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DIFFUSE GALACTIC GAMMA-RAY EMISSION BEFORE CTA

Institute for Cosmic Ray Research, Kashiwa

Feb 20, 2019

What means “diffuse” ?

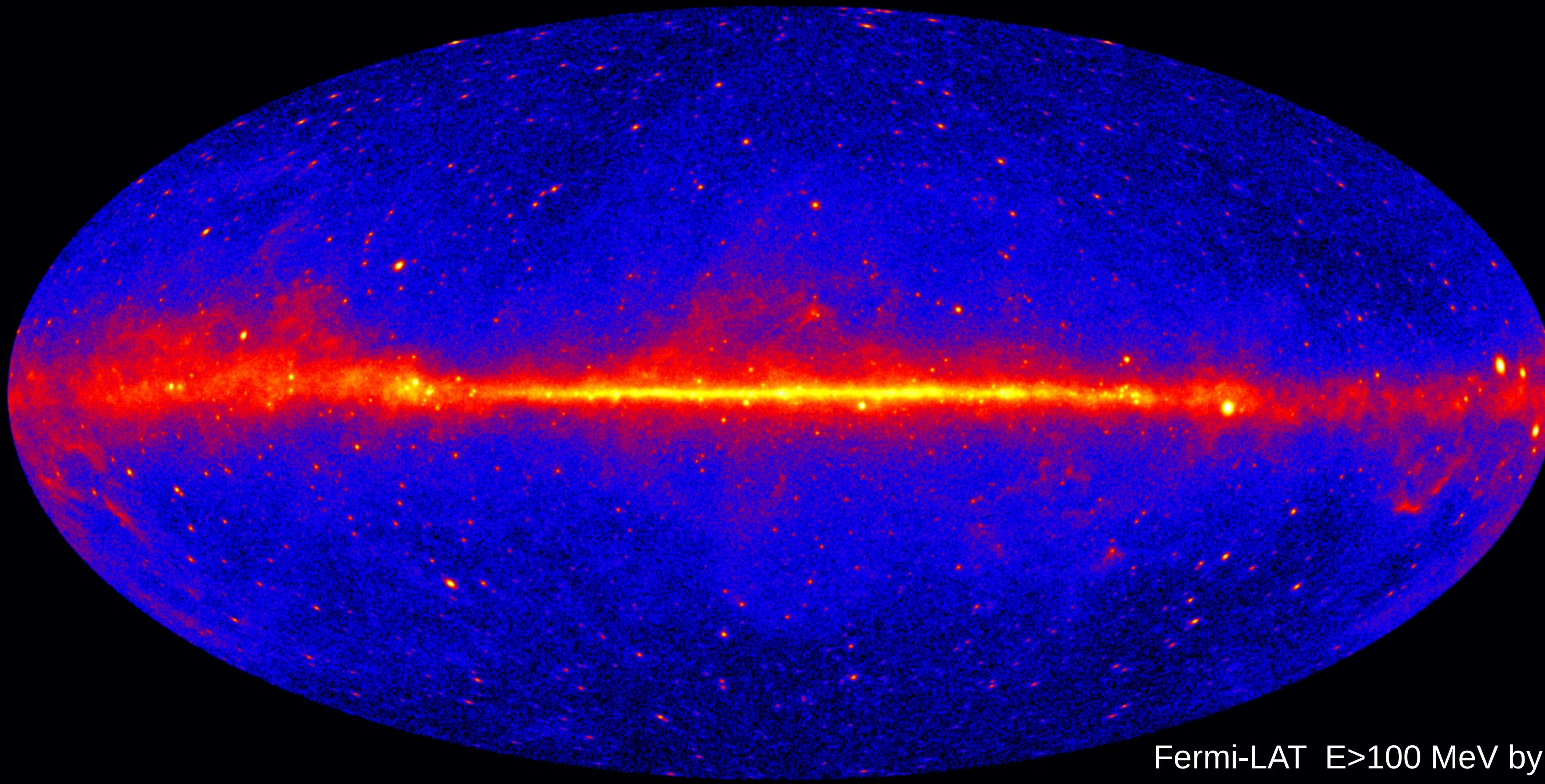
Dictionary:
“Diffuse” : = wide spread; not localized or confined; with no distinct margin

Astronomer:
“Diffuse” : = all emission that cannot be resolved into individual sources
***Careful, this depends decisively on instrument characteristics*.**

Astrophysicist:
“Diffuse” : = all emission processes that are related to interstellar, interplanetary, and/or intergalactic matter

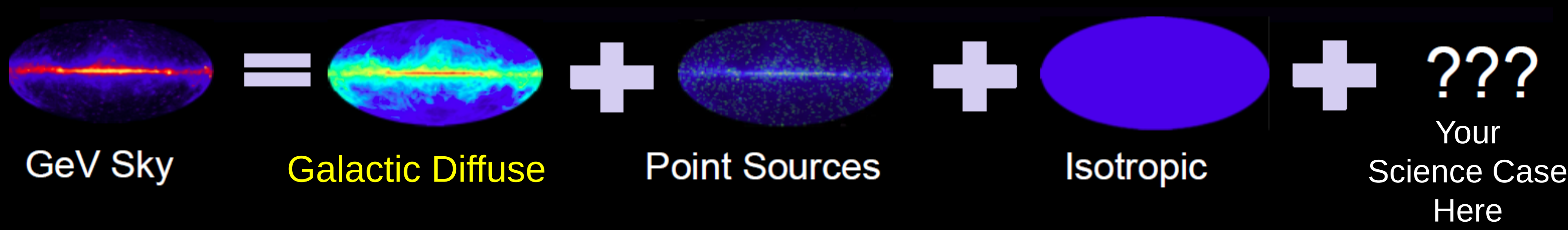
Now let‘s start looking at the high-energy γ-ray sky!

The Gamma-ray Sky @ GeV



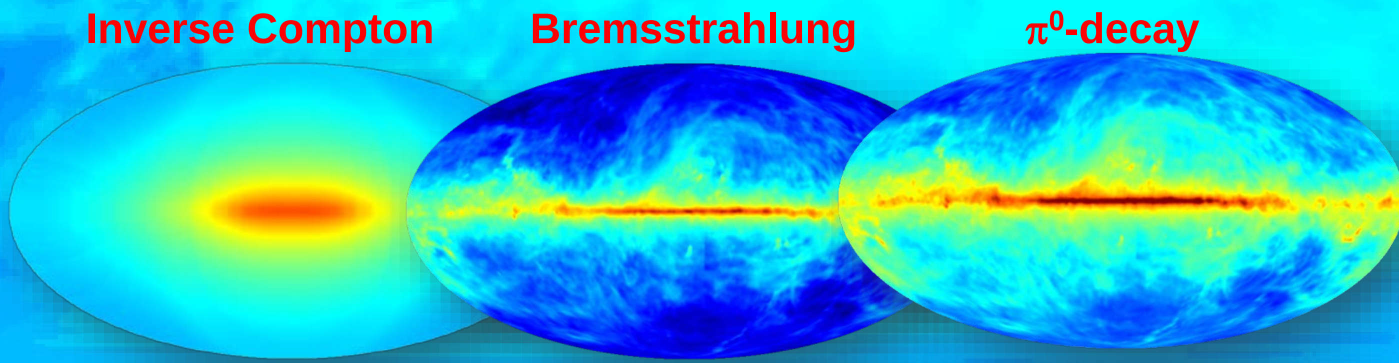
Fermi-LAT E>100 MeV by 3FGL
[LAT collaboration 2015]

~ 70% of all observed photons are attributed to the diffuse Galactic emission

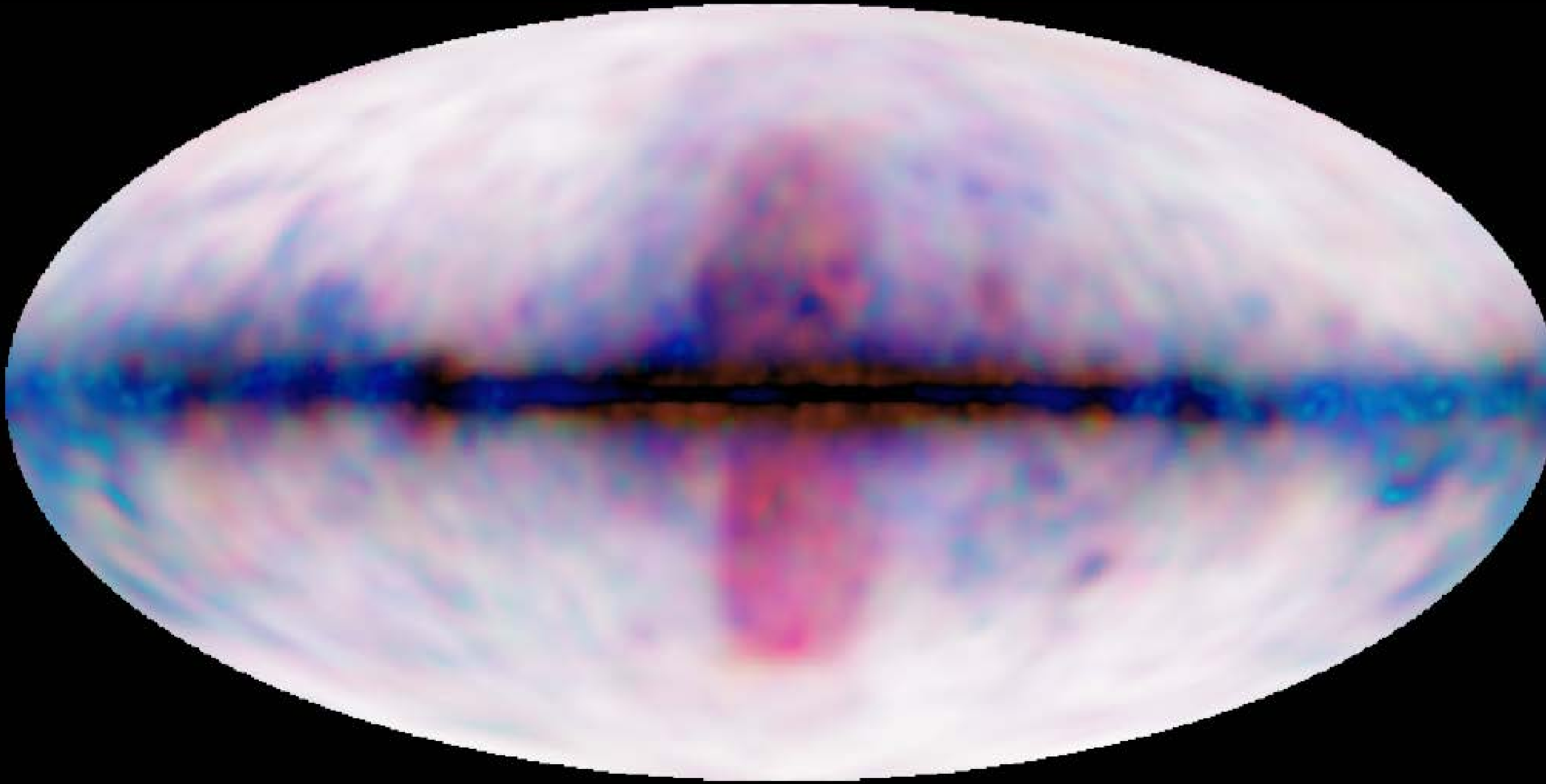


Diffuse Continuum Gamma Radiation

- Cosmic Rays present throughout our Galaxy
- B-fields (evident via synchrotron radio maps)
- Interstellar radiation fields (CMB, IR, OPT/UV)



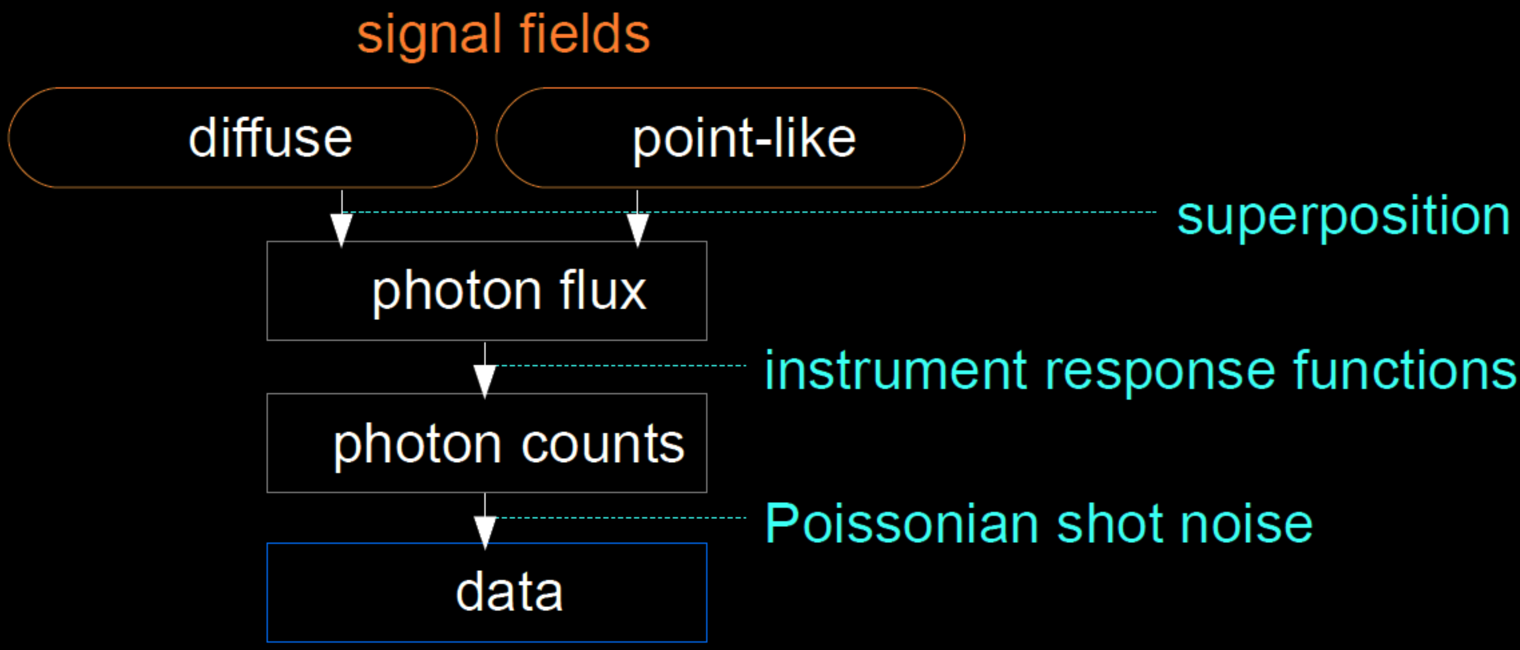
Alternatives: The Gamma-Ray Sky by D^3PO



Fermi-LAT 0.6 < E < 307 GeV
by D^3PO algorithm *[Selig ea 2015*]

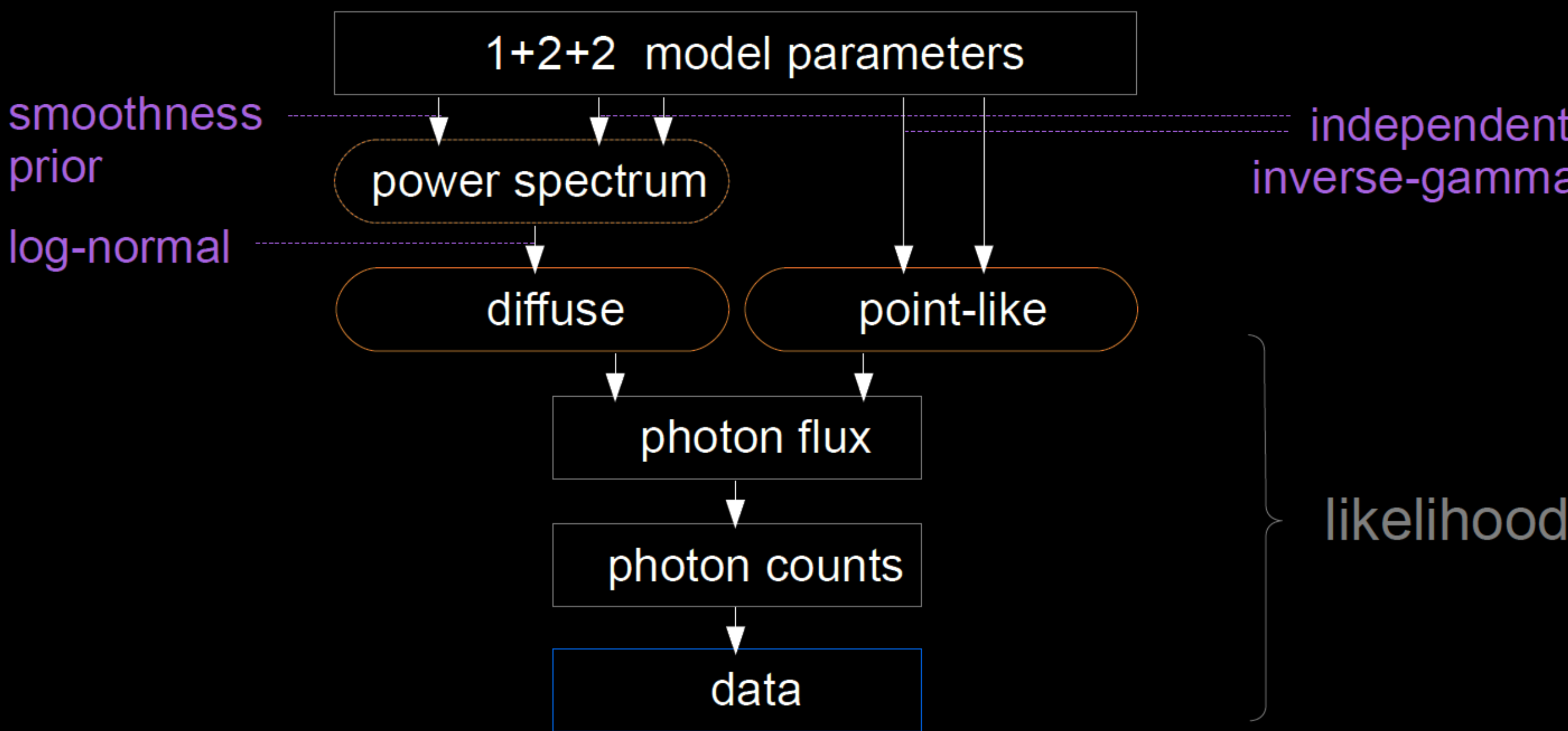
D3PO as a application from Information Field Theory

$$F(x) = F_0 \times \left[e^{s(x)} + e^{u(x)} \right]$$

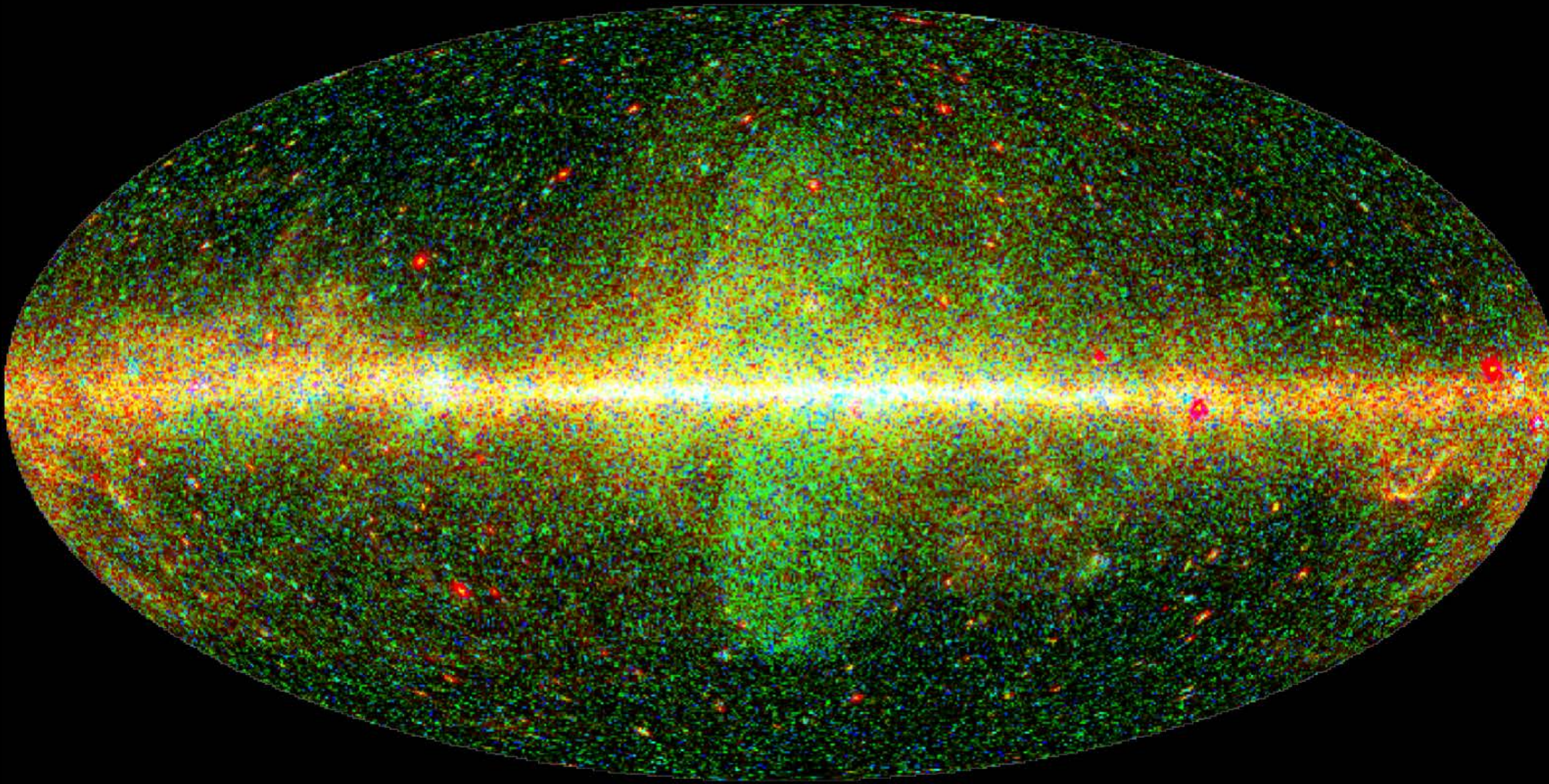


taken from Thorsten Enßlin

$$F(x) = F_0 \times \left[e^{s(x)} + e^{u(x)} \right]$$

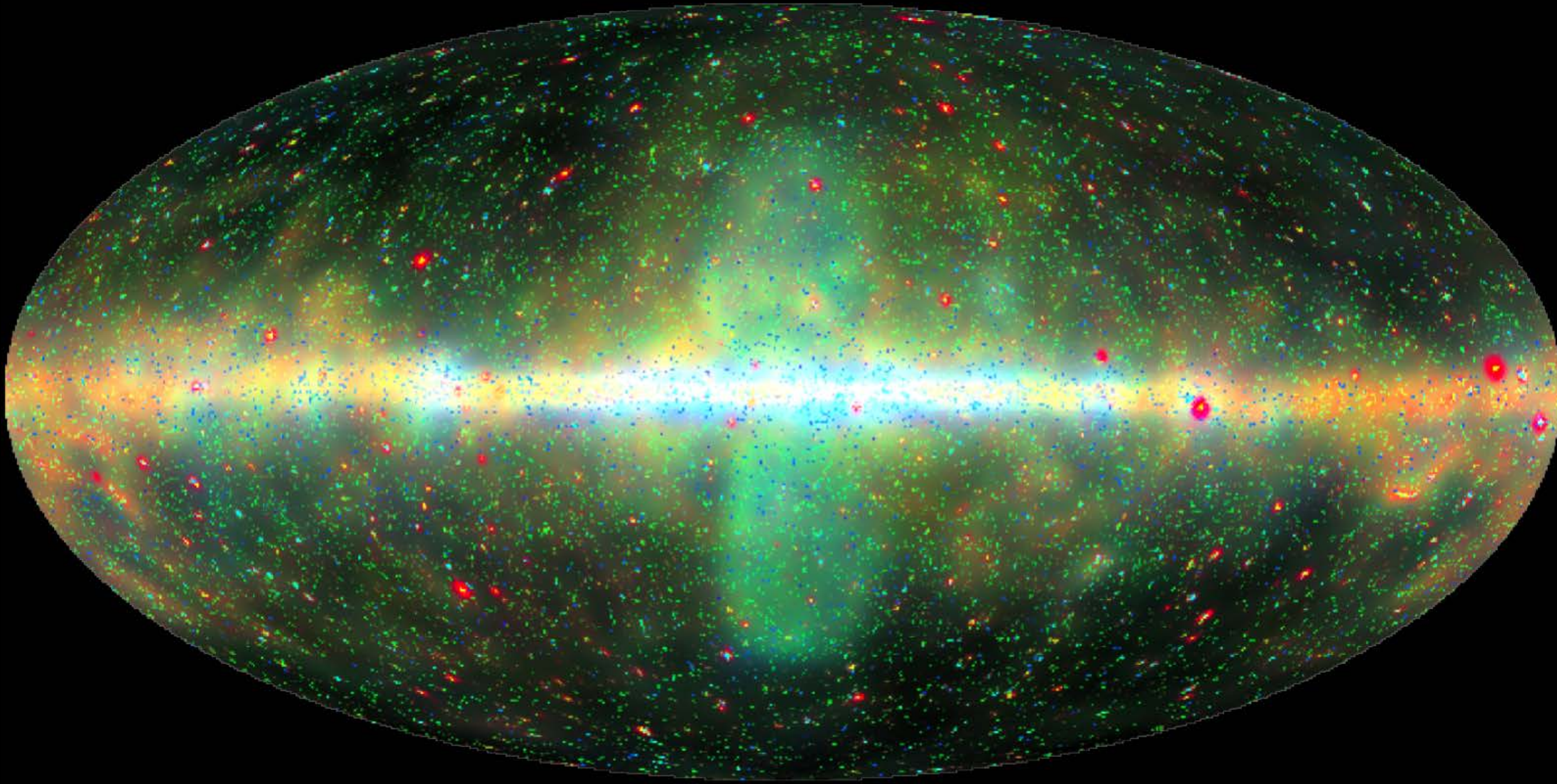


taken from Thorsten Enßlin



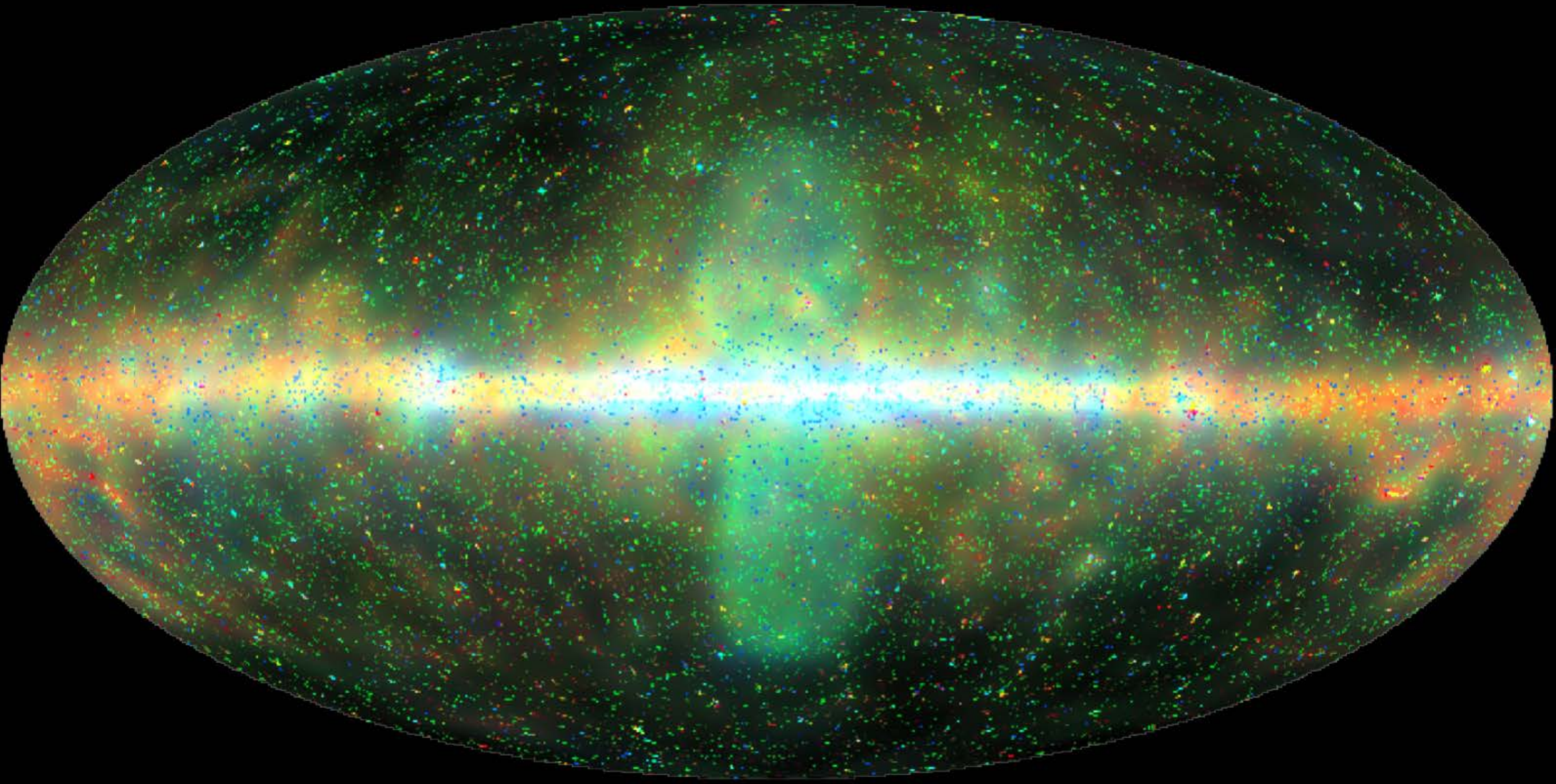
log-data

taken from Thorsten Enßlin



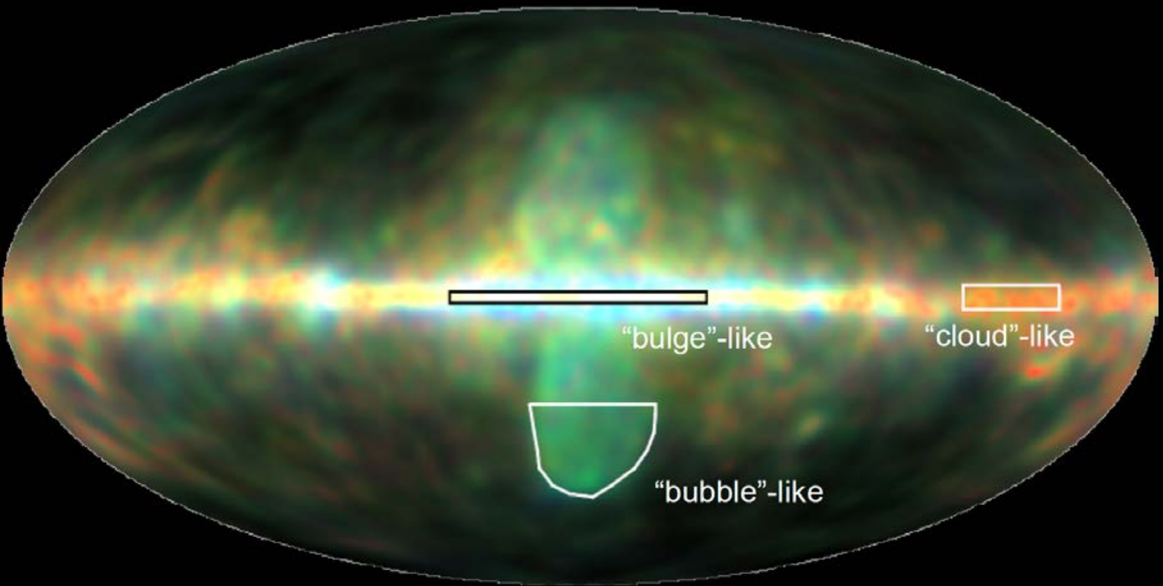
log-data … denoised

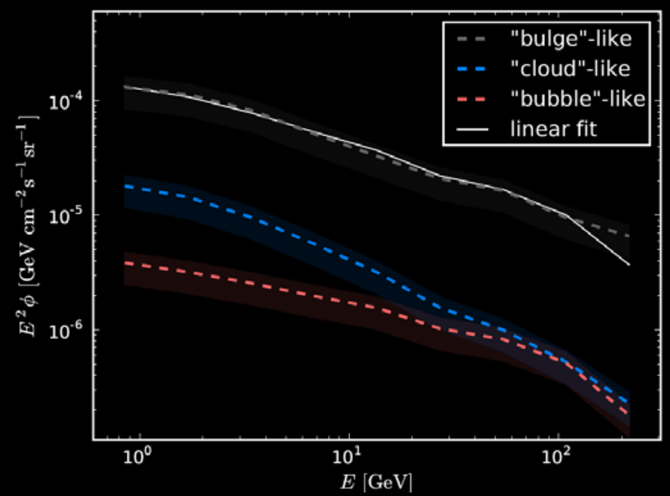
taken from Thorsten Enßlin

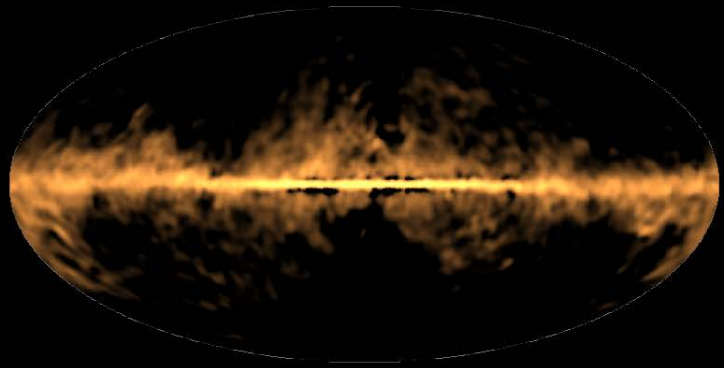


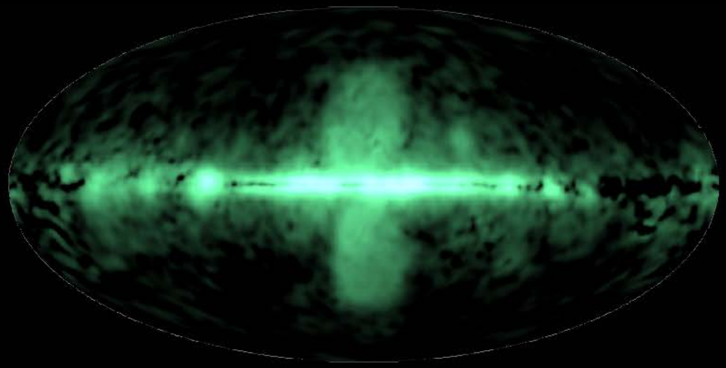
log-data … denoised … deconvolved

taken from Thorsten Enßlin







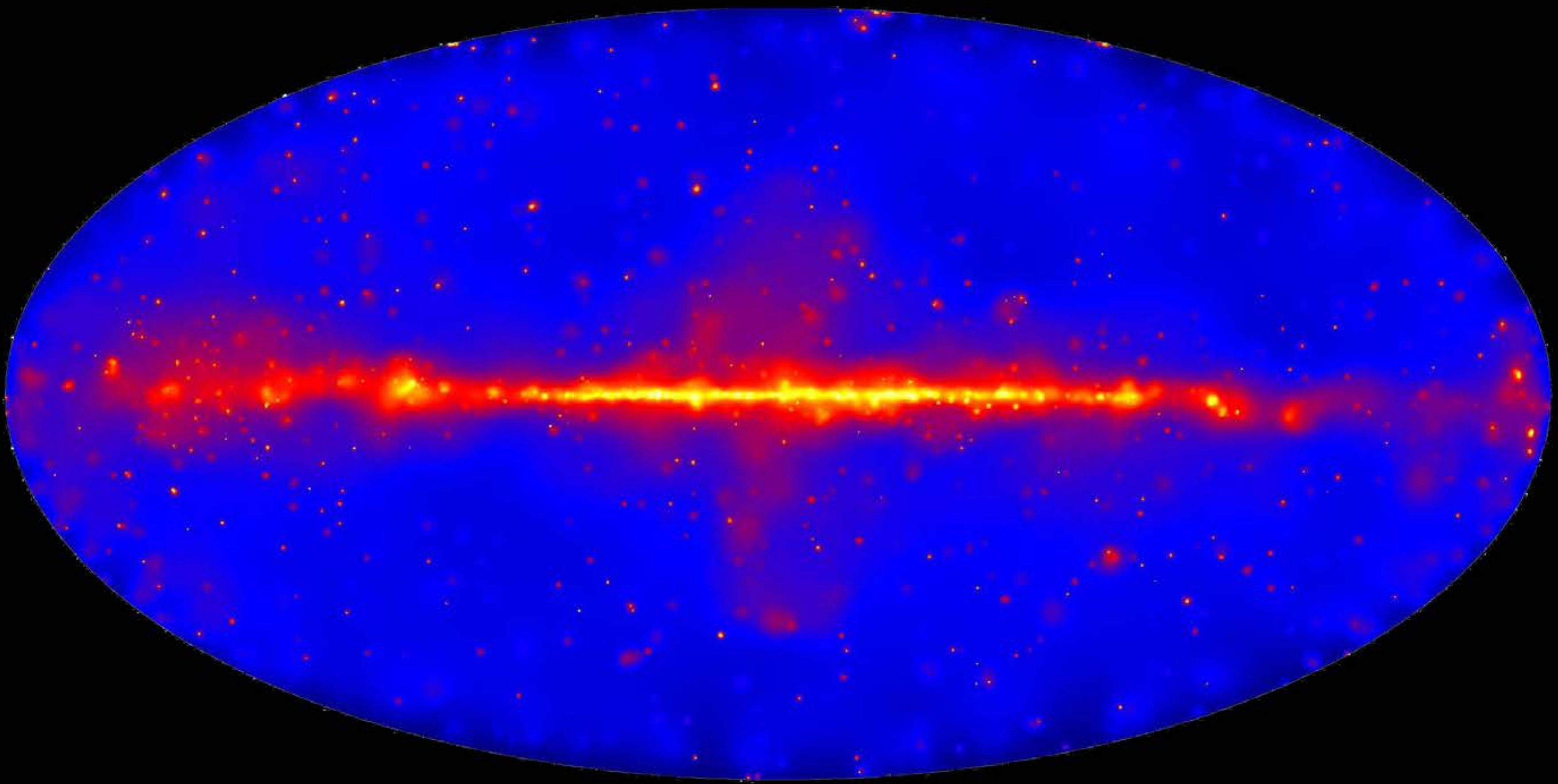


CLOUD-LIKE

BUBBLE-LIKE

☞ D^{4}PO upcoming [*Pumpe ea 2018, A&A 619, A119*]

…as f(Eγ): The Gamma-Ray Sky above 50 GeV



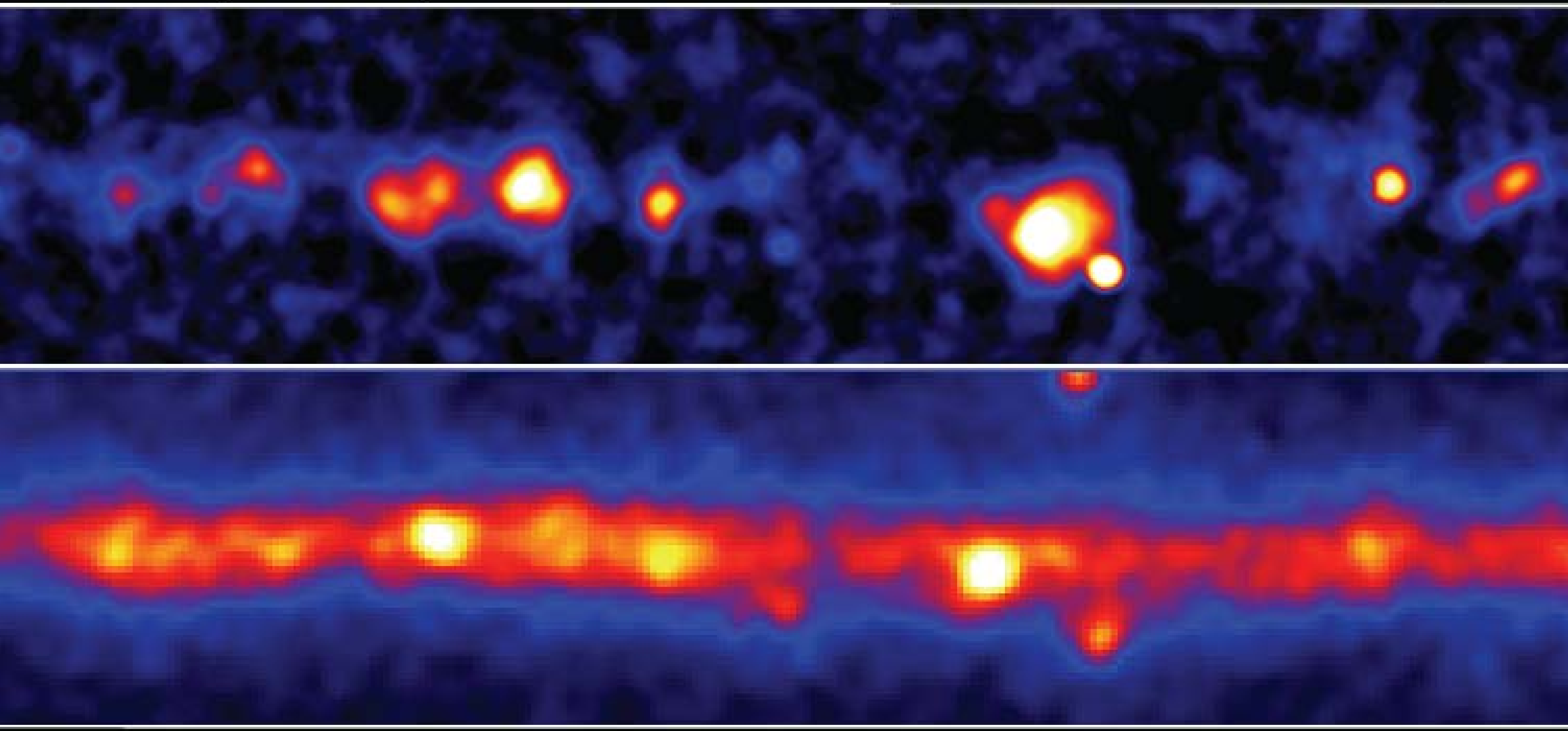
Fermi-LAT E > 50 GeV by 2FHL
[LAT collaboration 2015]

☞ median location uncertainty of 1.8 arcmin! (68%)

The transition regime from GeV to TeV

Extended sources, size typically few 0.1°
few 10 pc

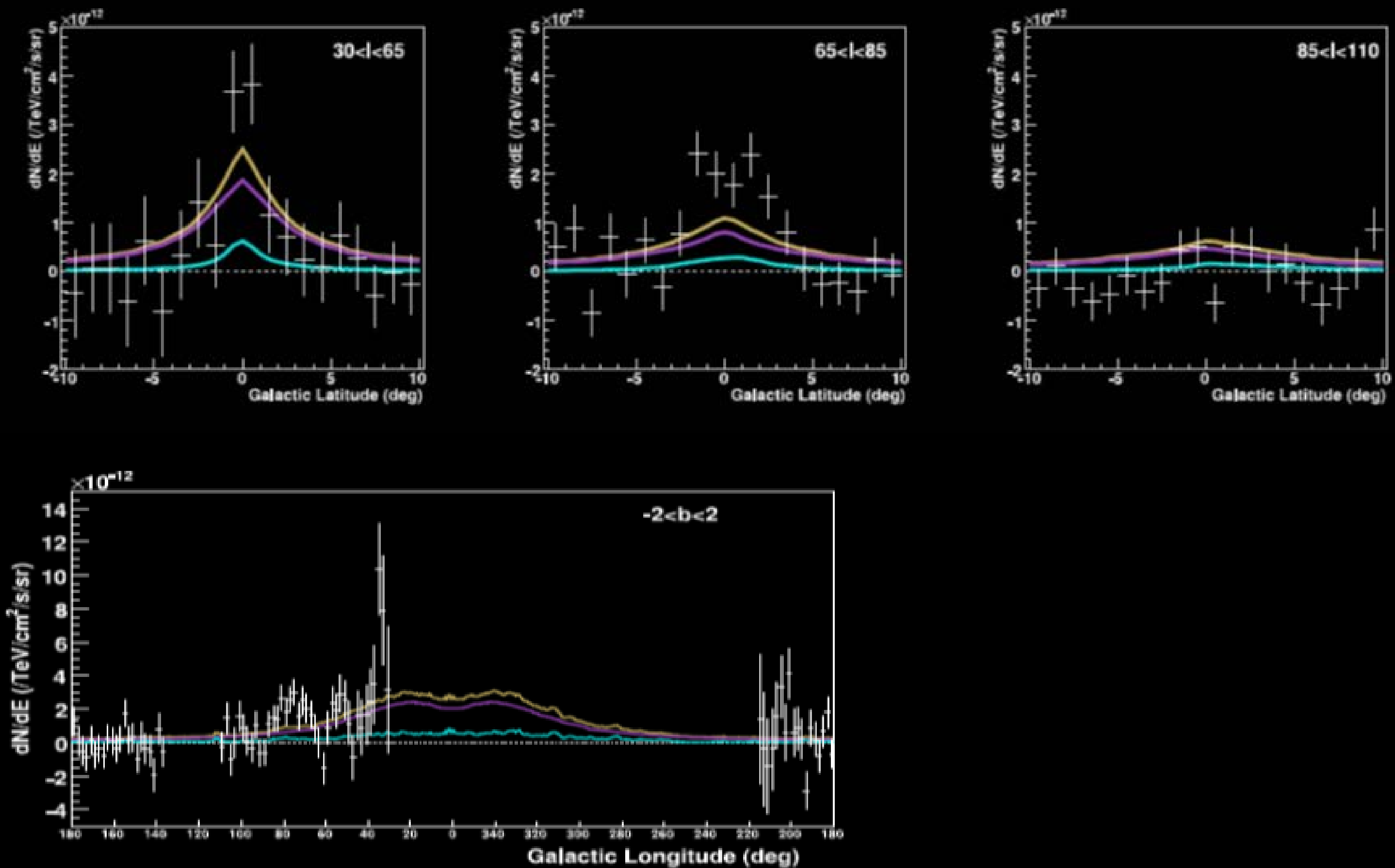
H.E.S.S. (~ 1 TeV)



Fermi-LAT (>1 GeV)

☞ Multi-TeV: **MILAGRO**; ARGO-YBJ

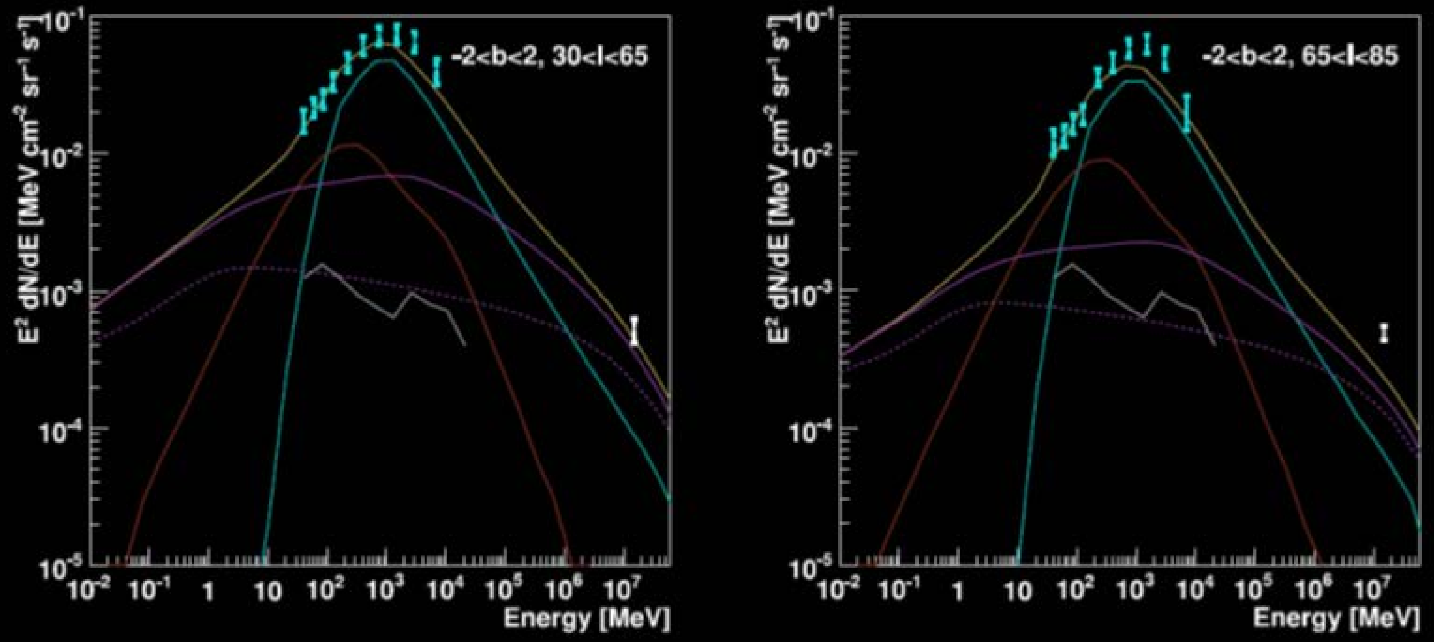
Abdo ea 2008: A MEASUREMENT OF THE SPATIAL DISTRIBUTION OF DIFFUSE TeV GAMMA-RAY EMISSION FROM THE GALACTIC PLANE WITH MILAGRO



(median energy 15 TeV)

☞ Multi-TeV: **MILAGRO**; ARGO-YBJ

no-interarm region　　　　interarm region



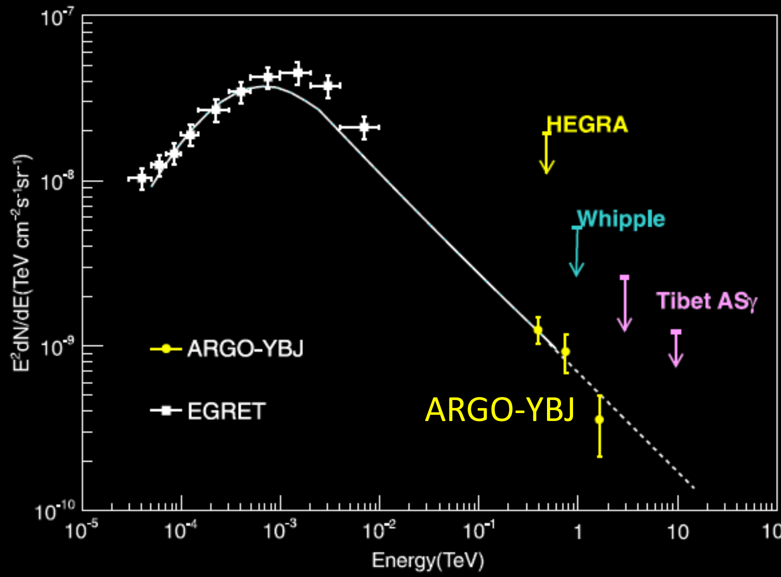
Abdo ea 2009: MILAGRO OBSERVATIONS OF MULTI-TeV EMISSION FROM GALACTIC SOURCES IN THE *FERMI* BRIGHT SOURCE LIST

…measurement of the diffuse emission (Abdo et al. 2008) at its highest value, in the inner Galaxy (30< *l* < 65, |*b*| < 2). Using this value, we expect 5.3×10−17 TeV−1 s−1 cm−2 in a 1 bin at 35 TeV, which is only about ~15% contamination for the weakest sources …. The GALPROP conventional model, for comparison, would only constitute~3% contamination.

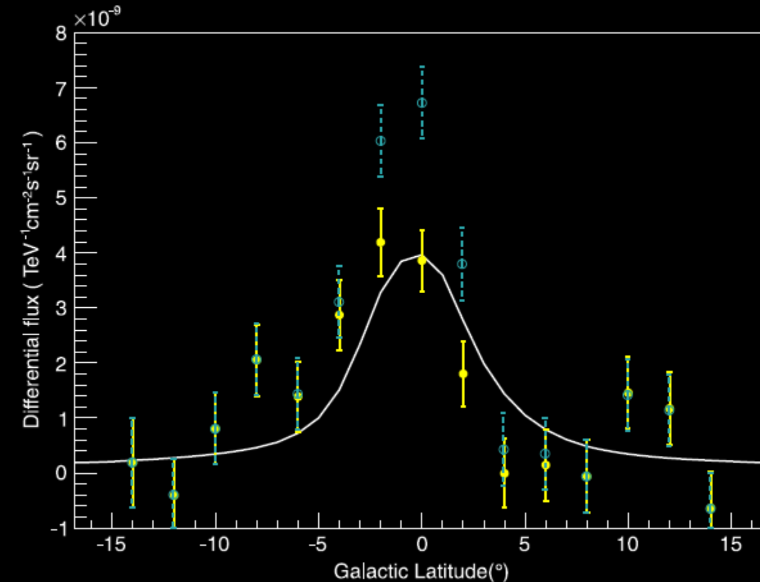
Discrepancy between measurement and spectral model is factor 5!

☞ Multi-TeV: MILAGRO; ARGO-YBJ

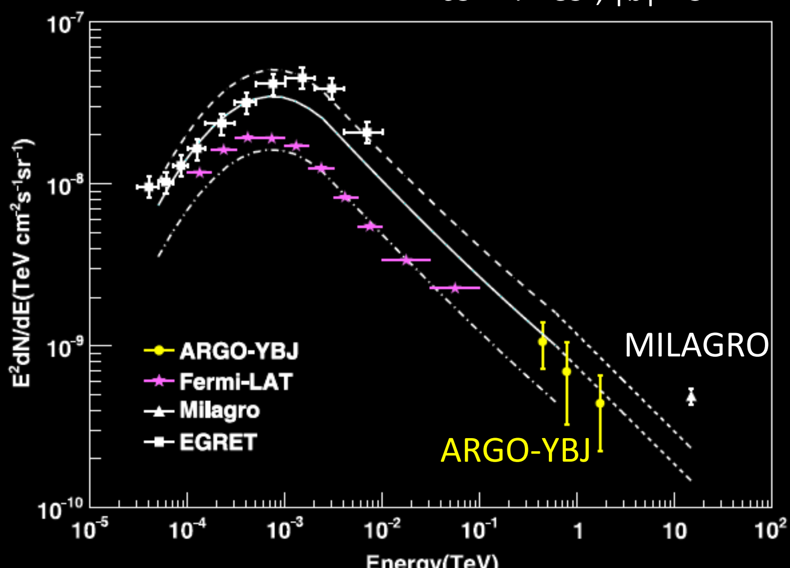
25° < l < 100°, |b| < 5°



25° < l < 100°



65° < l < 85°, |b| < 5°



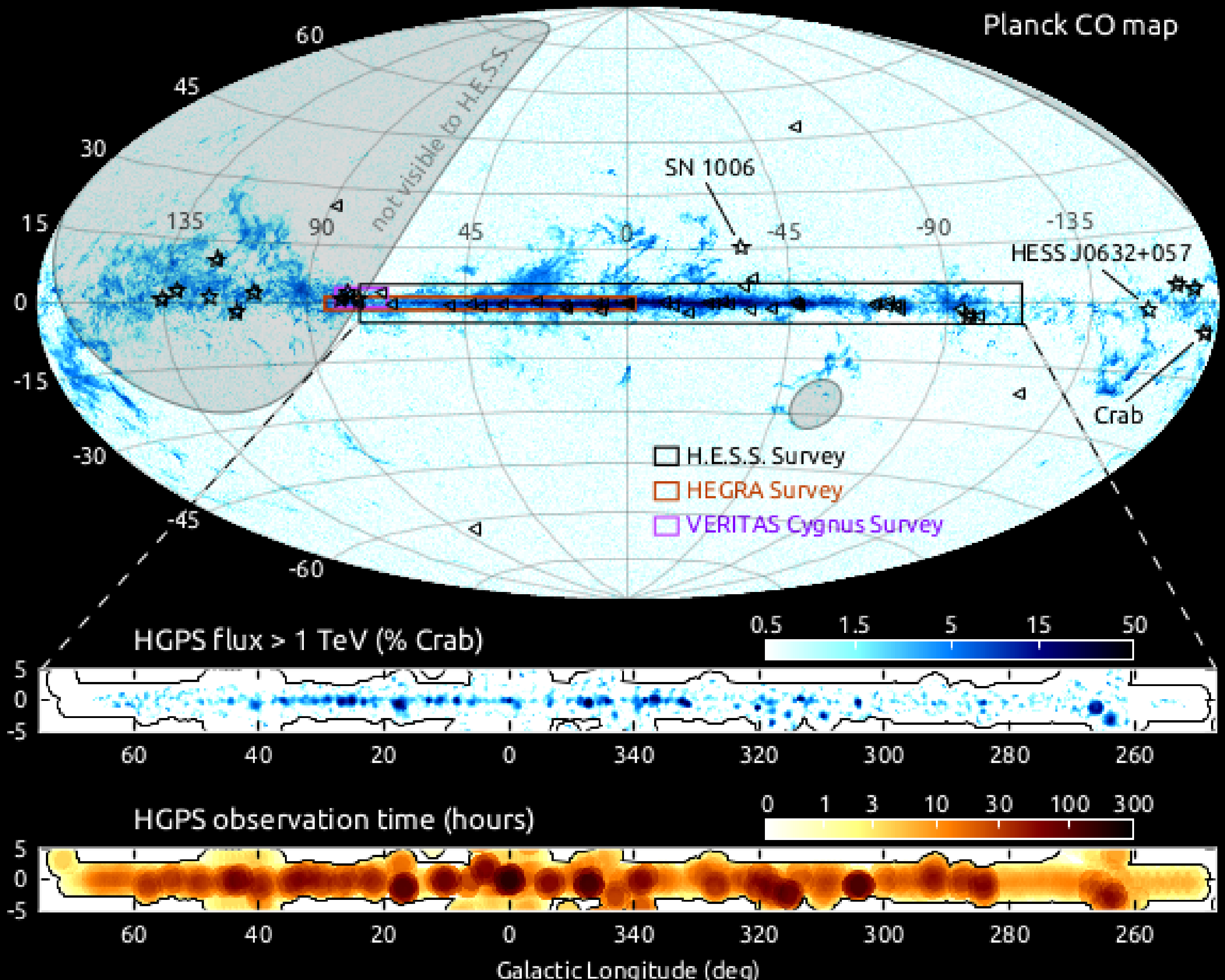
Results:

- **no discrepancy to LAT diffuse model**
- **no MILAGRO-like multi-TeV excess**

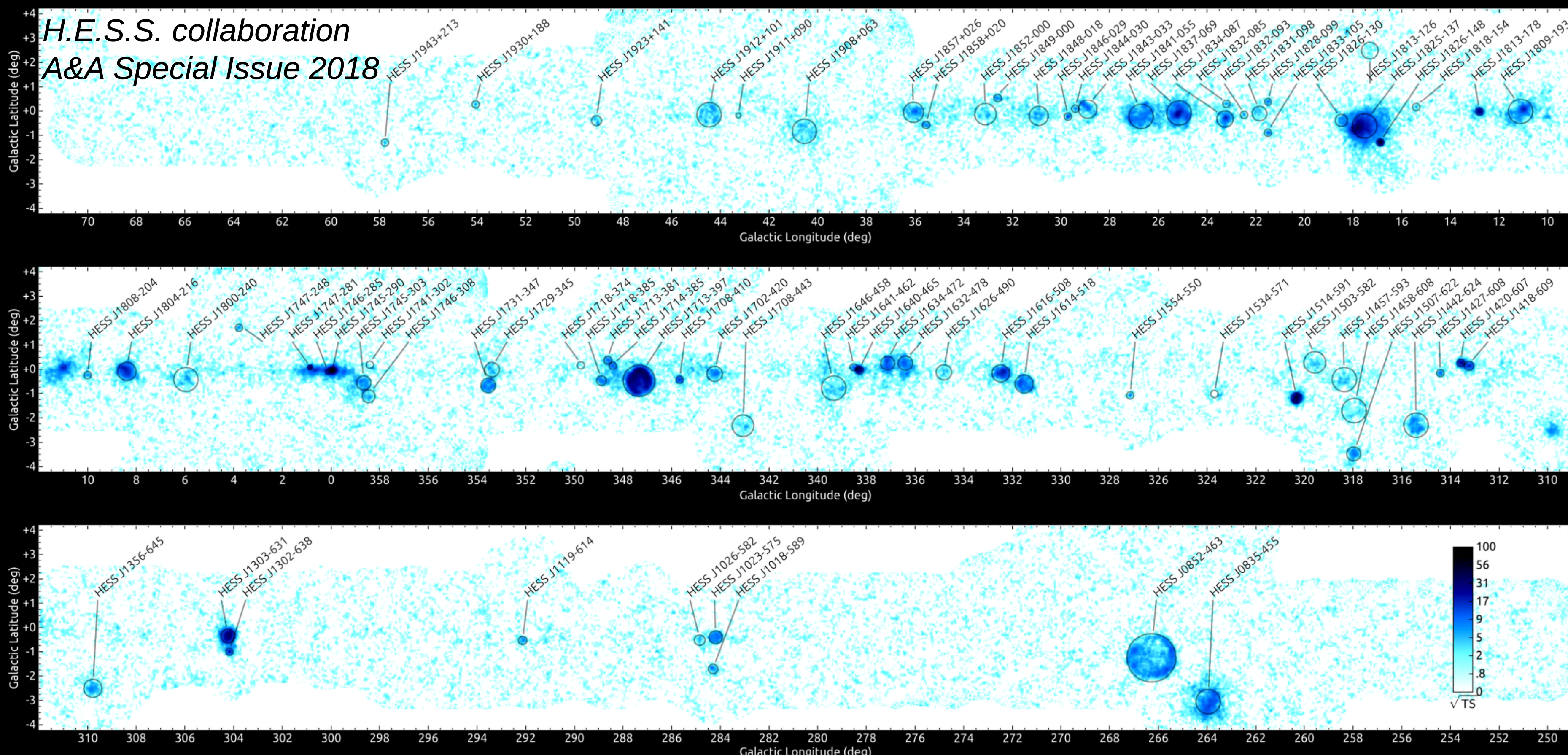
[Bartoli ea 2015, ApJ 806:20]

The Galactic Gamma-ray Sky as seen by H.E.S.S.

H.E.S.S. collaboration
A&A Special Issue 2018

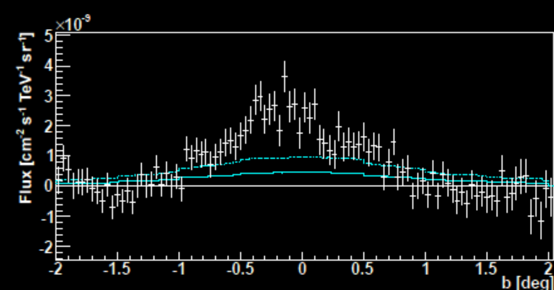


The Galactic Gamma-ray Sky as seen by H.E.S.S.



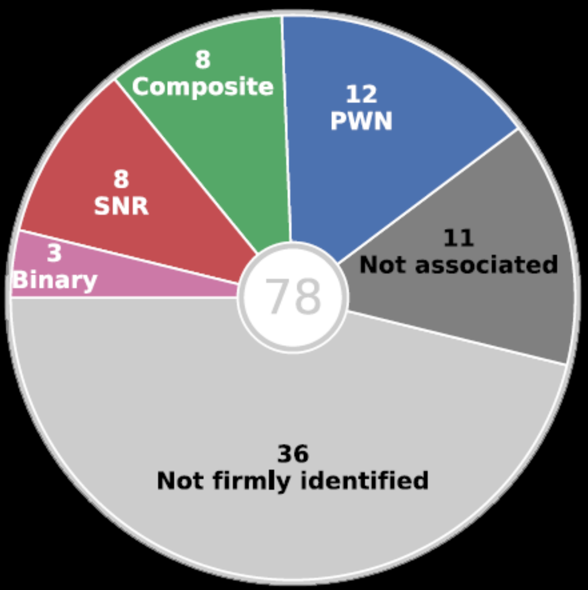
Diffuse Galactic TeV-emission has been assessed, too:

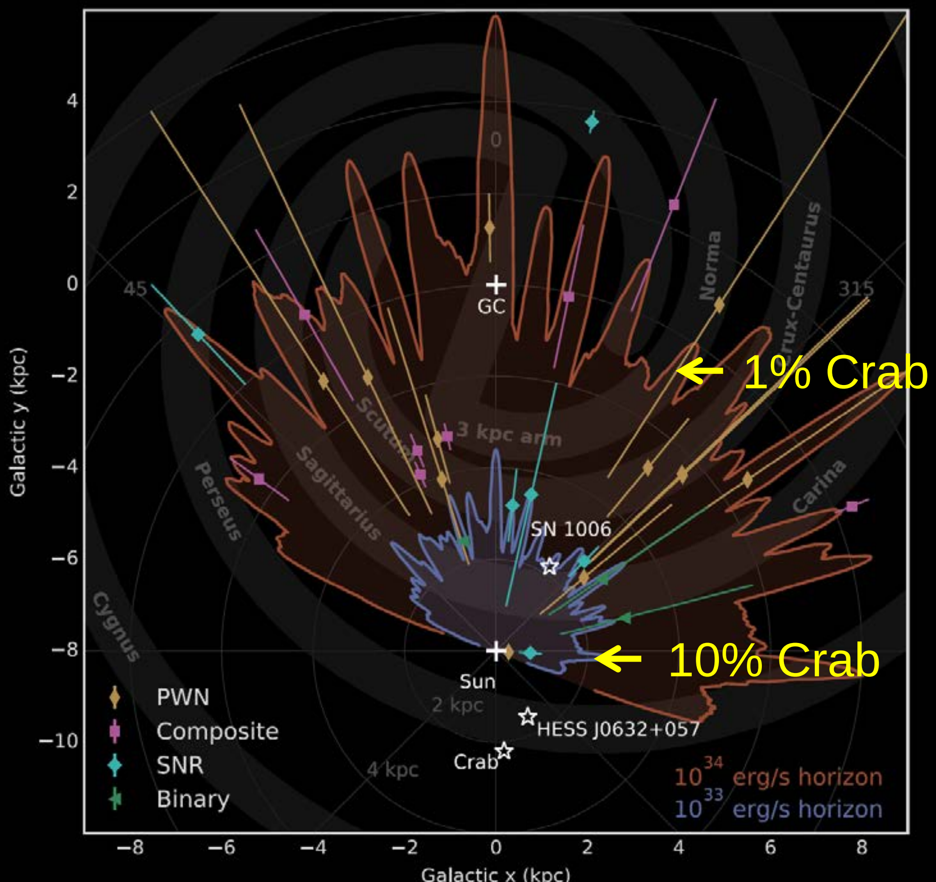
- Galactic Center Ridge emission [Nature 2006, 2016]
- Diffuse Galactic γ-ray emission with H.E.S.S. [PRD 2014] →
- HGPS: b=0 centered 1D-Gaussian [A&A 2018]



The Galactic Gamma-ray Sky as seen by H.E.S.S.

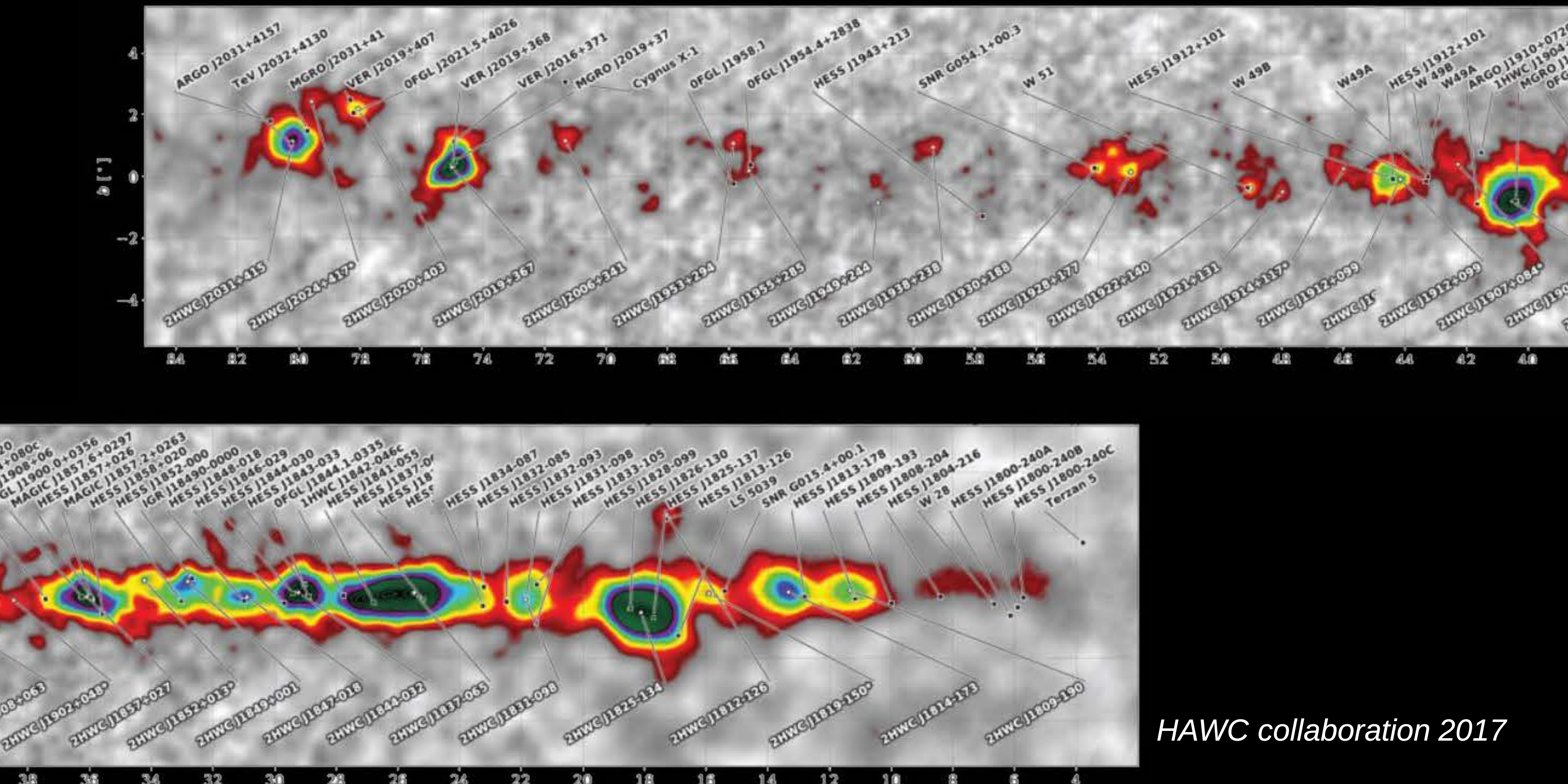
Telescopes	H.E.S.S. I
Observations	2004 to 2013
Total exposure	3000 hours
Energy range	0.2 – 100 TeV
Sky region	-110° < l < 65° -3.5° < b < 3.5°
Resolution (R68)	0.07 deg





H.E.S.S. collaboration
A&A Special Issue 2018

The northern Galactic Plane as seen by HAWC



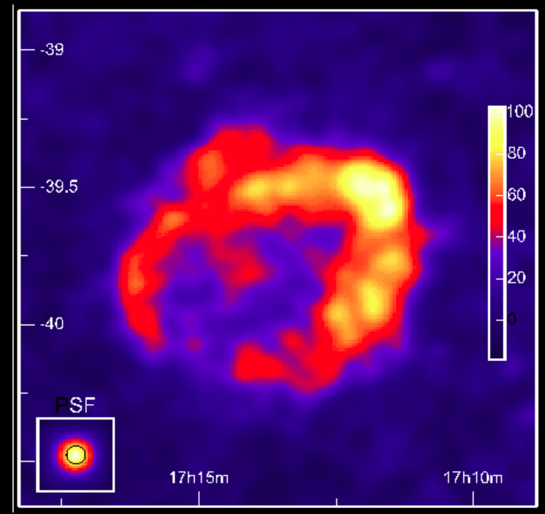
HAWC collaboration 2017

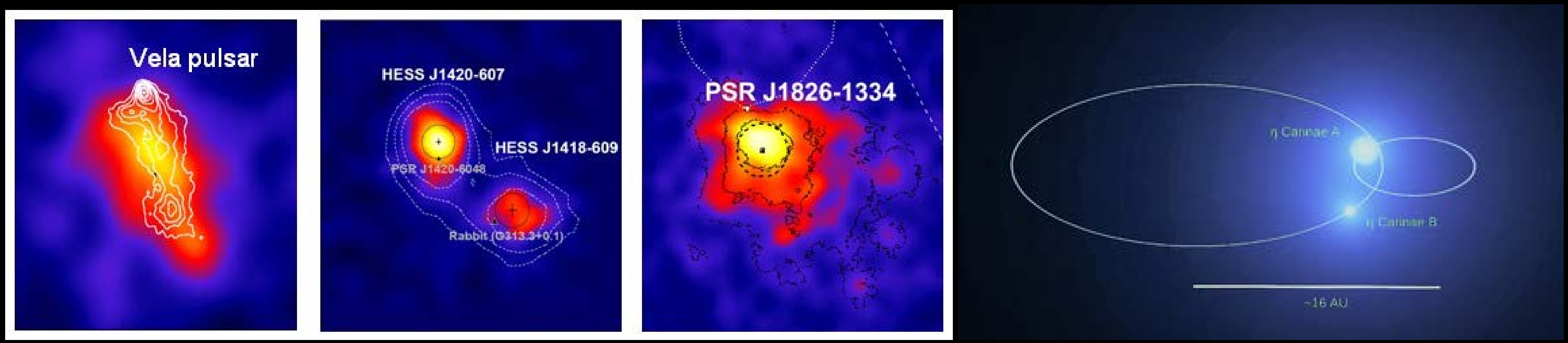
Necessities: 1) Sources

Sufficient power and ability to particle Acceleration up to Knee (PeV)

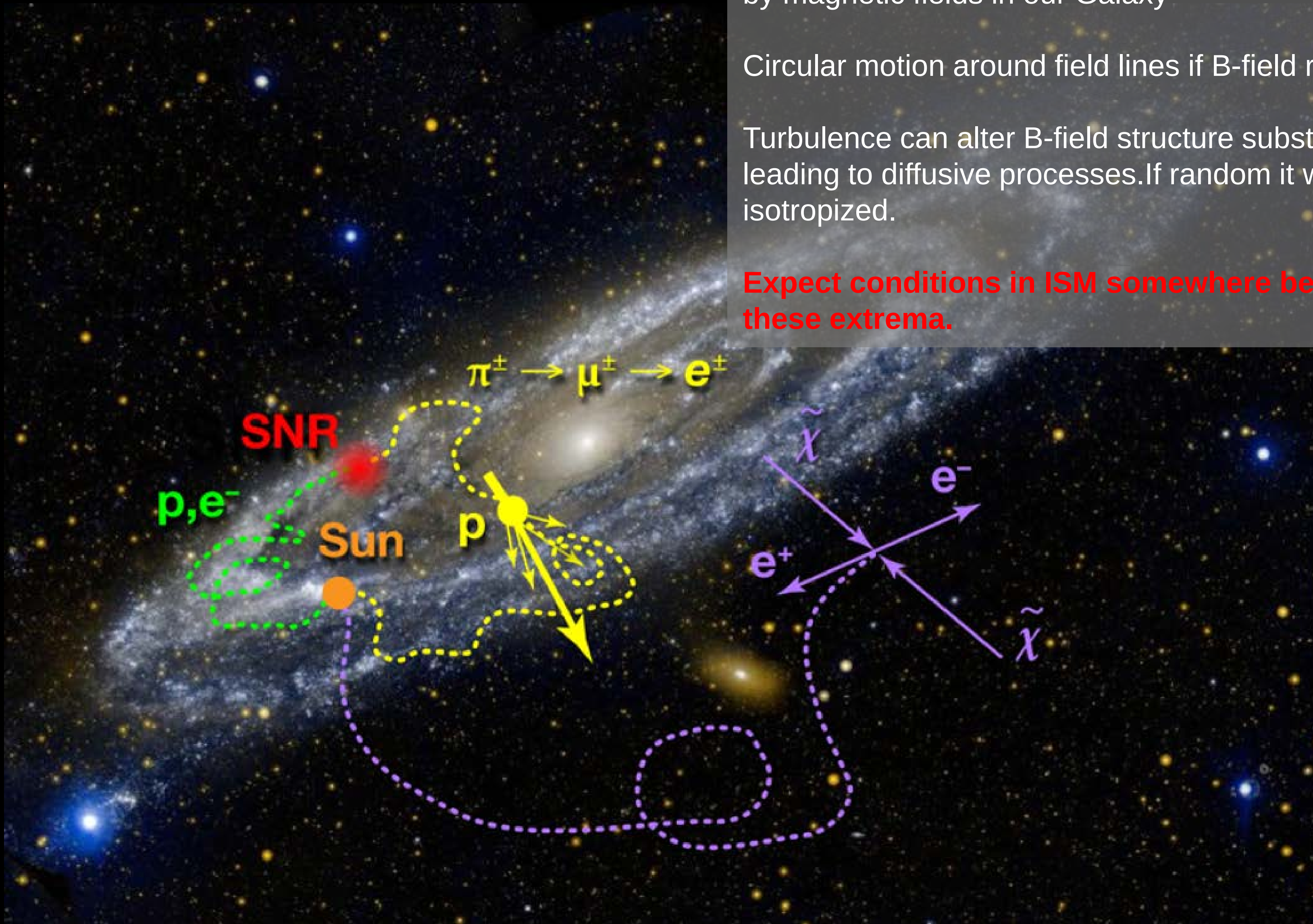
According to current understanding there are three candidate classes:

- Supernova Remnants
- Pulsar/PWNs
- Stellar winds





Necessities: 2) B-field



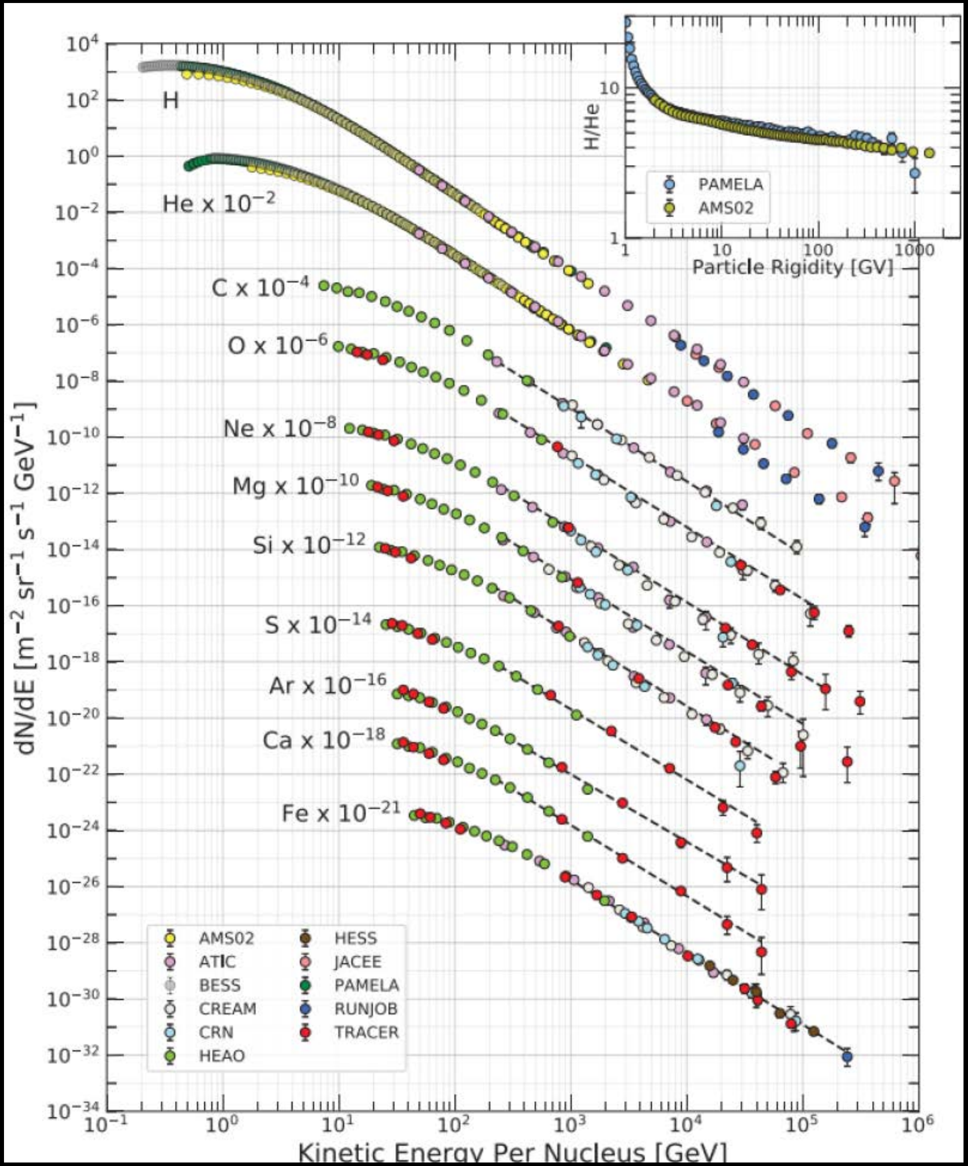
CRs move at relativistic speed but are affected by magnetic fields in our Galaxy

Circular motion around field lines if B-field regular.

Turbulence can alter B-field structure substantially, leading to diffusive processes.If random it will be isotropized.

Expect conditions in ISM somewhere between these extrema.

Necessities: 3) CR distributions



Observables

- Composition
- Energy dependence

However:

Arrival directions are isotropized
-> no CR sources, only proxies or EM

Low-energy flux is solar modulated

Flux at Earth typical for Milkyway?

Necessities: 3) CR distributions

Observables

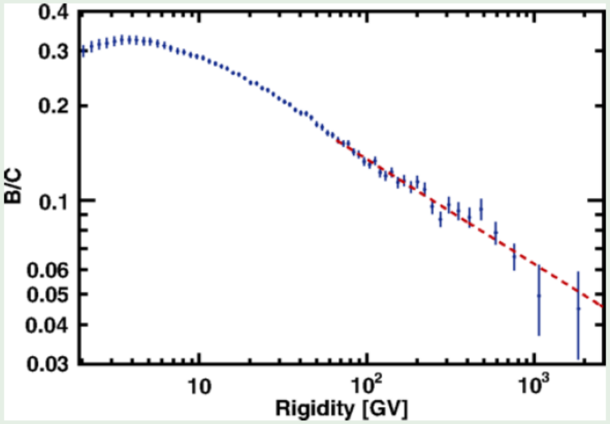
- Secondary-to-Primary ratios

Interactions between CR primaries and ISM result in secondary CR particles (charged particles, nuclei, neutral particles).

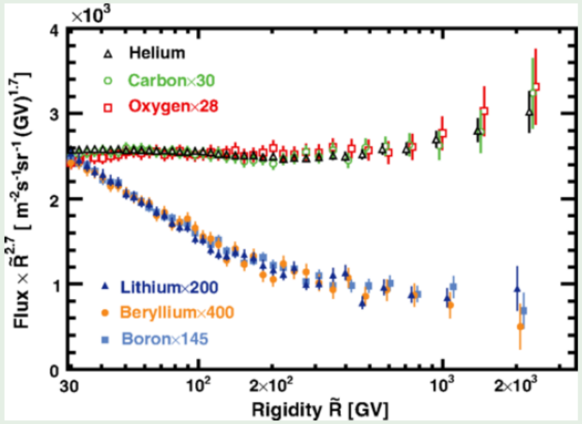
A ratio between secondary to primary CR nuclei or isotopes is indicative for particle transport physics

To study secondary/primary ratios one needs accurate knowledge about the interaction kinematics (x-sections, multiplicities etc.)

AMS results



Phys. Rev. Lett. 117, 231102 (2016)



Phys. Rev. Lett. 120, 021101 (2018)

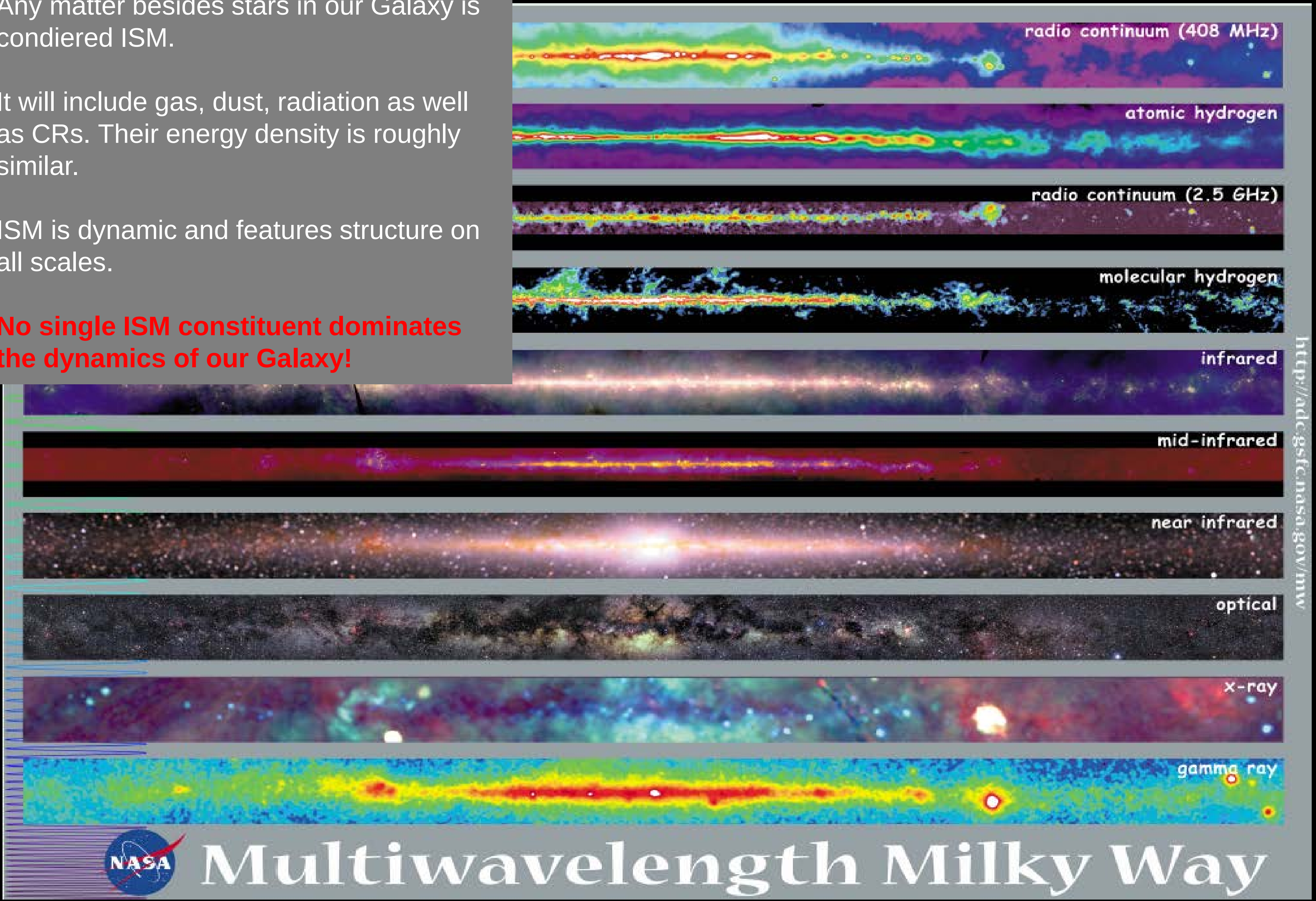
Necessities: 4) Interstellar Matter

Any matter besides stars in our Galaxy is condiered ISM.

It will include gas, dust, radiation as well as CRs. Their energy density is roughly similar.

ISM is dynamic and features structure on all scales.

No single ISM constituent dominates the dynamics of our Galaxy!



Necessities: 4) Gas & Dust distributions

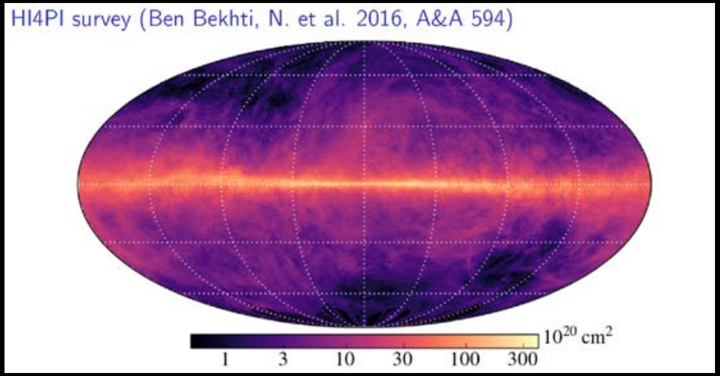
Gas and dust in our Galaxy provide the target for production of secondary CRs.

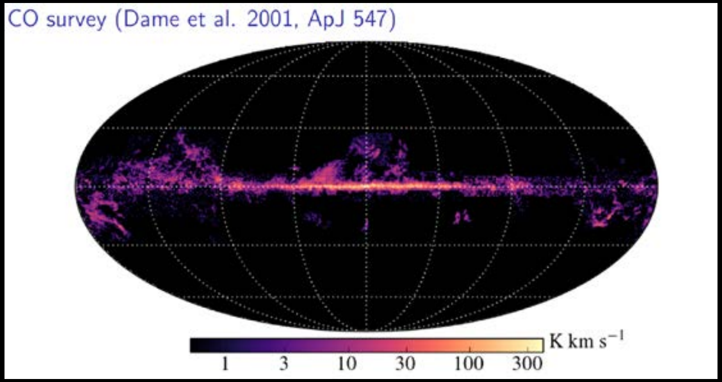
Gas and dust split into a ratio of approx. 100, meaning most of the mass is in the gas phase.

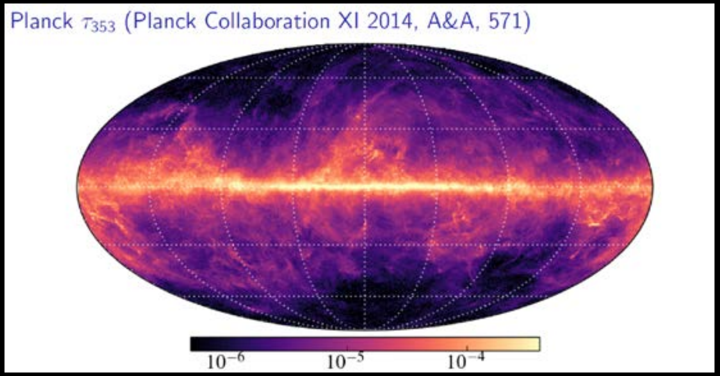
Its composition is mostly hydrogen (~70% mass fraction) and helium (~28 mass fraction).

Whereas hydrogen is comparably easy to observe, helium is not. Similary between their distributions is therefore only assumed.

Prime tracer of HI is the 21-cm line emission, for H_2 a proxy in the 2.5-cm line emission of CO is used. It can be converted to deduce the mass fraction of molecular hydrogen.







Necessities: 5) Radiation fields

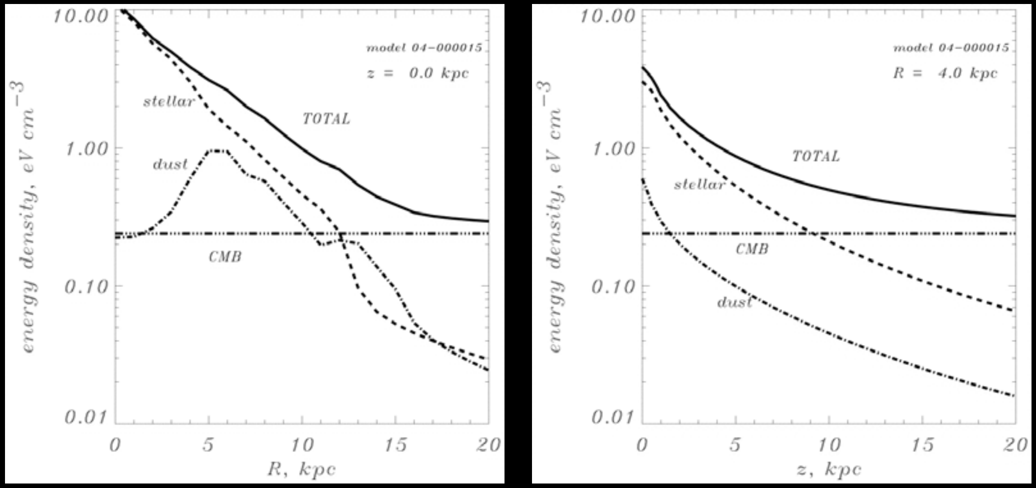
Stars, dust and the Cosmic Microwave Background constitute the principal components of the Galactic Radiation field.

As we observe at position Earth and the star and dust components differ at Galactic locations, a model of the radiation field needs to be inferred. It should deduce the contributions from stellar distributions, from dust and connect observed properties at Earth via radiative transport.

Over decades, the radiation field provided with the GALPROP code provided the most credible model for radiation fields in our Galaxy.

The most decisive imprint of radiation fields will be made out via Inverse Compton scattering (IC). The process is anisotropic and one needs to calculate IC contributions throughout the (3D)-Galaxy.

There is sufficient simplicity in such global models, and many parameters are weakly constrained. This is particularly problematic for the Galactic Center region and the inner Galaxy.

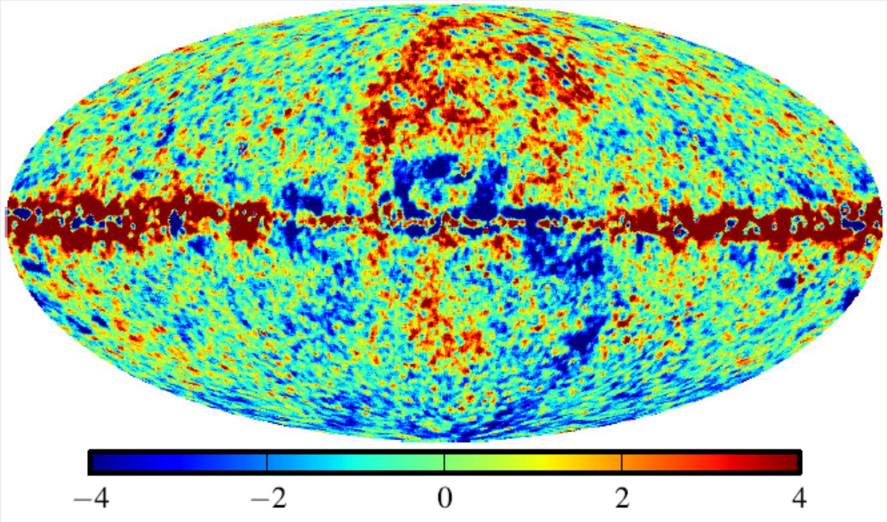


Example for the frequency- and location dependence of the radiation fields as of the model put forward with the GALPROP code
[Strong Moskalenko Reimer 2000]

Diffuse Continuum Gamma Radiation

Propagation models

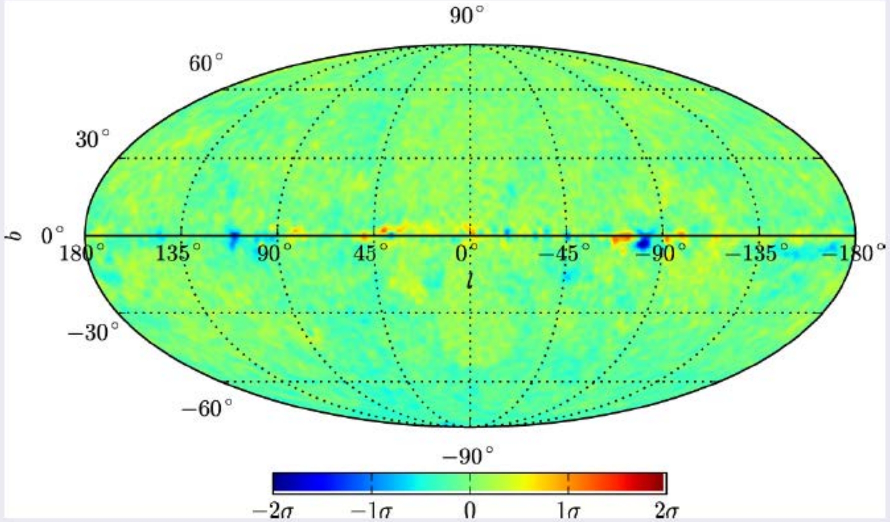
- CRs calculated assuming models for sources and propagation.



Ackermann et al. 2012, ApJ, 750, 3

Template models

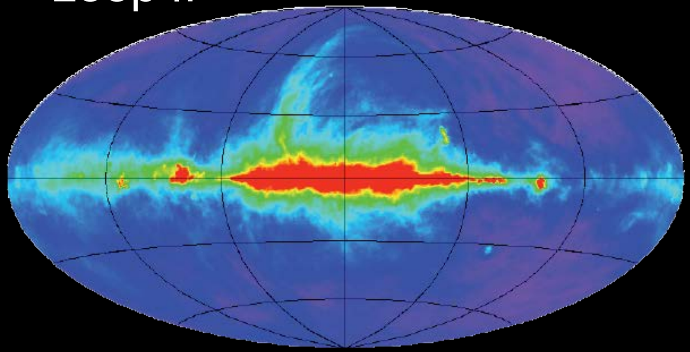
- CRs calculated assuming each template is hit with constant CR flux.



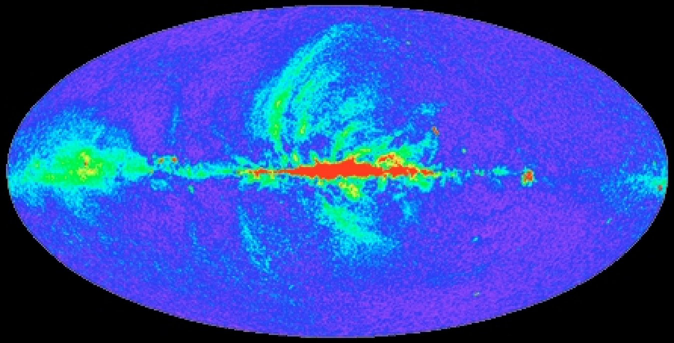
Acero et al. 2015, ApJS, 223, 26

The Local Bubble and Beyond

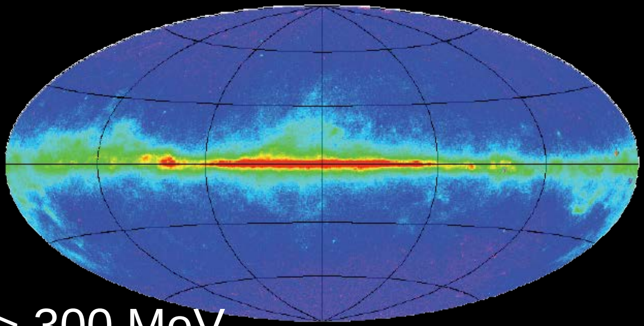
Loop I:



Haslam 408 MHz

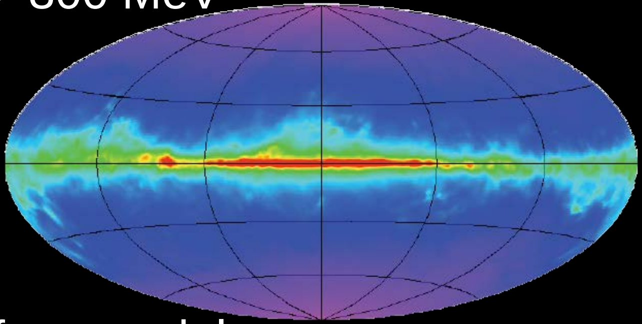


WMAP polarized emission 23 GHz



Fermi E > 300 MeV

↑
?
↓

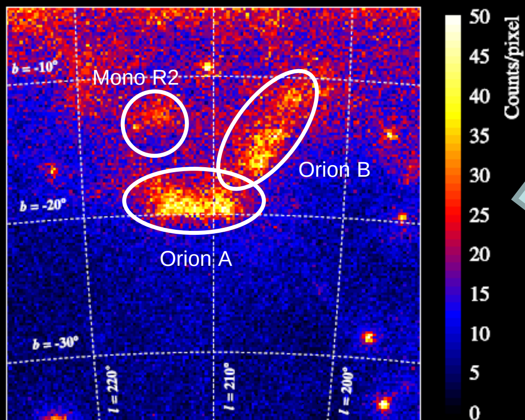


Fermi diffuse model

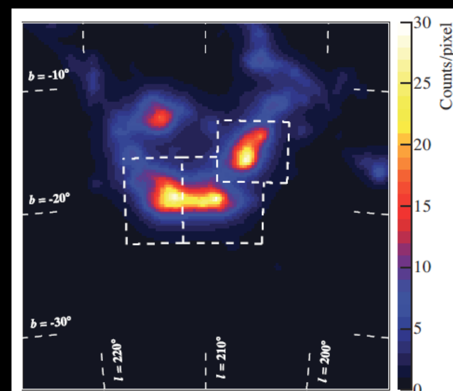
There appears to exist arc-like excesses against the diffuse model:
Fainter than pion production and bremsstrahlung as calculated from HI tracer, fainter than IC as templated in diffuse model. ☞ ***The realm of diffuse templates!***

The Local Bubble and Beyond

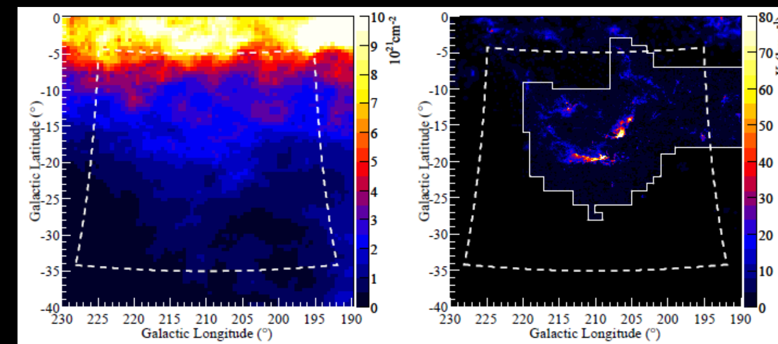
Nearby molecular clouds: Orion (d ~ 400 pc)



E > 200 MeV



LAT collaboration ´12

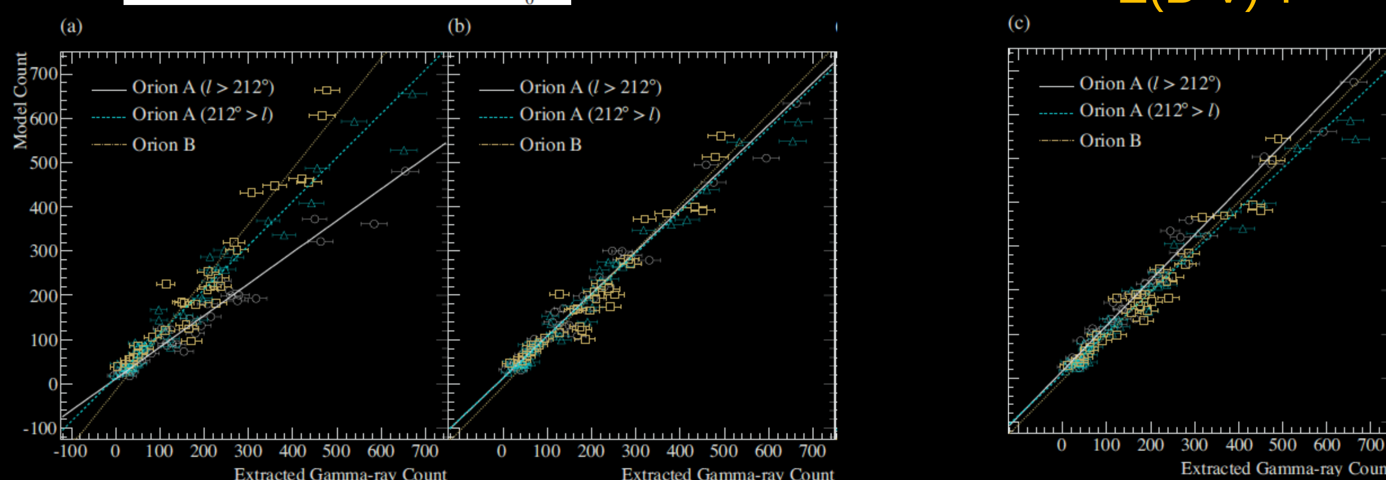


HI CO

$$N(H_2) = X_{CO}\, W(^{12}C^{16}O\, J = 1 \rightarrow 0)$$

Alternatives?
E(B-V) ?

A more closer look on the X_{CO} :

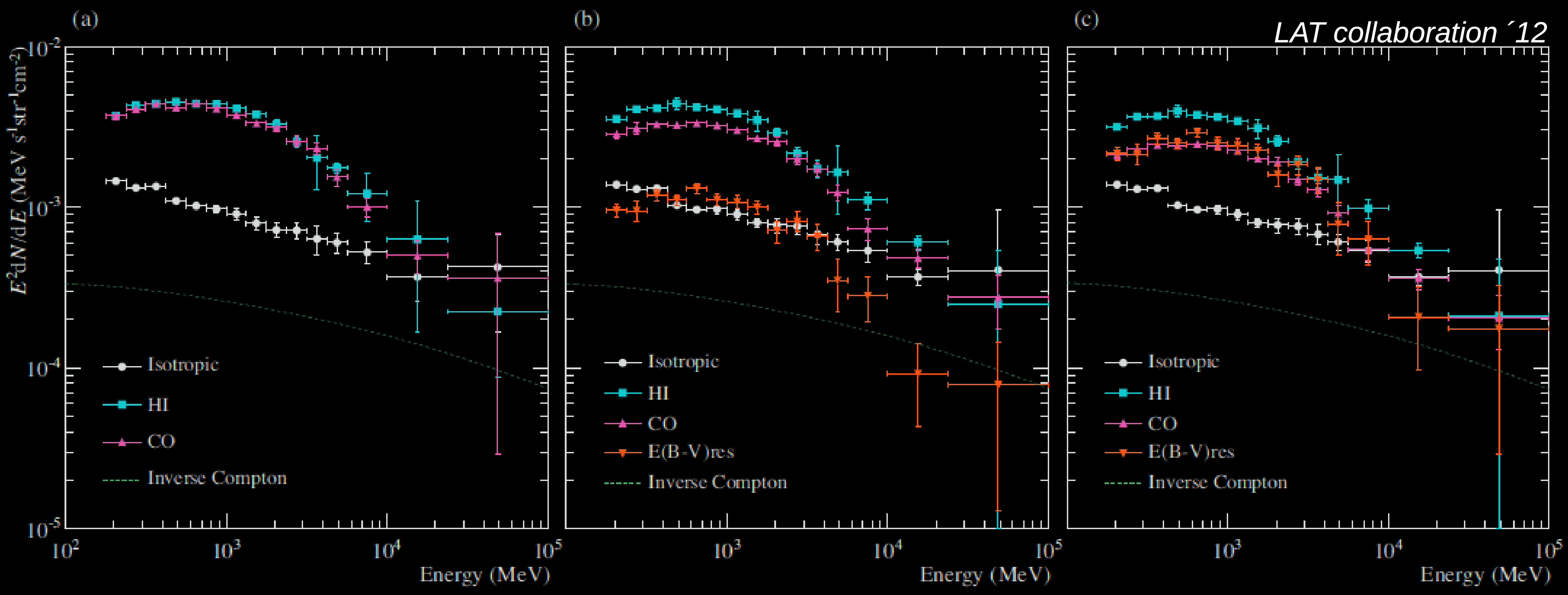


Xco: 1.63 × 10^{20} cm^{-2} K^{-1} km^{-1} s 1.35 - 2.34 × 10^{20} cm^{-2} K^{-1} km^{-1} s

The Local Bubble and Beyond

Nearby molecular clouds: Orion (d ~ 400 pc)

Consequently, spectral extraction of relative emission components differs:



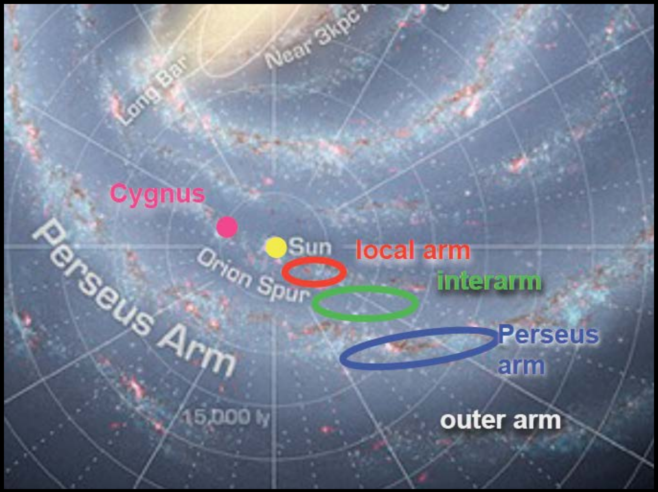
Xco static

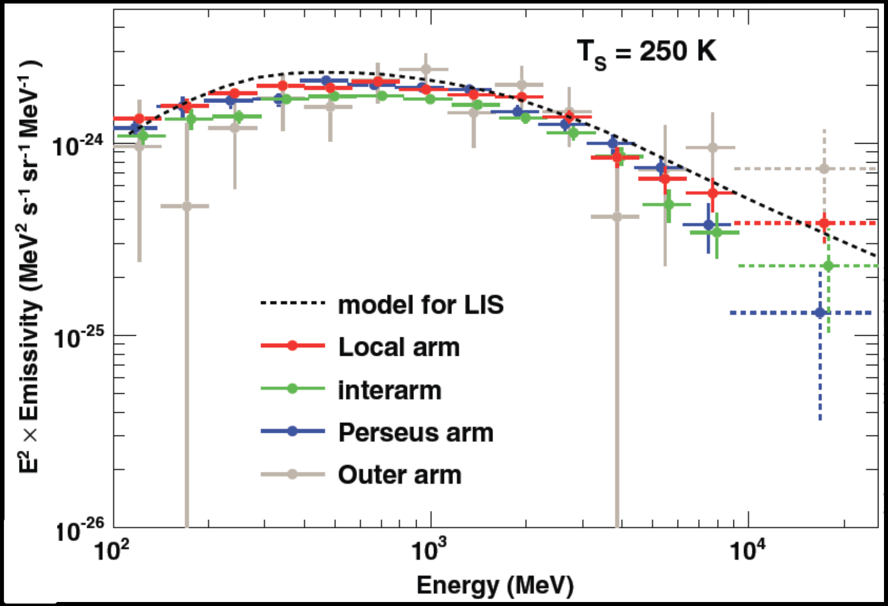
Xco variable

Xco partily compensated by E(B-V)

- Nonlinear conversion between H_2 and CO in diffuse molecular gas?
- Unseen part in velocity integrated CO intensity (aka W_{CO}) ?

Moving out: Through the Spiral Arms

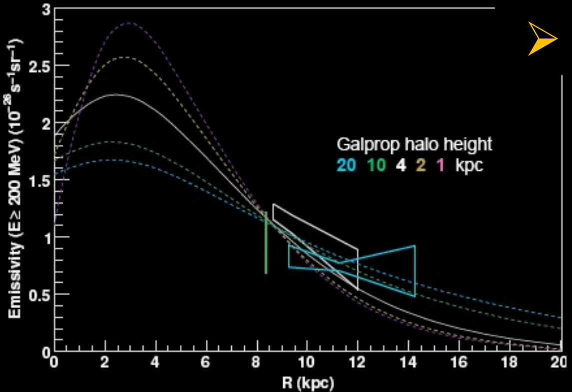




LAT collaboration ´11

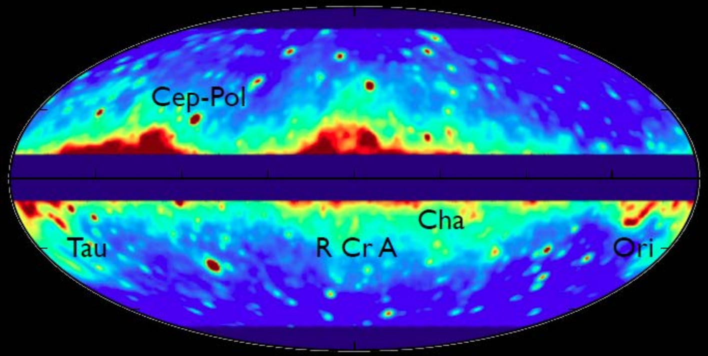
- consistent with LIS spectrum,
  comparable in clouds with $10^3 < M < 8 \times 10^6\ M_\odot$

- little arm/interarm contrast
  → loose coupling with the kpc-scale surface density of gas or star formation



- shallow emissivity gradient in the outer Galaxy:
  too shallow even for a large halo size !
  ? large amounts of missing gas / badly understood tracers ?
  ? non-uniform diffusion ?
  ? simplistic diffuse emission model ?

To the rescue...

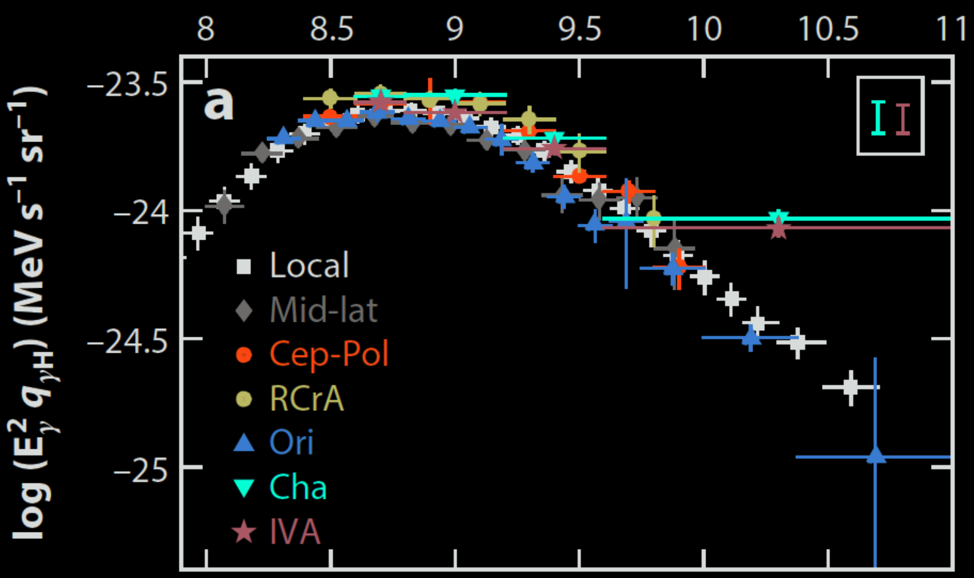


[Casandjian 2015]

compare two targets:

(i) gas at (10º < |b| < 70º)
(= local within ~ 1 kpc)

(ii) individual nearby clouds
(within a few 100 pc)



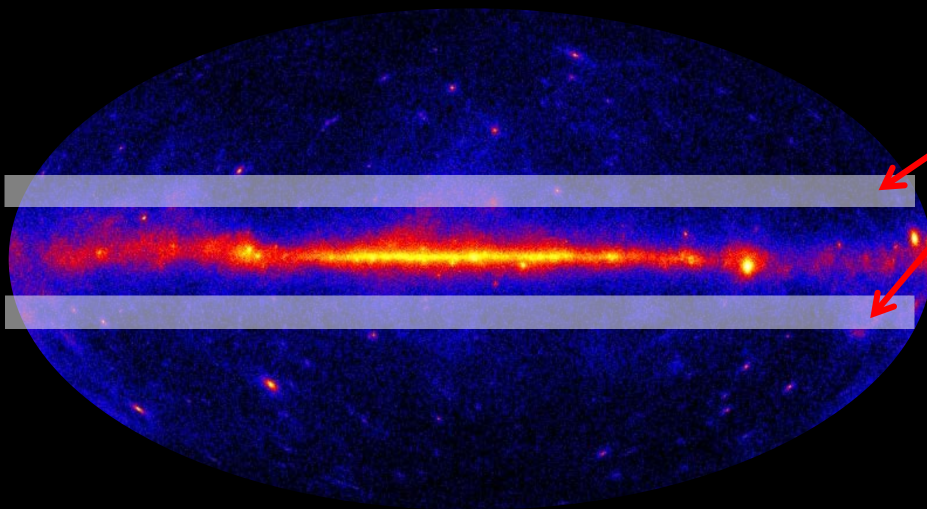
[Grenier ea 2015]

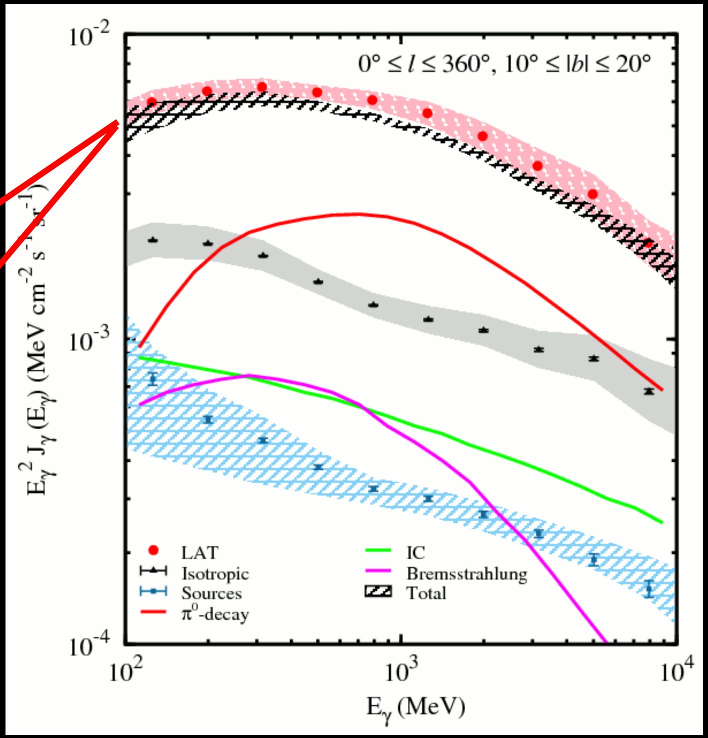
results: < 30% spatial/spectral variations

☞ no large effects from local injection/propagation effects

Full-fledged diffuse modeling in the Milkyway

100 MeV – 10 GeV





LAT collaboration ´09

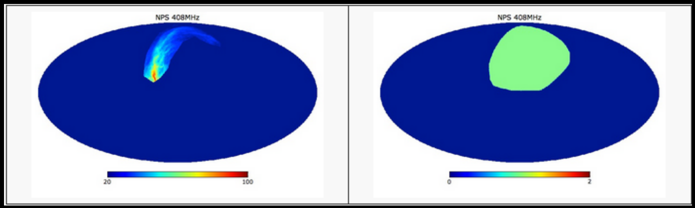
→ standard CR interaction models adequate (which do justice to locally measured CR abundances, CR sec/prim ratios, long/lat distr.)
→ Fermi/LAT errors are systematics dominated

since then: quality of LAT data exceeds progressively realism of CR propagation model / diffuse emission templates!

Full-fledged diffuse modeling in the Milkyway

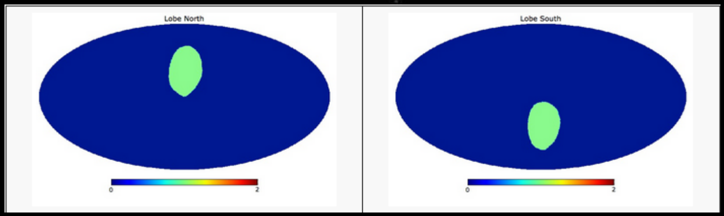
→ **"analysis model"** based on templated emission components (IC, ISO)
+ a ring-emissivity model for HI and CO (for H_2)
+ an extinction E(B-V) template following the spirit of unseen "dark" gas

- model grid of 0.125°
- interstellar radiation fields via *GALPROP templates*
- cube of 30 energy planes from 50 MeV to 600 GeV
- GALPROP-derived template for Inverse Compton
- dedicated templates for large-scale regions of excess emission

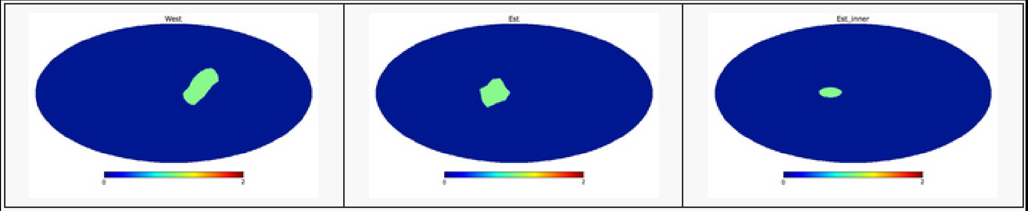


← Loop I / NPS

Galactic Lobes→



Galactic Plane excess regions →



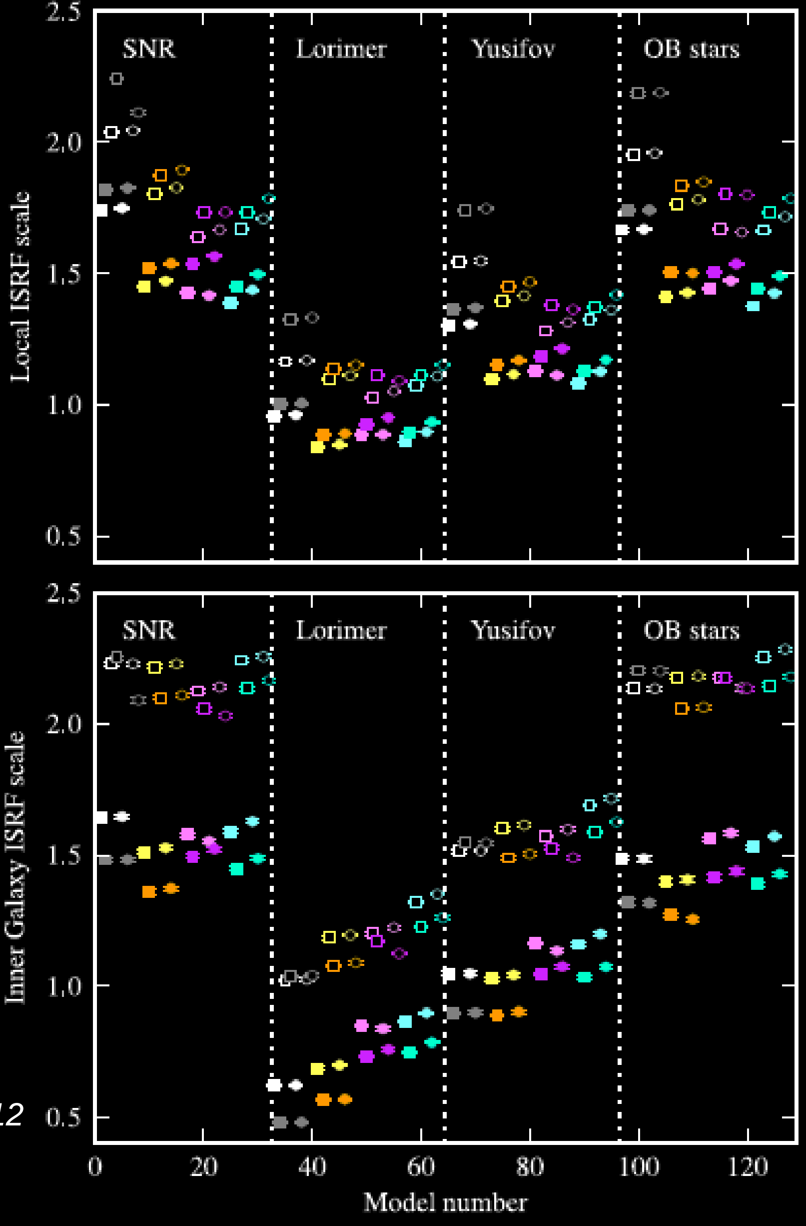
Result: *Fermi diffuse model became a point-source analysis model!*
Aim to minimize residuals goes on the expense of consistent physics !
Almost impossible to interpret when interesting physics shows up !

Full-fledged diffuse modeling in the Milkyway

→ **"propagation- model"** based on CR propagation physics that fit CR data, and allow predictions for γ-ray emissivities

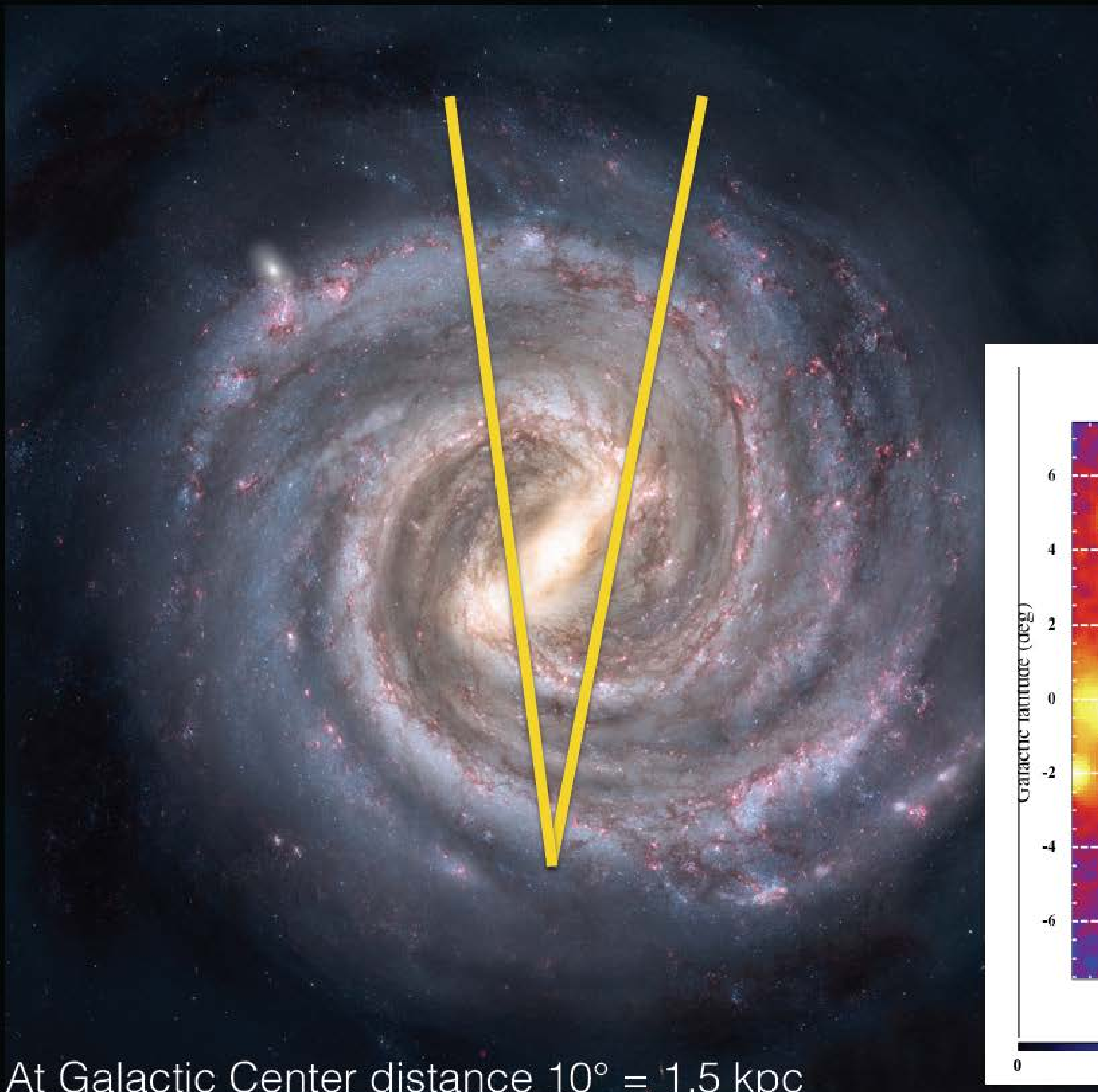
→ thus far, GALPROP in axial-symmetric cylindrical geometry commonly used

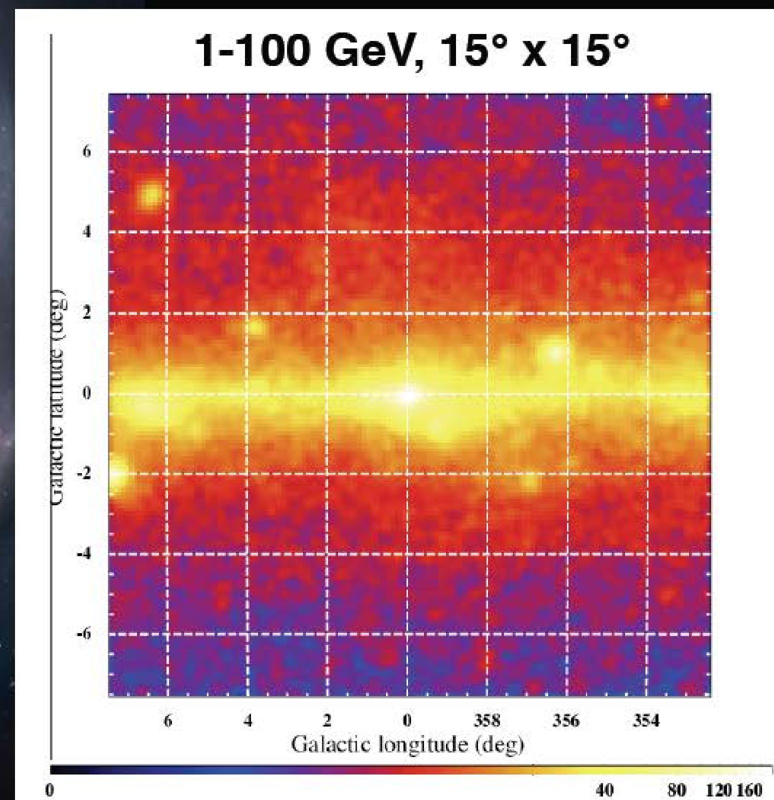
→ normalizations (scaling) introduced here & there:



LAT collaboration '12

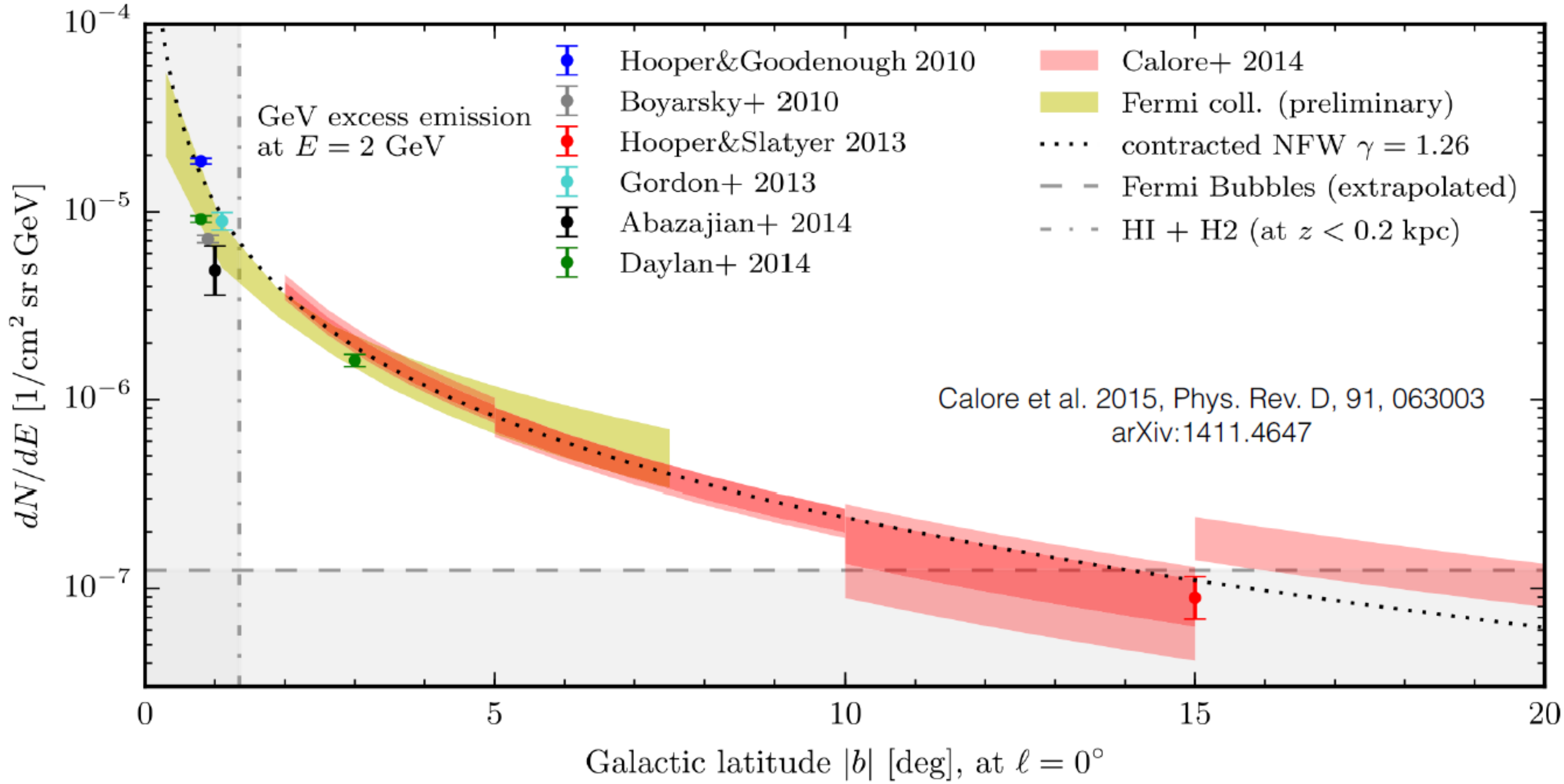
Pathological? Diffuse GeV excess emission from GC





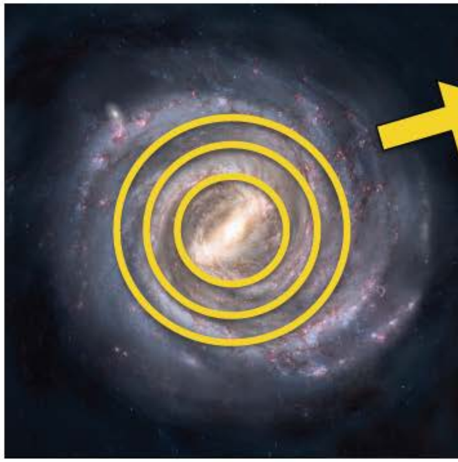
Diffuse GeV excess emission from GC, cont.

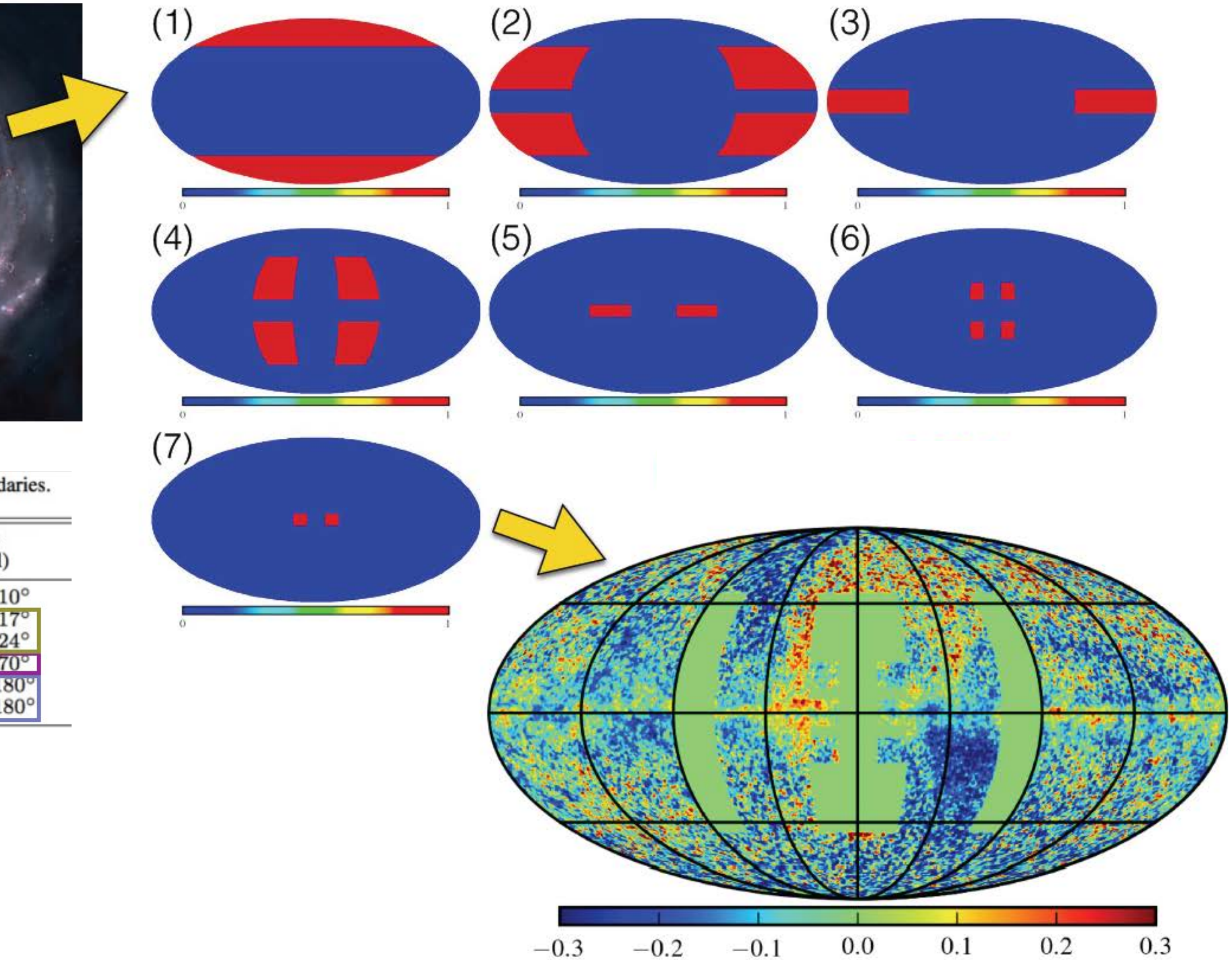
Many groups have reported a spatially extended excess of gamma-ray emission in the inner Galaxy peaking at ~2 GeV in E^2 dN/dE and consistent with a contracted NFW profile



Spectrum, spatial profile, and inferred annihilation cross section are consistent with WIMP hypothesis within uncertainties — *can an astrophysical interpretation be excluded?*

Sytematics of Diffuse Model





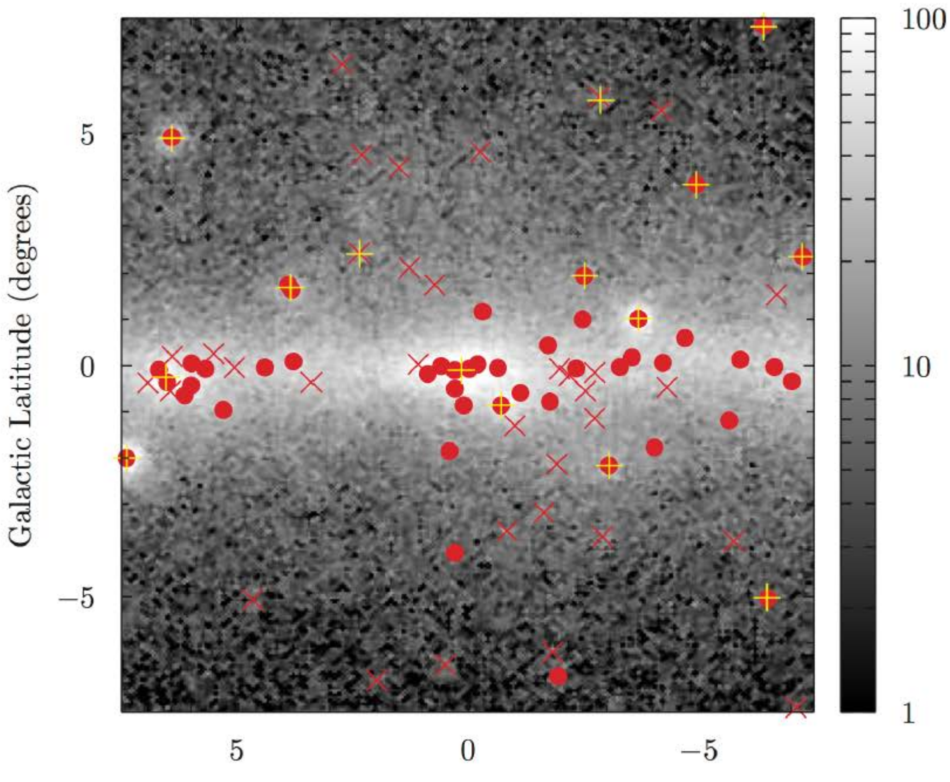
Galactocentric ring boundaries.

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

[Fermi-LAT Ajello ea 2016]

Point Source Contributions

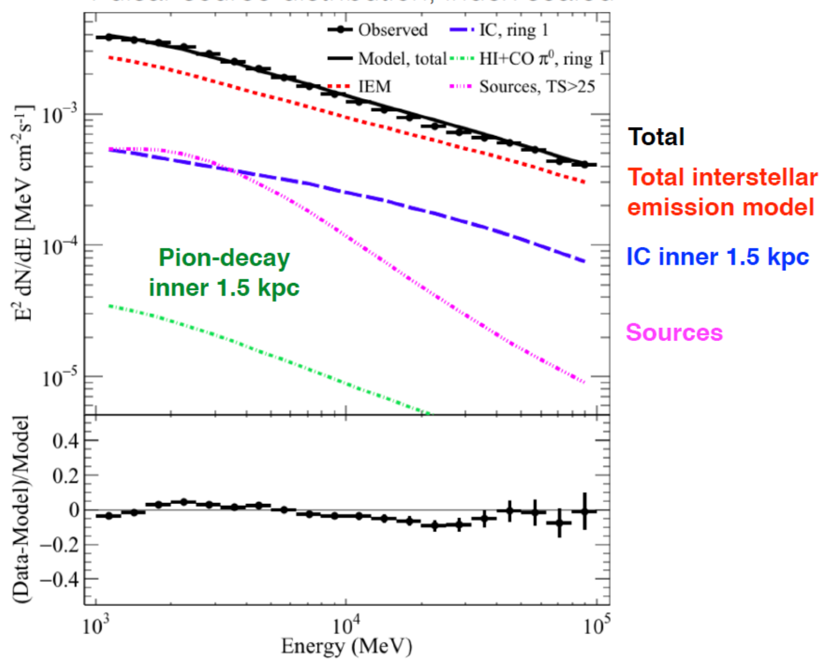
Finds "true" point sources and CR-induced emission consistent with PSF



For each baseline diffuse model, **self-consistently fit point sources and diffuse emission** in 15° x 15° region of interest using iterative approach

Intensity within 15° x 15° region of interest

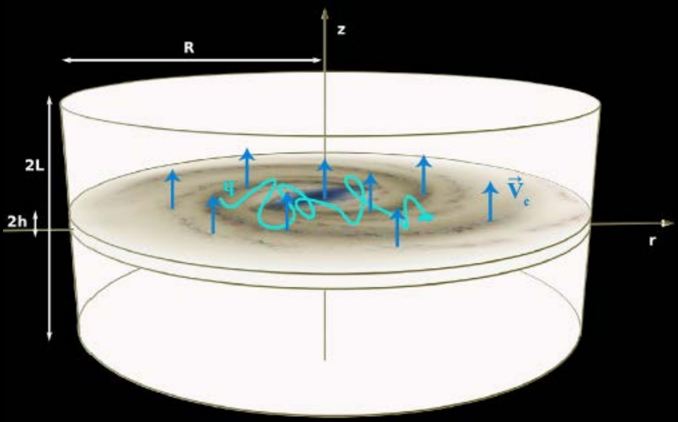
Pulsar source distribution, index scaled



Integrating of the inferred flux distribution of sub-threshold sources could explain entire excess

[Fermi-LAT Ajello ea 2016]

Therefore back to CR propagation physics, but at new level of realism



from simple slab and halo approximation
to full 3D propagation, matter & source distributions in spiral arms, realistic B-field models, stochastic sources & energy losses on local scales (TeV!)

- improvements on math-numerical, geometry, & physics side
- still need to solve the beastly transport equation:

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (\mathrm{D}_{xx} \nabla \psi - \mathbf{v} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left\{ \dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi \right\} - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

GALPROP

Cosmic Particle Transport

THE NEXT GENERATION

Astroparticle Physics 55 (2014) 37–50

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ELSEVIER

PICARD: A novel code for the Galactic Cosmic Ray propagation problem

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ABSTRACT

In this manuscript we present a new approach for the numerical solution of the Galactic Cosmic Ray propagation problem. We introduce a method using advanced contemporary numerical algorithms while retaining the general complexity of other established codes. In this paper we present the underlying numerical scheme in conjunction with tests showing the correctness of the scheme. Finally we show the solution of a first example propagation problem using the new code to show its applicability to Galactic Cosmic Ray propagation.

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1. Introduction

The Galactic Cosmic Ray propagation problem, i.e., the question how Cosmic Rays are transported from their sources to arbitrary locations in the Galaxy, becomes ever more relevant with recent advances in observational techniques. Such observations yield the flux of primary Cosmic Rays (see, e.g., [9,12,2,3]) or also of secondaries at Earth. For neutral secondary particles also directional information can be extracted from the data (see, e.g., [1]). Together with a physical description of the transport process of Cosmic Rays these data should allow a better understanding of the physics involved in Cosmic Ray transport.

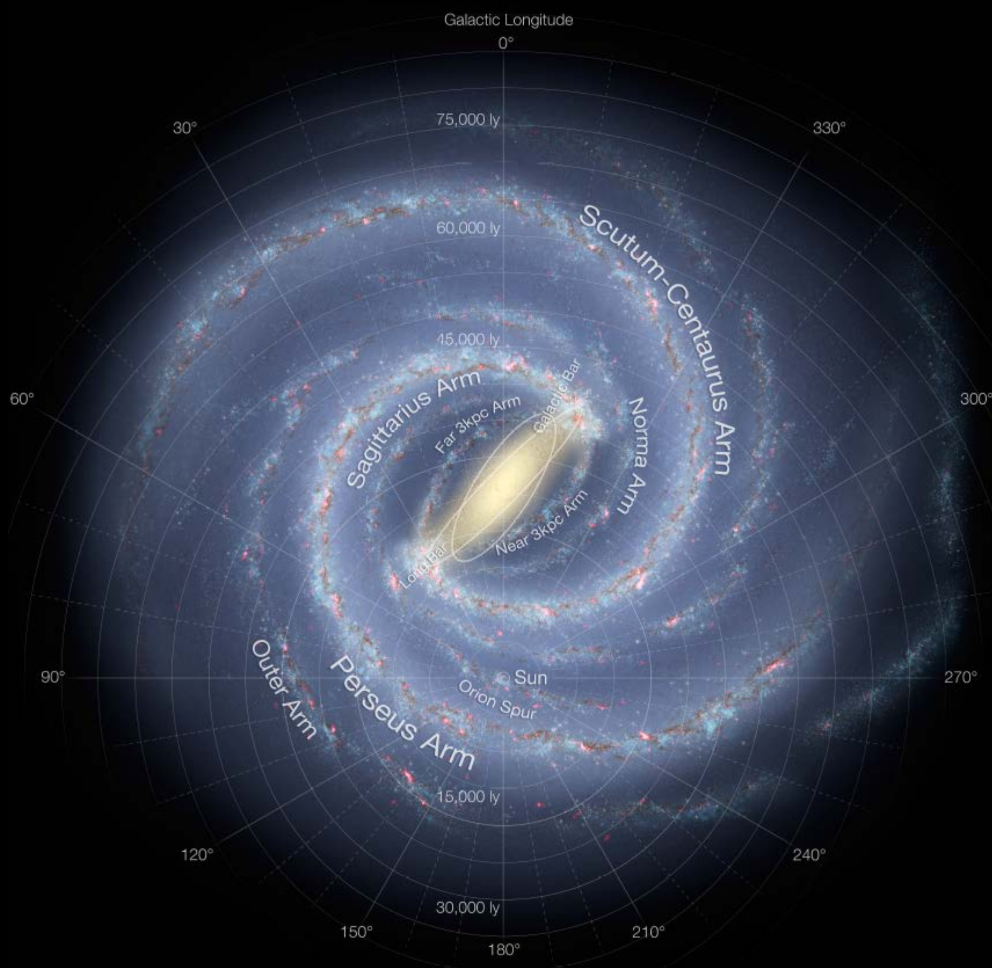
The transport of Galactic Cosmic Rays is a diffusion-loss problem (see [15]). That is we have to find a solution of the partial differential equation:

losses by fragmentation and radioactive decay for the current Co
mic Ray species.

This partial differential equation has been solved using differ
numerical codes or analytical approximations or a mixture of bo
Use of analytical solutions or approximations within a numer
code decreases the numerical cost to find a solution and giv
more direct idea of the underlying dependence of the solutio
different parameters. Analytical methods, however, are not su
to investigate the Cosmic Ray propagation problem in a rea
environment, i.e., an environment, where all functions that d
mine the final outcome of Eq. (1) are allowed to vary arbit
in configuration- and momentum-space.

With the increasing precision of Galactic Cosmic Ray mea
ments an analytical approach is far from being able to expla
fine details in the measurements. Also a discussion of >1 Te

Towards better GeV-TeV propagation models then…

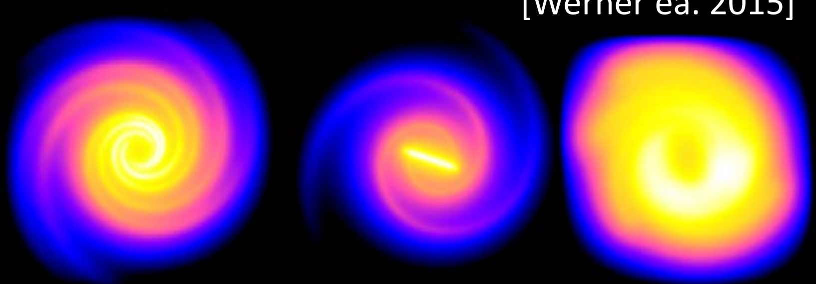


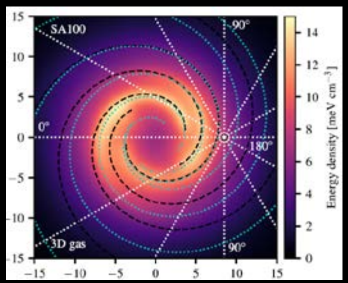
This is only an artists impression.

We have remarkably contrasting views about the geometry of our Galaxy!

As soon as we leave 2D axisymmetry,
a full new parameter space is being introduced to CR transport!

[Werner ea. 2015]

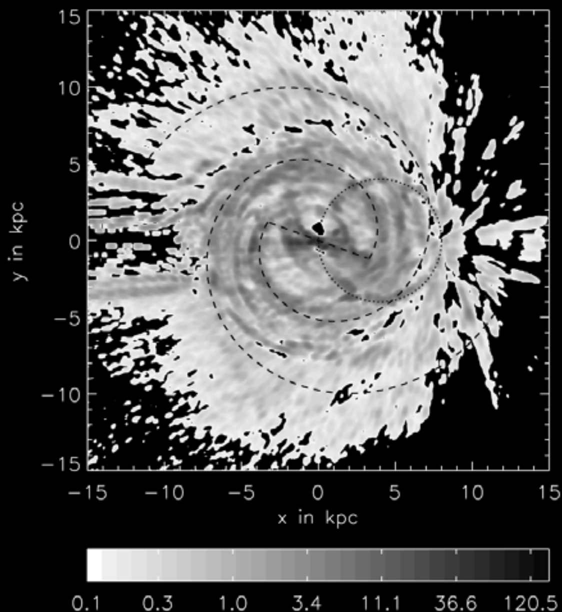




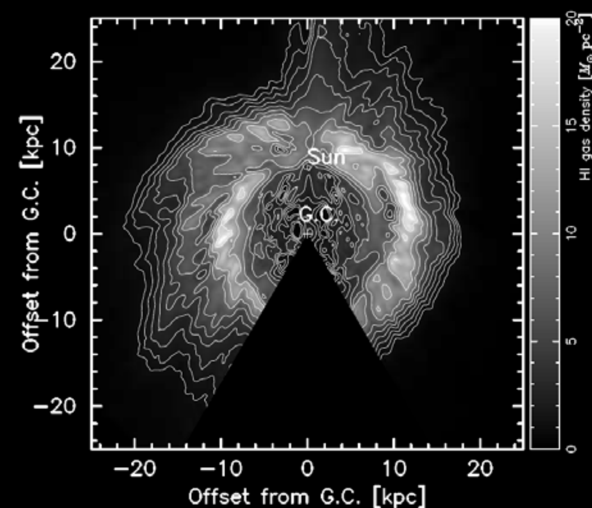
[Johannesson ea. 2018]

Towards better GeV-TeV propagation models then…

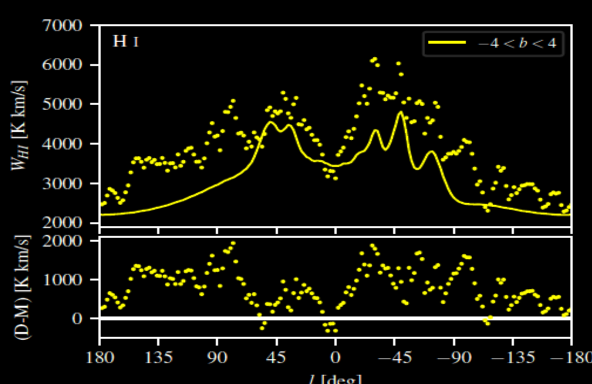
3D gas distributions using kinematic distances

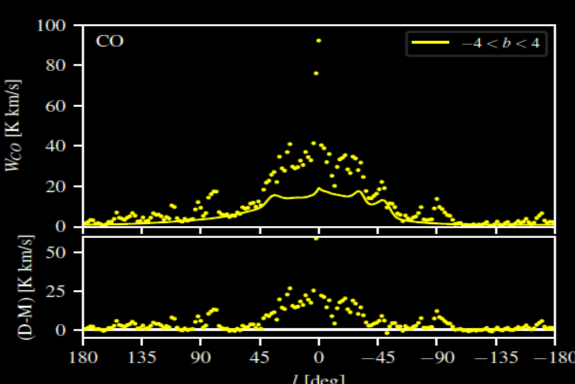


CO from Pohl et al. 2008.



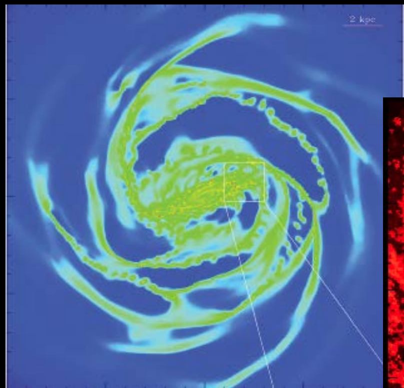
H I from Nakanashi & Sofue 2015.



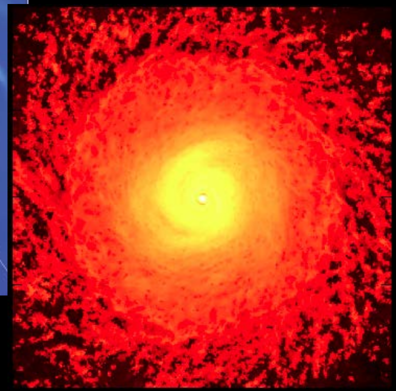


[Johannesson ea. 2018]

Towards better GeV-TeV propagation models then…



Renaud ea 2013



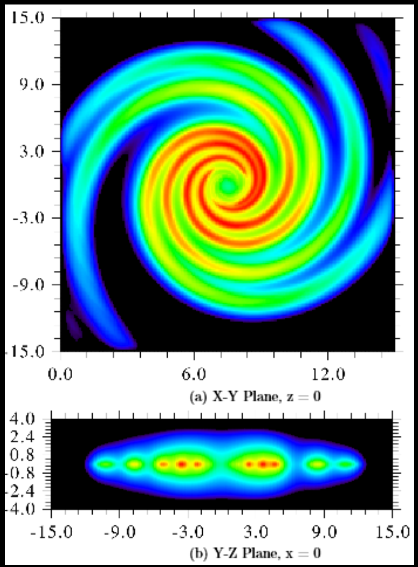
Pfrommer ea 2017

We don't know how our Milkyway looks like, precisely!

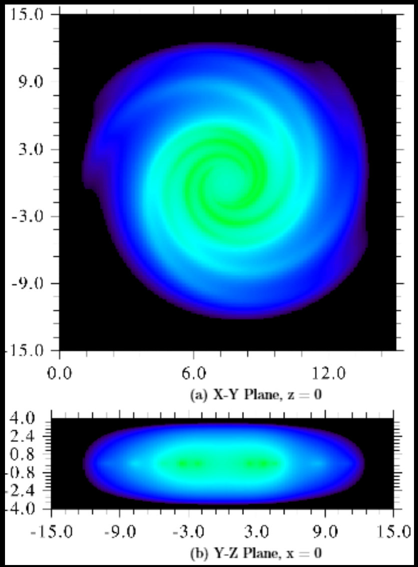
☞ PICARD: axisymmetric,
Steiman 4-arm,
Dame 2-arm,
Cordes-Lazio NE2001
Pfrommer AREPO$_{MHD}$

e.g. CRp distribution by *PICARD in 4-arm model:*

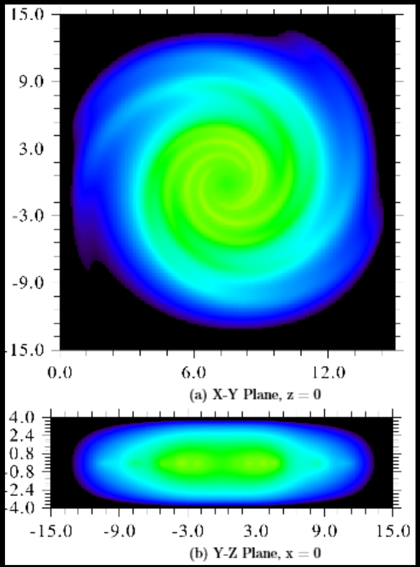
1 GeV



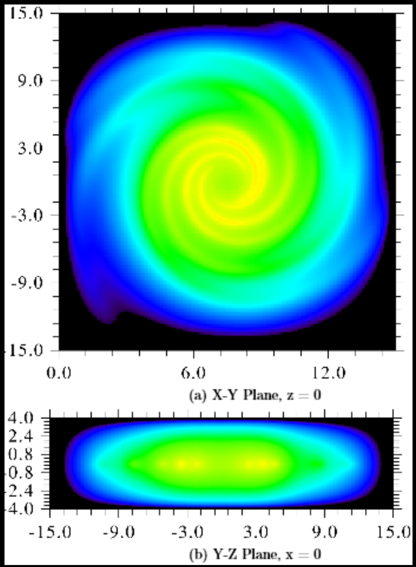
10 GeV



100 GeV



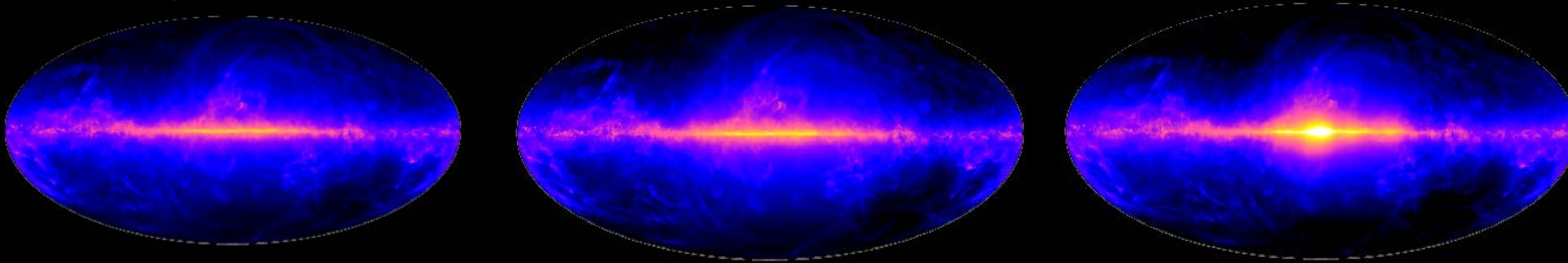
1 TeV



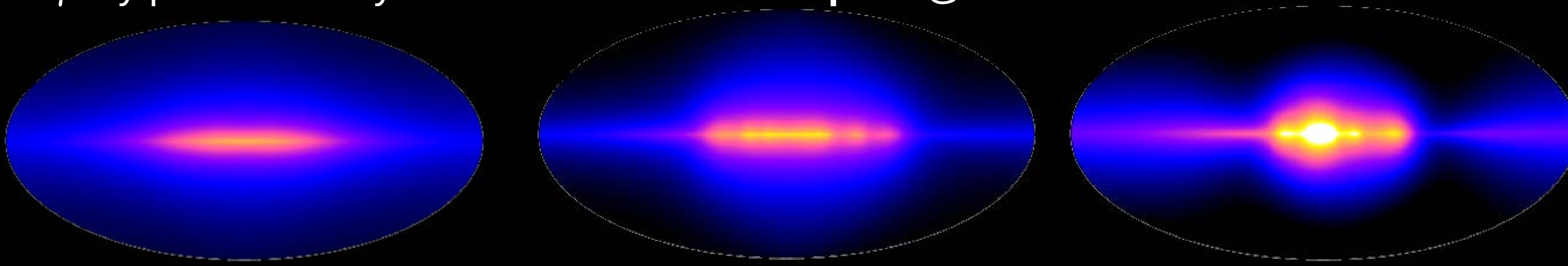
Towards better GeV-TeV propagation models then…

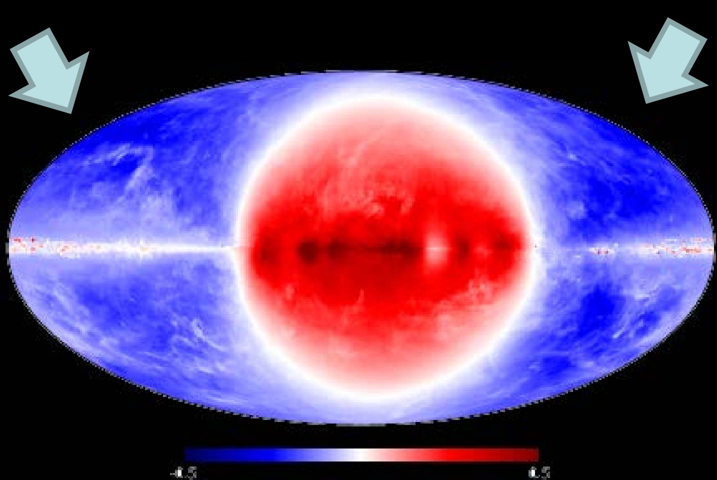
γ-ray predictions by *PICARD*: **total intensity @ 100 GeV**

axisymmetric 4-arm 2-arm



γ-ray predictions by *PICARD*: **Inverse Compton @100GeV**





difference (residuals) between axisymmetric and 4-arm model (still using identical set of propagation parameters)

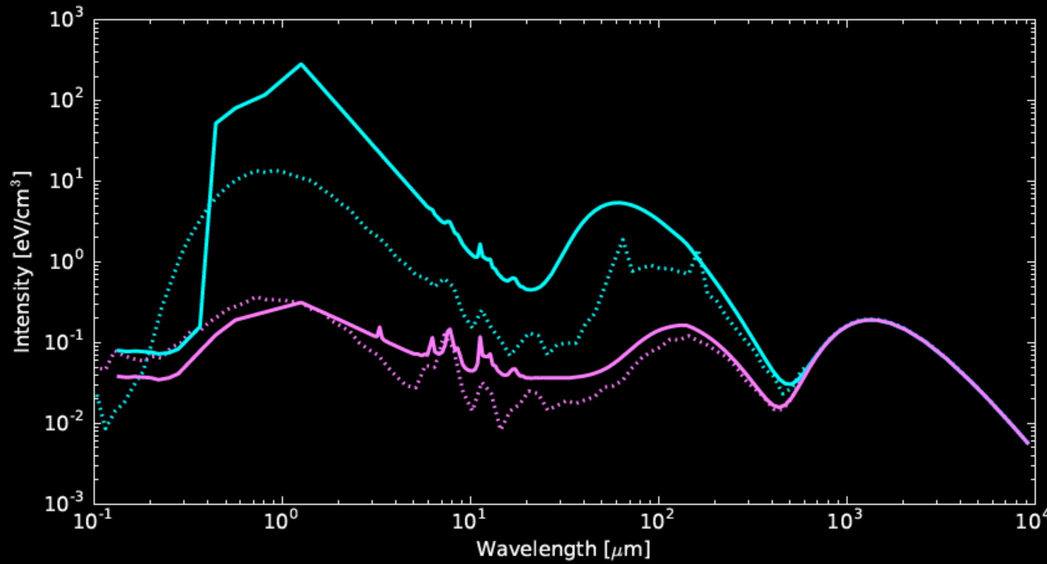
☞ **major differences in 3D model predictions!**

[Kissmann ea 2013, 2014, 2015, 2017]

Towards better GeV-TeV propagation models then…

an observation-driven Interstellar Radiation Field

[Popescu ea 2017, Niederwanger ea 2019]



Galactic Center

solid: PICARD

dashed: GALPROP

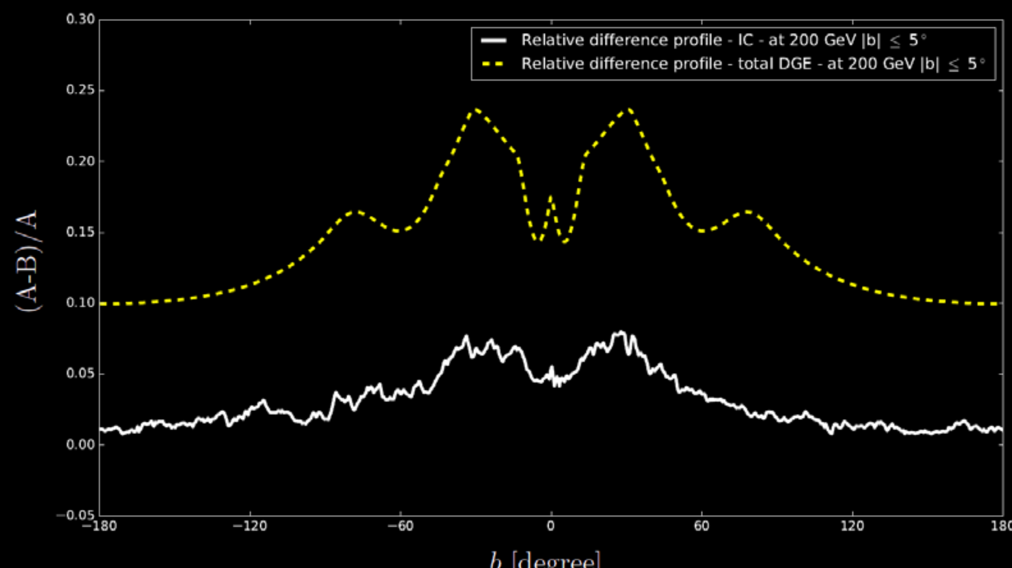
Earth

solid: PICARD

dashed: GALPROP

up to 25% difference in IC

up to ~10 % difference total



Towards better GeV-TeV propagation models then…

an observation-driven Interstellar Radiation Field

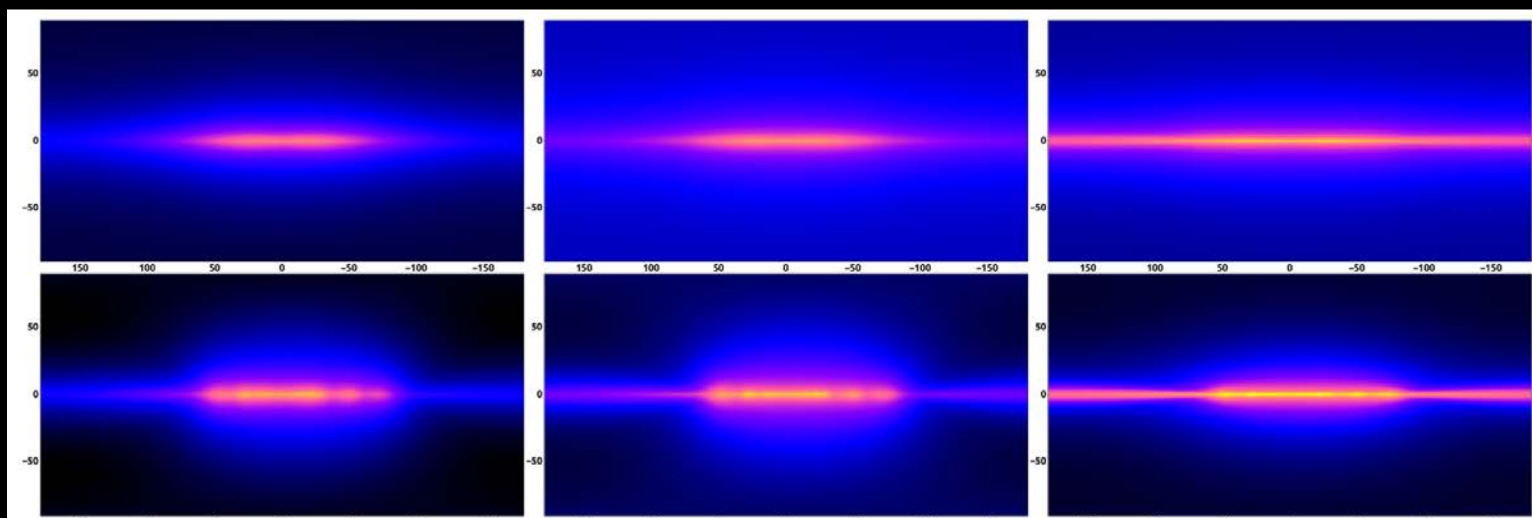
[Popescu ea 2017, Niederwanger ea 2019]

IC predictions from PICARD

10 GeV 1 TeV 100 TeV

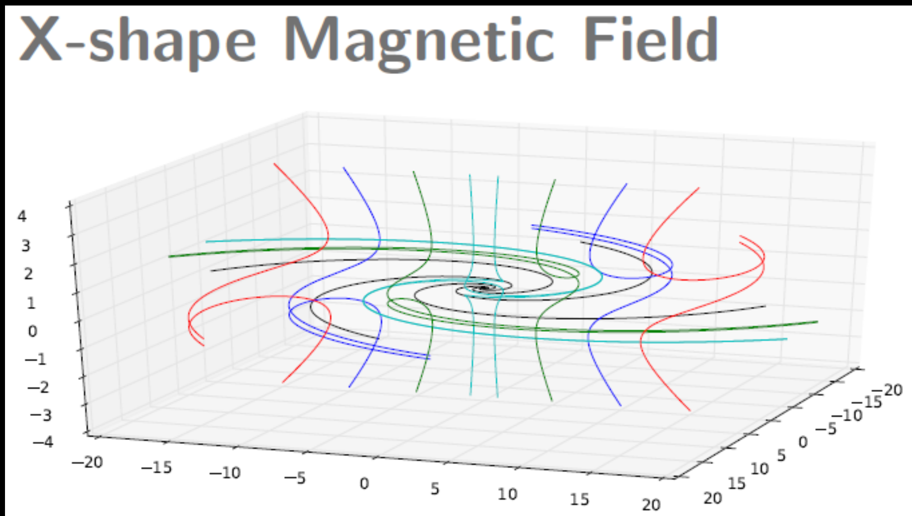
axisymmetric

4-arm model



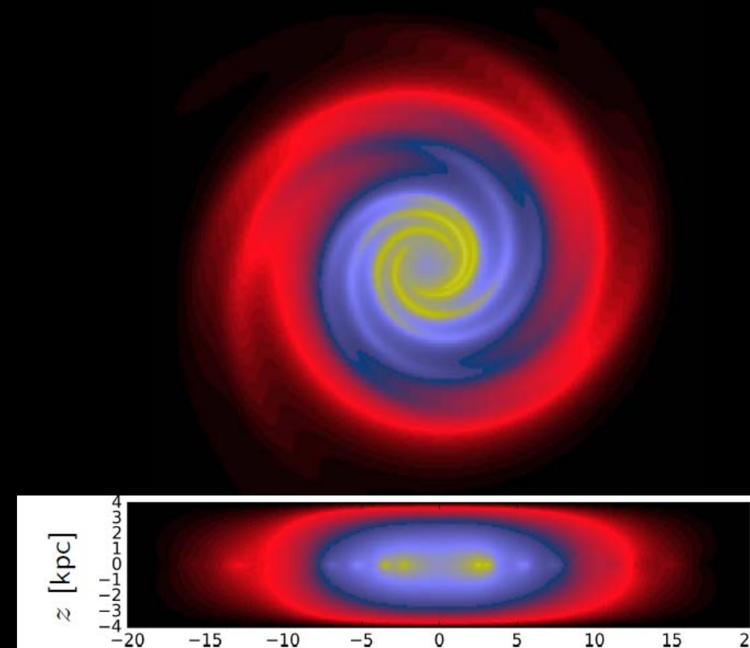
Towards better GeV-TeV propagation models then…

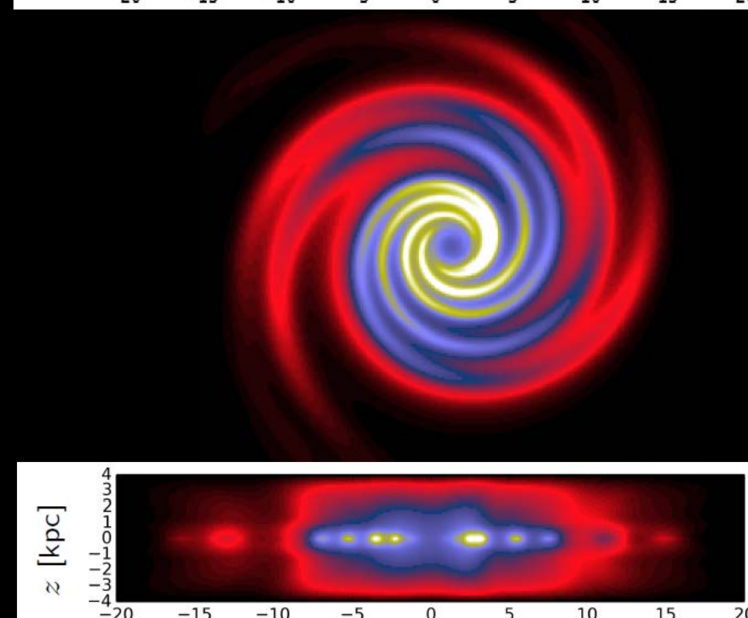
3D B-field geometry



Diffusion Models

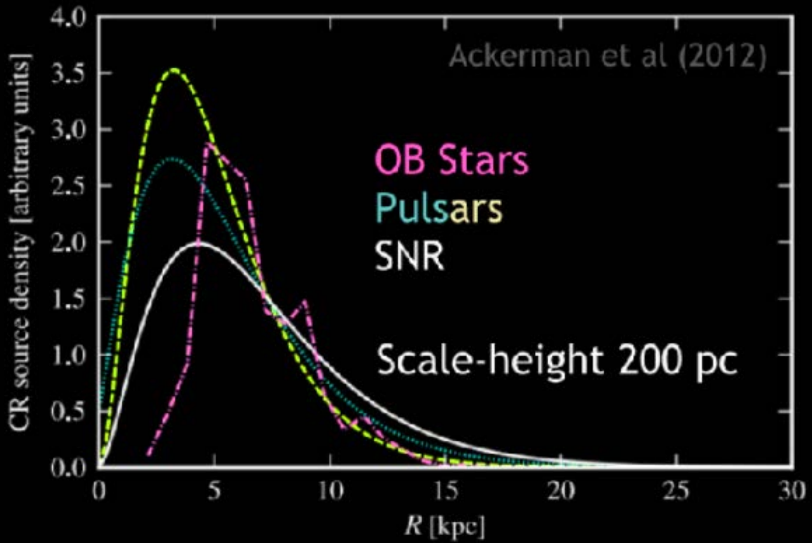
1. Isotropic
2. Along spiral arms
3. Along X-shape magnetic field by Ferrière and Terral (2014)





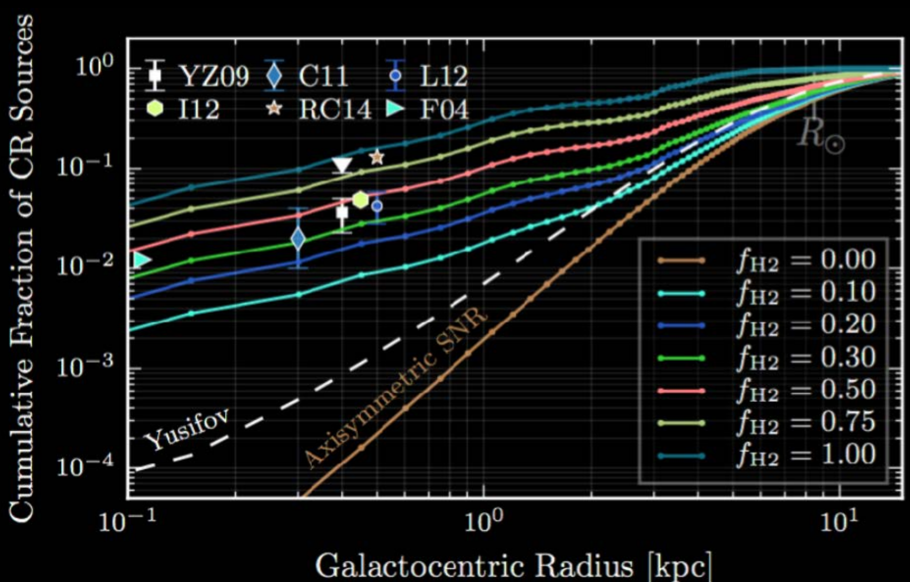
Towards better GeV-TeV propagation models then…

an observation-driven source CR source model



spiral arms?

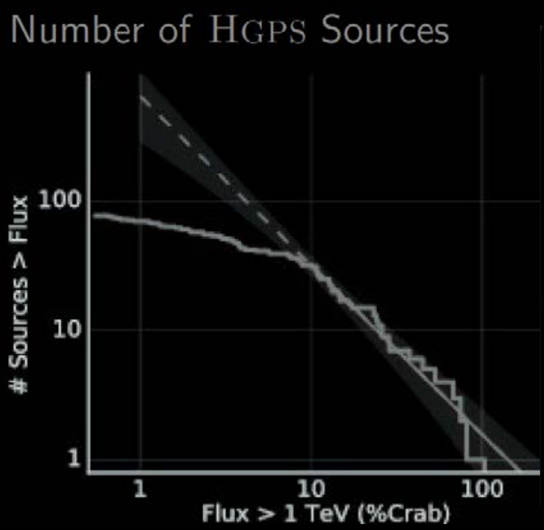
?

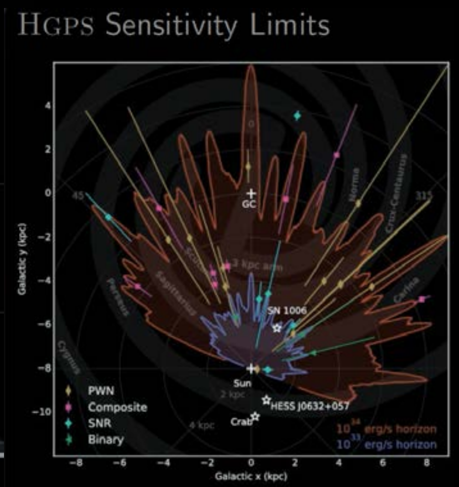


Carlson ea 2016

Towards better GeV-TeV propagation models then…

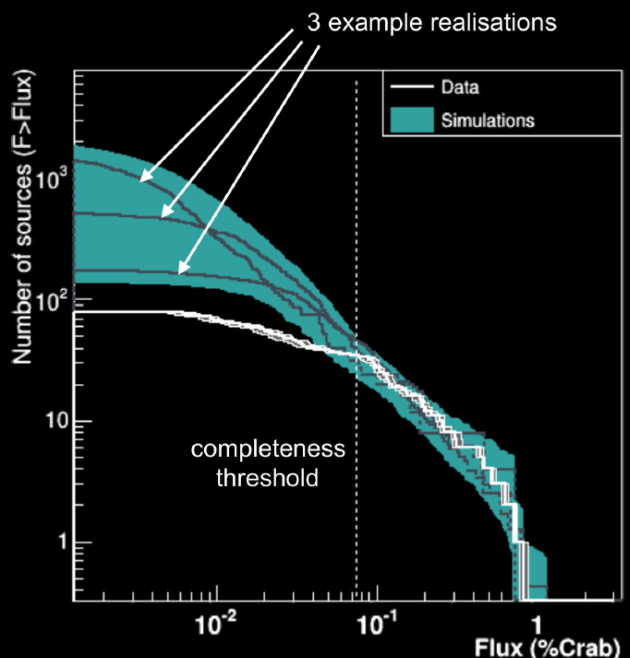
an observation-driven source term for the transport equation

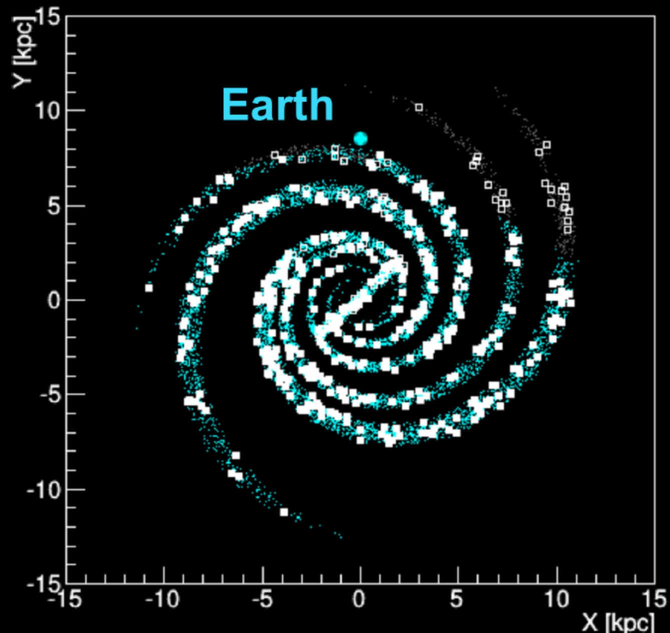




Step 1:

- **Source distribution MC [Egberts ea 2018]**
- **Projected onto 3D-Galaxy model**



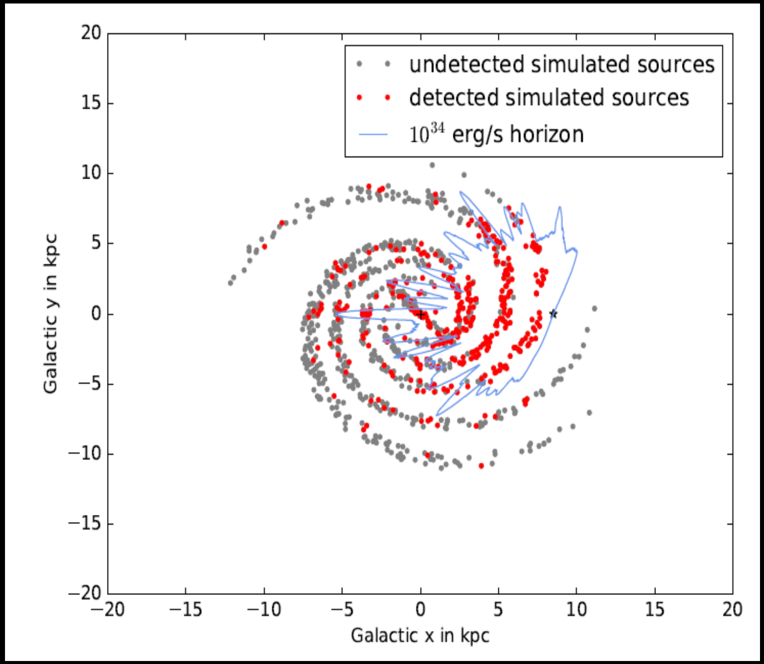


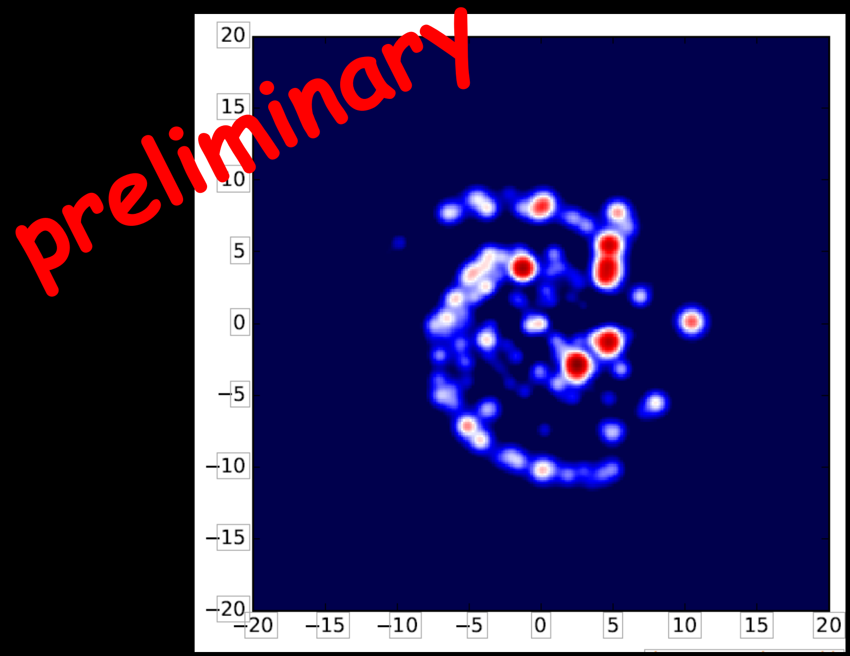
Towards better GeV-TeV propagation models then…

an observation-driven source term for the transport equation

Step 2:

- **H.E.S.S. catalog sources placed at l,b and according to observed Lγ**
- **categorized into suspected hadronic or leptonic emission dominance**
- **Galaxy filled to completeness limit according to log N-log S**





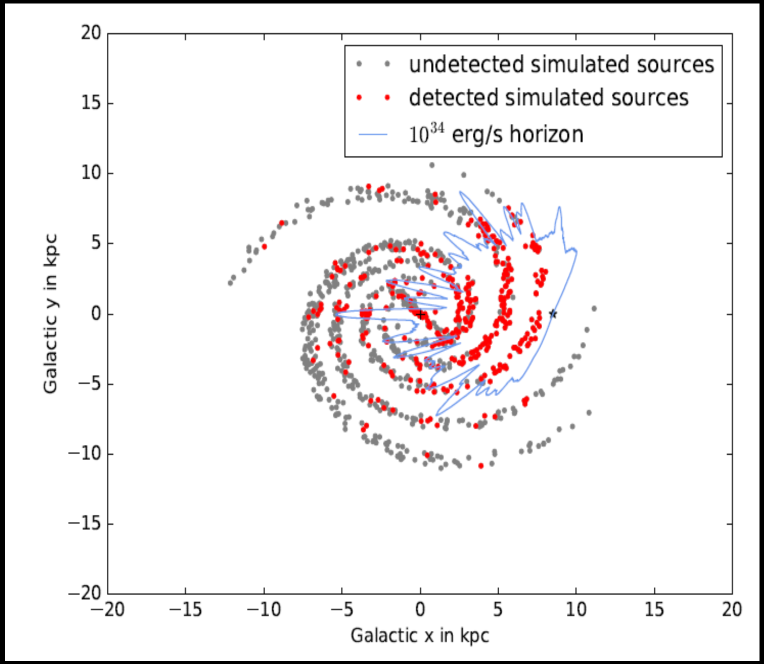
Electrons (TeV-scale) in Galactic plane

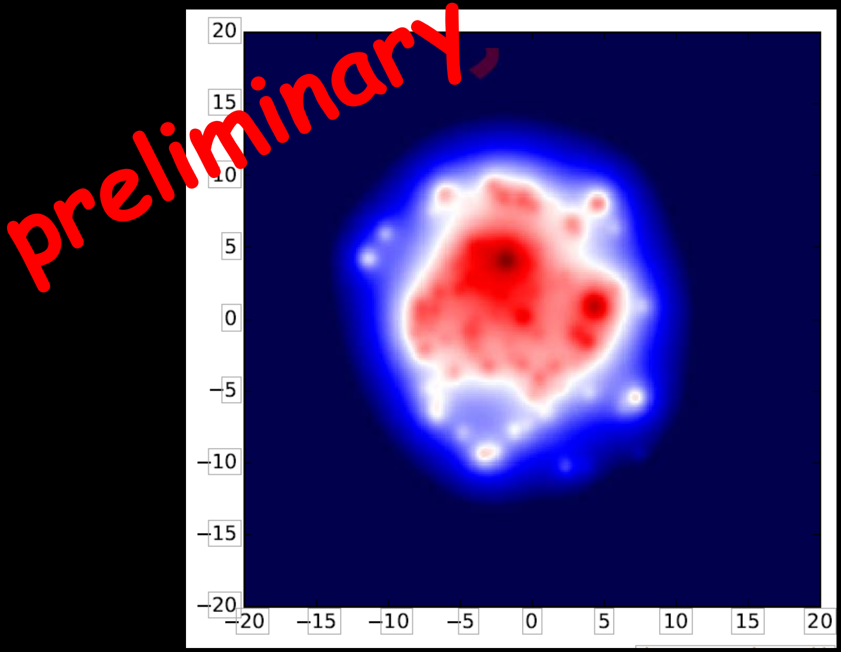
Towards better GeV-TeV propagation models then…

an observation-driven source term for the transport equation

Step 2:

- **H.E.S.S. catalog sources placed at l,b and according to observed Lγ**
- **categorized into suspected hadronic or leptonic emission dominance**
- **Galaxy filled to completeness limit according to log N-log S**

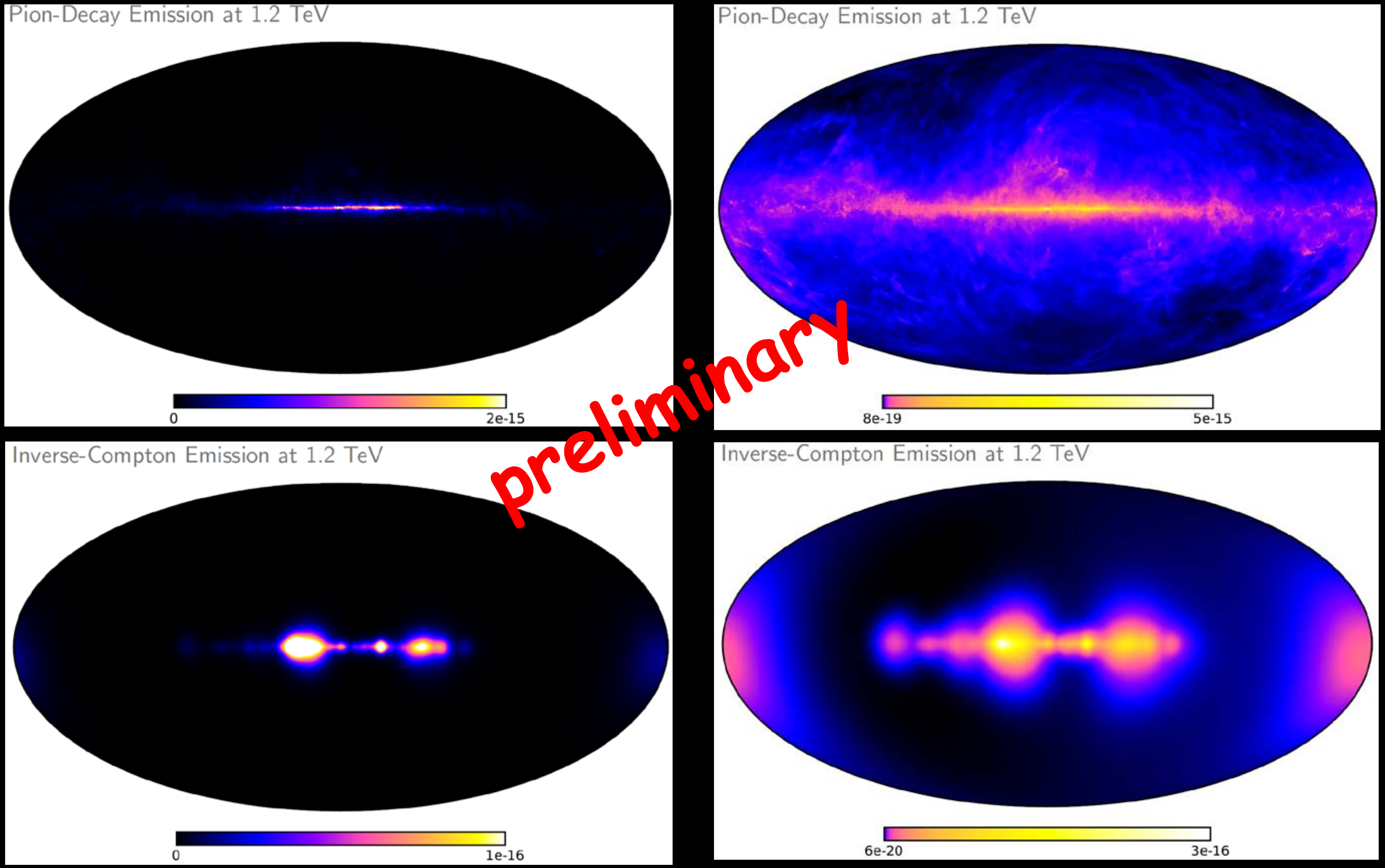




Carbon (TeV-scale) in Galactic plane

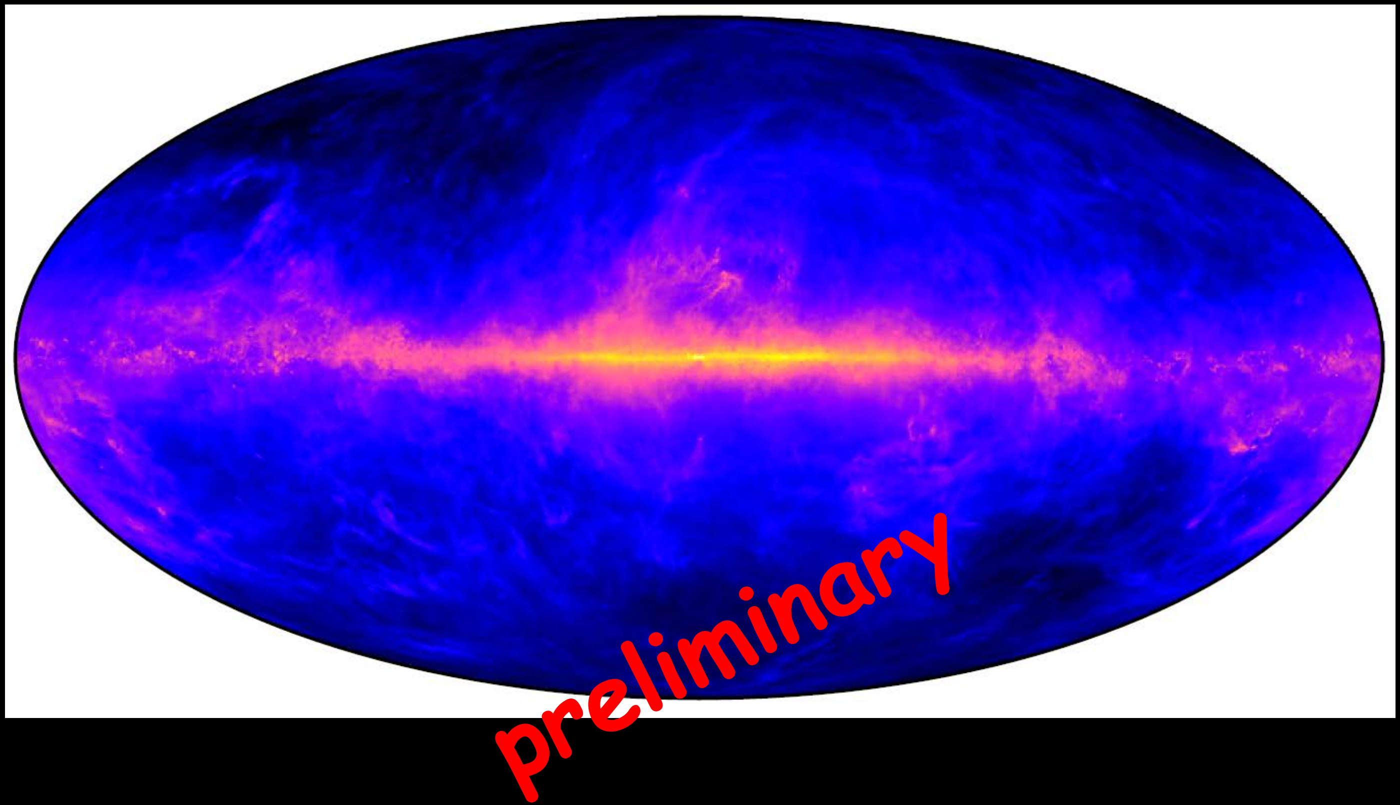
Towards better GeV-TeV propagation models then…

☞ preditctions for the VHE diffuse emission (e.g. neutral pion or IC @1.2 TeV)



Towards better GeV-TeV propagation models then…

☞ preditctions for the VHE diffuse emission: total diffuse @ 1.2 TeV



This is currently being compared to H.E.S.S. data analyzed withing the newly developed Run-Wise simulation analysis framework [Holler ea 2018].

☞ stay tuned for measurement of the VHE diffuse emission throughout the HGPS survey region later this year

3D transport models seems ready to investigate:

- ? Galactic Diffuse Emission models do not predict GeV intensity correctly [f(l,b,E)]
  -> scaling of predictions vs. consistent set of propagation parameters

- ? Galactic Center Excess in GeV *
  ☞ source of DM annihilation or sub-threshold sources?

- ? There is the GC bulge emission in TeV *
  ☞ stochastic particle injection at PeV or D_{xx} as function of galacticentric radius?

- ? There is indication for non-uniform diffusion ☞ Differencey among 2^{nd}aries, Geminga *

- ? High-energy electron spectrum is subject of alternative interpretations *

- ? Alternative proxies for 3D CR source distribution models

- ? Contribution of unresolved (sub-threshold) sources in different Galactic source classes

- ? Fermi bubbles *

- ? Large-scale anisotropy in the CR flux *

Conclusion

- There is rich physics in the diffuse Galactic Gamma-ray emission.
- Understanding the Galactic foreground opens access to precision measuremnts in the VHE, e.g. source morphology, extension, anisotropies …
- Propagation scales at TeV energies require 3D models and decapc grid resolution.
- Diffuse emission is guaranteed to exist at detectable level in the H.E.S.S. data
  ☞ PICARD predictions ready to be tested
- Analysis of IACT data usually supresses large-scale gradients (small camera FoV vs. background maker)
  ☞ RWS analysis framework in joint French-Austrian project developed

Expected CTA sensitivity will elevate diffuse emission problem and unresolved source contribution to a new level (or menace)!

We started to prepare for it.

→ simplyfied PICARD predictions were part of CTA sky model for the data challenge

→ diffuse emission measurement with H.E.S.S. well before CTA (PICARD & RWS)