The FERMI excess investigated over the whole gamma-ray sky

Using a true multimessenger analysis to support interpretation (PRD, 1707.08653)

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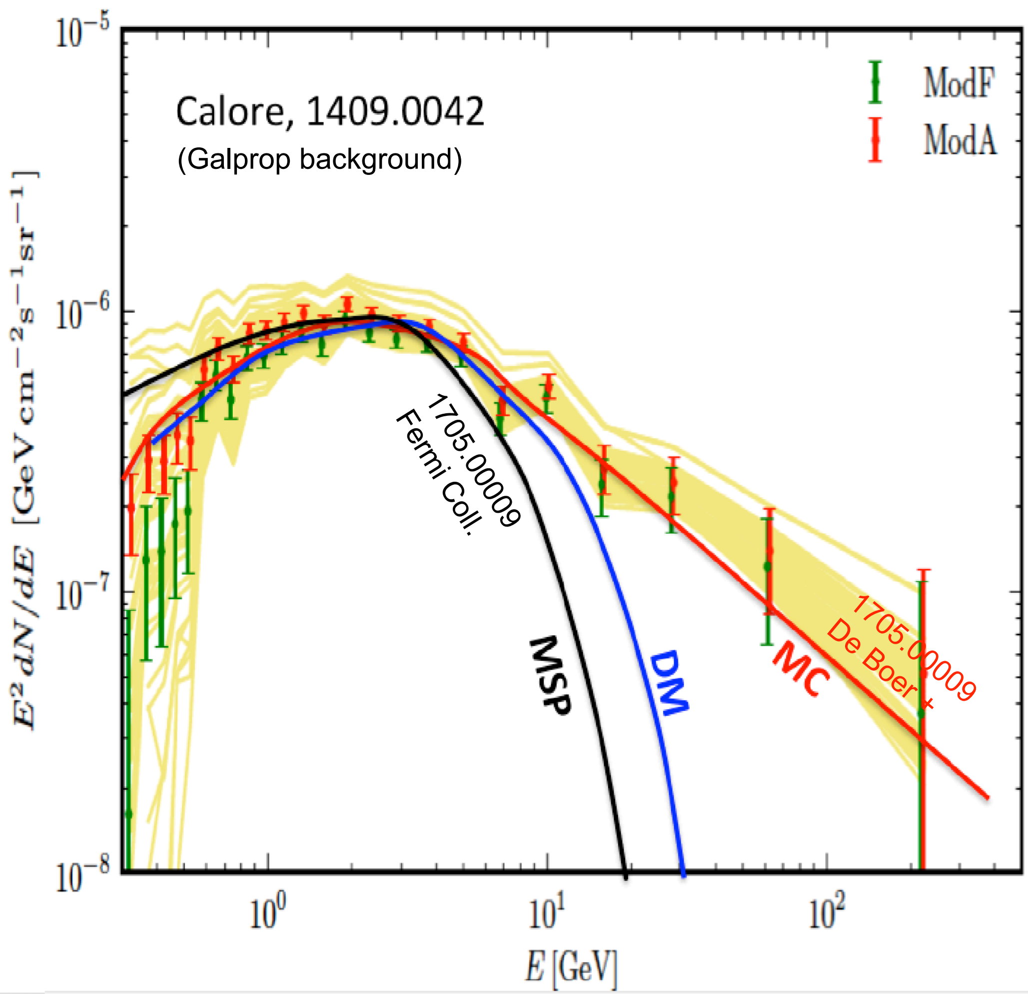
Three possible explanations proposed for excess:
(all having spectrum peaking at 2 GeV)



DM from Daylan+
1402.6703(Hooper, Linden)

MSP, from Bartels+
1506.05104 (Weniger)

MC, from de Boer+,
1707.08653, 1712.06644

- **How to distinguish?**
- **Spectral distribution**
- **Morphology**
- **„Speckling“**

How to determine the excess?

Two methods used:

- **SPATIAL templates:**
  - **INPUT:** spatial information of target materials for each physical process (gas maps, photon field), subdivided in course annuli to allow for varying CR densities (fitted as free normalization in each ring)
  - **OUTPUT:** Energy spectra of each physical processes

- **SPECTRAL templates:**
  - **INPUT:** energy spectra for each known physical process (π^0, BR, IC, Bubbles, Excess, Isotropic)
  - **OUTPUT:** High resolution morphology of each physical process (allows to resolve molecular clouds!)

Fine-print for the methods

- **Spatial templates:** large uncertainties in gas maps, assume cylindrical symmetry for gas maps and CR density

- **Spectral templates:** need to know spectra of each process. Are the data precise enough to avoid the fit of 5 normalization constants for 5 physical processes to 30 energy bins being stuck in wrong minima?

Methods to determine templates

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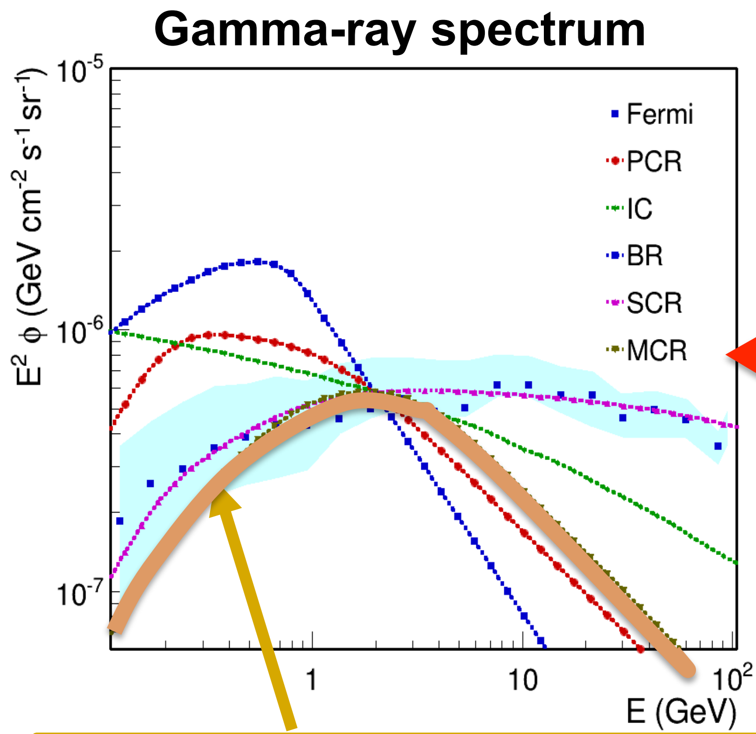
- Take them from propagation models and use spatial templates to get spectral templates for processes not in propagation models (Bubbles, Excess)
- Try to get templates for π^0, IC and BR by assuming power laws for CR spectra with slope given by local CR spectra
- Try to get all templates directly from gamma-ray data by minimizing chi2 of the whole sky and varying the templates

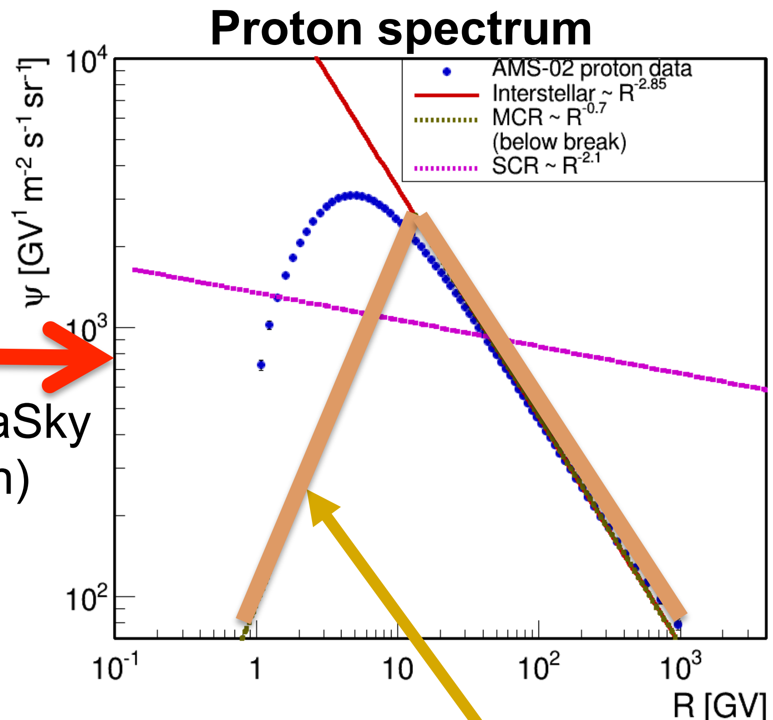
Fortunately, all methods yield consistent results for the morphology of each physical process.

Note: all processes in each direction determined simultaneously. No need to subtract background.
Avoids discussion of contribution of Bubble in Excess region!

Excess Template
(from fitting gamma-ray data)



GammaSky
(Dragon)

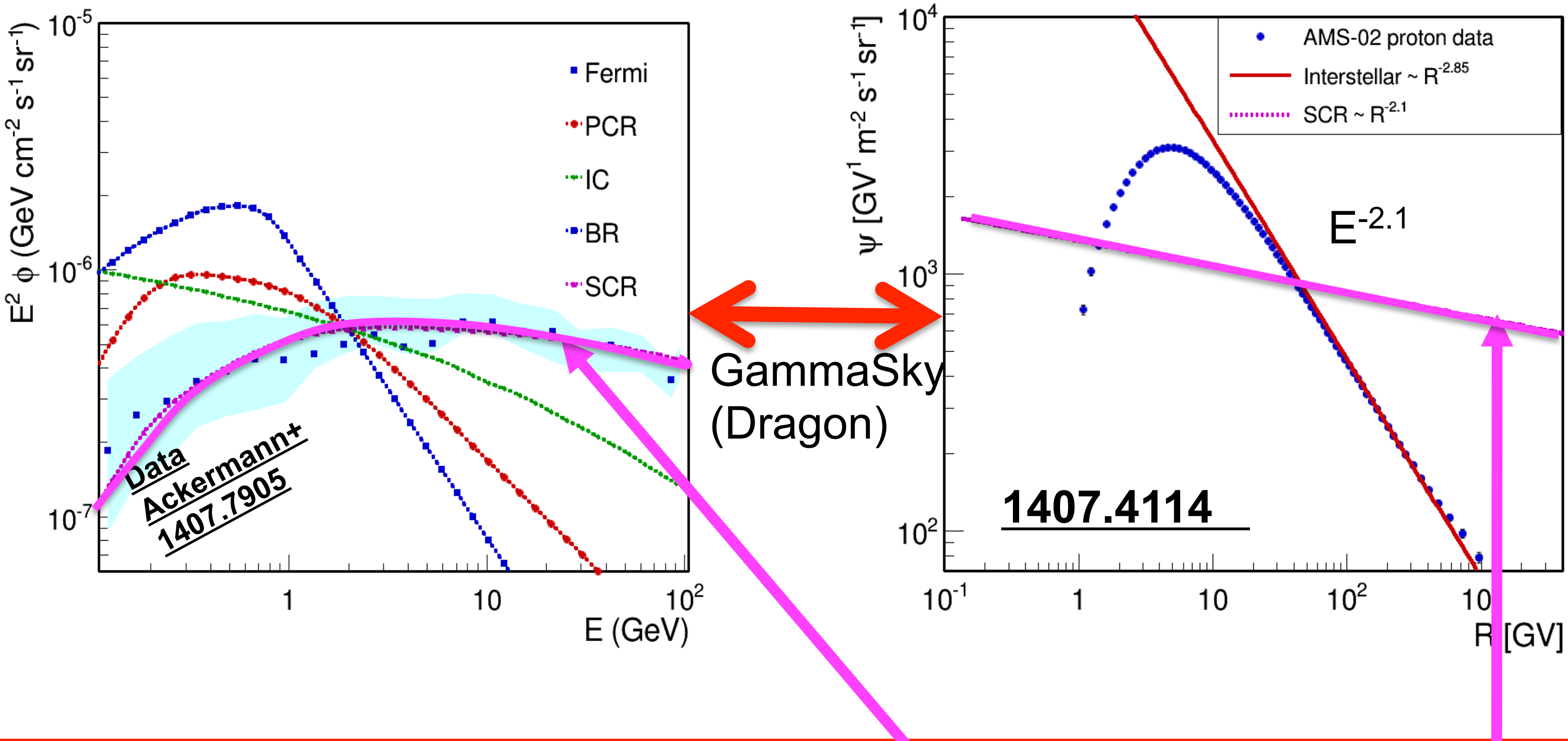


The excess template is similar to the π^0 template at high energies, but has a reduced emissivity below 2 GeV, which can be described by a break in the proton spectrum around 12 GV.

Bubble template

Gamma-ray spectrum

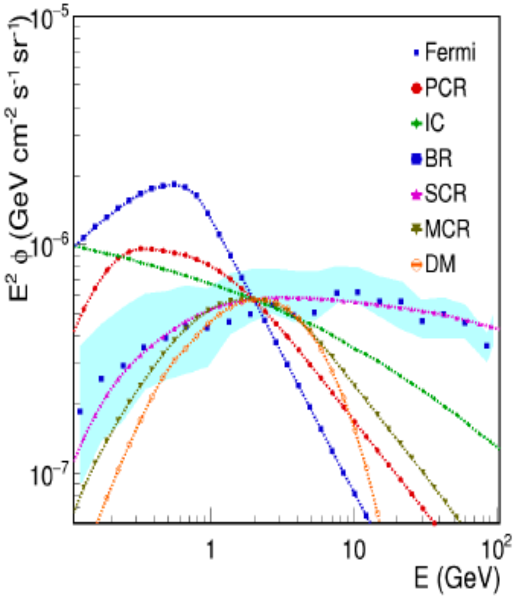
Proton flux spectrum



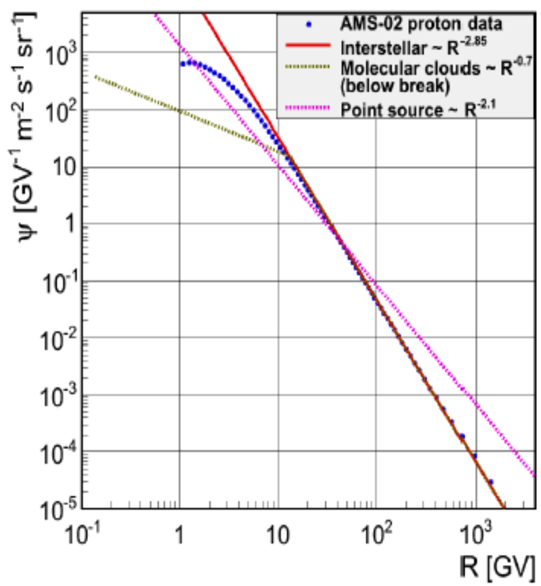
Bubbles: The Bubble spectrum (blue band) corresponds to π^0 production from a $1/E^{2.1}$ proton spectrum, as expected for sources (see later)

Summary of templates and corresponding CR spectra

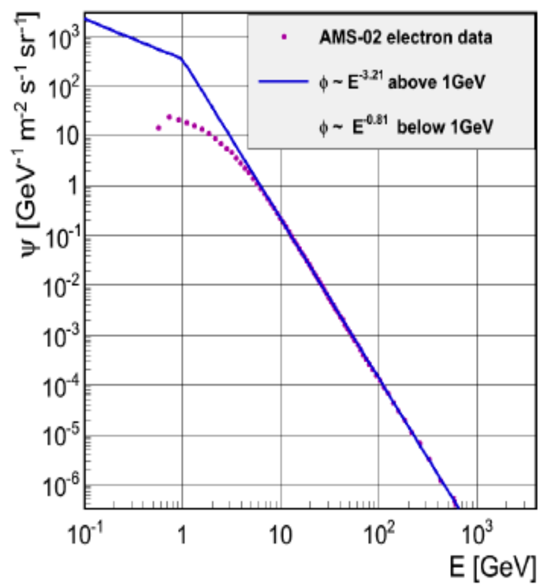
gamma-ray templates



proton CR spectra



electron CR spectra



From gamma-ray data we derive 3 populations of protons:
Protons with $1/E^{2.1}$spectrum (Bubbles)
Interstellar protons with $1/E^{2.85}$ spectrum (as observed locally)
Protons with $1/E^{2.85}$ spectrum, but break below 12 GeV (Excess)

Fit procedure
(9 yrs of Fermi Pass 8 CLEAN data)

Fit gamma-ray spectrum in each ROI by a linear combination of the templates with the normalizations n1-n6 as free parameters for 30 energy bins (0.1 - 300 GeV):

$|\Phi\rangle = n_1|\pi^0\rangle + n_2|BR\rangle + n_3|IC\rangle + n_4|\mathrm{isotropic}\rangle + n_5|\mathrm{Bubble}\rangle + n_6|\mathrm{Excess}\rangle$

Plotting the coefficients n1-n6 as function of longitude and latitude provides the morphology in a sky map.

Surprising results:

1) **Excess has morphology of CO maps (tracing molecular clouds (MCs))**
2) **Bubble template traces Bubbles in halo, but has also strong component in the disk with morphology of ^{26}Al line (traces sources)** (see dB+, 1407.4144)

Comparison of CO and Excess sky maps

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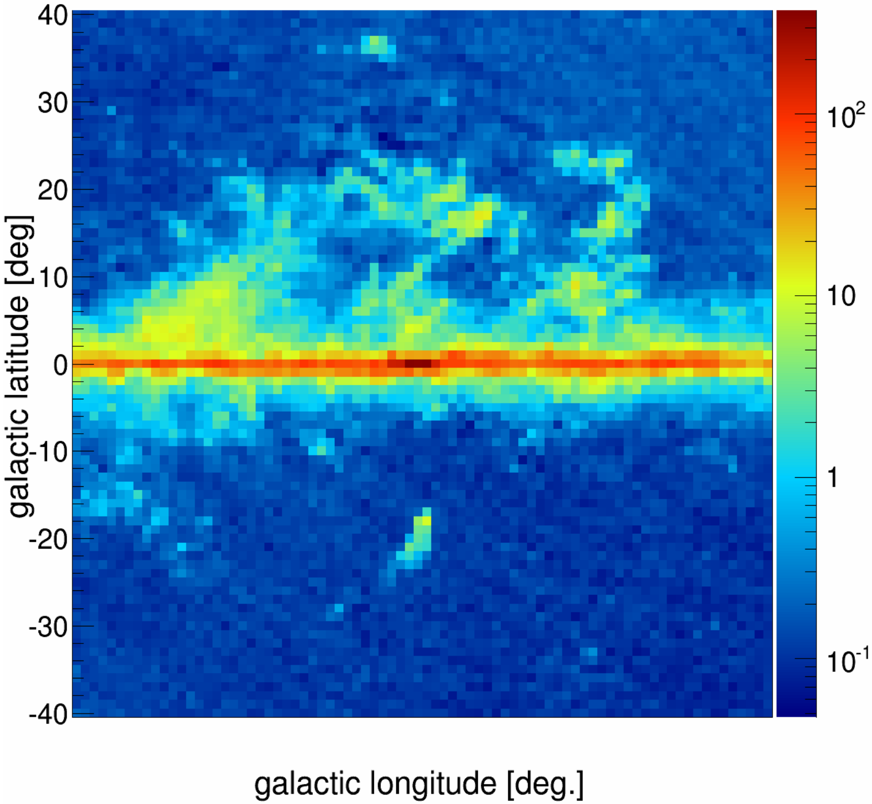
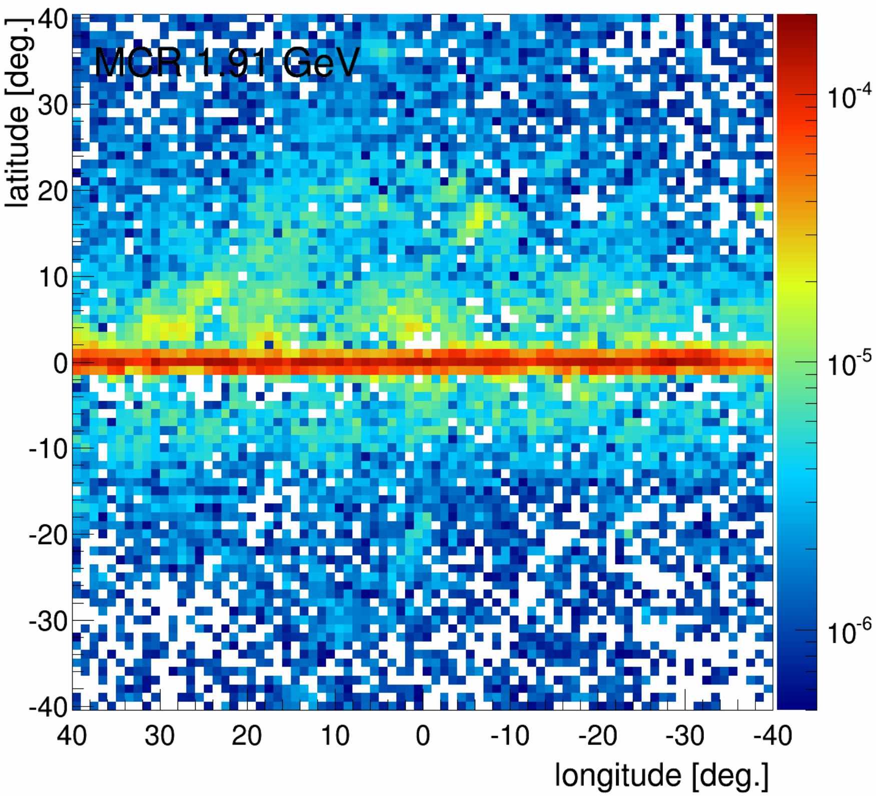
Sky map of CO lines (MCs)

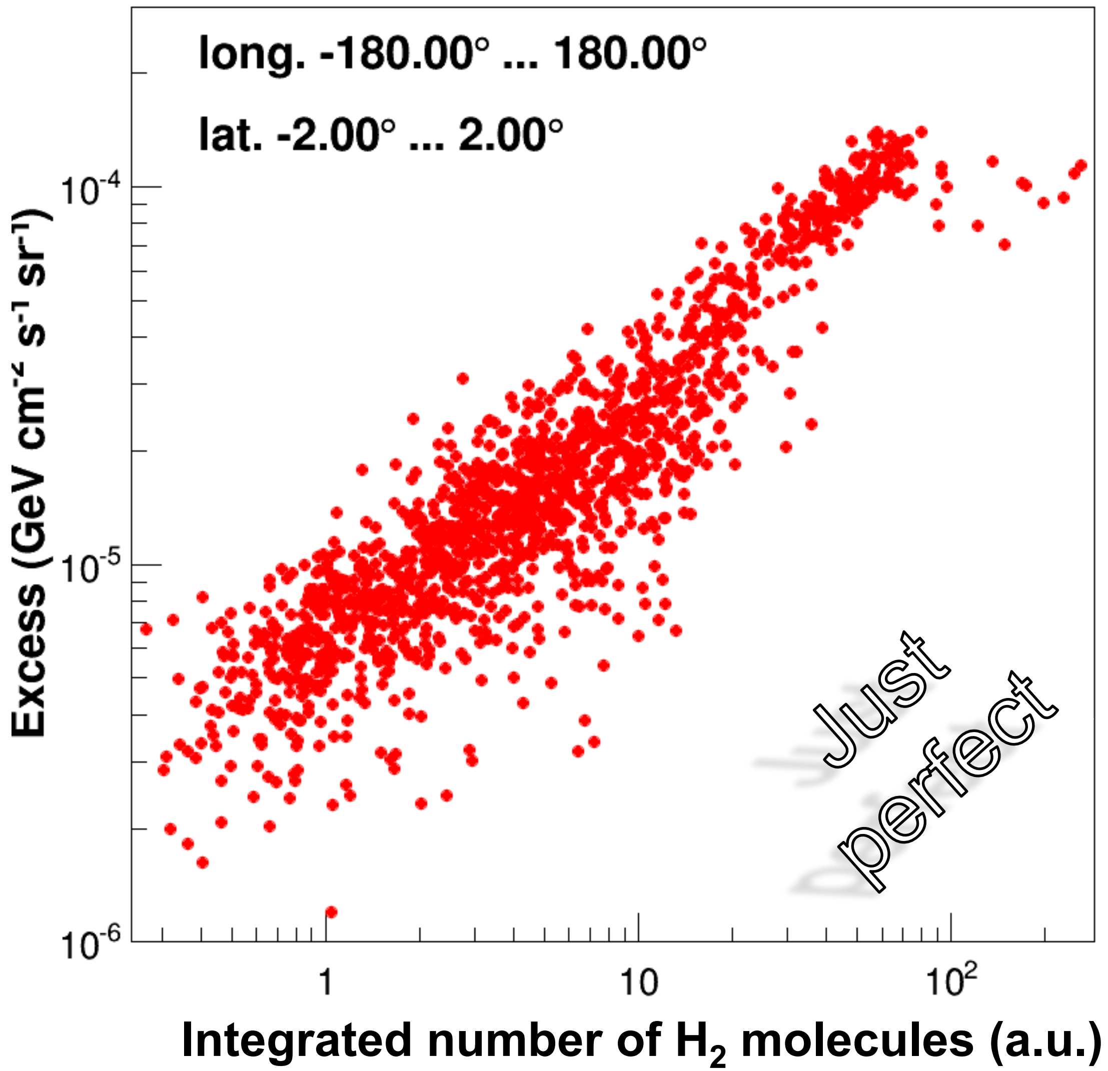


Sky map of excess



Intensity variation of excess („speckling") clear, as first observed by Lee+, 1412.6099 by statistical methods. Speckling correlated with CO map speckling. How strong is correlation?

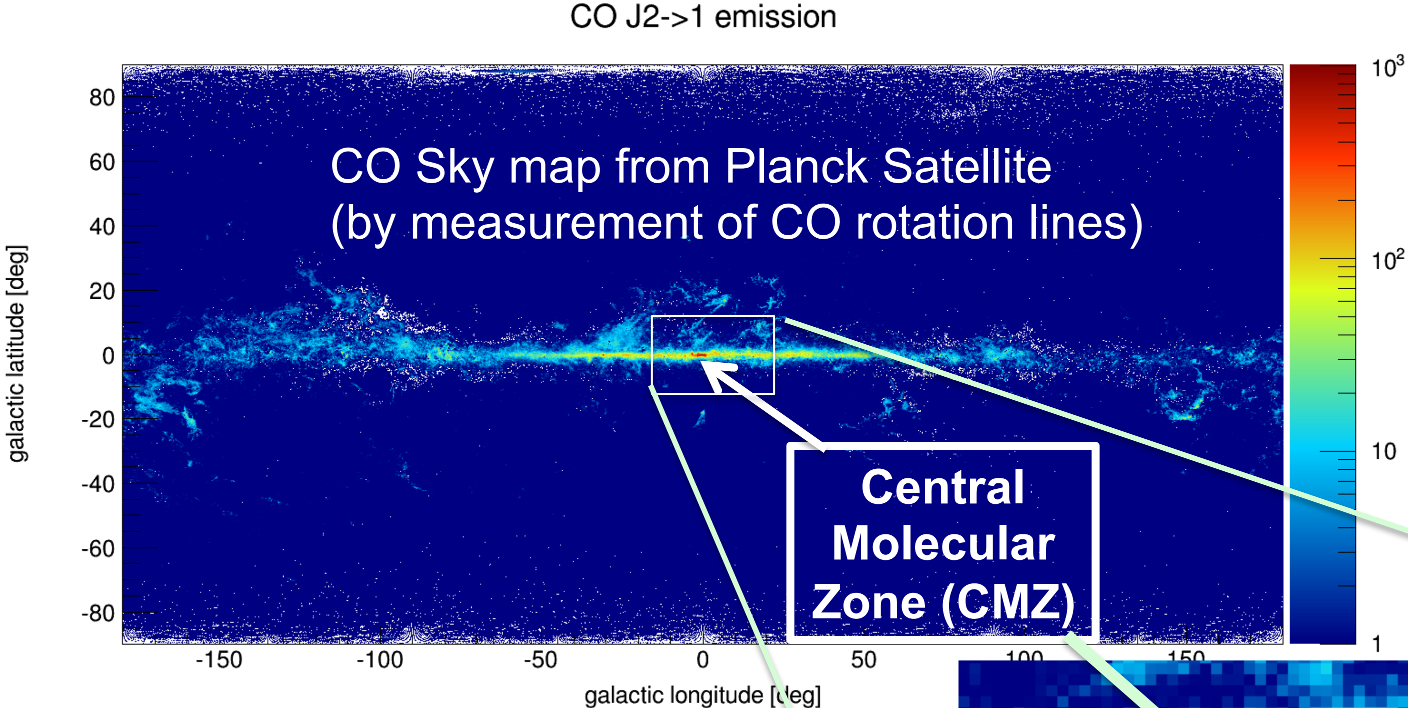
Correlation between sky maps from Excess and CO

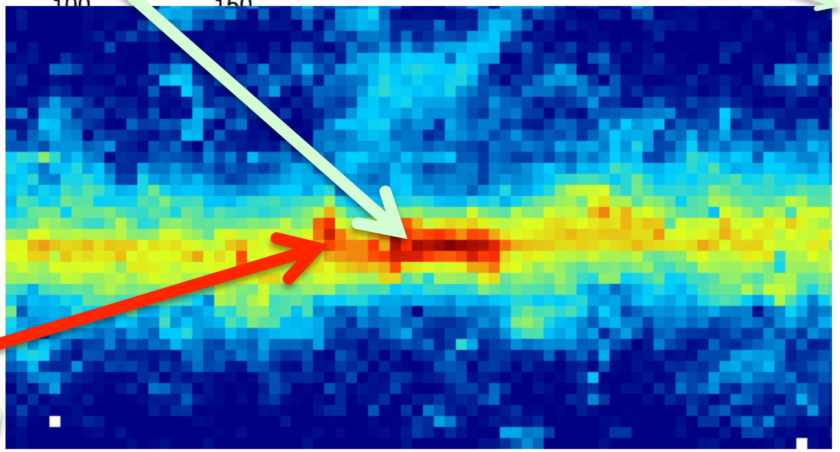


Why could MC spectrum resemble excess?

- **Expect in MCs (compared to diffuse gas): suppressed emissivity below a few GeV (= shift of maximum = excess!) and enhanced emissivity above 50 GeV.**
- **Why such changes of spectrum?**
  - **Suppressed emissivity at low energies because of energy losses and/or magnetic cutoffs** (see e.g. Ivlev+, 1802.02612)
  - **Enhanced emissivity above 50 GeV because of sources inside MCs -> Protons produce gamma-rays in shocked gas with hard $1/E^{2.1}$ spectrum BEFORE diffusive escape,** predicted by Berezhko+. 0404307 and observed in 1309.3955, dB+, 1407.4144)

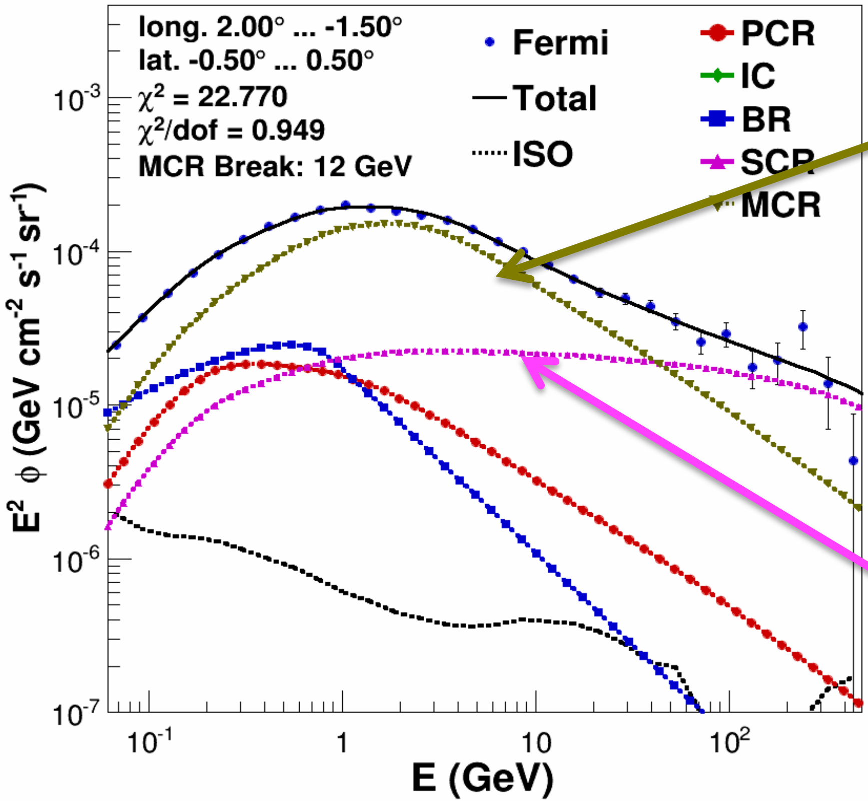
CO sky map from Planck traces MCs





Central Molecular Zone (CMZ)
-1.5° < l < 2°
-0.5° < b < 0.5°
Mass CMZ: 5.10^{7}M$_\odot$ (5% of total MC gas)
(Black hole **GC: 4.10^{6}M$_\odot$**)
Excess has rectangular shape of CMZ!

Template fit to Central Molecular Zone in Galactic Center



Maximum at 2 GeV described by „Molecular Cloud Cosmic Rays“ (MCR template)

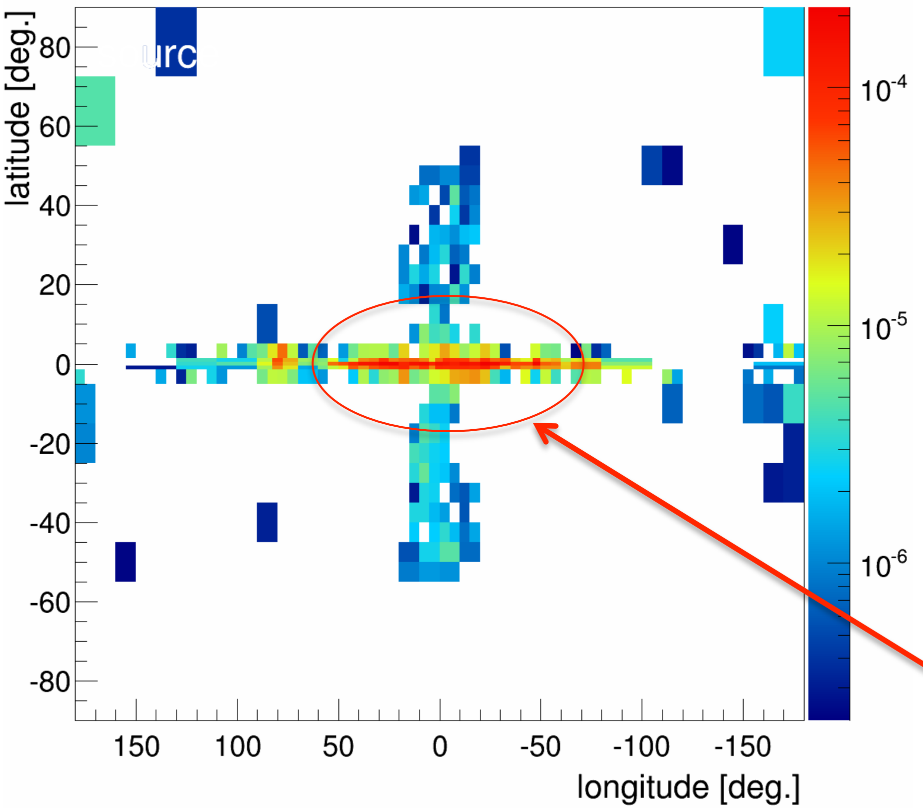
Tail described by „Source Cosmic Rays“ (SCR template) from CRs inside sources

Remember:

SCRs -> spectral tail and follow source distribution (traced by ^{26}Al line)

MCR -> spectral shift and follow MCs (traced by CO rotation line)

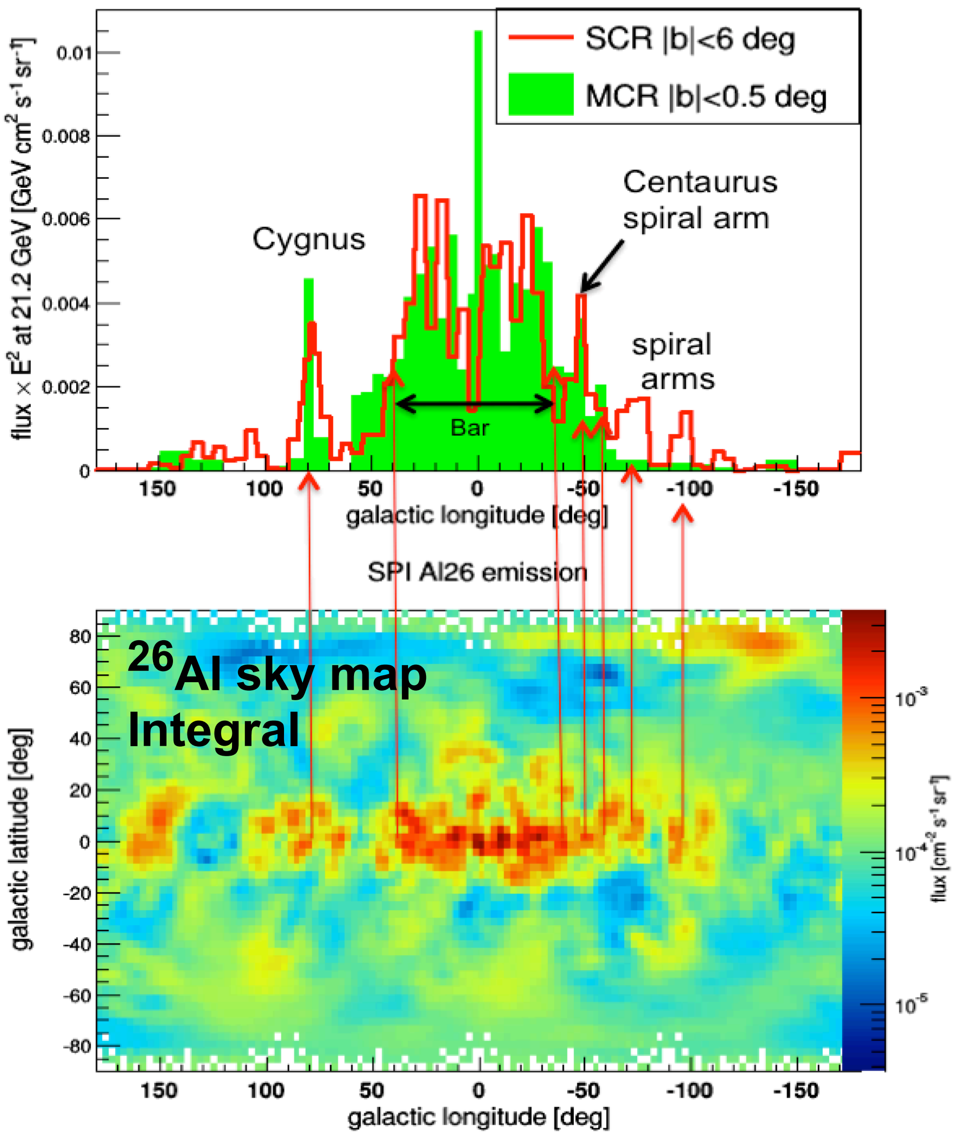
Morphology of Bubble template



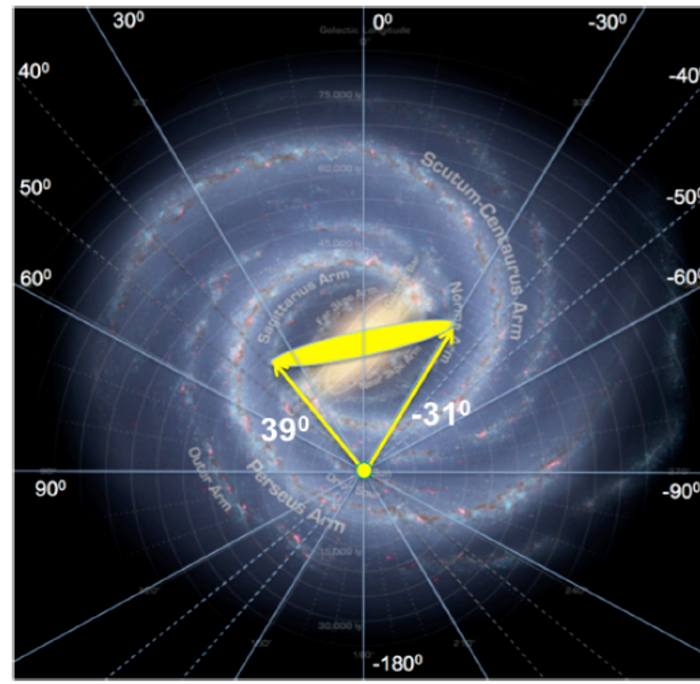
Spectrum stays hard up to 10 kpc above the disk, suggesting that the Bubbles are advective outflows of gas from the GC by CR pressure (see Breitschwerdt, Nature, 2008 and dB+ 1407.4114)

Bubble template also found in disk. Morphology?

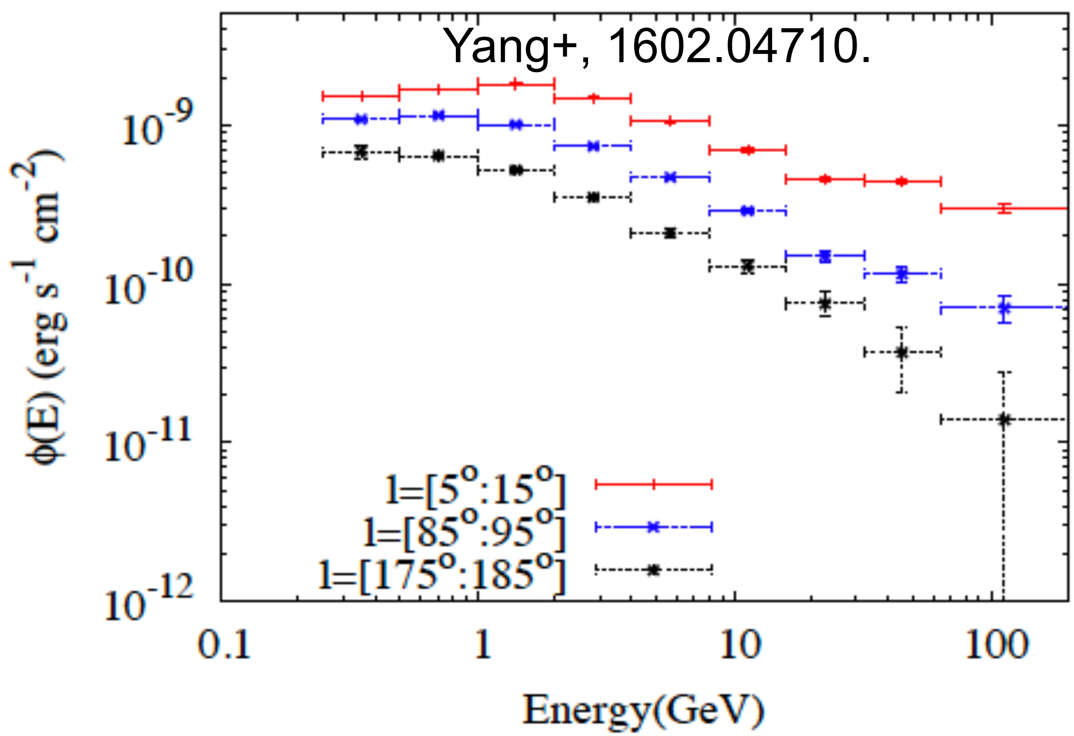
Bubble template in disk follows sources



Triple correlation between (SCR, MCR and ^{26}Al) = (Tail, Shift and Sources)



Spectral hardening towards GC explained by source CRs (SCR)



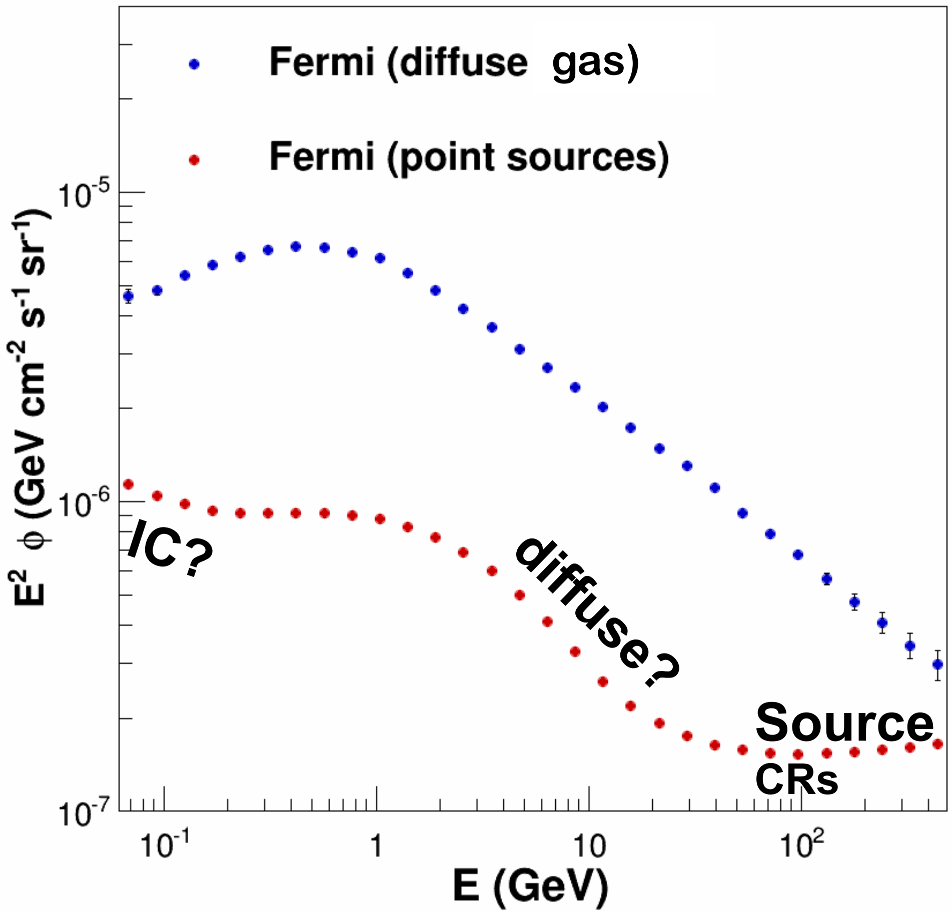
Hardening perfectly described by the SCRs with the morphology of the ^{26}Al line, see dB+, 1407.4144 and 1707.08653.

Attempts to solve the hardening by anisotropic propagation: see
Gaggero+, 1411.7623
Guo+, 1801.05904
Acero+, 1602.07246
Yang+, 1502.04710

However, if the hardening originates from UNPRO-PAGATED SCRs, no way to get good fit.

Emissivity from freshly accelerated protons in sources can only put in by hand with morpology from e.g. ^{26}Al maps.

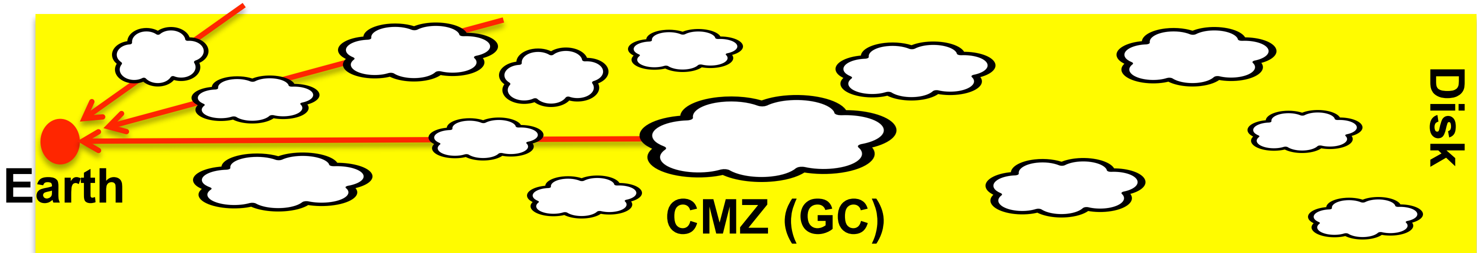
Stacked gamma-ray spectrum from resolved points sources
(from FERMI 3FGL catalog)



Note:

The hard $1/E^{2.1}$ is expected from CRs producing π^0 in the shocked gas

Why should excess be observed in halo, if due to molecular clouds?

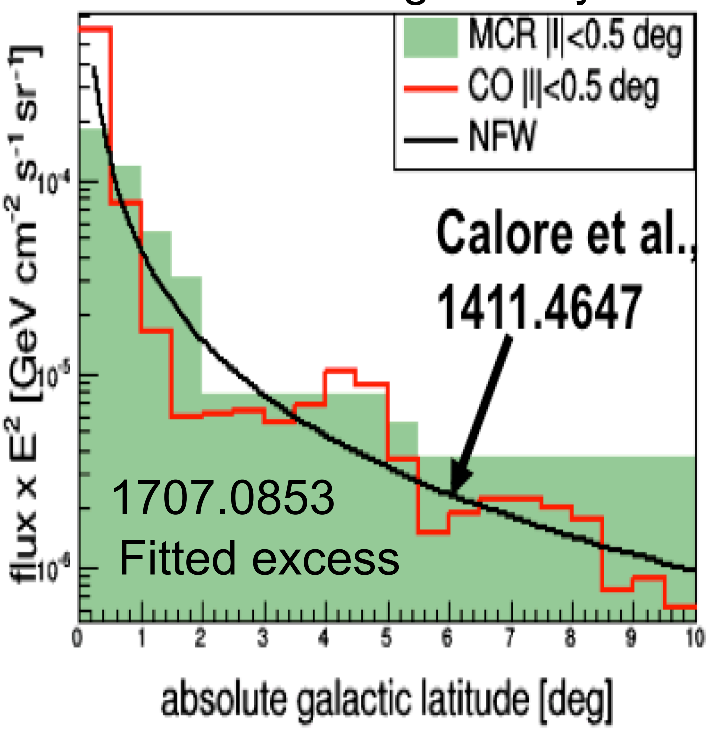


Latitude distribution of

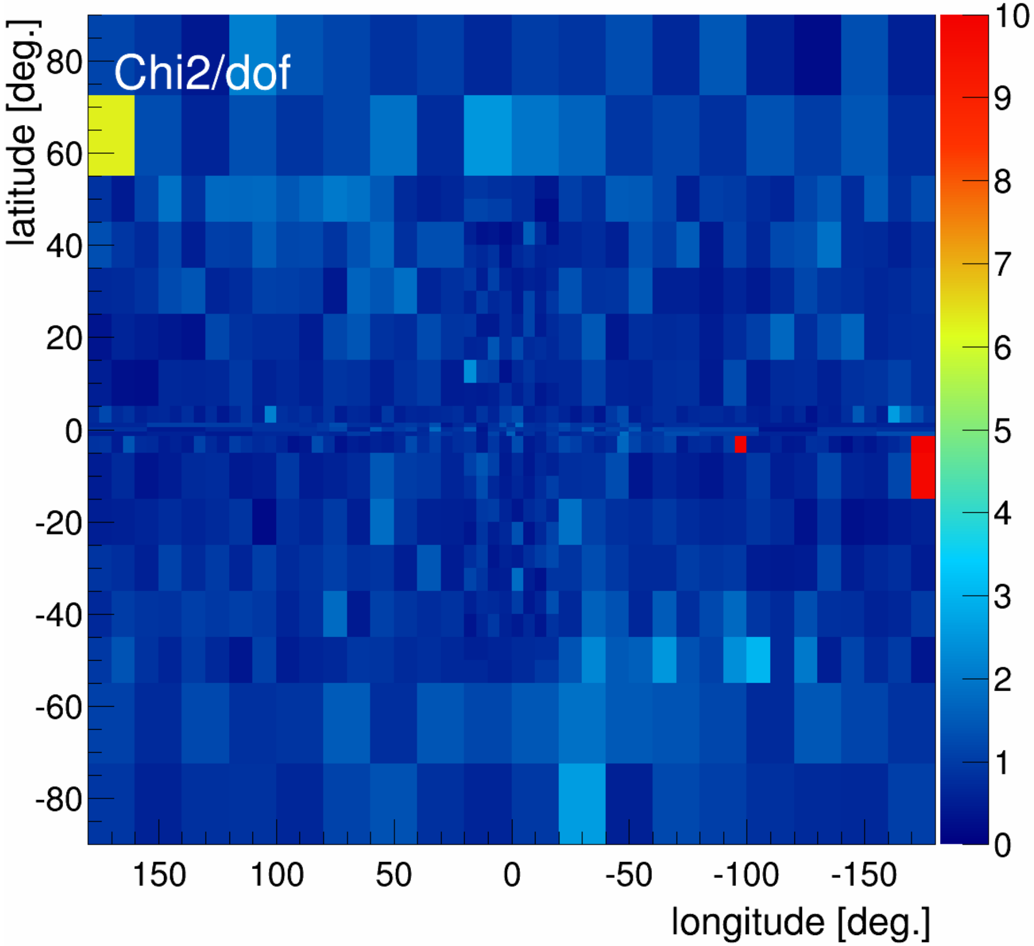
1) **CO sky map (red line)**
2) **NFW profile (black line)**
3) **GeV excess (green histo)**

all agree.

Multiwavelength analysis



Excellent χ^2 over whole gamma-ray sky



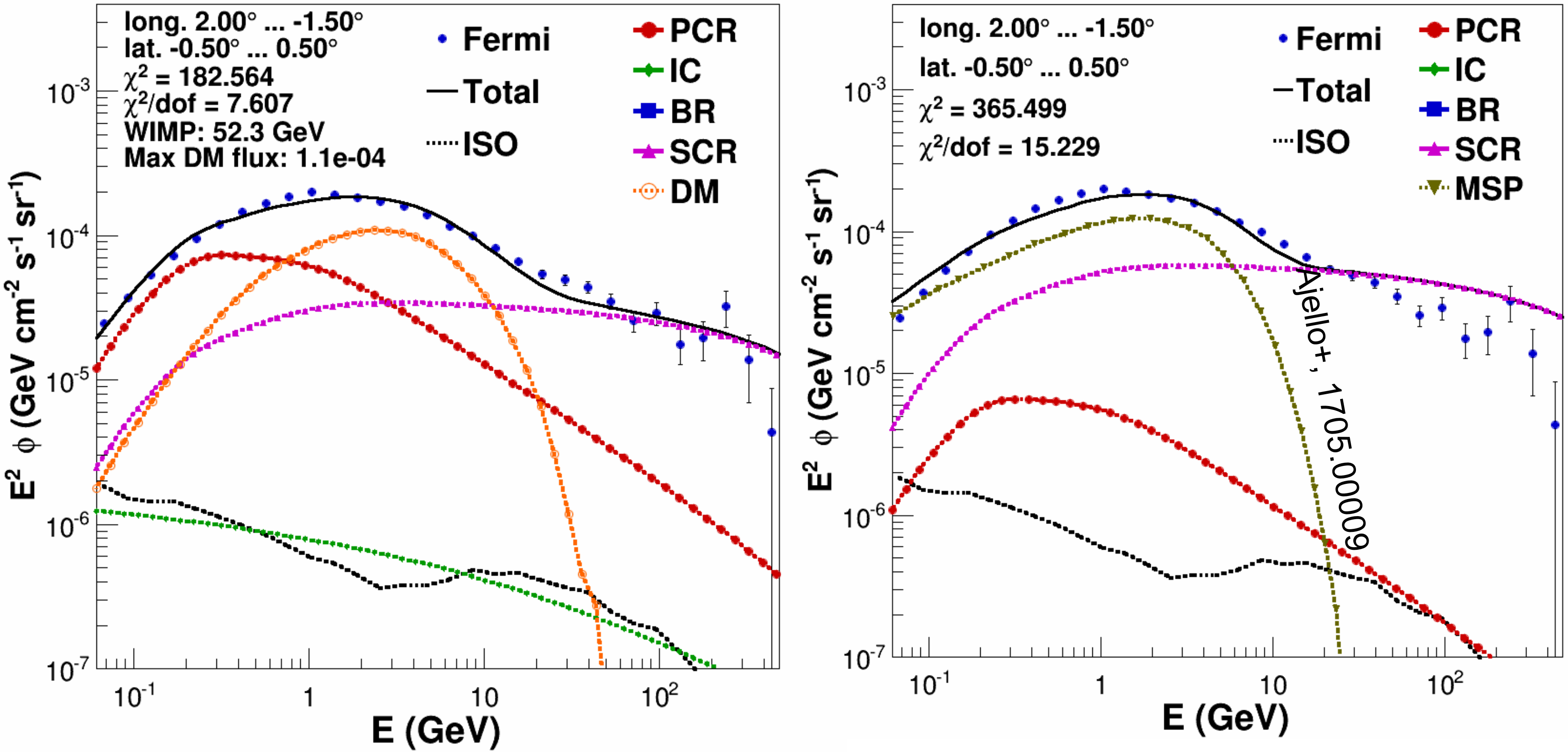
Only 5 physical processes describe the gamma-ray sky.

No need for special treatment of Bubbles, Loop I, dark neutral gas.

No need to know spatial gas templates.

Fit determines contribution of all backgrounds to excess, so no neeed for subtraction (especially difficult for Bubbles, if one uses spatial templates)

Replacing MCR with DM or MSP template in CMZ



X^2 in GC considerably worse for DM and MSP compared with MC hypothesis
Reason: DM and MSP have sharp high energy cut-off, MC not.

Comparing MCR with MSP in the halo (cut out $|b|<2^0$)

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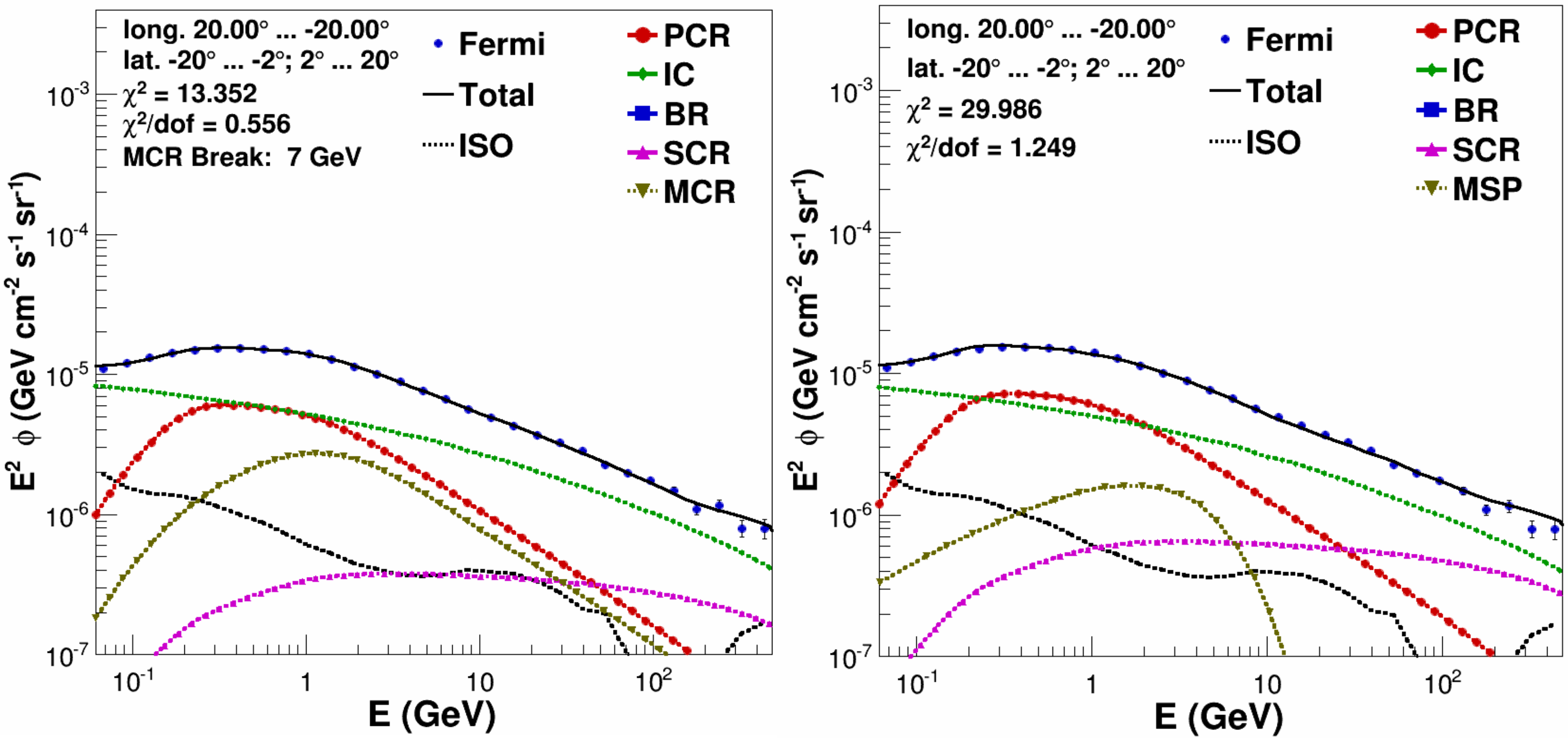
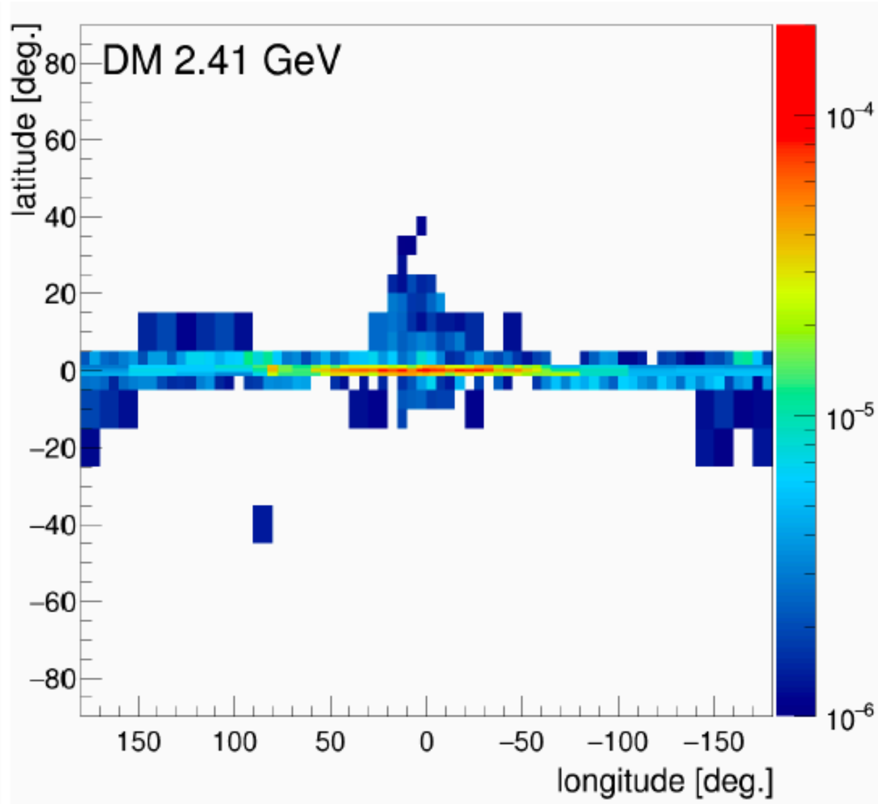
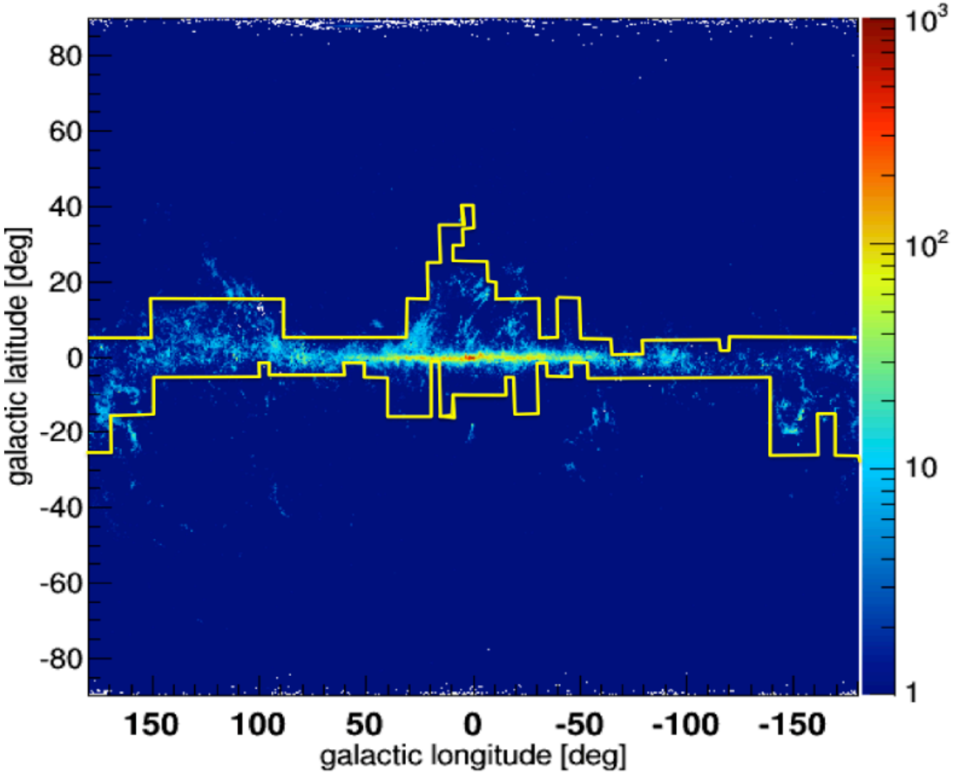


In halo excess small, so MSP only factor two higher χ^2 compared to MCR. Need high spatial resolution of spectral template fits to resolve MCs which allows to distinguish between MC and other hypotheses.

Excess follows CO distribution



WdB + 1707.08653



Conclusion on GeV excess

- **The whole gamma-ray sky is described by:**

$$|\Phi\rangle = n_1|\pi^0\rangle + n_2|BR\rangle + n_3|IC\rangle + n_4|isotropic\rangle + n_5|Bubbles\rangle + n_6|Excess\rangle$$

if one allows the latter two to be present in the disk following ^{26}Al and CO morphology, respectively

- **We compared the dark matter -, the molecular cloud -, and the millisecond pulsar hypothesis to explain the Fermi GeV excess.**

Which hypothesis describes which aspects of excess?

	Spectrum (GC)	Morphology	Speckling	Remarks
DM	X	X	X	Morphology of CO instead of NFW, if whole sky is fitted; spectral shape only ok below 10 GeV
MSP	X	?	✔?	Spectral shape only ok below 20 GeV, need order of magnitude more MSPs than observed to determine morphology and speckling
MC	✔	✔	✔	spectral shape perfect (no cutoff!), follows morphology and speckling of CO map

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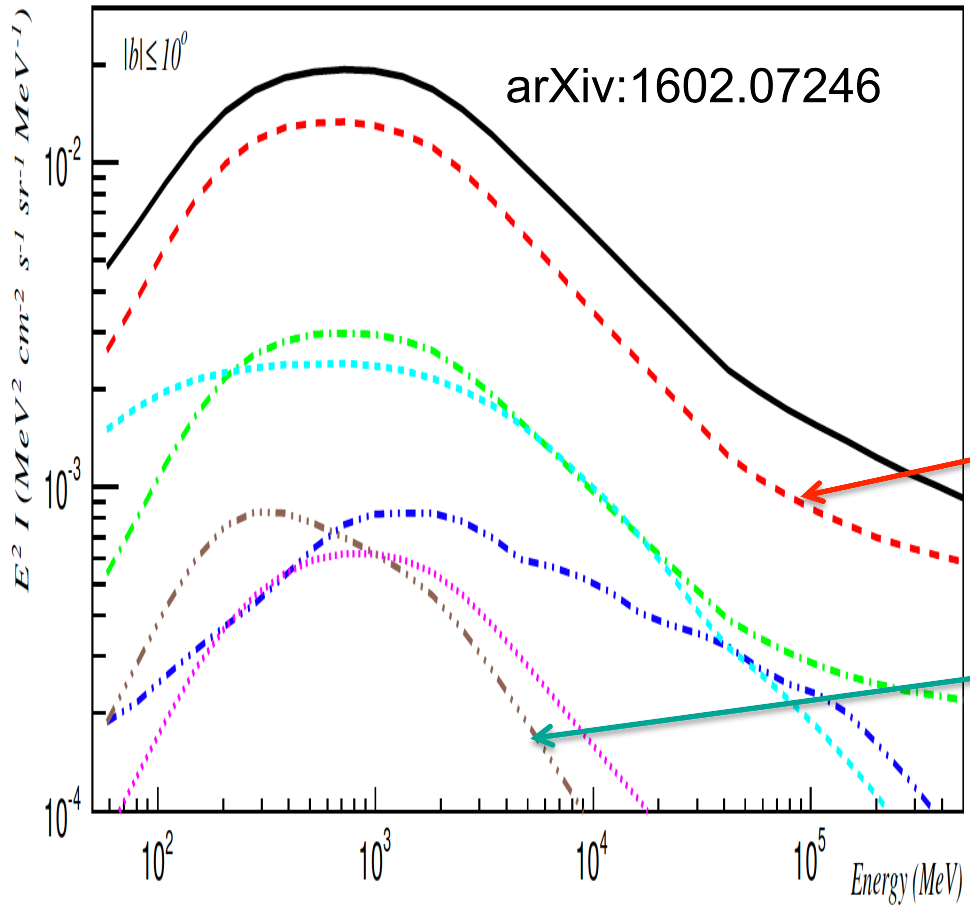
Fermi diffuse model corrected for MC spectral features ad hoc



Fermi Coll. „discovered“ contributions from MCR and SCR without noticing it and made ad hoc corrections.

SCR: the HI gas emissivity was increased above 50 GeV

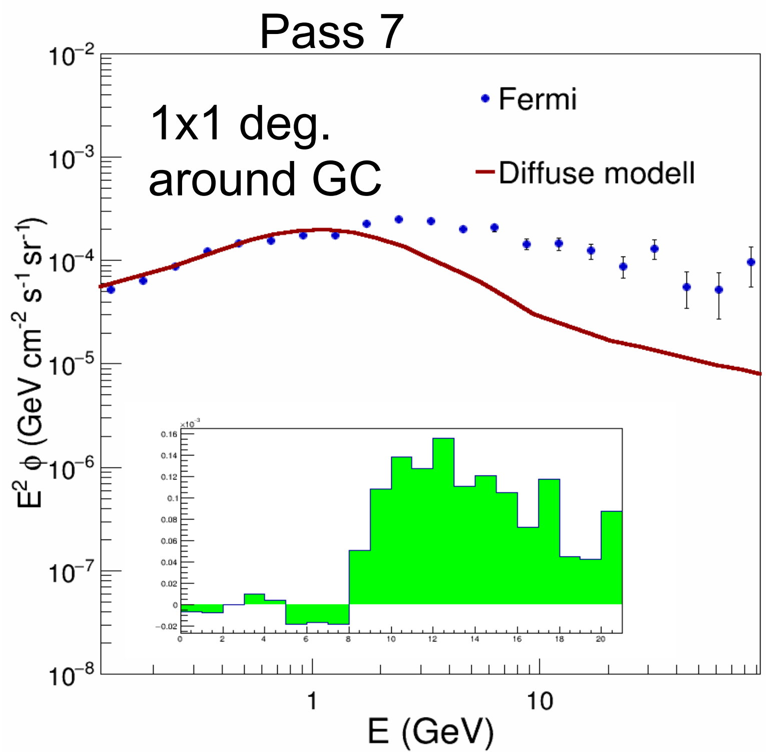
MCR: the H1 emissivity below a few GeV was decreased by a **negative** correction (plotted positive).

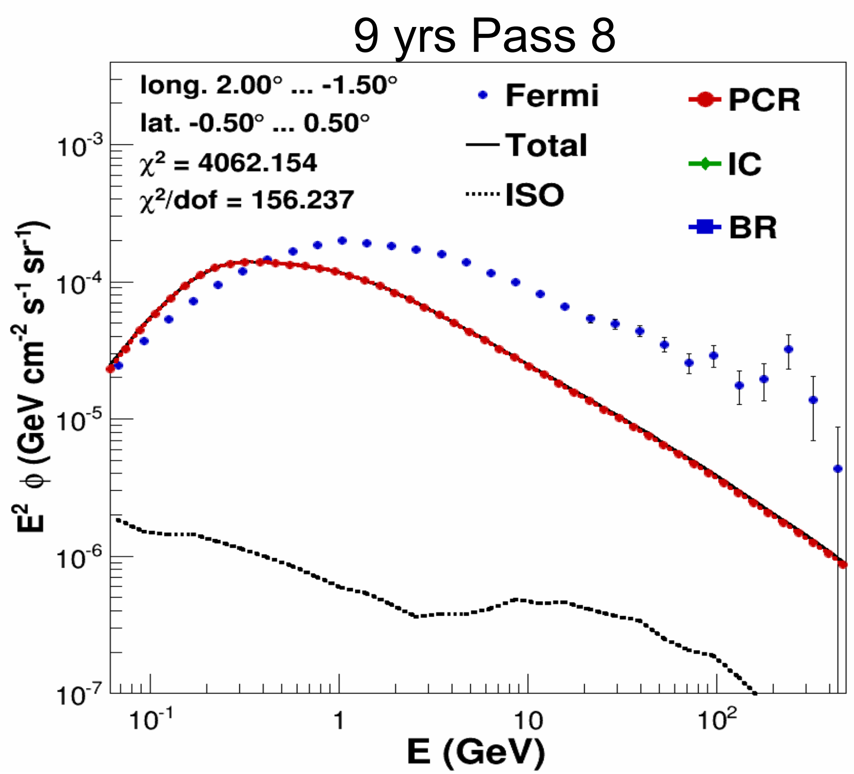
Both corrections should have been applied to the CO map

Diffuse model or propagation models have no good description of Galactic disk

Diffuse model

Galprop





Features of MCs are absent in present models, so they do not describe shift of maximum and large tail