Fermi Observations of TeV Gamma-ray Sources

Hiroyasu Tajima
on behalf of Fermi LAT and GBM Collaborations
KIPAC
SLAC National Accelerator Laboratory
(Stanford Linear Accelerator Center)
Stanford University

January 9, 2010
CTA Japan Workshop
ICRR, Japan

Outline

- Introduction
  - The first year LAT catalog
- Active Galactic Nuclei (AGN)
- Supernova remnants (SNR)
- Gamma-ray bursts (GRB)
- Extragalactic background light (EBL)

- This is not a comprehensive list of Fermi astrophysics

Note: All results in this talk are preliminary unless published

Fermi/LAT Collaboration

Stanford University & SLAC
NASA Goddard Space Flight Center
Naval Research Laboratory
University of California at Santa Cruz
Sonoma State University
University of Washington
Purdue Univeristy-Calumet
Ohio State University
University of Denver

Commissariat a l'Energie Atomique, Saclay
CNRS/IN2P3 (CENBG-Bordeaux, LLR-Ecole polytechnique, LPTA-Montpellier)

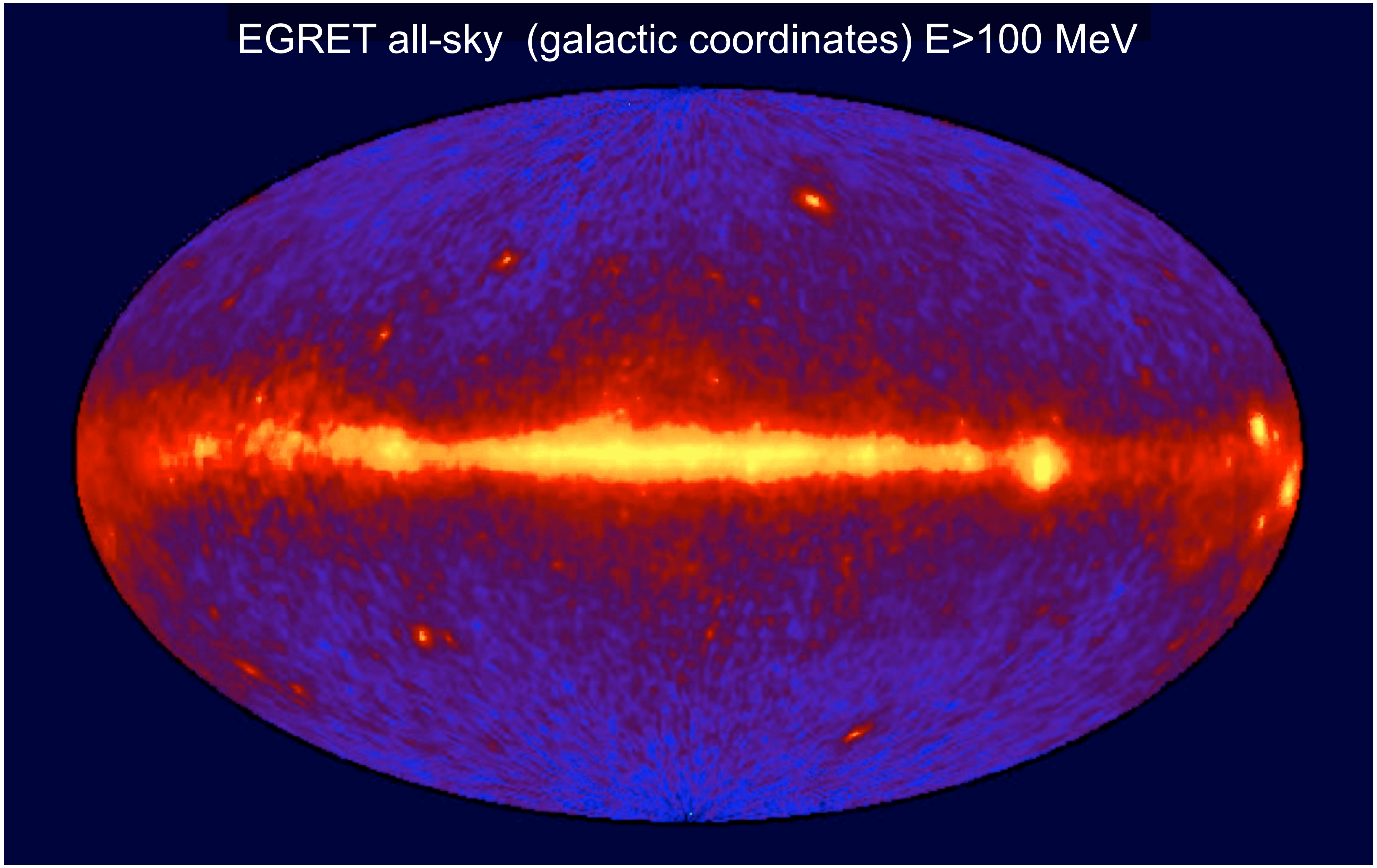
Hiroshima University
Institute of Space and Astronautical Science
Tokyo Institute of Technology
RIKEN

Instituto Nazionale di Fisica Nucleare
Agenzia Spaziale Italiana
Istituto di Astrofisica Spaziale e Fisica Cosmica

Royal Institute of Technology, Stockholm
Stockholms Universitet

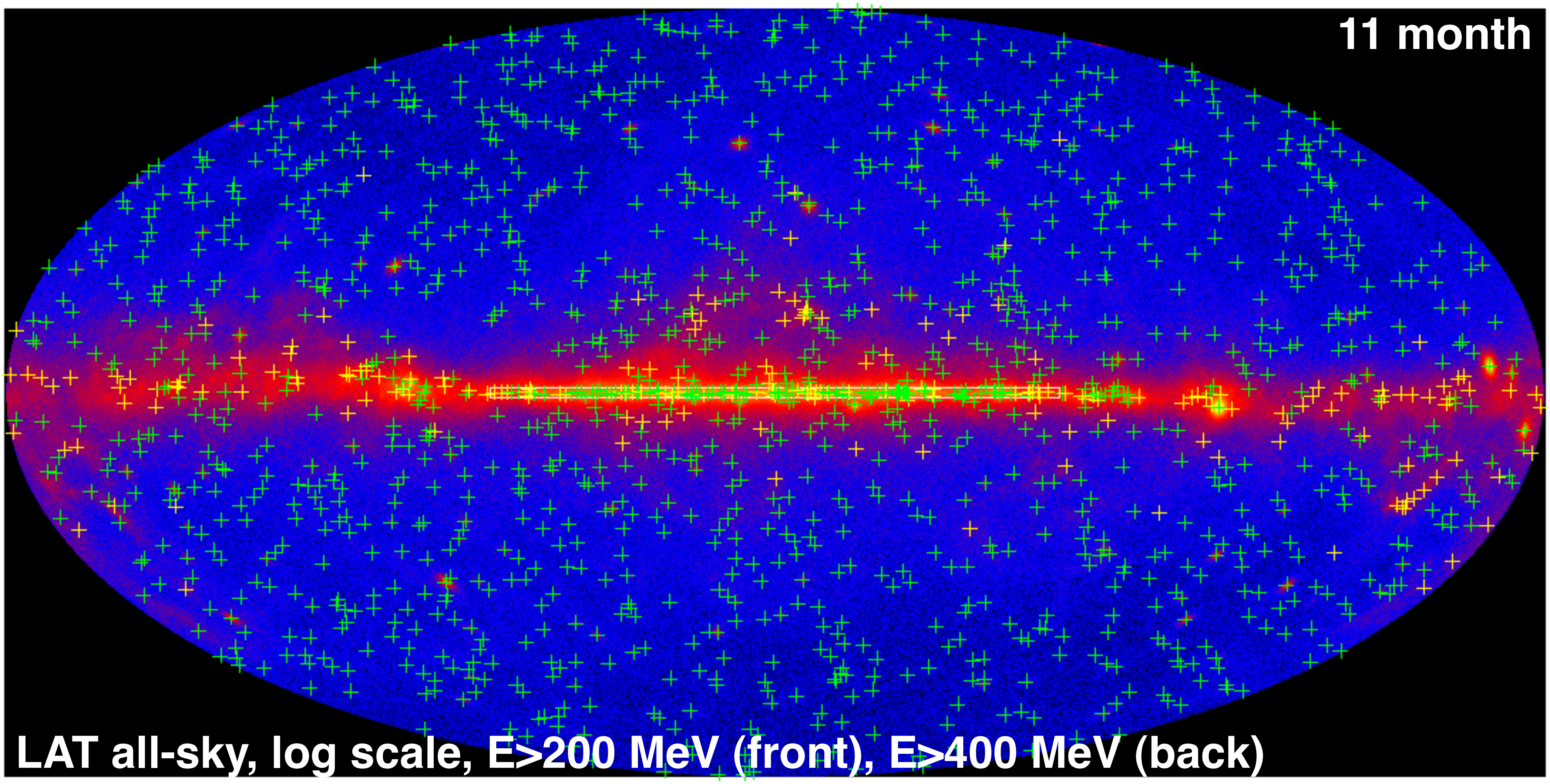
Predecessor, EGRET

- EGRET: 1991–2000
  - 271 gamma-ray sources (Hartman et al. 1999)
    - Only 38% (101 sources) have clear “identifications”



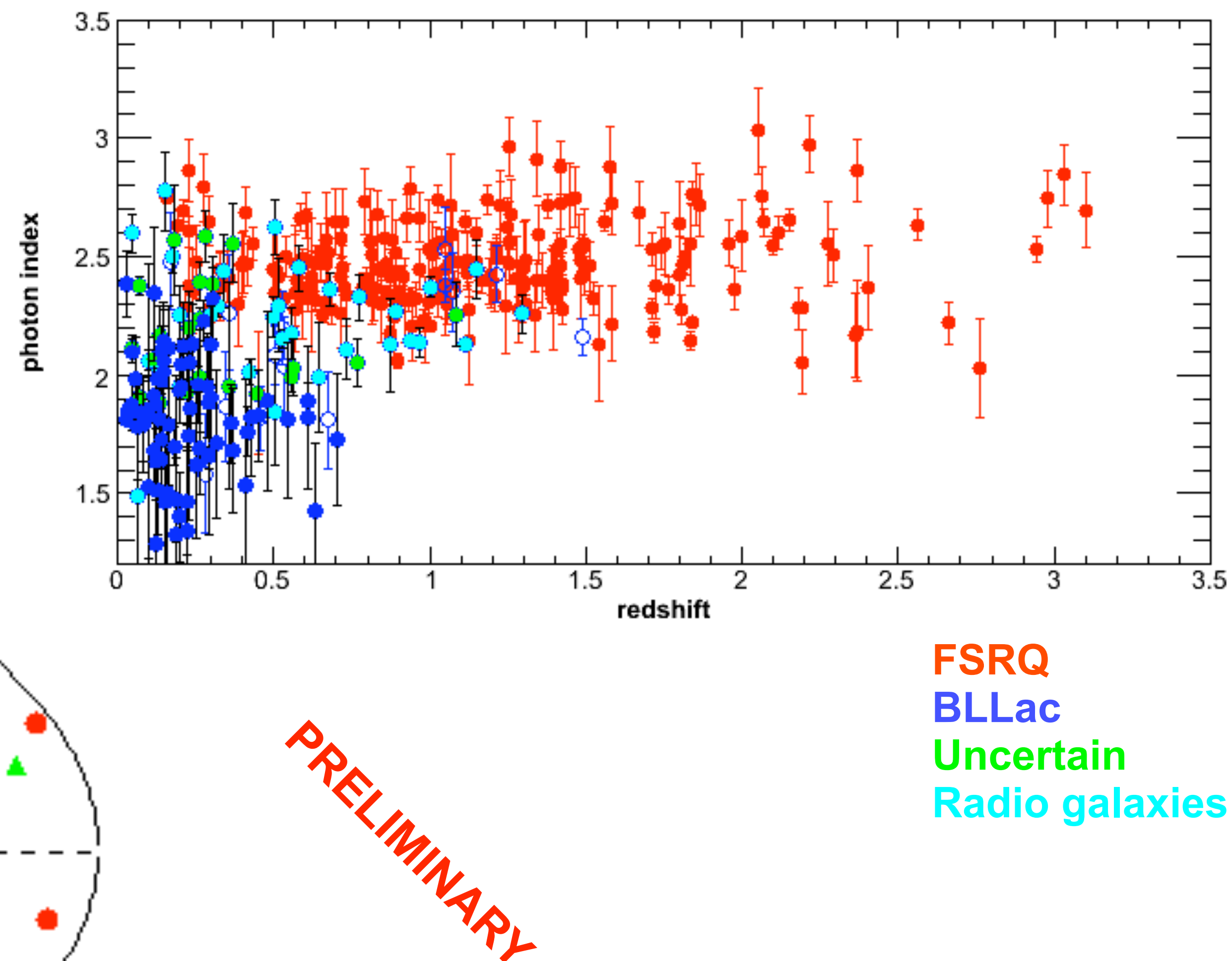
The First LAT Catalog (1FGL)

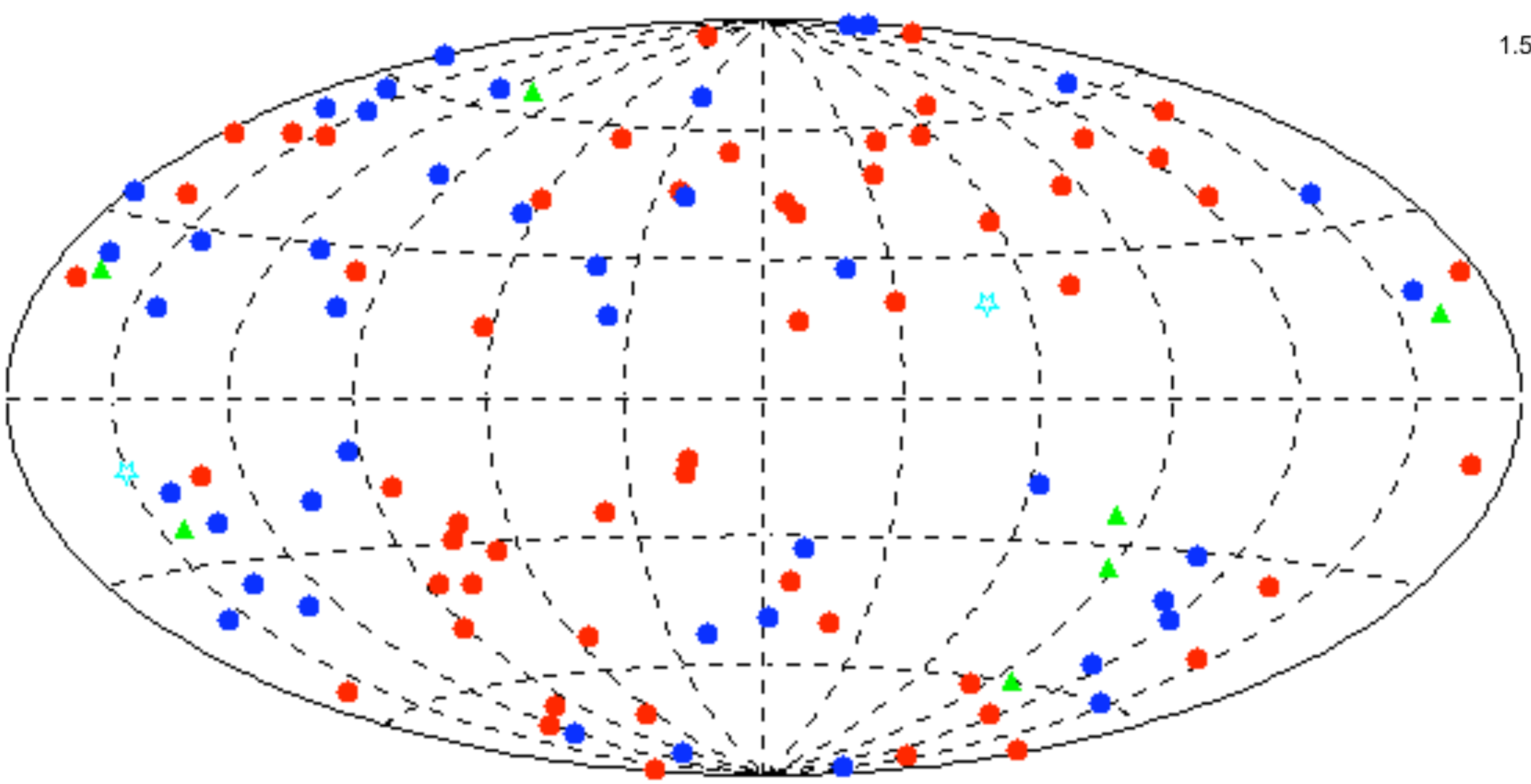
- Fermi LAT 11 month data set (23.3 Ms livetime)
  - >1000 sources for TS = 2 Δlog(likelihood) > 25 (~4σ for 4 D.o.F.)
  - Typical 95% error radius is 10'. Absolute accuracy is better than 1'
  - Caveat: The Galactic ridge (|lat| < 1°, |lon| < 60°) has serious difficulties: do not use them without detailed analysis



The First LAT AGN Catalog (1LAC)

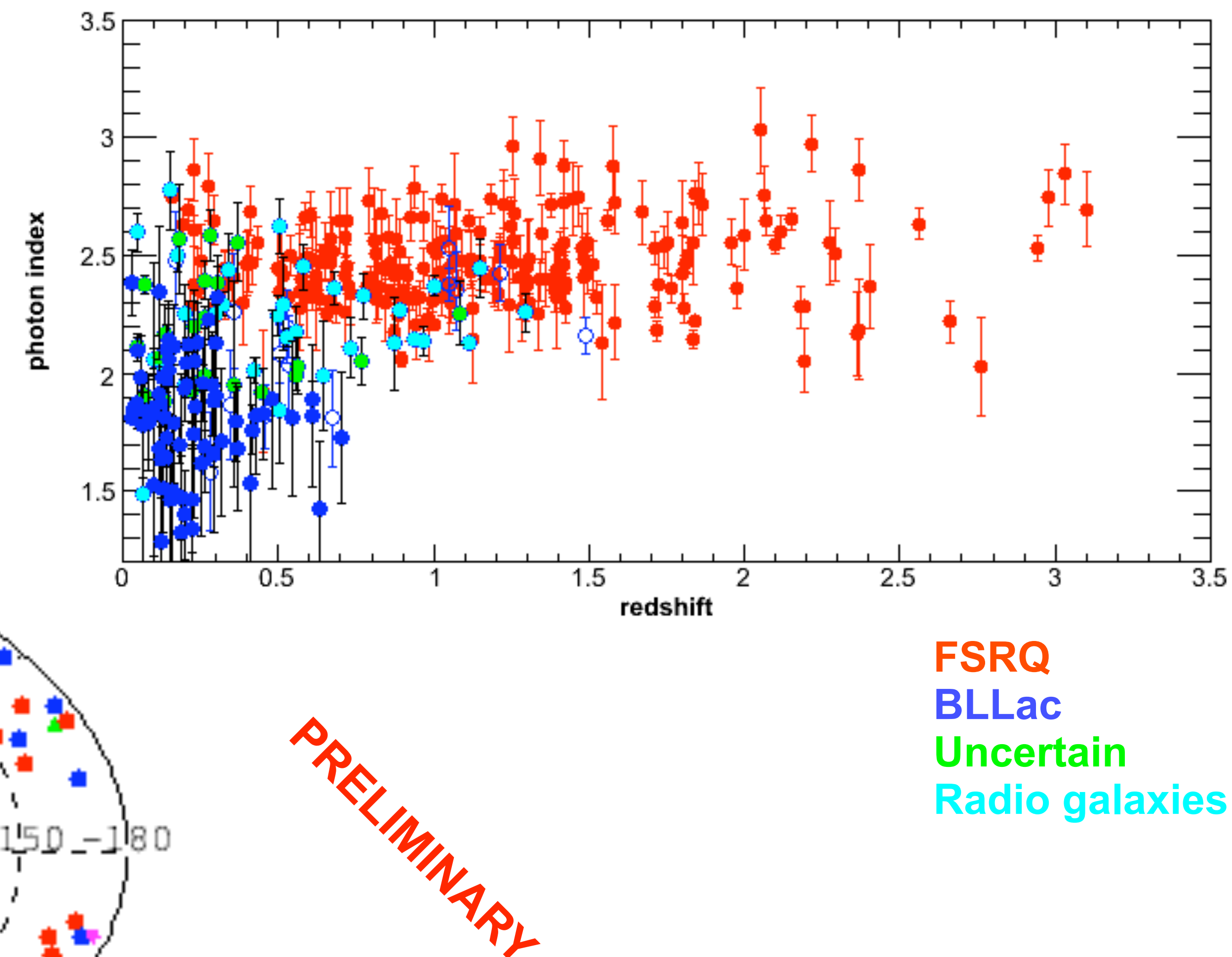
- 1079 TS>25 (~5σ), |b|>10° sources based on 11 month data set
- 668 high-confidence (P>80%) associations with AGNs
  - +186 lower-confidence (40%<P<80%) associations
  - 286 FSRQ
  - 285 BL Lac (141 with measured z)
  - 69 unknown class
  - ~10 Radio galaxies

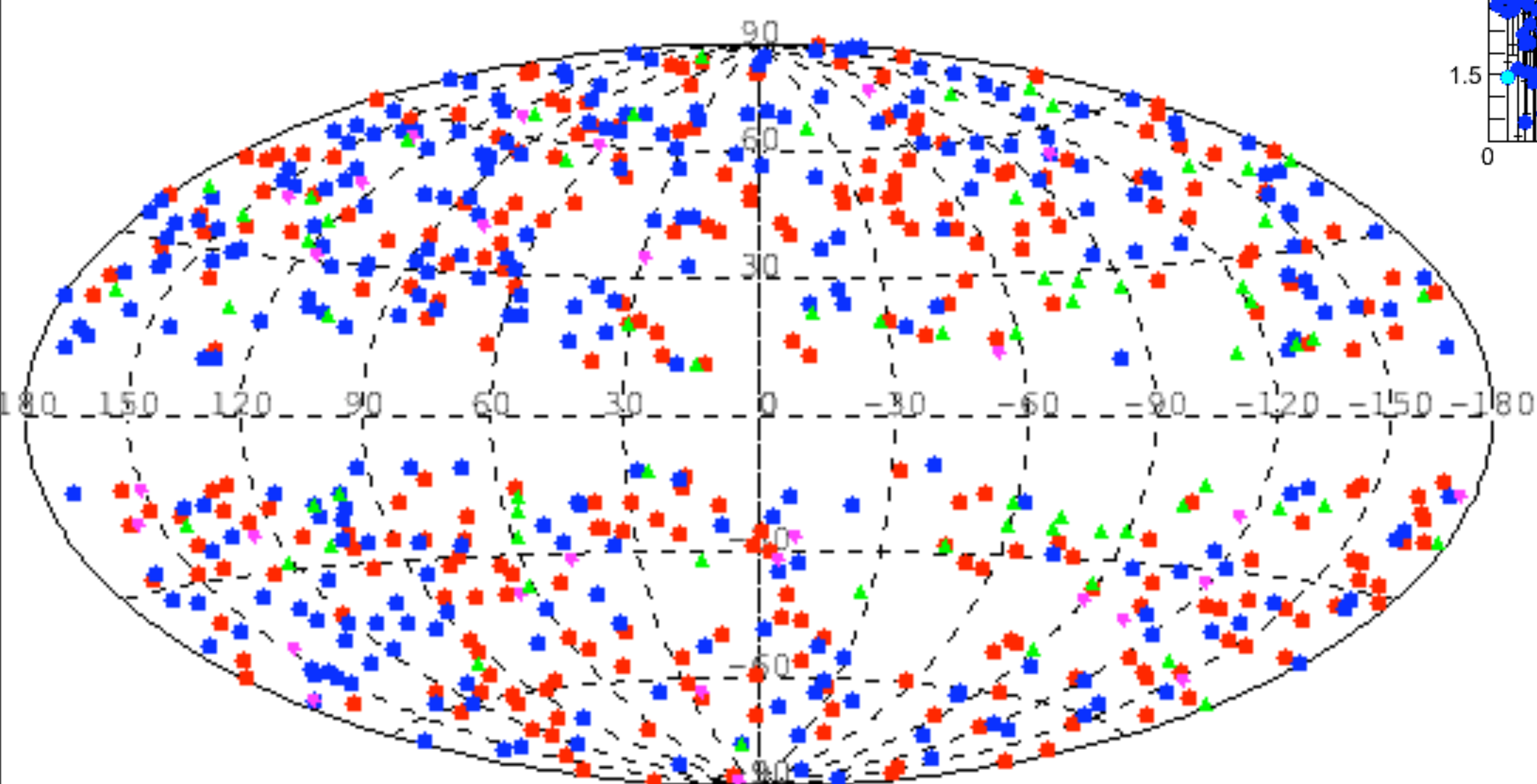




The First LAT AGN Catalog (1LAC)

- 1079 TS>25 (~5σ), |b|>10° sources based on 11 month data set
- 668 high-confidence (P>80%) associations with AGNs
  - +186 lower-confidence (40%<P<80%) associations
  - 286 FSRQ
  - 285 BL Lac (141 with measured z)
  - 69 unknown class
  - ~10 Radio galaxies





LAT Observations of TeV AGNs

- **21/28 TeV AGNs detected by Fermi-LAT (5.5 months), now 25/30**
  - **mostly BL Lacs, mostly HSPs**
  - **2 RGs: Centaurus A, M87**
  - **Most of the bright TeV blazars have been in low states since Fermi launched**

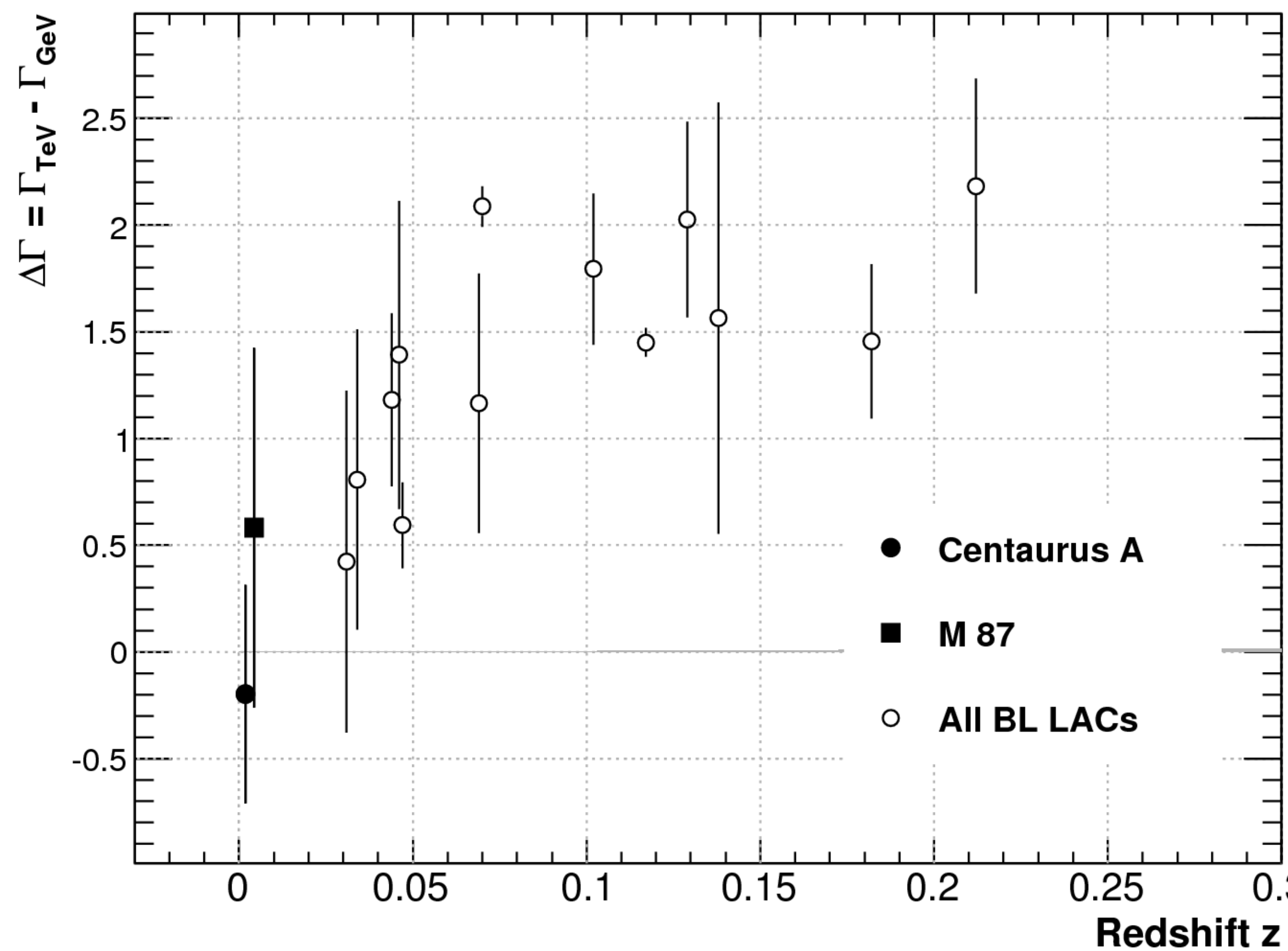
Name	TS [1]	Parameters of fitted power-law spectrum: Flux (>200 MeV) $F \pm \Delta F_{stat} \pm \Delta F_{sys}$ $[10^{-9} cm^{-2} s^{-1}]$	Photon Index $\Gamma \pm \Delta\Gamma_{stat} \pm \Delta\Gamma_{sys}$ [1]	Decorr. energy [GeV]	Highest energy photons: 1^{st} [GeV]	5^{th} [GeV]	Probability of constant flux: 10 day [1]	28 day [1]
3C 66A	2221	$96.7 \pm 5.82 \pm 3.39$	$1.93 \pm 0.04 \pm 0.04$	1.54	111[a]	54	< 0.01	< 0.01
RGB J0710+591	42	$0.087 \pm 0.049 \pm 0.076$	$1.21 \pm 0.25 \pm 0.02$	15.29	74	4	0.98	0.94
S5 0716+714	1668	$79.9 \pm 4.17 \pm 2.84$	$2.16 \pm 0.04 \pm 0.05$	0.82	63	9	< 0.01	< 0.01
1ES 0806+524	102	$2.07 \pm 0.38 \pm 0.71$	$2.04 \pm 0.14 \pm 0.03$	1.54	30	4	0.05	< 0.01
1ES 1011+496	889	$32.0 \pm 0.27 \pm 0.29$	$1.82 \pm 0.05 \pm 0.03$	1.50	168	32	0.54	0.50
Markarian 421	3980	$94.3 \pm 3.88 \pm 2.60$	$1.78 \pm 0.03 \pm 0.04$	1.35	801	155	0.06	0.02
Markarian 180	50	$5.41 \pm 1.69 \pm 0.91$	$1.91 \pm 0.18 \pm 0.09$	1.95	14	2	0.98	0.54
1ES 1218+304	147	$7.56 \pm 2.16 \pm 0.67$	$1.63 \pm 0.12 \pm 0.04$	5.17	356	31	0.53	0.06
W Comae	754	$41.7 \pm 3.40 \pm 2.46$	$2.02 \pm 0.06 \pm 0.05$	1.13	26	18	0.01	< 0.01
3C 279	6865	$287 \pm 7.13 \pm 10.2$	$2.34 \pm 0.03 \pm 0.04$	0.59	28	21	< 0.01	< 0.01
PKS 1424+240	800	$34.35 \pm 2.60 \pm 1.37$	$1.85 \pm 0.05 \pm 0.04$	1.50	137	30	< 0.01	0.16
H 1426+428	38	$1.56 \pm 1.05 \pm 0.29$	$1.47 \pm 0.30 \pm 0.11$	8.33	19	3	0.83	0.39
PG 1553+113	2009	$54.8 \pm 3.63 \pm 0.85$	$1.69 \pm 0.04 \pm 0.04$	2.32	157	76	0.40	0.54
Markarian 501	649	$22.4 \pm 2.52 \pm 0.13$	$1.73 \pm 0.06 \pm 0.04$	2.22	127	50	0.57	0.18
1ES 1959+650	306	$25.1 \pm 3.49 \pm 2.83$	$1.99 \pm 0.09 \pm 0.07$	1.60	75	21	0.91	0.29
PKS 2005-489	246	$22.3 \pm 3.09 \pm 2.14$	$1.91 \pm 0.09 \pm 0.08$	1.01	71	8	0.86	0.97
PKS 2155-304	3354	$109 \pm 4.45 \pm 3.18$	$1.87 \pm 0.03 \pm 0.04$	1.13	299	46	< 0.01	< 0.01
BL Lacertae	310	$51.6 \pm 5.81 \pm 12.2$	$2.43 \pm 0.10 \pm 0.08$	0.85	70	4	0.61	0.23
1ES 2344+514	37	$3.67 \pm 2.35 \pm 1.62$	$1.76 \pm 0.27 \pm 0.23$	5.28	53	3	0.76	0.46
M 87	31	$7.56 \pm 2.70 \pm 2.24$	$2.30 \pm 0.26 \pm 0.14$	1.11	8	1	0.43	0.57
Centaurus A	308	$70.8 \pm 5.97 \pm 5.80$	$2.90 \pm 0.11 \pm 0.07$	0.47	6	4	0.38	0.97

arXiv:0910.4881

LAT Observations of TeV AGNs

- 21/28 TeV AGNs detected by Fermi-LAT (5.5 months), now 25/30
  - mostly BL Lacs, mostly HSPs
  - 2 RGs: Centaurus A, M87
  - Most of the bright TeV blazars have been in low states since Fermi launched

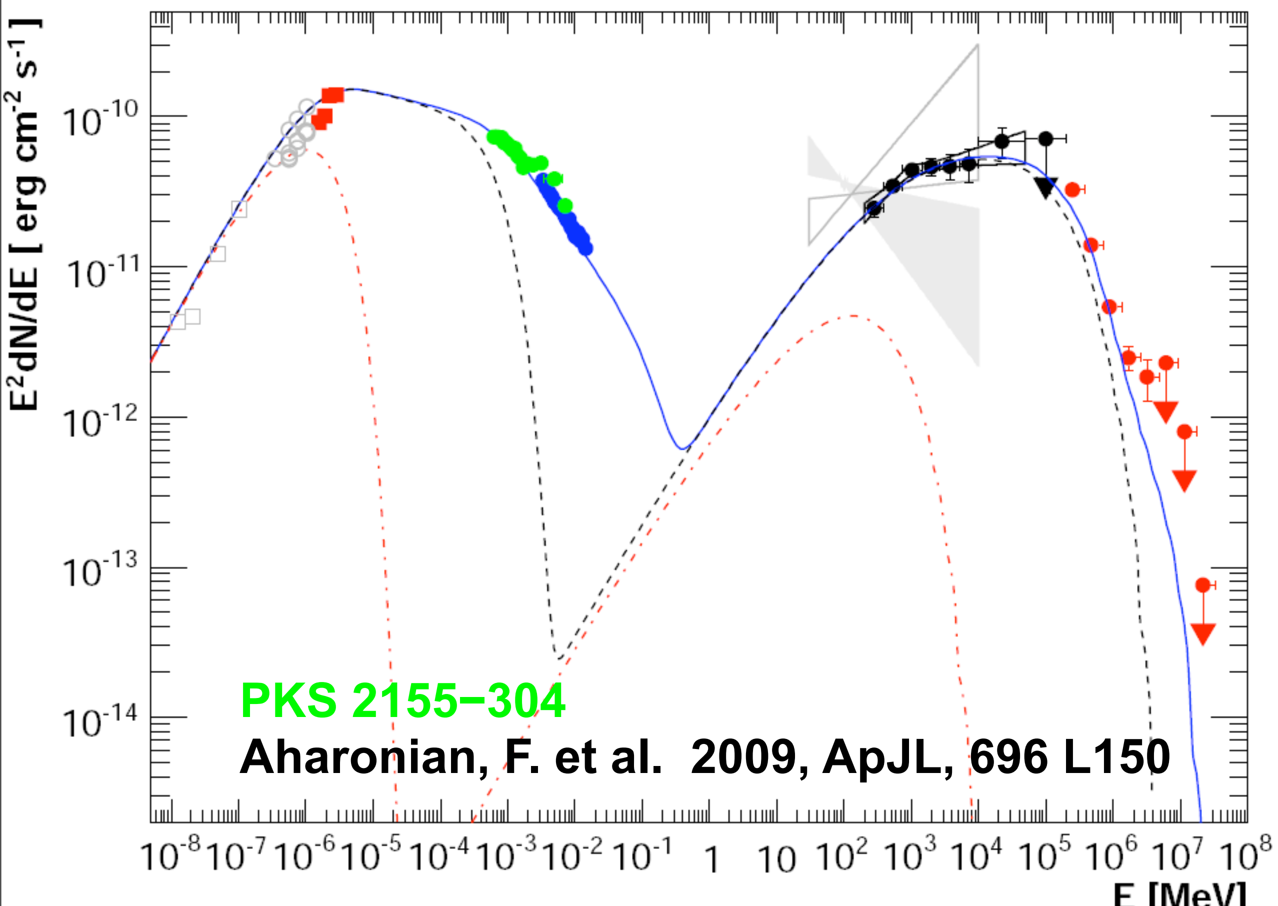
Name	T
3C 66A	22
RGB J0710+591	
S5 0716+714	16
1ES 0806+524	1
1ES 1011+496	8
Markarian 421	39
Markarian 180	
1ES 1218+304	1
W Comae	7
3C 279	68
PKS 1424+240	8
H 1426+428	
PG 1553+113	20
Markarian 501	6
1ES 1959+650	3
PKS 2005-489	2
PKS 2155-304	33
BL Lacertae	3
1ES 2344+514	
M 87	
Centaurus A	3

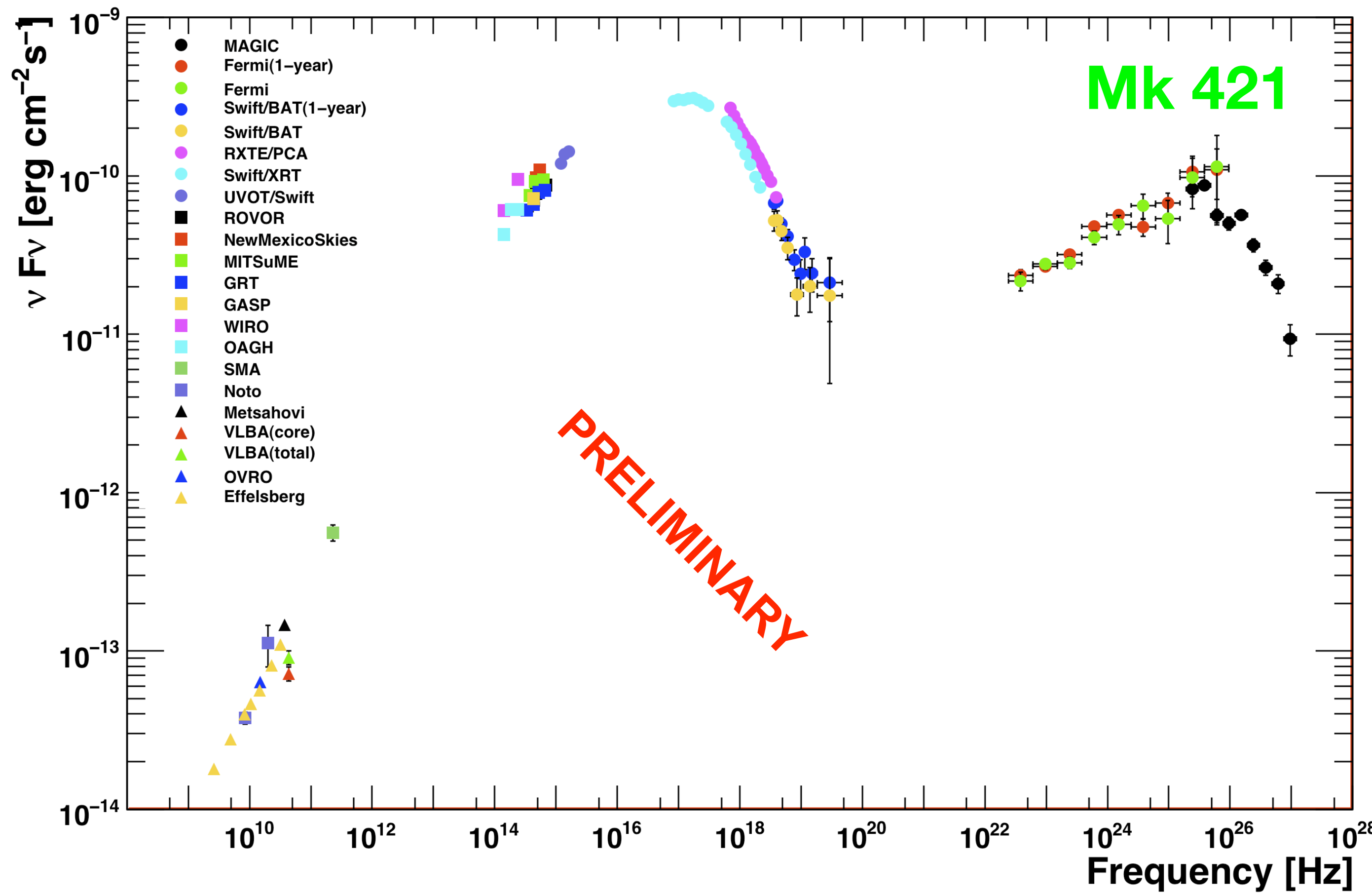


arXiv:0910.4881

Multi-Wavelength Campaign

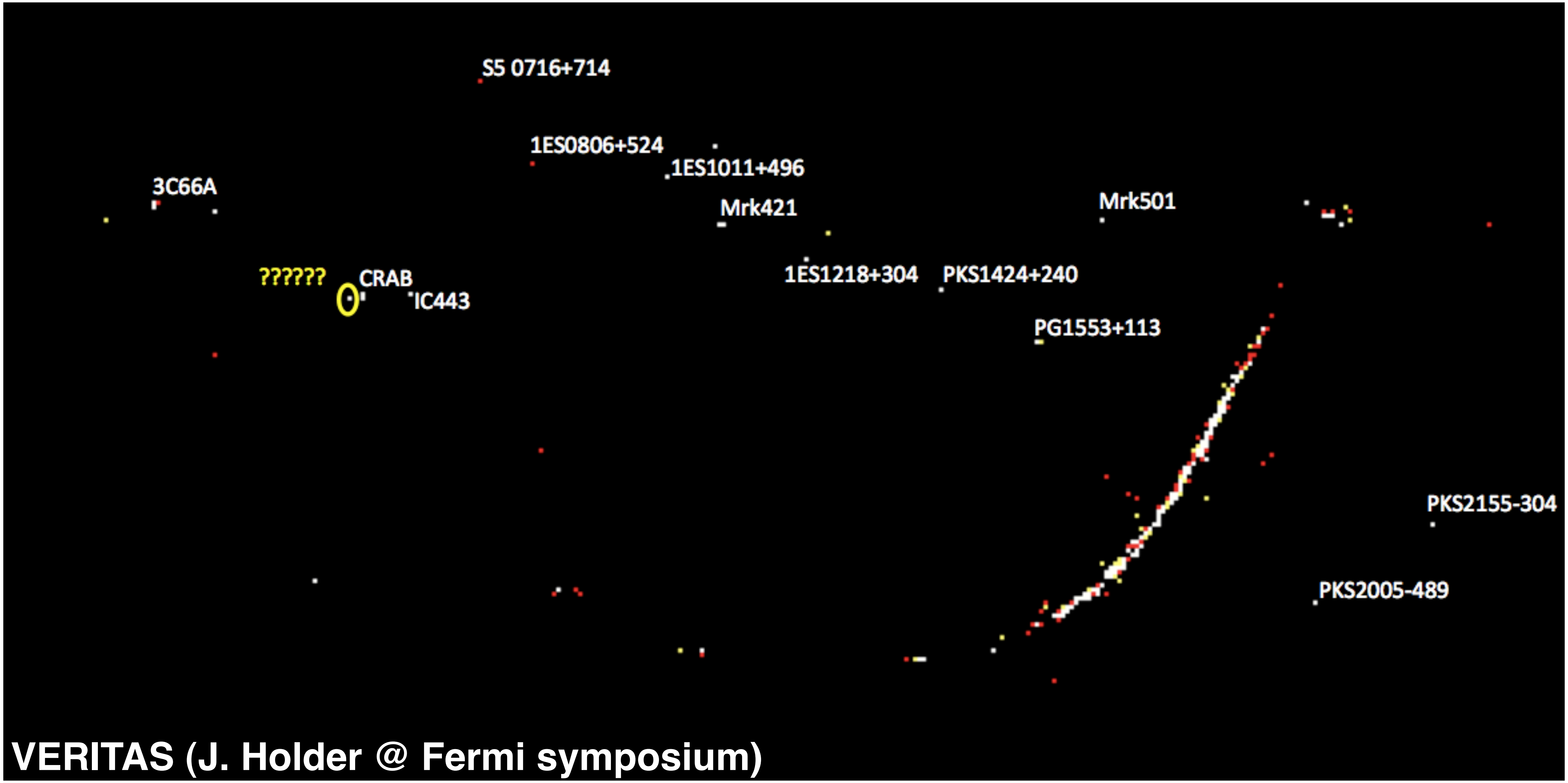
- **PKS 2155–304**
  - **First simultaneous GeV-TeV SED**
  - **Unexpected correlations in X-ray flux and GeV spectral index, optical and TeV fluxes, and independent X-ray and TeV gamma-ray**
  - **Challenges for SSC (Synchrotron self-Compton) models**
- **Mk 421**
  - **Most complete SED for Mk 421 to date**





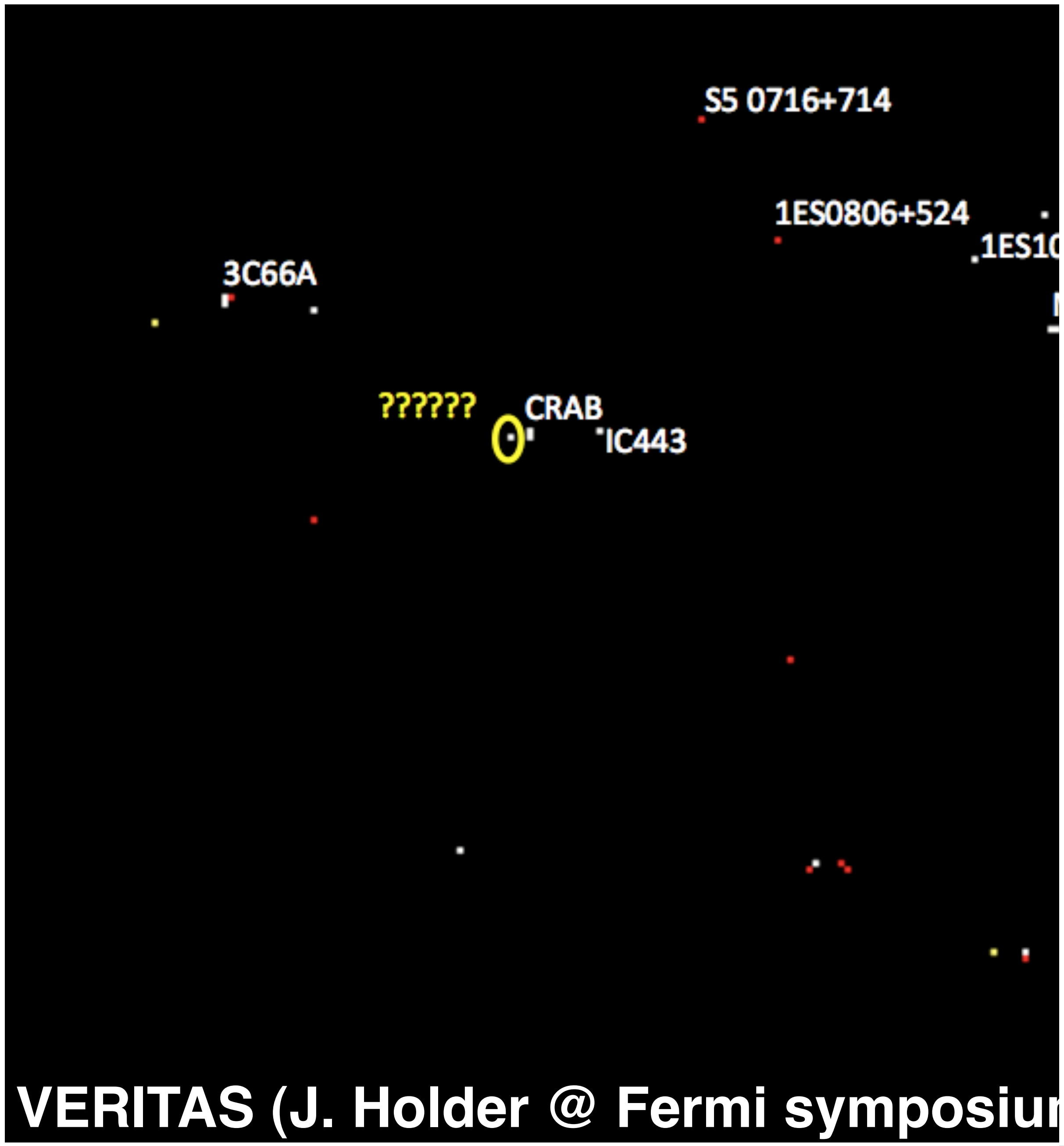
TeV Emissions from LAT AGNs

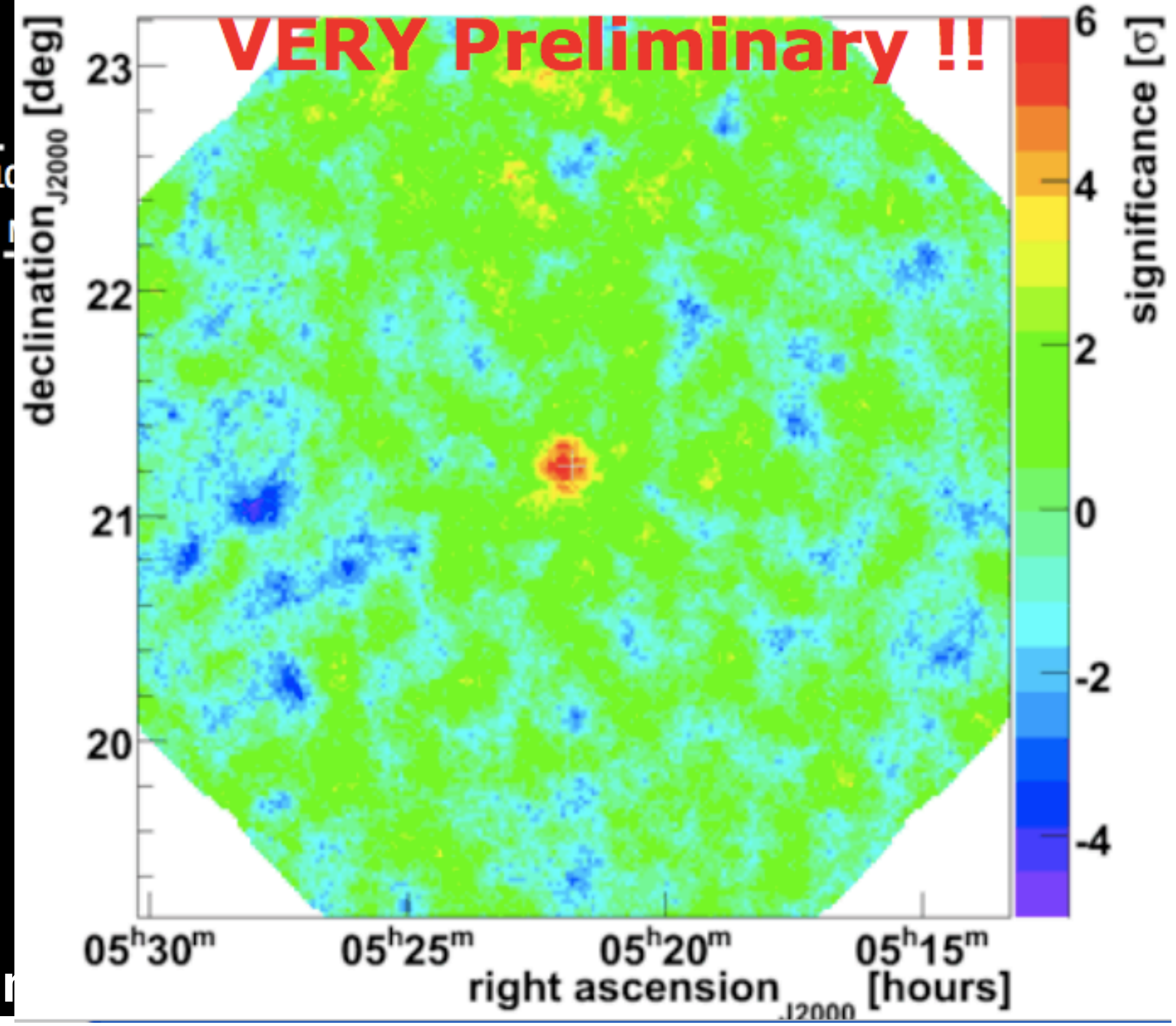
- LAT count map above 30 GeV
- VERITAS discovery of TeV source, VER J0521+21 (Atel 2260)
  - Most likely a radio-loud AGN, RGB J0521.8+2112



TeV Emissions from LAT AGNs

- LAT count map above 30 GeV
- VERITAS discovery of TeV source, VER J0521+21 (Atel 2260)
  - Most likely a radio-loud AGN, RGB J0521.8+2112



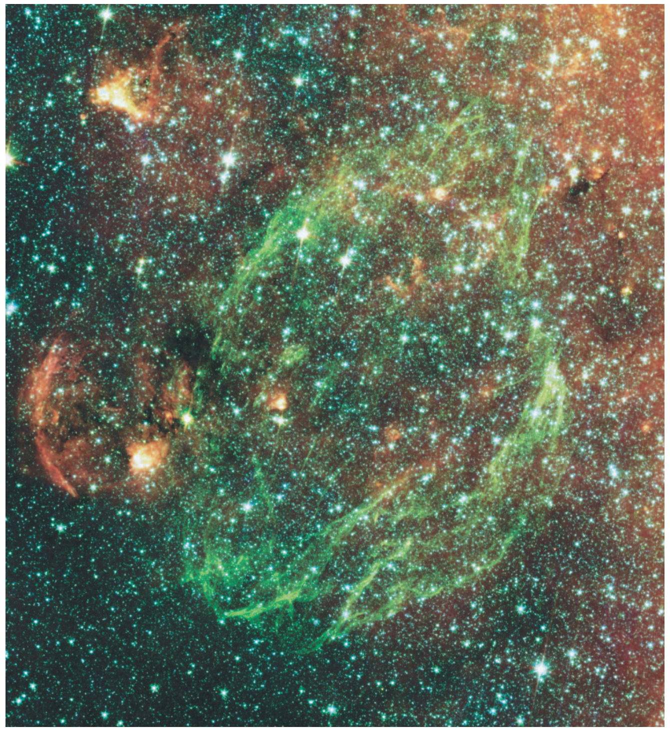


SNR W44 Gamma-ray Image

- Deconvolved image indicates shell-like gamma-ray emission
- Maximum likelihood analysis prefer ring-like morphology rather than disk-like morphology (> 8 σ)

Middle-aged (~ 2.0×10^4 yr)
mixed-morphology SNR
(radio: shell, thermal X-ray: centrally filled)
Distance: ~ 3 kpc

Cloud-shell interactions
CO (Seta et al. 2004)
OH maser (Hoffman et al. 2005)



Green: Spitzer IRAC 4.5 μm
traces shocked HII
Reach et al. (2006)

Abdo et al. just appeared in Science Express on Jan/7th
<http://www.sciencemag.org/cgi/content/abstract/science.1182787>

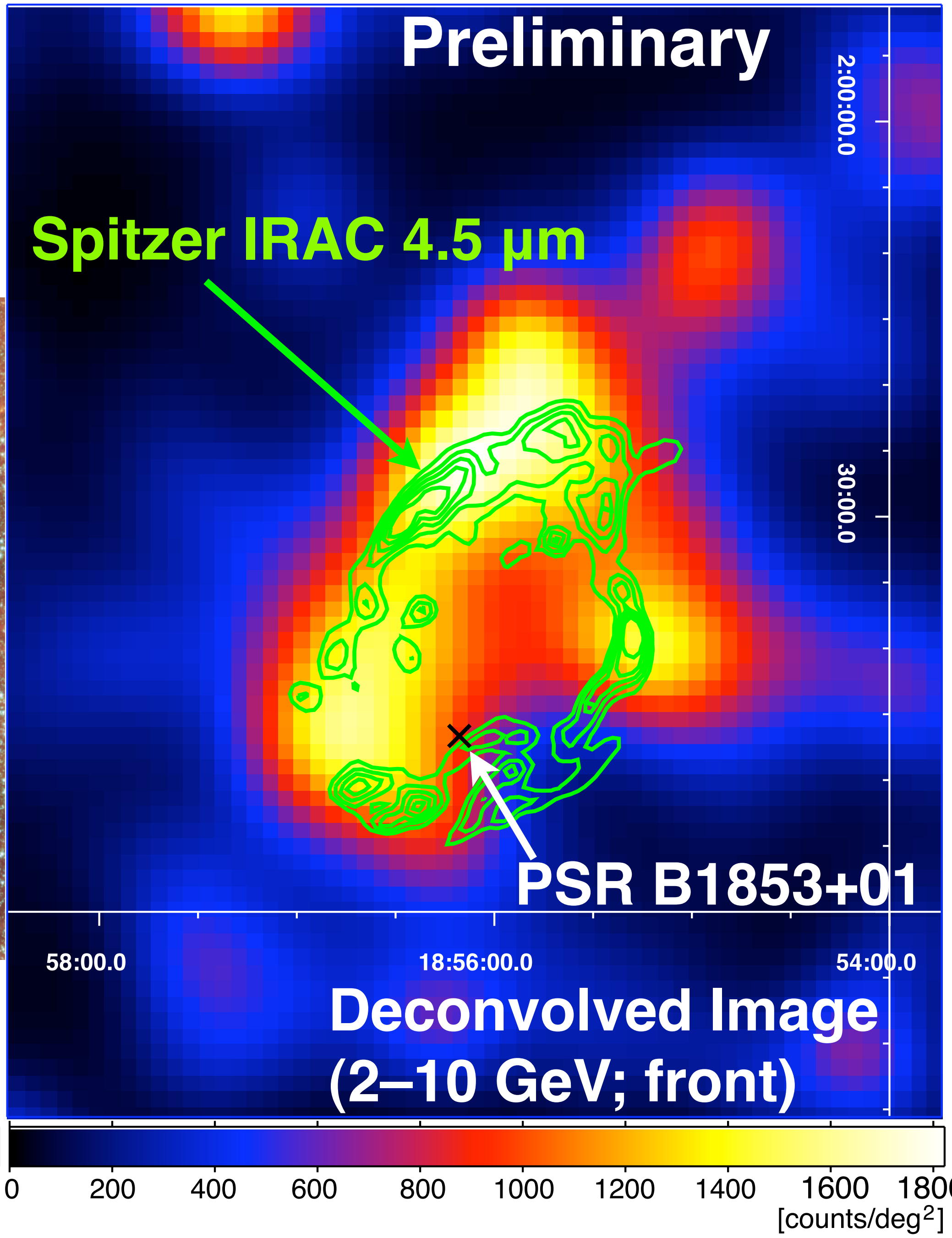
SNR W44 Gamma-ray Image

- Deconvolved image indicates shell-like gamma-ray emission
- Maximum likelihood analysis prefer ring-like morphology rather than disk-like morphology (> 8 σ)

Middle-aged (~ 2.0×10^4 yr)
mixed-morphology SNR
(radio: shell, thermal X-ray: centrally filled)
Distance: ~ 3 kpc

Cloud-shell interactions
CO (Seta et al. 2004)
OH maser (Hoffman et al. 2005)

Green: Spitzer IRAC 4.5 μm
traces shocked HII
Reach et al. (2006)



Abdo et al. just appeared in Science Express on Jan/7th
<http://www.sciencemag.org/cgi/content/abstract/science.1182787>

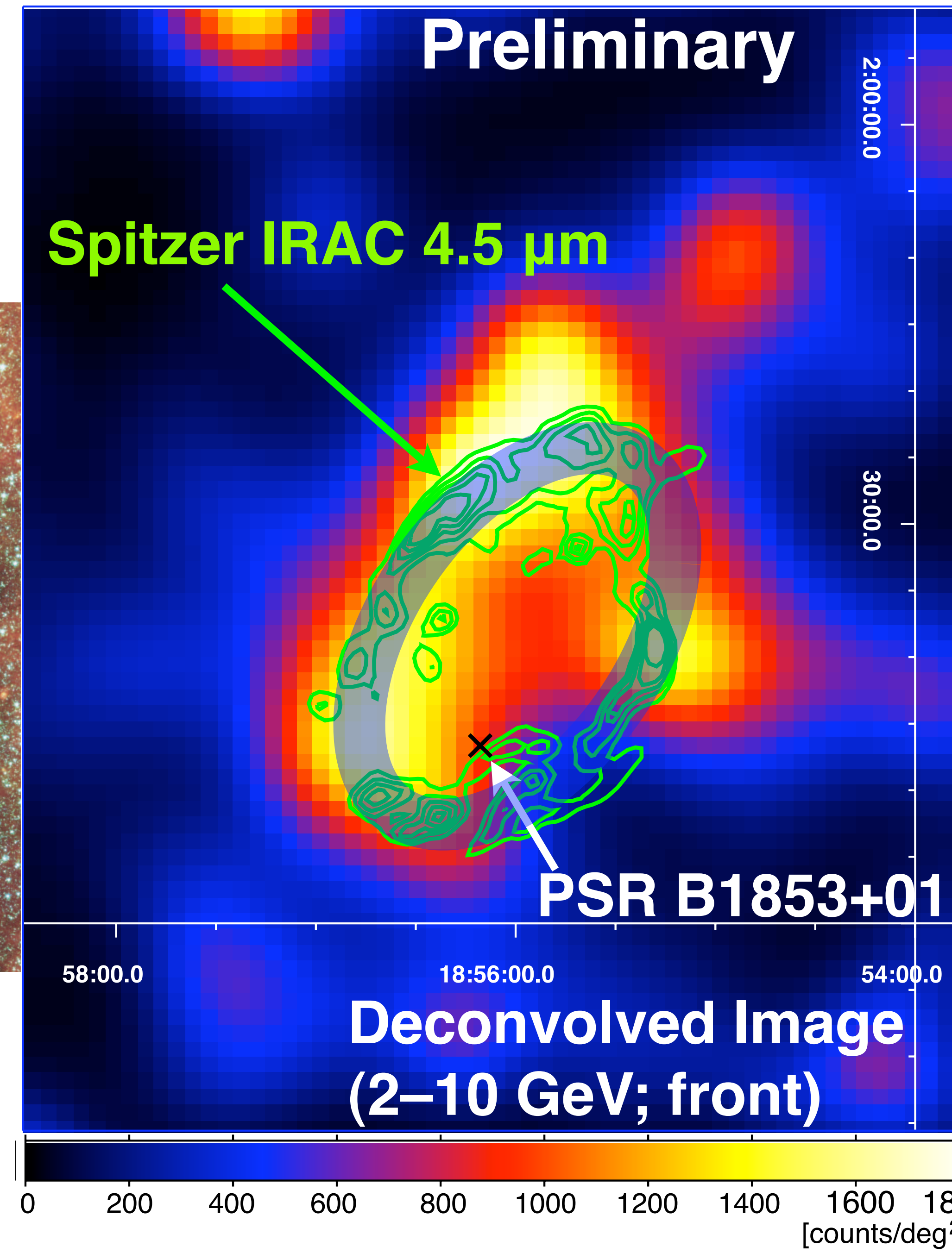
SNR W44 Gamma-ray Image

- Deconvolved image indicates shell-like gamma-ray emission
- Maximum likelihood analysis prefer ring-like morphology rather than disk-like morphology (> 8 σ)

Middle-aged (~ 2.0×10^4 yr)
mixed-morphology SNR
(radio: shell, thermal X-ray: centrally filled)
Distance: ~ 3 kpc

Cloud-shell interactions
CO (Seta et al. 2004)
OH maser (Hoffman et al. 2005)

Green: Spitzer IRAC 4.5 μm
traces shocked HII
Reach et al. (2006)



Abdo et al. just appeared in Science Express on Jan/7th
<http://www.sciencemag.org/cgi/content/abstract/science.1182787>

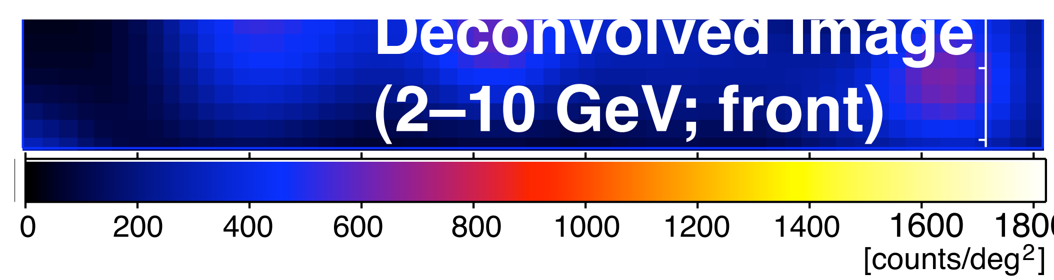
SNR W44 Gamma-ray Image

- Deconvolved image indicates shell-like gamma-ray emission
- Maximum likelihood analysis prefer ring-like morphology rather than disk-like morphology (> 8 σ)

Middle-aged (~ 2.0×10^4 yr)
mixed-morphology SNR
(radio: shell,
Distance: ~ 3

Cloud-shell i
CO (Seta et a
OH maser (H

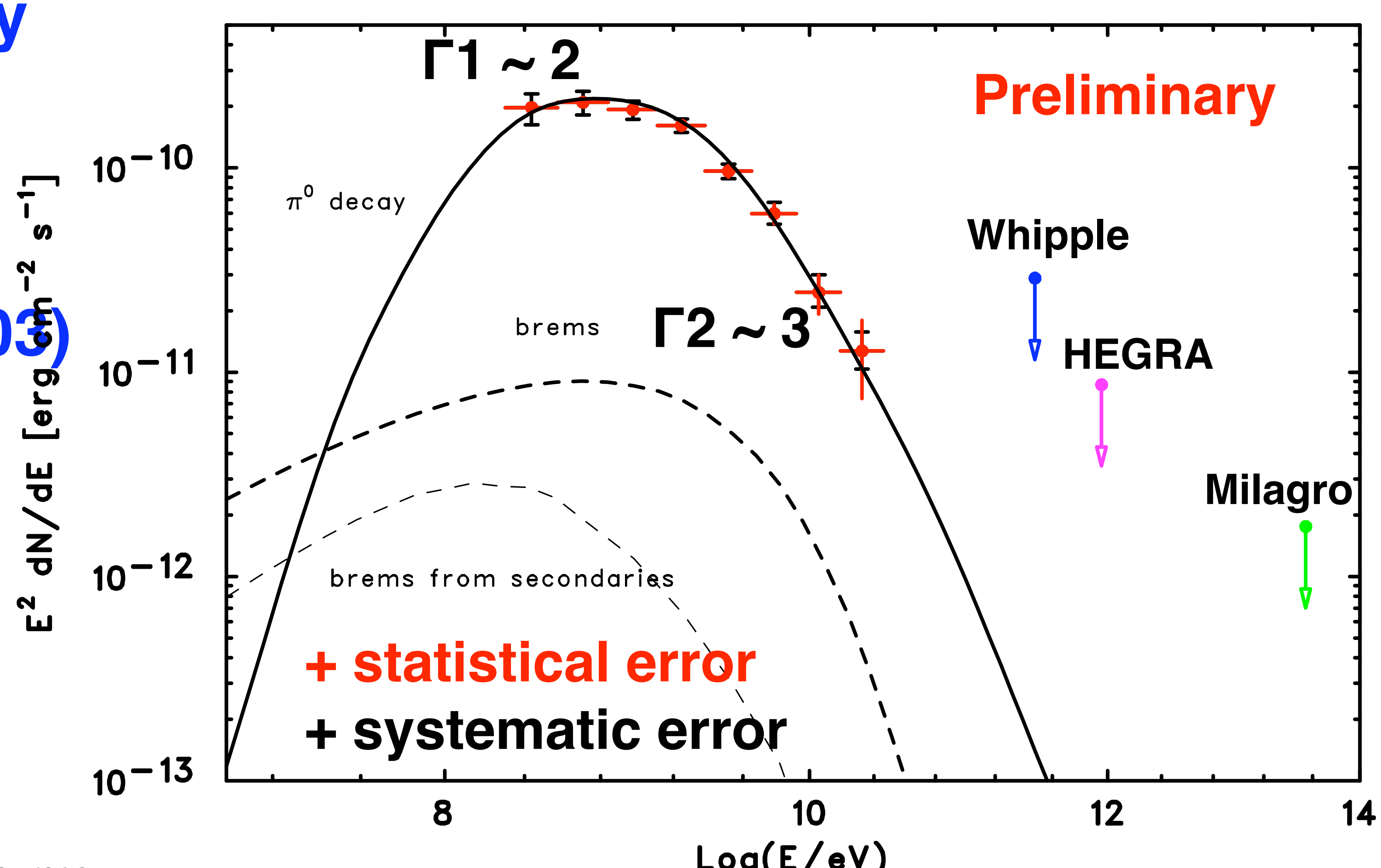
Green: Sp
traces sh
Reach et



Abdo et al. just appeared in Science Express on Jan/7th
<http://www.sciencemag.org/cgi/content/abstract/science.1182787>

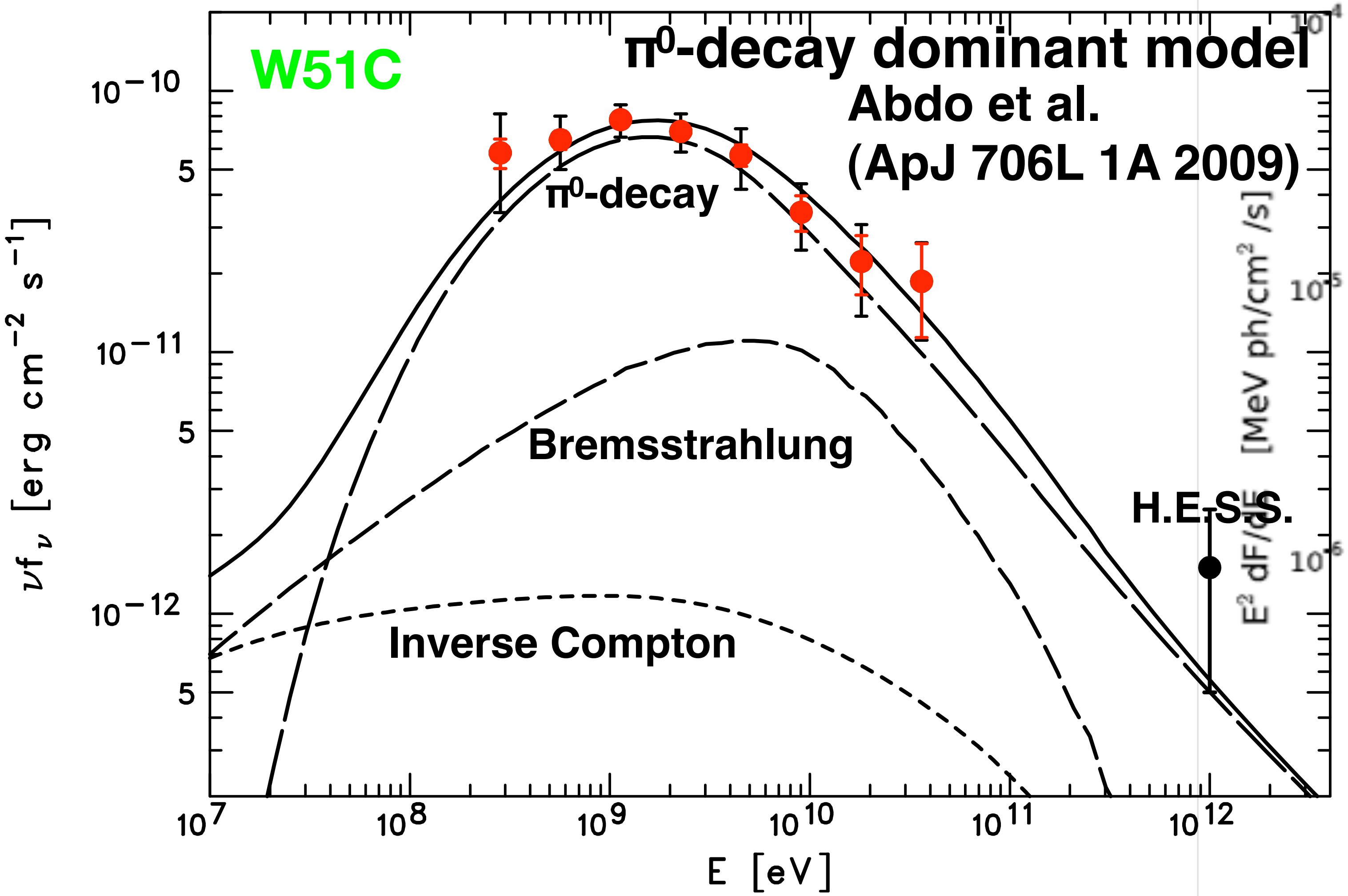
W44 Spectrum

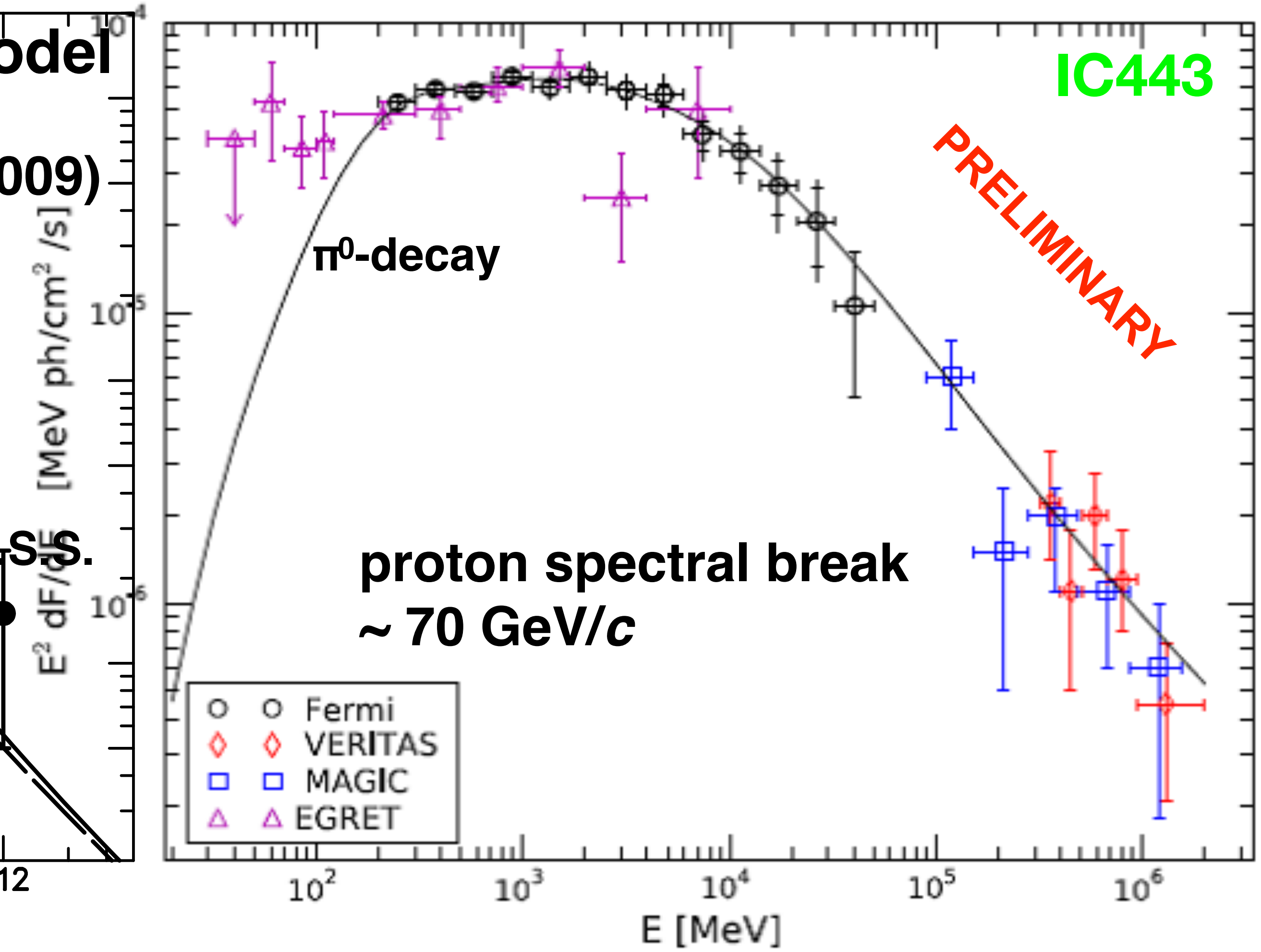
- Simple PL is rejected with 14σ
- π^0-decay dominant model is most natural explanation
- Electron bremsstrahlung cannot completely be ruled out
  - Brems: amount of electrons should be comparable to protons
  - Inverse Compton: $W_e \sim 10^{51}$ erg or quite intense photon field needed
- Protons need to have a spectral break at ~ 10 GeV/*c*
  - Fast escape of high energy particles with damping of magnetic turbulence due to the dense environment (Ptuskin & Zirakashvili 2003)



SNR W51C and IC443

- Middle-aged SNRs interacting with molecular clouds by LAT
  - W51C: age ~ 3×10^4 yr, distance ~ 6 kpc, $L = 10^{36}$ (D/6 kpc)^2 erg s^{-1}
  - IC443: age ~ (3~30)$\times10^4$ yr, distance ~ 1.5 kpc
- Spectral steepening similar to the W44 spectrum
  - π^0-decay model can reasonably explain the data
  - Leptonic scenarios have similar difficulties as W44

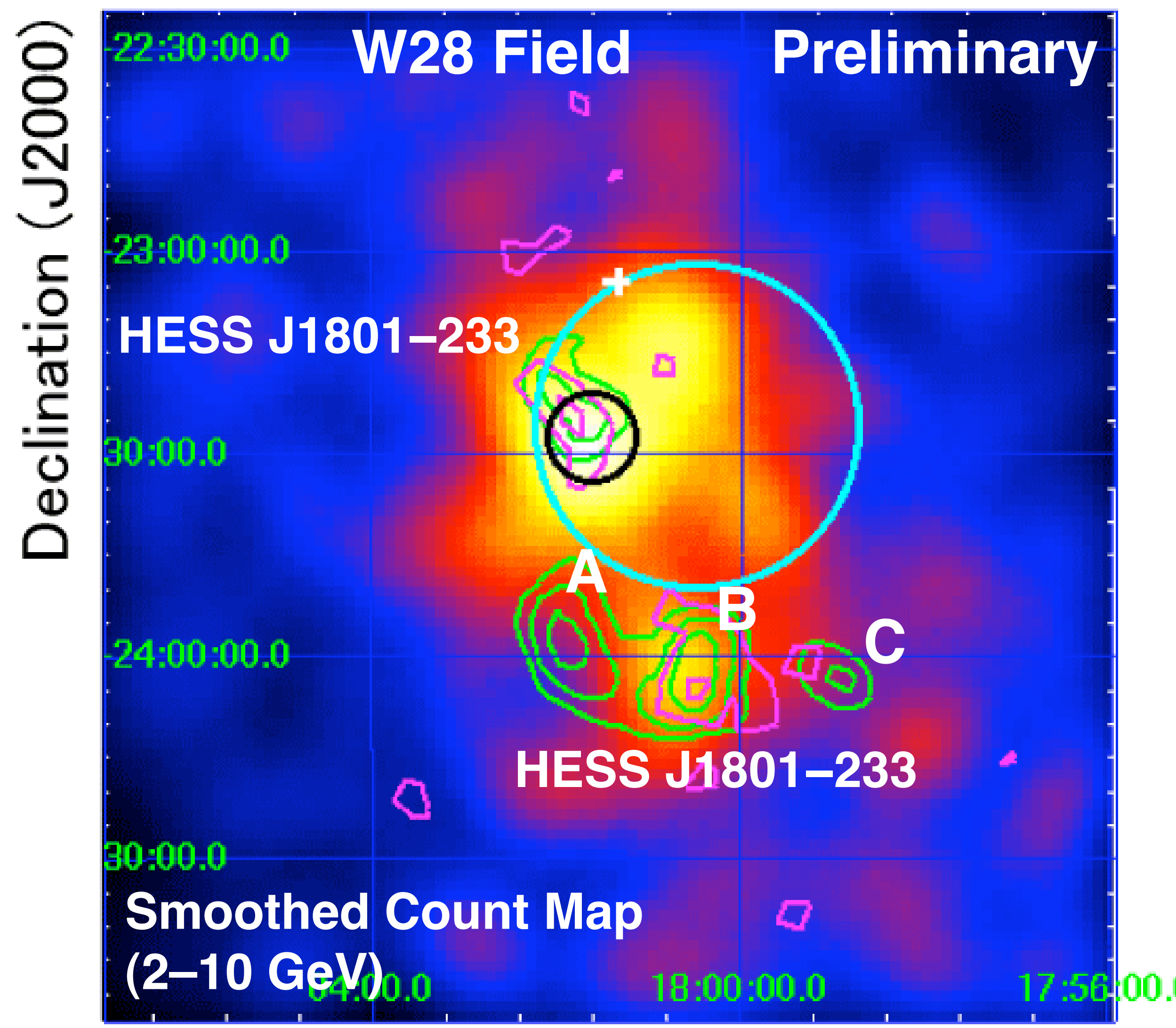




Fermi Observations of Middle-Aged SNR

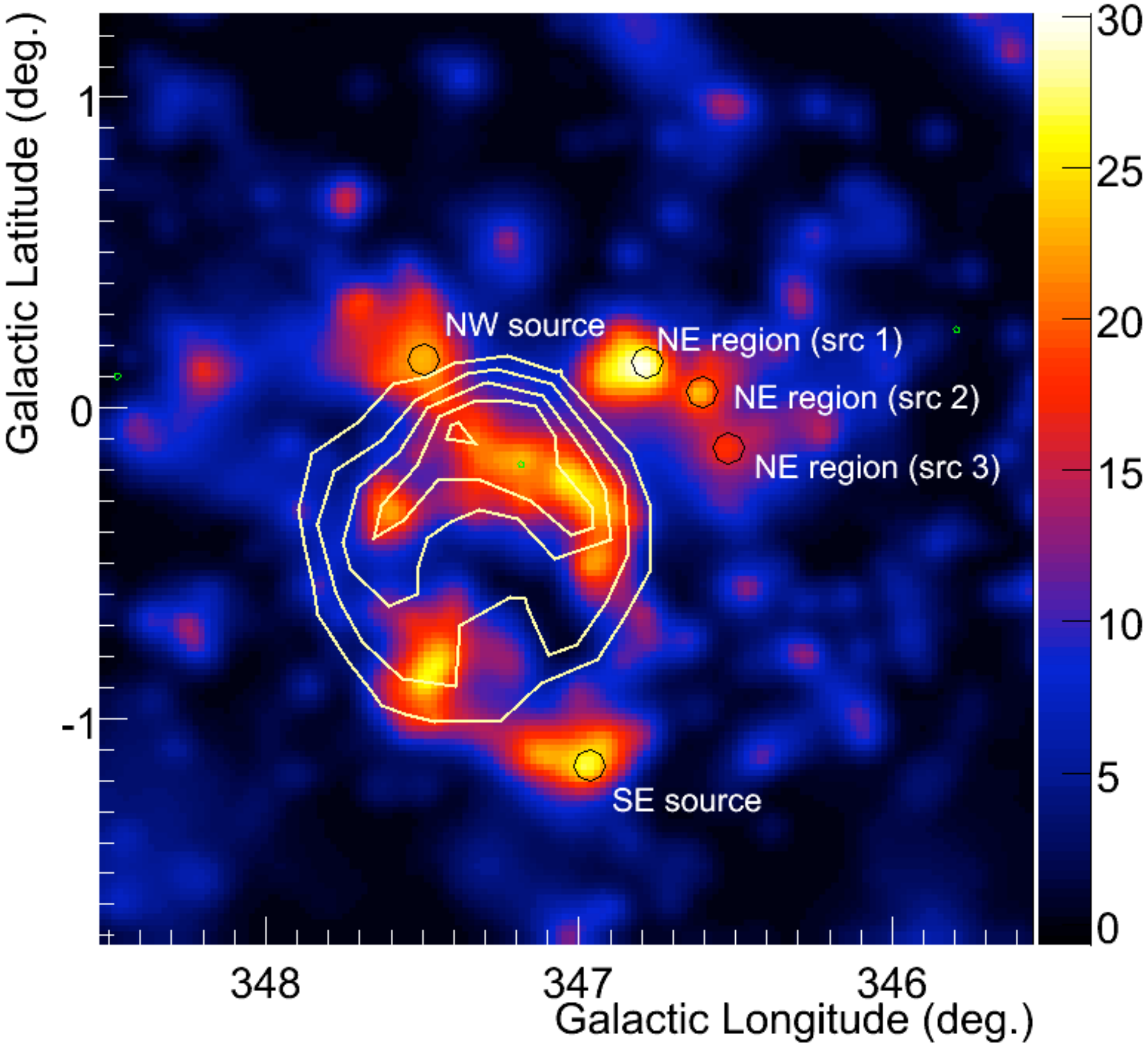
- Common features of middle-aged SNRs observed by Fermi
  - Interacting with molecular clouds
  - Spectral steepening between GeV and TeV
- SNRs observed by Fermi may give new clues on
  - Effect on cosmic ray acceleration from interacting molecular clouds
- Ensemble of SNRs with different cutoff may explain cosmic-ray spectral index of ~2.7
  - Shock acceleration @ ~2.0
  - Propagation effect is not sufficient to describe the difference
  - Note: #(middle aged SNRs) >> #(young SNR)

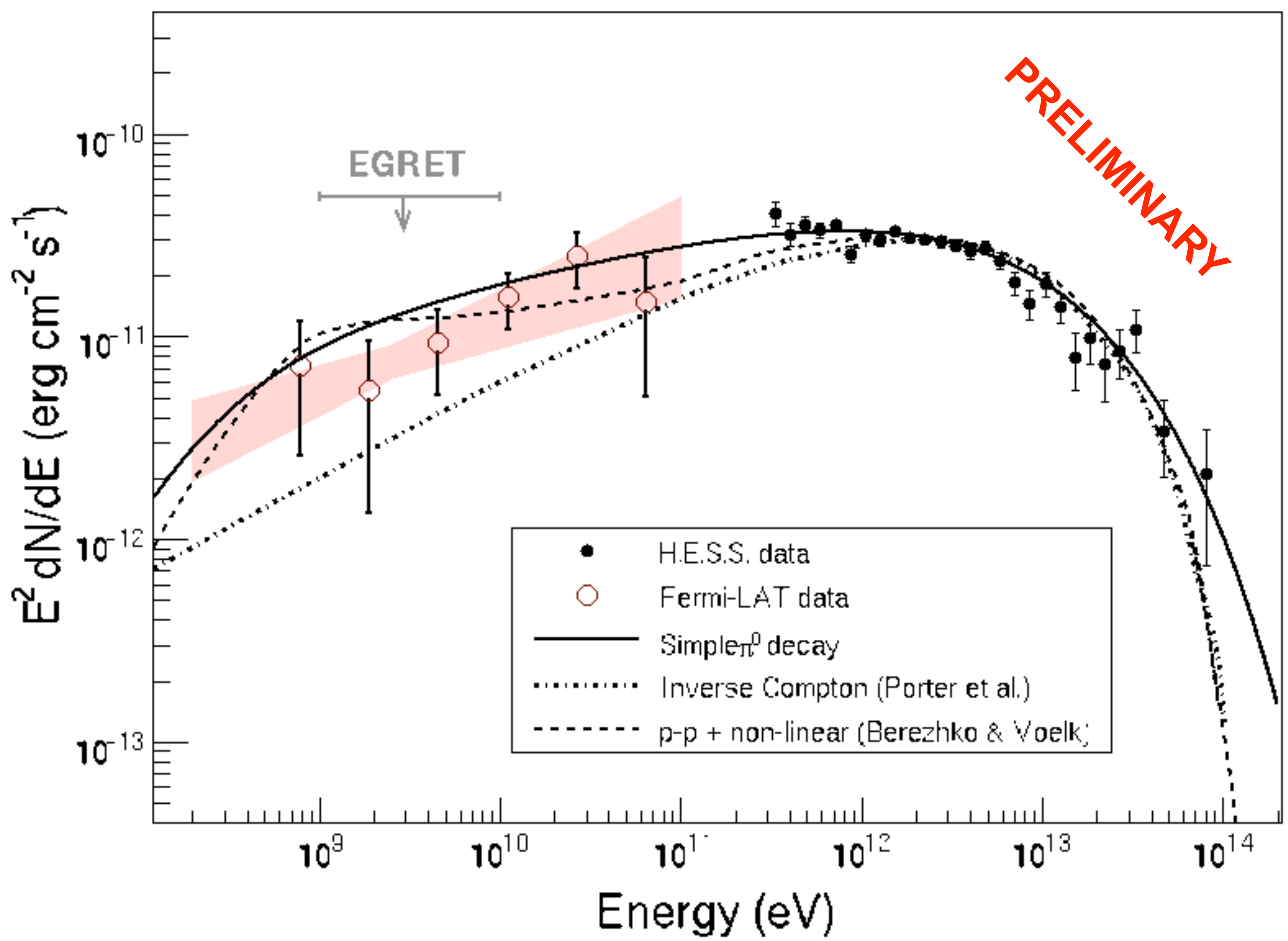
Color: Fermi-LAT
Green contours: TeV (HESS) 4, 5, 6σ
Magenta contours: NANTEN $^{12}CO(1\text{–}0)$ 0–10 km s^{-1}
Cyan circle: radio boundary
+: PSR J1809–2332



Young SNR RX J1713.7-3946

- TS map after subtraction of preliminary 1FGL catalog sources
  - Very complicated GeV emissions
  - North sources coincides with molecular clouds (CO and HII region)
- Requires more statistics to distinguish hadronic or leptonic nature of gamma-ray emissions

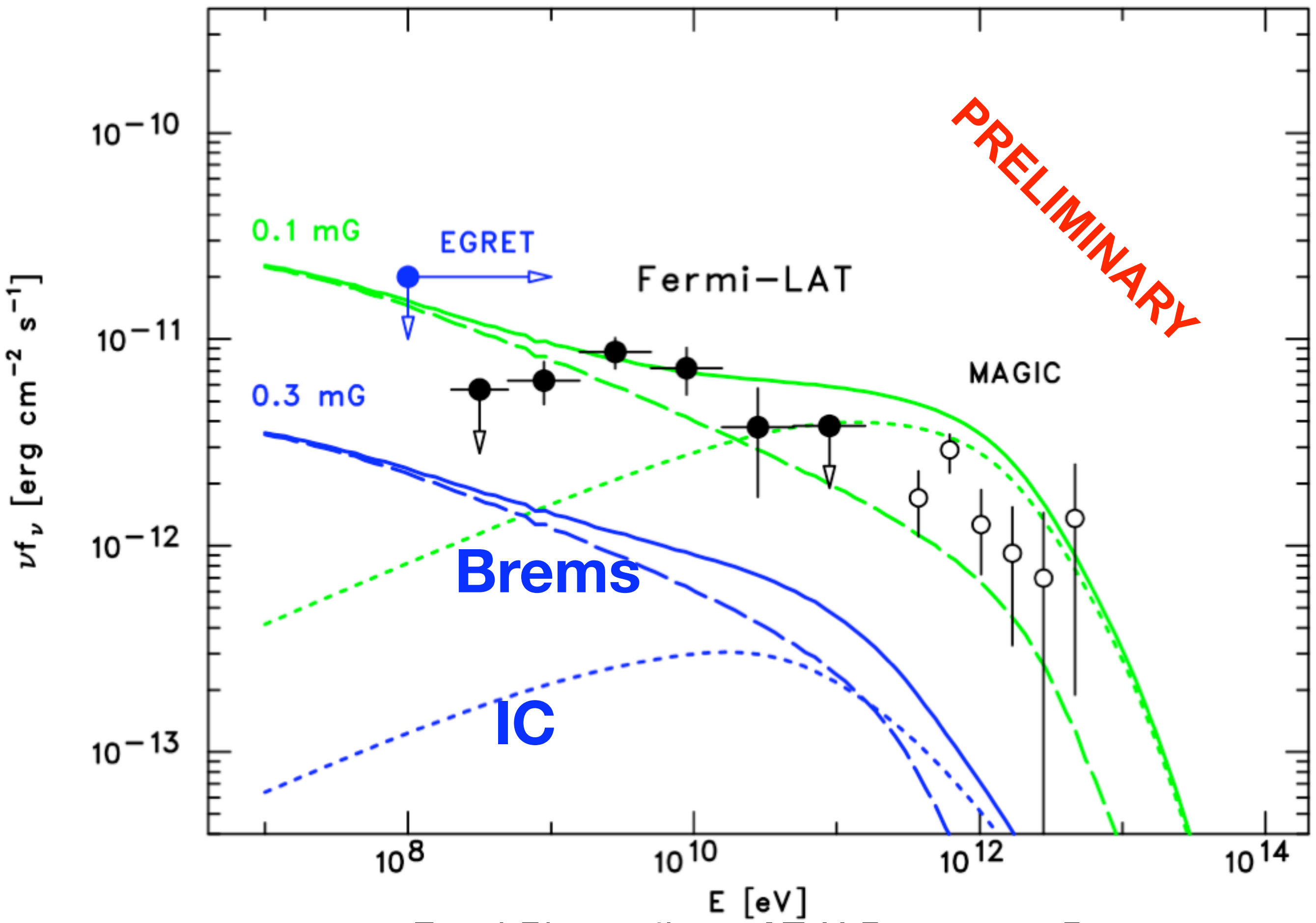


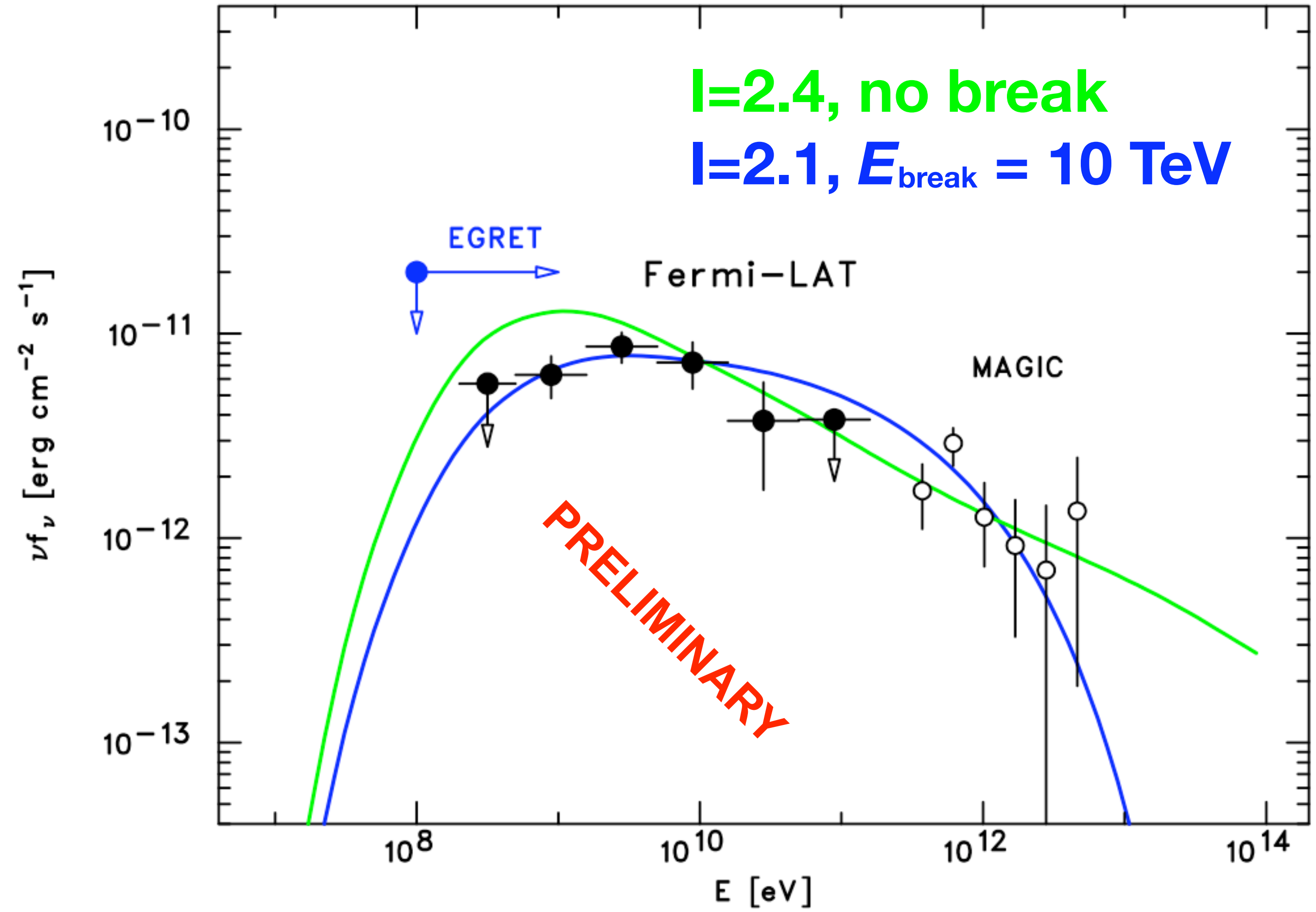


SNR Cassiopeia A

- Last SNR witnessed by human (AD 1680)
- No apparent spectral break in LAT and MAGIC spectrum
- Both leptonic and hadronic interpretation possible
  - Leptonic (Bremsstrahlung + IC)
    - B ~ 0.12 mG, $W_e \sim 1 \times 10^{49}$ erg
  - Hadronic (π^0 decay)
    - B > 0.12 mG, $W_p \sim 5 \times 10^{49}$ erg

to appear in ApJ





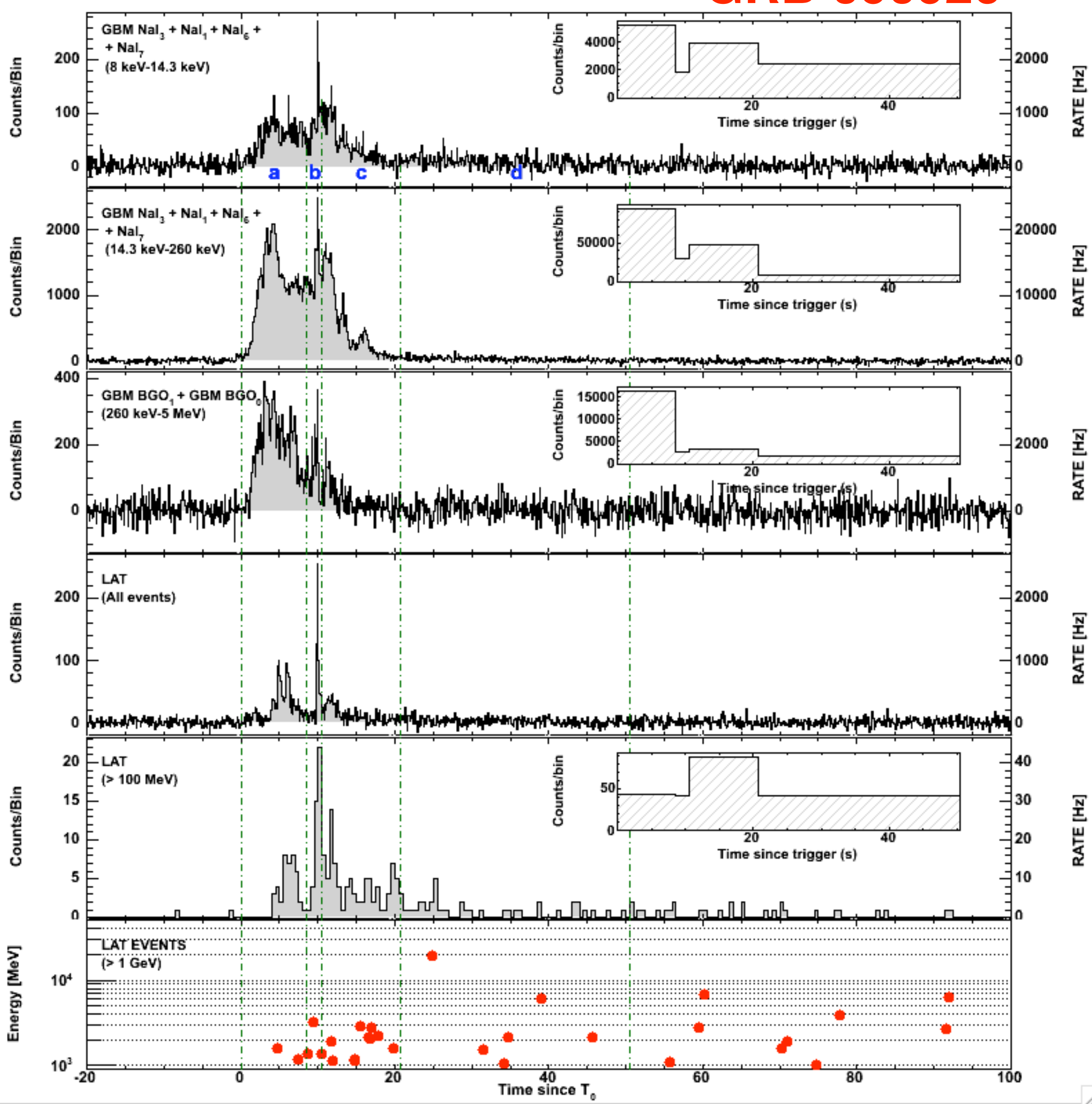
Common Features of LAT GRBs

GRB	duration	# of events > 100 MeV	# of events > 1 GeV	Highest Energy (arrival time)	Delayed HE onset	Long-lived HE emission	Extra component	Redshift
080825C	long	~10	0	~0.6 GeV (~T_0+28 s)	✔	✔	?	
080916C	long	>100	>10	~13 GeV (~T_0+17 s)	✔	✔	hint	4.35
081024B	short	~10	2	~3 GeV (~T_0+0.6 s)	✔	✔	?	
081215A	long	—	—	—	—	—	—	
90217	long	~10	0	~1 GeV (~T_0+15 s)	X	X	?	
90323	long	~20	>0	—	—	✔	—	3.57
90328	long	~20	>0	—	—	✔	—	0.736
90510	short	>150	>20	~31 GeV (~T_0+0.8 s)	✔	✔	✔	0.903
90626	long	~20	>0	—	—	✔	—	
090902B	long	>200	>30	~33 GeV (~T_0+82 s)	✔	✔	✔	1.822
90926A	long	>150	>50	~20 GeV (~T_0+25 s)	✔	✔	✔	2.106

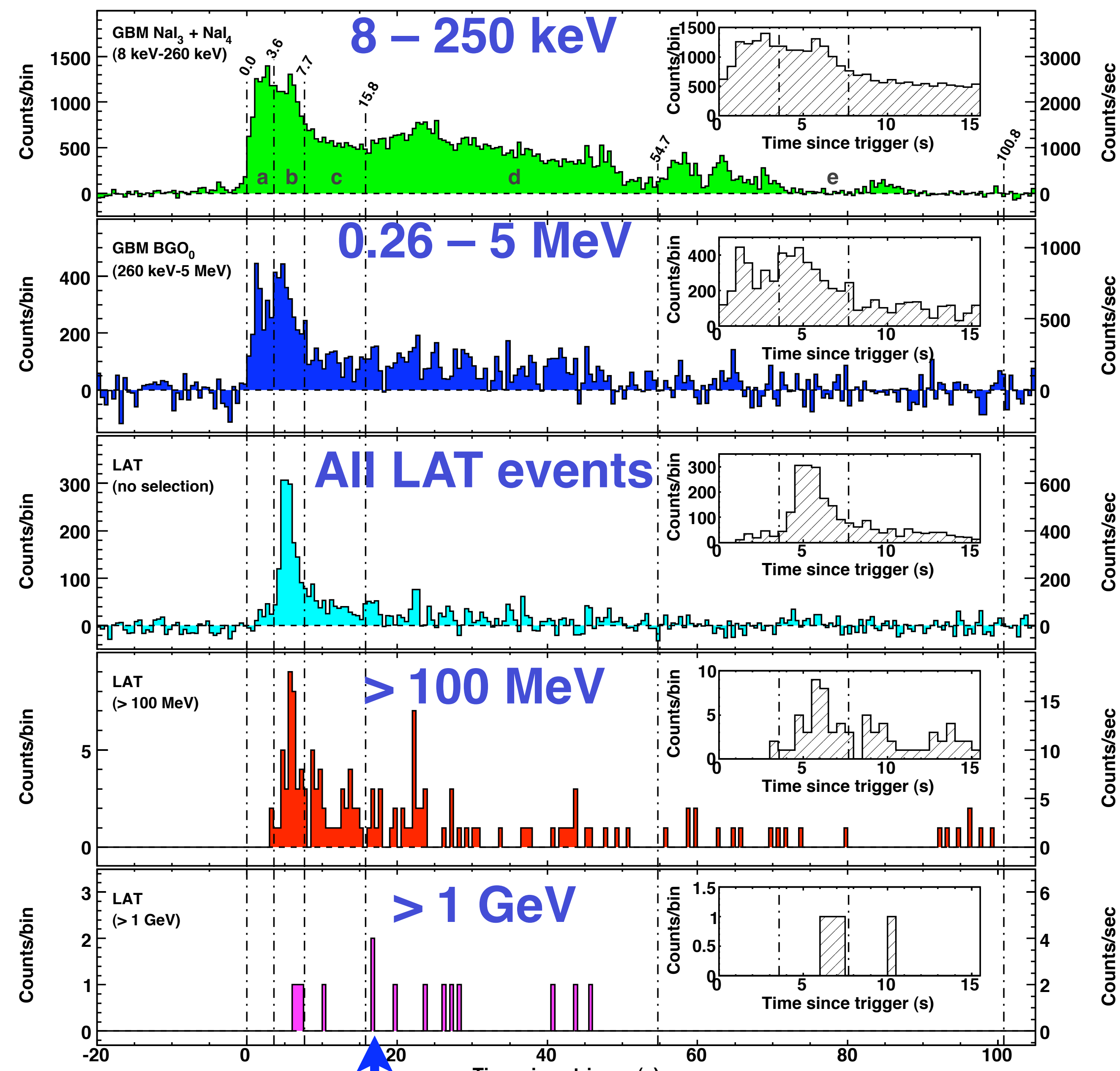
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \rightarrow e^{+}e^{-}$ in the first peak?
  - No evidence of spectral cut-off
- Late arrival of highest energy gamma rays

GRB 090926



GRB 080916C



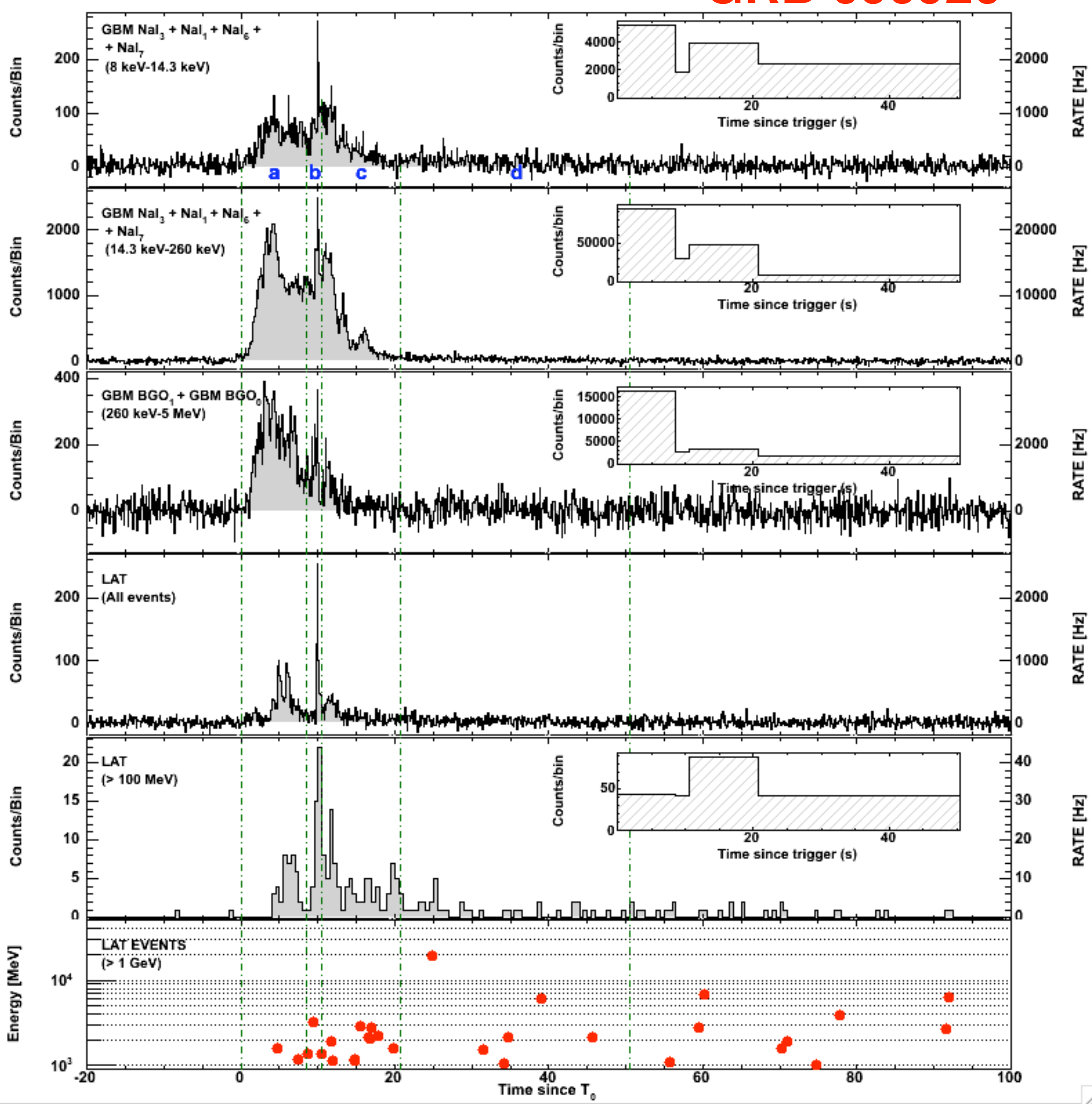
Science 323 1688A (2009)

13.2 GeV photon

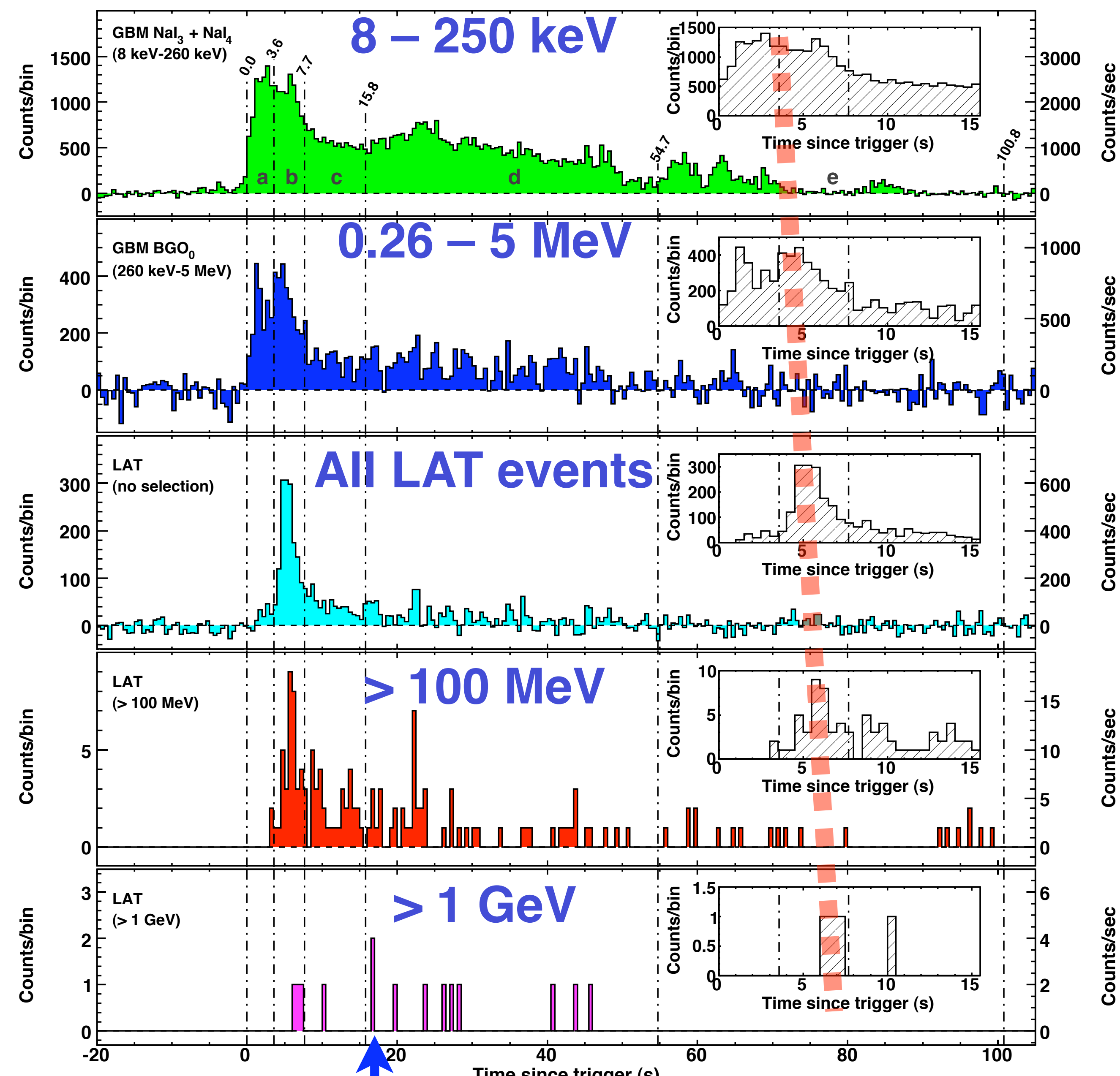
Delayed HE Gamma-ray Emission

- Opacity due to $\gamma\gamma \rightarrow e^{+}e^{-}$ in the first peak?
  - No evidence of spectral cut-off
- Late arrival of highest energy gamma rays

GRB 090926



GRB 080916C



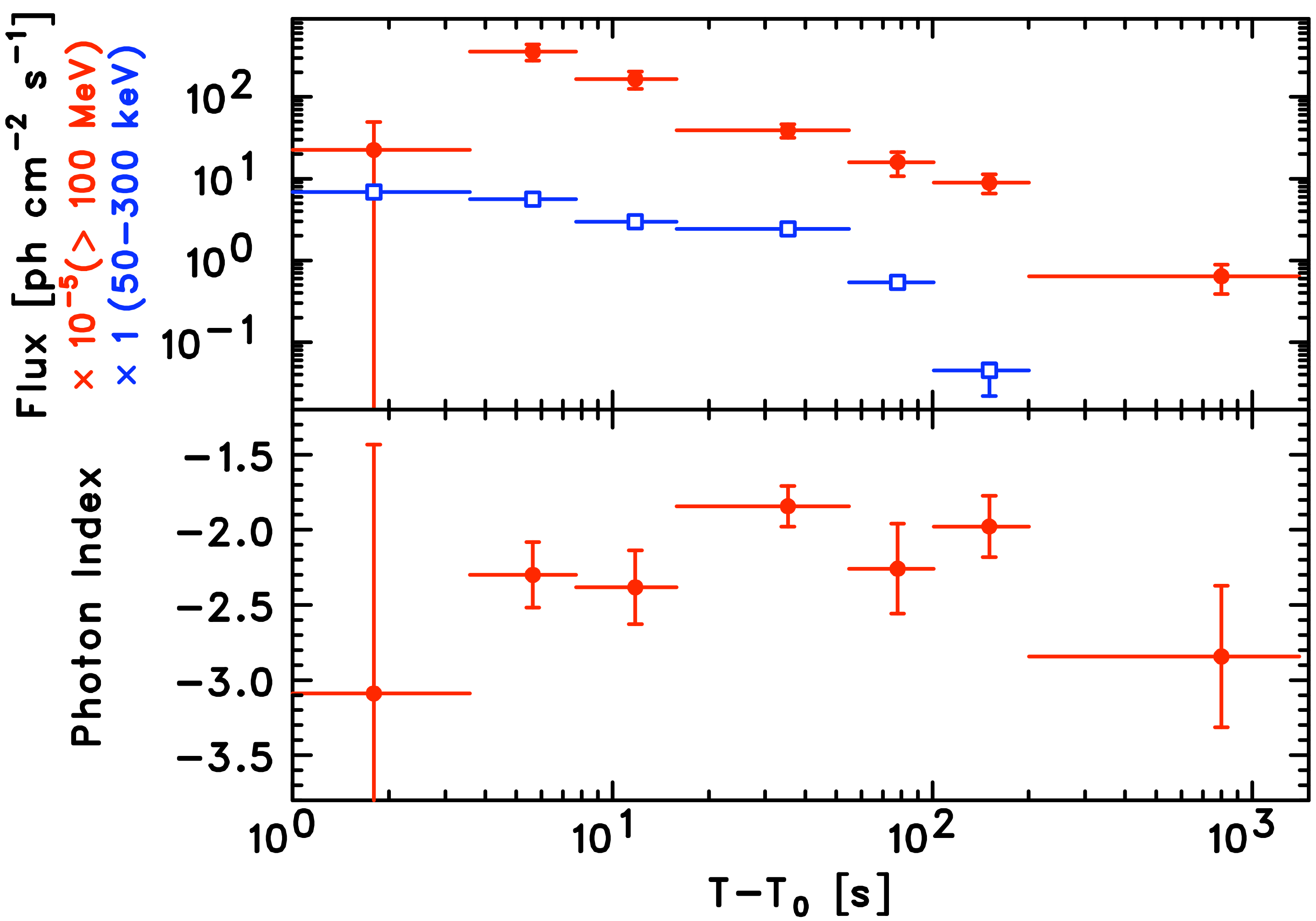
Science 323 1688A (2009)

13.2 GeV photon

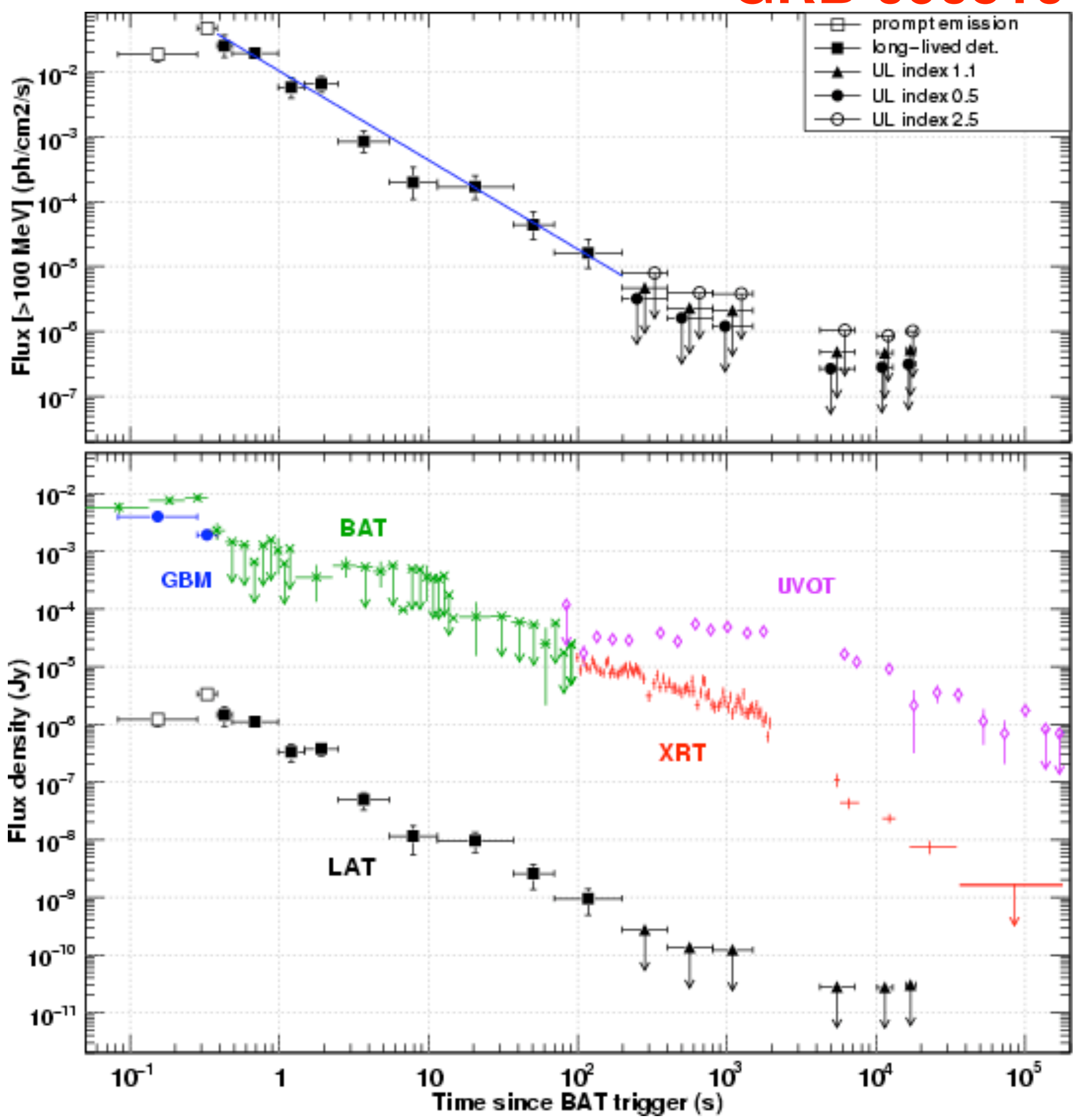
GRB Long-Lived HE Emission

- HE (>100 MeV) emission shows different temporal behavior
  - Temporal break in LE emission while no break in HE emission
    - Indication of cascades induced by ultra-relativistic ions?
    - Angle-dependent scattering effects?

GRB 080916C

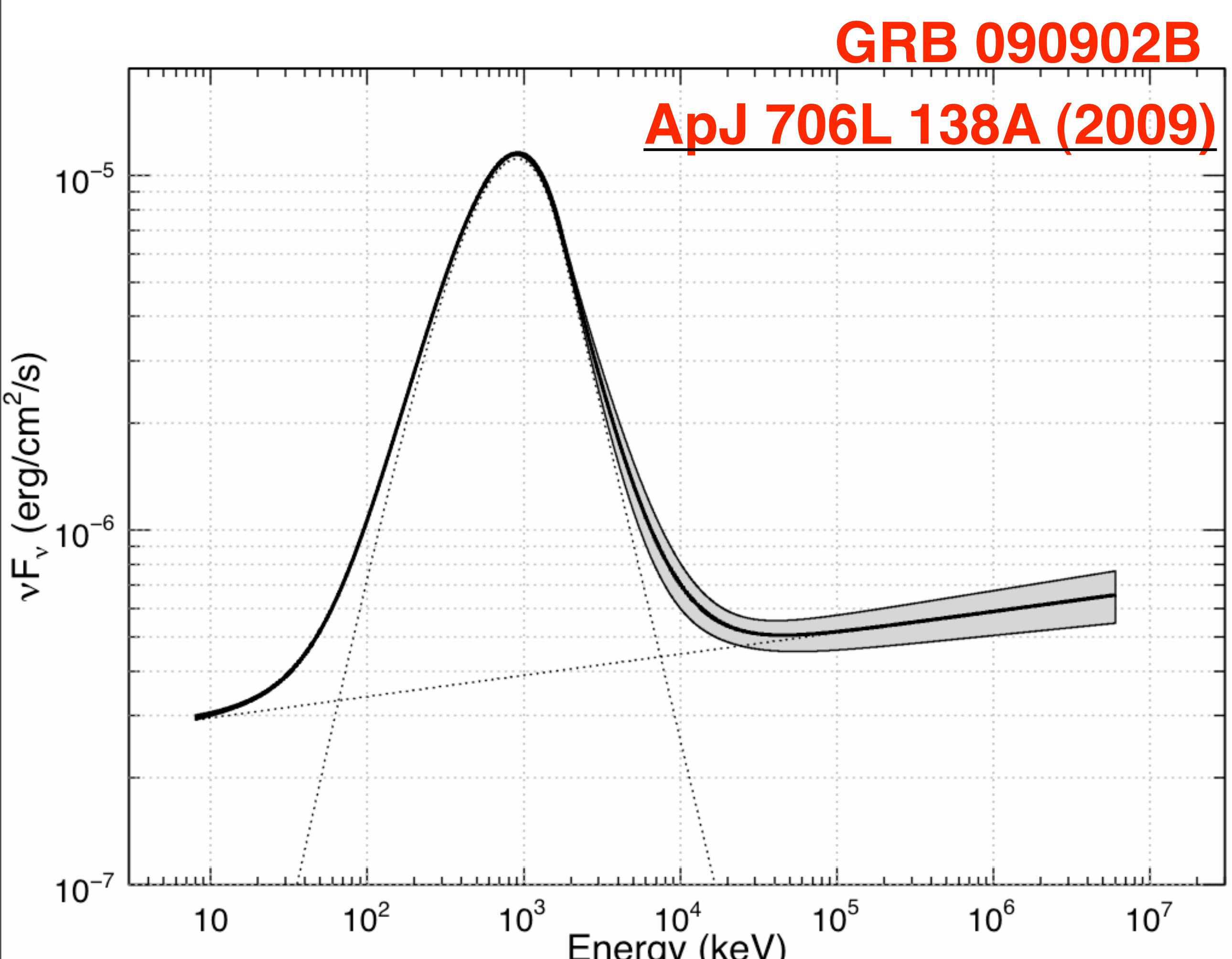


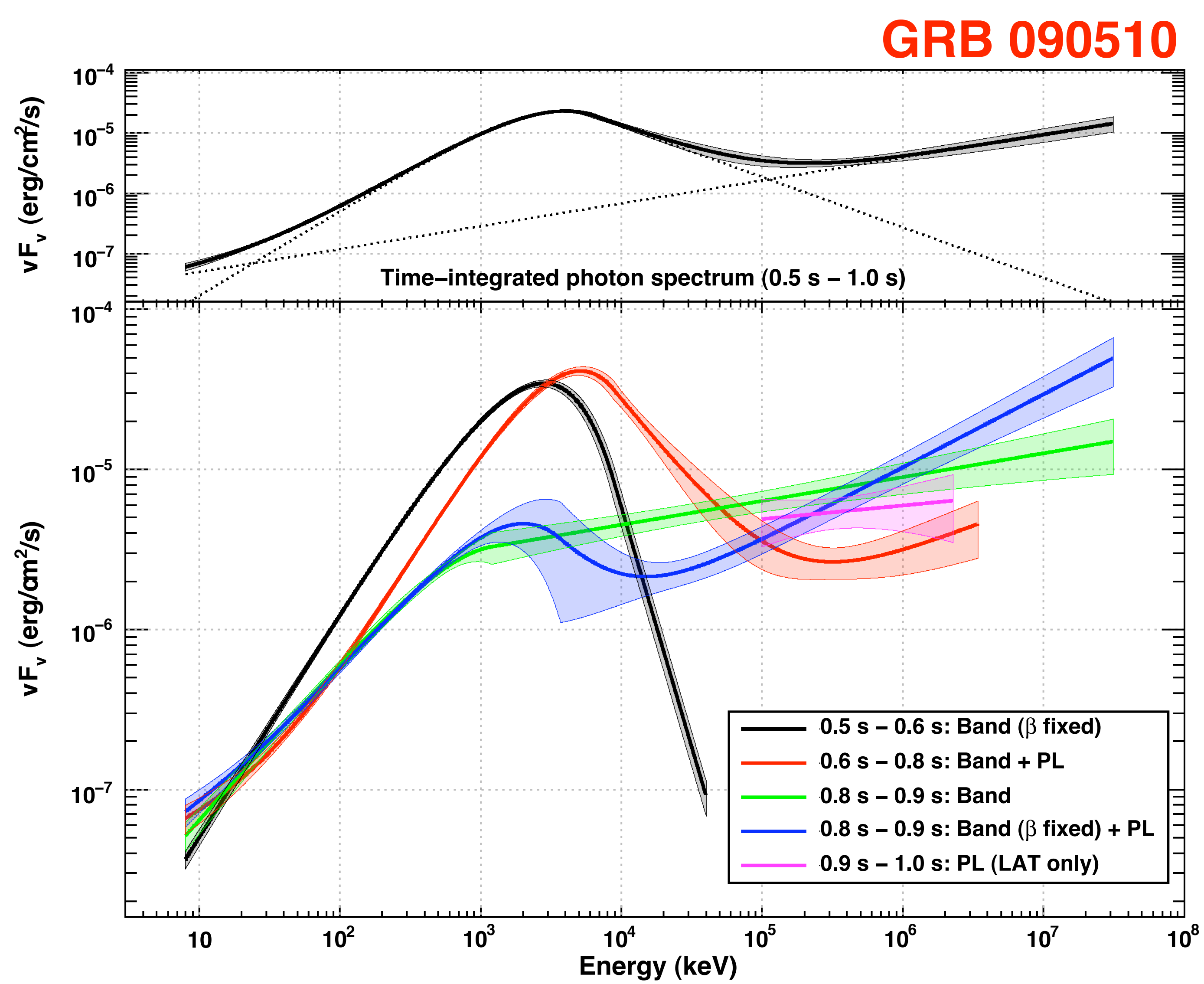
GRB 090510



Extra Component

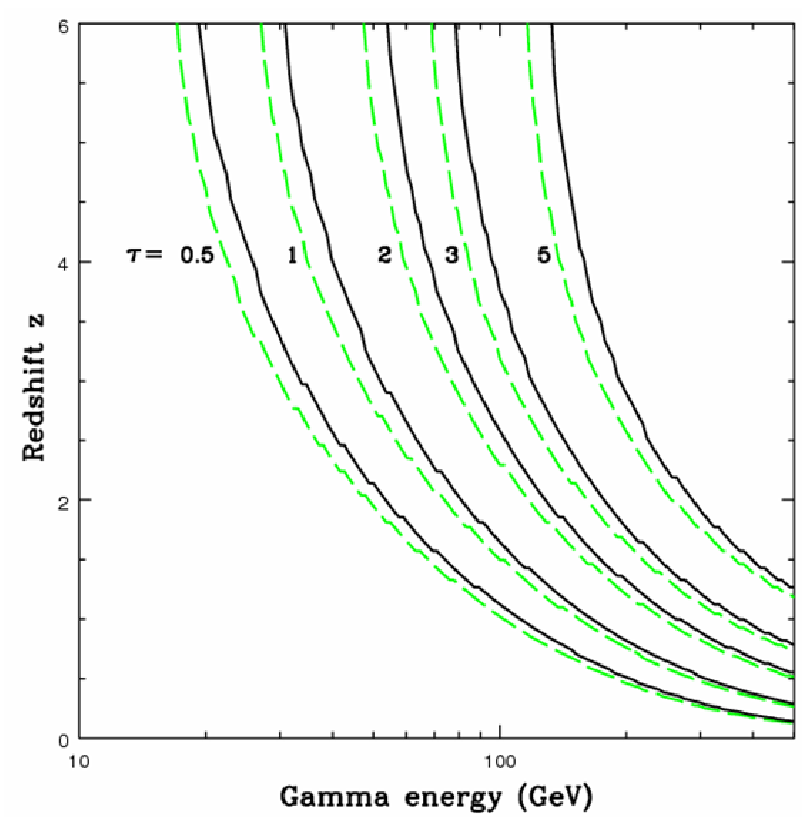
- Extra spectral component inconsistent with Band function
  - Both in low- and high-energy regions
- This is a challenge to theoretical model
  - Low energy excess difficult to explain by inverse Compton
  - Early afterglow?

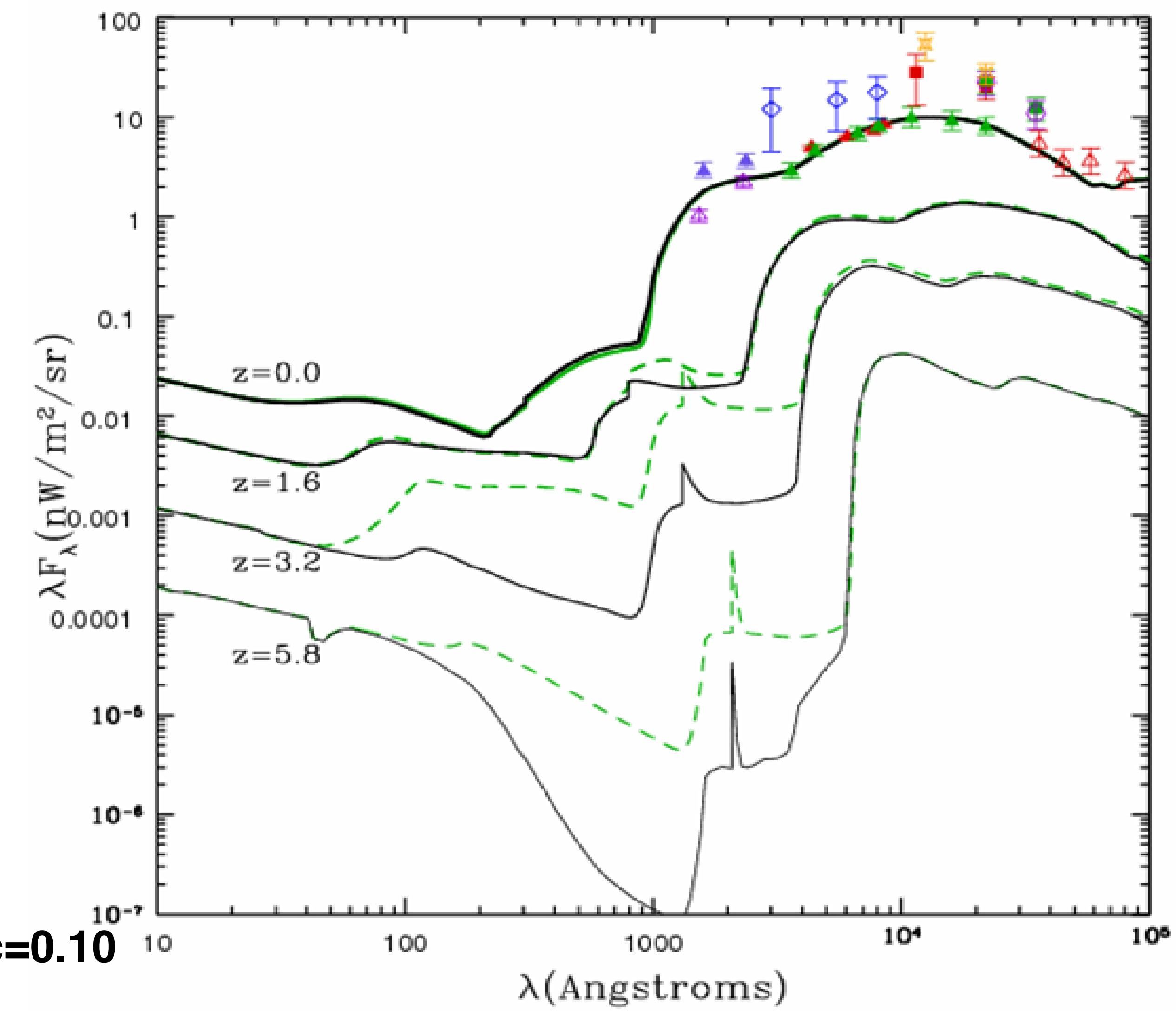




Extragalactic Background Light

- EBL is sensitive to star formation history, dust extinction, light absorption and re-emission by dust
  - Direct measurements of the IR-UV EBL are very difficult because of foreground subtraction
- HE gamma rays are sensitive to EBL in IR to UV band via $\gamma\gamma \rightarrow e^{+}e^{-}$ process
  - EBL will steepen AGN/GRB spectra above > 10 GeV



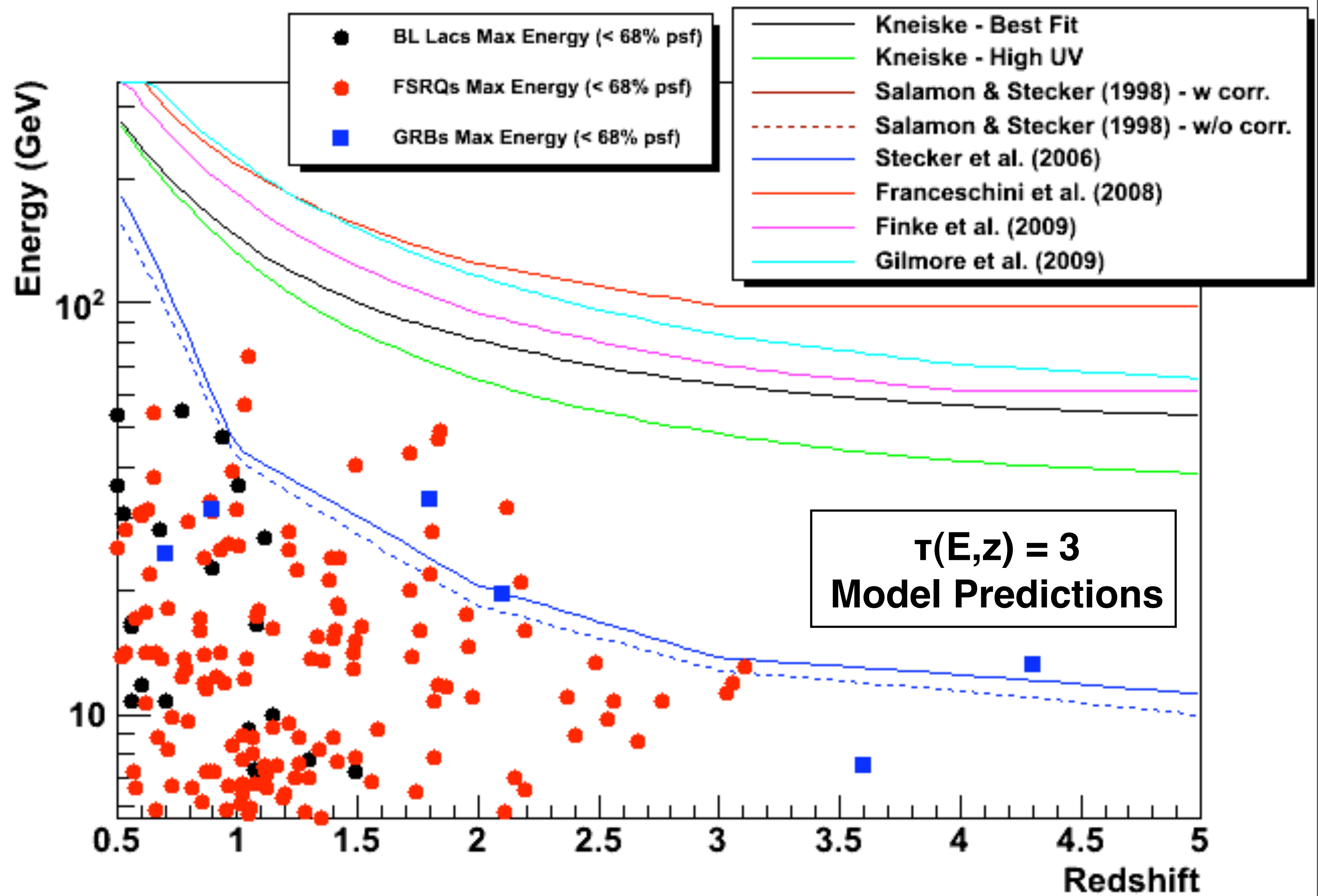


Hopkins et al. 2007, fesc=0.10

S&B Model 'C', f=0.02

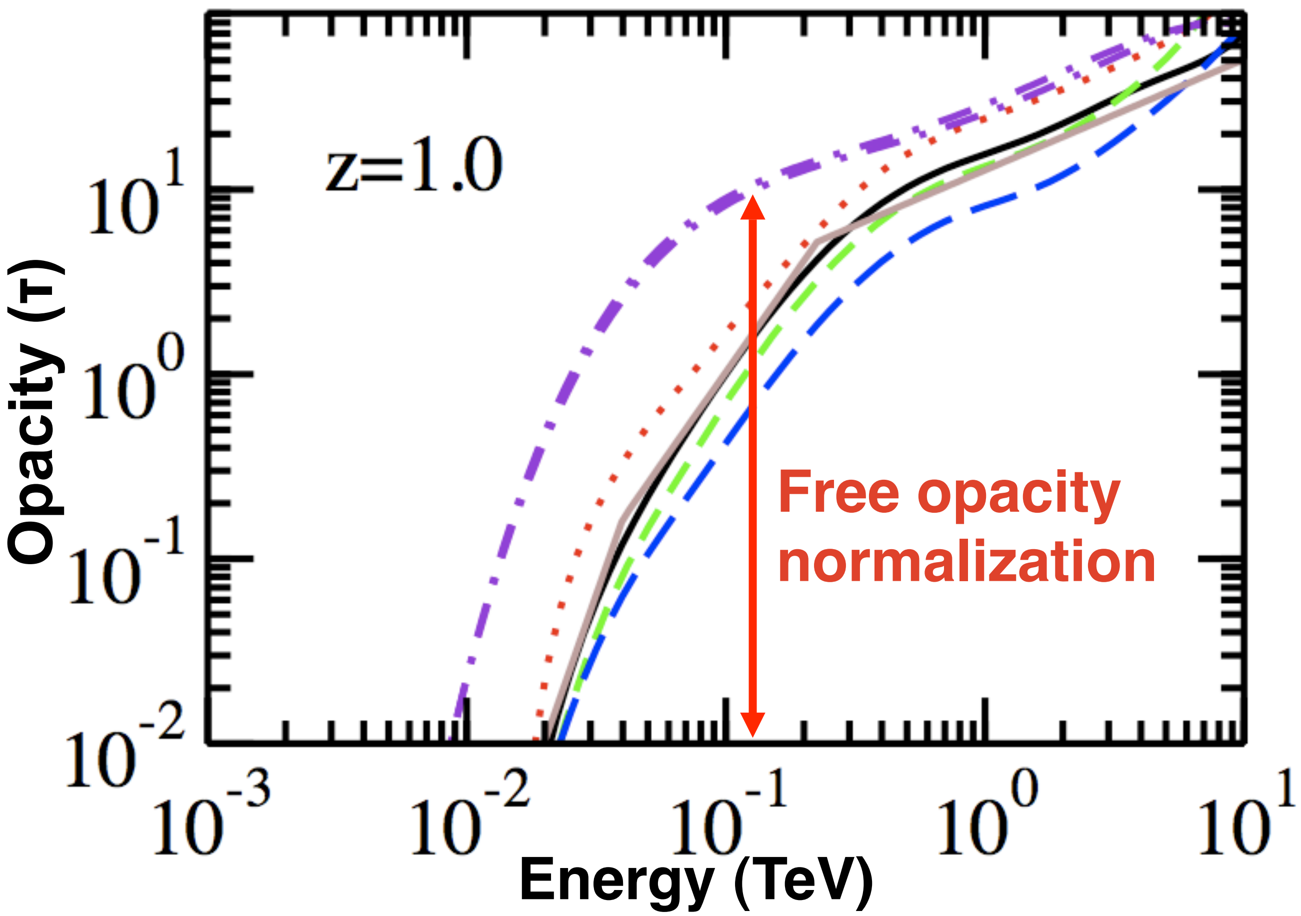
Probing EBL with AGN and GRB

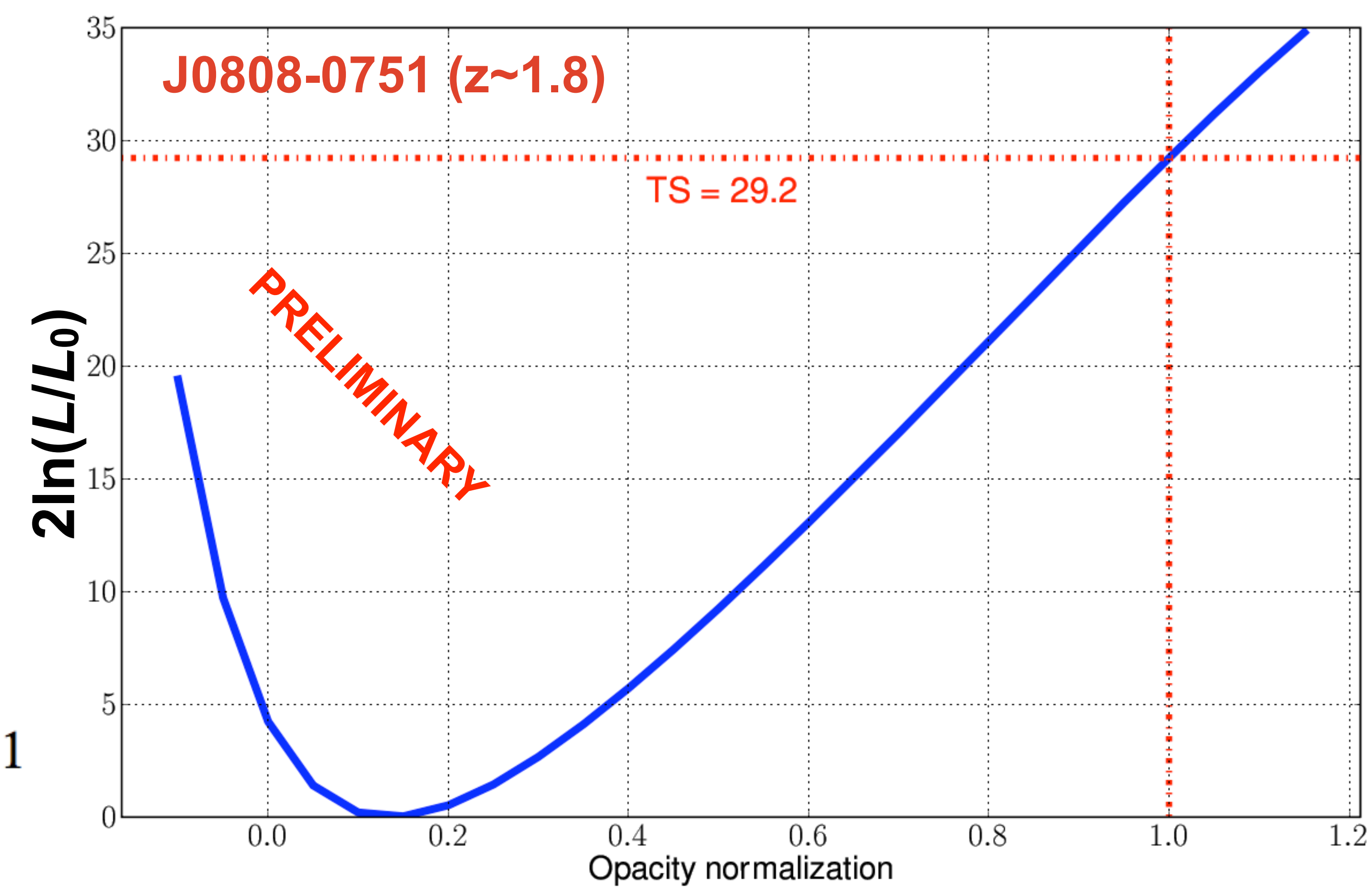
- 10–100 GeV gamma rays can probe EBL in early universe
- Requires many sources at various redshifts to untangle EBL effect and intrinsic spectra
  - Fermi will have ~1000 of blazars and ~100 of GRBs with redshift
- Distinguish competing models



Constraining EBL Models

- Test each model by null-hypothesis test
  - **Power-law x EBL absorption**
    - Vary normalization for EBL absorption
- An example with J0808-0751 with Stecker's baseline model
  - **Consistent with normalization = 0 (no EBL)**
  - **Inconsistent with normalization = 1 at 5.6σ significance**
    - Stecker's baseline model excluded





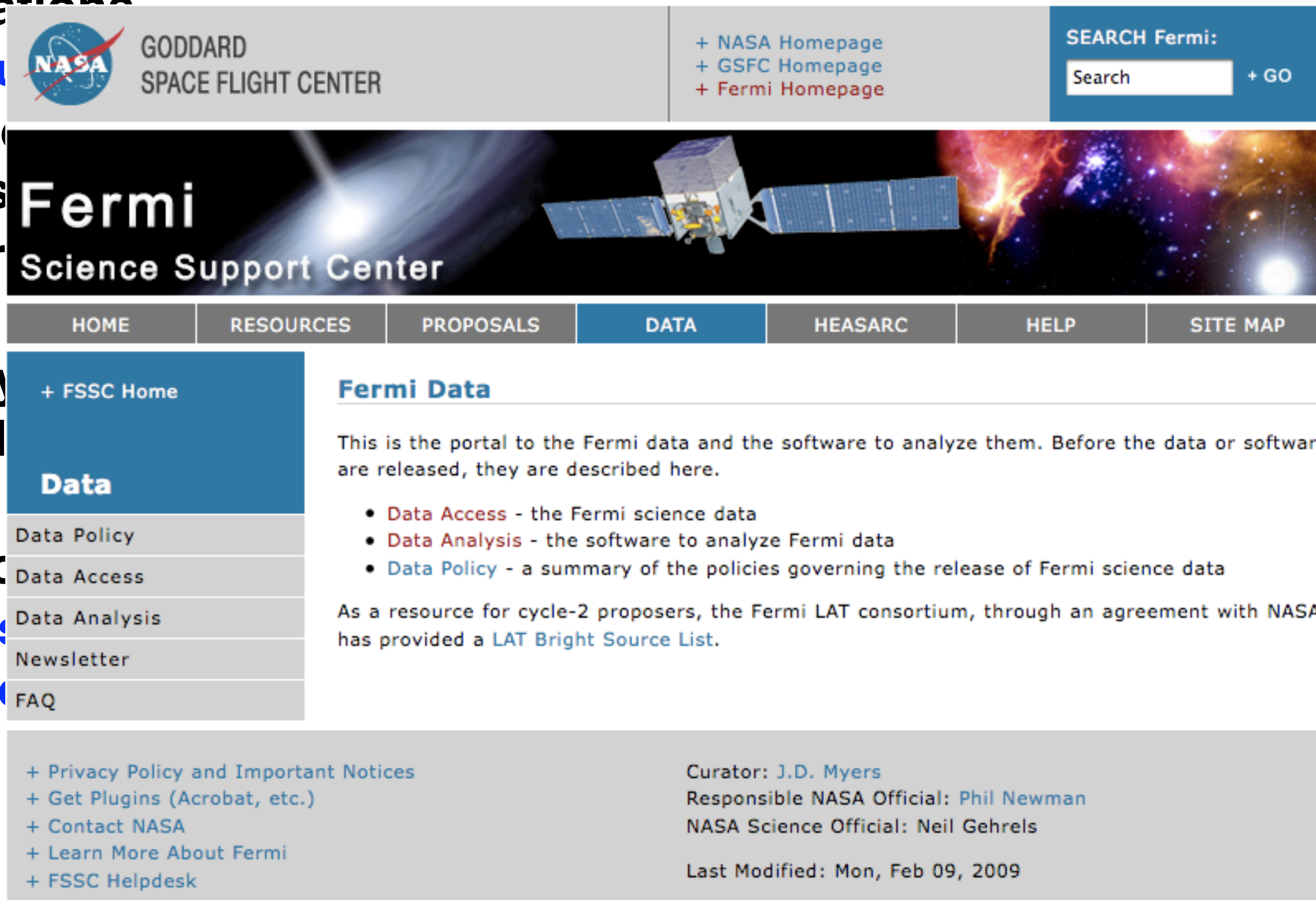
Summary

- Fermi LAT demonstrating very exciting science in an early stage of its operations
  - Already surpassing EGRET in many area
- Discovery of spectral steepening at a few GeV in several middle-aged SNRs
- Very different behaviors of GeV gamma-ray emissions from MeV emissions from GRBs
- Gamma-ray emission > 10 GeV from AGN/GRB start constraining EBL models

- Data are now public
  - data access: http://fermi.gsfc.nasa.gov/ssc/data/access/
  - analysis tool: http://fermi.gsfc.nasa.gov/ssc/data/analysis/

Summary

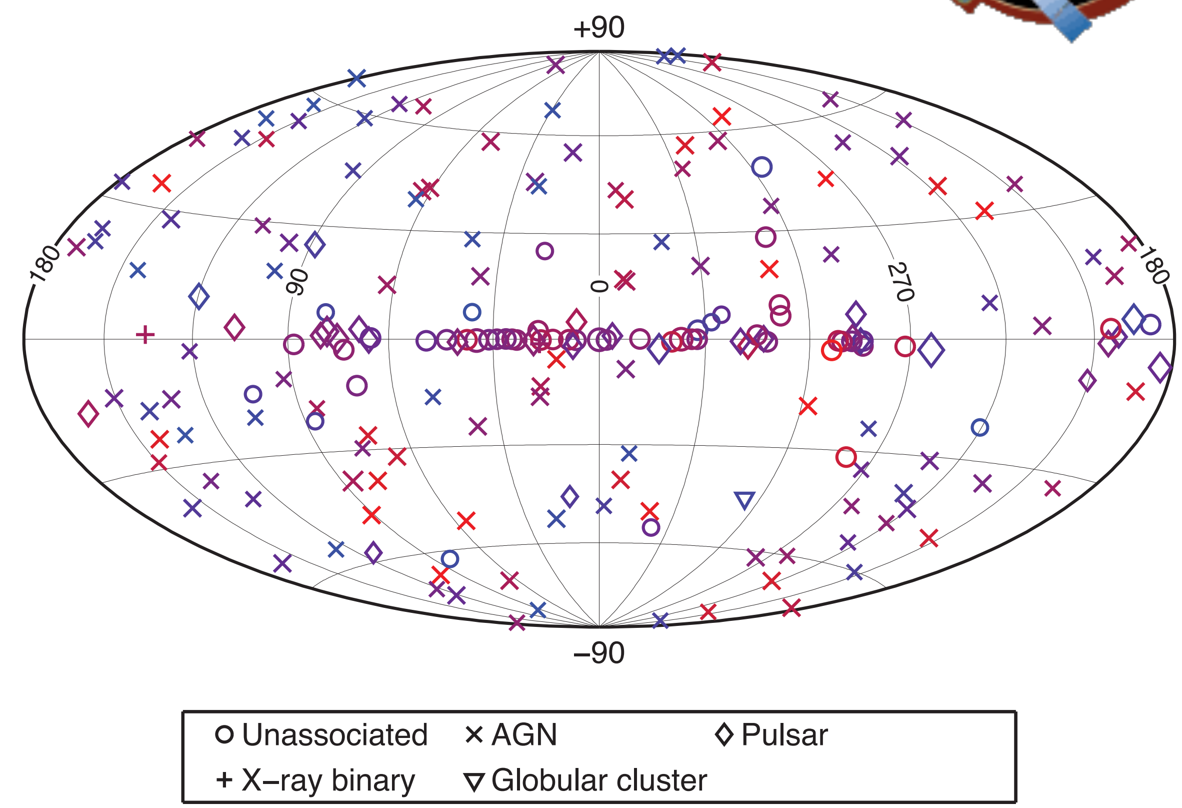
- Fermi LAT demonstrating very exciting science in an early stage of its operations
  - Already su
- Discovery
  aged SNRs
- Very differ
  emissions
- Gamma-ray
  EBL model
- Data are no
  - data acces
  - analysis t

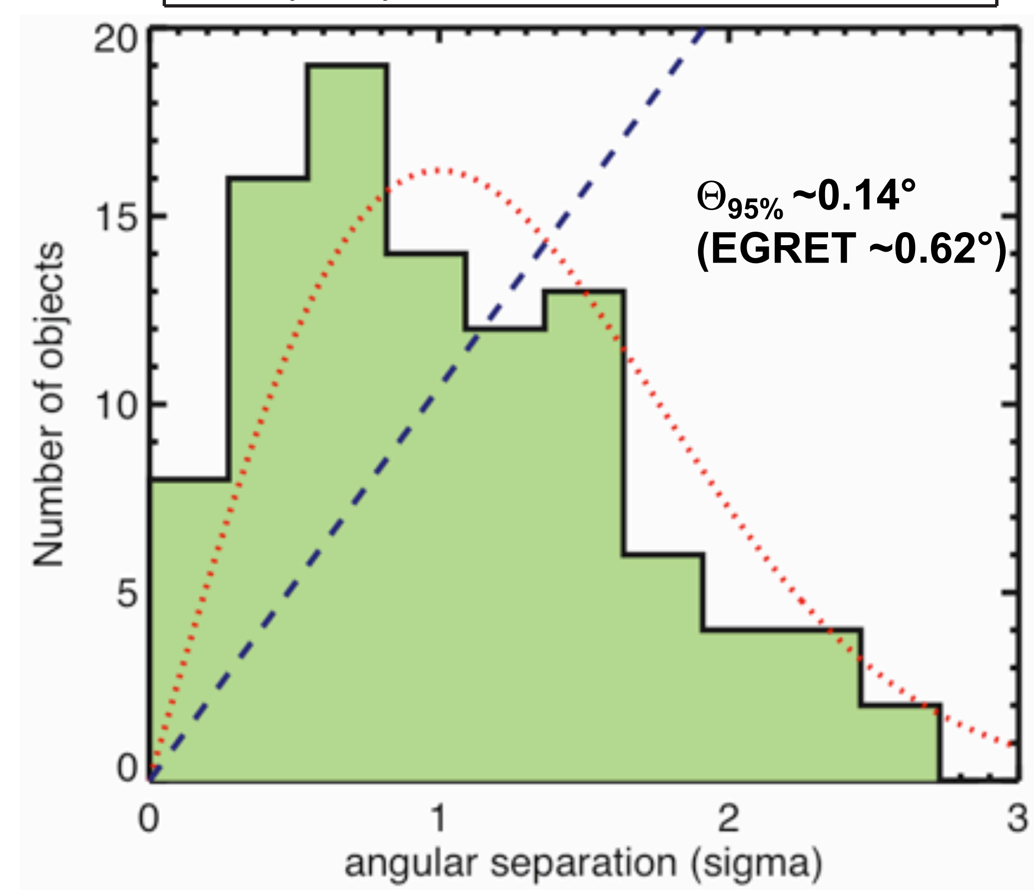


Backup

Source Associations (3 Month List)

Class	Number
FSRQ	62
BL Lac	46
Radio galaxy	11
Other blazar	2
Radio/X-ray pulsar	15
LAT γ-ray pulsar	14
HMXB	2
Globular cluster	1
LMC	1
Special cases	13
Unidentified	38



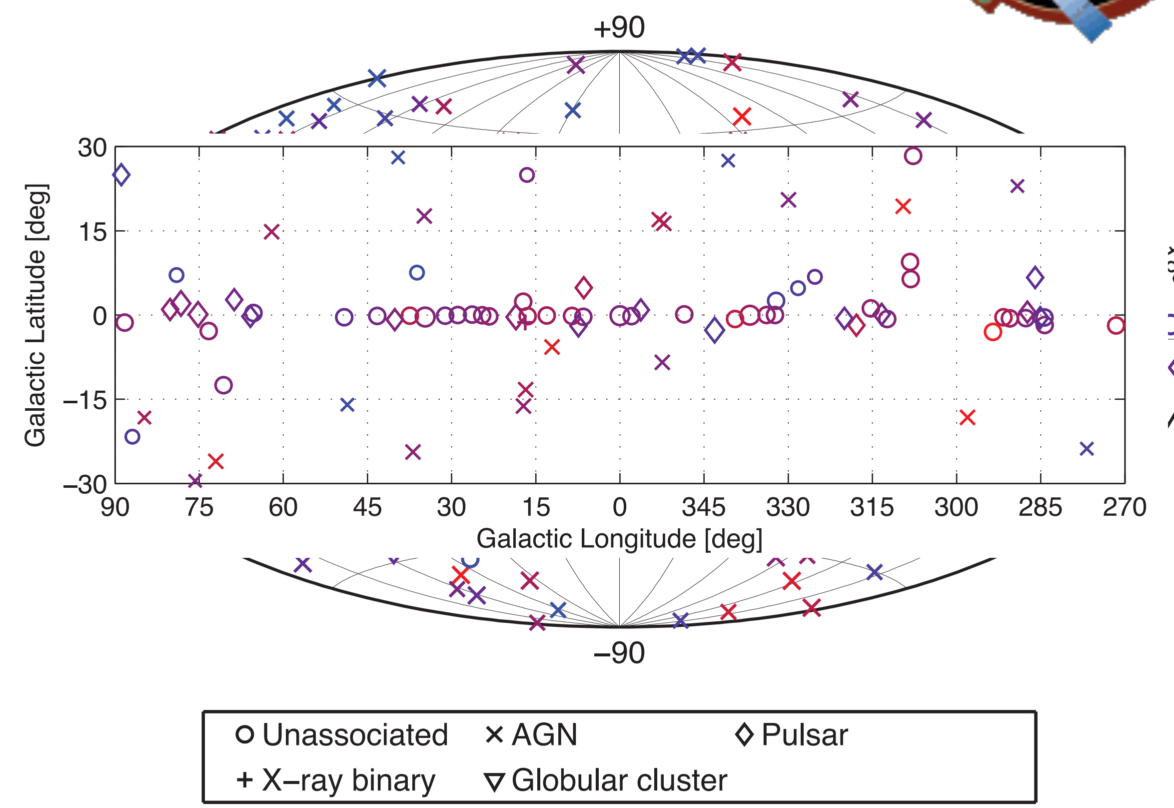


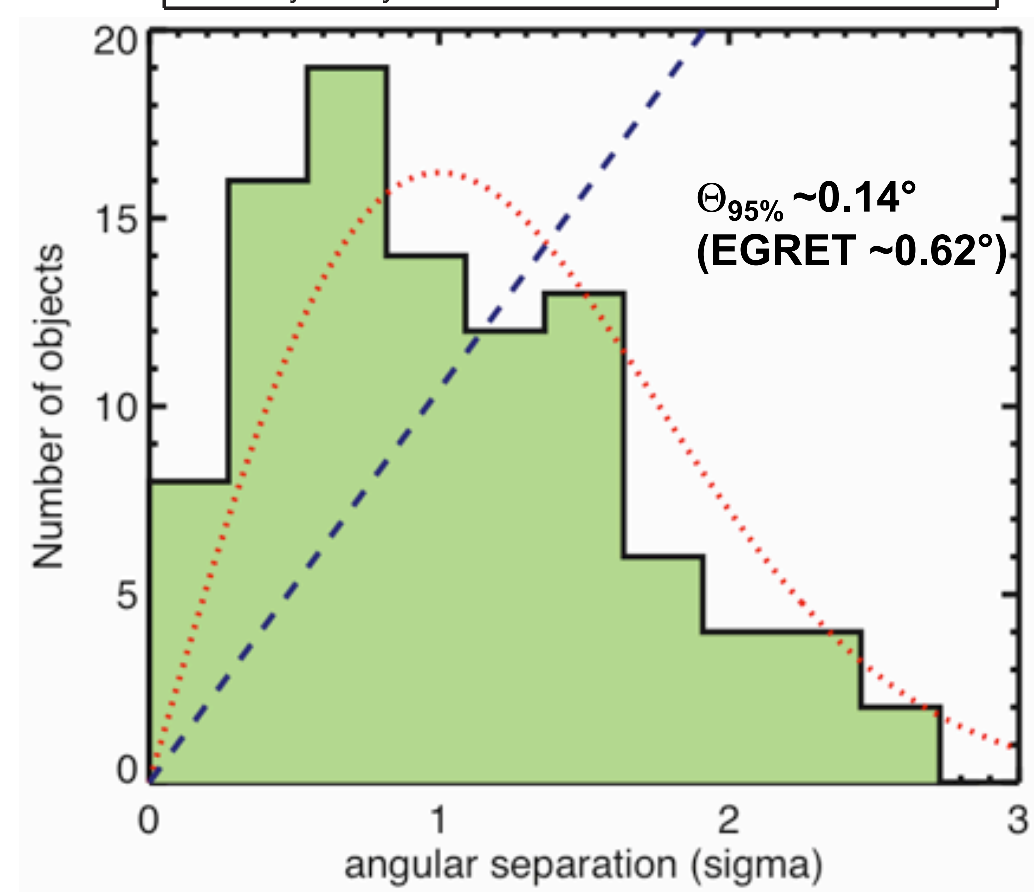
- >80% of sources have "associations": 121 AGN class, 29 pulsars
- Thanks to better angular resolution ⇒ better localization and S/B

Source Associations (3 Month List)

Class	Number
FSRQ	62
BL Lac	46
Radio galaxy	11
Other blazar	2
Radio/X-ray pulsar	15
LAT γ-ray pulsar	14
HMXB	2
Globular cluster	1
LMC	1
Special cases	13
Unidentified	38

- **>80% of sources have "associations": 121 AGN class, 29 pulsars**
- **Thanks to better angular resolution ⇒ better localization and S/B**

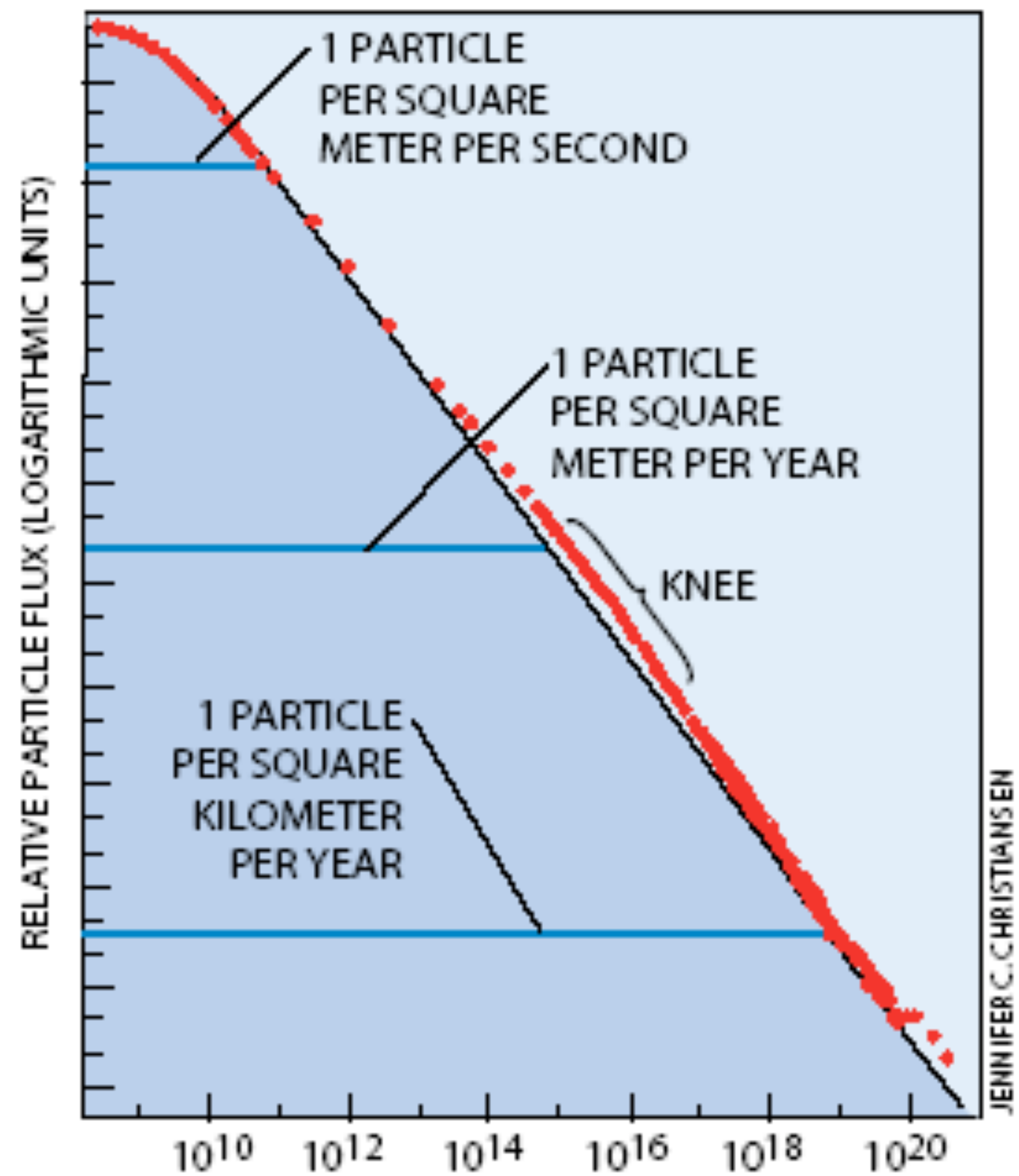




Cosmic Particle Accelerators

- Origin of cosmic ray protons?
  - Galactic SNRs (Supernova Remnants) are considered as the best candidates for cosmic-rays below "Knee"
    - Only circumstantial evidence
      - Diffusive shock acceleration (Blanford&Eichler 1977)
      - CR energy sum consistent with SNR kinetic energy (Ginzburg&Syrovatskii 1964)
    - No observational evidence for hadronic acceleration
    - Spectral index (~2.7) is difficult to explain
  - Cosmic-rays above "Knee" are considered extragalactic
    - Gamma-ray bursts (GRB)
    - Active Galactic Nuclei (blazar)
    - Merging galaxy clusters

Scientific American, (c) 1998



SNR/PWN Associations with LAT

- Potential associations in LAT 3-month bright source list

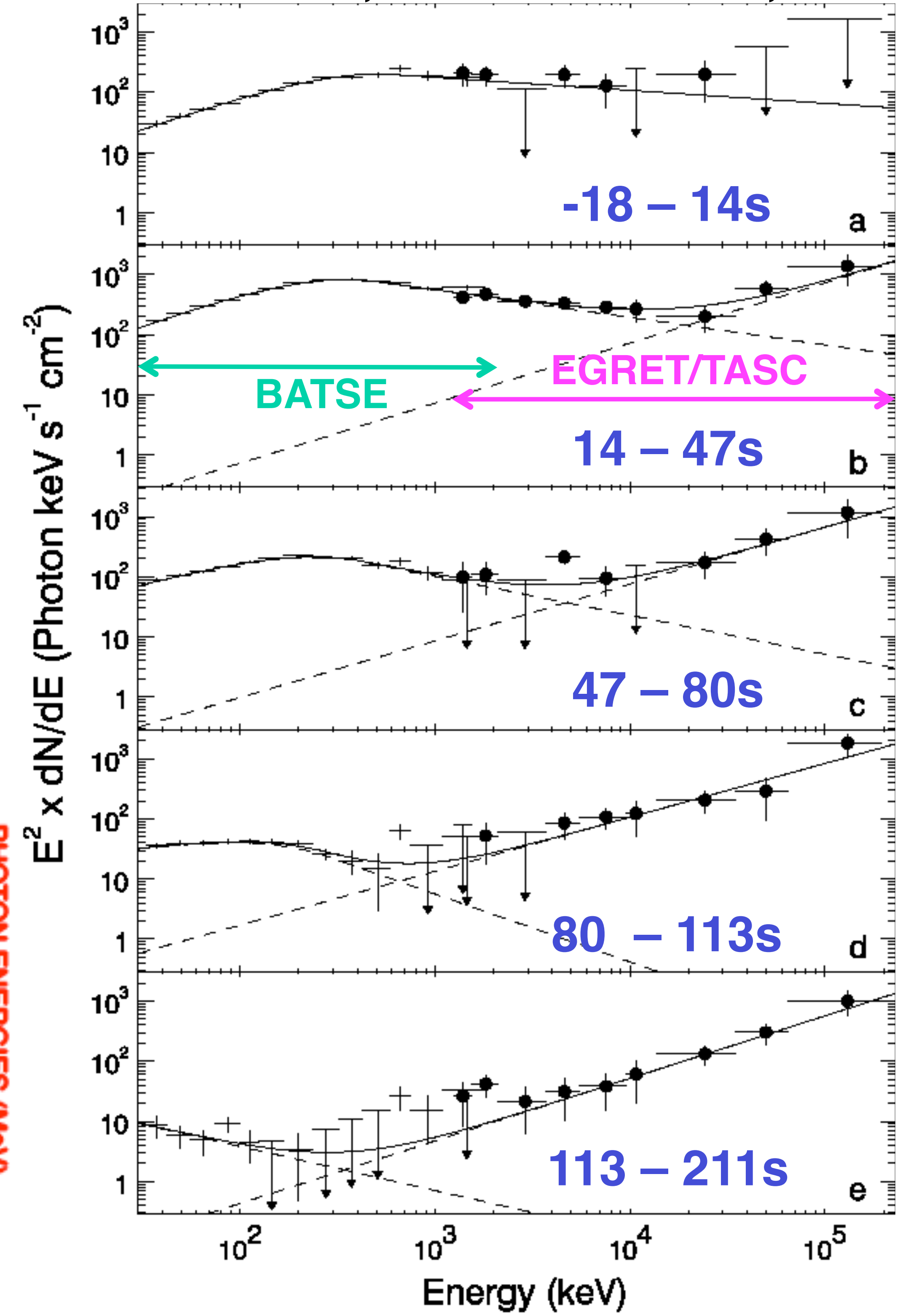
0FGL Name	l	b	Associations	Age ($x10^3$ y)	Molecular clouds
J0617.4+2234	189.08	3.07	SNR G189.1+3.0 (IC 443)	3~30	✔
J1018.2-5858	284.30	-1.76	SNR G284.3-1.8 (MSH 10-53), PSR J1013-5915	~10	✔
J1196.4-6055	290.52	-0.60	SNR G290.1-0.8 (MSH 11-61A), PSR J1105-6107	10~20	✔
J1615.6-5049	332.35	-0.01	SNR G332.4+0.1 (MSH 16-51), PWN G332.5-0.28, PSR B1610-50	~5	?
J1648.1-4606	339.47	-0.71	PSR J1648-4611		
J1714.7-3827	348.52	0.10	SNR G348.5+0.1 (CTB37A)	?	✔
J1801.6-2327	6.54	-0.31	SNR G6.4-0.1 (W28)	35~150	✔
J1814.3-1739	13.05	-0.09	PWN G12.82-0.02		
J1834.4-0841	23.27	-0.22	SNR G23.3-0.3 (W41)	148?	✔
J1855.9+0126	34.72	-0.35	SNR G34.7-0.4 (W44)	~20	✔
J1911.0+0905	43.25	-0.18	SNR G43.3-0.2 (W49B)	1~4	✔
J1923.0+1411	49.13	-0.40	SNR G49.2-0.7 (W51C)	~20	✔
J1954.4+2838	65.30	0.38	SNR G65.1+0.6	40~140	X

- It is very difficult to distinguish SNRs, PWNe and pulsars
  - Source confusions due to SNR/PWN/pulsar in close vicinity
  - One of useful tool is morphological identification

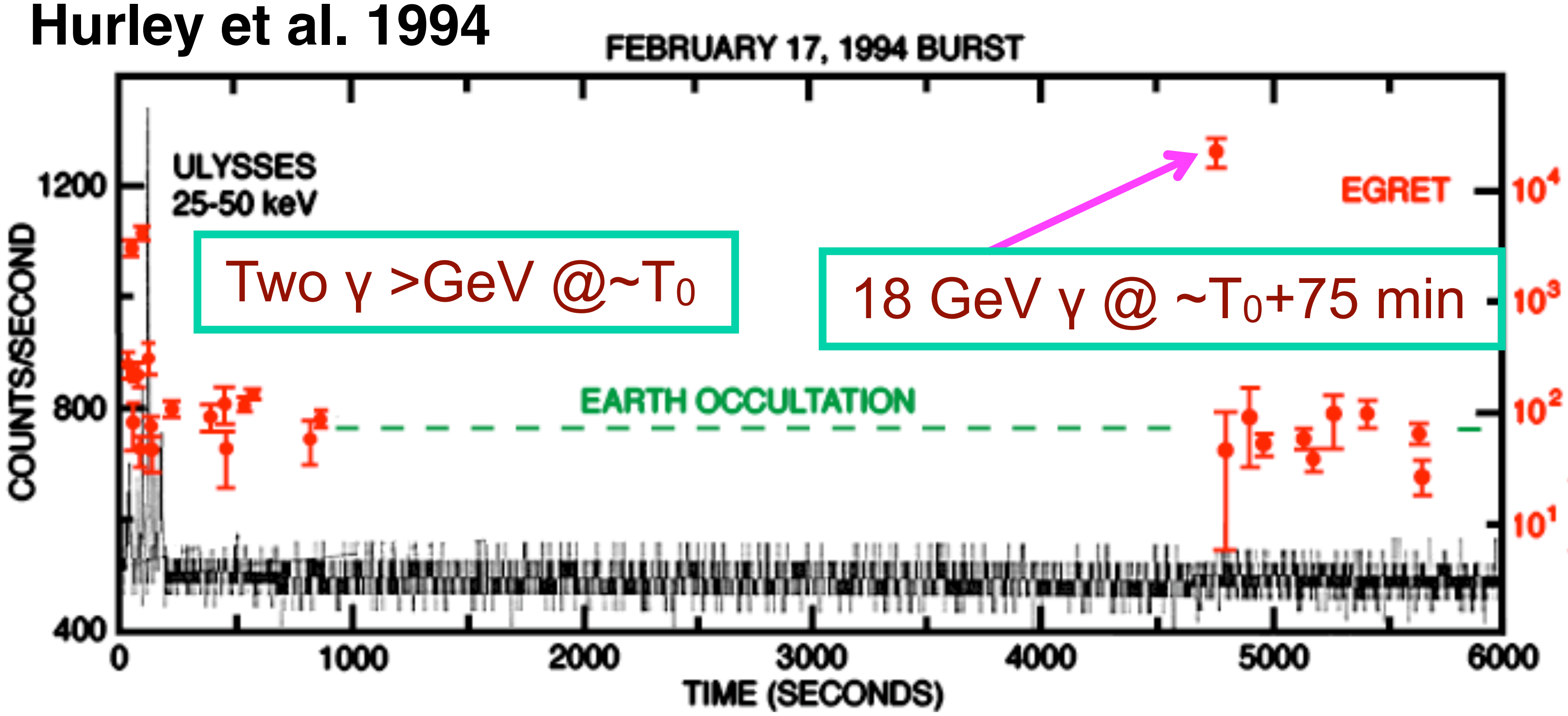
High-Energy Emissions from GRB (Past)

- **EGRET observations of delayed HE gamma-ray emissions**
  - It is not straightforward to explain by conventional electron synchrotron models
  - Proton acceleration? Origin of UHECR?

Gonzalez, Nature 2003 424, 749



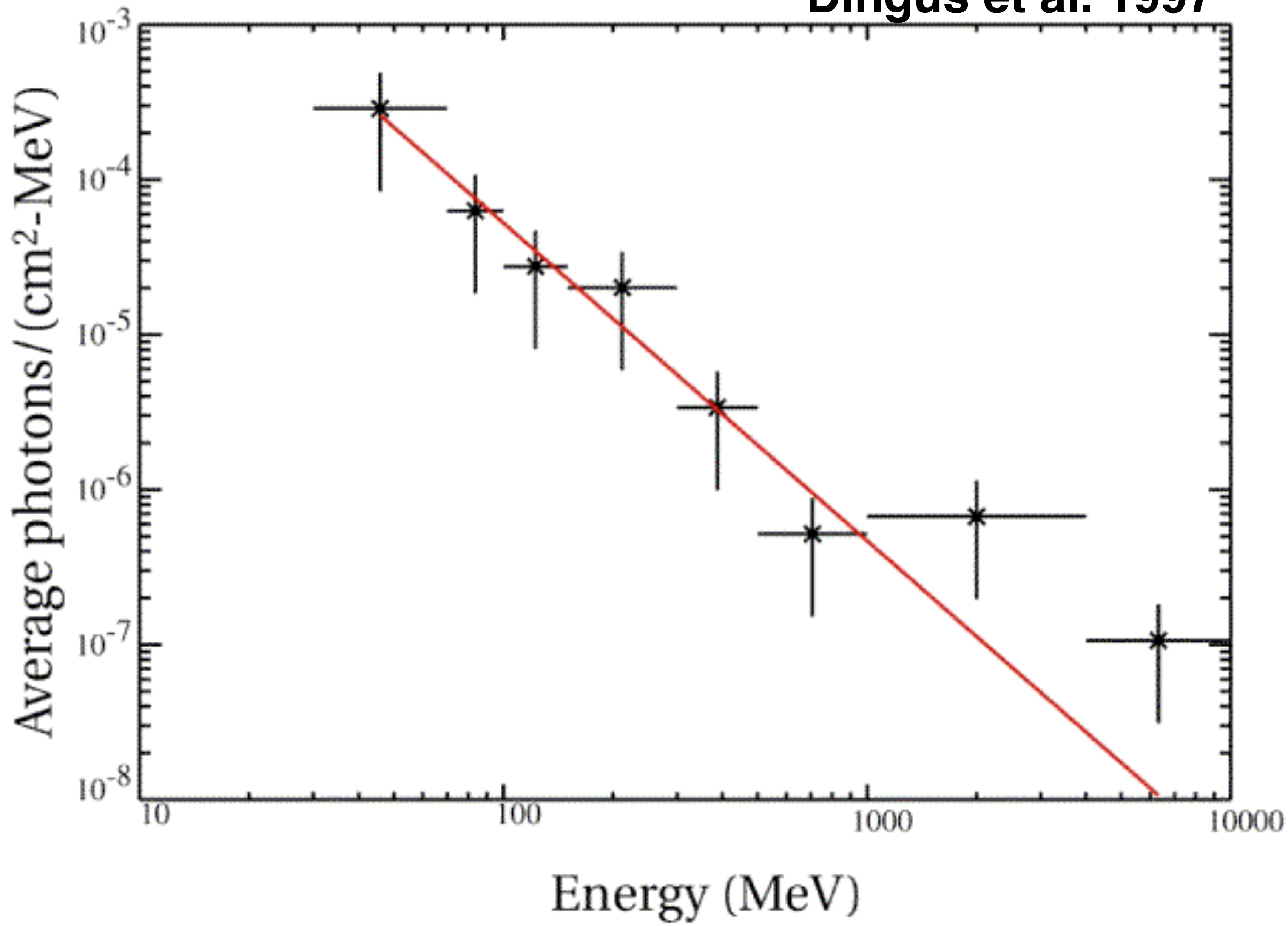
Hurley et al. 1994



EGRET High-Energy GRB Spectra

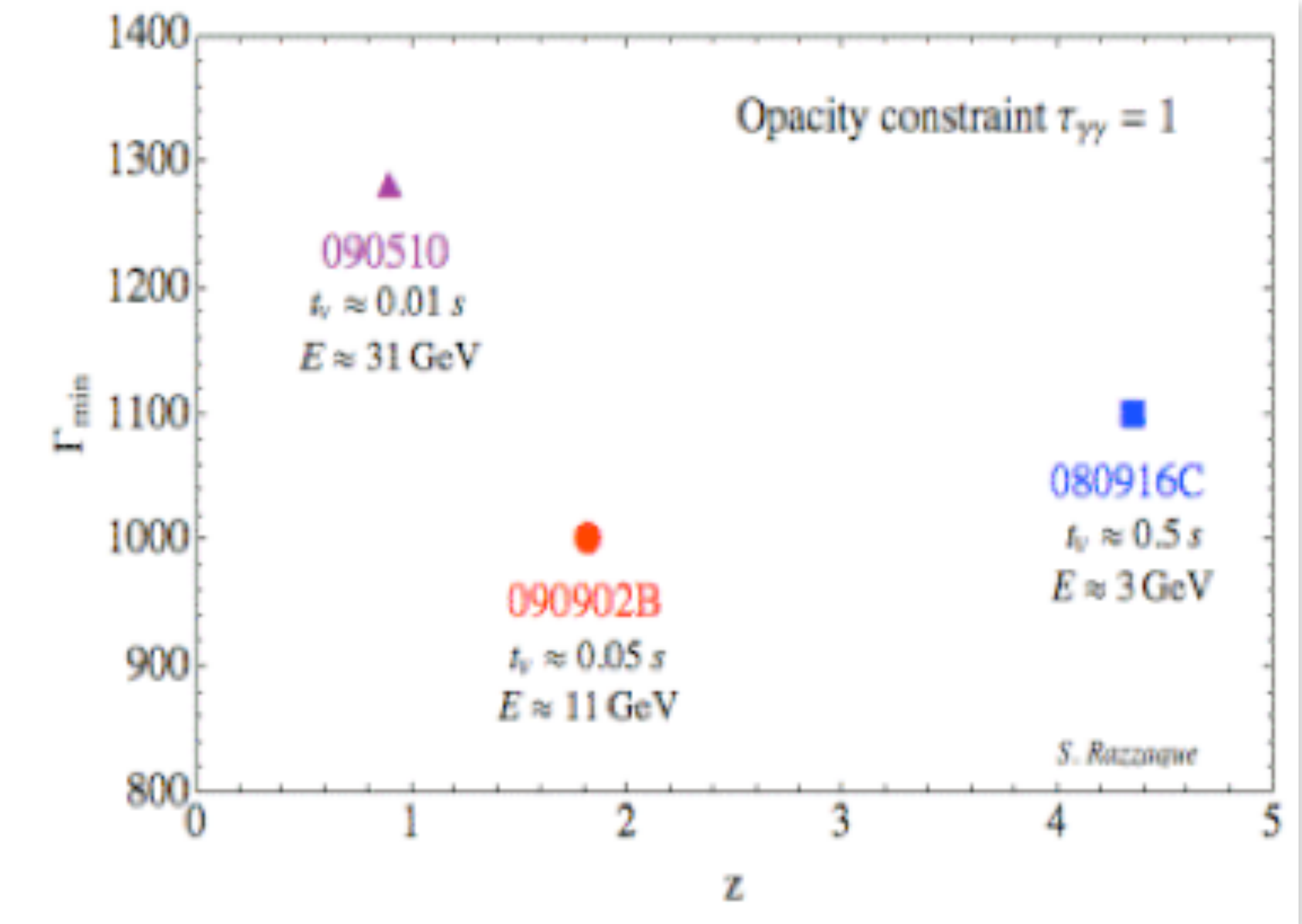
- 5 EGRET bursts with >50 MeV observations in 7 years
  - No evidence of cutoff or extra HE component in the summed spectrum

Dingus et al. 1997



Constraints on Bulk Lorentz Factor

- Large luminosity and short variability time imply large optical depth due to $\gamma\gamma \rightarrow e^+e^-$
  - Small emission region: $R \sim c\Delta t$
  - $\tau_{\gamma\gamma}(E) \sim (11/180)\sigma_T N_{>1/E}/4\pi R^2$
    - $\tau_{\gamma\gamma}$(1 GeV) ~ $7\mathrm{x}10^{11}$ for fluence=10^6 erg/cm^2, z=1, Δt=1 s
- Relativistic motion ($\Gamma \gg 1$) can reduce optical depth
  - Lager emission region: $R \sim \Gamma^2 c\Delta t$
  - Reduced # of target photons: $N_{>1/E} \propto \Gamma^{2\beta+2}$ (note: $\beta \sim -2.2$)
    - Blue shift of energy threshold: $E_{th} \propto \Gamma$
    - Blue shift of spectrum: $N(E) = (\Gamma E)^{\beta+1}$
  - Overall reduction of optical depth: $\Gamma^{2\beta-2} \sim \Gamma^{-6.4}$



Implications on Quantum Gravity

- **Lorentz invariance violation**
  - **Dispersion relation:**

$$\Delta t = \frac{(1+n)}{2H_0}\frac{(E_h^n - E_l^n)}{(M_{\mathrm{QG},n}c^2)^n}\int_0^z \frac{(1+z')^n}{\sqrt{\Omega_m(1+z')^3+\Omega_\Lambda}}\,dz'$$

- **GRB 080916C (z=4.35)**
  - **E_h ~ 13 GeV @ Δt~16.5 s**
    $\Rightarrow M_{\mathrm{QG},1}$ > 1.3 x 10^{18} GeV/c^2
- **GRB 090510 (z=0.903)**
  - **E_h ~ 31 GeV @ Δt~0.86 s**
    $\Rightarrow M_{\mathrm{QG},1}$ > 3.0 x 10^{19} GeV/c^2

GRB 090510