Fermi
Gamma-ray
Space Telescope

Dark Matter and γ-ray Line Searches with Fermi LAT

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On behalf of The Fermi LAT Collaboration

June 28th, 2013

9th Patras Workshop on Axions, WIMPs and WISPs
Schloß Waldthausen
24- 28 June 2013

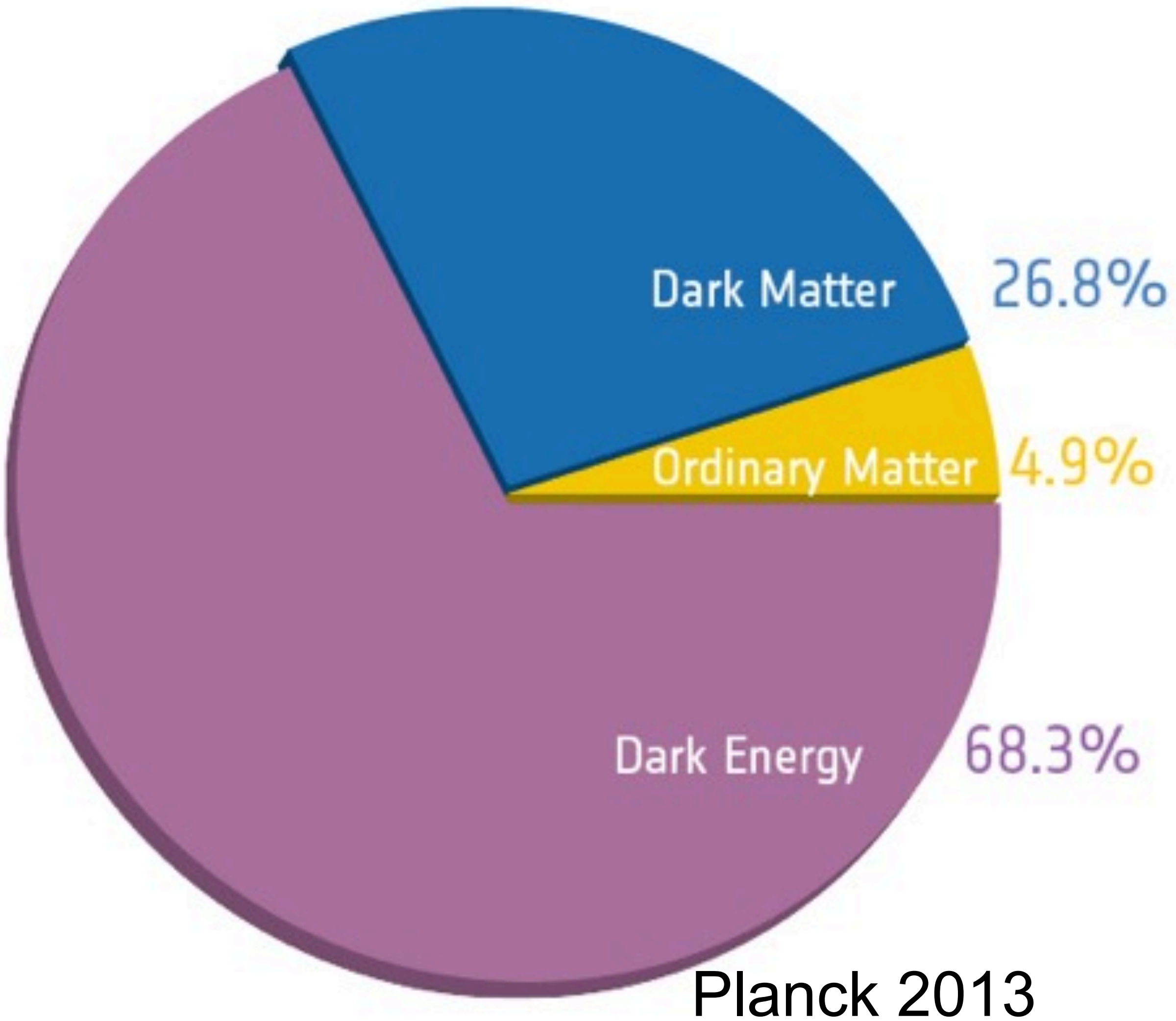
Dark Matter

In ΛCDM

$$\Omega_{CDM} h^2 \simeq 0.12$$

Hubble parameter

$$h \simeq 0.67$$



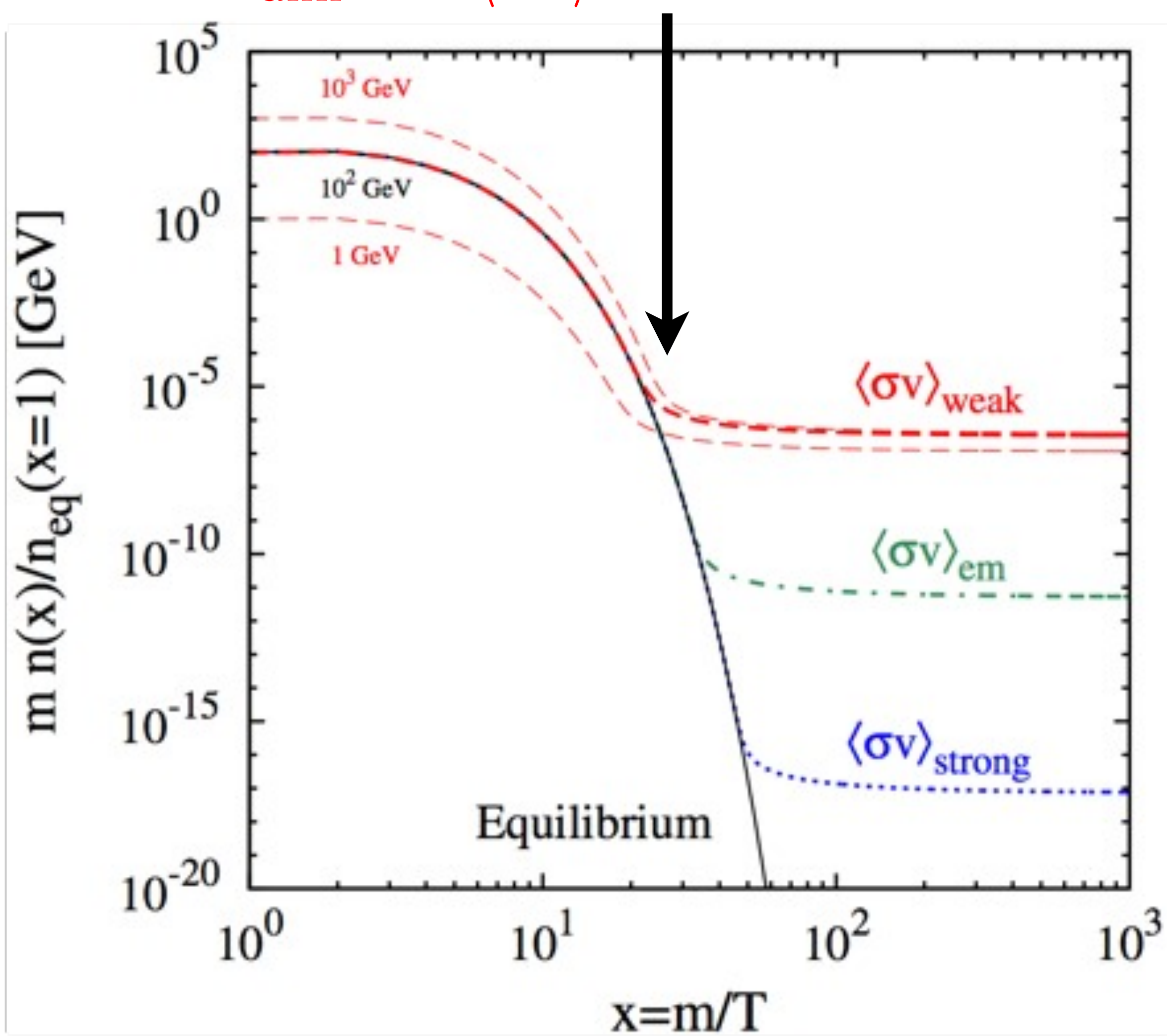
Planck 2013

↪ **Beyond standard model physics needed!**

Weakly Interacting Massive Particle

Annihilation rate ~ Expansion rate

$\Gamma_{\rm ann} = n\langle\sigma v\rangle \sim H$ (freeze-out)



Any massive particles with 'sizable' interactions, freeze-out from chemical equilibrium, leaving a relic abundance

$$\Omega h^2 \simeq \frac{3\times 10^{-27}{\rm cm^3 s^{-1}}}{\langle\sigma v\rangle_{\rm fo}}$$

=0.12

Thus predicts annihilation x-section of the electroweak scale:

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

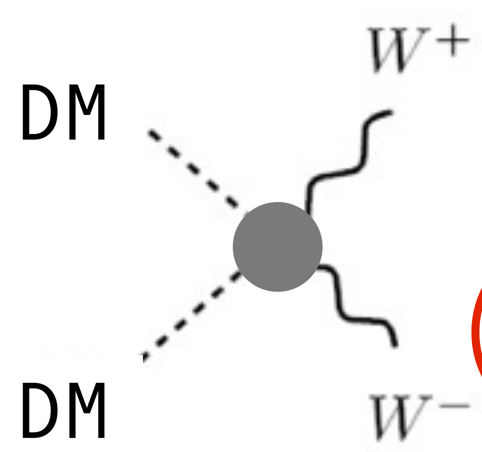
— Exceptions: p-wave, coannihilation, resonances, thresholds, Sommerfeld effect...

DM particle candidate with EW couplings, typical mass of 1 GeV to 100 TeV, with relic abundance thermally produced.

WIMP paradigm: gamma-rays

Correct relic density for DM implies

$$\langle \sigma v \rangle \sim 10^{-26} \mathrm{cm}^3/\mathrm{s}$$



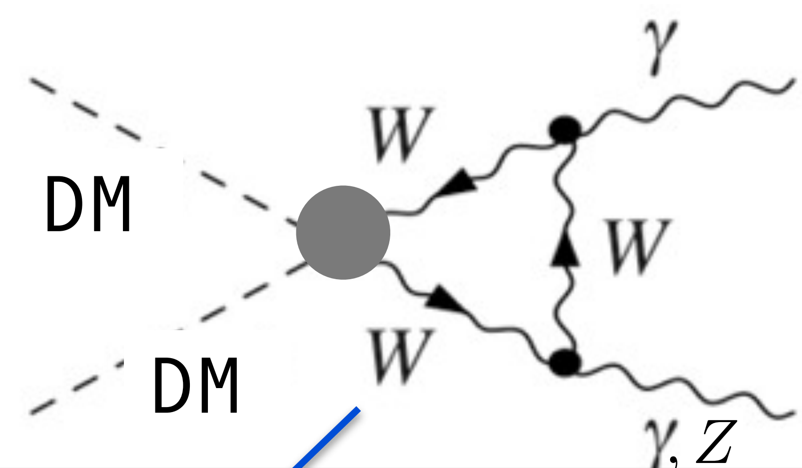
Can directly or via fragmentation produce

$$\gamma, \nu, e^{\pm}, p, \bar{p} \ldots$$

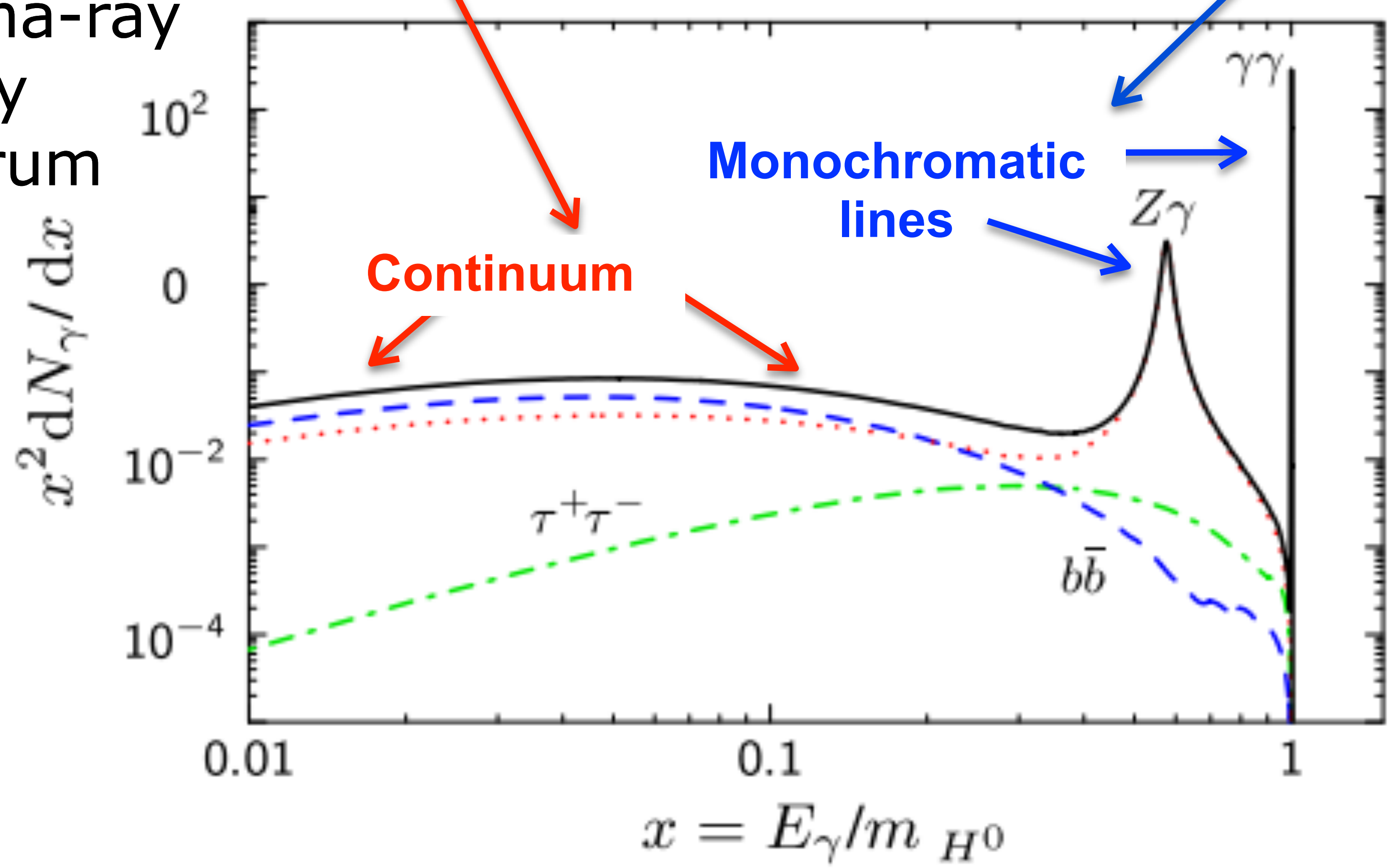
Neutral initial state and charged final state

⇒ monochromatic photons at loop-level

$$\langle \sigma v \rangle_{\gamma\gamma} \sim \langle \sigma v \rangle \times \alpha^2 \sim 10^{-30} \mathrm{cm}^3/\mathrm{s}$$



Gamma-ray energy spectrum



- The Energy spectra encode intrinsic DM particle properties
- The gamma-line(s) (or IB/FSR…) is a clean DM signal (no astro-physical bkg)

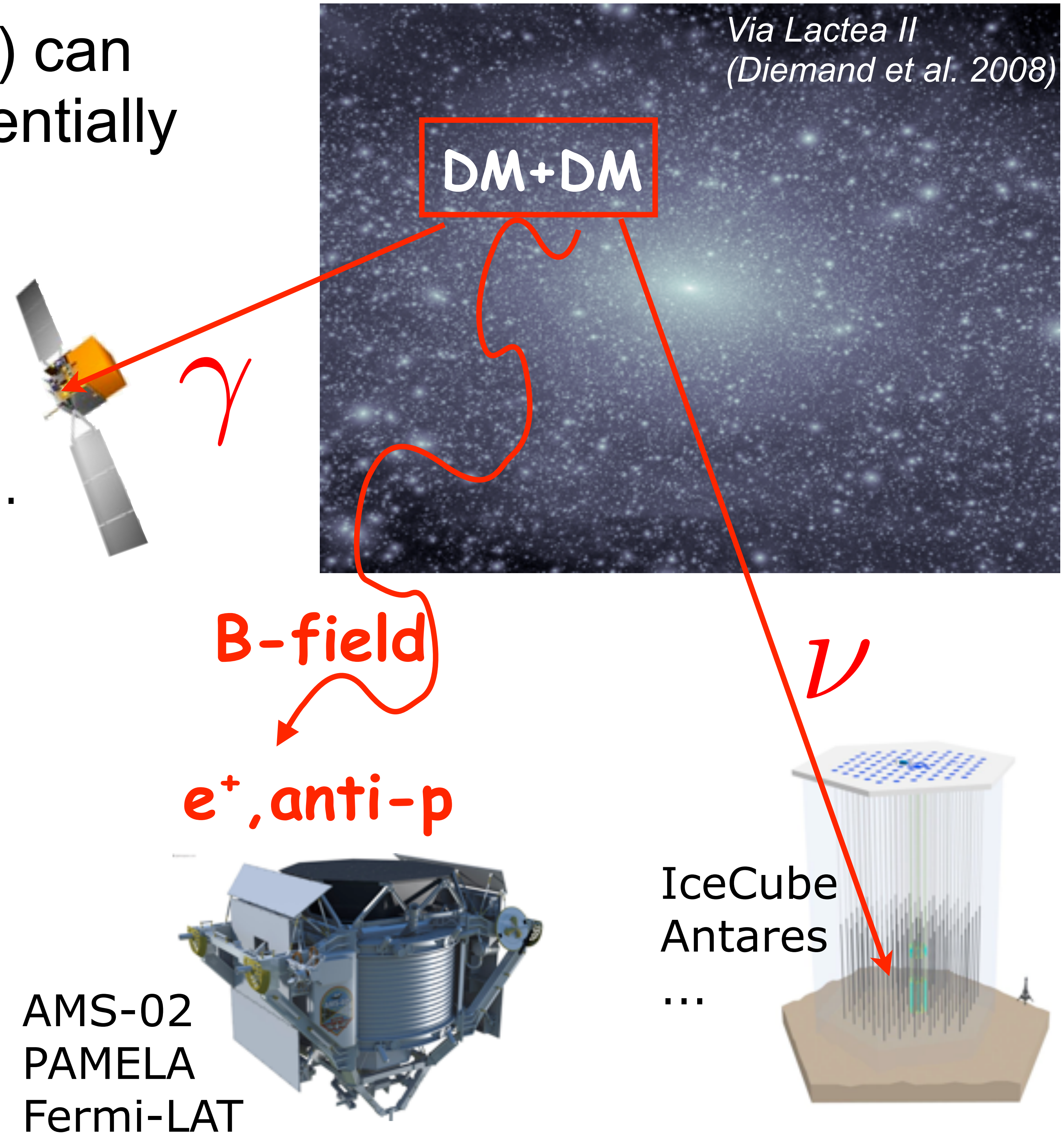
➞ "smoking gun" signal!

Indirect Dark Matter Search

Annihilations (or decays) can produce a variety of potentially detectable SM particles

Ground based instrument:
Cherenkov detectors;
as HESS, MAGIC, VERITAS, ...
Space satellite:
Fermi-LAT, ...

- Intensity variation along different lines of sight would map the DM spatial distribution



Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe

$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{4\pi}\sum_f \frac{dN_f}{dE}B_f \int_{LOS} dl(\psi)\,\frac{1}{2}\frac{\rho(l)^2}{m_\chi^2}$$

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Photon Flux
(events/area/time/energy)

Energy
spectrum

Direction
(dwarf galaxy, the whole sky, etc)

Gamma-rays from WIMPs

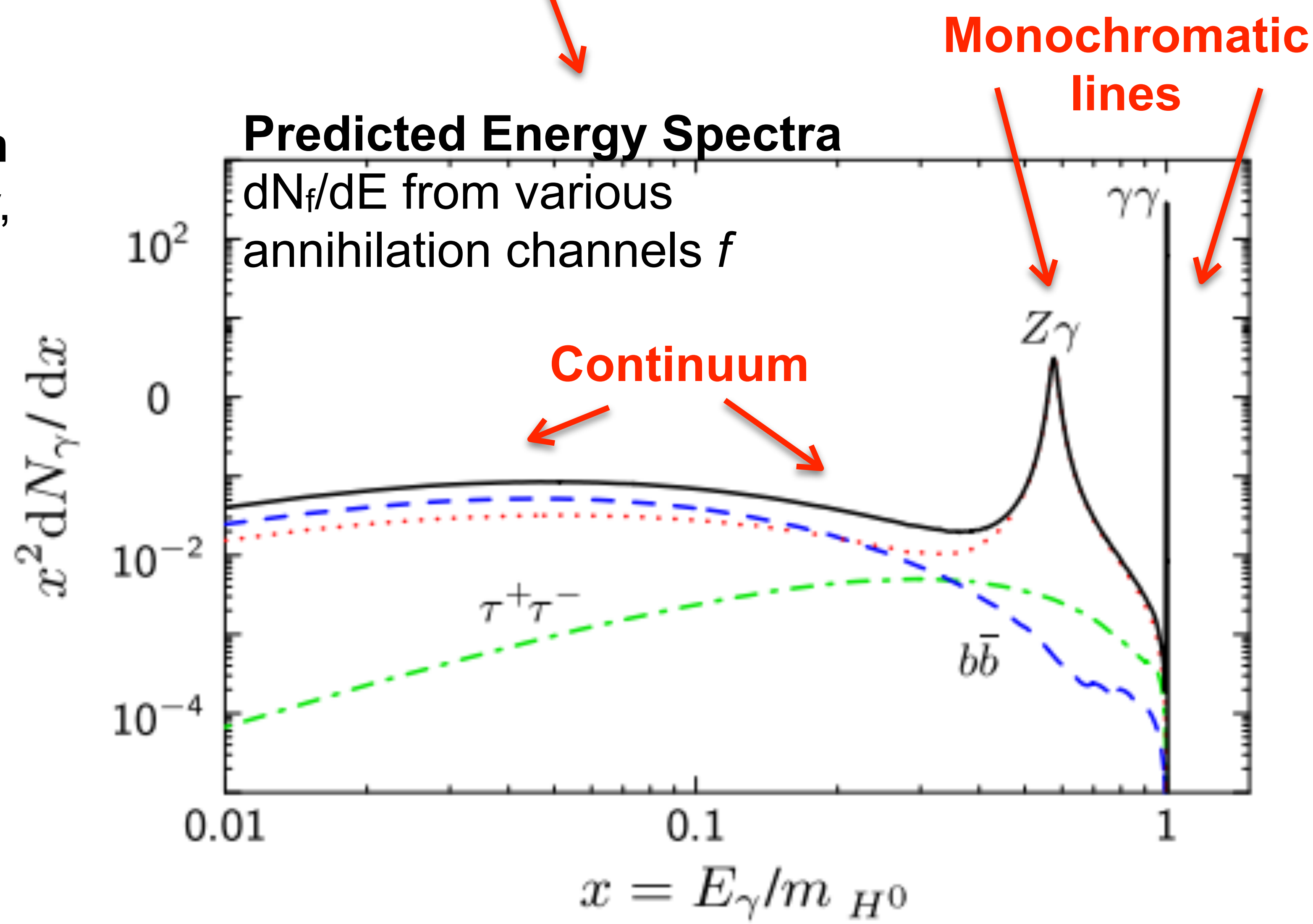
Flux from annihilating DM particles

What we observe | **Intrinsic Particle Properties**

$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{4\pi}\sum_f \frac{dN_f}{dE}B_f \int_{LOS} dl(\psi)\frac{1}{2}\frac{\rho(l)^2}{m_\chi^2}$$

DM Annihilation Cross Section
averaged cross-section × velocity,
@ freeze-out ≃ $3{\cdot}10^{-26}$ cm^3/s

Predicted Energy Spectra
dN_f/dE from various annihilation channels f



Gustafsson et al. PRL 99.041301

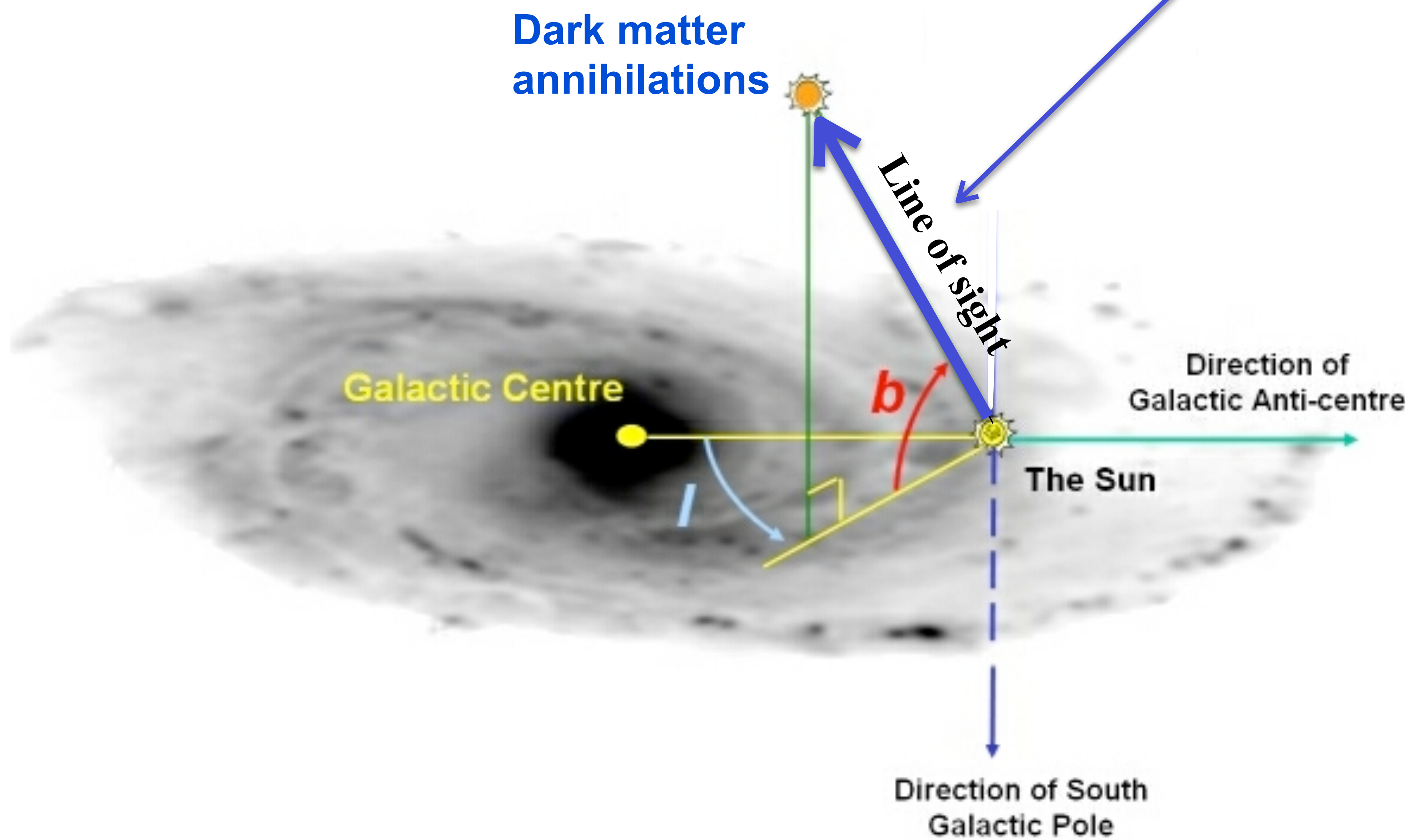
Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe | Intrinsic Particle Properties | Astrophysics (J-factor)

$$\Phi_\chi(E,\psi) = \frac{\langle\sigma_\chi v\rangle}{4\pi}\sum_f \frac{dN_f}{dE}B_f \int_{LOS} dl(\psi)\,\frac{1}{2}\frac{\rho(l)^2}{m_\chi^2}$$

WIMP number density squared



Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe | **Intrinsic Particle Properties** | **Astrophysics (J-factor)**

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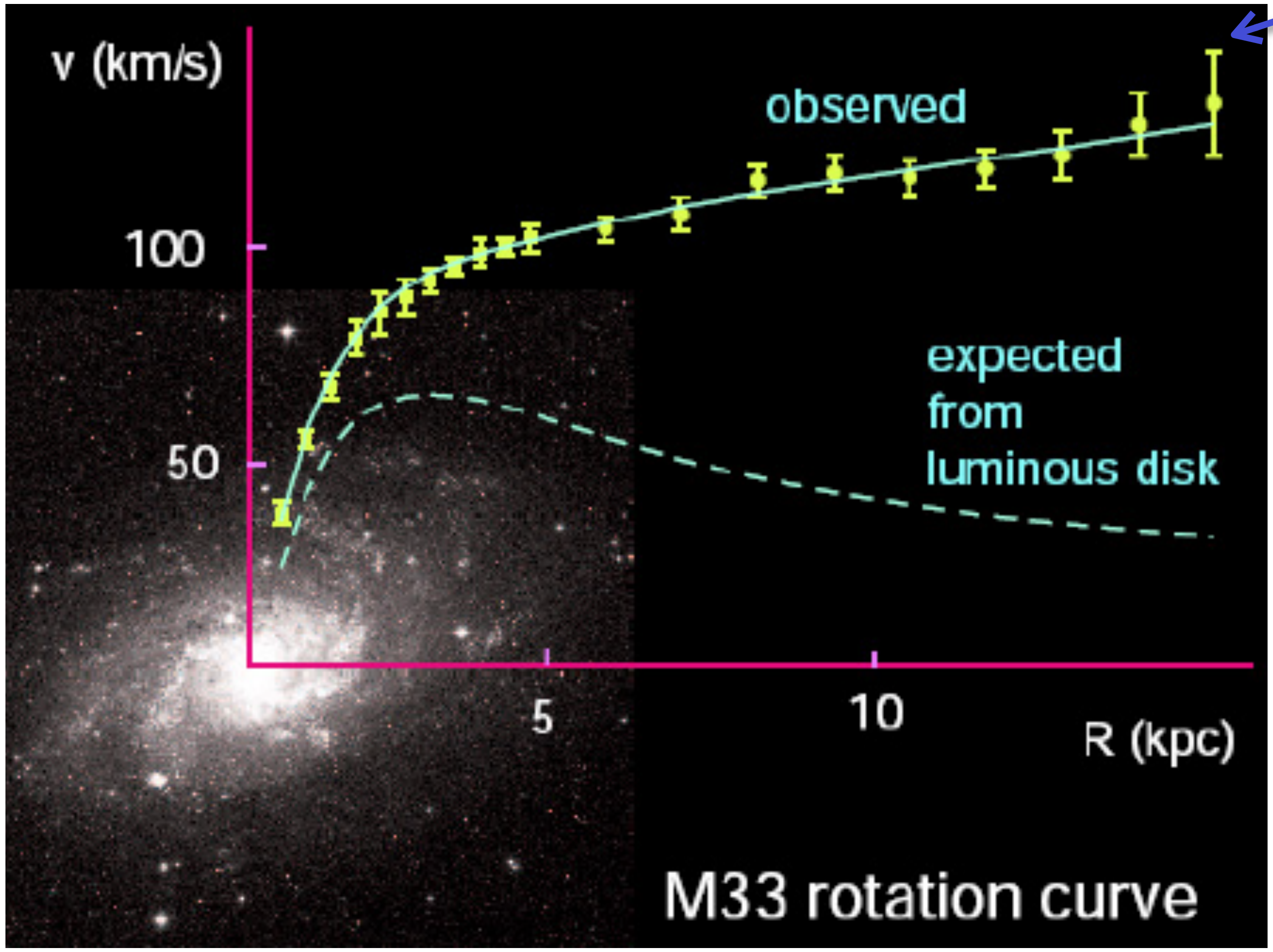
DM density

WIMP number density squared

Dark matter distributions (from obs. and sim.)



Gamma-rays from WIMPs

Flux from annihilating DM particles

What we observe | Intrinsic Particle Properties | Astrophysics (J-factor)

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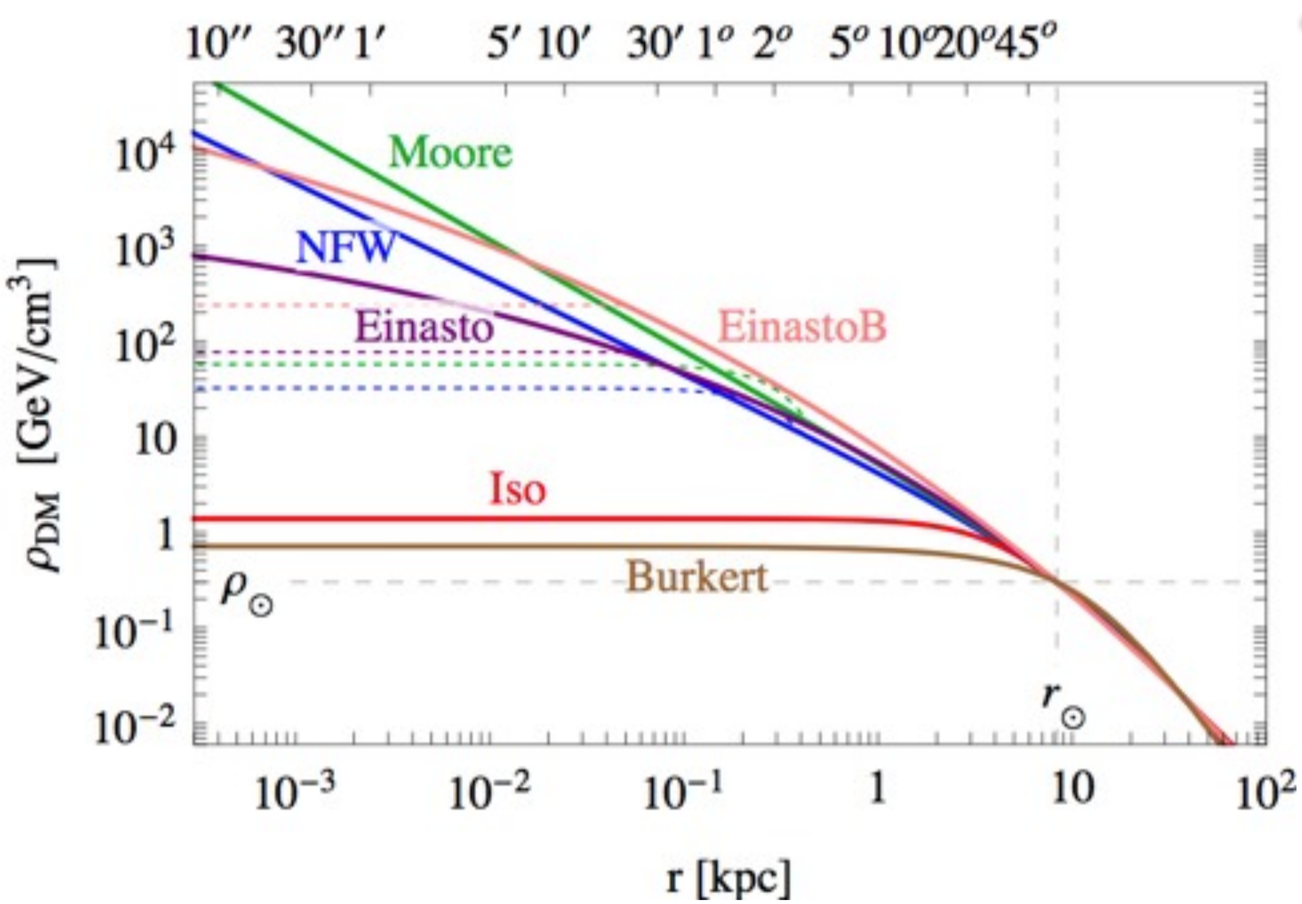

Gamma-rays from WIMPs

Flux from annihilating DM particles

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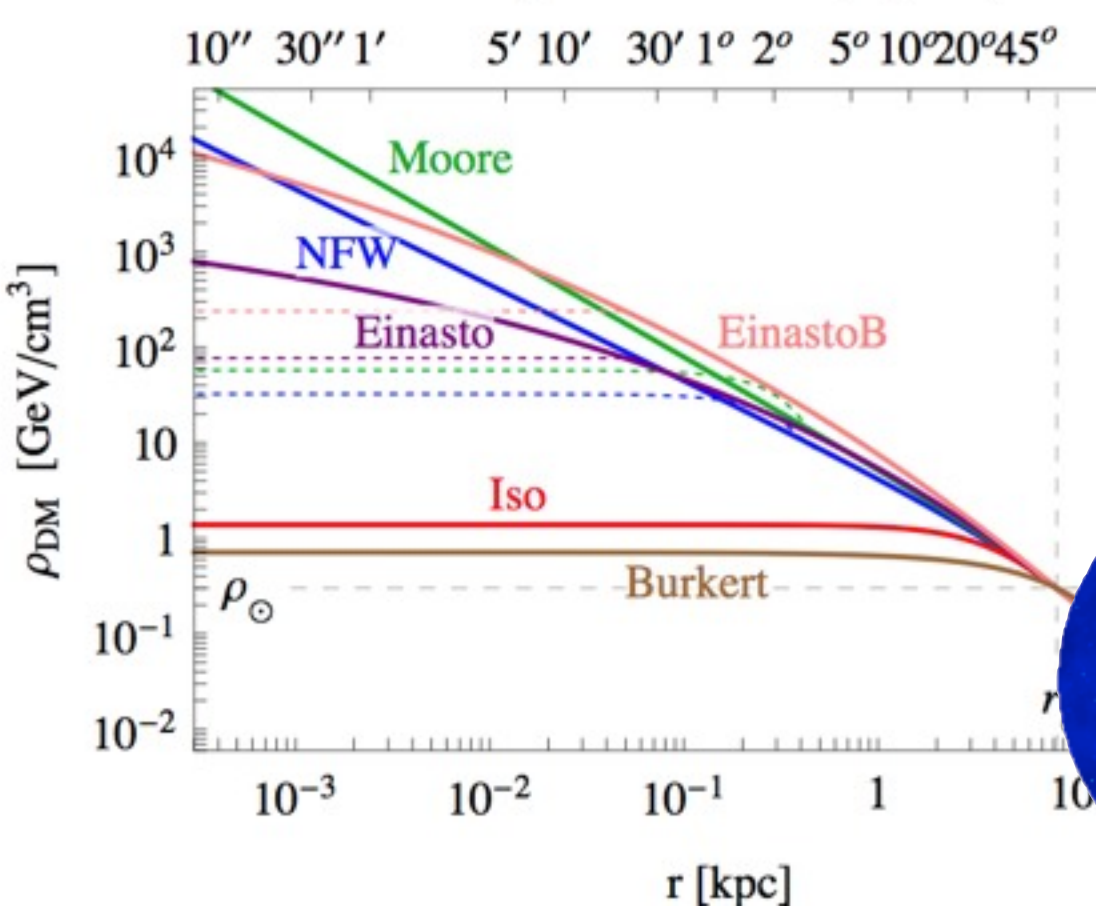
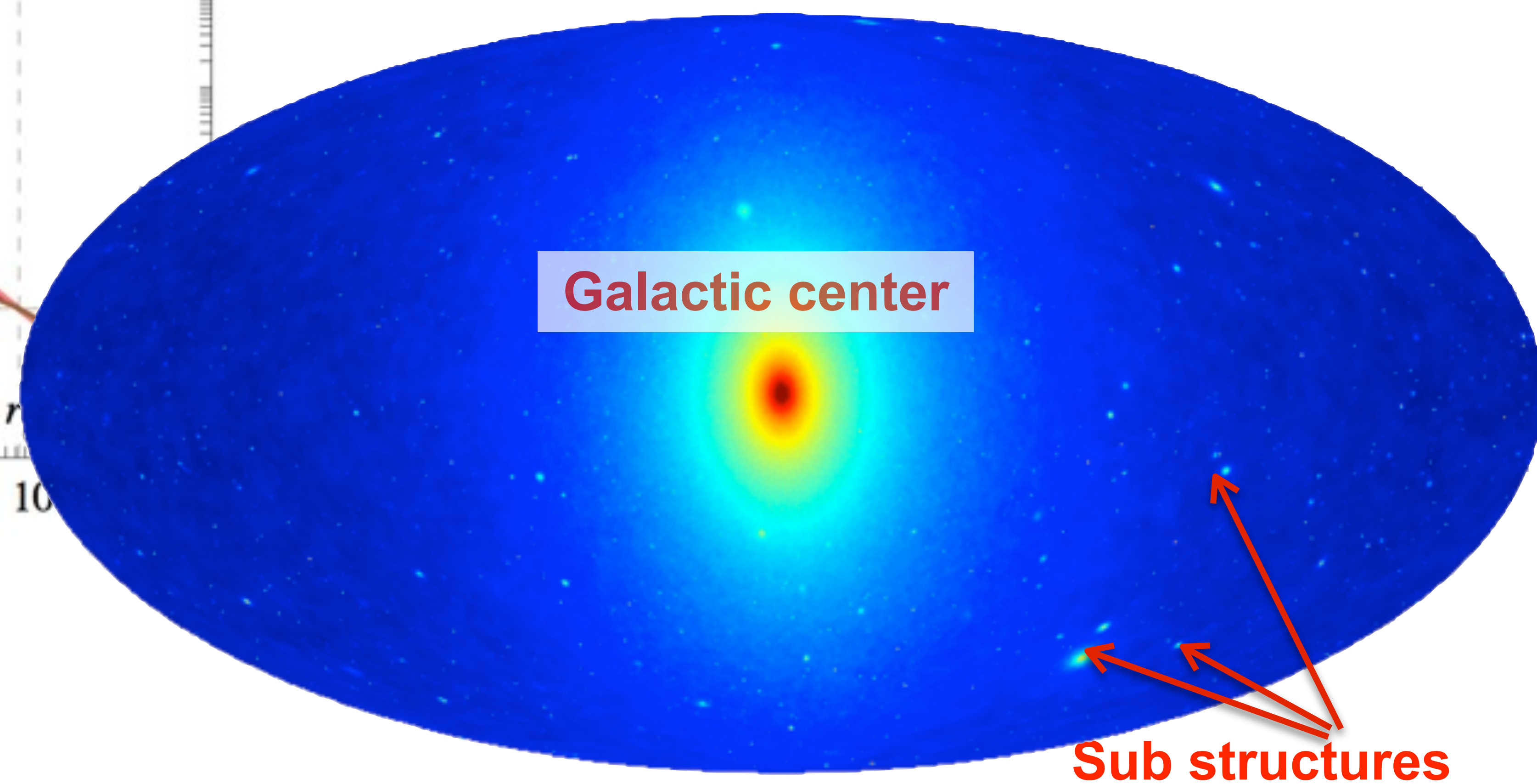


Signal morphology
(in Galactic coordinates)



Sub structures
(e.g. dwarf galaxies)

(J-factor)

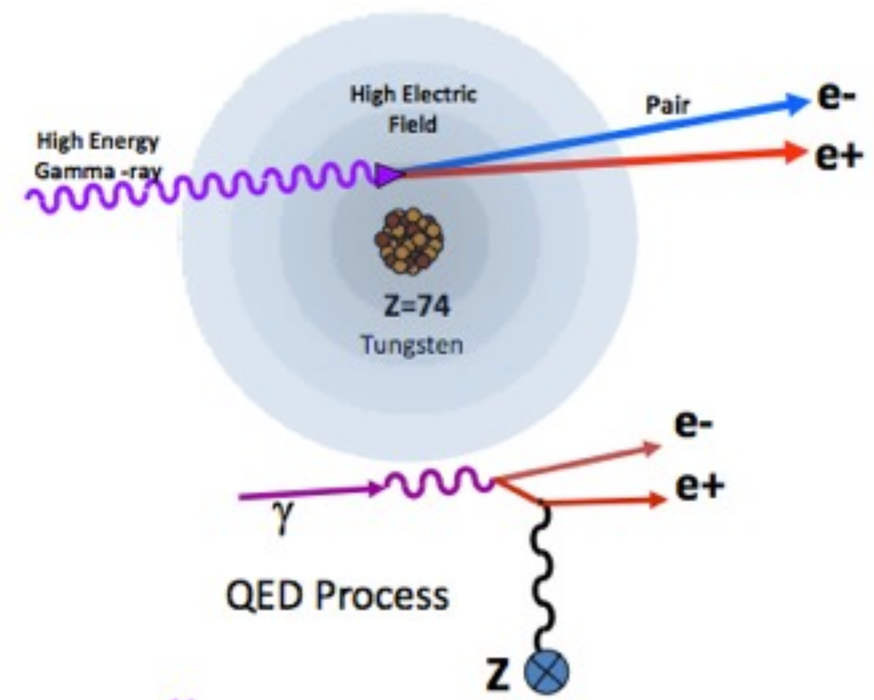
Fermi Large Area Telescope (LAT)

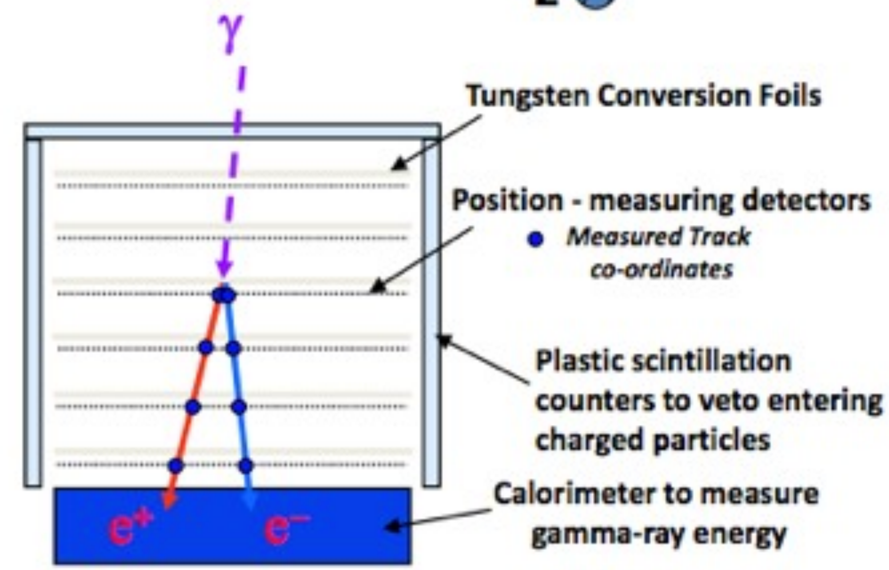
On board the Fermi Gamma-ray Space Telescope

– Launched June 2008, mission to at least 2016

❑ Pair conversion detector

- Silicon strip tracker
  (with tungsten converter foils)
- Electromagnetic CsI calorimeter
- Anti-coincidence shield
  (plastic scintillators to veto charged particles)





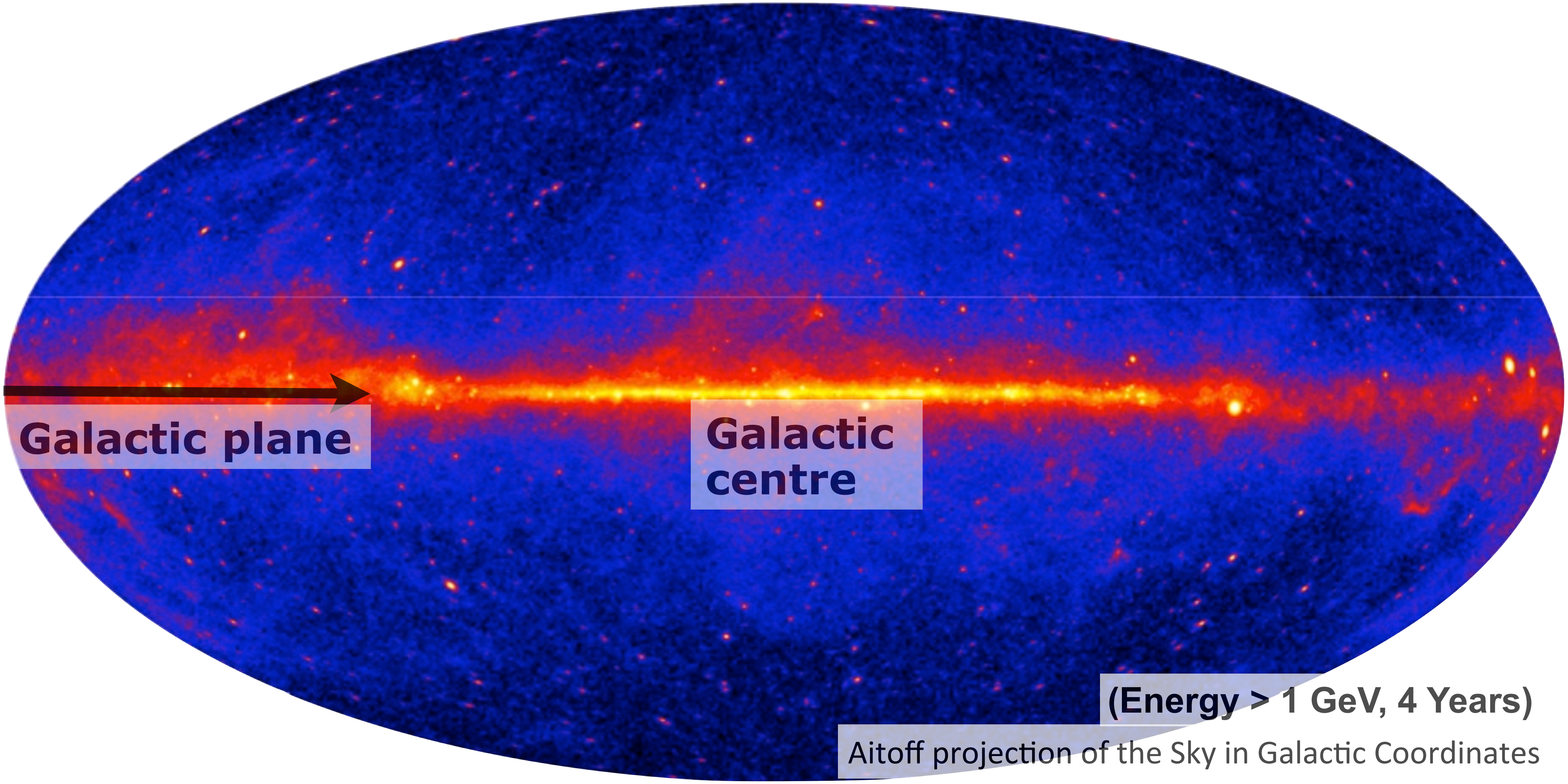
❑ Key features for DM searches

- Effective area ~0.8 m^2
- Energy range: 20 MeV to >300 GeV
  resolution: σ_E<15% (for E>10 GeV)
- Angular resolution:
  <0.2° (for E>10 GeV)
- Full-sky coverage (~2.4sr)
  - All sky in 2 orbits (3 hrs)

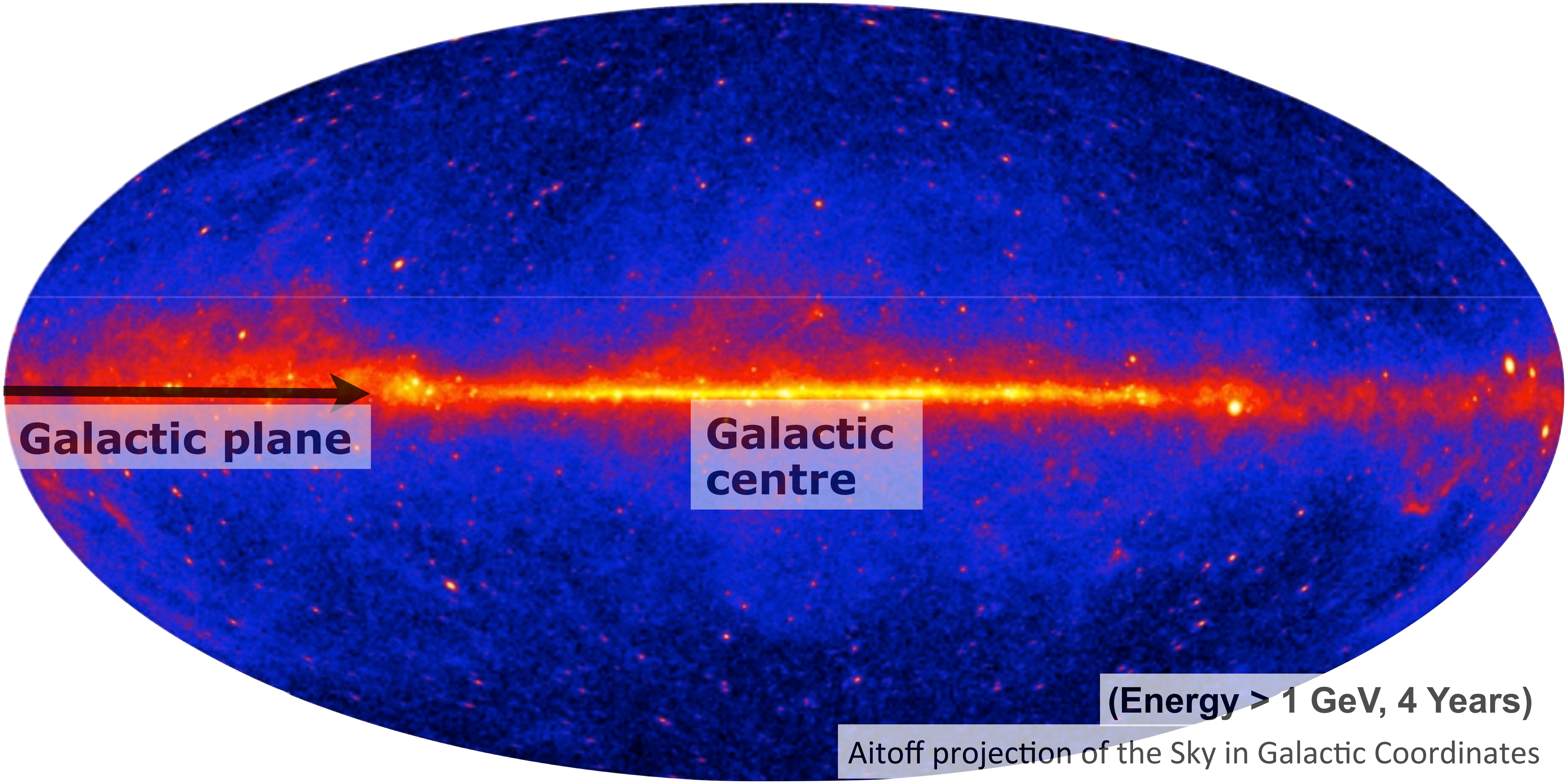
Public Data Release:
All γ-ray data made public within 24 hours (usually less)

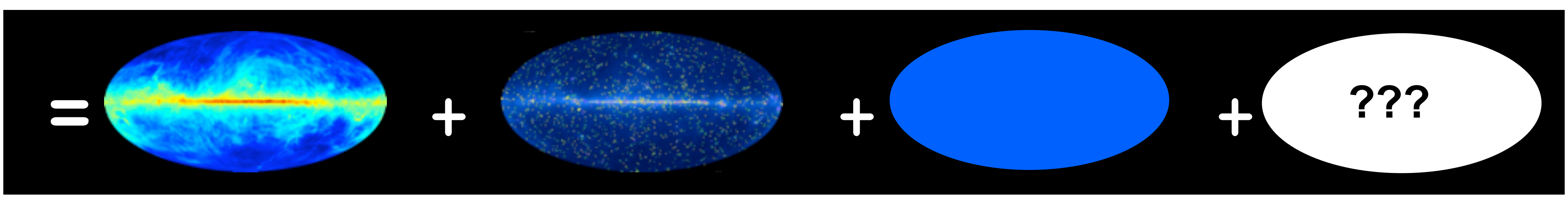
Fermi LAT Collaboration:
~400 Scientific Members, NASA / DOE & International Contributions

The Gamma-ray Universe as seen by Fermi-LAT



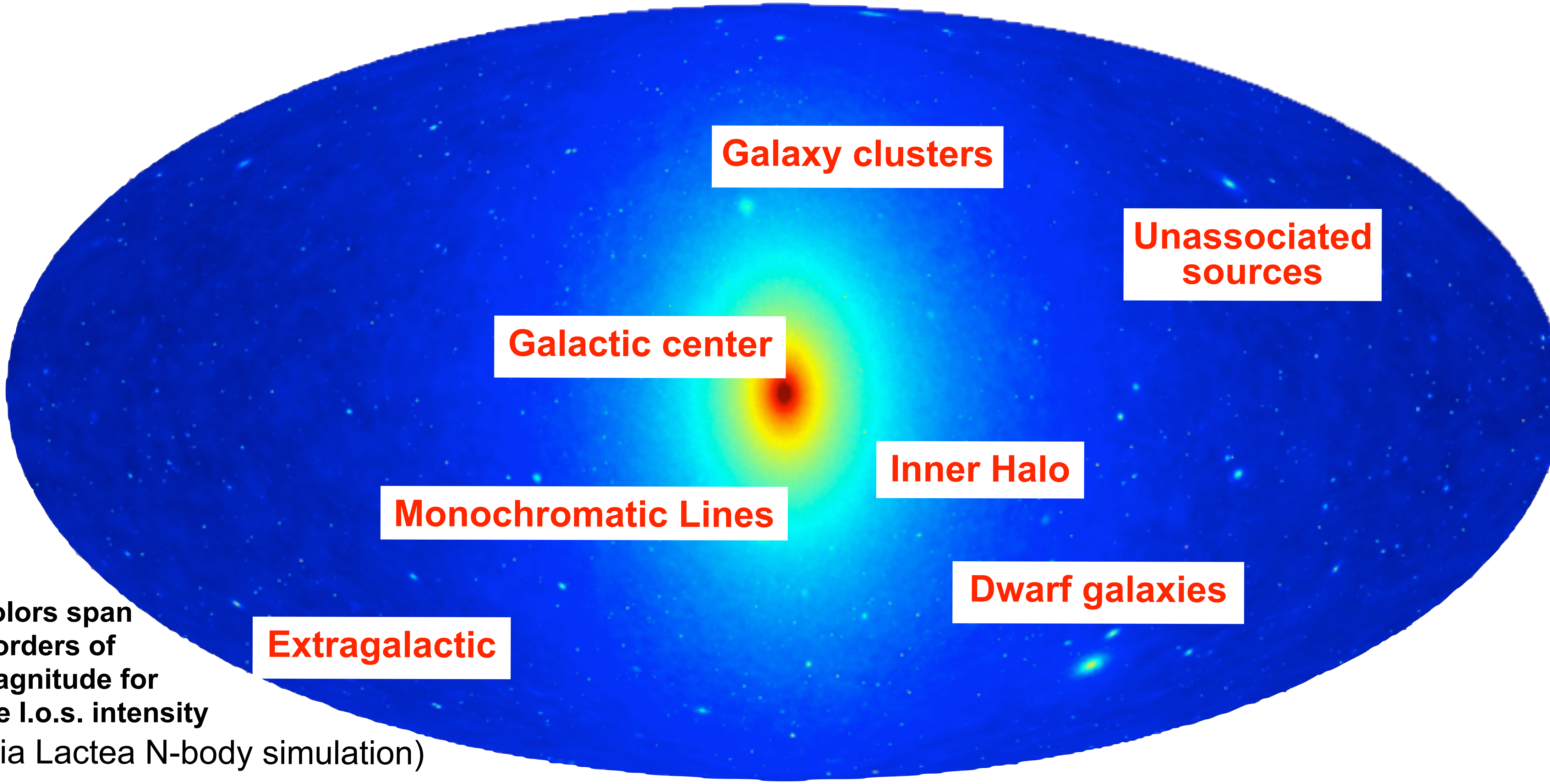
Are there any hiding DM signals?



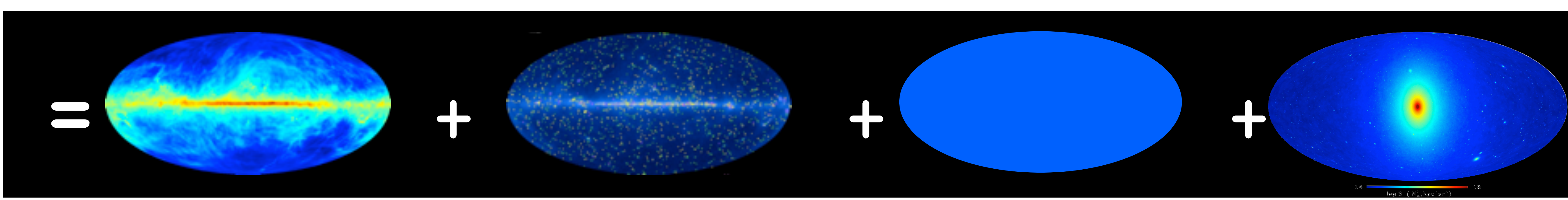


Galactic **Point Sources** **Isotropic** **...DM signal?**

Are there any hiding DM signals?

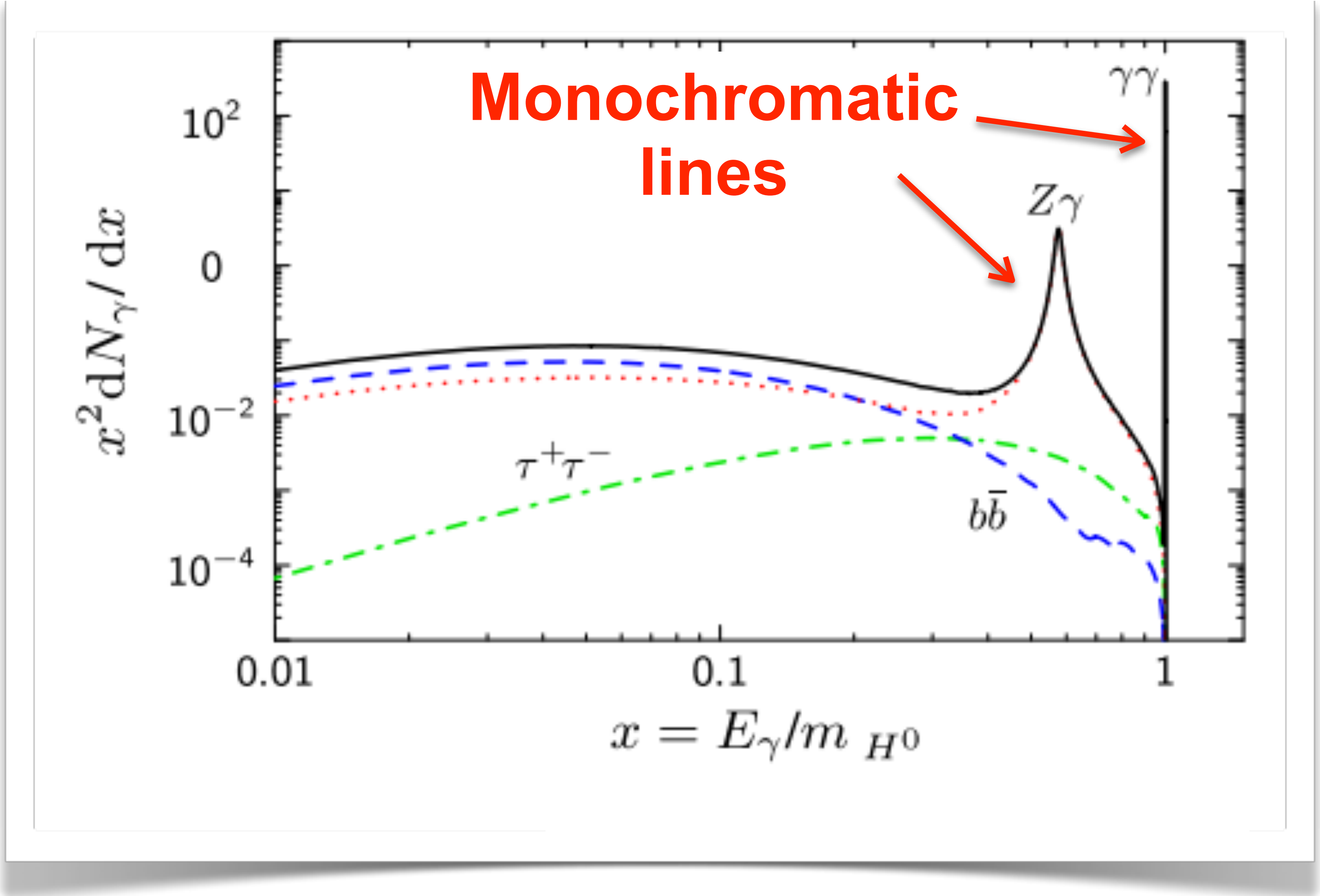


Colors span 4 orders of magnitude for the l.o.s. intensity
(Via Lactea N-body simulation)



Galactic **Point Sources** **Isotropic** **...DM signal?**

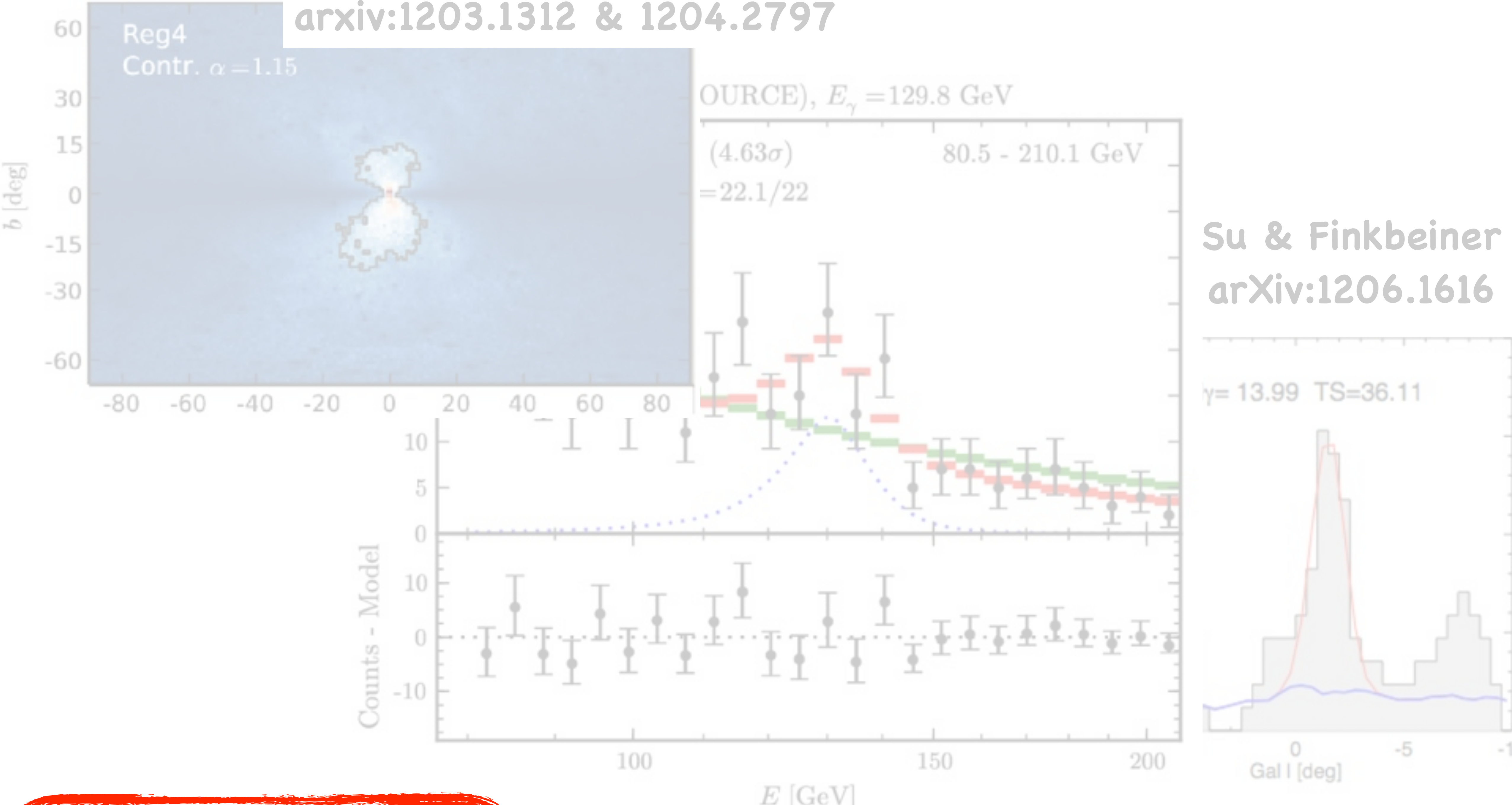
Search for gamma-ray lines



Tentative Observation of a Gamma-ray Line at the Fermi-LAT

Bringmann et al and Weniger
arxiv:1203.1312 & 1204.2797

Su & Finkbeiner
arXiv:1206.1616



22 July 2012
8th Patras Workshop, Chicago

Christoph Weniger
Max-Planck-Institut für Physik, München

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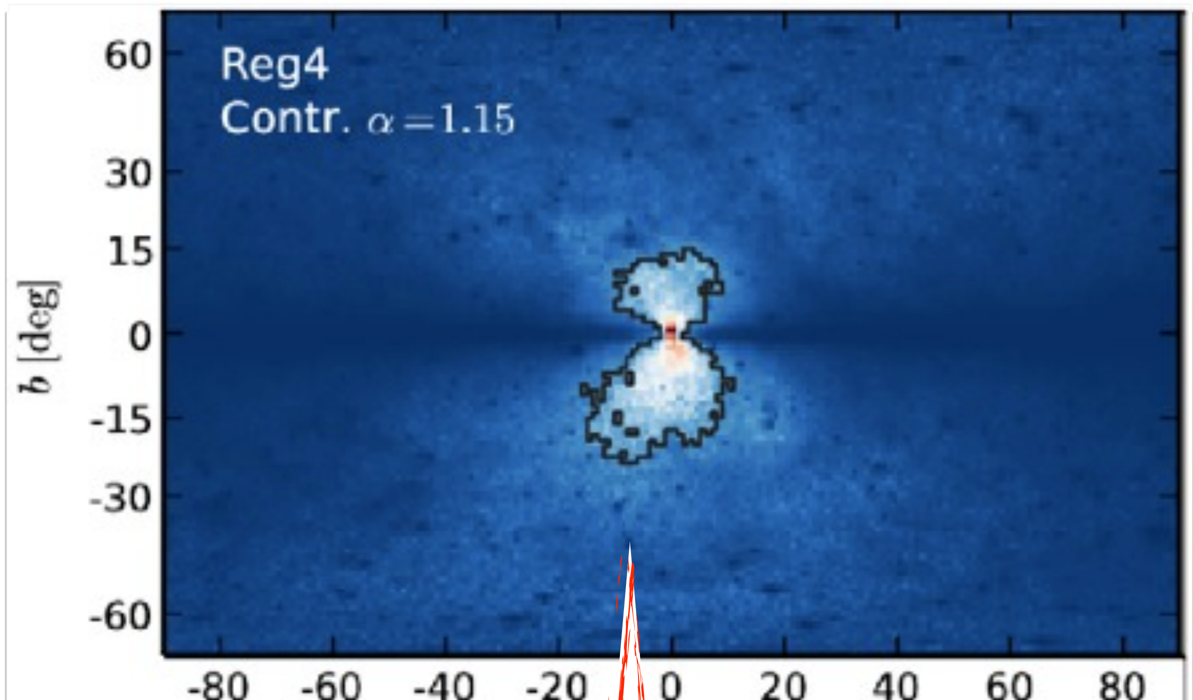

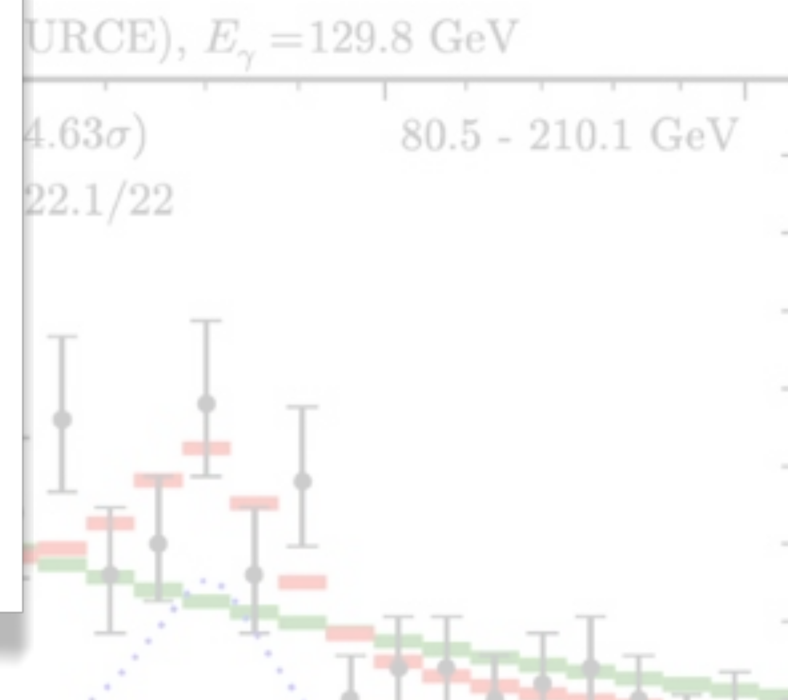

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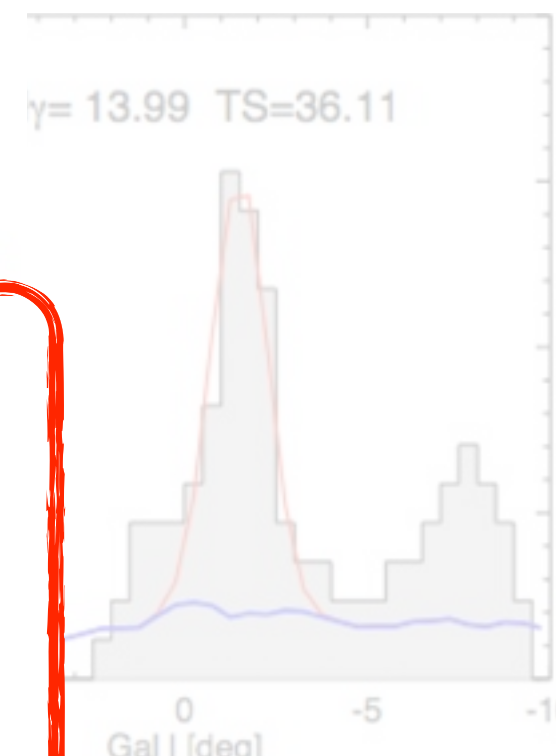


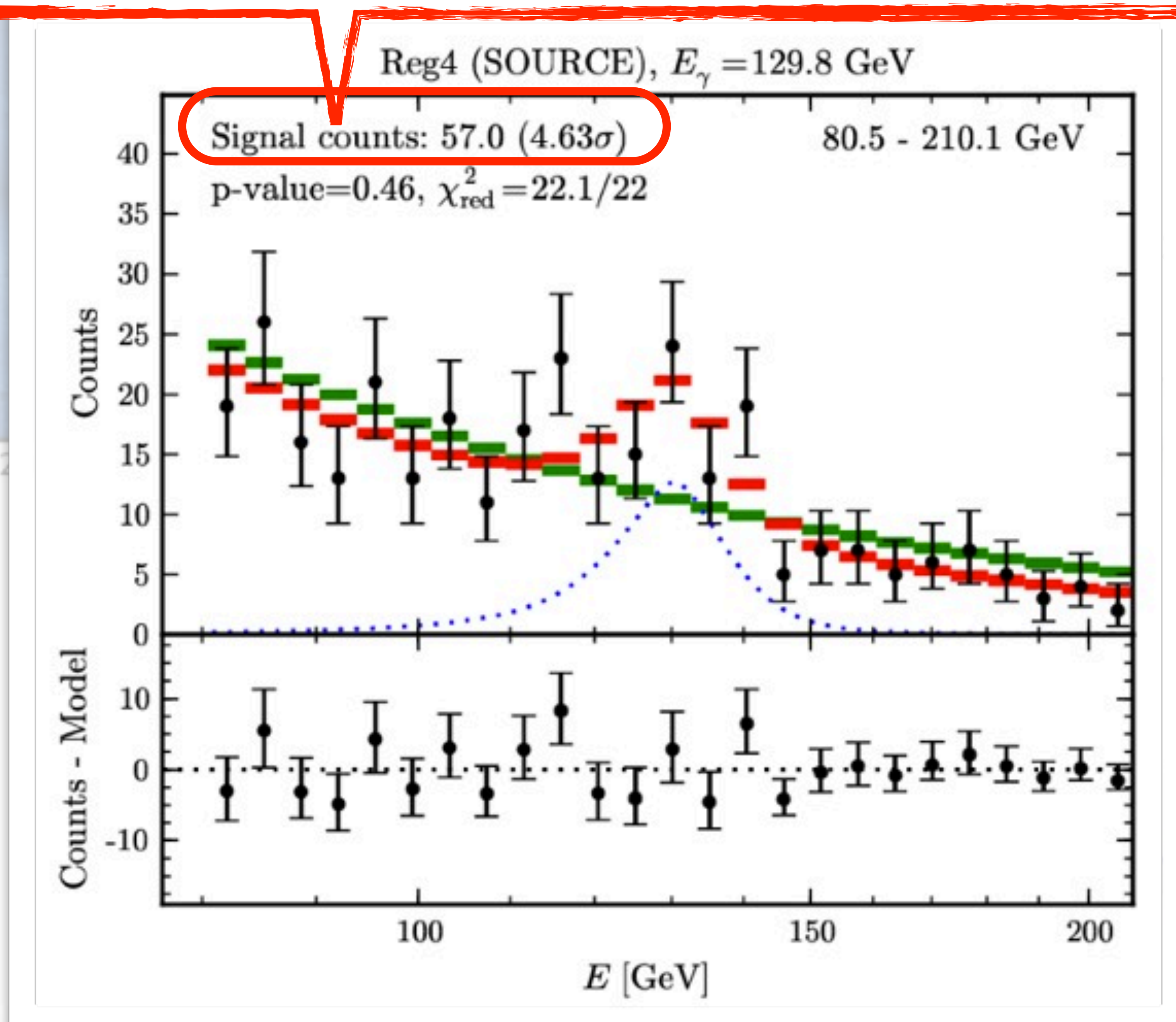
Bringmann et al

Finds a narrow spectral feature at 130 GeV near the Galactic centre:

- Find optimized sky regions for DM line searches
- Signal particularly strong in 2 out of their 5 test sky regions

Weniger

- **Fit a 130 GeV monochromatic line with 4.6 σ (local) and 3.3 σ (global) significance with a signal-to-bkg fraction of s/b≈50%.**



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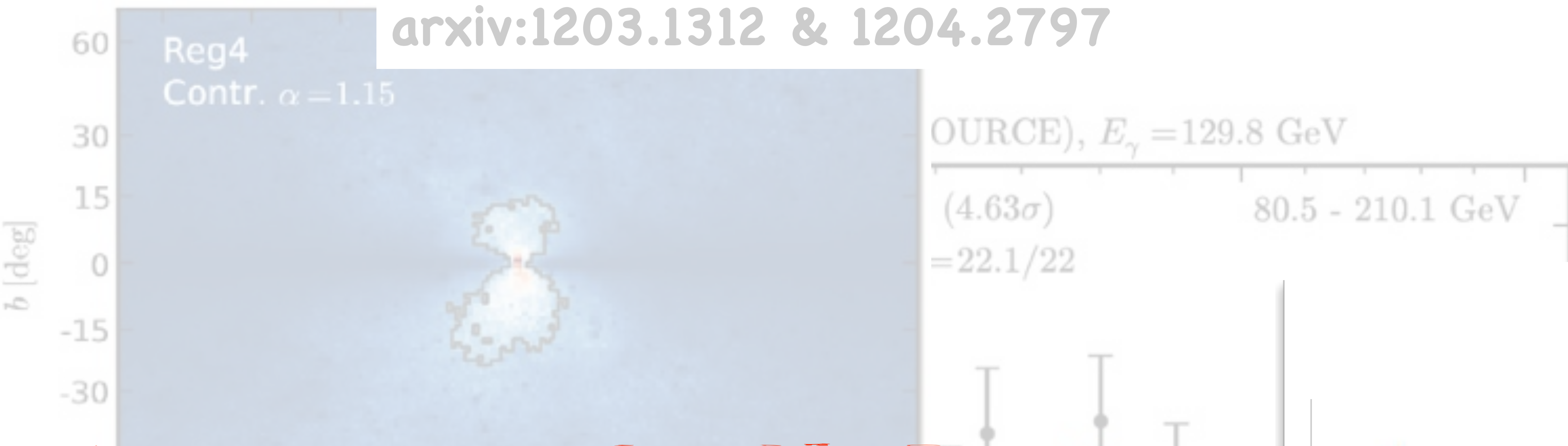

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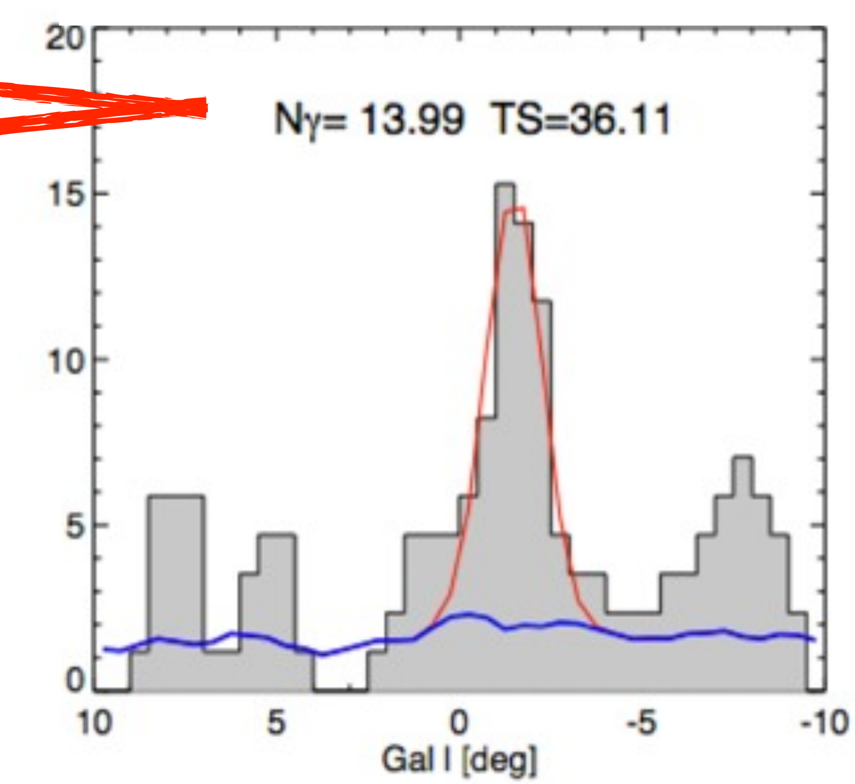


Su & Finkbeiner

Show that the spectral feature is close to, but slightly (~1.5°) offset, from the Galactic centre

- Include DM spatial morphologies, and data-driven backgrounds, in their likelihood analysis.
- 5.1σ global statistical significance (6.6σ local), after a trials factor of ~6000
- possible indications of two nearby lines

Christoph Weniger
Max-Planck-Institut für Physik, München

New Fermi-LAT line search

Fermi LAT collaboration
[ArXiv:1305.5597]

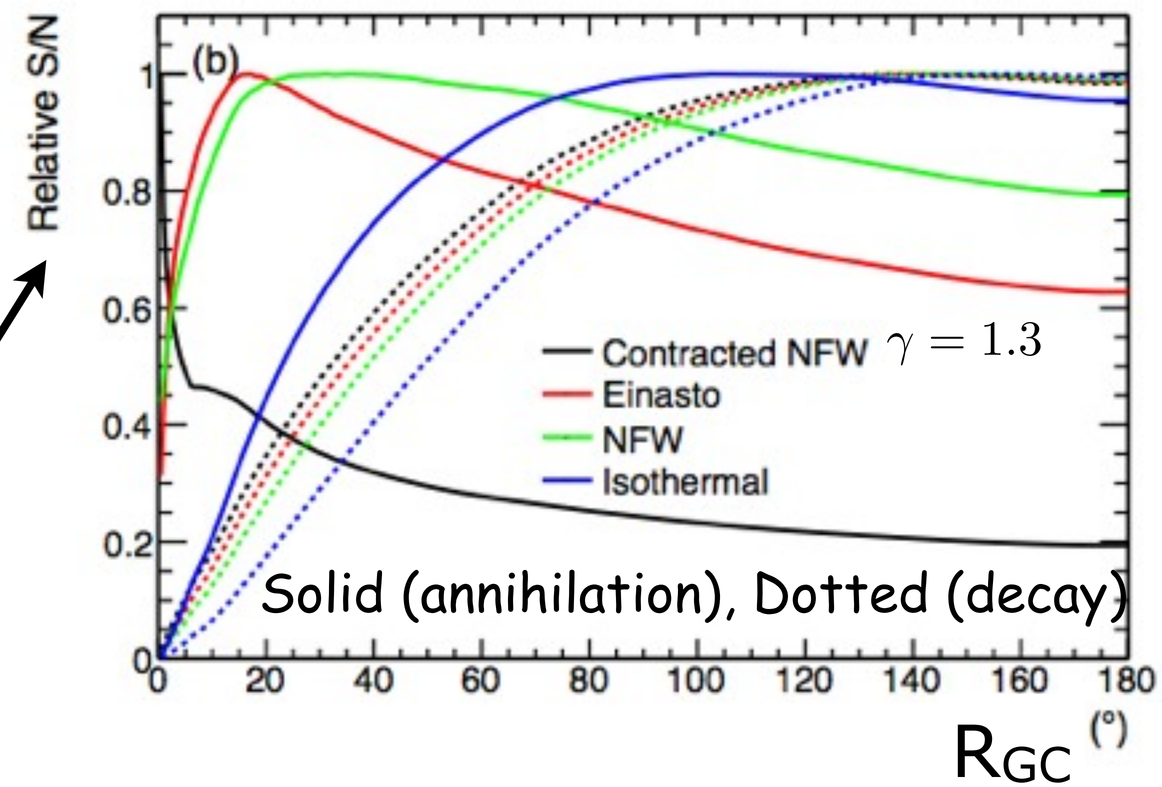
Sky Region of Interest (ROI)

Find radius R_{GC} and angle *Δl* that optimize DM *signal-to-bkg* ratio.

– For a given DM profile signal (S) and template diffuse gamma-ray background (B), maximize

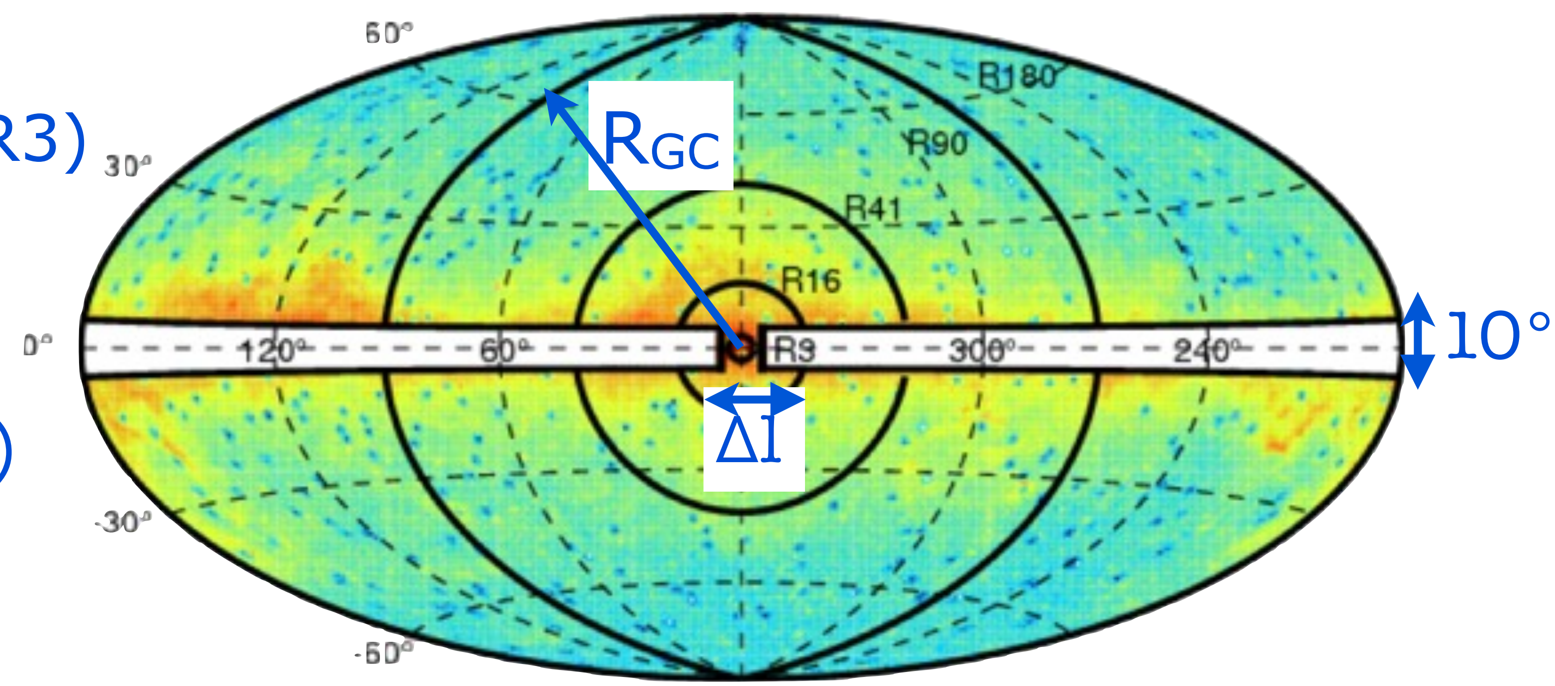
$$S/N_{\mathrm{ROI}} = \frac{\int^{ROI} S(\hat{p})\, \mathcal{E}(\hat{p}) d\Omega}{\sqrt{\int^{ROI} B(\hat{p})\, \mathcal{E}(\hat{p}) d\Omega}},$$

Exposure



Search in 5 ROIs:

- Contracted NFW, 3° circle (R3)
- Einasto Optimized (R16)
- NFW Optimized (R41)
- Isothermal Optimized (R90)
- DM Decay Optimized (R180)

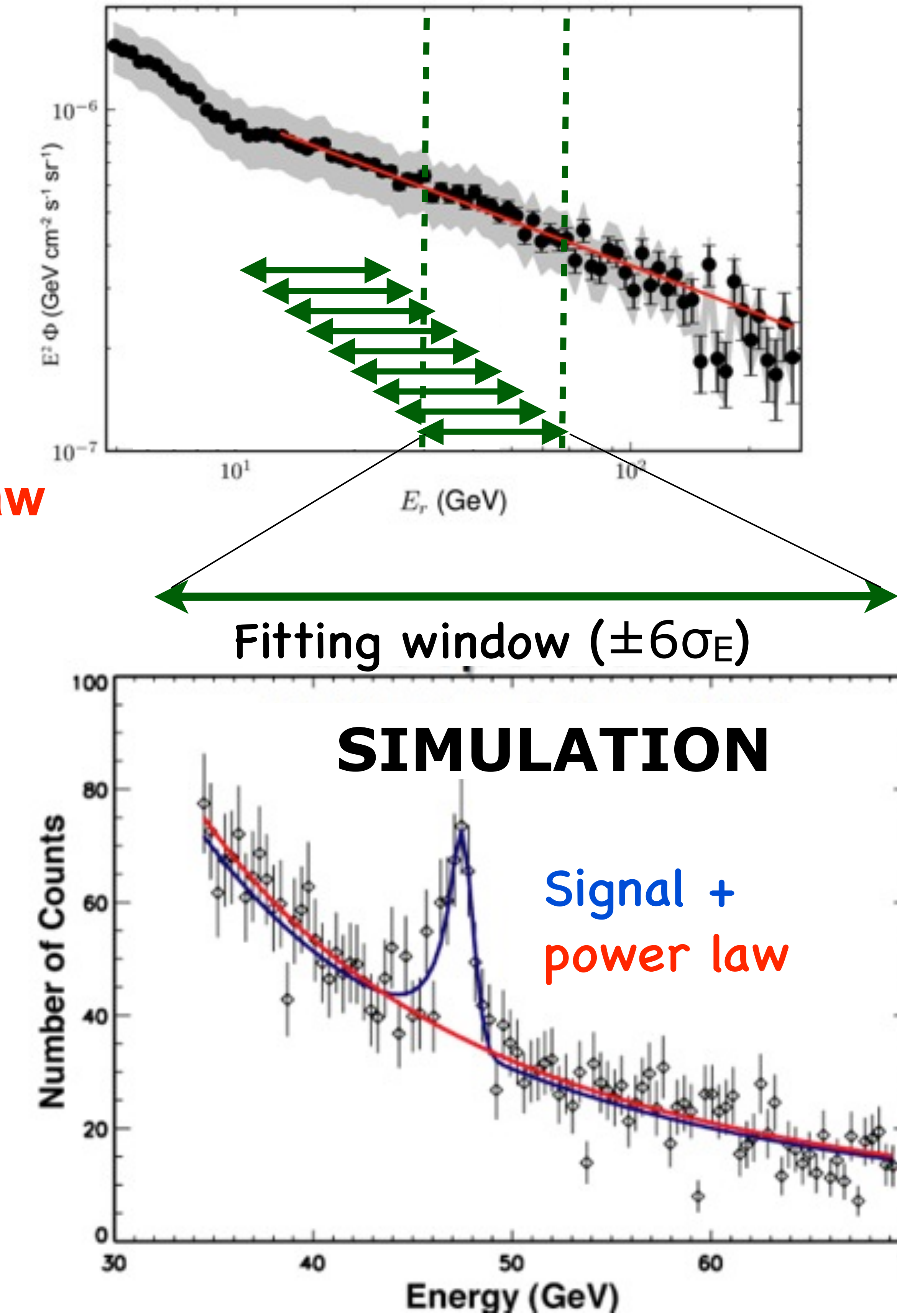


Spatial distribution for 10-100 GeV energy

Monochromatic Line Search

Line search from 5-300 GeV

- Use a sliding $\pm 6\sigma_E$ energy window technique
- Energy steps of 0.5 σ_E



- **Background modeled as single power-law** (in each energy window)
- **Standard: "1D" PDF for the line shape**

$$C(E') = n_{sig} D_{eff}(E'|E\gamma) + \frac{n_{bkg}}{c_{bkg}} \left(\frac{E'}{E_0}\right)^{-\Gamma_{bkg}} \eta(E')$$

normalization

Effective Area Corrections

- D_{eff}, effective energy dispersion
- n_{sig}, n_{bkg} and Γ_{bkg} free in fits

New "2D" PDF for the Energy Dispersion

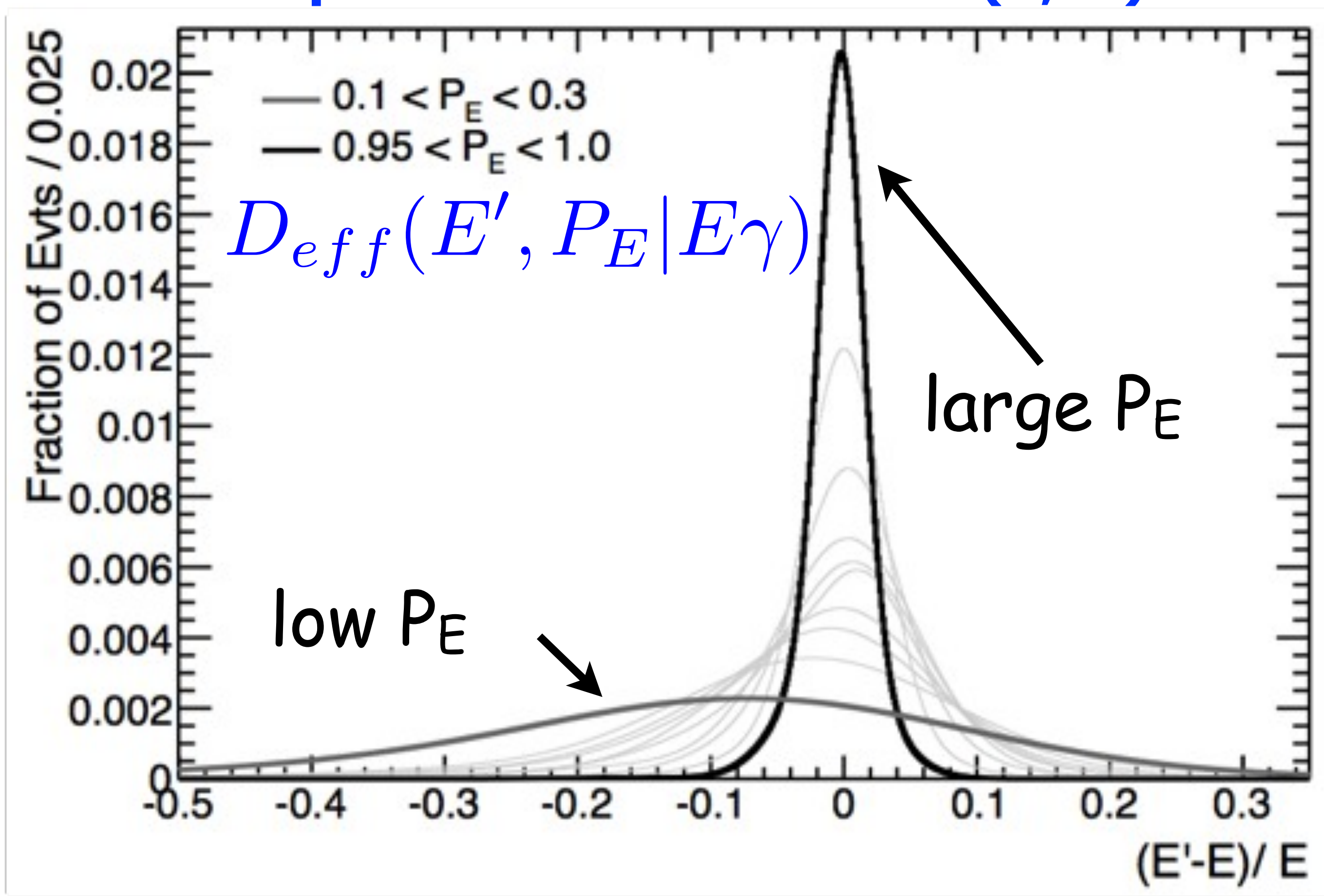
Updated analysis, adds a 2nd dimension to line model: P_E

- P_E is the probability that measured energy is close to the true energy
- Line shape **determined event by event** from a 2D pdf – function of both E and P_E

Predicted Spectrum = Signal Model + Power-law Background

$$\mathbf{C}(\mathbf{E}, \mathbf{P}_\mathrm{E}) = \mathbf{n}_{\mathbf{sig}} \mathbf{D}_{\mathbf{eff}}(\mathbf{E}, \mathbf{P}_\mathbf{E} | \mathbf{E}\gamma) + \frac{\mathbf{n}_{\mathbf{bkg}}}{\mathbf{c}_{\mathbf{bkg}}} \left(\frac{\mathbf{E}}{\mathbf{E}_0} \right)^{-\mathbf{\Gamma}_{\mathbf{bkg}}} \eta(\mathbf{E})$$

Dispersion — "2D" PDF in (E,P_E)



Including P_E in energy dispersion model

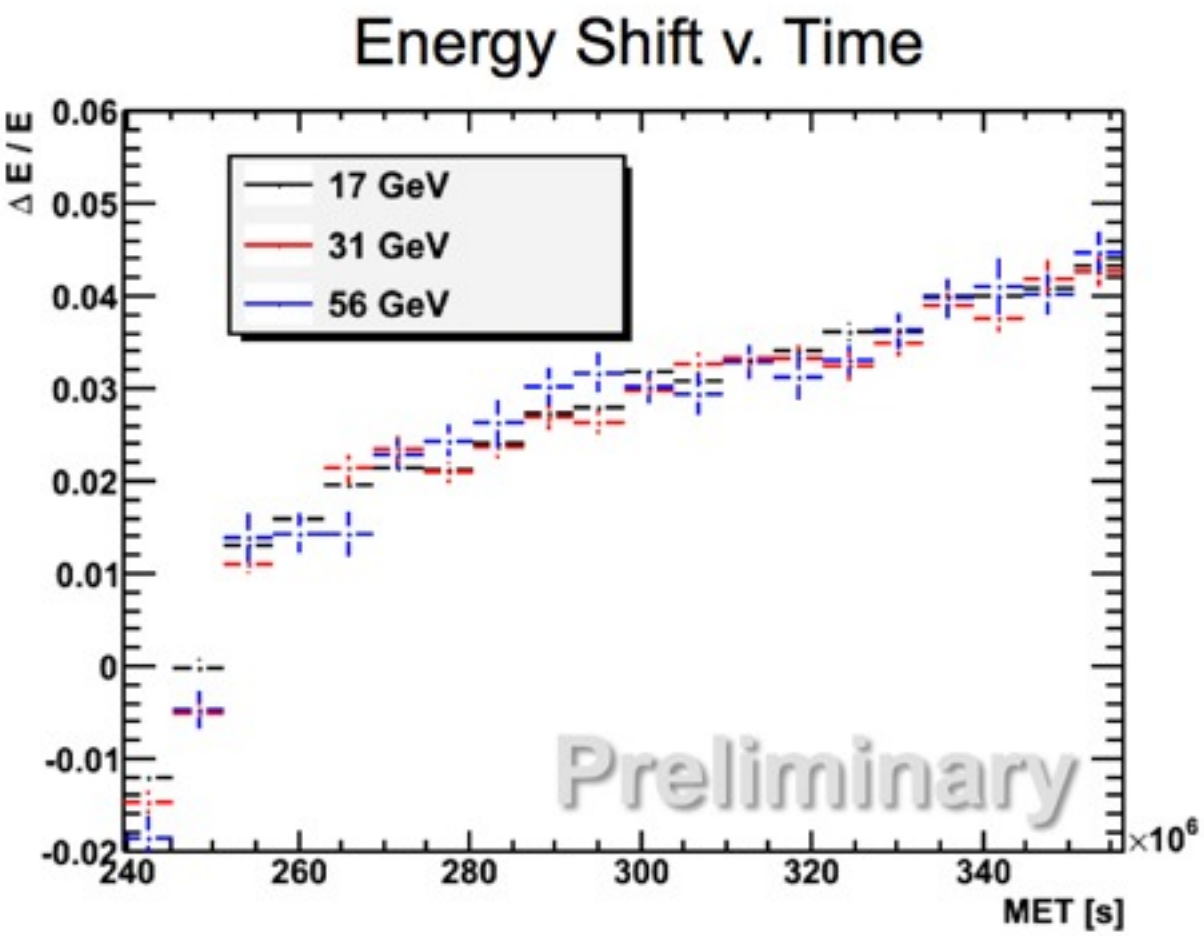
⇒ ~15% improvement to signal sensitivity (when there is signal) and counts upper limit (when there is no signal).

⇒ Includes a more complete understanding of the expected shape of a gamma-line

Data Improvement

- **Data reprocessed** (P7CLEAN_REP)
  - ✓ Updated calorimeter response
    - ➡ Affects energy reconstruction: up to 5% shift in energy scale
    - ➡ Improves PSF at high energies

(80%+ overlap of events after reprocessing)



- **DATA SELECTION** (P7CLEAN_REP)

Selection	Celestial data	Limb data
Observation Period	2008 August 4–2012 April 4	2008 August 4–2012 October 6
Mission Elapsed Time[a] (s)	[239557447, 356434906]	[239557447, 371176784]
Energy range (GeV)	[2.6, 541]	[2.6, 541]
Zenith range (deg)	$\theta_z < 100$	$111 < \theta_z < 113$
Rocking angle range (deg)[b]	$\lvert\theta_r\rvert < 52$	$\lvert\theta_r\rvert > 52$
Data quality cut[c]	Yes	Yes
Source masking (see text)	Yes	No

Signal significance & Trial Factors

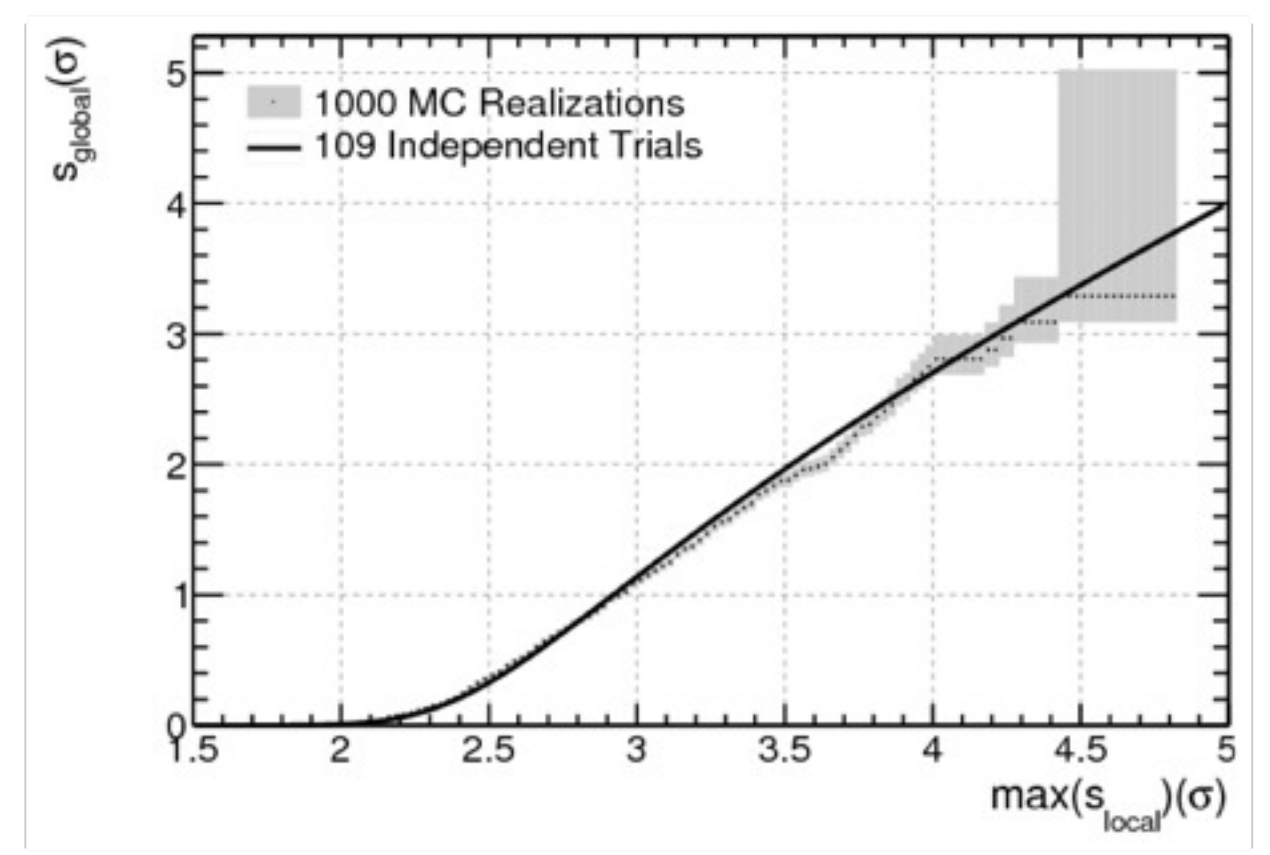
- Test statistic (TS) and local significance (s_{local}) by ratio of —unbinned extended— maximum likelihood of signal to null hypothesis fit

$$TS = 2\ln\frac{\mathcal{L}(n_{\rm sig} = n_{\rm sig,best})}{\mathcal{L}(n_{\rm sig} = 0)}\,, \quad \mathcal{L} = \frac{e^{-C_{\rm tot}}}{n!}\prod_i^n C(E_i', P_{E_i})$$

$$s_{\rm local} = \sqrt{TS}\,, \quad 95\%\,\text{CL when } \Delta TS = -2.71 \text{ from best fit}$$

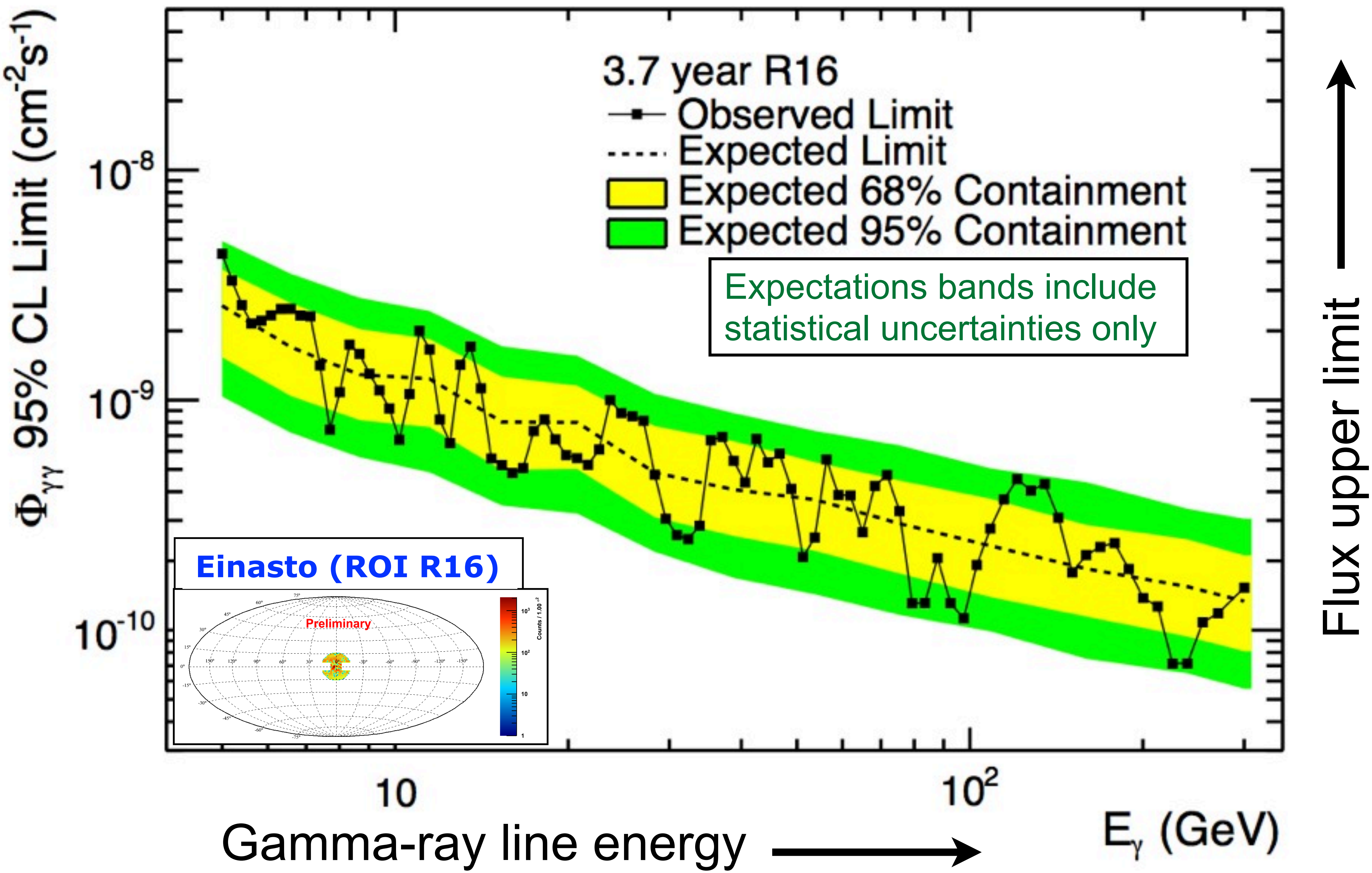
- Trials factor = P_{global}/P_{local}. 396 trials (5 ROI & 0.5σ_E steps) reduces to effectively 109 independent trials

  (Independency: ROIs ~87%, ΔE_γ steps ~32%)

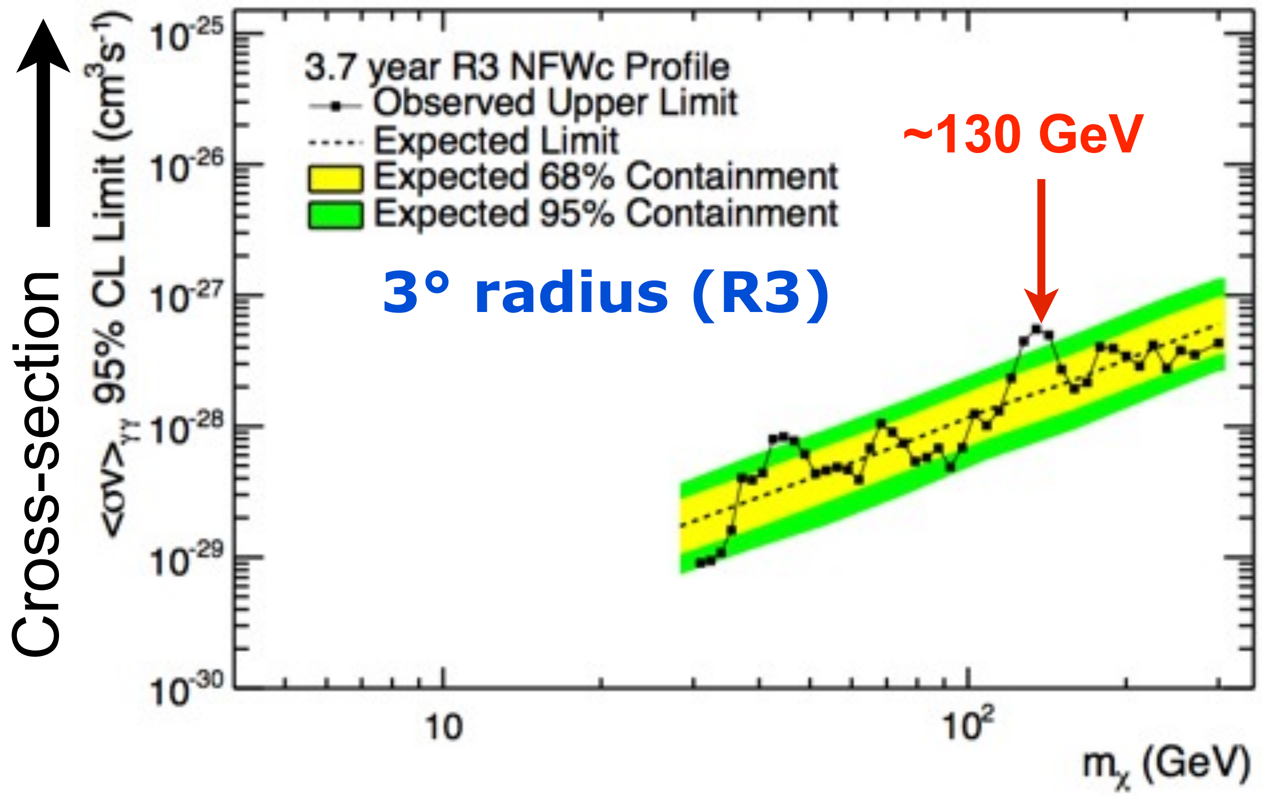


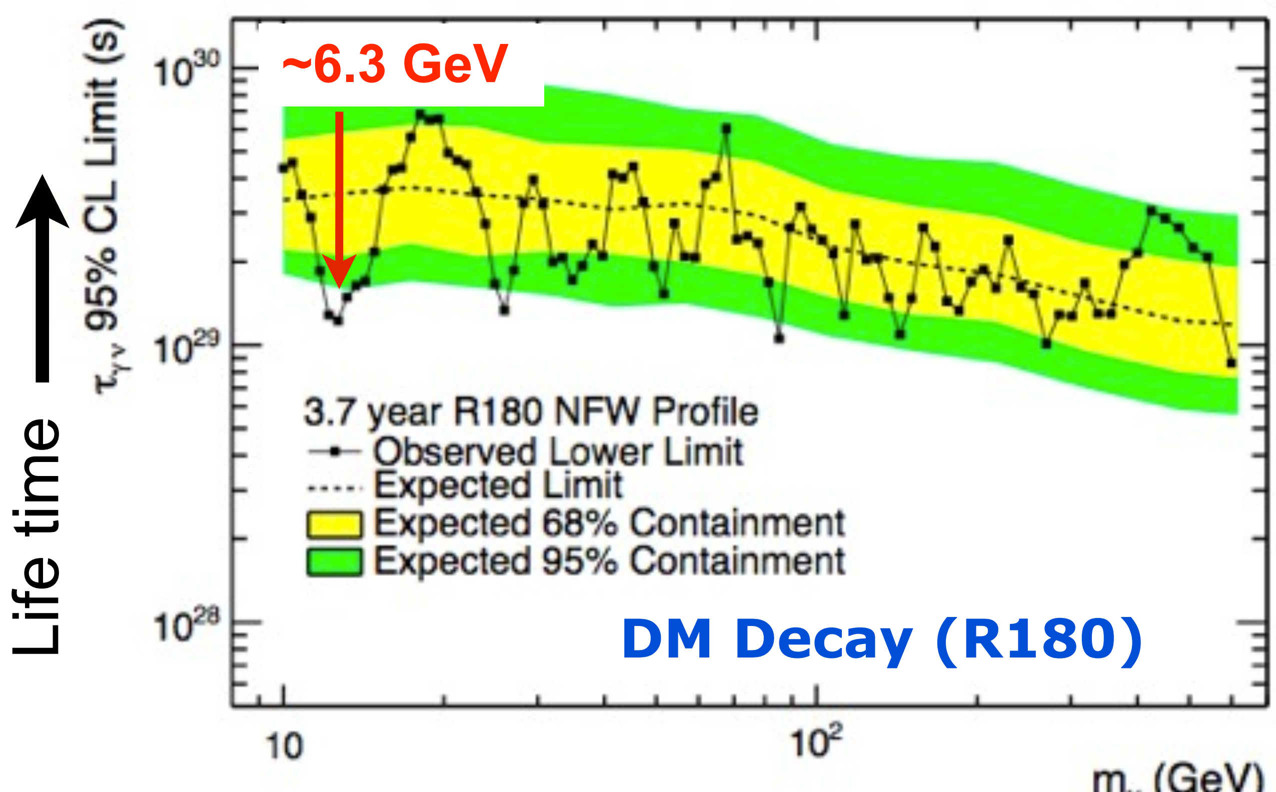
Line Search Results

Spectral line 95% CL Flux upper limit

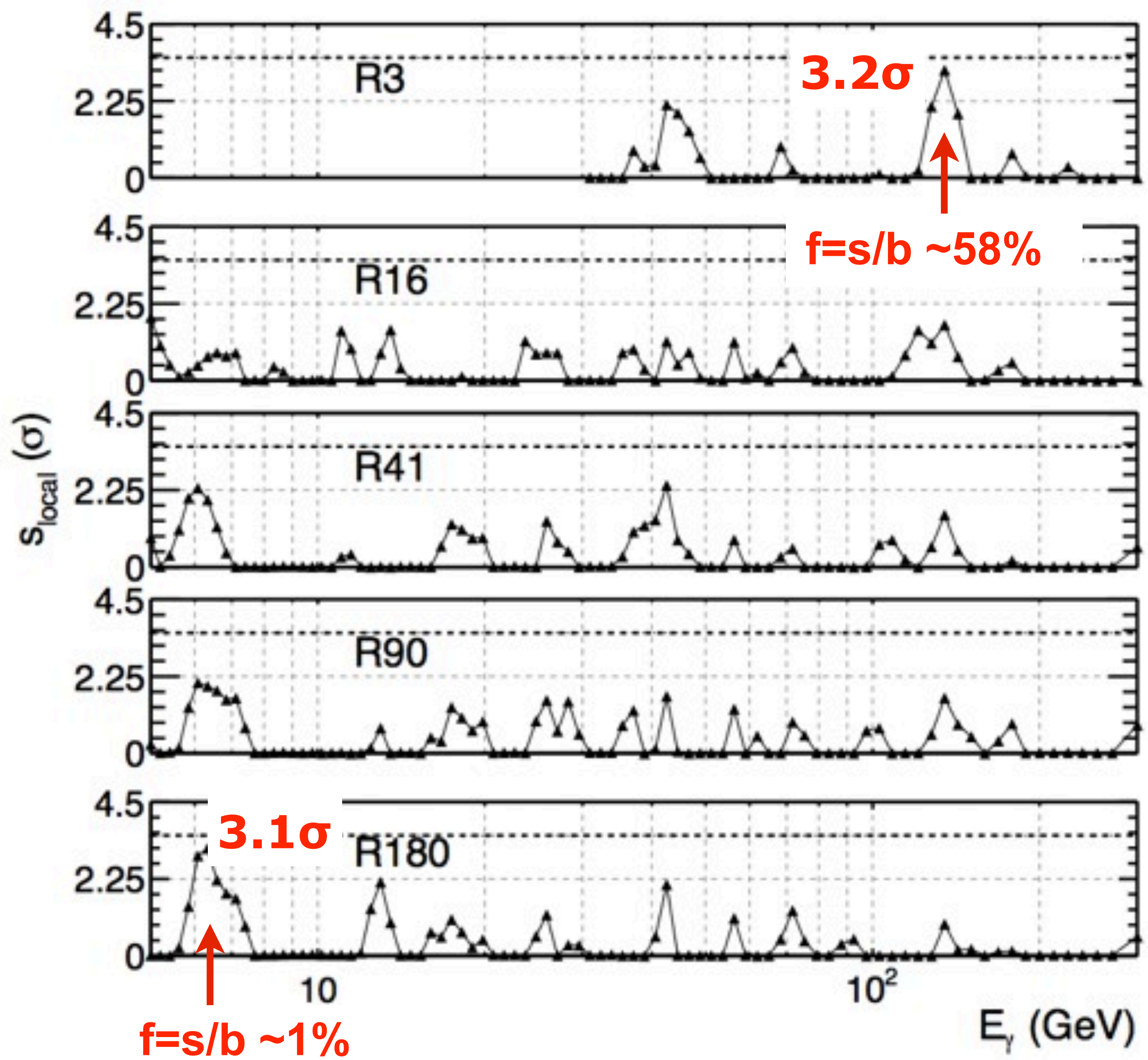


95% CL limits on $\langle\sigma v\rangle_{\gamma\gamma}$ and $\tau_{\gamma\nu}$



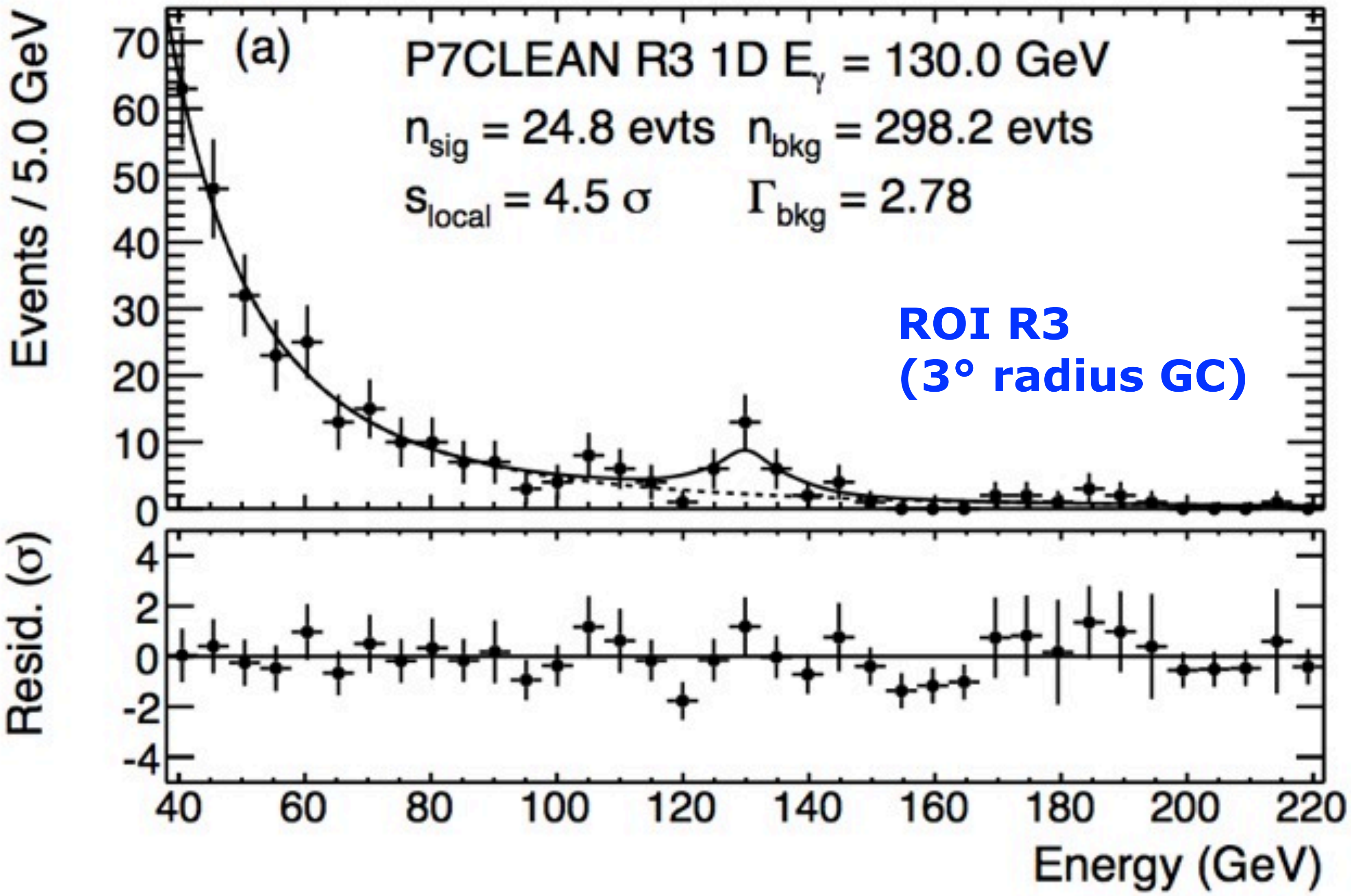


Local significances in # of sigma
(2σ global sigma dashed line)



No globally significant line detected
– All fits have global significance < 1.6σ

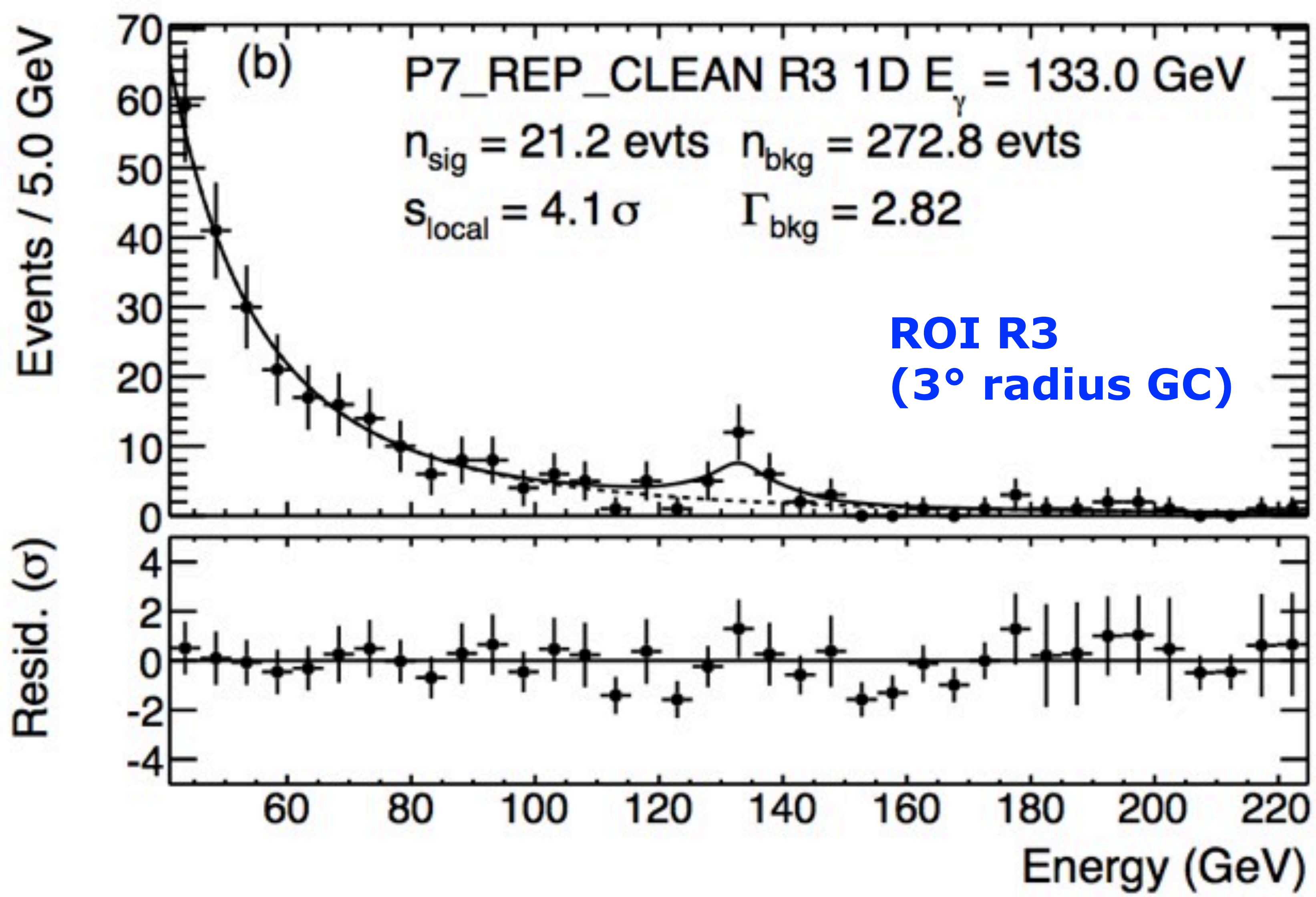
Fermi-LAT Line search near 130 GeV



- **4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data**
  1D PDF (no use of P_E), P7CLEAN data

As Weniger's significance 4.6σ

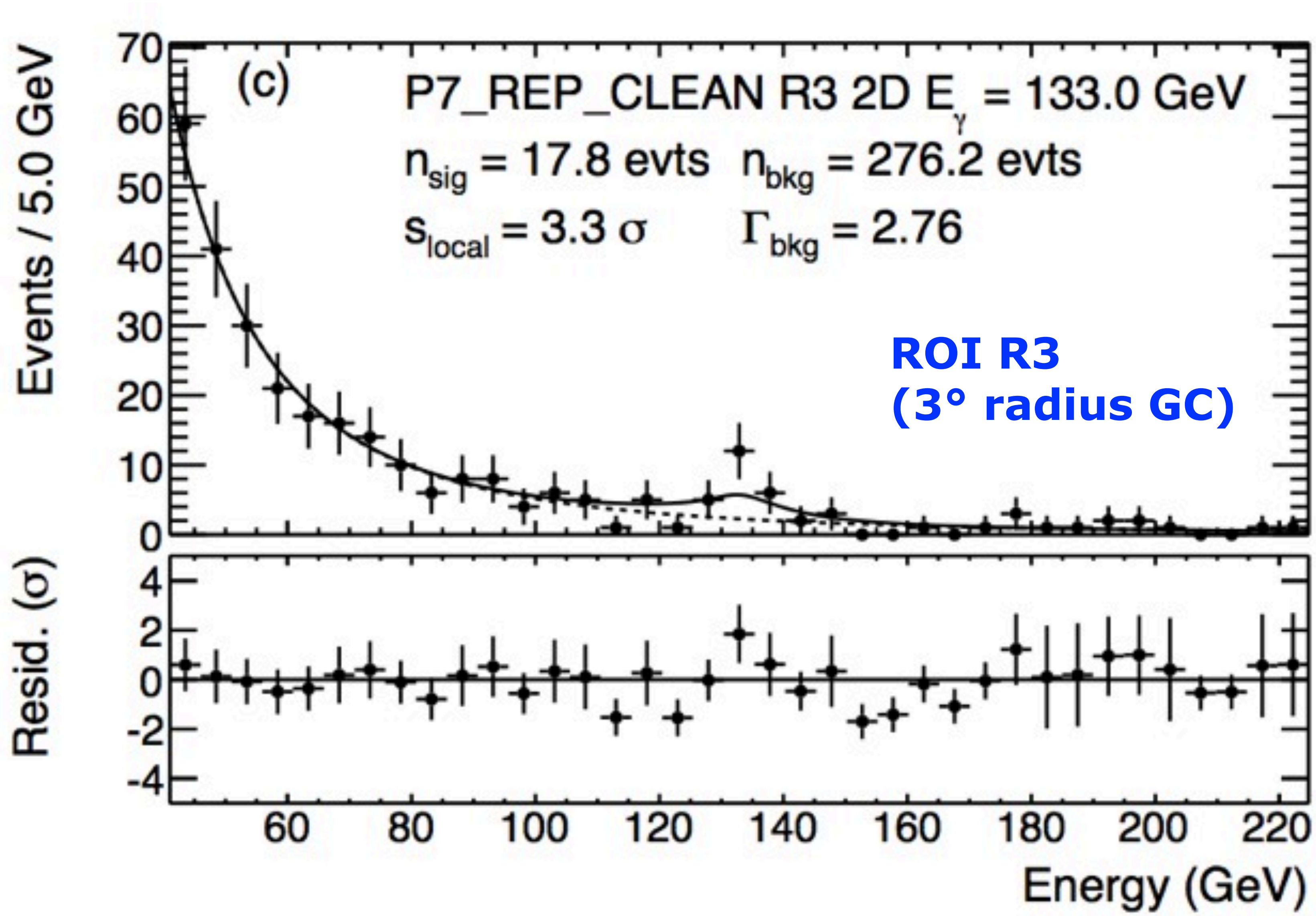
Fermi-LAT Line search near 130 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN

Peak shifts from 130 to ~133 GeV

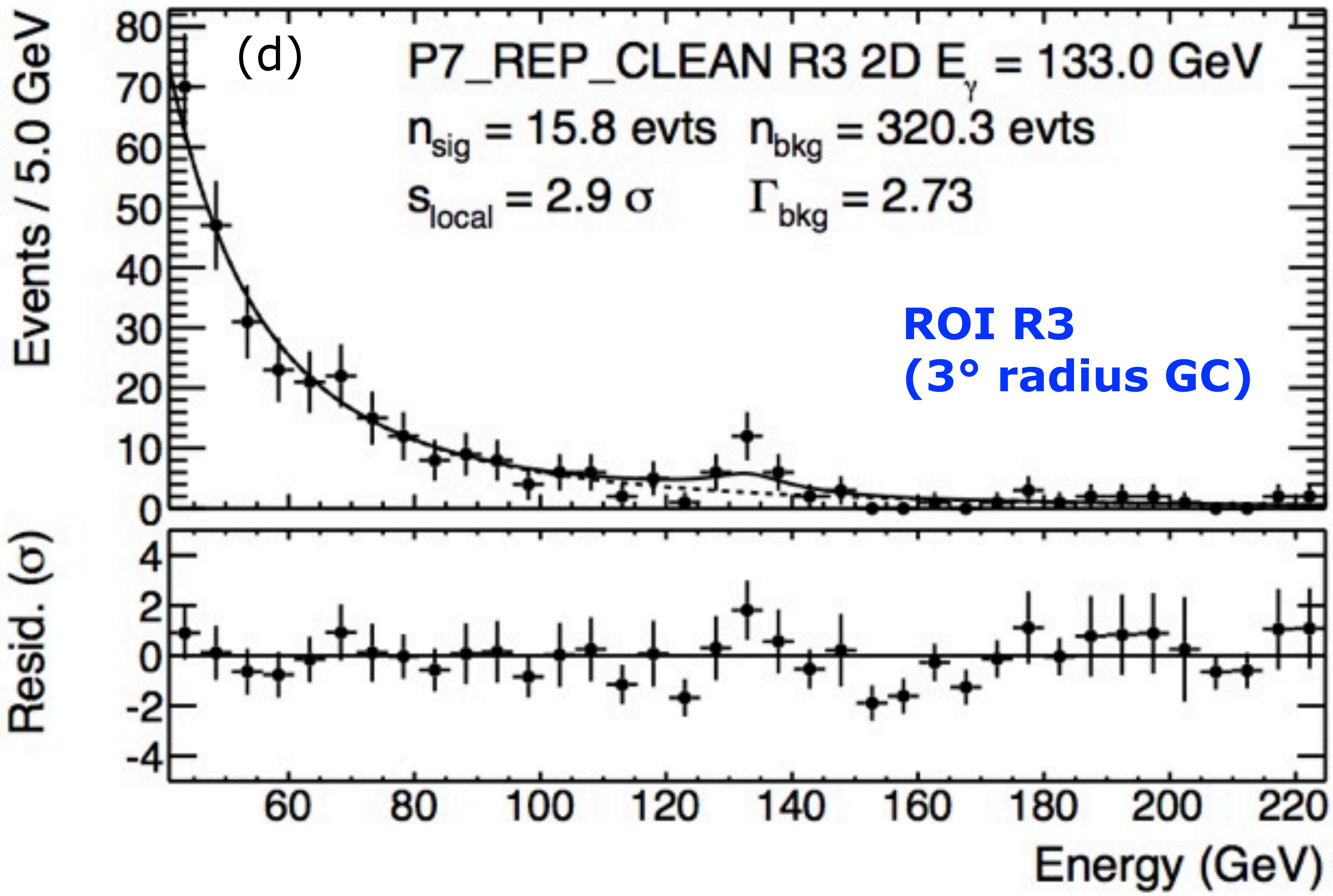
Fermi-LAT Line search near 130 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN
- **3.3σ (local) 2D fit at 133 GeV with 3.7 year reprocessed data**
  2D PDF (P_E in data), P7REP_CLEAN

Peak 'too' narrow

Fermi-LAT Line search near 130 GeV



- 4.5σ (local) 1D fit at 130 GeV with 3.7 year unreprocessed data
  1D PDF (no use of P_E), P7CLEAN data
- 4.1σ (local) 1D fit at 133 GeV with 3.7 year reprocessed data
  1D PDF (no use of P_E), P7REP_CLEAN
- 3.3σ (local) 2D fit at 133 GeV with 3.7 year reprocessed data
  2D PDF (P_E in data), P7REP_CLEAN
- **2.9σ (local) 2D fit at 133 GeV with 4.4 year reprocessed data**
  2D PDF (P_E in data), P7REP_CLEAN

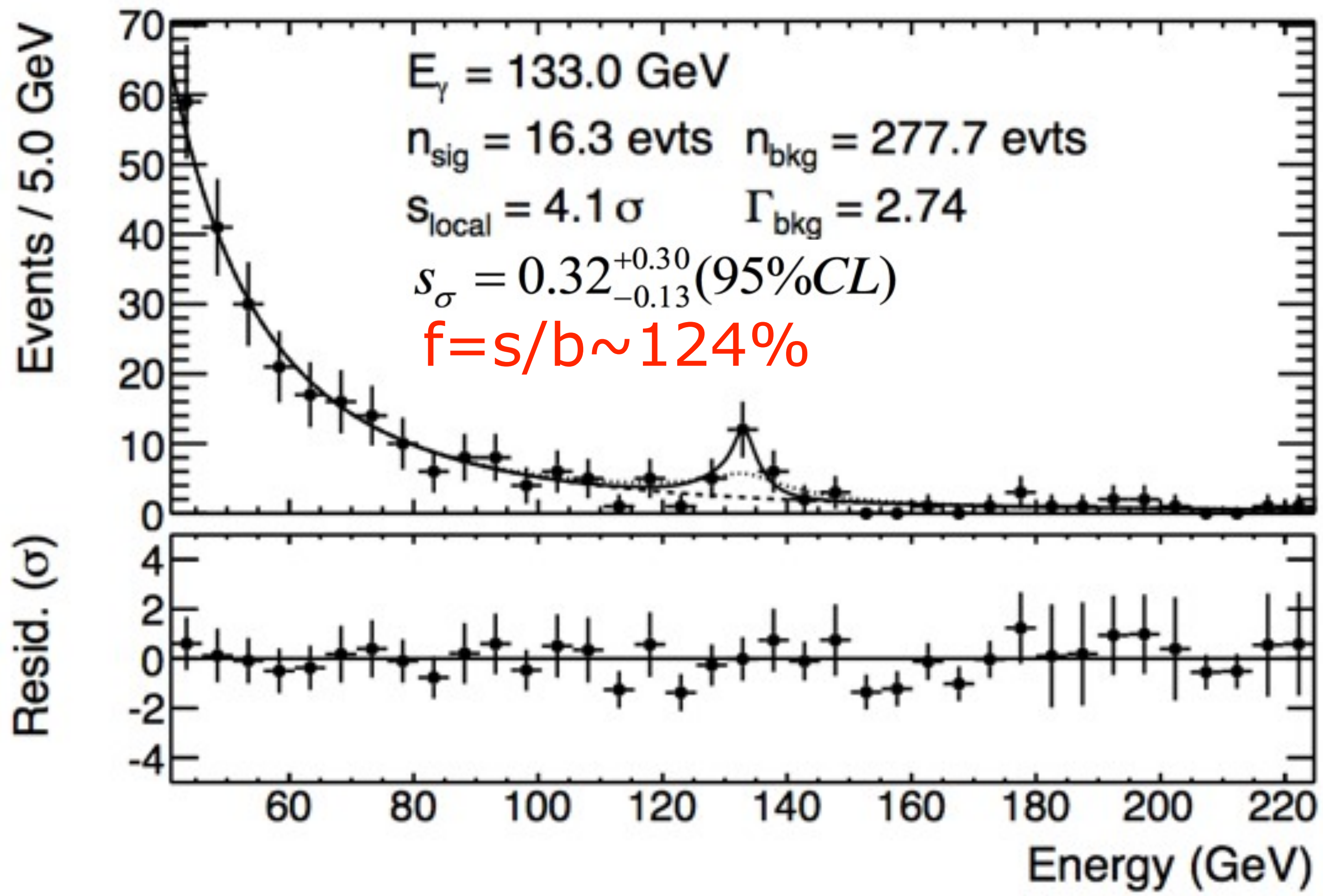
Few new events

Width of the 130 GeV feature?

Artificially, let a width scale factor (s_σ) float in fit while preserving line shape

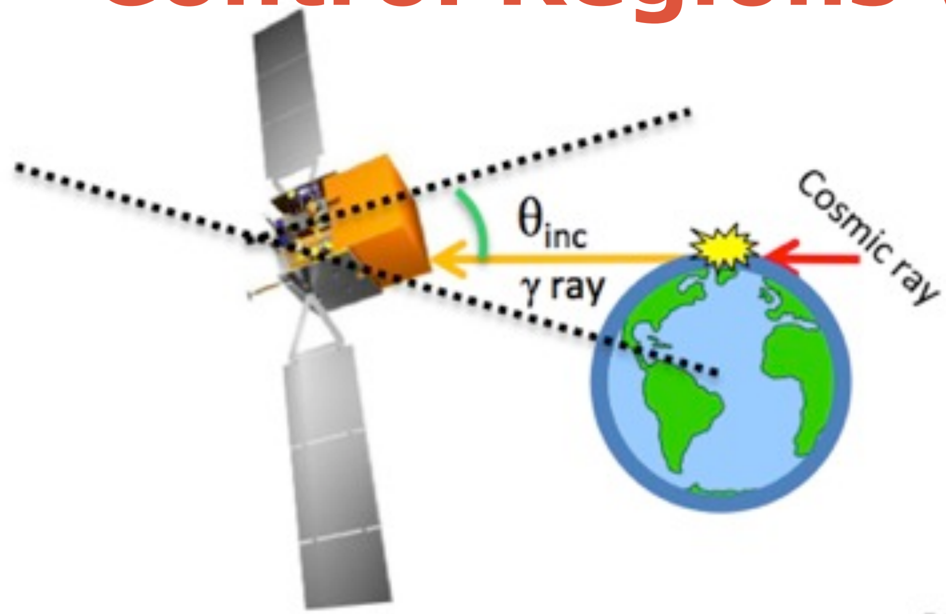
$$s_\sigma = 0.32^{+0.30}_{-0.13}(95\%CL)$$

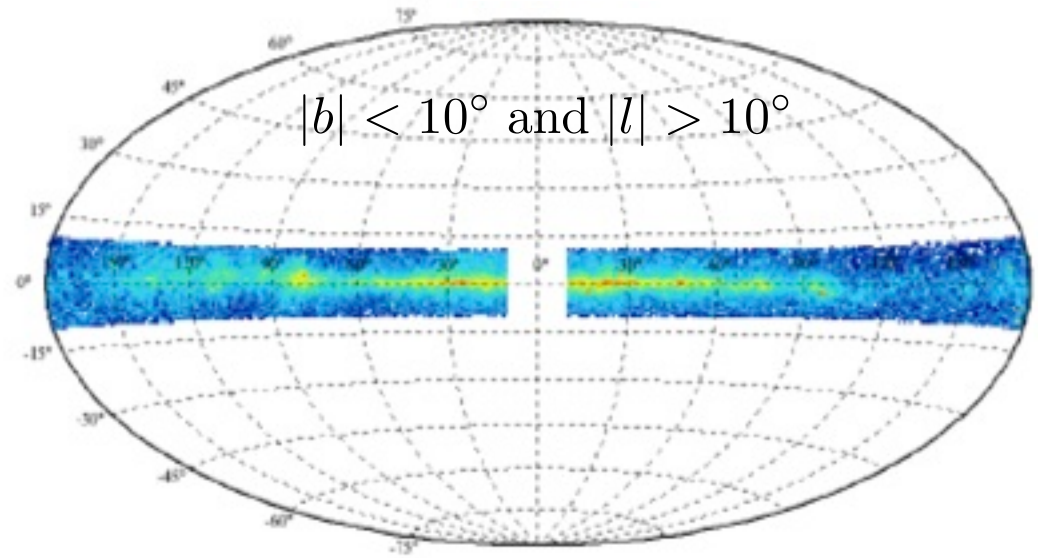
[4.1σ(local), s/b~1 —2D fit @133 GeV, 3.7yrs reprocessed data in ROI R3]



- ➡ **Feature is ~0.32 times narrower than expected energy dispersion of a monochromatic line**
- ➡ **Best-fit width not compatible with the dispersion found in beam tests and detector simulations**

Control Regions (No DM signal regions)

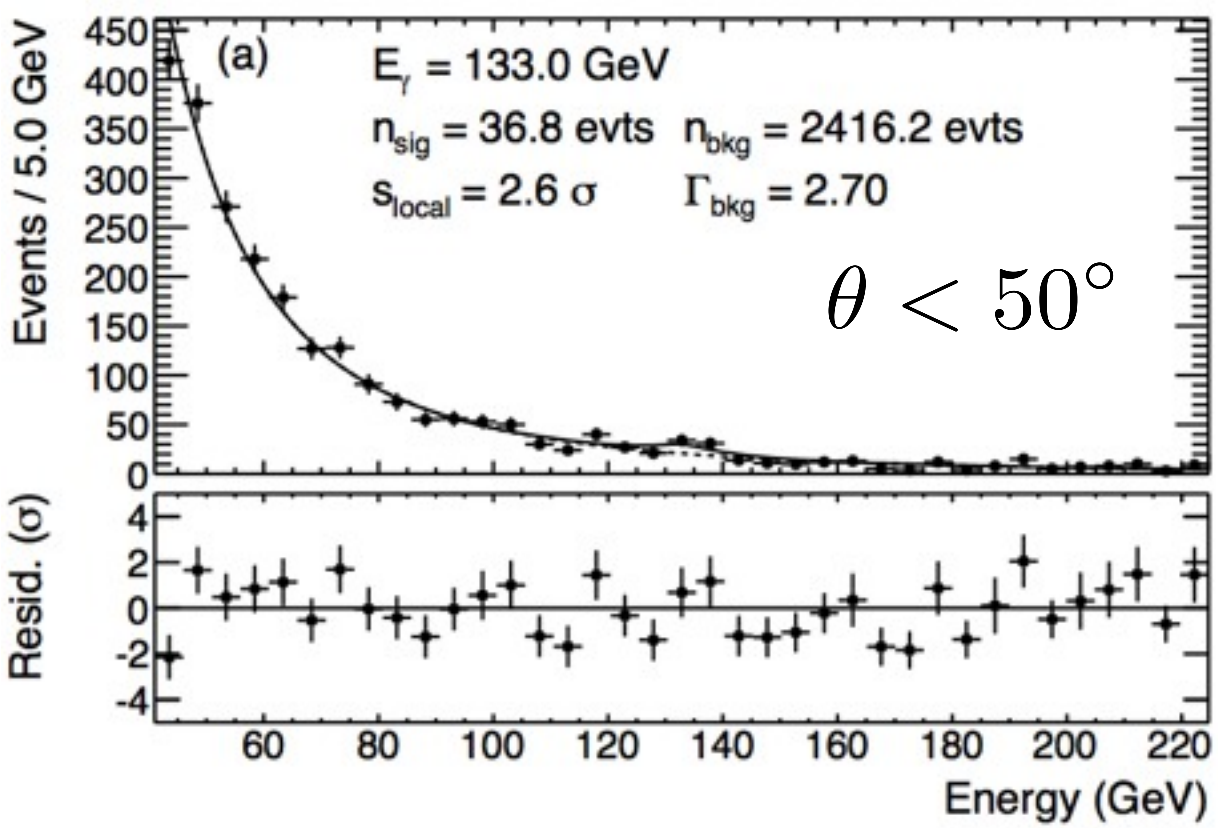




Earth Limb: expect a bright smooth power-law spectrum

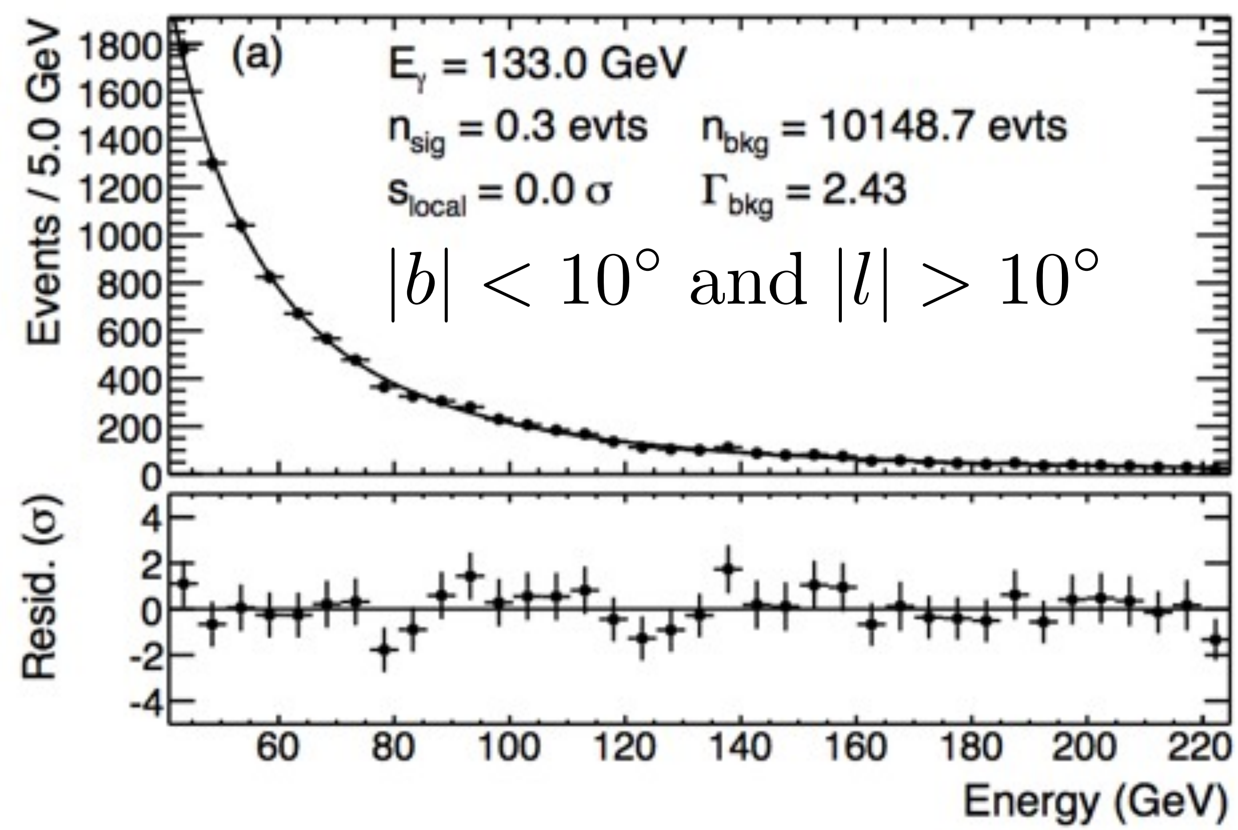
Weaker feature around 130 GeV

2.0σ, s/b≈14±7% (GC:3.3σ, s/b≈58±18%)



Galactic Disk: expect bright and astrophysical source dominated

No features seen around 130 GeV



Systematic Uncertainties

Three classes of possible effects:

1. signal to flux conversion $\delta\mathcal{E}$; e.g. exposure, effective area
2. signal strength rescaled $\delta n_{\rm sig}$; e.g. line shape, search step-size
3. induce or mask a signal δf; e.g. bkg curvature, CR contamination

	Quantity	Energy	R3	R16	R41	R90	R180
1	$\delta\mathcal{E}/\mathcal{E}$	5 GeV	±0.10	±0.10	±0.11	±0.12	±0.14
	$\delta\mathcal{E}/\mathcal{E}$	300 GeV	±0.10	±0.10	±0.12	±0.13	±0.16
2	$\delta n_{\rm sig}/n_{\rm sig}$	All	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$	$^{+0.07}_{-0.12}$
3	δf	5 GeV	±0.020	±0.020	±0.008	±0.008	±0.008
	δf	50 GeV	±0.024	±0.024	±0.015	±0.015	±0.015
	δf	300 GeV	±0.032	±0.032	±0.035	±0.035	±0.035

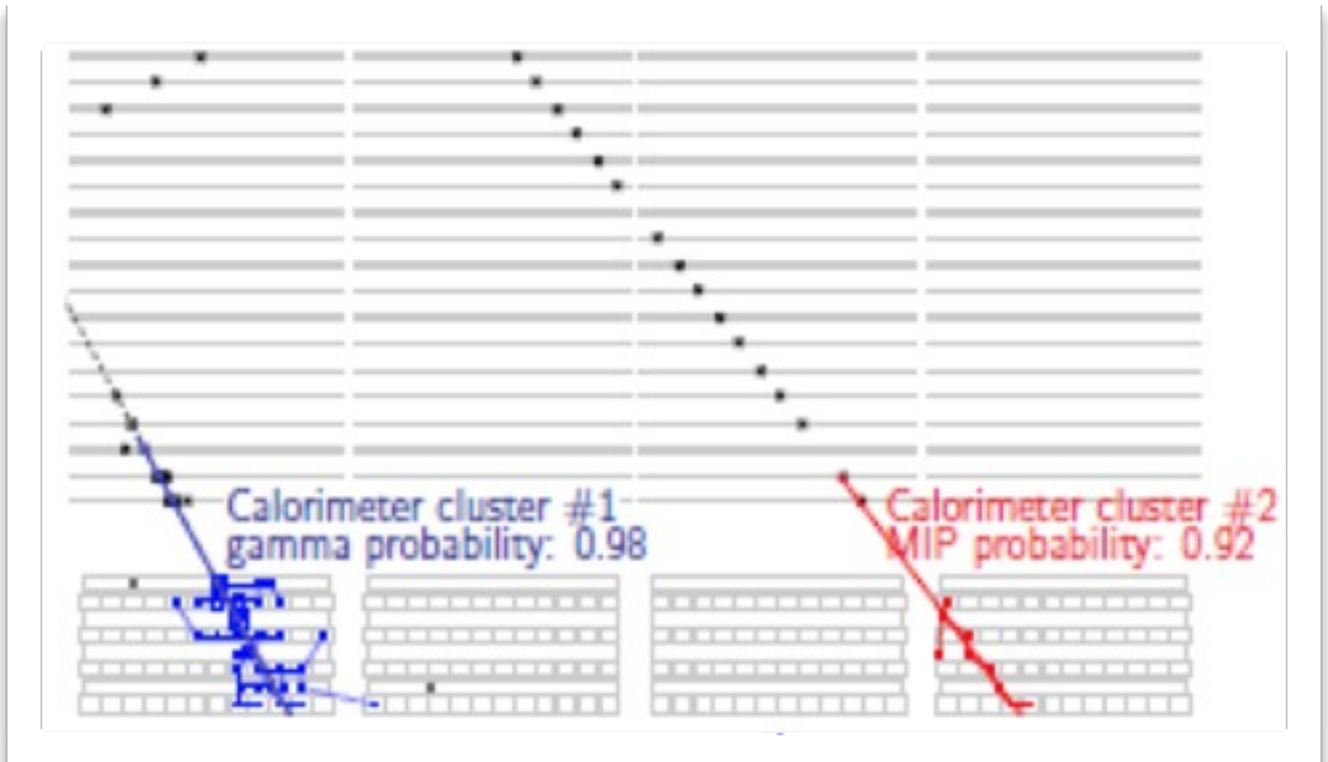
3.3σ feature @ 133GeV in R3 have much larger! signal fraction f >40%

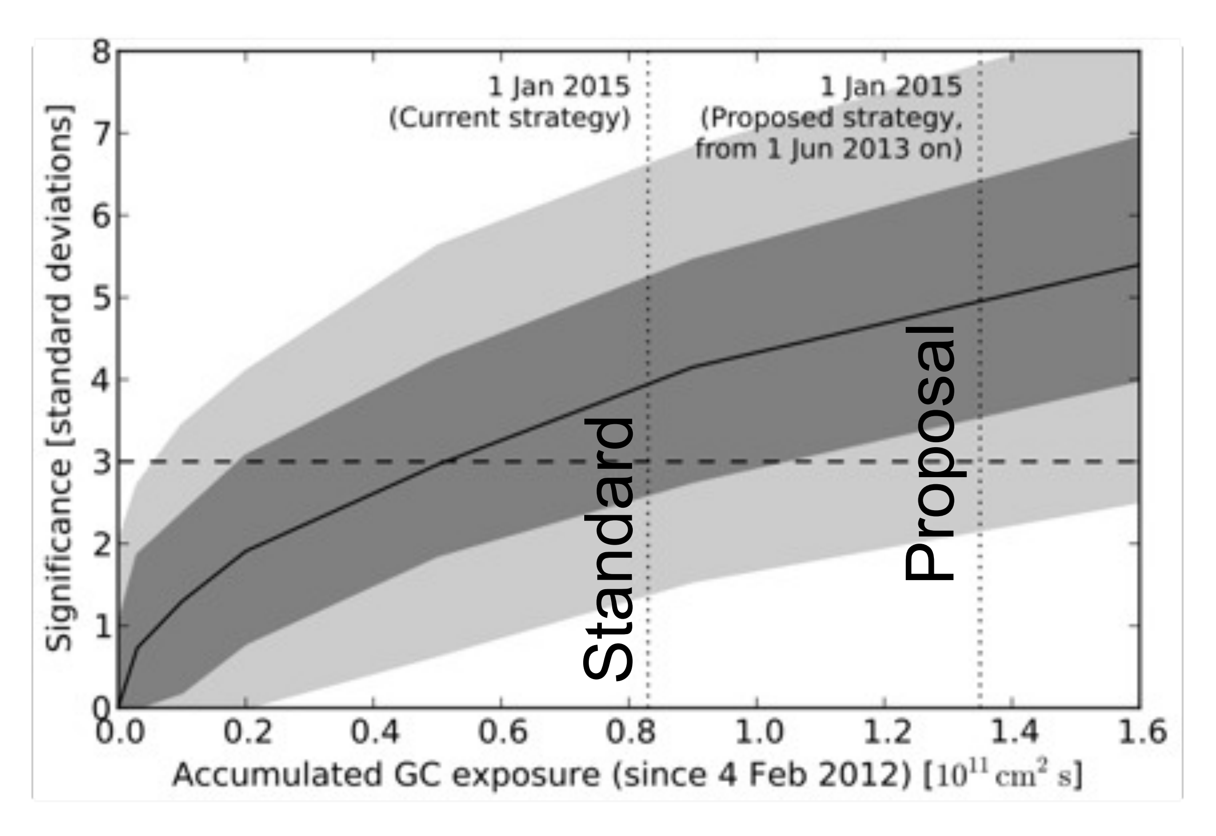
A systematic effect could explain the 3.1σ feature @ 6.3 GeV w/ f ~1%

Spectral line search: near term prospect

Fermi LAT: improv event analysis (Pass8) and weekly limb observations

- White paper proposals on possible observing modifications
  - LAT-team — http://fermi.gsfc.nasa.gov/ssc/proposals/
  - Weniger et al. — ArXiv:1305.4710





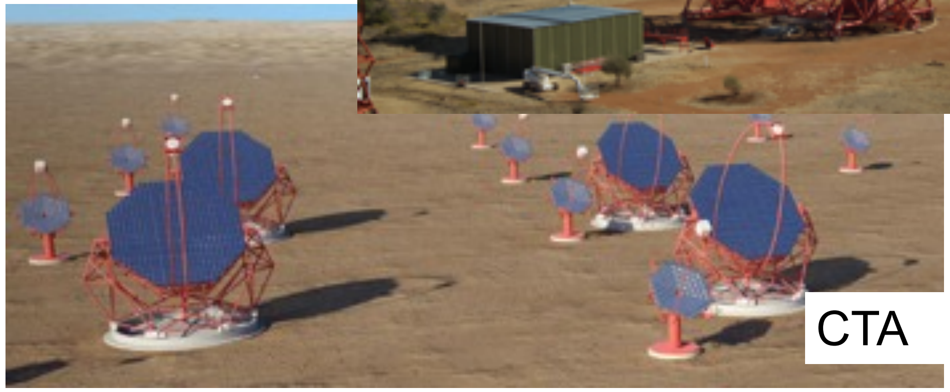
Fermi-LAT upcoming Pass 8:

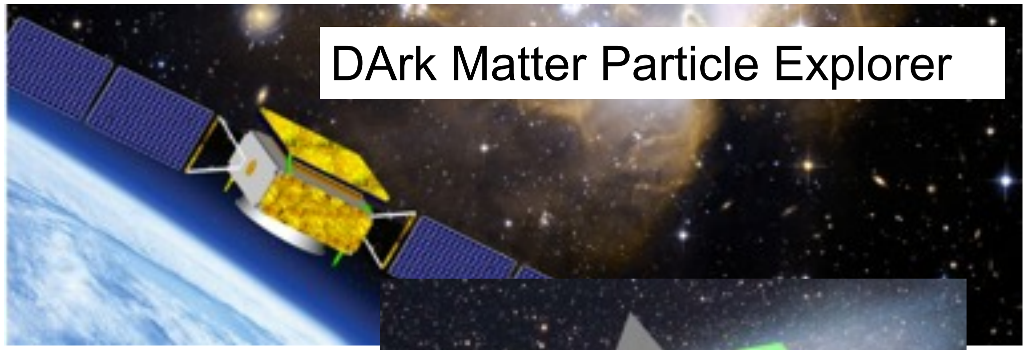
- ~25% increase in gamma-data
- Possibly better energy resolution
- Mitigate CAL/TKR miss-alignment

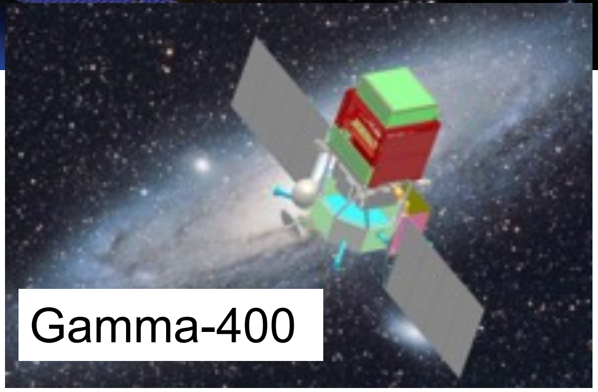
White paper proposal: Optimize Galactic centre observation-angle and exposure

Future gamma-ray measurements

- **H.E.S.S. II:** Cherenkov telescope. 50 hours of GC observation could be enough to rule out/confirm the 133 GeV feature at 5σ
  - In operation since July 2012
- **CTA:** km^2 Cherenkov Telescopes Array. 50GeV-100 TeV, 5-10 times as sensitive as current ACT
  - Production phase 2014
- **CALET:** On ISS. 10GeV-10TeV, ~2% energy res., area $0.5m^2$/5.8?
  - Launch planned 2014
- **DAMPE:** Chinese satellite. 5GeV-10TeV ~1% energy res., area ~$0.3m^2$
  - Launch planned 2015-2016
- **Gamma-400:** Russian satellite. 0.1GeV-10TeV, ~1% energy res., area ~$0.5m^2$.
  - Launch planned 2018







Summary

- ✓ Cosmic gamma-ray searches provide a promising probe to discover canonical WIMP dark matter
  - Energy spectrum ⇒ reveals intrinsic WIMP properties
  - Flux distribution ⇒ reveals DM distribution
- ✓ Discovery of a 130 GeV spectral line near the Galactic center would be a striking signal of a dark matter particle
  - Fermi-LAT finds no global significant (<1.6σ) spectral line from 5–300 GeV in 5 ROIs
    - Some aspects of a 133 GeV line-like feature require more follow up
      - Significantly narrower than expected energy resolution
      - Similar feature seen in Limb
      - Does not appear in the inverse ROI
- ✓ Upgraded Fermi-LAT data, HESS II and next generation instruments will provide exciting results