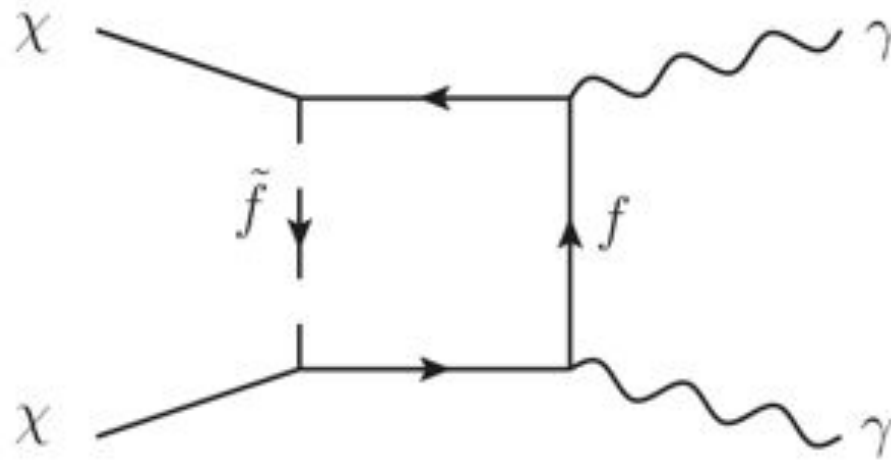
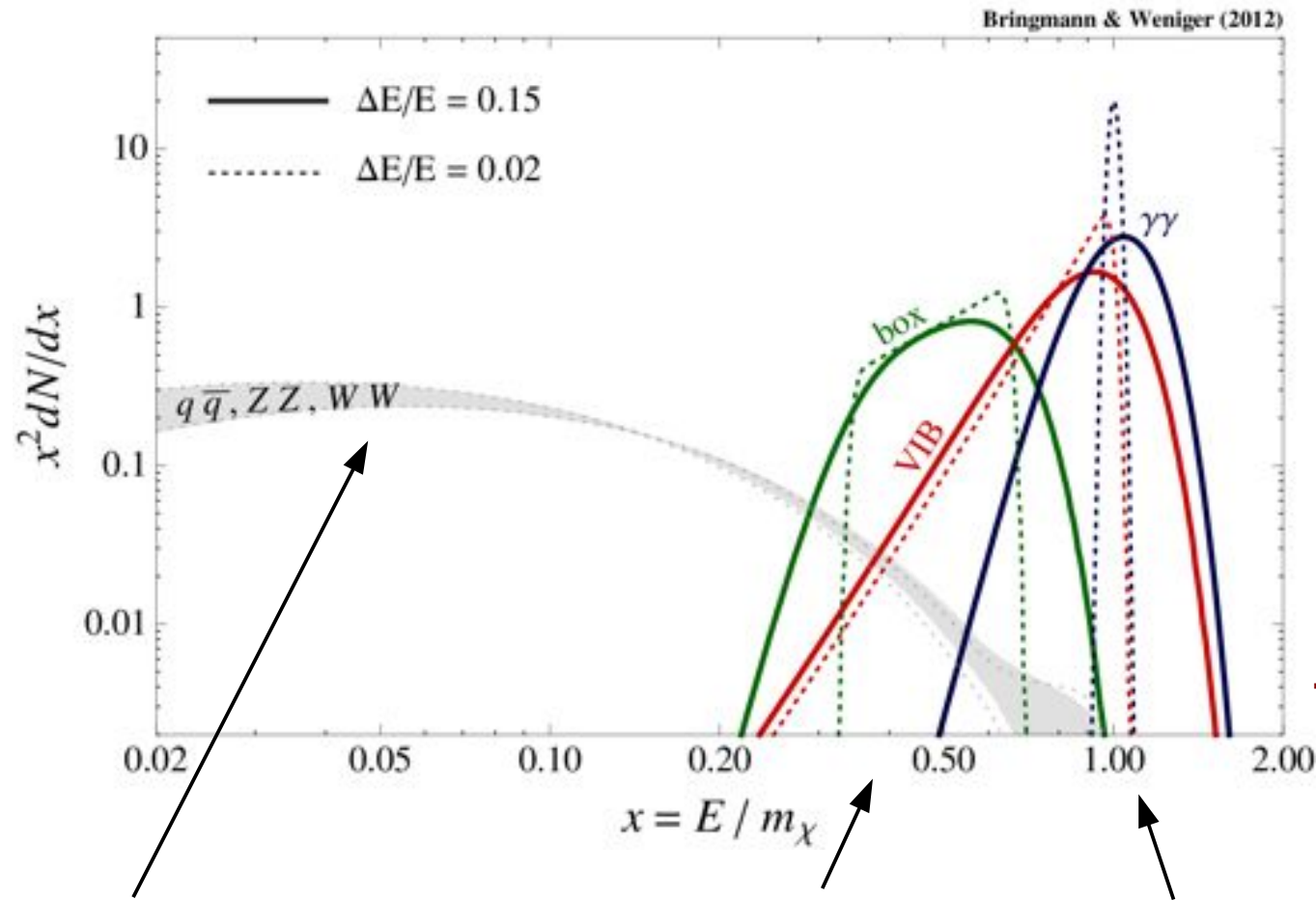


Tentative observation of a gamma-ray line at the Fermi Large Area Telescope



- T. Bringmann, X. Huang, A. Ibarra, S. Vogl & CW, JCAP 1207 (2012) 054
CW, JCAP 1208 (2012) 007
L. Bergström, G. Bertone, J. Conrad, C. Farnier & CW, to appear in JCAP
T. Bringmann & CW, arXiv:1208.5481
D. Finkbeiner, M. Su & CW, arXiv:1209.4562

Various DM annihilation gamma-ray spectra



[Lars Bergström's talk this morning]

Continuum emission

(“Secondary photons”)

- from fragmentation of quarks/massive gauge bosons (via π^0 decay)

Virtual Internal Bremsstrahlung (VIB)

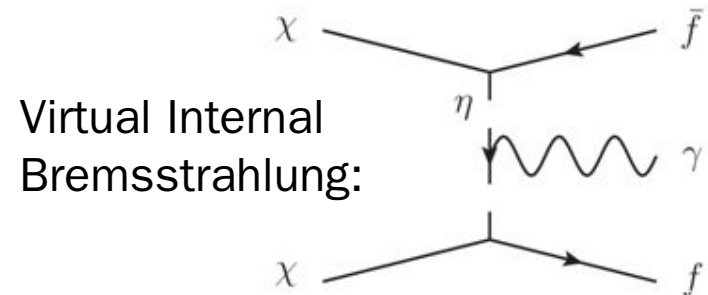
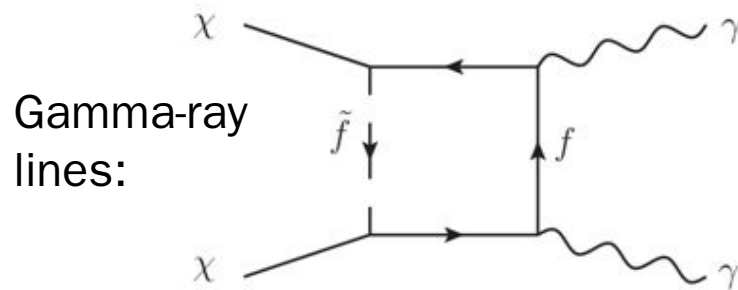
- radiative correction to processes with charged final states
- Generically suppressed by $O(\alpha)$

Gamma-ray lines

- from two-body annihilation into photons
- forbidden at tree-level, generically suppressed by $O(\alpha^2)$

“Smoking guns” (high-risk-high-gain)²

Gamma-ray line claims since March 2012



1) *Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation*
Bringmann, Huang, Ibarra, Vogl & CW, JCAP 1207 (2012) 054

2) *A tentative gamma-ray line from dark matter annihilation at the Fermi LAT*
CW, JCAP 1208 (2012) 007

“In regions close to the Galactic center, we find a 4.6 sigma indication for a gamma-ray line at 130 GeV.”

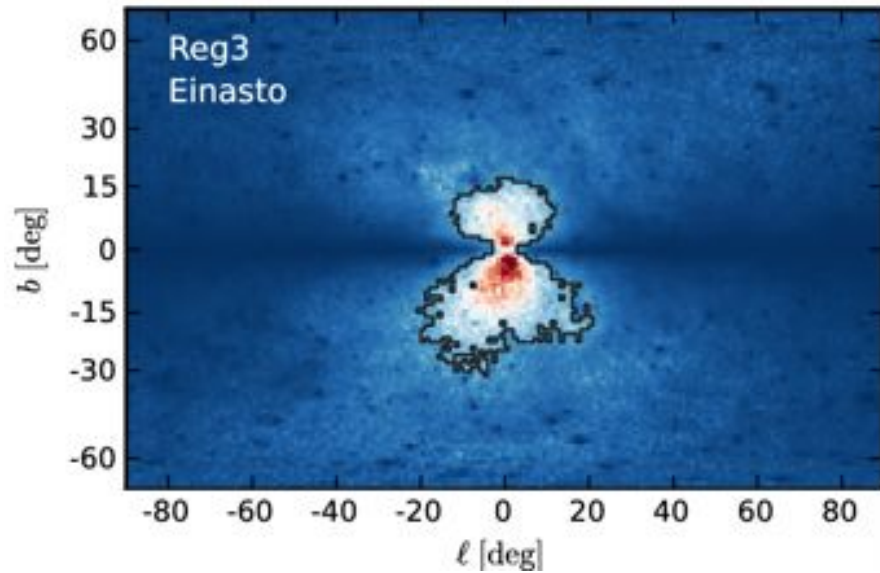
3) *Fermi 130 GeV gamma-ray excess and dark matter annihilation in sub-haloes and in the Galactic center*
Tempel, Hektor and Raidal, JCAP 1209 (2012) 032

4) *Strong evidence for gamma-ray lines in the inner galaxy*
Su & Finkbeiner, arxiv:1206.1616

“Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5 sigma (...).”

How to search for lines

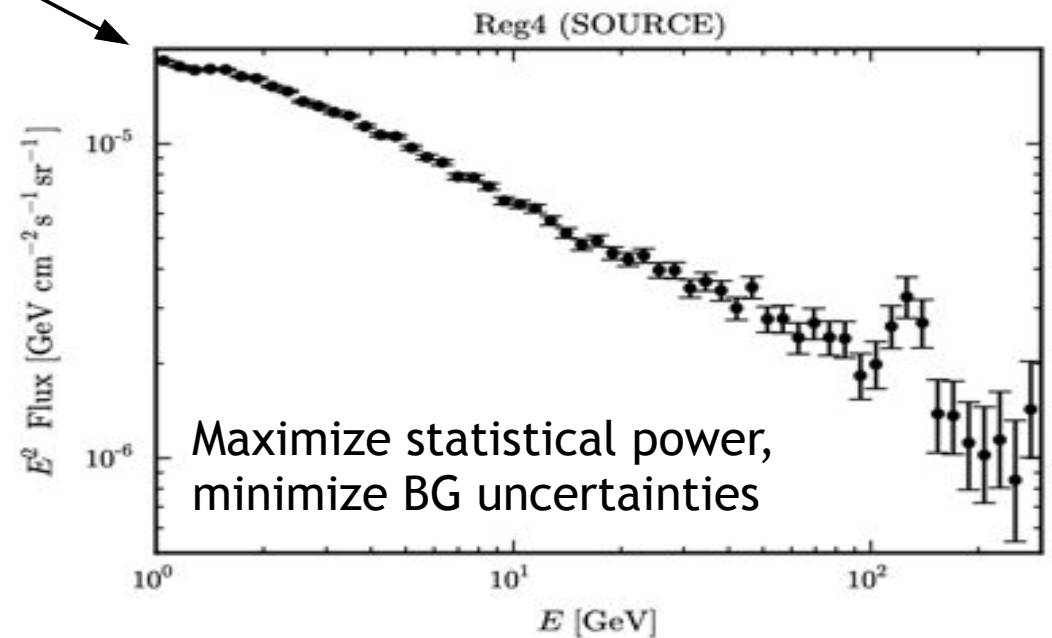
ROI selection



Maximize S/N

$$\int_{\Delta\Omega} d\Omega$$

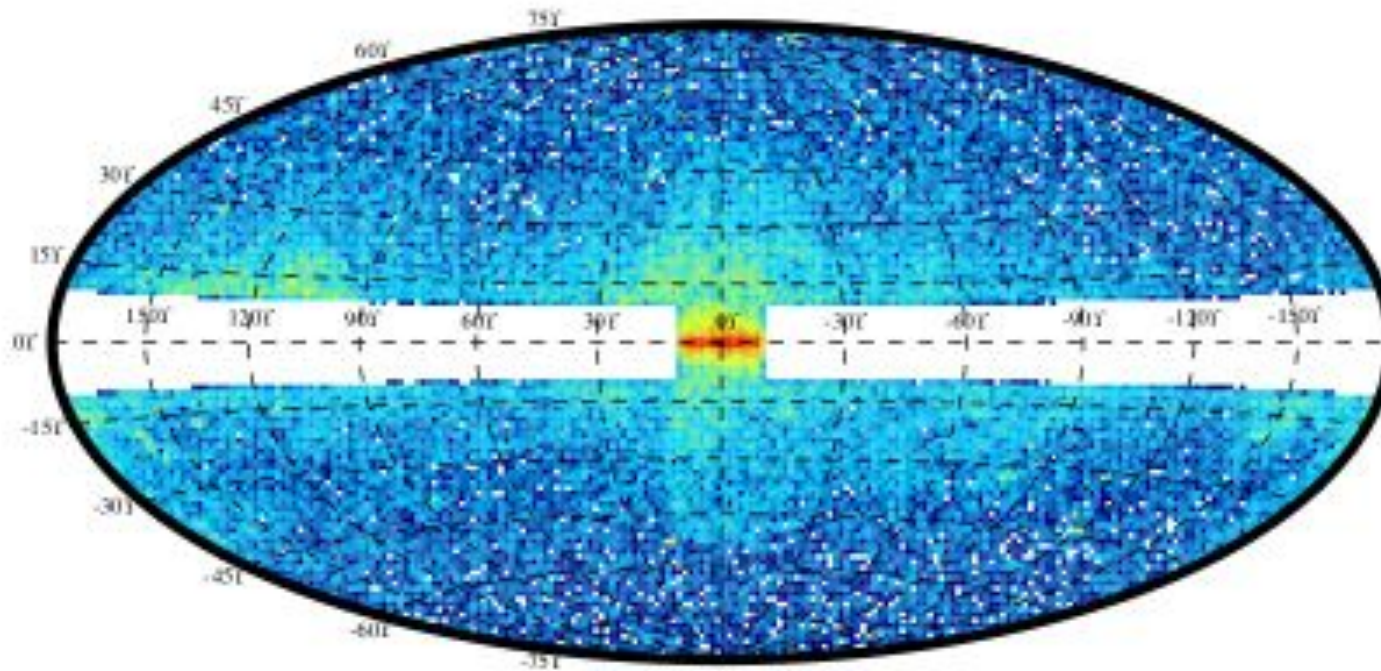
Spectral analysis



ROI in previous studies by the LAT team

Galactic center + high latitudes

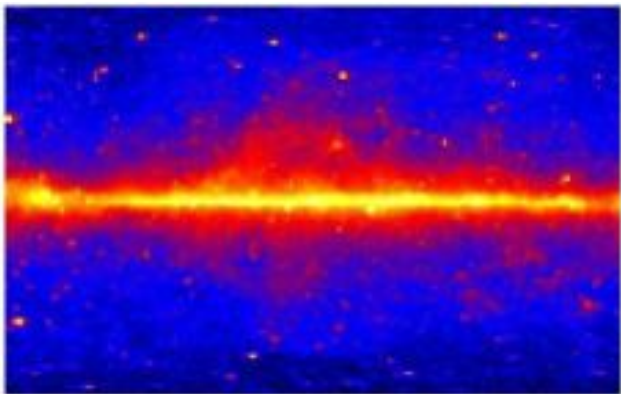
Compromise region for different profiles and DM annihilation and decay



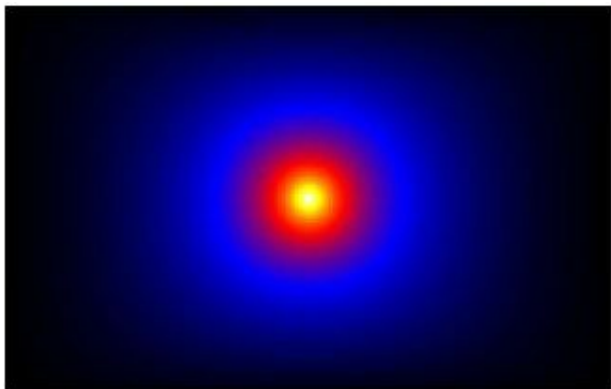
$$|b| > 10^\circ \quad \text{plus} \quad |l|, |b| < 10^\circ$$

Our poor man's method to select ROIs:

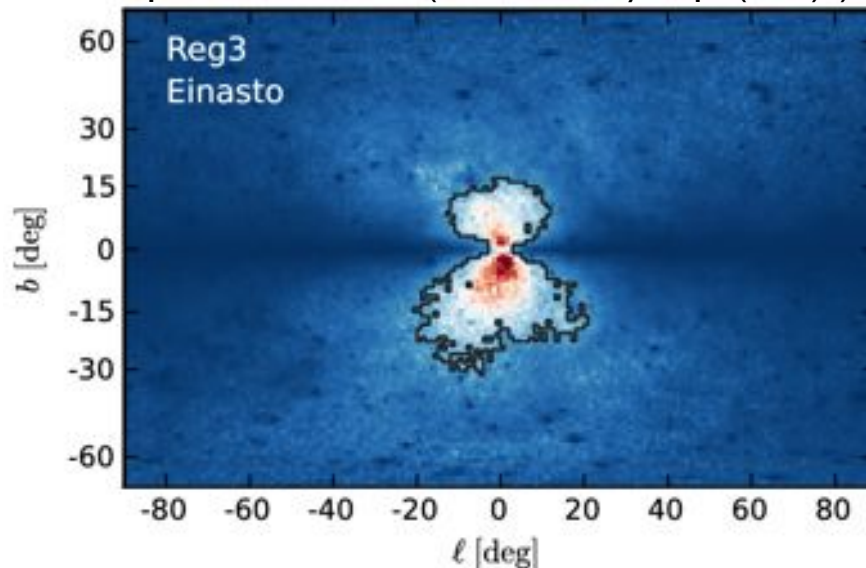
BG morphology:



Signal morphology:



Optimized ROI (max. SIG/\sqrt{BG})



- Pixel-by-pixel optimization of ROI
- Background: 1-20 GeV LAT countmap
- Signal: Einasto, NFW, cored isothermal & contracted DM profiles

Fluxes measured by the LAT

CLEAN vs SOURCE at 130 GeV:

$A_{eff_SOURCE} / A_{eff_CLEAN} = 1.12$

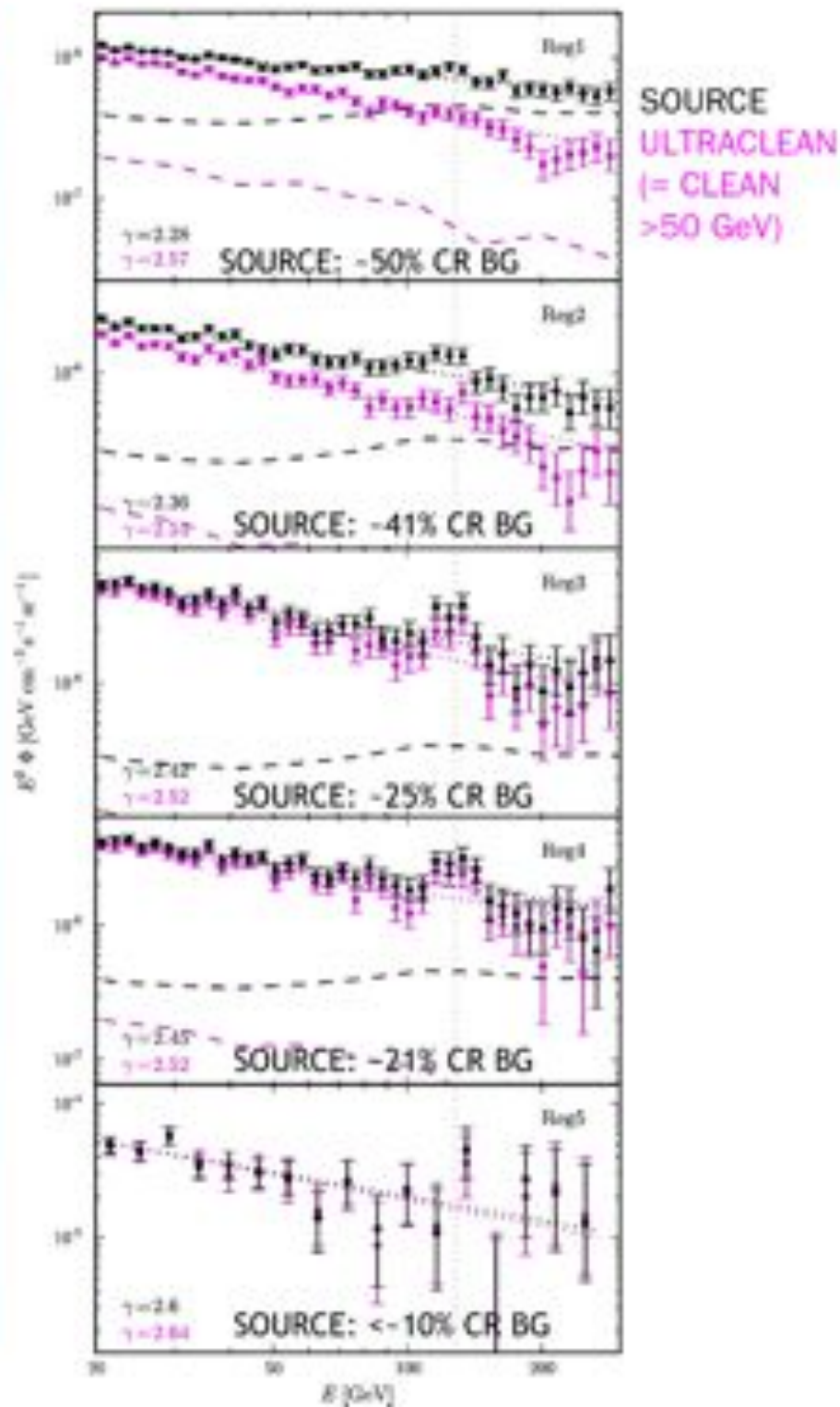
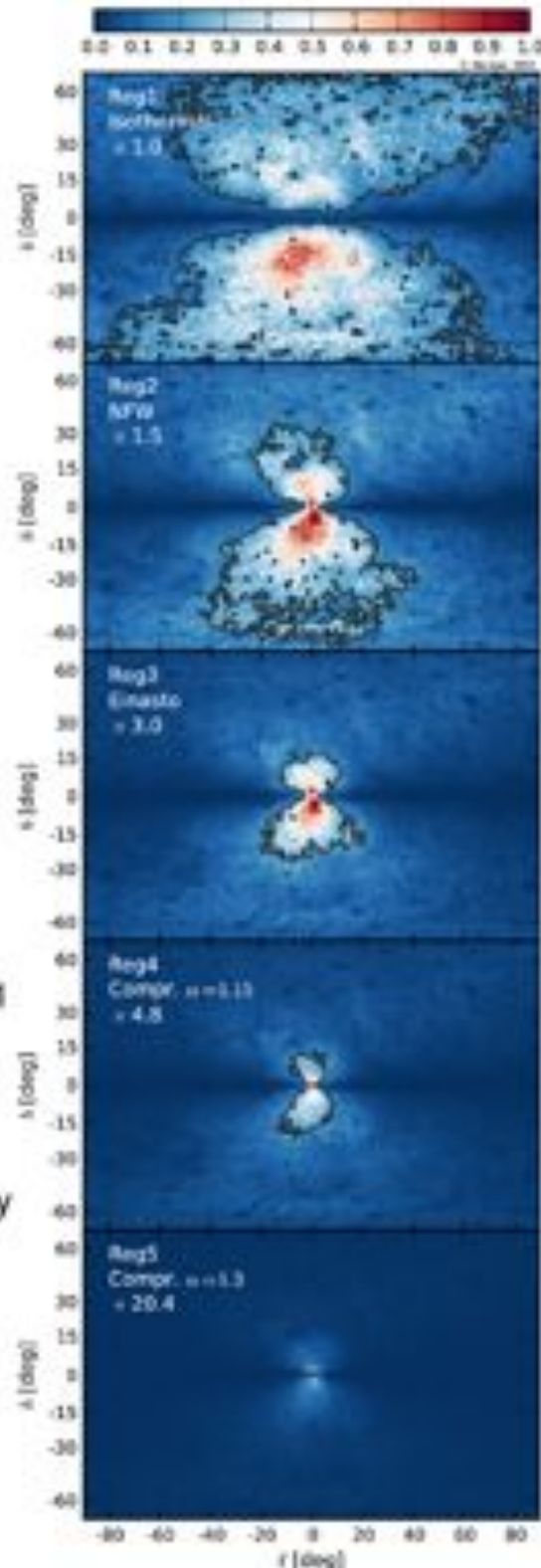
$(S/N)_{SOURCE} / (S/N)_{CLEAN} = 0.9 - 1.1$

S/N are similar for SOURCE and CLEAN class, in increasingly better for small ROIs

→ search in both, correct for that by two independent trials

But: beware of possible spectral features in CR BG contamination

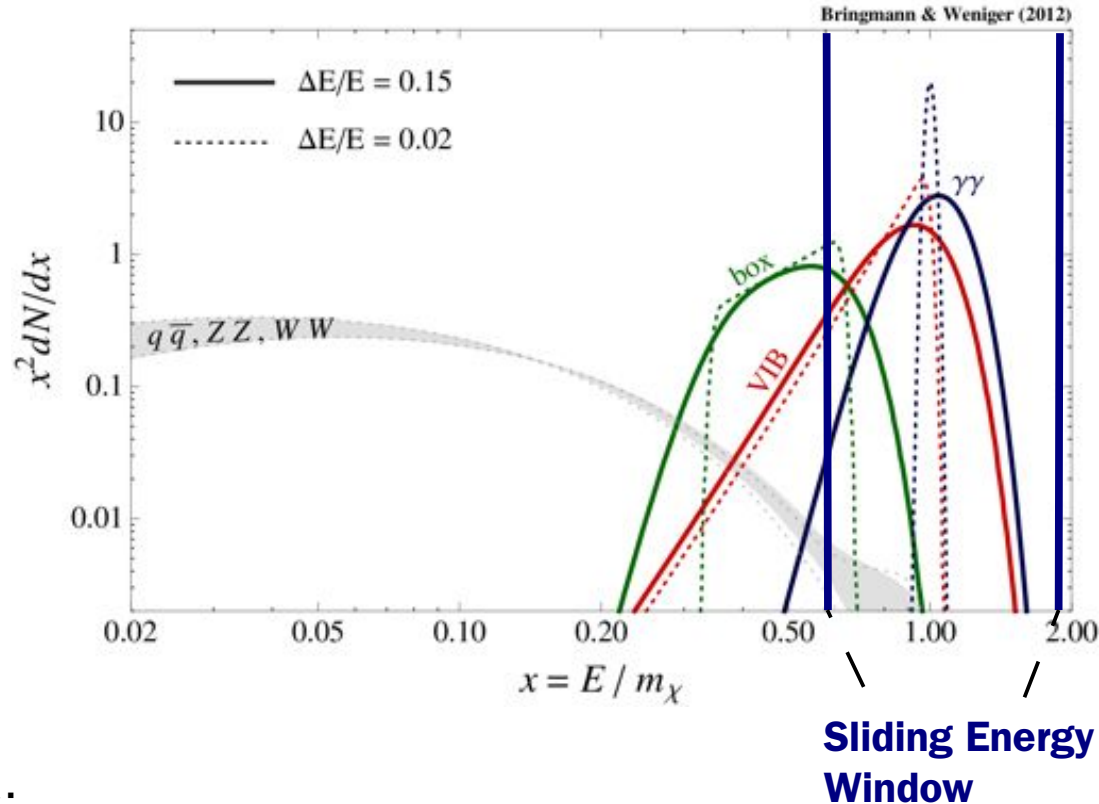
[see Eric Charles' talk]



SOURCE
ULTRACLEAN
(= CLEAN
>50 GeV)

Spectral Analysis

“Sliding energy windows”: For a certain gamma-ray line energy, the spectral analysis is performed within a small energy window around that line energy



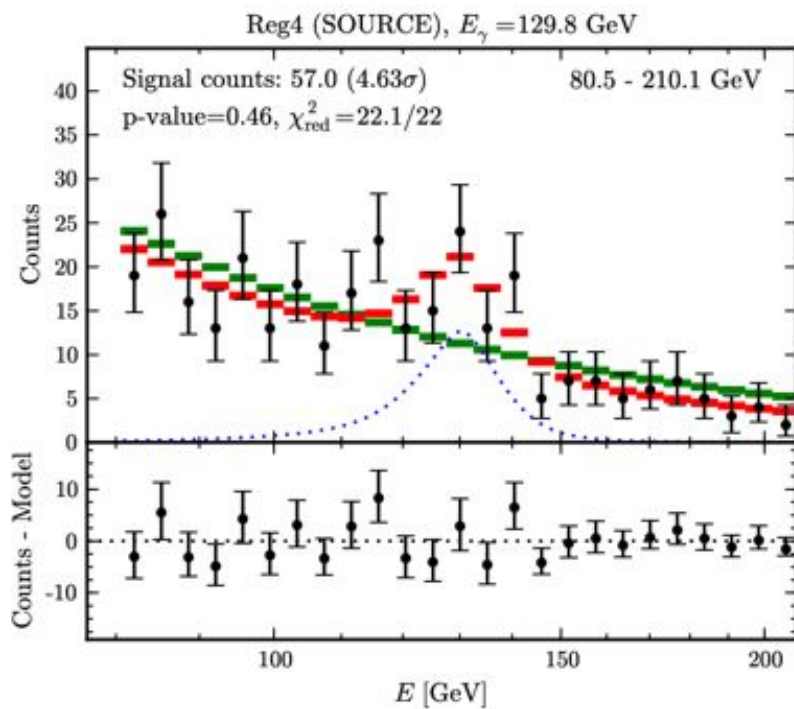
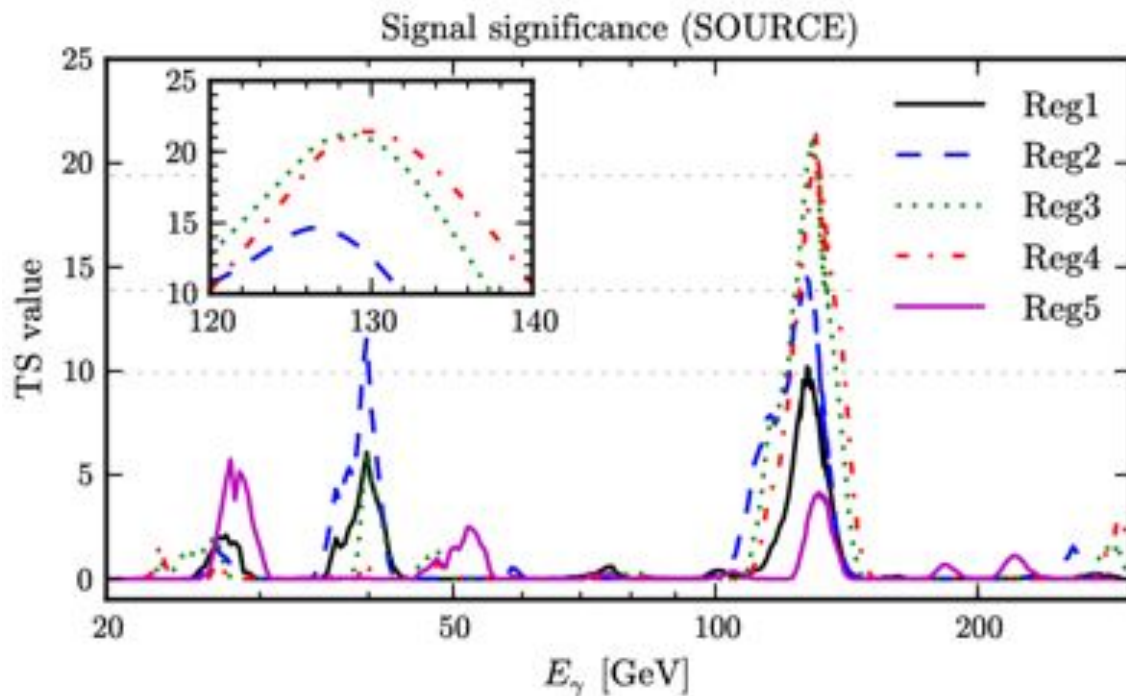
What it does:

- Secondary photons in DM signal can be neglected
- Astrophysical backgrounds can be approximated by power-laws

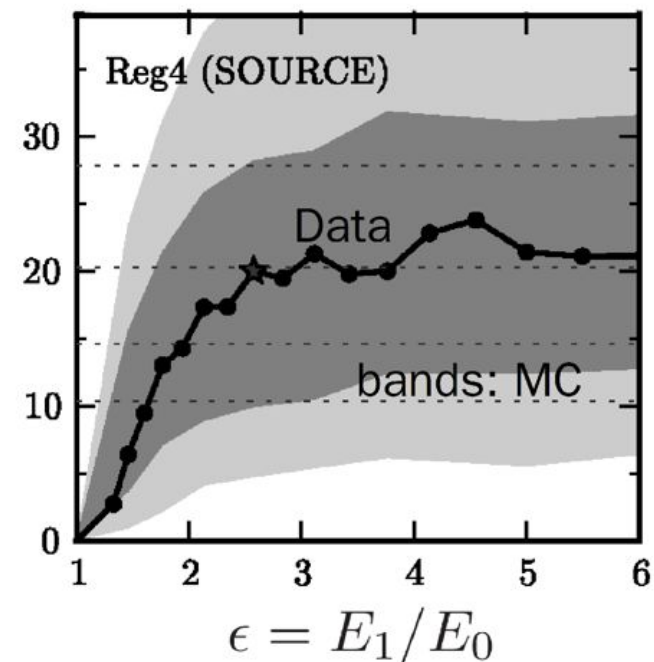
→ Simple fit with PL background + Line signal

- Key question: what window size?

Results



Dependence on window size



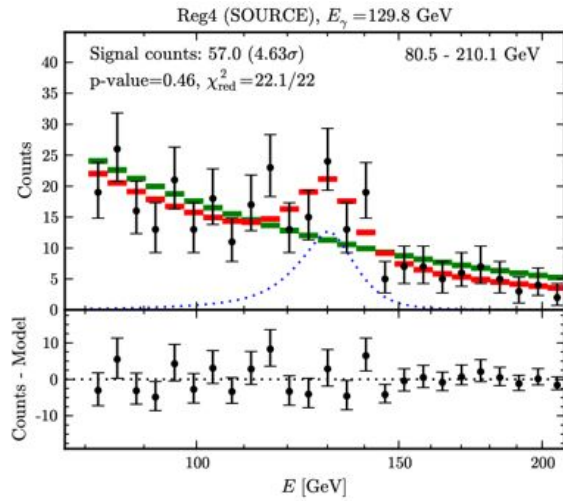
Powerlaw + line fit (1D PDF) in energy range 80.5 – 210.1 GeV

Local significance: 4.6σ
Global significance: 3.2σ

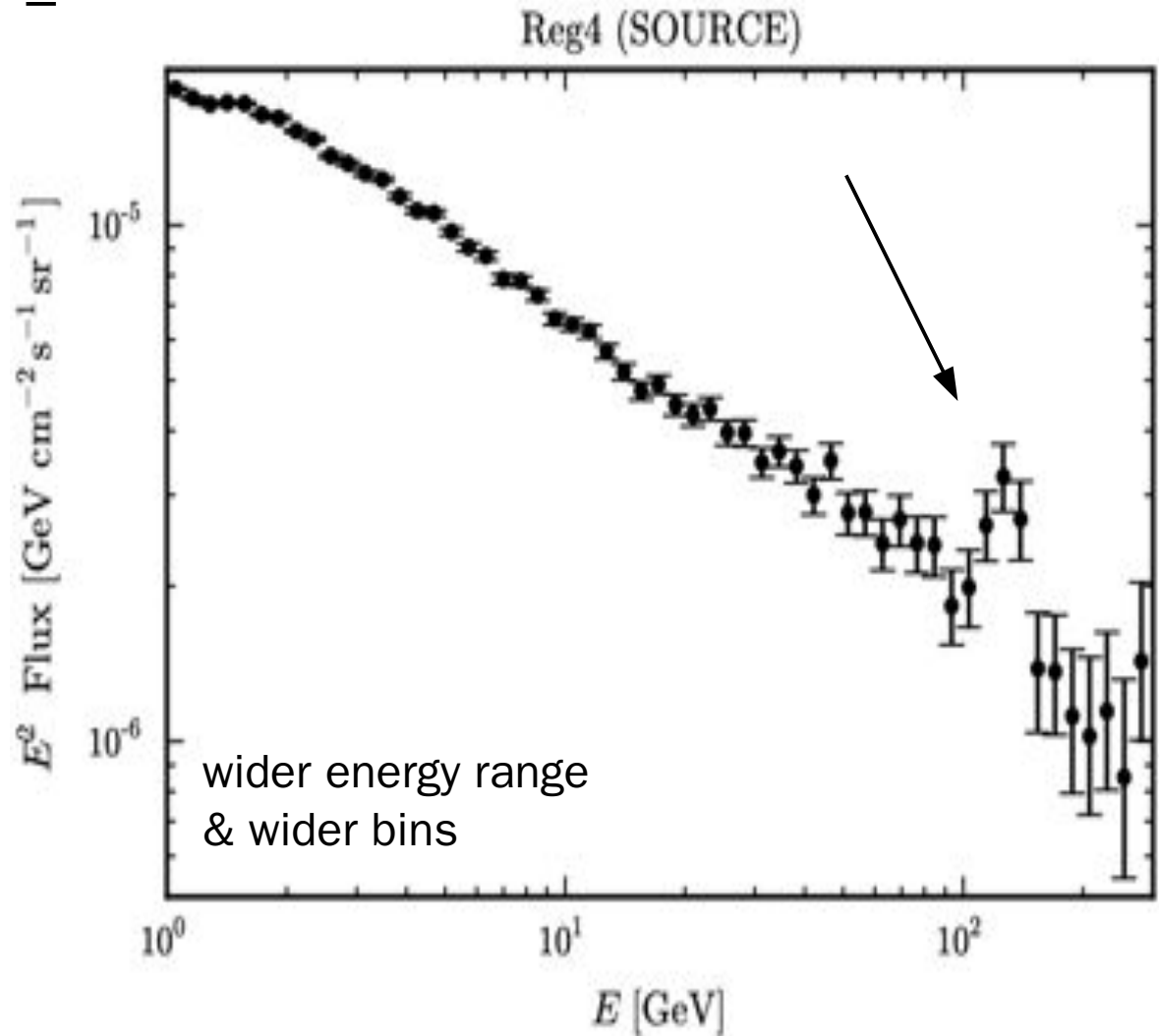
$$E_\gamma = 129.8 \pm 2.4_{-13}^{+7} \text{ GeV}$$

(CLEAN events: 4.4 local)

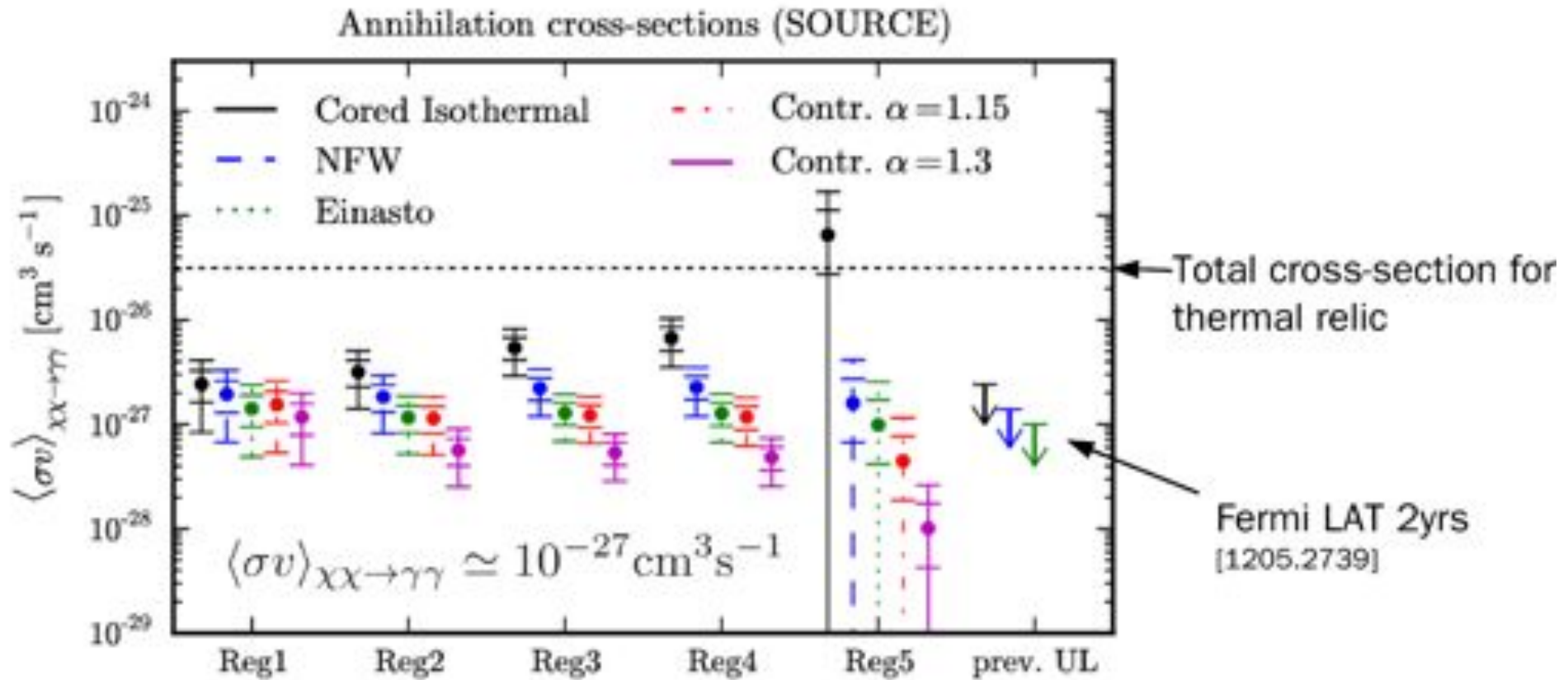
The 130 GeV feature



==



Annihilation cross-section & DM profile

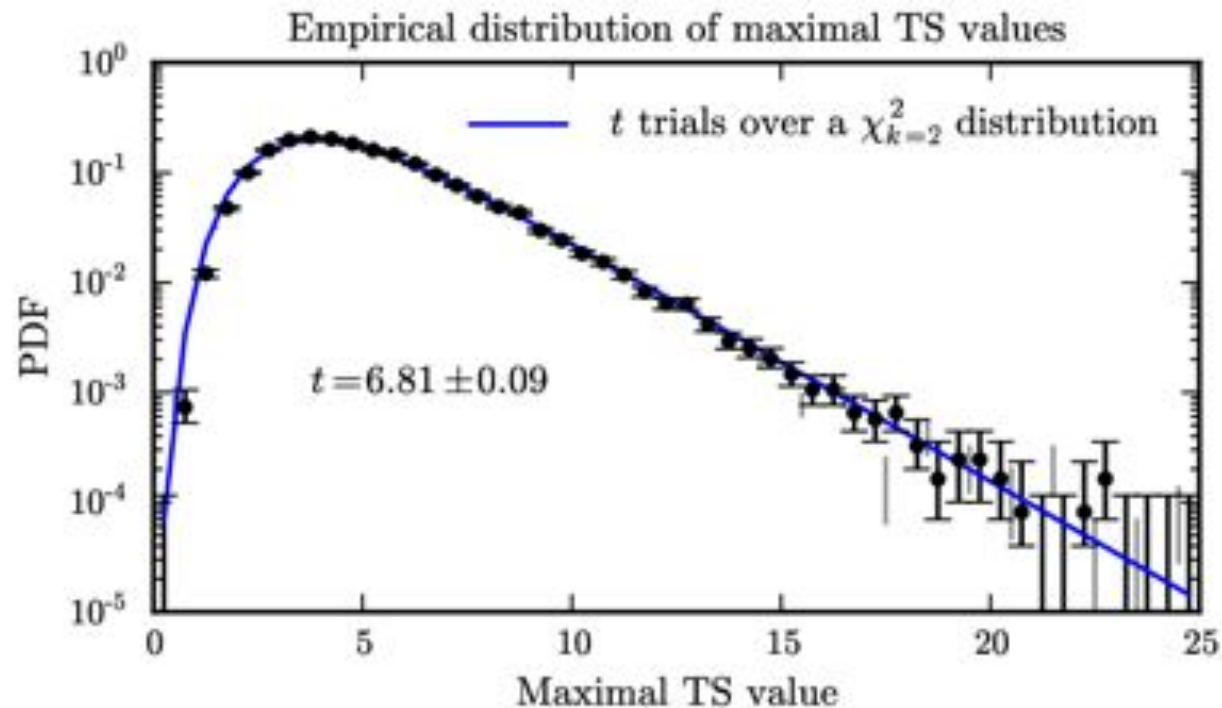


- Annihilation cross-sections are consistent for **Einasto & NFW profiles**
- Branching ratio for thermal relic would be very large:

$$\text{BR}(\chi\chi \rightarrow \gamma\gamma) \sim 5\% \gg 10^{-4}$$

Trials correction

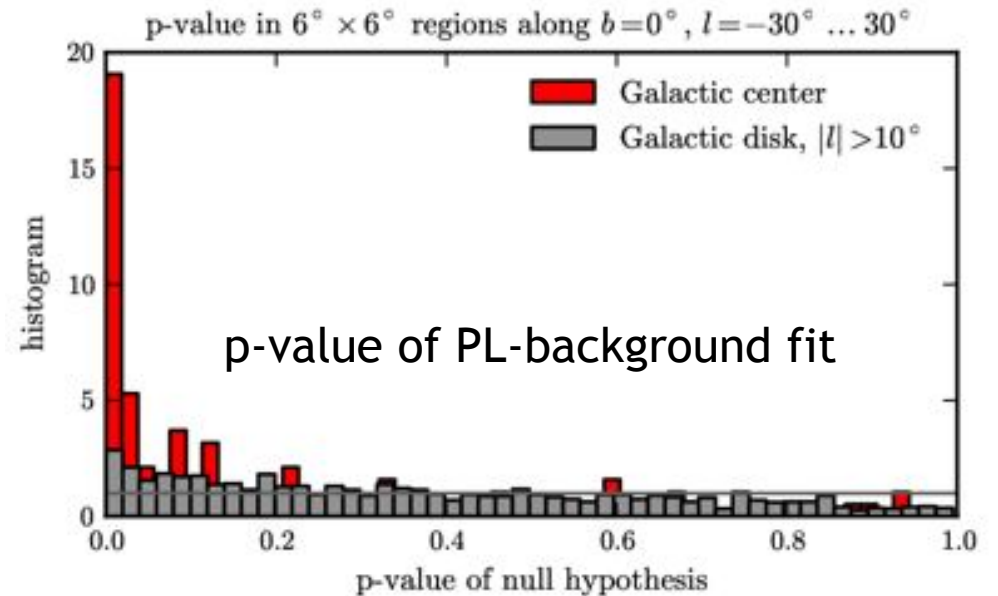
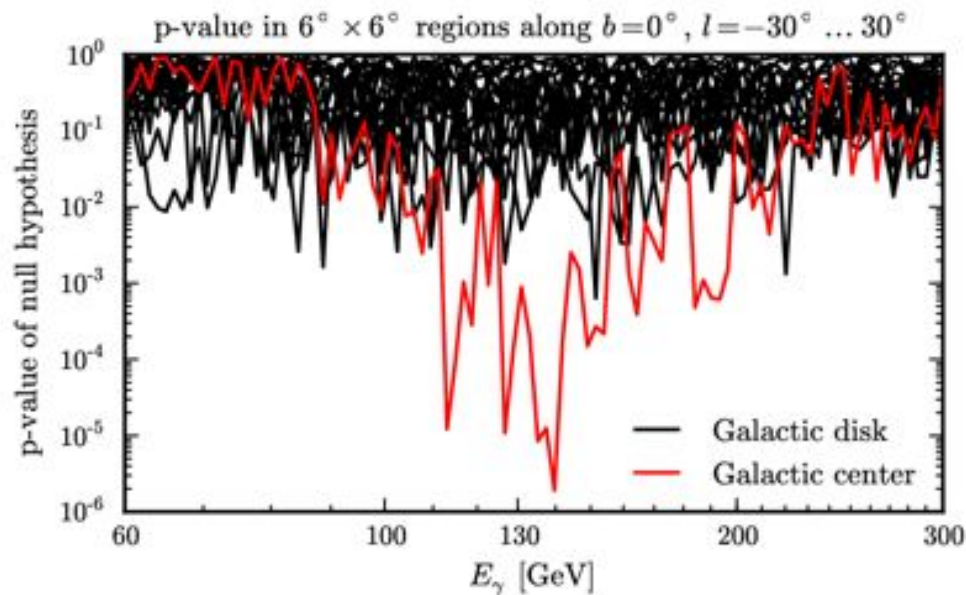
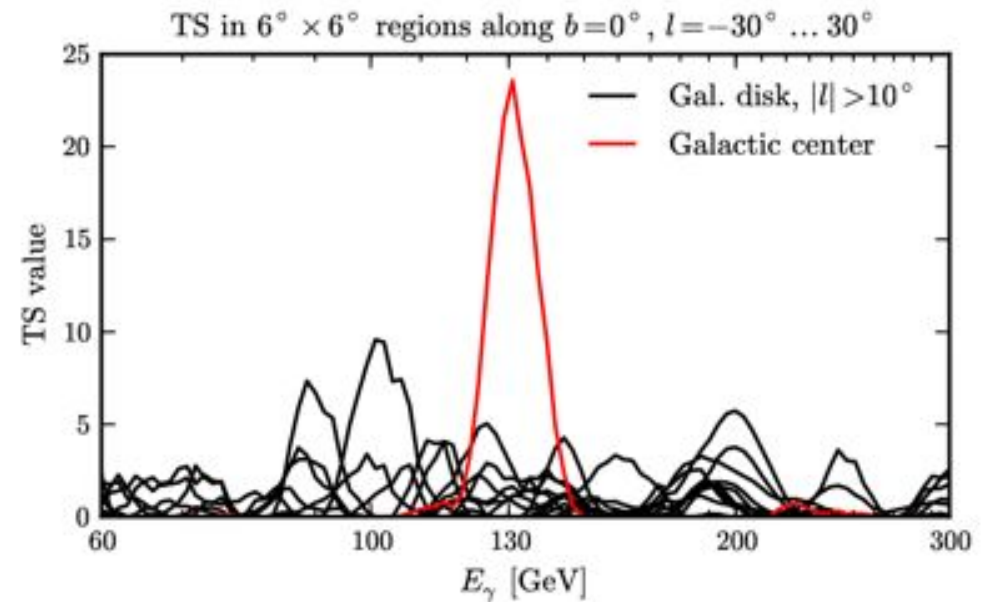
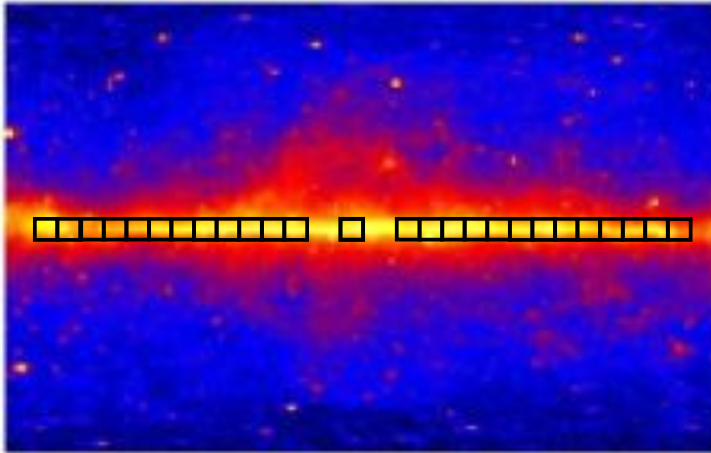
- To calculate trial factors for scan from 20 to 300 GeV, we performed
 - a **Monte Carlo analysis** (25000 samples) of spectra without signal
 - a **subsampling analysis** of anti-galactic-center data (~21000 random test regions from $|| > 90^\circ$ data) and searched for lines.



- Trials from
 - correlated ten target regions times two event classes: ~10 trials (3.0 sigma for 20 trials)
 - scan from 20 to 300 GeV: 6.81 “independent search regions”
→ **globally 3.2 sigma**

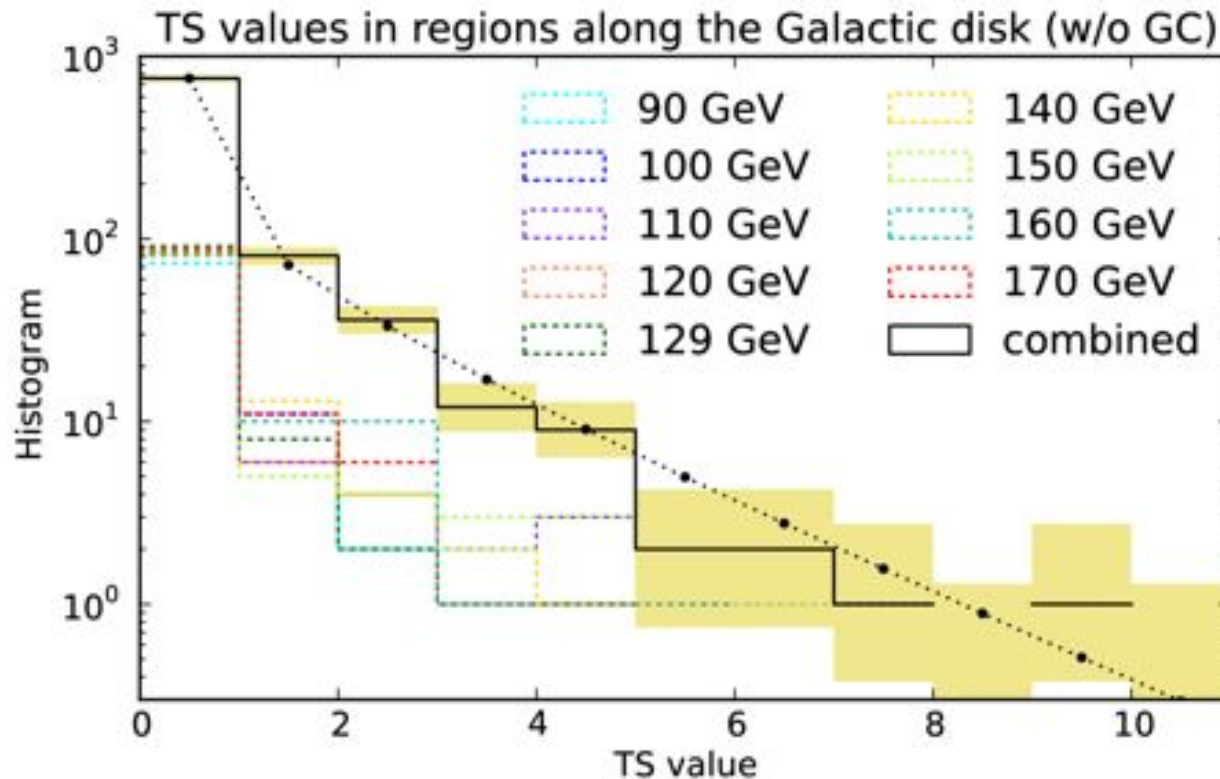
Signature is at the GC only (1)

Scan along the galactic disk:



Signature is at the GC only (2)

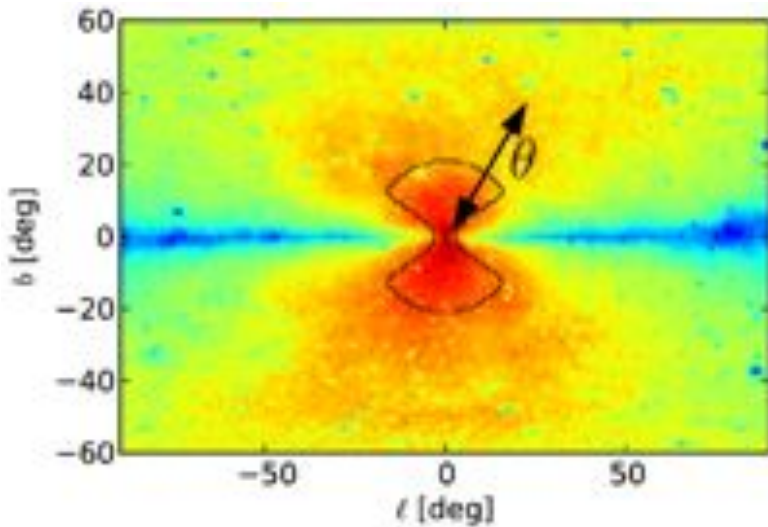
- TS value along the Galactic disk in $6 \times 6 \text{ deg}^2$ regions, excluding regions close to the GC.



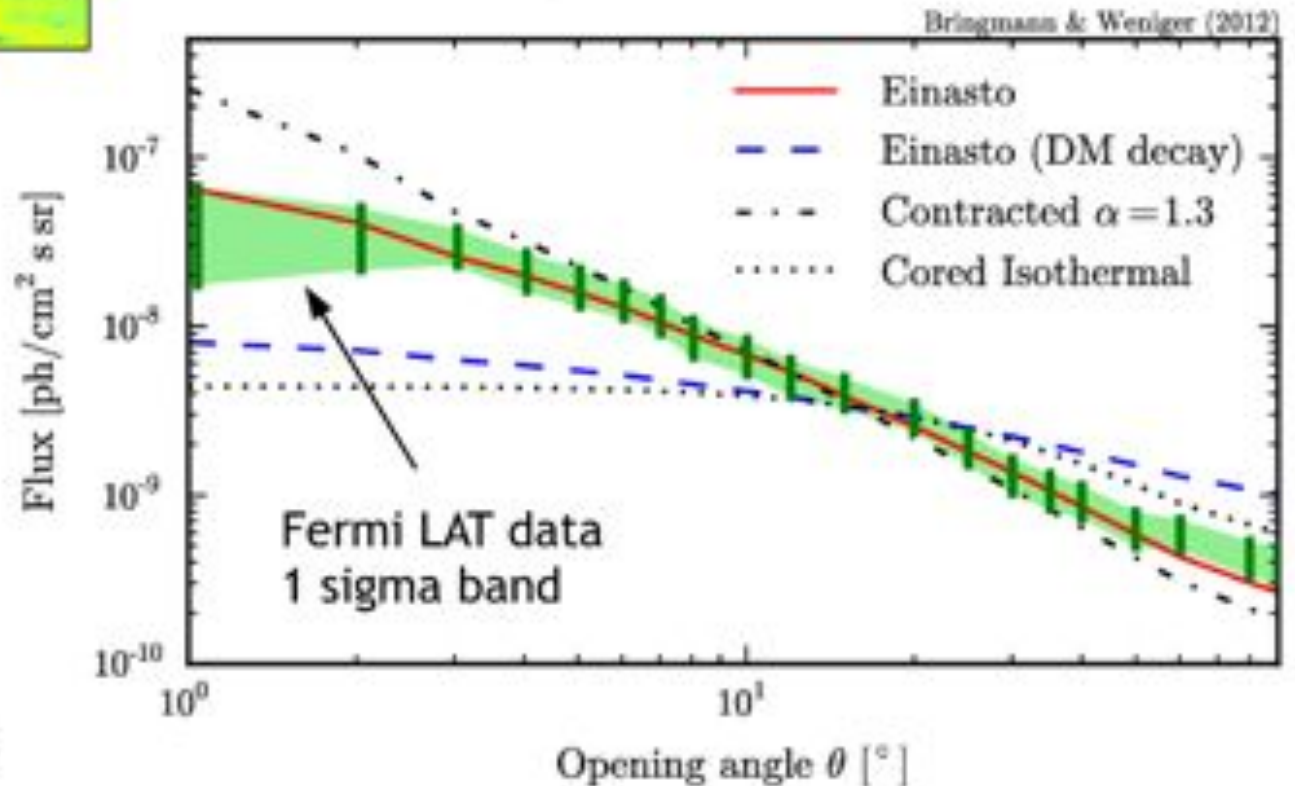
- There are places away from the GC with local >3 sigma indication for a line
- This is exactly what is expected for a large number of trials (dashed line)

Compatible with Einasto/NFW profiles

ROI with variable size:

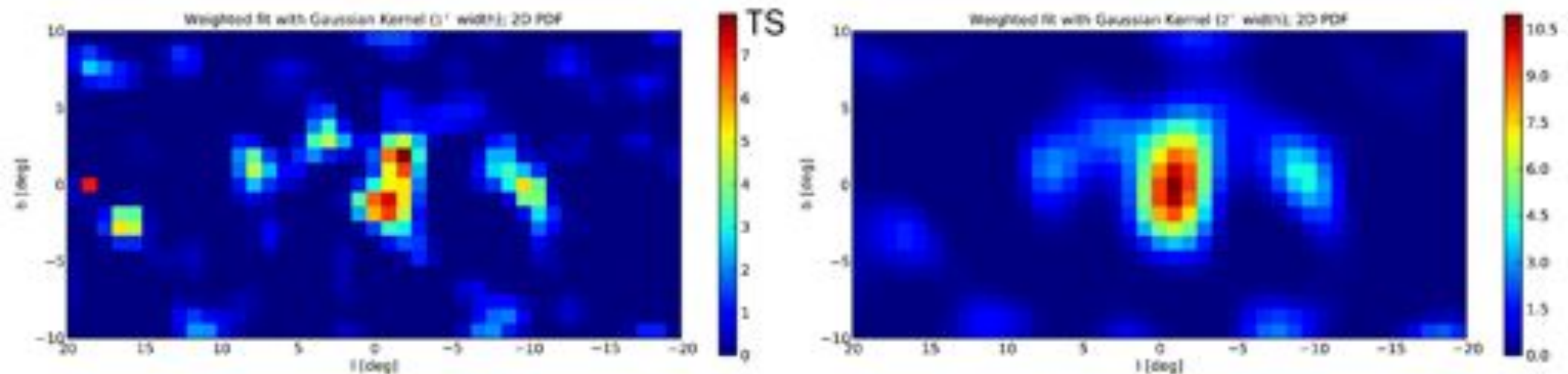


- The signature does not come from a single 1deg region in the sky (PSF of LAT)
- It is roughly symmetric around the GC (checked by masking half ROIs)
- Distribution compatible with standard NFW or Einasto DM profiles

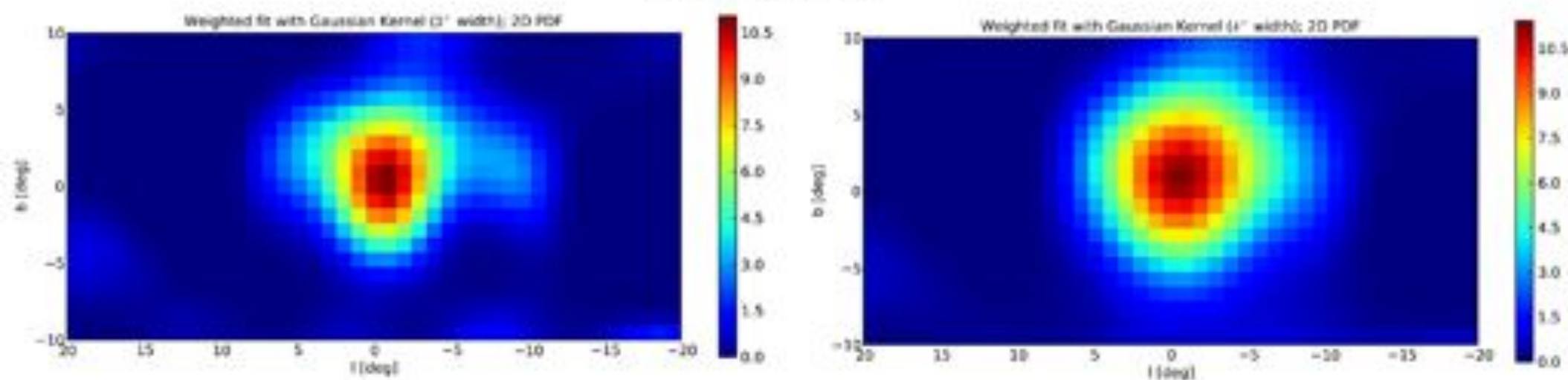


This does not affect the signal significance!

TS maps



PRELIMINARY

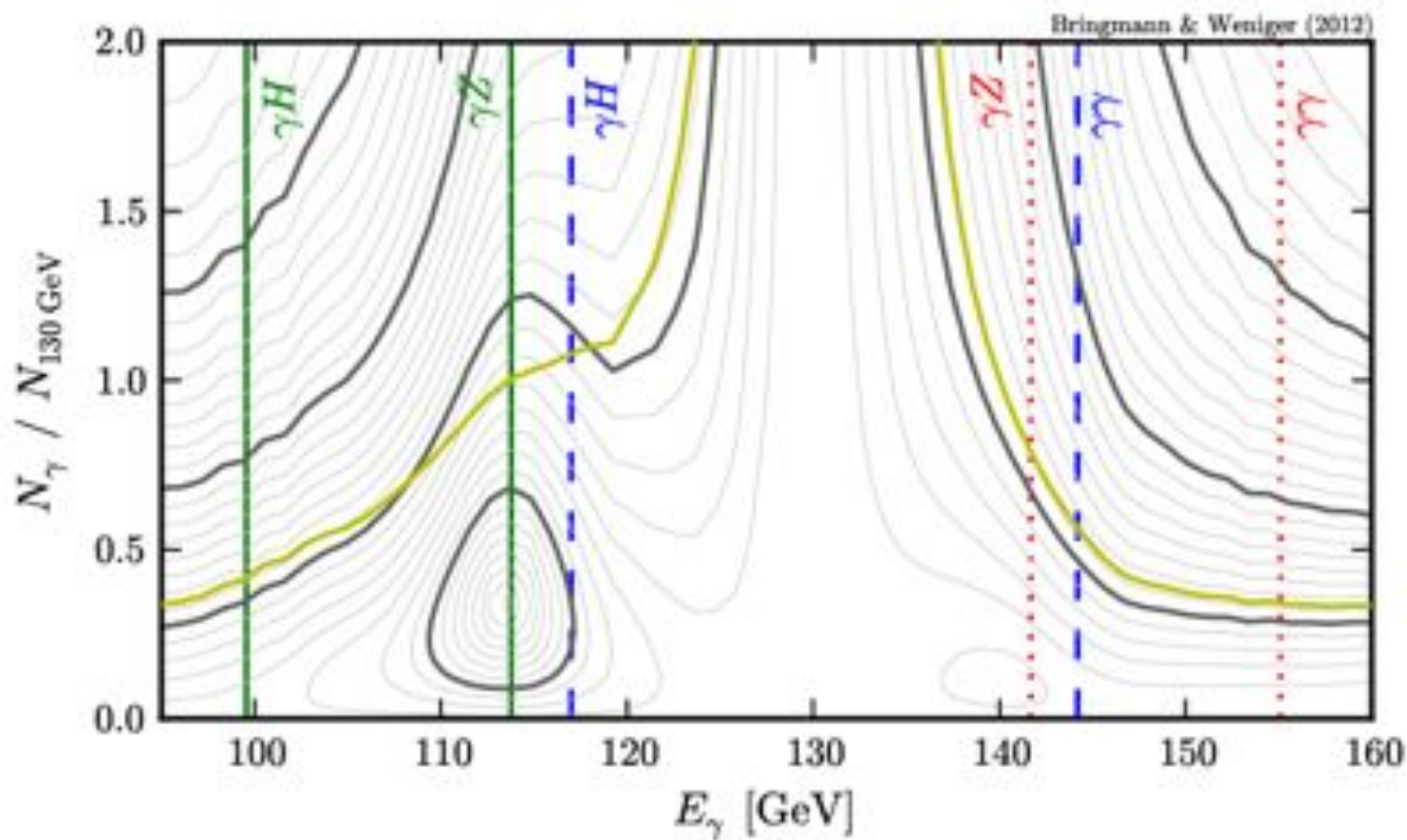


130 GeV line + PL BG in energy range [65, 250] GeV

[see also Eric Charles' talk]

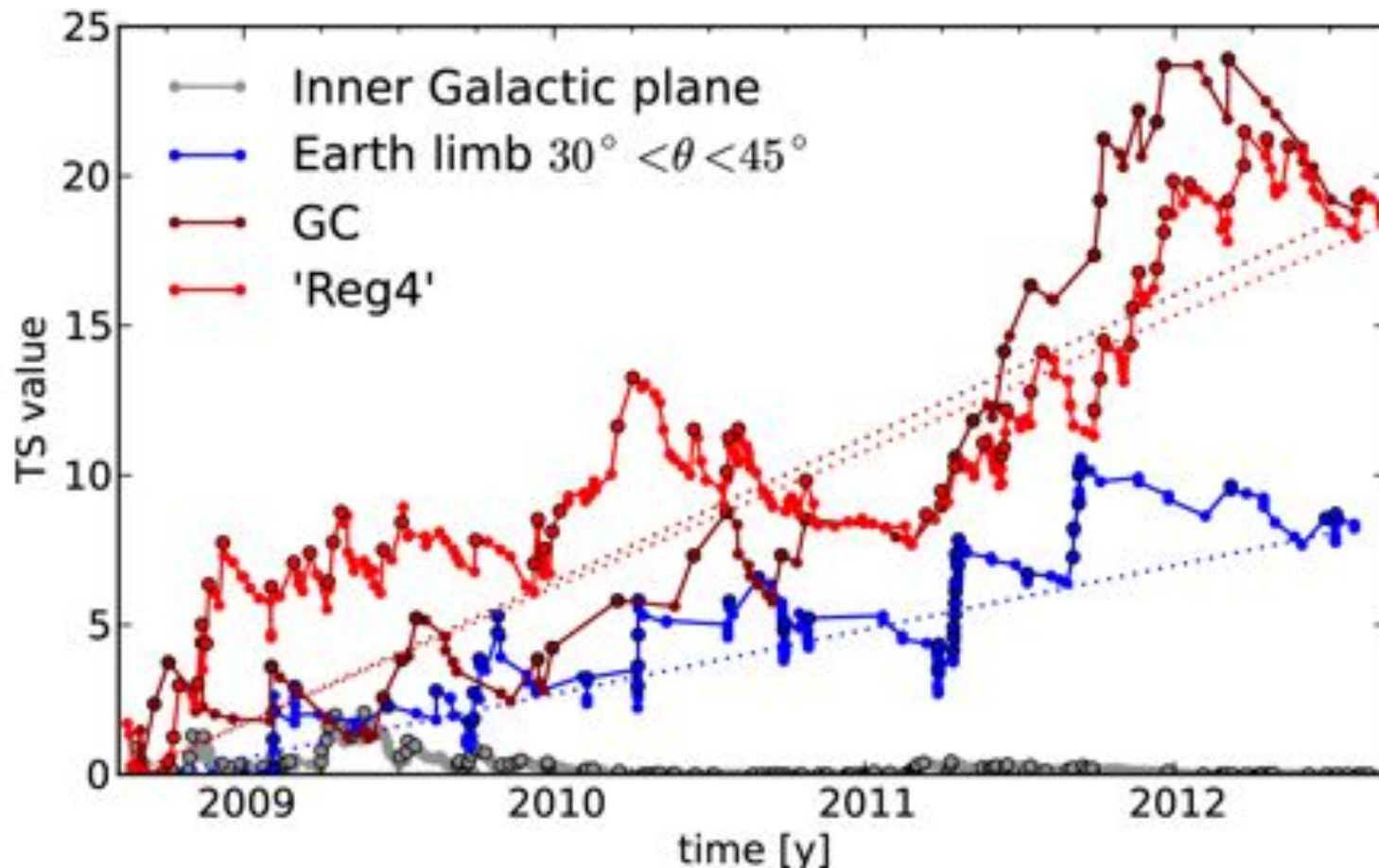
Indications for a second line?

$$\chi\chi \rightarrow \gamma\gamma, \gamma Z^0, \gamma H^0$$



- 1.4 sigma hint for second line, compatible with gamma Z
- Upper limits in other cases
(fits performed in SOURCE class Reg4)

Time evolution of signal



Time evolution of TS value

- All curves are compatible with non-variability
- Dots show new events >80 GeV, circles new events close to 130 GeV
- Signal is slightly falling since ~April

[Limb line: Elliott Bloom's talk]

Situation now (unreprocessed PASS7)

- Data up to 19 Oct 2012 (+16% events)
- stronger cuts in gtmktime (-8% events)
- 6% larger #events

2D PDF
(energy +
incidence angle
information)

Larger E-window
(higher statistical
power)

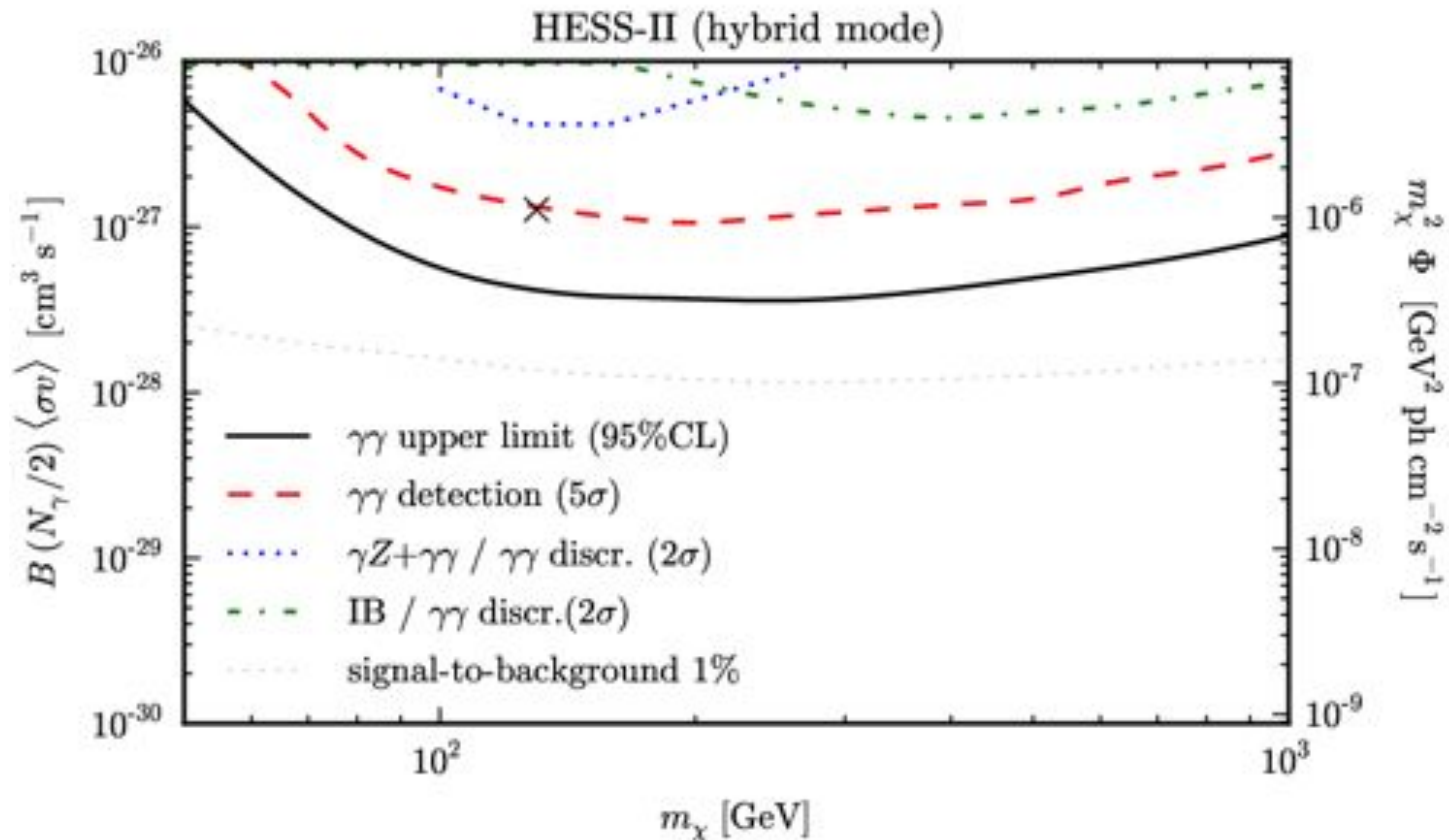
PRELIMINARY

TS values:

| | | | | | | | |
|-------------|----------------|---|----------------|---|----------------|---------|--------------|
| Reg3 CLEAN | 18.1 | → | 15.4 | → | 12.1 | ← | 15.8 |
| Reg4 CLEAN | 19.0 | | 17.6 | | 14.0 | ← Now → | 17.9 |
| Reg3 SOURCE | 21.1 | → | 19.7 | → | 17.1 | ← | 22.1 |
| Reg4 SOURCE | 21.4 | | 22.1 | | 19.5 | | 24.5 |
| | 80.5-210.2 GeV | | 80.5-210.2 GeV | | 80.5-210.2 GeV | | 65 – 260 GeV |
| | [1204.2729] | | | | | | |

- Local significance drops slightly when adopting 2D PDF.
[See next talk by Andrea Albert]
- Overall little change since April 2012:
 - ~4.0 sigma (3.7 to 4.2) sigma in Reg4 CLEAN
 - ~4.5 sigma (4.4 to 4.9) sigma in Reg4 SOURCE
- **We need significantly more data**

HESS-II to the rescue?



HESS-II (hybrid)

- Assuming 50 hours of GC observation
- enough to rule out signature or confirm it at 5 sigma (if systematics are under control)
- Observations start in March 2013

[parameters from J. Lefaucheur+ (Gamma 2012, Heidelberg)]

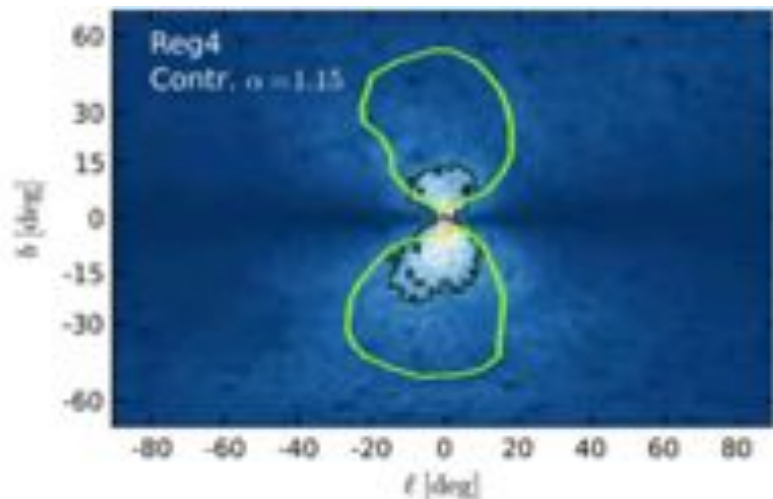
Summary

The LAT data contains an excellent candidate for a gamma-ray line from DM annihilation. Its cause is unclear.

- Rare statistical fluctuation: maybe. But in light of the importance of such a result, there is no way around following this up carefully.
- Instrumental cause: cannot be excluded right now (beware the Earth limb!). But: why distribution compatible with NFW/Einasto profiles? Why just at the Galactic center?
- Dark Matter Annihilation? Right now nothing more than an optimistic interpretation. But the signature is there, has all the properties one would like to see from a DM signal, and it needs to be understood.
- ...we need more data (→ a matter of time, PASS8, HESS-II, Limb Observations, ToO)

Backup Slides

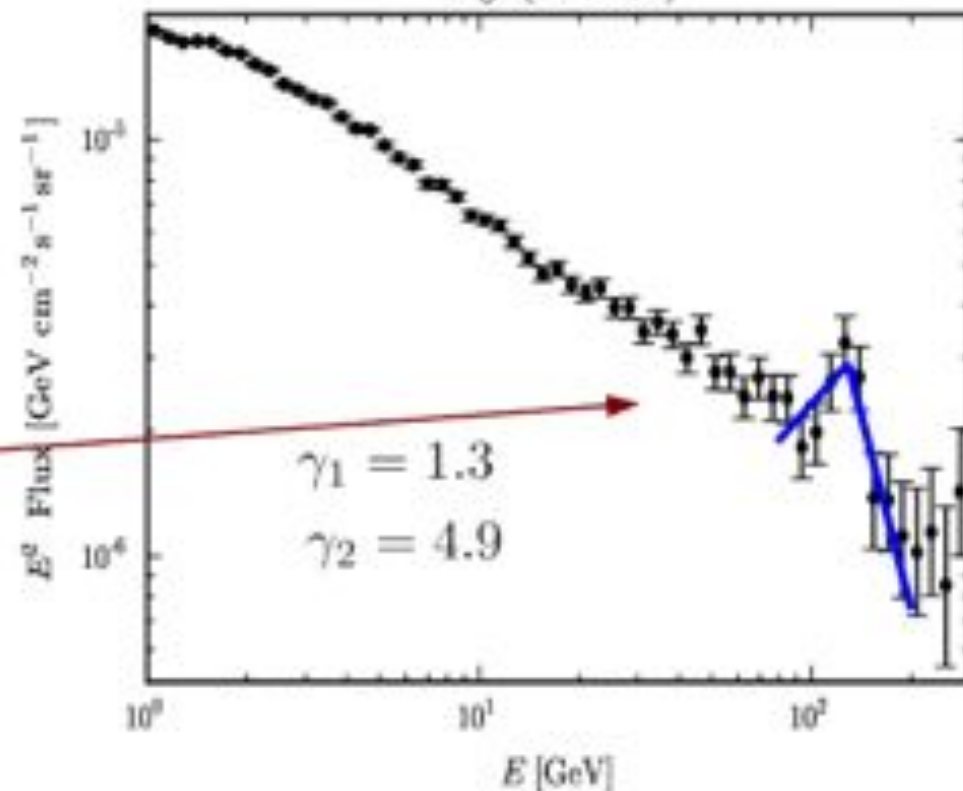
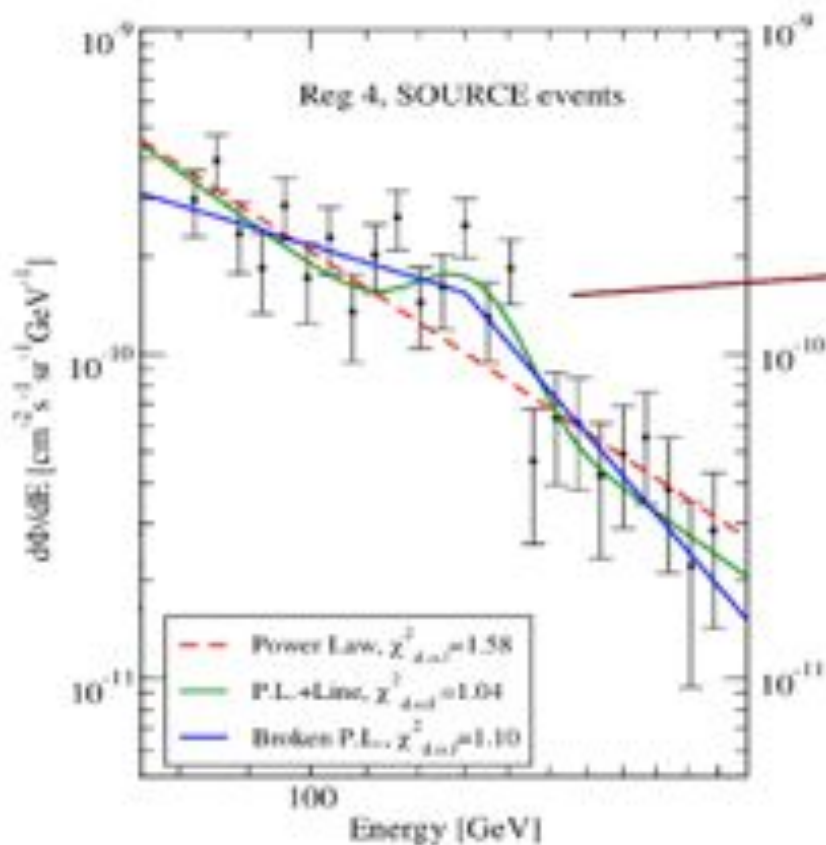
Broken Power Laws?



Linden & Profumo [1204.6047]:

- I) Target regions overlap with Fermi Bubbles
- II) Bubble spectrum is possibly a broken power-law
→ „Spurious Line“

Reg4 (SOURCE)

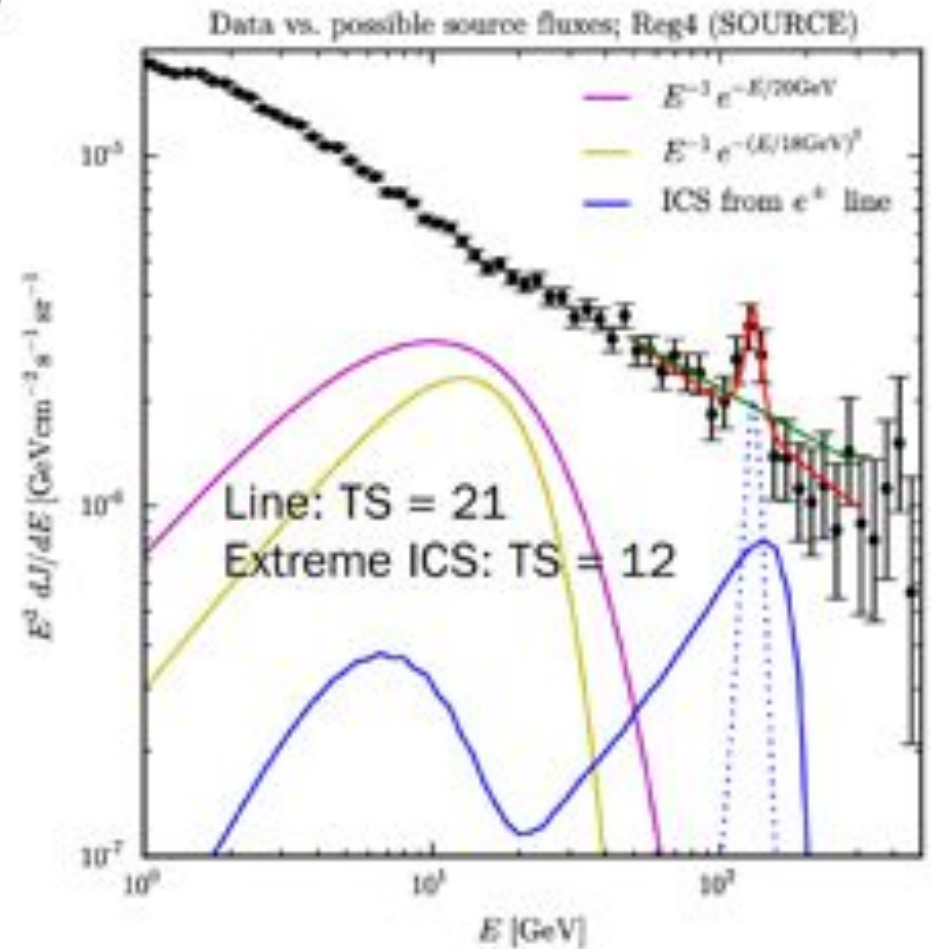
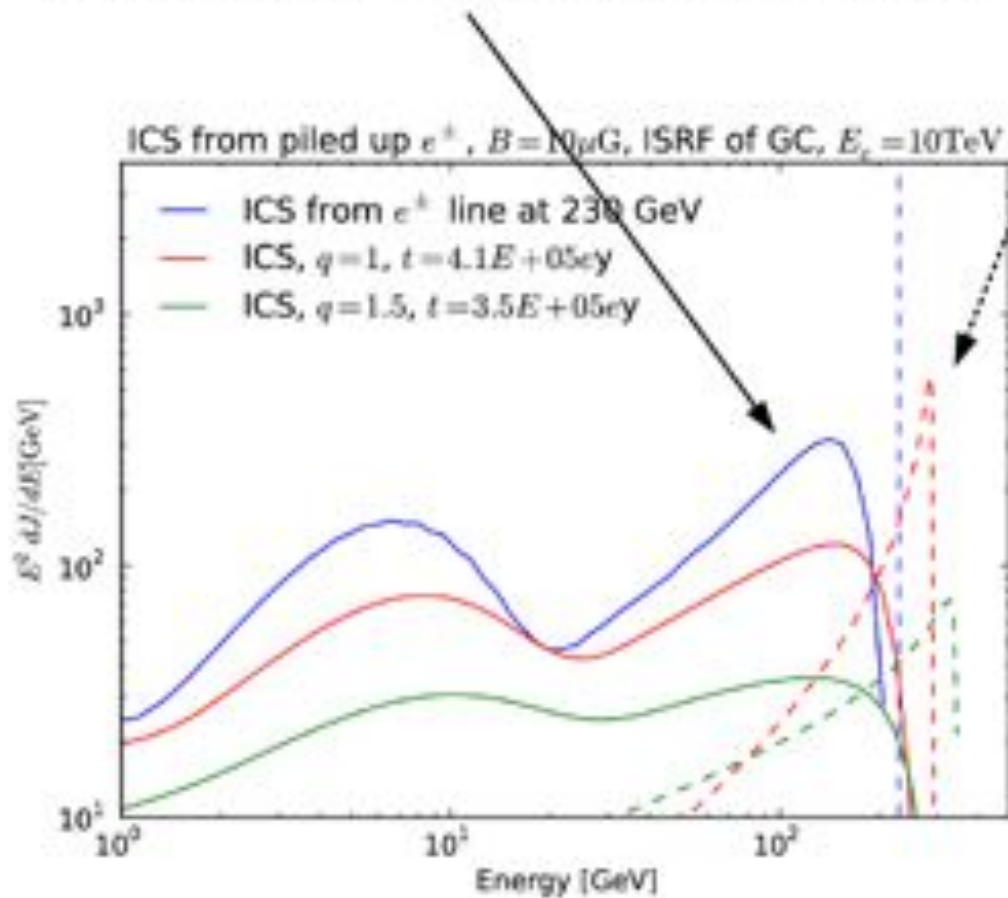


- * Standard background fluxes missing in the fit
- * A flat spectrum radio quasar? [1001.4097]:
Break energies < 10 GeV, hardest break from 2.2 to 4.9
- * But: cannot be a single source

Toy model for sharp gamma-ray emission

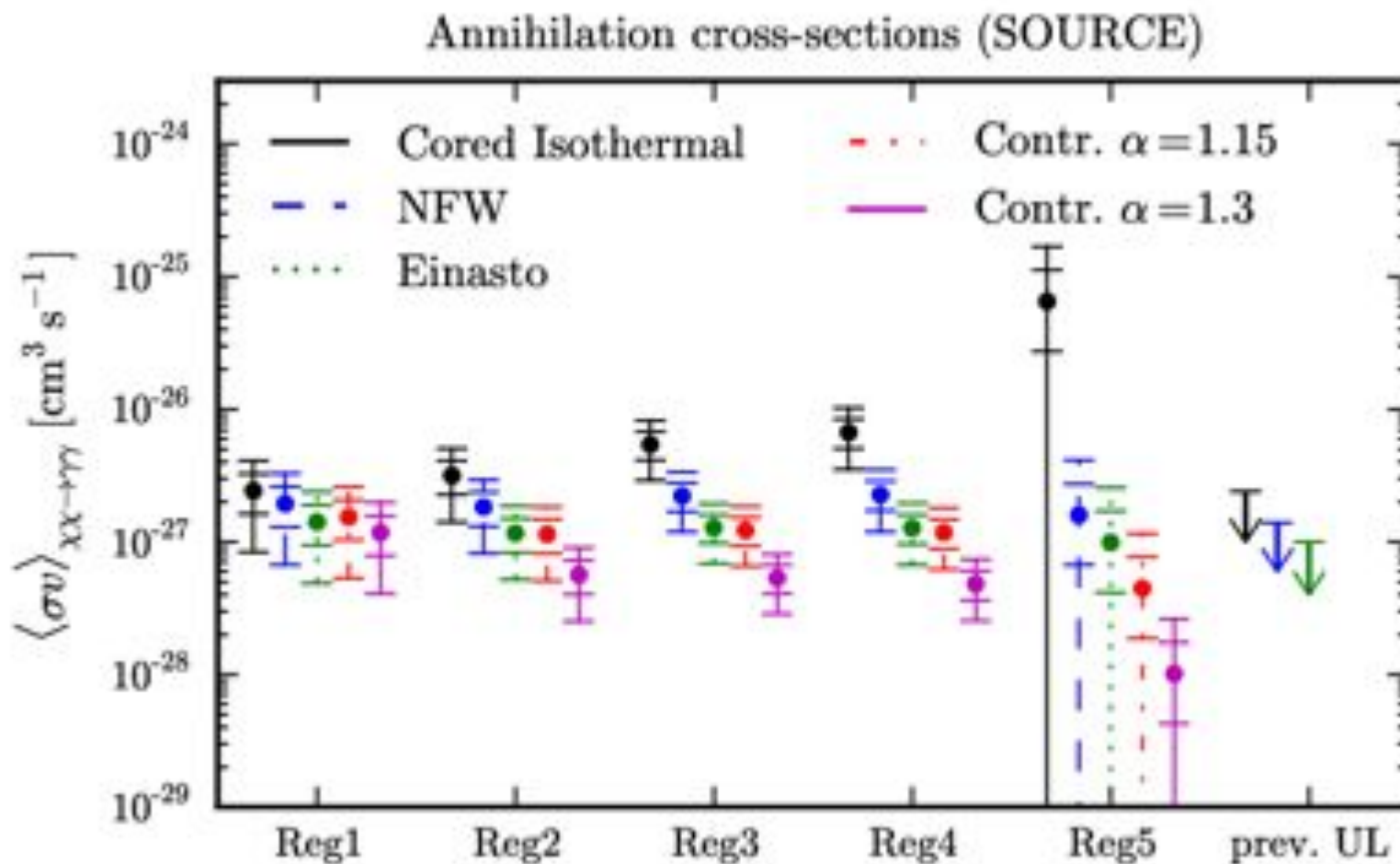
Scenario:

- 1) Inject hard electron spectrum (spectral index 1 to 1.5) and cutoff at ~ 10 TeV into GC.
- 2) Synchrotron losses on a dominating uniform magnetic field.
- 3) Electrons pile up \rightarrow Idealized, this gives an **electron line**.
- 4) **Inverse Compton Scattering on the ISRF**

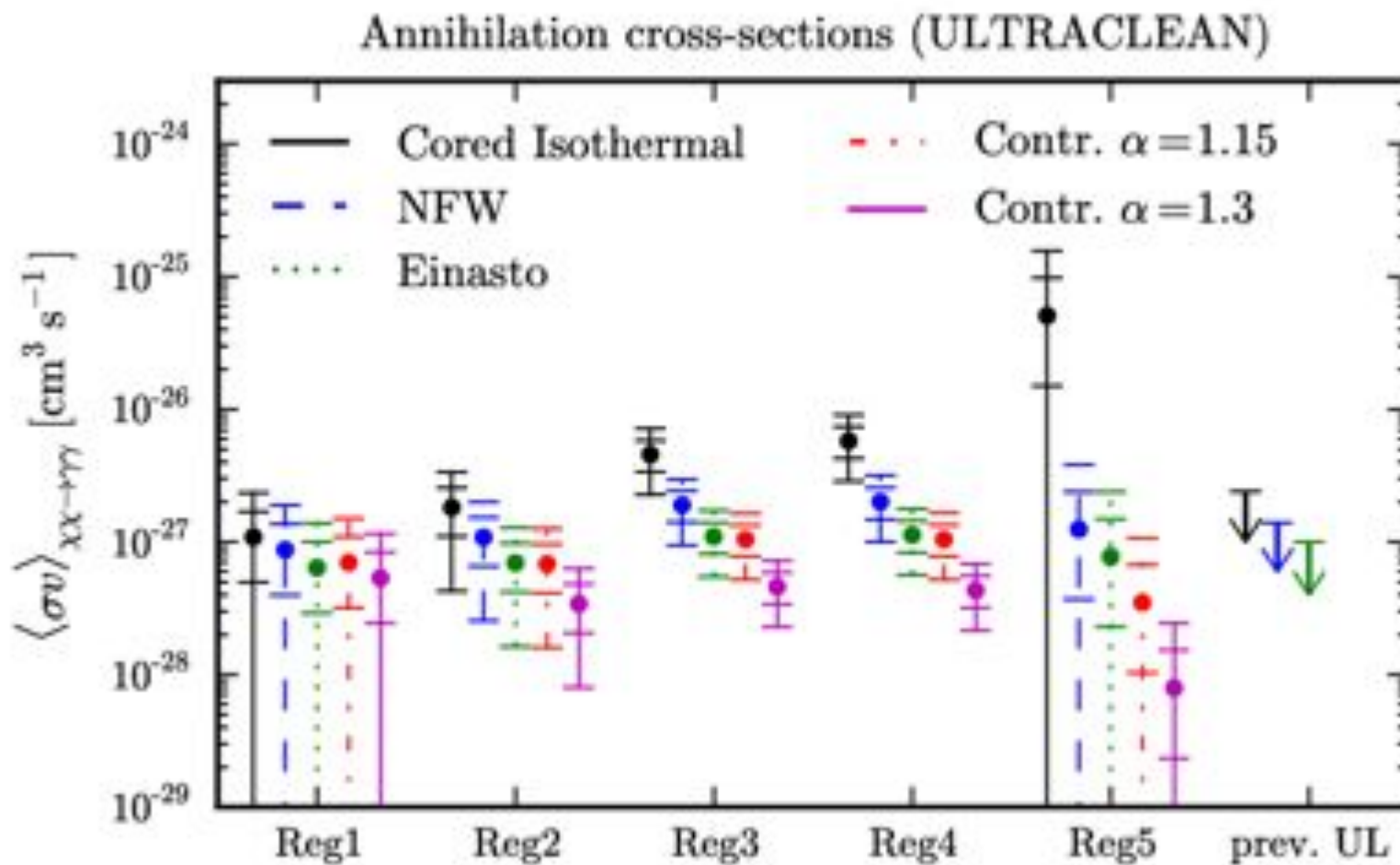


Even extreme ICS emission is disfavoured by $\sim 3\text{-sigma}$

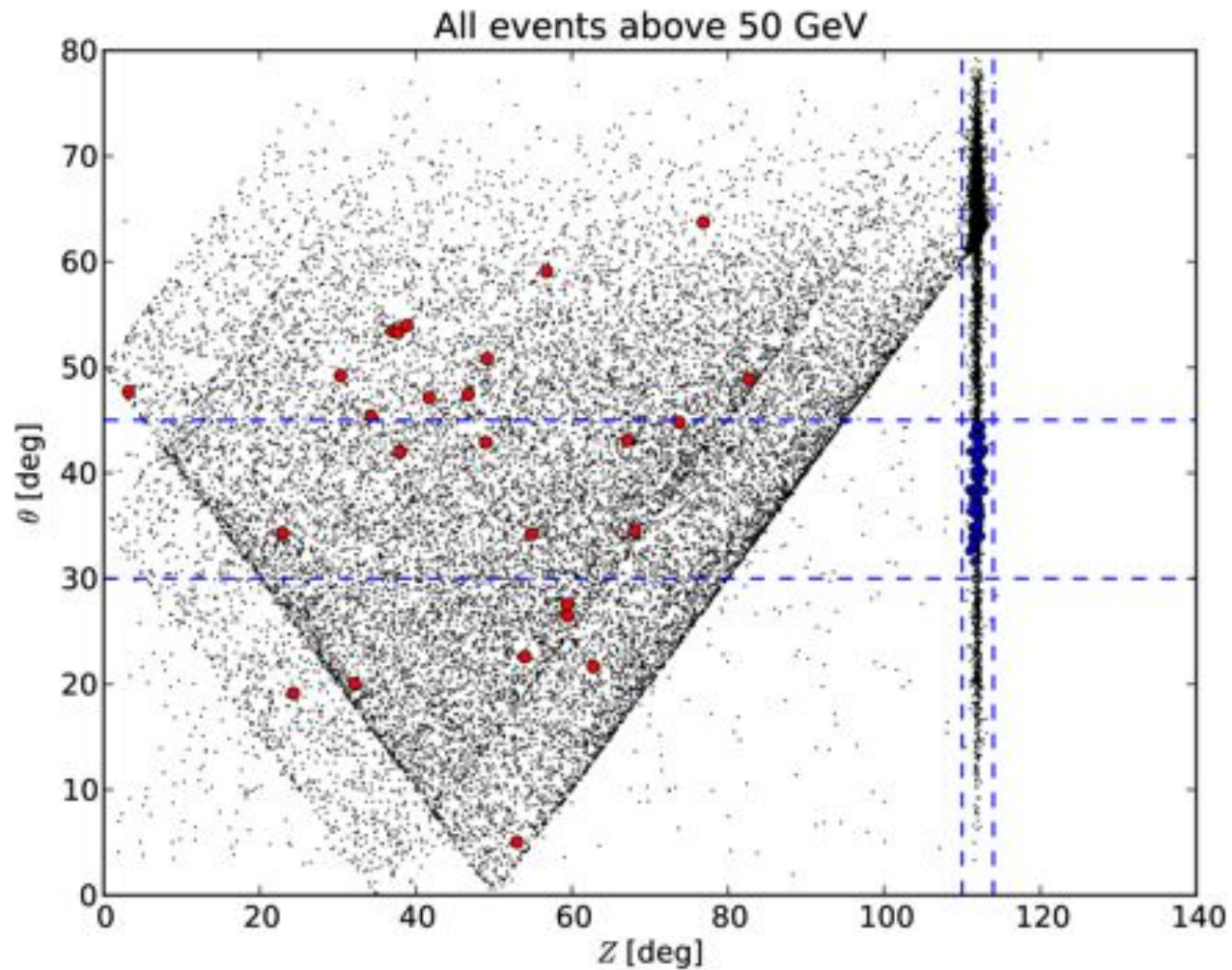
Cross-sections



Cross-sections

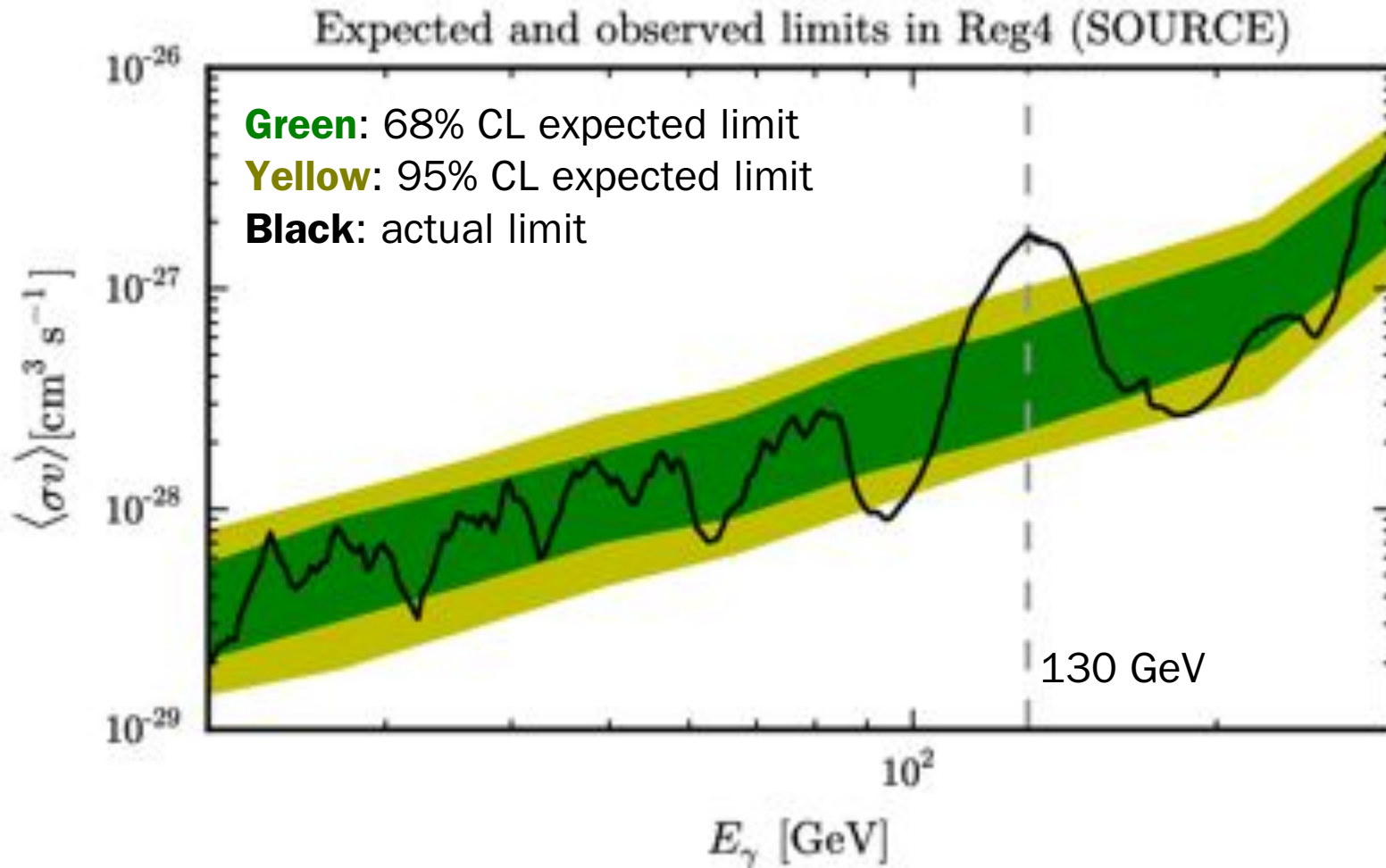


The incidence angle vs zenith angle plane



Expected vs observed limits

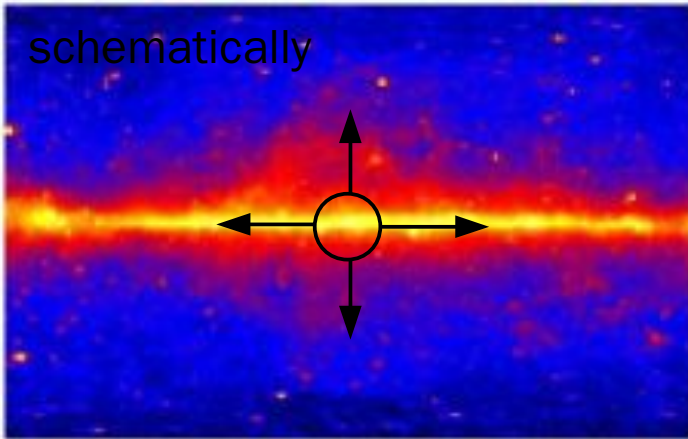
A tribute to the Higgs Boson



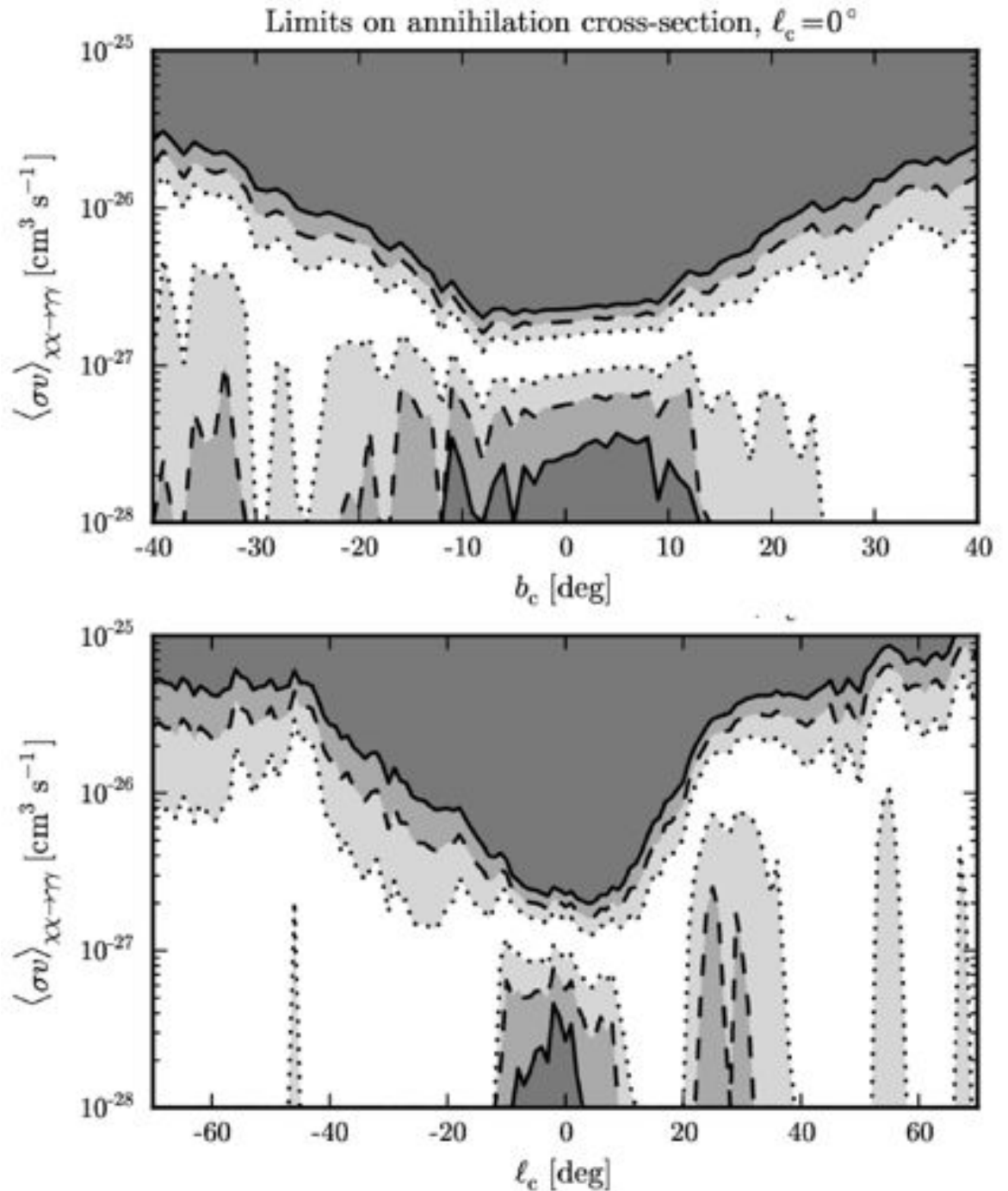
(Limits derived from mock data over the null hypothesis)

Signature is at the GC only (3)

Target region: circle with 10deg radius, moved along the galactic disc / along $l=0$.

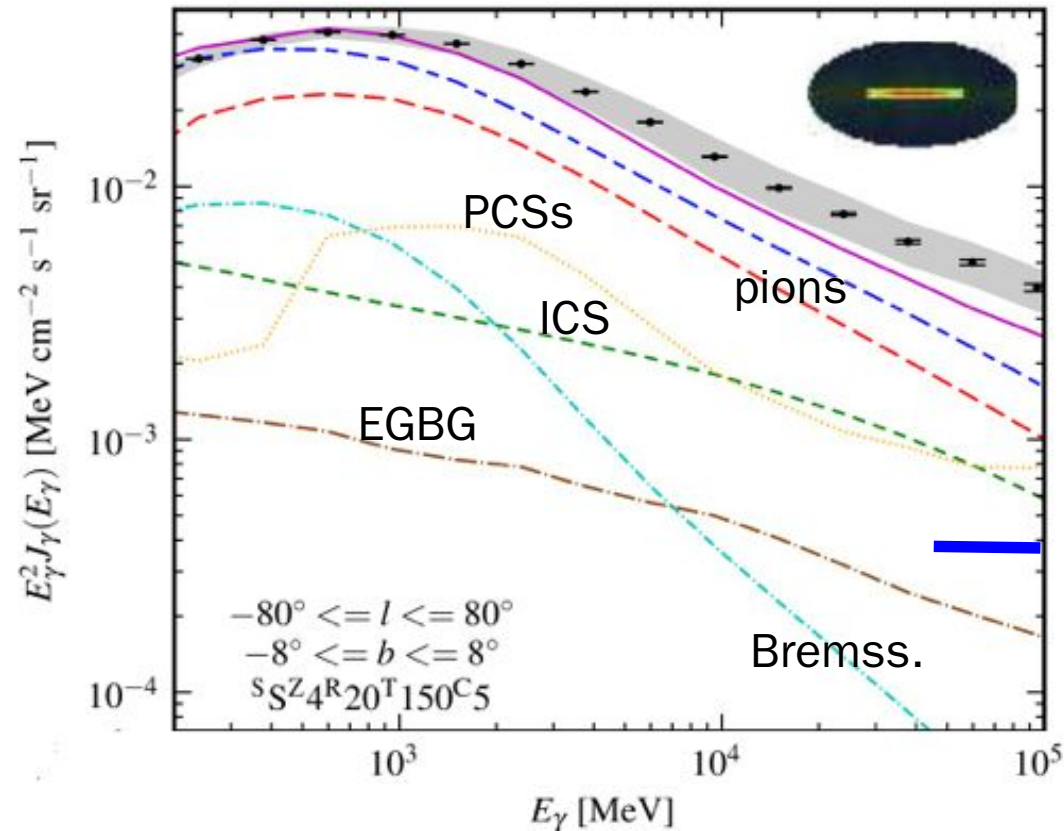


Non-zero annihilation cross-sections at 3sigma are only preferred when target region intersects with galactic center.



Approximating backgrounds with a power-law

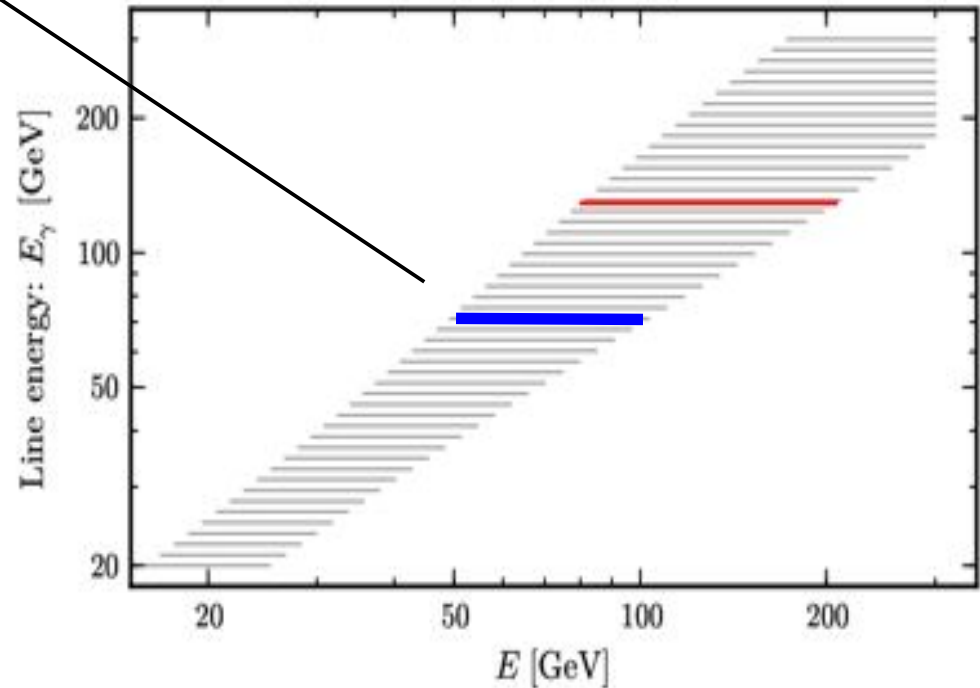
Expected backgrounds:



[1202.4039, Fermi-LAT coll.]

Approximating background by a single power-law is a very reasonable 1st order approximation when looking for lines.

Adopted energy window size:



Line significance at different incidence angles

