High-Energy Gamma-Rays toward the Galactic Centre

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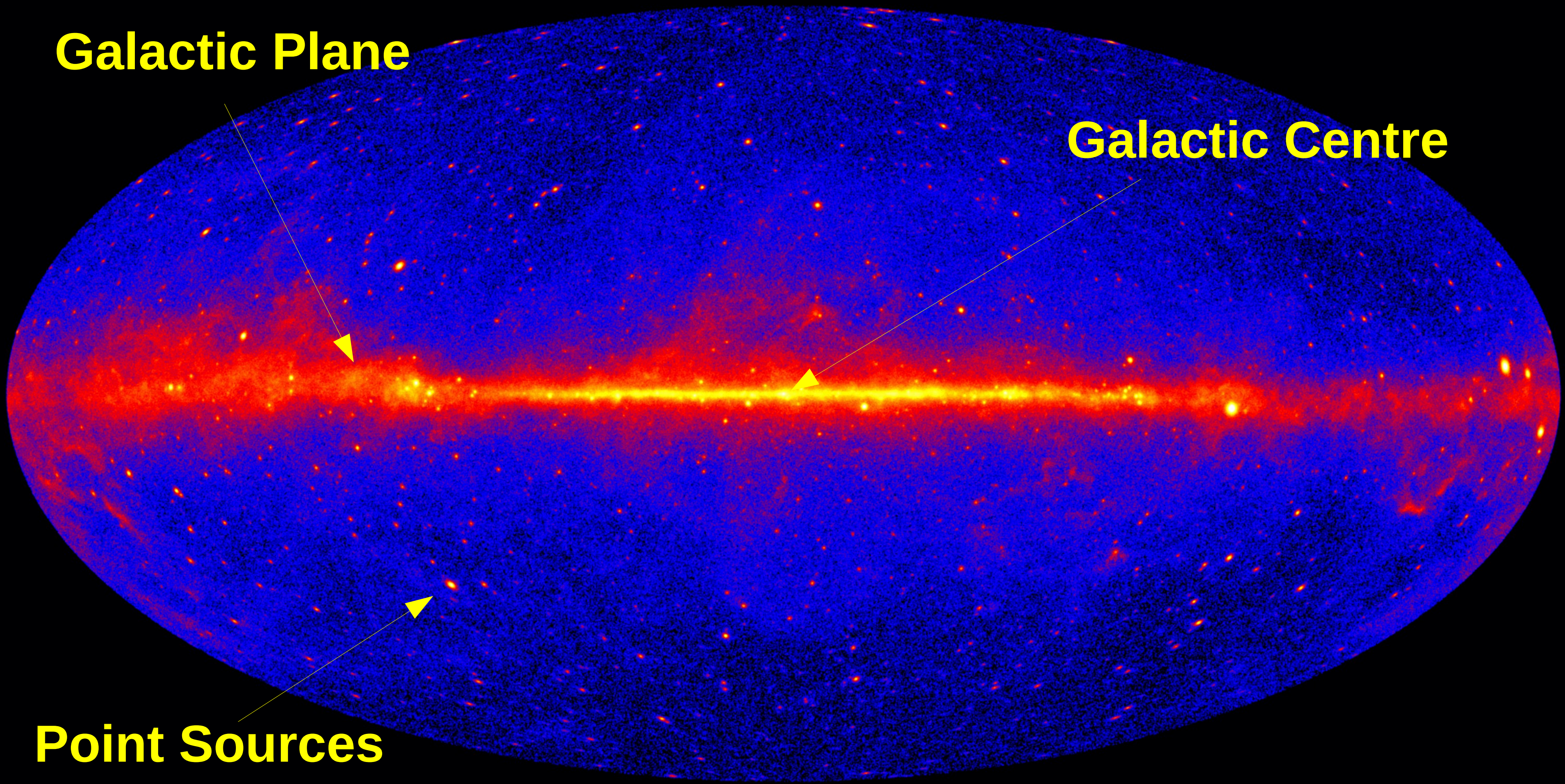
Fermi LAT 5-Year Sky Map > 1 GeV



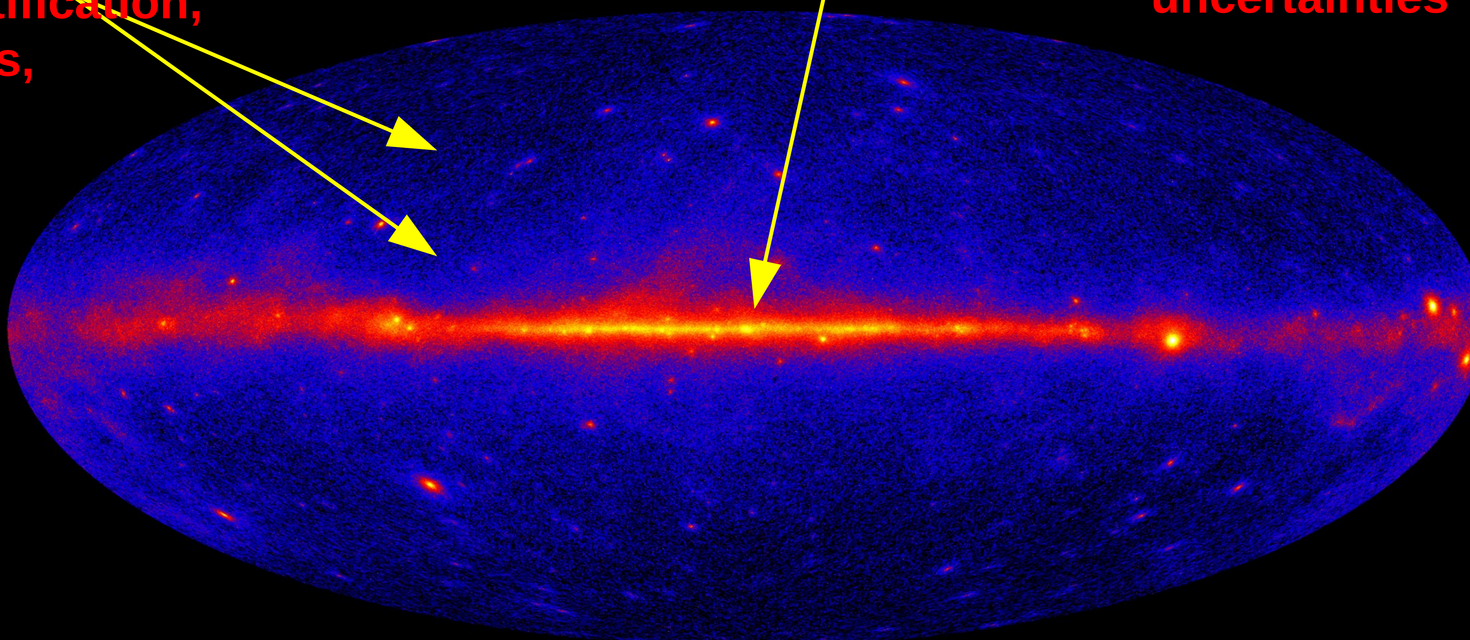
Diffuse γ-ray emission produced by cosmic rays interacting with interstellar medium (ISM). Comprises majority of the total γ-ray flux!

Where to look for gamma-ray signatures of dark matter?

Galactic Centre: good statistics, strong background/foreground + source confusion

Satellites: low background + good source identification, low statistics,

Halo: large statistics, diffuse Galactic emission uncertainties



Spectral lines: no astrophysical uncertainties, low statistics

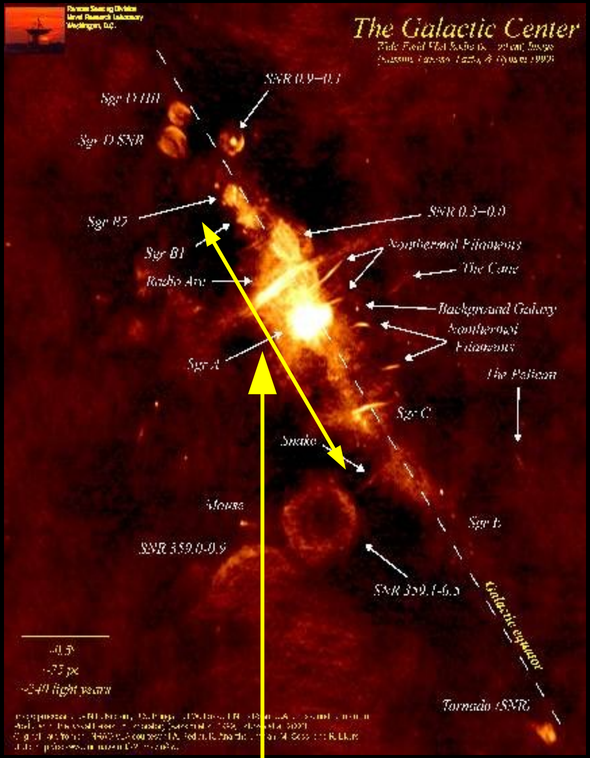
Extragalactic diffuse: large statistics, foreground subtraction + astrophysical source populations

Galaxy clusters: low background, low statistics

What is Interesting about the GC?

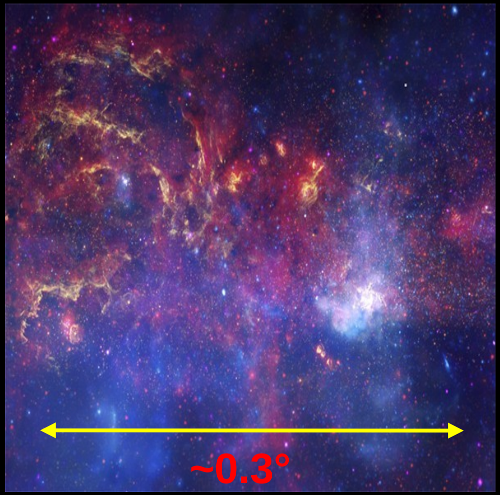
- **The region surrounding the GC is complicated containing**
  - **Potential signal of particle dark matter**
  - **Intense emission by cosmic rays interacting with the ISM**
  - **Many astrophysical sources**
- **It is the most confused region of the `high-energy' gamma-ray sky**
- **Numerous groups have analysed the Fermi data and found an `excess' of emission with various explanations being advanced**

Radio (90 cm)

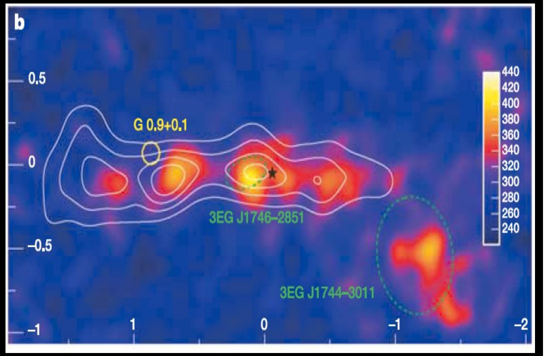


~0.4° effective 68% radius > 1 GeV (front)

Optical/Infrared/X-ray



HESS TeV γ-rays

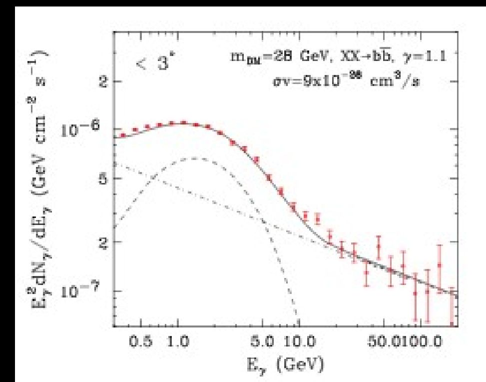


l = ±2°

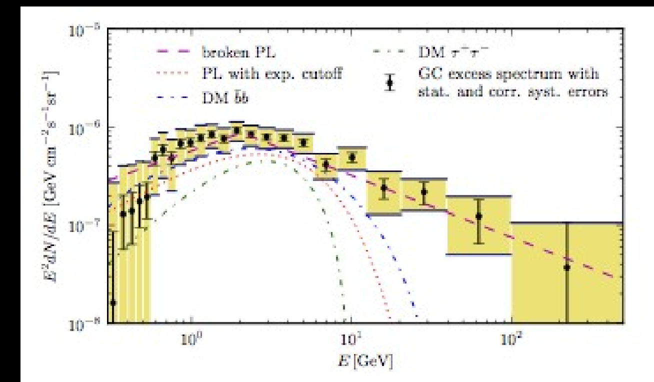
The Fermi `GeV-excess'

- Not to be confused with the EGRET `GeV-excess', which was an instrumental issue (see Fermi-LAT collab. PRL 103, 251101 [2009])
- The Fermi GeV-excess is an excess of emission with respect to interstellar emission and point-source models for the region about the GC that are based on knowledge of ISM tracers and cosmic-ray propagation models
- The questions: is this excess explainable by some modelling uncertainty for the components of the existing models, or is a `new' component definitely required? For the latter, is it in the cosmic ray injector class (accelerators, dark matter), or a collection of weak point sources, or …?
- Conclusive answer of the first question is very difficult

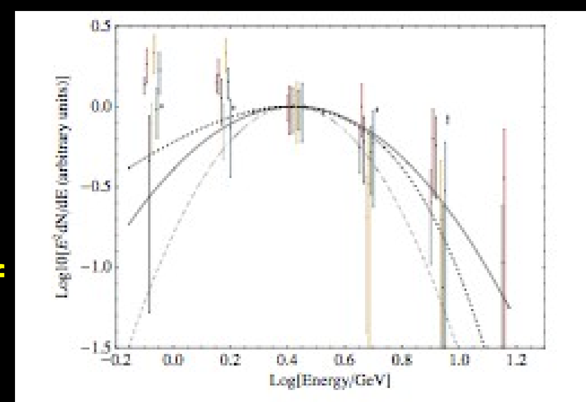
Hooper & Goodenough 2009



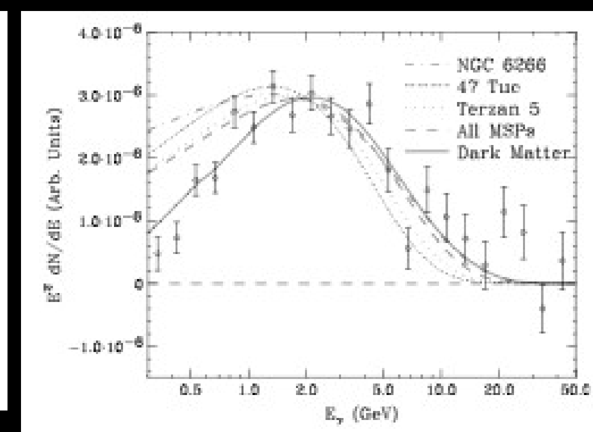
Calore et al. 2015



Abazajian et al. 2014



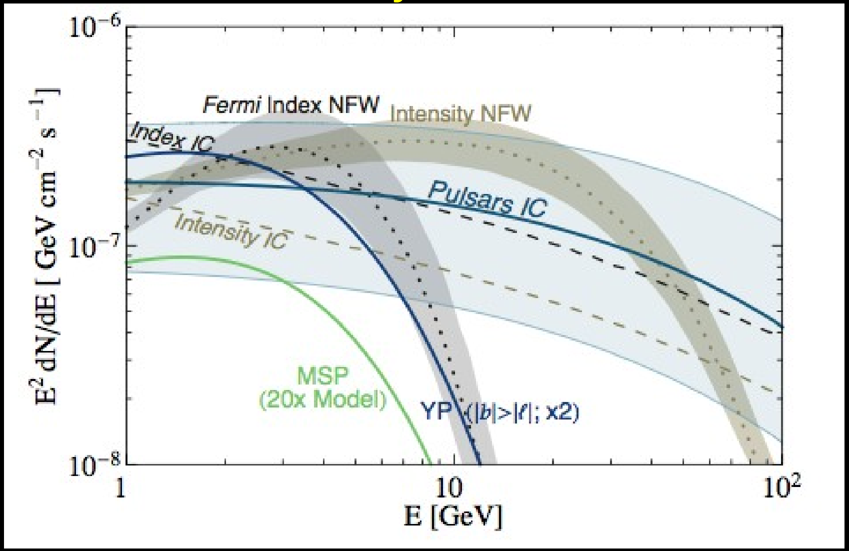
Daylan et al. 2016



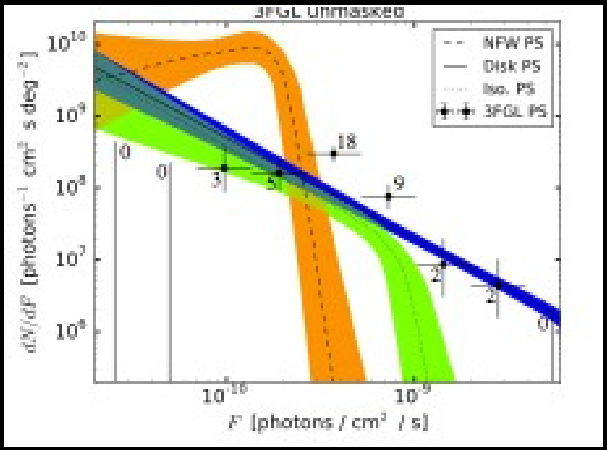
Interpretations

- Dark matter (H&G, Daylan et al.)
- Unresolved sources, e.g., millisecond pulsars (Gordon&Macias, Azerbajian et al.)
- `Normal' pulsars (O'Leary et al.)
- Other studies have investigated statistically whether the characteristics are consistent with `smooth' or `point' (unresolved sources): Lee et al., Bartels et al.

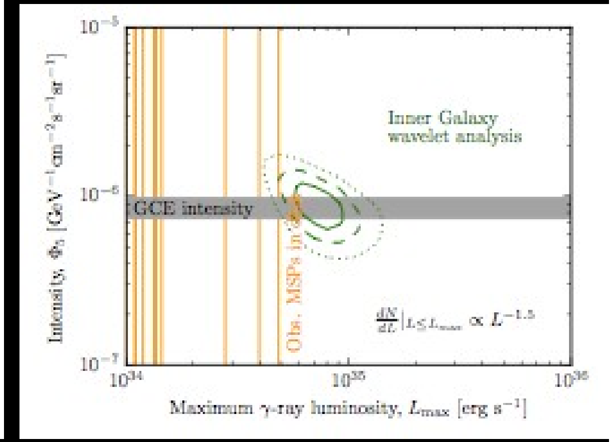
O'Leary et al. 2016



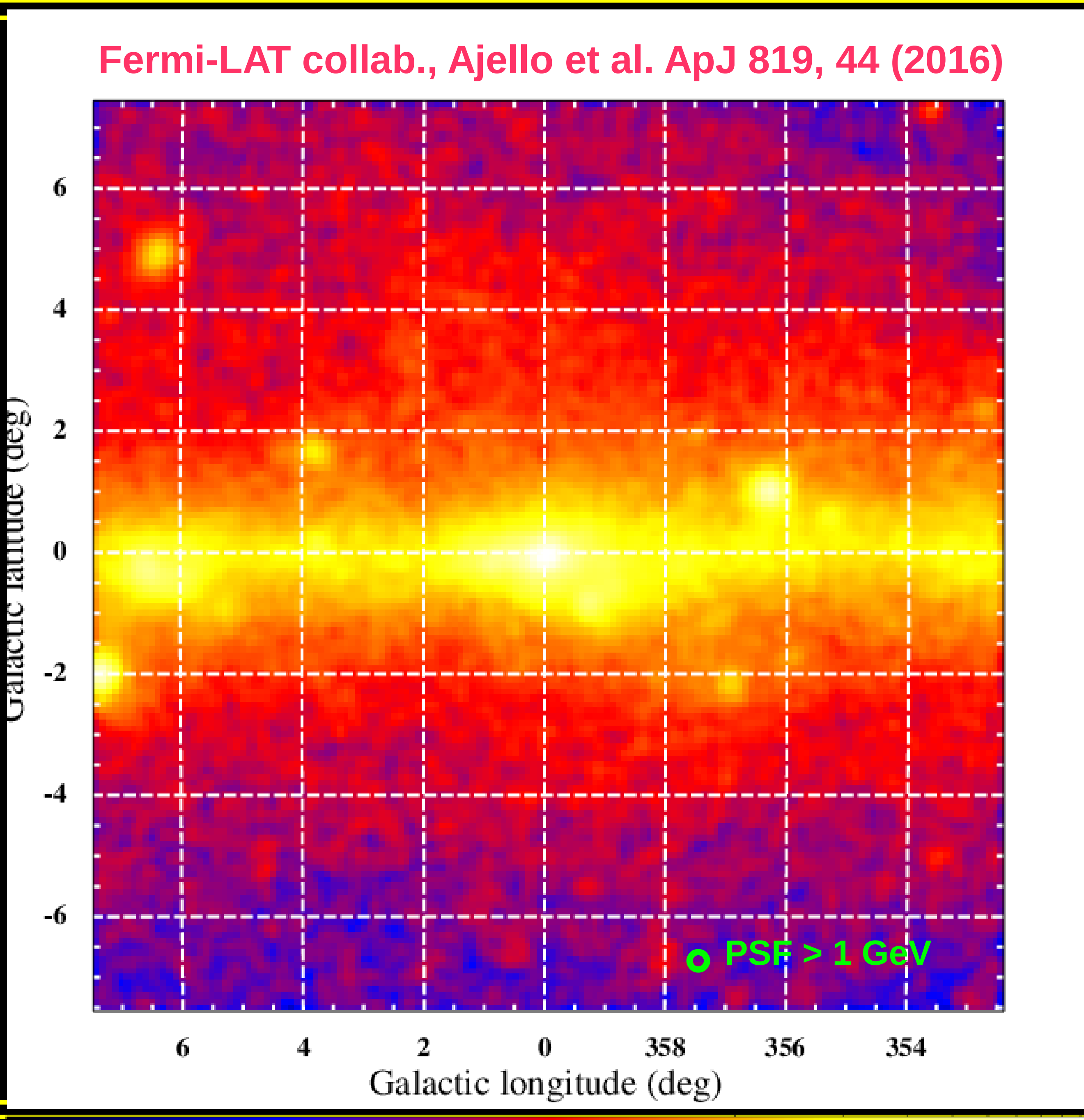
Lee et al. 2016



Bartels et al. 2016



Characterisation of the Emission from 15°x15° Region About the Galactic Centre

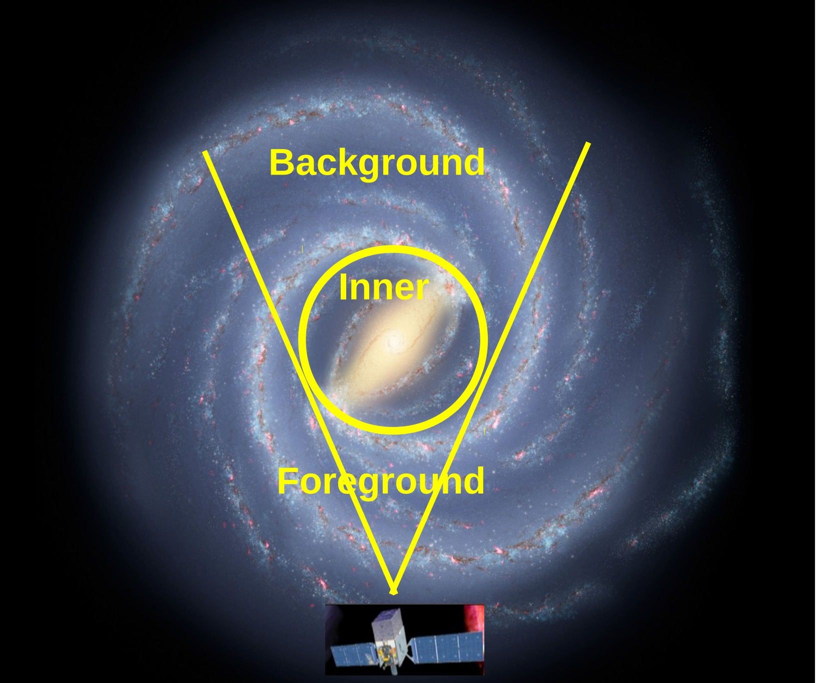


i2 Months Data,
Front converting
CLEAN events > 1
GeV, Pass 7
eprocessed

Disentangling the Many Sources of Gamma-Ray Emission is Challenging ...

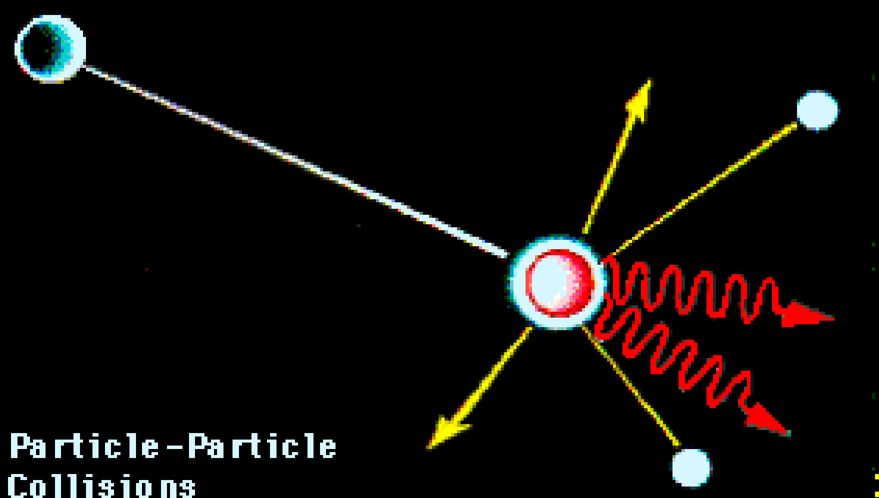
The emission toward the inner Galaxy consists of a number of components:

- Outer Galaxy
- Foreground MW
- Region surrounding GC
- Point or small extended sources (over all distances)
- Unresolved sources (over all distances)
- Extragalactic emission
- Isotropic background produced by misclassified cosmic rays (CRs)

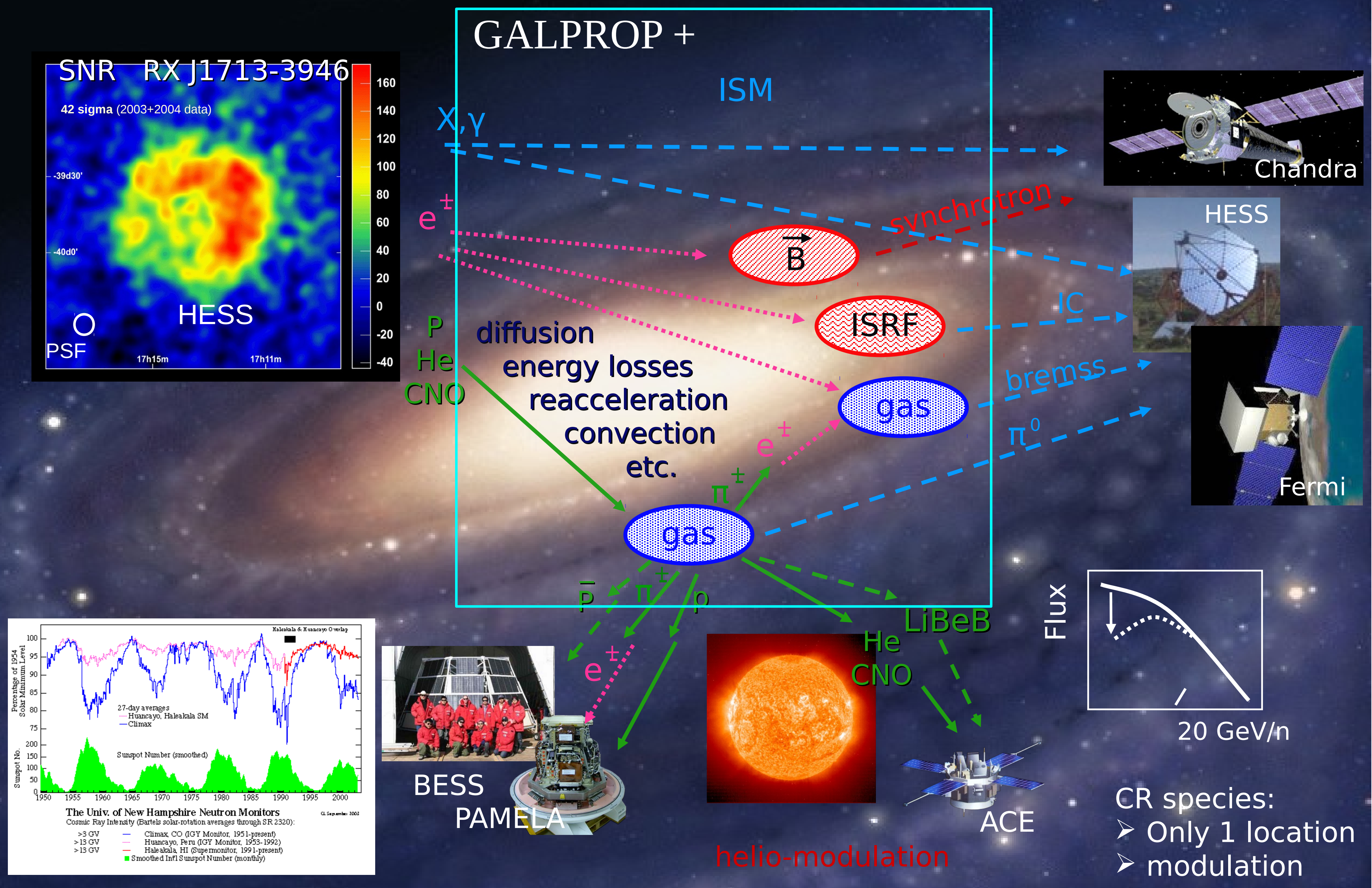


Use GALPROP cosmic ray propagation/diffuse emission code

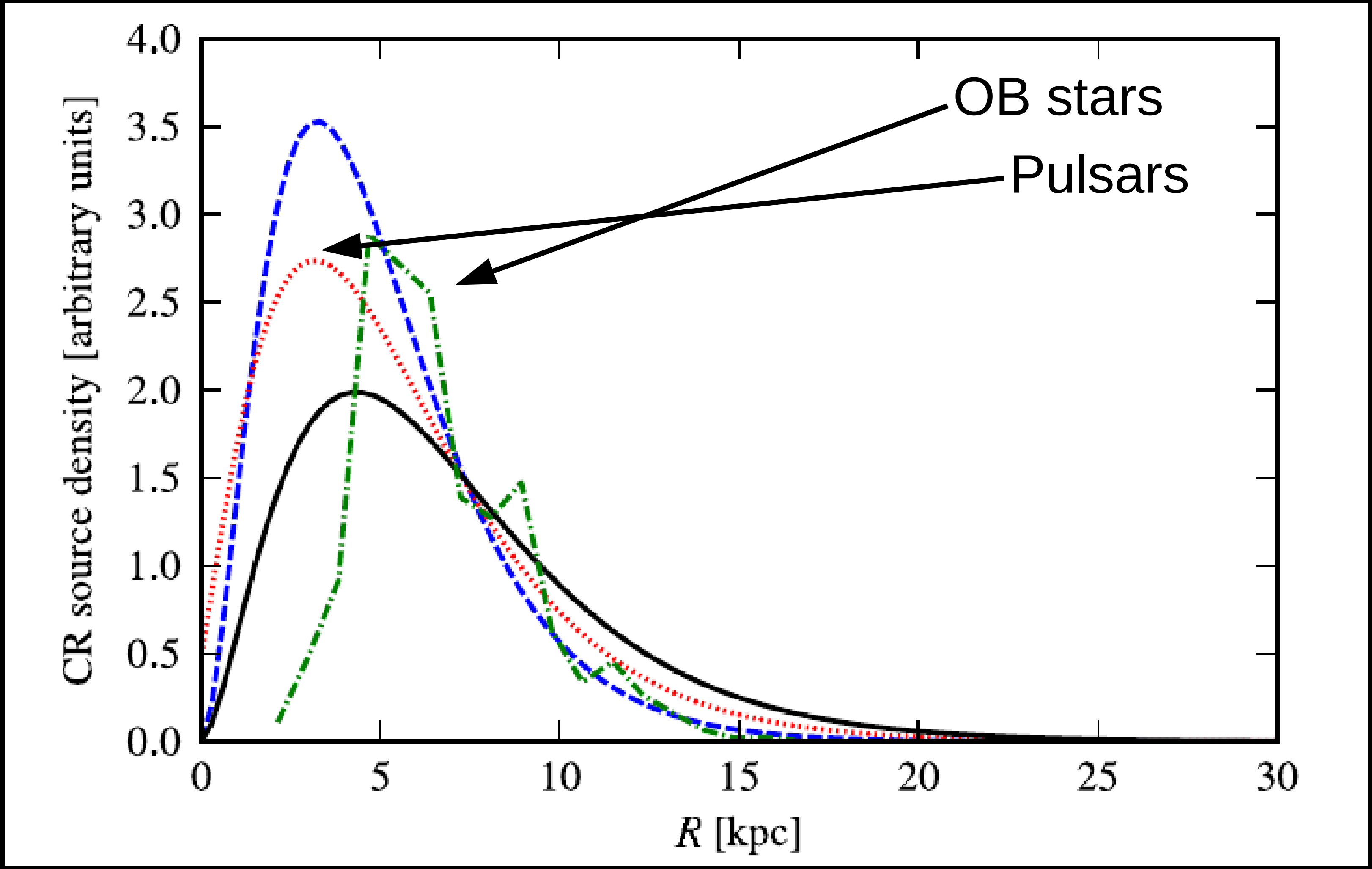
http://galprop.stanford.edu



Cosmic Rays and Interstellar Emission

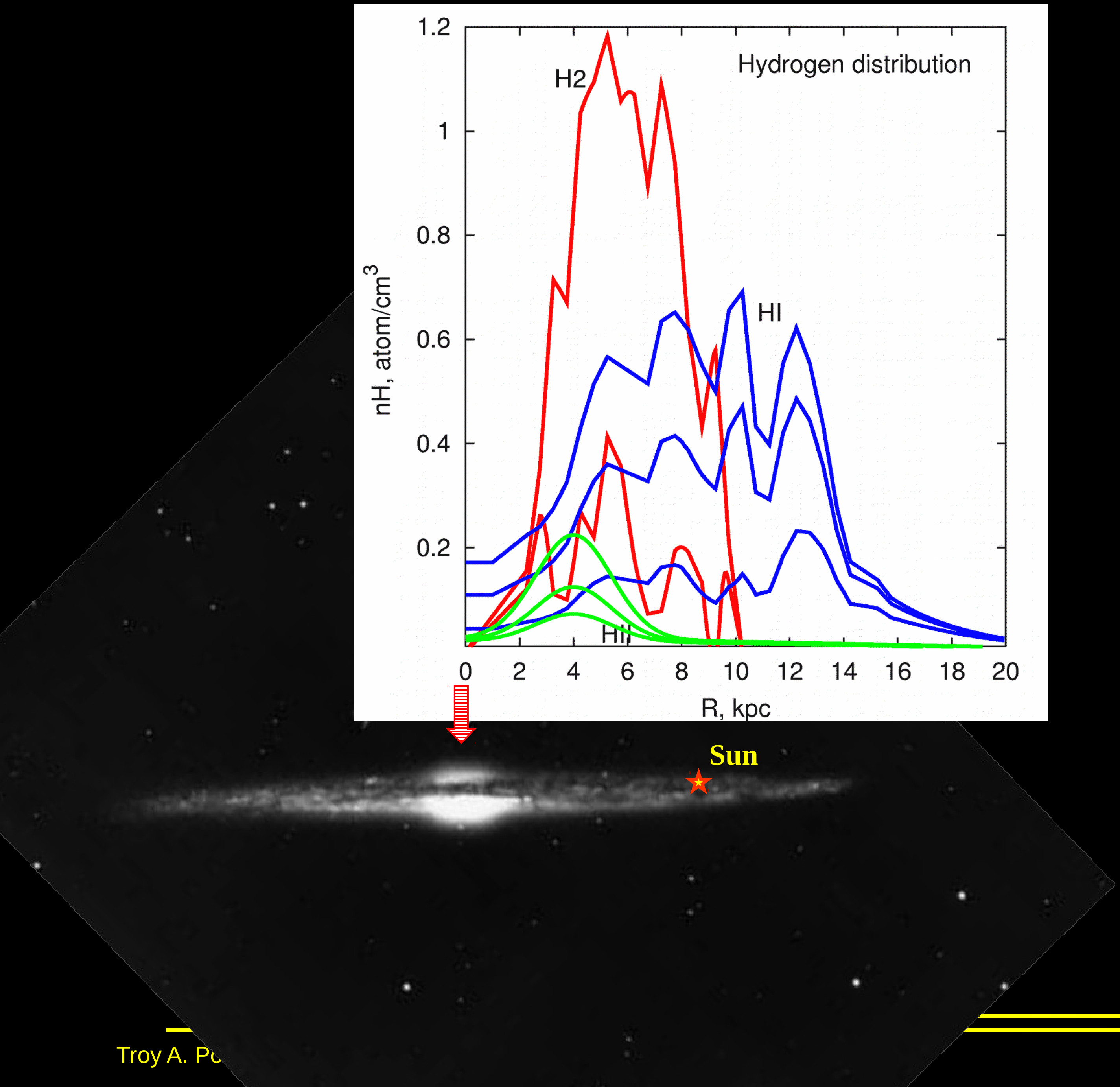


Cosmic Ray Source Distributions for Baseline IEMs



See Ackermann et al. ApJ 750, 3 (2012)

Gas distribution in the Milky Way



Molecular hydrogen (H_2) traced using CO J=1→0 transition, concentrated in clouds near Galactic plane (z_{scale} ~ 70 pc)

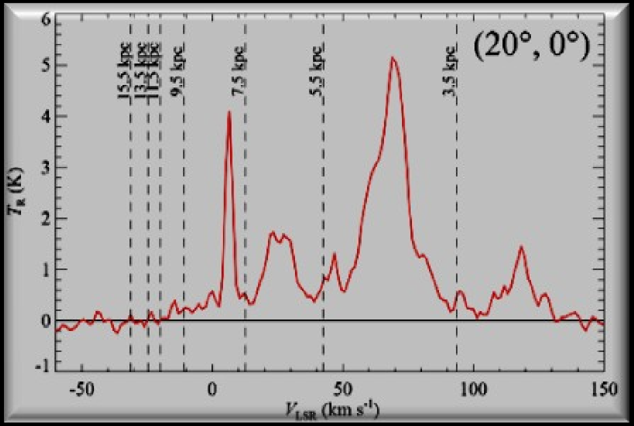
Atomic hydrogen (HI) ~smoother and wider distribution out to ~30 kpc (z_{scale}~ 0.5 kpc)

Ionised hydrogen (HII) also contributes with lower density but exists out into halo (z_{scale} ~ 1 kpc)

Distribution of interstellar gas

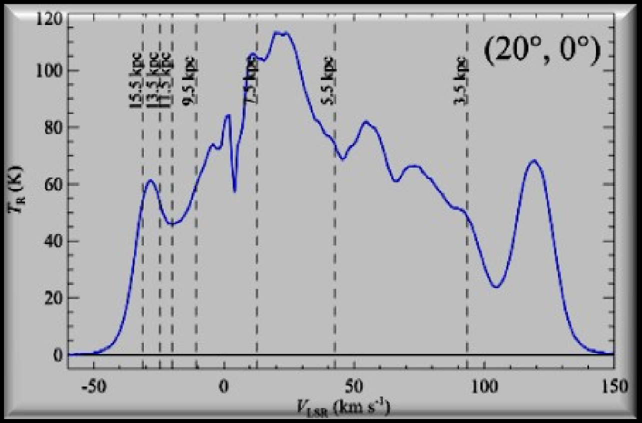
- Neutral interstellar medium – most of the interstellar gas mass
  - 21-cm H I & 2.6-mm CO (surrogate for H_2)
  - Differential rotation of the Milky Way – plus random motions, streaming, and internal velocity dispersions – is largely responsible for the spectrum
  - Using rotation curve V(R) and assumption of circular rotation about GC enables a unique line-of-sight velocity-Galactocentric distance relationship
  - This is the best – but far from perfect – distance measure available
- Column densities: $N(H_2)/W_{CO}$ ratio assumed; a simple approximate correction for optical depth is made for N(H I); self-absorption of H I remains

CO



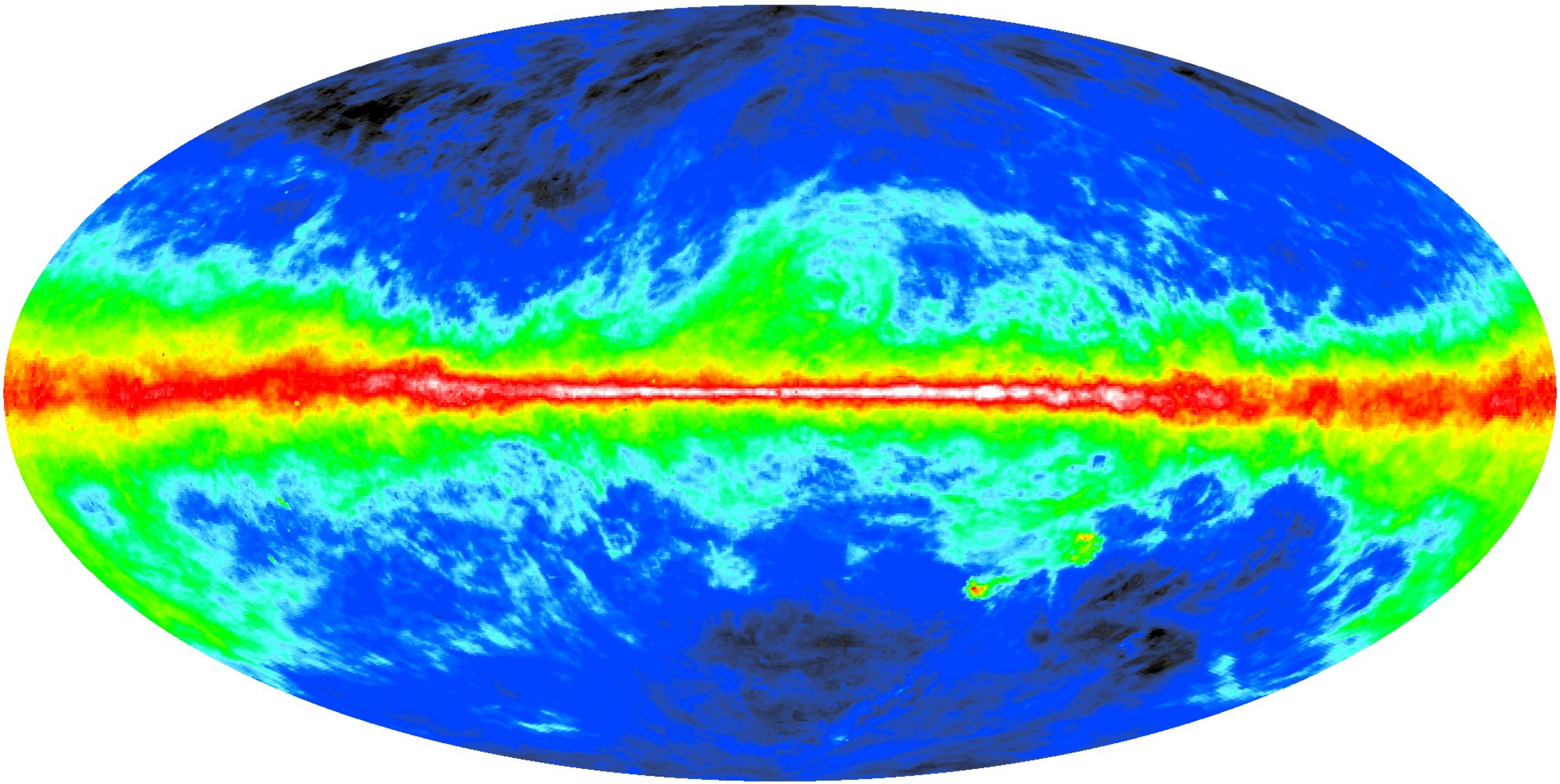
Dame et al. (2001)

H I



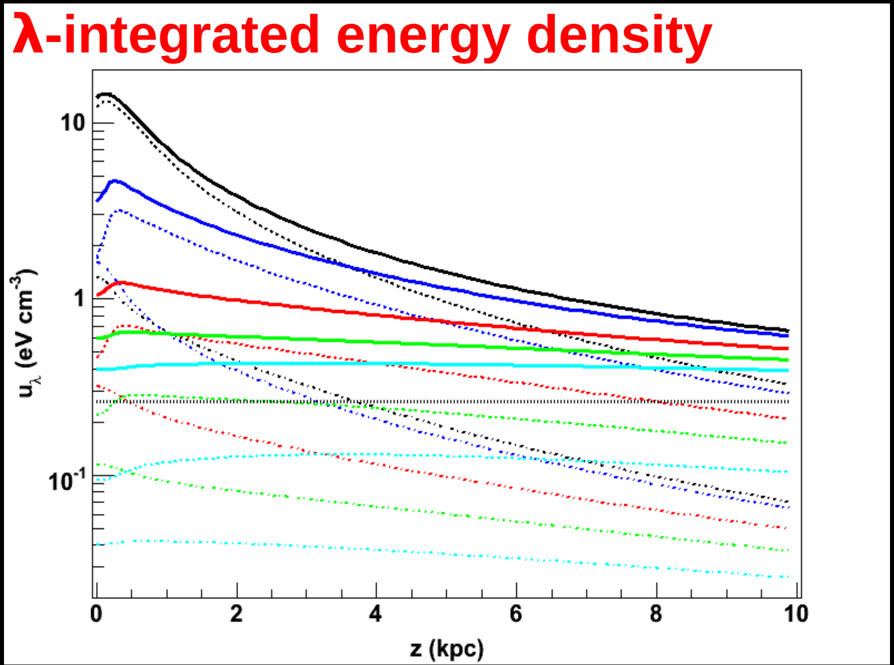
Kalberla et al. (2005)

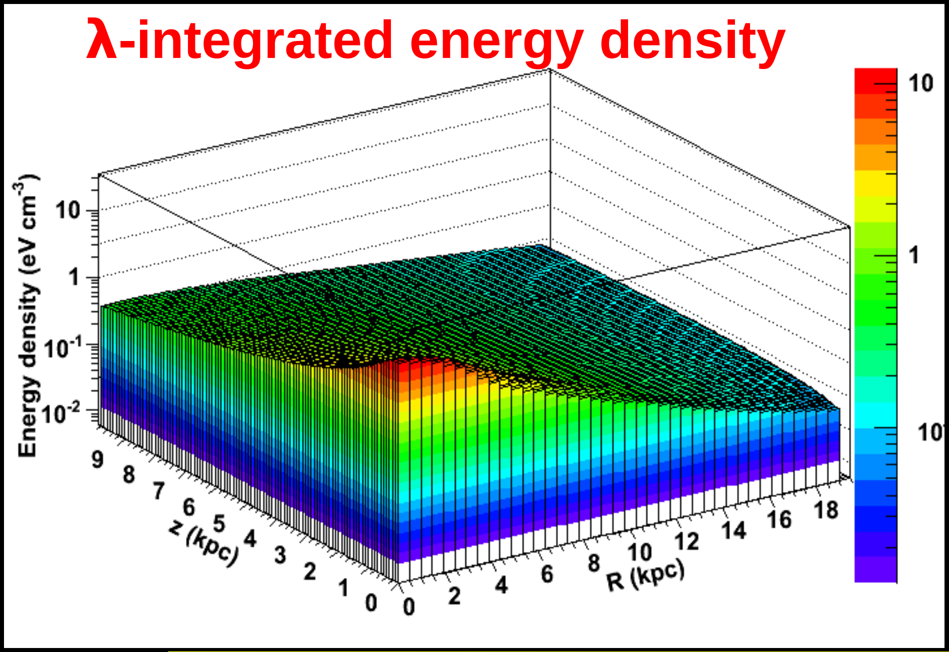
All-sky HI map (Leiden-Argentine-Bonn)



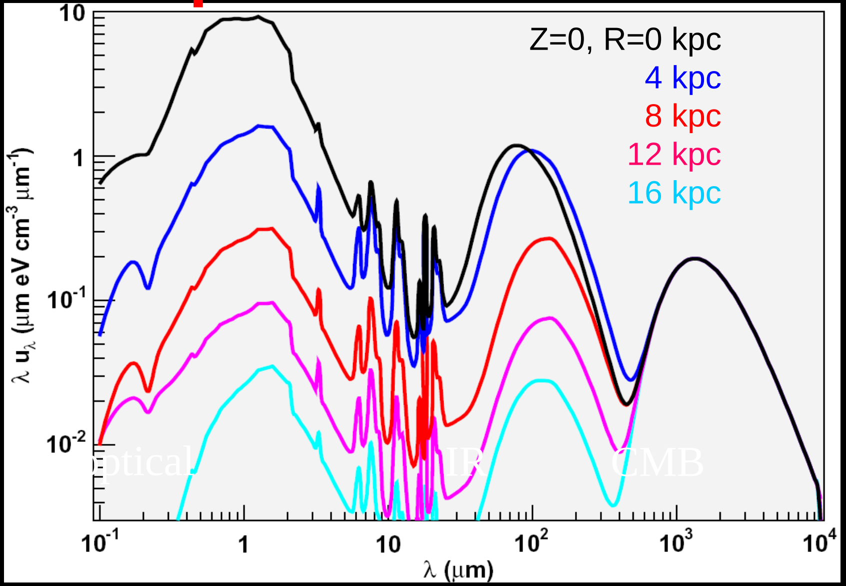
Interstellar Radiation Field

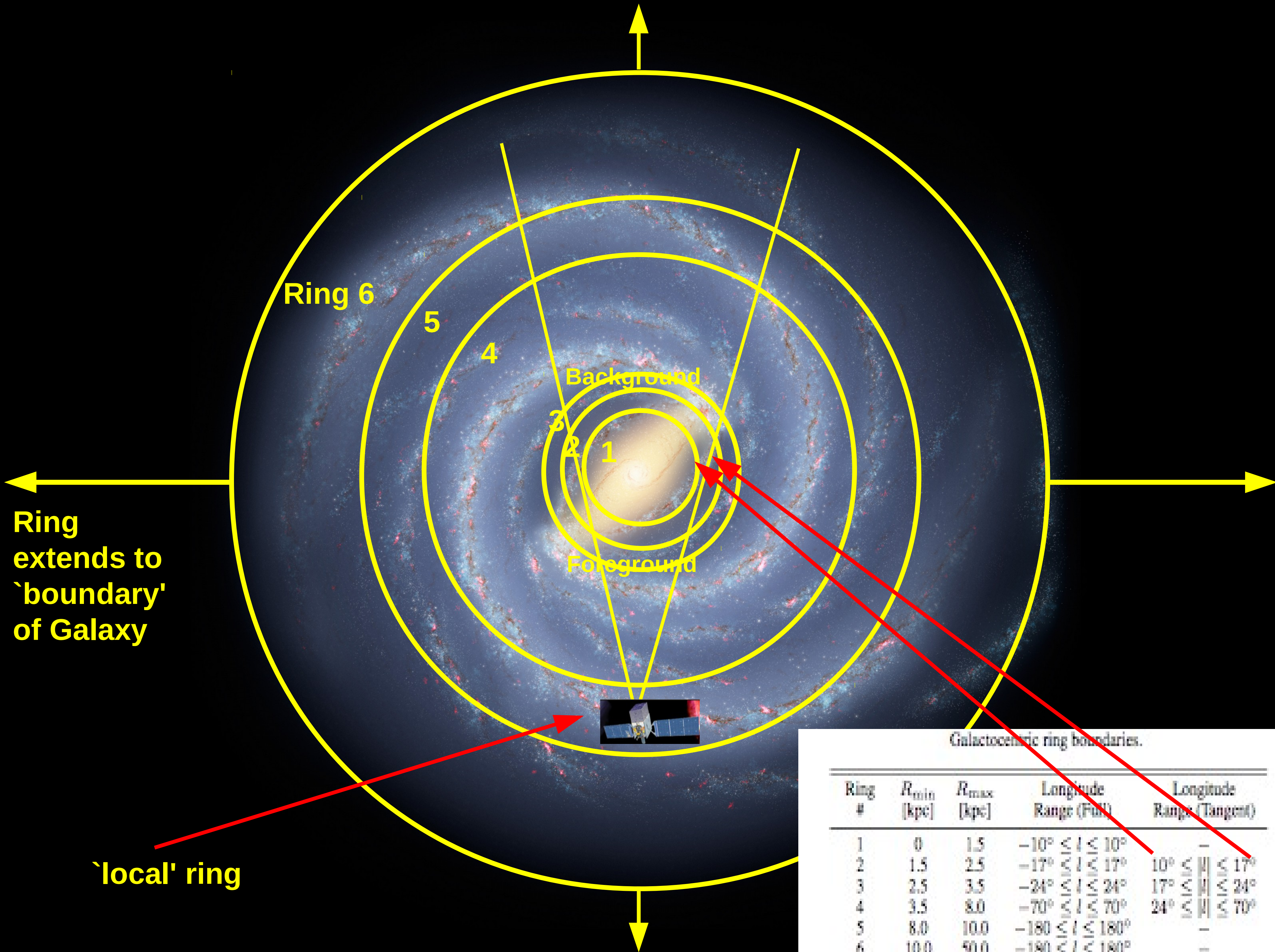
- Detailed modelling required because dust in the ISM is strongly absorbing of starlight
- Need: stellar and dust densities, stellar luminosity model, radiation transfer calculation (typically MC)
- Spectral intensity is strongly dependent on position





In-plane SED





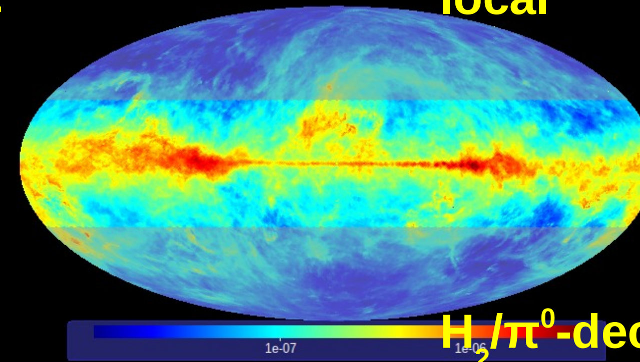
Galactocentric ring boundaries.

Ring #	$R_{\min}$ [kpc]	$R_{\max}$ [kpc]	Longitude Range (Full)	Longitude Range (Tangent)
1	0	1.5	$-10° \leq l \leq 10°$	–
2	1.5	2.5	$-17° \leq l \leq 17°$	$10° \leq \lvert l \rvert \leq 17°$
3	2.5	3.5	$-24° \leq l \leq 24°$	$17° \leq \lvert l \rvert \leq 24°$
4	3.5	8.0	$-70° \leq l \leq 70°$	$24° \leq \lvert l \rvert \leq 70°$
5	8.0	10.0	$-180 \leq l \leq 180°$	–
6	10.0	50.0	$-180 \leq l \leq 180°$	–

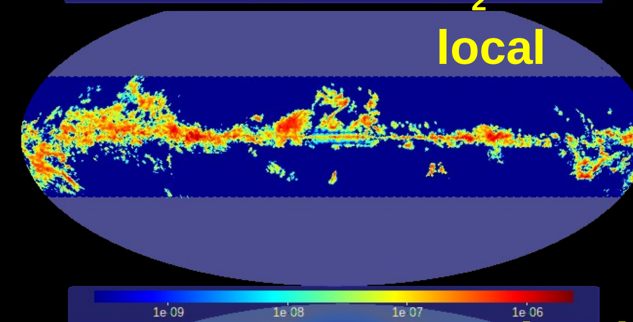
Scaling Procedure Overview

- For each source model generate GALPROP intensity maps separated in Galactocentric rings for π^0-decay and brem (HI, H_2, HII), and IC → brem (all) and π^0-decay (HII) held constant
- Fit to high latitude data (|b| > 50°) to obtain `isotropic' component → determines structureless gamma-ray component + background regardless of origin
- Fit the GALPROP ring templates in sky regions where only a single (or couple) of components dominate, e.g., the local gas-related emission and IC are determined using data outside the plane; the in-plane data mainly determines the gas-related emission for all other rings
- Also include a local radio loop template
- Use 3rd Fermi Catalogue (3FGL – 4 years) for point sources in various tuning regions
- Exclude some regions where unmodelled extended components (e.g., Fermi bubbles, Cygnus would bias fit) and (importantly) do not use the 15°x15° region about the GC

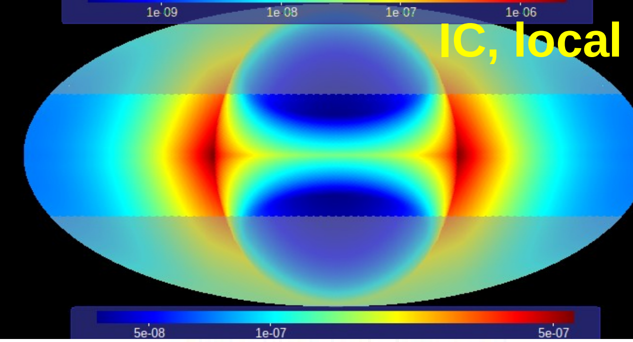
HI/π^0-decay, local



H_2/π^0-decay, local



IC, local



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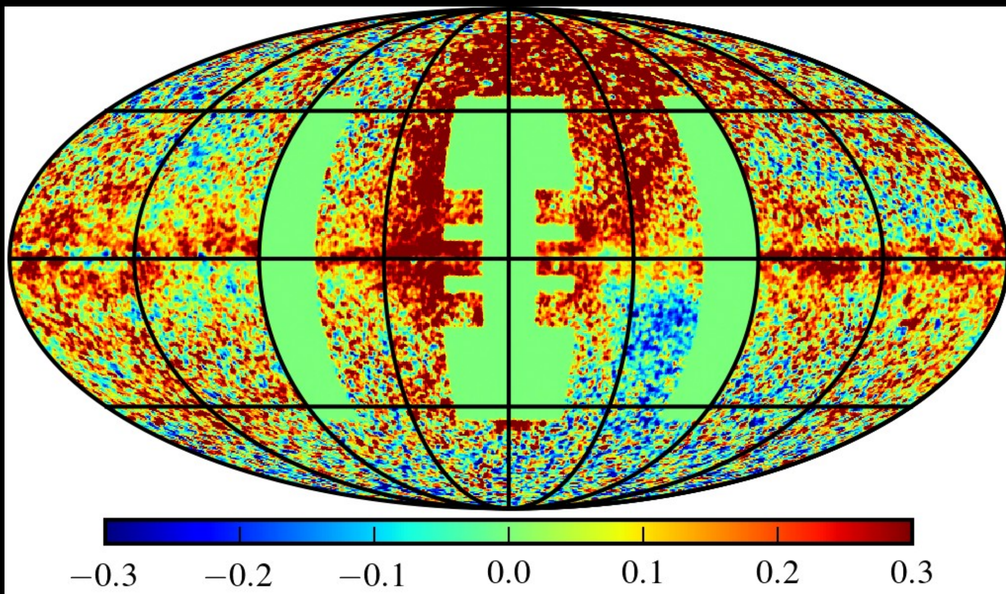
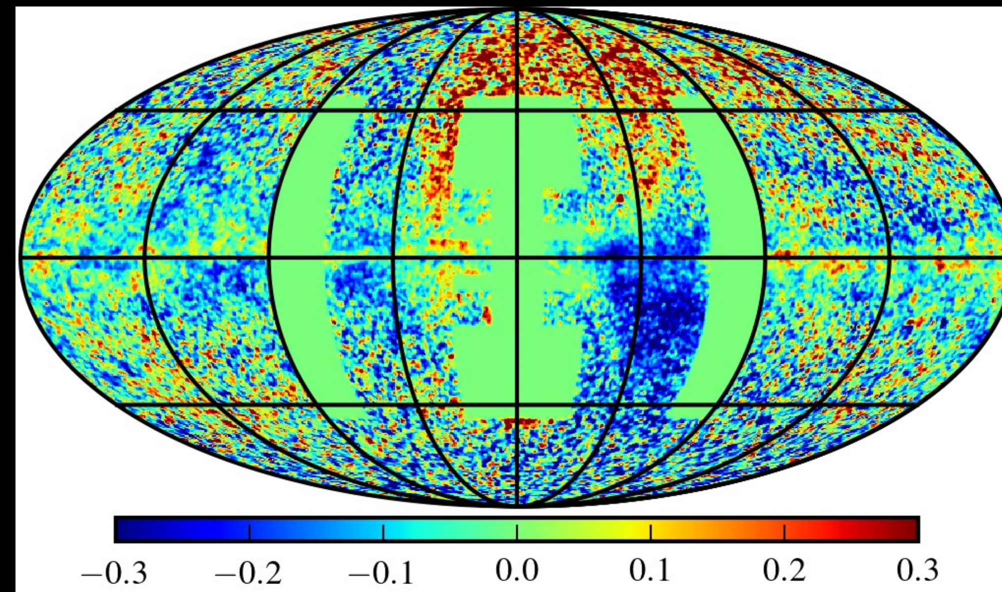
Scaled Interstellar Emission Model (IEM) vs. Baseline

Pulsars baseline 1-3 GeV



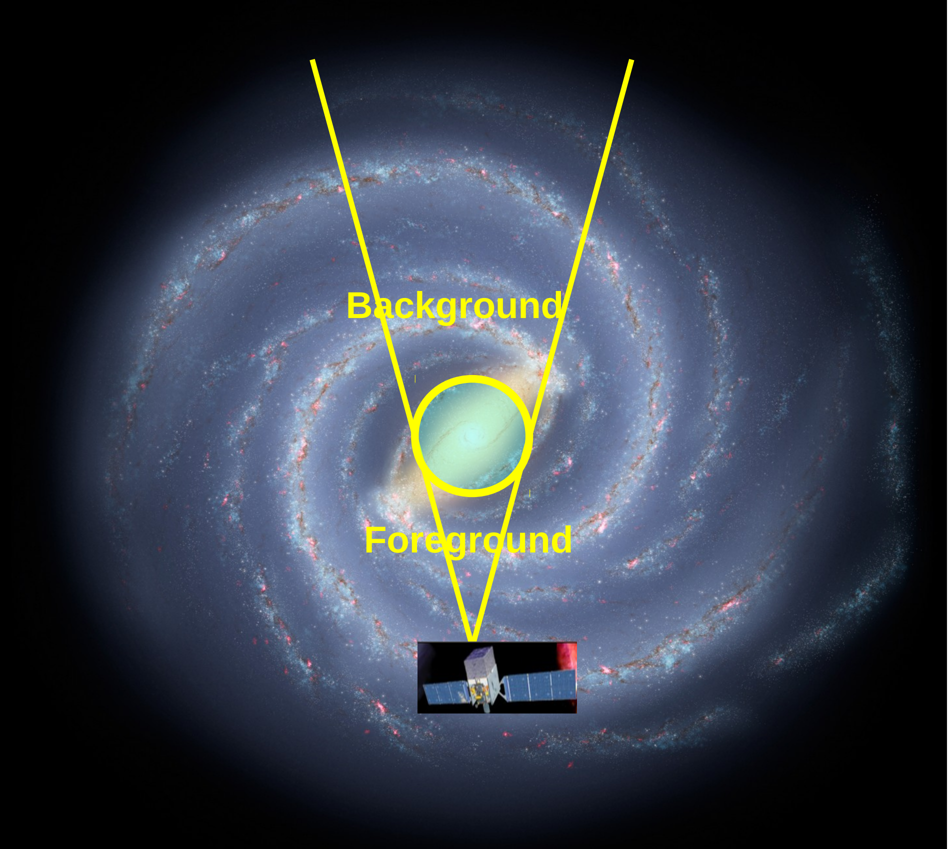
Pulsars tuned intensity 1-3 GeV



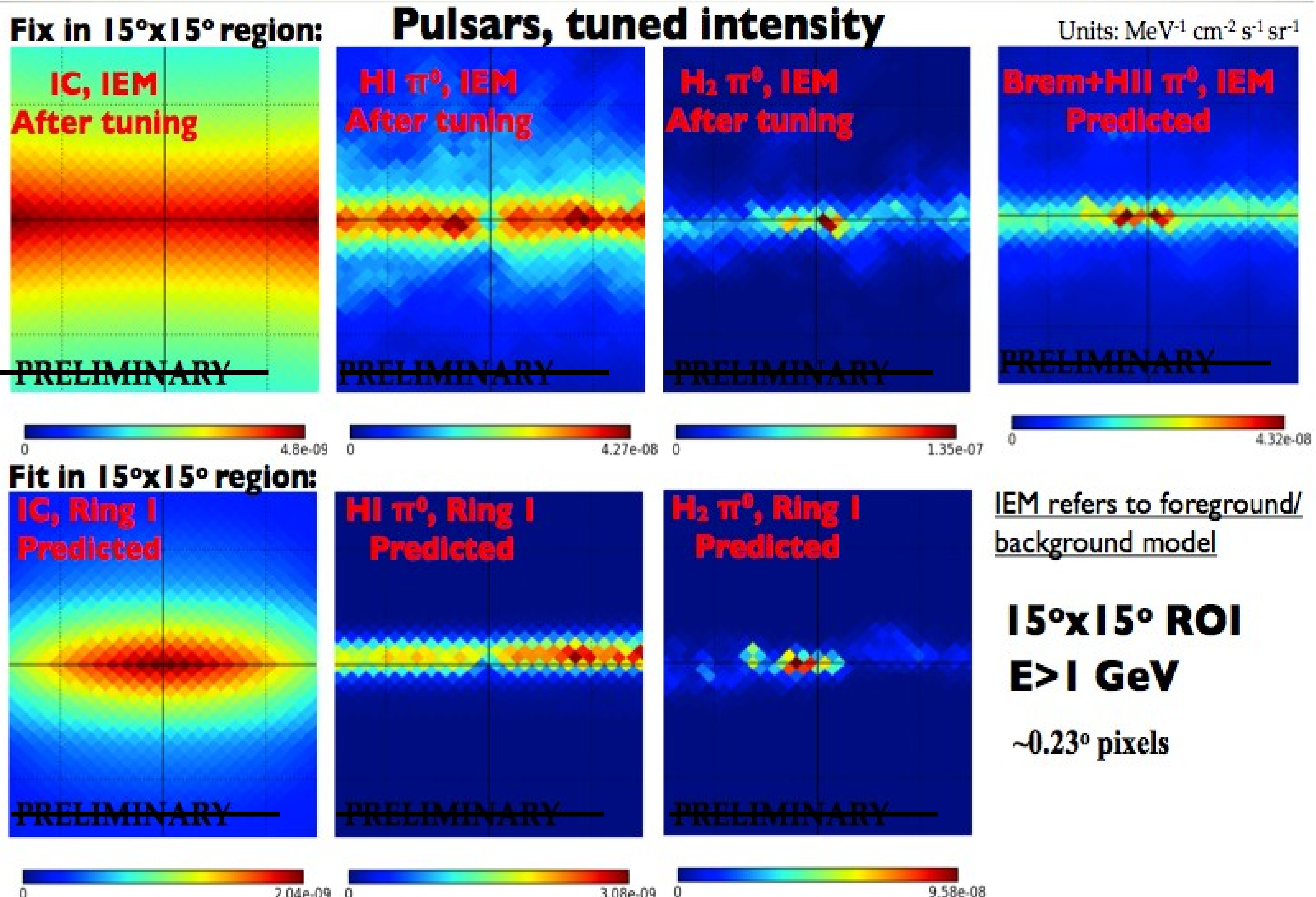
- Scaling reduces the under-prediction by the baseline IEM → this is the case for the full energy range that we use (1-100 GeV), even though only the lowest energies are shown above (large green regions are not used for tuning)
- There are 4 IEMs: Pulsars/OBstars intensity tuned, and `index' tuned → the latter variant has additional degrees of freedom for the spectral index of the gas-related interstellar emission inside the solar circle
- The fractional residuals for each tuned model are very similar, but differ in small details → there is no `best' IEM

Modelling the 15°x15° RoI

- The emission from the inner RoI is modelled for each IEM
- Point sources candidates are determined using a method employed for the Fermi catalogues to identify seeds and optimise spatial positions
- Each IEM (held constant) + seeds + ring 1 interstellar emission components are fit using max-likelihood
- Procedure iterated (with seed finding) until no significant point-like excesses remain in residuals
- Bremsstrahlung and HII/π^0-decay for the inner region are held constant at GALPROP predictions because they are sub-dominant

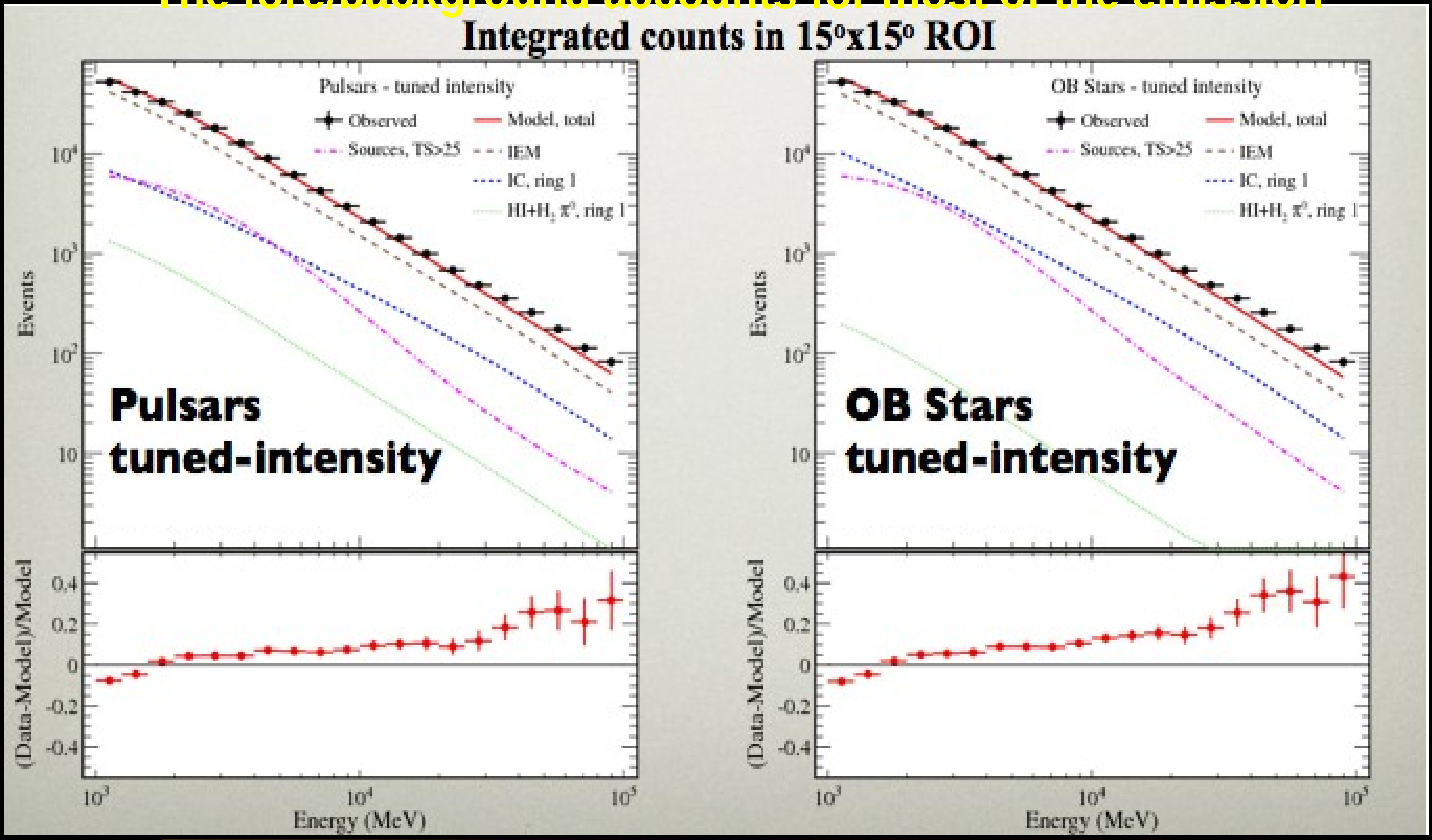


Components of Model Across 15°x15° RoI



Results – Intensity Scaling

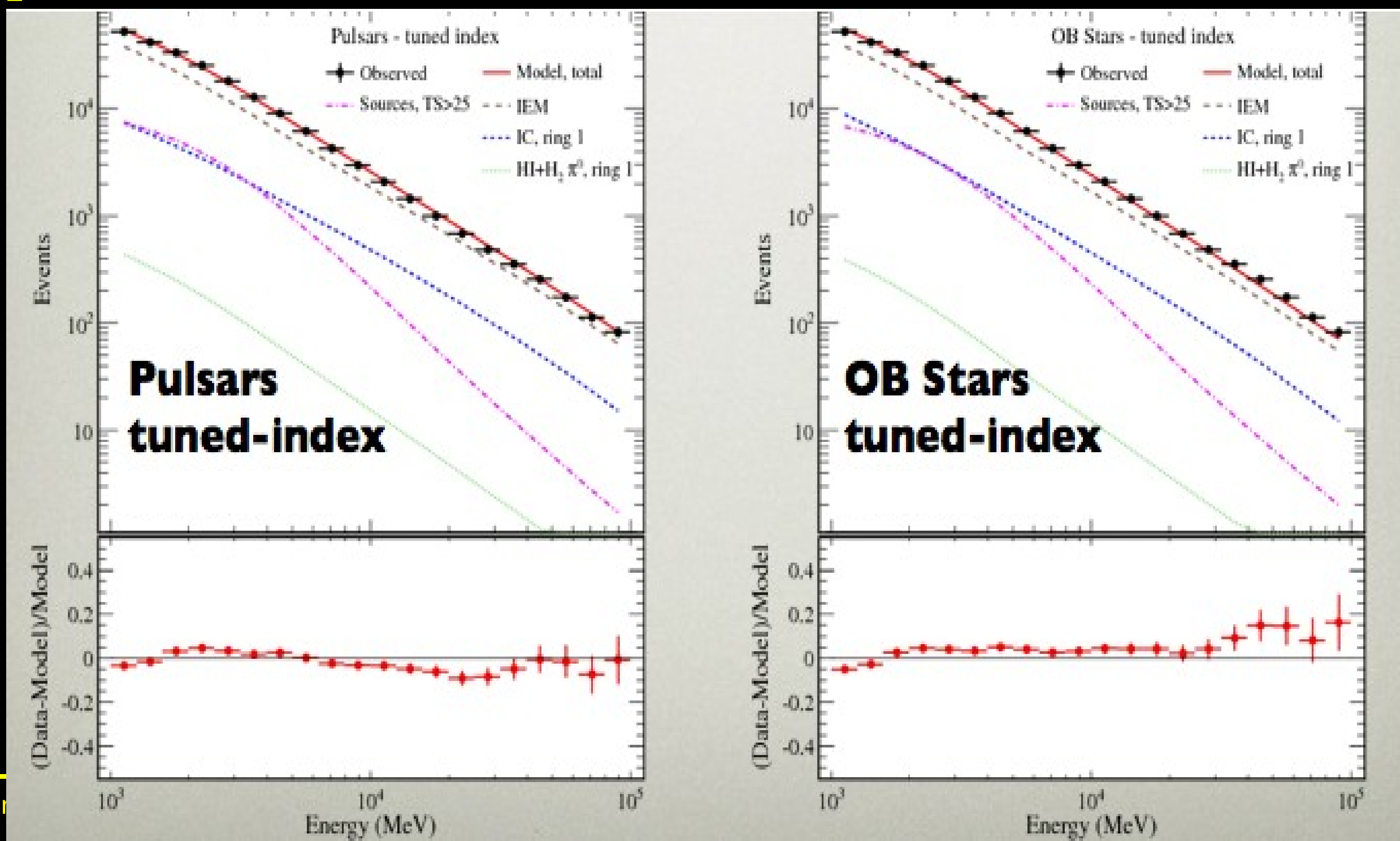
- Data-model agreement is ~5-10% averaged over the 15x15 deg region up to ~30 GeV
- The fore/background accounts for most of the emission



Results – Index Scaling

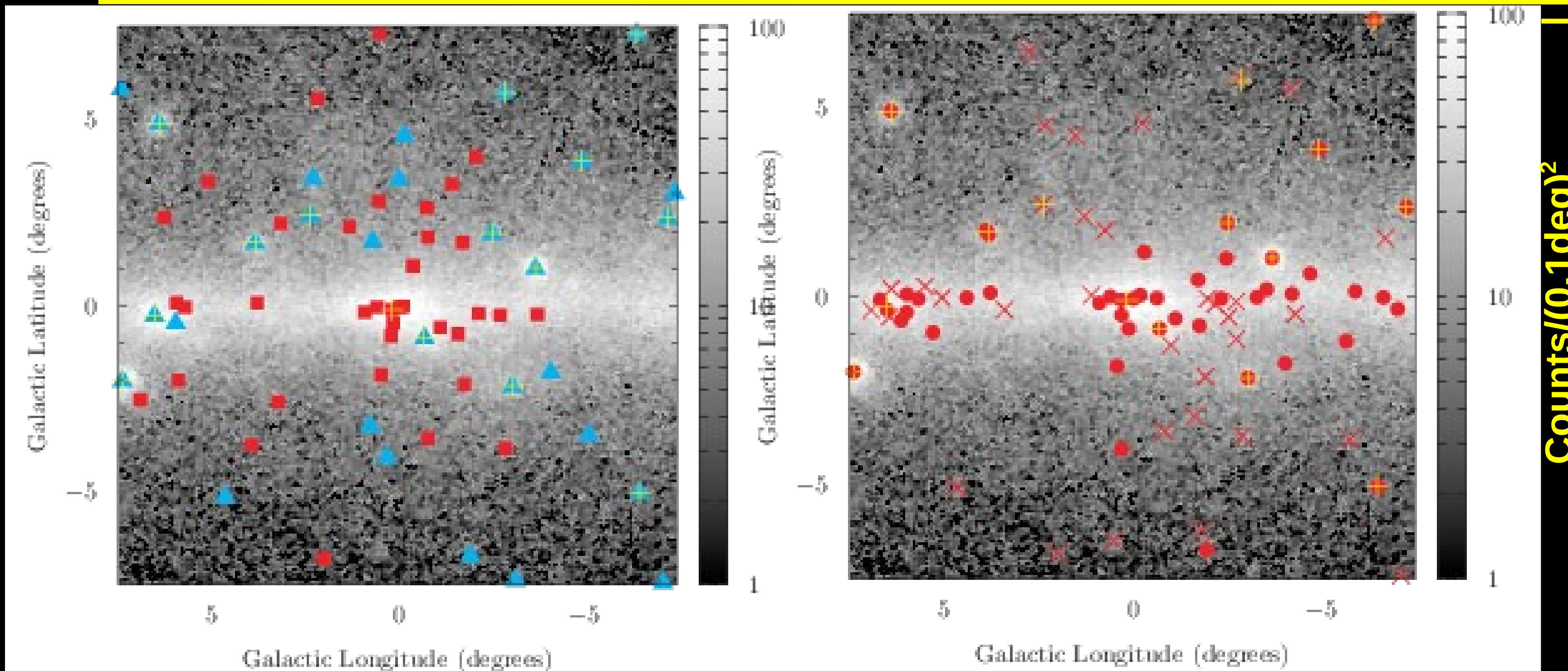
- Agreement better for tuned index IEMs
- For all IEMs the fitted IC for ring 1 is much brighter (7-30x) than predicted – can be due to more intense ISRF or CR $e^{\pm}$ over the inner region
- Point sources comparable to IC
- HI/H_2 π^0-decay much dimmer than predicted

Integrated flux in 15°x15° ROI, E>1GeV, 10^{-8} ph cm^{-2} s^{-1}			
IC, Ring 1	π^0, Ring 1	IC, IEM	π^0, IEM
41-59	1-8	24-33	151-164



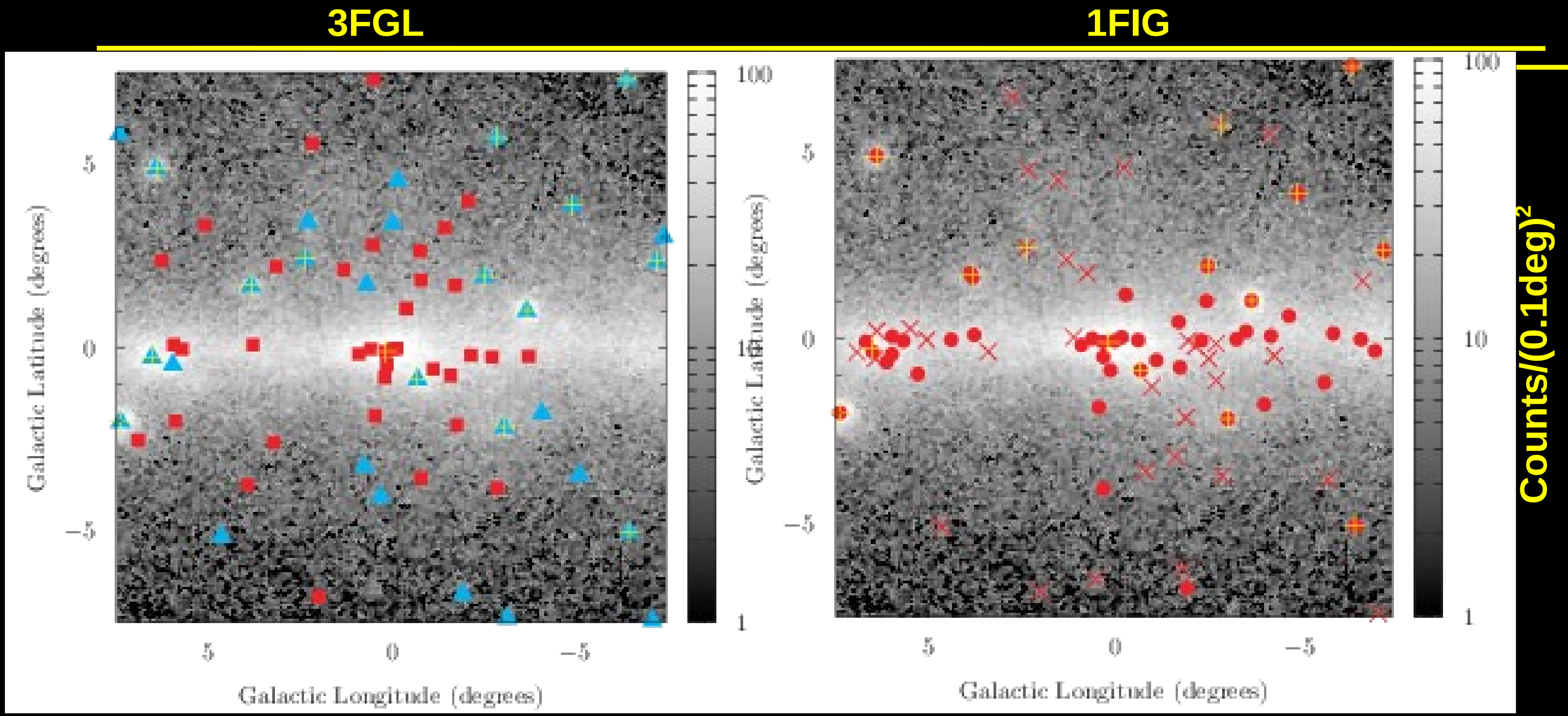
Results – Point Sources

3FGL 1FIG



- We obtain 48 point sources over the RoI with significance ~ 4σ or higher (threshold for inclusion in Fermi catalogue) – the 3FGL (4 years, > 100 MeV) has approximately 25% more point sources over the same region
- Approximately 60% additional point source candidates that do not satisfy the 4σ threshold are also extracted from the region by our analysis → the exact number depends on the IEM
- 3 previously unidentified (in γ-rays) SNRs found in this analysis, but approximately 75% of 1FIG sources without associations

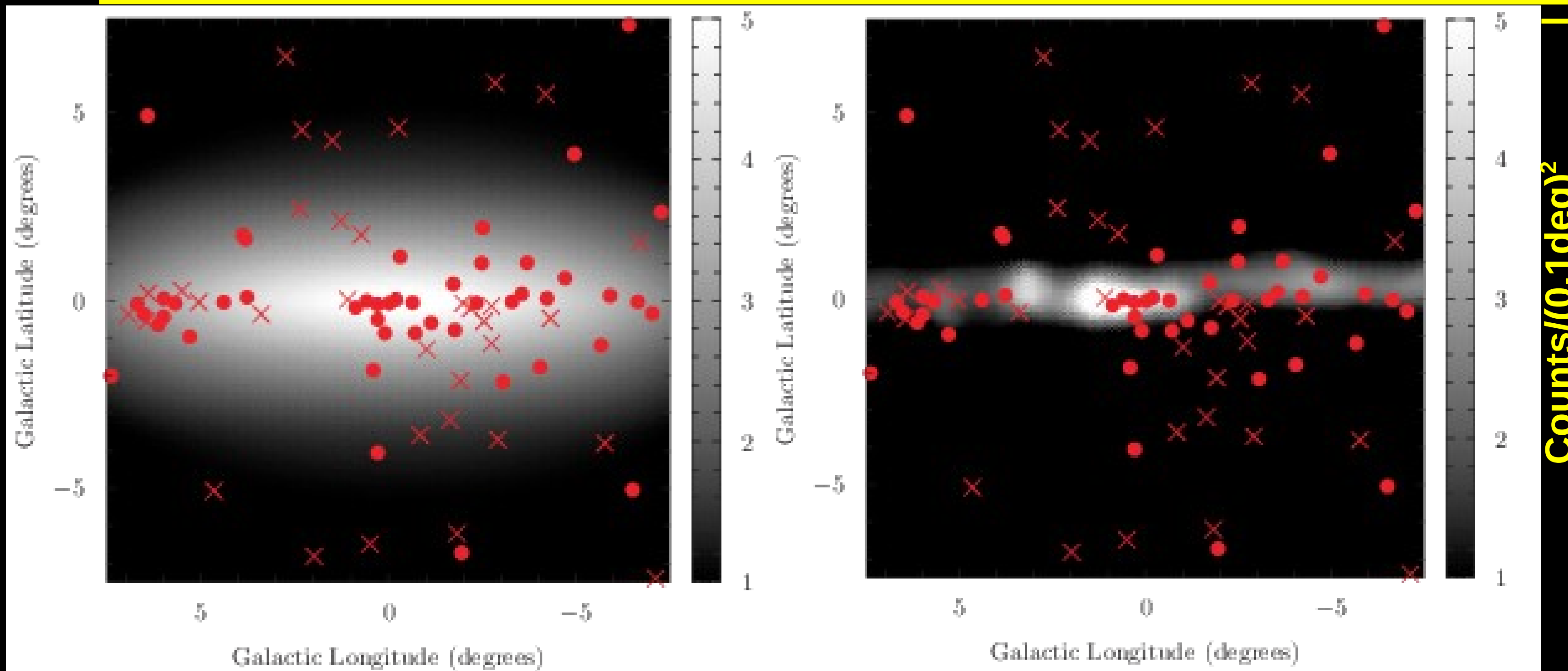
Results – Point Sources



- The unique aspect of this study is that it is the only work that self-consistently derives point sources and interstellar emission
- The spatial distribution that we obtain is different to that of the 3FGL
- There is a substantial fraction of the 1FIG sources and candidates unassociated and with a good chance being due to mismodelled interstellar emission

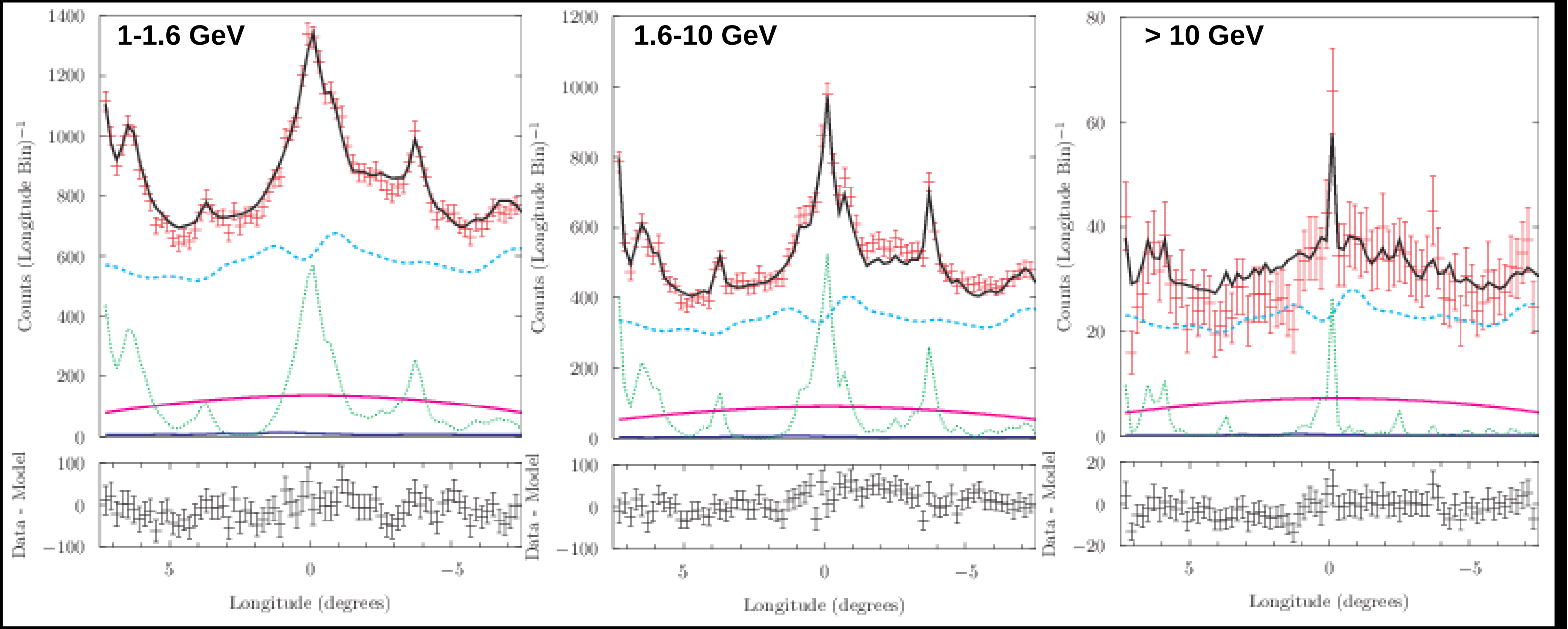
Results – Point Sources

1FIG, sub-threshold, IC　　　　1FIG, sub-threshold, CO



- Overlay 1FIG sources, sub-threshold candidates with components of ring 1 interstellar emission
- Appears some correlation of sources and candidates with molecular component of ring 1 interstellar emission, but not complete
- For the TS < 100 sources there is much larger variability in combined flux over the 4 IEMs used in the study than for larger TS sources

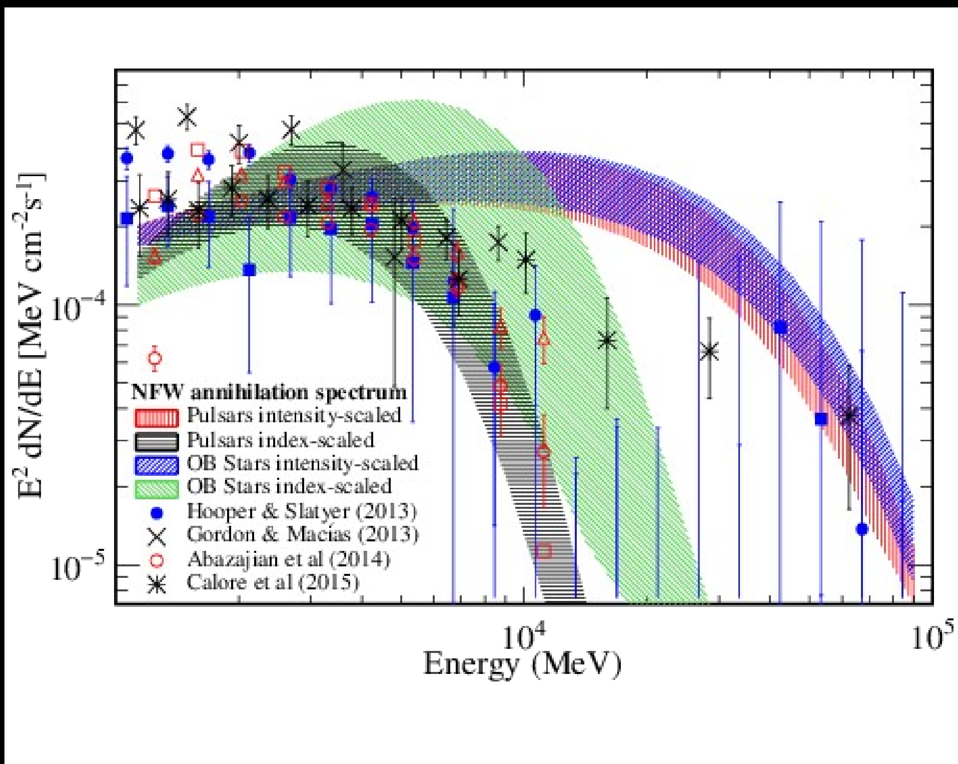
Longitude Profiles

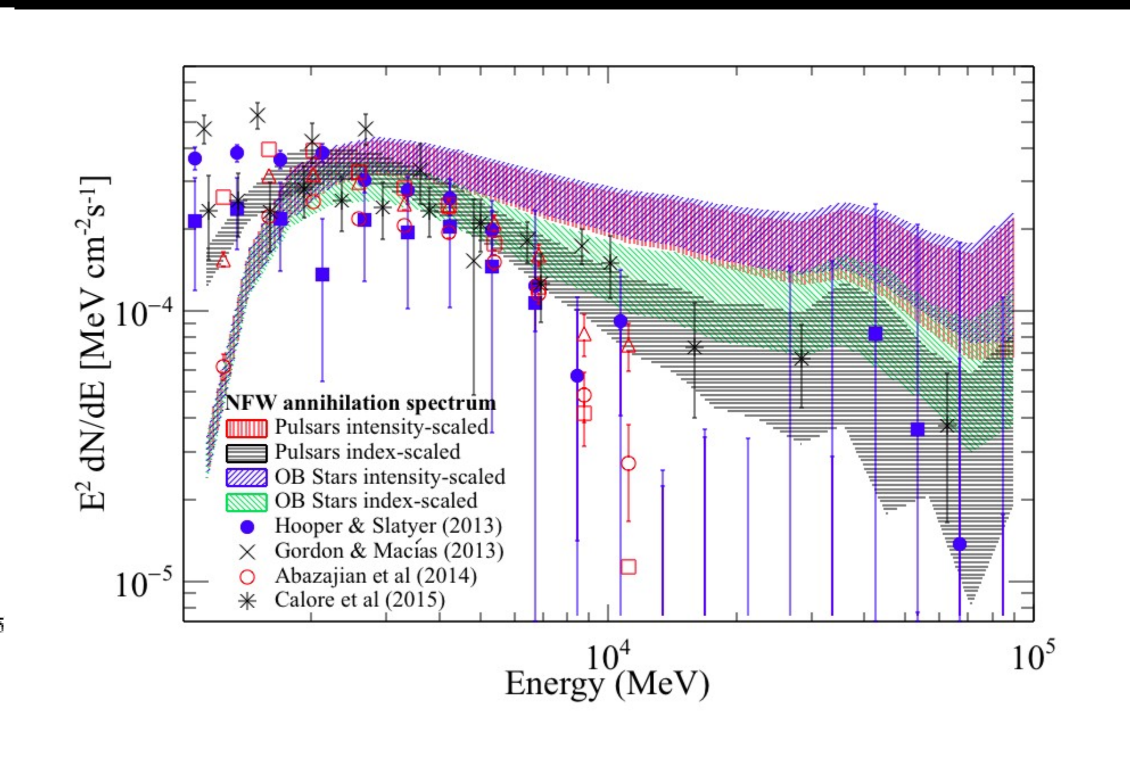


- The model with interstellar emission from the fore/background and inner annulus and point sources (1FIG + sub-threshold candidates) accounts for ~99% of the emission
- Some weak residual but requires adoption of a spatial and spectral model and refitting concurrently with the interstellar emission and point sources to determine its flux

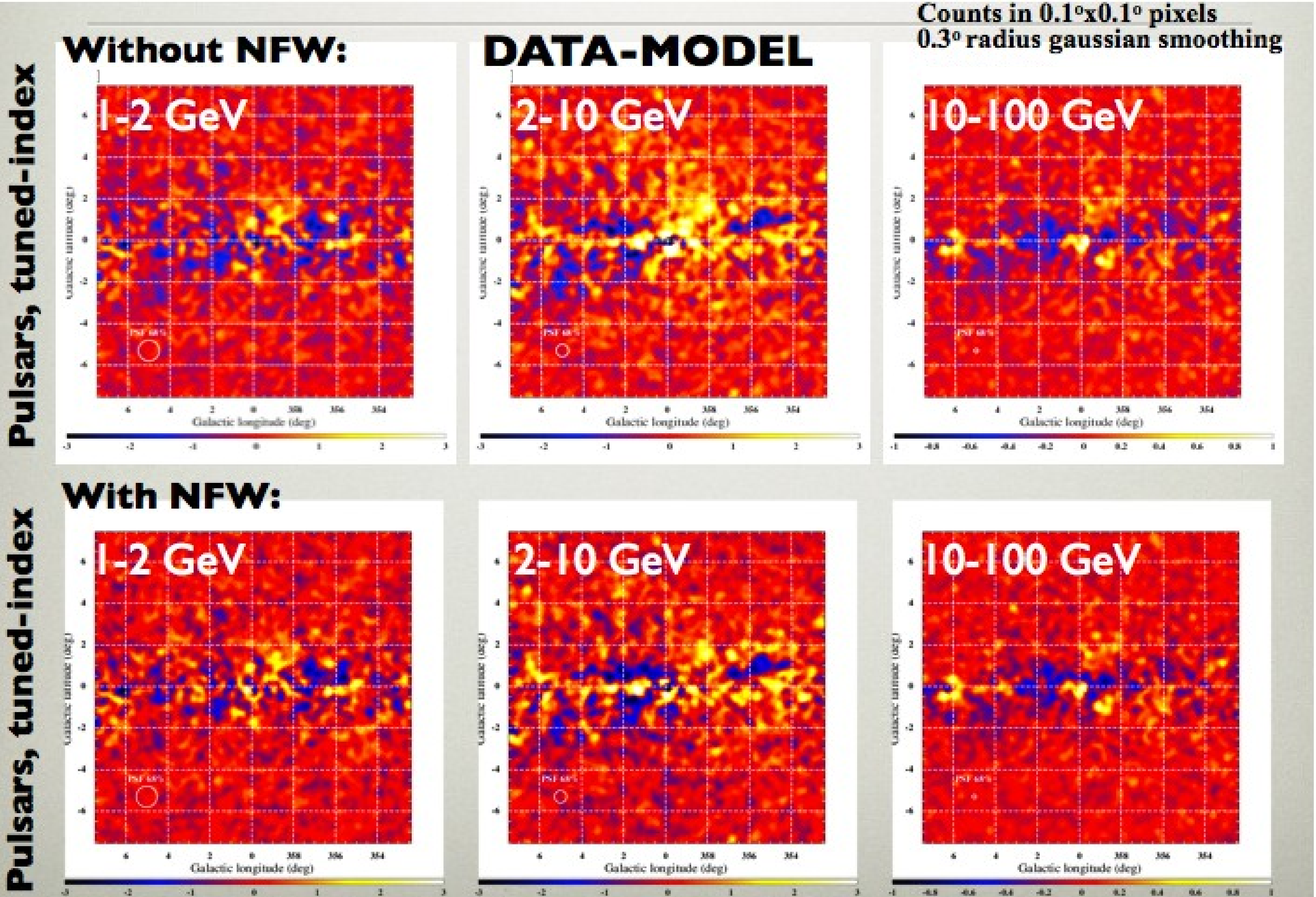
Results – Residual Model Templates

- Test if an additional component centred on GC contributes to data (2D Gaussian, NFW, or gas-like distribution as proxy for unresolved sources)
- The peaked profiles with long tails (NFW, NFW-c) yield the most significant improvements in the data-model agreement but ….
- The resultant model spectrum depends strongly on the fore/background model



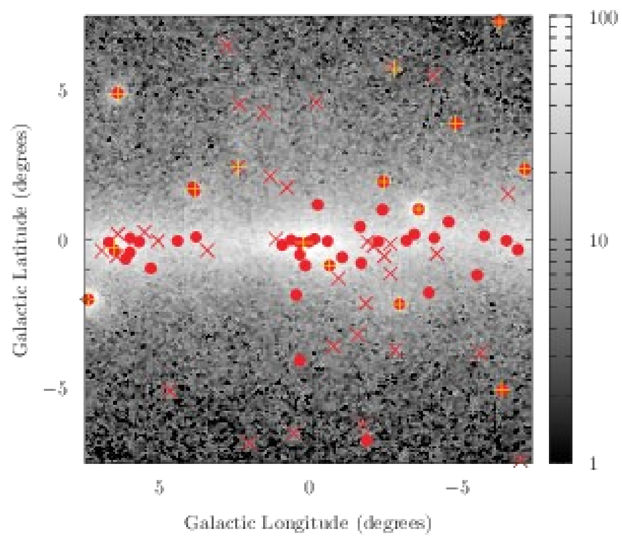


Results – Residual Model Template

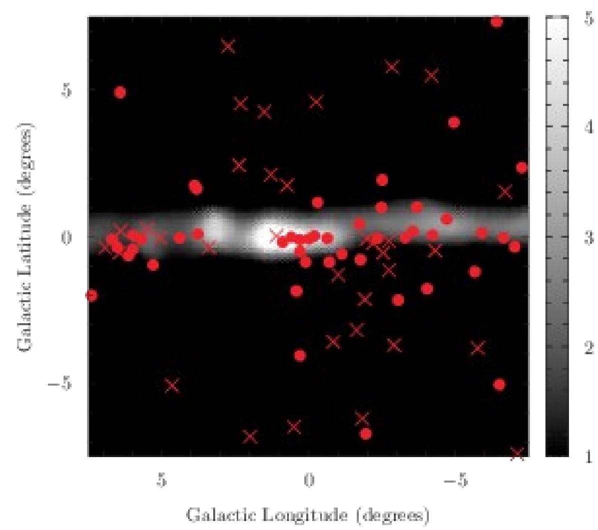


Where to Next?

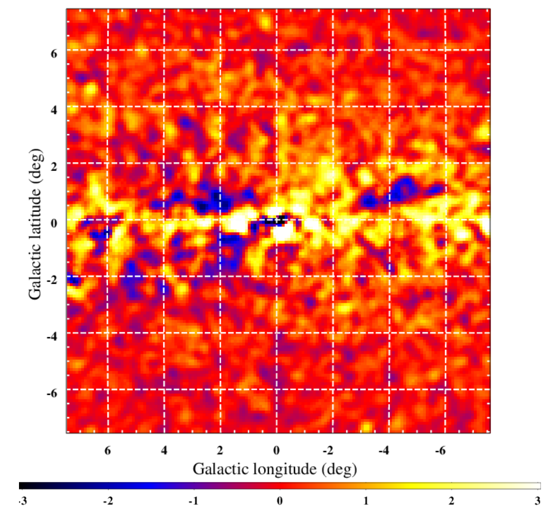
1FIG, TS<25 + data



1FIG, TS<25 + ring 1 CO



Residual without NFW



- Point-source distribution has by-eye correlation with IEM components and residual
- Suggests mismodelling of interstellar emission that is still to be understood. Some this can be due to:
  - Gas maps not tracing full density distribution (very likely) + artifacts from ring decomposition (likely)
  - IC (ISRF – very likely, CRes – likely)
  - Other components (additional CR srcs, discrete gamma-ray srcs) + need for 3D modelling

Summary

- The majority of gamma-rays coming from the inner Galaxy are likely described by a combination of the expected emission processes: interstellar emission from cosmic particles and discrete sources
- There are residuals – positive and negative – across the region remaining even with our current best estimates of these `standard' emission processes
- To understand the origin of these we need to invest time in improving how ISM tracers and other components used to construct interstellar emission models are treated
- This is not an easy task but we have work underway on several fronts that is making progress to address this issue
- The bottom line is: most likely what is seen in gamma rays toward the inner Galaxy has a prosaic instead of exotic/new physics origin, but to answer this to a high-degree of certainty requires more work