The 130 GeV line(s) as a signal of Dark Matter Annihilation

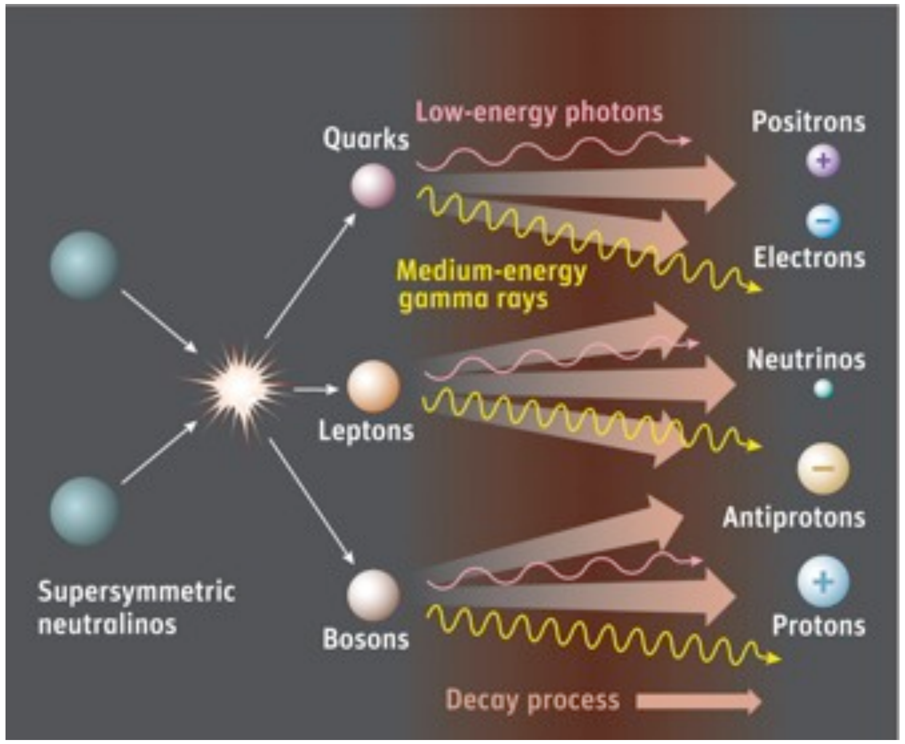
Work done with Piero Ullio, Maryam Tavakoli, Hani Santosa (SISSA), Carmelo Evoli (DESY) and Luca Maccione (LMU)

JCAP, 05, 004 2012 (arXiv:1106:5073), PRD 86 083525 2012 (arXiv:1207:1468), arXiv:1303:5775 and work in progress.

Ilias Cholis (FNAL)

5/14/2013

Outline



- Spectral features from DM and the 130 GeV line(s) case
- Discussing the background gamma-ray contributions/ discussion on model's uncertainties
- Implement to DM annihilation in the galactic main halo searches
- Discussing constraints on the associated continuum spectrum to the 130 GeV line signal toward the GC
- Probing the entire sky: robustness of the DM line signal to different backgrounds
- Dark disk and connection to cosmological simulations
- Conclusions

Looking for DM annihilation signals in gamma-rays

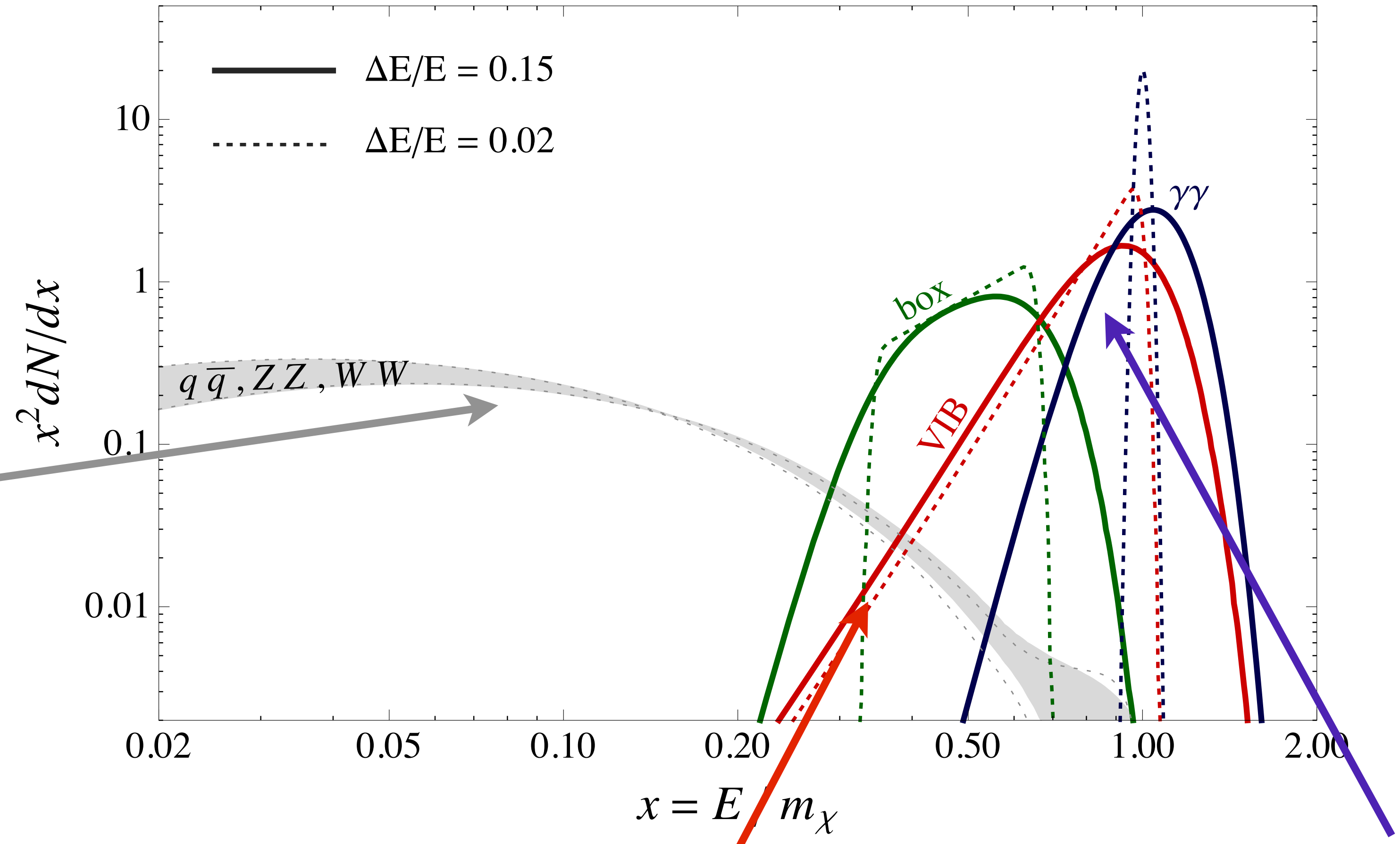
For a DM annihilation signal

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

- Hardening of a spectrum without a clear cut-off localized in a certain region (Fermi bubbles)
- Hardening of a spectrum with a clear cut-off: ~10 GeV DM claims towards the Galactic Center (GC) inner few degrees (see Tim's talk)
- Line or lines
- One of the most likely targets is the GC (though backgrounds also peak), others are the known substructure (dSphs) or Galaxy clusters

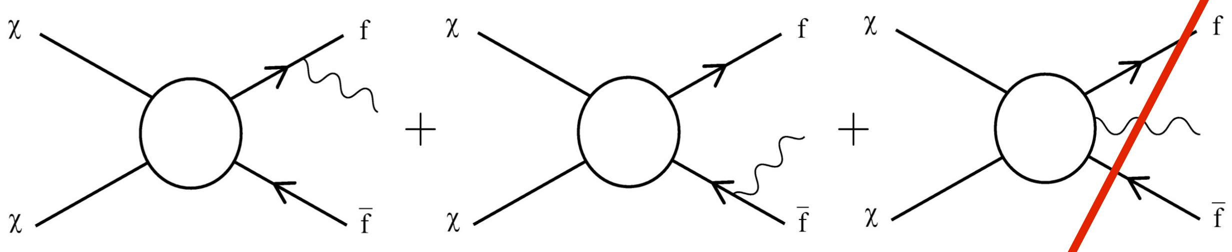
DM annihilation spectra

Bringmann & Weniger (2012)



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

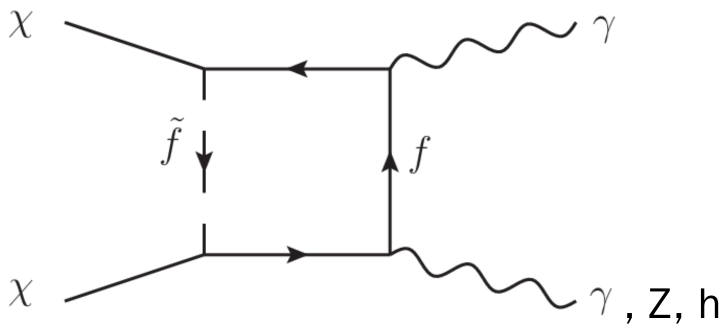
Two body annihilation to photons. Almost monochromatic Line, but suppressed at O(a^2).



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



The 130 GeV line claim

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

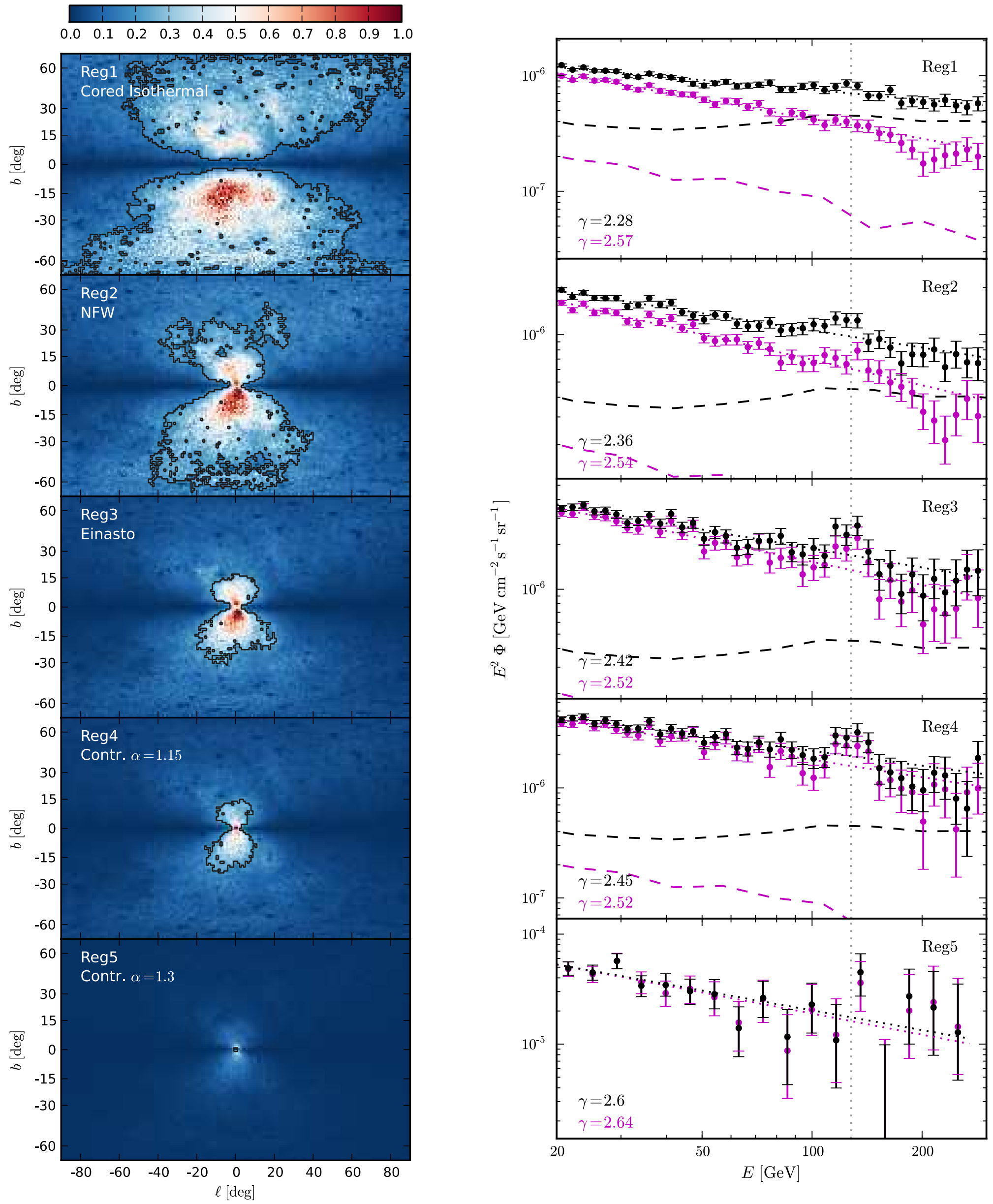
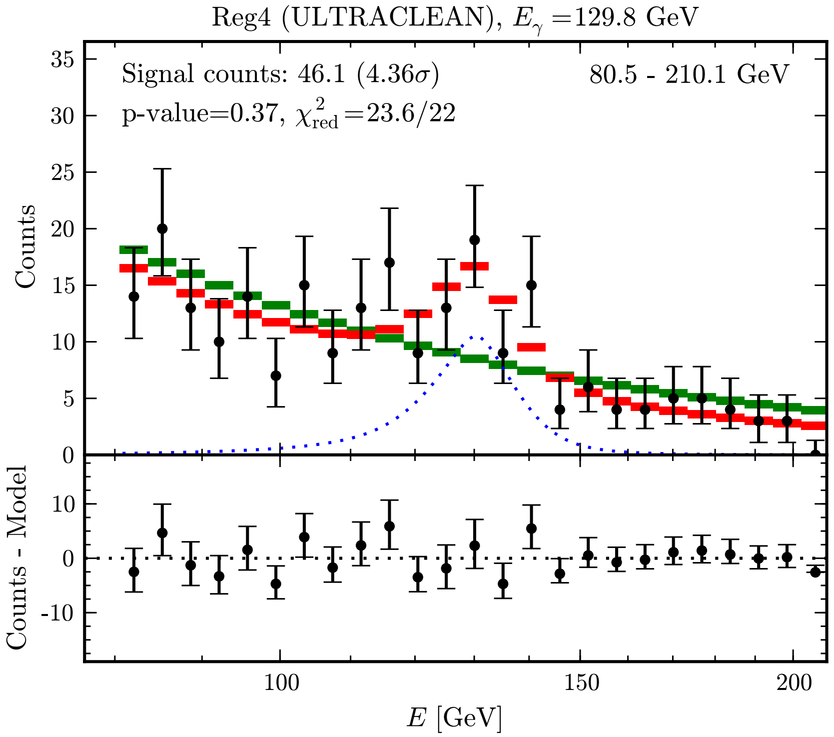


Figure 1. *Left panel:* The *black lines* show the target regions that are used in the present analysis in case of the SOURCE event class (the ULTRACLEAN regions are very similar). From *top* to *bottom*, they are respectively optimized for the cored isothermal, the NFW (with $\alpha = 1$), the Einasto 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(4.6σ) detection of a gamma-ray line at $129.8 \pm 2.4^{+7}_{-13}$GeV



Cross-section for the line if taken as: $\chi\chi \rightarrow \gamma\gamma$

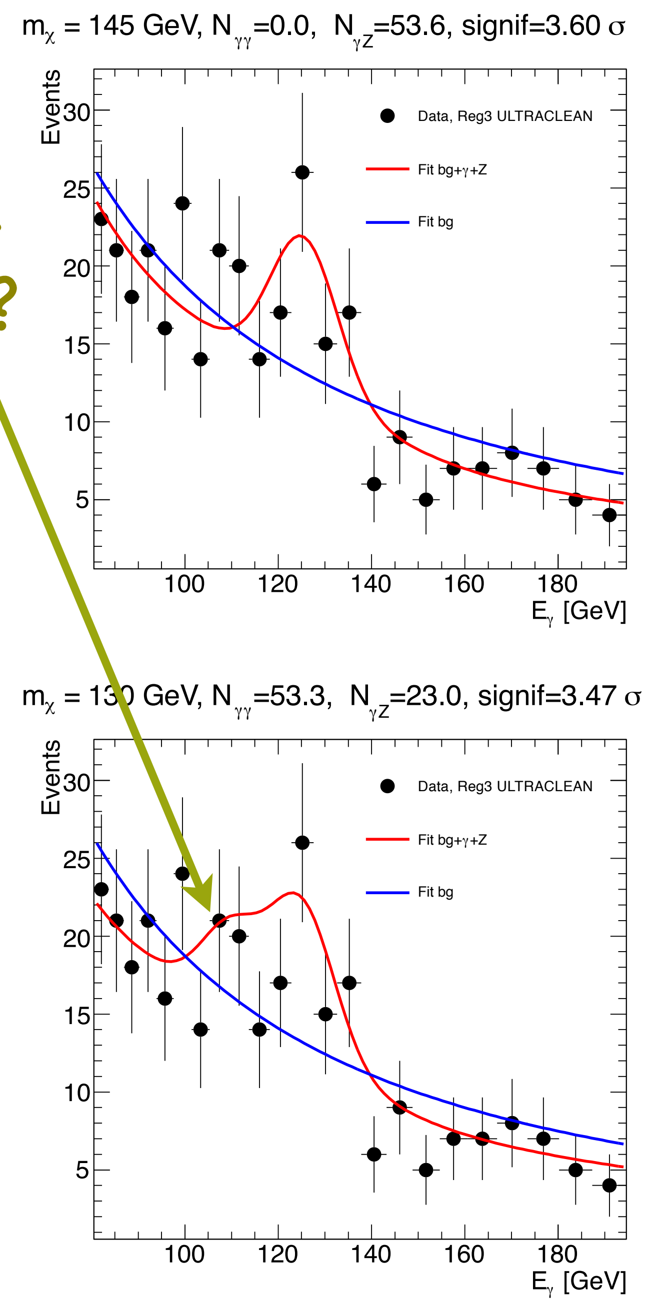
Most evident for the cases of more concentrated DM profiles (contracted NFW) or Einasto Profiles.

Einasto DM profile: $1.27 \pm 0.32 \times 10^{-27} cm^3/s$

NFW DM profile: $2.27 \pm 0.57 \times 10^{-27} cm^3/s$

Observing 2 lines at 111 and 129 GeV

2nd line?



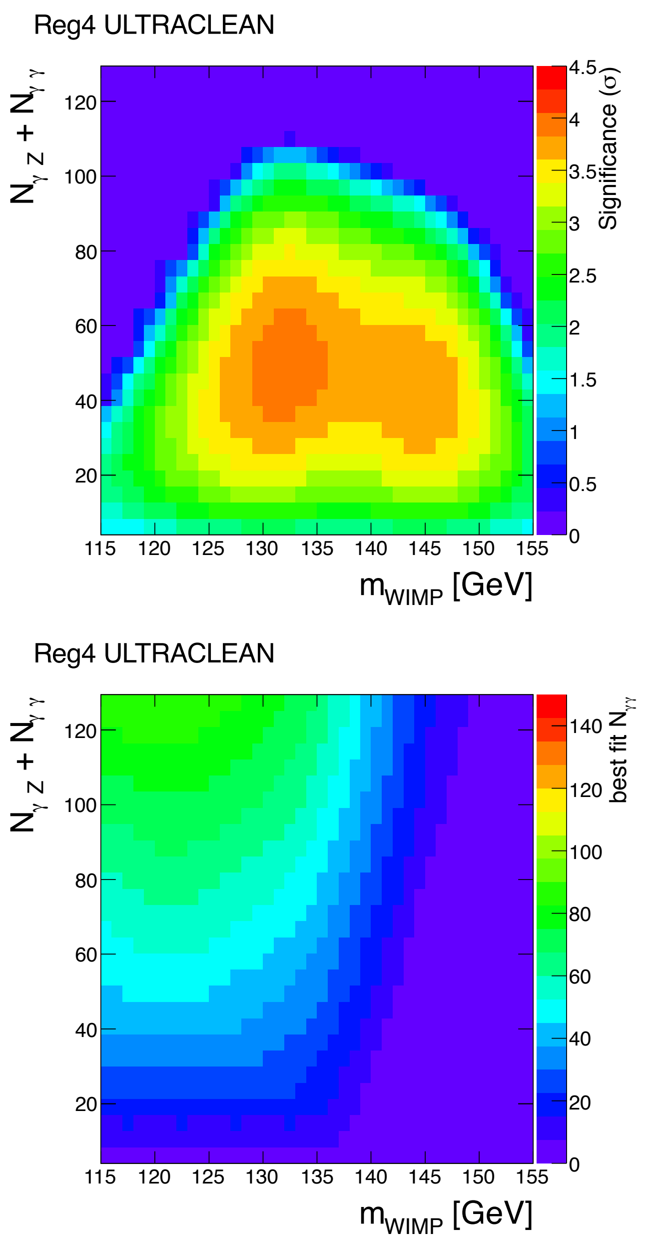
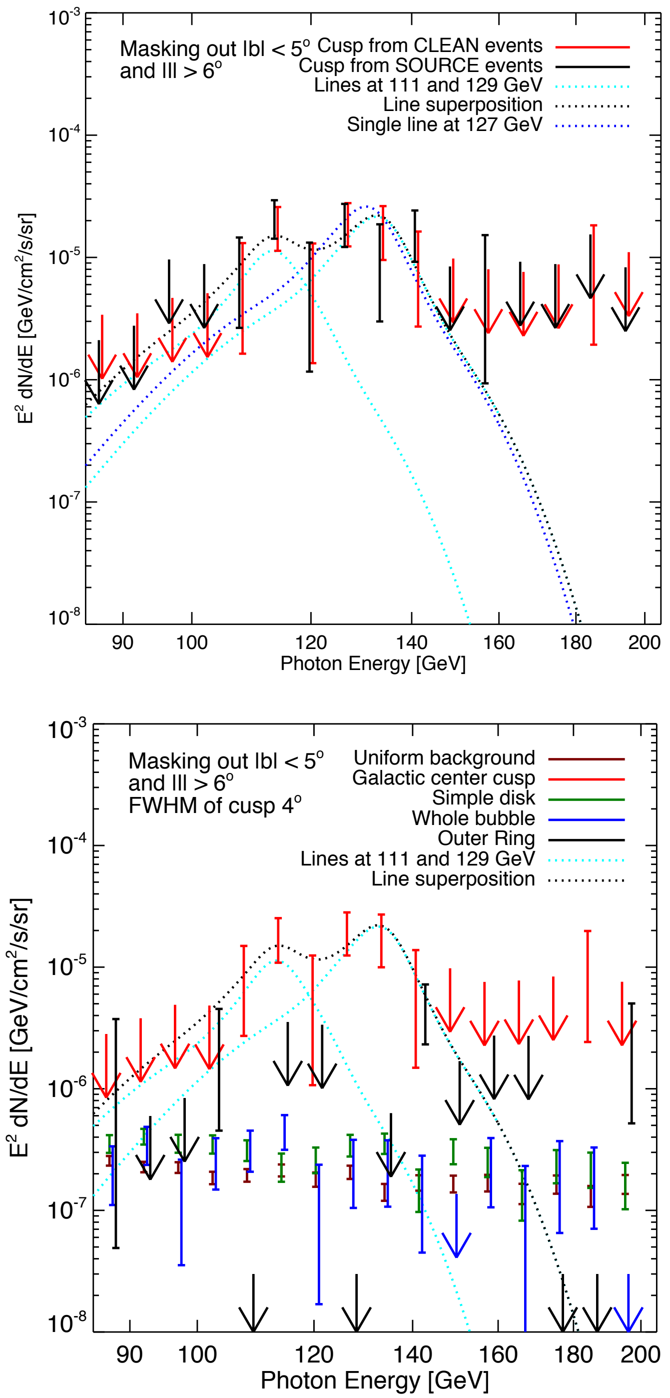


FIG. 1: Sample spectrum predicted by dark matter annihilation into a single γZ line (top panel) or two lines produced by $\gamma\gamma$ and γZ (bottom panel). Data from Ref. [6] is overlaid.

FIG. 3: Top, local statistical significance of the signal versus WIMP mass and total yield due to $\gamma\gamma$ and γZ lines in the Reg4 region of interest defined in Ref. [6]. Bottom, the contribution from $\gamma\gamma$ at each point in the plane.

Rajaraman,Tait,Whiteson, JCAP 09, 003, 2012 (1205.4723)

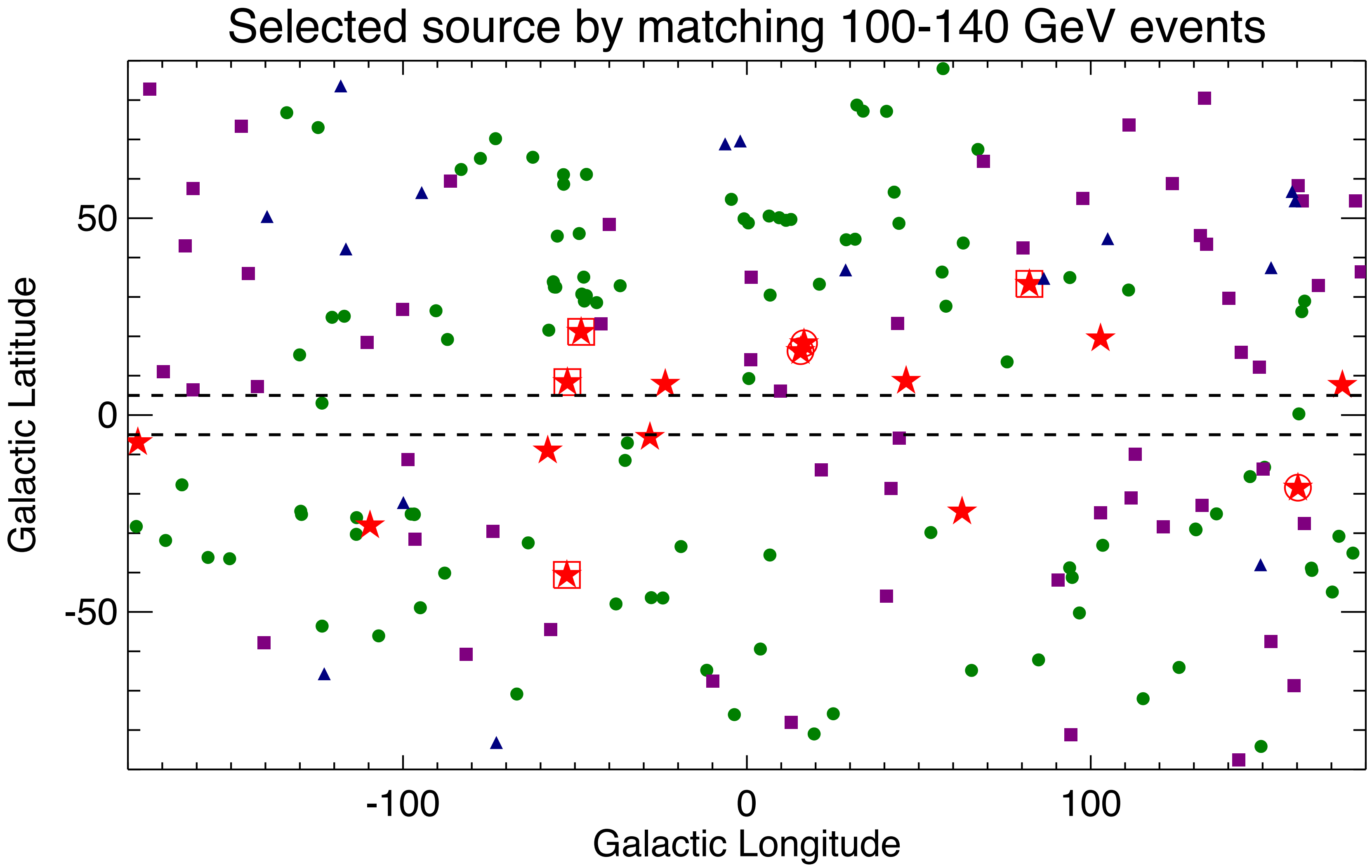
Slight Preference of Fits in the GC towards 2 lines



Su & Finkbeiner, 1206.1616

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)



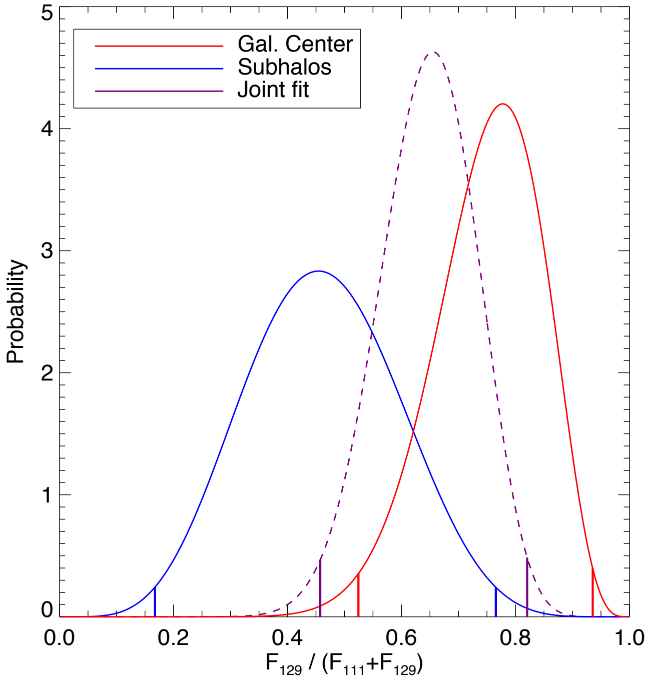
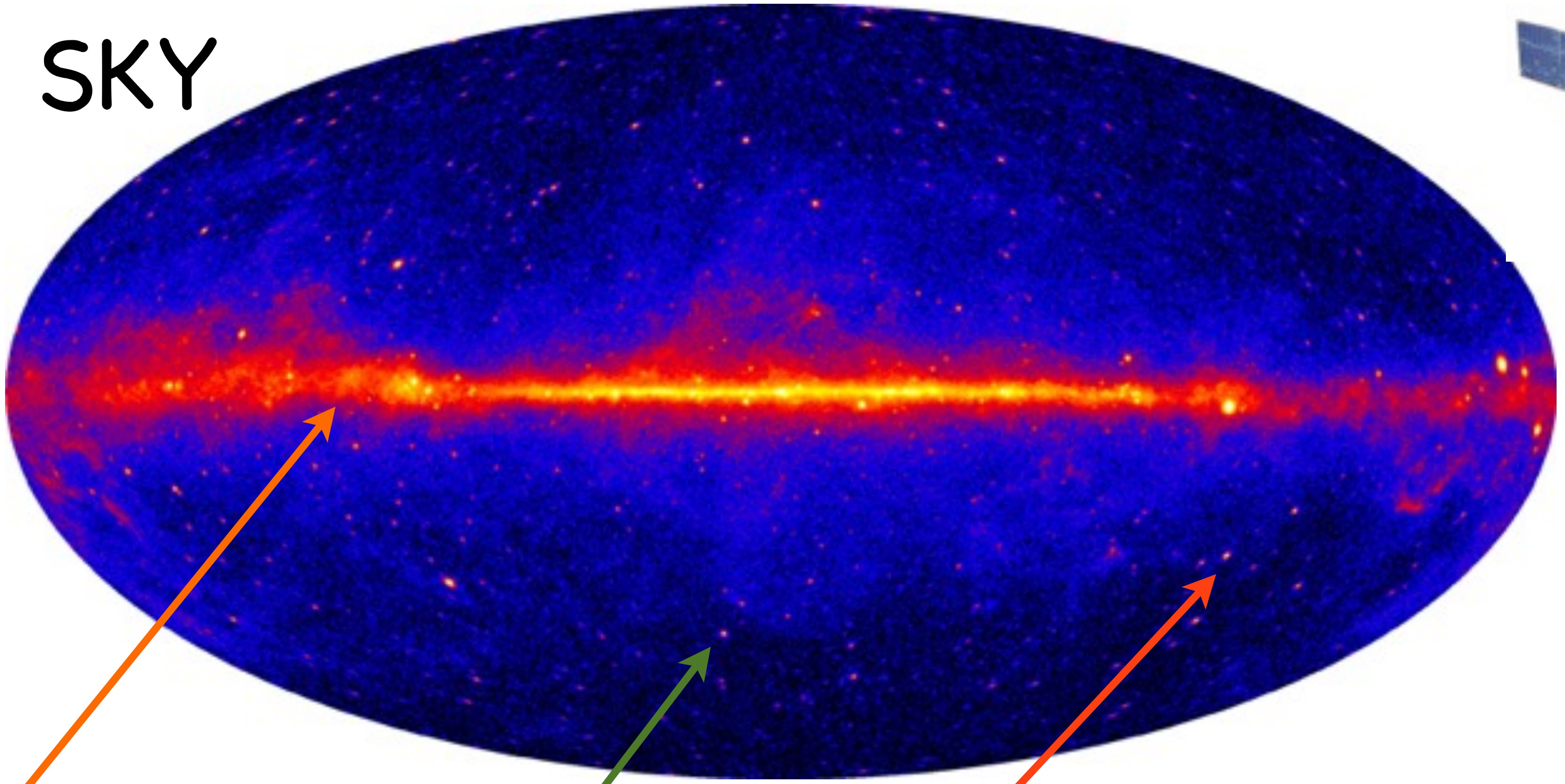


FIG. 7.— Probability of obtaining the observed counts, in the energy bins centered on 111 and 129 GeV, in the Galactic center and subhalos as a function of the line fraction $f \equiv F_{129}/(F_{111} + F_{129})$. We find that the best fit ratio of the 129 GeV line to 111 GeV line is 1.5, and the 2σ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

Gamma-ray Backgrounds

Fermi 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) (1873 detected in the first 2 years)

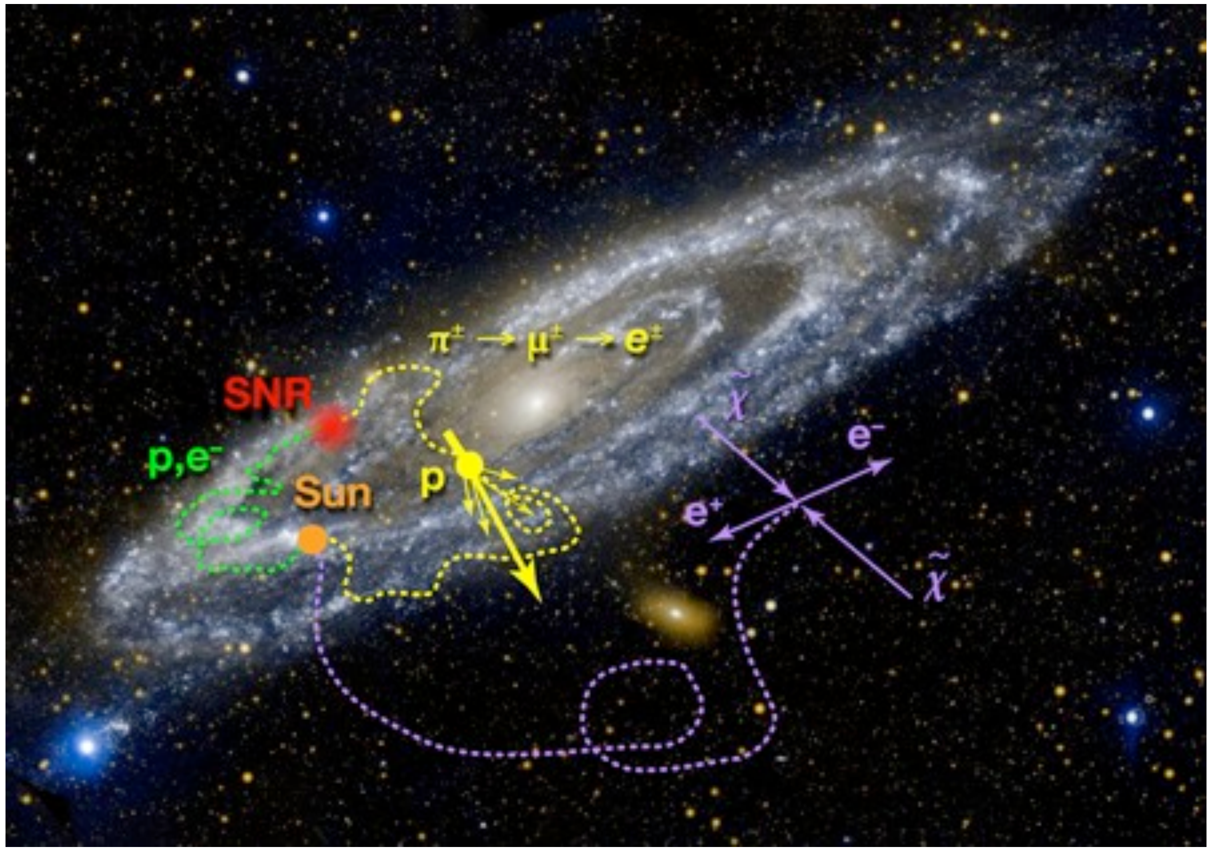
iii)Extragalactic Isotropic

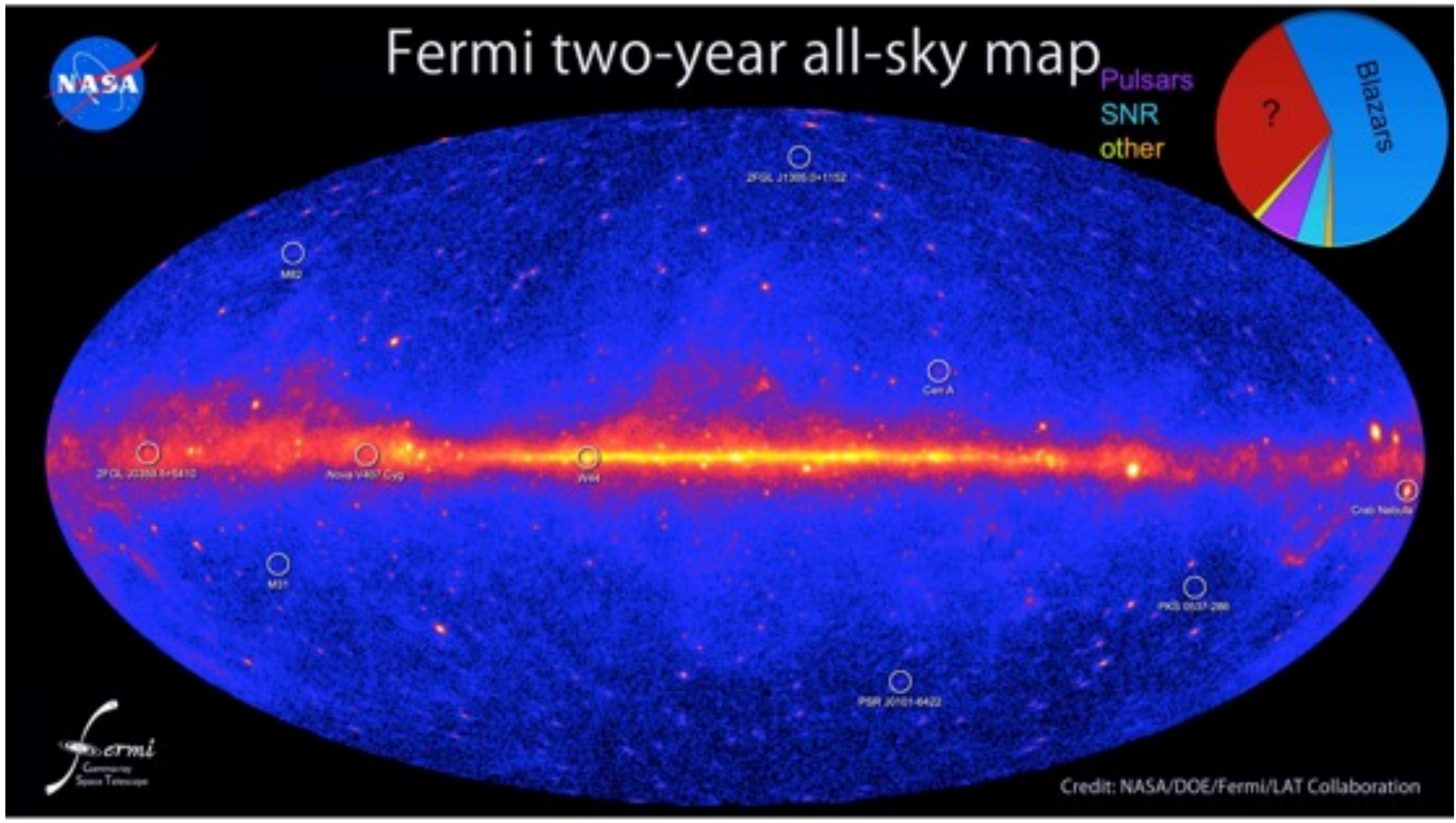
iv)"extended sources"

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

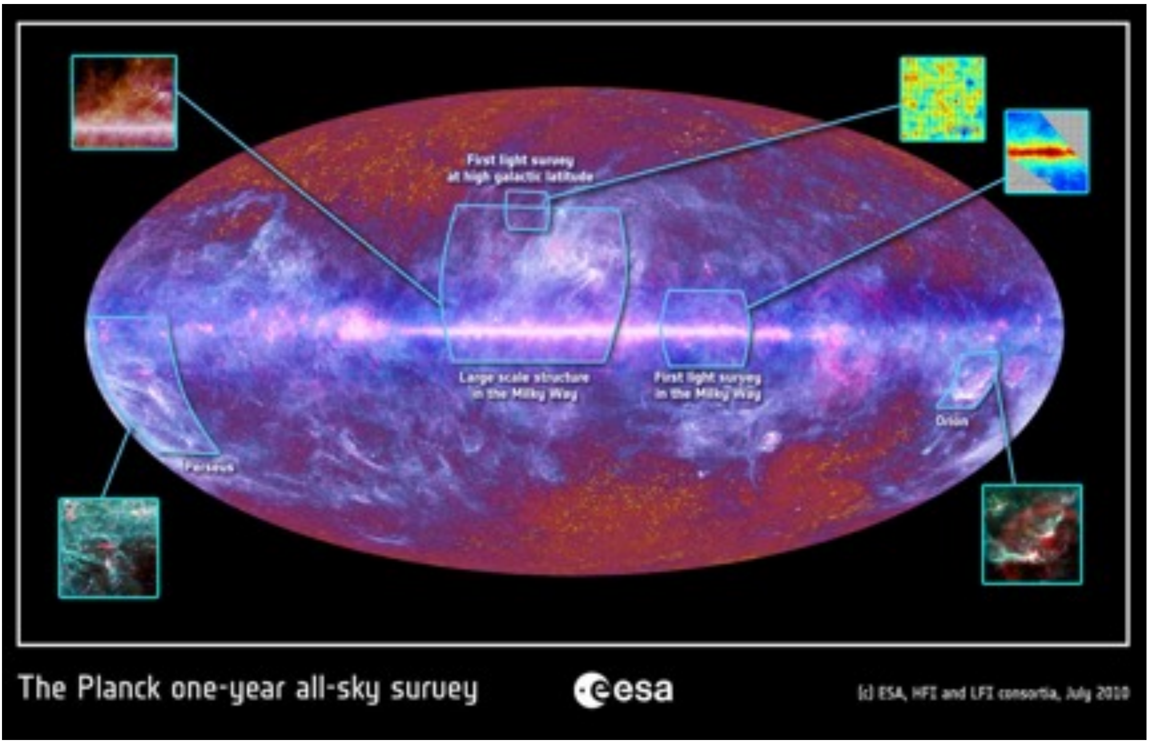
Relevance of cosmic-ray measurements

With CR spectral measurements we can understand the properties of the ISM, and probe sources of high energy CRs. Antimatter CRs indirectly also probe DM. Combine with gamma-ray and radio observations.





Credit: NASA/DOE/Fermi/LAT Collaboration



The Planck one-year all-sky survey

(c) ESA, HFI and LFI consortia, July 2010

Galactic diffuse backgrounds; data and assumptions

Work done with P. Ullio, M. Tavakoli, C. Evoli and L. Maccione

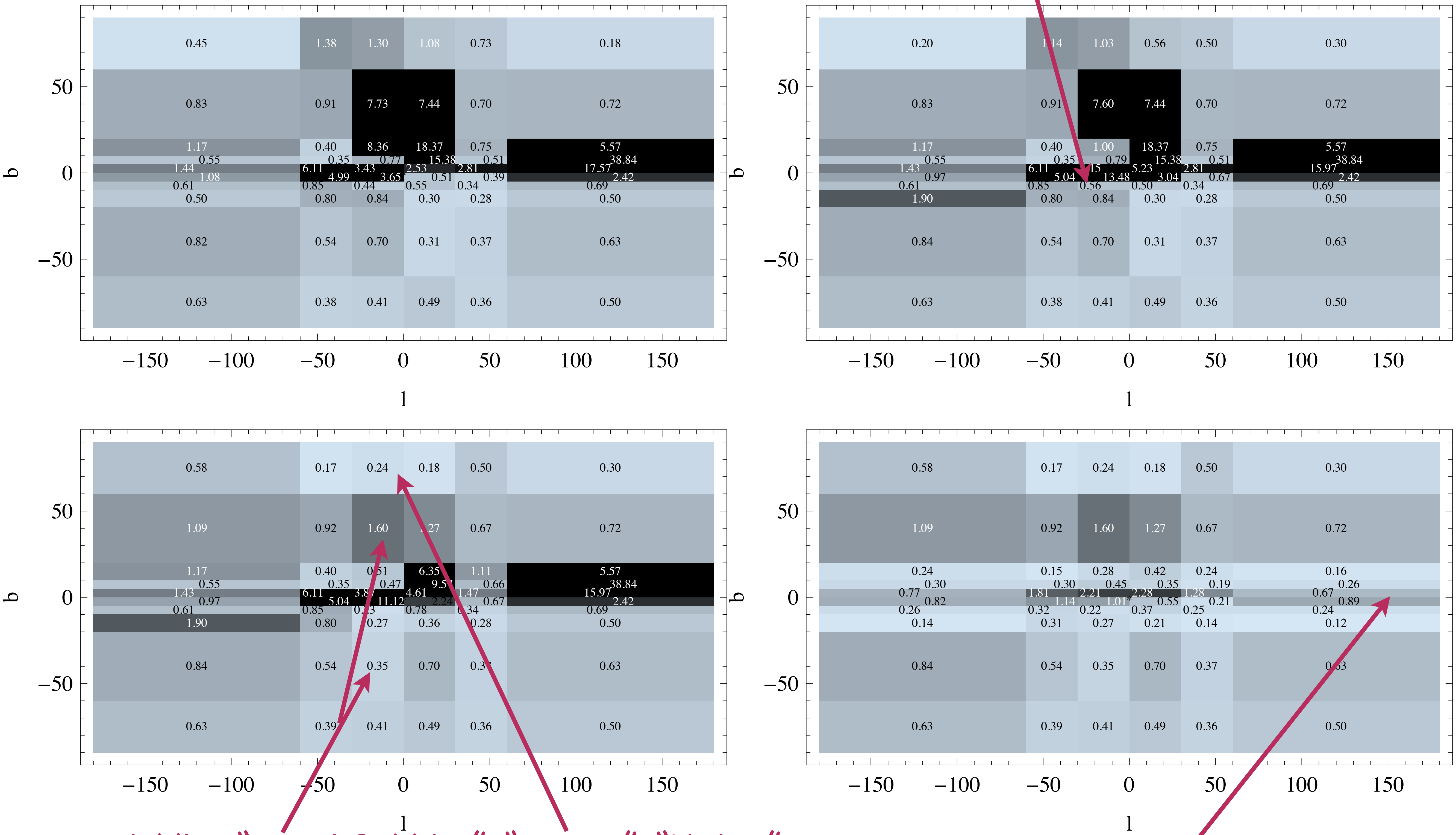
We use the ULTRACLEAN data selection (minimizing CR contamination) after 4yr, with energy between 1 GeV and 200 GeV.
Break the sky in 60 windows and calculate the agreement between the modeled total diffuse gamma-ray spectrum and that from the data.

Cosmic Ray Propagation Model to calculate separately the pi0 and the bremsstrahlung components (from models on HI, H2 and HII ISM gas distribution) and the ICS component. We check for the latter different assumptions for the interstellar medium and their impact on the limits to DM annihilation channels. We also use all the available information from CR data.
Include point sources and extended galactic diffuse sources (dominant at low galactic latitudes).
Include Isotropic Extra-Galactic Gamma-Ray Background.
For conservative DM limits at high latitudes we calculated the minimal non-DM Extragalactic gamma-ray background.

Consistency with Fermi Gamma-ray spectra

Galactic diffuse model from DRAGON CR propagation code

Adding Dust Information ("Dark Gas")

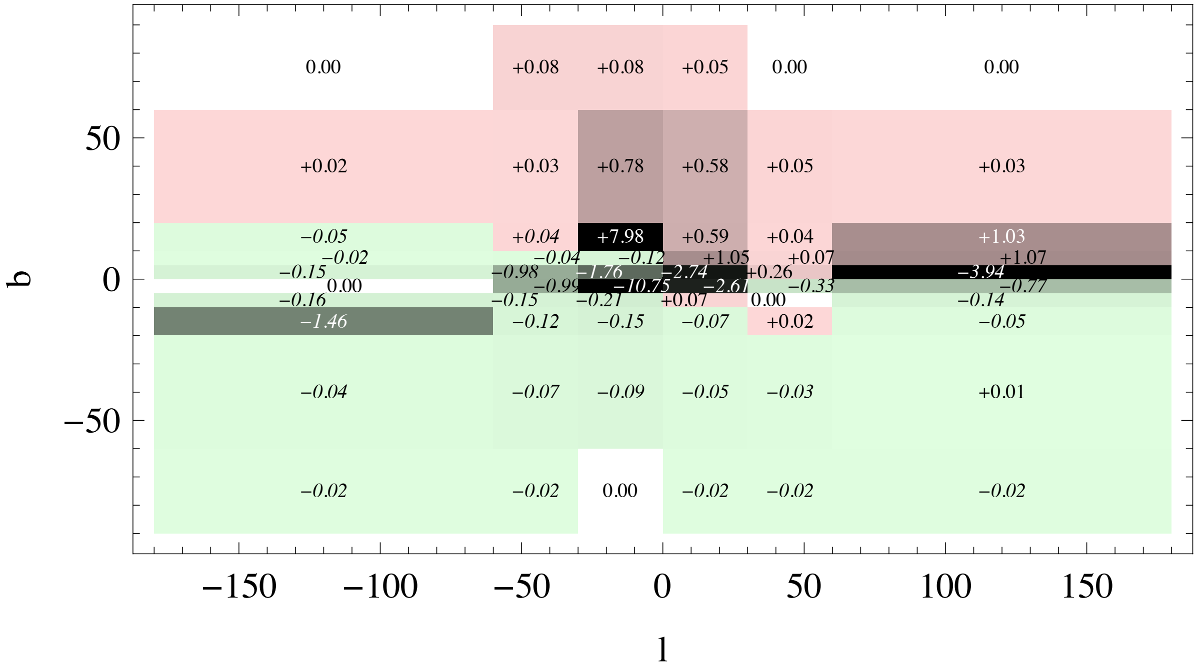


Adding "Fermi Bubbles", "Loop I", "N. Arc"
(see Su, Slatyer, Finkbeiner ApJ 724, 1044, 2010)

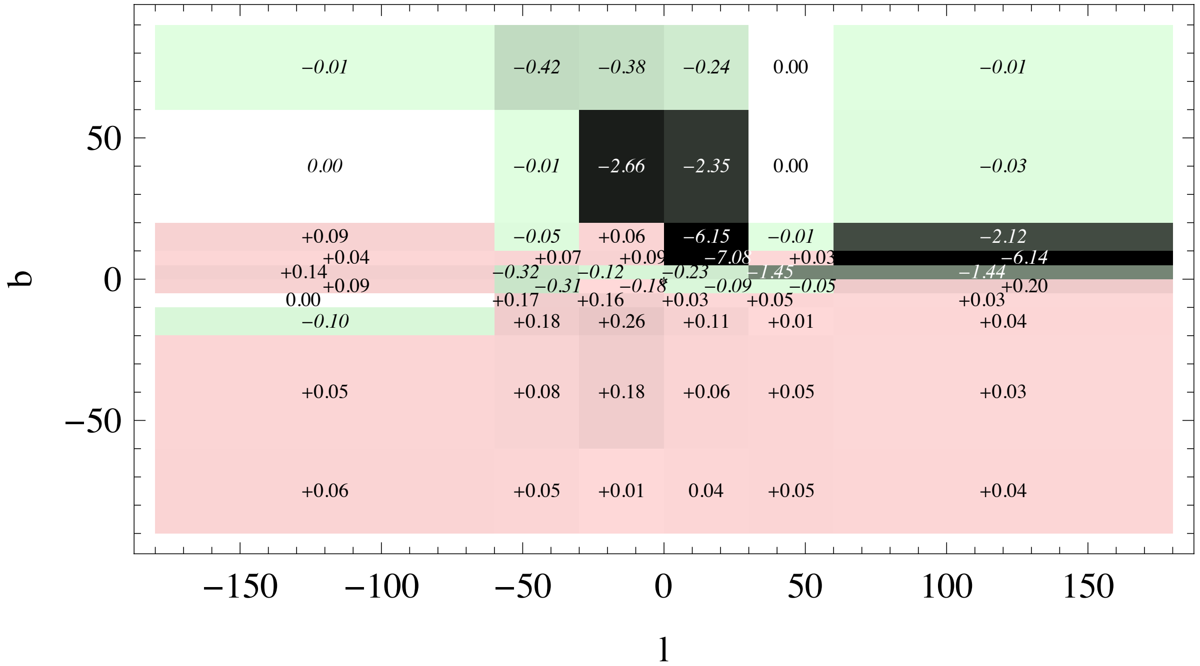
Additional Gas uncertainties

1305.xxxx

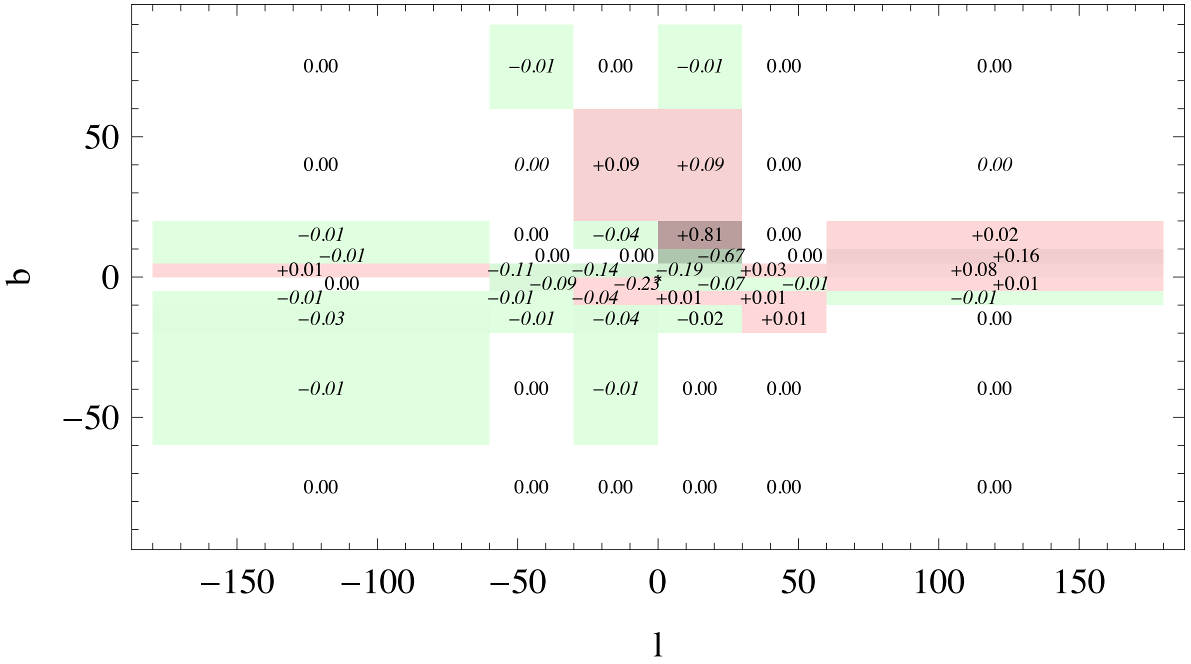
Studying the Gas distribution and Radiation Field uncertainties



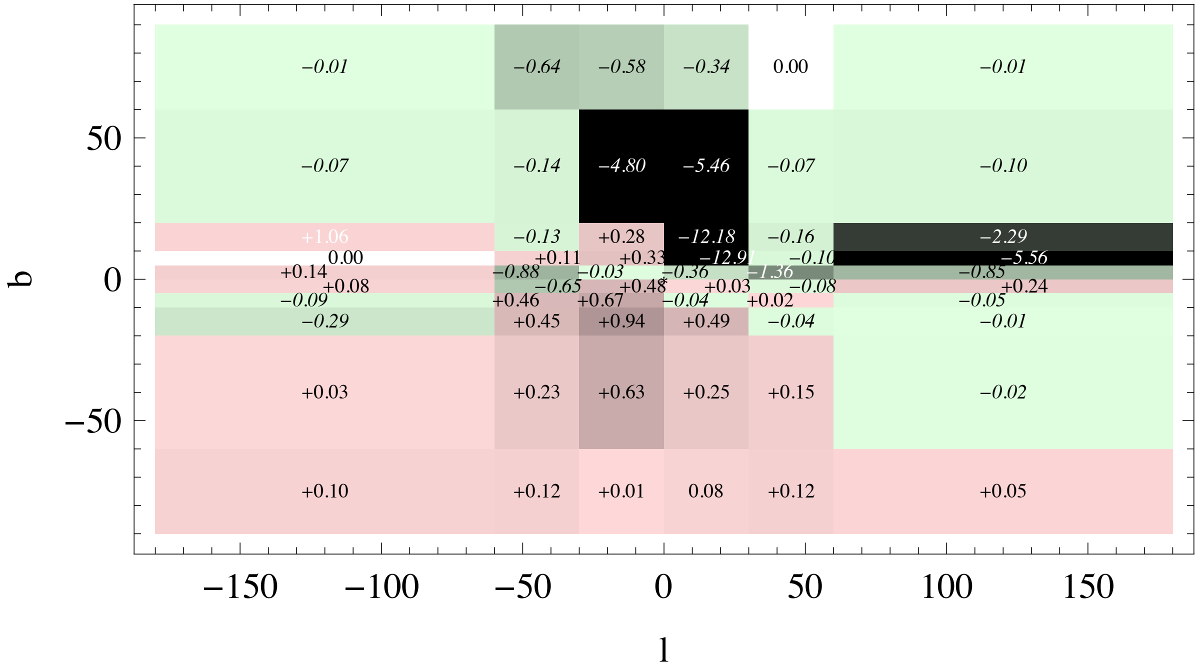
Different ISM gas



Different star disk distribution



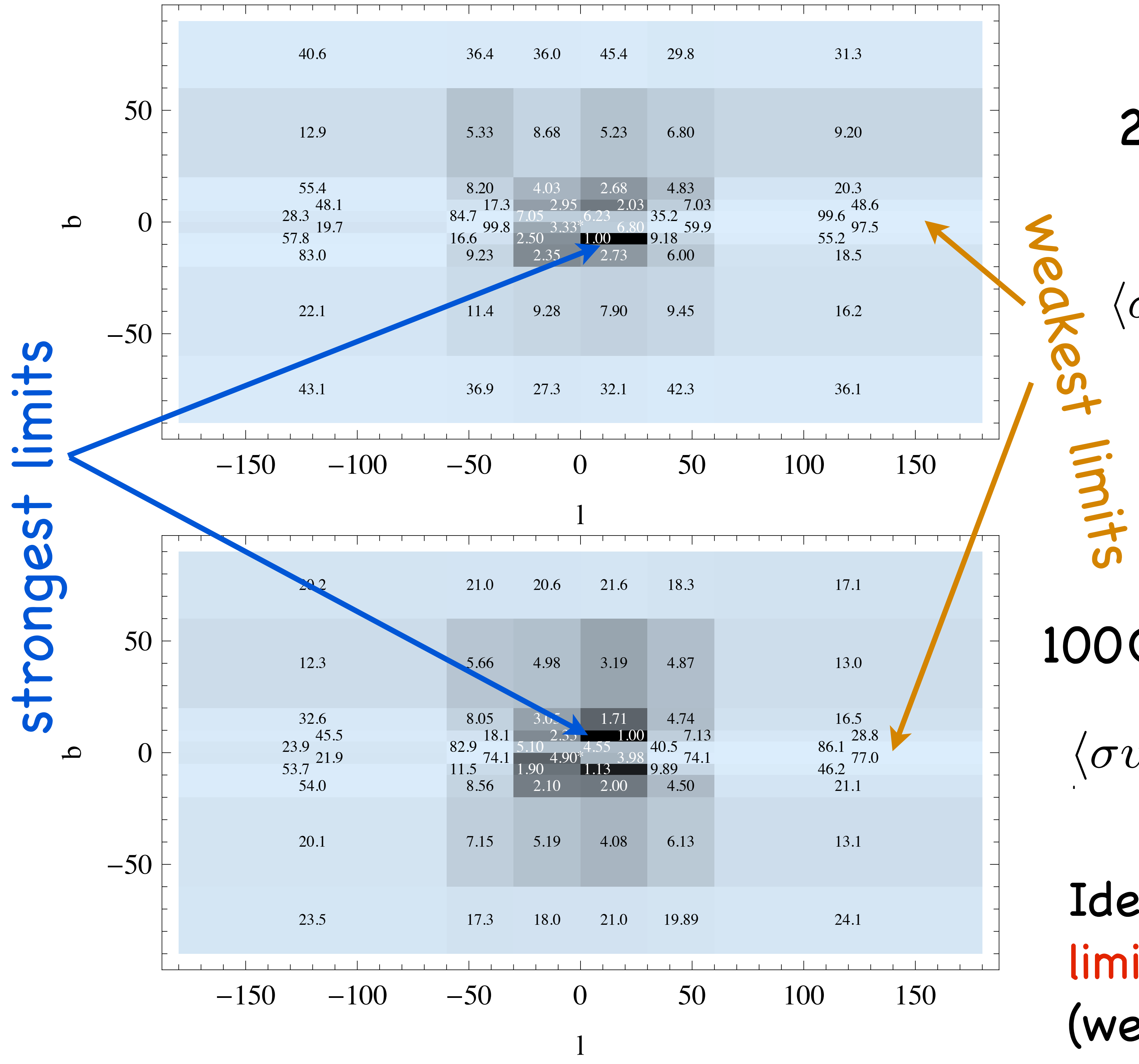
Different star bulge distribution



Different star/ISM composition

Probe systematic uncertainties in the gamma-ray diffuse backgrounds

DMA limits:Two examples on limits from the entire sky



2.5TeV DM annihilating to muons

$$\langle\sigma v\rangle^{3\sigma}_{min} = 1.20 \times 10^{-24}\,\mathrm{cm}^3\mathrm{s}^{-1}$$

$$\langle\sigma v\rangle^{3\sigma} \;/\langle\sigma v\rangle^{3\sigma}_{min}$$

100GeV DM annihilating to Ws

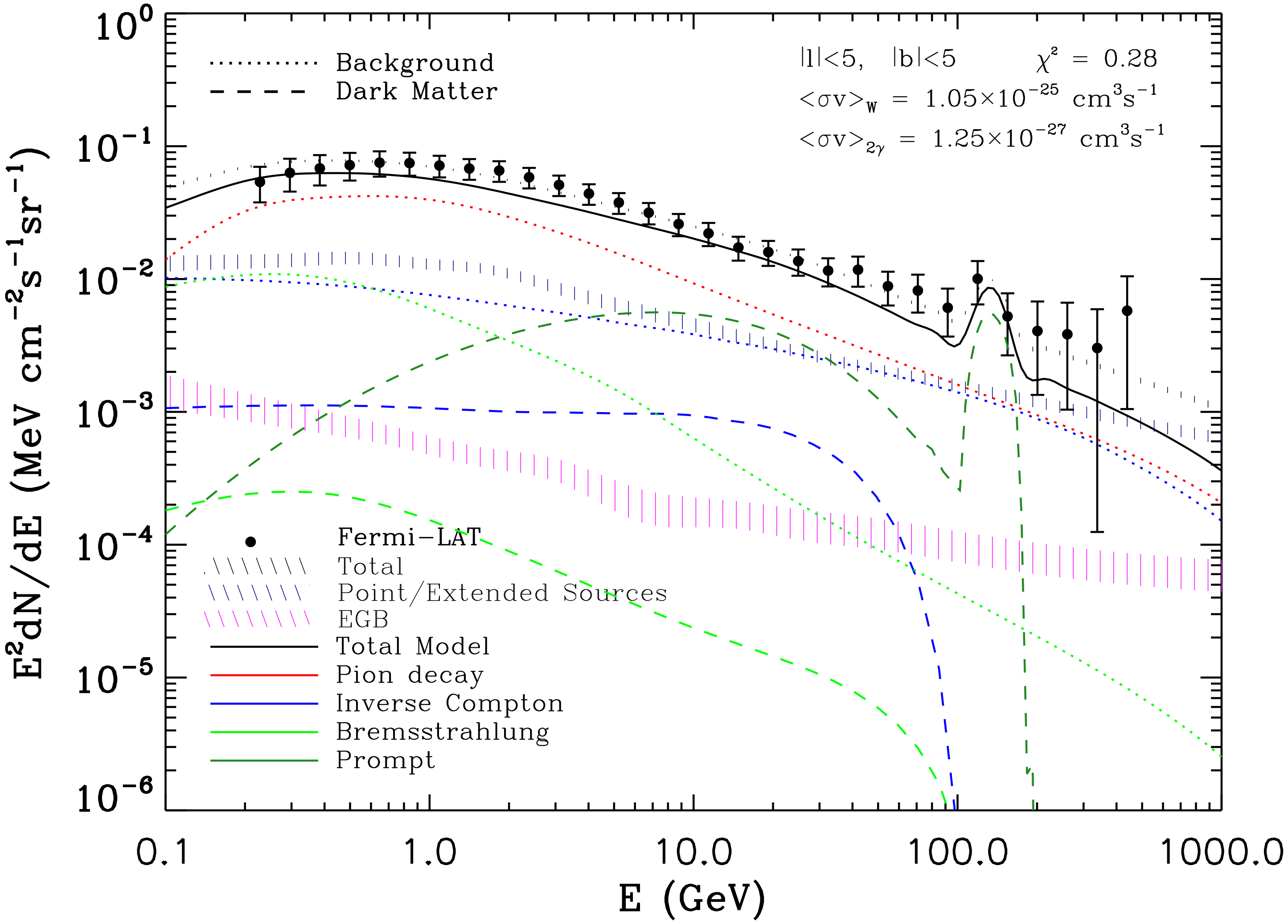
$$\langle\sigma v\rangle^{3\sigma}_{min} = 9.3 \times 10^{-26}\ \mathrm{cm}^3\mathrm{s}^{-1}$$

Identifying regions of robust limits on DM annihilation (weak dependence on background assumptions)

Limits on the Continuous Spectrum associated to the line

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

We expect to have an associated continuum spectrum from annihilations at tree level. Derive constraints for a set of basic channels.



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

Annihilation in a cuspy profile.

Annihilations to:

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

Fluxes can be linearly combined.

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

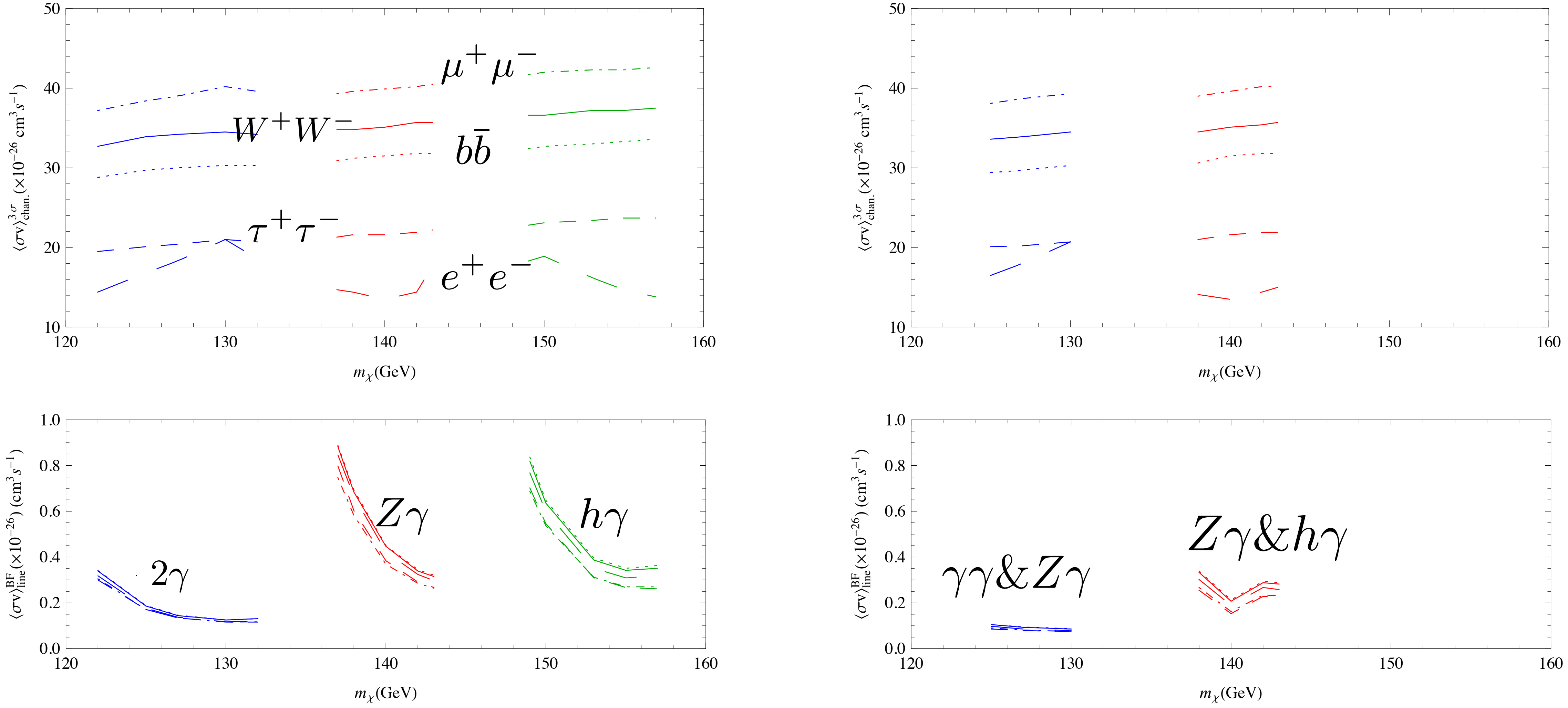
$$\frac{d\Phi_\gamma}{dE} = \int\int \frac{\langle\sigma v\rangle}{4\pi}\frac{dN_\gamma}{dE}_{DM}\frac{\rho^2_{DM}(l,\Omega)}{2\,m_\chi^2}dld\Omega$$

PRD 86, 083525 (2012)
IC, M. Tavakoli, P. Ullio

Limits

single line

double line



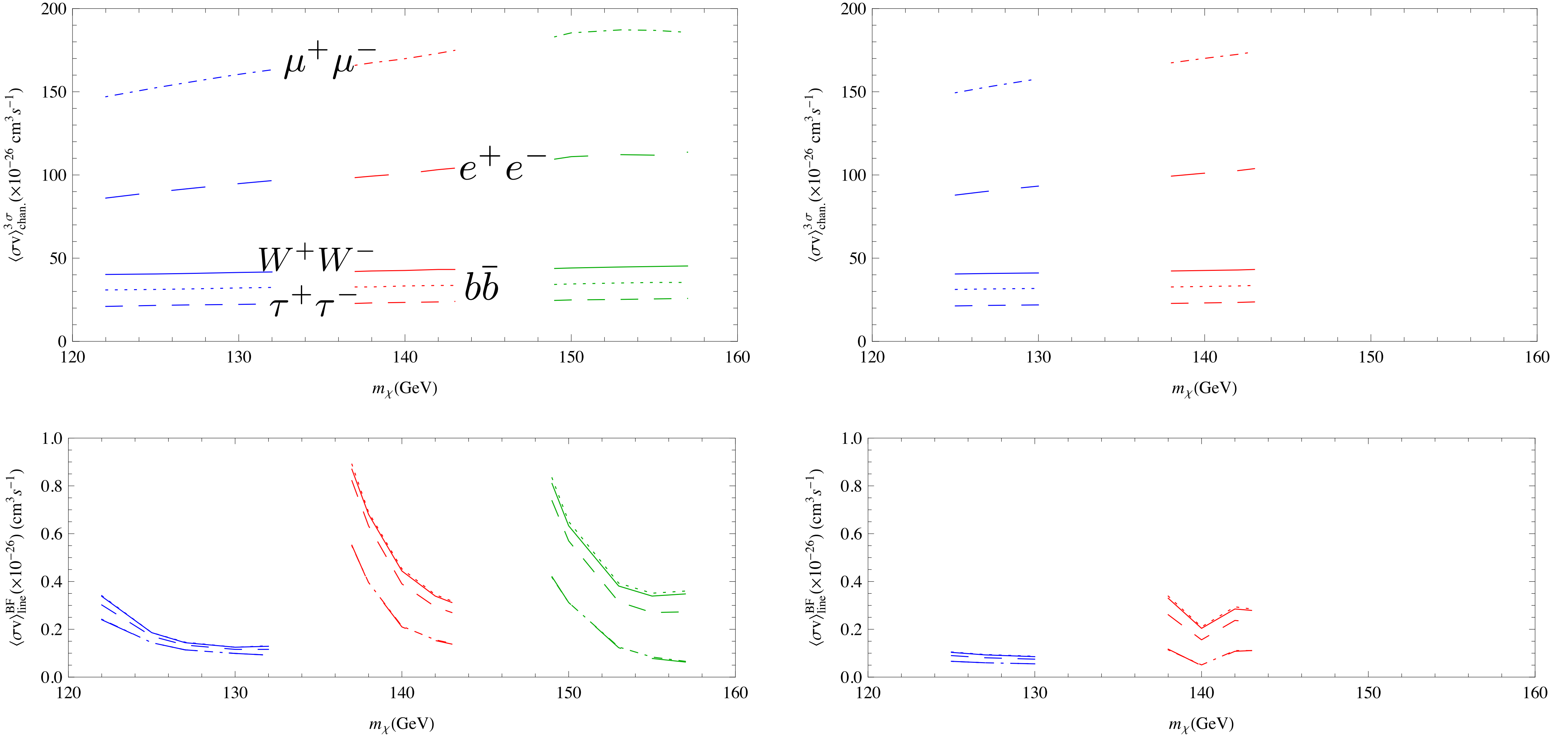
Chan.	Line	127 GeV (2γ)	140 GeV $(Z\gamma)$	150 GeV $(h\gamma)$
W^+W^-	Free	34.2(40.8)	35.1(42.6)	36.6(44.1)
W^+W^-	Fixed	34.5(41.4)	35.4(43.2)	37.2(44.7)
$b\bar{b}$	Free	30.0(31.5)	31.5(33.3)	32.7(34.5)
bb	Fixed	30.3(31.8)	31.8(33.6)	33.0(34.8)
$\tau^+\tau^-$	Free	20.4(21.9)	21.6(23.4)	24.1(24.9)
$\tau^+\tau^-$	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.

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

Conservative limits



Excluding the Inverse Compton scattering component, (assuming a suppressed radiation field towards the GC) from the DM annihilation contribution.

Other analyses

Cohen et al. JHEP 1210, 134, 2012 (1207.0800)

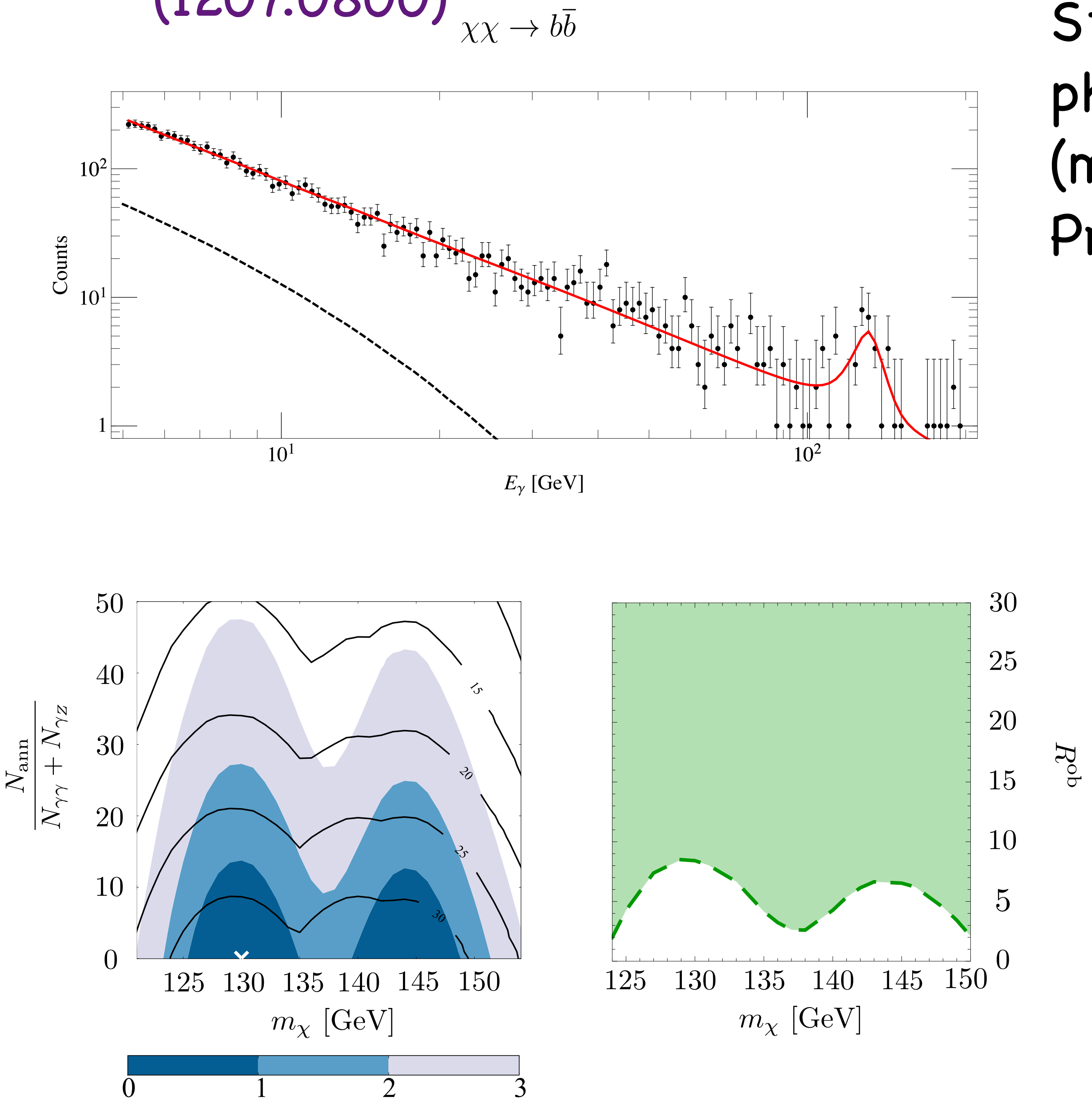
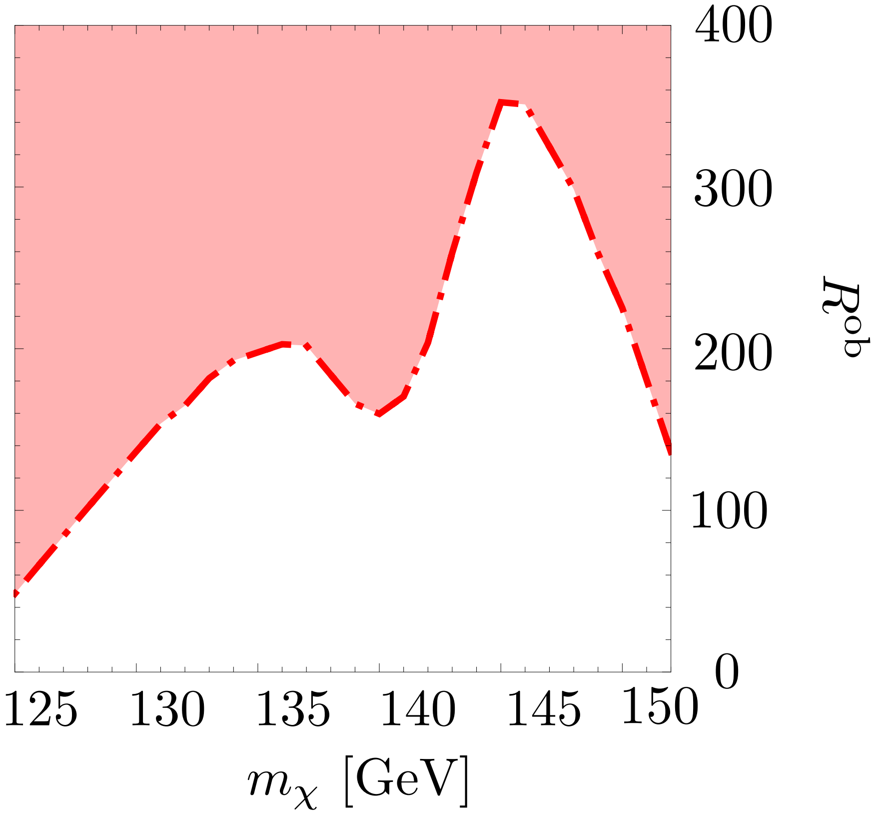


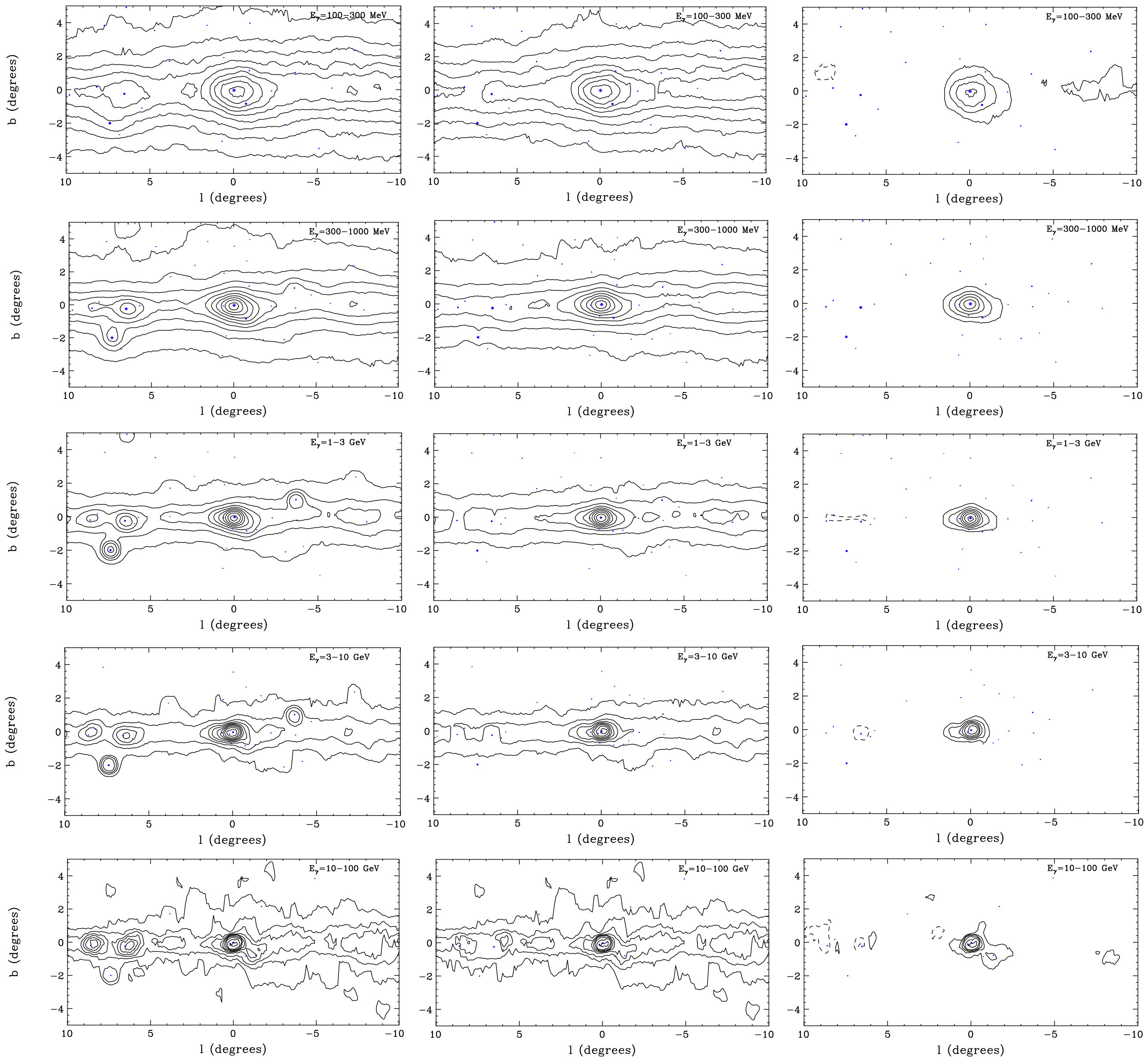
FIG. 9: The *top* plot gives the photon counts within 3° degrees of the Galactic Center with the inner degree masked. The solid red line shows the best fit model, which is given by the white cross in the bottom left plot. This best fit point has $N_{\rm ann} = 0$; for reference the dashed black line shows the continuum spectrum for 130 GeV dark matter annihilating into $b\,\bar{b}$ with an arbitrary normalization. On the *bottom left*, we show 1, 2, and 3 σ confidence regions (filled contours) for $N_{\rm ann}/(N_{\gamma\gamma}+N_{\gamma Z})$ as a function of mass for dark matter annihilation to $b\,\bar{b}$. The ratio $N_{\gamma Z}/N_{\gamma\gamma}$ is allowed to freely vary for each point in the grid. The solid black lines are the contours for $N_{\gamma\gamma}+N_{\gamma Z}$. The best fit point is marked with a cross at $m_\chi = 130$ GeV, $\theta_{\gamma Z/\gamma\gamma} = 0$, and $N_{\rm ann} = 0$. On the *bottom right*, we show the shape analysis constraint. The shaded region corresponds to parameters where the fit is 2 σ or worse with respect to the best fit point.

Stronger constraints, but lack of physical model for background (modeled by a single power-law). Probing the inner most 3 deg.

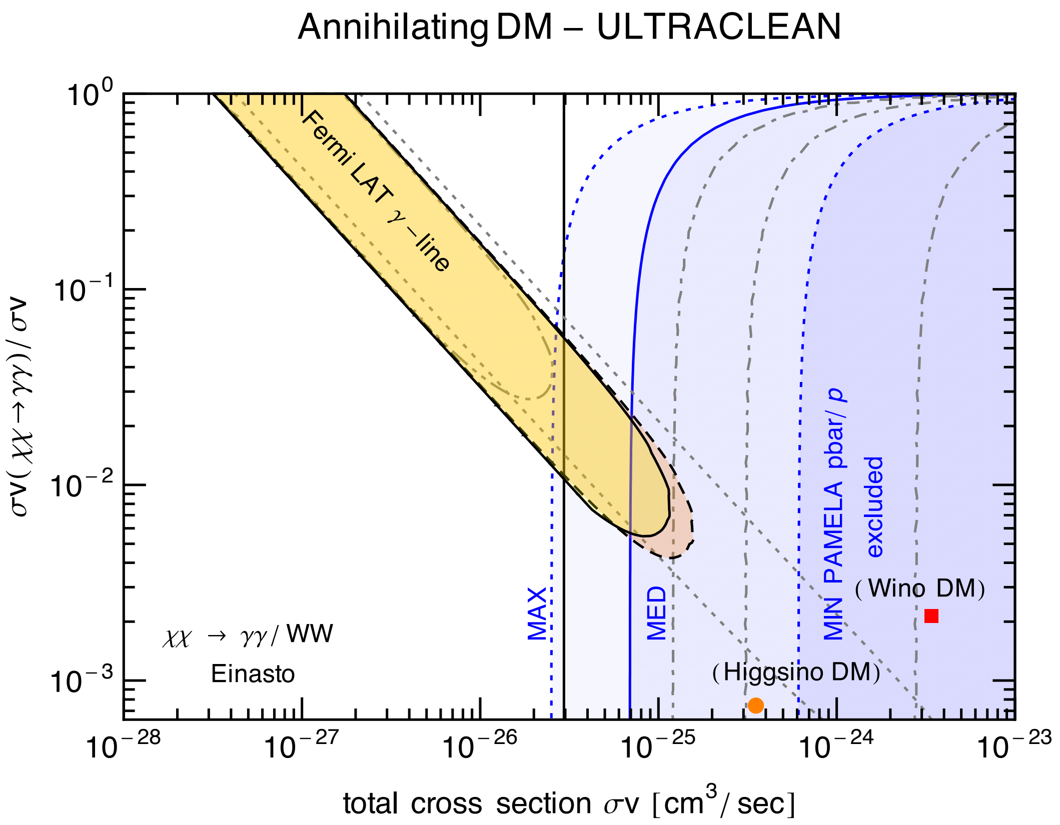
Ignoring background:



Hooper&Linden PRD 84, 123005, 2011 (1110.0006)



Buchmuller&Garny JCAP 1208, 035, 2012 (1206.7056)



Only one energy bin between 10-100 GeV. Good for light DM searches and for DM models that have prompt gamma-ray emission that peaks around ~10-20 GeV. (~100 GeV Wino DM)

A specific example for the line that doesn't work

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

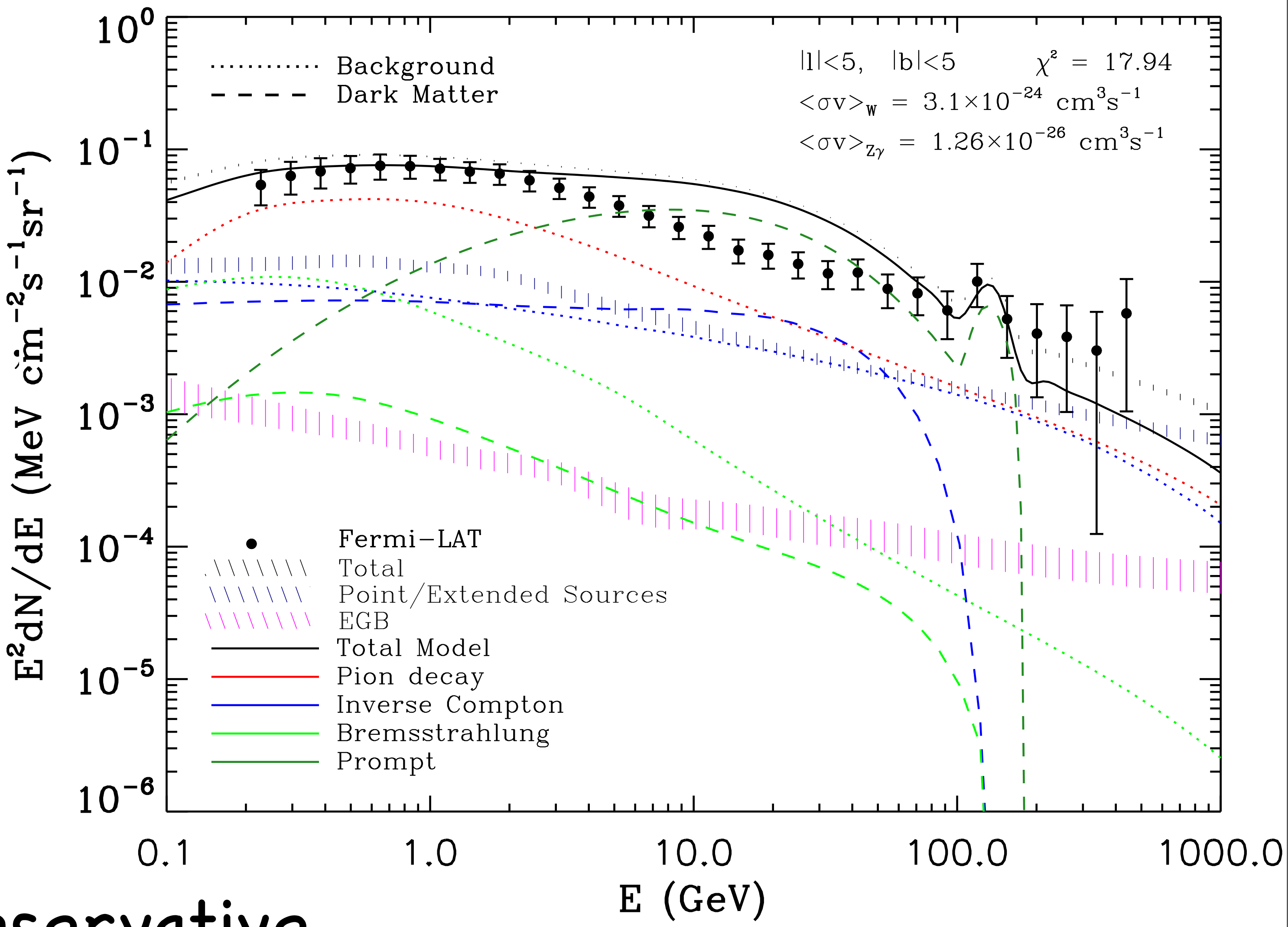
$$m_\chi = 145 \;\; \mathrm{GeV}$$

Cross-section to the line:

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

Total annihilation cross-section:

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

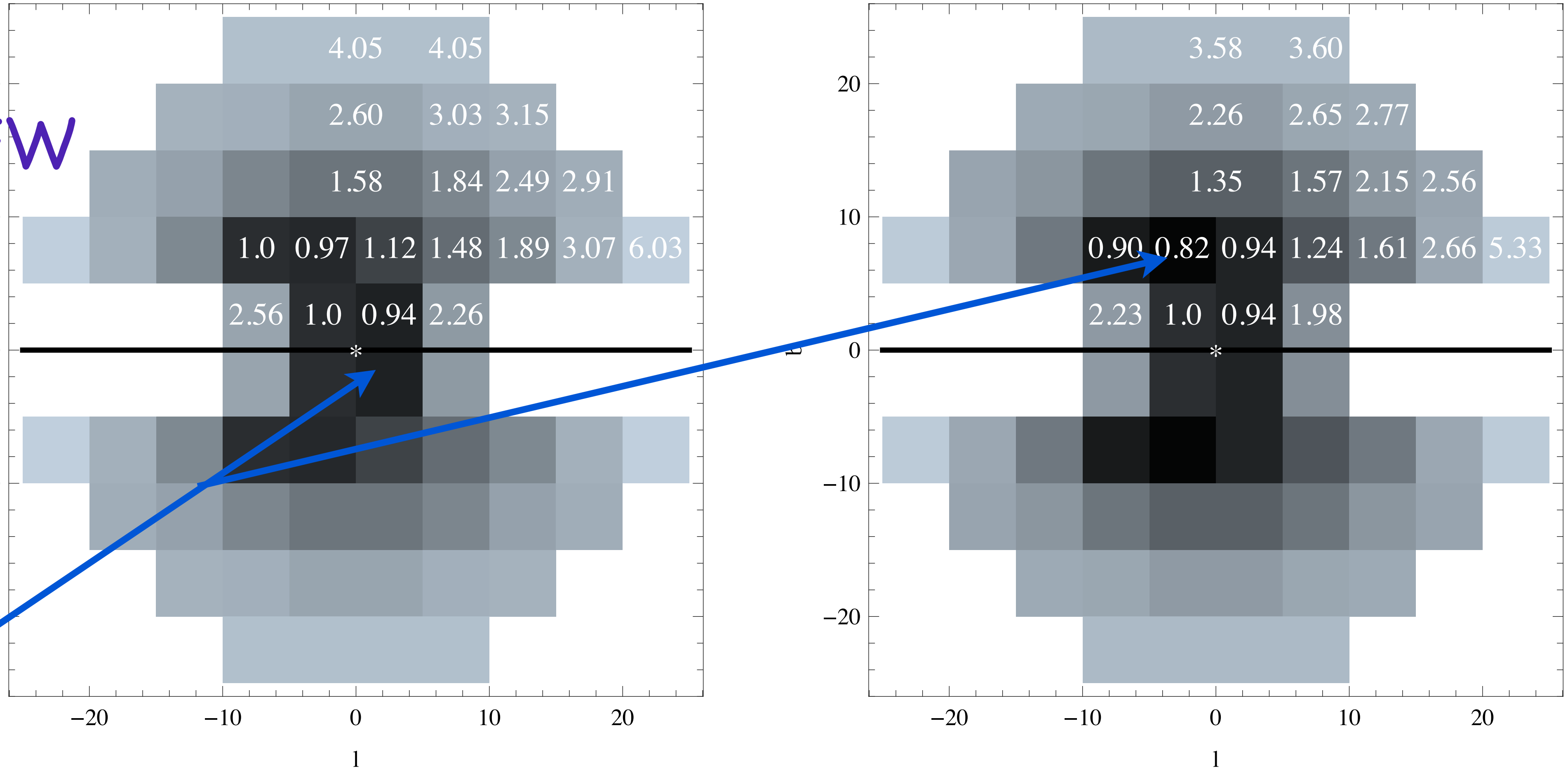


Excluded even by the most conservative limits where no gamma-ray background is included

DM profile from the continuum

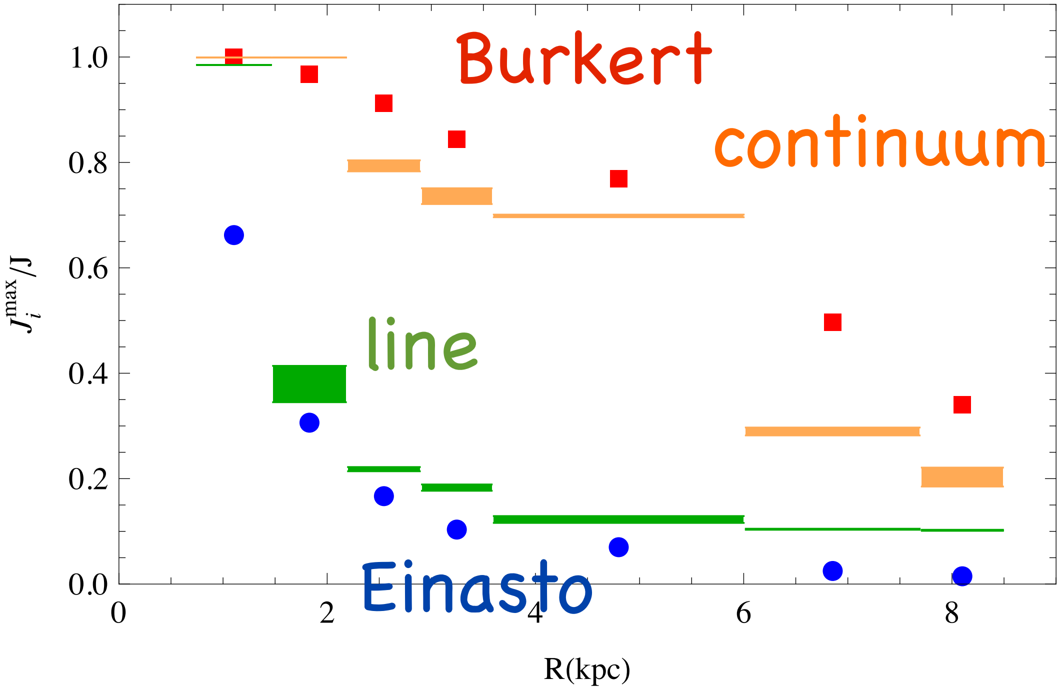
NFW

stronger constraints

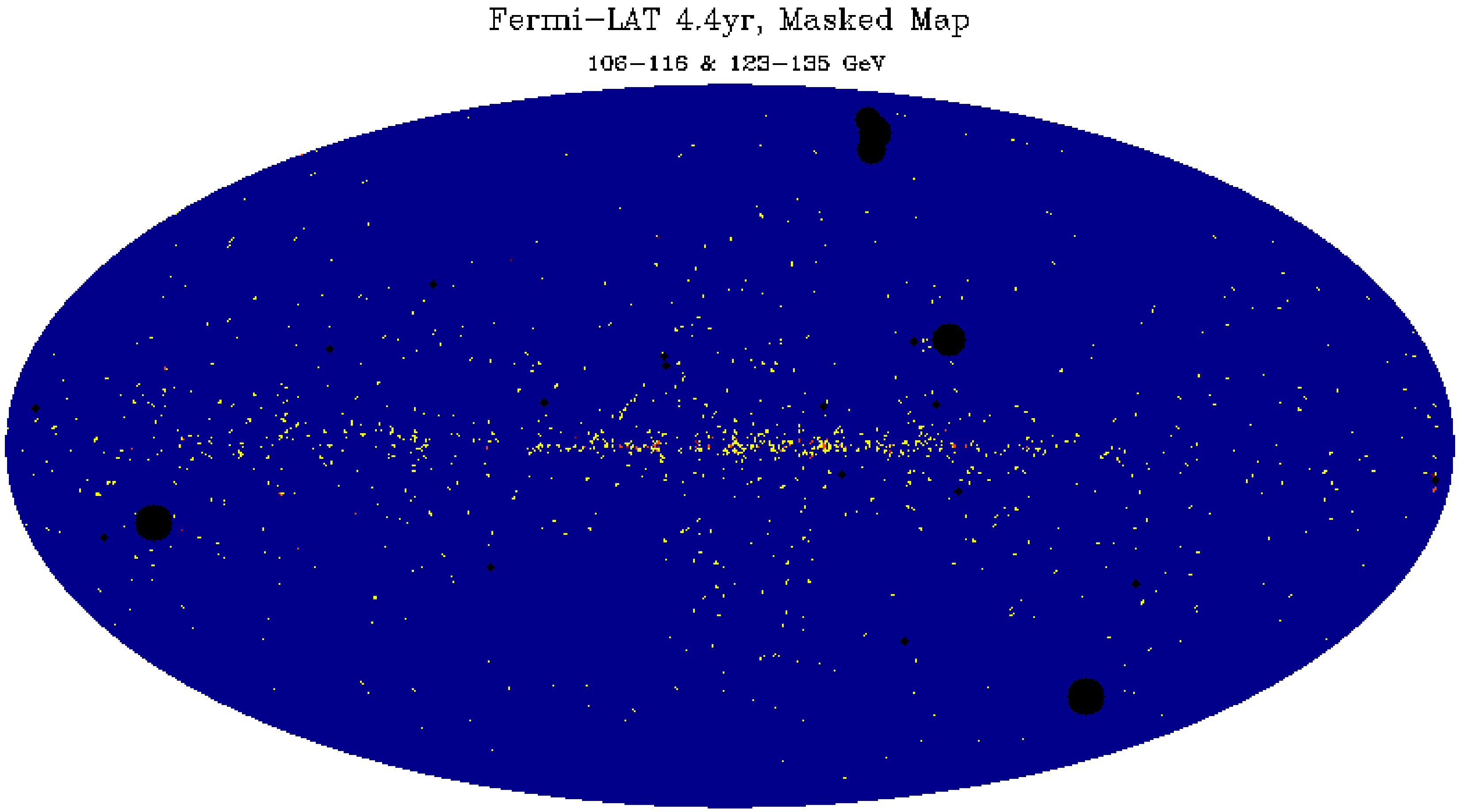


Einasto (with assumptions that lead to less concentrated than the NFW)

Preference for the cuspier DM distribution profiles even from the continuum. Otherwise one gets the tightest limits far from where the line signal is observed to peak.



Using the full-sky line data; Template analysis and DM subhalos; checking consistency on backgrounds and DM profiles



work with H. Santosa, M. Tavakoli and P. Ullio arXiv:1303.5775

Including a dark disk (to account for the unassociated p.s. distribution)

$$\Gamma_{ann} \;=\; \frac{1}{2m_\chi^2}\langle\sigma_{ann} \mid v \mid\rangle \;\times\; \left(\rho_{sph}^2 + \rho_{DD}^2 + 2\rho_{sph}\cdot\rho_{DD} + \rho_{sub}^2\right)$$

Maximizing the likelihood:

$$\ln\mathcal{L} = \sum_i k_i \ln\mu_i - \mu_i - \ln(k_i!)$$

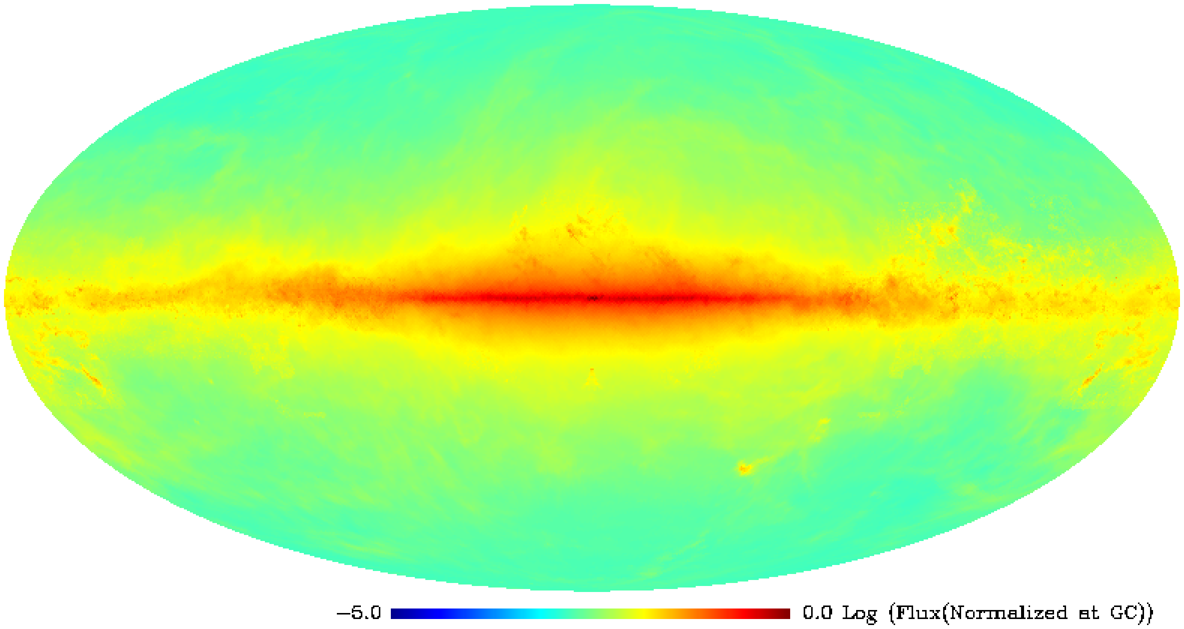
Theoretical model (template based):

$$\begin{aligned}\mu_i \;&=\; N\cdot \mathrm{Back}_i + A\cdot[(2-\alpha)^2\cdot \mathrm{SphDM}_i \\ &+\; \alpha^2\cdot \mathrm{DarkDisk}_i + \alpha(2-\alpha)\cdot \mathrm{MixedDM}_i \\ &+\; \mathrm{SubDM}_i] + B\cdot \mathrm{Iso}_i.\end{aligned}$$

Template analysis, examples

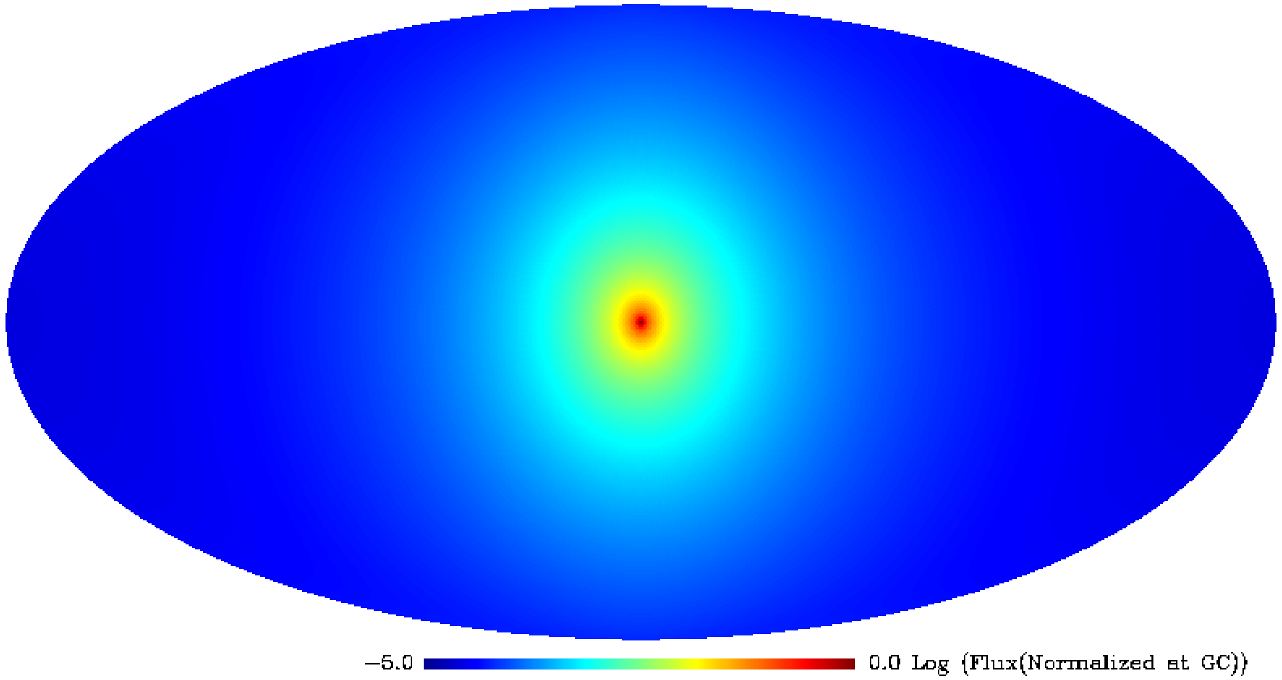
Galactic Diffuse Background at 106−116 & 123−135 GeV

"Back" template



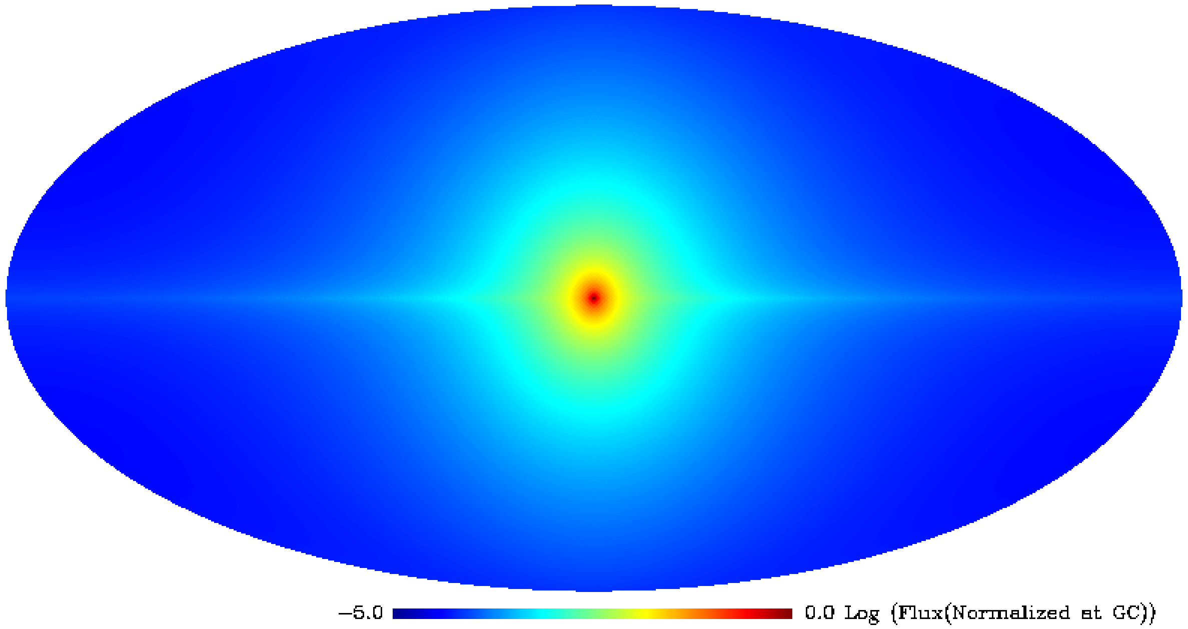
Spherical DM halo

"SphDM" template



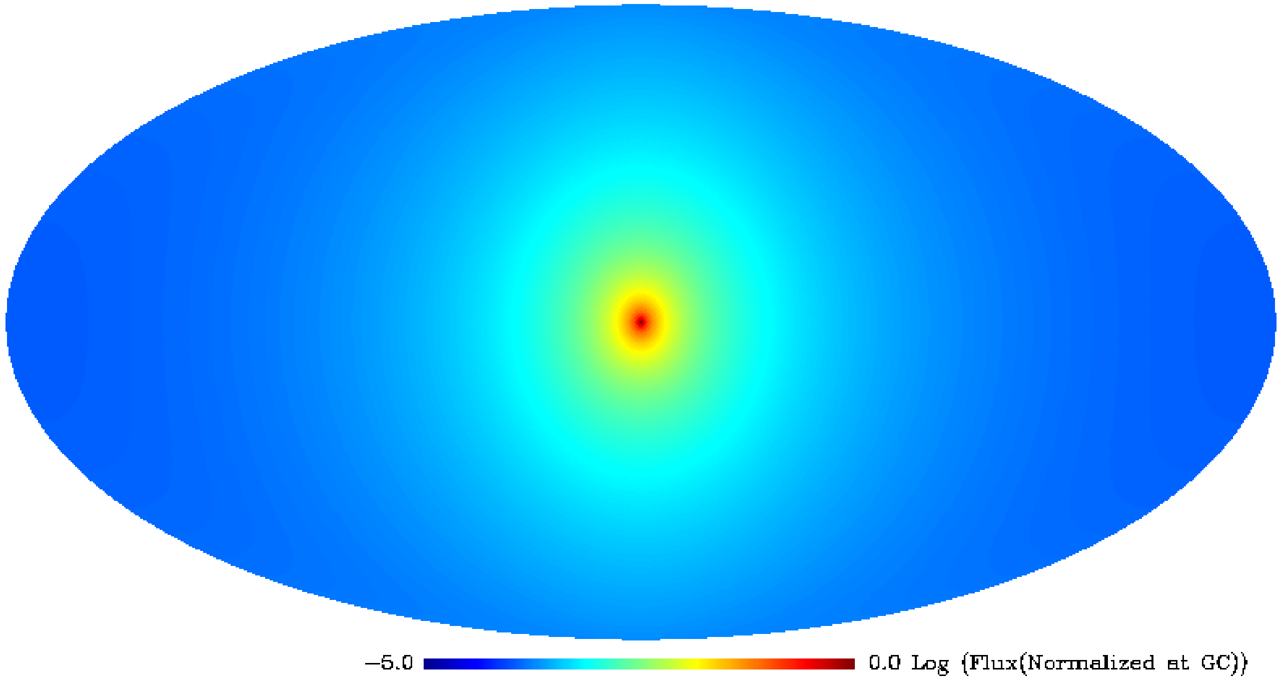
Spherical DM halo with a maximal dark disk Template

"SphDM" + "DarkDisk" + "MixedDM" combined template



Spherical DM halo & substructures

"SphDM" + "SubDM" template



$$\rho_{sph}(r) = \rho_{Ein} \exp\left\{-\frac{2}{\delta}\left[\left(\frac{r}{r_c}\right)^{\delta} - 1\right]\right\}$$

$$\rho_{DD}(R,z) = \rho_{0_{DD}} \exp\left[\frac{1.68\,(R_{\odot} - R)}{R_{1/2}}\right] \exp\left[-\frac{0.693\,|z|}{z_{1/2}}\right]$$

Testing different assumptions and robustness of DM template signal

$\times 10^{-28}$ cm^3 s^{-1}

DM profiles / Backgrounds	σv	F_{iso}	Back ph.	DM ph.	Iso ph.	TS
Ein. ($\delta = 0.13$) / Back A	1.5 (4.5)	5.73	1146	40 (121)	214	9.1
Ein. ($\delta = 0.17$) / Back A	2.2 (7.1)	5.55	1146	43 (138)	207	6.1
Ein. ($\delta = 0.22$) / Back A	2.7 (8.5)	5.38	1157	41 (127)	201	2.8
Ein. ($\delta = 0.13$) / Back B	1.6 (4.8)	5.87	1134	44 (129)	219	11.9
Ein. ($\delta = 0.13$) / Back C	1.5 (4.6)	5.81	1144	39 (124)	217	9.2
Ein. ($\delta = 0.13$) / Back D	1.3 (4.3)	6.05	1137	36 (115)	226	7.8

$$TS \equiv -2ln\frac{\mathcal{L}_{null}}{\mathcal{L}_{bestfit}}$$

DM positive TS is independent of diffuse background assumptions (taken to be within the studied range of background uncertainties).

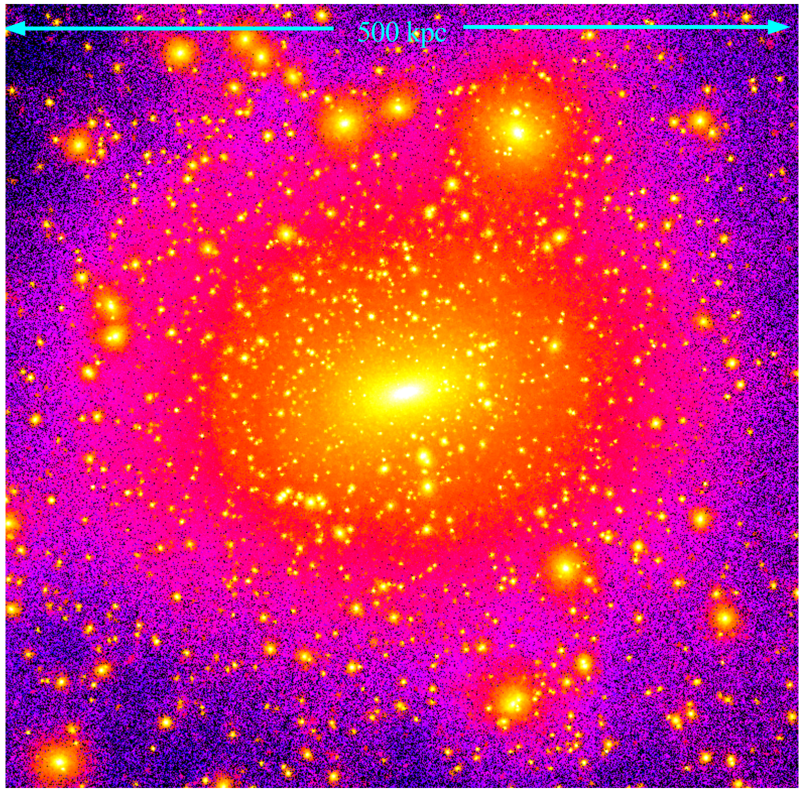
DM distribution profile cuspy-ness is as suggested from smaller angular windows gives a positive TS only for the most concentrated DM profiles. DM decay CAN NOT explain such a line signal morphologically neither in small nor at large angular scales.

DM profiles / Backgrounds	σv	F_{iso}	Back ph.	DM ph.	Iso ph.	TS
Ein. ($\delta = 0.13$); DD $z_{1/2} = 0.5$ / Back A	2.8	5.72	1143	43	213	8.7
Ein. ($\delta = 0.13$); DD $z_{1/2} = 1.0$ / Back A	2.6	5.69	1144	42	212	8.0
Ein. ($\delta = 0.13$); DD $z_{1/2} = 1.5$ / Back A	2.5	5.64	1146	43	210	7.7
Ein. ($\delta = 0.13$); DD $z_{1/2} = 3.0$ / Back A	2.4	5.60	1145	45	209	7.6
Ein. ($\delta = 0.17$); DD $z_{1/2} = 0.5$ / Back A	4.2	5.56	1143	49	208	5.6
Ein. ($\delta = 0.22$); DD $z_{1/2} = 0.5$ / Back A	4.7	5.40	1154	43	201	2.4
Ein. ($\delta = 0.13$); DD $z_{1/2} = 0.5$ / Back B	3.1	5.91	1130	48	221	11.5
Ein. ($\delta = 0.13$); DD $z_{1/2} = 0.5$ / Back C	2.8	5.79	1141	43	216	9.0
Ein. ($\delta = 0.13$); DD $z_{1/2} = 0.5$ / Back D	2.5	6.04	1135	38	225	7.5

Only a thin dark disk, is preferred by the template fits (morphologically). Our isotropic gamma-ray calculations also add up into the isotropic gamma-ray measurement.

DM subhalos bound in the Milky Way?

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

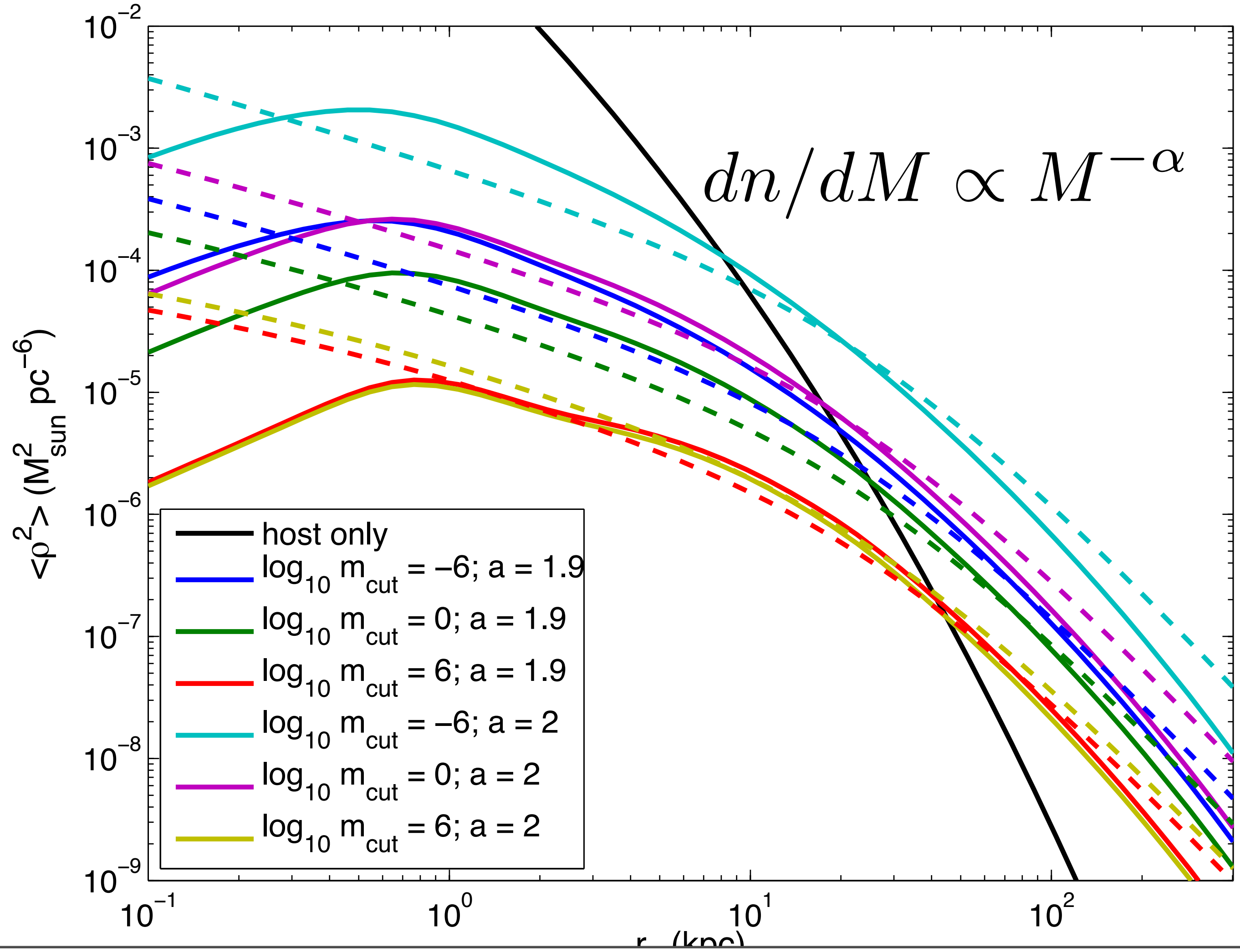


Calculate the number of line photons per subhalo for the given period of observation:

$$N^{ch} = \mathcal{N}_{\gamma}^{ch} \frac{\langle \sigma_A v \rangle_{ch}}{2} \frac{L}{m_{\chi}^2} \frac{\tau_{exp} A_{exp}}{4\pi\lambda^2}$$

Simulation Assump.	Q.A	Q.B
VLII	0 (0)	0.213 (0.024)
biased - case I	0.0198 (0.00344)	0.473 (0.0874)
biased - case II	0.0139 (0.0024)	0.342 (0.0618)
anti-biased - case I	0.0746 (0.0176)	1.24 (0.296)
anti-biased - case II	0.0898 (0.0196)	1.62 (0.361)

TABLE I: Relevance of substructures for detection of the monochromatic photons as referred to the questions A to B as posed in the text, using cross section which fits GC (fits the whole sky). Answers are provided in case of the subhalo sample from the VLII simulation itself and from extrapolations of it in case of biased or anti-biased distributions with the parameter choice $m_{cut} = 10^3\,M_\odot$ & $a = 1.9$ (case I) and $m_{cut} = 10^{-6}\,M_\odot$ & $a = 2$ (case II). Changing the overall normalization of the subhalo number density would shift the results provided in the table accordingly, e.g., by a factor of about 2 if adopting the normalization of the Aquarius simulation [46].



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 the 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.

Conclusions: Filling in the picture: Constraints on the line DM annihilation from gamma-ray spectrum and morphology

- Study on the spectrum in the inner part of the Galaxy where the line has been detected suggest a suppressed cross-section to the associated continuum by O(1000) compared to the expected... In general for annihilating DM in the galaxy limits are stronger from the inner few degrees but suffer also from strong extrapolations on the main DM halo and form background assumptions at high energies (small statistics of high E gammas)

- Robust constraints can come from regions off the galactic disk where backgrounds are under better control (typically larger windows). Even after taking these into account line is still too bright compared to a non-detected associated continuum emission.

- at high latitudes: extragalactic DM annihilation at high redshifts OR considering the case of annihilating DM from the main halo (without/or including substructure). Leads to suppression of the annihilation rate to the line. Derived from both morphologic and spectral arguments

- Limits can also come from CRs (tightest for generic hadronic channels come from antiprotons but possibly in the future from anti-deuterons, also CMB power spectra, relic density calculations (for Sommerfeld enhanced models).

Thank you