Detection of Extended Gamma-ray Emission from Fornax A and Measurement of the Extragalactic Background Light

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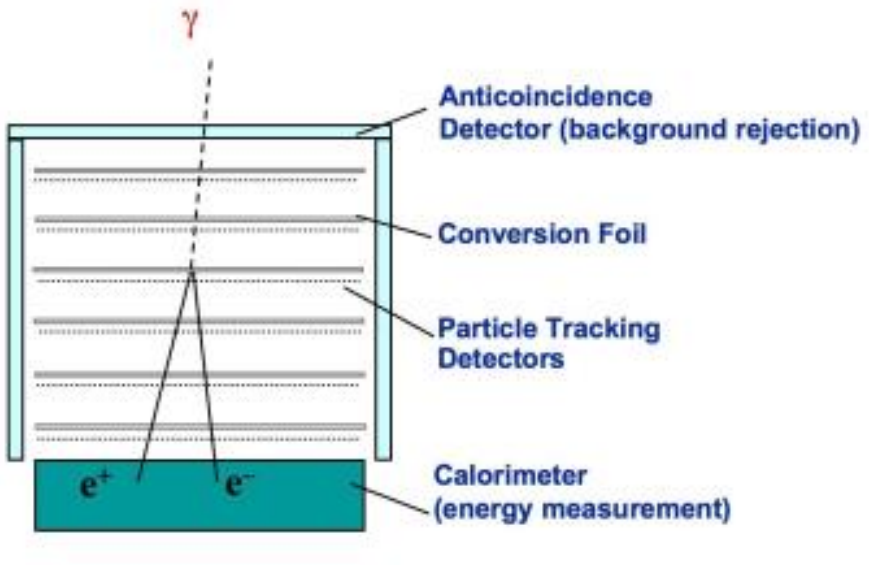
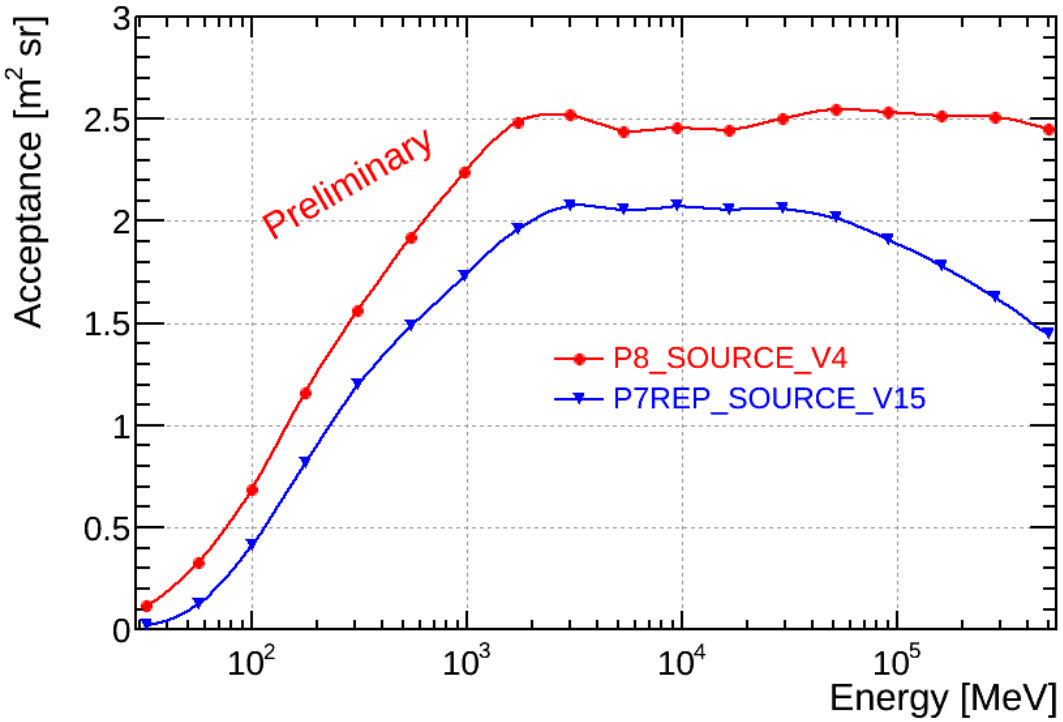
Fermi-LAT (Large Area Telescope)

- Pair production telescope
  - High-Z material converts gamma-rays into electron-positron pairs
- Sensitive to gamma-rays between about 20 MeV and greater than 300 GeV
- Tracker, Calorimeter, and Anti-Coincidence Detector (ACD)



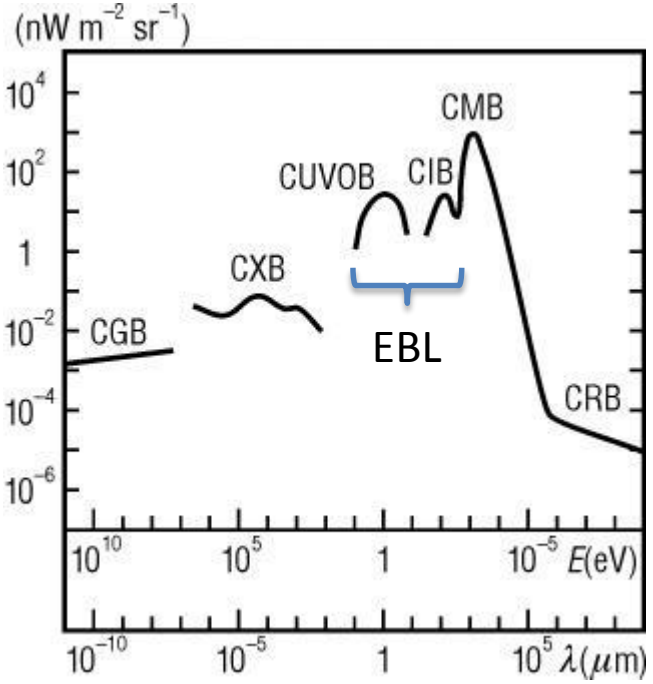
Pass 8

The newest photon event reconstruction to come out of the Fermi-LAT Collaboration (due for public release in about a month)



Extragalactic Background Light (EBL)

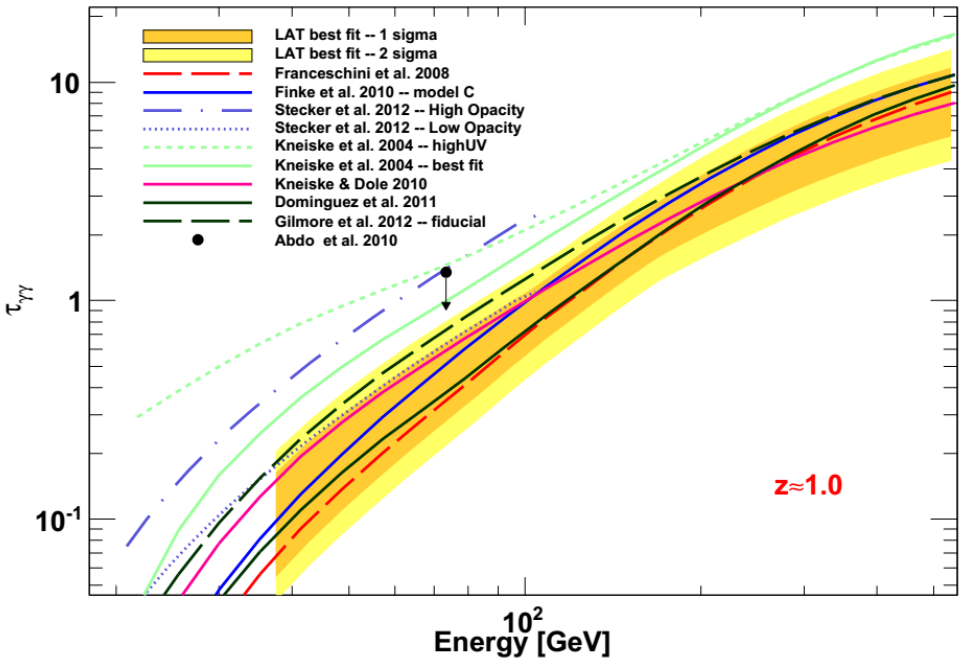
- Accumulated radiation from star formation and active galactic nuclei (AGN)
- ~0.1 – 1000 μm
- Direct measurements are difficult because of zodiacal light, sunlight reflecting off local cosmic dust



"Extragalactic-background-power-density" by pkisscs@konkoly.hu - Own work by the original uploader. Licensed under Public Domain via Wikimedia Commons - http://commons.wikimedia.org/wiki/File:Extragalactic-background-power-density.jpg#/media/File:Extragalactic-background-power-density.jpg

EBL Measurements

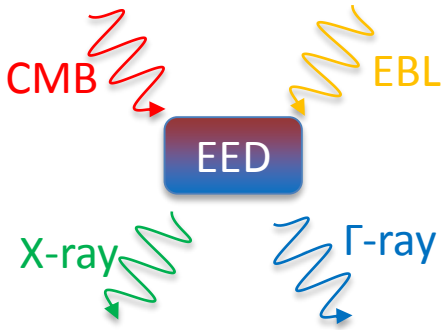
- Lower limits have been calculated using counts of extragalactic sources -- (A&A 515, A19 2010)
- Many people have tried to model the EBL, for example, the Fermi-LAT used spectra from 150 BL Lacs to estimate the EBL using attenuation due to gamma-ray absorption with EBL photons



Science 30 November 2012: **338** (6111), 1190-1192

Measuring the EBL using emission from radio galaxy lobes

- Radio galaxy lobes provide an observable collection of energized electrons
- Cosmic microwave background (CMB) radiation inverse Compton (IC) scatters to X-rays off the electrons



- Since we know the CMB accurately and have good observations in X-ray, we can characterize the electron energy distribution (EED)
- If we assume IC processes and a low enough contamination from other sources of emission, we could measure IC scattered EBL photons and thus get a measurement of the EBL, currently poorly measured

Fornax A

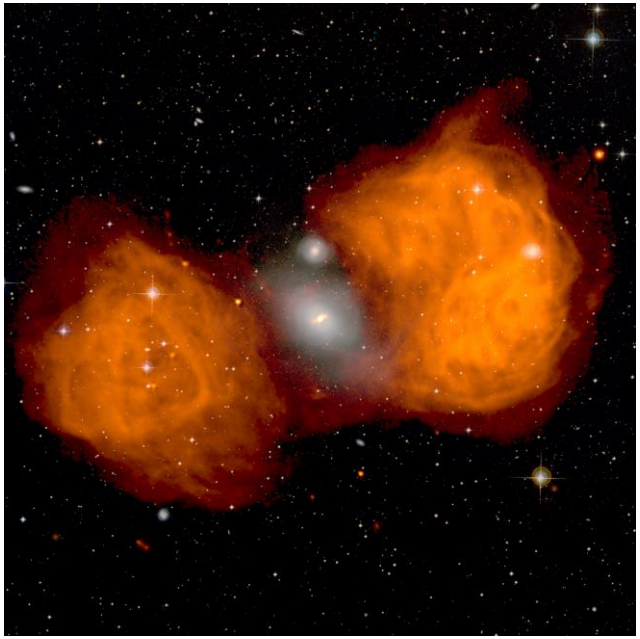
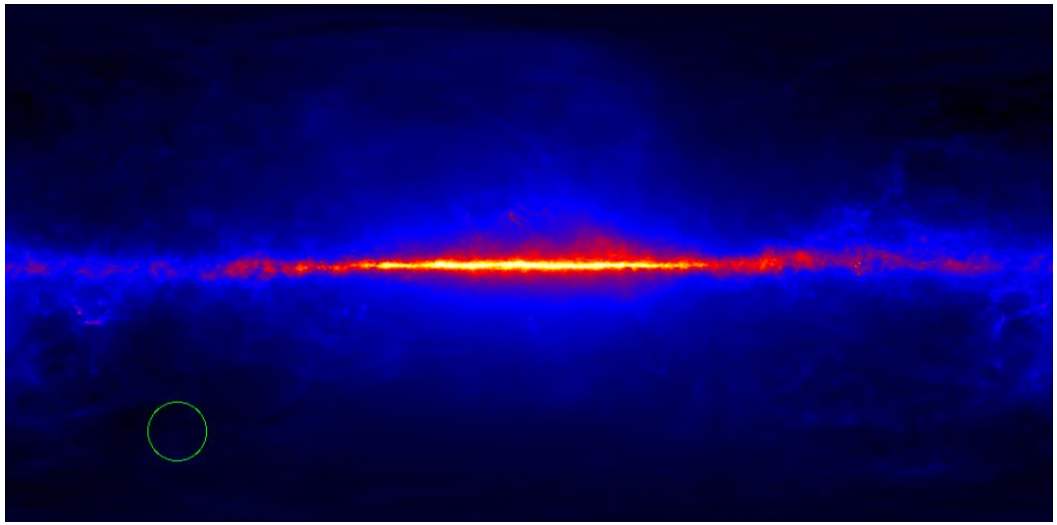


Image courtesy of NRAO/AUI and J. M. Uson

- Radio galaxy (NGC 1316)
- About 1 degree between the galaxy lobes
- z = 0.005871

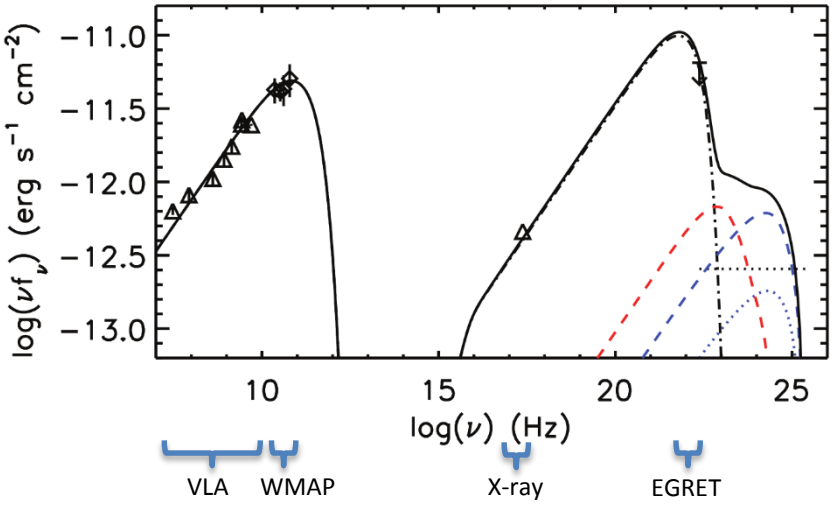
Resides in a quiet region of the gamma-ray sky, (240°, -57°) in galactic coordinates



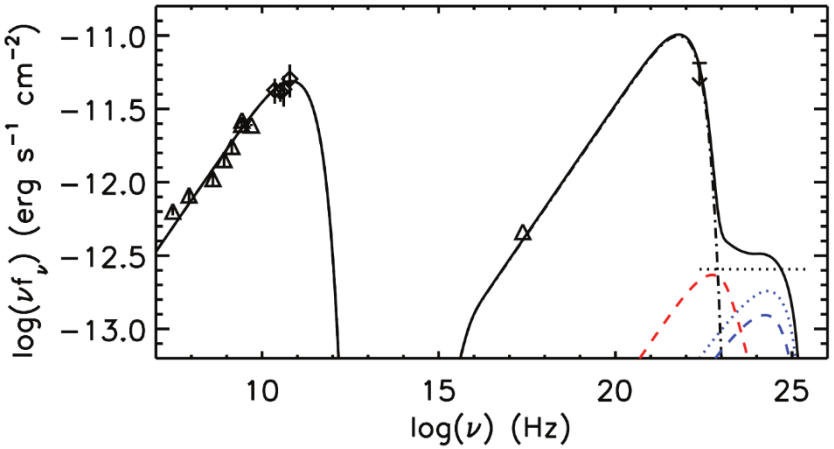
Fornax A as an ideal source

Fornax A has an EED which up-scatters EBL light into the Fermi-LAT detection range

EBL Upper bound



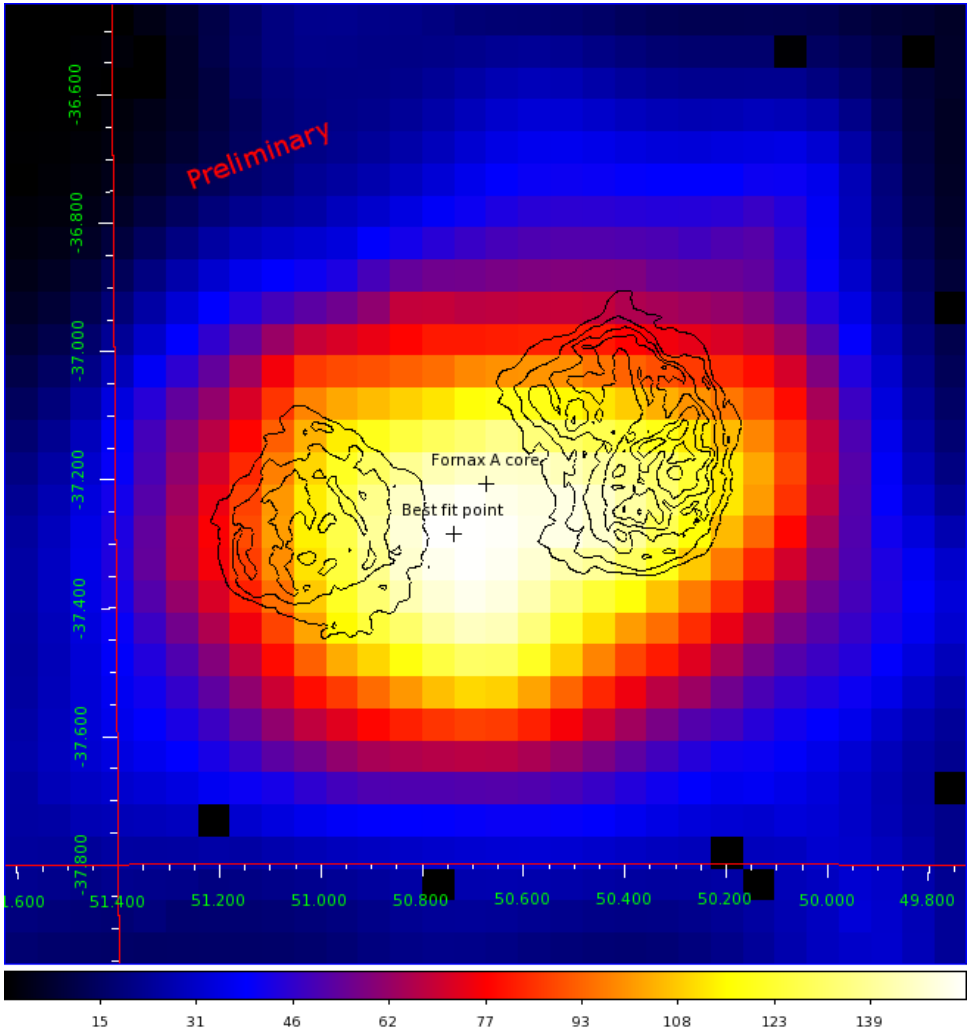
EBL Lower bound



Georganopoulos, M., et al. 2008, ApJ, 686, L5

Model SED
IC due to CMB
IC due to host galaxy optical photons
IC due to CIB
IC due to COB
Fermi LAT sensitivity

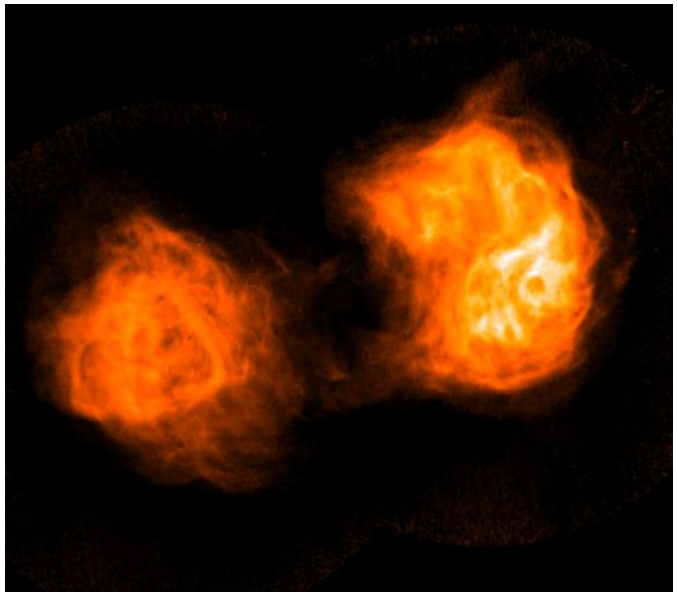
Spatial Extension



- In order to use the gamma-rays to measure the EBL, we need to be sure they are coming from the galaxy lobes
- We are limited by poor angular resolution (PSF between ~5° and 0.2°), so checking for extension is challenging
- ← A point source test statistic (TS) map is made by moving a test point source over every position in the region and checking the likelihood
  - Great method for checking for missing point sources, not really rigorous enough to look for extent
- Better “pure gamma-ray” studies are in the works now, but, if we consider information from other wavelengths…

Detection of Extended Emission

- Used VLA radio data (Fomalont et al. 1989) as a spatial map model of the Fornax A lobes
- Obtained a 6 sigma result that the Pass 8 Fermi LAT data is fit by the extended model better than a point model



Pass 7 ← Same exposure time (73 mo) → Pass 8

Model	TS (relative to point source)
Point	--
Lobes	16.8 (4.1σ)
Point+Lobes	17.2 (4σ, +2 DOF)

Model	TS (relative to point source)
Point	--
Lobes	40.4 (6.3σ)
Point+Lobes	40.4 (6.3σ, +2 DOF)

The point flux converges to zero

Test for Core Contamination

- We are not seeing any photons coming from the core of Fornax A
- To quantify our confidence of this, we used the profile likelihood method to force some photons to a point source at the core location and watch how much the likelihood changes

Significance			
	Lobes flux (E>100 MeV)	Point flux (E>100 MeV)	Percent change of lobes flux
1σ	4.98e-9	9.31e-10	-22%
2σ	3.43e-9	2.35e-9	-46%
3σ	2.05e-9	3.74e-9	-68%

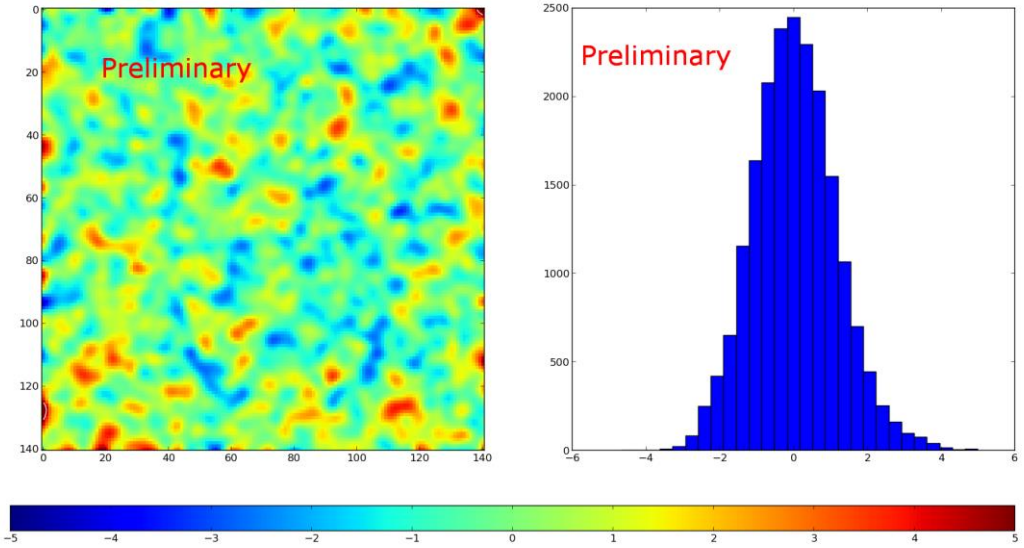
All flux in units ($ph/cm^2/s$)

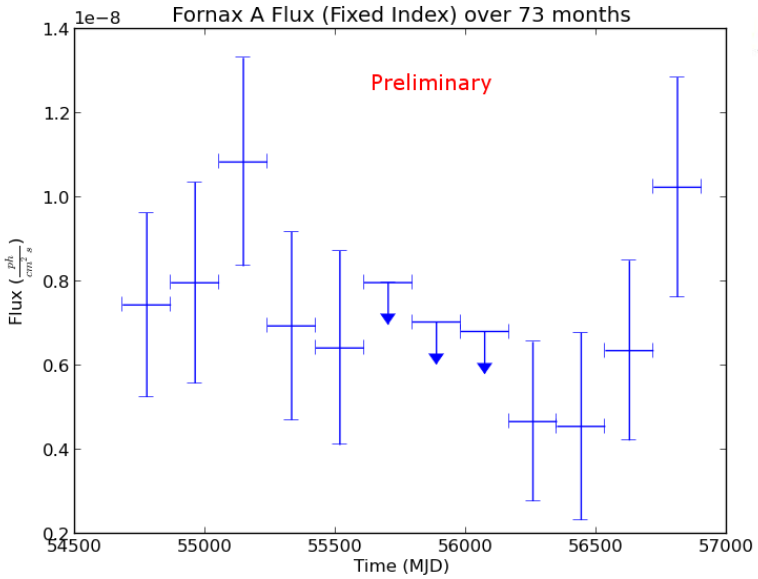
This means, for example, that we are confident at the 2 sigma level that the Fornax A lobes flux is, at lowest, 46% lower when we consider core contamination.

More Tests

Check the region for any missing background sources with a residual significance map

→ The model looks good





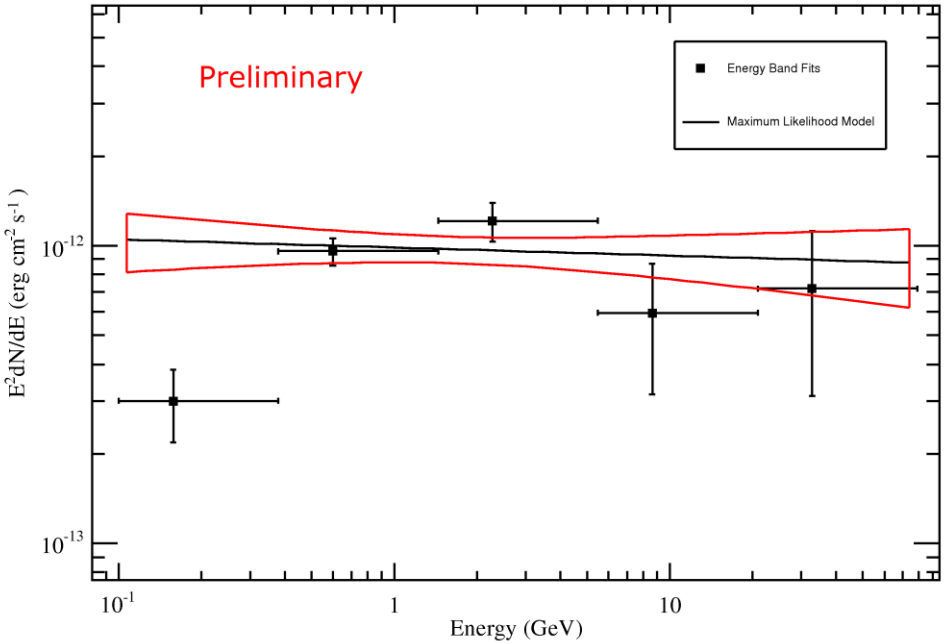
Check for fluctuations in the source over time with a light curve

→ Fornax A is not variable

(only 1.25σ significance for variability)

Spectrum

Model	TS (relative to power law)
Power Law	--
Log Parabola	4.7 (+ 1 DOF)
Broken Power Law	5.7 (+ 2 DOF)
Broken Power Law with Exponential Cutoff	2.4 (+ 4 DOF)



None of these models are statistically better than the power law.

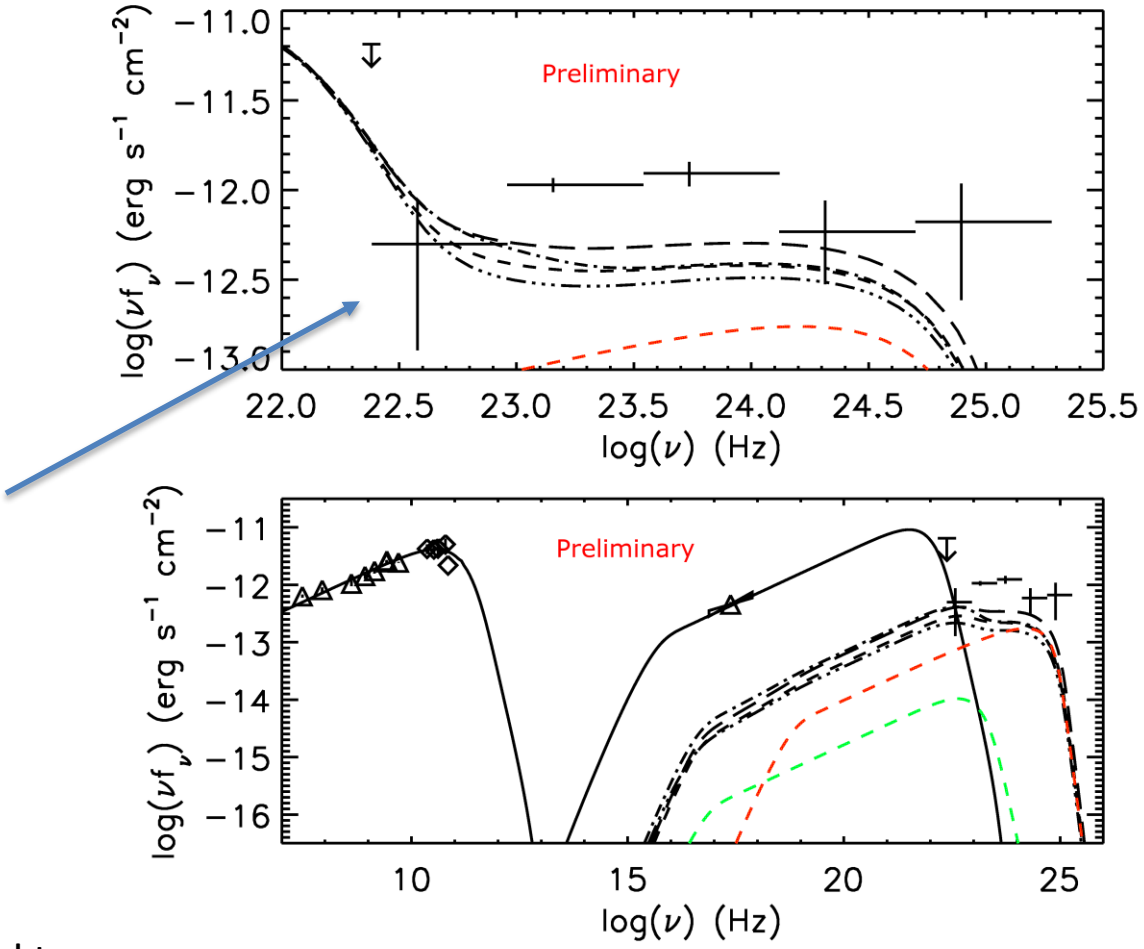
The maximum likelihood model above is a power law: $\frac{dN}{dE} = N_0 \left(\frac{E}{E_0}\right)^{\gamma}$

$N_0 = 6.16$ $E_0 = 1$ GeV

$\gamma = -2.03$

Multiwavelength Spectrum

One interesting feature of this Fermi-LAT SED is the lowest energy bin, which is sinking down rather than up. The model there comes from the very well-resolved CMB level.



We think this can only be explained two ways:

1. The EBL is higher than expected, more in line with the original Stecker model, which is in conflict with recent measurements
2. There are potentially hadronic processes contributing

Conclusions

- Extended gamma-ray emission from Fornax A has been detected at high confidence (6 sigma)
- Lower limits placed on the lobe emission considering contamination from the core (-46% at 2 sigma confidence)
- We see that either the EBL is higher than expected, or there are hadronic processes at play

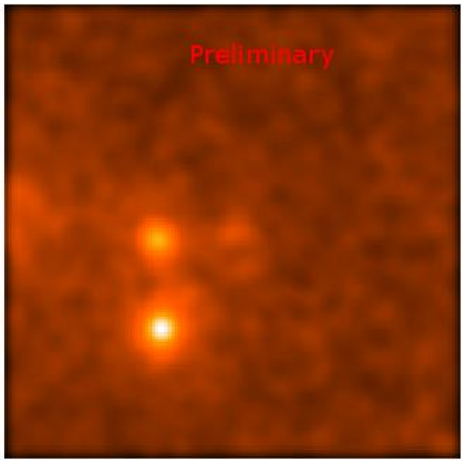
Future Plans

- More tests on the extension, particularly ones without prior assumptions of the morphology
- Further work on the EBL modeling
- Analysis at lower energies than 100 MeV

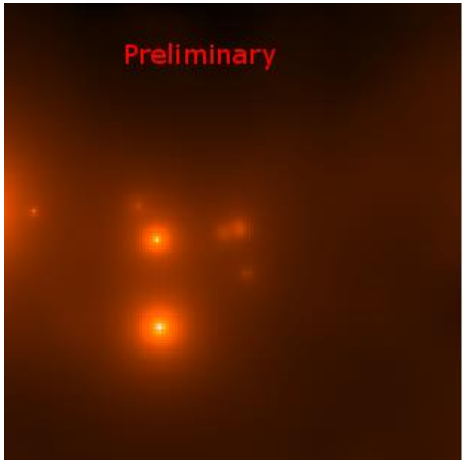
Supplementary Slides

Analysis Details

Data set	Pass 8 “Jean’s Monthly FT1 files”, P302
(RA, DEC) J2000	50.673825, -37.208227
Time range (MET)	239557417 – 431481603 (August 4, 2008 – September 4, 2014) (73 mo)
Radius of ROI	10 degrees
Energy range	100 MeV – 300 GeV
Maximum zenith	100 degrees
Event class	128 (Source)
Science Tools	v09-35-01
IRFs	P8_SOURCE_V5
gtmktime filter	DATA_QUAL == 1 && LAT_CONFIG == 1
diffuse sources	template_4years_P8_V2_scaled.fits isotropic_source_4years_P8V3.txt
PSC	3FGL (v 2.1)



Counts map



Model map

- The point source fit converged with 6 background point sources (1 not in the catalog)
- Fornax A detected as a point source with a TS of 165 with a power law spectrum
- Index: -2.03 +/- 0.07
- Flux (>100 MeV): (6.4 +/- 1.1)e-9 ph/cm^2/s

Systematics Tested

- Earth limb contamination
  - There doesn't seem to be any
- Front/Back separated analysis
  - Individually they look normal, but not sure why the fit changes slightly with explicit summed likelihood
- A_{eff} systematics (bracketing IRFs)
  - Flux (> 100 MeV): (6.363 +0.085 -0.101)e-9
  - Index: (-2.026 +0.033 -0.034)

More Studies To Do

- Scaling the Interstellar Emission Model (IEM)
- Use the Pass 8 PSF classes in summed likelihood
- Look at divided EDISP classes

Earth Limb Contamination

Zenith angle cut	TS	Flux (ph/cm^2/s)	Index (-1)
100 degrees	165	6.4e-9 +/- 1.1e-9	2.03 +/- 0.07
80 degrees	123	6.2e-9 +/- 1.2e-9	2.04 +/- 0.08
65 degrees	73	5.6e-9 +/- 1.4e-9	1.98 +/- 0.11

Even using extreme cuts on the zenith angle, the resulting flux and spectral index do not change. So, there is no significant earth limb contamination.

Front/Back Likelihood

	TS	Flux (e-9) (ph/cm^2/s)	Prefactor (e-13)	Index (-1)
Normal analysis	165	6.4 +/- 1.1	6.16 +/- 0.67	2.03 +/- 0.07
Front	109	6.5 +/- 1.2	6.00 +/- 0.77	2.06 +/- 0.09
Back	63	6.2 +/- 0.5	6.40 +/- 0.38	1.98 +/- 0.04
Front + Back (Explicit Summed Likelihood)	170	6.3 +/- 1.0	6.08 +/- 0.64	2.02 +/- 0.07

- The fit does not change when using only front or back
- Not sure why the explicit summed likelihood isn't exactly the same as the normal analysis

Model Map with Labels