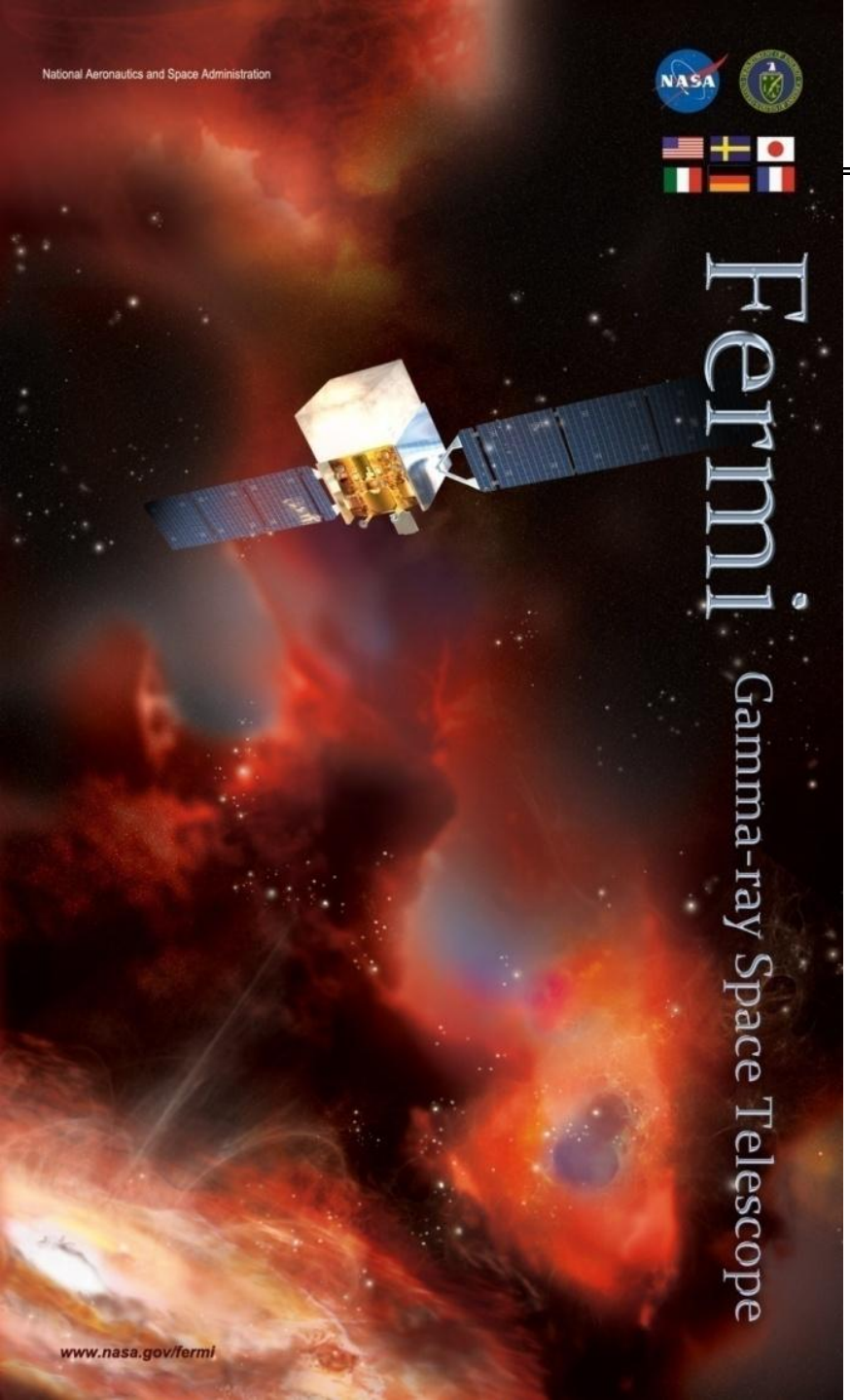


GeV Observations of Star-forming Galaxies with the *Fermi* LAT

Marco Ajello and **Keith Bechtol**
for the ***Fermi*** **LAT Collaboration**

219th AAS Meeting

10 January 2012

SLAC NATIONAL ACCELERATOR LABORATORY

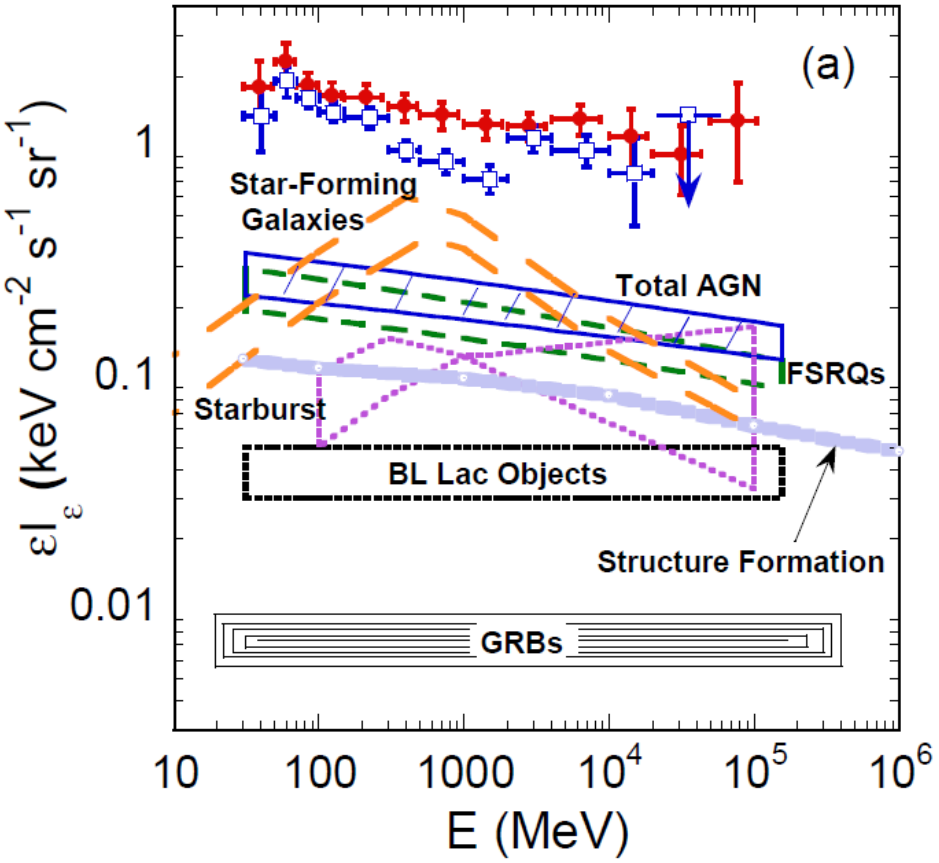
KIPAC

Key Science Questions

Origin and transport of cosmic rays (nuclei + electrons/positrons)

Hubble view towards the nuclear starburst of M82

"Guaranteed" contribution of unresolved galaxies to extragalactic diffuse gamma-ray background

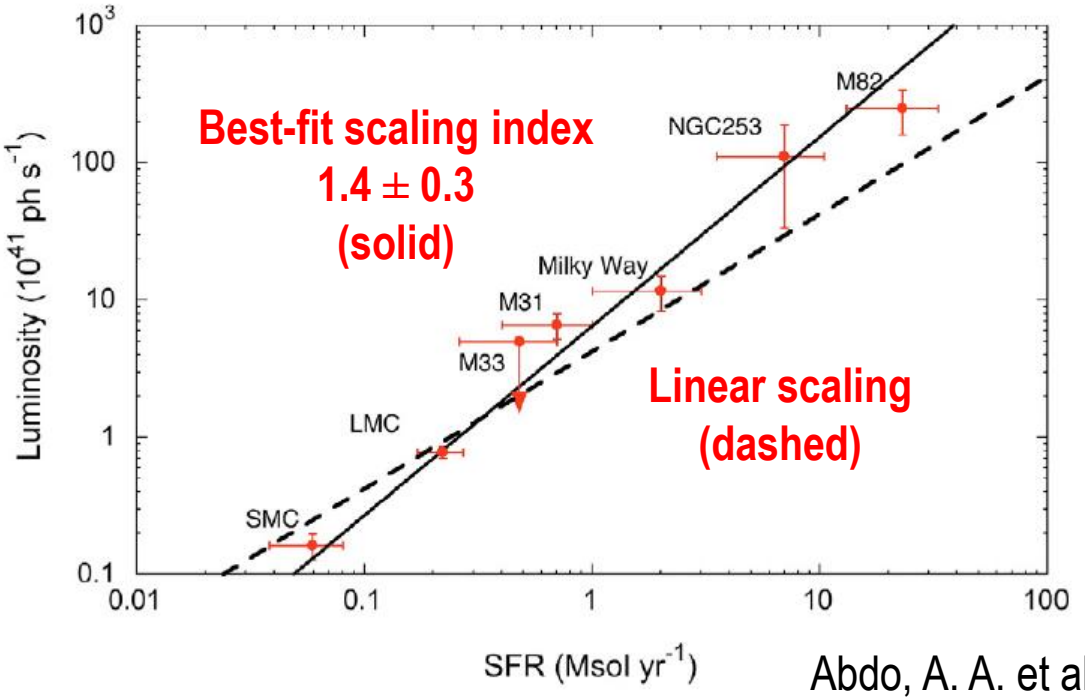


Pavlidou & Fields 2002, reviewed by Dermer 2007

Context of Current Work

- *CGRO* EGRET era (before 2008)
  - Large Magellanic Cloud the only external galaxy detected in gamma rays
- *Fermi* LAT + Imaging Air-Cherenkov Telescopes
  - GeV and TeV detection of archetypal starburst galaxies M82 and NGC 253
  - GeV detection of quiescent Local Group galaxies M31, SMC

Gamma-ray Luminosity (> 0.1 GeV)



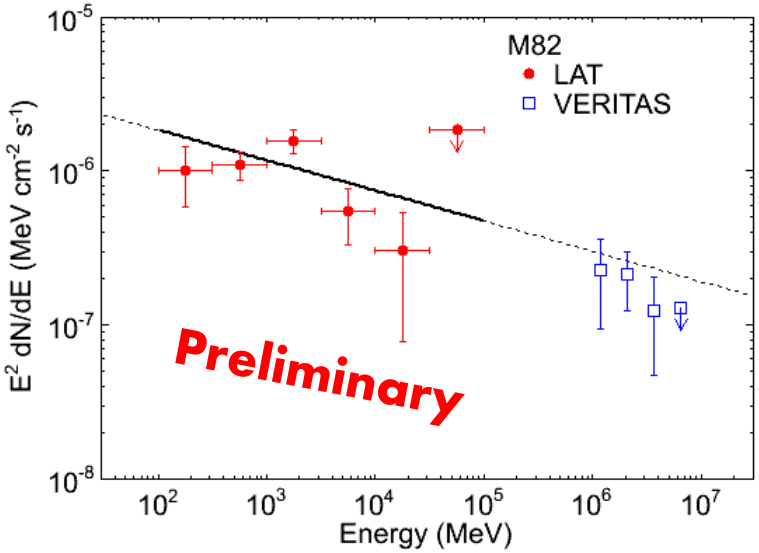
Fitting with Local Group galaxies only

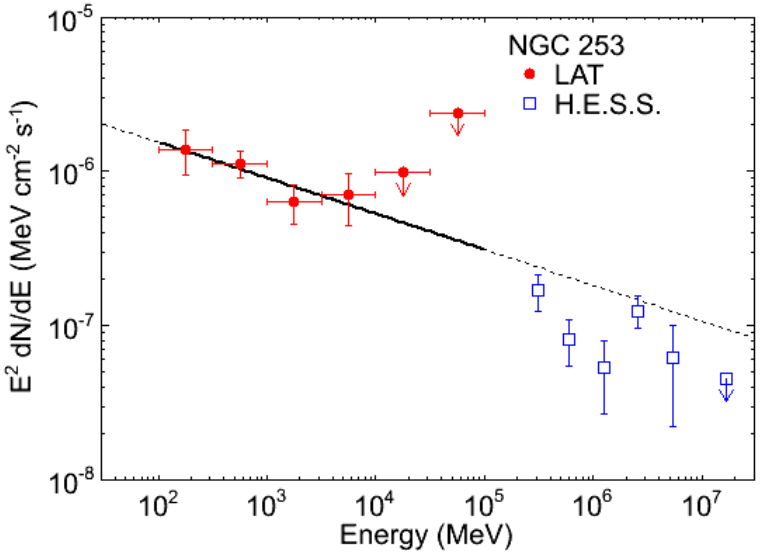
Abdo, A. A. et al. 2010, A&A, 523, L2

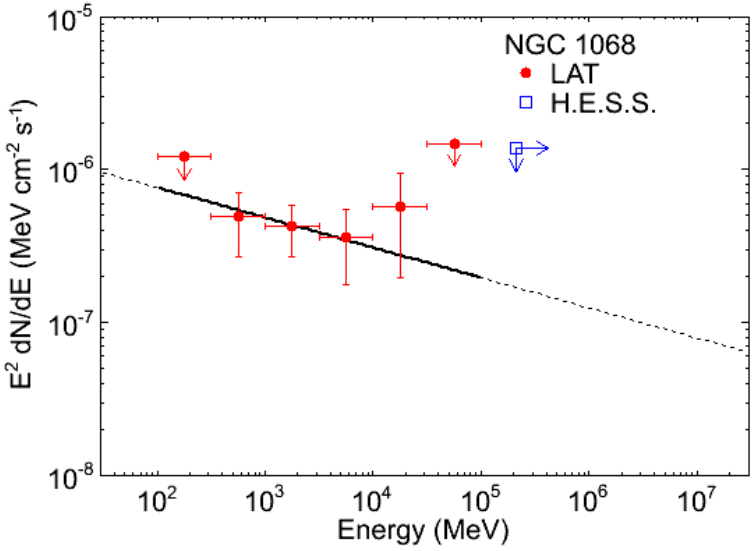
"Population Study"

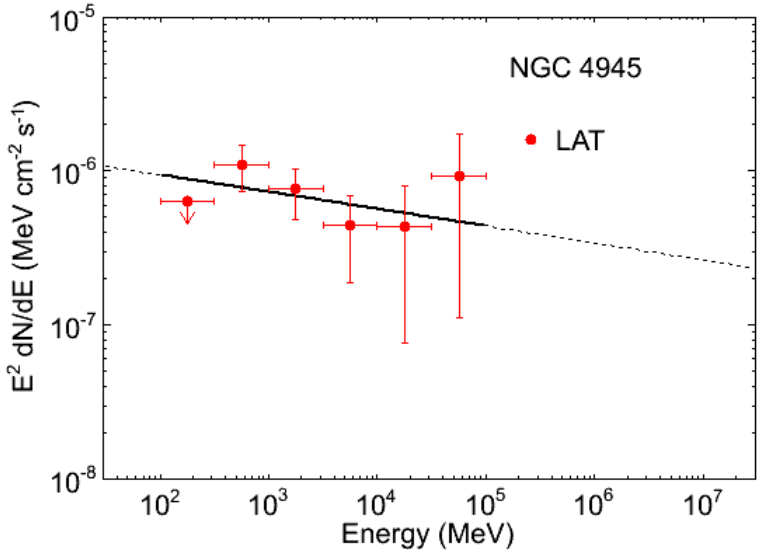
- Selected for IR brightness and dense molecular gas content
  - Molecular gas as fuel for star formation, traced by HCN (J=0-1) line emission (Gao & Solomon 2004)
- Galaxy sample (69 total)
  - 64 galaxies beyond Local Group
  - Combine with 5 previously studied Local Group galaxies
- *Fermi* LAT observations
  - 36 months
  - 0.1 – 100 GeV
  - 4 significant detections of starburst galaxies
- Identify galaxies hosting AGN as those detected by *Swift* BAT (14 – 195 keV)

SEDs of LAT-detected Starbursts

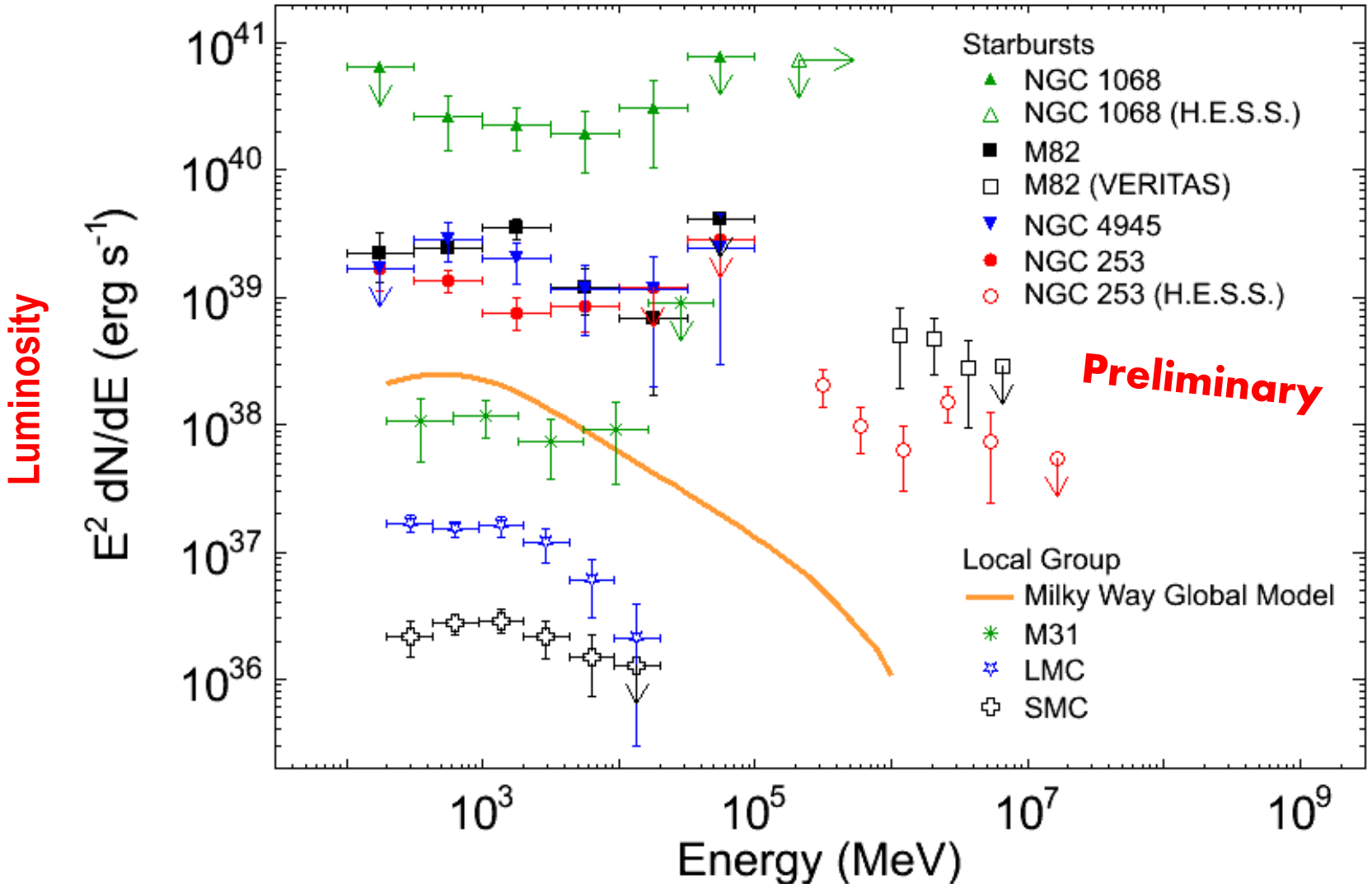






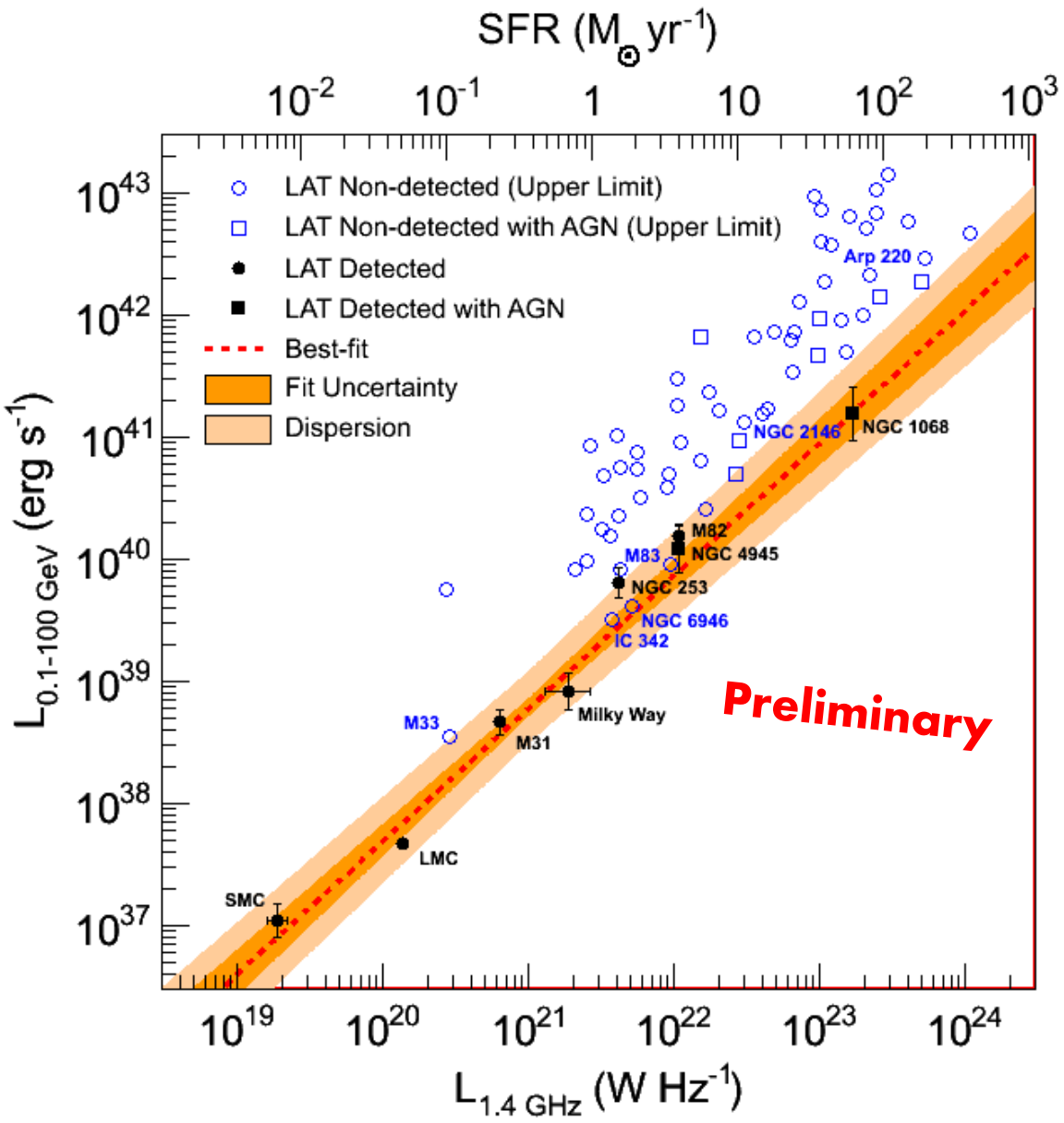


Comparative SEDs



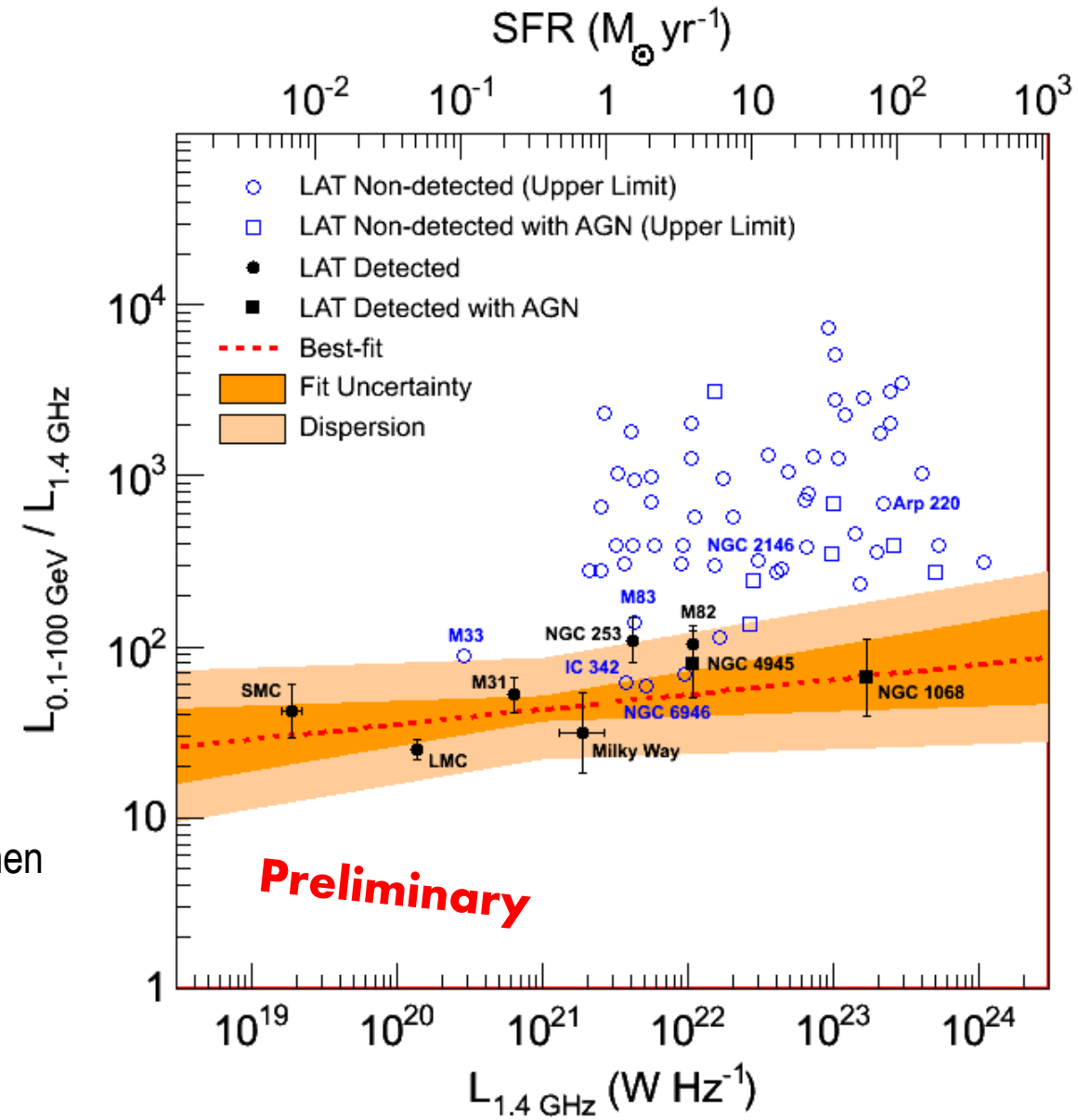
Multiwavelength Relations

Gamma-ray vs radio continuum luminosity



Multiwavelength Relations

Gamma-ray vs radio continuum luminosity ratio



Scaling index 1.10 ± 0.05
Scatter = 0.2 dex
(does not significantly change when removing galaxies with AGN)

Multiwavelength Relations

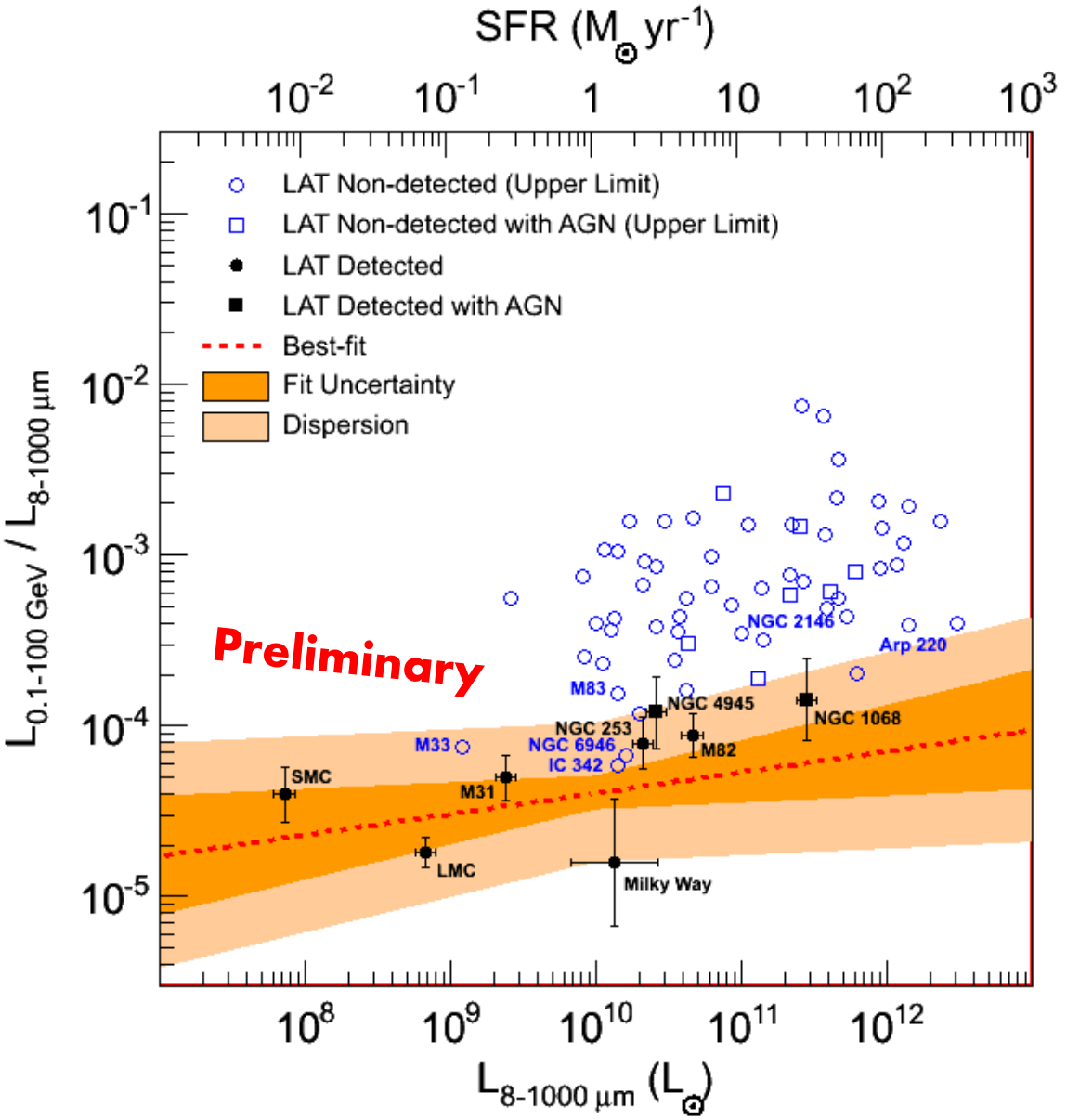
Gamma-ray vs total IR (8-1000μm) luminosity ratio

Ratio of energy output between wavebands

Scaling index 1.16 ± 0.07
Scatter = 0.3 dex

Removing galaxies with AGN
Scaling index 1.08 ± 0.10
Scatter = 0.3 dex

Not surprising given empirical correlation between IR and radio continuum luminosity



Correlation Significance

- Kendall τ coefficient (non-parametric, rank correlation test)
  - Generalized to include upper limits
- Compare coefficients of actual data and *observable* permutations

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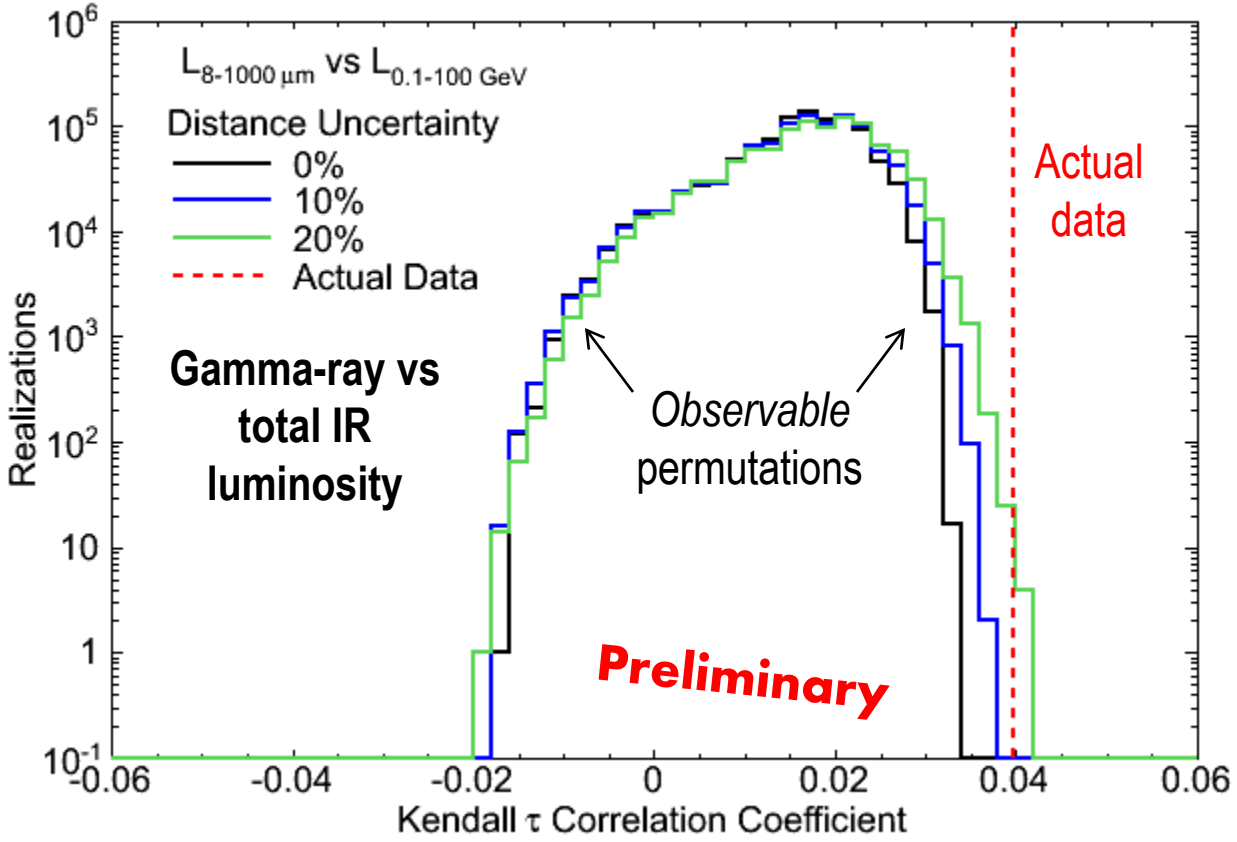
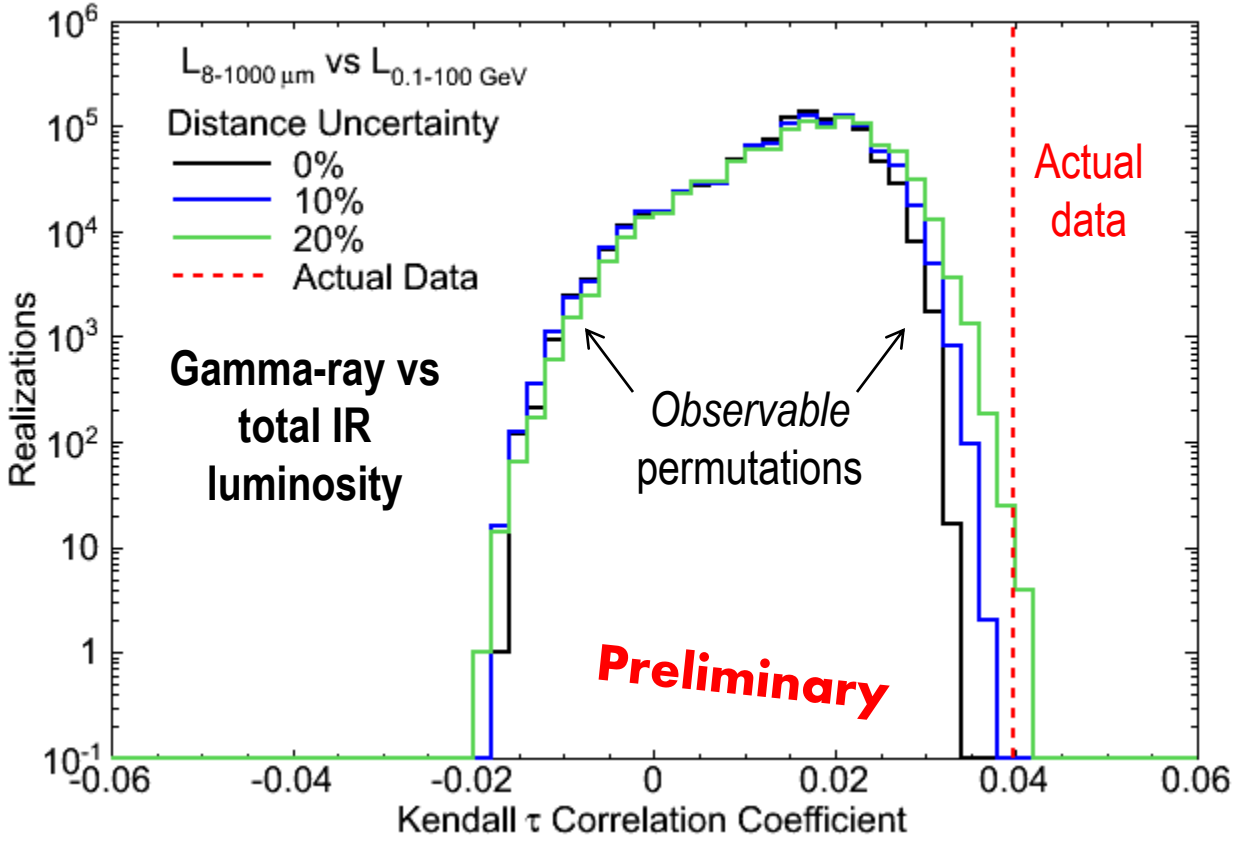


Correlation Significance

- Kendall τ coefficient (non-parametric, rank correlation test)
  - Generalized to include upper limits
- Compare coefficients of actual data and *observable* permutations

Correlation P-values of $< 10^{-5}$ considering all galaxies, $\sim 10^{-3}$ after excluding *Swift* BAT detected AGN (including NGC 1068 and NGC 4945)

Assume 20% distance uncertainty

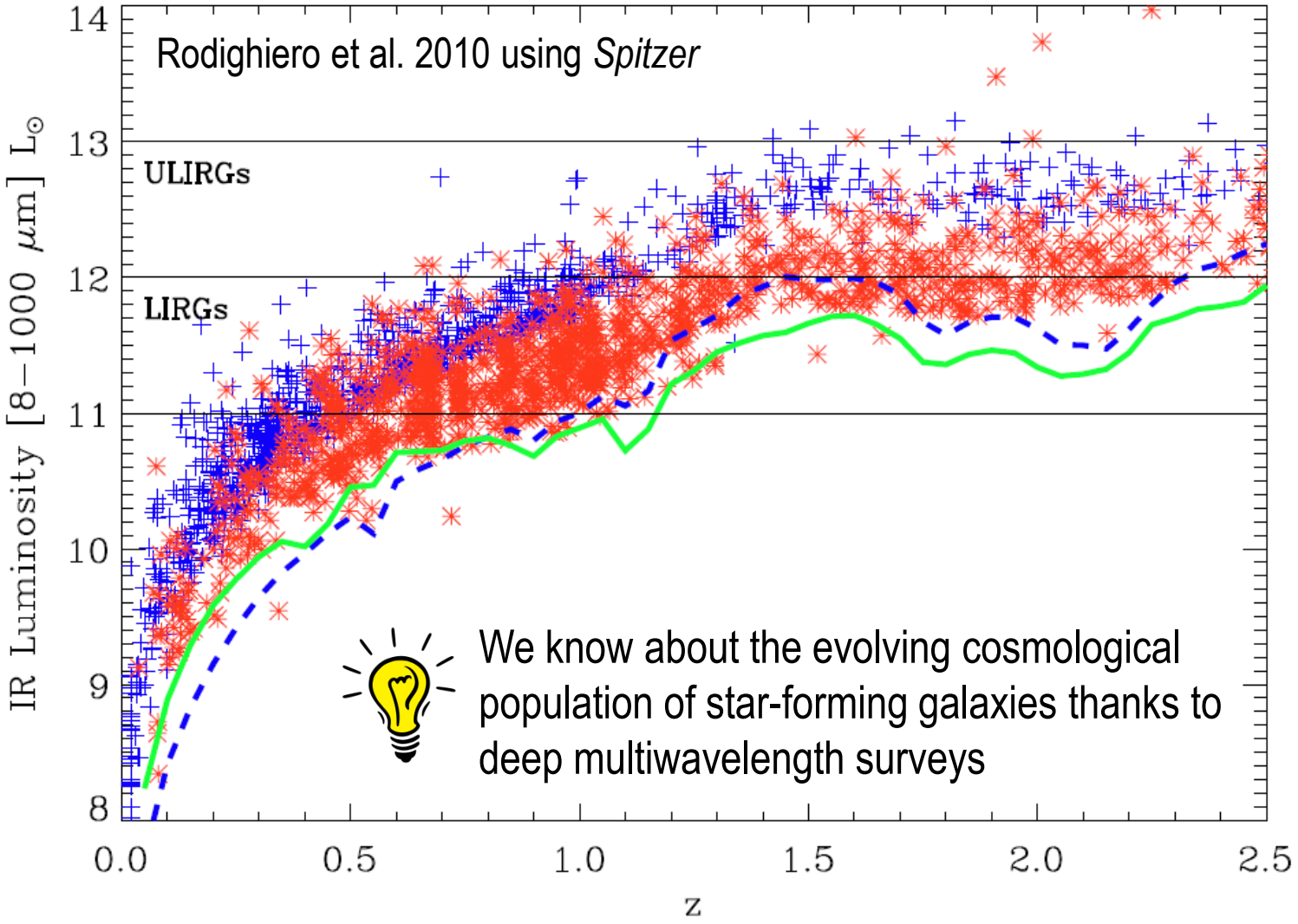


Physics of Cosmic Rays

- Gamma-ray luminosity scales almost linearly with photometric estimates of the current SFR (total IR, radio continuum luminosity)
  - Covers at least 3 orders of magnitude ⇨ suggests CR luminosity related to short-lived massive stars

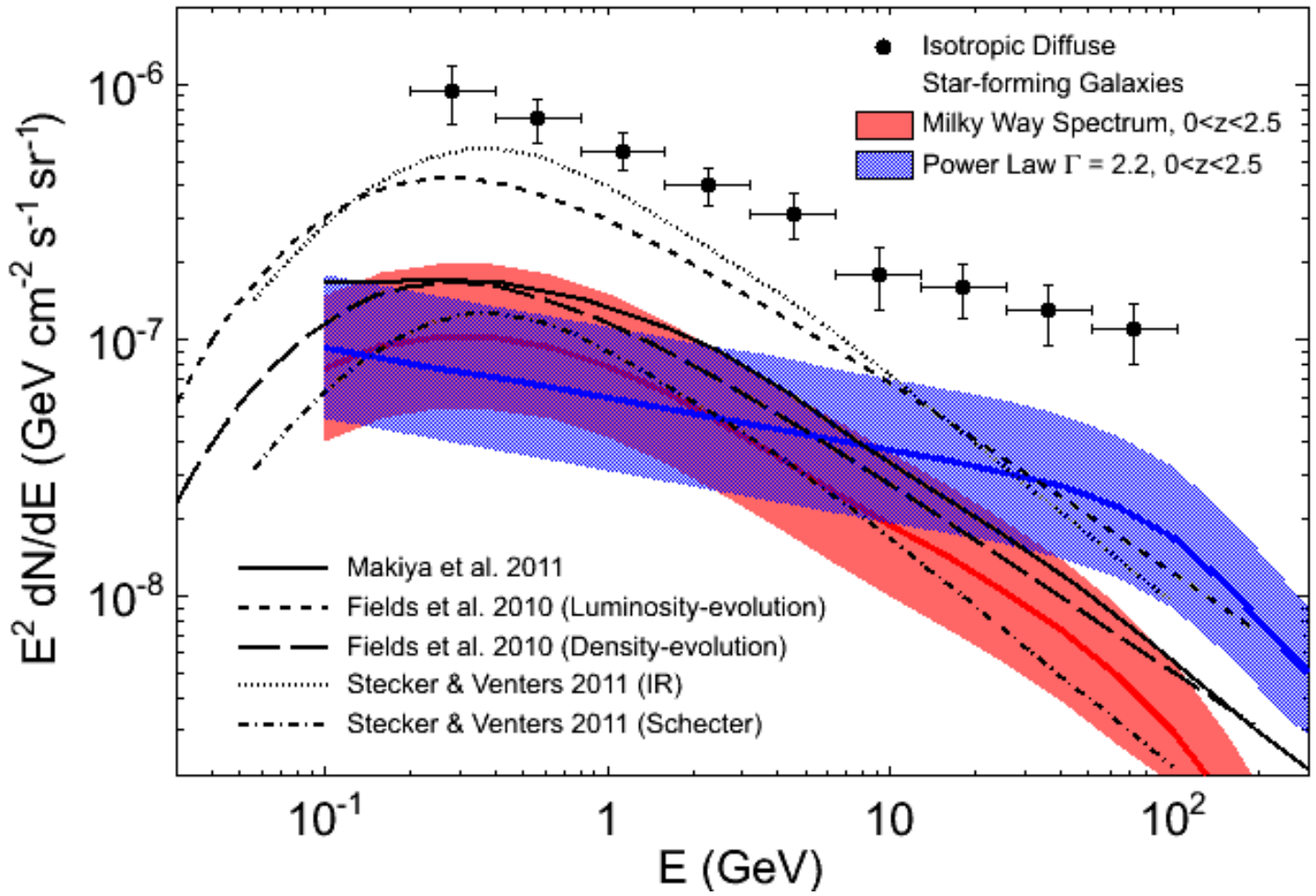
- Normalization of scaling relation provides constraint on product of **cosmic-ray luminosity** and **efficiency** of converting cosmic-ray energy to gamma rays
  - Check paradigm that SNRs are primary accelerators of cosmic rays in galaxies (interpreting gamma-rays as mostly hadronic in origin)

Contribution to Isotropic Diffuse



Assume that the scaling relations are redshift -independent

Contribution to Isotropic Diffuse



Consider two spectral models to bracket uncertainty

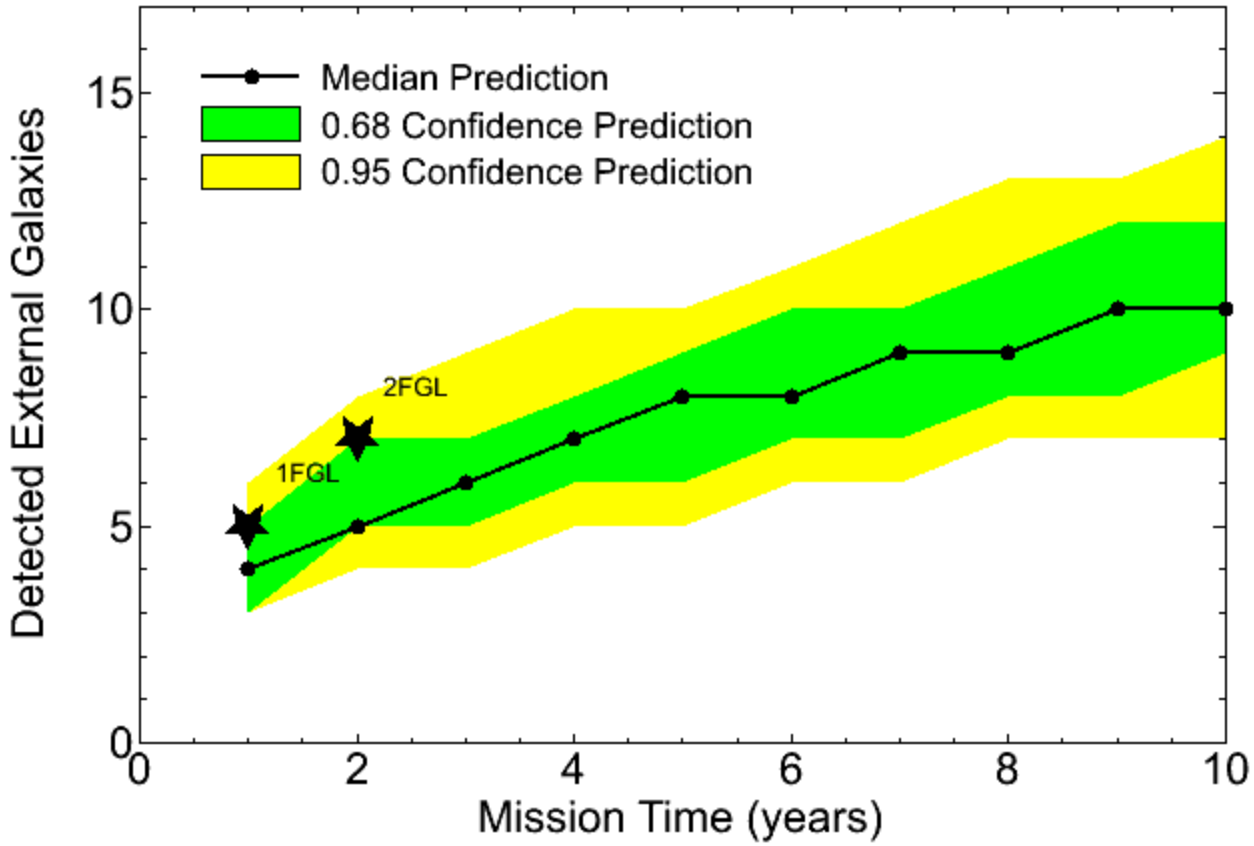
Shaded bands represent uncertainty in scaling relation parameters

EBL absorption Franceschini et al. 2008

Unresolved star-forming galaxies contribute 4-23% of isotropic diffuse component flux 0.1 – 100 GeV

Anticipated LAT detections

- Scaling relation between gamma-ray and total IR luminosity (including dispersion ⇨ probabilistic)
- Assume point-source, power law spectrum with index 2.2



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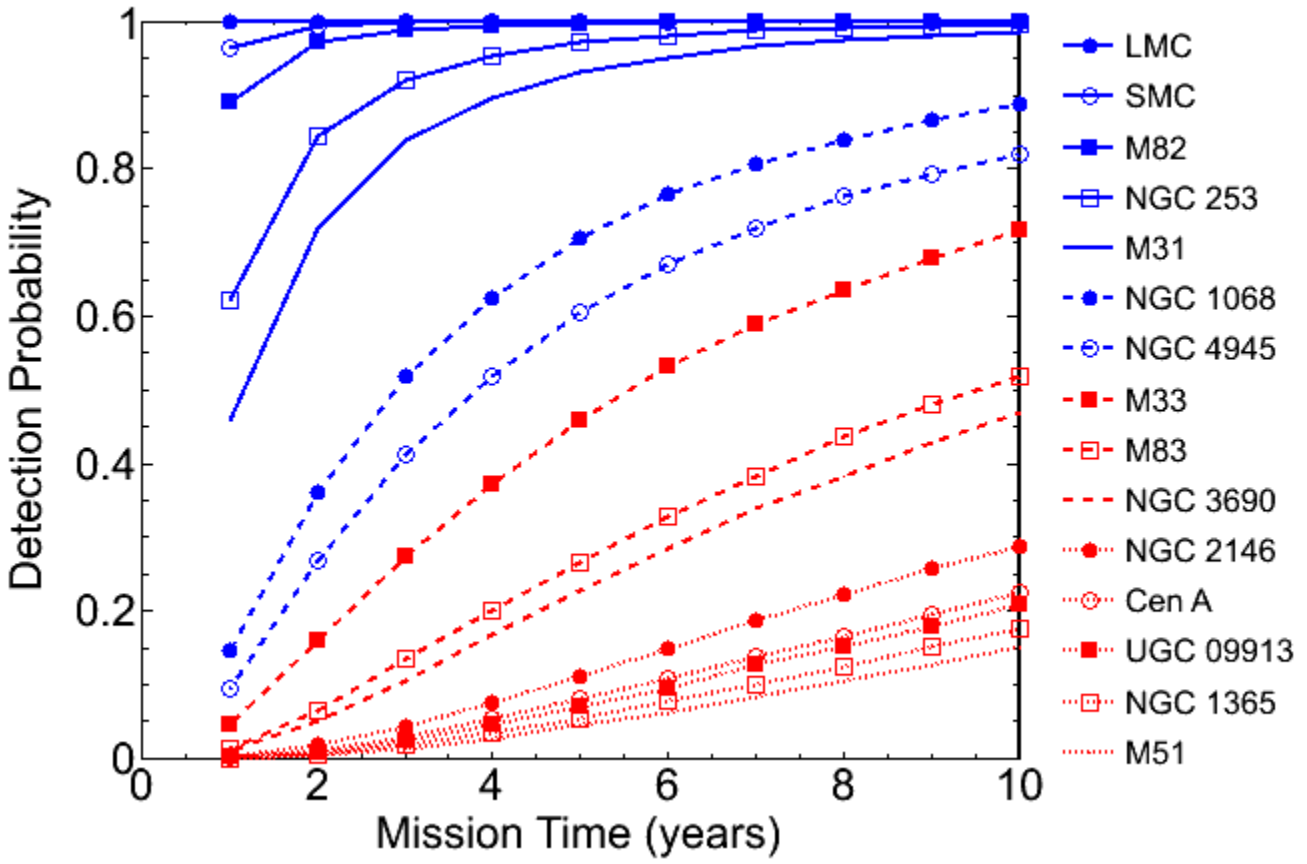


LAT-detected

Not LAT-detected

Cen A ⇨ AGN

Take-away Points

1. Gamma-ray “population studies” of galaxies now possible

2. Confirm quasilinear scaling relation between gamma-ray luminosity and photometric tracers of SFR

3. Unresolved star-forming galaxies contribute 4-23% of isotropic diffuse component flux 0.1 – 100 GeV

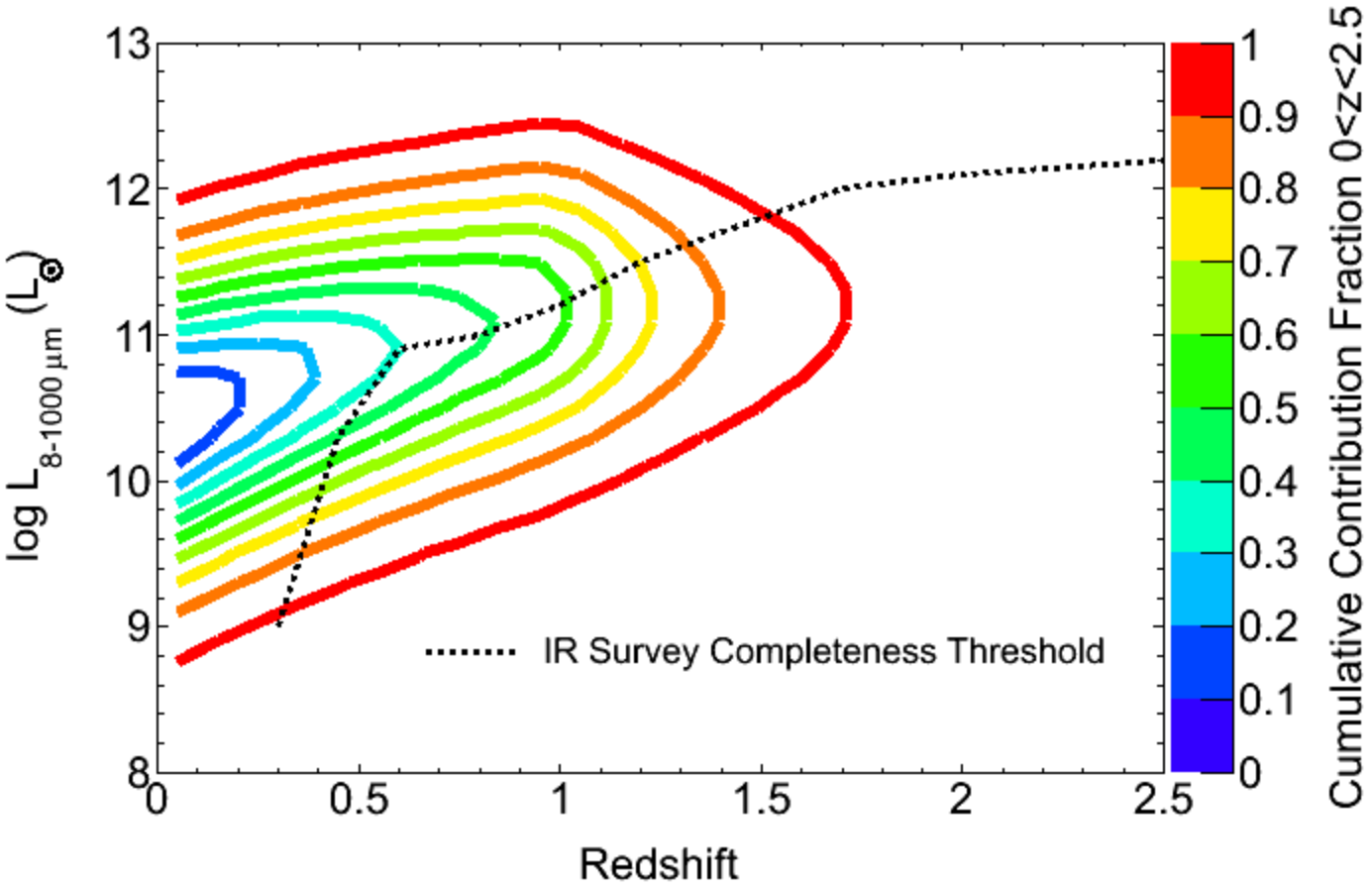
4. Scaling relation would predict roughly 10 external galaxies to be detected during 10-year *Fermi* mission

Fermi Gamma-ray Space Telescope

Extras / Back-ups

Contribution to Isotropic Diffuse

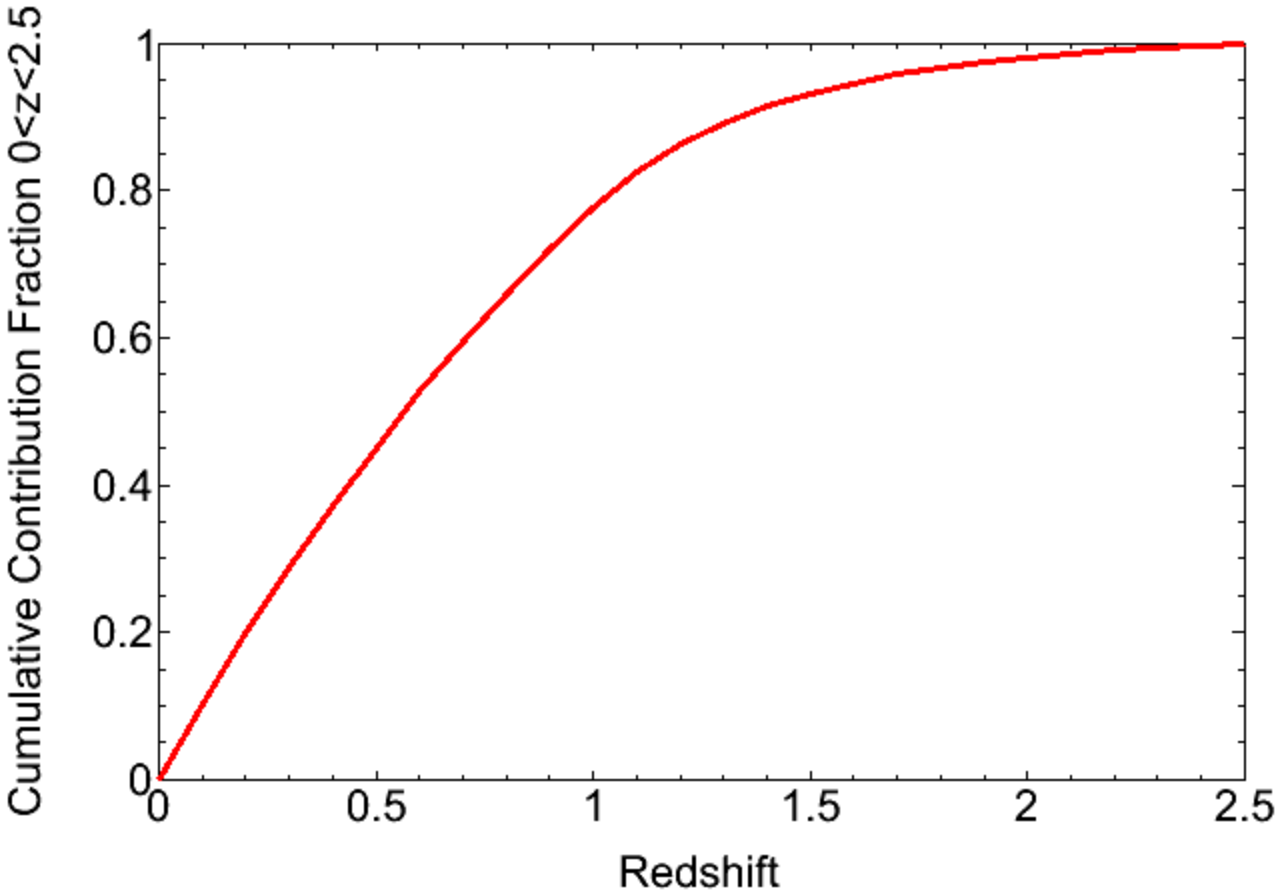
Fraction compared to total contribution 0 < z < 2.5



Largest contribution from analogs of Milky Way / M31 and startbursts similar to M82 / NGC 253

Contribution to Isotropic Diffuse

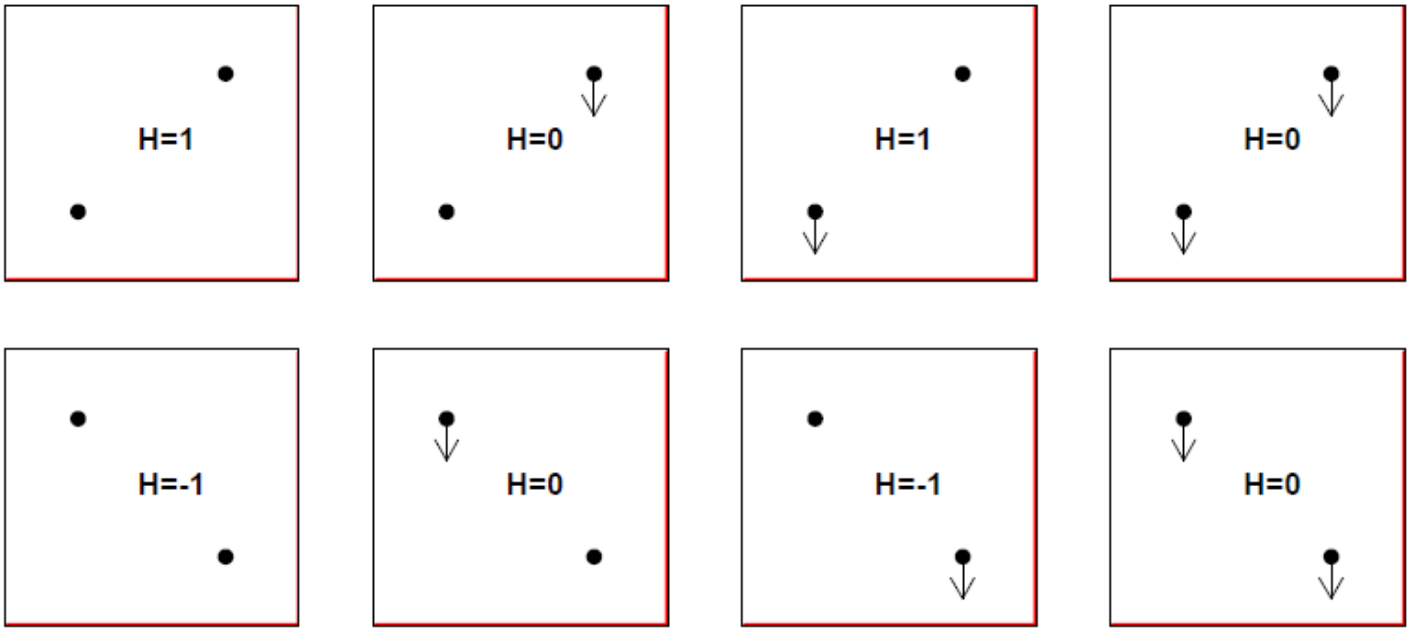
Fraction compared to total contribution 0 < z < 2.5



Contribution from galaxies with z > 1.5 rapidly diminishing

Kendall τ correlation test details

- τ coefficient is sum of rank values ("*H*") over all pairs of points
  - τ=1 corresponds to monotonically increasing data with no upper limits

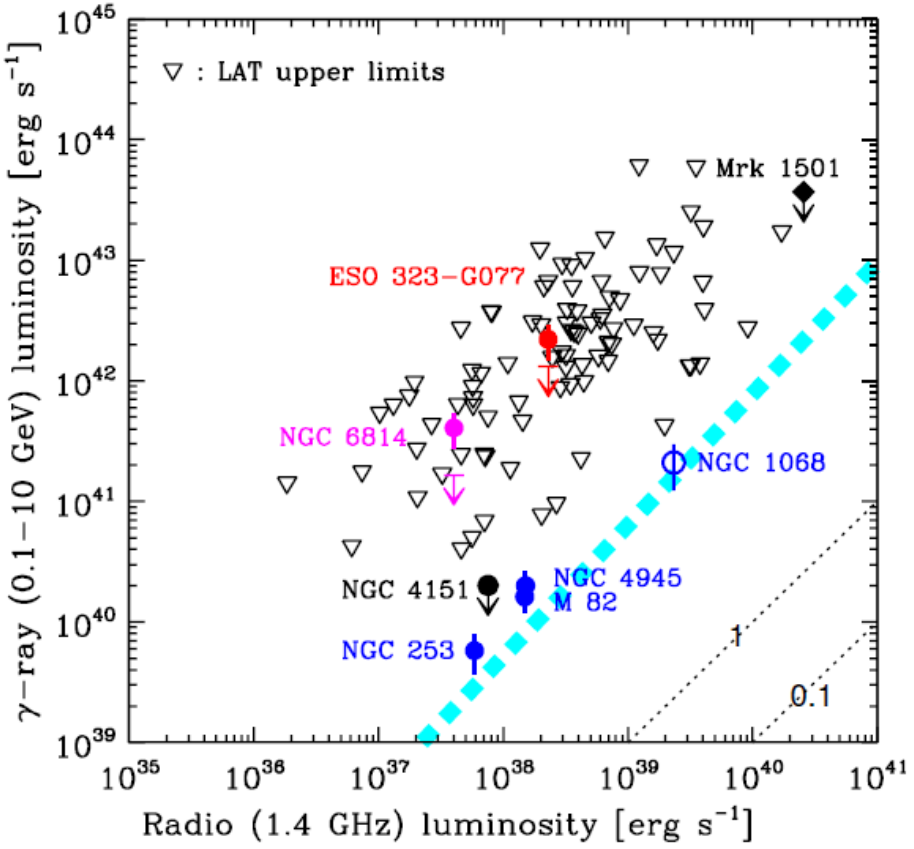


Test can be generalized to include upper limits

X-ray selected radio-quiet Seyferts

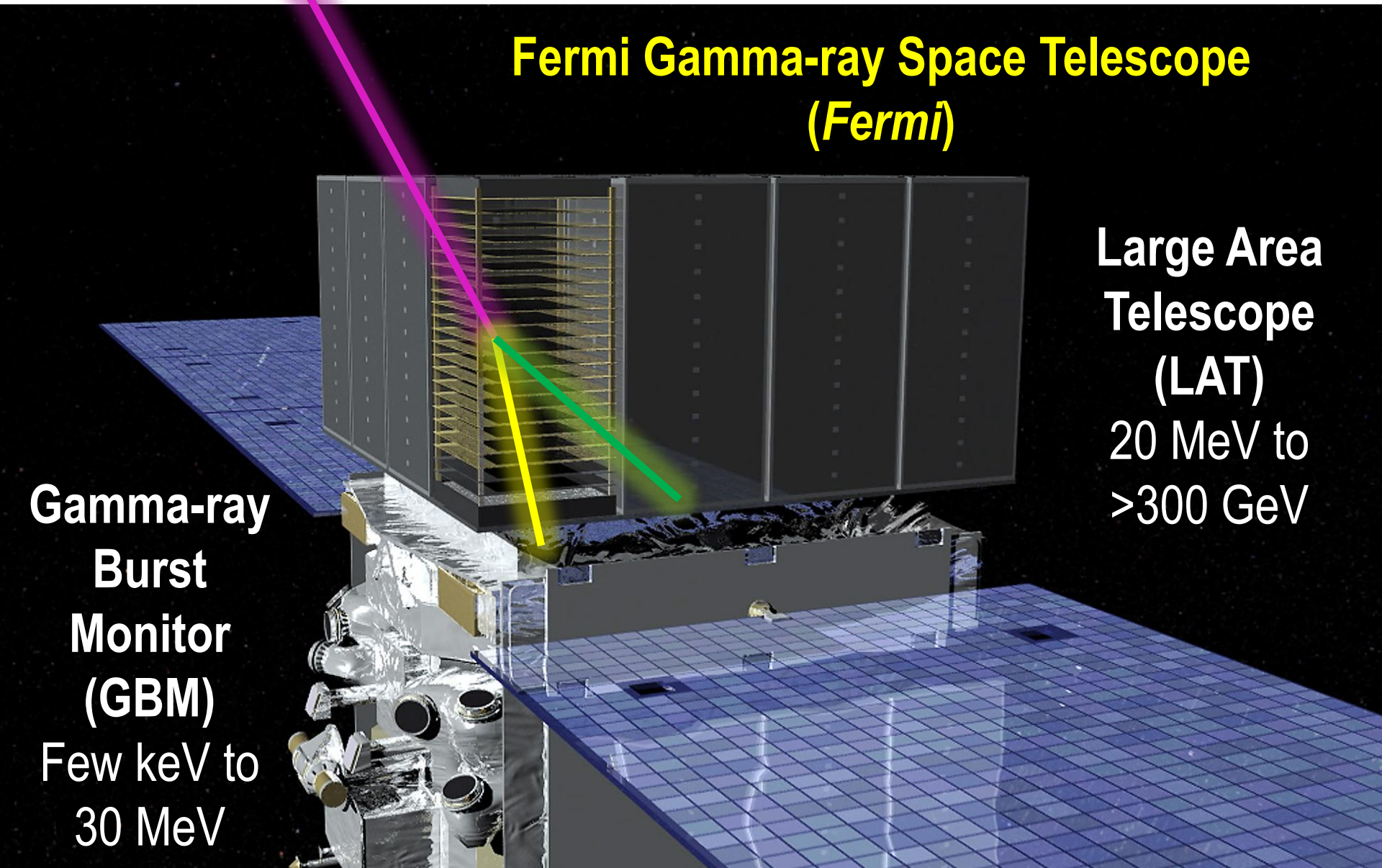
- NGC 1068 and NGC 4945 are composite systems
  - *Gamma rays from AGN or cosmic rays?*
  - See Lenain et al. 2010

- Parallel *Fermi* LAT analysis of radio-quiet Seyfert galaxies
  - 120 objects selected by *Swift* BAT hard X-ray flux (14-195 keV)
  - Same analysis conditions as for star-forming galaxies
  - Possible association of LAT sources with ESO 323-G077, NGC 6814
  - Could ***not*** establish as new gamma-ray source class

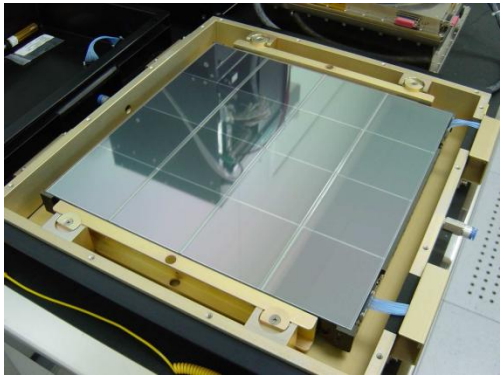


See talk by M. Hayashida
305.06 in "AGN, QSO, Blazars V"
Wednesday 11 Jan @ 10 am

Pair-Conversion Technique

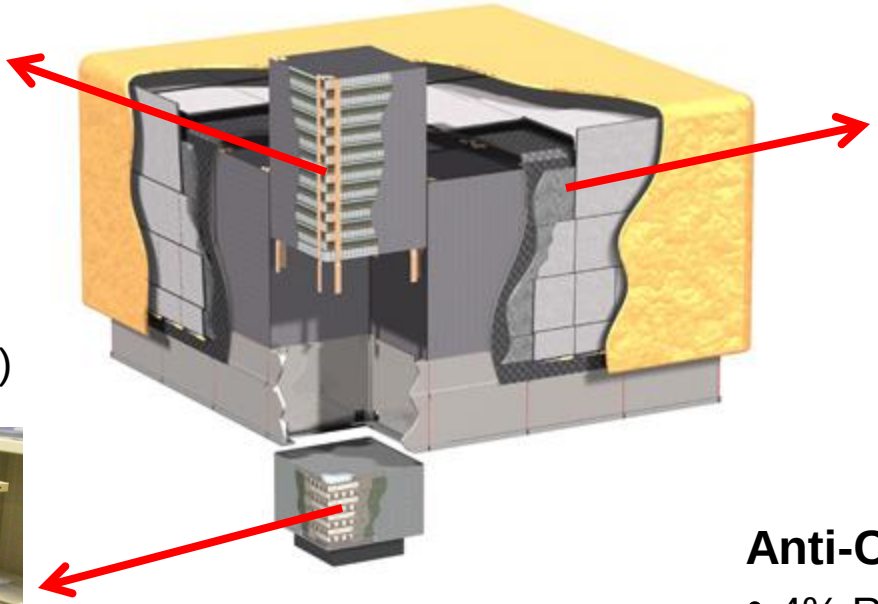


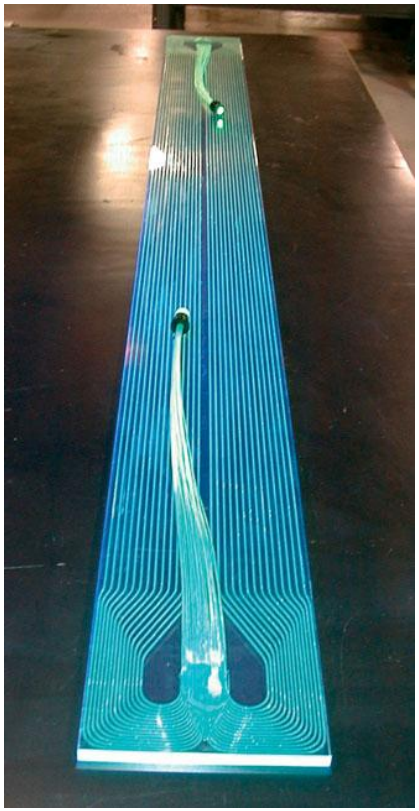
LAT Detector Subsystems



Precision Converter and Tracker

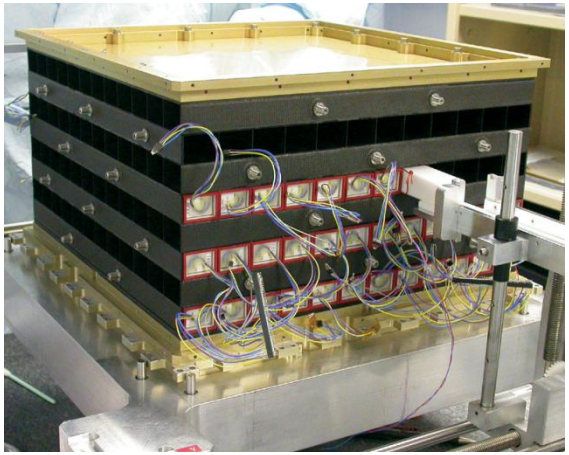
- Single sided SSD (40 cm, 228 um) ~ 80 m^2
- W foil interleaved (12x3% RL, 4x18% RL)
- 18 xy planes
- 1.5 RL





Imaging Calorimeter

- 8.6 R.L.
- 1536 CsI crystals
- Hodoscopic (12 x 8 layers)



Anti-Coincidence Detector

- 4% RL
- Segmented (89 plastic scintillator tiles, 8 ribbons)
- 0.9997 efficiency

(+ Data Acquisition System)

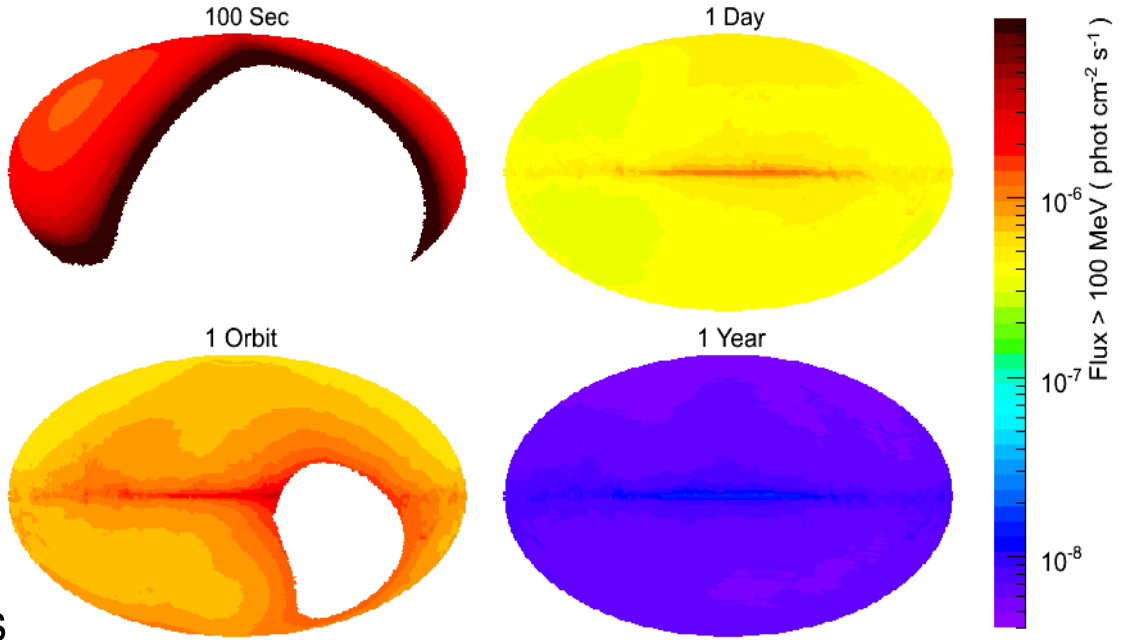
500 Hz sent to ground

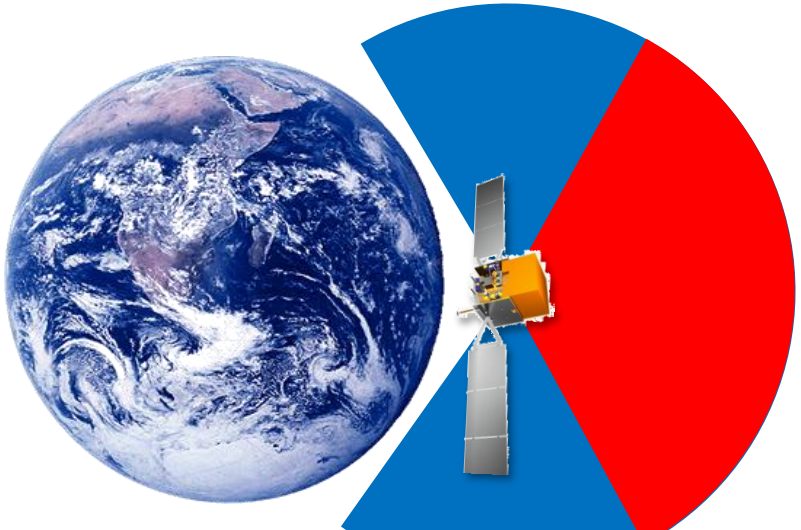
Fermi Gamma-ray Space Telescope

- Launched 11 June 2008
- 3 years of successful operations
- Expected lifetime of 10+ years

Observation Modes

- Sky-survey mode
  - Normal operations mode
  - Full-sky every 2 orbits (~3 hrs)
- Target of Opportunity
  - Autonomous re-pointing for GRBs
  - Slew to keep target in FoV
  - Proposed pointed observations



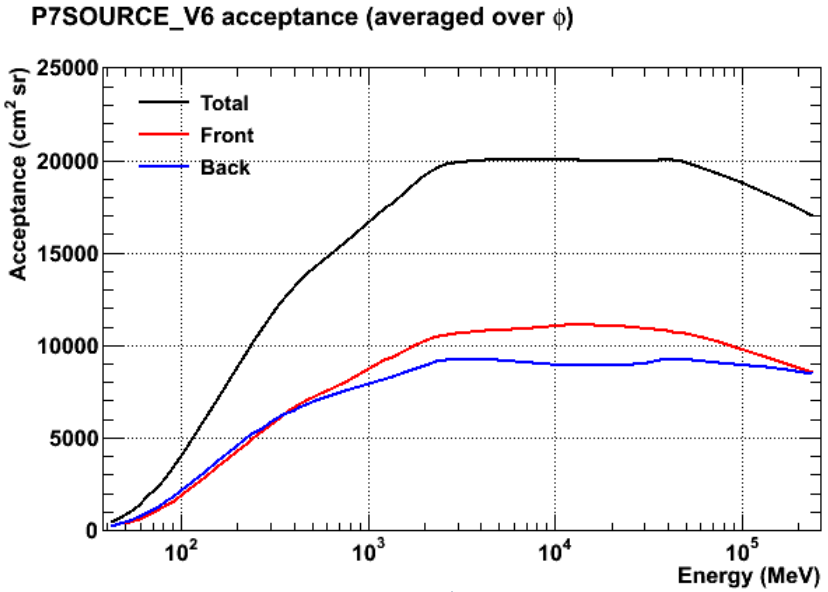


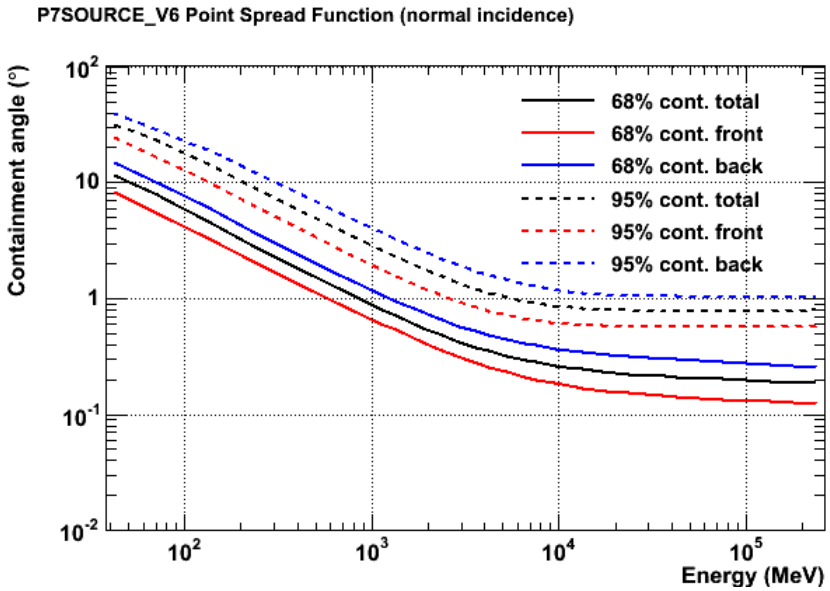
Wide Field of View

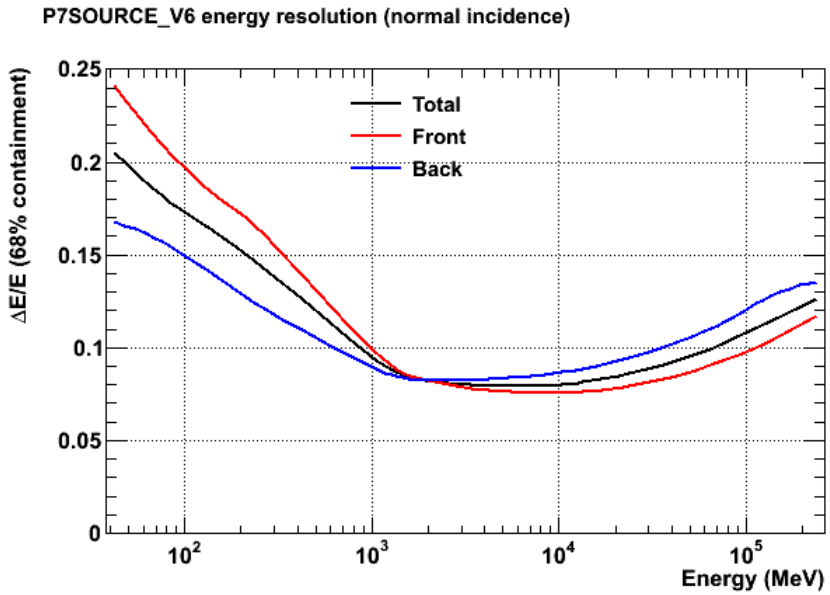
LAT : ~2.4 sr, 20% of sky

GBM: Almost entire sky not occulted by Earth

Instrument Performance







Effective Area = geometric area
× trigger efficiency
× selection efficiency

Low Earth Orbit
Cosmic ray flux >10^3 gamma ray flux

Fermi Gamma-ray Space Telescope

Fermi LAT Collaboration