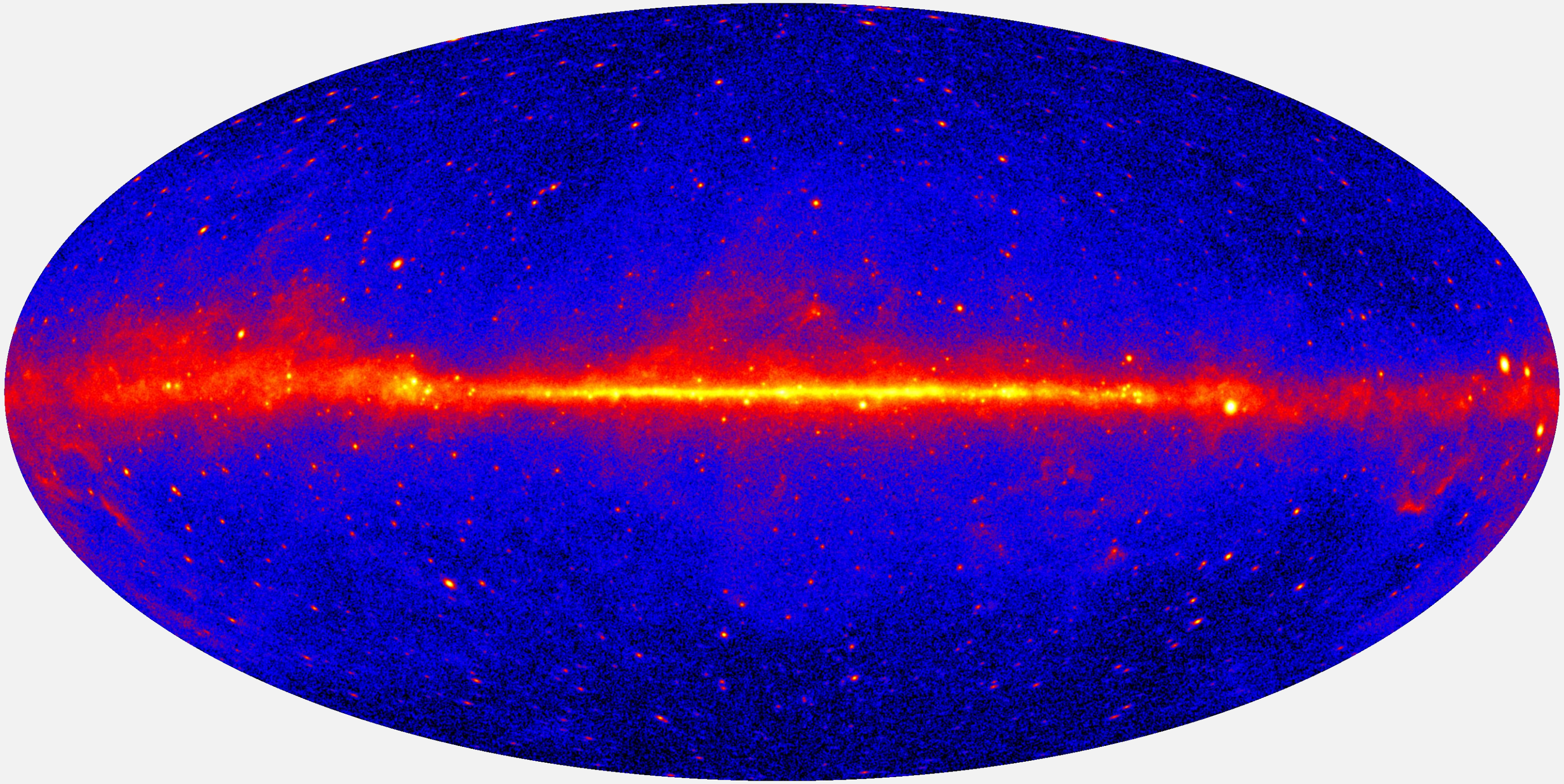
The Spectrum of Isotropic Diffuse Gamma-ray Emission between 100 MeV and 820 GeV



Keith Bechtol on behalf of the *Fermi*-LAT Collaboration

9 June 2014

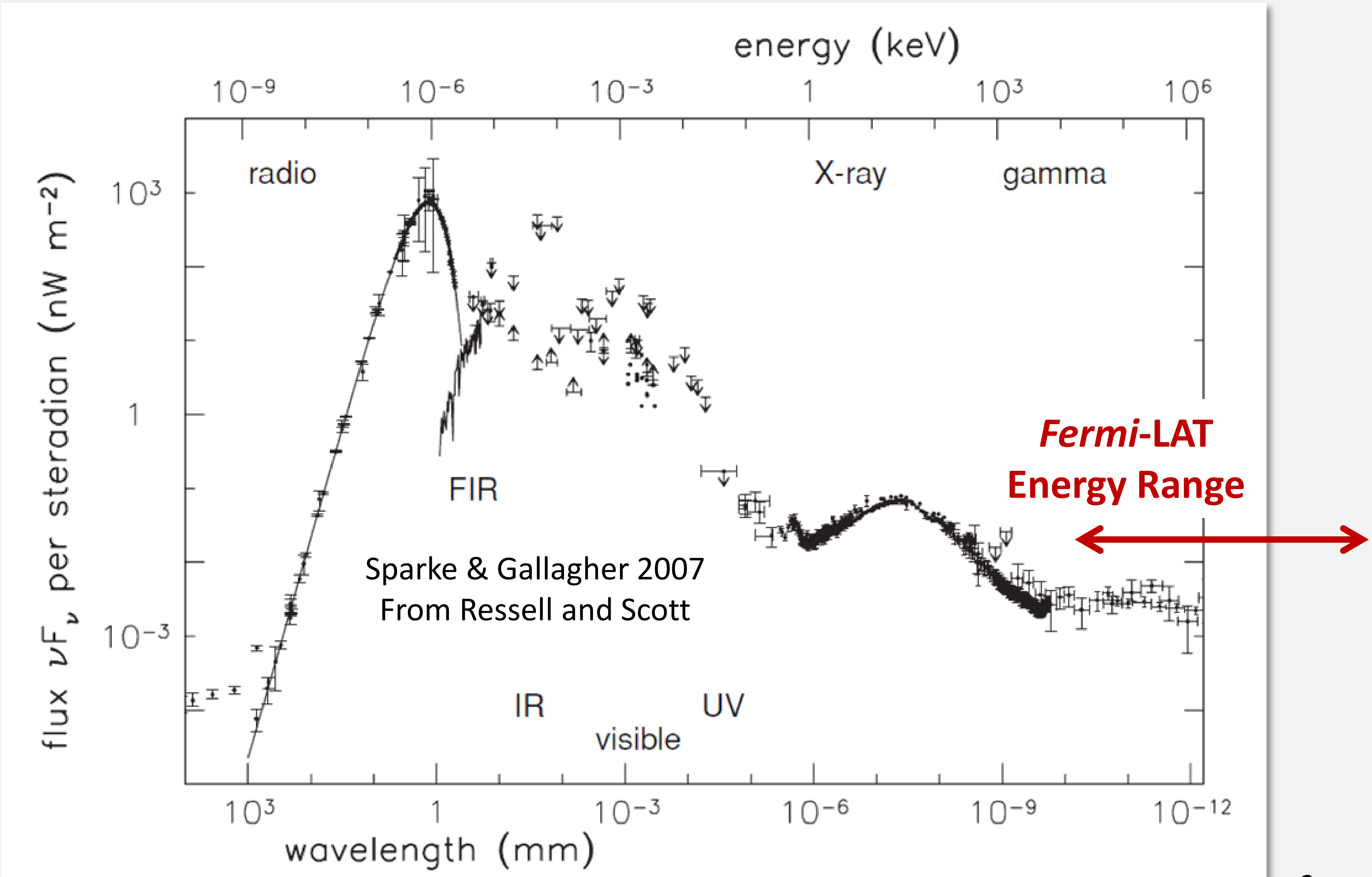
High-Energy Messengers Workshop

Kavli Institute
for Cosmological Physics
at The University of Chicago

Fermi-LAT Collaboration

Extragalactic Background Light (EBL)

Cumulative intensity of all extragalactic emissions

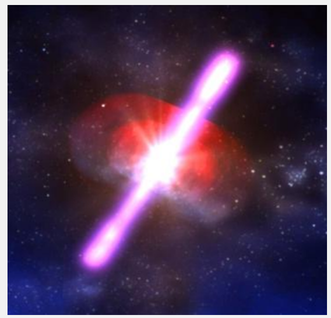


Physics of the Extragalactic Gamma-ray Background

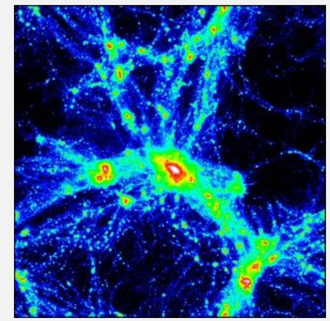
Universe is transparent to gamma rays at energies below ~100 GeV

Gamma-ray background provides cosmic census of high-energy phenomena

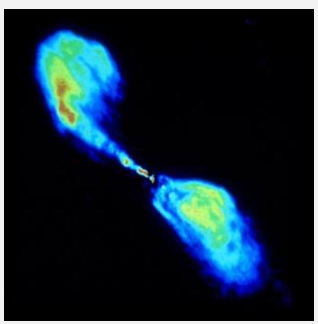
Blazars



GRBs



Dark matter annihilation / decay
(upper limits)

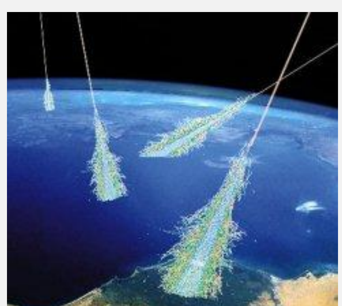


Radio galaxies

Galaxy clusters
(upper limits)

Unknown sources / processes

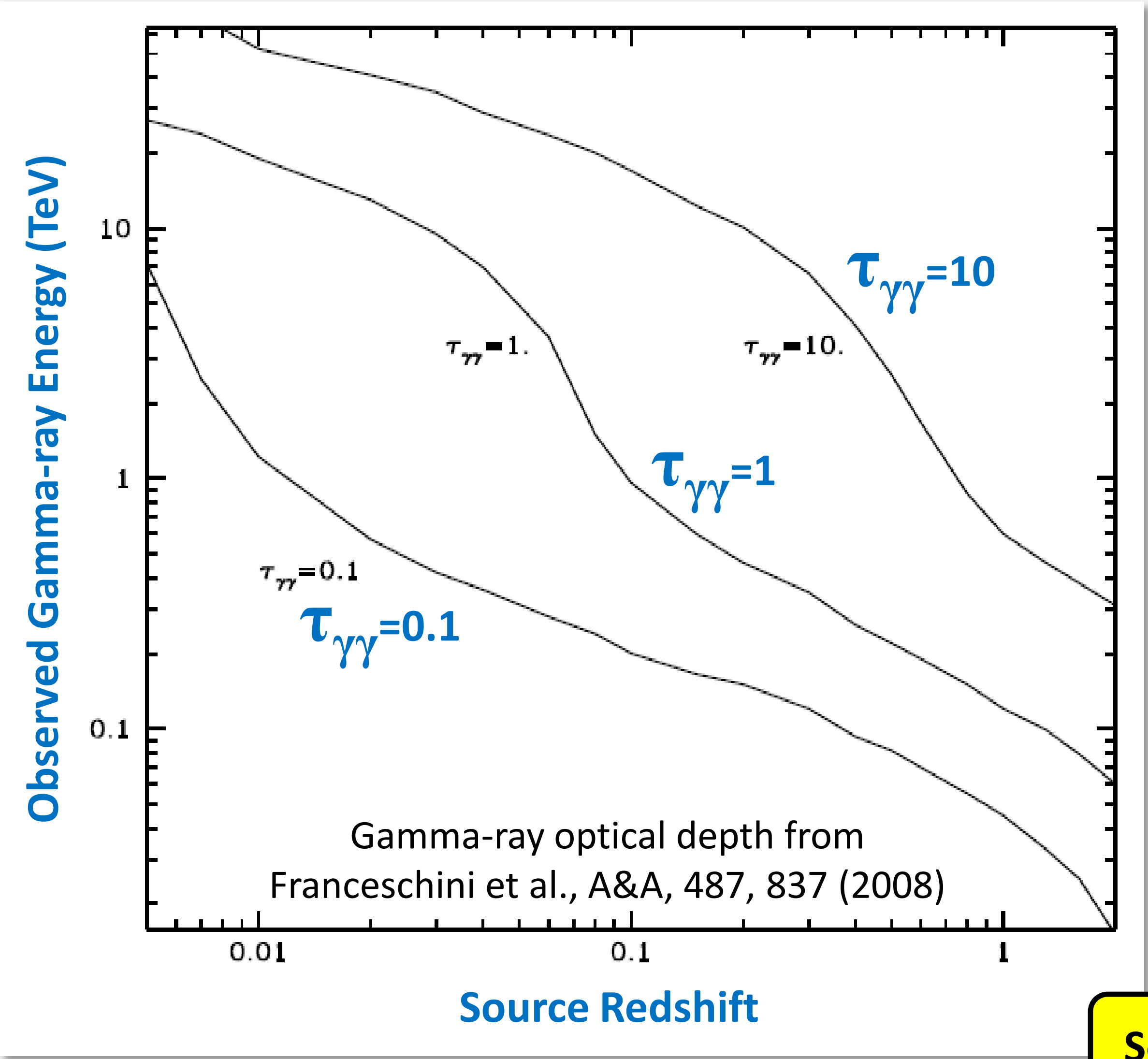
Star-forming galaxies



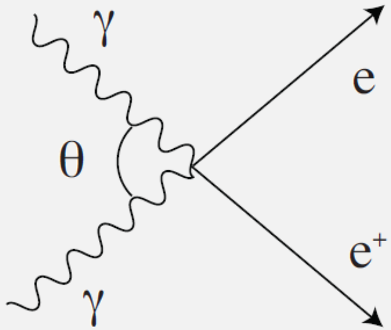
Cascades
(upper limits)

See talks on Monday afternoon

Physics of the Extragalactic Gamma-ray Background

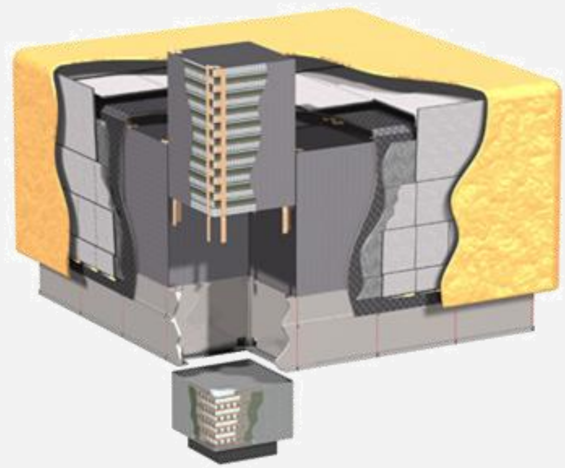


Above ~100 GeV, we expect a gamma-ray horizon due to electron/positron pair production on the IR/optical/UV extragalactic background light



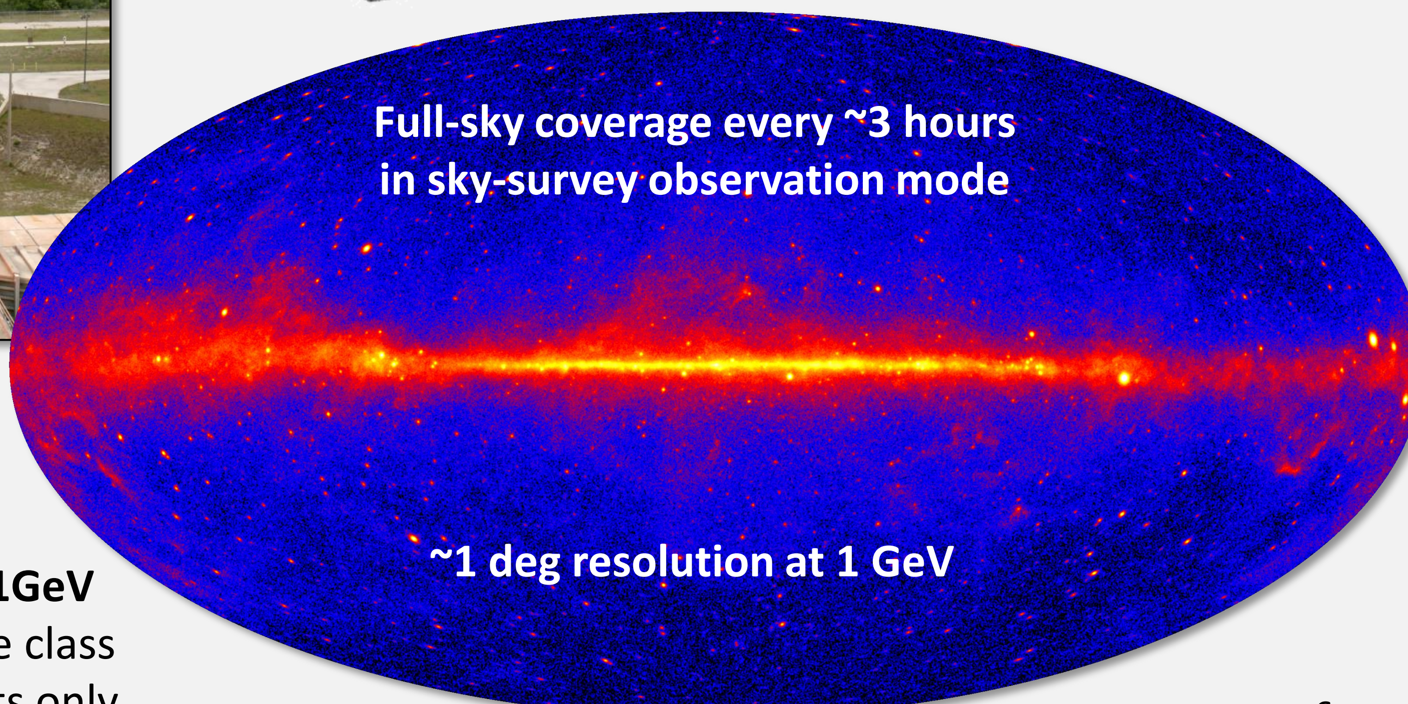
See talks on Tuesday afternoon

Fermi-LAT Overview



Large Area Telescope (LAT)

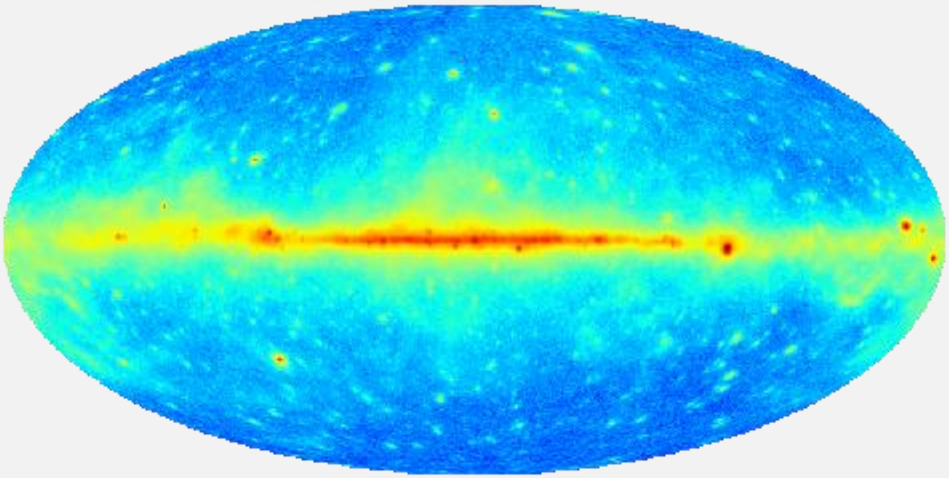
Pair-conversion telescope (20 MeV to >300 GeV) with precision **tracker** and imaging **calorimeter** surrounded by a segmented **anti-coincidence detector**



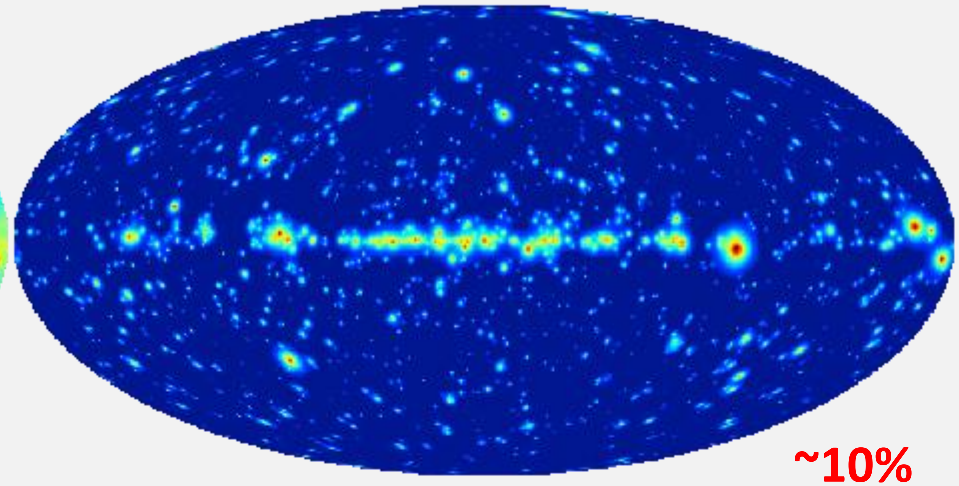
5-year counts map >1GeV
Reprocessed P7 Source class
Front-converting events only

Gamma-ray Sky as Seen by *Fermi*

LAT photons above 300 MeV

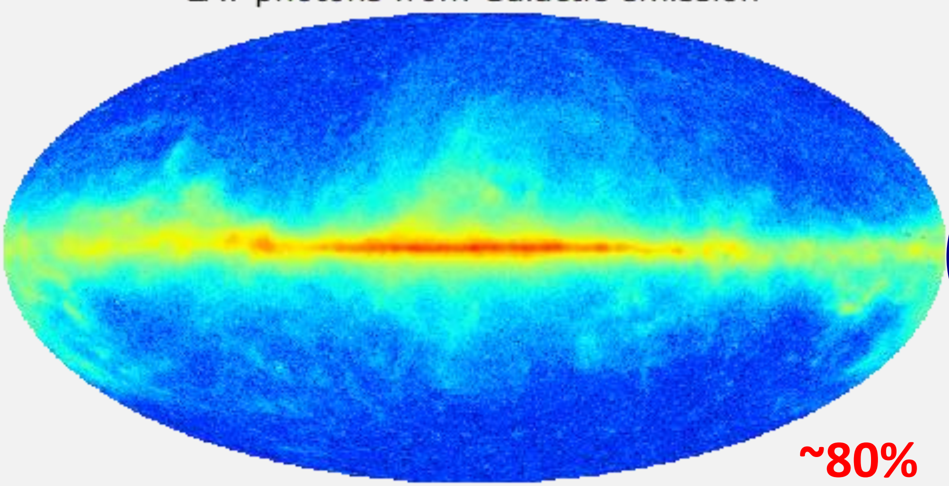


Point Sources



~10%

LAT photons from Galactic emission



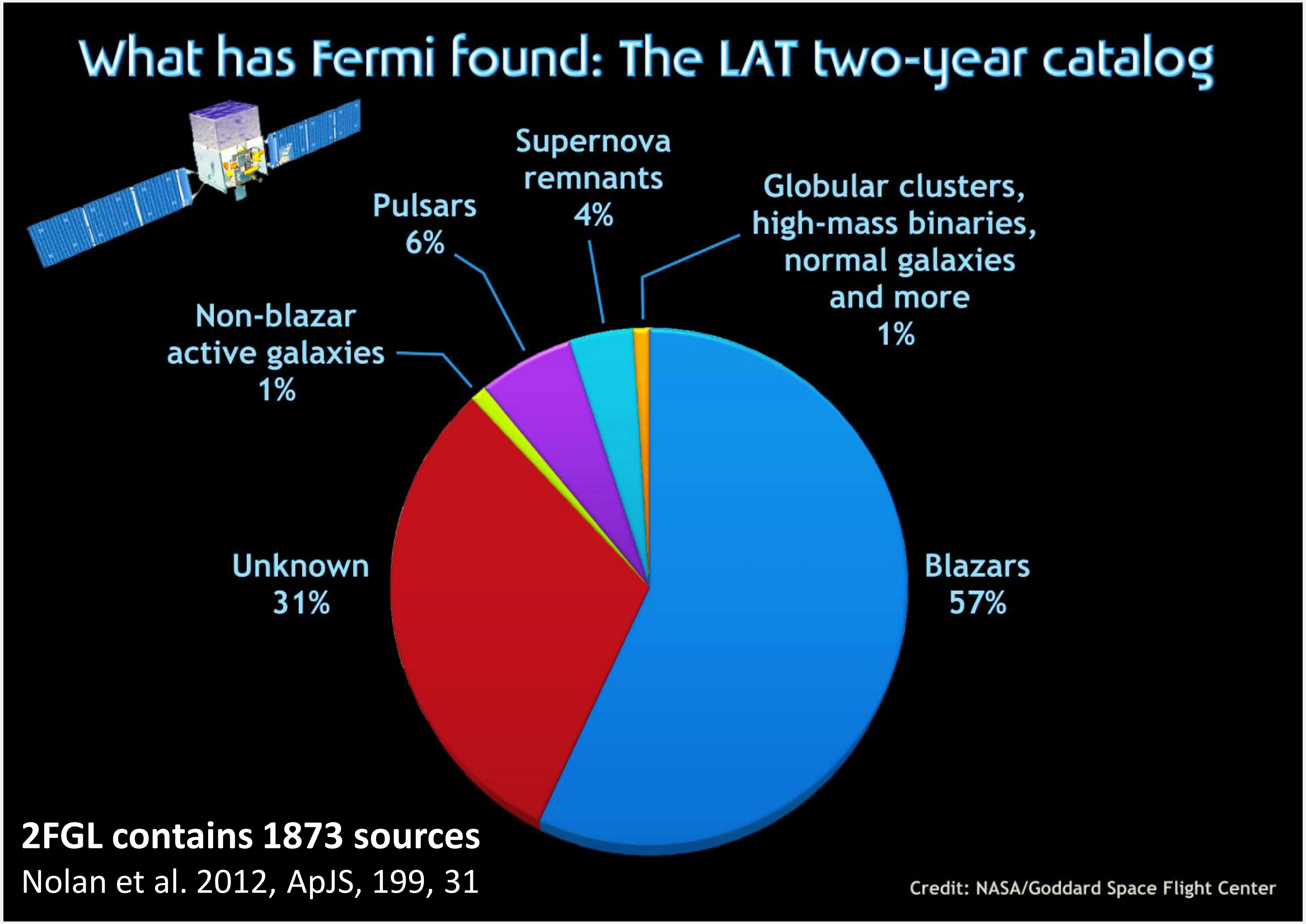
~80%

Nearly isotropic all-sky component (includes residual cosmic-ray background)

~10%

Fermi-LAT Individually Resolved Sources

Deeper surveys extract fainter sources ➔ residual intensity attributed to IGRB is *observation dependent* (total EGB is *fundamental quantity*)



Observational Challenges

Terminology

- Isotropic Gamma-ray Background (IGRB)
- Total Extragalactic Gamma-ray Background (Total EGB)

Total EGB = IGRB + individually resolved extragalactic sources

1. **Detector-level background (i.e., cosmic rays + secondaries)**

   Events misclassified as cosmic gamma rays

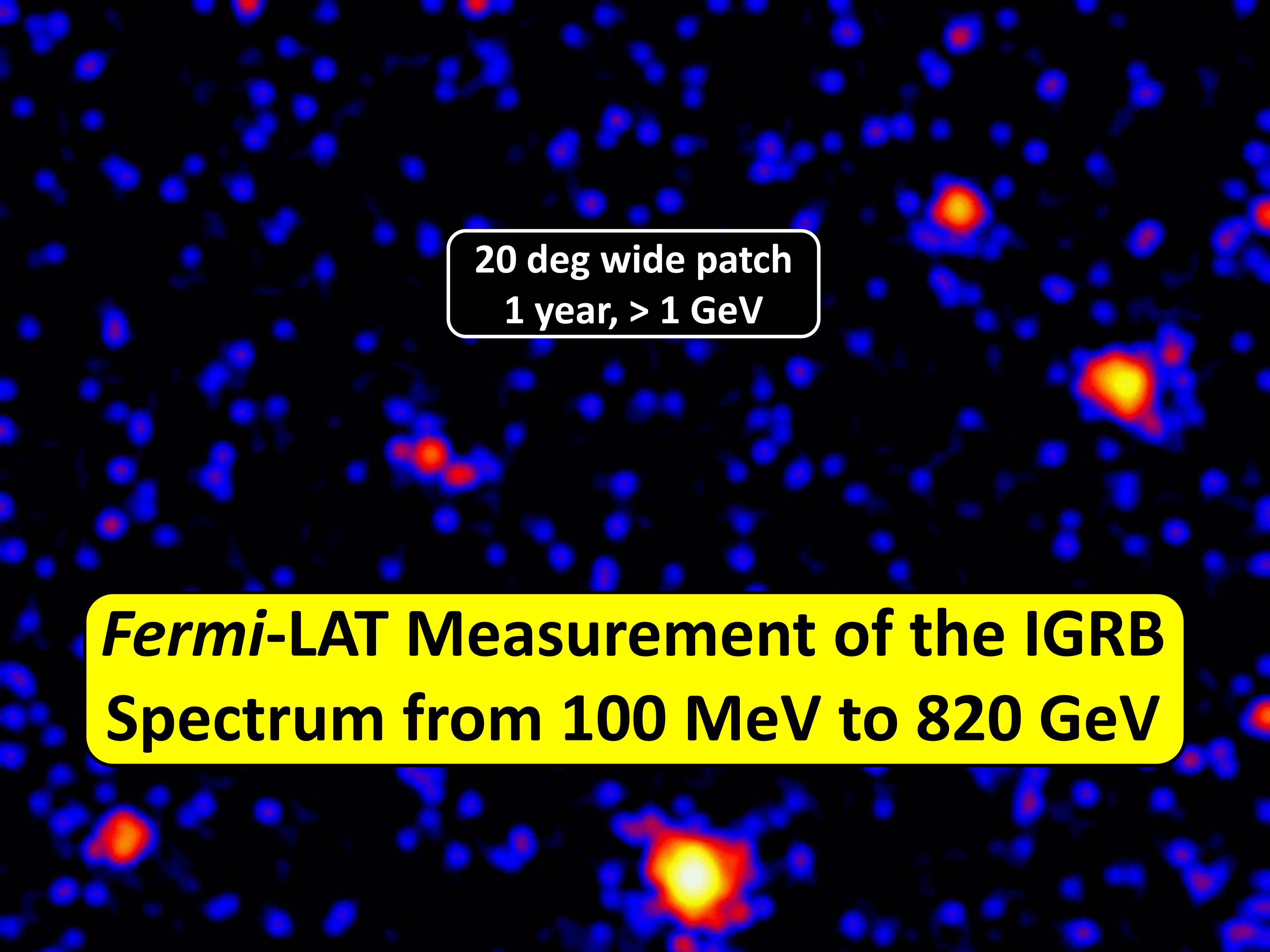
   Quasi-isotropic distribution in sky coordinates

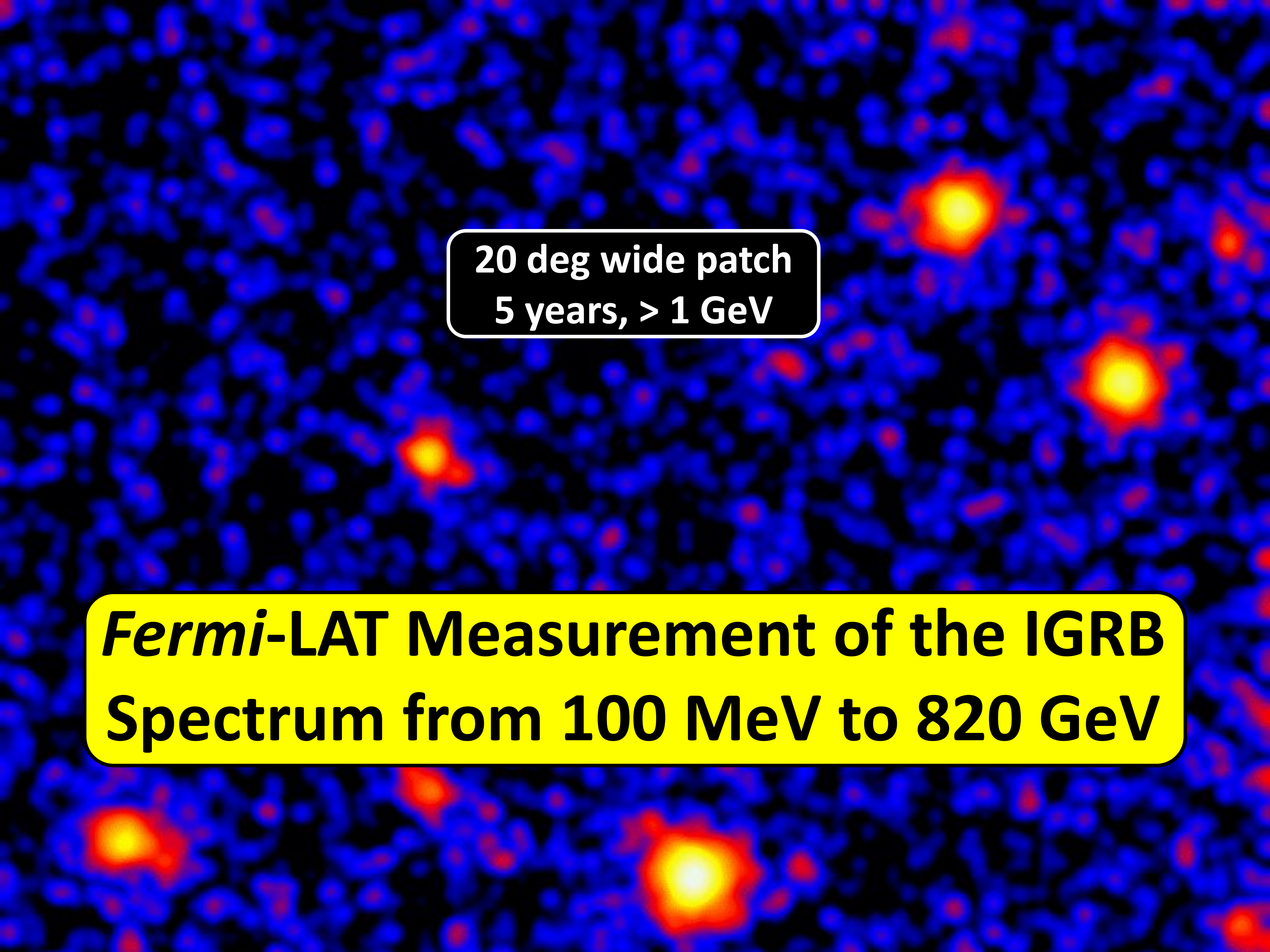
   Cosmic-ray intensity can exceed that of IGRB by up to ~10^6

2. **Diffuse Galactic foreground**

   Comparable to IGRB intensity even at Galactic poles

Fermi-LAT Measurement of the IGRB Spectrum from 100 MeV to 820 GeV





Fermi-LAT Measurement of the IGRB Spectrum from 100 MeV to 820 GeV

IGRB Analysis Methodology

1. **Define event selection**

   ✓ Custom event selections optimized for low-energy and high-energy IGRB analysis

2. **Template fitting to determine isotropic intensity**

   ✓ Model gamma-ray sky as linear combination of spatial-spectral templates

3. **Subtract residual cosmic-ray background from isotropic component**

   ✓ Detector-level simulation

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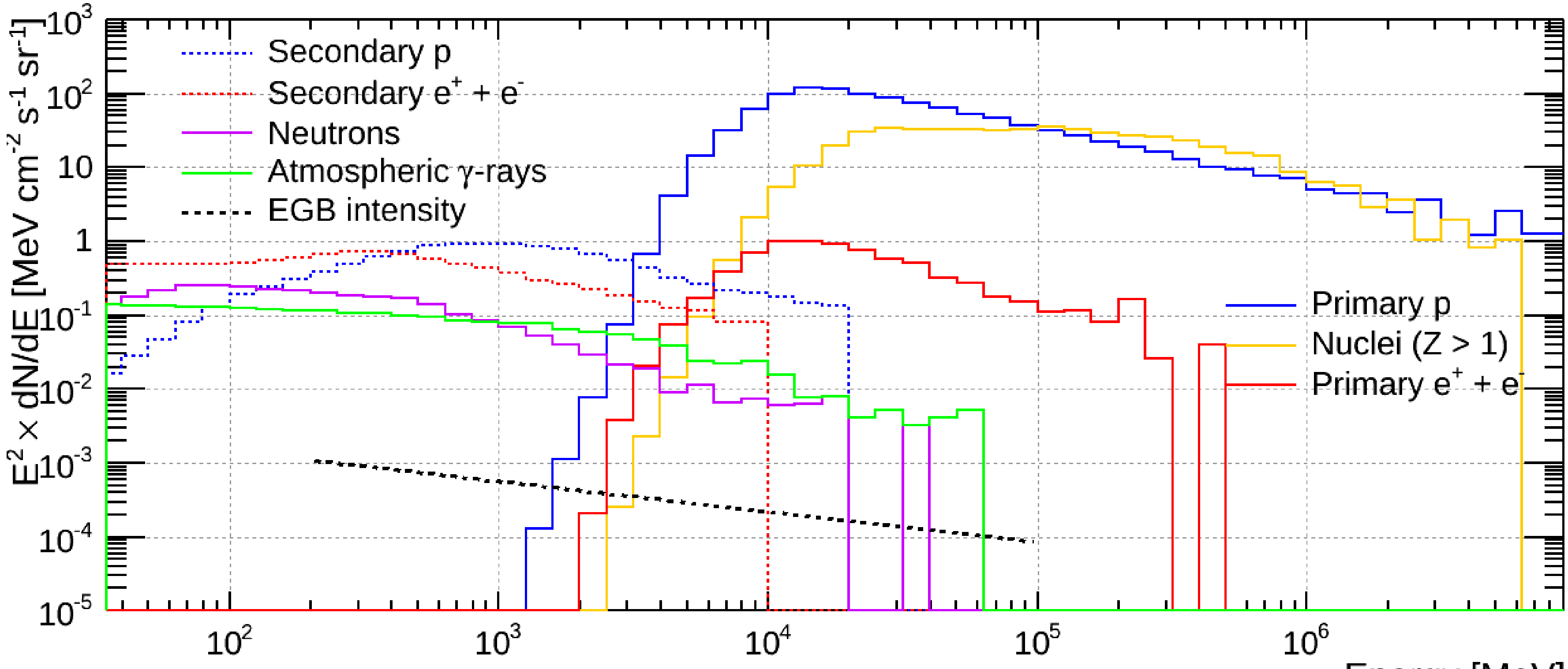
Detector-level (Cosmic-ray) Backgrounds in *Fermi* 's Low Earth Orbit

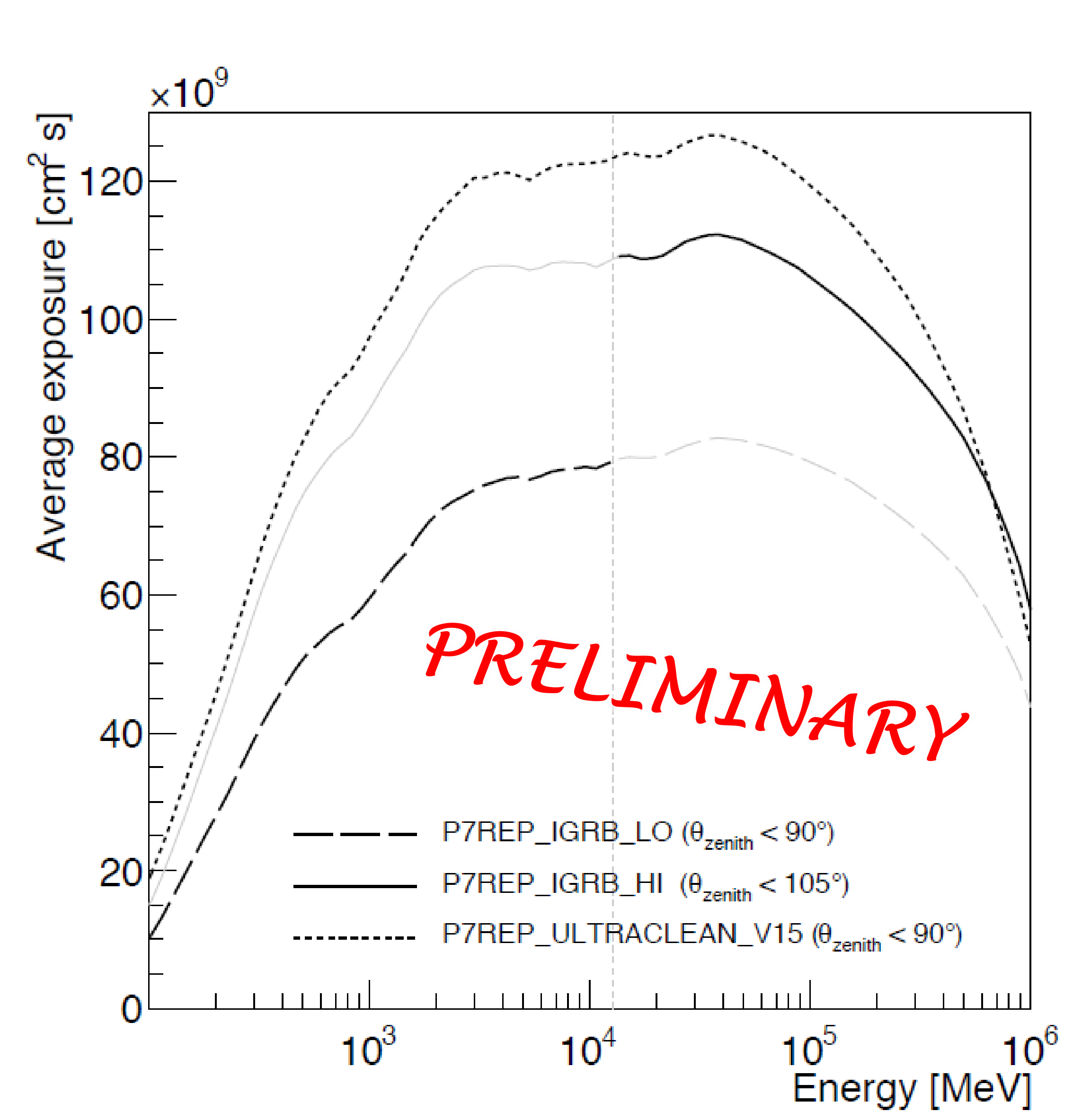
Particle fluxes below a few GeV are dominated by atmospheric secondaries, including actual gamma rays from the Earth's atmosphere



Ackermann et al. 2012, ApJS, 203, 4

Since particle background composition varies significantly over LAT energy range, devise **two custom event selections** optimized for **low-energy (<13 GeV)** and **high-energy (>13 GeV)** IGRB analysis

Exposure with Specialized Event Selections



50 months of sky-survey observations

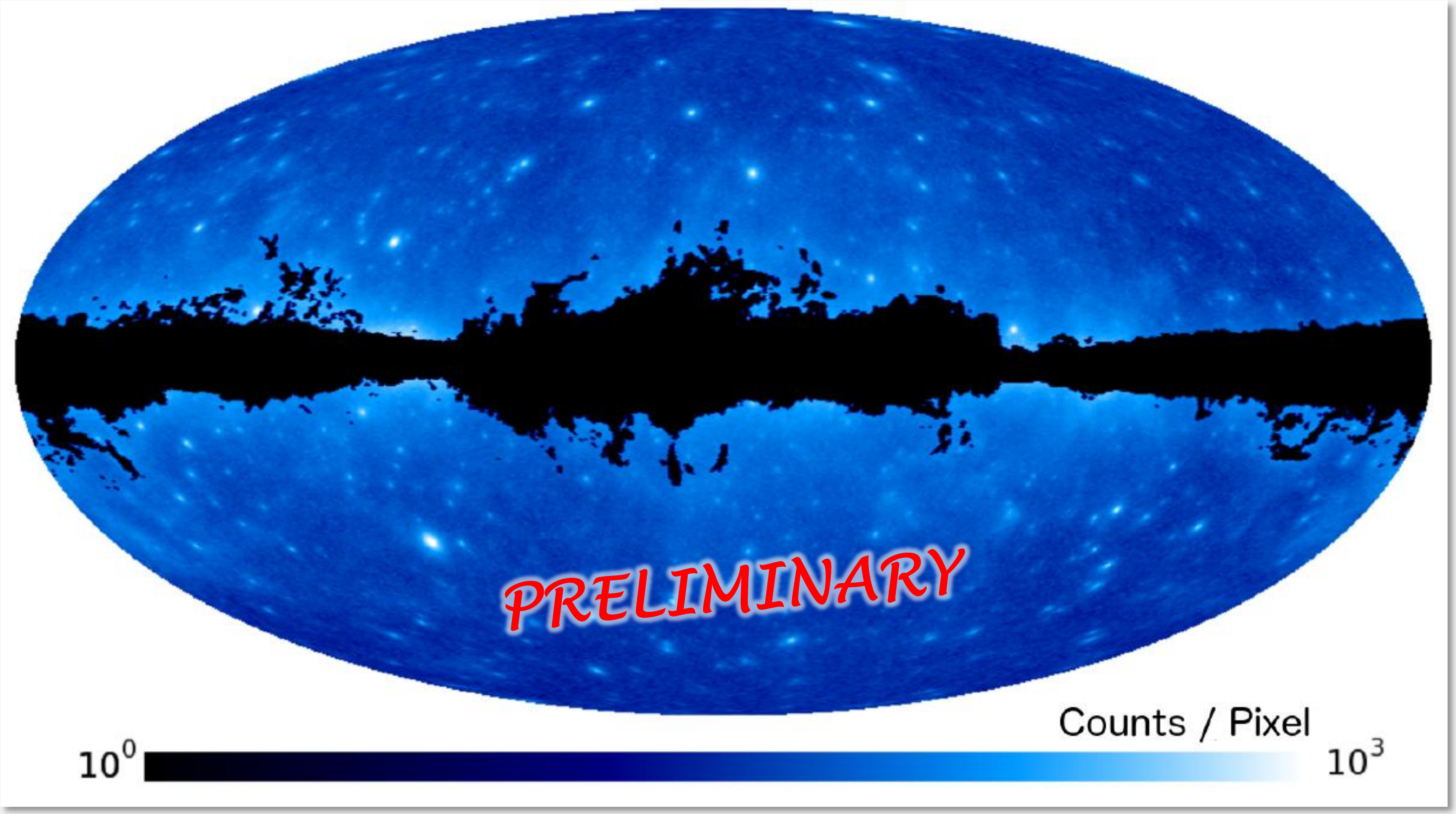
"Low-energy" and "high-energy" event samples both cover full energy range to allow consistency checks in overlap

Corresponding cosmic-ray background event rates estimated via a dedicated large-scale Monte Carlo simulation

Relative to standard P7 Ultraclean selection, cosmic-ray background rate reduced by factor 3 around 200 MeV (where background rate is highest) and acceptance increased >500 GeV

Galactic Foreground Mask

Exclude lines of sight with significant column densities of molecular gas and/or atomic hydrogen beyond local Solar neighborhood (17% of all-sky solid angle)



Counts map >0.1 GeV with mask applied

IGRB Analysis Methodology

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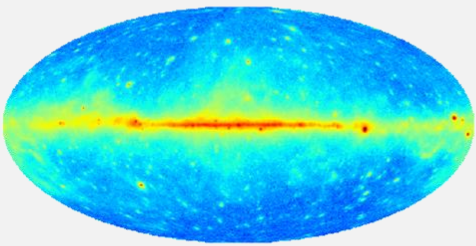
   - ✓ Custom event selections optimized for low-energy and high-energy IGRB analysis

2. **Template fitting to determine isotropic intensity**
   - ✓ Model gamma-ray sky as linear combination of spatial-spectral templates

3. **Subtract residual cosmic-ray background from isotropic component**
   - ✓ Detector-level simulation

Template Fitting Procedure (Maximum Likelihood)

Gamma-ray Sky



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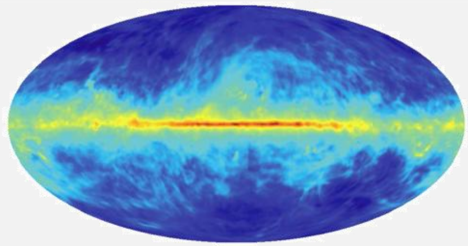
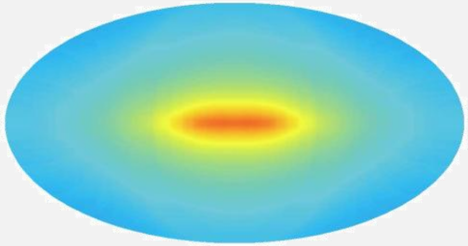
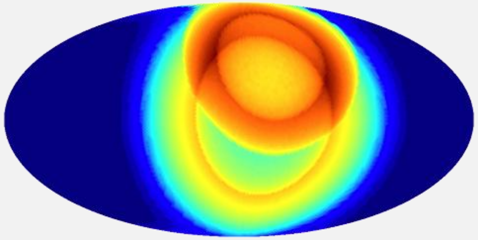
Diffuse Galactic Foreground



Interstellar gas



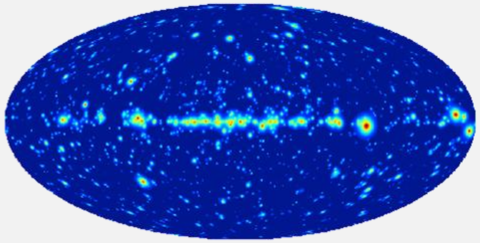
Inverse Compton



Loop I and Local Loop

\+

Resolved Sources



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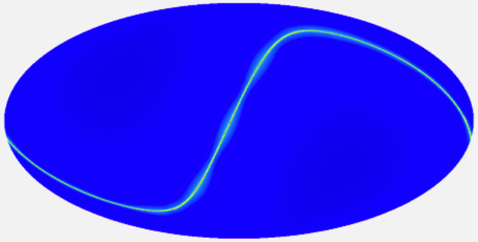
Solar Limb and Radiation Field



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Isotropic All-sky Component

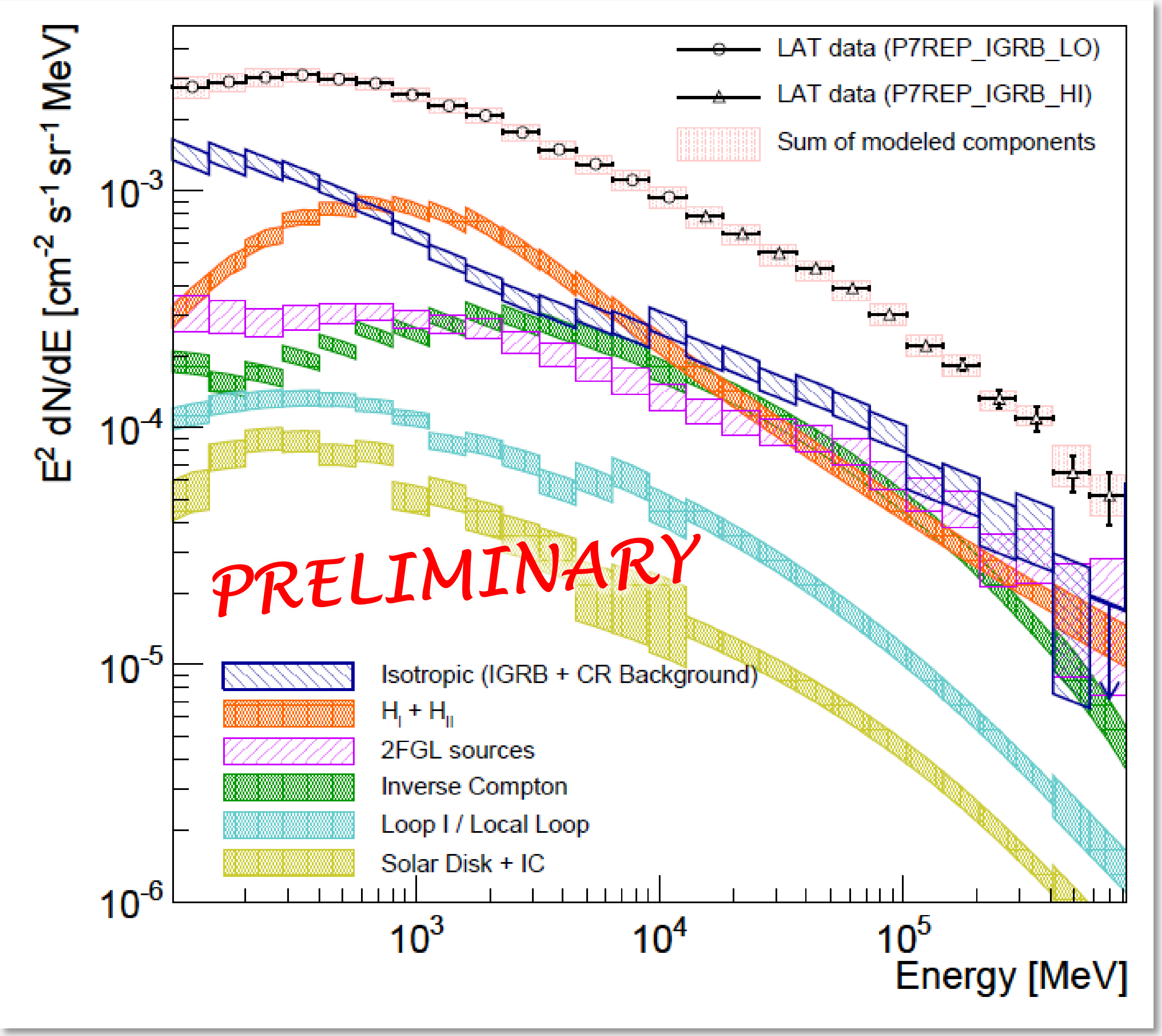
Residual cosmic-ray background + IGRB

Two Energy Regimes

Low-energy (<13 GeV):
Normalizations fitted separately in each energy bin for all components

High-energy (>13 GeV):
Normalizations of Galactic foreground components set by average fit result from 6 – 51 GeV

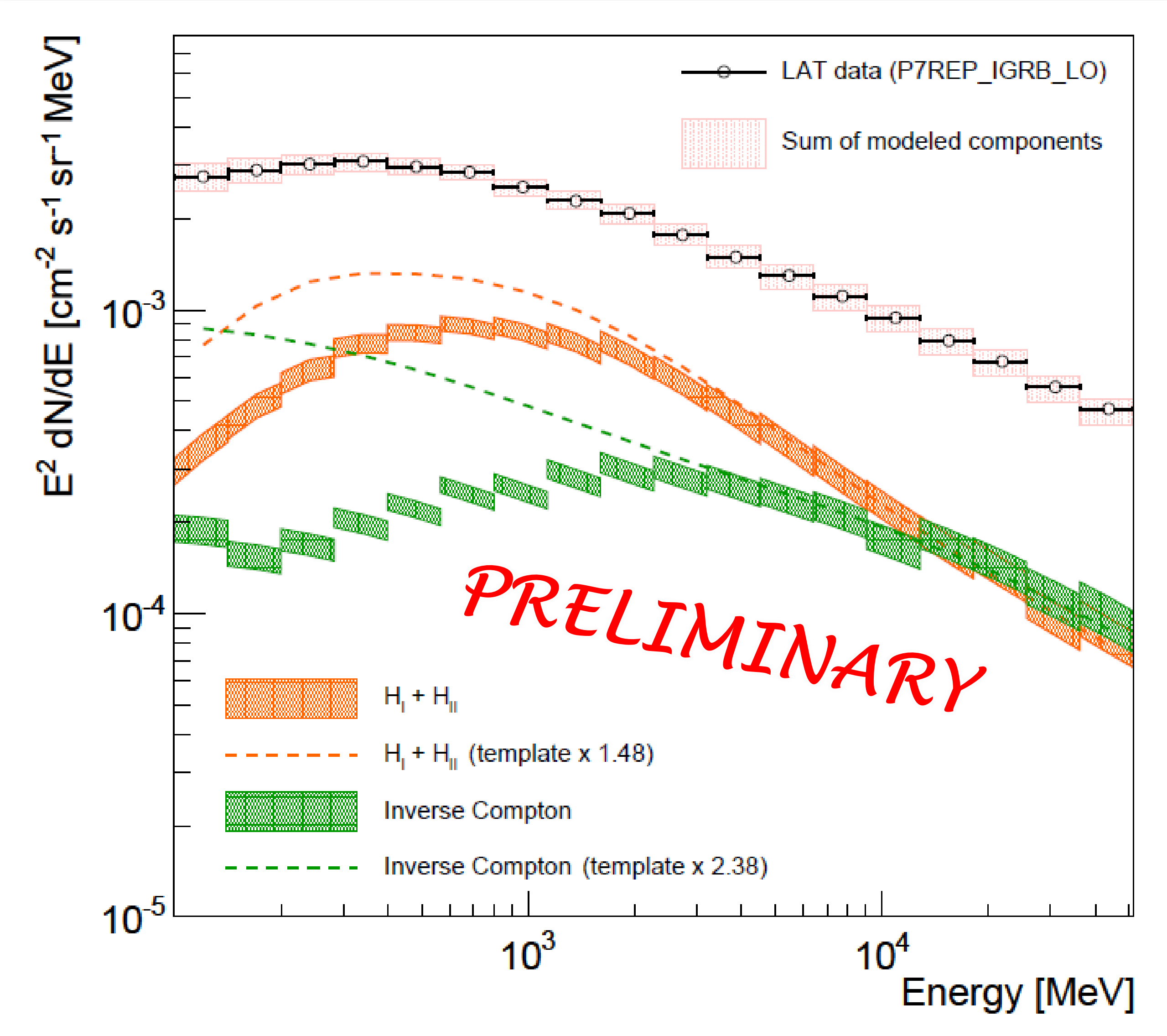
Template Fitting Results



Average intensities at Galactic latitudes |b| > 20 deg attributed to each model component for **baseline Galactic foreground model**

Error bars include statistical uncertainty and systematic uncertainty from LAT effective area parameterization

Systematic Uncertainty from Galactic Foreground: Benchmark Models (GALPROP)



Good agreement between baseline Galactic foreground model spectral shapes and fit to LAT data above few GeV

Bin-by-bin fit can partially compensate for spectral deviations from model, but model over-prediction below 1 GeV may indicate incomplete understanding of cosmic-ray source distribution, interstellar radiation field, etc.

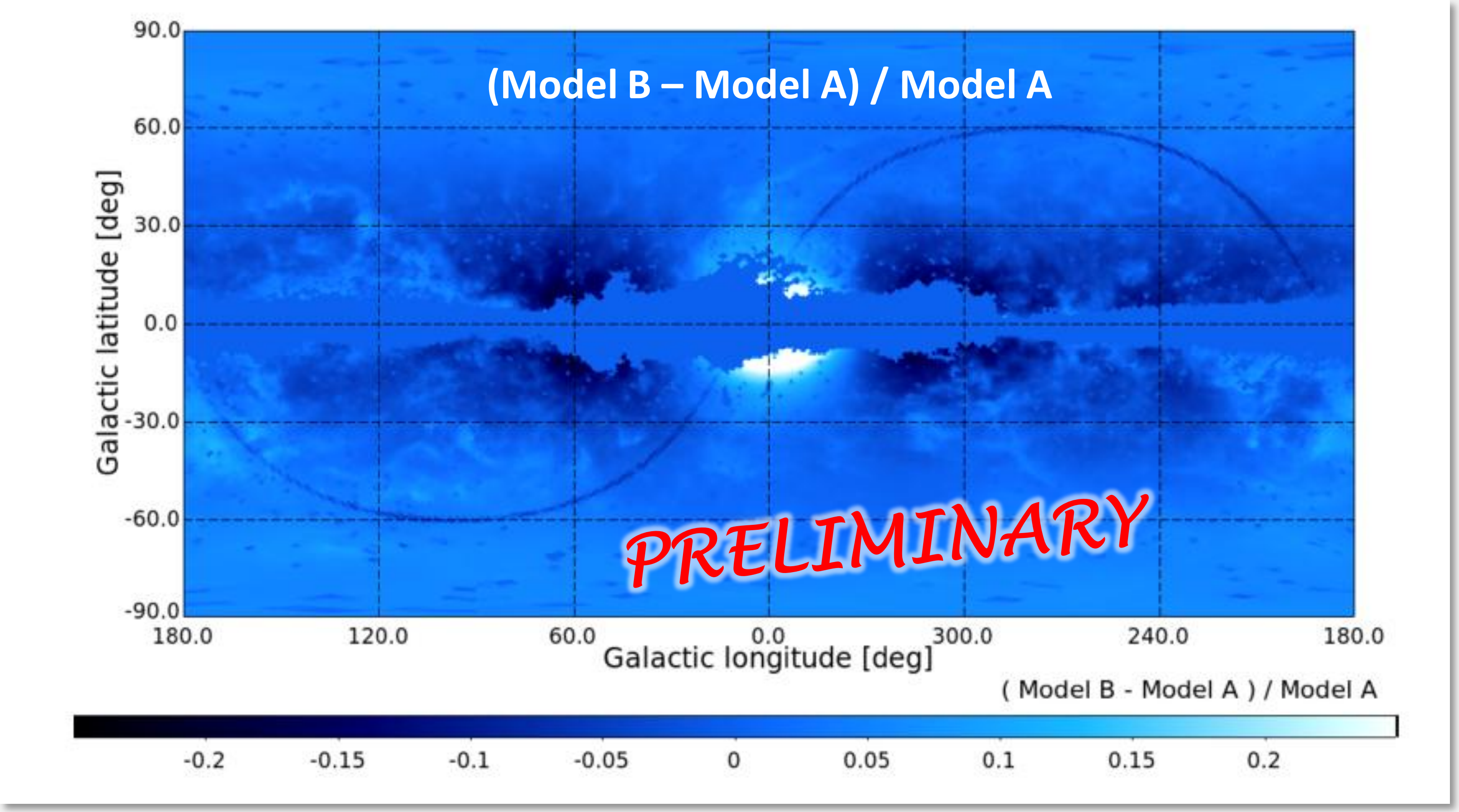
Motivates consideration of alternative Galactic foreground models

Systematic Uncertainty from Galactic Foreground: Benchmark Models (GALPROP)

Model A (baseline): Similar to models in Ackermann et al. 2012, ApJ, 750, 3

Model B: Add population of electron-only sources near Galactic center

Model C: Vary cosmic-ray diffusion rate with Galactocentric height and radius



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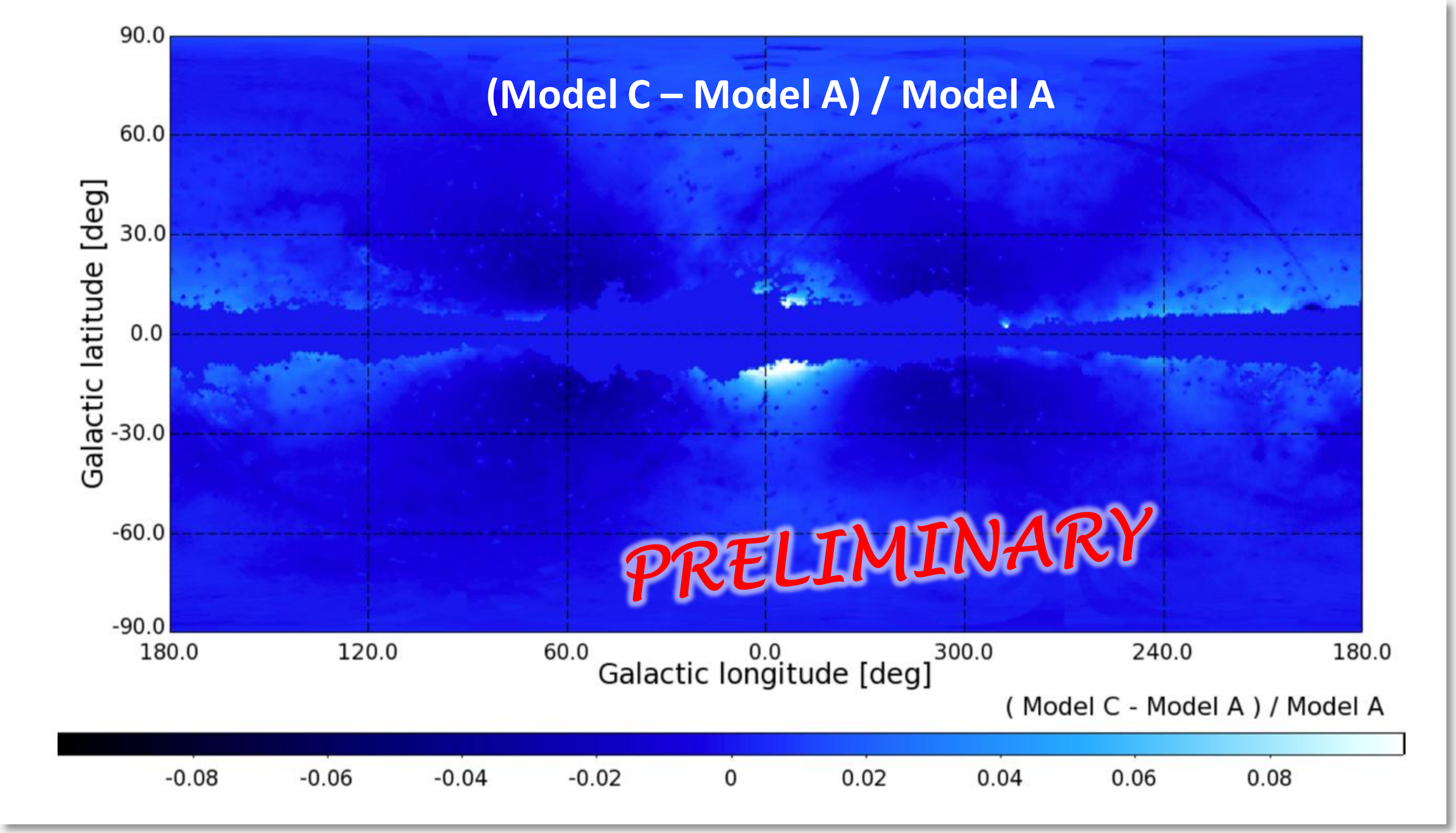


Systematic Uncertainty from Galactic Foreground: Additional Systematic Checks

Test the following variants for baseline Galactic foreground model A

- Increase radiation field in Galactic bulge (×10)
- Lower Galactic random magnetic field strength (from 7.5 to 3 μG)
- Test plain diffusion model without reacceleration
- Different cosmic-ray source radial distribution (SNRs vs. pulsars)
- Variation in cosmic-ray halo size (4 or 10 kpc vs. 5 kpc)
- Test two different templates for the "*Fermi* Bubbles"
- Vary dust to atomic hydrogen ratio (±10%)

Check consistency of IGRB intensity inferred from distinct regions

- Inner / outer Galactic hemispheres
- North / south Galactic hemispheres

IGRB Analysis Methodology

1. **Define event selection**
   - ✓ Custom event selections optimized for low-energy and high-energy IGRB analysis

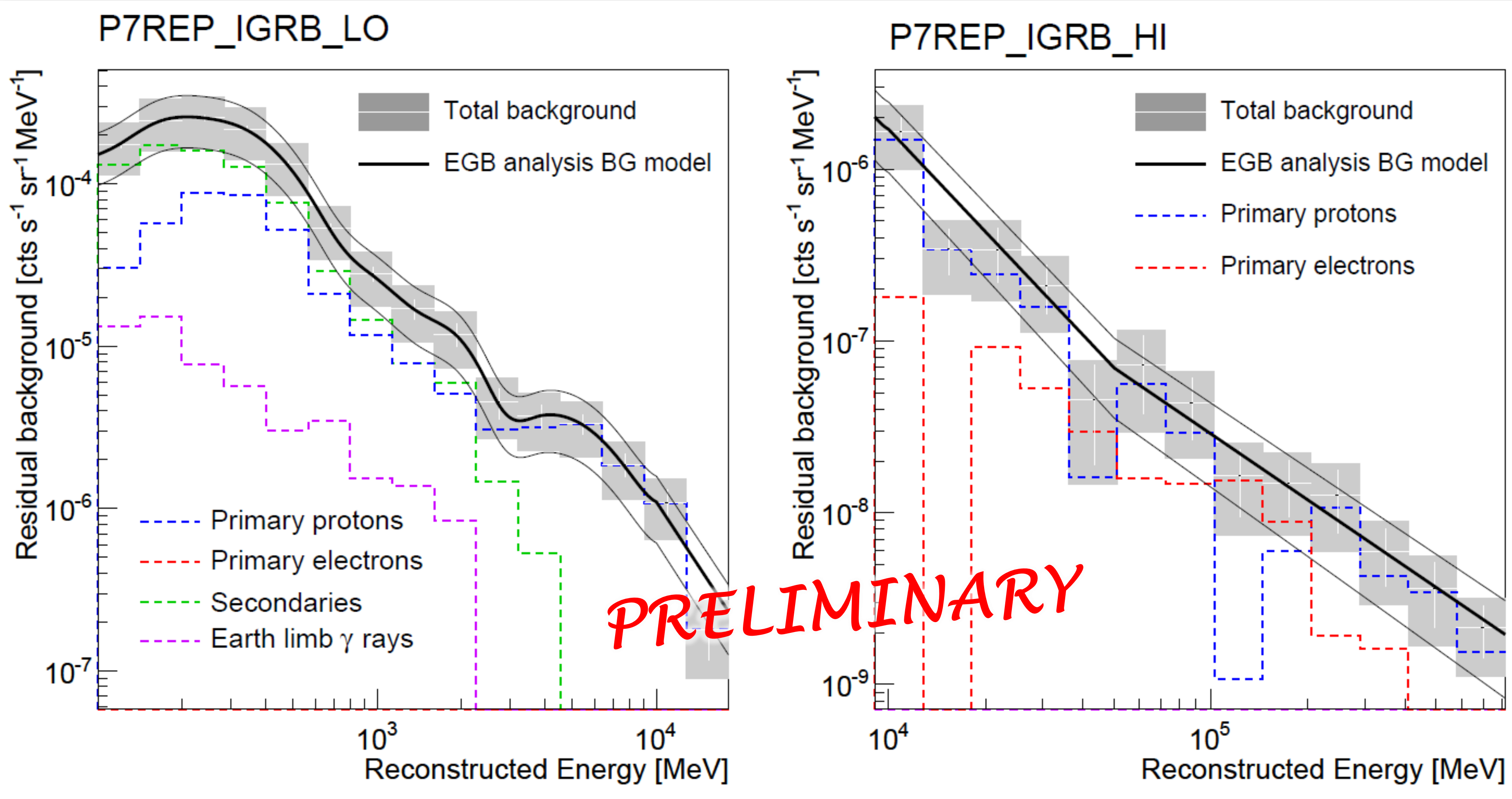
2. **Template fitting to determine isotropic intensity**
   - ✓ Model gamma-ray sky as linear combination of spatial-spectral templates

3. **Subtract residual cosmic-ray background from isotropic component**
   - ✓ Detector-level simulation

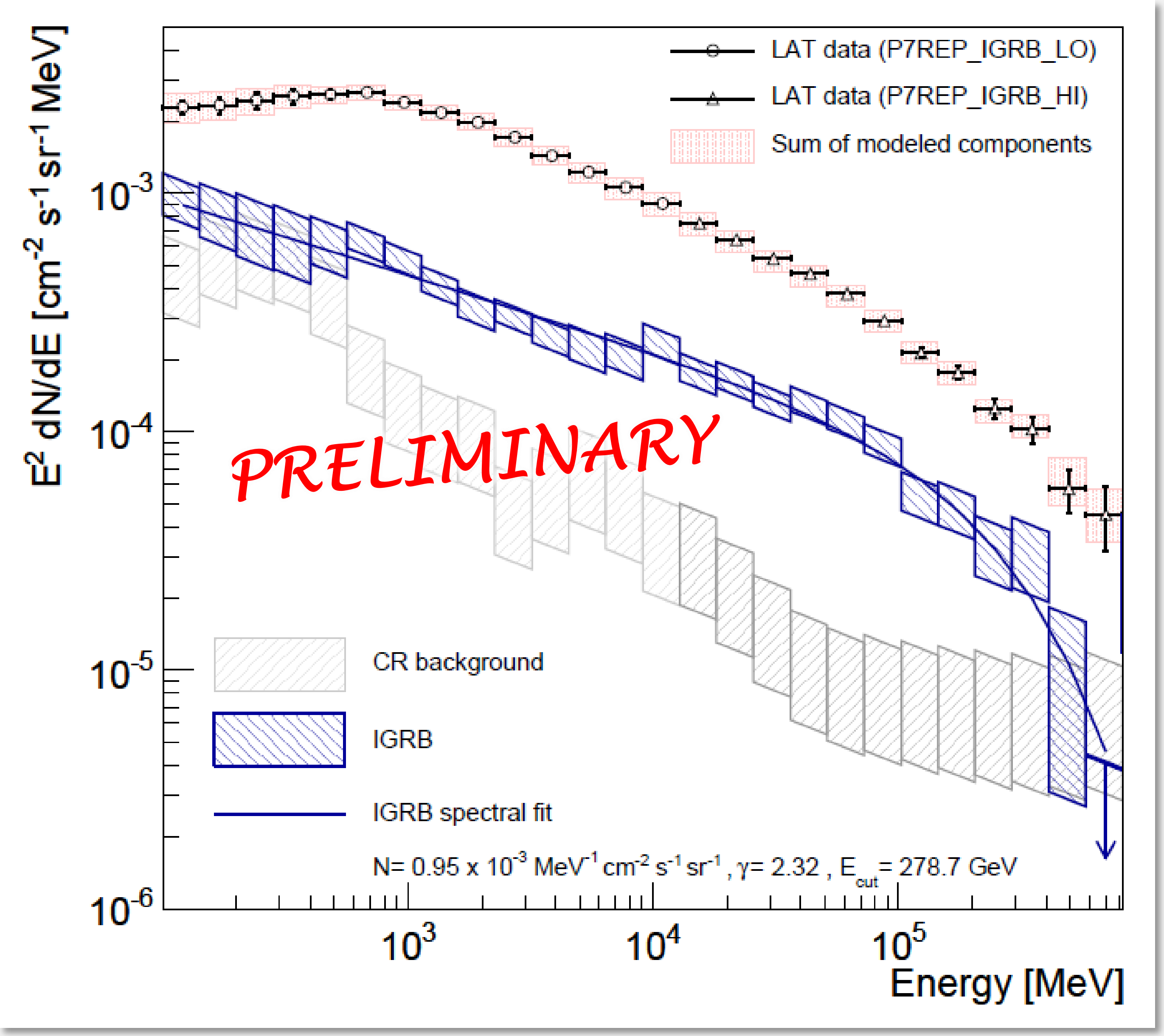
Residual Cosmic-ray Backgrounds

Extensive detector-level simulations used for initial estimate, then rates adjusted to match distributions of reconstructed event properties found in on-orbit data.

Difference between raw simulation and data-driven approach < 35% over all energies.



Subtract Cosmic-ray Backgrounds



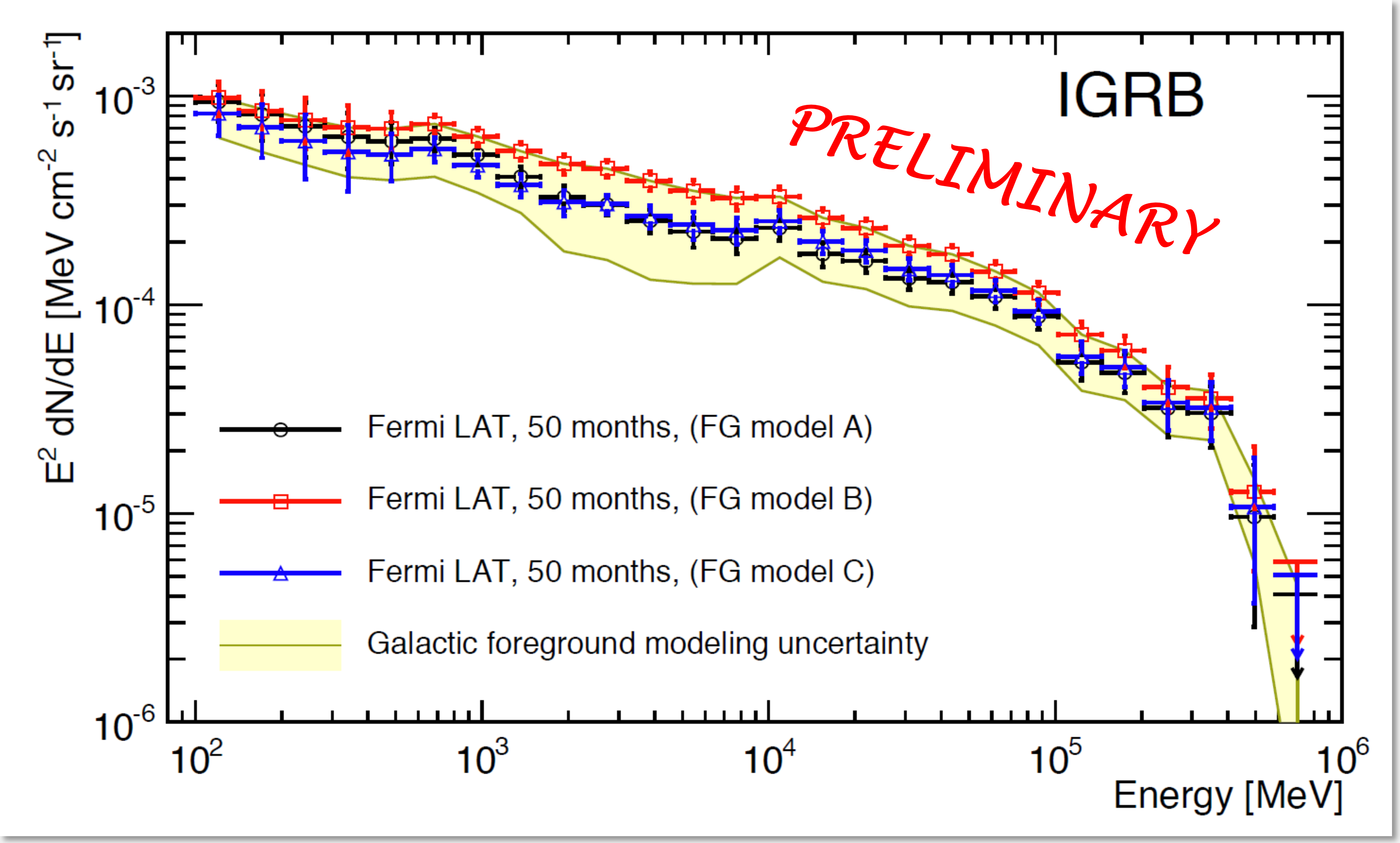
IGRB intensity determined by subtracting residual cosmic-ray background from isotropic component in each energy bin

Uncertainties reflect statistical uncertainty from template fitting, systematic uncertainty in LAT effective area, and systematic uncertainty in residual cosmic-ray background levels

Baseline Galactic foreground model A

Isotropic Gamma-ray Background

Systematic uncertainty from Galactic foreground represented by yellow band



IGRB Parametric Fit Results:
A significant High-energy Cutoff

$$\frac{dN}{dE} = I_{100}\left(\frac{E}{100\,\mathrm{MeV}}\right)^{-\gamma} \exp\left(\frac{-E}{E_{\mathrm{cut}}}\right)$$

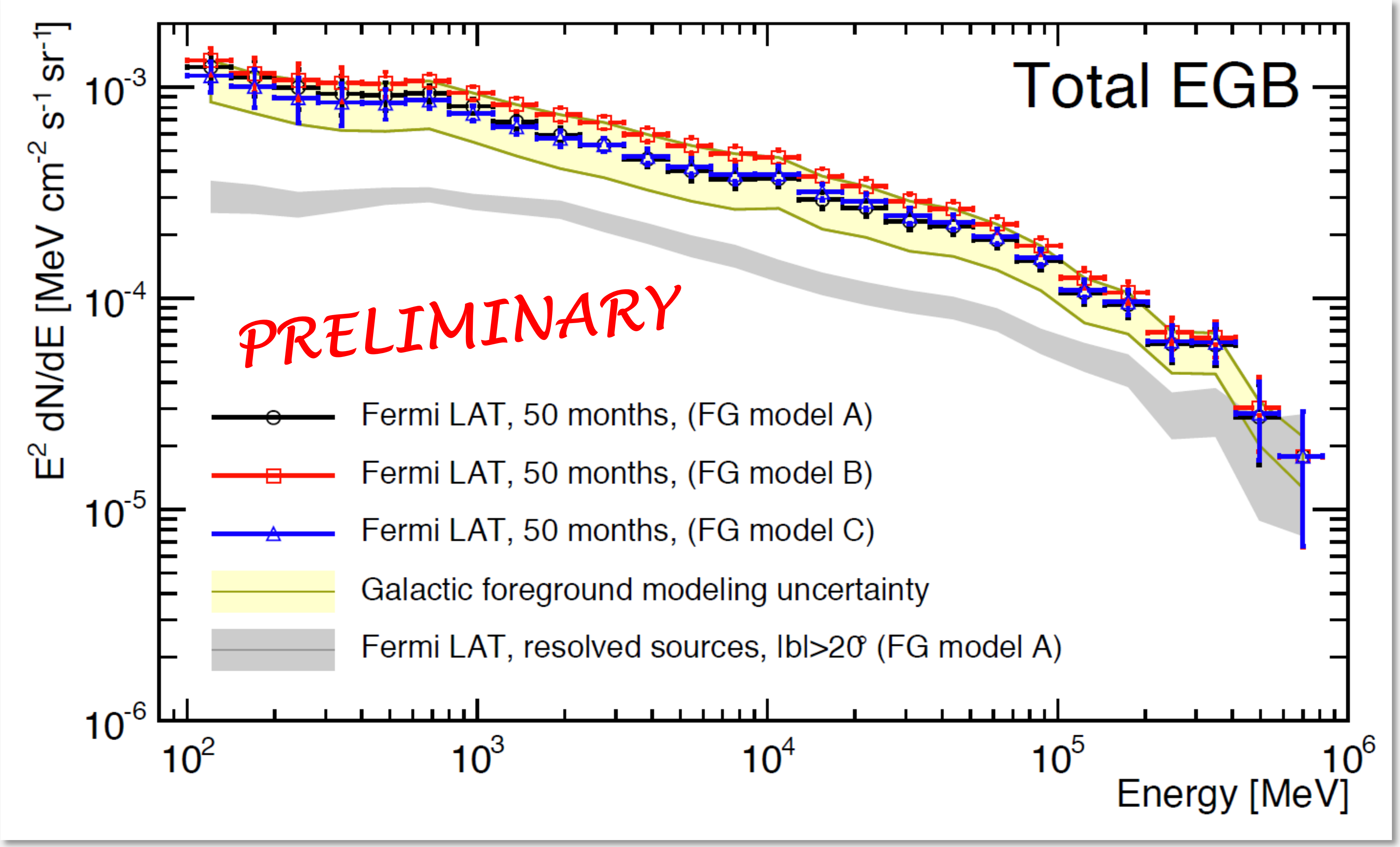
➔ Systematic uncertainties dominate over most of energy range, so χ^2 values cannot be easily interpreted in terms of statistical significance

Galactic Foreground Model	I_{100} [$\mathrm{MeV^{-1}\ cm^{-2}\ s^{-1}\ sr^{-1}}$]	γ	E_{Cut}	$I_{>100}$ [$\mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}$]	χ^2/ ndof Power Law Exponential Cutoff	χ^2 / ndof Power Law
A	$(0.95 \pm 0.08) \times 10^{-7}$	2.32 ± 0.02	279 ± 52	$(7.2 \pm 0.6) \times 10^{-6}$	13.9 / 23	87.5 / 25
B	$(1.12 \pm 0.08) \times 10^{-7}$	2.28 ± 0.02	206 ± 31	$(8.7 \pm 0.6) \times 10^{-6}$	7.9 / 23	151 / 24
C	$(0.78 \pm 0.07) \times 10^{-7}$	2.26 ± 0.02	233 ± 41	$(6.2 \pm 0.6) \times 10^{-6}$	10.7 / 23	106.5 / 24

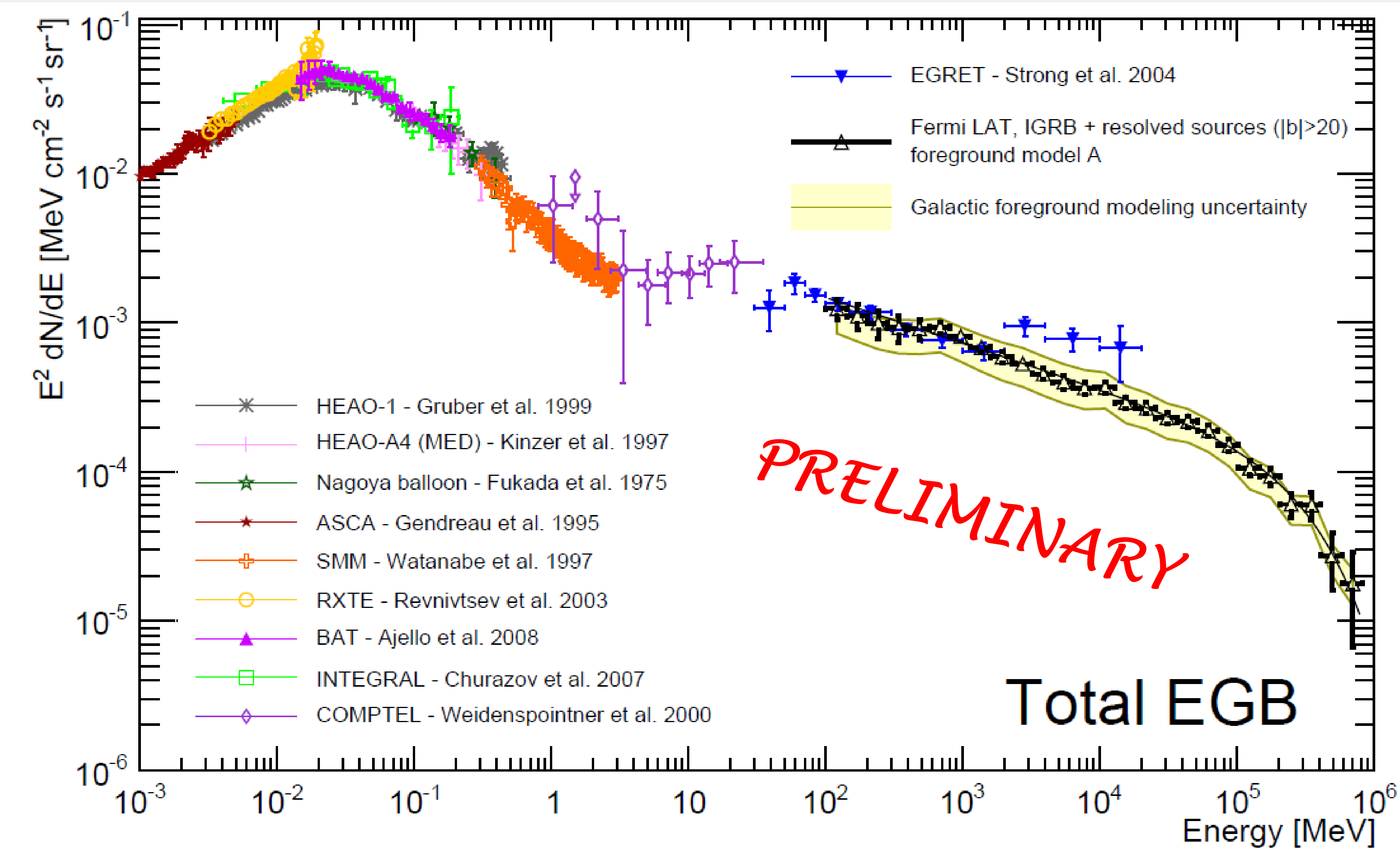
Summarizing Galactic foreground systematic studies, fitted normalization of the IGRB varies by +15% / -30% with respect to foreground model A, power law slope varies between 2.26 – 2.34, and cutoff energy varies between 206 – 374 GeV

Total Extragalactic Gamma-ray Background

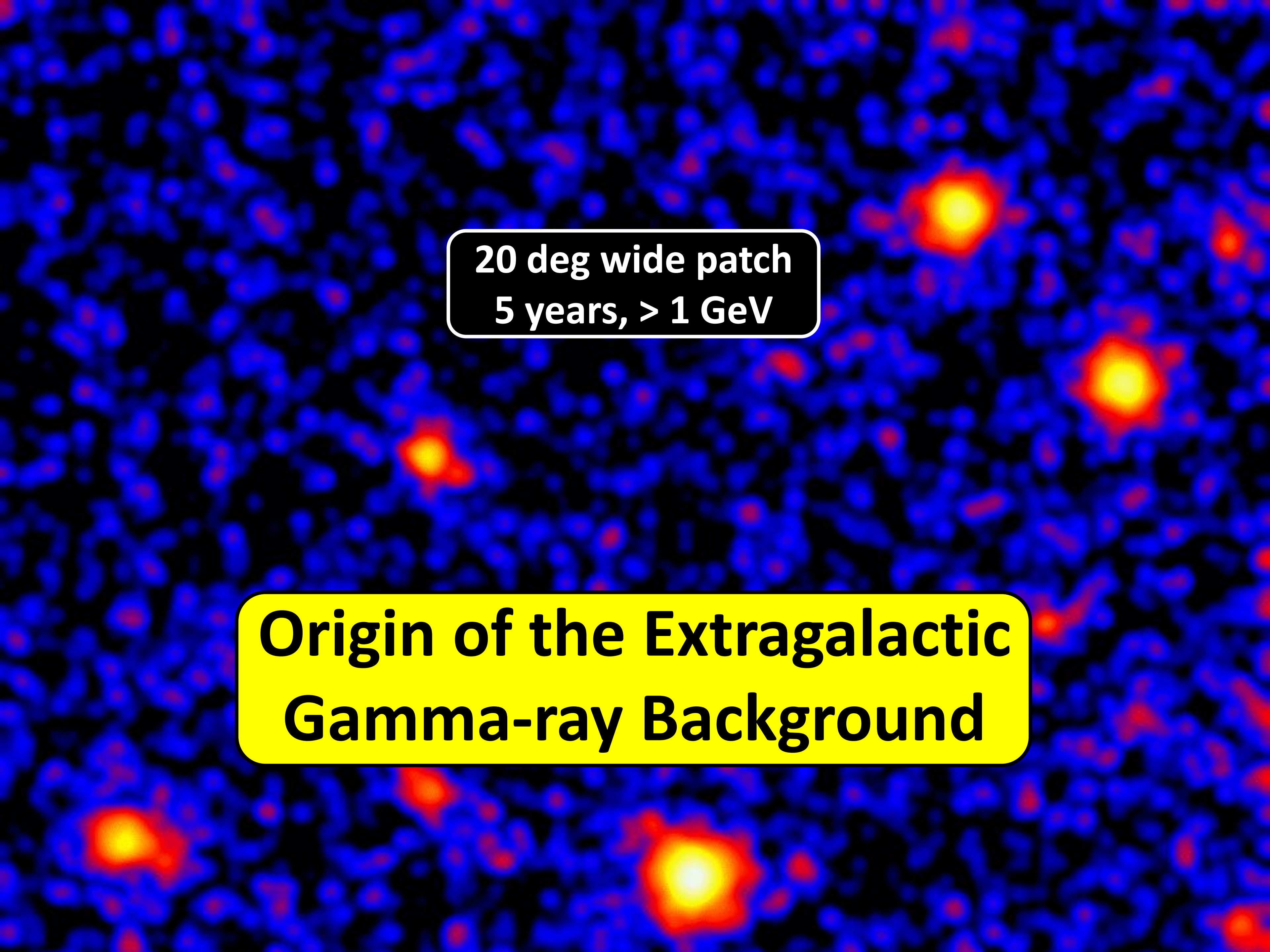
Systematic uncertainty from Galactic foreground represented by yellow band



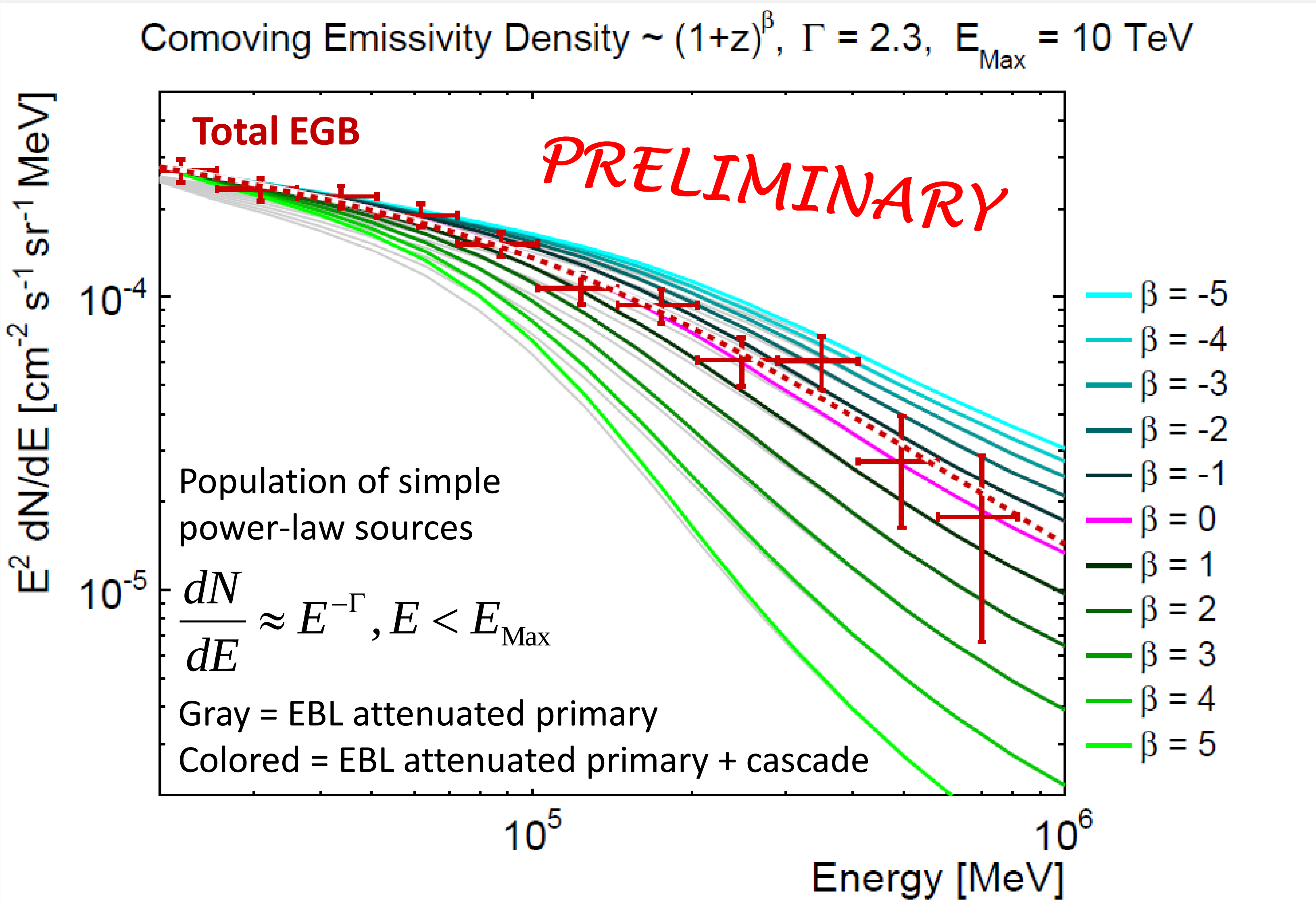
High-energy Extragalactic Background Light



Origin of the Extragalactic Gamma-ray Background



Simple Source Population Scenarios with EBL Attenuation and Secondary Cascades



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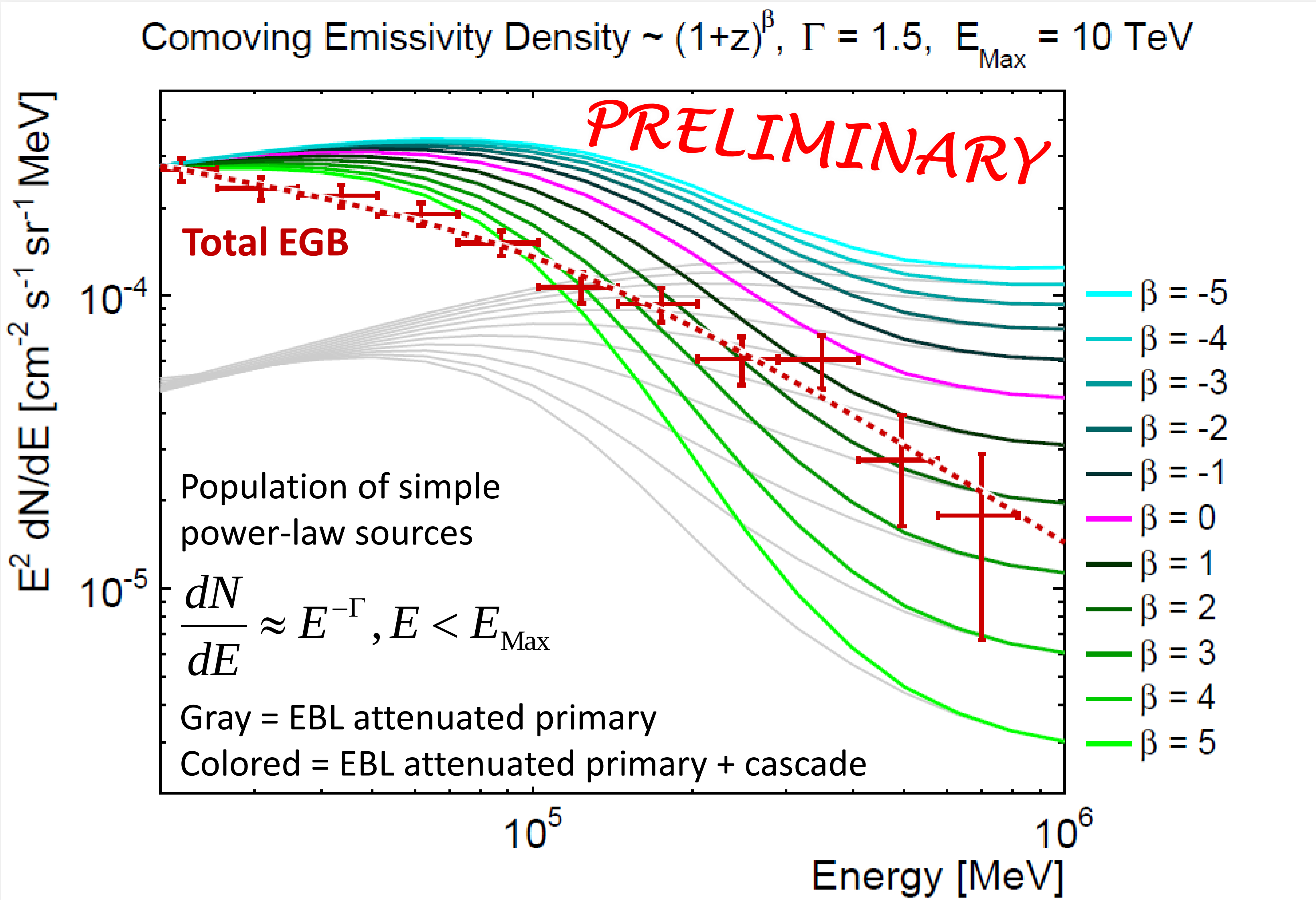
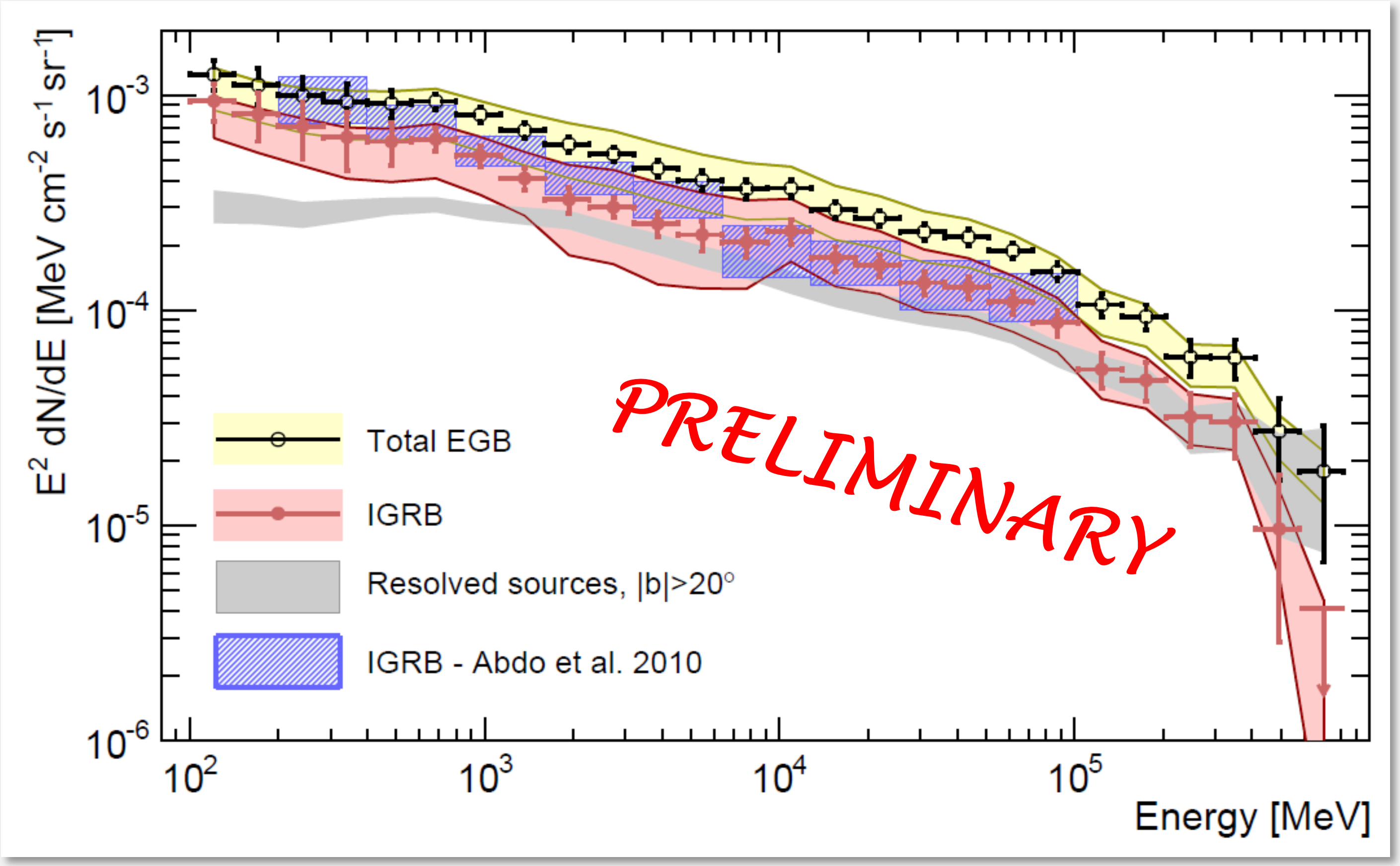
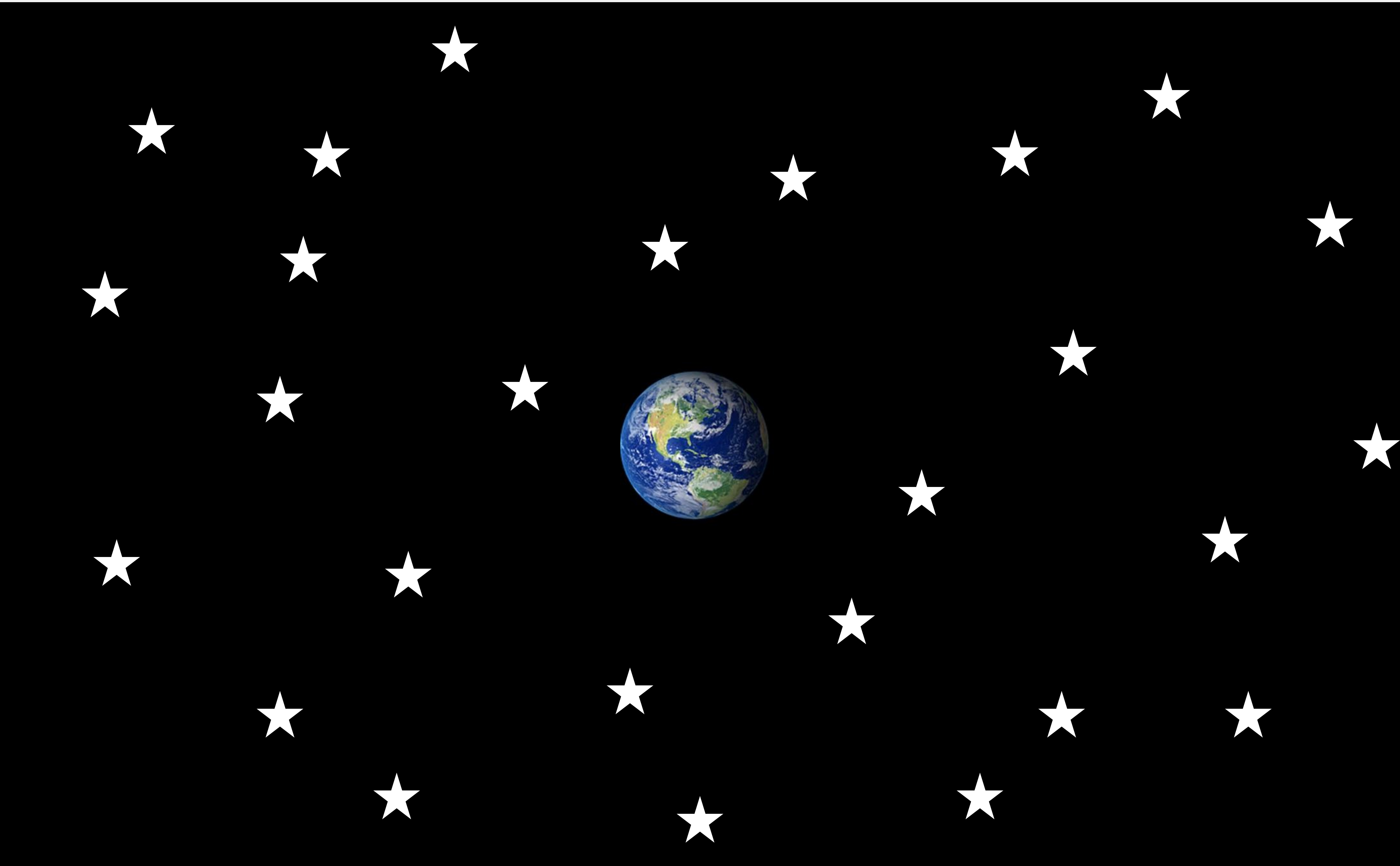




- **Updated LAT measurement of IGRB spectrum**
  - Extended energy range: 200 MeV – 100 GeV → 100 MeV – 820 GeV
- **Significant high-energy cutoff feature in IGRB spectrum**
  - Consistent with simple source populations attenuated by EBL
- **Roughly half of total EGB intensity above 100 GeV now resolved into individual LAT sources**

Supplemental Material

"Olber's Paradox"
Why is the Night Sky Dark?



"Olber's Paradox"
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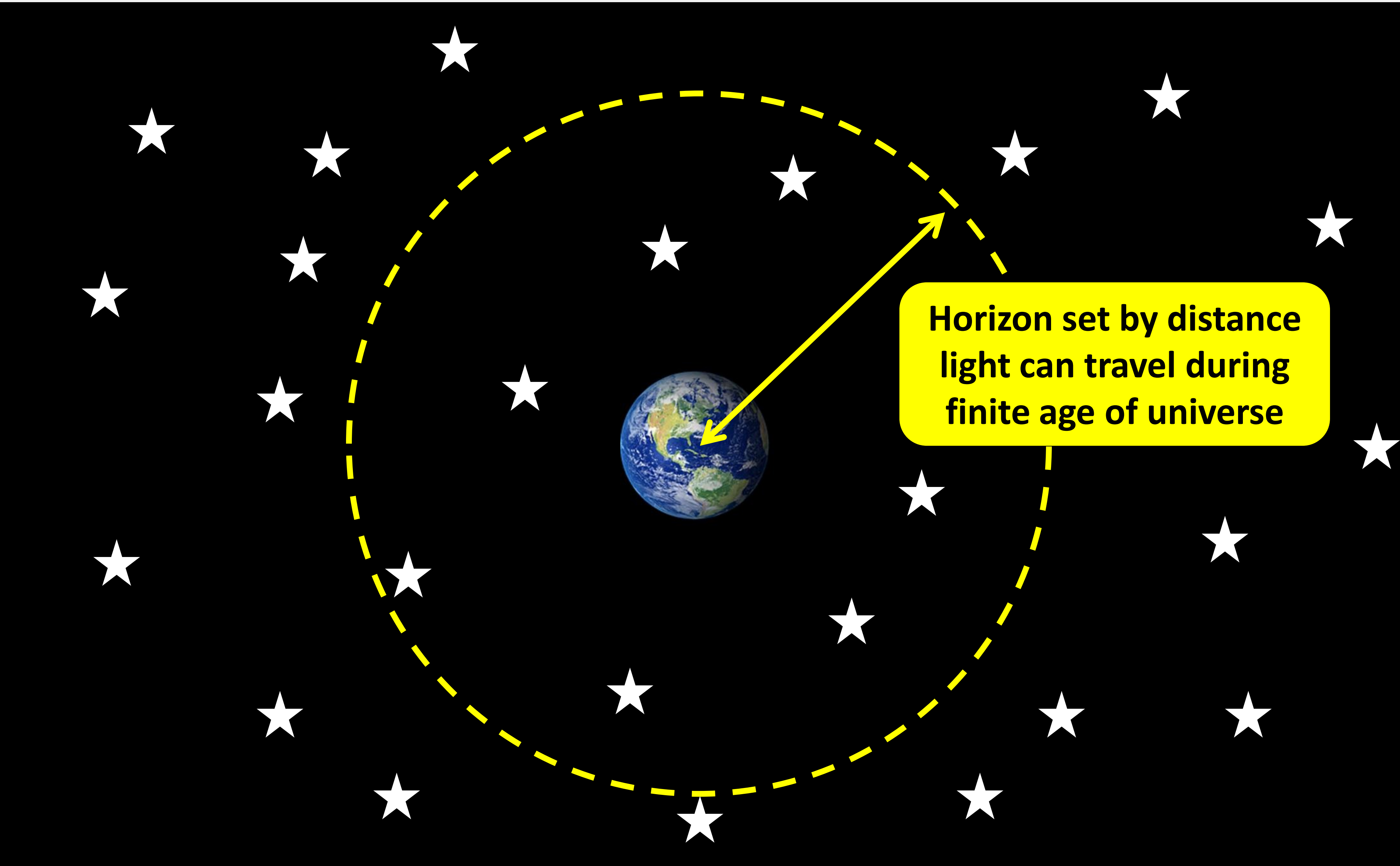
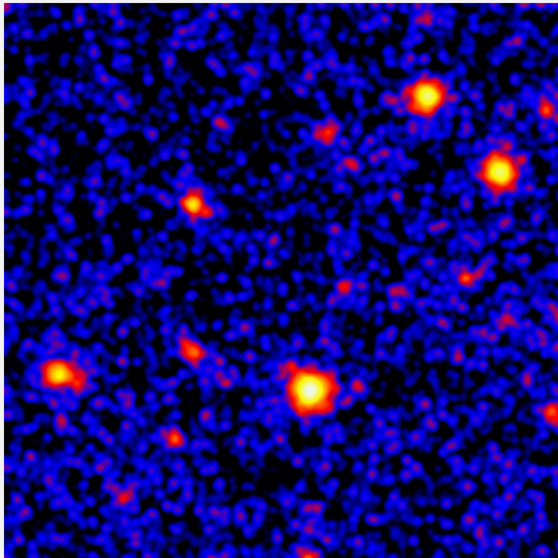
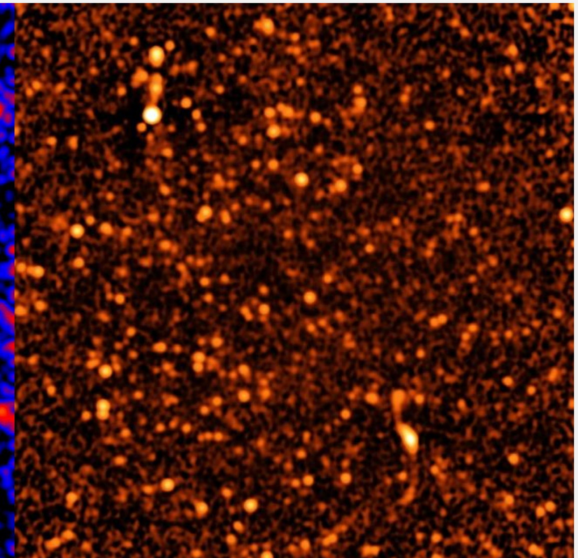


Gamma Rays as Part of the Non-thermal Universe

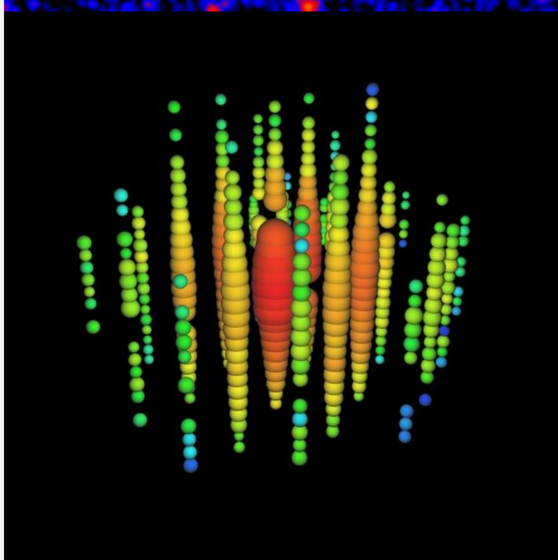
The origin of the **extragalactic gamma-ray background** is not definitively established …

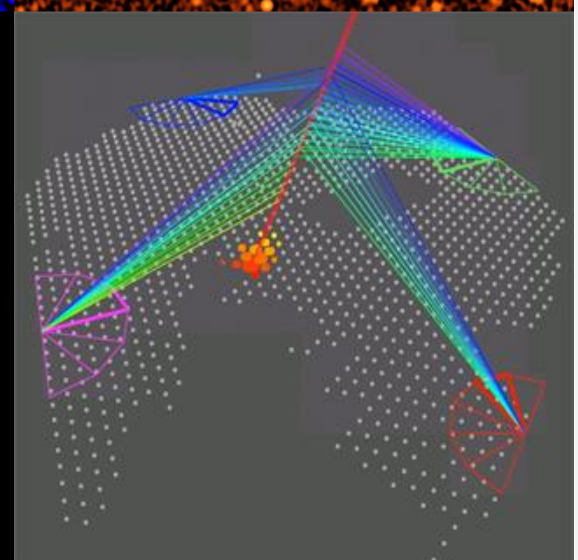




nor the **extragalactic radio background** …

nor **high-energy cosmic neutrinos** …

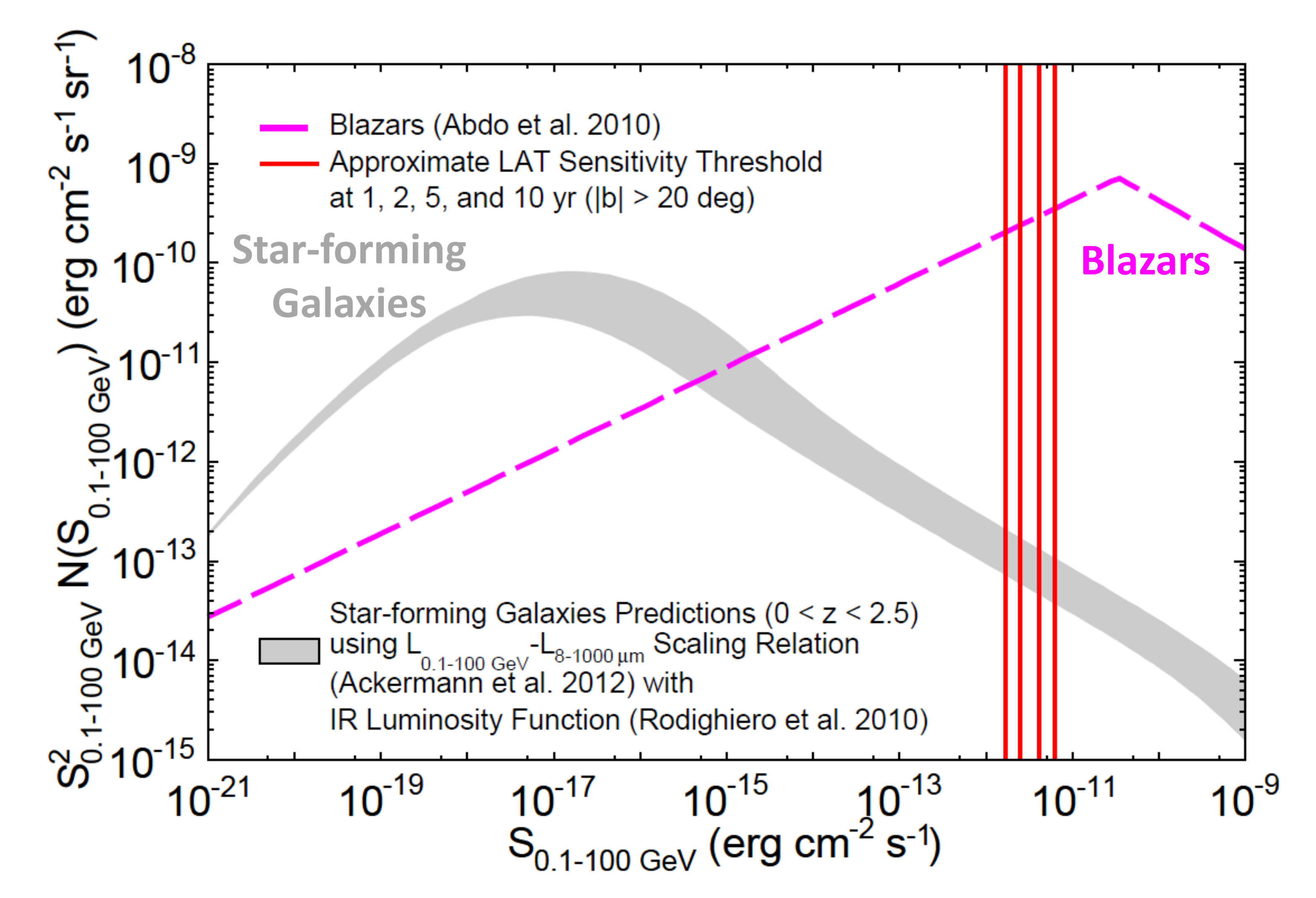




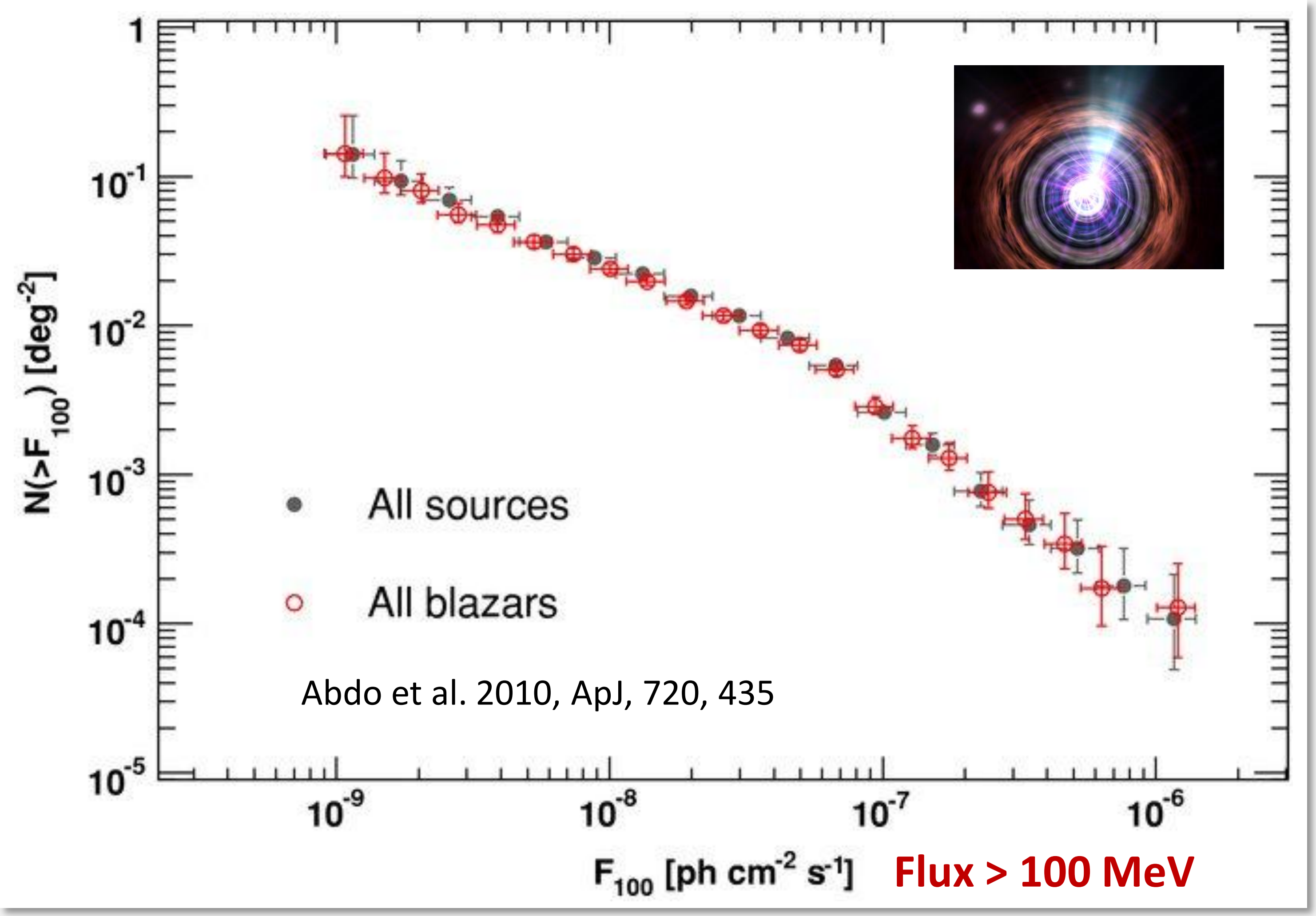
nor **ultra-high-energy cosmic rays** …

Comparing Extragalactic Source Populations

Most of the cumulative intensity from blazars (bright, rare) has already been resolved with the LAT. Opposite is true of star-forming galaxies (faint, numerous).



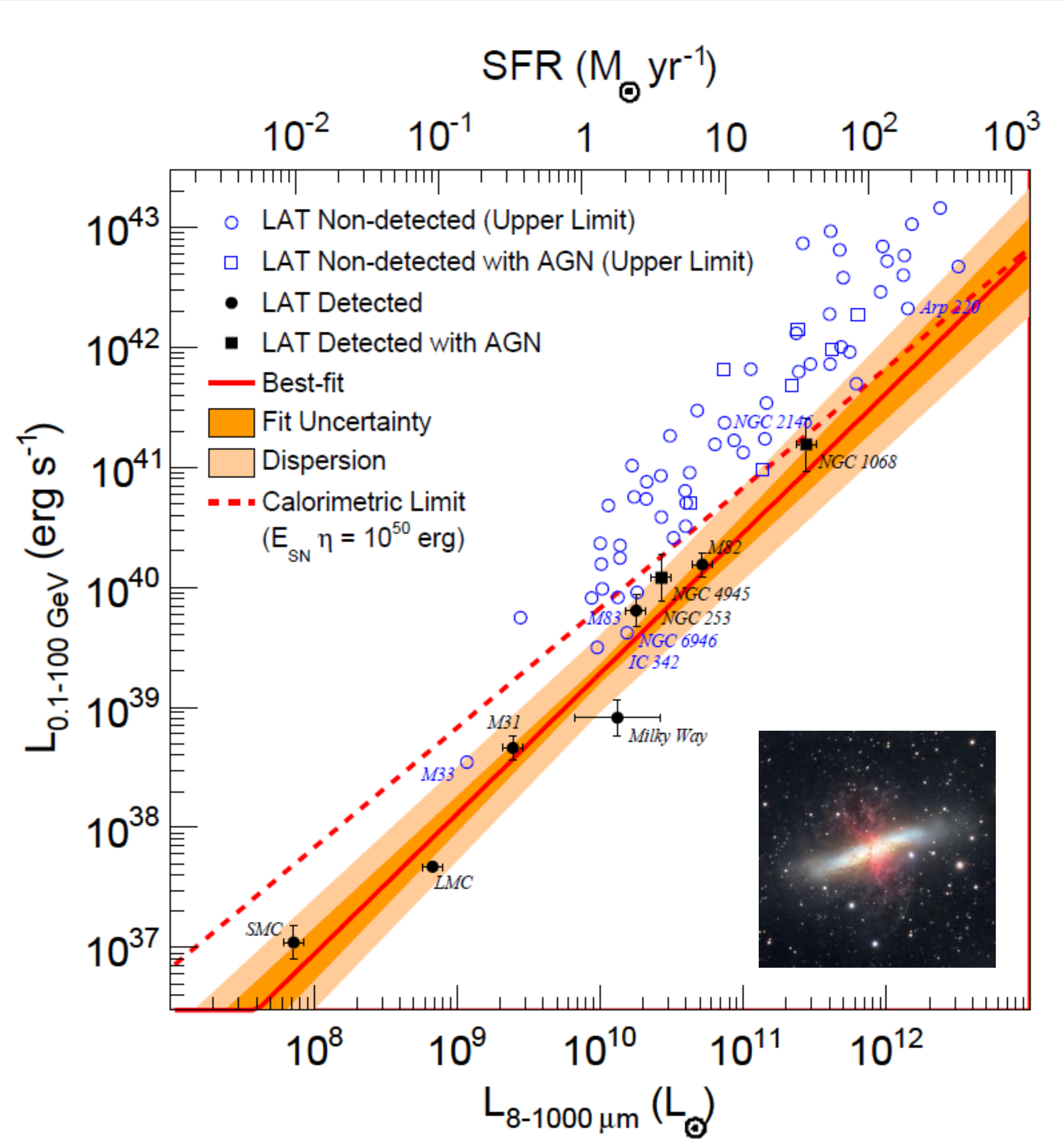
Blazars:
Observed Flux Distribution



Over 1000 blazars detected to cosmologically significant redshifts with the LAT

Flux distribution can be estimated from relative firm empirical basis

Star-forming Galaxies: Multiwavelength Scaling Relations



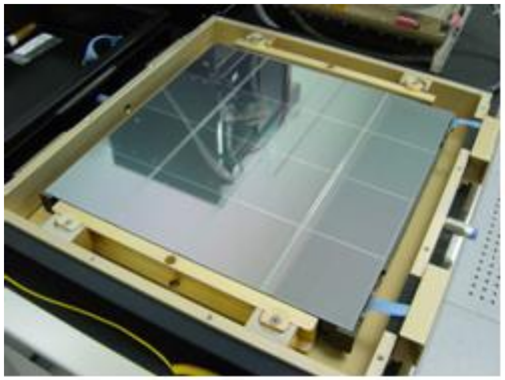
Cumulative intensity of star-forming galaxies almost entirely unresolved

Contribution to EGB estimated with multiwavelength scaling relations or physical models calibrated in local universe

For example, gamma-ray luminosity of Local Group and nearby starburst galaxies is quasi-linearly correlated with star-formation rate
(traced by total IR luminosity)

Ackermann et al. 2012, ApJ, 755, 16

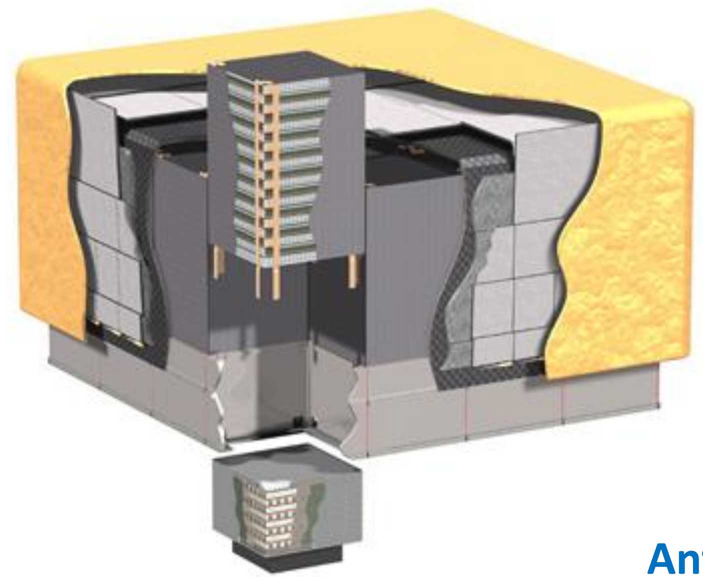
Fermi LAT in Detail

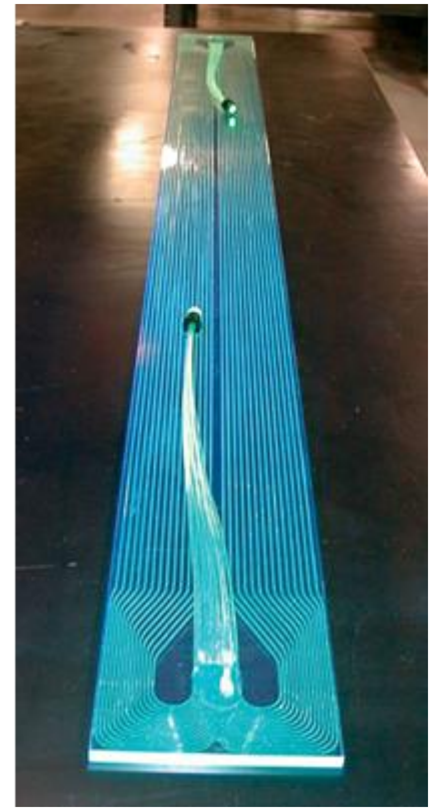


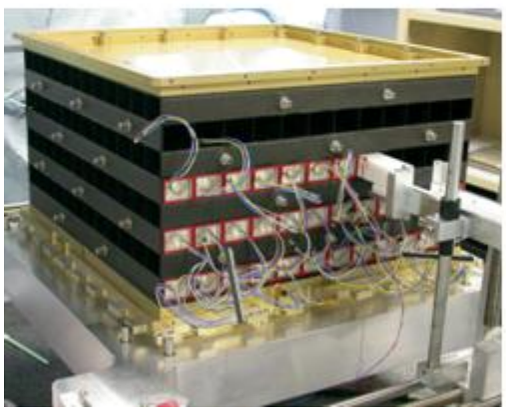
Precision Converter and Tracker

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

Thin/Front Thick/Back







Imaging Calorimeter

- 8.6 RL
- 1536 CsI crystals
- Hodoscopic (12 x 8 layers)

(+ Data Acquisition System)

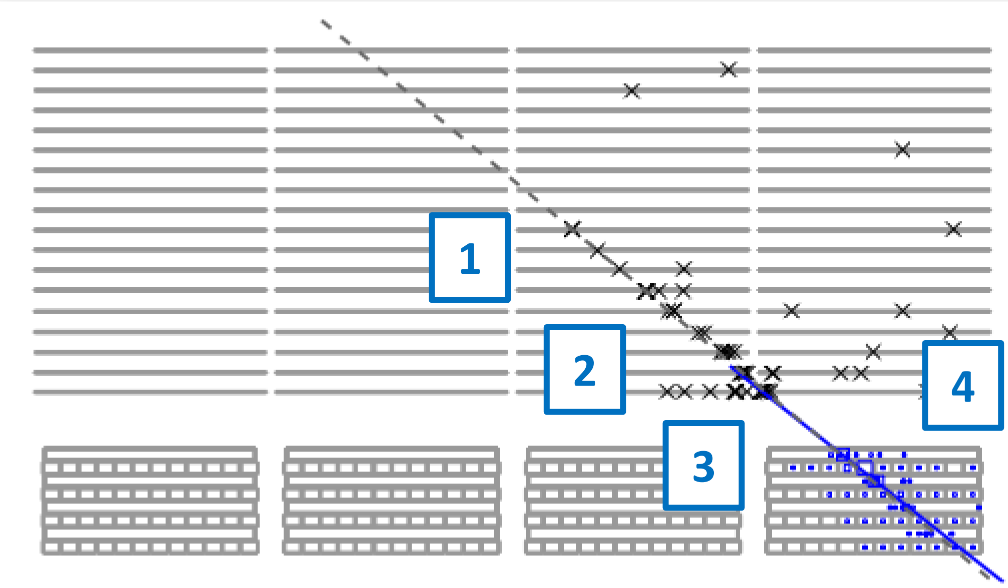
- 500 Hz sent to ground

Anti-Coincidence Detector

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

Atwood et al. 2009, ApJ, 697, 1071

LAT Event Reconstruction and Classification

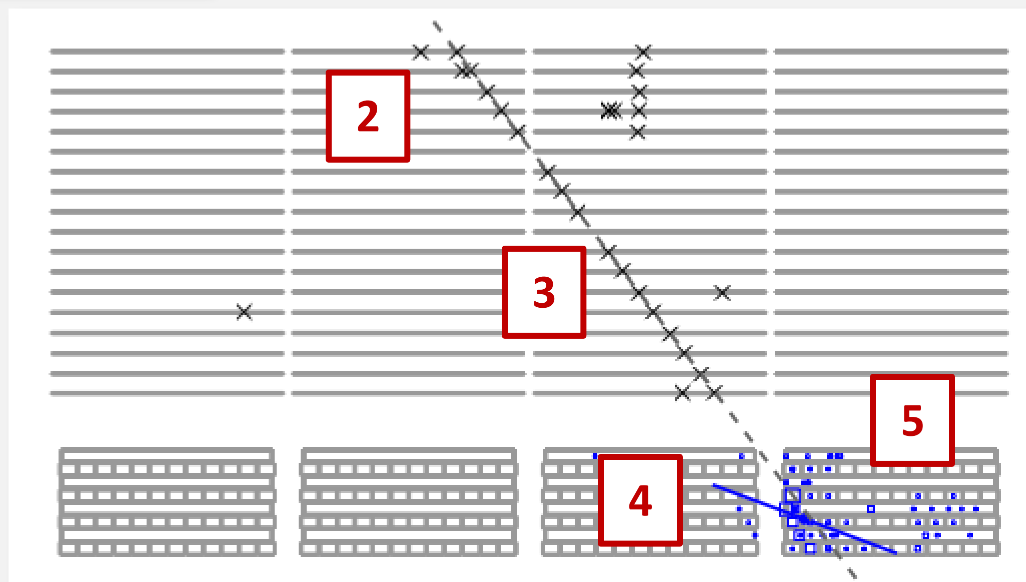


Nearly ideal gamma-ray candidate

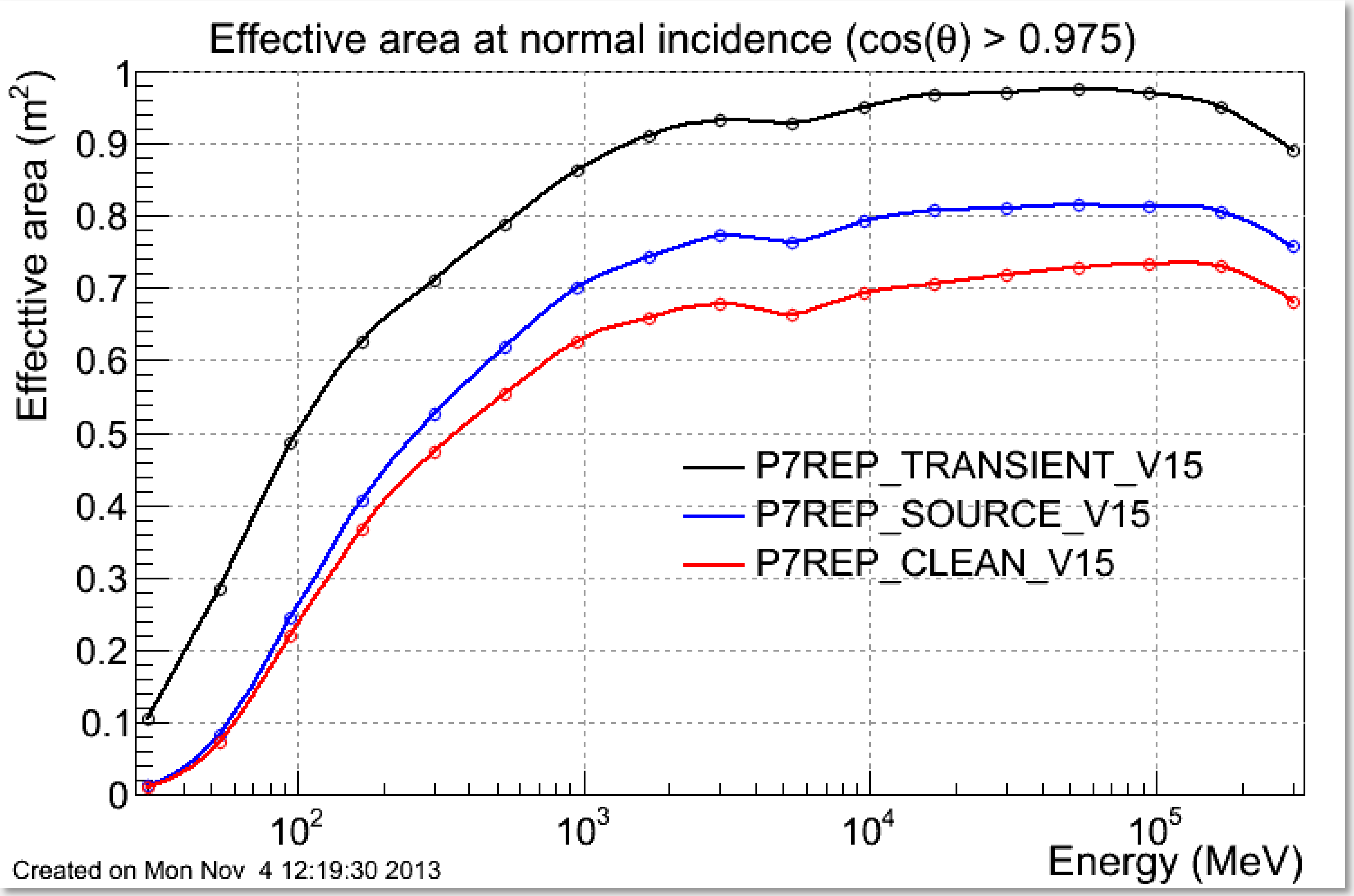
1. Track starts in middle of TKR
2. Extra hits near track
3. TKR ionization consistent with electron-positron pairs
4. CAL axis aligned with track
5. CAL energy confined near axis

Nearly ideal proton candidate

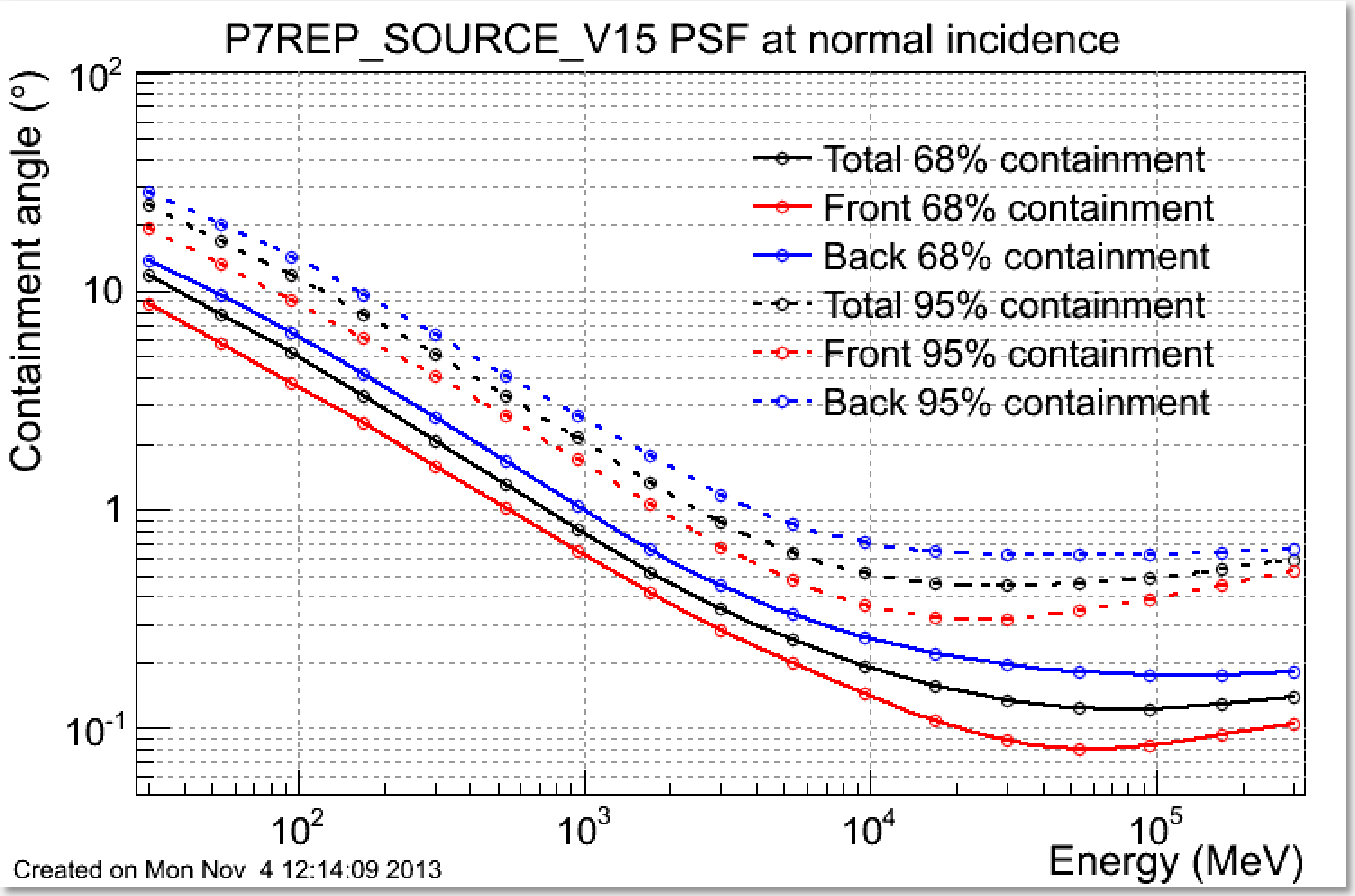
1. Signal in surrounding ACD (not shown)
2. Starts at top of TKR
3. Few extra hits near track
4. CAL axis not-aligned with TKR
5. CAL energy "lumpier"



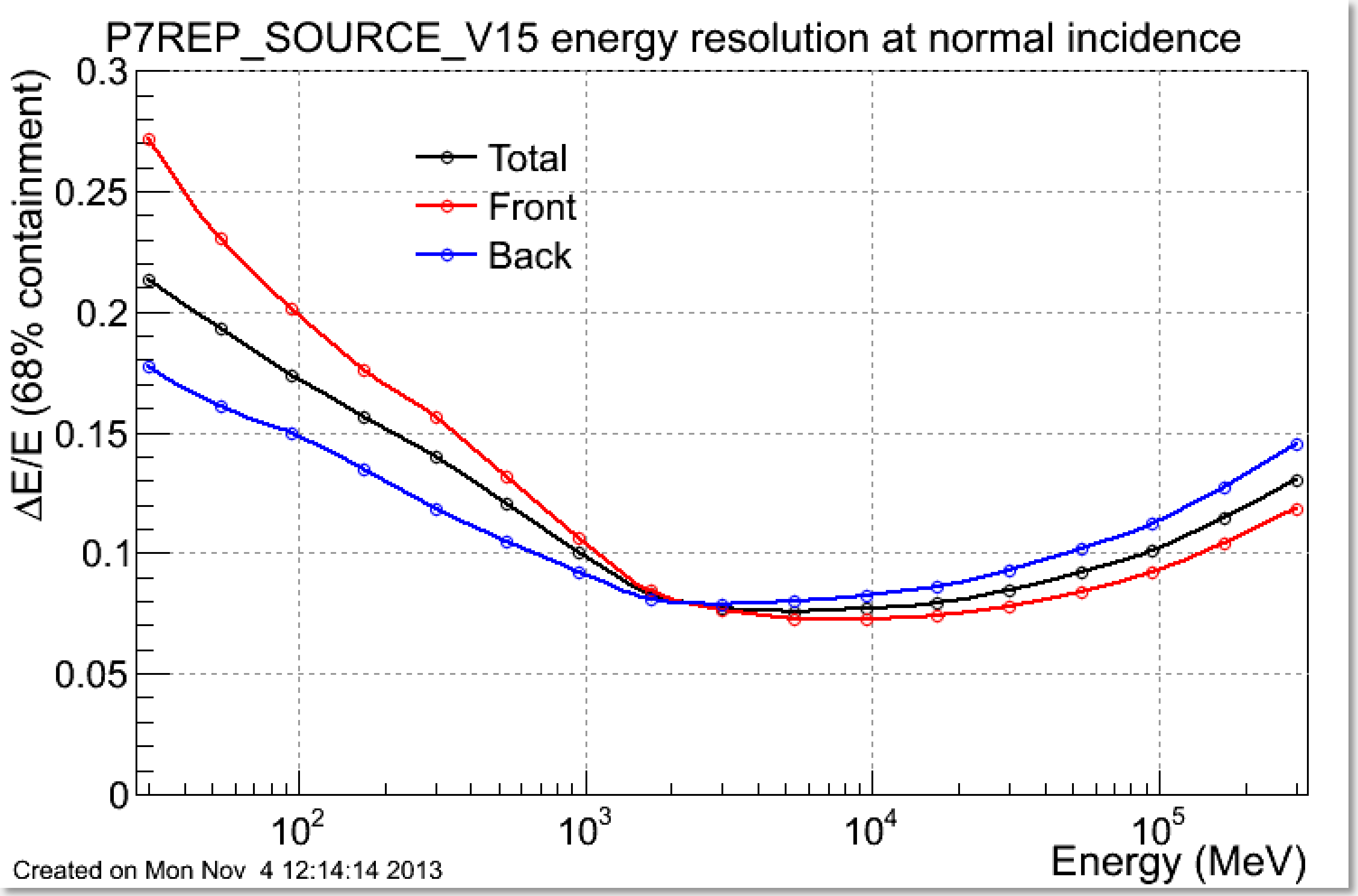
P7 Performance Plots (IRFs)



P7 Performance Plots (IRFs)

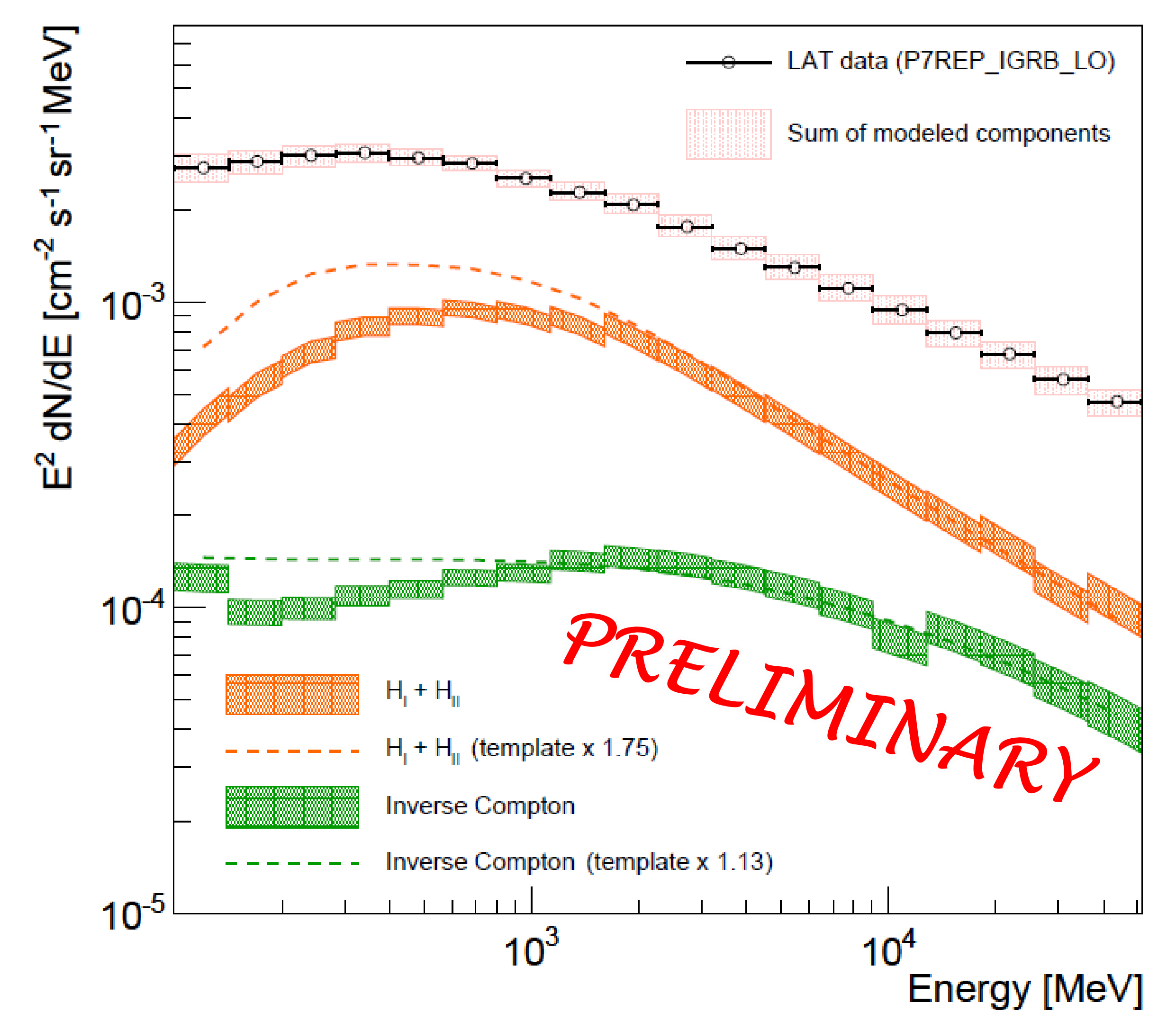


P7 Performance Plots (IRFs)



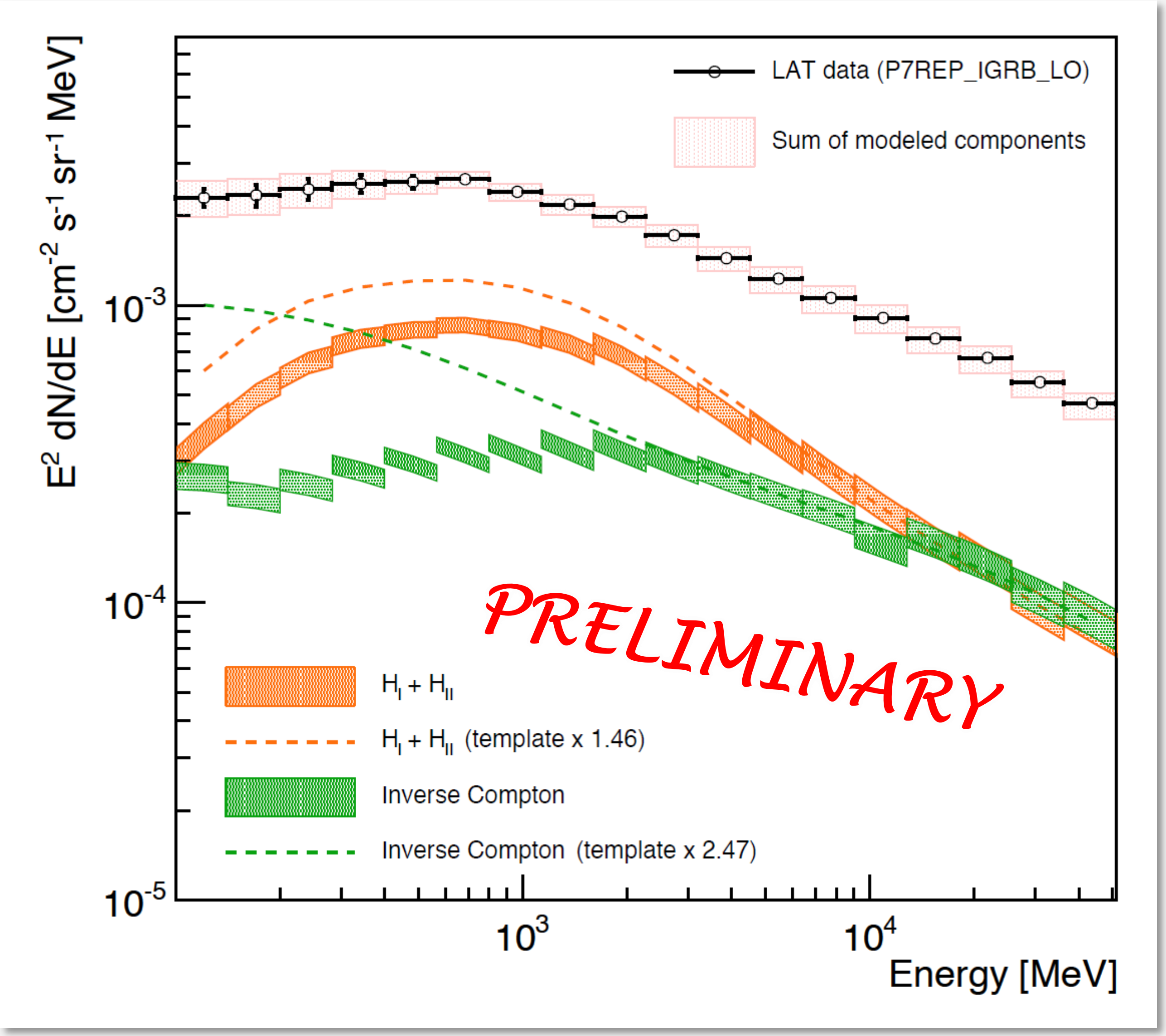
Systematic Uncertainty from Galactic Foreground: Benchmark Models (GALPROP)

Galactic Foreground Model B

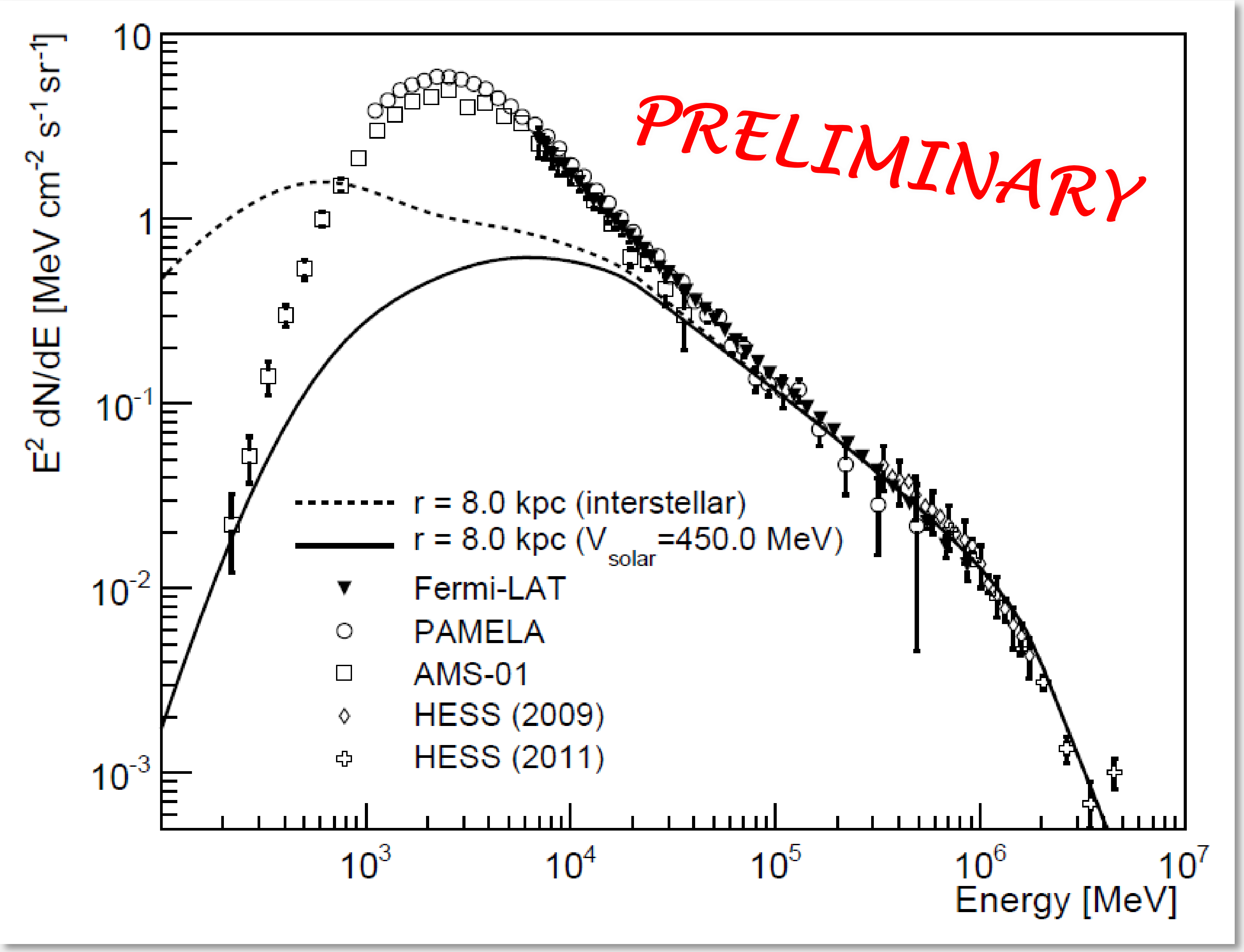


Systematic Uncertainty from Galactic Foreground: Benchmark Models (GALPROP)

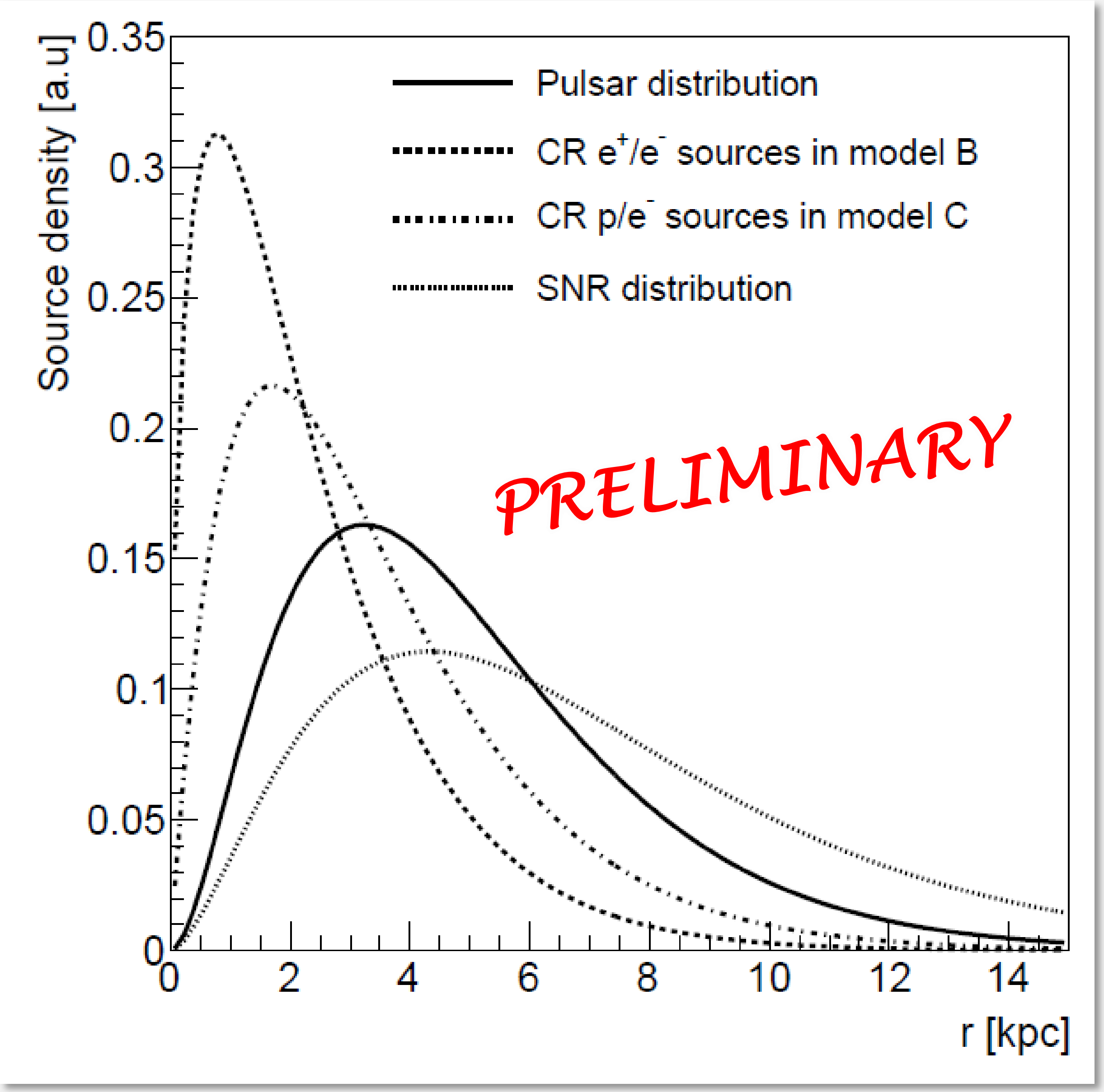
Galactic Foreground Model C



Galactic Foreground Model B: Electron Spectrum

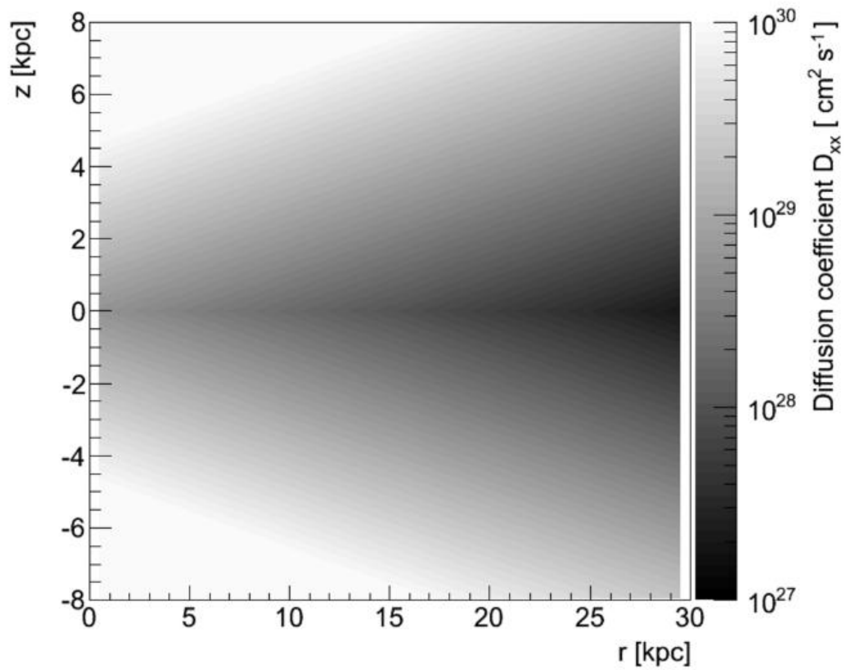


Radial Distribution of Cosmic-ray Sources

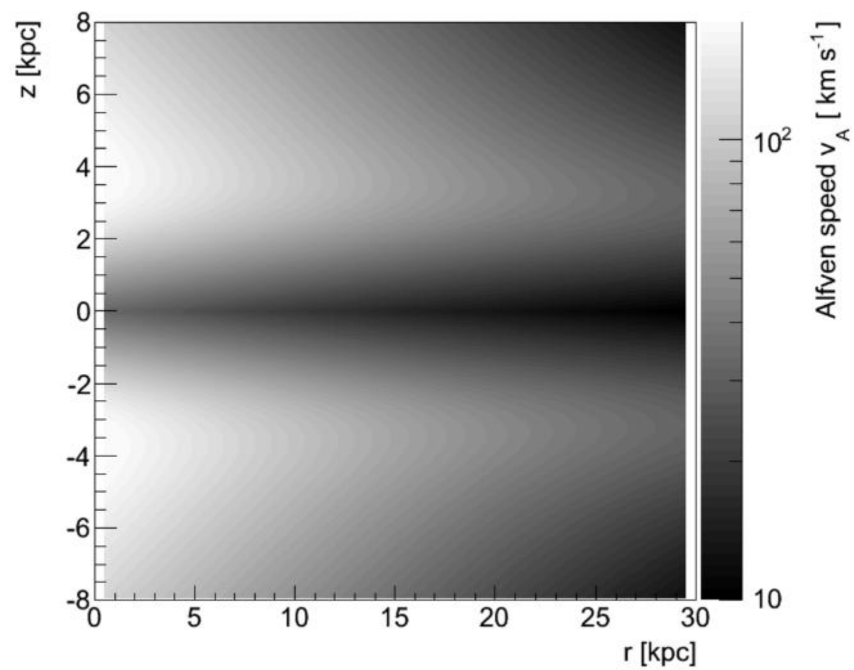


Galactic Foreground Model C: Diffusion Coefficient and Alfven Speed

Diffusion Coefficient



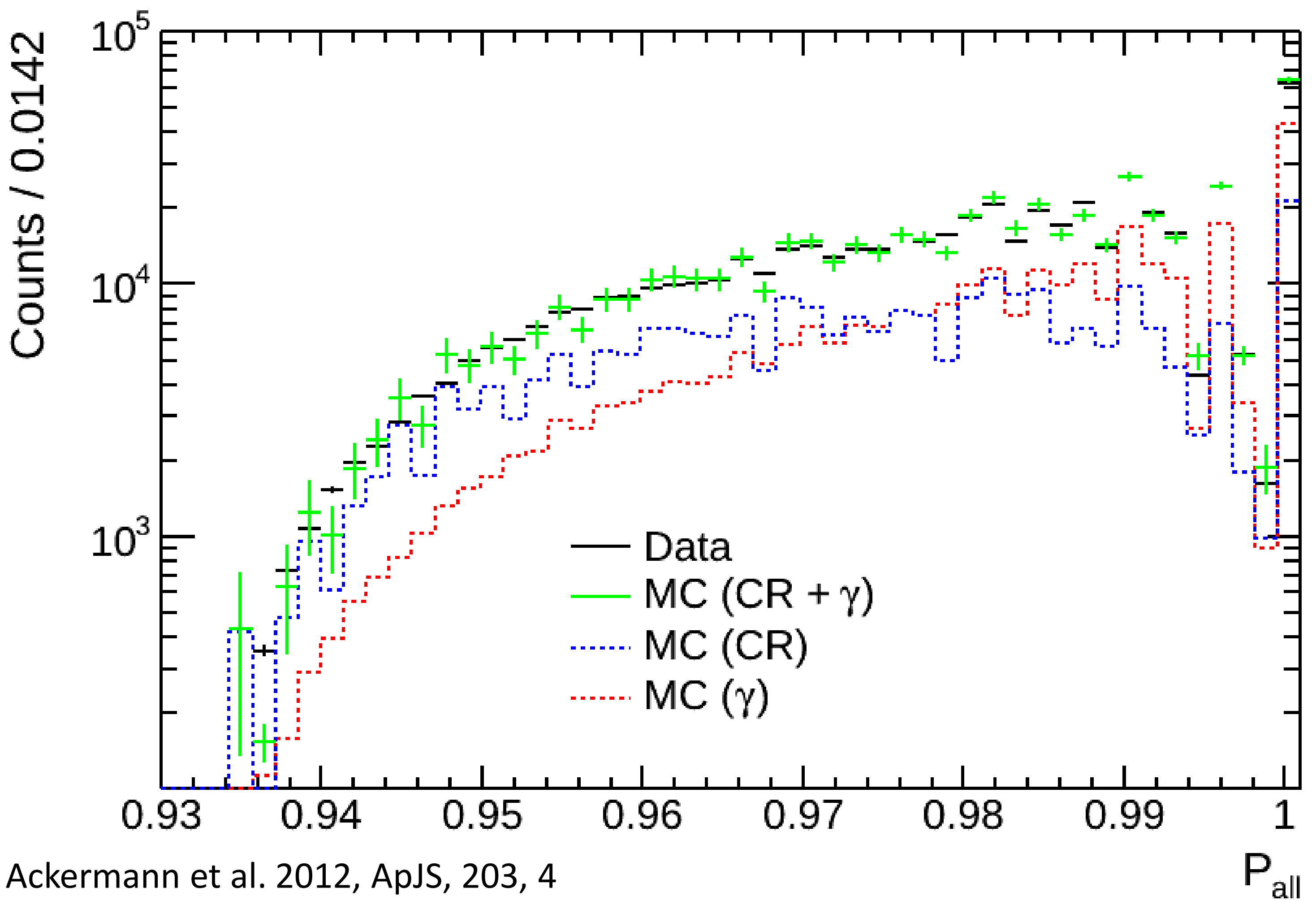
Alfven Speed



PRELIMINARY

Estimating Residual Cosmic-ray Background Rates from On-orbit Data

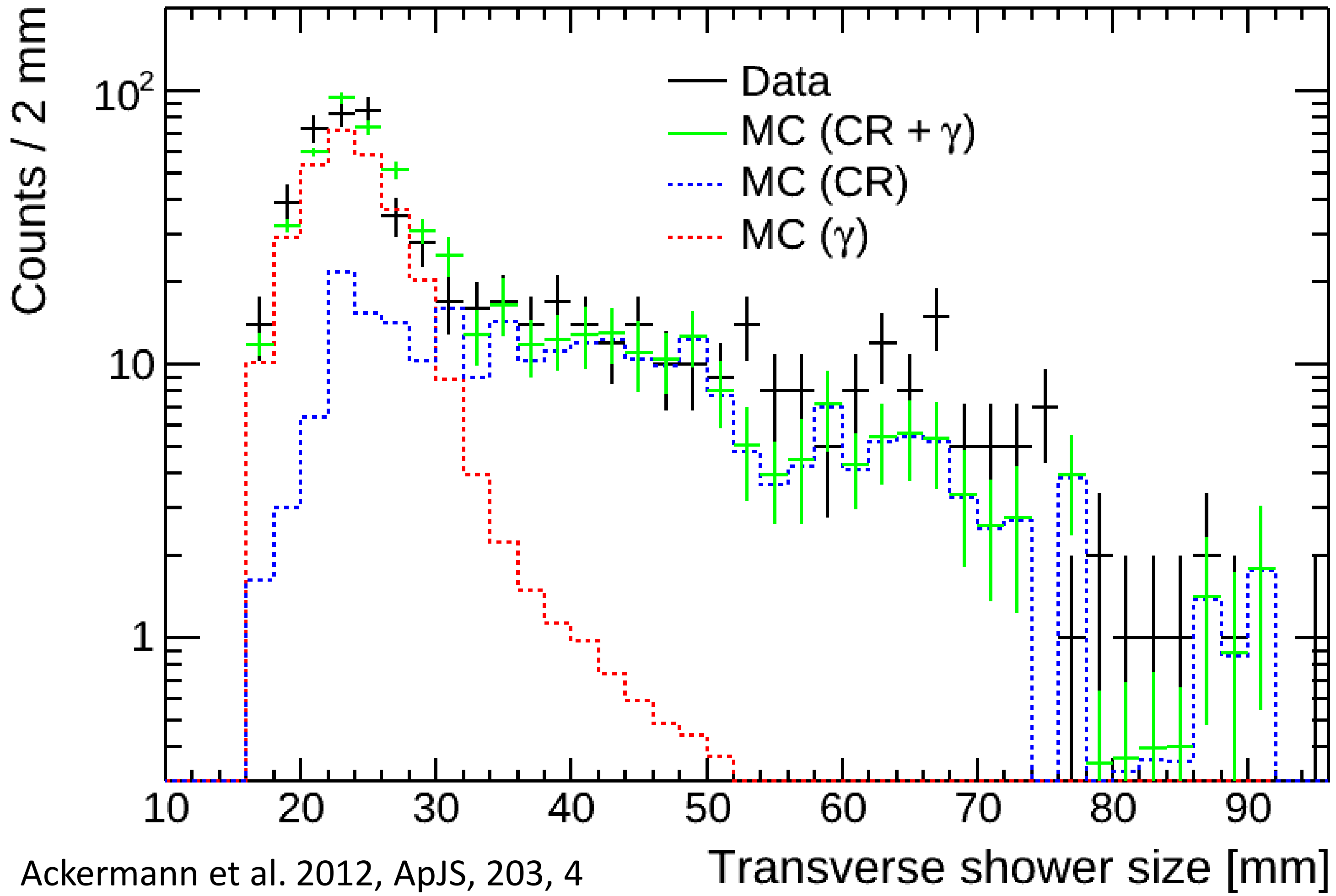
Example for P7SOURCE: Distribution of multivariate event classifier output in 200 – 400 MeV range used to calibrate residual cosmic-ray rates at low energies



Ackermann et al. 2012, ApJS, 203, 4

Estimating Residual Cosmic-ray Background Rates from On-orbit Data

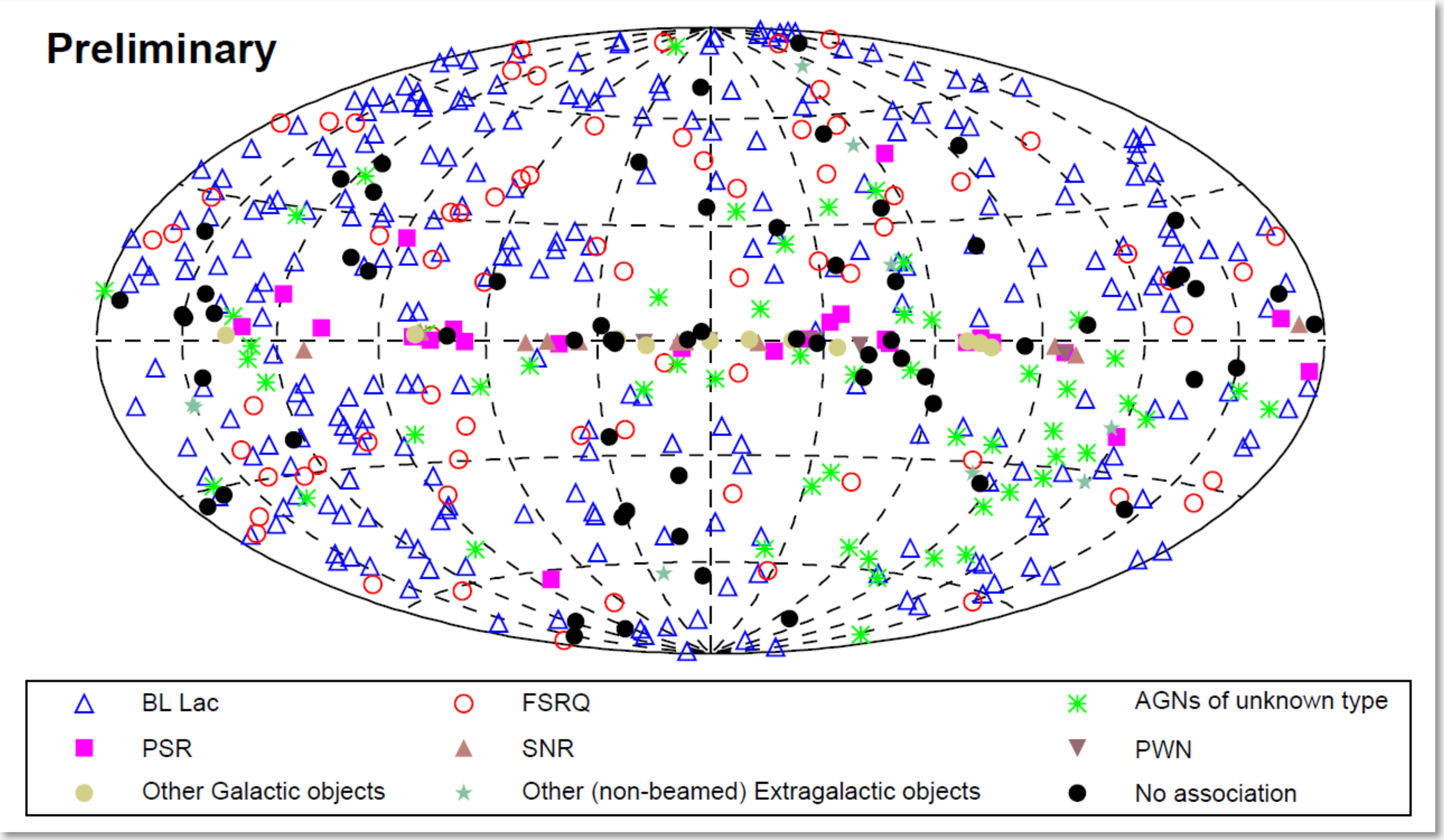
Example for P7SOURCE: Distribution of transverse shower size output in 200 – 400 MeV range used to calibrate residual cosmic-ray rates at low energies



Ackermann et al. 2012, ApJS, 203, 4

LAT Sources Detected Above 10 GeV

514 Sources in First *Fermi*-LAT Catalog of Sources Above 10 GeV (1FHL)

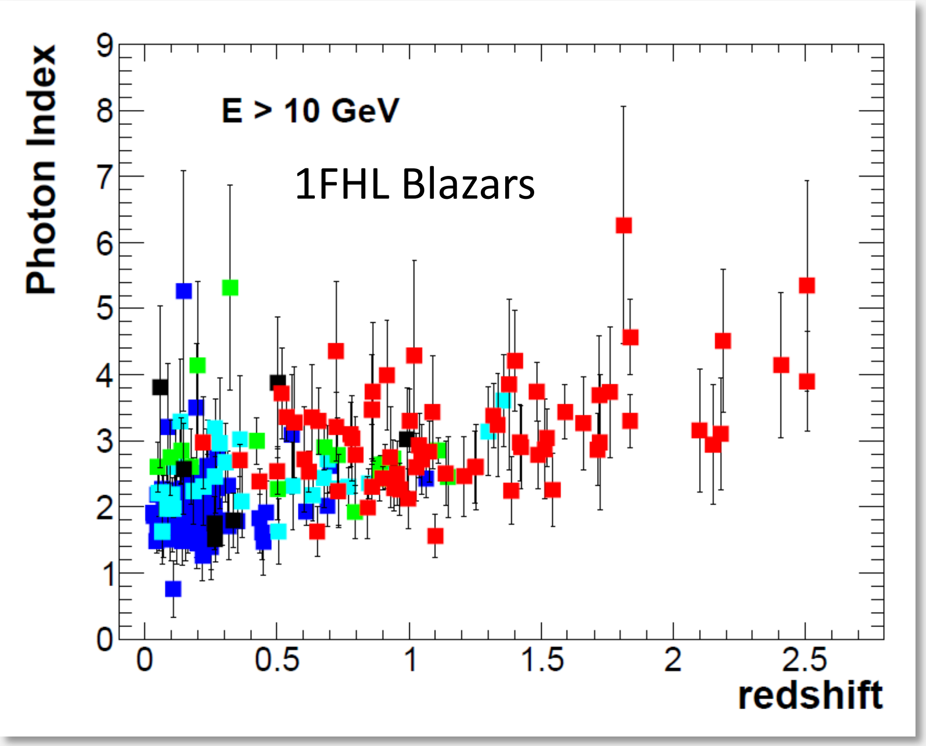


3 years, 10 – 500 GeV, P7 Clean events

Ackermann et al. 2013, ApJS, 209, 34

LAT Sources Detected Above 10 GeV

Source Class	#	Fraction of 1FHL (%)
Blazar, BL Lac	259	50.4
Blazar, FSRQ	71	13.8
Unknown type AGN	58	11.3
Pulsar	27	5.3
SNR	11	2.1
PWN	6	1.2
Other Galactic	11	2.1
Other extragalactic	6	1.2
Unassociated	65	12.6



FSRQ
HSP-BL Lac
ISP-BL Lac
LSP-BL Lac
BL Lac

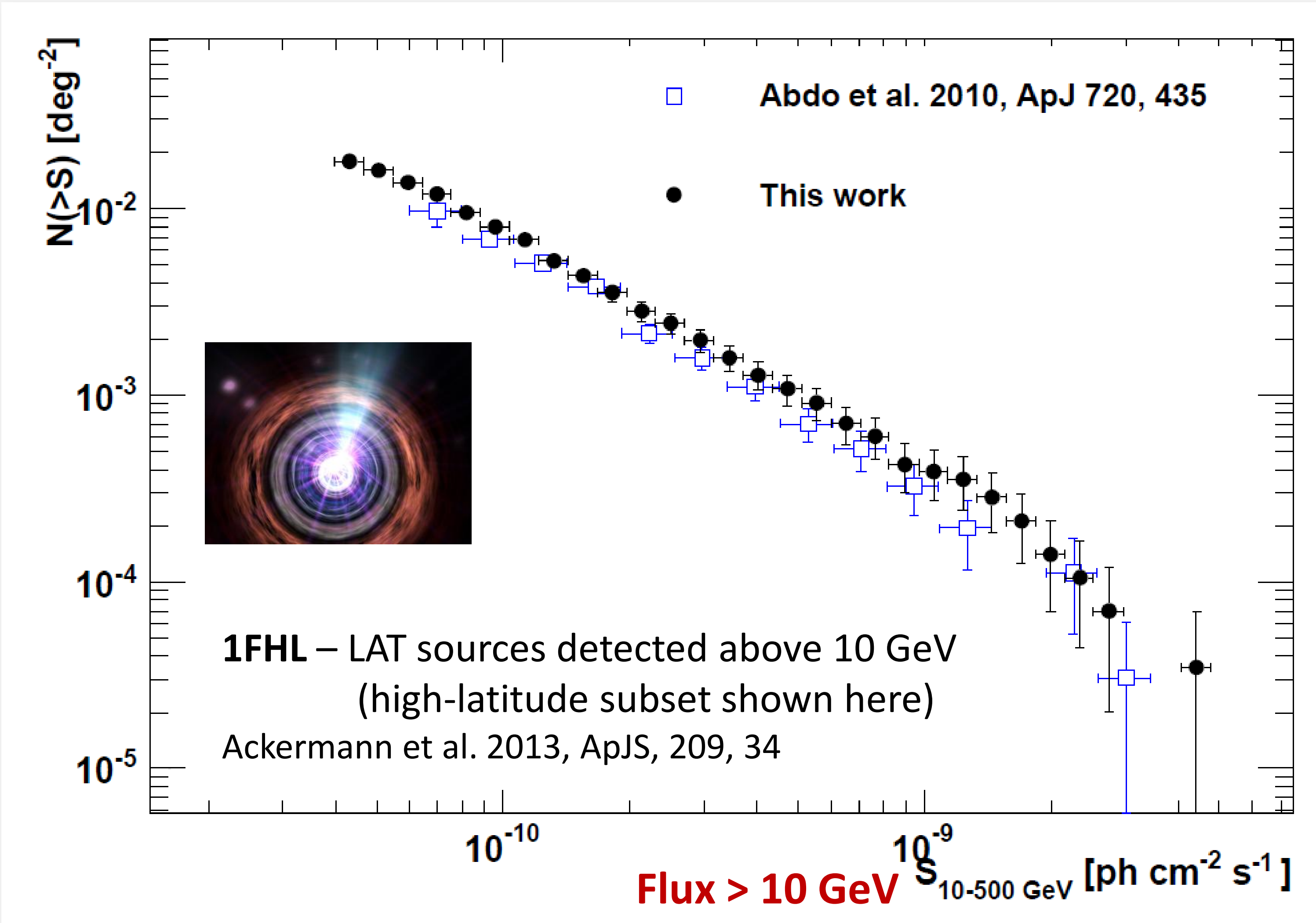
BL Lac blazars are most abundant source type

63 1FHL sources not in 2FGL

84 1FHL sources associated with known VHE sources

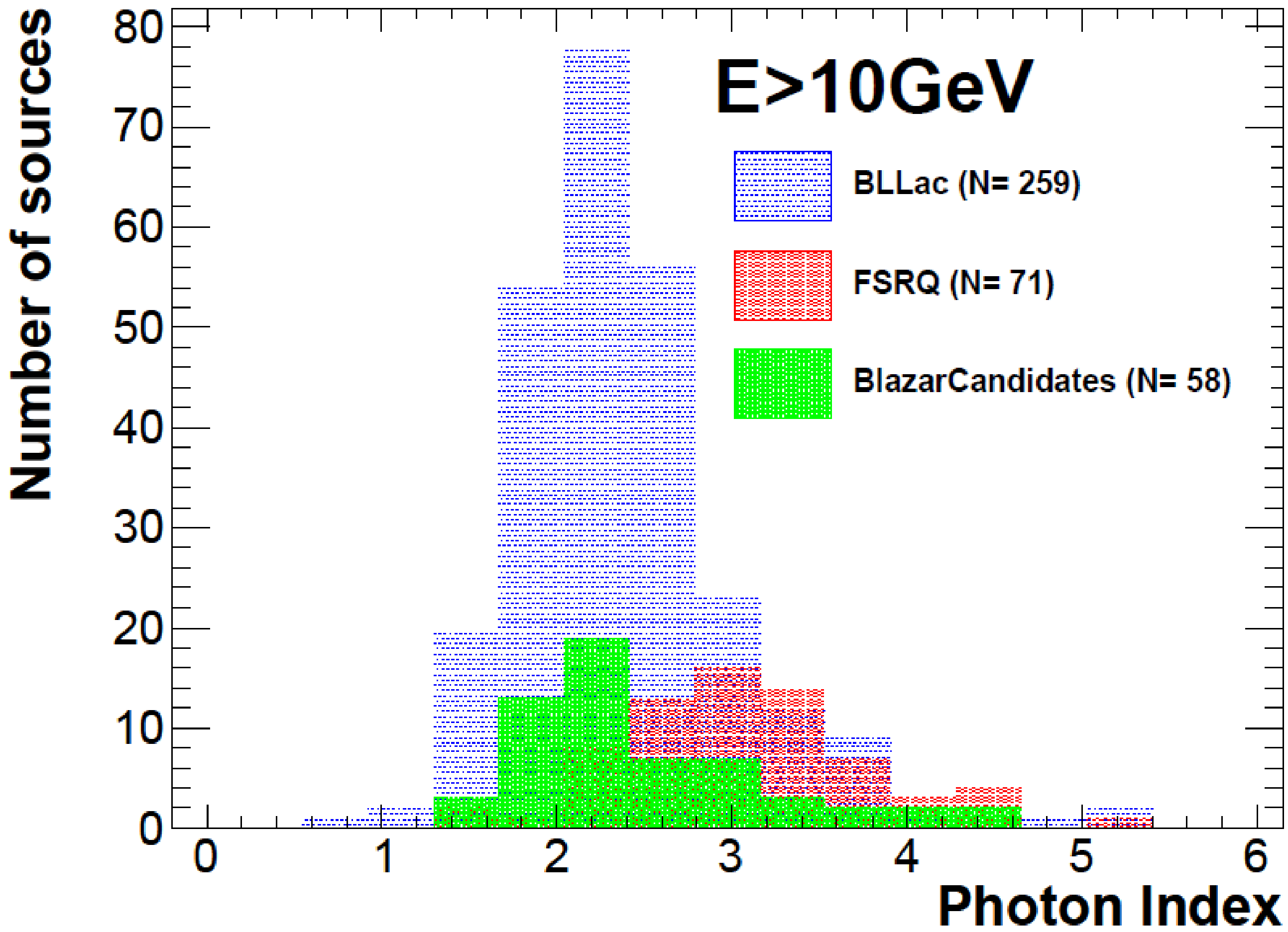
Ackermann et al. 2013, ApJS, 209, 34

Blazars:
Observed Flux Distribution



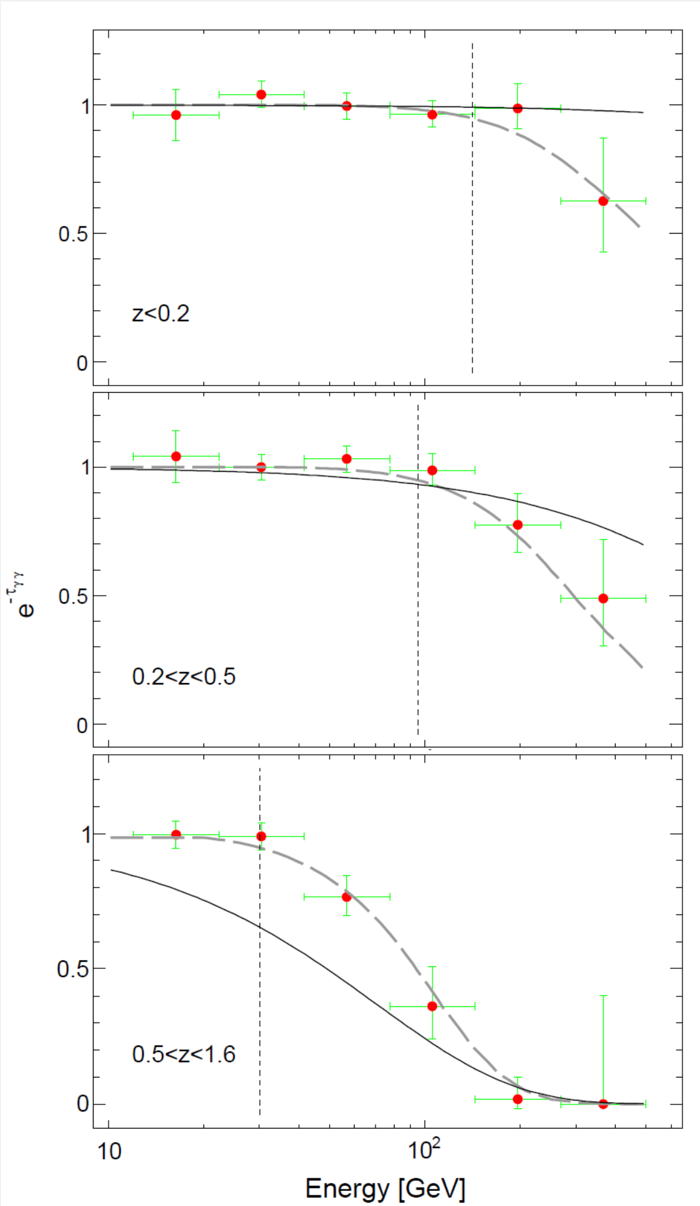
Roughly half of the total EGB intensity above 100 GeV now resolved into individual sources with the LAT (mainly BL Lacertae type blazars)

Power Law Photon Index Distribution for Blazars Detected with the LAT above 10 GeV



Ackermann et al. 2013, ApJS, 209, 34

EBL Attenuation for Individually Resolved Blazars



EBL attenuation feature as function of energy (observed / expected flux) for blazars in 3 redshift intervals

Vertical dashed line = critical energy below which < 5% of source photons are expected to be absorbed

Long dashed line = EBL model of Franceschini et al. 2008

Solid line = best-fit model assuming sources have intrinsic exponential cutoff, and follow blazar sequence model

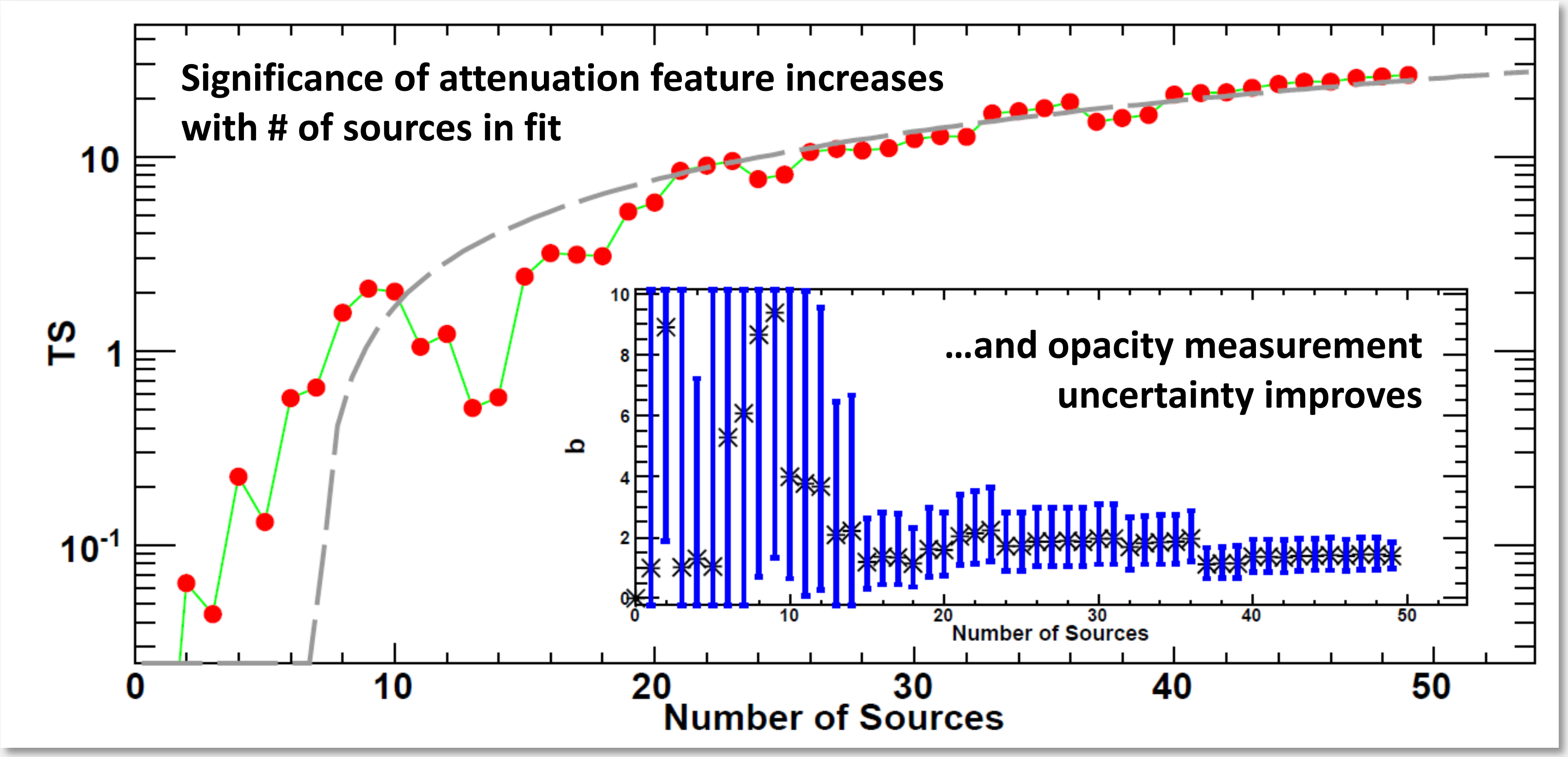
Ackermann et al. 2012, Science, 338, 1190

EBL Attenuation for Individually Resolved Blazars

Model intrinsic blazar spectra by extrapolating the log-parabola fit at energies below the critical energy (< 5% attenuation expected from EBL model)

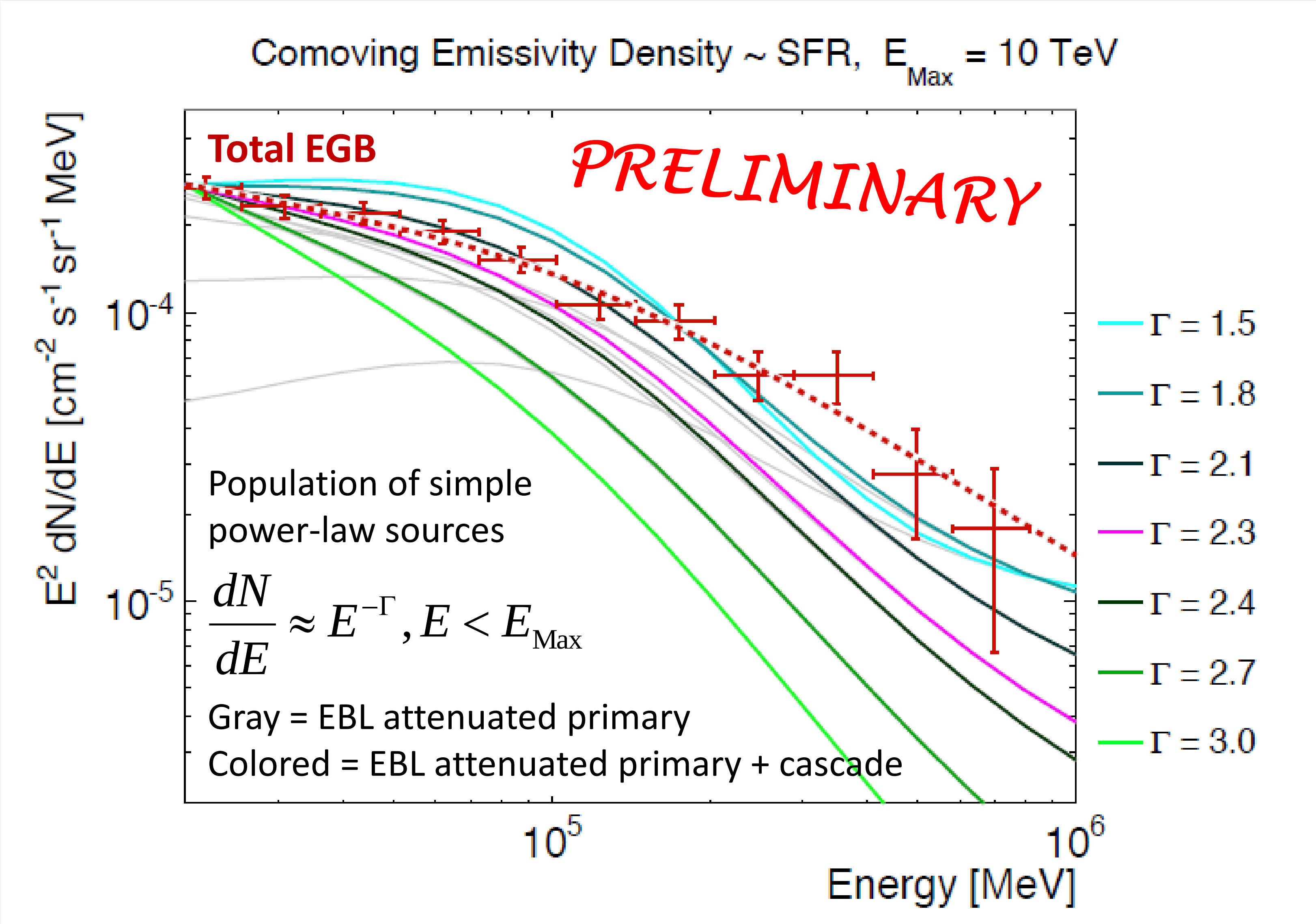
Shared opacity parameter (*b*) fit simultaneously using all sources

Attenuation $\exp(\tau_{\gamma\gamma}(E,z))$ with optical depth $\tau_{\gamma\gamma}(E,z) = b \cdot \tau_{\gamma\gamma}^{\mathrm{model}}(E,z)$

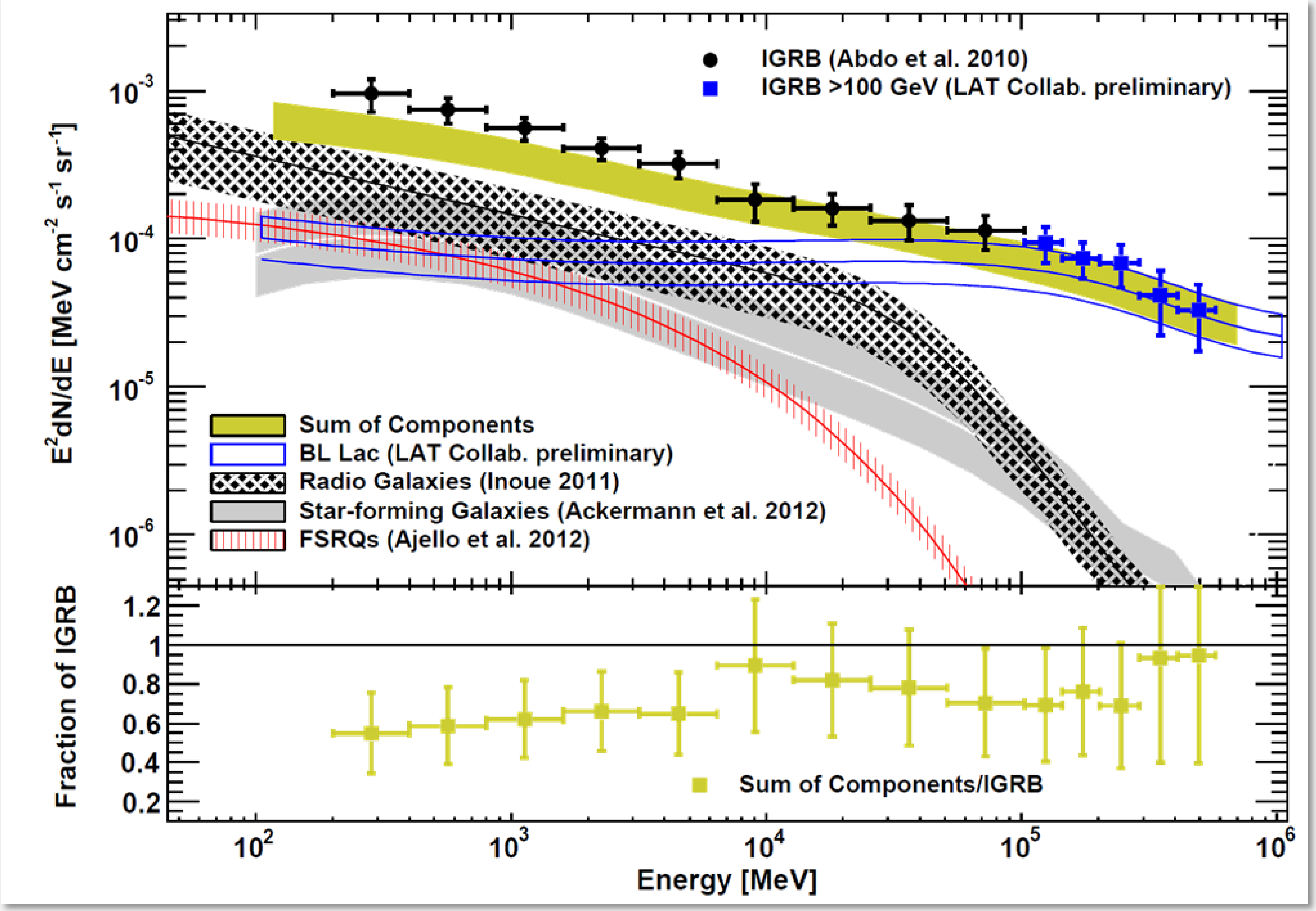


Ackermann et al. 2012, Science, 338, 1190

Simple Source Population Scenarios with EBL Attenuation and Secondary Cascades



Expected Contributions to the IGRB (circa 2013)



Extragalactic Radio Background

Apparent extragalactic intensity at ~GHz frequencies measured with ARCADE-2 and in other surveys is factor ~4 larger than expected from known extragalactic source populations (note that a significant fraction of the total expected emission from star-forming galaxies has already been resolved)

See for example

Fixen et al. 2009
arXiv:0901.0555

Vernstrom et al. 2013
arXiv:1311.6451

Fornengo et al. 2013 (right)
arXiv:1311.7451