Tentative Observation of a Gamma-ray Line at the Fermi-LAT

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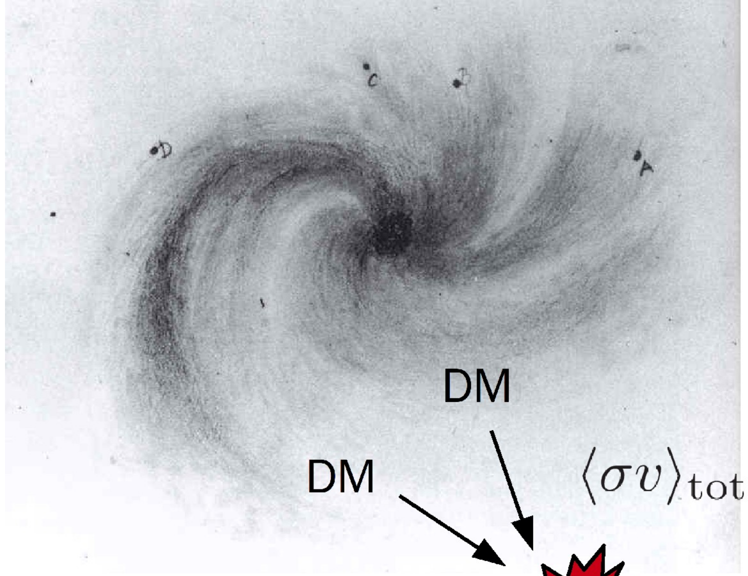
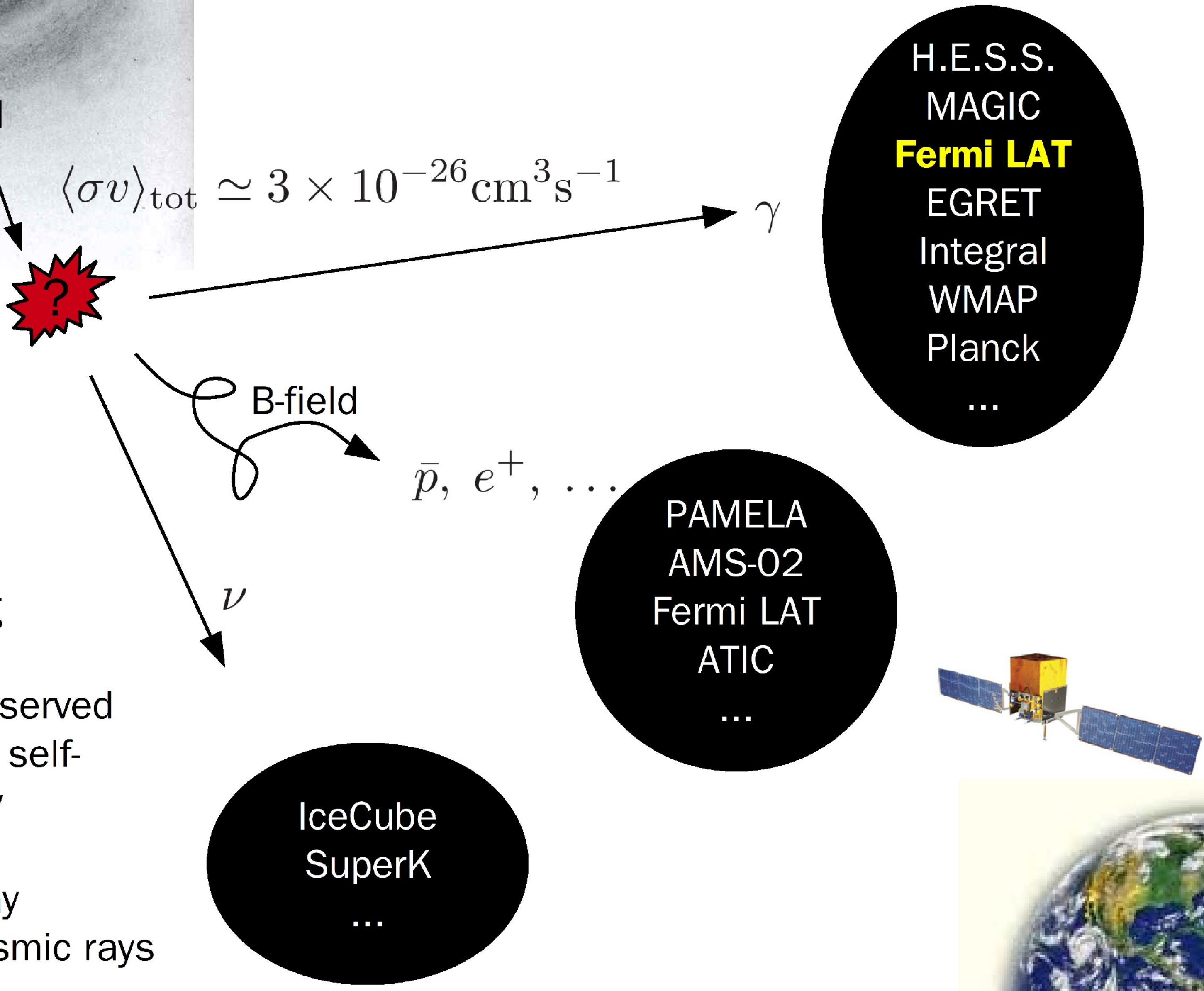
arxiv:1203.1312 & arxiv:1204.2797 (accepted for JCAP)
In collaboration with T. Bringmann, X. Huang, A. Ibarra, S. Vogl
+onging work with L. Bergström, G. Bertone, T. Bringmann, J. Conrad, C. Farnier, D. Finkbeiner and M. Su

Outline

- Motivation for gamma-ray line searches
- Analysis of Fermi LAT data
- Discussion
- Conclusions

Indirect Dark Matter Searches





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

The Gamma-Ray Signal

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"

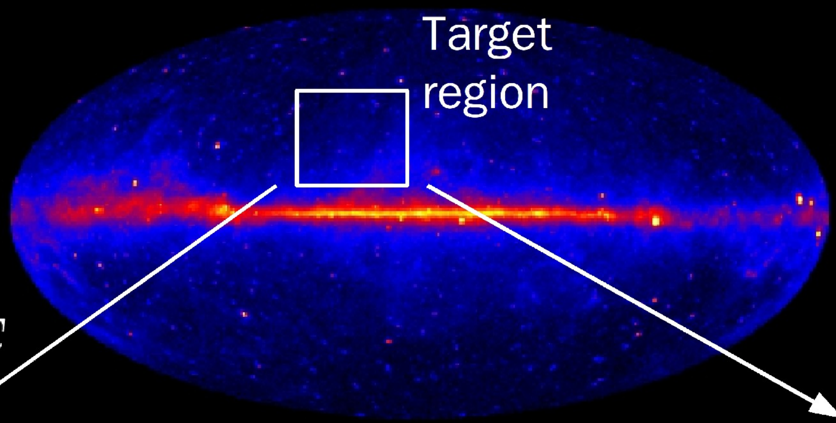
→ Characteristic **Energy Spectrum**

„Astrophysics Factor"

→ Characteristic **Spatial Dependence** (point-like or extended)

On Signal/Background Discrimination

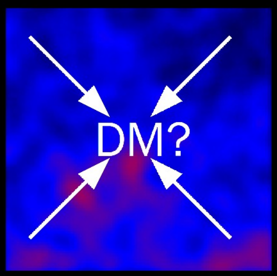
Measured Events:
$(E_i,\ \Omega_i)$



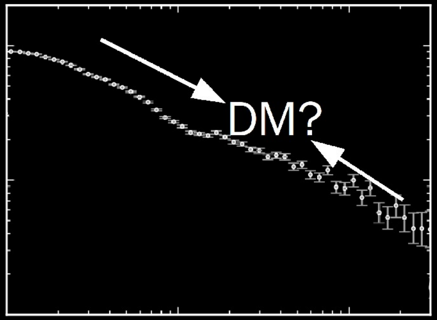
$$\int_{E_0}^{E_1} dE$$

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

Countmap:



Energy
spectrum:



<u>Spatial</u> BG extrapolation
("Astrophysical Factor")

- Dwarf Galaxies
- Galaxy Clusters
- Angular power spectrum
- EGBG ...

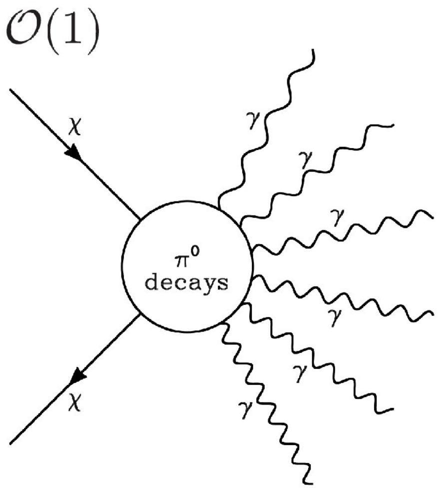
→ works for <u>all</u> signal spectra

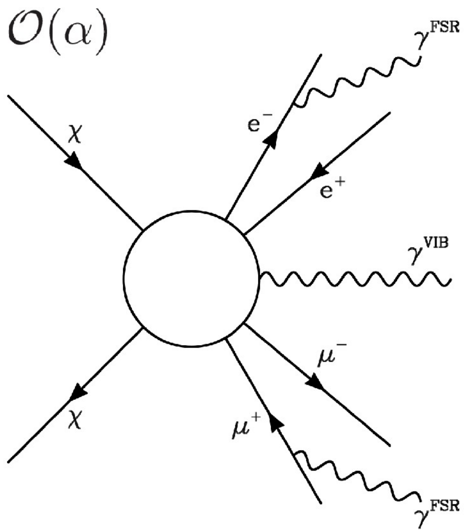
<u>Spectral</u> BG extrapolation
("Particle Physics Factor")

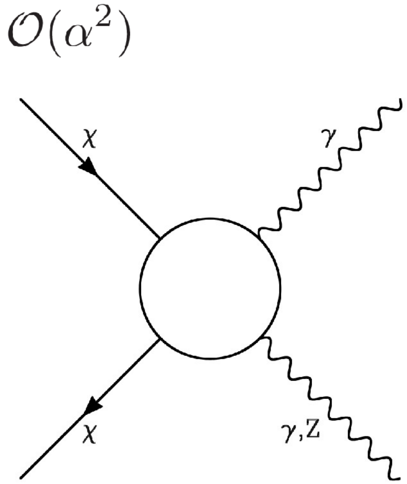
- Gamma-ray lines
- Internal Bremsstrahlung

→ works <u>everywhere</u> in the sky

Components of the photon energy spectrum







Secondary photons

- Produced in the fragmentation of quarks/bosons (pi0 decay)
- Soft spectrum
- Difficult to distinguish from astrophysical fluxes

Internal Bremsstrahlung (IB)

- Accompanies charged final states
- Appears at O(α)
- Harder spectrum
- IB = Final State Radiation (FSR) + Virtual Internal Bremsstrahlung (VIB)

Gamma-ray lines

- Produced in two-body annihilatino into photons or photon+Z/h boson
- Appears at O(α^2)
- Hardest spectrum

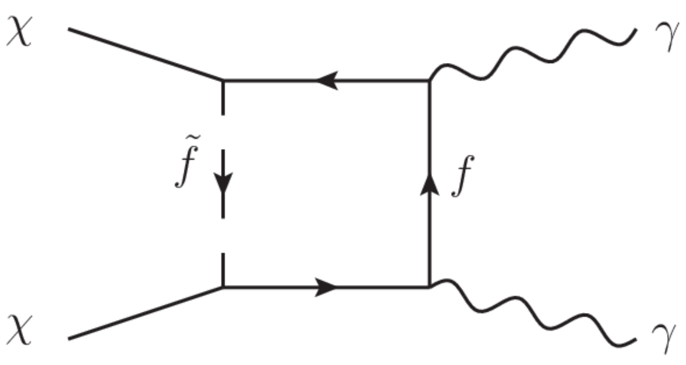
[Figs. from Kuhlen (2010)]

Gamma-Ray Lines

Characteristic Features

- Are produced in two-body annihilation

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



- Simple energy spectrum

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

- Process is **one-loop suppressed**

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

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)]
  → W bosons close to kin. threshold running in the loop
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]
  …

→ “Smoking gun signature”!

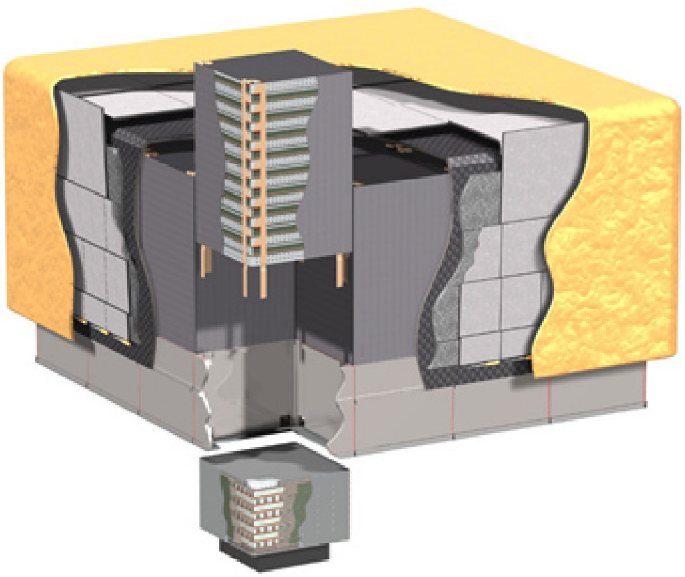
Gamma-ray line search

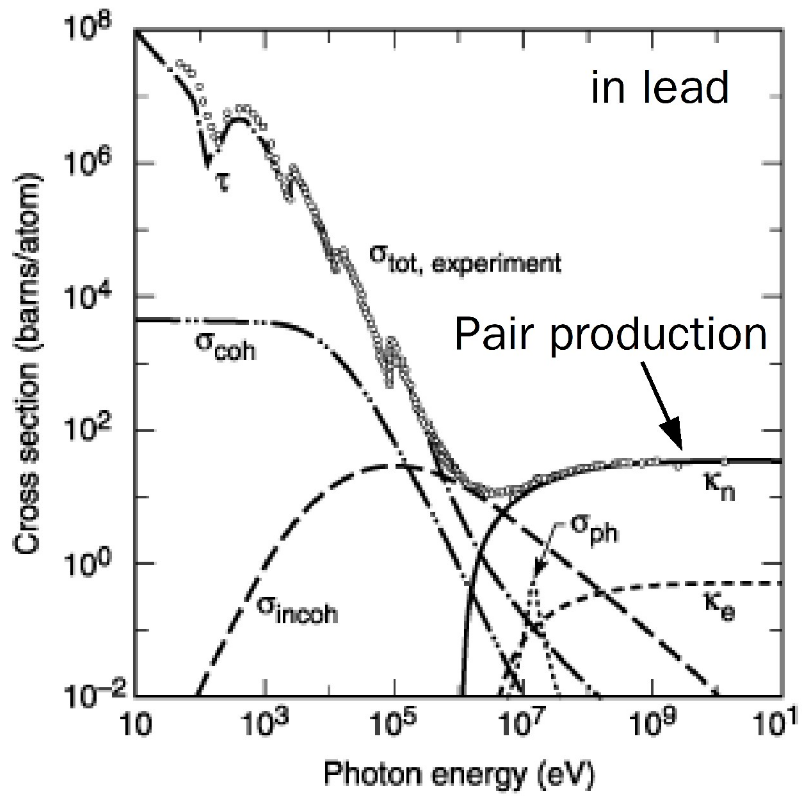
in Fermi LAT data

The Fermi Large Area Telescope (LAT)

Launch: June 2008

- Main Instrument on the **Fermi Gamma-Ray Space Telescope**
- Pair conversion instrument
- 30 MeV to >300 GeV energy range
- 2.4 sr field of view





Main components (in 16 towers)

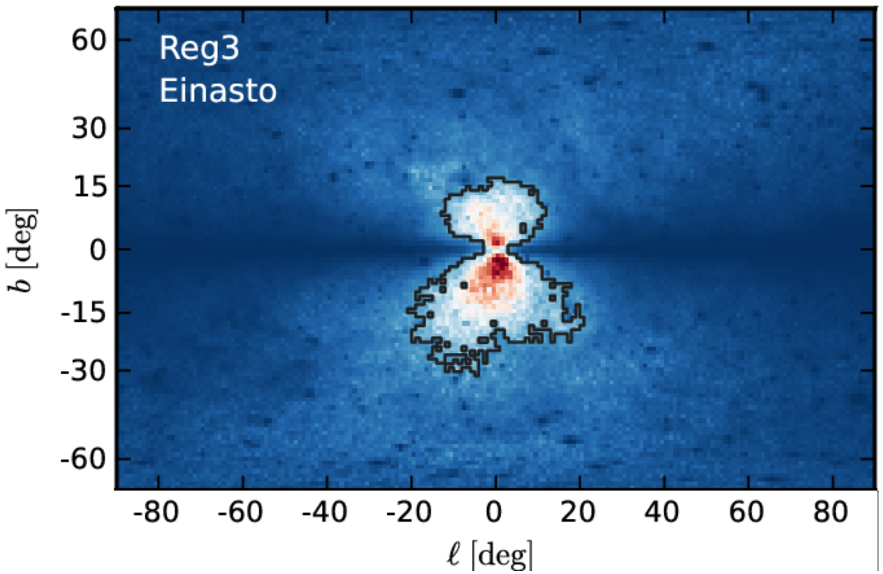
- Plastic anticoincidence detector
- Tungsten conversion foils
- Silicon strip detectors
- Cesium Iodine Calorimeter

High-level data is publicly available

http://fermi.gsfc.nasa.gov

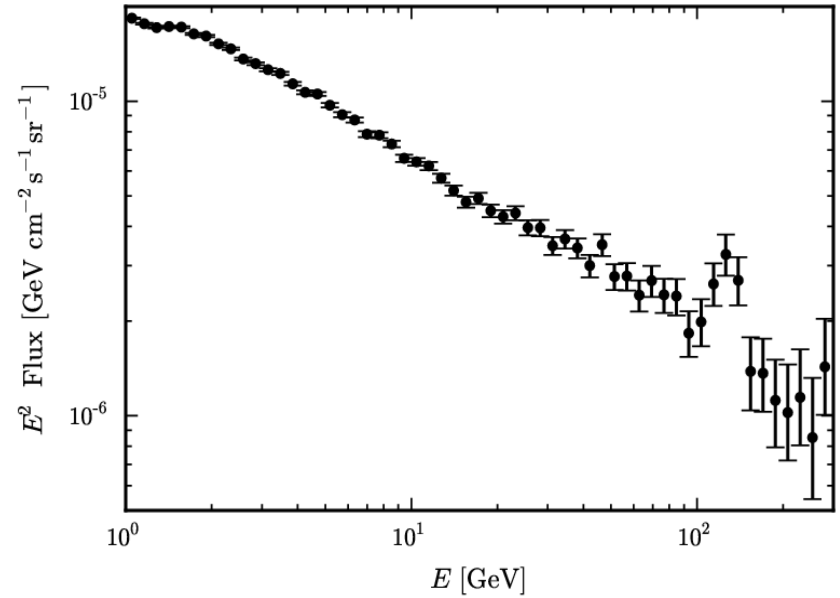
General strategy

I) Target region selection



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

II) Analysis of energy spectra



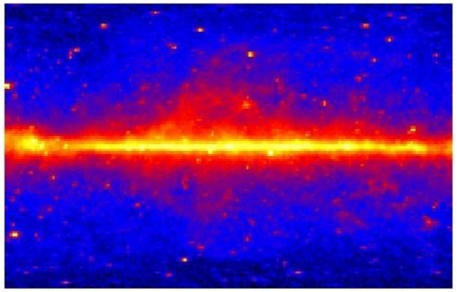
- Target: Annihilation signal from Galactic center
- Aim: Maximize signal-to-noise ratio
- Problem: Specification of signal & background morphologies

- Forget about spatial information (integral over dΩ)
- Perform a "bump-search" in the integrated energy spectrum

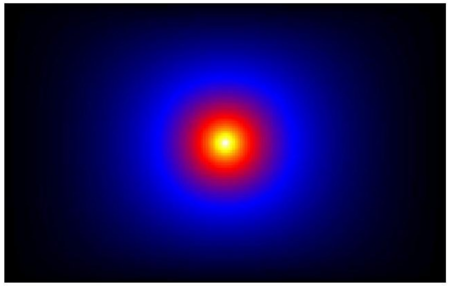
I) Adaptive target region selection

Fermi-LAT photons above 1 GeV are binned into 1x1deg^2 pixels.

- **Background morphology estimated from data**
  We use events between 1 and 20 GeV for background estimation, and search for lines above 20 GeV.



- **Signal morphology** derived for a few reference dark matter profiles (centered at Galactic center)
  - Cored isothermal
  - NFW
  - Contracted profiles
  - Einasto



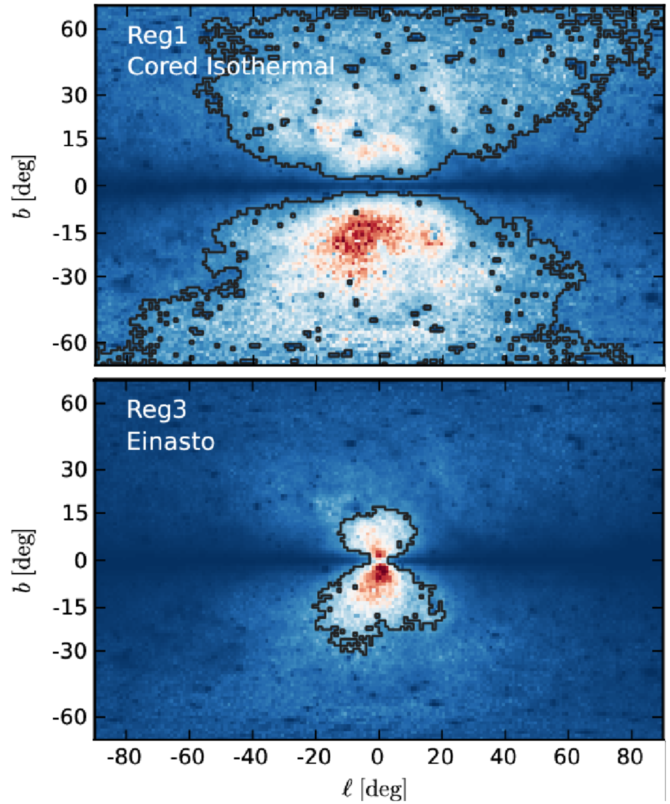
- **Pixel-by-pixel optimization of target region**
  Goal: Find subset of pixels T that maximizes S/N

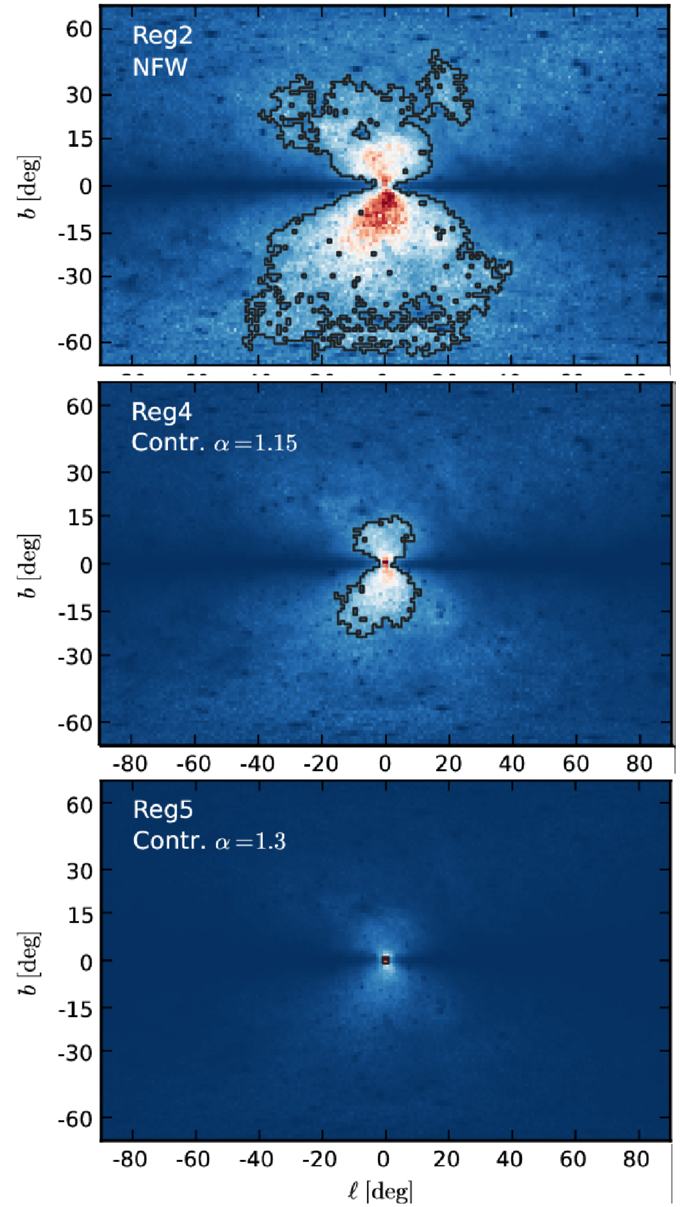
$$(\mathcal{S}/\mathcal{N})_T = \frac{\sum_{i\in T} \mu_i}{\sqrt{\sum_{i\in T} c_i^{1\mathrm{to}20\mathrm{GeV}}}}$$

Expected signal events

Measured events

Target regions for different dark matter profiles

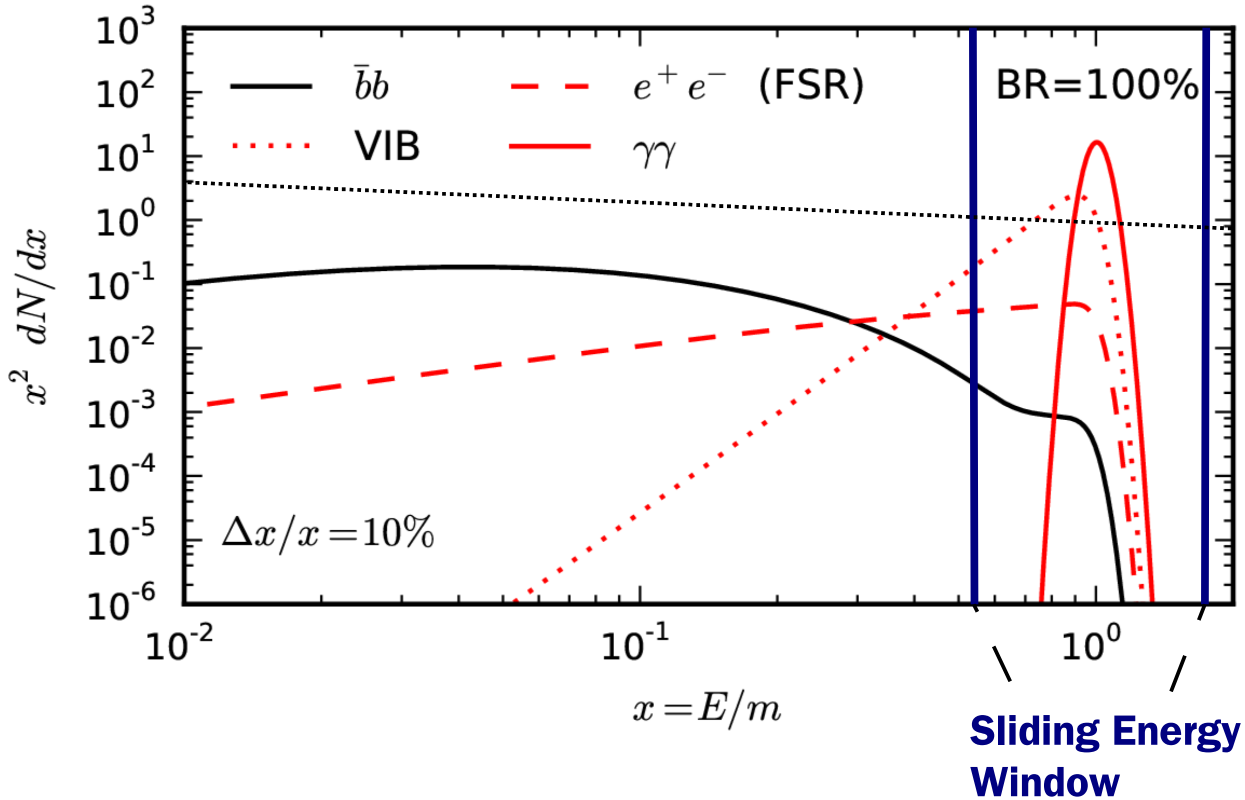




- Steeper dark matter halo profiles → smaller target region
- Galactic center always included (except for cored isothermal profile)
- Slight north/south asymmetry as consequence of asymmetric diffuse fluxes at ~1 GeV

II) Spectral Analysis: Bump hunting

All spectral fits are performed within a small energy window around the gamma-ray line position



„Sliding energy window technique"

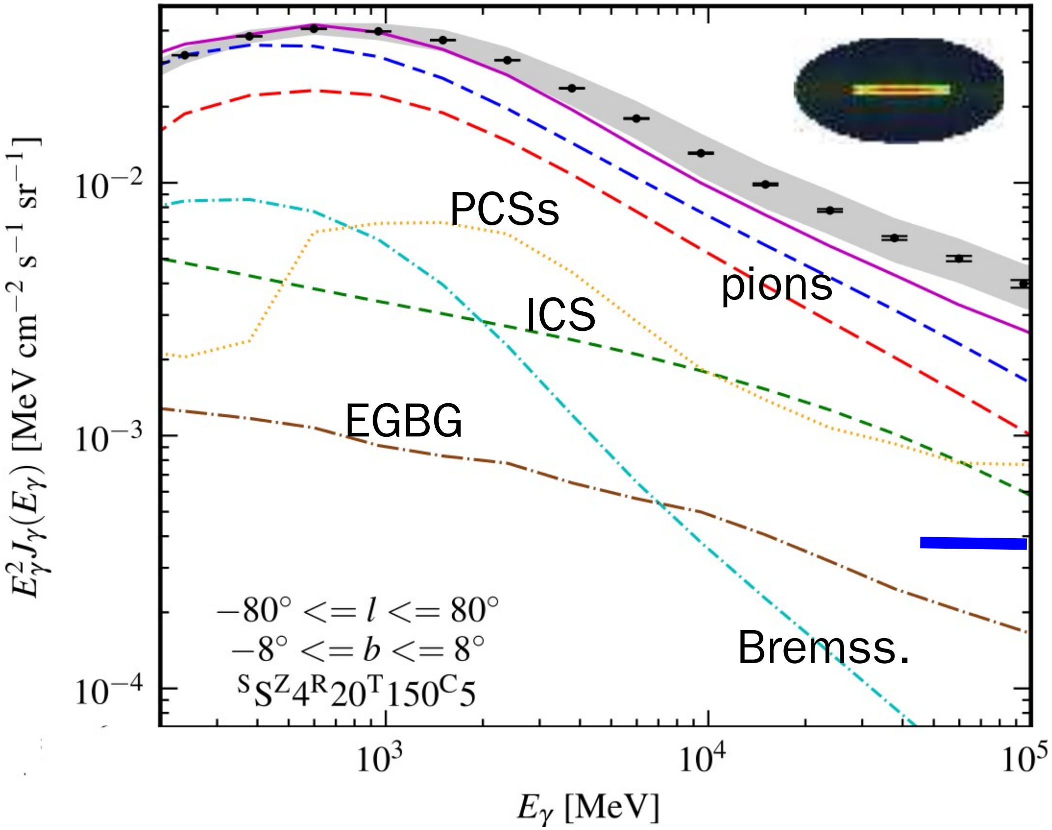
- Secondary photons from DM signal can be neglected
- Fit with a simple power-law background + line signal model (3 parameters):

$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta E^{-\gamma} \qquad TS = -2\ln\frac{\mathcal{L}_{\text{null}}}{\mathcal{L}_{\text{alt}}}$$

- Trading systematical for statistical errors

Background fluxes vs window size

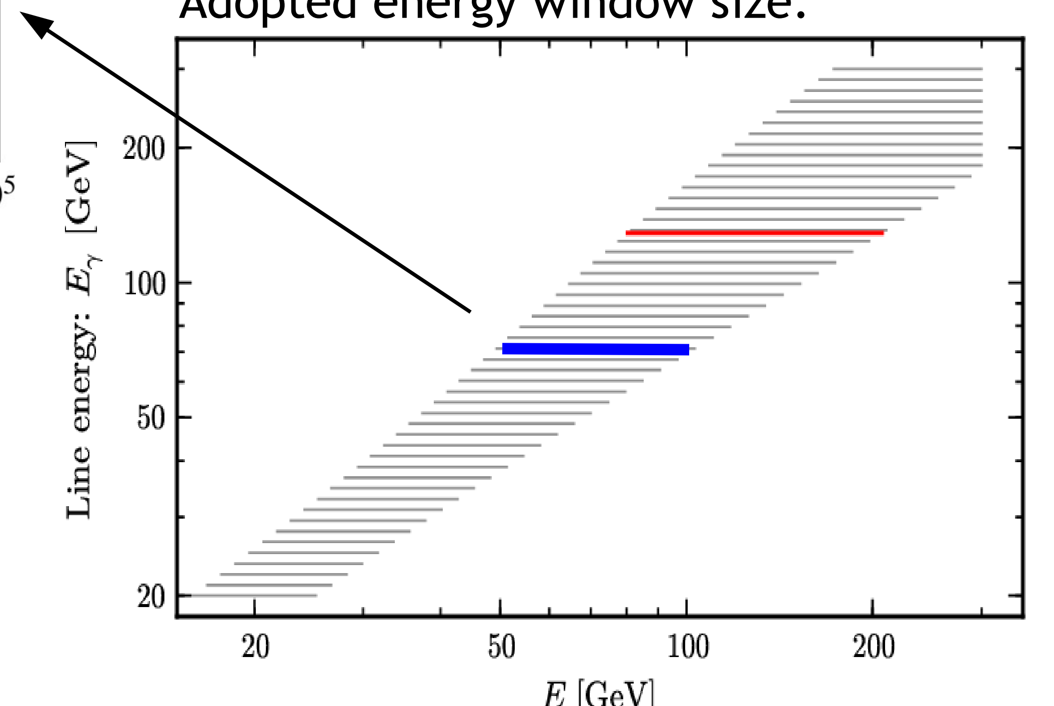
Expected astrophysical fluxes:



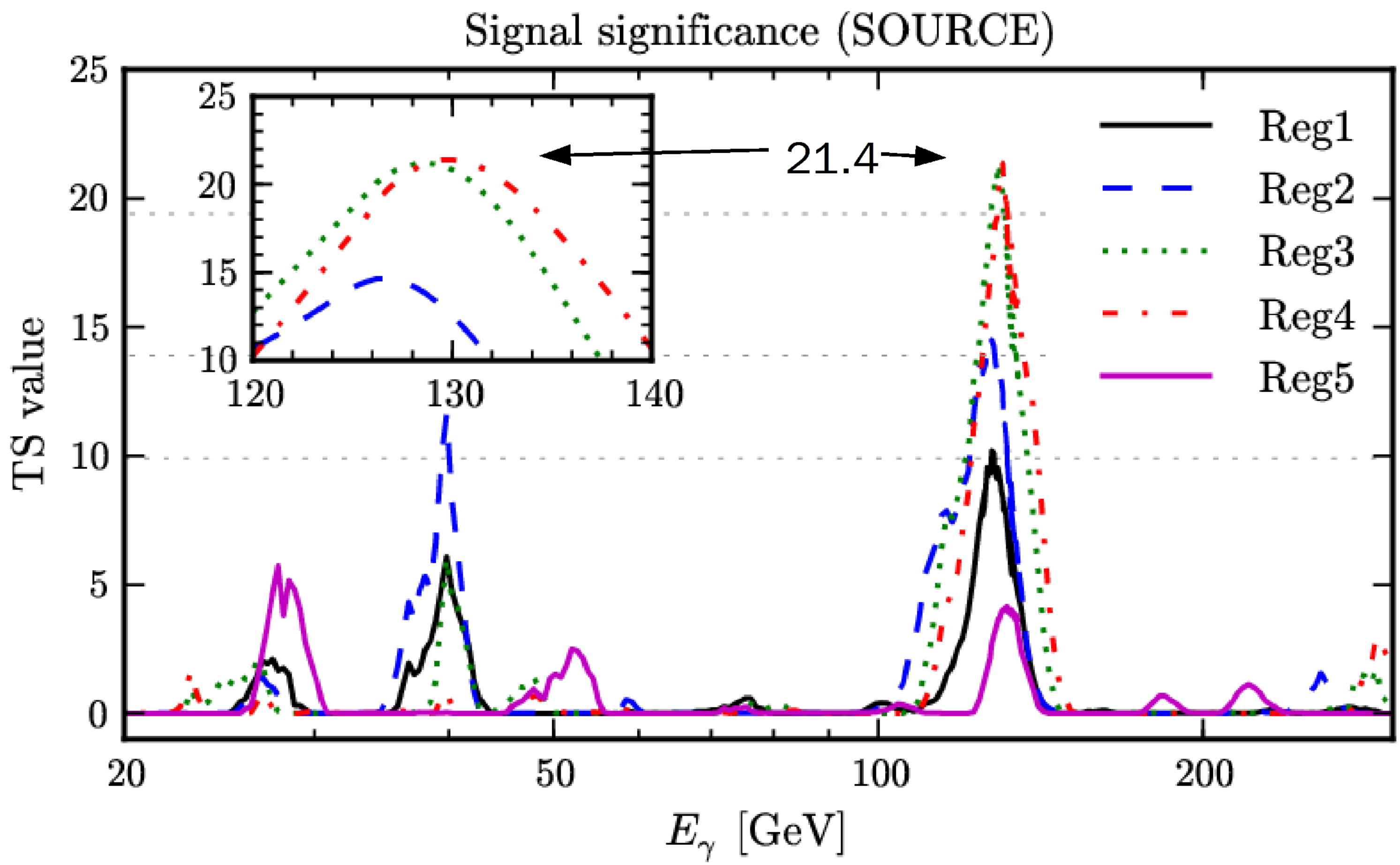
[1202.4039, Fermi-LAT coll.]

Approximating background fluxes with a single power-law <u>is</u> a very reasonable 1st order approximation when looking for lines.

Adopted energy window size:



III) Results



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

Local significance: 4.6σ

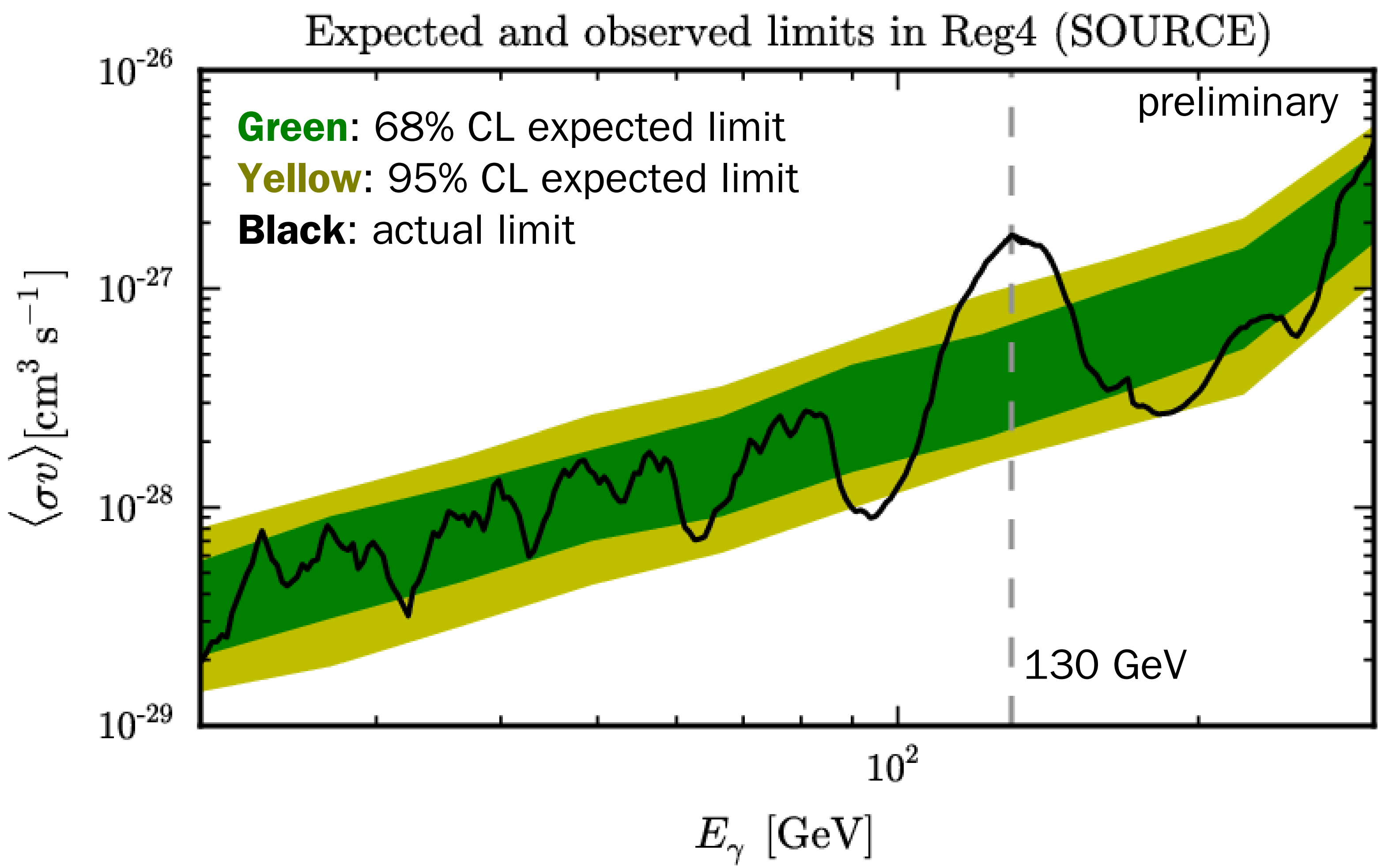
Assuming Einasto profile with 0.4 GeV/cm^3 local density:

$$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27}\mathrm{cm}^3/\mathrm{s}$$

Global significance (spatial and spectral trial correction): ~3.3σ

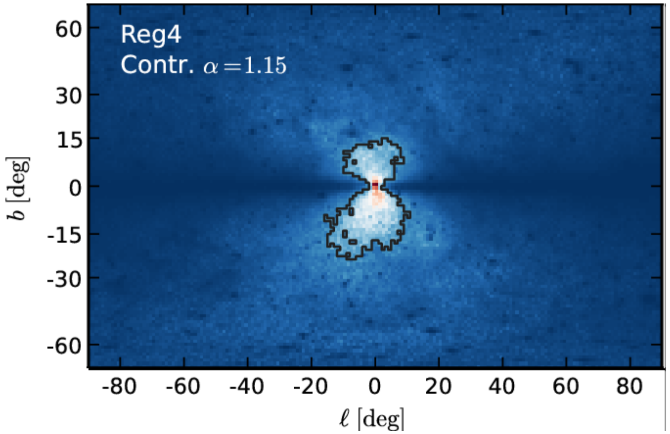
Based on 43 month of P7V6 source class, similar for clean events.

Sensitivity vs observed limits

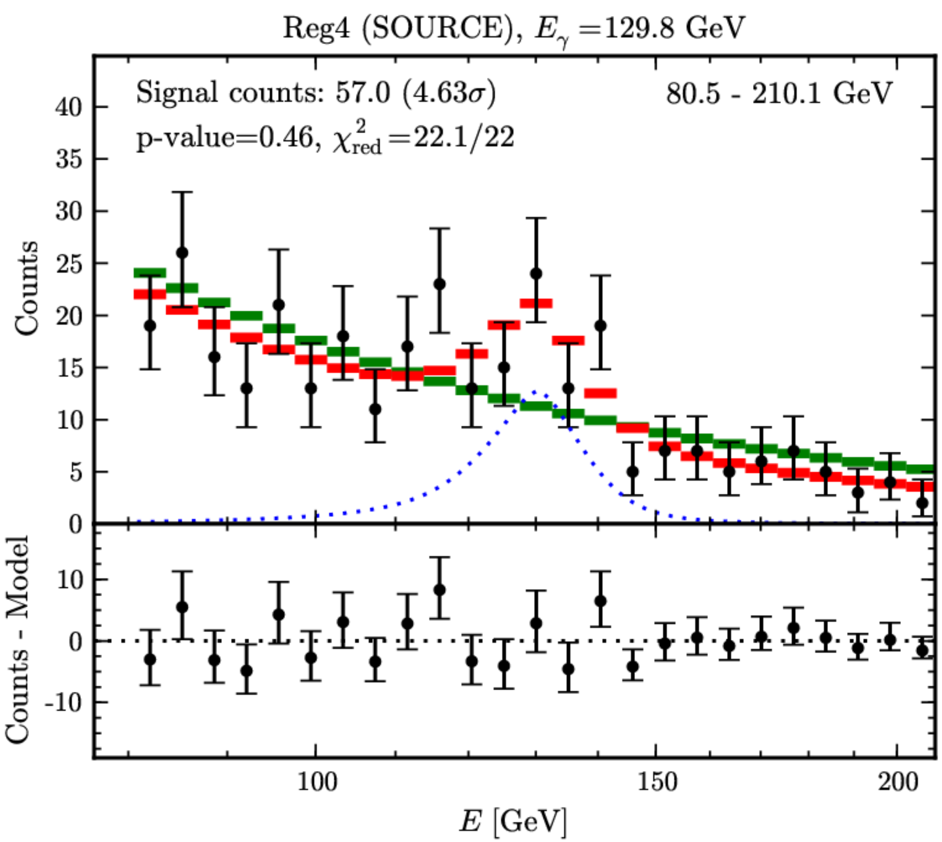


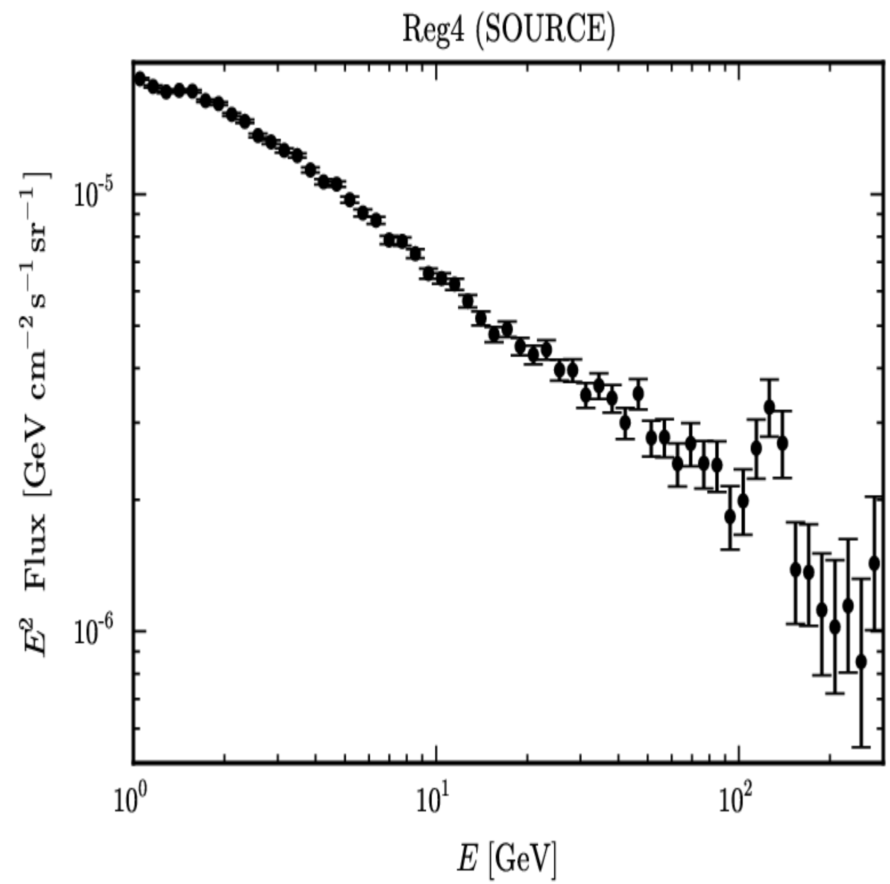
(Derived from null model mock data)

The signature is sharp

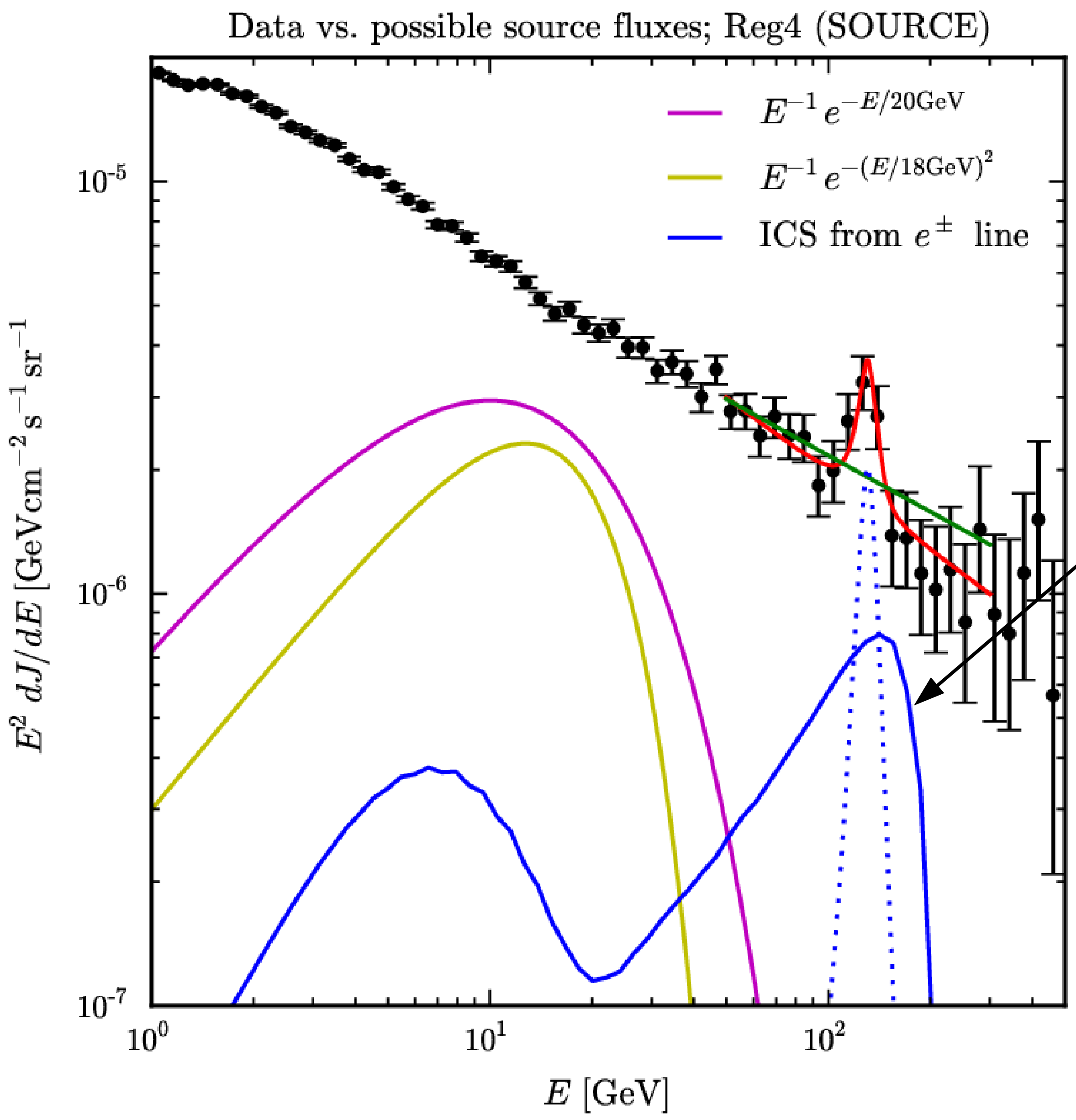


Signal width <17% (95%CL)





The signature is sharp

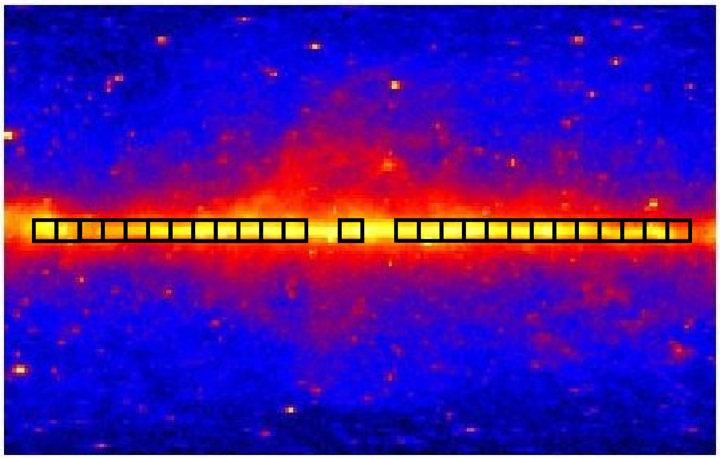


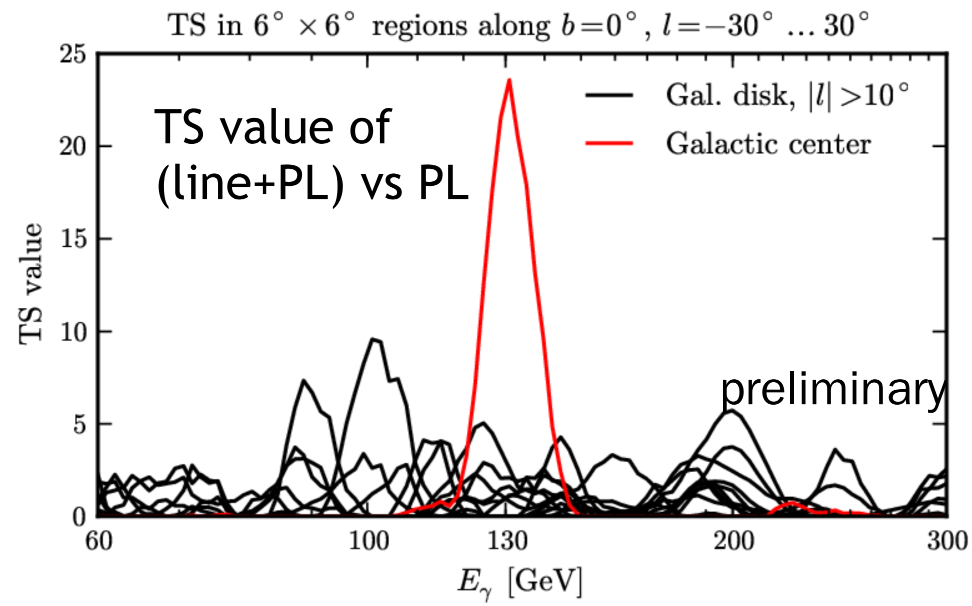
Line: TS = 21.4

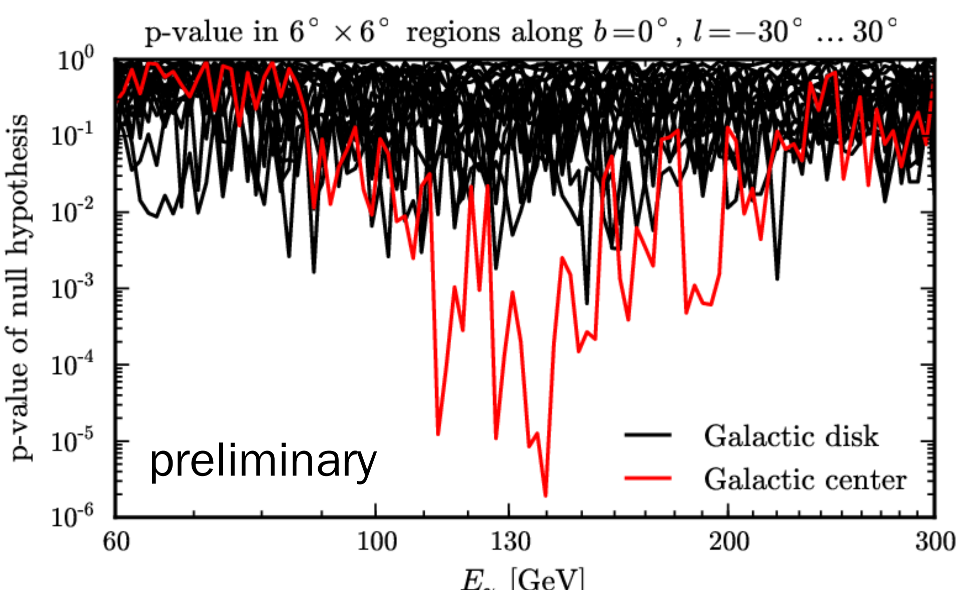
ICS from monoenergetic electrons: TS ~ 12

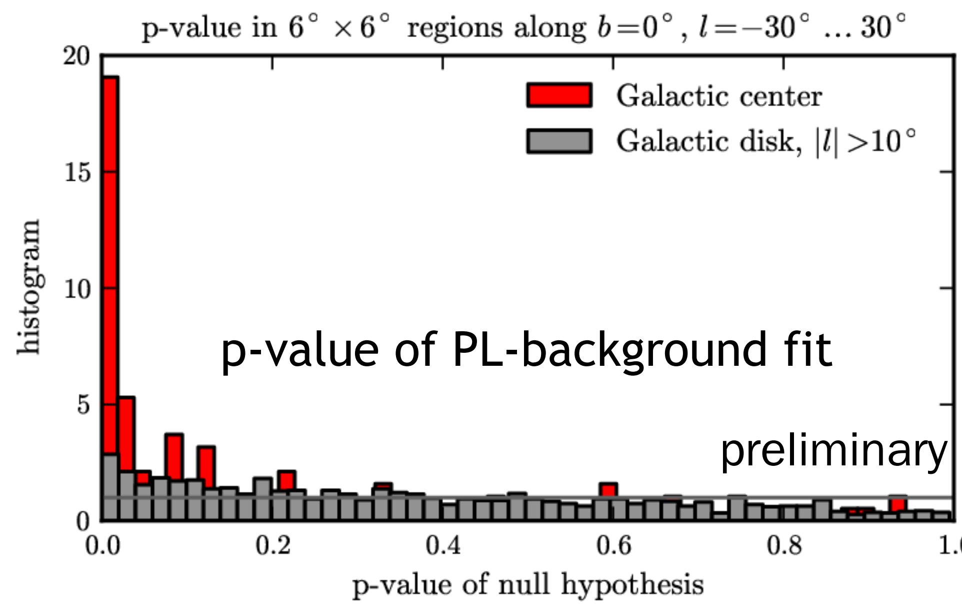
At Galactic center only

Scan along the galactic disk:



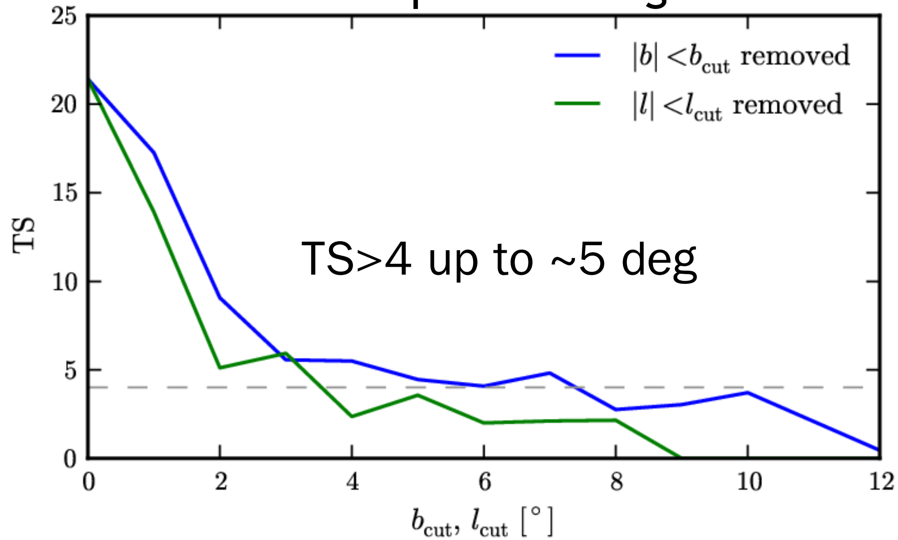




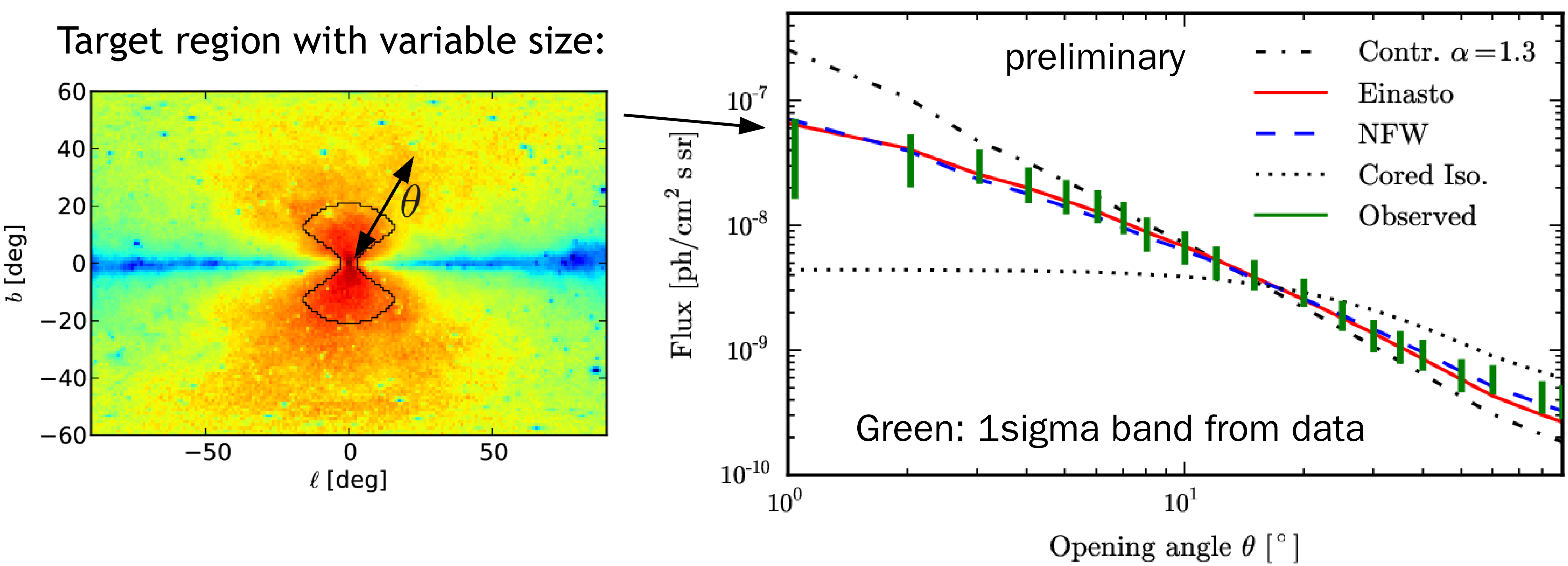


Spatially extended

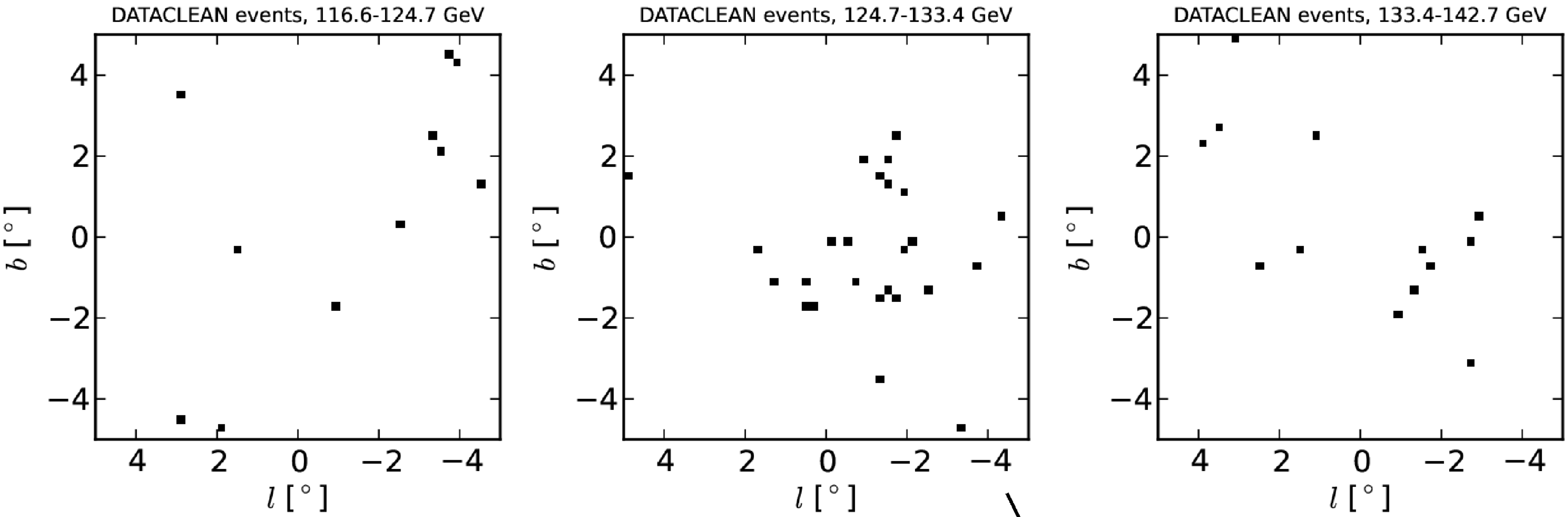
TS from outer parts of Reg4:

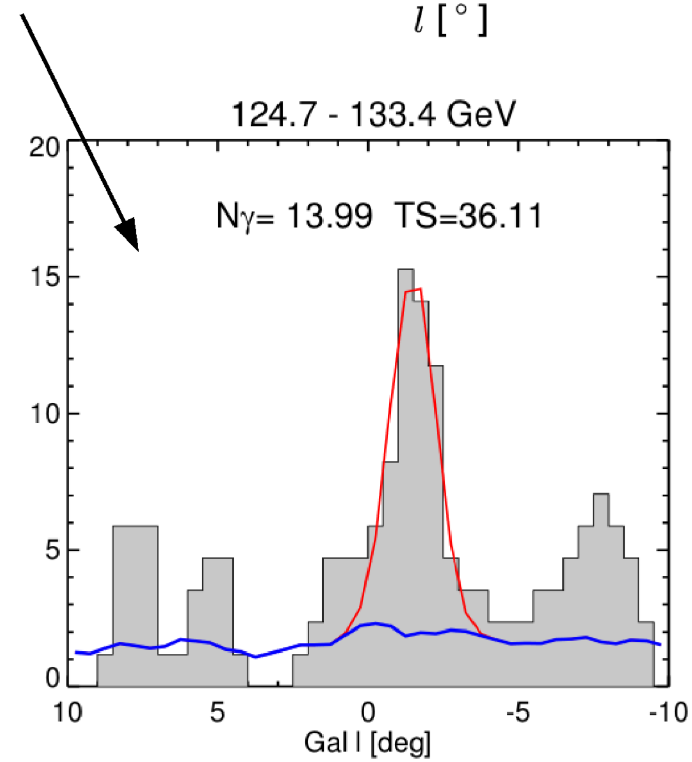


Target region with variable size:



Displaced from the Galactic Center

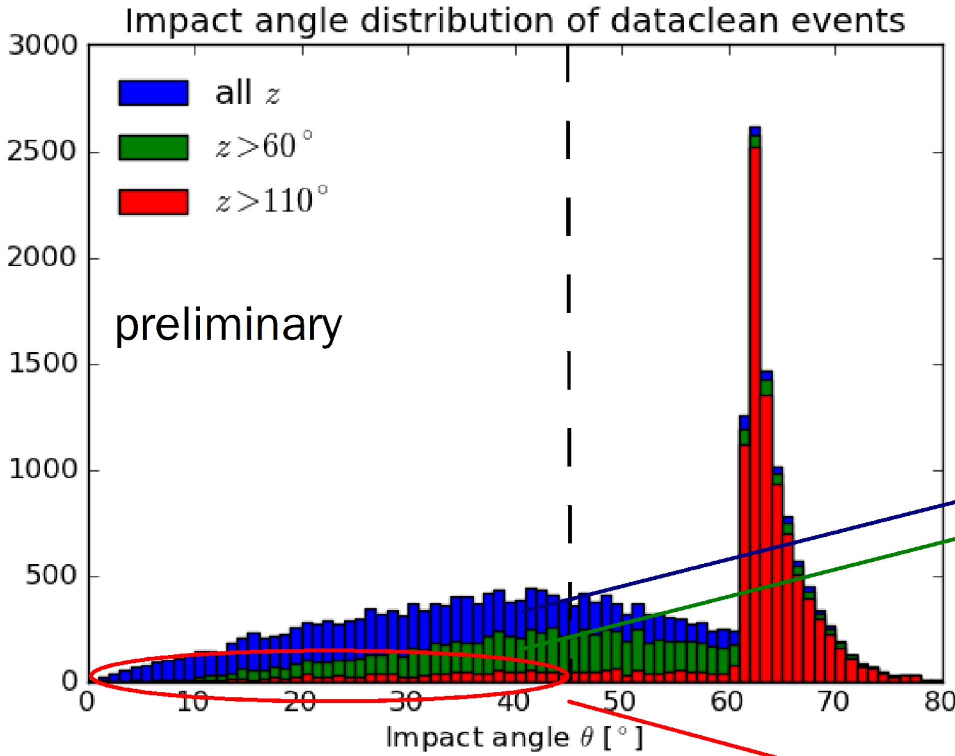


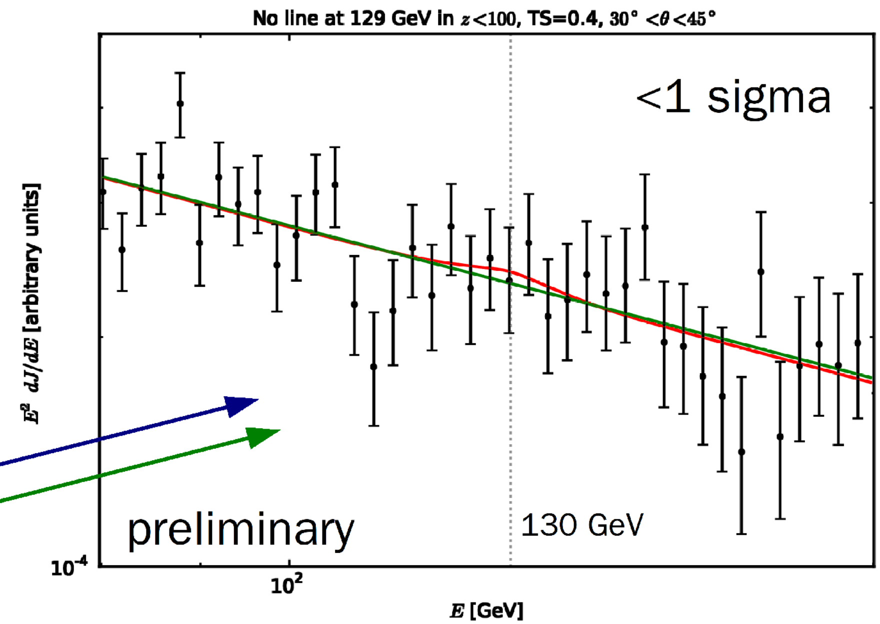


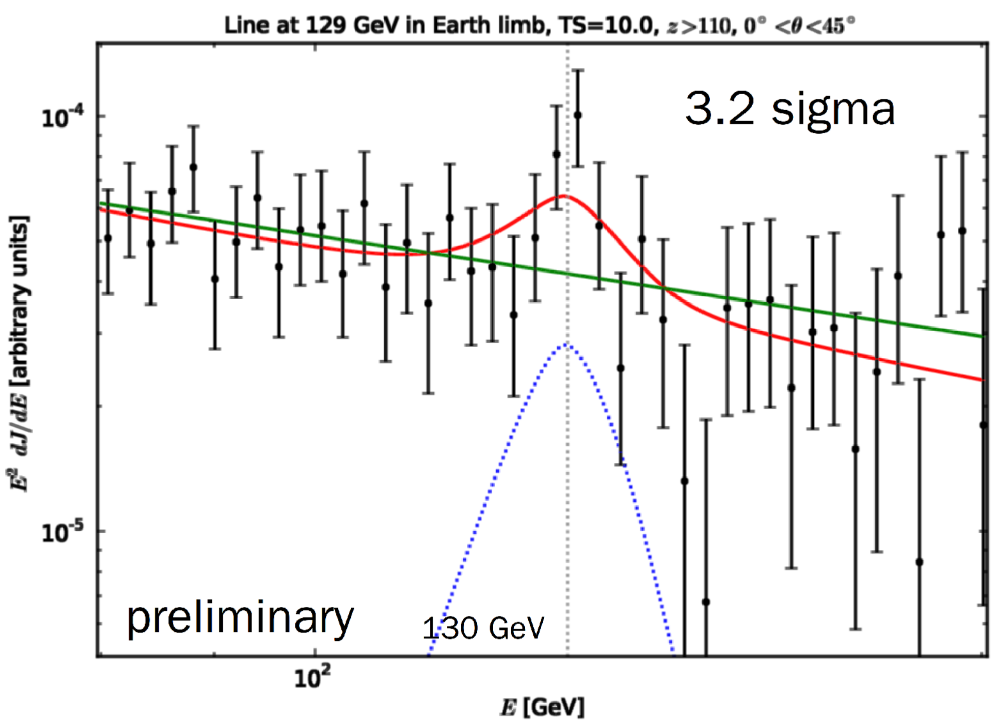
Photons responsible for high TS appear to be significantly displaced by O(100pc) (if GC is origin).

[Su/Finkbeiner 2012]

Instrumental indications in Earth limb/albedo?



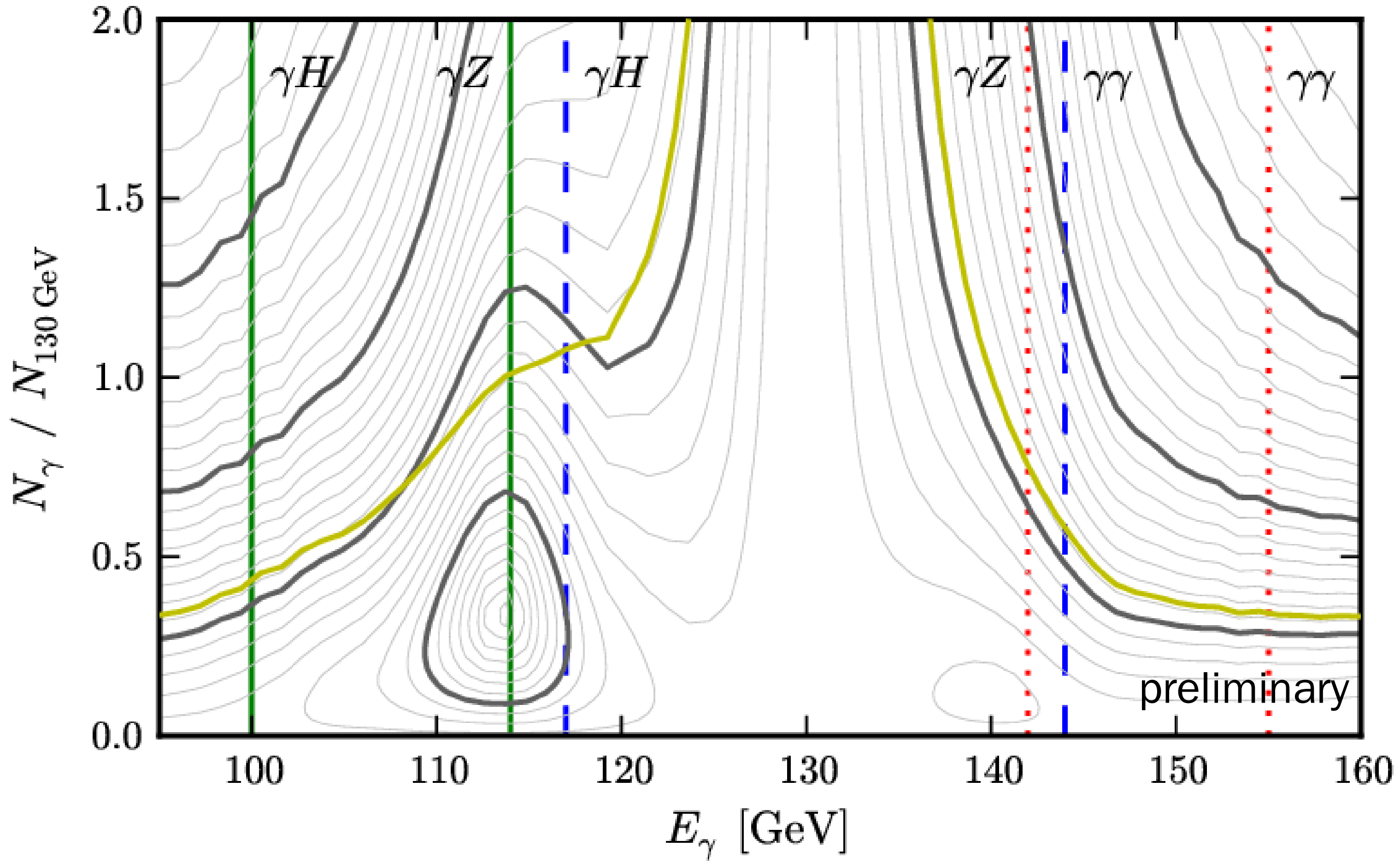




A 130 GeV line in low impact angle events from the earth atmosphere:
- statistical (comes with a large trial factor)?
- systematic (why only there and at the GC)?

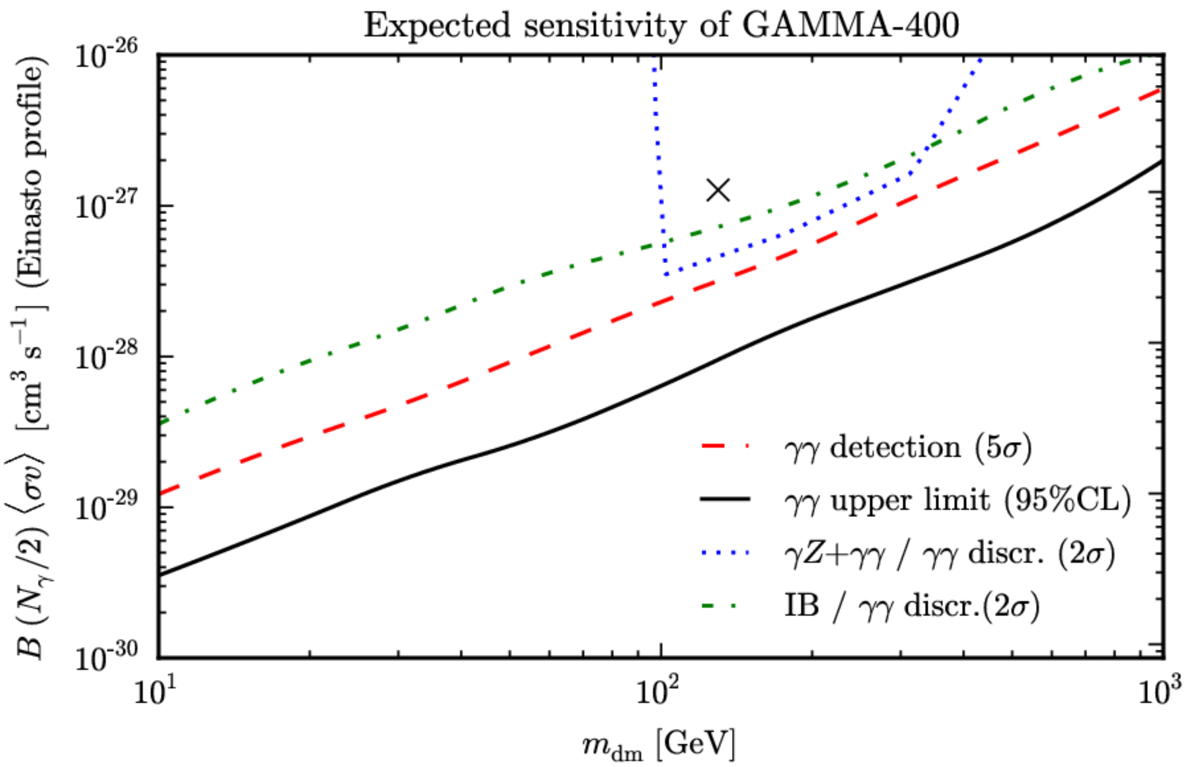
[suggested in Su/Finkbeiner 2012]

How many lines?



- The canonical final states are : $\gamma\gamma,\ \gamma H,\ \gamma Z$
- One can derive upper limits on the other two lines
- Weak indication for γZ ?

Prospects for e.g. GAMMA-400



GAMMA-400

- 5 years of survey mode
- Allows discrimination between VIB and monochromatic photons
- detection of γZ down to 20% relative branching ratio

[Bergström, Bertone, Conrad, Farnier, CW, in preparation]

Conclusions

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

- **Good astrophysical explanations** are difficult to find. Different toy scenarios are disfavoured w.r.t. a line by the data.
- **Instrumental causes** cannot be excluded (see Earth limb), but: why strongest where one expects the DM signal?; why compatible with NFW/Einasto profile? Much more work required.
- **Statistical fluctuation**: maybe the most likely explanation? You get what you are looking for.

Outlook for close future:

- More data (Pass 8, pointed observation)
- Study of instrumental effect (Earth albedo, Pass 8)
- Study of apparent displacement of signal center by 200 pc
- Astrophysical and WIMP model building

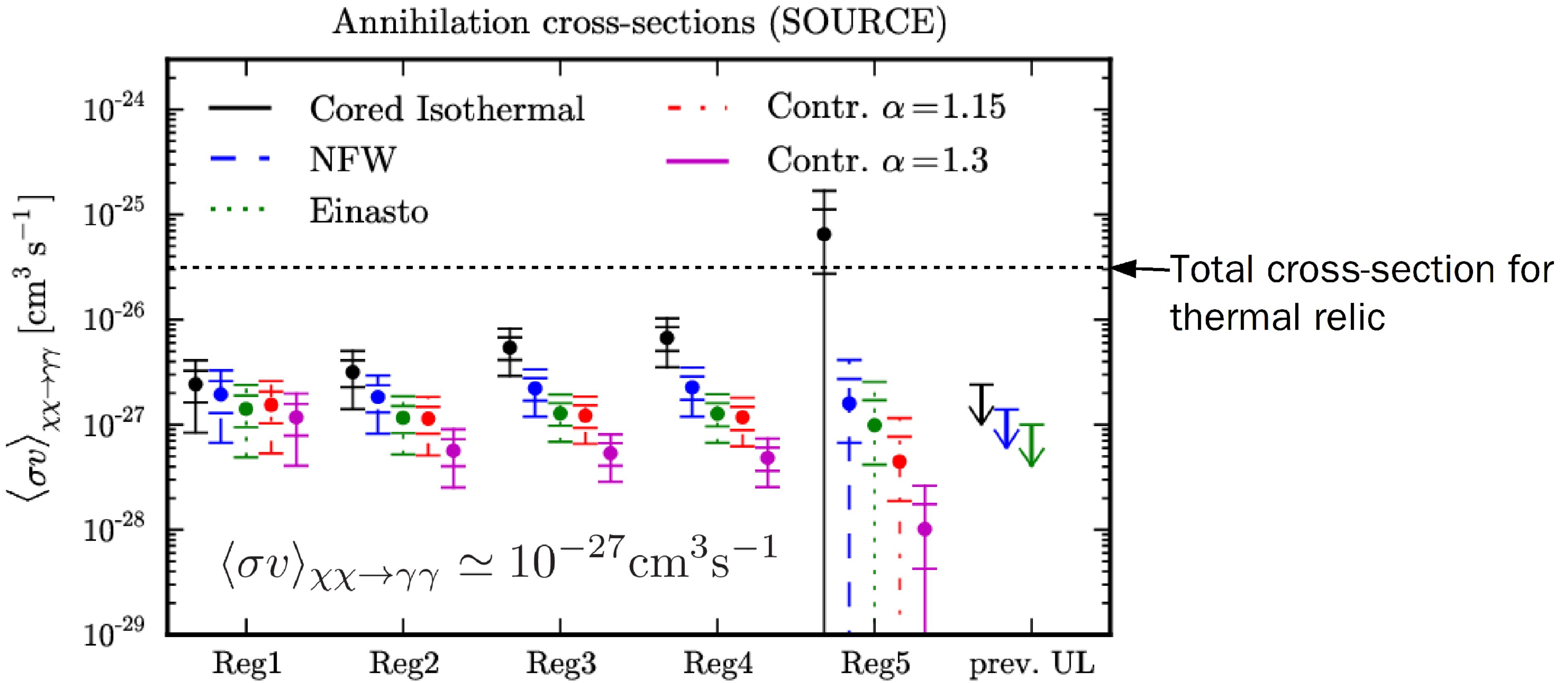
Outlook for far future:

- Further tests with HESS-II, CTA and GAMMA-400

Thank you
& stay tuned!

Backup Slides

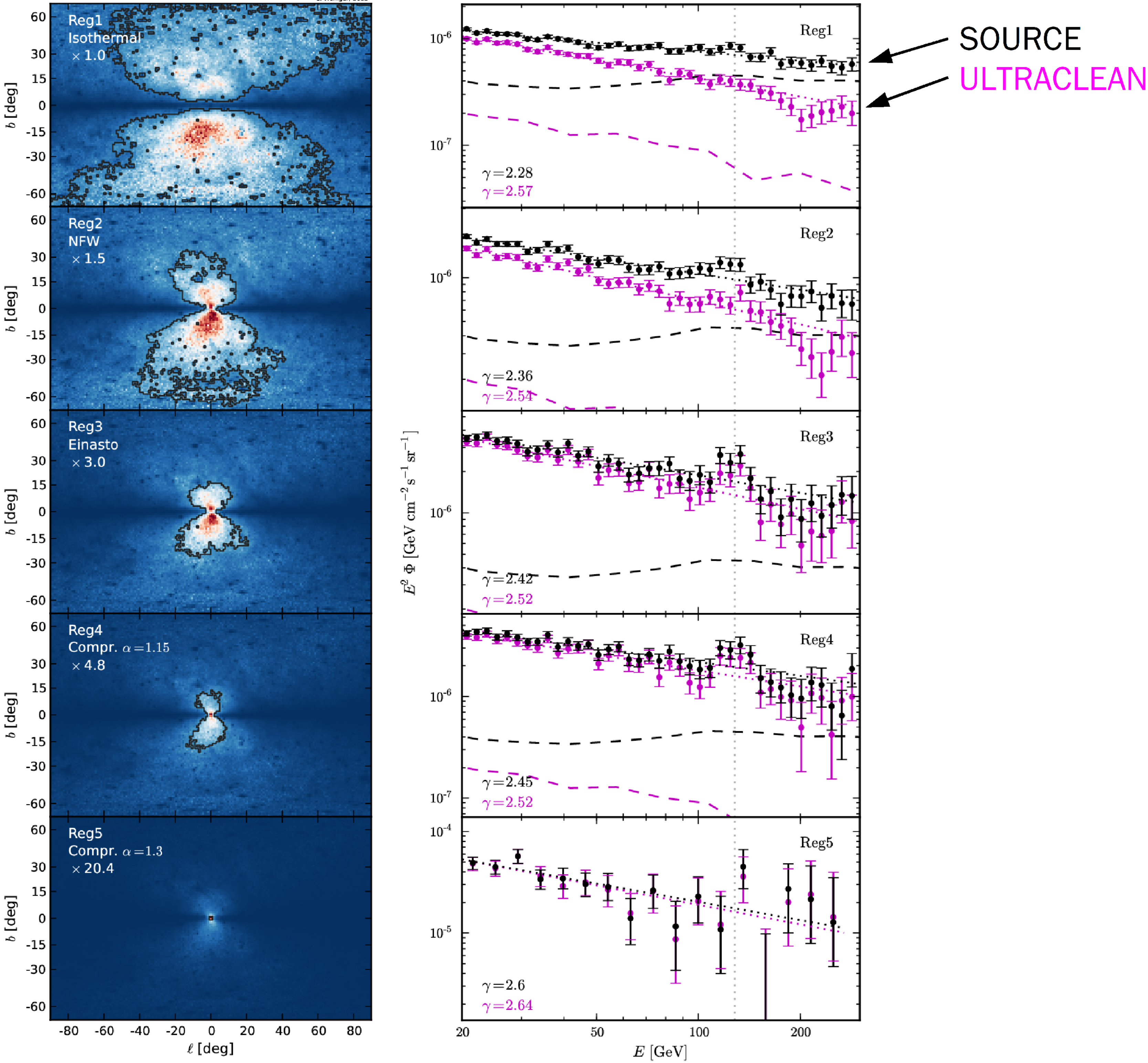
Which dark matter profiles work?



- Consistent values are obatined for **Einasto & NFW profiles**
- **Isothermal** or **contracted profiles** with α=1.3 favour **inconsitent** values
- Upper Limits from presentations of the Fermi LAT coll. [1205.2739]

- Branching ratio for thermal relic is surprisingly large:

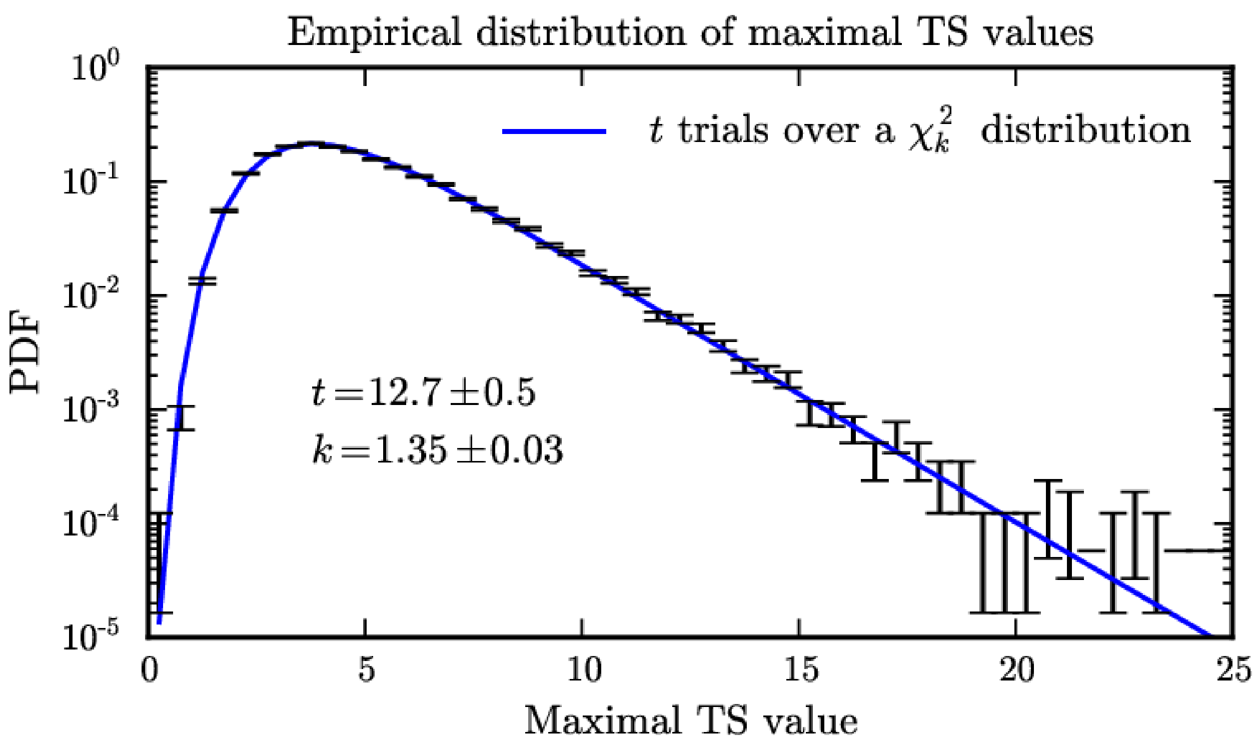
$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim 5\% \gg 10^{-4}$$



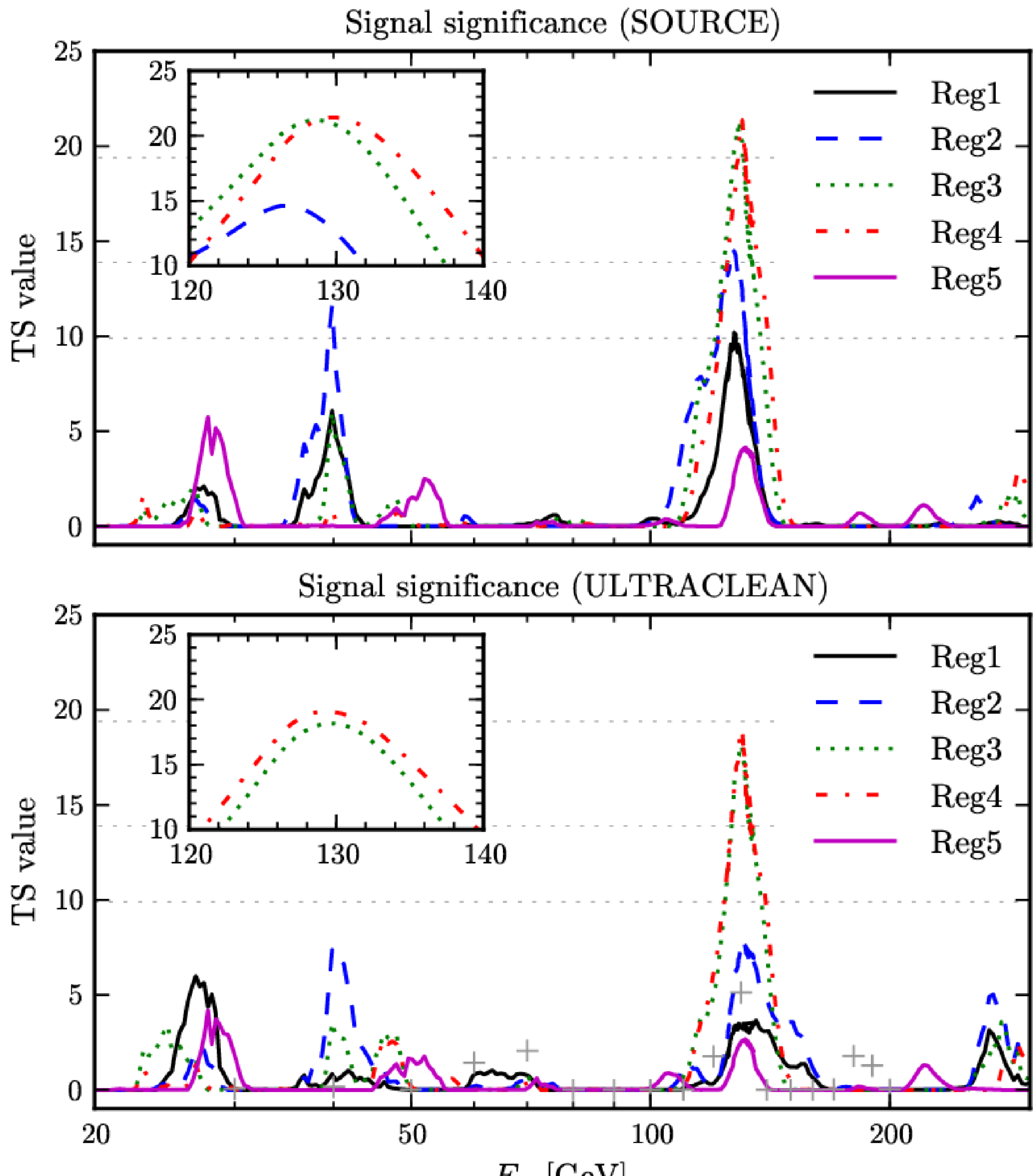
Reg1
Isothermal
× 1.0
Reg2
NFW
× 1.5
Reg3
Einasto
× 3.0
Reg4
Compr. α = 1.15
× 4.8
Reg5
Compr. α = 1.3
× 20.4
b [deg]
ℓ [deg]
γ = 2.28
γ = 2.57
γ = 2.36
γ = 2.54
γ = 2.42
γ = 2.52
γ = 2.45
γ = 2.52
γ = 2.6
γ = 2.64
E² Φ [GeV cm⁻² s⁻¹ sr⁻¹]
E [GeV]
SOURCE
ULTRACLEAN

Look Elsewhere Effect & Instrumental Effects

- The signal does **not** appear in other sky regions. We checked this by
  - moving the target regions around (see above)
  - performing a **bootstrap analysis** of anti-galactic-center data (~40000 random test regions from |l|>90deg data)

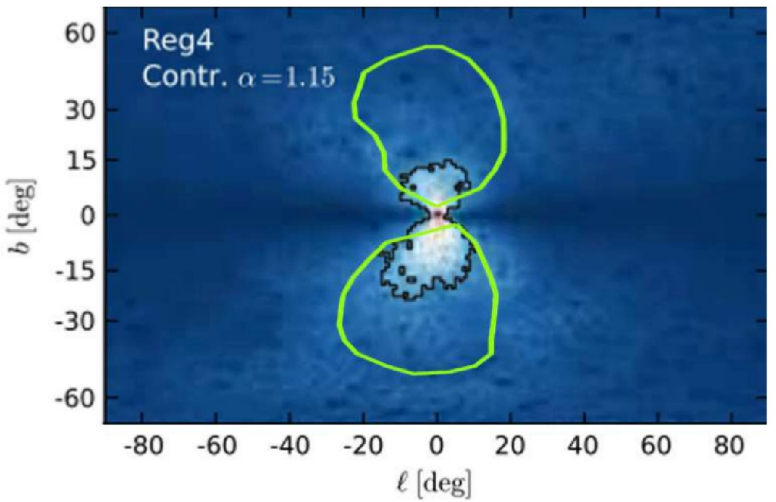


- Taking into account the look-elsewhere effect, the significance is about **3.3σ** (ten target regions times the scan from 20 to 300 GeV)
- **Cosmic-ray contamination** and **artefacts in effective area** would very likely show up in large parts of the sky, not just where one expects the DM signal.



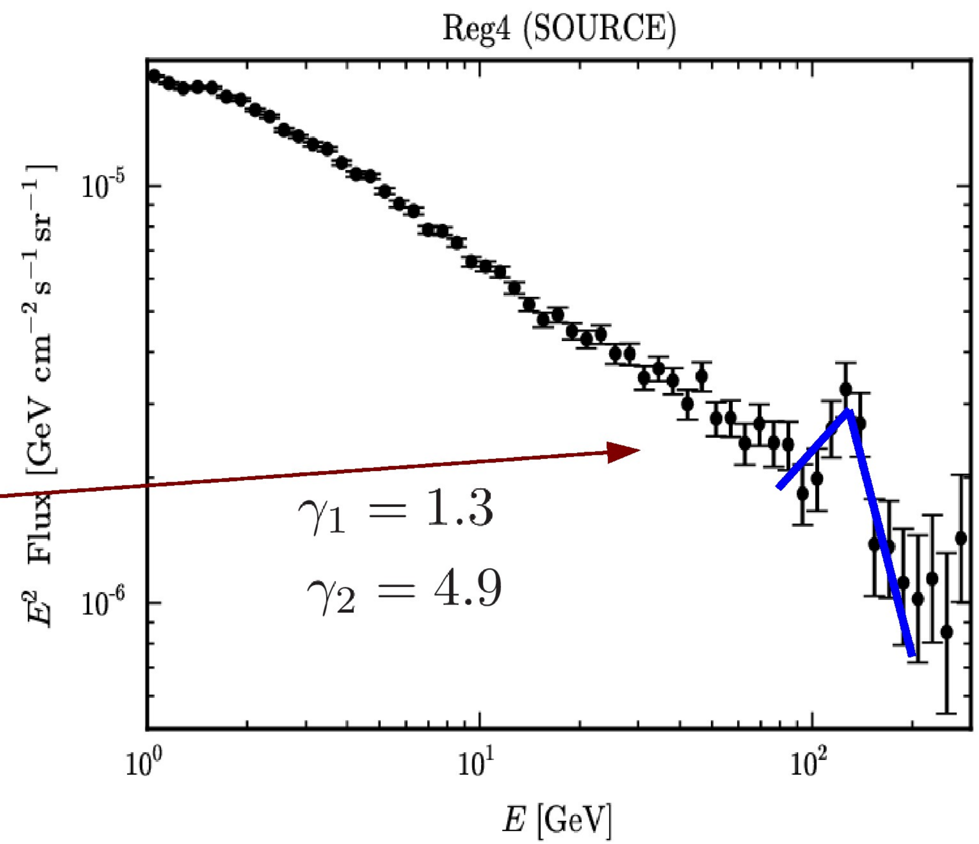
Signal significance (SOURCE)
TS value
Reg1
Reg2
Reg3
Reg4
Reg5
Signal significance (ULTRACLEAN)
TS value
Reg1
Reg2
Reg3
Reg4
Reg5
E_γ [GeV]

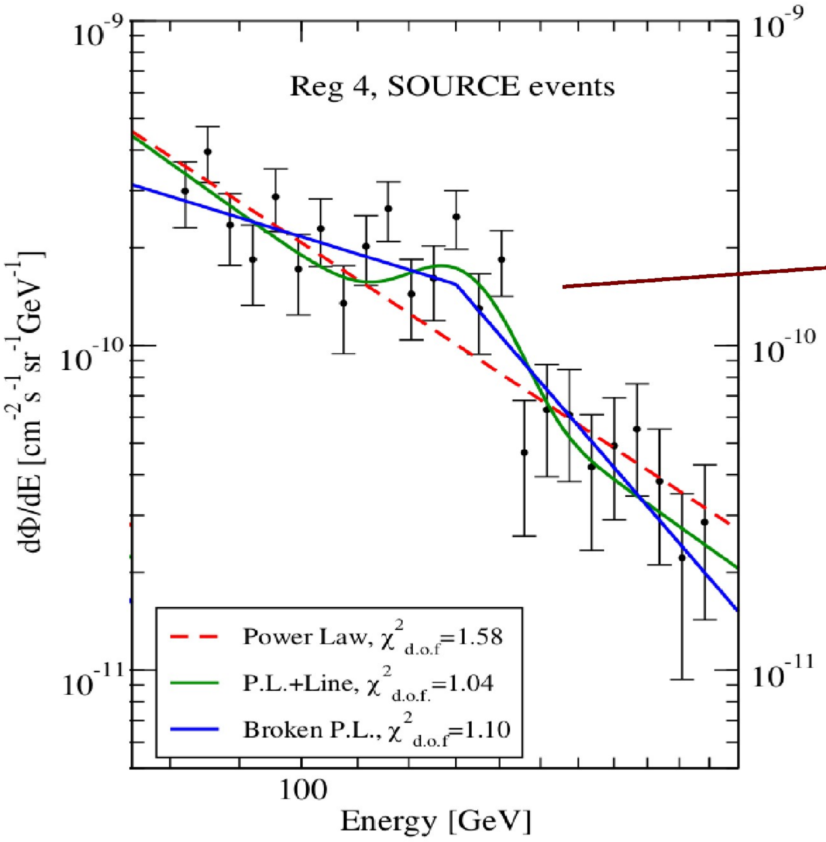
Broken Power Laws?



Linden & Profumo [1204.6047]:

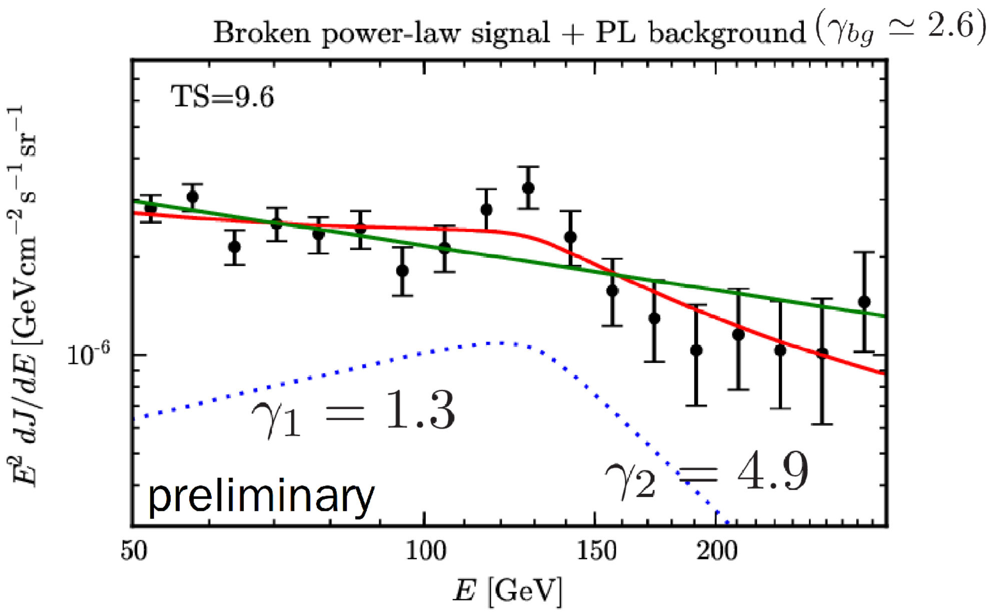
I) Target regions overlap with Fermi Bubbles
II) Bubble spectrum is possibly a broken power-law
→ „Spurious Line“

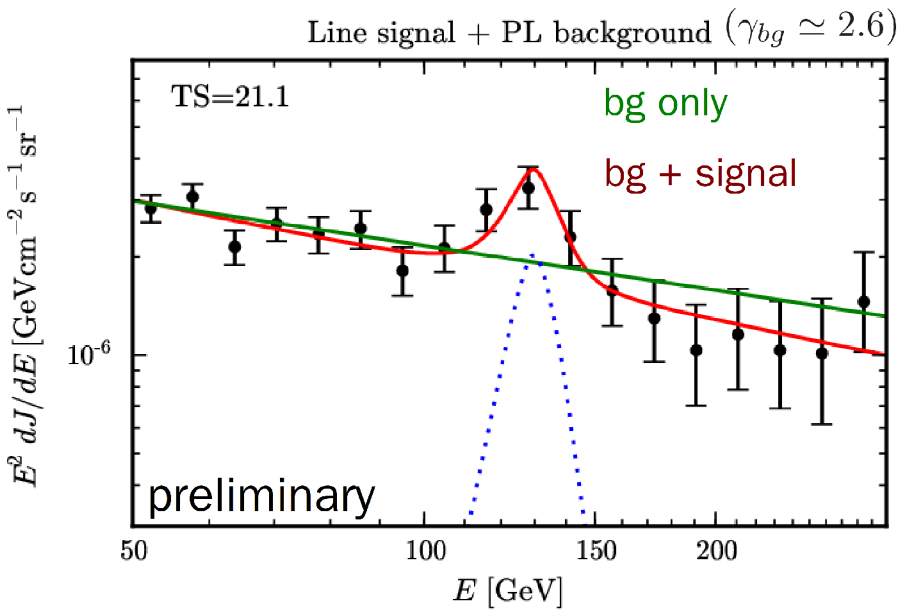




* Standard background fluxes missing in the fit
* A flat spectrum radio quasar? [1001.4097]:
  Break energies < 10 GeV, hardest break from 2.2 to 4.9
* But: cannot be a single source

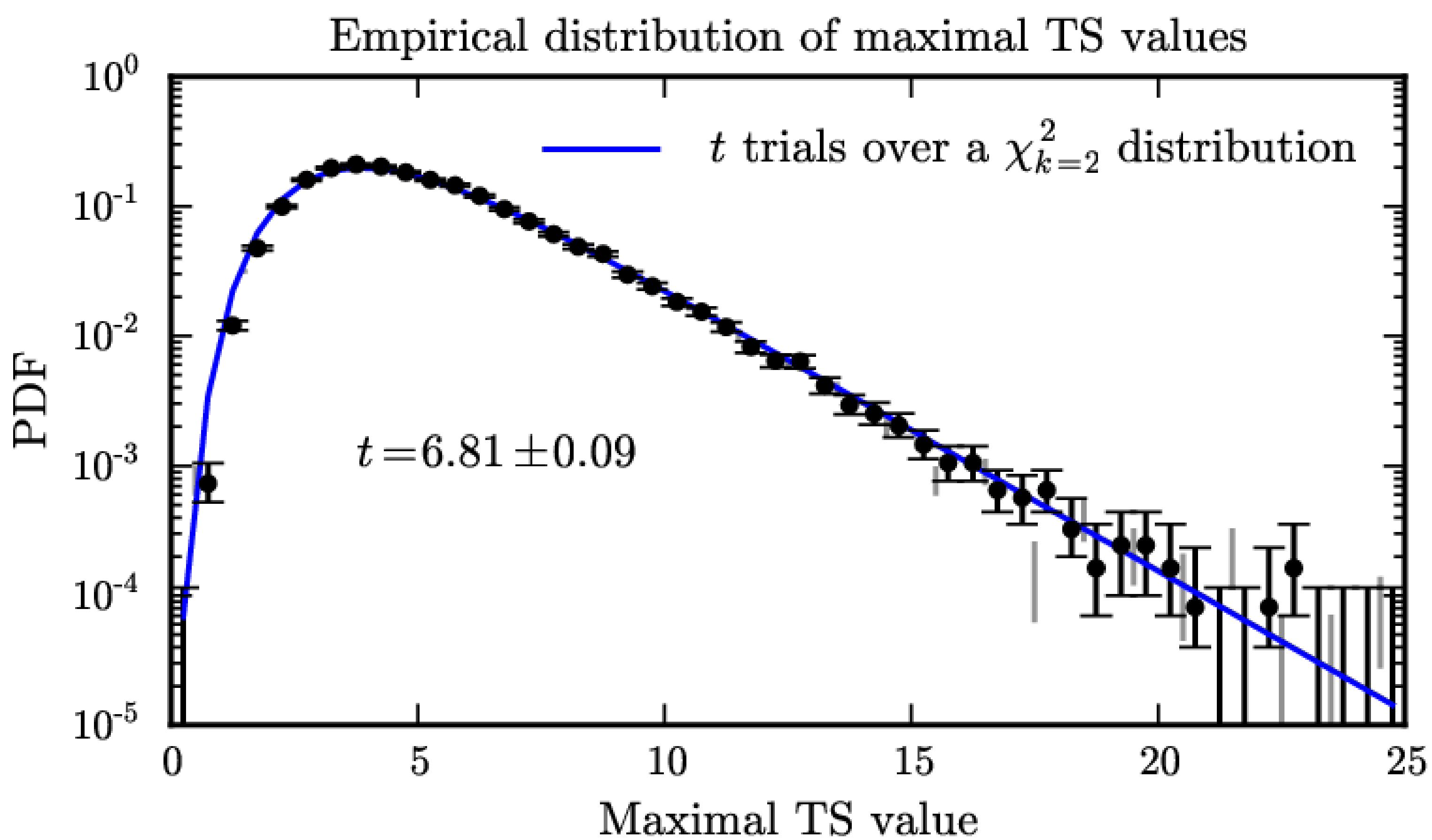
Broken Power Laws?





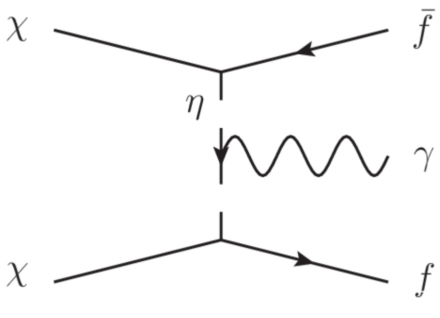
In these fits, the suggested broken PL is disfavoured by ~3 sigma.
Extremer breaks would lead to better fits.

Monte Carlo for p-value



TS=21.4 → 3.2 sigma global significance

II) Virtual Internal Bremsstrahlung (VIB)



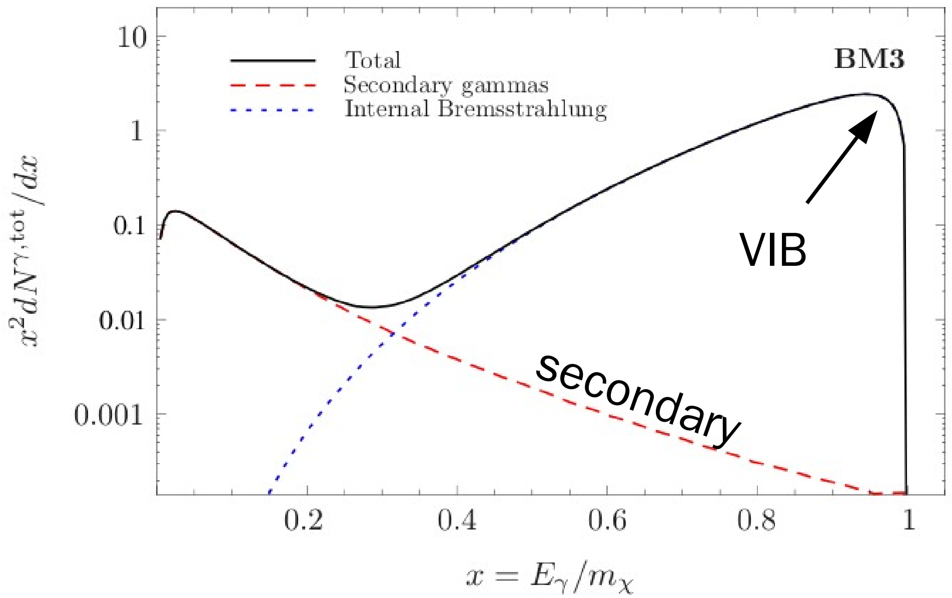
t-chanel

Characteristic features

- dominates FSR when
  - 3-body final state lifts e.g. helicity suppression
  - final states are scalars
- model-dependent spectrum
- produces sharp "bumps"

- Important in models with degenerate mass spectrum (LSP DM in coannihilation region)

Example: stau coannihilation region



[Bringmann et al., 2004]

Quick summary of gamma-ray line searches

Search with EGRET for a gamm-ray line from the galactic center
Pullen, Ranga-Ram & Kamionkowski, PRD 76 (2007) 063006
0.1 - 10 GeV, Spectral analysis, Galactic Center → Upper Limits

Fermi LAT Search for Photon Lines from 30 to 200 GeV and Dark Matter Implications
Abdo et al. (Fermi LAT collaboration), PRL 104 (2010) 091302
30 - 200 GeV, Spectral analysis, Galactic Center + High Latitudes → Upper Limits

Hunting Dark Matter Gamma-ray lines with the Fermi LAT
Vertongen & CW, JCAP 1105 (2011) 027
1 - 300 GeV, Spectral analysis, Galactic Center or High Latitudes → Upper Limits

A tentative gamma-ray line from dark matter annihilation at the Fermi LAT
CW, arxiv:1204.2797 (first discussed in Bringmann, Huang, Ibarra, Vogl & CW, arxiv:1203.1312)
20 - 300 GeV, Spectral analysis, Different optimized target regions → 130 GeV feature

...Tempel, Hektor & Raidal, arxiv:1205.1045; Boyarsky, Malyshev, Ruchayskiy, arxiv:1205.4700...
→ 130 GeV feature

Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum
Ackermann et al. (Fermi LAT collaboration, 2012), arxiv:1205.2739, accepted for PRD
7 - 200 GeV, Spectral analysis, Galactic Center + High Latitudes → Upper Limits

Strong evidence for gamma-ray lines in the inner galaxy
Su & Finkbeiner, arxiv:1206.1616
80 - 200 GeV, Spatial regression analysis → 130 GeV feature

...

I) Target Region Selection

Criteria for a good target region:

1) Sufficient Exposure (nearly uniform at Fermi LAT)
2) Large signal-to-noise ratio (minimize <u>statistical</u> errors) S/N

$$S \propto \int_{\Delta\Omega} d\Omega \frac{dJ_{\rm signal}}{d\Omega} \qquad B \propto \int_{\Delta\Omega} d\Omega \frac{dJ_{\rm bg}}{d\Omega} \qquad N \propto \sqrt{S+B} \approx \sqrt{B}$$

3) Large Signal-to-background ratio S/B (minimize <u>systematical</u> errors)
4) Reliable modeling of backgrounds (not much of a problem for lines)

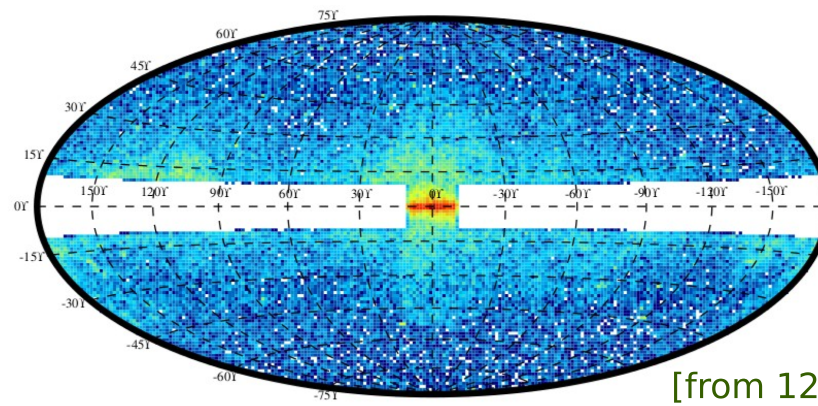
Previous Examples:

EGRET:
[Pullen et al., 2007]

$$|\ell|, |b| < 5^\circ$$

Previously, not much effort was put into the details.

Fermi LAT collaboration:



[from 1205.2739]

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