}}$$

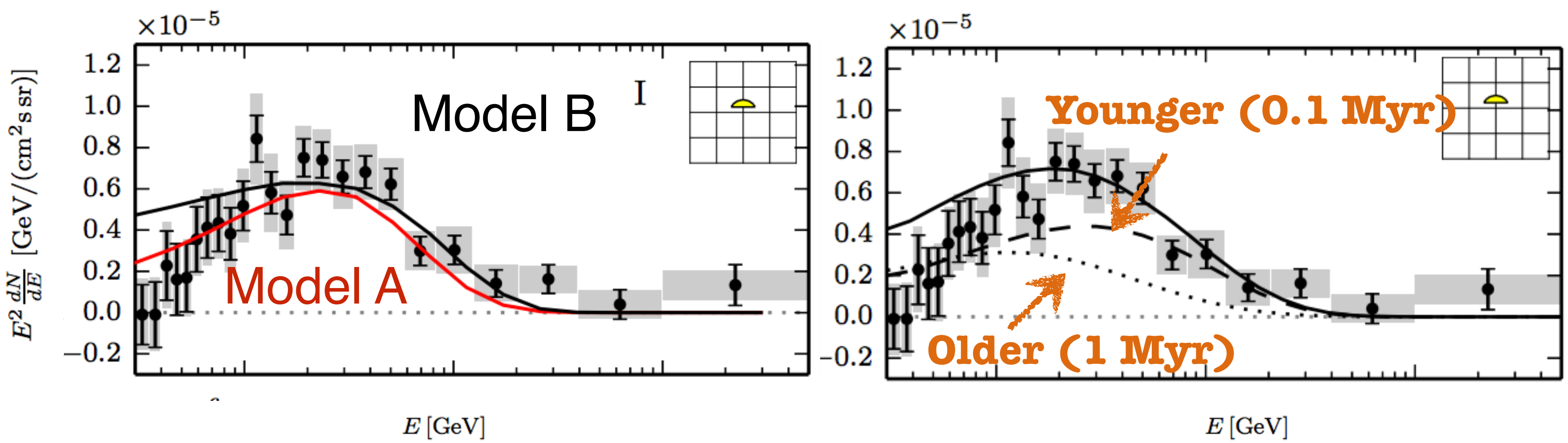
Leptonic outbursts at the GC

- Injection of high-energy CR in the past, at the GC (from the central black hole or starburst activity)
- Time dependent phenomenon (not steady state solution)
- Emission from inverse Compton and bremsstrahlung (no hadronic emission - gas correlated)



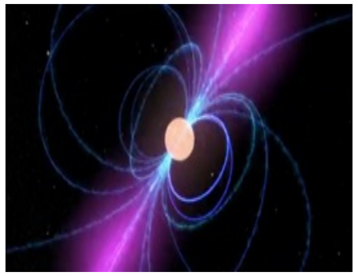
One outburst:
p-value=0.14

Two outbursts:
p-value=0.44



→ Hard injection indices (<2), at least two bursts & high re-acceleration

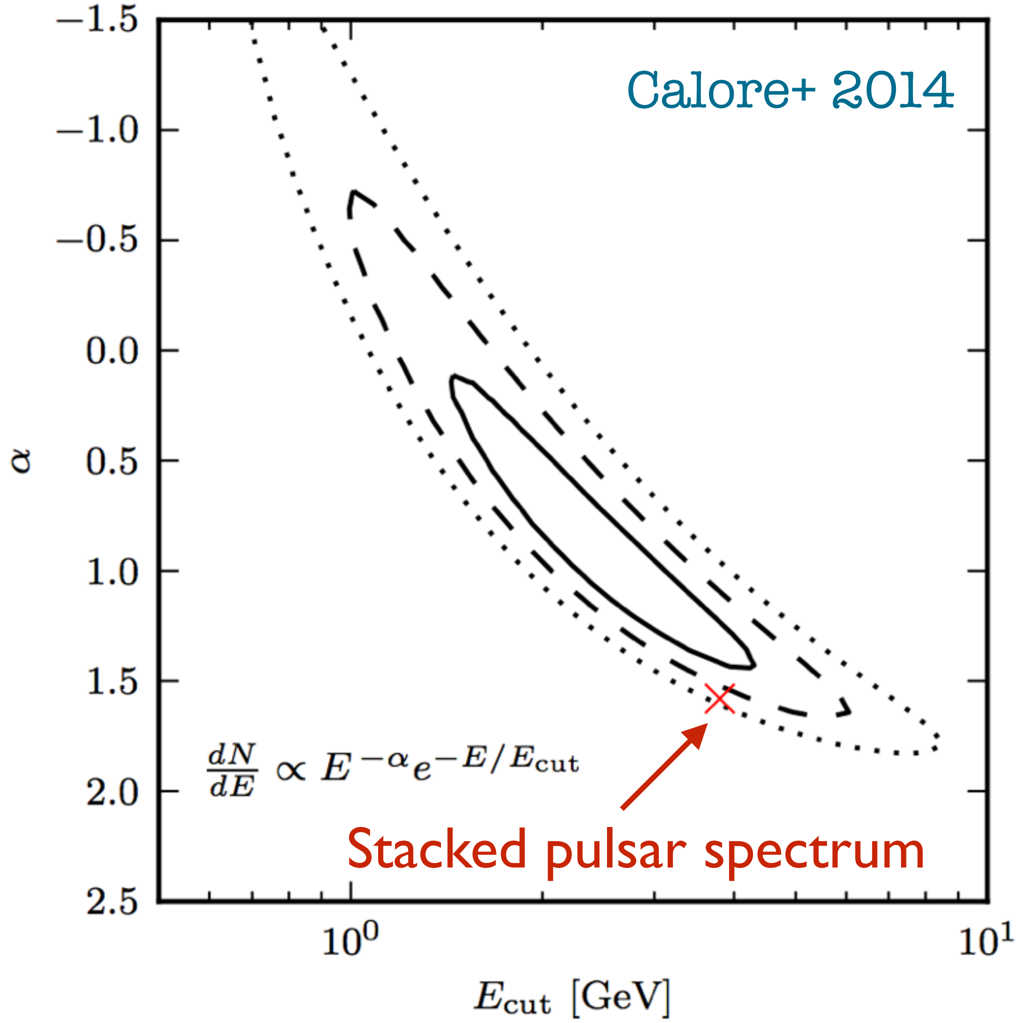
Unresolved point sources



Young Pulsars and Millisecond Pulsars

Wang+ 2005; Abazajian 2011; Gordon & Macias 2013; Hooper+ 2013; Yuan & Zhang 2014; Hooper+ 2013; Calore+ 2014; Cholis+ 2014; Petrovic+2014; Yuang+2014; and many others

Spectrum?



Morphology?

- **Disc-like** population => at most 10% of the excess emission.

  Calore+ 2014

- **Bulge** population => viable explanation.

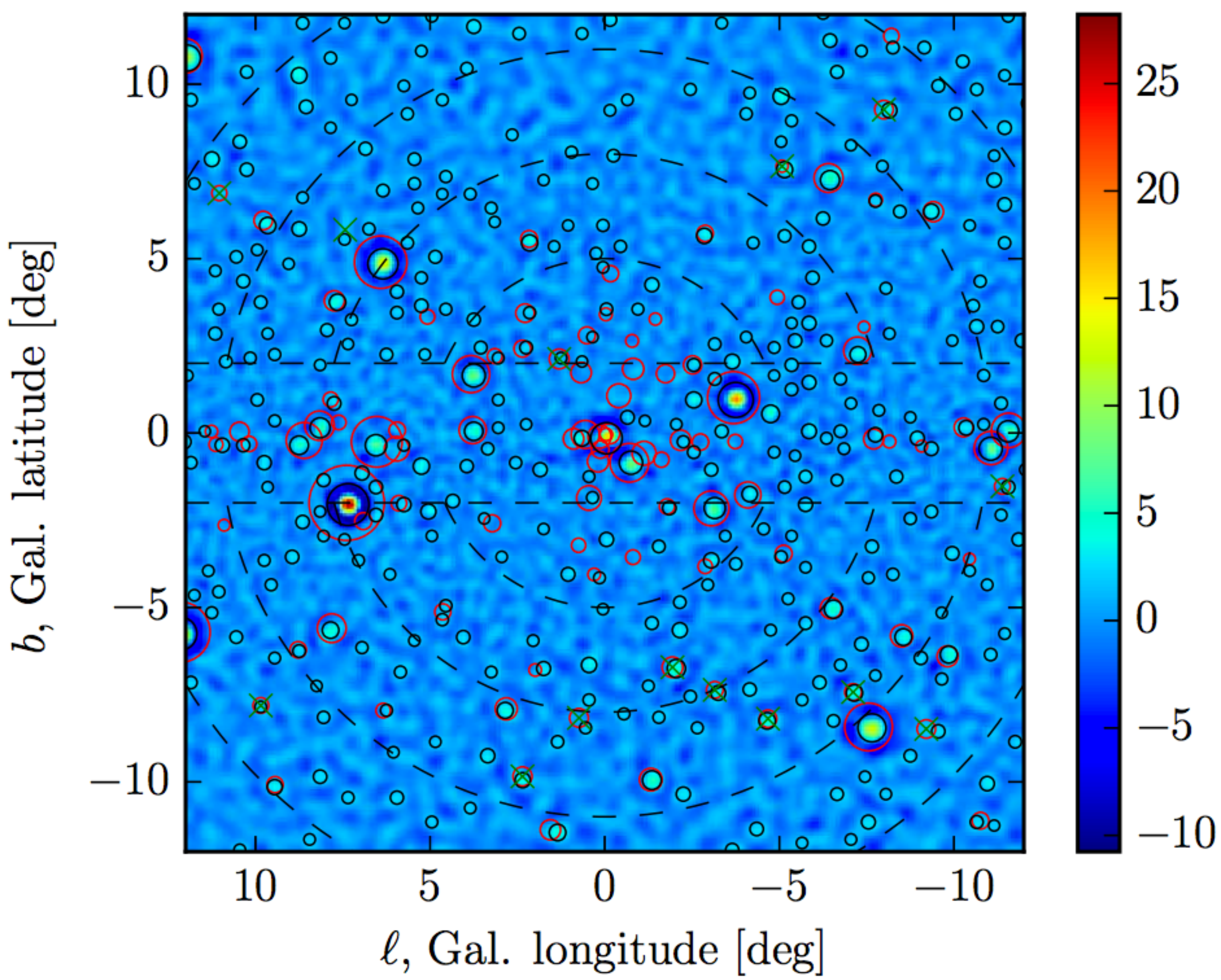
  Petrovic+2014, Yuang+2014
  O'Leary+2015

- Strong support from wavelet decomposition of the gamma-ray sky and one-point non-Poissonian photon counts statistics.

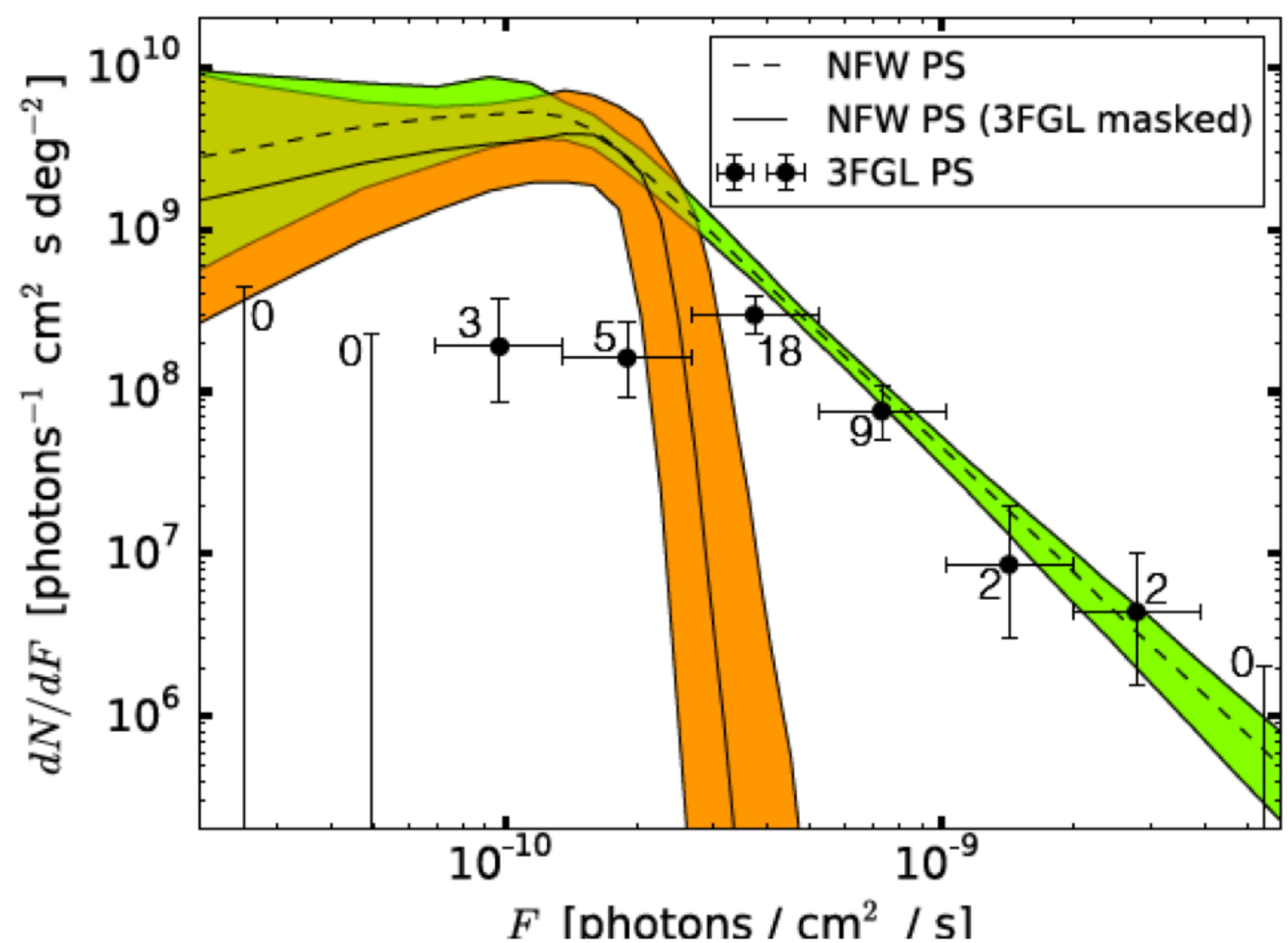
  Lee+2015, Bartels+2015

Unresolved point sources

Bartels+, 1506.05104

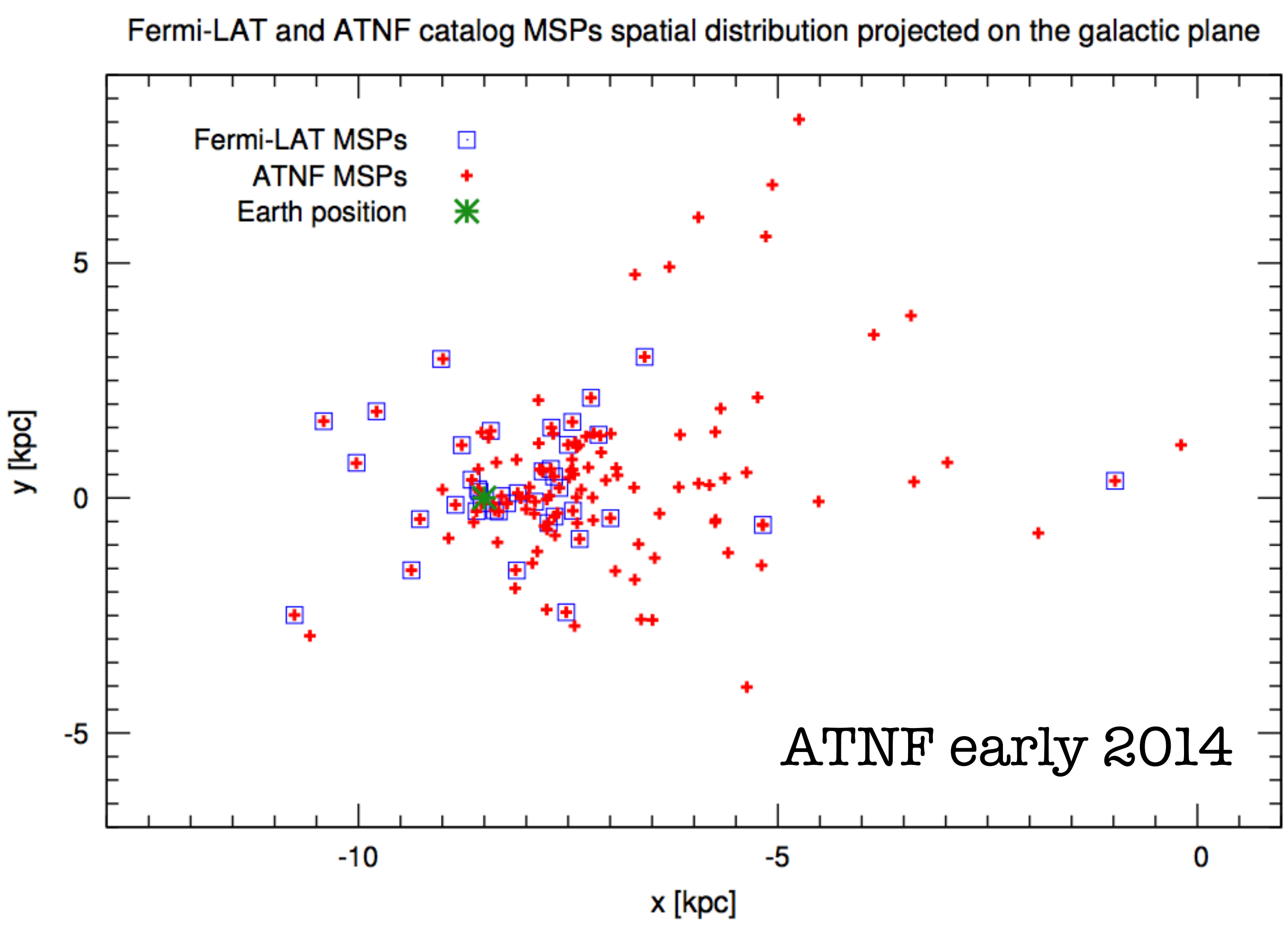


Lee+,1506.05124



- Two independent techniques reach similar conclusions: significant contribution from dim point sources.
- phenomenological description of sources (luminosity function and a NFW-like spatial distribution)

A challenge for radio searches



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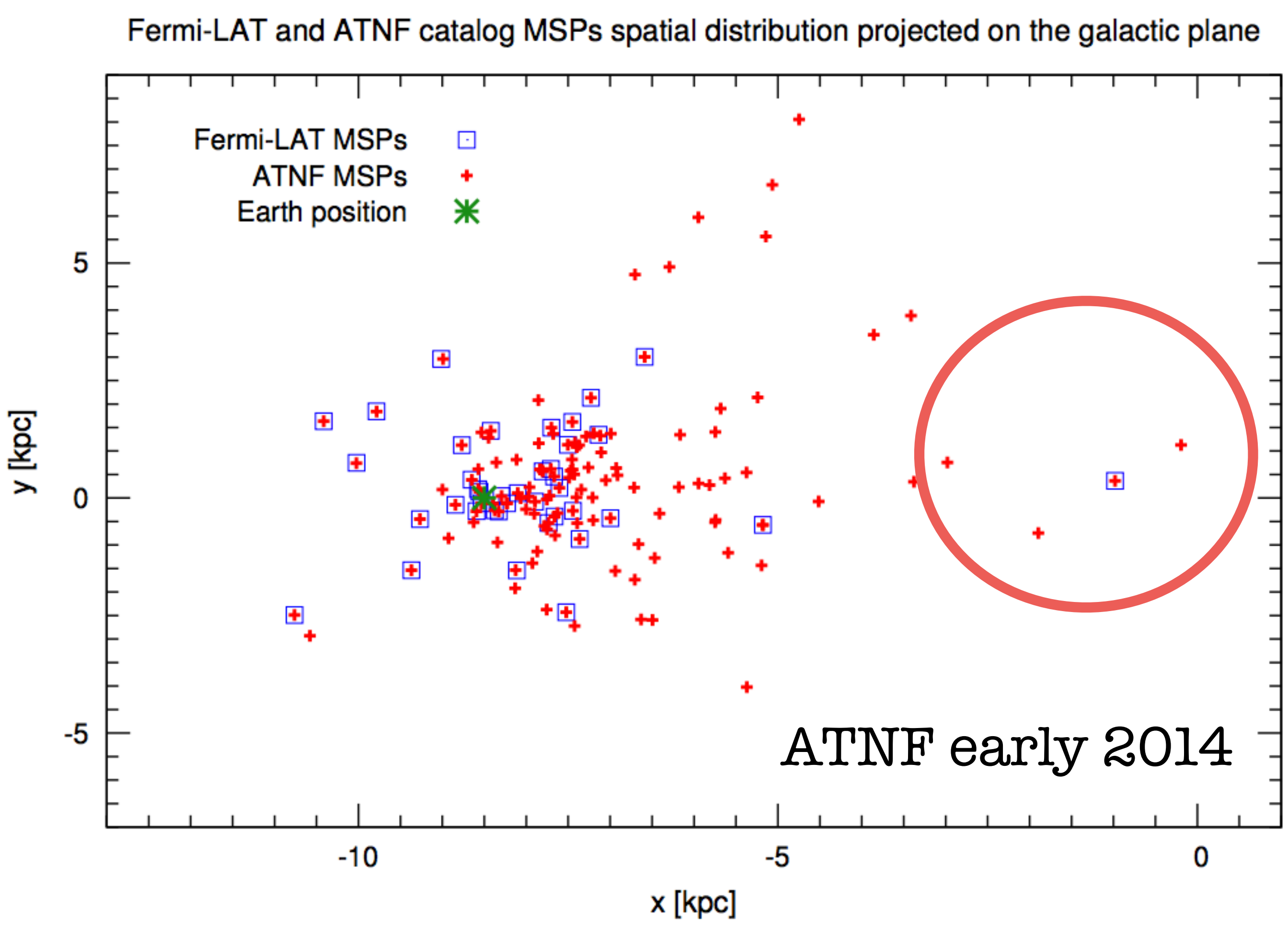

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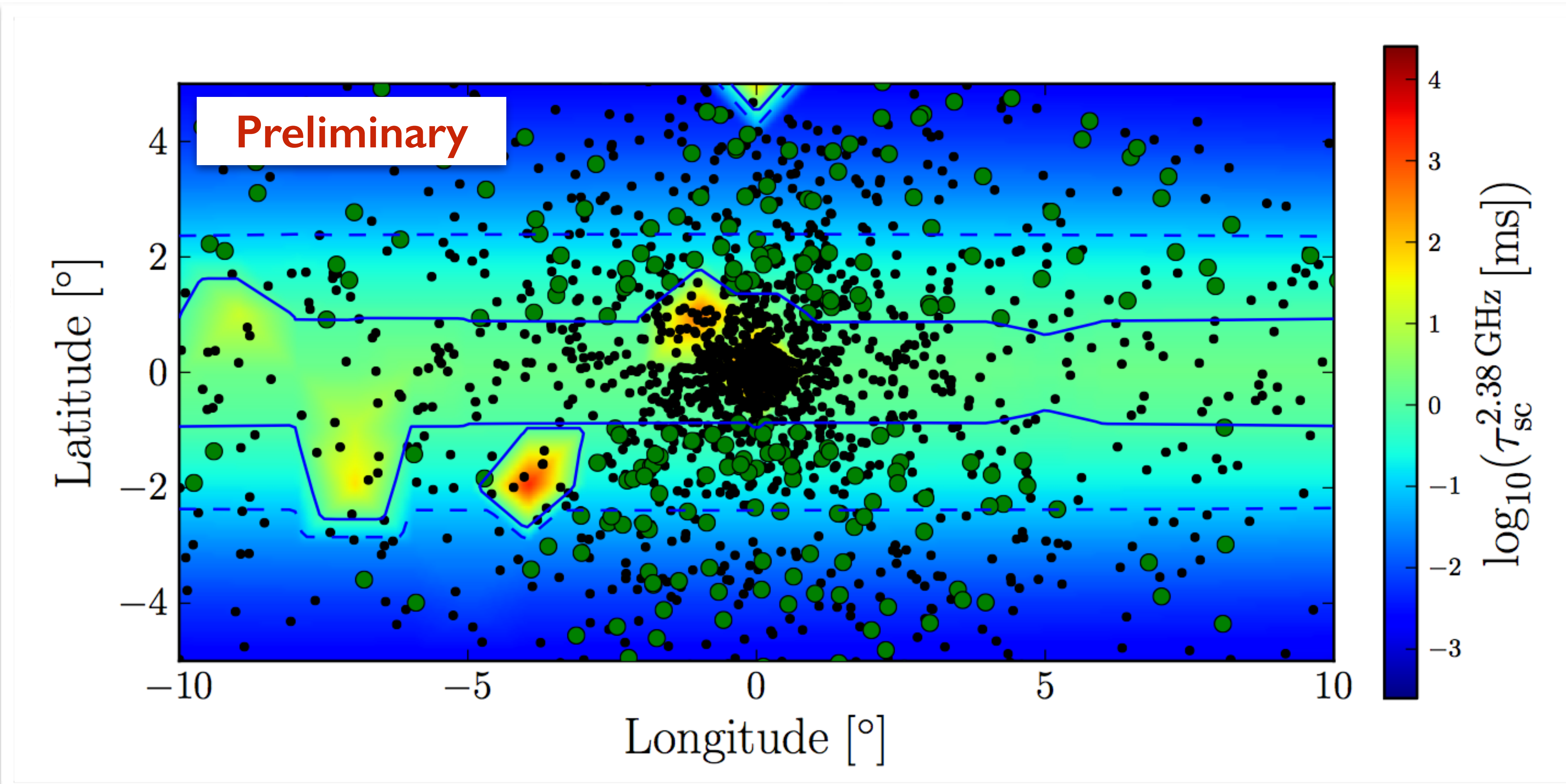
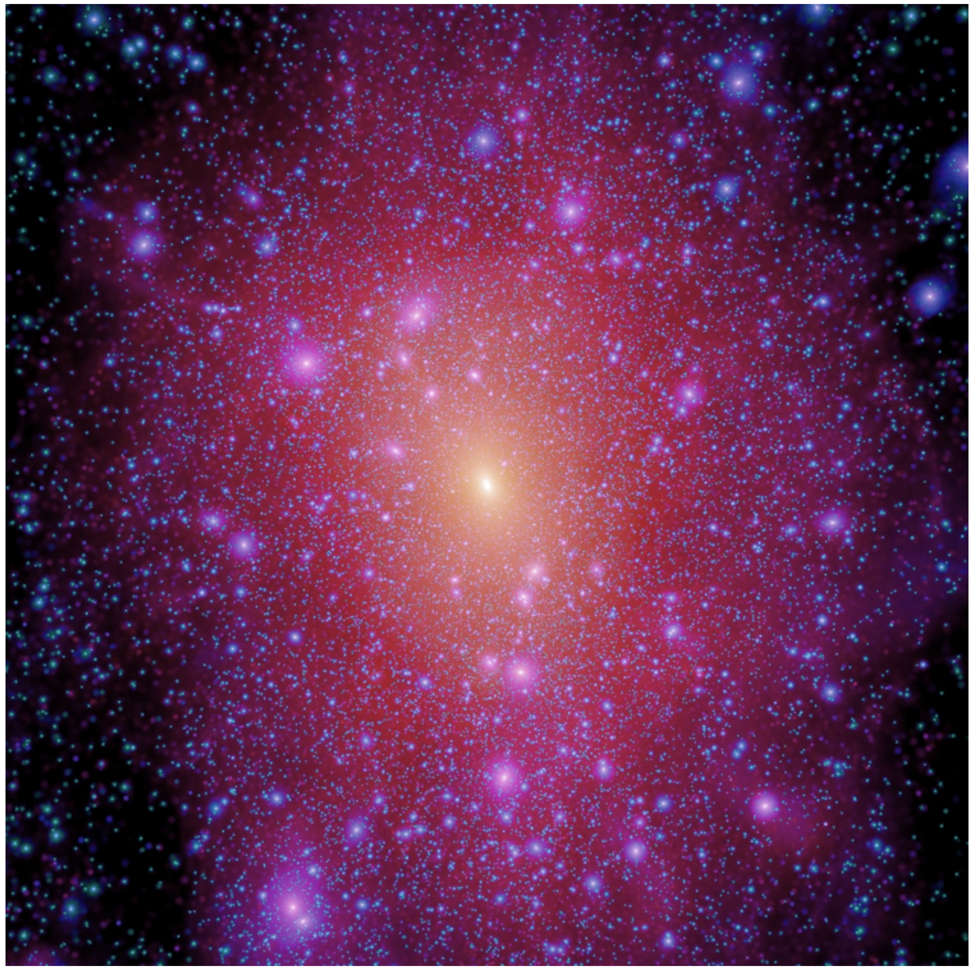


10 hours observation time with SKA, 2.38 GHz.

Calore, Di Mauro, Donato, Massaro, Weniger. In preparation

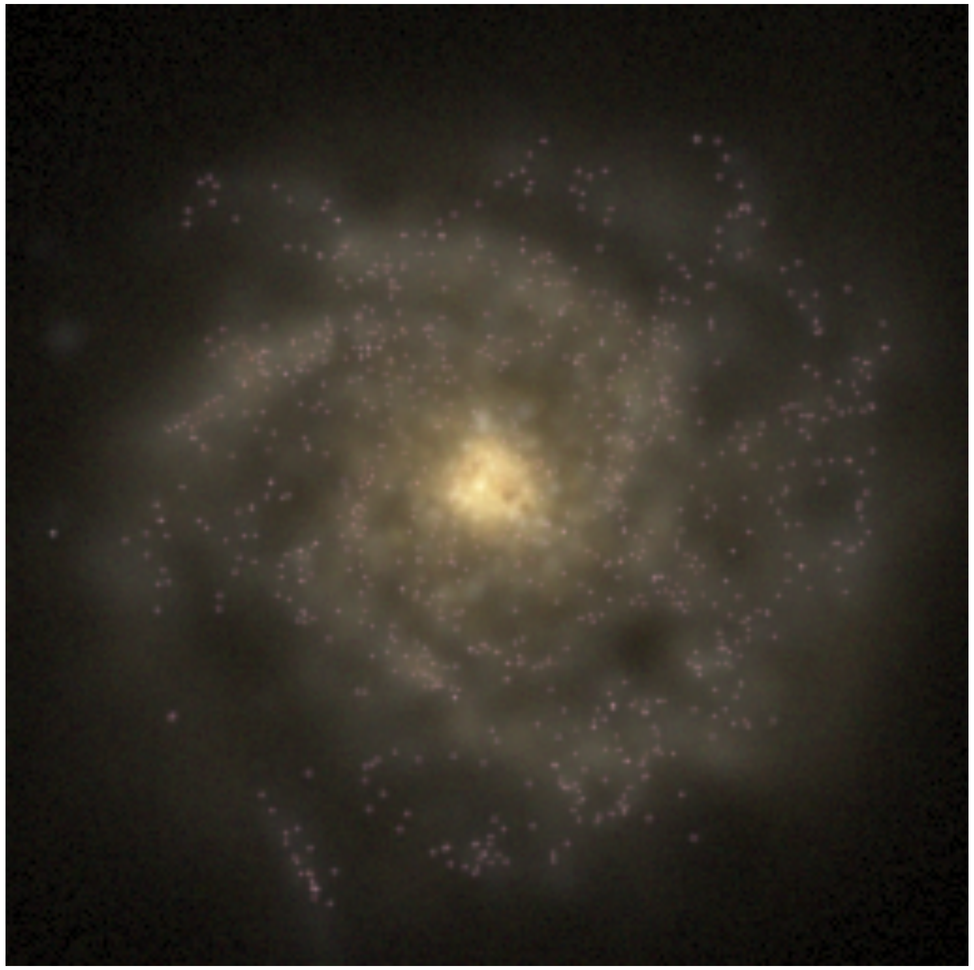
Dark matter spatial profile?

Pure DM simulations
DM only



Aquarius 2008

Hydrodynamic simulations
DM+baryons



EAGLE 2015

Question: What is the simulated dark matter density profile for Milky Way-like galaxies in the EAGLE simulations?

arXiv: 1509.02164, 1509.02166

Selection of "good" Milky Ways

$$5 \times 10^{11} < M_{200}/\mathrm{M}_\odot < 1 \times 10^{14}$$

(i) The simulated rotation curve fits well the observed MW kinematical data in ref. [5]. We explain the method followed to derive the rotation curves from the simulation, the data used in the analysis and the goodness of fit definition in section 3.1.

(ii) The total stellar mass of the simulated galaxies is within the 3σ MW range derived from observations, $4.5 \times 10^{10} < M_*/\mathrm{M}_\odot < 8.3 \times 10^{10}$ [50]: 335, 12, and 2 galaxies satisfy this constraint in the EAGLE IR, EAGLE HR and APOSTLE IR respectively.[2]

(iii) The galaxies contain a substantial stellar disc component. See section 3.2.

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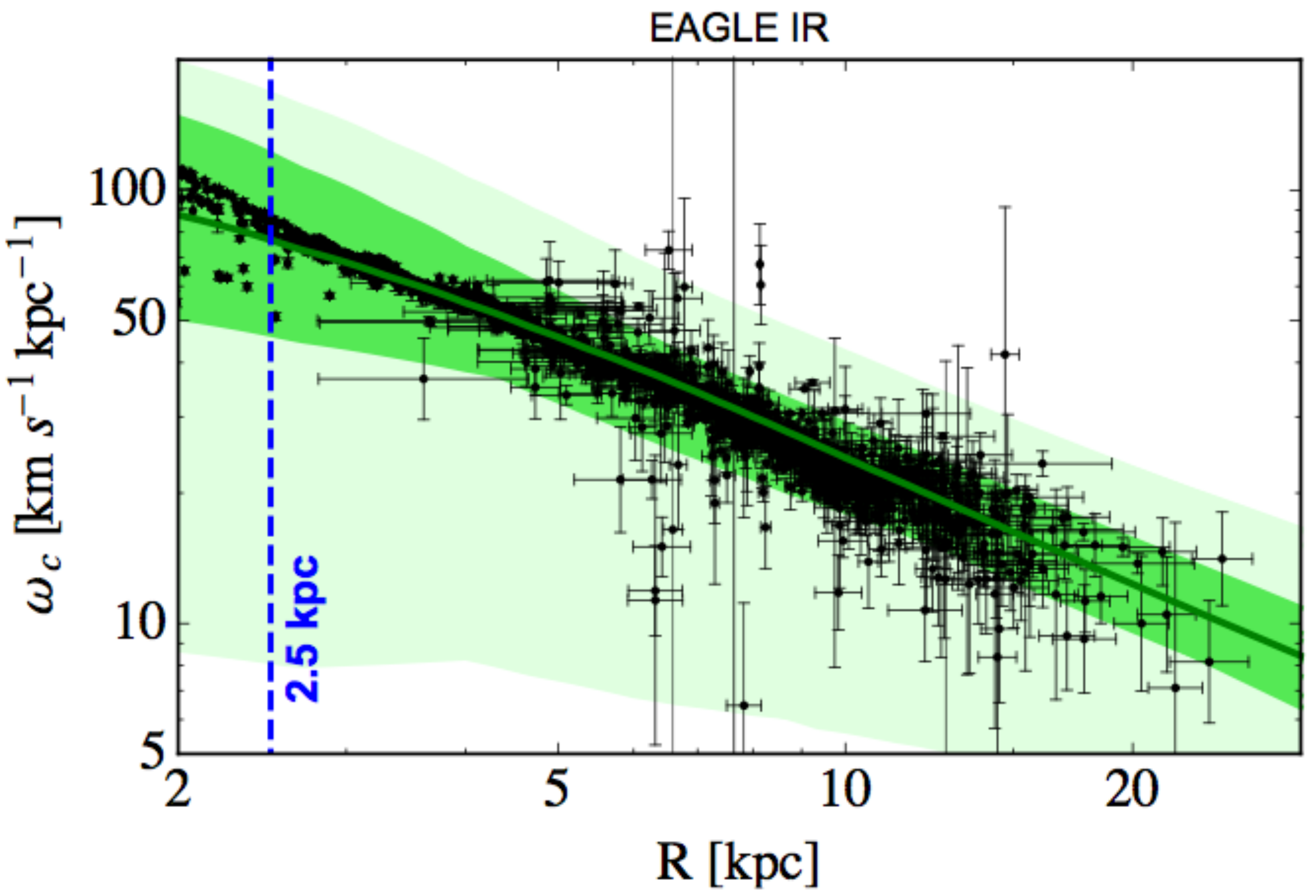

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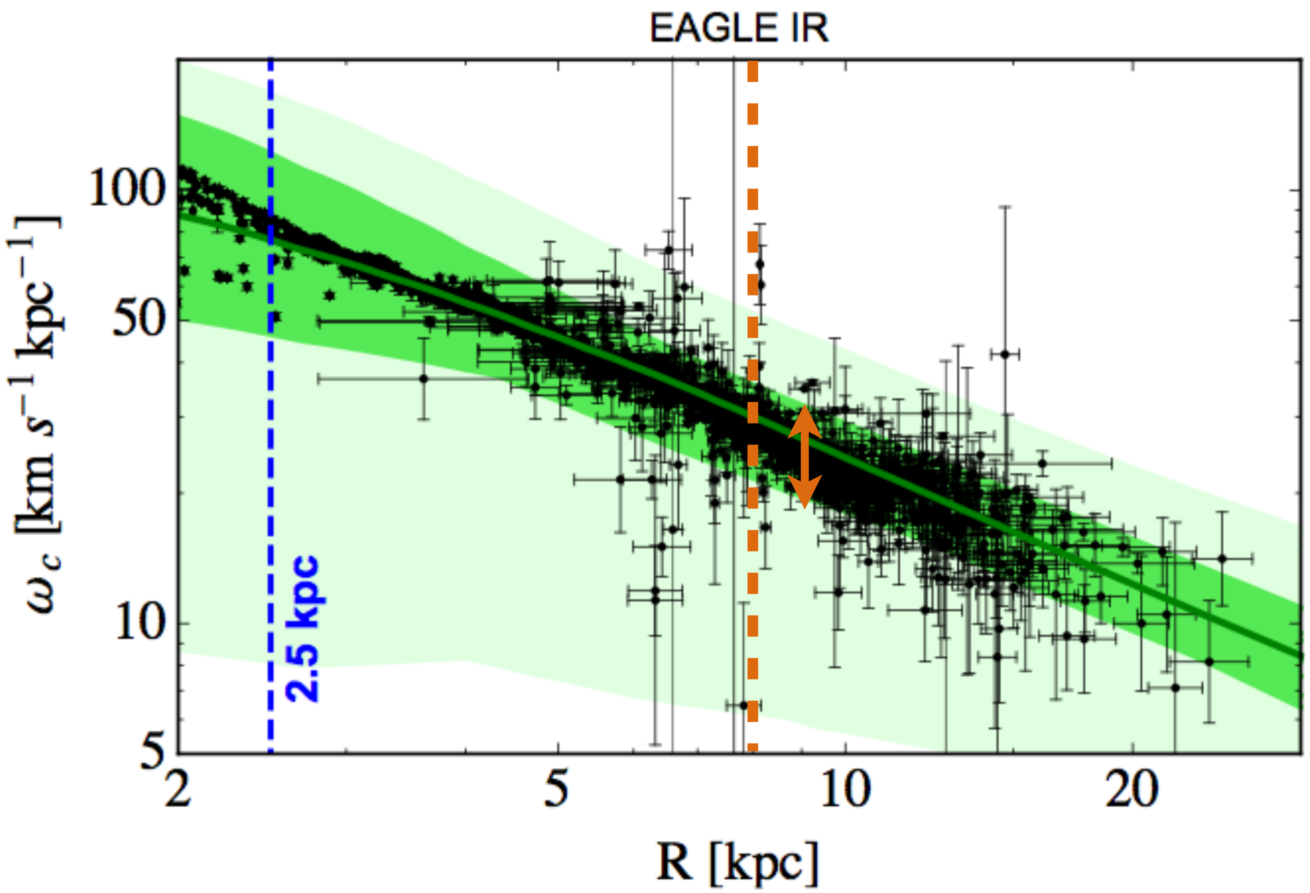

$$\rho_\odot(R_\odot = 8\,\mathrm{kpc}) = 0.44 - 0.59\,\mathrm{GeV/cm}^3$$

arXiv: 1509.02164

Selection of "good" Milky Ways

$$5 \times 10^{11} < M_{200}/\mathrm{M}_\odot < 1 \times 10^{14}$$

(i) The simulated rotation curve fits well the observed MW kinematical data in ref. [5]. We explain the method followed to derive the rotation curves from the simulation, the data used in the analysis and the goodness of fit definition in section 3.1.

(ii) The total stellar mass of the simulated galaxies is within the 3σ MW range derived from observations, $4.5 \times 10^{10} < M_*/\mathrm{M}_\odot < 8.3 \times 10^{10}$ [50]: 335, 12, and 2 galaxies satisfy this constraint in the EAGLE IR, EAGLE HR and APOSTLE IR respectively.[2]

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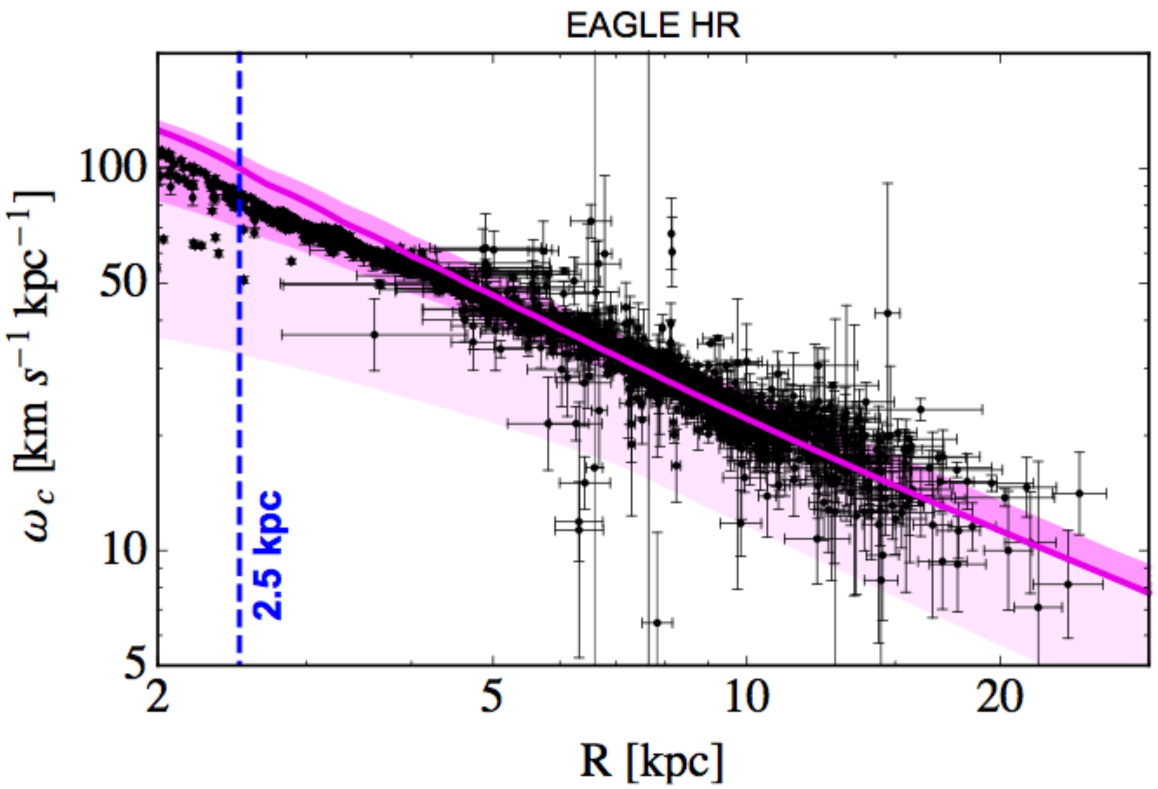

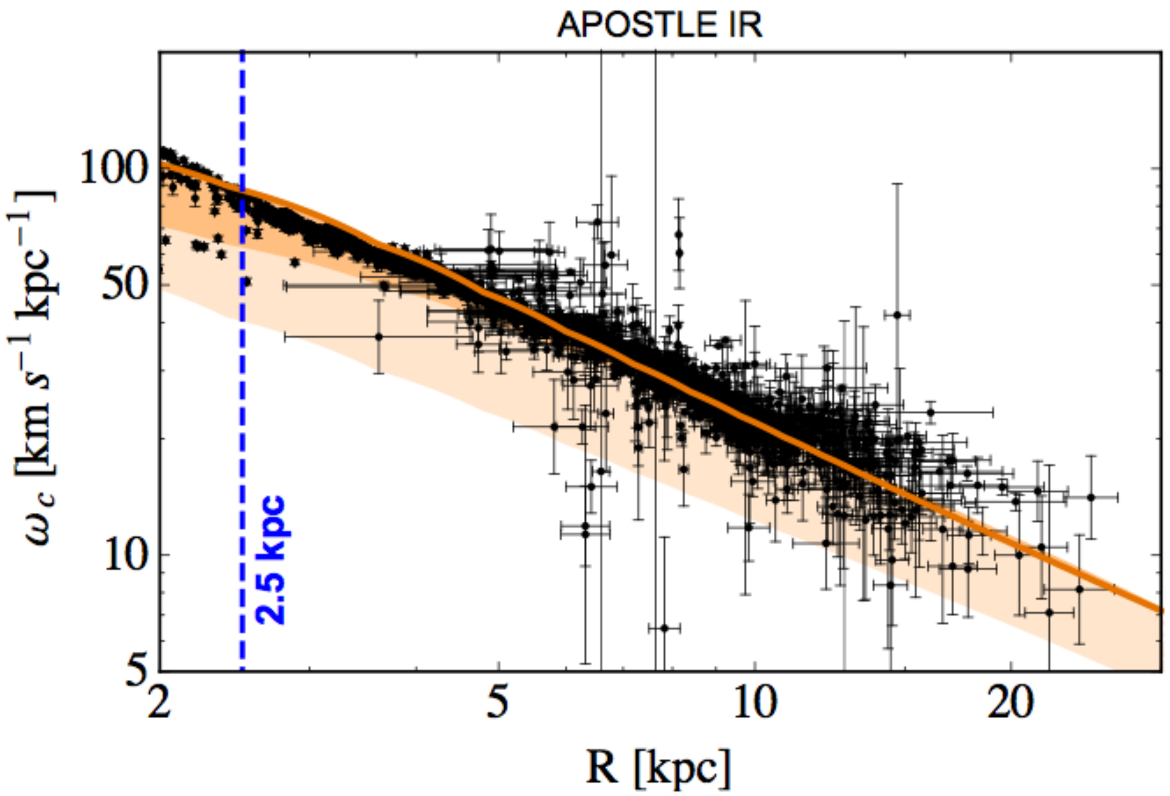

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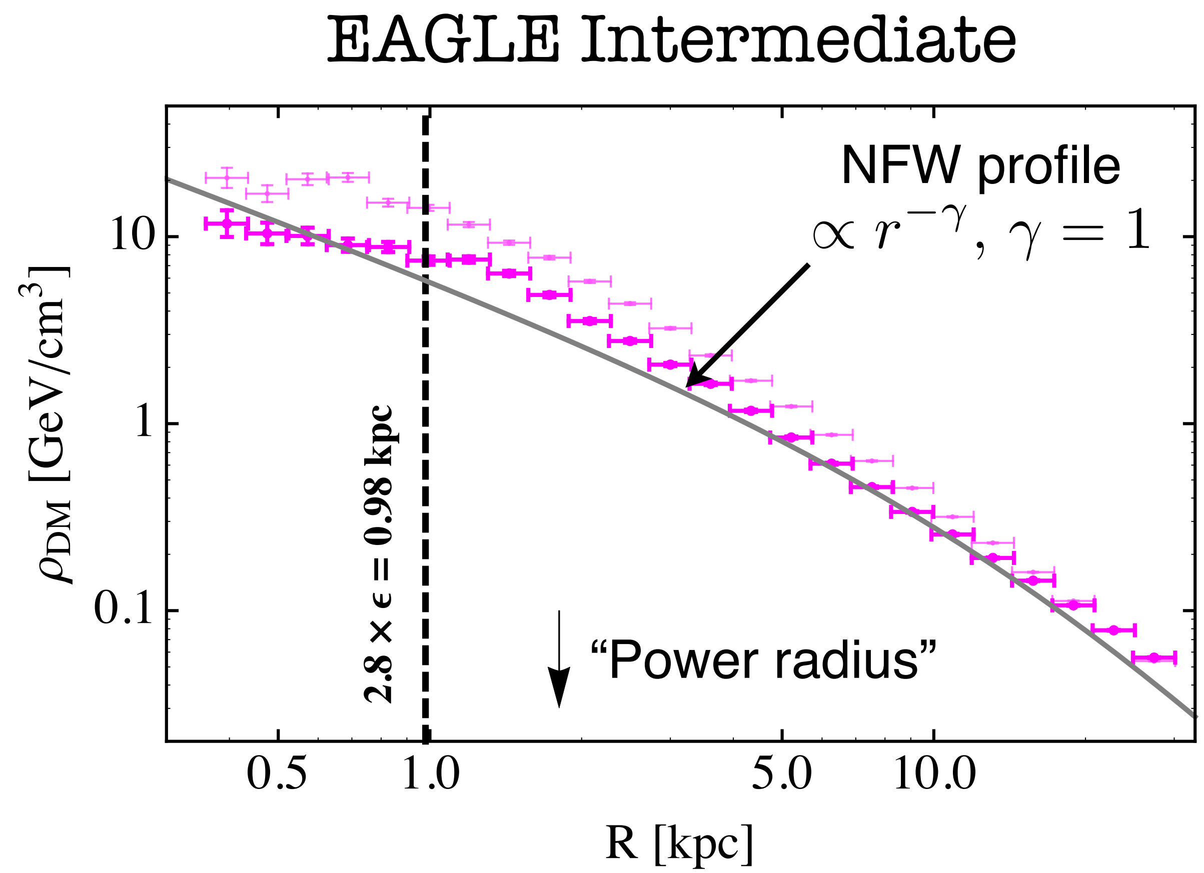
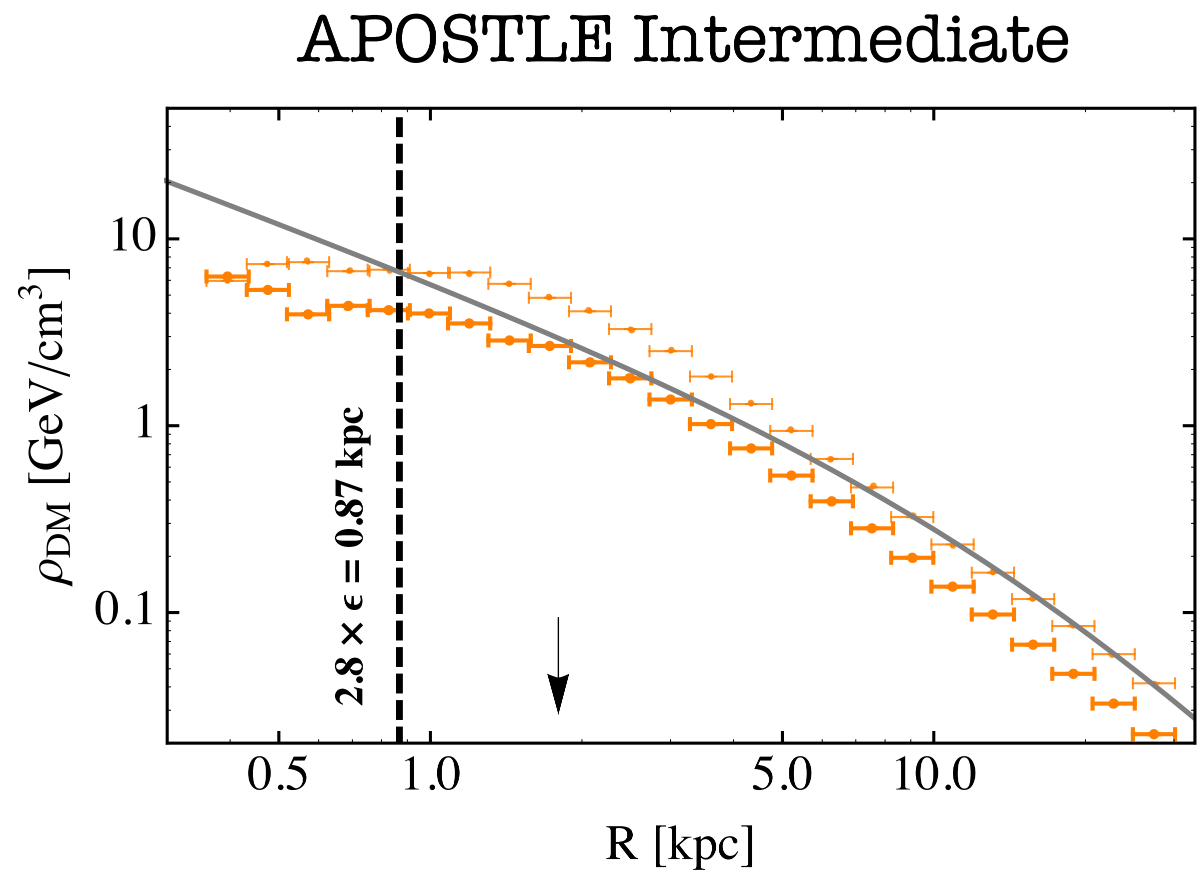
Dark matter spatial profile in EAGLE





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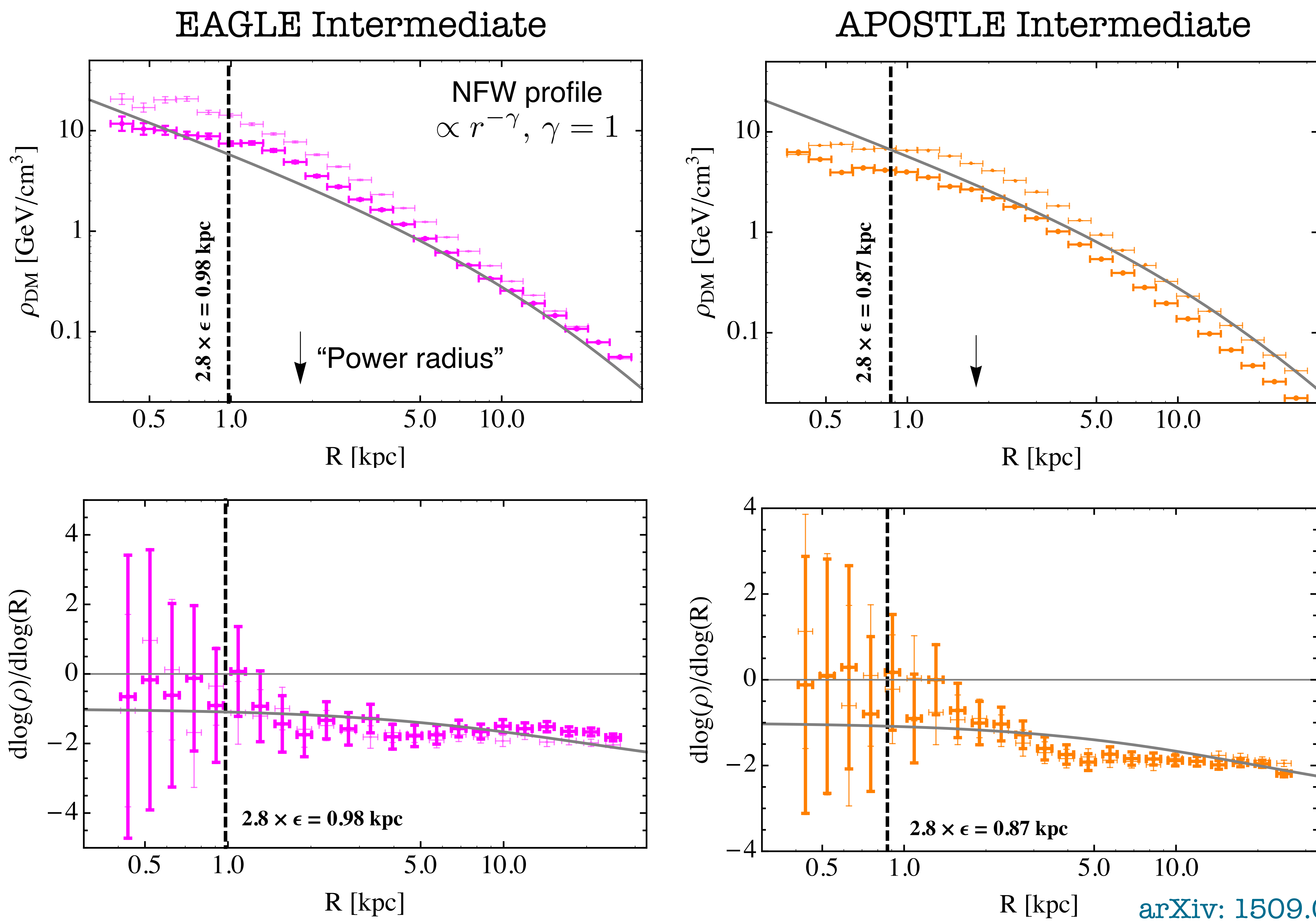

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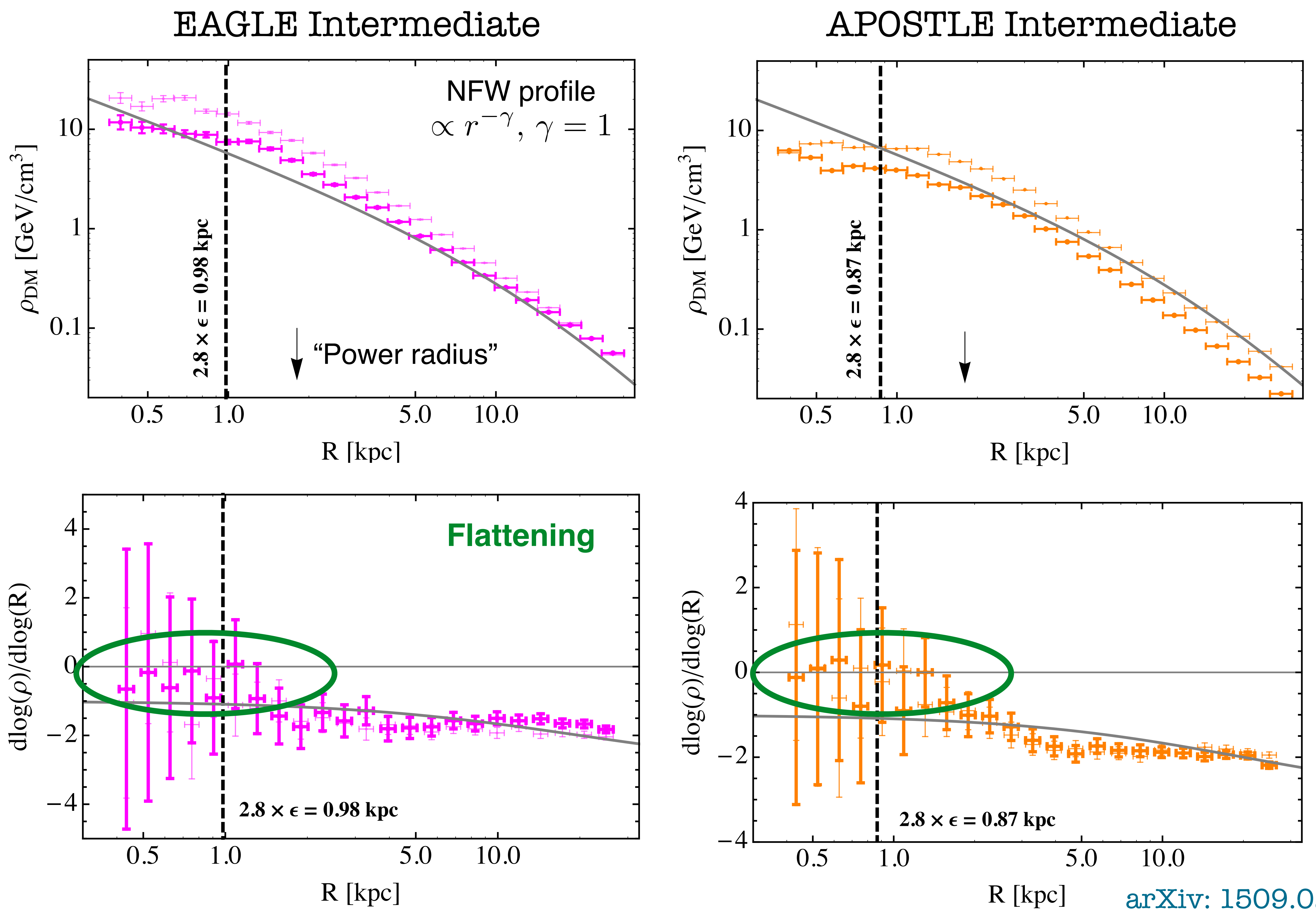

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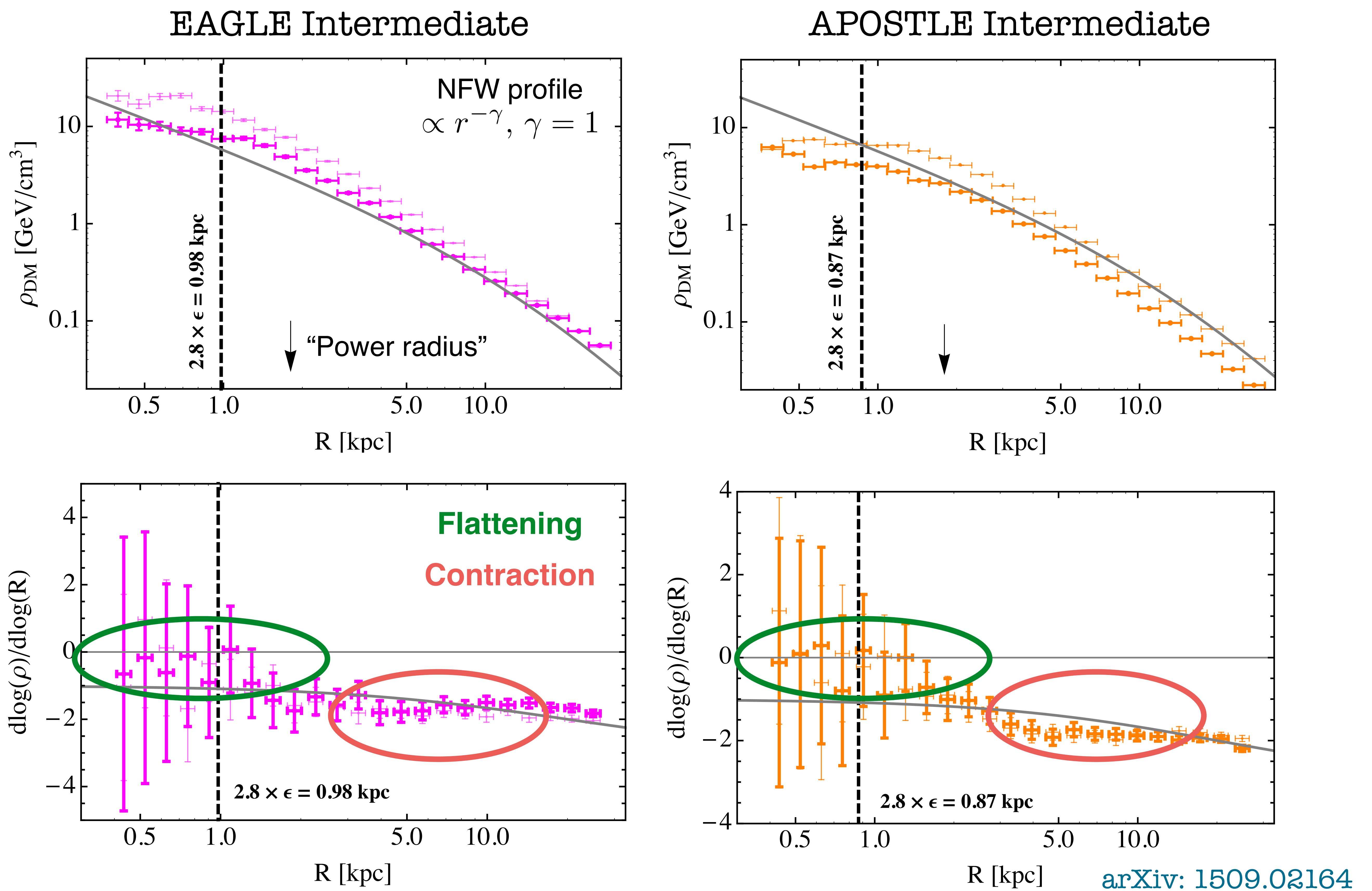


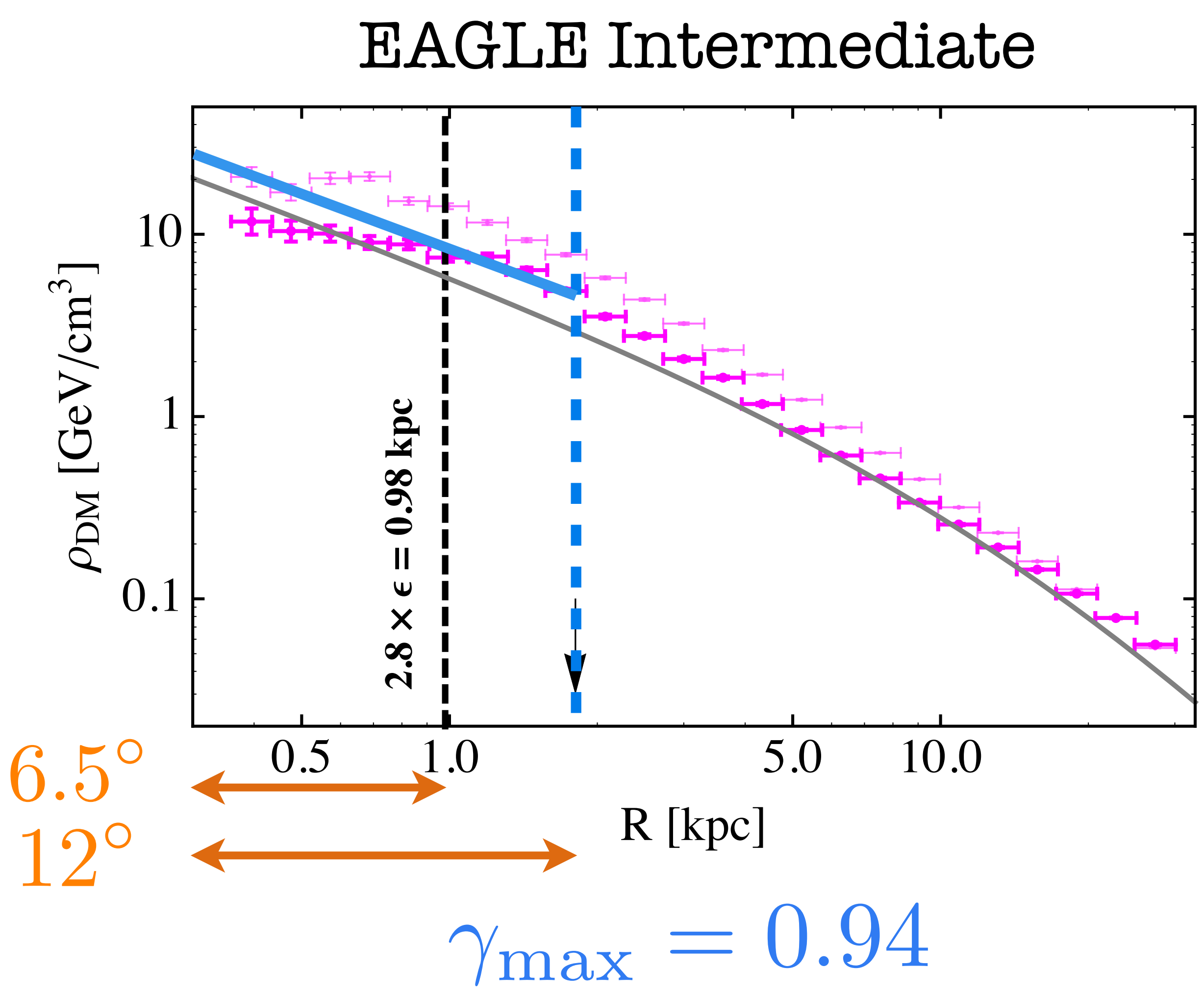
arXiv: 1509.02164

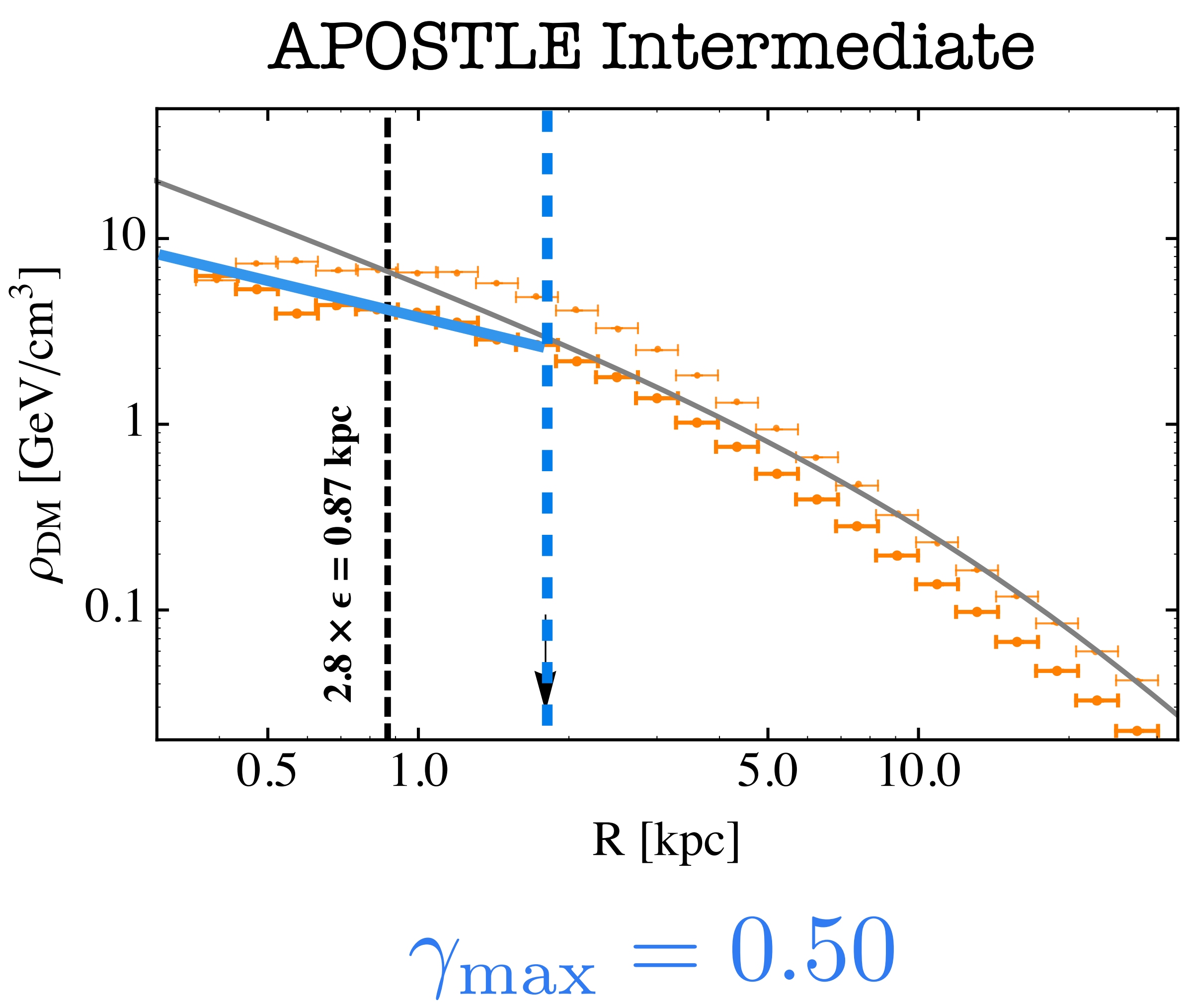
Dark matter spatial profile in EAGLE

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

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

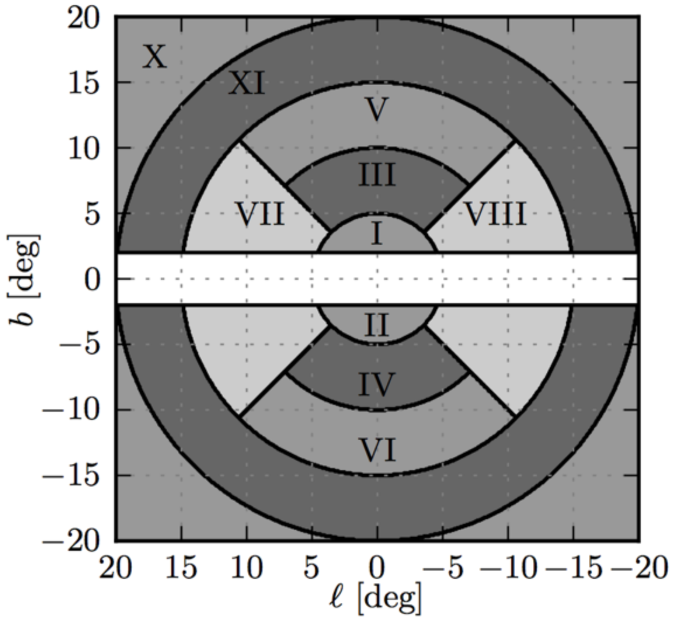
APOSTLE IR (2 haloes): $0.50 < \gamma_{\rm max} < 0.62$ at $R_{\rm P03} = 1.8$ kpc.





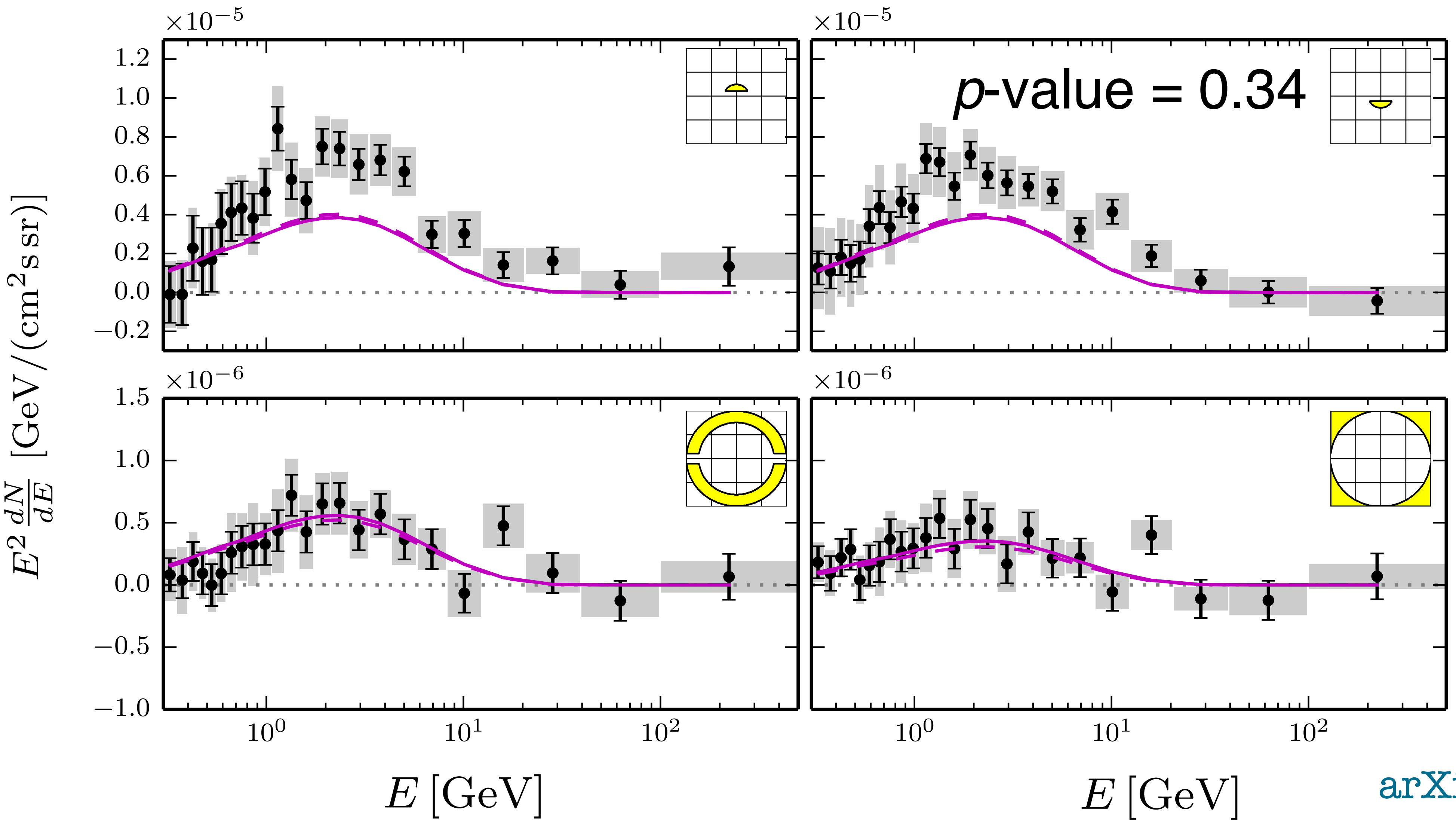
arXiv: 1509.02164

Fit to the GeV excess



$$\chi^2 = \sum_{i=1}^{10} \sum_{j,k=1}^{24} (d_{ij} - \mu_{ij})(\Sigma^i_{jk})^{-1}(d_{ik} - \mu_{ik})$$

$$\frac{d\Phi_\gamma}{dE} = \frac{\langle \sigma v \rangle}{8\pi\, m_\chi^2} \frac{dN_\gamma}{dE} \int_{\rm l.o.s.} ds\, \rho^2(r(s,\psi))$$



arXiv: 1509.02164

Challenges & Outlook

- ✓ Improved understanding of the **Galactic diffuse emission**
  - more realistic description of Galactic centre (CR sources)
  - high resolution gas maps and interstellar radiation field model
- ✓ **Dark matter**?
  - independent confirmation… dwarfs? (no tension so far!)
  - improved understanding of halos in hydrodynamic simulations
- ✓ **Outburst events**?
  - dependence of the spectrum in the region considered
  - possible breaks in the spectrum
  - radio counterparts?
- ✓ **Unresolved sources**?
  - energy dependence in template fitting
  - spectral fit pf sources
  - multi-wavelength

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Still a lot of work to do to possibly unveil dark matter in the centre of the Milky Way!

Backup

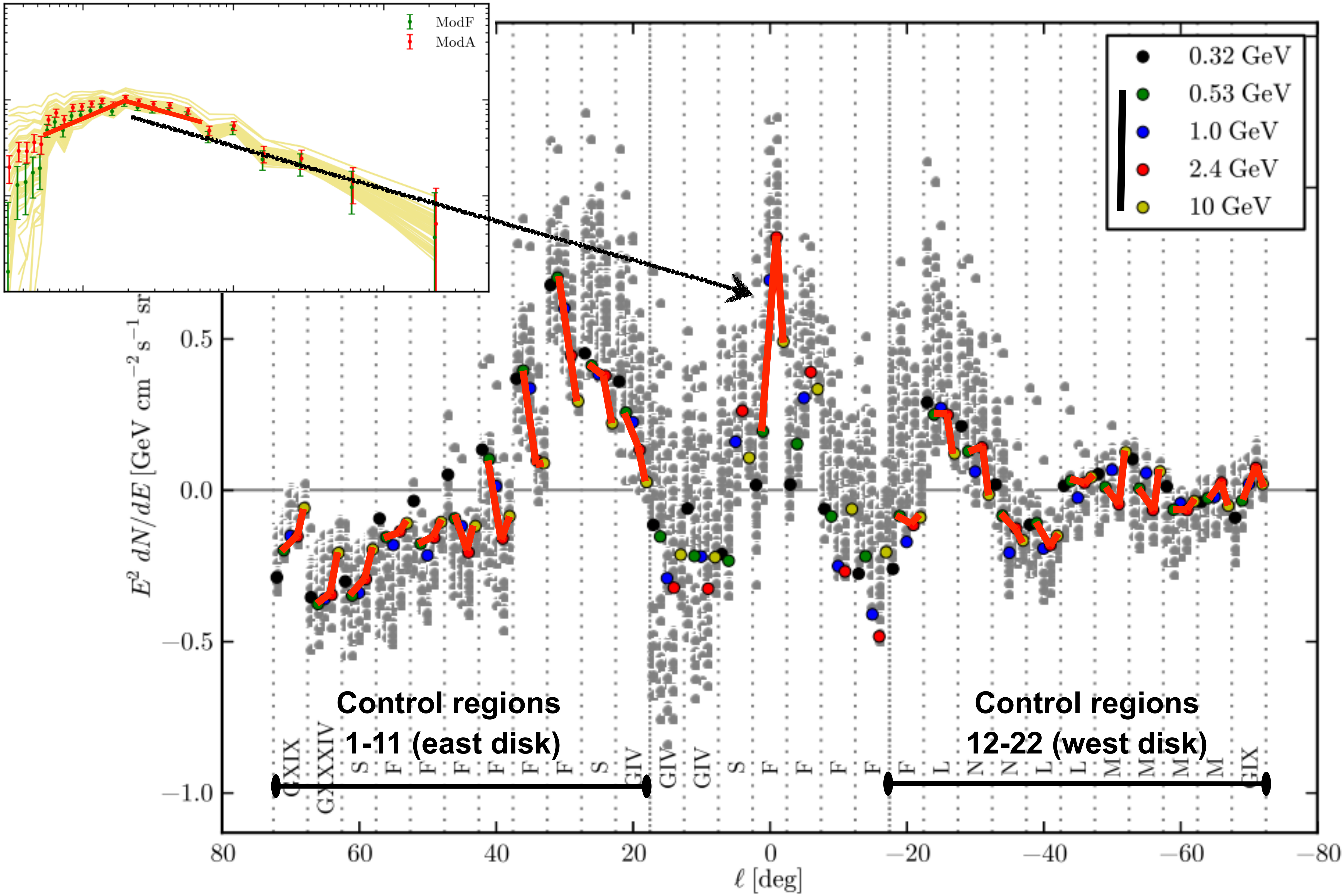
60 Galactic diffuse home-brew models

Building models* for the diffuse galactic emission, by varying the following parameters:

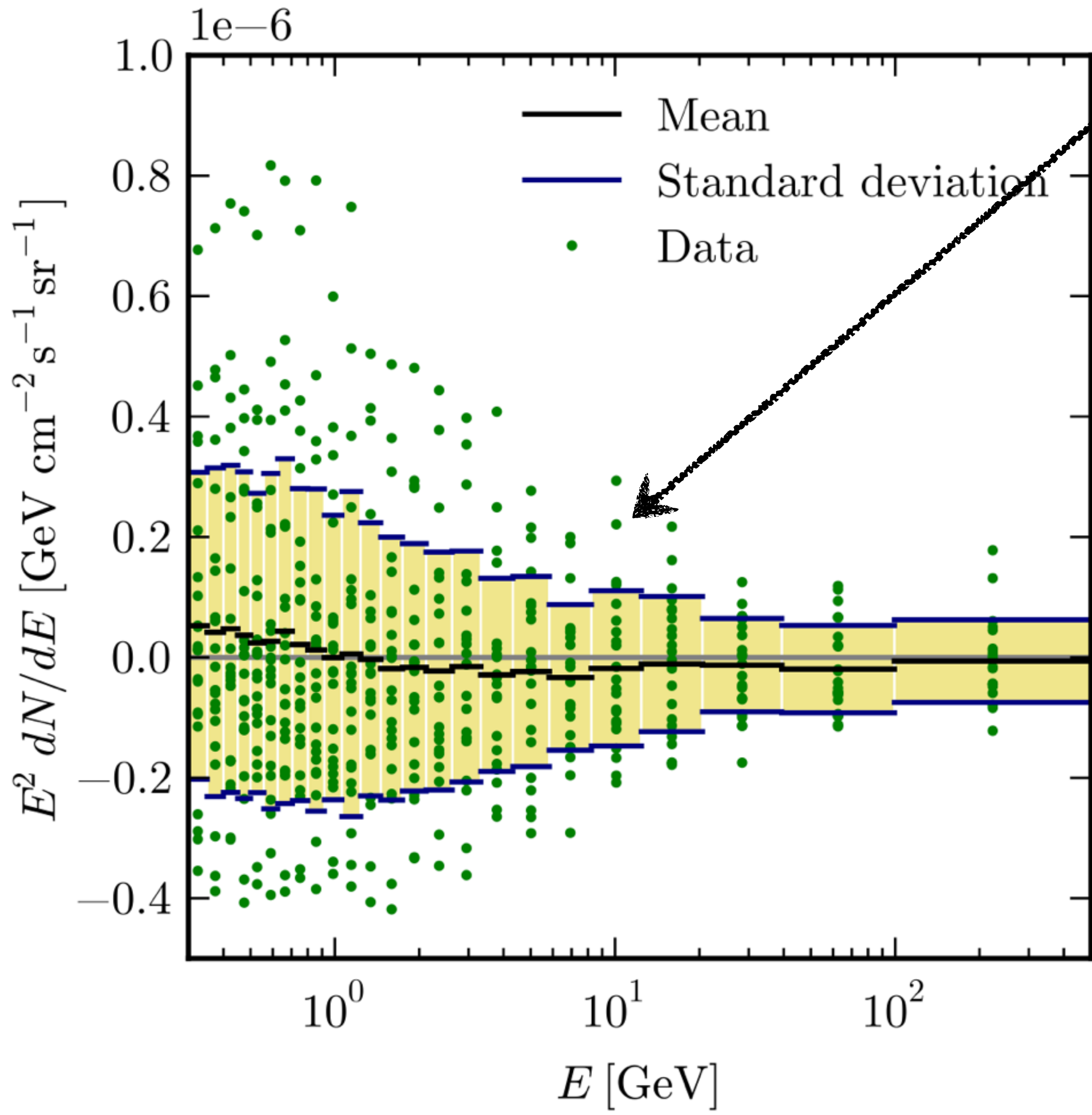
- geometry of the diffusion zone: $4 \leq z_D \leq 10$ kpc and $r_D = 20$ or 30 kpc;
- source distributions: SNR, pulsars, OB stars;
- diffusion coefficient at 4 GV: $D_0 = 2 - 60 \times 10^{28}\ \mathrm{cm^2\,s^{-1}}$;
- Alfvén speed: $v_\mathrm{A} = 0 - 100\ \mathrm{km\,s^{-1}}$;
- gradient of convection velocity: $dv/dz = 0 - 500\ \mathrm{km\,s^{-1}\,kpc^{-1}}$;
- ISRF model factors (for optical and infrared emission): $0.5 - 1.5$;
- B-field parameters: $5 \leq r_c \leq 10$ kpc, $1 \leq z_c \leq 2$ kpc, and $5.8 \leq B(r=0, z=0) \leq 117$ μG.

*Models from Ackermann+ 2012 (128 models) or from new GALPROP runs.

Empirical model systematics



The 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

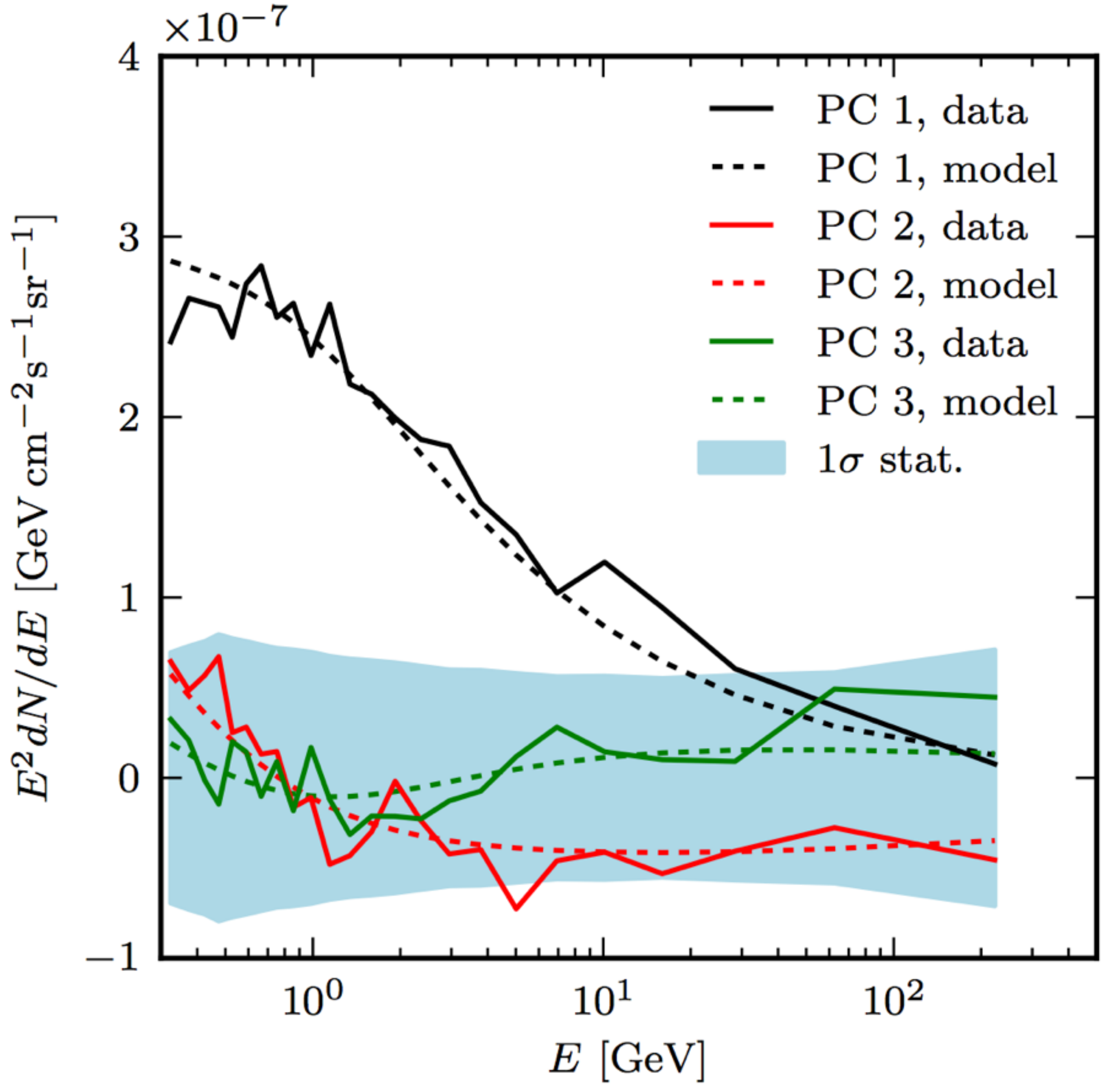
Principal component analysis

Can we model the covariance matrix?

$$\Phi_{\mathrm{res}}(E) = \Phi_{\mathrm{data}}(E) - \sum_{\mathrm{i=ICS},\pi^0} (x_i + \delta x_i)\Phi_i(E)\frac{E}{E_*}^{-\delta\gamma_i}$$

$$\delta x_i = 0,\ \delta\gamma_i = 0 \rightarrow \Phi_{\mathrm{res}} = 0$$

$$\Sigma_{ij} \propto \Phi_{\mathrm{res}}(E_i, E_j)$$



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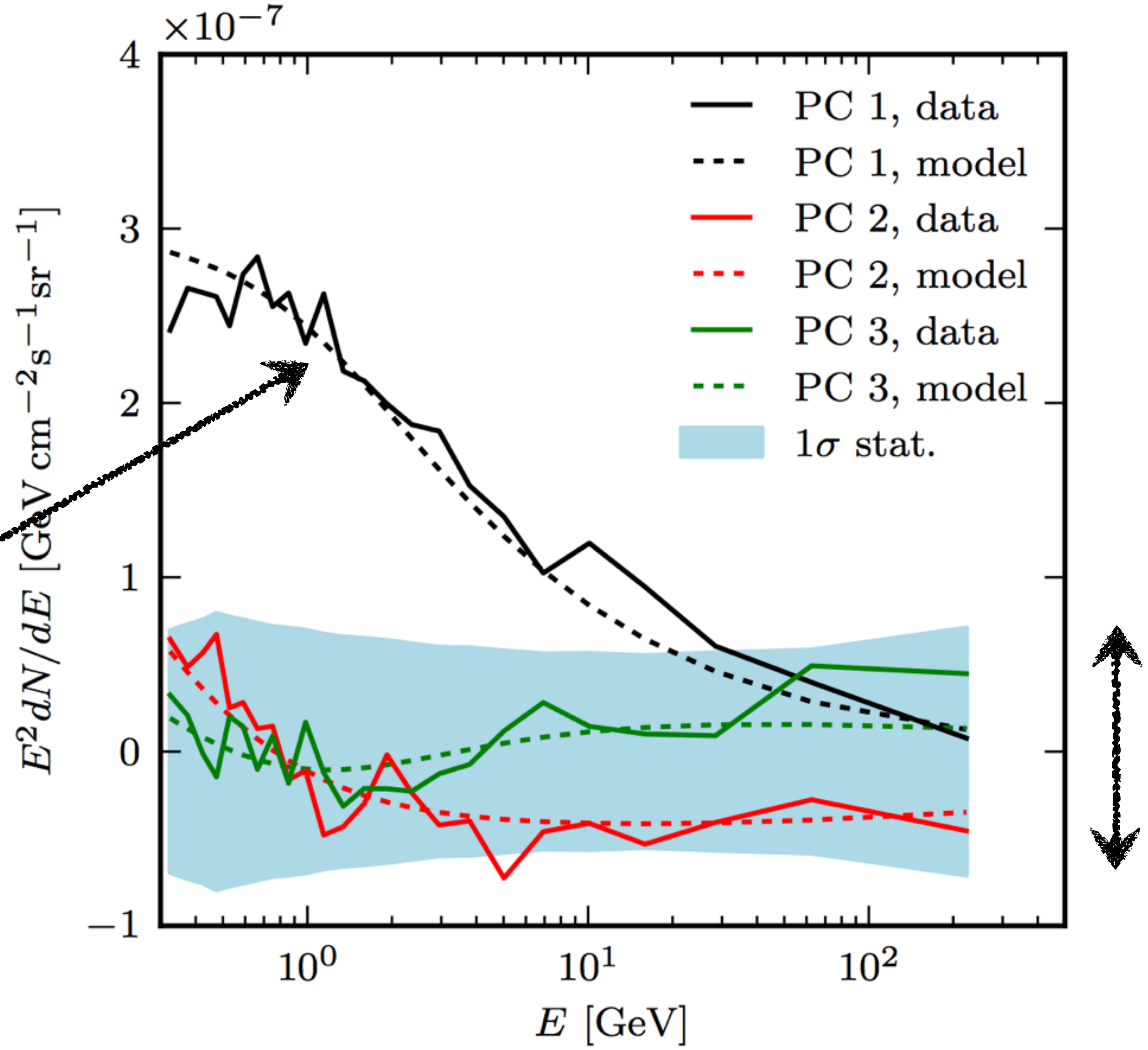
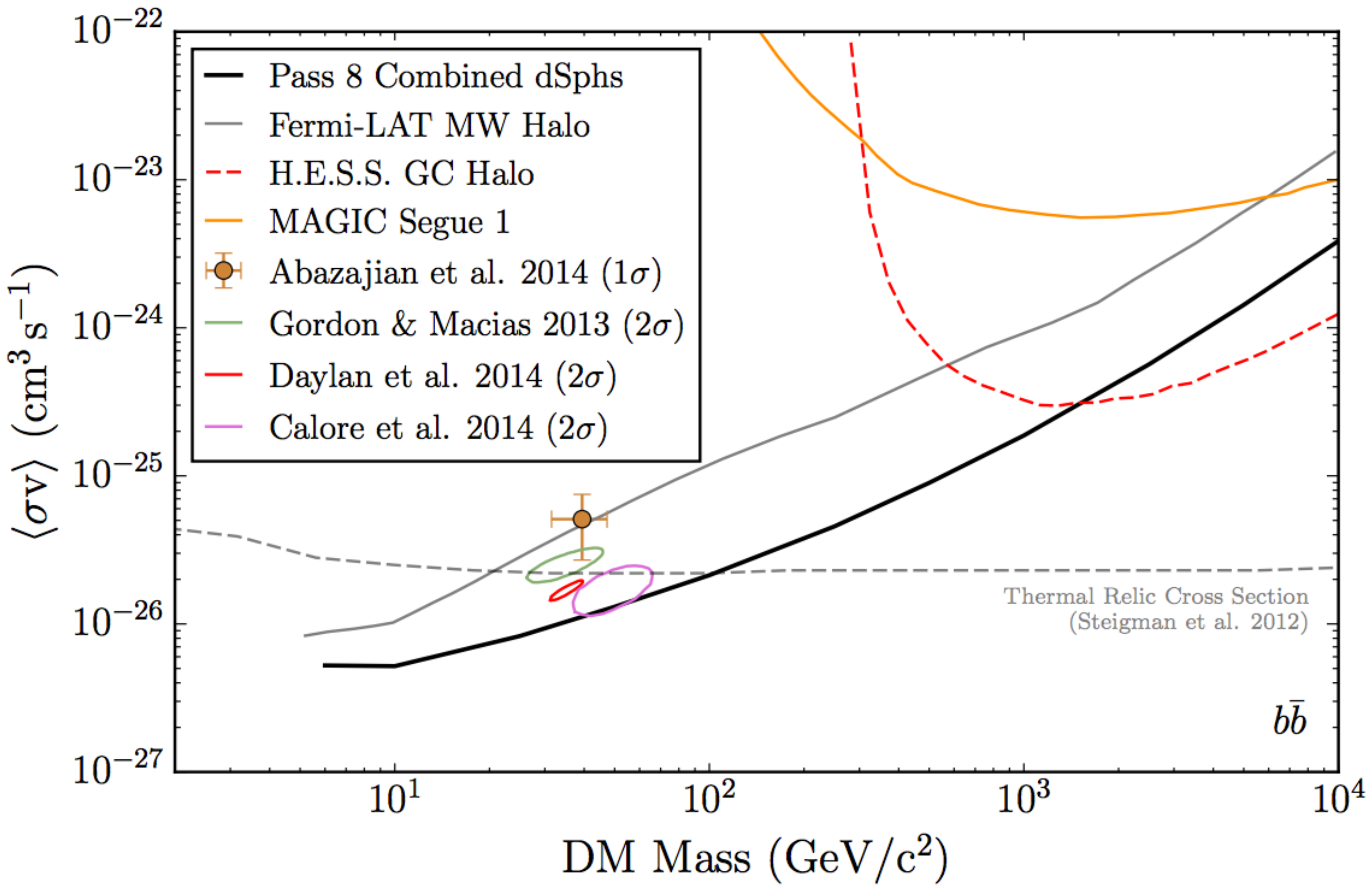


$$\Sigma_{ij} \propto \sum_{\text{k=ICS},\pi^0} (\Delta x_k^2 + \Delta\gamma_k^2 \ln(E_i/E_*)\ln(E_j/E_*))\Phi_k(E_i)\Phi_k(E_j)$$

Consistency with dSph: present and future



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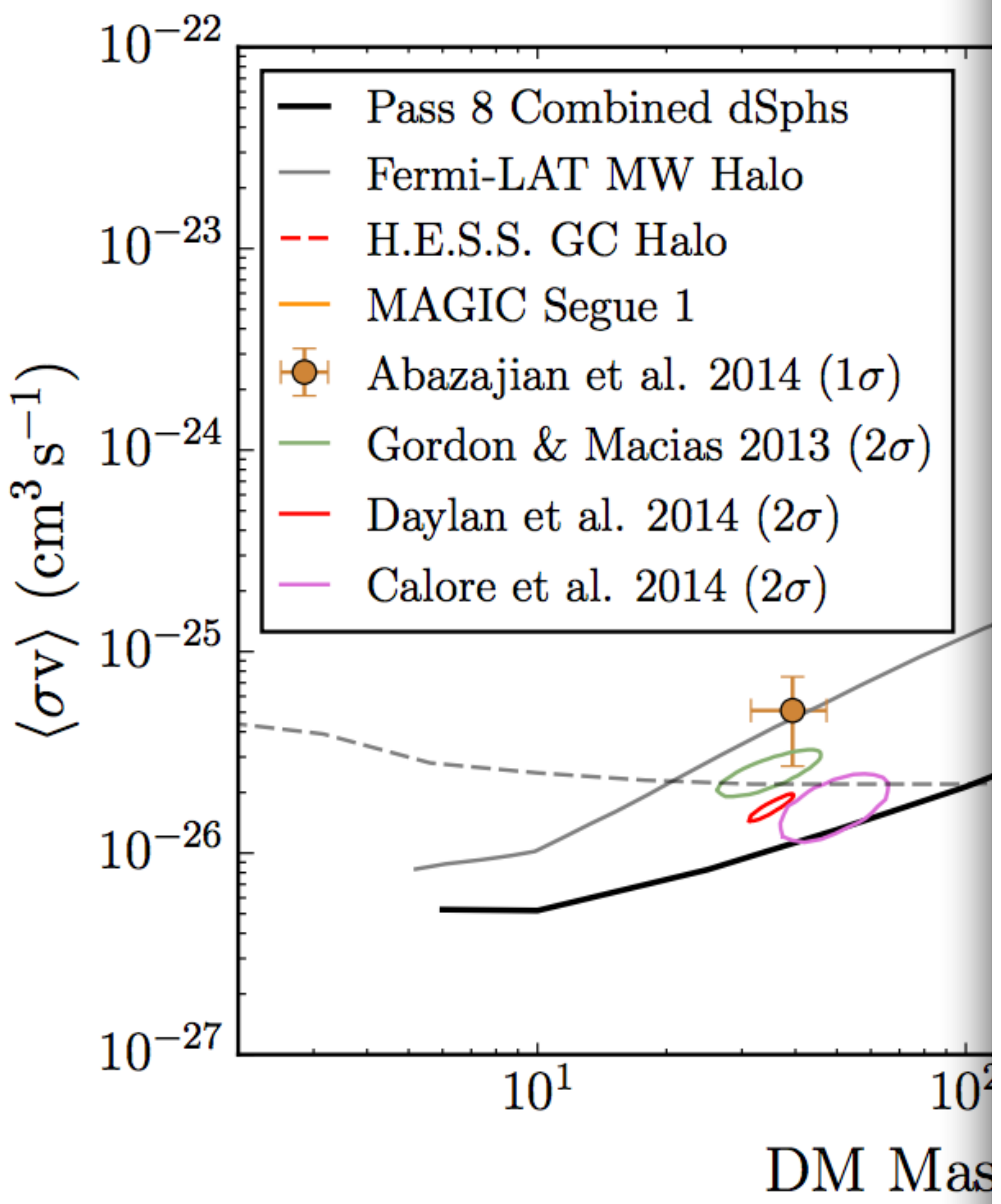

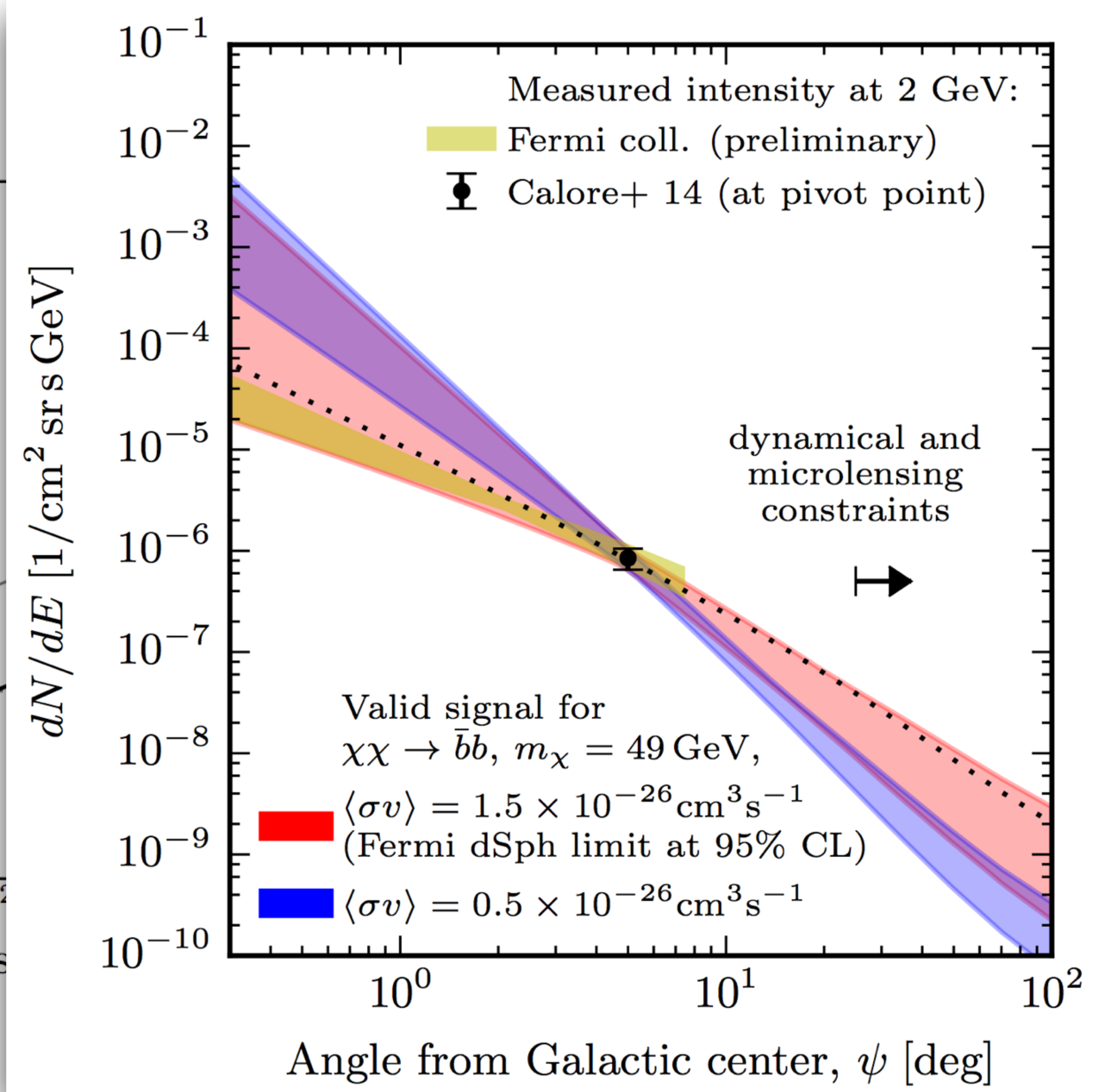

EAGLE simulations

Name	L (Mpc)	N	m_g ($M_\odot$)	m_{dm} ($M_\odot$)	ϵ (pc)
EAGLE HR	25	2×752^3	2.26×10^5	1.21×10^6	350
EAGLE IR	100	2×1504^3	1.81×10^6	9.70×10^6	700
APOSTLE IR	–	–	1.3×10^5	5.9×10^5	308
APOSTLE HR (I)	–	–	1.0×10^4	5.0×10^4	134
APOSTLE HR (II)	–	–	5.0×10^3	2.5×10^4	134

Table 1. Parameters of the simulations discussed in this paper. L is the comoving sidelength of the simulation cube, N the number of simulation particles prior to splitting, m_g the initial gas particle mass, m_{dm} the DM particle mass, and ϵ the Plummer-equivalent physical softening length. The resolution limit is usually taken to be $2.8 \times \epsilon$, i.e. 1.96, 0.98 and 0.87 kpc for EAGLE IR, EAGLE HR and APOSTLE IR, respectively.

Activity of the Galactic centre

Injection of high energetic cosmic rays at the Galactic centre during a burst-like event in the past.

Signs of the past activity of the GC:

- Formation of Fermi bubbles => large-scale outflows generated by (a) jet from MBH or (b) starburst events about 10 million years ago.
- X-ray reflection nebulae at the GC => Sgr A* activity about 300 yr ago.
- Galactic center Lobe (ROSAT data) => $E_{\rm kin} \sim 10^{55} {\rm erg}$ $\tau \sim 10^{6} {\rm yr}$
- OB stellar association: evidence 6 Myr ago + 2 clusters in the inner 50 pc formed 10 million years ago => hints for a global event with enhanced star formation rate.

see for example discussion in Su+ 2010

Slide from G. Ponti