The Extragalactic Gamma-ray Background

A Census of High Energy Phenomena in the Universe

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Fermilab Particle Astrophysics Seminar

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SLAC NATIONAL ACCELERATOR LABORATORY

KIPAC

Fermi LAT Collaboration

Discussion points

» **Gamma-ray sky**

- Defining the extragalactic gamma-ray background (EGB)

» ***Fermi* LAT**

» **Extragalactic population census**

- **Searching for galaxy clusters**
- **Finding star-forming galaxies**
- DETOUR **Physics of cosmic rays**

» **Extending the EGB spectral measurement**

Gamma-ray astronomy

» Access to extreme physics laboratories of the cosmos

- Natural particle accelerators

» Complementary information to cosmic-ray (CR) studies

- *Point back to their origin*

Hadronic processes

Pion decay

$$p + \text{ion} \rightarrow \pi^0 + \pi^\pm$$

$$\pi^0 \rightarrow \gamma\gamma \qquad \pi^\pm \rightarrow e^\pm + \text{neutrinos}$$

Leptonic processes

Inverse Compton

$$e^* + \gamma \rightarrow e + \gamma^*$$

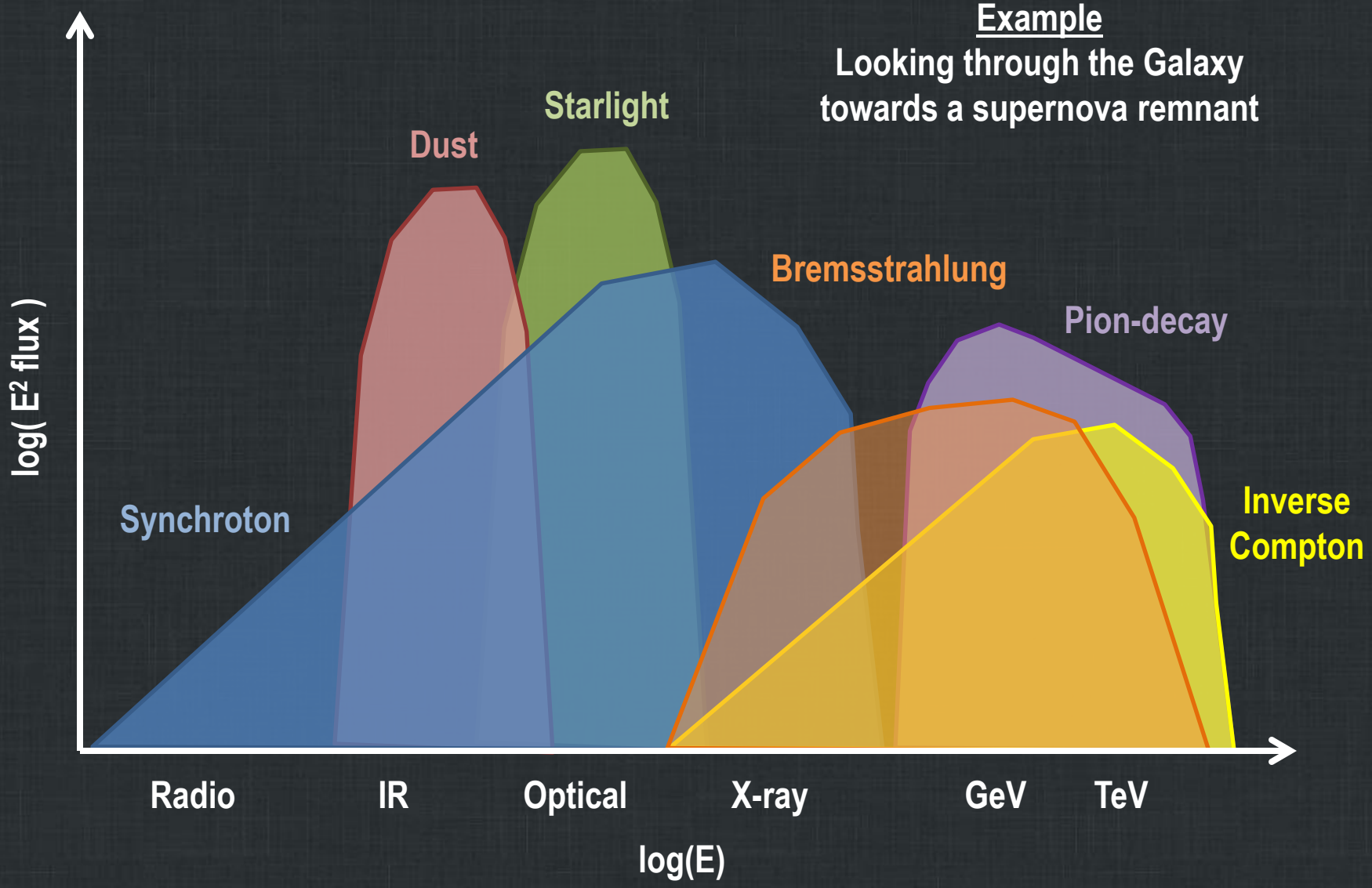
Bremsstrahlung

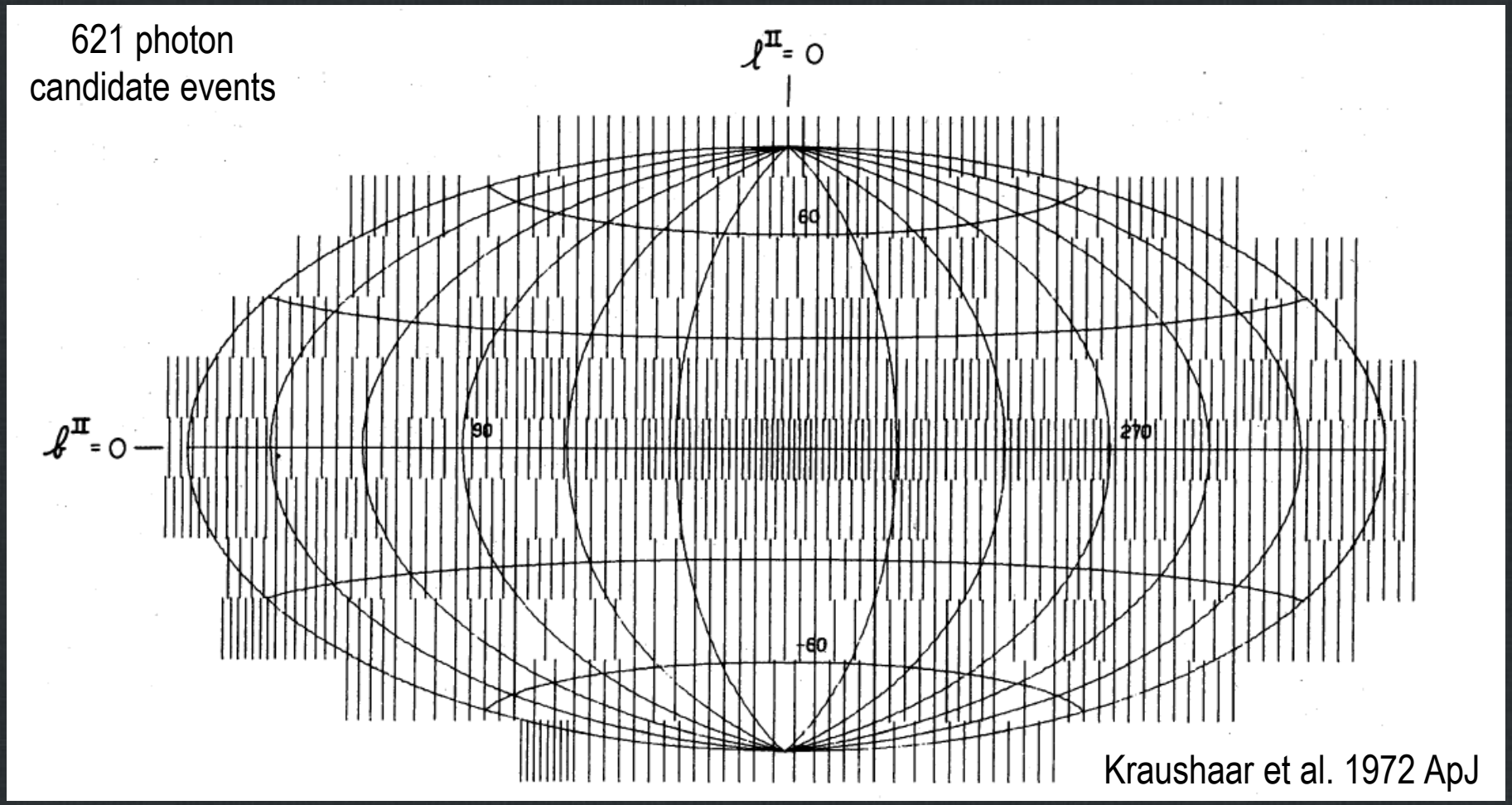
$$e^* + \text{ion} \rightarrow e + \text{ion} + \gamma^*$$

Synchroton

$$e^* + \text{B-field} \rightarrow e + \text{B-field} + \gamma^*$$

Non-thermal emission sketch



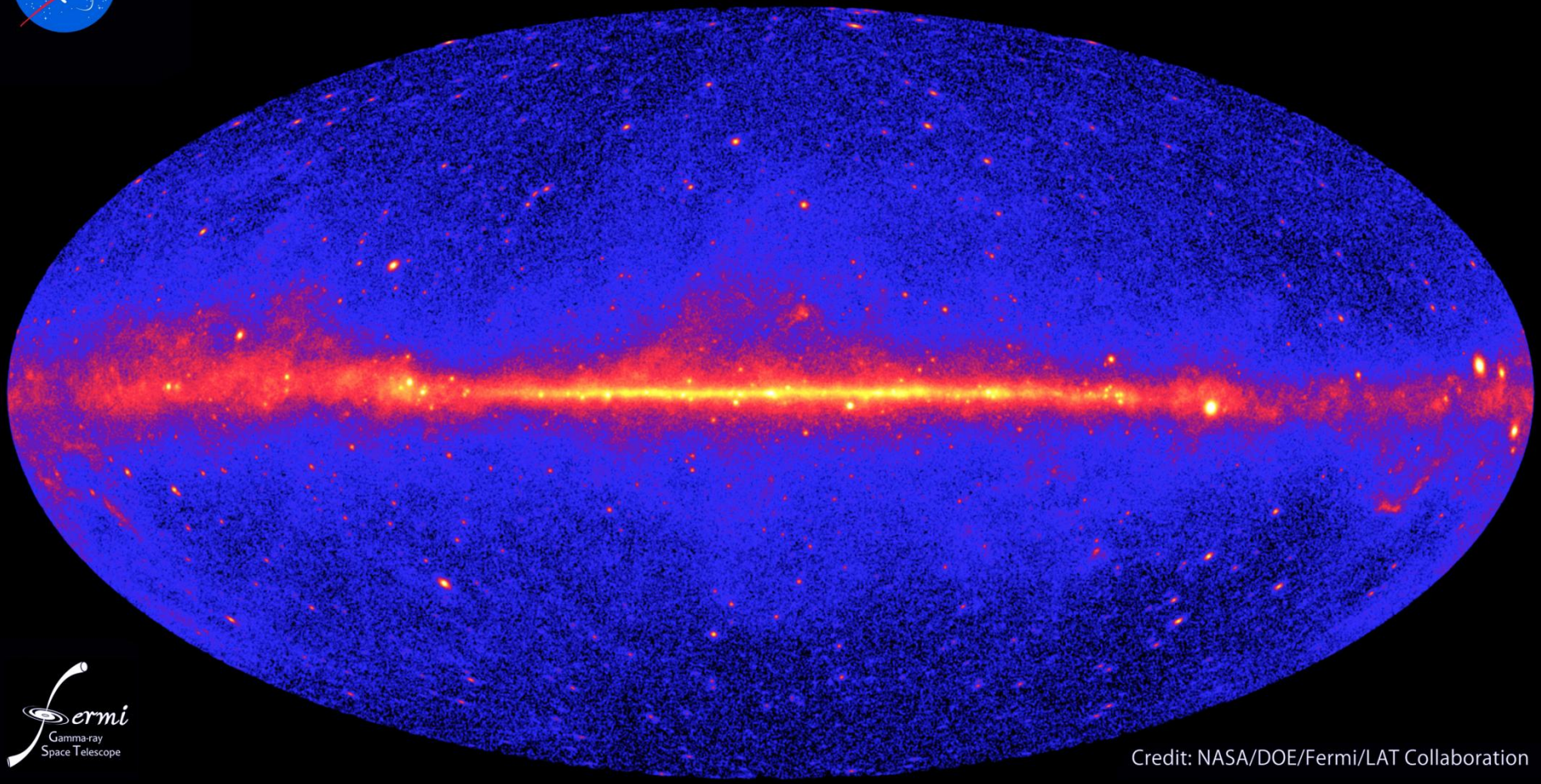


Gamma-ray sky seen by OSO-3 satellite during 1967-1968

(shown as relative intensity in **Galactic** coordinates)

First identification of isotropic component (Clark et al. 1968 ApJ)

Fermi two-year all-sky map

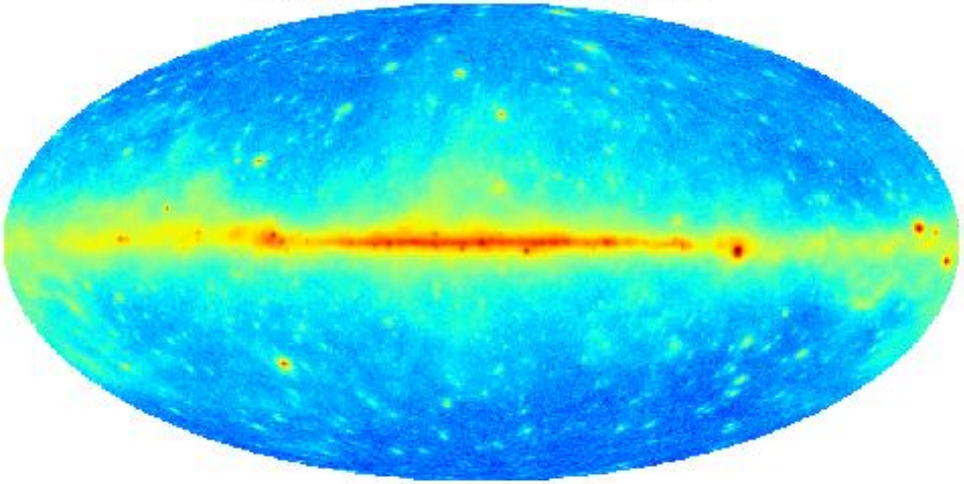


Credit: NASA/DOE/Fermi/LAT Collaboration

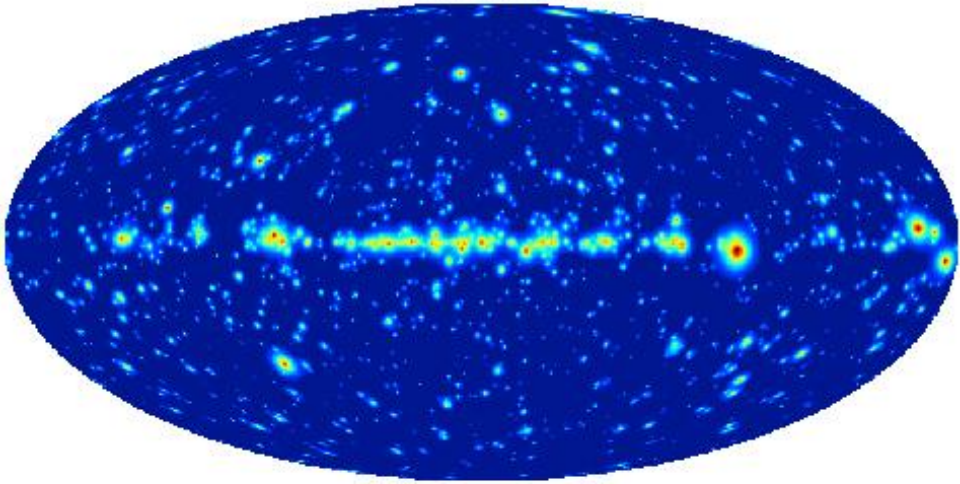
Photon energies > 1 GeV

Spatial Decomposition

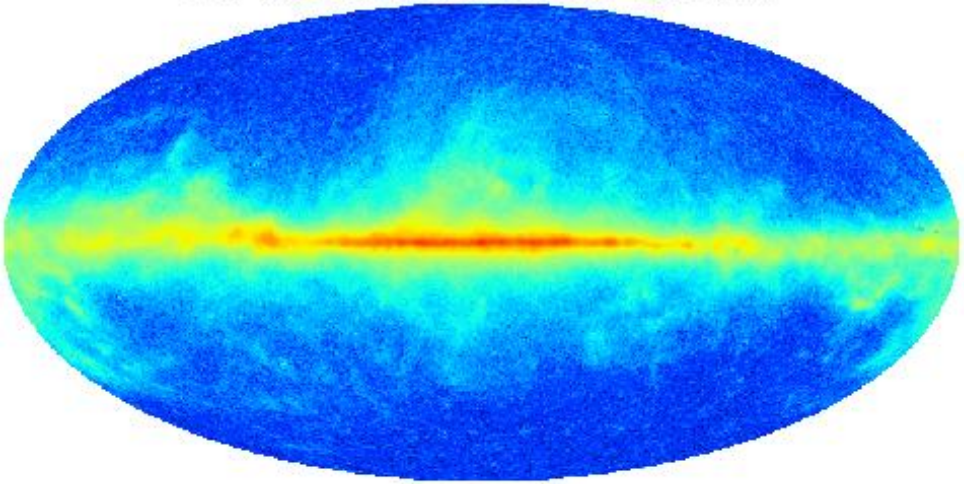
LAT photons above 300 MeV



Point Sources

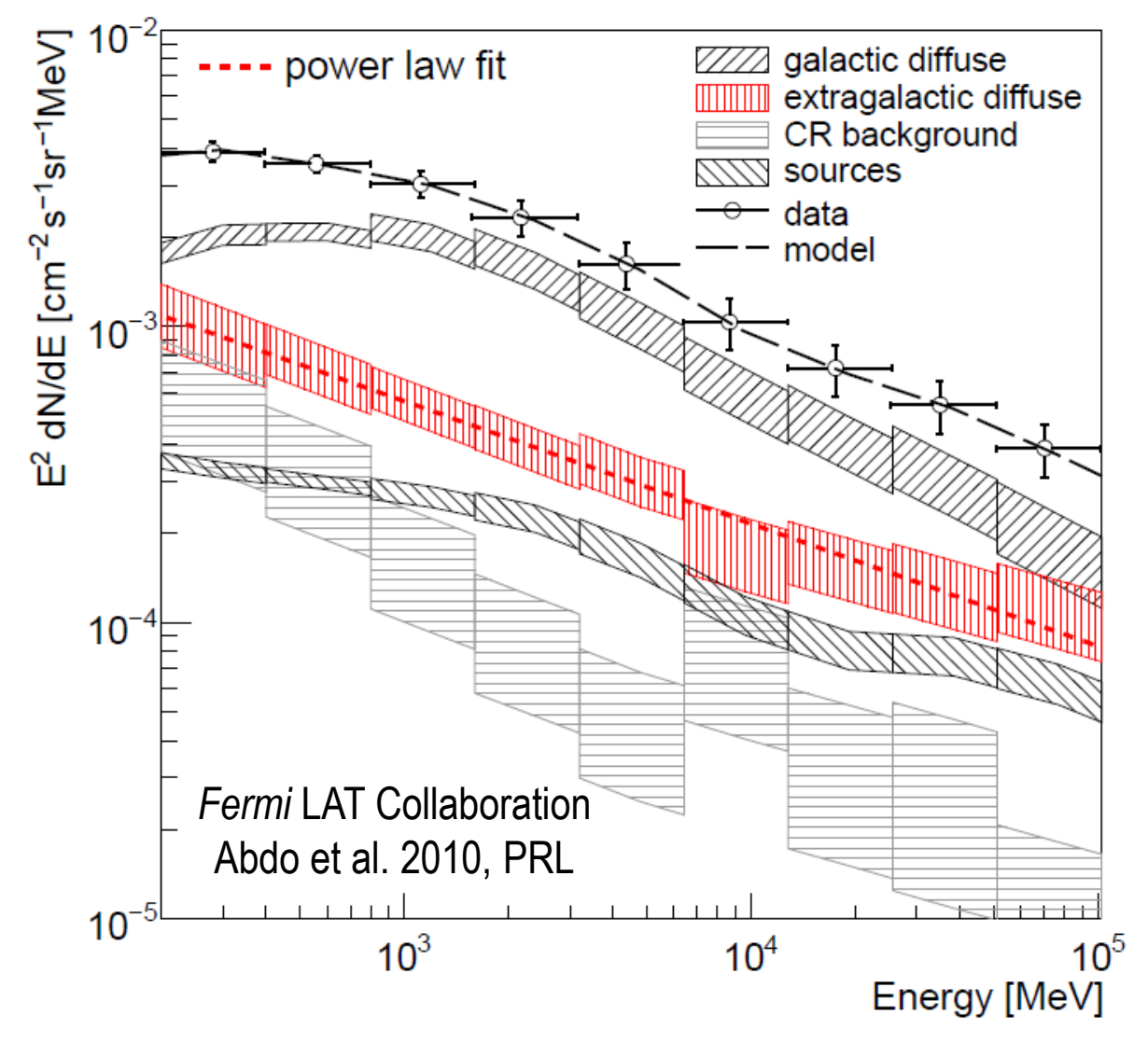


LAT photons from Galactic emission

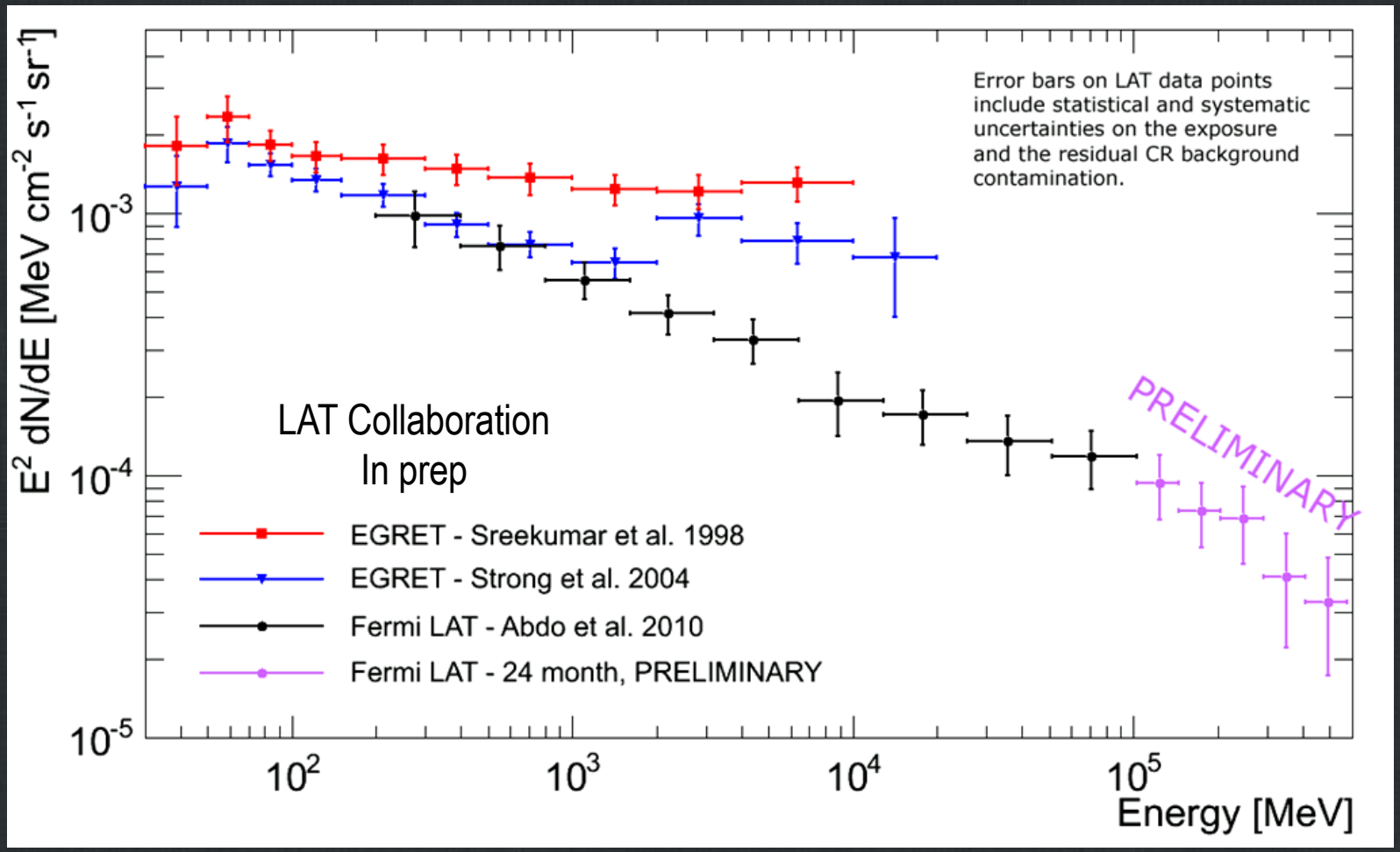


Anisotropic features on large angular scales associated with **Galactic diffuse emission** and **resolved sources**

Spectral Decomposition

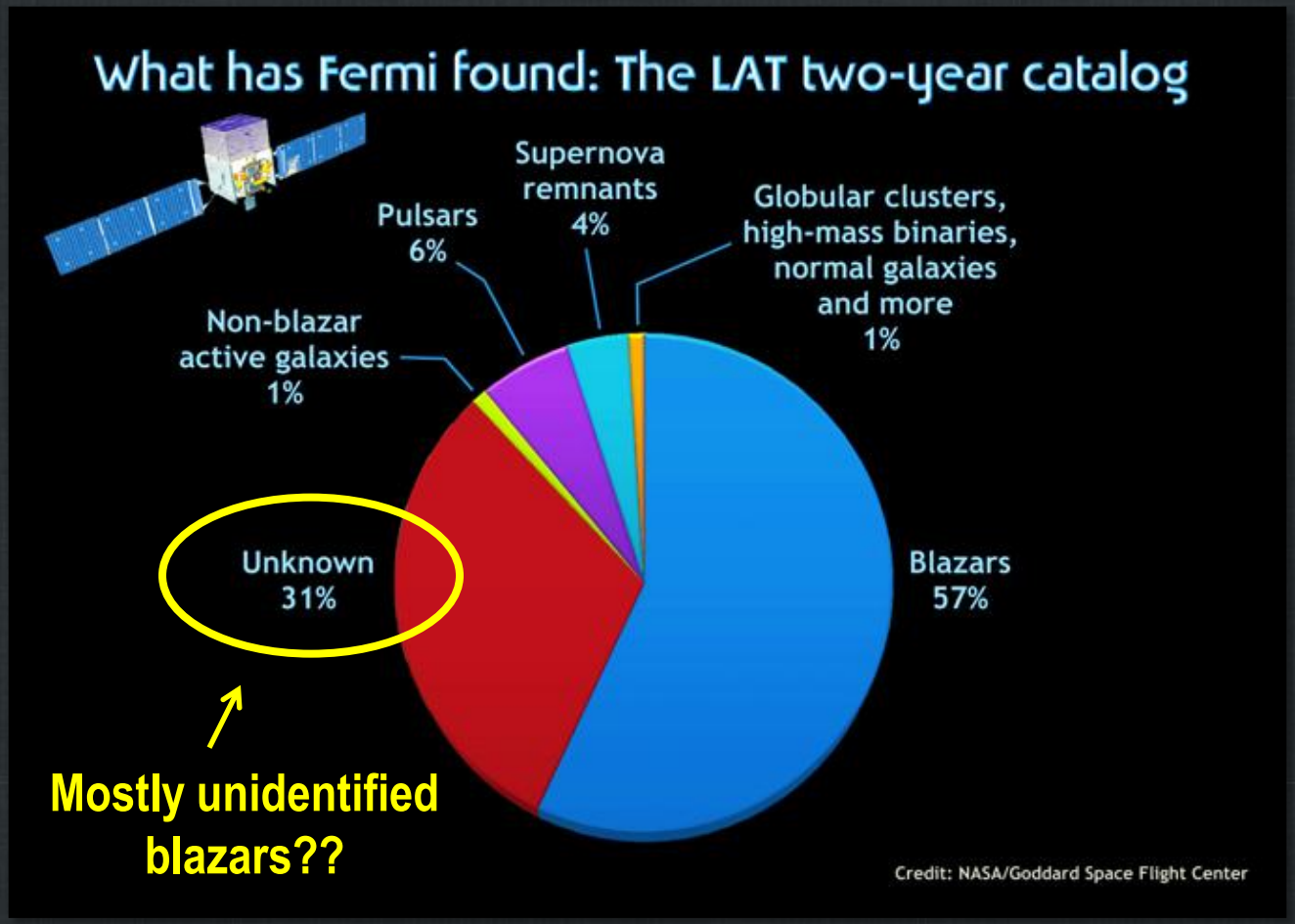


Spectrum of Extragalactic diffuse gamma-ray background (EGB)



Most commonly presented as the *intensity of unresolved isotropic component* as opposed to *total intensity of extragalactic radiation*

Why the strange definition??

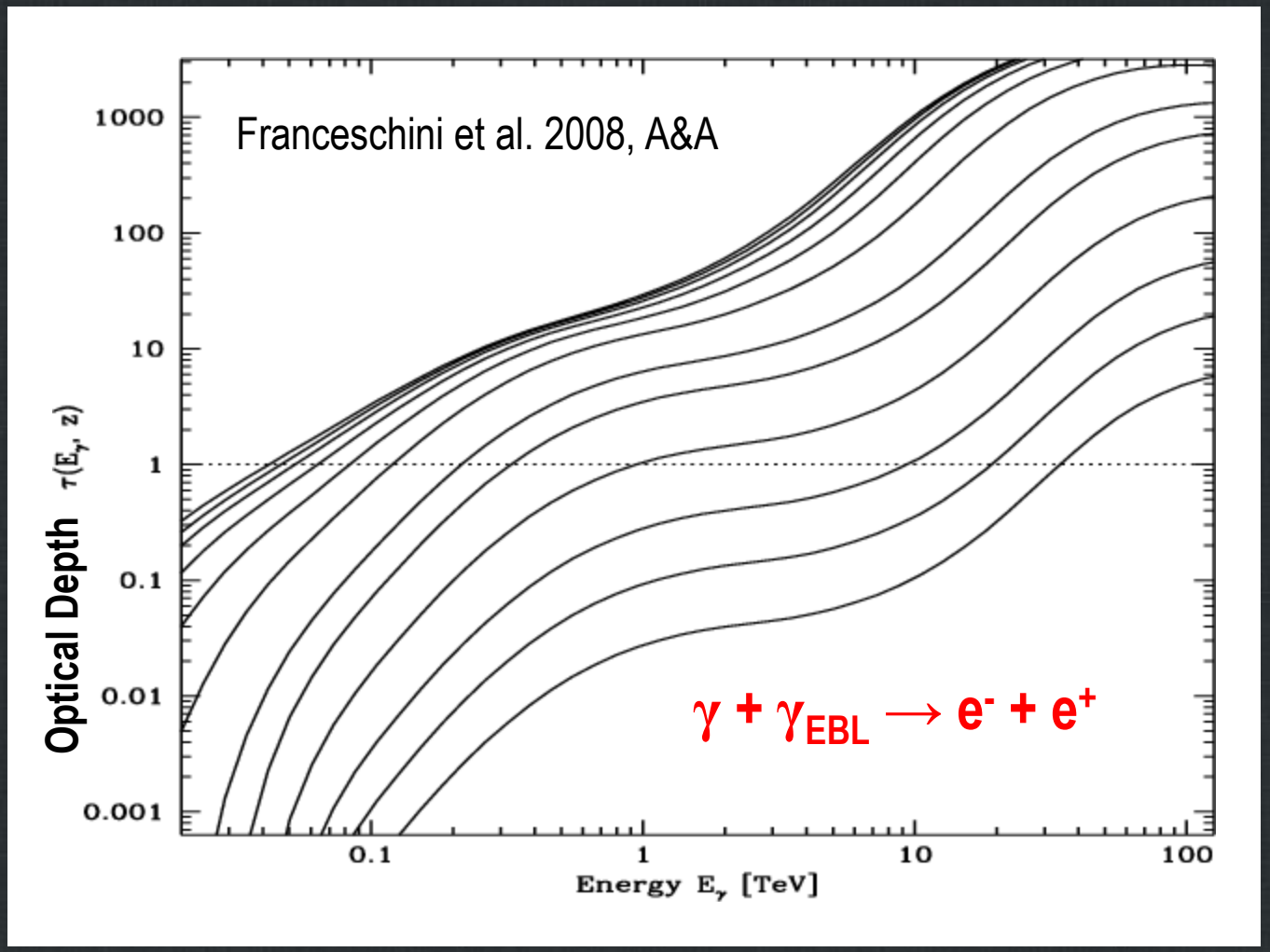


Not entirely clear which sources are Galactic vs. extragalactic

cannot yet exclude possibility of significant contribution from Milky Way halo, or even our Solar System

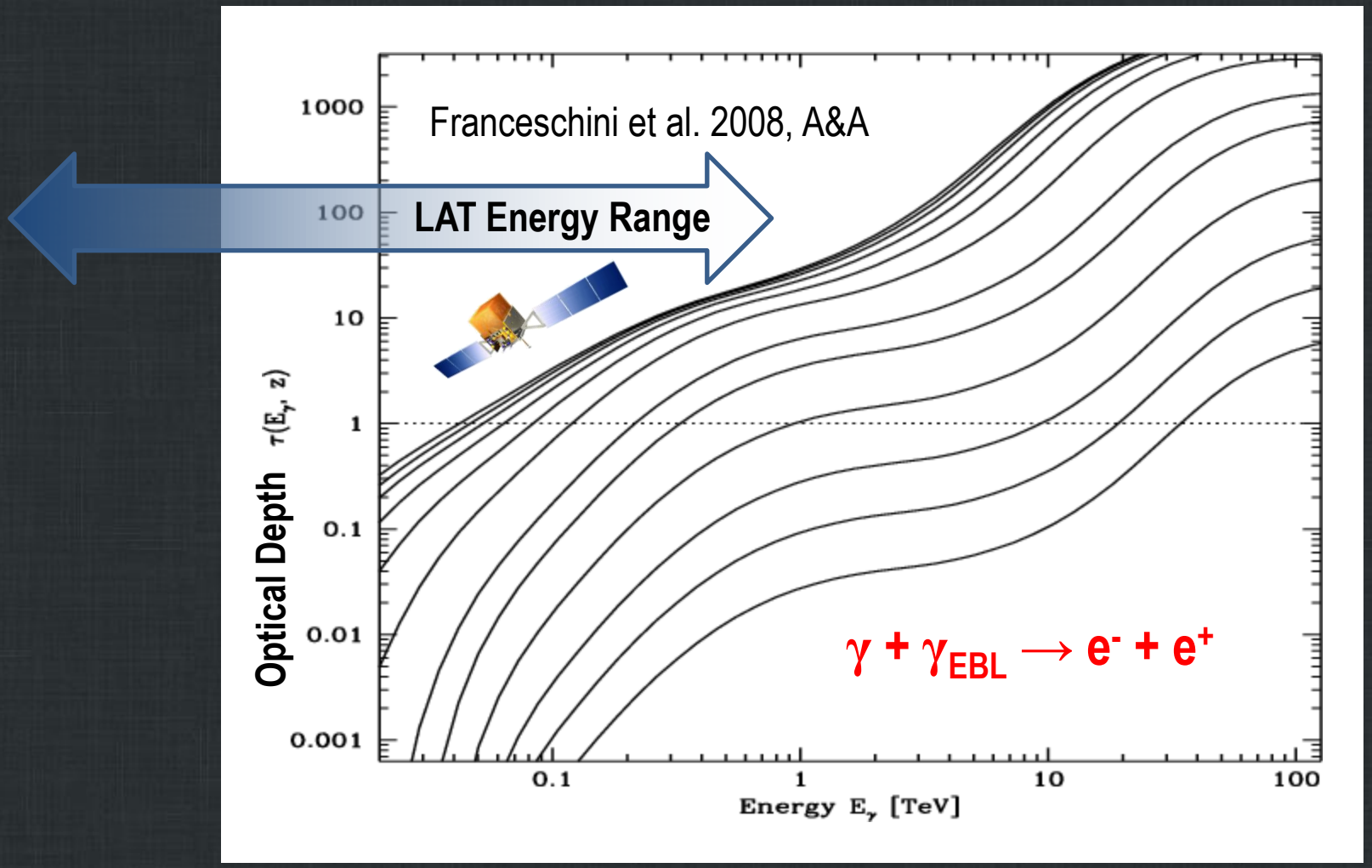
focusing our attention on the unknown…

Photo-pair attenuation on EBL



Contours indicate increasing redshift from bottom to top
z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4

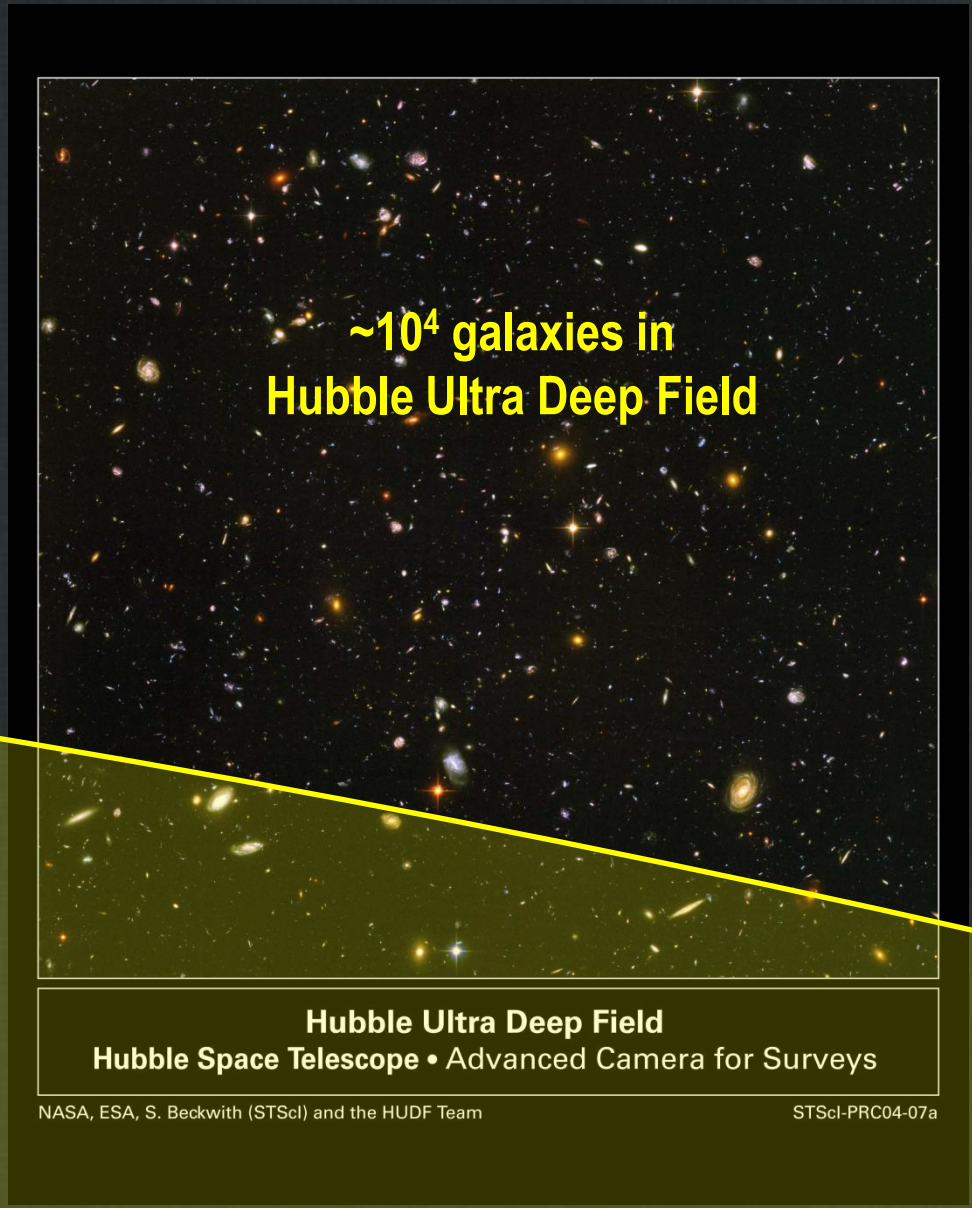
Photo-pair attenuation on EBL



Contours indicate increasing redshift from bottom to top
z = 0.003, 0.01, 0.03, 0.1, 0.3, 0.5, 1, 1.5, 2, 2.5, 3, 4

Approximate 68% containment circle for 1 GeV photons for the LAT (shown to scale)

~1000 Hubble Ultra Deep Fields would fit inside approximate PSF (~10^7 galaxies)



We are exploring a cosmologically significant volume…

are we seeing a collection of individual sources

or diffuse emission?

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» ***Fermi* LAT**

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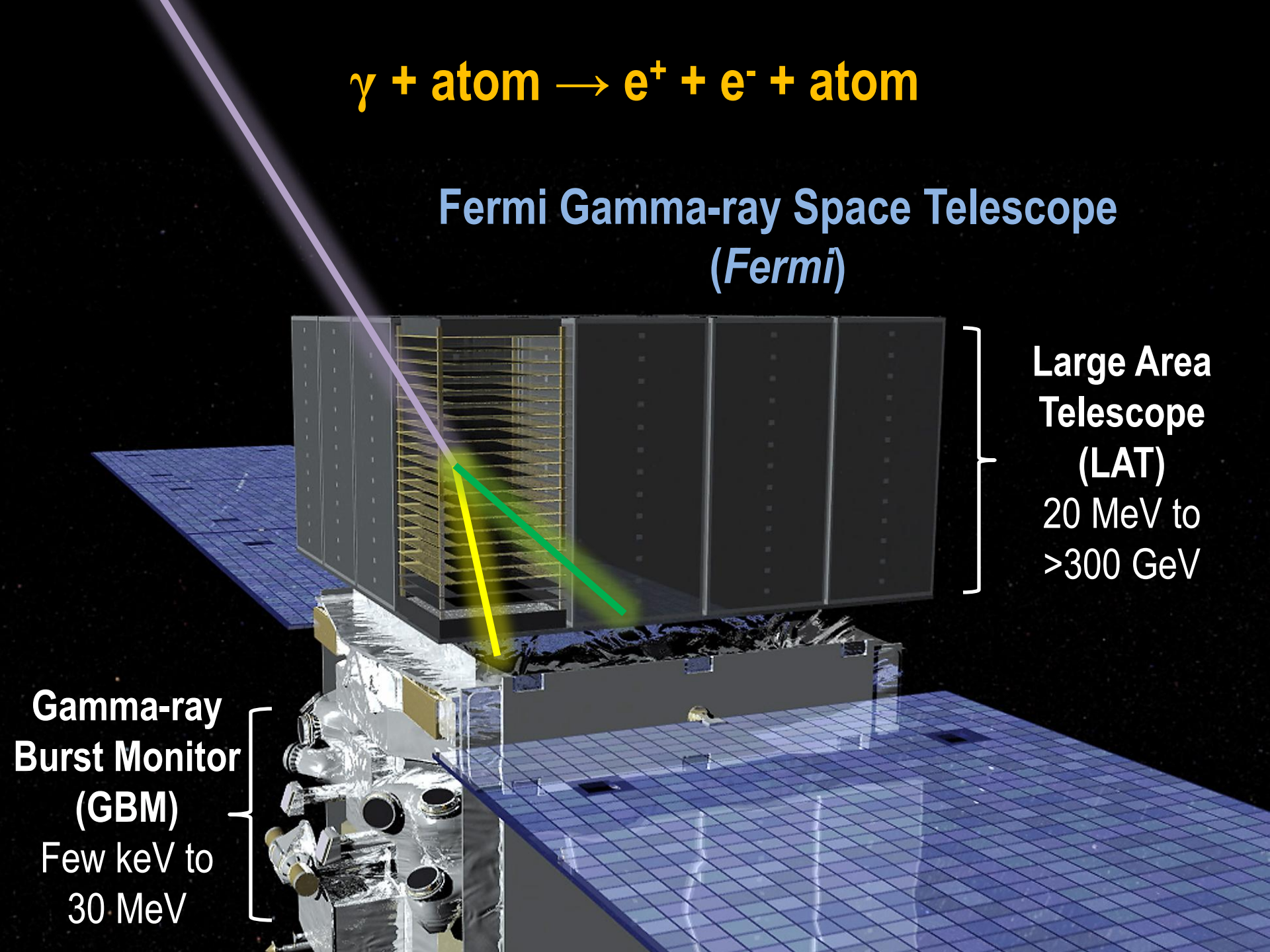
- DETOUR **Physics of cosmic rays**

» **Extending the EGB spectral measurement**

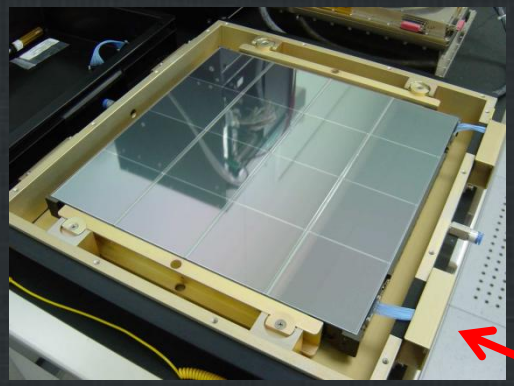
Fermi Gamma-ray Space Telescope

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

γ + atom $\rightarrow$ e^+ + e^- + atom

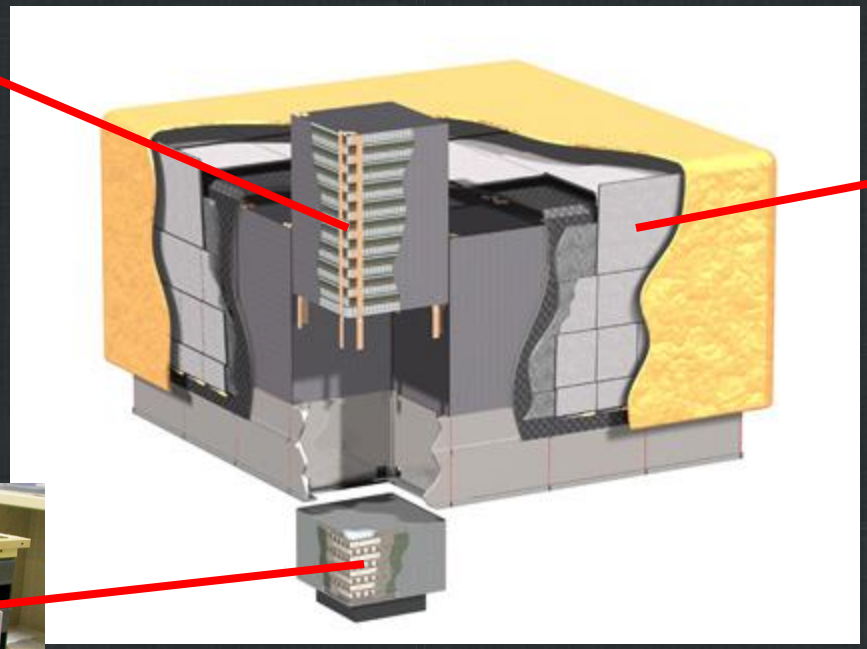


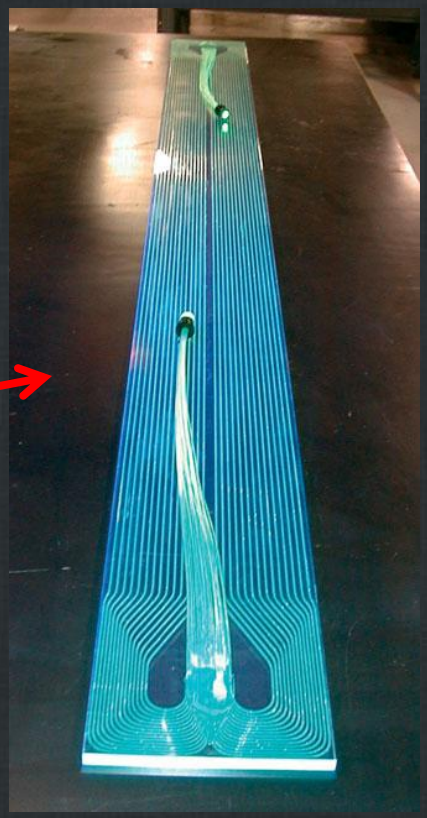
Large Area Telescope (LAT) in detail



Precision Converter and Tracker

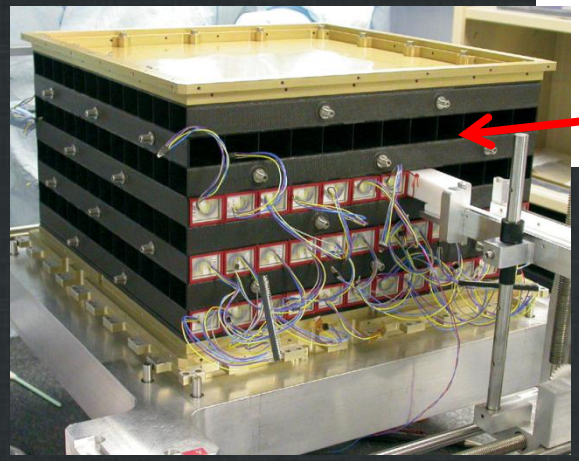
- Single sided SSD (40 cm, 228 um) ~ 80 m^2
- W foil interleaved (12x3% RL, 4x18% RL)
- 18 xy planes
- 1.5 RL





Imaging Calorimeter

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



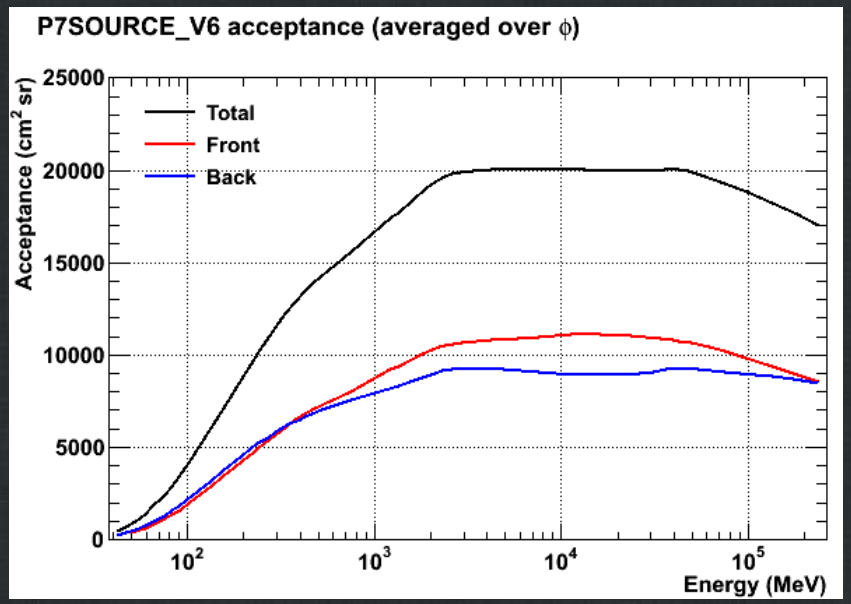
(+ Data Acquisition System)

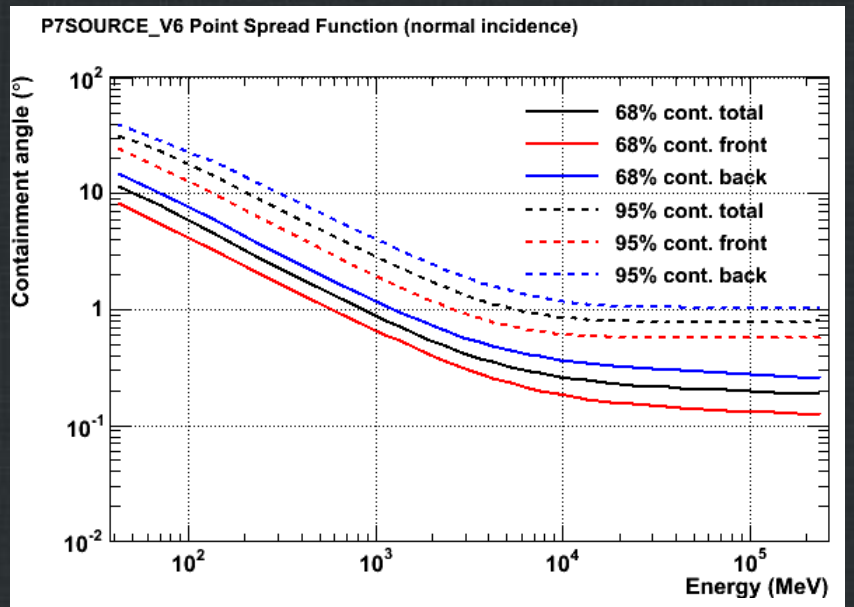
500 Hz sent to ground

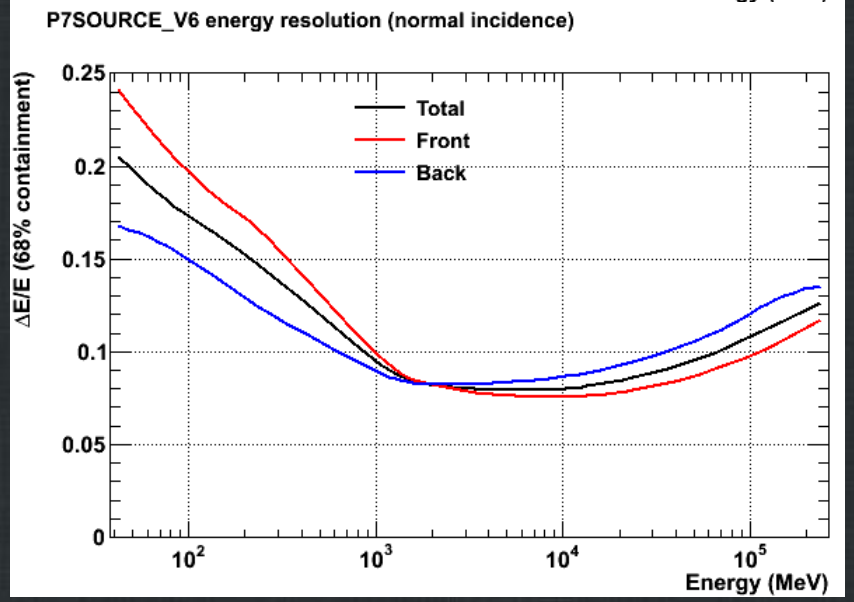
Anti-Coincidence Detector

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

Detailed LAT performance







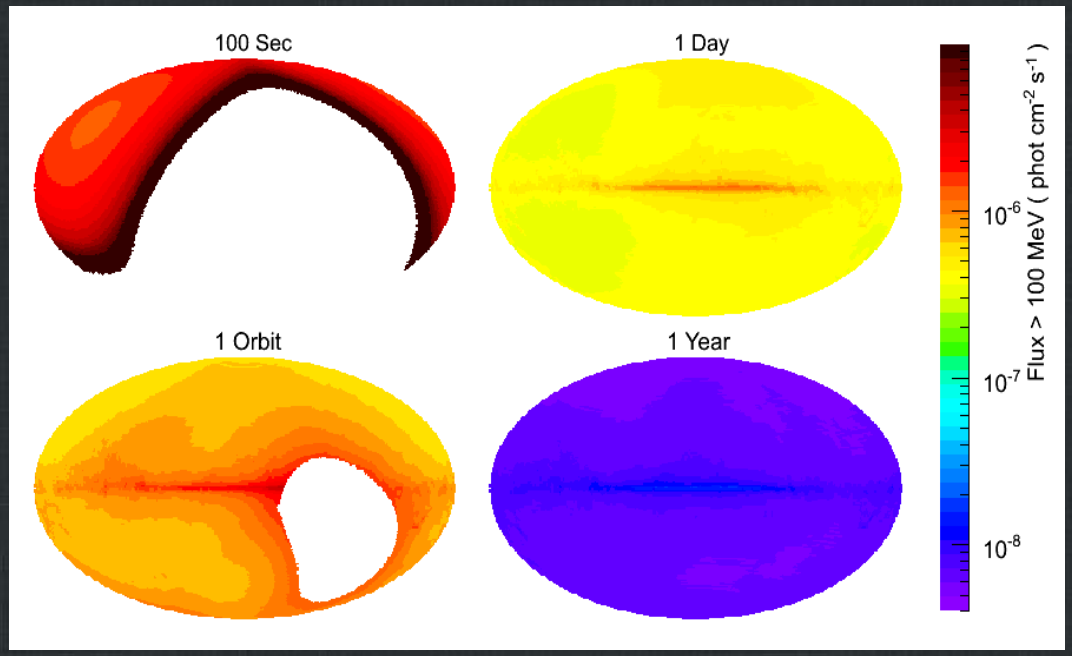
Effective Area = geometric area
× trigger efficiency
× selection efficiency

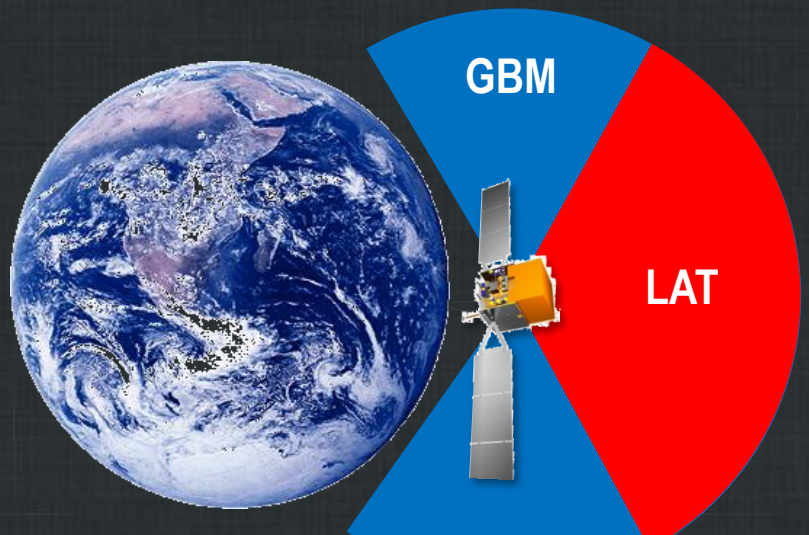
Low Earth Orbit
Cosmic ray flux >10^3 gamma ray flux

LAT observing strategy

» **Sky-survey**
- Full-sky every 2 orbits (~3 hrs)
- Normal mode

» Target of Opportunity
- Autonomous re-pointing (GRBs)
- Proposed pointed observations
- Slew to keep target in field of view





Wide Field of View

LAT : ~2.4 sr, 20% of sky

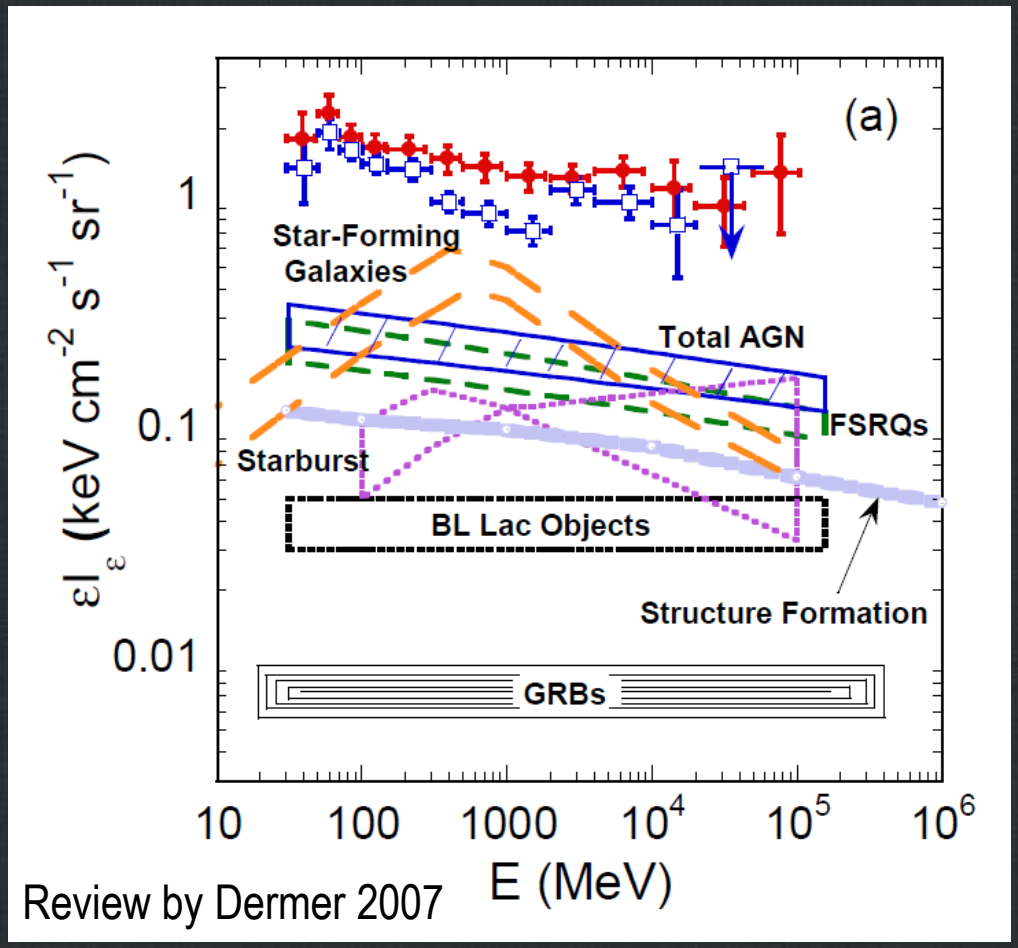
GBM: Nearly entire sky not occulted by the Earth

Pre-*Fermi* ideas for EGB origin

» Established sources
- Blazars (FSRQs, BL Lacs)
- Gamma-ray bursts (GRBs)

» Less certain
- Star-forming galaxies
- Galaxy clusters (i.e. structure formation)
- Other AGN types
- …

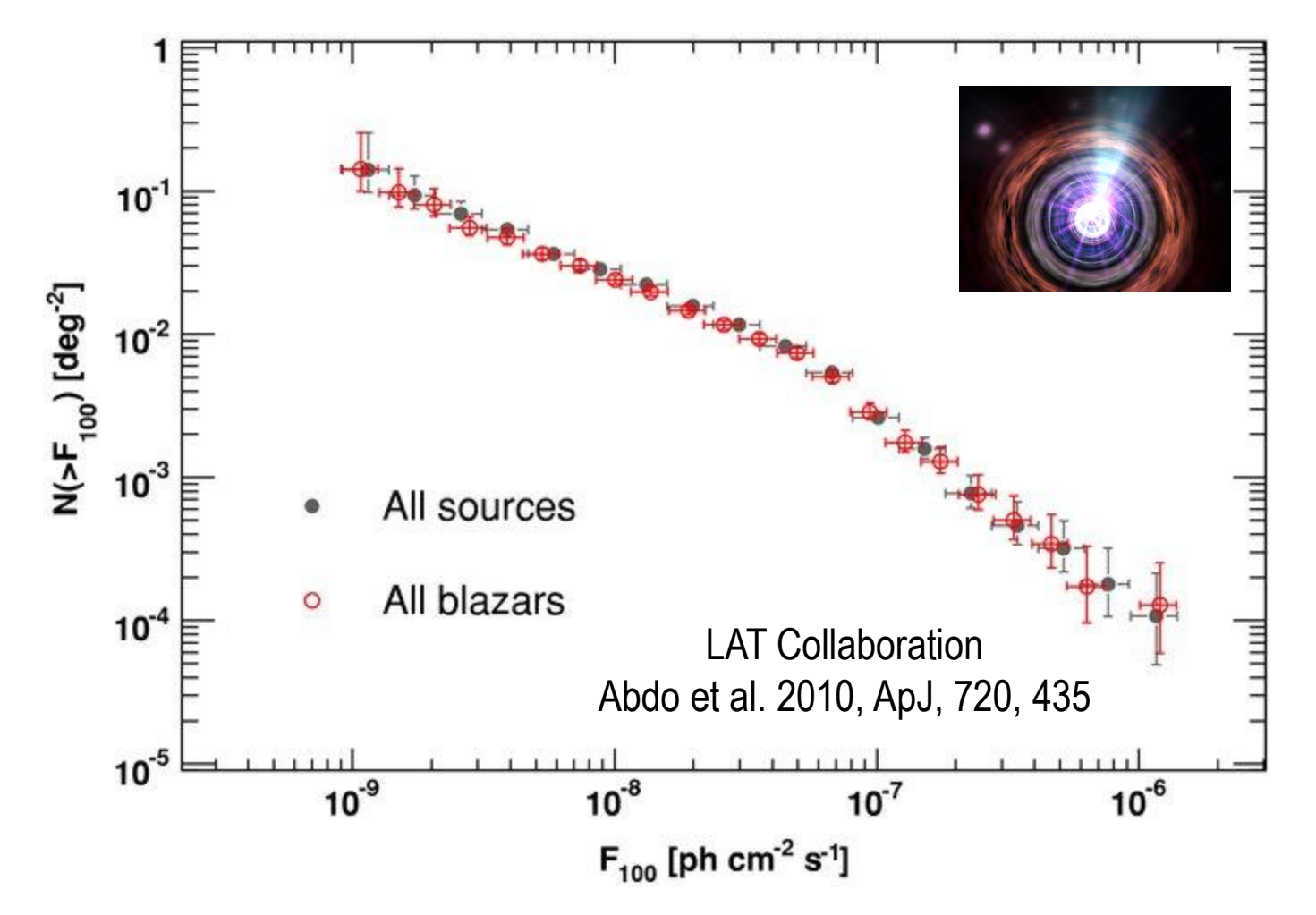
» Truly diffuse origin
- Electromagnetic cascades
- …



Review by Dermer 2007

» Galactic and extragalactic dark matter annihilation

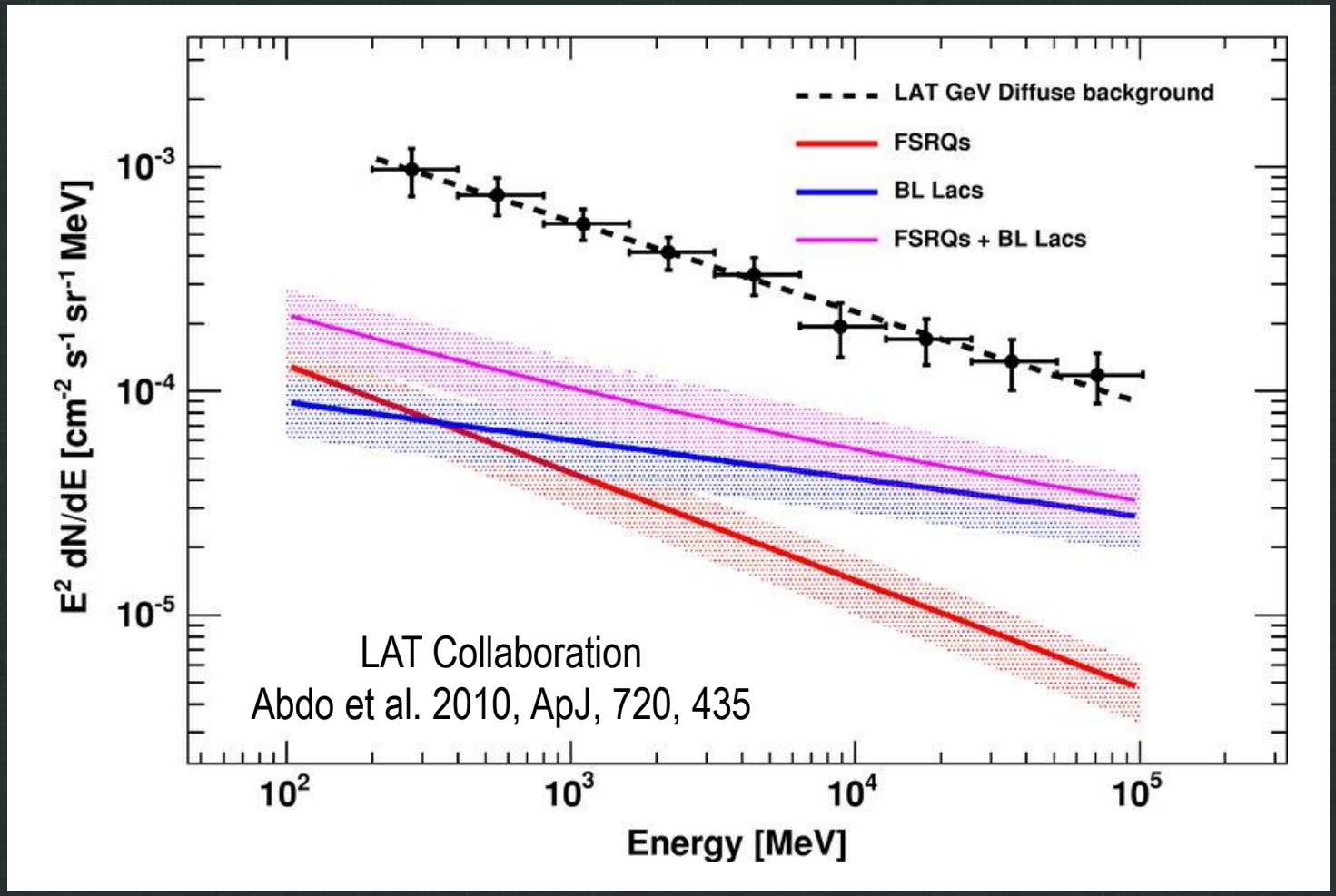
Fermi LAT blazars and the EGB



Nearly all individually resolved gamma-ray sources away from the Galactic plane are likely to be blazars

Fermi LAT blazars and the EGB

Blazars account for 20-30% of the EGB intensity between 0.1-100 GeV



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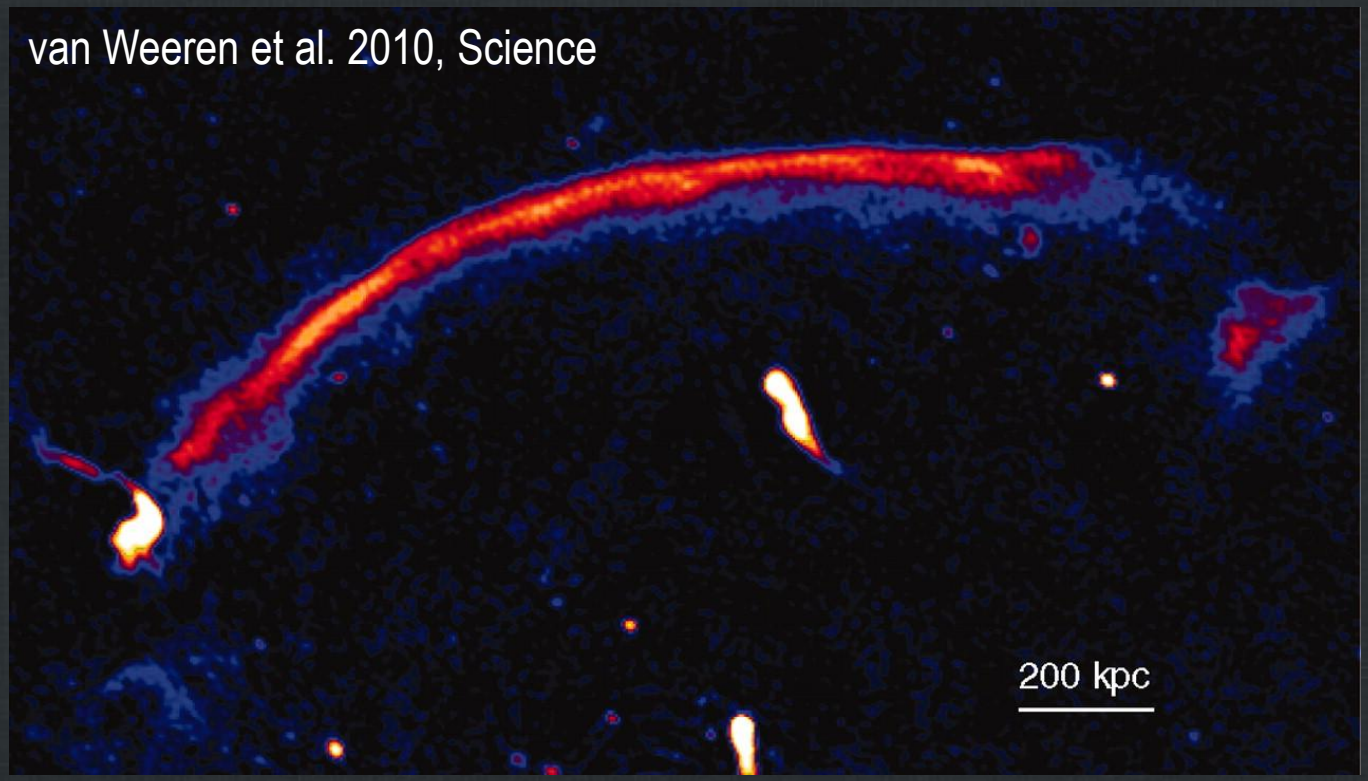
Fermi LAT search for galaxy clusters



» Unique reservoirs of CR nuclei
- Injection by AGN, galaxies, large scale structure formation shocks
- Record of non-thermal history

» Astrophysics of the intergalactic medium
- Non-thermal pressure support, magnetic fields, origin of radio features

Galaxy cluster selection

1. X-ray flux selection (highest mass / distance-squared)
   - e.g. Coma, Centaurus, Ophiuchus, Perseus, Norma, Fornax

2. Non-thermal signatures (radio halos / relics)
   - e.g. A2163, A2029, A2744

3. Exceptional X-ray luminosity and/or temperature
   - e.g. Bullet, RJ1347.5−1145

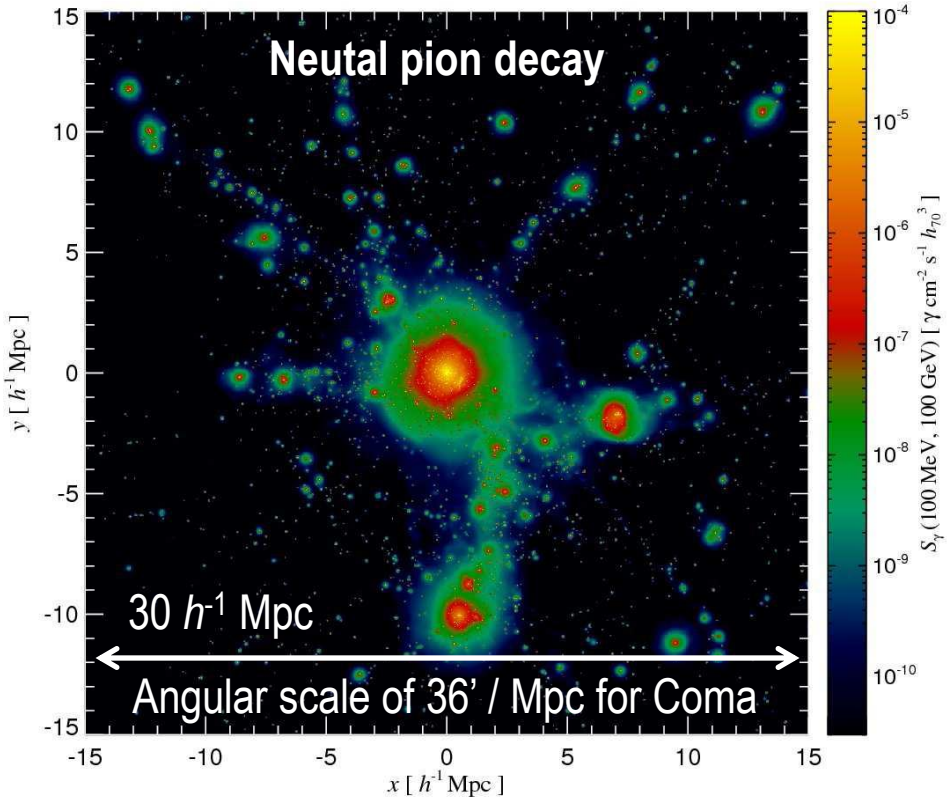
31 clusters in final sample

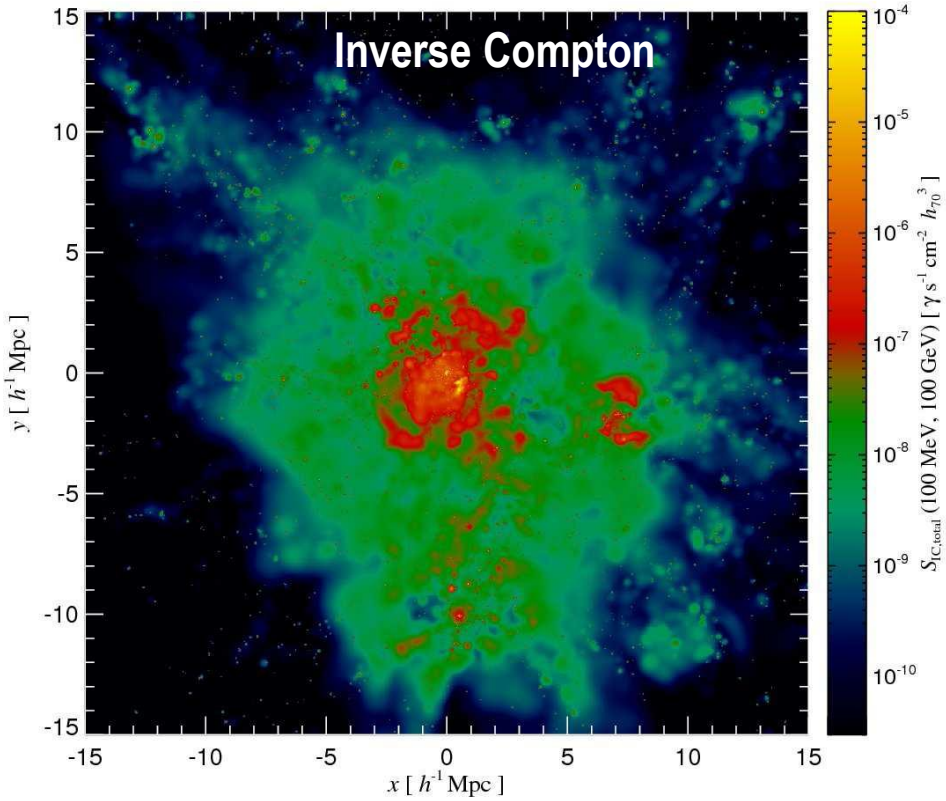
Fermi LAT cluster search

» 18 months of observations, analysis range 0.2-100 GeV

» Point-like and spatially extended King profiles

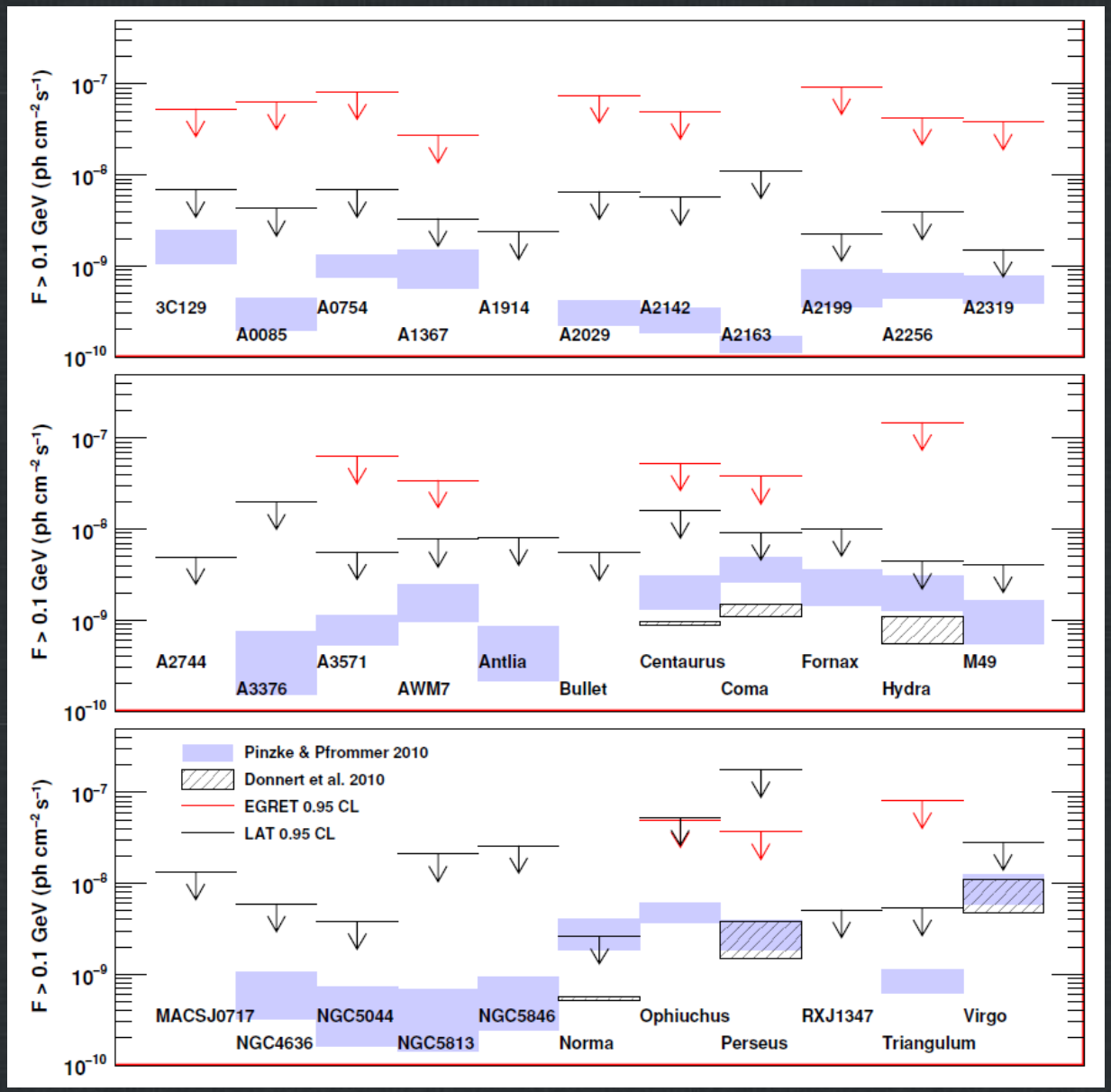
Predictions of Pfrommer et al. 2008 >0.1 GeV for Coma-like cluster





GeV gamma-ray upper limits

LAT Collaboration
Ackermann et al. 2010
ApJL, 717, 71



Typical flux upper limits >0.1 GeV of 0.5-1.0 x 10^{-8} ph cm^{-2} s^{-1}

Approaching model predictions for several clusters

Interpretation of cluster limits

» CR nuclei

- Volume-averaged limits
- Assume CR distribution follows thermal gas
- Limits combined with simple CR models imply CR energy densities less than few percent of thermal gas (EGRET-era limits were 10-30%)
- *CR pressure support unlikely to significantly bias hydrostatic mass estimates*

» CR leptons

- Disfavor acceleration efficiencies > 0.1% (Blasi & Gabici 2004)
- Combine *Fermi* LAT limits with radio data (synchroton) and intergalagtic radiation fields (inverse Compton)
- Lower limits on magnetic field strength (e.g. >0.15 μG for Coma)

See also Pinzke, Pfrommer, Bergstrom 2011 arXiv:1105.3240
For dark matter see arXiv:1002.2239

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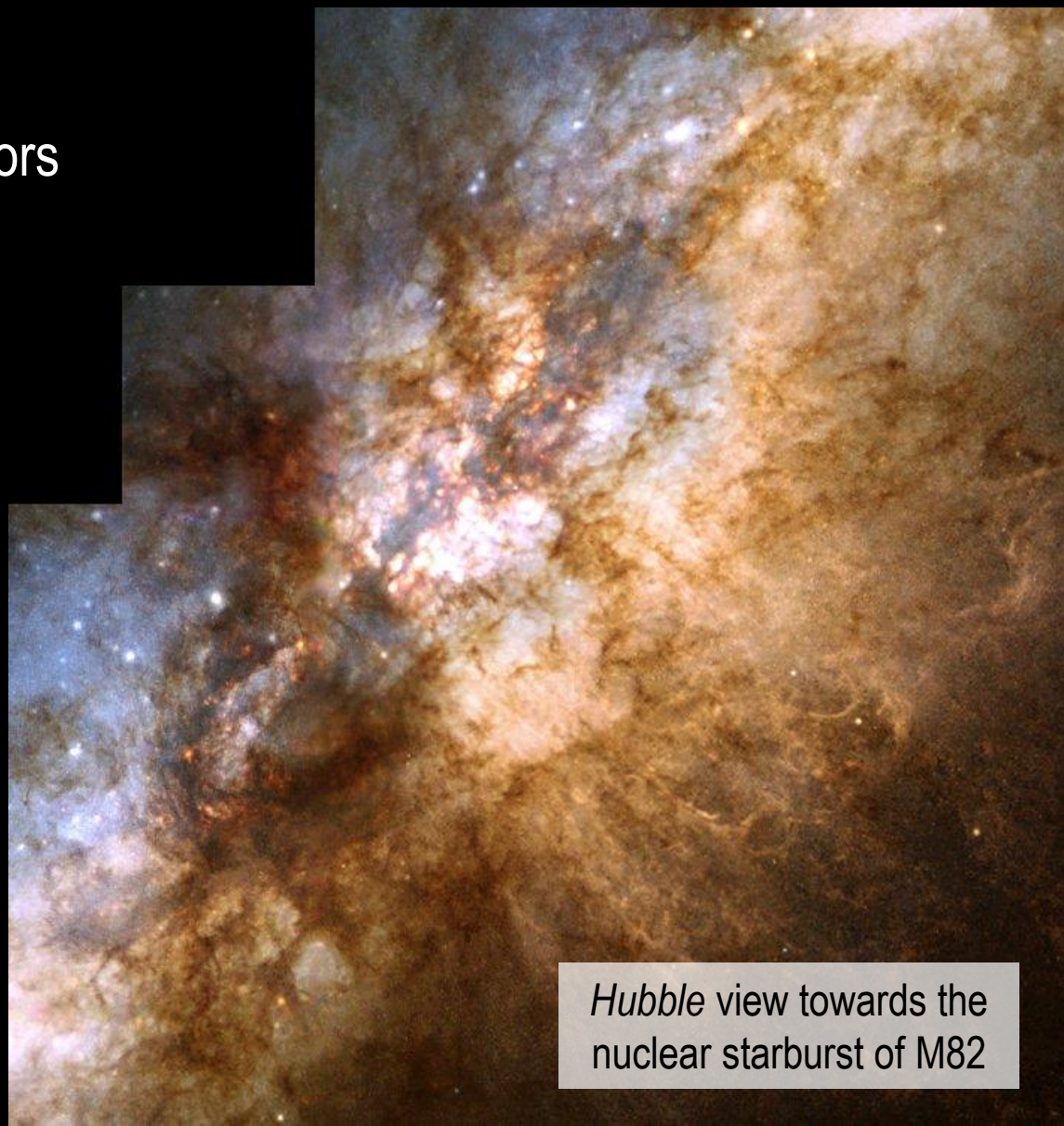
Fermi LAT finds star-forming galaxies

- » Rapid star-formation
  - Proposed CR accelerators
- » Targets for CR interaction
  - Dense interstellar gas
  - Intense radiation fields



Hubble view towards the nuclear starburst of M82

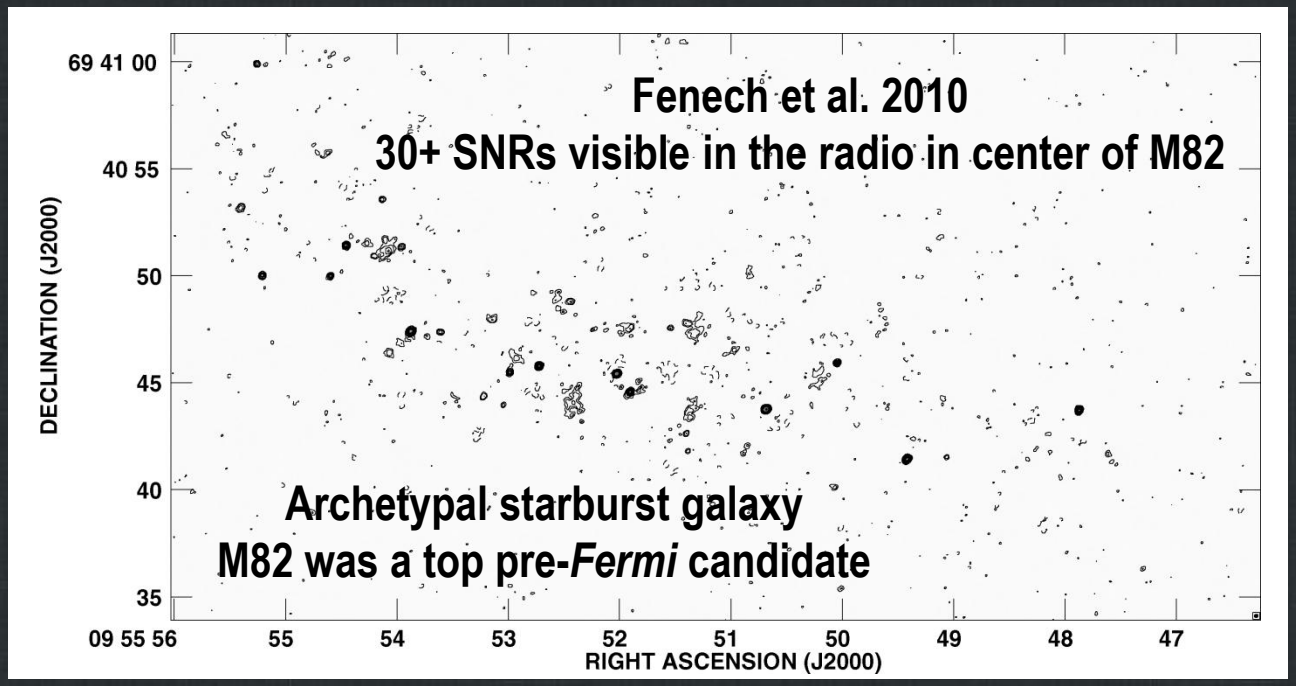
Star-forming galaxies

» Pre-*Fermi*

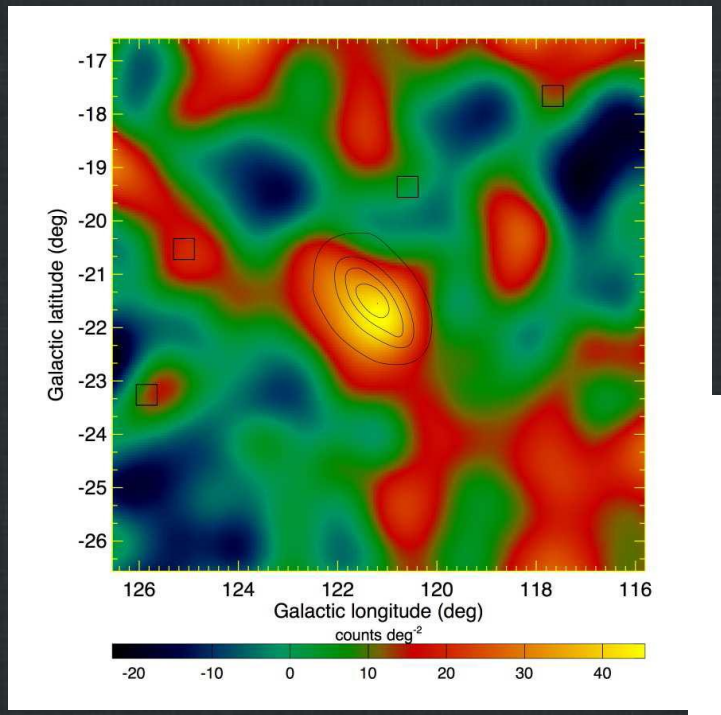
- LMC the only galaxy (other than Milky Way) detected by ISM emission at gamma-ray energies

» *Guaranteed* contribution to EGB (Pavlidou & Fields 2002)

- Predicted contribution comparable to that of blazars



Our sister galaxy M31 (Andromeda)

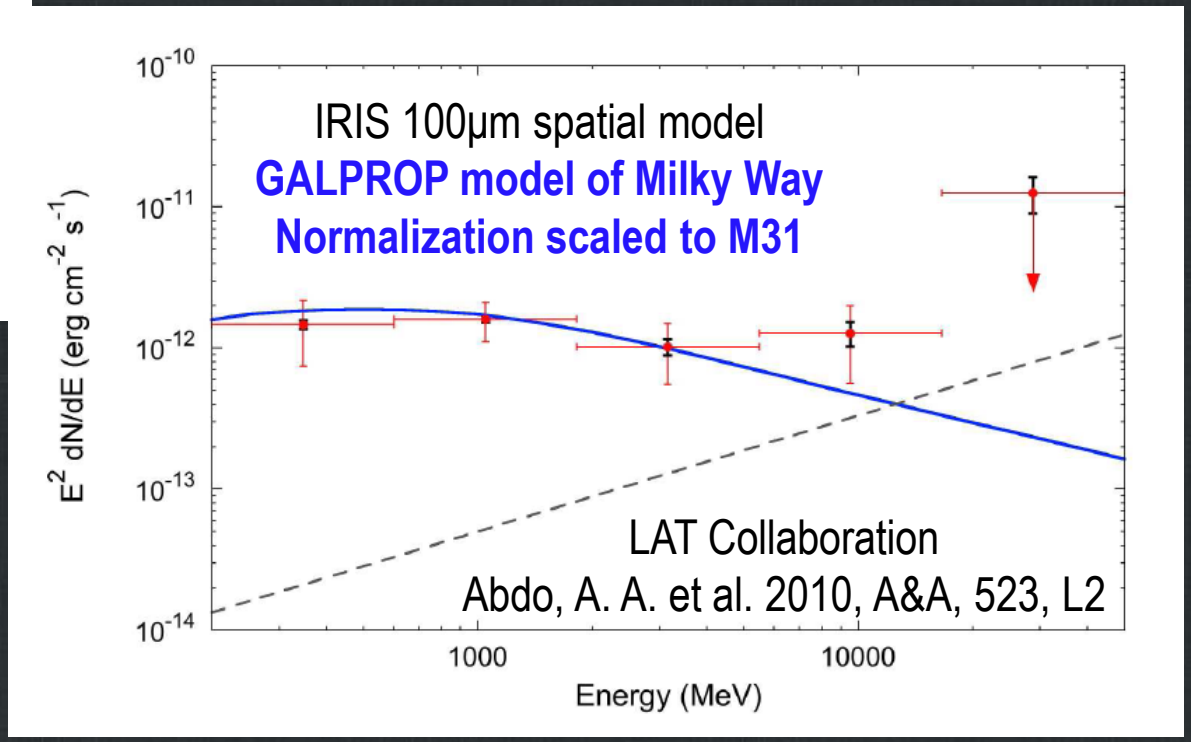


Smoothed residual counts map

0.2-20 GeV; 10° x 10° region

IRIS 100μm contours (black)

Not yet spatially resolved by the LAT



Spectrum consistent with Milky Way, but roughly half as luminous

Star-forming galaxies population study

» Selected by IR brightness and dense molecular gas content

- Fuel for star formation
- Traced by HCN (J=0-1) line emission (Gao & Solomon 2004)

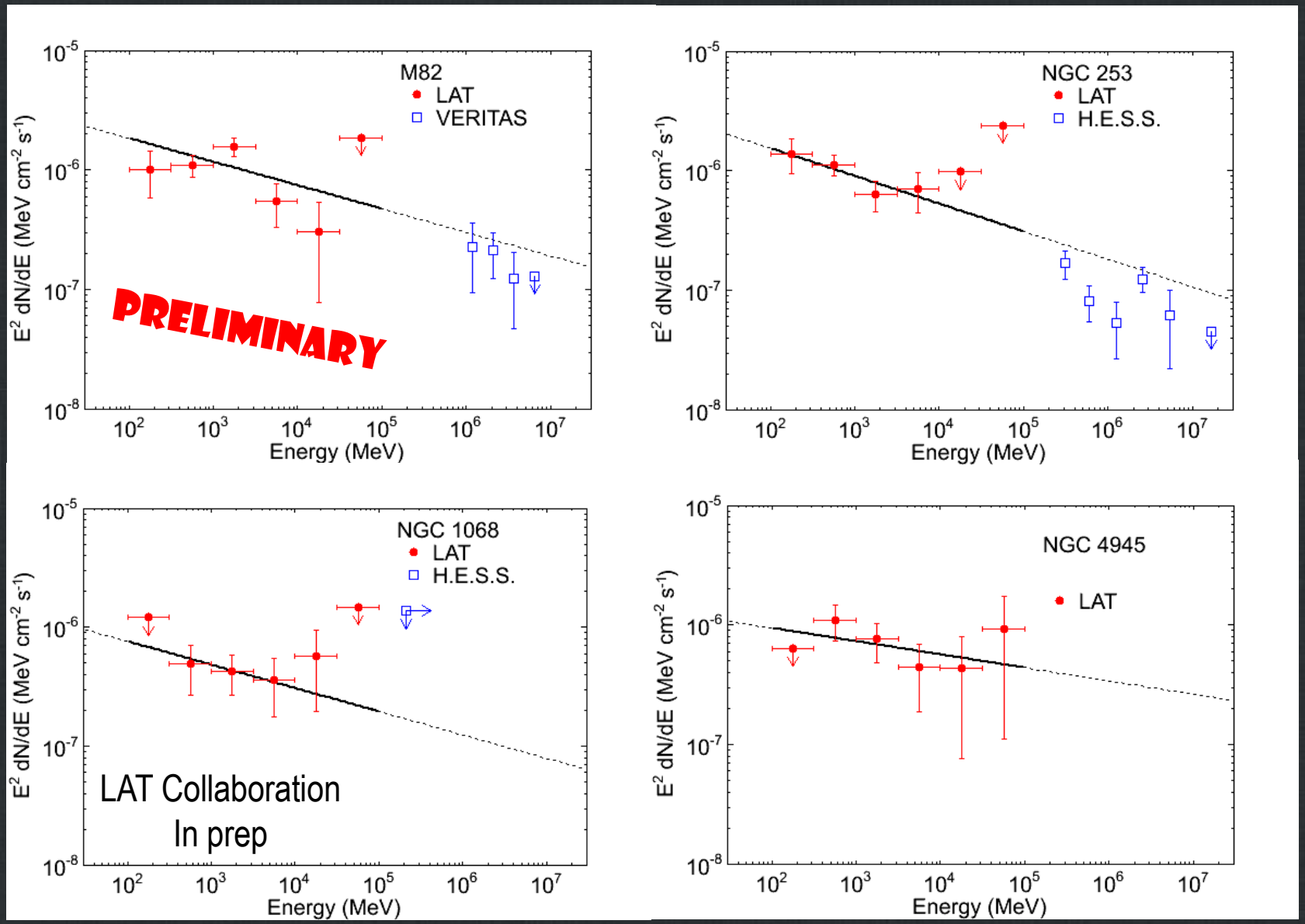
» Galaxy sample

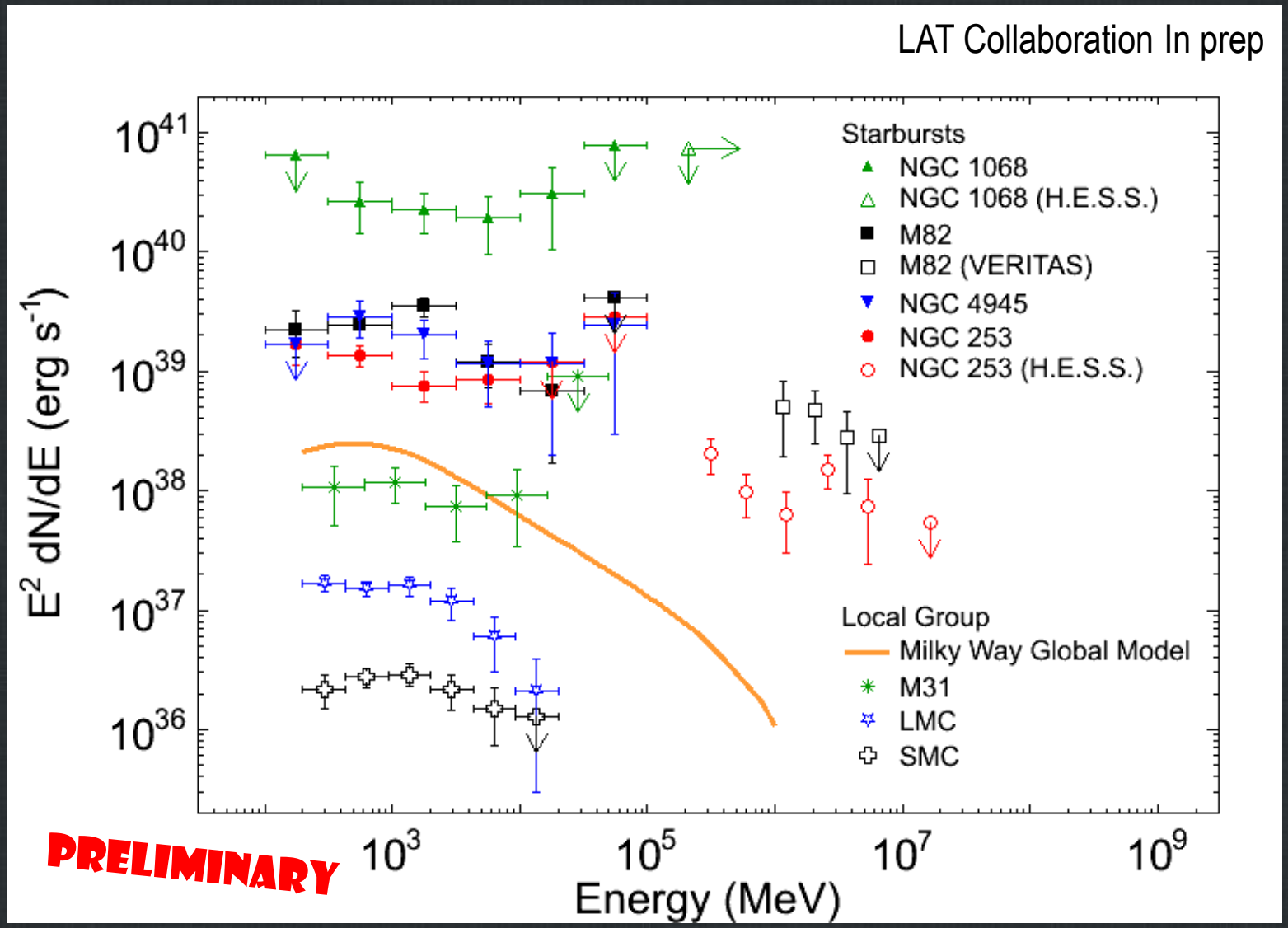
- 64 galaxies beyond Local Group
- Combine with 5 previously studied Local Group galaxies

» *Fermi* LAT observations

- 36 months
- 4 significant detections of starburst galaxies

SEDs of LAT-detected starbursts

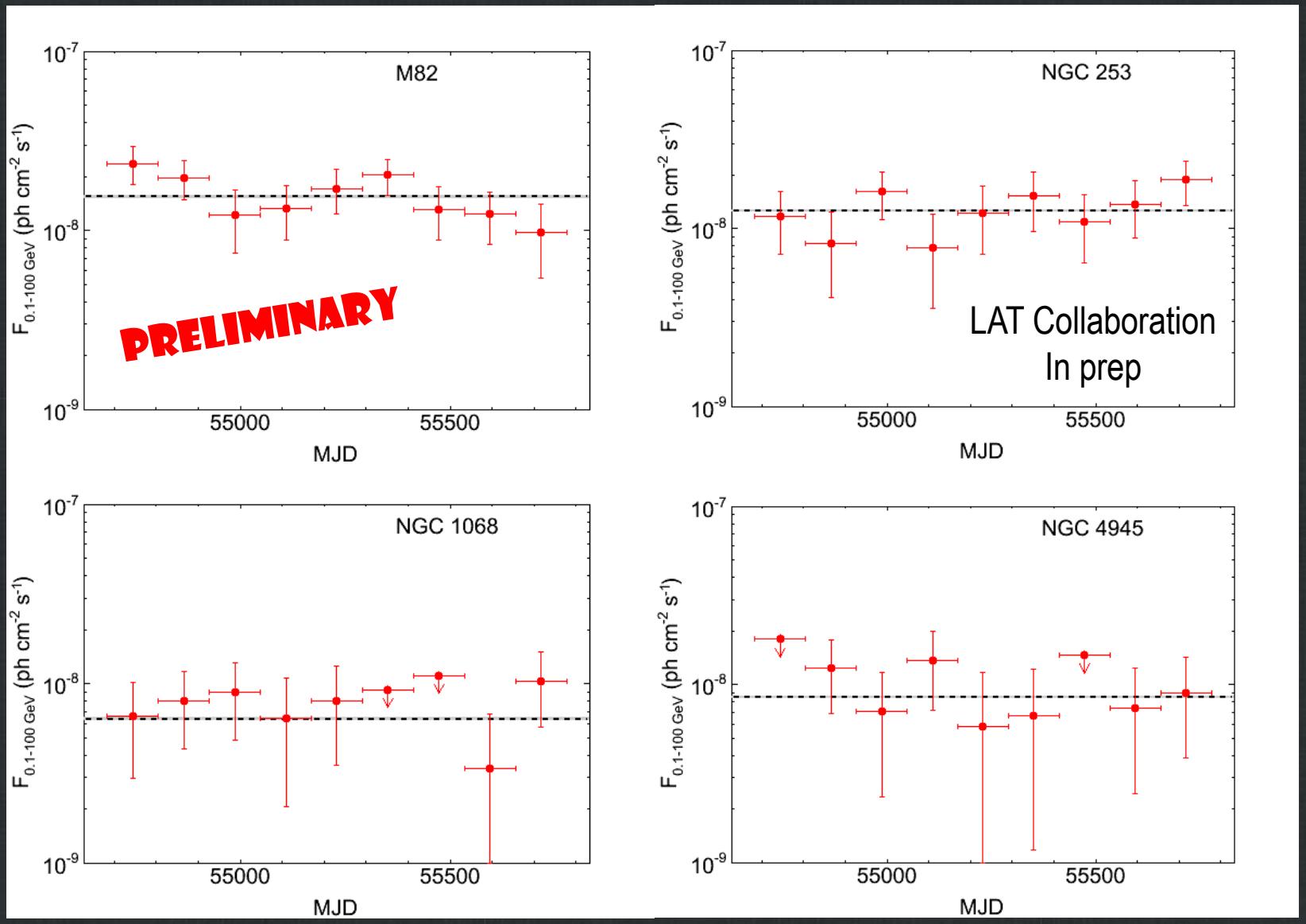




Starbursts M82 & NGC 253 have hard spectra (index ~2.2) extending to multi-TeV energies

Milky Way has index ~2.75 above the pion bump (repeats parent CR spectrum)

Steady gamma-ray emission

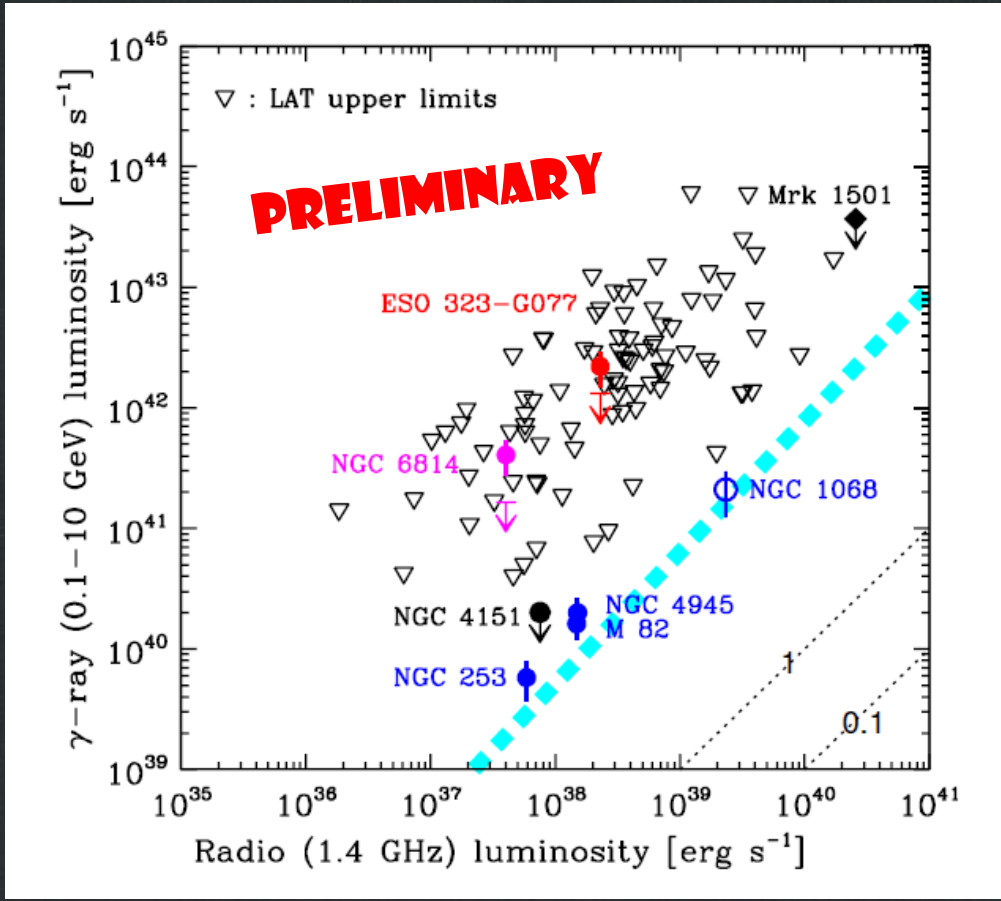


Origin of gamma rays from starbursting Seyfert 2 galaxies

» NGC 1068 and NGC 4945 are composite systems
- *Gamma rays from AGN or CRs?*

» 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 star-forming galaxies for consistency
- No conclusive detections

» Ideally would compare VLBI core radio luminosities, but these are not as widely available



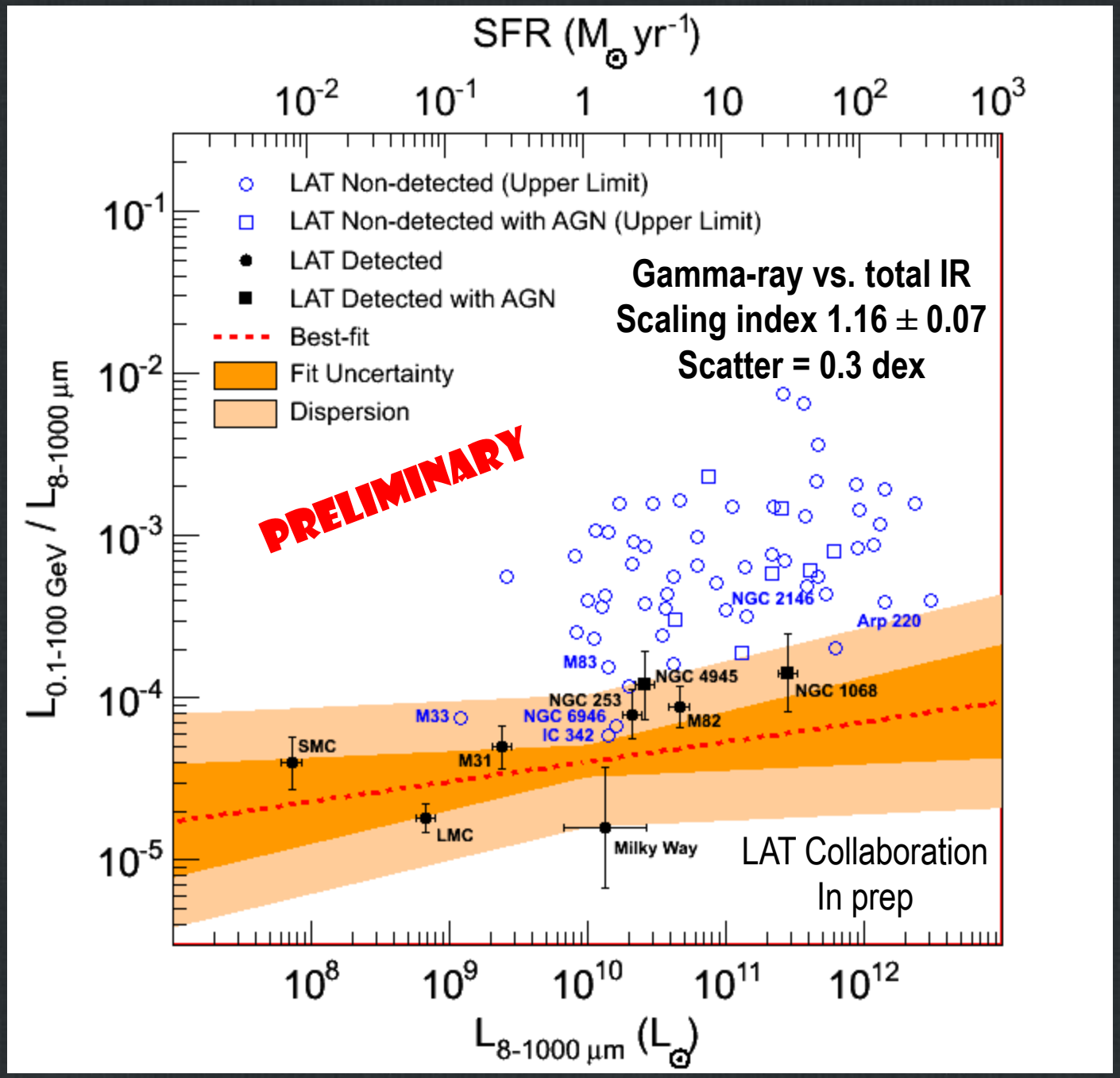
LAT Collaboration
In prep

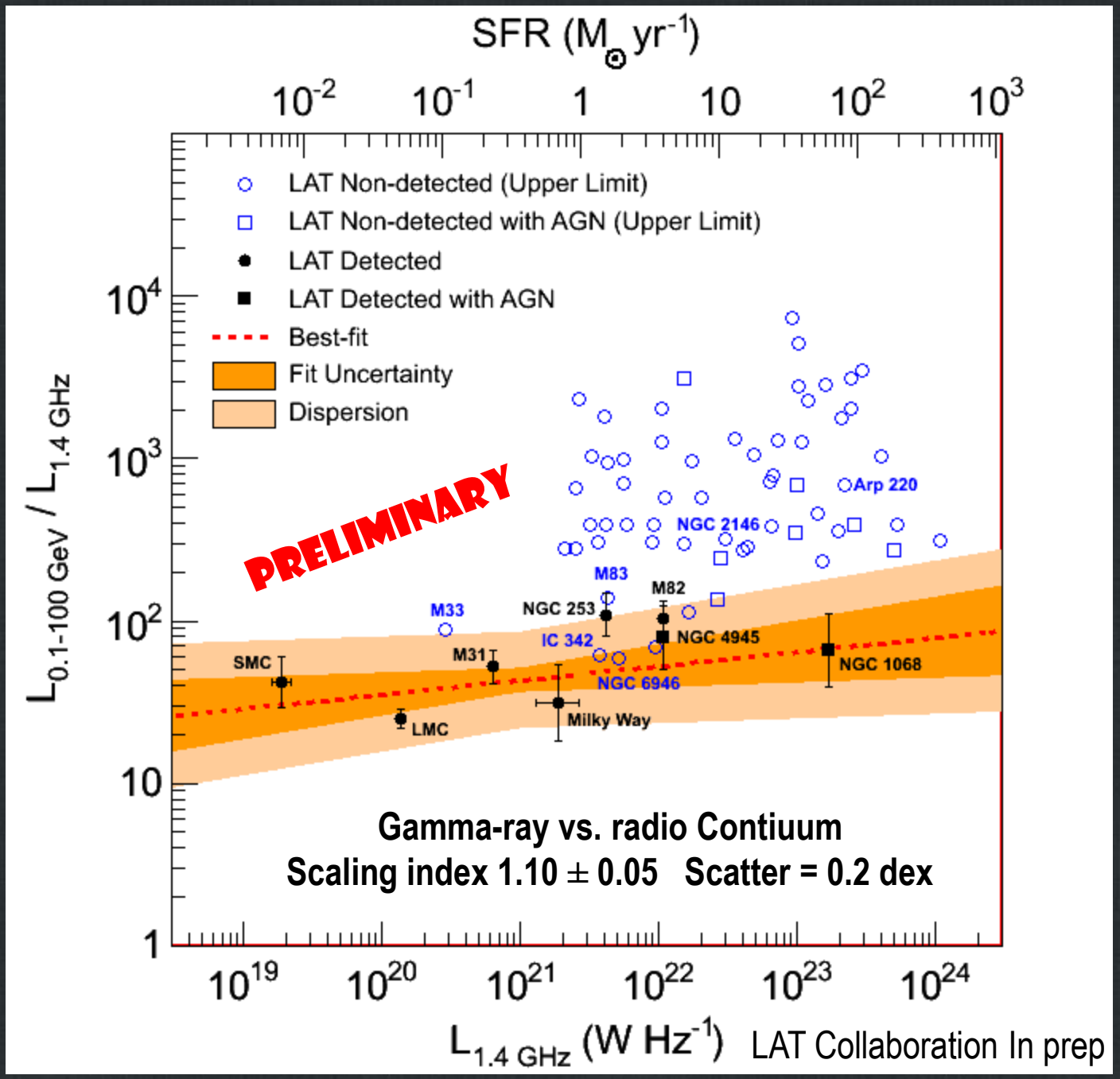
Multiwavelength tracers of SFR

» 3 photometric estimators
- Radio continuum at 1.4 GHz (Yun et al. 2001)
- Total IR 8-1000 microns (Kennicutt 1998)
- HCN (J=1-0) line luminosity (Gao & Solomon 2004)

» Radio continuum and HCN estimators calibrated off total IR
- Consistency check for individual galaxies

» Supernova rates can be estimated from stellar initial mass function


SFR ($M_\odot$ yr^{-1})
10^{-2}
10^{-1}
1
10
10^{2}
10^{3}
LAT Non-detected (Upper Limit)
LAT Non-detected with AGN (Upper Limit)
LAT Detected
LAT Detected with AGN
Best-fit
Fit Uncertainty
Dispersion
Gamma-ray vs. total IR
Scaling index 1.16 ± 0.07
Scatter = 0.3 dex
PRELIMINARY
$L_{0.1\text{-}100\ GeV}$ / $L_{8\text{-}1000\ \mu m}$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
NGC 2146
Arp 220
M83
NGC 4945
NGC 1068
NGC 253
NGC 6946
IC 342
M82
M33
SMC
M31
LMC
Milky Way
LAT Collaboration
In prep
10^{8}
10^{9}
10^{10}
10^{11}
10^{12}
$L_{8\text{-}1000\ \mu m}$ ($L_\odot$)



LAT Collaboration In prep

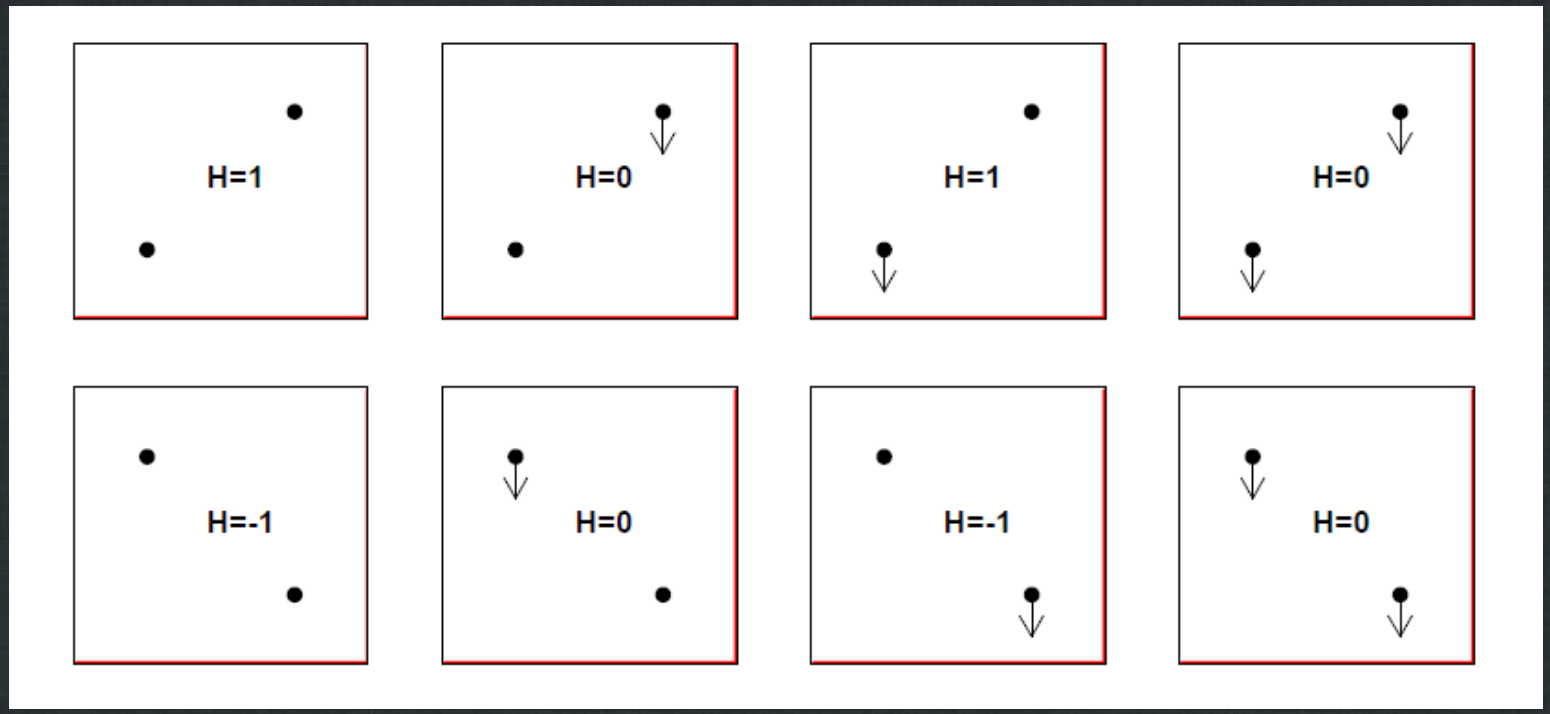
Correlation significance test

» Kendall tau correlation coefficient

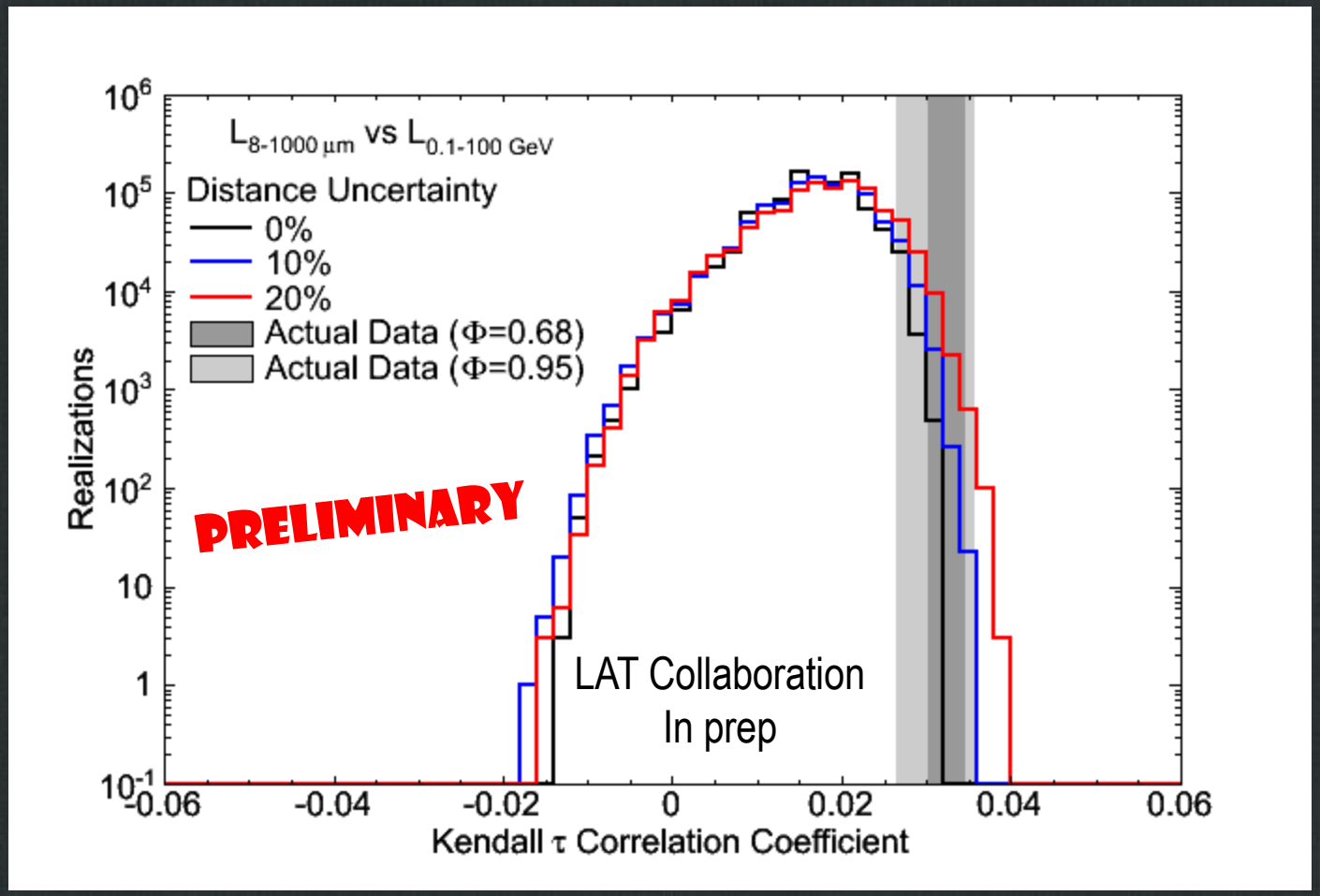
- Non-parametric, rank correlation test (i.e. how monotonic are data?)
- *Can be generalized to include upper limits*

» Tau coefficient is sum of rank values ("*H*") over all pairs of points

- Tau=1 corresponds to monotonically increasing data with no upper limits

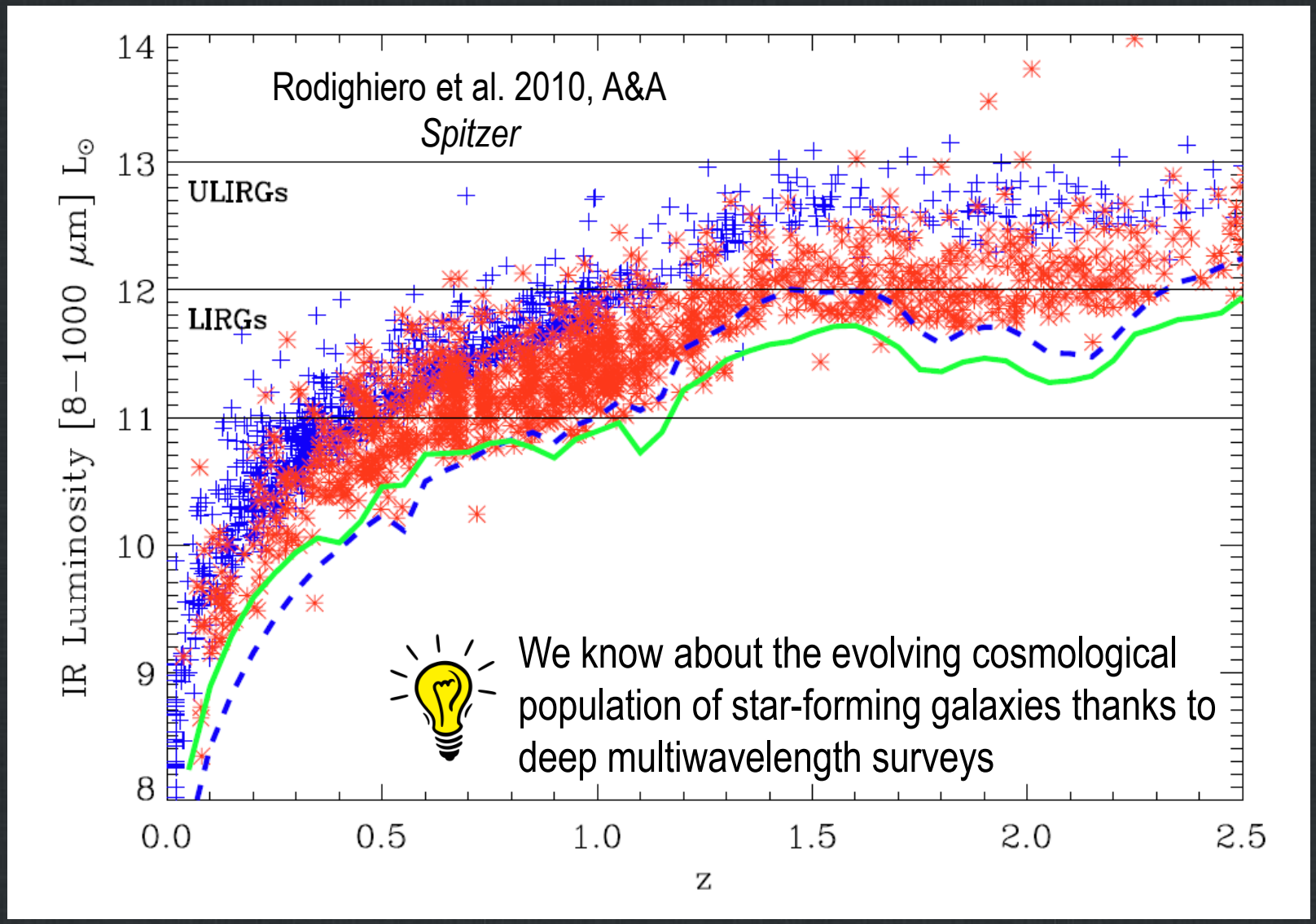


Correlation significance test

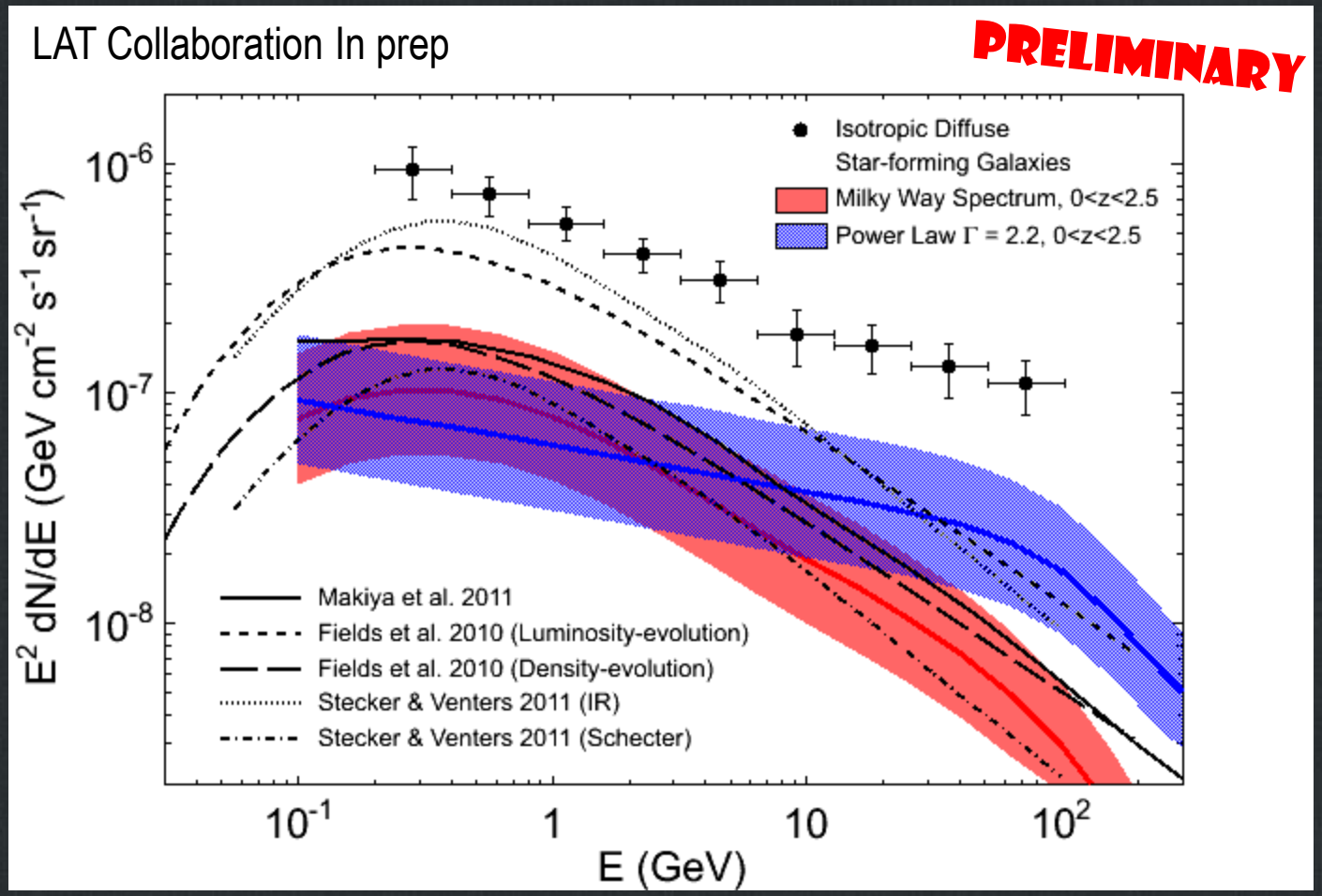


Solid curves represent distribution of correlation coefficients under the "null-hypothesis" that luminosities are uncorrelated, generated by scrambling gamma-ray luminosities between galaxies and imposing a LAT flux sensitivity limit. Gray bands represent range of correlation coefficients that could be obtained from actual data given uncertainties in LAT flux measurements.

Combine with multiwavelength surveys



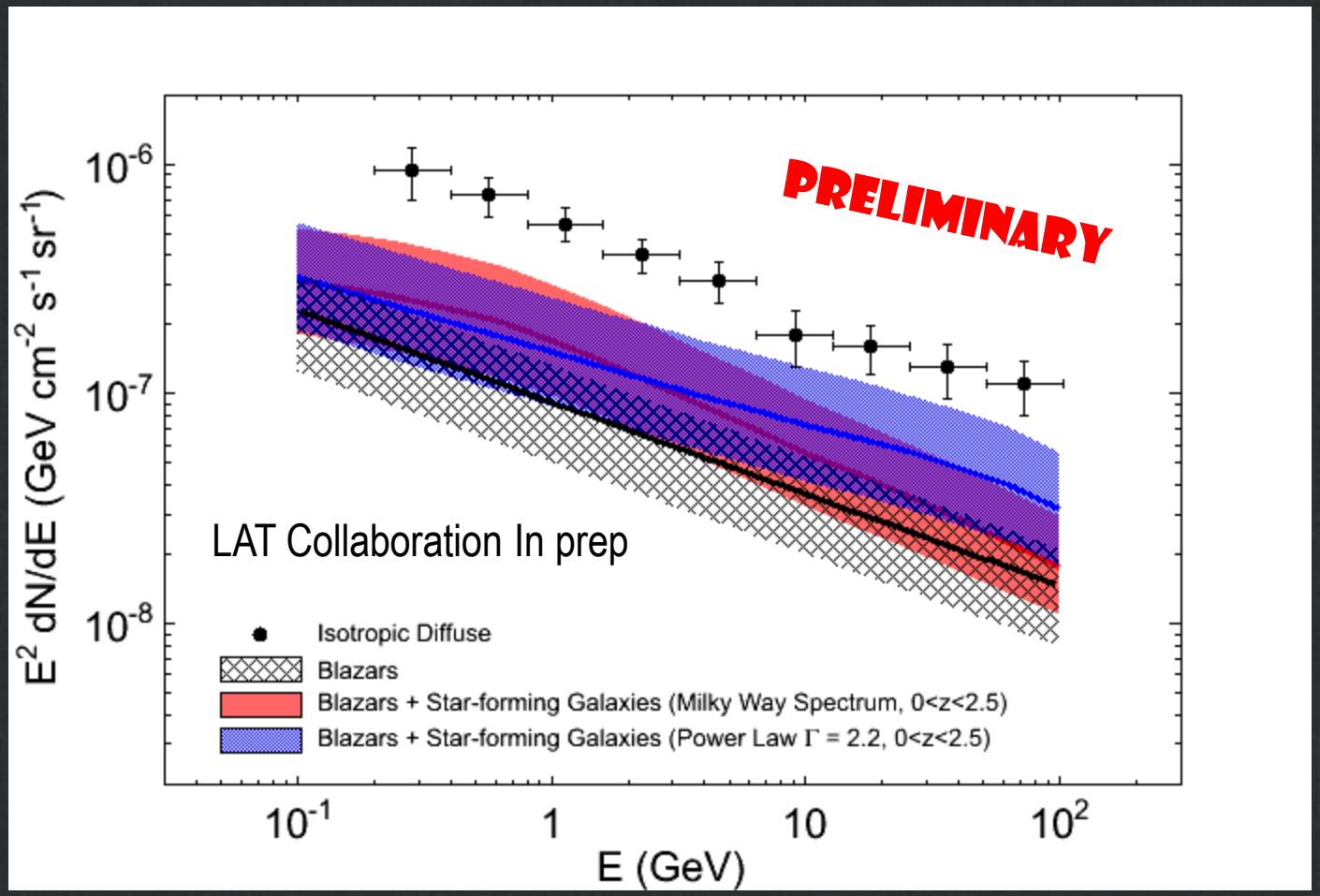
Star-forming galaxies only



» Consider two spectral forms (bracket uncertainty in transition)

» Star-forming galaxies constitute 5-20% of EGB 0.1-100 GeV intensity

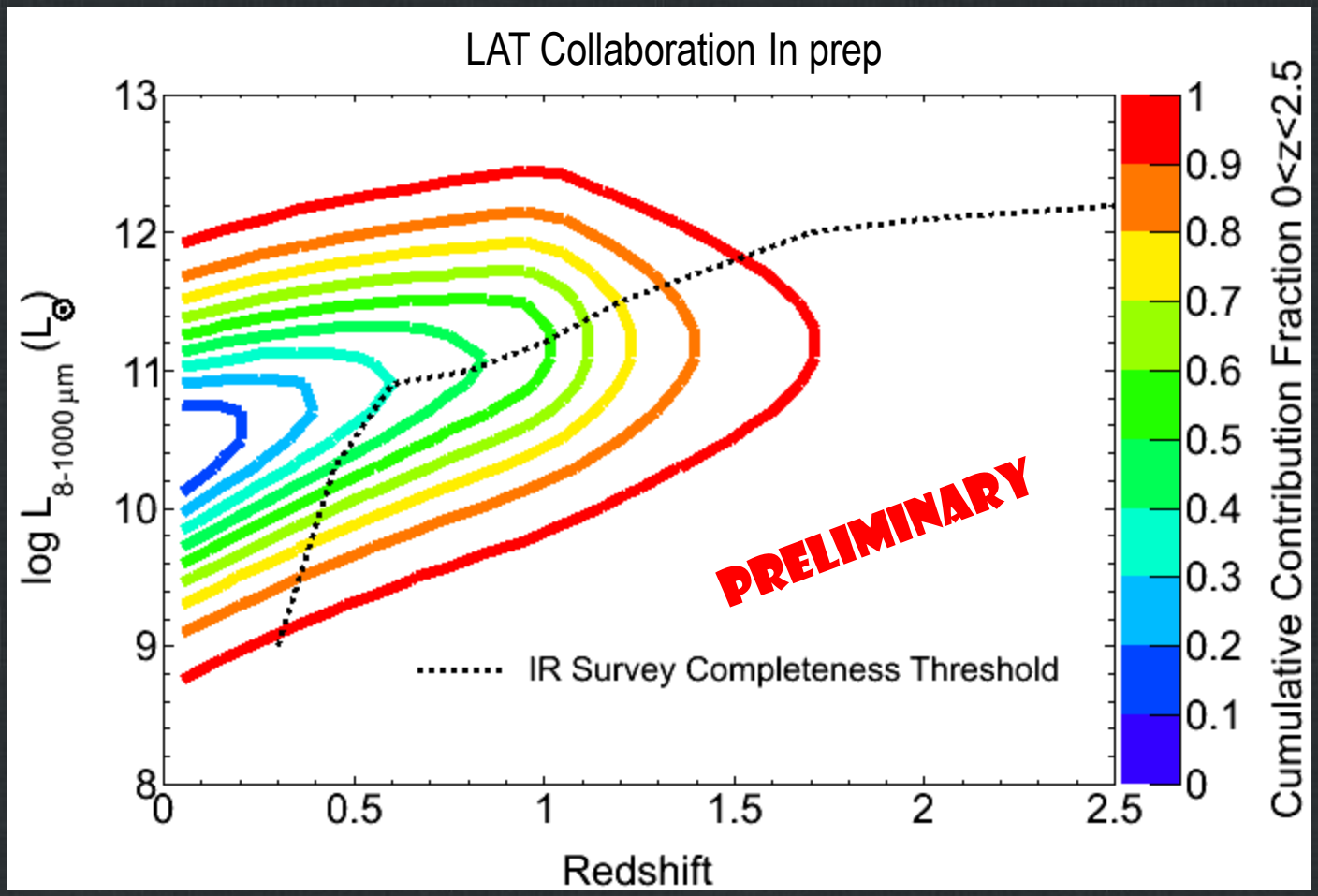
Sum of star-forming galaxies and blazars



Star-forming galaxies and EGB

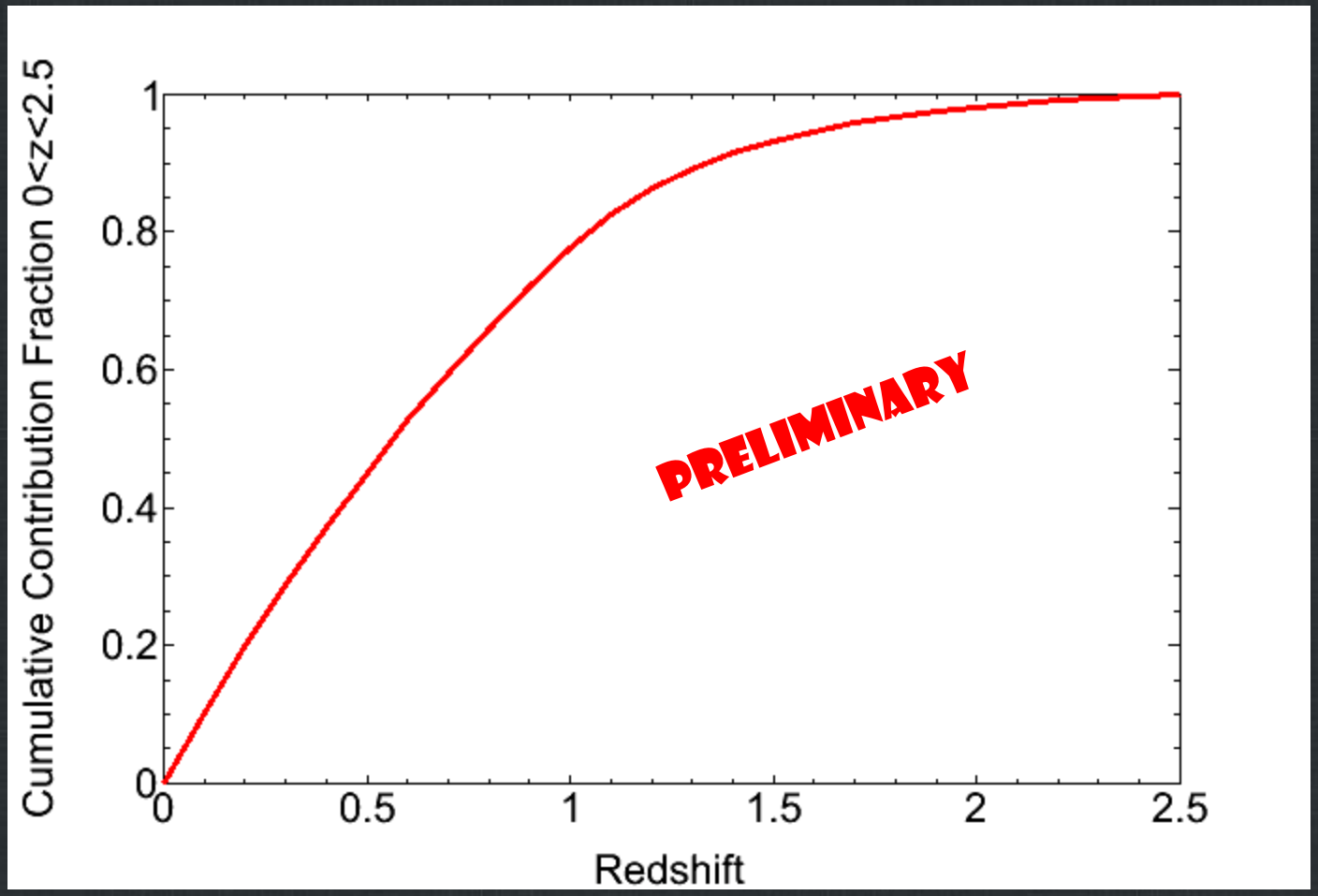
» Normalized to total contribution up to z=2.5

» Large contribution of low-z Milky Way and M82 / NGC 253 analogues



Star-forming galaxies and EGB

» Normalized to total contribution up to z=2.5



Predictions for 10-year *Fermi* LAT mission

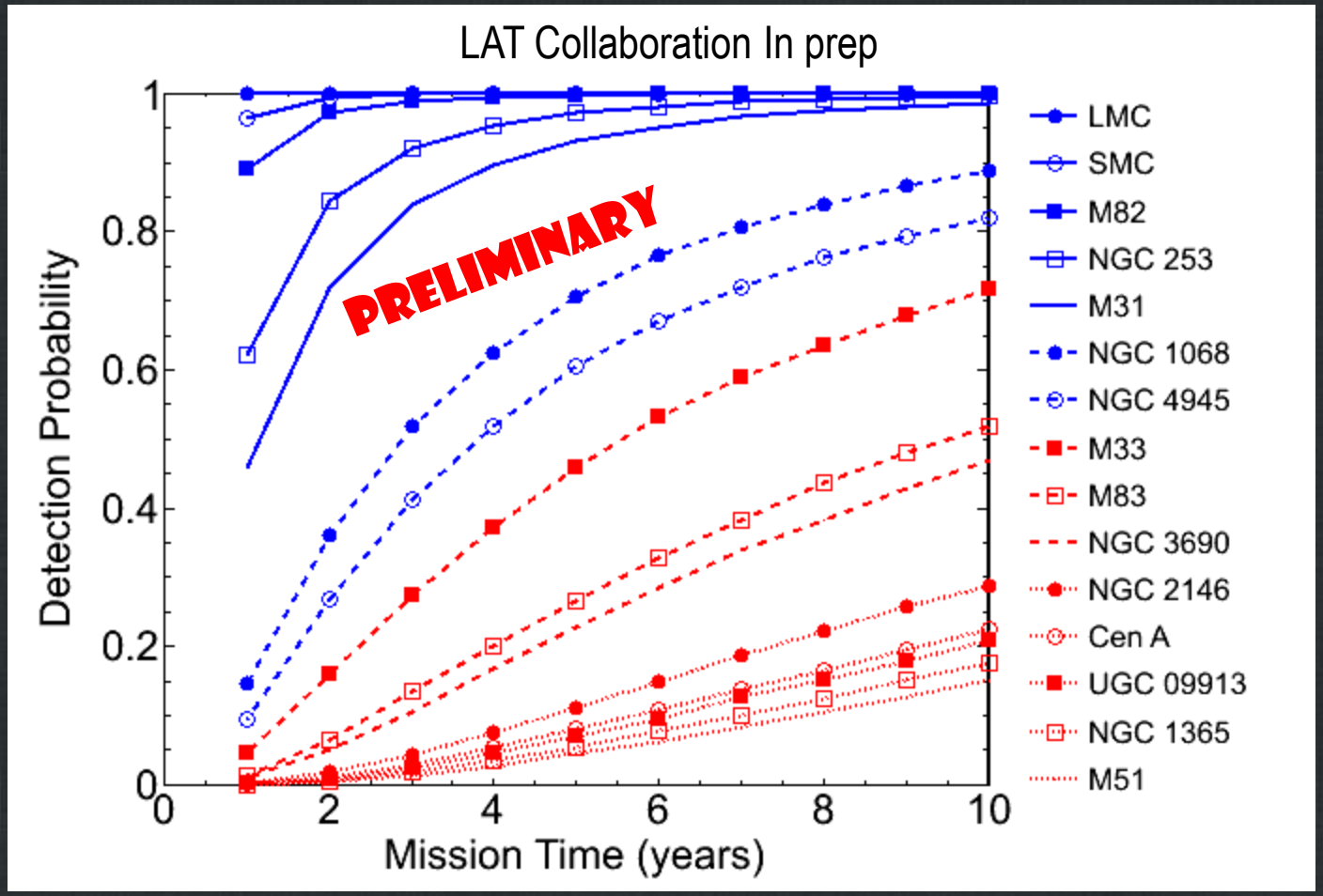
1. IRAS all-sky flux-limited sample in IR (60 micron)
2. Calculate LAT flux sensitivity at positions of galaxies
3. Estimate gamma-ray fluxes from scaling relation
   - Perform many realizations with scatter to include dispersion (probabilistic)
4. Count number of galaxies above threshold in each realization

Details

» Point source, power law index 2.2

» “4 sigma” statistical significance

Individual galaxies

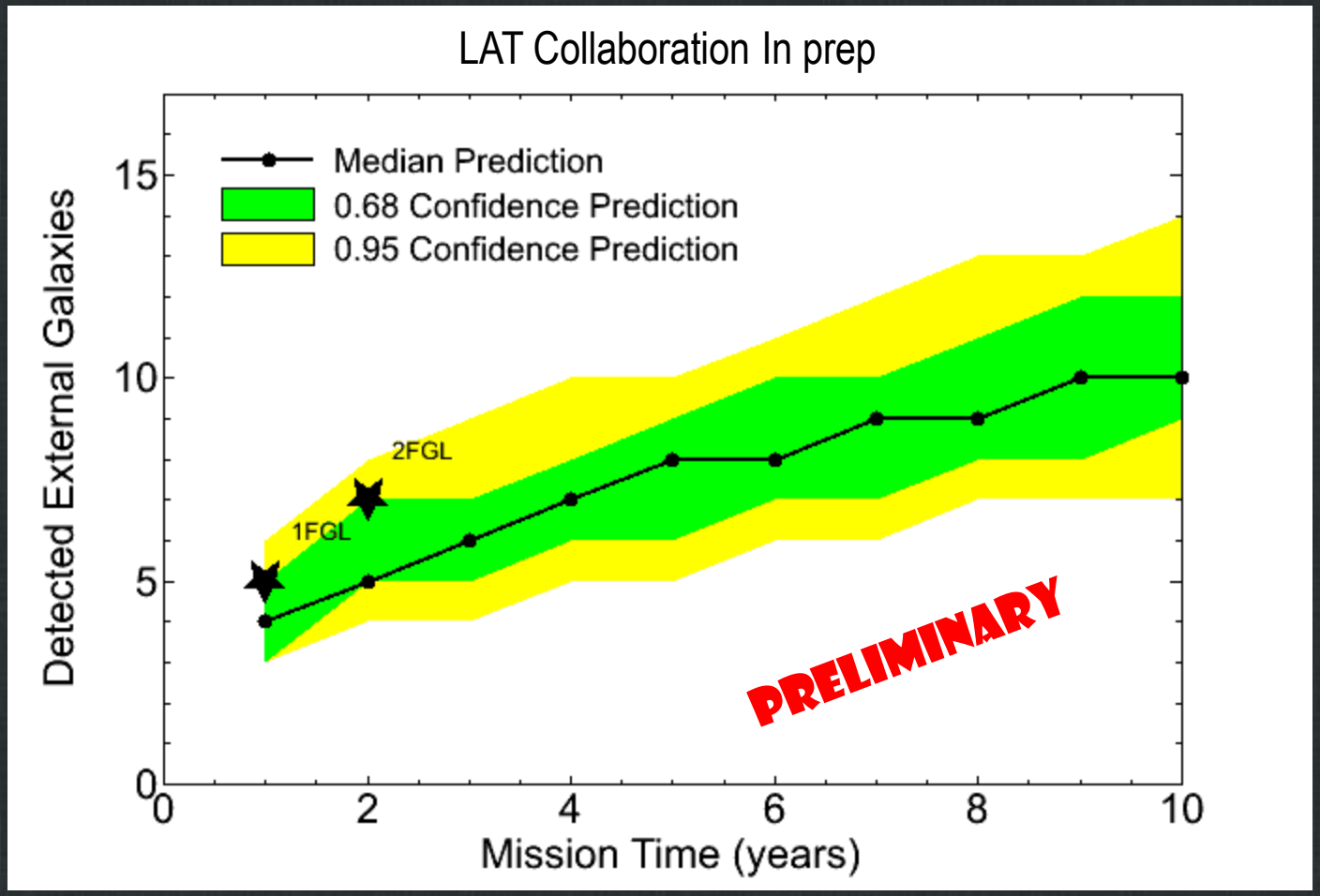


Cen A is likely dominated by AGN

LAT-detected

Not yet LAT-detected

Total number of LAT-detected galaxies



» Consistency check for the scaling relation

» Expect a few more galaxies in coming years

Discussion points

» **Gamma-ray sky**

- Defining the extragalactic gamma-ray background (EGB)

» ***Fermi* LAT**

» **Extragalactic population census**

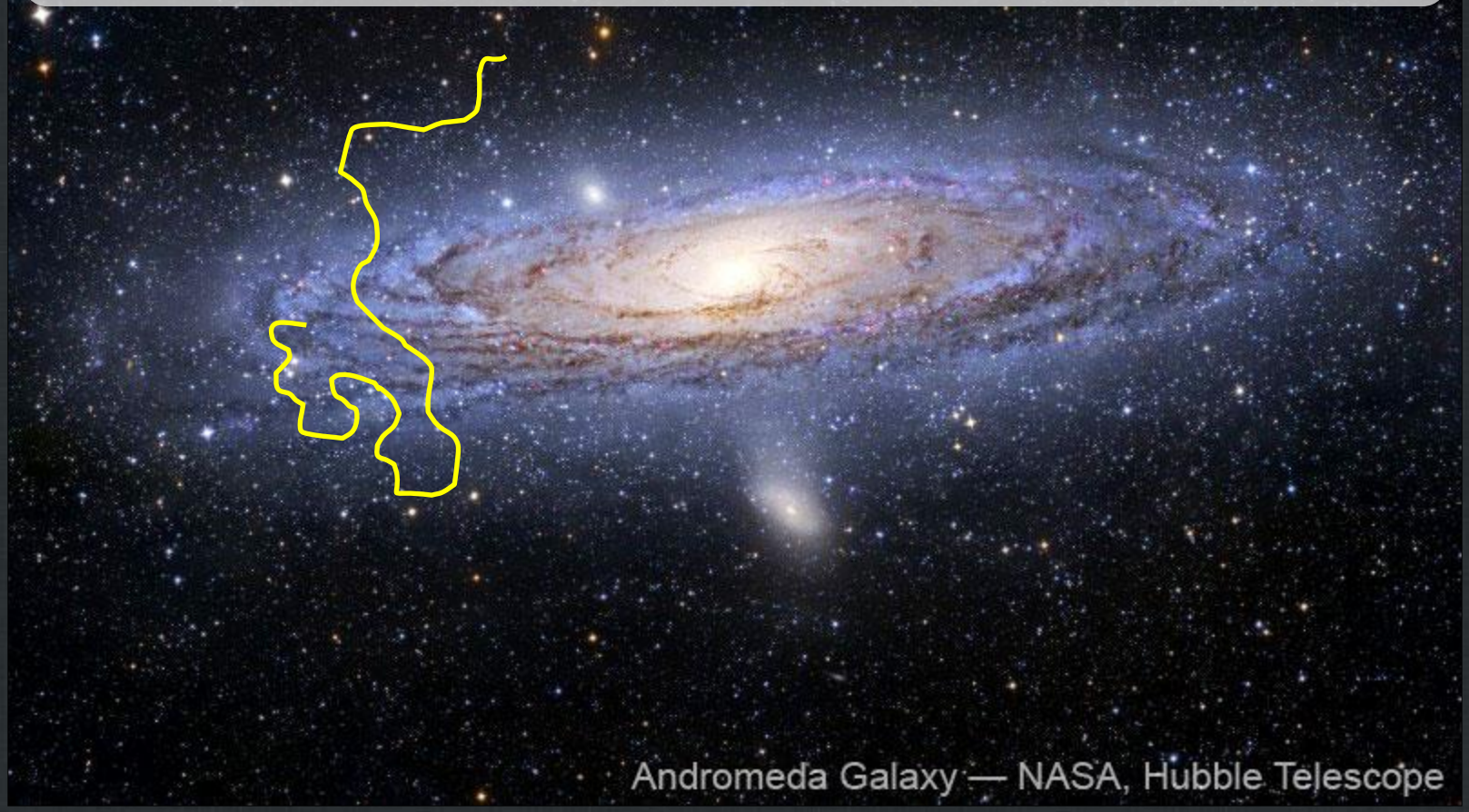
- **Searching for galaxy clusters**
- **Finding star-forming galaxies**
- DETOUR **Physics of cosmic rays**

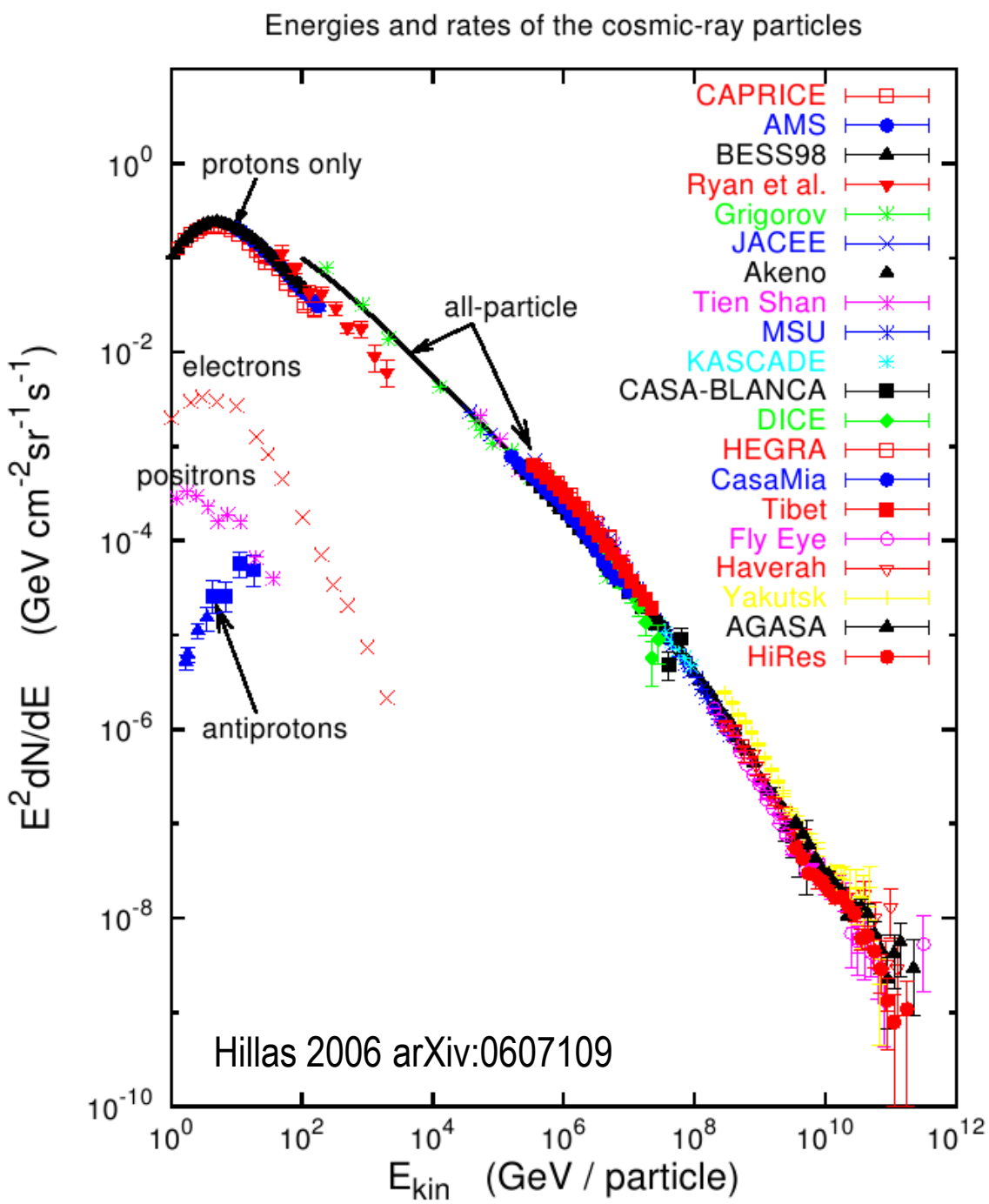
» **Extending the EGB spectral measurement**

DETOUR

Cosmic-ray Physics

Gamma-ray luminosity is product of
CR luminosity and **efficiency of turning CR energy into gamma-ray energy**





Supernova paradigm for Galactic cosmic rays

Key ideas

- Magnetic field amplification at SNR shocks
- ~10% of SNR kinetic energy to acceleration of CR nuclei
- Injection spectral index ~2 (can be softened by diffusion)

1st order Fermi acceleration
Diffusive Shock Acceleration

Testing the paradigm

1. Quasi-linear scaling of gamma-ray luminosity with SFR
   - CR luminosity related to SFR (?)

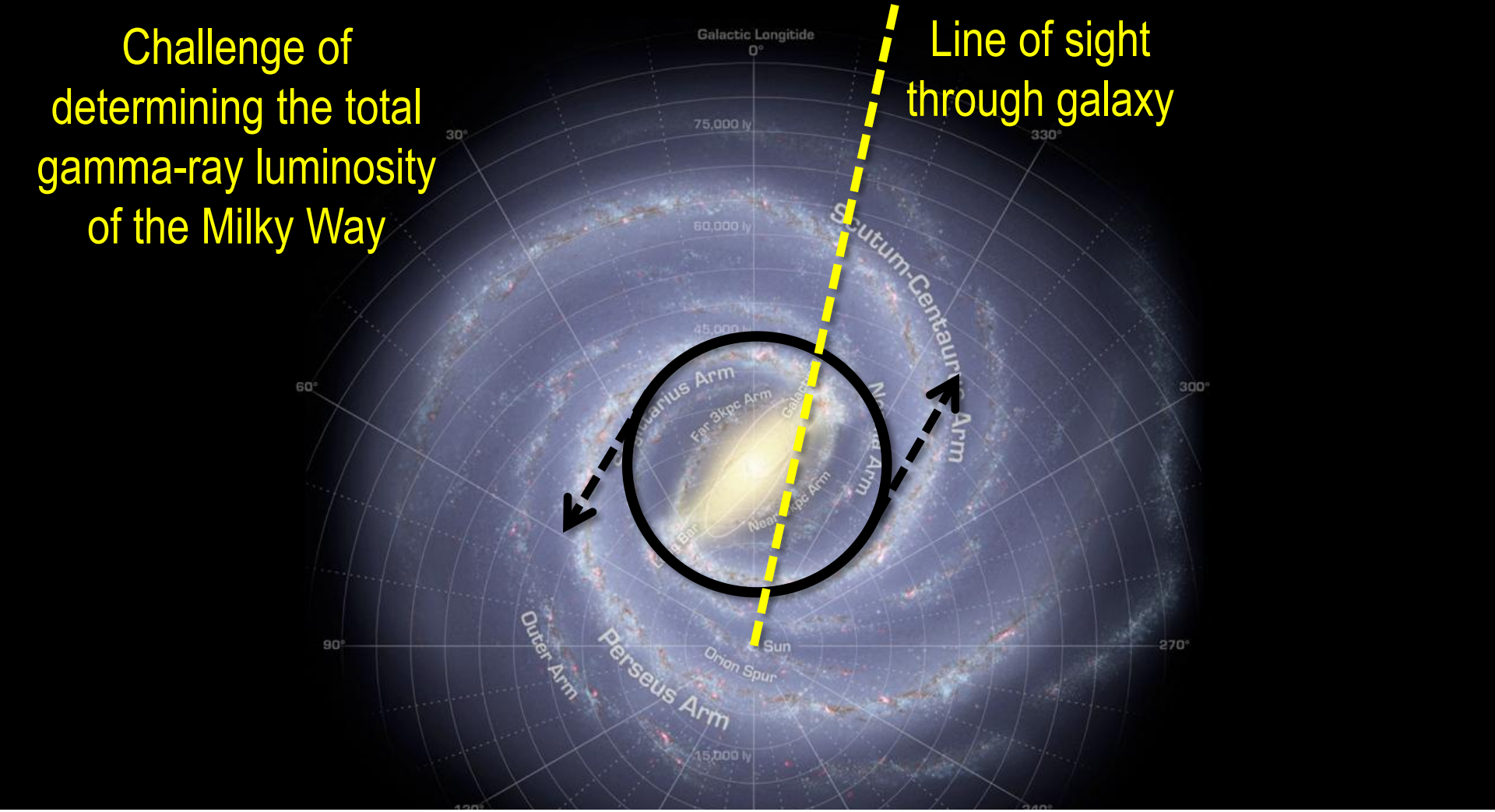
2. Estimate galactic supernova power as function of SFR

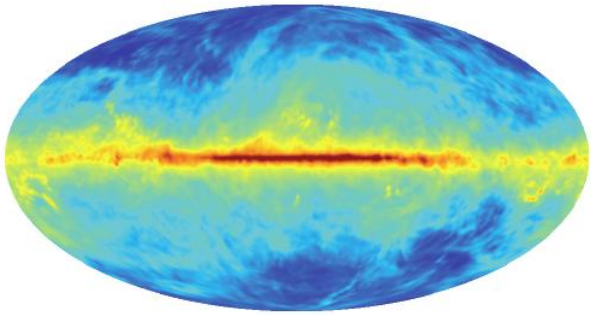
CR acceleration efficiency x **Efficiency of transforming CR energy to gamma-rays** ~ 10^{-3}

Assume CR luminosity is proportional to the number of accelerators

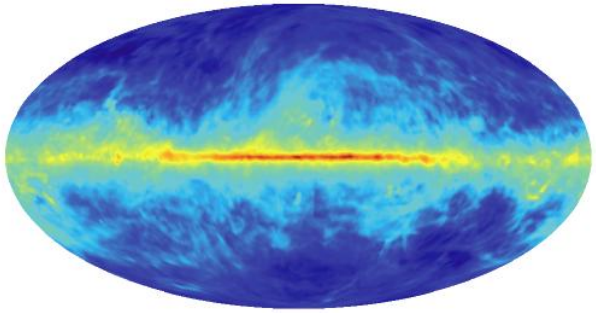
Able to perform a consistency check for the Milky Way

Challenge of determining the total gamma-ray luminosity of the Milky Way

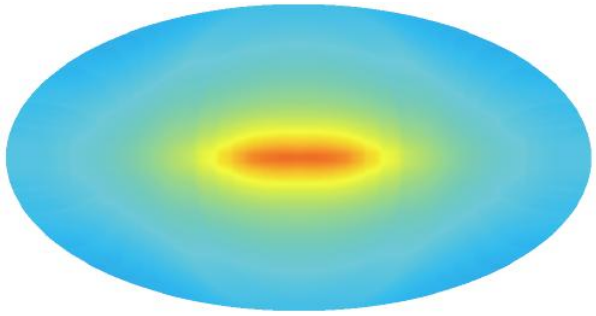




Neutal pion decay



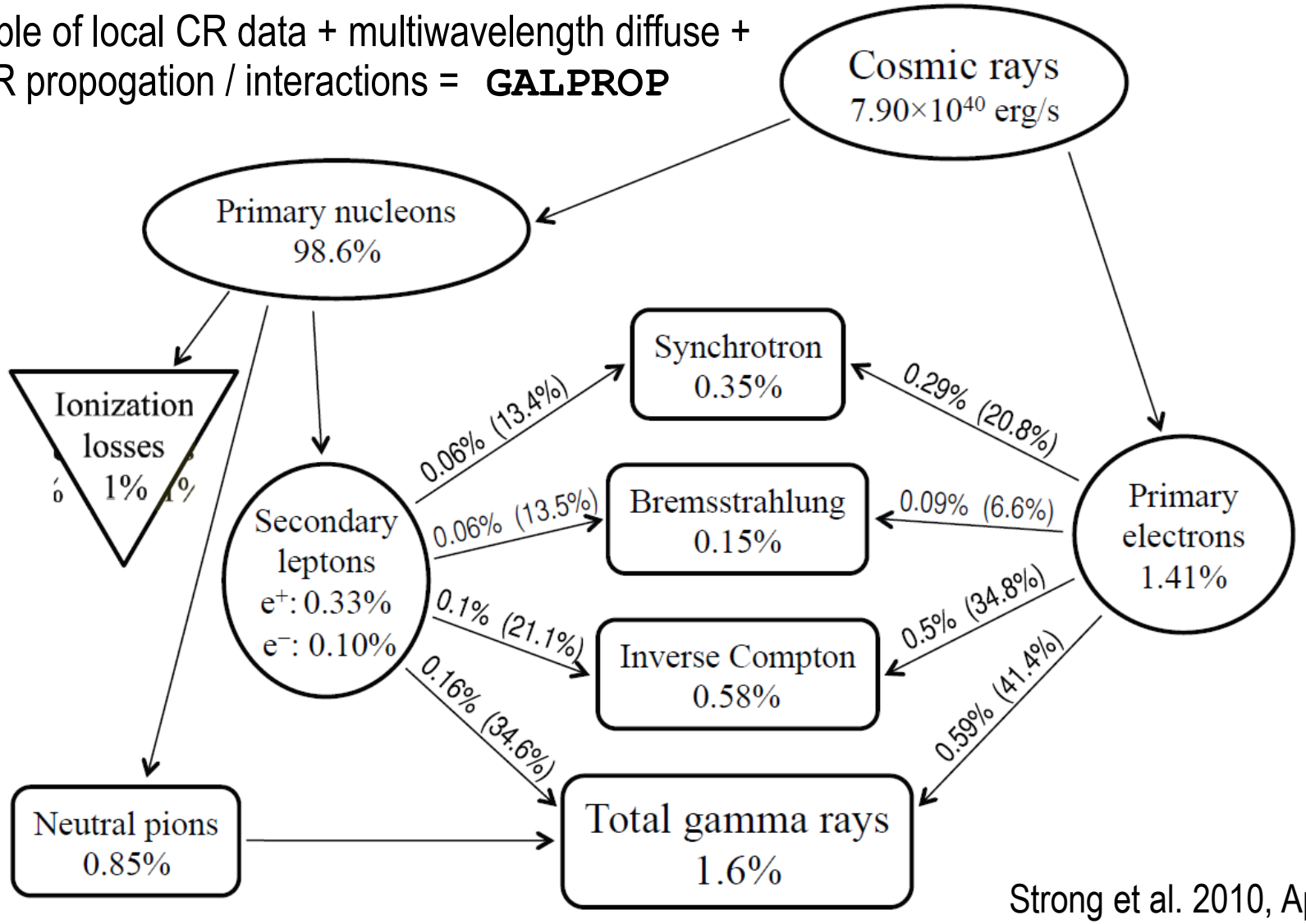
Bremsstrahlung



Inverse Compton

Cosmic ray to gamma ray efficiency

Ensemble of local CR data + multiwavelength diffuse + CR propogation / interactions = **GALPROP**



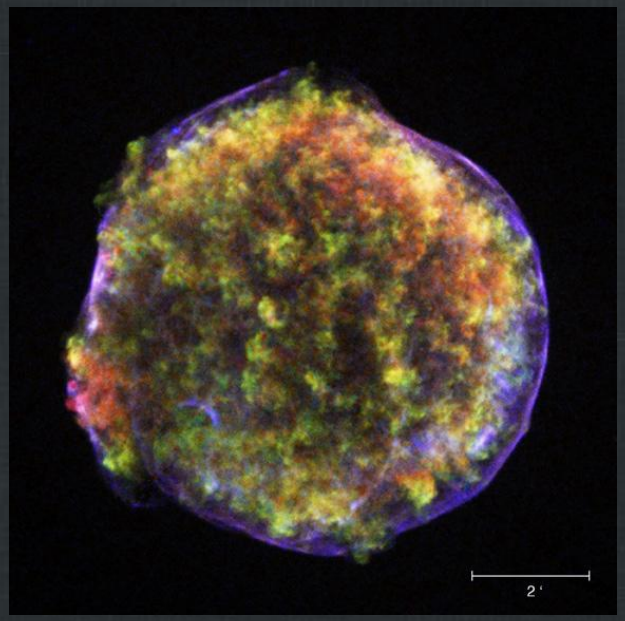
Strong et al. 2010, ApJ

Supernova to CR efficiency

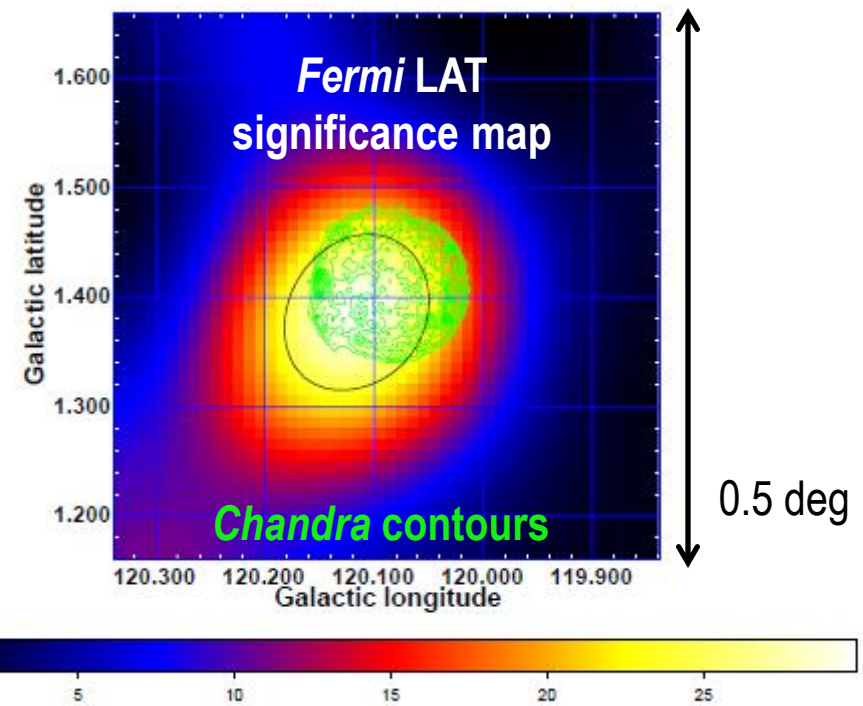
» Pionic gamma rays at the source would be most direct evidence for acceleration of CR nuclei

» Several SNRs detected by gamma-ray telescopes

- *What fraction of observed gamma rays are **hadronic** origin?*



Chandra **image of historic Tycho SNR (1572)**



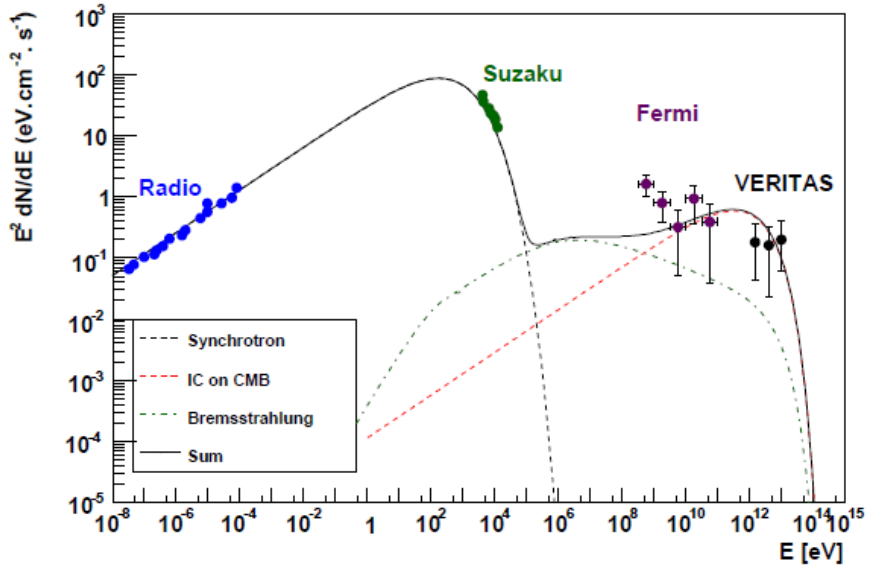
LAT Collaboration, Giordano et al. 2011, ApJL, in press

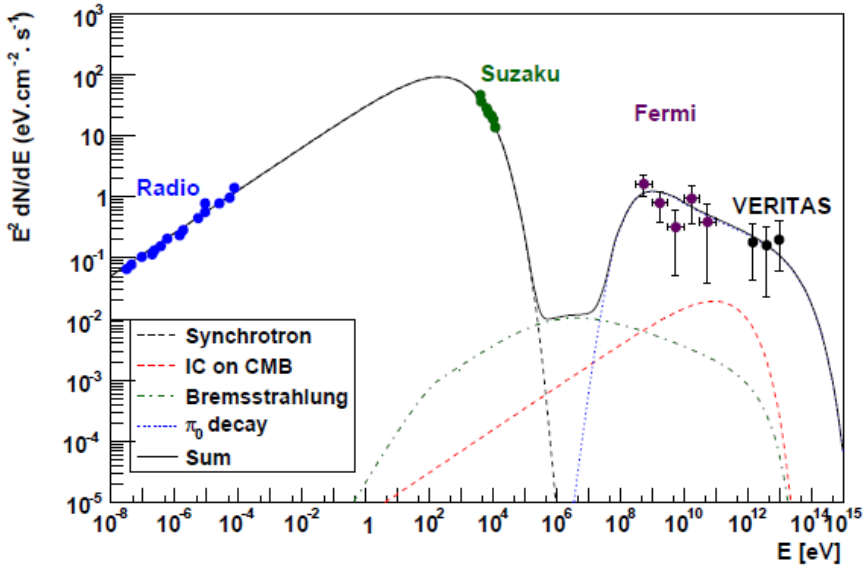
Supernova to CR efficiency

» Broad-band SED disfavors leptonic interpretation of gamma-ray emission

- Photon index 2.3 ± 0.2 likely repeats underlying CR nuclei spectrum

» 6-15% of SN energy transferred to CR nuclei





LAT Collaboration Giordano et al. 2011, ApJL, in press

Cosmic rays in other galaxies

» Scaling relationship of gamma-ray luminosity with SFR slightly non-linear (index 1.15±0.1)

» Assume that number of CR accelerators scales with SFR and typical acceleration efficiency is universal

» Galaxy similar to M82 with 10x SFR of Milky Way is ~50% more efficient in terms of converting CR energy to gamma rays

- Interpretation depends on fraction of gamma rays attributed to interactions of CR nuclei in ISM
- Larger hadronic emission component favored, but diffuse leptonic emission and discrete sources must also contribute
- Place upper bound on the interaction efficiency of CR nuclei

Discussion points

» **Gamma-ray sky**

- Defining the extragalactic gamma-ray background (EGB)

» ***Fermi* LAT**

» **Extragalactic population census**

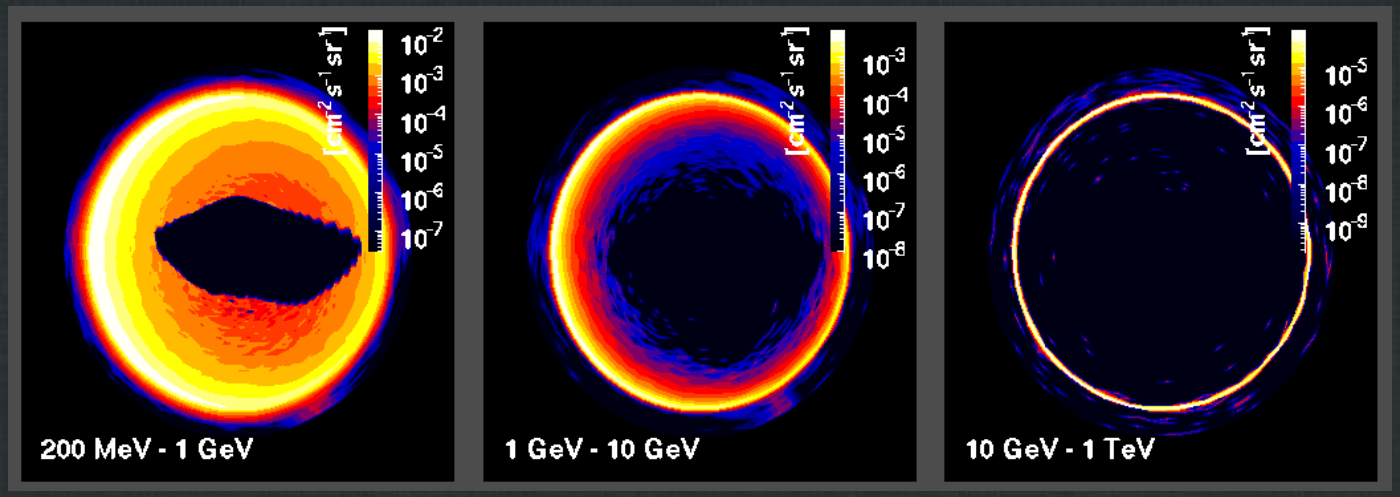
- **Searching for galaxy clusters**
- **Finding star-forming galaxies**
- DETOUR **Physics of cosmic rays**

» **Extending the EGB spectral measurement**

Extending *Fermi* LAT EGB spectrum

» Lower energies (down to ~20 MeV)

- CR electrons / positrons
- CR-induced gamma rays from Earth's atmosphere

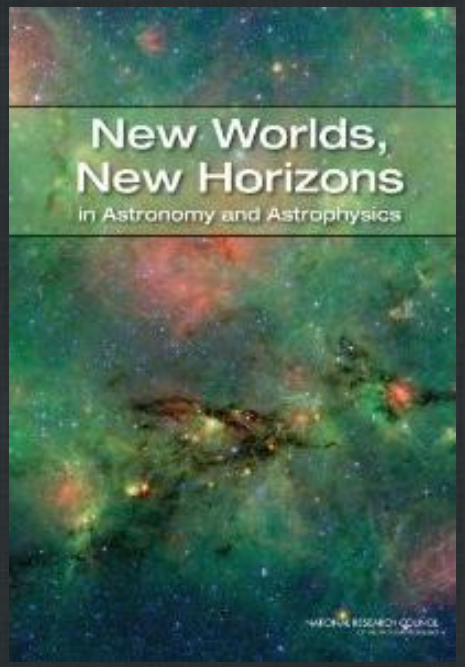


» Higher energies (up to ~TeV)

- Validation of particle background model in low-Earth orbit, event selection, & effective area
- Challenge of low statistics

TeV gamma-ray outlook

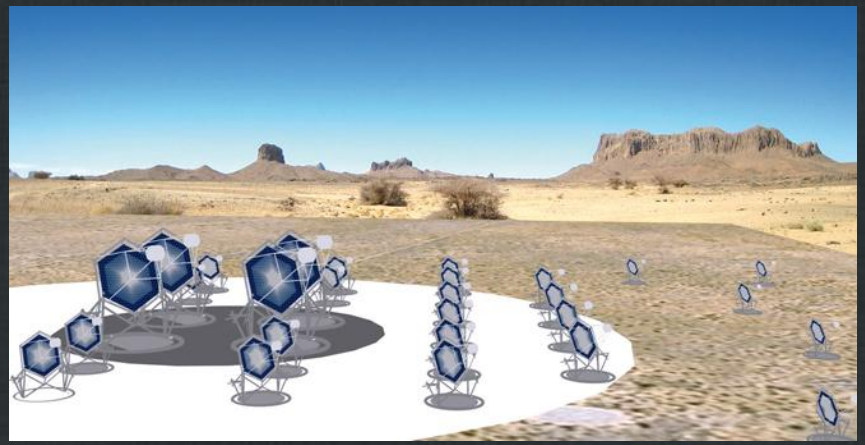
» Proposed Cherenkov Telescope Array (CTA)
- Proven technology on a larger scale
- 3 different telescope sizes
- Energy Range: tens of GeV to multi-TeV
- Field of view: 5 – 10 deg



» No EGB measurement possible; sensitive to EBL attenuation & individual sources above ~50 GeV

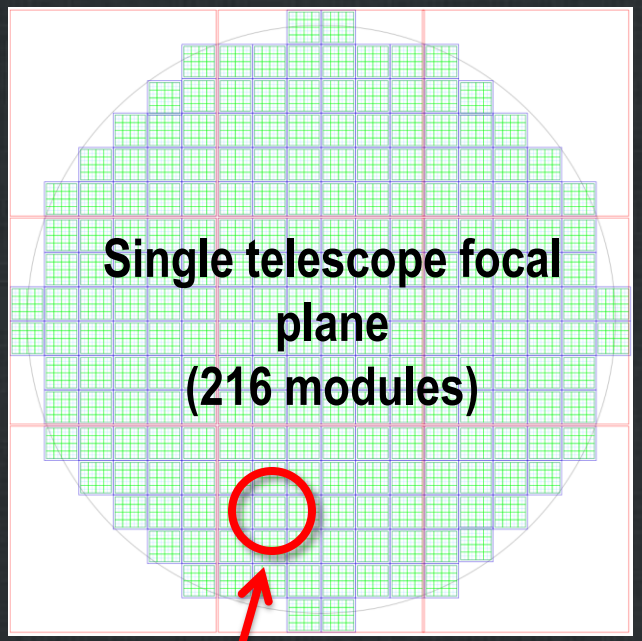
Current Generation
e.g. VERITAS
4 telescopes

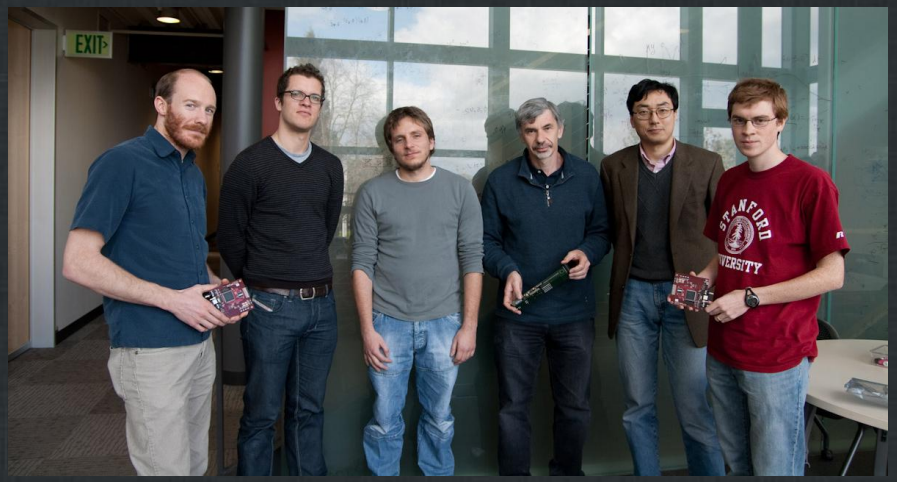
Next Generation
CTA
~50+ telescopes

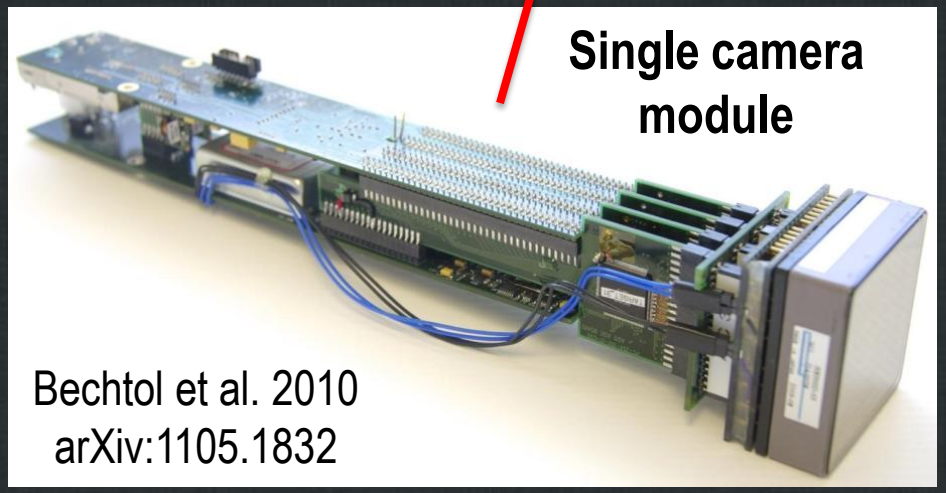


CTA camera readout electronics at SLAC

- » Low-cost electronics scaling up to ~10^6 total camera pixels
- » Focal plane instrumented with photomultiplier tubes
  - Waveform reconstruction requires GHz sampling
  - Testing digitizer chips at SLAC







Summary

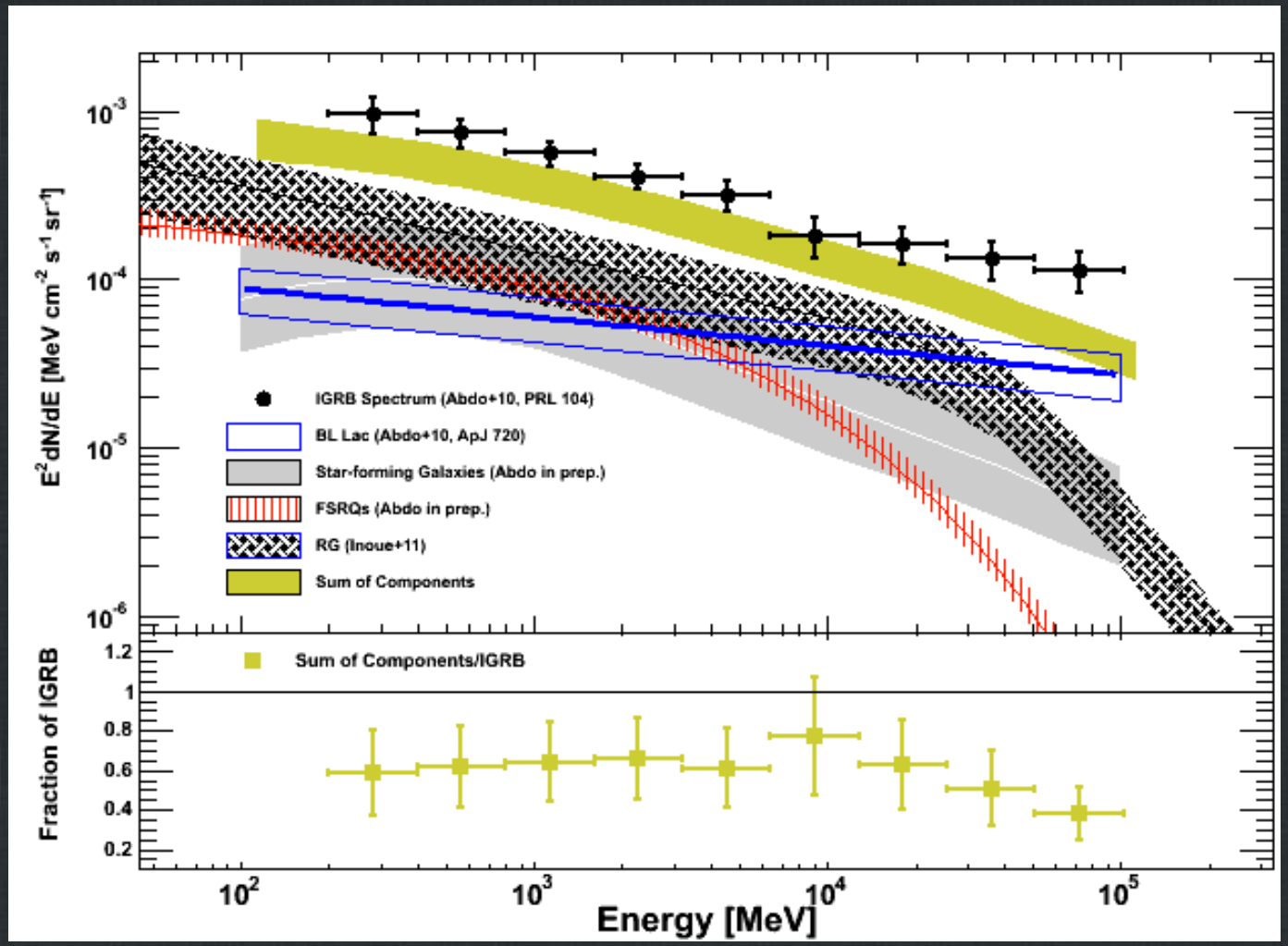
» EGB includes emission from high-energy phenomena across the Universe

- Not yet entirely understood in terms of established extragalactic gamma-ray source classes
- Extension of spectral measurement may provide hints

» Added bonus – CR physics

- Explore non-thermal components of intergalactic medium
- Clues towards the origin of Galactic CRs

EGB Current Status



Cluster cosmology with Dark Energy Survey

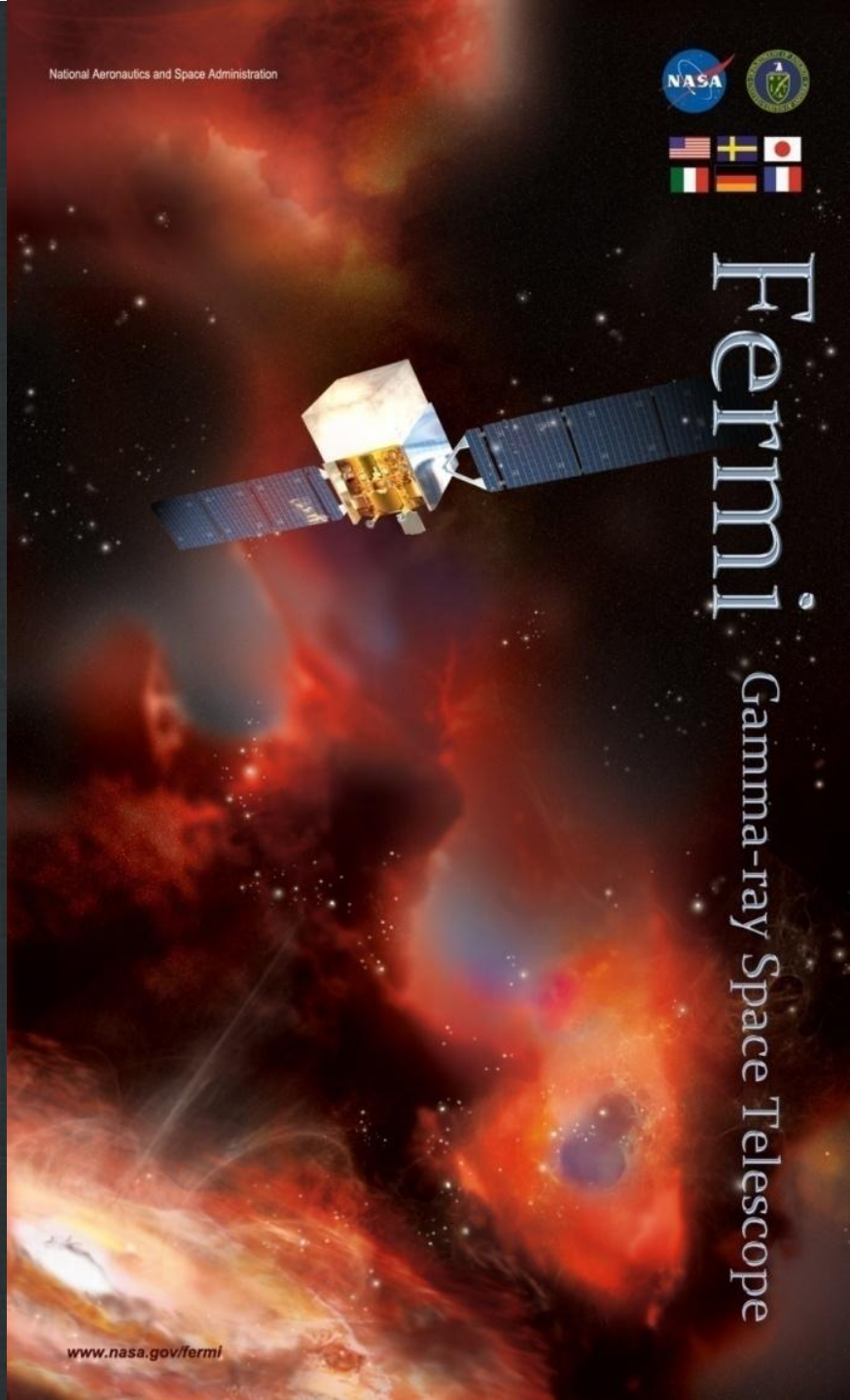
» Dark Energy Survey

- Compelling science, good timing
- Enjoy data analysis including development of tools, understanding systematics
- Working in collaborative atmosphere

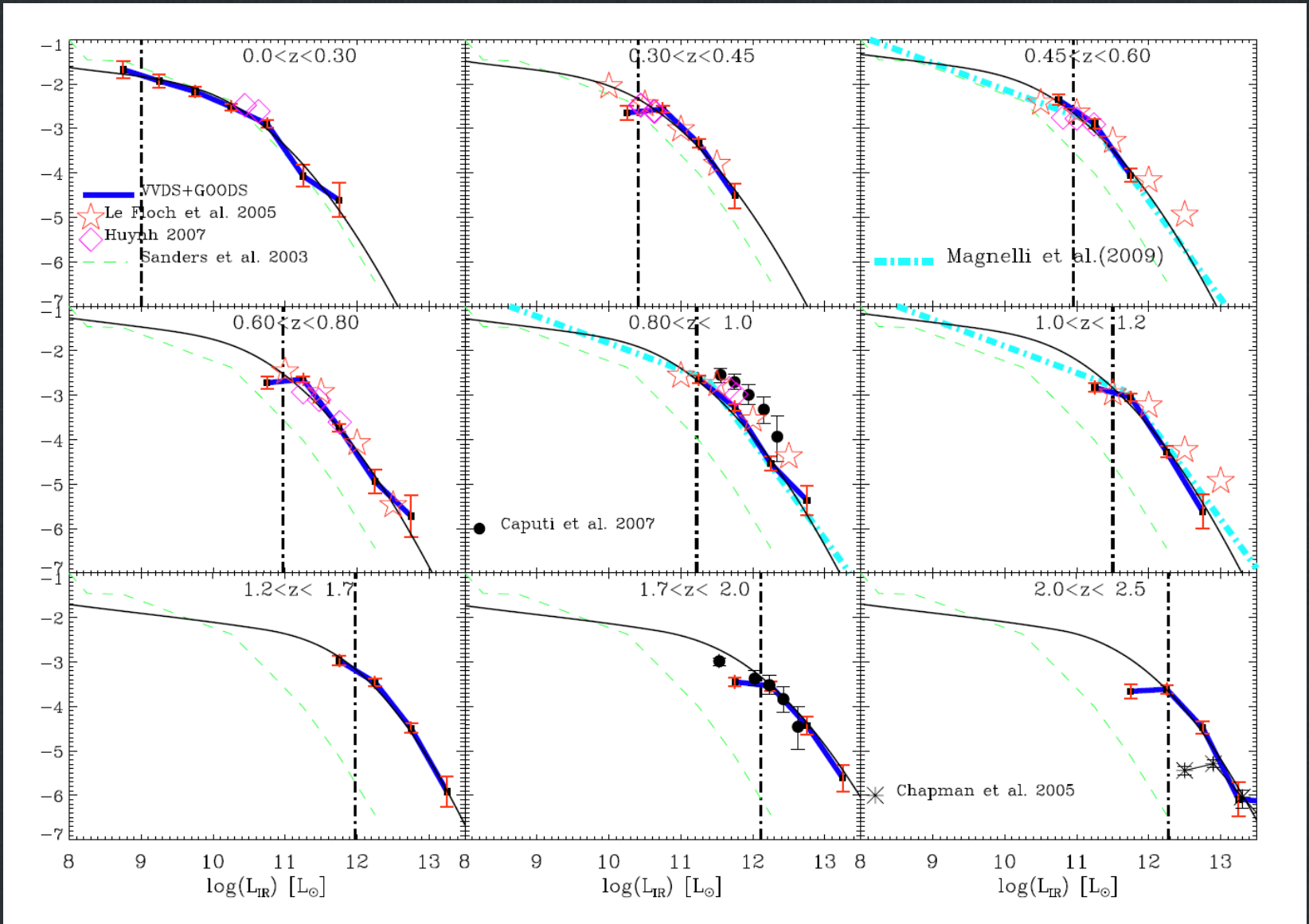
» Interested in galaxy clusters

- Weak lensing magnification mass estimates
- Systematics associated with selection function
- Complementing multiwavelength surveys (X-ray, SZ)

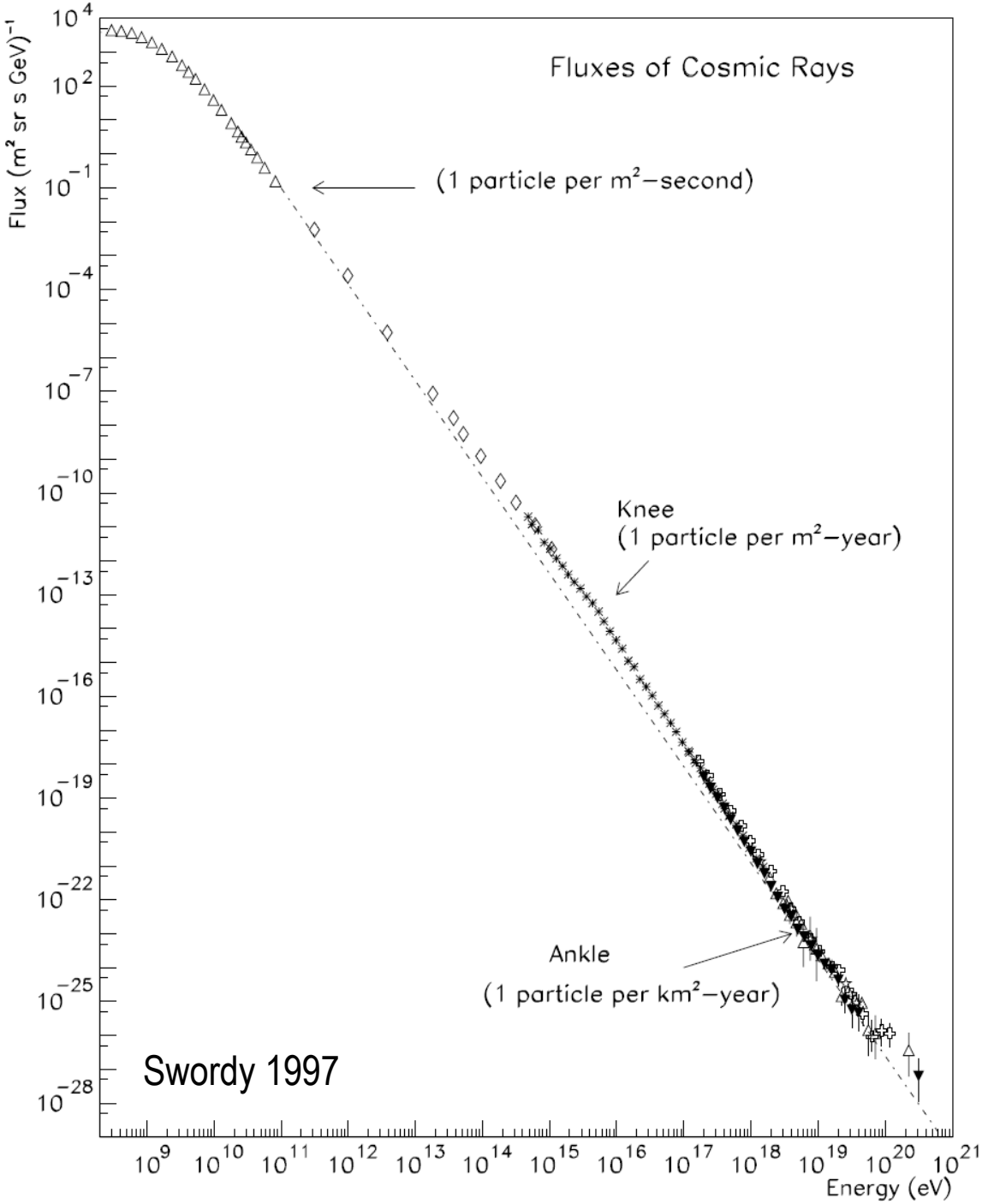
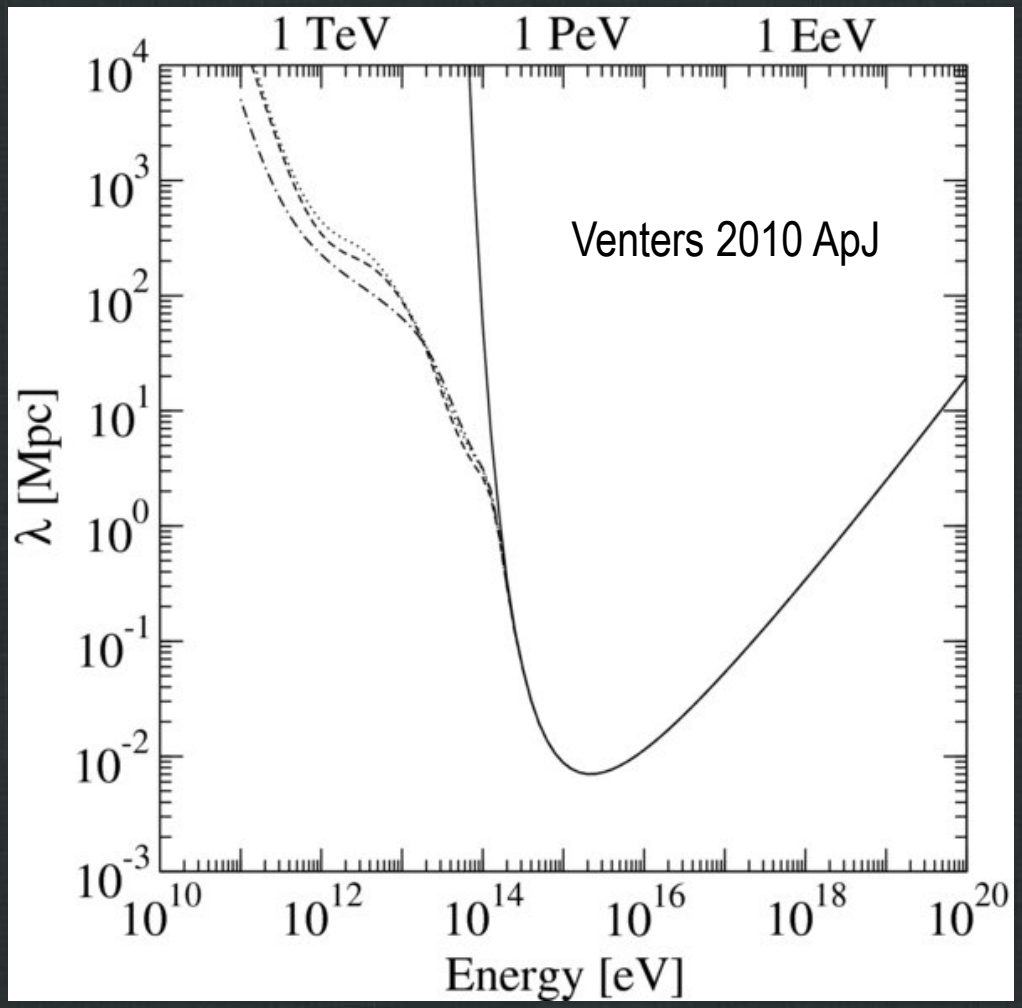
Backups


National Aeronautics and Space Administration
NASA
Fermi
Gamma-ray Space Telescope
www.nasa.gov/fermi

Star-forming Galaxies and the EGB



Rodighiero et al. 2010, A&A


Fluxes of Cosmic Rays
Flux (m² sr s GeV)⁻¹
(1 particle per m²−second)
Knee
(1 particle per m²−year)
Ankle
(1 particle per km²−year)
Energy (eV)
Swordy 1997

Gamma-ray interaction length