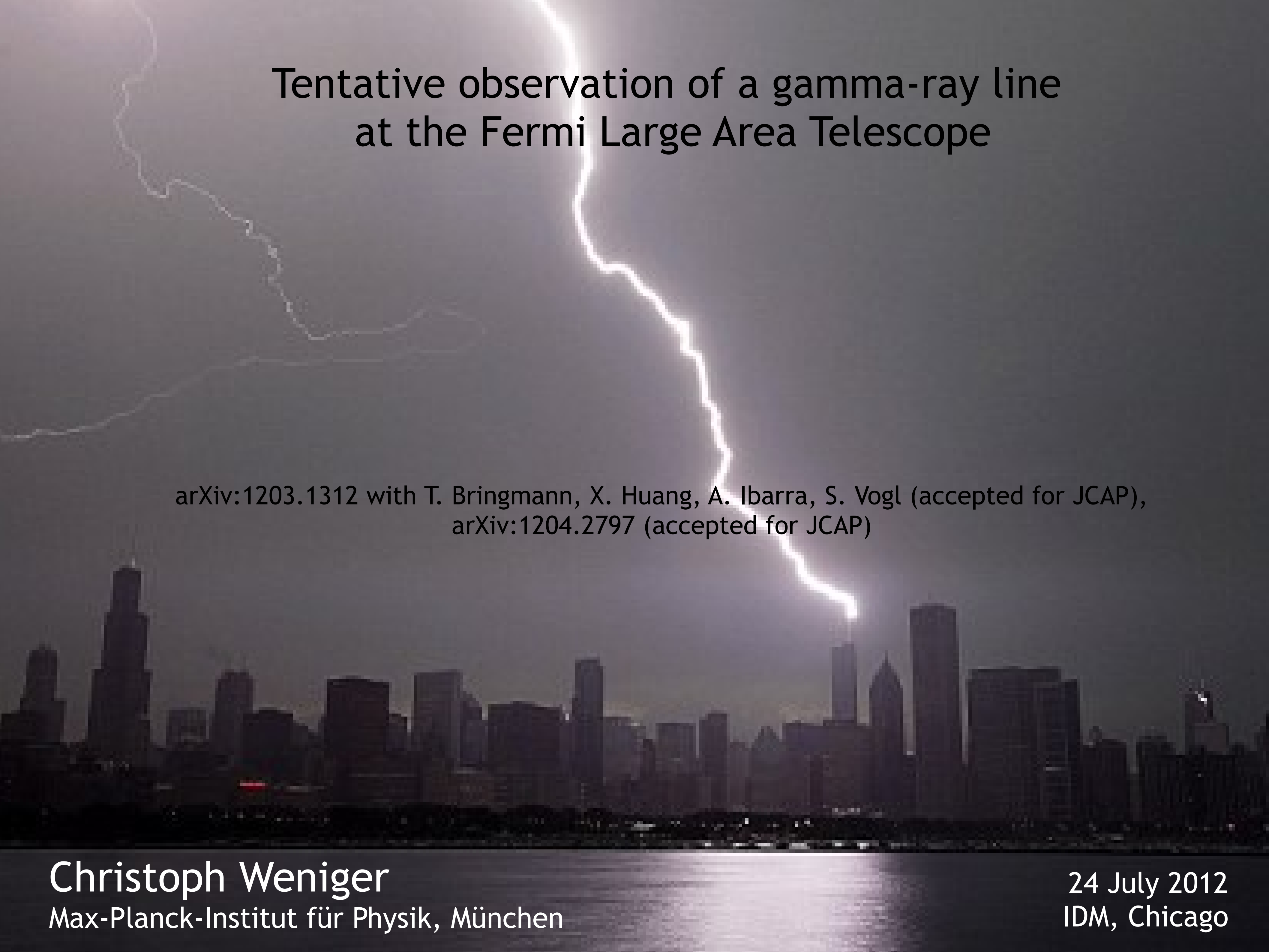
Tentative observation of a gamma-ray line at the Fermi Large Area Telescope



arXiv:1203.1312 with T. Bringmann, X. Huang, A. Ibarra, S. Vogl (accepted for JCAP),
arXiv:1204.2797 (accepted for JCAP)

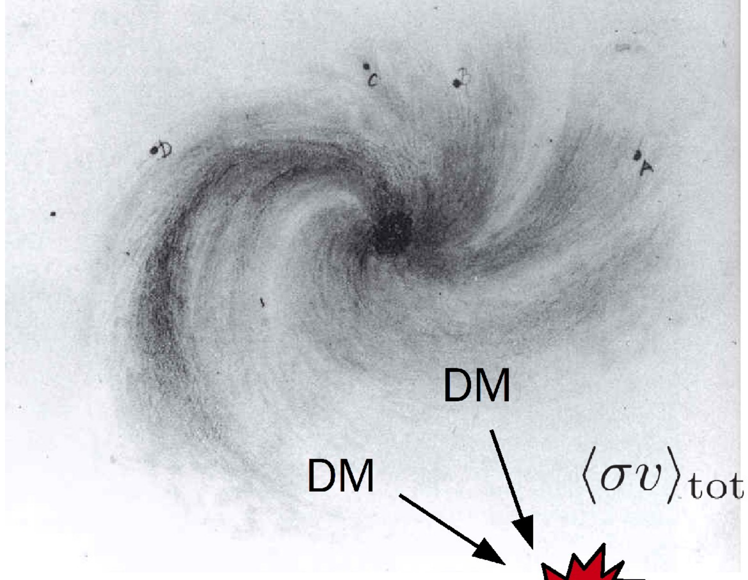
Christoph Weniger
Max-Planck-Institut für Physik, München

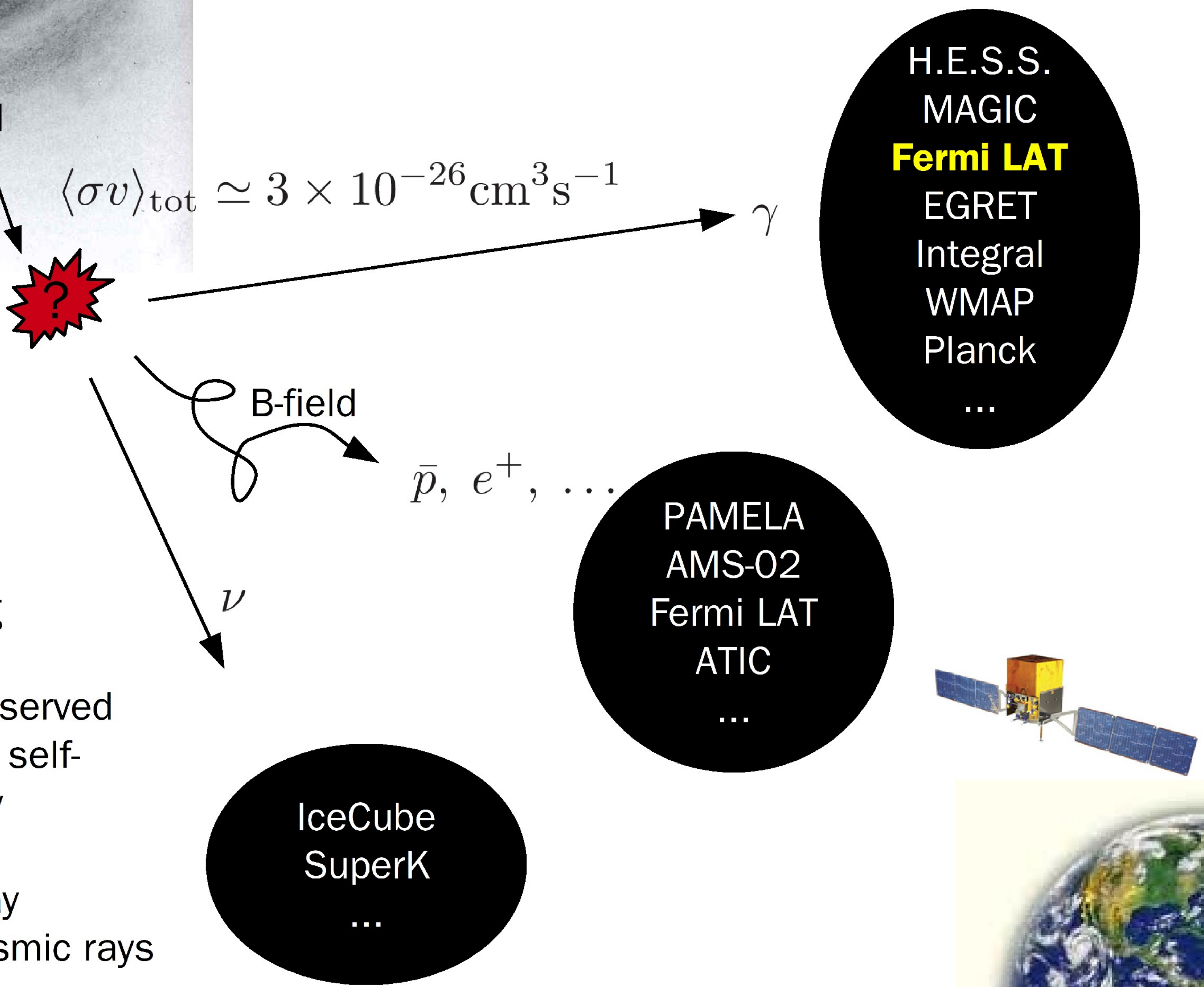
24 July 2012
IDM, Chicago

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"

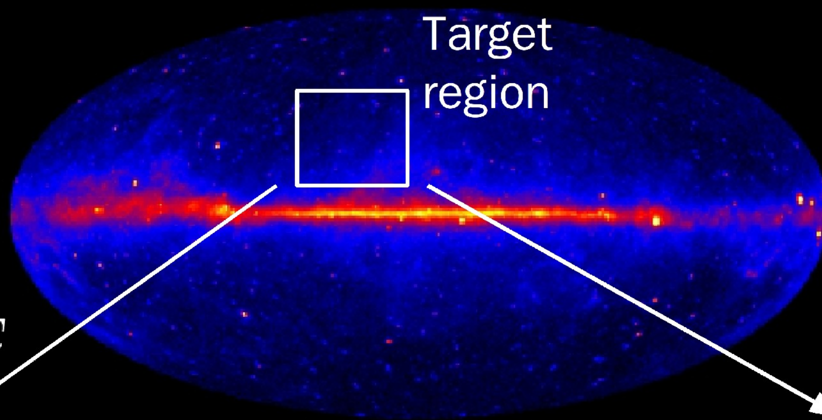
„Astrophysics Factor"

Characteristic **Energy Spectrum**

Characteristic **Spatial Dependence**

On Signal/Background Discrimination

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

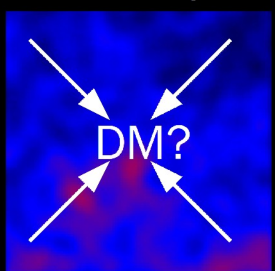


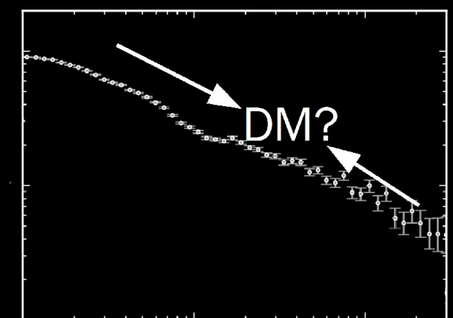
$$\int_{E_0}^{E_1} dE$$

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

Energy
spectrum:

Countmap:





<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

Gamma-Ray Lines

- Are produced in two-body annihilation

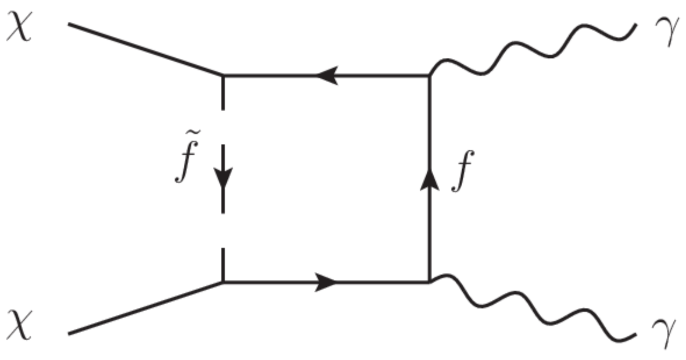
$$\chi\chi \to \gamma\gamma,\ \gamma Z,\ \gamma h$$

- Trivial energy spectrum

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

- Process is **one-loop suppressed**

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



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)]

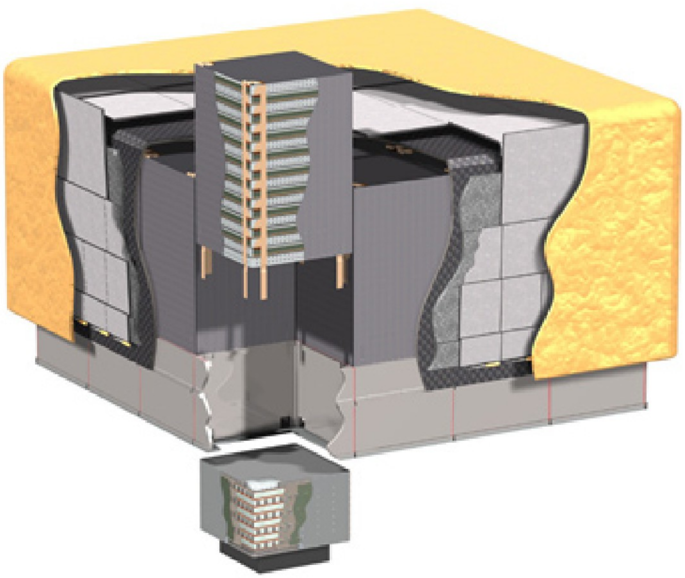
  …

→ “Smoking gun signature” / “Wishful thinking”

The Fermi Large Area Telescope (LAT)

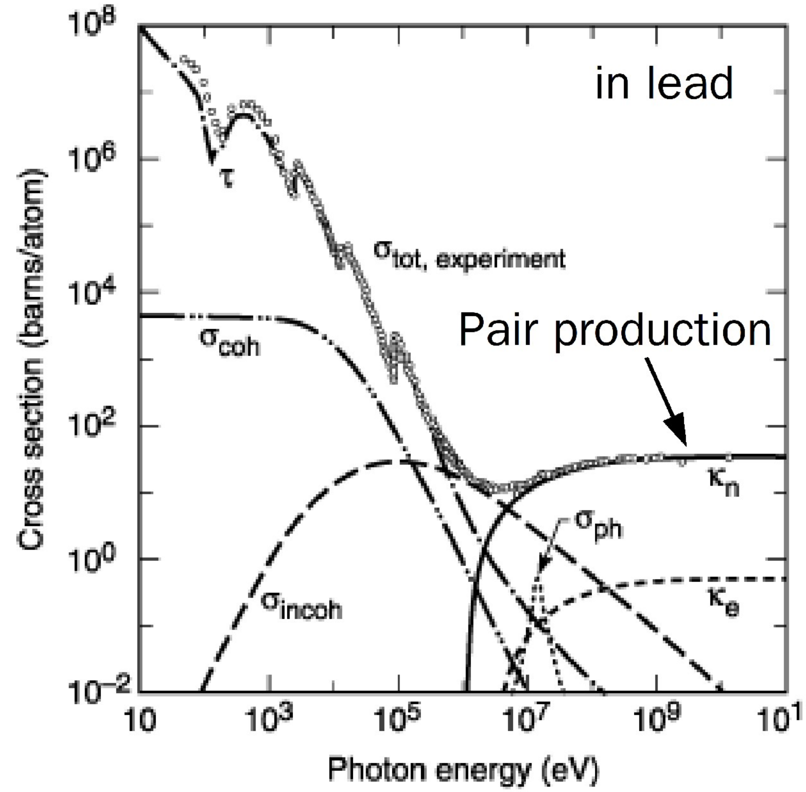
Launch: June 2008

- 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

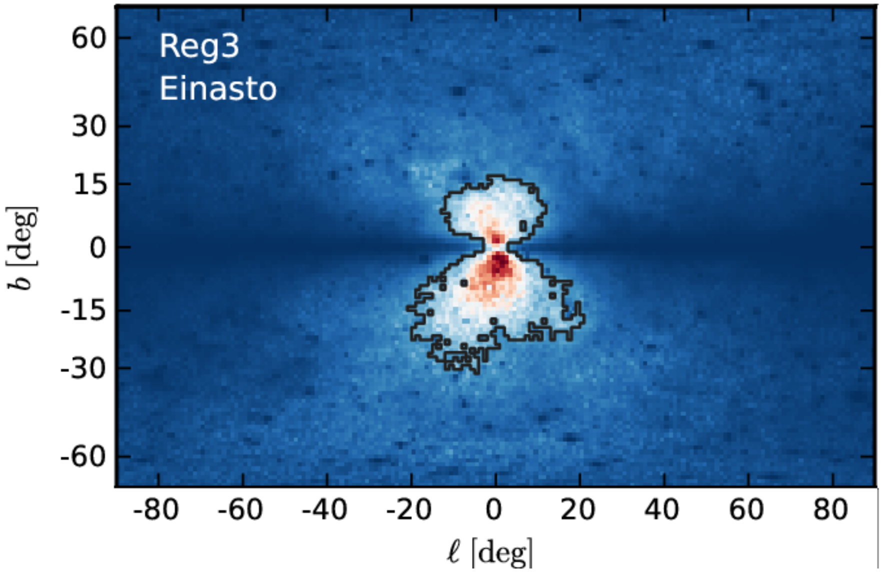


High-level data is publicly available

http://fermi.gsfc.nasa.gov

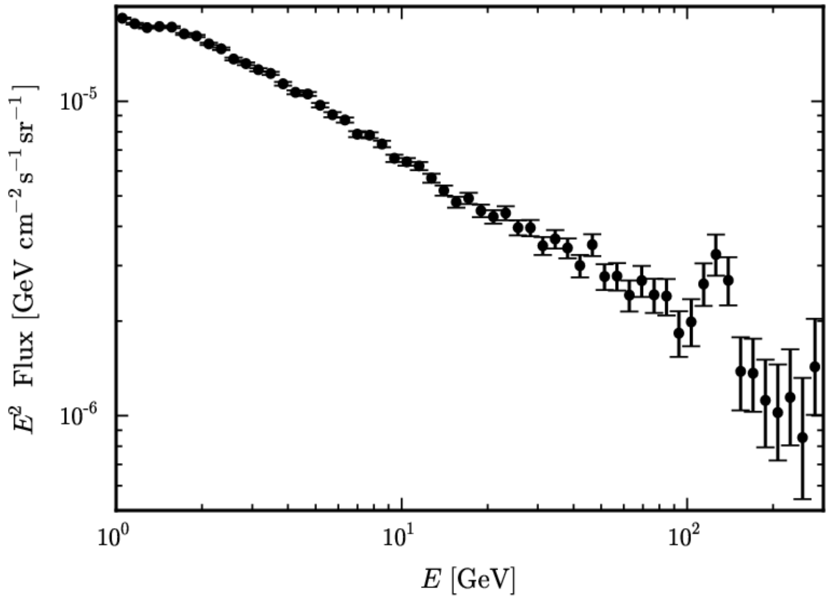
General strategy

I) Target region selection



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

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) Target Region Selection

Criteria for a good target region:

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

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

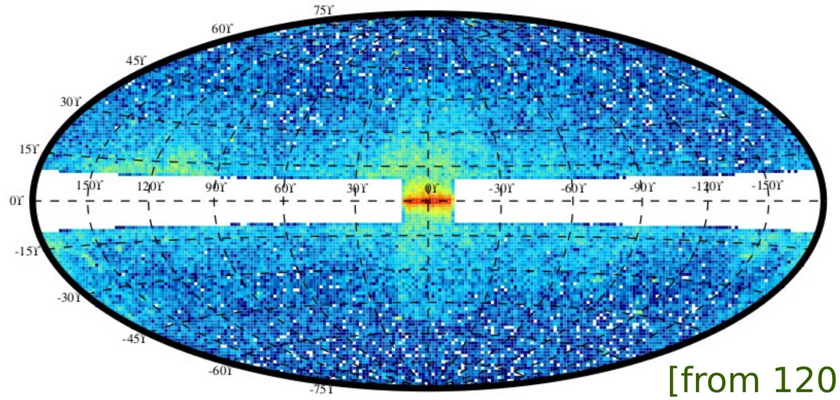
3) Large Signal-to-background ratio S/B (minimize systematical errors)
4) Reliable modeling of backgrounds (not much of a problem for lines)

Previous Examples:

EGRET:
[Pullen et al., 2007]

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

Fermi LAT collaboration:



[from 1205.2739]

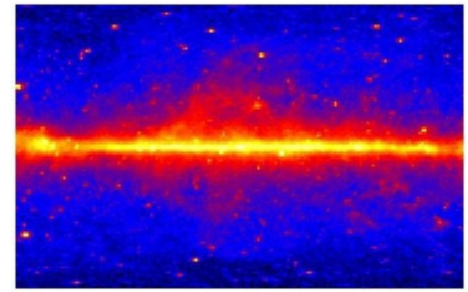
$$|b| > 10^\circ \quad \text{plus} \quad |\ell|, |b| < 10^\circ$$

Previously, not much effort was put into the details.

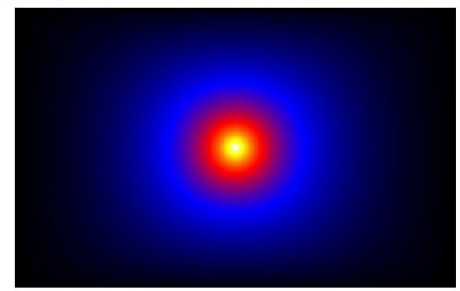
Adaptive target region selection

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



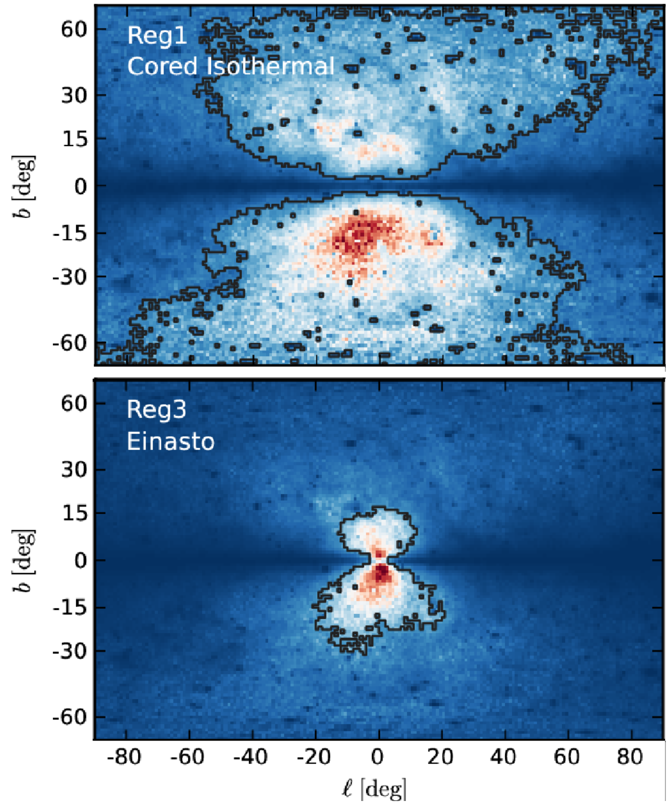
- **Pixel-by-pixel optimization of target region**
  Goal: Find subset of pixels T that maximizes S/N

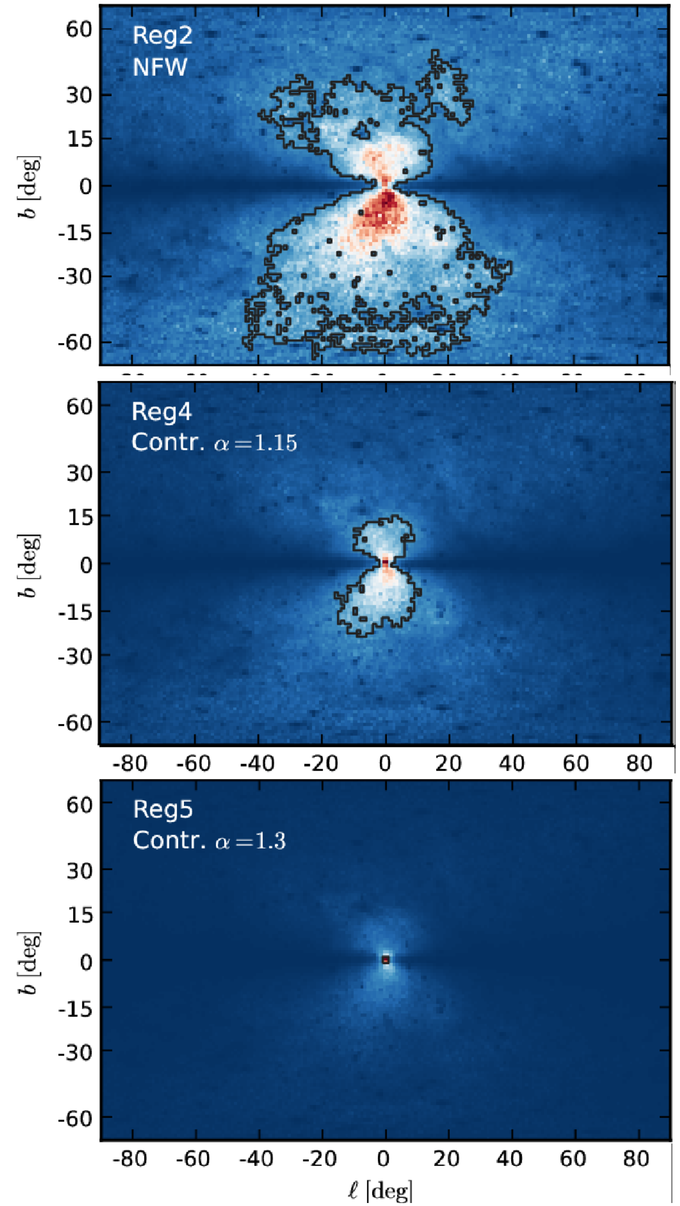
$$(\mathcal{S}/\mathcal{N})_T = \frac{\sum_{i\in T} \mu_i}{\sqrt{\sum_{i\in T} c_i^{1\mathrm{to}20\mathrm{GeV}}}}$$

Expected signal events (μ_i)

Measured events ($c_i^{1\mathrm{to}20\mathrm{GeV}}$)

Target regions for different dark matter profiles

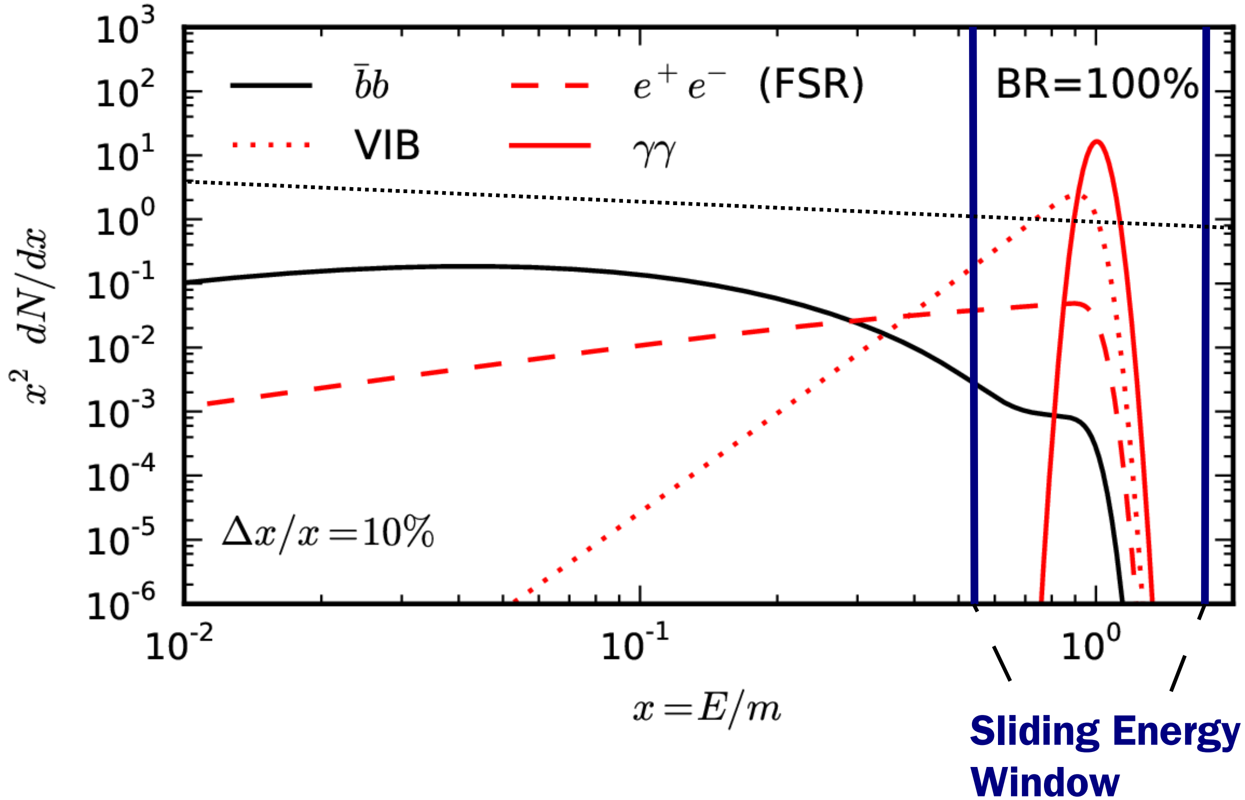




- Steeper dark matter halo profiles → smaller target region
- Galactic center always included (except for cored isothermal profile)
- Slight north/south asymmetry as consequence of asymmetric diffuse fluxes at ~1 GeV

II) Spectral Analysis: Bump hunting

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

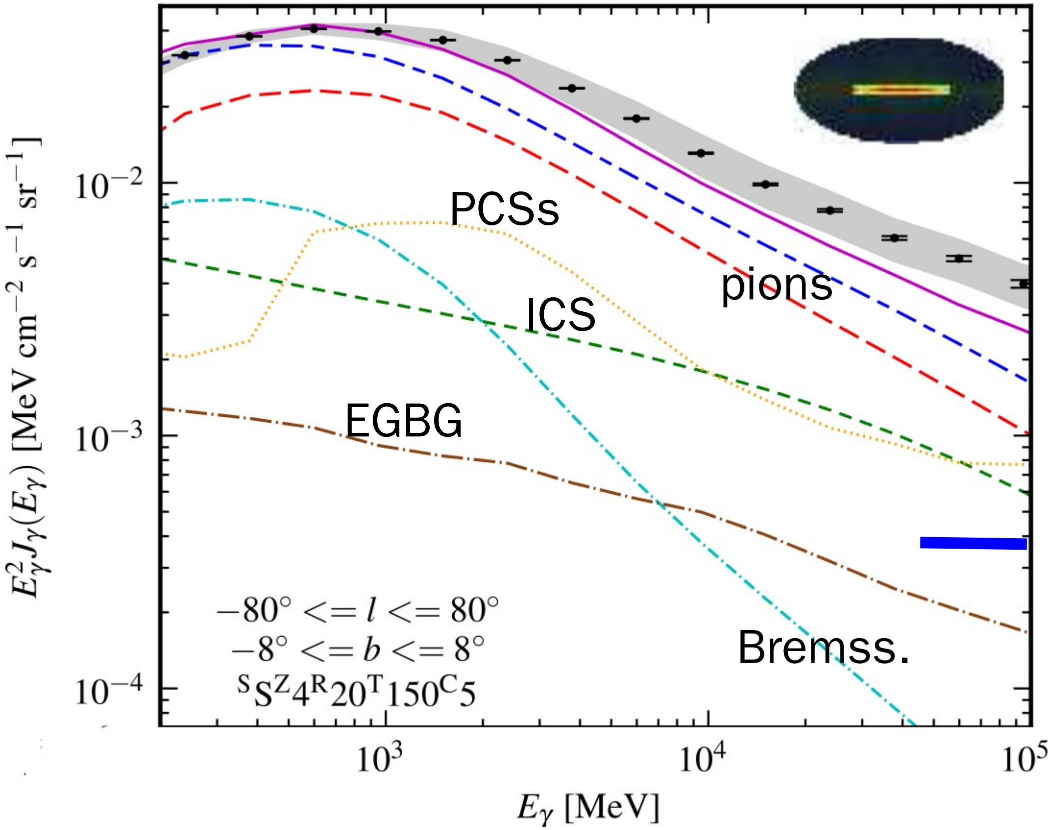


„Sliding energy window technique"

- Secondary photons from DM signal can be neglected
- At 1st order, all backgrounds can be approximated by power-law
- → Trading systematical for statistical errors

Background fluxes vs window size

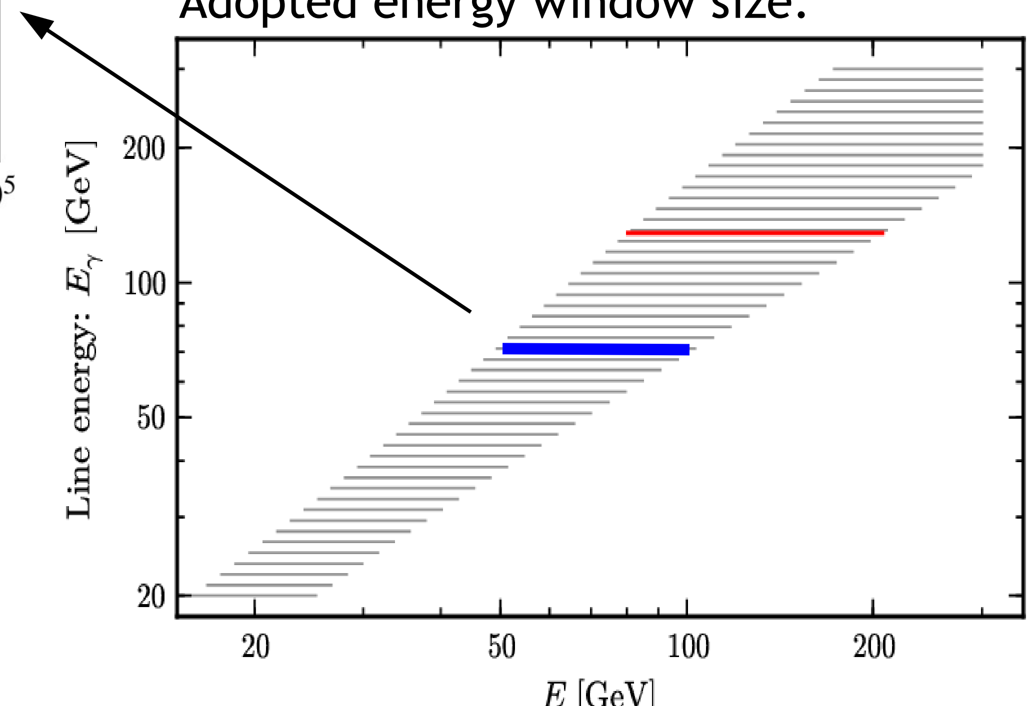
Expected astrophysical fluxes:



[1202.4039, Fermi-LAT coll.]

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

Adopted energy window size:



Statistical analysis

We perfrom a **binned likelihood analysis**, using the likelihood function (we use **many** bins, practically in the **unbinned limit**)

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

with

$$c_i: \ \text{observed events} \qquad P(c|\mu) = \frac{\mu^c e^{-\mu}}{c!}$$
$$\mu_i: \ \text{expected events}$$

- Power-law background + line model (three free parameters)

$$\frac{dJ}{dE} = S\ \delta(E - E_\gamma) + \beta E^{-\gamma}$$

- Convolution with energy dispersion and exposure yields expected event number

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

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

Spectral Analysis – Likelihood analysis

- **Signal significance** for fixed m_χ follows from the TS value (**maximum likelihood ratio test**)

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

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

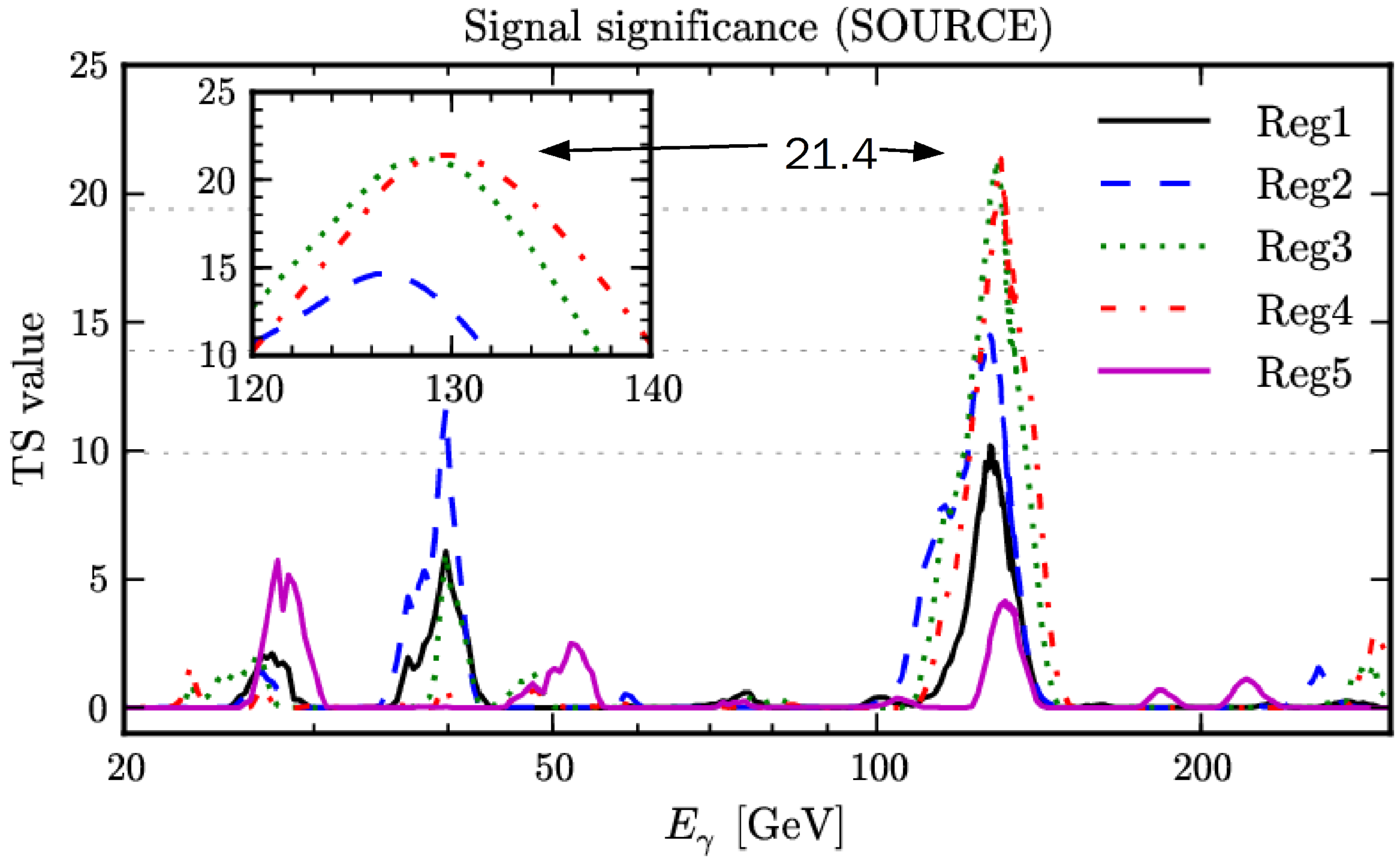
$$\mathcal{L}_{\mathrm{null}} : \text{ Best-fit model without DM}, S = 0$$

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

Significance before trial correction: $\sqrt{TS}\ [\sigma]$

- **95% CL upperlimits** are derived using the **profile likelihood method:** increase S until $\Delta(-2\ln\mathcal{L}) = 2.71$, while profiling over other parameters

III) Results



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

Local significance: 4.6σ

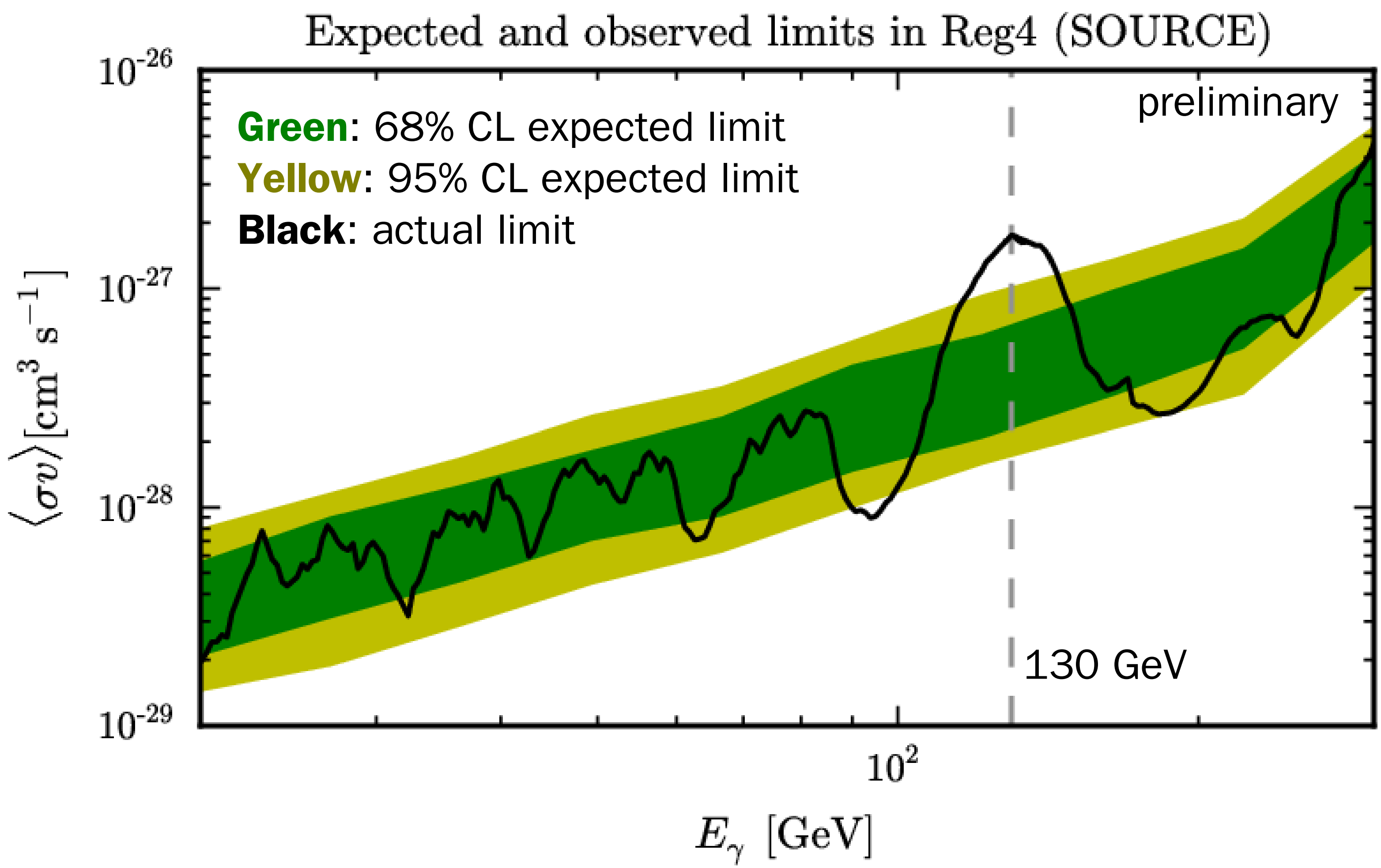
Assuming Einasto profile with 0.4 GeV/cm^3 local density:

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

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

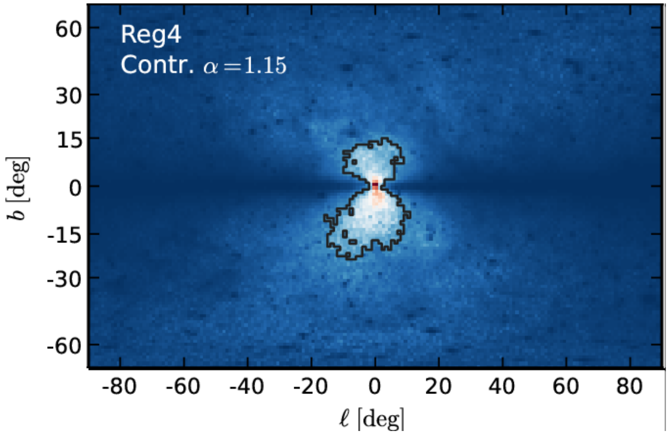
Based on 43 month of P7V6 source class, similar for clean events.

Sensitivity vs observed limits

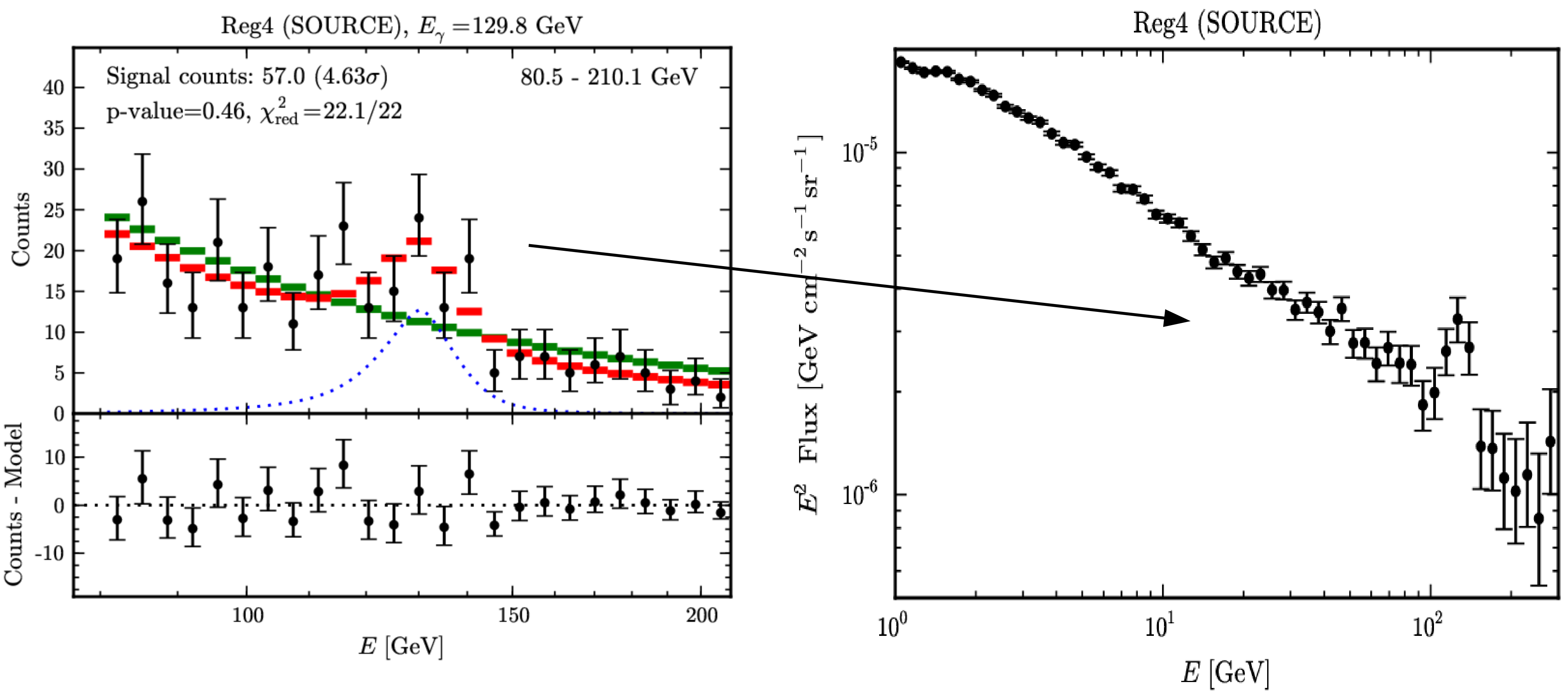


(Derived from null model mock data)

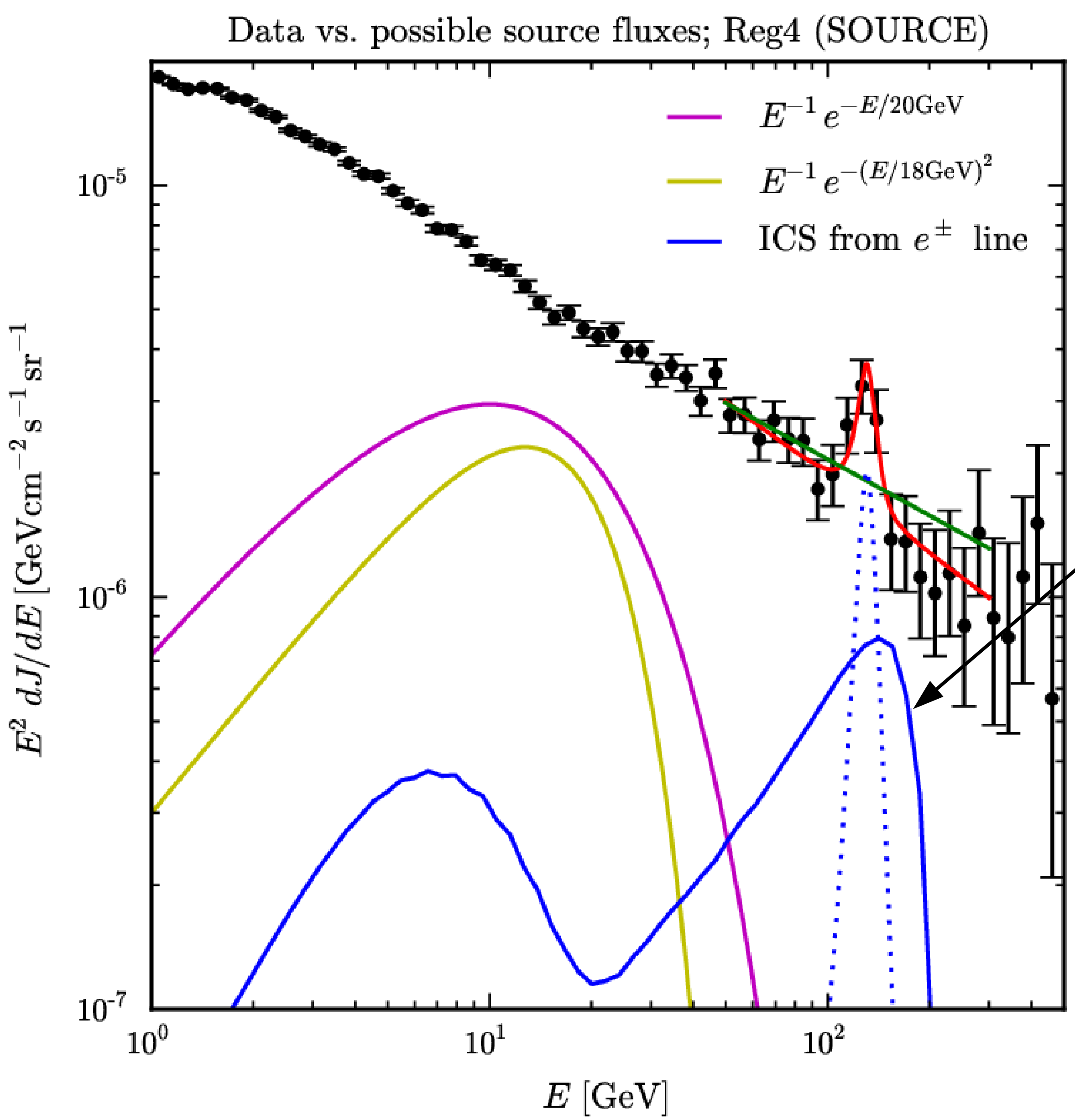
The signature is sharp



Signal width (RMS): <17% (95%CL)



The signature is sharp

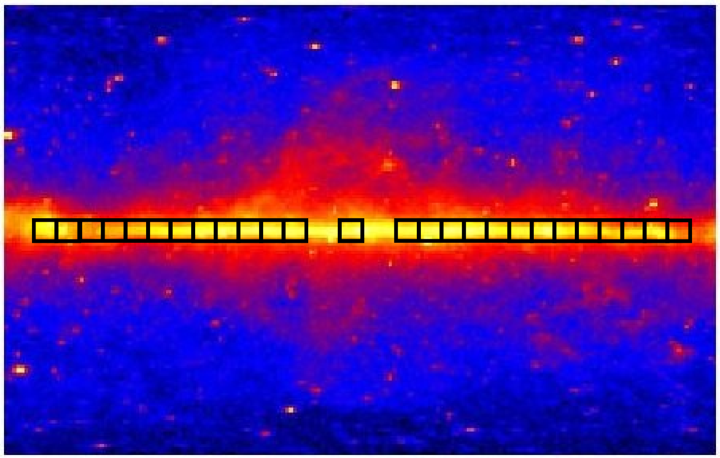


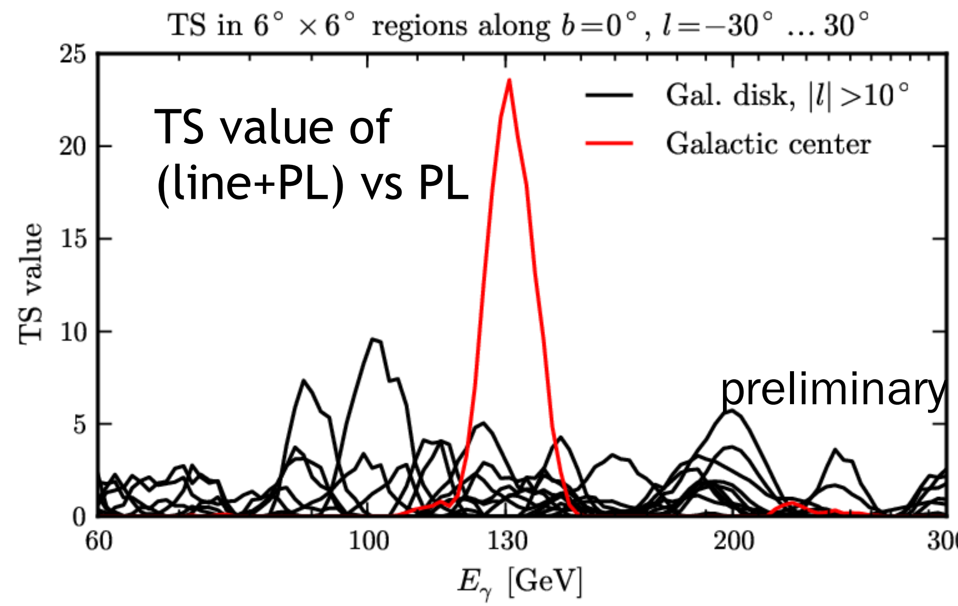
Line: TS = 21.4

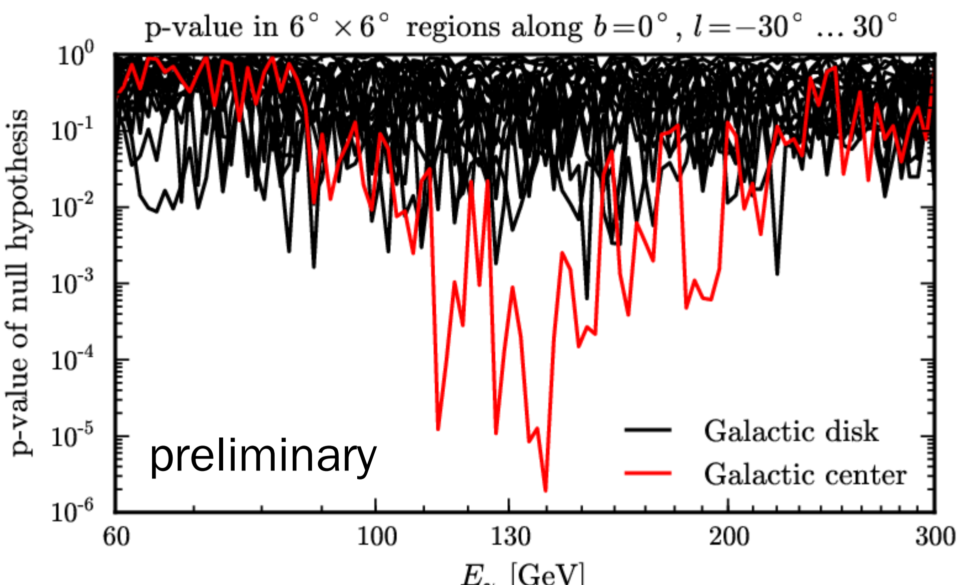
ICS from monoenergetic electrons: TS ~ 12

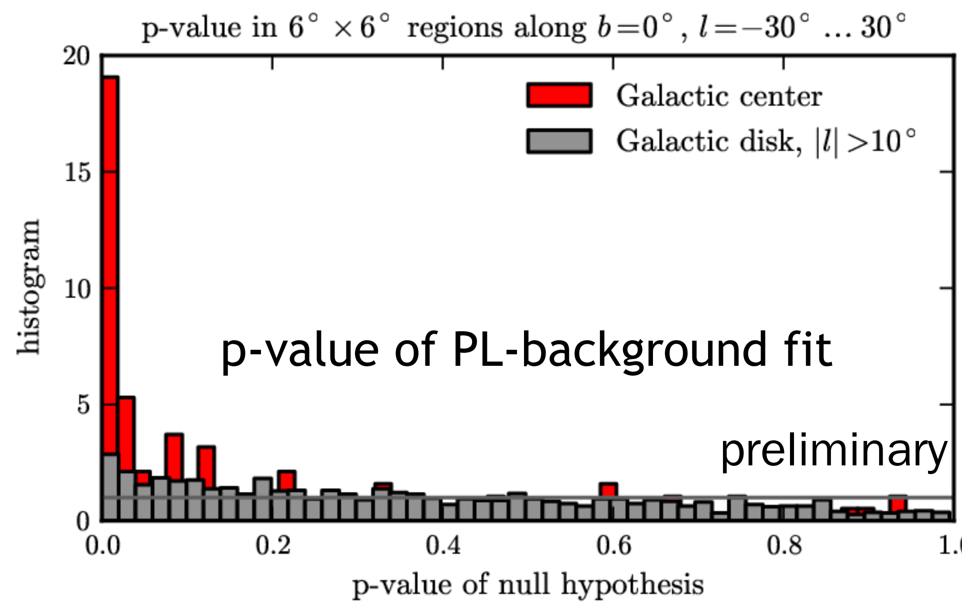
At Galactic center only

Scan along the galactic disk:



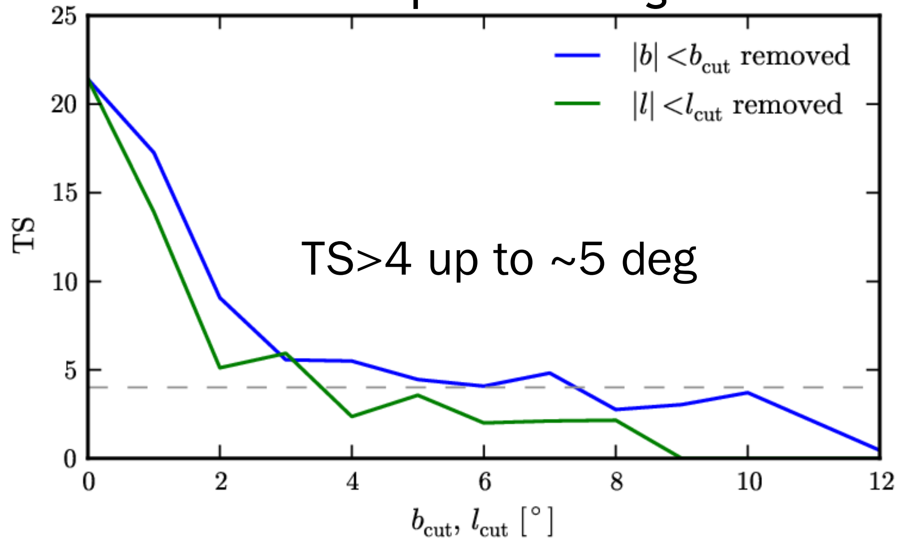




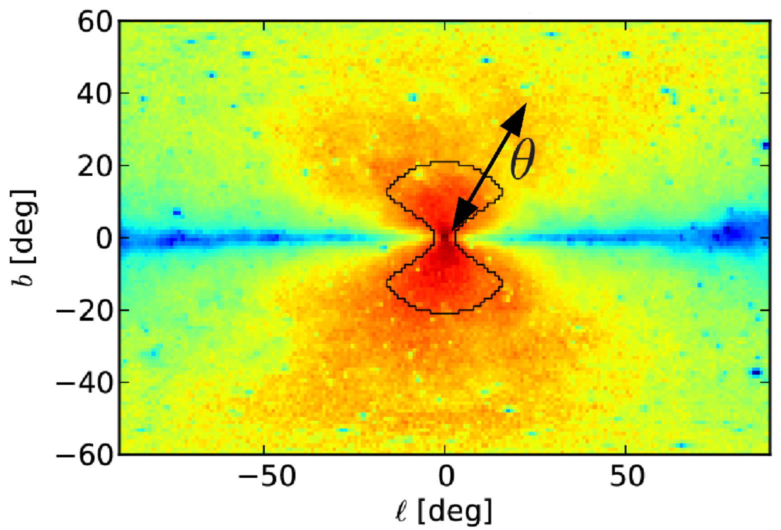


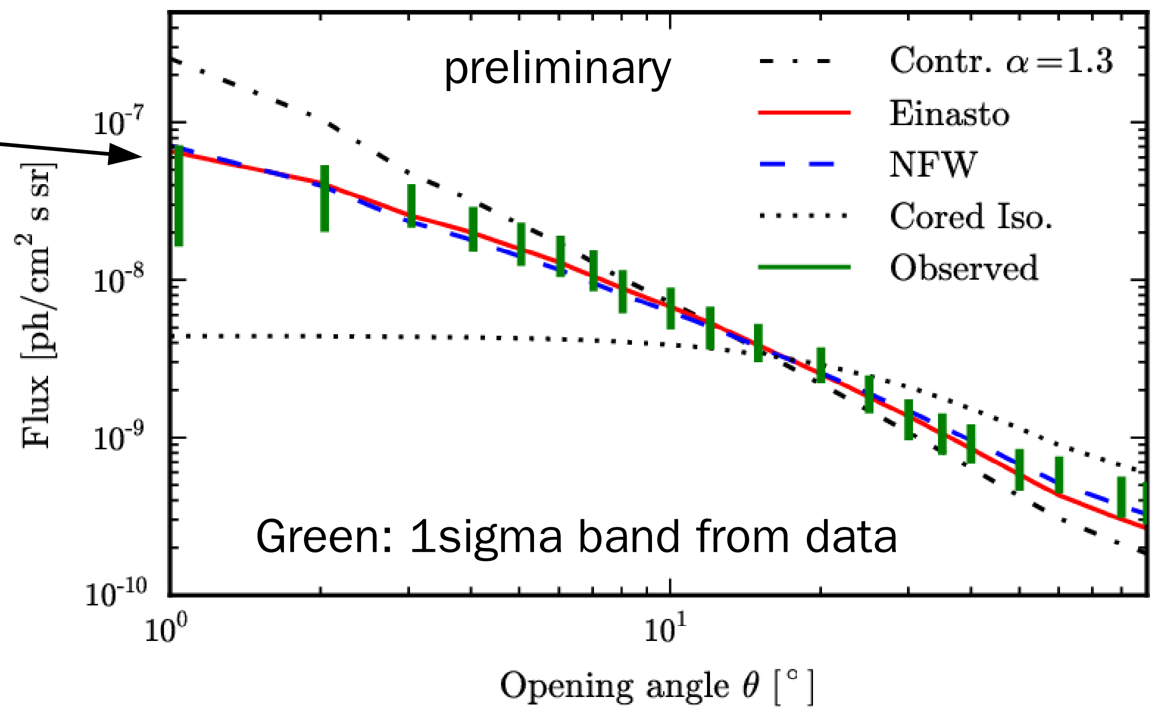
Spatially extended

TS from outer parts of Reg4:

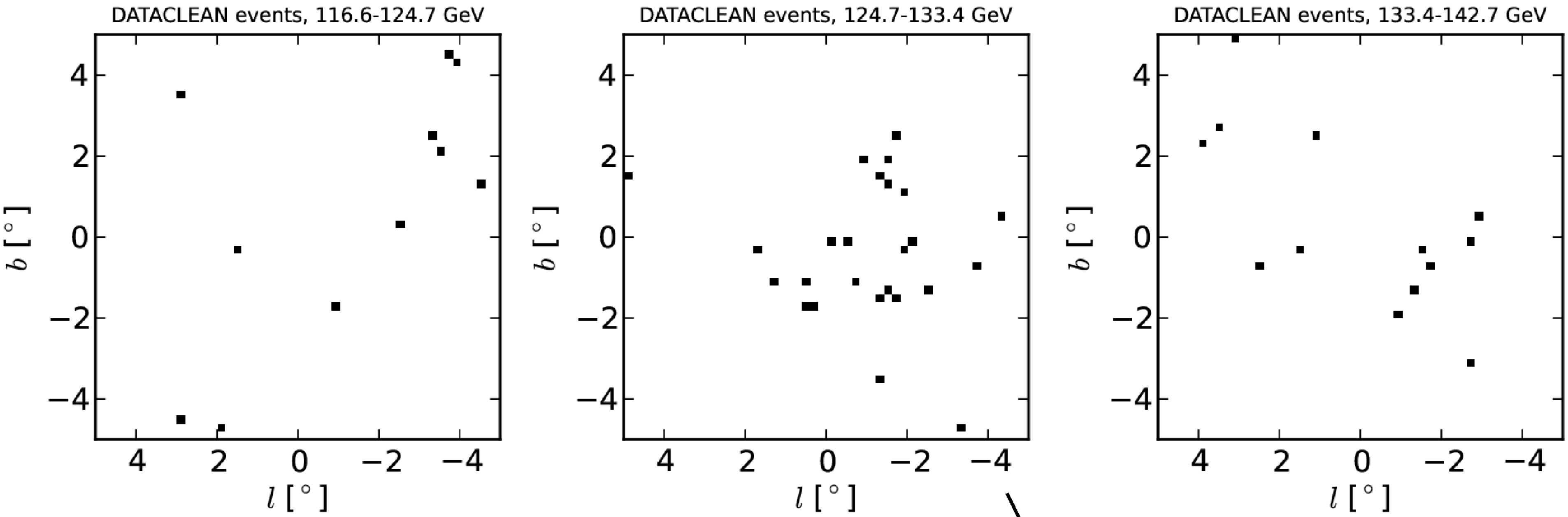


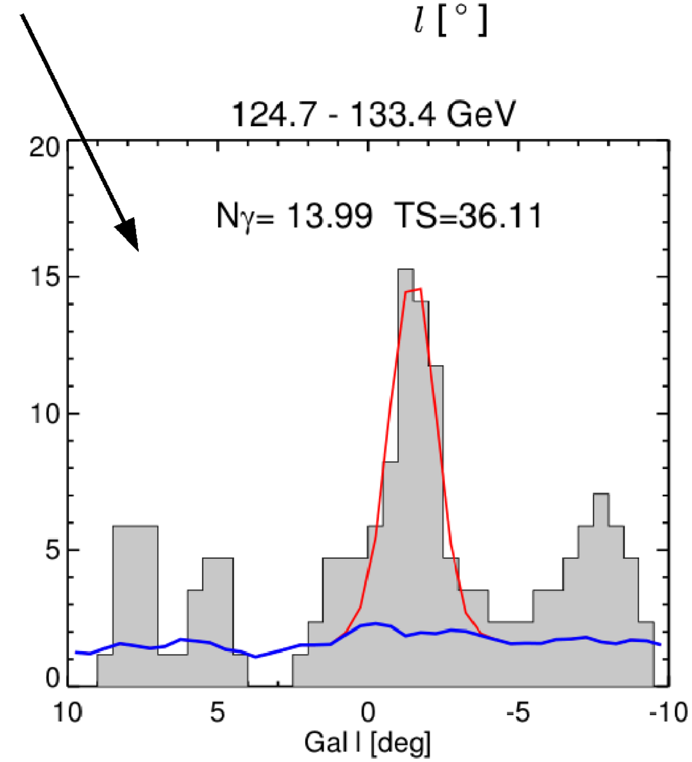
Target region with variable size:





Displaced from the Galactic Center





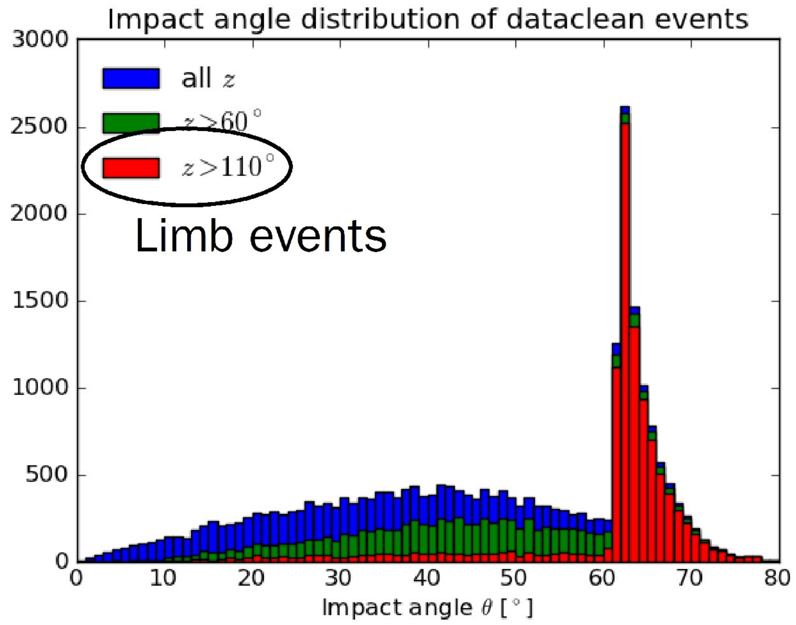
[Su/Finkbeiner 2012]

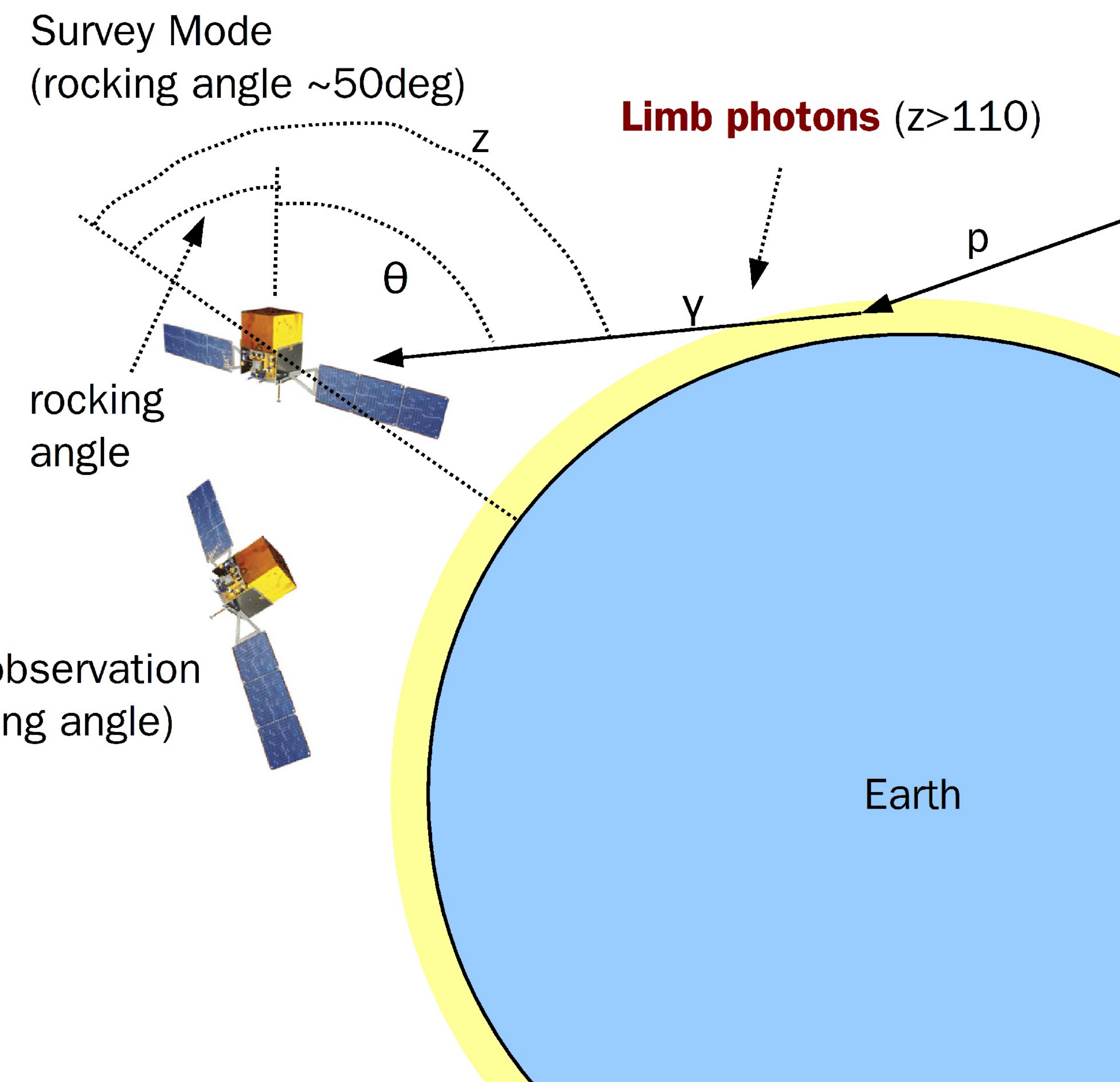
Photons responsible for high TS appear to be significantly displaced by O(100pc) (if GC is origin).

(Talk by Meng Su this afternoon!)

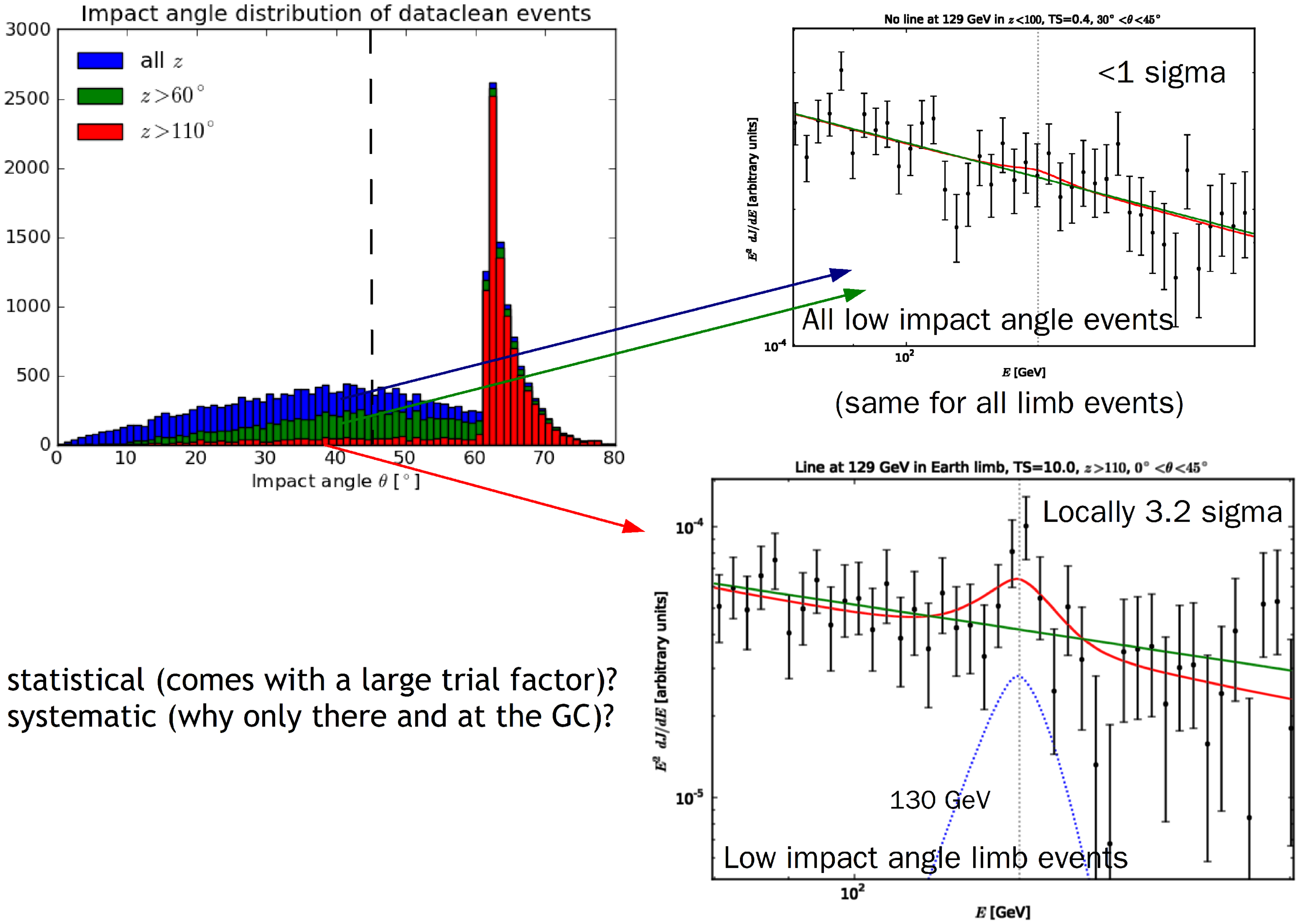
(Talk by Michael Kuhlen tomorrow!)

The Earth limb/albedo as test sample





A 130 GeV line in part of the limb data



- statistical (comes with a large trial factor)?
- systematic (why only there and at the GC)?

Conclusions

- The public LAT data contains an excellent candidate for a gamma-ray line from DM annihilation at ~130 GeV. The cause is unclear.

- Good astrophysical explanations are difficult to find. Different toy scenarios are disfavoured w.r.t. a line by the data.
- Maybe indication for instrumental effect in Earth limb. But: why strongest where one expects the DM signal? Why compatible with NFW/Einasto profile? Why just in low incident events?
- Statistical fluctuation: quite significant, but maybe the most likely explanation? You get what you optimized for.

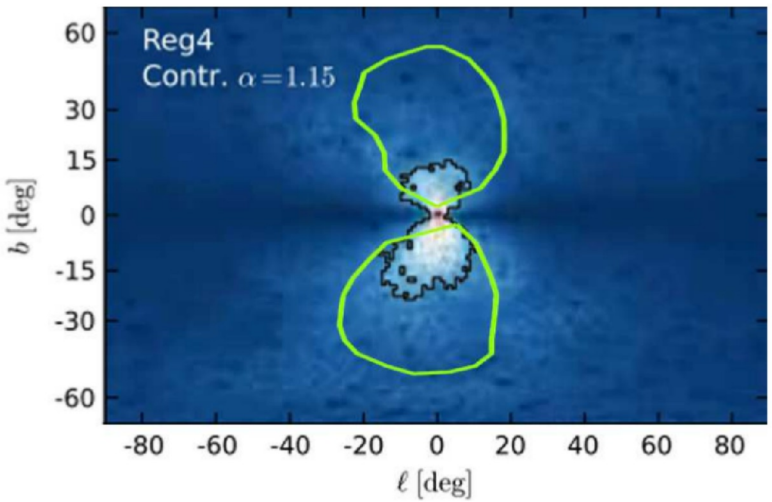
<u>Outlook:</u>

- More data (including Pass 8)
- Study of instrumental effect (Earth albedo, Pass 8)
- Study of apparent displacement of signal center by 200 pc
- Any sign for continuum part of signal?
- HESS-II
- CTA, GAMMA-400

Thank you
& stay tuned!

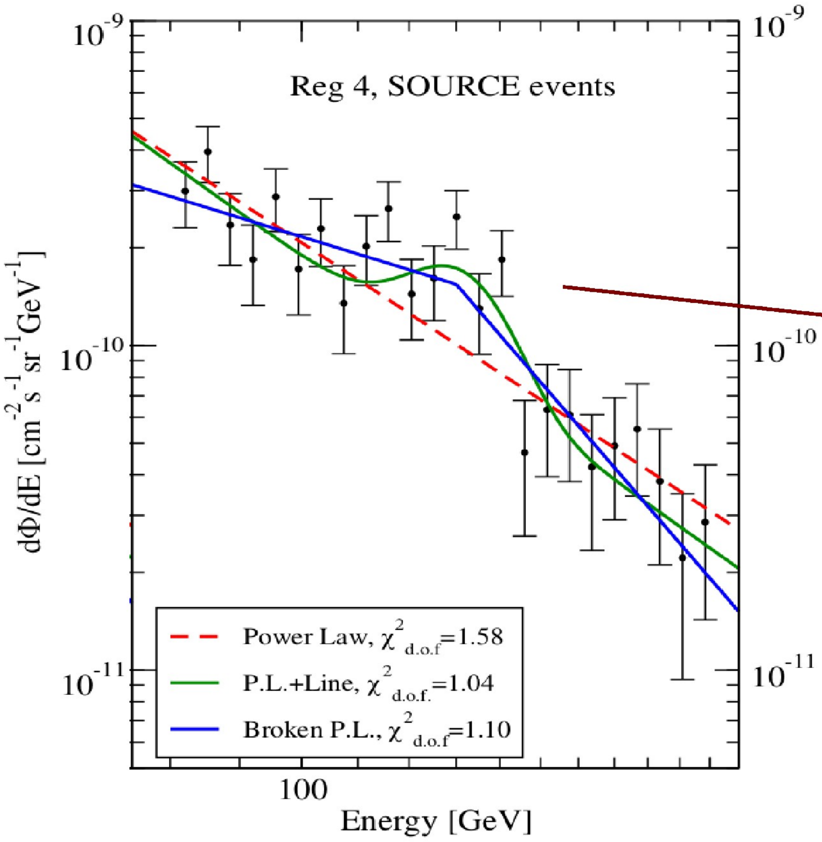
Backup Slides

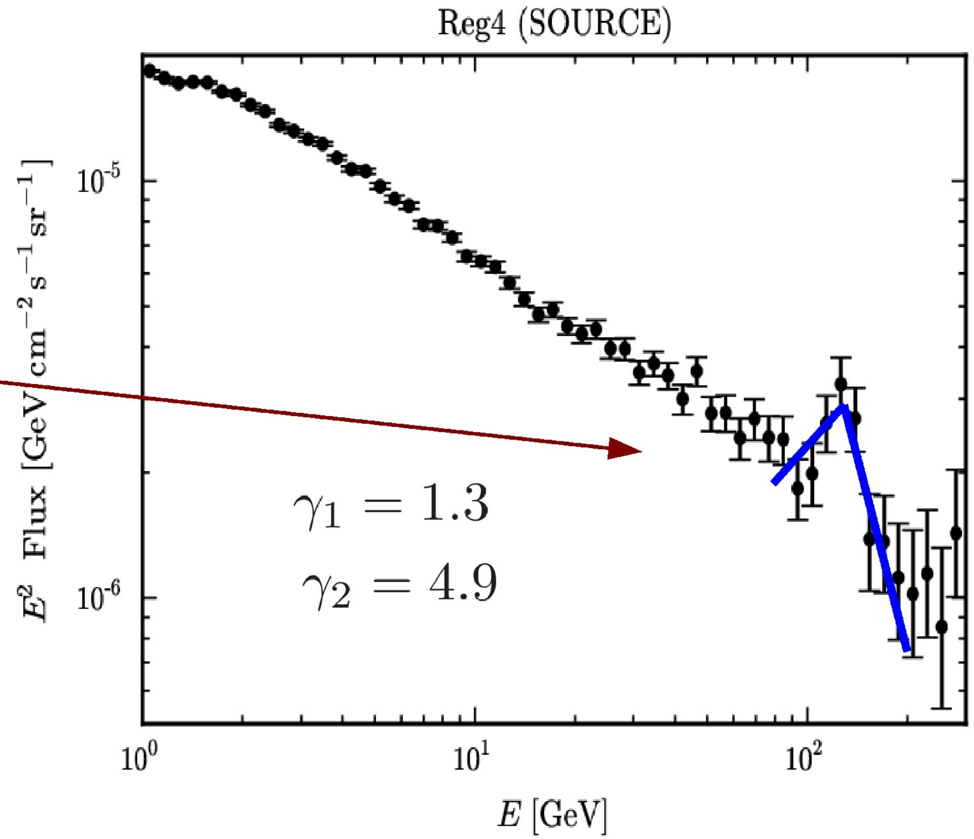
Broken Power Laws?



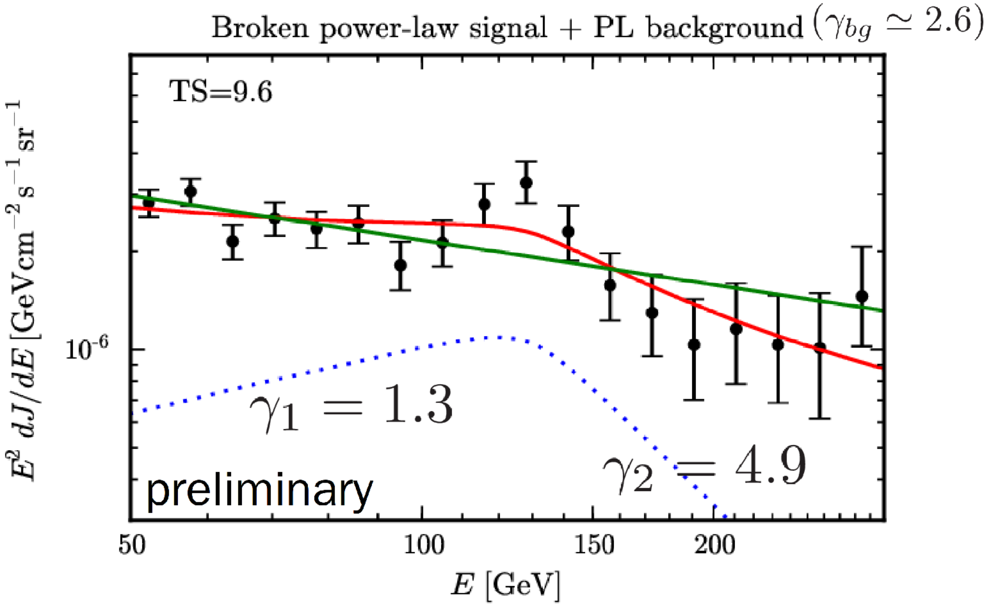
Linden & Profumo [1204.6047]:

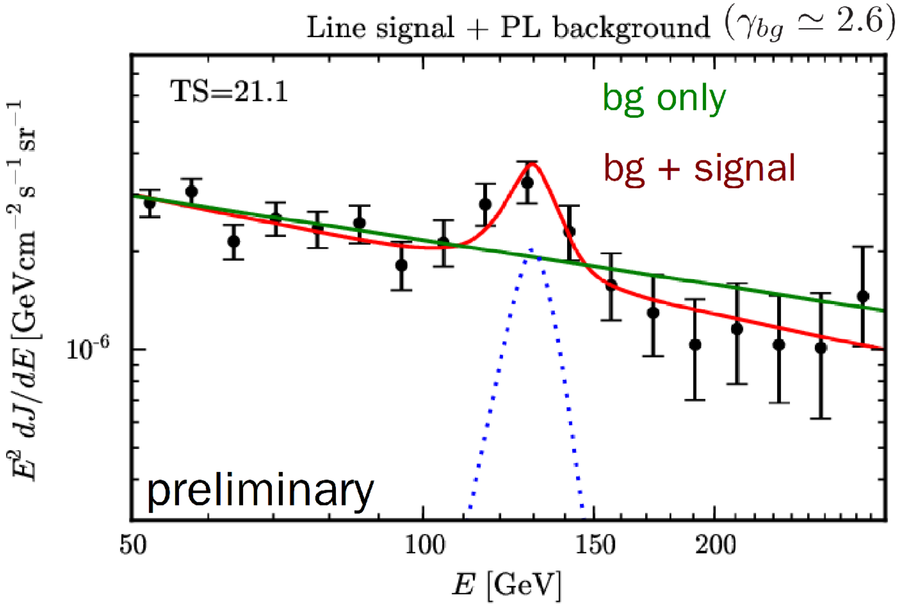
I) Target regions overlap with Fermi Bubbles
II) Bubble spectrum is possibly a broken power-law
→ „Spurious Line"





Broken Power Laws?

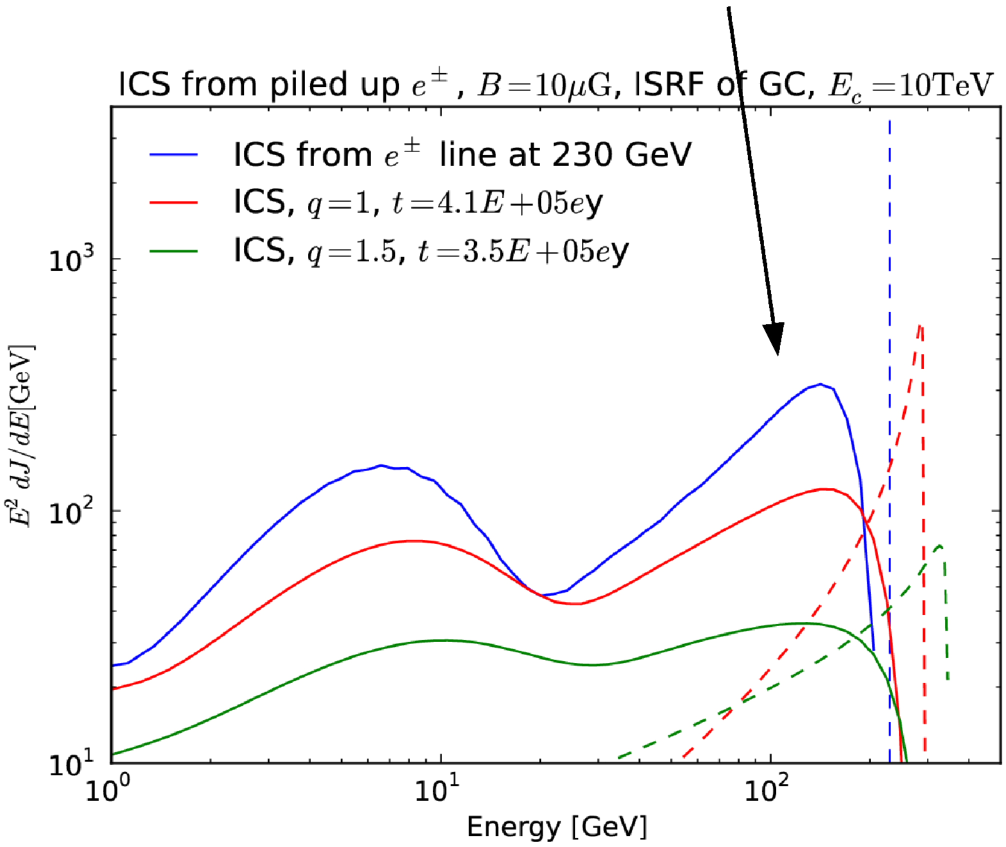


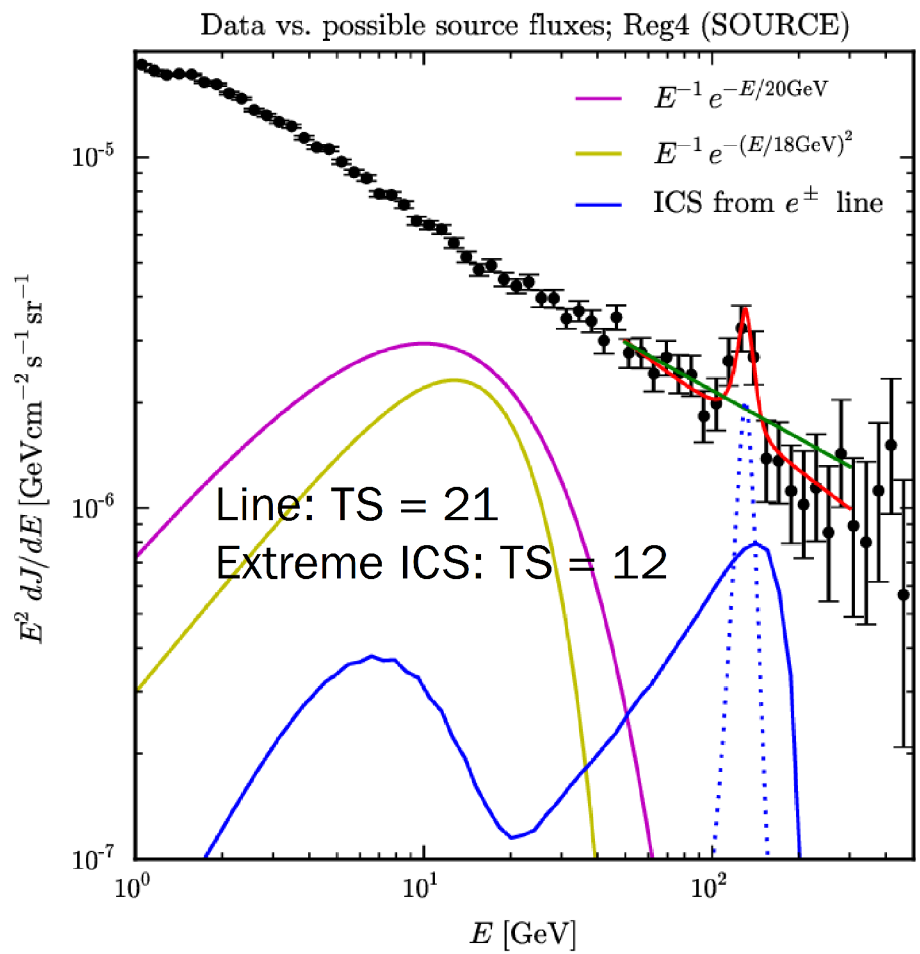


A toy example: ICS emission

Toy scenario:

1) **Inject hard electron spectrum** (spectral index 1 to 1.5) and cutoff at ~10 TeV into GC.
2) Let it cool down by **synchrotron losses** on the dominanting magnetic field.
3) In the ideal case, electron pile up → Even more idealized, this gives an **electron line**.
4) **Inverse Compton Scattering** on the ISRF





But: even this scenario is disfavoured by the data (at ~3sigma)

Dependence on energy window size

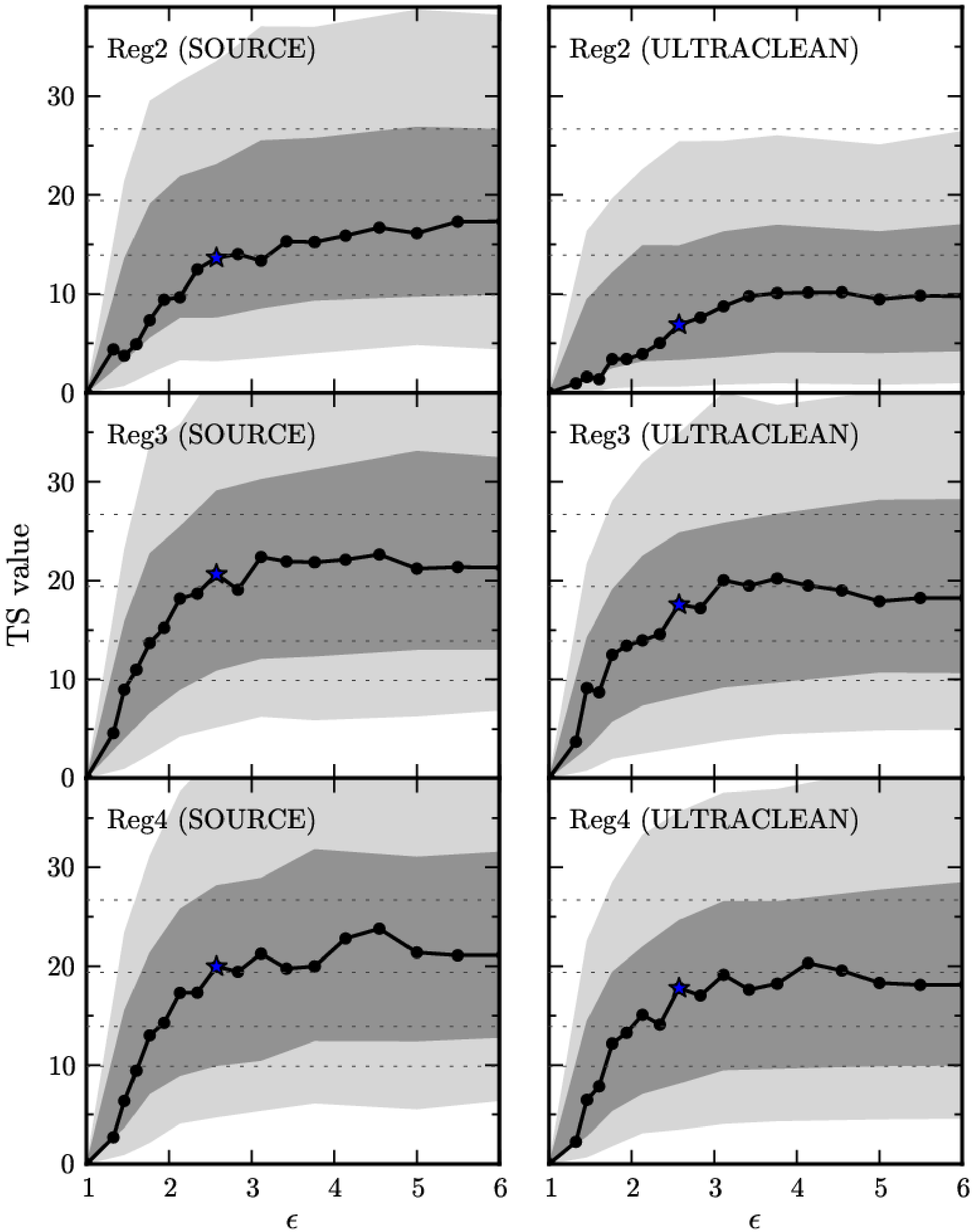
Gray bands: Monte Carlo results for TS value, assuming best-fit signal

Black line: Observed TS value as function of window size

Blue stars: actually adopted energy window / quoted TS value

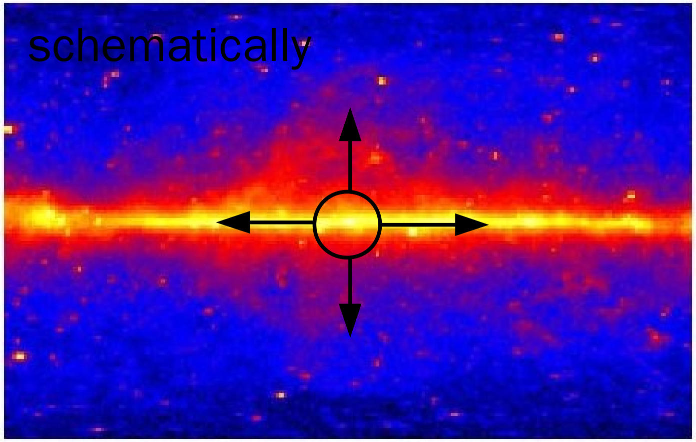
→ The TS value is <u>stabe</u> w.r.t. to changes of the window size.

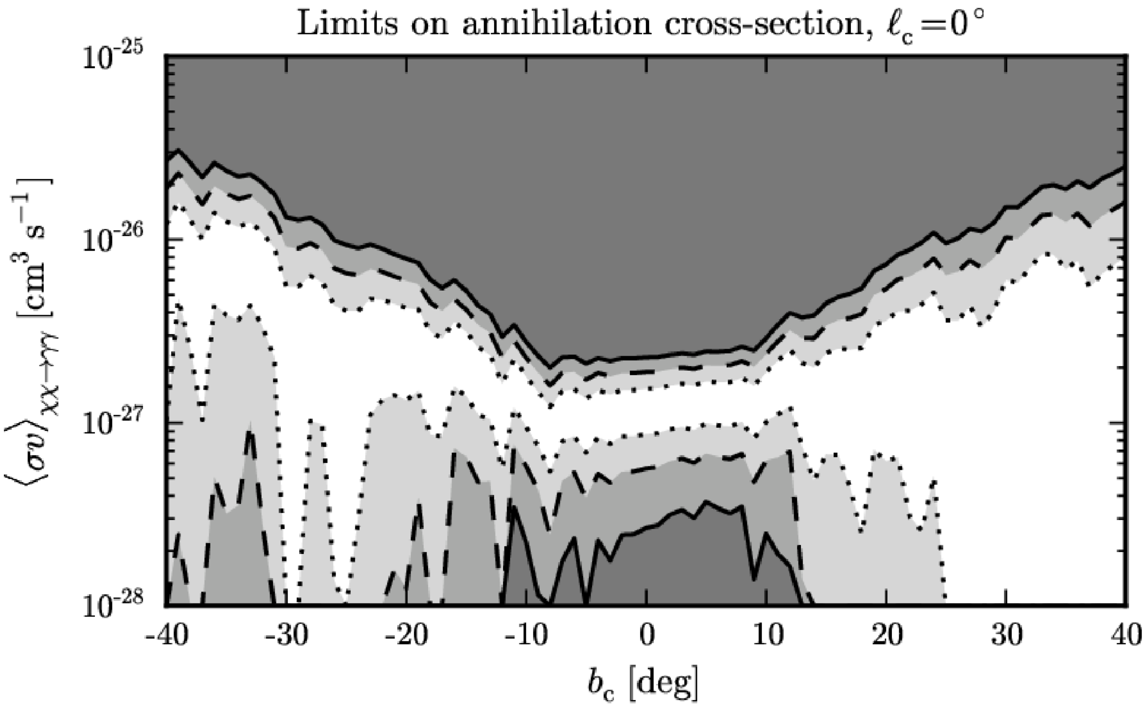
$$E_0 = E_\gamma/\sqrt{\epsilon}$$
$$E_1 = \min(300\ \mathrm{GeV}, E_\gamma\sqrt{\epsilon})$$

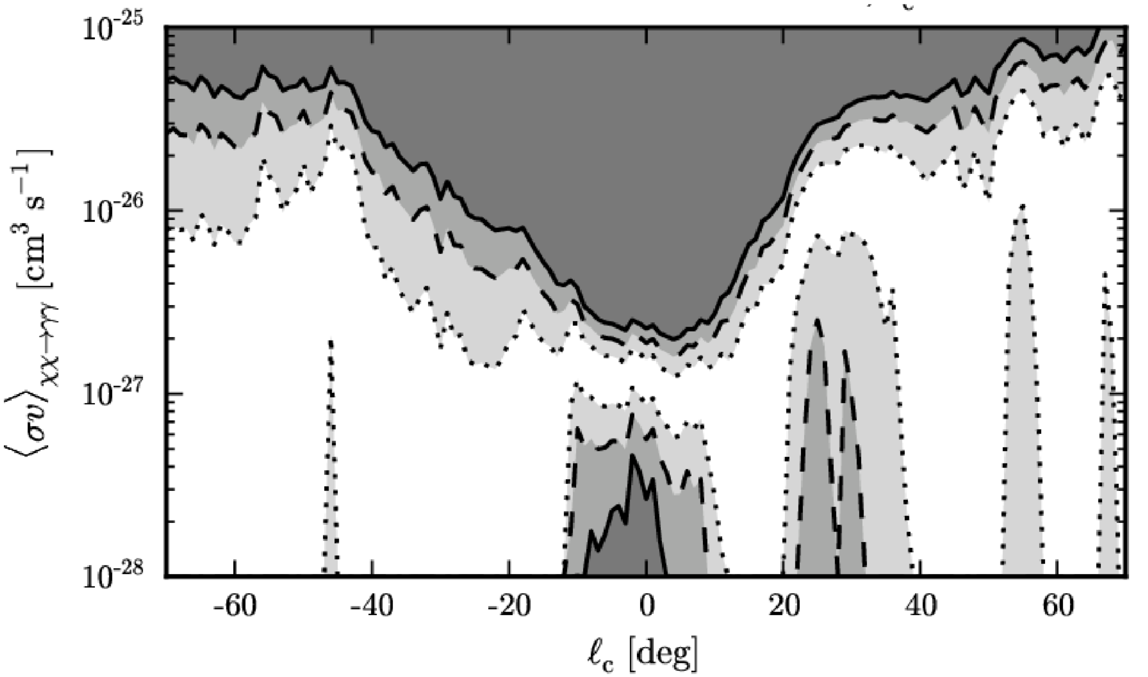


Spatial dependence

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



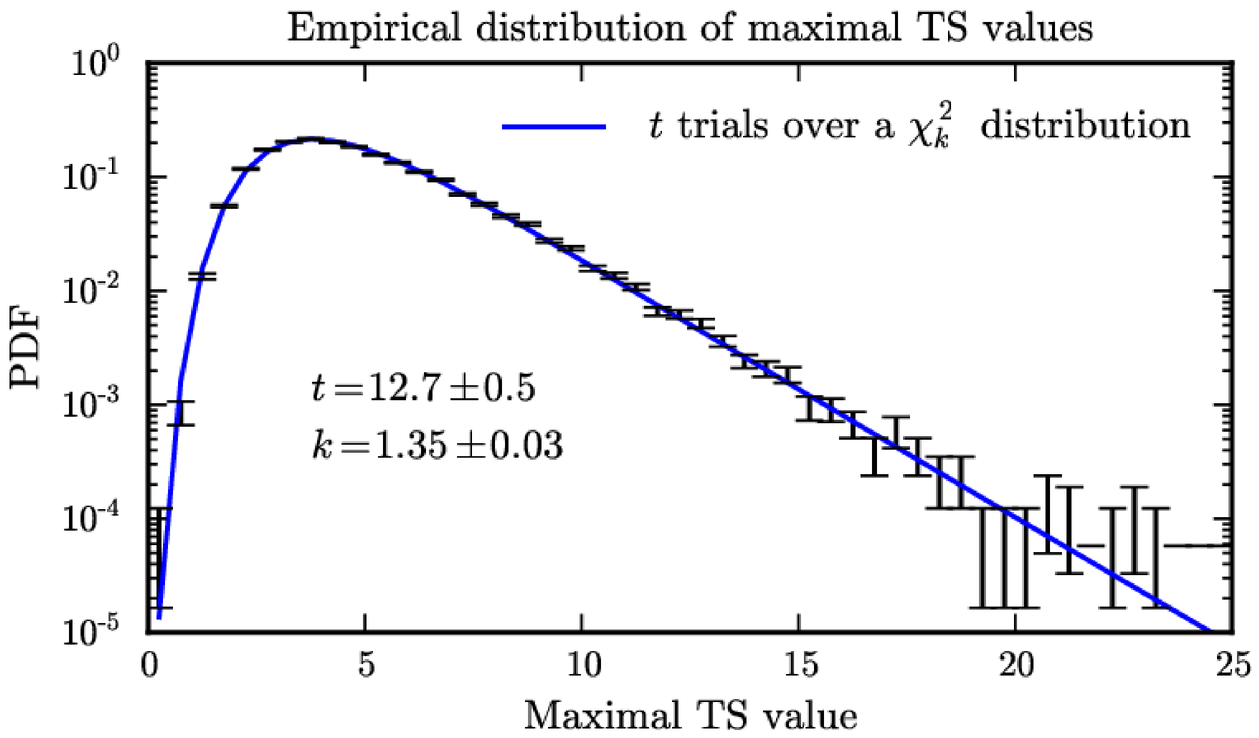




Non-zero annihilation cross-sections at 3sigma are only prefered when target region intersects with galactic center.

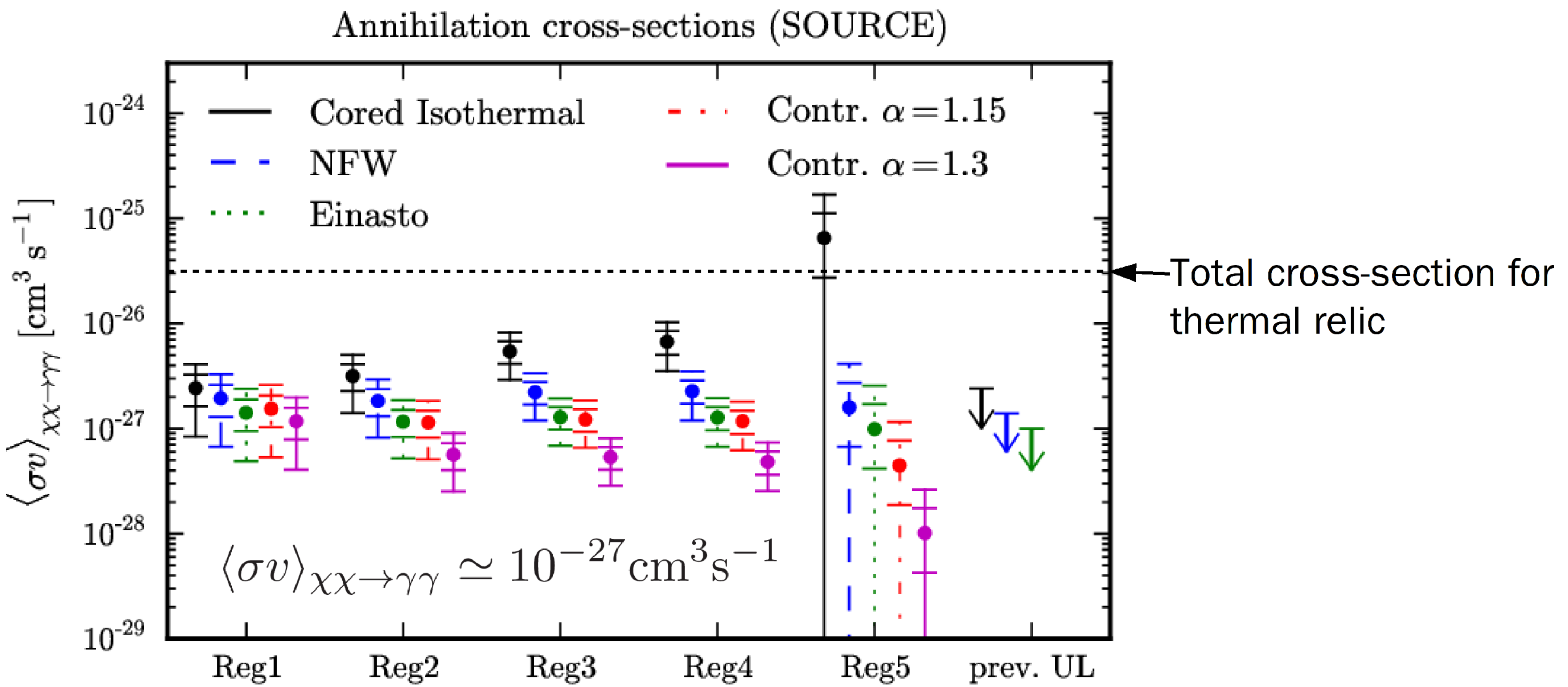
Look Elsewhere Effect & Subsampling Analysis

- 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 likely show up in large parts of the sky.

Annihilation cross sections



- 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. [Edmonds, thesis 2011]

- Branching ratio for thermal relic is surprisingly large, but not impossible:

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