Fermilab

The Fermi Galactic Center Excess; Background Model Systematics and Interpretations

Discuss the excess:

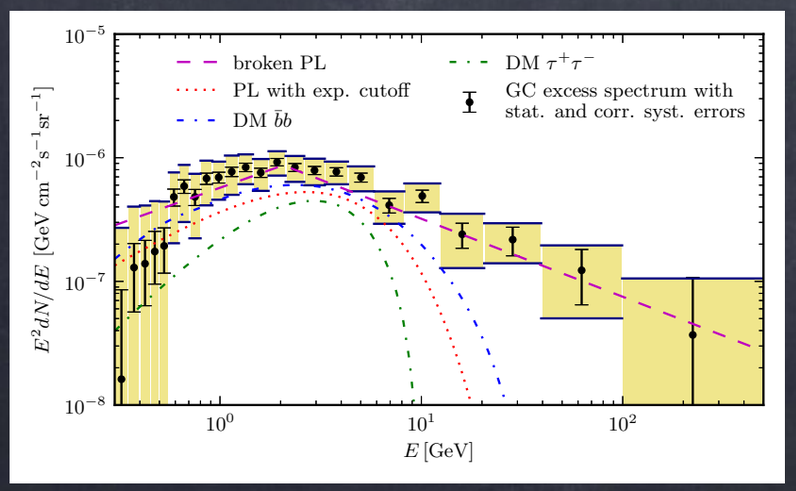
(Convince you the excess is REAL and relatively well understood)

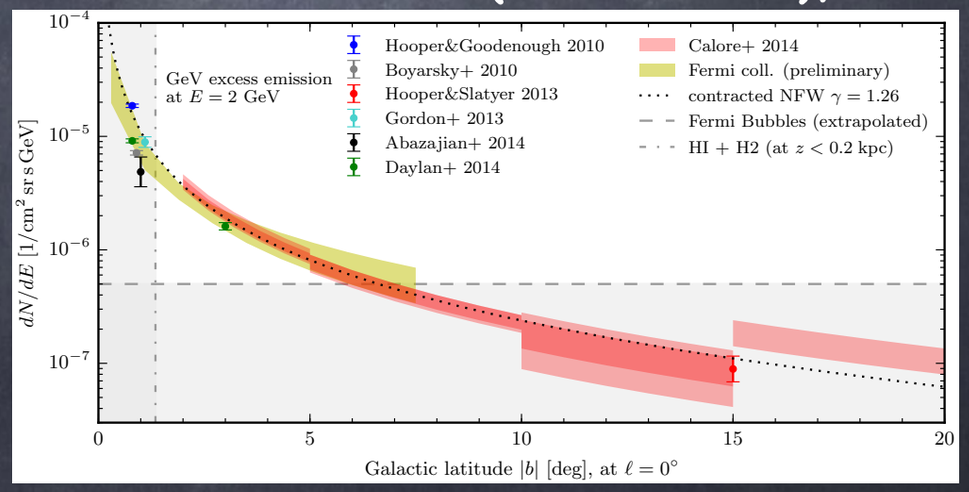
Hooper & Goodenough: (1010.2752), Linden & Hooper (1110.0006), Abazajian & Kaplinghat (1207.6047), Hooper & Slatyer (1302.6589) Huang, Urbano & Xue (1307.6862),Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, 1402.6703, Calore, Cholis, Weniger JCAP 2015 (1409.0042).

Discuss on the interpretation:

(DM vs Millisecond Pulsars vs Bursts of CRs)

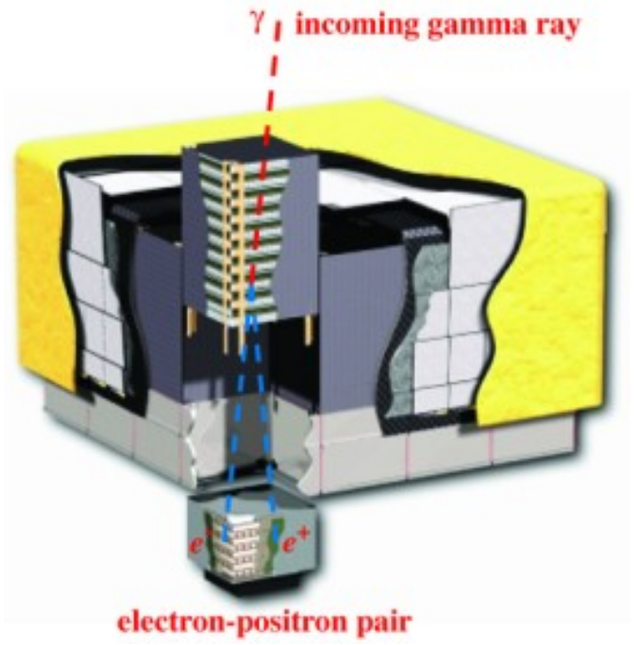
Hooper, Cholis, Linden, Siegal-Gaskins & Slatyer PRD 2013 (1305.0830), Gordon & Macians (1306.5725) Cholis, Hooper, Linden JCAP 2015 (1407.5625), Calore, Cholis, McCabe, Weniger JCAP 2015 (1411.4647), Cholis, Calore, Evoli, Hooper, Linden, Weniger (in prep.)





Ilias Cholis, Mitchell Workshop, 5/20/2015

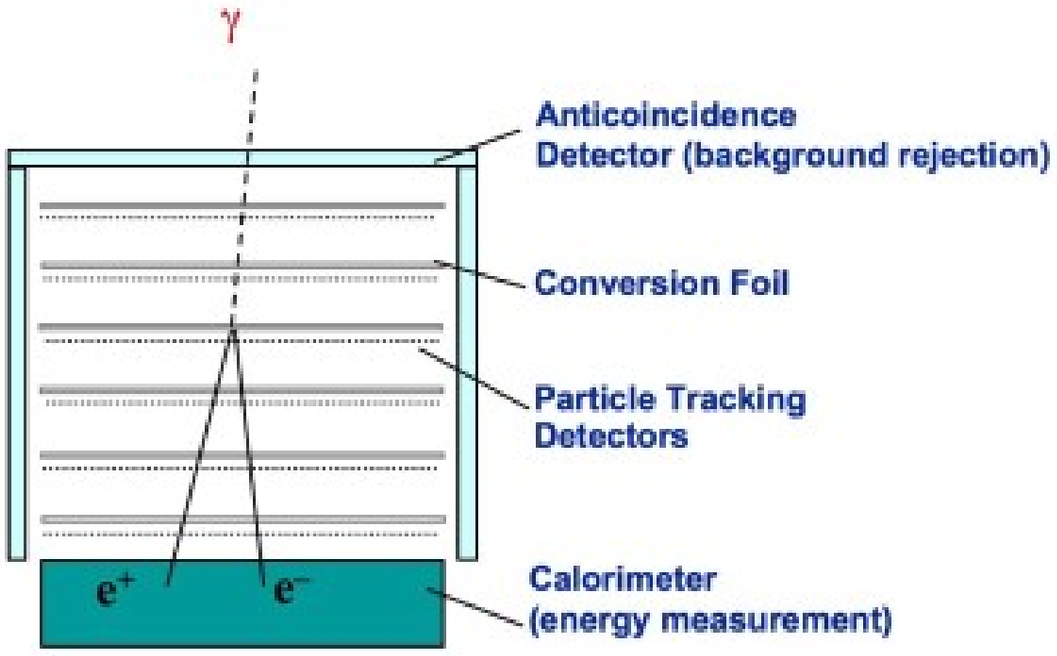
Fermi Large Area Telescope



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



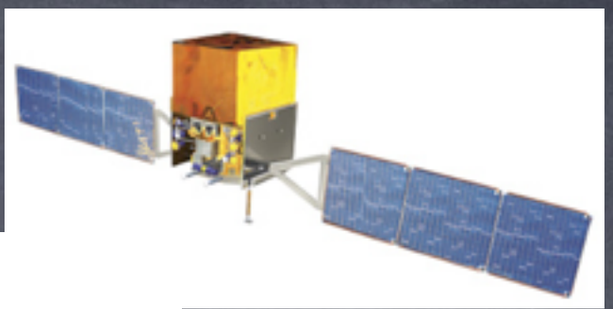
Main components:

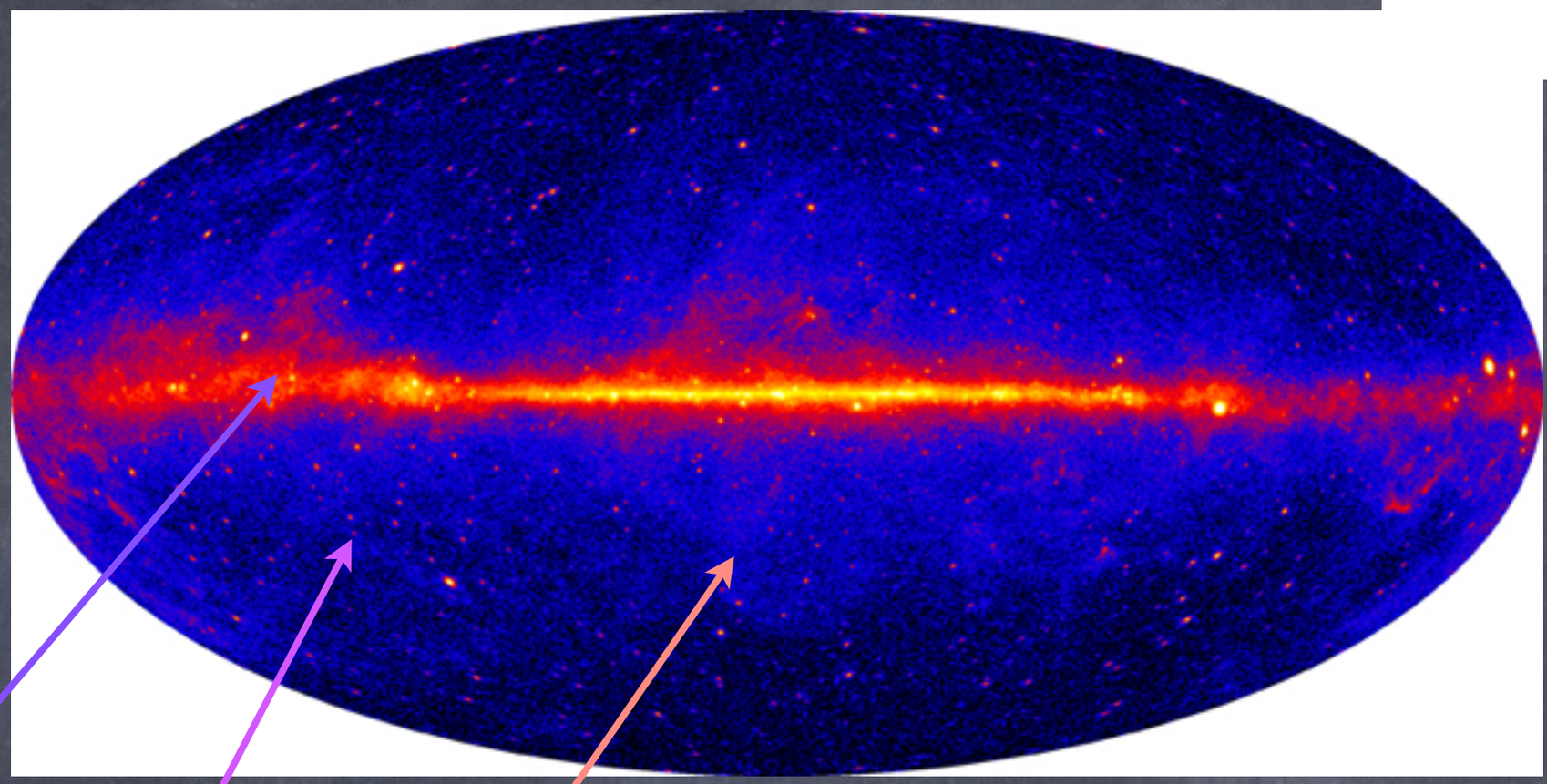
Anti-coincidence shield (plastic scintillator) with photomultiplier tubes

Tracker (silicon strip detectors) with conversion foils (tungsten)

Electromagnetic Calorimeter (CsI)

The Fermi-LAT Gamma-ray SKY





Known sources for the observed gamma-rays are:

i)Galactic Diffuse: decay of pi0s (and other mesons) from pp (NN) collisions (CR nuclei inelastic collisions with ISM gas), bremsstrahlung radiation off CR e, Inverse Compton scattering (ICS): up-scattering of CMB and IR, optical photons from CR e

ii)from point sources (galactic or extra galactic) (3033 detected in the first 4 years)

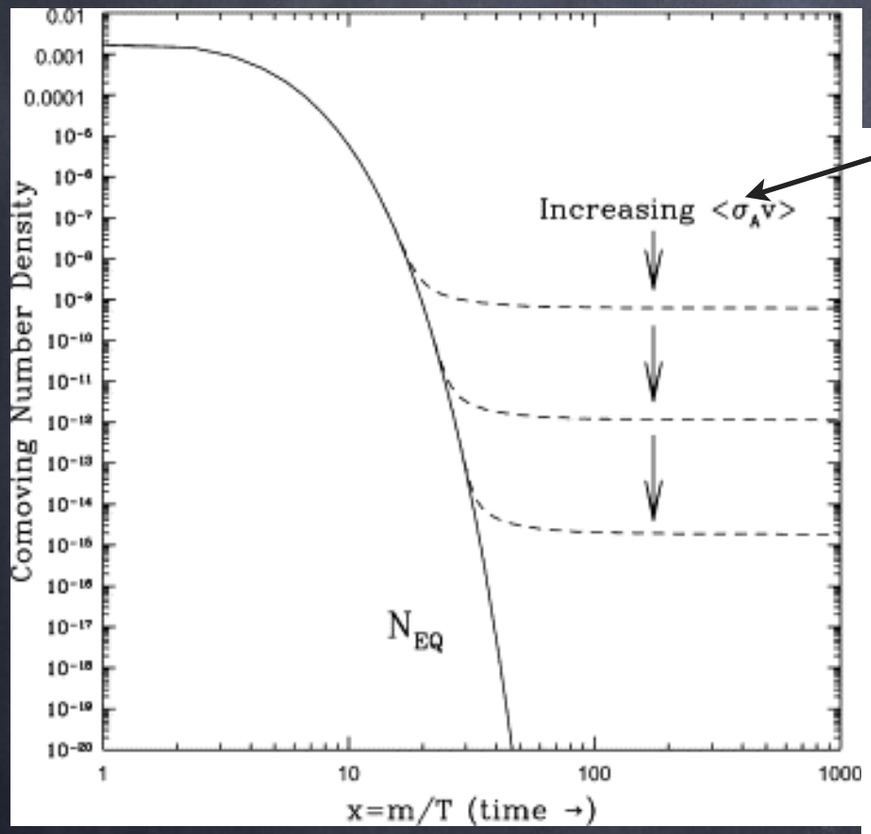
iii)Extragalactic Isotropic

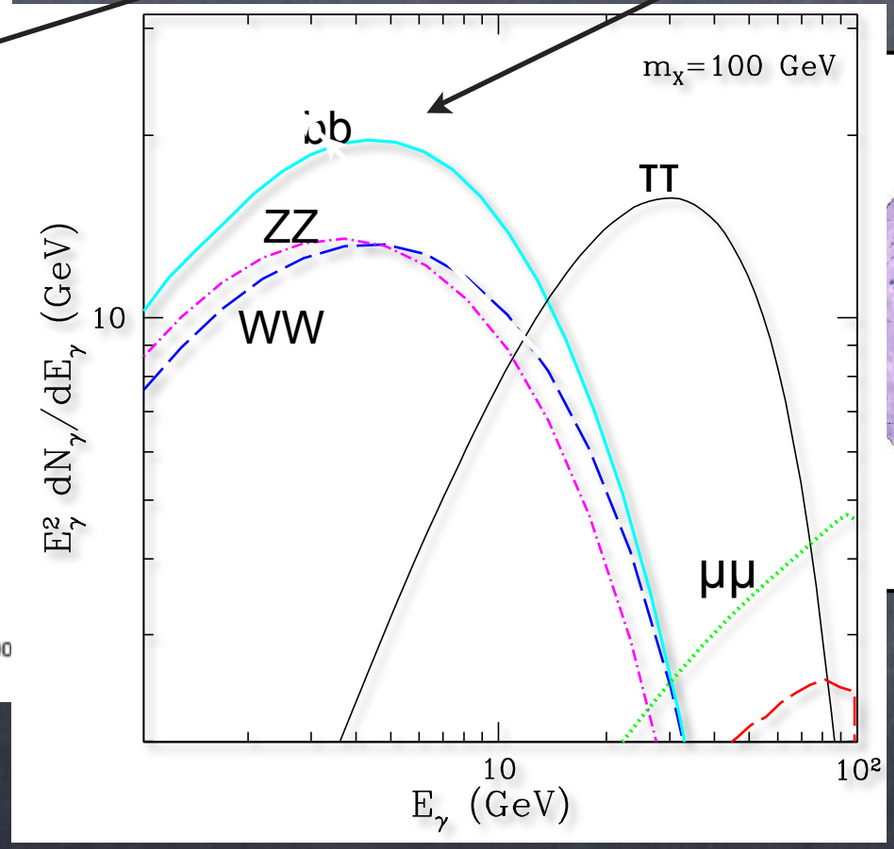
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

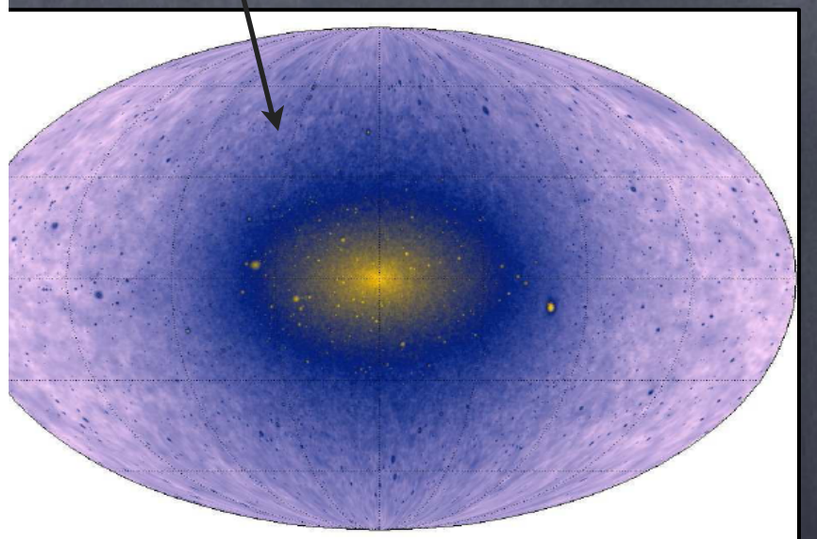
iv)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe: $$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle\sigma v\rangle}{4\pi}\frac{dN_\gamma}{dE}_{DM}\frac{\rho^2_{DM}(l,\Omega)}{2\,m^2_\chi} dl d\Omega$$

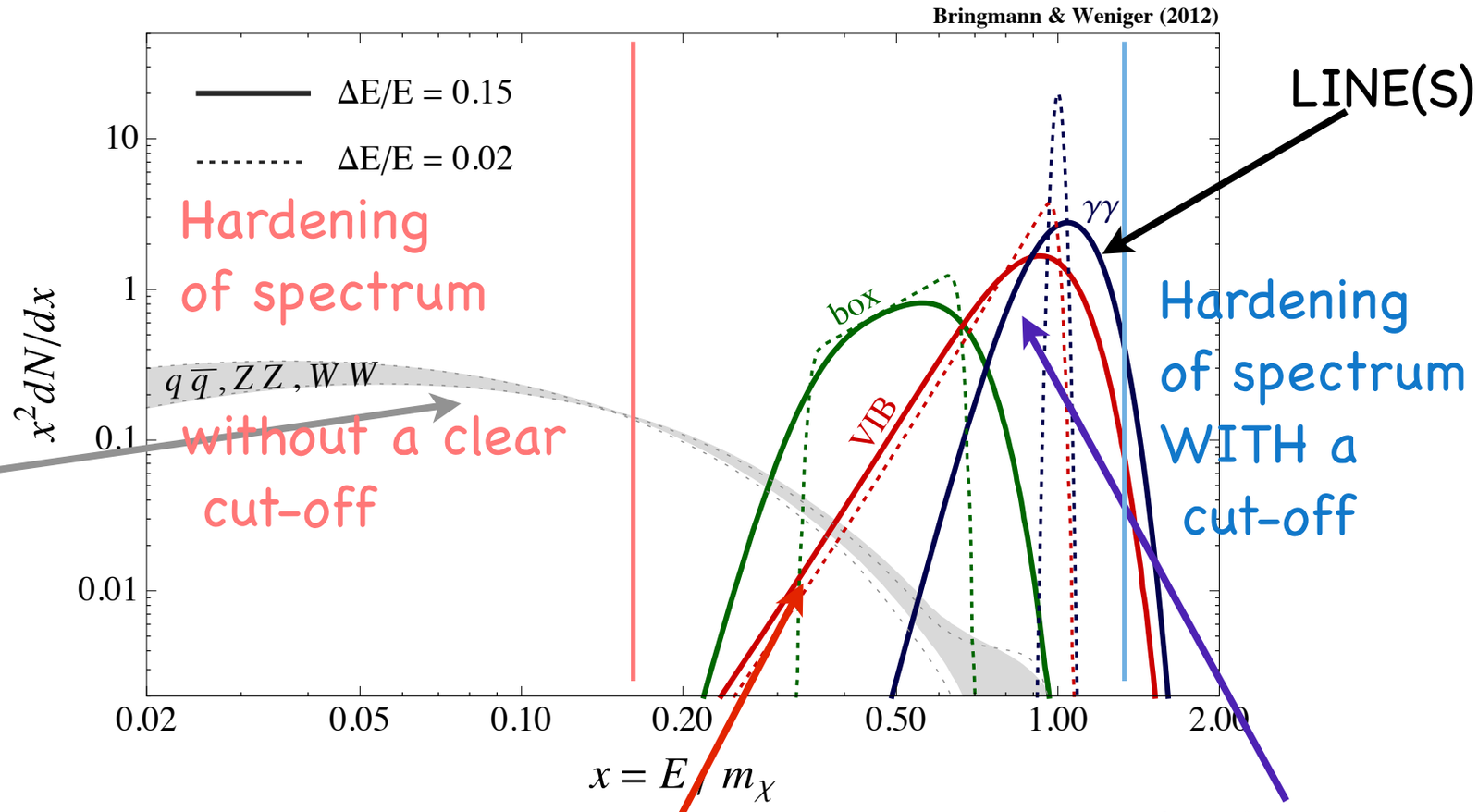


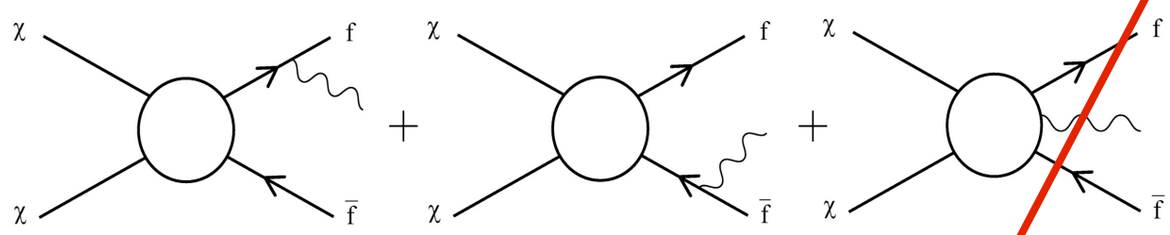




DM annihilation spectra

Continuum emission, tree level, relatively hard spectrum, but featureless

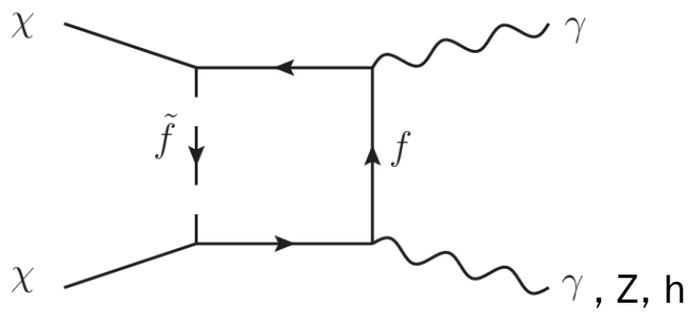




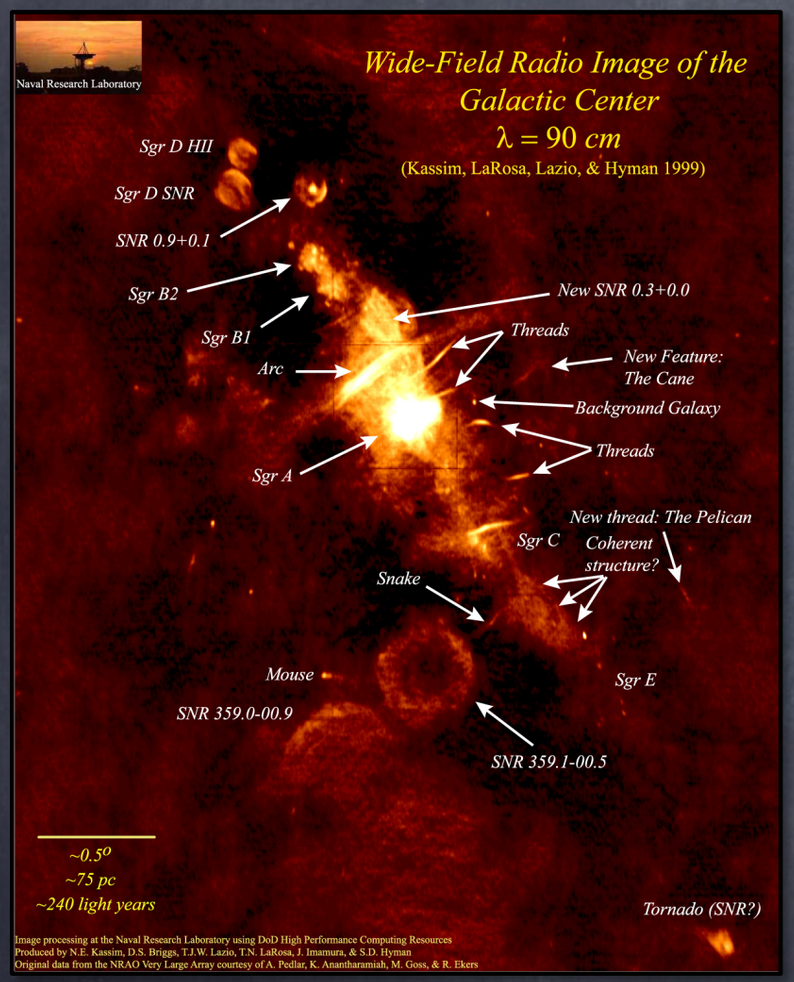
Final state radiation Virtual Internal Bremss.

Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).

Comes from radiative corrections to processes with charged particles. Suppressed by O(a), but with a much harder spectrum; FSR has an additional suppression factor of (mf/Mchi)^2

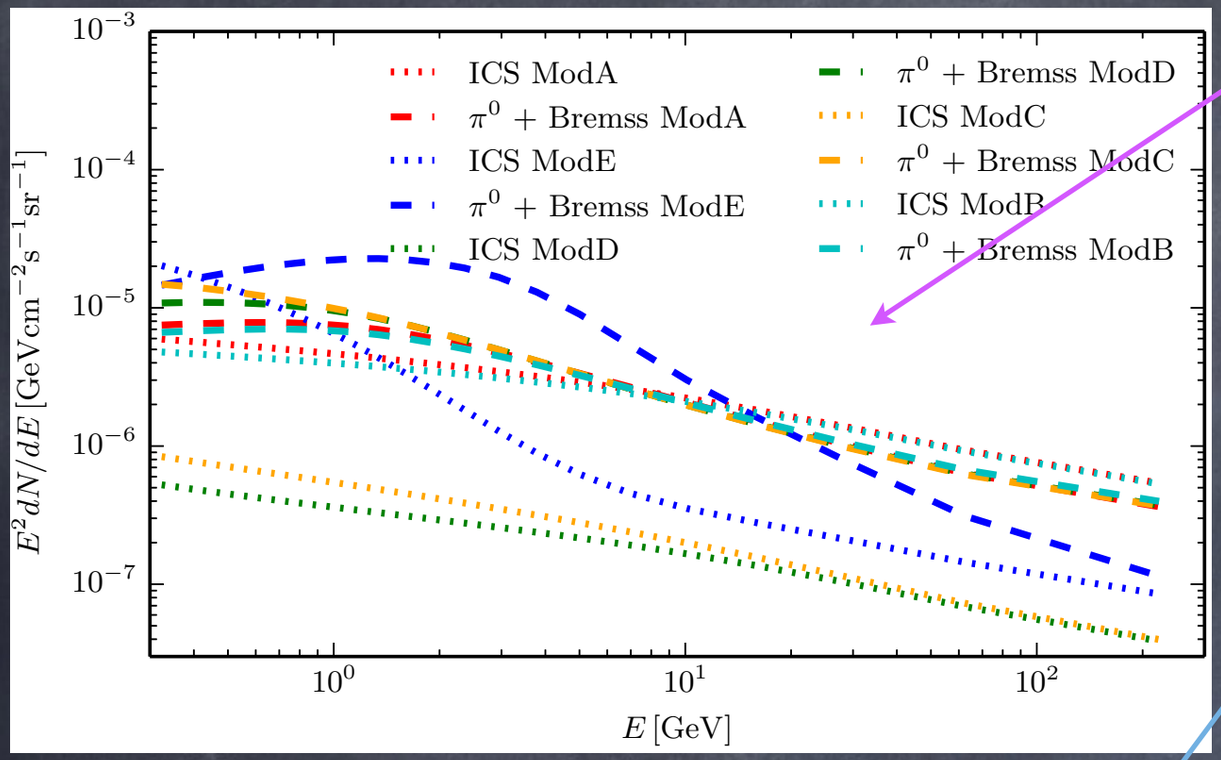


One of the most likely targets is the GC (though backgrounds also peak), others are the known substructure (dSphs) or Galaxy clusters



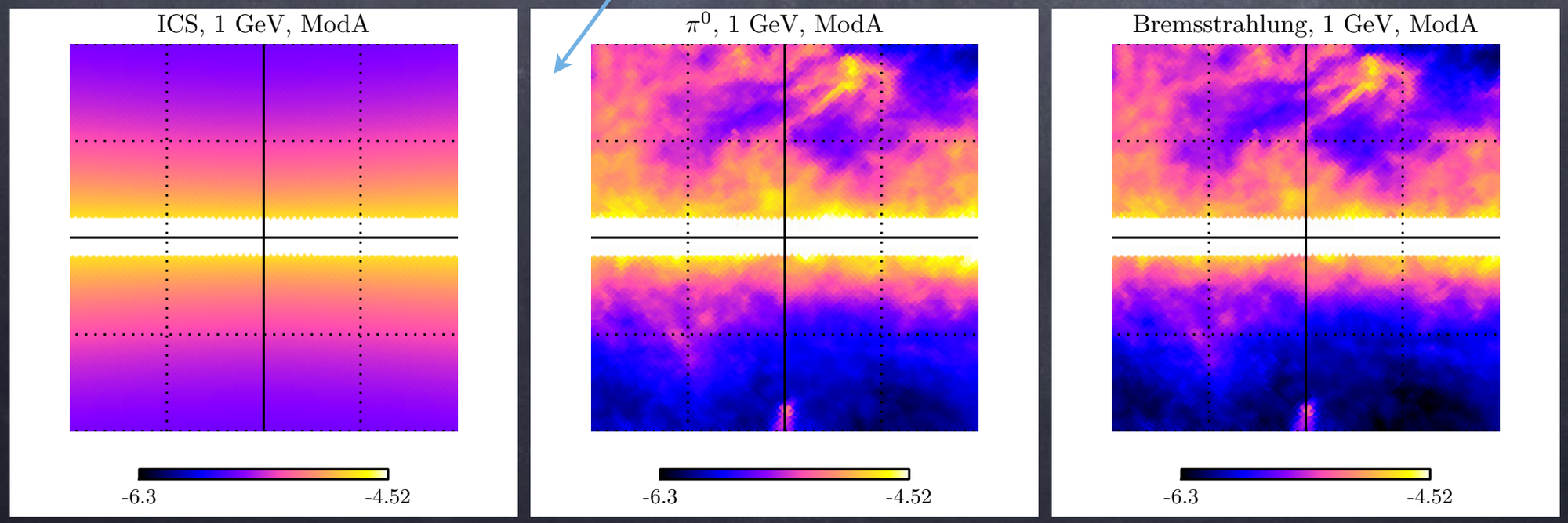
- The region of the galactic center is complex with uncertainties in the gas and the CR distribution
- A DM annihilation signal also peaks with significant uncertainties though on the DM distribution
- Take advantage of multi-wavelength searches, different gamma-ray spectra and distinctively different morphologies between the backgrounds and a DM signal

On the gamma-ray backgrounds ALONG THE LINE OF SIGHT towards the inner galaxy



Calore, Cholis, Weniger, 2014

- Spectrally the galactic diffuse gamma-ray components can be modeled (WITH significant variations though). In addition we can model their morphology on the galactic sky, WHICH varies with energy AND depends the physical assumptions (fast/slow diffusion, strong convection, energy losses)
- Extended sources can also be modeled (morphologically and spectrally)and subtracted (yet with some uncertainties related to the mechanism producing their signal)



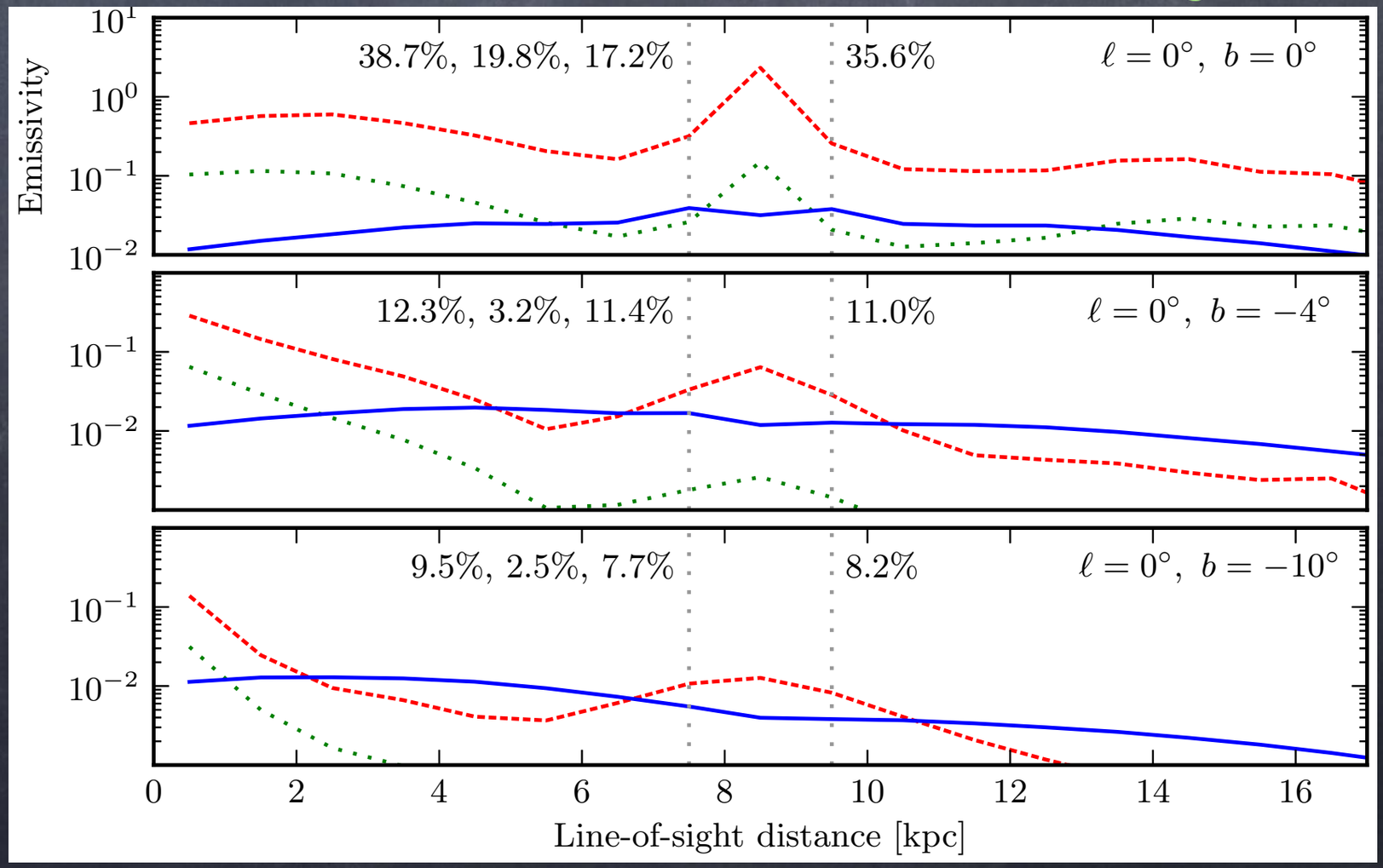
- Extragalactic point sources can either be resolved or unresolved extragalactic sources (AGNs, Star forming or starburst galaxies etc). But are isotropic and thus can not contribute significantly to an excess in the inner galaxy. Misidentified GeV scale CRs are also isotropic due to diffusion.

- Galactic point sources that can give strong gamma-ray signals in the GeV range include SNRs in the inner part of the Galaxy and pulsars (see later slides).

We live inside the Milky Way;
thus we see A LOT of emission
from distances closer to us than the GC:

THUS WE NEED TO ACCOUNT FOR THESE UNCERTAINTIES.

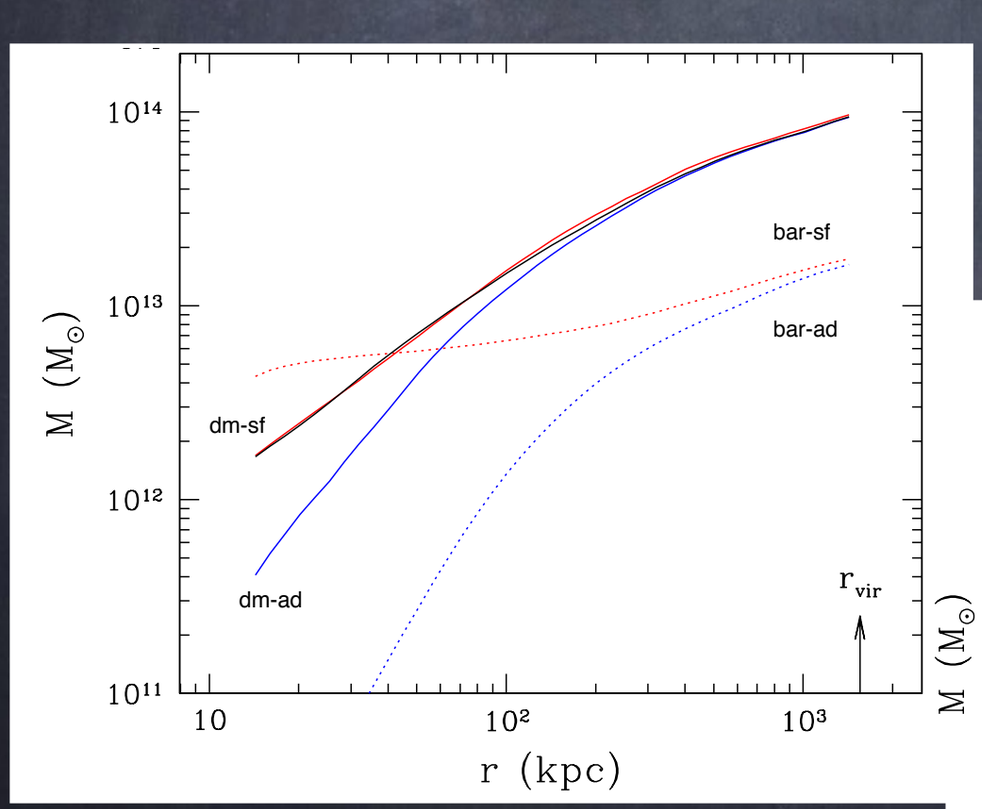
IMPORTANT CAVEAT!!! Calore, Cholis, Weniger, 2014



On the DM distribution in the inner galaxy

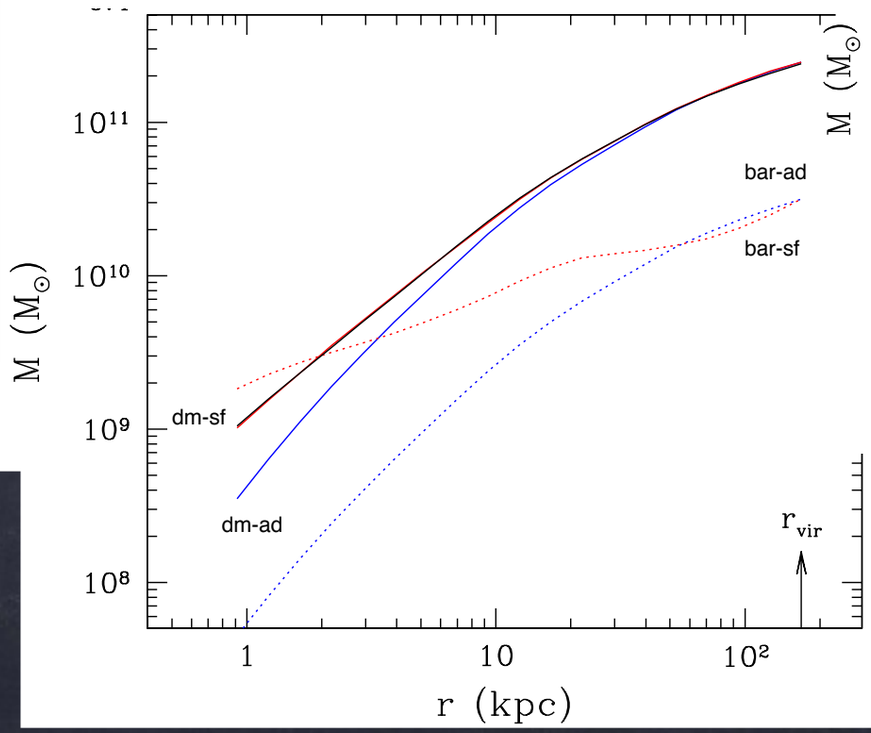
From hydrodynamical simulations there are suggestions from different groups in favor of contraction in the Milky-Way like halos with an inner slope gamma from 1.0 up to 1.5.
Yet there still are groups suggesting flattening of the halo profile if baryonic feedback processes are efficient.
Assuming NFW-like profile with some uncertainty in the inner slope is the way to treat any search for a signal of DM from the inner galaxy.

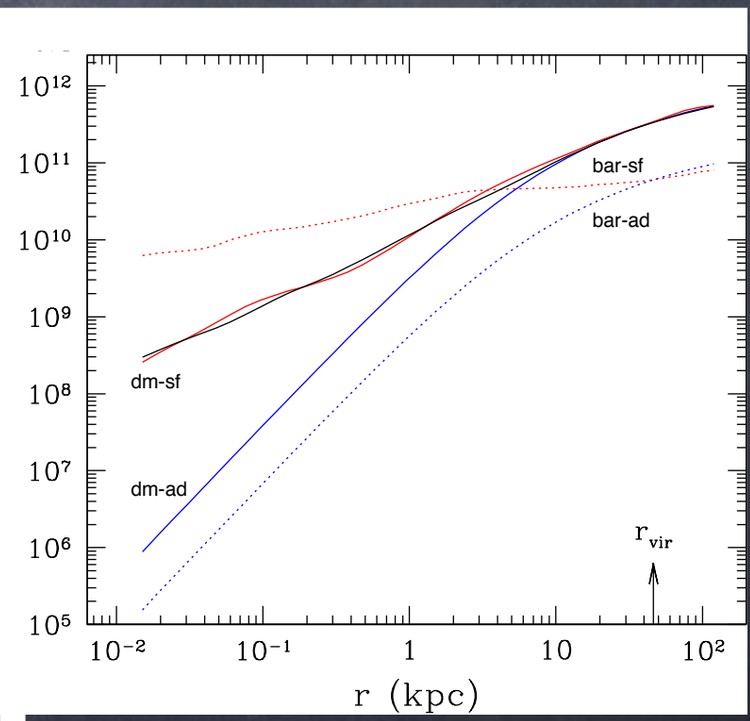
Gnedin et al. 1108.5736



Nagai 2006 ApJ 650, 538

Gottglober et al. 1005.2687



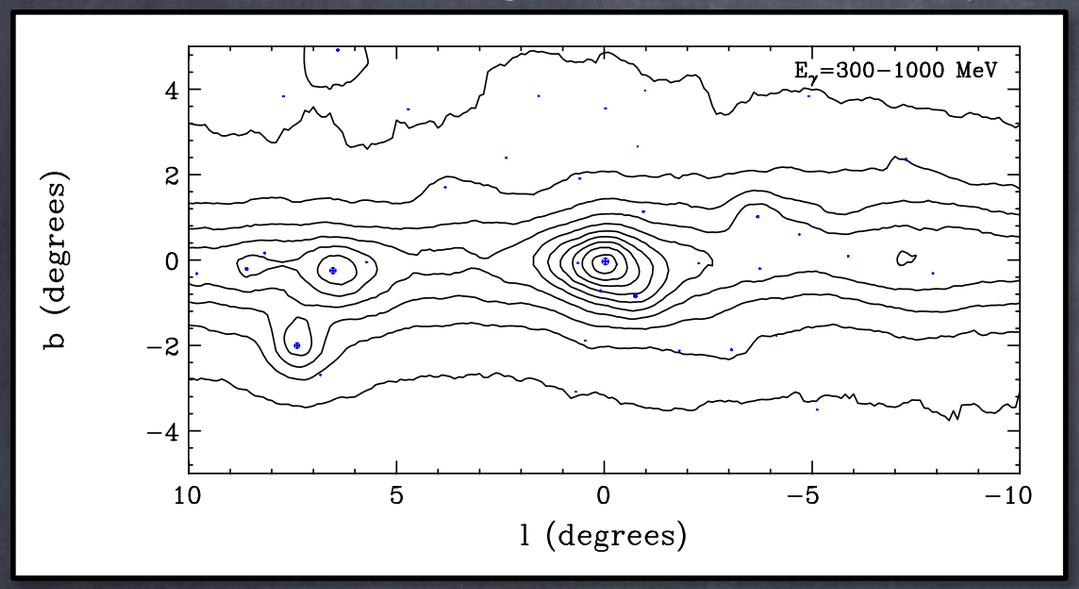


Levine at al. 2008 ApJ 678, 154

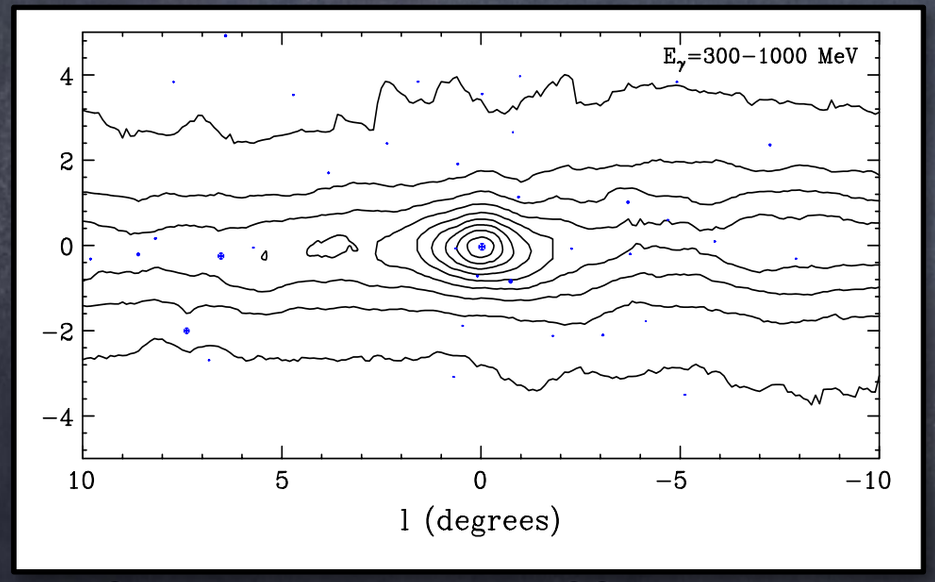
Looking for excesses in the inner galaxy

Hooper&Linden 1110.0006

Smoothed Raw gamma-ray map



− POINT SOURCES (2yr catalogue)



Model for Galactic Diffuse Emission

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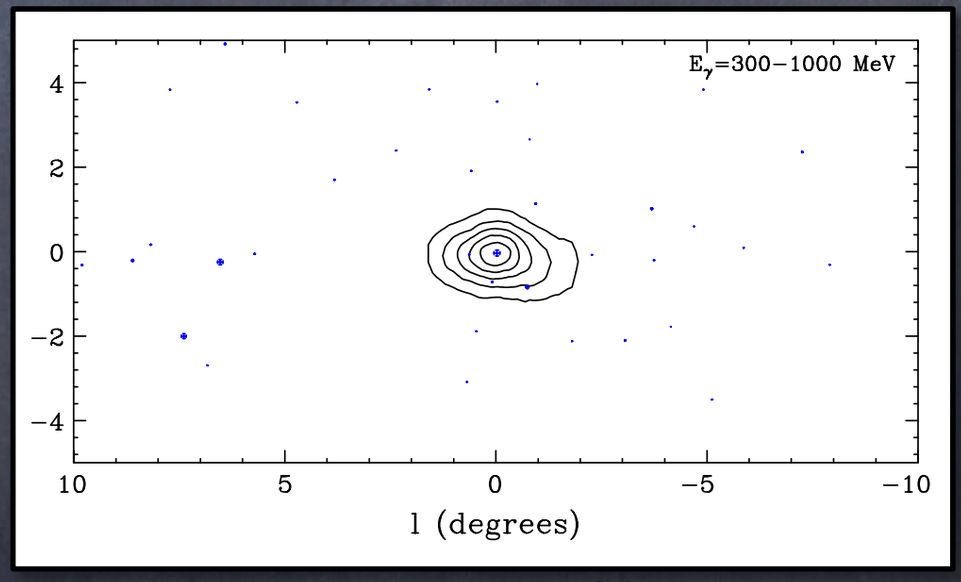
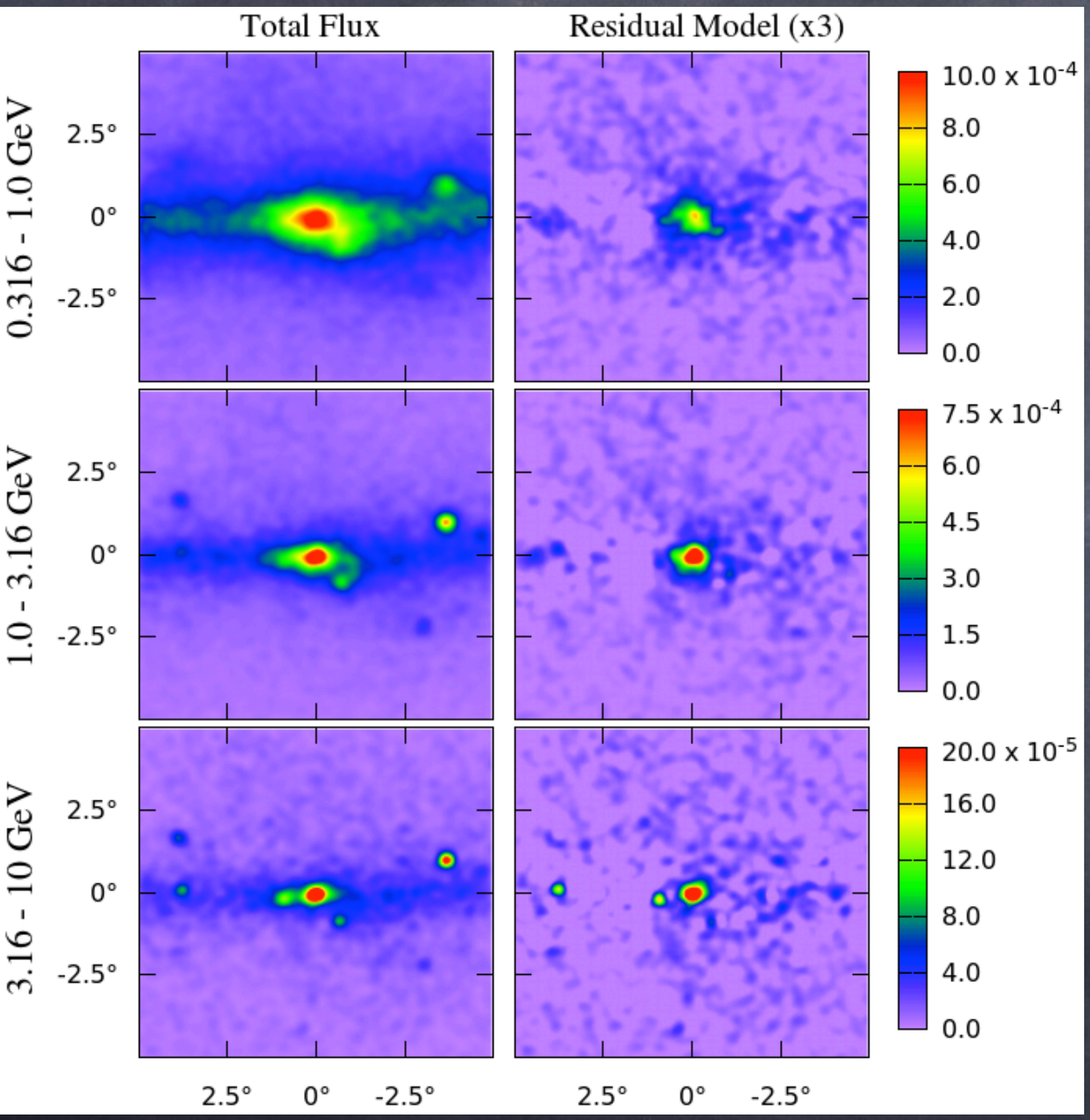


Excess Diffuse Emission

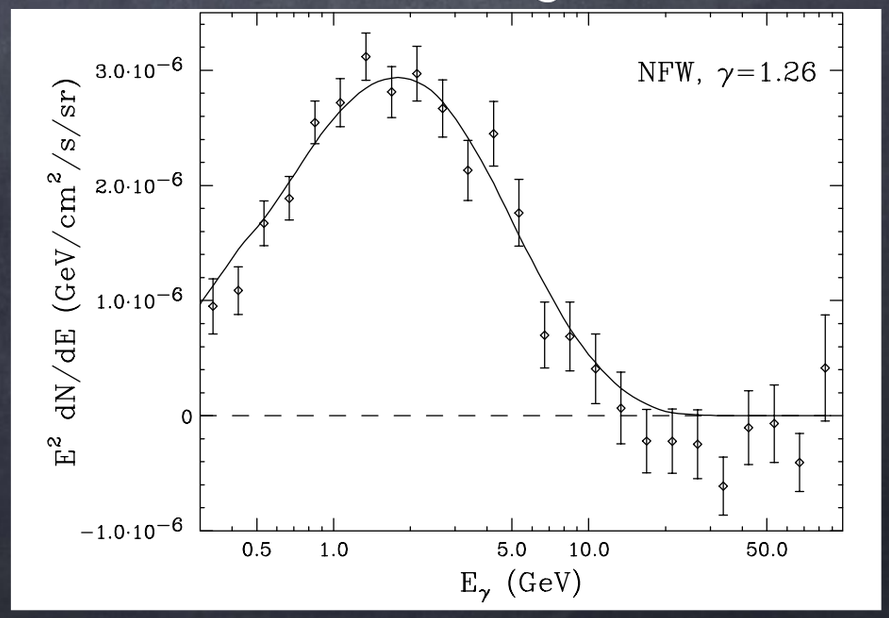
Similar results to earlier Hooper & Goodenough papers in 0910.2998 and 1010.2752 and later from: Abazajian & Kaplinghat (1207.6047), Gordon & Macias (1306.5725)

Repeating the exercise in different energies (updated analysis, using a new class of photon cuts allowing for better angular resolution)



Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, 1402.6703

- A clear excess emission in the galactic center emerges
- 90% of the total emission in the inner few degrees is removed
- Residuals not related to the galactic center (GC) are up to ~5% as bright as the GC residual
- Excess emission cuts-off at ~10 GeV (is in some dis-agreement with later findings)

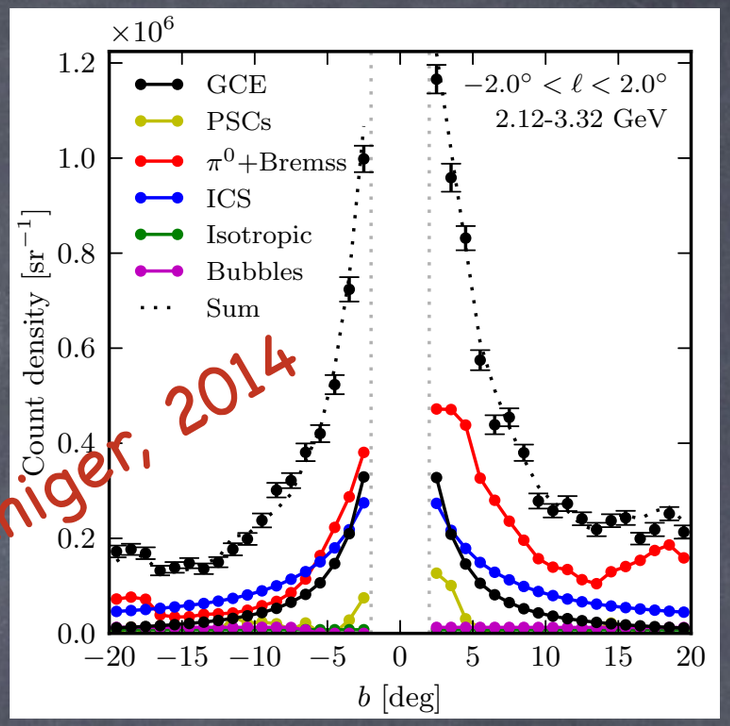


Going to High Latitudes

For a DM signal you want to look outside the galactic disk but still just above the galactic center (also dSph galaxies can be an alternative target)

Advantages of going outside the inner few degrees:
i) if a DM signal: you have a prediction on how the spectrum should look (same shape) and how its normalization should be (contracted NFW)
ii) Different region on the galactic sky suffer from different uncertainties in the background models: In the inner part of the Galaxy point source subtraction is a very important uncertainty, the gas density is also an important uncertainty and also the radiation field is an other. At higher latitudes : Fermi Bubbles, possibly unknown gas (unaccounted for in spectral line observations). Also propagation assumptions on the CRs may differ significantly between different regions of the Galaxy (due to strong wind outflows or magnetic fields causing anisotropic and preferential diffusion).

40 degrees in latitude



Calore, Cholis, Weniger, 2014

Excess emission towards the GC that extends up to possibly ~100 GeV and certainly above 10 GeV

It extends with a lower limit of 10 degrees away from the Galactic Center at 95% CL.

See also Slatyer&Hooper2013, Huang, Urbano & Xue 2013

Important Questions regarding the Robustness of the DM-like signal

- How well have we probed the relevant uncertainties? Are the different methods used to probe the excess signal in the inner few degrees and at higher latitudes DIFFERENT/ORTHOGONAL ENOUGH?

- How well do we understand the diffusion/propagation of CRs in the inner part?

- Can we build up a new distribution of sources in the inner 1-2 kpc that have the right properties but are not close by to us? How would we see them?

- How about dSphs? (I will come back to this in a bit)

- How about galaxy clusters? (not optimistic yet due to large contamination from both background and foreground emission)

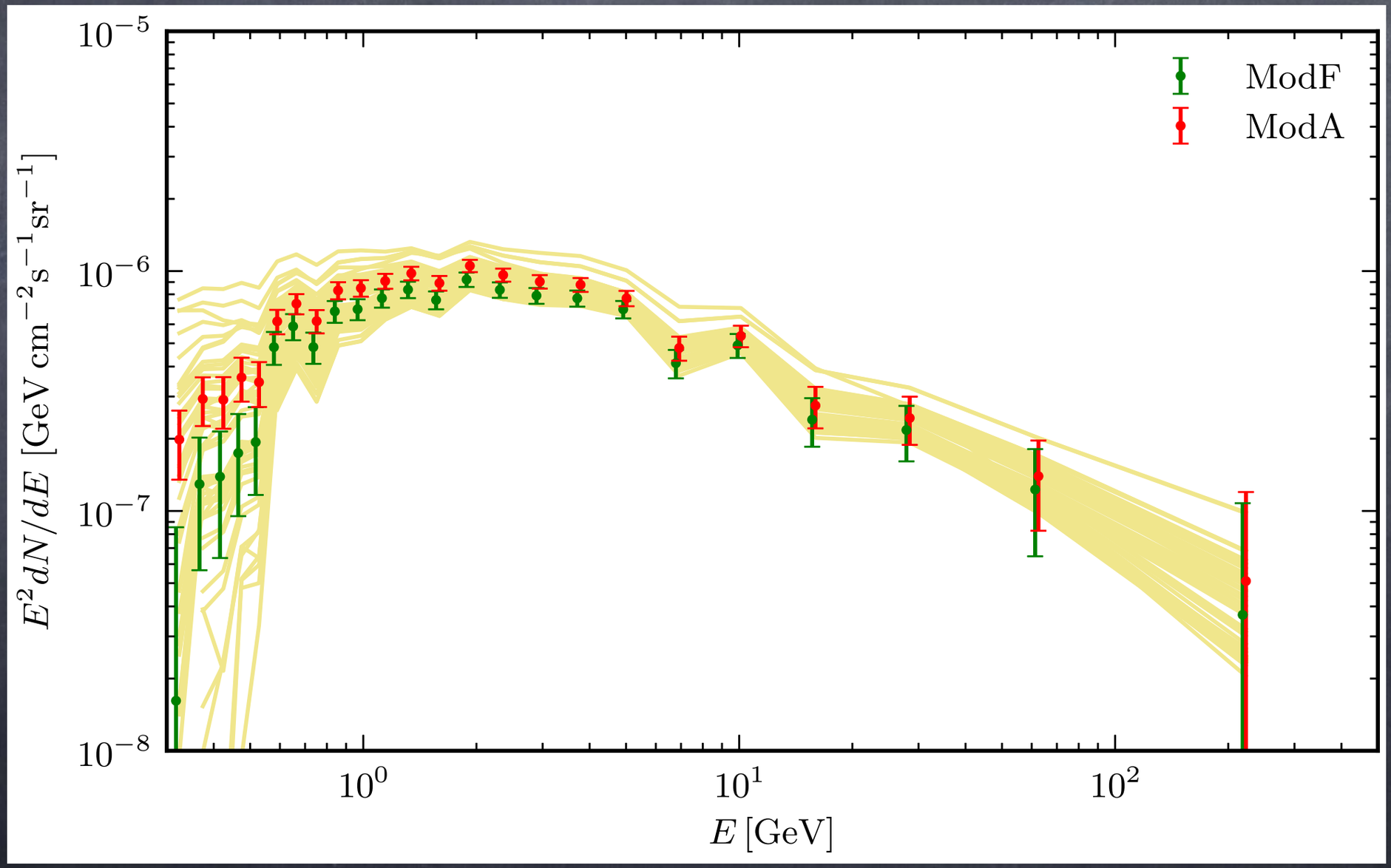
- How about the extragalactic diffuse emission and cross-correlating with other wavelengths (a new era for gamma-ray astronomy).

Accounting for the galactic diffuse emission uncertainties

- Properties of the diffusion zone within which cosmic rays (CR) diffuse before escaping to the intergalactic medium
- How fast do CRs diffuse? are there convective winds and how strong?
- How important are the effects of CR diffusive re-acceleration (diffusion in momentum space)
- Distribution of cosmic rays sources (does it follow SNRs?, pulsars? OB stars?)
- Spectral properties of CRs. Are they the same everywhere?
- How well do we understand the gas distribution along the line of sight and towards the inner Galaxy?
- How well do we understand the galactic magnetic field that affects the energy losses of CR electrons
- How well do we understand the interstellar radiation field properties? (these are the target photons that get up-scattered into gamma-rays from CR electrons).

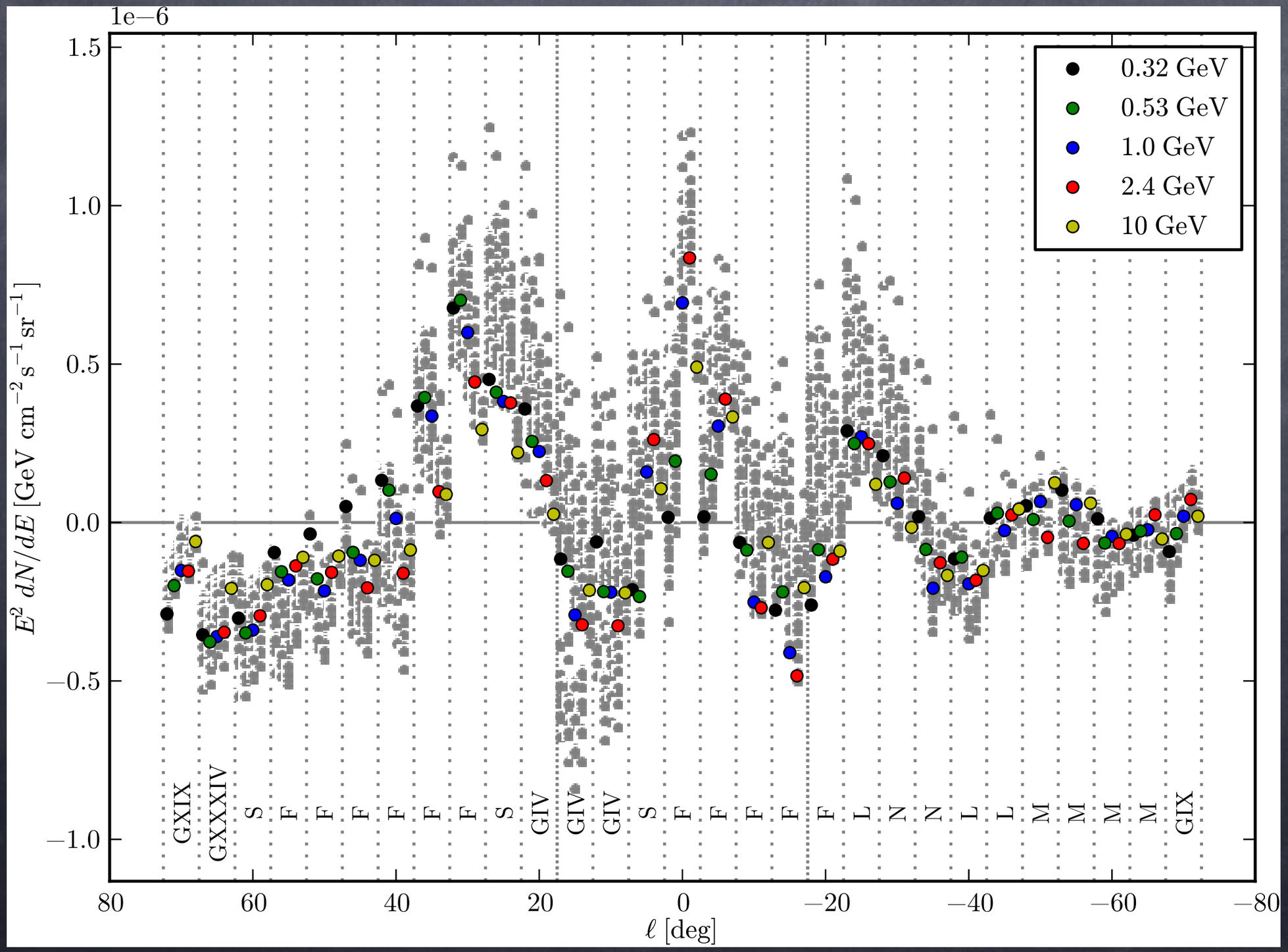
We used models from the existing literature and created our own (60 models shown in our paper).

It turns out that it actually does not affect dramatically the excess spectrum:



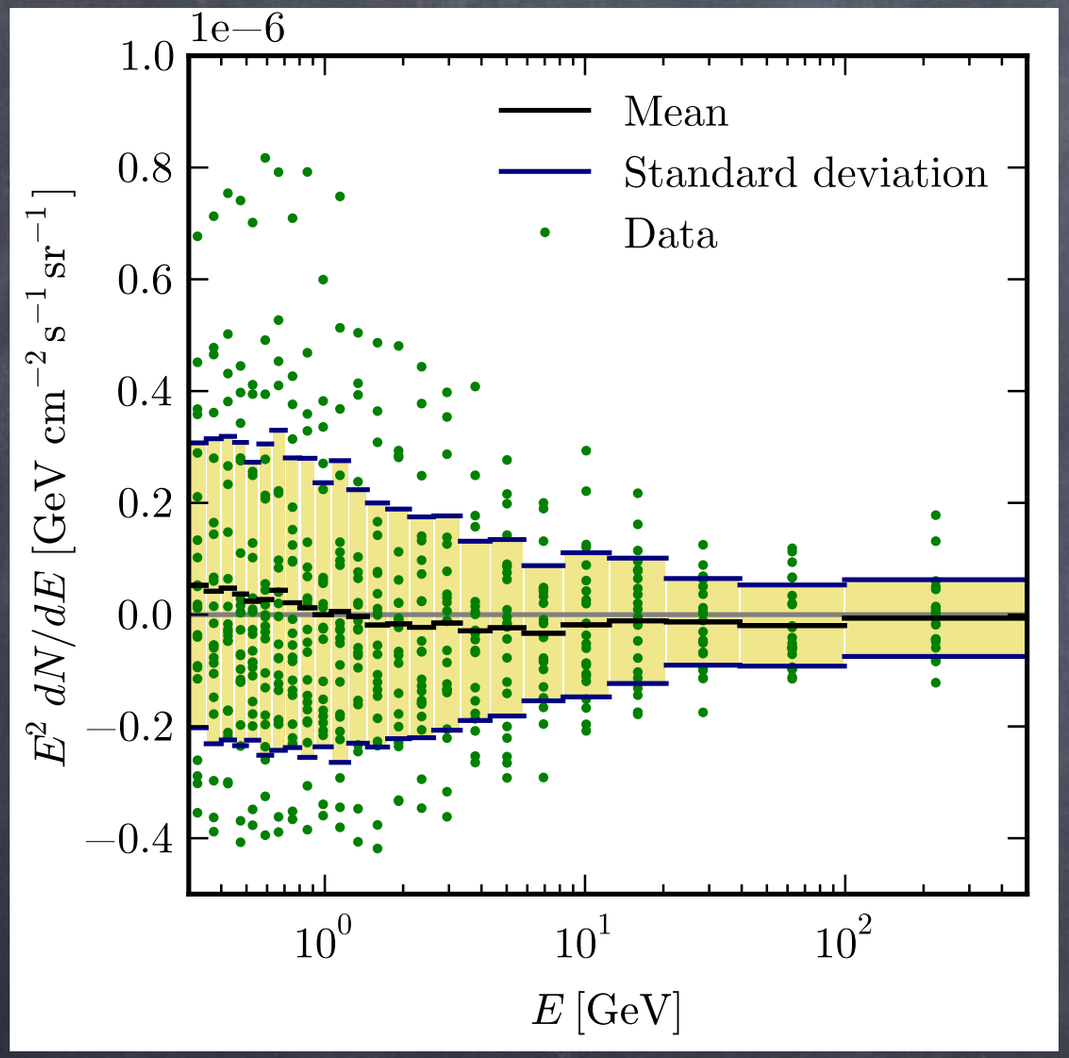
Calore, Cholis, Weniger, 2014

An alternative way, look along the galactic disk:
We basically repeat the same procedure but now change the window that we fit by moving it along the galactic disk; cross-checking every time with our 60 diffuse emission models

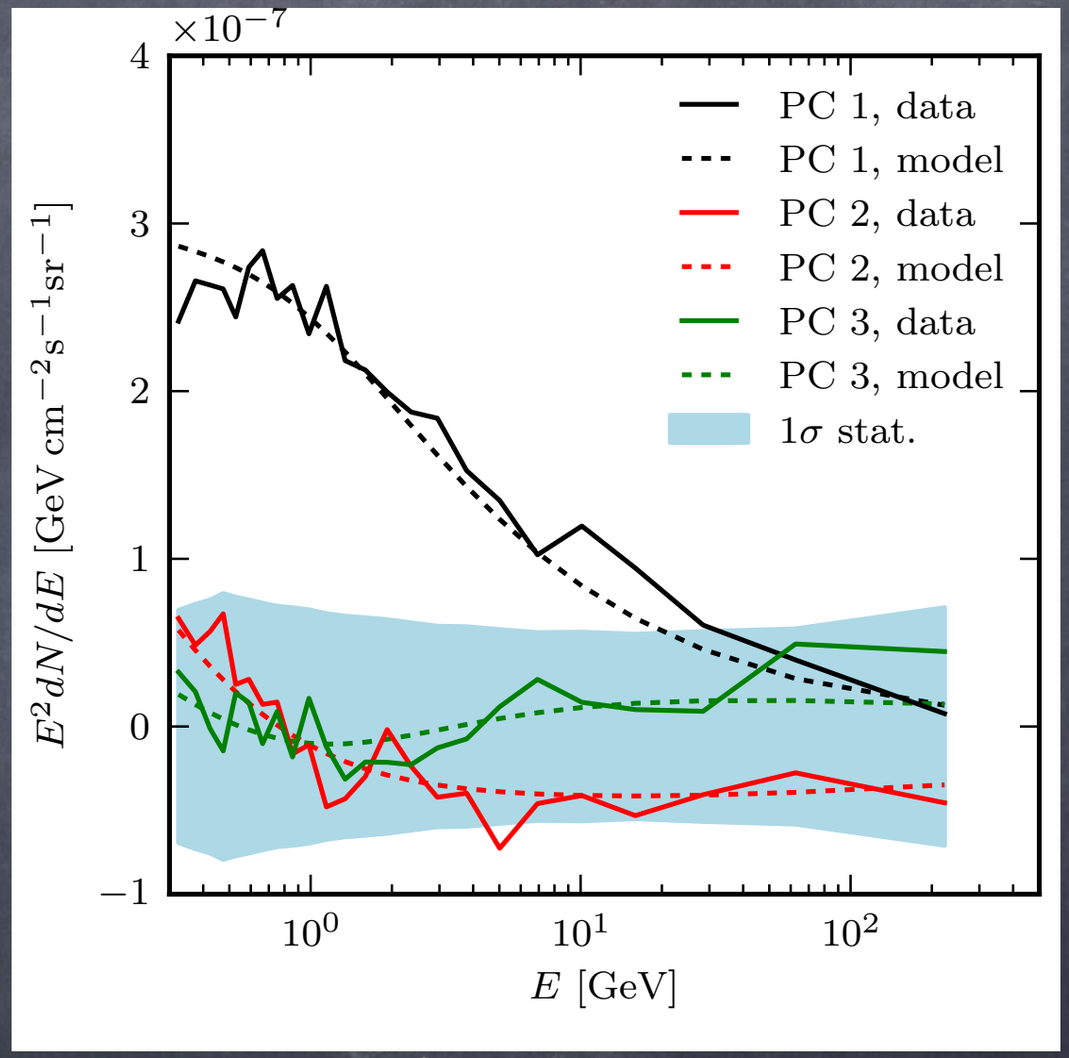


Calore, Cholis, Weniger, 2014

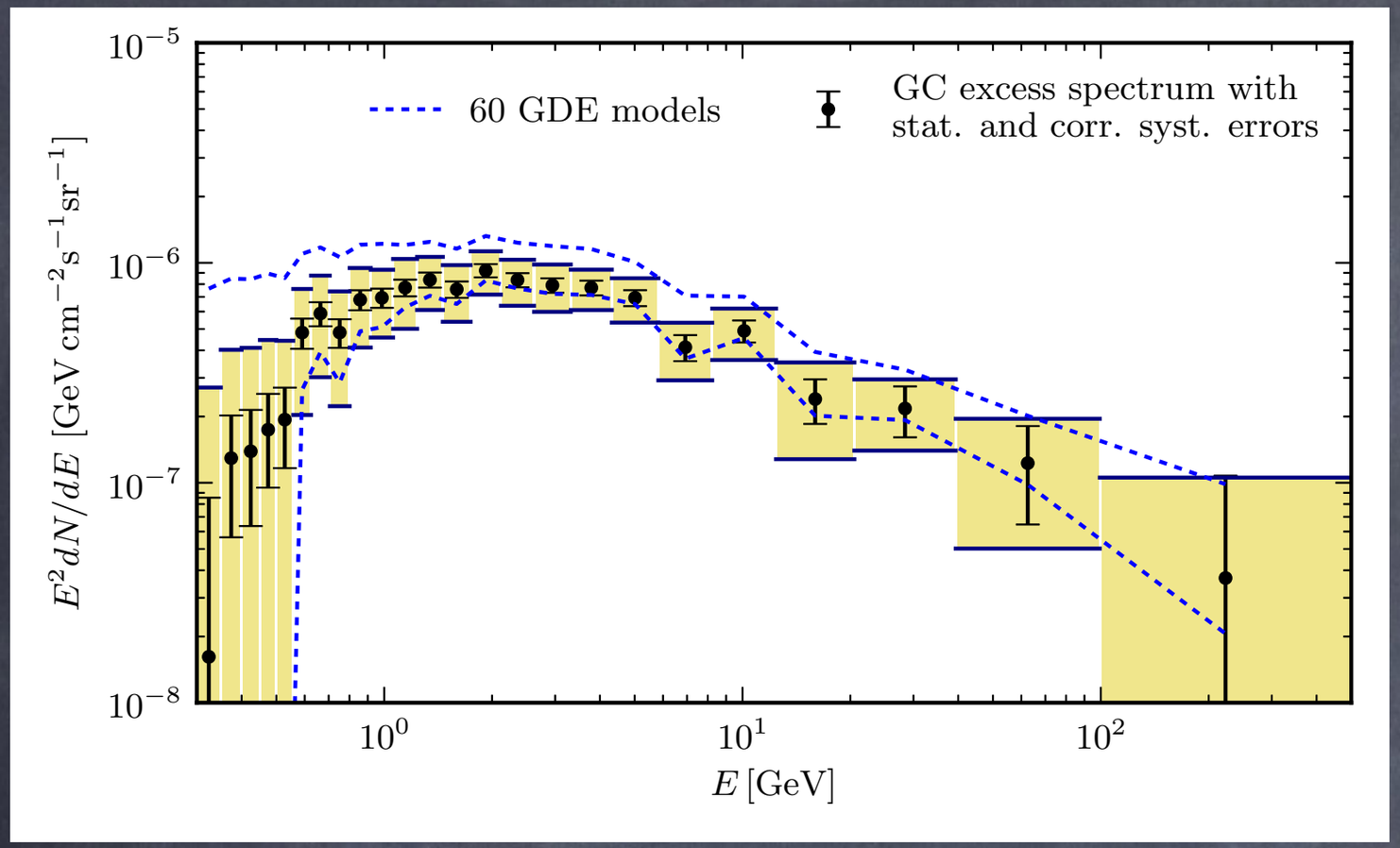
One can then calculate a covariance matrix which allows to properly quantify the correlated systematic errors (associated to the lack of better understanding of the galactic diffuse emission) which uncertainties are bigger than the statistical one (associated to number of gamma-ray events):



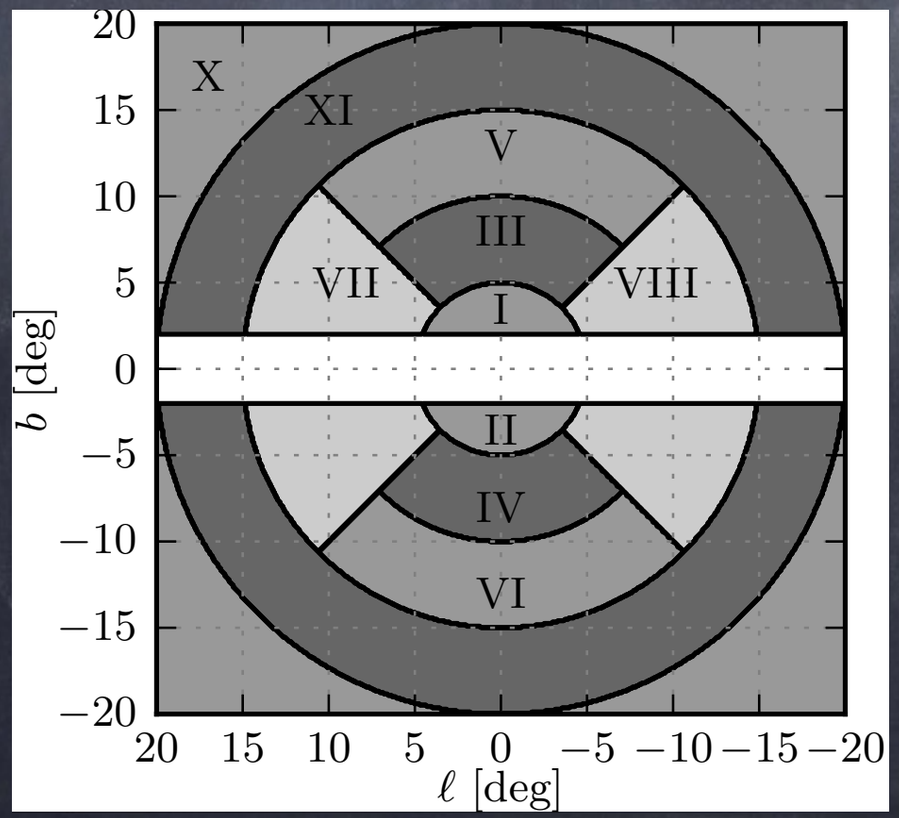
Residuals of the transported GCE template. No evident bias is seen. Green points show all 22 regions tested.

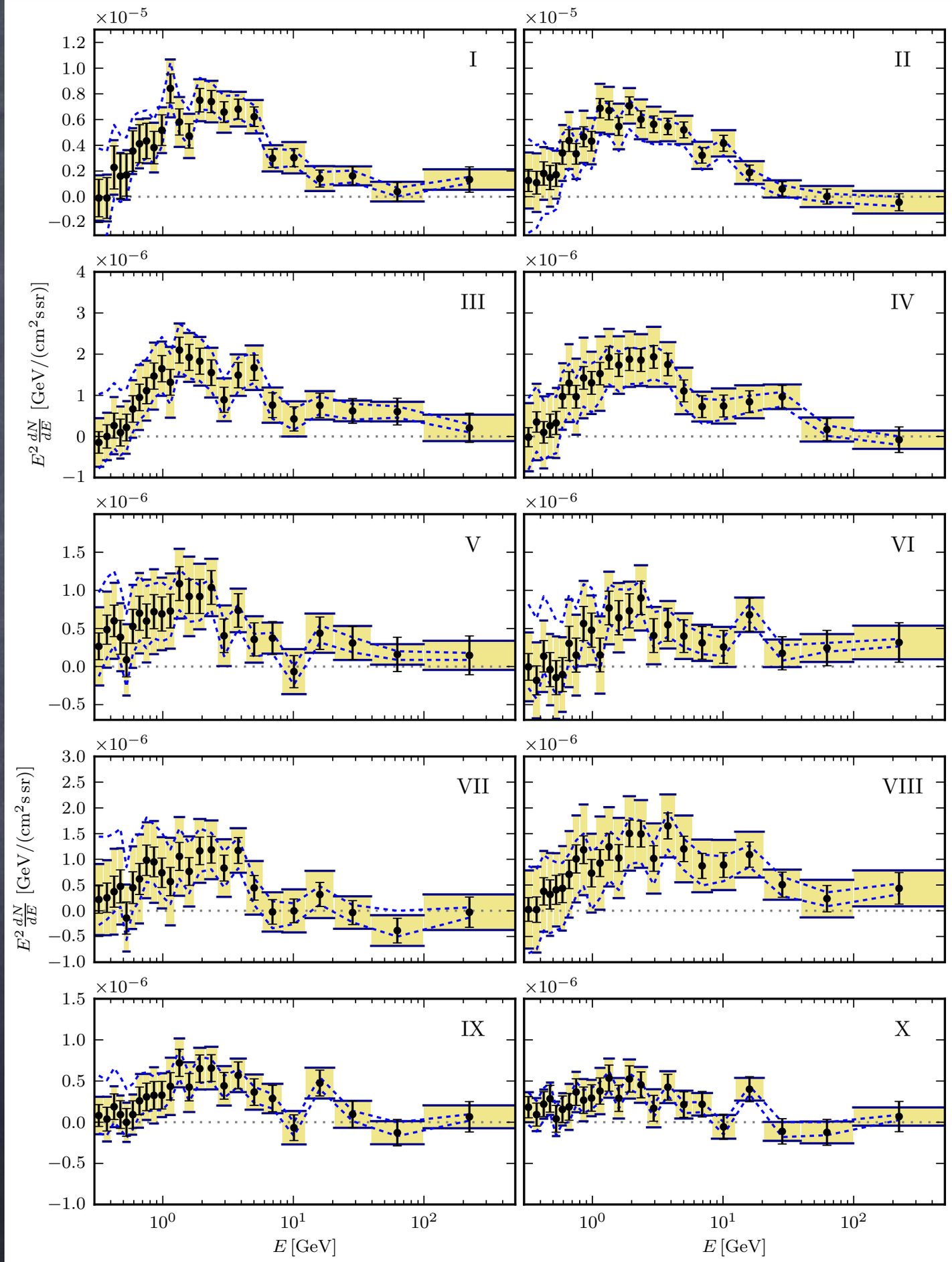


Decomposition of the covariance matrix in terms of principal comp. Only the first 3 are important. Only the 1st is above the statistical errors. The observed variations can be traced back to uncertainties in the pi0 and ICS slopes and amplitudes.



One can repeat the same exercise to smaller regions:

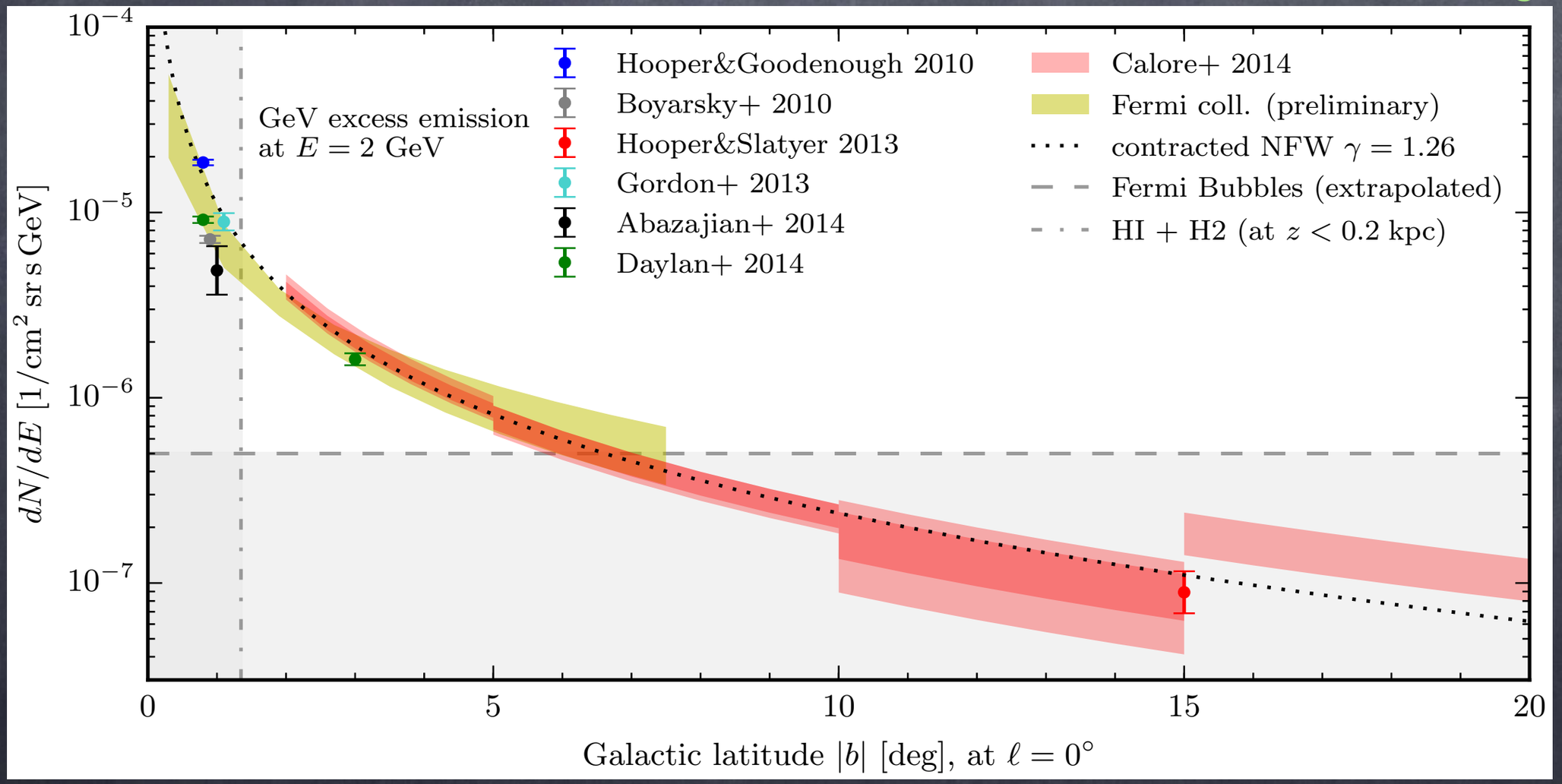



I
II
III
IV
V
VI
VII
VIII
IX
X
$\times 10^{-5}$
$\times 10^{-6}$
$E^2 \frac{dN}{dE}$ [GeV/(cm^2 s sr)]
E [GeV]

A different way of seeing the level of agreement between individual results

The flux associated to the excess emission at 2 GeV vs galactic latitude:

Calore, Cholis, McCabe, Weniger, 2014



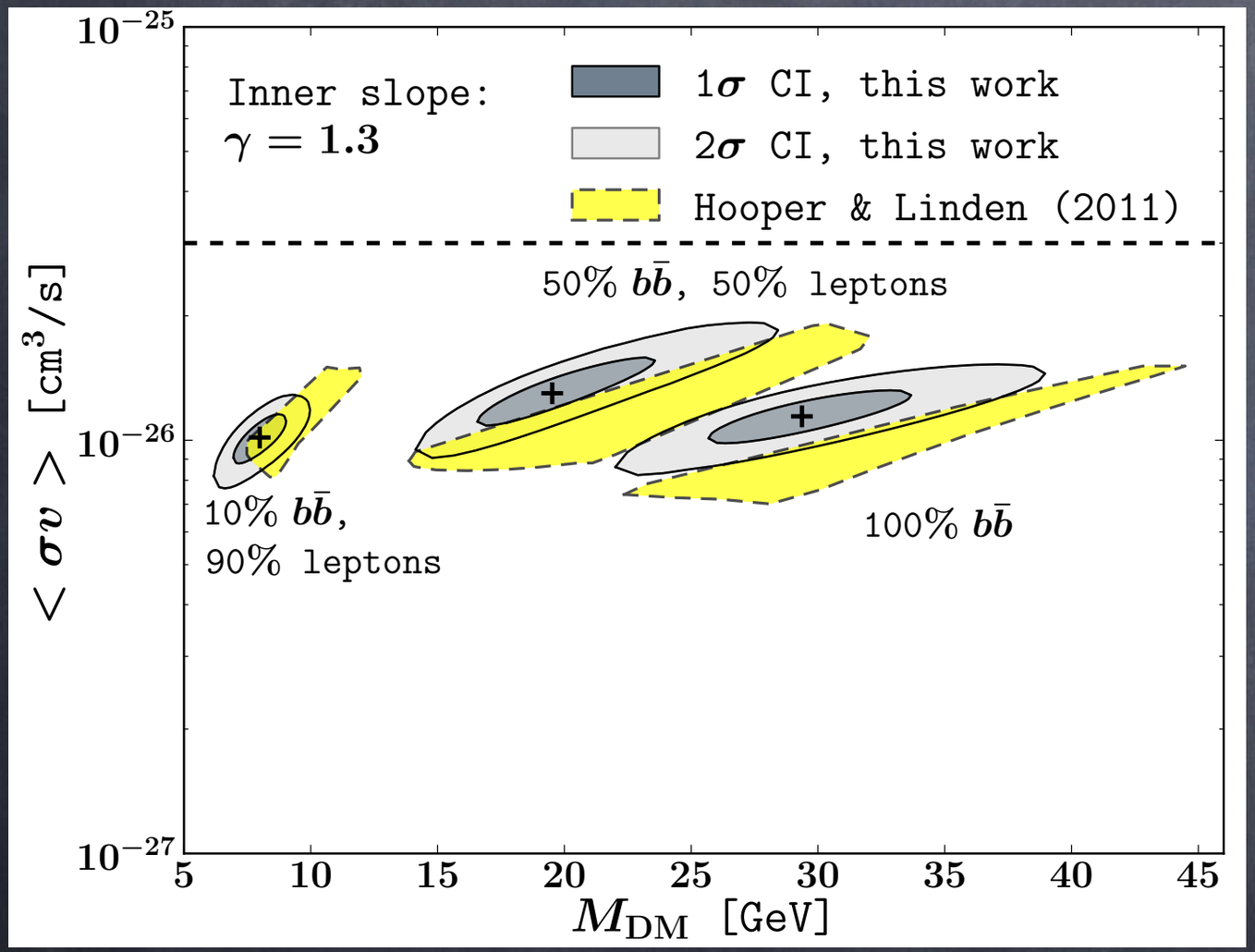
The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission (that is wether it is DM or MSPs or CR outbursts).

If this is a DM annihilation signal:

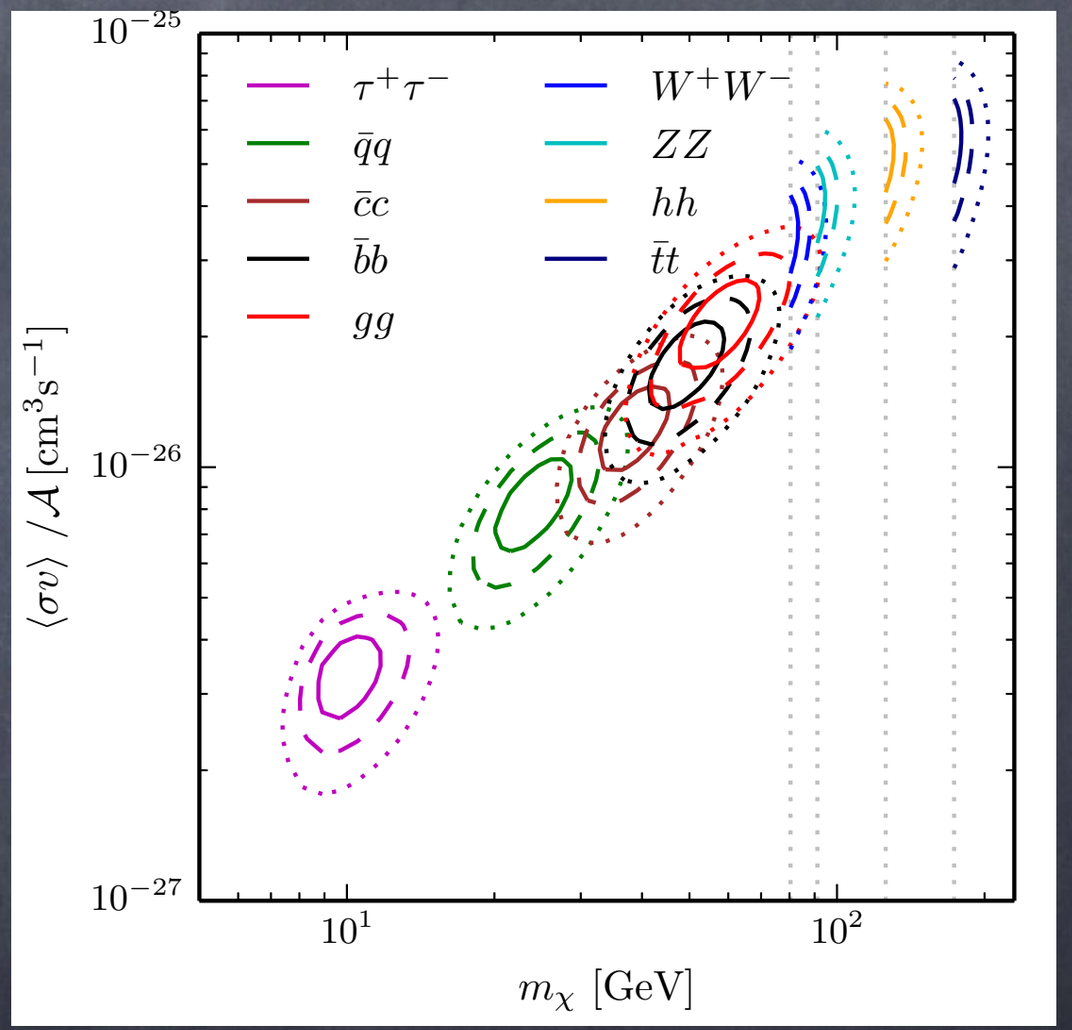
The range of possibilities (phenomenologically) becomes much larger.

Because of the correlated errors.

BEFORE:



AFTER:

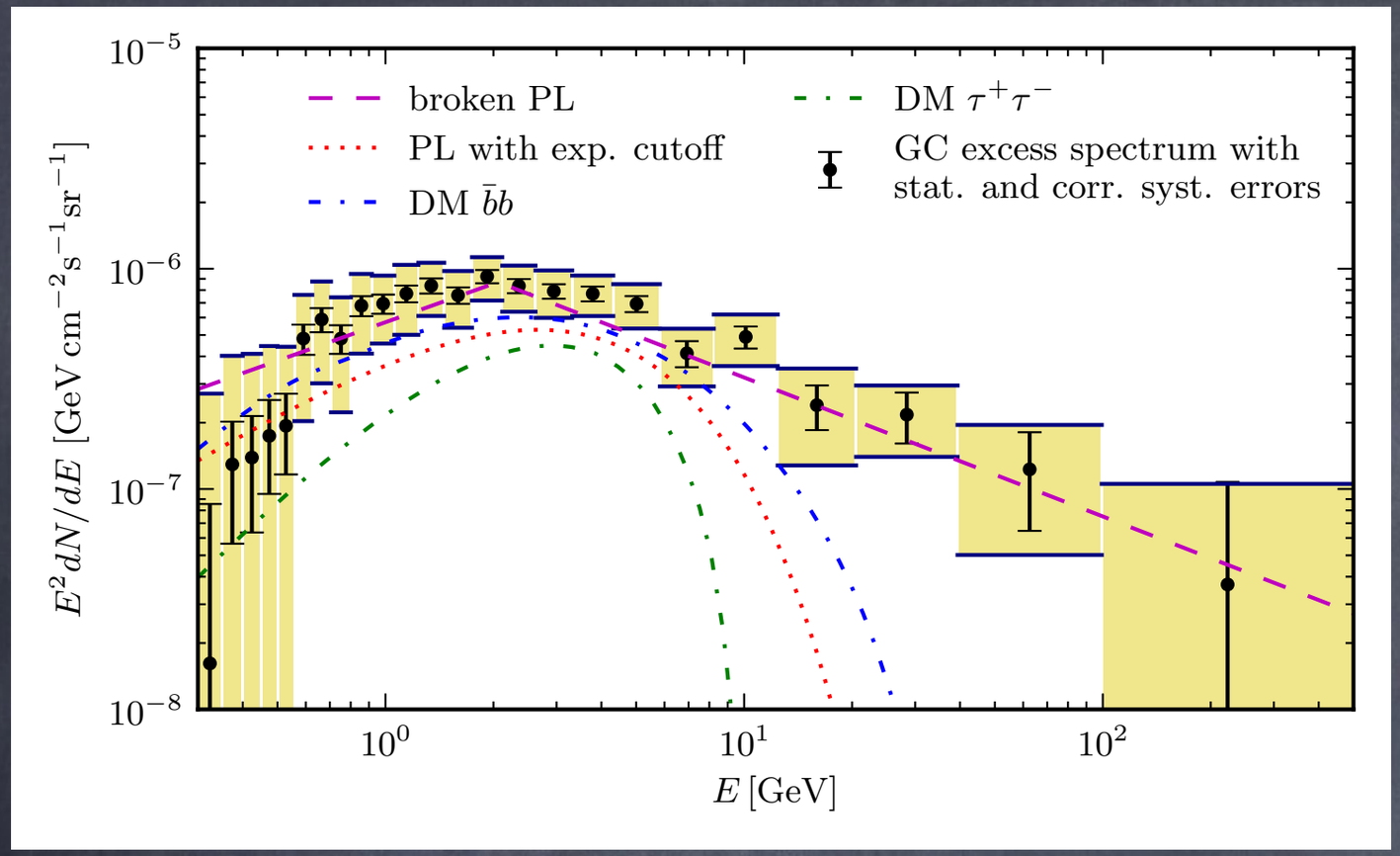


Gordon & Macias (1306.5725)

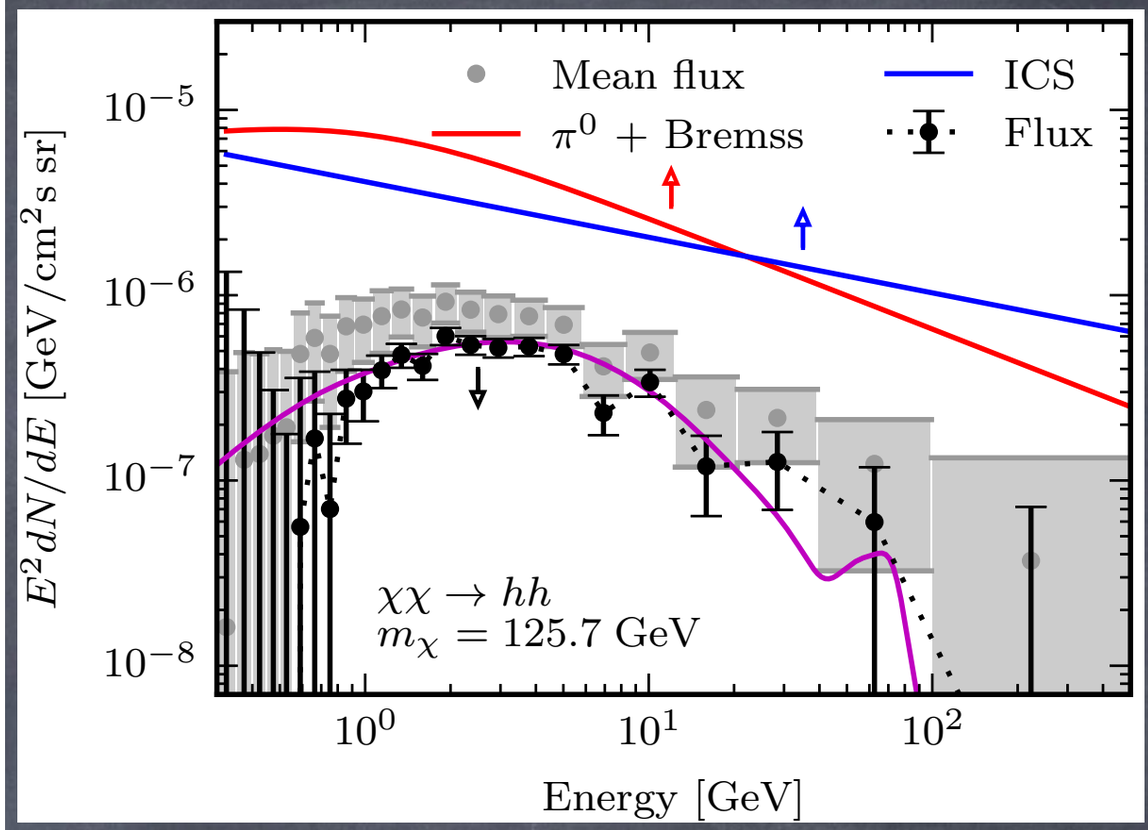
Calore, Cholis, McCabe, Weniger, 2014

The mass range preferred is actually higher. Even though still light DM models can work.

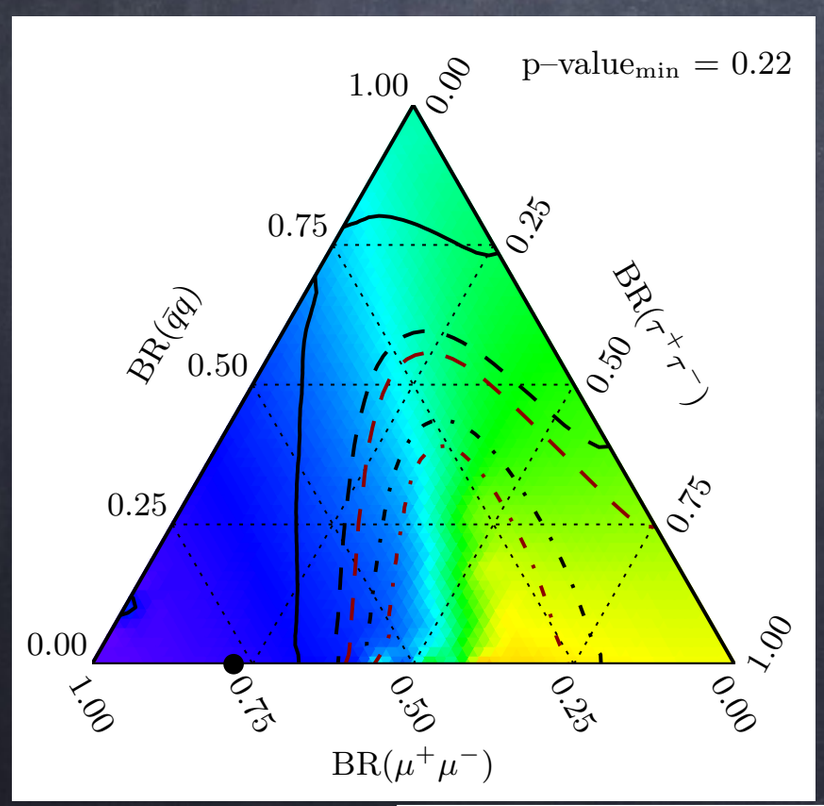
(see also P. Agrawal, B. Battel, P. Fox, R. Harnik, 1411.2592)

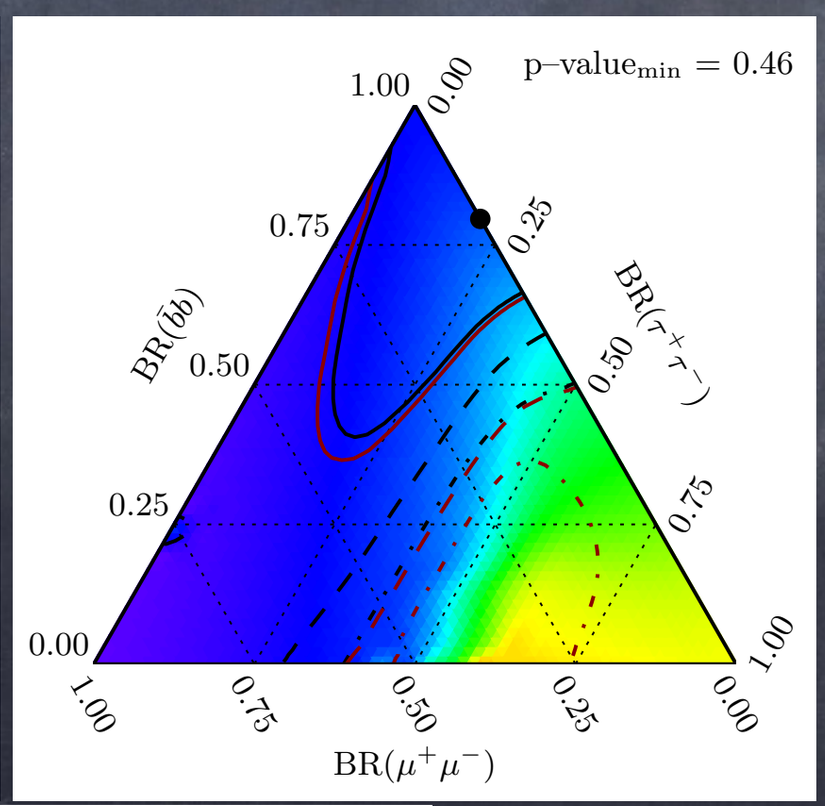


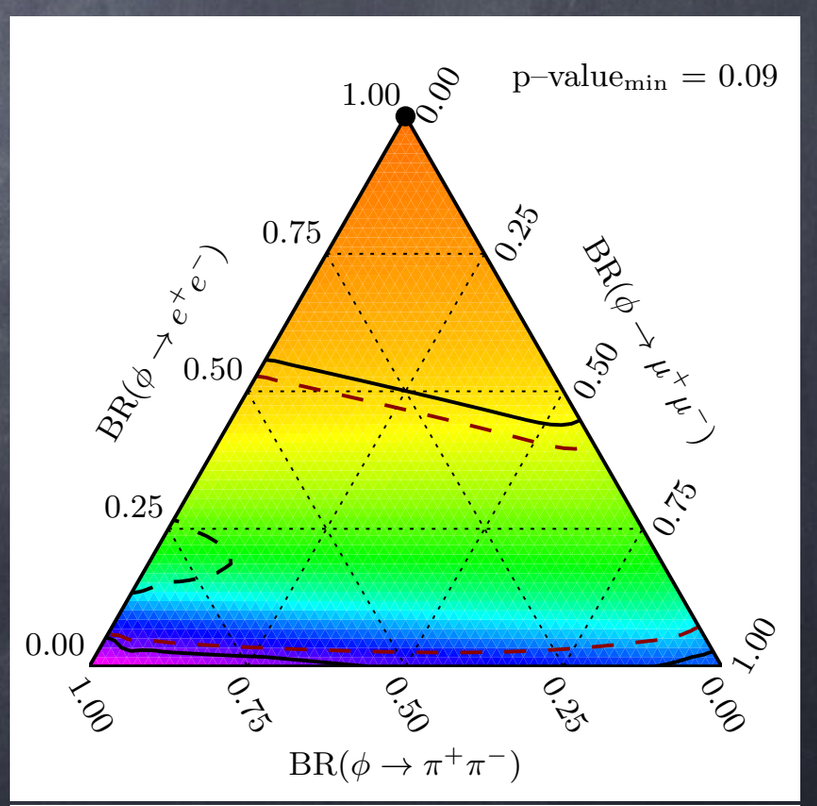
Calore, Cholis, Weniger, 2014

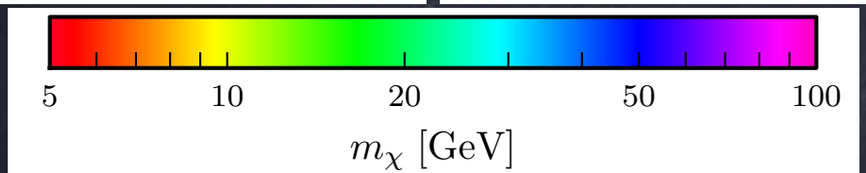


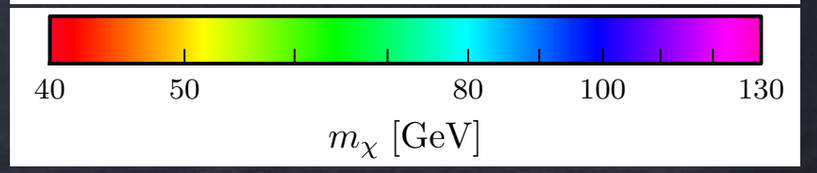
Calore, Cholis, McCabe, Weniger, 2014



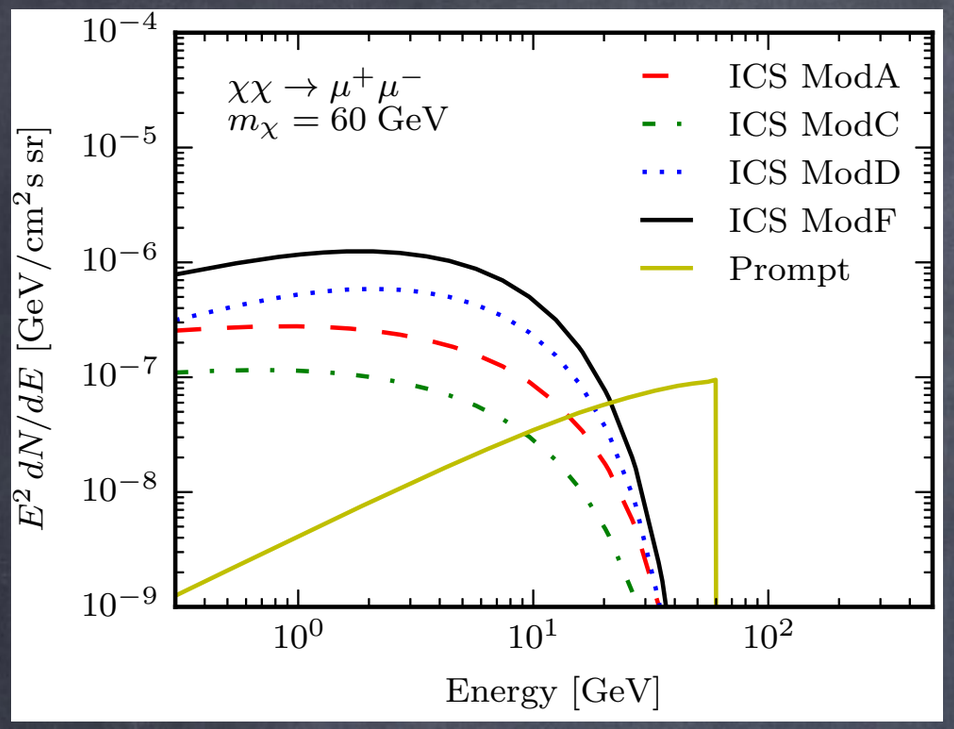




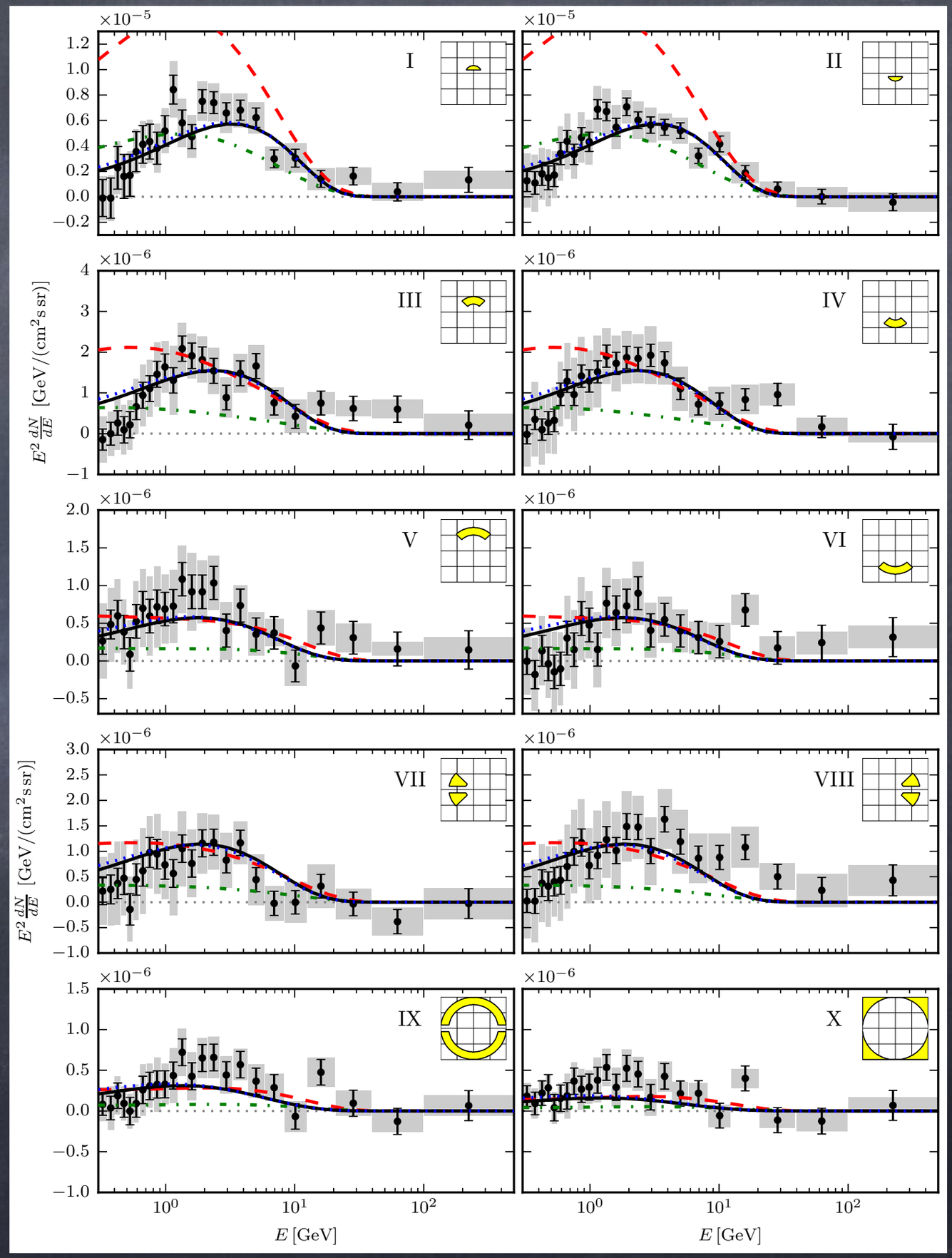




One can also study the ICS signal from DM annihilations (including astrophysical uncertainties):

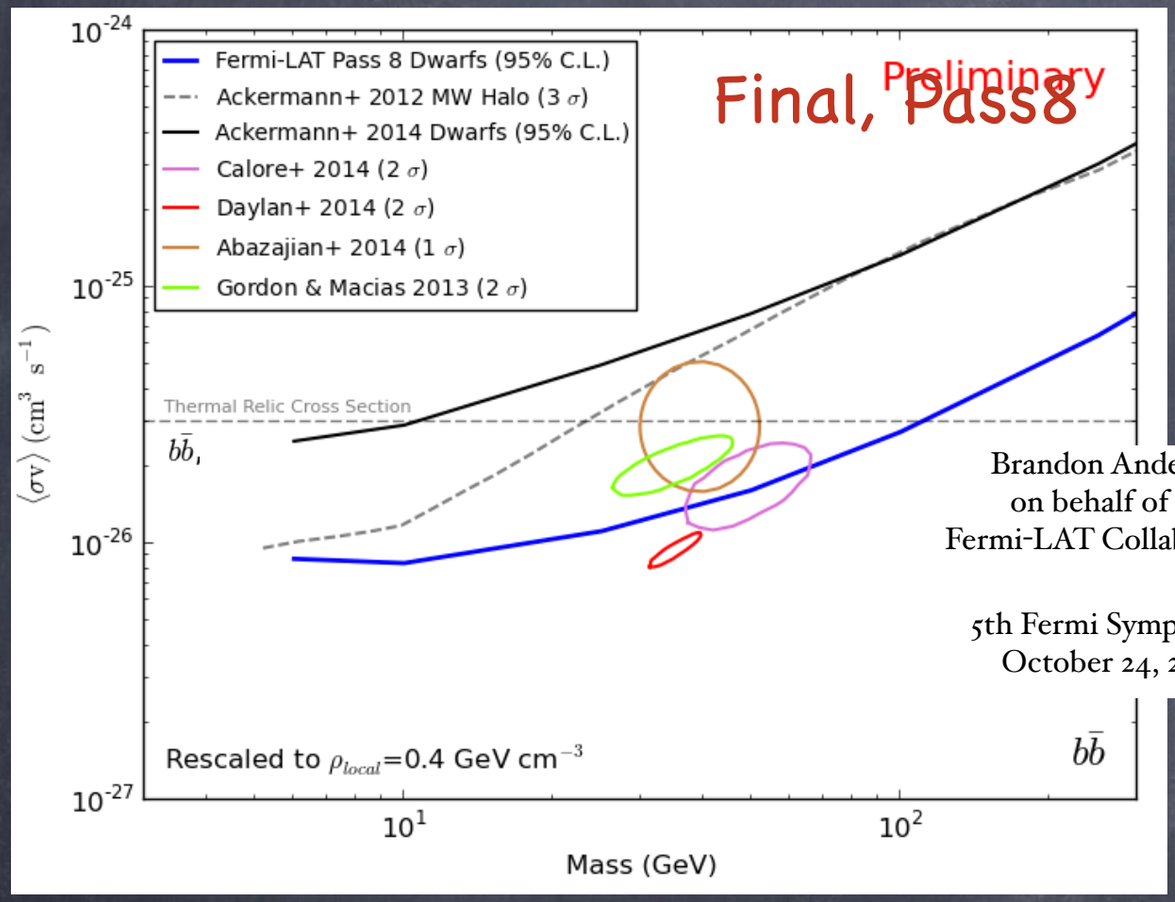


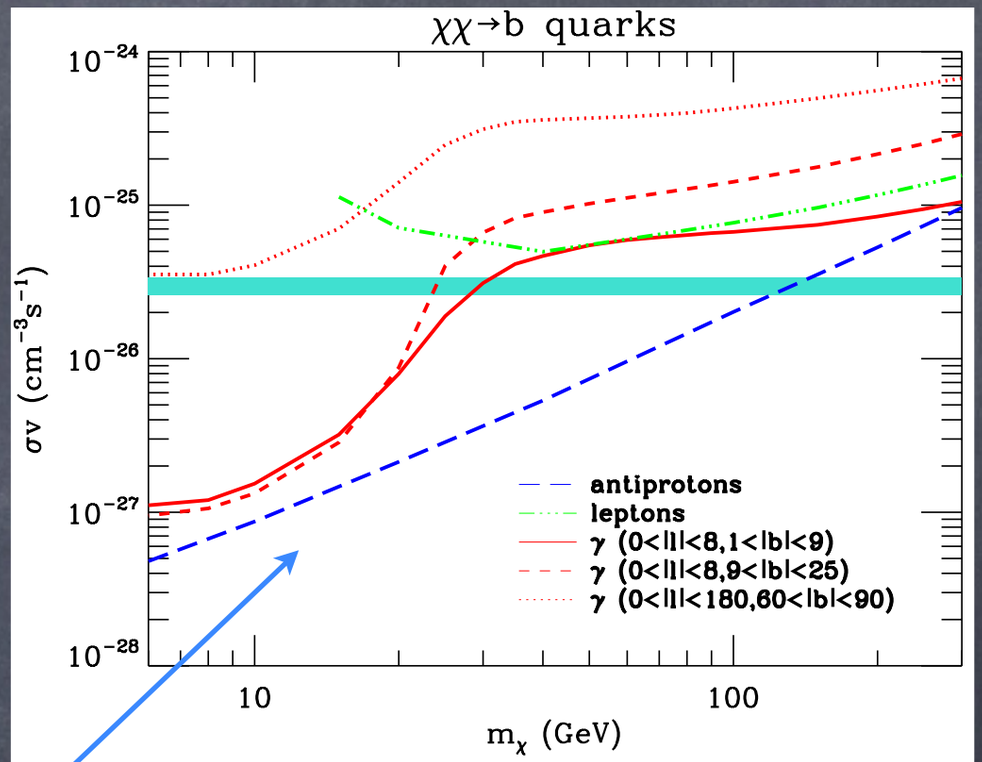
Understanding the morphology of the signal in various windows can be crucial; FOR ANY model that wants to explain the GC excess via CR electrons(positrons) whether of DM origin or Not.

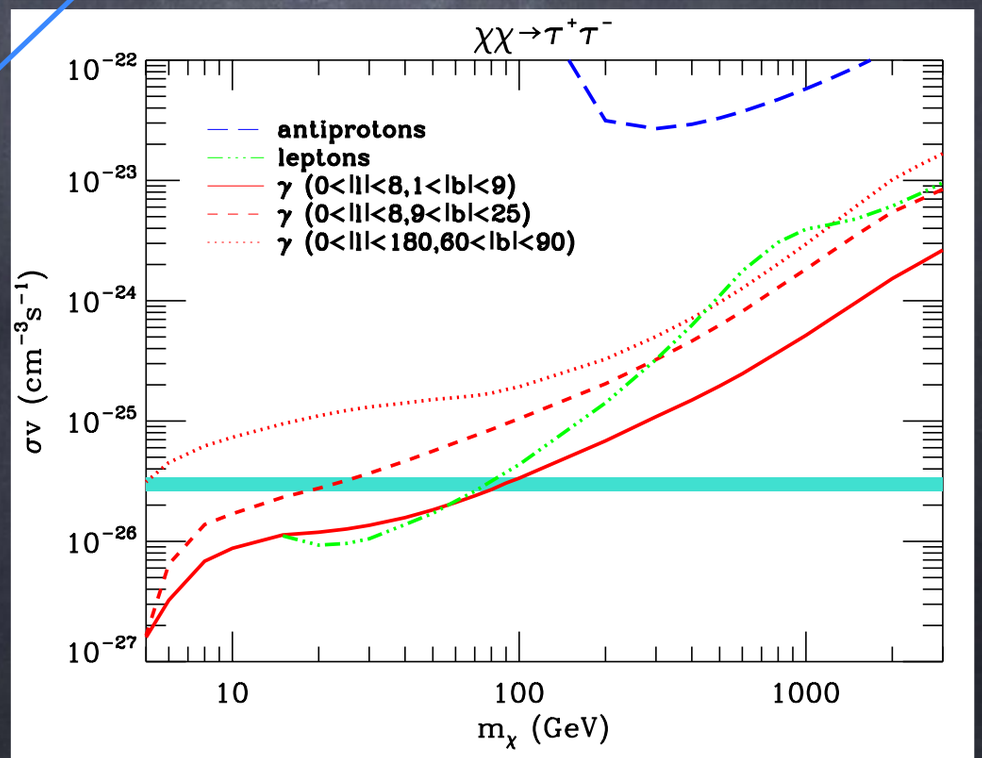


One last thing; If this is a DM annihilation signal:

The amplitude of the signal is in general agreement with constraints from other indirect probes: Dwarf spheroidal galaxies, other DM galactic substructures antiprotons, gamma-rays from other regions of the galactic sky, the CMB.







Ullio (1308.4135)

Tavakoli, Cholis, Evoli, U

strong limits from dwarf spheroidal galaxies (see results at 1503.02641)

Antiprotons can still give stronger limits for b-quarks by a factor of ~2.

For DM models with high BRs to leptons the AMS-02 data actually provide the best limits instead.

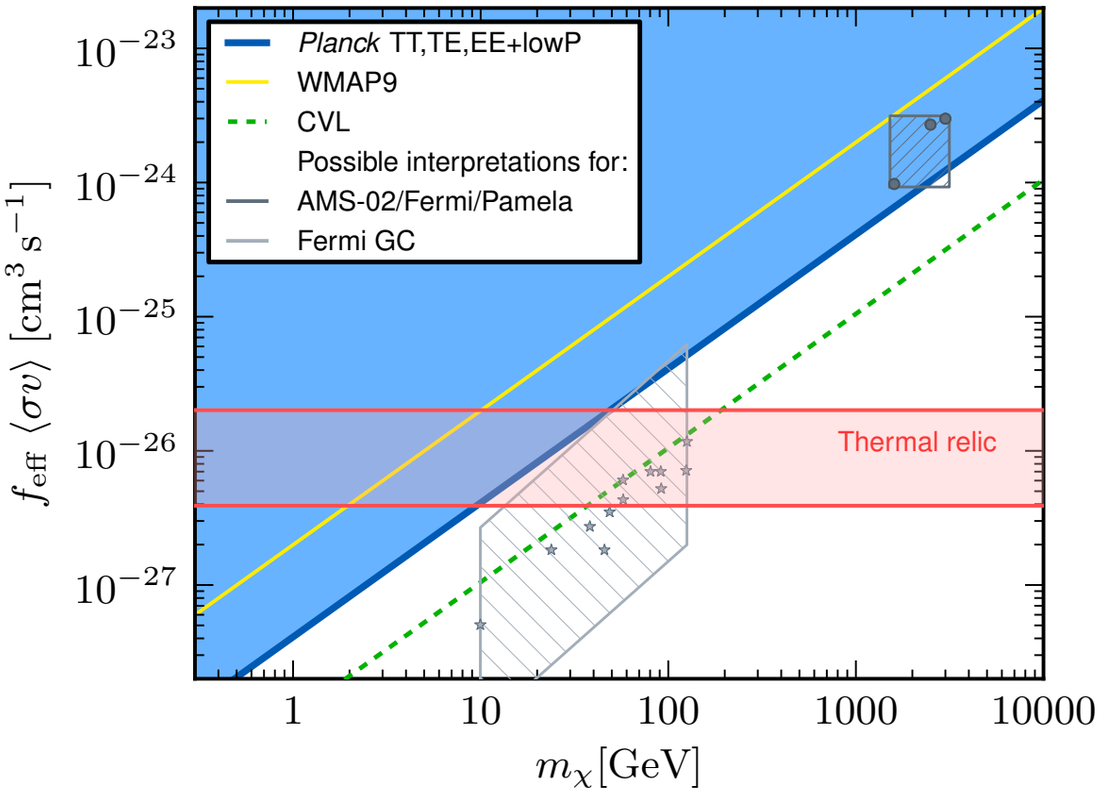


Fig. 41. Constraints on the self-annihilation cross-section at recombination, $\langle\sigma v\rangle_{z_*}$, times the efficiency parameter, $f_{\rm eff}$ (Eq. 81). The blue area shows the parameter space excluded by the *Planck* TT,TE,EE+lowP data at 95 % CL. The yellow line indicates the constraint using WMAP9 data. The dashed green line delineates the region ultimately accessible by a cosmic variance limited experiment with angular resolution comparable to that of *Planck*. The horizontal red band includes the values of the thermal-relic cross-section multiplied by the appropriate $f_{\rm eff}$ for different DM annihilation channels. The dark grey circles show the best-fit DM models for the PAMELA/AMS-02/*Fermi* cosmic-ray excesses, as calculated in Cholis & Hooper (2013) (caption of their figure 6). The light grey stars show the best-fit DM models for the *Fermi* Galactic centre gamma-ray excess, as calculated by Calore et al. (2014) (their tables I, II, and III), with the light grey area indicating the astrophysical uncertainties on the best-fit cross-sections.

A non-DM interpretation: Millisecond Pulsars (MSPs)?

How about a collection of Unresolved MSPs ?

Consider a large population of unresolved points sources distributed throughout the inner 100 parsecs of the Galaxy could produce the observed signal, Most likely scenario ~10^3 millisecond pulsars.

Why MSPs? : The observed spectra of Fermi's observed MSPs are qualitatively similar to that from the extended emission from the Galactic Center.

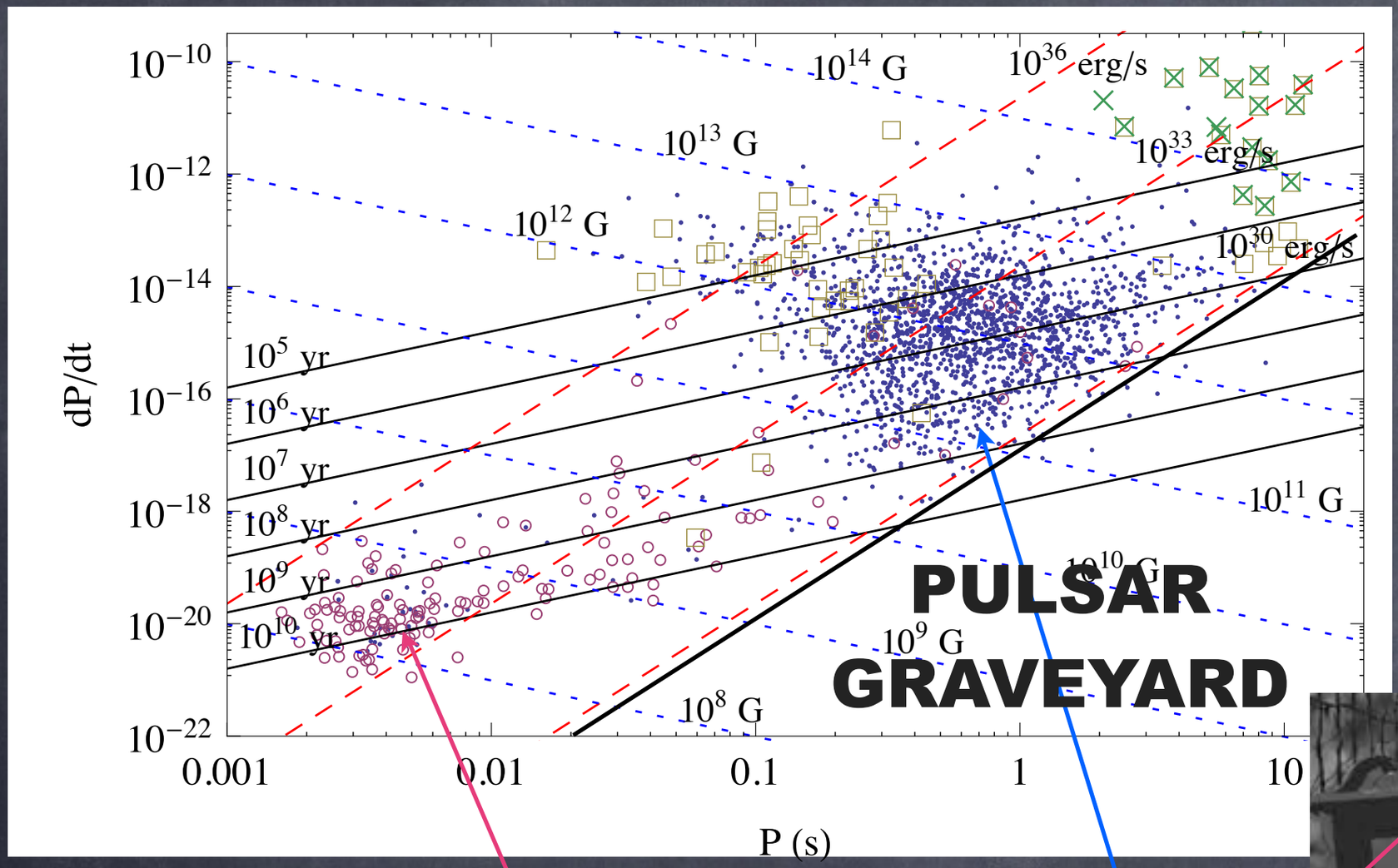
Still the Galactic Center emission appears to have a significantly harder spectral index below ~1-2 GeV and a high energy tail.

Also the suggested morphology in the inner few degrees of the observed flux implies a very concentrated distribution of sources ($F \propto r^{-2.6}$), while the observed stellar distribution is much more shallow ($n_{star} \propto r^{-1.25}$)
Yet, MSPs are born as a result of star-star interactions, so in that environment they may have been formed over the last many Gyrs at a preferable rate (and distribution).
Within the inner 2 degrees BOTH DM annihilation and MSPs ARE VIABLE

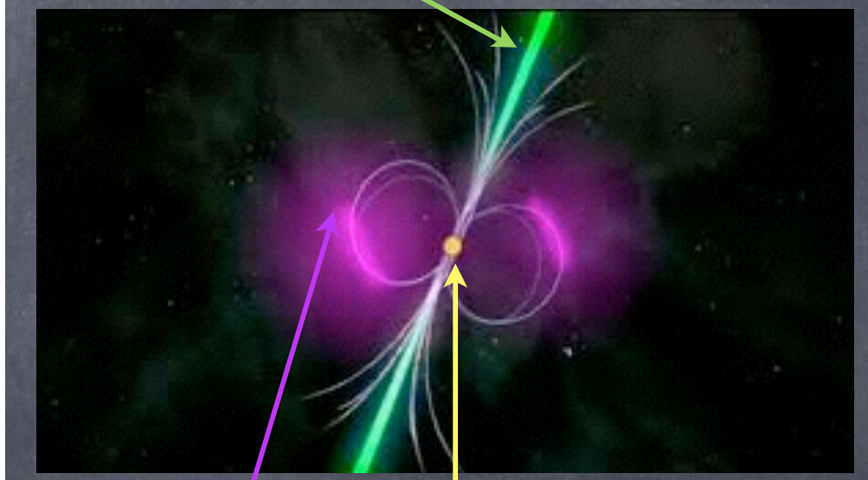
A bit about Pulsars in General

Basic model assumed Magnetic dipole radiation (n=3)

$$\tau = \frac{P}{(n-1)\dot{P}}\left[1 - \left(\frac{P_0}{P}\right)^{n-1}\right]$$

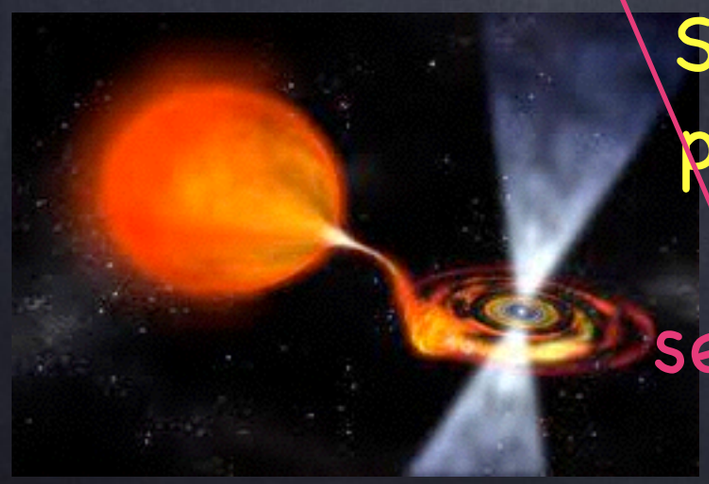


synchrotron pulse



Neutron Star

Gamma-Rays



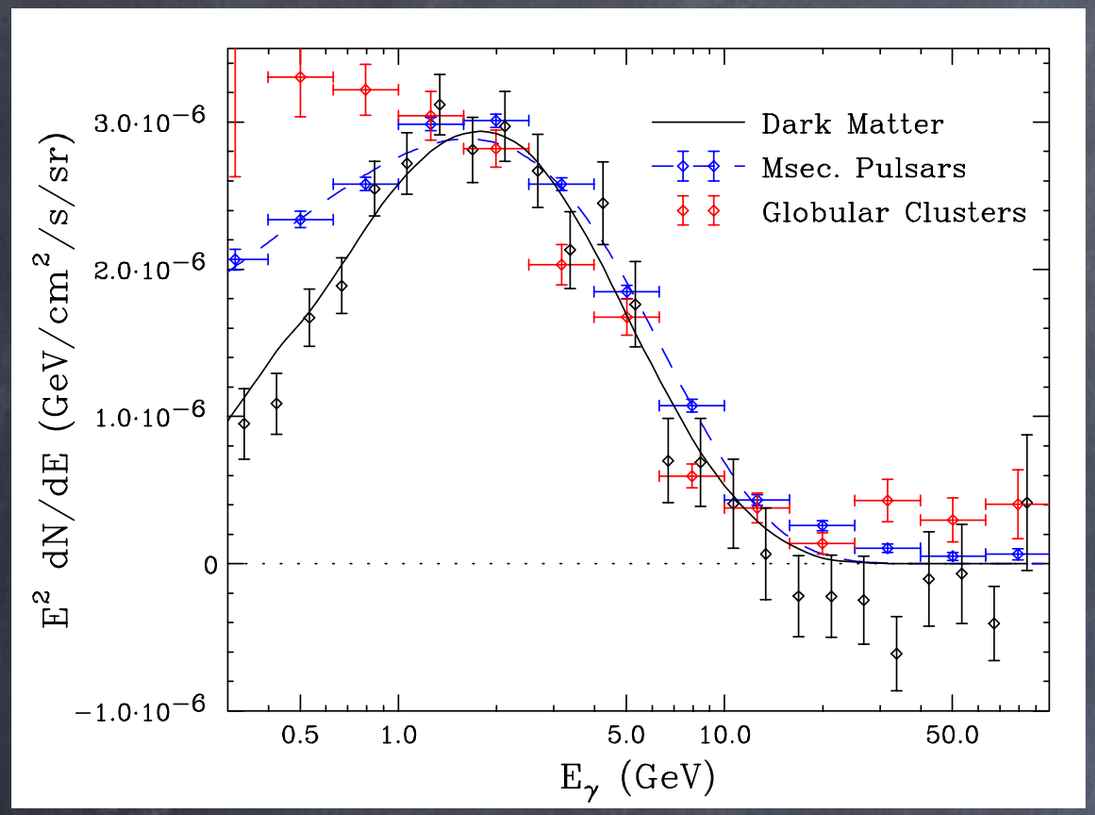
Spinning Up of a normal pulsar (with a period of seconds) to a milli-second ("zombie") pulsar: NEED A COMPANION

$$\dot{E} = -\frac{B_s^2 R_s^6 \Omega^4}{6c^3} \approx 10^{31} B_{12}^2 R_{10}^6 P^{-4}\,\mathrm{erg\ s^{-1}}$$

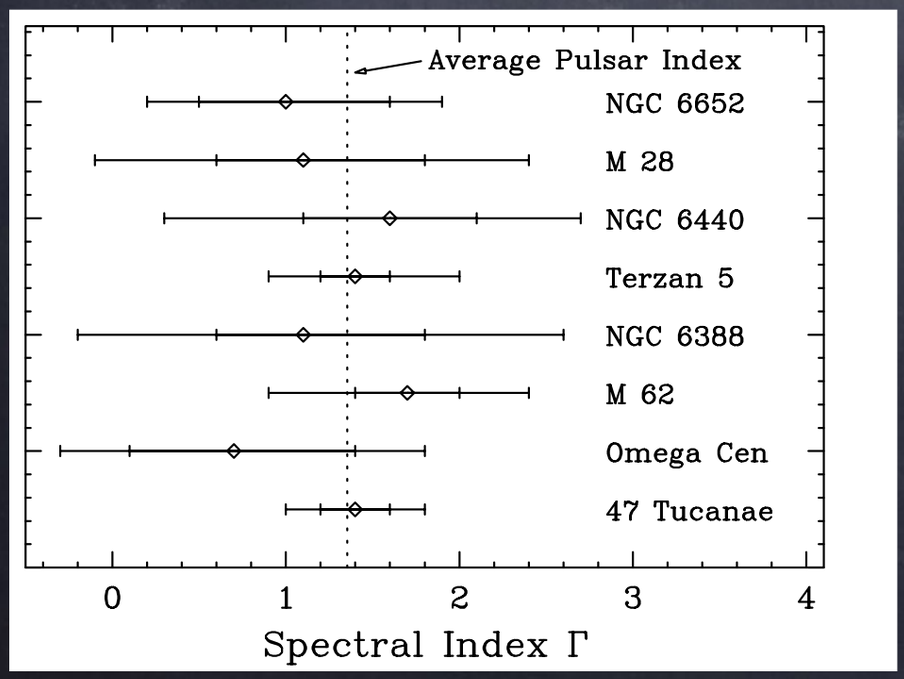
$$\dot{P} = 3.3 \times 10^{-15} (B/10^{12}\,\mathrm{G})^2 (P/0.3\,\mathrm{s})^{-1}$$

Spectral Arguments

Known MSPs (61 individual MSPs from Fermi & 36 Globular Cluster spectra)



Cholis, Hooper, Linden (1407.5625)



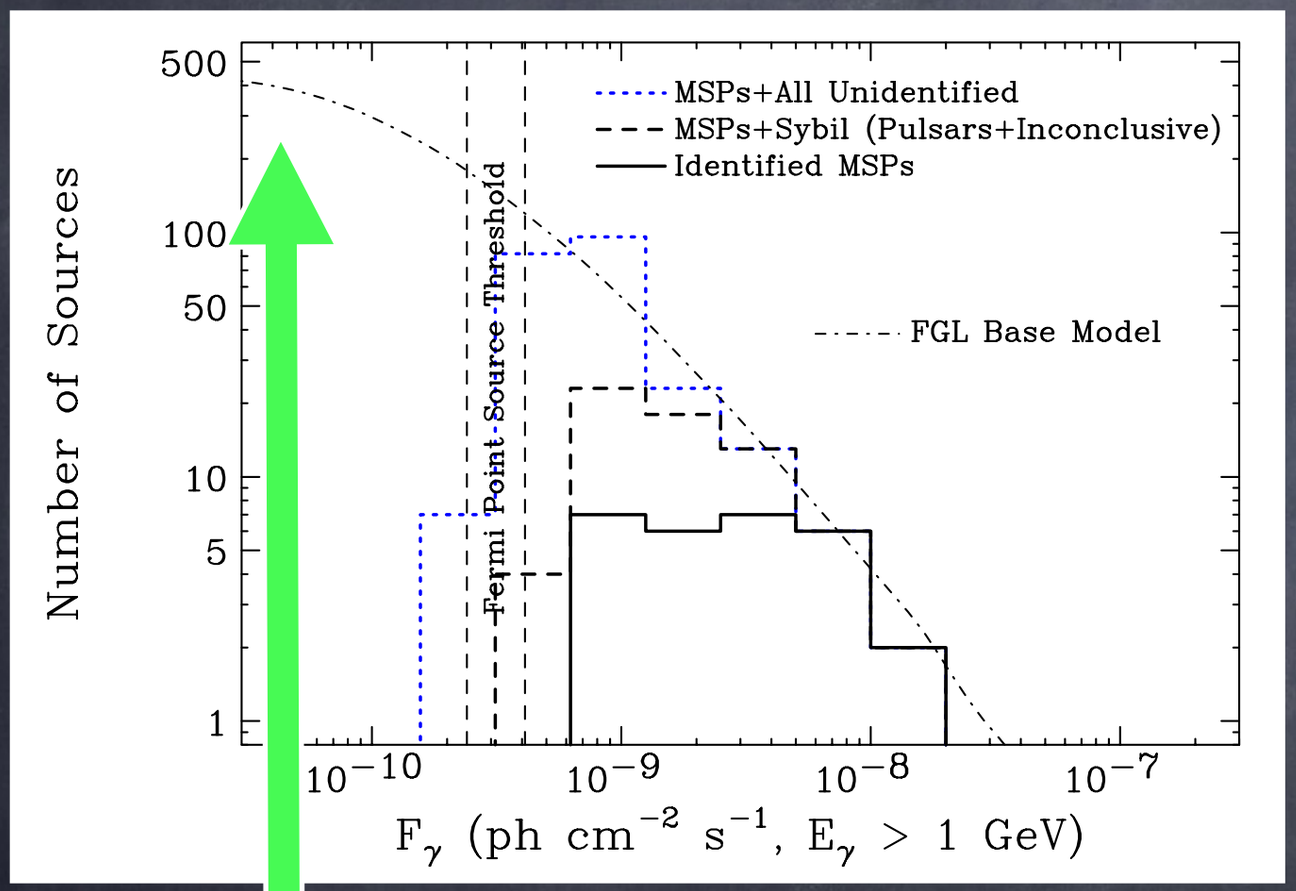
If we change the power-law to E^-1 (Ecut=2.75 GeV), E-^0.5 (Ecut=2.0 GeV)we can get a better fit to the excess.

BUT excluded from the data on the left at a high significant level.

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer (1305.0830)

"We should have seen them elsewhere" arguments

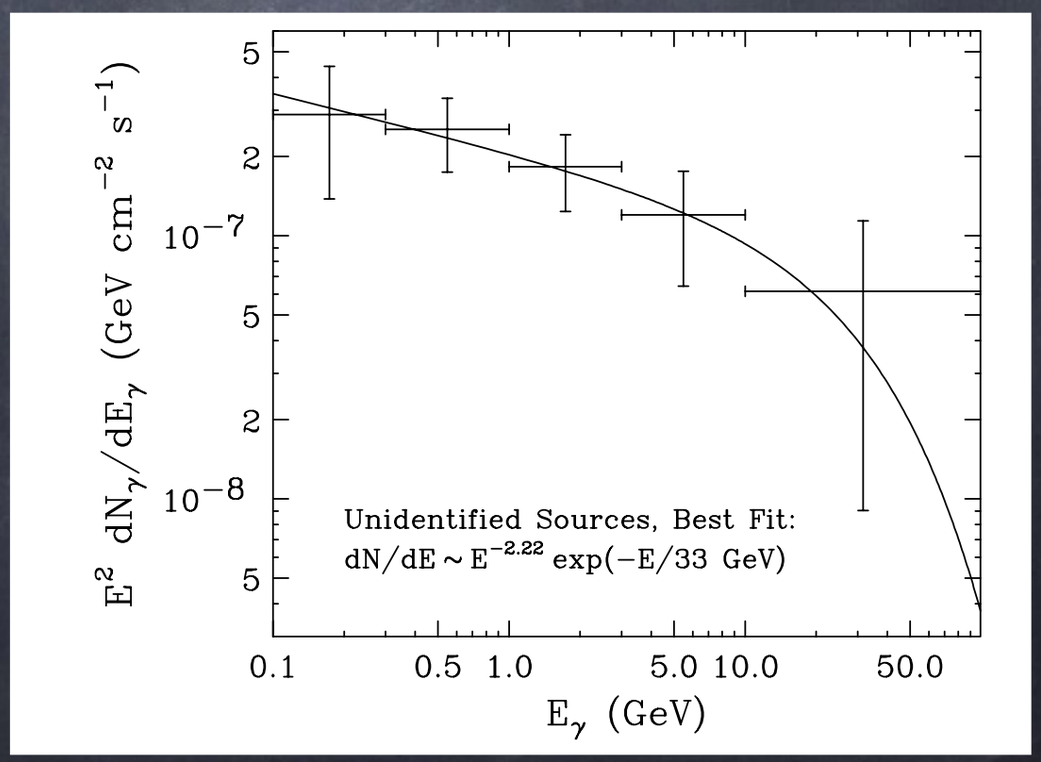
$n(r,z) \propto \exp(-r^2/2\sigma_r^2)\ \exp(-|z|/\langle|z|\rangle)$: spatial distribution in the Galaxy



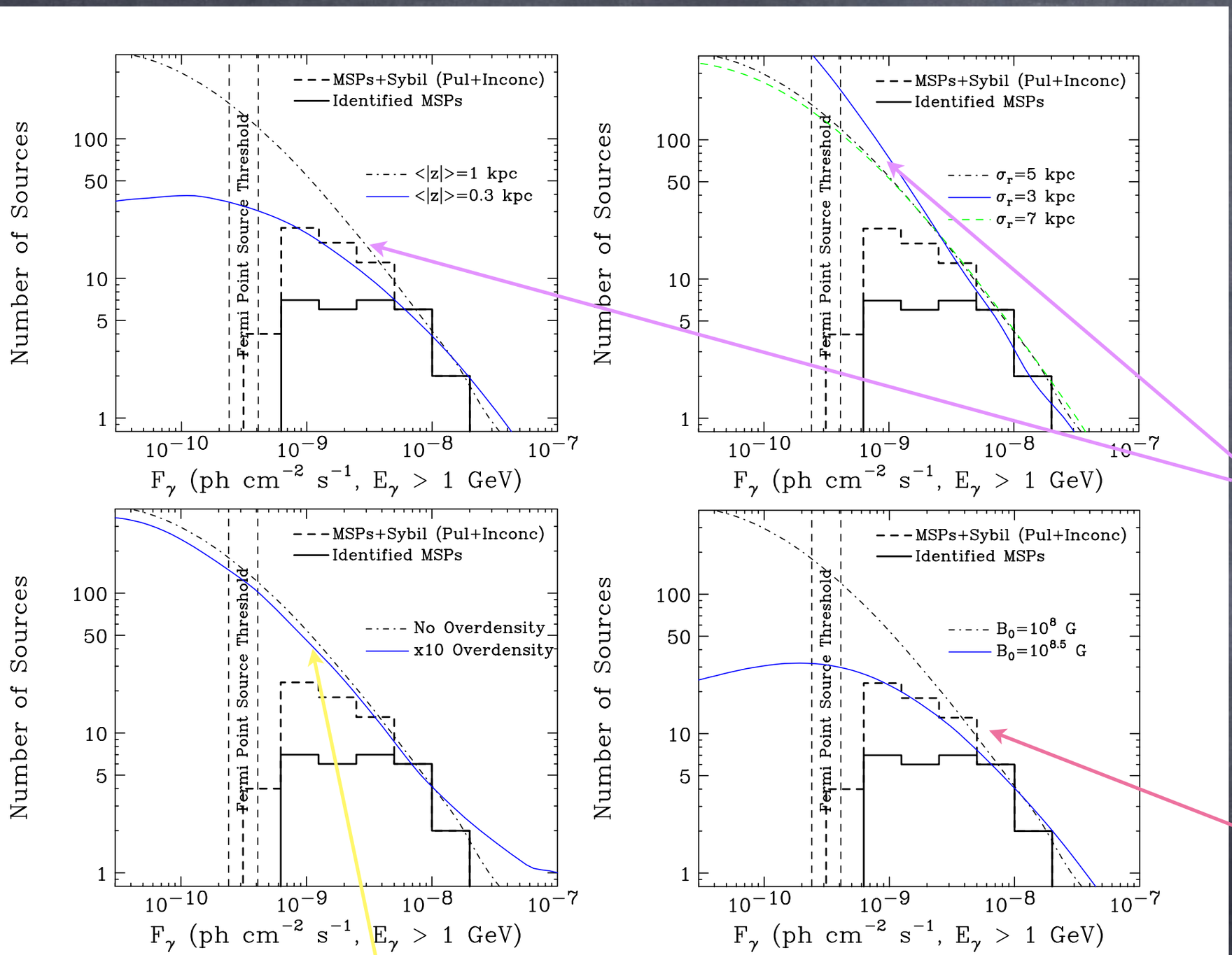
:Based on some reference assumptions on the MSP spatial and B-field distribution, that still over-predict the number of dimmer but observable sources

As reference we need 1-3x10^3 MSPs in the inner 2 kpc bellow threshold

Fermi unresolved p.s. above |b|>10:
Disagrees with the excess spectrum.
They are dominated by the AGN sample



We should have seen them elsewhere



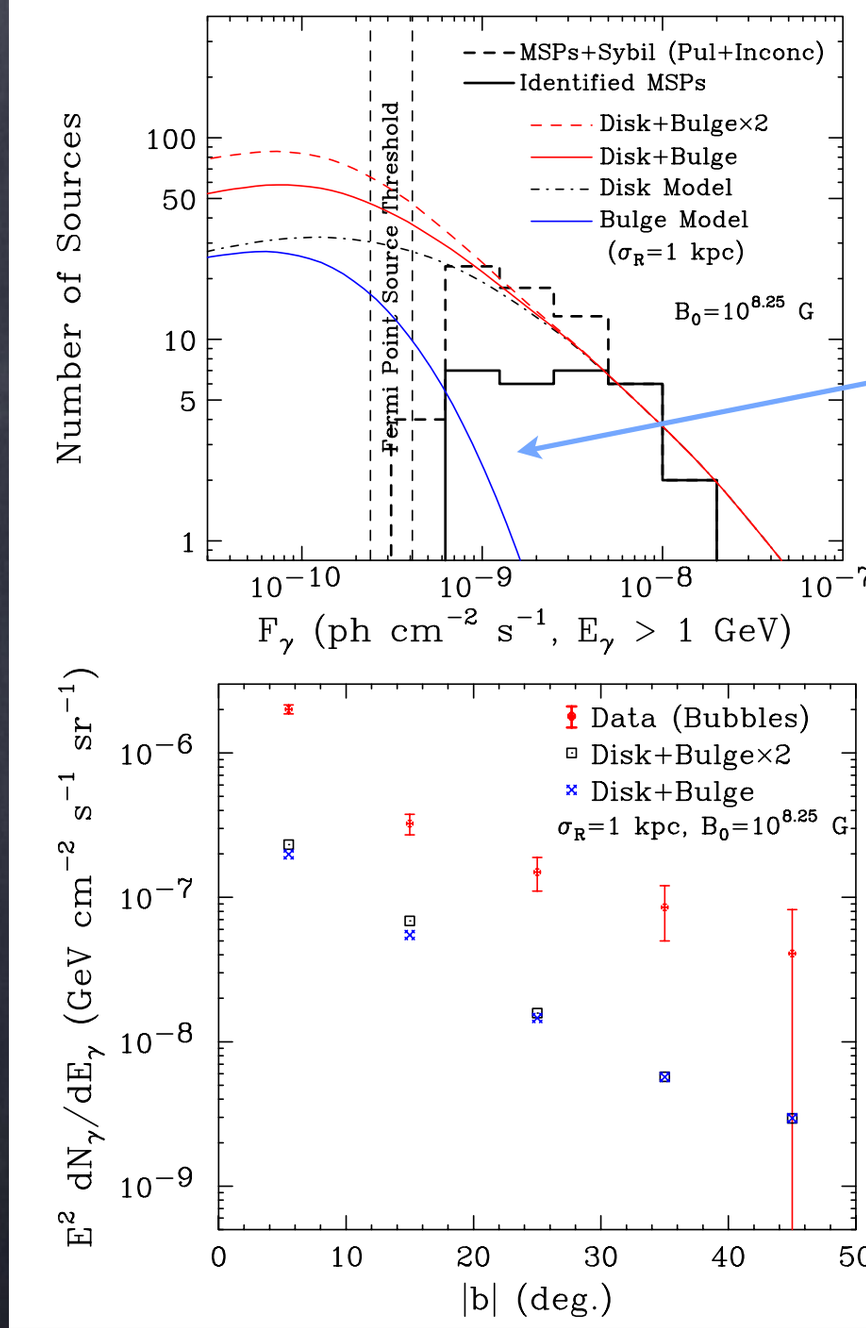
Models that would give enough MSPs in the inner 2 kpc over-predict the number of MSPs that should have already been observed by LAT at locations closer to the Earth

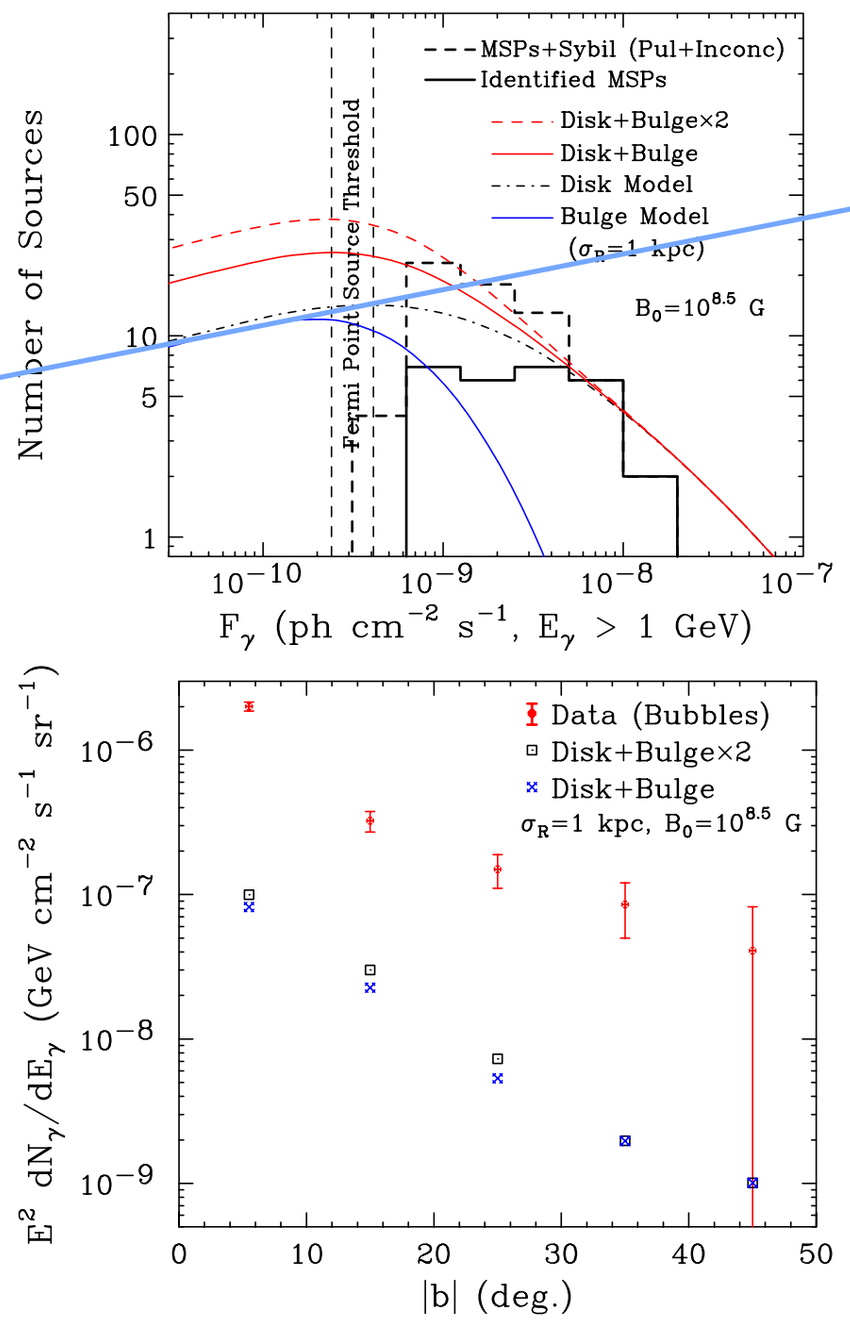
Preferred B-field assumptions do not give a dim MSP population

Hooper, Cholis, Linden, Siegal-Gaskins, Slatyer (1305.0830)

Being in at a local overdensity/underdensity can not affect much the results

Adding a bulge (but staying in agreement with observations)





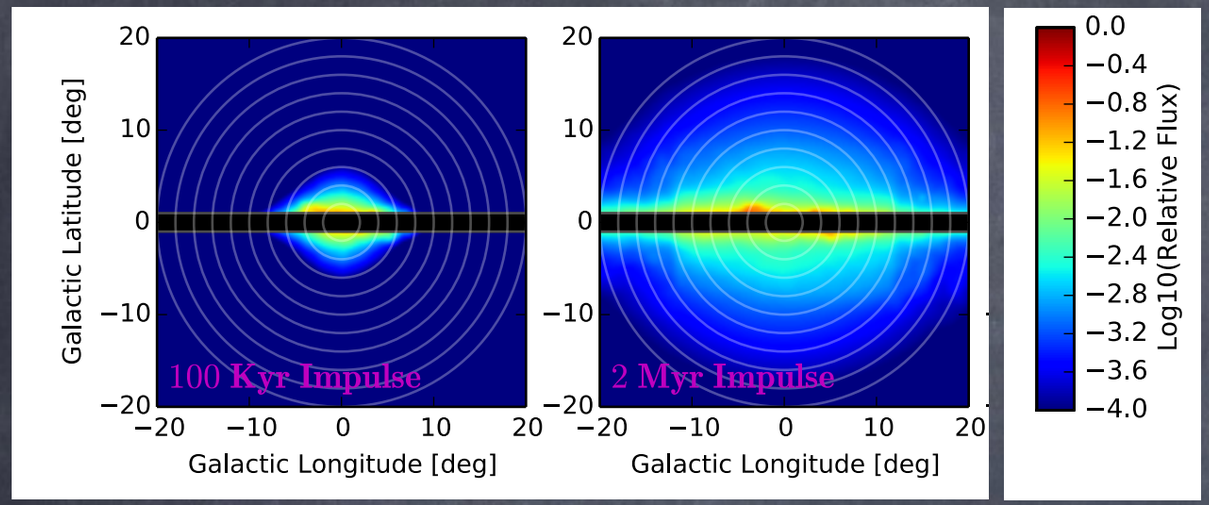
Having a bulge can result in adding dim MSPs (since there are no local MSPs from the bulge). Yet that does not help much, especially above |b|>5 where the bulge population can not contribute.

Rough approx. for Bulge MSP distr. :

$$n(R) \propto \exp(-R^2/\sigma_R^2)$$

Also from connection to LMXBs (progenitors or MSPs) we have arguments that MSPS can not explain more than ~0.1 of the amplitude of the GeV excess in the inner 5 degrees (Cholis, Hooper, Linden 1407.5625)

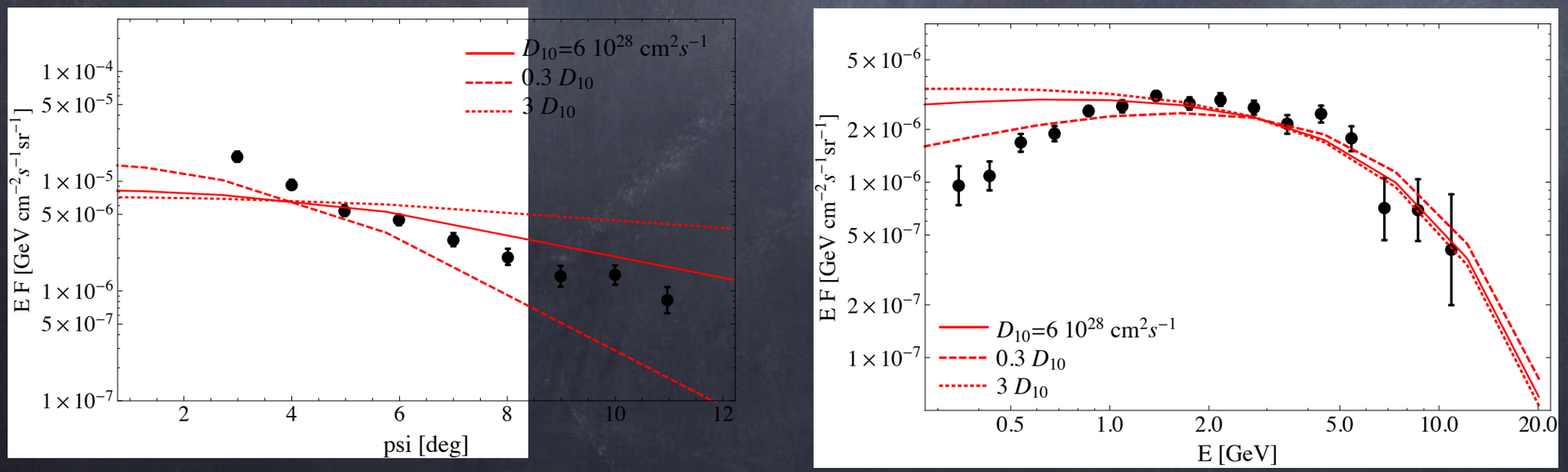
Outbursts of Cosmic Rays from the Galctic Center



The main reason is simply that CR protons scatter off the interstellar gas, thus producing a disky / filamentary gamma-ray structure.

Carlson & Profumo (1405.7685)

CR electrons can potentially avoid the morphological issues that protons encounter (that is if ICS dominated over bremsstrahlung emission)

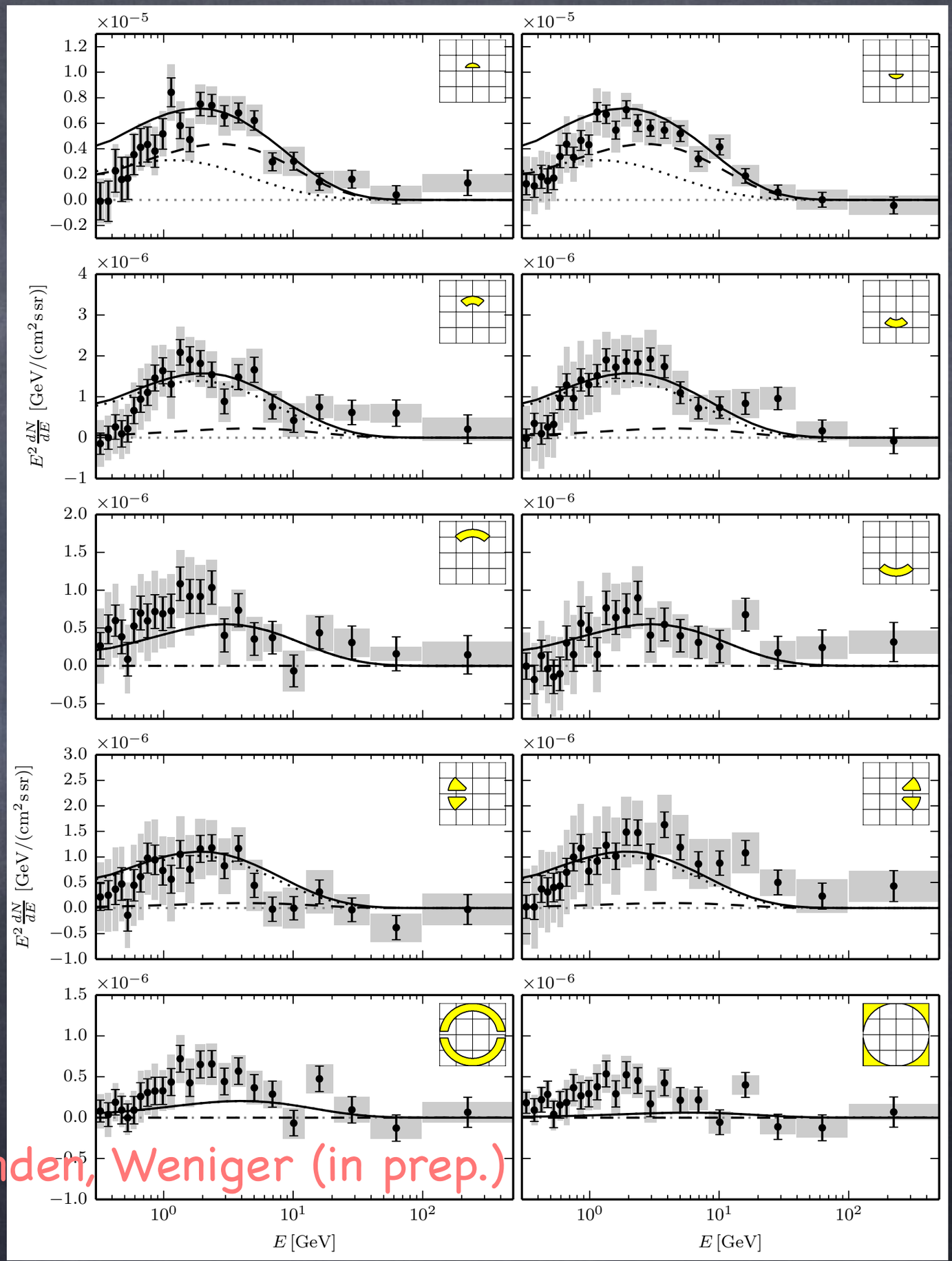


Petrovic, Serpico & Zaharijas (1405.7928)

Testing the morphology and the physical assumptions (both on the GC propagation conditions and on the outbursts)

A example of a combination of CR electrons injected at 0.1 and 1 Myrs ago with an injection index of 1.2 (exceptionally hard compared to Fermi 1st order acceleration BUT could be motivated by strong diffusive re-acceleration in the inner O(10) pc of the Galaxy) and cut-offs at 20 and 40 GeV respectively. Typical energy outputs of 10^51 ergs can naturally occur.

Cholis, Calore, Evoli, Hooper, Linden, Weniger (in prep.)

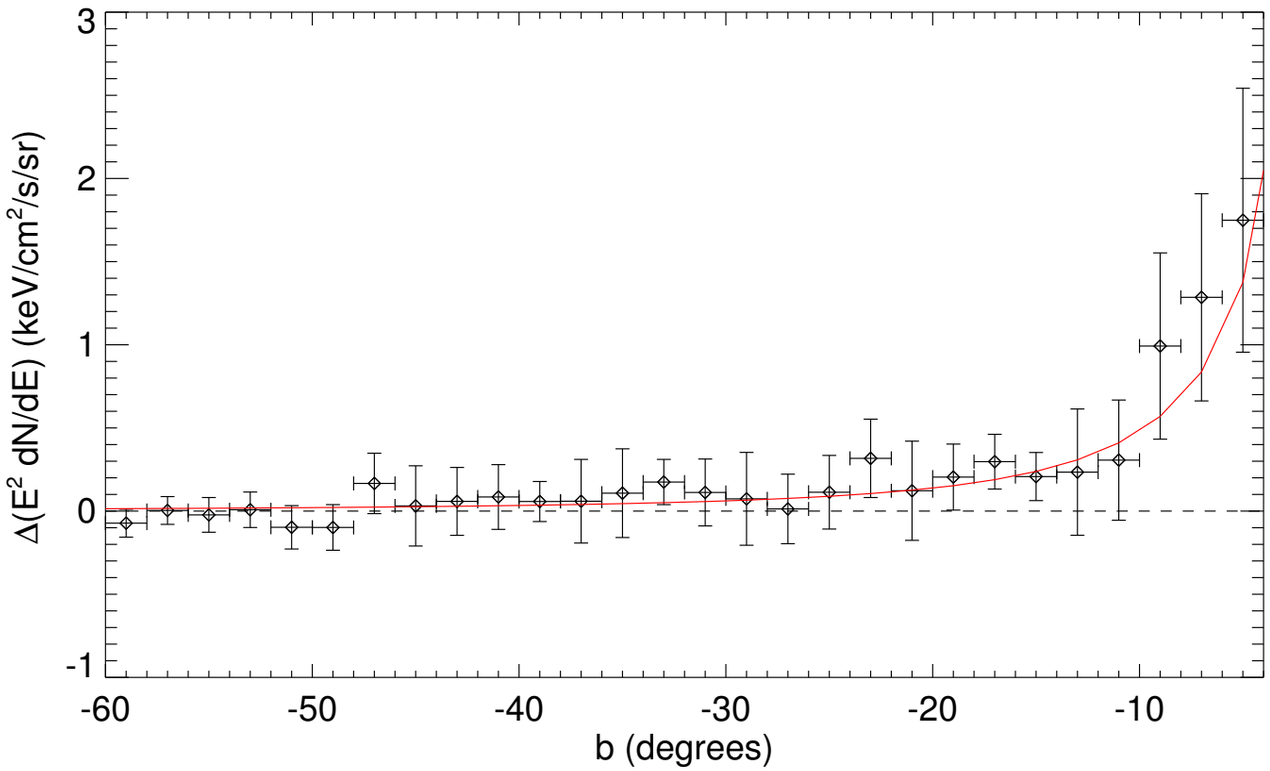


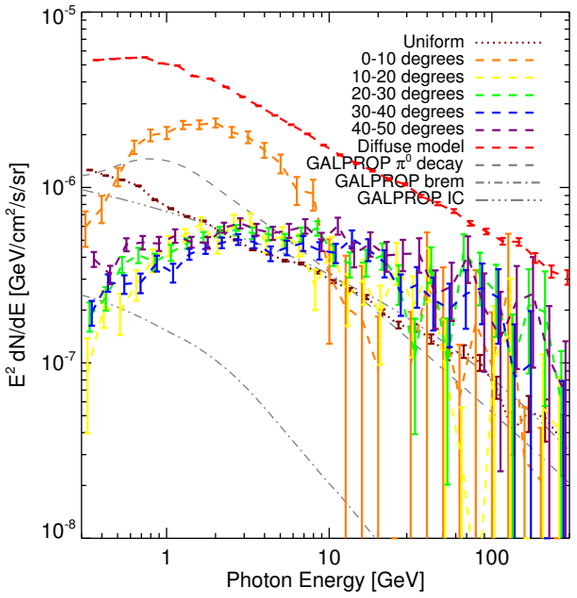
Conclusions...and further thinking

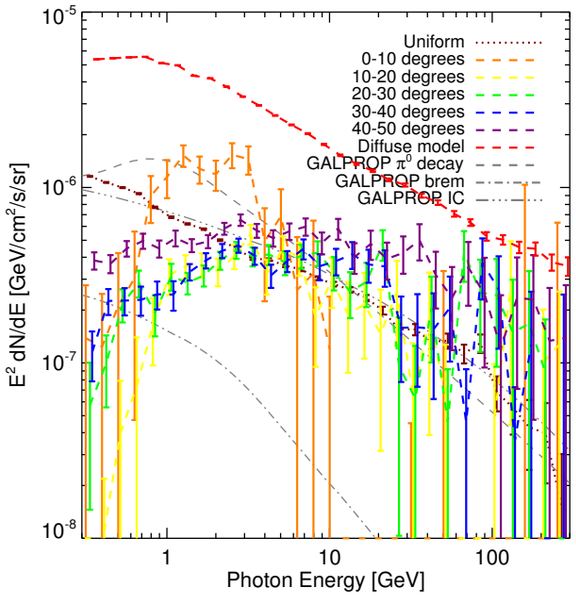
- The excess is robust to background model systematics, very well correlated to the galactic center.
- The emission is observed both at the inner degrees and at higher-latitudes.
- The DM case has been explored and seems compelling.
- For the DM case we need to start looking in other indirect detection probes: CRs other gamma-ray targets.
- Dwarf spheroidals is the next one. Further advances in extragalactic gamma-ray astronomy but also at other wavelengths will strengthen the indirect DM searches in the future as well. Also some direct detection signal?
- The MSPs explanation has problems in terms of both the spectrum and the normalization of the needed "signal" (can account for only 5-10% of the signal).
- Outburst of CRs... Especially CR electrons can produce an ICS signal that could possibly be spherical in nature
- We need to further understand emissions as those giving the Fermi Bubbles (what is it that creates them) ... and also move beyond the standard leaky box approximation for the study of CRs.

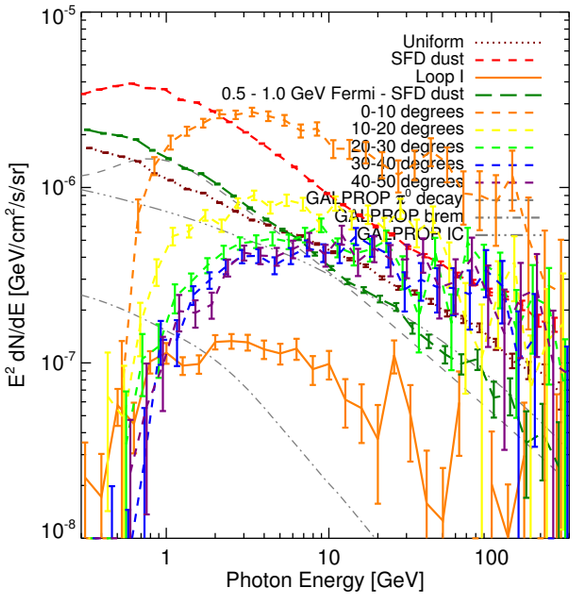
Thank you!

Additional Slides

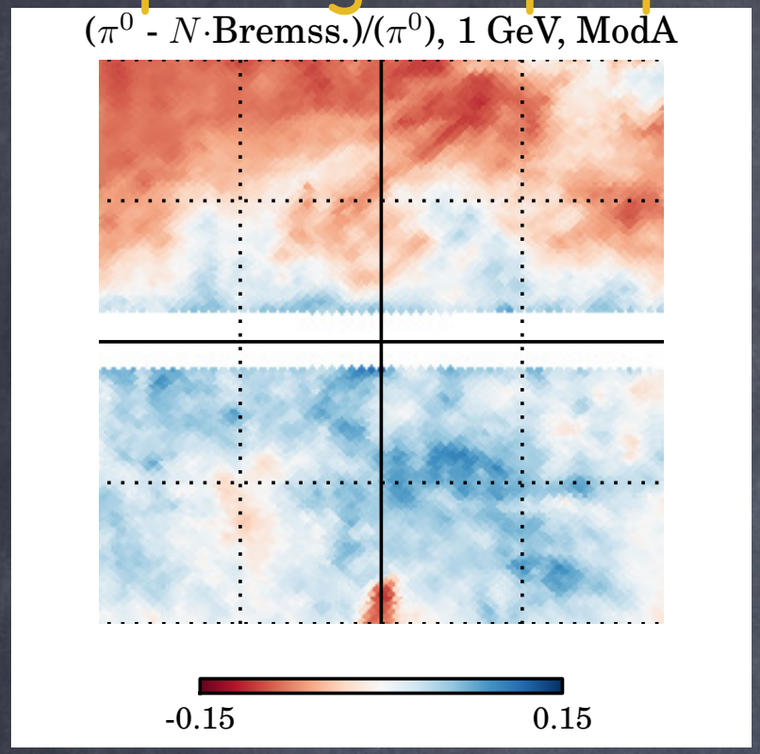


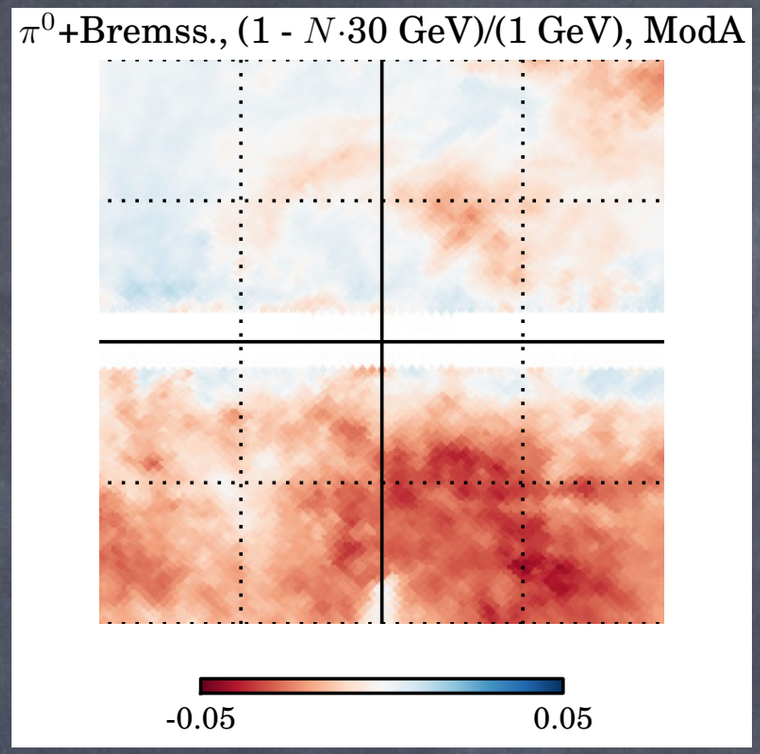


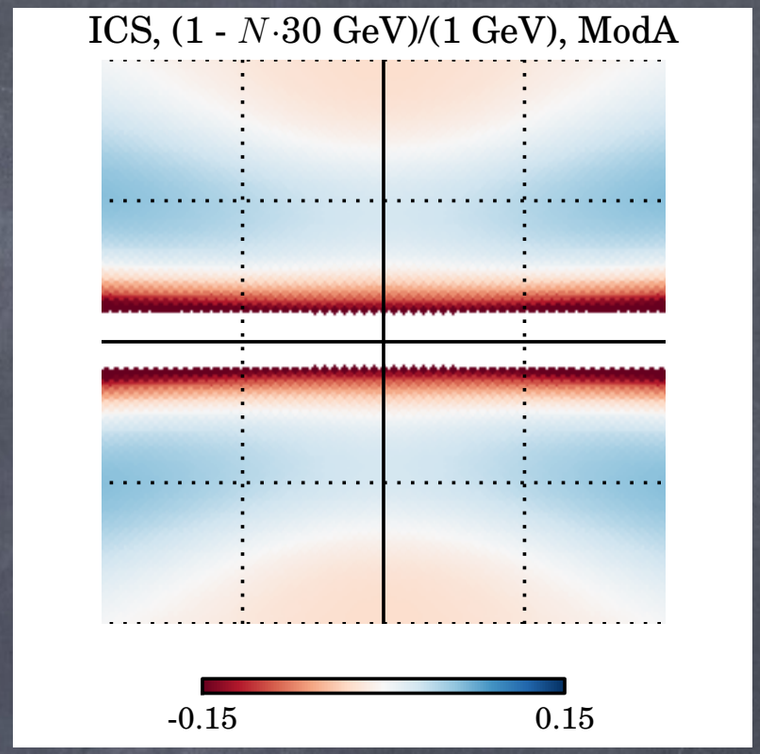




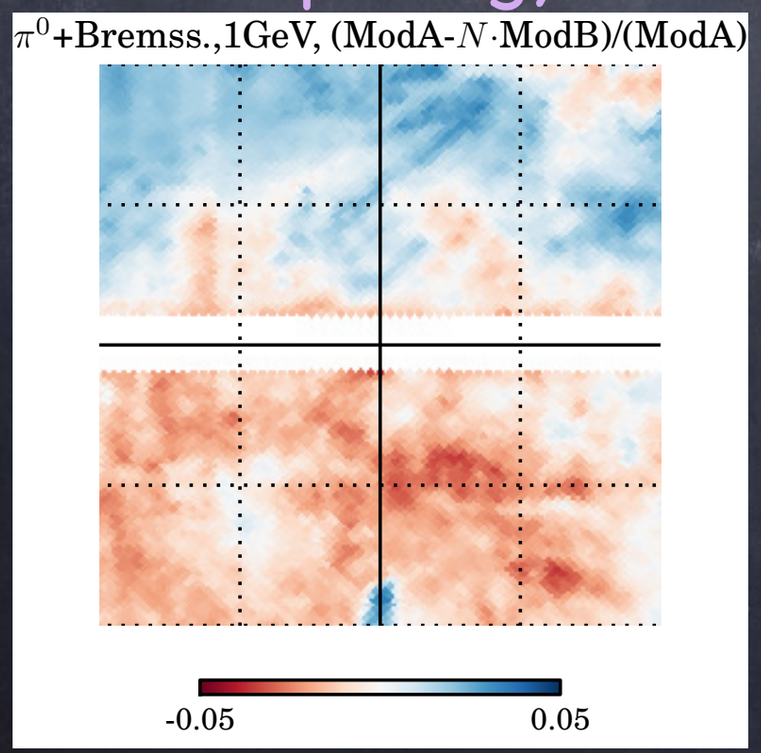
We need to account for the energy dependence of the morphological properties of the emission:

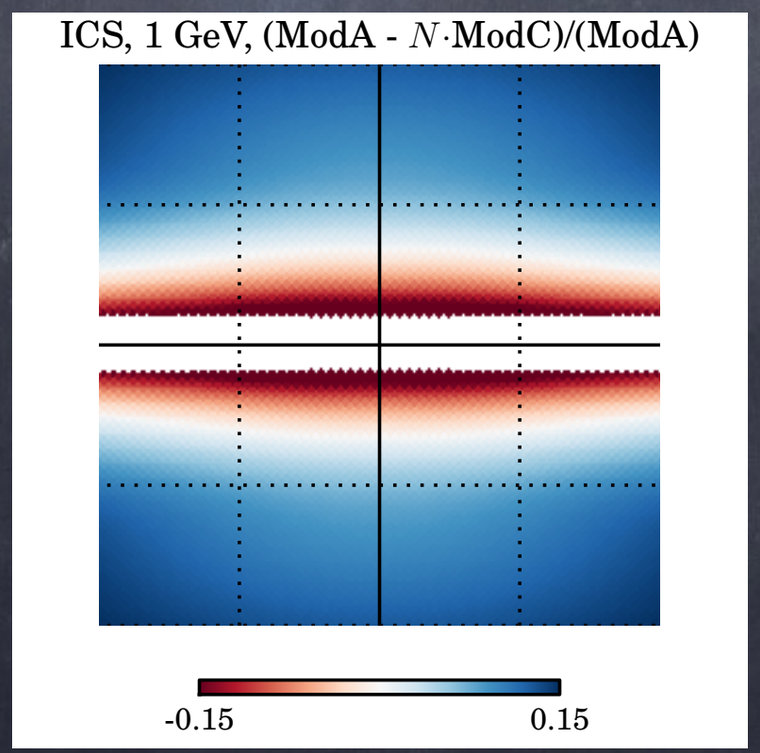


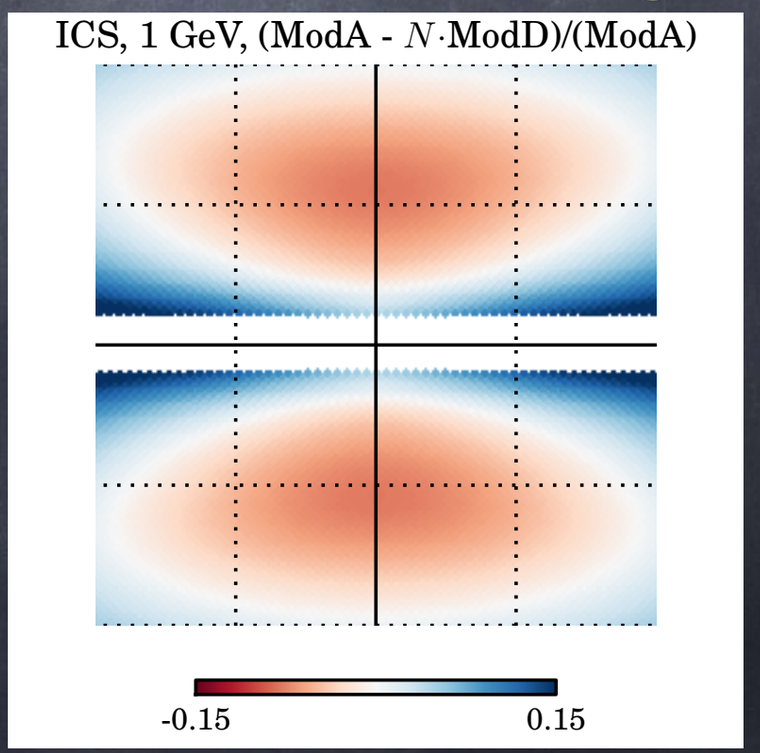




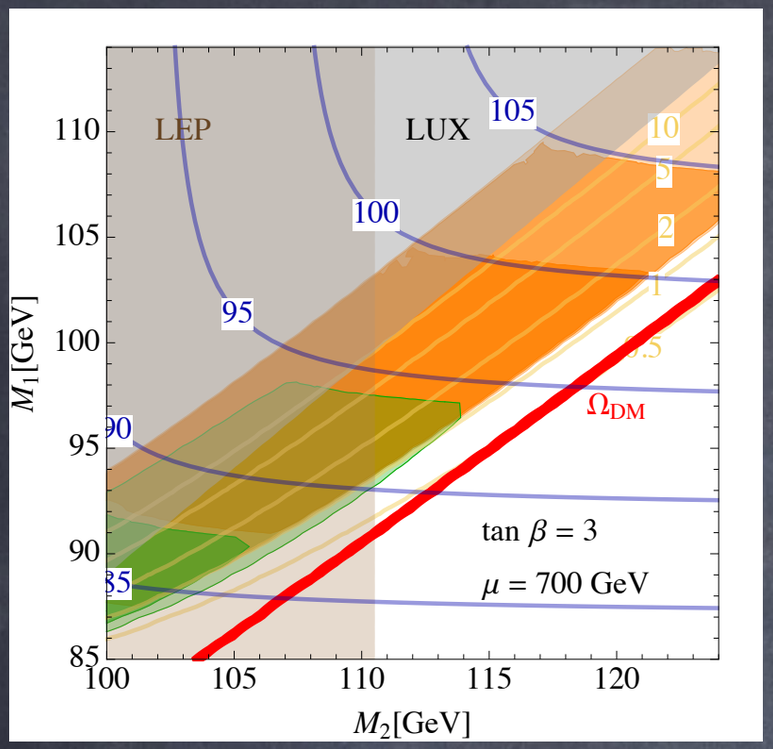
And even more importantly on the model dependence of the morphology of the emission: Calore, Cholis, Weniger, 2014







A specific example on MSSM



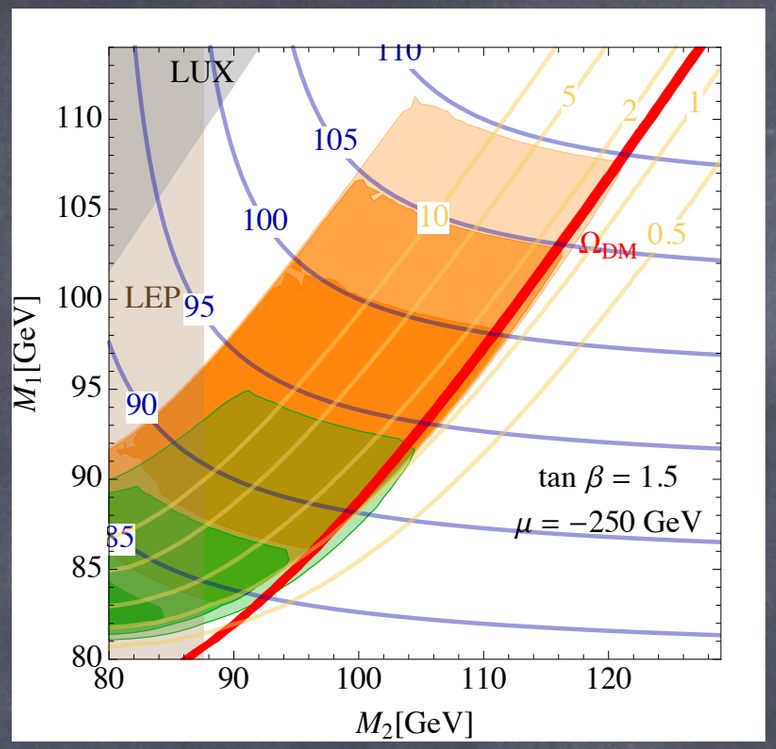
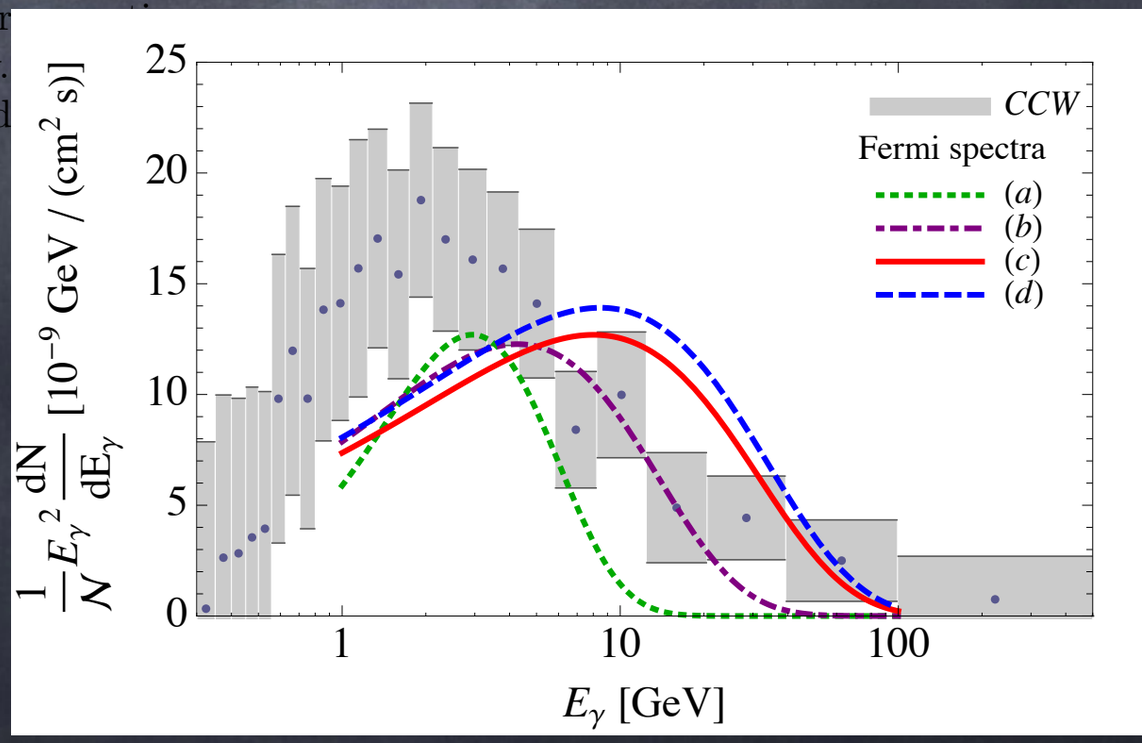


Figure 6: *Mixed MSSM neutralino.* We display the 1,2,3σ best-fit GCE regions for the WW final state in the $M_2 - M_1$ plane for CCW (green) and Fermi spectrum (b) (orange). We also overlay constraints from LEP chargino searches (brown) and LUX (gray). In the (red) region denoted $\Omega_{\rm DM}$ the thermal relic abundance for the DM is within 3σ of the observed value. For convenience, we also show the mass of the DM and the annihilation cr to WW as blue and yellow contours in units of GeV and 10^{-26} cm$^2/s$ respectively. plot we have fixed $\mu = 700$ GeV, $\tan\beta = 3$, while in the right plot we have fixed GeV, $\tan\beta = 1.5$.

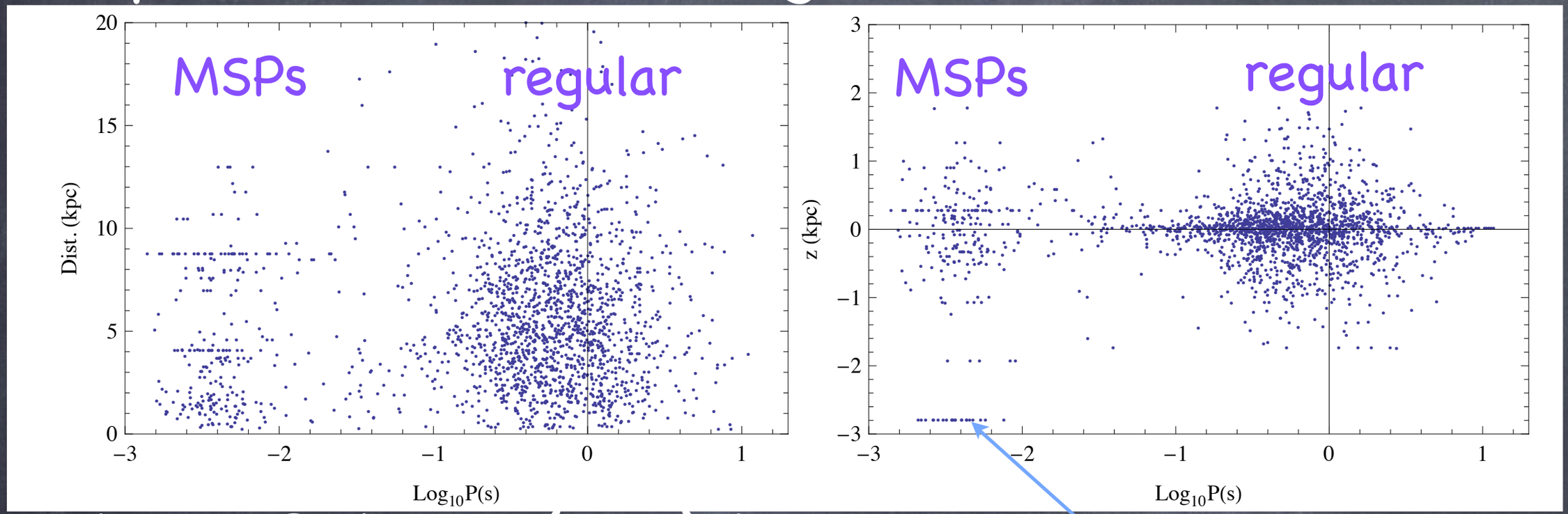
P. Agrawal, B. Battel, P. Fox, R. Harnik
1411.2592



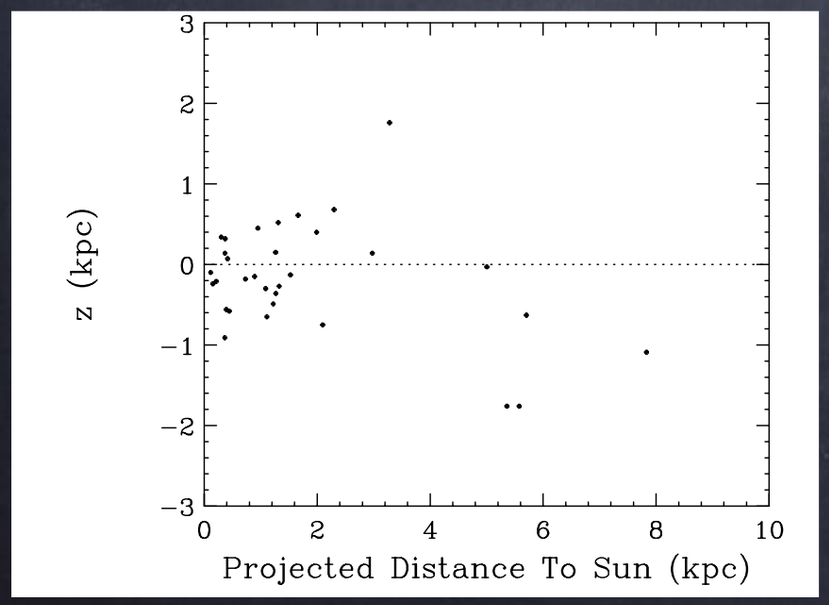
What is the information on their location

MSPs have a characteristic time of Gyrs and kick velocities ~10 km/s Will travel ~1 kpc inside the Galaxy. Thus a non Glob Clust. population can not be very concentrated.

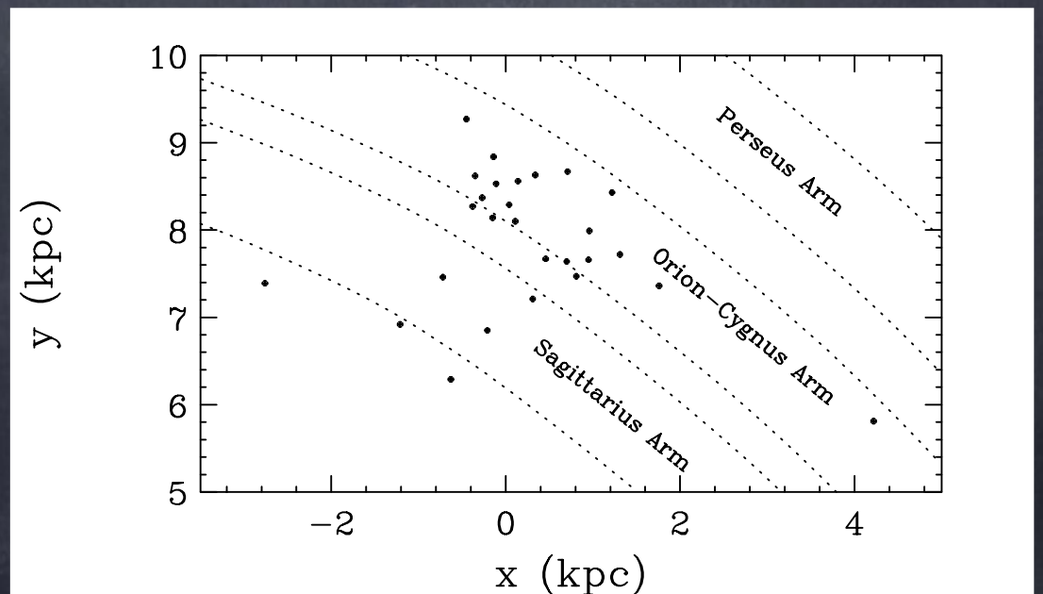
ALL pulsars (ATNF catalogue)



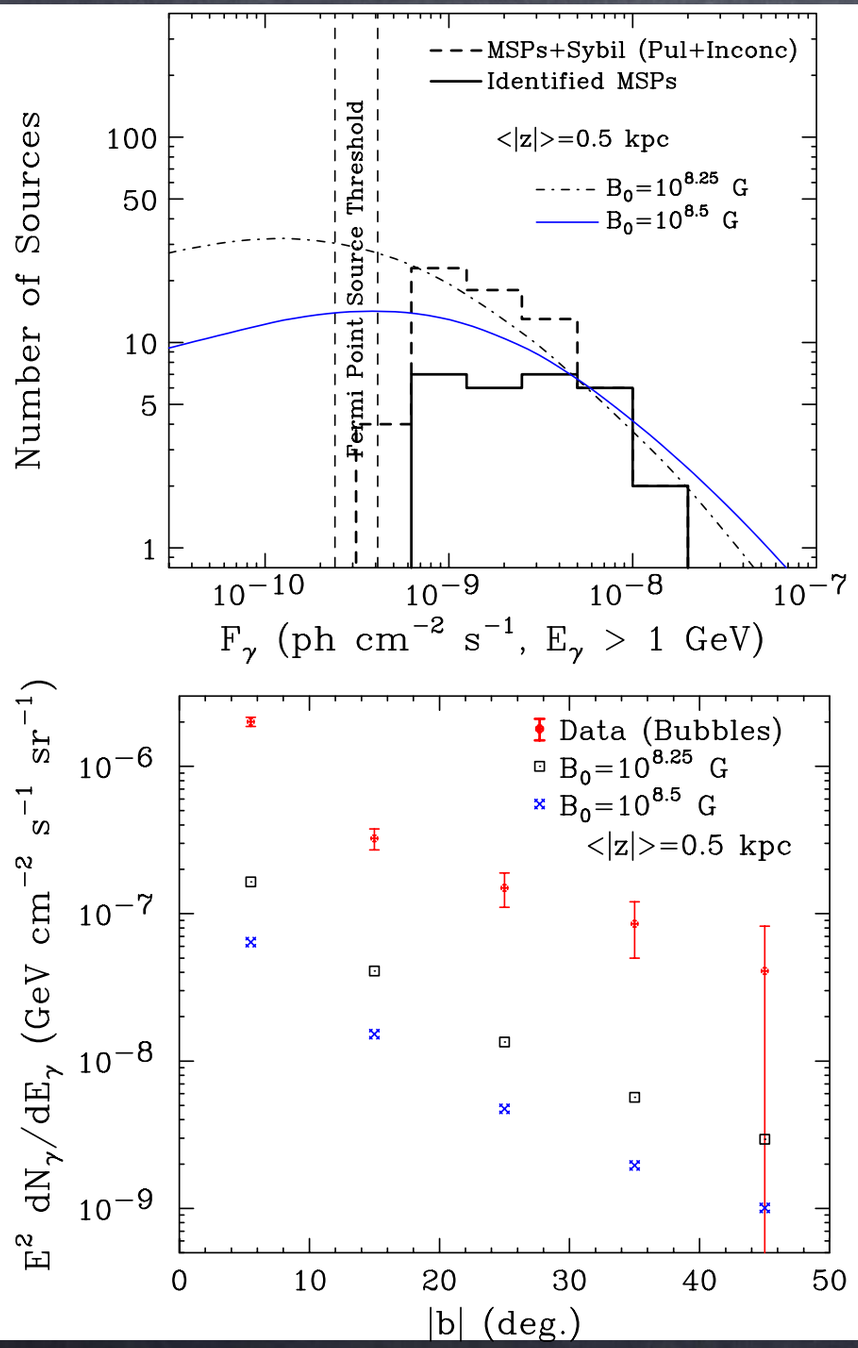
Fermi MS Pulsars (37<) in 2013

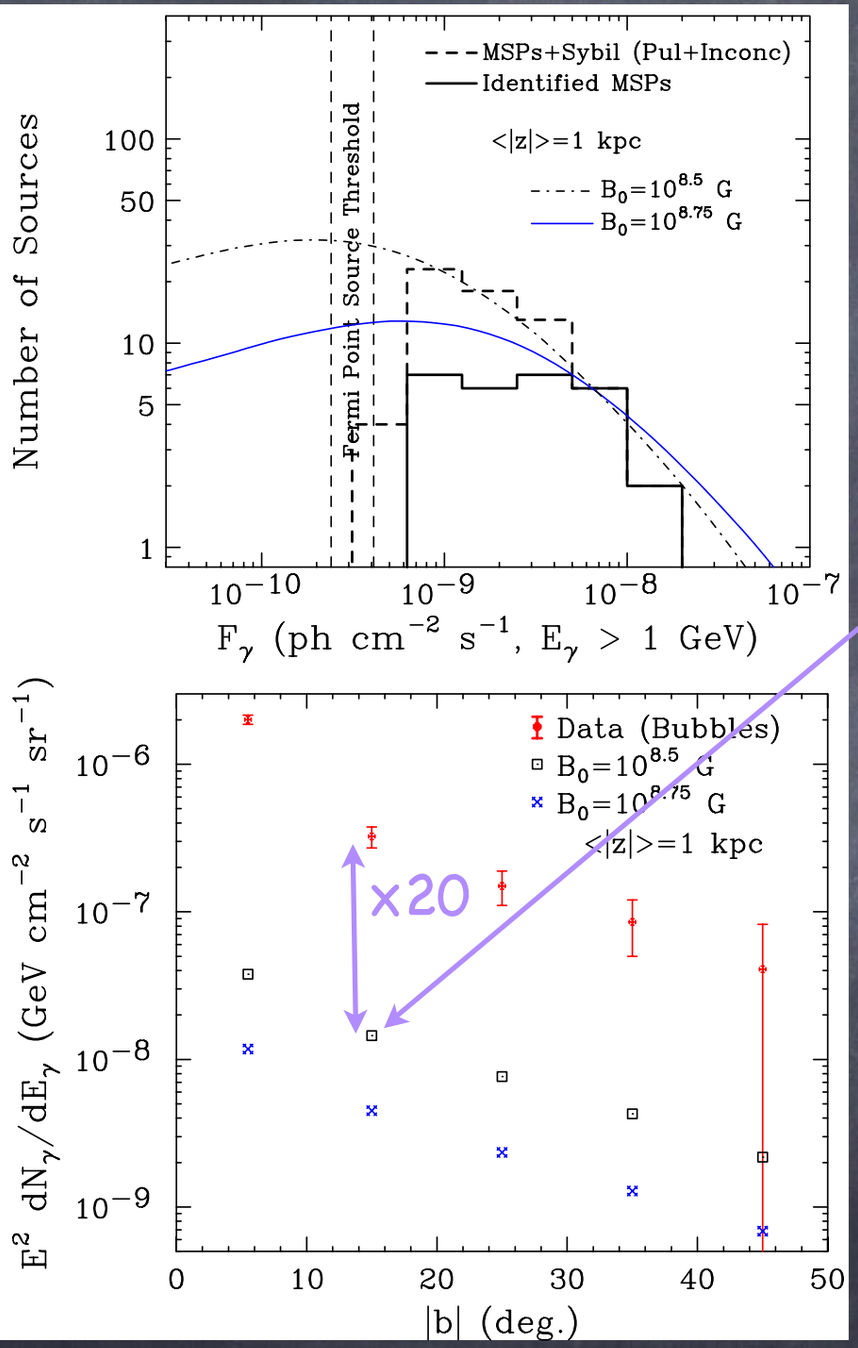


In gamma -rays they are close by.



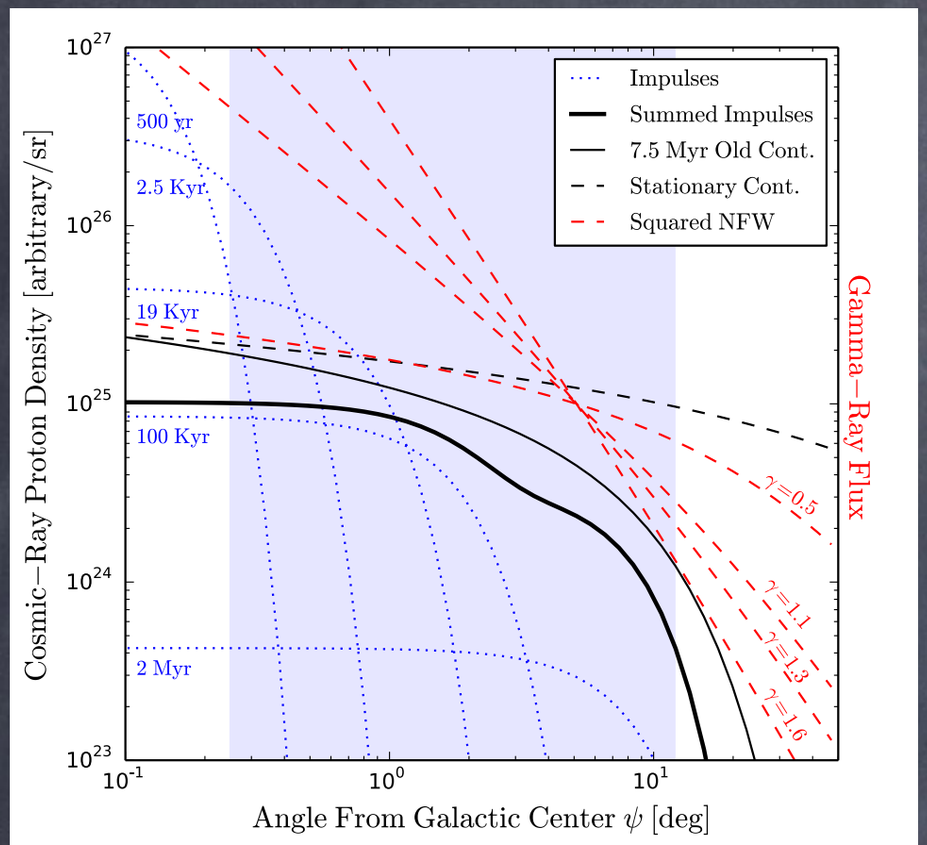
Assumptions that agree with everything

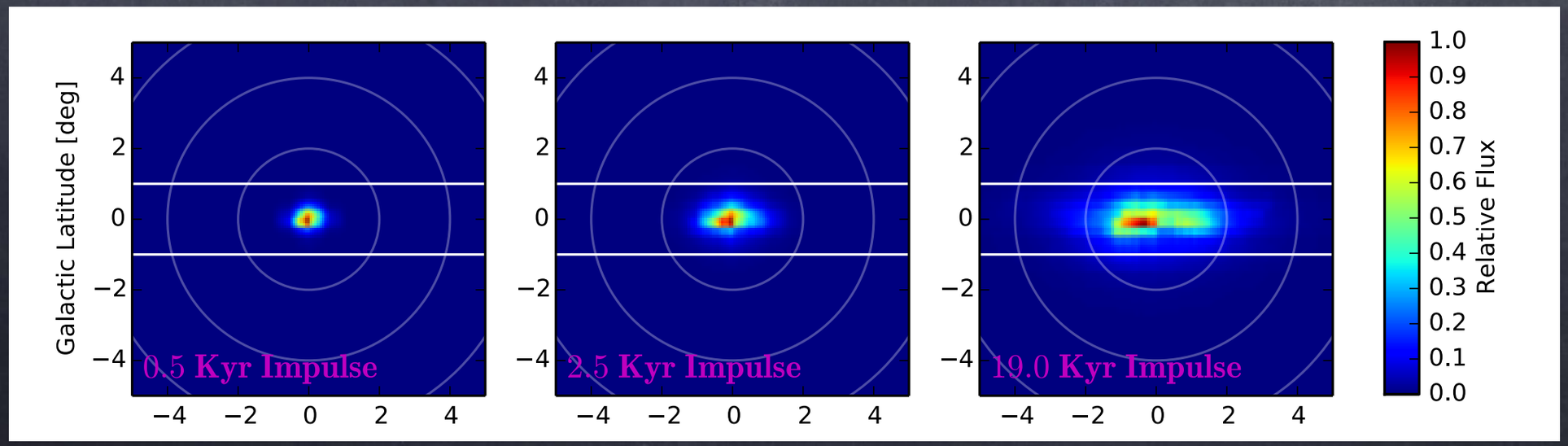




MSP models that are consistent with the observed (suggested) population can give only 5-10% of the observed diffuse emission in the inner 2kpc of the Galaxy.

Outbursts of Cosmic Rays from the Galctic Center



While CR protons can explain the, averaged spectrum, and the averaged angular dependence of the excess, they fail to explain the robustly observed sphericity of the excess, as has been confirmed by Daylan et al. at low latitudes and Calore et al. at higher latitudes.

Carlson & Profumo (1405.7685)