Smoking gun or damp squib?

Gamma-ray line(s) in the Fermi LAT data

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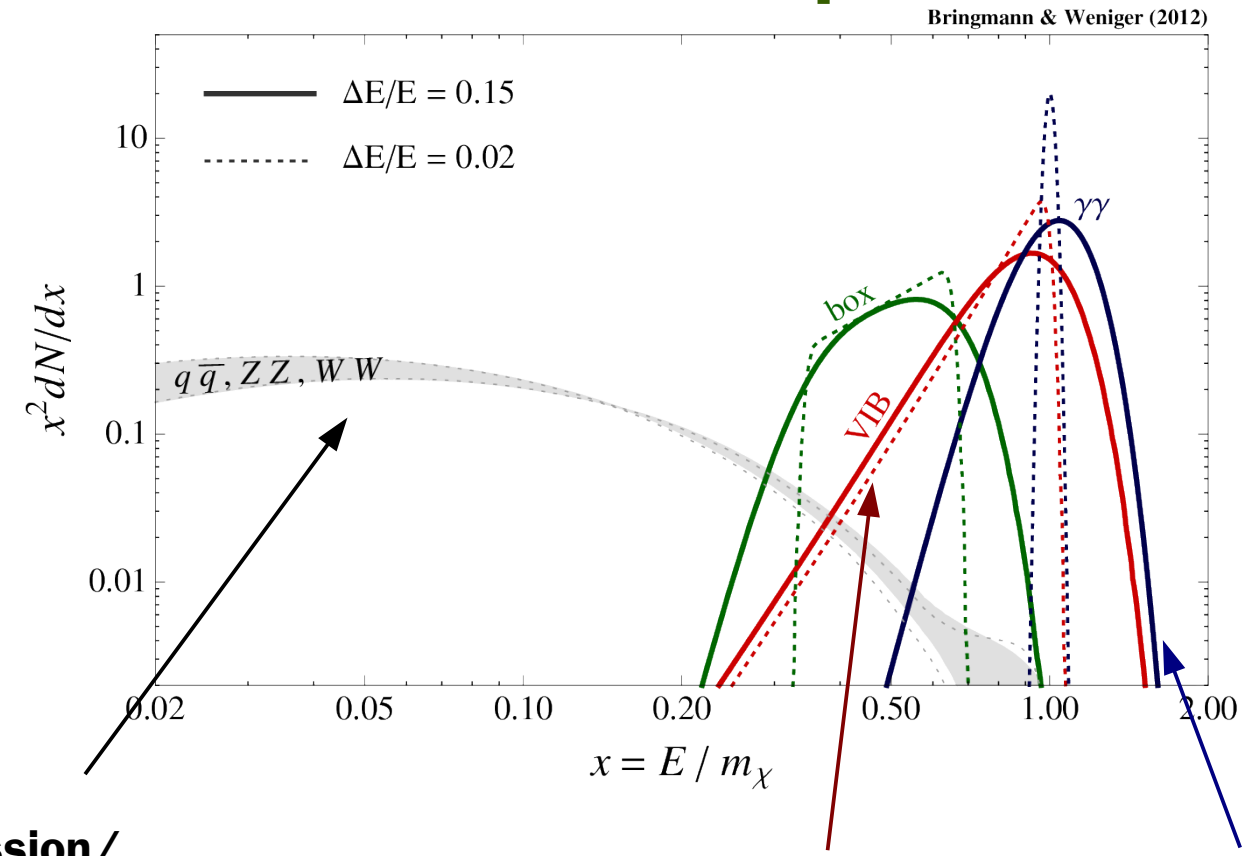
Light Dark Matter Workshop
University of Michigan

Summary of the situation
one year after the first paper:

Confusing.

Annihilation spectra



Continuum emission/ secondary photons

- often largest component
- featureless spectrum
- difficult to distinguish from astrophysical background

$$\chi\chi \to \bar{q}q \to \pi^0 \ldots$$

$$\pi^0 \to \gamma\gamma$$

Internal Bremsstrahlung (IB)

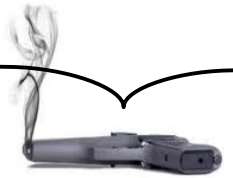
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

$$\chi\chi \to \bar{f} f \gamma$$

Gamma-ray lines

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

$$\chi\chi \to \gamma\gamma$$



(smoking guns)

Annihilation into monochromatic photons

Gamma-ray lines

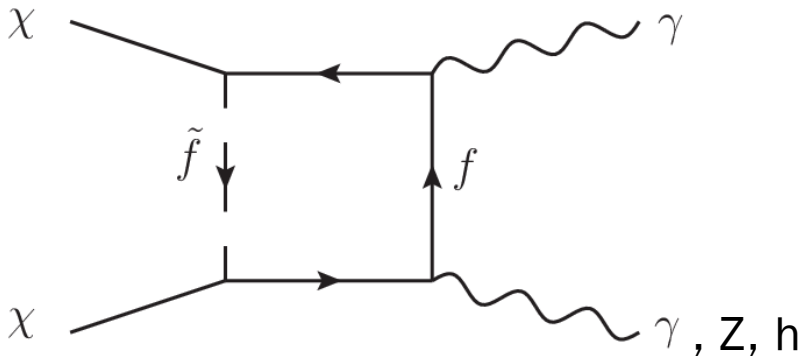
- are produced via two-body annihilation

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

- have a trivial energy spectrum

$$\frac{dN}{dE} \propto \delta(E - E_\gamma) \qquad E_\gamma = m_\chi \left(1 - \frac{m_P^2}{4m_\chi^2}\right)$$

Direct annihilation into photons is loop-suppressed:



Generic branching ratios are frustratingly small:

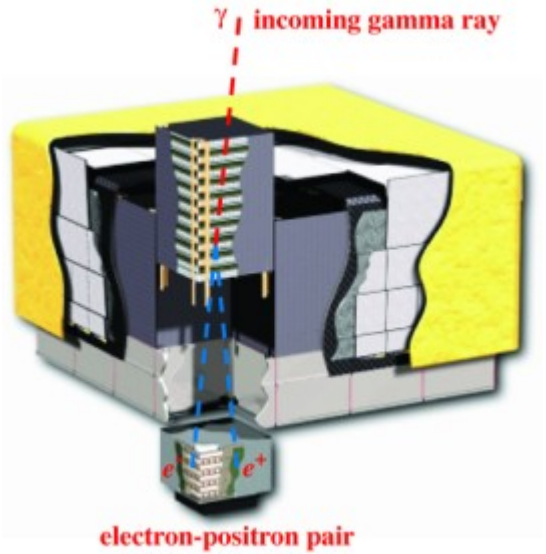
$$\mathrm{BR}(\chi\chi \to \gamma\gamma) \sim \alpha_{\mathrm{em}}^2 \sim 10^{-4}$$

This would be impossible to detect.

But, larger line fluxes are not impossible:

- 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)]
- ...

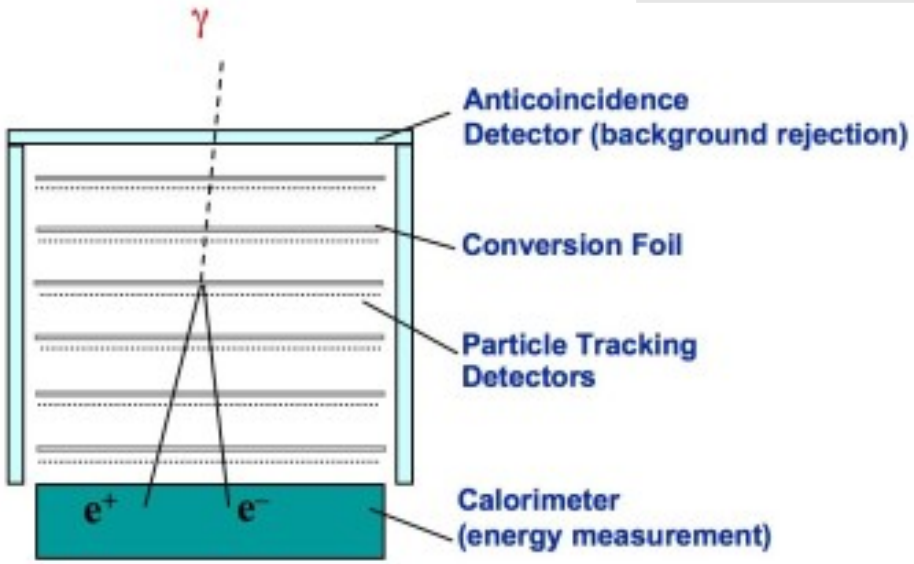
Fermi Large Area Telescope



The Fermi LAT is a pair conversion detector on board the Fermi Gamma-Ray Space Telescope.

Characteristics:

- Energy range: 20 MeV to above 300 GeV
- Field of view (FOV): 2.4 sr
- **UNIFORM SKY COVERAGE**
- Energy resolution: <10% (above 10 GeV)
- Angular resolution: < 0.15º (above 10 GeV)
- Launched: 2008
- Will continue at least until end of 2016



Main components:

Anti-coincidence shield (plastic scintillator) with photomultiplier tubes

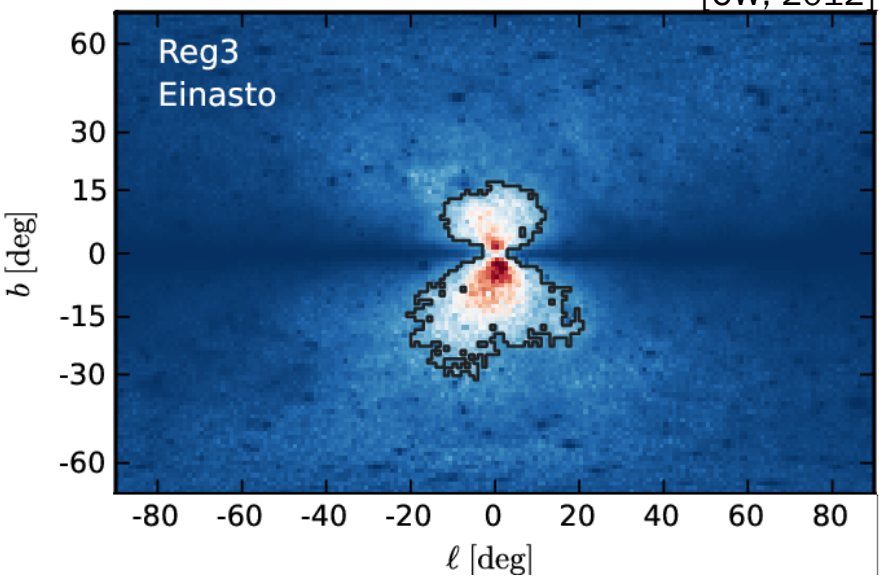
Tracker (silicon strip detectors) with conversion foils (tungsten)

Electromagnetic Calorimeter (CsI)

Searching for lines

I) Identify target region

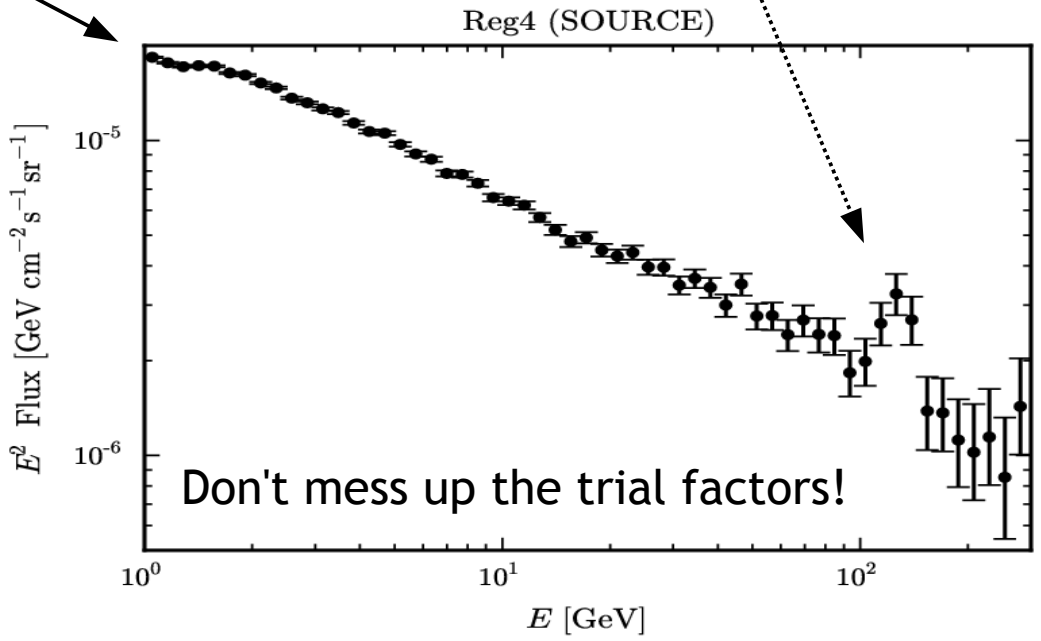
[CW, 2012]



Maximize S/N!

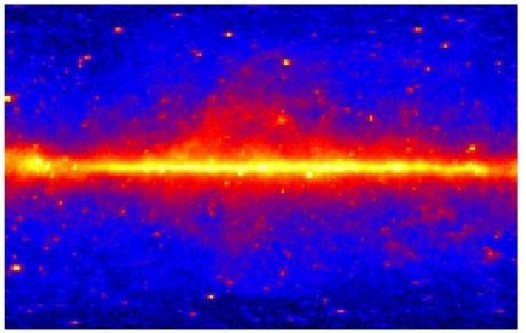
$$\int_{\Delta\Omega} d\Omega$$

II) Spectral analysis



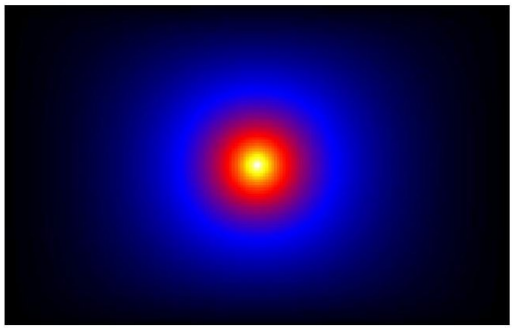
I) An adaptive method for target region selection

- **Background morphology estimated from data**
  - events between 1 and 20 GeV used for background estimation
  - events above 20 GeV used for line searches



- **Signal morphology** derived for a few reference dark matter profiles (centered at Galactic center)
  - Cored isothermal profile
  - Generalized NFW profile with free inner slope

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



  - Einasto profile

- **Pixel-by-pixel optimization of target region** (using (1deg)^2 pixels)
  Goal: Find set of pixels T that maximized

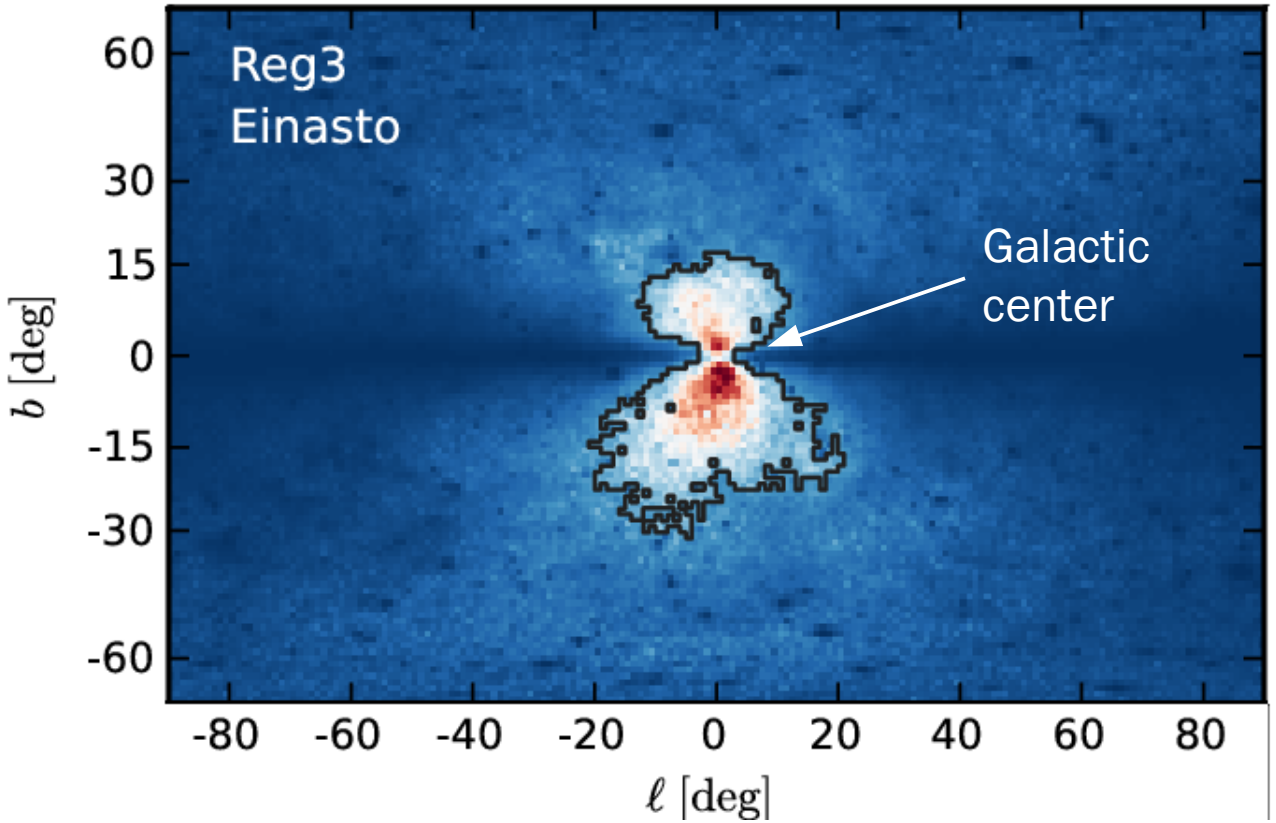
$$(\mathcal{S}/\mathcal{N})_T = \frac{\sum_{i\in T}\mu_i}{\sqrt{\sum_{i\in T} c_i^{\rm 1to20GeV}}}$$

Expected signal

Measured events

Algorithm: see [Bringmann et al. (2012)]

An adaptive method for target region selection



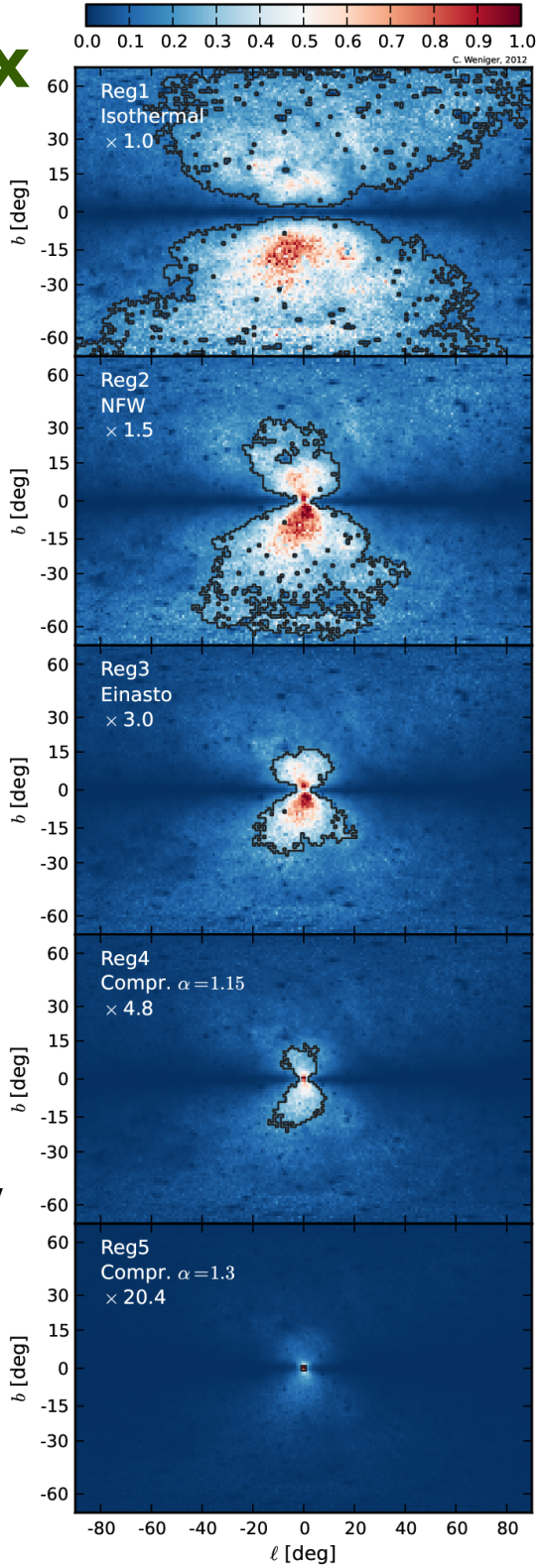
Example: Einasto profile

- **Black line**: Optimized region
- **Color**: Signal-to-background ratio

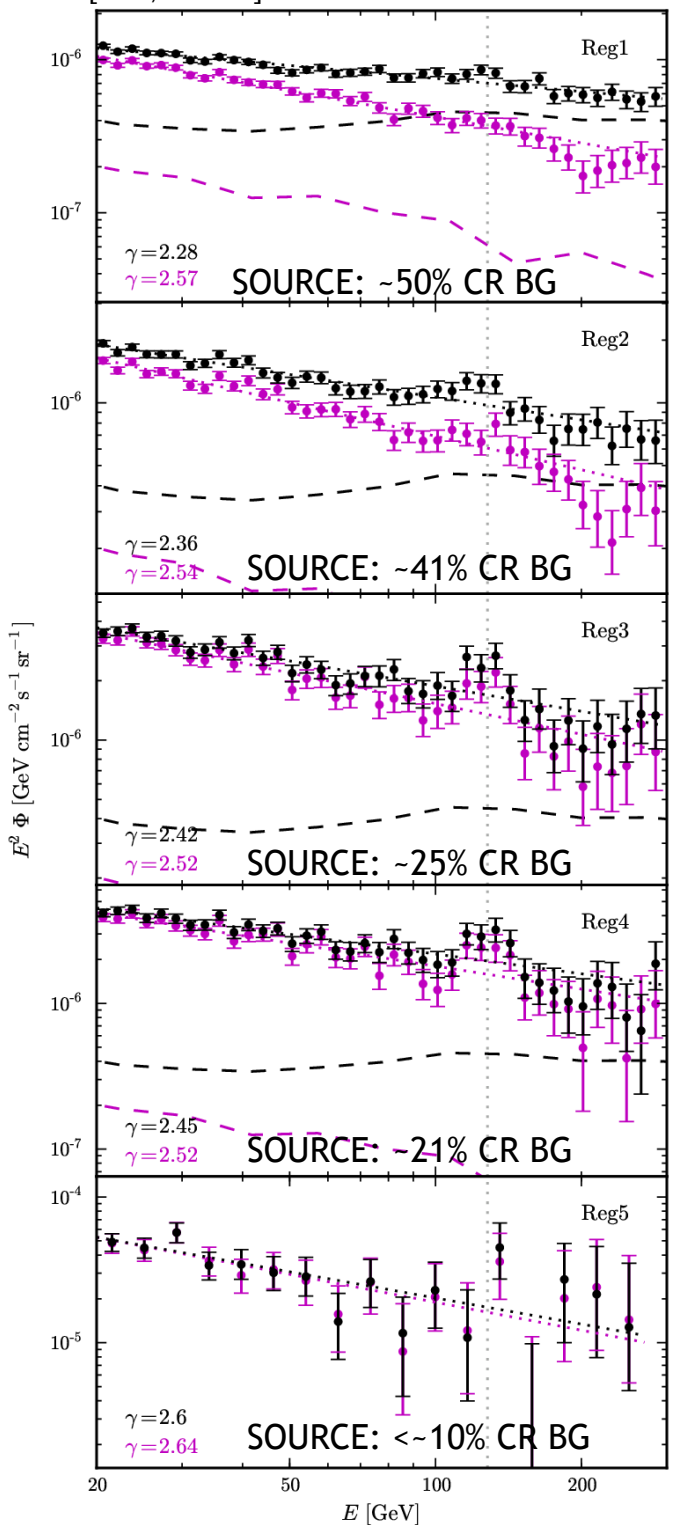
Notable properties:

- The region is slightly north/south asymmetric.
- Most of galactic disc is excluded.
- The galactic center is included.

Gamma-ray flux measured by the LAT inside the ROIs



[CW, 2012]



Two event classes:

SOURCE

ULTRACLEAN (= CLEAN >50 GeV)

CLEAN vs SOURCE at 130 GeV:

Aeff_SOURCE/Aeff_CLEAN~1.12

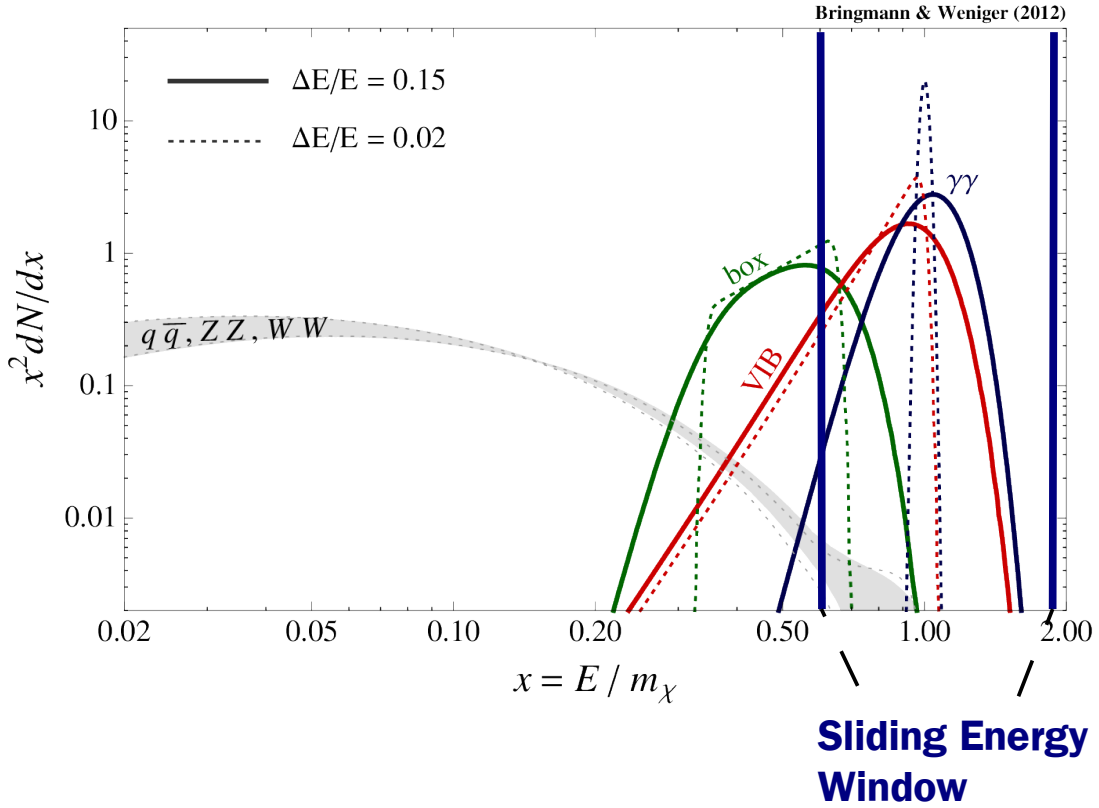
(S/N)_SOURCE/(S/N)_CLEAN~0.9-1.1

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

II) Spectral Analysis

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



- Continuum photons from DM signal can be neglected
- Astrophysical backgrounds can be approximated by power-laws

- Key question: what window size?
  → depends on number of events and expected background curvature

Likelihood analysis

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

$$\mathcal{L} = \prod_i P(c_i|\mu_i) \qquad \text{with} \qquad \begin{array}{l} c_i : \text{ observed events} \\ \mu_i : \text{ expected events} \end{array} \qquad P(c|\mu) = \frac{\mu^c e^{-\mu}}{c!}$$

- **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

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

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

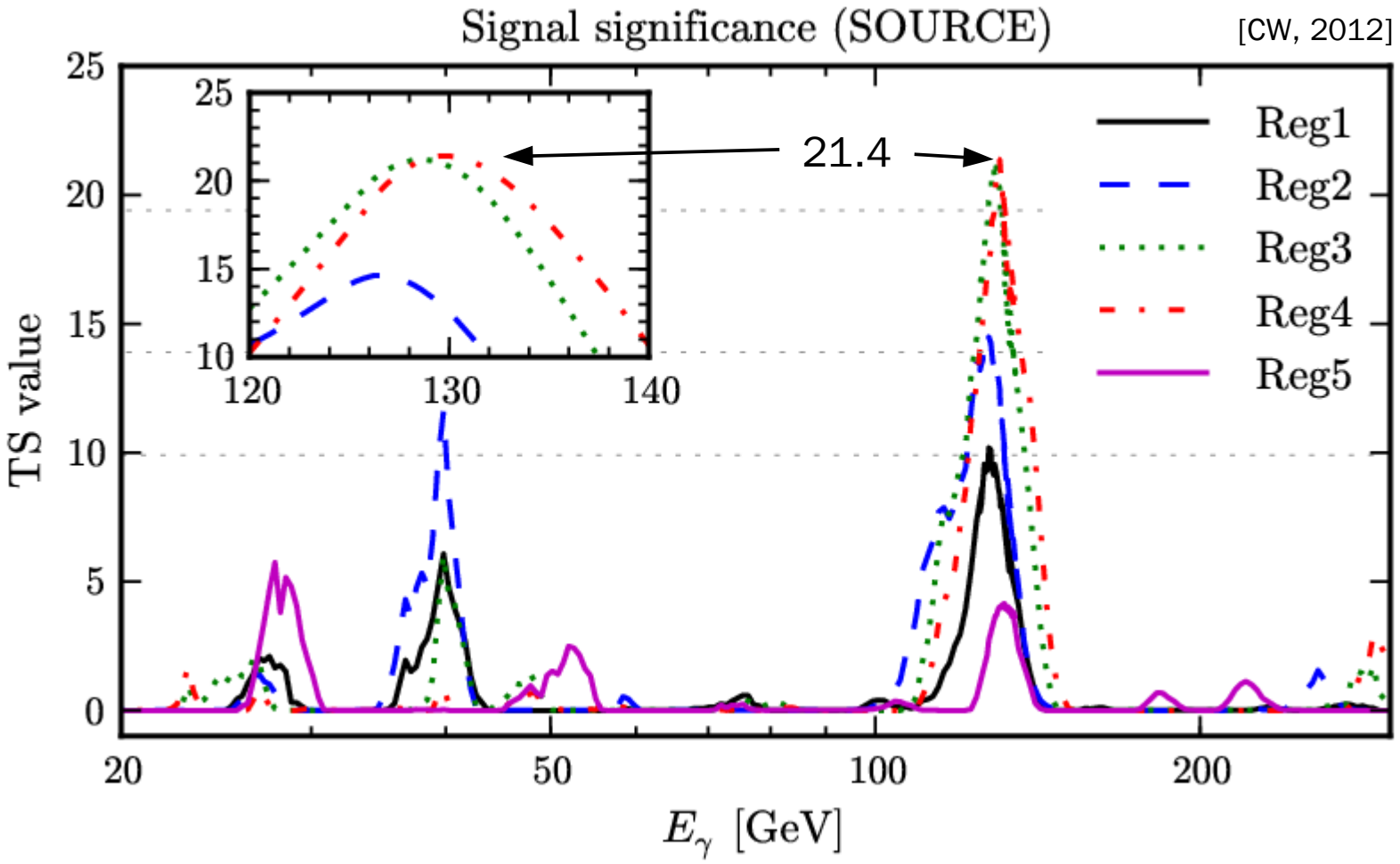
- **Signal significance** for fixed m_χ from the TS value (maximum likelihood ratio)

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

$\mathcal{L}_{\text{alt}}$: 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 before trial correction: (in units of Gaussian sigma) $\sqrt{TS}\ [\sigma]$

LARGE TS values at 130 GeV!

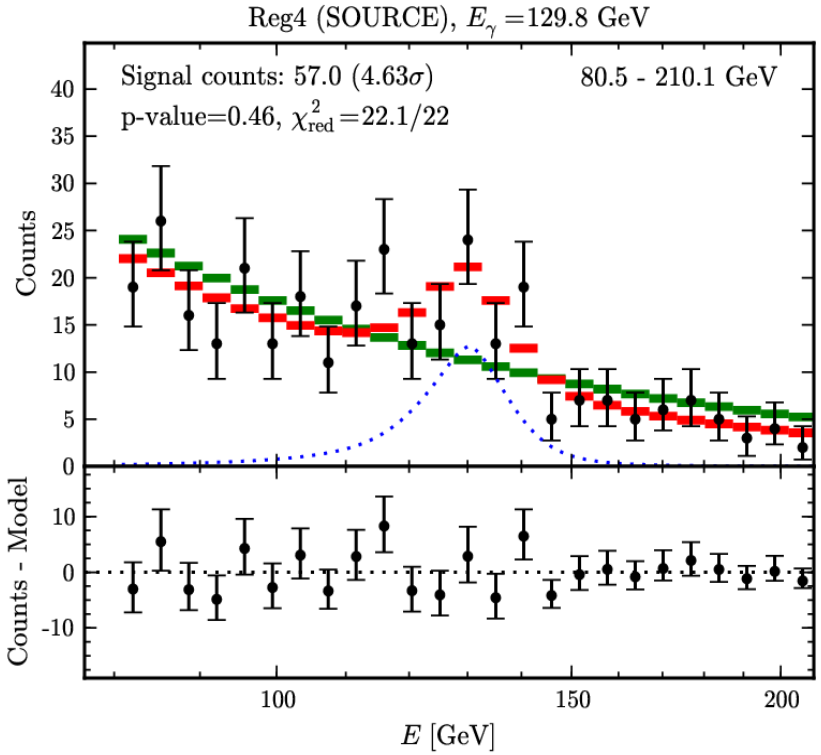


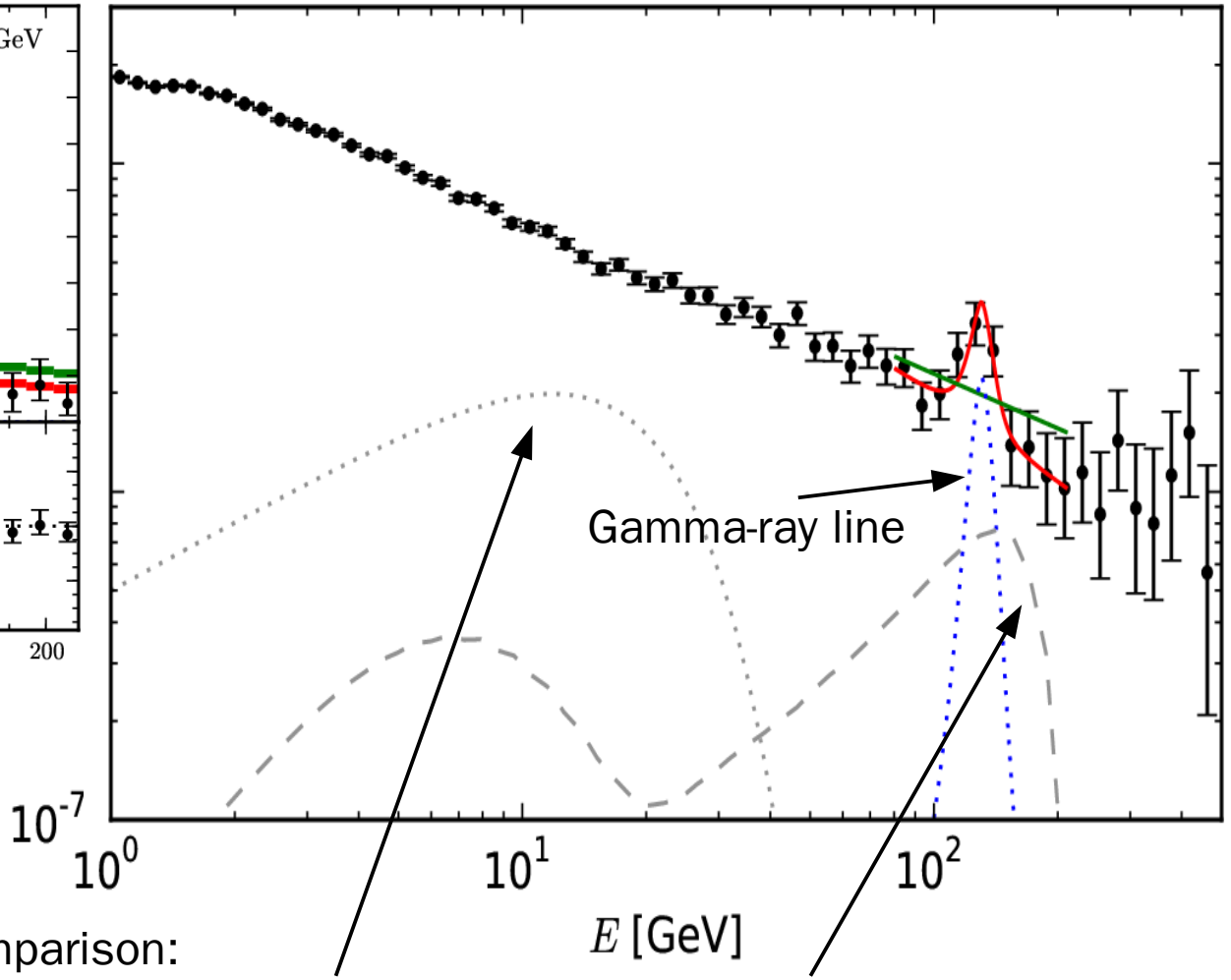
Local significance: 4.6 sigma
Global significance: ~3.2 sigma

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

$$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} \simeq 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}$$

The signature is very narrow





For comparison:

Superexponential cutoff

Inverse Compton emission from 230 GeV electrons at GC

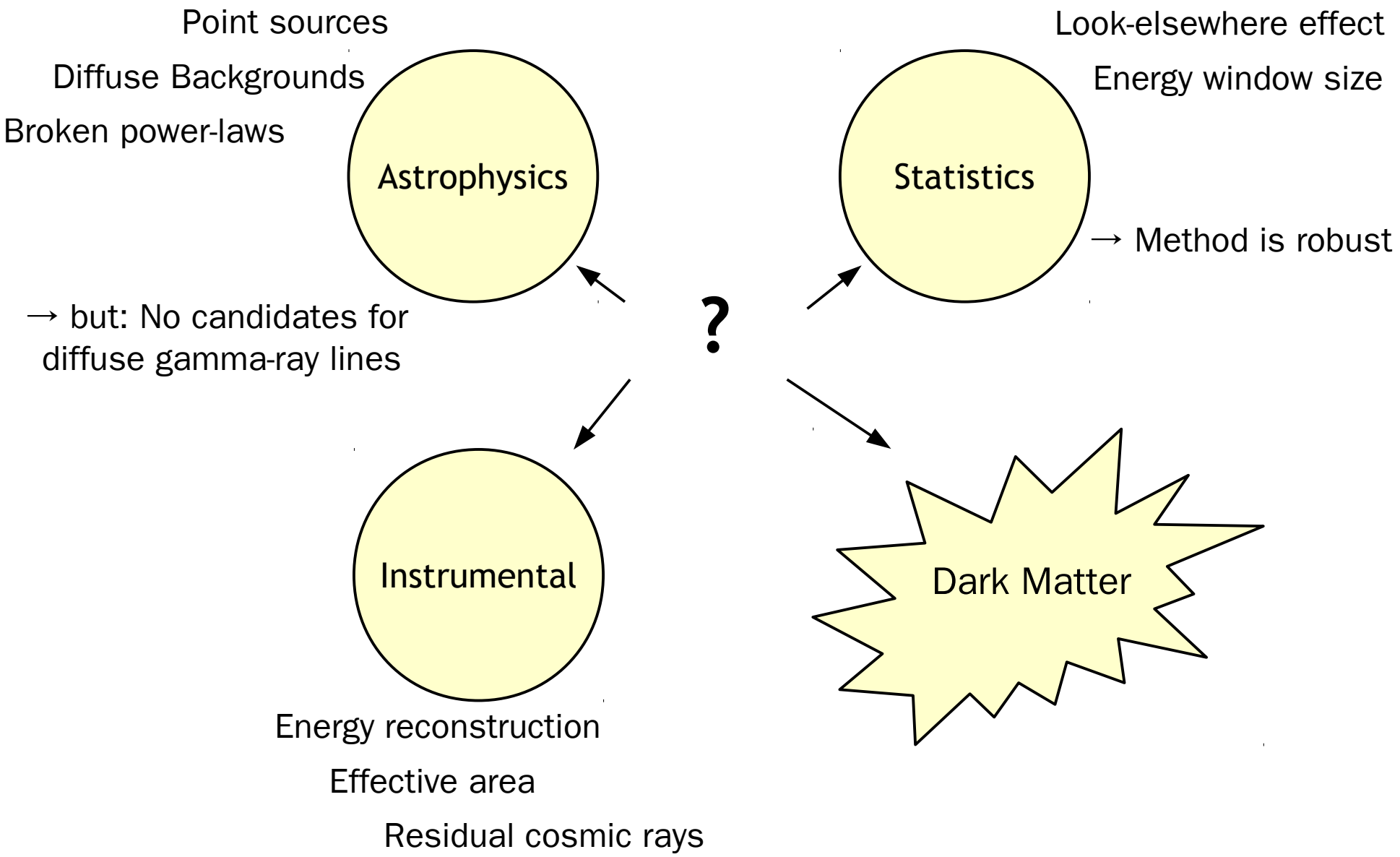
Signal width (RMS): <17% (95%CL)

Follow-up studies:
Dark matter models, astrophysical explanations, instrumental effects, searches for corroborating evidence from other targets

A large number of groups studied almost all aspects of the signature:

Profumo, Linden, JCAP 1207 (2012) 011
Ibarra, Gehler, Pato, JCAP 1207 (2012) 043
Tempel, Hektor, Raidal, arXiv:1205.1045
Dudas et al., arXiv:1205.1520
Cline, PRD86 (2012) 015016
Choi, Seto, PRD86 (2012) 043515
Kyae, Park, arXiv:1205.4151
Lee, Park, Park, arXiv:1205.4675
Boyarsky, Malyshev, Ruchayskiy, arXiv:1205.4700
Rajaraman, Tait, Whiteson, arXiv:1205.4723
Acharya et al., arXiv:1205.5789
Buckley, Hooper, PRD86 (2012) 043524
Geringer-Samet, Koushiappas, PRD86 (2012) 021302
Su, Finkbeiner, arXiv:1206.1616
Li, Yuan, PLB715 (2012) 35
Chu et al., arXiv:1206.2279
Das, Ellwanger, Mitropoulos, JCAP 1208 (2012) 003
Kang et al., arXiv:1206.2863
Weiner, Yavin, arXiv:1206.2910
...
and ~100 more
...

So what?

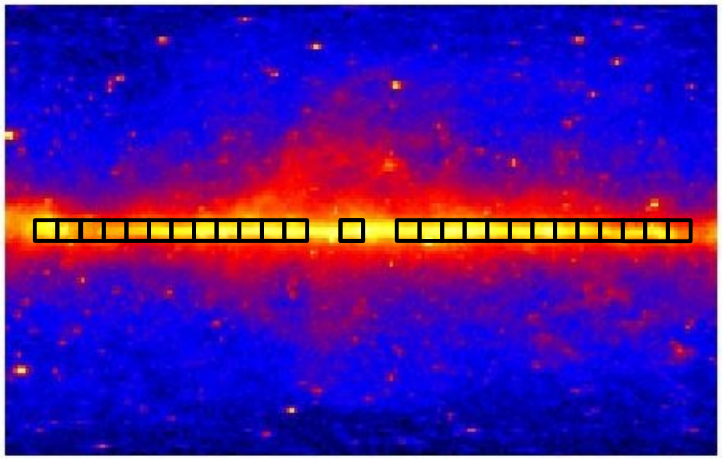


→ Nothing obvious is wrong (but Earth limb?)

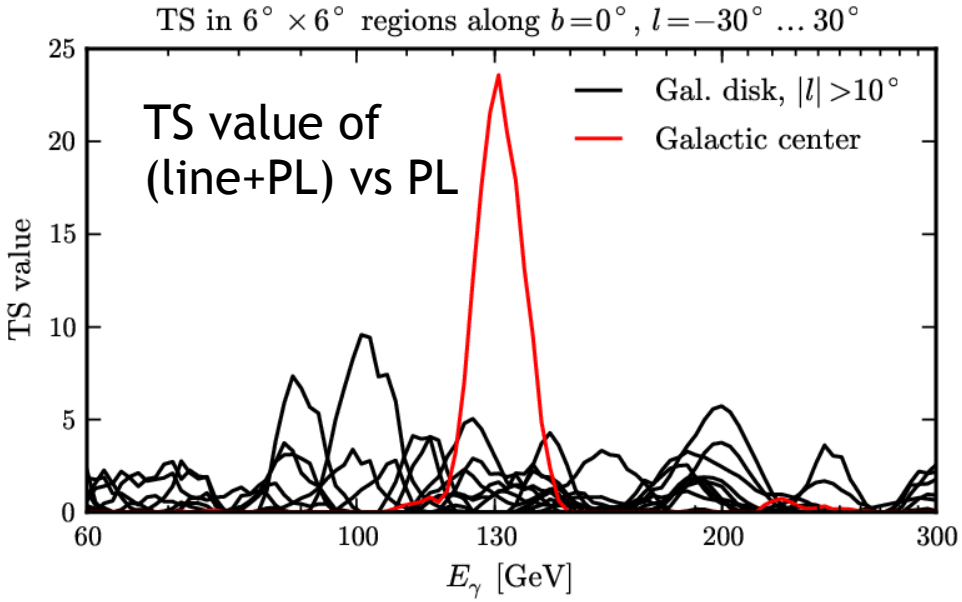
But: final word must come from LAT Instrument team

Spatial properties of the 130 GeV feature

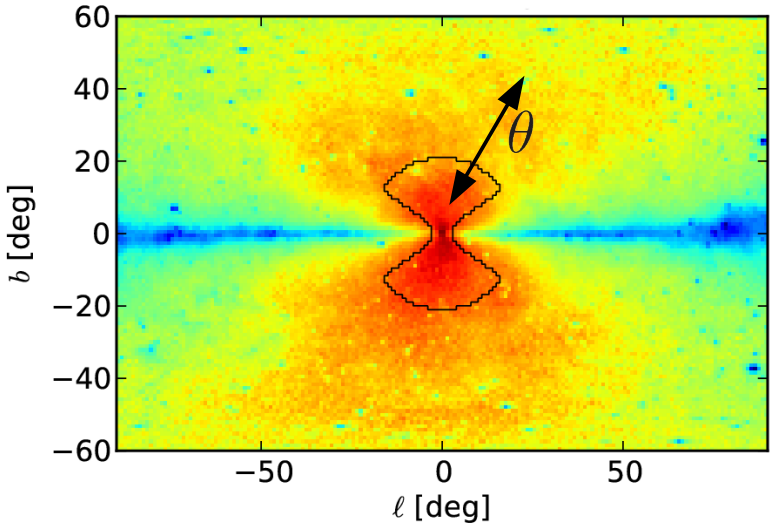
At Galactic center only:



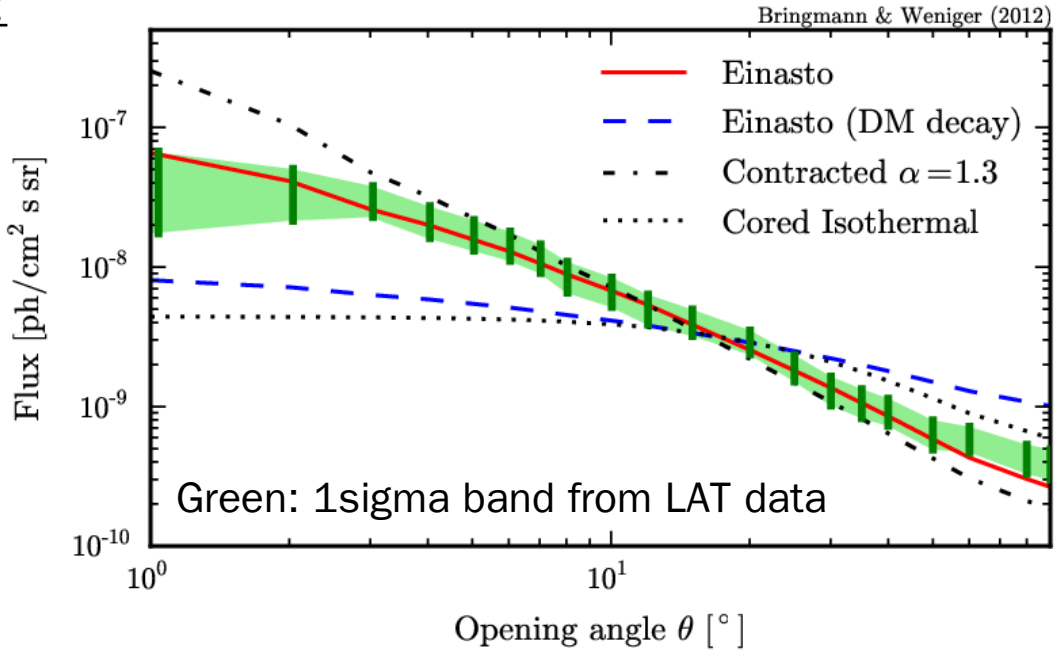
The signature does not reappear in other parts of the Galactic disk



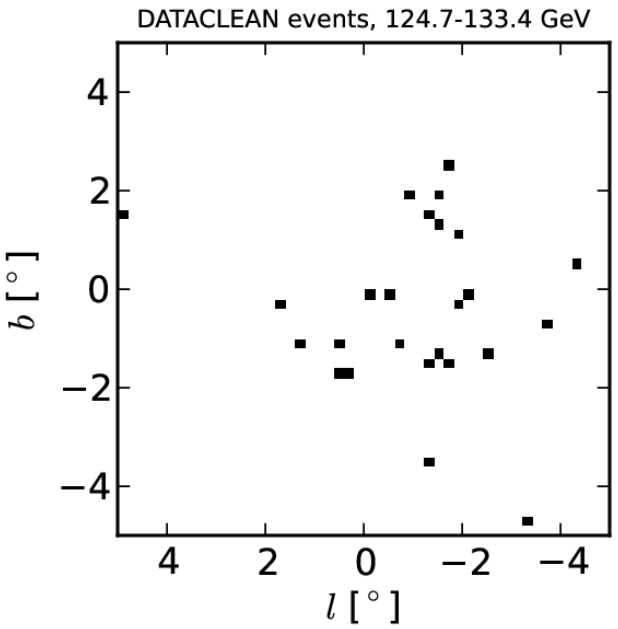
Compatible with Einasto DM profile:



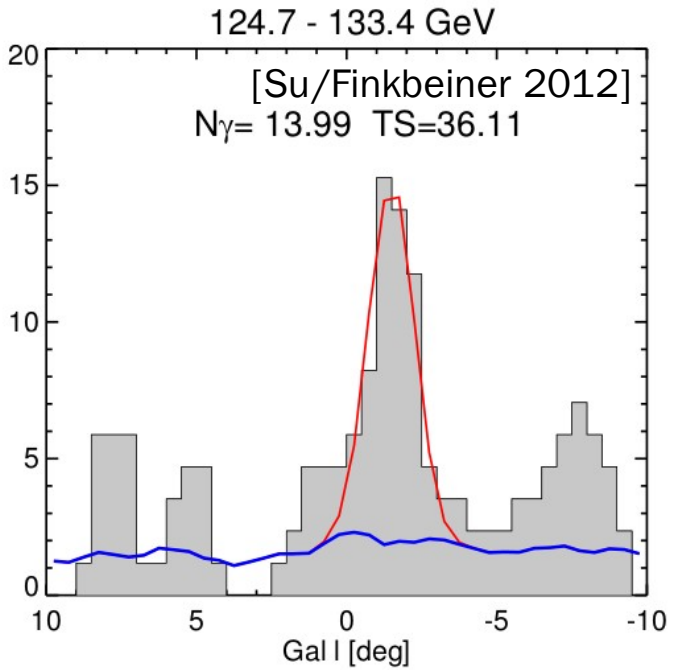
A scan over different target regions shows that signal morphology is compatible with expectations for DM signal



Displaced from the Galactic Center?

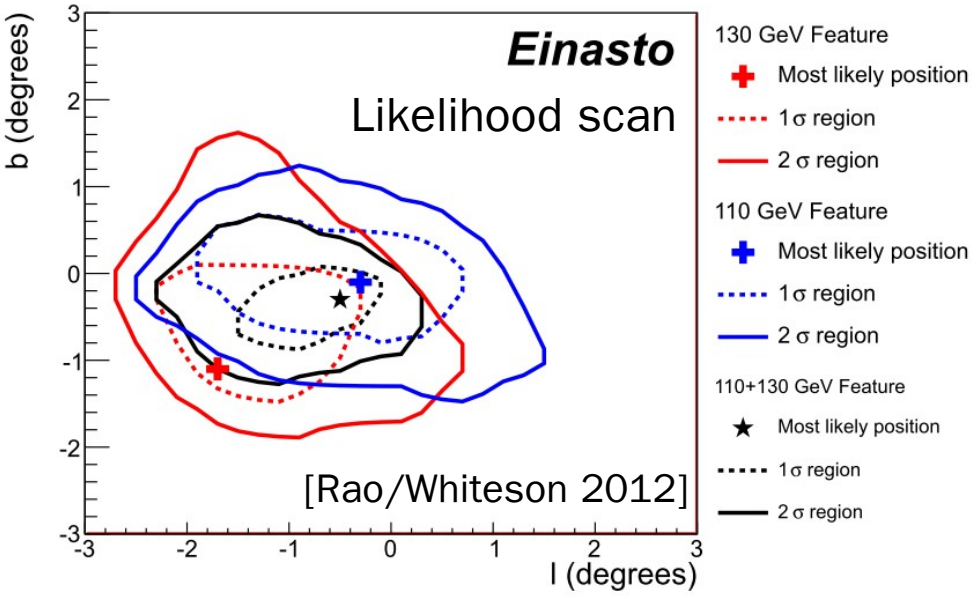


Projection along Gal. latitudes



Photons responsible for high TS appear to be significantly displaced by O(100pc) from the GC. Significance of displacement depends on method (about 1-3 sigma).

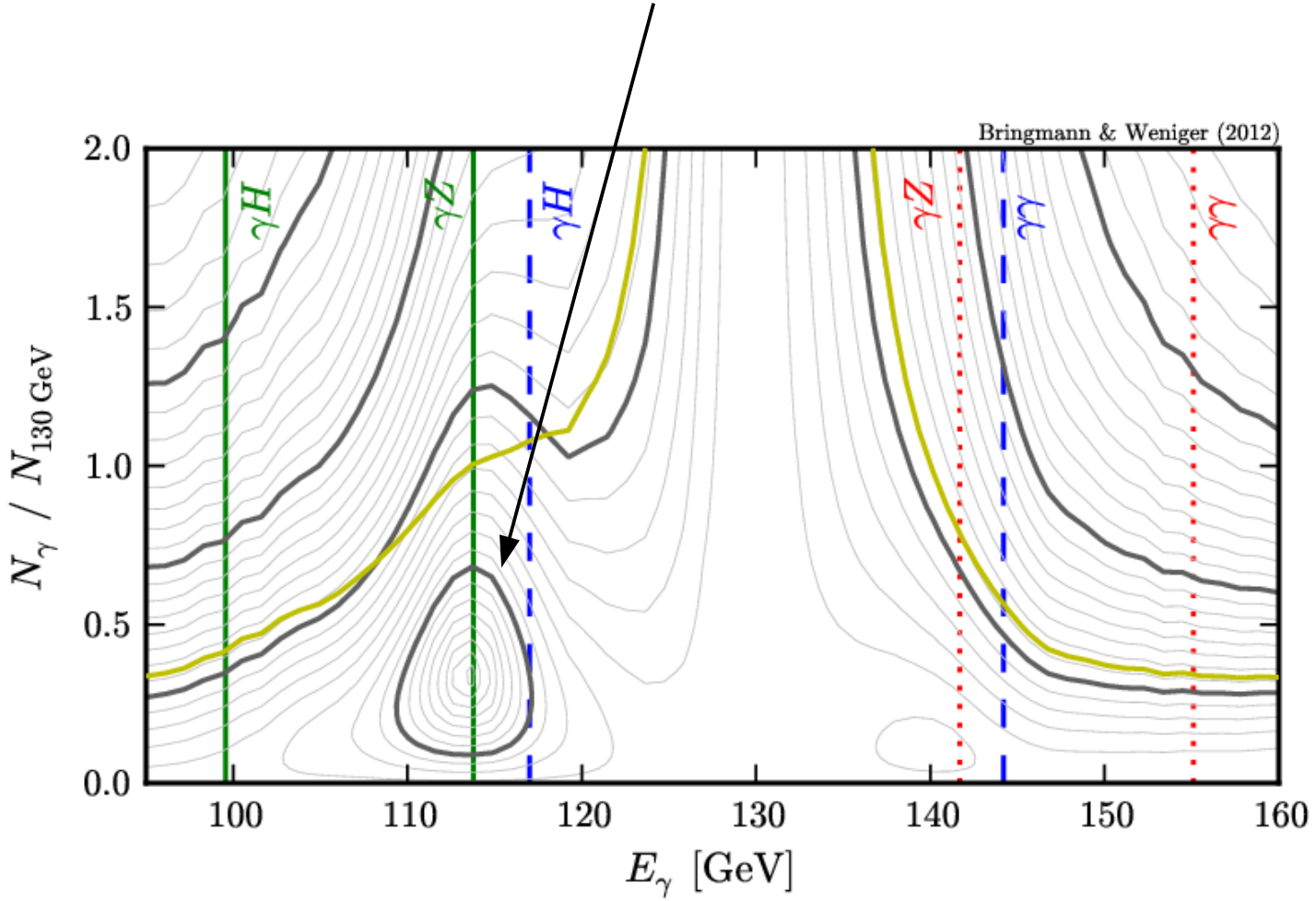
A DM halo with a slightly displaced point of highest density might actually be consistent with spiral galaxies with a significant bar [see Kuhlen+ 2012] But: is density contrast large enough to explain a displaced signal?



A second line?

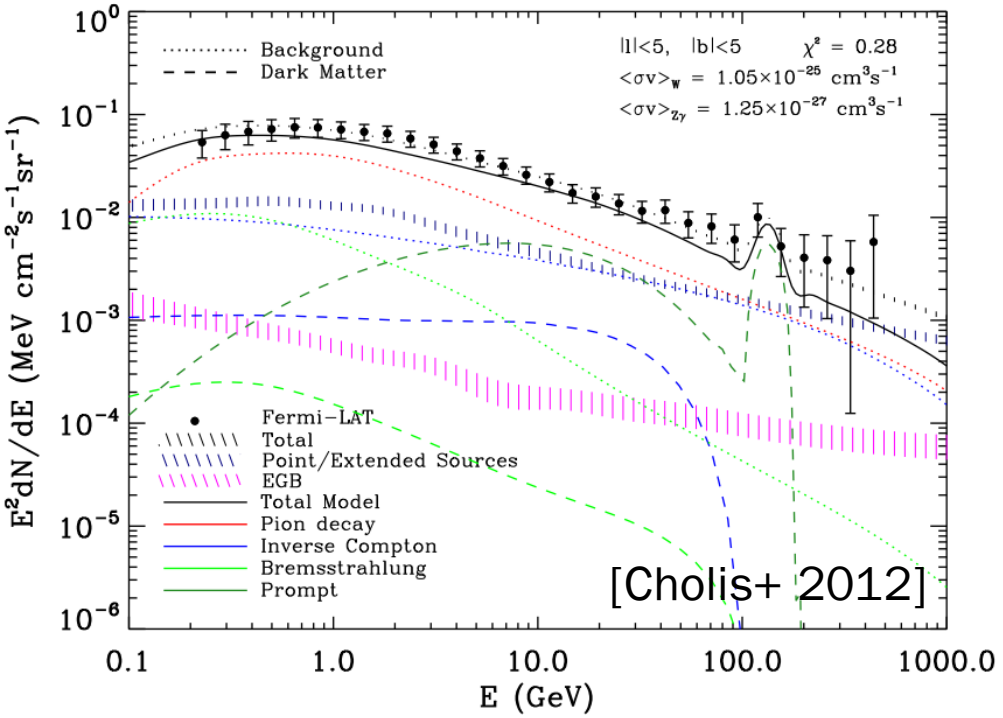
Standard model final states that produce gamma-ray lines: $\chi\chi \to \gamma\gamma,\ \gamma Z^0,\ \gamma H^0$

If the 130 GeV feature is due to annihilation into photon pairs, annihilation into gamma Z would produce a line at 114 GeV. There is weak indication for such a line in the data.



[see Cohen et al., Rajaraman et al., Su&Finkbeiner 2012]

No indication for continuum emission, yet



[see also Buchmüller+ and Cohen+ 2012]

Searches for continuum part of the signal

- No indication for continuum emission from ~100 GeV WIMPs was found
- Upper limits on continuum emission (depends on annihilation channel):

$$\frac{\langle \sigma v \rangle_{\gamma\gamma}}{\langle \sigma v \rangle_{\rm cont}} \gtrsim \mathcal{O}(0.1)$$

→ Need LARGE branching fraction into gamma-gamma final states

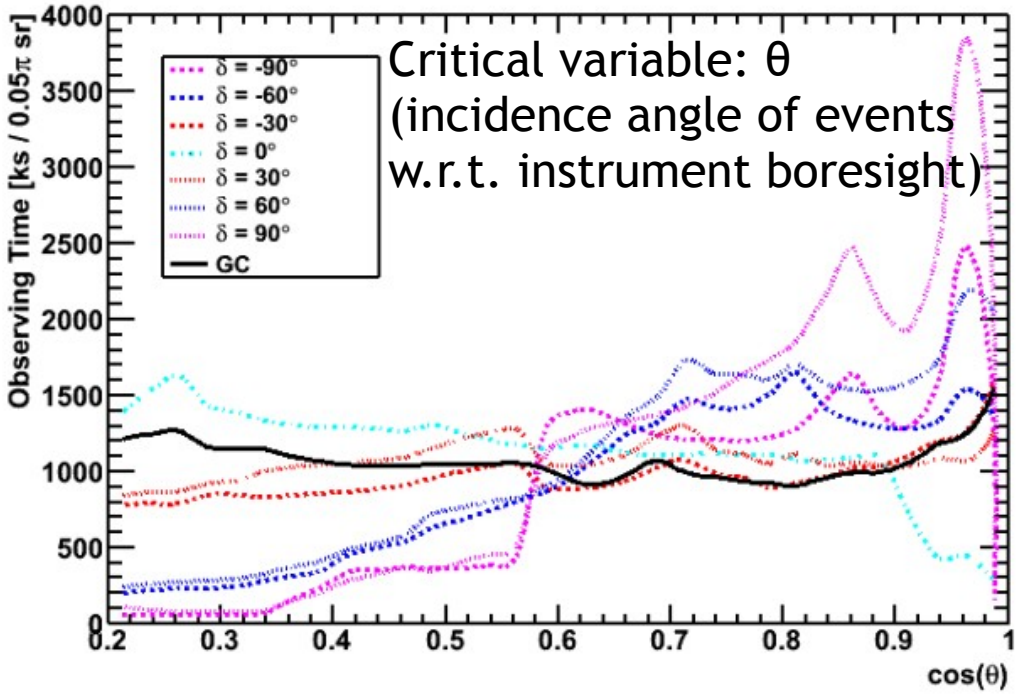
An instrumental effect?

- Contamination with residual cosmic ray background in photon sample
  → Very unlikely. Should affect poles more than the GC.

- Increased effective area at 130 GeV
- Decreased effective area before/after 130 GeV
- Energy redistribution
- ???

Can be tested with photon samples away from the GC

Galactic disc "Earth Limb"



[E. Charles' talk, Fermi Symposium 2012]

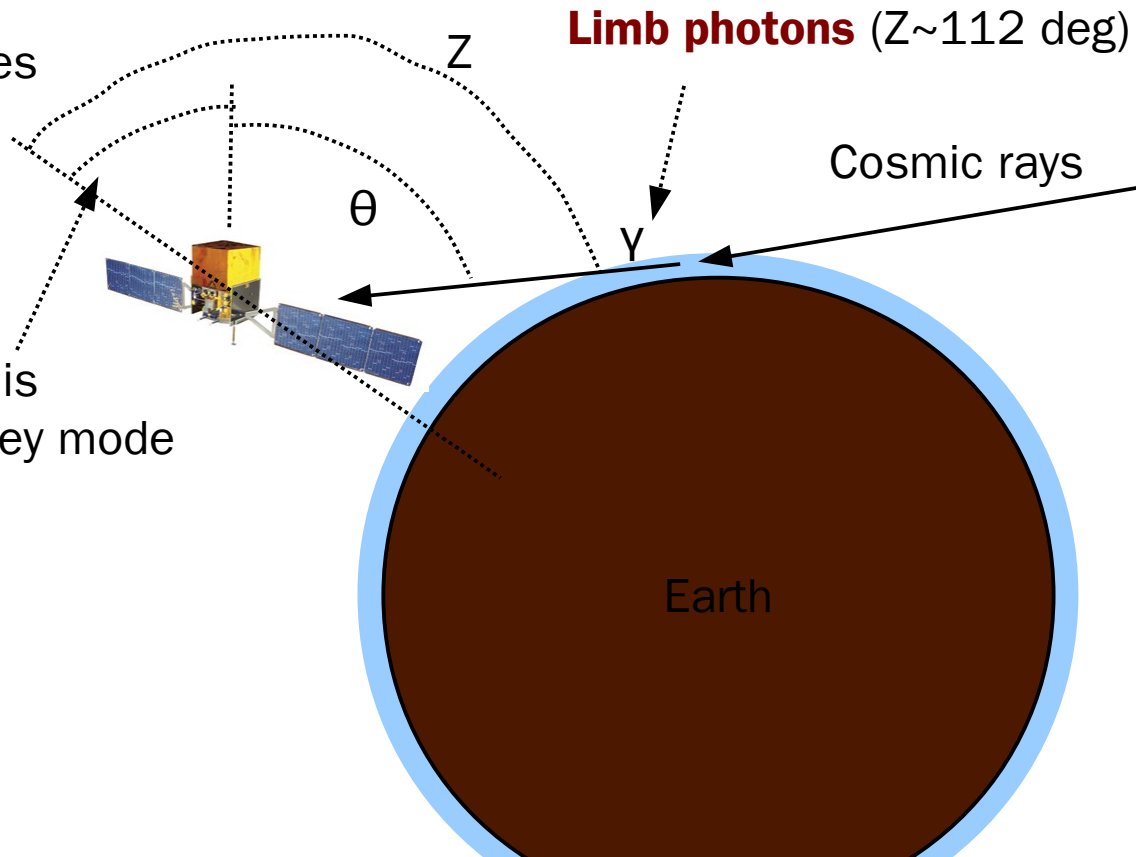
The Earth limb

Parameters:

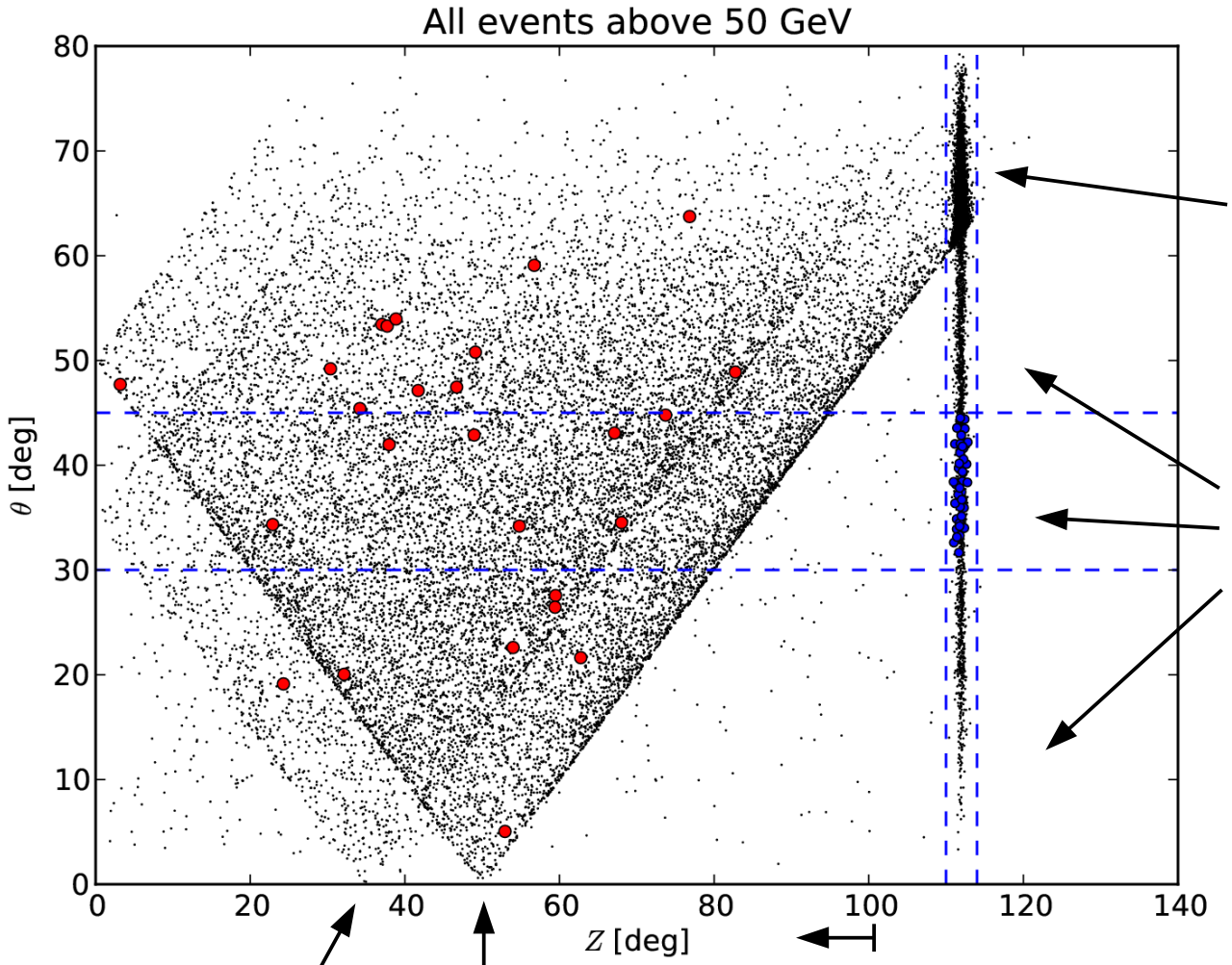
- Θ (incience angle): Polar coordinate of event in instrumental frame (w.r.t. LAT boresight)
- Z (zenith angle): angle between event and LAT zenith axis
- Rocking angle: angle between LAT boresight and zenith of LAT

Earth Limb:

- Photons from cosmic-ray - atmosphere interaction have Z~112 deg, which implies θ >~ 112 deg – 50 deg ~ 62 deg in standard survey mode
- Θ<60 deg possible during ToO observations with larger rocking angle



The incidence angle vs zenith angle plane



Earth limb photons observed in normal survey mode

Earth limb photons observed when rocking angle >50deg (pointed observation)

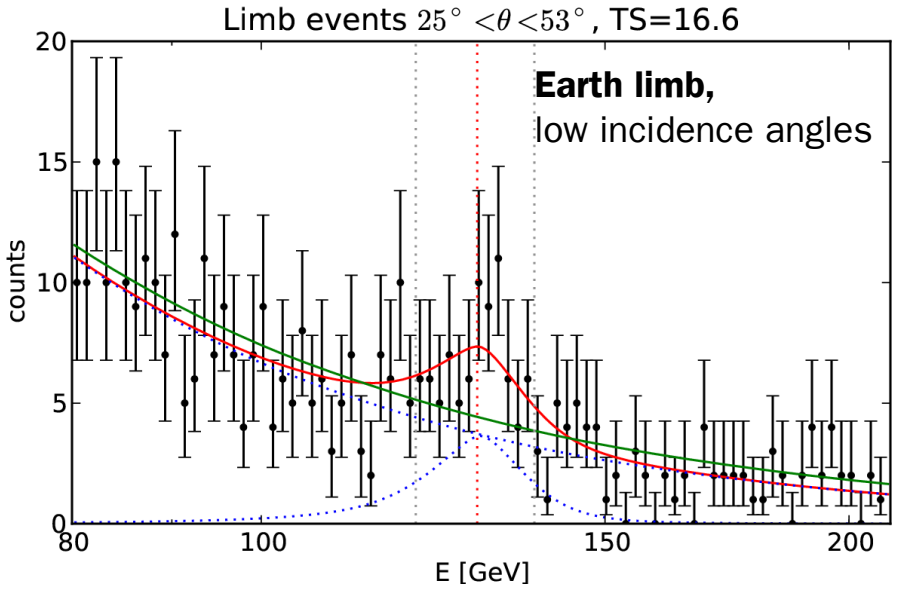
Events used in standard analyses

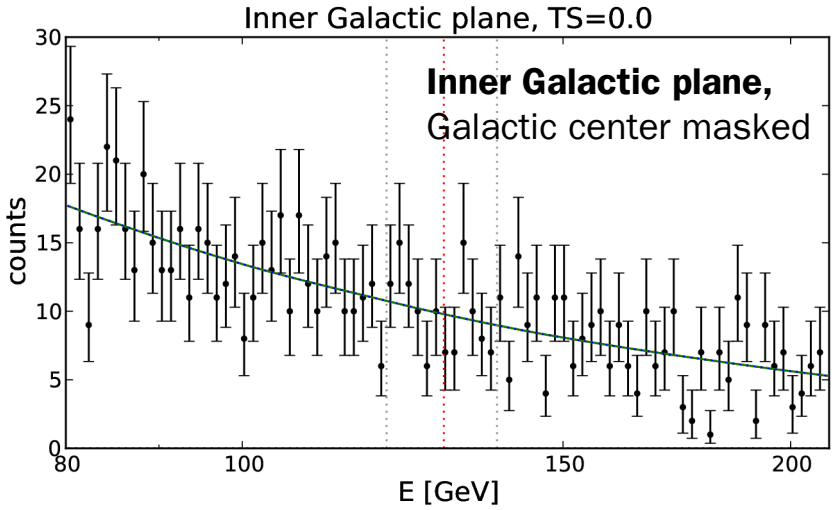
Rocking angle before Sep 2009

Rocking angle since Sep 2009

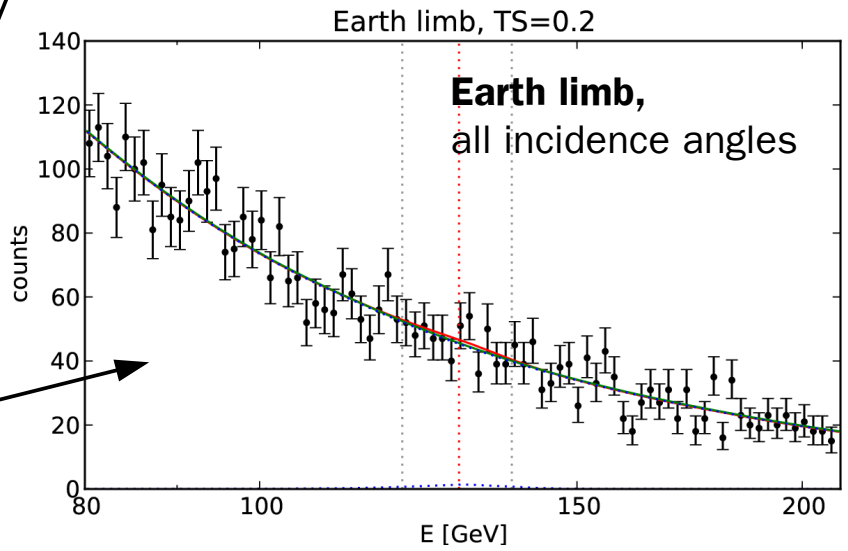
- **Red** events: Galactic center line
- **Blue** events: a suspicous line in the Earth limb...

The Earth limb at low incidence angles
A red flag?





Green flag?

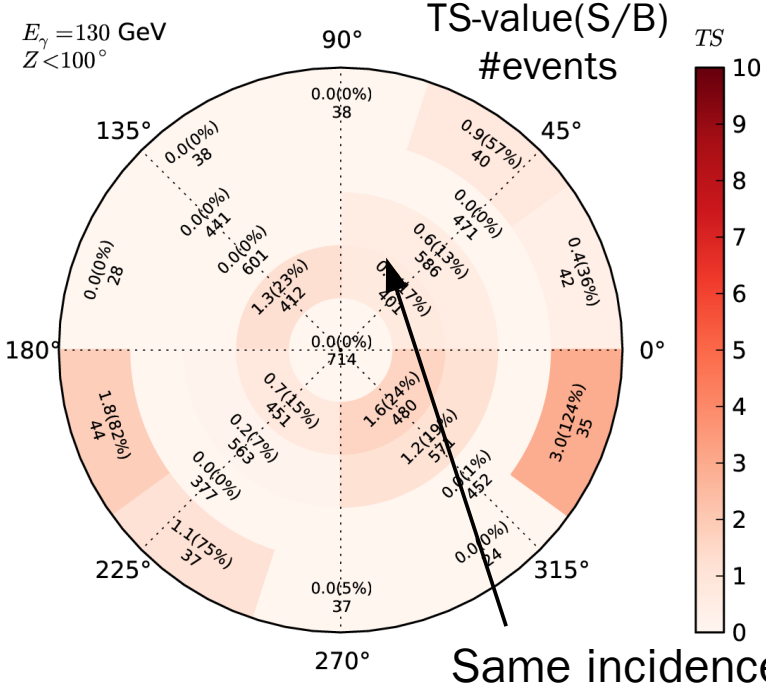


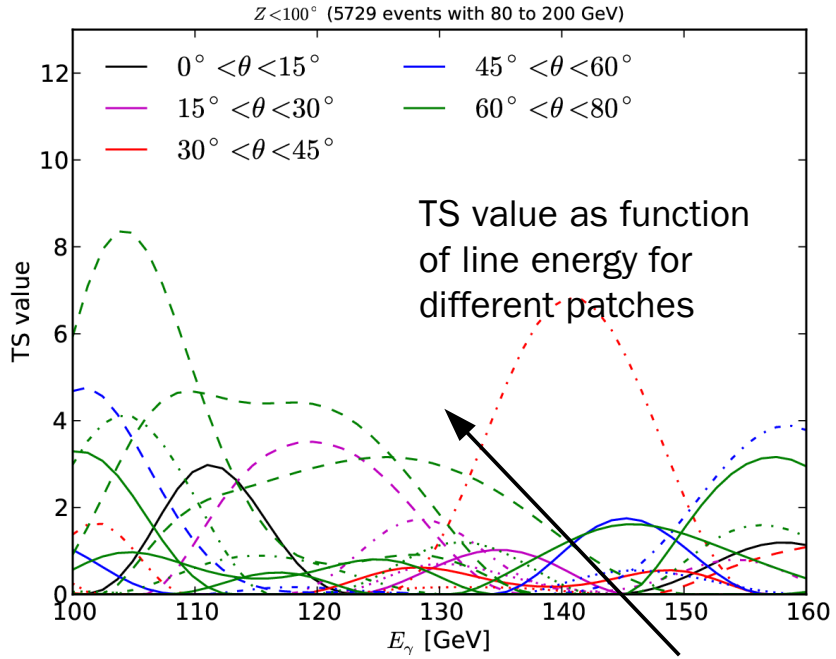
[Finkbeiner et al., 2012]

The LAT from the top

Standard analysis
cuts: Z<100 deg

Significance for 130 GeV line in **instrumental** coordinates (different incidence angle zones)

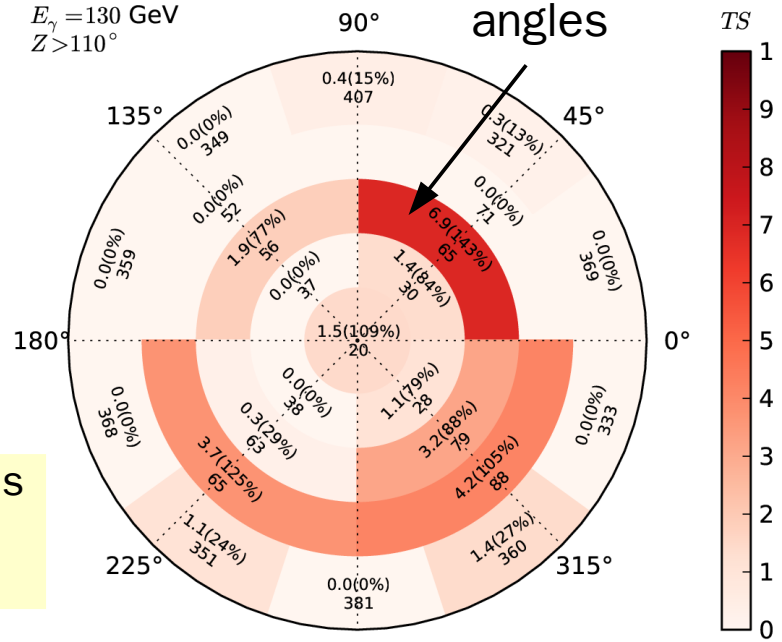


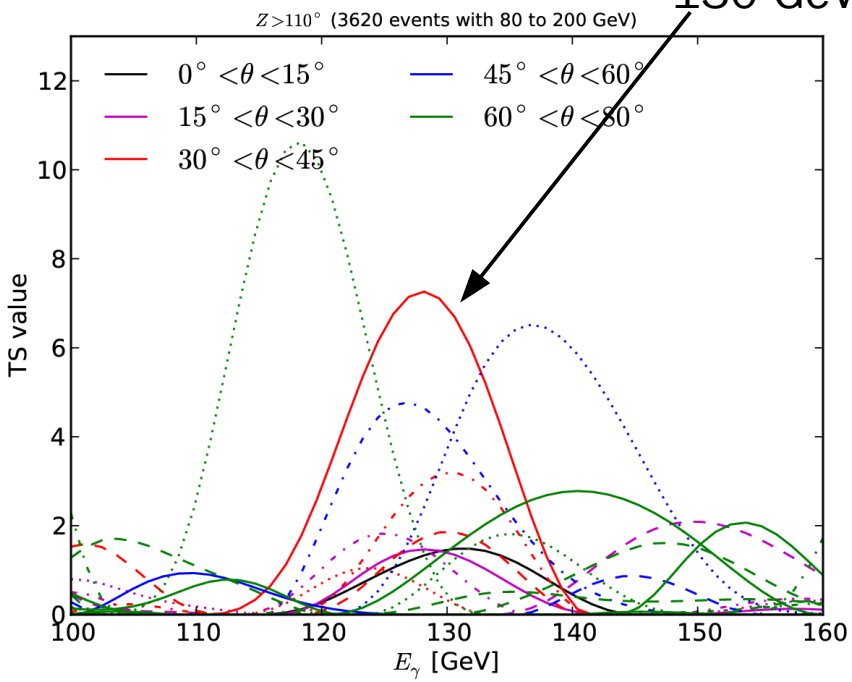


Same incidence angles

130 GeV

Earth Limb:
Z>110 deg





→ Effect (if real) does not only depend on incidence angles

[Finkbeiner, Su, CW, 2012]

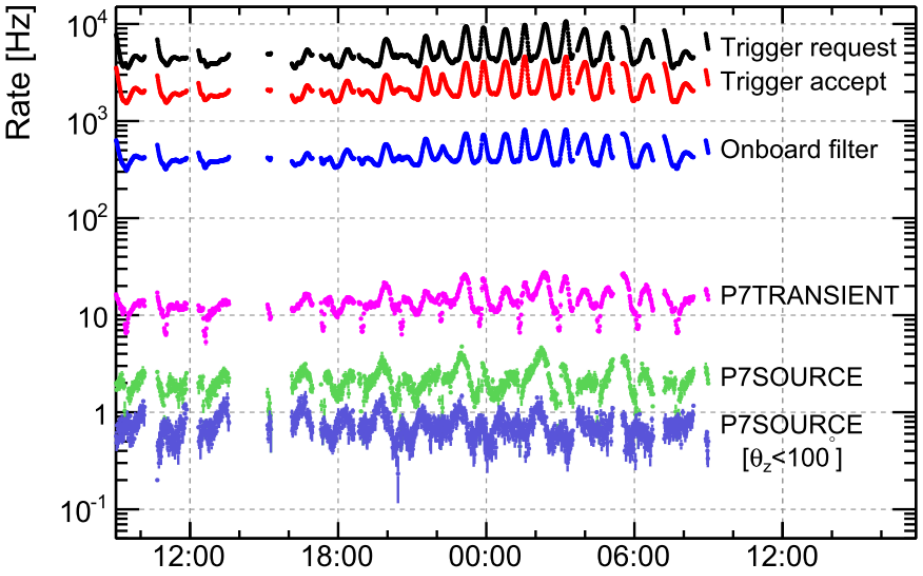
Why at the Galactic center?

Obvious concerns:

- The Galactic center is brightest spot in the sky (except Earth limb)
  → Photon trigger rate ~1 Hz. Effects should be linear.

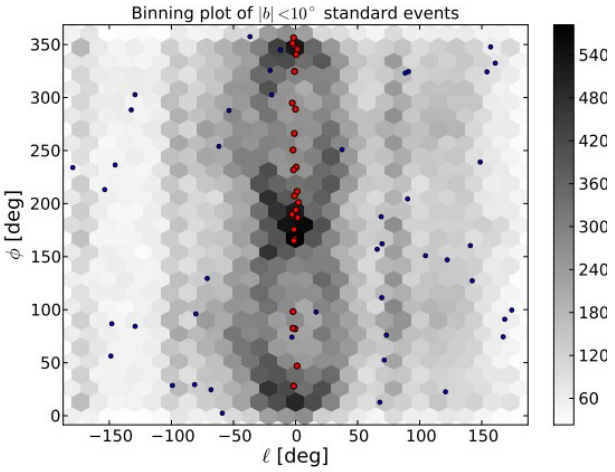
- Galactic center spectrum is hard
  → Not much harder than Gal. plane

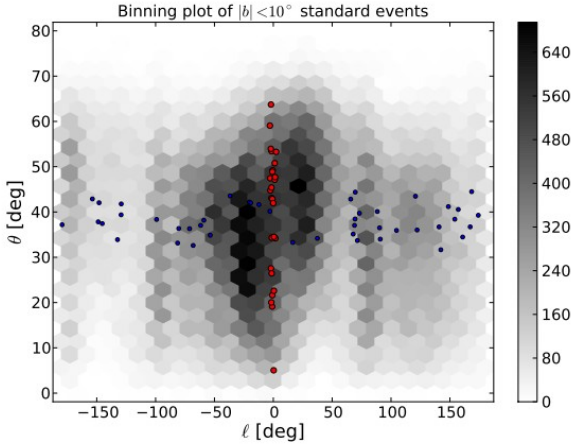
Sample	$N(>100$ GeV)	$\frac{N(>100\text{ GeV})}{N(>30\text{ GeV})}$	$\frac{N(>300\text{ GeV})}{N(>100\text{ GeV})}$
Standard events	5093	13.4%	9.6%
Inner Galactic plane	703	16.9%	9.8%
Galactic center	82	17.4%	9.8%
Galactic center line	26	–	–
Earth limb	3120	10.2%	9.2%
Earth limb line	45	–	–



[1206.1896]

- Galactic center is observed under complex incidence angle distribution
  → True for azimuth (solar panel alignment), but not for polar incidence angle
  BUT: selecting only
  phi~0, 180deg events does
  not reveal any line feature





Summary of 130 GeV features found in the Fermi LAT sky up to now

- **130 GeV line at Galactic Center**
  something between 3.35σ and 6.5σ (<2σ – 5σ global) depending on the method; weak indications for a second line at ~114 GeV
  [Bringmann et al., CW, Tempel et al., Su&Finkbeiner, prel. Fermi coll., 2012]
- **Earth Limb line**
  A >3σ line at 130 GeV in low-incidence-angle Earth limb data
  [Finkbeiner et al., Hektor et al., prel. Fermi coll., 2012]
- **Galaxy Clusters**
  3.6σ indication for two lines at 110 and 130 GeV in a stacked analysis of 18 galaxy clusters (requires factor ~1000 substructure boost to explain the signal)
  [Hektor et al., 2012]
- **Unassociated sources**
  3.3σ indication for two lines at 110 and 130 GeV in stacked analysis of unassociated LAT point sources
  [Su&Finkbeiner 2012]
- **("Hotspots"?)**
  ~3σ indication for lines (at different energies) along the Galactic disk?
  [Boyarsky et al, prel. Fermi coll 2012]
- **The Sun**
  3.2σ indication for a ~130 GeV line in a 5deg circle following the Sun
  [Whiteson 2013]

Question: What do these features have in common?
None of them is strong enough to claim a "signal" just yet.
All at ~3 sigma level (and GC one rules).

What does the LAT collaboration say?

4th Fermi Symposium, 28 Oct – 2 Nov, Monterey, CA

The LAT team sees the GC feature. A coherent interpretation has not yet emerged. As usual, more data is needed.

Ongoing searches for systematics (preliminary):

- In P7rep (including updated calorimeter calibration), **the peak moves to ~135 GeV**
- **3 sigma line in the Earth limb data** (using inverse rocking angle cut; maybe related to P7TRANS to P7CLEAN efficiency)
- **Nothing suspicous found in inverse ROI** (Galactic disk), which is "mysterious"

Preliminary results from the search for gamma-ray lines from DM annihilation:

- Using 2D PDFs, the significance drops slightly
- Using reprocessed data, the significance drops slightly
- LAT team finds **no globally significant excess, in their own optimized ROIs**
- **In a 4x4 deg^2 box around GC, the local significance is 3.35 sigma**

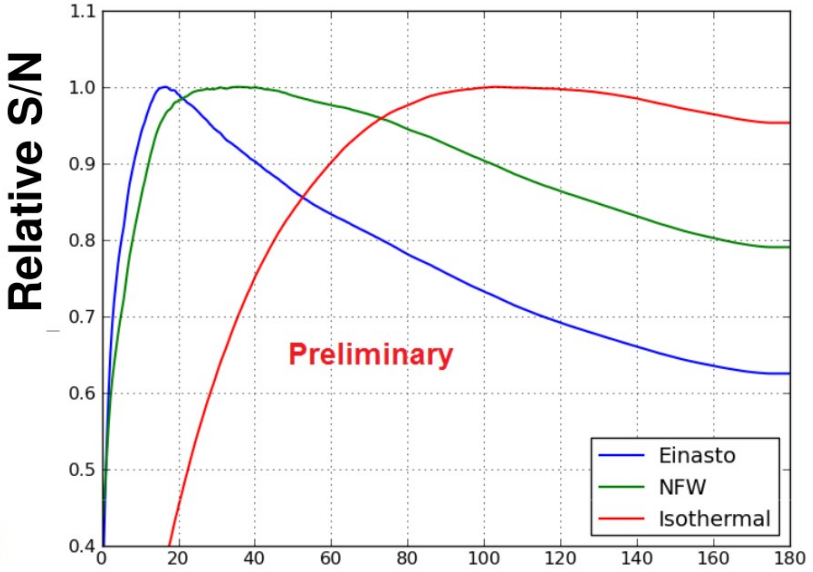
→ They use **different ROIs and different data**, so results are right now impossible to confirm independently. Release of P7rep expected ~~end of 2012~~ in a few weeks

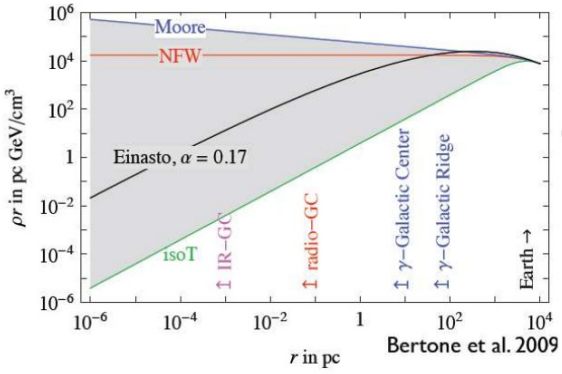
[For details see talks by Eric Charles, Elliott Bloom and Andrea Albert; Fermi Symposium 2012]

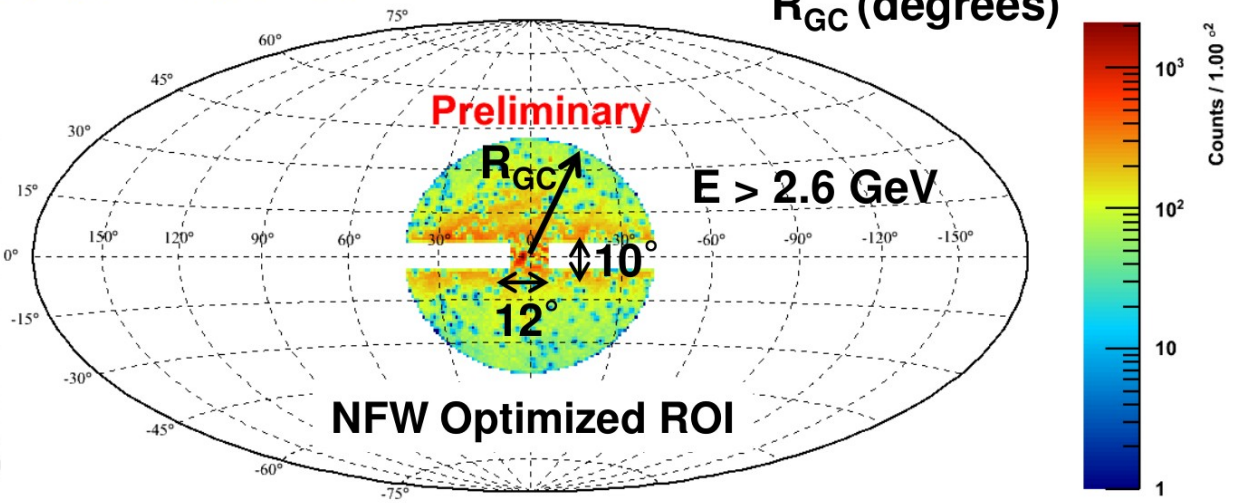
[Slides from A. Albert; Fermi Symposium 2012]

Region of Interest (ROI) Optimization

- Many have shown ROI optimization importance in line searches
  - e.g. C. Weniger JCAP 1208 (2012) 007
- Find R_{GC} that optimizes sig/sqrt(bkg)
  - ROI choices made a priori using MC
  - sig from J factor in that ROI
  - bkg from MC simulation of galactic diffuse model
    - http://fermi.gsfc.nasa.gov/ssc/data/access/lat/Model_details/Pass7_galactic.html
- Search in 5 ROIs
  - R0 (12°x10° GC box)
  - R16 (Einasto Optimized)
  - R41 (NFW Optimized)
  - R90 (Isothermal Optimized)
  - R180 (2 year Analysis ROI)



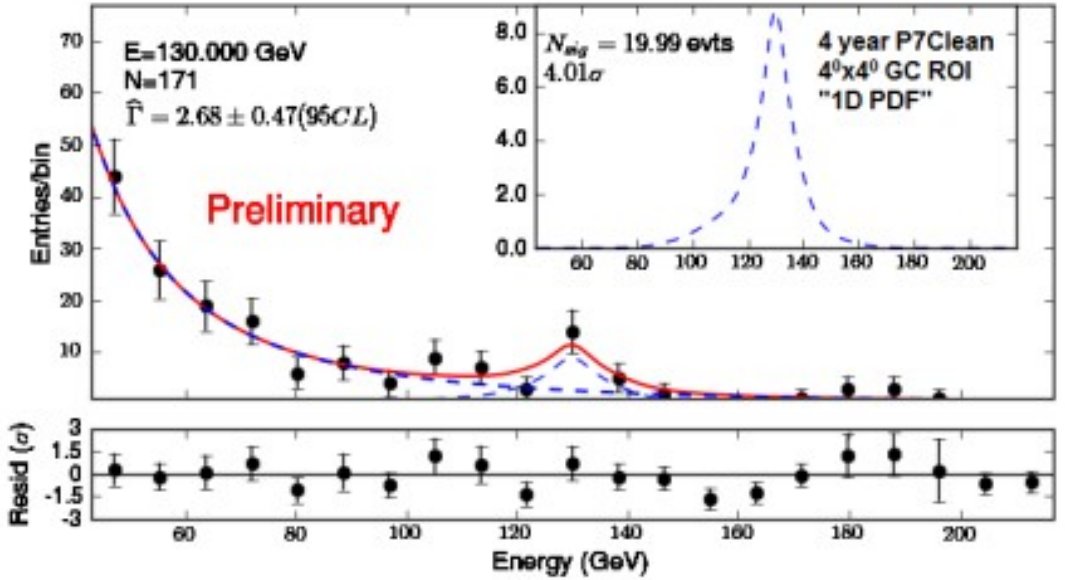




[Slides from A. Albert; Fermi Symposium 2012]

Line-like Feature near 135 GeV

- 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)



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

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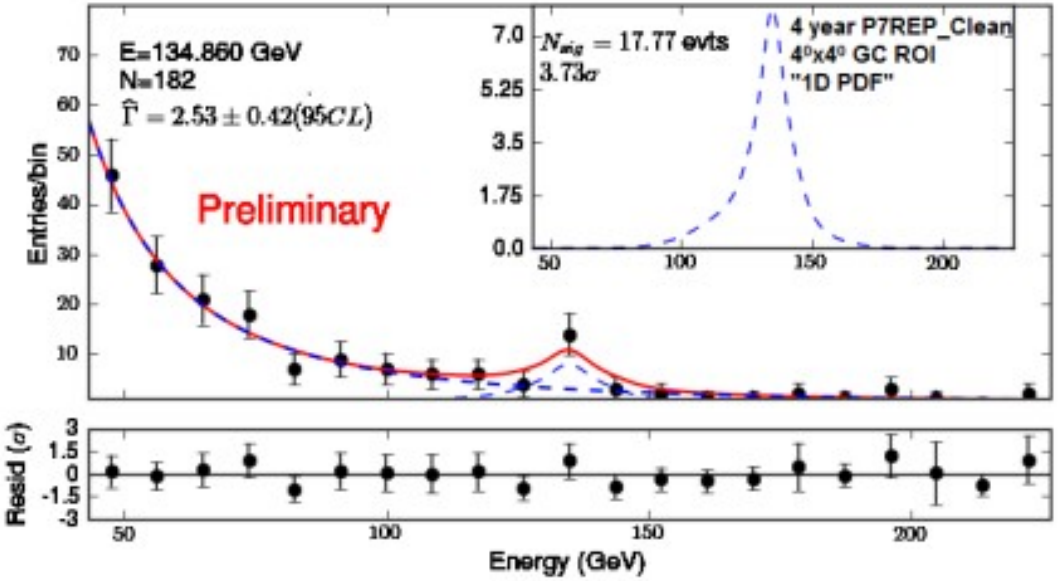
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)



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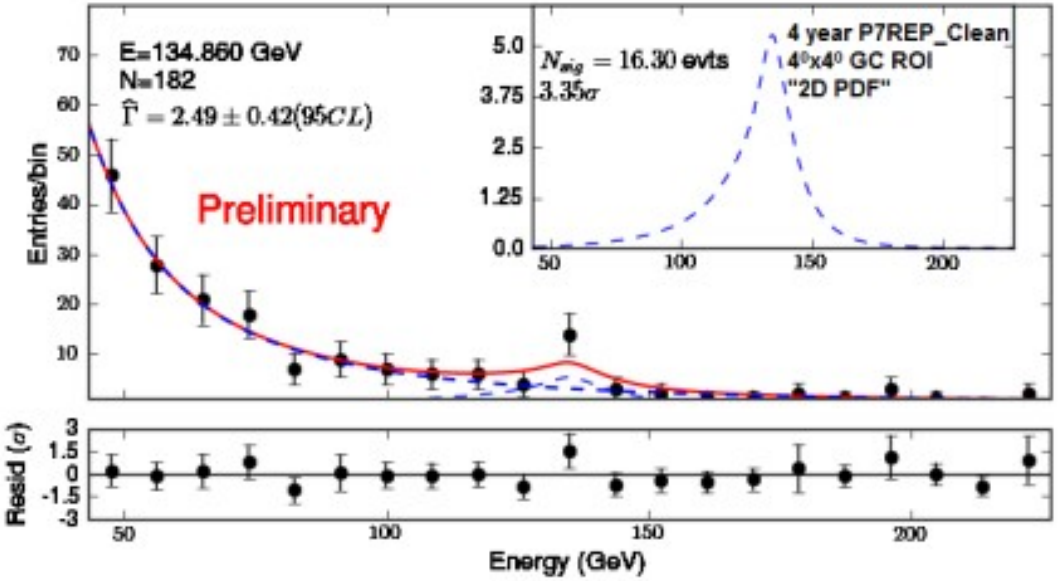
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global



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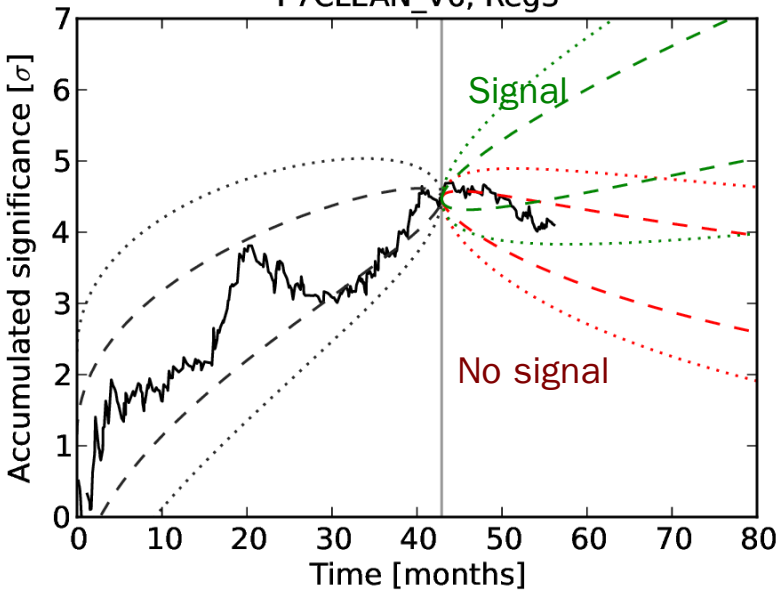
Not one of our a priori ROIs

Our analysis: situation now (16 Apr 2013)

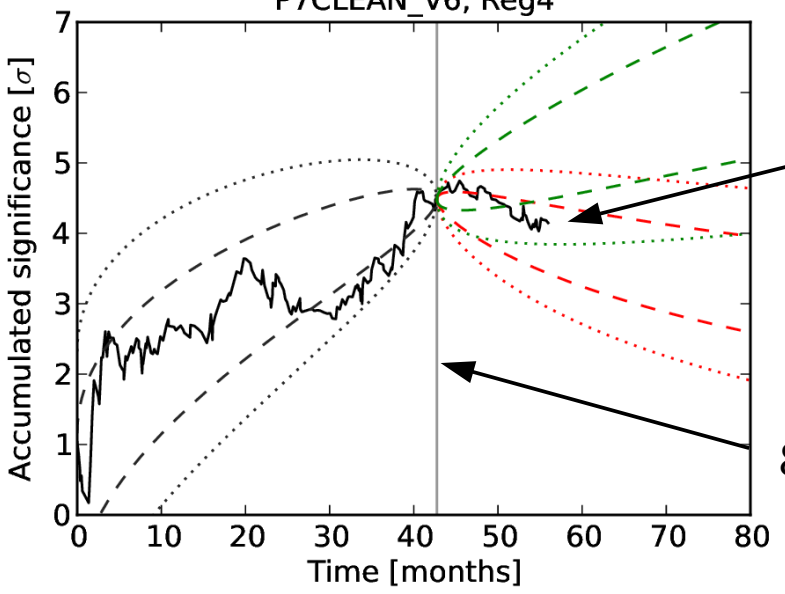
CLEAN

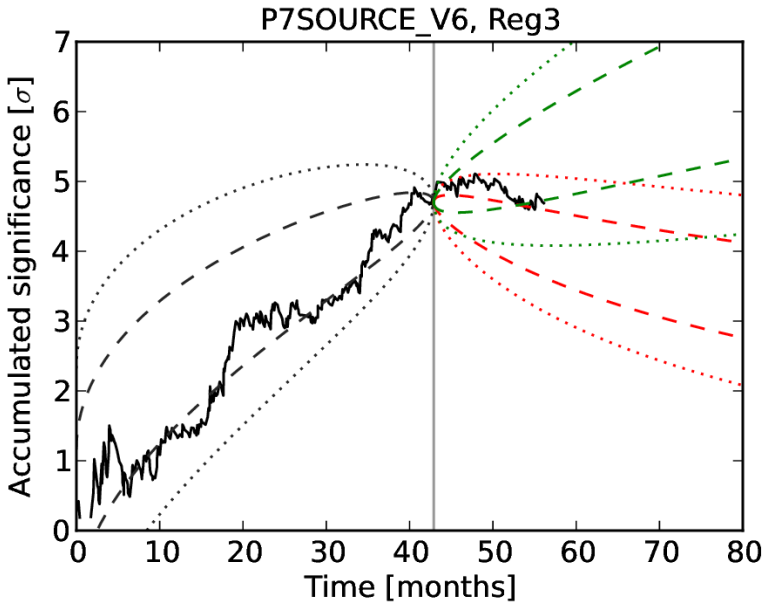
SOURCE

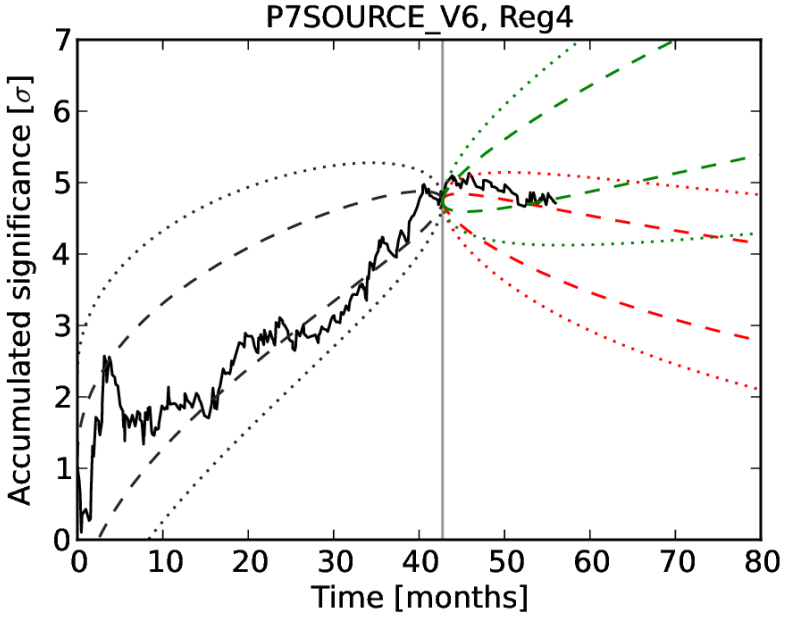
Reg3



Reg4



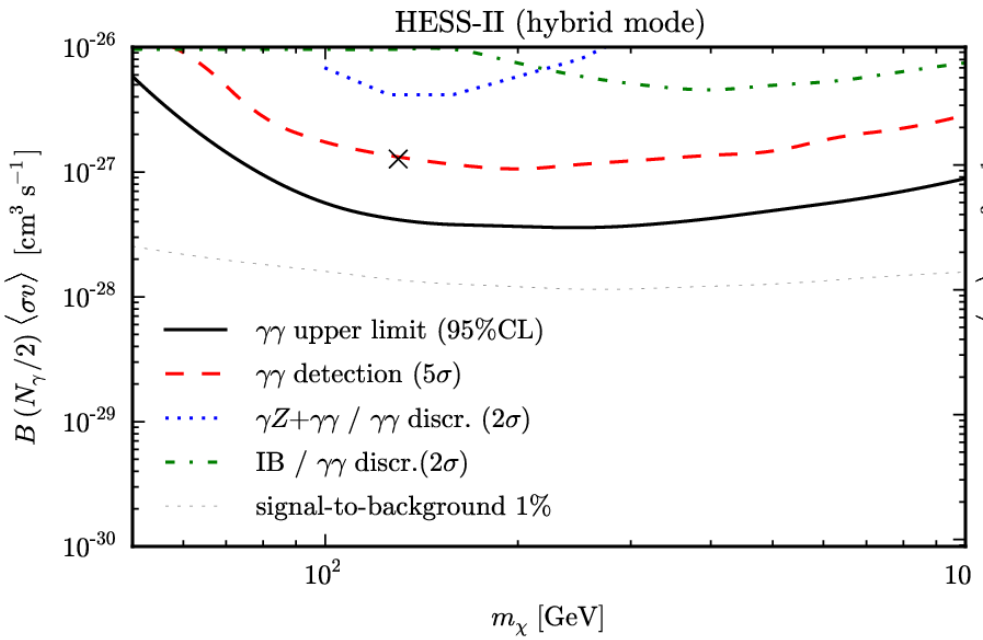


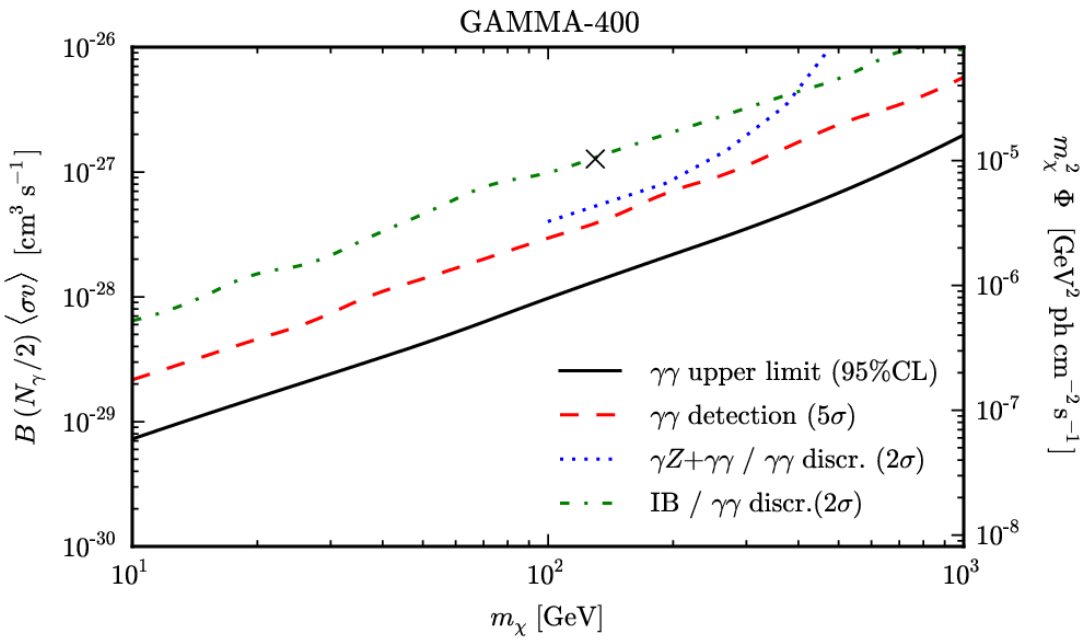


Bands: Analytical projection for ±1σ and ±2σ bands, assuming Gaussian noise with S/B~0.35 (details in CW 2013, 1303.1798); projections do not take into account expected improvements with PASS8

65-260 GeV energy range;
129.8 GeV line energy;
1D PDF

HESS-II / GAMMA-400 to the rescue?





[Bergström et al., 2012]

HESS-II (hybrid mode)

- 50 hours of observation of galactic center
- enough to rule out signature or confirm it at 5 sigma (if systematics are under control)
- GC close to zenith from March 2013 on
- 230 hours per season in principle possible
- results end of 2014?

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

GAMMA-400

- 5 years of survey mode (5sigma detection would take ~10 months)
- Allows discrimination between VIB and monochromatic photons
- detection of γZ down to 20% relative branching ratio
- launch in 2018?

Conclusions

- The LAT data contains a significant spectra feature at the Galactic center that is a candidate for a line signal from dark matter annihilation.

  There are indications for

  - ~~an astrophysical cause~~
  - instrumental effects (Earth limb, 2d fit)
  - a rare statistical fluctuation (data since Apr 2012, 2d fit, P7rep)
  - a genuine signal of dark matter annihilation (Spatial distribution, second line, galaxy clusters, unassociated point sources?, Sun?)

  → Situation right now as confusing as it could be

- We are in an extremely comfortable position: we will know more very soon.
  → more data until at least 2016, PASS8, GC observations?, HESS-II, GAMMA-400