Gamma-ray emission from the inner Galaxy

Observational status and interpretations

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Seminar
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NWO

Outline

- Motivation: Searches for dark matter annihilation signals
- The gamma-ray sky as seen by Fermi
- Modeling of Galactic diffuse gamma-ray emission
- An “excess” at GeV energies from the inner Galaxy
- Interpretations & the case for millisecond pulsars
- Outlook & Conclusions

We looked for dark matter

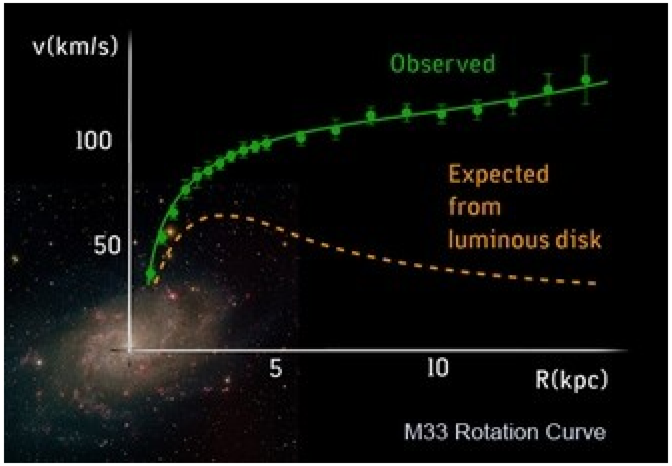
and (probably) found astrophysics.

Introduction.

Evidence for dark matter is omnipresent

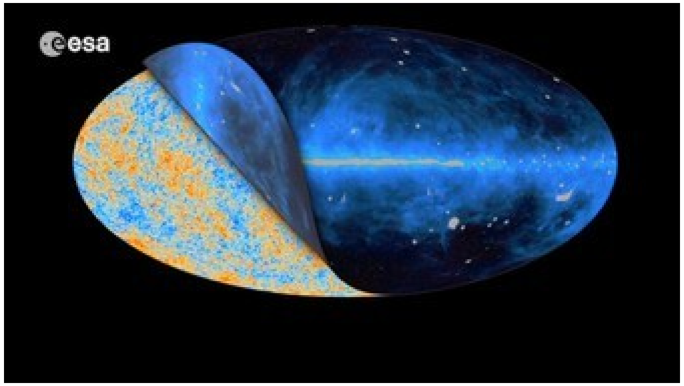
Evidence for the existence of **non-baryonic** dark matter in the Universe comes from gravitational observations at different length scales (from sub-galactic to cosmological scales).

Galaxy rotation curves

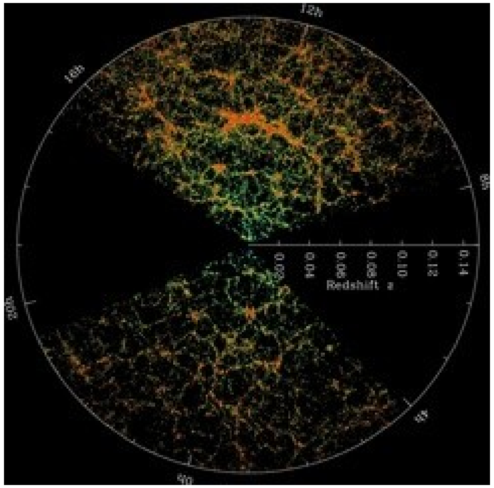


Galaxy clusters

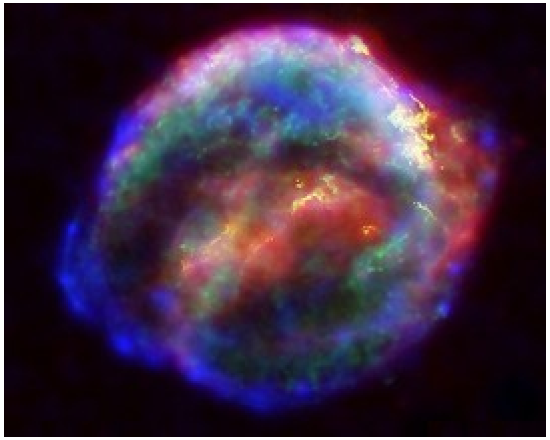
Cosmic microwave backgroun

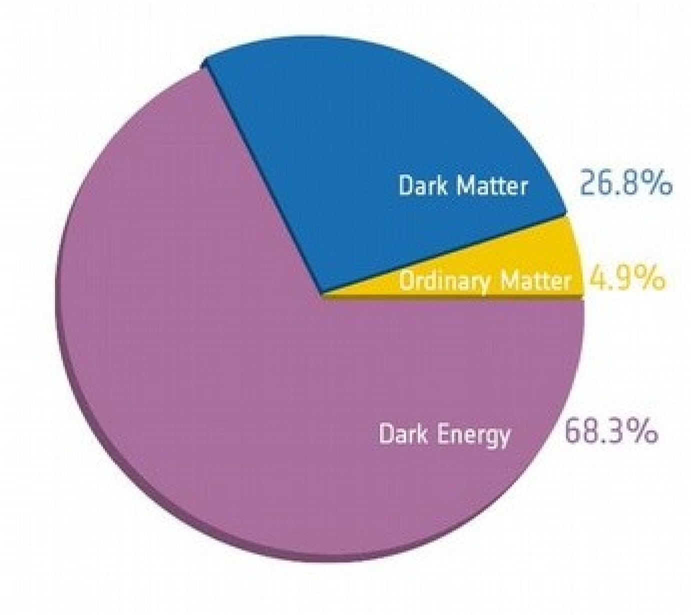


Large scale structures



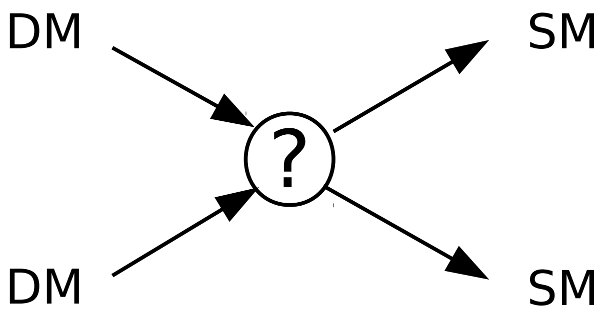
Supernova Type 1A

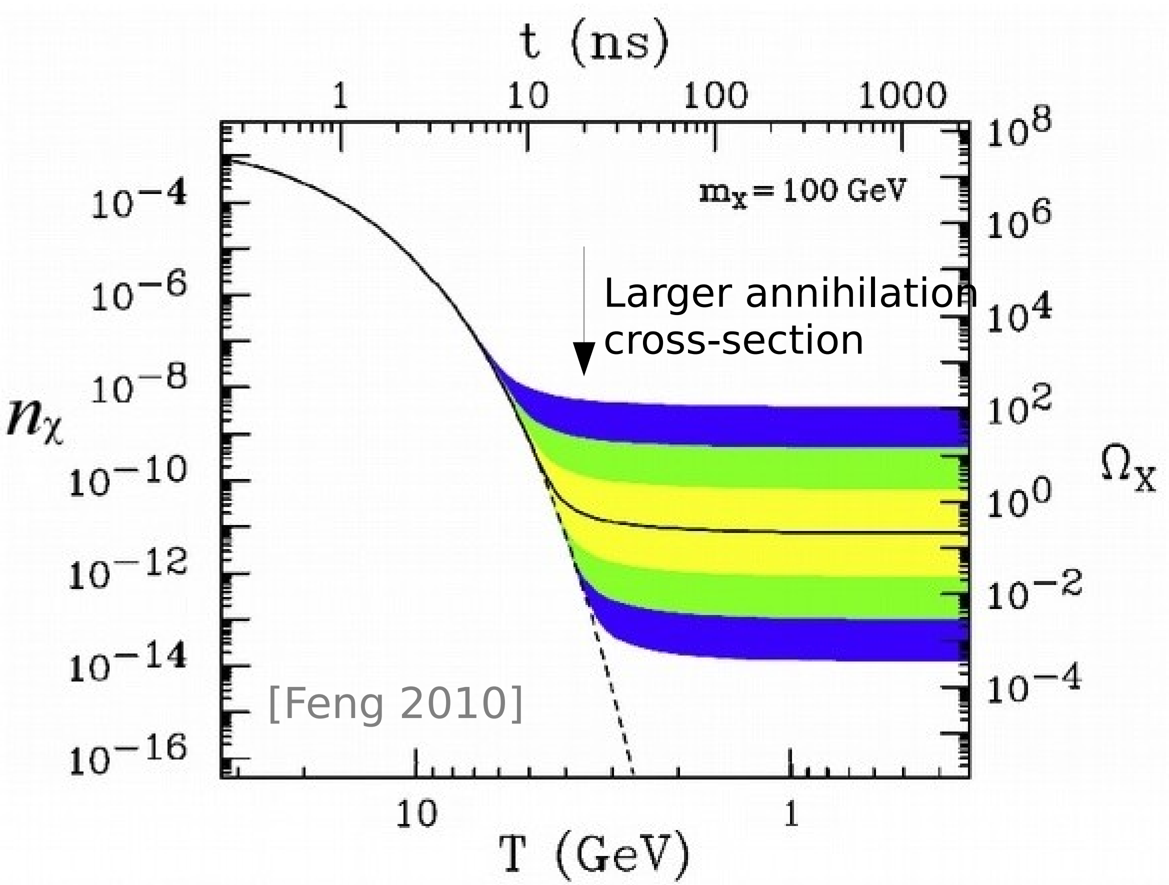




85% of all matter in the Universe is **dark** and **non-baryonic**

Weakly Interacting Massive Particles (WIMPs) in the early Universe: The freeze-out mechanism





Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle \left[n^2 - n_{\rm eq}^2\right]$$

Velocity-averaged annihilation cross-section in early Universe is fixed by observed mass density of DM.

$$\frac{\Omega_\chi h^2}{0.1} \approx \frac{3\times 10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle\sigma v\rangle}$$

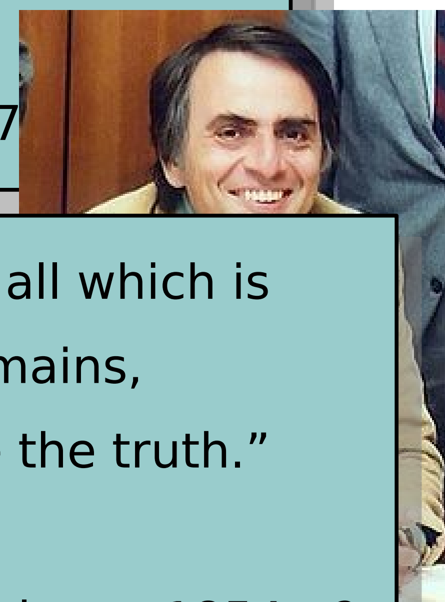
This is very close to experimental sensitivities!

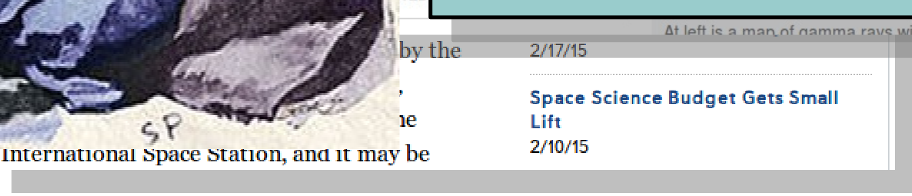
This provides a rough estimate for annihilation rate of DM particles today.

Many false alarms in “indirect searches”?

No testimony is sufficient to establish a miracle, unless the testimony be of such a kind, that its falsehood would be more miraculous than the fact which it endeavors to establish.

Extraordinary claims require extraordinary evidence.

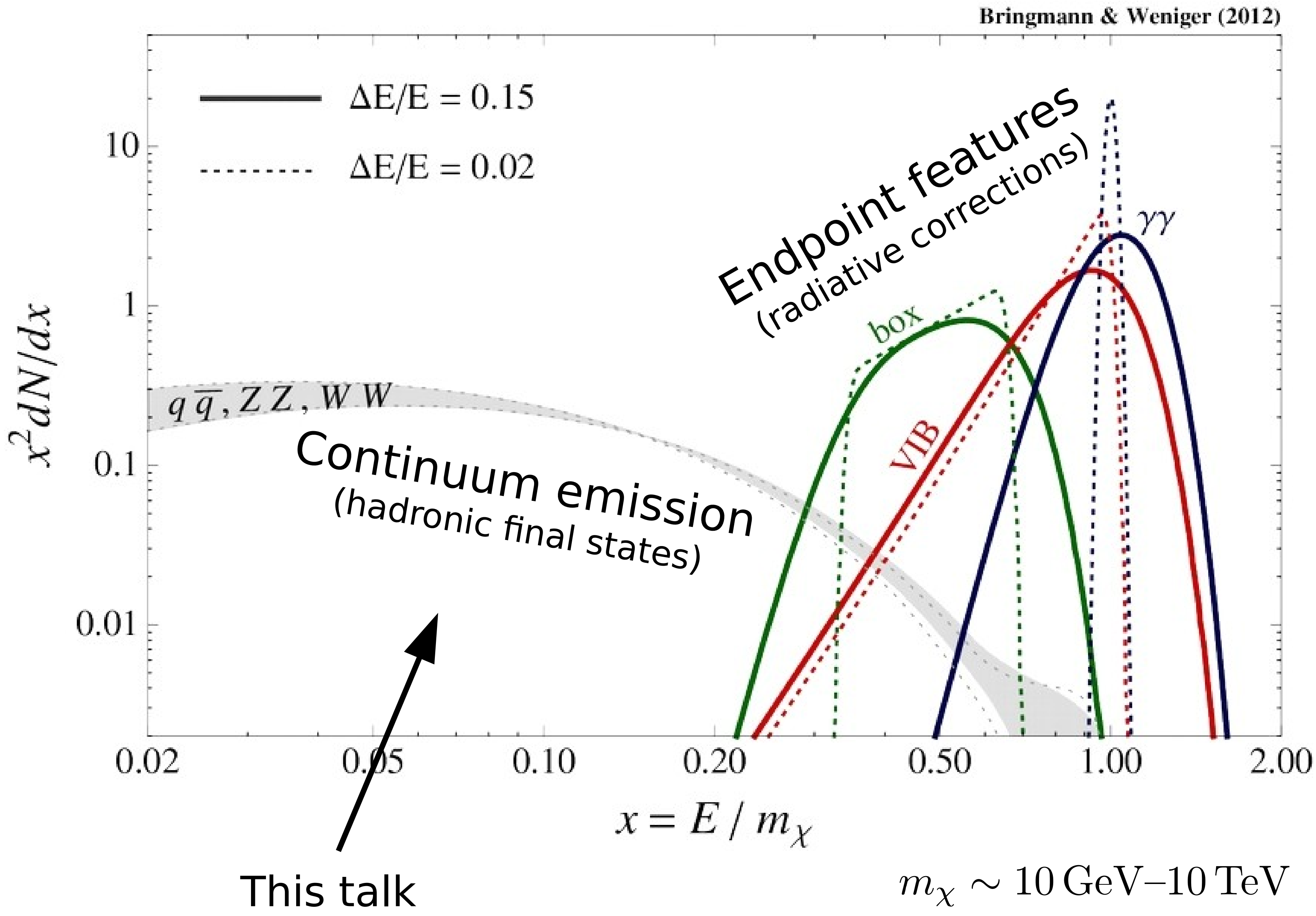




“…when you have eliminated all which is impossible, then whatever remains, however improbable, must be the truth.”

Sherlock Holmes, 1854 - ?

Photon energy spectrum

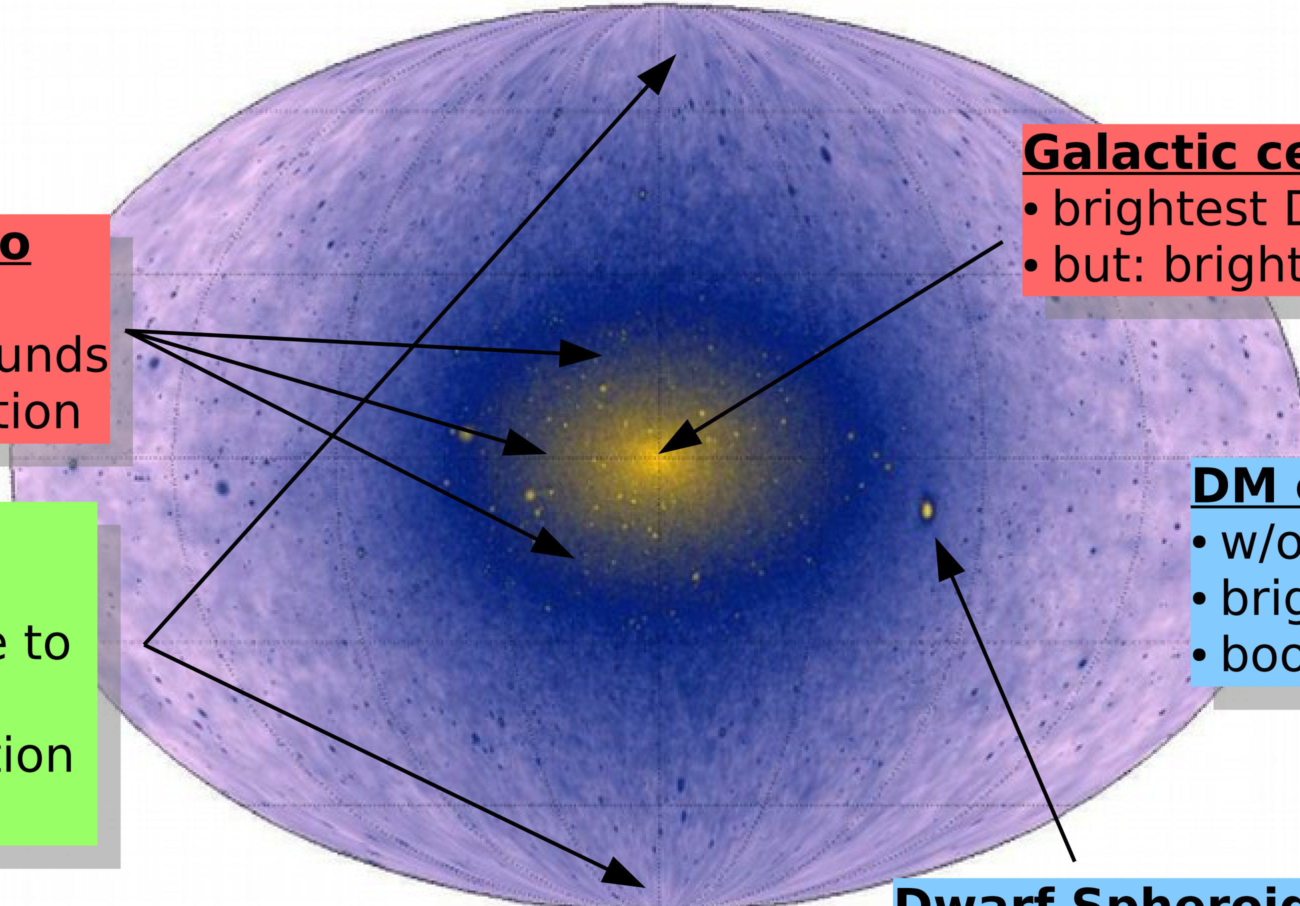


$m_\chi \sim 10\,\mathrm{GeV}\text{–}10\,\mathrm{TeV}$

Why the Galactic center?

Signal is proportional to column square density of DM

$$\frac{d^2\phi}{d\Omega dE} = \frac{\langle \sigma v_{\rm rel}\rangle}{8\pi m_\chi^2}\frac{dN_\gamma}{dE} \times \int_{\rm l.o.s.} ds\ \rho_{\rm DM}(\vec{r}[s,\Omega])^2$$



Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Extragalactic
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Galactic center (~8.5 kp
- brightest DM source in sky
- but: bright backgrounds

DM clumps
- w/o baryons
- bright enough?
- boost overall signa

Dwarf Spheroidal Galaxies
- harbour small number of stars
- otherwise dark (no gamma-ray emission)

[review on N-body simulations: Kuhlen, Vogelsberger & Angulo (2012)]

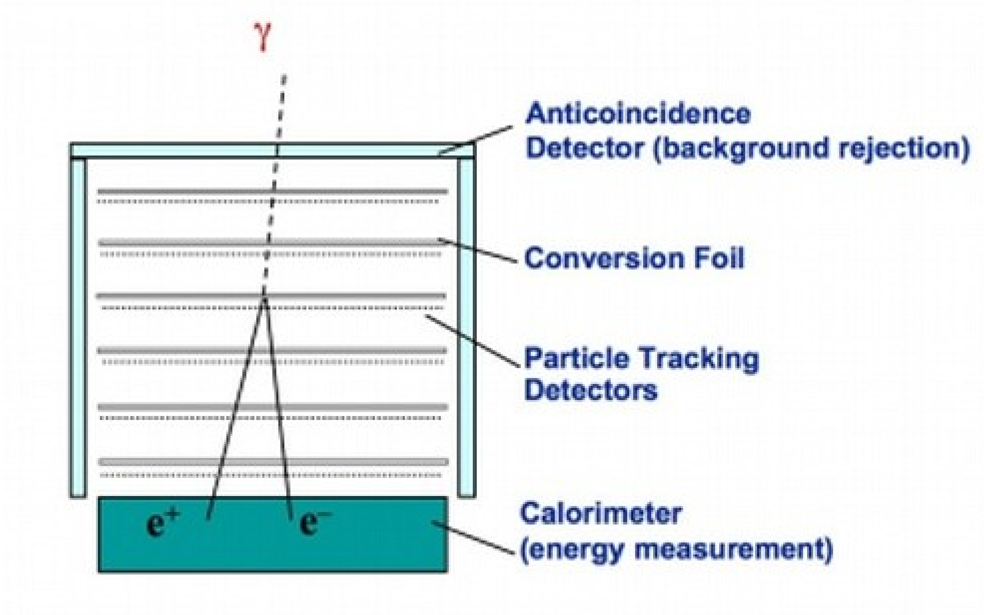
Modeling diffuse gamma-ray emission.

The Fermi Large Area Telescope

The Fermi LAT is a **pair conversion detector** on board the Fermi Gamma-Ray Space Telescope.

Characteristics

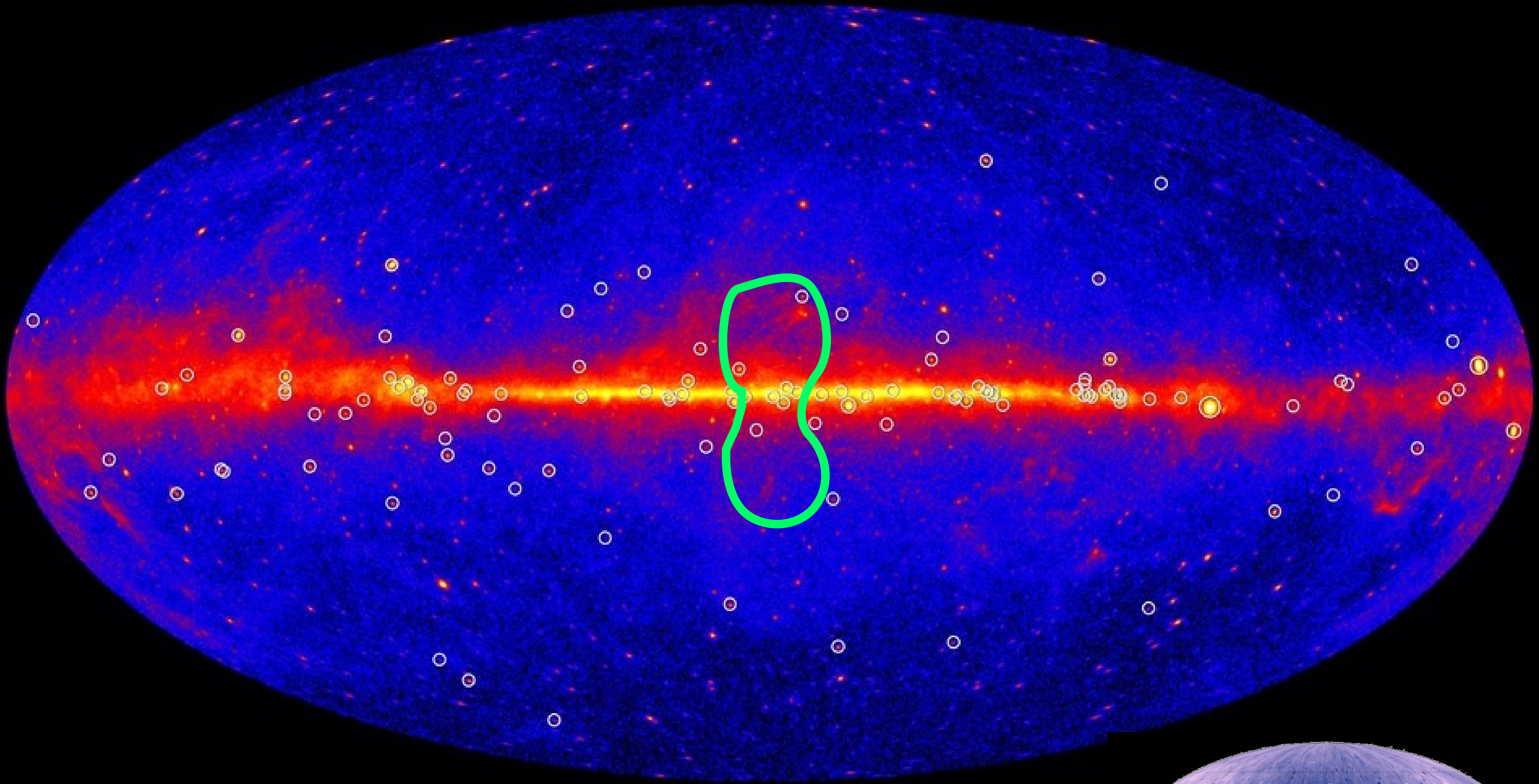
- Energy range: 20 MeV to above 300 GeV
- Field of view (FOV): 2.4 sr
- Energy resolution: <10% (above 10 GeV)
- Angular resolution: < 0.15º (above 10 GeV)
- Launched: 2008

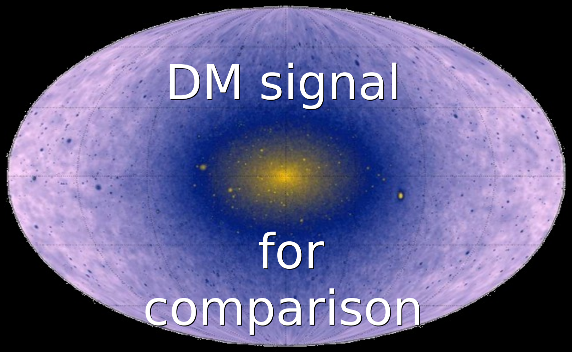


Main components

- Anti-coincidence shield (plastic scintillator) with photomultiplier tubes
- Tracker (silicon strip detectors) with conversion foils (tungsten)
- Electromagnetic Calorimeter (CsI)

The LAT view on the gamma-ray sky

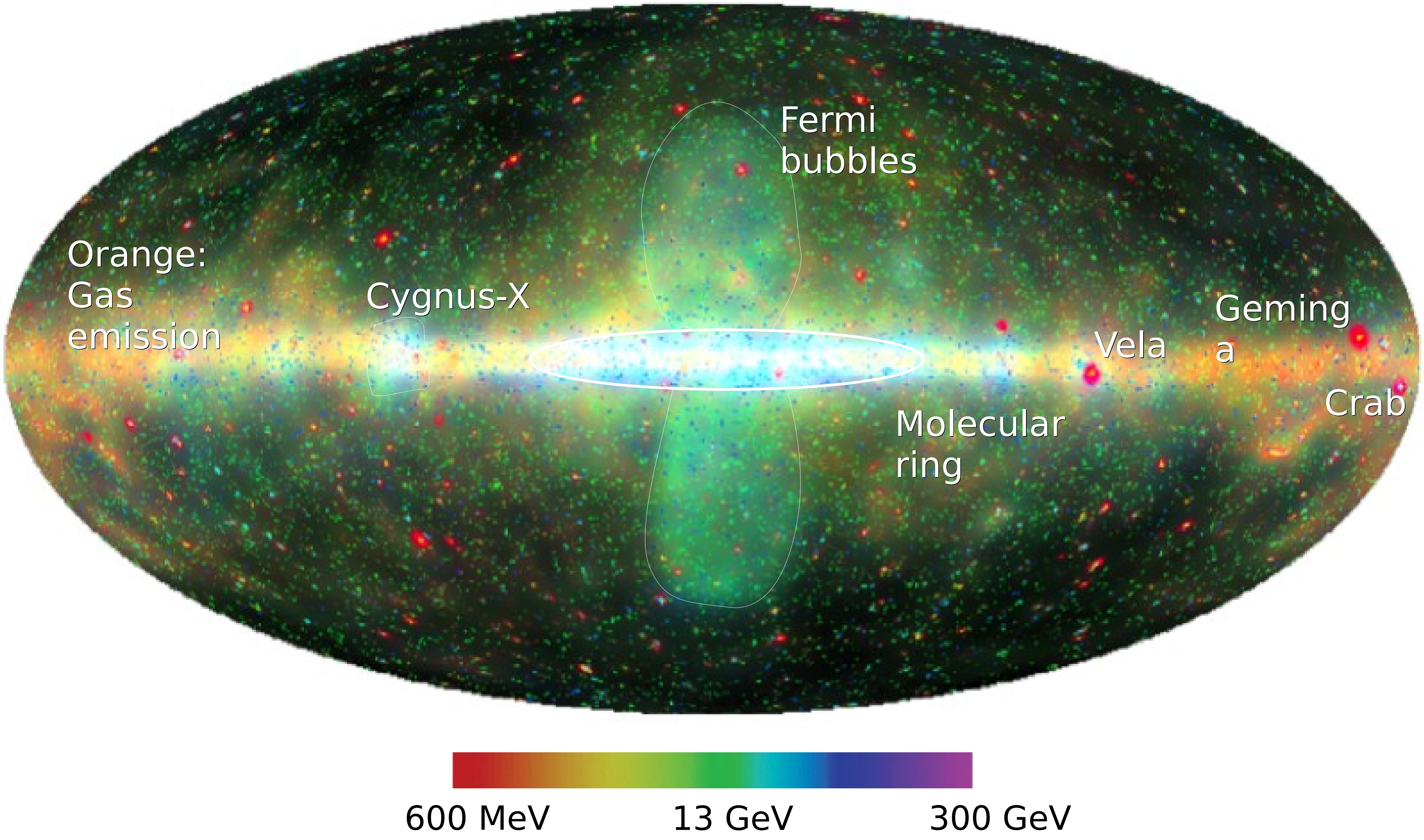




Five years of data taking > 1 GeV
Gamma-ray pulsar positions are indicated as circles

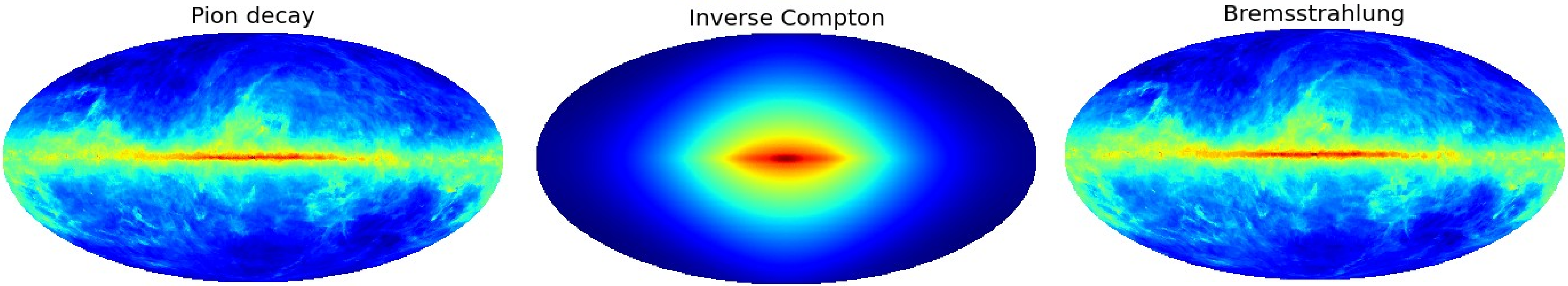
http://svs.gsfc.nasa.gov/vis/a010000/a011300/a011342/

Fermi LAT sky in pseudo colors

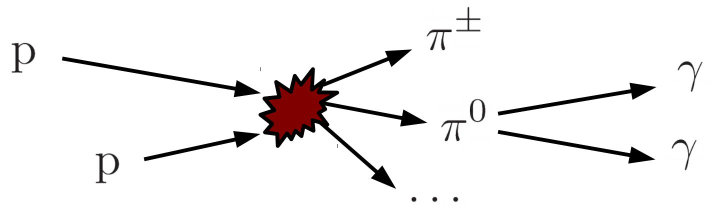


Selig+ 2014, 6.5 years of data, using D^3PO algorithm

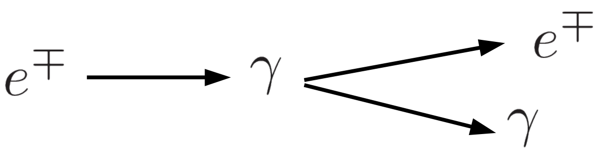
Contributions to Galactic diffuse gamma rays



Neutral pions



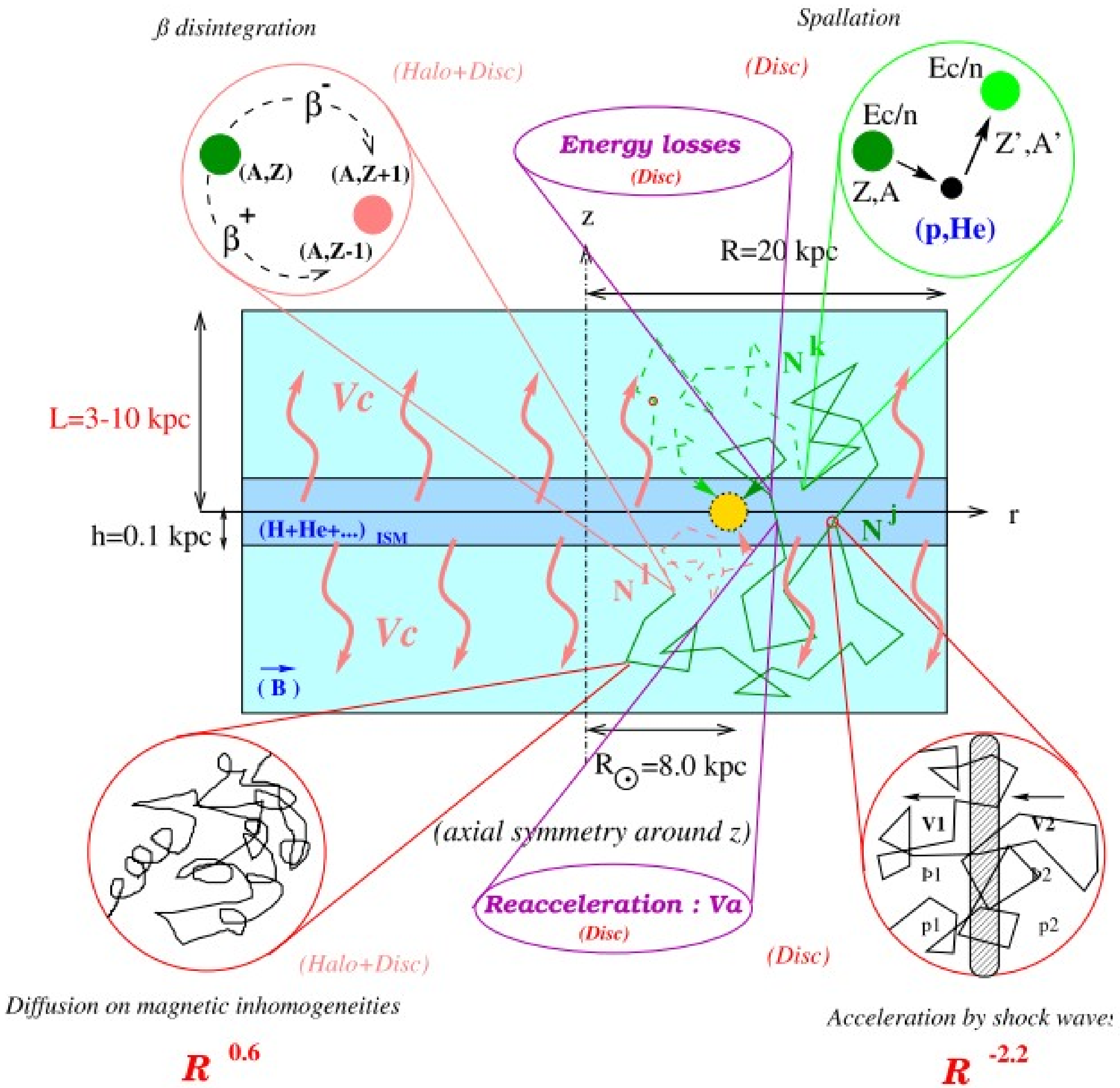
Inverse Compton



Predictions rely on

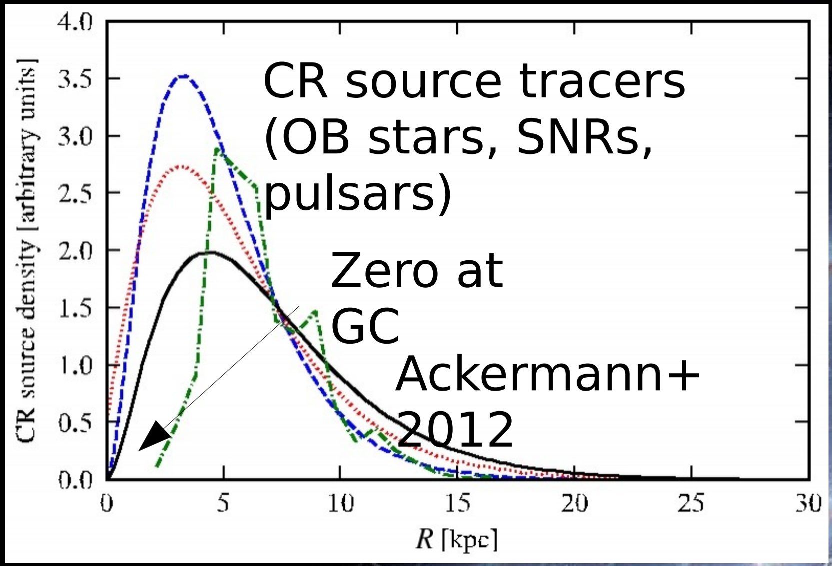
- Distribution and composition of interstellar medium
- Distribution and spectrum of interstellar radiation field
- Distribution and injection spectra of cosmic ray sources
- Average Galactic magnetic field
- Properties of diffusion halo
- Hadronic scattering cross-sections
- ...

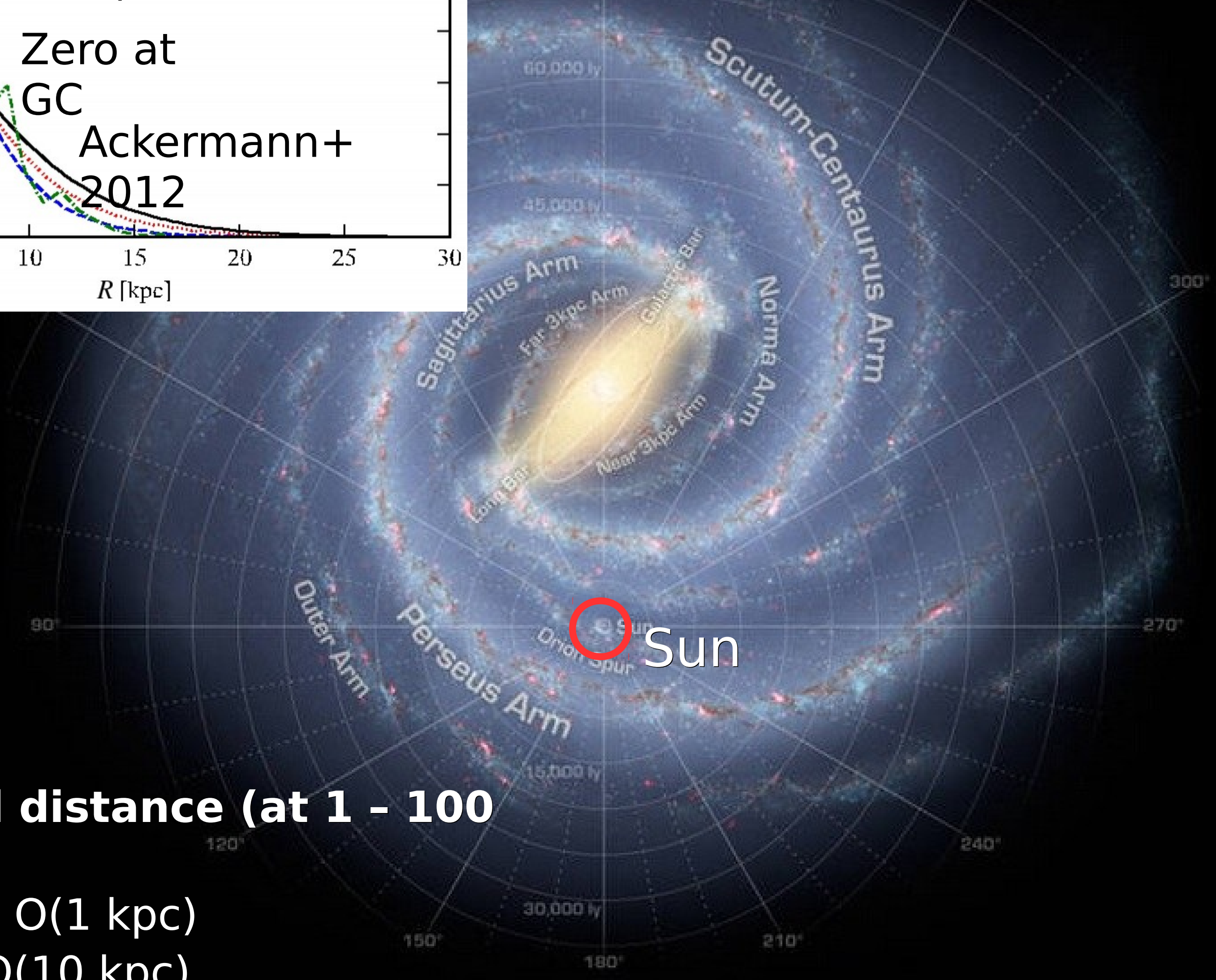
Galactic cosmic-ray propagation



Lavalle & Salati 2012

Distribution of cosmic-ray sources





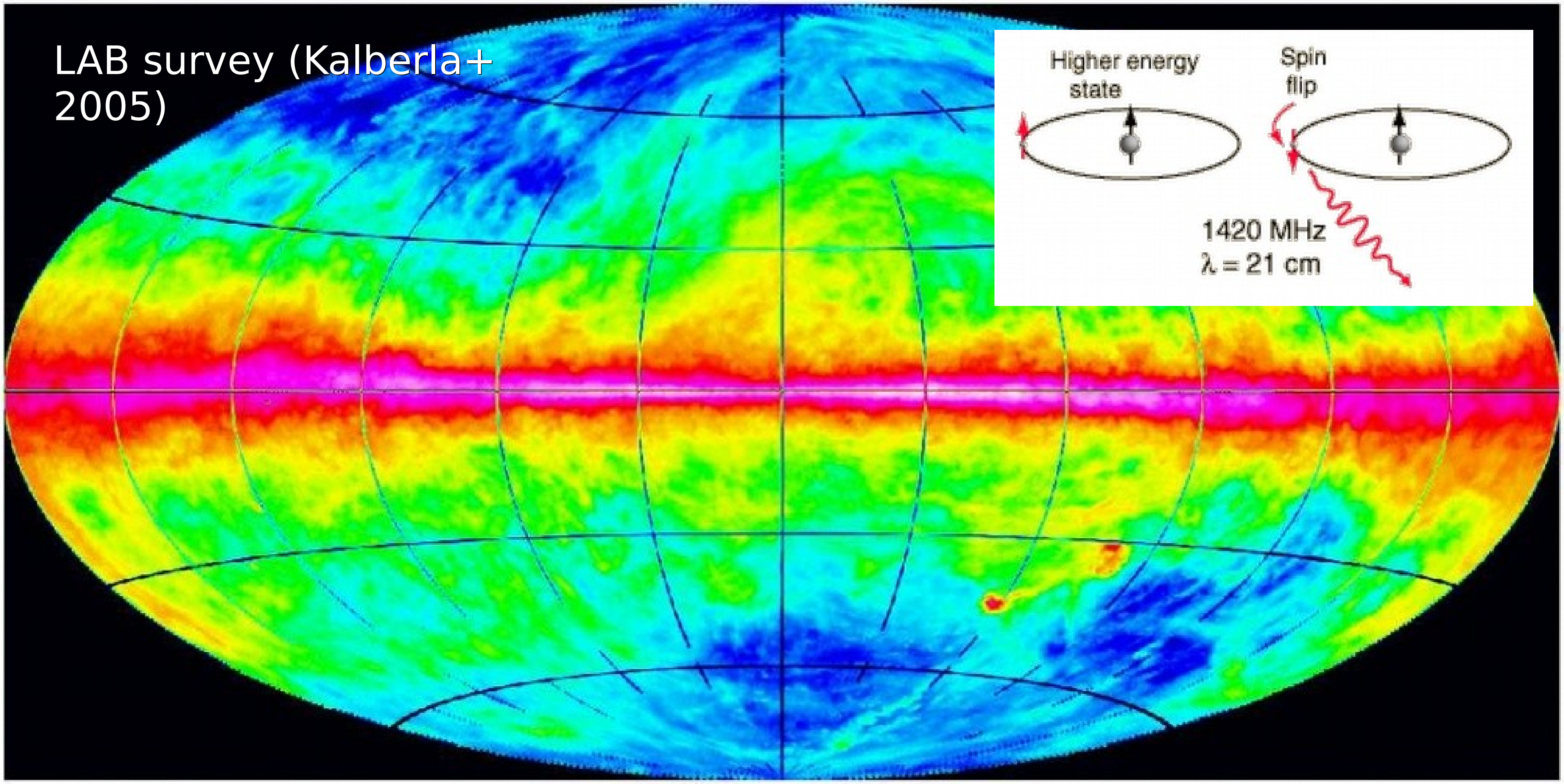
Typical travel distance (at 1 – 100 GeV)

CR electrons: O(1 kpc)

CR protons: O(10 kpc)

http://www.nasa.gov/mission_pages/sunearth/news/gallery/galaxy-location.html

Neutral hydrogen (H I) from 21 cm line



H I tracer

- LAB survey (Kalberla+ 2005)
- Decomposition along line-of-sight using Doppler shift

GALPROP; Ackermann+ 2012

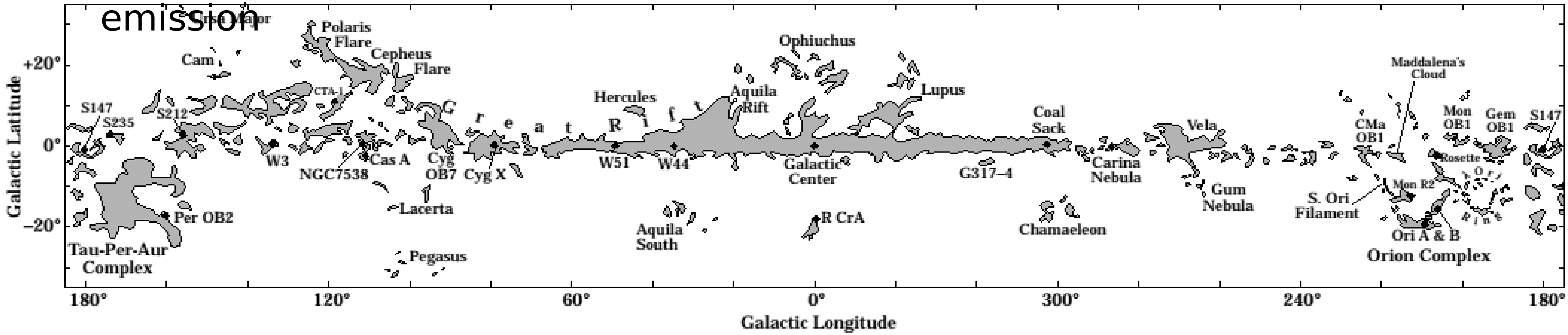
$$v_{\rm LSR} = R_\odot \left(\frac{V(R)}{R} - \frac{V_\odot}{R_\odot} \right) \sin(l) \cos(b)$$

- Distributed in rings (boundaries: 0.0, 1.5, 2.0, 2.5, …, 6.5, 7.0, 8.0, 10.0, kpc)

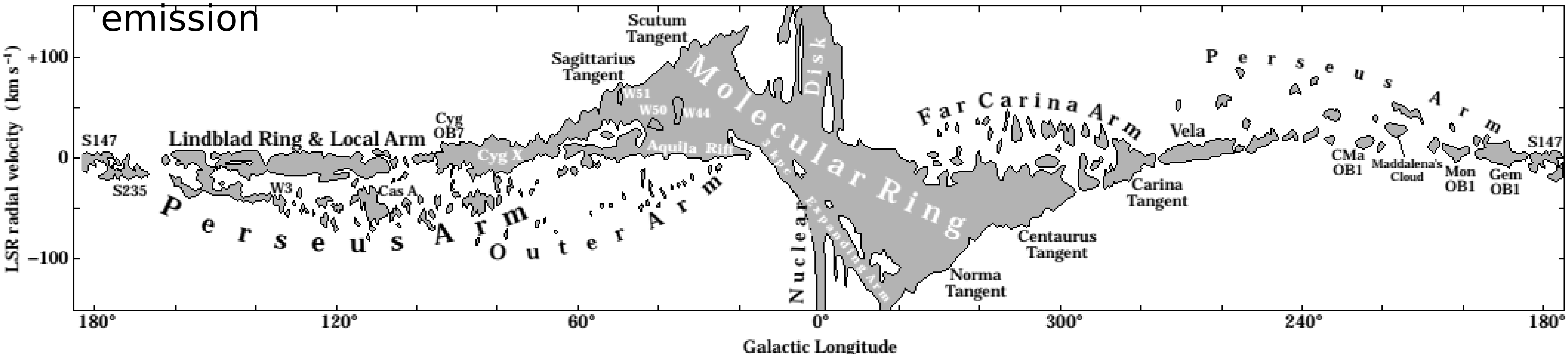
Molecular gas (H_2) from CO 2.6 mm line

Longitude-latitude map of CO emission

Dame+ 2001



Longitude-velocity map of CO emission

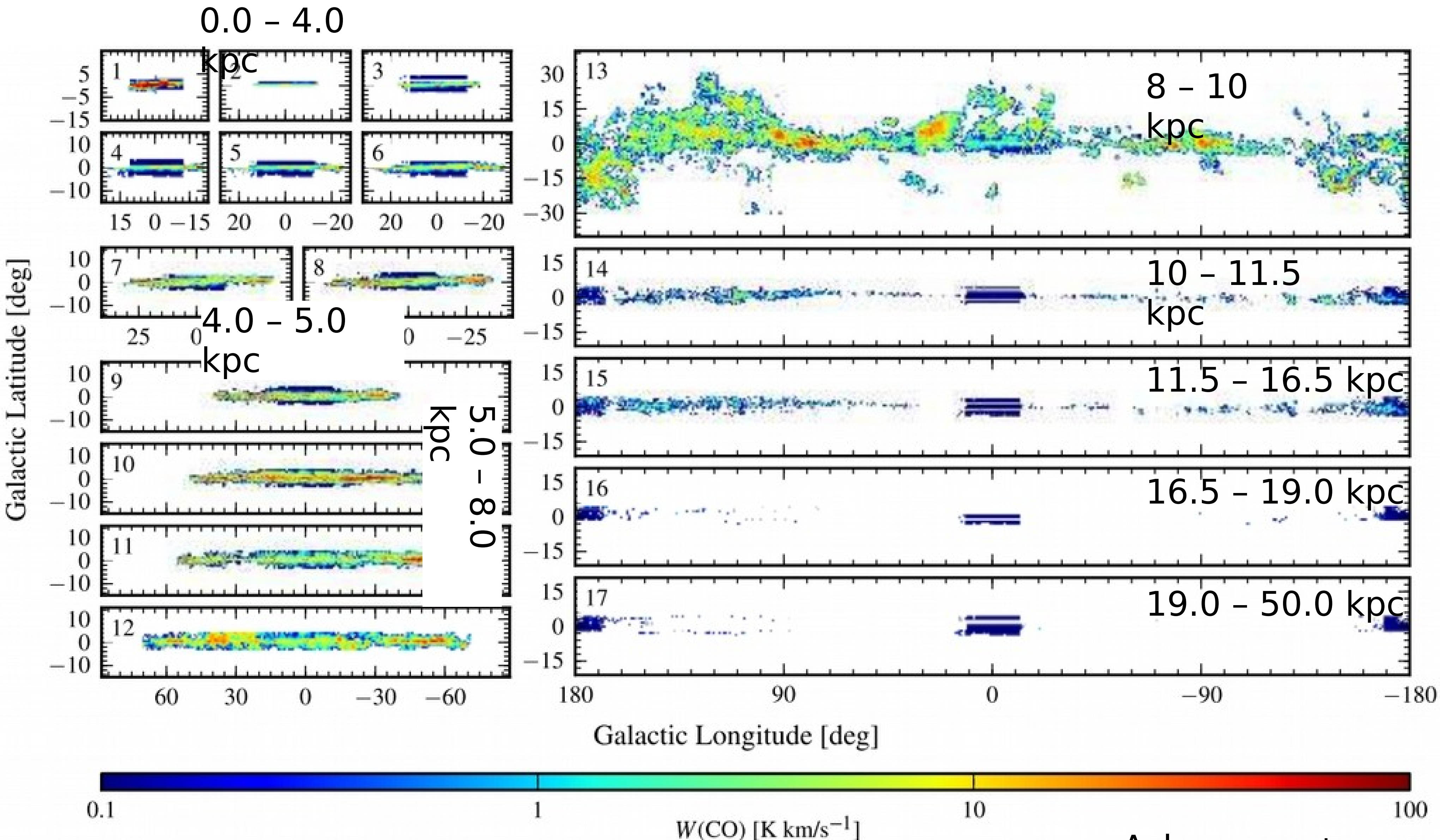


GALPROP; Ackermann+ 2012

Tracing H II

- Dame+ 2001 CO-line survey
- Decomposition along line-of-sight using Doppler shift as above, same boundaries
- Scale height ~80 pc (compared to up to 300 pc for H I)
  ⇒ mid-latitude emission is local

Example: Spatial decomposition of CO map

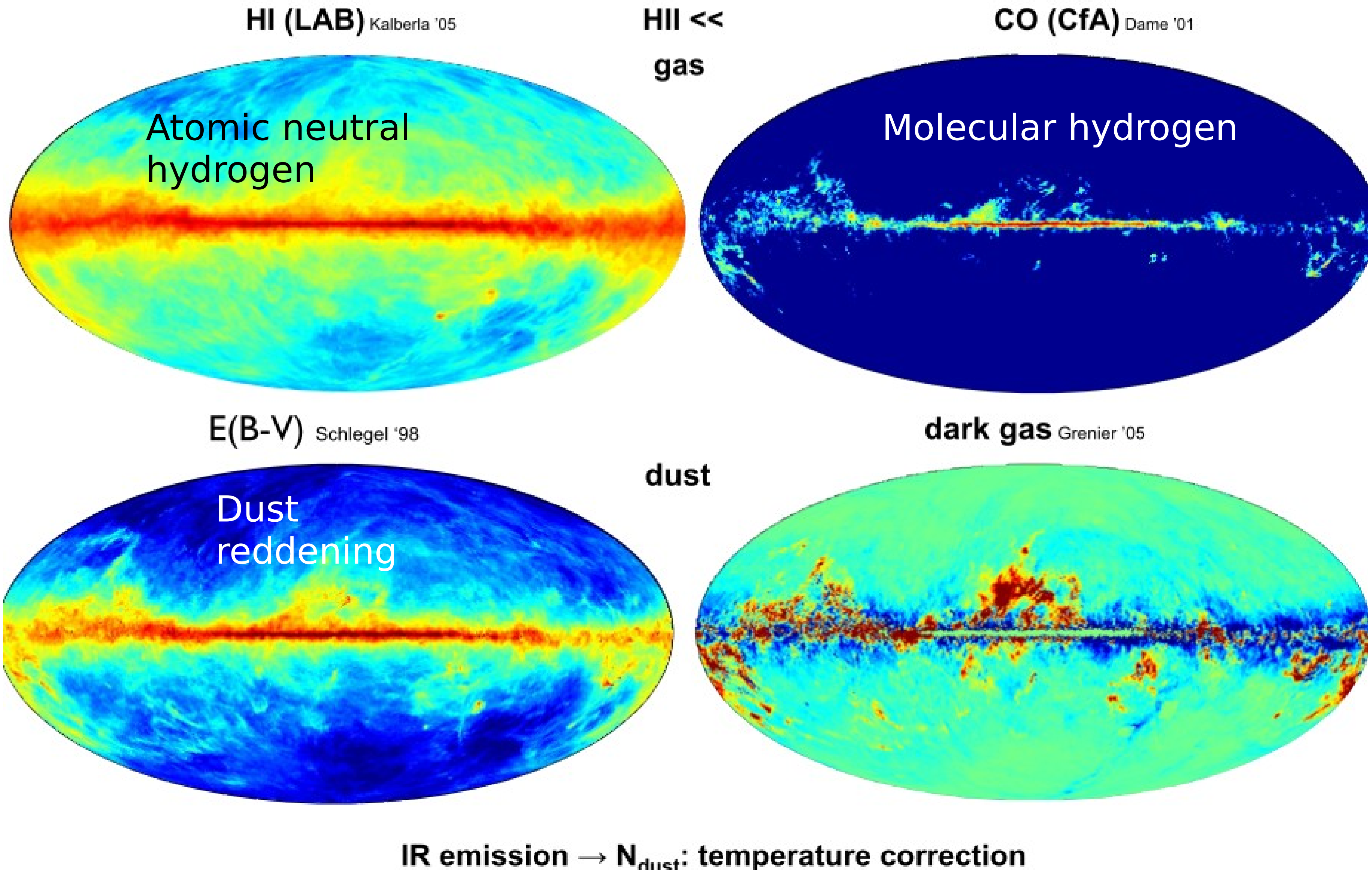


Ackermann+ 2012

Spatial decomposition

- Significant column densities all the way towards the GC (inner degrees)
- No molecular hydrogen above 5 deg in the inner ~5 kpc

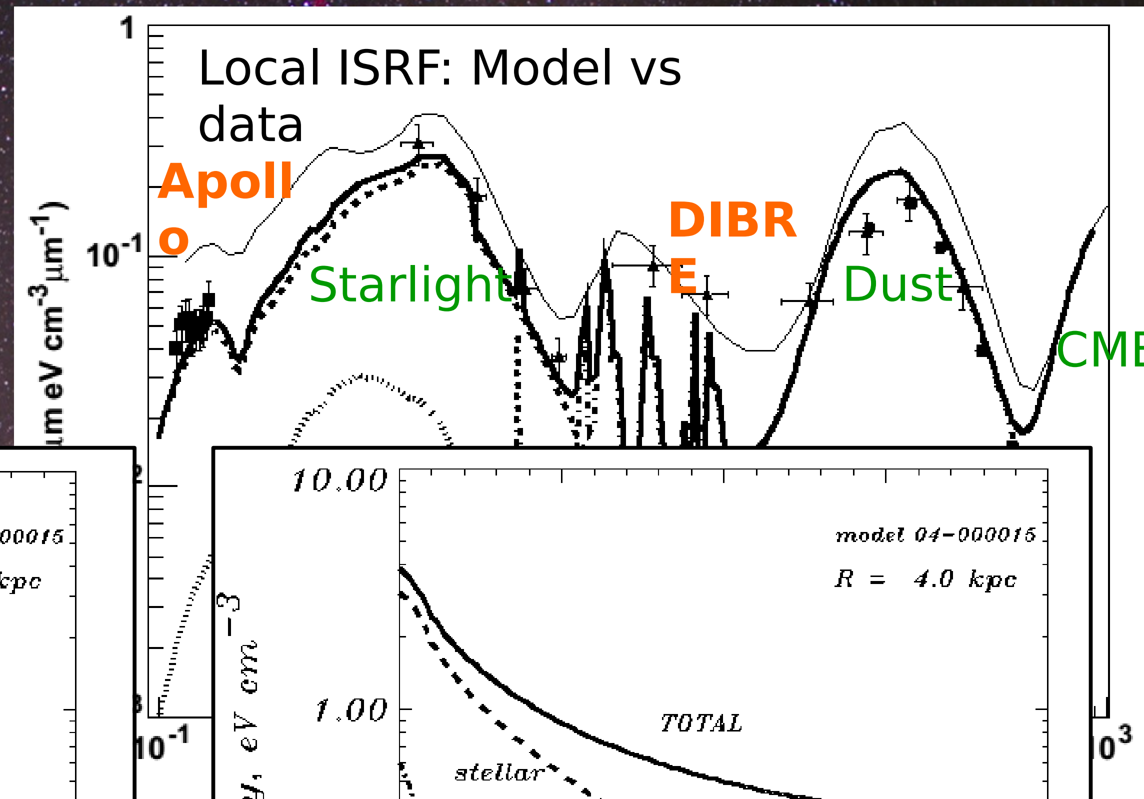
Dark gas corrections

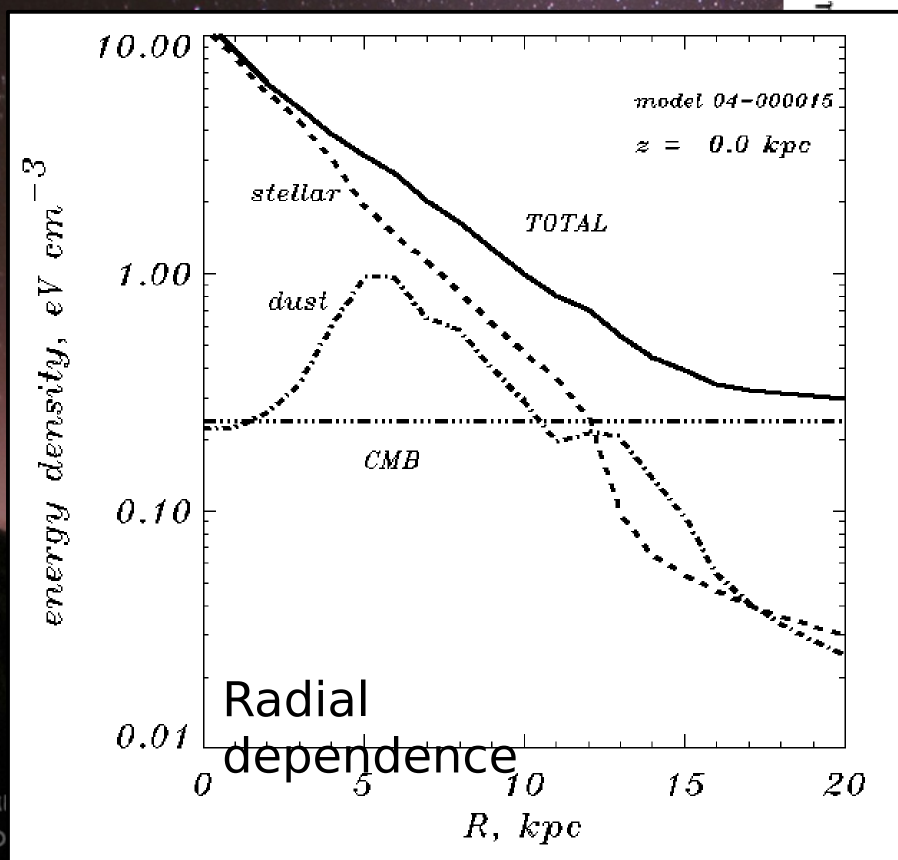


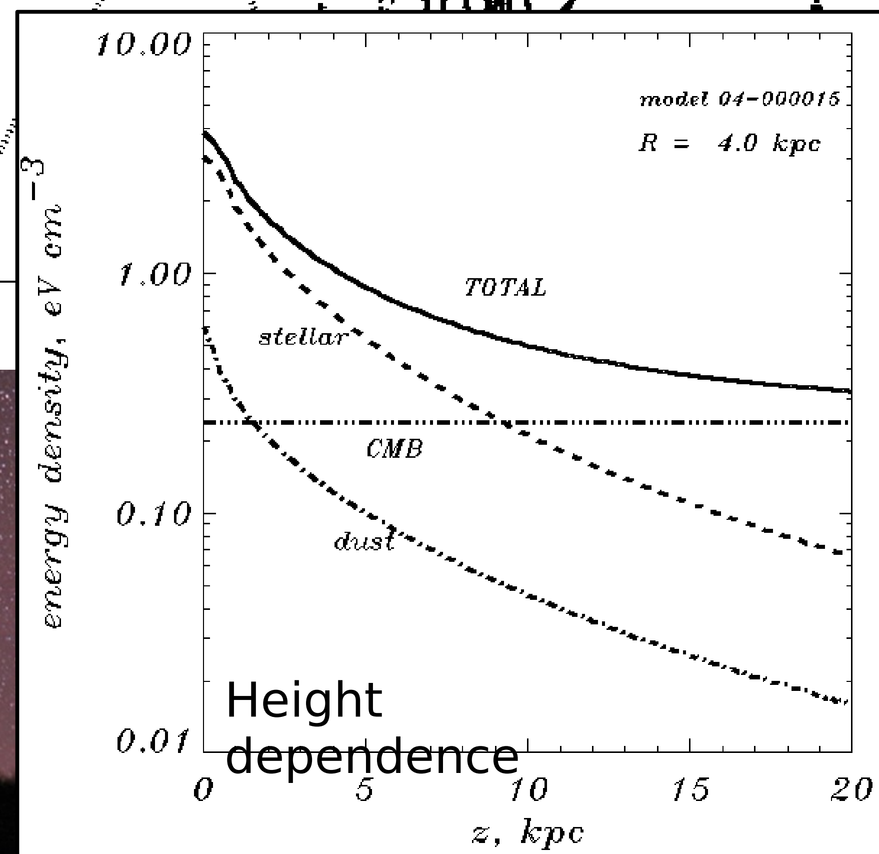
[slides from I. Grenier 2010]

Interstellar radiation field

Strong+ 2000; Porter & Strong 2005; Moskalenko+ 2006; Porter+ 2008

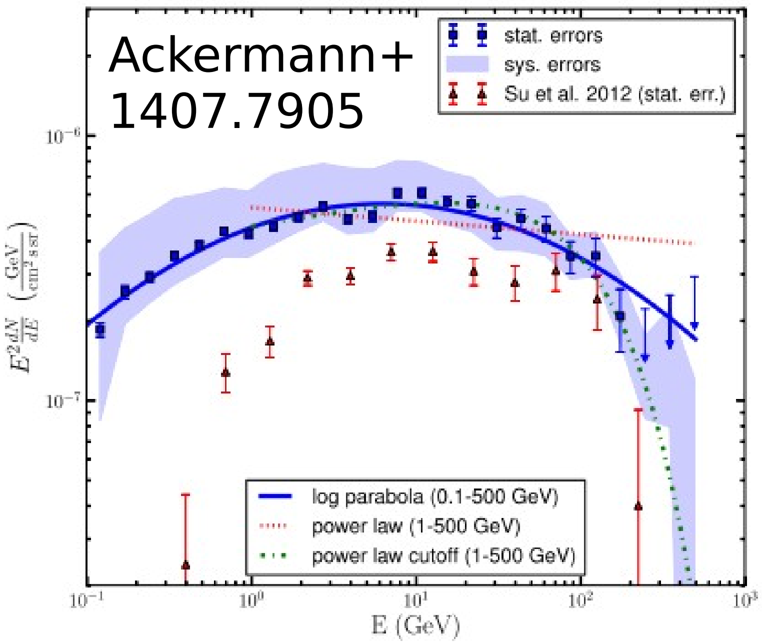




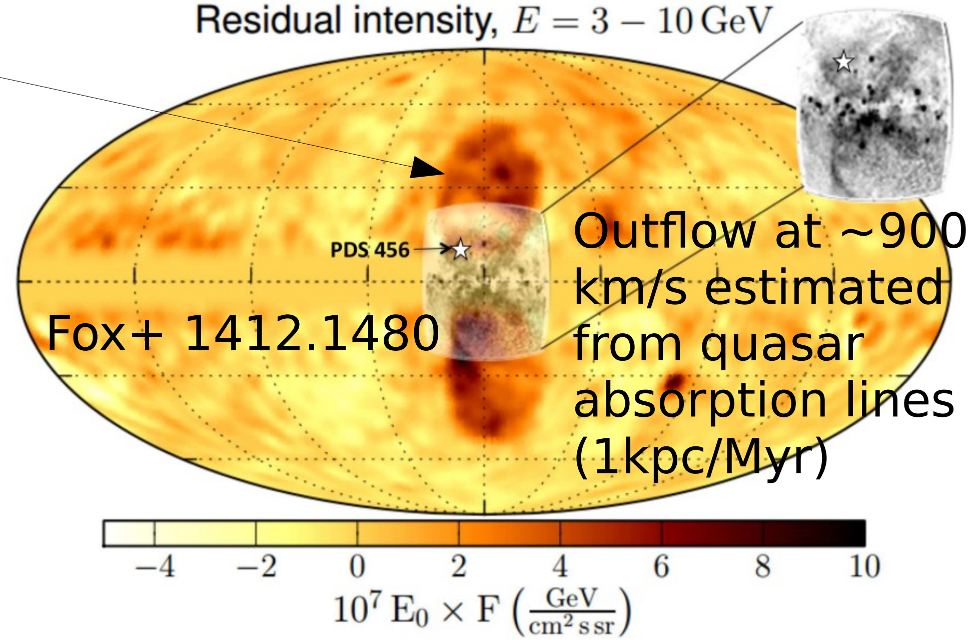


The Fermi Bubbles

Fermi Bubbles
[Su+ 2010; Dobler+ 2010; Ackermann+ 2014]



Ackermann+ 1407.7905



Fox+ 1412.1480

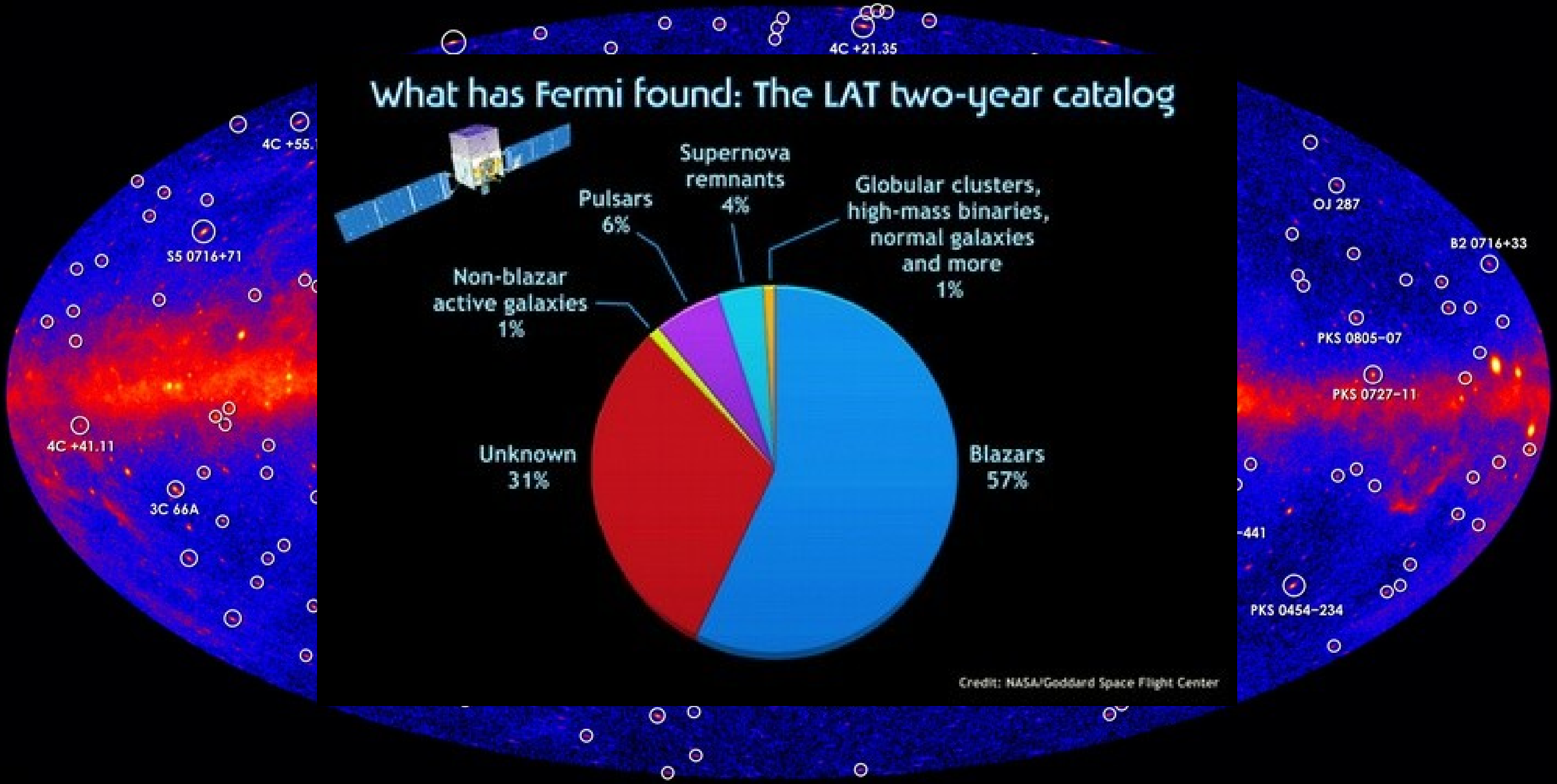
Outflow at ~900 km/s estimated from quasar absorption lines (1kpc/Myr)

Possible explanations

- Jets from the black hole
  [Guo & Mathews 2012, Yang+ 2012]
- Feedback from nuclear star formation
  [Crocker & Aharonian 2011, Carretti+ 2013; Lacki 2014]
- Shocks from accretion flows onto Sgr A*
  [Cheng+ 2011, Mou+ 2014]
- Spherical outflow from Sgr A*
  [Zubovas+ 2011]

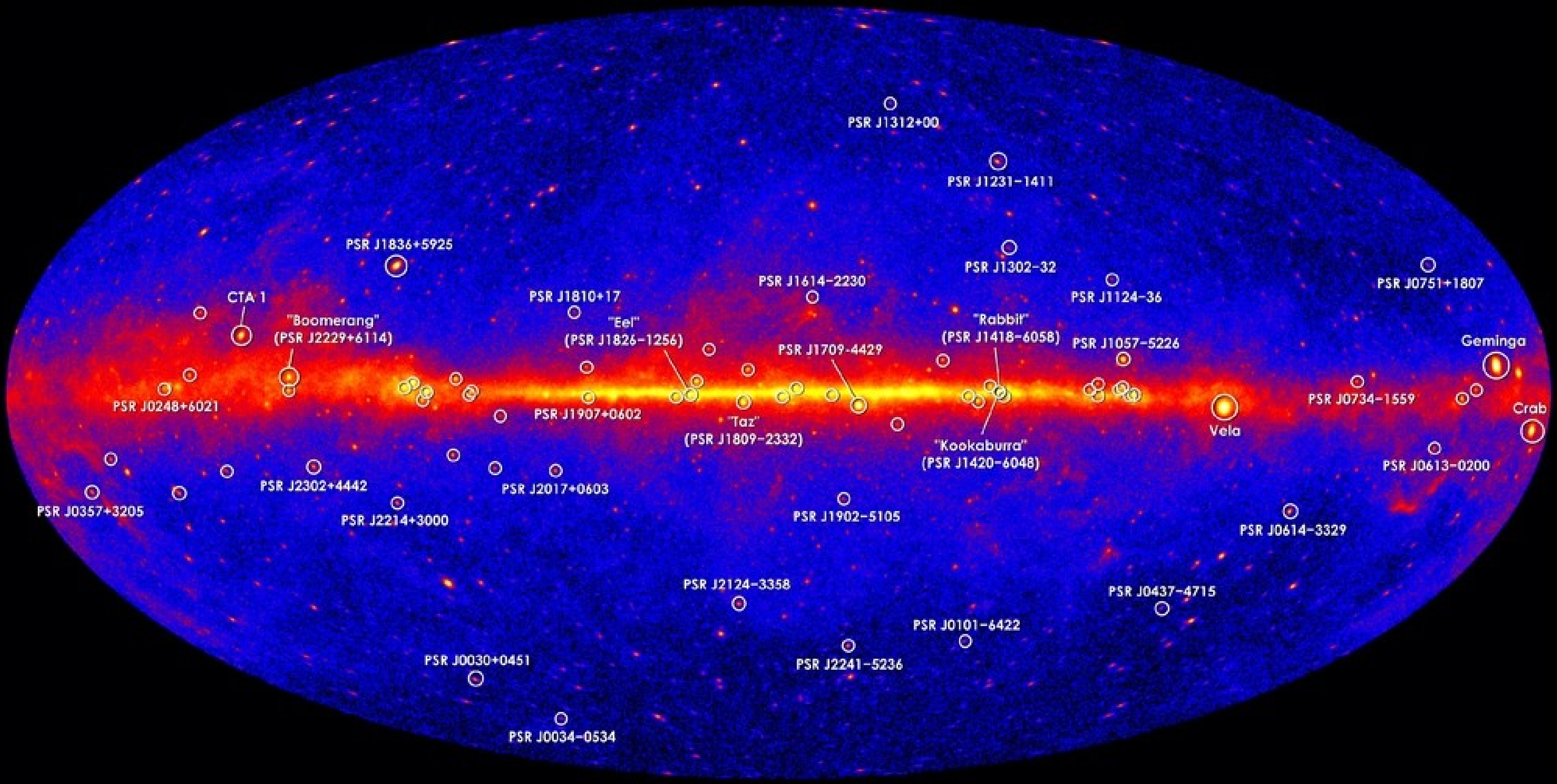
Are modeled with simple template.

Blazars

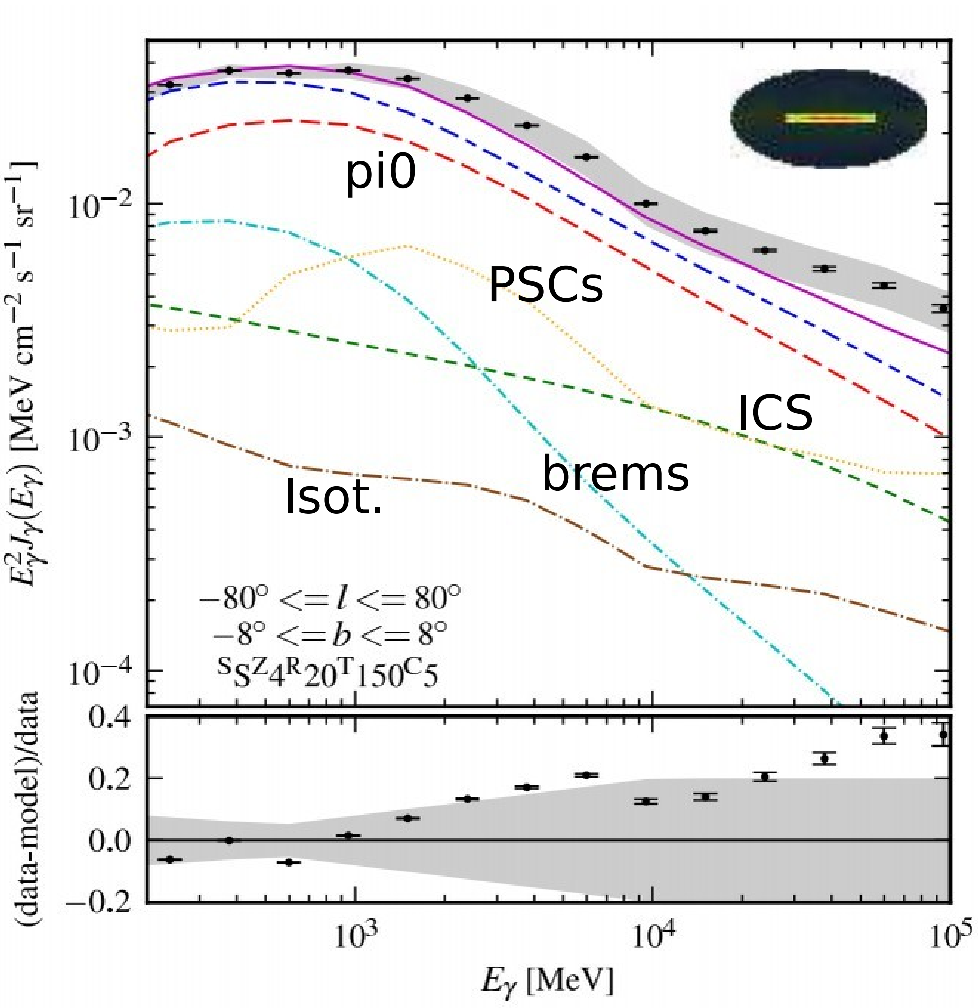


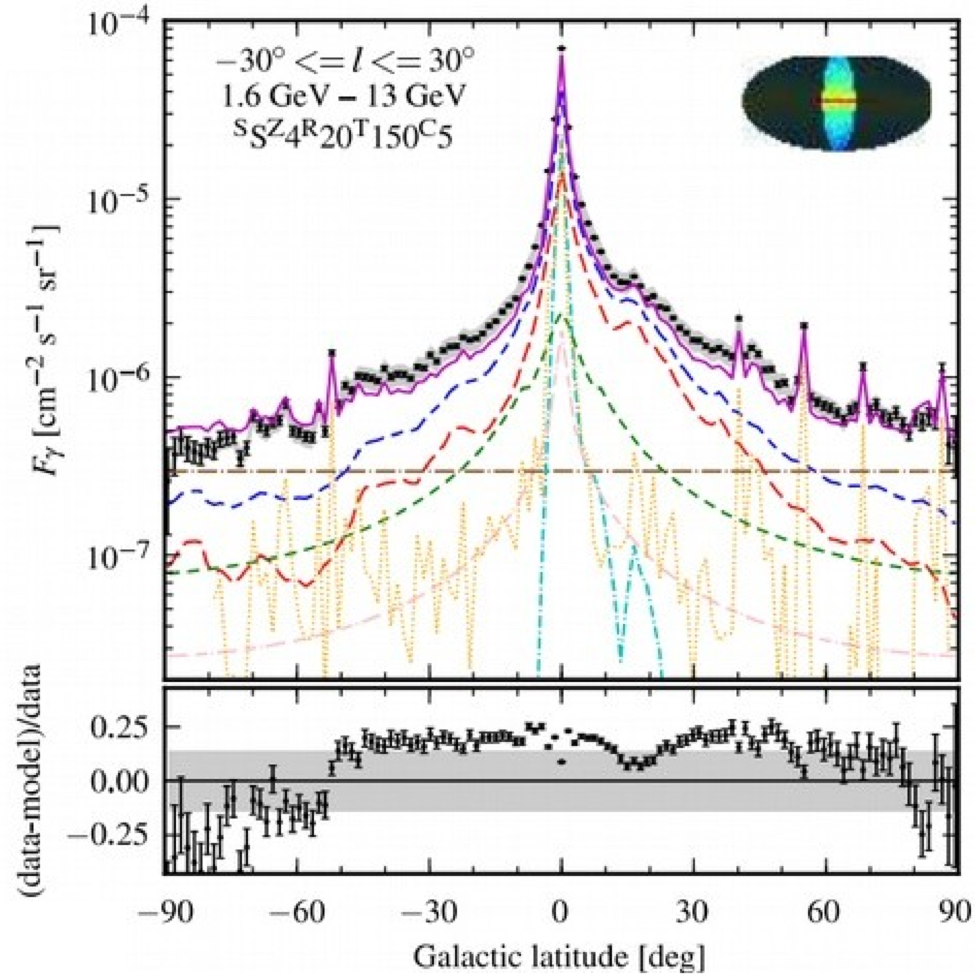
What has Fermi found: The LAT two-year catalog
Supernova remnants 4%
Globular clusters, high-mass binaries, normal galaxies and more 1%
Pulsars 6%
Non-blazar active galaxies 1%
Unknown 31%
Blazars 57%
Credit: NASA/Goddard Space Flight Center
4C +21.35
4C +41.11
S5 0716+71
3C 66A
OJ 287
B2 0716+33
PKS 0805-07
PKS 0727-11
PKS 0454-234

Pulsars


PSR J1312+00
PSR J1231−1411
PSR J1836+5925
PSR J1302−32
PSR J1614−2230
PSR J1124−36
PSR J0751+1807
CTA 1
PSR J1810+17
"Boomerang"
(PSR J2229+6114)
"Eel"
(PSR J1826−1256)
PSR J1709−4429
"Rabbit"
(PSR J1418−6058)
PSR J1057−5226
Geminga
PSR J0248+6021
PSR J1907+0602
"Taz"
(PSR J1809−2332)
PSR J0734−1559
Crab
Vela
"Kookaburra"
(PSR J1420−6048)
PSR J0613−0200
PSR J2302+4442
PSR J2017+0603
PSR J0357+3205
PSR J2214+3000
PSR J1902−5105
PSR J0614−3329
PSR J2124−3358
PSR J0437−4715
PSR J0101−6422
PSR J2241−5236
PSR J0030+0451
PSR J0034−0534

Results spatial and spectral



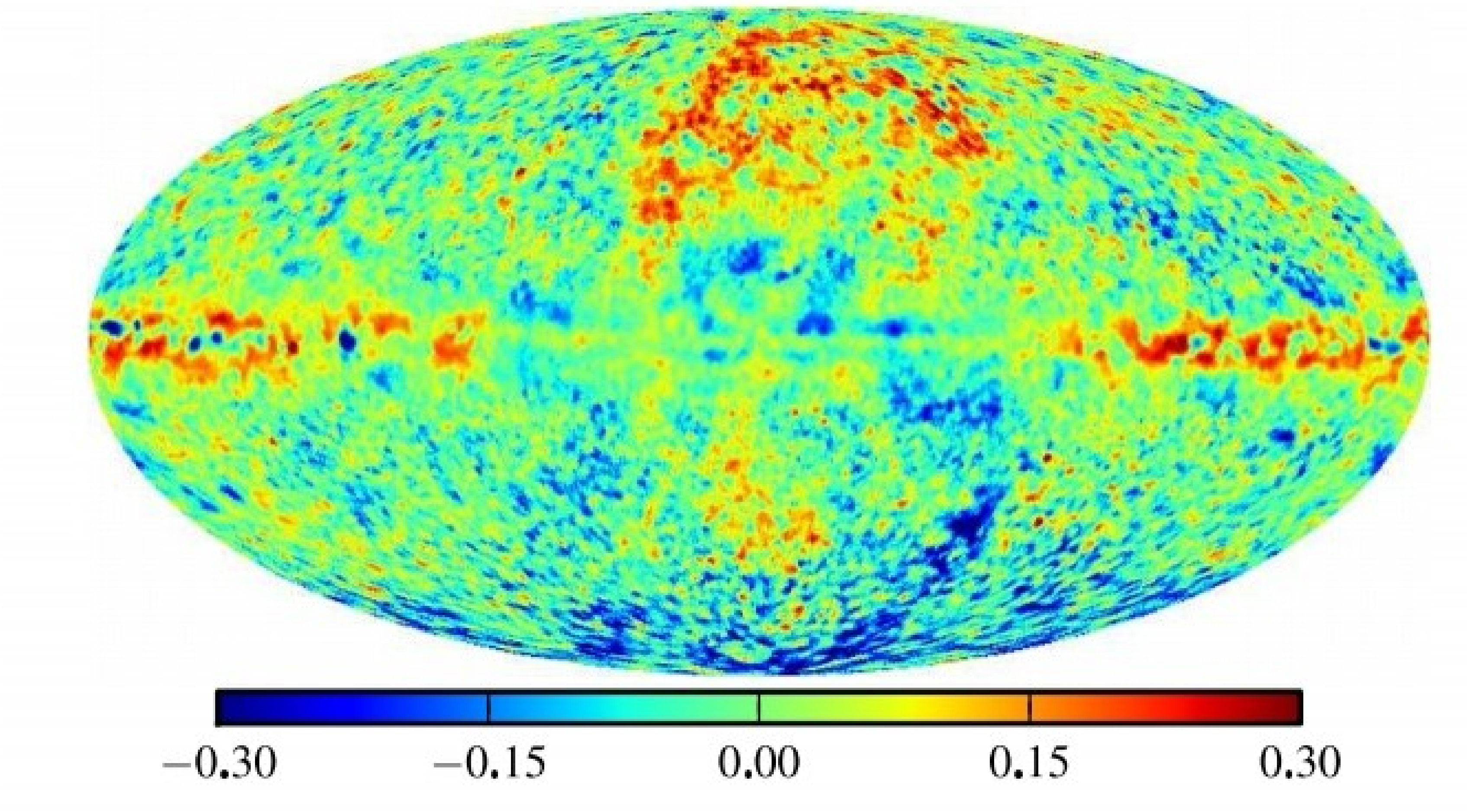


Ackermann+ 2012

General performance of models

- Models that reproduce the local cosmic ray measurements reproduce gamma-ray observations in the Galaxy reasonably well
- Residuals at high energies remain, possibly indicating variations in the diffusion properties towards the inner Galaxy [e.g. Gaggero+ 2014]

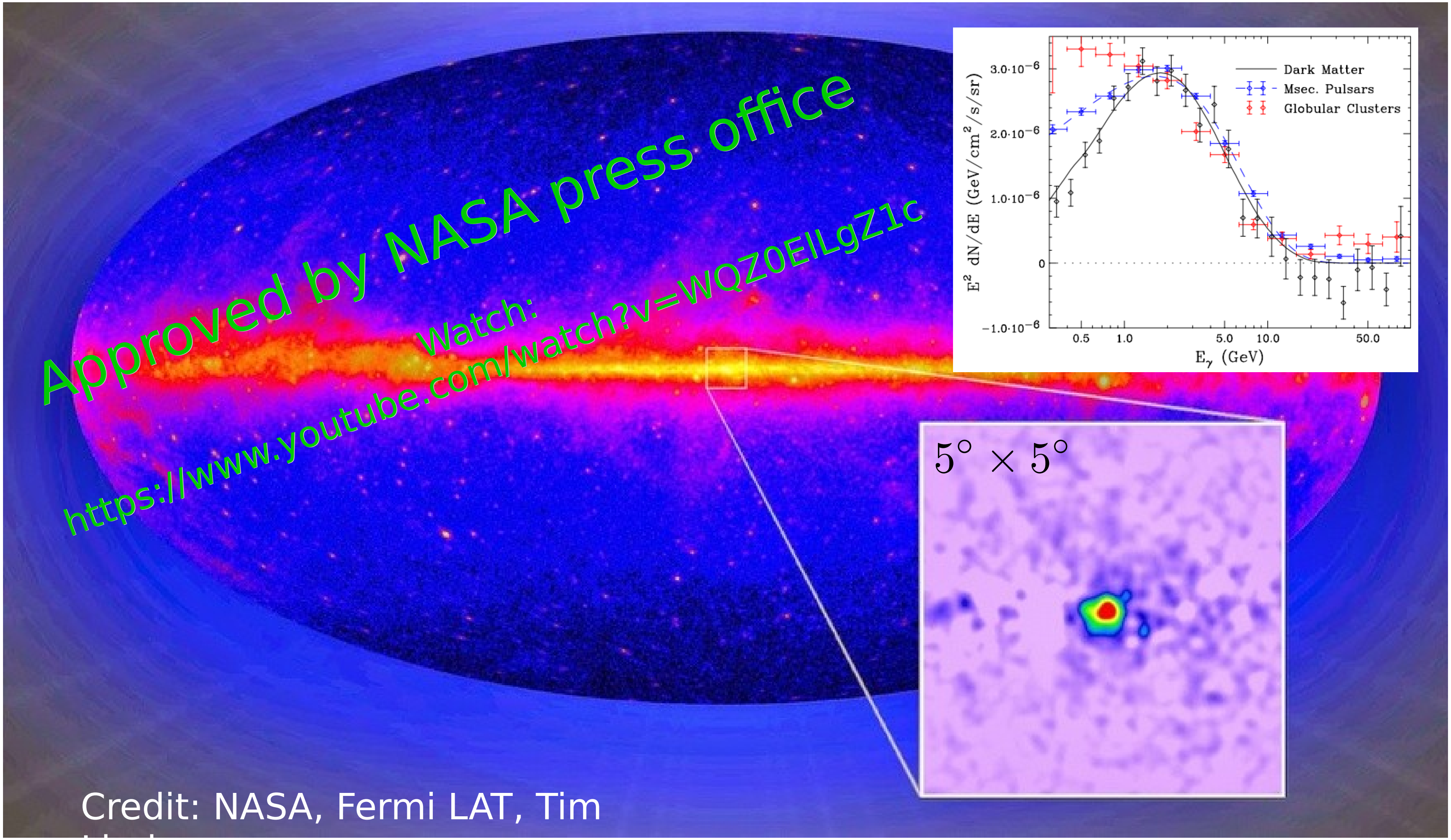
Fractional residuals



(model-data)/data (200 MeV – 100 GeV)

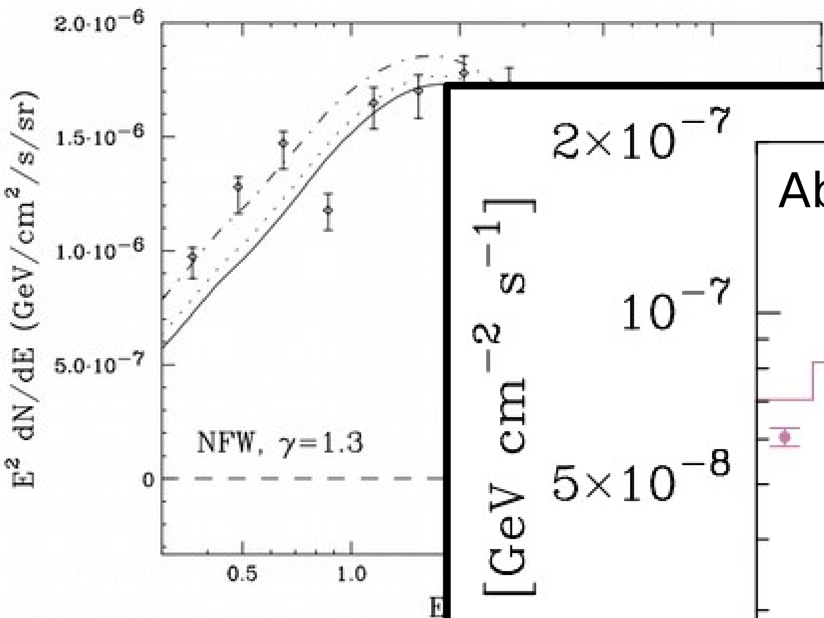
The Fermi GeV excess.

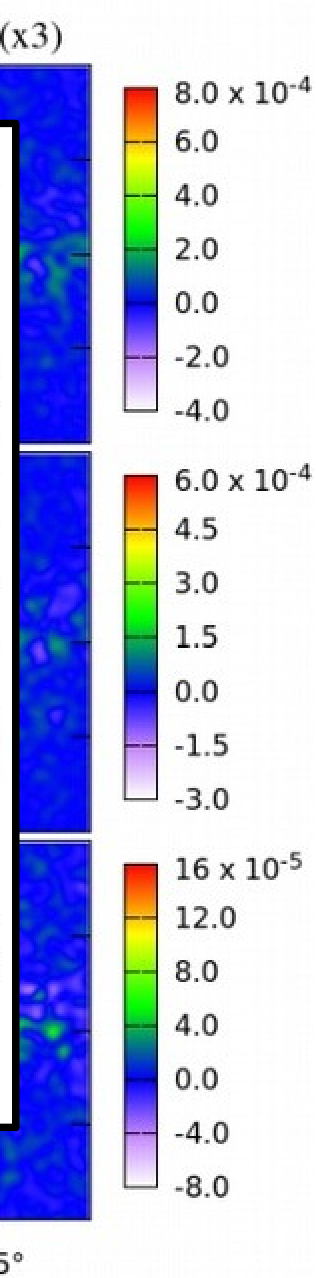
The Fermi Galactic center GeV excess

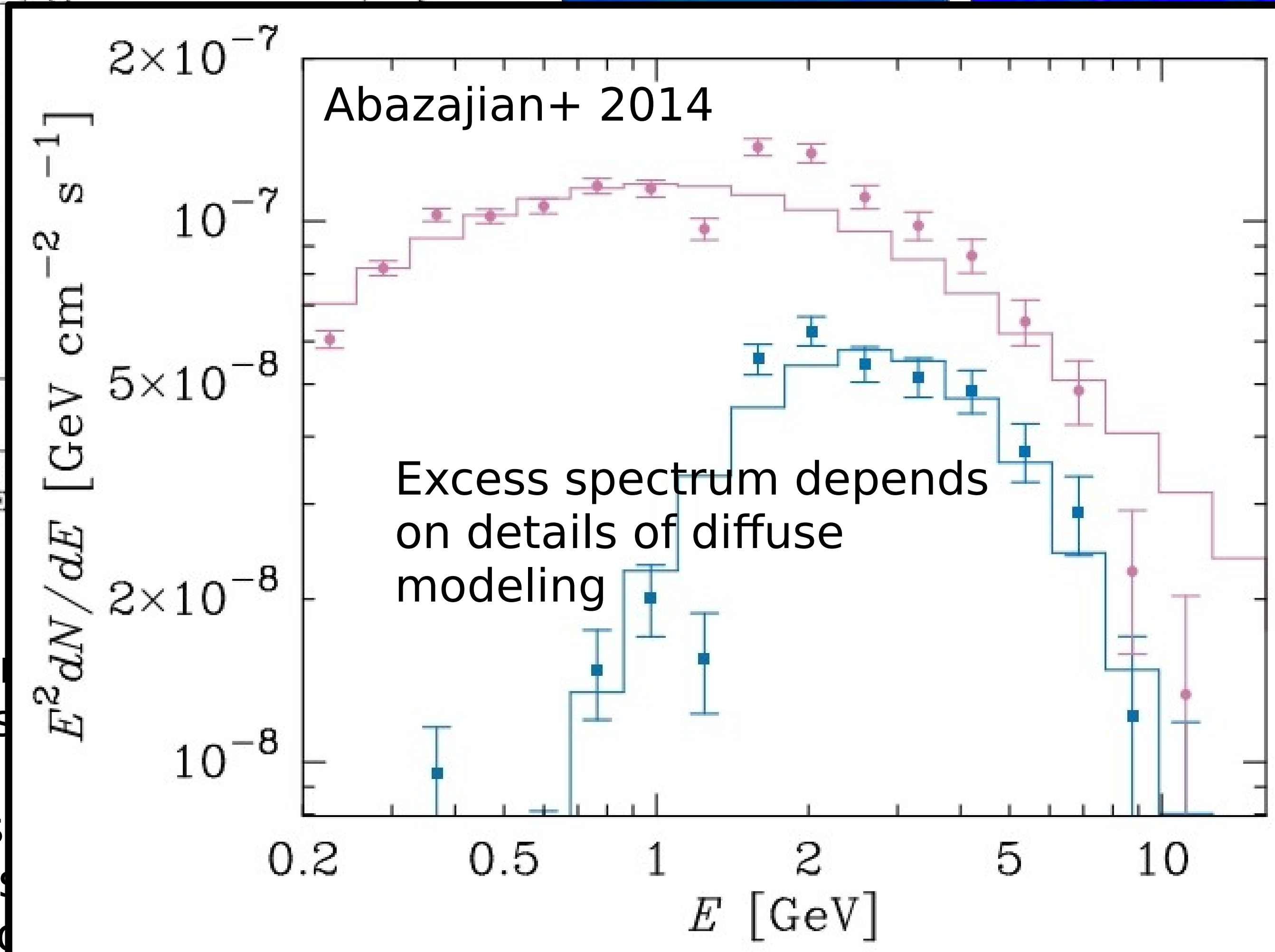


Goodenough & Hooper 2009, Vitale+ (Fermi coll.) 2009, Hooper & Goodenough 2011, Hooper & Linden 2011, Boyarsky+ 2011 (no signal), Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Huang+ 2013, Gordon & Macias 2013, Macias & Gordon 2014, Zhou+ 2014, Abazajian+ 2014, Daylan+2014, Calore+ 2014, Gaggero+ 2015

The Galactic Center







Daylan+ 2014 r

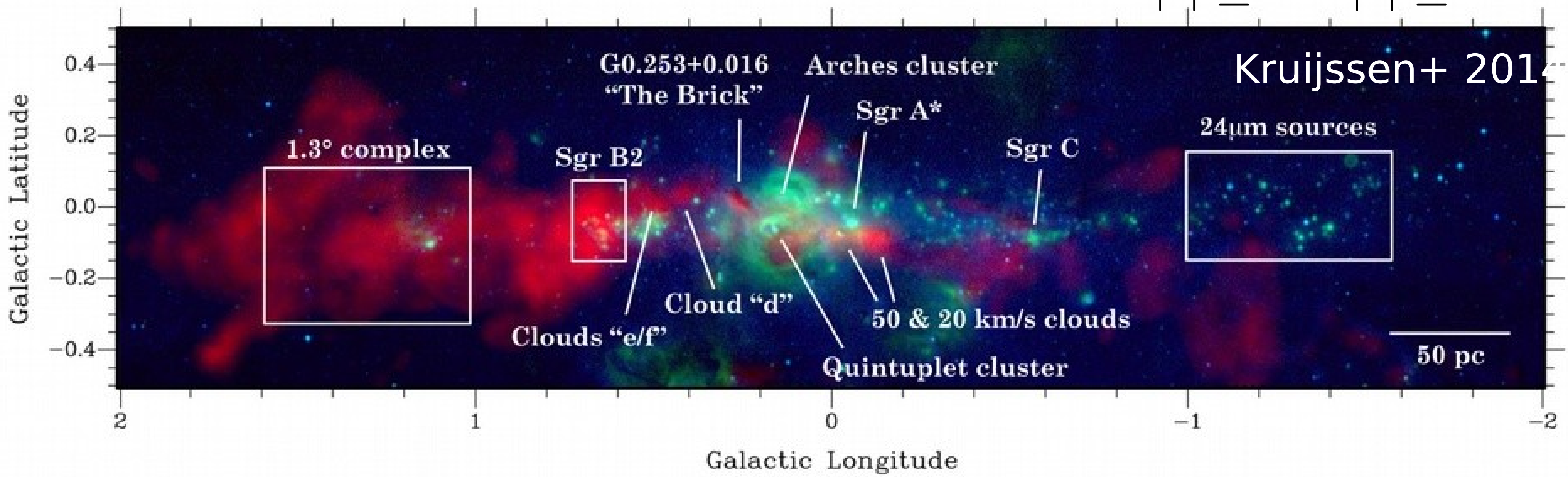
- Extended exces
  above
  - Diffuse emiss
  - Sgr A* Fermi s
  - Other 2FGL sc
- Morphology

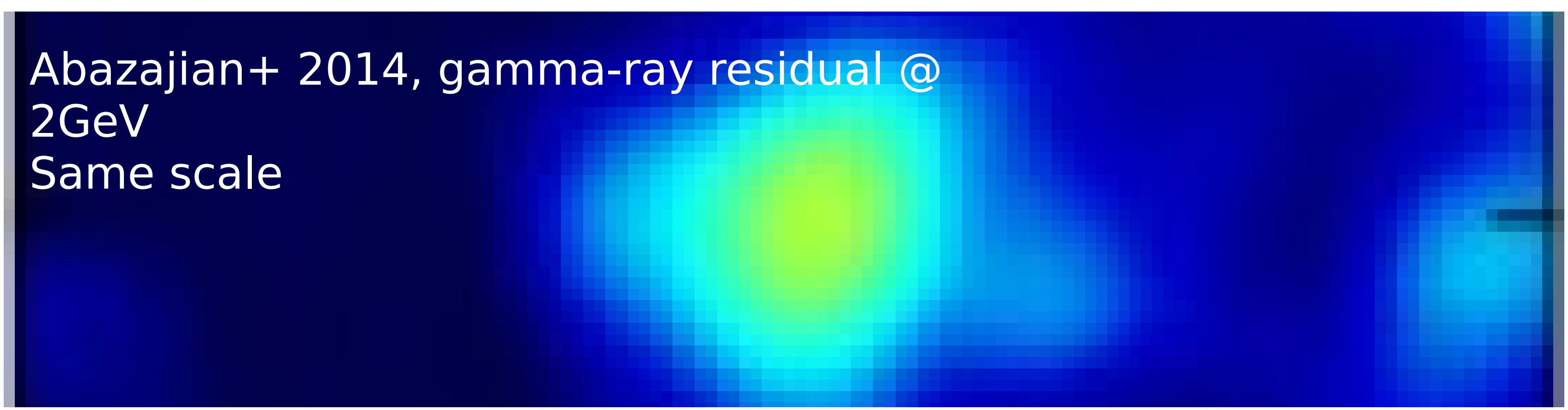
$$\frac{dn}{dV} \sim r^{-\Gamma} \qquad \Gamma \sim 2.5$$

The Galactic Center

- Gas dominated by central molecular zone (CMZ)
- Contains around ~5% of all current star formation and about 10% of all molecular gas
- Gas density x100 that of the Galactic disk

Star forming regions $|\ell| \leq 2^\circ \quad |b| \leq 0.5^\circ$

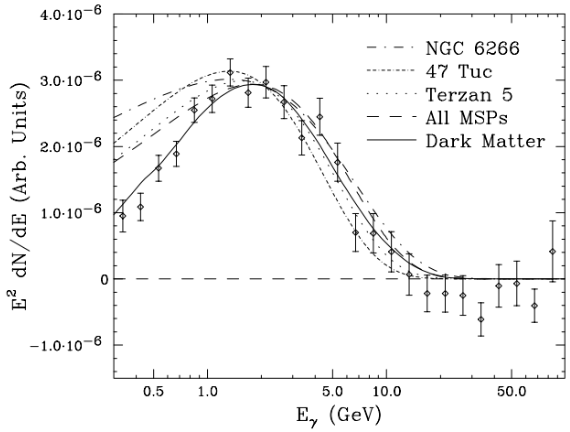




The excess at low and mid-latitudes

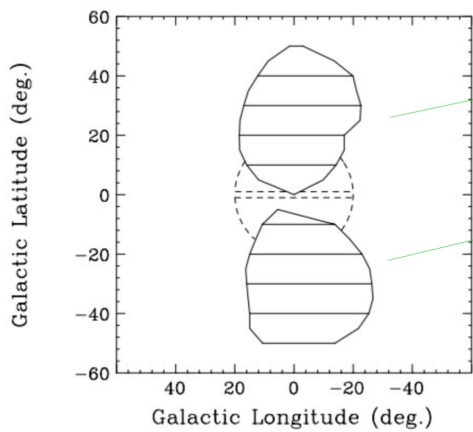
Excess at the Galactic center $|\ell|,|b| \lesssim 2^\circ$

Goodenough & Hooper 2009
Hooper & Goodenough 2011
Hooper & Linden 2011
Boyarsky+ 2011
Abazajian & Kaplinghat 2012
Gordon & Macias 2013
Macias & Gordon 2014
Abazajian+ 2014
Daylan+2014

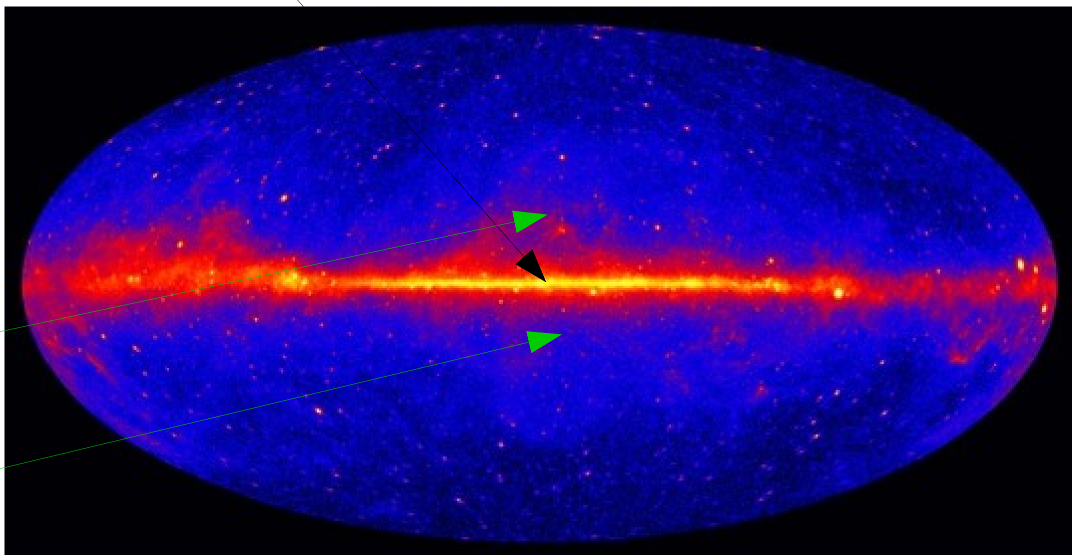


Excess at mid-latitudes (as expected for an extended DM signal)

Hooper & Slatyer 2013
Huang+ 2013
Zhou+ 2014
Daylan+ 2014

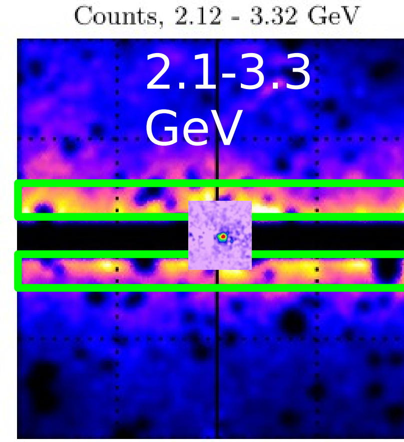


[Hooper & Slatyer 2013]



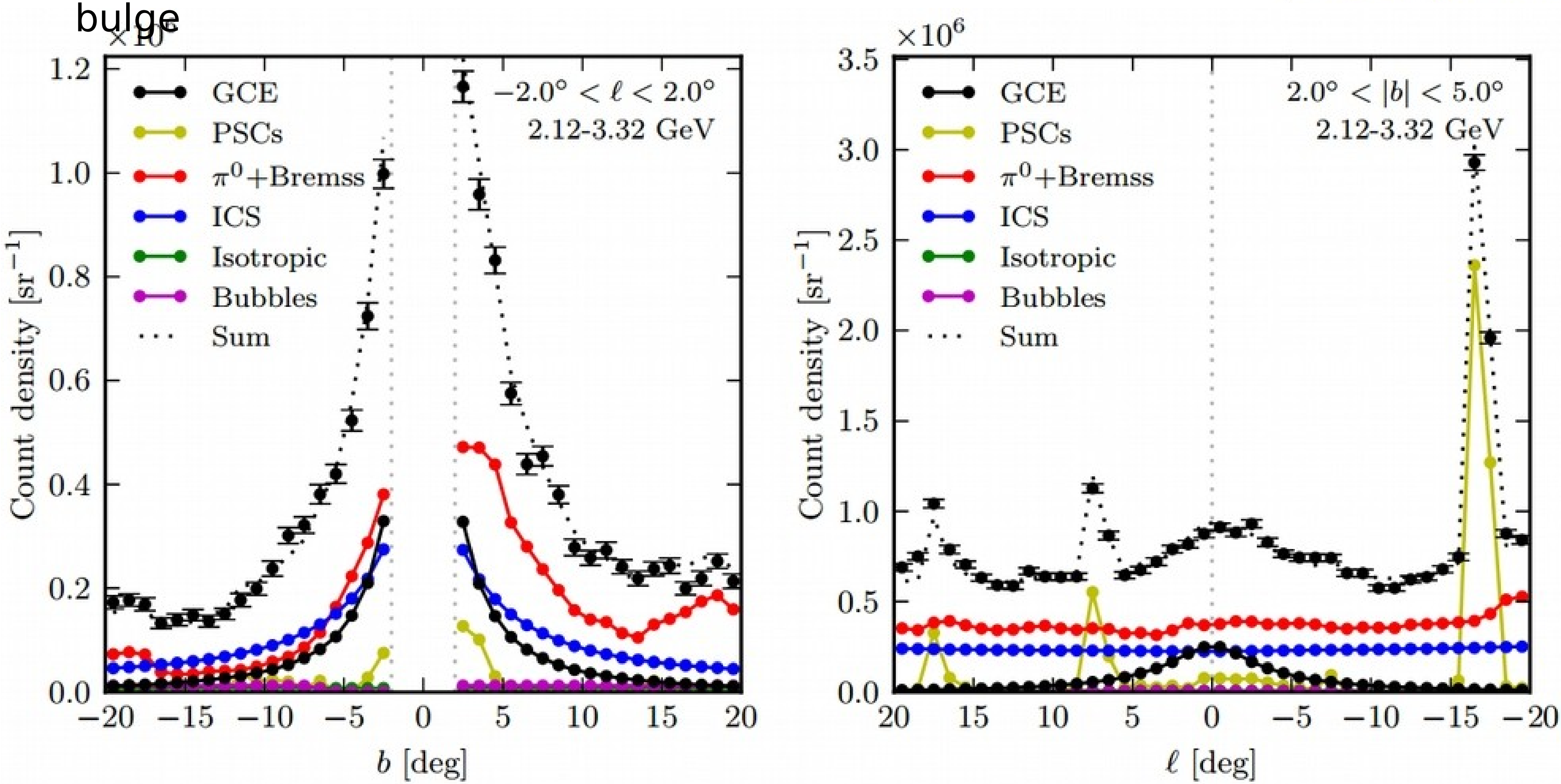
$|\ell| \lesssim 20^\circ, \quad 2^\circ \lesssim |b| \lesssim 2^\circ$

Fluxes at low latitudes



Calore, Cholis, CW 2014

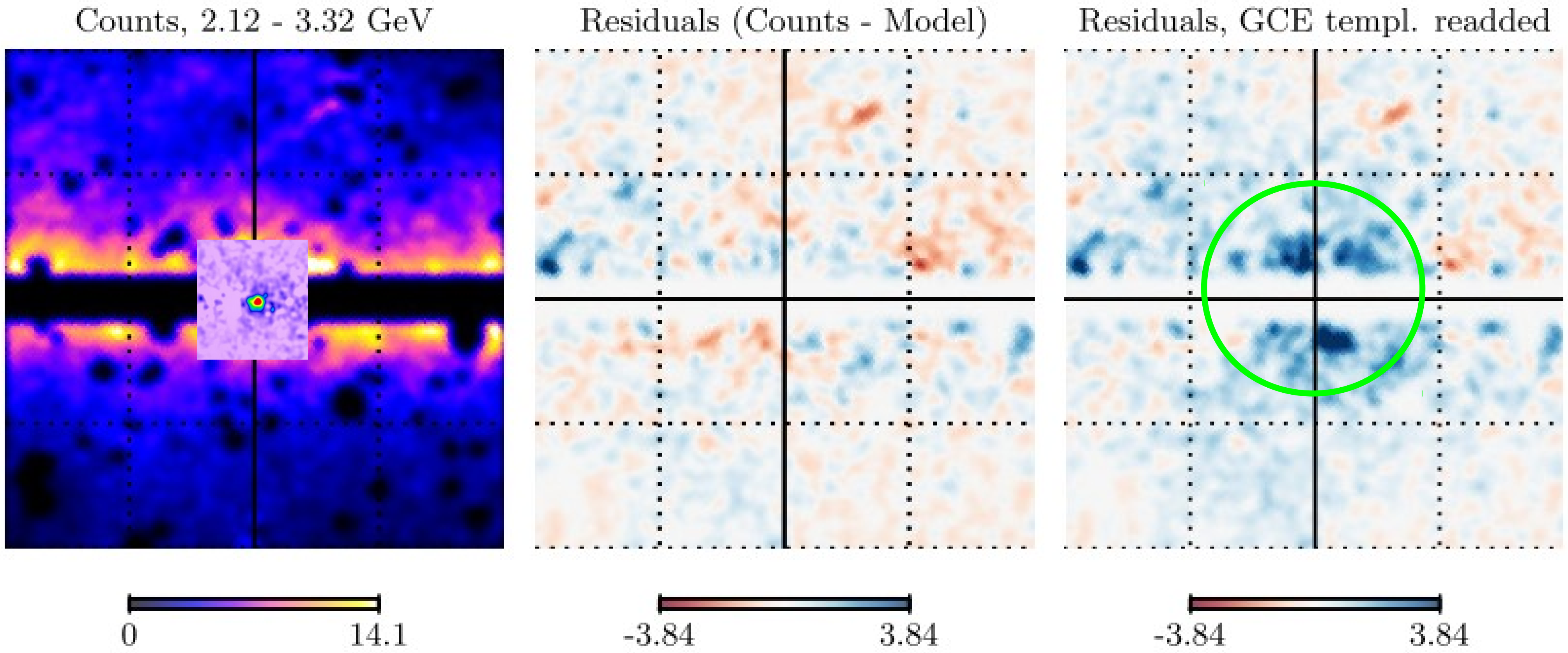
- Reanalysis of "inner Galaxy" ROI
- We allow for extreme variations in ISRF, magnetic field, diffusion properties
- The "excess" is relatively robust w.r.t. all variations
  → Seems to be genuine emission from the Galactic bulge



Typical residuals after foreground subtraction

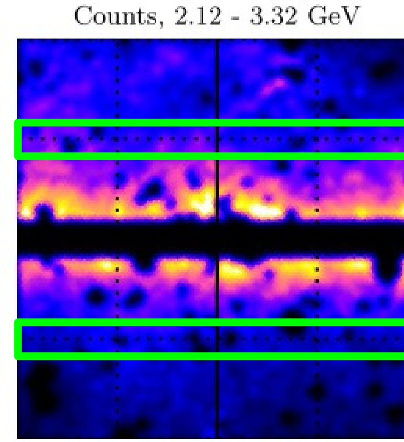
Calore, Cholis, CW 2014

40 deg x 40 deg

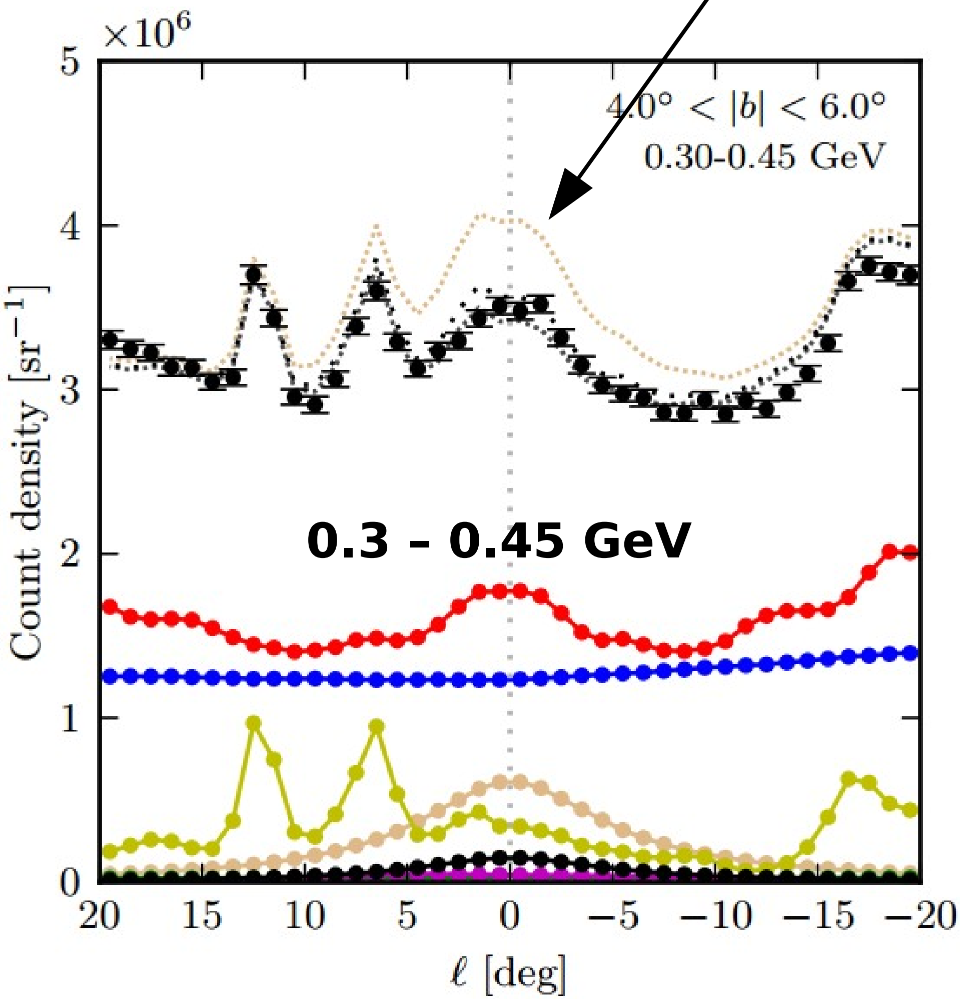


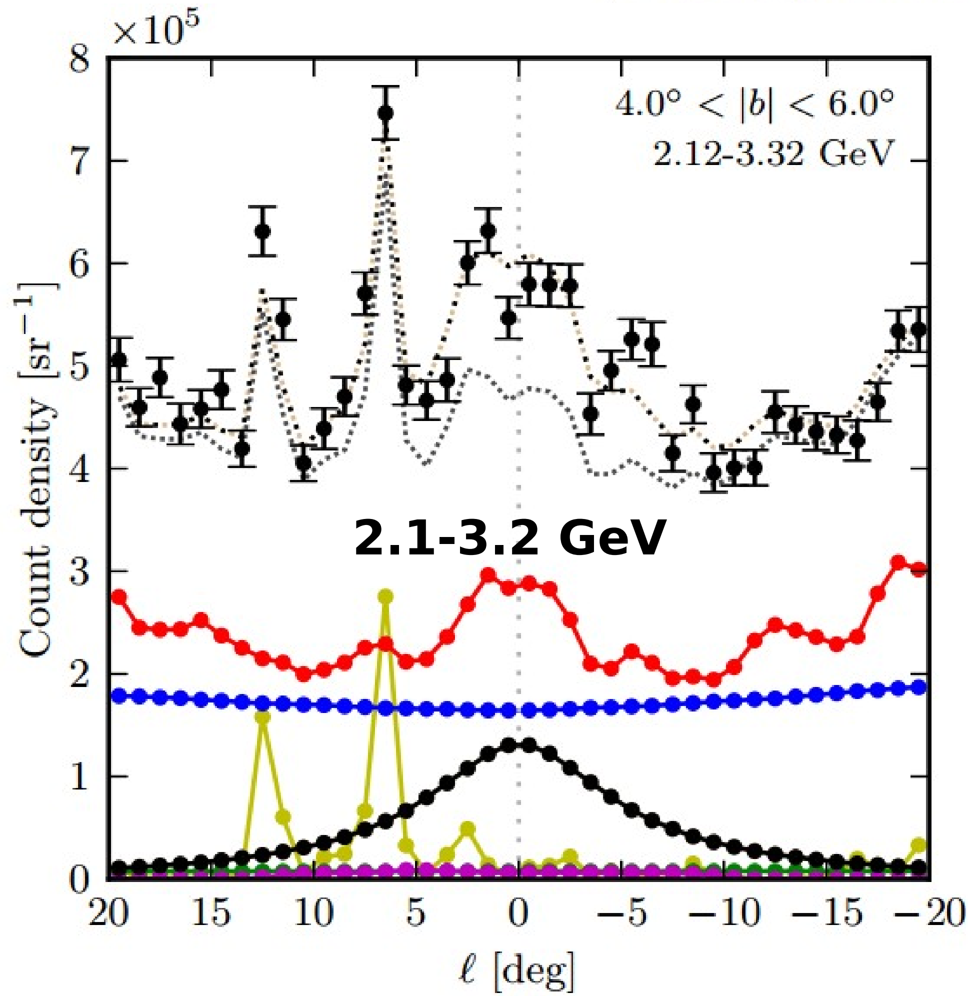
- Left: Point source mask clearly visible
- Middle: Residuals at the level of <20% are observed
- Right: Re-adding the DM template clearly shows an extended excess around the GC

Fluxes at mid-latitudes



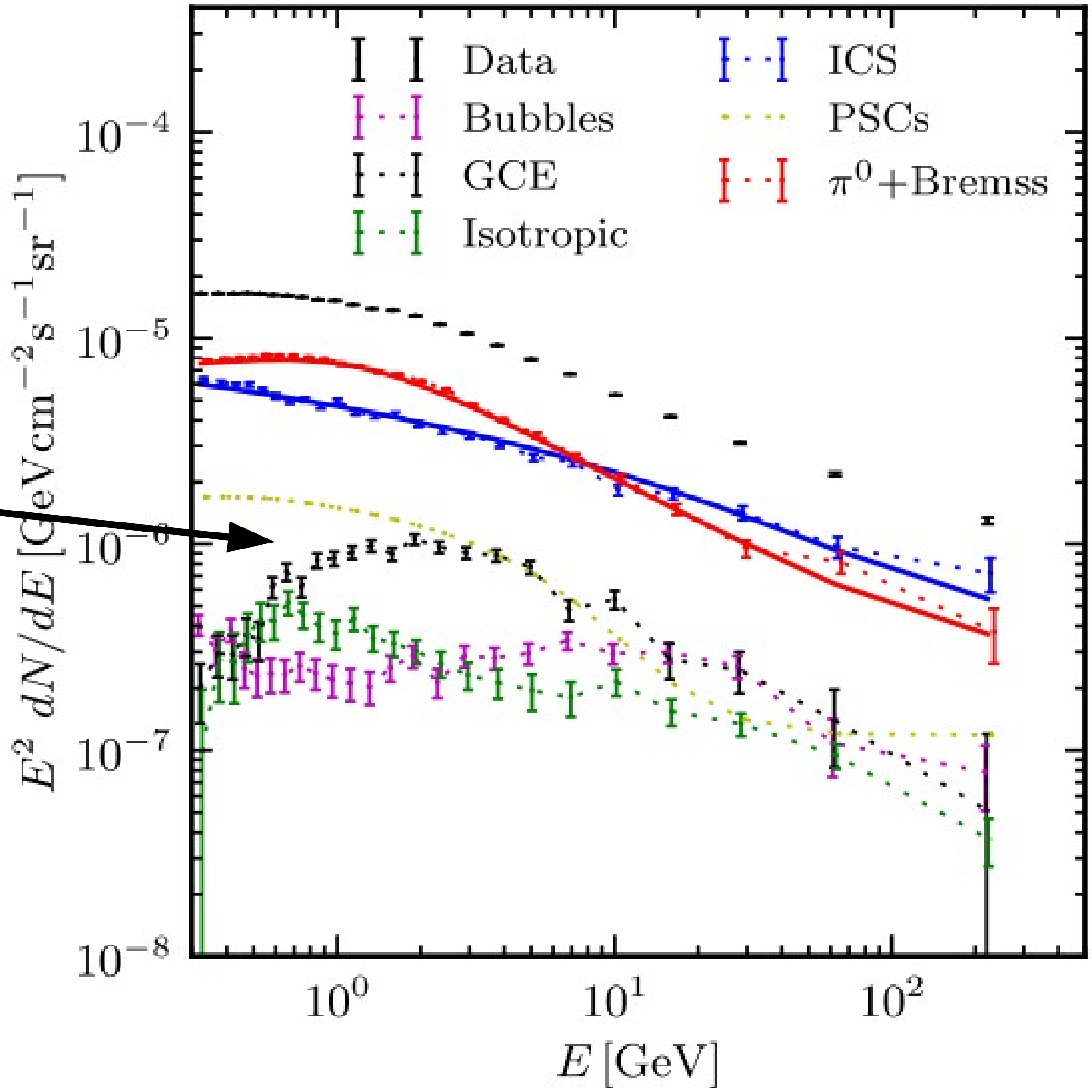
Extrapolation for $\frac{dN}{dE} \propto E^{-2}$





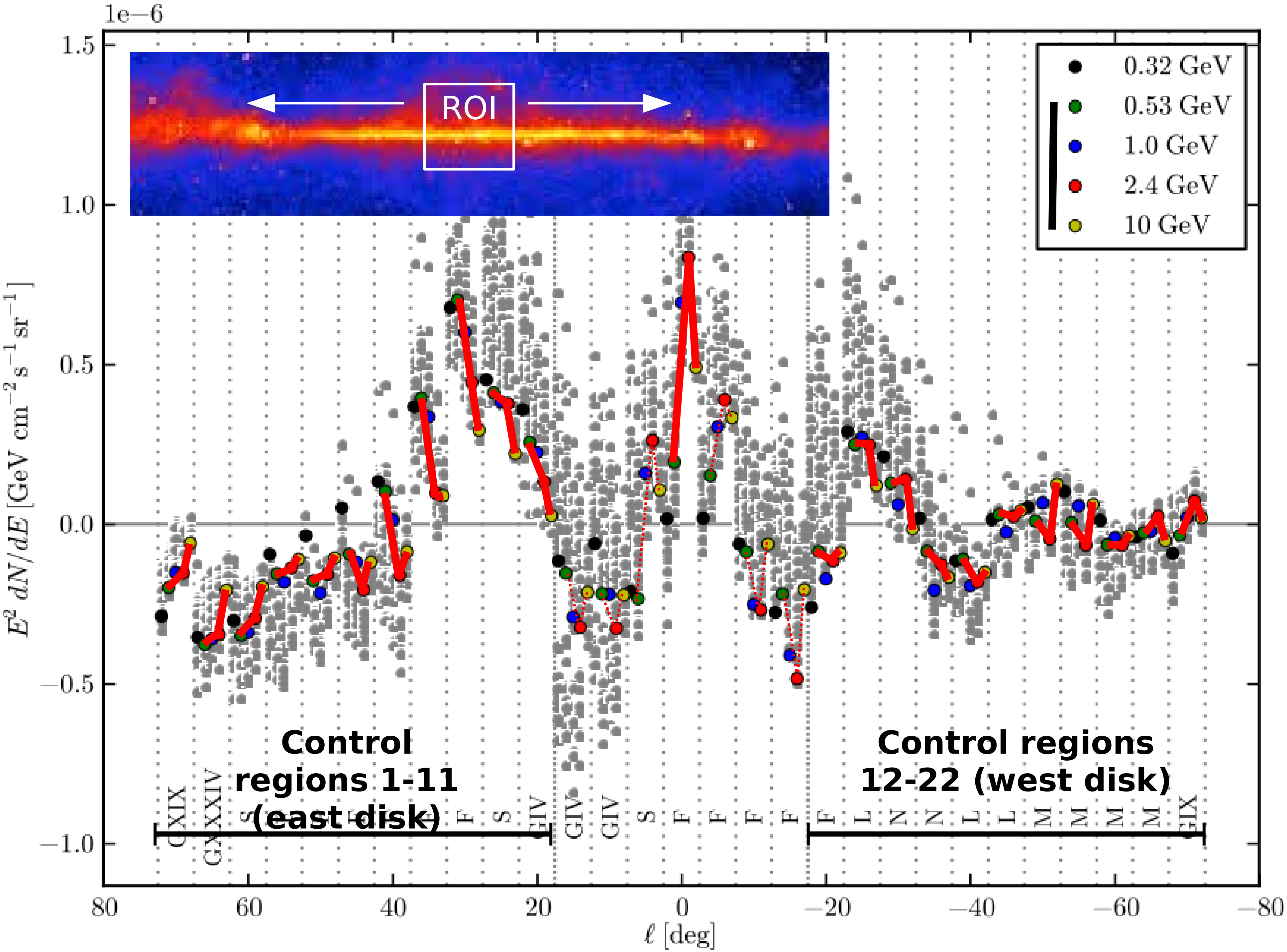
Component spectra

$$\left.\frac{dN}{dE}\right|_{\text{meas. res.}}$$

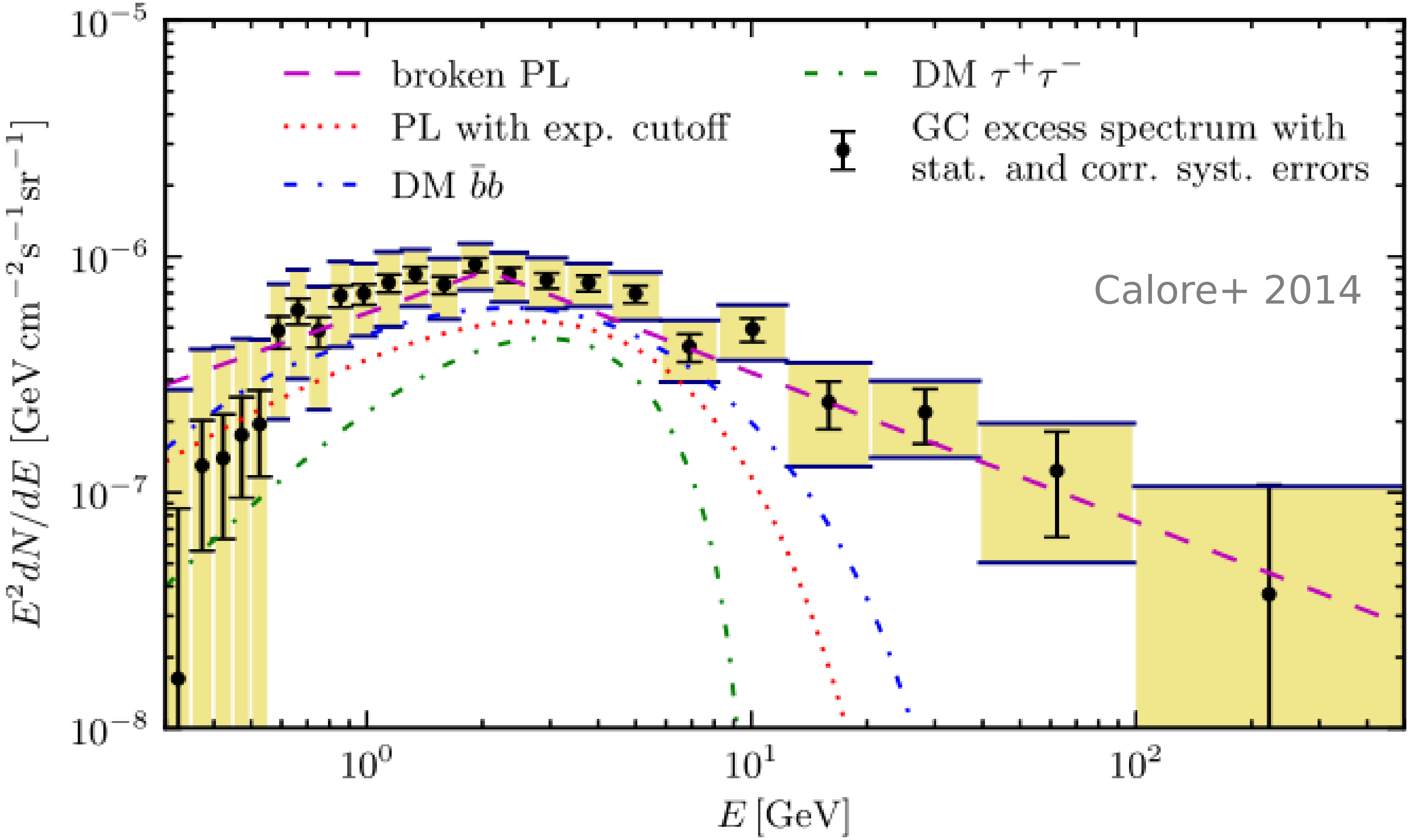


$$\left.\frac{dN}{dE}\right|_{\text{real}} = \frac{dN}{dE}_{\text{meas. res.}} + \delta\left.\frac{dN}{dE}\right|_{\pi_0} + \delta\left.\frac{dN}{dE}\right|_{ICS} + \delta\left.\frac{dN}{dE}\right|_{rest}$$

Excess spectra in control regions

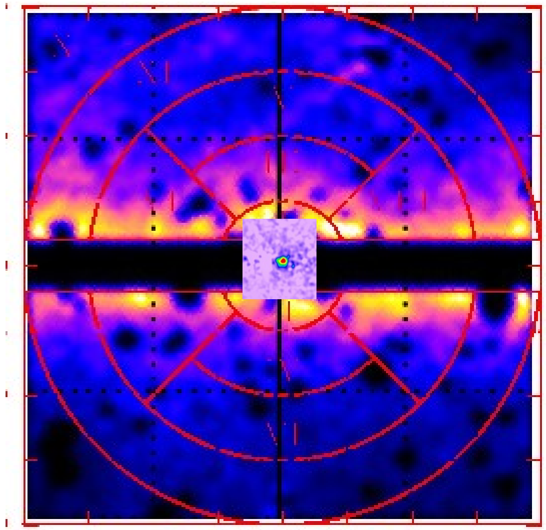


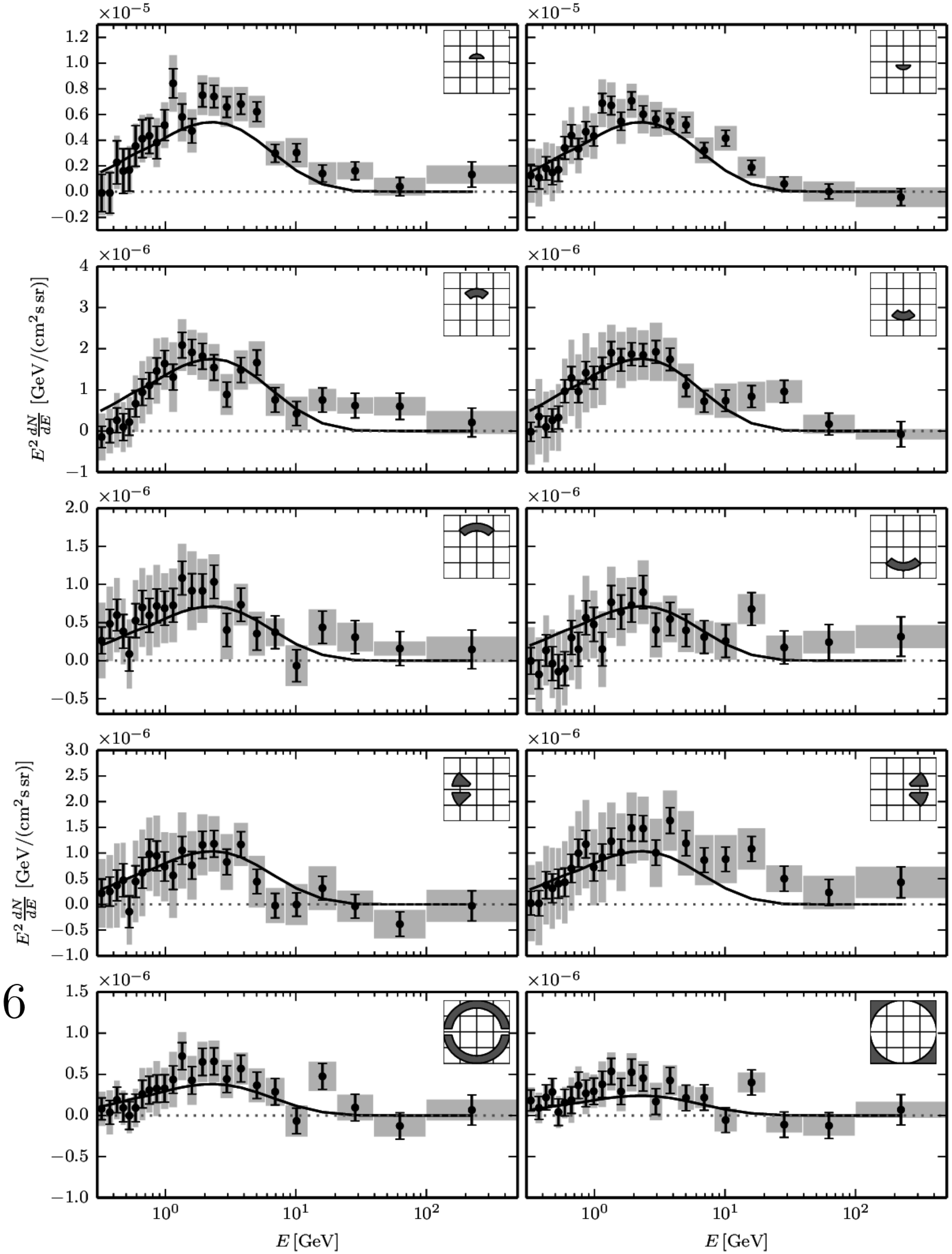
Low/high energy tails of spectrum very uncertain



Spectrum	Parameters	χ^2/dof	p-value
broken PL	$\alpha_1 = 1.42^{+0.22}_{-0.31}$, $\alpha_2 = 2.63^{+0.13}_{-0.095}$, $E_{\text{break}} = 2.06^{+0.23}_{-0.17}$ GeV	1.06	0.47
DM $\chi\chi \to \bar{b}b$	$\langle\sigma v\rangle = 1.76^{+0.28}_{-0.27} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 49^{+6.4}_{-5.4}$ GeV	1.08	0.43
DM $\chi\chi \to \bar{c}c$	$\langle\sigma v\rangle = 1.25^{+0.2}_{-0.18} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 38.2^{+4.6}_{-3.9}$ GeV	1.07	0.44
PL with exp. cutoff	$E_{\text{cut}} = 2.53^{+1.1}_{-0.77}$ GeV, $\alpha = 0.945^{+0.36}_{-0.5}$	1.37	0.16
DM $\chi\chi \to \tau^+\tau^-$	$\langle\sigma v\rangle = 0.337^{+0.047}_{-0.048} \times 10^{-26}$ cm^3 s^{-1}, $m_\chi = 9.96^{+1.1}_{-0.91}$ GeV	1.52	0.065

Spatial distribution of excess emission





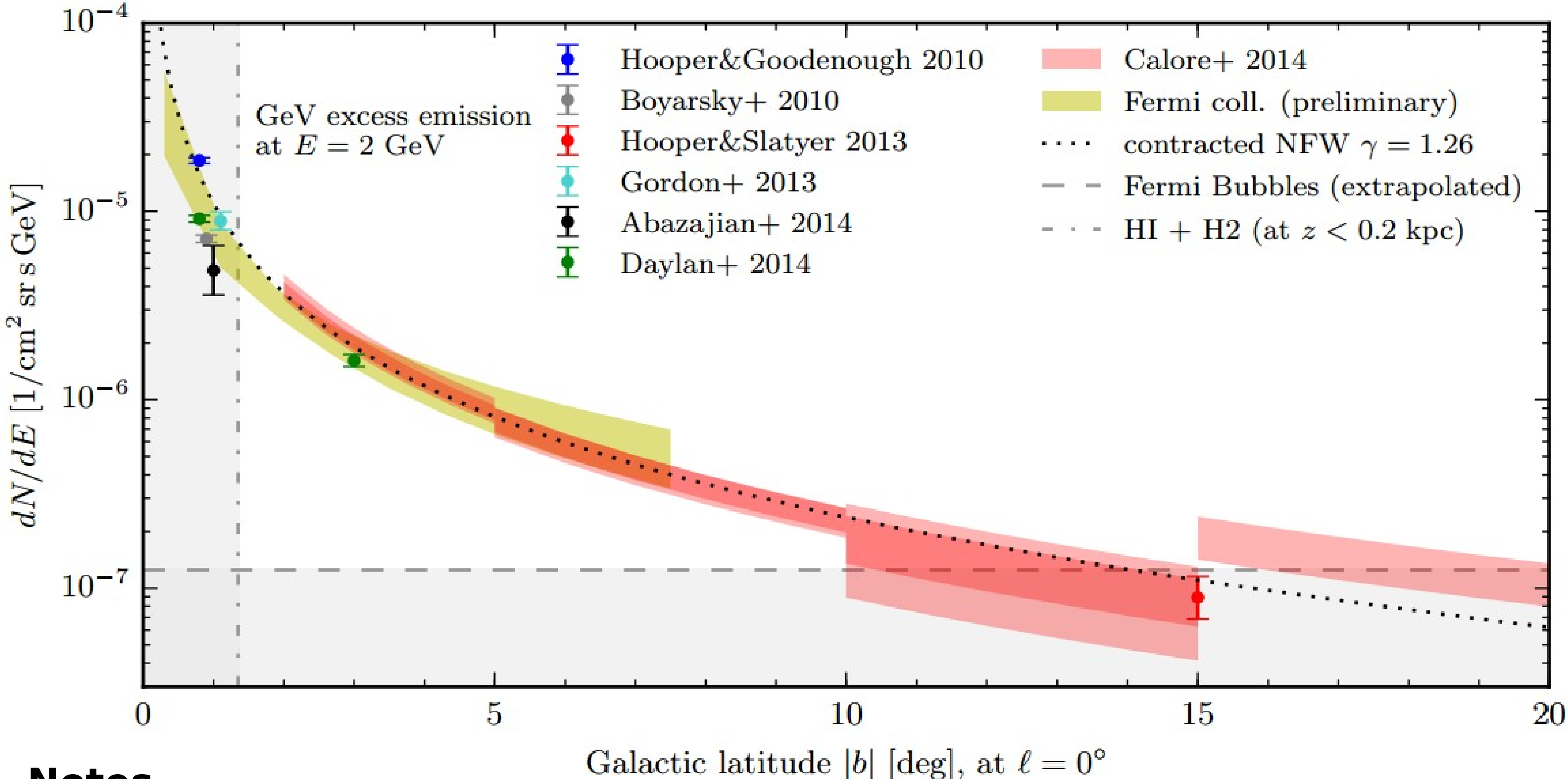
Can be fit with a contracted NFW profile and DM annihilation into b-quarks, for DM masses around 50 GeV

$$\rho_{\rm DM} = \frac{1}{r^\gamma (r_s + r)^{2-\gamma}} \qquad \gamma \simeq 1.26$$

(based on Calore+ 2014)

INTERLUDE

Summary



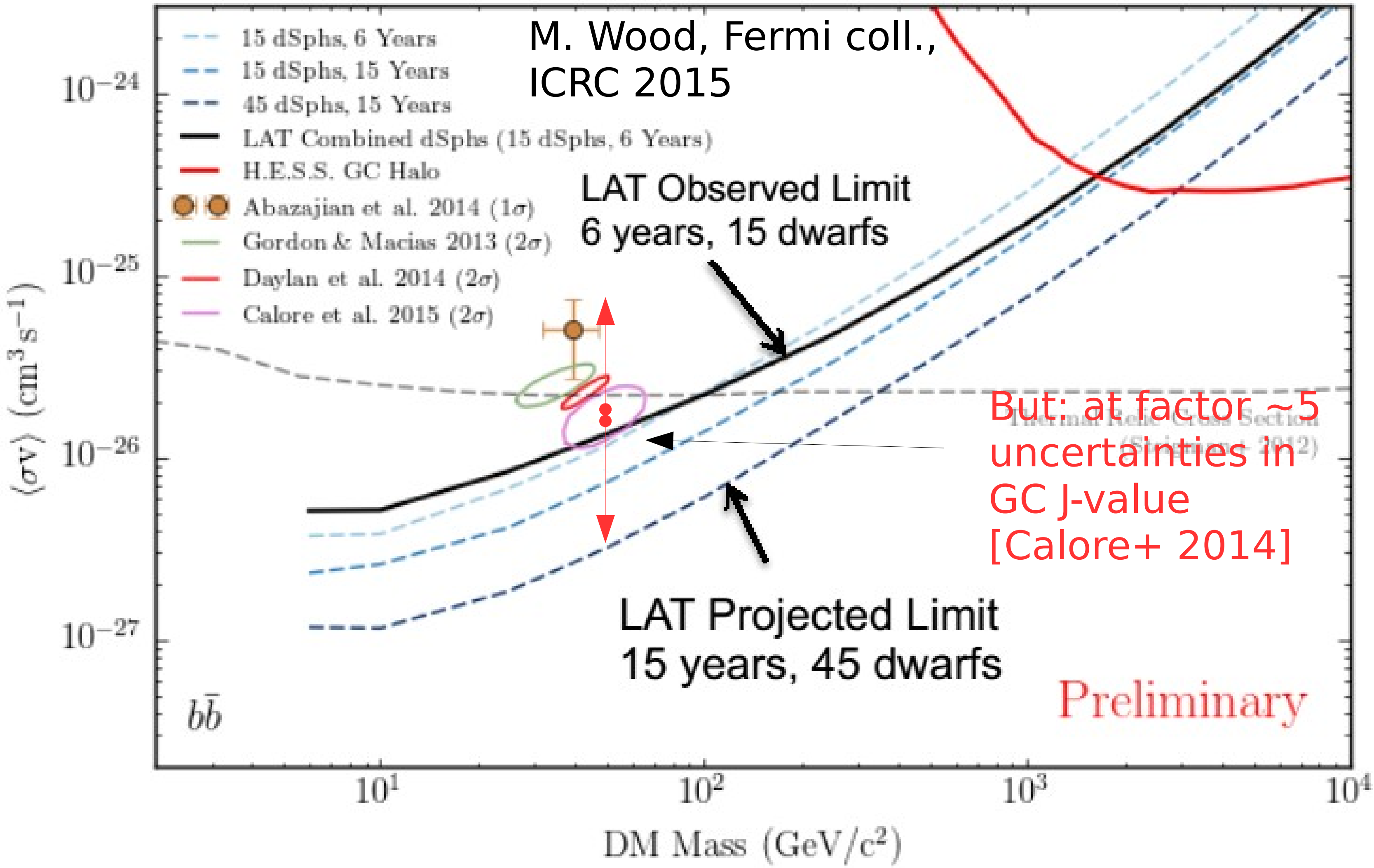
Notes

- What we call “excess” is most likely the gamma-ray emission from the Galactic bulge
  (this component is not included or modeled in most of the diffuse emission models)
- The emission is compatible with a uniform energy spectrum and spherically symmetric volume emissivity following an inverse power-law

$E_{\mathrm{peak}} \sim 2$ GeV $\quad \dfrac{dn}{dV} \propto r^{-2.5}$

Dark matter annihilation?

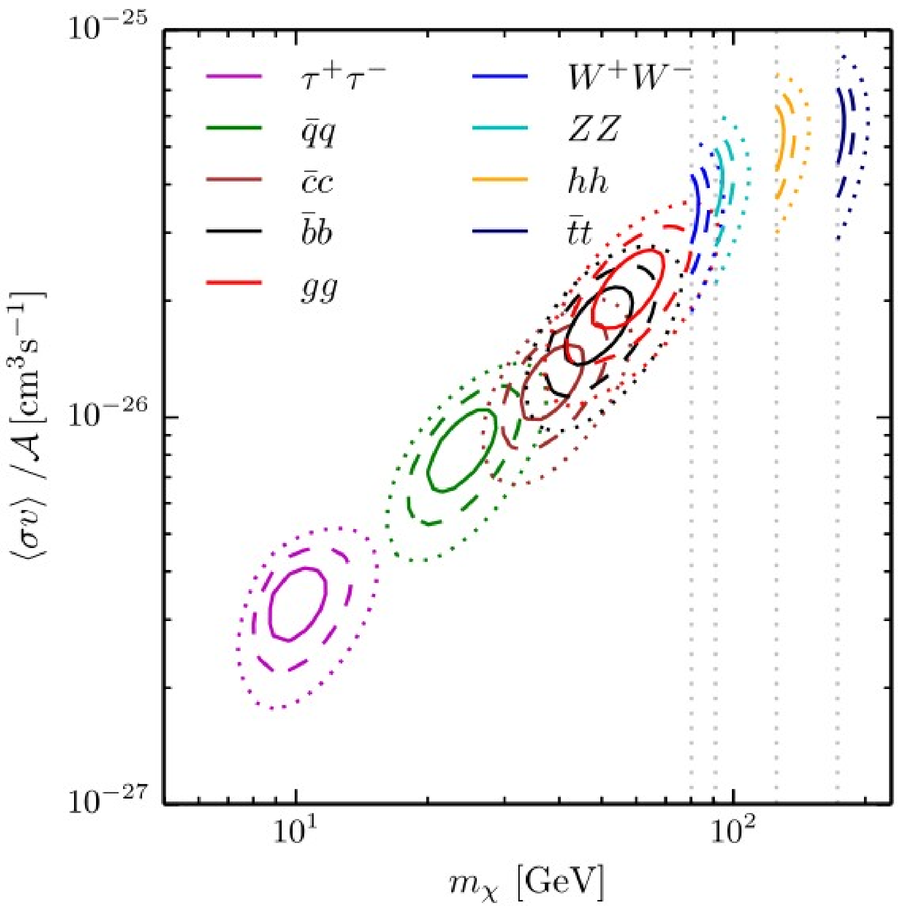
Comparison and future predictions



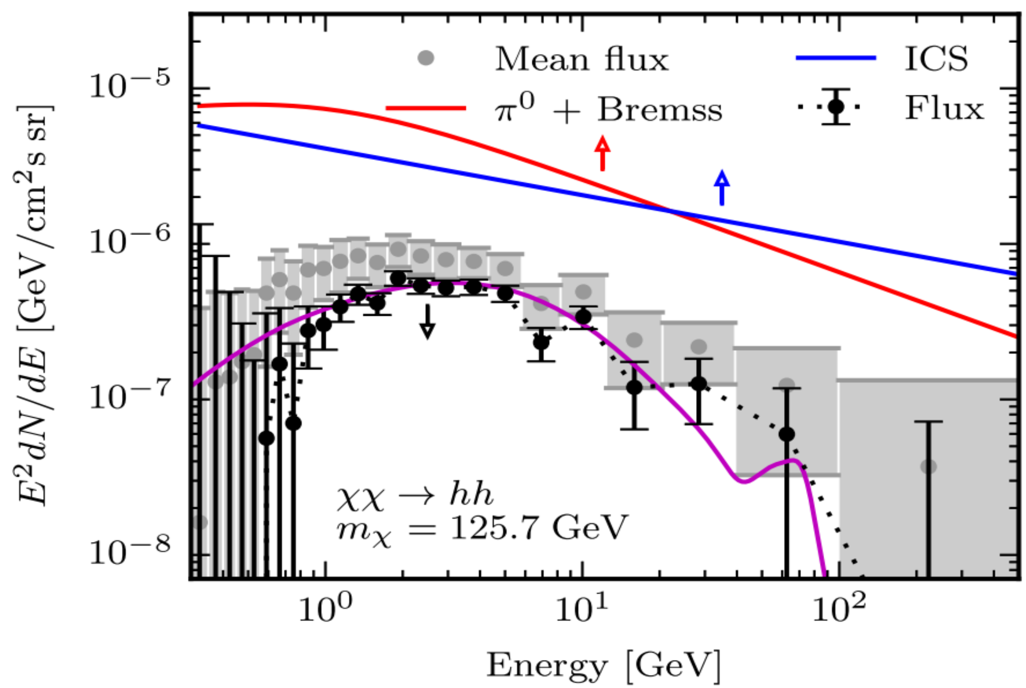
Future possible improvements

- More data: Up to 15 years (until 2023, formally approved until 2016)
- 3x more dwarfs
  → would lead to factor ~4 improvement of limits
  → strong enough to probe GC excess even for pessimistic DM

Fits with dark matter annihilation spectra



Channel	$\langle\sigma v\rangle$ (10^{-26} cm^3 s^{-1})	m_χ (GeV)	$\chi^2_{\rm min}$	p-value
$\bar{q}q$	$0.83^{+0.15}_{-0.13}$	$23.8^{+3.2}_{-2.6}$	26.7	0.22
$\bar{c}c$	$1.24^{+0.15}_{-0.15}$	$38.2^{+4.7}_{-3.9}$	23.6	0.37
$\bar{b}b$	$1.75^{+0.28}_{-0.26}$	$48.7^{+6.4}_{-5.2}$	23.9	0.35
$\bar{t}t$	$5.8^{+0.8}_{-0.8}$	$173.3^{+2.8}_{-0}$	43.9	0.003
gg	$2.16^{+0.35}_{-0.32}$	$57.5^{+7.5}_{-6.3}$	24.5	0.32
W^+W^-	$3.52^{+0.48}_{-0.48}$	$80.4^{+1.3}_{-0}$	36.7	0.026
ZZ	$4.12^{+0.55}_{-0.55}$	$91.2^{+1.53}_{-0}$	35.3	0.036
hh	$5.33^{+0.68}_{-0.68}$	$125.7^{+3.1}_{-0}$	29.5	0.13
$\tau^+\tau^-$	$0.337^{+0.047}_{-0.048}$	$9.96^{+1.05}_{-0.91}$	33.5	0.055
$[\mu^+\mu^-$	$1.57^{+0.23}_{-0.23}$	$5.23^{+0.22}_{-0.27}$	43.9	$0.0036]_{\cancel{\rm ICS}}$

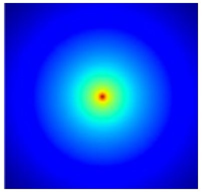


Effective operators

Interaction Structure	$\sigma_{\rm SI}$ suppression	$\sigma_{\rm SD}$ suppression	s-wave?
$\bar{X}X\bar{q}q$	1	$q^2 v^{\perp 2}$ (SM)	No
$\cancel{\bar{X}\gamma^5 X\bar{q}q}$	q^2 (DM)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	Yes
$\cancel{\bar{X}X\bar{q}\gamma^5 q}$	0	q^2 (SM)	No
$\bar{X}\gamma^5 X\bar{q}\gamma^5 q$	0	q^2 (SM); q^2 (DM)	Yes
$\bar{X}\gamma^\mu X\bar{q}\gamma_\mu q$ (vanishes for Majorana X)	1	$q^2 v^{\perp 2}$ (SM) q^2 (SM); q^2 or $v^{\perp 2}$ (DM)	Yes
$\cancel{\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu q}$	$v^{\perp 2}$ (SM or DM)	q^2 (SM)	No
$\cancel{\bar{X}\gamma^\mu X\bar{q}\gamma_\mu\gamma^5 q}$ (vanishes for Majorana X)	$q^2 v^{\perp 2}$ (SM); q^2 (DM)	$v^{\perp 2}$ (SM) $v^{\perp 2}$ or q^2 (DM)	Yes
$\bar{X}\gamma^\mu\gamma^5 X\bar{q}\gamma_\mu\gamma^5 q$	$q^2 v^{\perp 2}$ (SM)	1	$\propto m_f^2/m_X^2$
$\cancel{\bar{X}\sigma^{\mu\nu}X\bar{q}\sigma_{\mu\nu}q}$ (vanishes for Majorana X)	q^2 (SM); q^2 or $v^{\perp 2}$ (DM) $q^2 v^{\perp 2}$ (SM)	1	Yes
$\cancel{\bar{X}\sigma^{\mu\nu}\gamma^5 X\bar{q}\sigma_{\mu\nu}q}$ (vanishes for Majorana X)	q^2 (SM)	$v^{\perp 2}$ (SM) q^2 or $v^{\perp 2}$ (DM)	Yes

[Kurmar & Marfatia 2013]

Direct searches

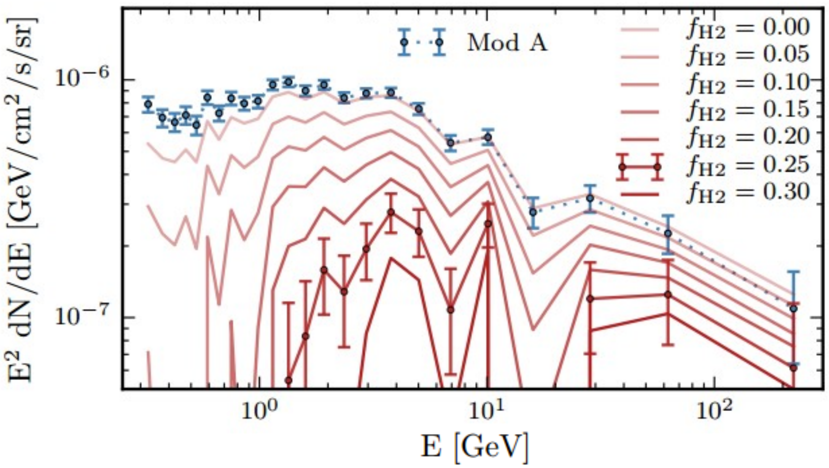


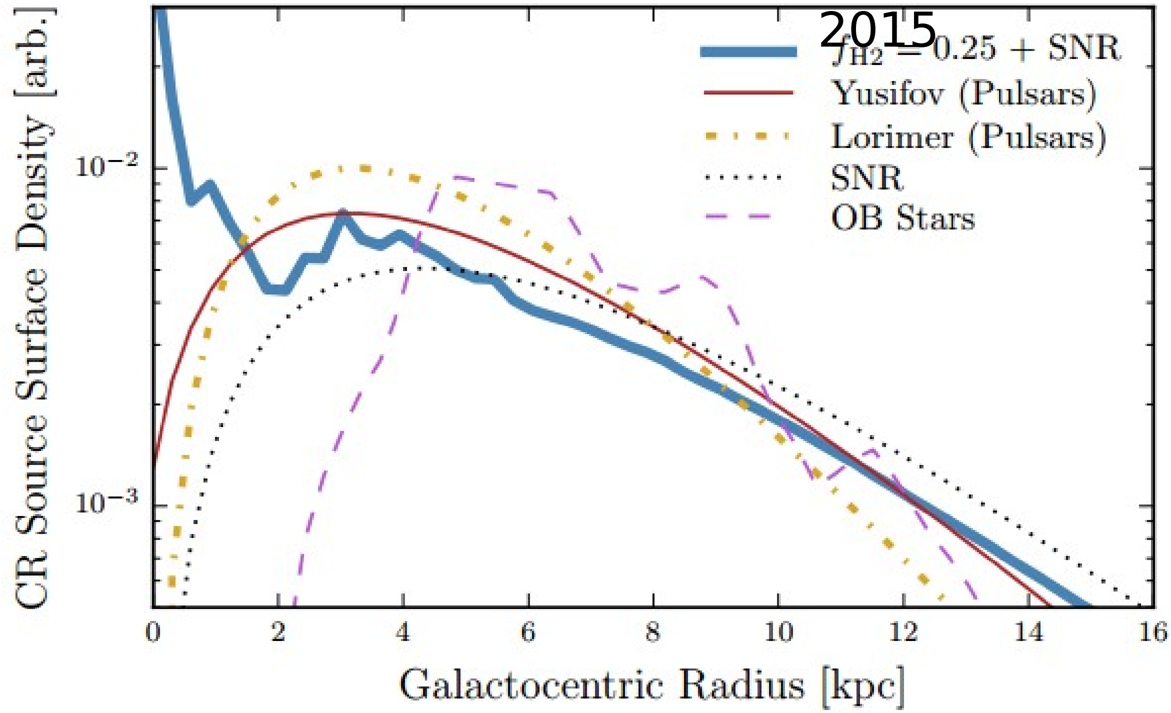
Galactic center excess

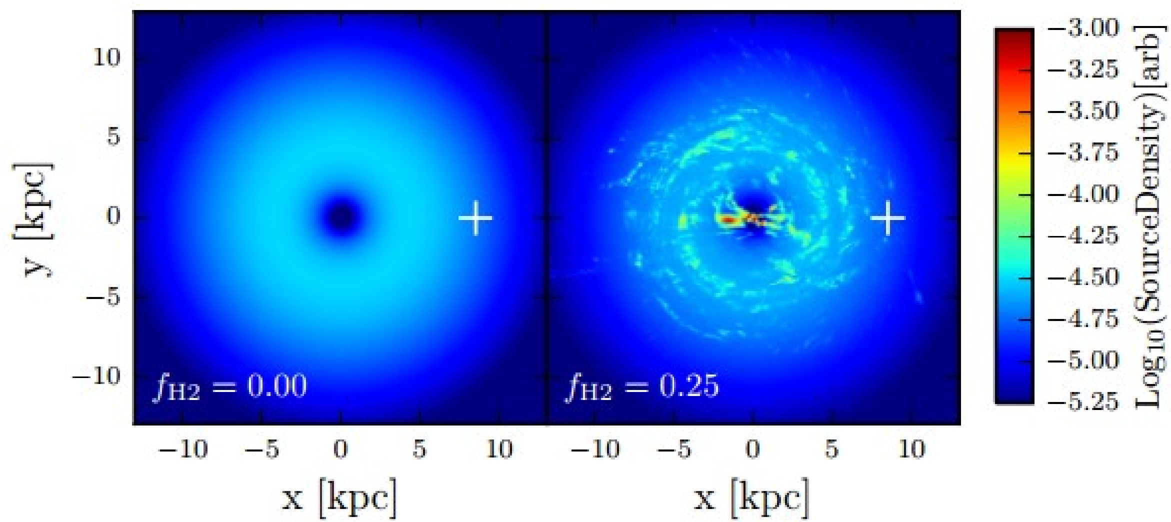
Astro explanations.

Star formation in the CMZ

Carlson+ 2015



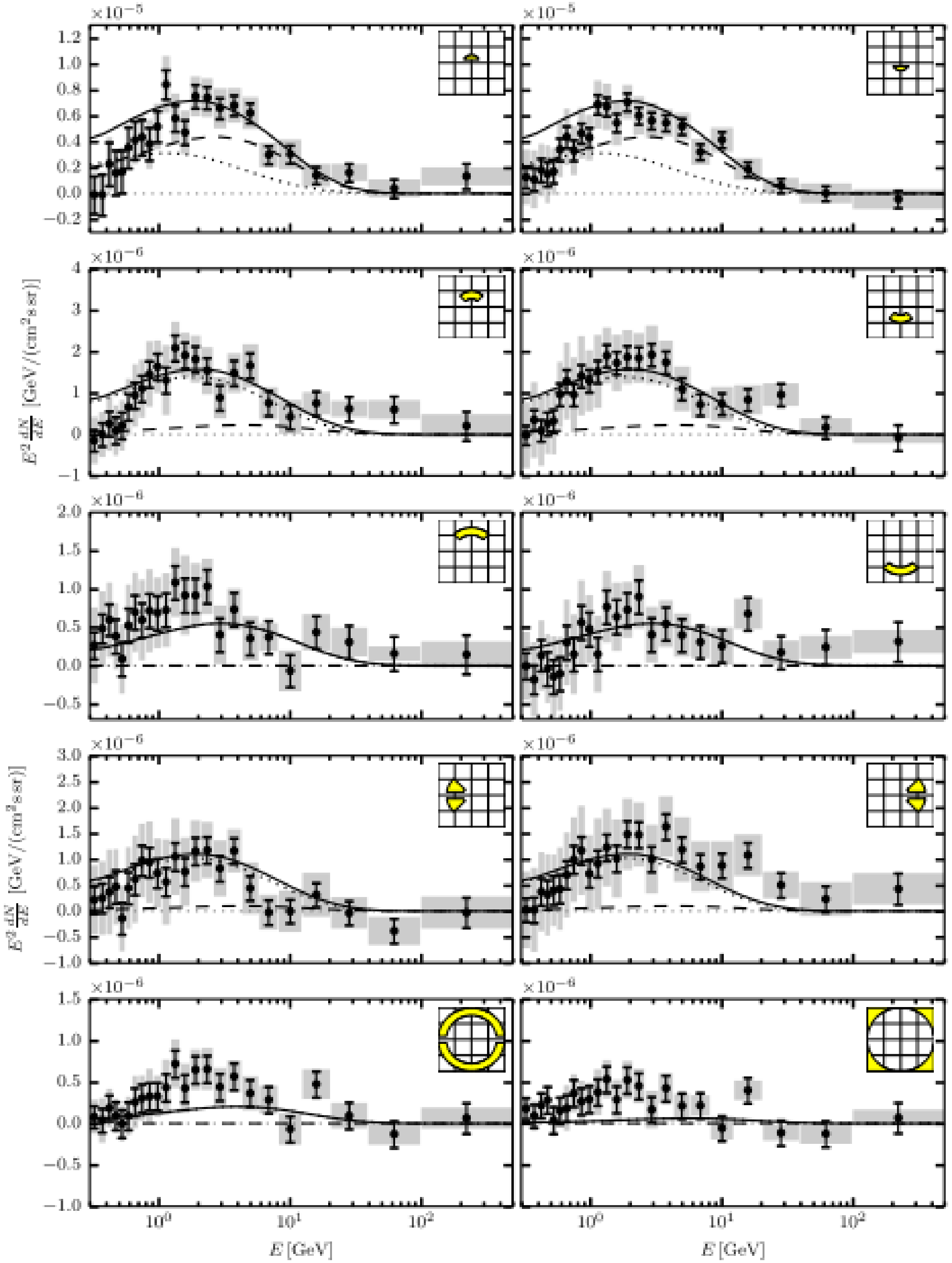




Note

- Previous Galactic diffuse emission models neglected CR injection in the inner Galaxy (with few exceptions, Ackermann+ 2013)
- Inverse Compton emission from electrons accelerated in the CMZ potentially accounts for a good fraction of the bulge emission
- However, the predicted spectra are usually too soft to fully account for the observations

Two leptonic outbursts?



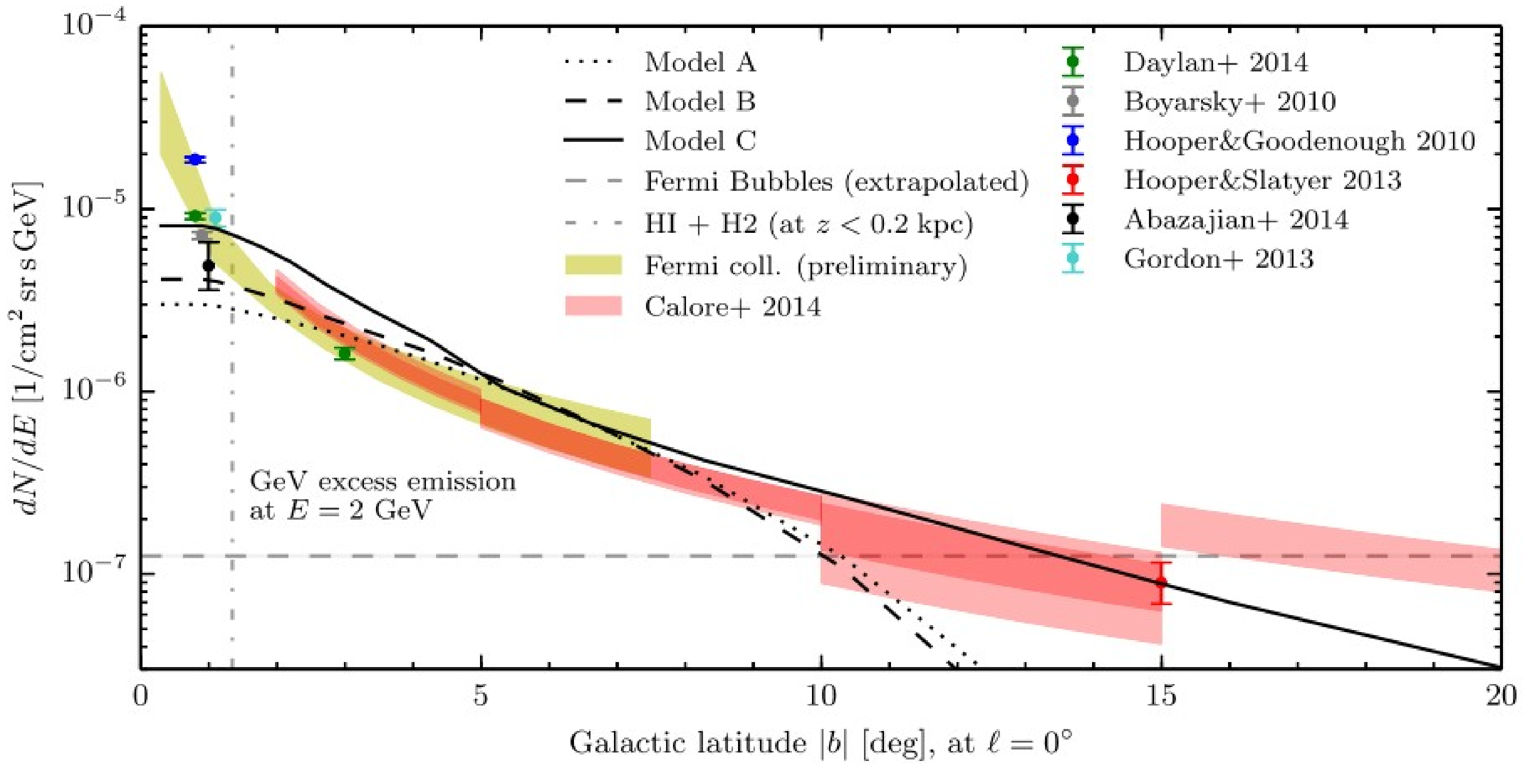
Parameter	Model A	Model B	Model C
α_1	1.2	2.0	1.1
α_2	NA	NA	1.0
$E_{\mathrm{cut},1}$	1 TeV	1 TeV	20 GeV
$E_{\mathrm{cut},2}$	NA	NA	60 GeV
τ_1 (Myr)	0.83	0.46	0.1
τ_2 (Myr)	NA	NA	1.0
N_1 (10^{51} erg)	2.89	9.87	0.1
N_2 (10^{51} erg)	NA	NA	0.88
δ	0.20	0.23	0.3
D_0 (10^{28} cm^2/s)	5.08	9.12	9.0
D_{zz}/D_{xx}	1.12	0.87	NA
v_A (km/s)	176	122	150
B_0 (μG)	11.5	11.5	11.7
r_c (kpc)	10.0	10.0	10.0
z_c (kpc)	2.0	2.0	0.5
dv_c/dz (km/s/kpc)	0.0	0.0	0.0
ISRF	1.0, 1.0	1.0, 1.0	1.8, 0.8
χ^2 ($p-$value)	277 (0.04)	317 (0.0004)	261 (0.14)

Some tuning is required to make it work reasonably well

- Extremely hard injection indices (<2)
- **One burst around 1 Myr**
- ~10^51 erg injected energy in CR e-
(~1000 SN)
- Still, does not well reproduce the

[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Even two bursts cannot explain everything

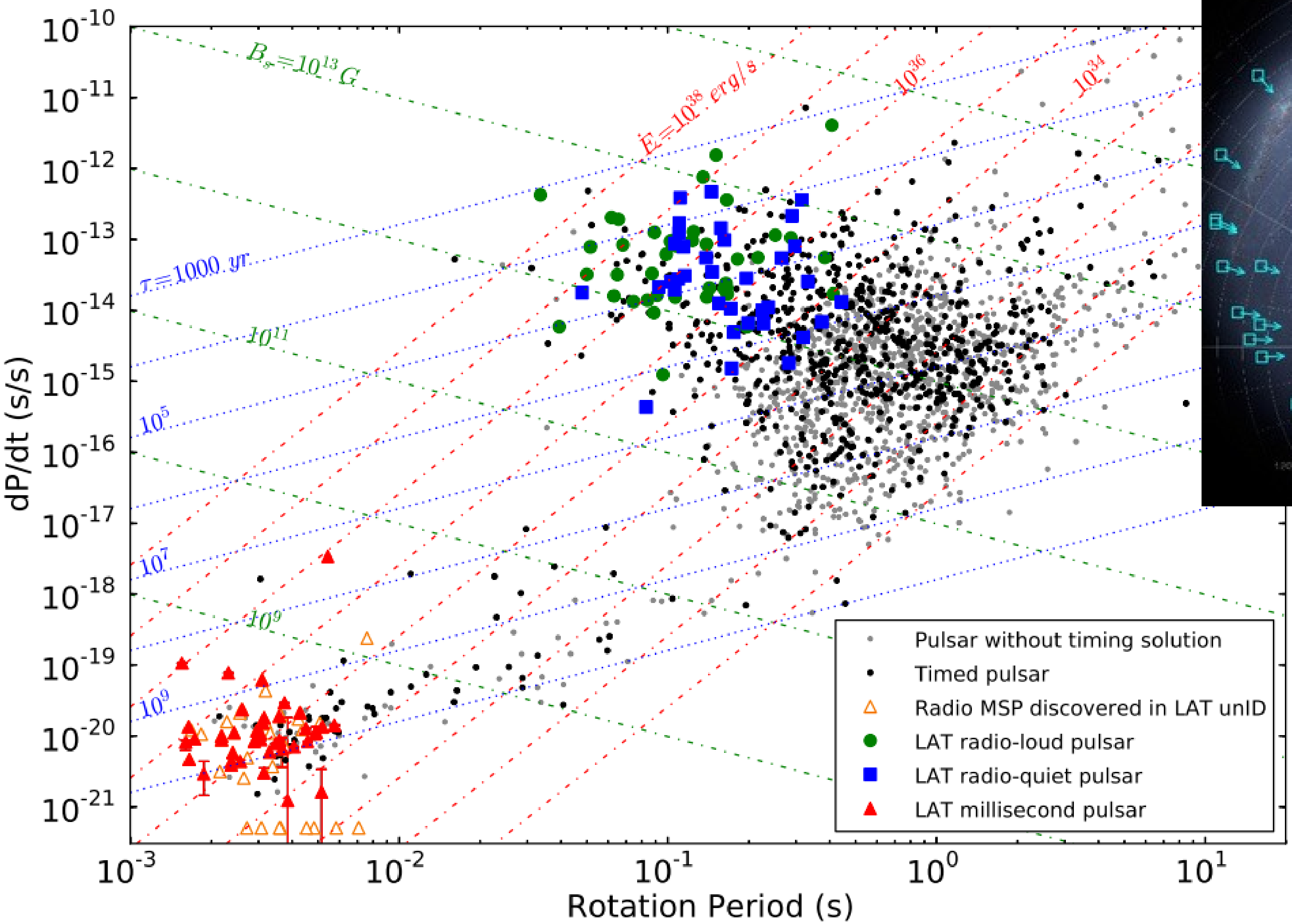


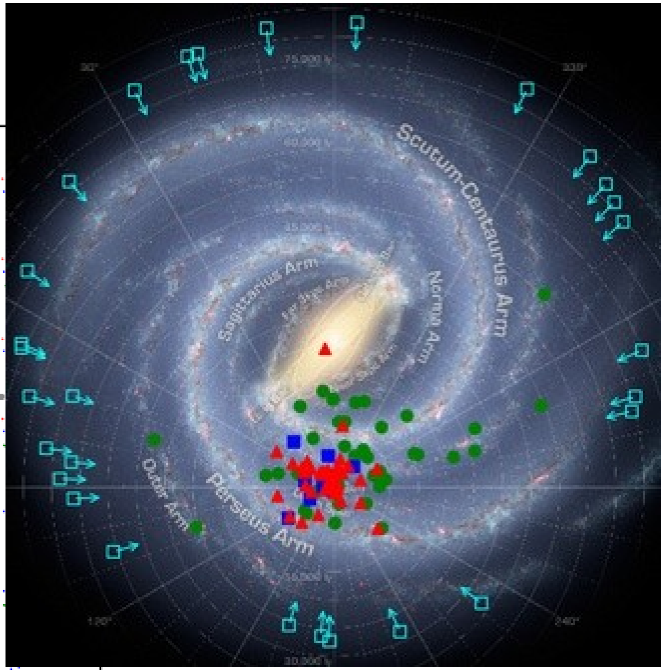
Summary

- It *is* possible to achieve a reasonable description of the data by using two bursts and tuning injection and propagation parameters
- However, the rise of the emission towards the inner few 10 pc is not predicted
- **A series of leptonic bursts are observationally viable, but not likely to explain all of the excess emission**

[Cholis, Evoli, Calore, Linden, CW, Hooper 2015]

Gamma-ray detected pulsars



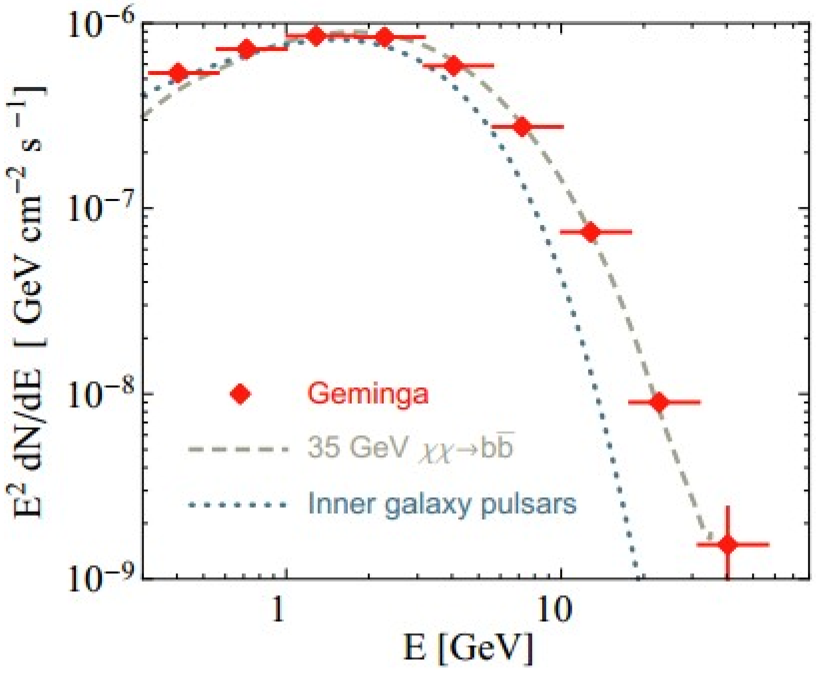


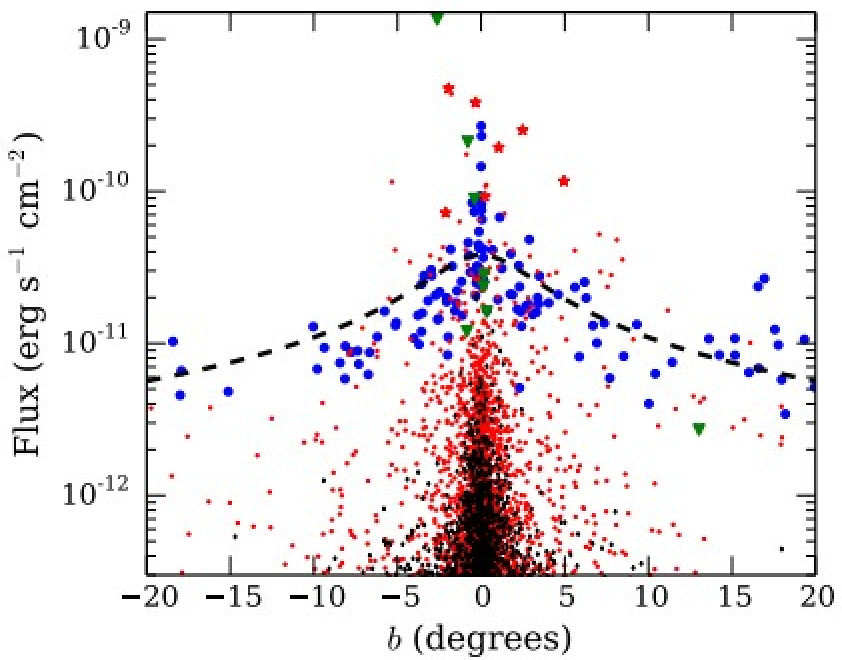
$$B_S = (1.5 I_0 c^3 P \dot{P})^{1/2} / 2\pi R_{NS}^3$$

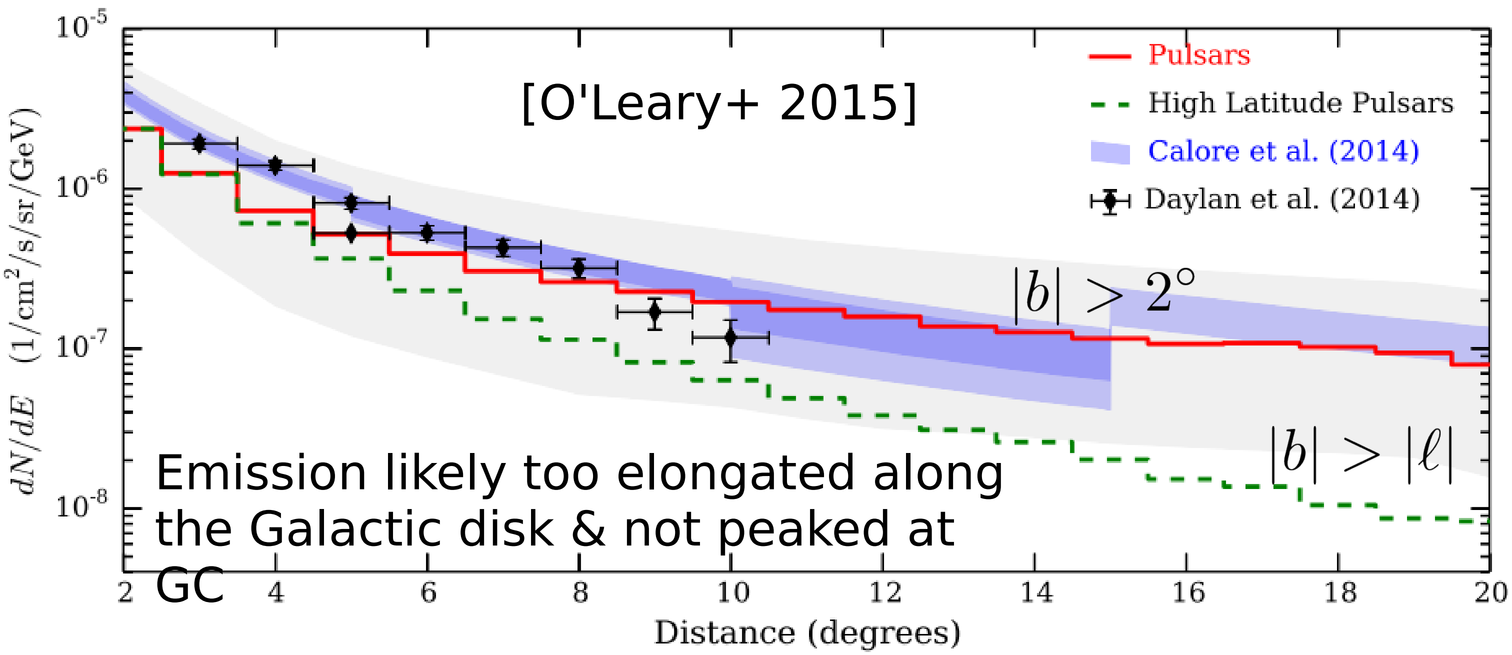
$$\tau_c = P/2\dot{P}$$

[Abdo+ 2013, 2nd Fermi Pulsar catalog]

Young pulsars

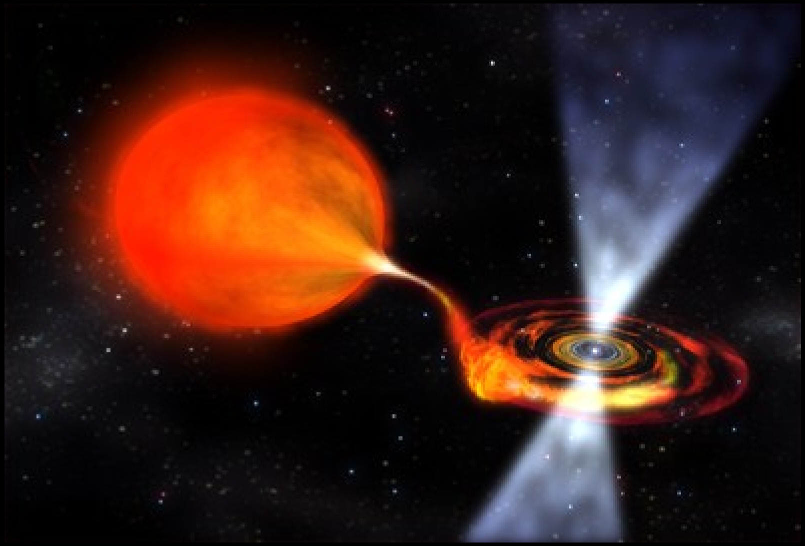




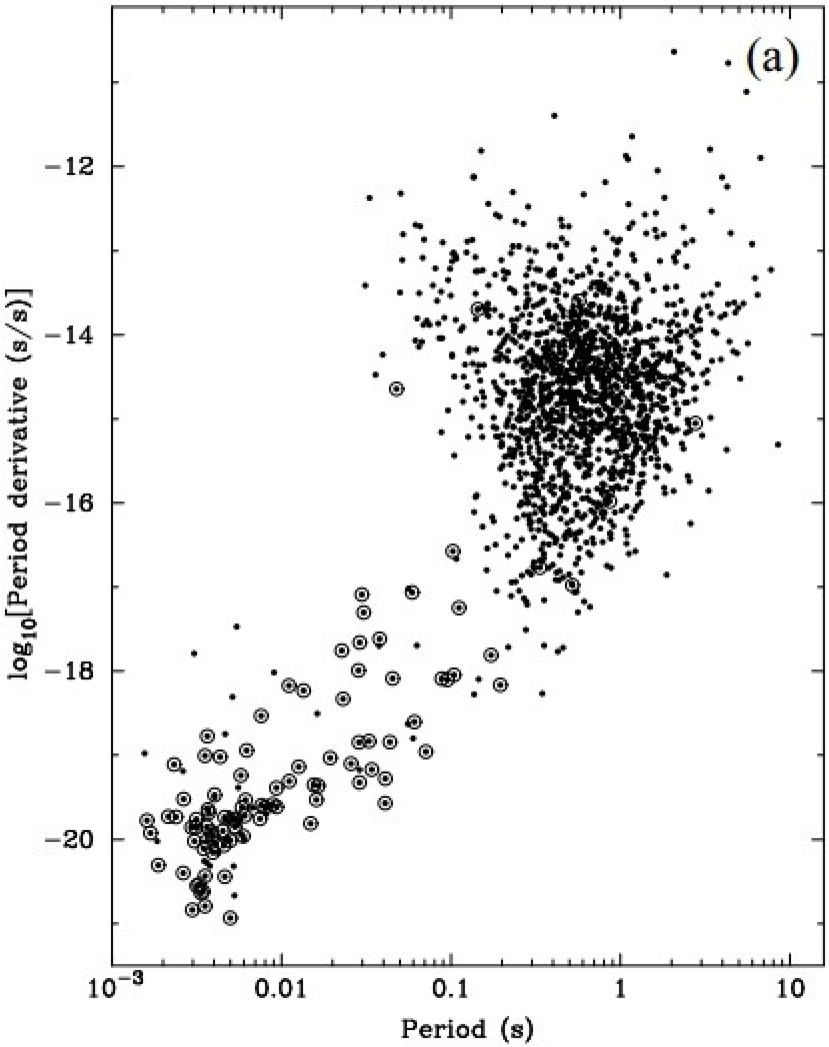


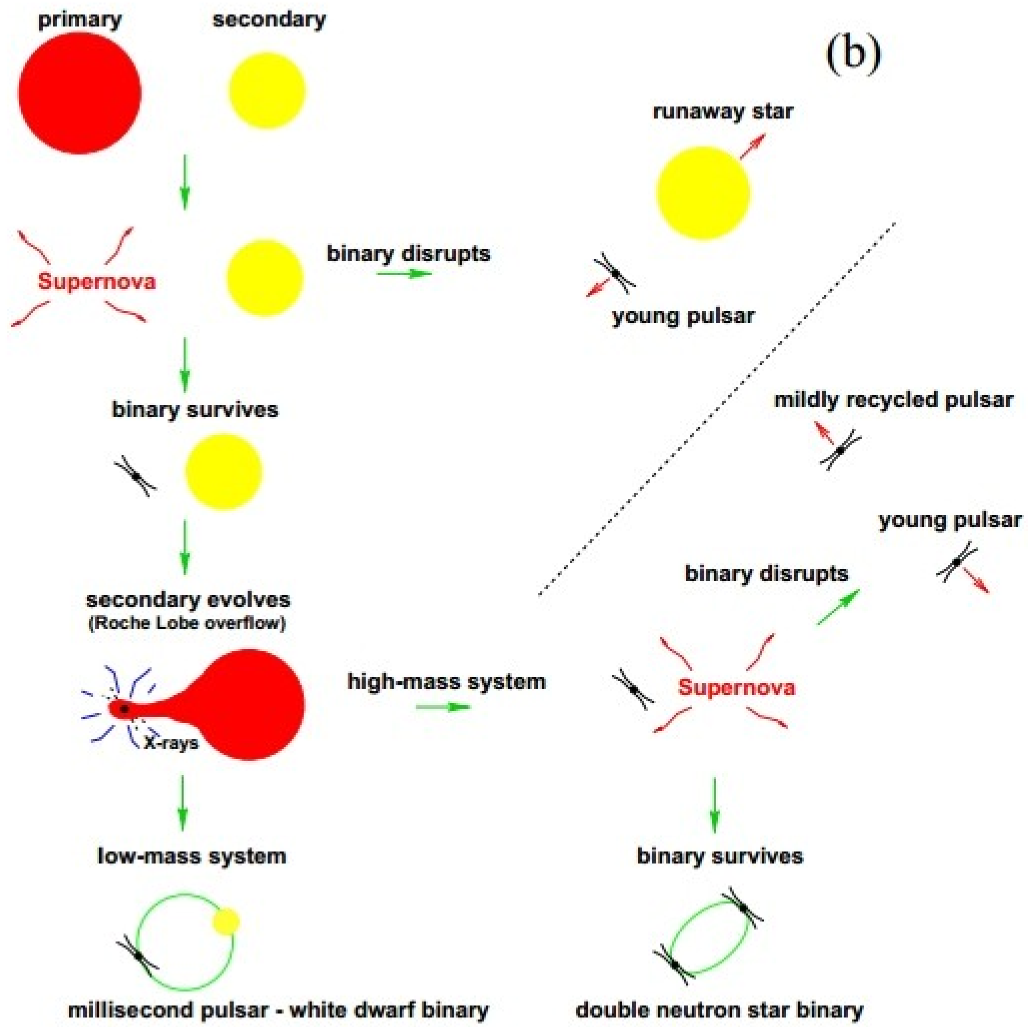
Emission likely too elongated along the Galactic disk & not peaked at GC

Millisecond pulsars.

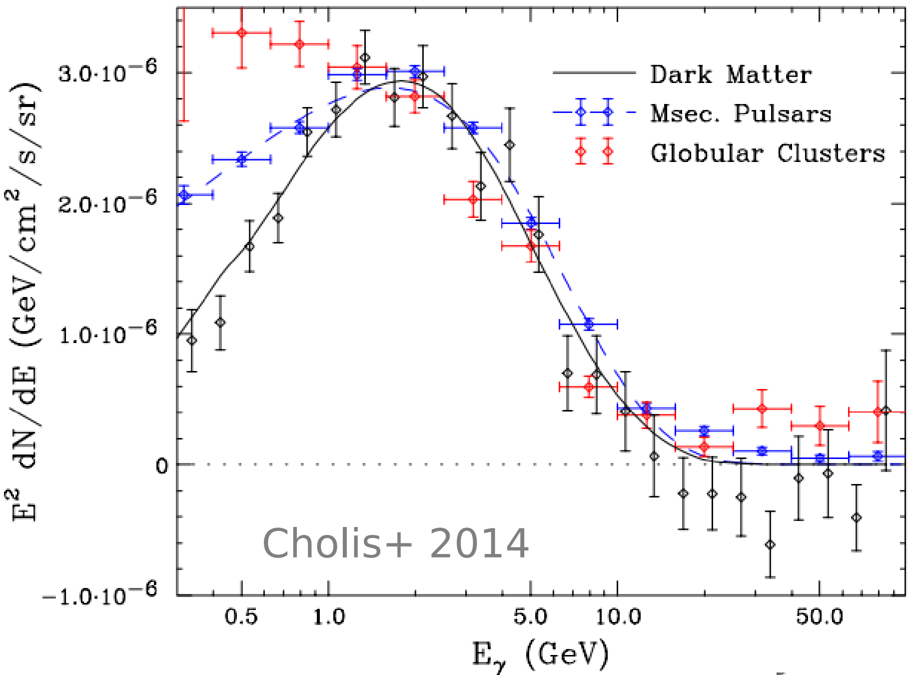


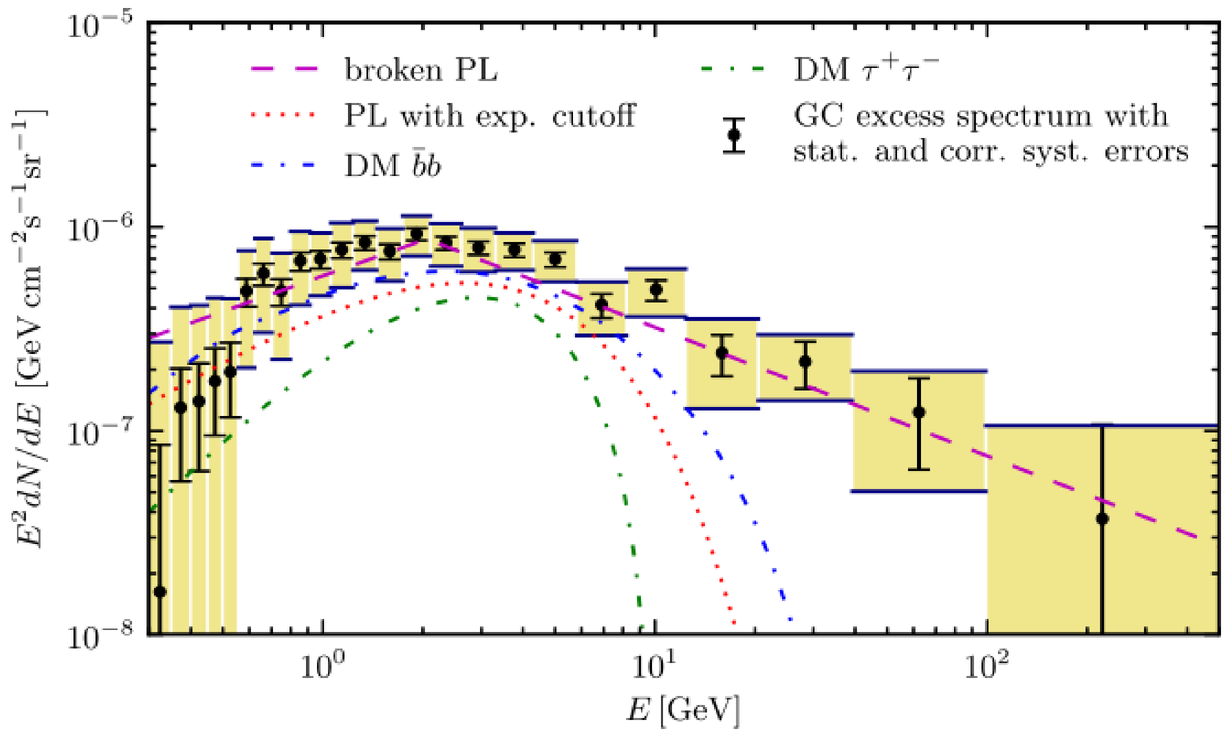
Millisecond pulsars





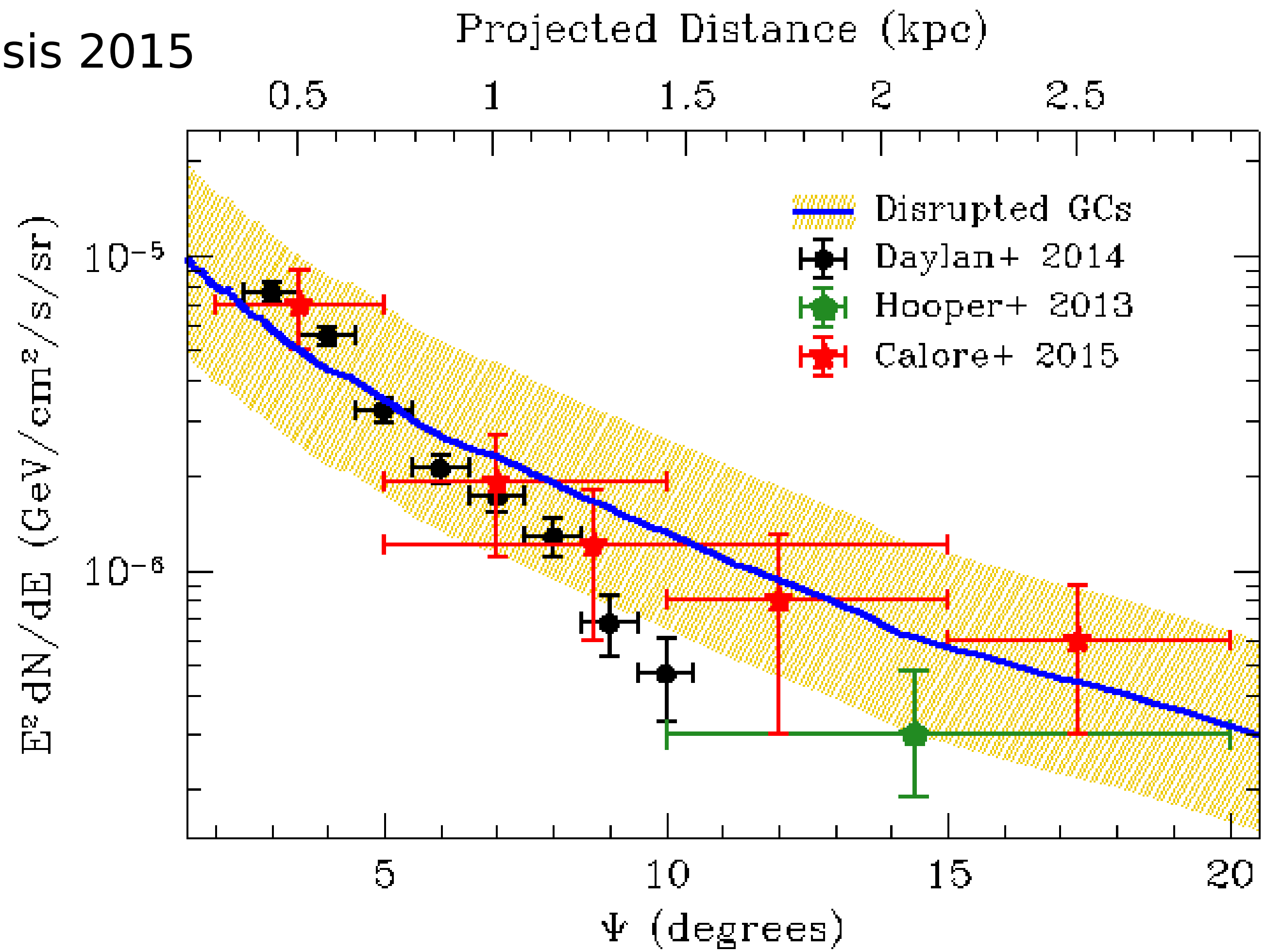
Spectrum fits well





Millisecond pulsars from disrupted globular clusters

Brandt & Kocsis 2015



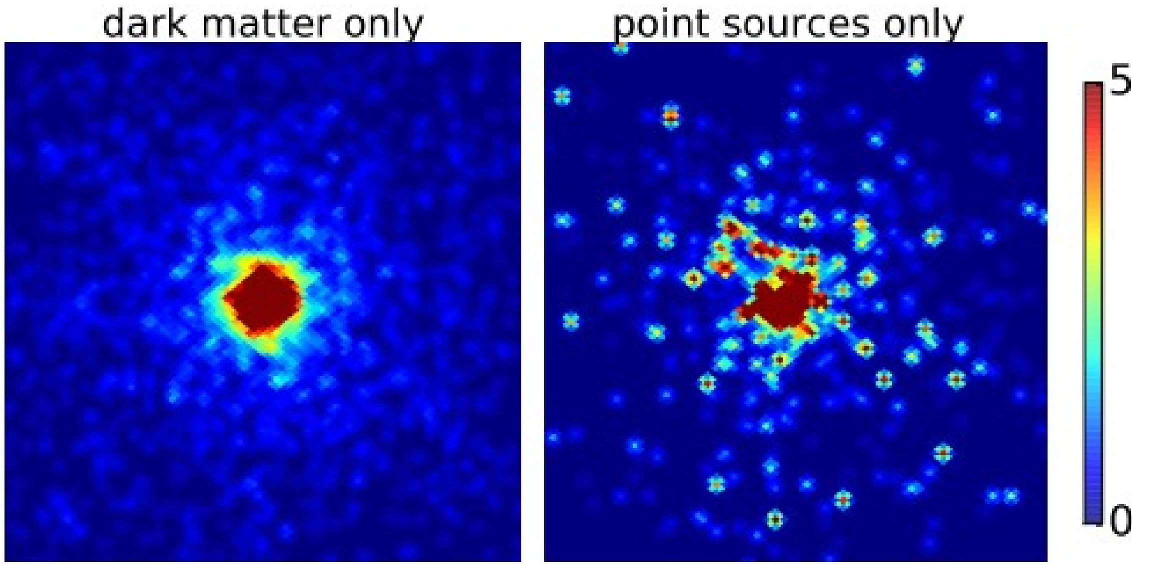
Possible formation history

- Field millisecond pulsars in the bulge could have been created in globular clusters that were tidally disrupted
- This scenario was suggested to explain both normalization and shape of the excess emission

An observational challenge

Point sources or diffuse emission?

- A signal composed of point sources would appear more “**speckled**” than a purely diffuse signal



(Credit: Lee+ 2014)

Proposed methods

- *One-point statistics*
  - Random contribution of point sources to individual pixels leads to non-Poissonian noise [Lee et al. 2014] (successfully used at high latitudes byMalyshev & Hogg 2011)
  - **BUT**: Requires modeling / subtraction of backgrounds → Subject to systematics
- *Local maxima of normalized wavelet transform:*
  - *“Wavelet transform”:* spatially constrained Fourier transform.
    Filters out structures of a specific size, like point sources. Removes diffuse emission.
  - *“Normalized”:* Null hypothesis is equivalent to smoothed Gaussian random

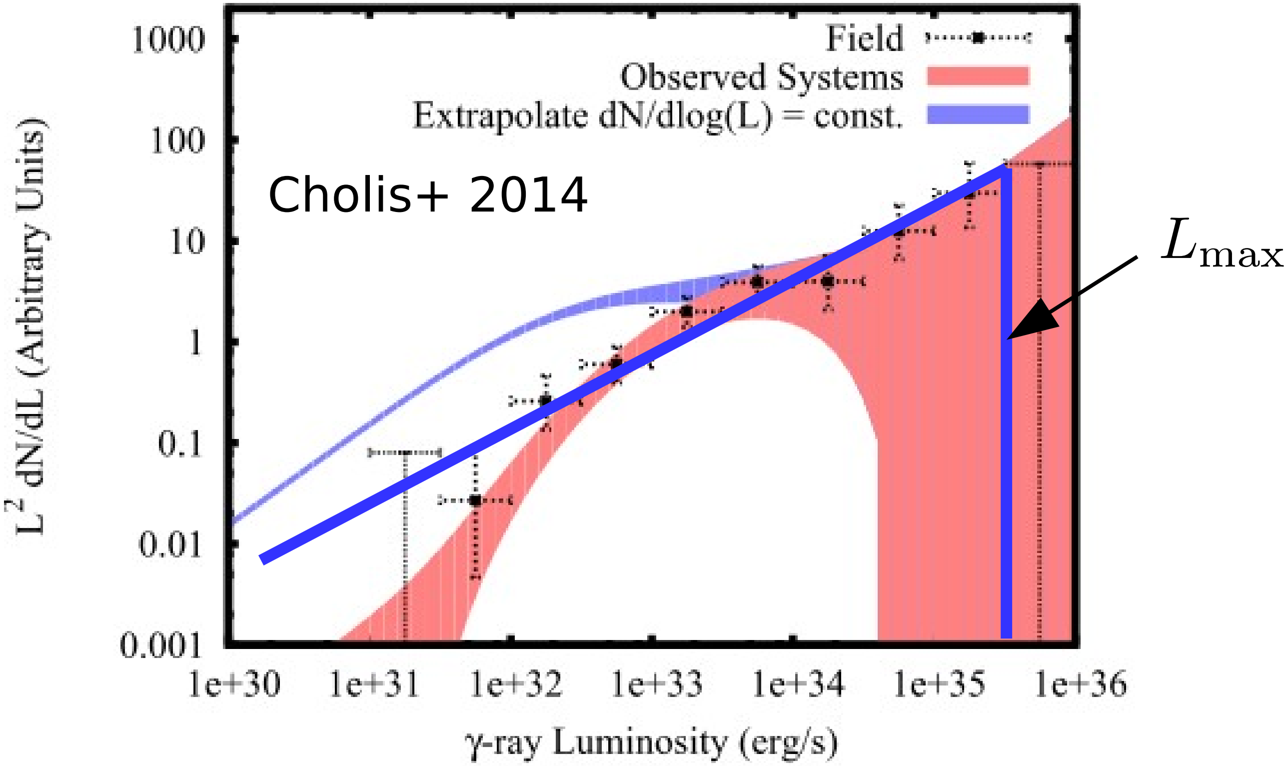
Effective modeling of MSPs

Modeling of unresolved sources

- We assume that they are distributed like required to explain the GCE (with a radial index of -2.5 or so)
- We simulate PSCs that follow a luminosity distribution

$$\frac{dN}{dL} \sim L^{-1.5}$$

  up to some cutoff L_{max}
- Main uncertainties: Slope, normalization and cutoff of the luminosity function. Here: slope fixed to -1.5



Peaks in the normalized wavelet transform

Definitions

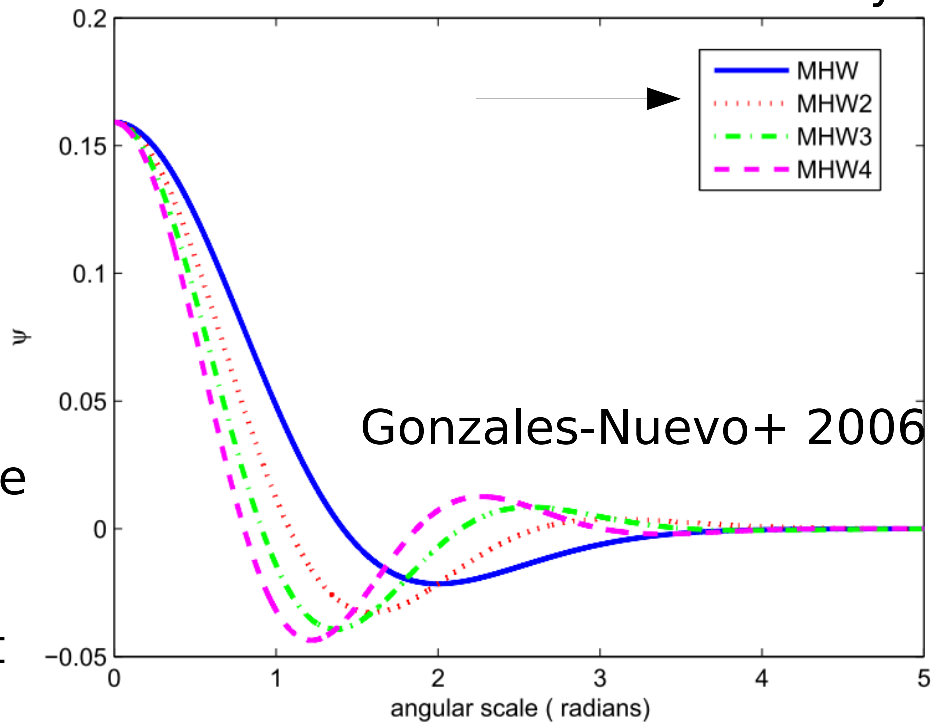
- First we perform a standard wavelet transform

$$\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega) \equiv \int d\Omega\, \mathcal{W}(\Omega - \Omega')\mathcal{C}(\Omega')$$

Wavelet

Count map (1-4 GeV)

The Mexican Hat Wavelet Family



Gonzales-Nuevo+ 2006

- We adopt the 2nd of the Mexican Hat Wavelet Family, which was shown to have a good performance w.r.t. background variations
  (used by Planck for detection of compact radio sources, Ade+ 2013)

- Instead of fluxes, we consider the signal-to-noise ratio (SNR) defined by

$$\mathcal{S}(\Omega) = \frac{\mathcal{F}_{\mathcal{W}}[\mathcal{C}](\Omega)}{\sqrt{\mathcal{F}_{\mathcal{W}^2}[\mathcal{C}](\Omega)}}$$

On sufficiently smooth data sets, and for a large number of photons, this behaves approximately like a normal distribution
→ Smoothed Gaussian random

- Peak identification is numerically

Wavelet transform of inner Galaxy data

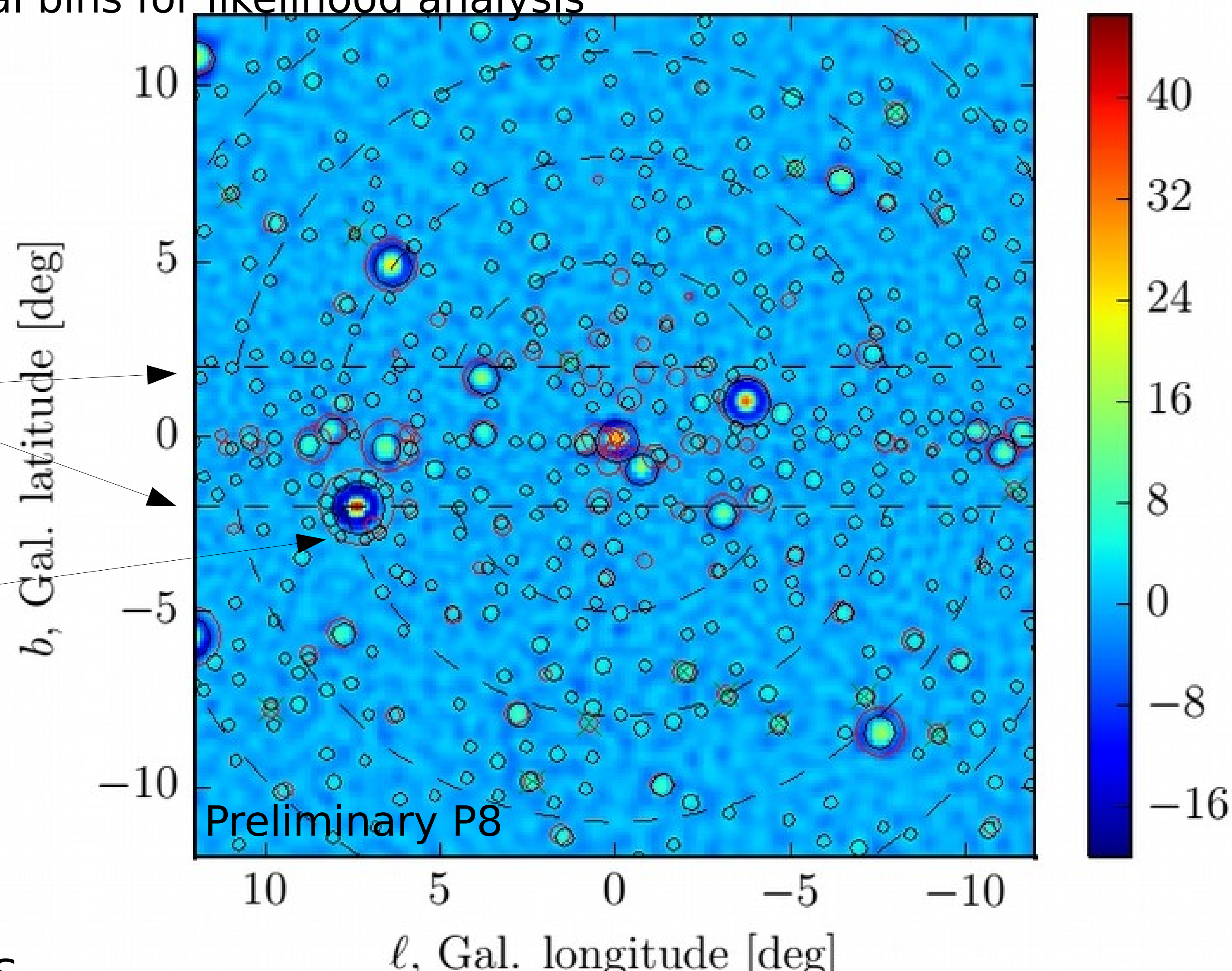
Image color: Value of normalized wavelet transform
Black circles: Wavelet SNR peaks with values above 2 (circle area ~ *S*)
Red circles: 3FGL sources for comparison (circle area ~ sqrt(TS) in 1-3 GeV band)
Green crosses: Unmasked sources (MSP-like)
Dashed lines: Spatial bins for likelihood analysis

Bartels, Krishnamurthy, CW 2015

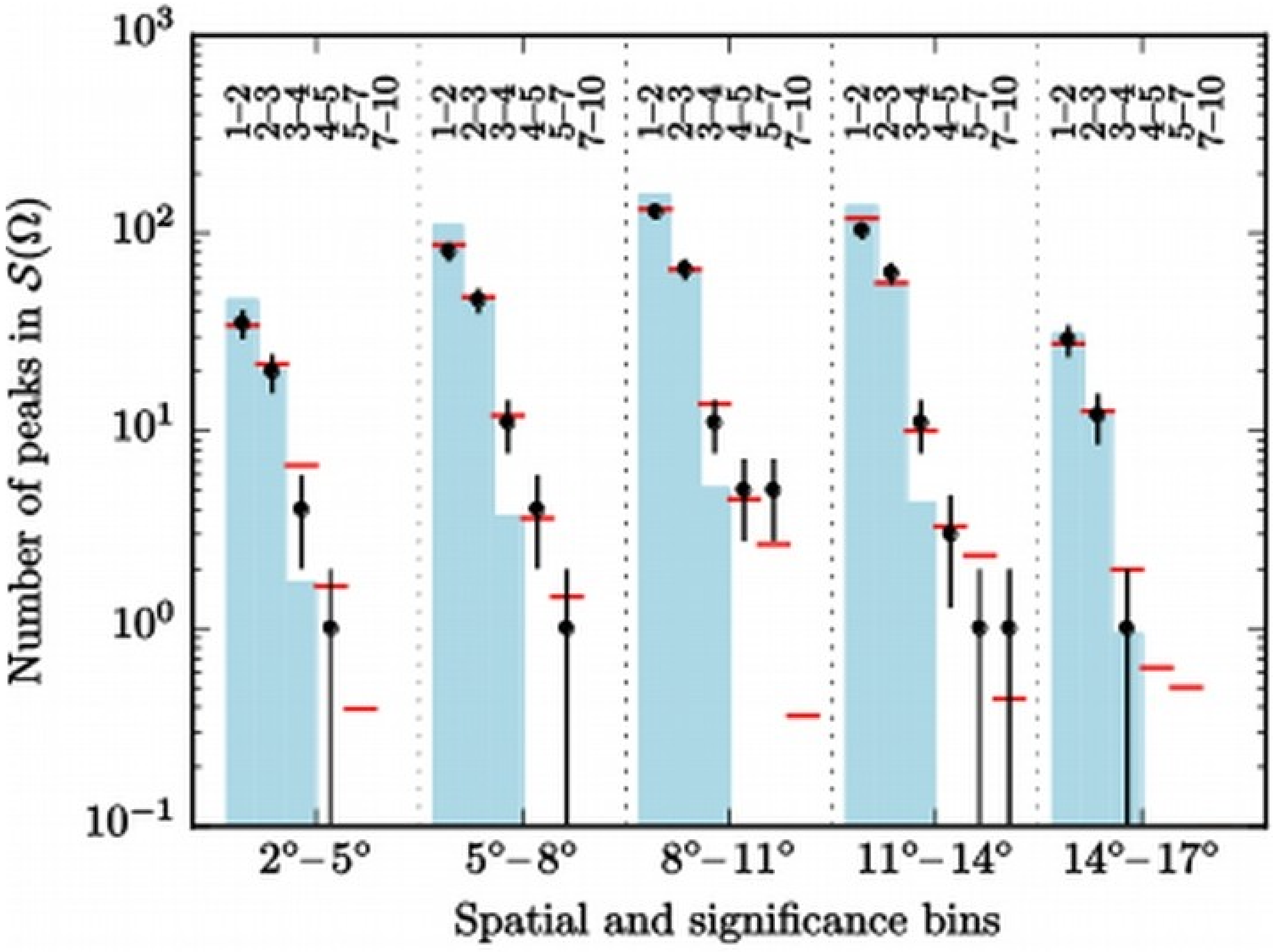
Based on:
Pass8 Fermi LAT data
Ultraclean events
Front+back converted
6 ½ years of data
1-4 GeV range

Masked disk
|b|>2 deg

Artifacts around bright sources (removed in later analysis)
→ Except for bright sources (where noise estimates includes source flux), we find good agreement between sqrt(TS) and S.



Histogram of peaks and MC results



Histogram

- **Error bars:** inner Galaxy data

Null-hypothesis

- **Red**: null-hypothesis
- **Gray**: Control region results

Fit for norm and Lmax

- **Green**: best-fit

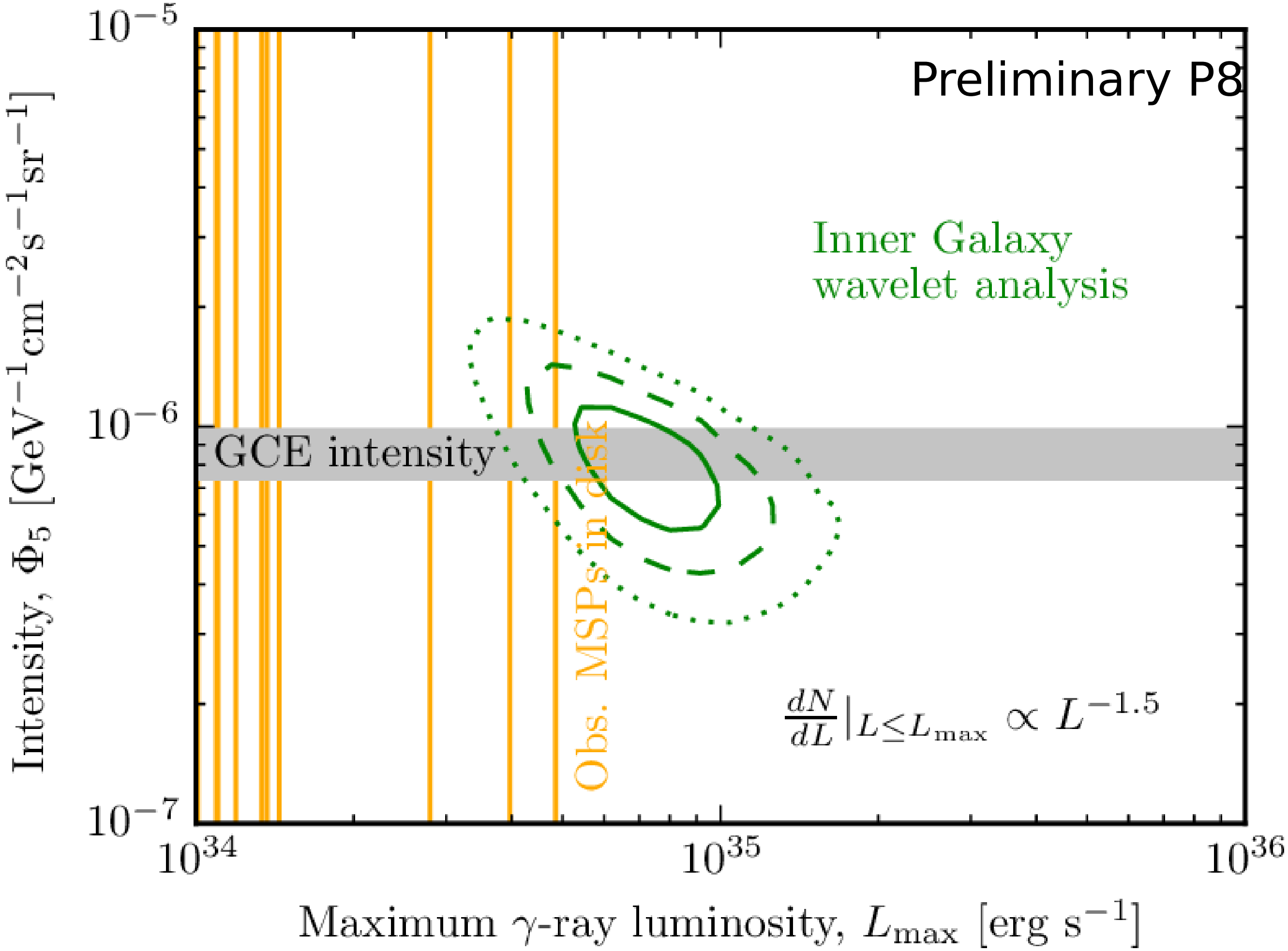
→ 8.3 sigma significance

MC predictions + simple estimates for disk population

We use a common maximum likelihood analysis (assuming that peaks are Poissonian distributed) to perform parameter estimation for the luminosity function:

$$(L_{\rm max}, n_{\rm MSPs})$$

Best-fit contours agree with MSP expectations

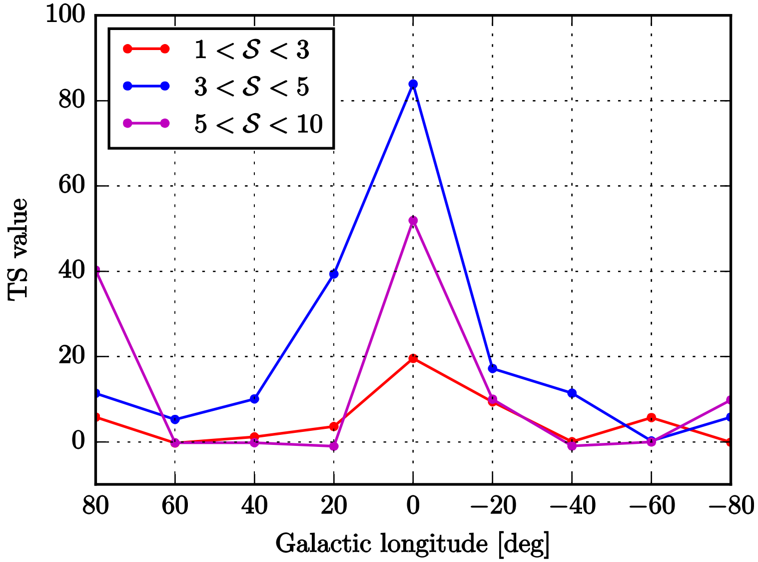


Results

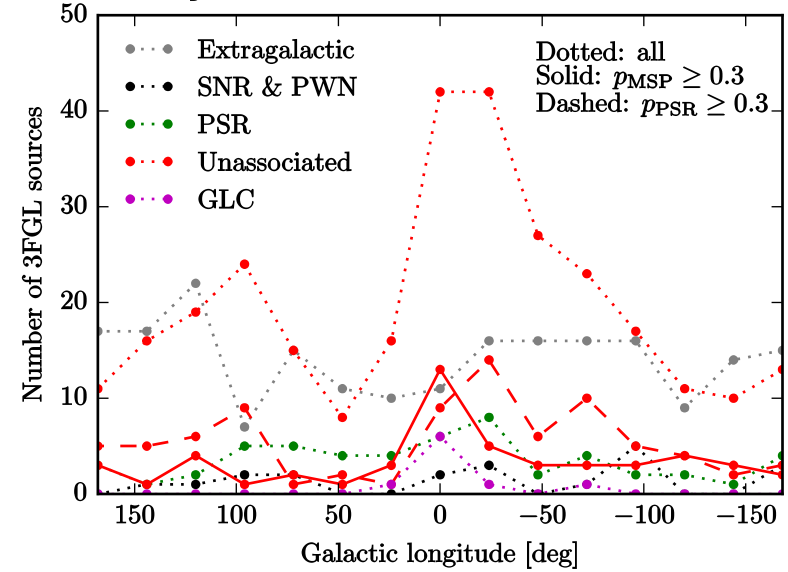
- For a luminosity function index around 1.5, a MSP population with the best-fit normalization would reproduce 100% of the excess emission
- The best-fit cutoff luminosity is compatible with gamma-ray emission from detected nearby MSPs (beware of large uncertainties due to uncertainties in the distance measure, Petrovic+ 2014, Brandt & Kocsis 2015)

Many things that one can check

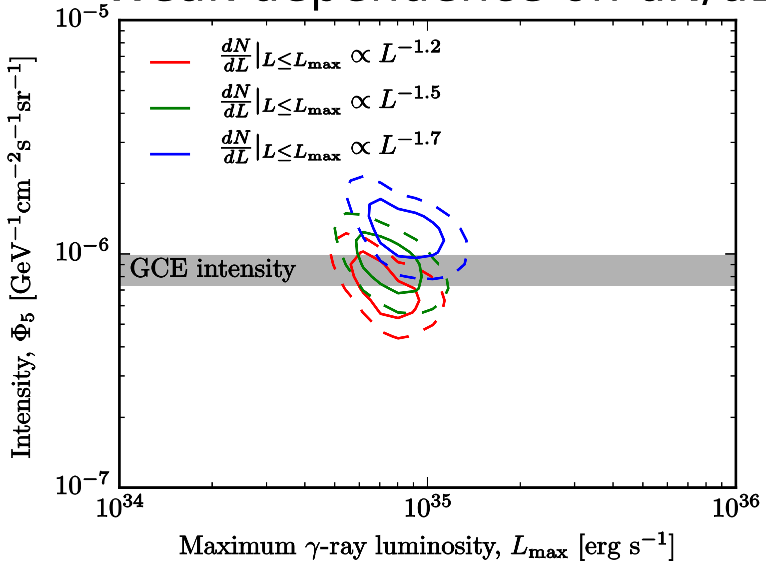
Concentrated inner Galaxy



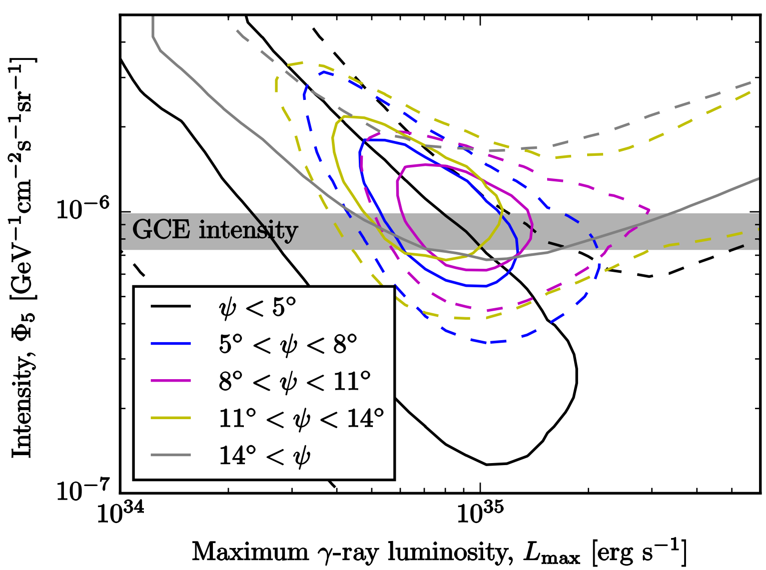
Likely MSPs



Weak dependence on dN/dL



Self consistent in sub ROIs



Conclusions

- There *is* a strong excess of ~GeV gamma-rays in the inner Galaxy, above expectations from *a priori* diffuse emission models (i.e. without CR sources in the inner Galaxy)

- Excess emission could be partly due to standard diffuse emission (e.g. associated with the central molecular zone), and partly to other components

- The excess as a whole resembles very well a vanilla signal from DM annihilation

- Millisecond pulsars
  - are the arguably most likely explanation of a large part of the excess emission
  - corroborating evidence for this is found by dedicated searches for sub-threshold source populations in the inner Galaxy
  - → Next thing is to try to find them in radio