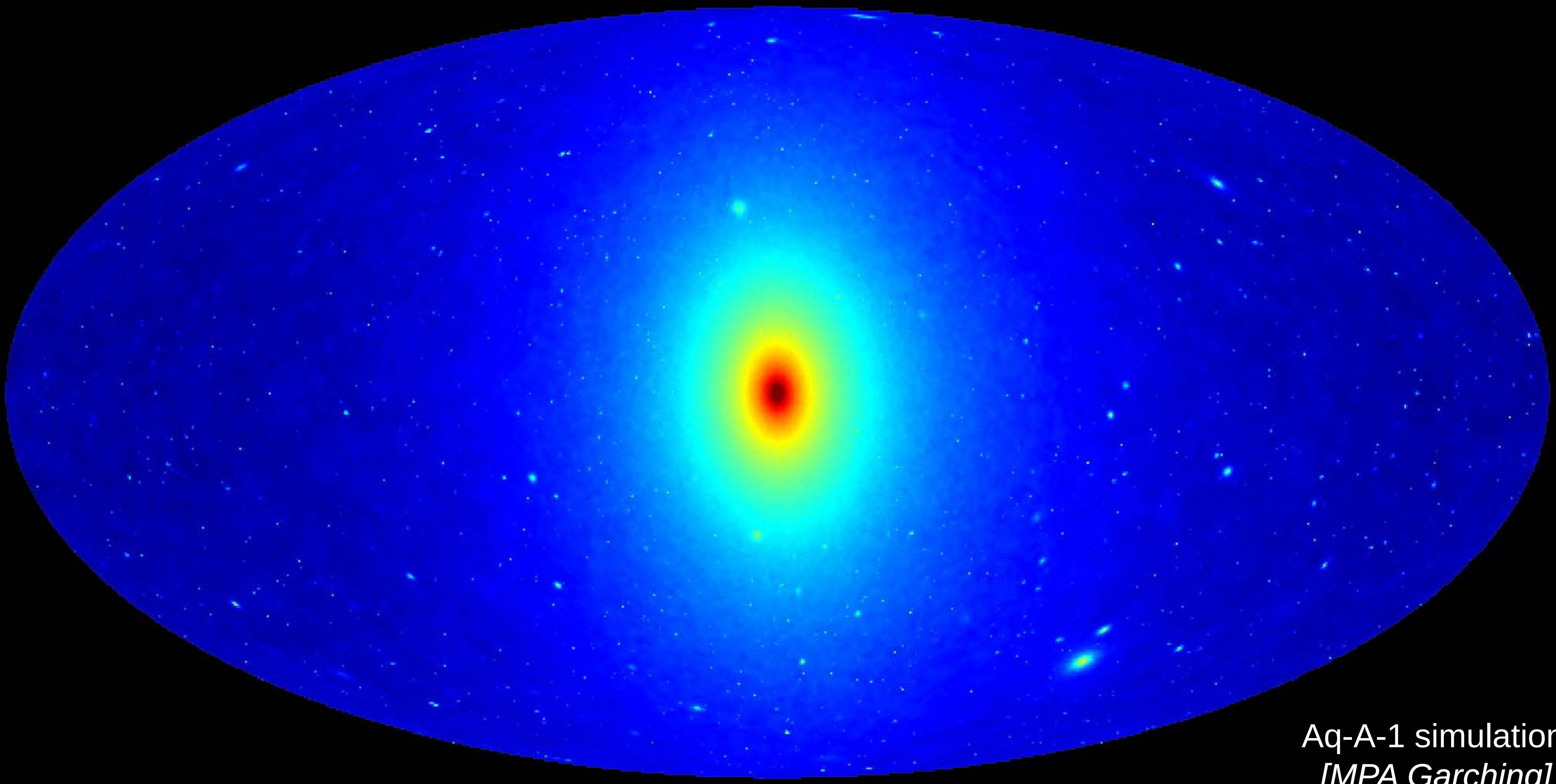
Olaf Reimer Leopold-Franzens-Universität Innsbruck

THE GALACTIC GAMMA-RAY SKY

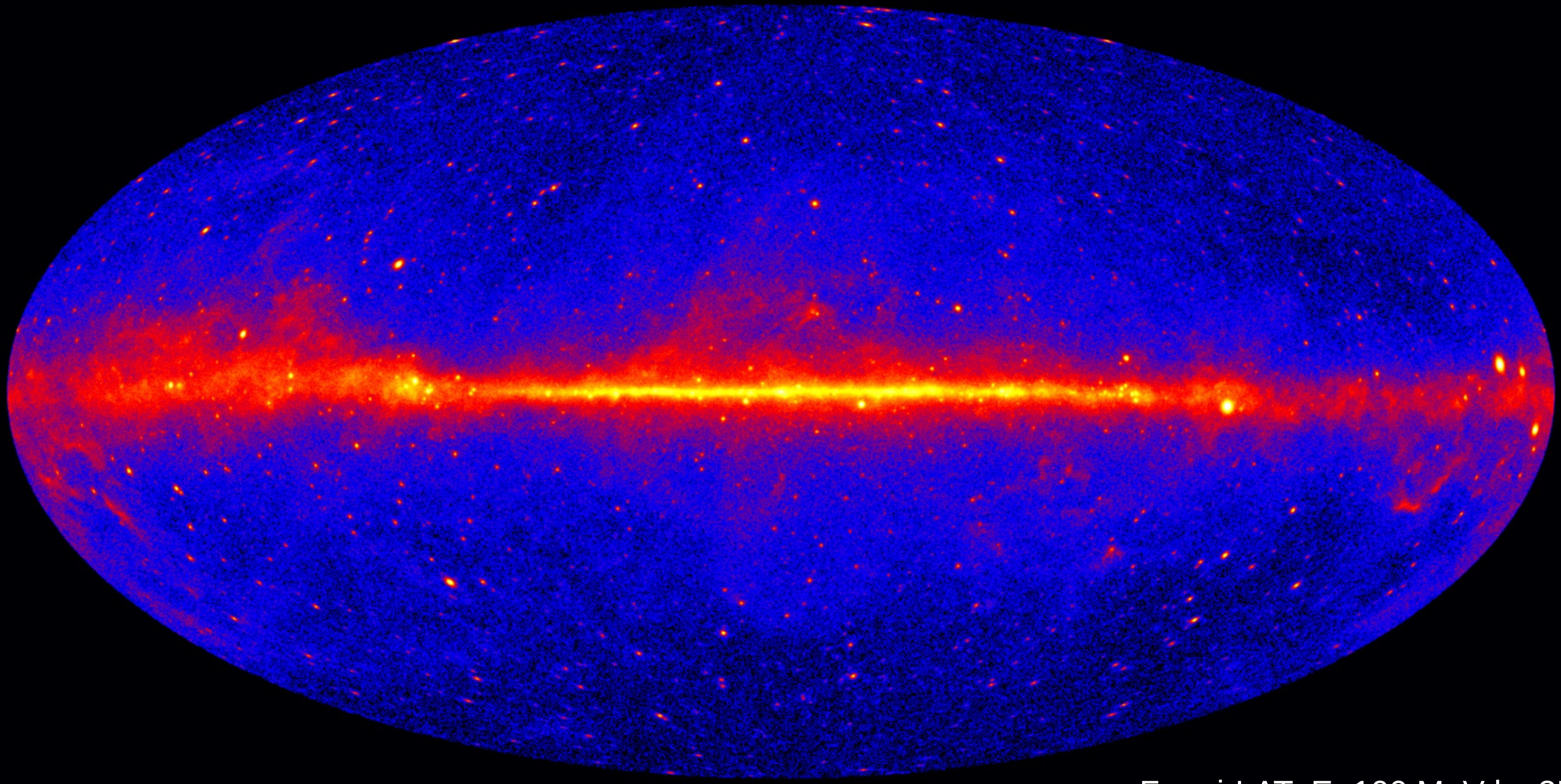
TeV Particle Astrophysics 2015, Kashiwa, October 27, 2015

…recalling last years γ-ray sky: (Joint TeVPA / IDM 2014)



Aq-A-1 simulation
[MPA Garching]

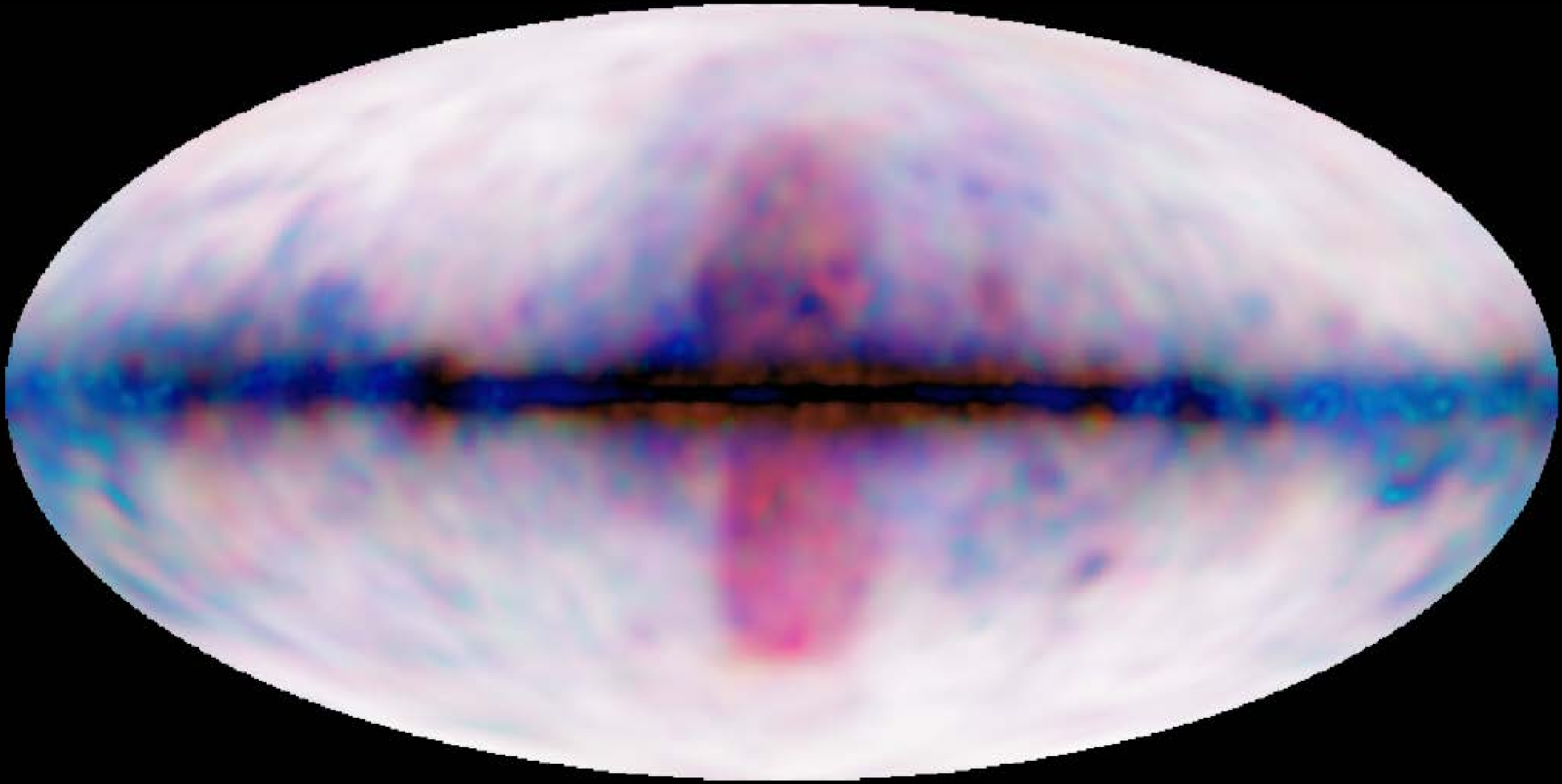
The Gamma-Ray Sky 2015



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

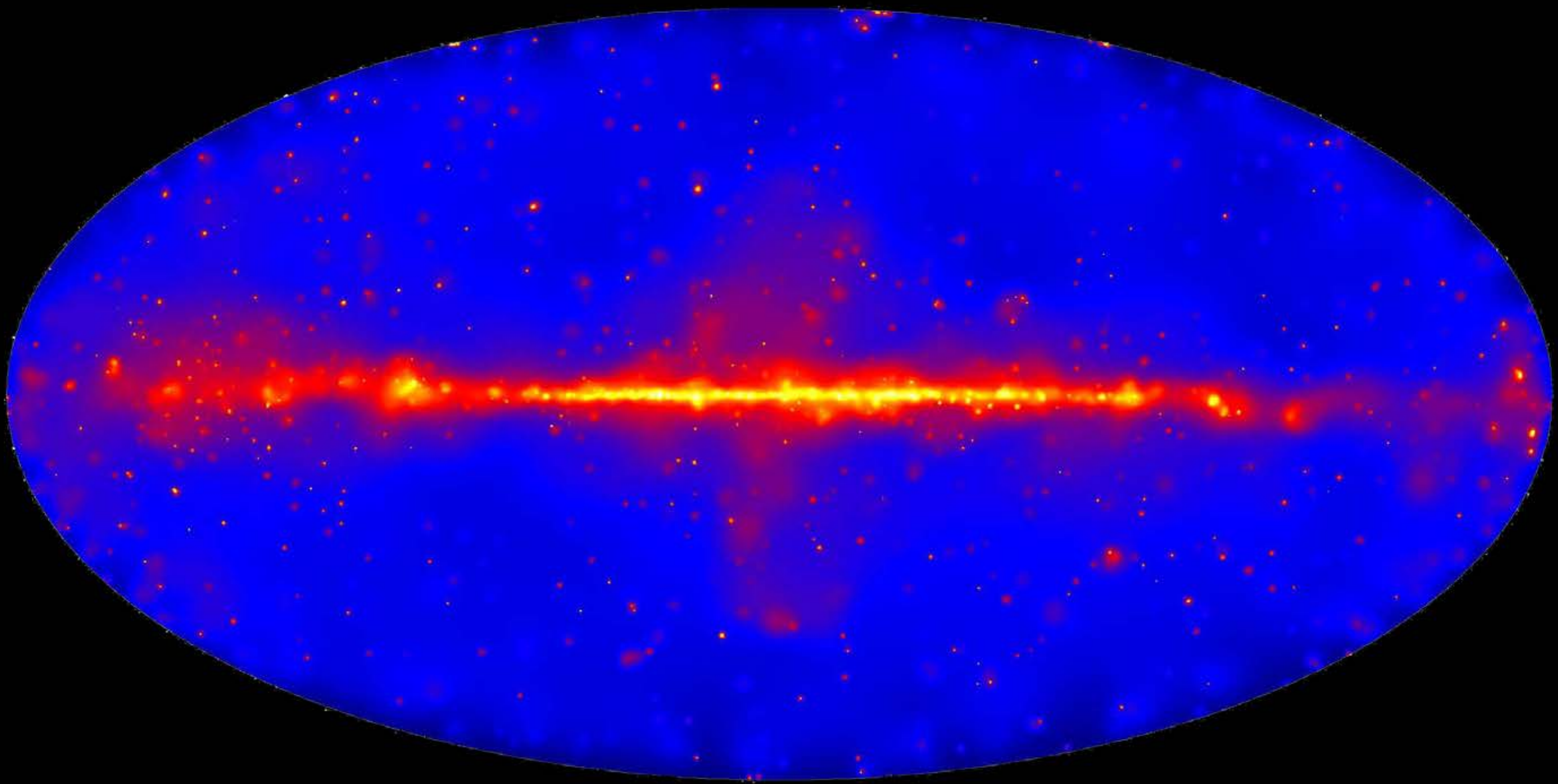
~ 70% of all observed photons coming from the diffuse Galactic emission

…or that? The Gamma-Ray Sky 2015



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

…or that? The Gamma-Ray Sky 2015

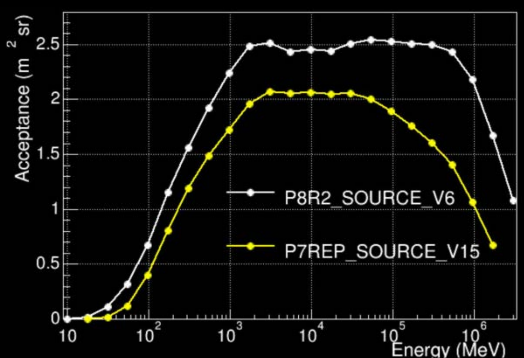


Fermi-LAT E > 50 GeV by 2FHL
[LAT collaboration 2015]

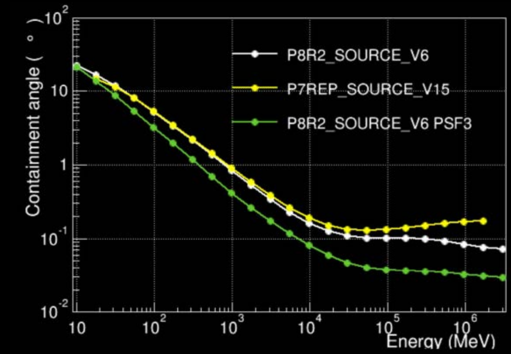
☞ median location uncertainty of 1.8 arcmin! (68%)

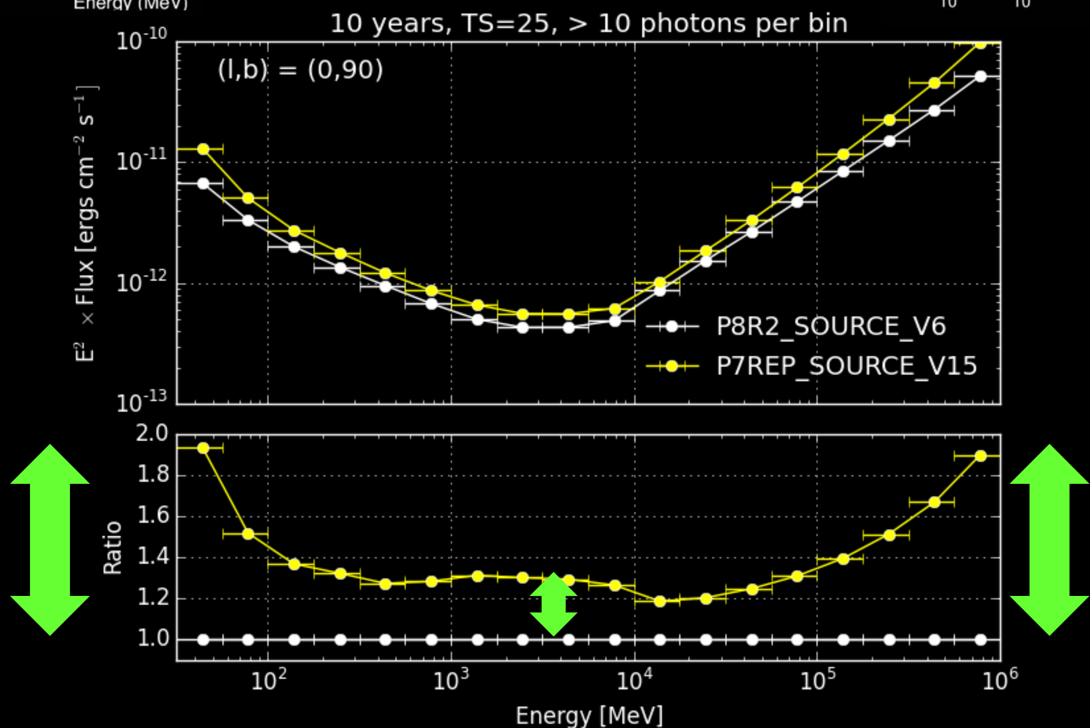
What's really new is Pass8, the new set of IRFs, public available via FSSC.

☞ **improved performance & analysis capabilities for Fermi-LAT**



← acceptance
effective area
energy reconstruction
psf reconstruction →





What's really new is Pass8, the new set of IRFs.

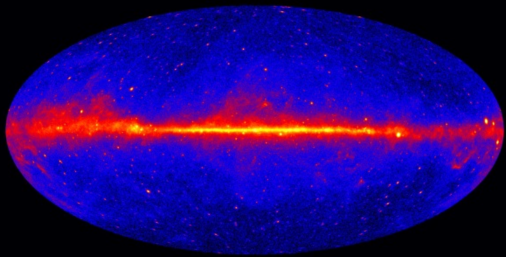
☞ **… the price to pay: a higher level of complexity for Fermi-LAT analysis**

- a reprocessed data set
- new/additional event classes
- two additional event type partitions: PSF event type: (PSF0 … PSF3)
  EDISP event type: quality of the energy recon
- consequently, each event class is partioned in 3 ways:
  - FRONT;BACK
  - PSF0;PSF1;PSF2;PSF3
  - EDISP0;EDISP1;EDISP2;EDISP3

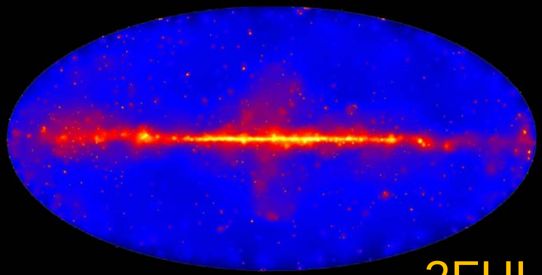
- No precomputed diffuse responses in standard data files!

Diffuse Model:
"As always, this model is designed to be used for point source analysis, and is **not appropriate** for the investigation of medium or large scale diffuse structures within the LAT data."

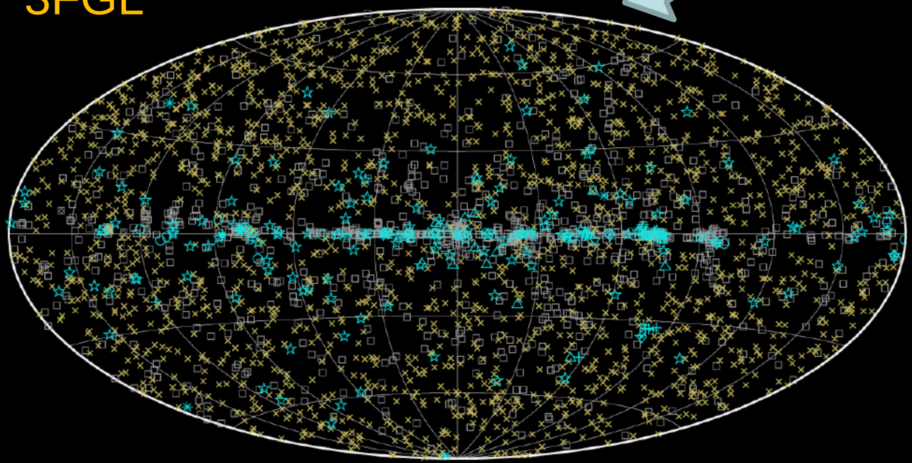
Numerology? Taxonomy!

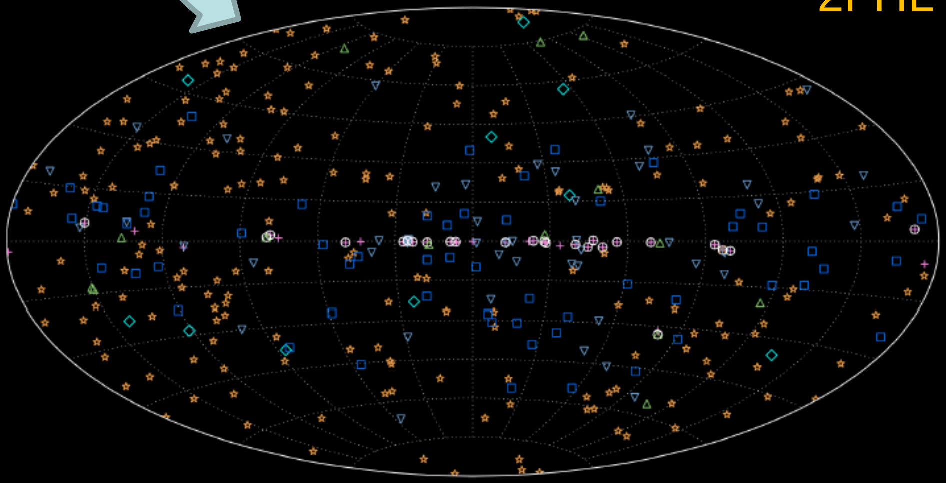


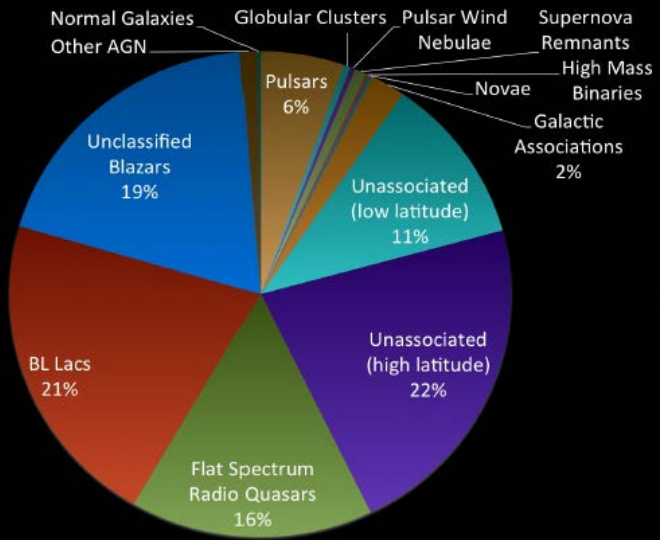
3FGL

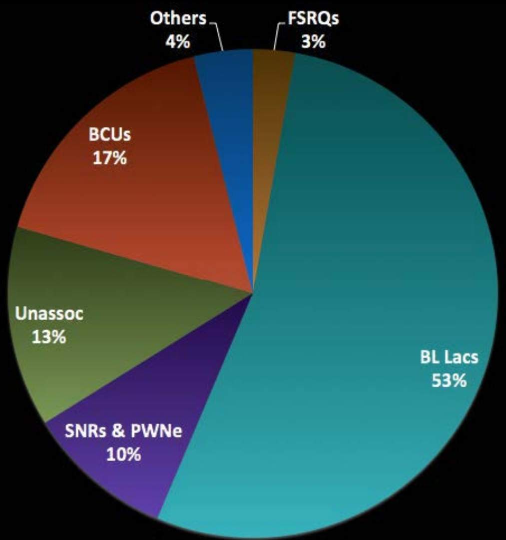


2FHL

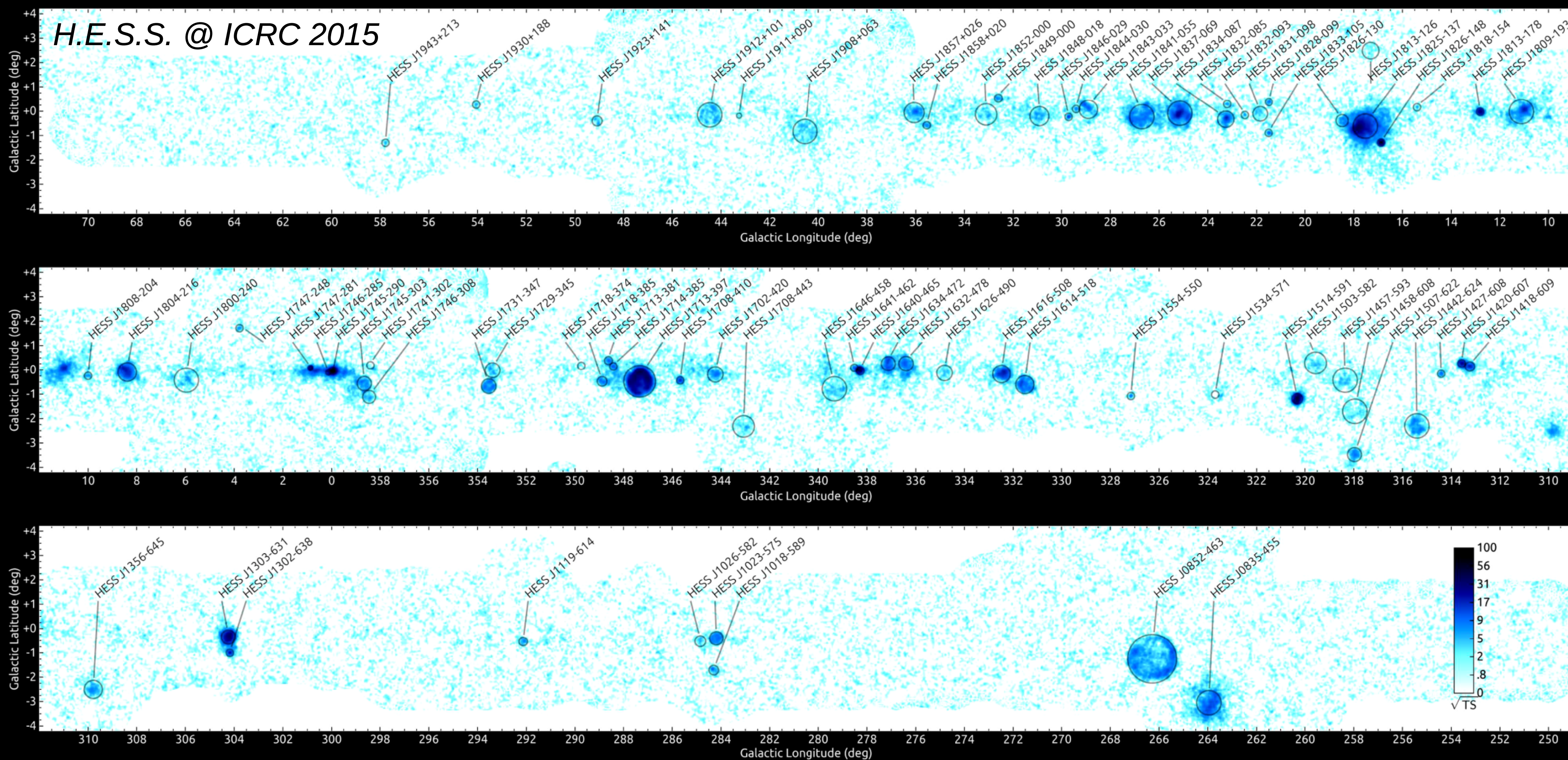






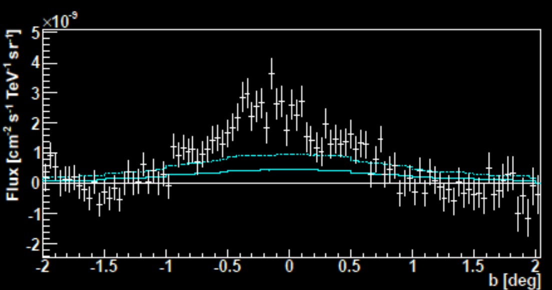


The Galactic Gamma-ray Sky as seen by H.E.S.S.



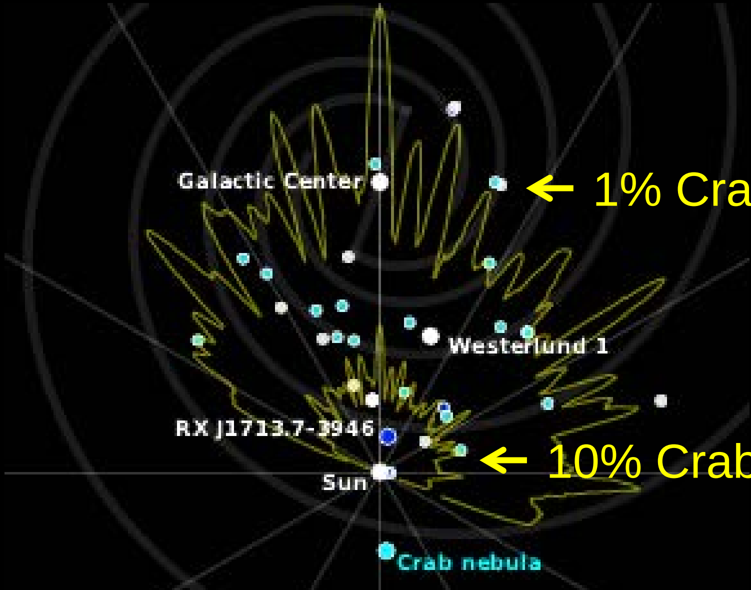
Diffuse Galactic TeV-emission has been measured, too:

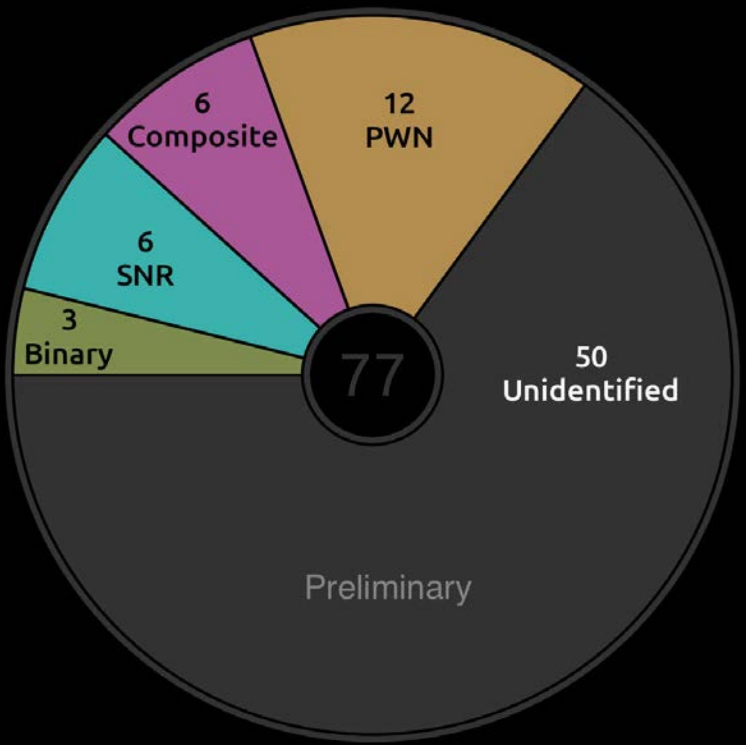
- Galactic Center Ridge emission [Nature 2006, ☞ later today]
- Diffuse Galactic γ-ray emission with H.E.S.S. [PRD 2014] →
- b=0 centered 1D-Gaussian [HGPS, ☞ Thursday]



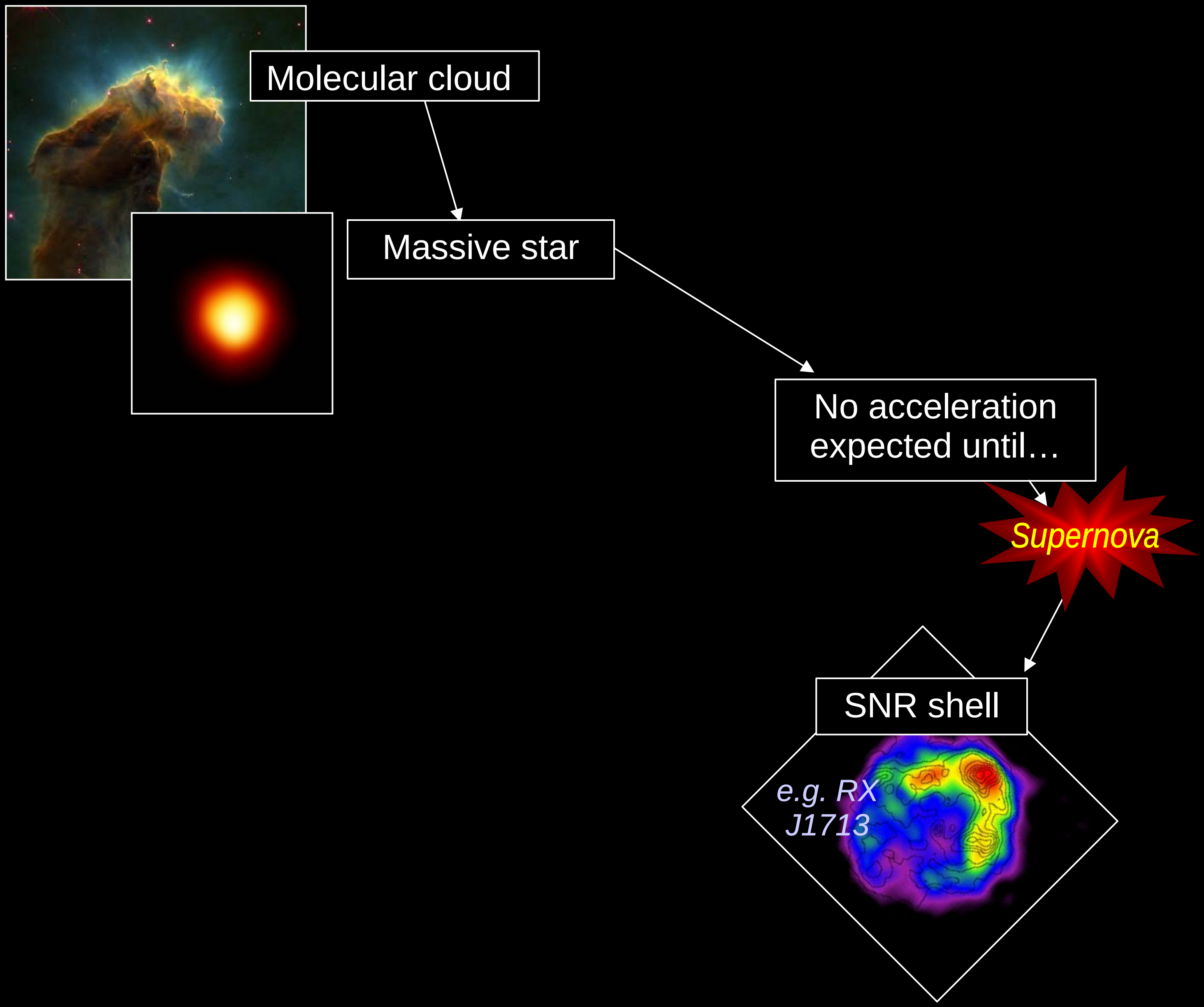
The Galactic Gamma-ray Sky as seen by H.E.S.S.

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

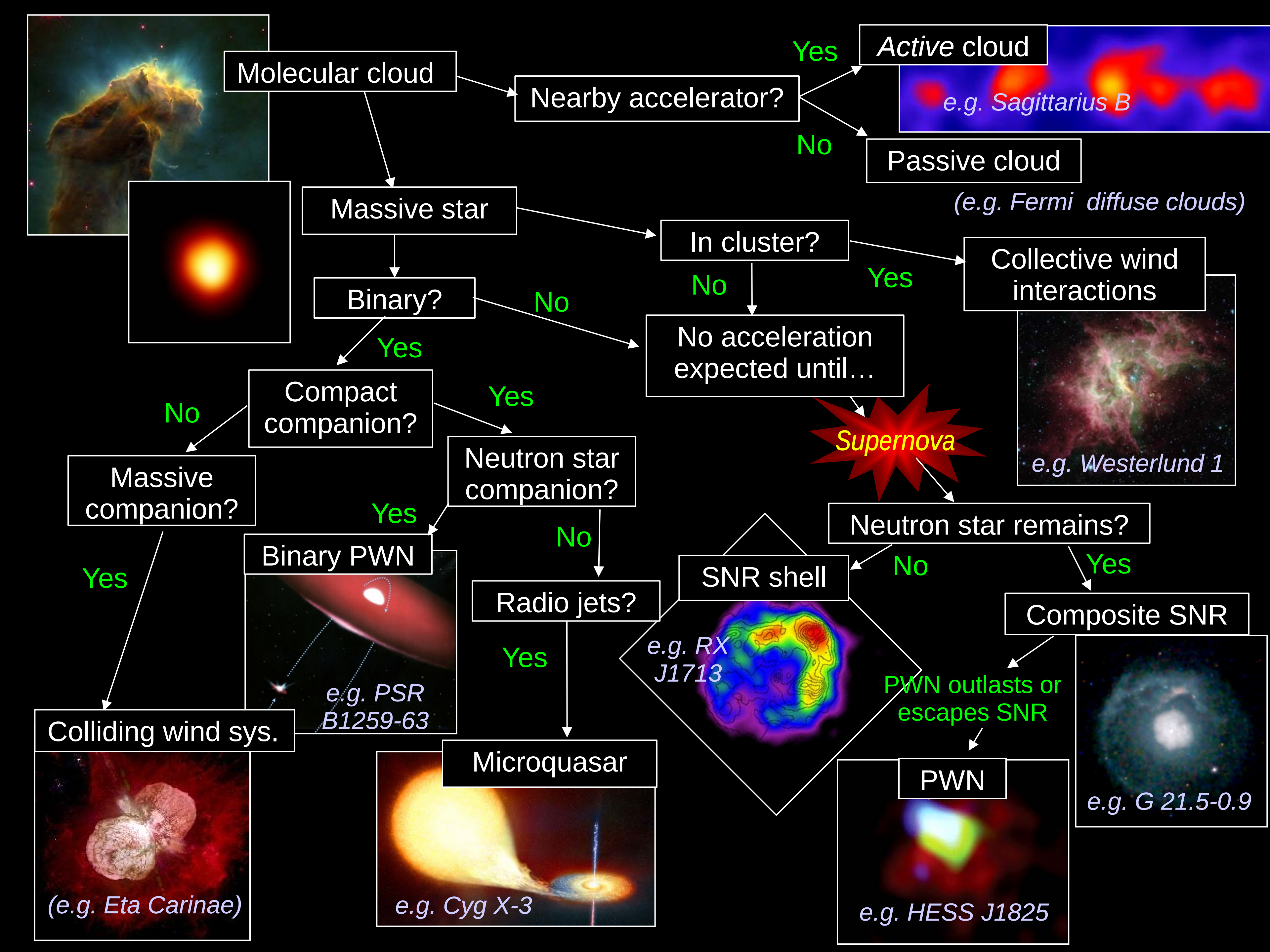




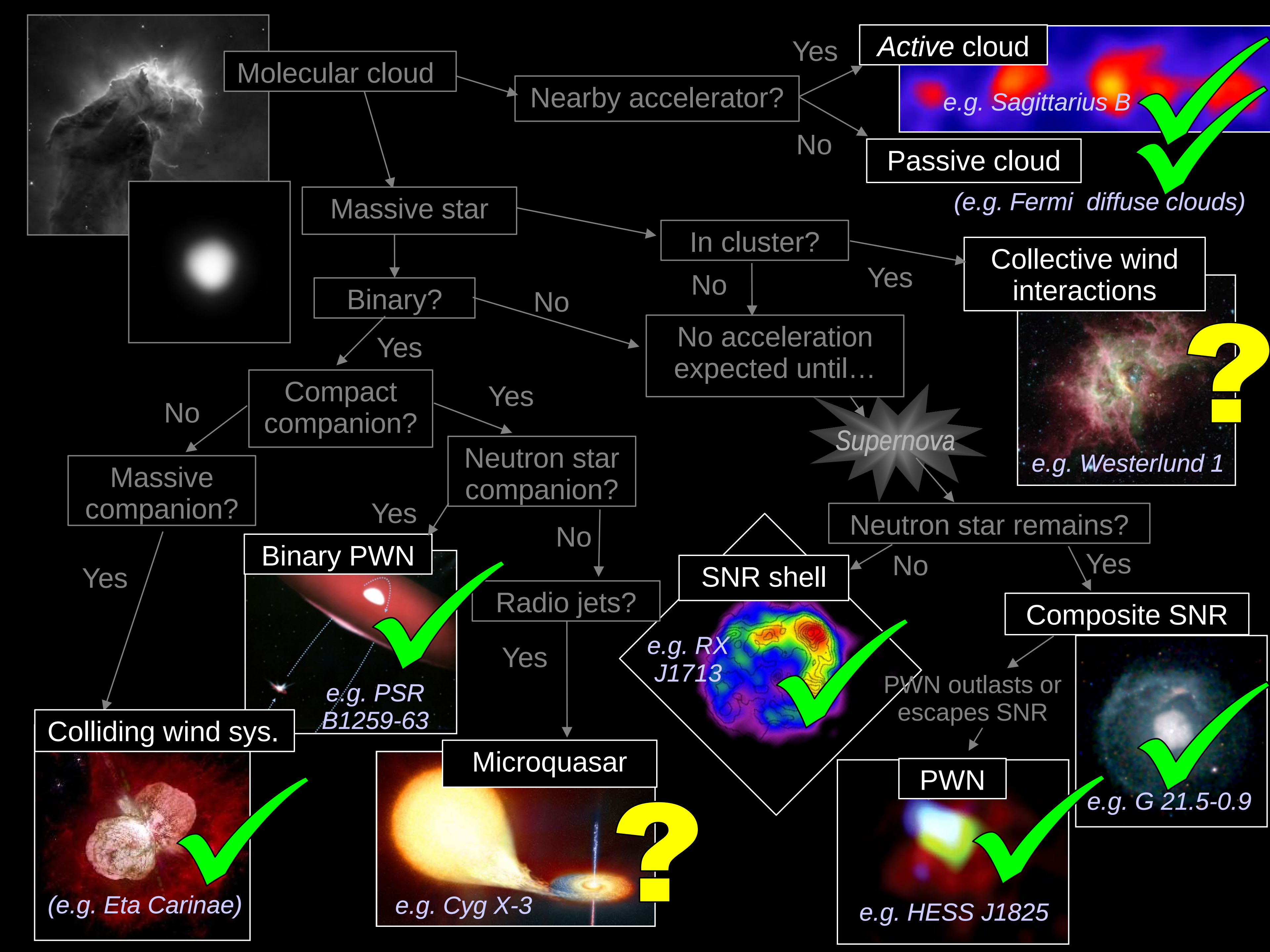
H.E.S.S. @ ICRC 2015



[adapted from Hinton & Skilton]



Molecular cloud
Nearby accelerator?
Yes
Active cloud
e.g. Sagittarius B
No
Passive cloud
(e.g. Fermi diffuse clouds)
Massive star
In cluster?
Yes
Collective wind interactions
e.g. Westerlund 1
No
No acceleration expected until…
Binary?
No
Yes
Supernova
Compact companion?
No
Yes
Massive companion?
Neutron star companion?
Yes
Binary PWN
e.g. PSR B1259-63
No
Radio jets?
Yes
Microquasar
e.g. Cyg X-3
Yes
Colliding wind sys.
(e.g. Eta Carinae)
Neutron star remains?
No
SNR shell
e.g. RX J1713
Yes
Composite SNR
e.g. G 21.5-0.9
PWN outlasts or escapes SNR
PWN
e.g. HESS J1825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PWN
e.g. HESS J1825

Neutron star remains? → Yes

☞ PSRs, PSRs everywhere!

160+ announced

radio-loud msPSRs

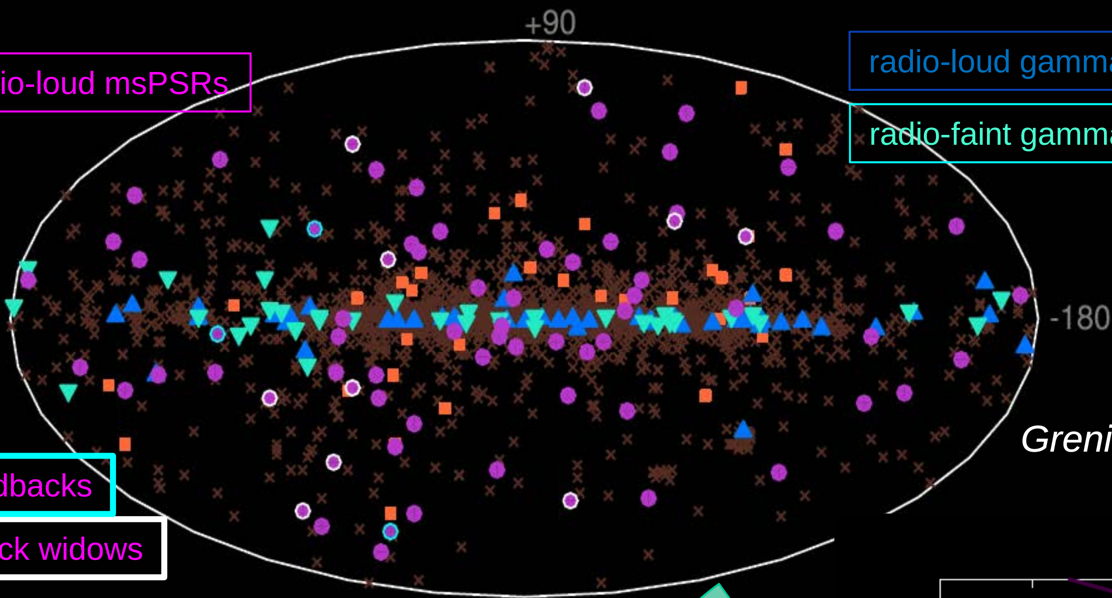
radio-loud gamma

radio-faint gamma

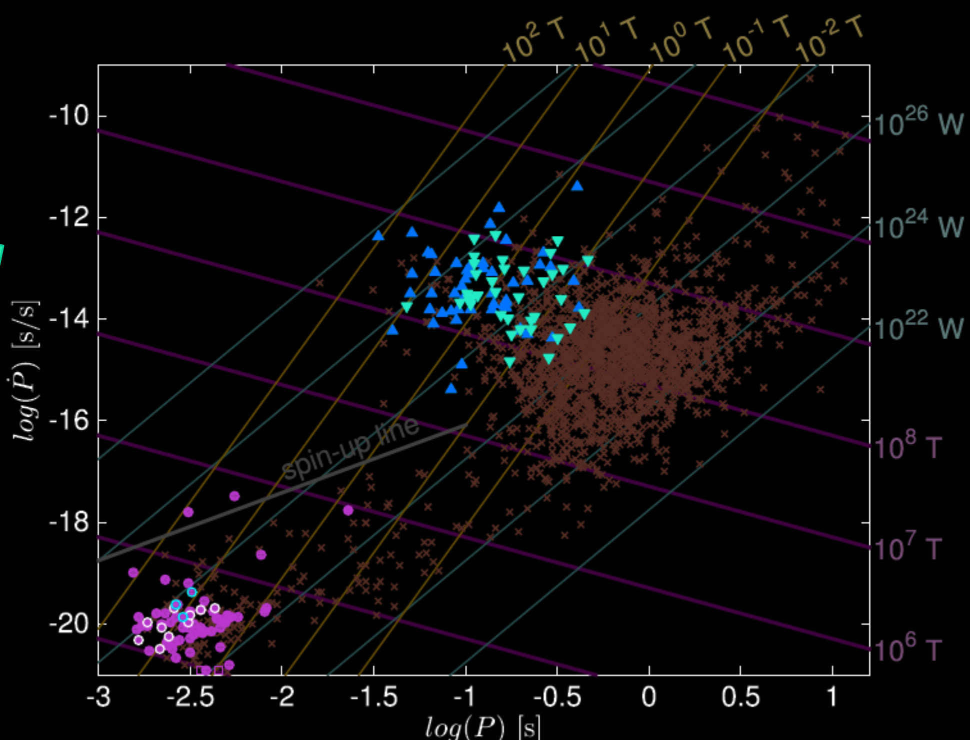
Redbacks

Black widows

candidate PSRs



Grenier & Harding 2015



"Spiders"

MSPs in binaries with low-mass companions & short orbital periods BW~0.02M☉; RB ~ 0.2M☉

Focus: Galactic continuum vs. time-domain

The Galactic Gamma-ray Sky is remarkably steady.

(Anticipation was different before launch of Fermi-LAT!)

Focus: Galactic continuum vs. time-domain

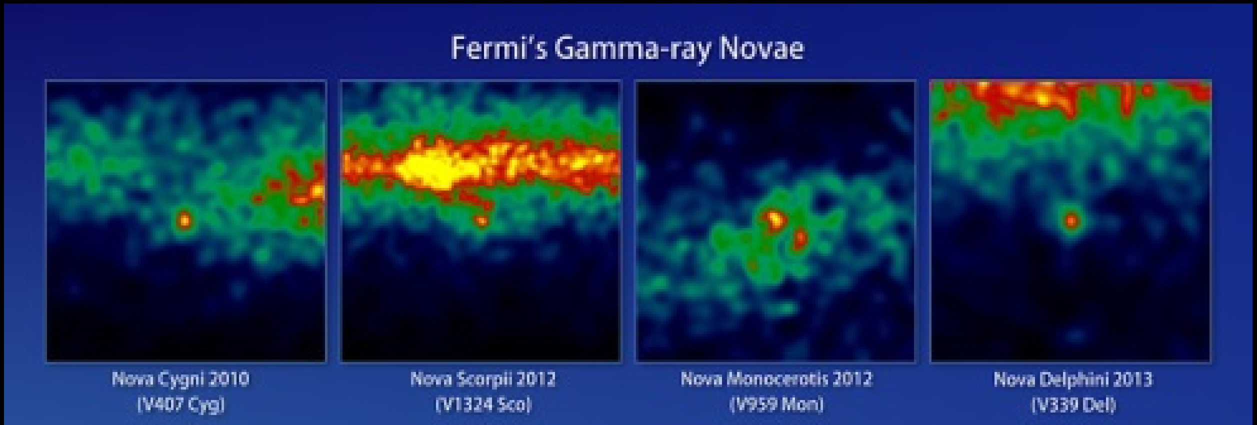
The Galactic Gamma-ray Sky is remarkably steady.
(Anticipation was different before launch of Fermi-LAT!)

Continuum: The vast majority of phenomena at the Galactic gamma-ray sky.

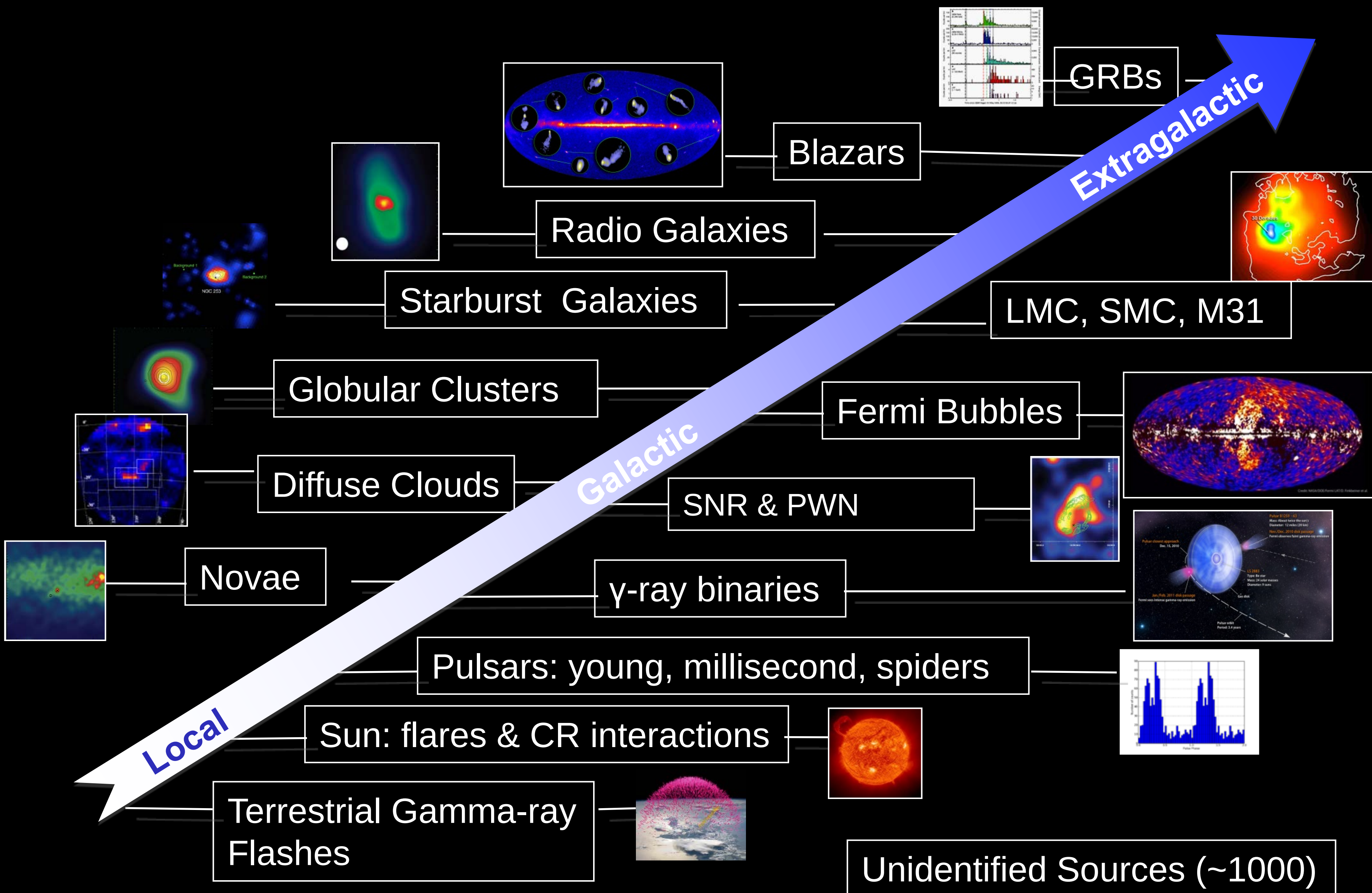
Regular Variability: PSRs (rotational period), Binaries (orbital periodicity)

Sporadic Variability: PSRs (mode-changes: e.g. PSR J2021+4026, flares: Crab!!) , Binaries (e.g. PSR B1259-63/LS 2883 post-periastron flares '10, '14!)

Transients: Novae (6!), Supernovae (…keep waiting for the one every 40 ±10 yr



Focus: Galactic Gamma-ray Sky



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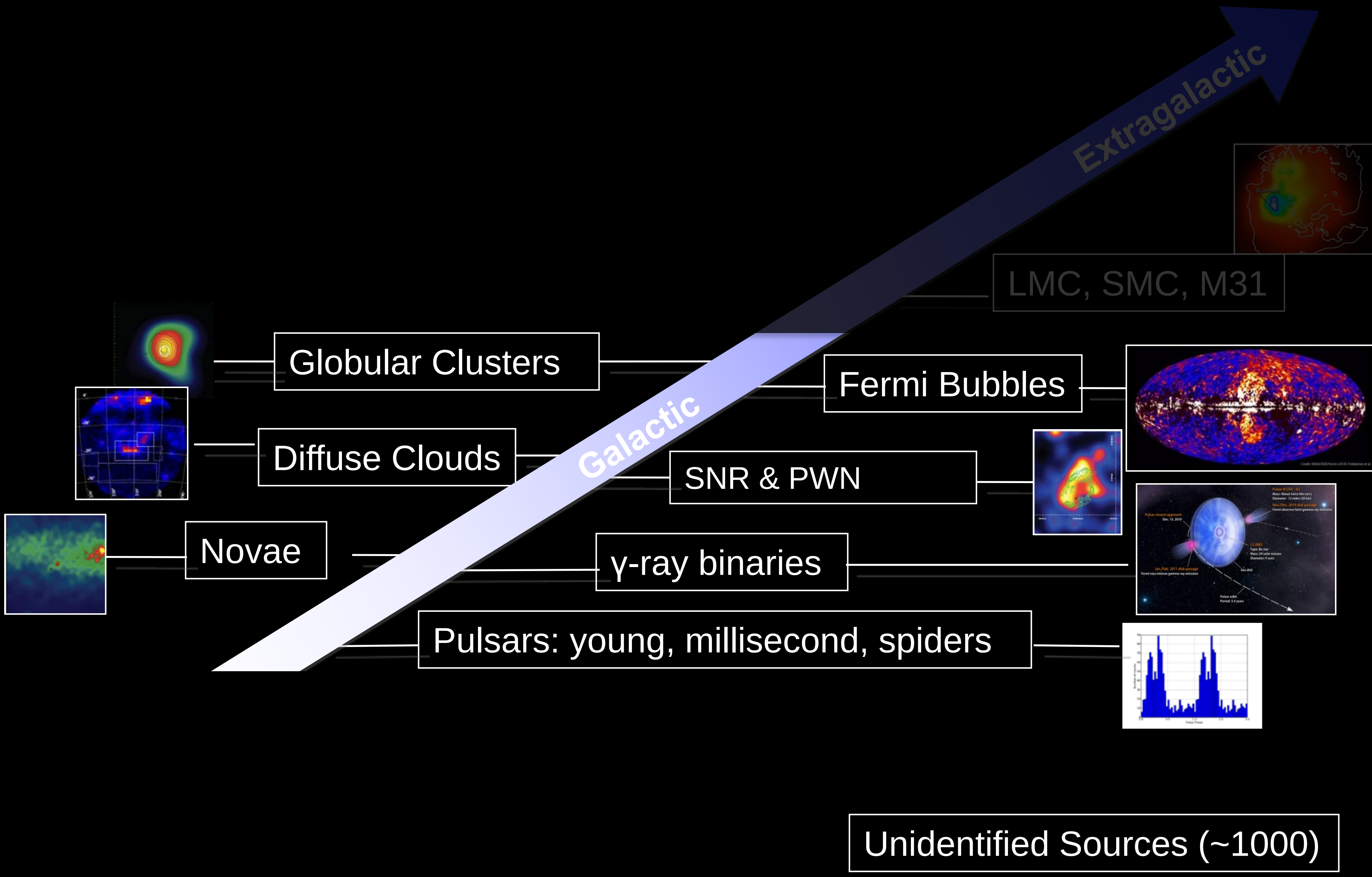

The Local Bubble and Beyond

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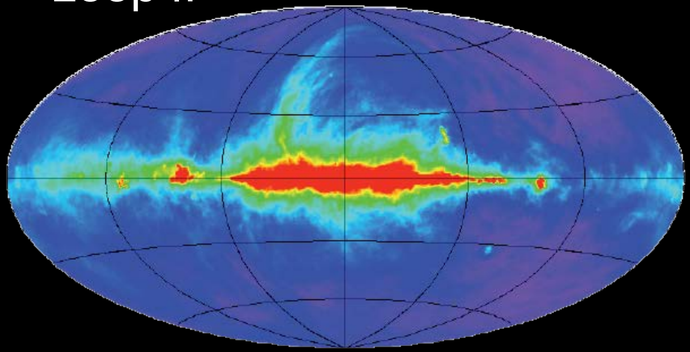
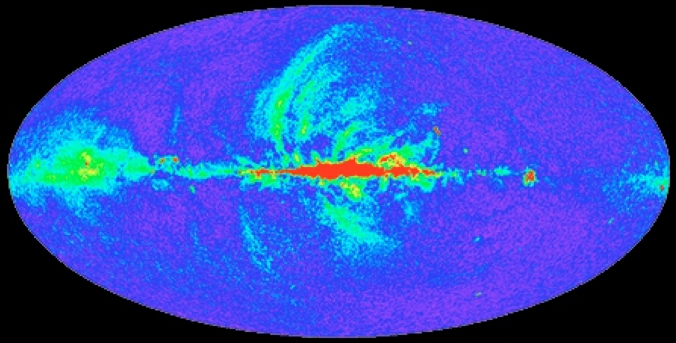
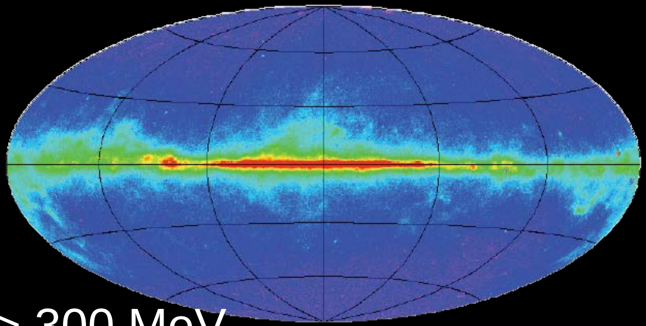
Loop I:



Haslam 408 MHz

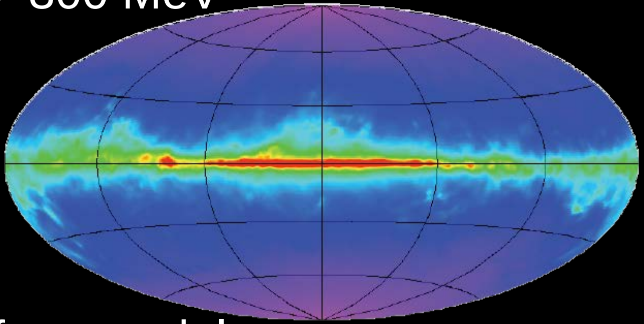


WMAP polarized emission 23 GHz



Fermi E > 300 MeV

↑
?
↓

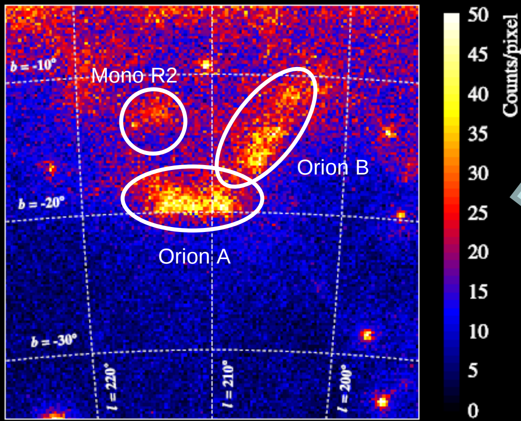


Fermi diffuse model

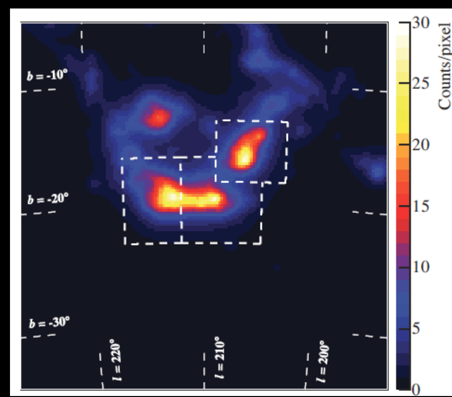
There appears to exist arc-like excesses against the diffuse model:
Fainter than pion production and bremsstrahlung as calculated from HI tracer, fainter than IC as templated in diffuse model. ☞ ***The birth of diffuse templates!***

The Local Bubble and Beyond

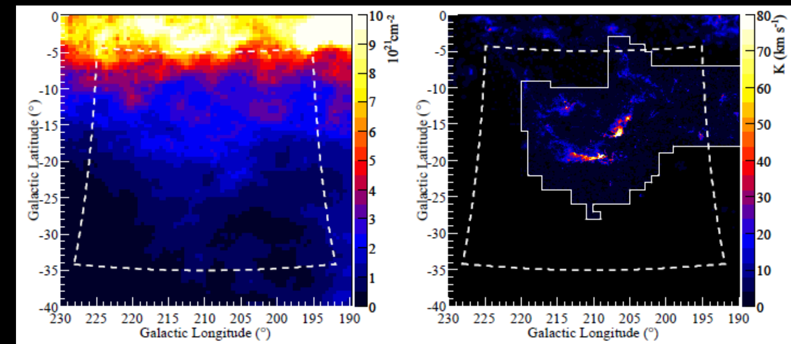
Nearby molecular clouds: Orion (d ~ 400 pc)



E > 200 MeV



LAT collaboration ´12



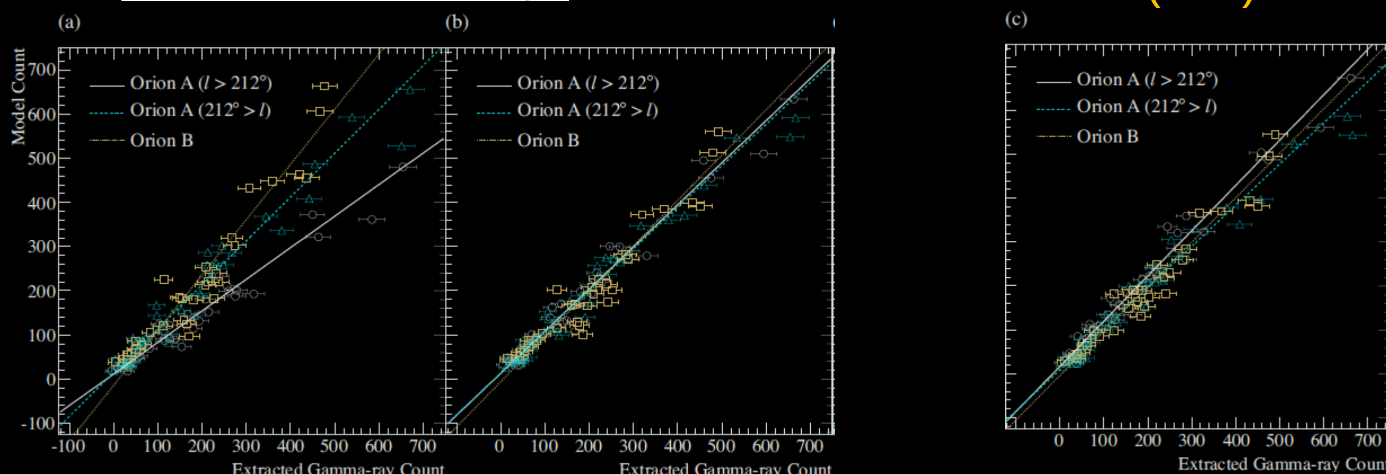
HI

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 CO correlation:

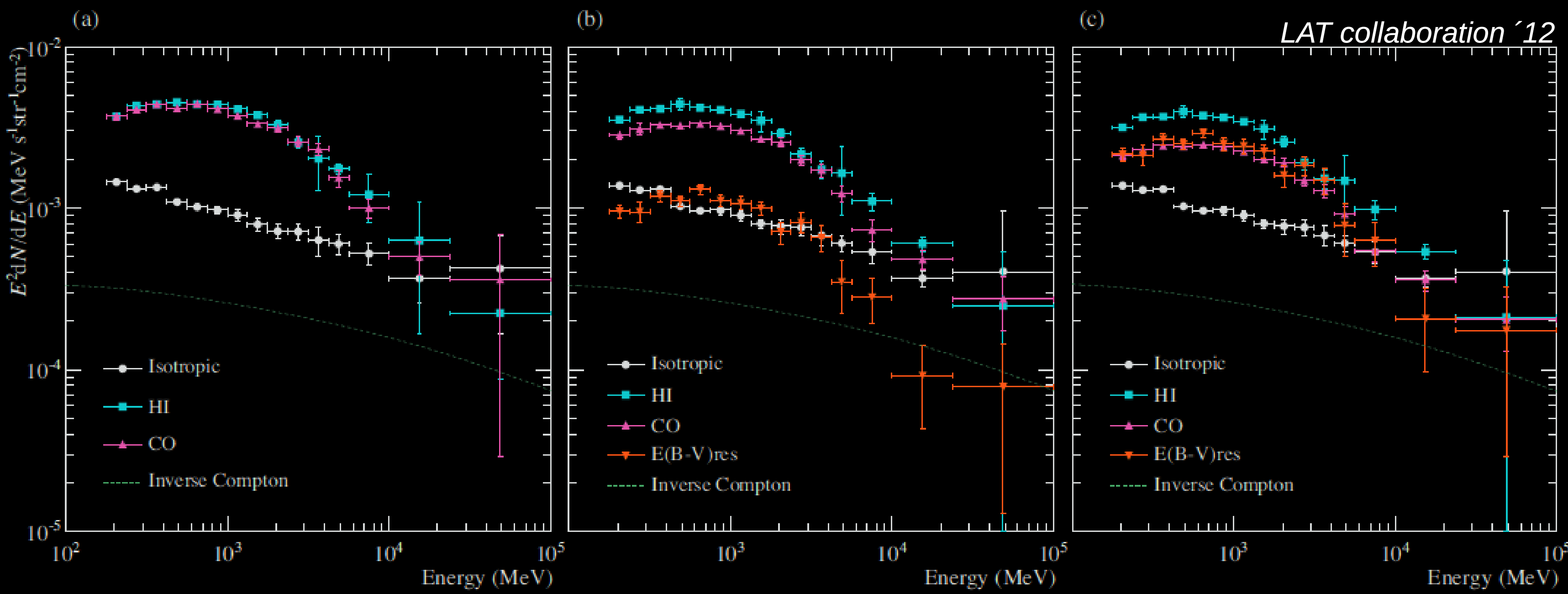


Xco: 1.63 × 10^{20} cm^{-2} K^{-1} km^{-1} s   1.35 - 2.34 × 10^{20} cm^{-2} K^{-1} km^{-1} s

The Local Bubble and Beyond

Nearby molecular clouds: Orion (d ~ 400 pc)

Consequently, spectral extraction of relative emission components differs:



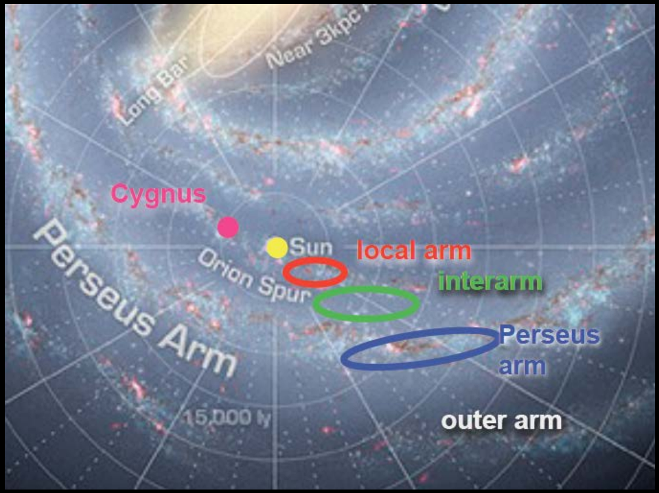
Xco static

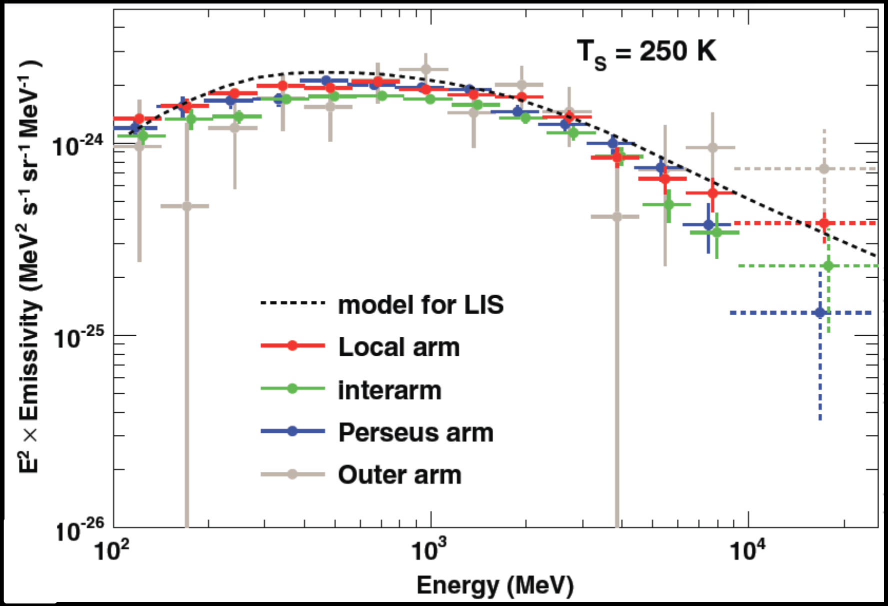
Xco variable

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

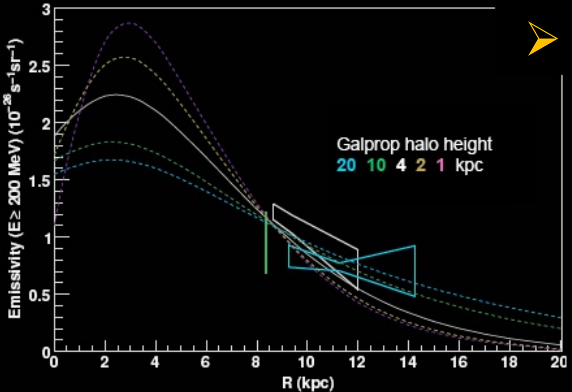




LAT collaboration ´11

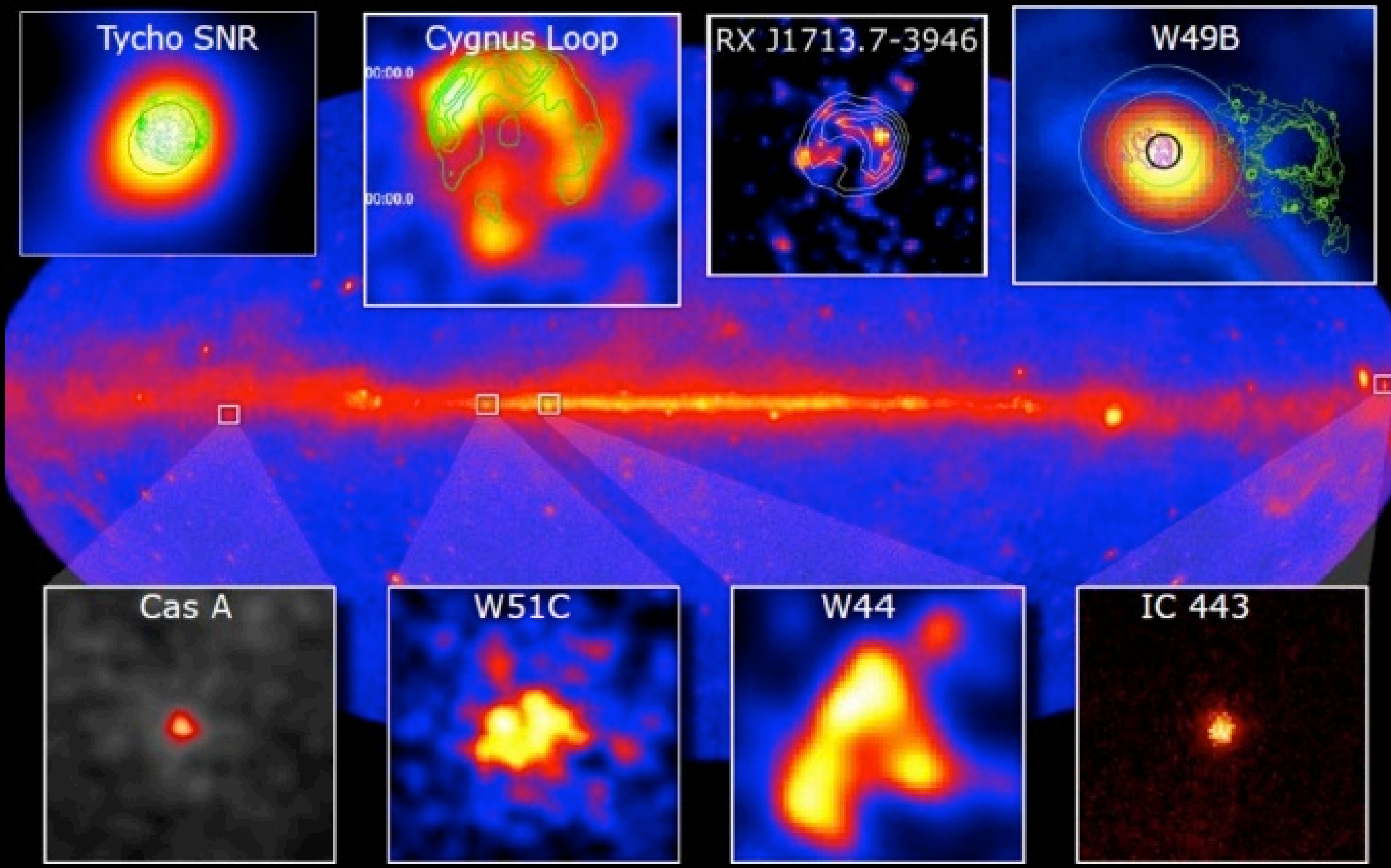
- consistent with LIS spectrum,
  comparable in clouds with $10^3 < M < 8 \times 10^6\ M_\odot$

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

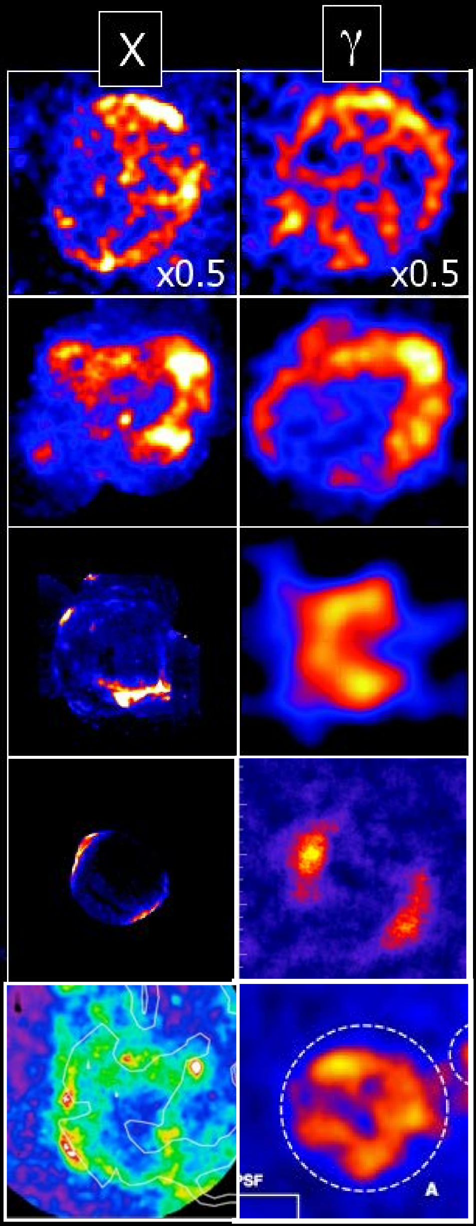


- shallow emissivity gradient in the outer Galaxy:
  too shallow even for a large halo size !
  ? large amounts of missing gas / badly understood tracers ?
  ? non-uniform diffusion ?
  ? simplistic diffuse emission model ?

SNRs in the GeV regime



SNRs in the TeV regime



RX J1713.7-3946

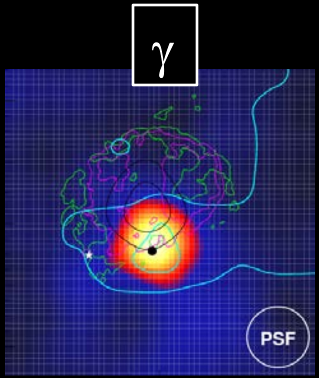
Vela Junior

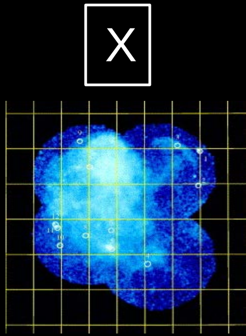
RCW 86

SN 1006

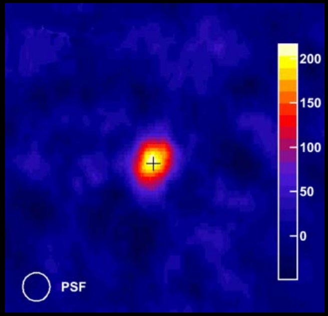
HESS J1731-347

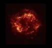
IC443



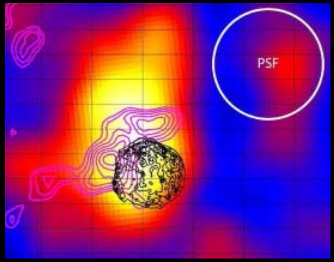


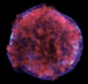
Cas A





Tycho





Generalities: leptonic vs. hadronic dominated emission

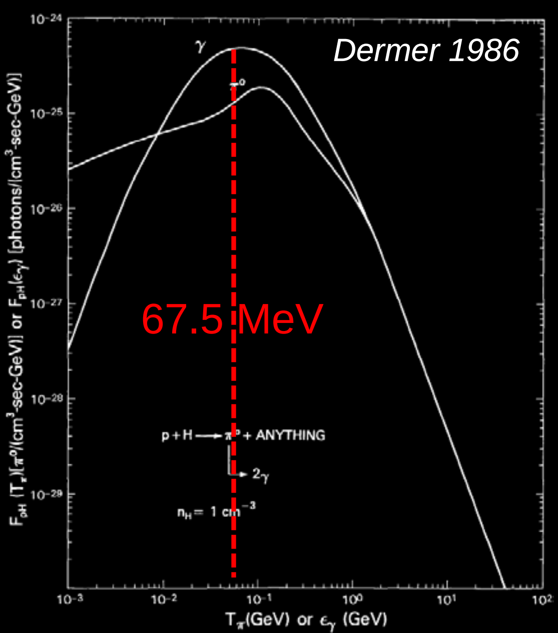
1) Detection of neutrinos: pending, unlikely in easy reach for km^3 detectors

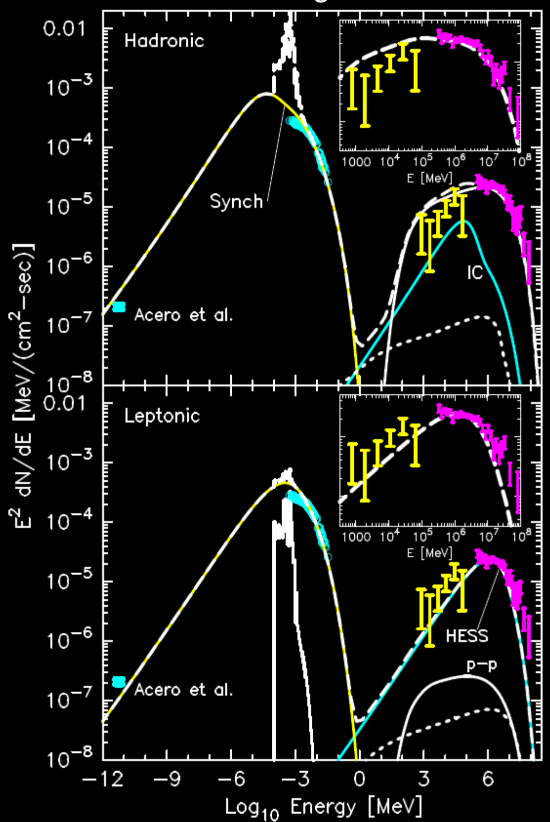
2) TeV-observations: shape of the high-energy IC component, cutoff in KN-regime (ambiguous, though)

3) GeV-observations: intensity & hardness of π^0 decay component (ambiguous, too)

e.g. Ellison+ 2011

4) $\pi^0 \rightarrow 2\,\gamma$ near production threshold (same process is major constitutent of diffuse emission)



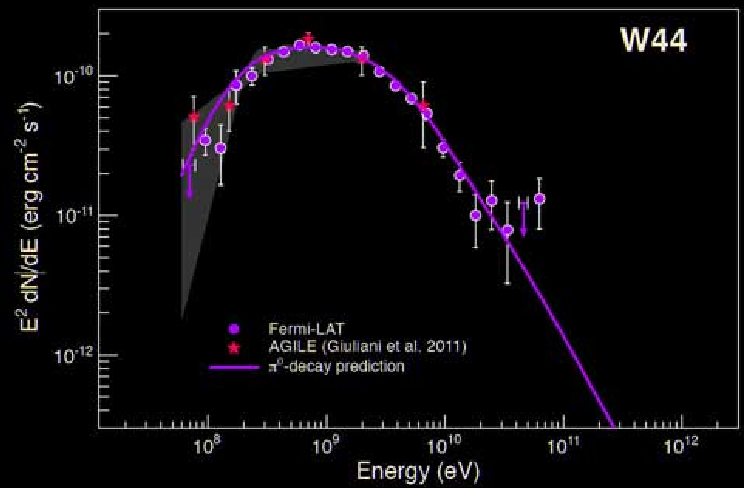


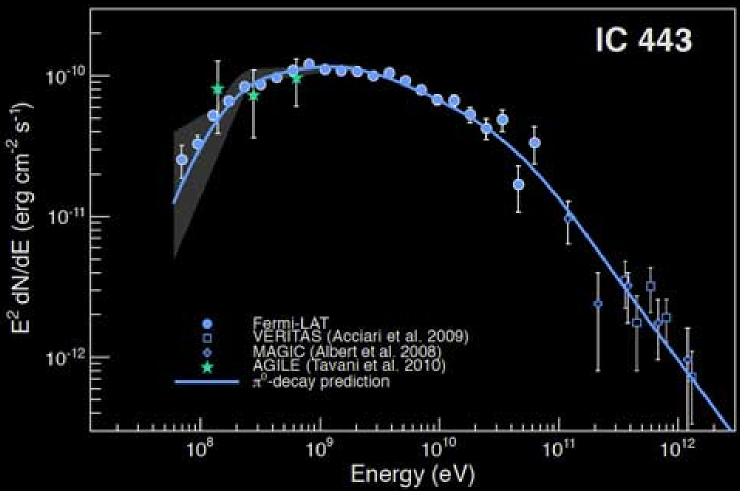
NASA Press Release Feb 2013:

"NASA's Fermi Proves Supernova Remnants Produce Cosmic Rays"

Image data from ESA Herschel and XMM-Newton

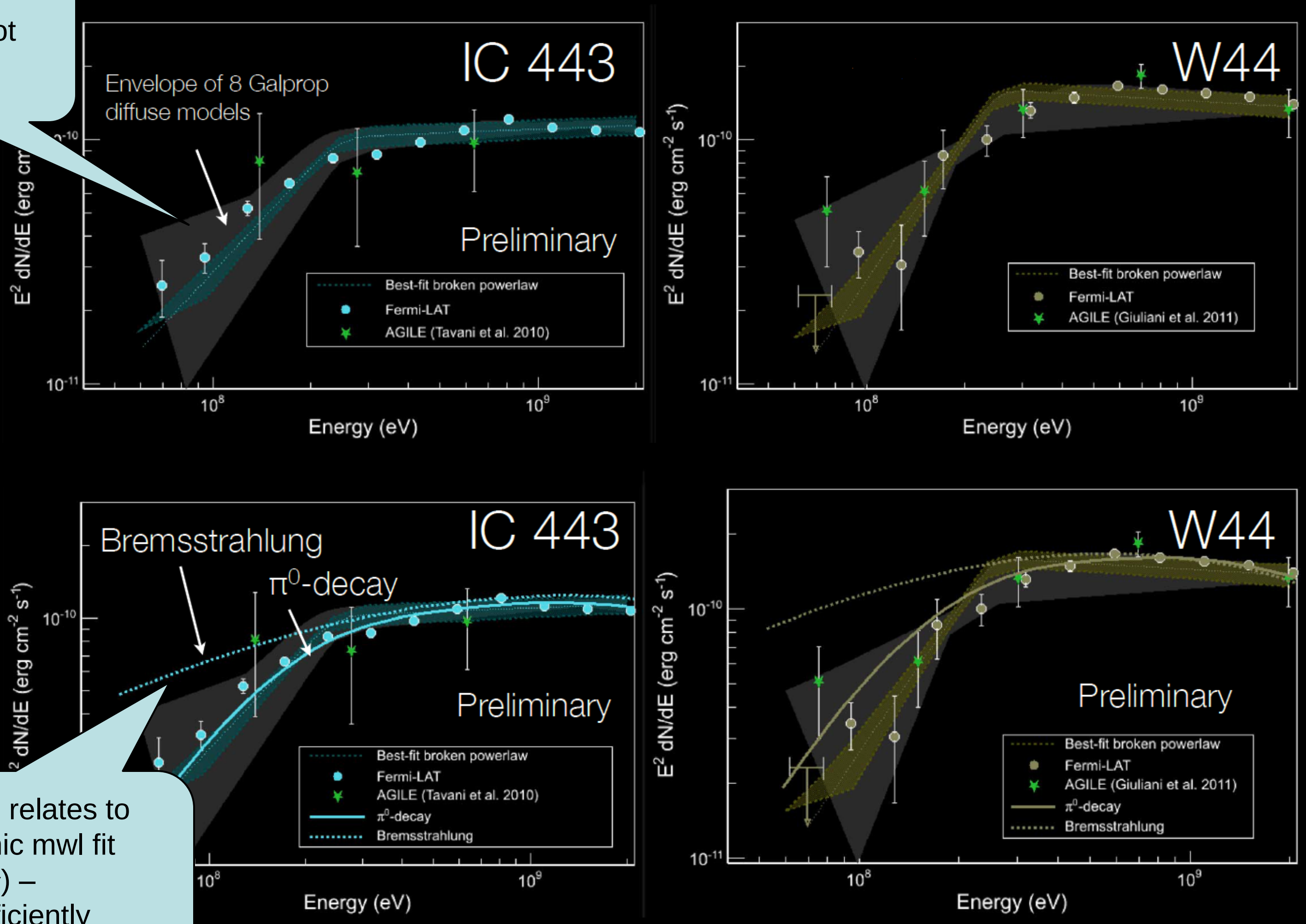
Image data from Chandra X-ray





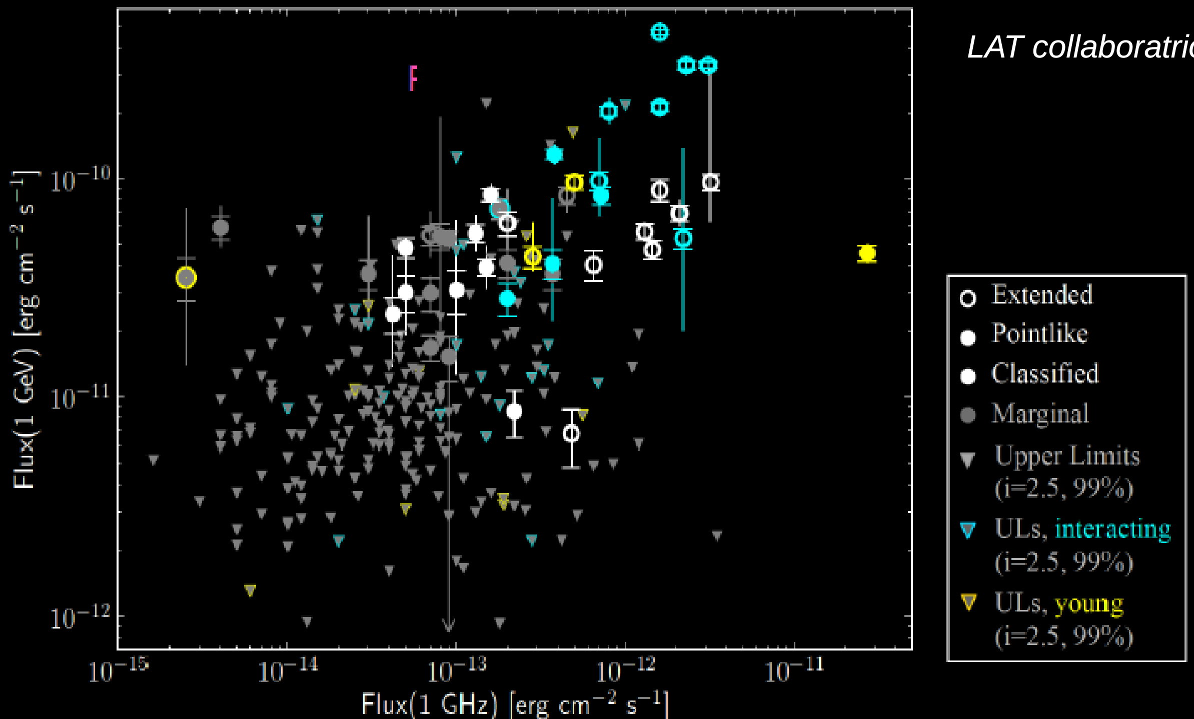
Subtleties to the pion bump detection

GALPROP models are not best-suited (scaling!)



Bremsstrahlung relates to simplistic leptonic mwl fit (radio synch + γ) – alternatives sufficiently disregarded?

upcoming: LAT SNR catalog



LAT collaboratrion @ ICRC 2015

36 candidates classified

17 extended

13 point-like

2 ambiguity through *diffuse model systematics*

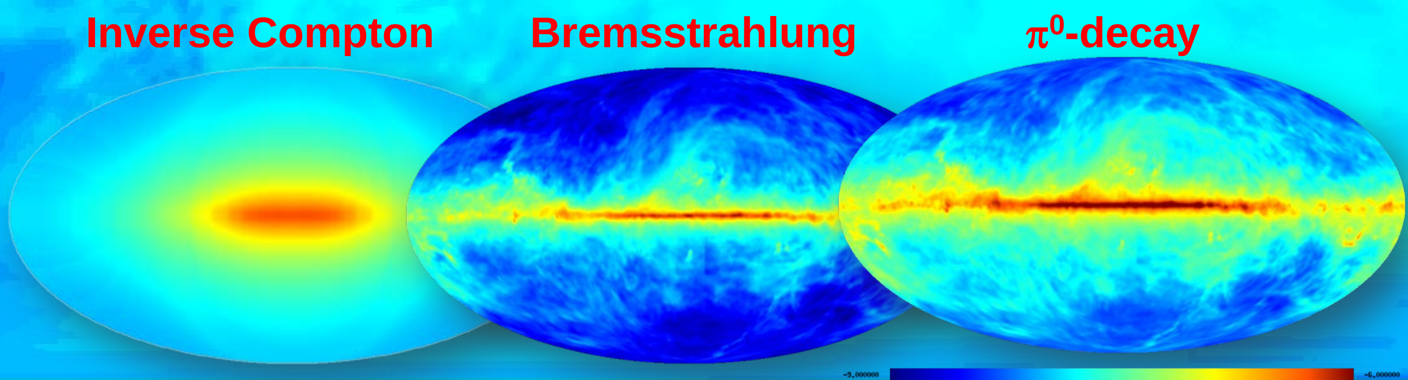
4 identified otherwise (Crab; MSH 10-53/1FGL J1018.6-5856; G5.4-1.2/PSRJ1801-2451; MSH 15-52)

14 candidates marginally classified

245 u.l.'s on non-detected radio-SNRs

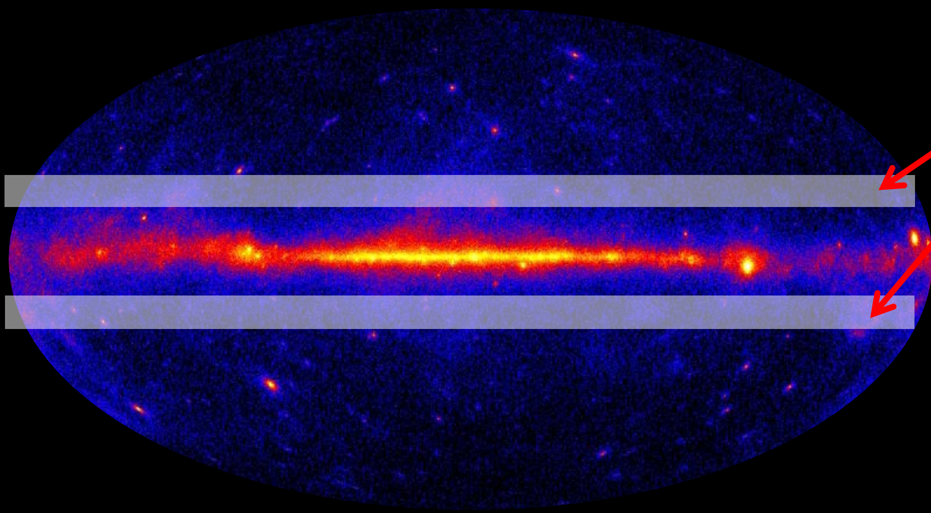
Diffuse Continuum Gamma Radiation

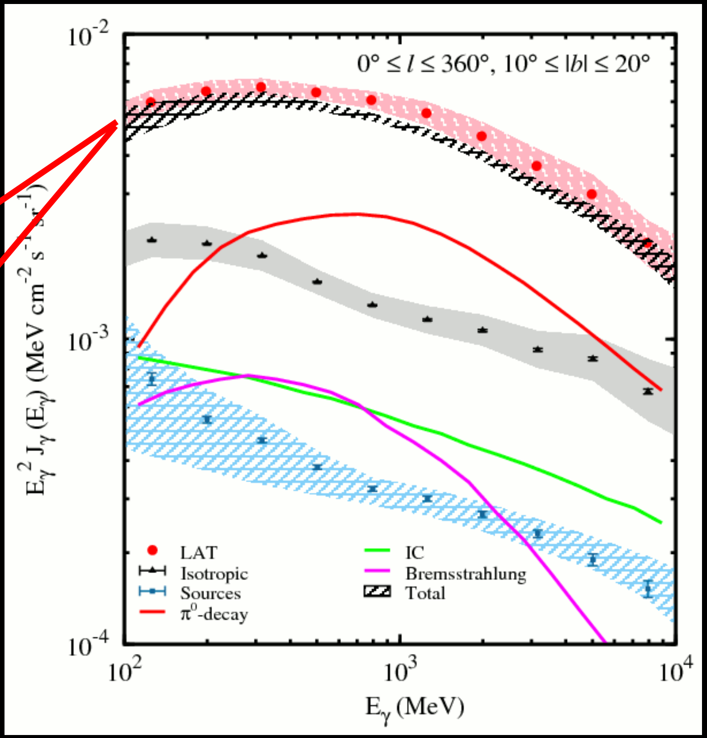
- Cosmic Rays present throughout our Galaxy
- B-fields (via synchrotron radio maps)
- Interstellar radiation fields (CMB, IR, OPT/UV)



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.)

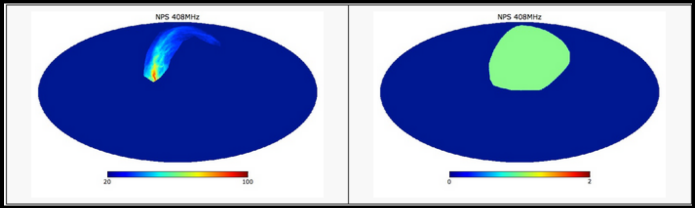
→ Fermi/LAT errors are systematics dominated, estimated to ~10%

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

Full-fledged diffuse modeling in the Milkyway

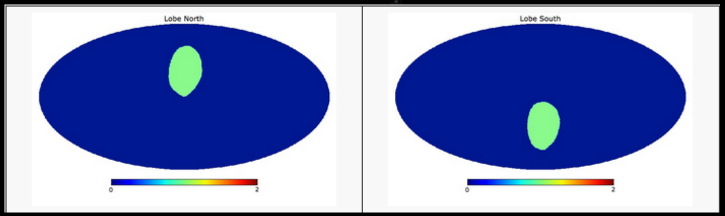
→ **"analysis model"** based on templated emission components (IC, ISO)
+ a ring-emissivity model for HI and CO (for H_2)
+ an extinction E(B-V) template following the spirit of unseen "dark" gas

- model grid of 0.125°
- interstellar radiation fields via *FRaNKIE*
- 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

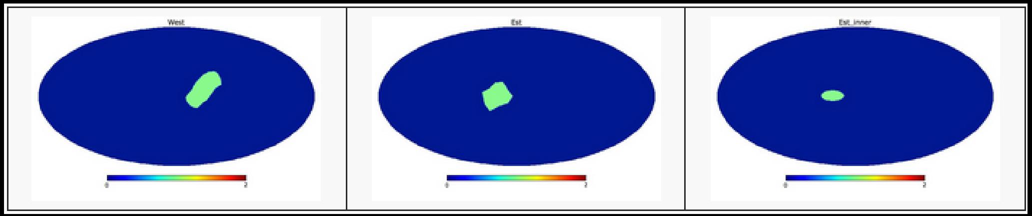


← Loop I / NPS

Galactic Lobes→



Galactic Plane excess regions →



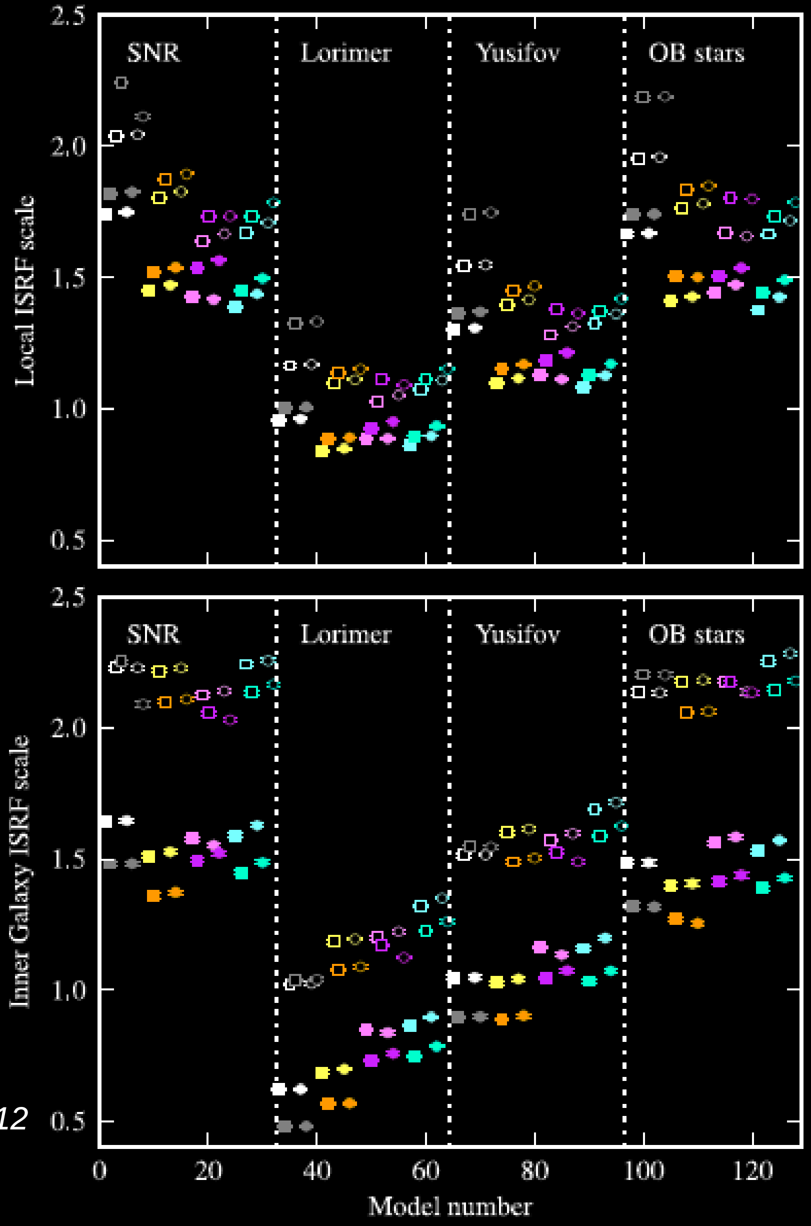
Result: *Fermi diffuse model became a point-source analysis model!*
Aim to minimize residuals goes on the expense of consistent physics !
Almost impossible to interpret when interesting physics shows up !

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

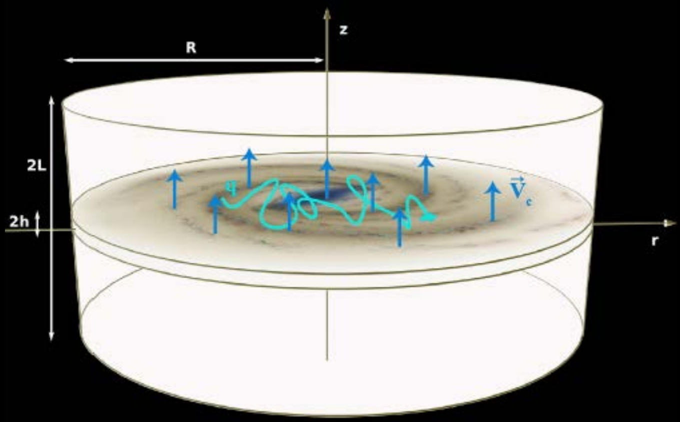
→ thus far, GALPROP 2D in axial-symmetric cylindrical geometry commonly used

→ normalization (scaling) here & there:



LAT collaboration '12

Thus: back to CR propagation physics, although at new level of realism



from simple slab and halo approximation (GALPROP 2D) to full 3D propagation, matter & source distribution in spiral arms, (ideally) matching B-field, stochastic sources & energy losses (TeV!)

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

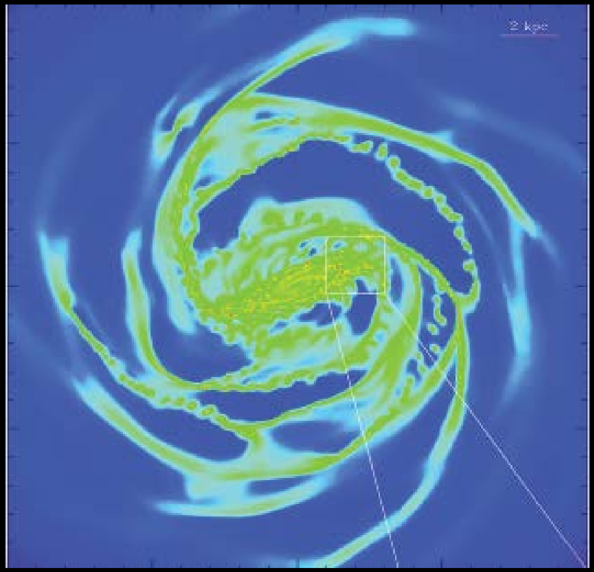
$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \nabla \cdot (\mathrm{D}_{xx} \nabla \psi - \mathbf{v} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left\{ \dot{p} \psi - \frac{p}{3} (\nabla \cdot \mathbf{v}) \psi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

GALPROP

DRAGON Code

☞ Evoli, Gaggero later today

Towards better GeV-TeV propagation models then…



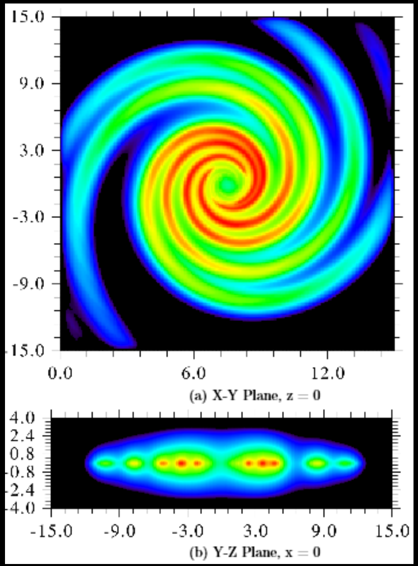
Renaud ea 2013

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

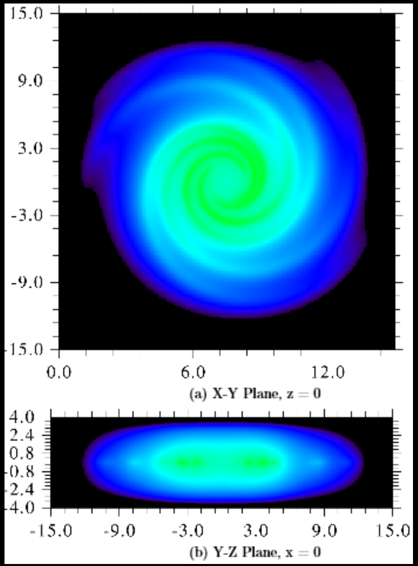
☞ PICARD: axisymmetric,
Steiman 4-arm,
Dame 2-arm,
Cordes-Lazio NE2001

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

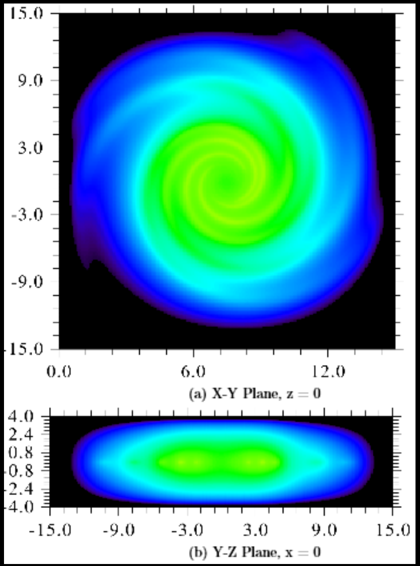
1 GeV



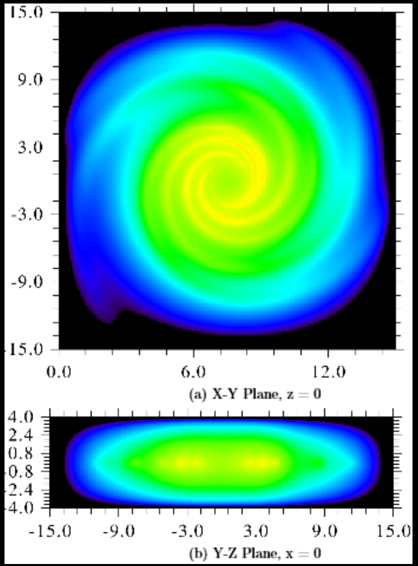
10 GeV



100 GeV



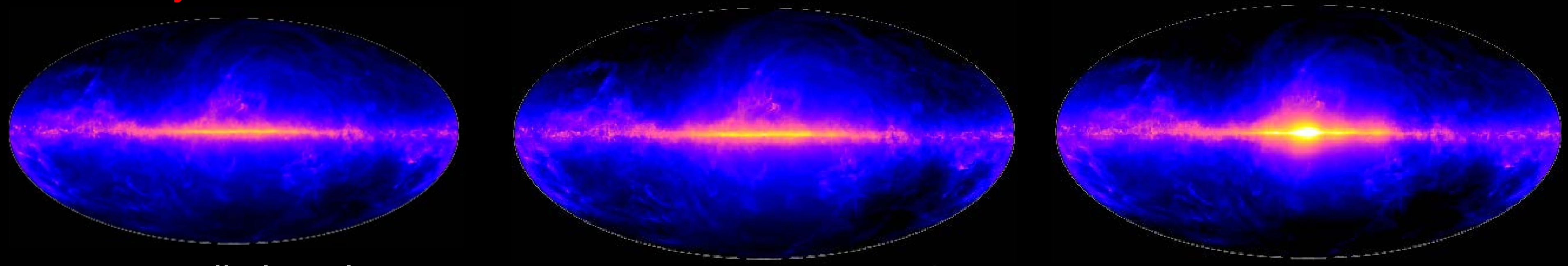
1 TeV



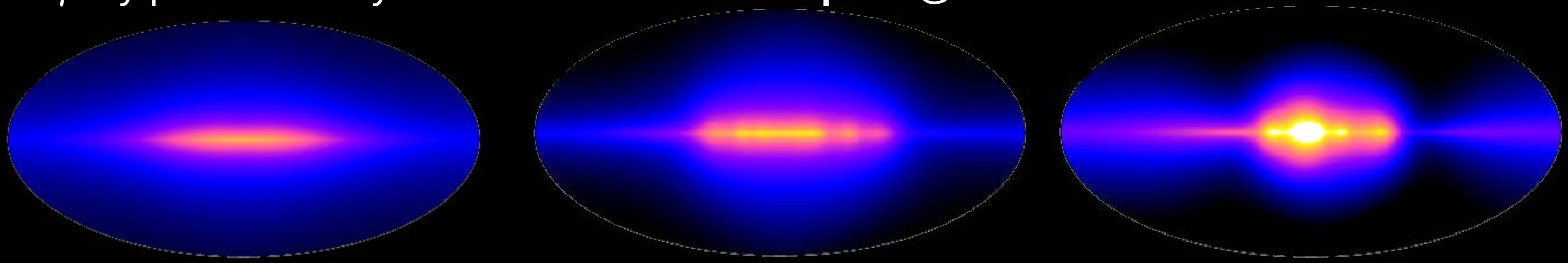
Towards better GeV-TeV propagation models then…

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

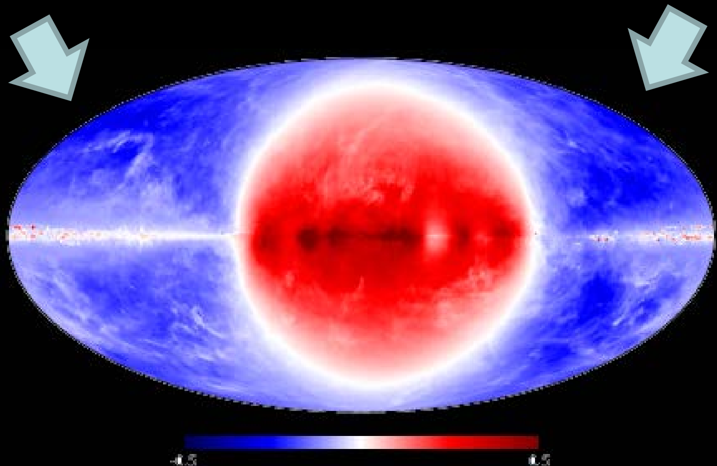
axisymmetric | 4-arm | 2-arm



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



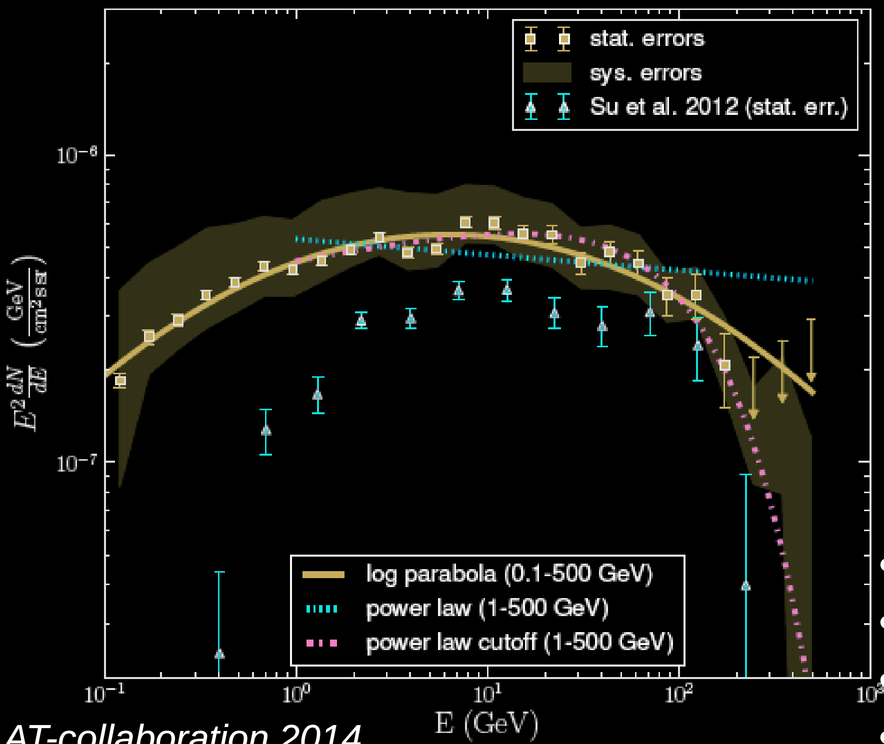
(like GALPROP 2D style)



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

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

The Fermi Bubbles



LAT-collaboration 2014

$$E_{\mathrm{cut}} = 113 \pm 19[\mathrm{stat}]^{+45}_{-53}[\mathrm{syst}] \ \mathrm{GeV}$$

$$\gamma = 1.87 \pm 0.02[\mathrm{stat}]^{+0.14}_{-0.17}[\mathrm{syst}]$$

$$(4.4 \pm 0.1[\mathrm{stat}]^{+2.4}_{-0.9}[\mathrm{syst}]) \times 10^{37} \ \mathrm{erg\ s^{-1}}$$

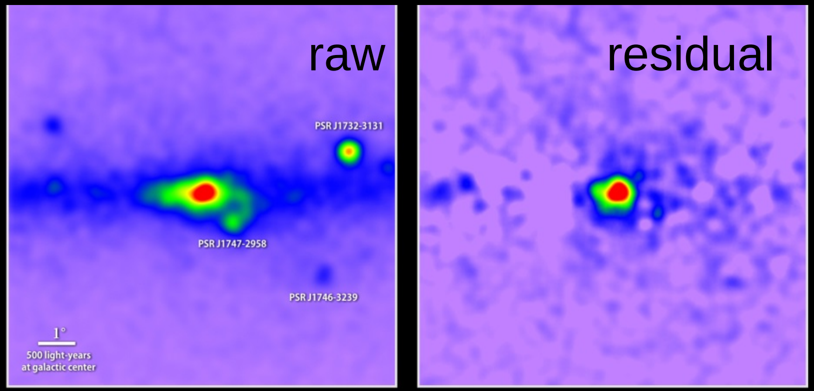
- north & south bubble with *similar* spectrum
- bubble shape *preserved* over energy
- *sharp* bubble boundaries
- substructure within “cocoon”, unlike jet

Extensive discussion of emission scenarios in literature meanwhile!
Presently **inconclusive:**

	lept.	had.
Gamma-ray spectrum	🙂	🙂
Microwave haze	🙂	🙁
No spectral changes	🙁	🙂
Narrow boundary	🙂	🙁
Absence of a visible shock front	🙁	🙂

The Galactic Center surplus, excess or anomaly

What am I talking about now?



Unprocessed map of 1.0 to 3.16 GeV gamma rays

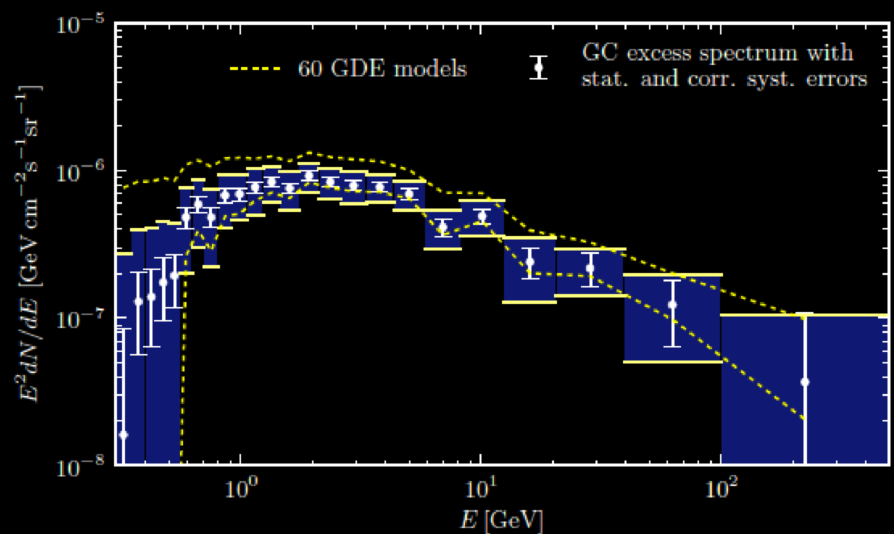
Known sources removed

"The Characterization of the Gamma-Ray Signal from the Central Milky Way:
A Compelling Case for Annihilating DM"]

[Daylan, Finkbeiner, Hooper, Linden…, arXiv]

Q: An excess above what, exactly?

Although different analysis techniques used, by now a common picture emerged:

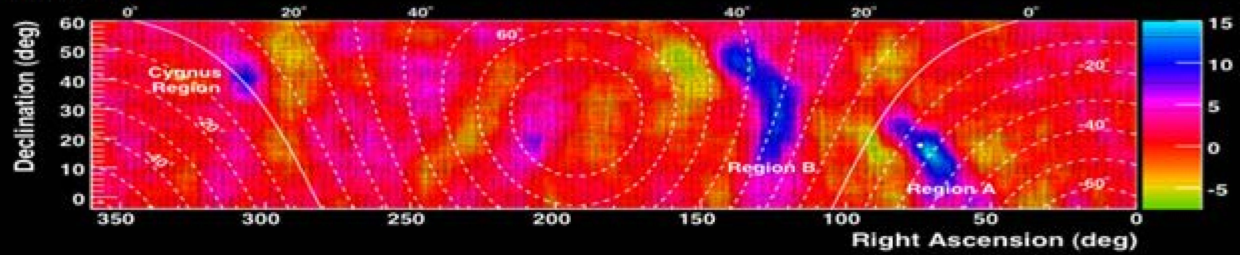


[Calore, Cholis & Weniger 2015]

Alternative views, this time in the category
DM vs. conventional astrophysics
(msPSRs,
CR propagation physics,
central bh activity …)

Yet another puzzle: TeV Cosmic Ray Anisotropy

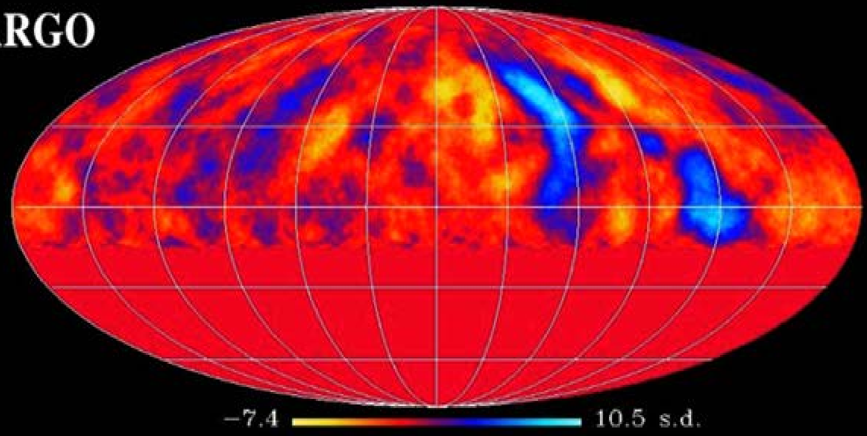
Milagro



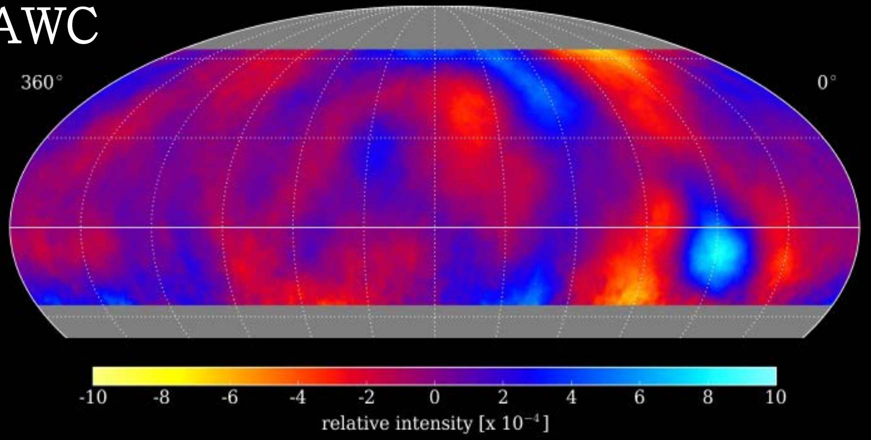
- Localized anisotropy on 5-10º size scale with a fractional excess up to 7×10^{-4} above the cosmic ray background (15 σ)
- Excess is ***not*** gamma rays, but hadronic cosmic rays
- Gyroradius of a 10 TeV proton in a 1 mG field is 0.01 pc (2000 AU)

Consequences for the very high energy gamma-ray sky?

ARGO



HAWC



Summary & Outlook

- **There is an incredible diversity and richness in the Galactic γ-ray sky!**
  - ☞ many sources, many source classes, even different phenomena within sources classes
  - ☞ unassociated sources (angular resolution, no or too many MWL counterparts)

- Best physics constraints from best-observed individual sources or population aspects. Discovery space, however, opens up at sensitivity limit / end of dynamic range of present instrumentation.

  Major obstacle is already (GeV) CRs in our Galaxy via diffuse Galactic γ-ray emission modeling, will soon be in TeV for IACTs & HAWC, as well as Neutrino astronomy.

- **"Yesterday's signal is today's background, will be tomorrow's calibration."**

  This relates directly to the *diffuse Galactic gamma-ray emission*.
  - ☞ CR data & propagation modeling constrain neutral messenger obs
  - ☜ gamma-ray obs constrain CR propagation physics

- "Galactic" physics starts to reach out into the extragalactic domain:

  [2015: H.E.S.S. ☞ PWN N157B; ☞ SNR N132D,
  ☞ superbubble 30Dor, Ø SN 1987A

  Fermi-LAT ☞ LMC, SMC, M31, …]