Dark Matter Searches with the Fermi LAT

Die Suche nach Dunkler Materie mit dem Gammateleskop Fermi LAT

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UNIVERSITY OF AMSTERDAM

GRAPPA

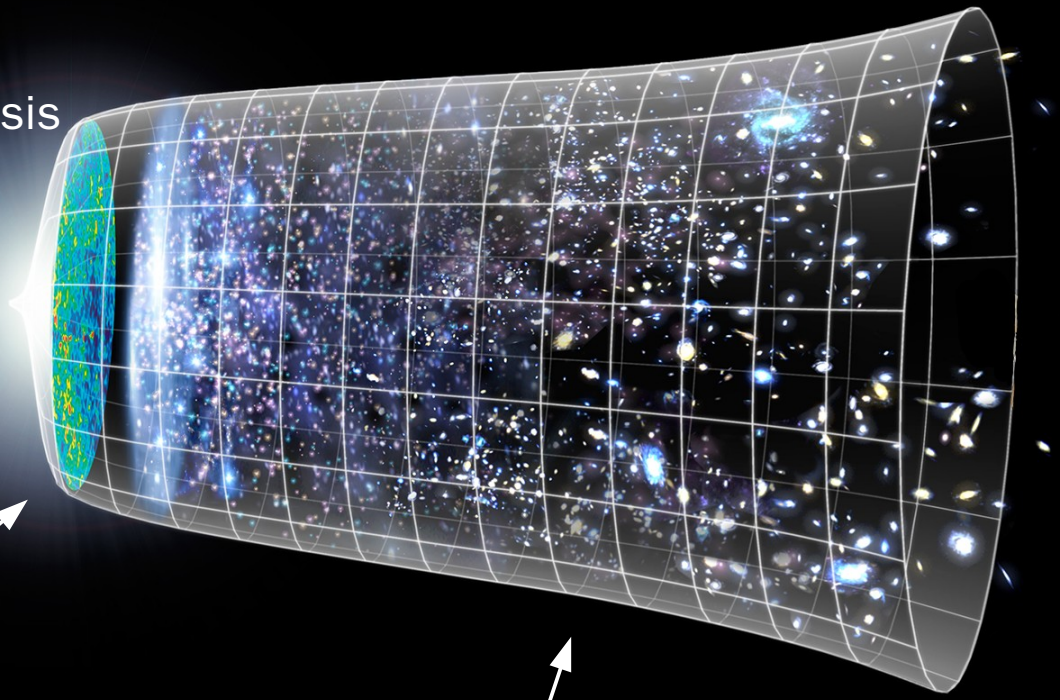
Disclaimer:

I am not a member of the Fermi LAT team.

Thanks to NASA policies, processed data is provided to the scientific community on the spot which allows to perform independent analyses.

Today's View on Dark Matter

Primordial
Nucleosynthesis



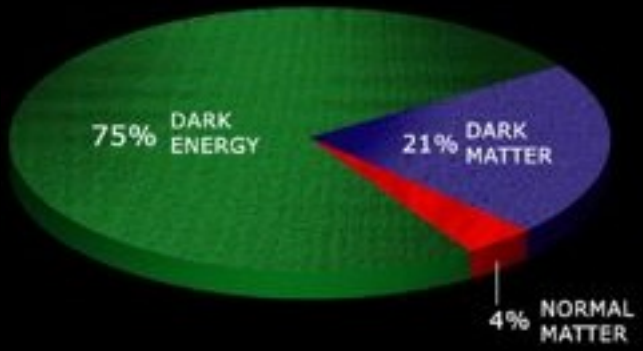
CMB Anisotropies

Microlensing
„Bullet Cluster“

Structure Formation
Large Scale Structures

Galaxy Clusters & X-rays
Spiral Galaxy rotation curves

Energy budget today:



→ Motivation to search for physics beyond the SM

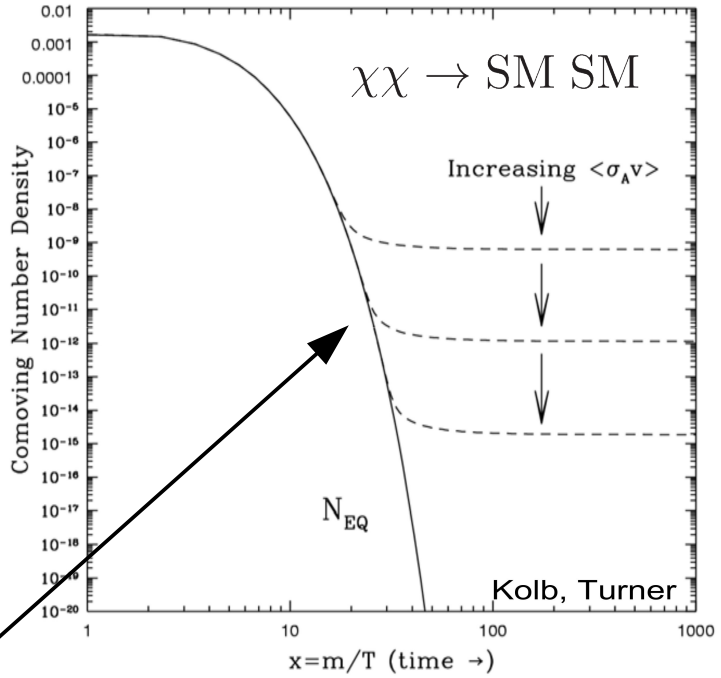
Weakly interacting massive particles

Number density is governed by Boltzmann equation:

$$\frac{dn}{dt} = -3Hn - \langle\sigma v\rangle \left[n^2 - n_{\rm eq}^2\right]$$

Interaction rate: $\Gamma \equiv \langle\sigma v\rangle n$

Hubble rate: $H \sim \frac{T^2}{M_{\rm pl}}$



Remember: $c = \hbar = k_B = 1$

$\Gamma \gg H$	$\Gamma \sim H$	$\Gamma \ll H$
$\chi\chi \leftrightarrow \bar{f}f$	$\chi\chi \to \bar{f}f$	$\chi\chi \not\to \bar{f}f$
DM in equilibrium with thermal SM bath	Interactions freeze out	Interactions decoupled

Full calculation: annihilation freezes out at

$$T \sim m_\chi/20$$

WIMP relic density:

$$\Omega_\chi h^2 \approx \frac{3 \times 10^{-27} {\rm cm}^3 {\rm s}^{-1}}{\langle\sigma v\rangle} \simeq 0.1$$

Indirect Searches for Dark Matter
Multi-messenger approach

χ

χ

?

γ

Gamma rays
- Very simple propagation (geodesics)
- Absorption or energy losses negligible
- Point towards their sources

B-field

$\bar{p},\ e^+,\ \ldots$

Charged Cosmic rays
- Electrons/positrons, nuclei
- Propagation distorted by galactic magnetic field
- Sizeable energy losses

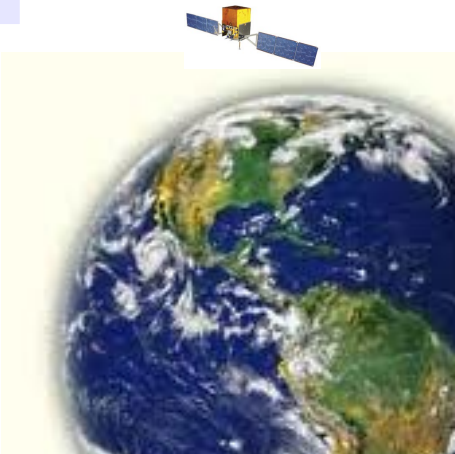
ν

Neutrinos
- Simple propagation
- But: very hard to measure

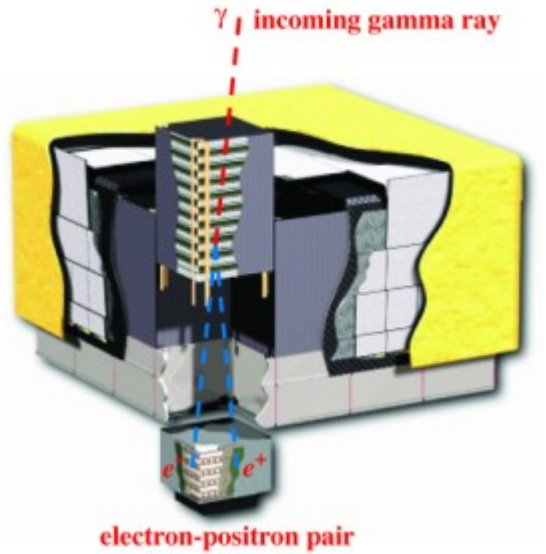
The dark matter **annihilation cross-section** today is roughly given by

$$\langle \sigma v \rangle_{\rm tot} \sim 3 \times 10^{-26} {\rm cm}^3 {\rm s}^{-1}$$

Since the conditions during freeze-out and today are very different, also the velocity averaged annihilation cross-sections can differ by orders of magnitude.



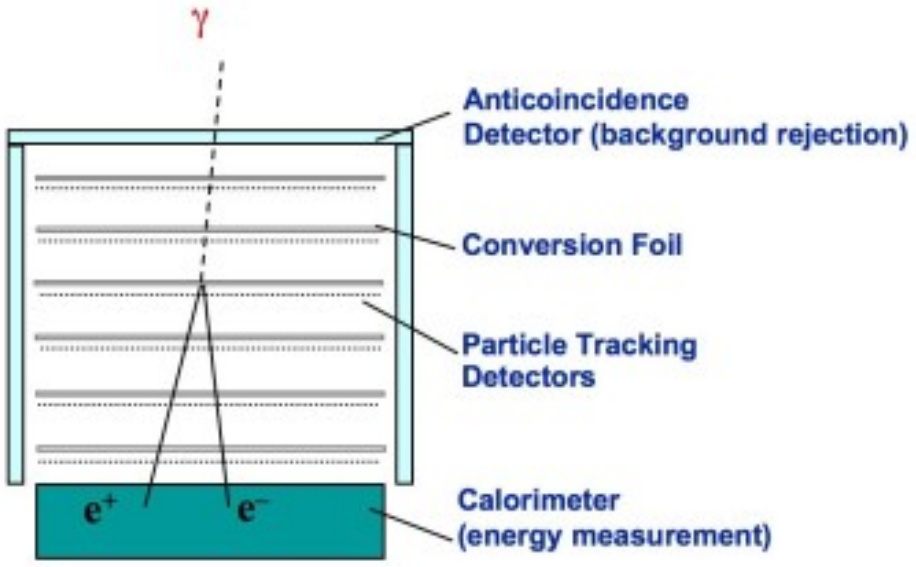
Fermi Large Area Telescope



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
- Energy resolution: <10% (above 10 GeV)
- Angular resolution: < 0.15° (above 10 GeV)
- Launched: 2008
- Will continue at least until 2014/2016



Main components:

Anticoincidence shield (plastic scintillator) with photomultiplier tubes

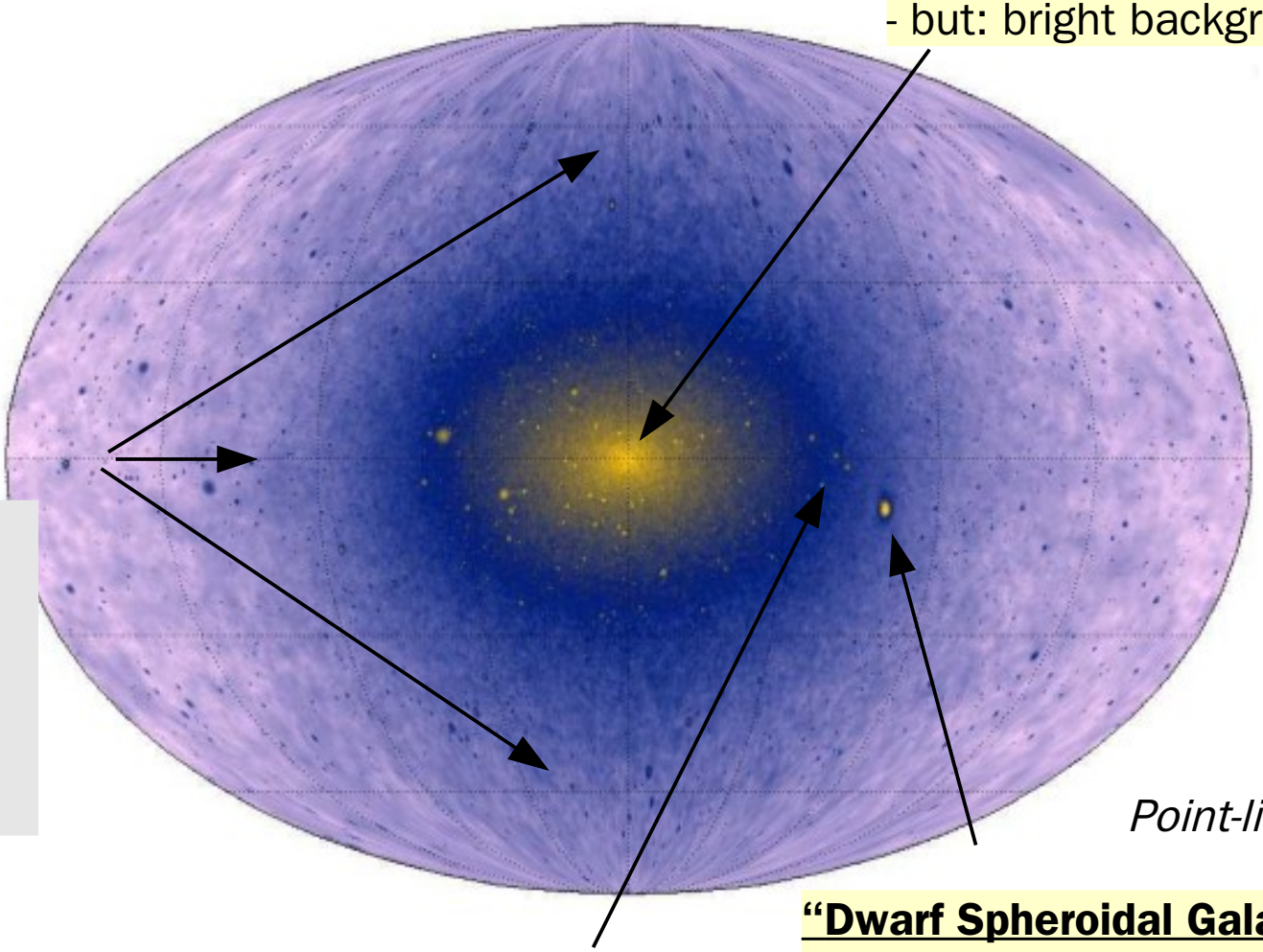
Tracker (silicon strip detectors) with conversion foils (tungsten)

Electromagnetic Calorimeter (CsI)

Potential targets

Dark matter signal predicted by N-body simulations (numerical simulations of structure formation).

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



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

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

Extended or diffuse signals

Point-like signals

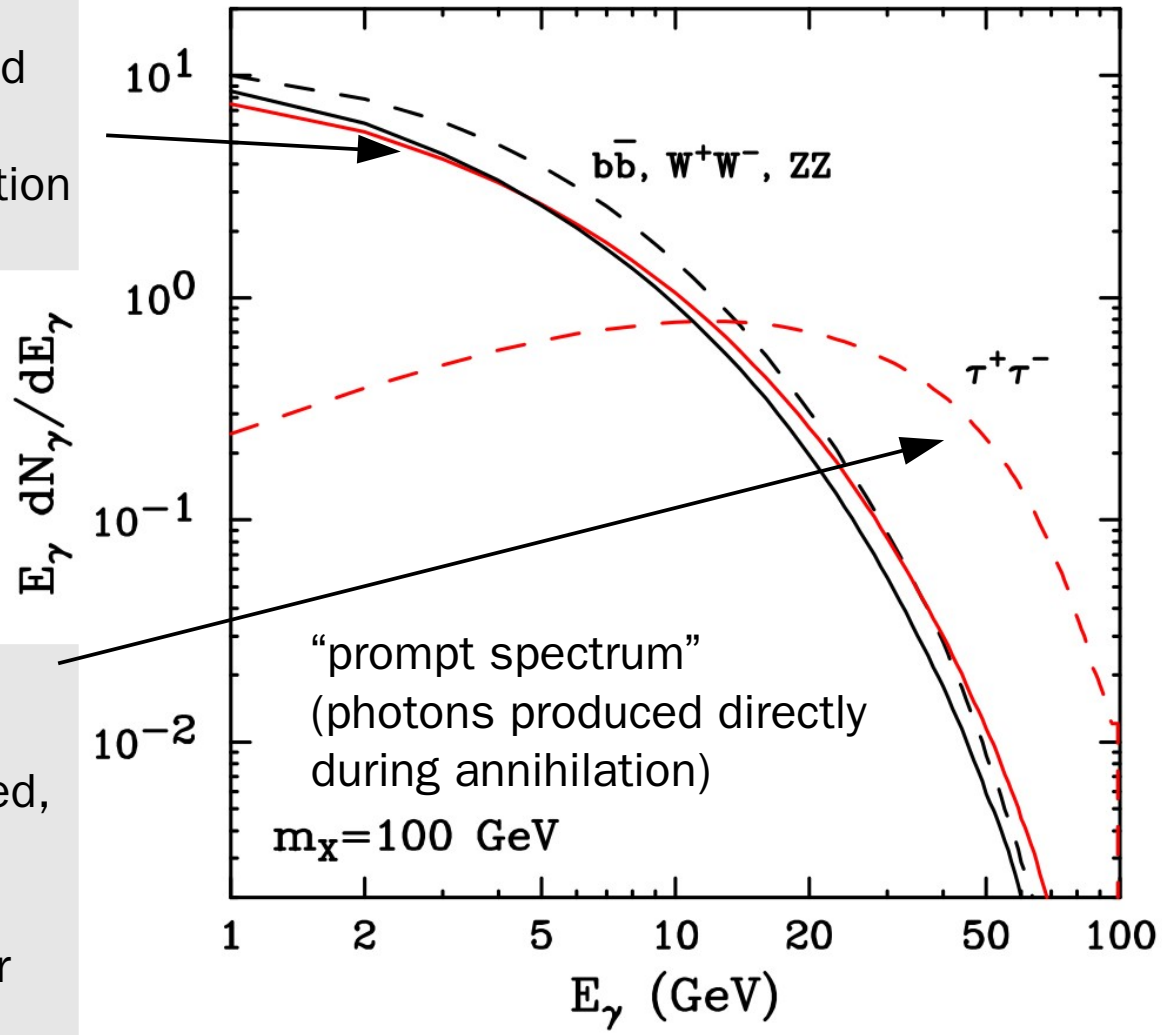
DM clumps
- w/o baryons
- bright enough?
- boost overall signal

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

Energy spectrum of annihilation signal

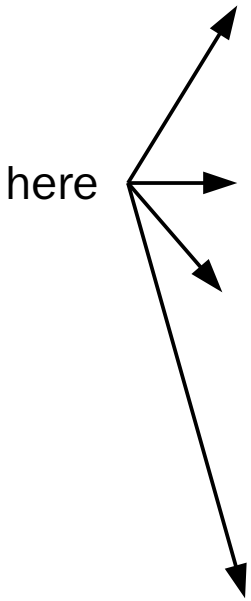
Hadronic modes (annihilation into quarks or massive gauge bosons) lead to quasi-universal spectra, since the photons are produced in a fragmentation and decay cascade.

Leptonic modes (annihilation into electrons, muons, taus etc) are more diverse. Lots of electrons are produced, which may subsequently give rise to additional gamma rays via inverse Compton scattering on the interstellar radiation field.



Dark Matter searches with Fermi LAT data

Central publications:



Galactic center (8) – All hell breaks loose
- Hooper & Slayter (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)

Dwarf spheroidals (6) – The crowbar of indirect DM searches
- 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) – Boost factors to the rescue
- Ackermann et al. (2010), Huang et al. (2011), Ando & Nagai (2012), Han et al. (2012)

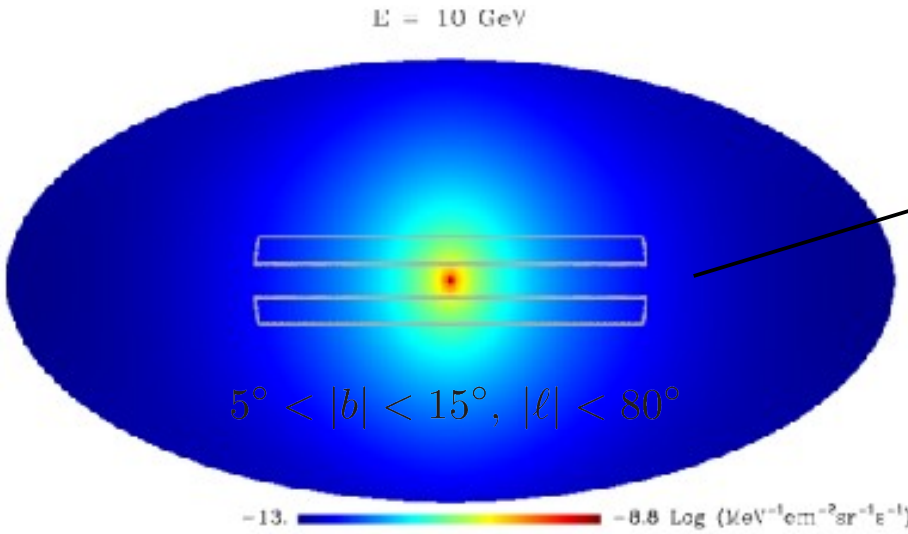
Galactic halo (2) – Not the Galactic center
- Ackermann et al. (2012), Huang et al. (2012)

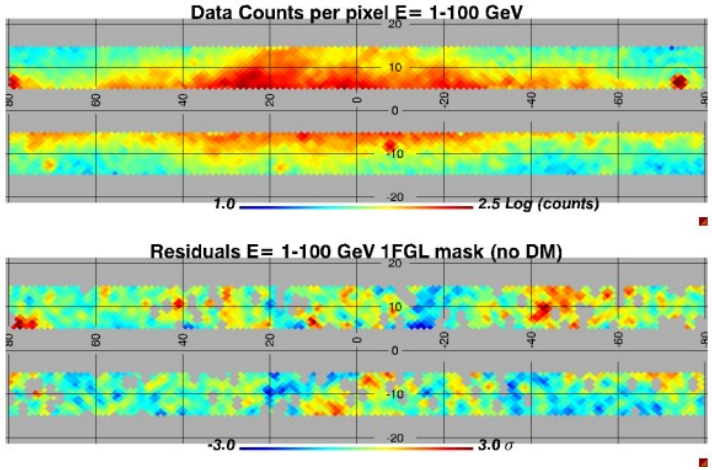
Angular power-spectrum of isotropic gamma-ray BG (1) – Uncertainties on cosmological scales
- Ackermann et al. (2012) + Ando & Komatsu (2013)

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
Underlined: Personally involved

Searches in the Galactic halo



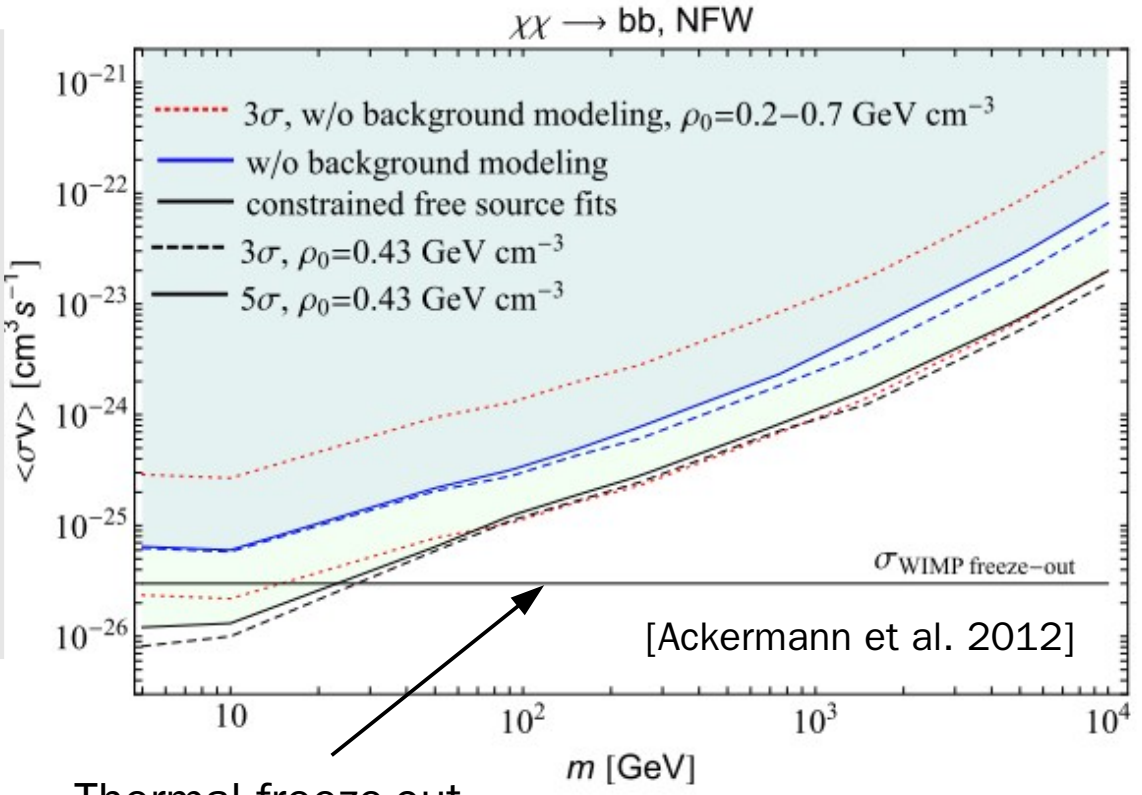


data

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, ⋯
  - unresolved point sources
    → must be marginalized over



No detection → Upper limits on signal flux

Thermal freeze-out

(See also Cirelli, Panci & Serpico 2010)

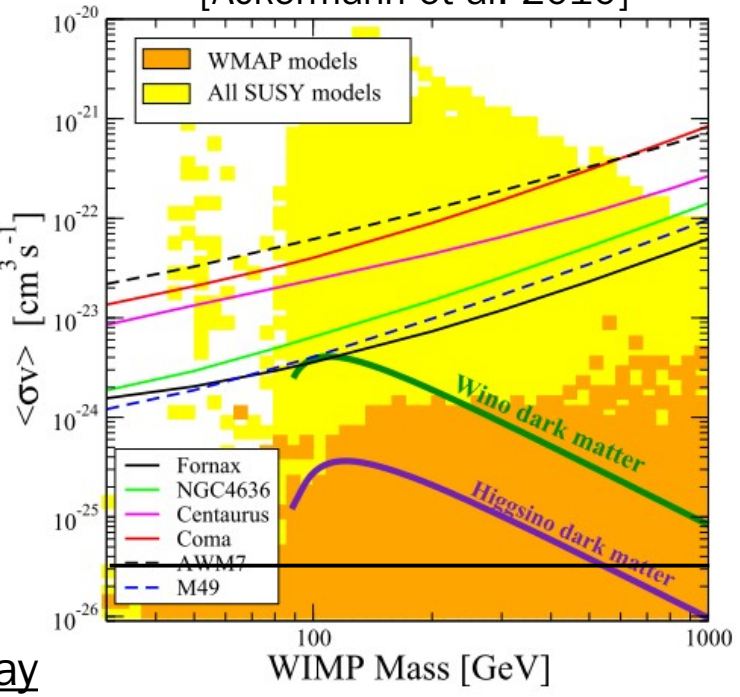
Galaxy Clusters

Nearby Galaxy clusters

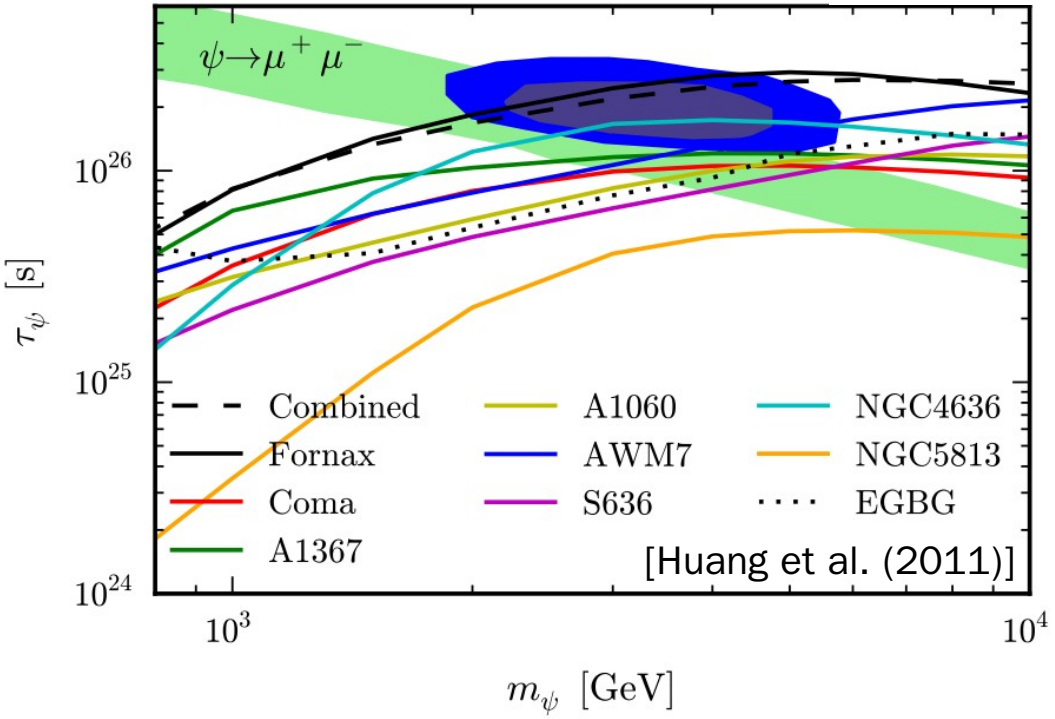
- Masses from X-ray observations
- Potentially O(1000) substructure boost → excellent for DM discovery
- Signal are extended w.r.t. LAT PSF → complicates the analysis significantly
- Several clusters can be combined in one likelihood fit
- Foregrounds from CR protons or electrons?

No detection → Upper limits on signal flux

[Ackermann et al. 2010]

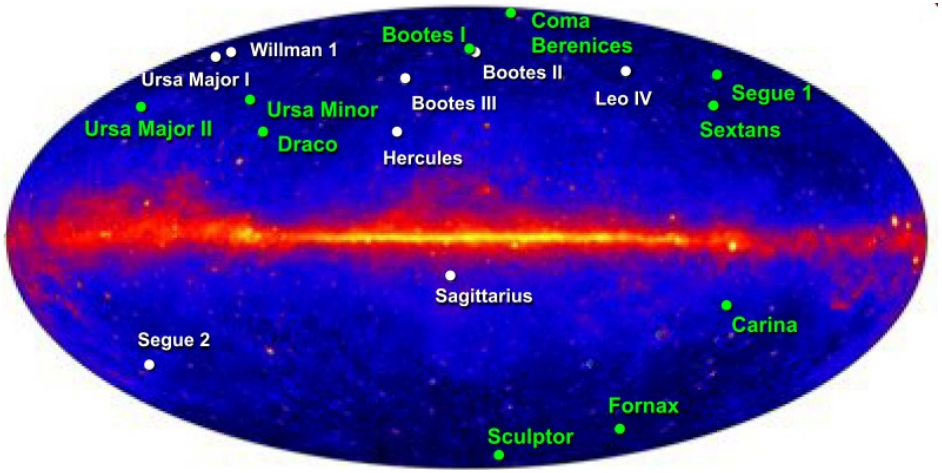


Limits on dark matter decay



See also: Dugger et al. (2010); Zimmer et al. (2011); Han et al. (2012)

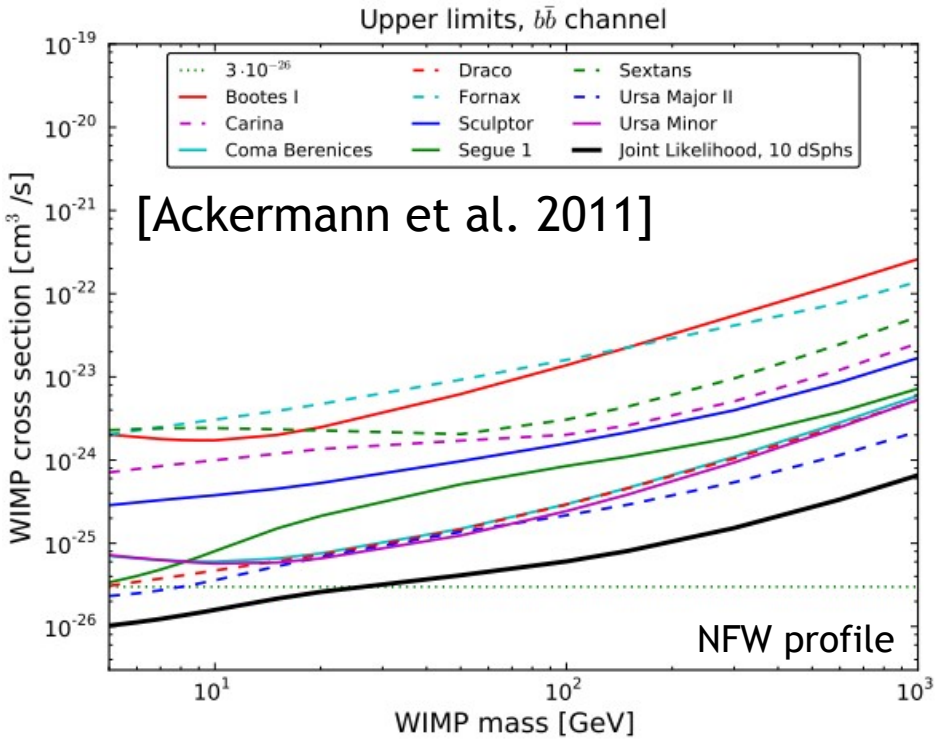
Dwarf Galaxies



[from Drlica-Wagner, Fermi Symp. 2012]

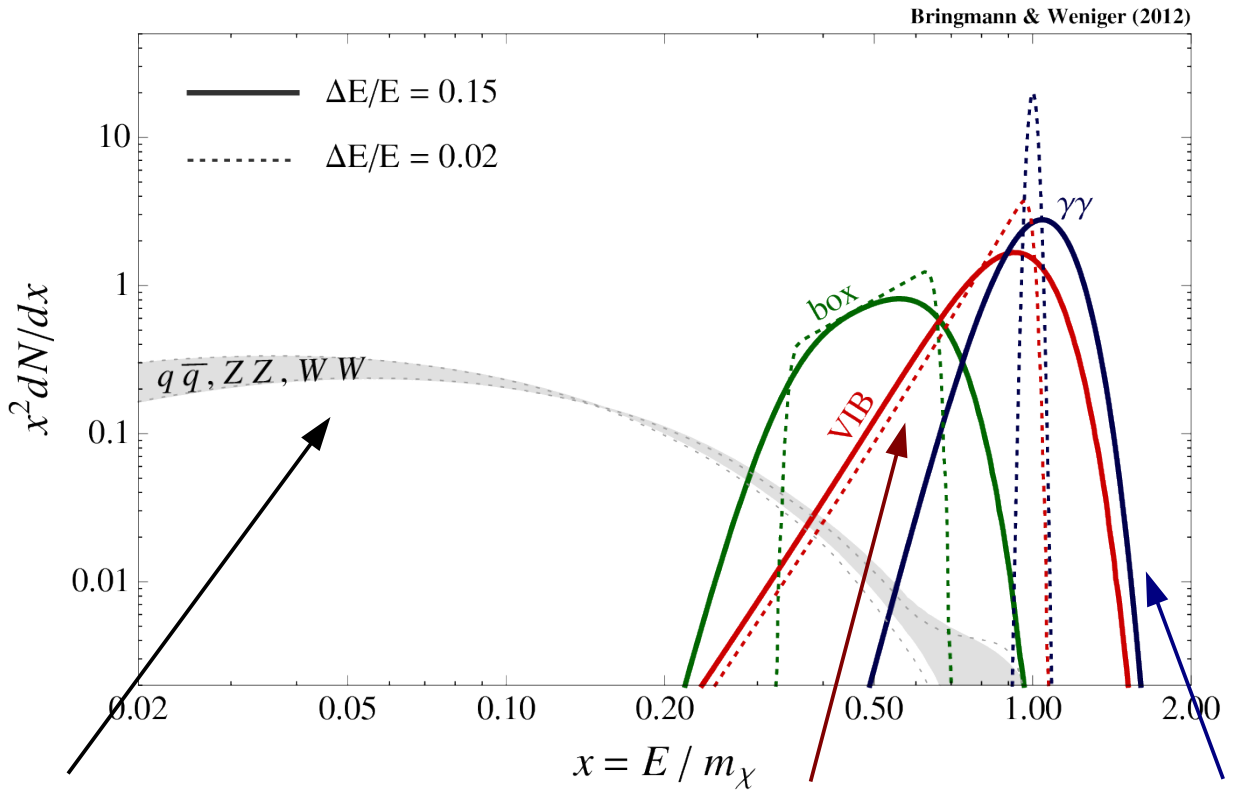
Dwarf galaxies are extremely promising

- 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

Smoking gun signatures for DM annihilation: Sharp features in the photon energy spectrum



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 $O(\alpha^2)$

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

Annihilation into monochromatic photons

Gamma-ray lines

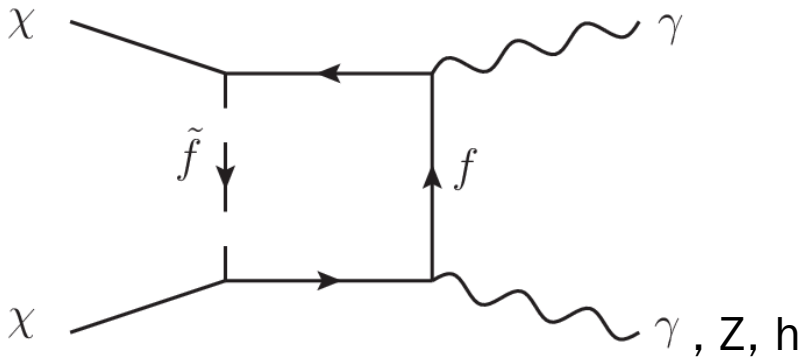
- are produced via two-body annihilation

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

- 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)]
- ...

Previous gamma-ray line searches

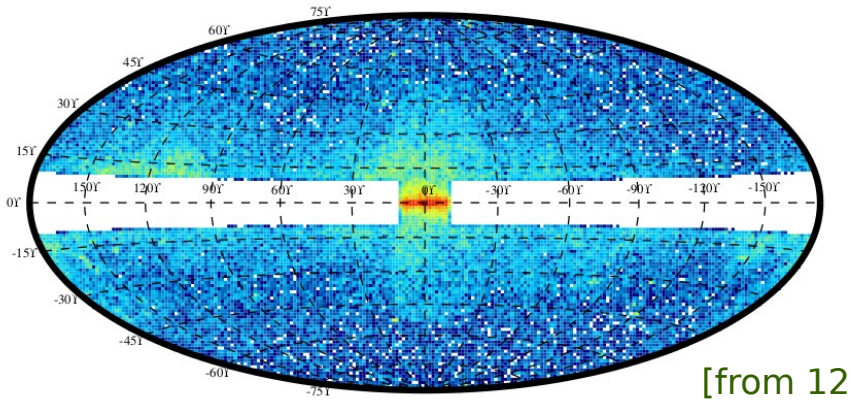
2010 - 2011: Upper Limits

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

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

Fermi LAT Search for Dark Matter in Gamma-ray Lines and the Inclusive Photon Spectrum
Ackermann et al. (Fermi LAT collaboration, 2012), PRD 86 (2012) 022002 (results already presented in 2011)
7 - 200 GeV, Spectral analysis, Galactic Center + High Latitudes → Upper Limits

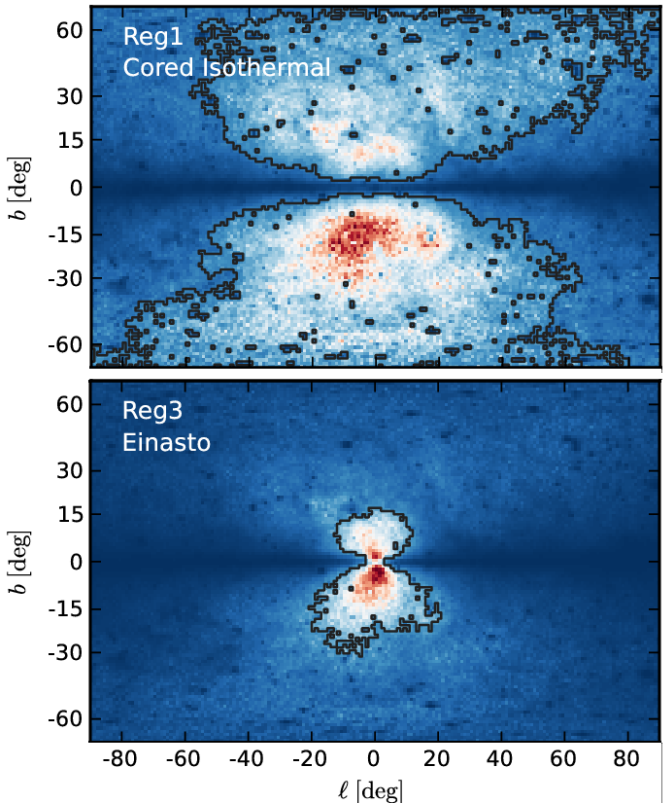
Typical region of interest used in previous searches:

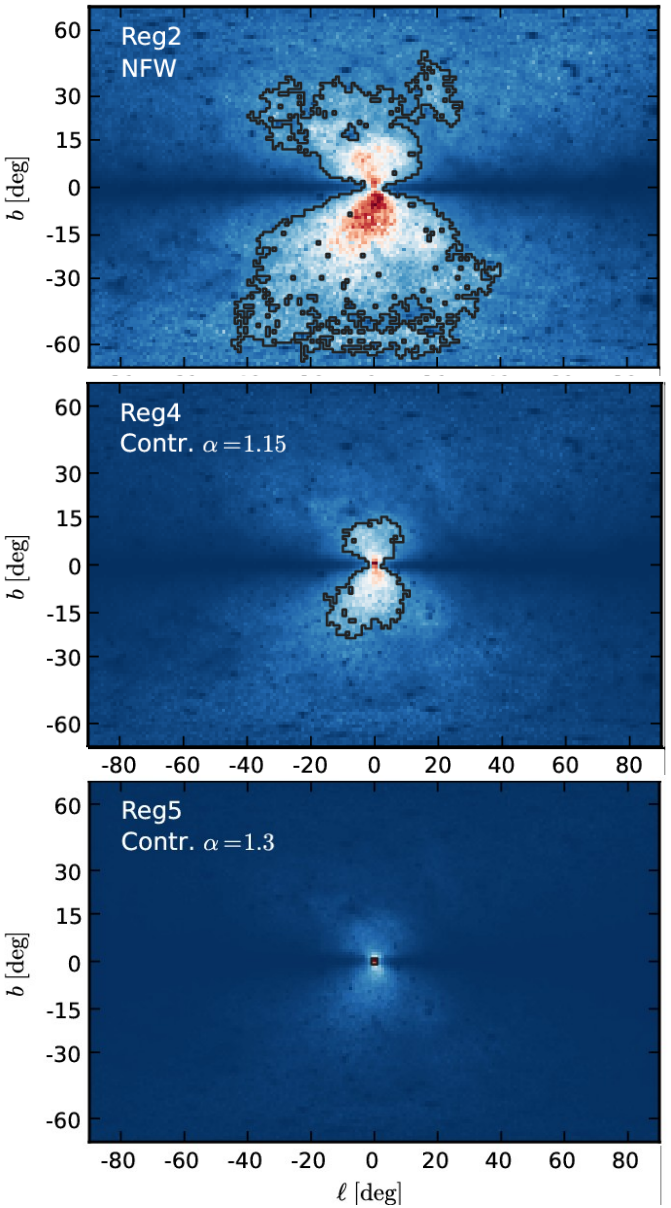


[from 1205.2739]

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

Target regions optimized for different dark matter profiles

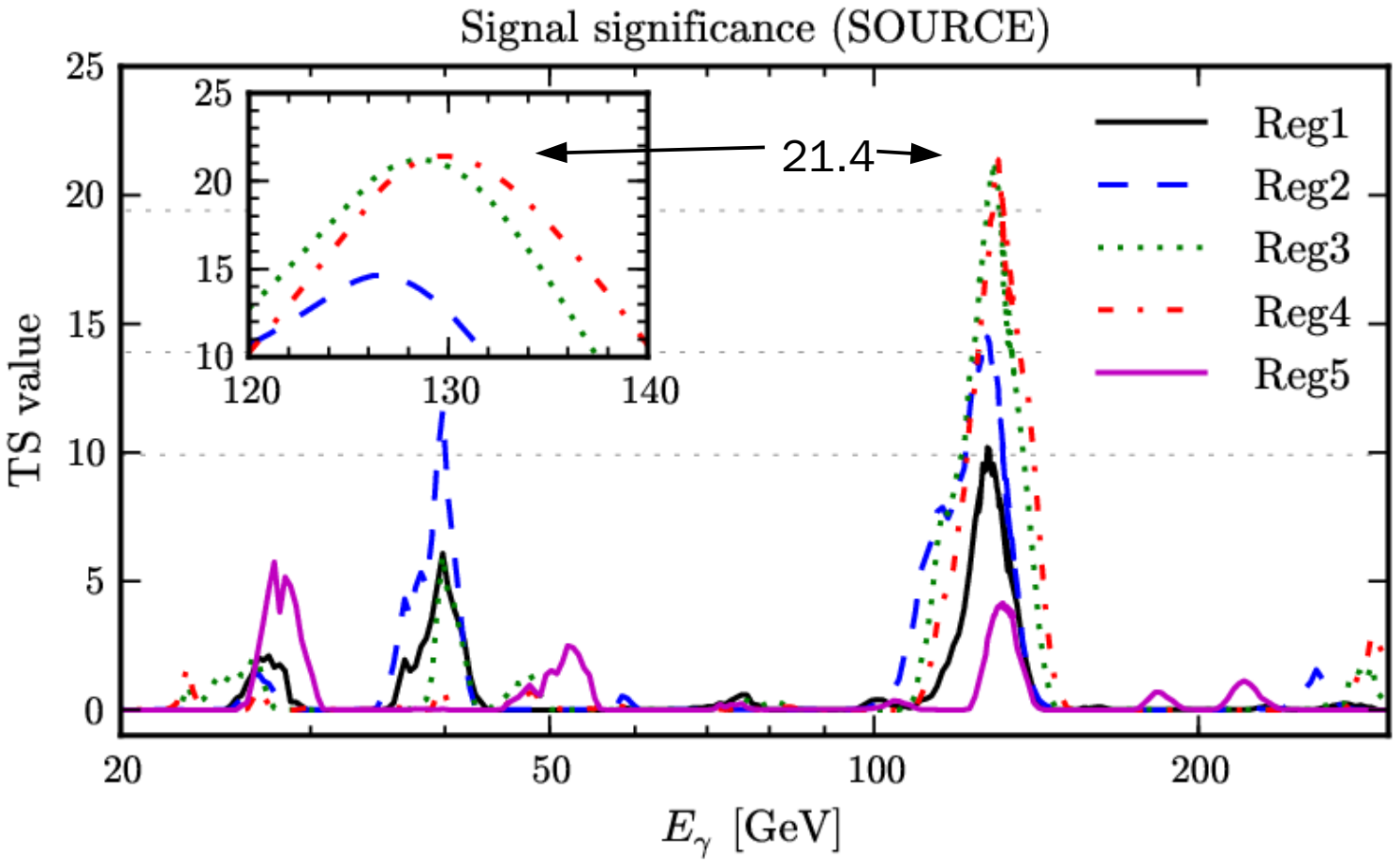




- Steeper dark matter halo profiles → smaller target region
- Galactic center always included (except for cored isothermal profile)
- Slight north/south asymmetry as consequence of asymmetric diffuse fluxes at ~1 GeV

[Bringmann et al., CW, 2012]

Results



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

Local significance: 4.6σ

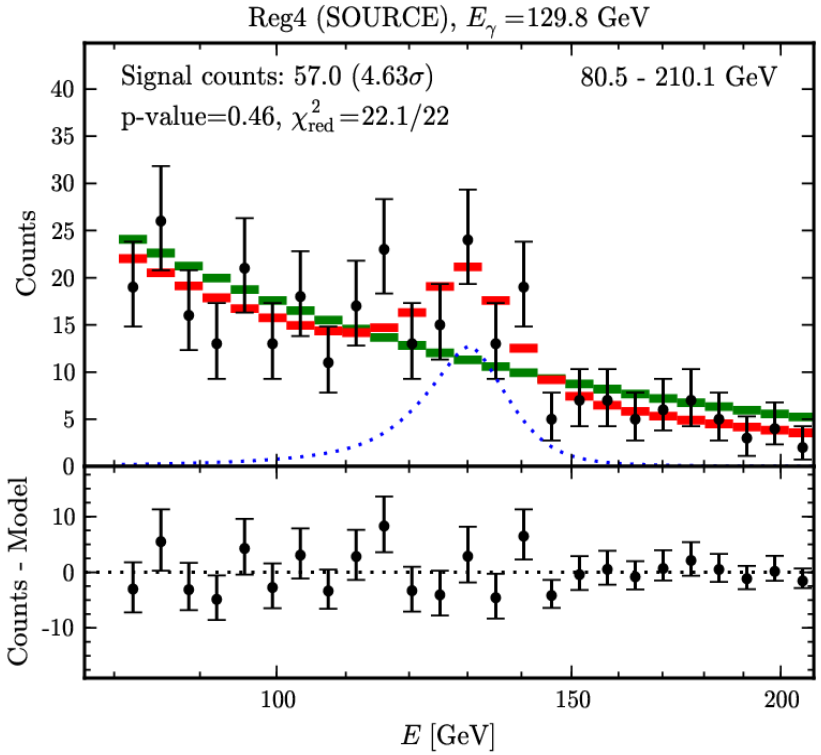
Assuming Einasto profile with 0.4 GeV/cm^3 local density:

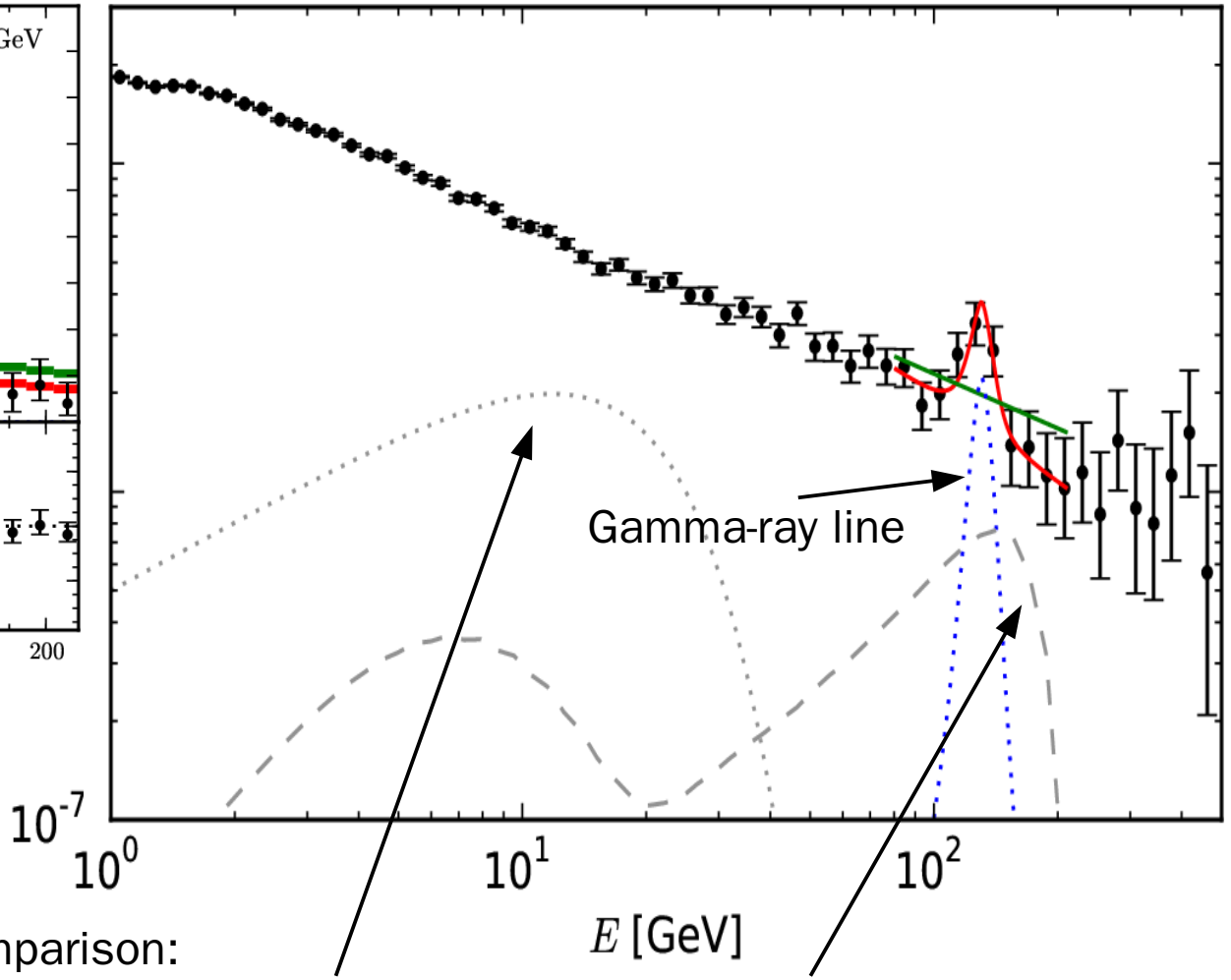
$$\langle \sigma v \rangle_{\chi\chi\to\gamma\gamma} = 1.27 \pm 0.32^{+0.18}_{-0.28} \times 10^{-27}\,\mathrm{cm}^3/\mathrm{s}$$

Global significance (spatial and spectral trial correction): ~3.2σ

Based on 43 month of P7V6 source class, similar for clean events.
Updates are shown below.

The signature is very narrow





For comparison:

Superexponential cutoff

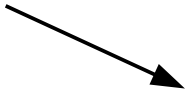
Inverse Compton emission from 230 GeV electrons

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

First studies of the 130 GeV feature

Fermi LAT Search for Internal Bremsstrahlung Signatures from Dark Matter Annihilation
Bringmann, Huang, Ibarra, Vogl & CW, JCAP 1207 (2012) 054
40 – 300 GeV, Spectral analysis, Different optimized target regions → 130 GeV feature

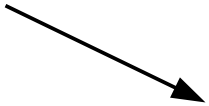
A tentative gamma-ray line from dark matter annihilation at the Fermi LAT
CW, JCAP 1208 (2012) 007
20 – 300 GeV, Spectral analysis, Different optimized target regions → 130 GeV feature



"In regions close to the Galactic center, we find a 4.6 sigma indication for a gamma-ray line at 130 GeV."

Fermi 130 GeV gamma-ray excess and dark matter annihilation in sub-haloes and in the Galactic center
Tempel, Hektor and Raidal, JCAP 1209 (2012) 032
Adaptive Kernel Smoothing, Monte Carlo analysis: → 130 GeV feature

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

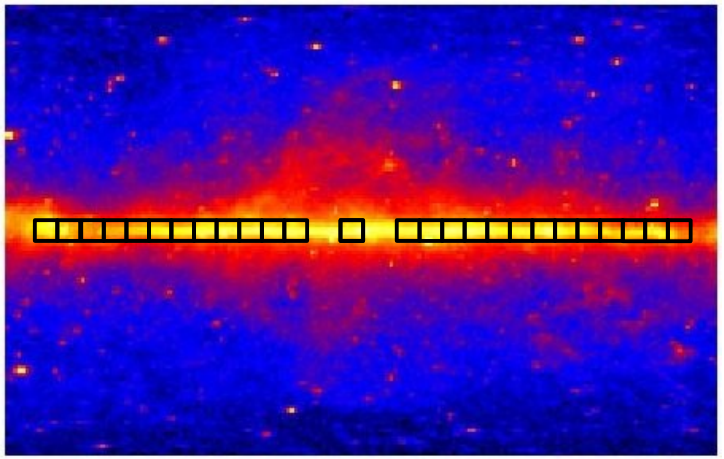


"Even better fits are obtained for off-center Einasto and power-law profiles, which are preferred over the null (no line) hypothesis by 6.5 sigma (...)."

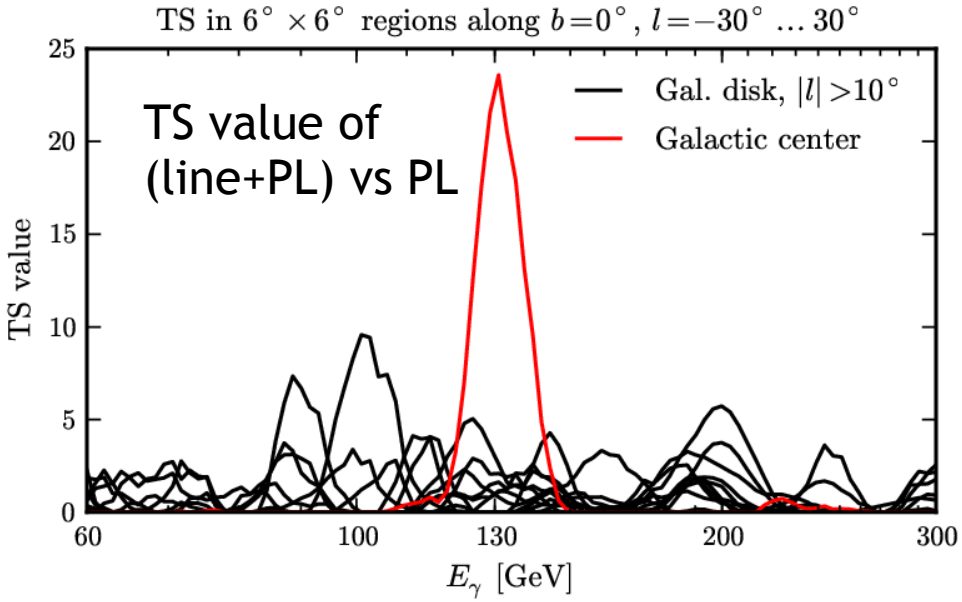
...

Some properties of the 130 GeV feature

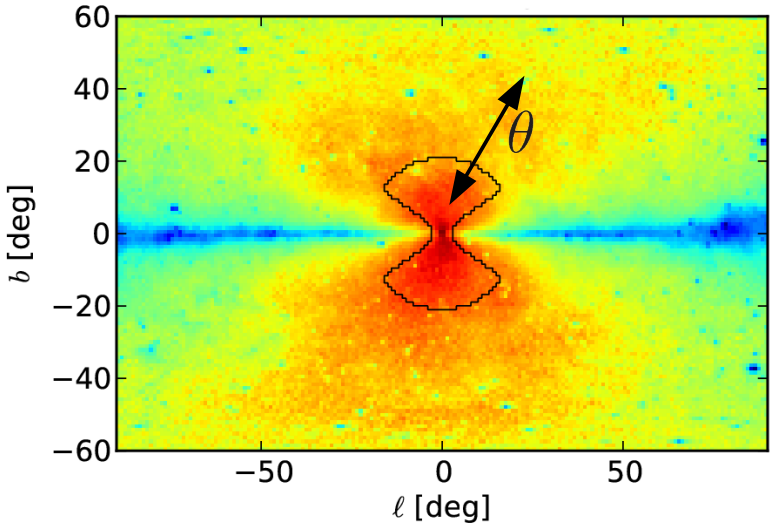
At Galactic center only:



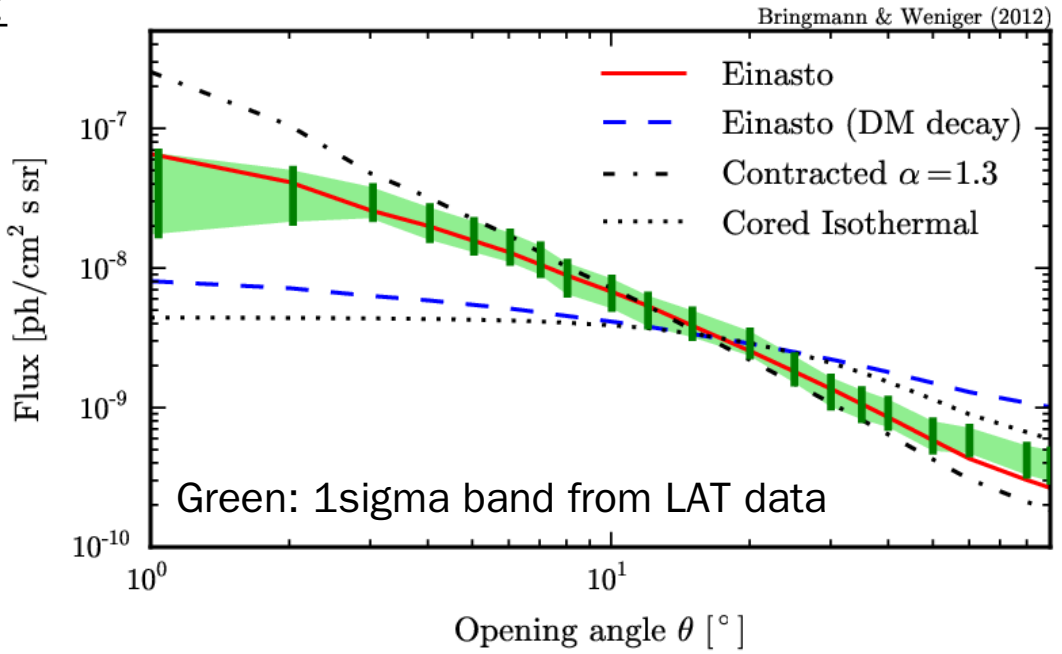
The signature does not reappear in other parts of the Galactic disk



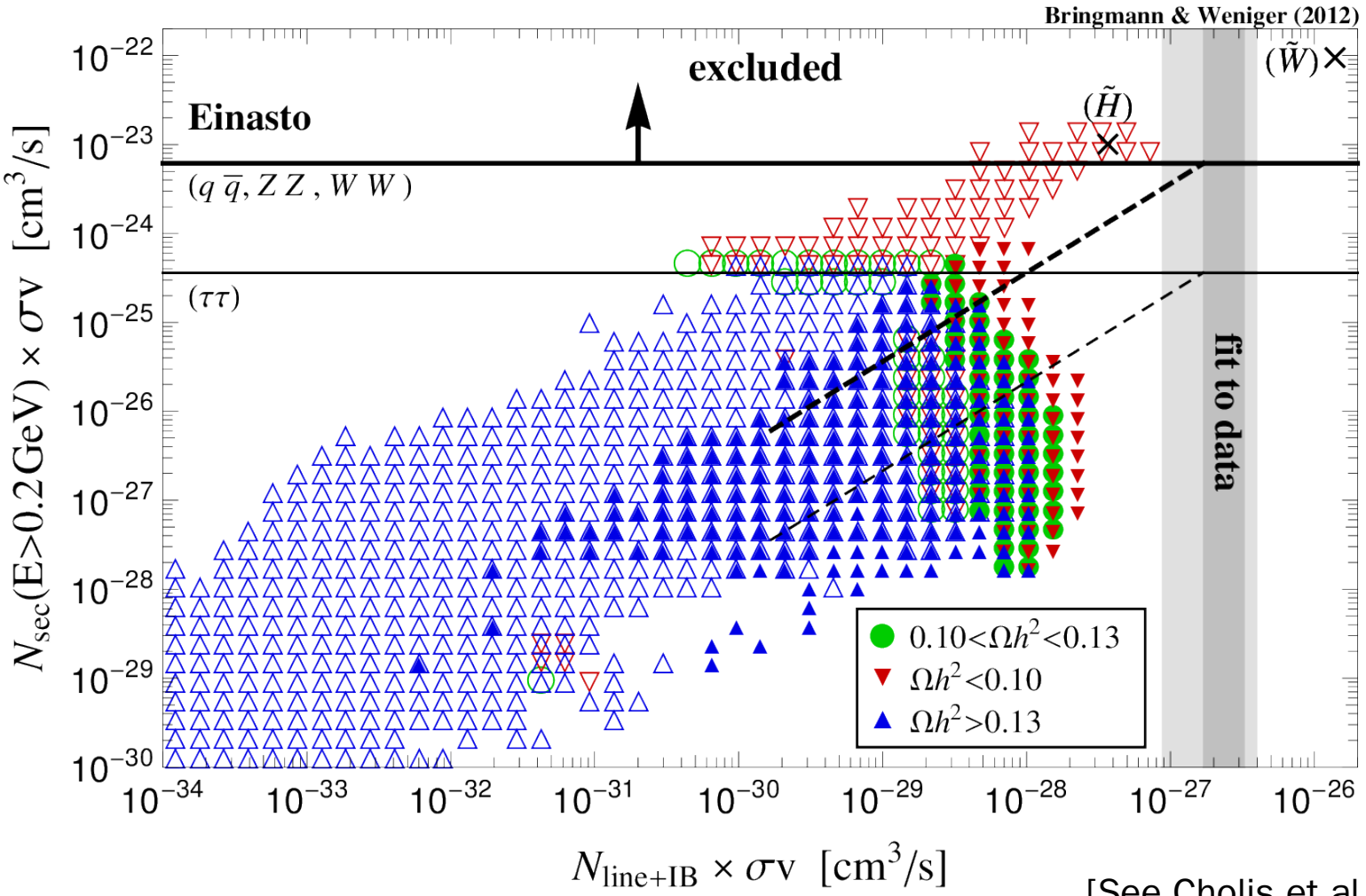
Compatible with Einasto DM profile:



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



Line vs. continuum part of DM signal



[See Cholis et al., Buchmüller et al, Cohen et al., 2012]

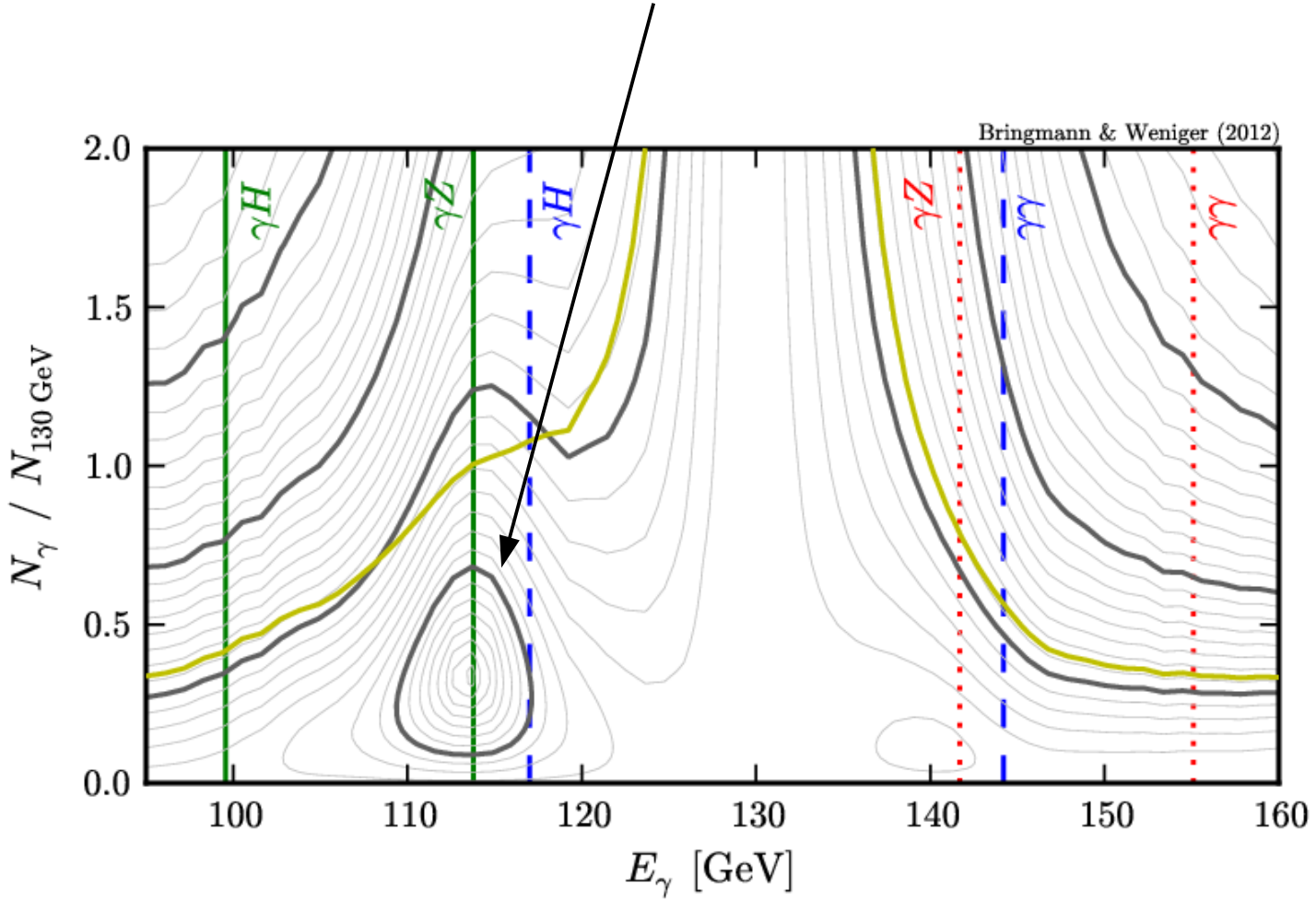
No continuum emission from DM is found up to now

- This is a challenge for theoretical models that try to explain the line in terms of dark matter annihilation → LARGE branching ratios into gamma-ray lines required!
- Plot: shows scan over SUSY scenarios (cMSSM, MSS-7, MSSM-9)

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 very weak indication for such a line in the data.



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

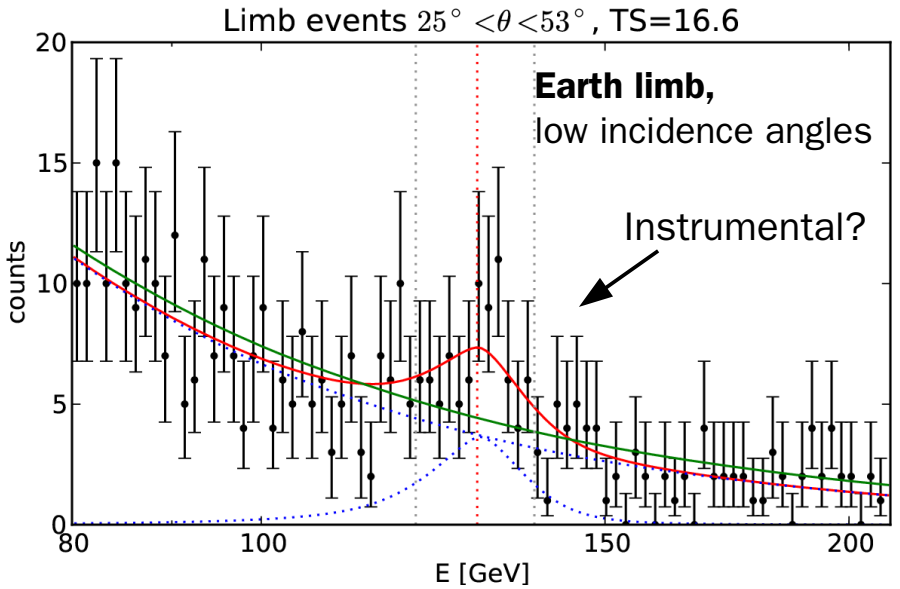
Follow-up studies:
Dark matter models, astrophysical explanations, instrumental effects, searches for corroborating evidence from other targets

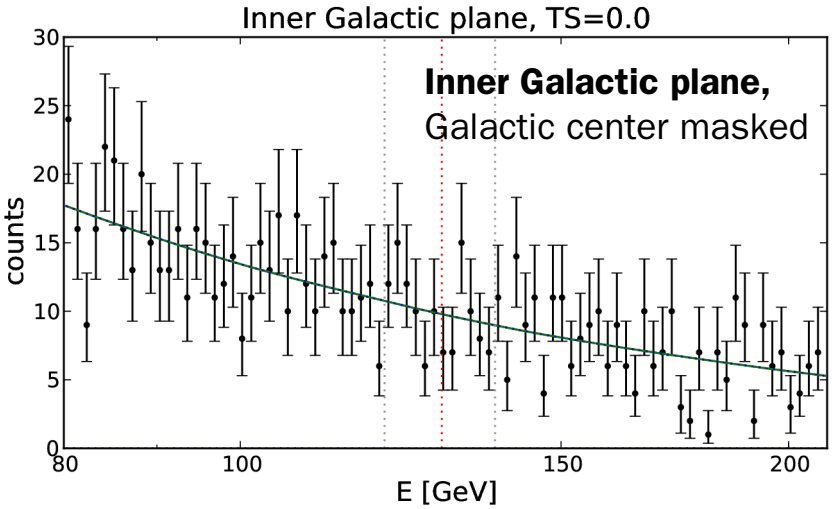
A large number of groups studied almost all aspects of the signature:

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
...

But...

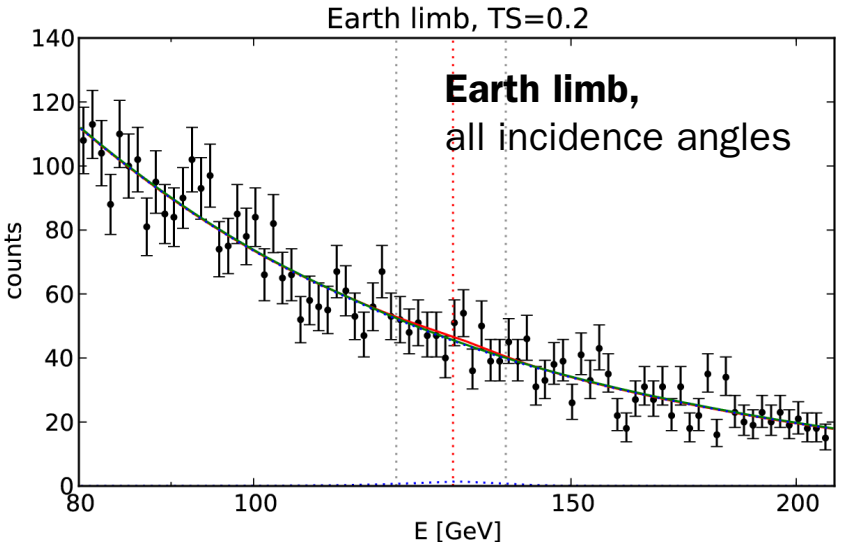
The Earth limb at low incidence angles
A red flag?





Low incidence angle (<60deg) **Earth limb events** show a feature at 130 GeV with >3σ.
→ Indication for instrumental effect?

BUT[2]:
- nothing is found in Galactic disk (masking the Galactic center) → surprising if it is an instrumental effect
- nothing is found in full Earth limb sample → no chance that this is a physical effect
- situation remains confusing



[Finkbeiner et al., 2012]

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 (with the GC one being the strongest).

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**

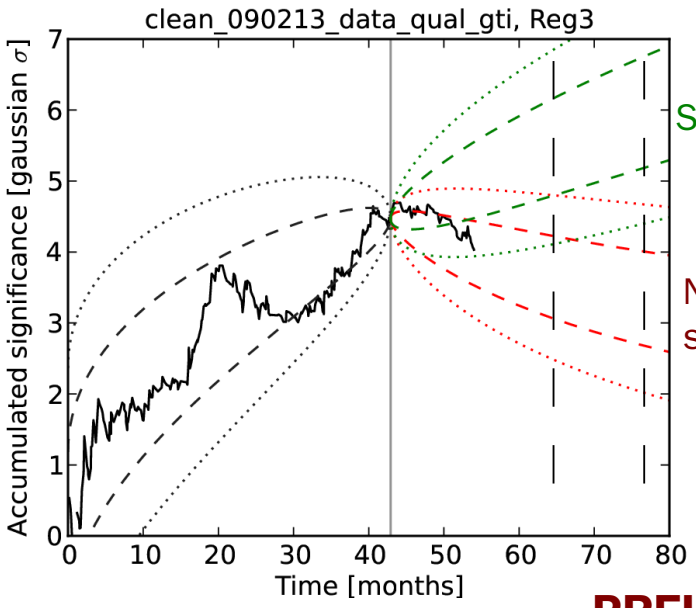
→ They use **different ROIs and different data**, so results are right now impossible to confirm independently. Release of P7rep expected ~~end of 2012~~ in a few weeks

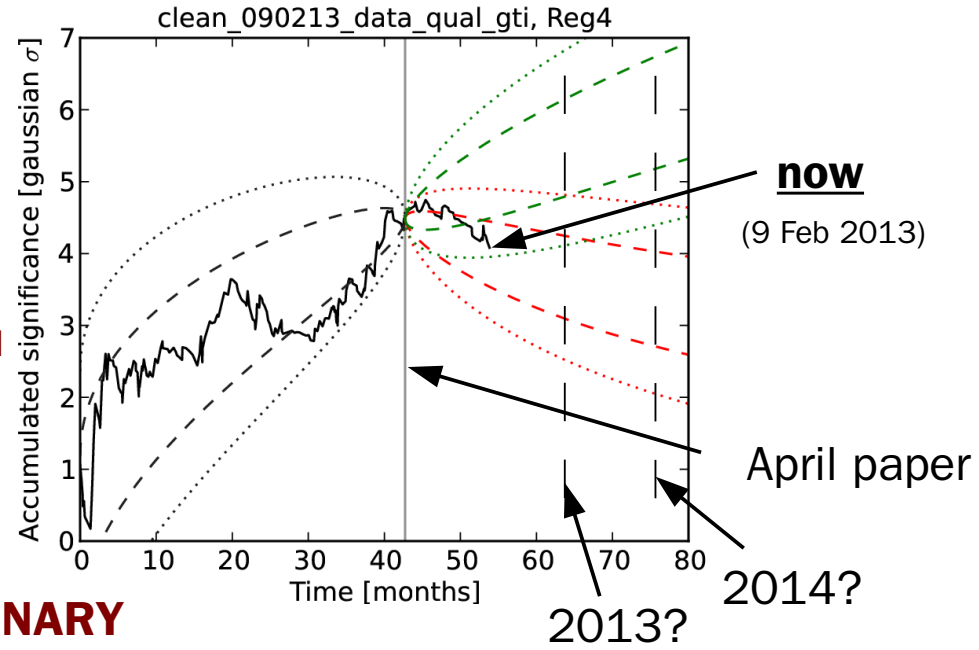
[For details see talks by Eric Charles, Elliott Bloom and Andrea Albert; Fermi Symposium 2012]

Our analysis: situation right now

Reg3 | Reg4

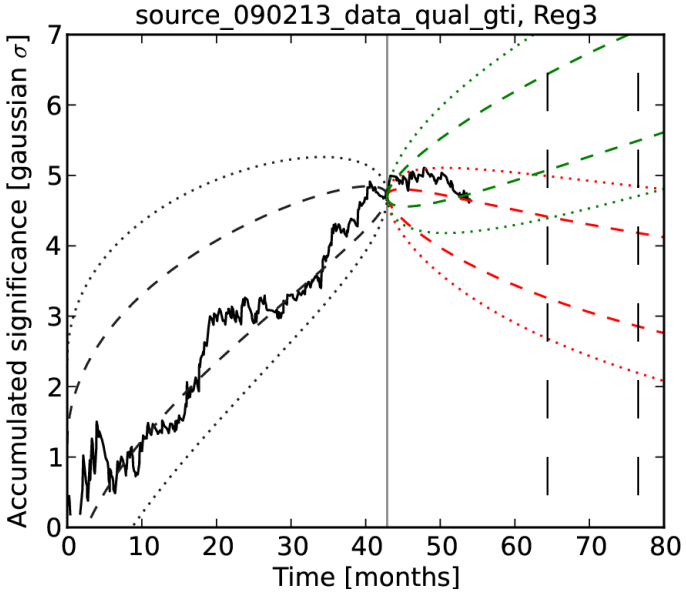
CLEAN

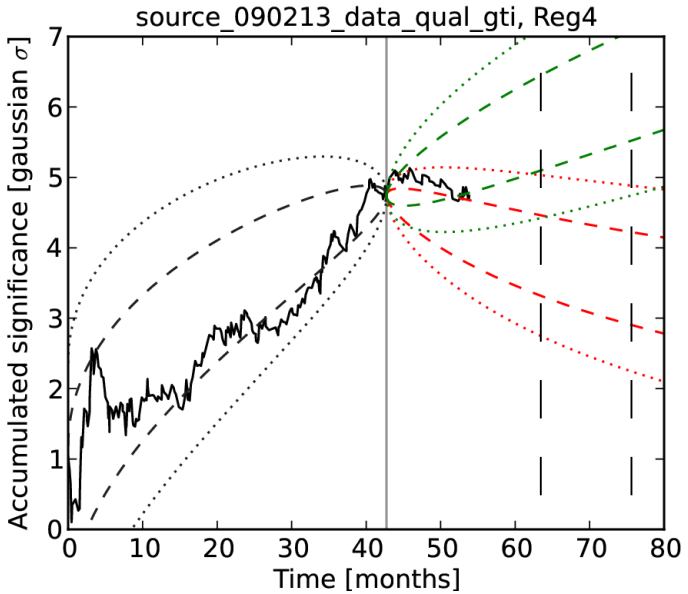




PRELIMINARY

SOURCE





Bands: Analytical projection for ±1σ and ±2σ bands, assuming Gaussian noise with S/B~0.4 and nelgecting uncertainties in fiducial TS value; projections do not take into account expected improvements with PASS8

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

Conclusions

- The Fermi LAT is an excellent instrument to search for signature from dark matter annihilation.

- Null results from searches in dwarf galaxies and the Galactic halo give very stringent constraints on WIMP dark matter and start to exclude models with low dark matter masses in the ~10 GeV range.

- The Galactic center data shows a line-like signature at ~130 GeV, which is not incompatible with a signal from dark matter annihilation

  Its cause is unclear.

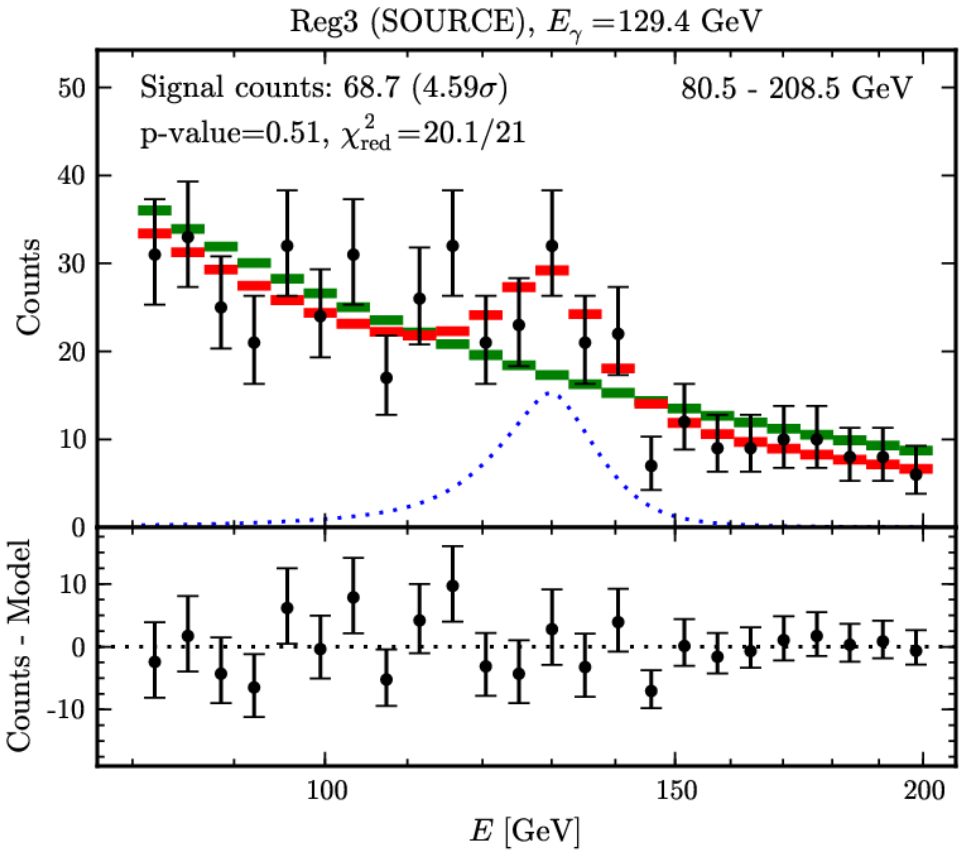
- The 130 GeV feature could be
  - Astrophysical (unlikely)
  - Instrumental (Earth limb?, Sun?, but why just at the center?)
  - Rare statistical fluctuation (could be, more data needed)
  - Dark matter annihilation ("consequences would be mind-blowing")

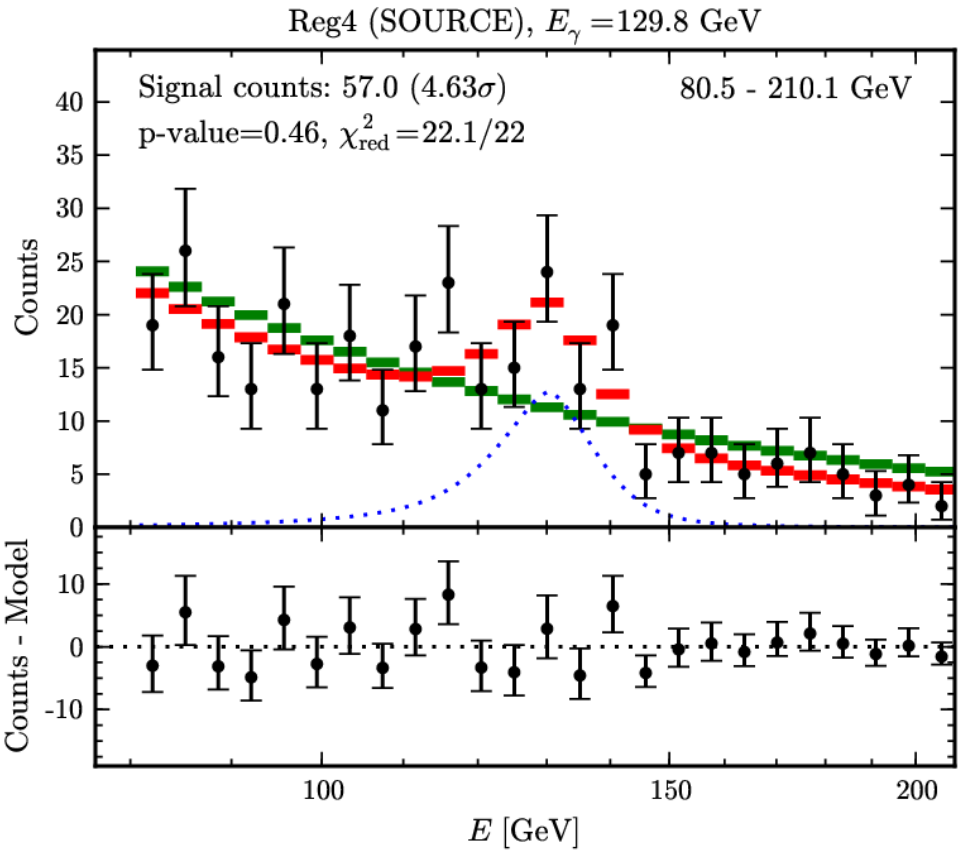
[A HEP blogger]

These are exciting times for dark matter searchers
(and hopefully for dark matter finders).

Thank you
& stay tuned!

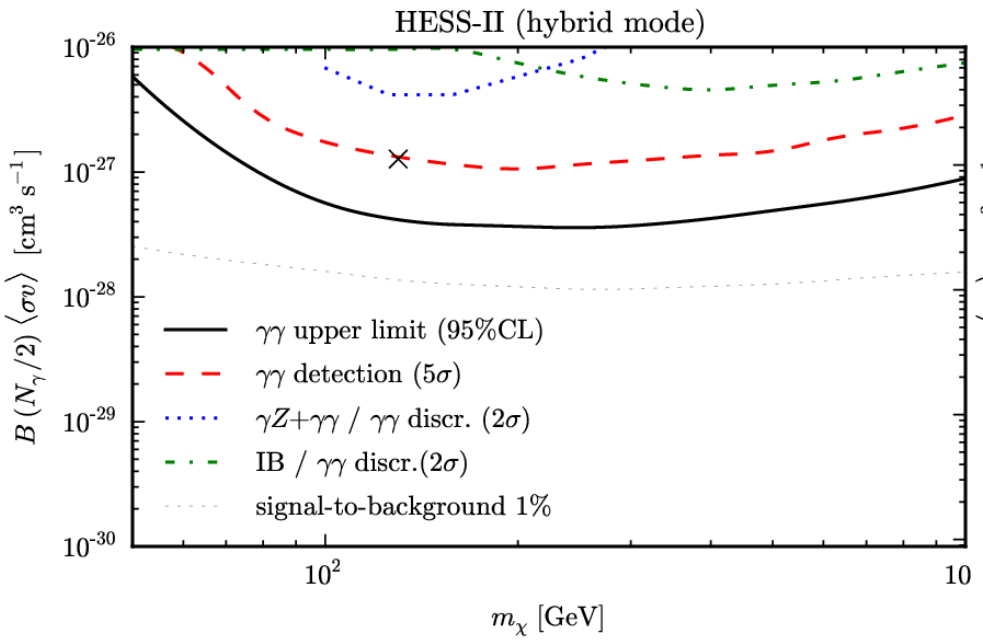
Fit Quality and Residuals

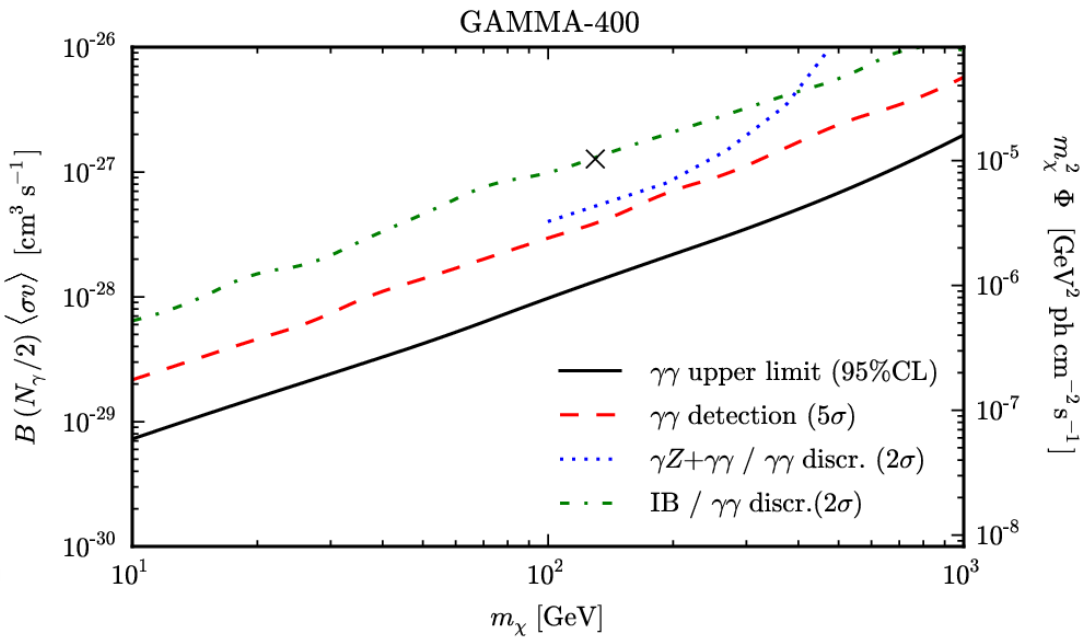




- **Red**: best-fit alternative model (bg + signal)
- **Green**: best-fit null model (background only)
- **Blue**: best-fit line signal alone

Prospects for HESS-II and GAMMA-400





HESS-II (hybrid)

- 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 in 2014?

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

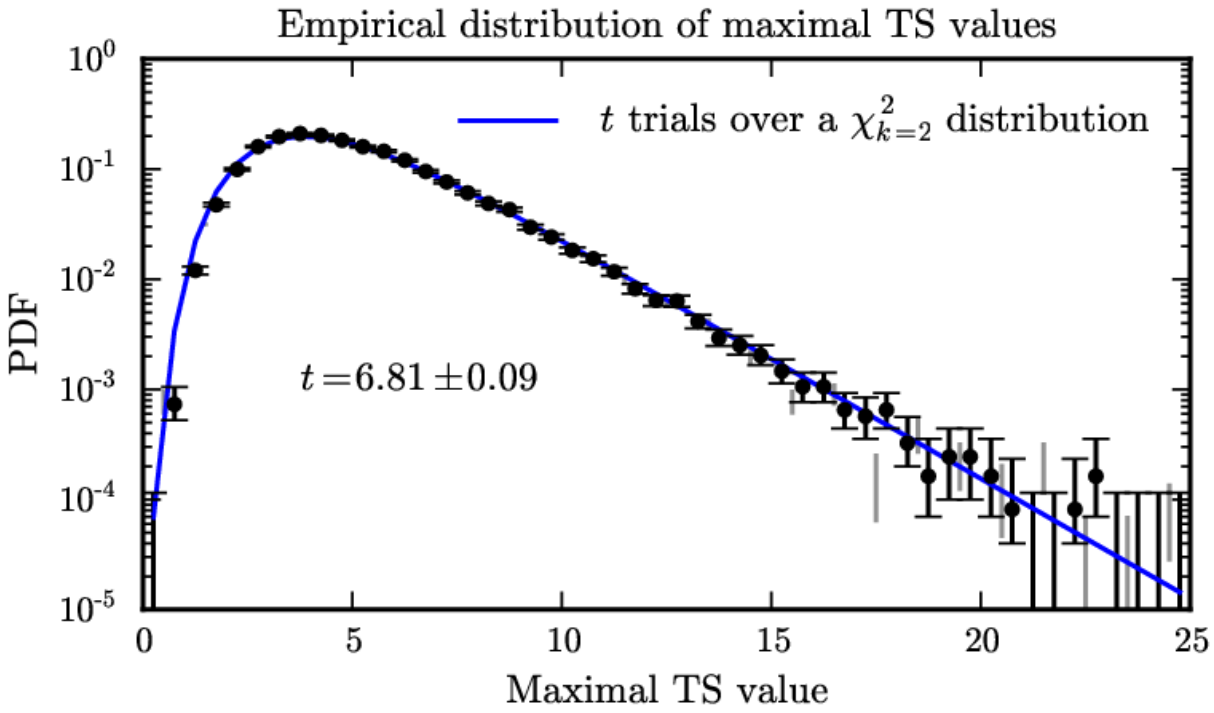
GAMMA-400

- 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?

Correcting for trials and global significance

- To calculate trial factors for the scan from 20 to 300 GeV, we performed
  - a **Monte Carlo analysis** (25000 samples) of spectra without signal
  - a **subsampling analysis** of anti-galactic-center data (~21000 random test regions from |l|>90deg data)

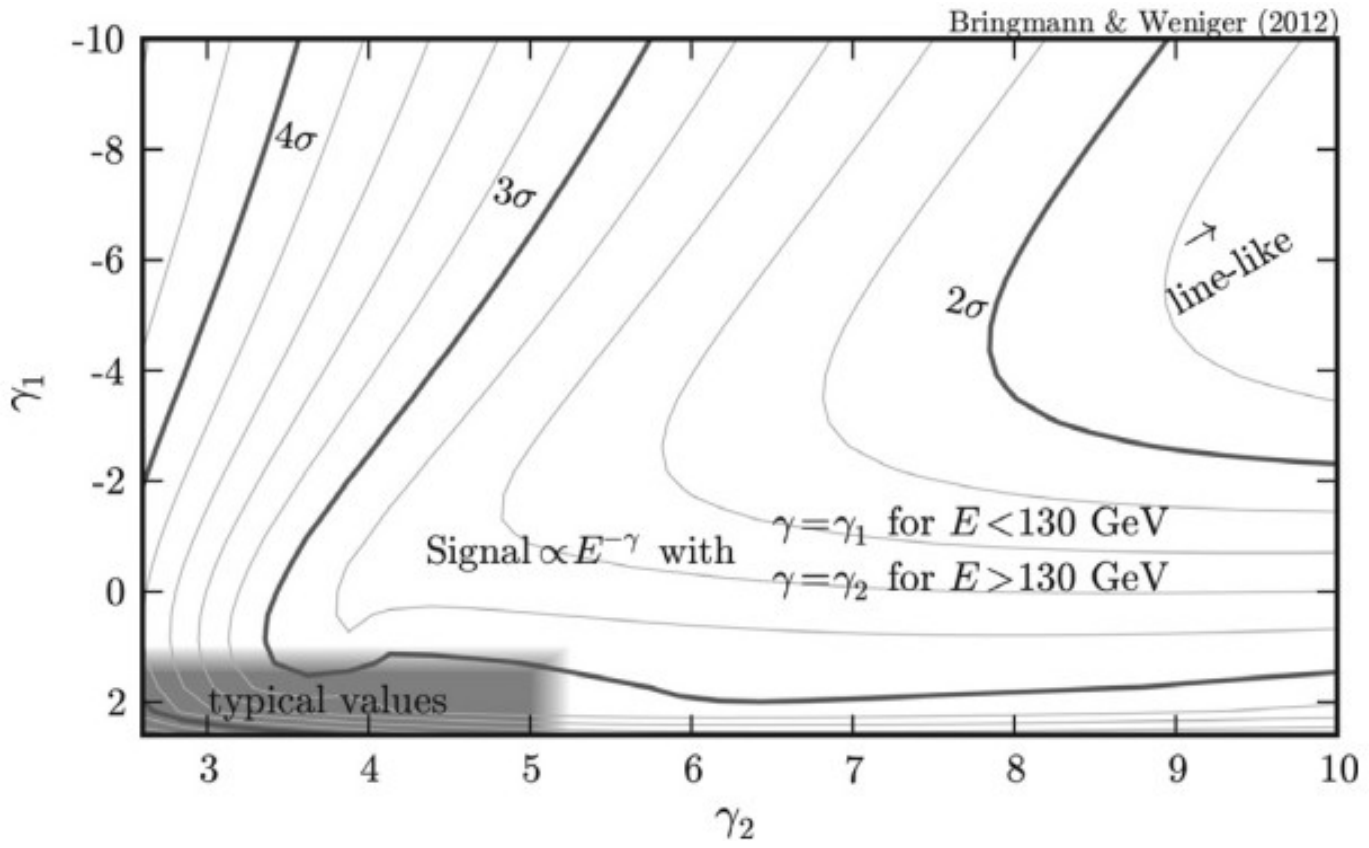
  and searched for lines.

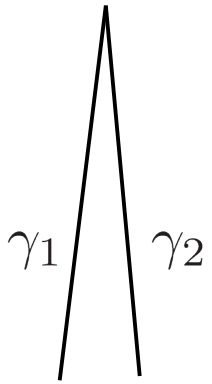


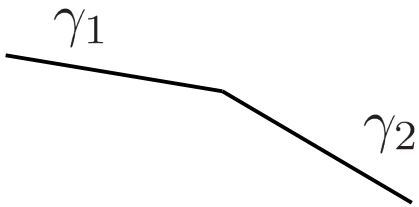
- Taking into account all trials, the significance is about **3.2σ** (ten target regions times the scan from 20 to 300 GeV)

Broken Power Laws?

Significance contours for broken power-law fit for different spectral slopes:







…probably not

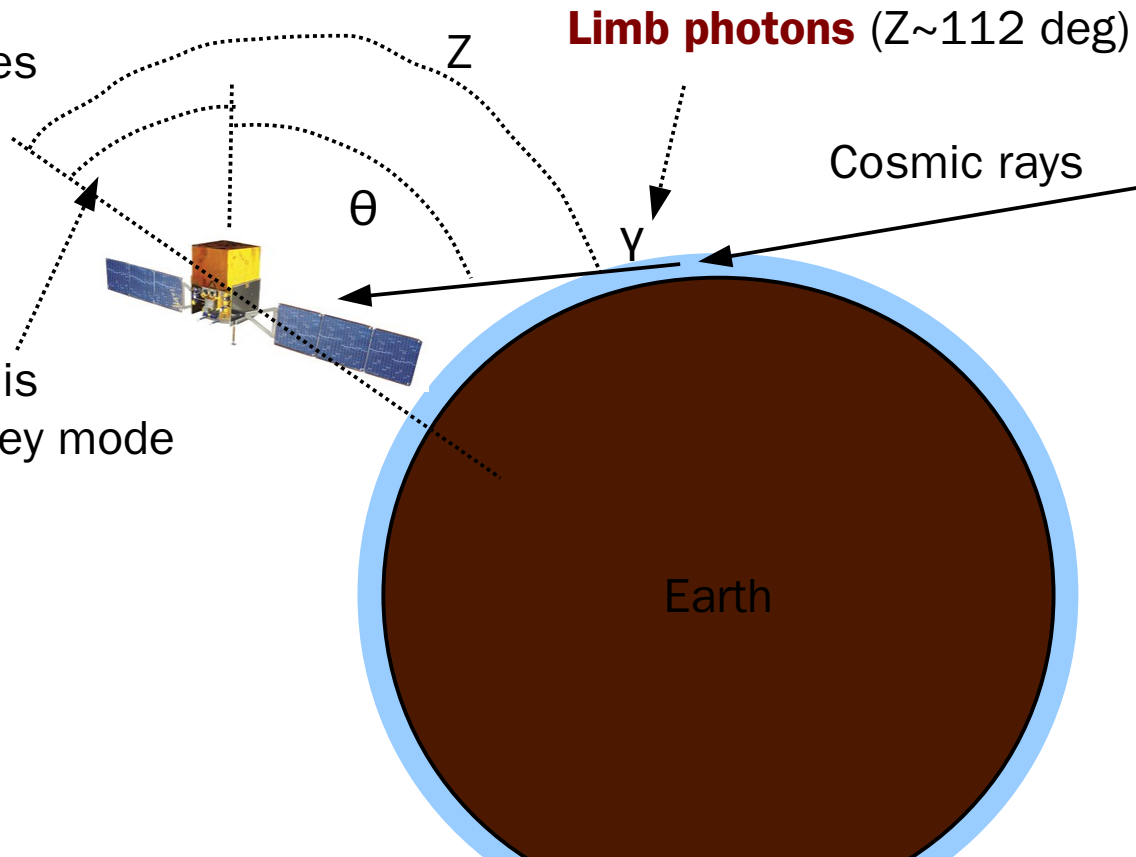
The Earth limb

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

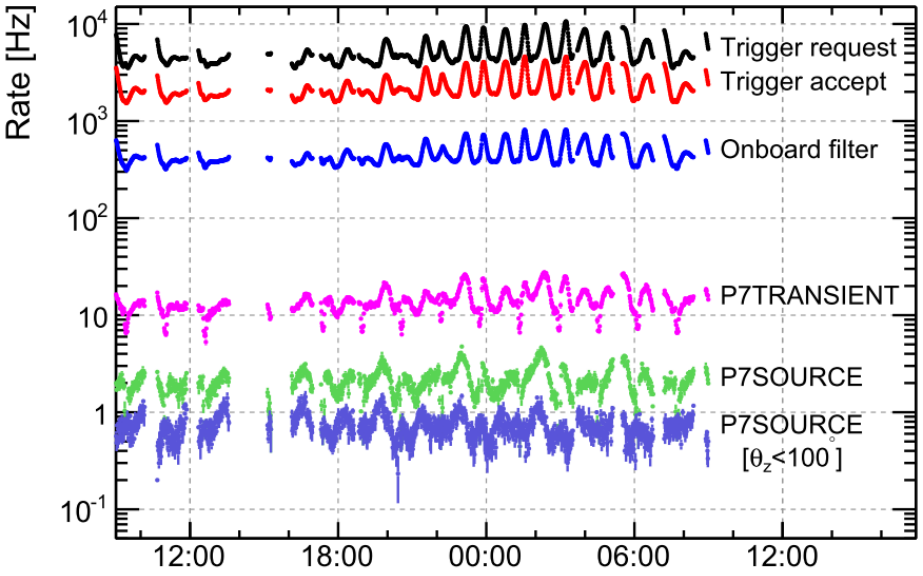


Why at the Galactic center?

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

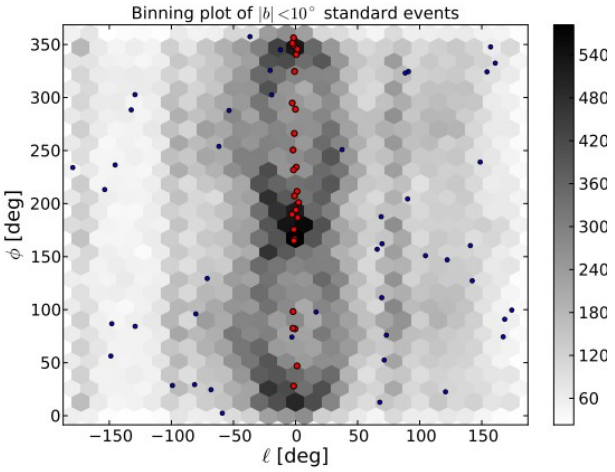
- Hypothesis: Galactic center spectrum is hard
  → Not much harder than Gal. plane

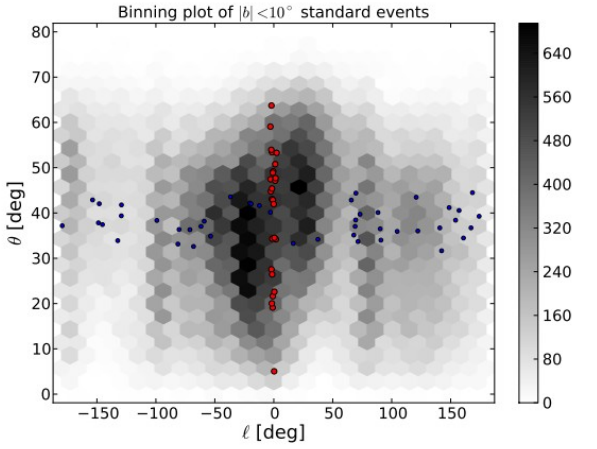
Sample	$N(>100$ GeV)	$\frac{N(>100\text{ GeV})}{N(>30\text{ GeV})}$	$\frac{N(>300\text{ GeV})}{N(>100\text{ GeV})}$
Standard events	5093	13.4%	9.6%
Inner Galactic plane	703	16.9%	9.8%
Galactic center	82	17.4%	9.8%
Galactic center line	26	–	–
Earth limb	3120	10.2%	9.2%
Earth limb line	45	–	–



[1206.1896]

- Hypothesis: 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

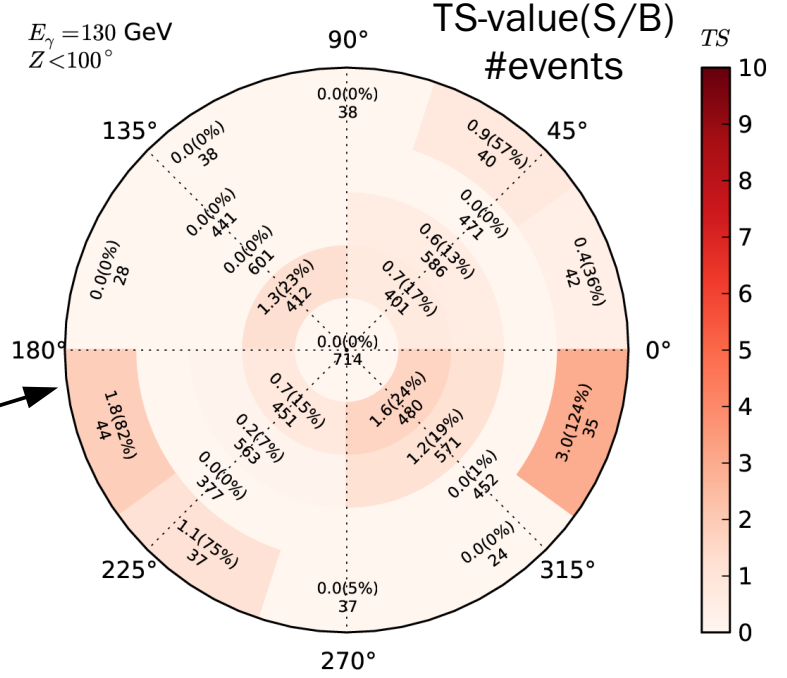


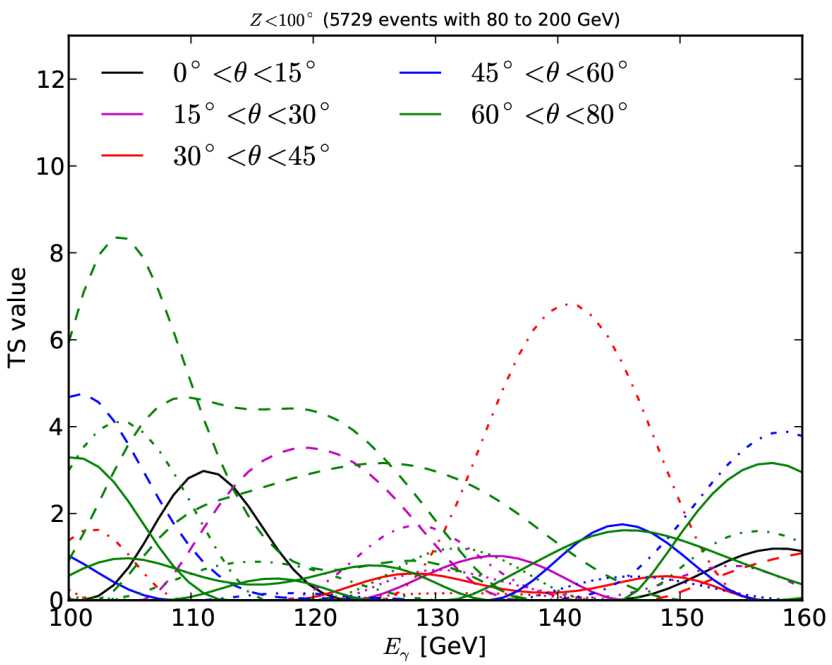


The LAT from the top

Standard analysis
cuts: Z<100 deg

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





Earth Limb:
Z>110 deg