Gamma-ray searches for dark matter: Stuck in Line

Image credits: Alamy

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Identifying and Characterizing Dark Matter
KITP, UCSB

Outline

- Concepts & current limits
- The 130 GeV feature
- Conclusions & Outlook

Gamma-Ray Signal from WIMP annihilation

The characteristic gamma-ray flux signal from dark matter annihilation (assuming $\chi = \bar{\chi}$) is given by

Signal intensity:
[photon flux per steradian per energy]

total annihilation cross-section

branching ratio into channel f

$$\frac{dJ_{\rm ann.}}{d\Omega dE_\gamma} = \int_{\rm l.o.s.} ds\ \rho_\chi^2(\vec{r}[s,\Omega]) \times \frac{\langle\sigma v\rangle_{\rm ann}}{8\pi m_\chi^2} \sum_f B_f \frac{dN_\gamma^f}{dE_\gamma}$$

dark matter density

dark matter mass

annihilation spectrum of channel f

Astrophysics:
Characteristic **Morphology**

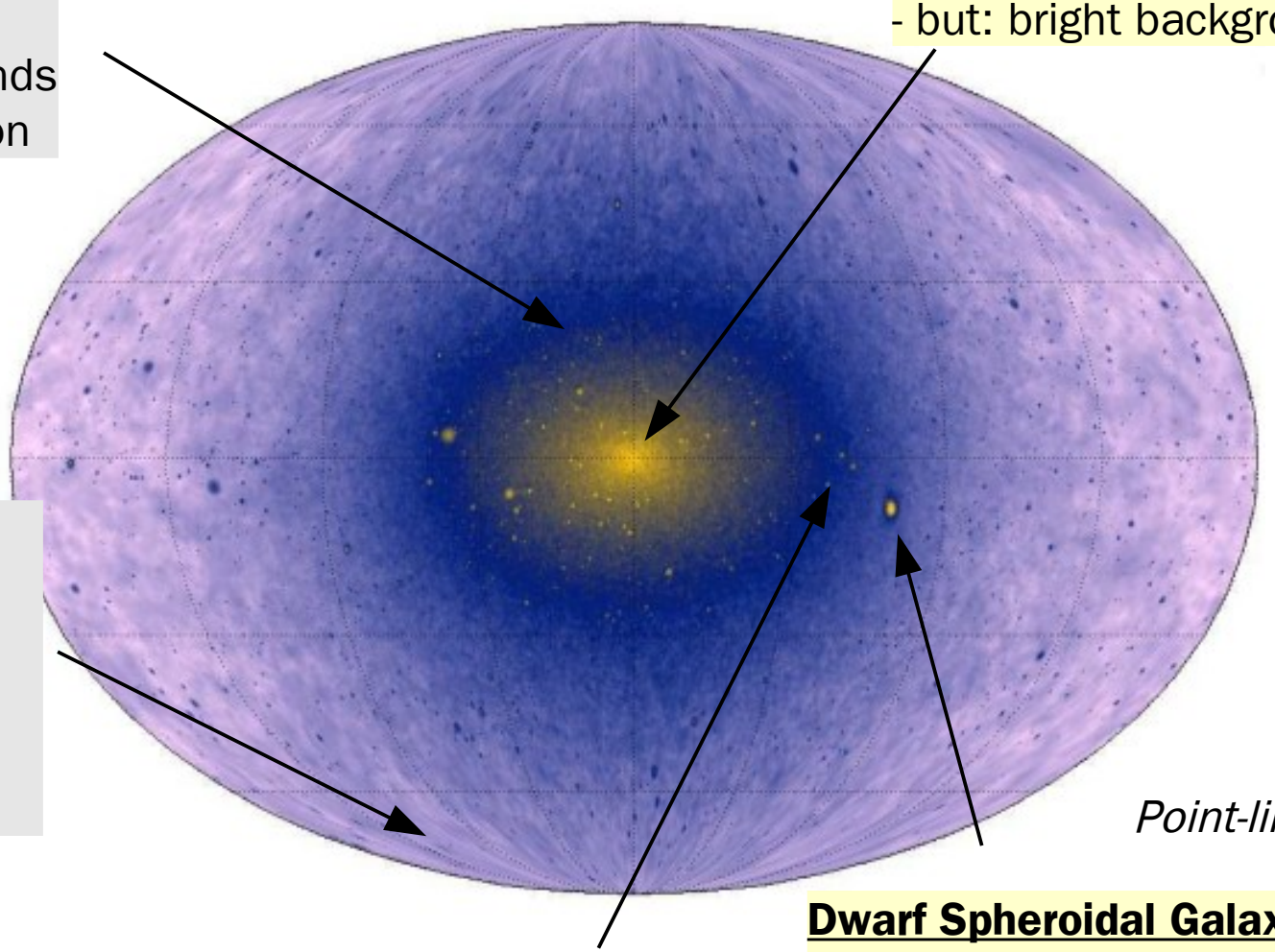
Particle physics:
Characteristic **Energy Spectrum**

Note that always $\langle\rho_\chi^2\rangle > \langle\rho_\chi\rangle^2$ for inhomogeneous distributions
→ quantified by "boost factor" (signal boost w.r.t. predictions from a smooth profile)

Targets

Galactic DM halo
- good S/N
- difficult backgrounds
- angular information

Galactic center (~8.5 kpc)
- brightest DM source in sky
- but: bright backgrounds



Extragalactic signal
- nearly isotropic
- only visible close to Galactic poles
- angular information
- Galaxy clusters?

Extended or diffuse signals

Point-like signals

DM clumps
- w/o baryons
- bright enough?
- boost overall signal

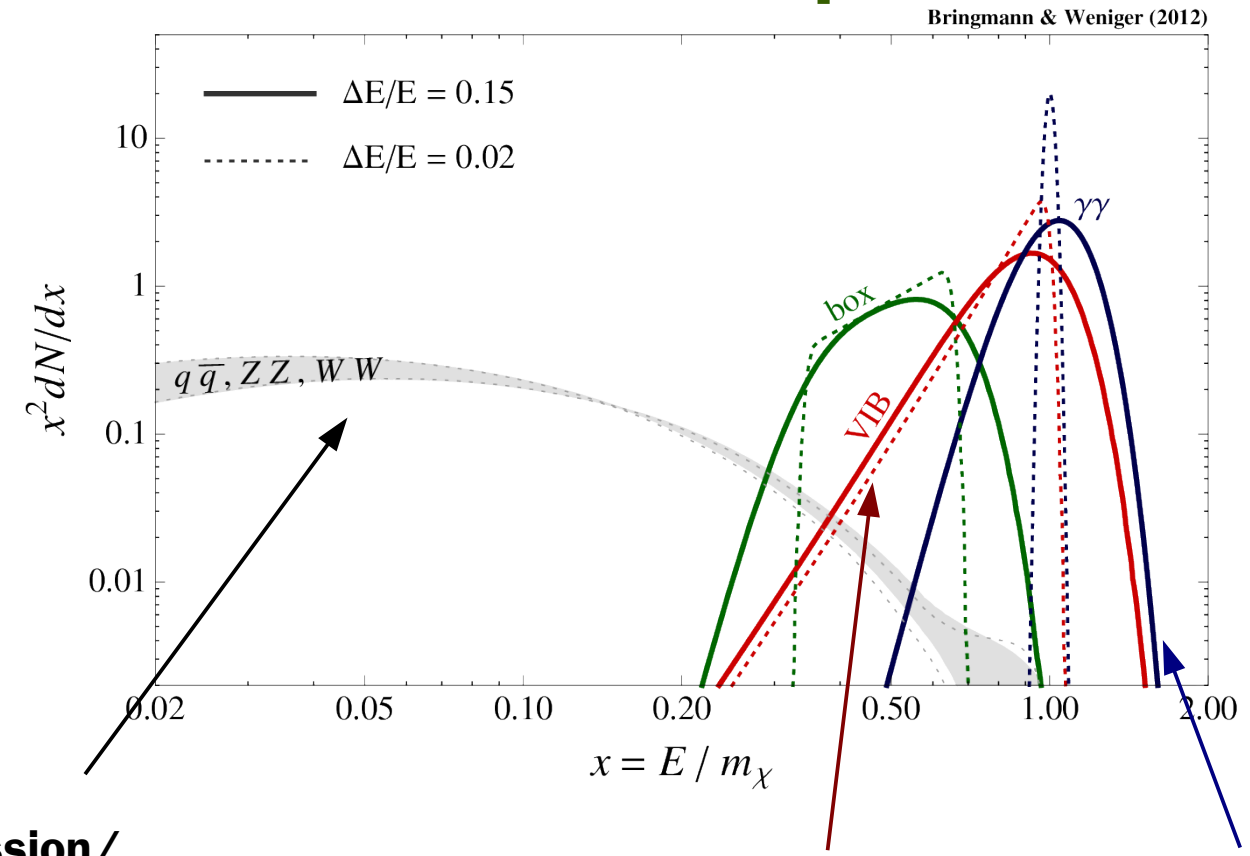
Mariangela Lisanti's talk

Dwarf Spheroidal Galaxies
- harbor small number of stars
- otherwise dark (no gamma-ray emission)

Louie Strigari's talk

[Kuhlen et al. 2007]

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)

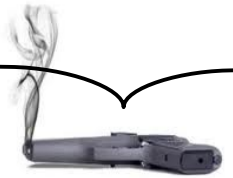
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

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

Gamma-ray lines

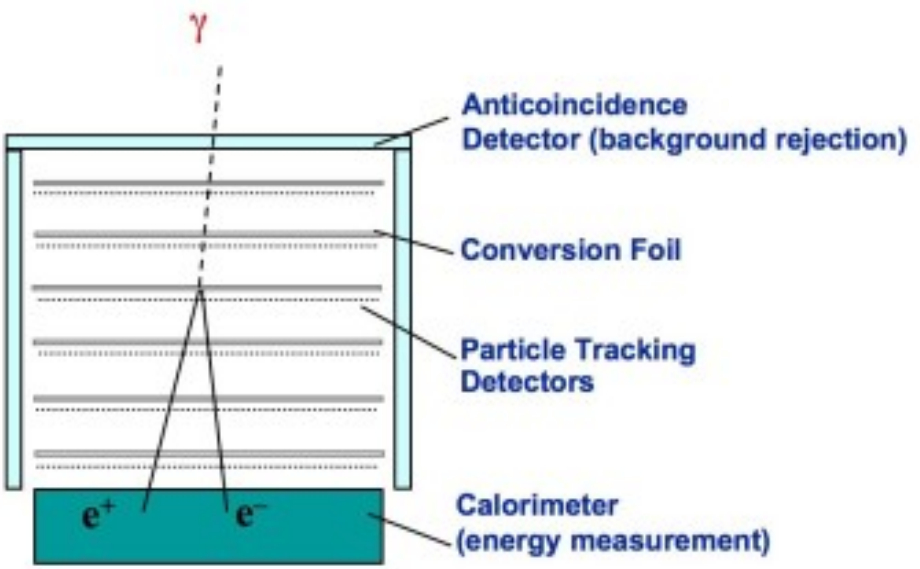
- from two-body annihilation into photons
- forbidden at tree-leve, generically suppressed by $O(\alpha^2)$

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



(smoking guns)

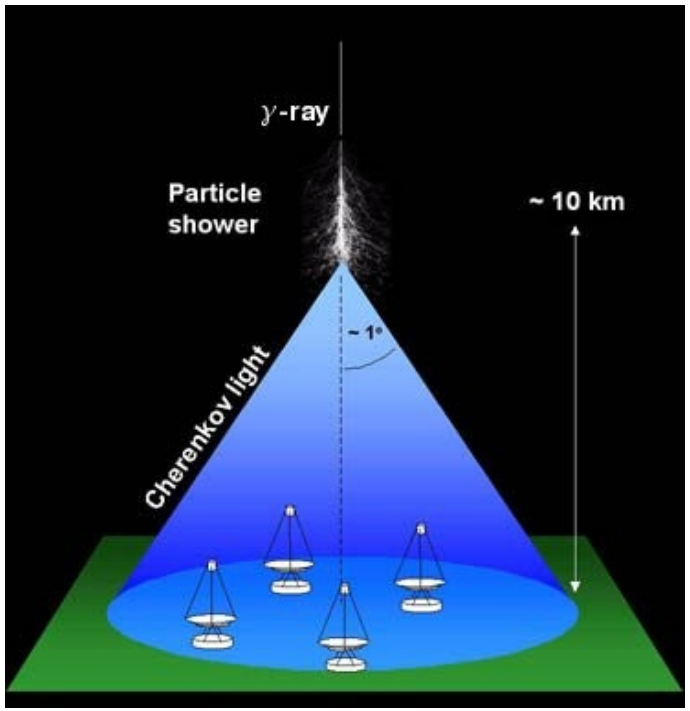
Current instruments



Fermi Large Area Telescope

- Pair conversion detector
- 20 MeV to >300 GeV
- Effective area 8,000 cm^2
- Field of view (FOV): 2.4 sr
- 2008 to at least 2016

- Excellent rejection of cosmic-ray background!

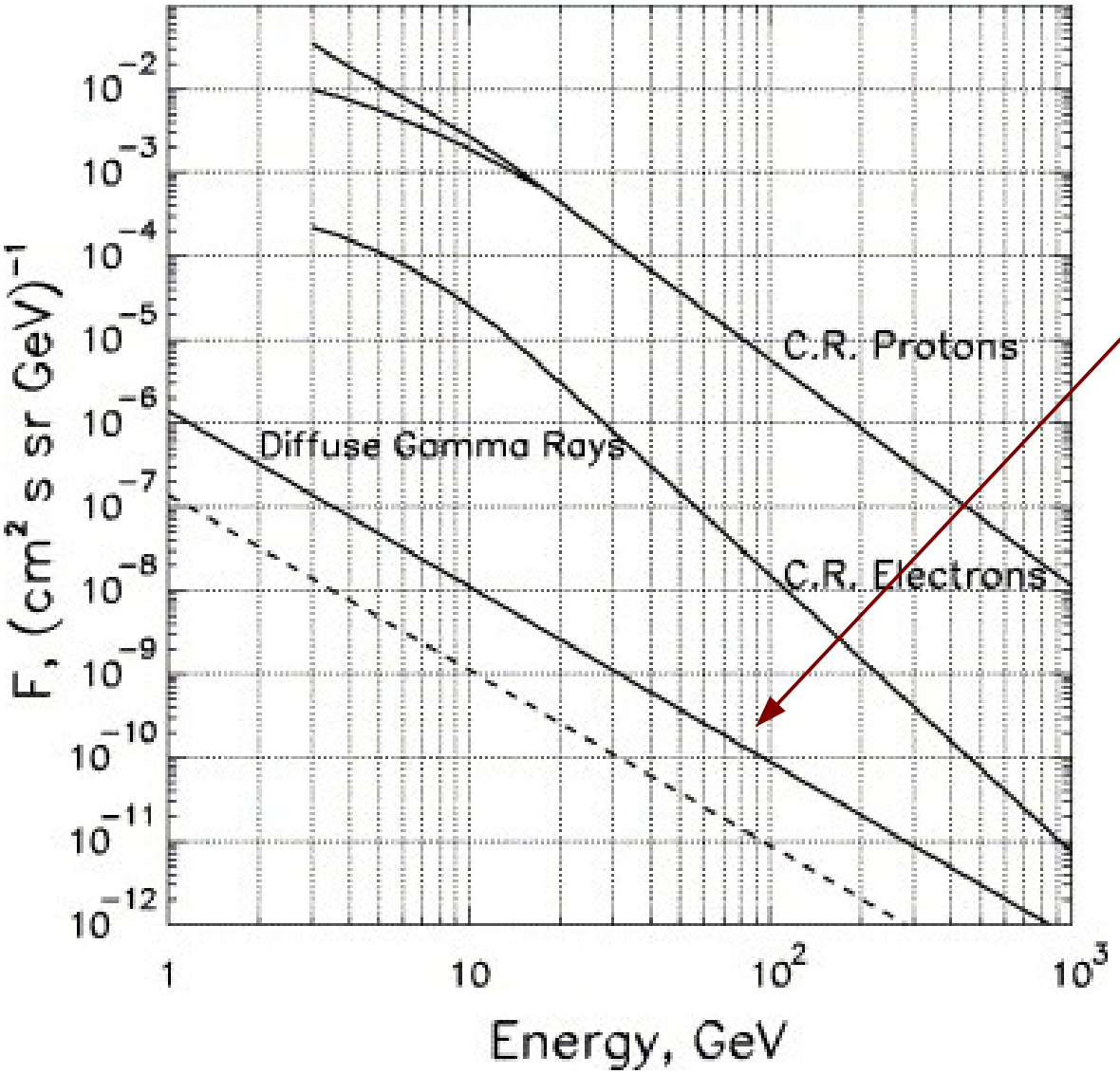


Imaging Atmospheric Cherenkov Telescopes

- Measure scintillation light of atmospheric particle cascades
- >50 GeV to multiple TeV
- 10^8 – 10^10 cm^2
- FOV: few degrees
- since 2002: H.E.S.S.
- since 2004: MAGIC
- since 2007: VERITAS

- No rejection of cosmic-ray electrons (but of protons & heavy nuclei)

The cosmic-ray background



Gamma rays are <u>sparse</u>!

- Required proton rejection: factor >1,000,000
- Required electron rejection: factor >1000

Typical example:
Draco, thermal annihilation cross-section, 1 TeV DM mass,
(hadronic channels, 50h observation time, 1km^2 effective area, 0.1deg opening angle, J~10^19 GeV^2/cm^5, 100 GeV threshold)

N(signal photons) ~ 12
N(bg photons) ~ 160

N(electrons) ~ 12,000
N(protons) ~ 8,000,000

[Moiseev et al., 2007]

Dark Matter searches with Fermi LAT data

Some central publications:

Galactic center (8) – The zone of avoidance
- Hooper & Slatyer (2013), Hooper et al. (2012), Hooper & Linden (2012), Hooper & Goodenough (2010)
- Boyarsky et al. (2011), Cholis et al. (2012), Cohen et al. (2012), Abazajian & Kaplinghat (2012)

here

Dwarf spheroidals (6)
- Abdo et al. (2010), Ackermann et al. (2011), Geringer-Sameth & Koushiappas (2011), Cholis Salucci (2012), Huang et al. (2012), Tasi et al. (2012)

Galaxy clusters (4)
- Ackermann et al. (2010), Huang et al. (2011), Ando & Nagai (2012), Han et al. (2012)

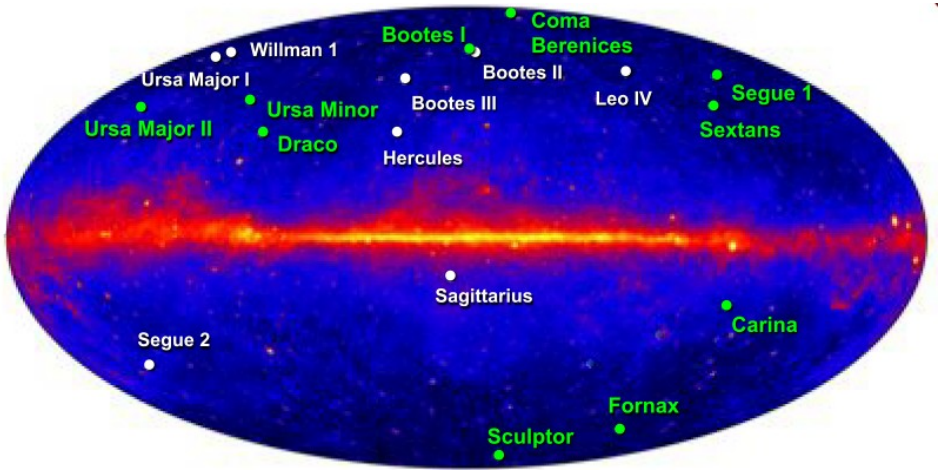
Galactic halo (2)
- Ackermann et al. (2012), Huang et al. (2012)

Angular power-spectrum of isotropic gamma-ray BG (1)
- Ackermann et al. (2012) + Ando & Komatsu (2013)

Gamma-ray lines & Co – All work and no play makes Jack a dull boy
- Abdo et al. (2010), Vertongen & CW (2011), Ackermann et al. (2012), Bringmann et al. (2012), CW (2012), Tempel et al. (2012), Su & Finkbeiner (2012)

Red: Fermi LAT collaboration
Black: non-LAT analyses

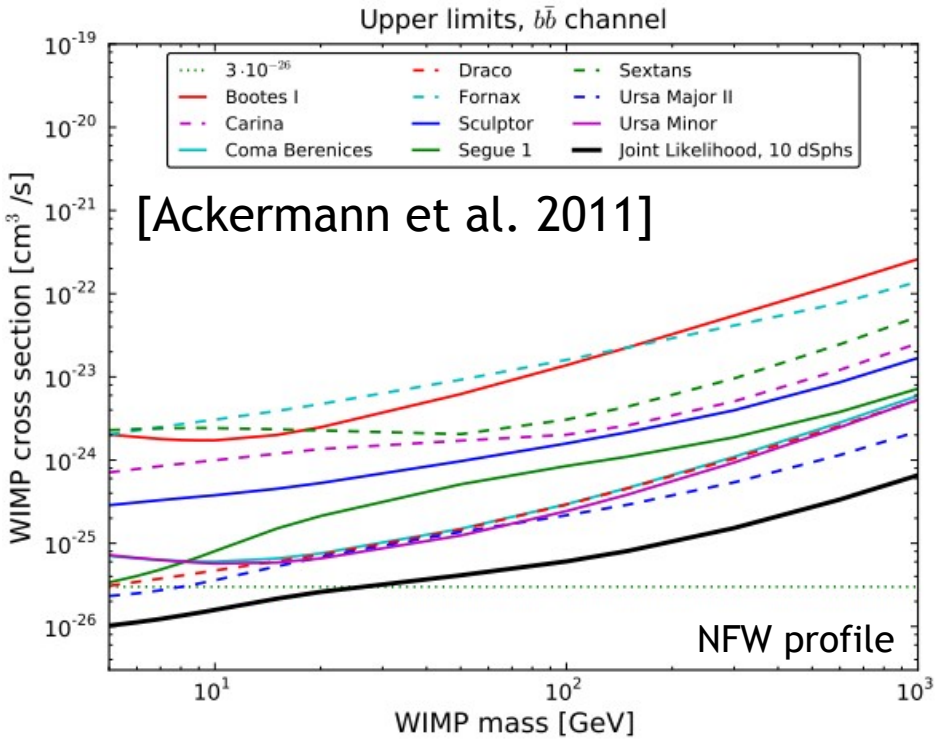
Dwarf Galaxies



[from Drlica-Wagner, Fermi Symp. 2012]

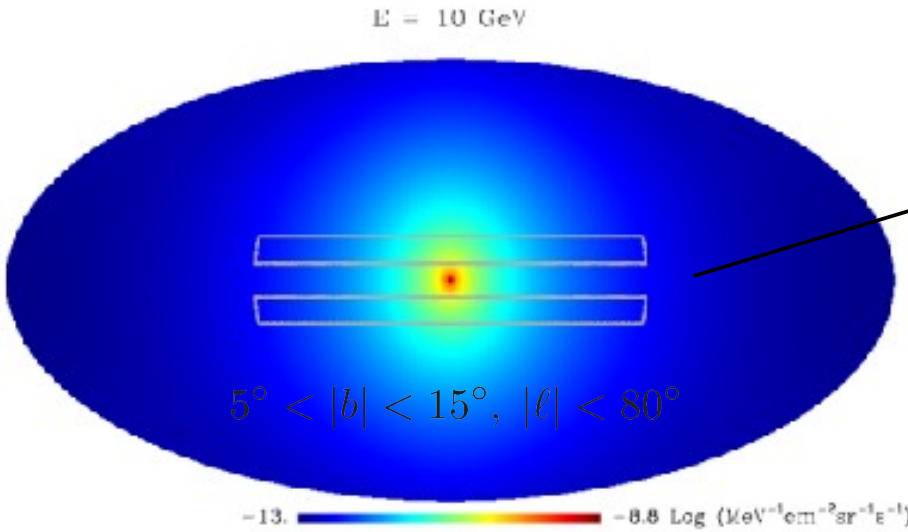
Dwarf galaxies are extremely promising

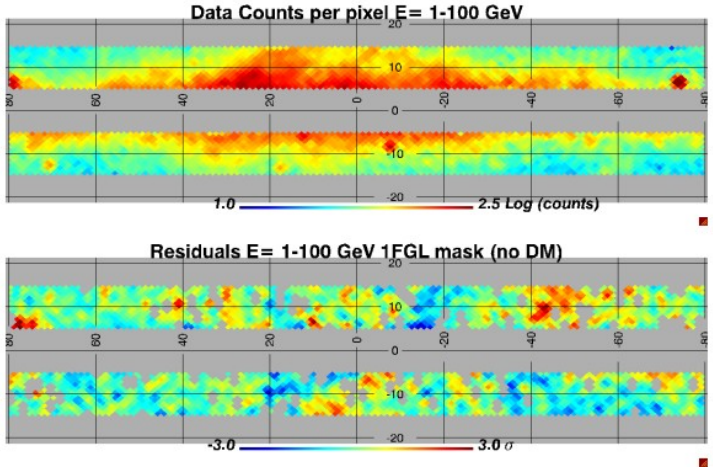
- Large M/L ratios ($\sim 1000 M_\odot/L_\odot$ and more)
- Promising: Combined likelihood analysis (not stacking) of many dwarfs
  → reduces J-value uncertainties
  → improves limits
- Current Fermi LAT limits exclude thermal annihilation cross-sections below 30 GeV (bb final states)
- but: different J-values in the literature are not consistent within their error-bars



See also: Scott et al. 2010; Geringer-Sameth & Koushiappas 2011; Mazziotta et al. 2012; Cholis & Salucci 2012; Salucci et al. 2011; Charbonnier et al. 2011

Searches in the Galactic halo



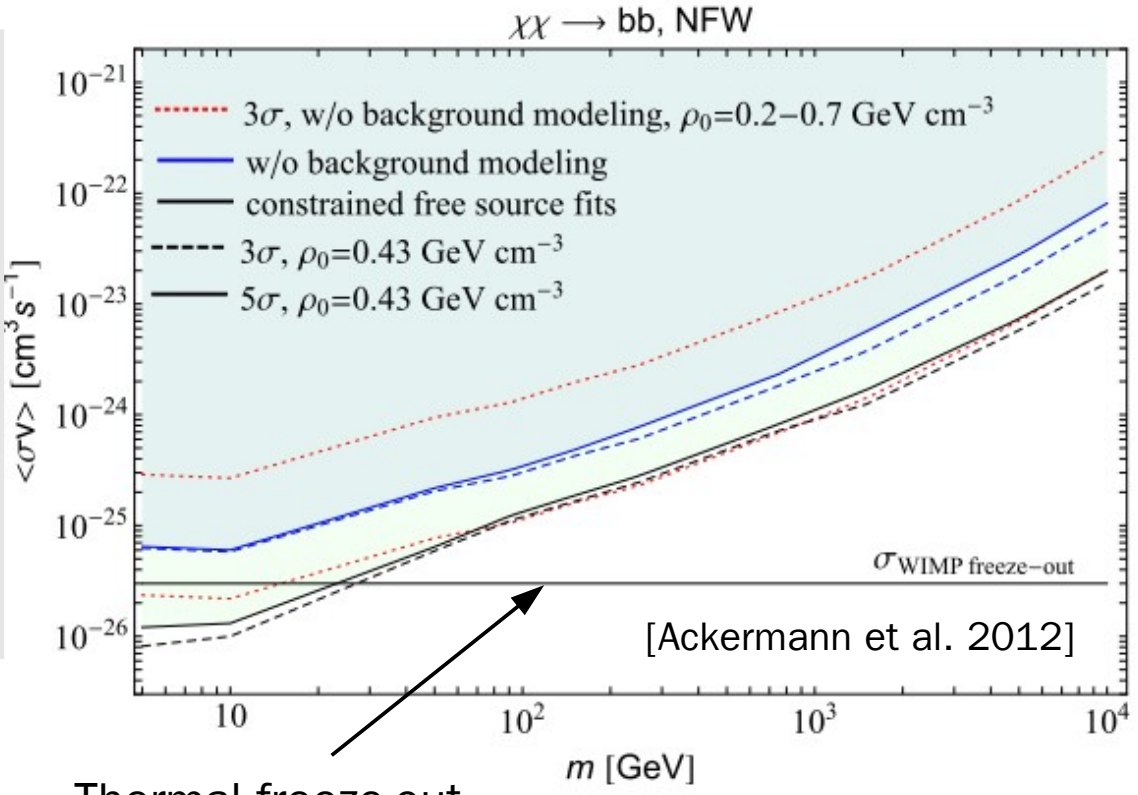


data

data-model

Galactic dark matter halo

- Large number of signal photons expected
- Avoids complicated Galactic disk
- Requires intimate understanding of astrophysical backgrounds:
  - CR source distribution & injection spectra
  - ISM distribution and composition
  - diffusion parameters, ⋯
  - point sources
    → marginalized over



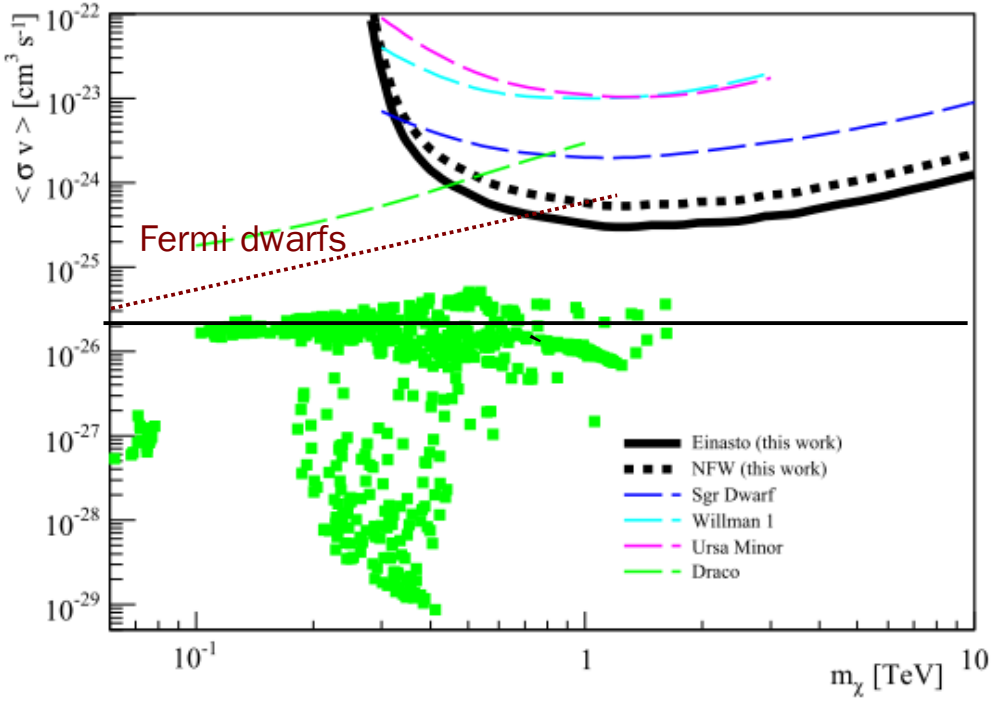
No detection → Upper limits on signal flux

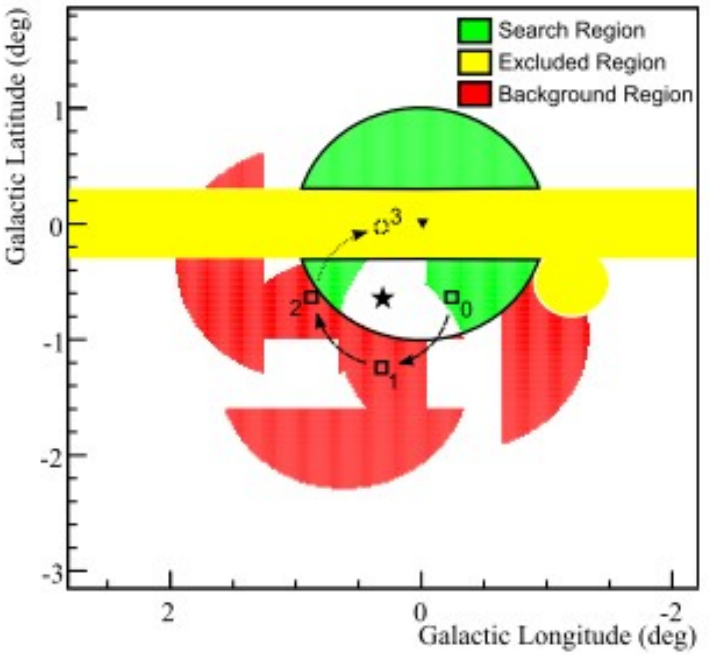
Thermal freeze-out

(See also Cirelli, Panci & Serpico 2010)

H.E.S.S. observations of Galactic center

Abramowski et al. 2011



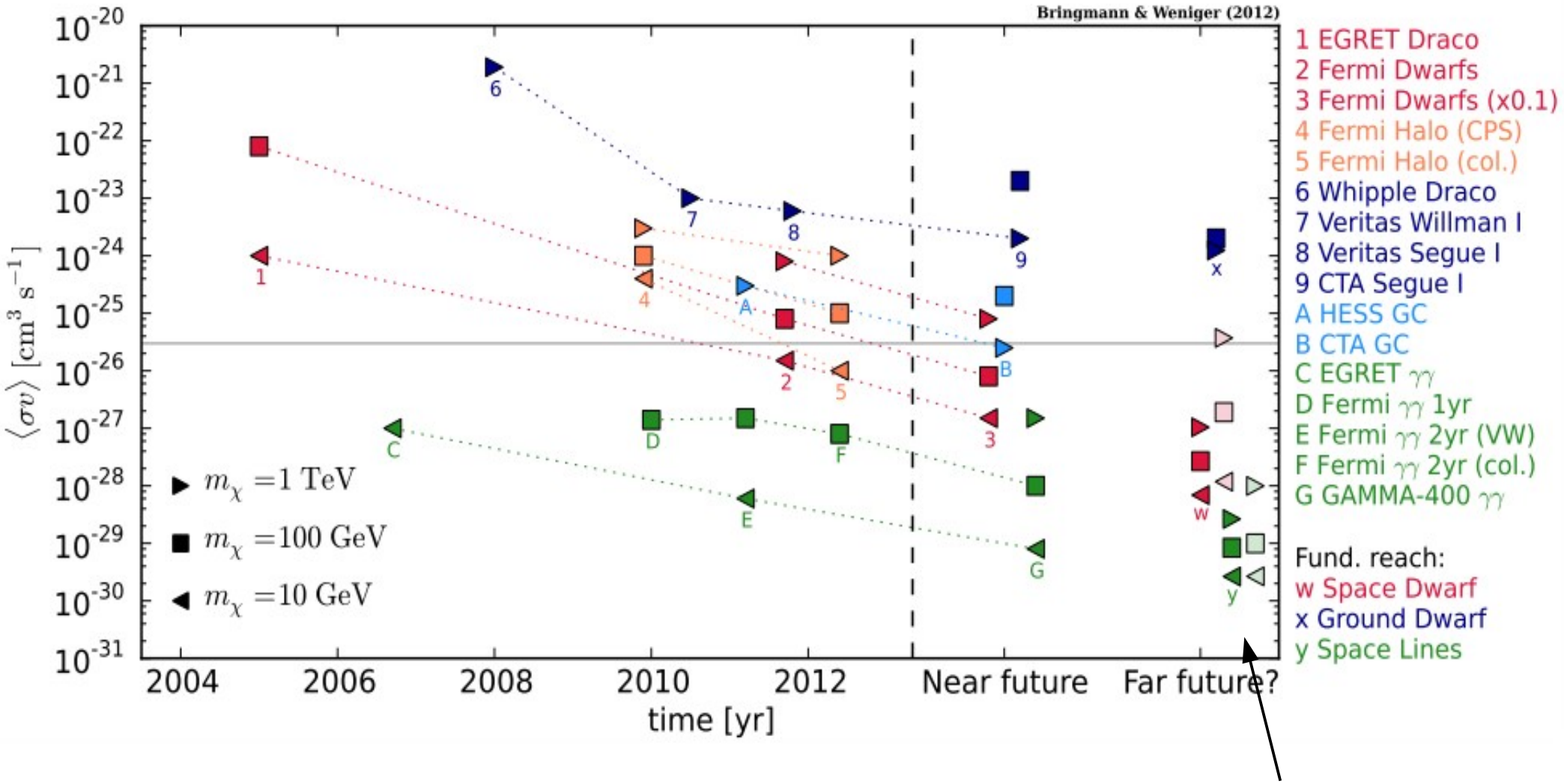


Galactic center is most promising target for DM searches with IACTs

- Large signal flux (easier to overcome CR BG)
- Target interesting for other purposes (long observation times)
- Difficult to observe for VERITAS or MAGIC (both on northern hemisphere)

- Gives >10 times stronger limits than dwarf spheroidals
- Still factor >10 away from thermal cross-section

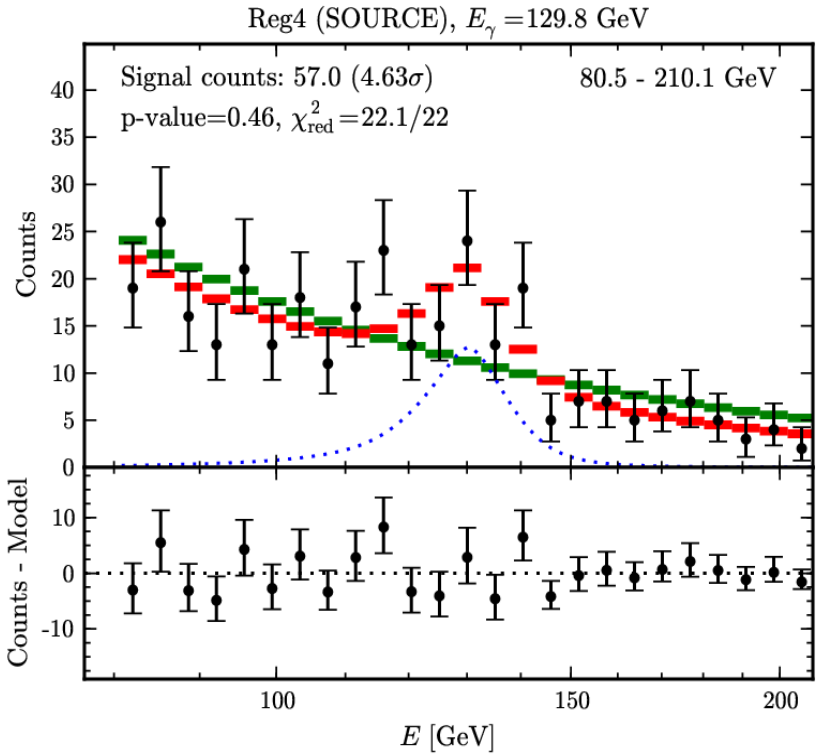
(Expected) limits as a function of time

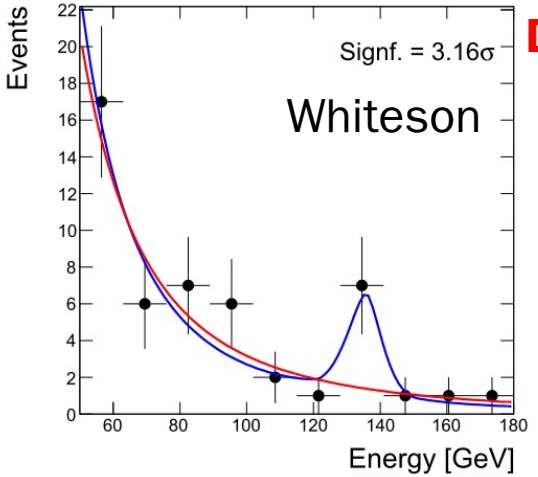


Limits on hadronic final states, for different DM masses

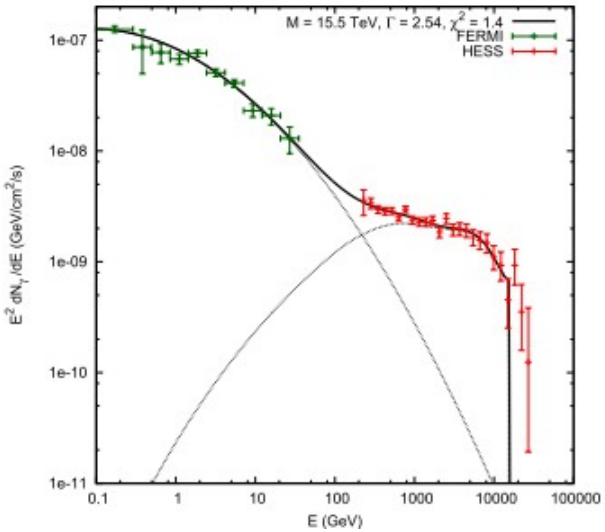
- Infinite observation time
- 1% BG + 1% instr. systematics

...tentative signals

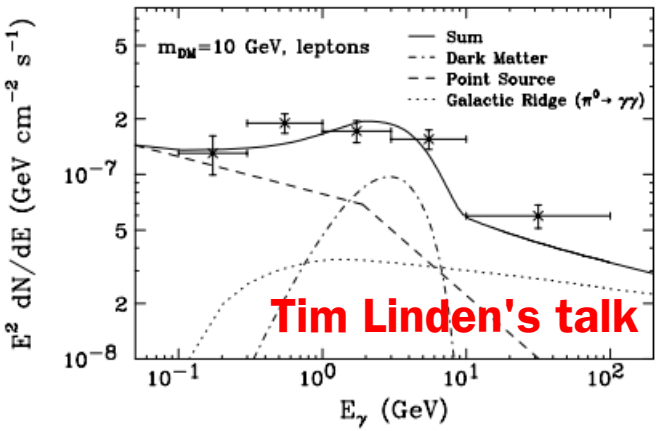




Daniel Whiteson's talk

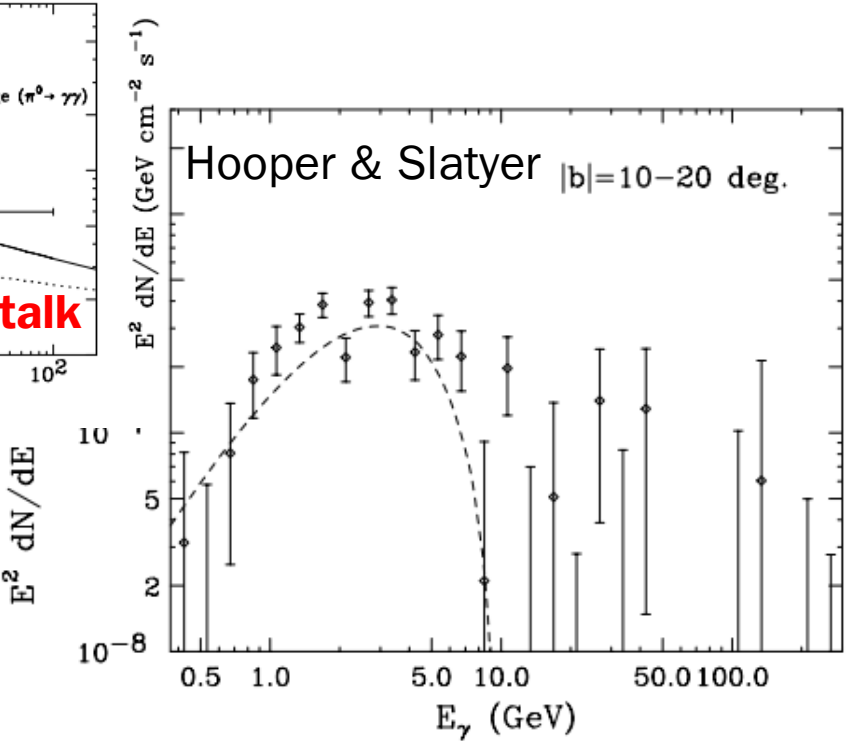


Belikov et al.

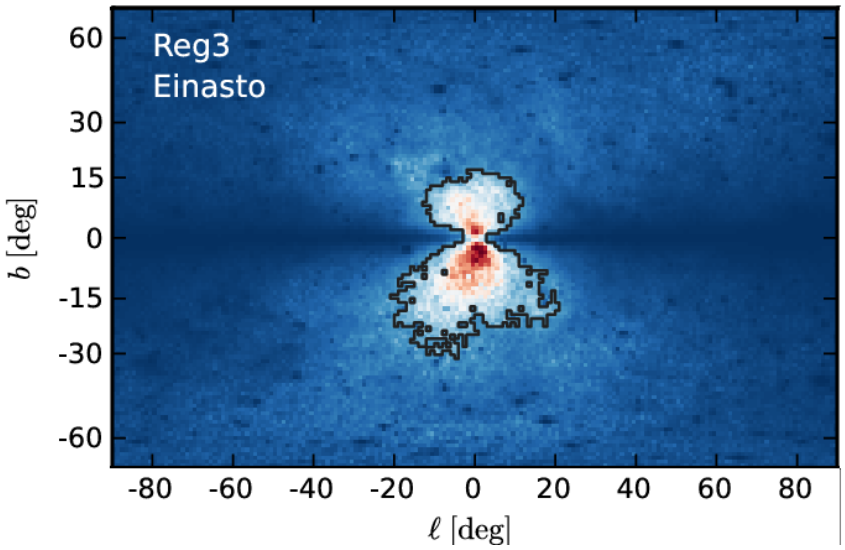


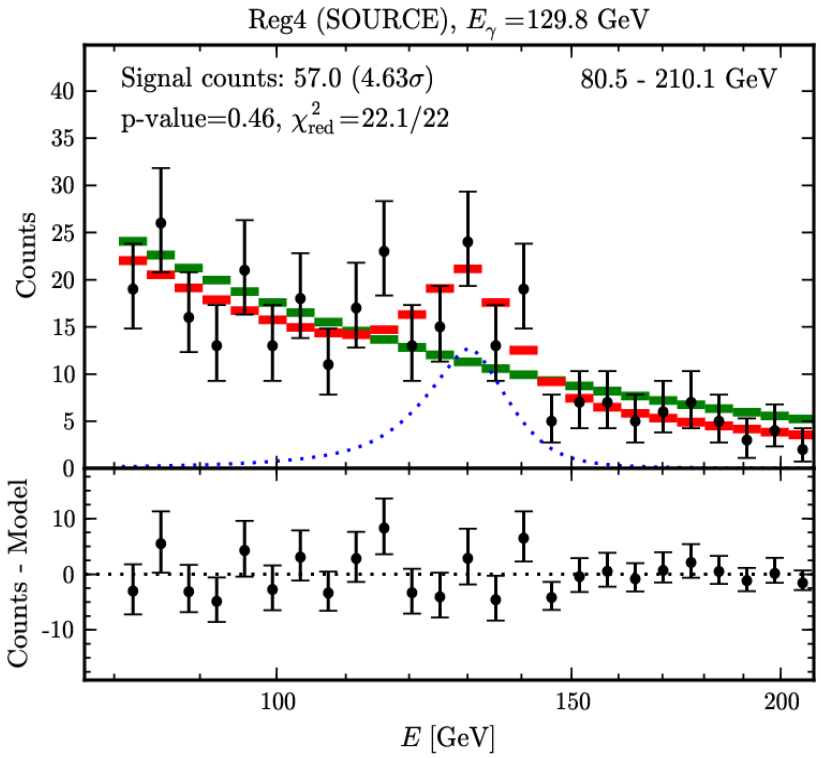
Tim Linden's talk

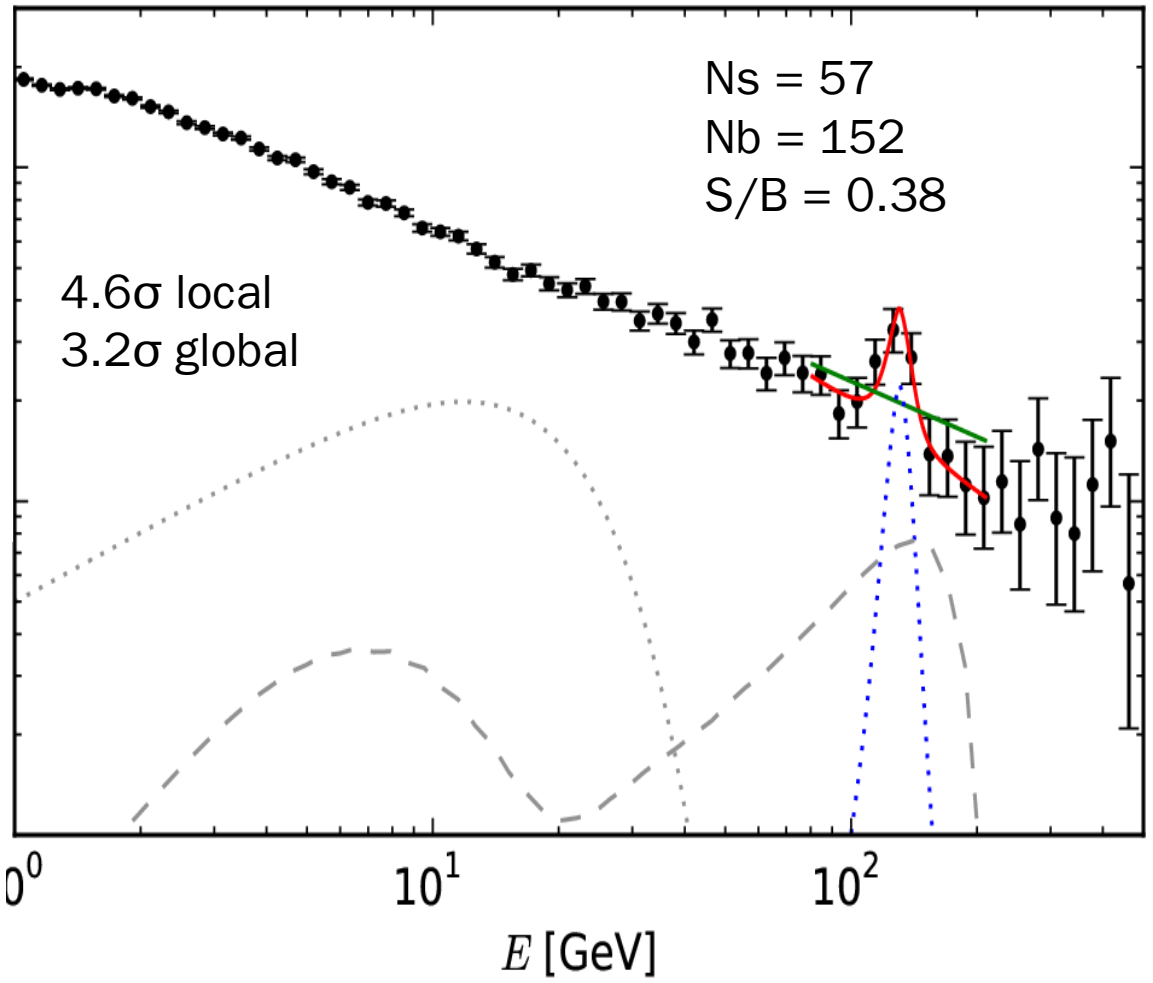
Hooper & Linden



The (in)famous 130 GeV feature







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

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

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

[Bringmann et al. 2012; CW 2012]

Gamma-ray lines

Gamma-ray lines

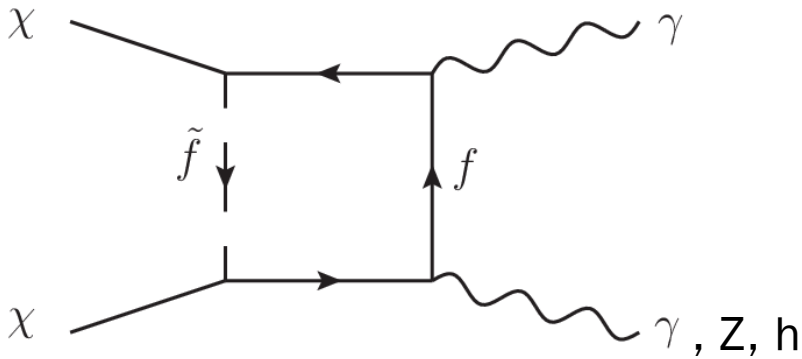
- are produced via two-body annihilation

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

- 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:

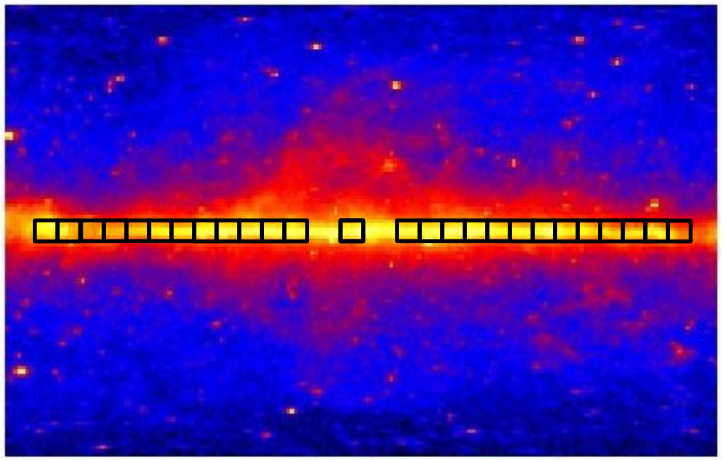
- Singlet Dark Matter [Profumo et al. (2010)]
- Hidden U(1) dark matter [Mambrini (2009)]
- Effective DM scenarios [Goodman et al. (2010)]
- "Higgs in Space!" [Jackson et al. (2010)]
- Inert Higgs Dark Matter [Gustafsson et al. (2007)]
- Kaluza-Klein dark matter in UED scenarios [Bertone et al. (2009)]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

Internal Bremsstrahlung / Cascade decays: Alejandro Ibarra & Miguel Pato

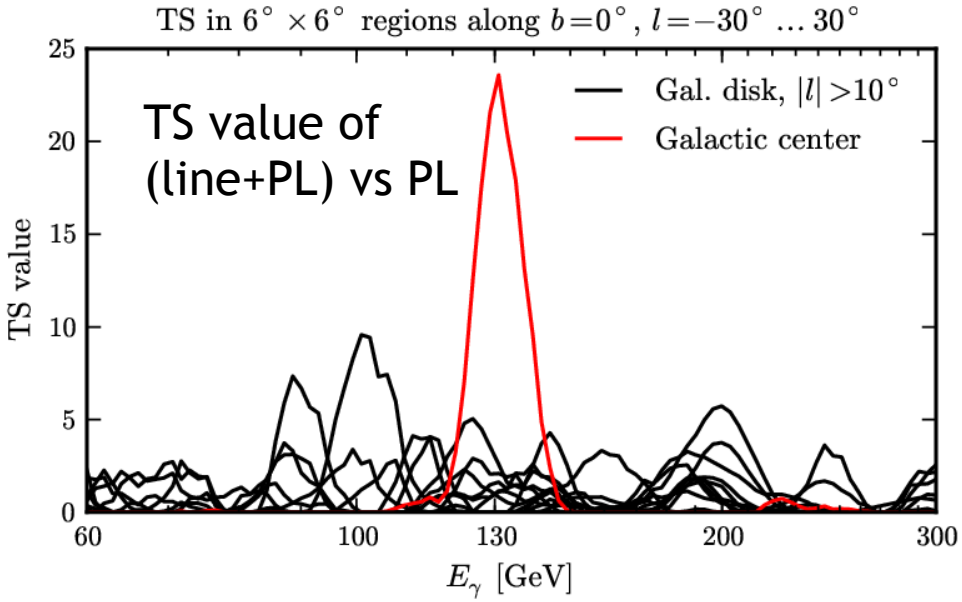
Feature properties

The signature is...

- ...only at the Galactic center (well, almost)



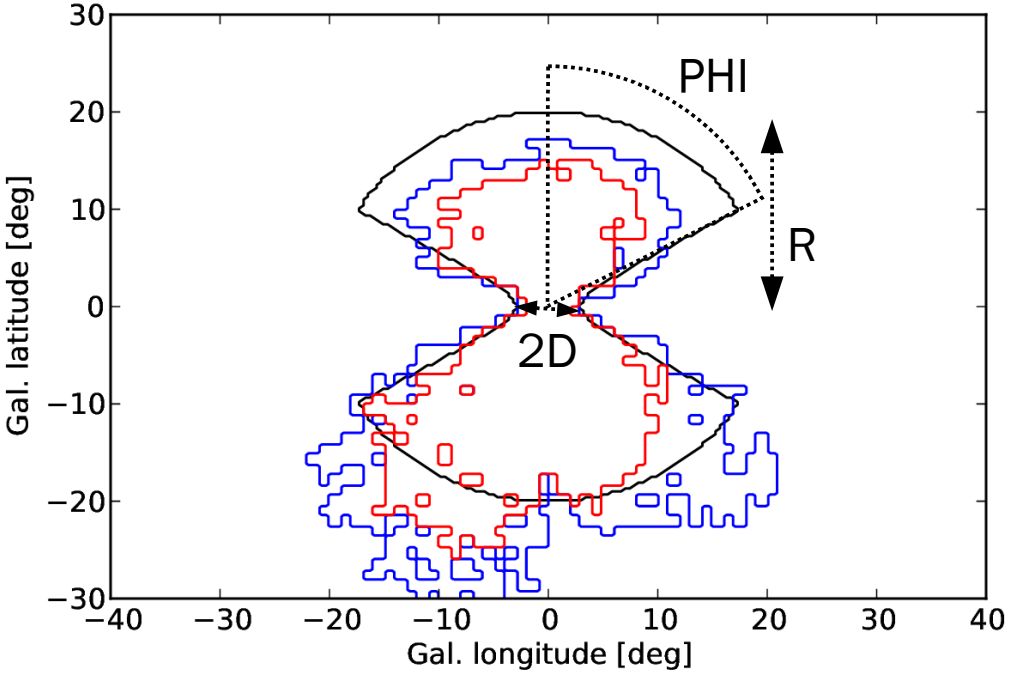
The signature does not reappear in other parts of the Galactic disk



- ...spatially extended: NOT a single or a few point sources [Tempel et al., Su & Finkbeiner, Bringmann & CW, Carlson et al.]
- ...displaced from the center westwards by ~1—2 deg: (at ~2σ CL) [Su & Finkbeiner]
- ...not alone: weak indication for a second feature at 114 GeV (<2σ CL) [Cohen et al., Rajaraman et al., Su & Finkbeiner]
- ...not complete: no associated continuum emission found so far [Buchmüller et al., Cohen et al., Cholis et al.]

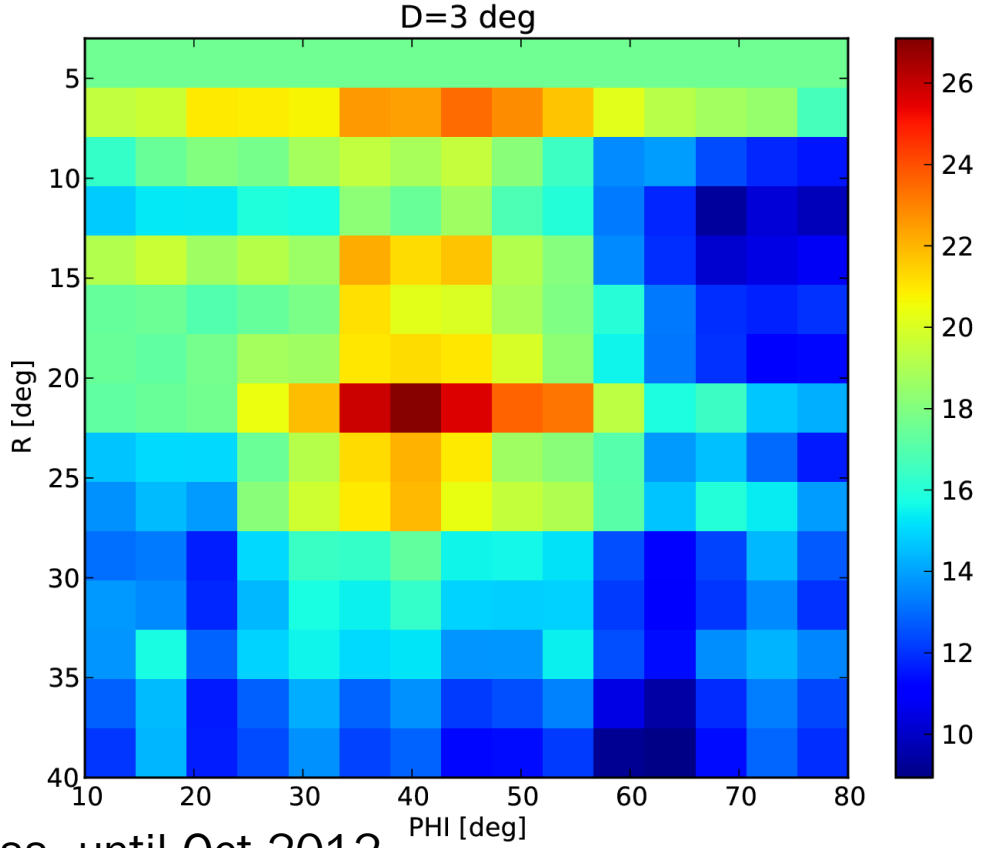
Ilias Cholis' talk

Feature properties



Scan over different hour-glass shaped ROIs:

Color: TS value for 130 GeV line



Highest significance obtained for regions with R~20 deg!
→ not just the inner few degree

CLEAN class, until Oct 2012

Seek and you shall find: Features around 130 GeV

- **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]

↓ - **Transient spectrum**
  16σ bump at 130 GeV

Instrumental effect?

Instrumental effects that can play a role

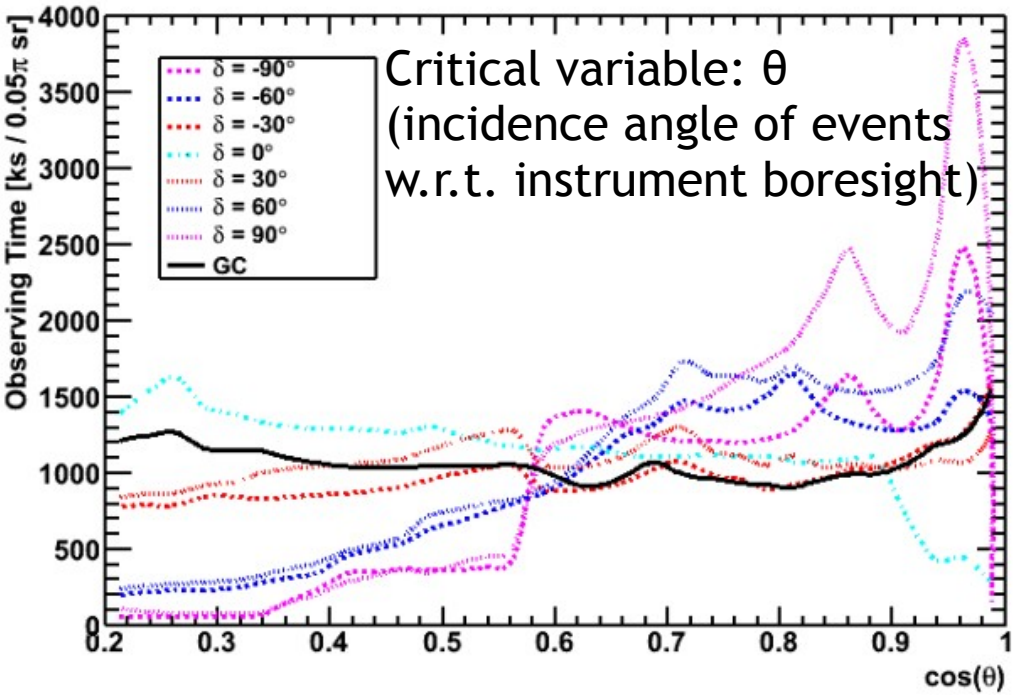
- Contamination with residual cosmic ray background in photon sample
  → Very unlikely. Should affect poles more than the GC.

- 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]

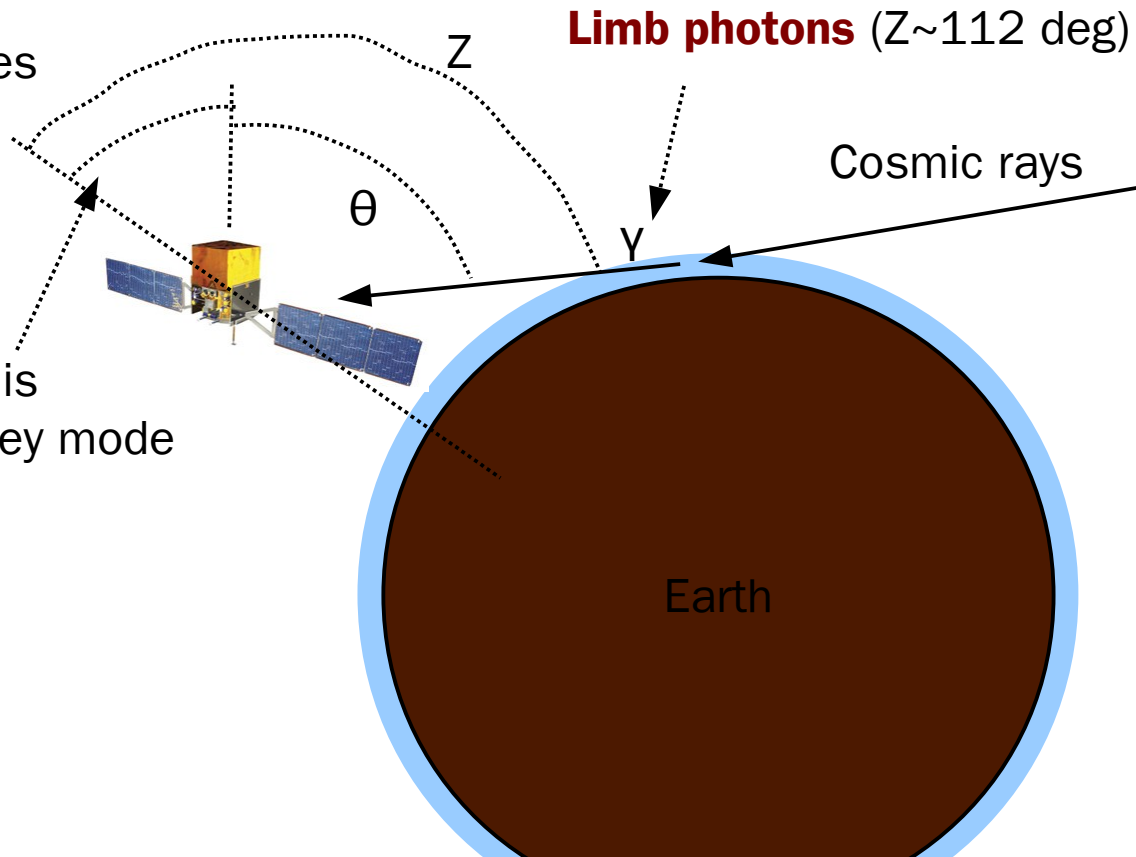
The Earth limb

Parameters:

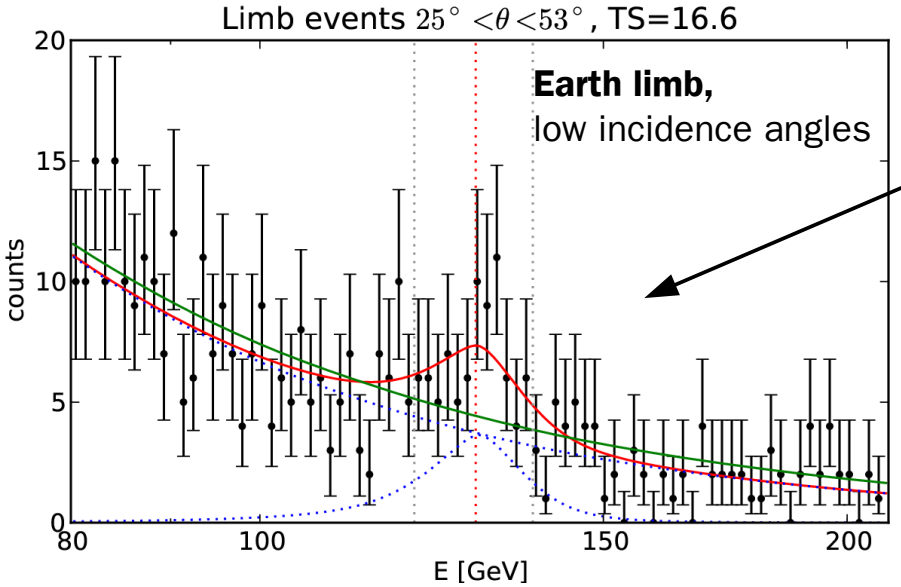
- Θ (incience angle): Polar coordinate of event in instrumental frame (w.r.t. LAT boresight)
- Z (zenith angle): angle between event and LAT zenith axis
- Rocking angle: angle between LAT boresight and zenith of LAT

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

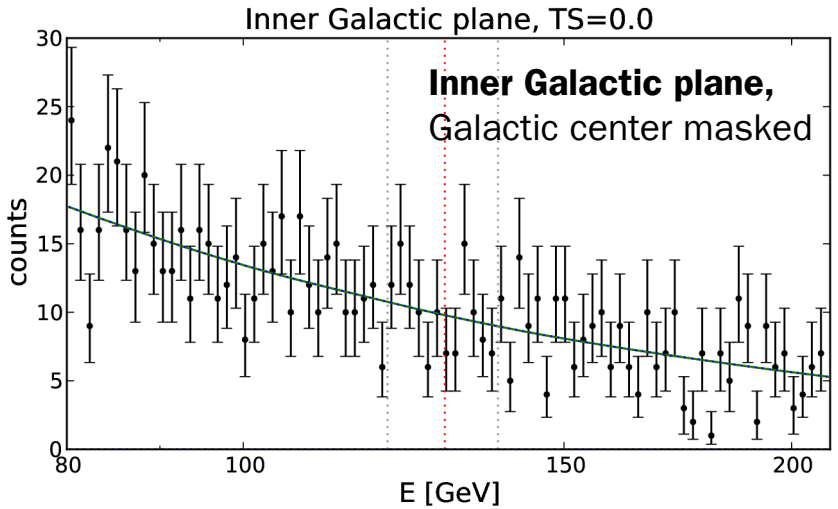


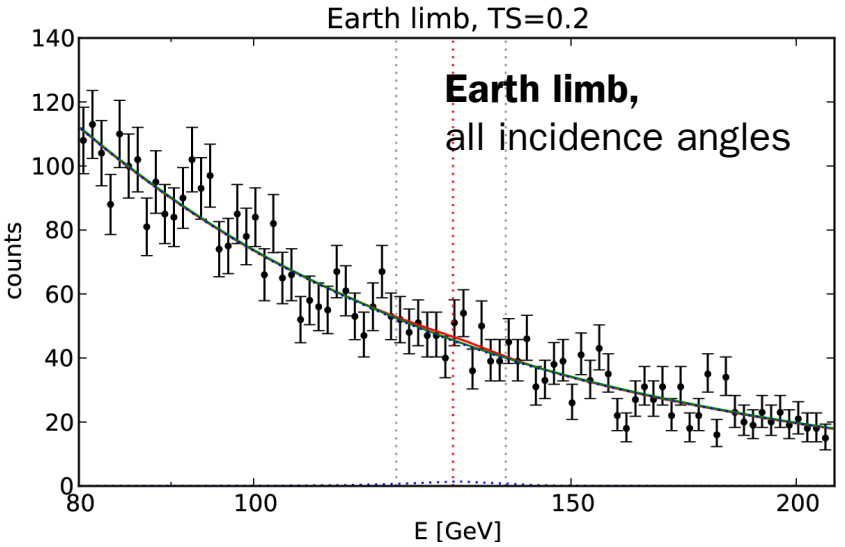
The Earth limb at low incidence angles
A red flag?



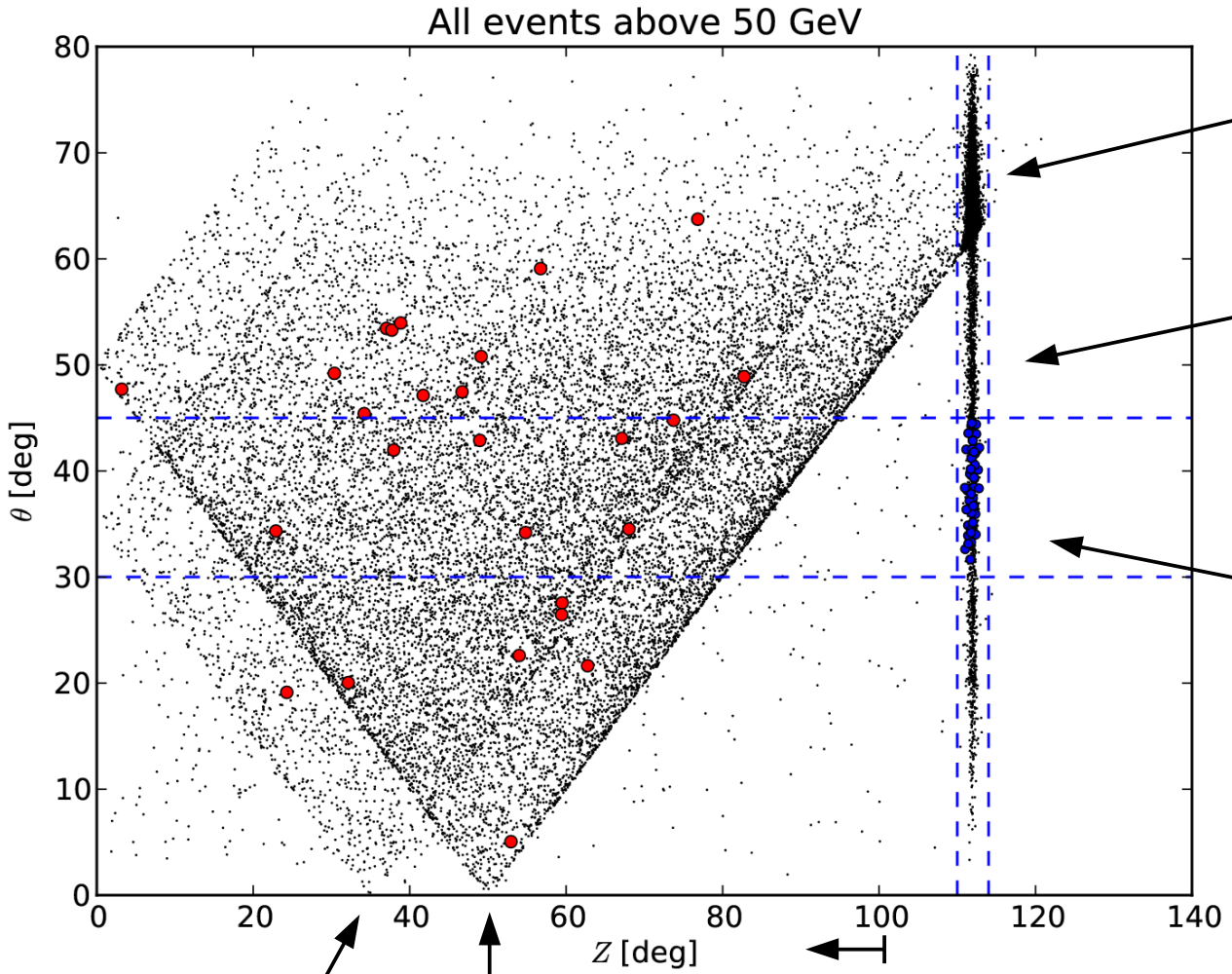
A 130 GeV feature in the low incidence angle Earth limb data!

BUT: Nothing in alternative test samples:





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)

"Bad incidence angles"

Events used in standard analyses

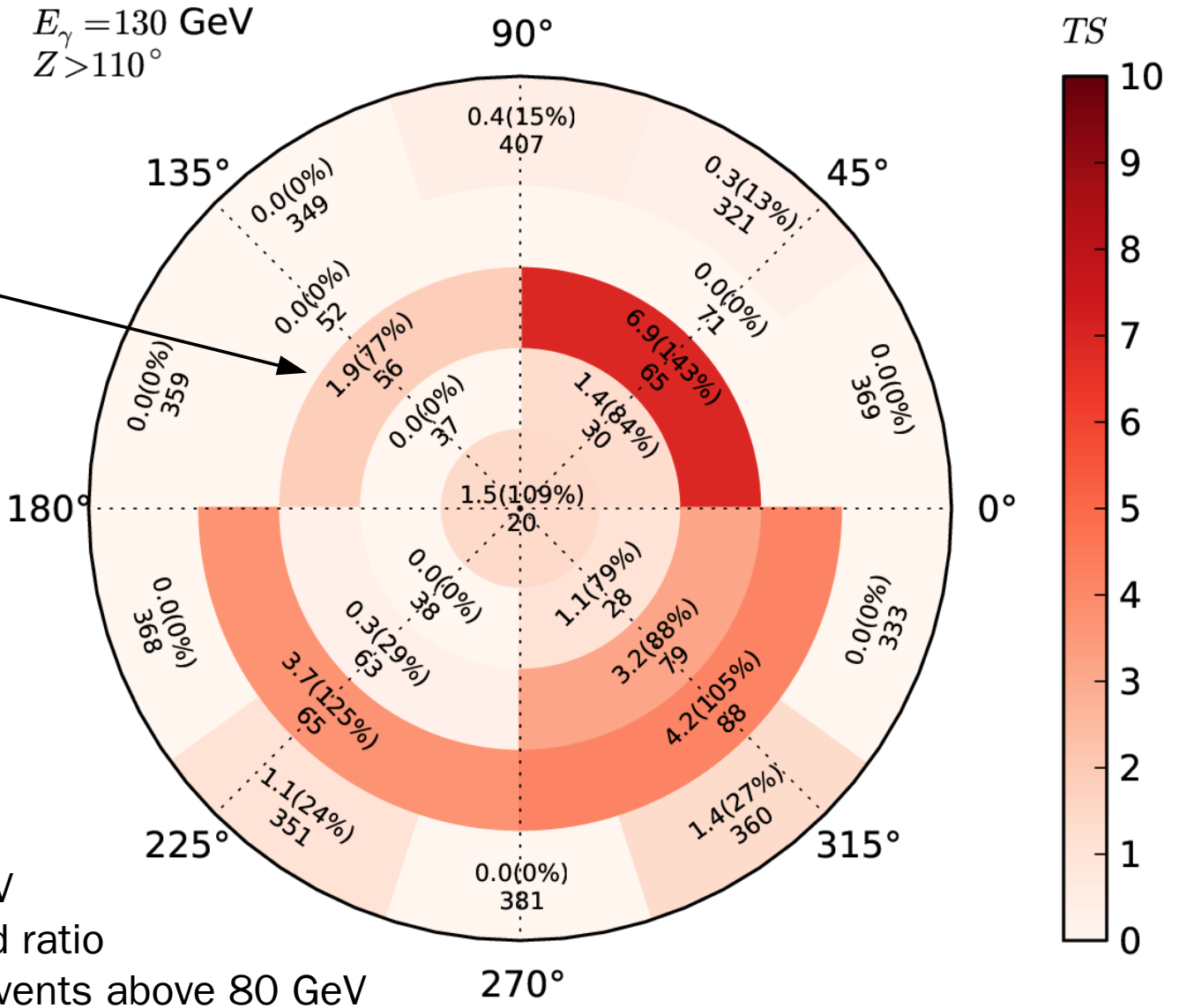
Rocking angle before Sep 2009

Rocking angle since Sep 2009

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

130 GeV lines in instrumental coordinates

Earth Limb:
Z>110 deg



Notation:
TS (S/B)
N(>80 GeV)

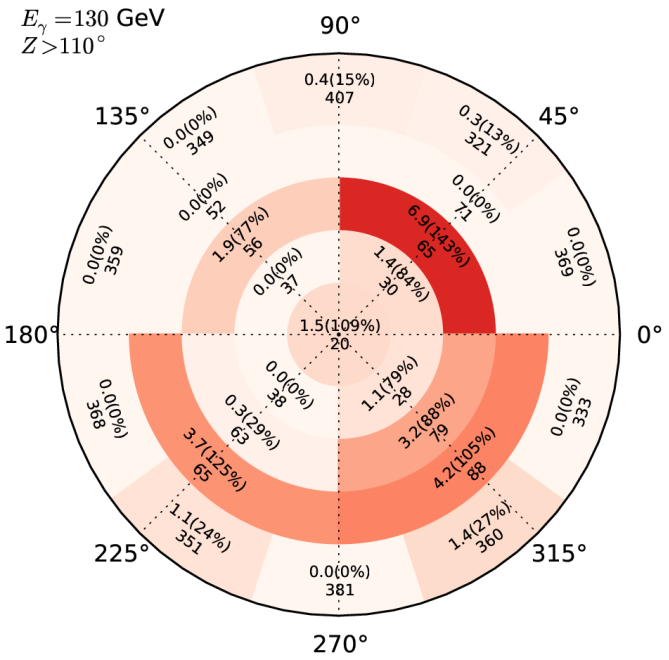
theta slices [deg]:
0, 15, 30, 45, 60, 80

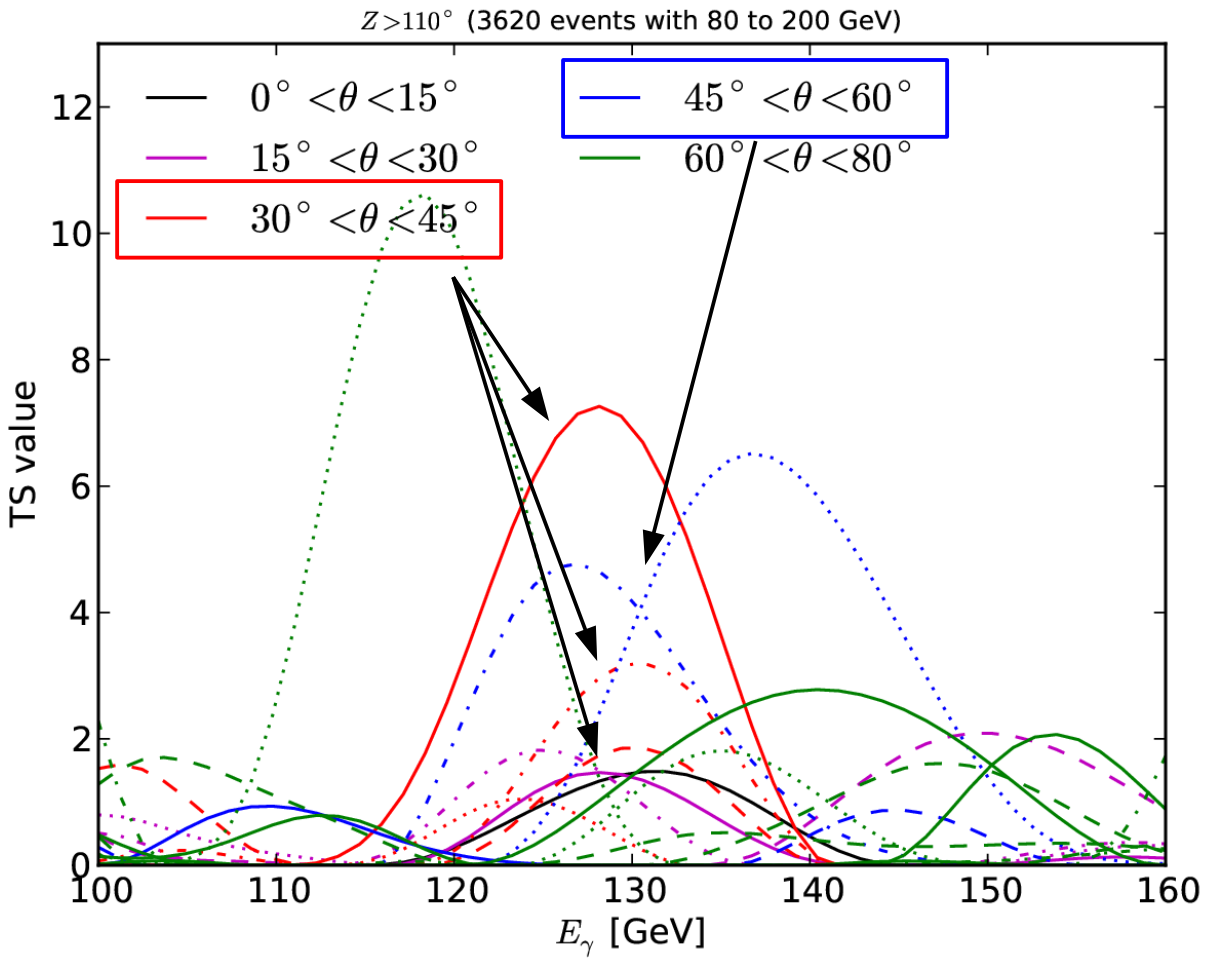
TS: TS for line at 130 GeV
S/B: Signal-to-background ratio
N(>80 GeV): number of events above 80 GeV

At incidence angles (theta) ~30 – 60 deg, there are indications for 130 GeV lines

The Earth limb

Earth Limb:
Z>110 deg



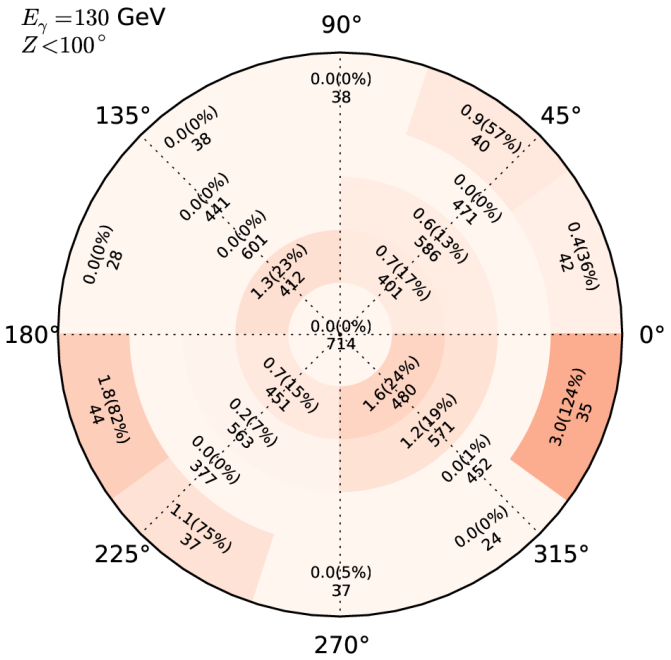


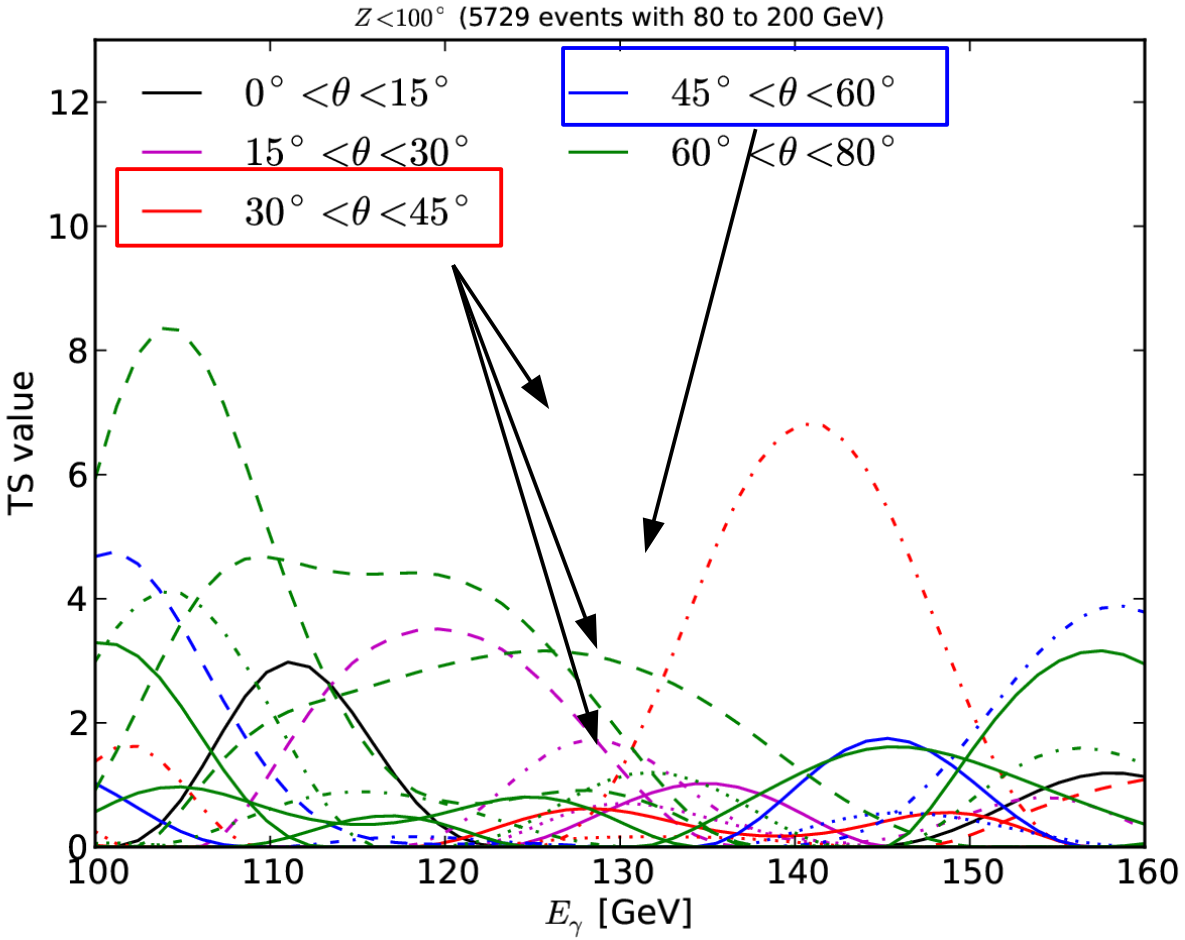
Number of events
at theta ~ 30 – 60 deg:
N(>80 GeV) = 539

Scanning from 100 to 160 GeV reveals **>2σ bumps** at 130 GeV in multiple incidence angle patches with theta ~ 30 – 60 deg

A much larger test sample: The rest of the sky

Standard analysis
cuts: Z<100 deg





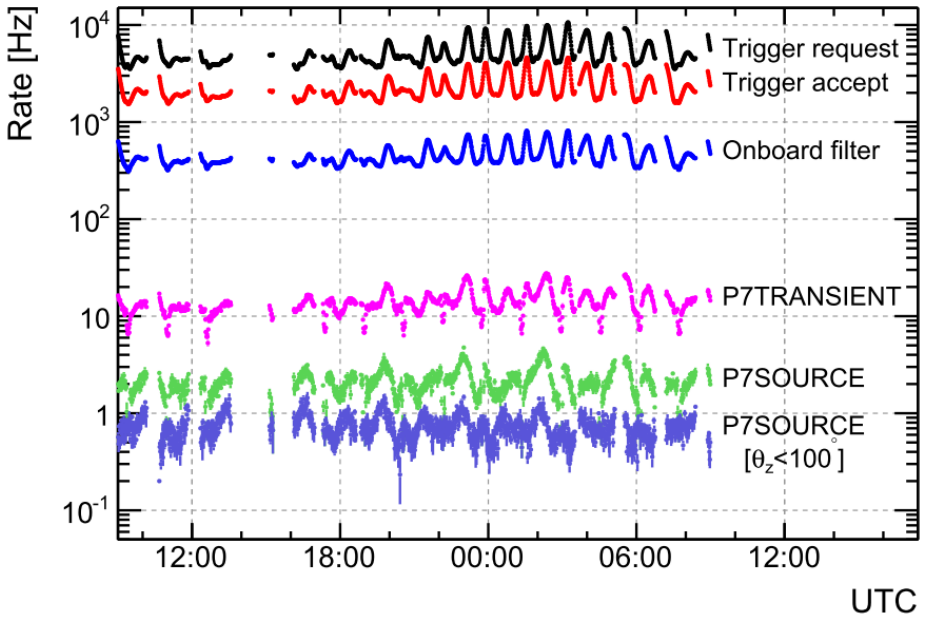
Number of events
at theta ~ 30 – 60 deg:
N(>80 GeV) = 4061

Scanning from 100 to 160 GeV reveals **~<1σ bumps** 130 GeV in multiple incidence angle patches with theta ~ 30 – 60 deg
Expected: 4.6 – 6.5σ !

Why at the Galactic center?

Argument I: The Galactic center is brightest spot in the sky (similar to Earth limb)
→ Instrumental effects most significant there.

But: Photon trigger rate ~1 Hz. Effects should be linear. Larger samples show nothing (see above).



Why at the Galactic center?

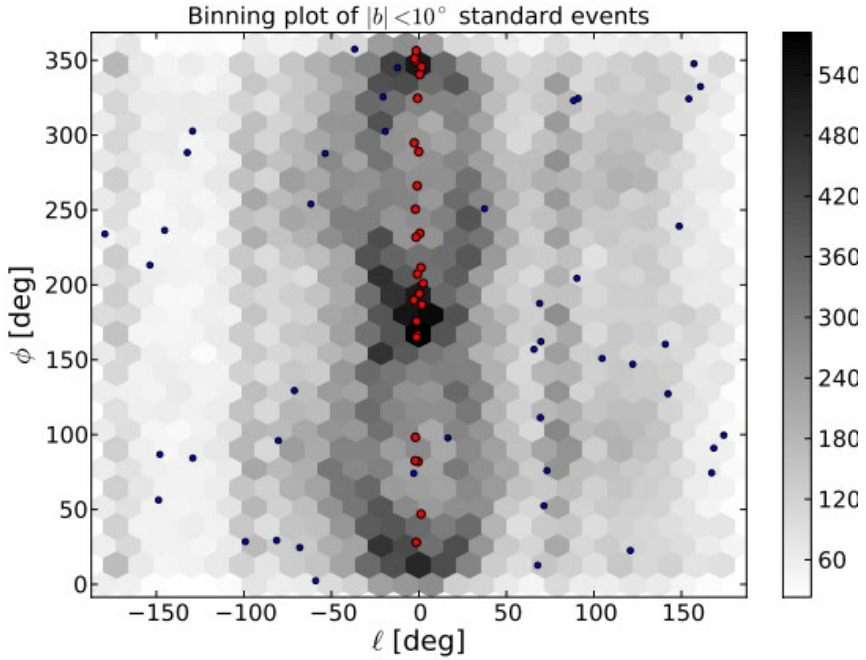
Argument II: Galactic center spectrum is hard → Energy remapping more significant there

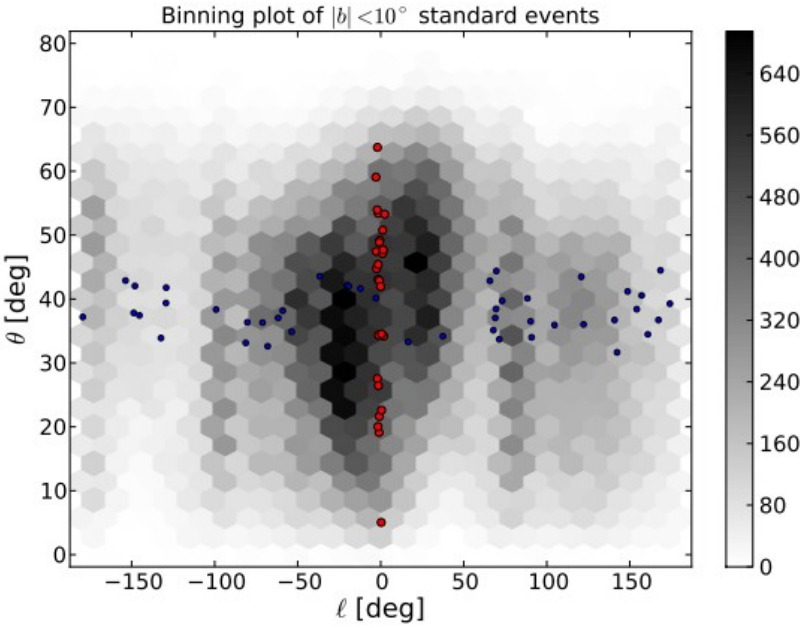
Sample	$N(> 100$ GeV)	$\frac{N(>100 \text{ GeV})}{N(>30 \text{ GeV})}$	$\frac{N(>300 \text{ GeV})}{N(>100 \text{ GeV})}$
Standard events	5093	13.4%	9.6%
Inner Galactic plane	703	16.9%	9.8%
Galactic center	82	17.4%	9.8%
Galactic center line	26	–	–
Earth limb	3120	10.2%	9.2%
Earth limb line	45	–	–

But: spectral slope does not vary more than 10% in different test regions.

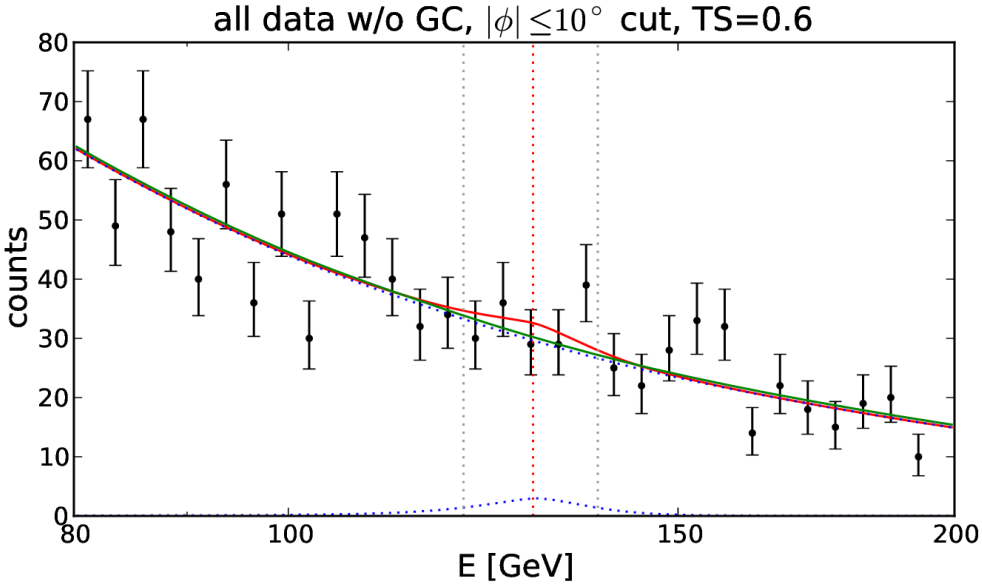
Why at the Galactic center?

Argument III: Galactic center is observed under complex incidence angle distribution
This is true for azimuth (solar panel alignment), but not for polar incidence angle.
→ Instrumental effect dominantly visible under specific incidence angles





BUT: selecting only
phi~0, 180deg events does
not reveal any line feature



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**

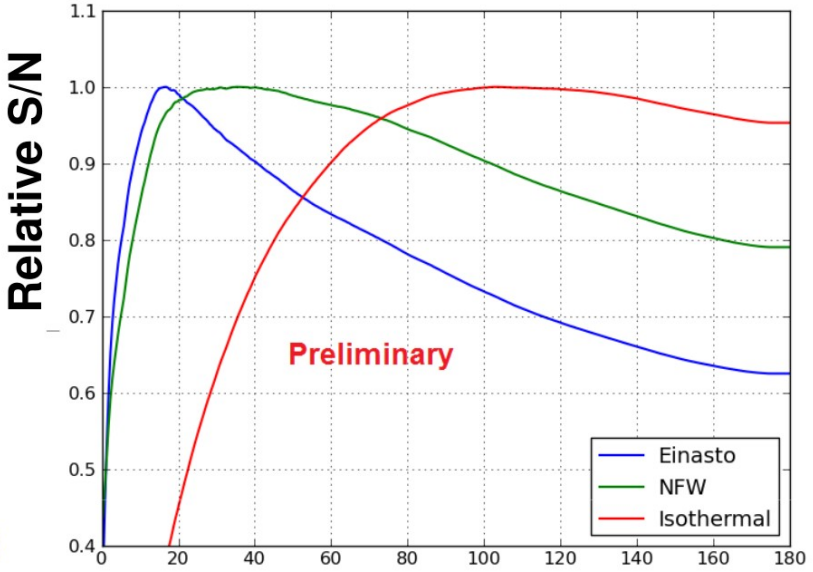
→ They use **different ROIs and different data**, so results are right now impossible to confirm independently. Release of P7rep expected ~~end of 2012~~ ~~in a few weeks~~ in a few months

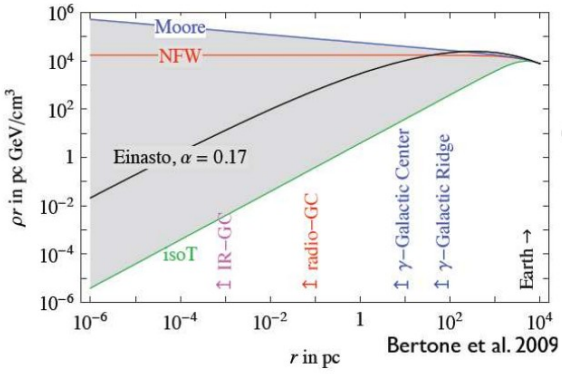
[For details see talks by Eric Charles, Elliott Bloom and Andrea Albert; Fermi Symposium 2012]

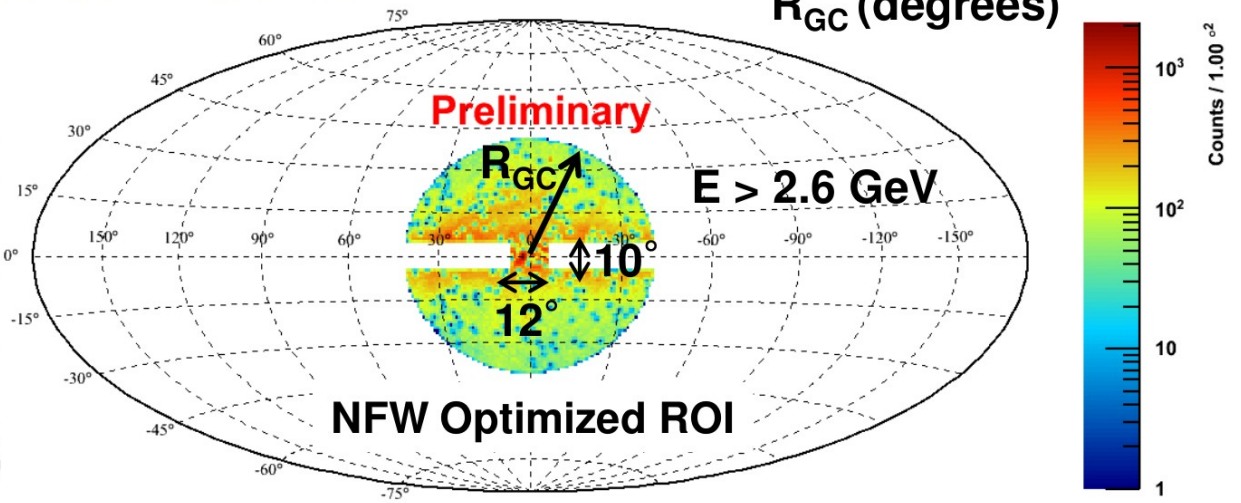
[Slides from A. Albert; Fermi Symposium 2012]

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)



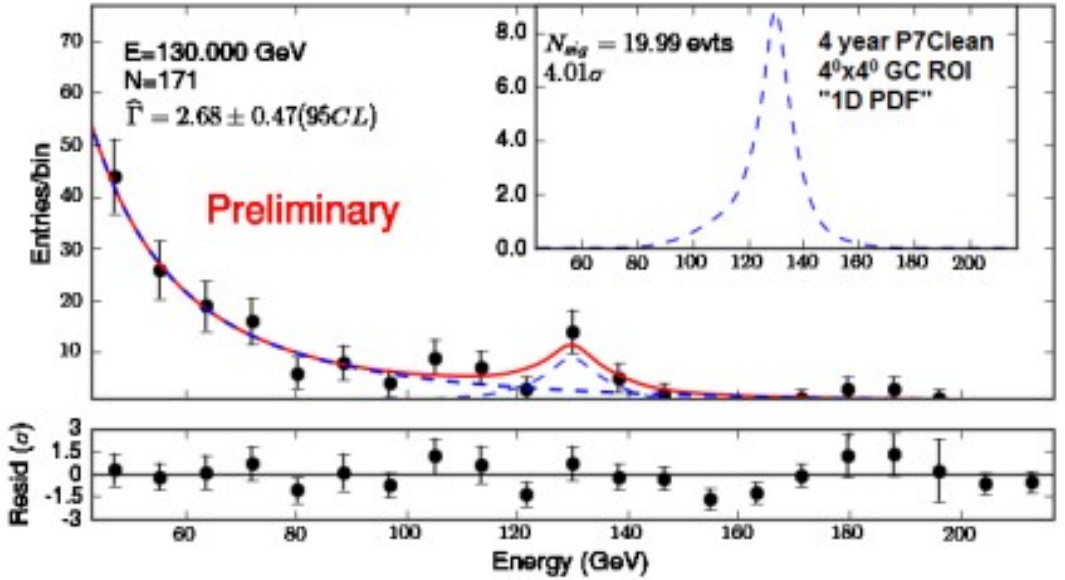




[Slides from A. Albert; Fermi Symposium 2012]

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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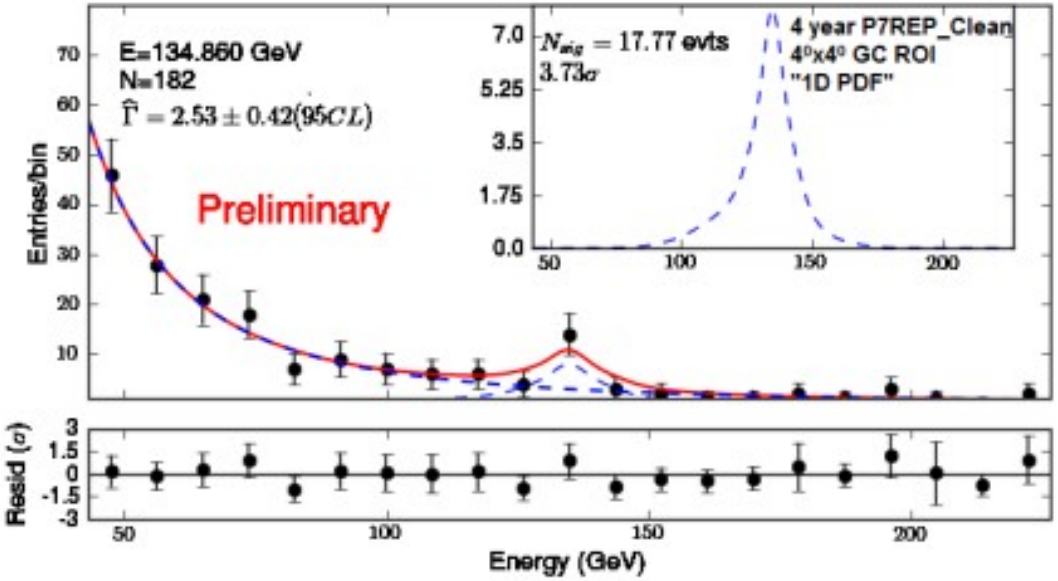
  - Use 1D PDF (no use of P_E)



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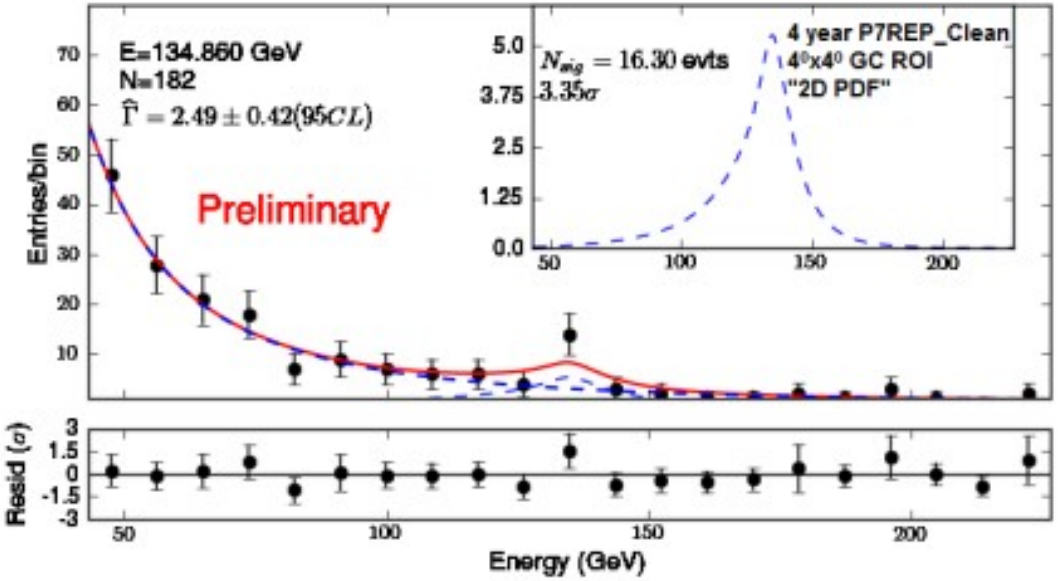
- 3.73σ (local) 1D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 1D PDF (no use of P_E)
- 3.35σ (local) 2D fit at 135 GeV with 4 year reprocessed data
  - Look in 4°x4° GC ROI
  - Use 2D PDF
    - P_E in data → feature is slightly narrower than expected
  - <2σ global



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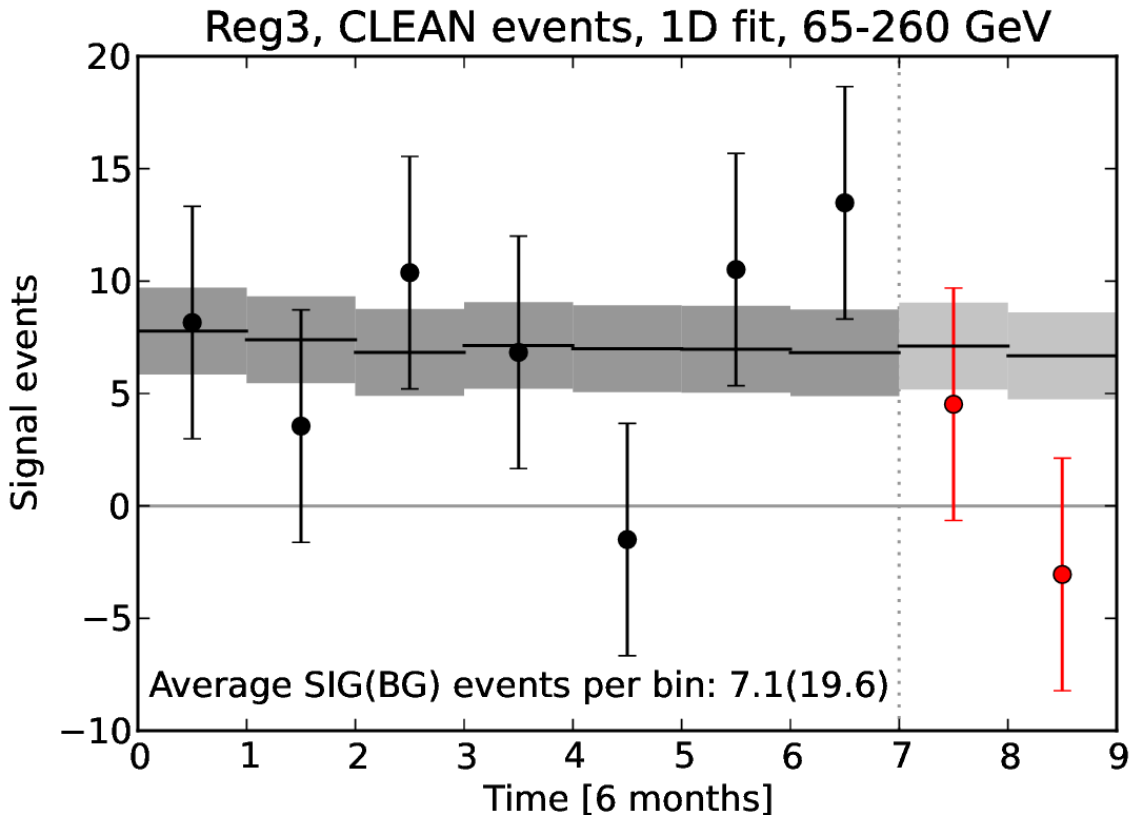
Not one of our a priori ROIs

Effective number of signal events after Feb 2012 (Reg3, CLEAN class)



Number of events in signal region (determined by likelihood fit) from 4 February 2012 to 4 February 2013:

Observed: 1.5
Expected: 14.2±3.7±7.3

→ A statistical fluke? Need more data.

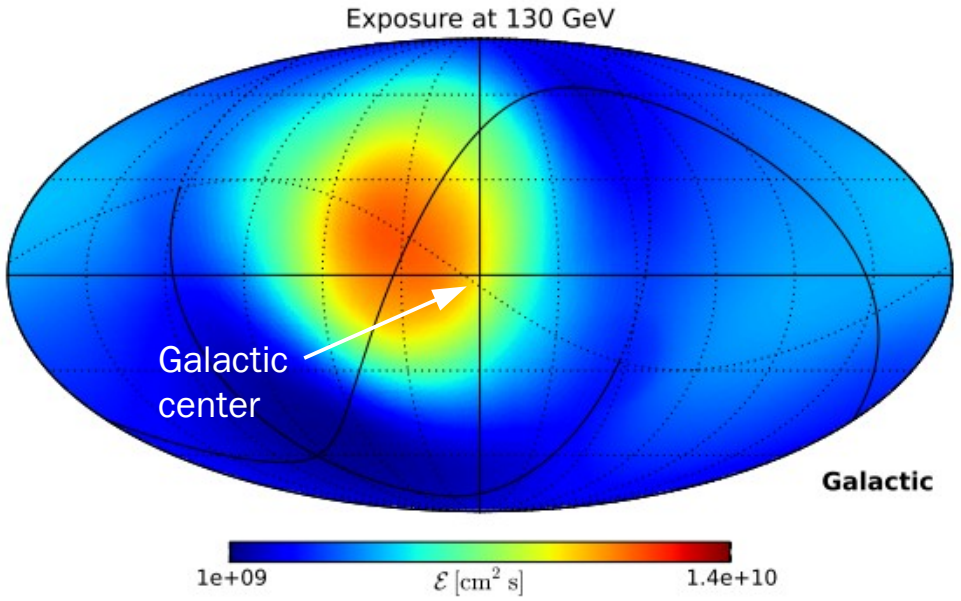
An alternative observation strategy

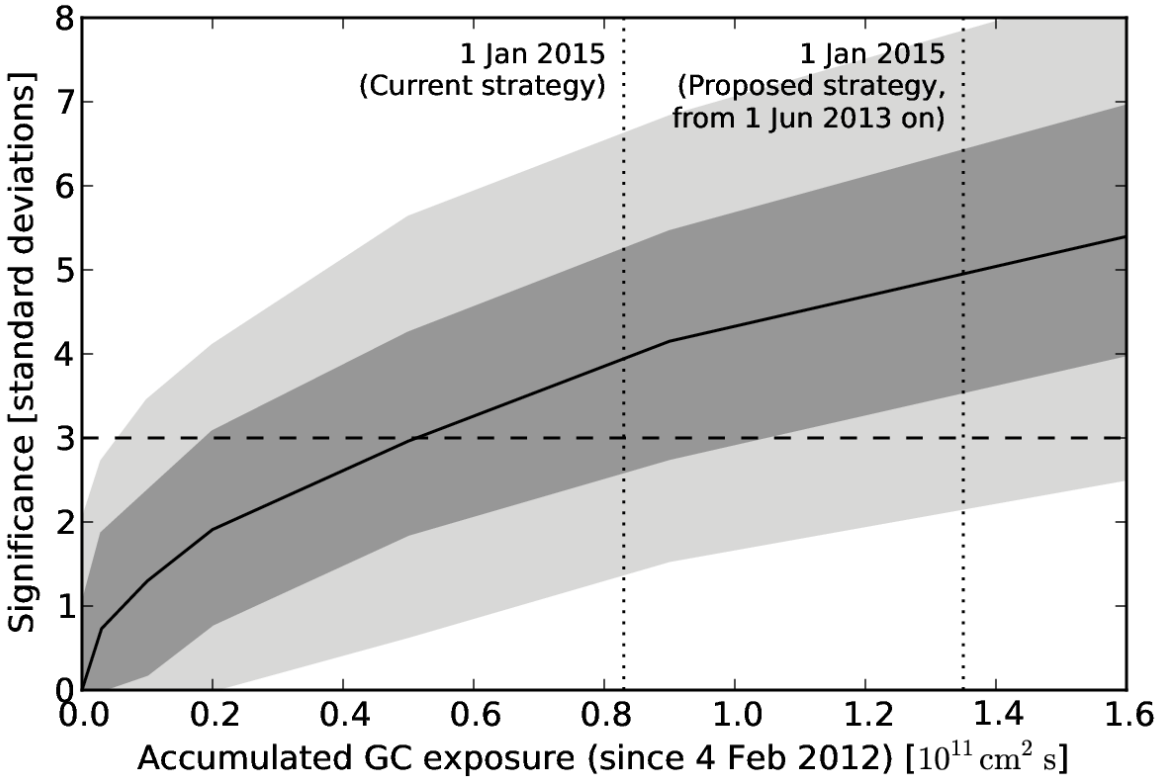
The worst case scenario: LAT mission stops and situation remains unclear
→ change in observation strategy now.

FGST operates in survey mode more than 90% of time
- full sky coverage every 3 hours
- uniform sky exposure after 55 days

Our proposal: "mixed observation"
- slew towards GC if it is above horizon
- otherwise regular survey mode

Expected features:
- GC exposure increases by factor ~2.2 → will allow confirmation / rejection of line hypothesis until end of 2015 with >3σ significance
- full sky coverage every day
- no region looses more than x2 exposure
- angular integrated exposure remains the same
- 5x faster accumulation of low-incidence angle Earth limb data





Conclusions

- Instruments just start to probe interesting parameter space. More to come from Fermi, H.E.S.S., VERITAS, MAGIC, CTA

- DM signal hints at Galactic center cover three orders of magnitude: 10 GeV, 130 GeV & 1-10 TeV

- The LAT data contains a significant spectral 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, transient spectrum)
  - 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** (not another DAMA/LIBRA)
  - Fermi LAT could do it!
    → more data until at least 2016, PASS8, GC observations?
  - more to come from HESS-II, GAMMA-400