Is the FERMI GeV Excess a Dark Matter Signal?

(The Fermi GeV-Excess and its Correlation with Molecular Clouds)

Using a true multimessenger analysis
(1407.4114, 1509.05310, 1610.08926, 1707.08653)

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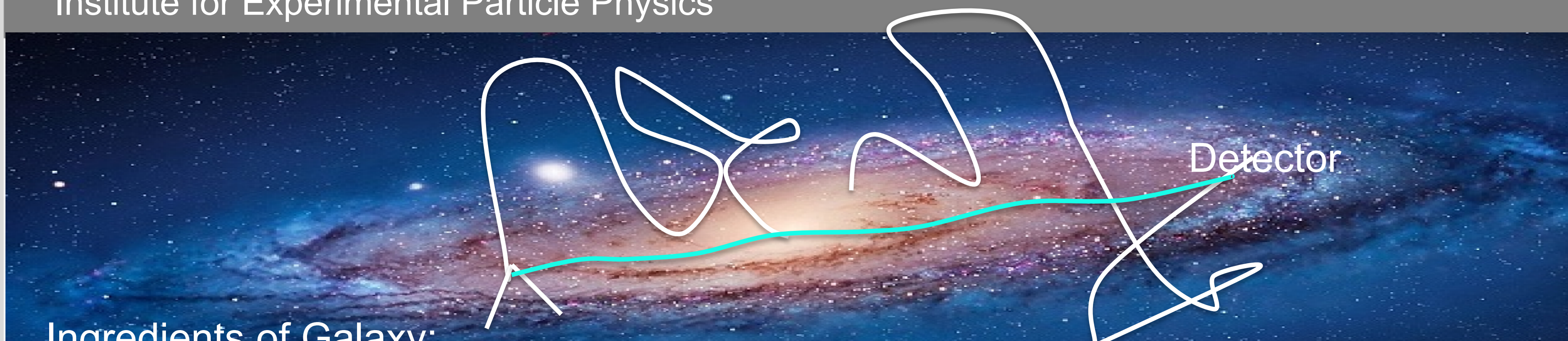

Ingredients of Galaxy:
Dense gas clouds of molecules with star formation and supernova explosions, accelerating charged particles. Accelerated particles interact with gas and photons of interstellar radiation field.

Galactic models (GALPROP, DRAGON,…)

- **Principle:**
  - **reconstruct gas maps from tracers, like CO rotation lines for molecular clouds, 21 cm line for hydrogen atoms, ^{26}Al line for sources,**
  - **measure spectrum of accelerated particles (cosmic rays) (can only be done locally in solar system) and model how they propagated from sources to our detectors**
  - **Calculate interactions of CRs with gas and interstellar radiation field (ISRF) using cross sections from accelerator**
  - **Interactions produce secondary particles, like spallation products of nuclei, gamma rays**
  - **Will concentrate on gamma rays from FERMI and CRs from AMS-02 space experiments. Naively expect that AMS-02 data would describe FERMI data. THIS DID NOT WORK.**
  - **FERMI has "GeV excess" WITH RESPECT TO Galactic Models**

Some features of CR spectra

- **CRs scatter** in plasma of other charged particles and perform some kind of Brownian motion, which can be described by diffusion equation
- **Energetic particles** diffuse faster, so escape earlier from the Galaxy (typically after a few million years)
- **Injection spectrum** from sources expected to have $1/E^{2.1}$ energy spectrum
- **Observed proton** spectrum softened to $1/E^{2.8}$ spectrum by escape
- **Observed electron** spectrum softened to $1/E^{3.2}$ spectrum by energy losses from inverse compton scattering, Bremsstrahlung, ionization and synchrotron radiation
- **HARDLY energy losses for protons**, so spectrum only softened by escape, so expect SAME spectrum everywhere in Galaxy.

Fermi GeV excess papers

Goodenough & Hooper, arXiv:0910.2998 (proposing DM)

- Vitale & Morselli, 2009
- Hooper & Goodenough, Phys. Lett. B697 (2011) 412
- Hooper & Linden, Phys. Rev. D84 (2011) 123005
- Boyarsky, Malyshev & Ruchayskiy, Phys. Lett. B705 (2011) 165
- Abazajian & Kaplinghat, PRD 86 (2012) 083511
- Hooper & Slatyer, Phys. Dark Univ. 2 (2013) 118
- Gordon & Macias, Phys. ReV. D88 (2013) 083521
- Macias & Gordon, PRD 89 (2014) 063515
- Abazajian, Canac, Horiuchi, Kaplinghat, Phys. Rev. D90 (2014) 023526
- Cholis, Evoli, Calore, Linden, Weniger, Hooper, JCAP 1512 (2015) 12
- Calore, Cholis & Weniger, JCAP 1503 (2015) 038
- Zhou, Liang, Huang, Li, Fan, Chang, Phys. Rev. D91 (2015) 123010
- Gaggero, Taoso, Urbano, Valli & Ullio, JCAP 1512 (2015) 056
- Daylan, Finkbeiner, Hooper, Linden, Portillo et al., Physics of Dark Universe 12 (2016) 1 (DM)
- De Boer, Gebauer, Neumann, Biermann, arXiv:1707:08653, PRD, August, 2017 (Molecular Clouds)
- Huang, Ensslin & Selig, JCAP 1604 (2016) 030
- Carlson, Linden, Profumo, Phys. Rev. D94 (2016) 063504
- Bartels, Krishnamurthy, Weniger, Phys. Rev. Lett. 116 (2016) (Millisecond pulsars)
- Macis, Gordon, Crocker, Coleman, Paterson, arXiv:1611.06644
- Lee, Lisanti, Safdi, Slatyer, Xue, Phys. Rev. Lett. 116 (2016) 5 (Millisecond pulsars)
- Ajello et al. 2016, Astrophys. J. 819, 44
- Ackermann et al., 2017, Astrophys. J. 840, 43
- Ajello et al., 2017, arXiv:1705.00009 + others + many theory papers

What is the GeV excess?

(inner Galaxy: $|b|<5^0$, $|l|<30^0$)

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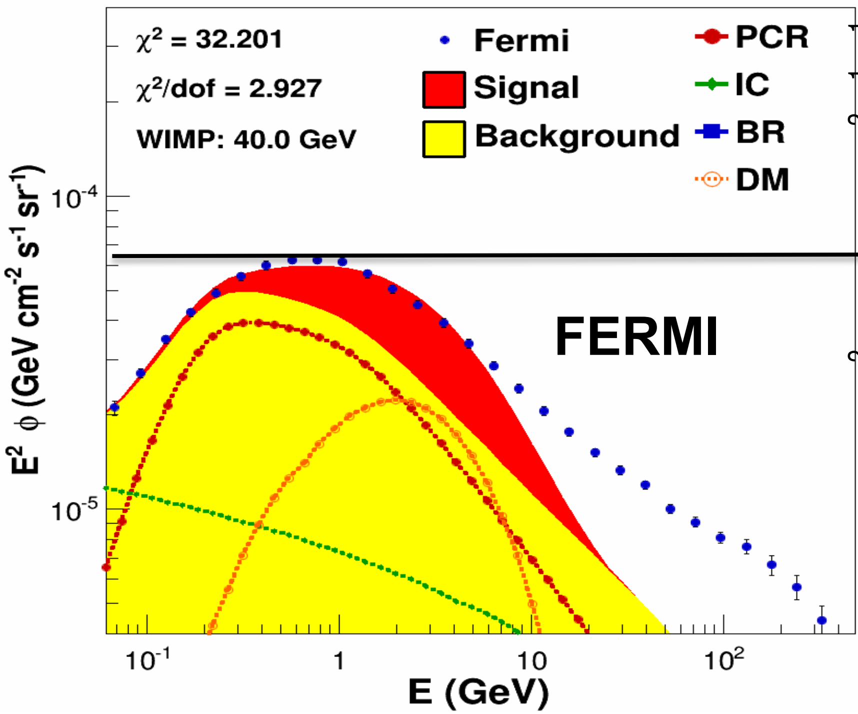
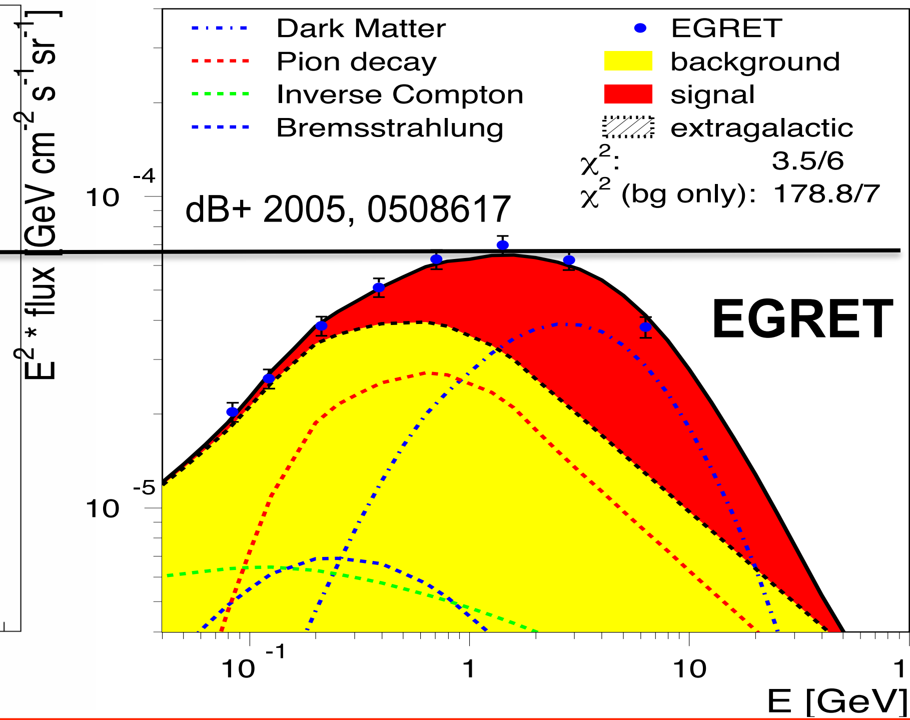




- **Similar excess seen with both satellites! EGRET data up to 10 GeV. FERMI data up to 300 GeV.**
- **BEWARE: a shift in the peak of the spectrum implies an excess if normalized at 0.1 GeV, but a DEPLETION, if normalized at 10 GeV**
- **Large tail In FERMI data provides clue for the origin of the excess Depletion observed inside MCs!**

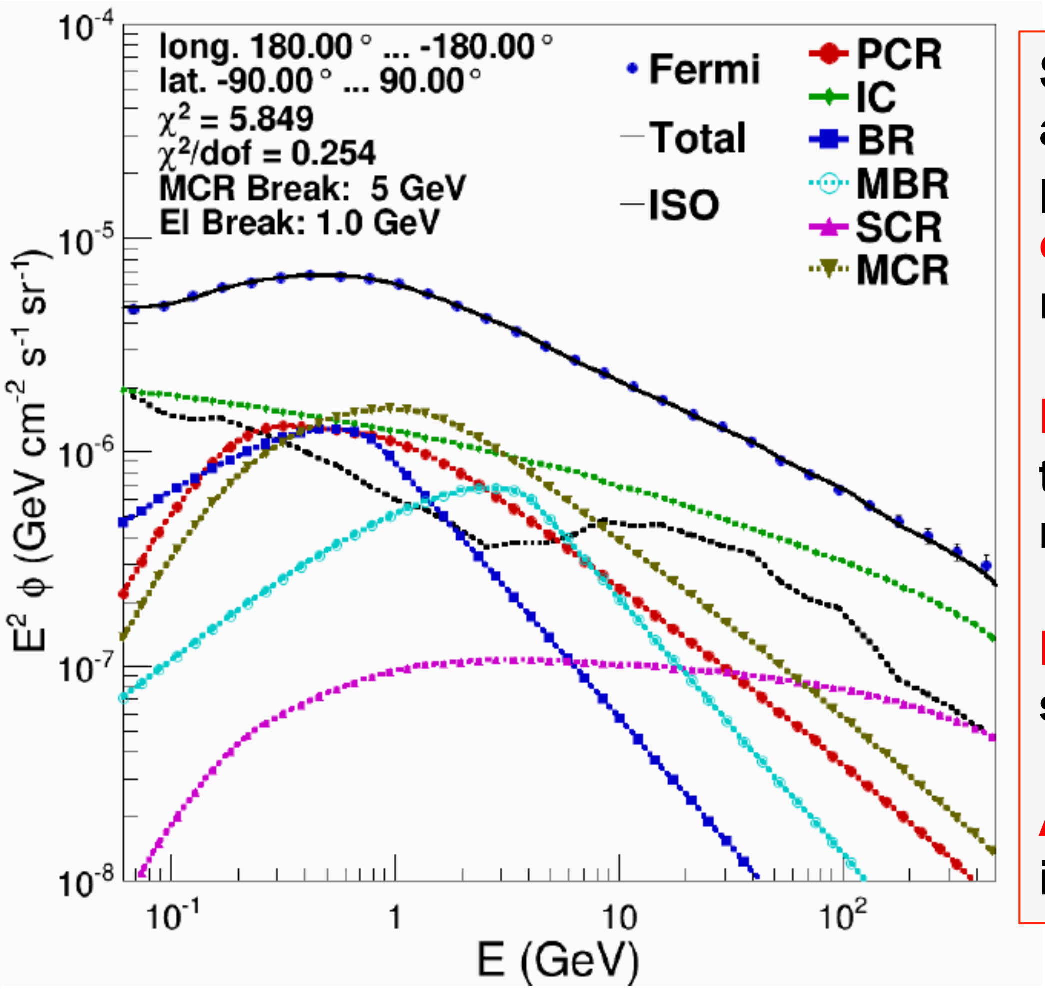
What is new in this analysis?

We take into account that CR spectra in molecular clouds are different from CR spectra in diffuse gas or halo. Fit spectral templates to data.

- **Why special templates for MCs?? Observed in Central Molecular Zone!**
- **Predicted by Ivlev, Dogiel,+, 1802.02612**
- **Note: spectral decomposition ONLY works reliably for good fits, i.e. when all processes are taken into account. A poor fit indicates missing processes**
- **Spectral decomposition allows spatial resolution to resolve MCs**
- **Spectral decomposition does NOT need 3D gas maps and 3D CR distributions**

Standard Templates	Templates in molecular clouds
π^0 by propagated CRs (PCR)	π^0 by propagated CRs in MC (MCR)
Bremsstrahlung by electrons (BR)	Bremsstrahlung in MC (MBR)
Inverse Compton by electrons (IC)	Negligible
Unpropagated Source CRs (SCR)	
Isotropic (extragalactic+background)	(RED MEANS NEW IN THIS ANALYSIS)

All-sky fit



Skymap in FOV can be described by a linear combination of spectra of 7 physical processes, so for all-sky fit only 7 free parameters needed, one normalization for each process.

Fit can be repeated for any FOV,, thus being able to resolve molecular clouds.

Name of the game: how to get spectral template for each process?

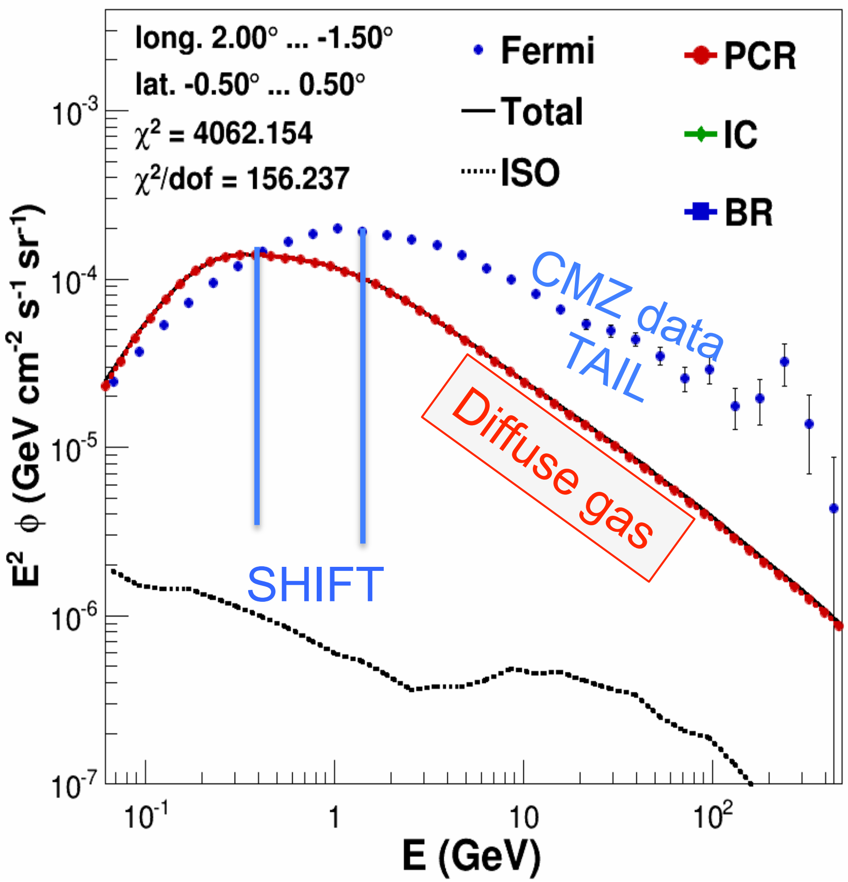
Answer: from DATA. (data driven, iterative procedure)

$$|\Phi\rangle = n_1|\pi^0\rangle + n_2|BR\rangle + n_3|IC\rangle + n_4|iso\rangle + n_5|SCR\rangle + n_6|MCR\rangle + n_7|MBR\rangle$$

(Red: NOT IN GALPROP or DRAGON)

Propagation models have NO good description of molecular clouds (MC)

Fermi data, 9 yrs Pass 8, CLEAN



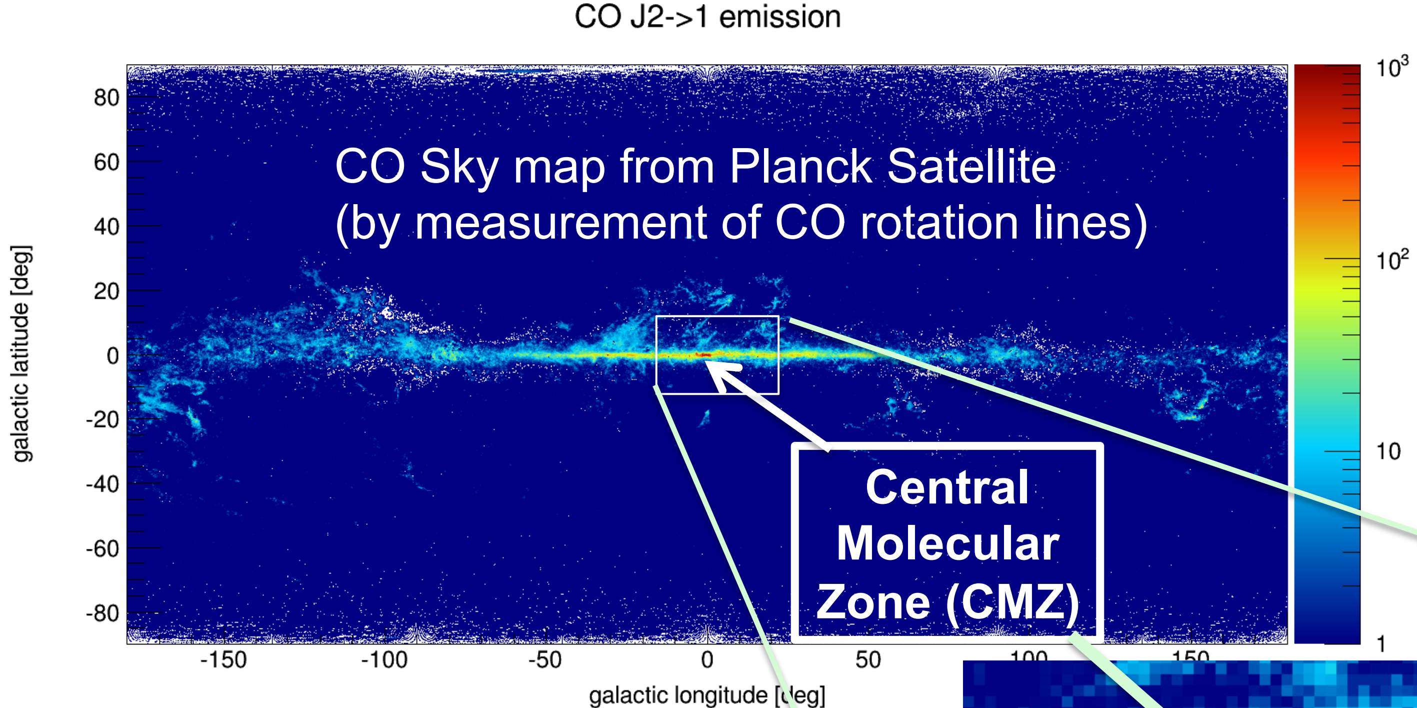
Gamma-ray production in CMZ overshines the foreground! CMZ spectrum COMPLETELY different from diffuse gas

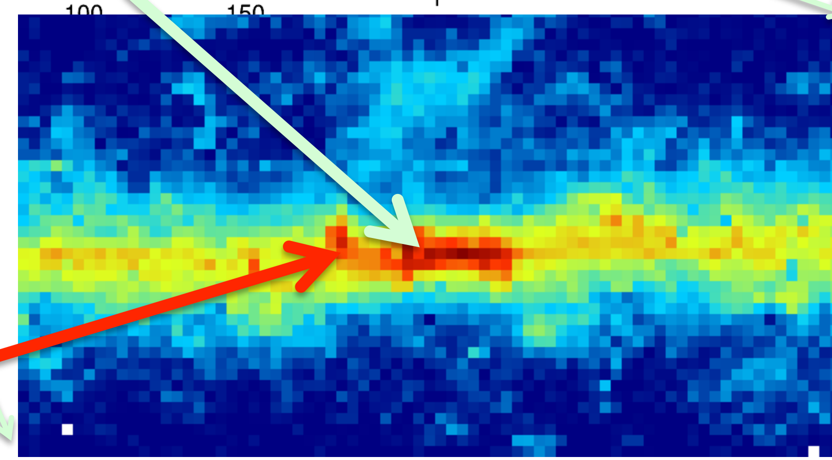
Features of MCs (shift and tail) are absent in diffuse gas. What causes them?

Difference between Galprop and CMZ spectrum is similar to GeV excess!

Is excess caused by different propagation inside MCs??

CMZ shows different CR spectra in 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)

(Super massive black hole **GC: $4.10^{6} M_{\odot}$**)

Foreground at 10% level!

Template fit to Central Molecular Zone in Galactic Center

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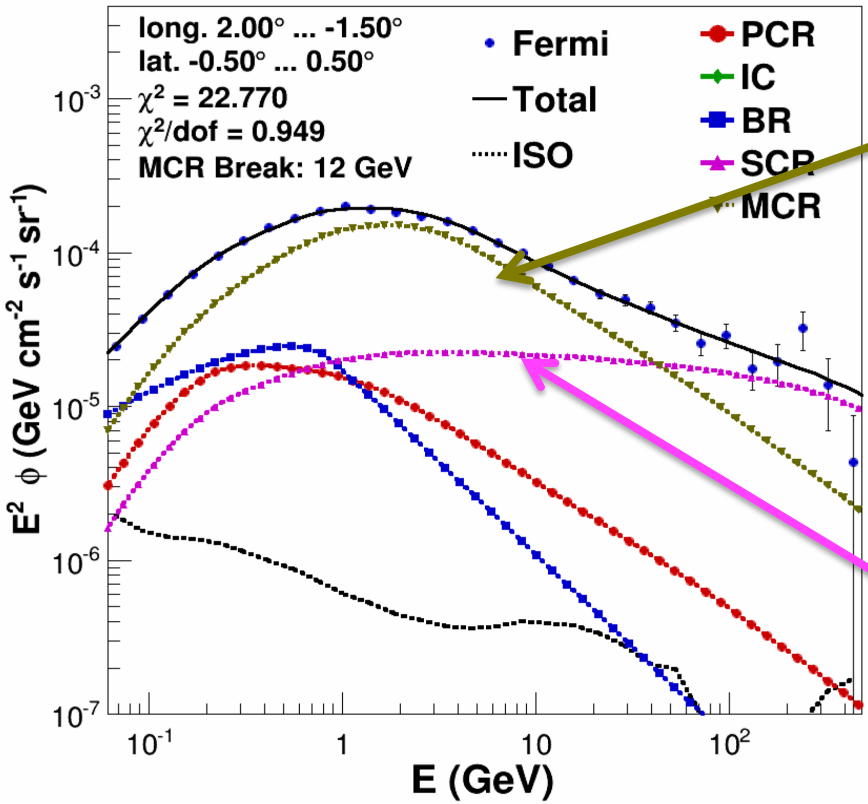


SHIFT of maximum described by „Molecular Cloud Cosmic Rays“ (MCR template)

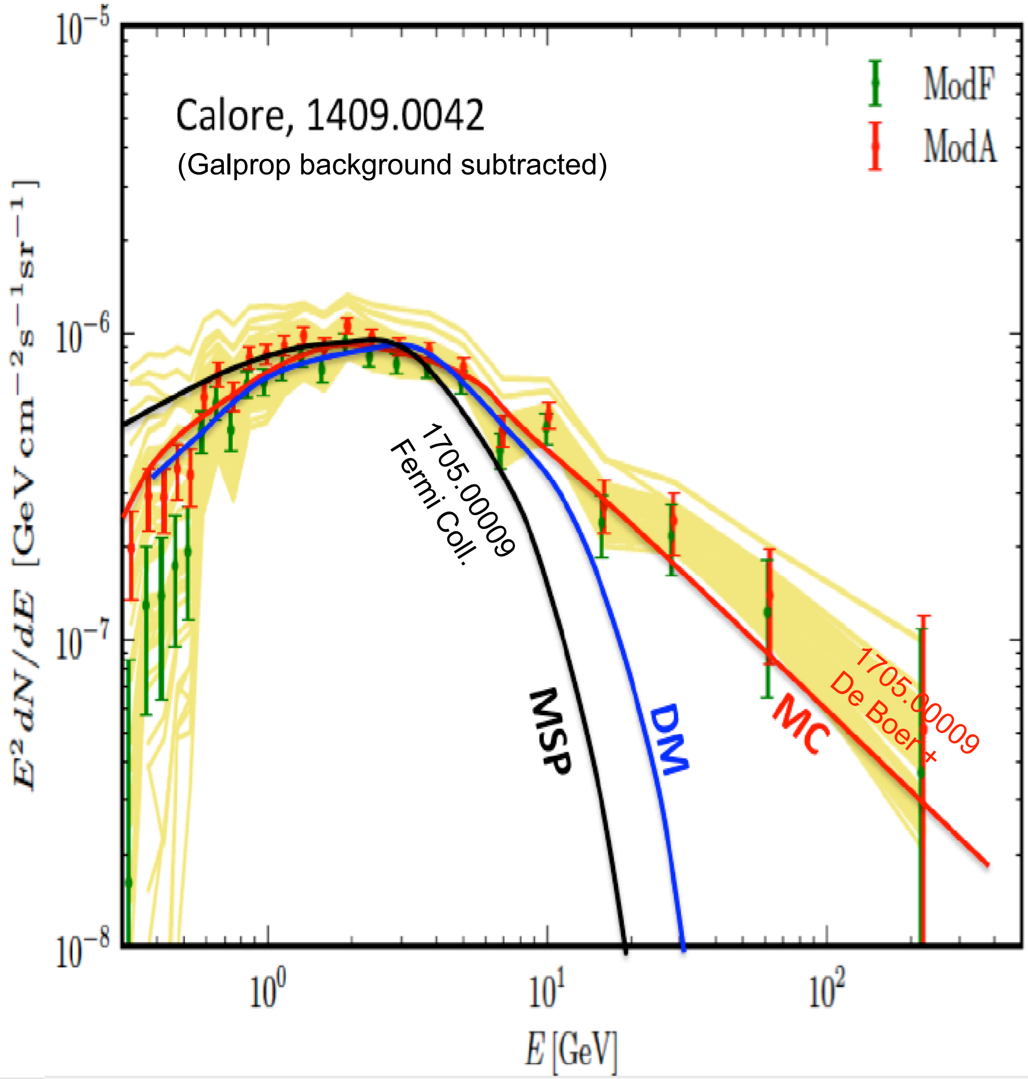
Tail described by „Source Cosmic Rays“ (SCR template) from CRs inside sources

Remember:

SCRs -> spectral tail following sources (traced by ^{26}Al line) +Bubbles
MCRs -> spectral shift following MCs (traced by CO rotation line)

Four possible explanations proposed for excess:

(all having spectrum peaking at 2 GeV)



DM from Daylan+ 1402.6703(Hooper, Linden)

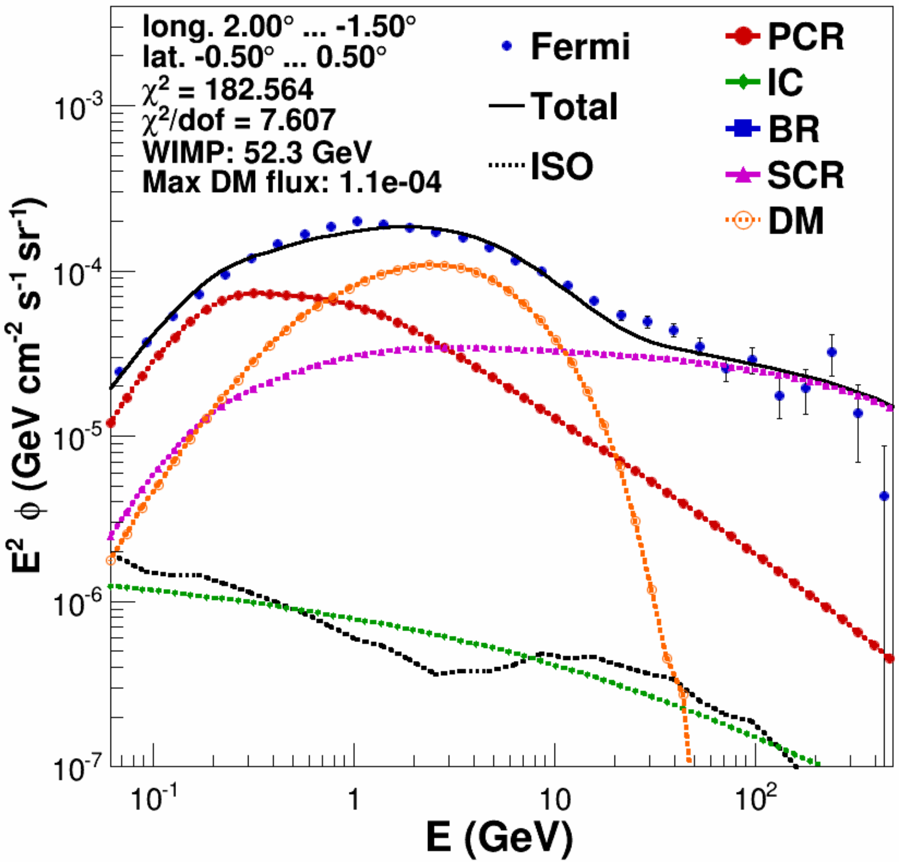
MSP, from Bartels+ 1506.05104 (Weniger)

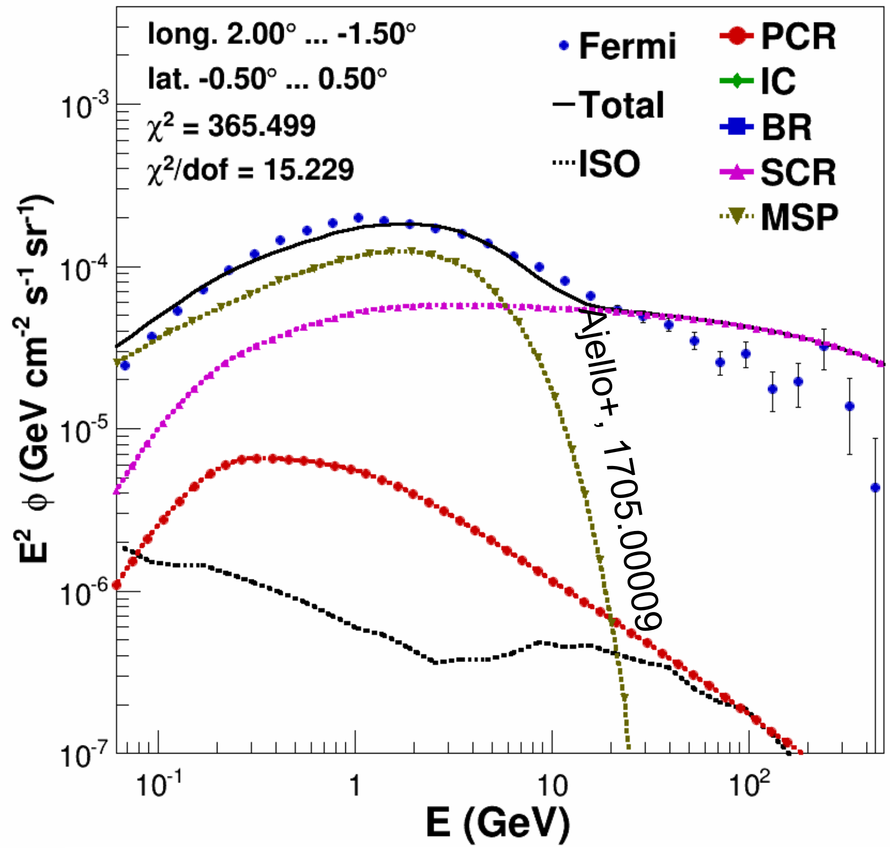
MC, from de Boer+, 1707.08653, 1712.06644

Detector effect, from Dogiel, Malyshev, 1810.05821

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

Replacing MCR by DM or MSP template in CMZ





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

Prediction of MCR template (Ivlev, Dogiel,+, 1802.02612)

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PENETRATION OF COSMIC RAYS INTO DENSE MOLECULAR CLOUDS: ROLE OF DIFFUSE ENVELOPES*

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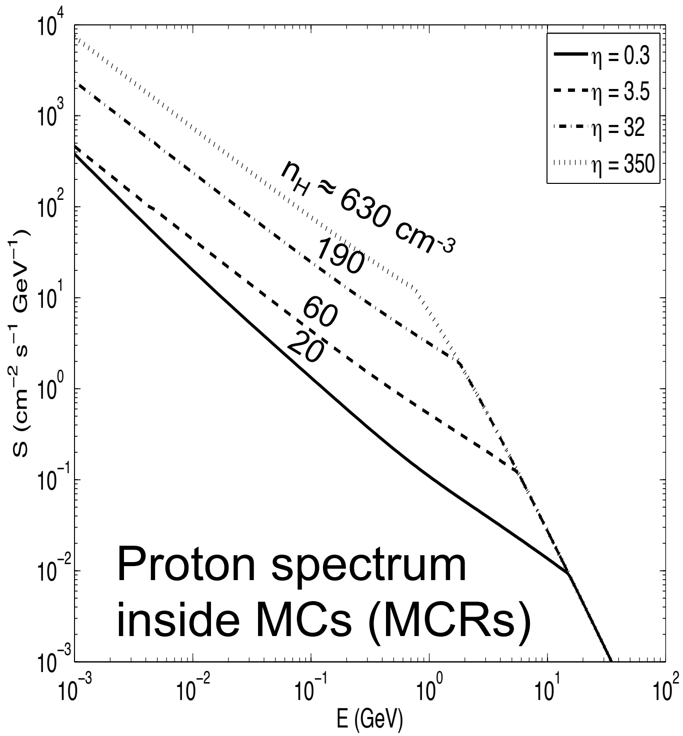
Draft version February 9, 2018

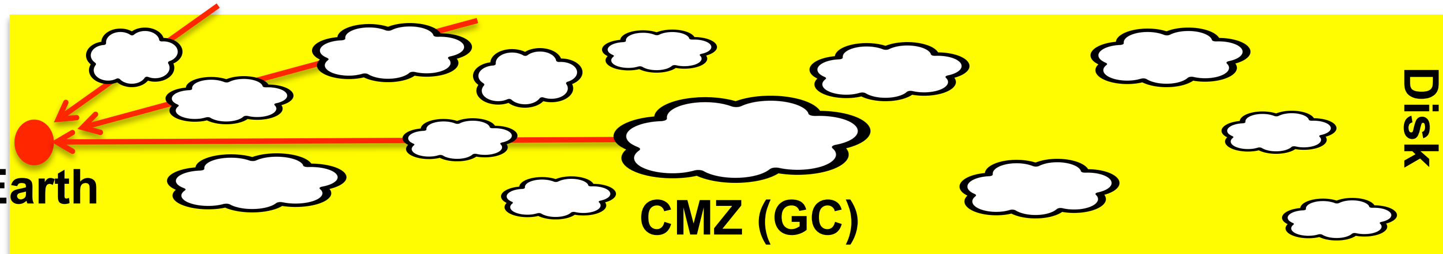
Predictions



- **Sharp break in proton spectrum**
- **Proton slope below break: -1**
  above break: as for local CRs
- **Break is higher for lower density**
- **Same break for electrons**
- **Electron slope: below break: -1**
  above break: as for local electrons

Purpose of talk: answer, if CRs suppression in MCs can explain the Fermi excess (= shift)

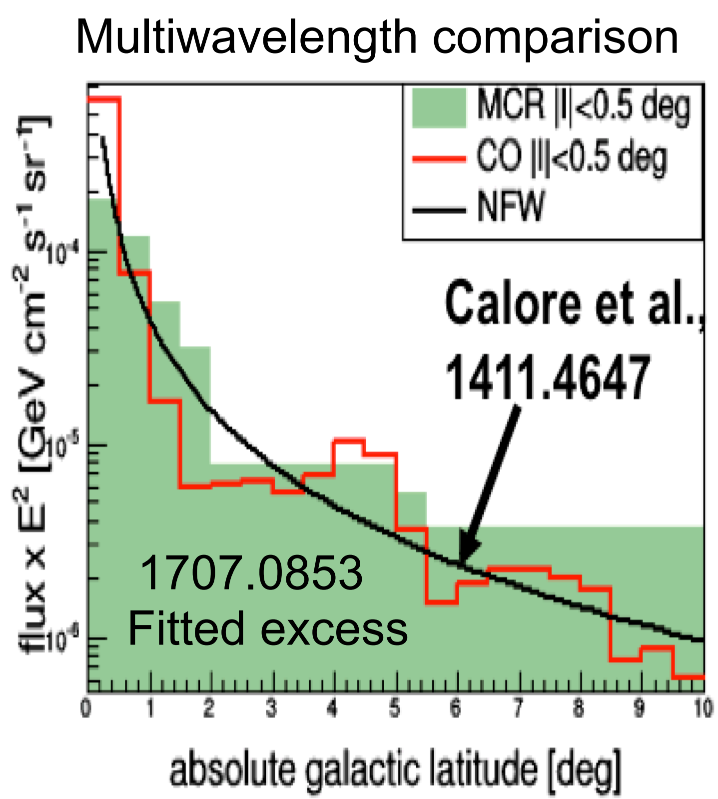
Why should excess be observed in halo, if due to molecular clouds?



Latitude distribution of

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

all agree.



Repeat: our template fit yields in halo similar excess as other analysis

Fit procedure

(9 yrs of Fermi Pass 8 CLEAN data)

Fit gamma-ray spectrum in each FOV by a linear combination of the templates with the normalizations n_1-n_7 as free parameters for 30 energy bins (0.059 - 513 GeV):

$$|\Phi\rangle = n_1|\pi^0\rangle + n_2|BR\rangle + n_3|IC\rangle + n_4|iso\rangle + n_5|SCR\rangle + n_6|MCR\rangle + n_7|MBR\rangle$$

(RED: NOT IN GALPROP or DRAGON)

Plotting the coefficients n_1-n_7 as function of longitude and latitude provides the morphology in a sky map (note: n_4 is same for all FOVs)

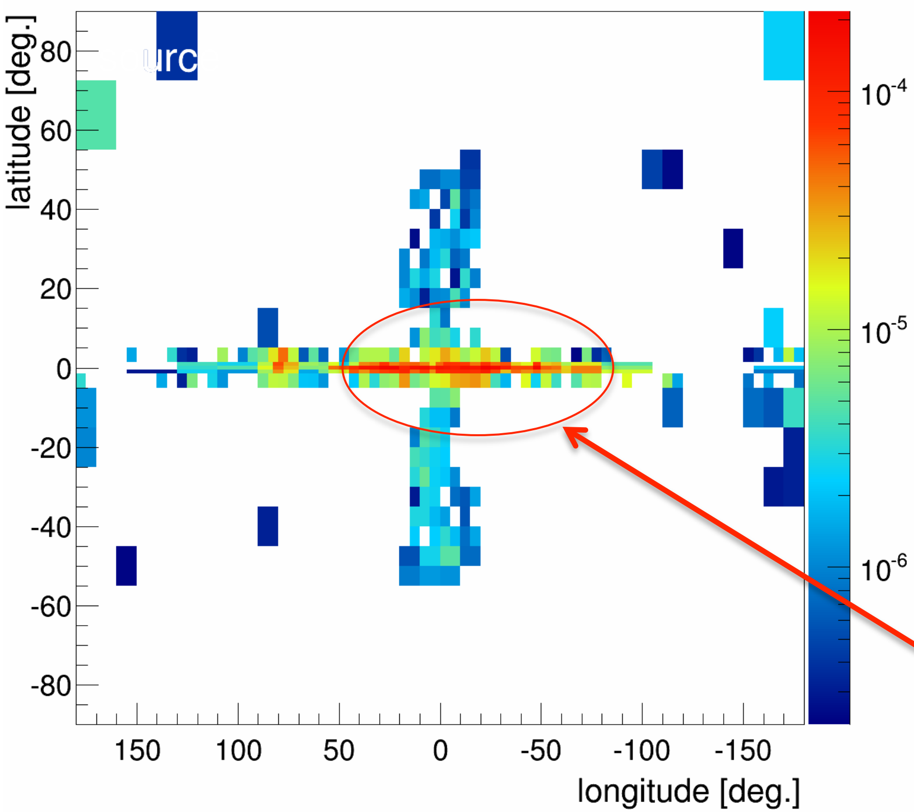
Surprising results:

1) **MCR template (= shift = excess) has morphology of CO maps (tracing molecular clouds (MCs))**
2) **SRC template with hard $1/E^{2.1}$ spectrum has the morphology of ^{26}Al line (traces sources). Are these the predicted Source Cosmic Rays (SCRs), expected from π^0 production of freshly propagated protons crossing shocked gas? SCR also found in Bubbles**

Morphology of SCR template

(π^0 production from $1/E^{2.1}$ proton spectrum)

Sky map of Bubble template

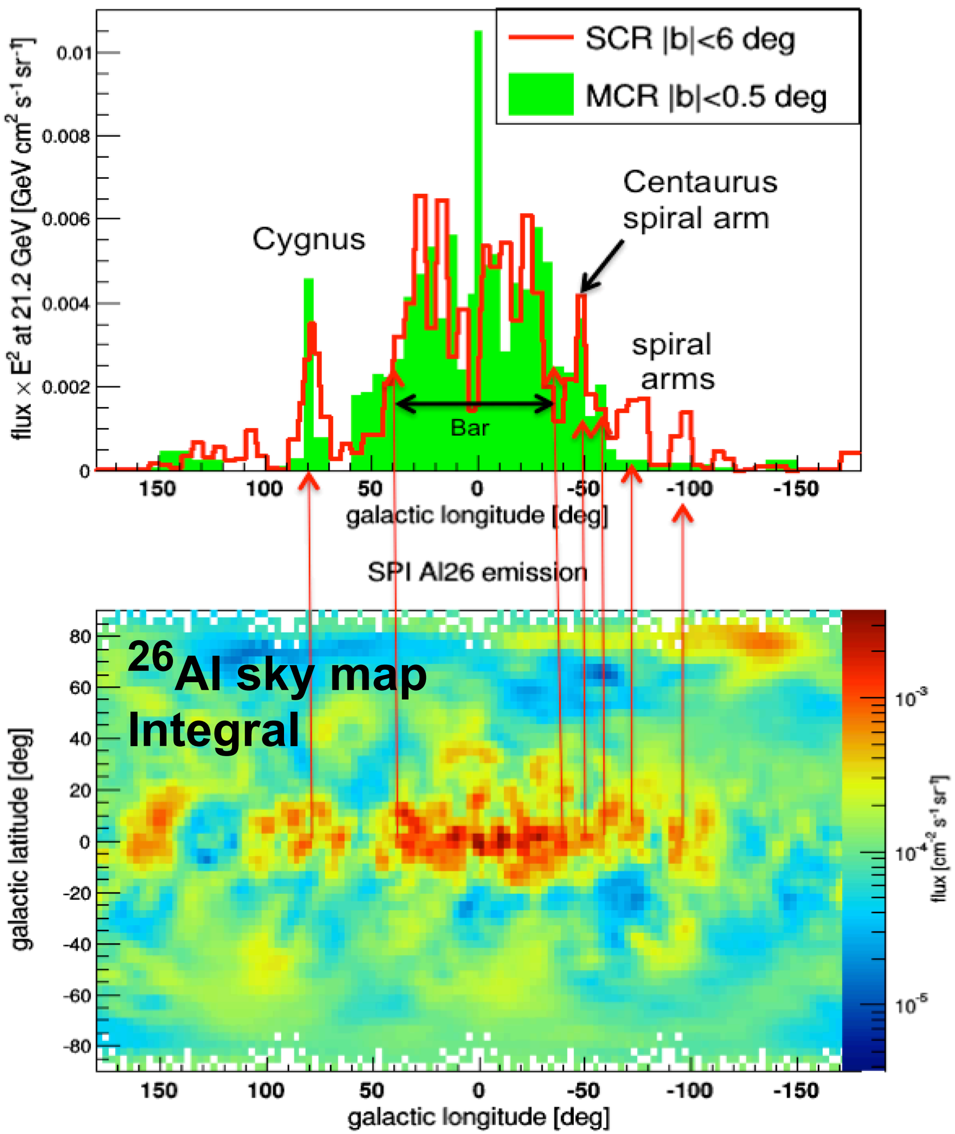


Surprise: SRC template both in halo (Bubbles) and disk

Fresh protons in halo suggests that the Bubbles are advective outflows of gas from the GC by CR pressure and temperature
(Breitschwerdt, Nature, 2008 and dB+ 1407.4114)

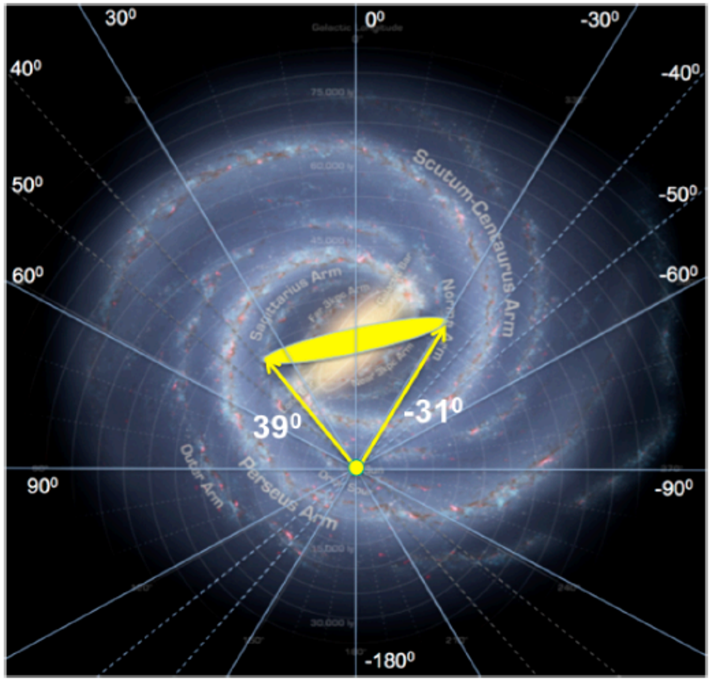
What is morphology in disk?

SCR template in disk follows sources

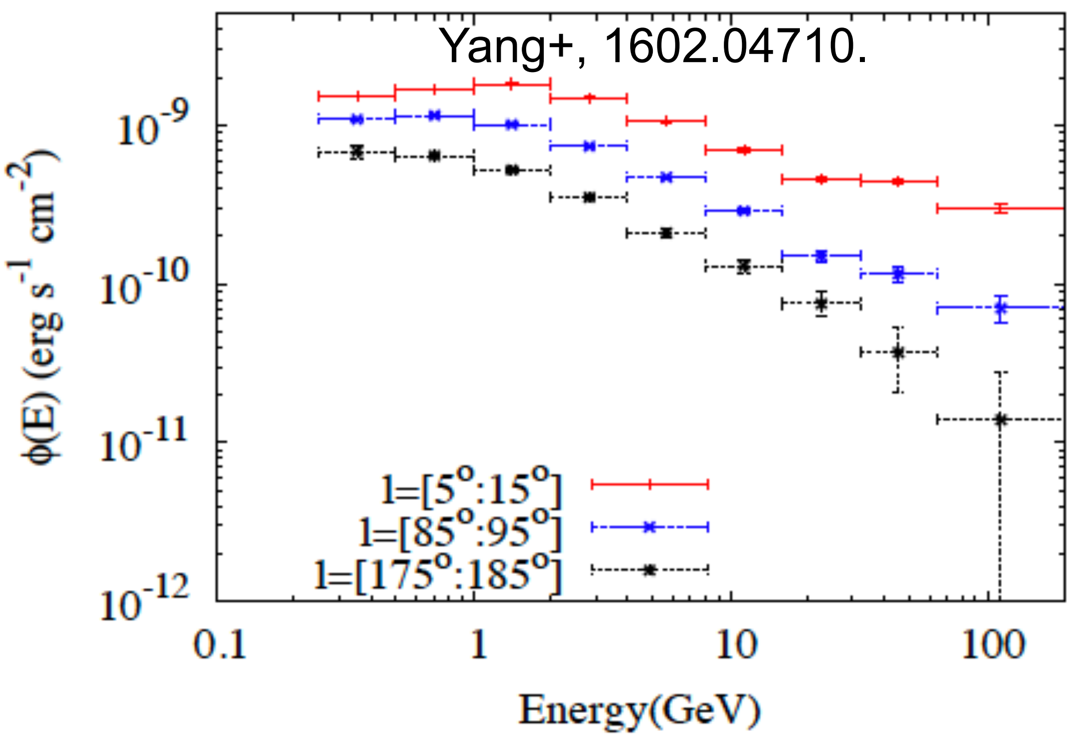


True multiwavelength analysis

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



Spectral hardening towards GC explained by source CRs (SCR)

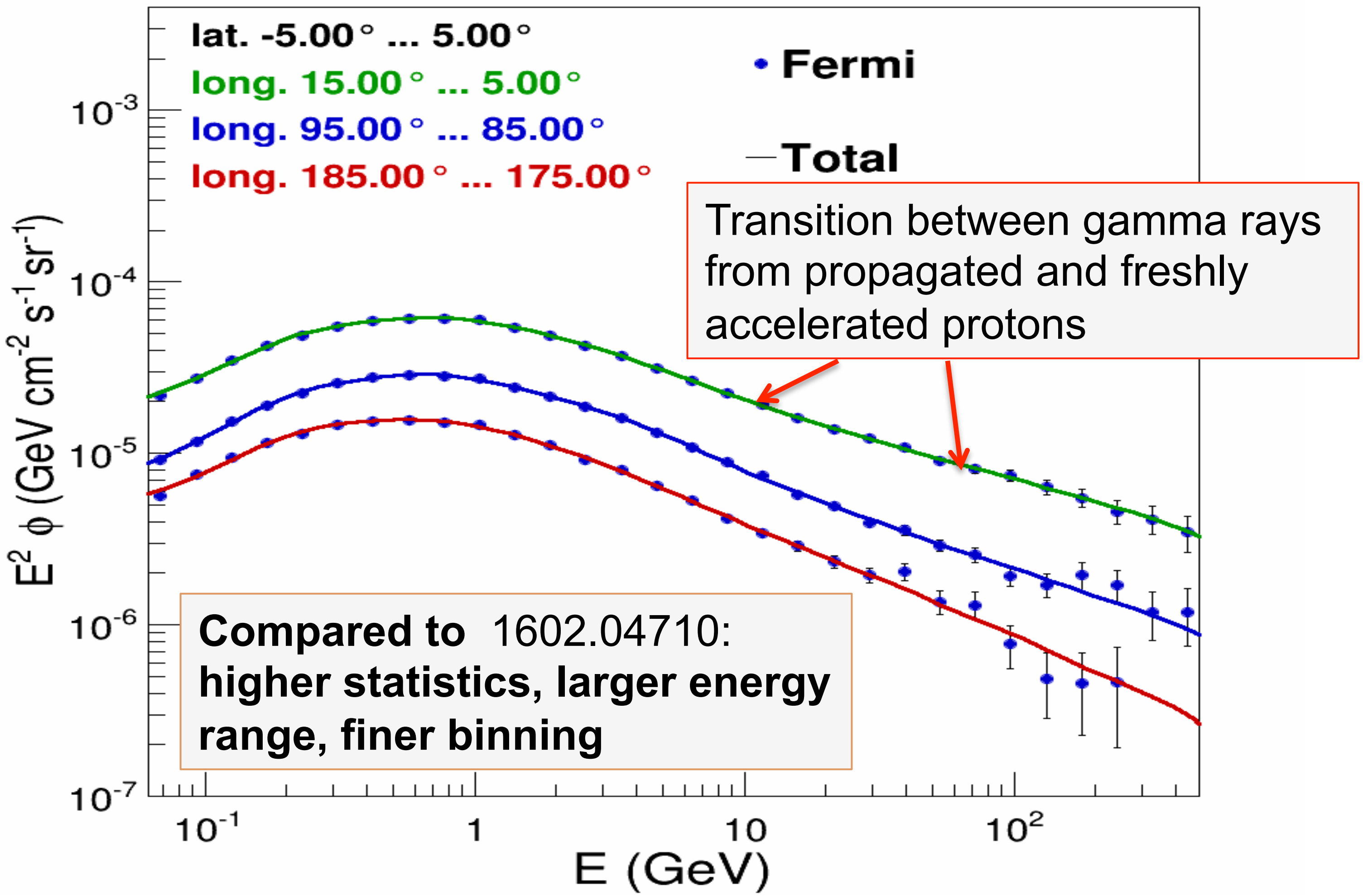


Attempts to solve the hardening by anisotropic propagation: see Gaggero+, 1411.7623 Guo+, 1801.05904 Acero+, 1602.07246 Yang+, 1602.04710

However, if the hardening originates from UNPRO-PAGATED SCRs, difficult to get good fit by prop.

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

Hardening well described by Source Cosmic Rays



MCR breaks in protons needed below 14 GeV

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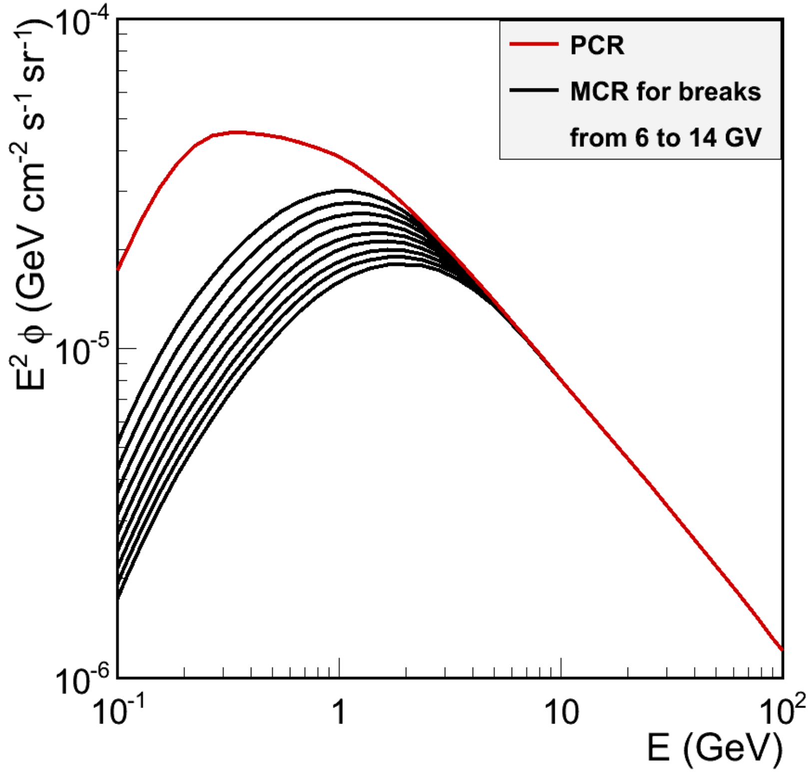
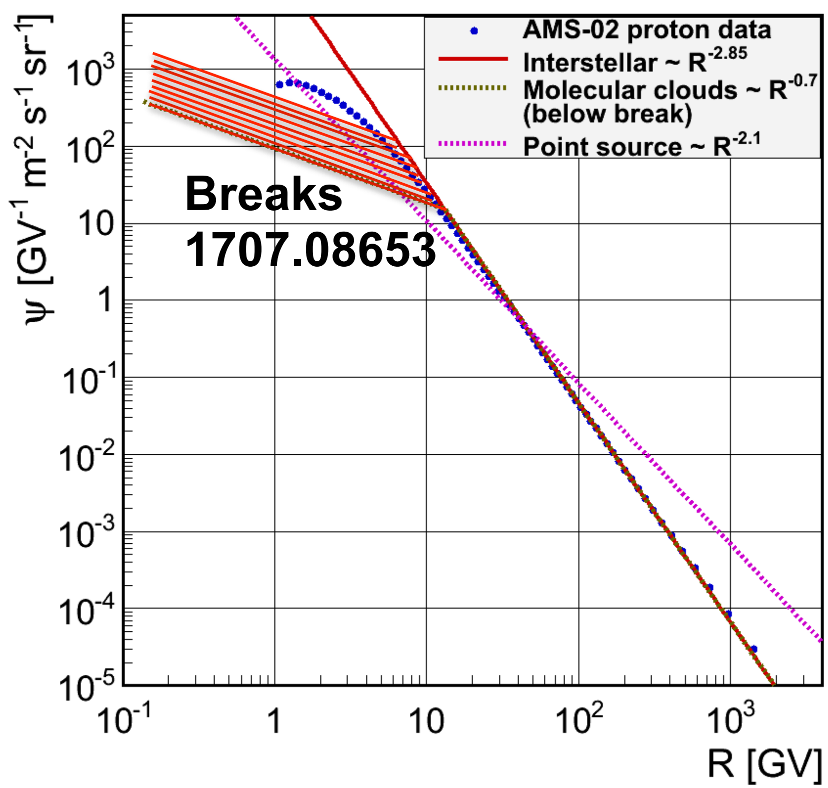
Gamma-ray spectra



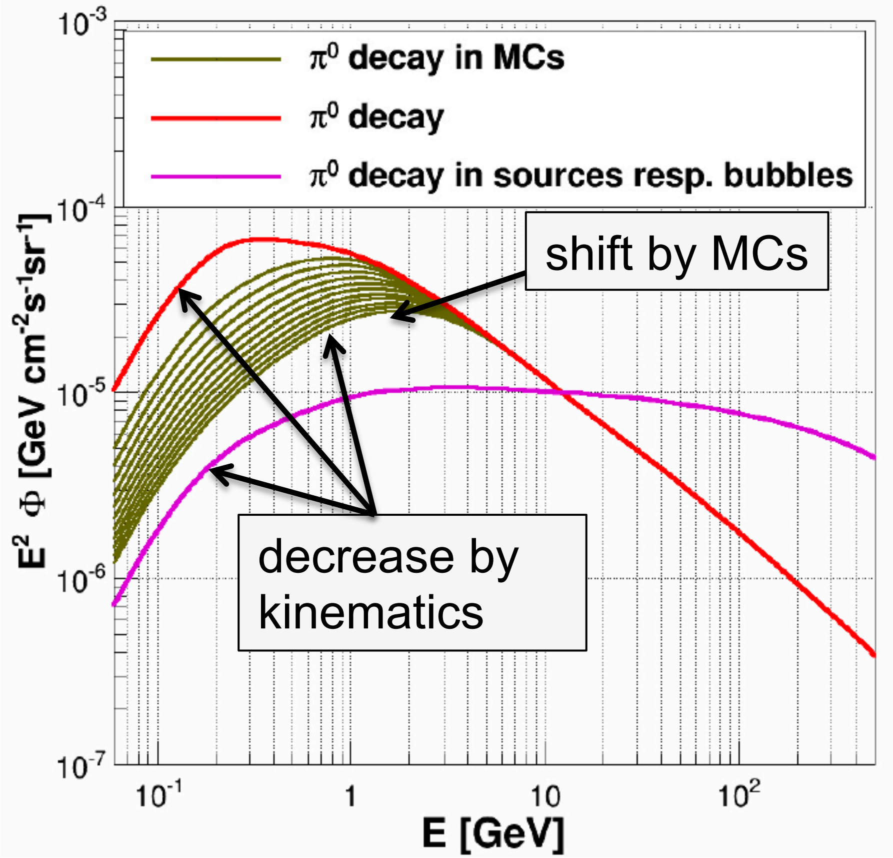
Proton spectra



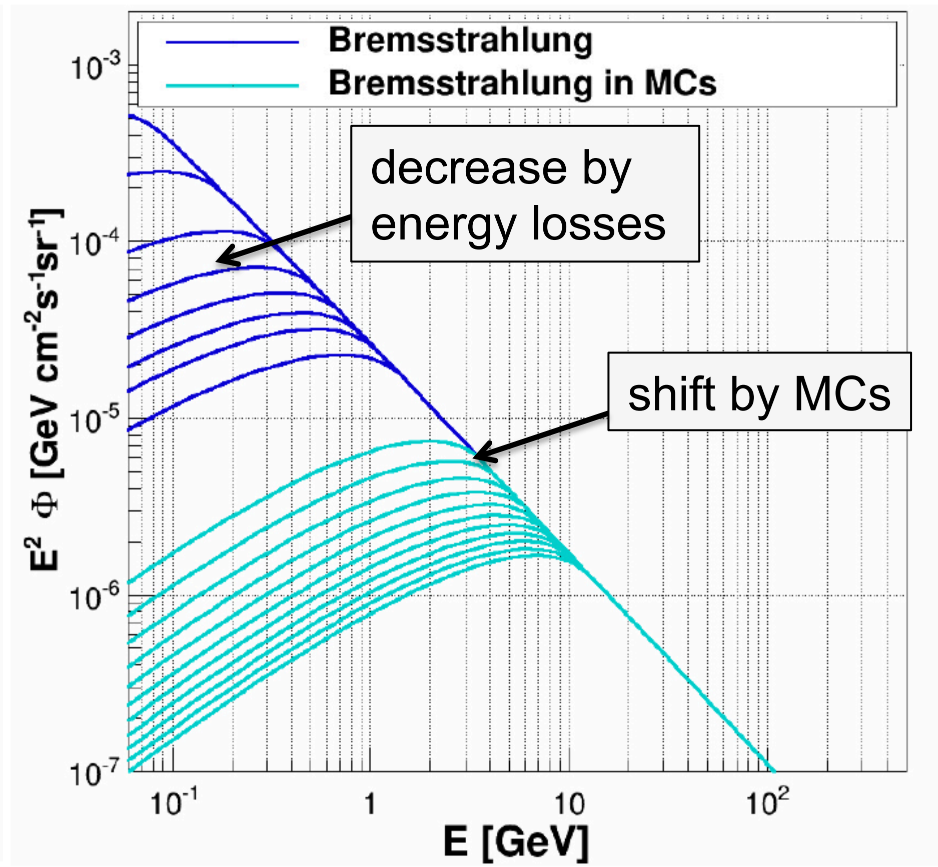
Try for each field-of-view which breaks fits best

Summary of gamma-ray templates

Proton induced

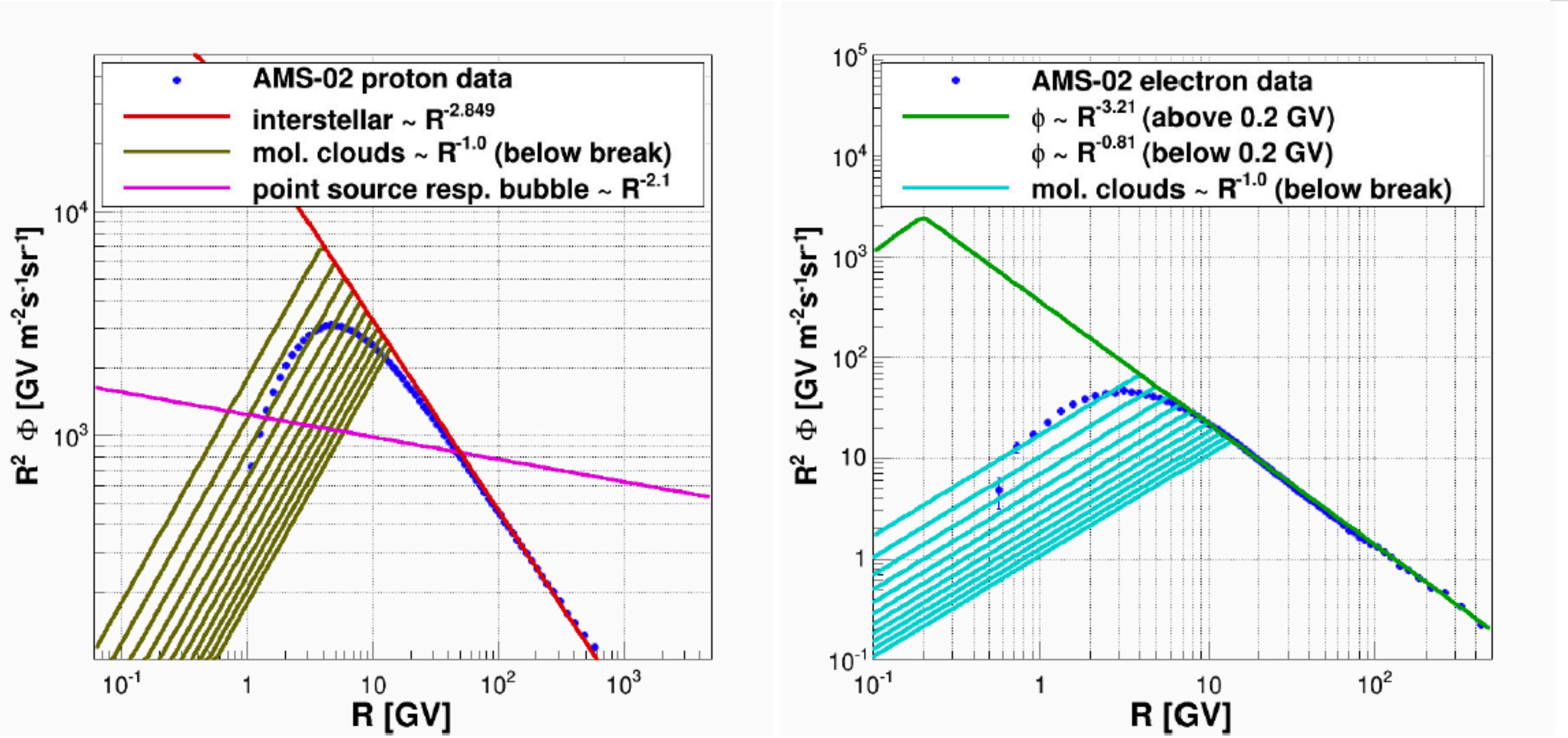


electron induced



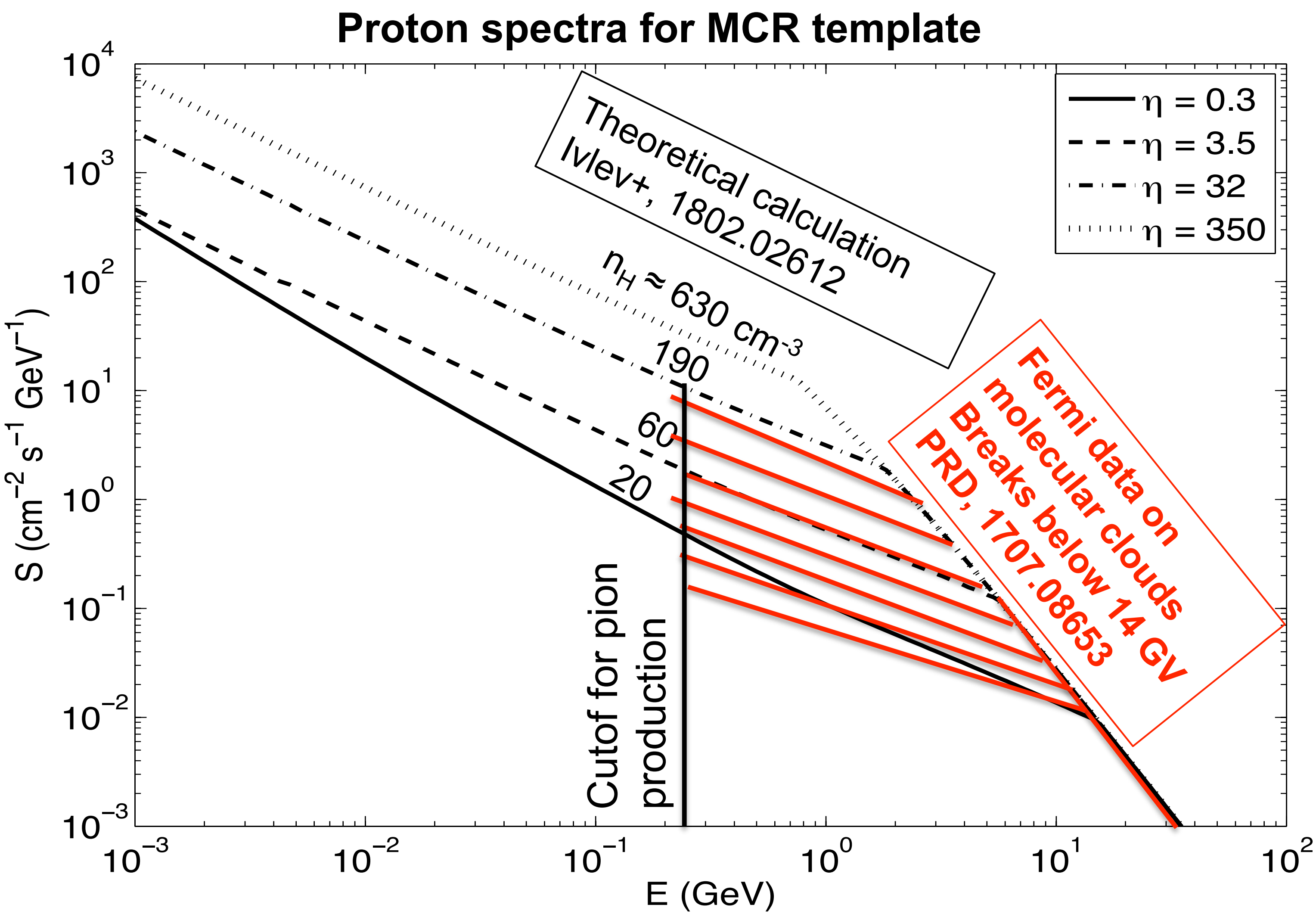
Try for each field-of-view which breaks fits best

Corresponding proton and electron spectra



(a) (b)

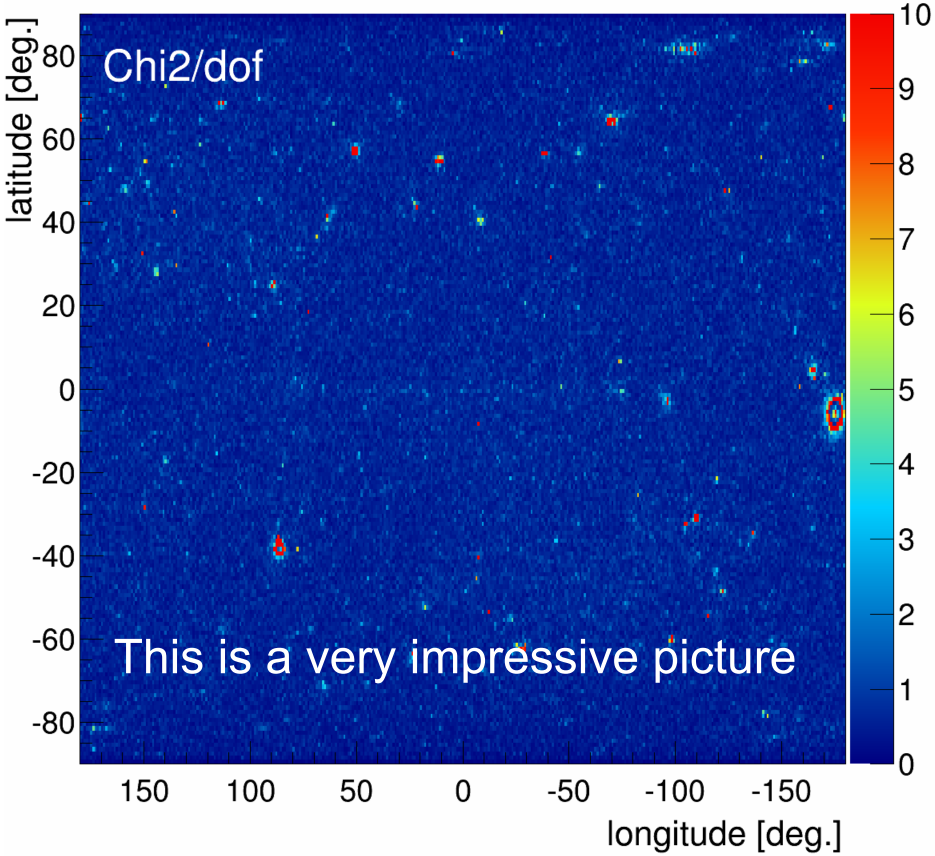
Penetration of low energy cosmic rays into molecular clouds suppressed by magnetic turbulence



Excellent χ^2 over whole gamma-ray sky

$$|\Phi> = n_1|\pi^0> + n_2|BR> + n_3|IC> + n_4|iso> + n_5|Bubble> + n_6|MCR> n_7|MBR>$$

Not in Galprop



Only 7 physical processes can describe the gamma-ray sky.

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

No need to know 3D spatial gas and CR distributions
No need for propagation codes

Spectral decomposition: no need for subtraction (especially difficult for Bubbles, if one uses spatial templates)

Comparison of CO and MCR sky maps

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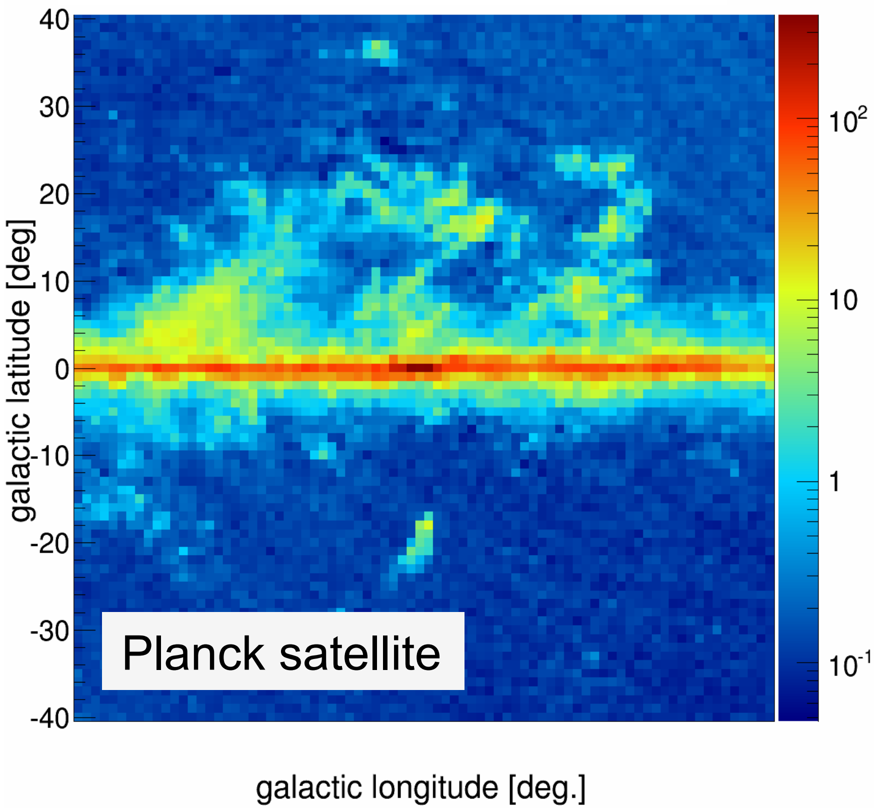
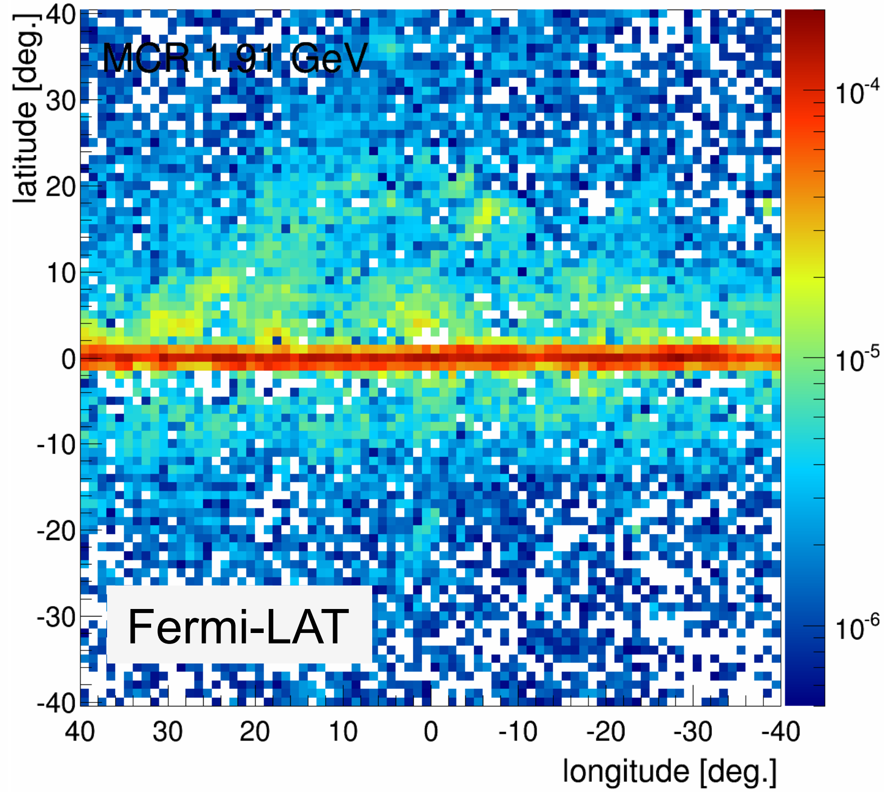
Sky map of CO lines (MCs)

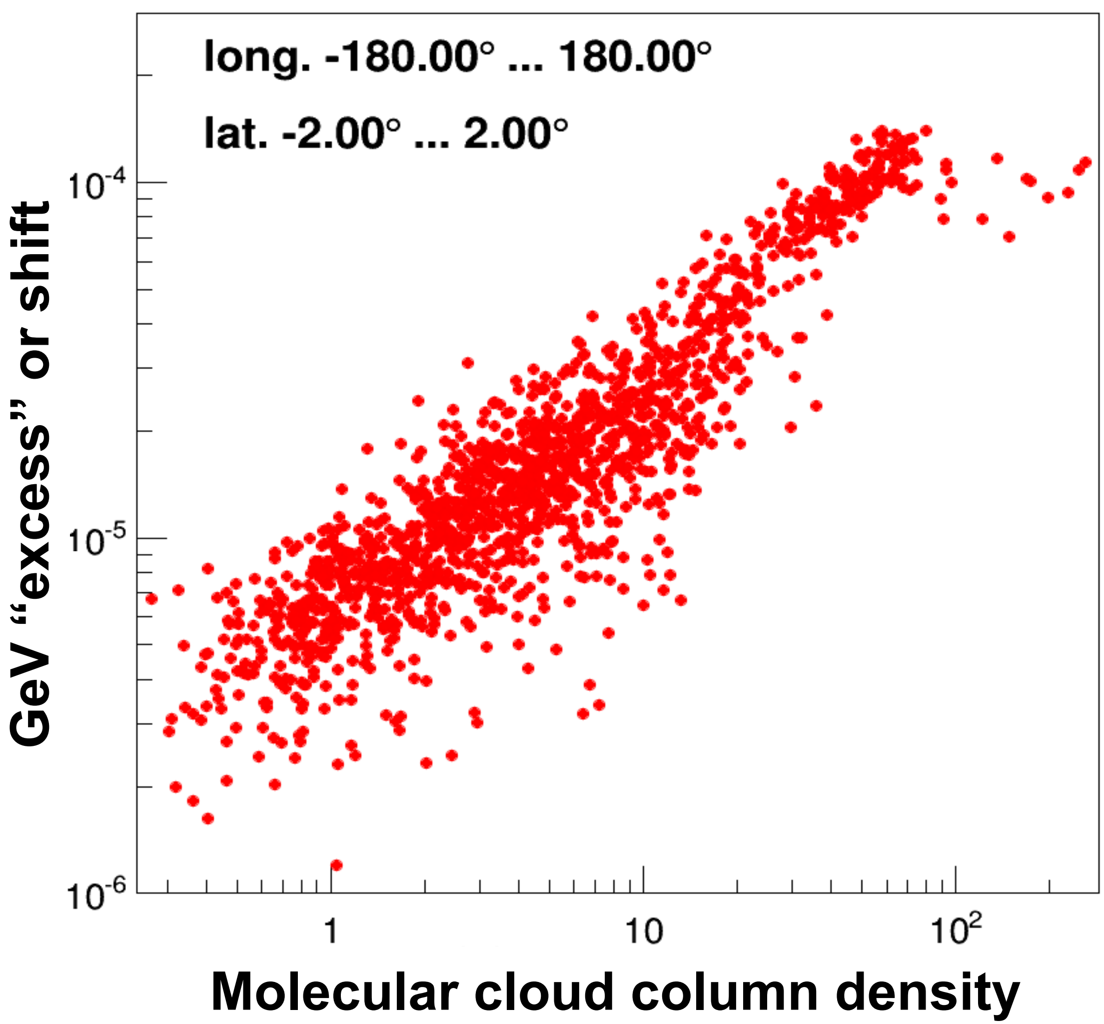


Sky map of MCR (=shift=excess= n_6)

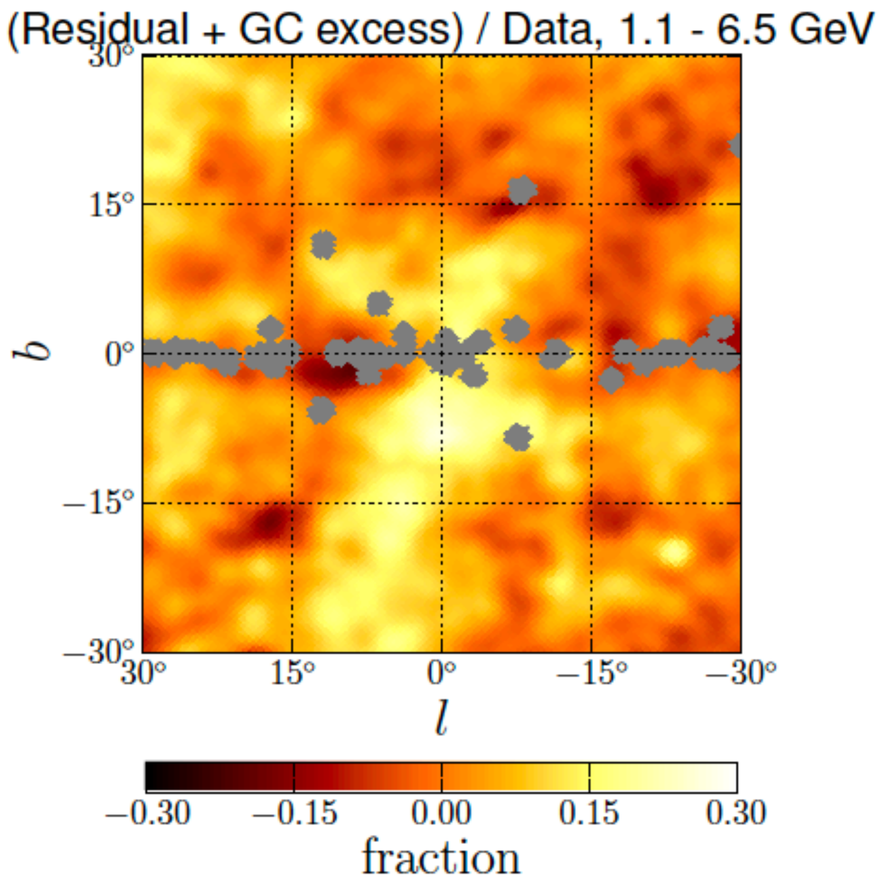


Intensity variation of excess („speckling“) clear, as first observed by Lee+, 1412.6099 by statistical methods. Speckling correlated with CO map speckling. How strong is correlation?

Correlation between sky maps from MCR and CO



Conclusion from Fermi Coll.(1704.03910)



Excesses with fractional amplitude similar to the one in the GC are found to be fairly common in control regions along the Galactic plane.
This is nothing else than "excess" from MCs)

Summary

	Spectrum (GC)	Morphology	Speckling
DM	X	X	X
	does not fit above 10 GeV	Not a DM profile	no speckling expected
MSP	X	?	✔?
	Does not fit above 10 GeV	only 10% observed	expect speckling
MC	✔	✔	✔
	fit perfect	as CO	as CO

The FERMI GeV excess is best explained by suppressed low energy CR spectra inside molecular clouds
This may be a physical effect of plasma waves or simply a detector effect from the poor angular detector resolution below 2 GeV

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BACKUP

Local MCs studied by FERMI (1205.6275)

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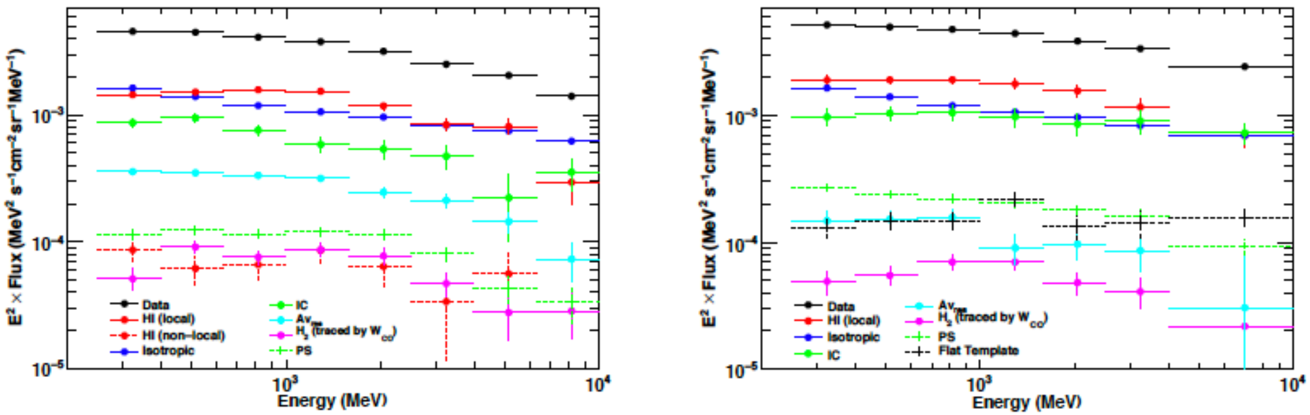
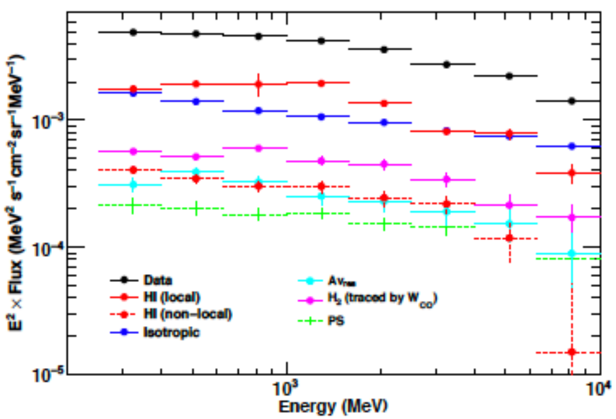
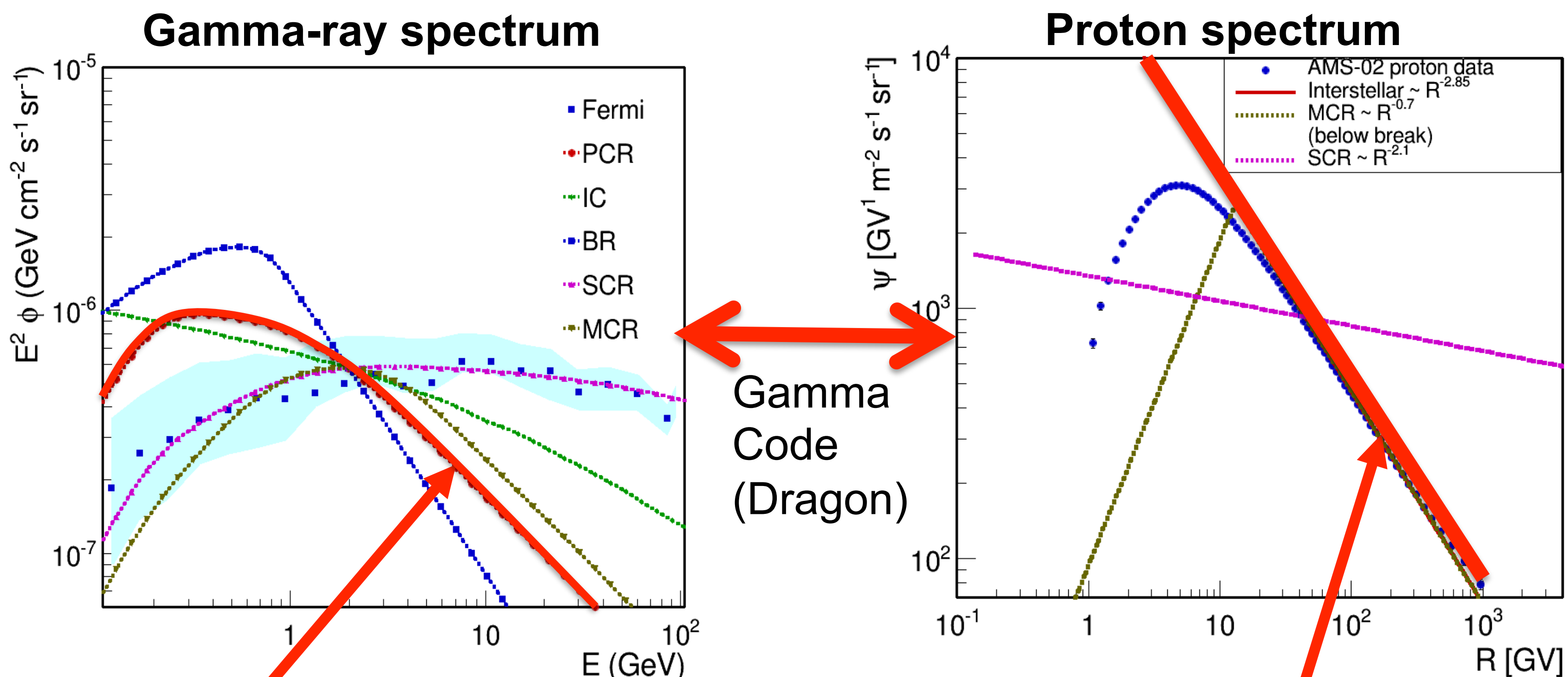




Local MC studied by FERMI Coll.
Contribution of MC in large Field-Of-View(FOV) well below isotropic contribution
Little sensitivity for such large foregrounds with large uncertainties
CMZ with only 10% foreground much higher sensitivity.

Fig. 12.— γ-ray spectra of each component (each gas phase, IC, isotropic component, point sources, and flat template model for the R CrA region) for the Chamaeleon (top left), R CrA (top right), and Cepheus and Polaris flare region (bottom left). The H I (non-local) for the R CrA region and the IC component for the Cepheus and Polaris flare are not shown here since they are negligible.

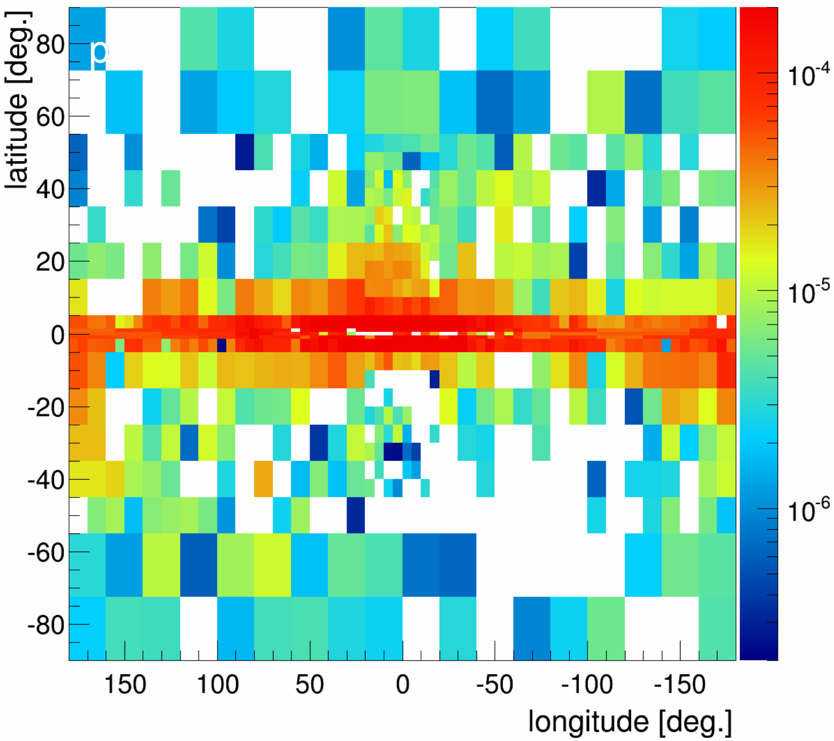
Relation between CR- and gamma-ray spectra



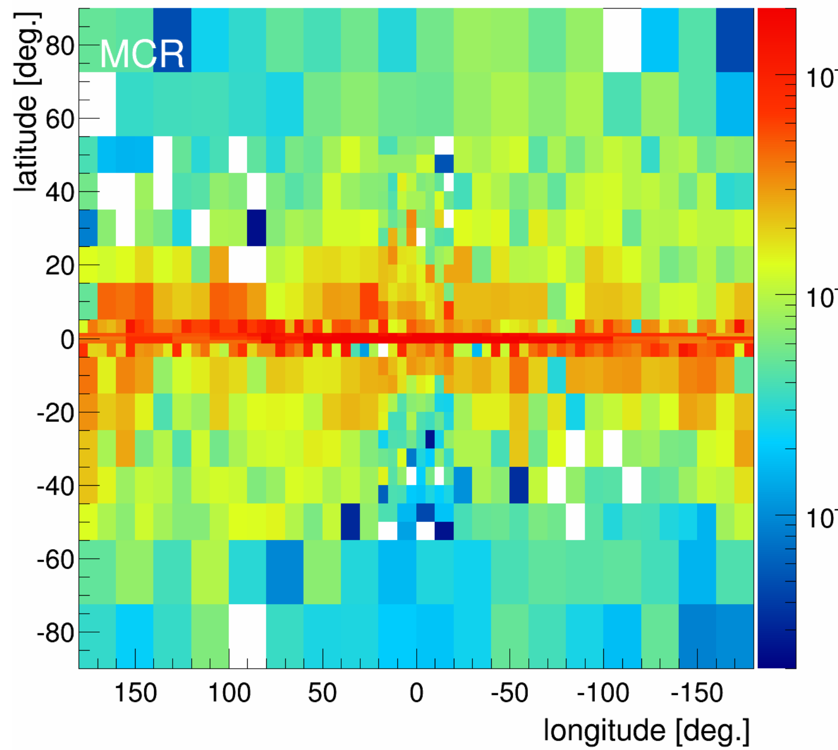
The pion production from diffuse gas template is best described by a power-law proton spectrum with index from AMS-02 data above solar modulation region. So interstellar spectrum has NO break (only obtainable from gamma-ray data, which sample spectrum beyond solar system)

Sky maps from proton induced gamma-rays in disk

PCR

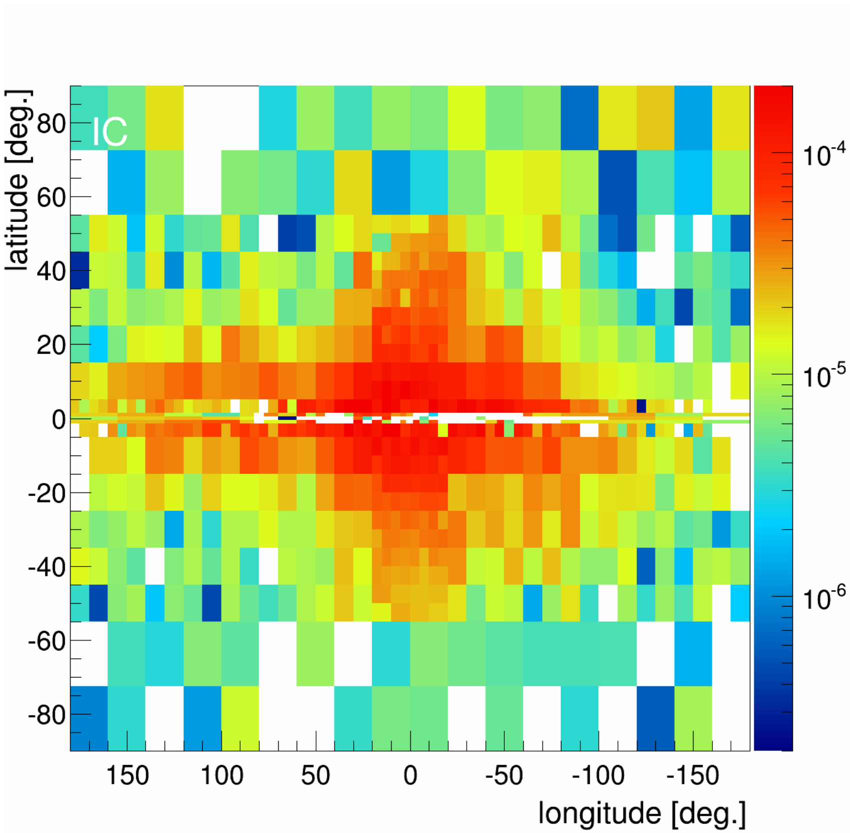


MCR



Sky maps from electron induced gamma-rays

IC



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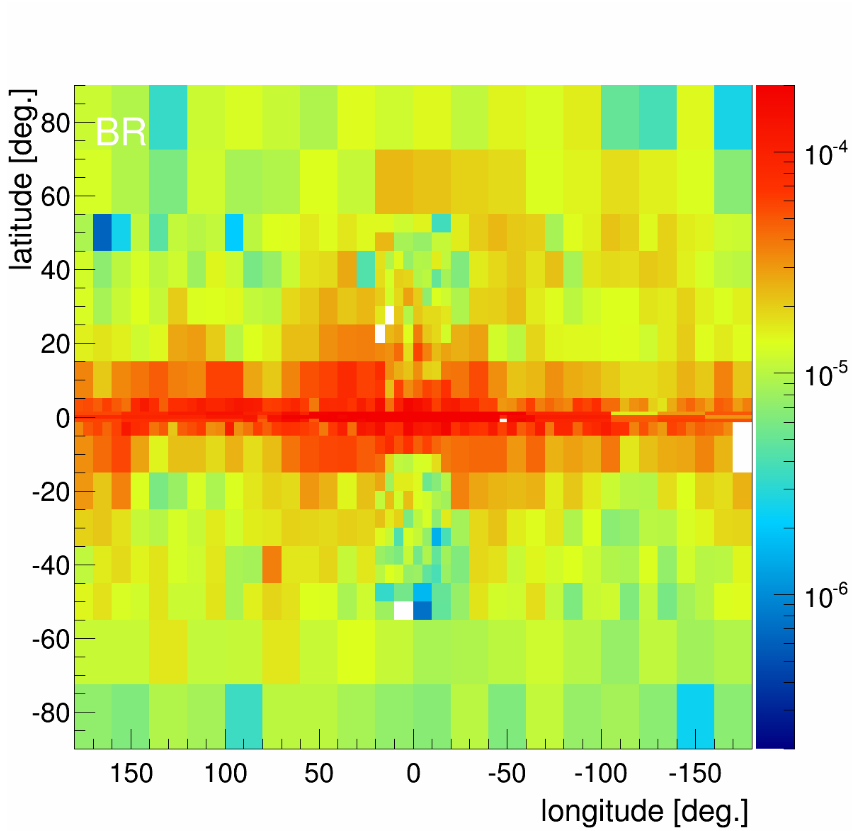
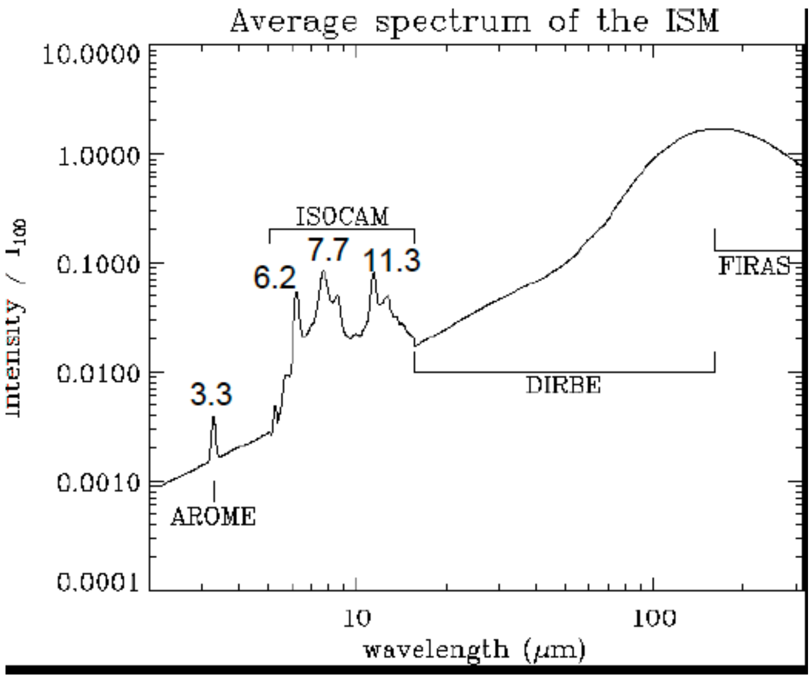
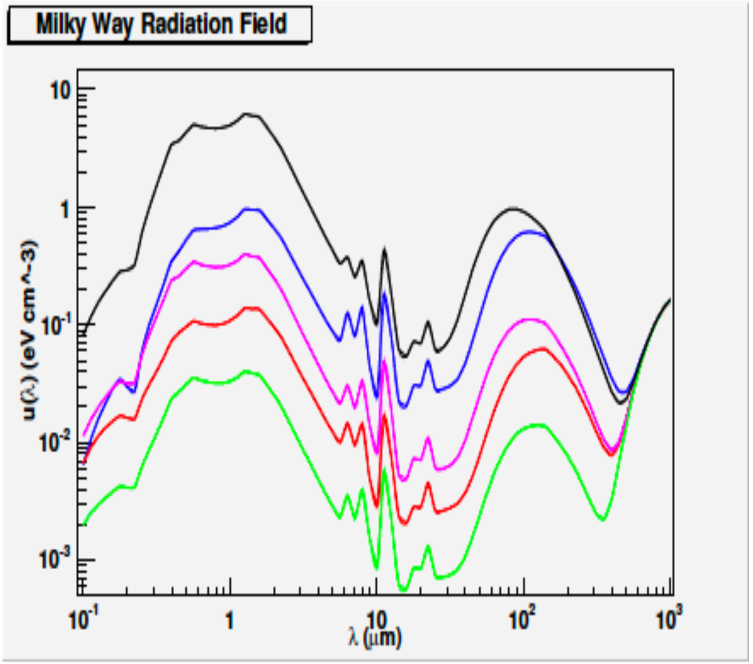


Interstellar Radiation Field

Compilation Glassgold, Berkeley



GALPROP



In molecular clouds starlight heats up dust and is reemitted in IR (140 um=20K)

IR needs 10x higher energy electrons to get same upscattered photon energy.
Electron spectrum falls like $1/E^3$, so IC intensity inside MCs reduced by $1/10^3$

SO IN OPTICALLY THICK MEDIA IC EXTREMELY SUPPRESSED