The Gamma Ray Line and Some Tests

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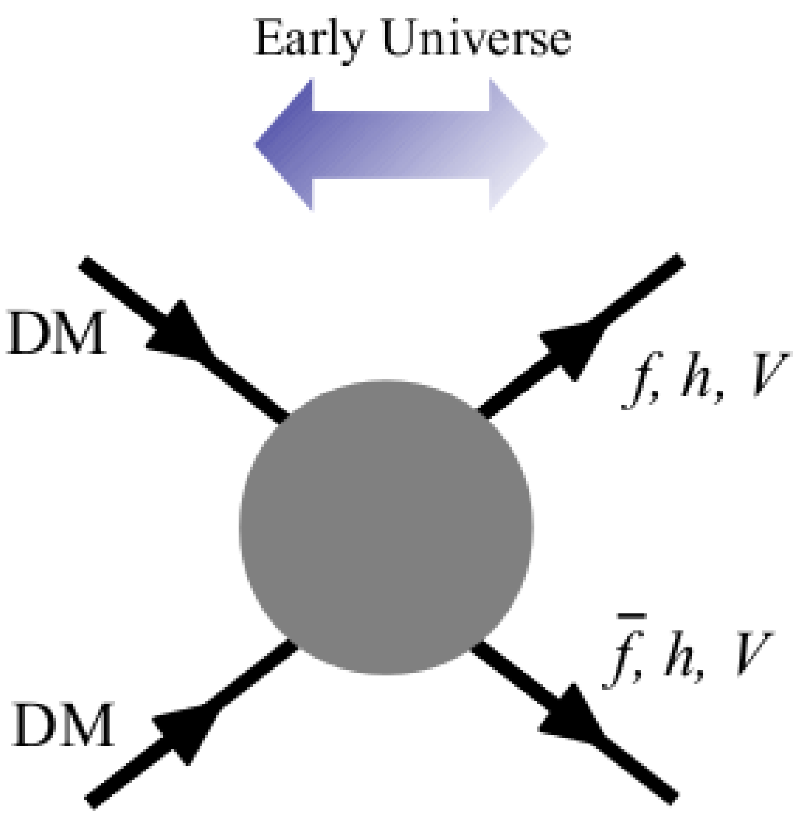
NAOC

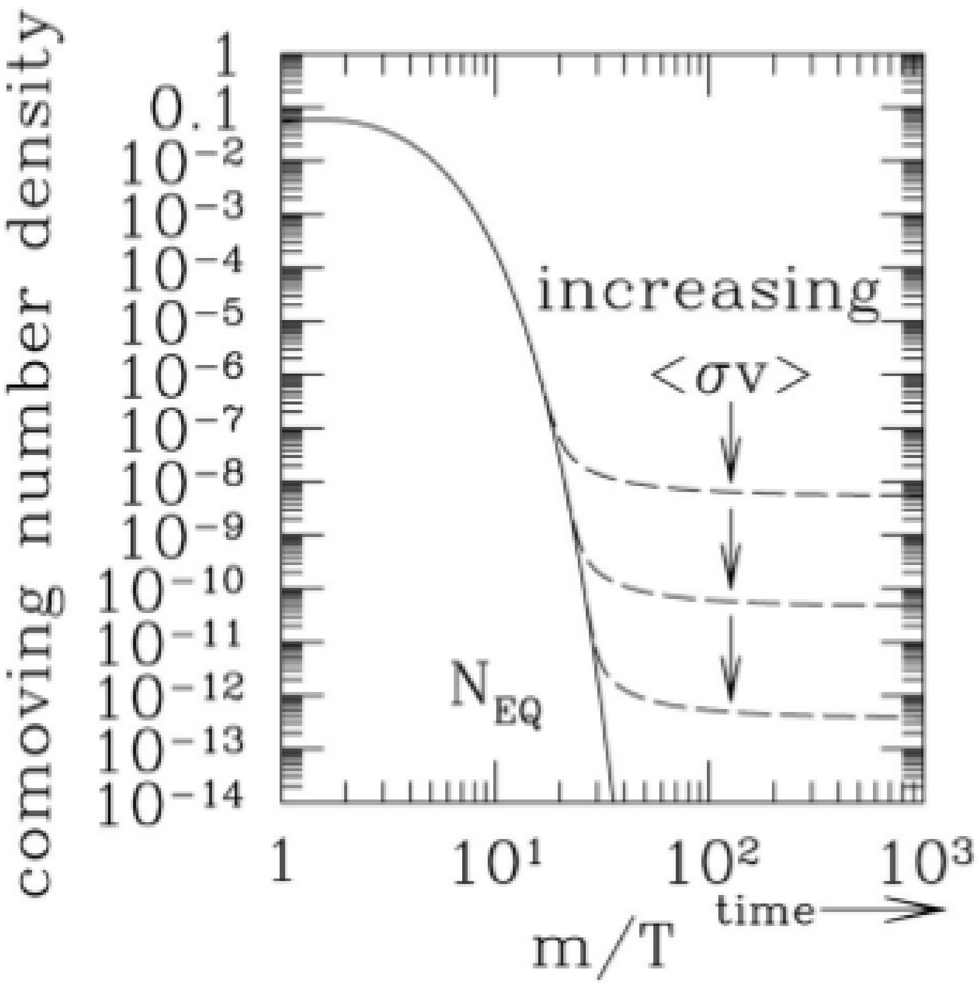
Based on JCAP 1207 (2012) 054, JCAP 1211 (2012) 048,
and work in progress with Qiang yuan, Xuelei Chen and Liang Gao

Dark matter annihilations: standard picture

From Ibarra's talk

Thermal production of WIMPs



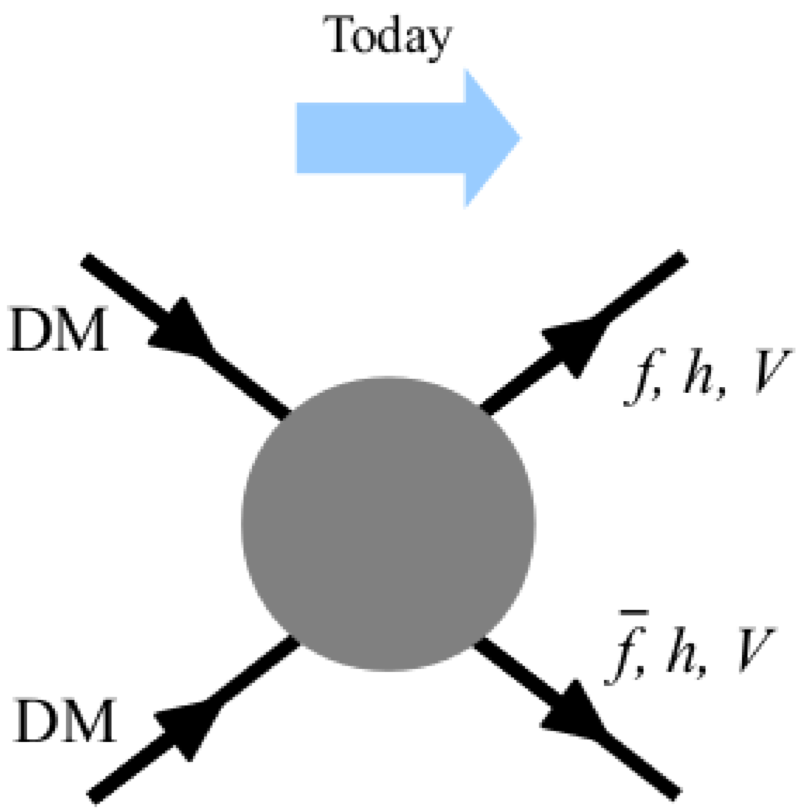


$$\Omega_{\rm DM} h^2 \simeq 0.11 \times \frac{3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}}{\langle \sigma_{\rm ann} v \rangle}$$

Dark matter annihilations: standard picture

Annihilations in galactic dark matter haloes

From Ibarra's talk

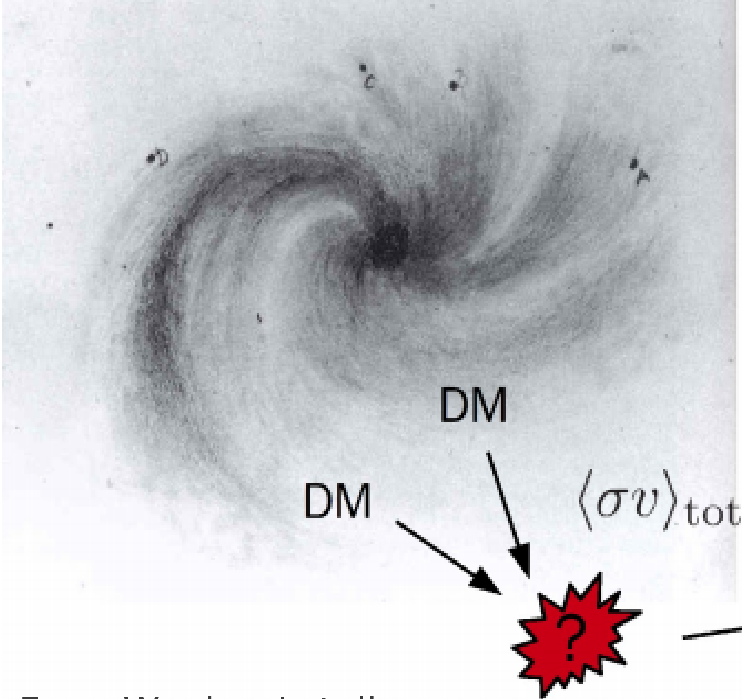


Canonical value of the velocity weighted annihilation cross-section

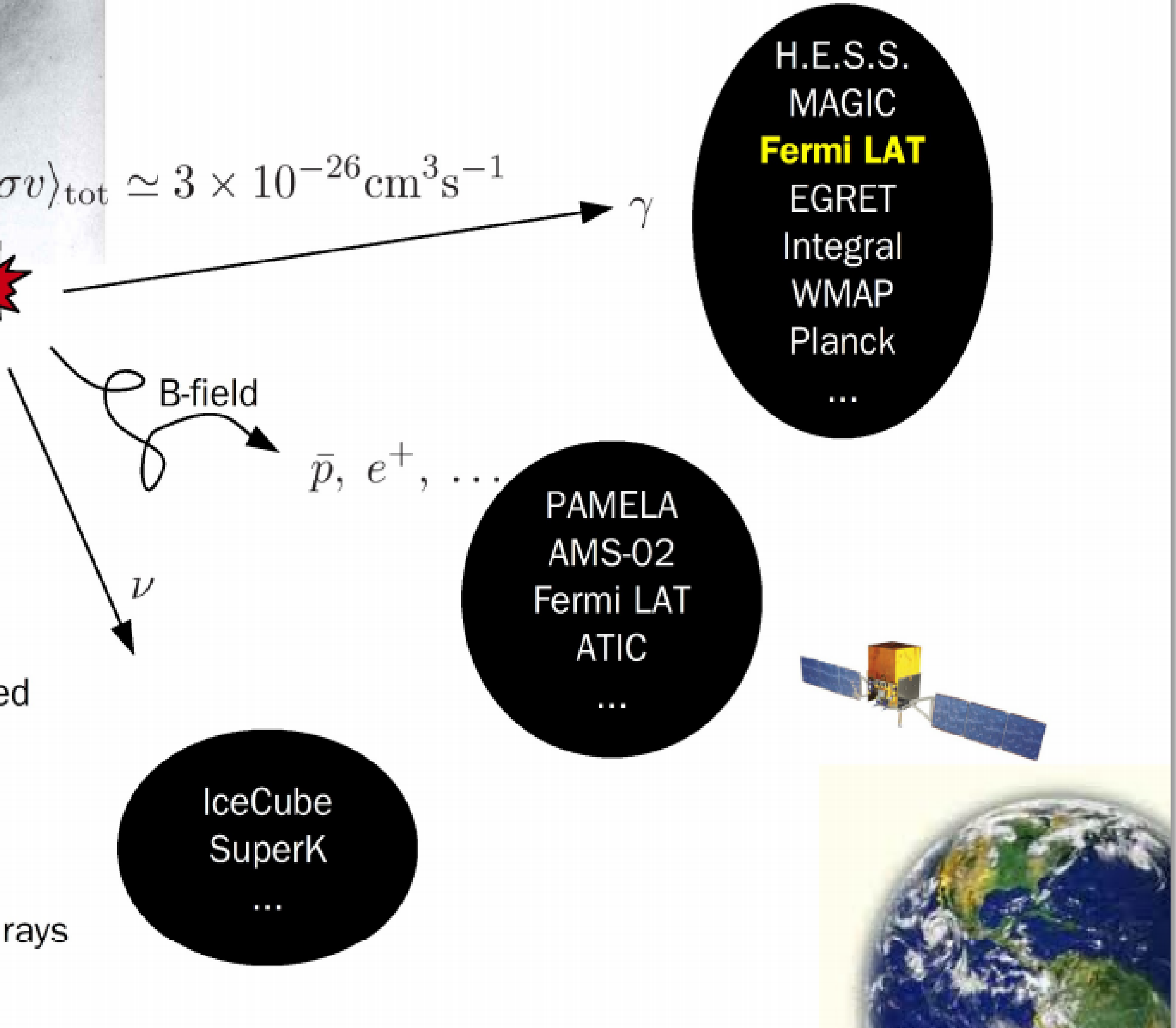
$$\boxed{\langle \sigma_{\rm ann} v \rangle \simeq 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}}$$

Target value for experiments

Indirect Dark Matter Searches



From Weniger's talk



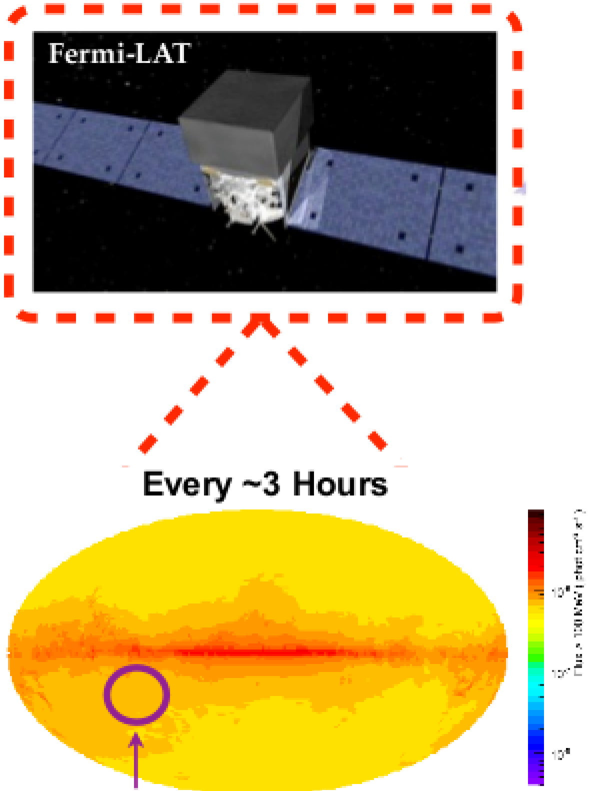
Searching WIMPs

- „Weakly Interacting Massive Particles"
- Compatible with observed relic density due to self-annihilation in early Universe
- Still annihilate today
  → contribute to cosmic rays

Features of Fermi-LAT

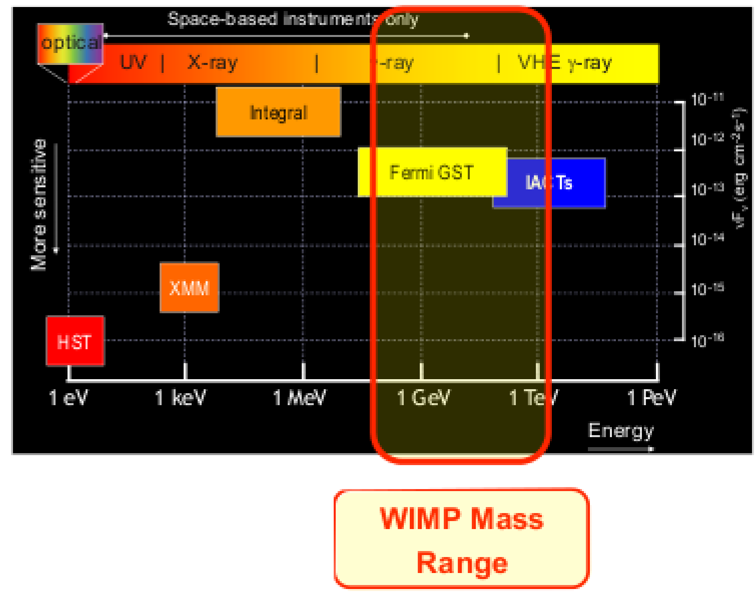
From Fermi Collaboration's talk

Large field of view: 20% of the sky at any instant!



ground based gamma ray telescopes are pointing, ~few degree field of view.

Energy range: 20 MeV to >300 GeV (~M_Z, ideally suited for WIMP searches).



Good angular resolution ~ 0.1 deg; and charged particle vs gamma separation...

(http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm)

The Gamma-Ray Signal

From Weniger's talk

The gamma-ray flux from dark matter annihilation at energy E in direction Ω:

$$\frac{dJ_{\mathrm{ann.}}}{d\Omega dE} = \frac{\langle\sigma v\rangle}{8\pi m_{\mathrm{dm}}^2}\frac{dN}{dE} \times \int_{\mathrm{l.o.s.}} ds\ \rho(\vec{r}[s,\Omega])^2$$

„Particle Physics Factor“

Characteristic **Energy Spectrum**

„Astrophysics Factor“

Characteristic **Spatial Dependence**

Gamma-Ray Lines

- Are produced in two-body annihilation

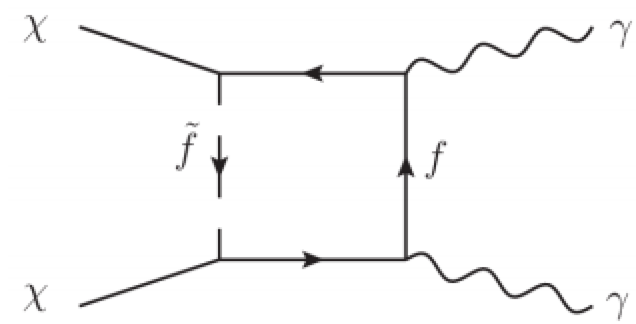
$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$

- Trivial energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \ \text{ with } \ E_\gamma \leq m_\chi$$

- Process is **one-loop suppressed**

$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$



From Weniger's talk

Some models with enhanced lines:

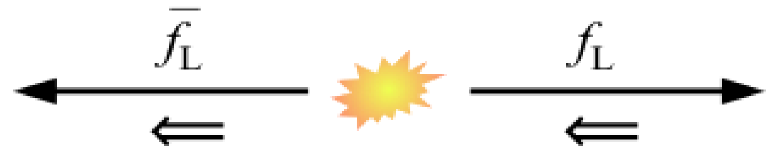
- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- “Higgs in Space!” [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]

...

→ “Smoking gun signature” / “Wishful thinking”

Virtual internal Bremsstrahlung

• Consider the annihilation DM DM $\longrightarrow f\bar{f}$, with DM a Majorana fermion or a scalar particle



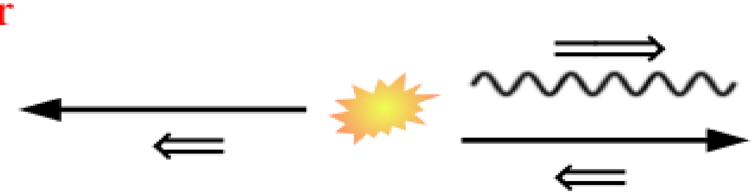
J_z=1

In the limit $v \longrightarrow 0$,
no preferred direction

J_z=0

Rate of DM DM $\longrightarrow f\bar{f}$ suppressed by $(m_f/m_{DM})^2$ if v=0. Otherwise by v^2.

• Consider the annihilation DM DM $\longrightarrow f\bar{f}\,V$, with DM a Majorana fermion or a scalar particle and V a vector



In the limit $v \longrightarrow 0$,
no preferred direction

J_z=0

J_z=0

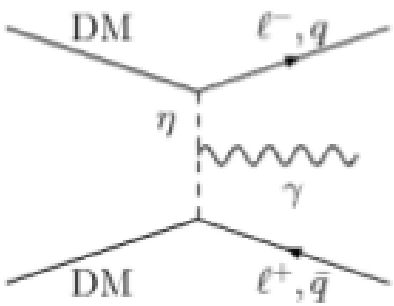
No suppression by mass insertion.
Suppressed, however, by the extra coupling constant and by the 3-body phase space.

Bergström
Flores, Olive, Rudaz

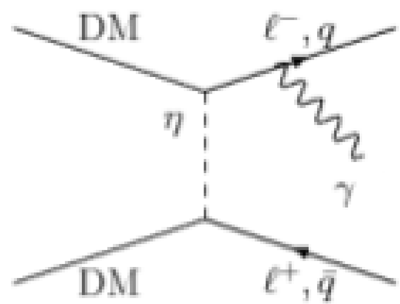
Simplified models with internal Bremsstrahlung

Consider a toy model with a Majorana dark matter particle, χ, an intermediate scalar particle η, and a right-handed SM fermion $\Psi = \mu, \tau, b$.

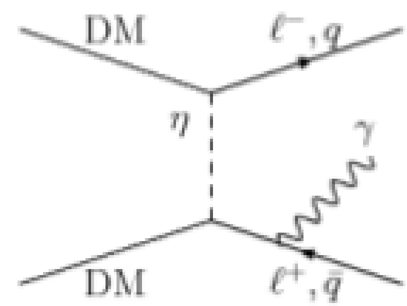
Interaction Lagrangian: $\mathcal{L}_{\rm int} = -y\bar{\chi}\Psi_R\eta + \mathrm{h.c.}$



Virtual internal Bremsstrahlung

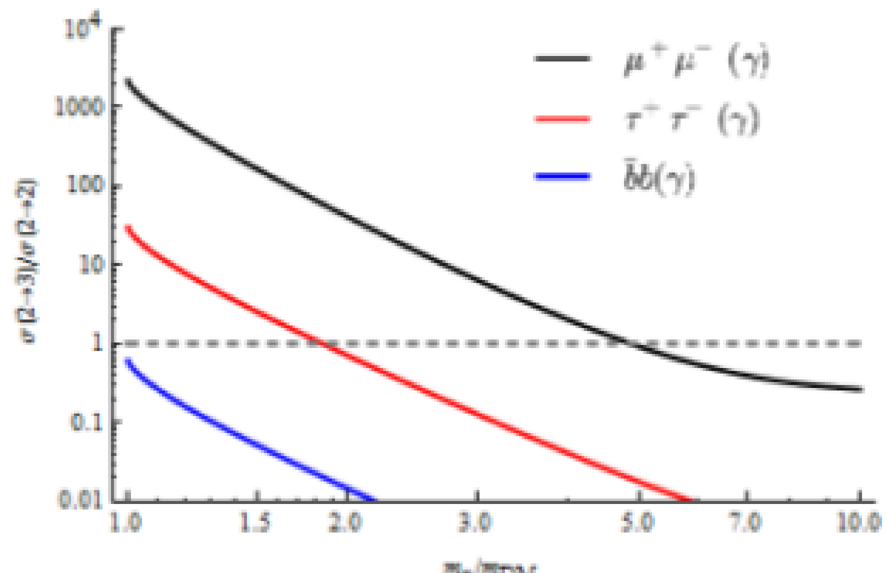


Final state radiation



Final state radiation

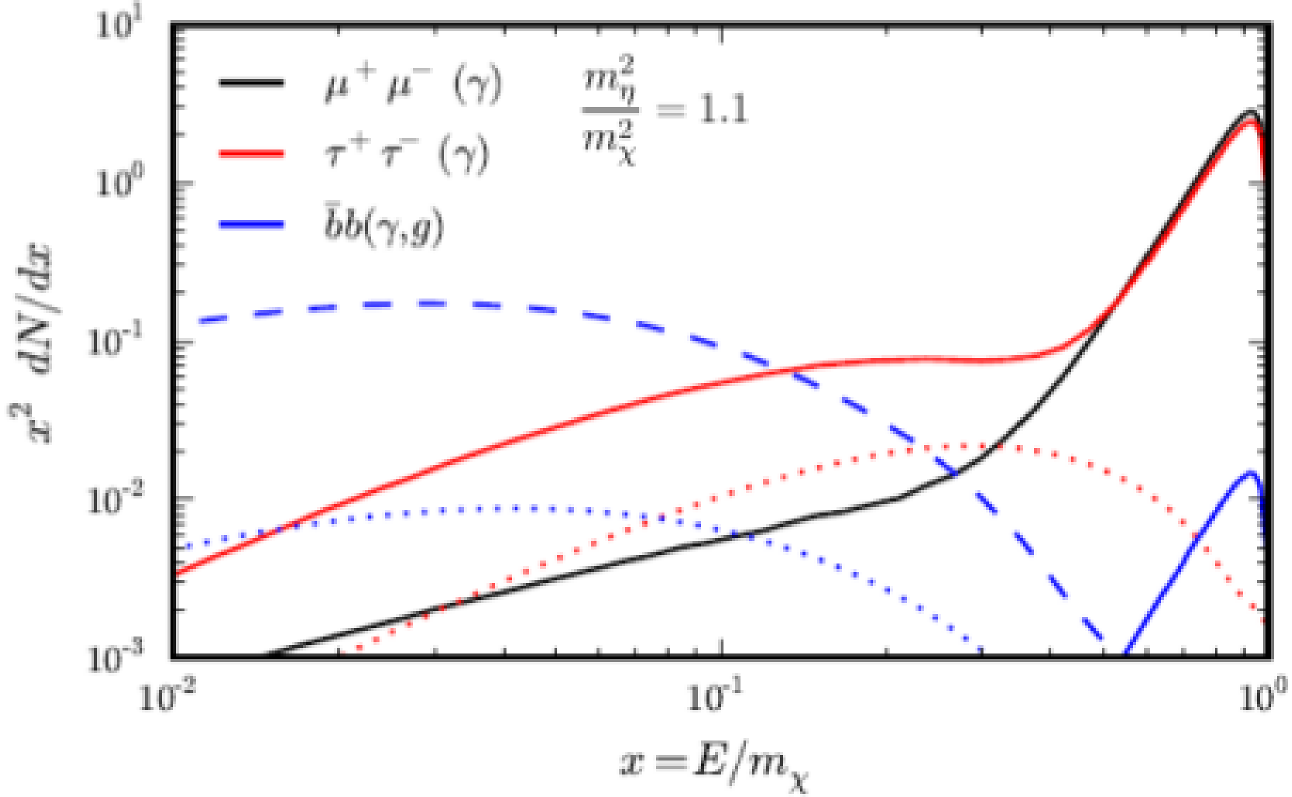
The cross section of the $2 \to 3$ process is enhanced when $m_\eta/m_{DM} \simeq 1$.



Bergström
Flores, Olive, Rudaz

Simplified models with internal Bremsstrahlung

Bonus: if η is sufficiently degenerate in mass with the dark matter particle, the gamma-ray spectrum displays a characteristic feature



Bringmann, Huang, AI, Vogl, Weniger arXiv:1203.1312

Choose the best target region

A good target region features:

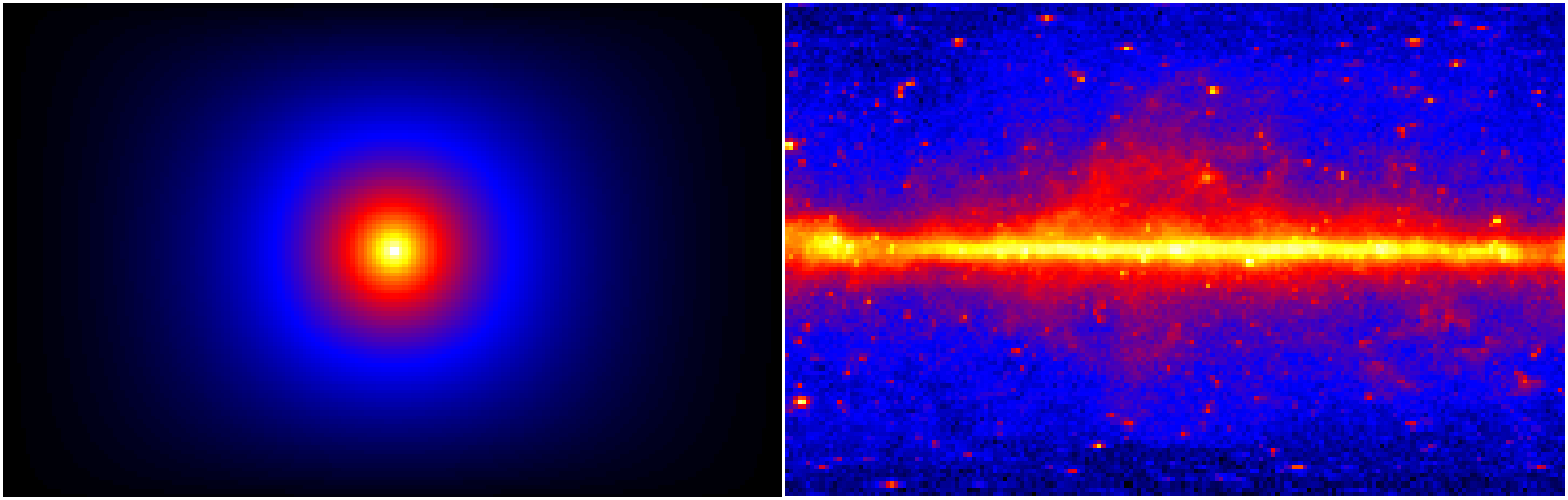
1) sufficient exposure (uniform at Fermi LAT),
2) large signal-to-noise ratio, to minimize statistical errors,
3) large signal-to-background ratio, to minimize systematical errors,
4) understandable backgrounds (no big problem when looking for lines)

Choose the best target region

- Signal morphology from Galactic Dark Matter Halo

$$\rho_{\rm dm}(r) \propto \frac{1}{r^{\alpha}(1 + r/r_s)^{3-\alpha}}$$

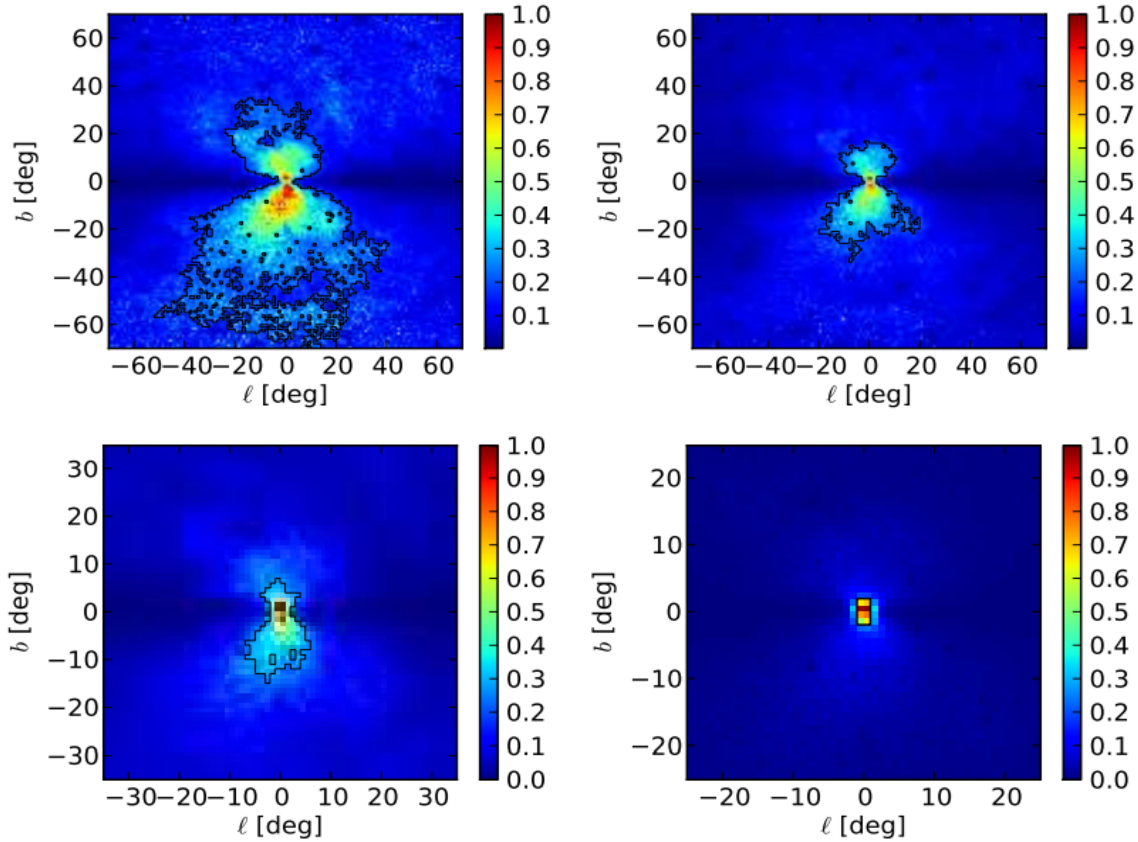
- Background morphology derived from measured LAT events at ~1 GeV



Choose the best target region

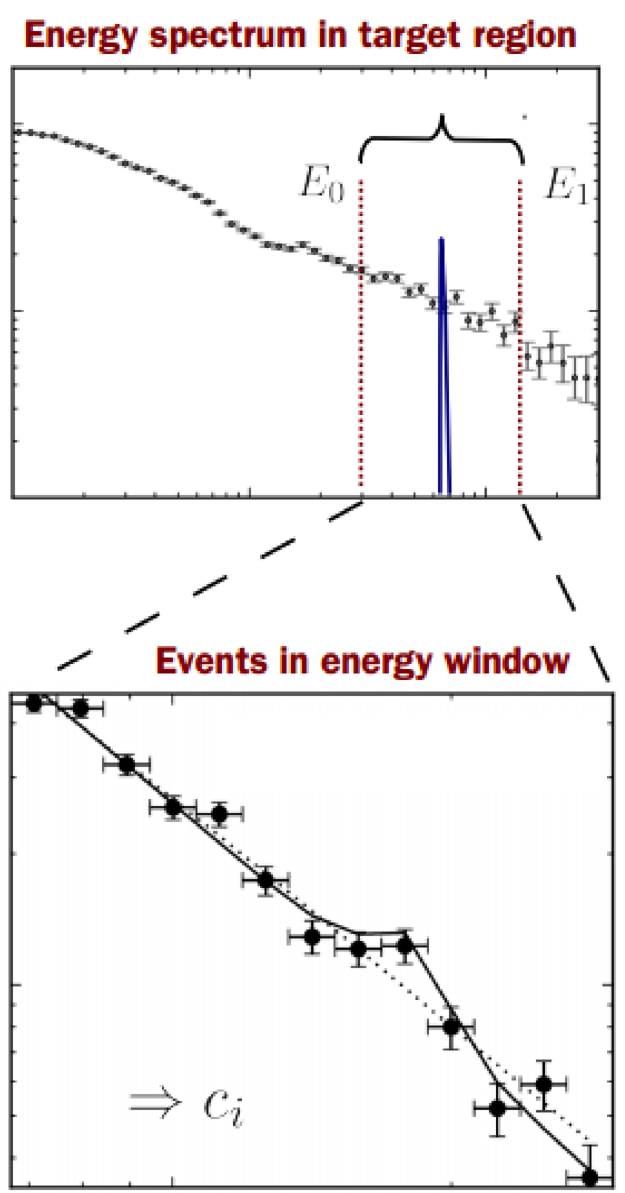
Target regions are optimized pixel-by-pixel
(one square degree size)

$$\mathcal{R}_{\mathcal{T}_o} \equiv \frac{\sum_{i \in \mathcal{T}_o} \mu_i}{\sqrt{\sum_{i \in \mathcal{T}_o} c_i}} ,$$



Spectral Analysis – Likelihood analysis

Event extraction:



(sketch)

We perfrom a **binned likelihood analysis**, using the likelihood function

$$\mathcal{L} = \prod_i P(c_i|\mu_i)$$

where

c_i : observed events

μ_i : expected events

$$P(c|\mu) = \frac{\mu^c e^{-\mu}}{c!}$$

The model:

$$\frac{dJ}{dE} = S\,\frac{dN}{dE} + \beta\, E^{-\gamma}$$

convolved with energy dispersion and exposure

$$\mu_i = \int_{\Delta E_i} dE \int dE'\ \mathcal{D}(E,E')\mathcal{E}(E')\frac{dJ}{dE'}$$

$\mathcal{D}(E,E')$: LAT energy dispersion

$\mathcal{E}(E)$: LAT exposure

Spectral Analysis

Significance of a line contribution for fixed m_χ follows from the TS value

$$TS = -2\ln\frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{alt}}}$$

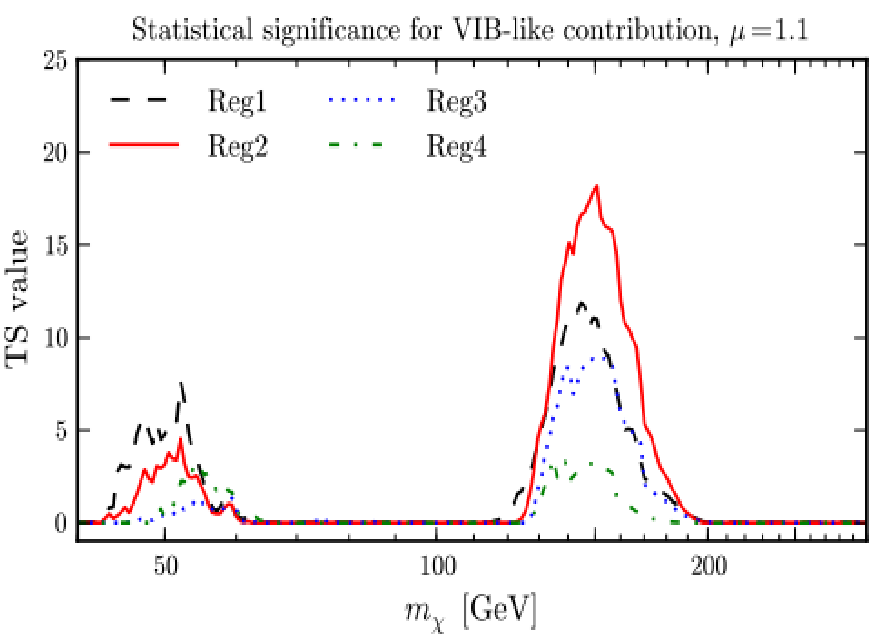
$\mathcal{L}_{\text{alt}}$: Best-fit model with DM, $S \geq 0$

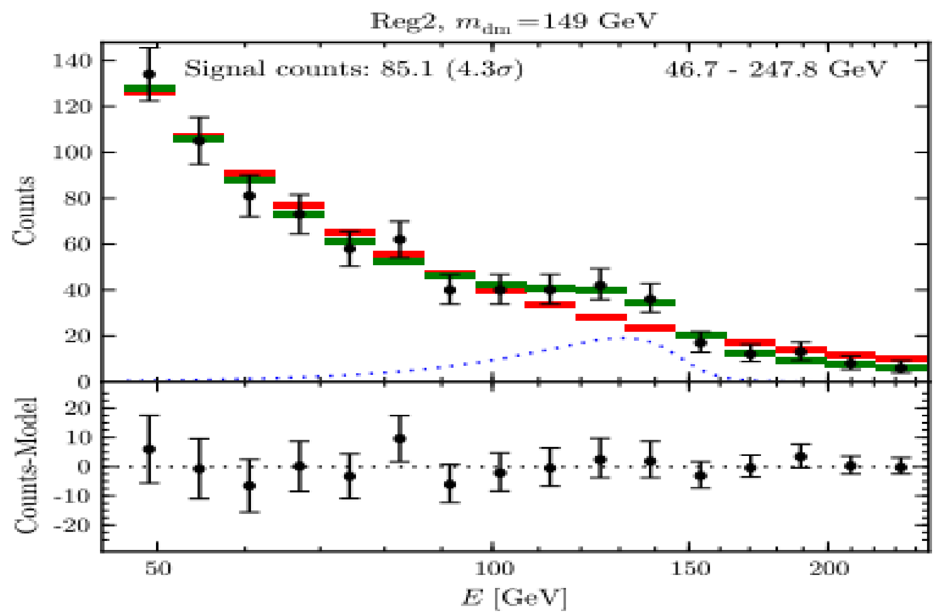
$\mathcal{L}_{\text{null}}$: Best-fit model without DM, $S = 0$

$(\Rightarrow \mathcal{L}_{\text{alt}} \geq \mathcal{L}_{\text{null}})$

Significance without trial correction : $\sqrt{TS}\sigma$

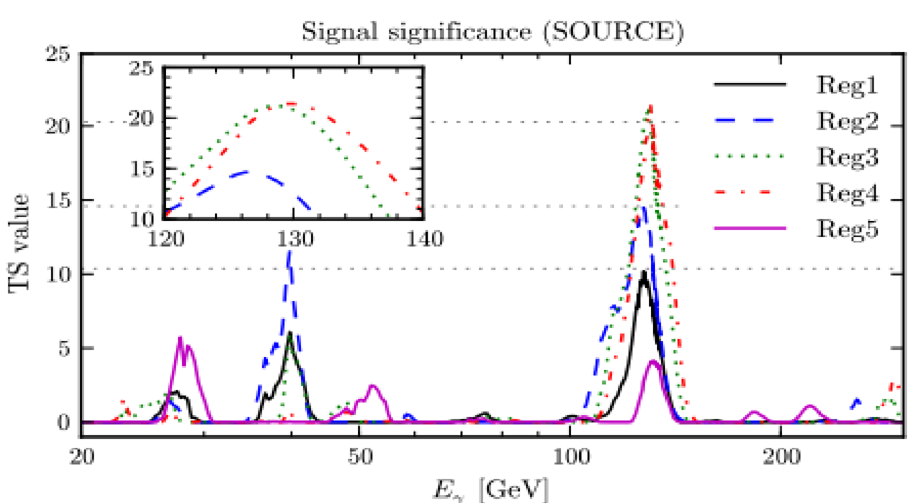
$m_\chi = (149 \pm 4)$ GeV
$\langle\sigma v\rangle = (5.7 \pm 1.4) \times 10^{-27}\ \text{cm}^3\ \text{s}^{-1}$
4.3 σ (3.1 σ with LEE) in Reg2

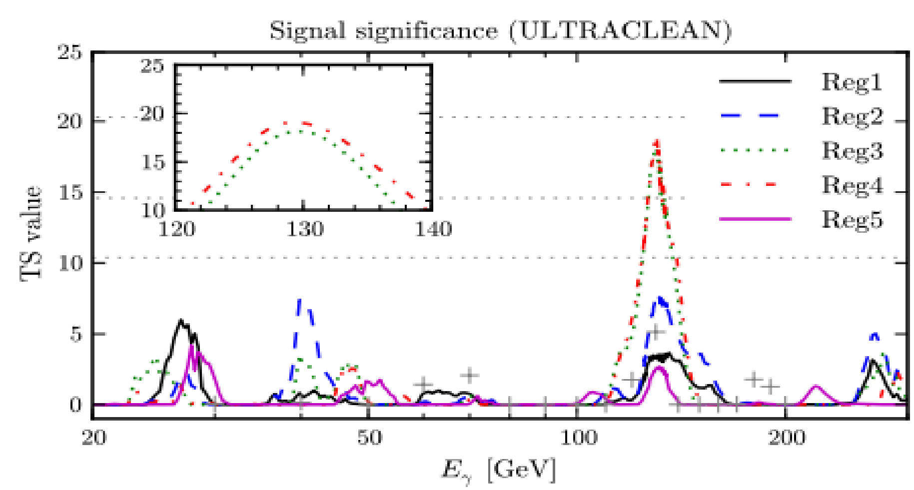




Tentative gamma ray line signal

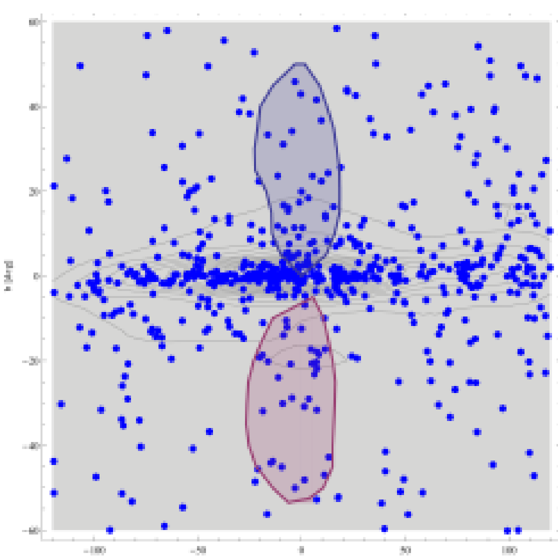
- Weniger (arXiv:1204.2797) did a more detailed analysis for gamma ray line searching, and he used the same method to choose the best target region.
- In his best fit, the mass of the dark matter is $m_\chi = 129.8 \pm 2.4^{+7}_{-13}$ GeV , and the cross section is $\langle\sigma v\rangle_{\chi\chi\to\gamma\gamma} = (1.27 \pm 0.32^{+0.18}_{-0.28}) \times 10^{-27}\ \mathrm{cm^3\ s^{-1}}$ for Einasto profile.

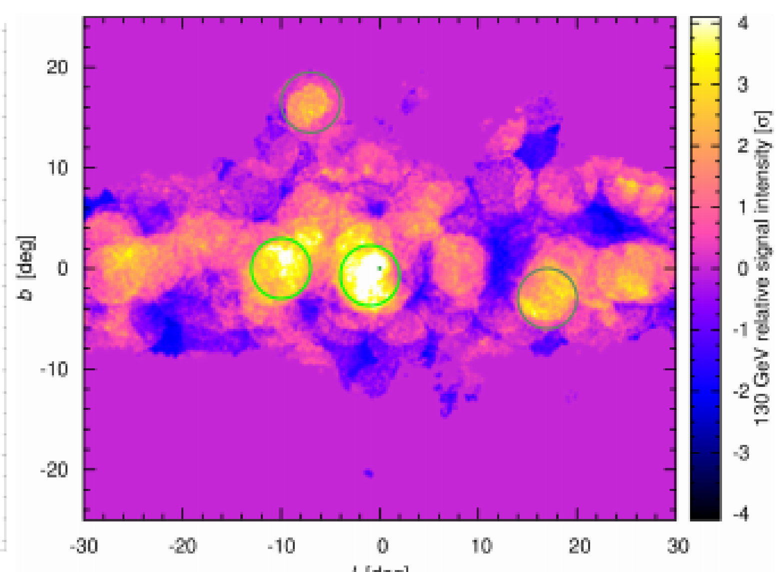




Tentative gamma ray line signal

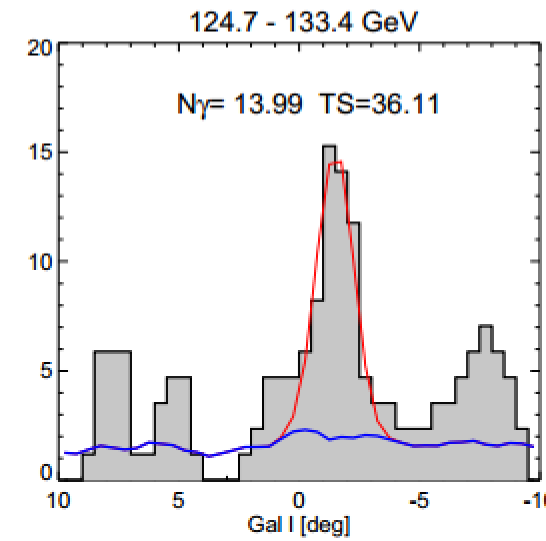
- Tempel et. al. (arXiv: 1205.1045) found that the spatial distribution of this tentative dark matter annihilation signal has no correlation with the shape of Fermi Bubble found by Su et. al.
- They also found a displacement of this extra emission from the galactic center.

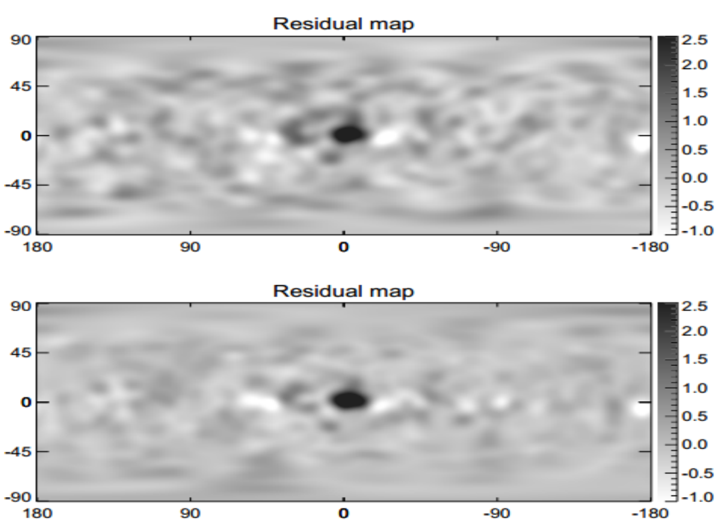


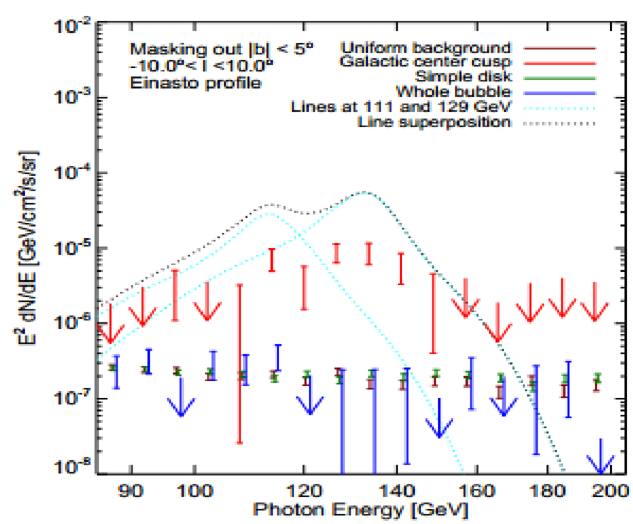


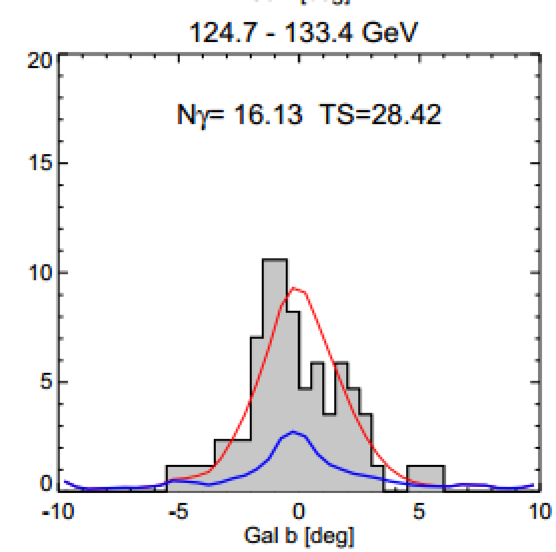
Tentative gamma ray line signal

- Meng Su and Douglas P. Finkbeiner (arXiv: 1206.1616) confirmed the signal is concentrated in the galactic center and the displacement.
- They also found that the extra emission could be fitted by two lines, one for gamma-Z, another for gamma-gamma.





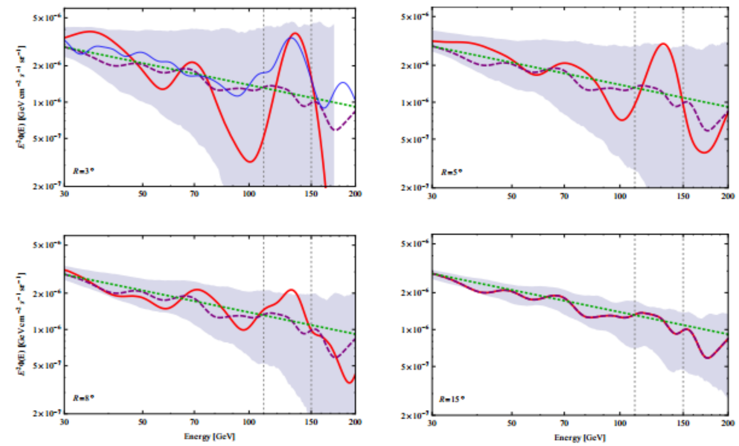




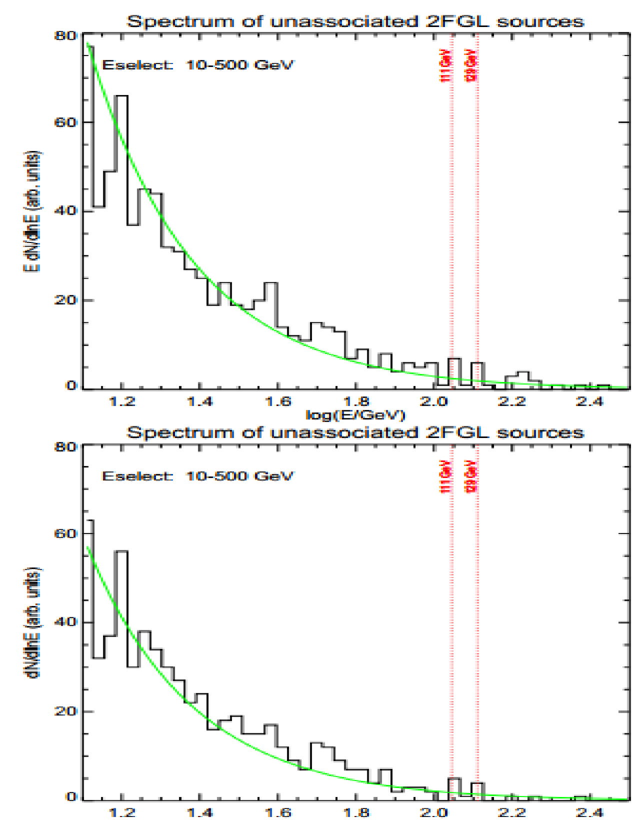
Tentative gamma ray line signal

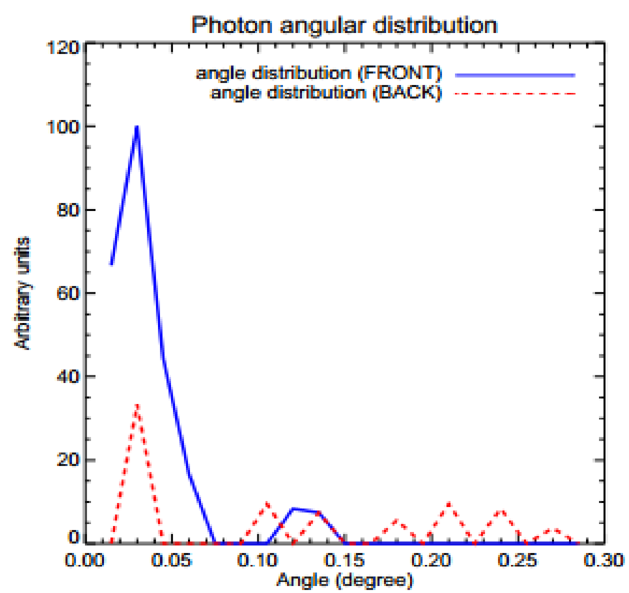
- Hektor et. al. (arXiv: 1207.4466) found a tentative gamma ray line signal from galaxy clusters.

Radius R (deg)	1	2	3	4	5	6	7	8	9	10	15
N (110…150 GeV)	2	4	6	10	16	24	30	35	40	48	101
N (20…300 GeV)	15	55	114	219	336	504	666	875	1105	1370	3044
N_{signal} (110…150 GeV)	1.6	2.2	2.0	3.2	4.5	5.6	7.2	9.5	8.8	7.4	4.6
Significance (σ)	2.0	2.7	2.7	3.2	3.2	3.1	3.1	3.0	3.0	3.0	2.9



- Meng Su and Douglas P. Finkbeiner (arXiv: 1207.7060) also found a tentative signal from Unassociated Fermi-LAT Sources, which could be dark matter substructures in our Milky Way.

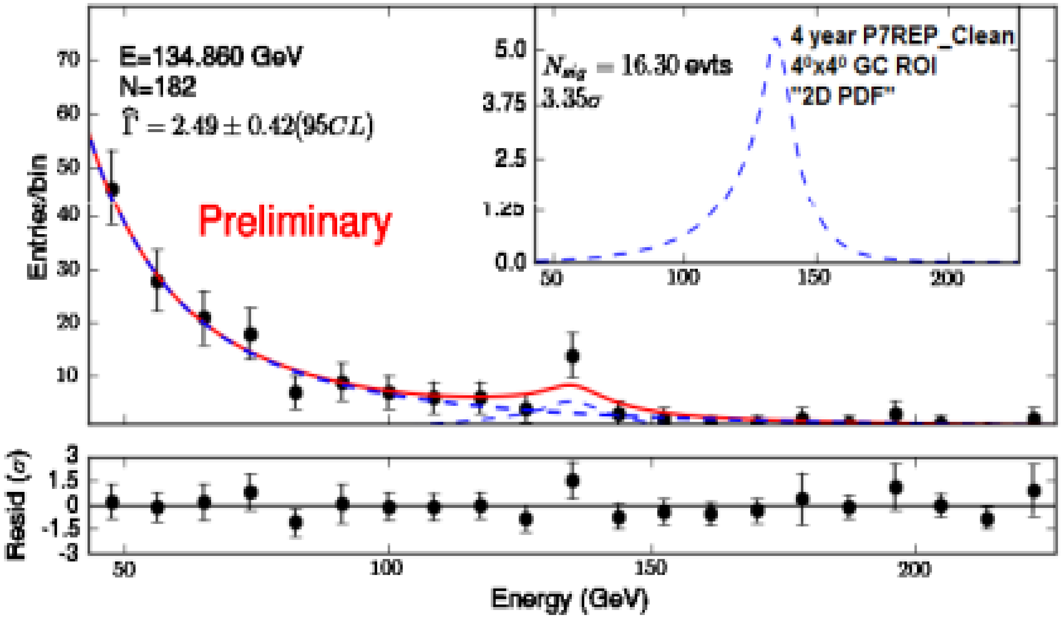




Line-like Feature near 135 GeV

From Fermi Collaboration's talk

- Our blind search does not find globally significant feature near 135 GeV
  - Reprocessing shifts feature from 130 GeV to 135 GeV
  - Most significant fit was in R0, 2.23σ local (<0.5σ global)
- Much interest after detection of line-like feature localized in the galactic center at 130 GeV
  - See C. Weniger JCAP 1208 (2012) 007 arXiv:1204.2797
- 4.01σ (local) 1D fit at 130 GeV with 4 year unreprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global

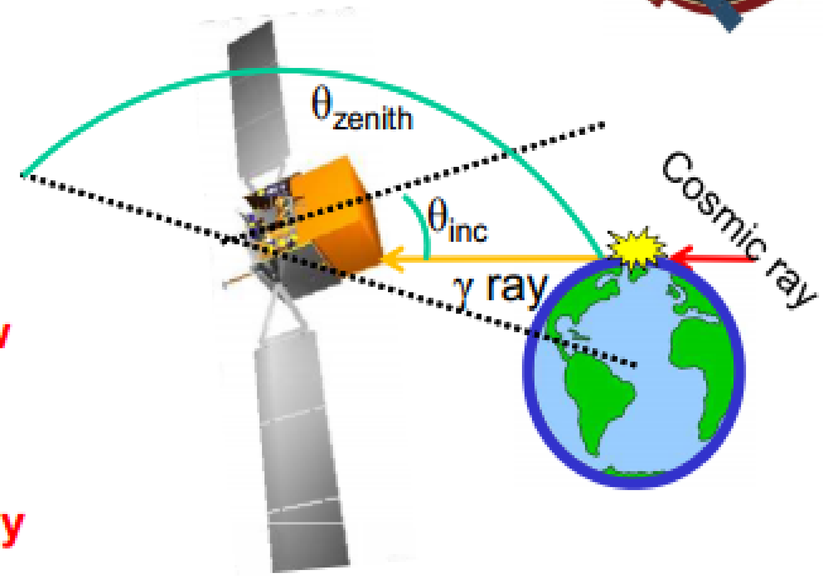


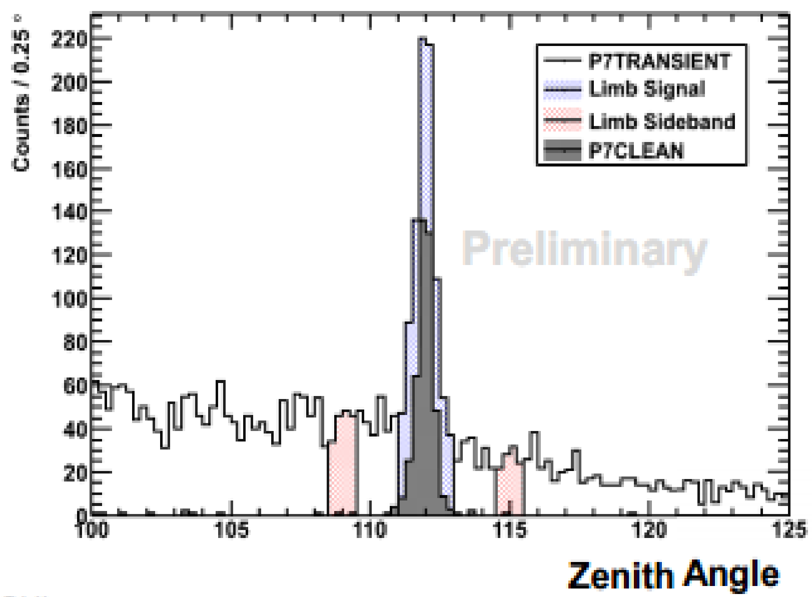
Note: Fit in 4°x4° GC ROI
Not one of our a priori ROIs

From Fermi Collaboration's talk

135 GeV in the Earth Limb spectrum (1)

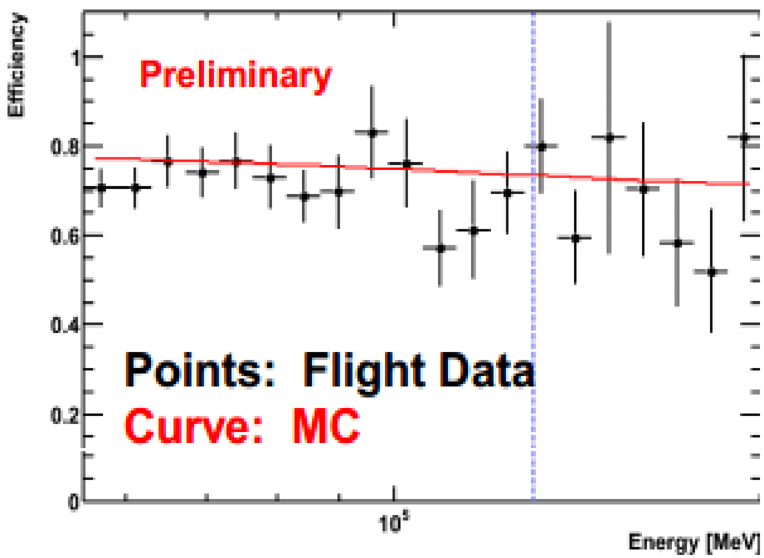
- Earth Limb is a bright, well understood source
  - γ rays from CR interactions in the atmosphere
    - Expected to be a smooth power-law
  - Can be used to study instrumental effects
    - Can see in loosest cuts → can study cut efficiencies
- Need to cut on times when the LAT was pointing at the limb
- Have made changes to increase our Limb dataset
  - Pole-pointed observations each week
  - Extended “targets of opportunity”
    - Trace limb while target is occulted



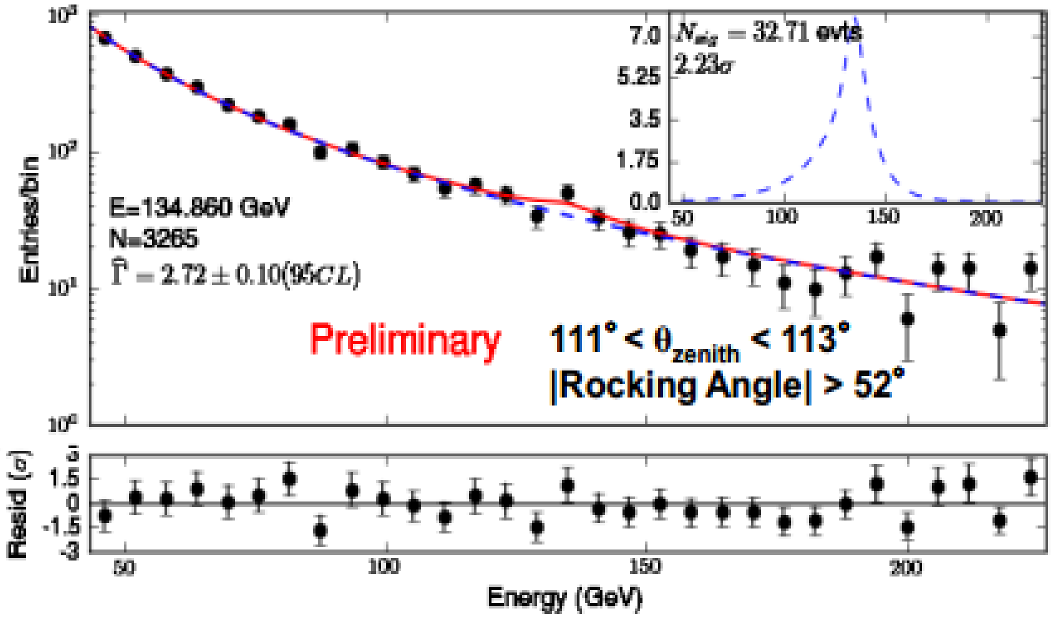


135 GeV in the Earth Limb spectrum (2)

P7Transient to P7Clean Efficiency



Fit to Limb data



- Dips in efficiency below and above 135 GeV
  - Appear to be related to CAL-TKR agreement
  - Could be artificially sculpting the energy spectrum
- Line-like feature in the limb at 135 GeV
  - Appears when LAT is pointing at the Limb
  - Surprising since limb should be smooth
  - S/N_{limb} ~18%, while S/N_{GC} ~30% - 66% (depending on ROI choice)
    - Limb feature not large enough to explain all the GC signal

Instrumental systematics?

- Similar feature is found in the earth limb data
- Similar feature is also found in a 5deg circle following the Sun by Whiteson (arXiv: 1302.0427)
- No feature is found in the anti-galactic center region

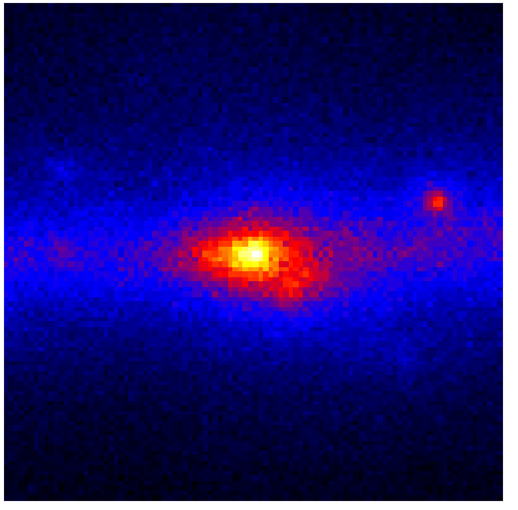
Need more data !

From the review shown above, it seems right now it's hard to exclude the possibility that this “signal” in the Fermi data is a dark matter annihilation signal to gamma ray line.

CONTINUOUS GAMMA-RAY EMISSION FROM THE INNER GALAXY

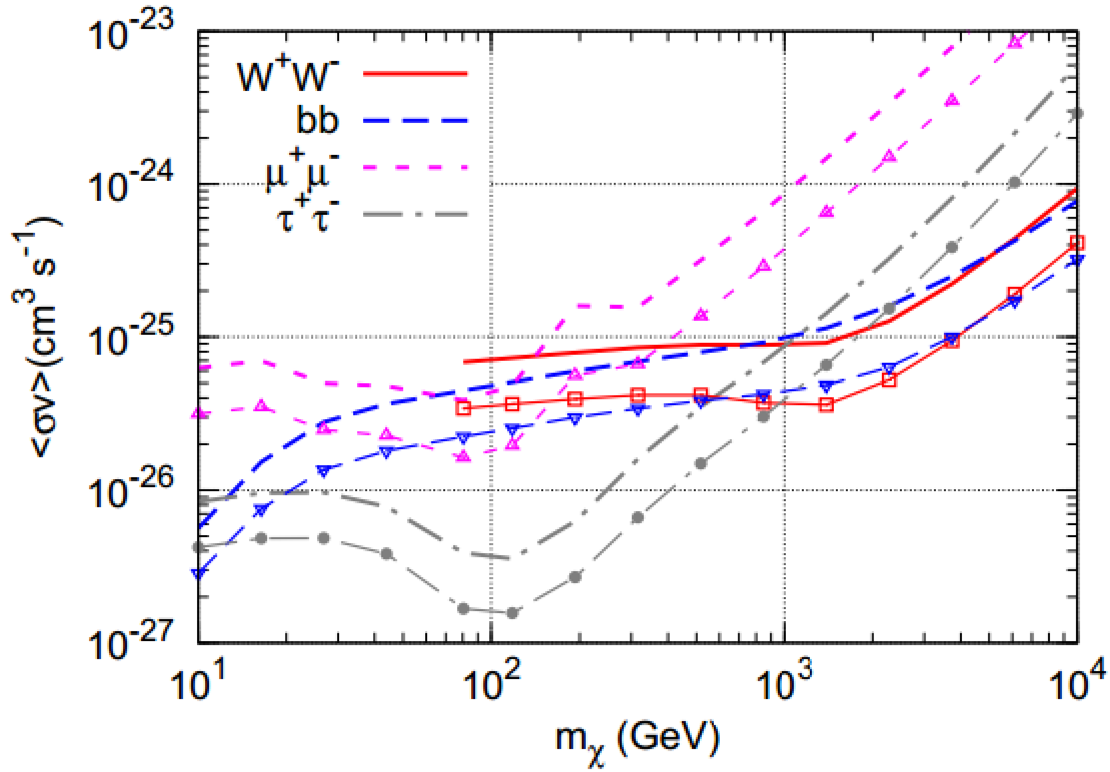
- Dark matter may be easier to annihilate into the charged particles at the tree level, then these annihilation products may induce significant continuous γ-ray flux.
- we will use the Fermi data from the inner Galaxy, because of its high dark matter density, to place limits on the DM annihilation cross section.

CONTINUOUS GAMMA-RAY EMISSION FROM THE INNER GALAXY



- we use the 3.7 years Fermi-LAT data in the region-of-interest (ROI) of a $10^\circ \times 10^\circ$ box centered around the GC.
- We assume the dark matter distribution is NFW profile or Einasto profile.
- We also take the DM substructures into account.
- For the DM annihilation we discuss $W^+W^-, b\bar{b}, \mu^+\mu^-$ and $\tau^+\tau^-$ final states.

CONTINUOUS GAMMA-RAY EMISSION FROM THE INNER GALAXY



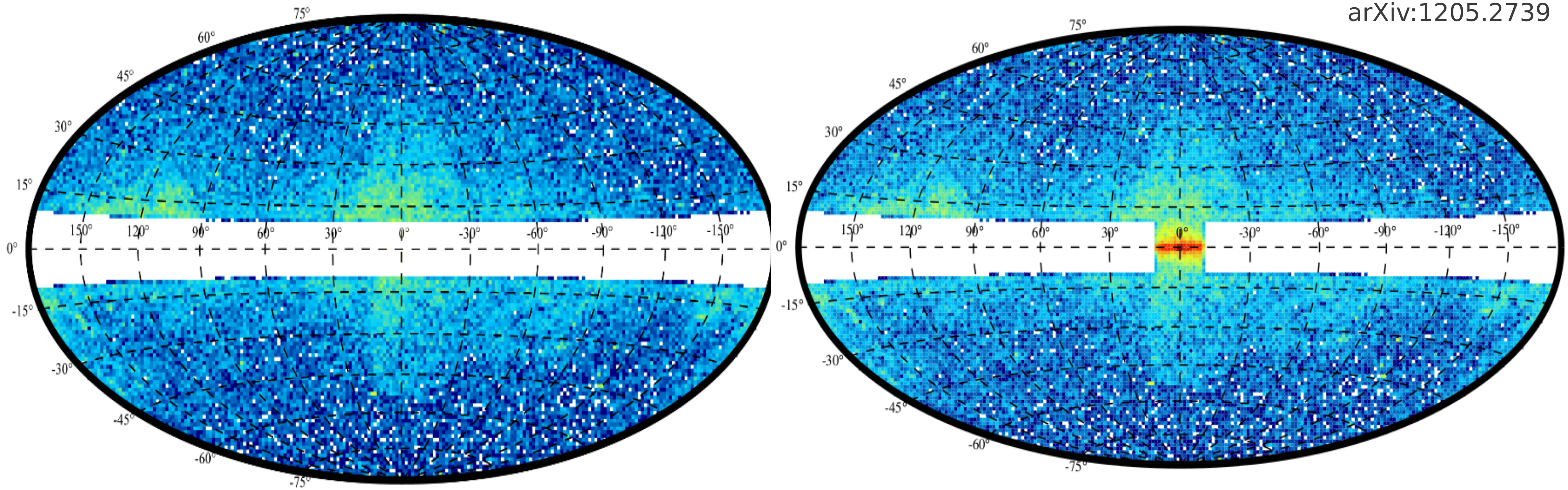
- For dark matter mass around 130 GeV, the continuous cross section can only be larger by a factor of $1.2 - 30$ compared with the cross section to gamma-gamma.
- These constraints suggest the charged particles in the loop have to be heavier than the DM particle so that the tree level process into the charged particles is forbidden.

LINE EMISSION FROM THE GALACTIC HALO

- The search for the line emission in the Galactic halo should be of great importance, especially in case that there might be significant contribution from DM substructures as shown by the cold DM simulations.
- We choose two sky region, $|b| > 10^\circ$(Reg. I) and $|b| > 10^\circ$ plus $|l| \leq 10^\circ$, $|b| \leq 10^\circ$(Reg. II)
- We use spectrum analysis, ignoring the spatial information, to search the gamma-ray line signal.

LINE EMISSION FROM THE GALACTIC HALO

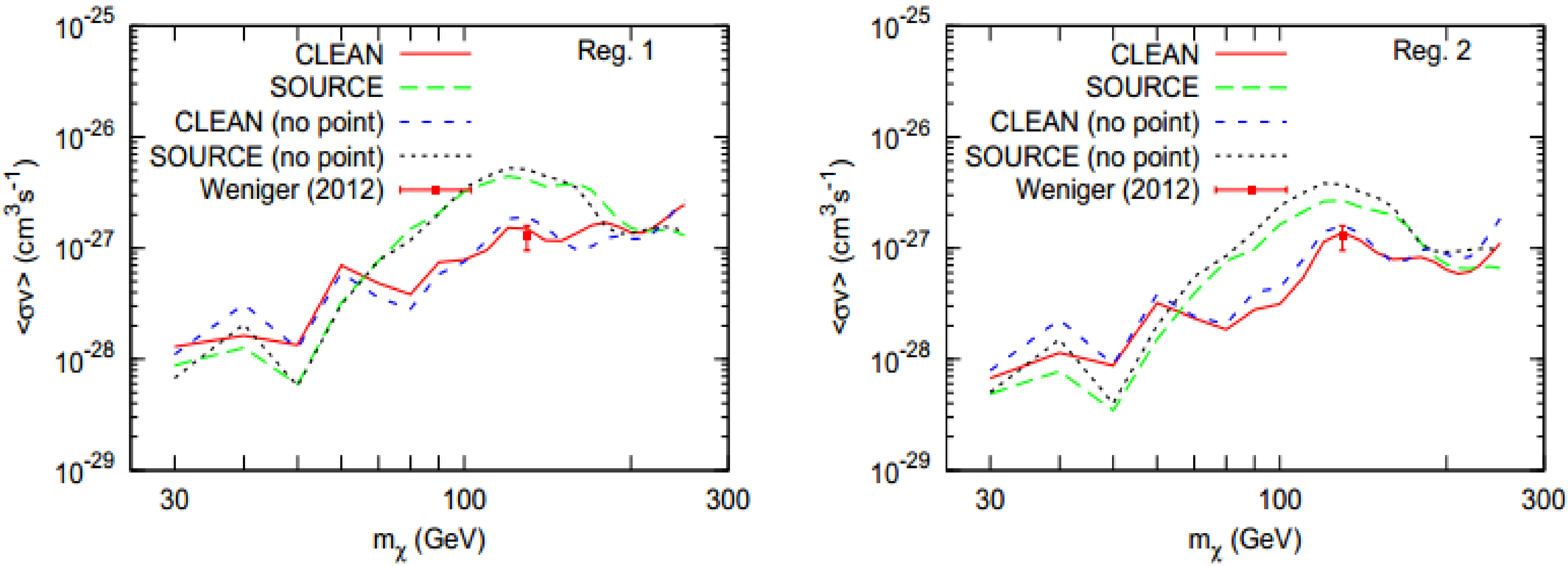
From Fermi-LAT Collaboration arXiv:1205.2739



	NFW	NFW+sub	EIN	EIN+sub
Reg. 1	20.2(17.7)	43.9(38.7)	22.0(19.3)	45.8(40.3)
Reg. 2	31.4(22.5)	55.4(43.6)	42.2(27.8)	66.2(48.9)

- We assume the dark matter distribution is NFW profile or Einasto profile, and we also take the DM substructures into account.
- We mask the point source, based on the second Fermi-LAT source catalog, in this region.

LINE EMISSION FROM THE GALACTIC HALO

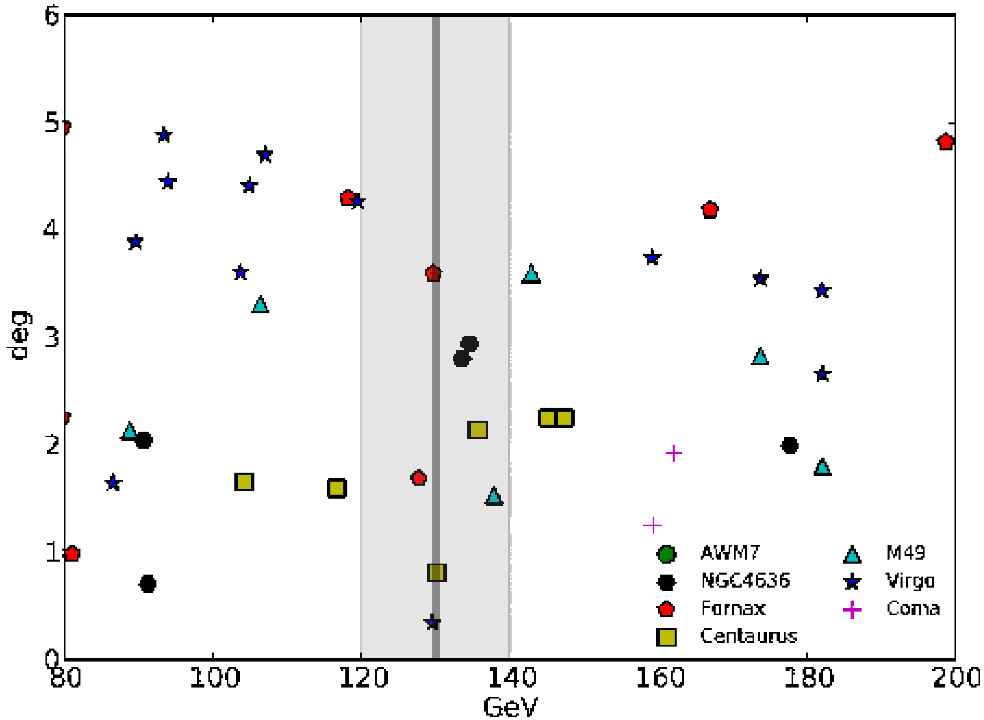


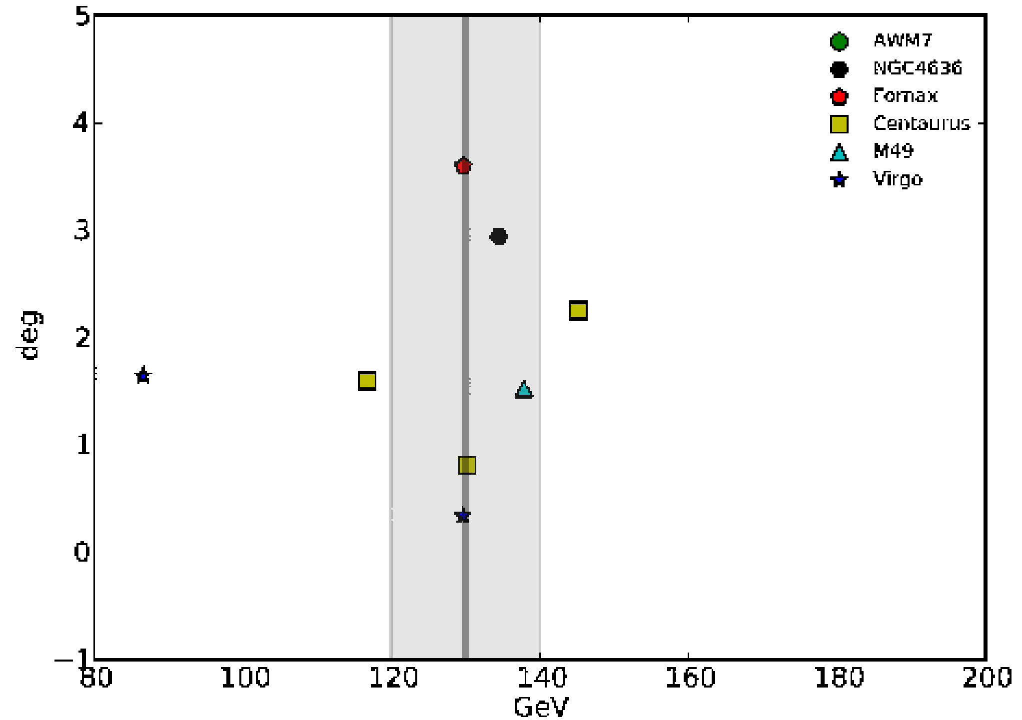
- No line emission from the Galactic halo is found in the Fermi data
- The “CLEAN” results of Reg. 2 are consistent with that derived by Fermi-LAT collaboration, in which two-year Pass 6 “ULTRACLEAN” data are used.
- For the“CLEAN” data we can only conclude that the present constraints from the Milky Way halo observations of the line-like emission are marginally consistent with that from the inner Galaxy if explaining it with DM annihilation.

LINE EMISSION FROM GALAXY CLUSTERS

- Seven clusters, Fornax, AWM7, M49, NGC4636, Centaurus, Coma and Virgo are chosen as our targets.
- We consider the effect of dark matter substructures, which could boost the J-factor to a factor of 1000.
- We treat these targets as extended sources.

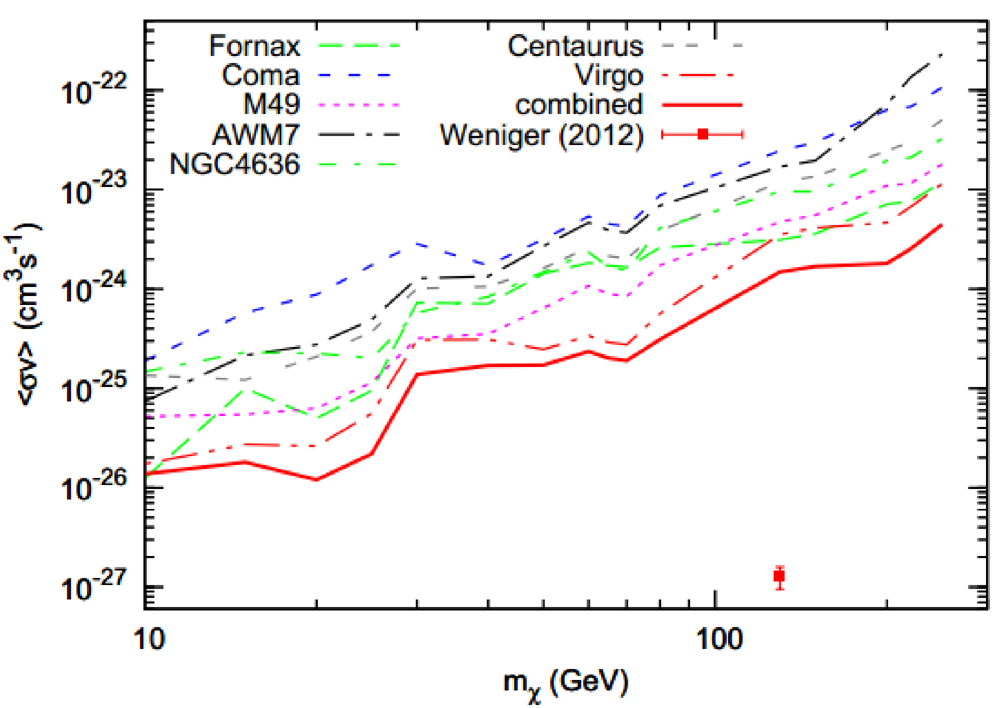
LINE EMISSION FROM GALAXY CLUSTERS

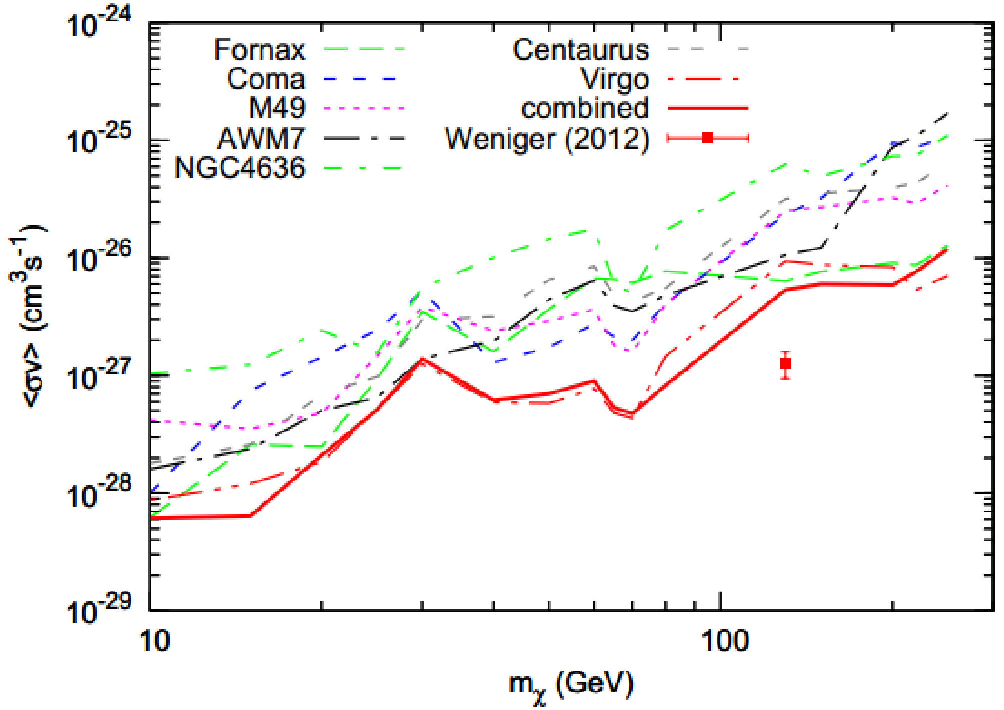




- Above plots show the individual photons with arrival directions within the virial radius of these clusters.
- It is interesting to find that for the "CLEAN" events, photons with energies between 120 and 140 GeV are more abundant than nearby energy ranges.

LINE EMISSION FROM GALAXY CLUSTERS





- Through likelihood fitting, we didn't find significant extra emission from dark matter annihilation to gamma-ray line.
- The constraints from galaxy clusters are quite weak and are still consistent with the DM interpretation of the inner Galaxy line emission, even for the case with significant substructure boost.

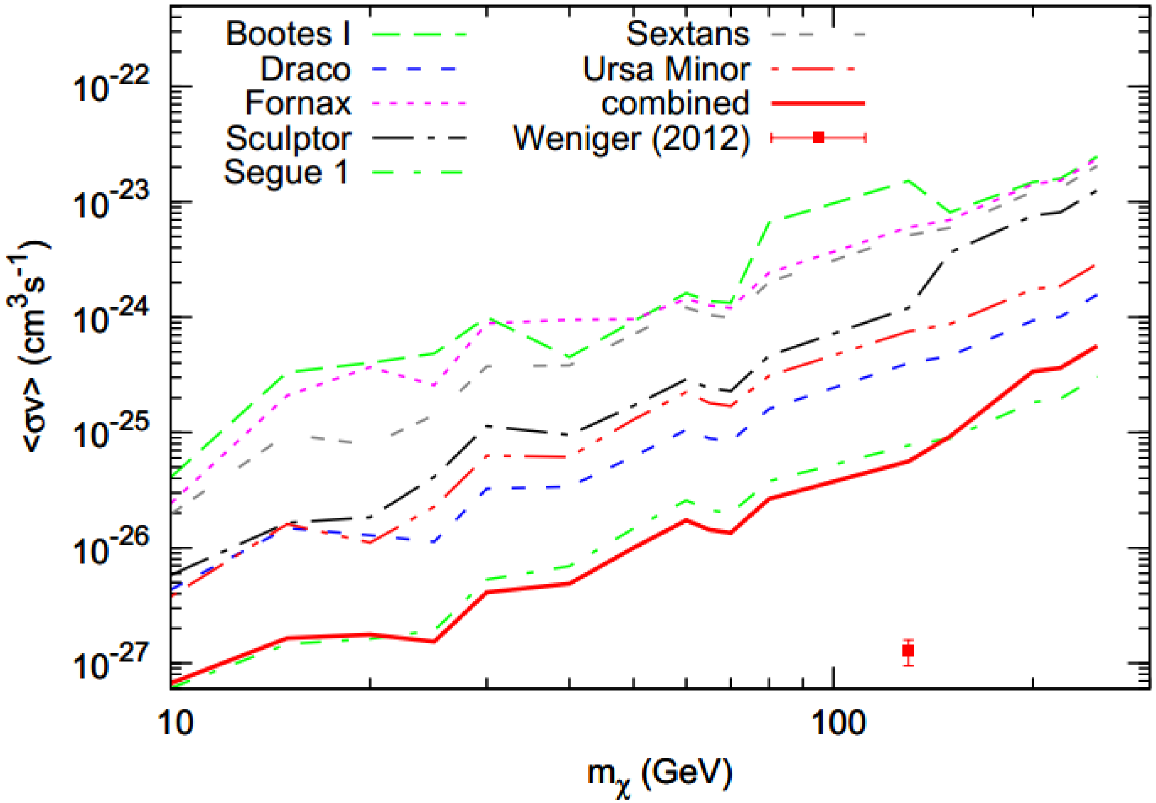
LINE EMISSION FROM DWARF GALAXIES

Name	l	b	d	$\overline{\log_{10}(J)}$	σ	ref.
	deg.	deg.	kpc	$\log_{10}[\mathrm{GeV}^2\mathrm{cm}^{-5}]$		
Bootes I	358.08	69.62	60	17.7	0.34	[15]
Carina	260.11	−22.22	101	18.0	0.13	[16]
Coma Berenices	241.9	83.6	44	19.0	0.37	[17]
Draco	86.37	34.72	80	18.8	0.13	[16]
Fornax	237.1	−65.7	138	17.7	0.23	[16]
Sculptor	287.15	−83.16	80	18.4	0.13	[16]
Segue 1	220.48	50.42	23	19.6	0.53	[18]
Sextans	243.4	42.2	86	17.8	0.23	[16]
Ursa Major II	152.46	37.44	32	19.6	0.40	[17]
Ursa Minor	104.95	44.80	66	18.5	0.18	[16]

From Fermi-LAT Collaboration, arXiv:1108.3546v3

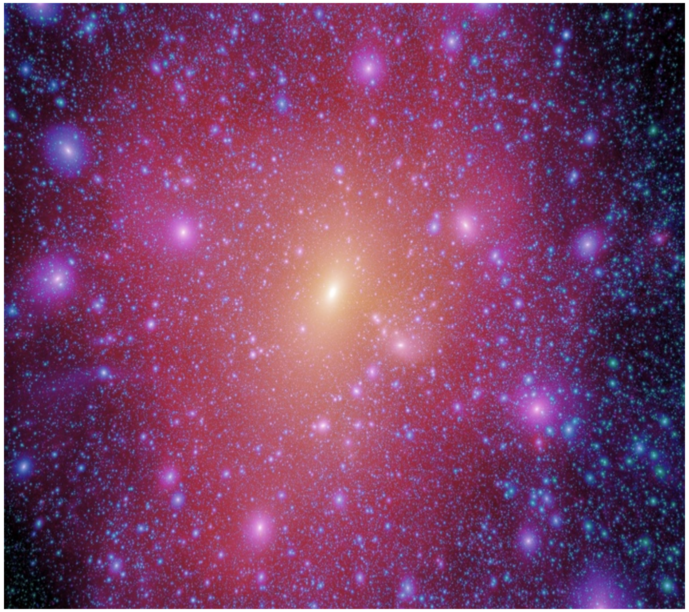
- In the work of Alex Geringer-Sameth and Savvas M. Koushiappas (arXiv:1206.0796), these authors tried to constrain line emission from dwarf galaxies.
- Here we do the likelihood fitting with point sources in the ROI and diffuse backgrounds involved, for the seek of completeness and independent check.

LINE EMISSION FROM DWARF GALAXIES



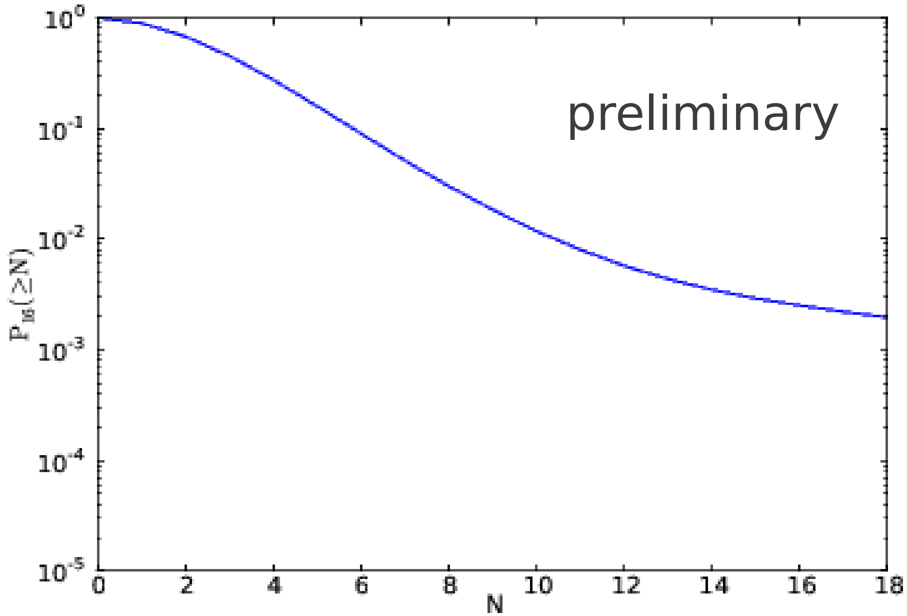
- We have found no significant γ-ray line emission in these target regions.
- We can see that the upper limits are still far away from the best fit point.
- This result is consistent with the upper limit derived in 1206.0796

LINE EMISSION FROM SUBHALOS



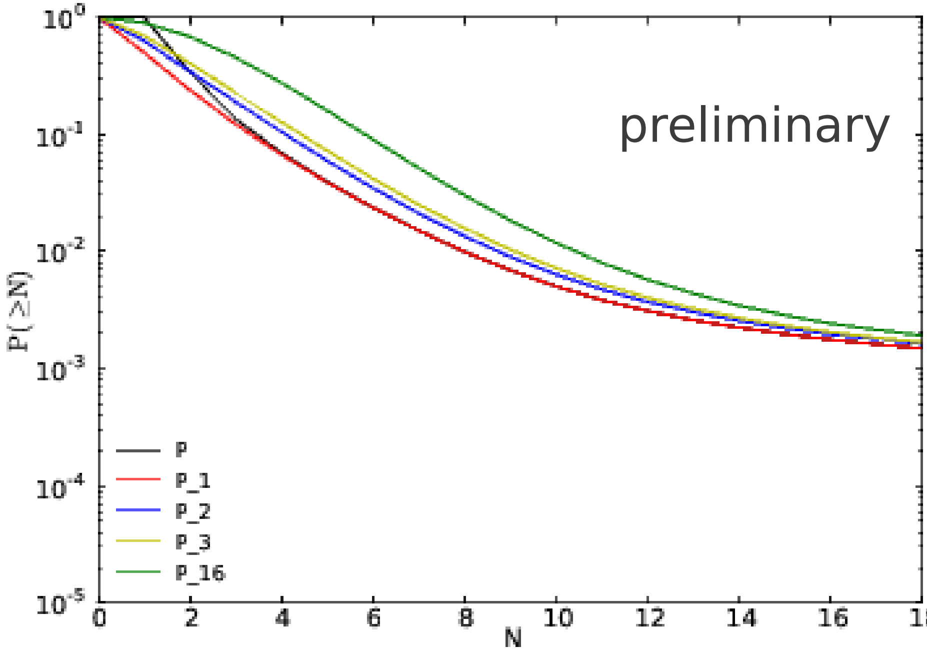
- Large scale N-body cold dark matter simulations, like the Aquarius Project (arXiv: 0809.0898) show many dark matter substructures may exist in our Milky Way.
- Su and Finkbeiner (arXiv: 1207.7060) also found a tentative signal, 11 signal photons from 16 sources, from Unassociated Fermi-LAT Sources, which could be dark matter substructures in our Milky Way.

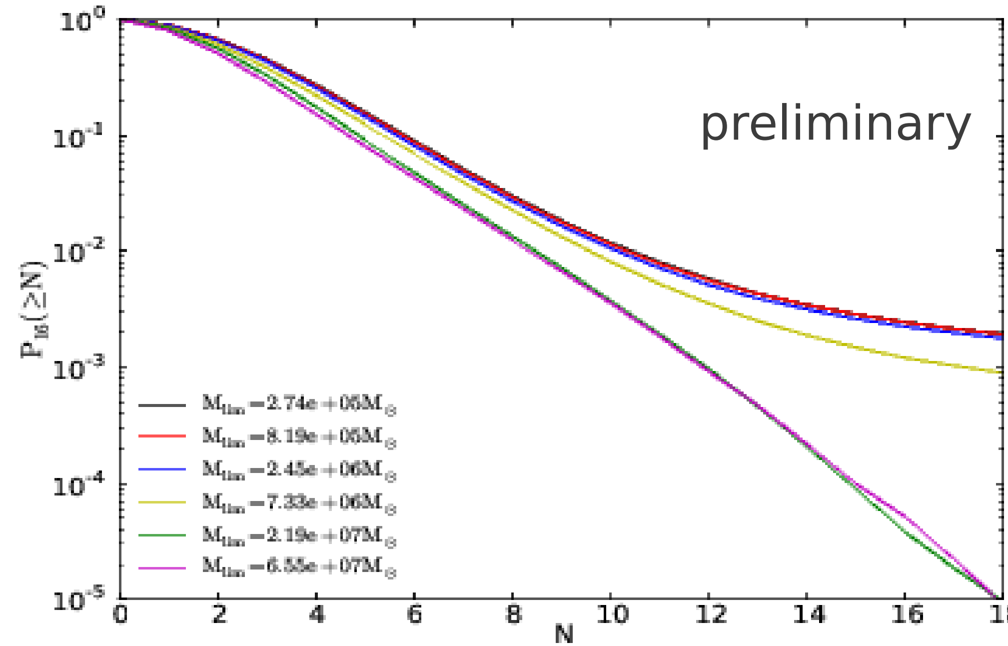
LINE EMISSION FROM SUBHALOS



- Using the dark matter substructures configuration from Aquarius, assuming these dark matter substructures as point sources, using the 4 years exposure map of Fermi-LAT, and randomly choosing the position of the Earth, we calculate the number of photons generated by DM annihilation to gamma ray line
- We do a Poisson Sampling by using the predicted number of photons as expected value to get the photons observed by Fermi-LAT

LINE EMISSION FROM SUBHALOS





- It seems that for large number of photons they are more likely from some brightest sources and considering more substructures will not increase the probability too much for observing large number of photons
- It seems that the brightest source as mentioned above locates in the low mass end, but more low mass substructures will not increase the probability

Conclusion

- There is a tentative gamma ray line signal in 130 GeV.
- The constraints on the annihilation cross section of continuous γ-ray emission from the Galactic center are as stringent as the "natural" scale assuming thermal freeze-out of DM, and this is "unnatural" compared with the best fit cross section for gamma-gamma.
- The present constraints from the Milky Way halo observations of the line-like emission are marginally consistent with that from the inner Galaxy if explaining it with DM annihilation.
- Possible concentration of photons in $120 - 140$ GeV from nearby clusters is revealed.
- Constraints from galaxy cluster (with substructures) are marginally consistent with the DM annihilation scenario to explain the ~ 130 GeV emission, and the constraints from dwarf galaxies are weaker.
- The probability to observe dark matter annihilation photons from substructures in our Milky Way is low.

The End

Thank You!