A modified survey strategy for Fermi

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White paper discussion

Outline

- Our perspective on the 130 GeV feature
  - April – June 2012
  - Developments afterwards
  - Situation now

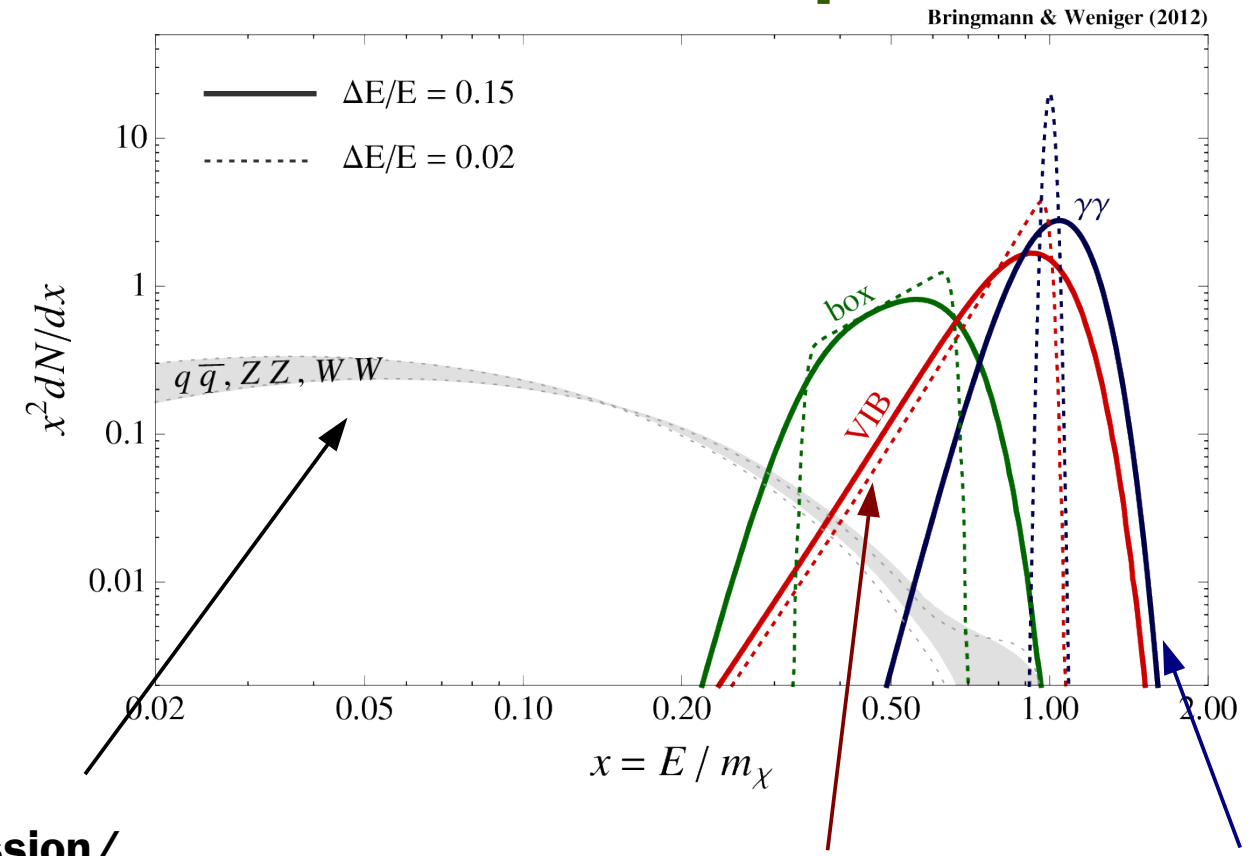
- Impact of “option3” or “option4” on
  - 130 GeV feature
  - Other dark matter searches
  - Further science goals

- Summary

130 GeV feature I

April - June 2012 (public data)
discovery of a beautiful line feature

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)

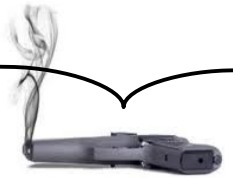
- radiative correction to processes with charged final states
- Generically suppressed by O(α)

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

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)

Gamma-ray flux measured by the LAT inside the ROIs

[Bringmann et al., CW Feb + Apr 2012]

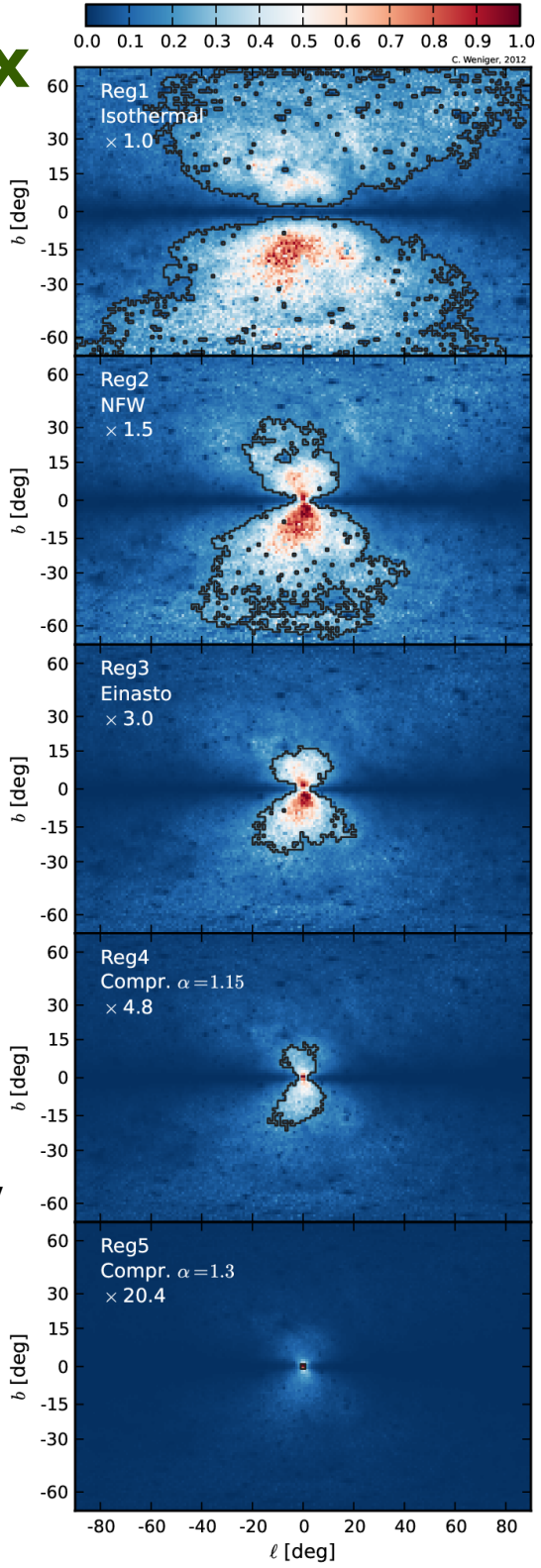
<u>CLEAN vs SOURCE at 130 GeV:</u>

Aeff_SOURCE/Aeff_CLEAN~1.12

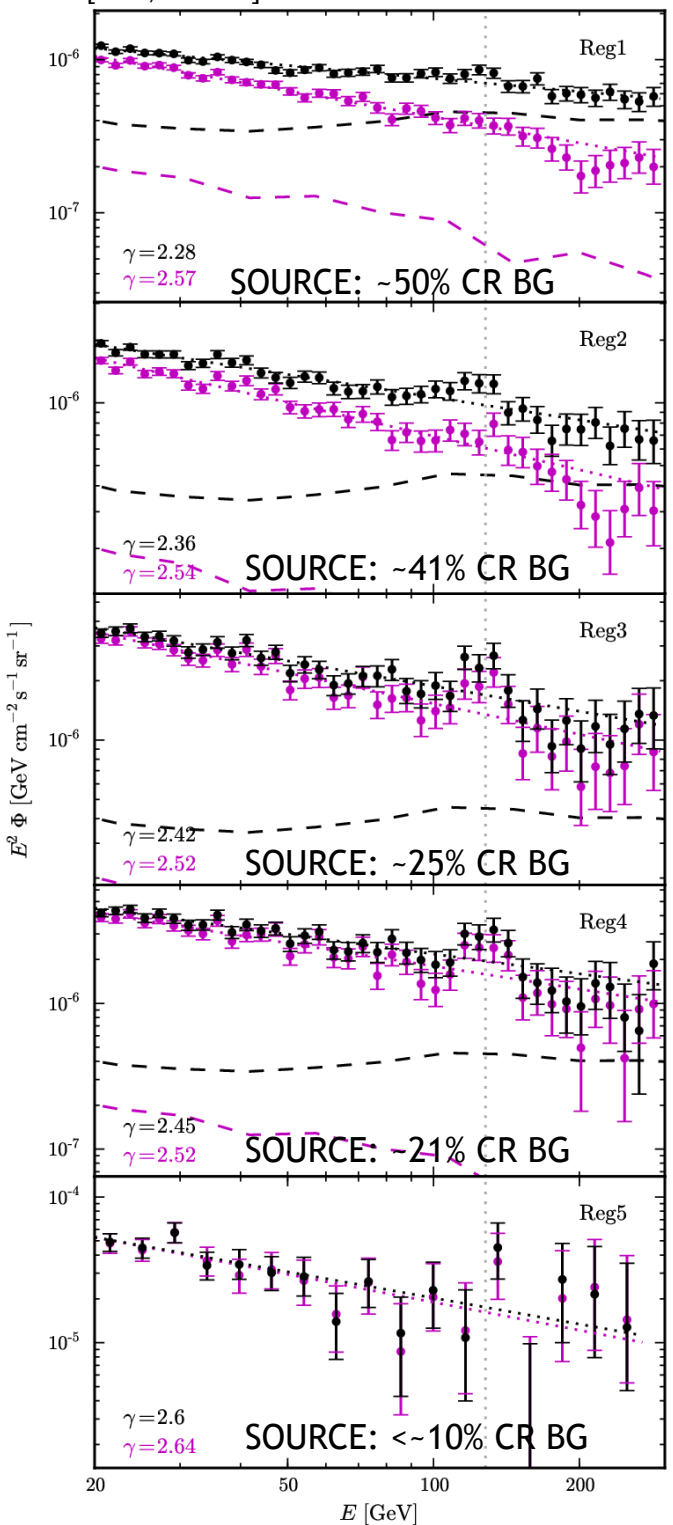
(S/N)_SOURCE/(S/N)_CLEAN~0.9-1.1

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



[CW, 2012]

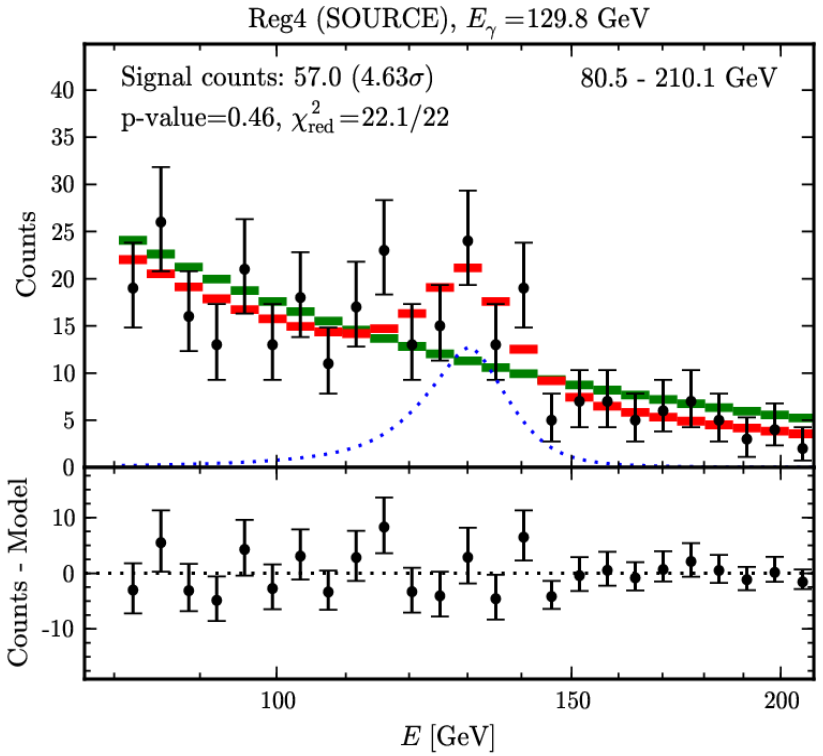


Two event classes:

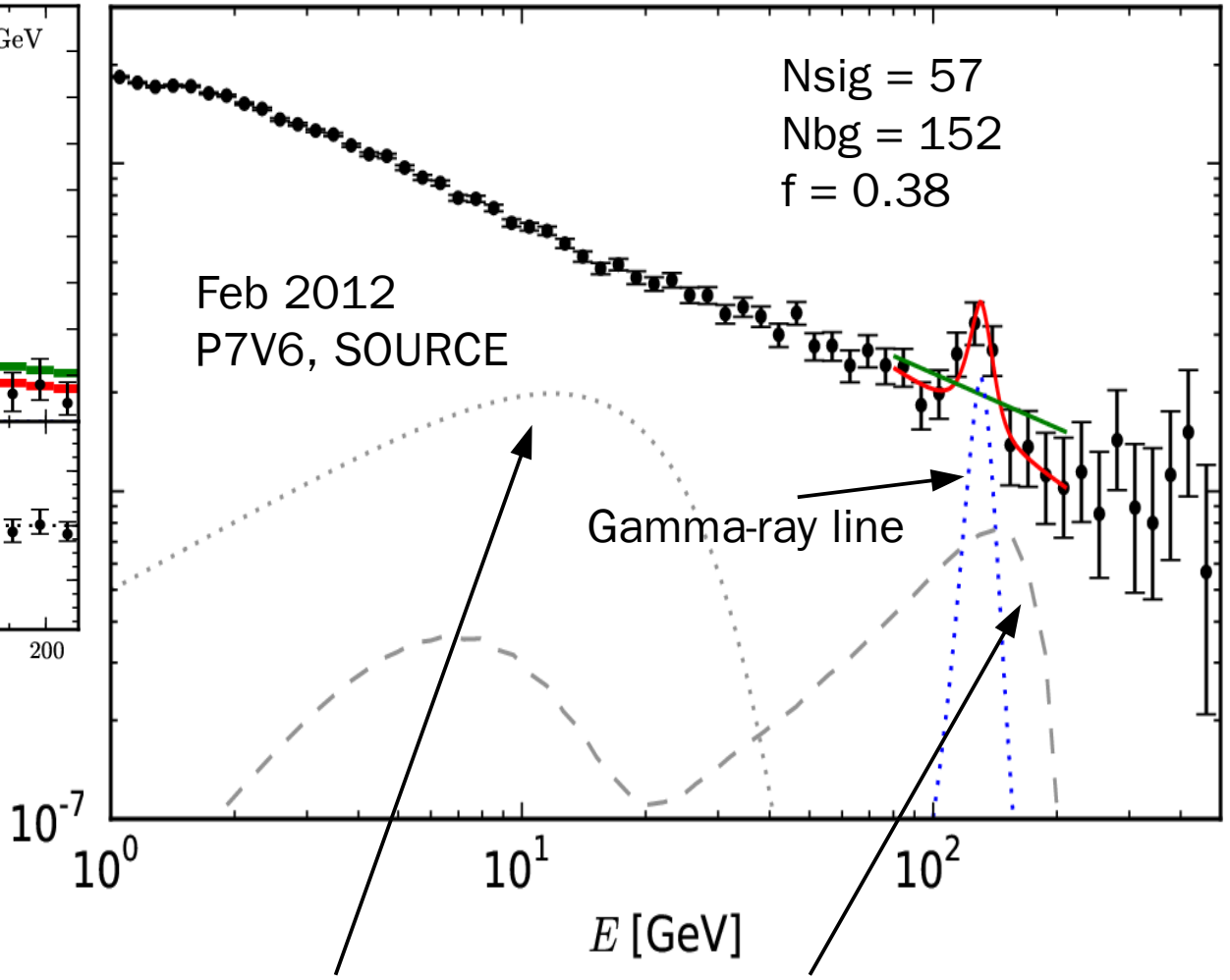
SOURCE

ULTRACLEAN (= CLEAN >50 GeV)

A line feature at 130 GeV



4.6σ significance
(3.2σ after trial correction)



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

Superexponential cutoff

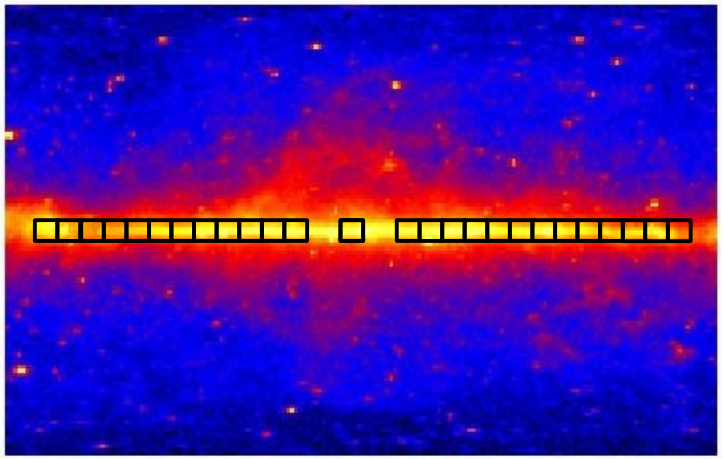
Inverse Compton emission from 230 GeV electrons at GC

"Fractional signal":

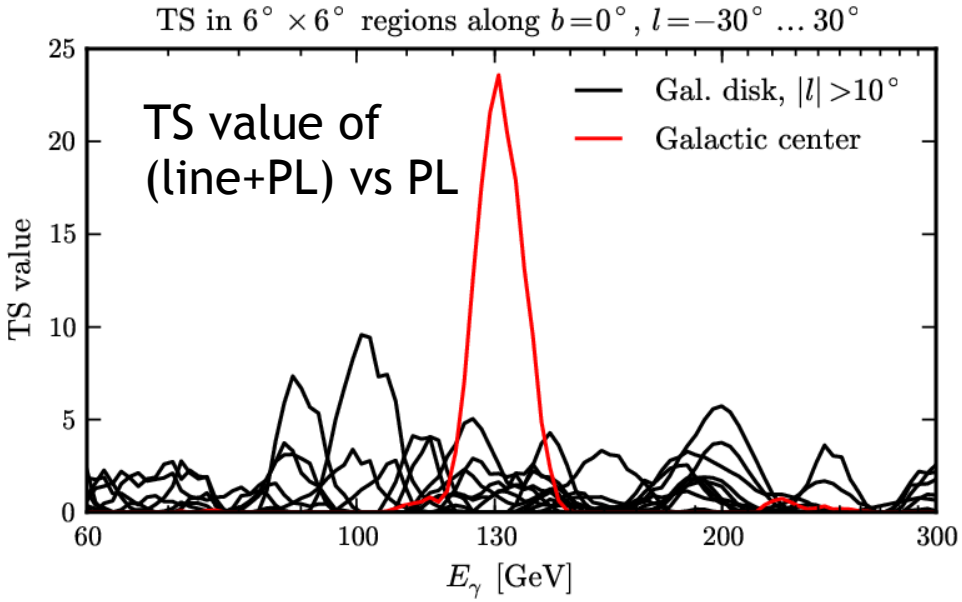
$$f = \frac{n_{\rm sig}}{b_{\rm eff}} \simeq \frac{TS}{n_{\rm sig}}$$

Spatial properties

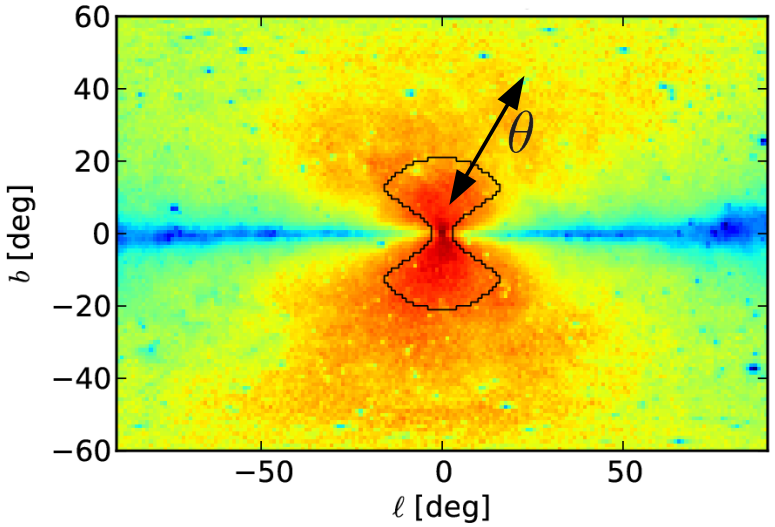
At Galactic center only:



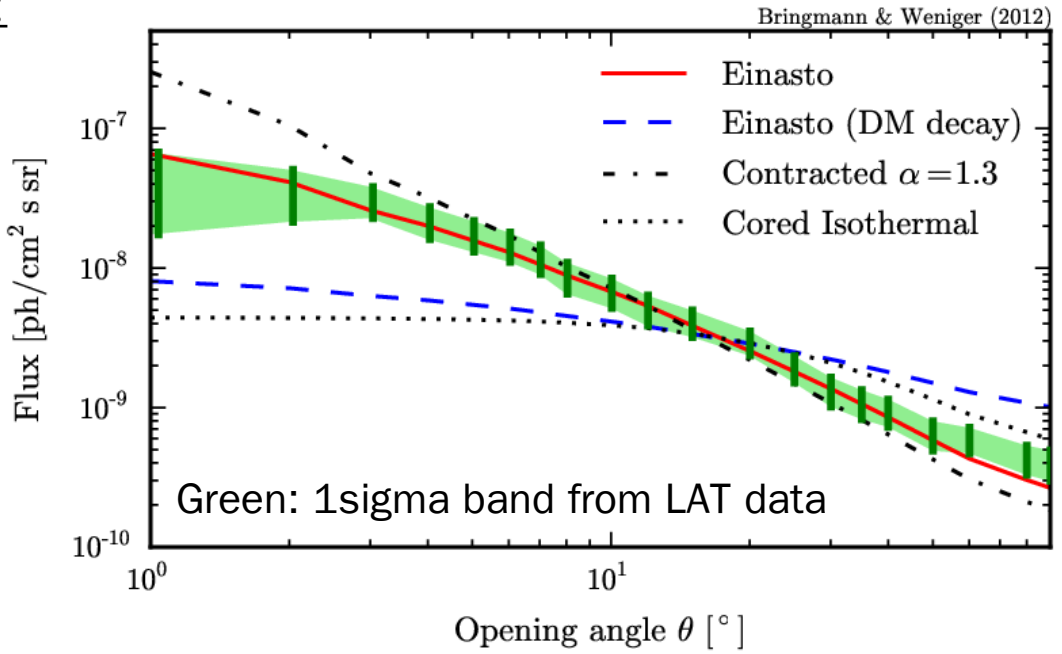
The signature does not reappear in other parts of the Galactic disk



Compatible with Einasto DM profile:

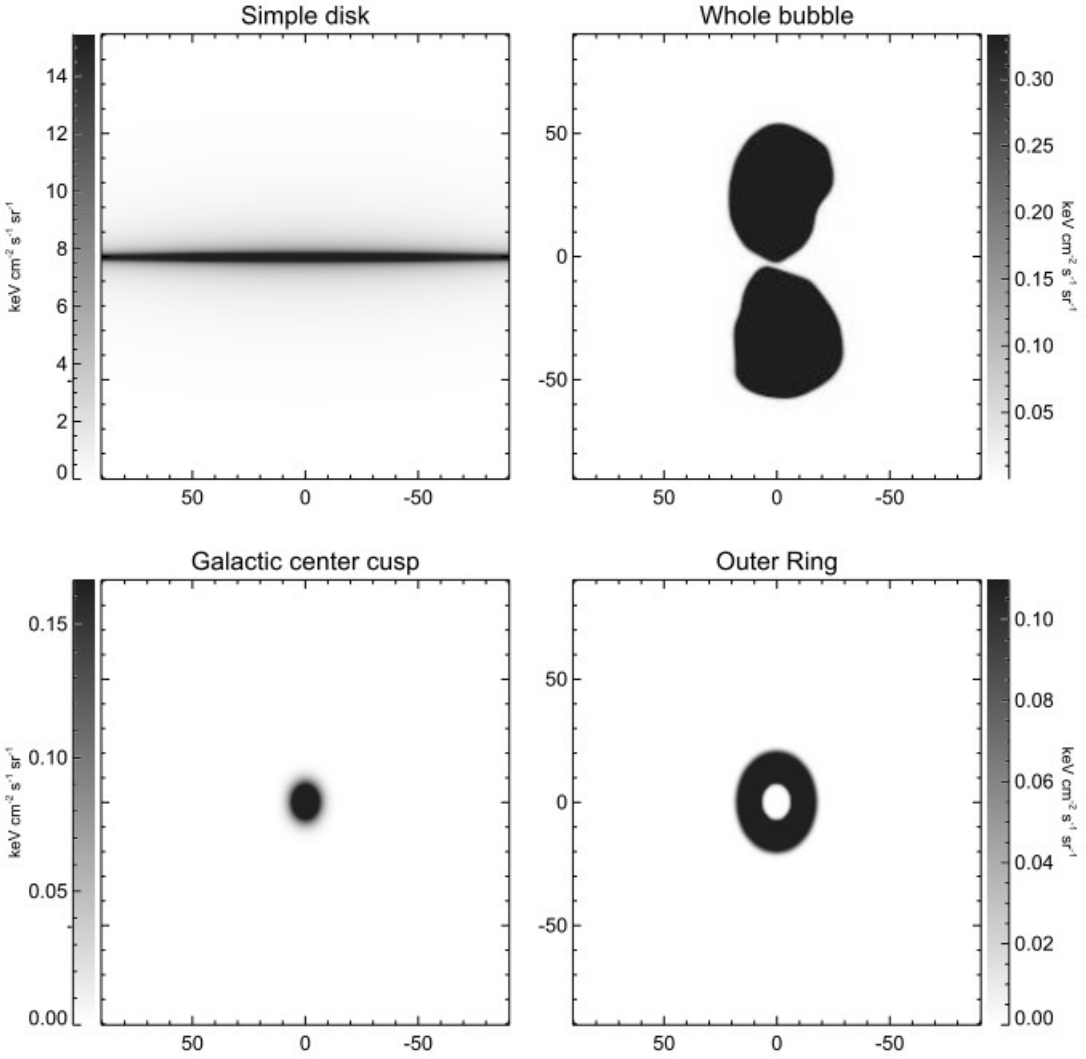


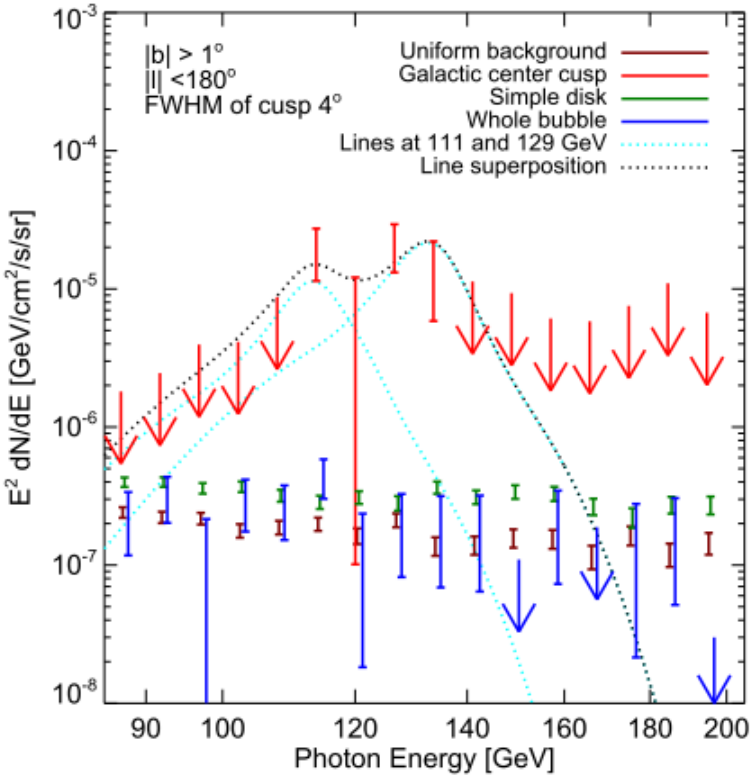
A scan over different target regions shows that signal morphology is compatible with expectations for DM signal



Template Regression Technique

[Su & Finkbeiner, Jun 2012]





- Better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5σ (5.0σ/5.4σ after trials factor correction for one/two line case).
- A pair of lines at 110.8±4.4 GeV and 128.8±2.7 GeV provides a marginally better fit.

130 GeV feature II

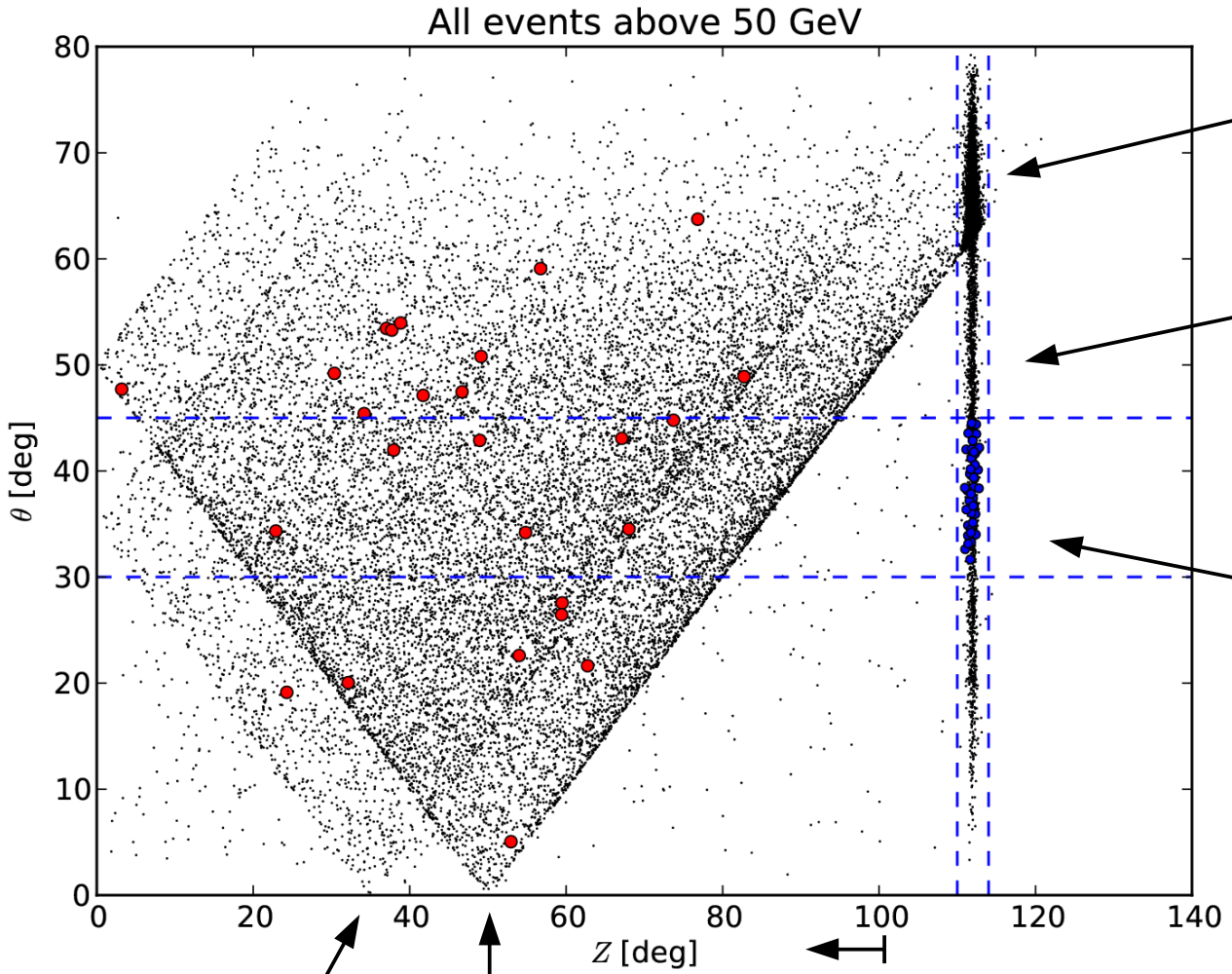
July 2012 – May 2013 (public data)
follow up investigations

List of identified 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, Fermi coll., 2013]
- **- Earth Limb line**
  A >3σ line at 130 GeV in low-incidence-angle Earth limb data
  [Finkbeiner et al., Hektor et al., Fermi coll., 2013]
- **- 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 2013]
- **The Sun**
  3.2σ indication for a ~130 GeV line in a 5deg circle following the Sun
  [Whiteson 2013]

But: there are also many places where the feature is <u>not</u> seen.

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"

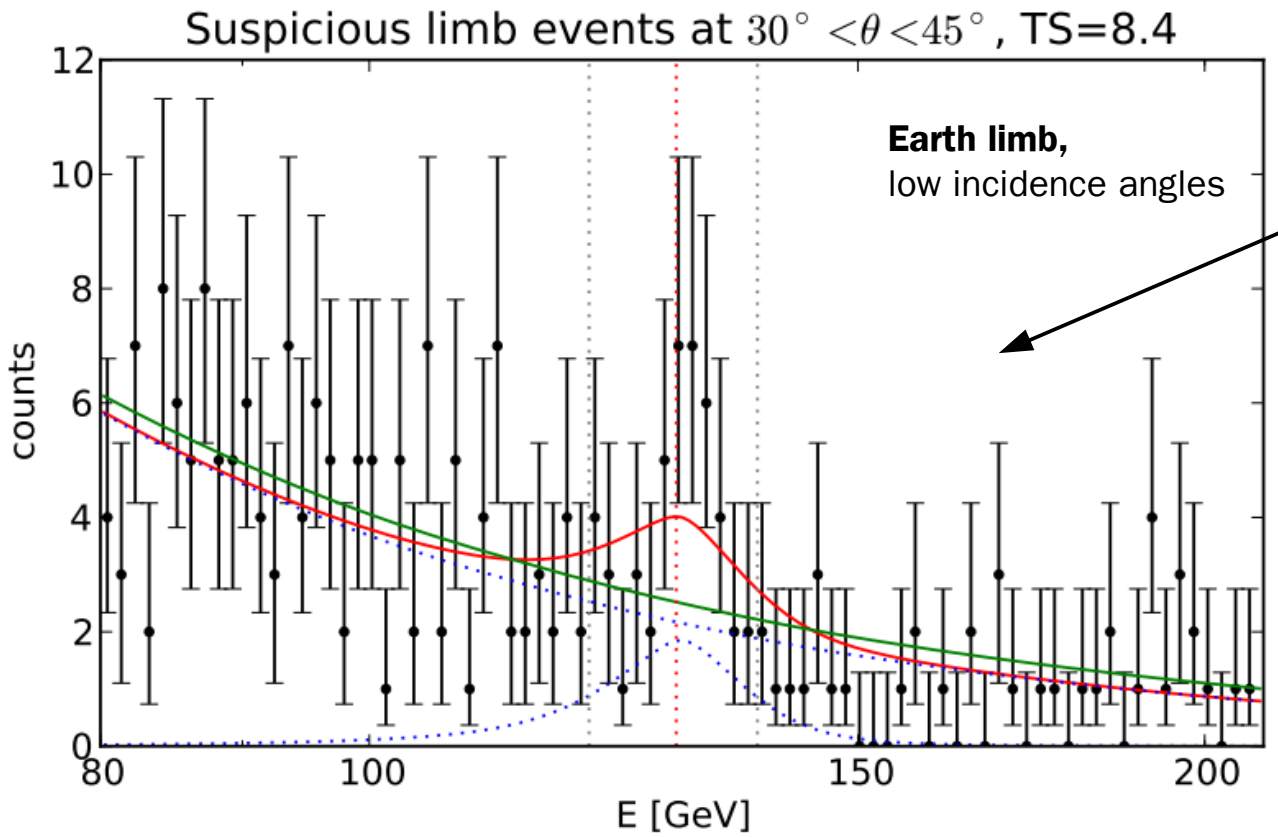
Events used in standard analyses

Rocking angle before Sep 2009

Rocking angle since Sep 2009

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

An instrumental effect? The 130 GeV excess in low incidence angle Earth limb data.



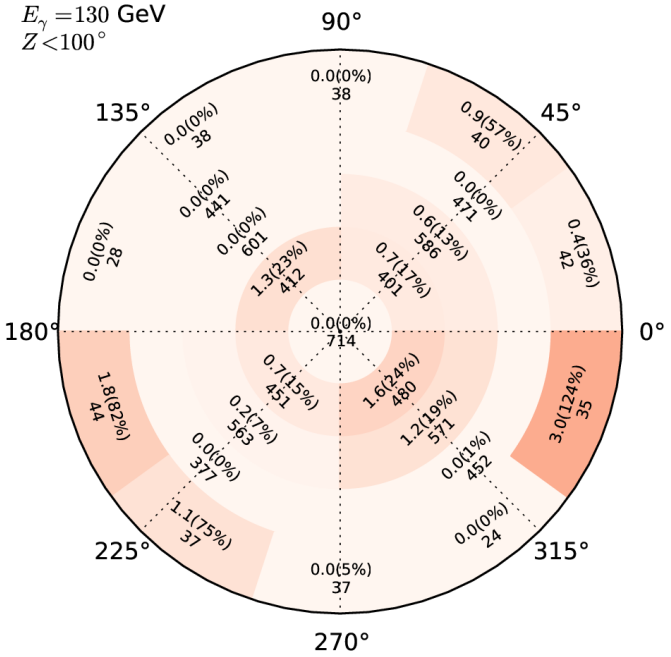
A 130 GeV feature in the low incidence angle Earth limb data!

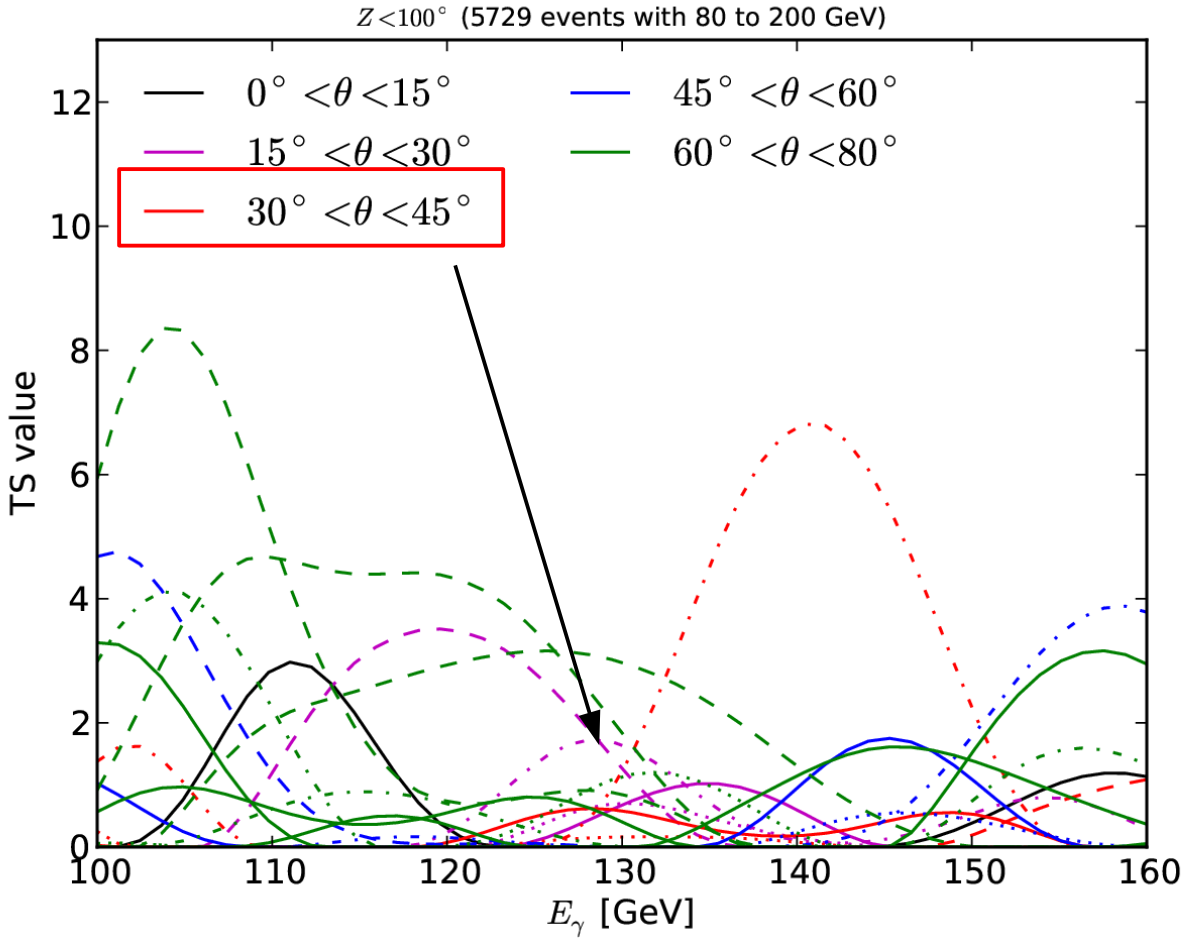
Significance depends on cuts. 2.9 sigma in P7V6.

[Finkbeiner et al. 2012]

The rest of the sky

Standard analysis
cuts: Z<100 deg



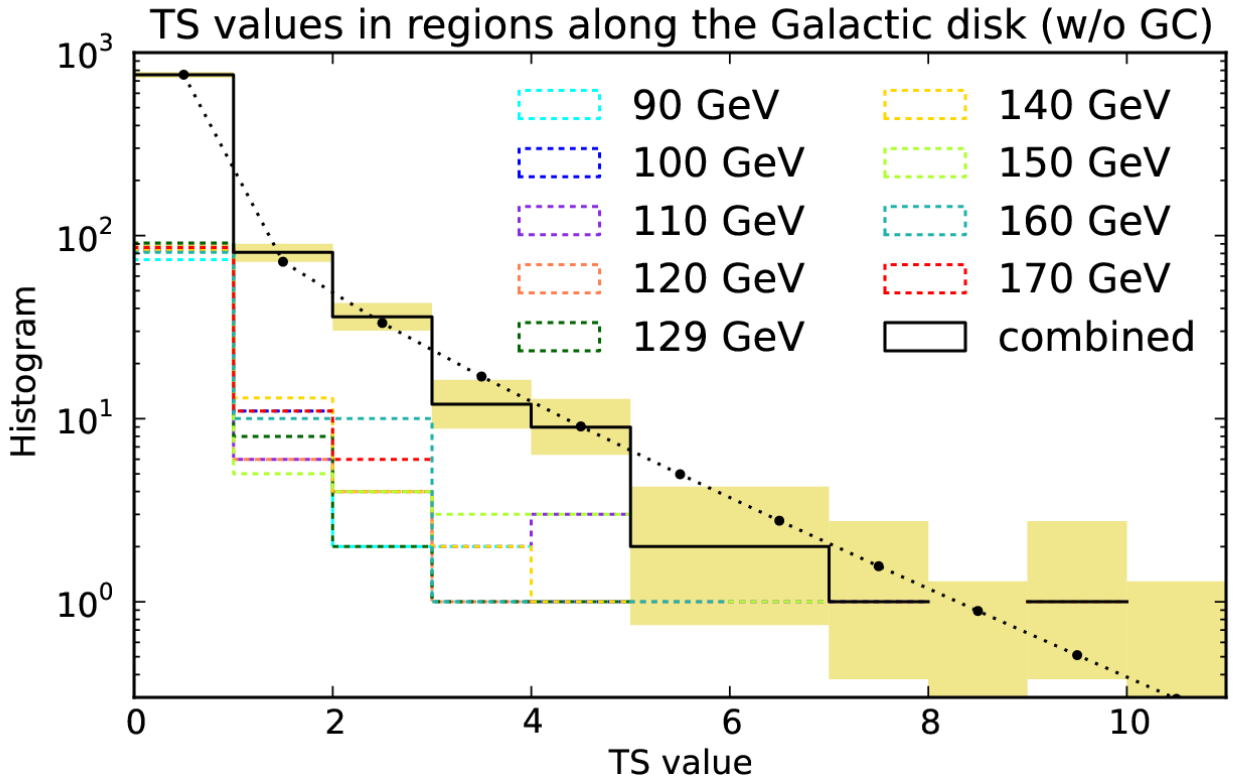


Search for spectral lines in the Z<100 deg subset of the data, in different incidence angle patches, does not reveal any significant feature at 130 GeV.

No “Hotspots” at 90 – 170 GeV energies

More tests

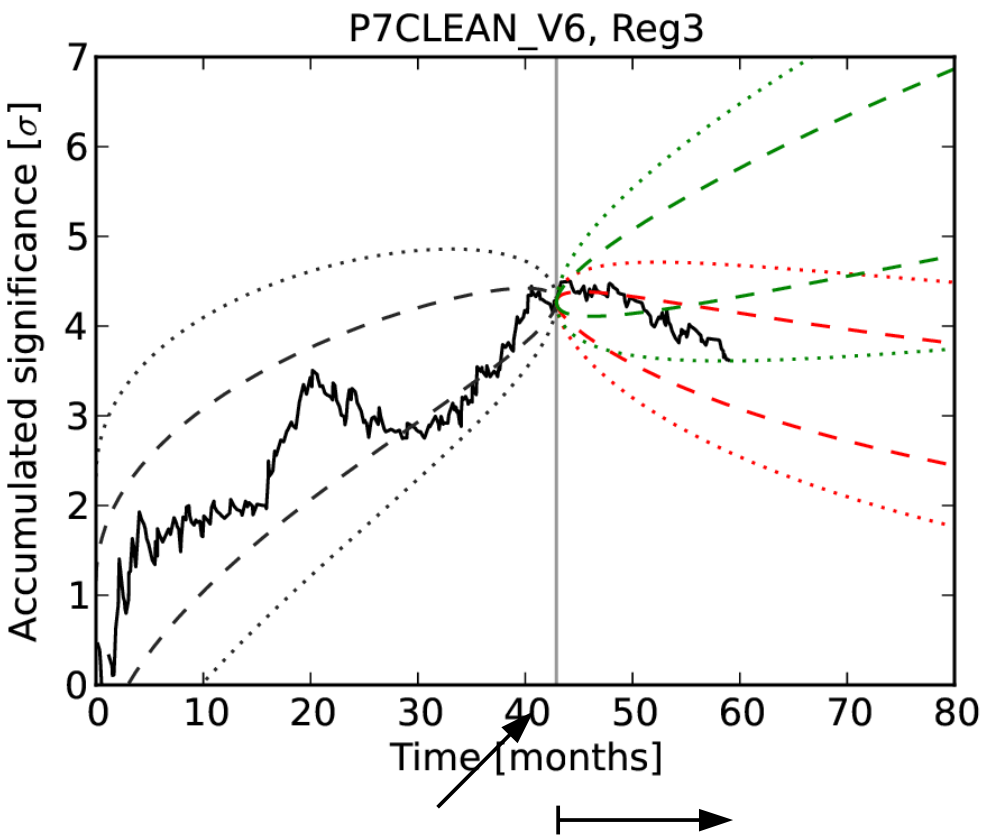
- TS value along the Galactic disk in 6x6 deg^2 regions, excluding regions close to the GC.

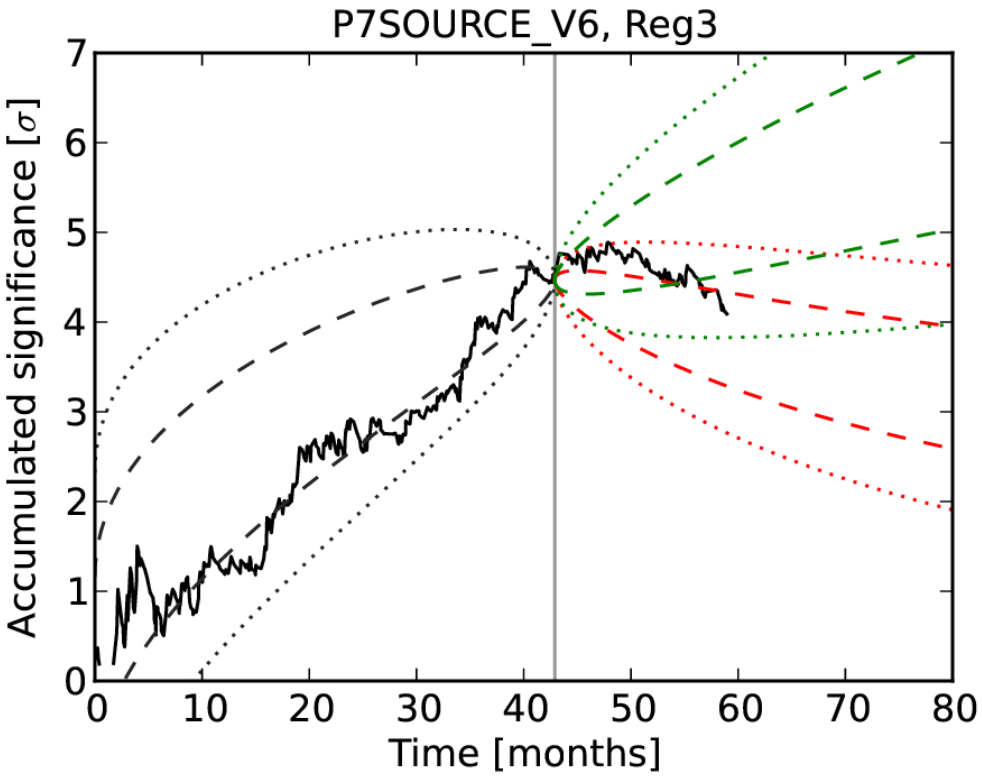


[Finkbeiner/Su/CW, 2012]

- There are places away from the GC with local >3 sigma indication for a line (largest 129 GeV line: TS=4.1)
- This is exactly what is expected for a large number of trials (dashed line) → globally insiginficant!

Our analysis (P7V6), until July 2013





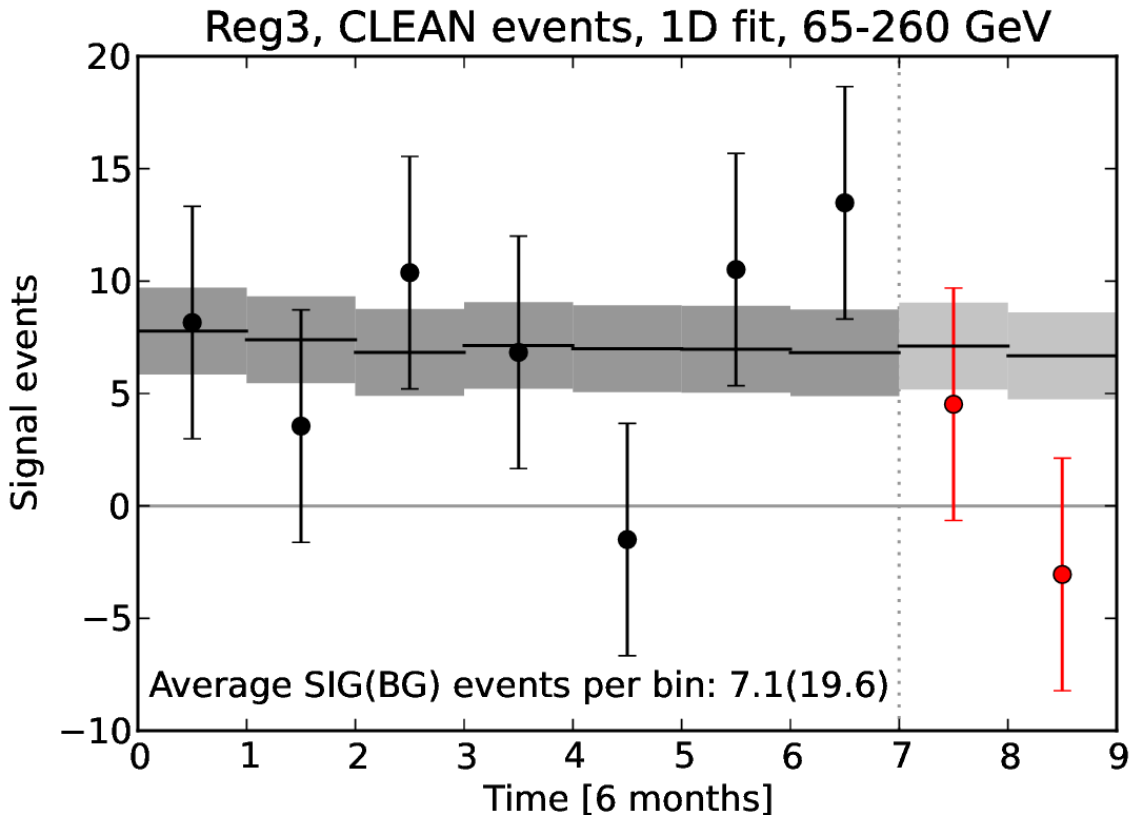
Definition of signal hypothesis

Trial-free measurement

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

Effective number of signal events in 6-month bins



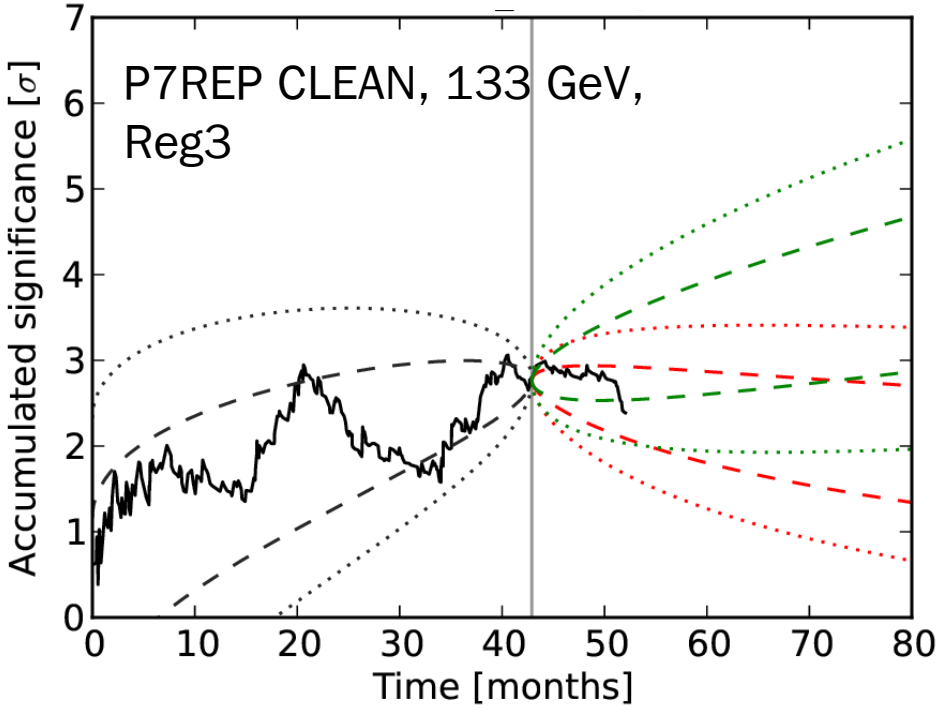
Number of events in signal region (determined by likelihood fit) from 4 February 2012 to 4 February 2013:

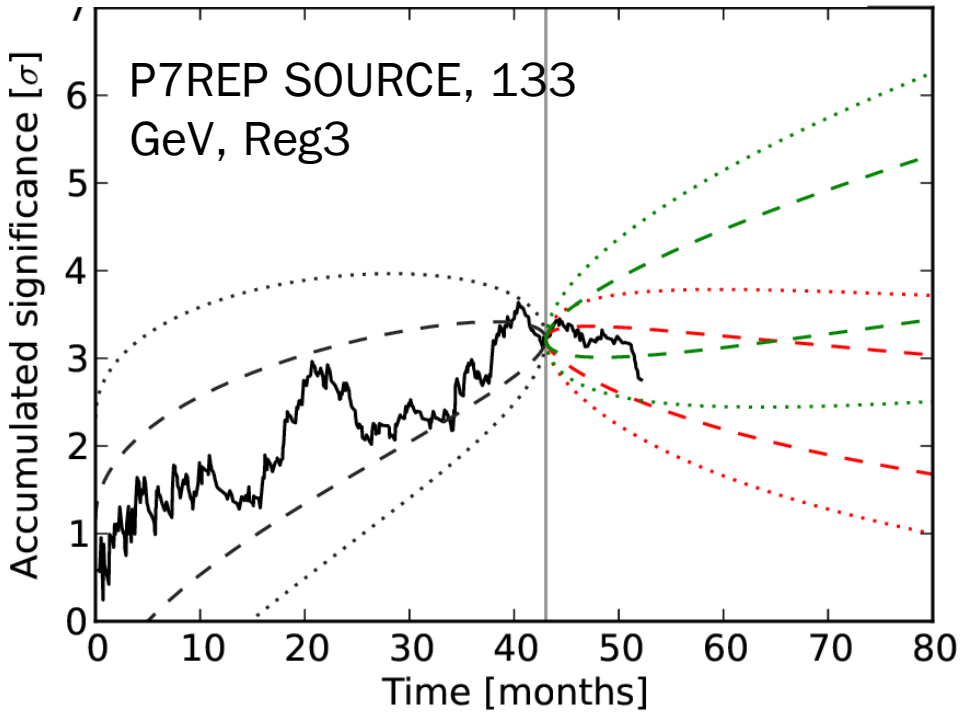
Observed: 1.5
Expected: 14.2±3.7±7.3

130 GeV feature III

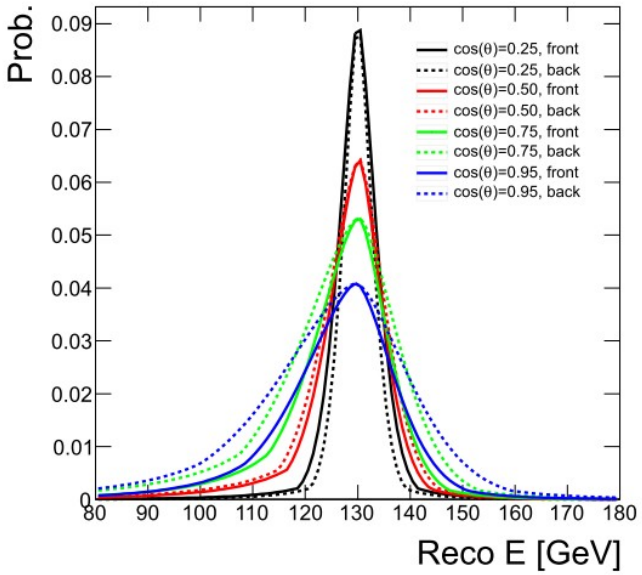
July 2013 (reprocessed data) current status

Results with reprocessed data: Our analysis: Time evolution & significance





(until 12 Dec 2012)



P7REP CLEAN	P7REP SOURCE
2.4σ (1-D), 2.0σ (2-D)	2.8σ (1-D), 2.4σ (2-D)
[in P7V6 4.3σ (1-D)]	[in P7V6 4.6σ (1-D)]

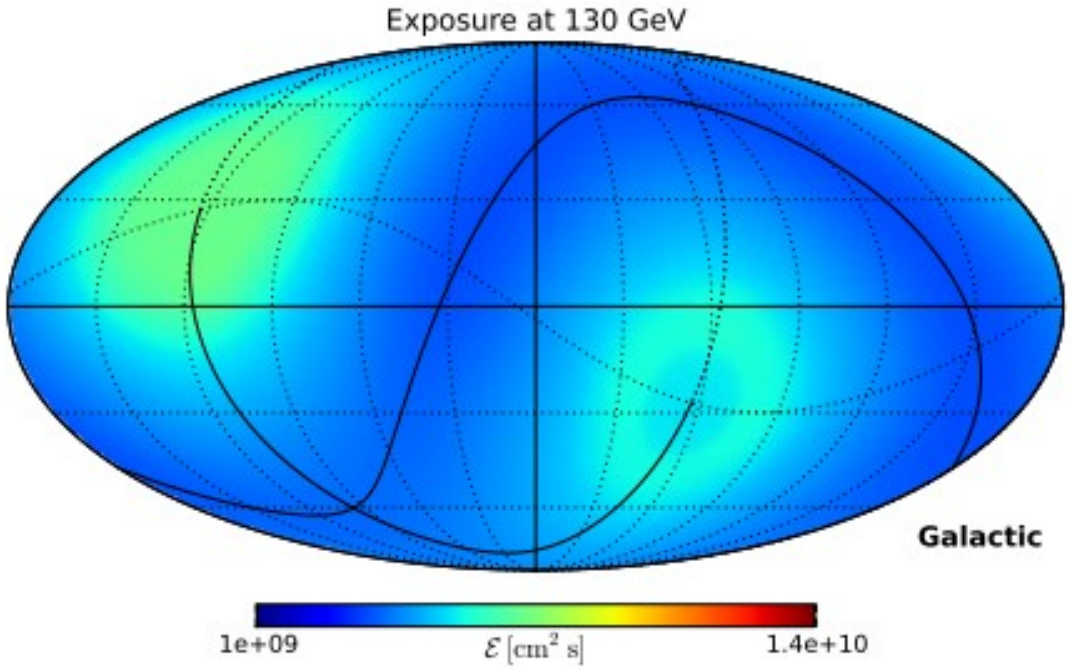
==> drop by ~2σ
(expected from event migration alone; ~0.6σ)
Also drop in Earth limb feature (3σ → ~2.0σ)

Modified survey mode

Impact on 130 GeV feature analysis

Current survey mode

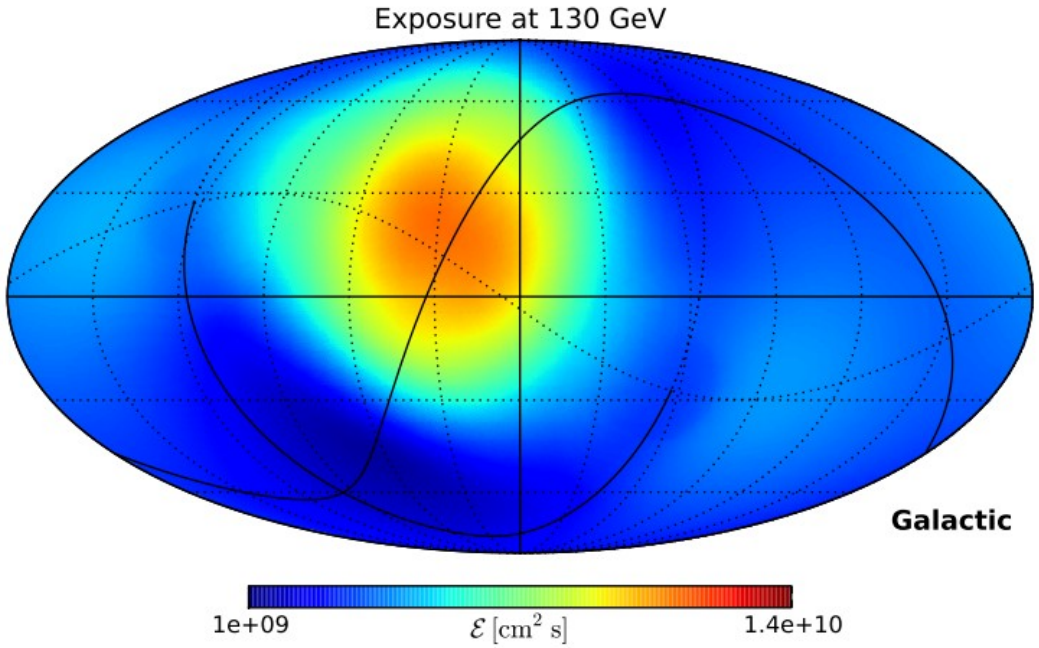
- Rocking between 50deg north and 50deg south of zenith axis every orbit (~1.5h) → complete coverage every 3h
- Precession period of orbital axis ~53 days → relatively uniform exposure



Modified survey mode

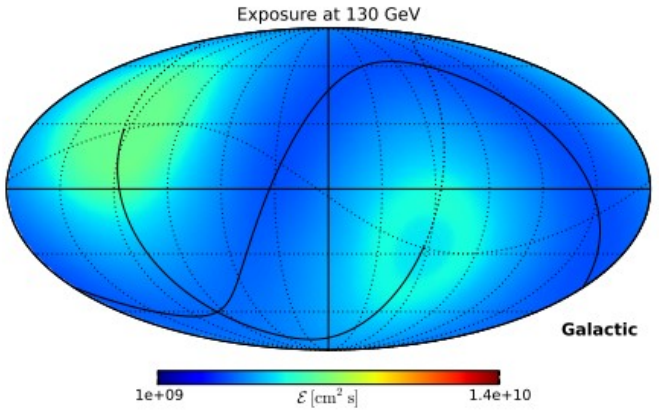
- Commence slew to target position when target is exiting 10 [option 1-3] (30) [option 4] deg from Earth occultation
- Make transition back to 50 deg rocking survey mode when target reenters 10 (30) deg from Earth occultation
- EAA is set to 30 (5) deg → LAT boresight will track to within 30 (5) deg of Earth limb and then hold steady

Option 1: RA, Dec = 261.4, -28.9
Option 2: RA, Dec = 261.4, 0
Option 3: RA = 261.4, Dec follows orbital axis (weekly updated)
Option 4: RA = 261.4, Dec follows orbital axis (weekly updated)

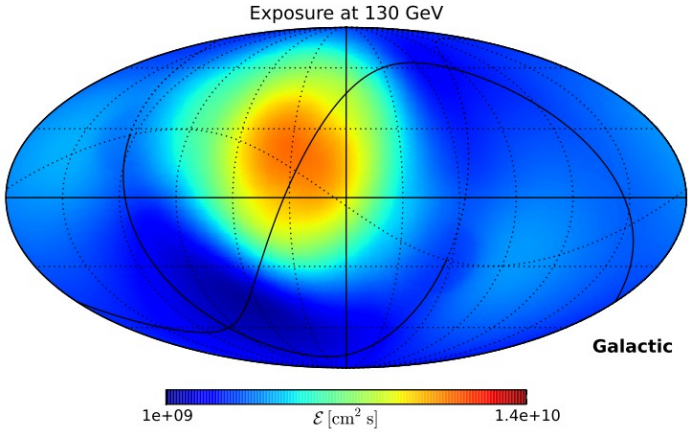


Exposure maps in comparison

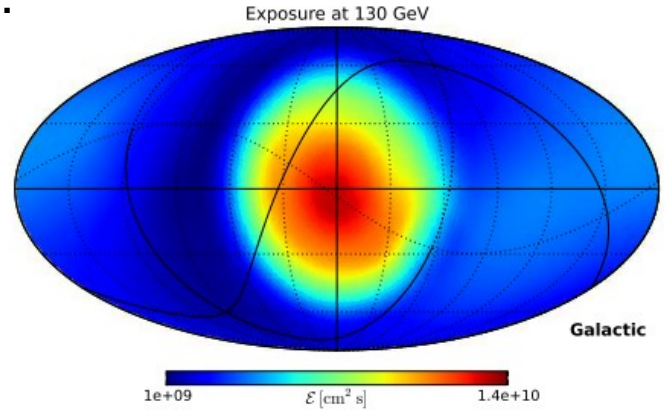
Current survey mode:



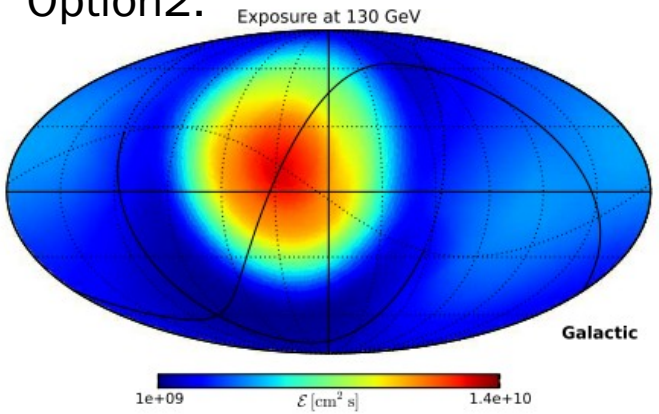
Option4 / option3:



Option1:



Option2:



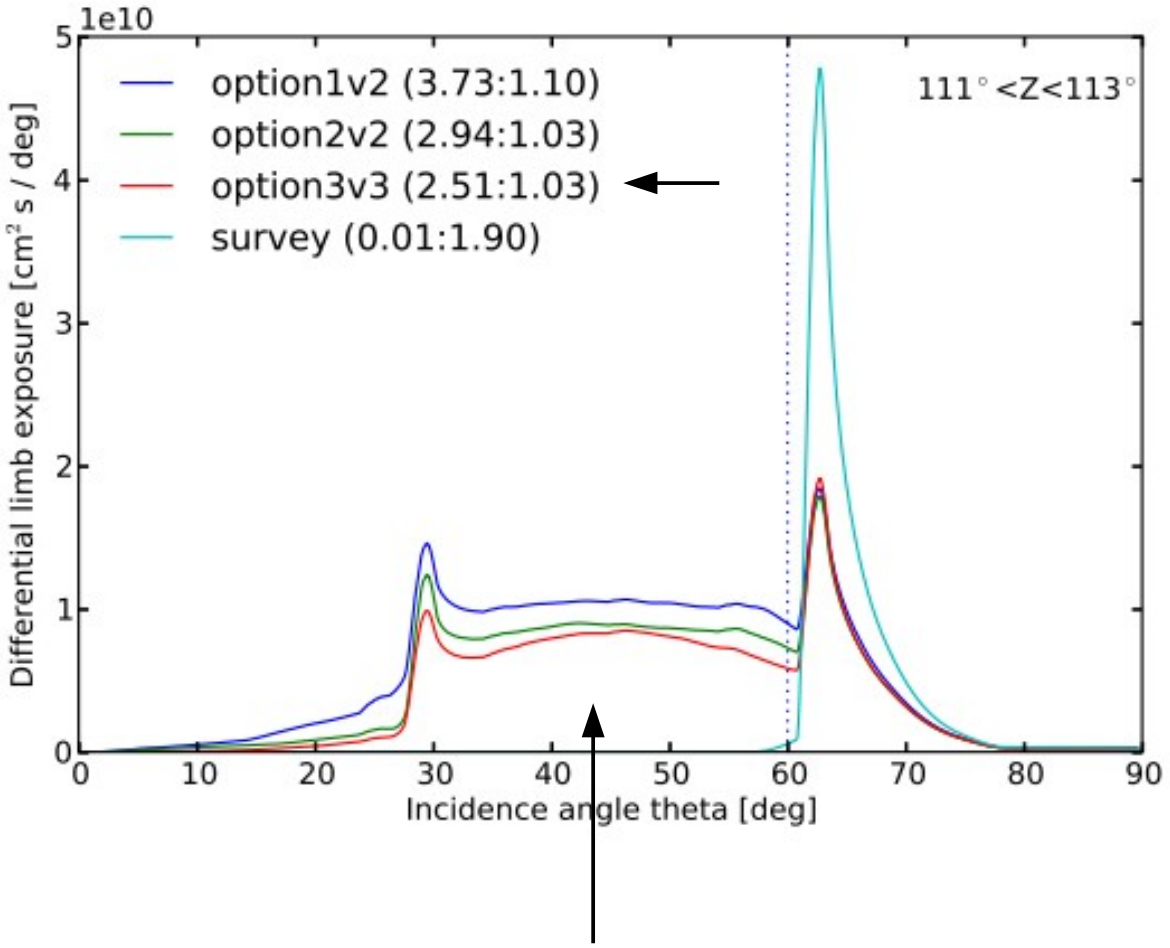
Mode	Mean exposure $[10^9\,\mathrm{cm}^2\,\mathrm{s}]$	GC exposure $[10^9\,\mathrm{cm}^2\,\mathrm{s}]$
survey	4.74	4.33
option1v2	4.38	13.1
option2v2	4.44	10.7
option3v3	4.56	9.67

Option3: 4% int. exposure loss w.r.t survey mode

Option4: <2% int. exposure loss w.r.t survey mode

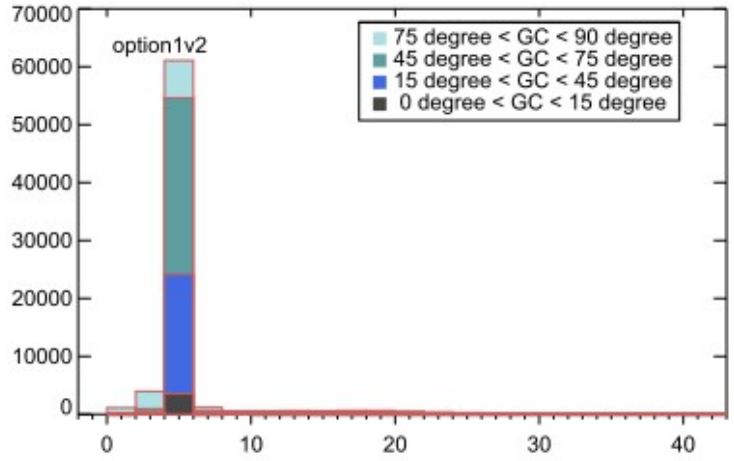
2.2 increase of exposure rate at GC

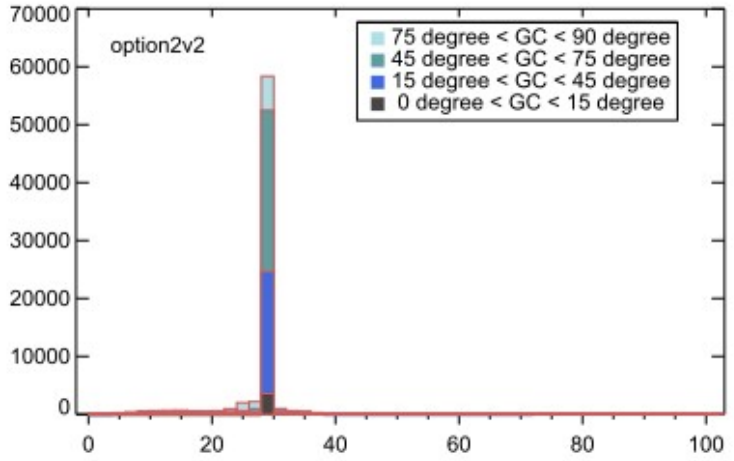
More Earth limb data at low incidence angles

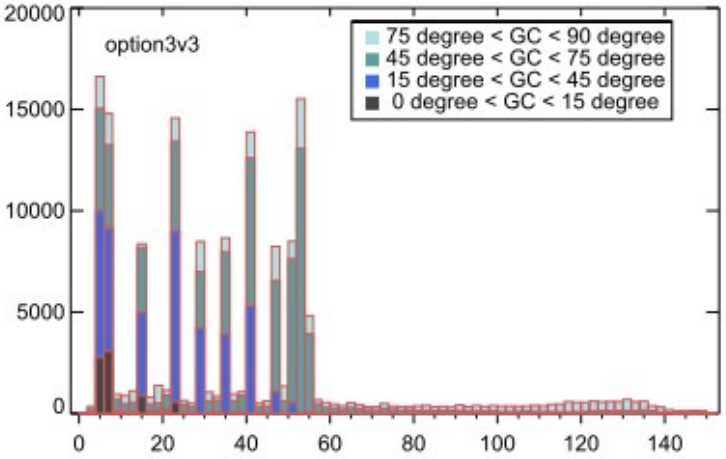


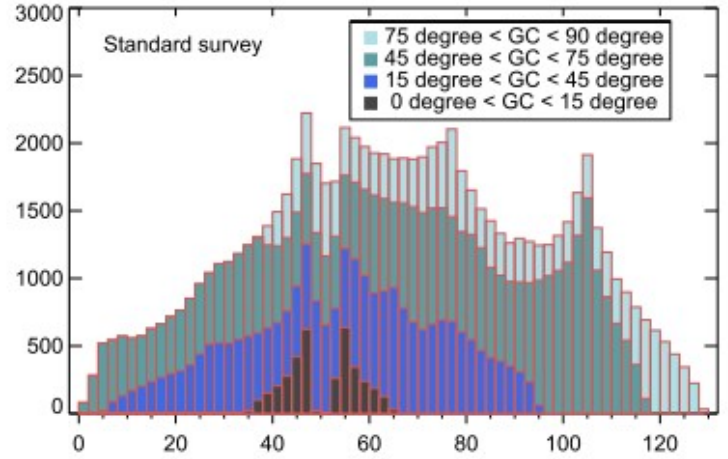
During the transitions from survey mode to pointed observation and back, the Earth limb comes into the FOV → large amount of additional low-incidence-angle limb data will be collected, valuable for systematic checks
→ five times faster accumulation of Earth limb data
(somewhat less for option4)

Incidence angle distribution for GC Obs.









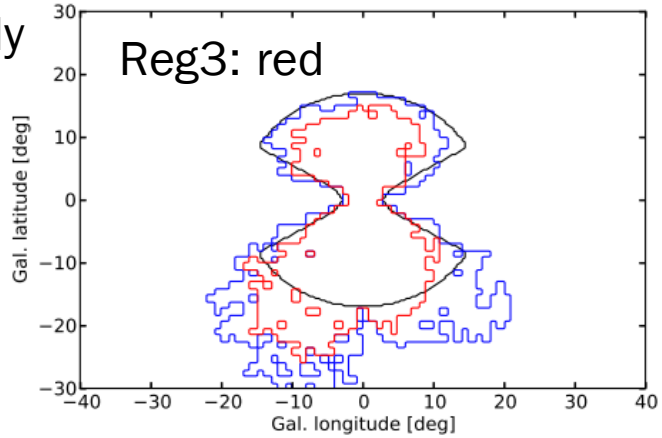
Option 3/4 has clear advantages w.r.t. Option 1 and 2, where the GC would be only observed under one specific angel → this would complicate systematic checks

What do we gain for the 130 GeV feature?

Definition signal hypothesis: line around April 2012, 1-D only

- Reg3 CW analysis (P7V6): 4.3σ f~0.35
- R3 Fermi analysis (P7REP): 4.1σ f~0.79
- R16 Fermi analysis (P7REP): 2.2σ f~0.20

$$f = \frac{n_{\mathrm{sig}}}{b_{\mathrm{eff}}} \simeq \frac{TS}{n_{\mathrm{sig}}}$$



Aug 2008 until Aug 2016 (Aug 2018) – no change – modified strategy from Dec 2013

- Reg3 CW analysis (P7V6): 6.4σ (7.2σ) 7.6σ (9.0σ)
- R3 Fermi analysis (P7REP): 6.2σ (6.9σ) 7.3σ (8.7σ)
- R16 Fermi analysis (P7REP): 3.3σ (3.7σ) 3.9σ (4.7σ)

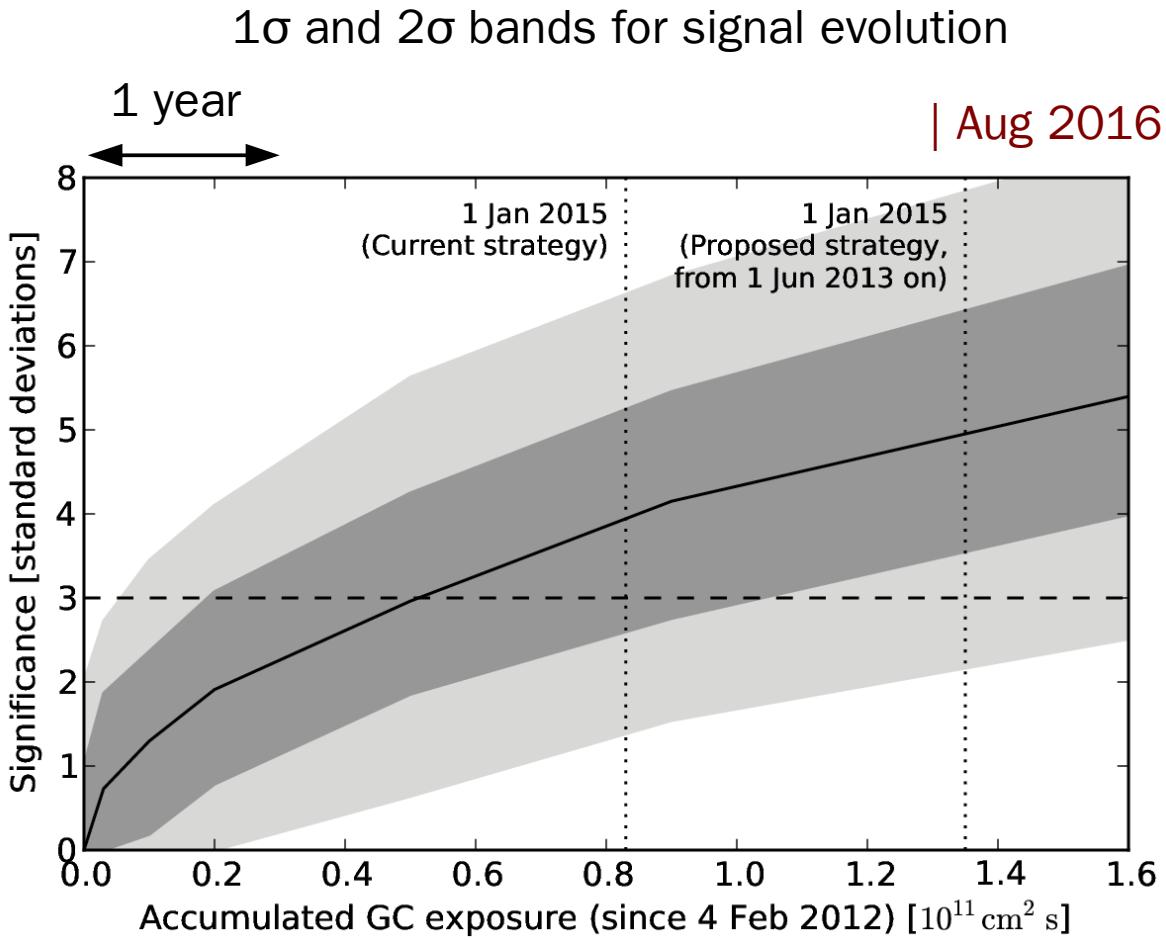
Feb 2012 to Aug 2016 (Aug 2018) – no change – modified strategy from Dec 2013

- Reg3 CW analysis (P7V6): 4.8σ (5.8σ) 6.4σ (8.0σ)
- R3 Fermi analysis (P7REP): 4.6σ (5.6σ) 6.1σ (7.7σ)
- R16 Fermi analysis (P7REP): 2.5σ (3.0σ) 3.2σ (4.1σ)

→ for a statistical fluke, this indicates the significance of the upper limit at which a signal can be excluded with the new data.

Result: For smallest significance (in R16), current survey mode might not be enough to rule out signature with >3σ until Aug 2016.
For all other cases: Situation should be settled on statistical grounds until Aug 2016

Example: Reg3 P7V6, data since Feb 2012



Even when a confirmation of the signal is expected until Aug 2016 with new data only (assuming a Reg3, R3 signal significances), this is *not guaranteed.*

But still: until Aug 2018 situation should be settled (except for R16). PASS8 goes in the same direction.

Discussion of goals

If it is a statistical fluke

- Behavior in last 1½ years might point in that direction (on top of systematics?)
- Current survey mode would be enough to exclude original signal hypothesis with high confidence at end of the mission (Aug 2018), and likely even before.

If it is an instrumental systematics

- Should be finally settled with PASS8 and more limb data?

If it is a real signal

- It will be clearly reproduced in data from Feb 2012 to Aug 2018.
- But: In that case, we should get as much data as possible.

Our proposal: Go for the Galactic center now.

- Switch back once signal excluded at 3 or 4 sigma? Otherwise continue taking data.
- Profit from the positive side effects on a set of other scientific goals.

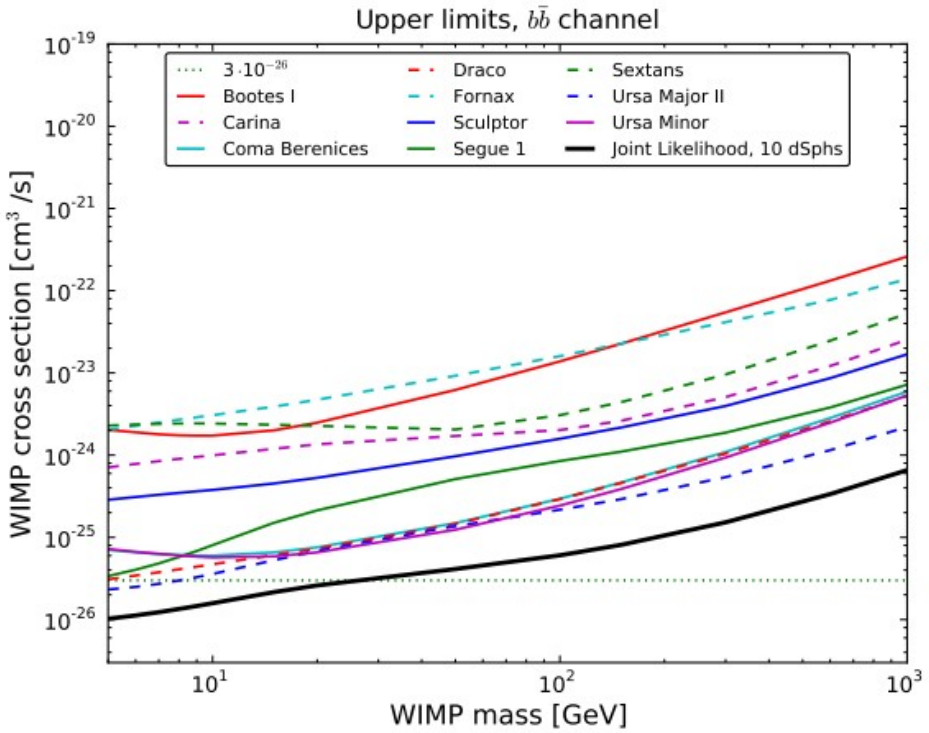
Proposal Digel et al. team: Wait until Aug 2014.

- If total TS>15 in R3, go for it.
  → On average 6.1 sigma confirmation until 2018 Aug.
- If TS<15, forget it.
  Signal would be excluded with >3 sigma if TS<15. Very clear.

Modified survey mode

Impact on other Science Goals

Dwarf Spheroidals, APS & Galactic Center



[Ackermann et al., 2012]

Impact on dwarf spheroidal exposure rate:

Ursa Major II: 0.70
Draco: 1.03
Ursa Minor: 0.74
Segue 1: 0.99
Sculptor: 0.47
Bootes I: 1.17
Carina: 0.88
Coma Berenices: 0.59
Fornax: 0.65
Sextans: 1.00

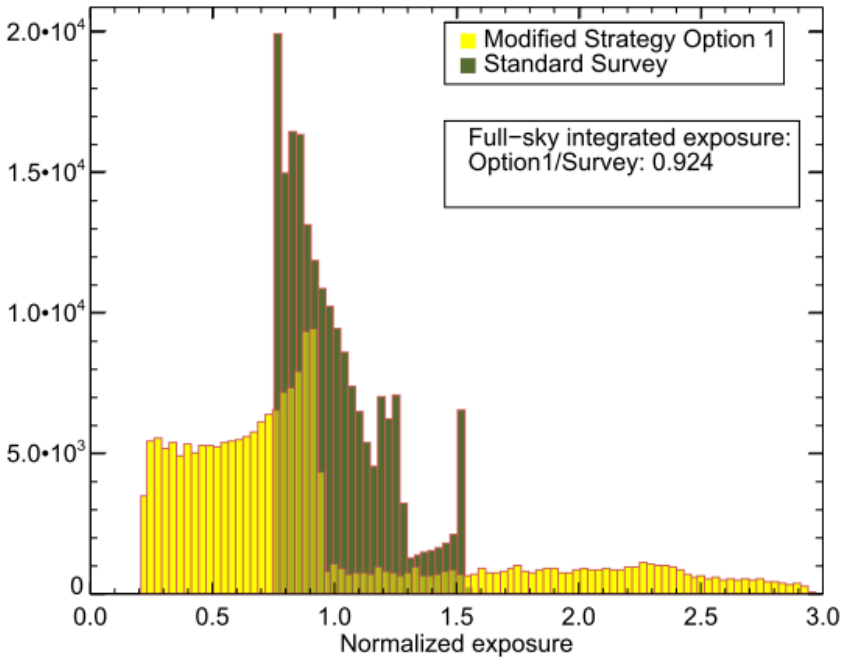
Weakens final limits from Fermi by <20 – 30% (Sculptor benchmark).

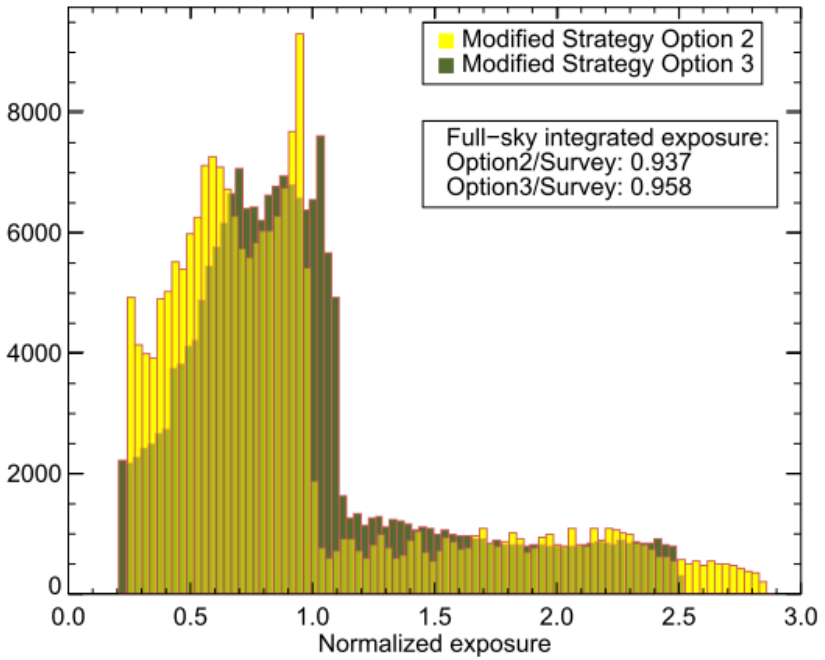
Relative increase of total exposure at the GC
(from Aug 2008, assuming change Dec 2013):
Until Aug 2016: 1.41
Until Aug 2018: 1.57
(change in exposure rate: 2.2)
→ could turn out to be critical for understanding of 3 GeV excess at Galactic center. [Hooper and others, 2010 - 2013]

High latitudes, exposure rate:

|b|>20 deg ratio: 0.87
|b|>40 deg ratio: 0.75
|b|>60 deg ratio: 0.64
→ will increase error-bars on APS by 10%

Distribution of exposure over sky pixels





Distribution of exposure after 53 days.

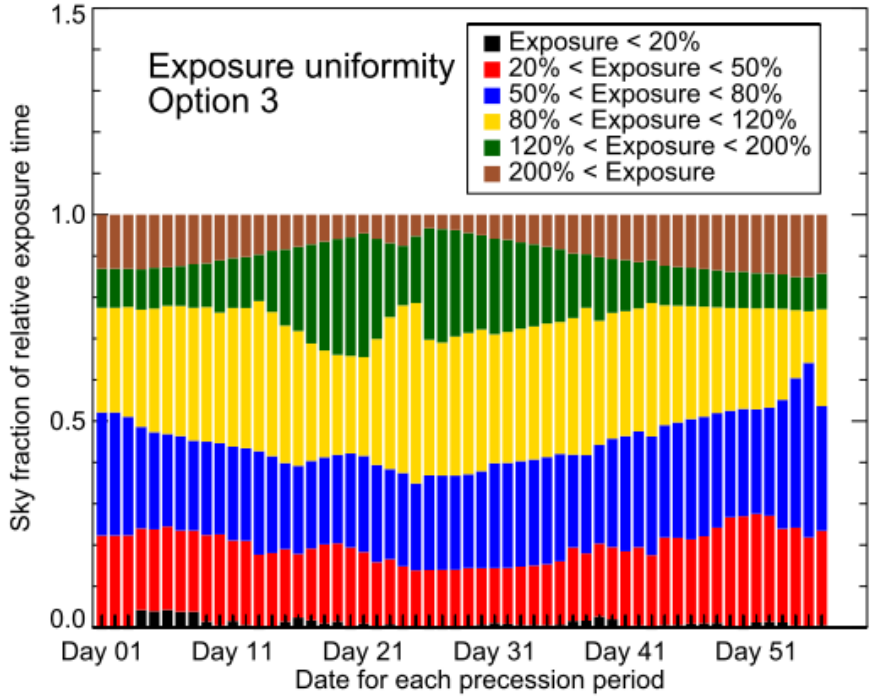
Exposure variation:

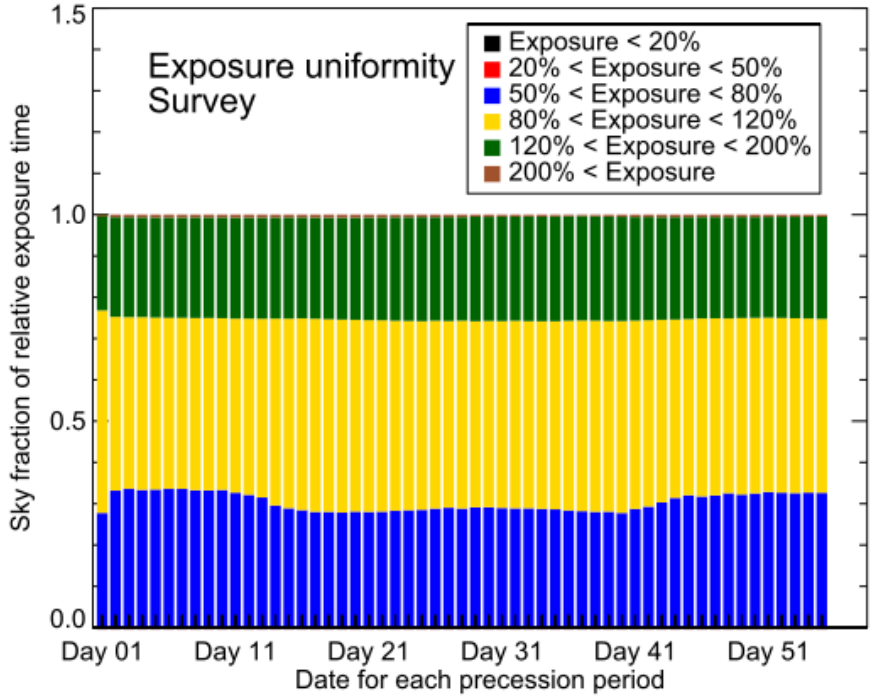
Current survey mode: 0.75 – 1.5 mean value

Option 3/4: 0.2 – 2.5 mean value

→ Deeper exposure of regions north-west of the GC

No blind spots





Pixel distribution of exposure normalized to daily mean.

On one-day time scales, only <5% of the sky is heavily underexposed (<0.2 mean value).
→ no strong impact for flares with >1day time scales.

On three-hour time scales, <10% are blind

Positive consequences:

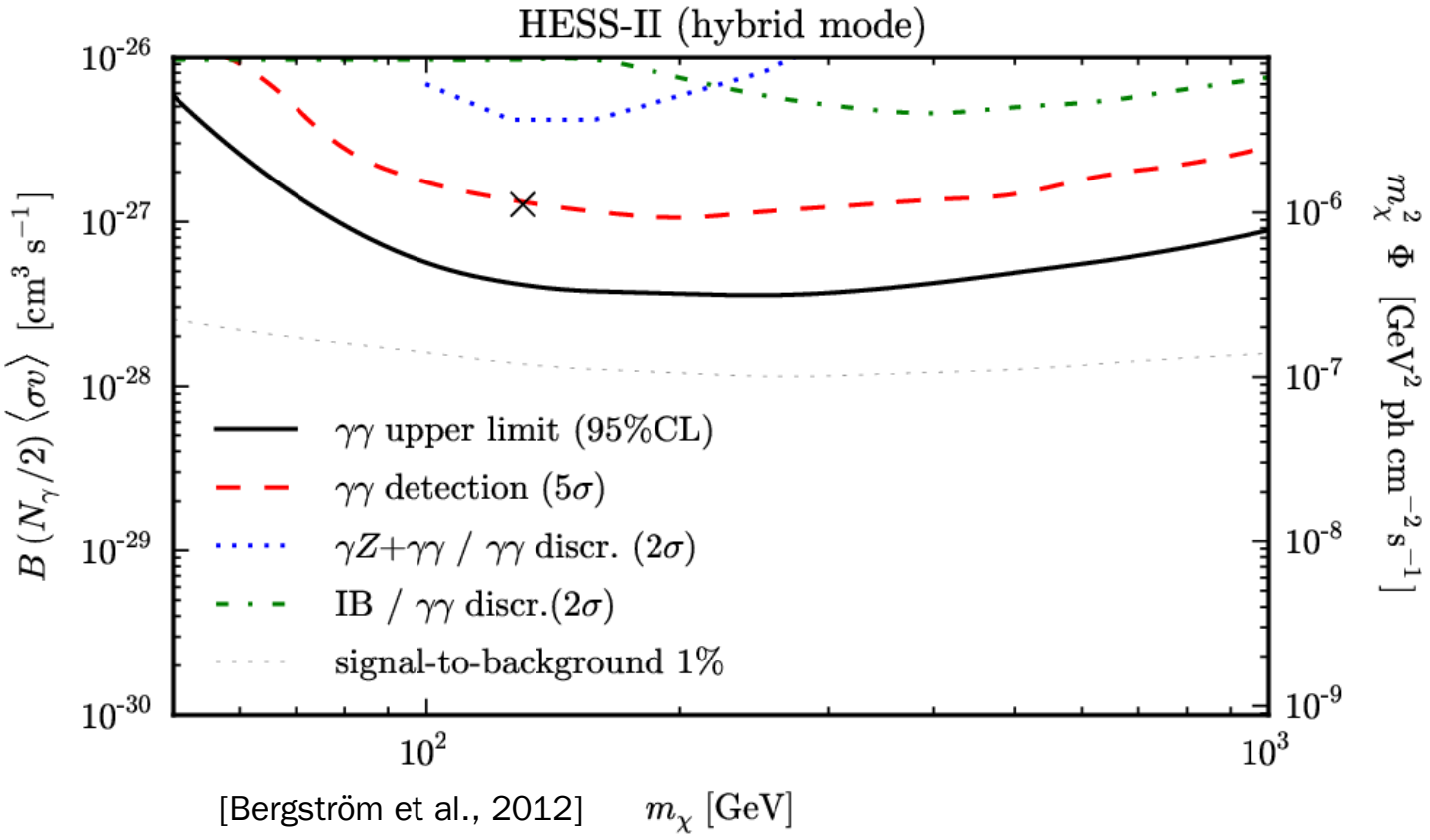
- Dark Matter searches at the Galactic center
  - Clarification of the 130 GeV feature
  - Reduced systematics at GC >10 GeV
- Earth limb systematic studies
- Diffuse emission
  - Improved source discrimination, Fermi Bubbles, connection with HESS
- Improved identification of hard sources at GC
- Variability studies
  - Better time domain sampling and higher flare detection sensitivity at GC
  - Increased chances for pulsation blind searches
- G2 cloud, Fermi only instrument with MeV-TeV coverage

Negative consequences:

- Dark matter searches with Dwarf spheroidals & Galaxy clusters, <20-30% weakening of final limits
- Extragalactic gamma-ray background & angular power spectrum, ~10% reduction
- Diffuse emission
  - LMC, SMC and M31 less exposed
- Exposure less uniform than now
  - Impact on source population studies, AGNs, dN/dS
- GRBs and short duration transients
  - more difficult for follow-up studies

[CW et al.; Digel et al., 2013]

HESS-II ?



[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? (most likely before Aug 2016)

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

Summary

- The 130 GeV feature
  - Looked very promising ~1 year ago.
  - Still in the reprocessed data, but less significant
  - No clear instrumental effect found that causes the excess
  - Could be statistical fluke / combination of different effects (trend points in that direction)
  - But: it is still too early to give it up as a dark matter signal candidate

    → Needs to be clarified, and Fermi LAT can do that. A modified survey strategy would greatly help and accelerate this process.
- The Galactic center is interesting for many reasons:
  - Dark matter searches (not just the line!)
  - Transient sources
  - Diffuse emission
  - G2 cloud