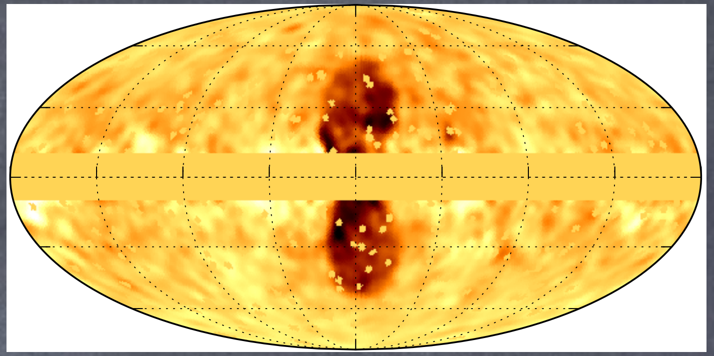
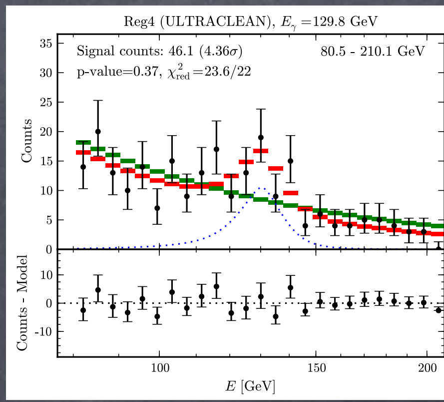
Searching for Dark Matter using the Gamma-Ray Sky



Include some important reference papers:

papers on the Fermi Bubbles

Dobler, Finkbeiner, Cholis, Slatyer, Weiner ApJ 2010 (0910.4583), Su, Slatyer, Finkbeiner (1005.5480)



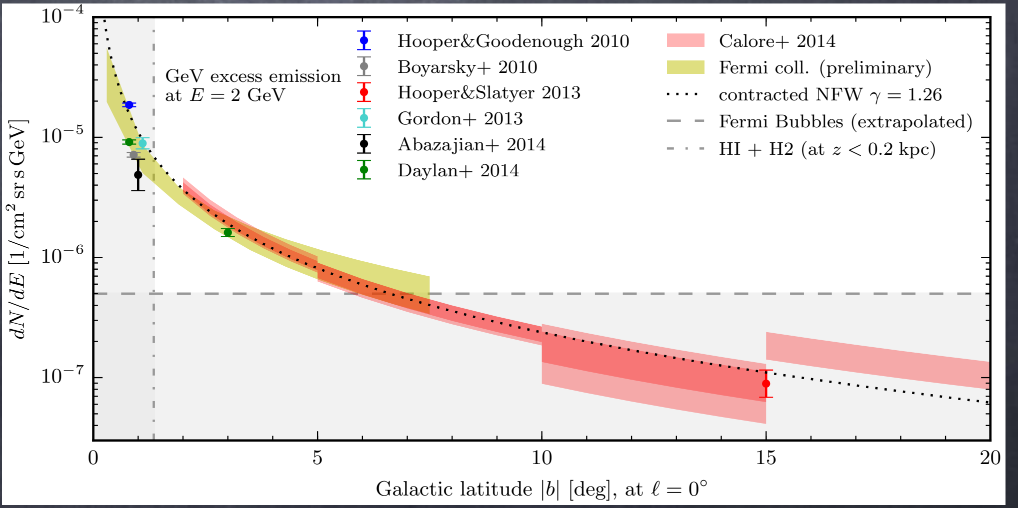
papers on the 130 GeV line

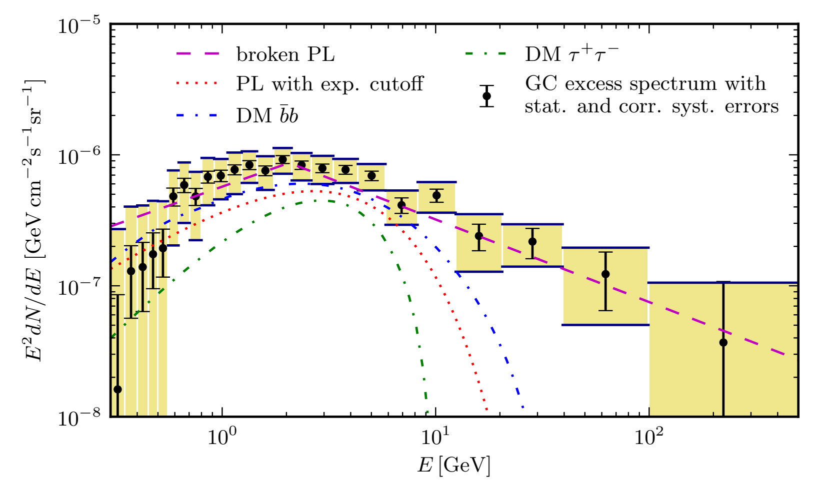
Weniger (1204.2797), Many more, Cholis,Tavakoli, Ullio PRD 2012 (1207.1468)

papers on the GC excess

Hooper & Goodenough: (1010.2752), Linden & Hooper (1110.0006), (1307.6862),Daylan, Finkbeiner, Hooper, Linden, Portilo, Rodd, Slatyer, 1402.6703, Calore, Cholis, Weniger JCAP 2015 (1409.0042).

Calore, Cholis, McCabe, Weniger JCAP 2015 (1411.4647)

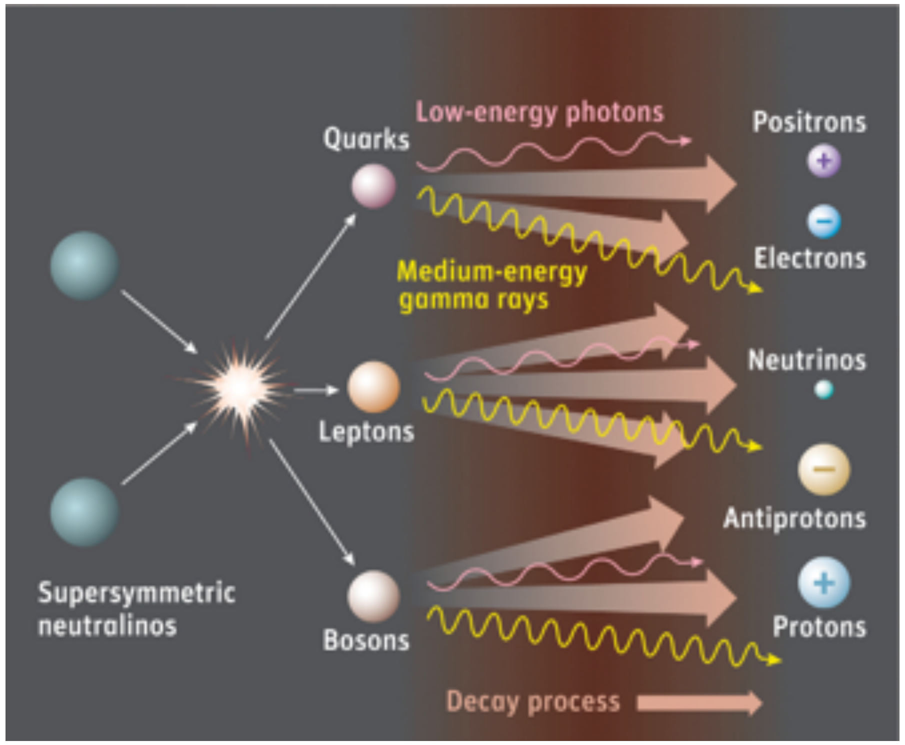




Ilias Cholis

Rice University, 2/11/2015

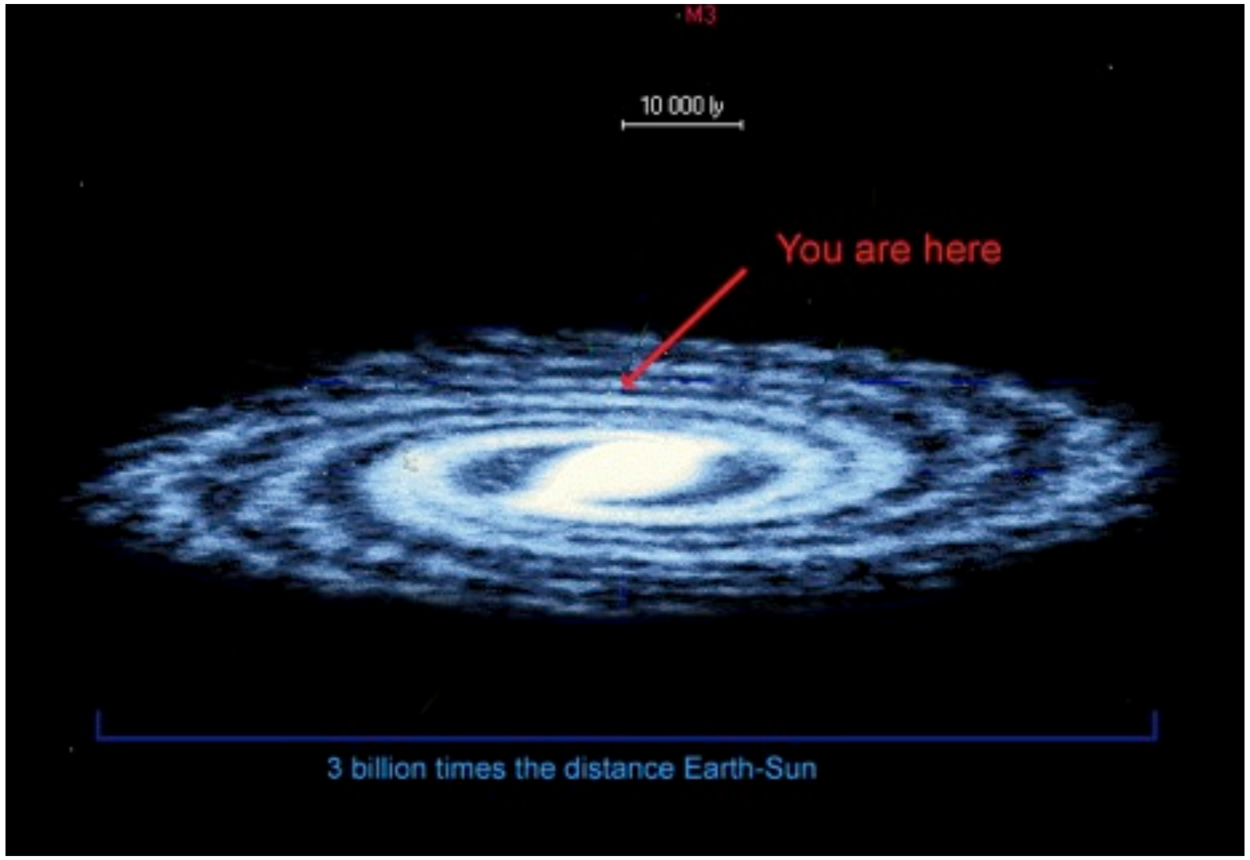
Outline

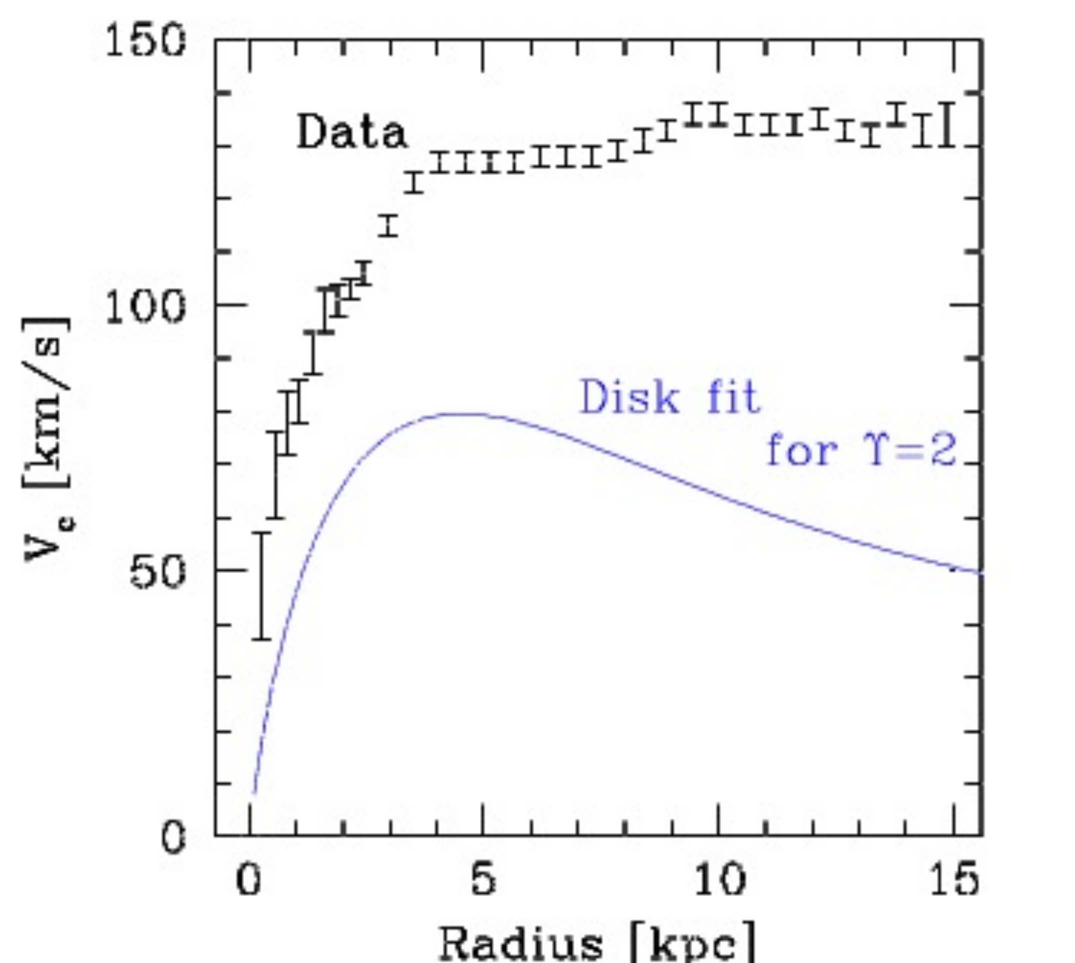


- Introductory on Dark Matter and gamma-rays
- Discussing the discovery of the Fermi Haze->Bubbles actually
- The story of the 130 GeV line, the particle physics and the cosmological simulations.
- The Galactic Center Excess
- Dwarf Spheroidal galaxies & extragalactic gamma-rays
- Conclusions

evidence for CDM (Cold Dark Matter)

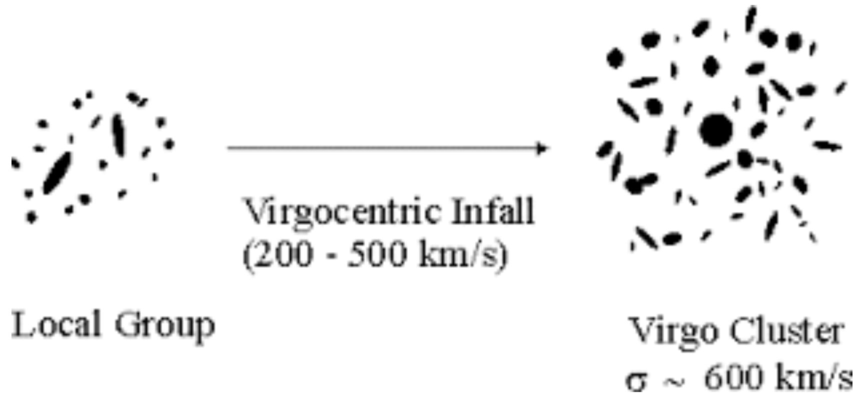
- galactic rotation curves

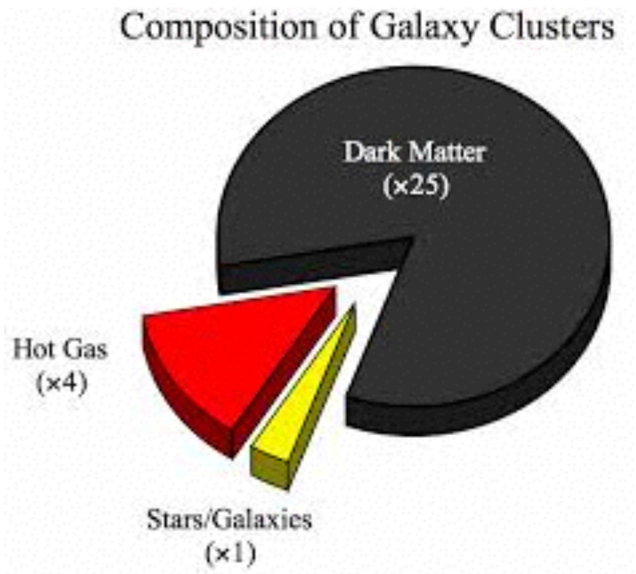




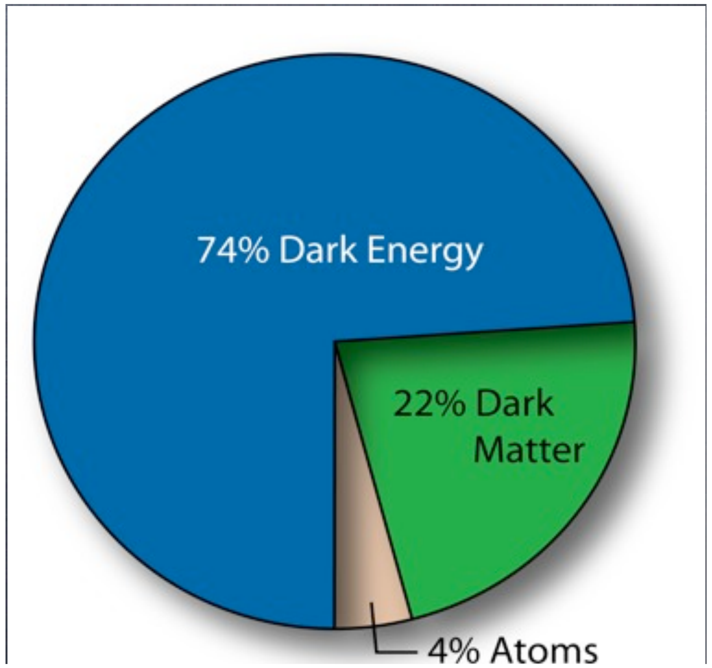
NGC 2403 rotation curve and model

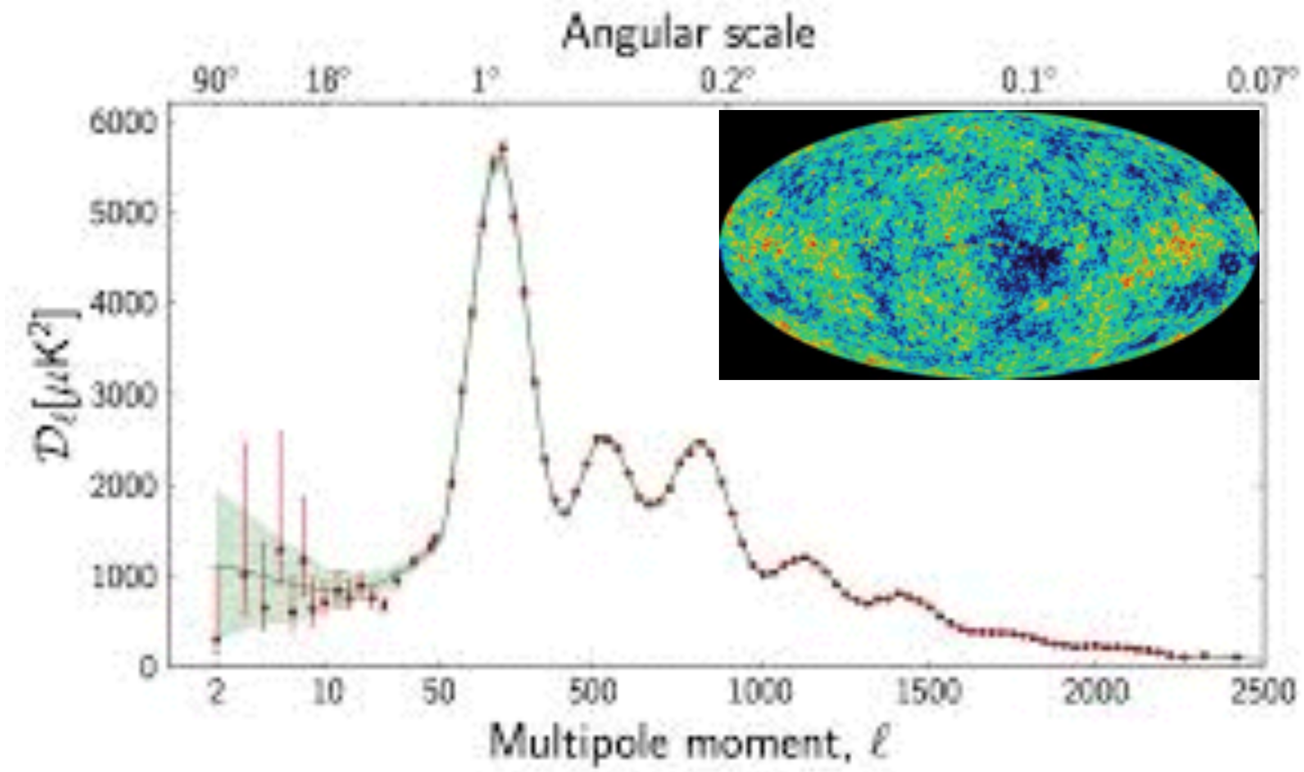
- velocity dispersion of galaxies in clusters



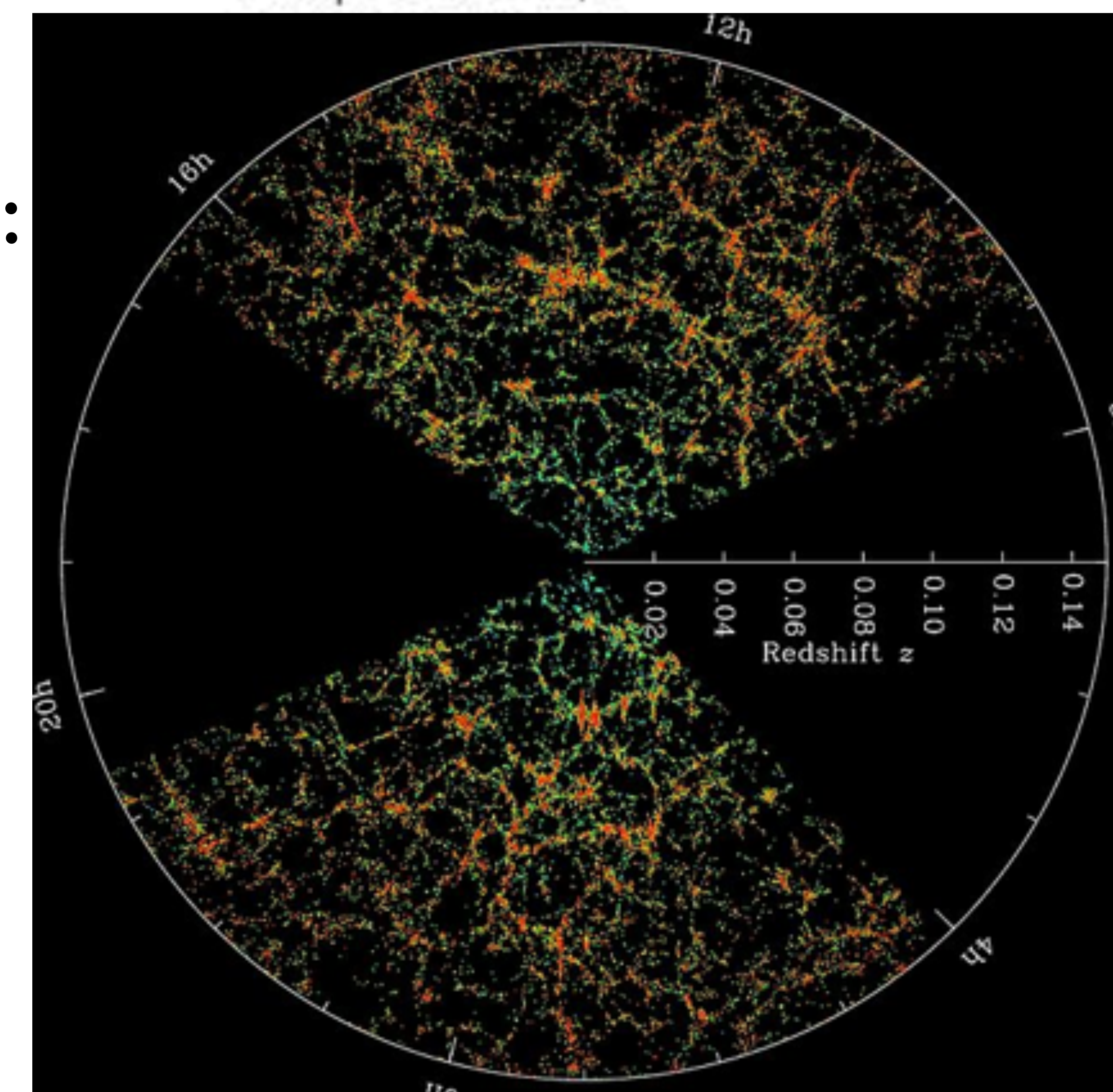


- CMB data and SN Ia data



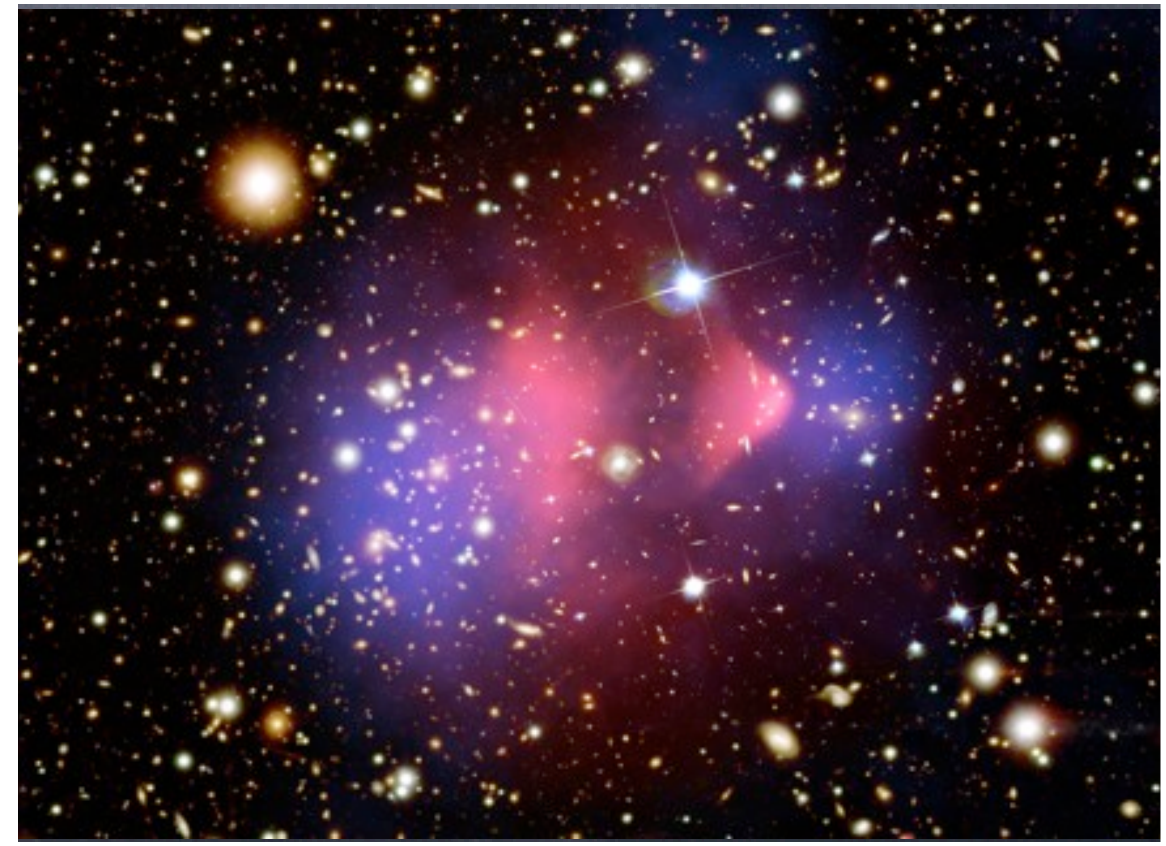


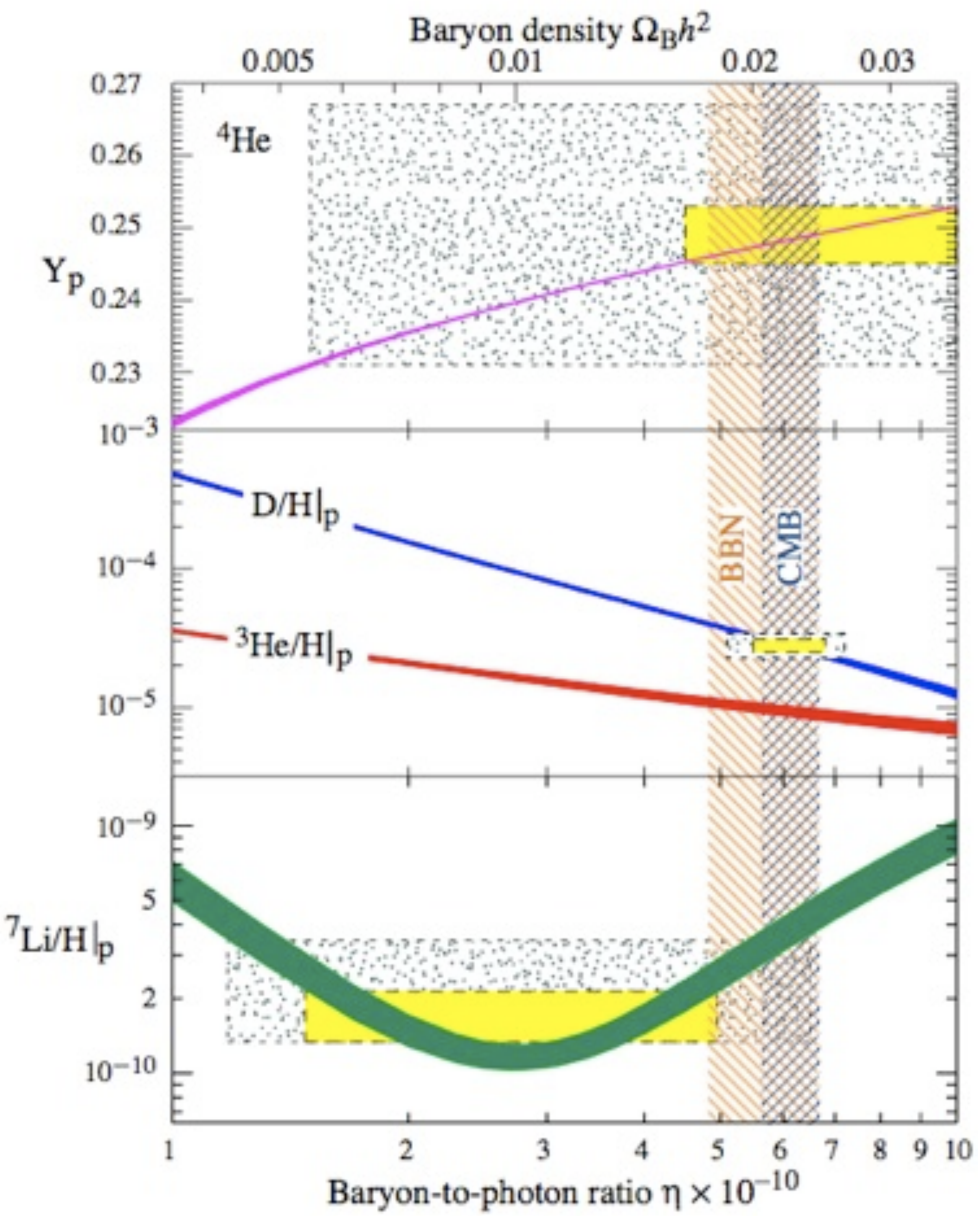
- Observed distribution of galaxies:



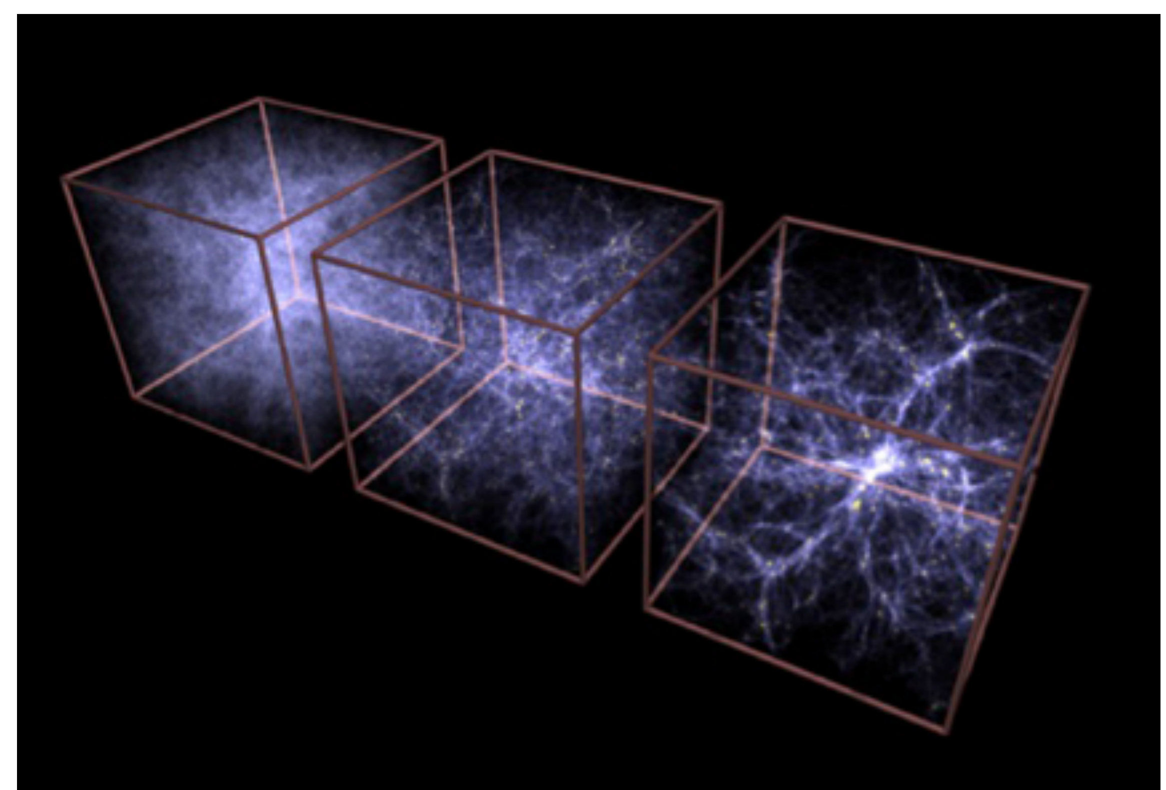
- strong lensing measurements of background objects (usually galaxies)

- collisions of galaxy clusters (e.g. bullet cluster)



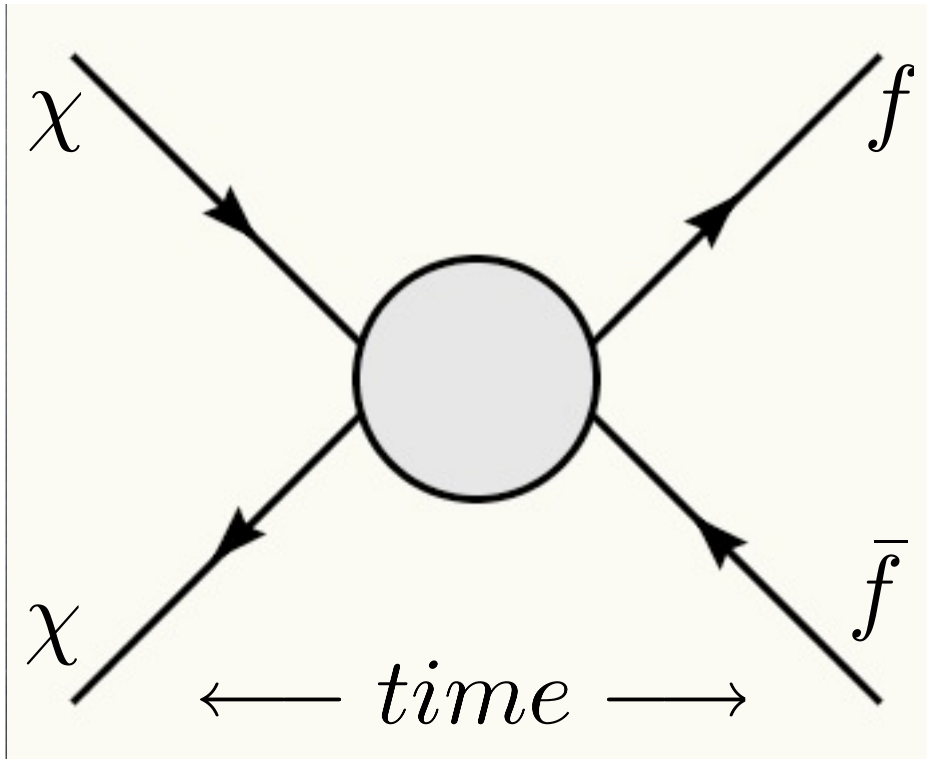


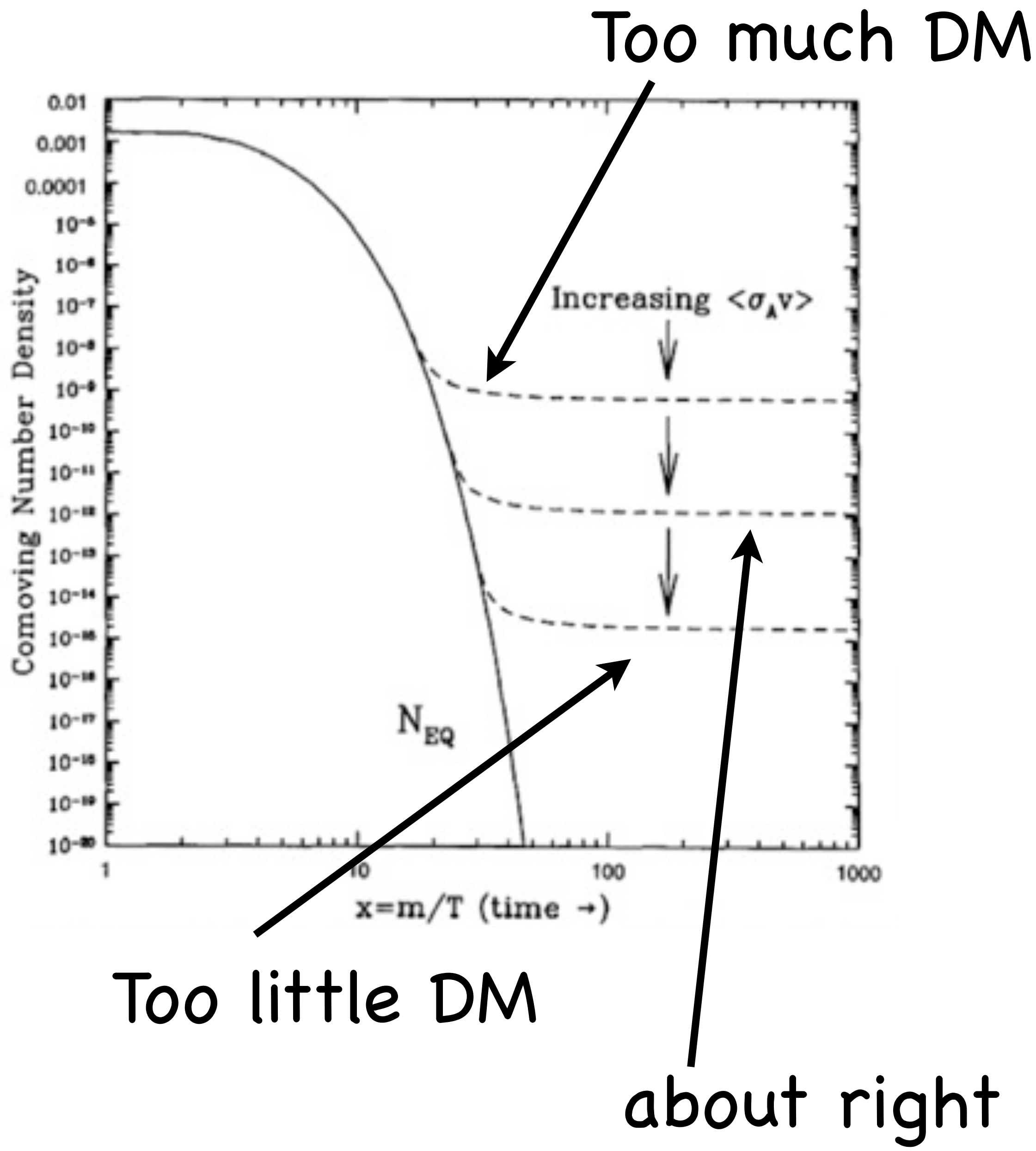
- success of BBN (DM is non-baryonic)
- growth of structure (cold DM)



WIMP DM

Assuming thermal equilibrium:



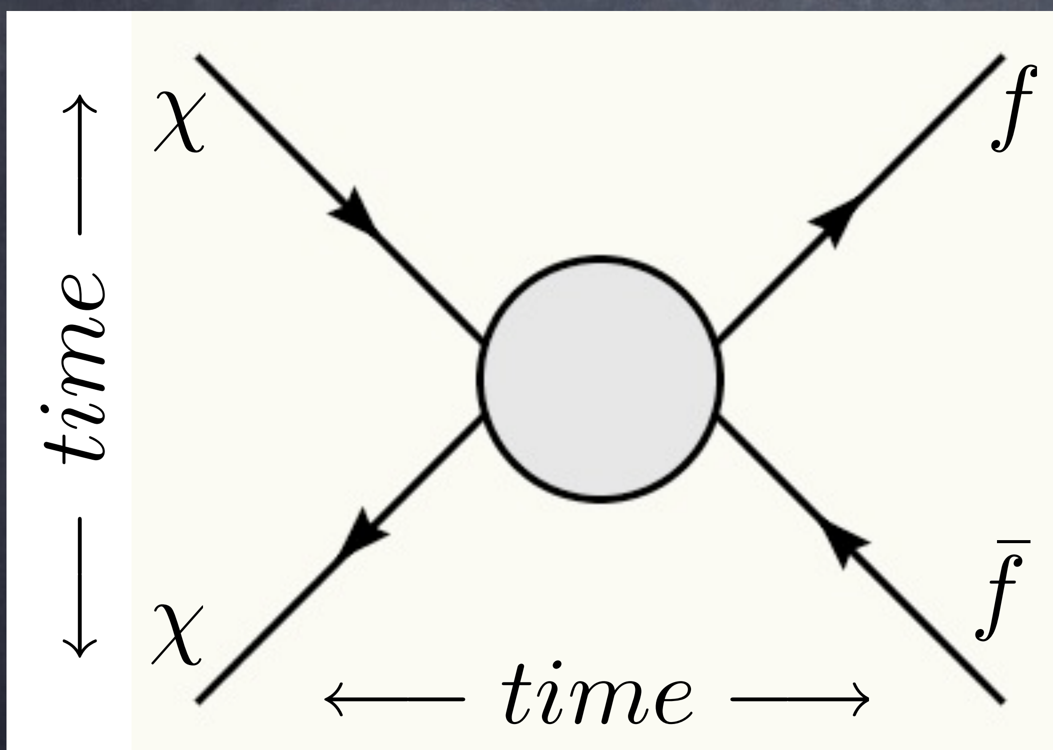


For: $T \ll M_\chi$ $\quad N_{eq} \propto e^{-M_\chi/T}$

$$\Omega h^2 \approx 0.1 \times \frac{3 \times 10^{-26} cm^3 s^{-1}}{\langle \sigma v \rangle} \approx 0.1 \times \frac{\alpha^2/(100 GeV)^2}{\langle \sigma v \rangle}$$

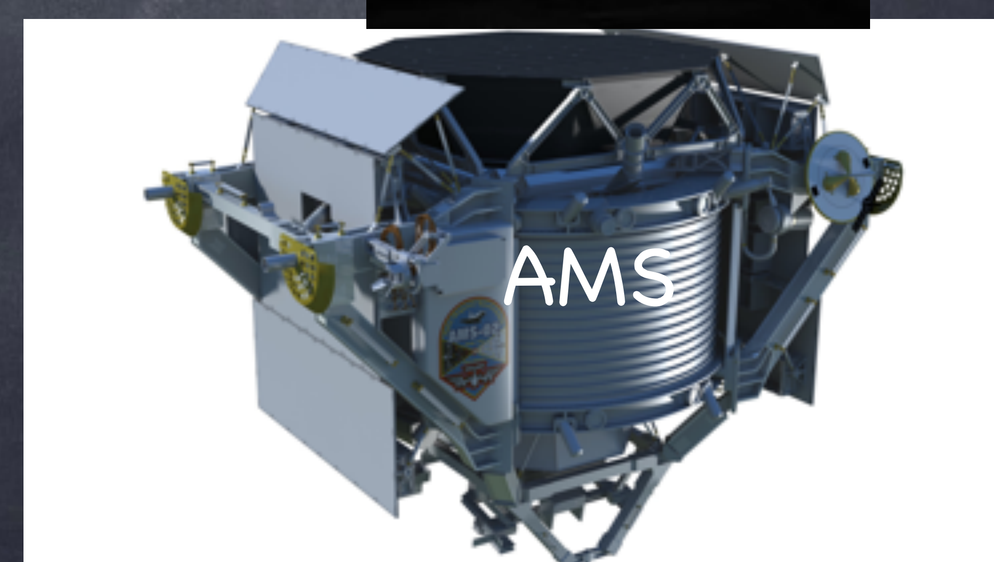
Thermal DM signals

Direct Detection scattering off normal matter, Xe, Ar, Ge, Si:

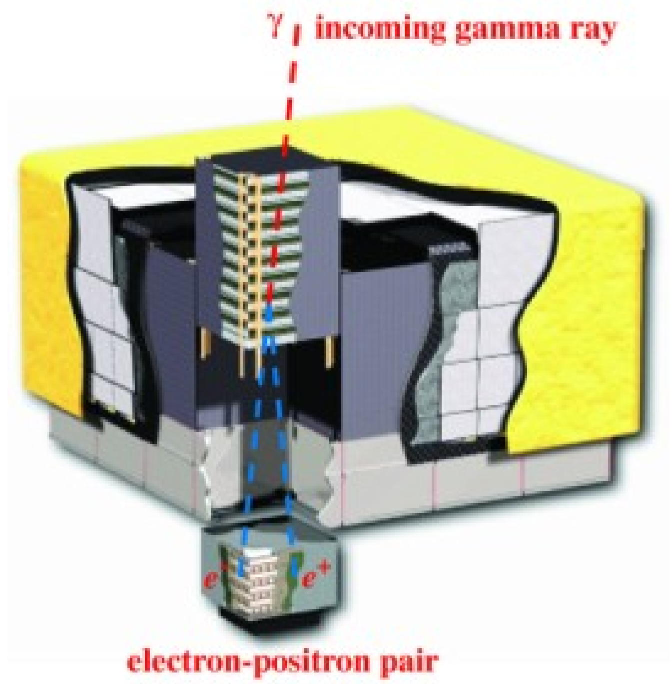


Dark matter production at colliders

Indirect detection: Dark matter annihilation into gamma-rays, cosmic rays, neutrinos



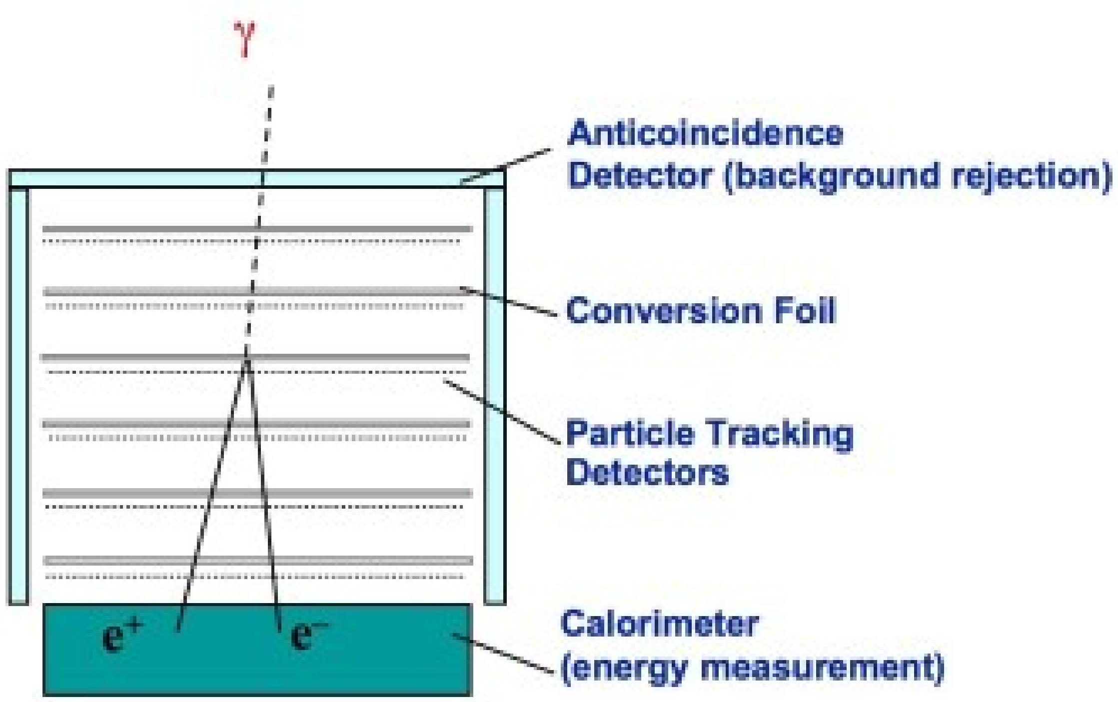
Fermi Large Area Telescope



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
- Will continue at least until 2014/2016



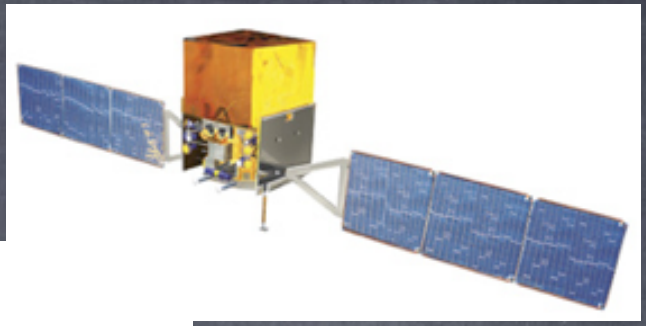
Main components:

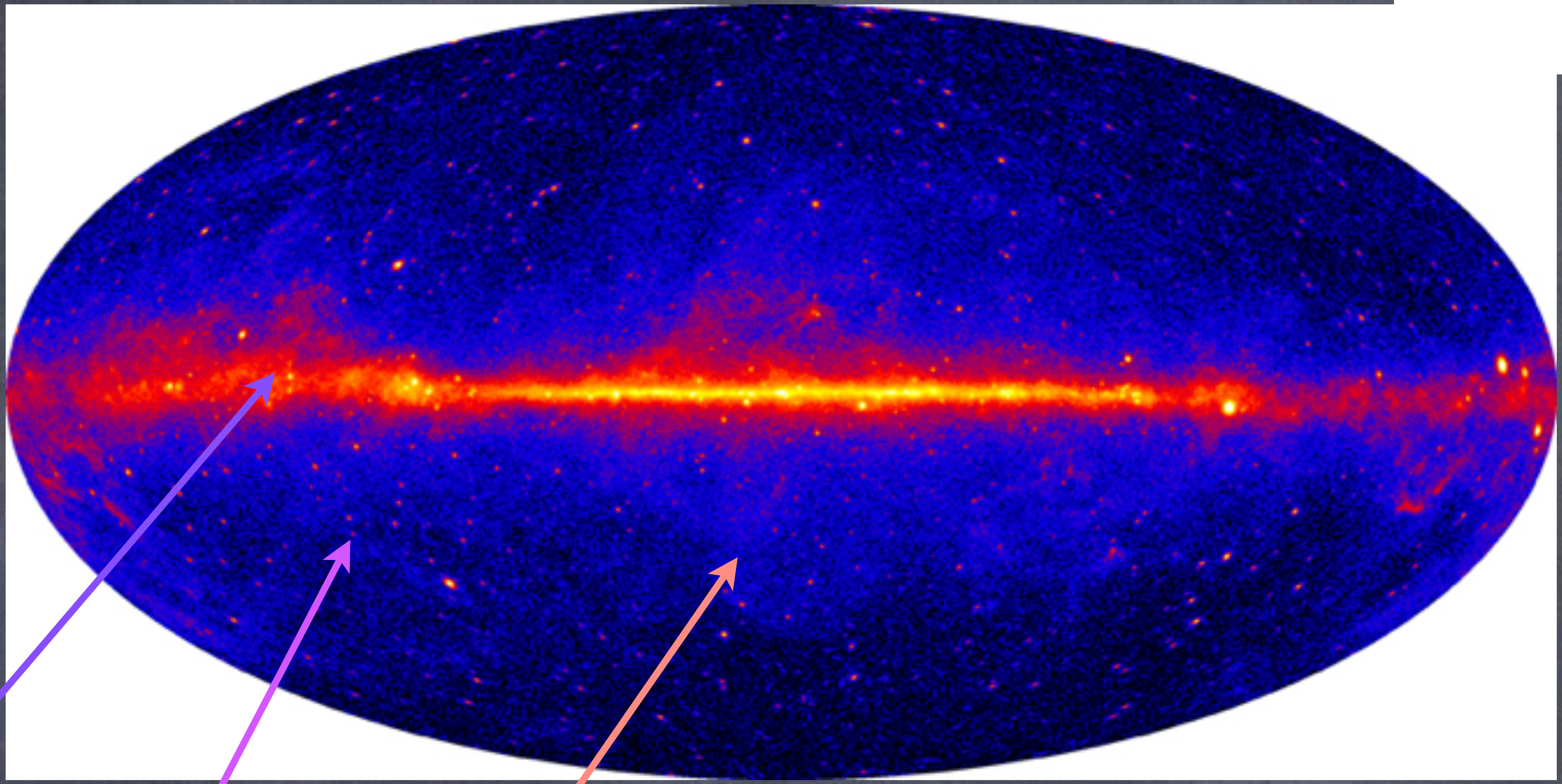
Anti-coincidence shield (plastic scintillator) with photomultiplier tubes

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

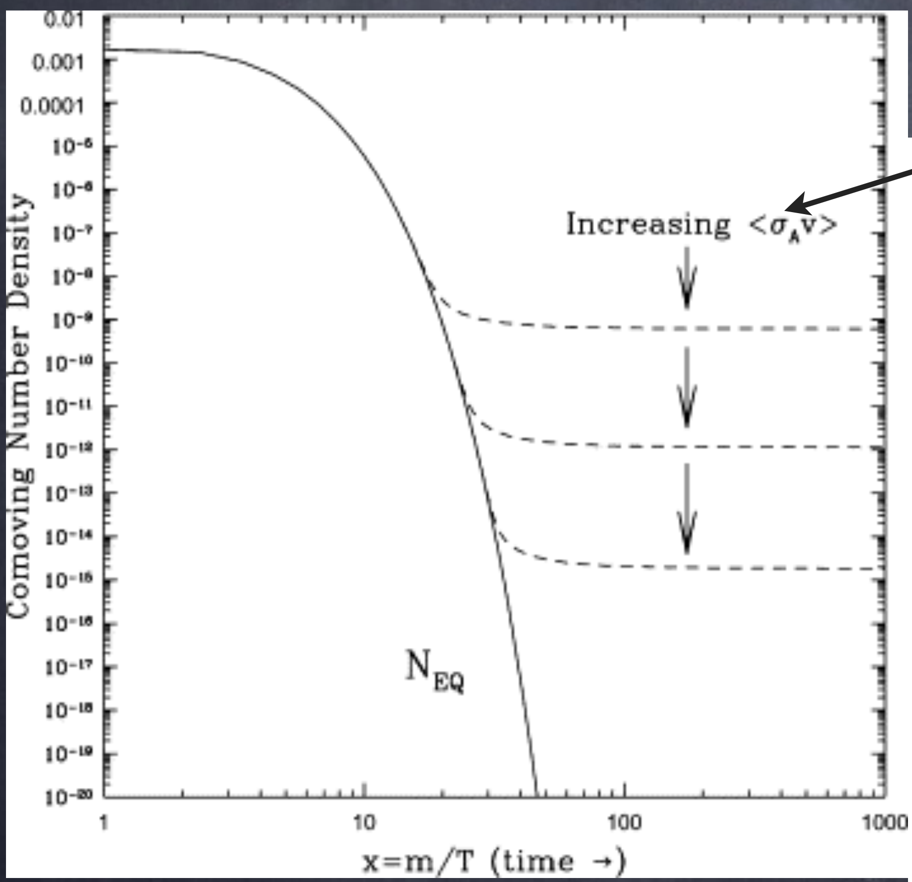
iv)"extended sources"(Fermi Bubbles, Geminga, Vela ...)

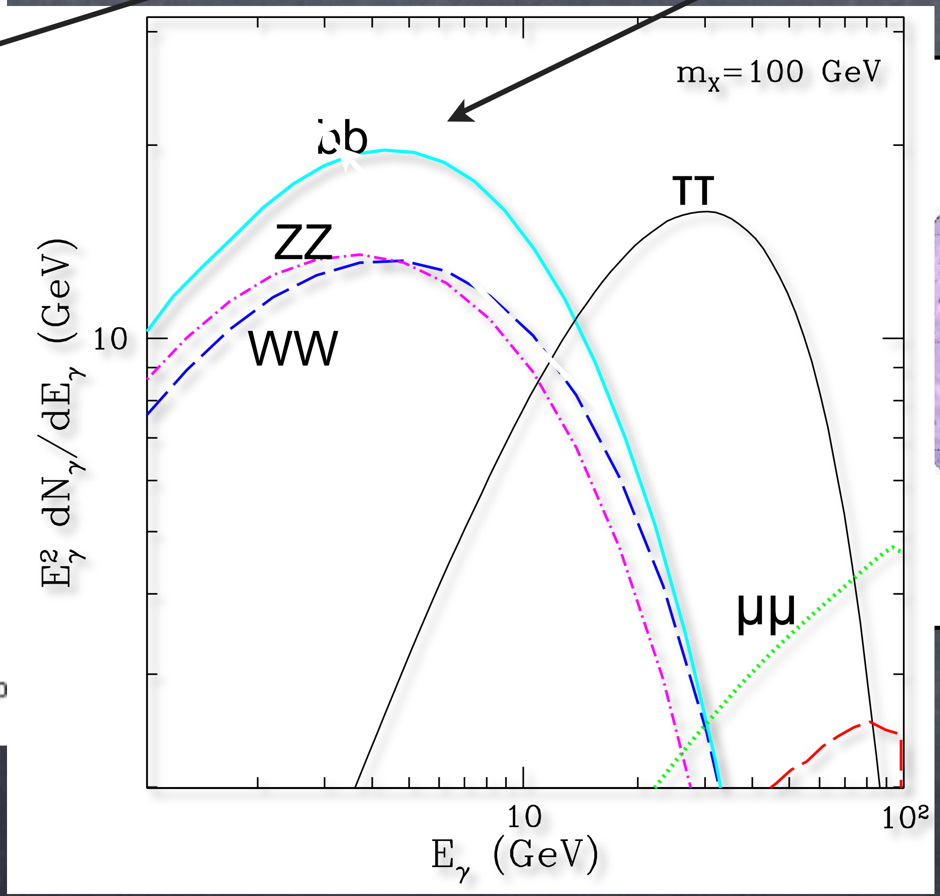
iv)misidentified CRs (isotropic due to diffusion of CRs in the Galaxy)

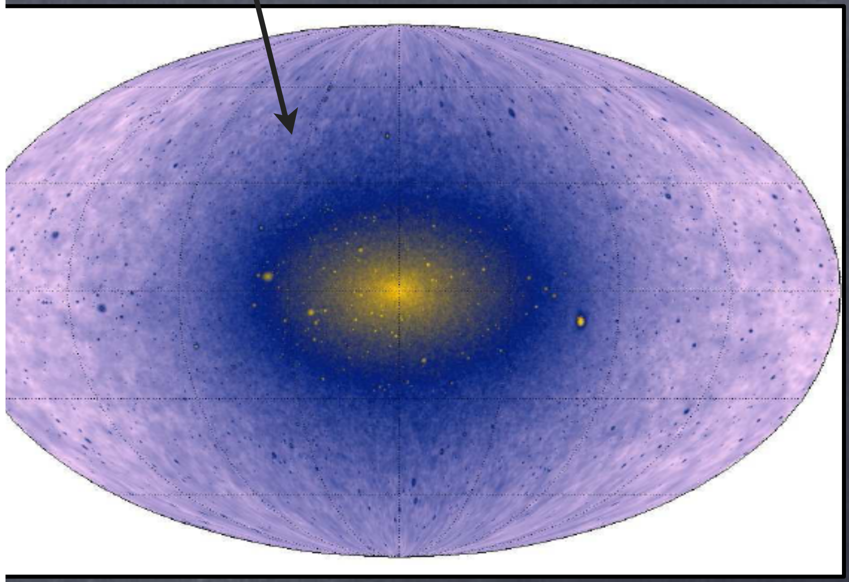
BUT ALSO the UNKOWN, e.g. Looking for DM annihilation signals

For a DM annihilation signal
We want to observe:

$$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle\sigma v\rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\,m_\chi^2} dl d\Omega$$



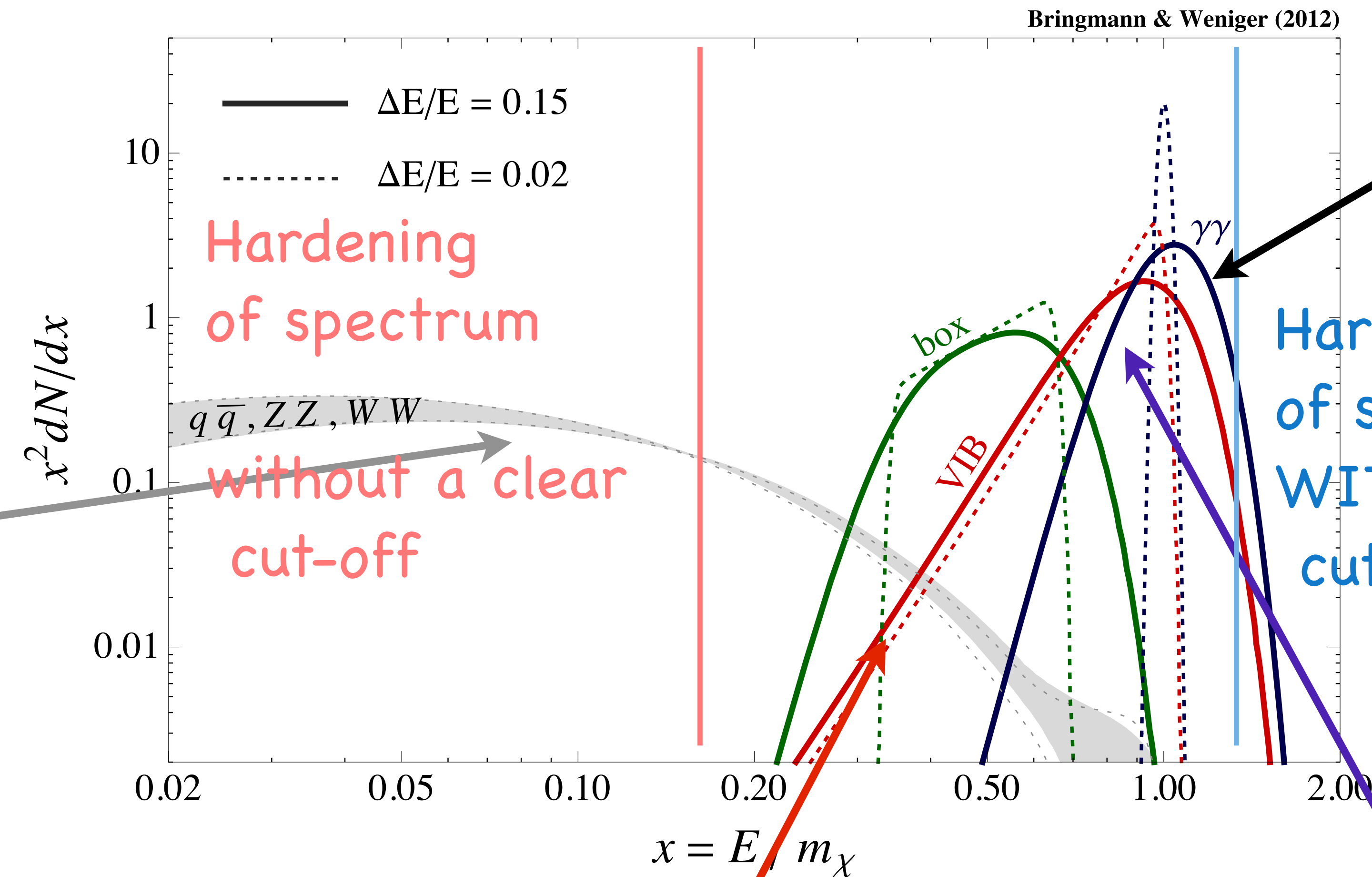




DM annihilation spectra

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

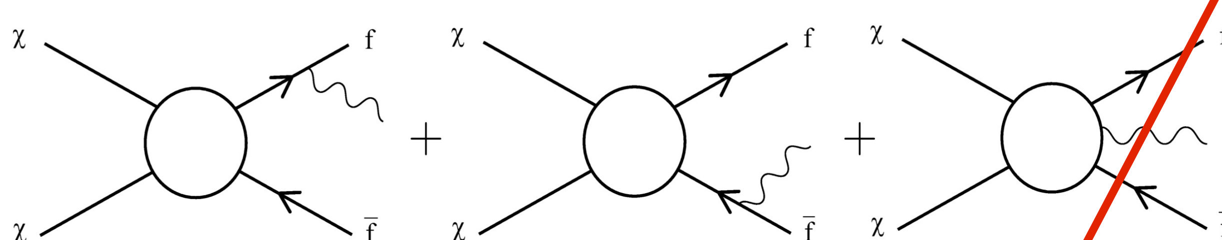
Hardening of spectrum without a clear cut-off



LINE(S)

Hardening of spectrum WITH a cut-off

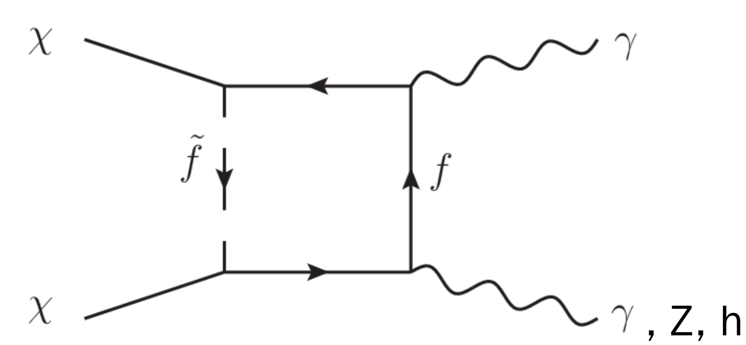
Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).



Final state radiation

Virtual Internal Bremss.

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

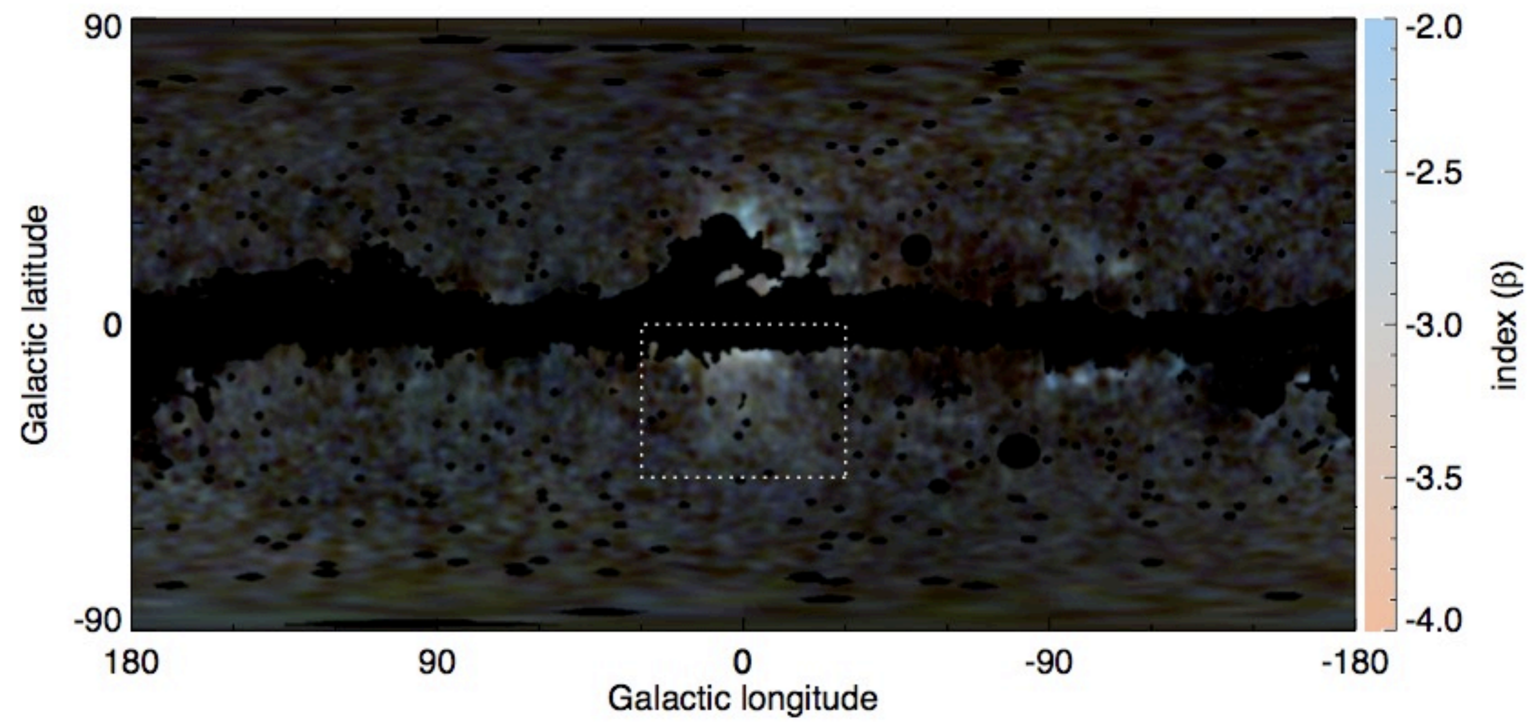


Fermi (gamma-ray) haze—>Bubbles

Since 2004 Finkbeiner had proposed the WMAP (microwave) haze, which suggests the existence of a population of electrons with a spectrum harder than the SNe accelerated electrons, of roughly spherical shape and extending out to at least 2kpc (5-10 kpc considering Fermi data).

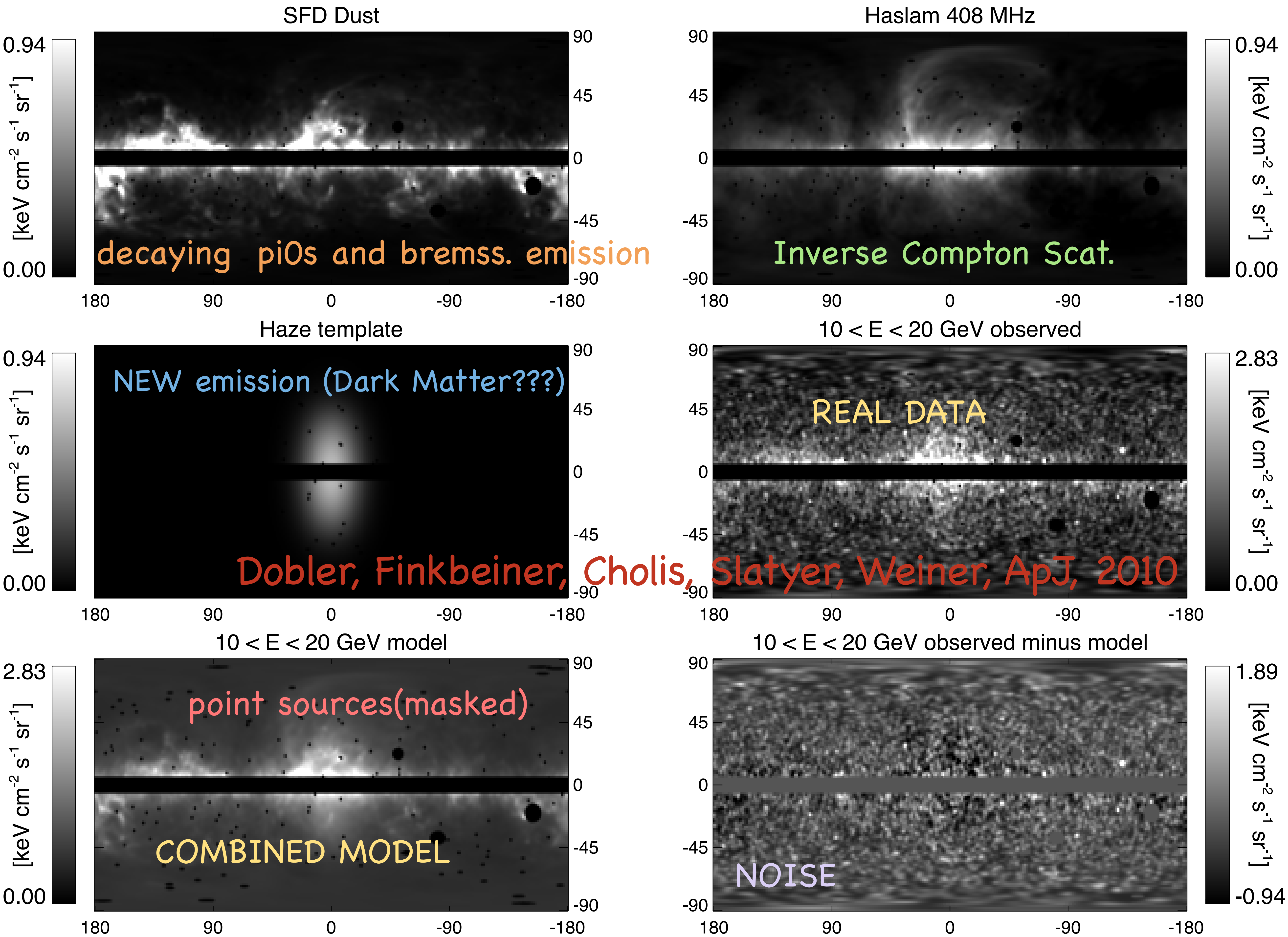
Such a population of hard electrons should also give an ICS signal as well. The Fermi haze is the gamma-ray counterpart of the microwave haze.

As in the case of the WMAP haze, all-sky templates were used to model the background components.

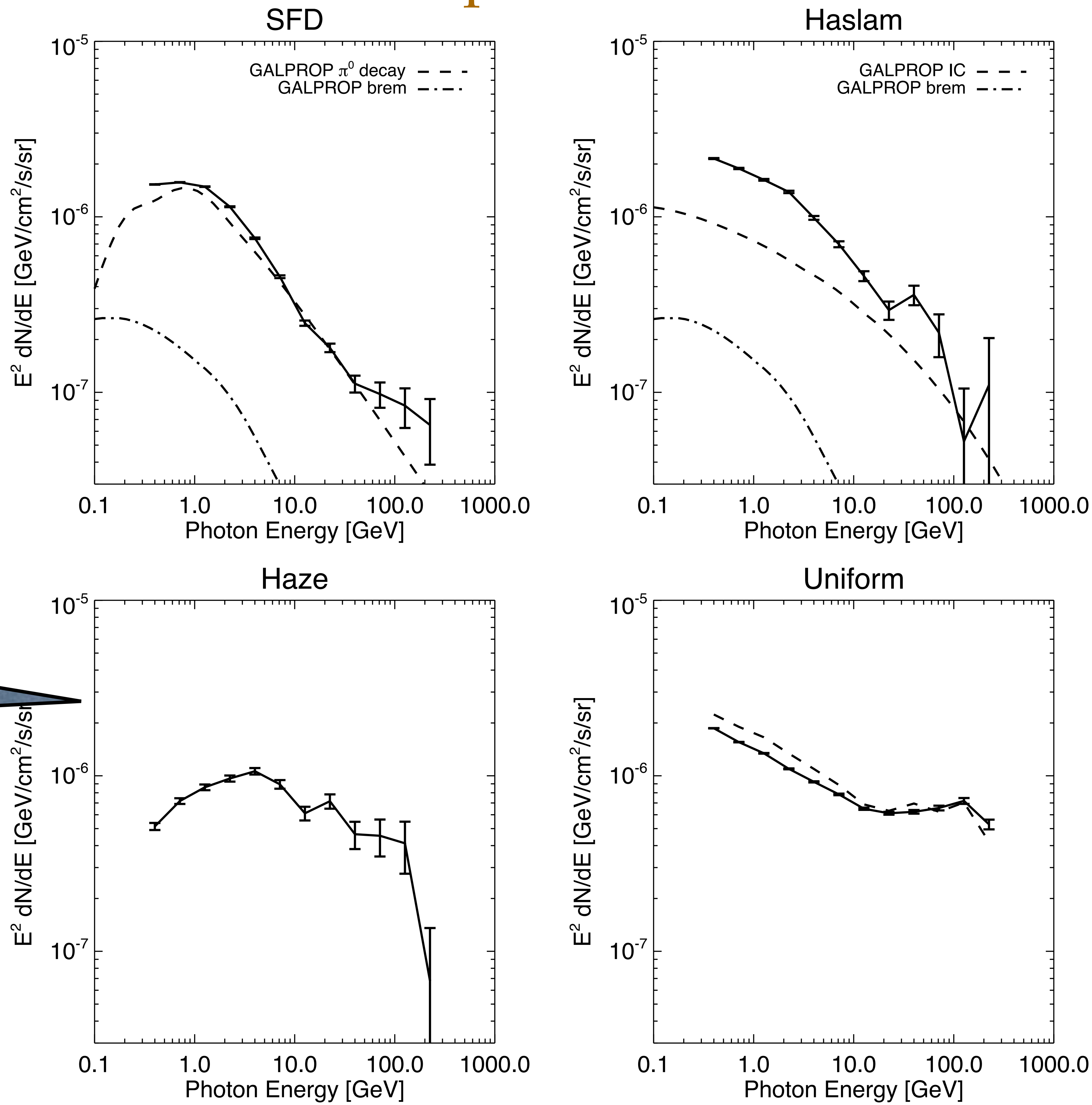


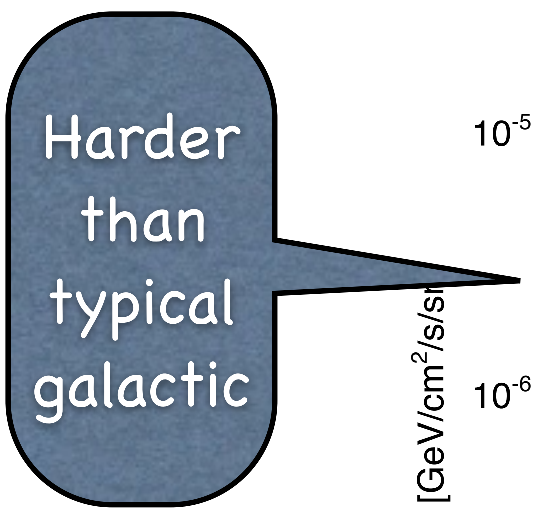
Different template sets have been used, that all resulted in the need for an extra gamma-ray template (the haze->Bubbles template) in order to fit well the entire gamma-ray sky. The haze->Bubbles template was in all cases non-disky and suggested a hard population of electrons, similarly to the microwave haze.

The first Fermi haze template



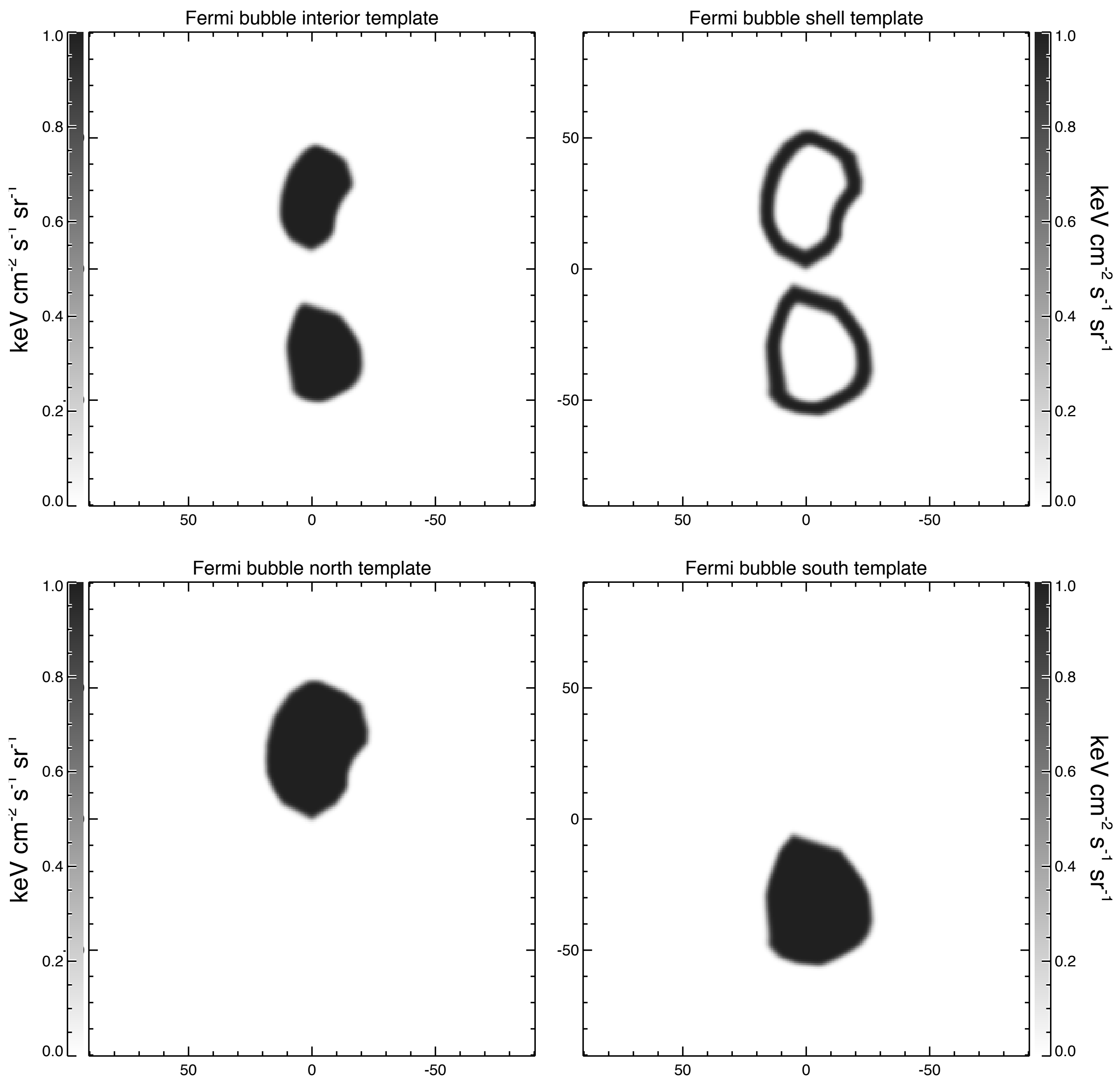
Spectra


SFD
GALPROP π^0 decay
GALPROP brem
Haslam
GALPROP IC
GALPROP brem
Haze
Uniform
E^2 dN/dE [GeV/cm^2/s/sr]
Photon Energy [GeV]
0.1
1.0
10.0
100.0
1000.0
10^{-5}
10^{-6}
10^{-7}


Harder than typical galactic

Su, Slatyer and Finkbeiner work

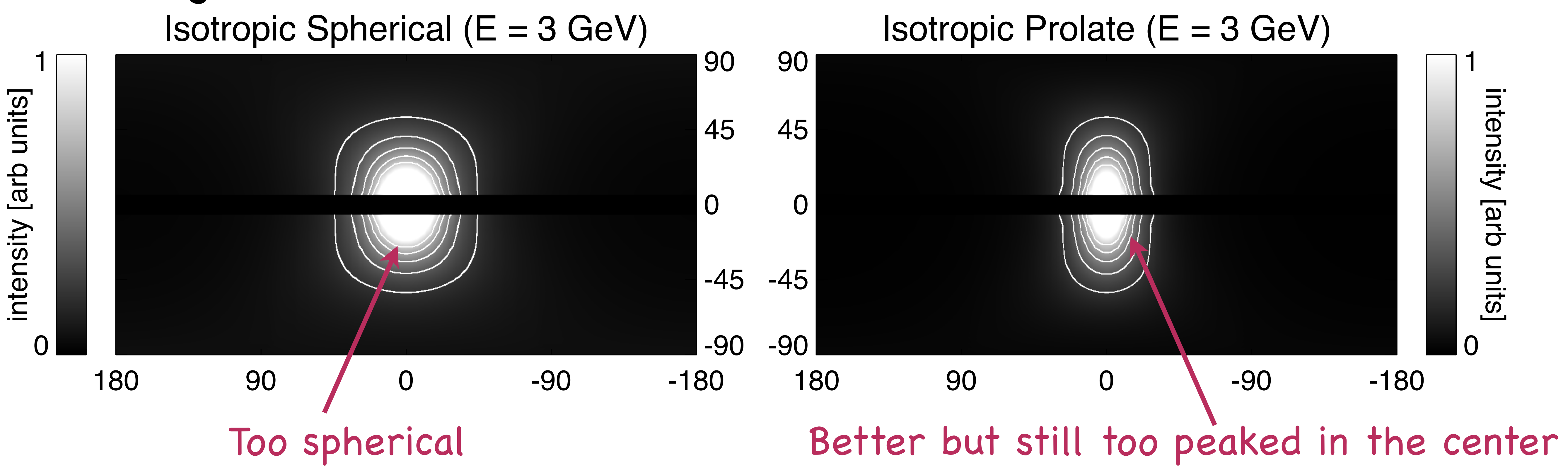
ApJ 724, 1044 (2010) (arXiv:1005.5480)



What about Dark Matter?

The DM smooth halo has an approximately Spherical distribution, a possible candidate.

DM can explain the haze signal (WMAP + Fermi) as has been shown in arXiv:0911.4954 (IC + N. Weiner) based on solely energetic/spectral arguments (XDM electrons with local annihilation BF ~ 100 (~50 at the haze region)).



Leptophilic DM models can explain the signal. Models that annihilate to taus or have large BRs to hadrons can not explain the angular morphology of the signal.

Anisotropic diffusion:

G. Dobler, I. Cholis, N.Weiner, ApJ 2011

$$\vec{\nabla}(D\vec{\nabla}\psi) = \frac{1}{r}\frac{\partial}{\partial r}(rD_{rr}\frac{\partial\psi}{\partial r} + rD_{rz}\frac{\partial\psi}{\partial z}) + \frac{\partial}{\partial z}(D_{zz}\frac{\partial\psi}{\partial z} + D_{zr}\frac{\partial\psi}{\partial r})$$

What we will assume is a strong magnetic field perpendicular to the galactic plane in the inner part of the Galaxy.

Random(irreg.) B-field component:

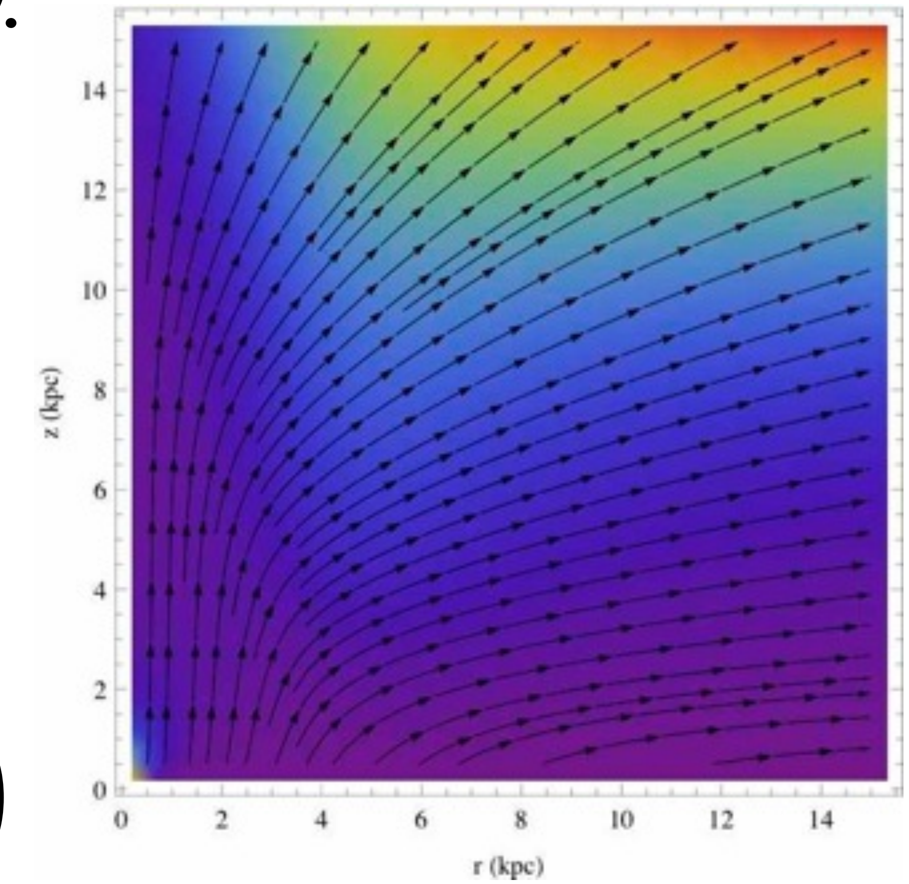
$$B_{irreg} = B_0 e^{(R_\odot - r)/r_1 - |z|/z_1}$$

$$R_\odot = 8.5kpc$$

Ordered B-field component:

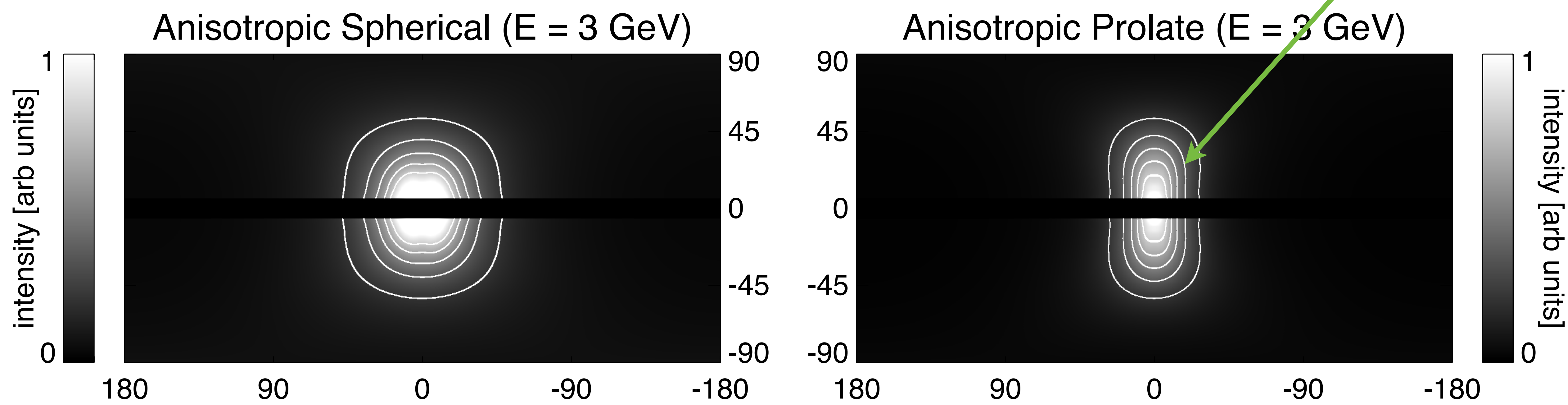
$$B_{\rm ord} = B_1 e^{-r/r_2 - |z|/z_2} \times \left(1 + K e^{-r/r_3 - |z|/z_3}\right)$$

$$\frac{D_{rr}}{D_{zz}} = \frac{1 + A^2 B_r^2}{1 + A^2 B_z^2}, \quad \frac{D_{rz}}{D_{zz}} = \frac{D_{zr}}{D_{zz}} = \frac{A^2 B_r B_z}{1 + A^2 B_z^2}$$



(extreme example)

Thus one can get:



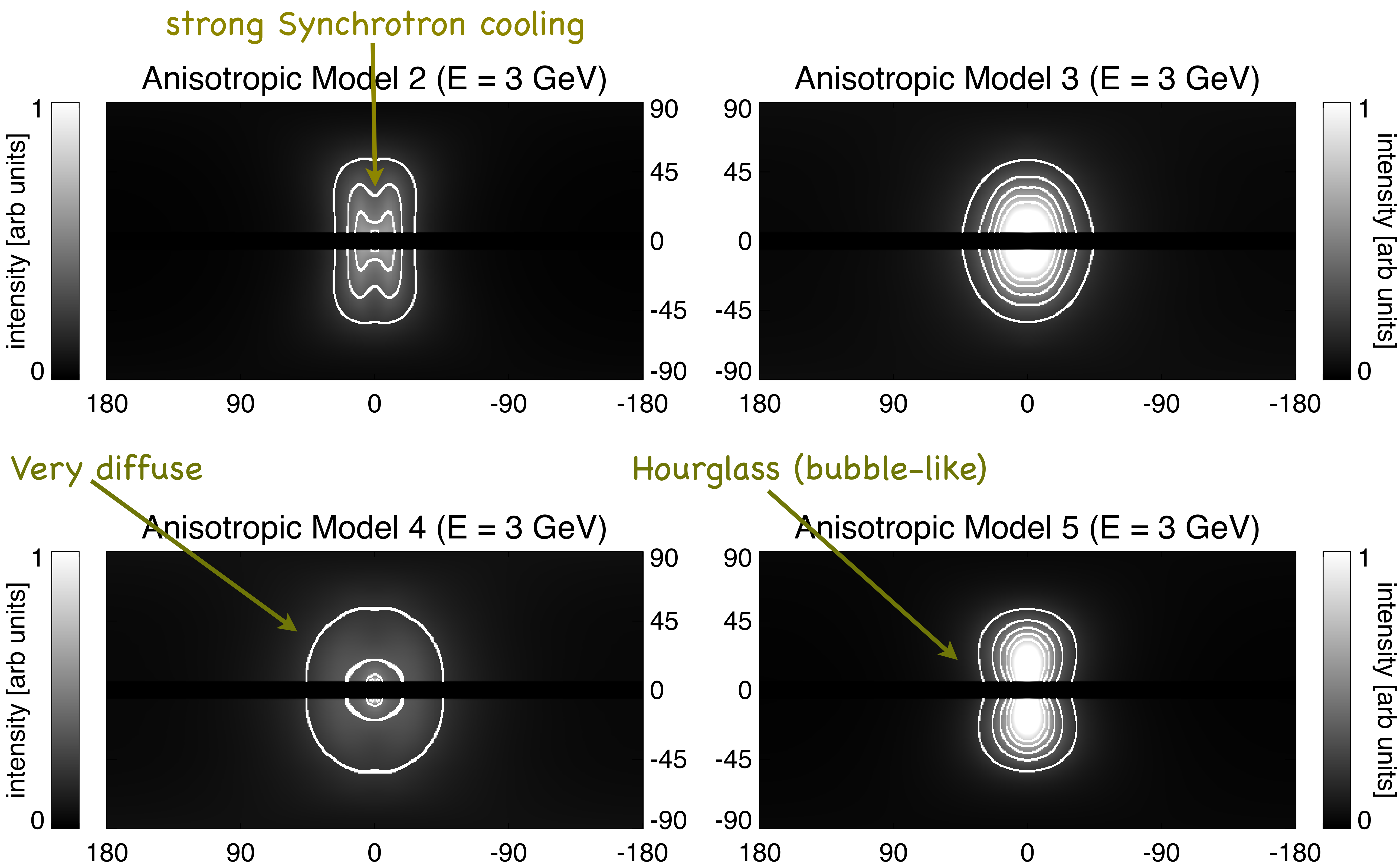
So with annihilating DM and specific assumptions on anisotropic and in-homogeneous diffusion we CAN fit the Fermi haze morphology spectrum and amplitude.

G. Dobler, I. Cholis, N.Weiner, ApJ 2011

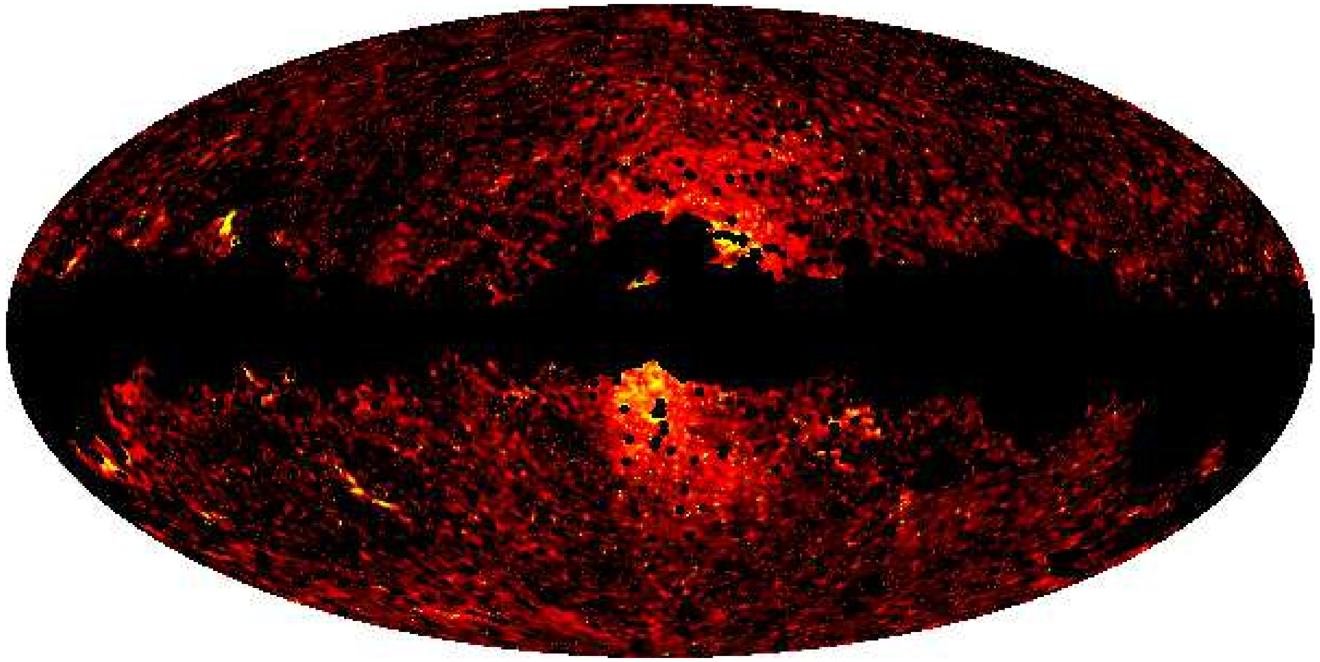
Different assumptions for the B-field can have apart from different synchrotron maps, different IC maps.

Model	$B_{\rm ord}$ Formula	B_0 (μG)	r_1 (kpc)	z_1 (kpc)	B_1 (μG)	K	r_2 (kpc)	z_2 (kpc)	r_3 (kpc)	z_3 (kpc)
1	$B_1 e^{-r/r_2-\lvert z\rvert/z_2} \times \left(1+Ke^{-r/r_3-\lvert z\rvert/z_3}\right)$	3	7	4	8	10	7	2	0.8	10
2	$B_1 e^{-r/r_2-\lvert z\rvert/z_2} \times \left(1+Ke^{-(r/r_3)^2}\sqrt{\cos(\lvert z\rvert/z_3 \times \pi/2)}\right)$	3	5	4	10	11	5	4	1	40
3	$B_1 e^{-r/r_2-\lvert z\rvert/z_2} \times \left(1+Ke^{-(r/r_3)^{1.5}-\lvert z\rvert/z_3}\right)$	3	10	2	10	6	10	3	1.2	20
4	$B_1 e^{-r/r_2-\lvert z\rvert/z_2} \times \left(1+Ke^{-(r/r_3)^{1.5}-(\lvert z\rvert/z_3)^{1.5}}\right)$	3.7	5	2	12.5	8	7	5	2.5	20
5	$B_1 e^{-r/r_2-\lvert z\rvert/z_2} \times \left(1+Ke^{-r/r_3-\lvert z\rvert/z_3}\right)$	3.7	5	2	3.7	12	5	2	2	6

Anisotropic diffusion of CRs can have a strong effect on the IC map from annihilating DM:



Later Results



Planck* intermediate results. IX. Detection of the Galactic haze with *Planck

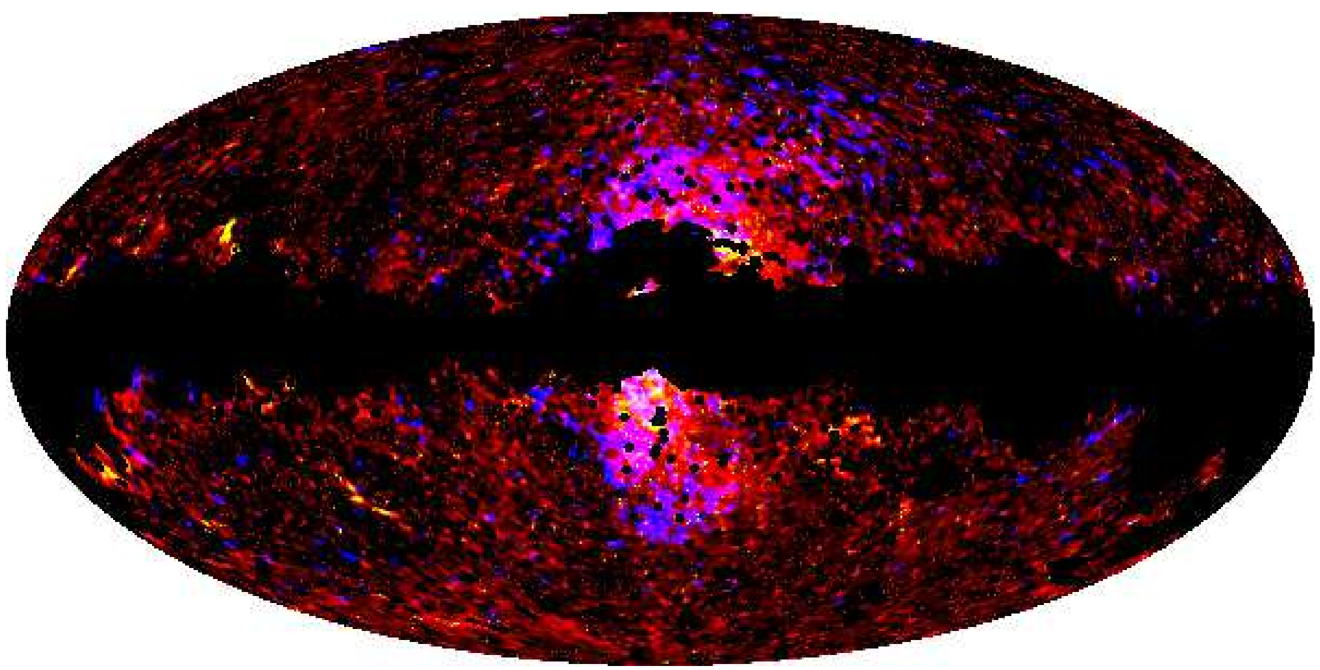
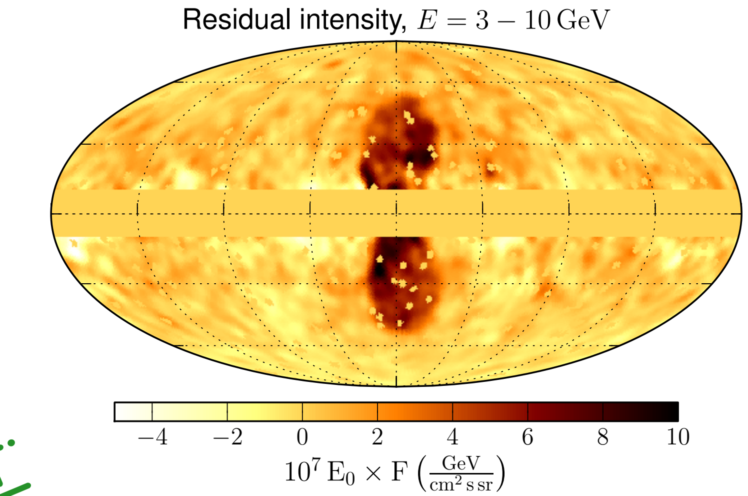
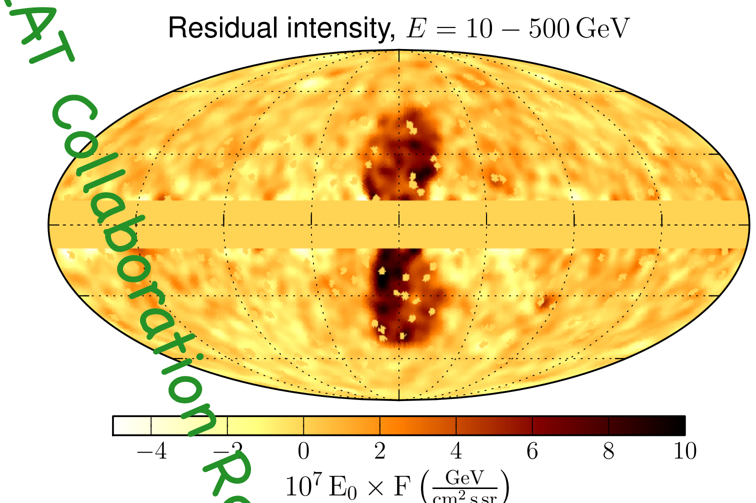
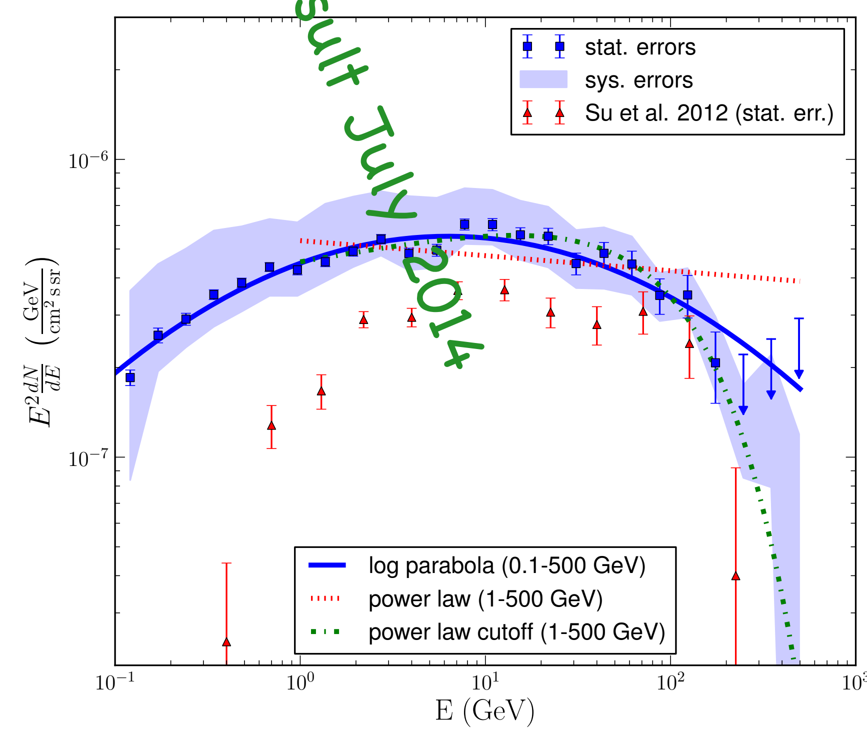


Fig. 9. *Top*: The microwave haze at *Planck* 30 GHz (red, $-12\ \mu$K < $\Delta T_{\rm CMB}$ < 30 μK) and 44 GHz (yellow, 12 μK < $\Delta T_{\rm CMB}$ < 40 μK). *Bottom*: The same but including the *Fermi* 2-5 GeV haze/bubbles of Dobler et al. (2010) (blue, 1.05 < intensity [keV cm^{-2} s^{-1} sr^{-1}] < 1.25; see their Fig. 11). The spatial correspondence between the two is excellent, particularly at low southern Galactic latitude, suggesting that this is a multi-wavelength view of the same underlying physical mechanism.





Fermi-LAT collaboration Result July 2014



Makes the DM interpretation more difficult to work since the magnetic fields are actually not that strongly ordered

The original 130 GeV line claim

Weniger, JCAP 1208, 007(2012) (1204.2797)

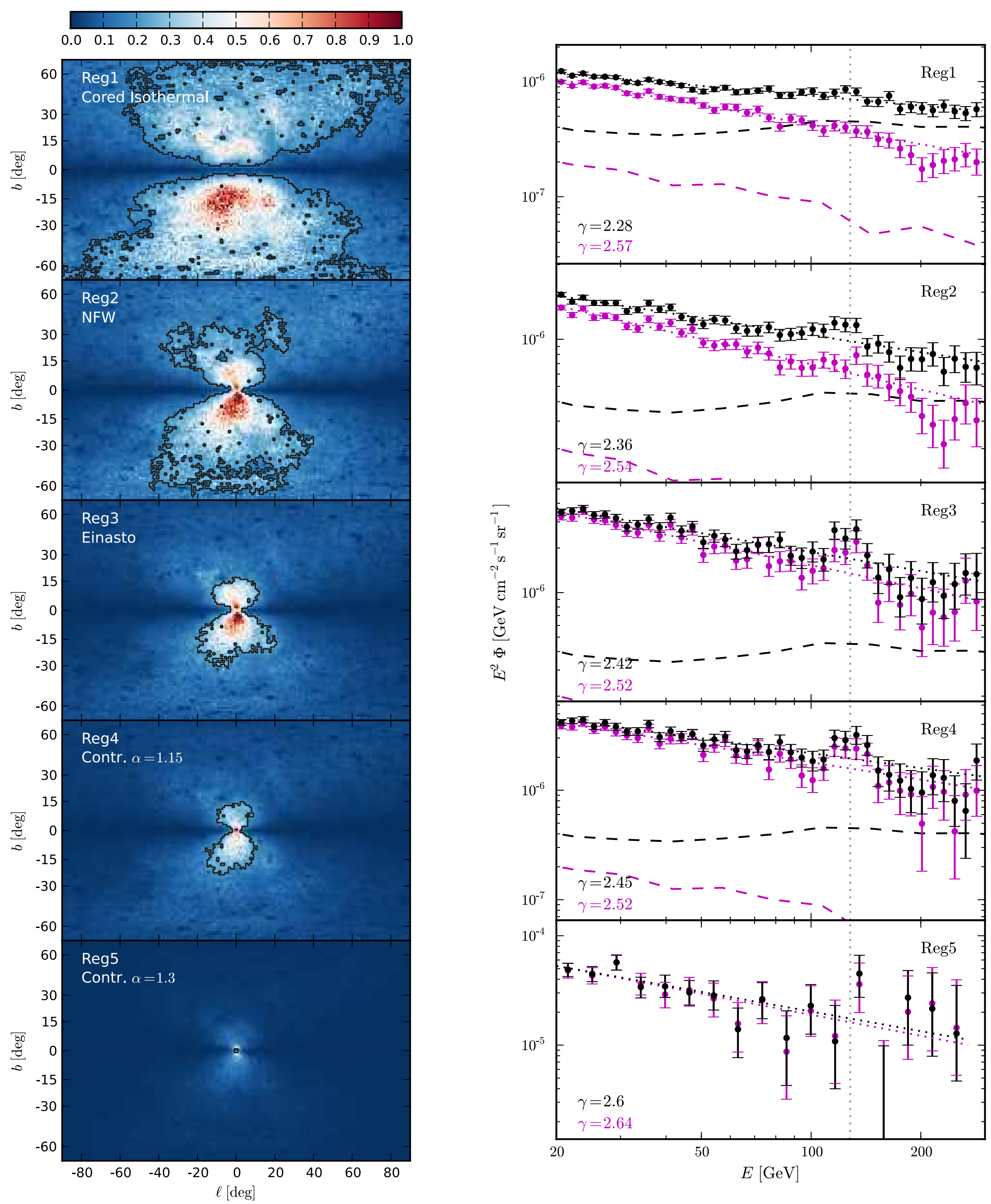


Figure 1. *Left panel:* The *black lines* show the target regions that are used in the present analysis in case of the SOURCE event class (the ULTRACLEAN regions are very similar). From *top* to *bottom*, they are respectively optimized for the cored isothermal, the NFW (with $\alpha = 1$), the Einasto and the contracted (with $\alpha = 1.15$, 1.3) DM profiles. The *colors* indicate the signal-to-*background* ratio with arbitrary but common normalization; in Reg2 to Reg5 they are respectively downscaled by factors (1.6, 3.0, 4.3, 18.8) for better visibility.
Right panel: From top to bottom, the panels show the 20–300 GeV gamma-ray (+ residual CR) spectra as observed in Reg1 to Reg5 with statistical error bars. The SOURCE and ULTRACLEAN events are shown in *black* and *magenta*, respectively. *Dotted lines* show power-laws with the indicated slopes; *dashed lines* show the EGBG + residual CRs. The *vertical gray* line indicates $E = 129.0$ GeV.

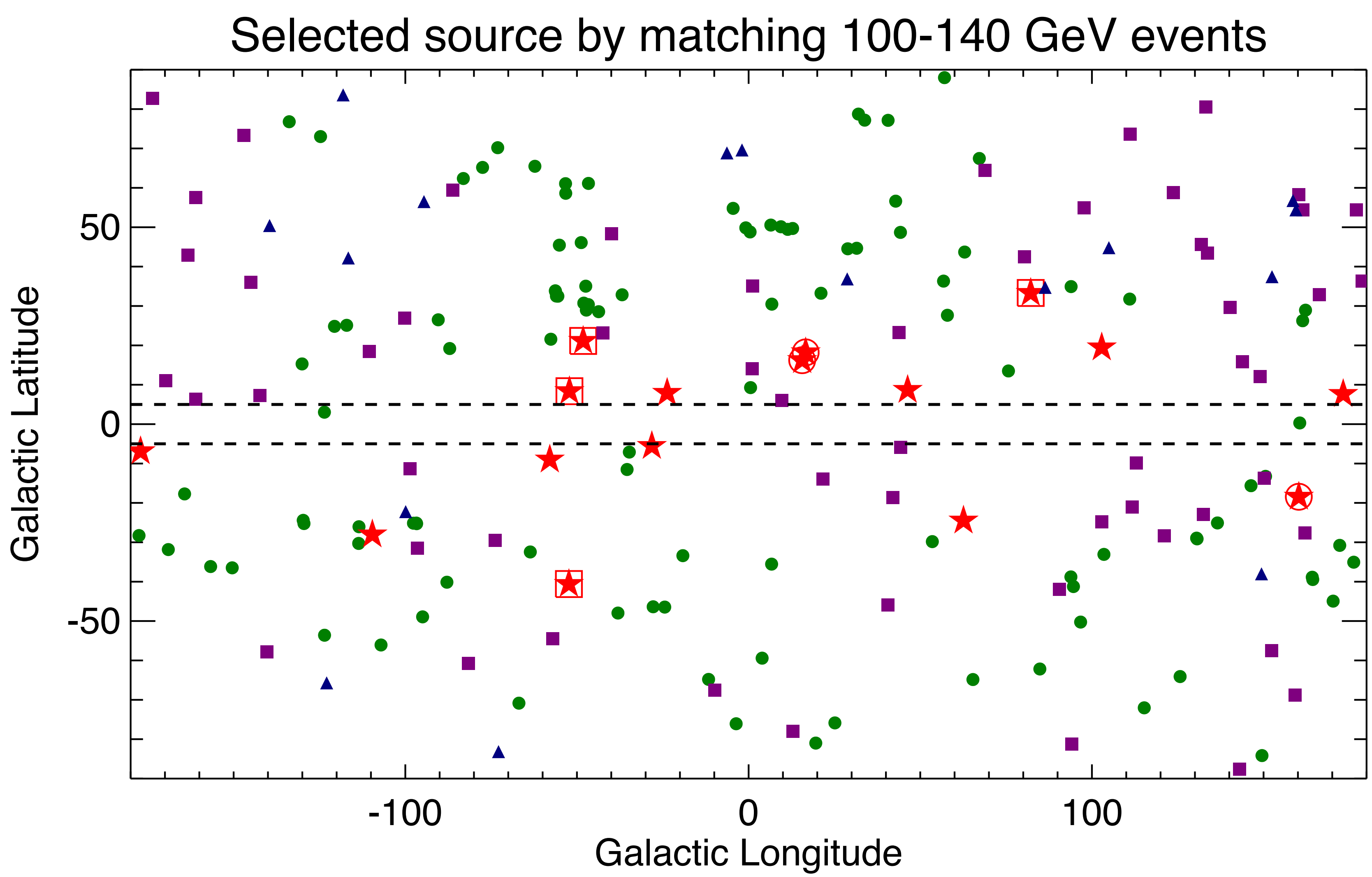
3.2 σ (4.6 σ) detection of a gamma-ray line at $129.8 \pm 2.4^{+7}_{-13}$ GeV

Using 43 months of Fermi data looking for a line at 20-300 GeV. Signal/excess is ~ 50 photons

- Take as background the observed gamma-ray map between 1-20 GeV and extrapolate its morphology on the sky to higher energies
- Assume a specific profile for the DM distribution in the galaxy
- Choose optimal search region (signal/noise)

Other regions where the 130 GeV line signal has/has not been claimed

- No detection towards the dwarf spheroidal galaxies
- Unassociated point sources in the Fermi 2 yr catalogue (Su&Finkbeiner 1207.7060)
- Sample of 6 Galaxy clusters (Hektor,Raidal&Tempel 1207.4466)



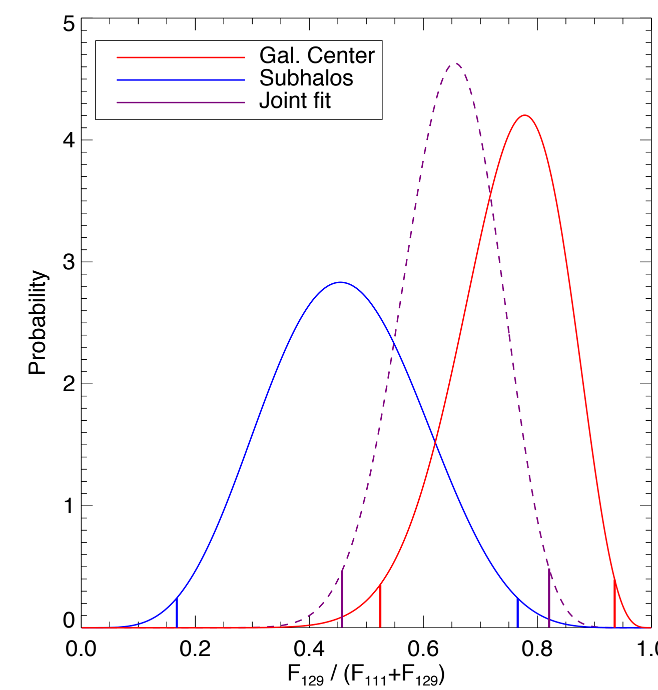


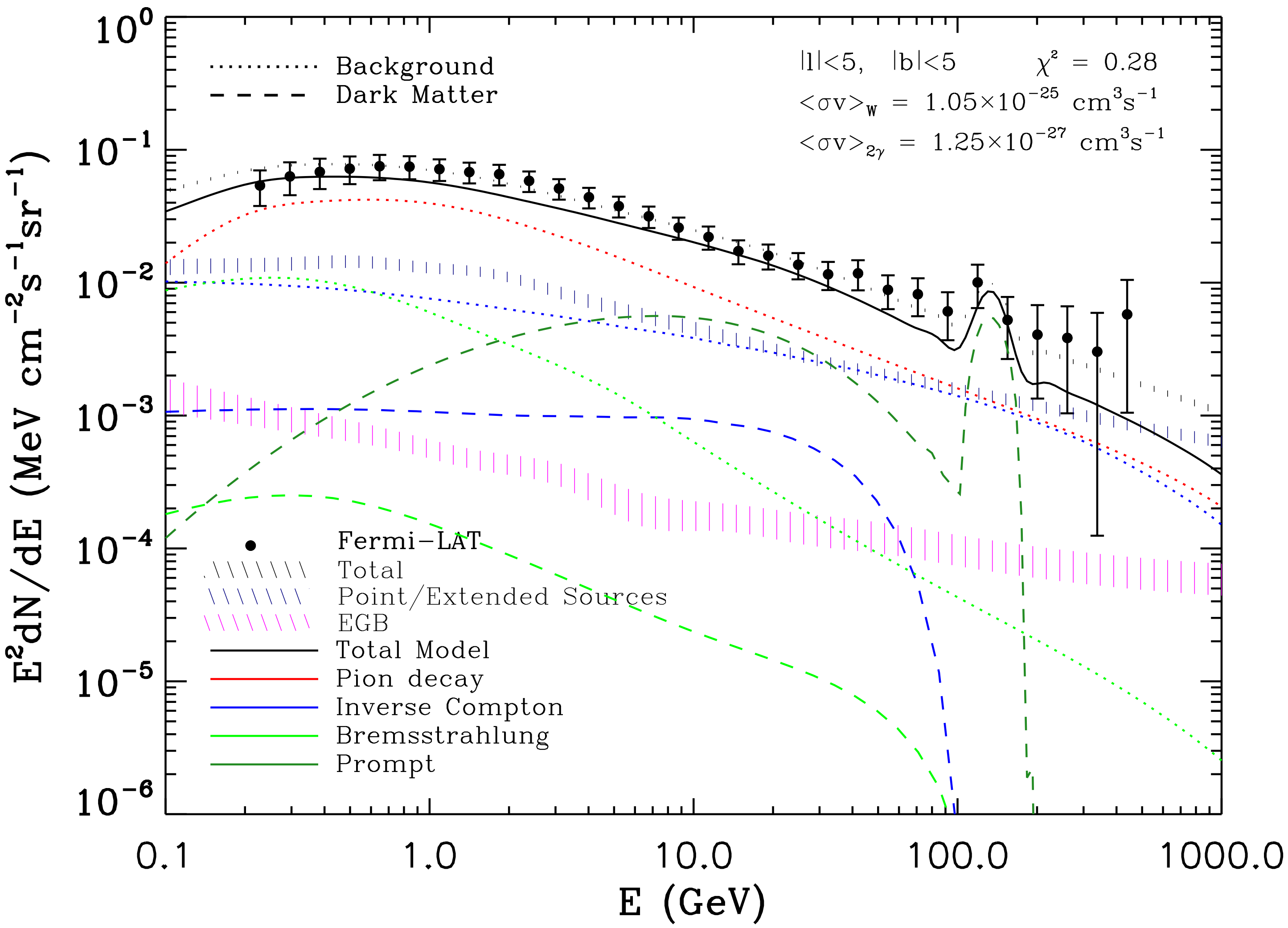
FIG. 7.— Probability of obtaining the observed counts, in the energy bins centered on 111 and 129 GeV, in the Galactic center and subhalos as a function of the line fraction $f \equiv F_{129}/(F_{111} + F_{129})$. We find that the best fit ratio of the 129 GeV line to 111 GeV line is 1.5, and the 2σ range of the line ratio is [0.84, 4.5]. See Section 3.6 for details.

Limits on the Continuous Spectrum associated to the line

The cross section to the line photons is $\langle \sigma v \rangle_{\gamma\gamma} \sim 1 - 2 \times 10^{-27} cm^3 s^{-1}$

There must be an associated continuum spectrum from annihilations at tree level. Derive constraints for a set of basic channels.

Ilias Cholis, Maryam Tavakoli, Piero Ullio PRD 86 083525 2012 (arXiv:1207:1468),



The line data prefer strongly the annihilation to the decay case.

Annihilation in a cuspy profile.

Annihilations to:

$\chi\chi \longrightarrow W^+W^-$, $\chi\chi \longrightarrow b\bar{b}$, $\chi\chi \longrightarrow \tau^+\tau^-$
$\chi\chi \longrightarrow \mu^+\mu^-$ and $\chi\chi \longrightarrow e^+e^-$

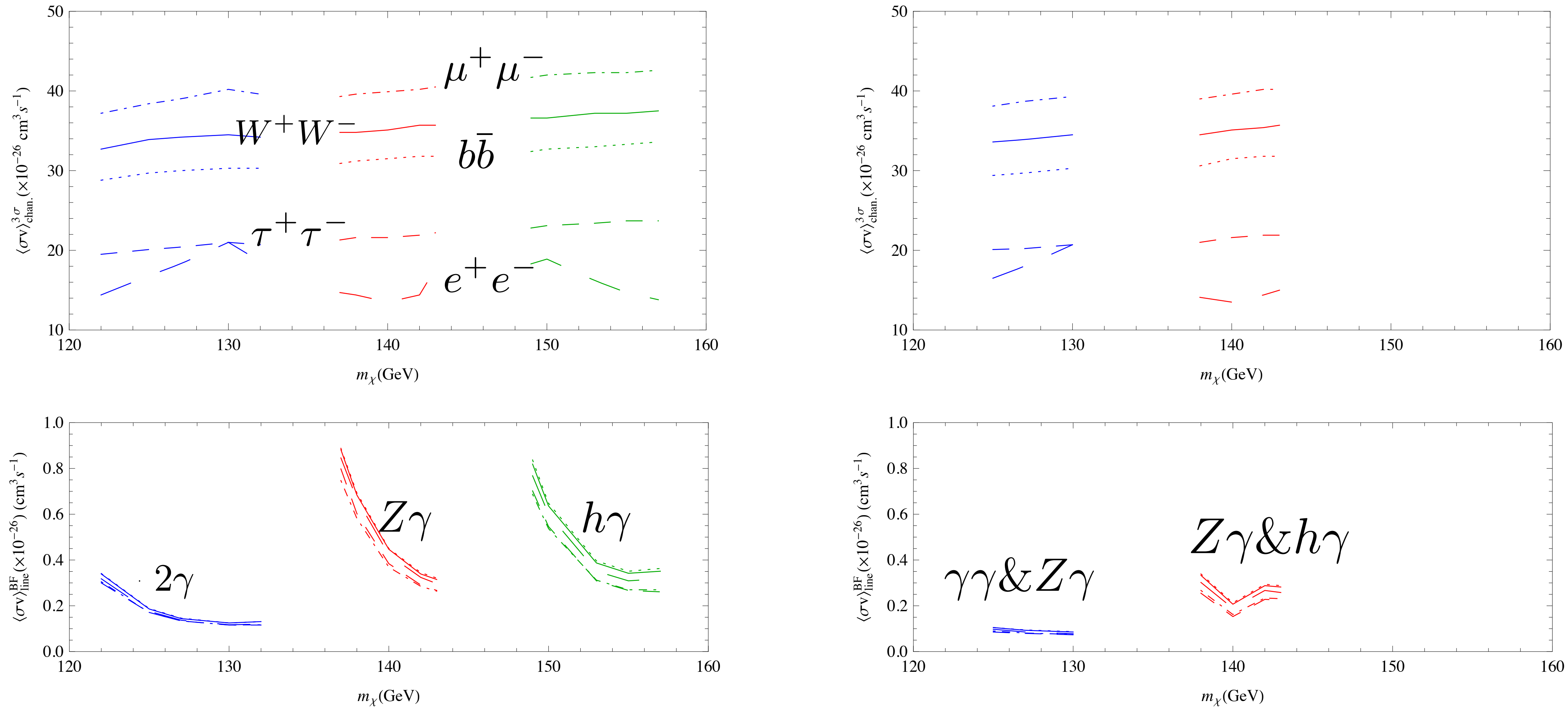
Limits can be linearly combined.

Annihilations to W^+W^- looking at $|b| < 5^\circ, |l| < 5^\circ$

$$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle \sigma v \rangle}{4\pi} \frac{dN_\gamma}{dE}_{DM} \frac{\rho^2_{DM}(l,\Omega)}{2\, m_\chi^2} dl d\Omega$$

Limits

single line | double line



IC, MT, PU PRD 2012

Chan.	Line	127 GeV (2γ)	140 GeV ($Z\gamma$)	150 GeV ($h\gamma$)
W^+W^-	Free	34.2(40.8)	35.1(42.6)	36.6(44.1)
W^+W^-	Fixed	34.5(41.4)	35.4(43.2)	37.2(44.7)
$b\bar{b}$	Free	30.0(31.5)	31.5(33.3)	32.7(34.5)
$b\bar{b}$	Fixed	30.3(31.8)	31.8(33.6)	33.0(34.8)
$\tau^+\tau^-$	Free	20.4(21.9)	21.6(23.4)	24.1(24.9)
$\tau^+\tau^-$	Fixed	20.7(21.9)	21.9(23.7)	23.4(25.2)
$\mu^+\mu^-$	Free	39.0(155.7)	39.9(169.8)	42.0(185.4)
$\mu^+\mu^-$	Fixed	41.1(156.3)	40.2(167.7)	42.3(184.5)
e^+e^-	Free	18.3(91.8)	13.5(100.8)	18.9(111.0)
e^+e^-	Fixed	18.3(92.1)	13.5(99.3)	19.2(110.4)

Fit the cross section to the line and derive 3 sigma (2-sided) limits to the continuous spectrum.

$\times 10^{-26}\ \mathrm{cm^3 s^{-1}}$

A specific example for the line that doesn't work

Axion/Wino mixed model for the line (Acharya et al. 1205.5789).

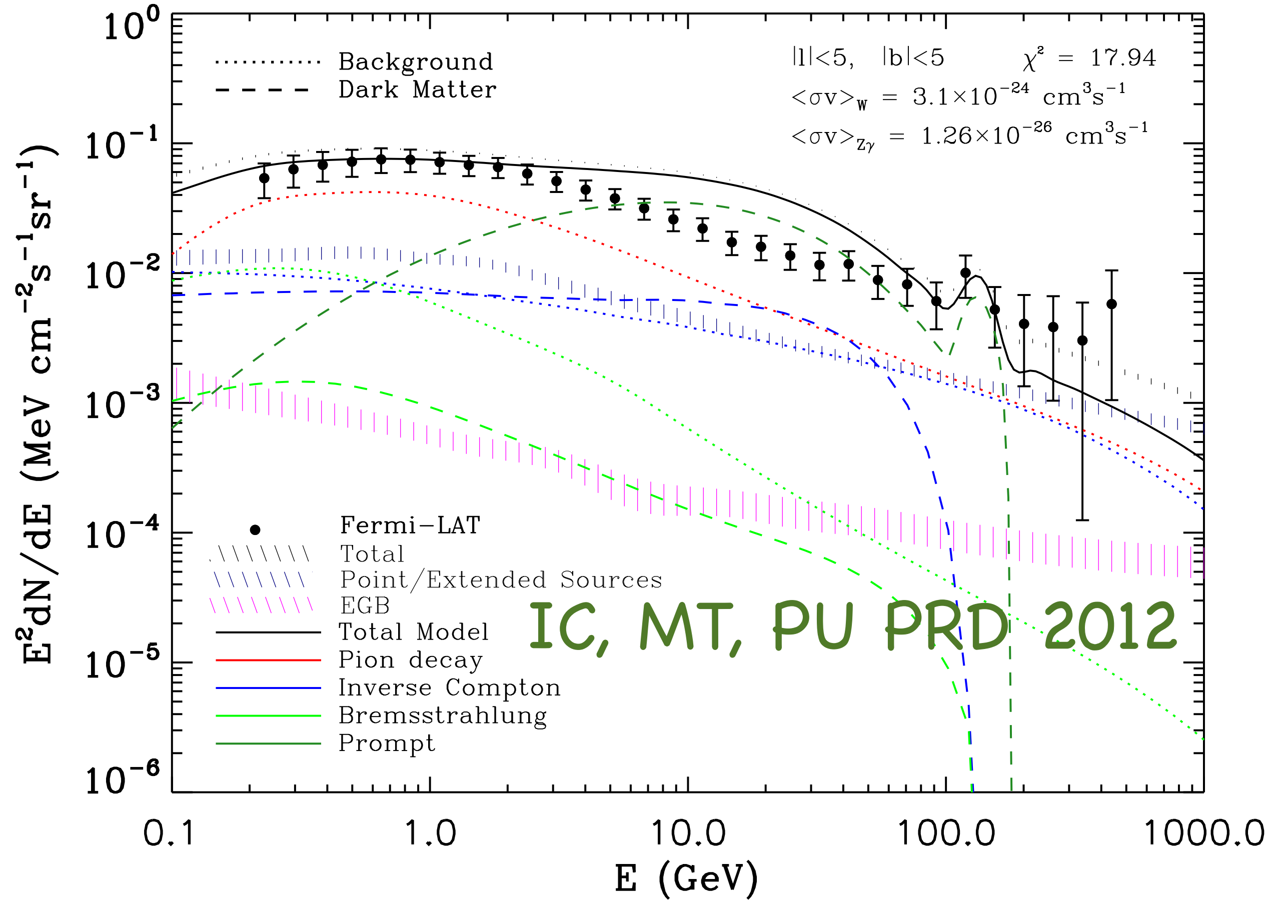
$$m_\chi \;=\; 145 \;\; \mathrm{GeV}$$

Cross-section to the line:

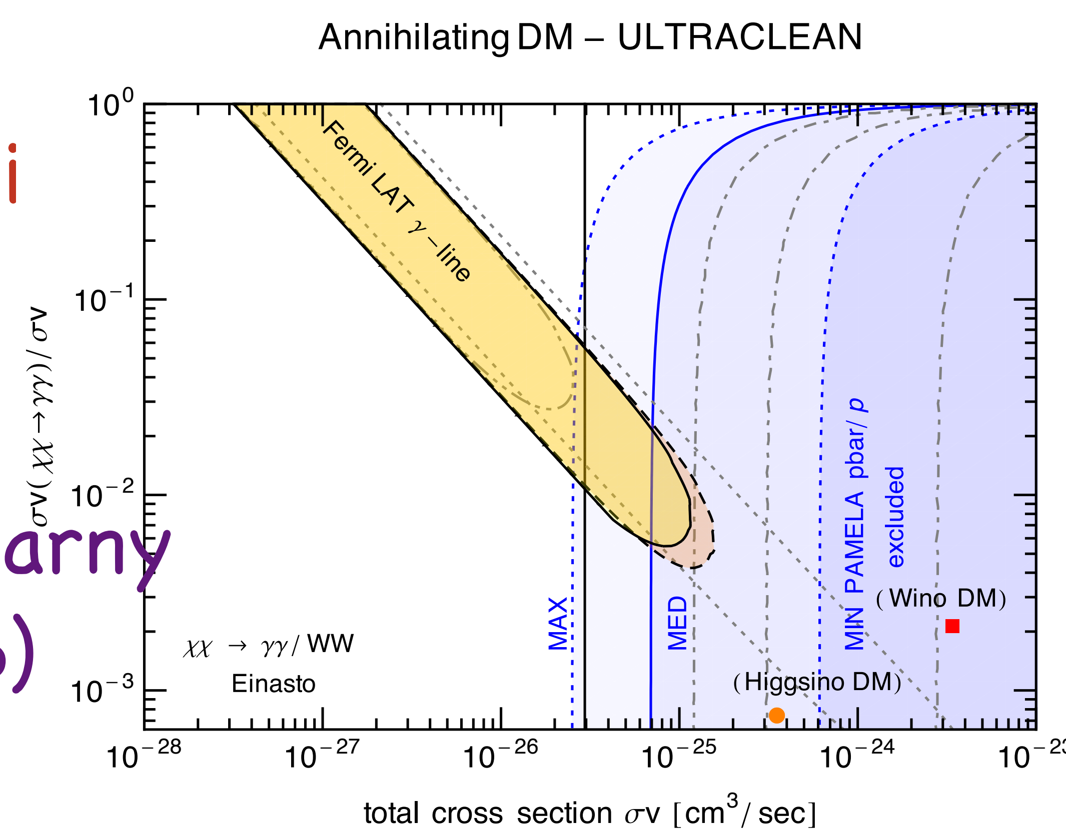
$$\langle \sigma v \rangle_{\chi\chi \longrightarrow Z\gamma} \;=\; 1.26 \times 10^{-26} \;\; \mathrm{cm^3 s^{-1}},$$

Total annihilation cross-section:

$$\langle \sigma v \rangle^{tot}_{\chi\chi} \;=\; 3.2 \times 10^{-24} \;\; \mathrm{cm^3 s^{-1}}$$



Excluded even by the most conservative limits where no gamma-ray background i included

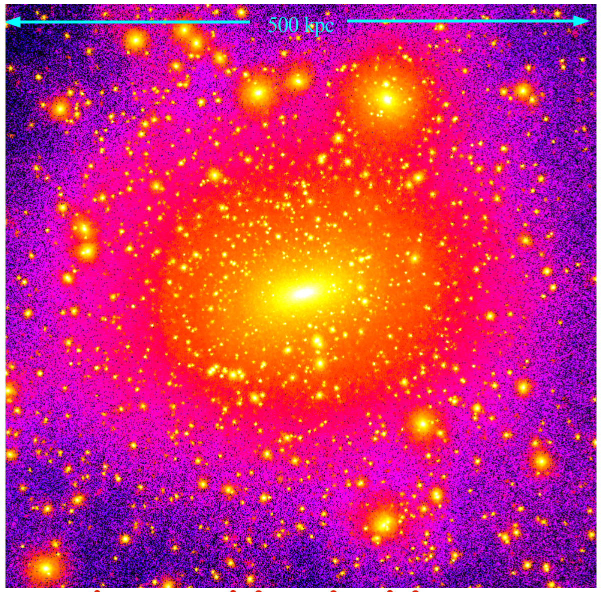


Buchmuller&Garny (1206.7056)

DM subhalos bound in the Milky Way?

I. Cholis, H. Santosa, M. Tavakoli and P. Ullio, arXiv:1303.5775

Simon D.M. White
A MilkyWay like Galaxy with LambaCDM



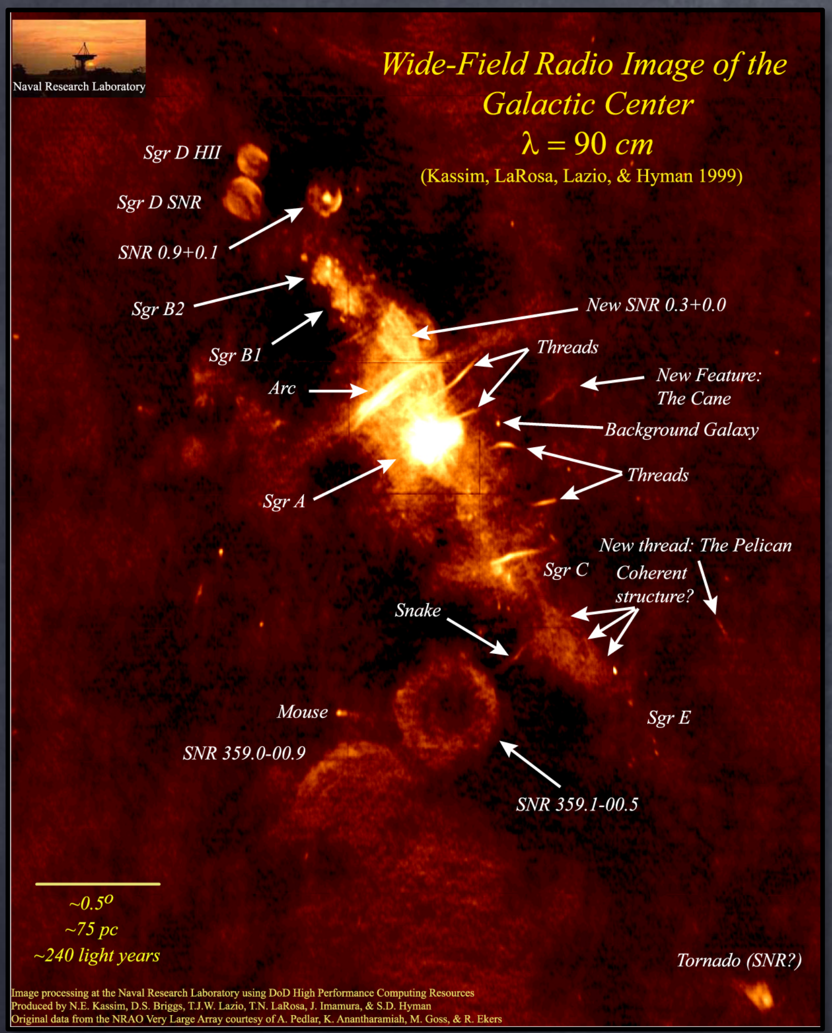
Only for the most optimistic cases of simulation assumptions do we get that DM substructures in the MW can account for the line signal at unknown detected point sources. Yet once extrapolating to smaller mass scales contradiction to existing measurements. We should have detected a line also at high latitudes.

Index "a"	m_{cut} ($M_\odot$)	biased	anti-biased
2.0	1.0×10^{-6}	96	87
2.0	1.0	20.8	20.4
1.9	1.0×10^{-6}	16.3	10.2
1.9	1.0×10^{3}	5.46	3.90
1.9	2.0×10^{4}	4.02	2.99

The only way out suppression by at least a factor of 3 for the DM annihilation cross-section, OR suppression of DMA at smaller scales (particle physics side or by suppressing their population).

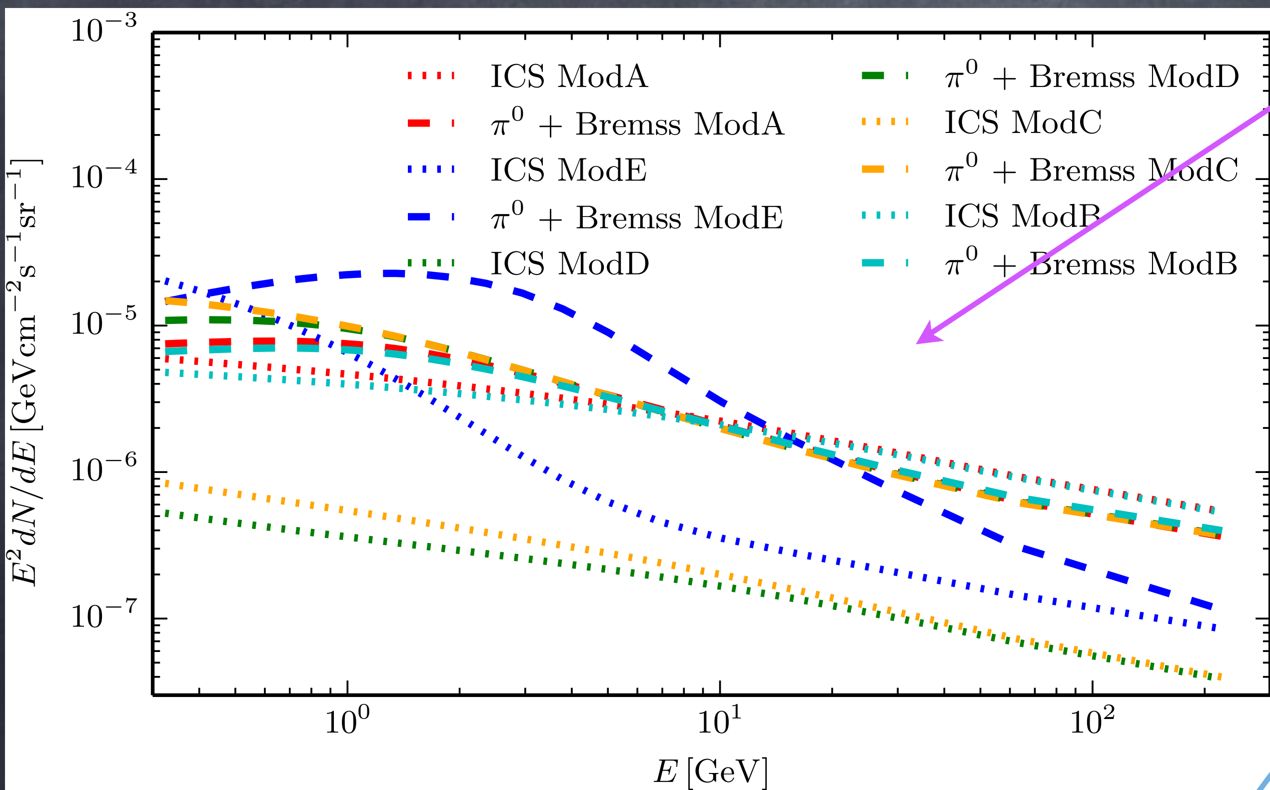
The suppression of DMA at the outer part of the Galaxy is derived both from template analysis/ flux analysis/ spectral analysis.

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

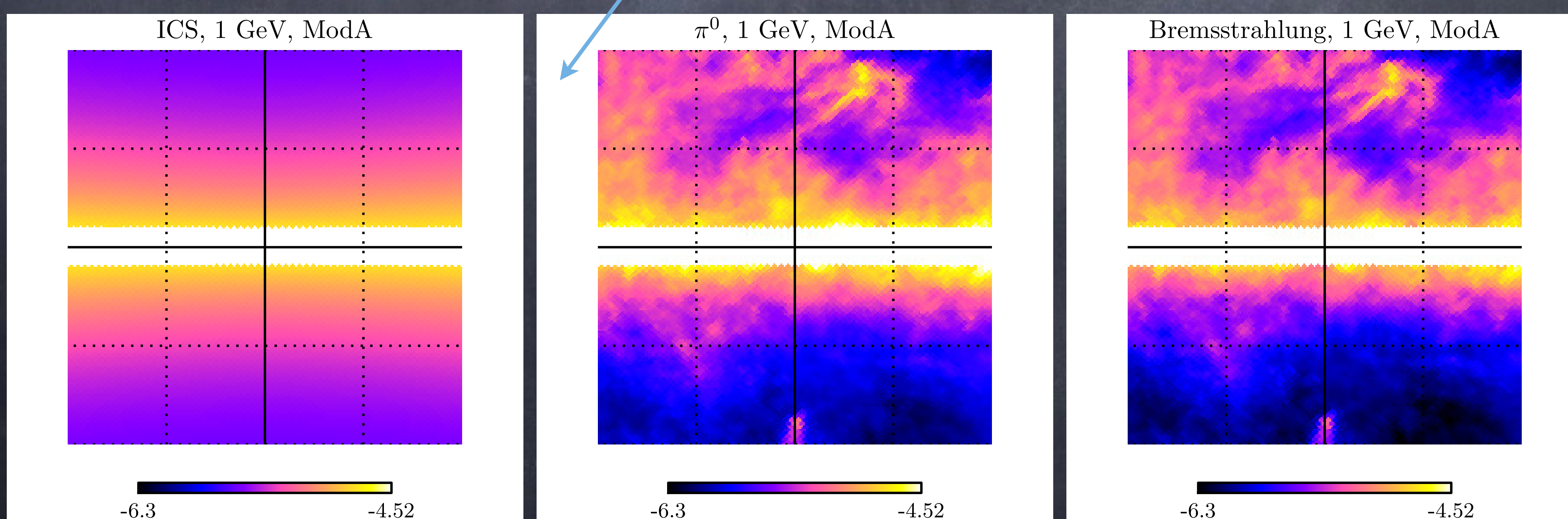
On the gamma-ray backgrounds ALONG THE LINE OF SIGHT towards the inner galaxy



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 (fas/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)

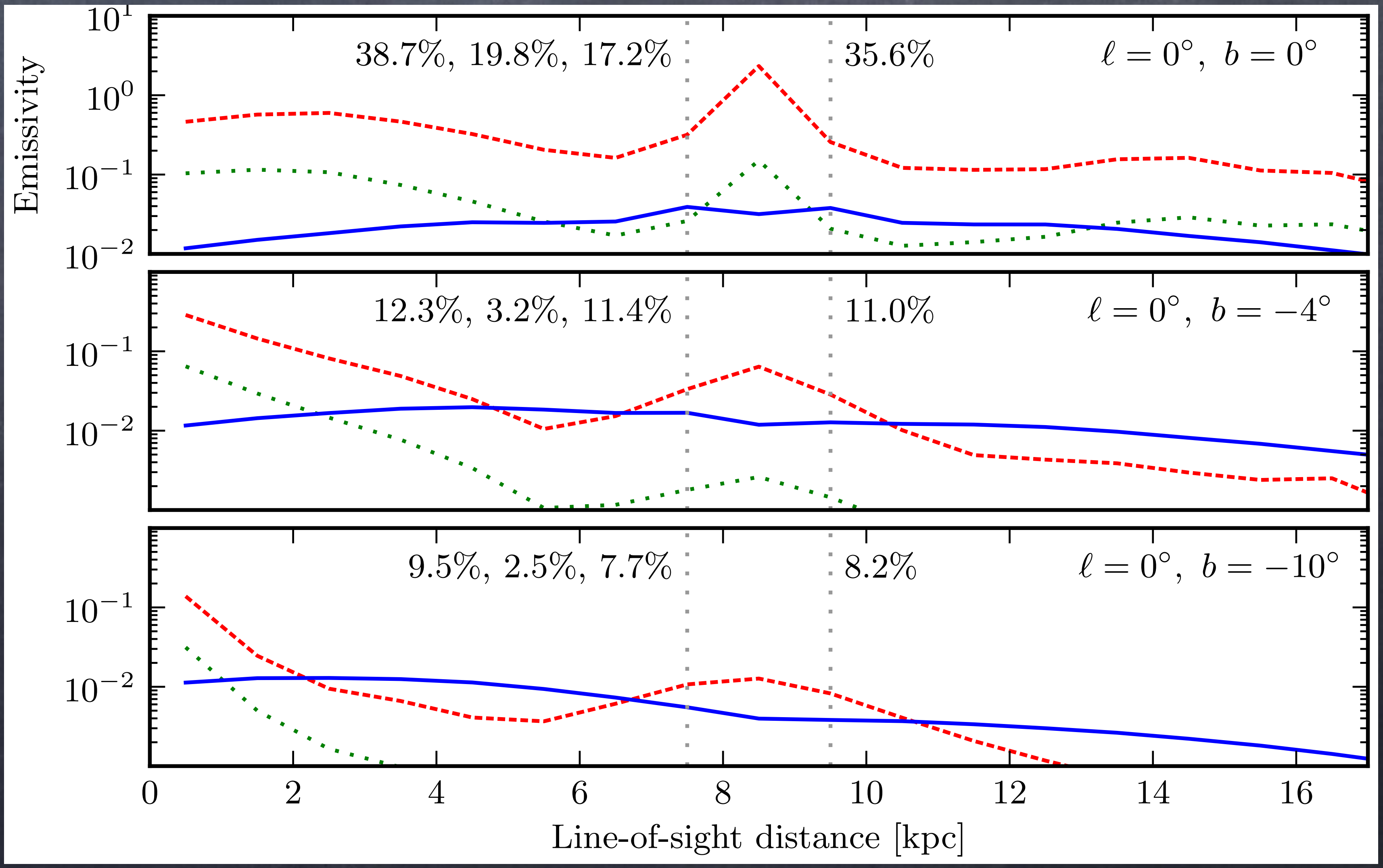


- Extragalactic point sources can either be resolved or unresolved extragalactic sources (AGNs, Star forming or starburst galaxies etc). But are isotropic and thus can not contribute significantly to an excess in the inner galaxy. Misidentified GeV scale CRs are also isotropic due to diffusion.
- Galactic point sources that can give strong gamma-ray signals in the GeV range include SNRs in the inner part of the Galaxy and pulsars (please ask me later).

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

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.



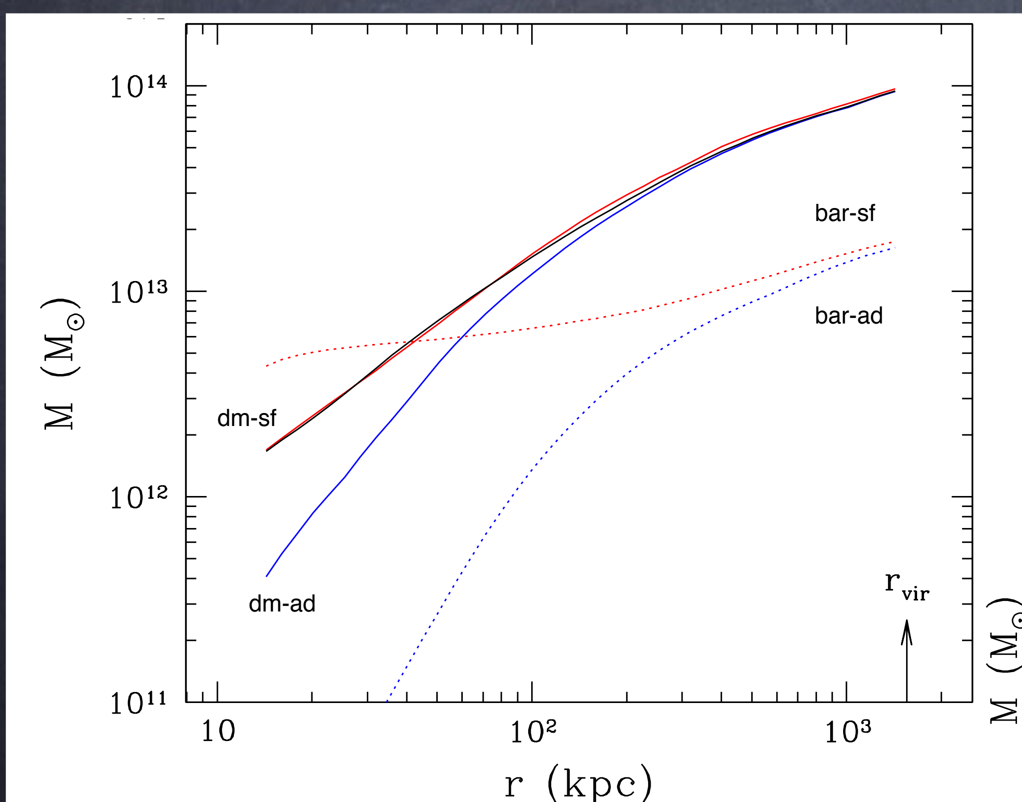
On the DM distribution in the inner galaxy

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.

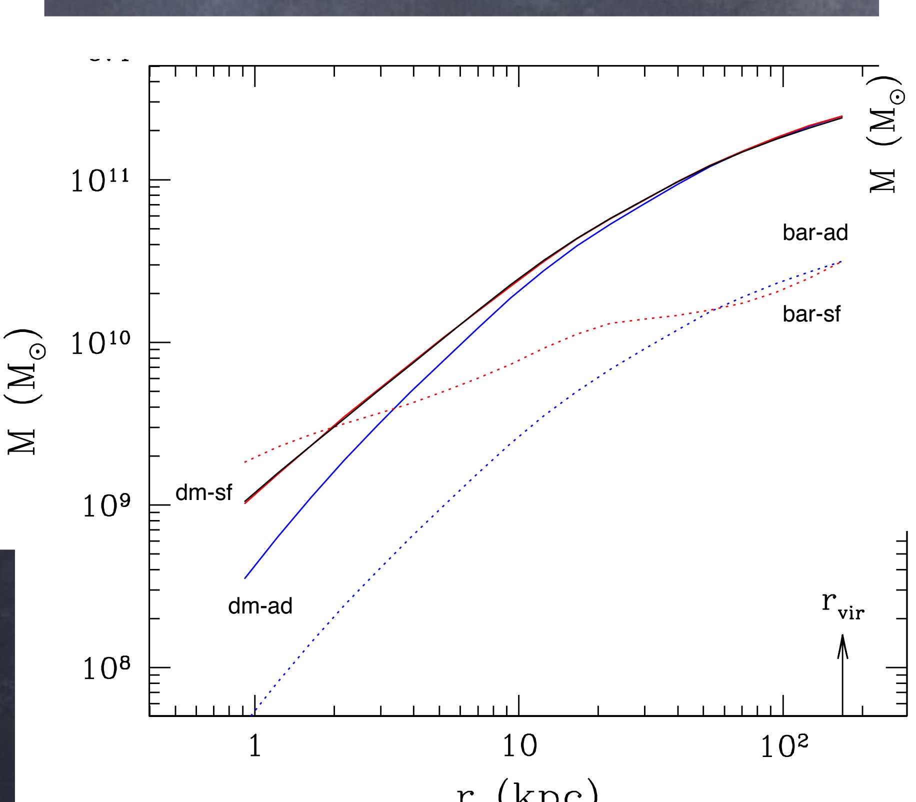
Assuming NFW-like profile with some uncertainty in the inner slope is the way to treat any search for a signal of DM from the inner galaxy.

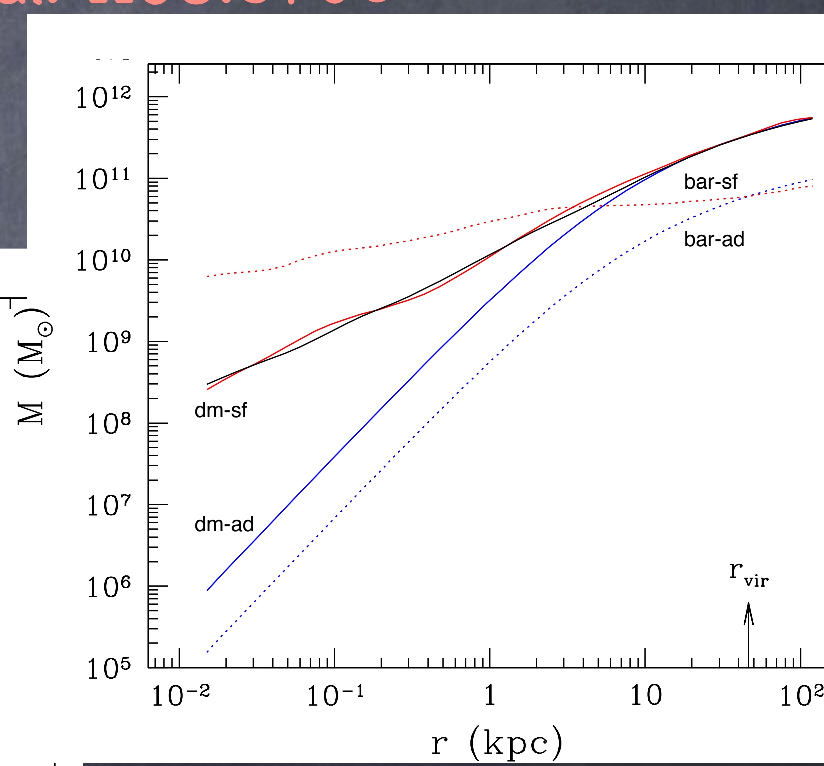
Gnedin et al. 1108.5736



Nagai 2006 ApJ 650, 538

Gottglober et al. 1005.2687



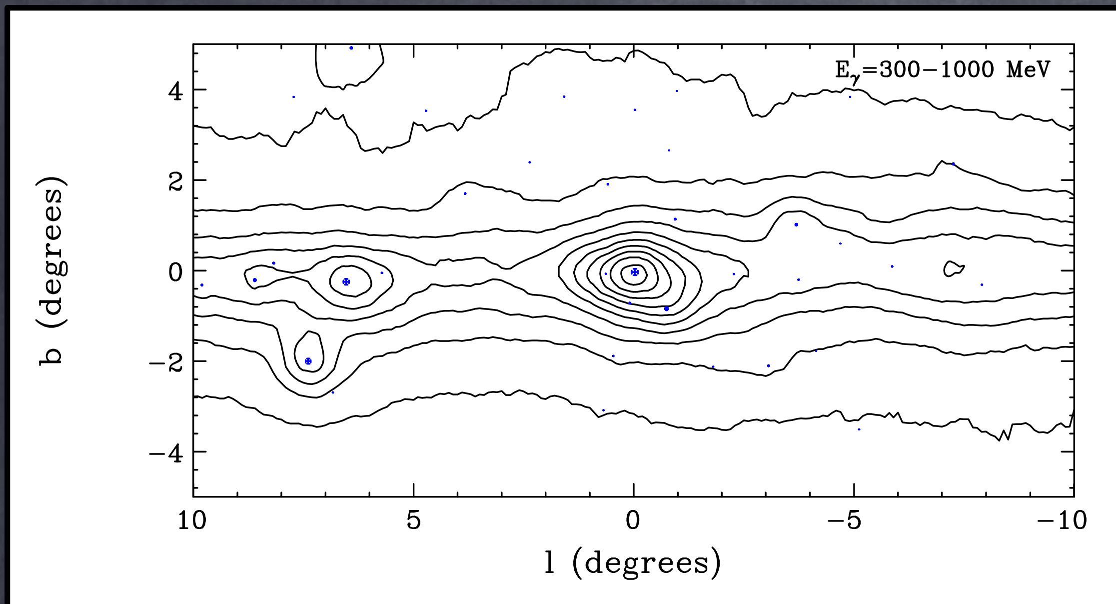


Levine at al. 2008 ApJ 678, 154

Looking for excesses in the inner galaxy

Smoothed Raw gamma-ray map

Hooper&Linden 1110.0006



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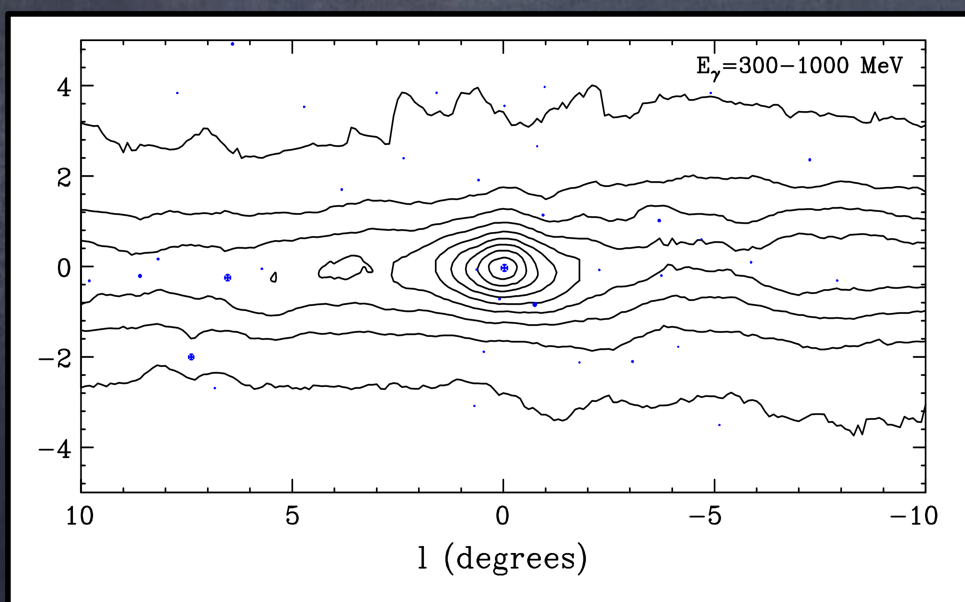
POINT SOURCES (2yr catalogue)

−



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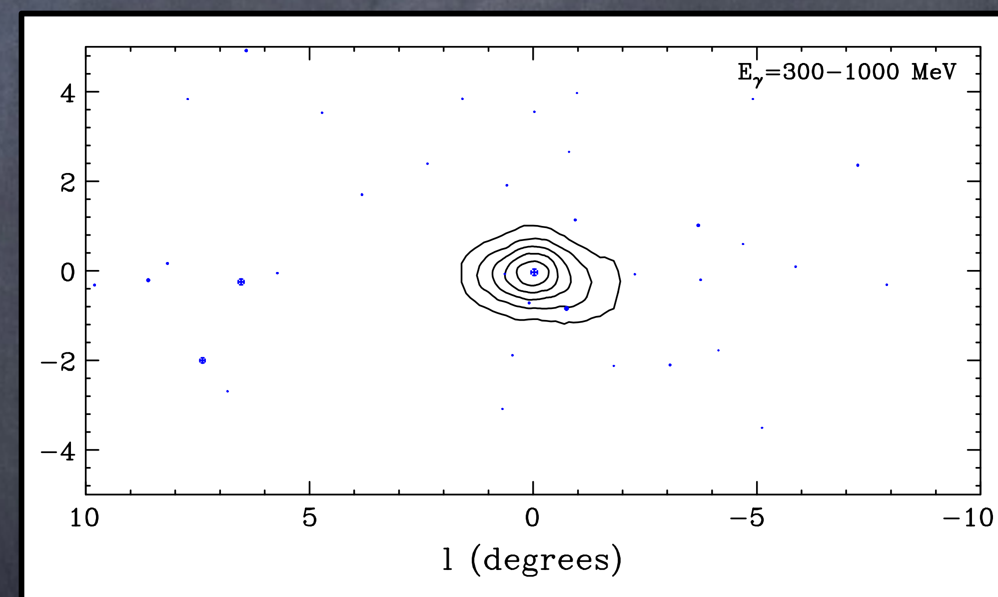
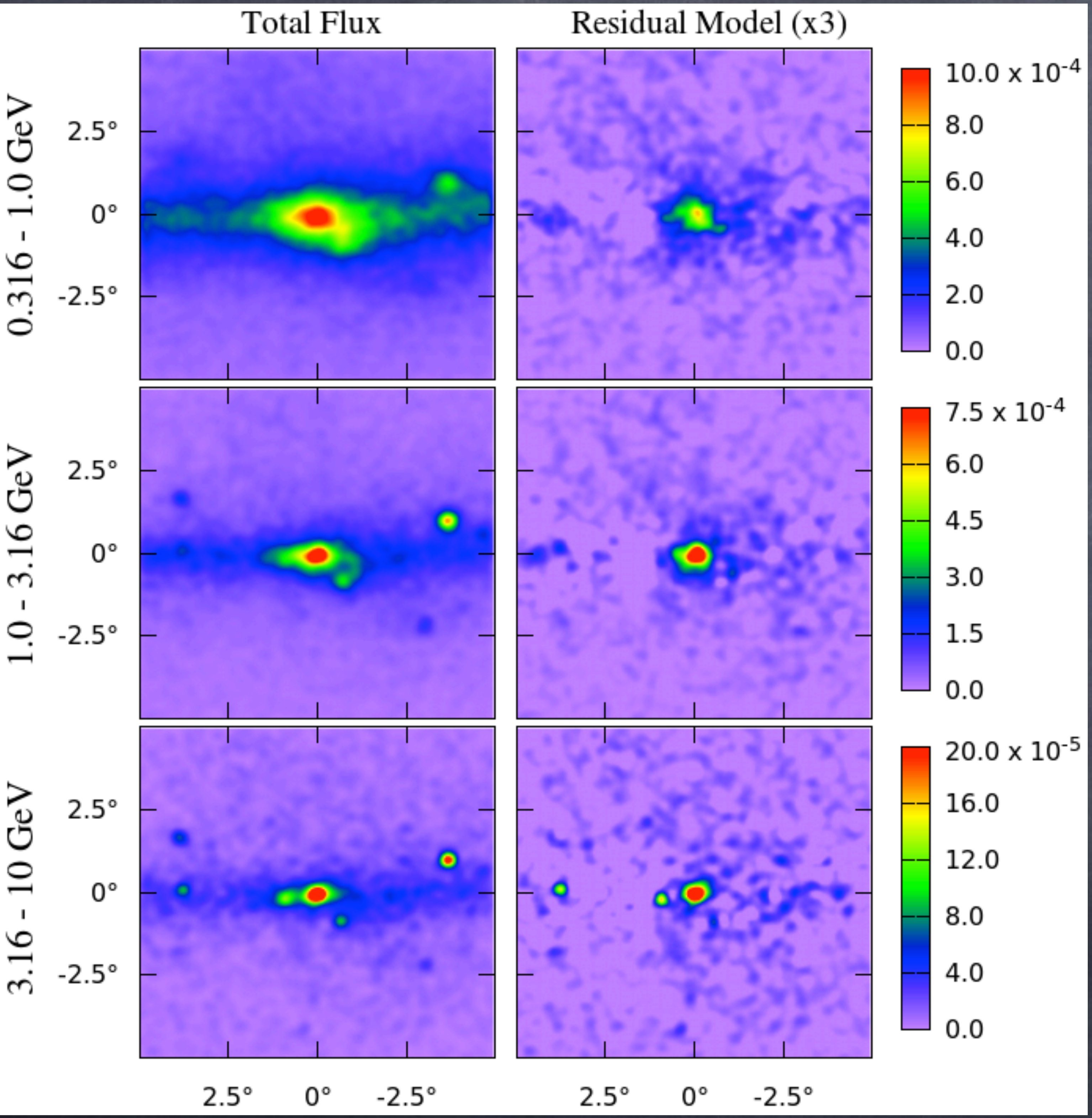


Model for Galactic Diffuse Emission

Excess Diffuse Emission

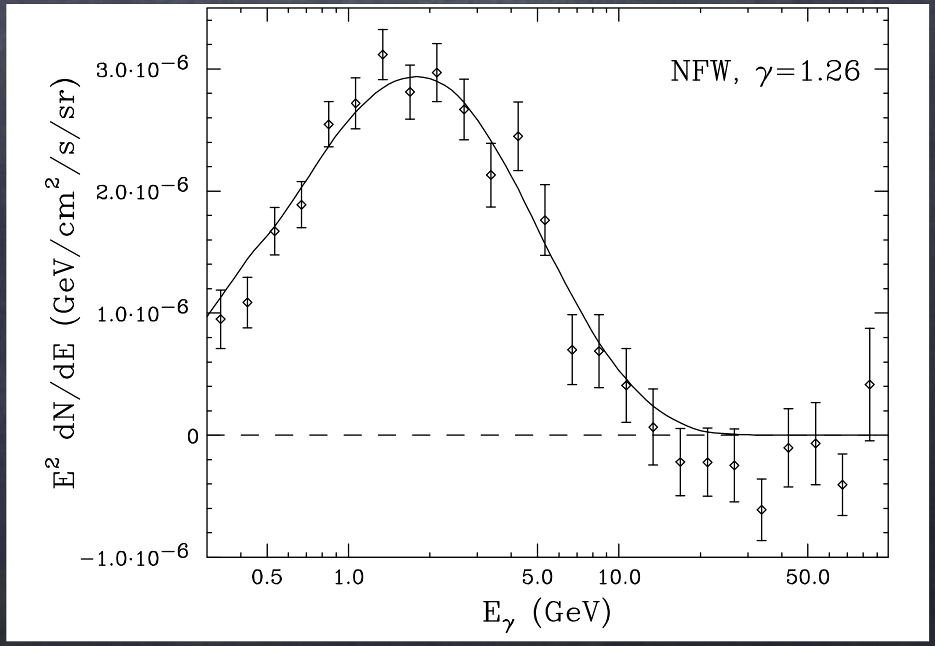
Similar results to earlier Hooper & Goodenough papers in 0910.2998 and 1010.2752 and later from: Abazajian & Kaplinghat (1207.6047), Gordon & Macias (1306.5725)

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

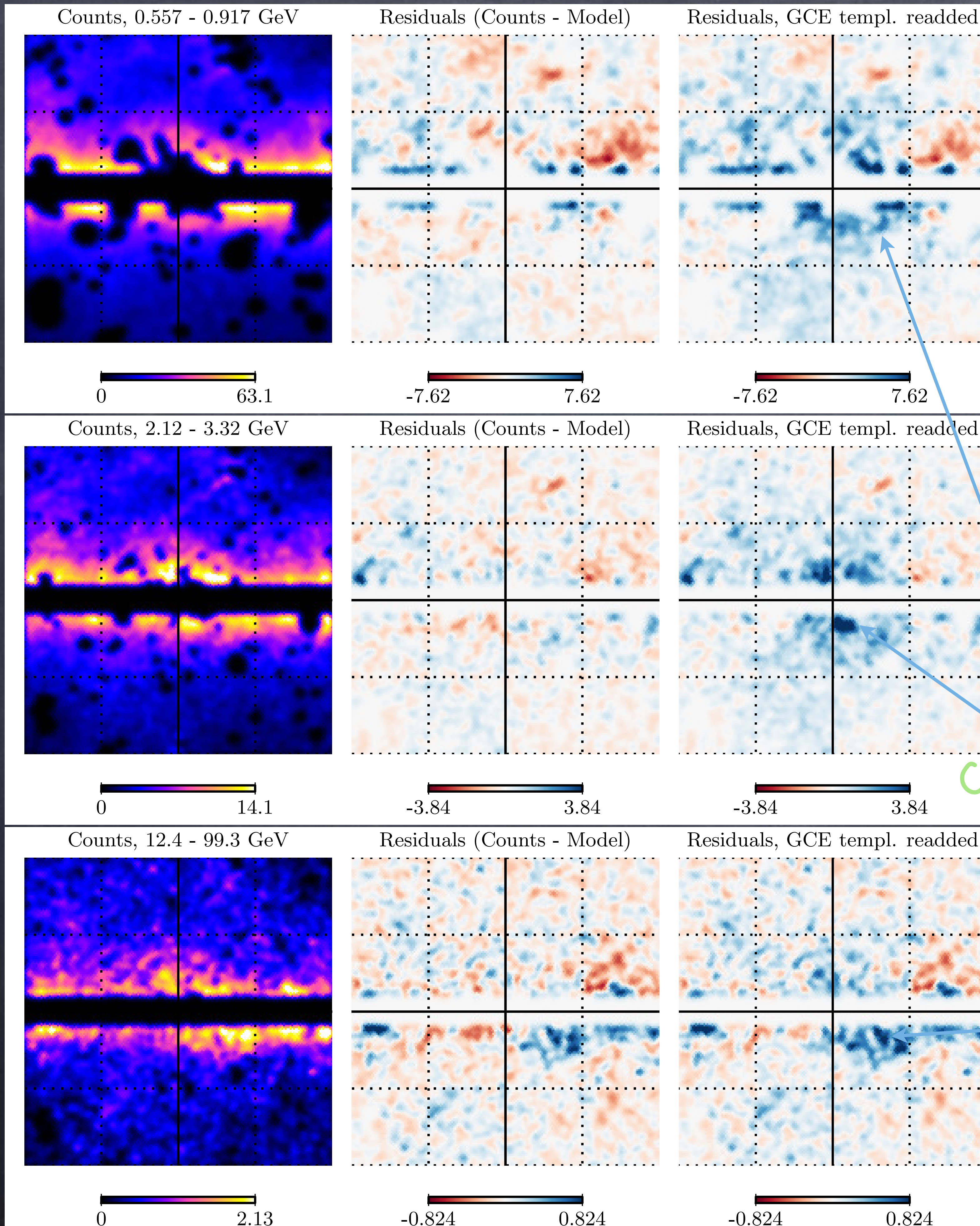
- A clear excess emission in the galactic center emerges
- 90% of the total emission in the inner few degrees is removed
- Residuals not related to the galactic center (GC) are up to ~5% as bright as the GC residual
- Excess emission cuts-off at ~10 GeV (is in some dis-agreement with later findings)



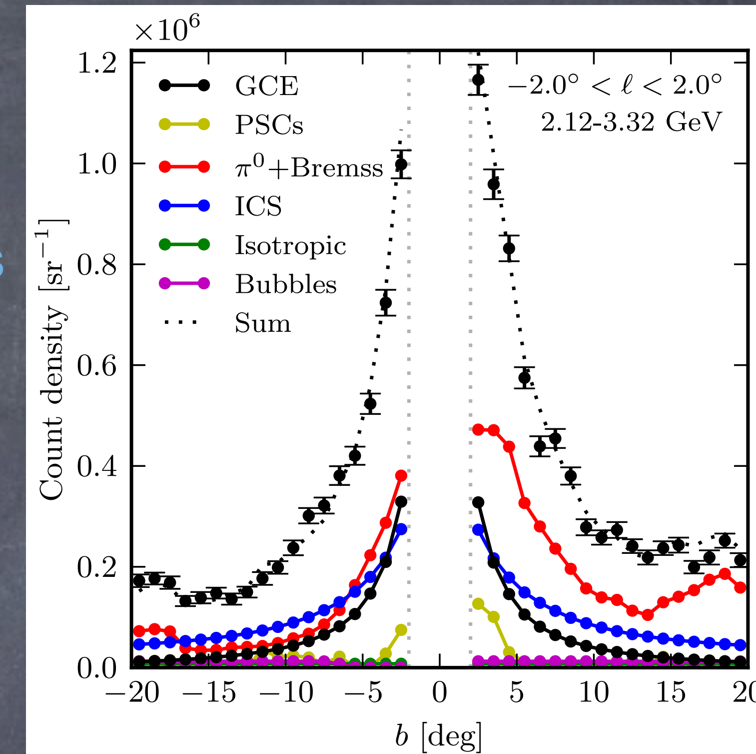
Going to High Latitudes

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 winds outflows or magnetic fields causing anisotropic and preferential diffusion).



40 degrees in latitude



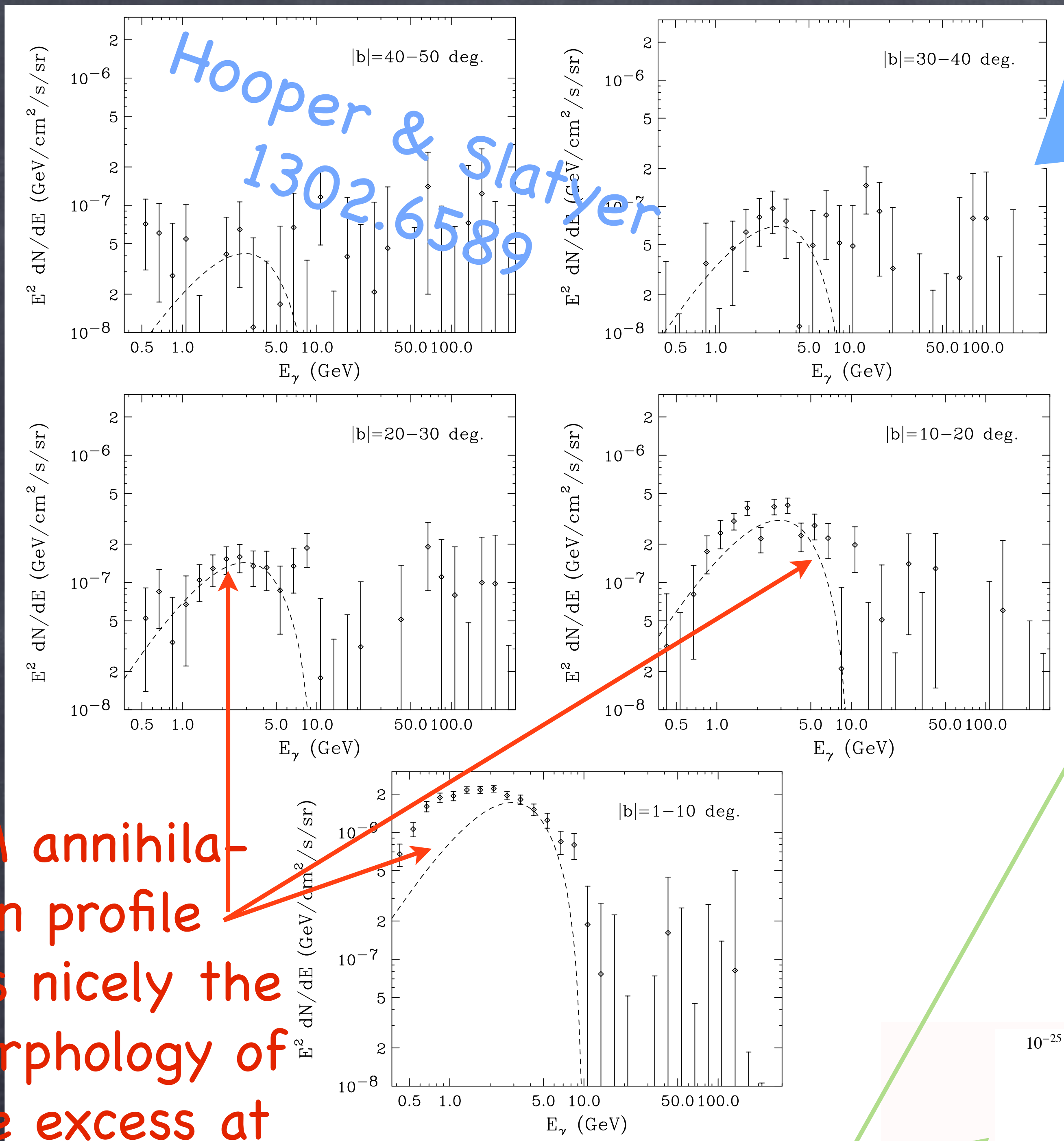
Calore, Cholis, Weniger, 2014

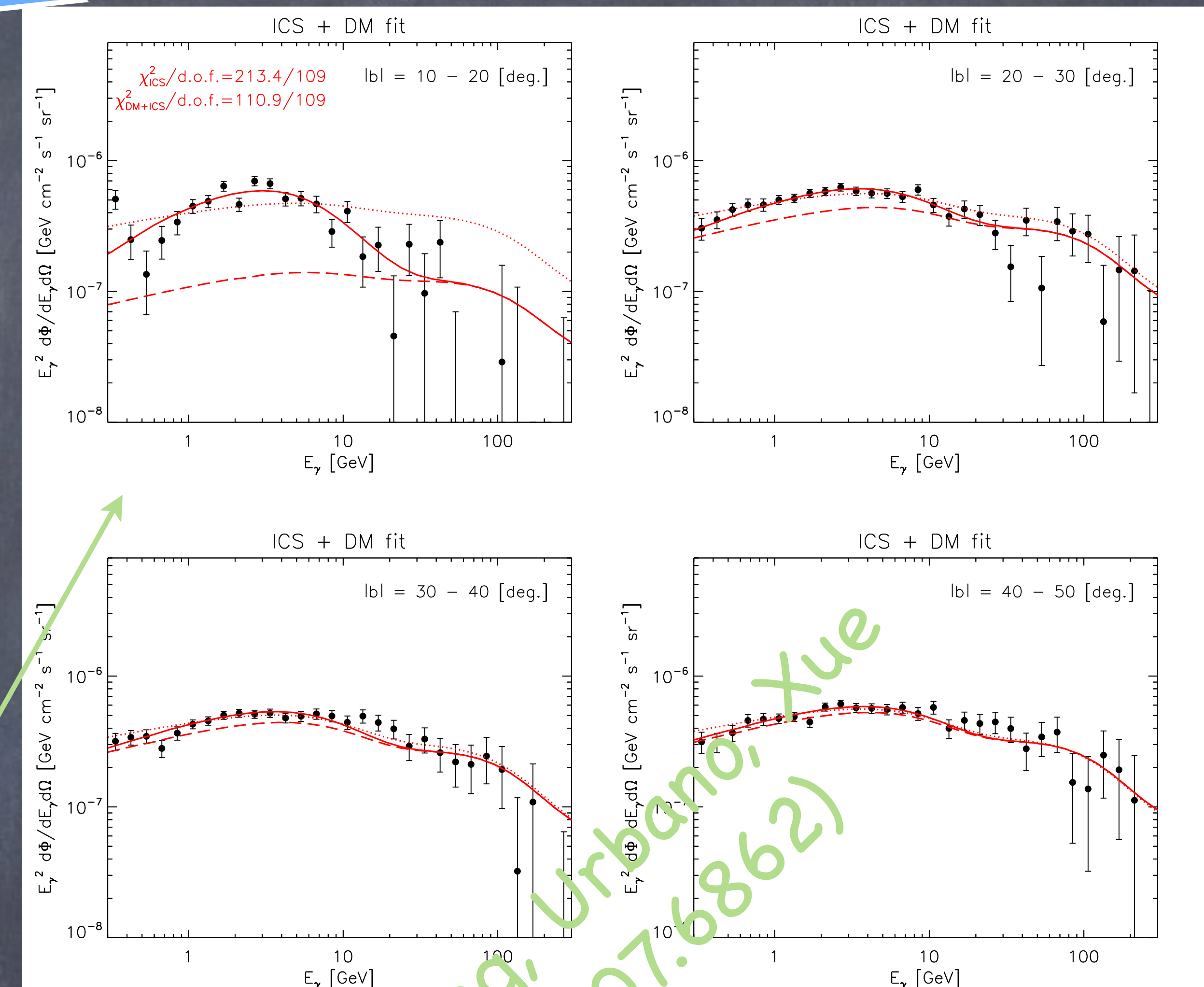
Excess emission towards the GC that extends up to possibly ~100 GeV and certainly above 10 GeV

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

Residuals in different parts of the galactic sky

Hooper & Slatyer 1302.6589





DM annihilation profile fits nicely the morphology of the excess at high latitudes

Huang, Urbano, Xue (1307.6862)

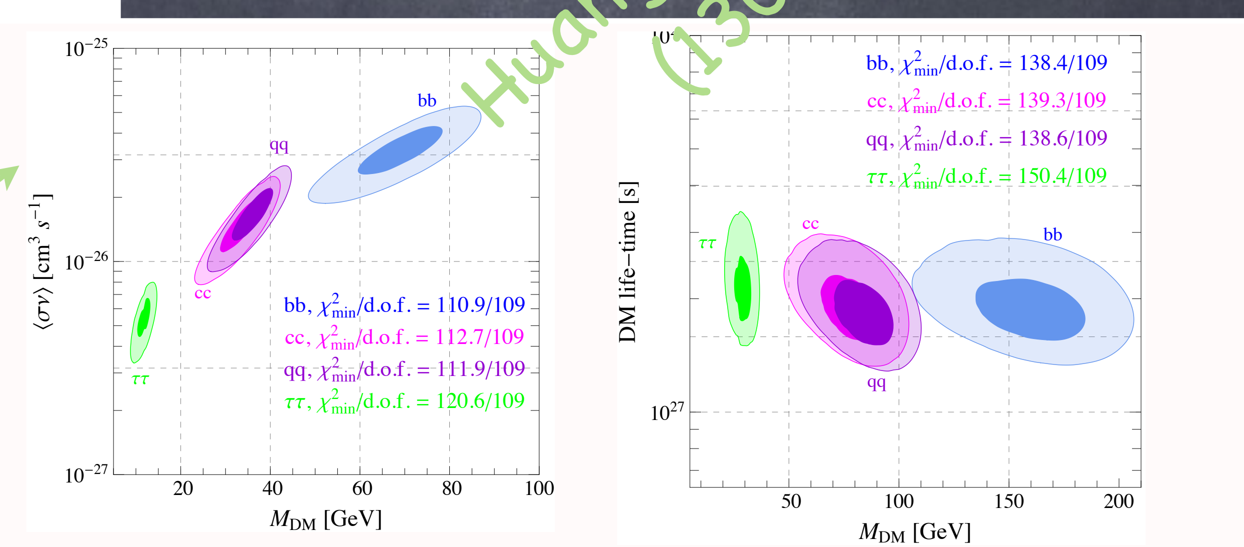


Figure 9: *Confidence regions (99% C.L. and 68% C.L.) for the annihilating (left panel) and decaying (right panel) DM component in the analysis of the Fermi bubbles spectrum (see text for details).*

Similar results at high latitudes from independent group

Important Questions regarding the Robustness of the DM-like signal

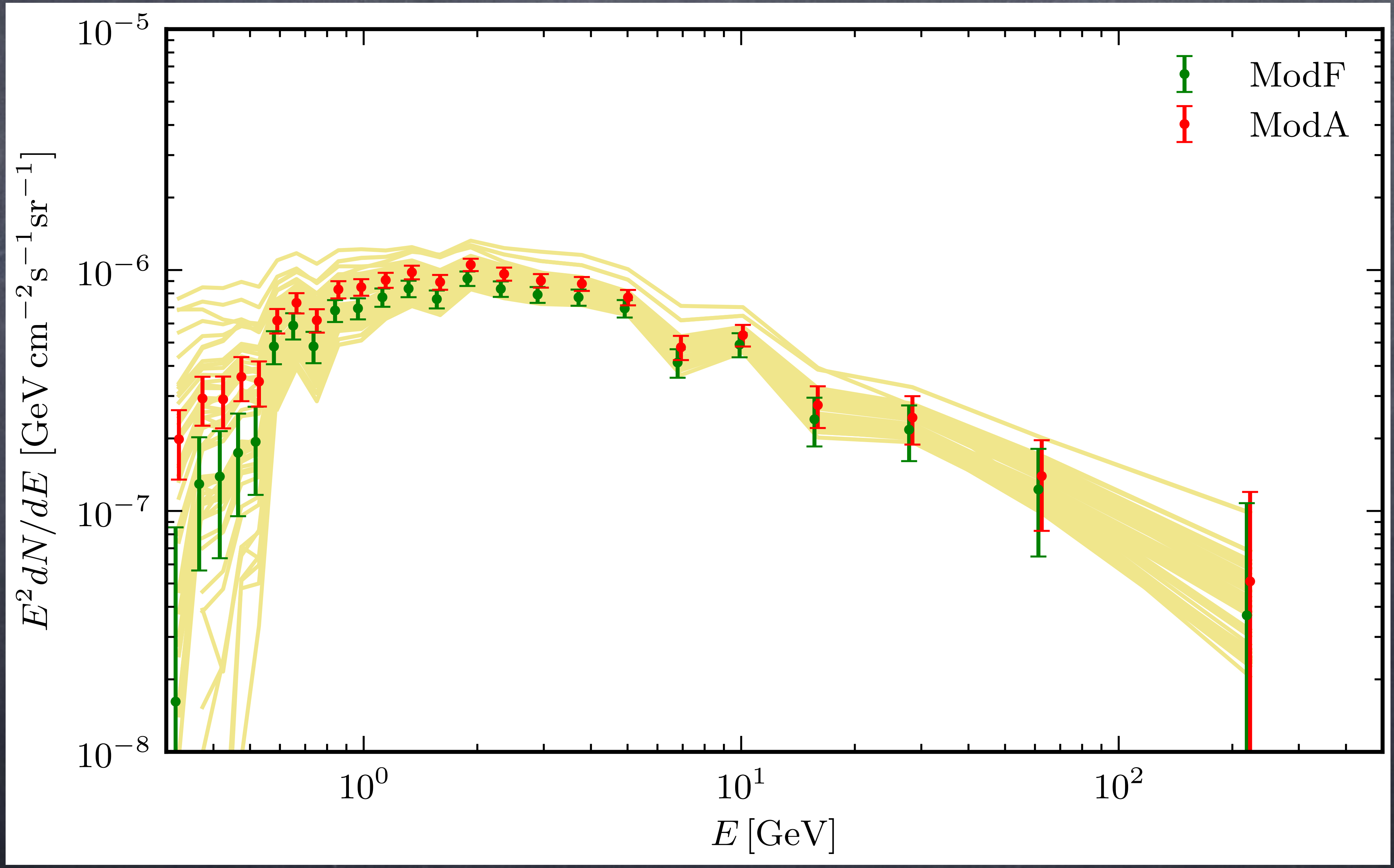
- How well have we probed the relevant uncertainties? Are the different methods used to probe the excess signal in the inner few degrees and at higher latitudes DIFFERENT/ORTHOGONAL ENOUGH?
- How well do we understand the diffusion/propagation of CRs in the inner part?
- Can we build up a new distribution 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? (see later discussion)

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).

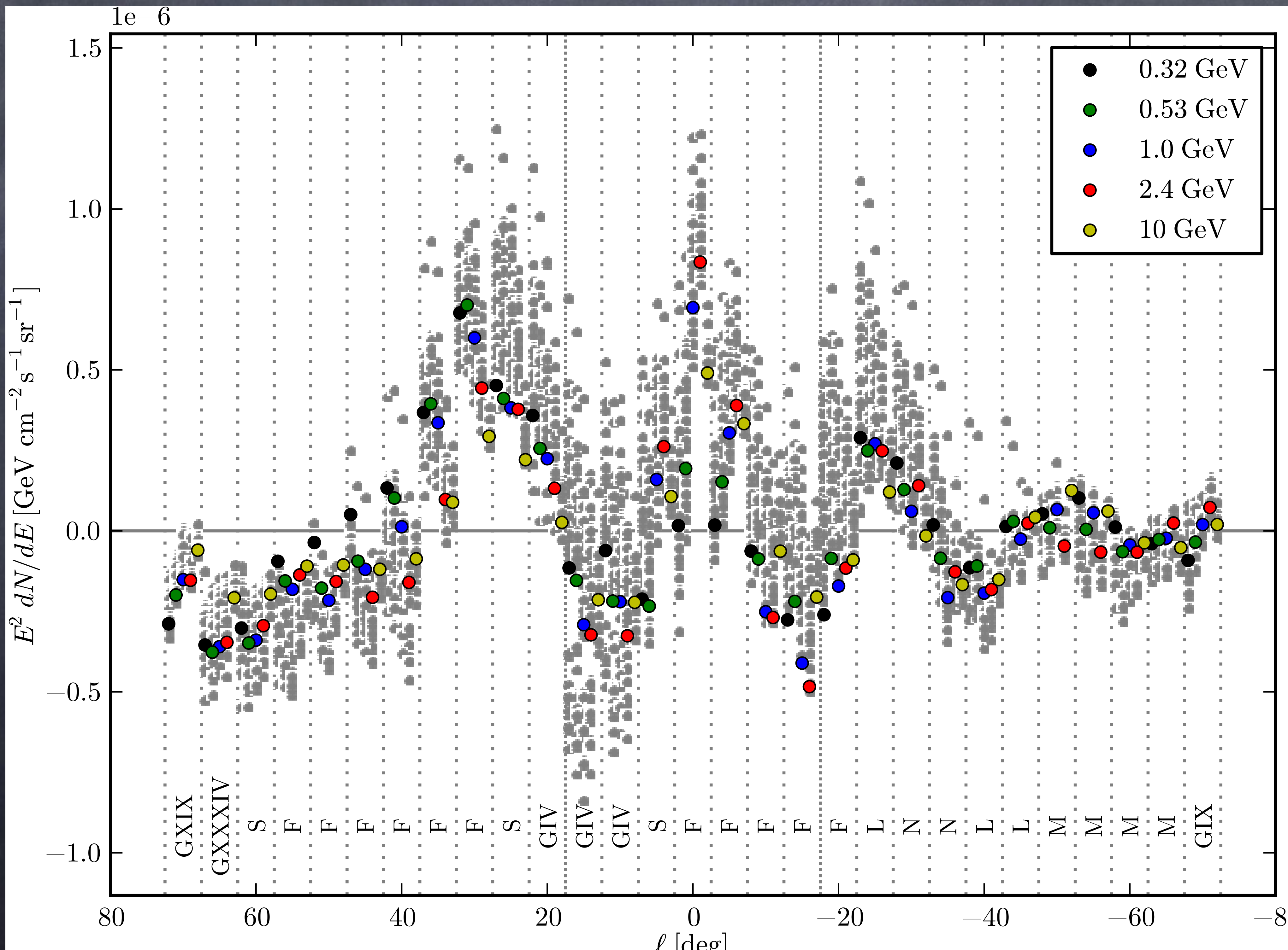
We used models from the existing literature and created our own (60 models shown in our paper).

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



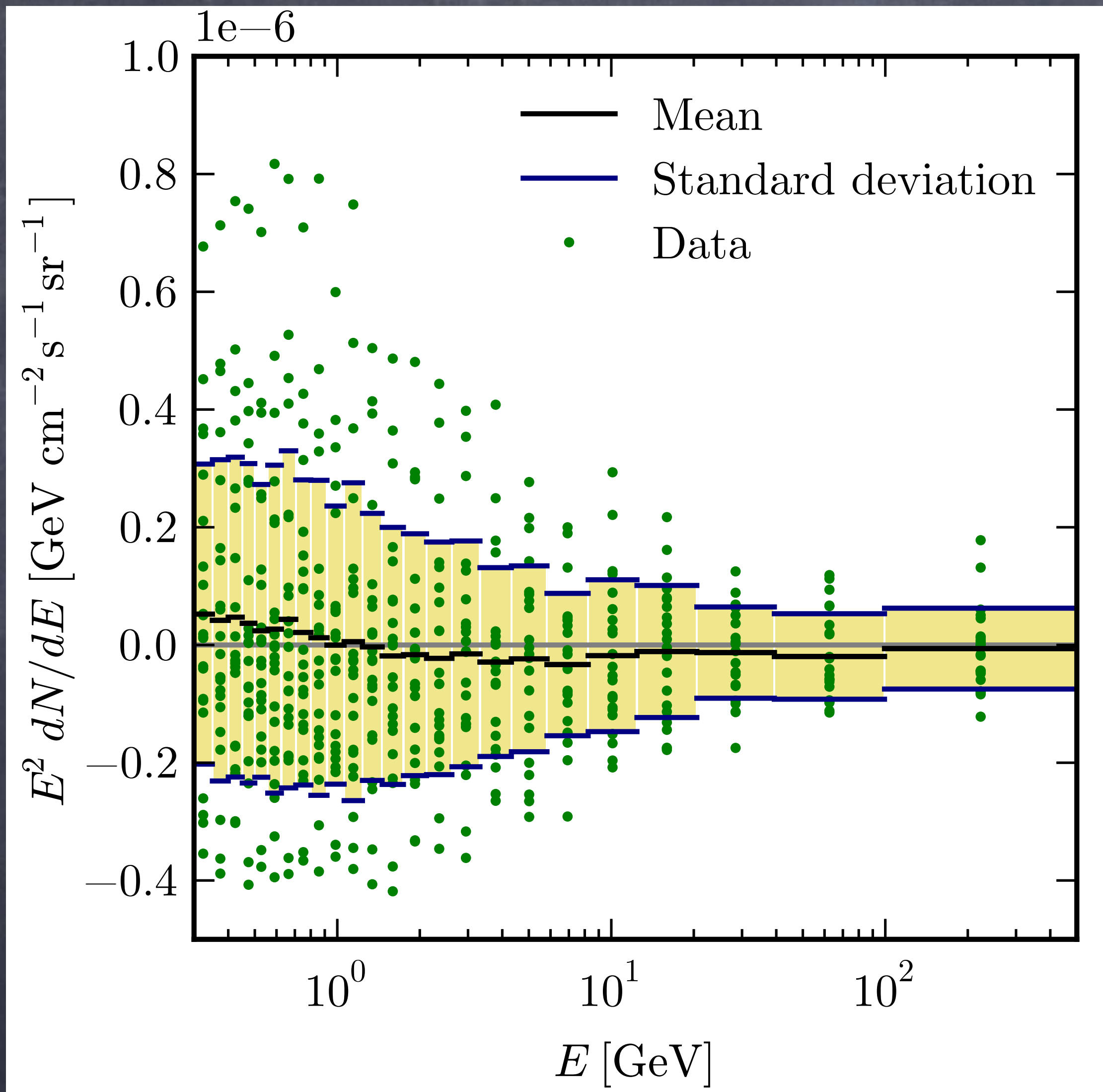
Calore, Cholis, Weniger, 2014

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

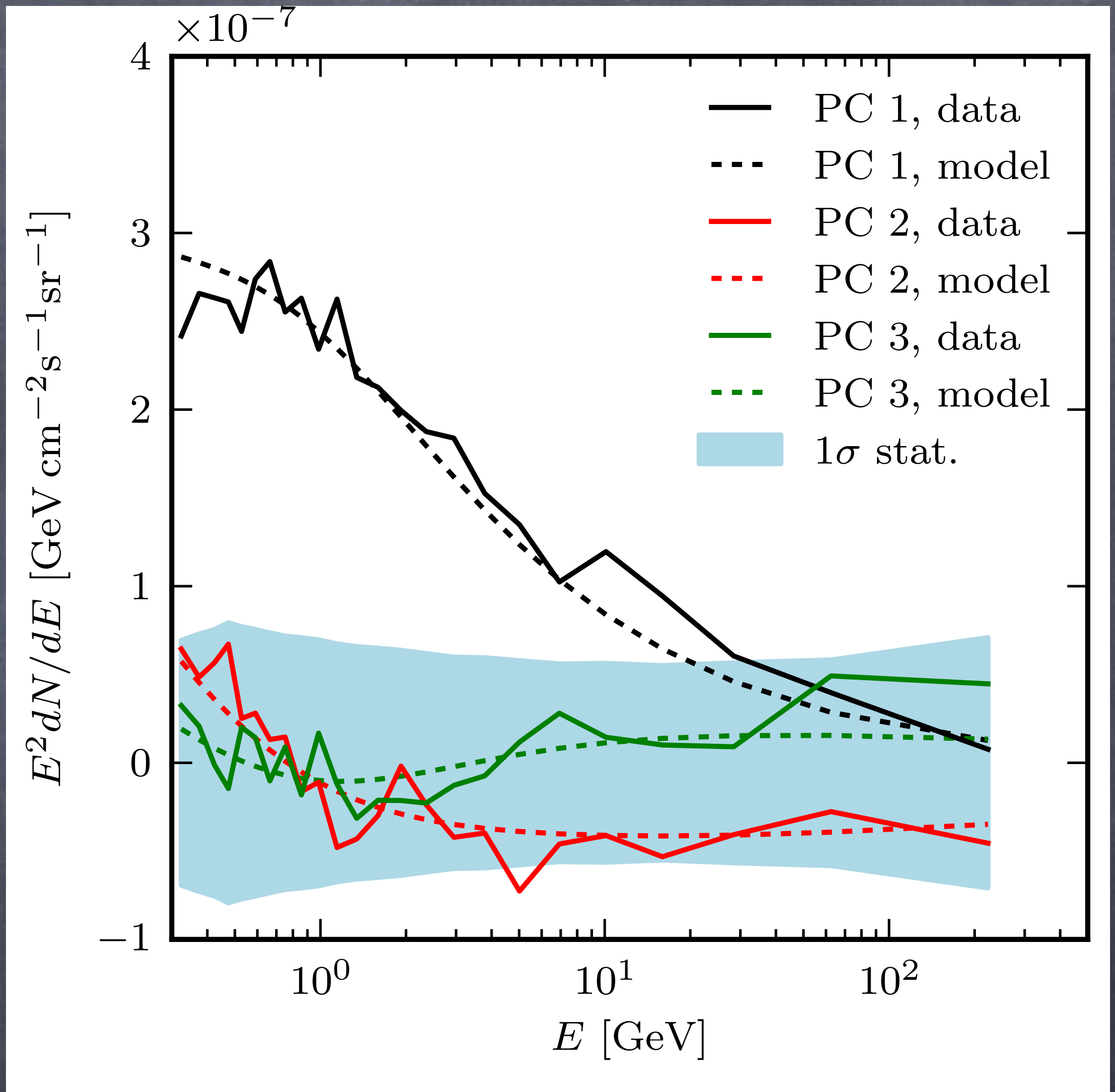


Calore, Cholis, Weniger, 2014

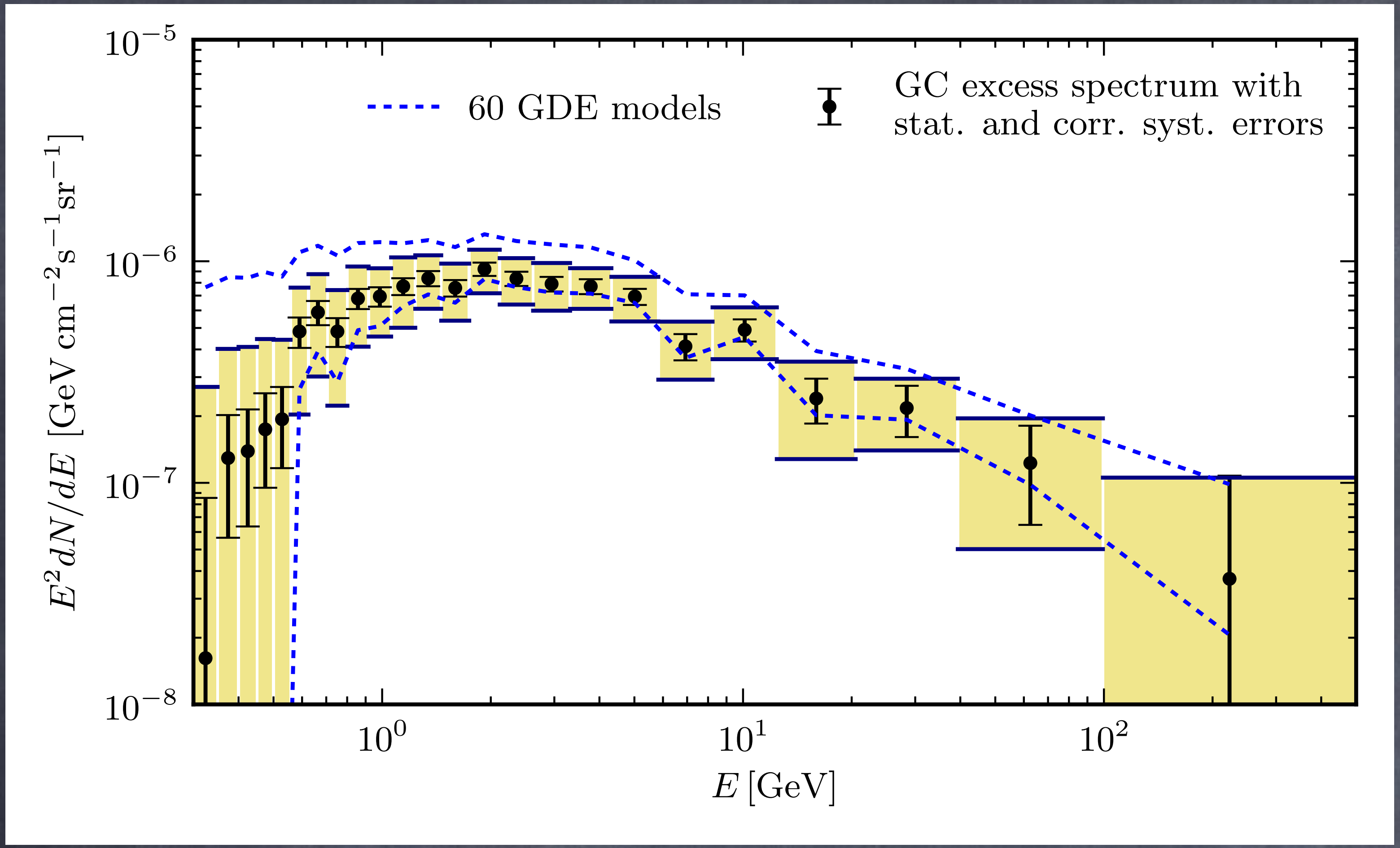
One can then calculate a covariance matrix which allows to properly quantify the correlated systematic errors (associated to lack of better understanding of the galactic diffuse emission)which are bigger than the statistical (associated to number of gamma-ray events):



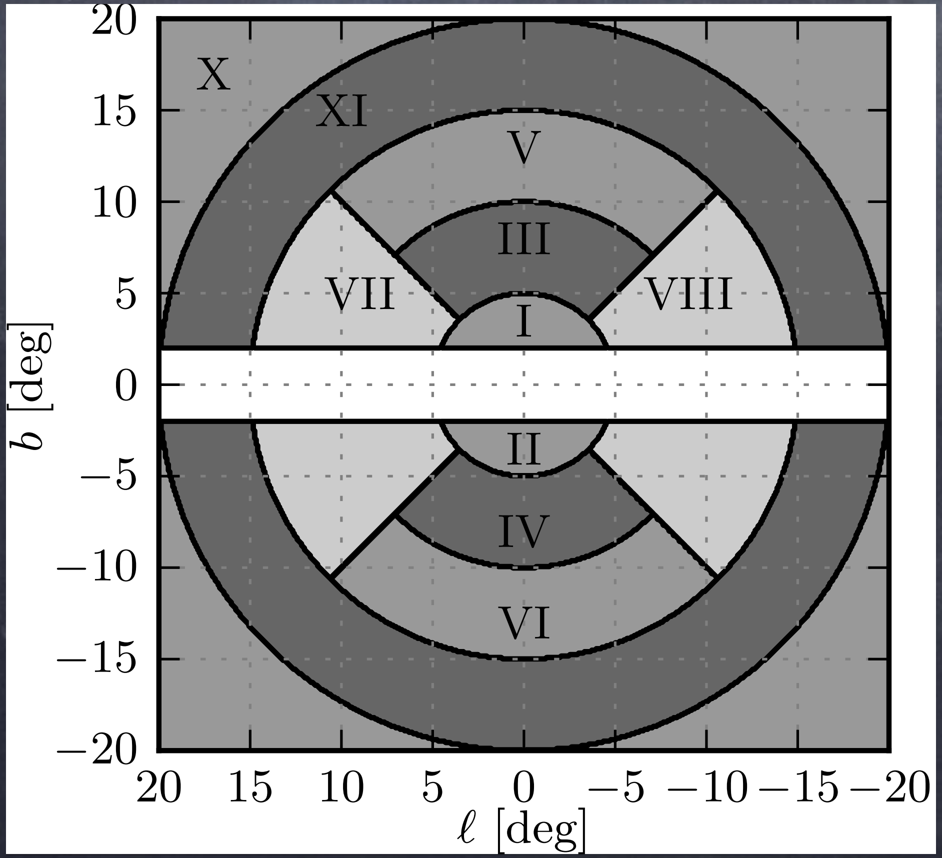
Residuals of the transported GCE template. No evident bias is seen. Green points show all 22 regions tested.

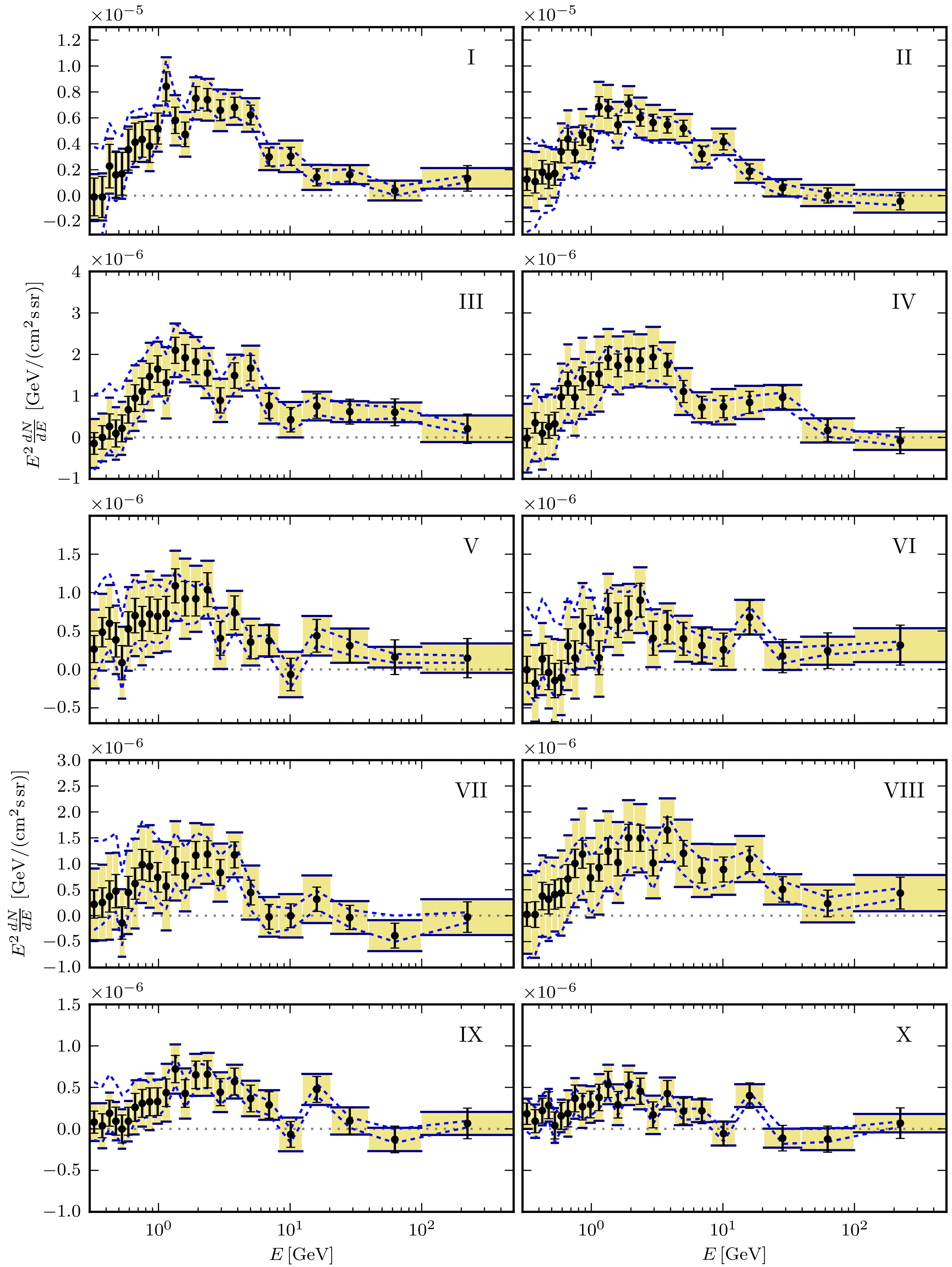


Decomposition of the covariance matrix in terms of principal comp. Only the first 3 are important. Only the 1st is above the statistical errors. The observed variations can be traced back to uncertainties in the pi0 and ICS slopes and amplitudes.



One can repeat the same exercise to smaller regions:

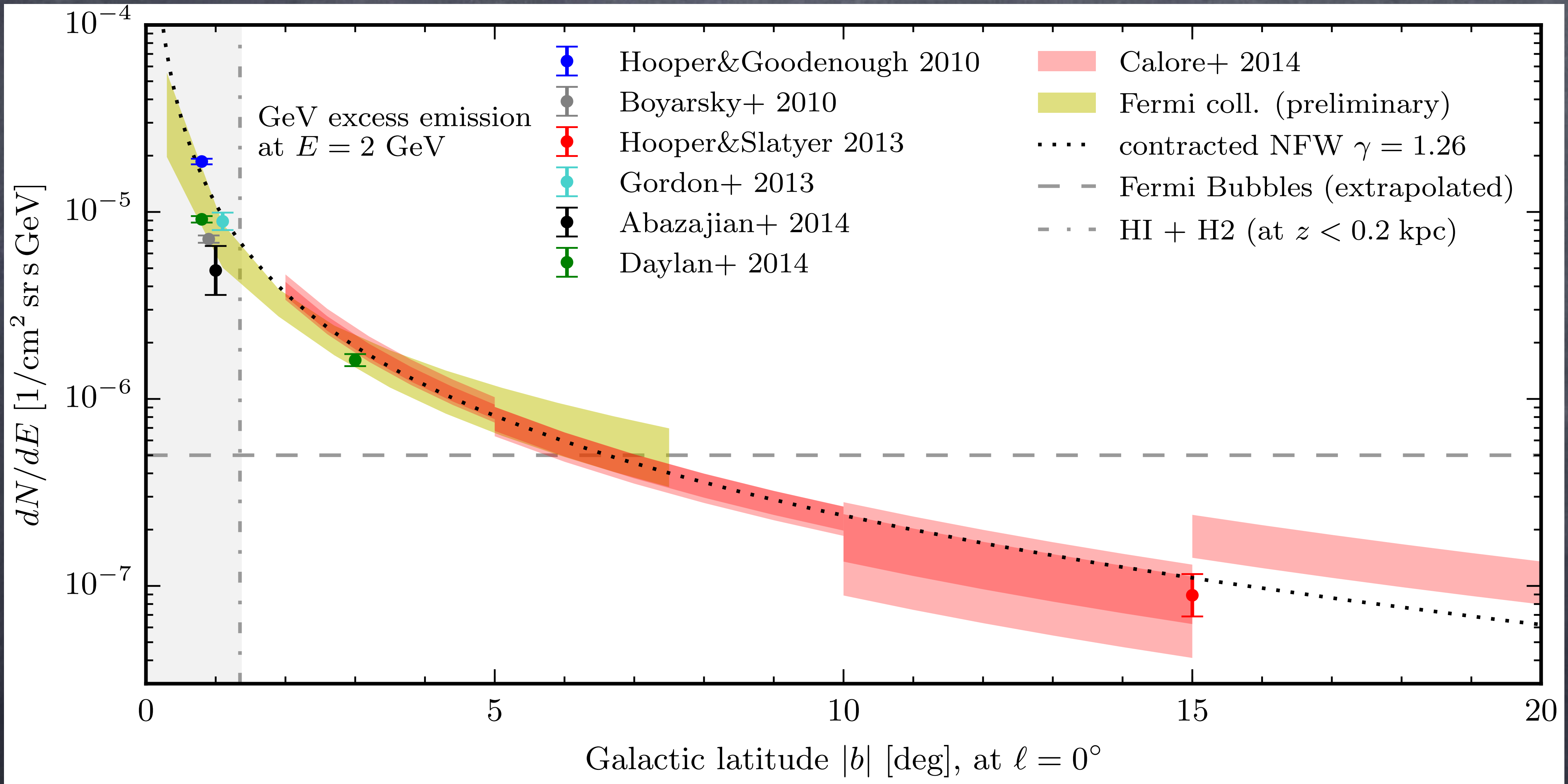




I
II
III
IV
V
VI
VII
VIII
IX
X
$\times 10^{-5}$
$\times 10^{-6}$
$E^2 \frac{dN}{dE}$ [GeV/(cm^2 s sr)]
E [GeV]

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



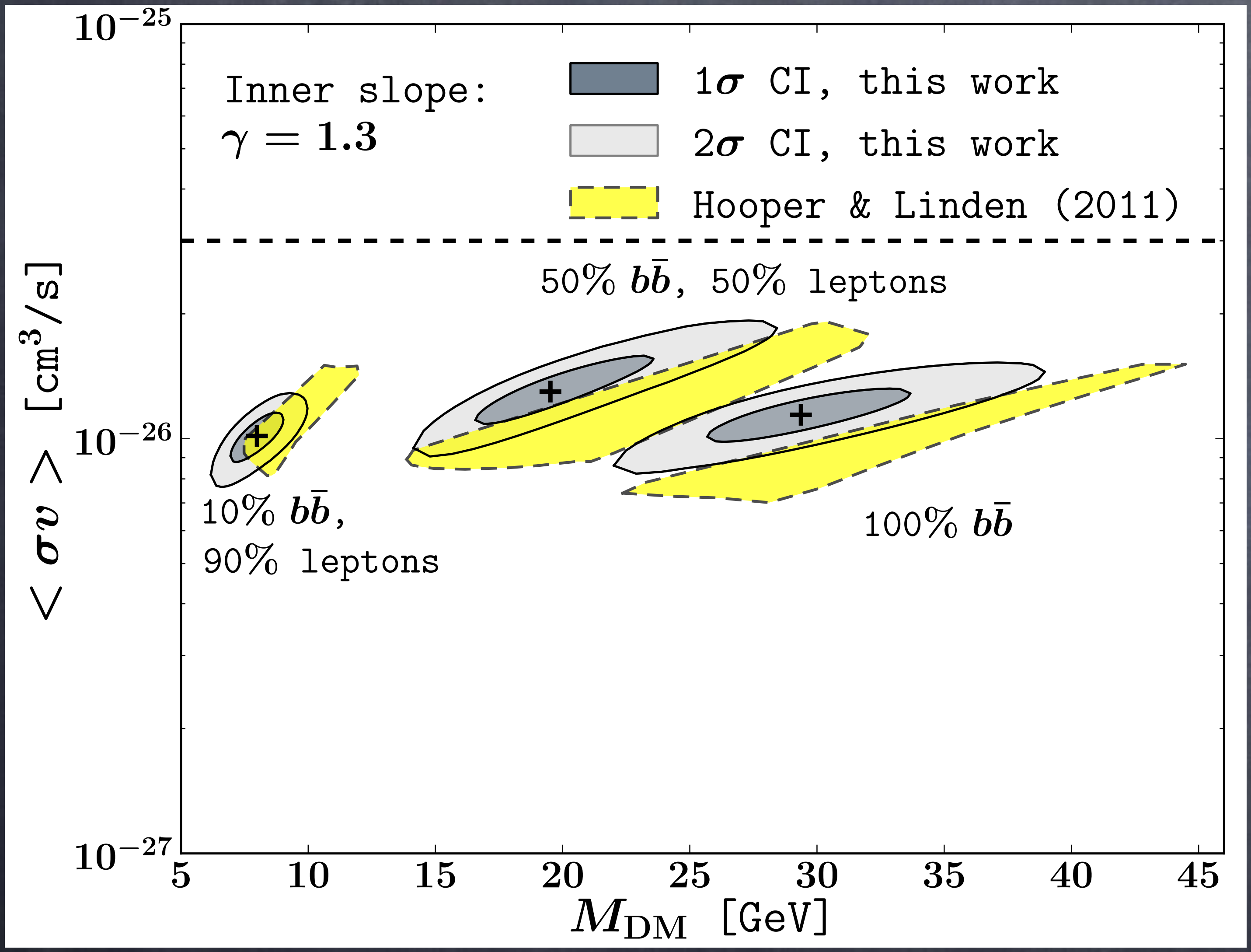
The excess signals from different analyses, agree within a factor of less than 2 in terms of total emission (that is wether it is DM or MSPs or CR outbursts).

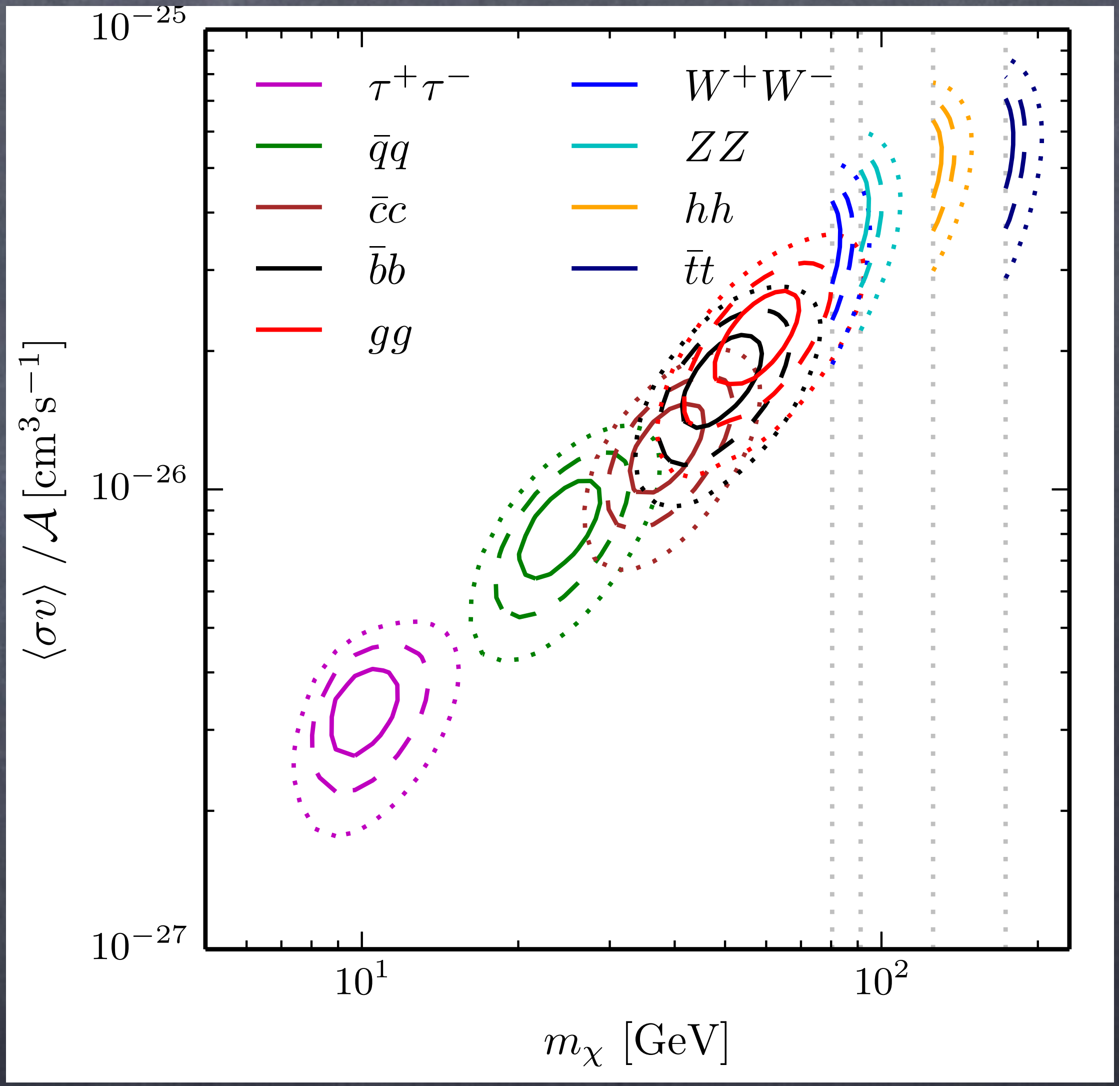
If this is a DM annihilation signal:

The range of possibilities (phenomenologically) becomes much larger. Because of the correlated errors.

BEFORE:

AFTER:

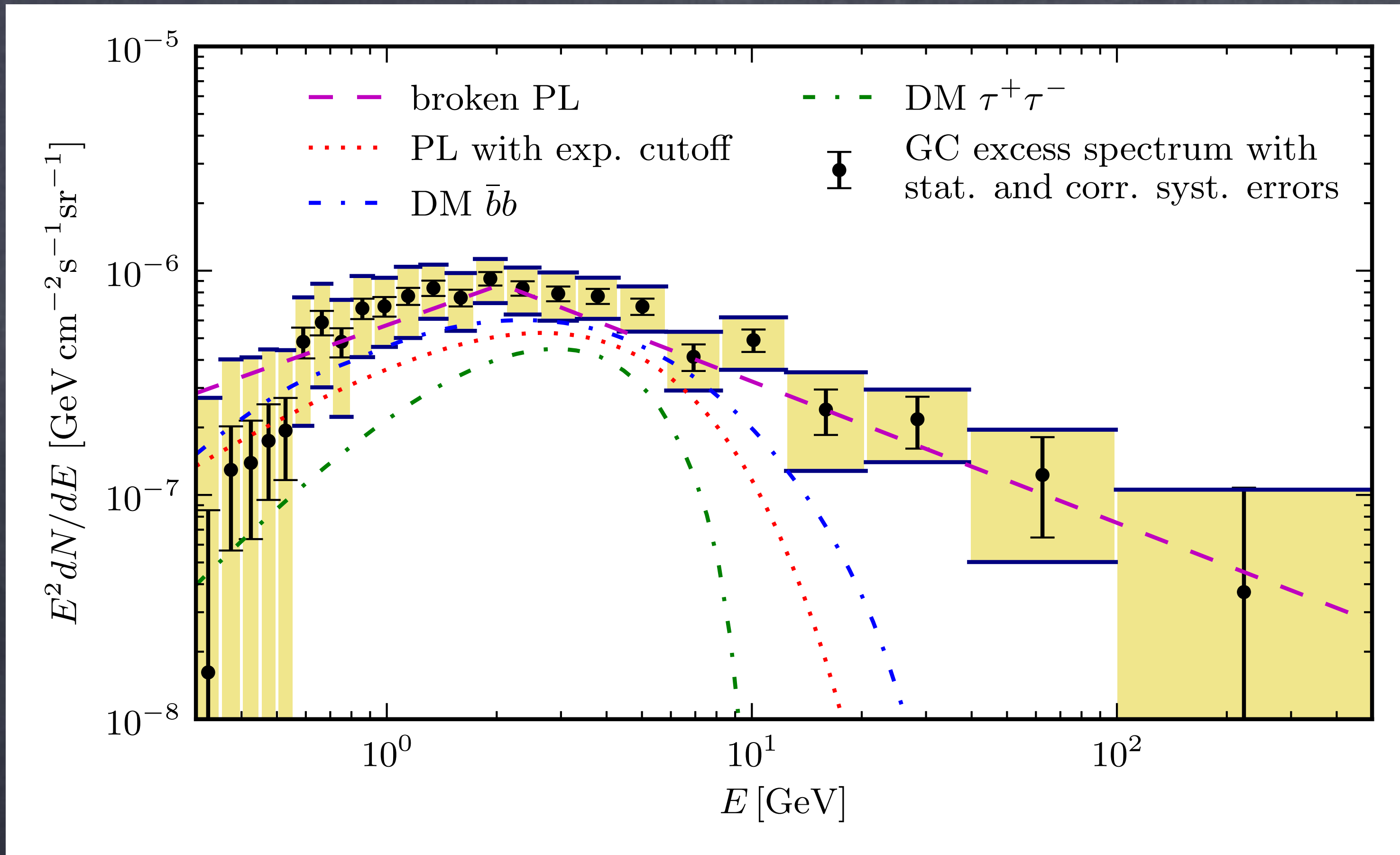


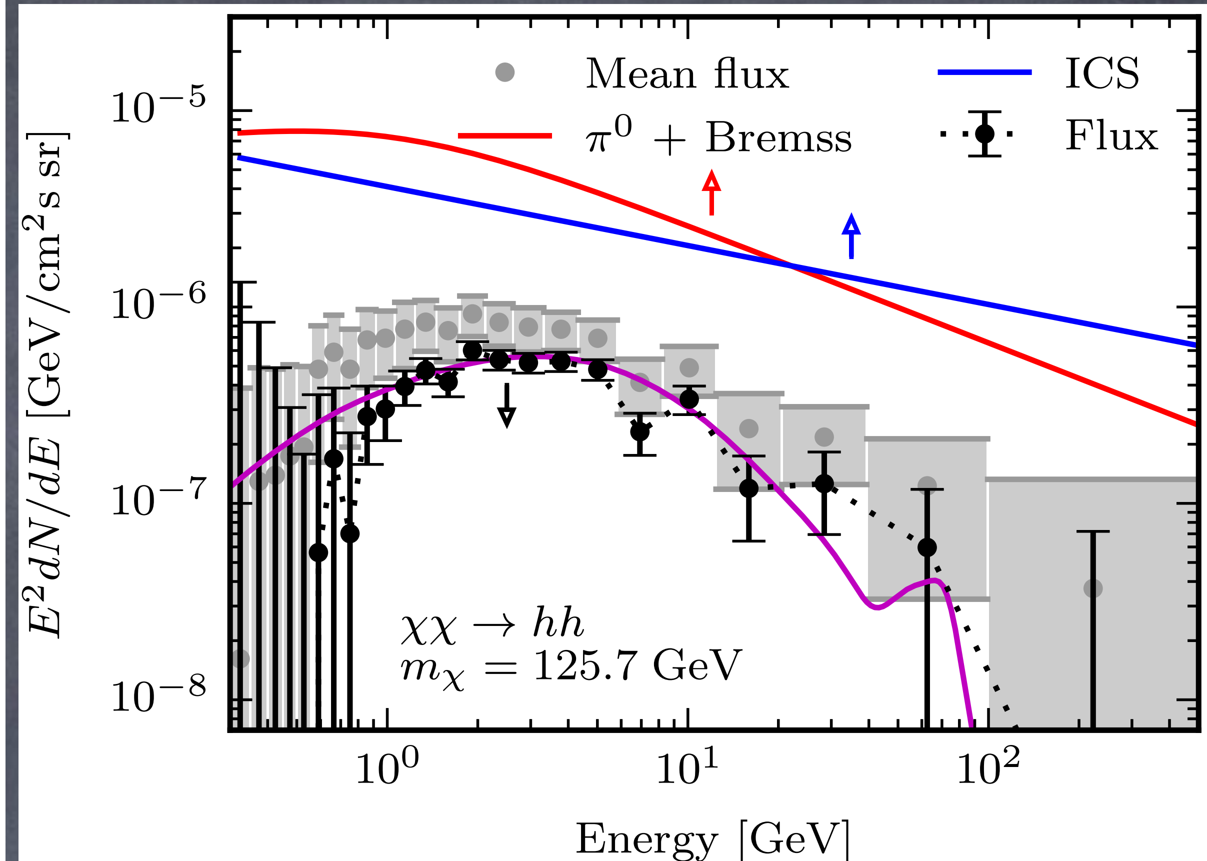


Gordon & Macias (1306.5725)

Calore, Cholis, McCabe, Weniger, 2014

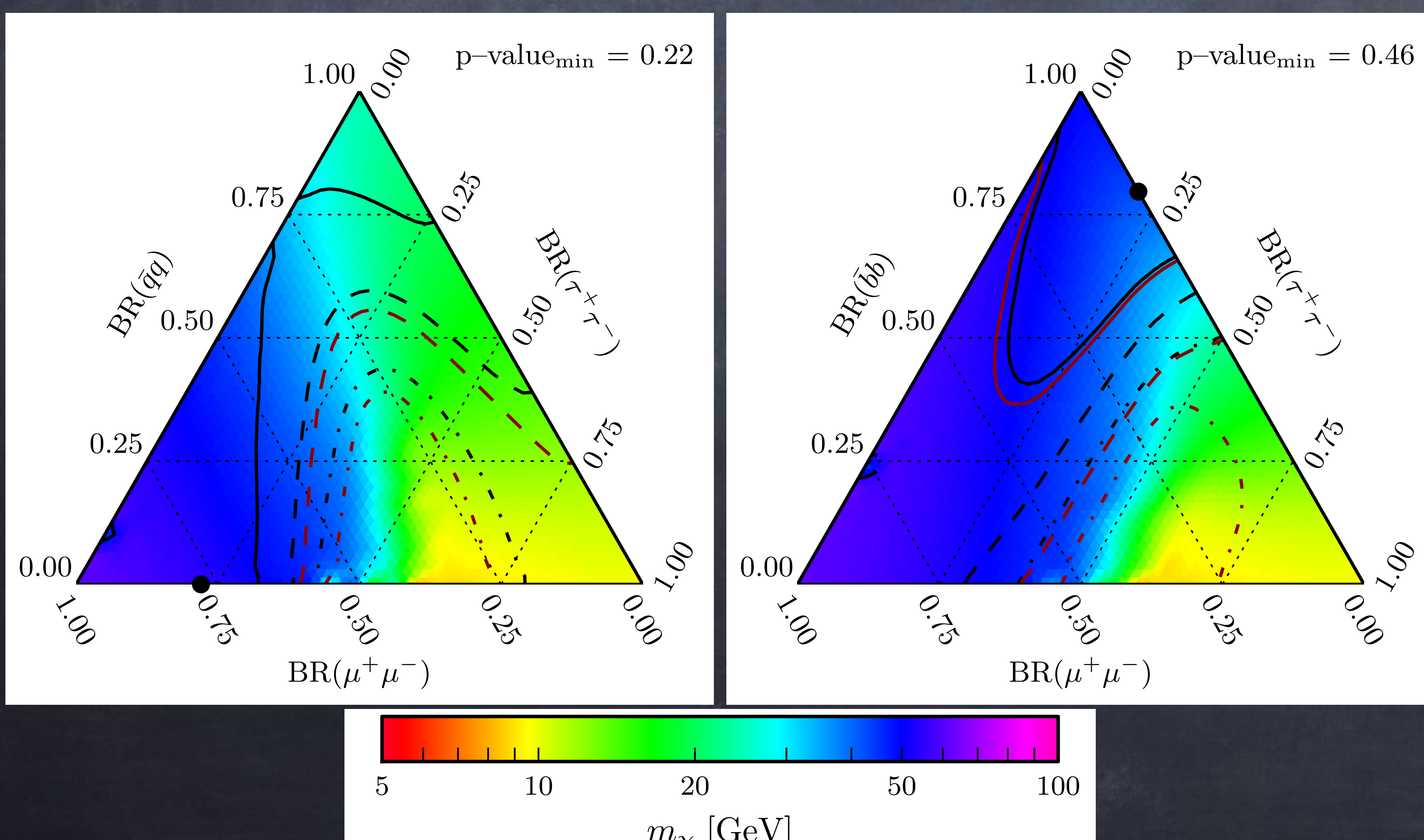
The mass range preferred is actually higher. Even though still light DM models can work. (see also P. Agrawal, B. Battel, P. Fox, R. Harnik, 1411.2592)

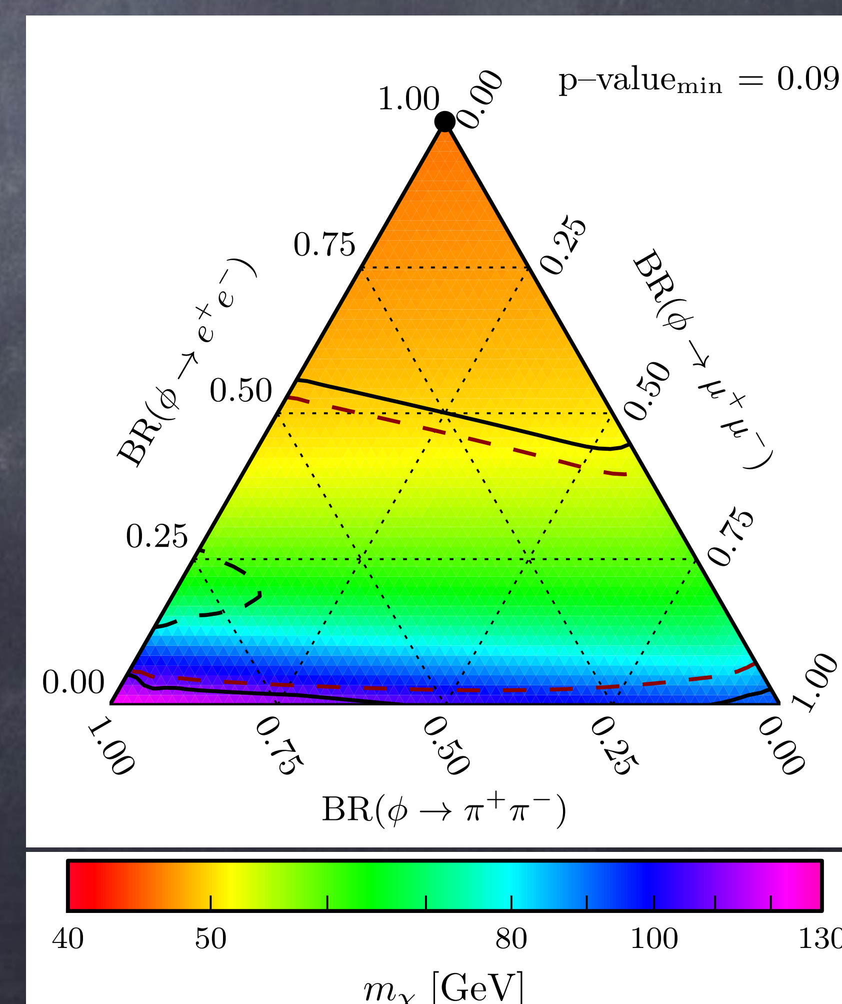




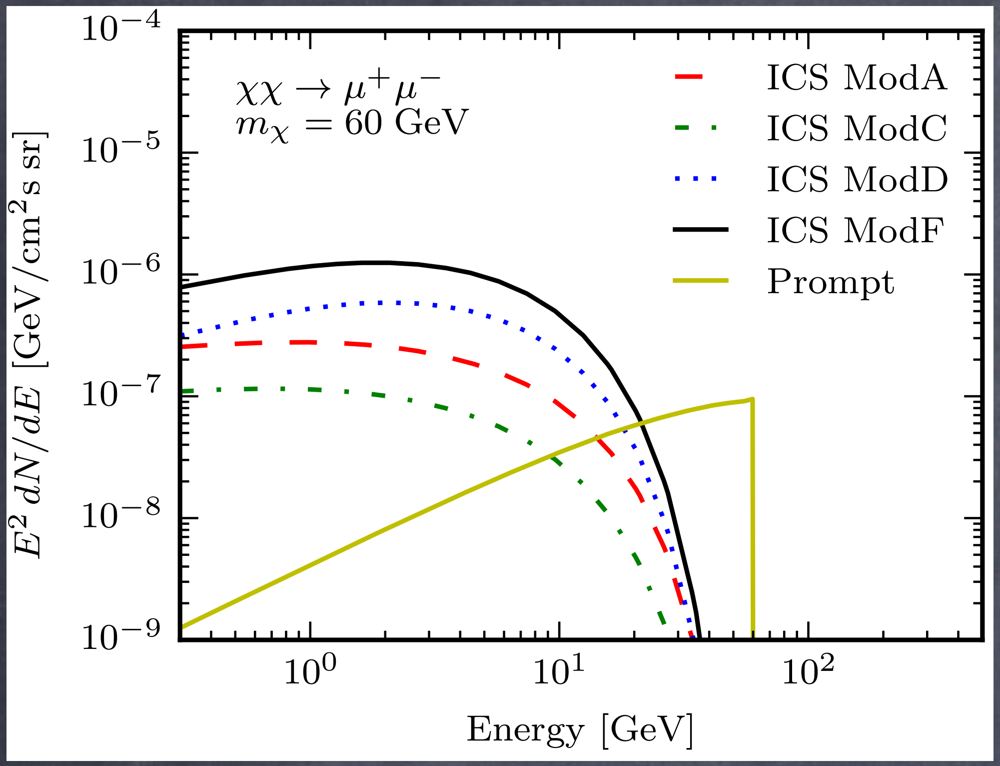
Calore, Cholis, Weniger, 2014

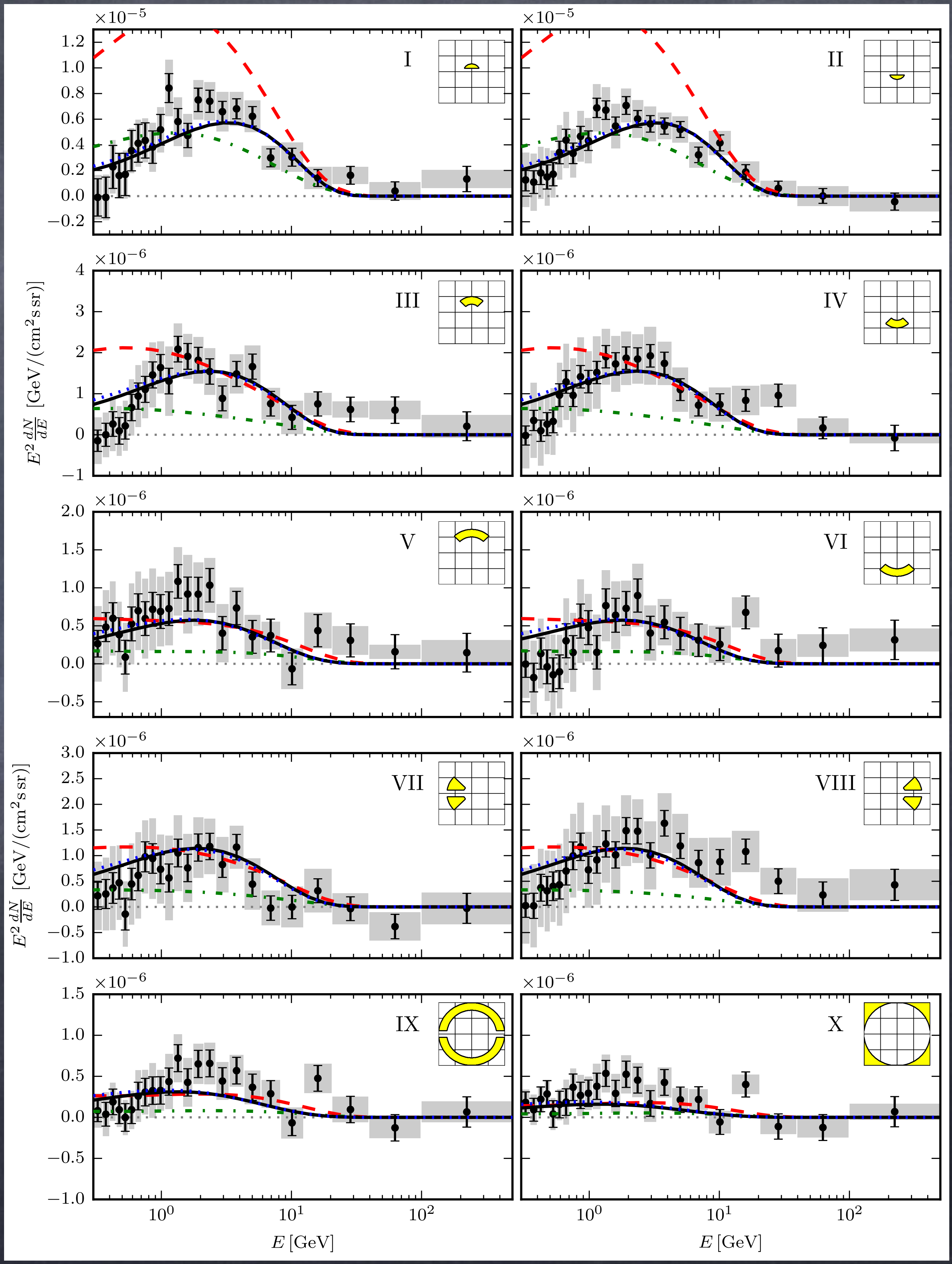
Calore, Cholis, McCabe, Weniger, 2014





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

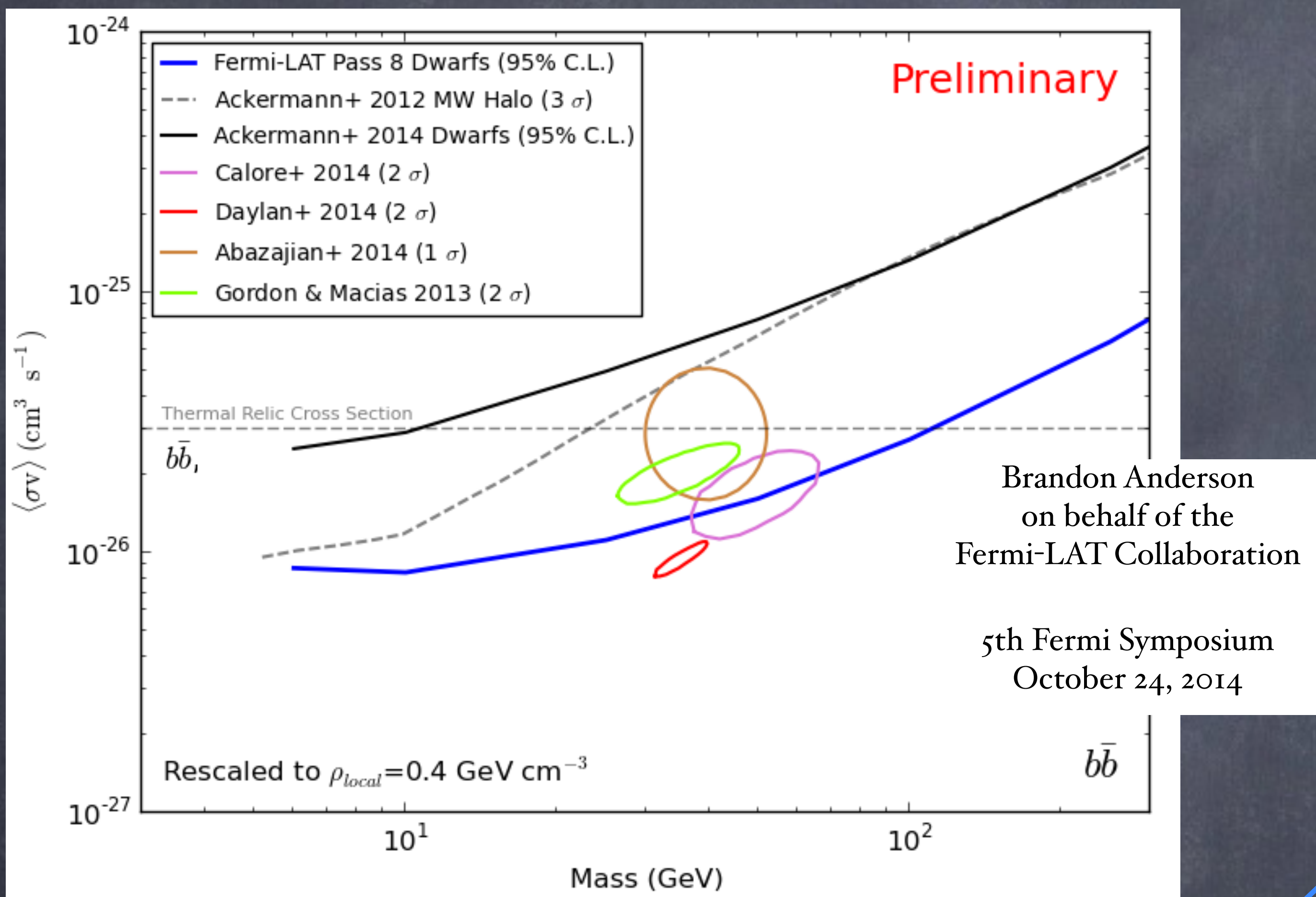


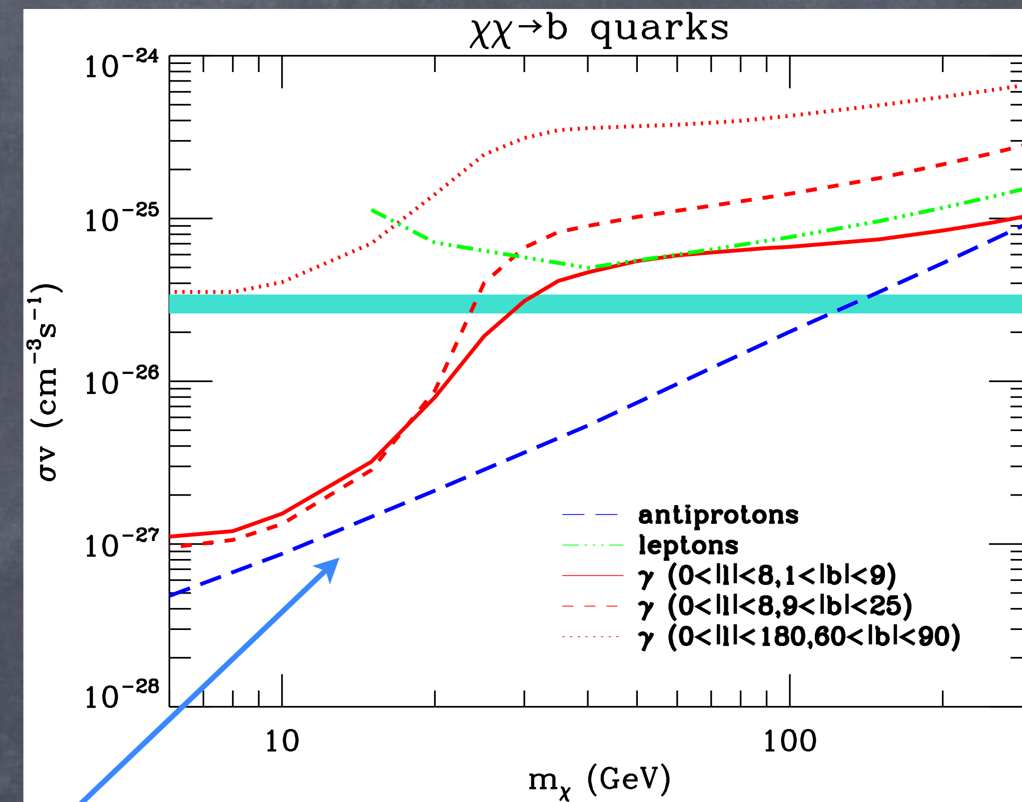


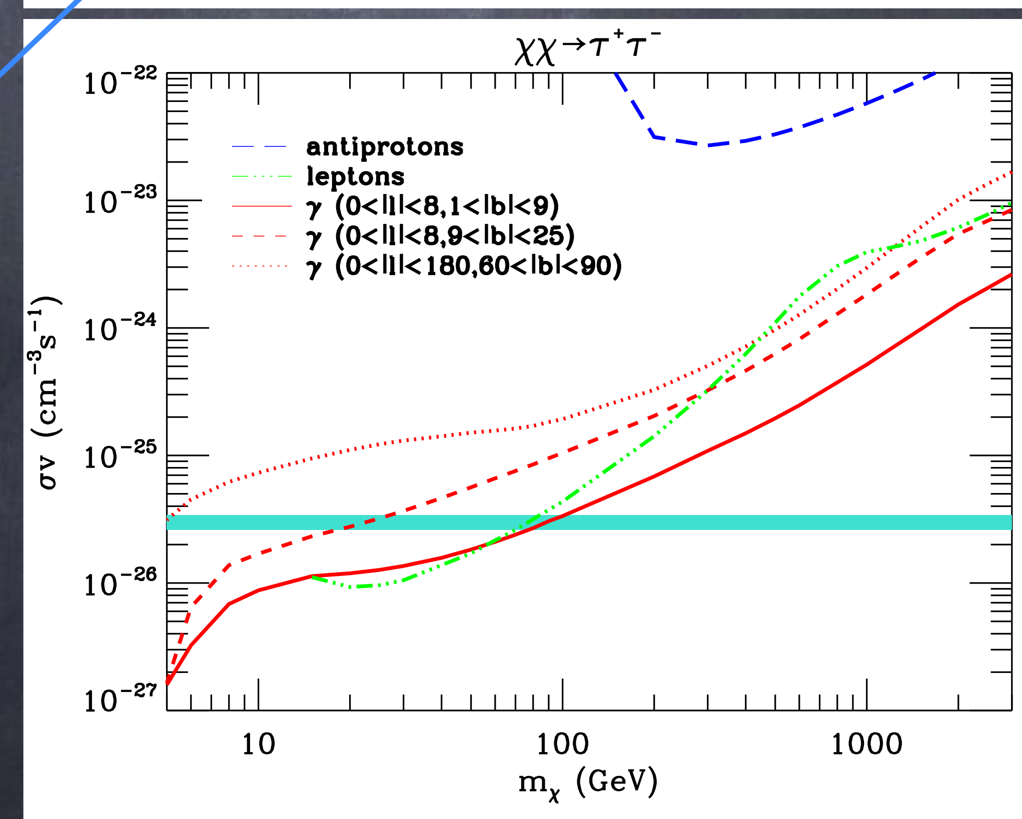
Understanding the morphology of the signal in various windows can be crucial; FOR ANY model that wants to explain the GC excess via CR electrons(positrons) whether of DM origin or Not.

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, antiprotons, gamma-rays from other regions of the galactic sky







Tavakoli, Cholis, Evoli, Ullio (1308.4135)

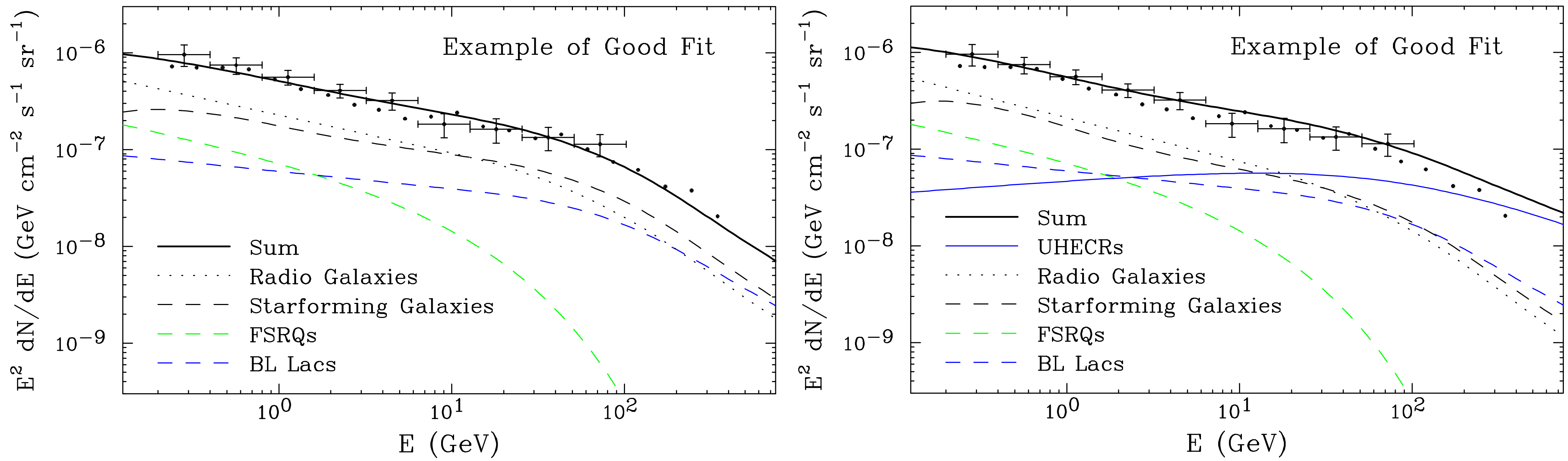
strong limits from dwarf spheroidal galaxies

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

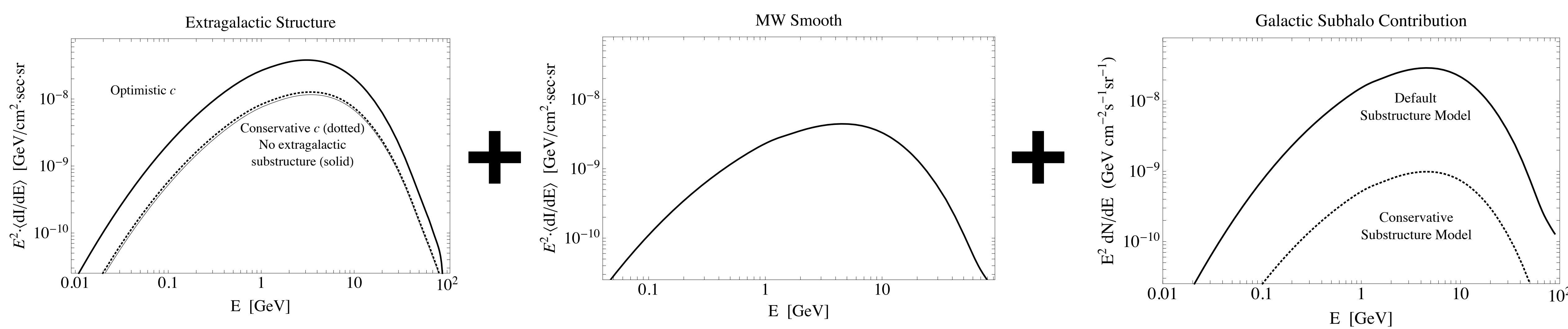
For DM models with high BRs to leptons the AMS-02 data actually provide the best limits instead.

Constraints from High Latitudes (mainly extragalactic)

Extragalactic diffuse gamma-rays are isotropically distributed. There are many astrophysical sources that suffer from relatively large uncertainties. Correlating to radio we can extract some of their properties and model them out. —> Build models for the non-DM contribution and derive limits on DM.

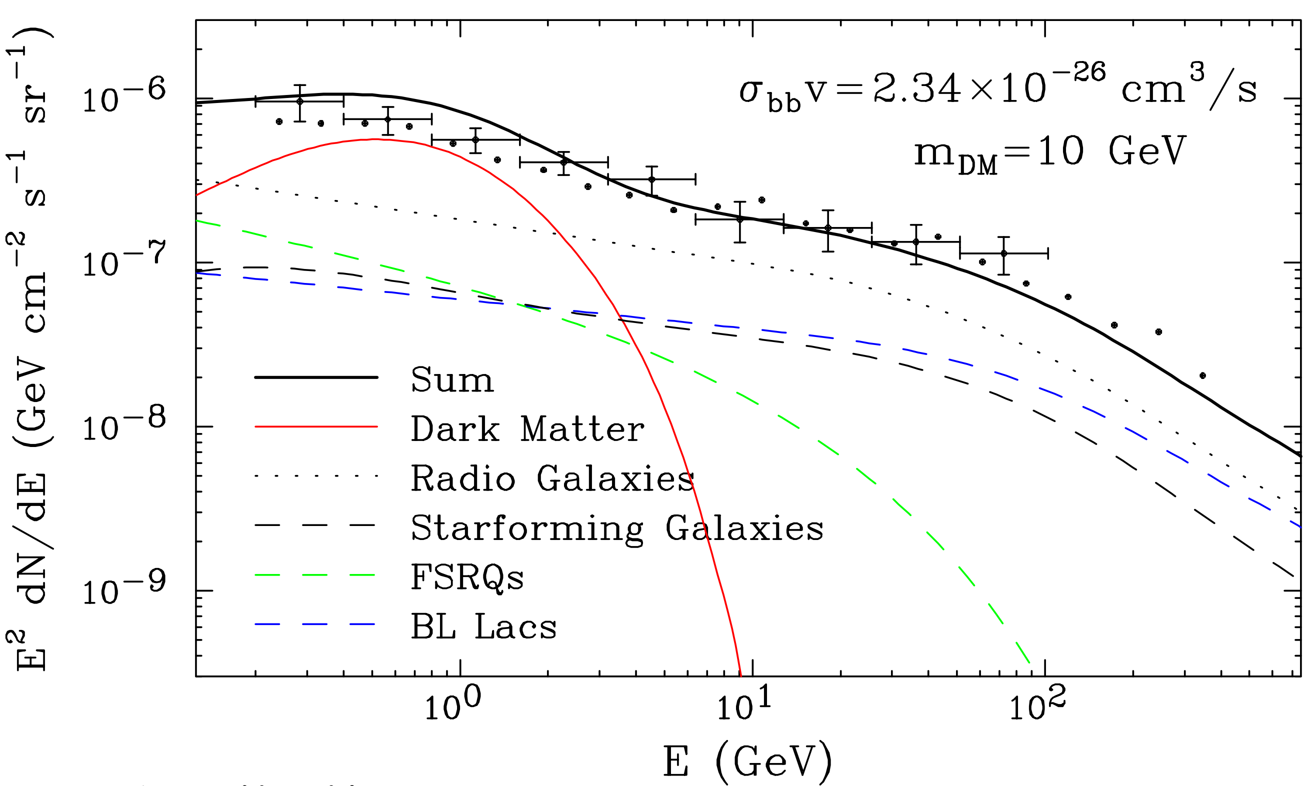


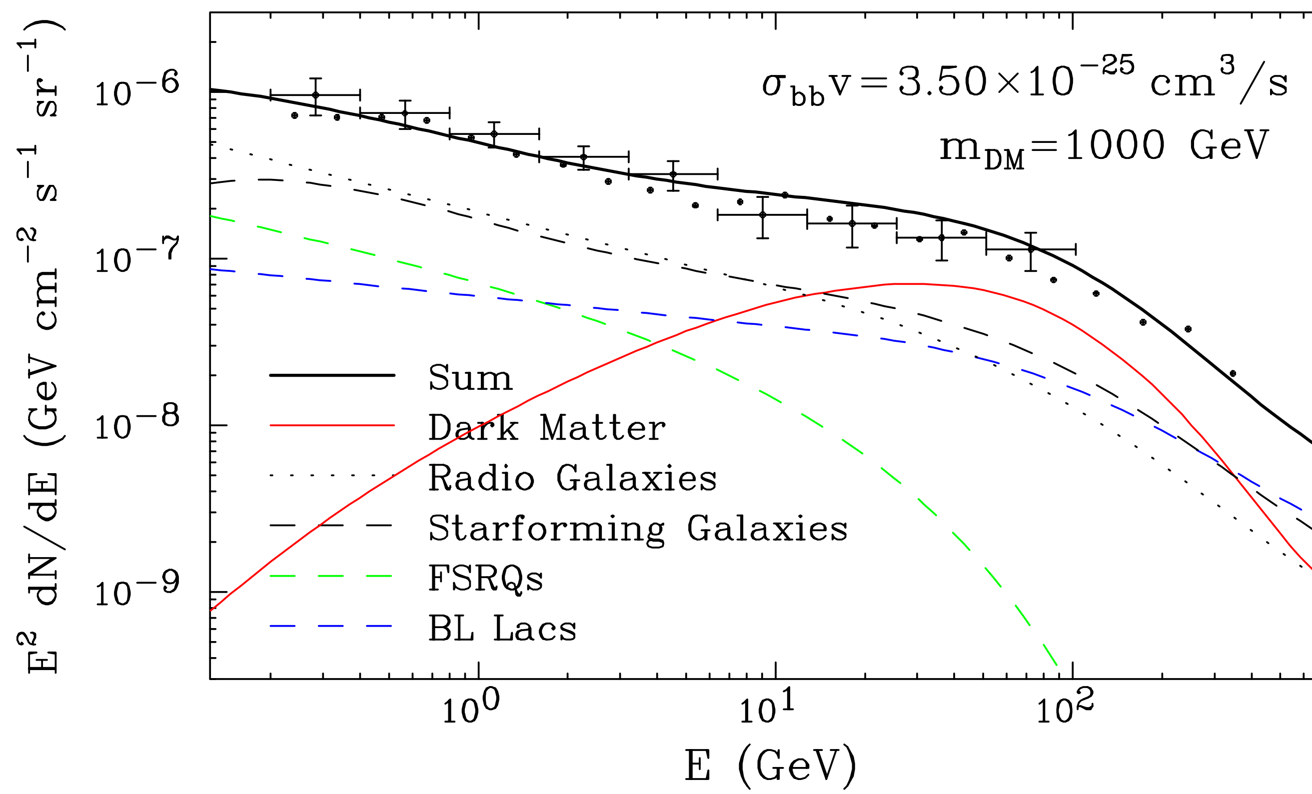
I.Cholis, S. McDermott, D. Hooper, JCAP 1402 (2014)



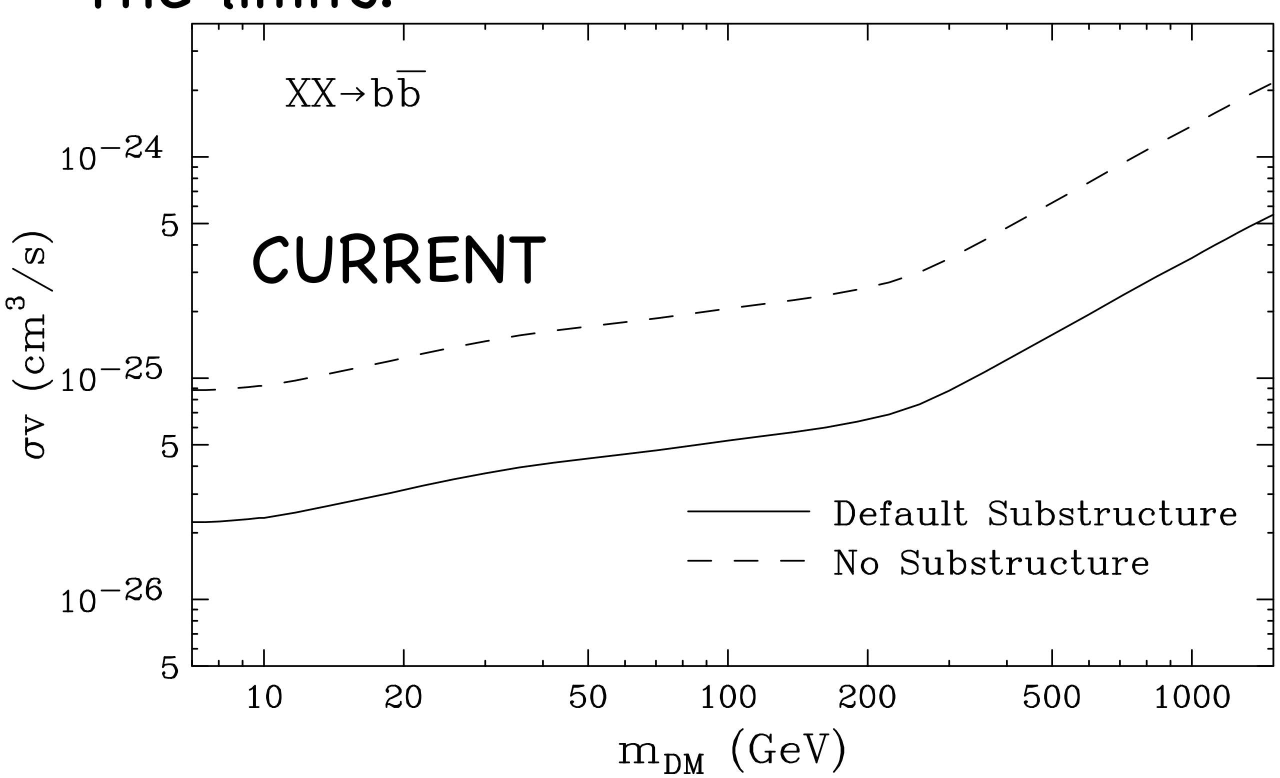
DM Limits

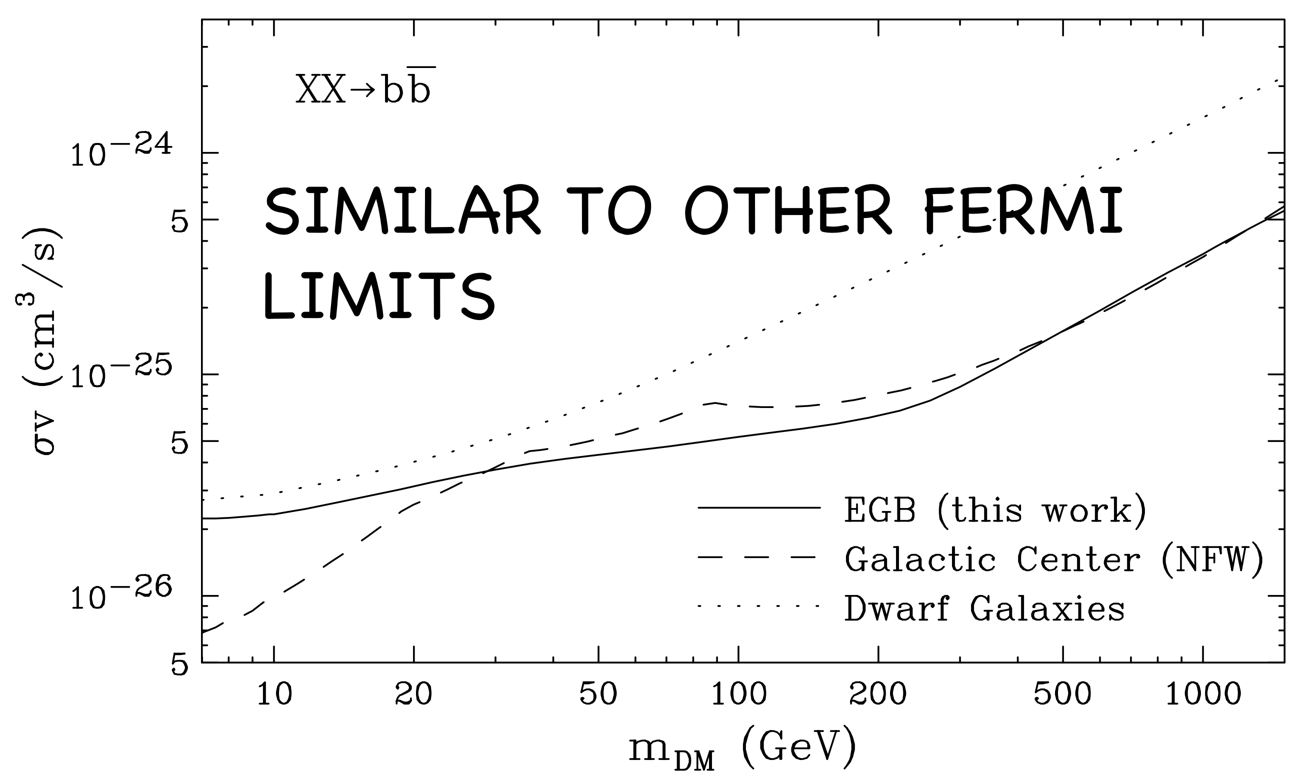
We marginalize of the uncertainties in the non-DM contribution. 2 examples:





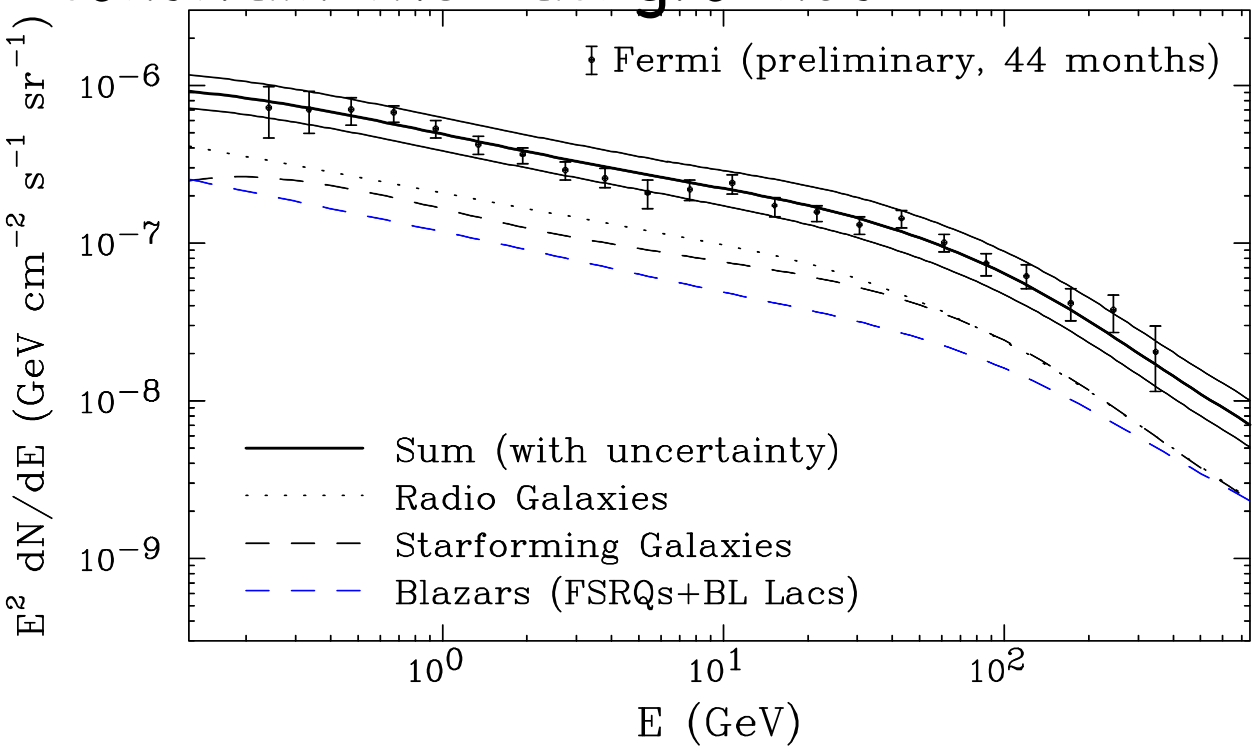
The limits:

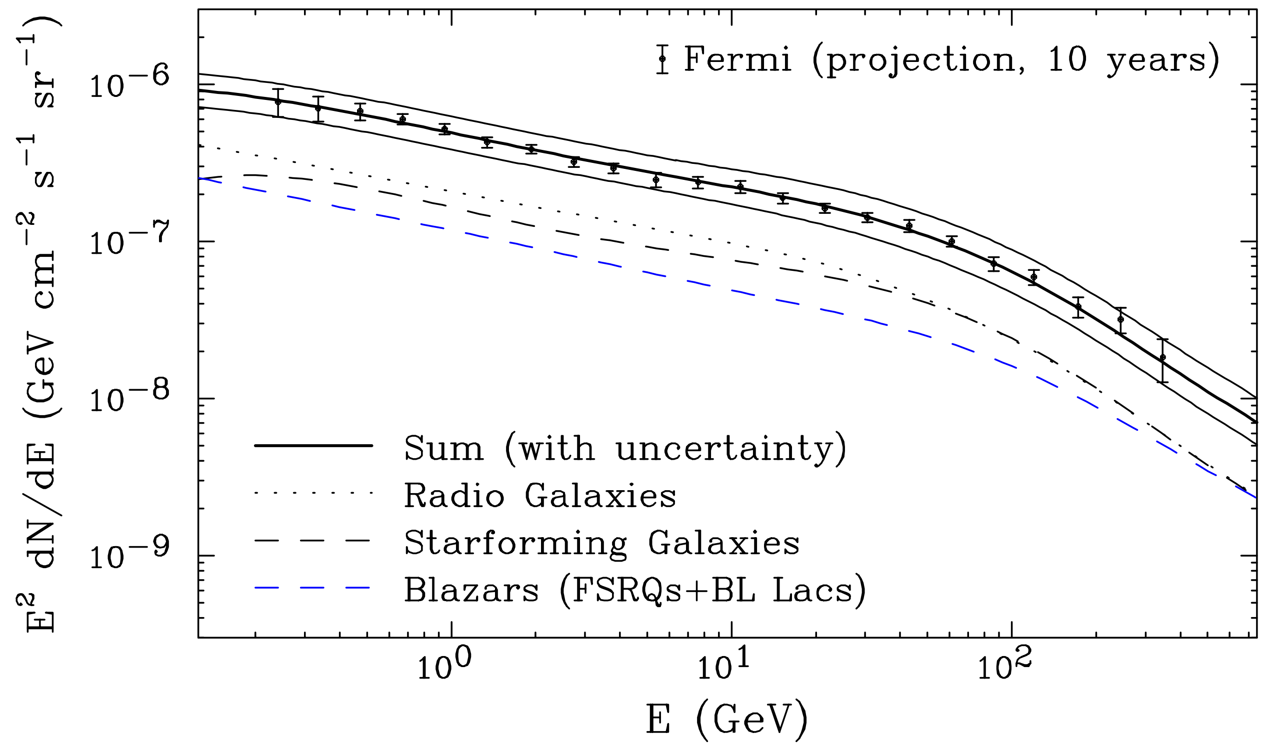


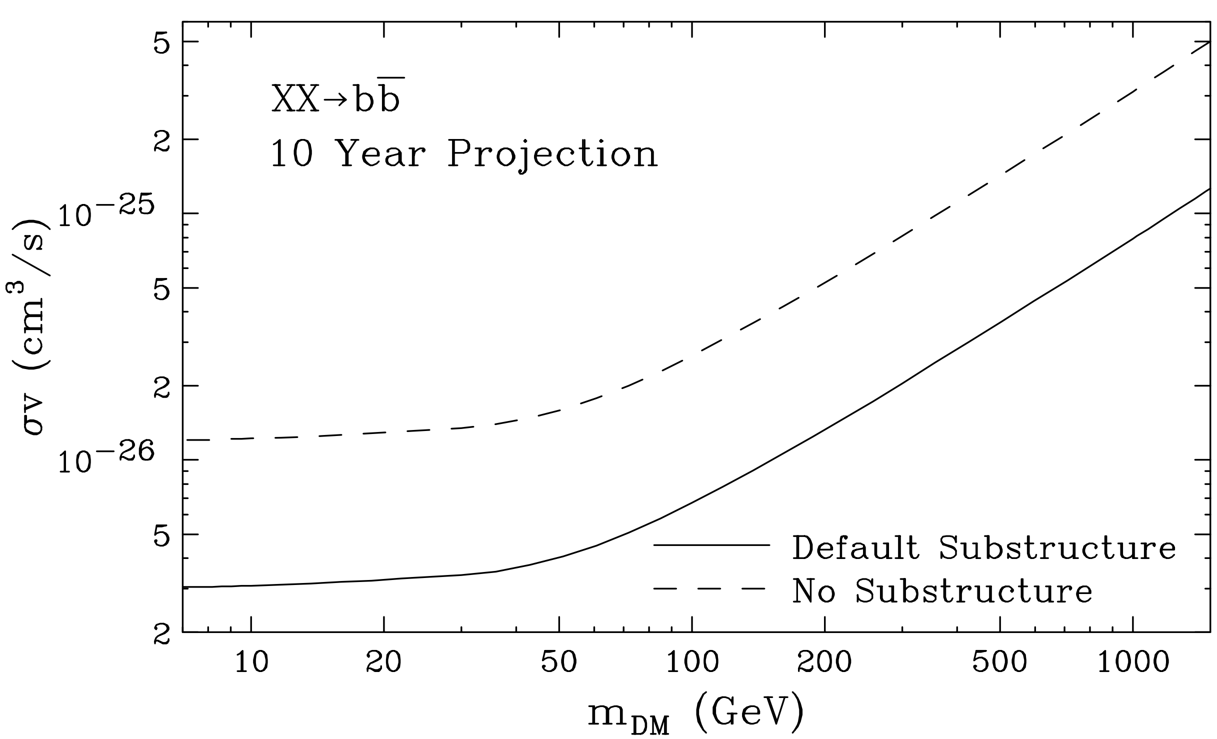


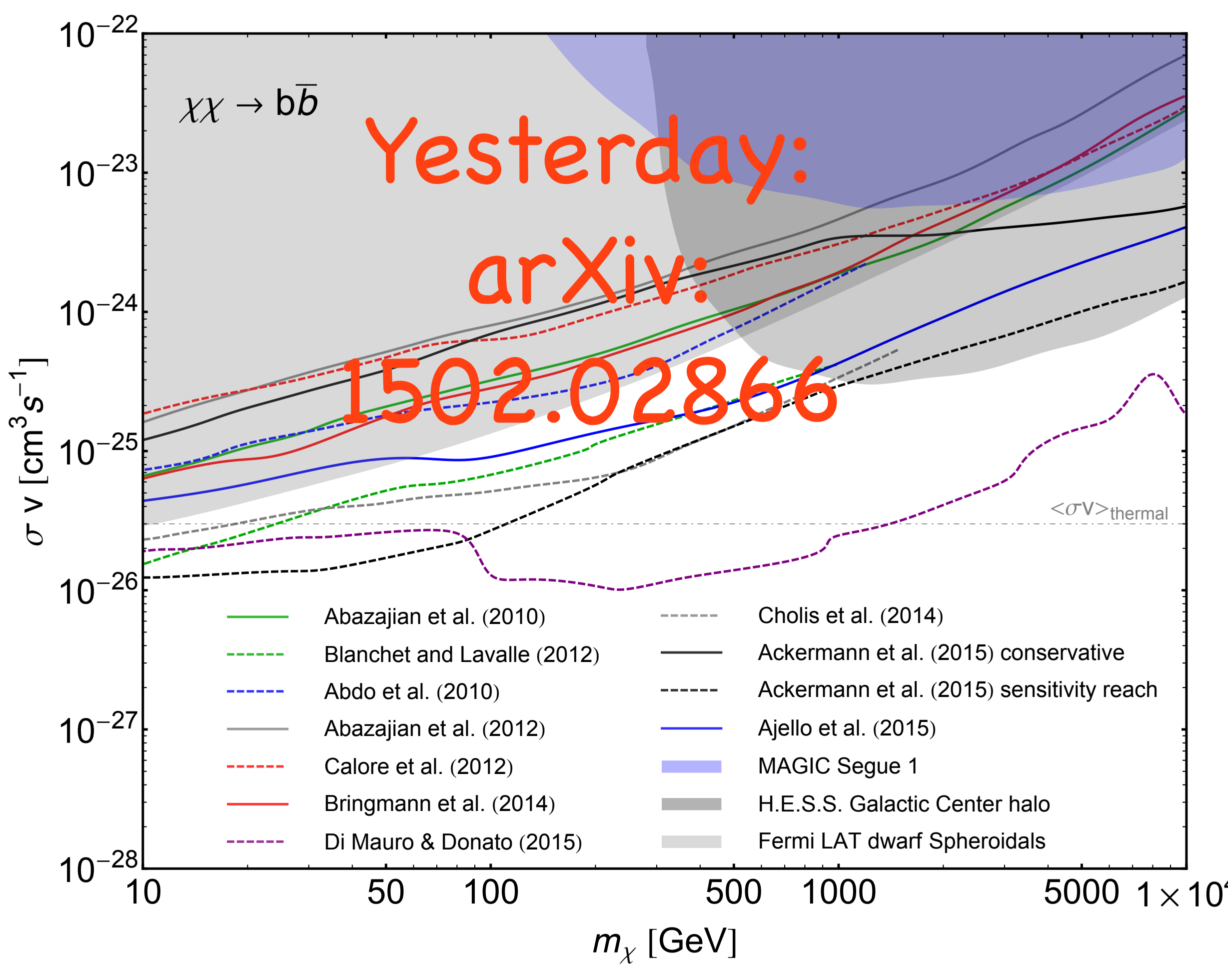
Projections for future:

More data, not just in gamma-rays but also in other wavelengths will let us constrain the backgrounds:









Maybe the most tight-limits by the end of the Fermi-LAT mission.

Conclusions...and further thinking

- The Fermi Bubbles do not have any significant DM signal, but is the first example of a template analysis in gamma-rays that resulted in finding a new emission component (unknown yet in origin), also have probed us to question the conventional propagation of CRs and to think in terms of microwaves and neutrinos

- the 130 GeV line does not seem to be a DM signal (maybe a statistical fluctuation). Yet a nice example of connections with particle physics and cosmological simulations

- The excess is robust to background model systematics, very well correlated to the galactic center, AND 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). Also some direct detection signal?

- Further advances in extragalactic gamma-ray astronomy but also at other wavelengths will strengthen the indirect DM searches in the future more than maybe any other indirect detection probe.

- In ANY possible DM signal we NEED to further think about BACKGROUNDS and ALTERNATIVE Astrophysical Explanations.

Thank you!