Robust identification of the Fermi GeV excess at higher Galactic latitudes

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F. Calore (GRAPPA, Univ. of Amsterdam),
I. Cholis (Fermilab, Chicago) &

Christoph Weniger

See also Francesca Calore's talk yesterday

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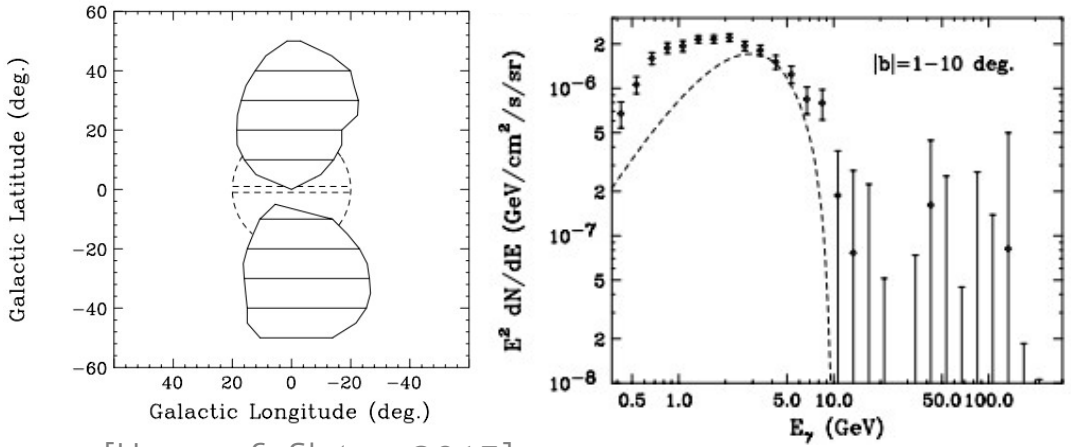
GRAPPA
GRavitation AstroParticle Physics Amsterdam

NWO

Previous work

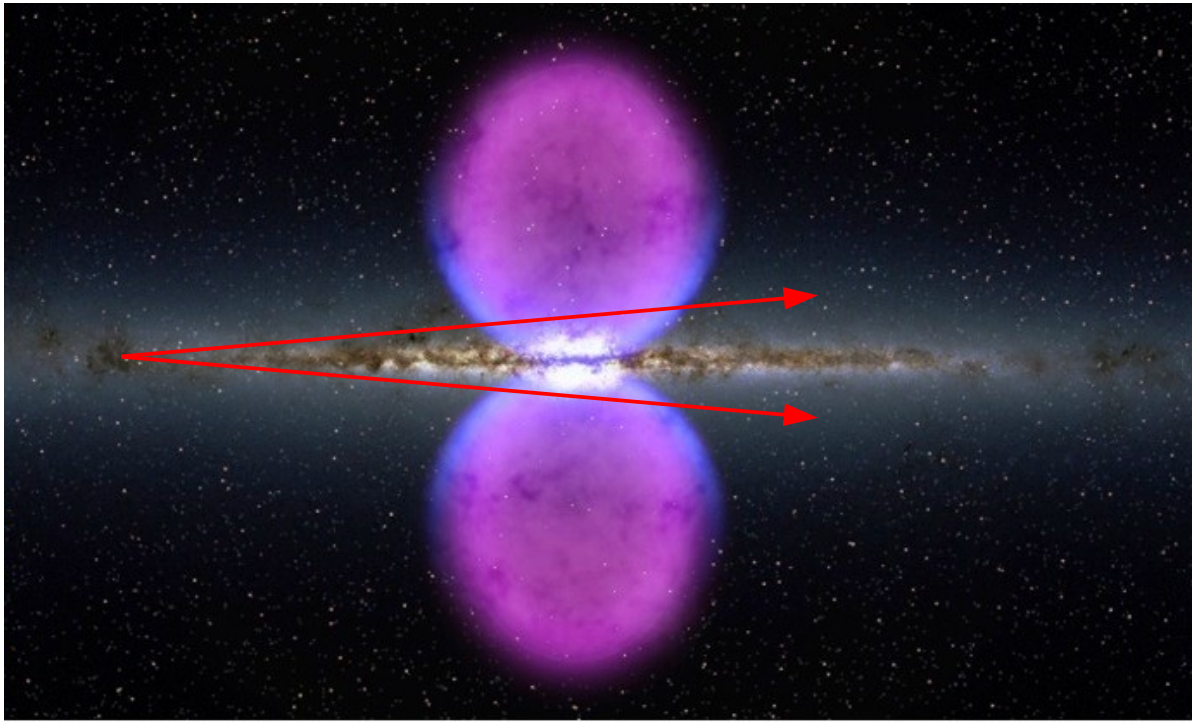
In the inner Galaxy (roughly |b|>1 deg to tens of deg)

Hooper & Slatyer 2013
Huang+ 2013
Daylan+ 2014

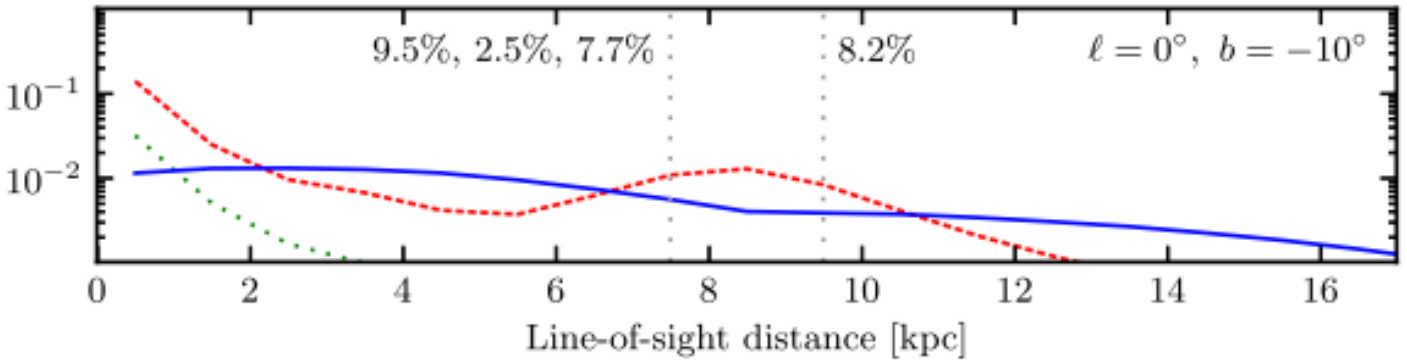


[Hooper & Slatyer 2013]

We are doing foreground subtraction (mostly)



Emissivity along line of sight:



"Excess" is everything that remains after subtracting:

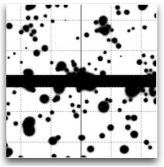
- Foreground (dominant)
- Galactic center emission from our standard Galprop model (sub-dominant)
- Fermi Bubble flux (sub-dominant at low latitudes)

We aim at robustly describing emission from Galactic central region / inner Galaxy

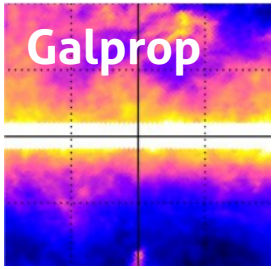
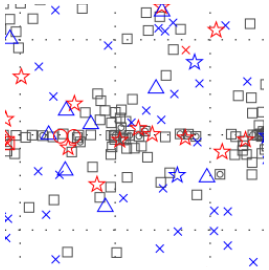
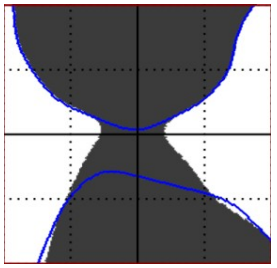
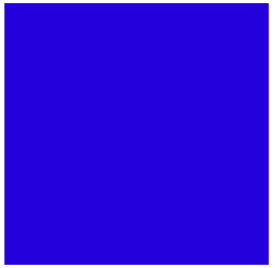
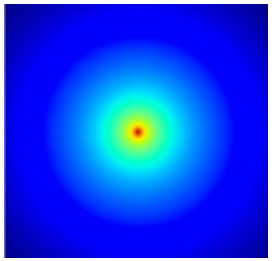
Reanalysis of excess emission in inner Galaxy

ROI:

- **"Inner Galaxy"**: $2^\circ \leq |b| \leq 20^\circ$ and $|\ell| \leq 20^\circ$
- We mask all **point sources** from the 2FGL



Components in the analysis:

π^0+Bremss free	ICS free	2FGL fixed	Bubbles constrained	Isotropic constrained	Excess template free
					

Energy dependent templates

Energy independent templates

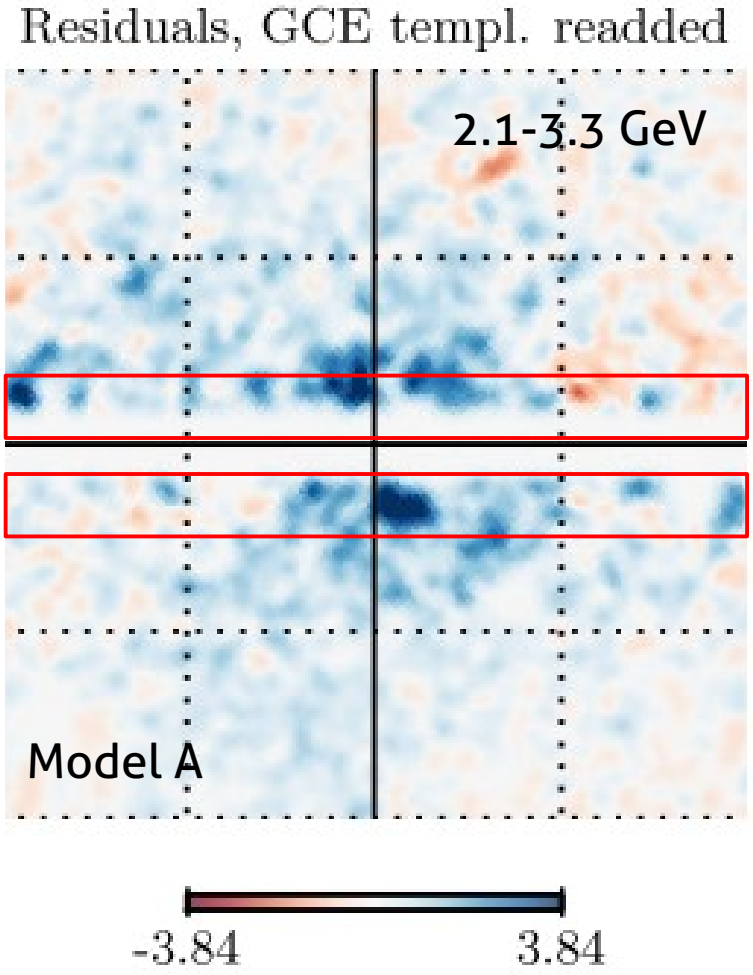
Fits independently in energy bins → Spectral information from Galprop models is neglected

Caveats:

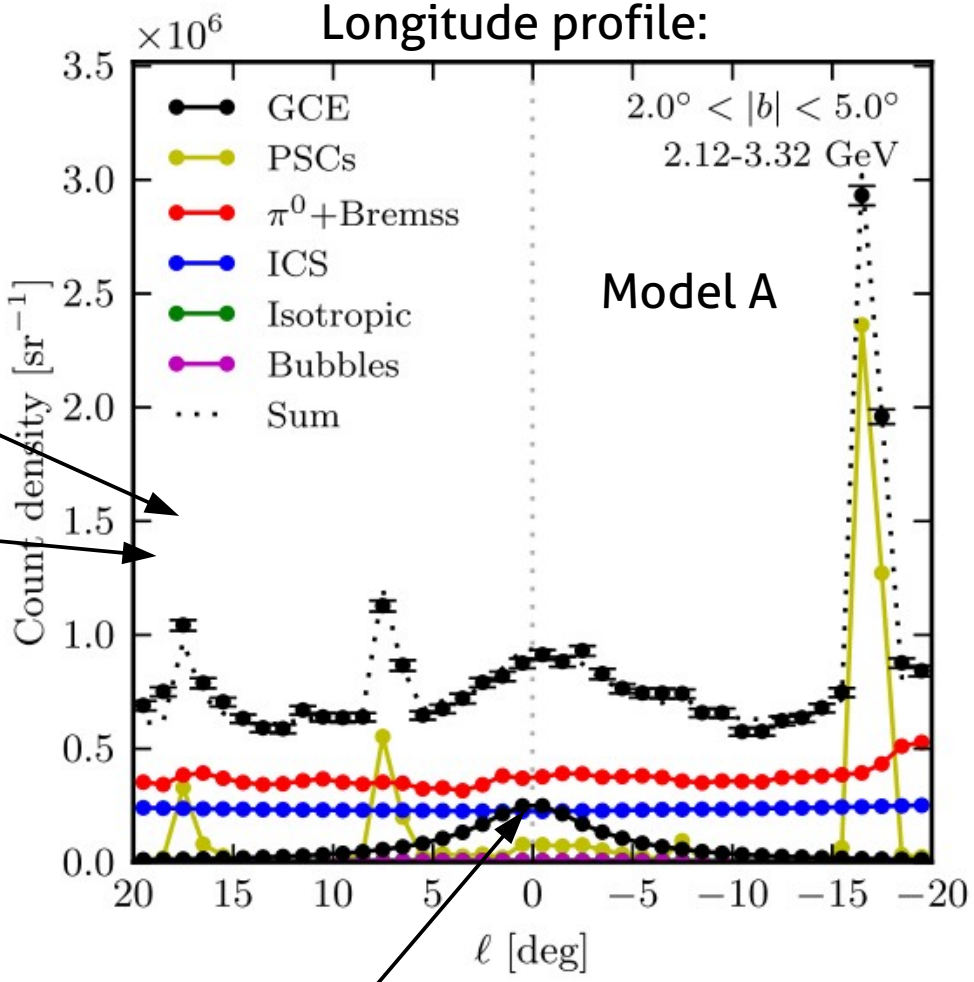
- Homogeneous & isotropic diffusion, reacceleration and convection
- Steady-state, no special activity at GC
- No physical model for Fermi Bubbles
- Standard gas maps

Details about the **60 adopted GDE models**:
→ F. Calore's talk yesterday

Flux absorbed by the excess template

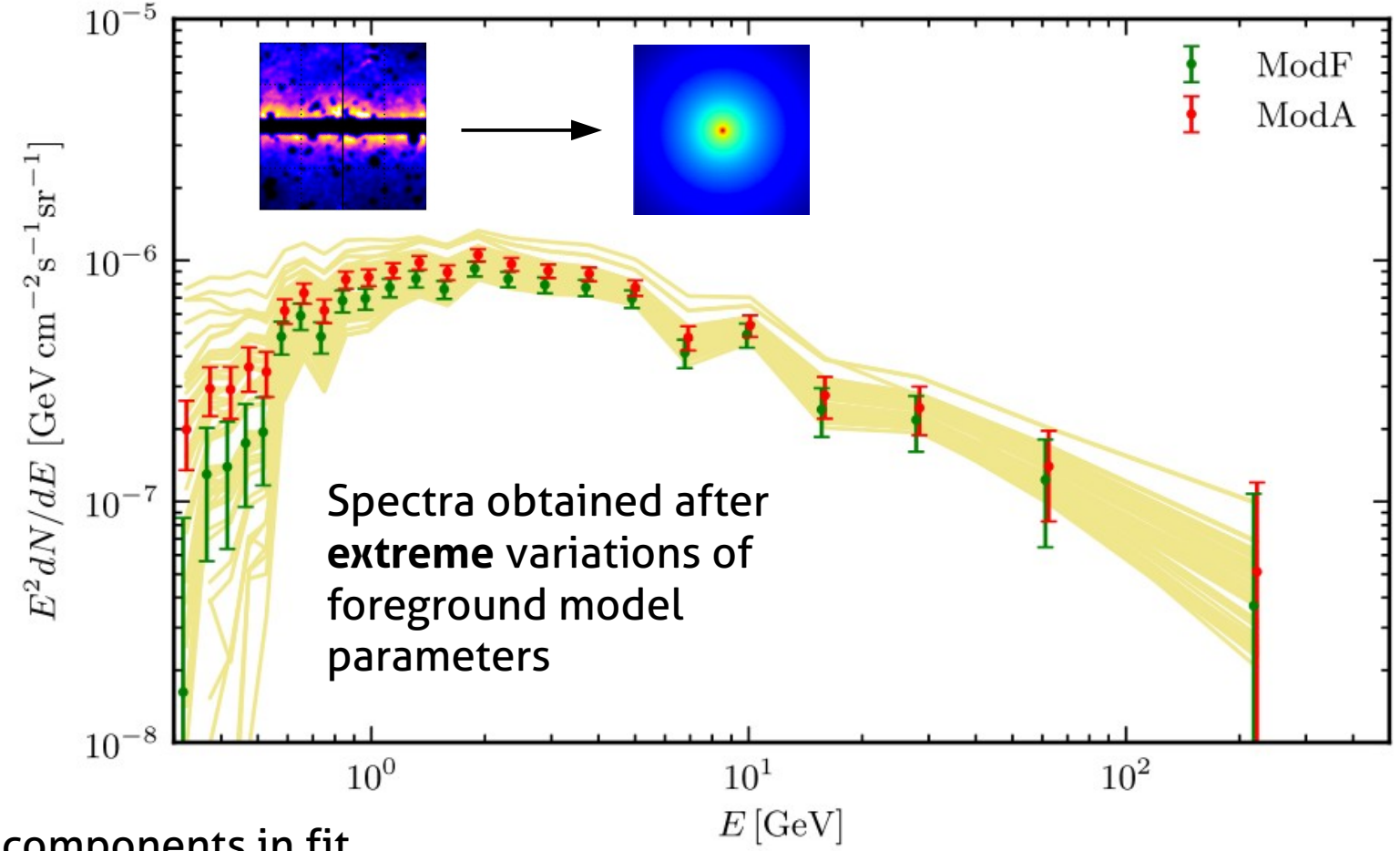


Longitude profile:

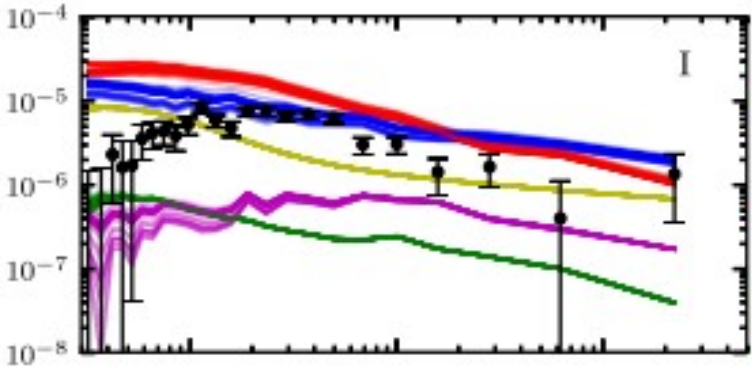


Flux in excess template exceeds expected ICS flux from inner region of Galaxy (for Model A) by at least a factor of five.

Theoretical model uncertainties



Individual components in fit only vary by ~O(2).



In all cases, the excess template spectrum

- rises from 300 MeV to ~1 GeV
- peaks at 1-3 GeV
- falls power-law like above 3 GeV (no cutoff at >10 GeV energies)

Potential problems

A.

Bad Fermi LAT PSF below 1 GeV

- Point source confusion / mix with Galactic diffuse emission
- Masking of point sources not sufficient (leakage)

} **Next slide**

B.

Instrumental effects

- Effective area drops rapidly below 1 GeV

C.

Galactic diffuse emission model

- Large unknowns related to interstellar gas
- Extreme foreground models are not extreme enough

} **Rest of talk** (addressed by estimating "empirical model systematics")

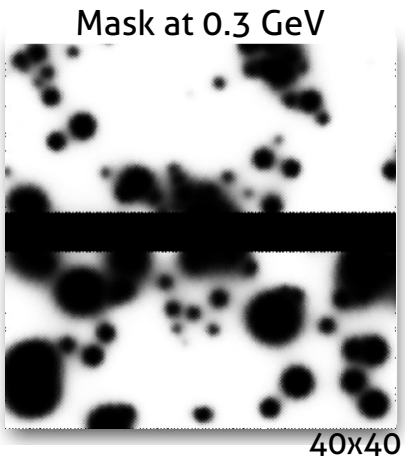
- Diffusion properties at Galactic center weakly constrained
- No physical model for Fermi bubbles
- Many unresolved point sources in Galactic bulge

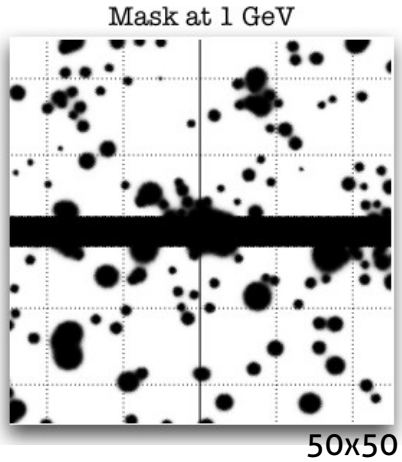
} **Not relevant here** We describe emission from inner Galaxy that remains after foreground subtraction, not model it.

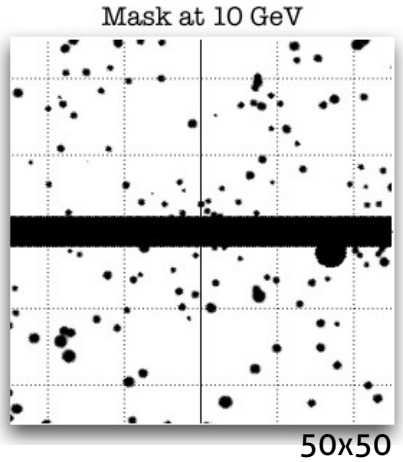
Resolved point sources are not critical

"Soft masking":
We mask regions where 2FGL source contribute more than 10% to the predicted diffuse flux.

This causes some leakage, which however does not affect our results.



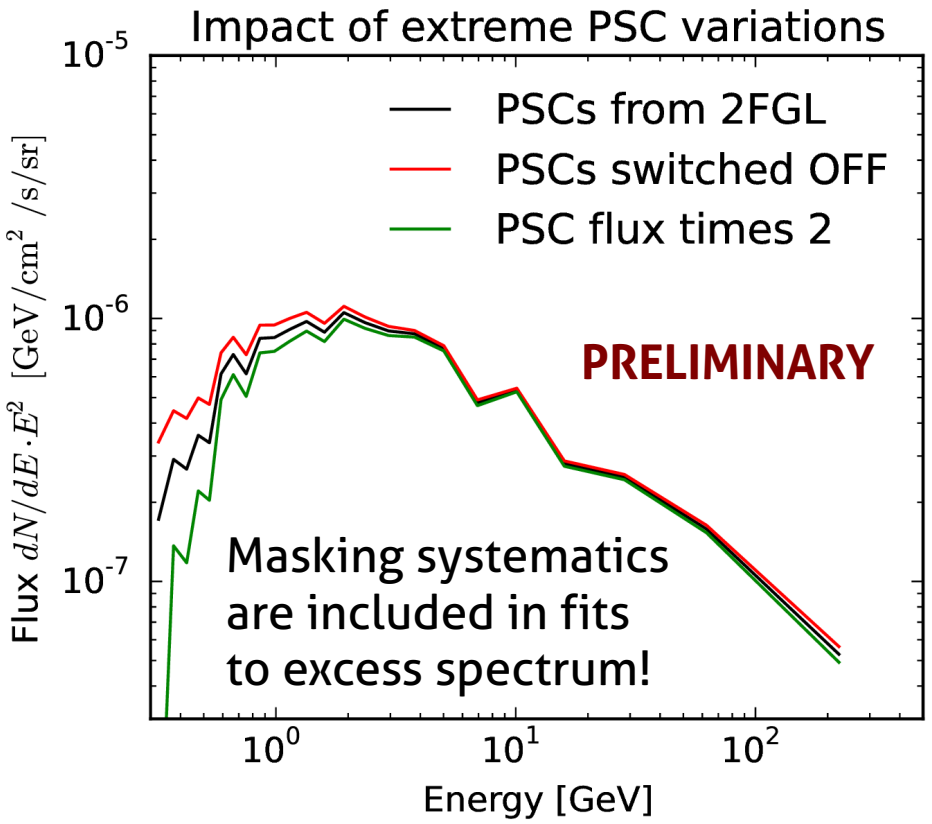




Even unrealistically extreme variations affect excess spectrum above 600 MeV by < 20%.

- Switching off PSCs completely does not remove suppression at low energies
  → no problematic over-subtraction
- Increasing PSCs fluxes by factor 2 has only mild impact on spectrum
  → leakage outside PSC mask not critical

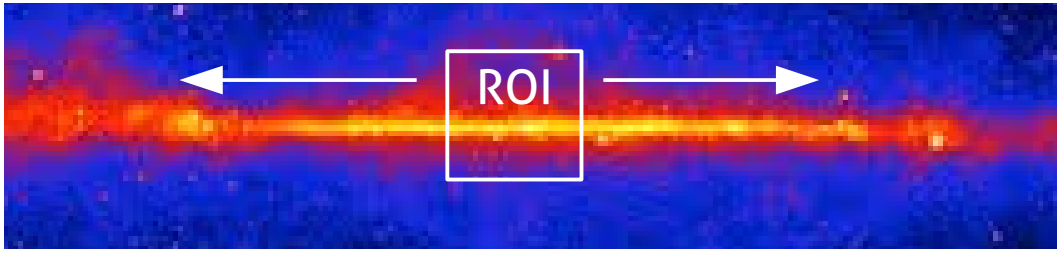
Note: If excess is dominantly due to **unresolved sources**, they do not modify the excess spectrum. They have to explain it.



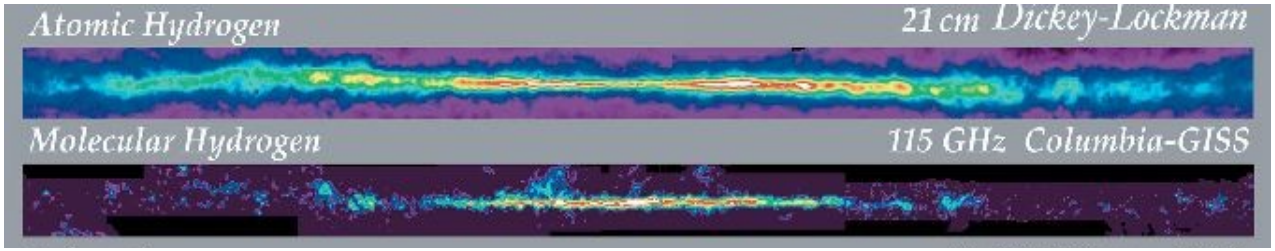
Excesses in the Galactic disk as estimate for empirical model systematics

We can use Galactic disk as test region to estimate the impact of uncertainties in **gas maps**, modeled **CR distribution**, **point source fits** and masking, and **instrumental effects** on excess template fit at Galactic center.

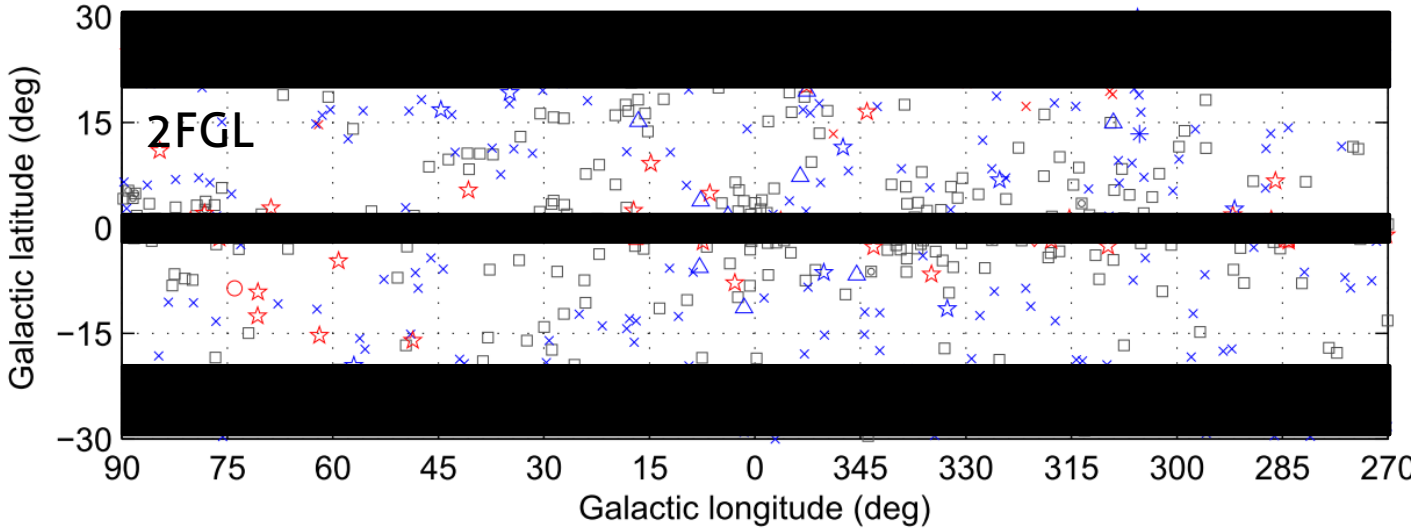
We move the ROI and excess template along disk, and redo our fits.



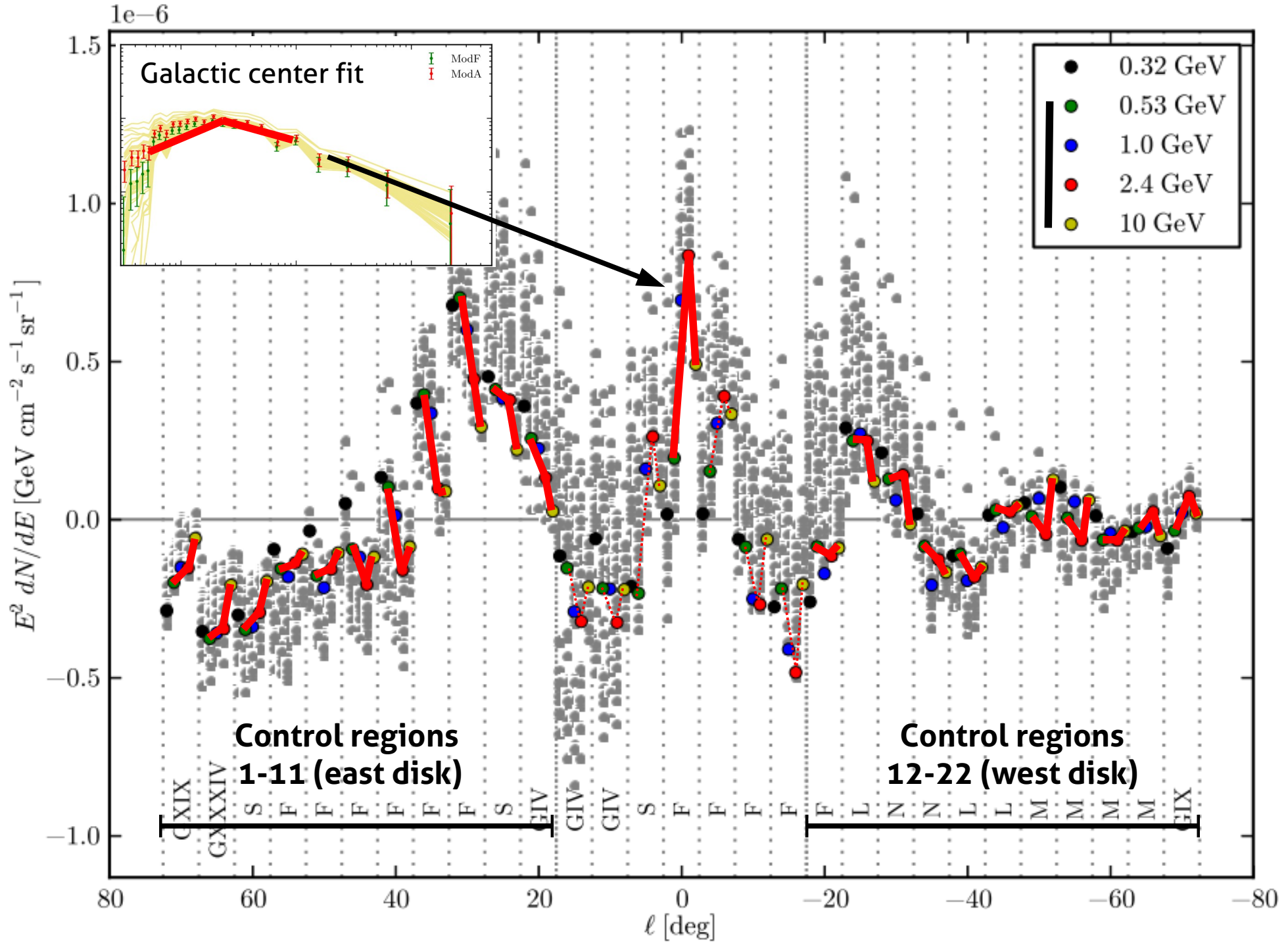
Longitudinal variations photon sources are relatively mild.



Relevant latitude range



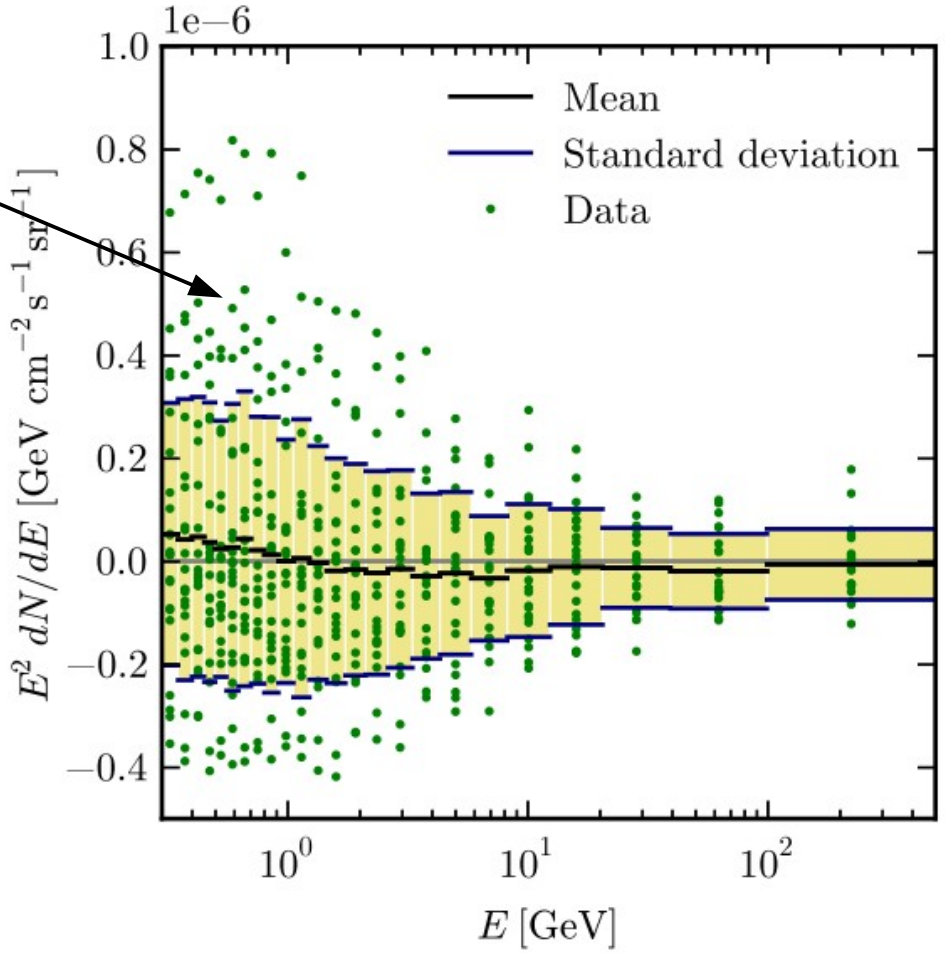
Flux in excess template shifted along the Galactic plane



Excess fluxes from test regions are correlated in energy

Flux absorbed by excess template in 22 test regions along the Galactic disk.

- Standard deviation is a first estimate for how inaccuracies in the foreground modeling affect the excess template



Observed excess emission in test regions is **correlated in energy.**

Fluctuations define an empirical **covariance matrix:**

$$\Sigma_{ij,\,\mathrm{mod}} = \left\langle \frac{dN}{dE_i}\frac{dN}{dE_j} \right\rangle - \left\langle \frac{dN}{dE_i} \right\rangle \left\langle \frac{dN}{dE_j} \right\rangle$$

Principal components of excess fluxes in test regions

Miss-modeling of diffuse foregrounds (ICS, pi0) in excess region is absorbed by excess template:

$$\frac{dN^{\pi^0}_{\rm true}}{dE} = \frac{dN^{\pi^0}_{\rm model}}{dE}(1+\delta\alpha)E^{-\delta\gamma}$$

At first order we have:

slope error

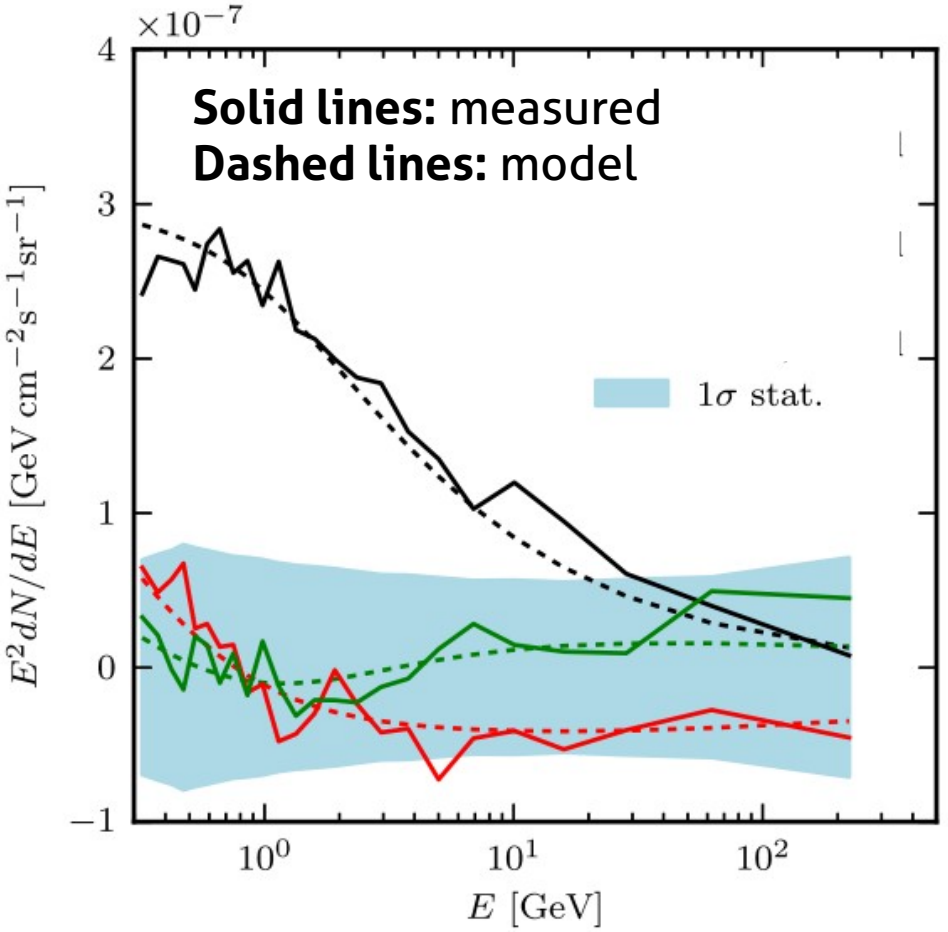
normalization error

$$\delta\frac{dN^{\rm GCE}}{dE} = -\delta\frac{dN^{\pi^0}}{dE} - \delta\frac{dN^{\rm ICS}}{dE}$$

Principal components of excess fluxes in test regions can be fully understood in terms of these uncertainties.

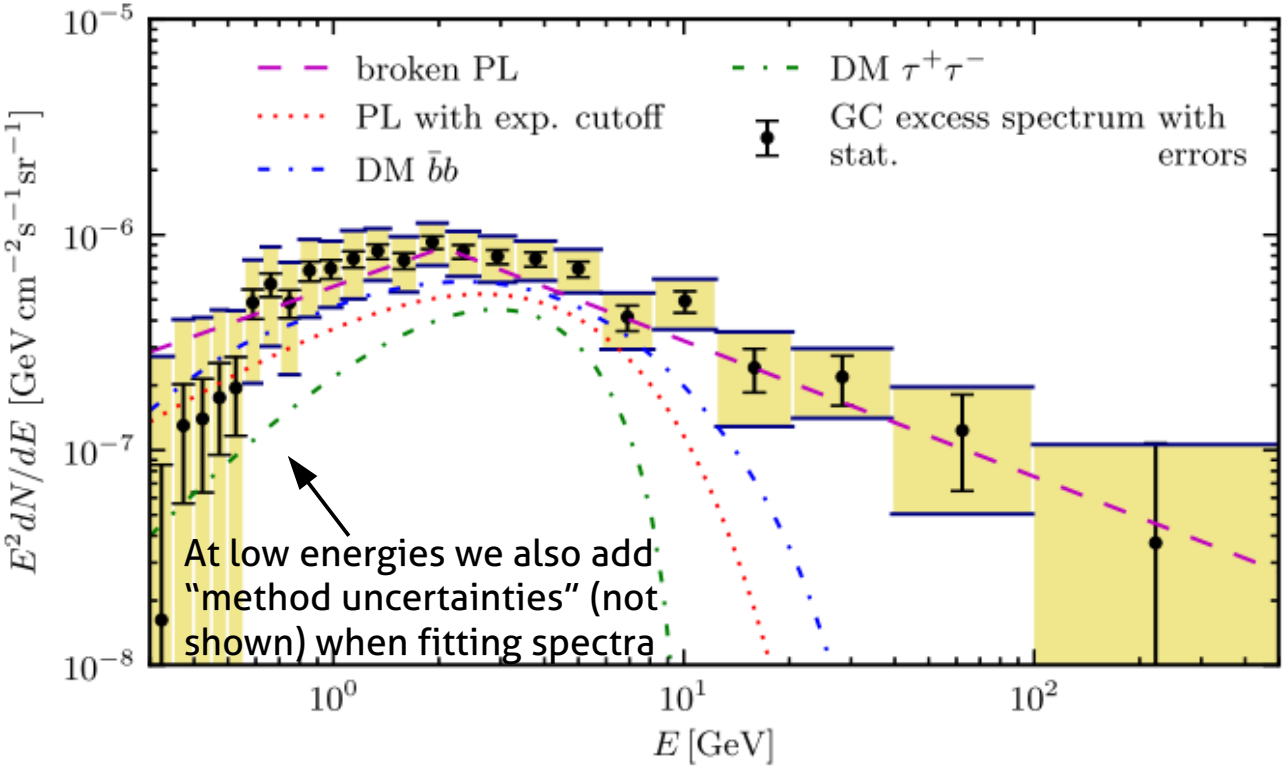
From fit to the main principal components we find that excess spectrum is affected (at 1 sigma)

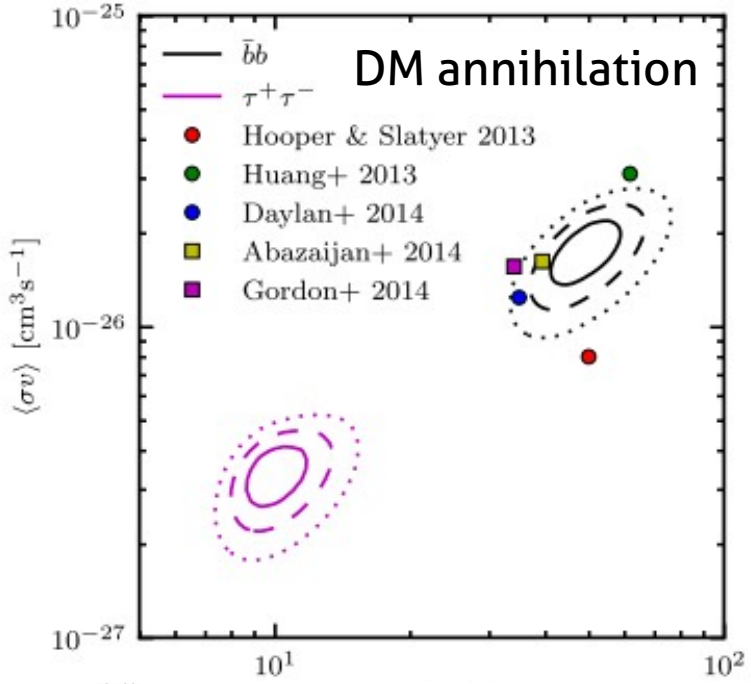
- by 3% of ICS and pi0 emission
- <0.01 spectral index variations

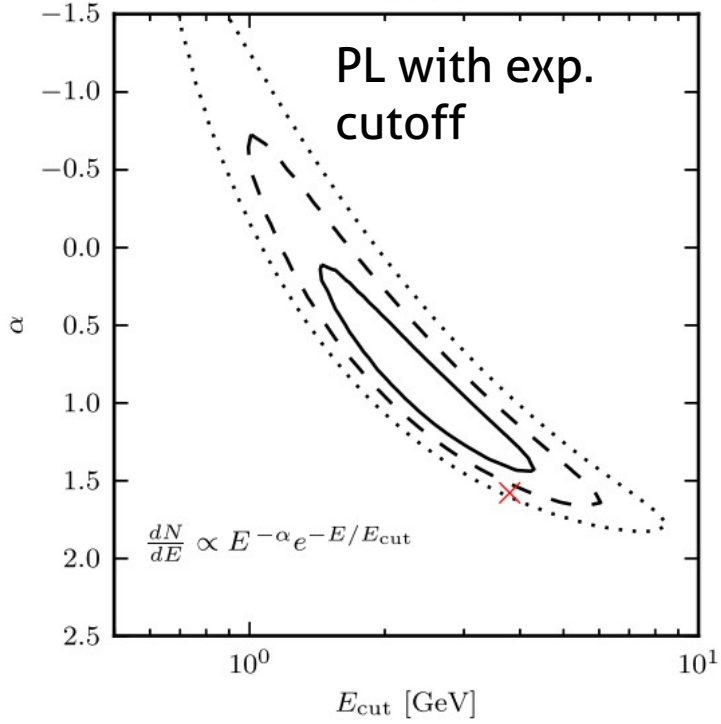


Impact on excess spectrum at Galactic center

Empirical model systematics (from excesses in Galactic disk test regions) are of the same order as the theoretical model systematics (from Galprop models), but **have in additional a clear statistical meaning**.







Parametric fits to excess spectrum

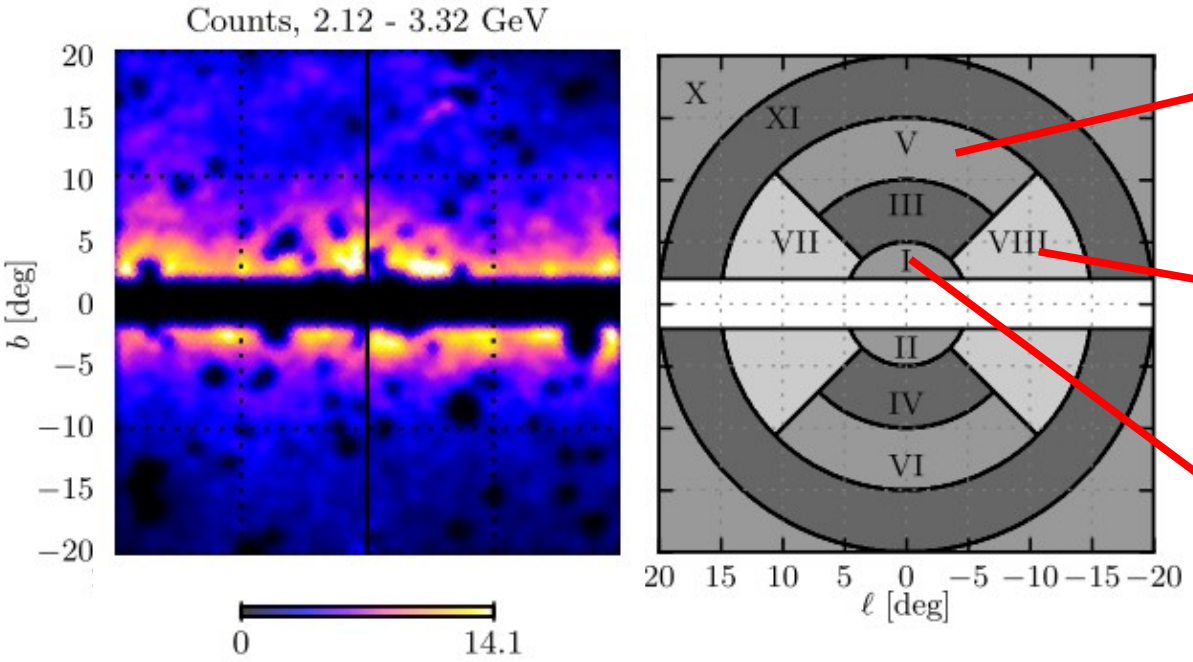
(including **<u>correlated</u>** errors)

- best-fit obtained with broken power-law
- equally good fits with hadronic final states from DM annihilation
- also PL with exp. cutoff gives reasonable fit

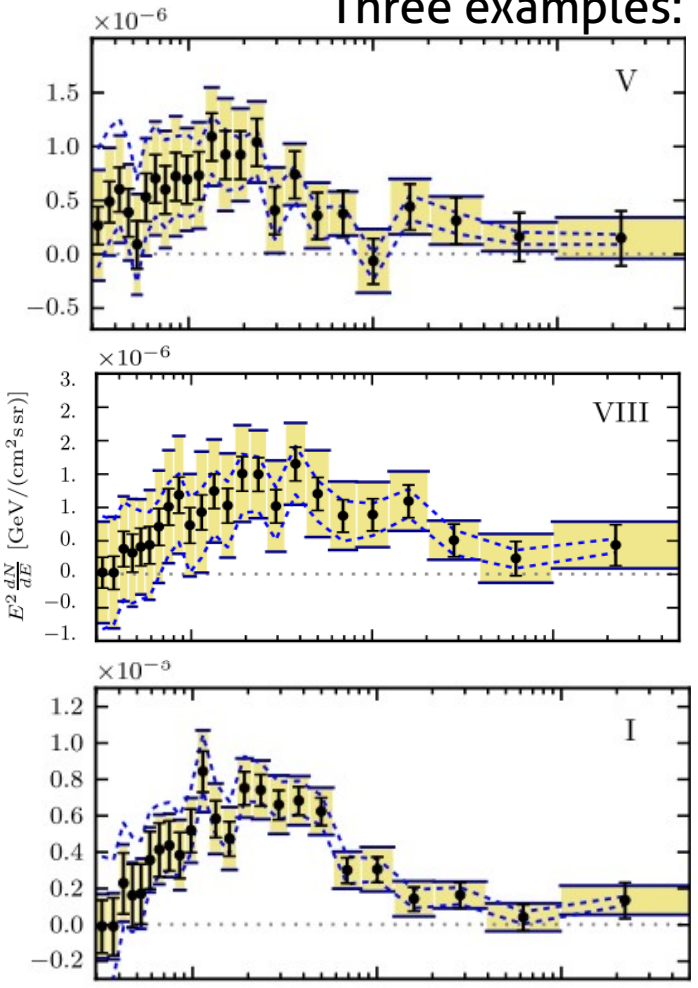
Non-parametric analysis of excess morphology

Method

- We split excess template in ten segments
- We repeat the analysis of theoretical and empirical model systematics for all segments



Three examples:



We find significant excess fluxes in all ten regions, decaying away from the GC.

Note: some segments are smaller than PSF at low energies

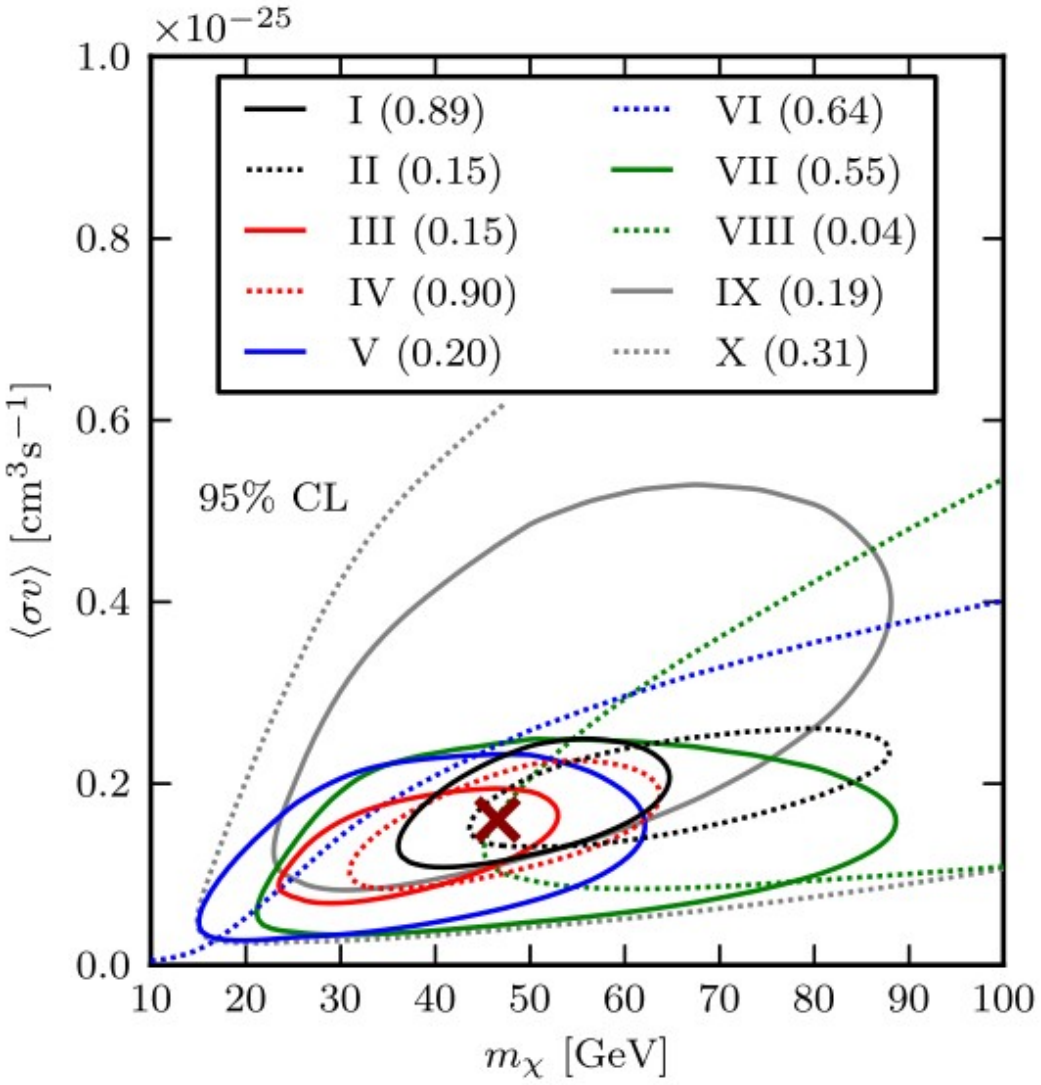
→ unproblematic for excess spectra inference, but can be relevant for their interpretation

Parametric analysis of excess morphology

Simple example (DM fit):
- Fit with bb spectrum from DM annihilation (free mass and normalization)
- Generalized NFW profile with 1.26 inner slope

Result
- In all ten regions, the 95%CL include the best-fit value
- Nonzero signal preferred in all but one regions

- No north/south or east/west asymmetry



Parametric fit with DM spectrum indicates that results are consistent with hypothesis of <u>one</u> single spectrum at 95% CL.

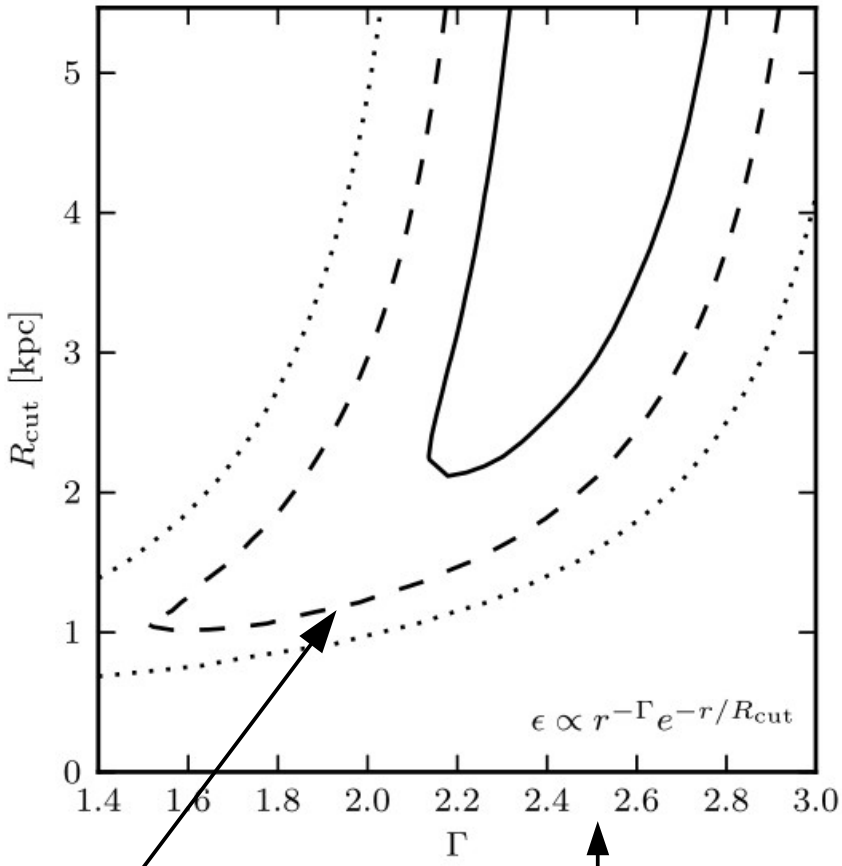
Radial extension away from GC

Method:

- We take the compatibility in excess spectra serious and test the hypothesis that the excess is due to one single extended source.
- Volume emissivity profile of exemplary source distribution:

$$q \propto r^{-\Gamma} e^{-r/R_{\rm cut}}$$

- We fit excess spectra in different regions, keeping the spectrum fixed (exemplary hadronic DM spectrum, but broken PL would work as well), but allowing the profile parameter to vary.



Leaving the slope free, we find a lower limit on the cutoff radius of at least 1.48 kpc (10.0 deg) at 95%CL.

For a fixed slope of 2.5 (values suggested by the GC analysis), the cutoff is larger.

~Slope suggested by Galactic center analysis

Many open questions

Dark Matter just works fine
- But: requires that additional astrophysical emission from bulge region remains relatively small

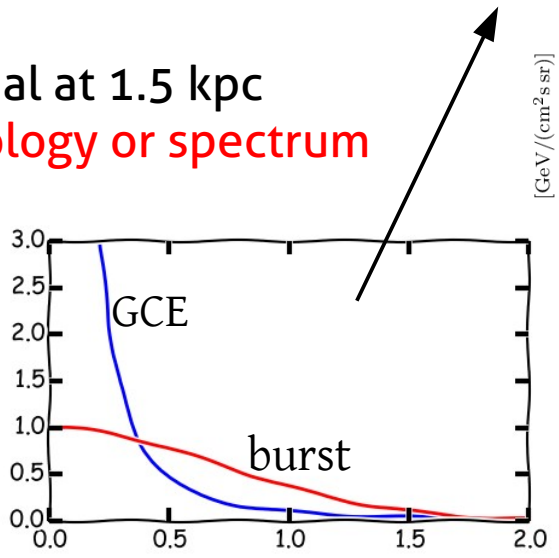
Milli-second pulsars

Wang+ 2005; Abazajian 2011; Gordon & Macias 2013; Hooper+ 2013; Yuan & Zhang 2014; Hooper+ 2013; Calore+ 2014; Cholis+ 2014
- Spectrum of known MSPs agrees reasonably well with our GCE spectrum
- Luminosity function claimed to be problematic
  Hooper+, Calore+, Cholis+ 2013

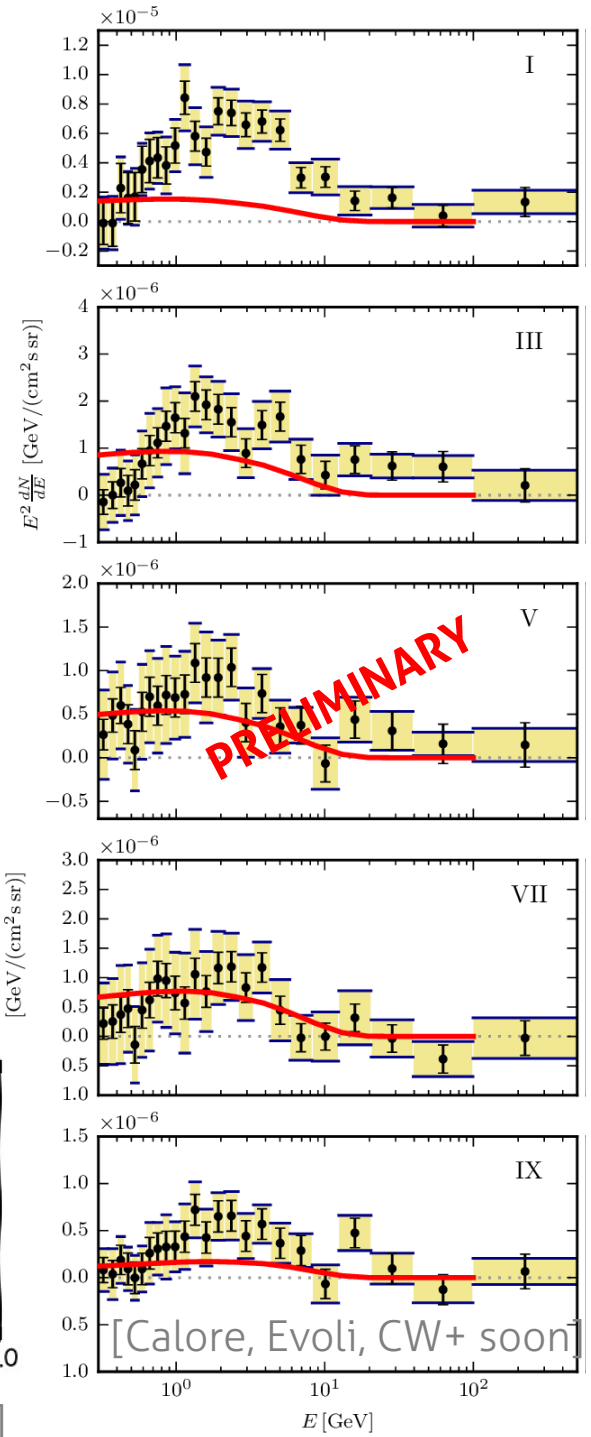
Recent active past of GC

Petrovic+ 2014; Carlson+ 2014
- Hadronic model: Not much target material at 1.5 kpc
- Leptonic model: Likely different morphology or spectrum

Example: Injection of electrons at GC, 1 Myr ago, 2.2 index
- Does not reproduce spectrum at low energies
- Gaussian morphology (underpredicts at few deg and >15 deg away from GC)



[benchmark from Petrovic+ 2014]



[Calore, Evoli, CW+ soon]

Conclusions

Method

- We perform a **subtraction of foreground emission** in the inner Galaxy ROI with the aim of characterizing the diffuse and extended gamma-ray emission from the Galactic bulge region (here 0.3 to 3 kpc from the GC)
- We estimate foreground model uncertainties in two ways:
  1) Theoretical model systematics using **60 extreme Galprop models**
  2) Empirical model systematics from **residual analysis in Galactic disk**
- This enables us to describe the emission from the Galactic bulge region with calibrated systematic errors

Results

- We **robustly confirm** the **existence of a diffuse extended emission** that peaks at 1 to 3 GeV and that exceeds predictions from standard Galprop models in that region by a factor of a few
- The spectrum of this emission is well compatible with a **broken power-law**, spectra from **dark matter annihilation**, or spectra compatible with **MSPs**
- The morphology of the emission is compatible with **spherical symmetry**, the energy spectrum appears to be uniform at 95% CL
- We find a **lower limit on the cutoff radius of 10 degree** (1.5 kpc) at 95% CL

This suggests: DM annihilation, large amount of unresolved point sources, maybe leptonic burst event

Outlook: multi-wavelength, multi-messenger, sub-threshold sources, satellites with better PSFs, dwarfs spheroidals, clusters, IGBG correlations, ...

Thank you