The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2246-27

Workshop on Cosmic Rays and Cosmic Neutrinos: Looking at the Neutrino Sky

20 - 24 June 2011

Fermi view of the gamma-ray sky and implications for ultrahigh-energy cosmic rays and neutrinos

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USA

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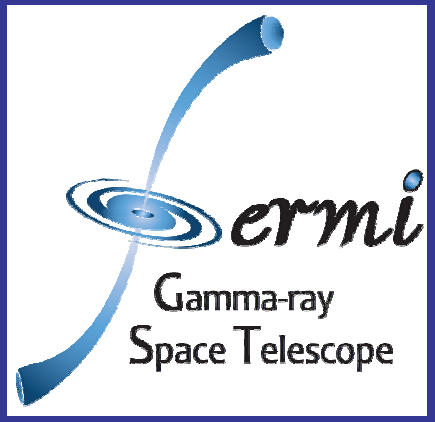
U.S. Naval Research Laboratory

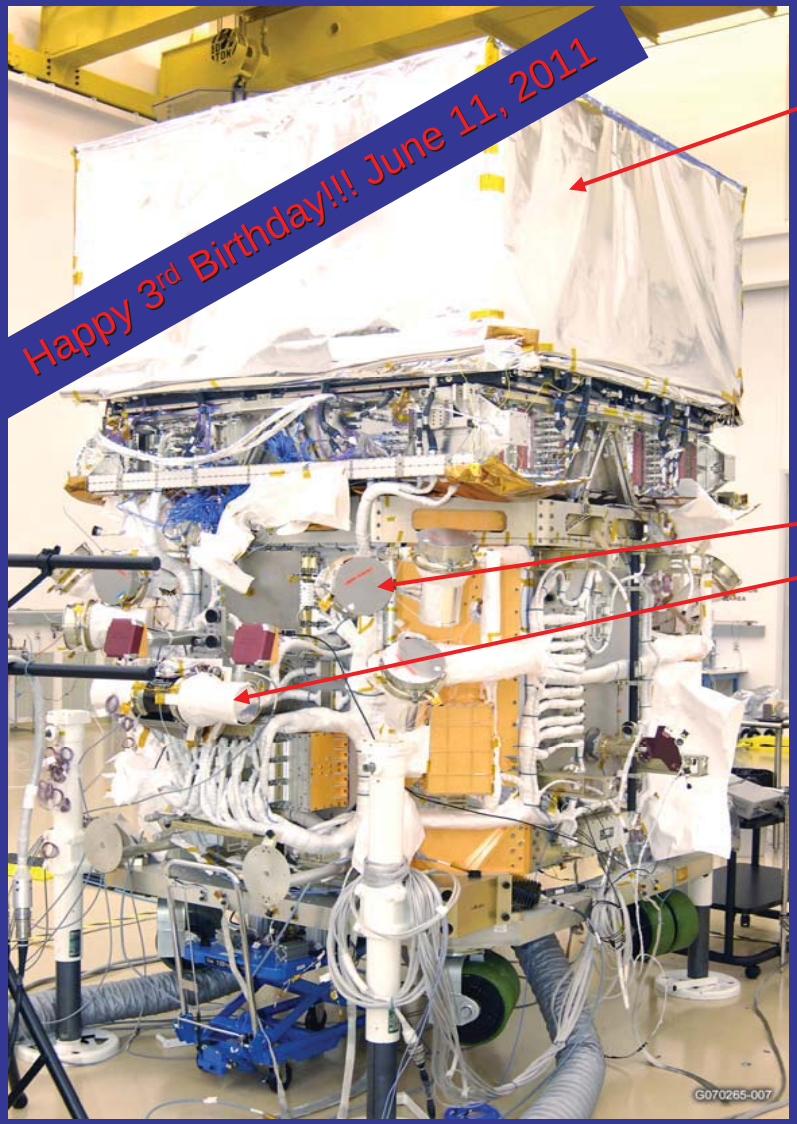


NUSKY 2011
20-24 June, Trieste, Italy

Talk Outline

- Selected (biased) view of *Fermi* gamma-ray sources which could be potential neutrino sources
  - Supernova remnants
  - Gamma Ray Bursts
  - Active Galactic Nuclei (Blazars)
- Will not present *Fermi* results on:
  - Gamma-ray Pulsars, recent Crab flare, starburst galaxies, radio-quiet AGNs, etc.
- Fermi diffuse emission results is covered by Vincenzo Vitale
- Gamma-ray dark sources are not covered
  - choked GRBs, jetted supernovae, etc.

Fermi Gamma Ray Space Telescope



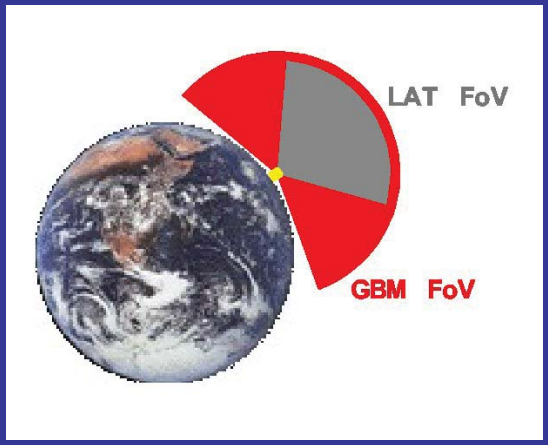
Large Area Telescope (LAT)

- Pair conversion detector
- Energy Range: 20 MeV to >300 GeV
- Effective Area: 9000 cm^2
- Field of View: 2 sr
- Angular resolution: <3.5° at >100 MeV

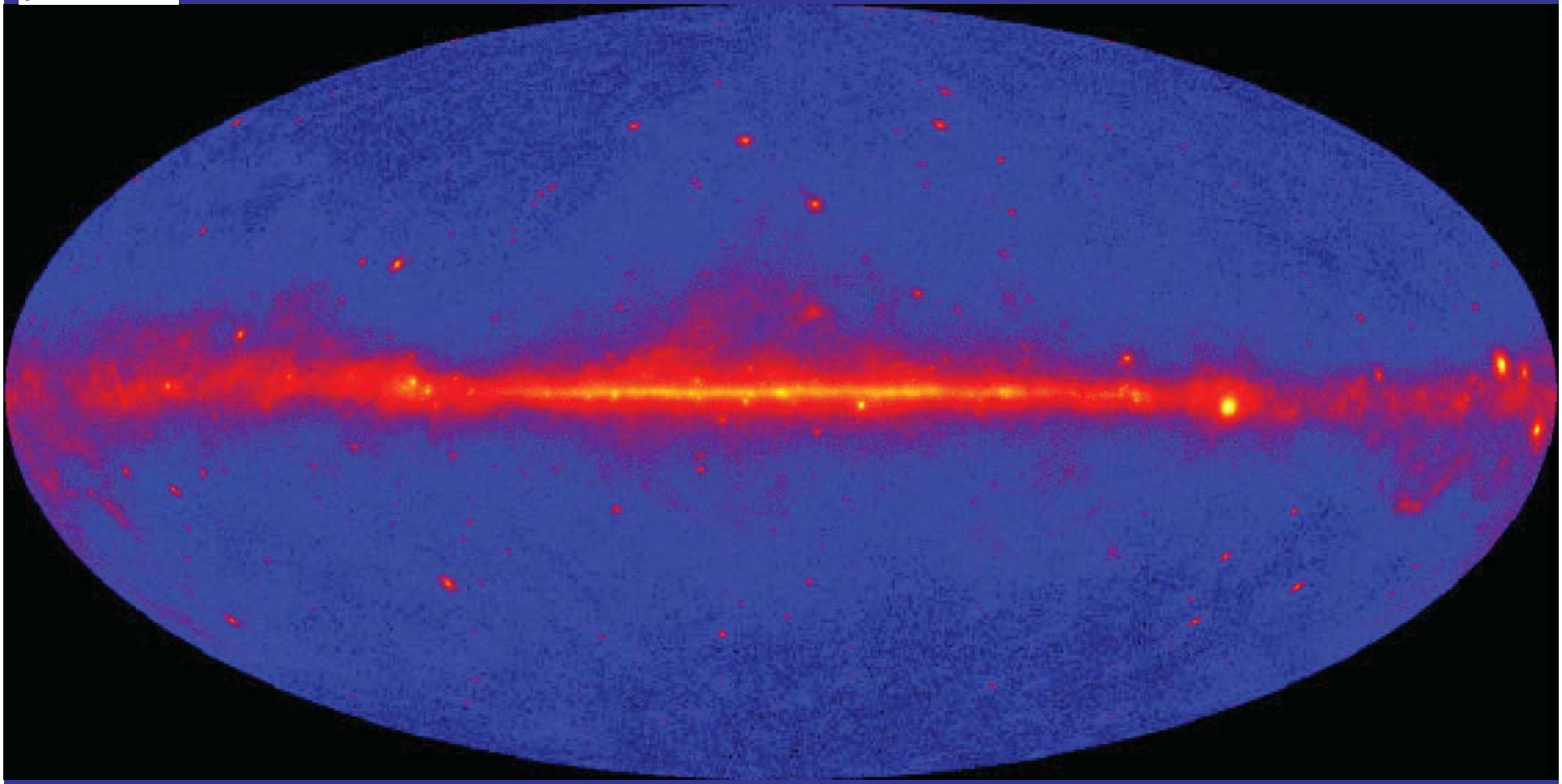
Gamma-ray Burst Monitor (GBM)

- 12 NaI detectors (8 keV - 1 MeV)
- 2 BGO detectors (150 keV - 30 MeV)
- Field of view: 8 sr

- Survey mode (3.5 hr full sky)
- Pointing mode
- Automatic pointing mode for GRBs



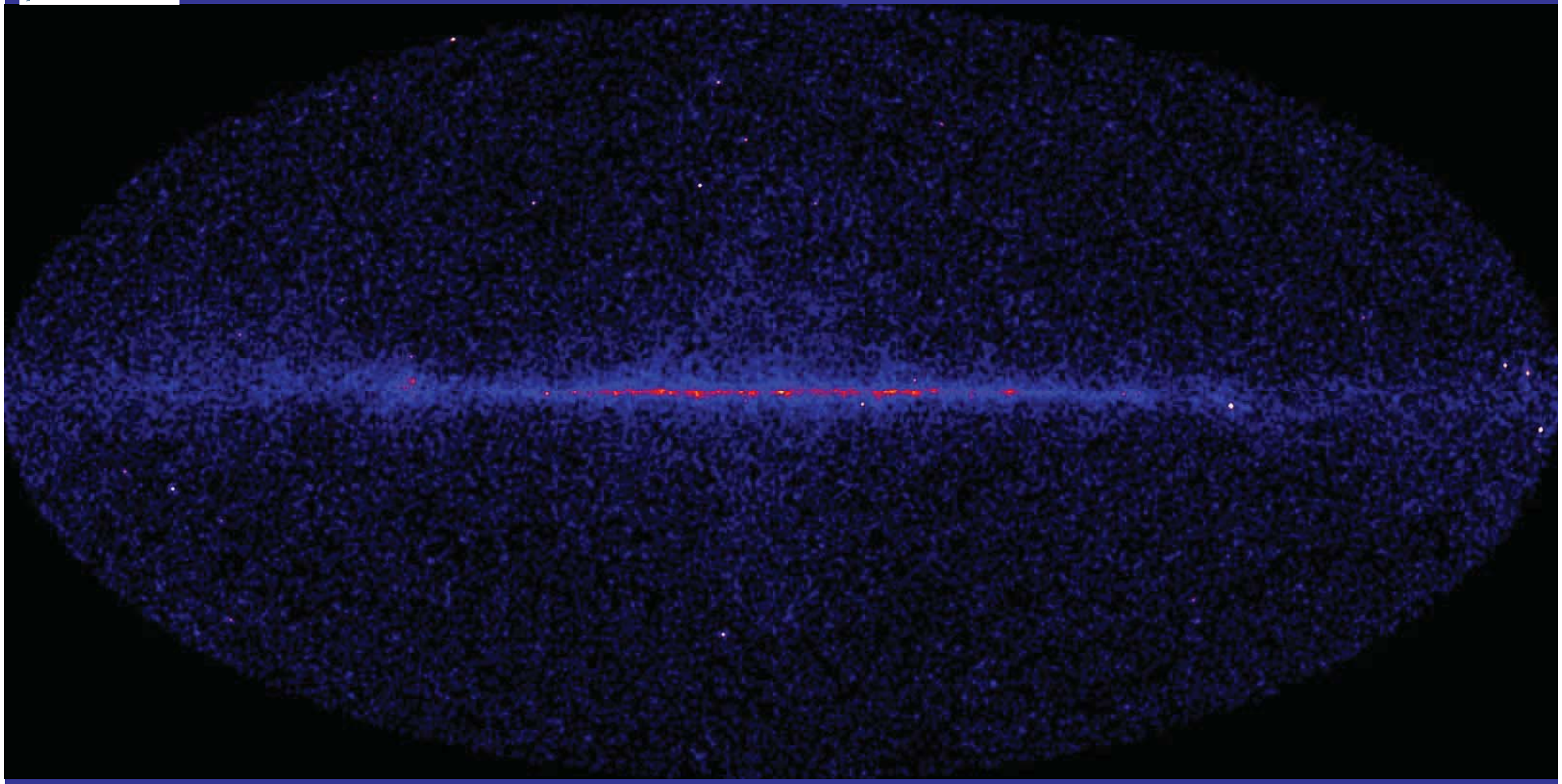
Fermi LAT Gamma Ray Sky Map



1 Year Fermi LAT data

>200 MeV front; >400 MeV back

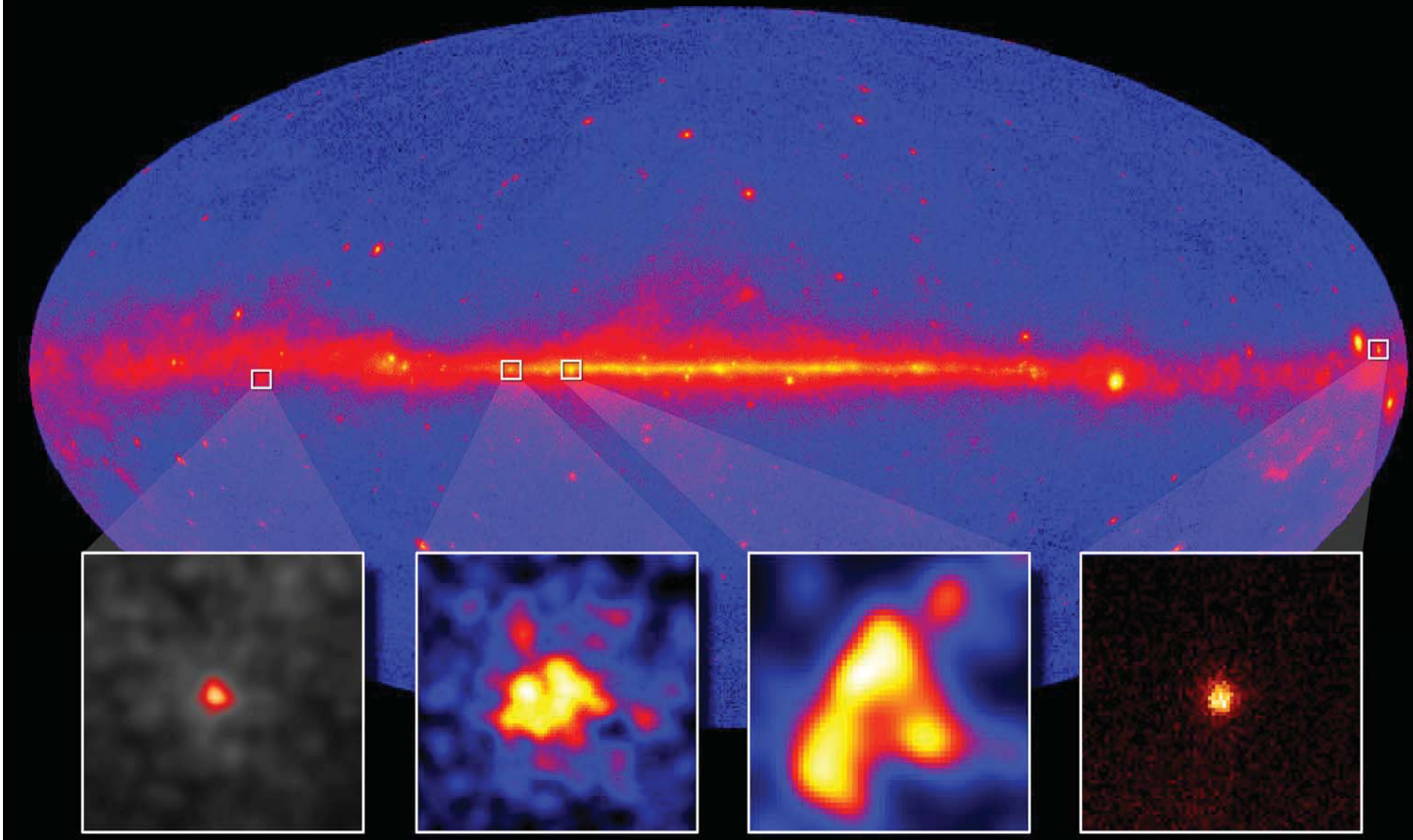
Fermi LAT Gamma Ray Sky Map



1 Year Fermi LAT data

10-100 GeV Preliminary

Fermi LAT view of Supernova Remnants



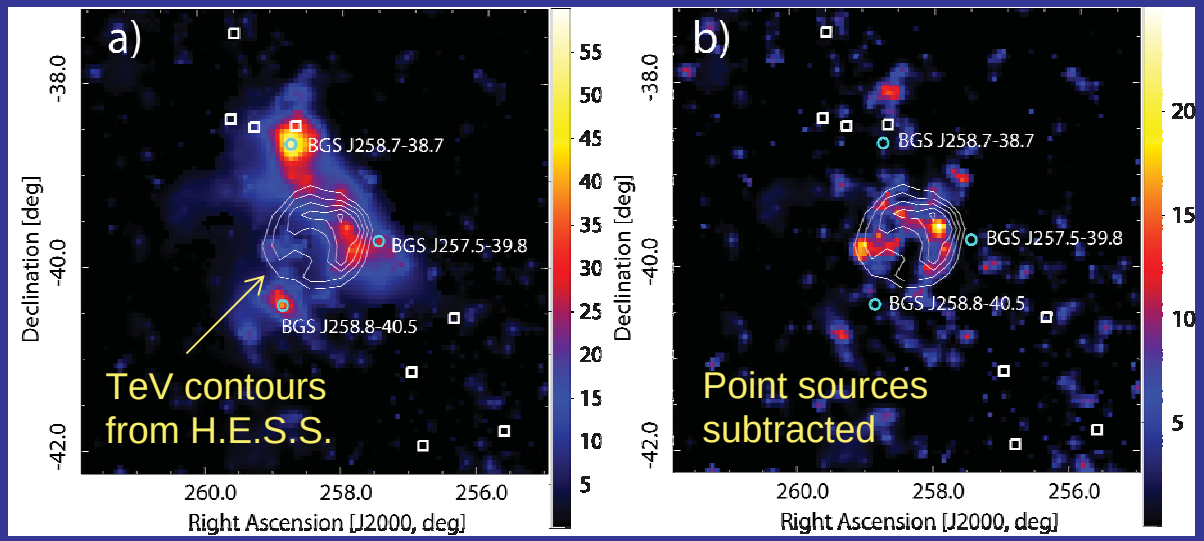
Fermi Gamma-ray Space Telescope

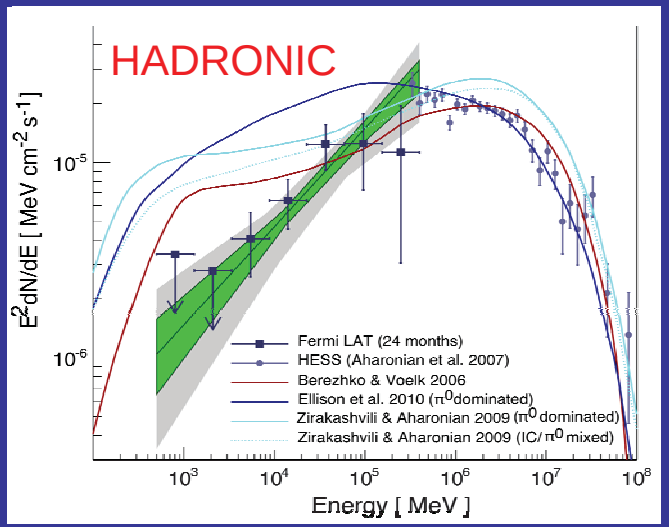
SNR RX J1713.7-3946

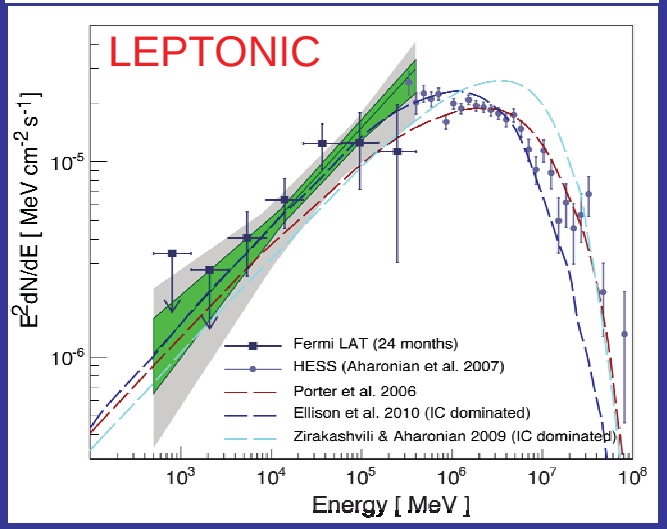
Young remnant: ~1600 yr at distance ~1 kpc
Bright TeV γ-ray source (HESS)

Very hard photon index:
$\Gamma_{LAT} = 1.5 \pm 0.1_{stat} \pm 0.1_{syst}$

LAT TS map >0.5 GeV *Abdo+ [Fermi Collab.] (in press)*







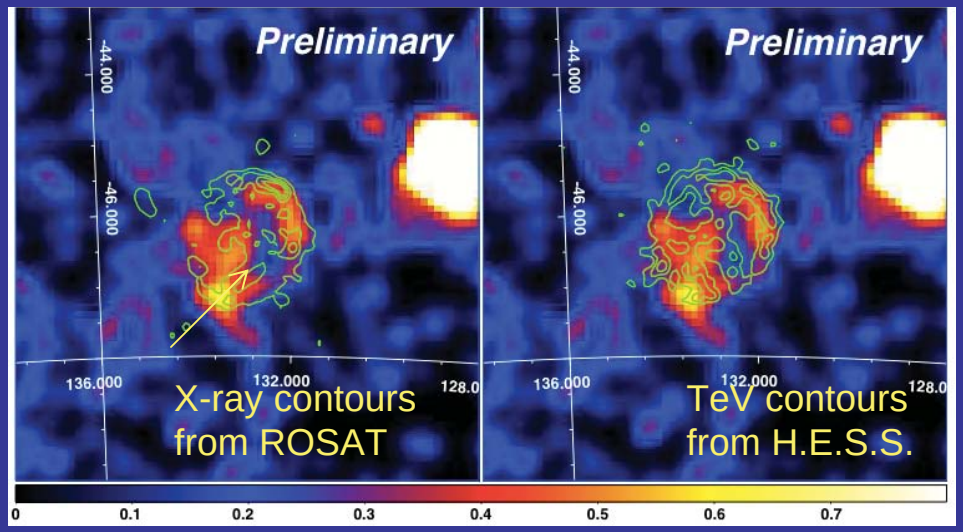
- Hadronic models (mostly π^0 decay) fail to fit LAT data
  - Contrary to previous expectations to be a ν source
- Leptonic models (mostly inverse Compton scattering) fit LAT+TeV data reasonably well
  - Required magnetic field 0.01 mG is smaller than ~0.1-1 mG from X-ray (*Uchiyama+ 2007*)

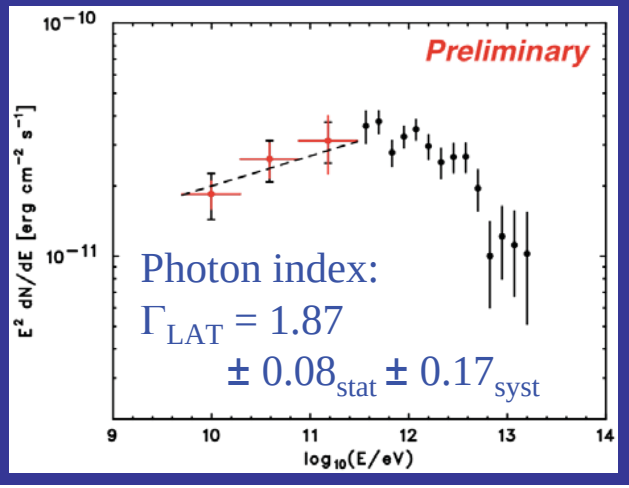
SNR RX J0852.0-4622 (Vela Jr)

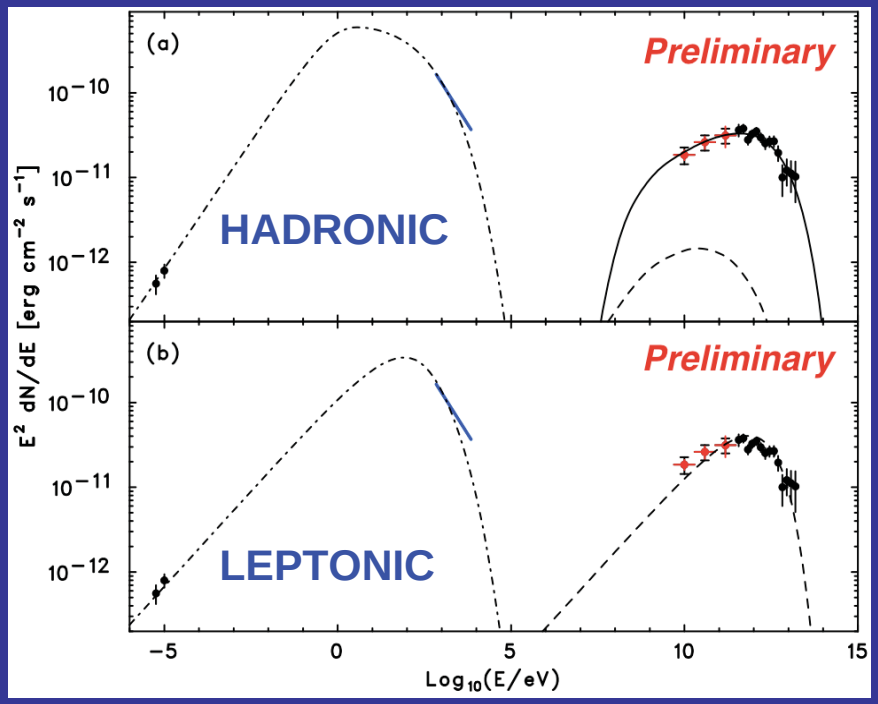
Young remnant: ~2000-4000 yr at distance ~0.75 kpc
Bright TeV γ-ray source (HESS)

LAT count map >10 GeV

Tanaka+ [Fermi Collab.] (in prep.)



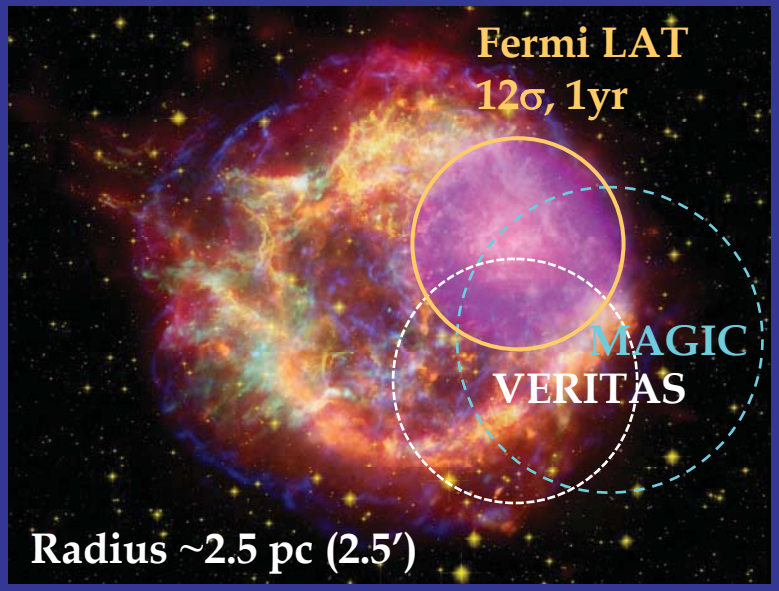


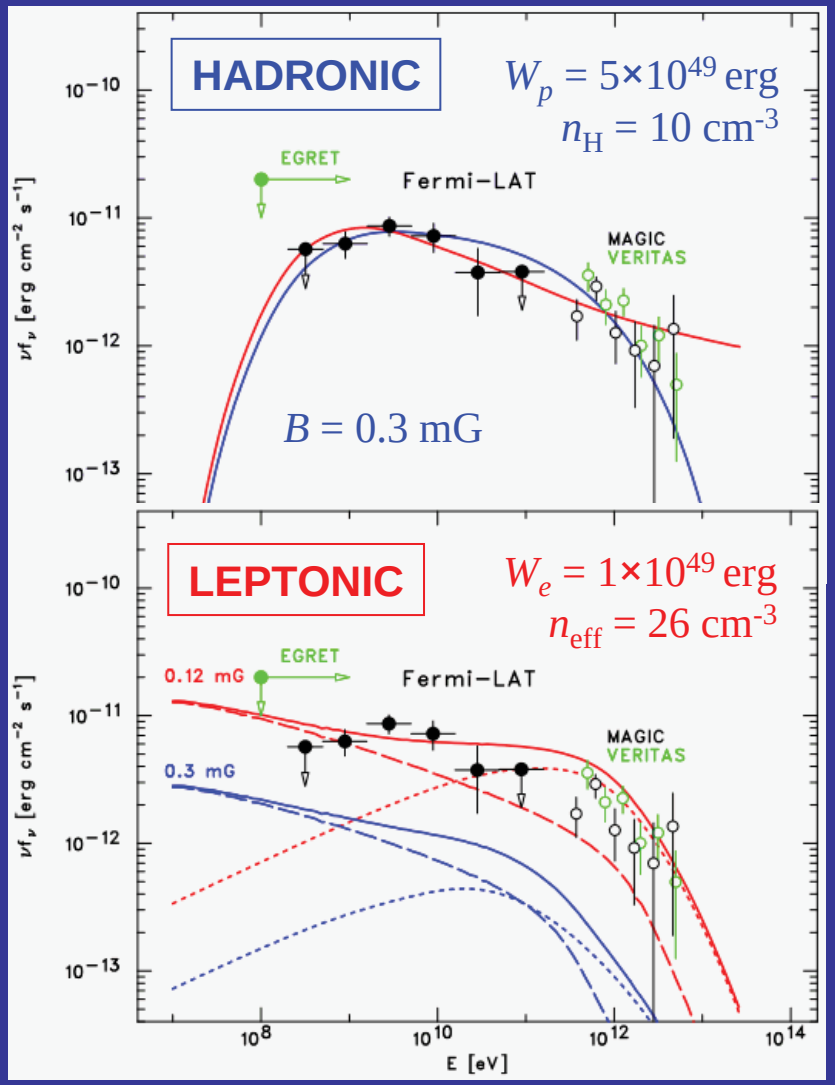


- Both Hadronic and Leptonic models fit spectra … But
  - Large 5×10^{50} erg energy in CRs is required in Hadronic model
  - In Leptonic model, required magnetic field 0.01 mG is smaller than ~0.1 mG from X-ray (*Berezhko+ 2009*)

SN 1680 (Cassiopeia A)

Very young remnant of historical type IIb SN: 331 yr at distance ~3.4 kpc





Very well-studied remnant by Chandra, Hubble, Spitzer telescopes

- Fermi LAT detection (*Abdo+ 2010*)
  - Photon index $\Gamma_{LAT} = 2.0 \pm 0.1$
- Faint TeV γ-ray source (VERITAS, MAGIC)
  - Flux (>1 TeV) ~ 3% of Cab

Likely in Sedov phase

B~0.1-0.5 mG in X-ray filaments (*Vink+Laming 03*)
(*Uchiyama+Aharonian 08*)

SN 1572 (Tycho's SN) – New!!

Very young remnant of historical type Ia SN: 439 yr at distance ~3 kpc

- Fermi LAT detection at 5σ
  - Photon index $\Gamma_{LAT} = 2.3 \pm 0.1$
- Dim TeV γ-ray source (VERITAS)
  - Flux (>1 TeV) ~ 1% of Cab
  - 5σ detection (2011)

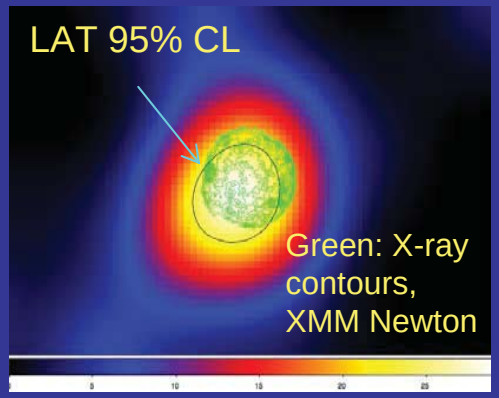
Well studied remnant in many wavelengths – helps model g-ray data

- Radius ~3.7 pc
- Reaching Sedov phase
- B~0.1-0.2 mG in X-ray filaments

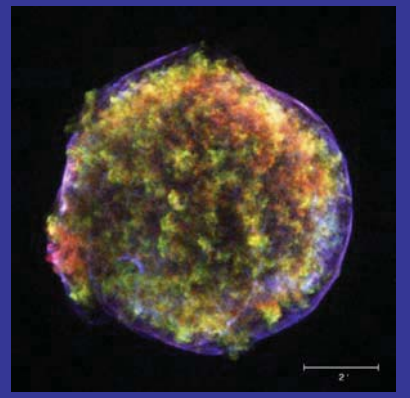
Hadronic model seem to explain multiwavelength data reasonably well

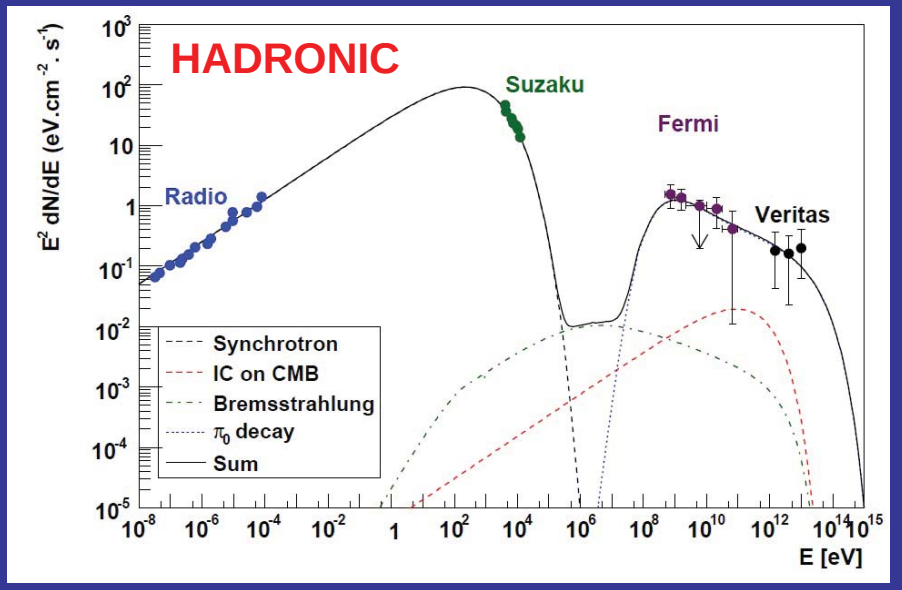
D (kpc)	N_H (cm^{-3})	E_{SN} (erg)	E_{CR} (erg)
3.50	0.24	2×10^{51}	1.50×10^{50}
2.78	0.30	1×10^{51}	0.61×10^{50}

LAT TS map >1 GeV



CHANDRA image

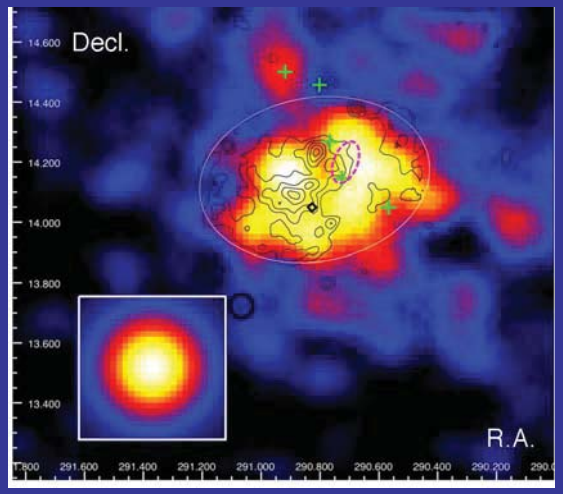


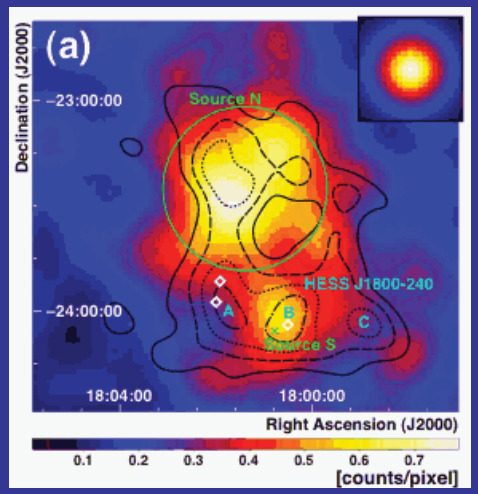


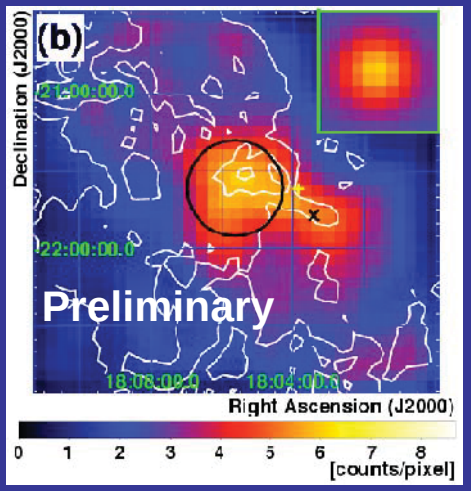
OLD SNRs: W51C, W44, IC443, etc.

Typical age: ~10,000 yr, often found interacting with Molecular Clouds

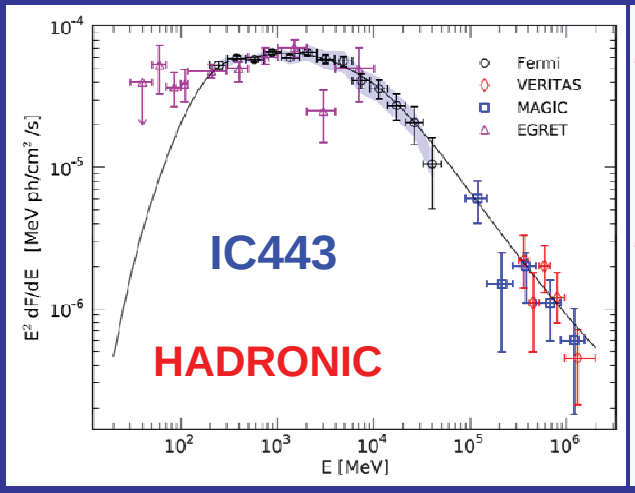
LAT count maps: W51C, W28, W30 (HESS J1804-216)

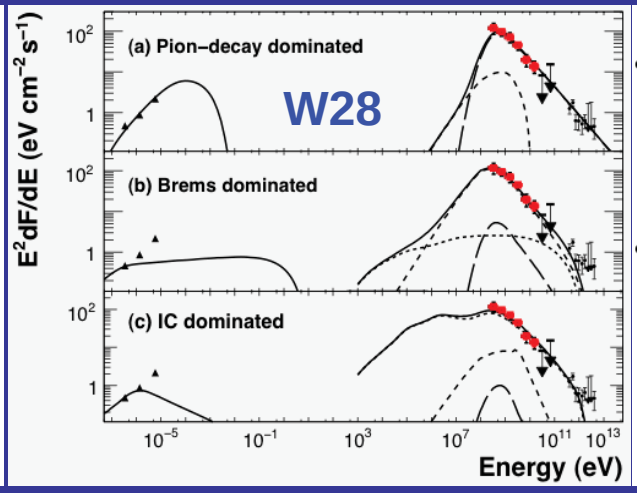


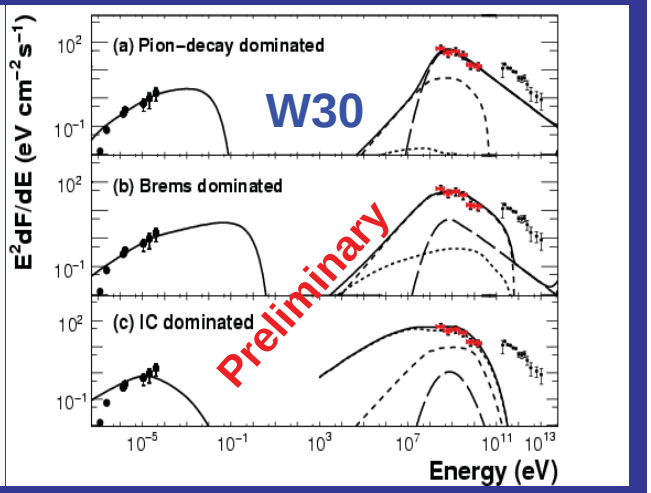




Hadronic models often works/favored, >TeV spectrum is very soft …







A Little Cousin of Supernovae

Surprising discovery of the first γ-ray nova by *Fermi* LAT on March 10, 2010

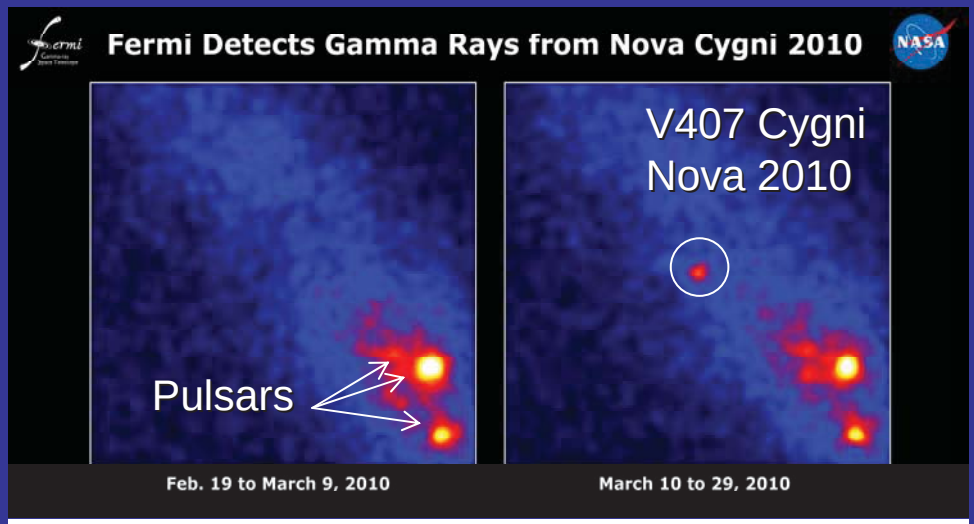
Announcement of optical detection by Nishiyama and Kabashima IAUC 2199 (2010) - Amateur astronomers

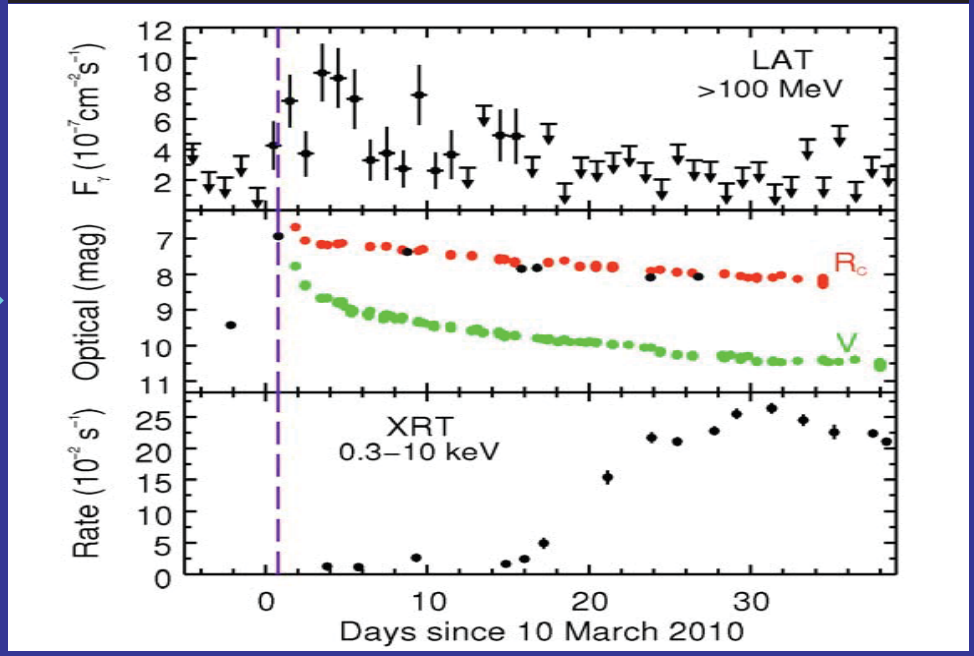
V407 Cygni Symbiotic binary system (2.7 kpc):
Mira-type pulsating star, most probably in its AGB phase
($M \sim$ few $M_\odot$, $R \sim 500\ R_\odot$)

Multi-wavelength light curves

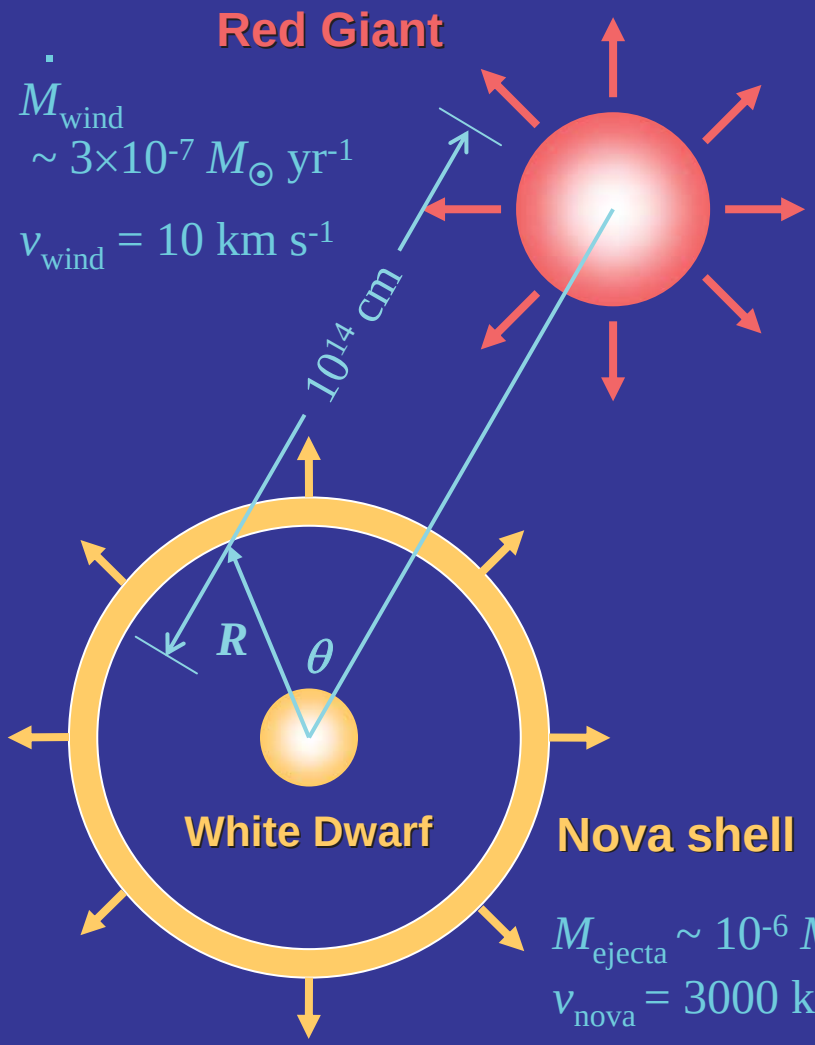
[Fermi Collab.] Abdo+2010

A *Nova* is a thermonuclear explosion on a white dwarf (WD) surface fueled by mass accreted from a companion star in a binary systems.

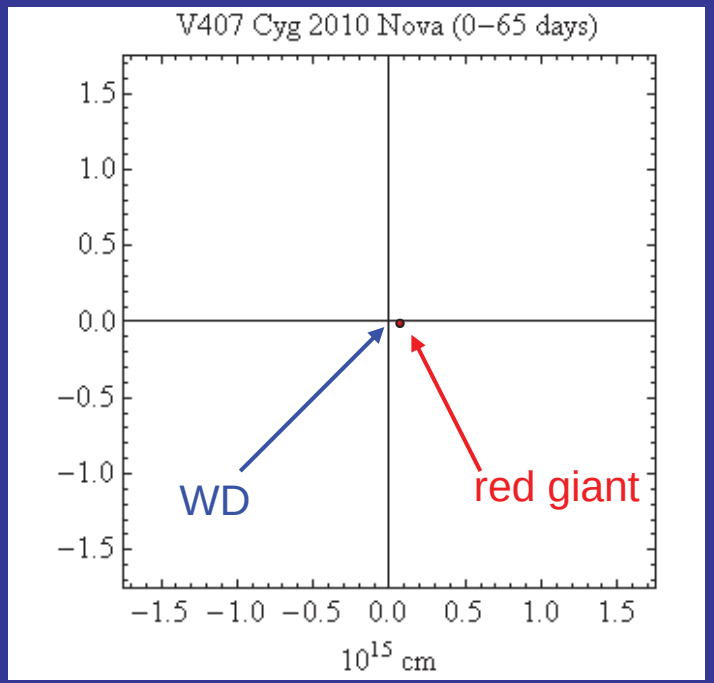




Gamma Ray Nova Model



Rapidly expanding nova shell in a dense circum-burst medium can produce shock and particles can accelerate in the shock, and interact to produce gamma rays



X-ray emission: Thermal bremsstrahlung from shock-heated gas

γ Ray Emission model (V407 Cyg)

Hadronic & leptonic models for *g* ray spectrum are statistically equivalent

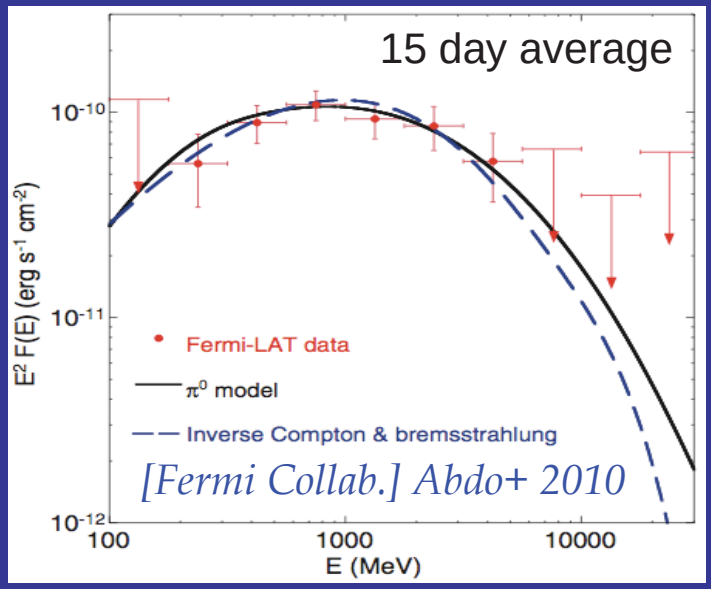
- π^0 decay: accelerated p's collide with ambient wind material from the Red Giant
- Inverse Compton: accelerated electrons up-scattering infrared photons from the Red Giant

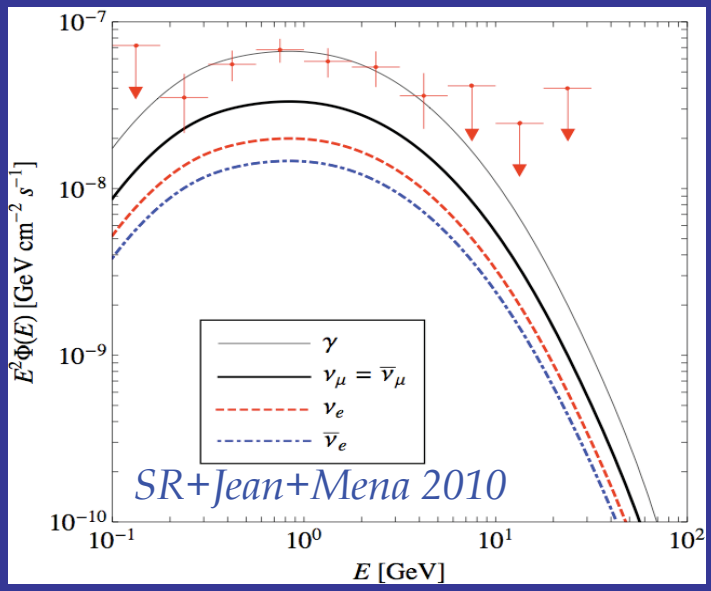
Kinetic energy of the nova shell ~10^{44} erg
Total energy in γ ray transient ~4×10^{41} erg
- Hadronic model ~9% of K.E.
- Leptonic model ~0.4% of K.E.

Expected ν fluxes of different flavors can be calculated using observed γ ray flux

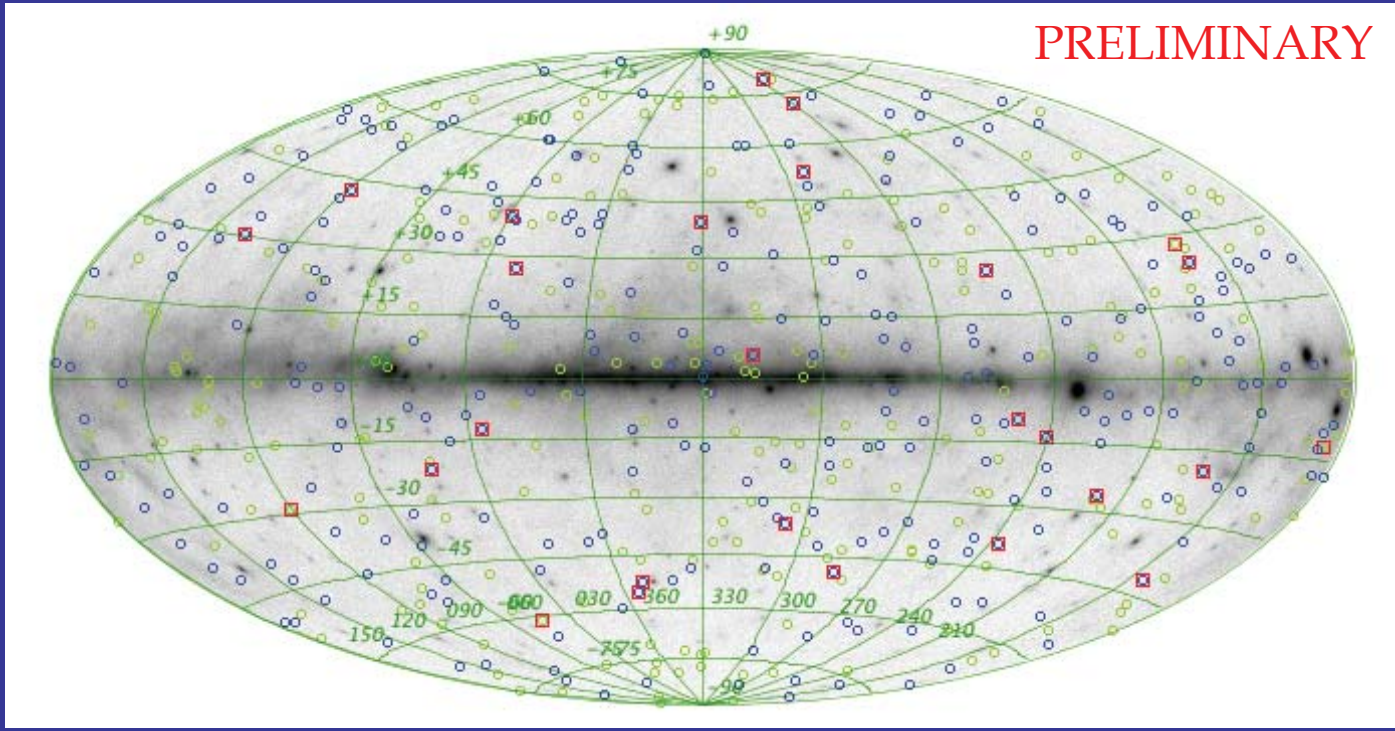
≥10 GeV ν fluence from the nova~10^{-4} erg cm^{-2}
≥100 MeV γ ray fluence ~3×10^{-3} erg cm^{-2}

Targets for future detectors with low threshold and high sensitivity





Fermi view of Gamma Ray Bursts



11 months Fermi LAT count map

- 530 GBM GRBs (since Aug 2008)
- 22 LAT GRBs (>100 MeV, TS > 16)
- 5 LAT LLE-only GRBs

Blue circles: In Field-of-view of LAT (<70˚): 275
Green circles: Out of the LAT FOV
Red squares: LAT detections

Delayed Onset of LAT Emission

GRB 080916C Multi band Light Curves

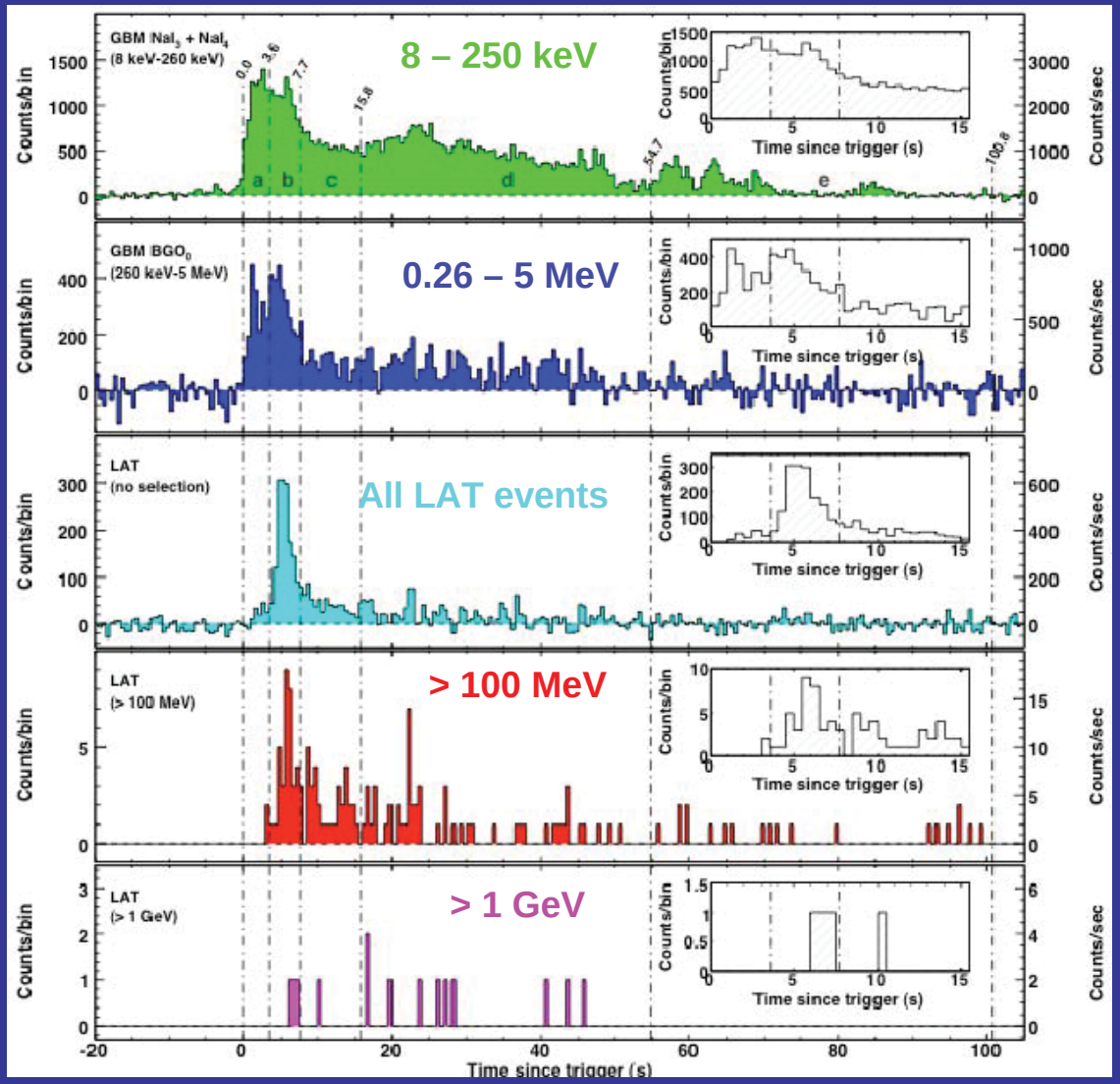
No significant emission in the LAT energy range for the first ~4 s

1st >100 MeV at ~4s

1st >1 GeV at ~6s.

Delayed >100 MeV emission is common in most other bright LAT GRBs as well

[Fermi Collab.] Abdo+2009

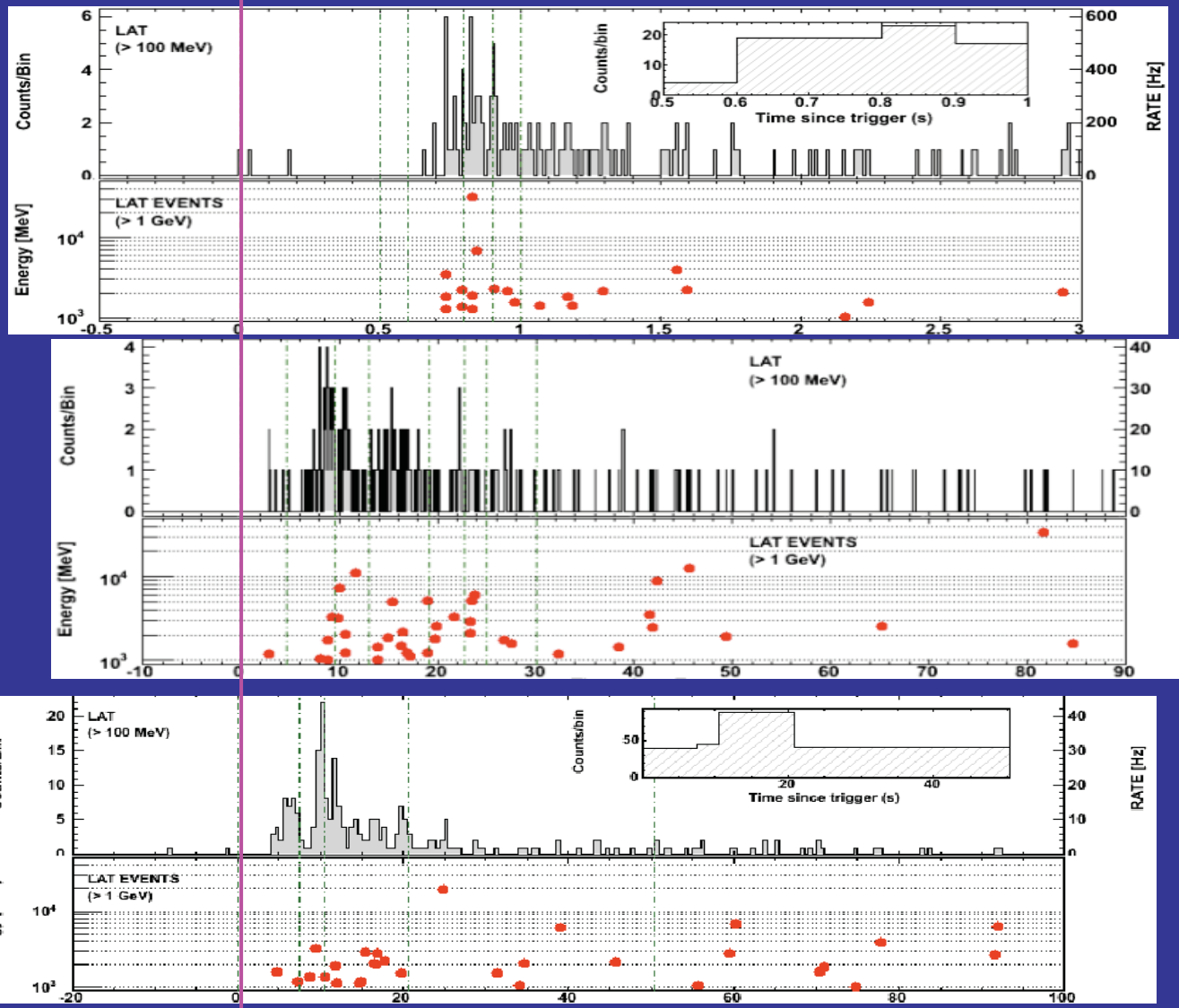


Delayed LAT onset in other GRBs

090510 (short)

090902B (long)

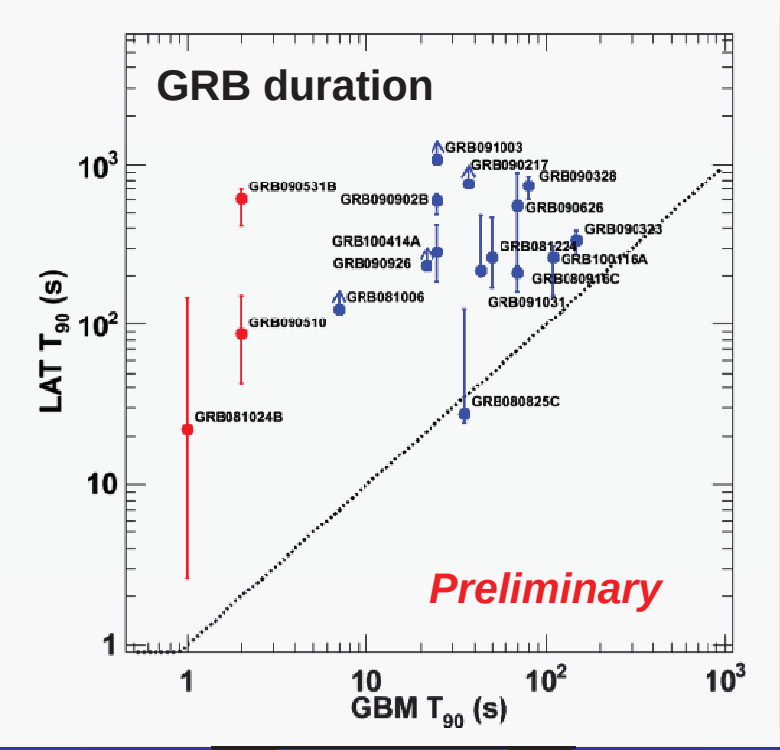
090926A (long)

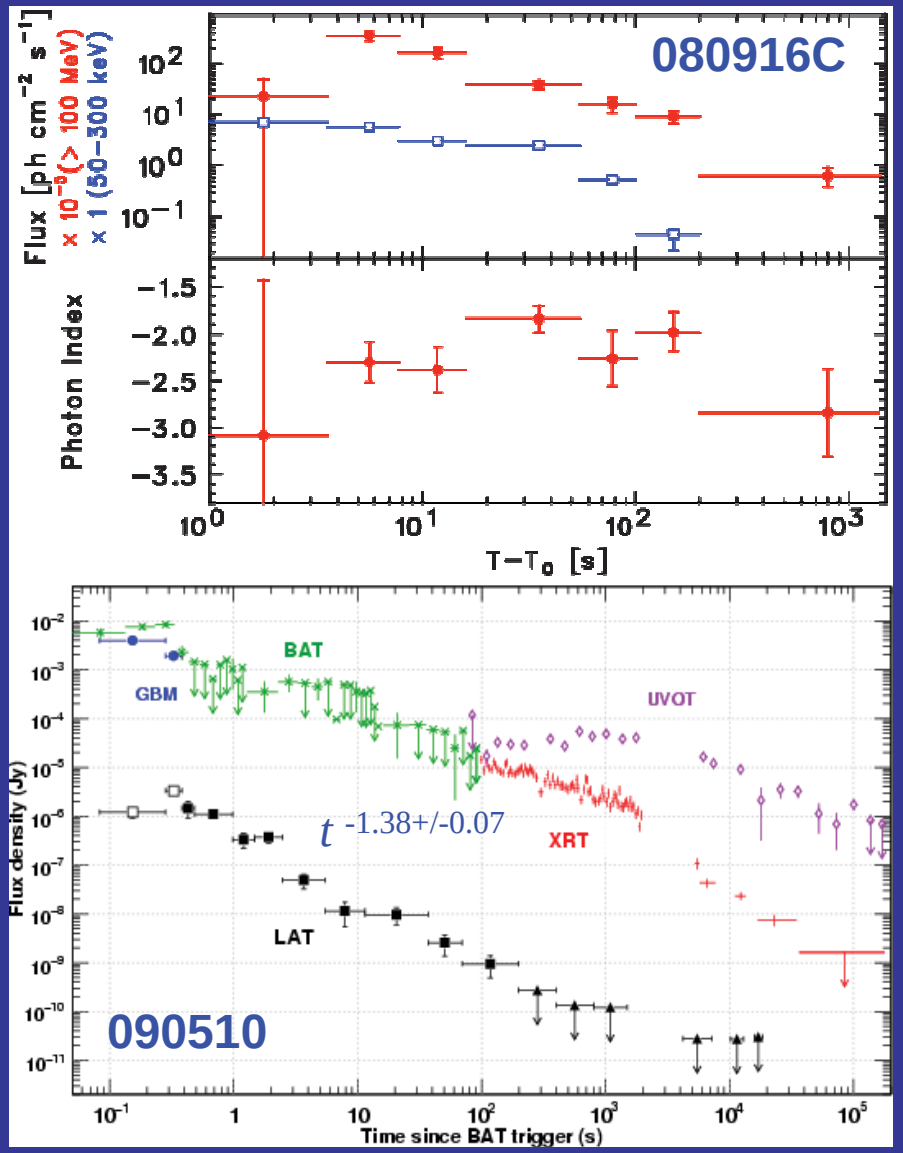


Extended LAT Emission

Bright LAT GRBs show significant high energy emission extending after the low energy emission disappears below detectability

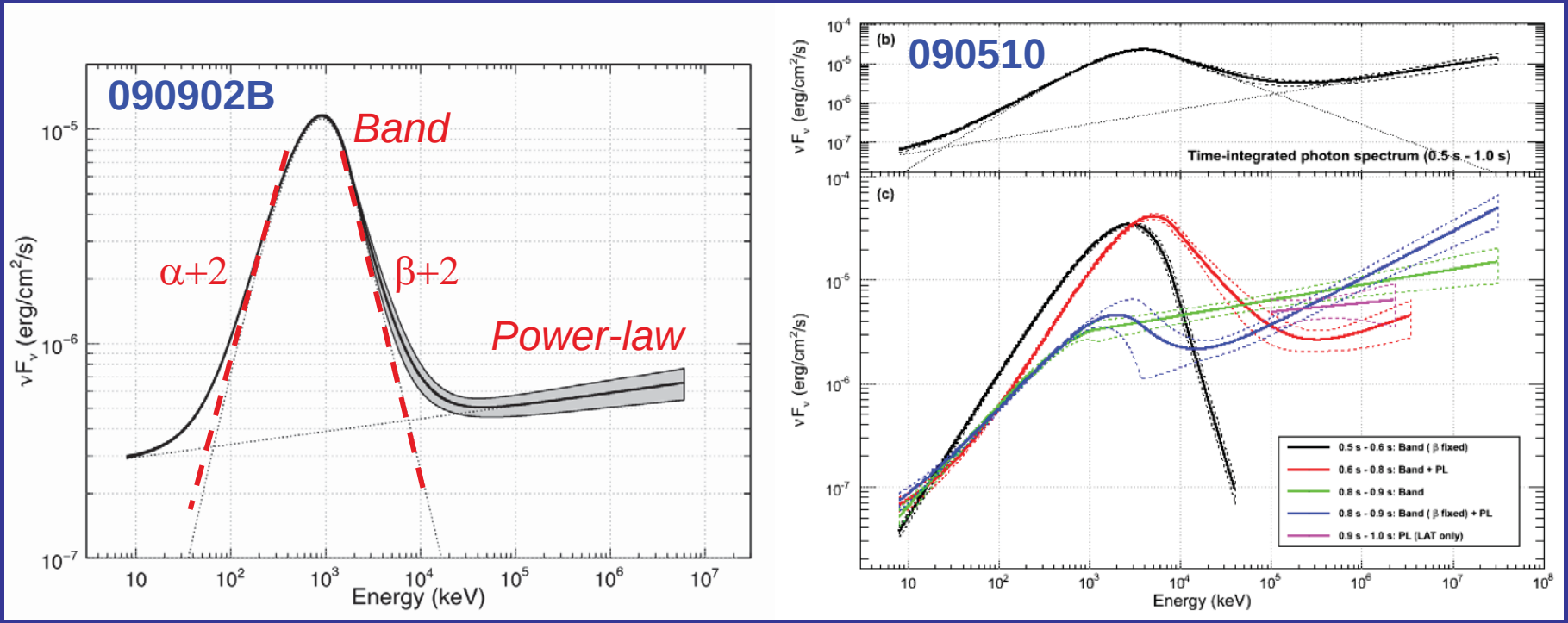
LAT emission is systematically longer …





Hard Power Law Component

Time-integrated and time-resolved spectroscopy of 2 bright LAT GRBs



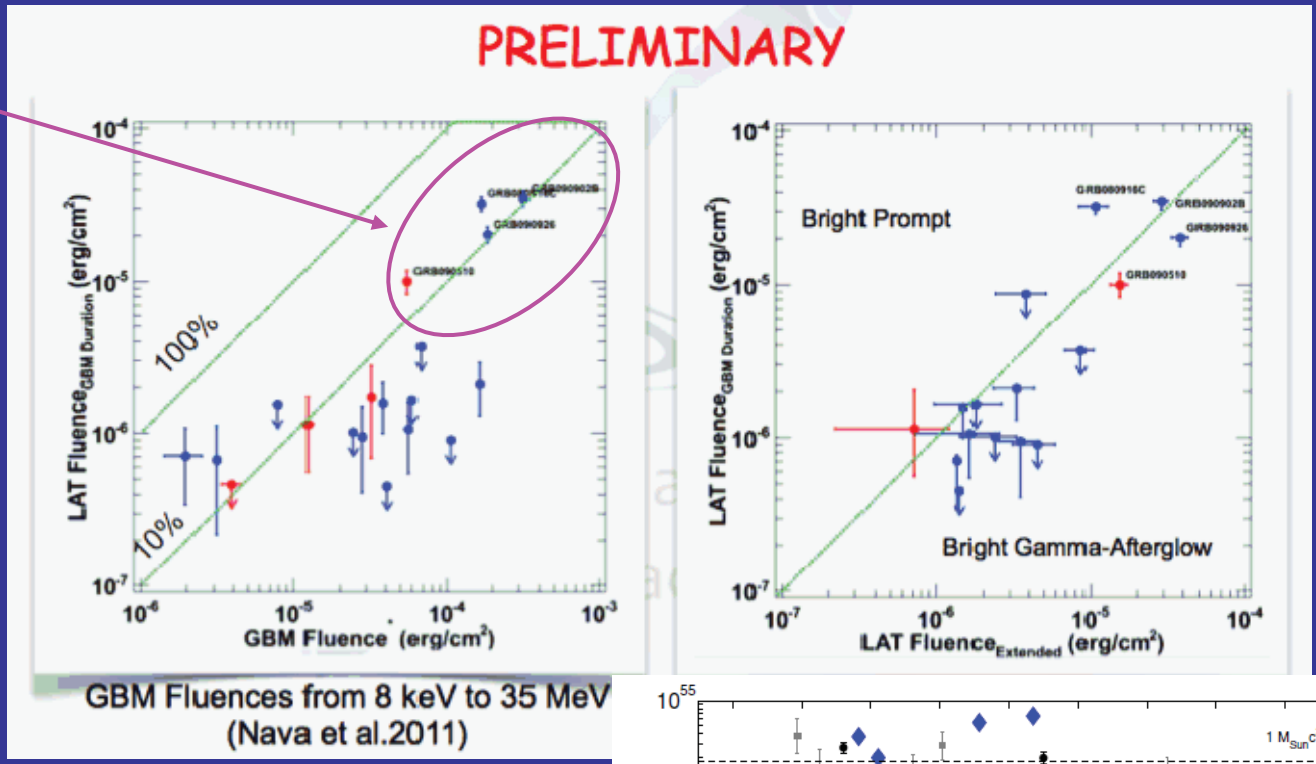
- Phenomenological Band function (2 smoothly connected power laws, 4 parameters) fit ~100 keV - few MeV data well
- Extra power-law component (2 parameters) is required to fit >100 MeV LAT emission and below ~100 keV in some cases

Which γ's carry the most energy?

Exceptionally high fluence in LAT! Fantastic 4!! (N. Omodei)

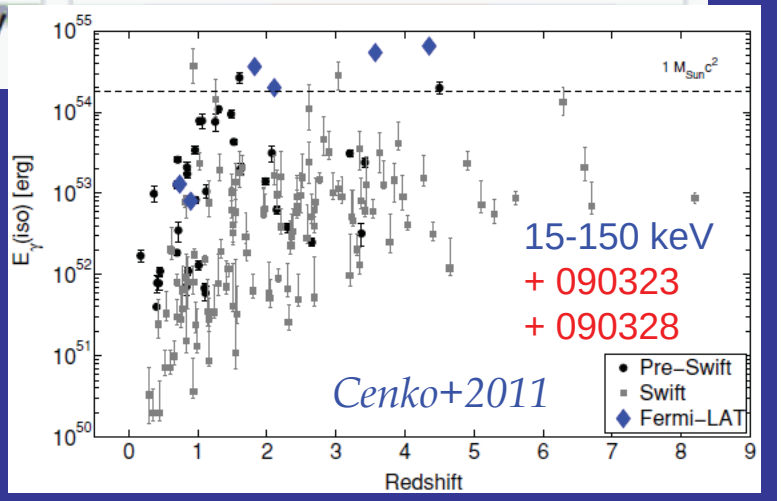
But these are not the nearest GRBs, neither are they dim at >10 GeV

➡ Most energetic class of GRBs



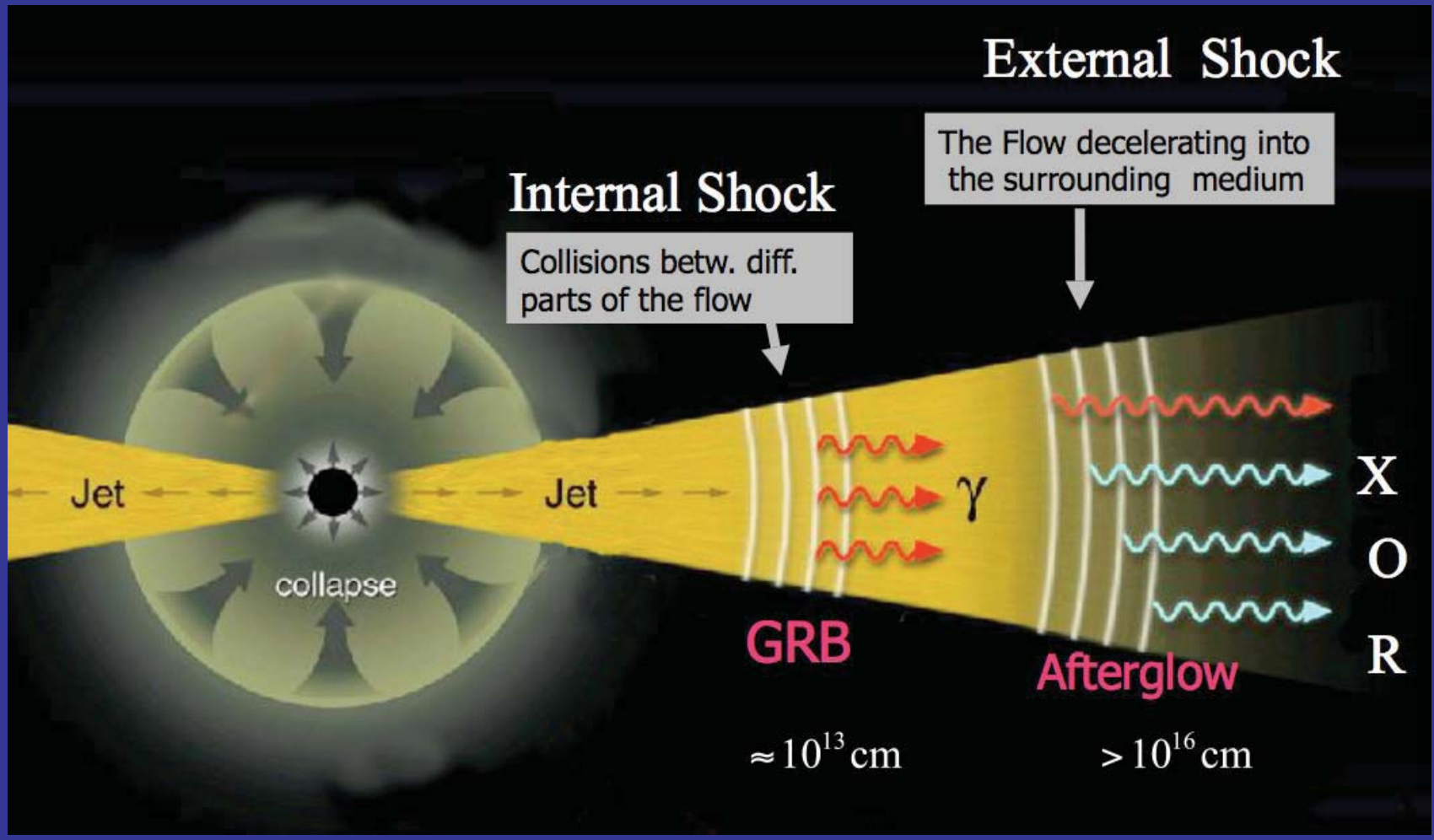
GRB	z	E_{max} (GeV)	L_γ (erg/s)
080916C	4.3	13	~ 2×10^{53}
090902B	1.8	33	~ 2×10^{53}
090510	0.9	31	~ 3×10^{53}
090926A	2.1	20	~ 1×10^{53}

➡



GRB Jet and Emission Model

The *"standard GRB model"* long-duration (>2 s) GRBs



Synchrotron emission by shocked electrons for prompt and afterglow emission

Jet Velocity: Bulk Lorentz Factor

Very high jet bulk Lorentz factor

Calculated from $\gamma\gamma \rightarrow e^+e^-$ pair production opacity argument ($\tau_{\gamma\gamma} = 1$) for ≥10 GeV source photons (co-spatial with keV-MeV photons) from GRBs detected with Fermi LAT

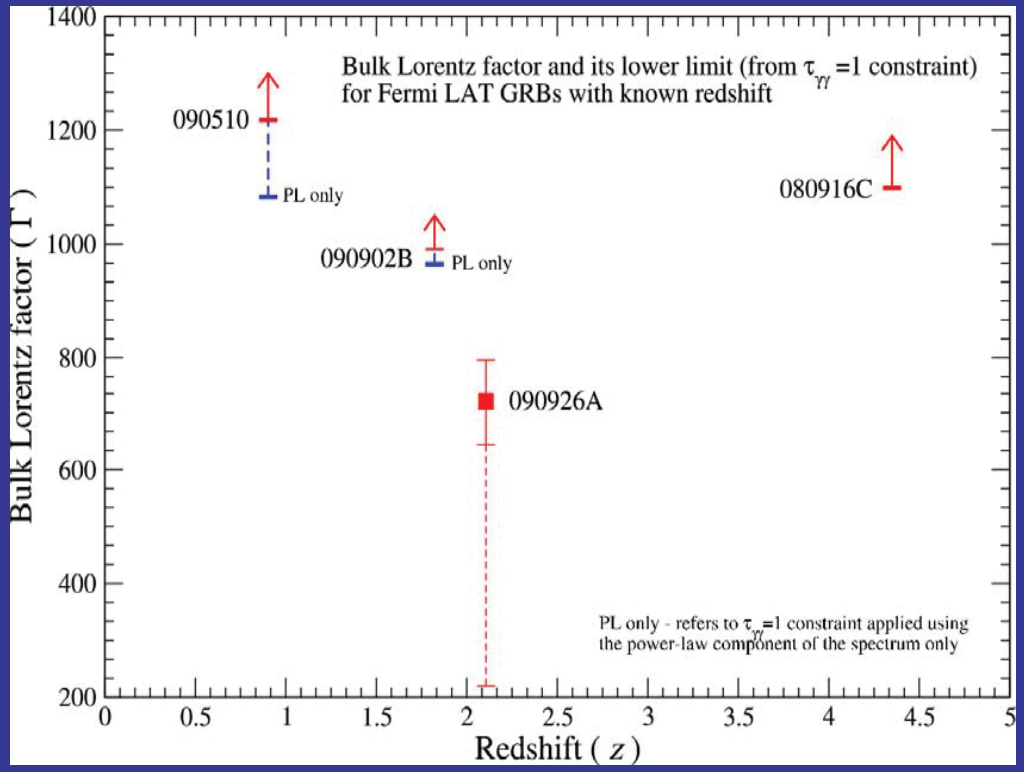
Some caveats

- The PL component may Originate from physically Separate region
- Radiation transport effect

Both lead to lower Γ by a factor ~2

Calculation of Γ from the onset of afterglow also results in high values, >1000

Minimum jet bulk Lorentz factors of bright Fermi LAT GRBs



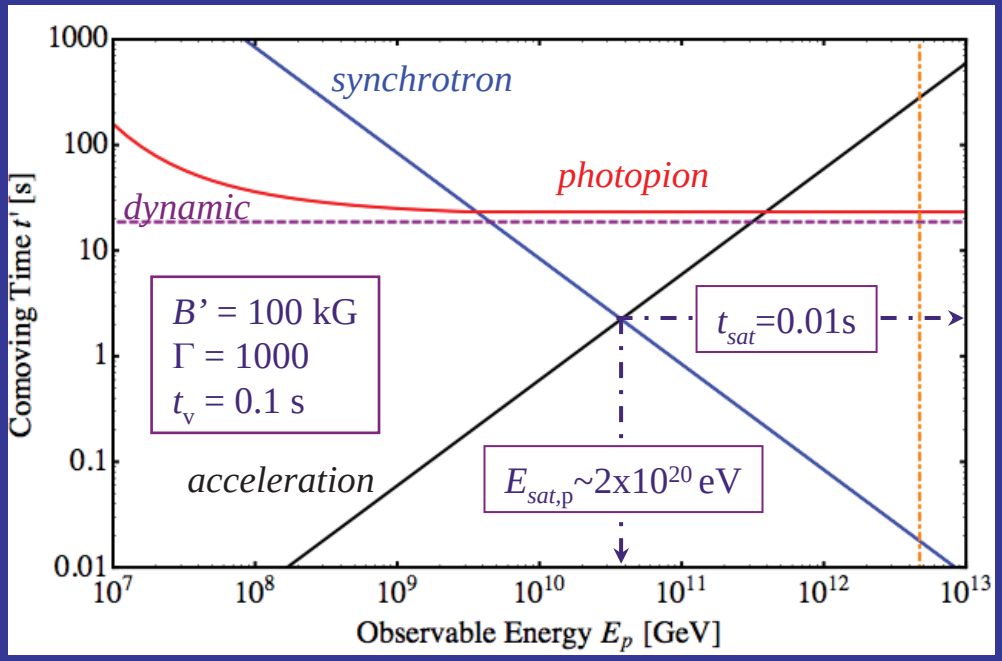
$$\tau_{\gamma\gamma}(E) = \frac{3}{4}\frac{\sigma_T d_L^2}{t_v \Gamma}\frac{m_e^4 c^6}{E^2(1+z)^3}\int_{\frac{m_e^2 c^4 \Gamma}{E(1+z)}}^{\infty}\frac{d\epsilon'}{\epsilon'^2}\, n\left(\frac{\epsilon'\Gamma}{1+z}\right)\varphi\left[\frac{\epsilon' E(1+z)}{\Gamma}\right]$$

UHECR Signature in GRB Emission

UHECR acceleration in magnetic field and its interactions may provide γ ray signature from GRBs, specially in *Fermi* LAT

- *proton-synchrotron radiation and associated e^+e^- cascade radiation*
- *Photohadronic interactions with observed keV - MeV γ rays and cascade emission*

GRB 080916C

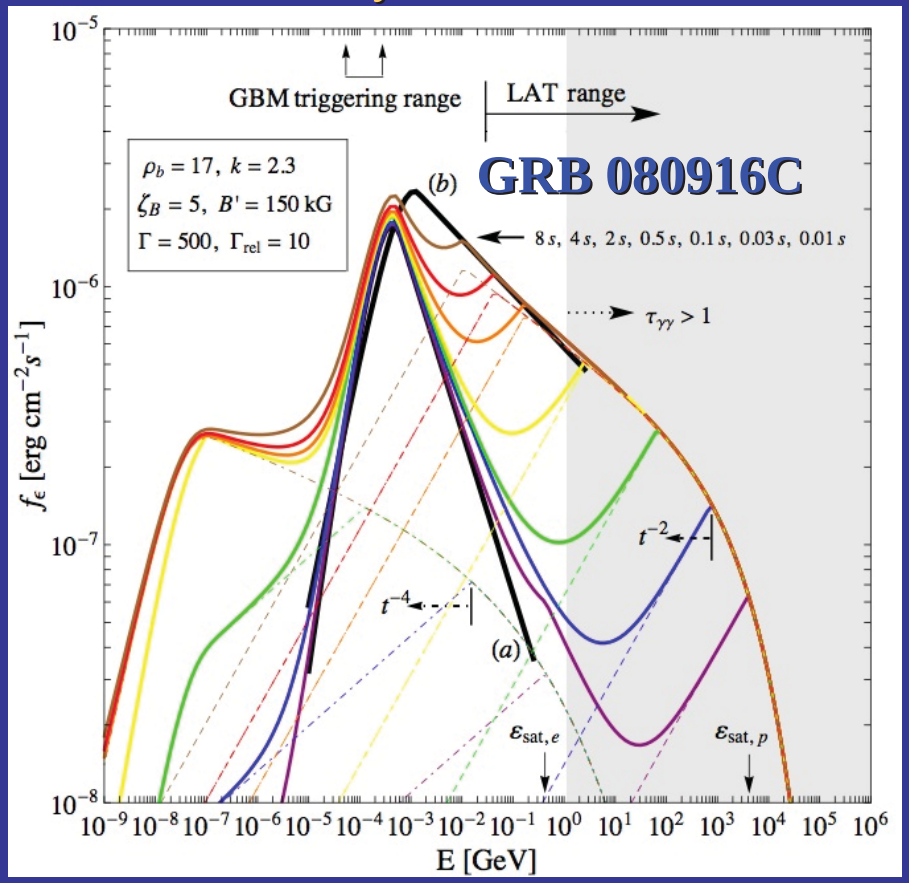


- Very high jet bulk Lorentz factor reduces photohadronic cooling, efficiency ~Γ^{-4} !
  - *Could work in other bright GBM bursts*
  - *A γγ cutoff in HE spectrum would be an indication*
- proton-synchrotron cooling is dominant in very high *B* field

Razzaque, Dermer, Finke & Atoyan, arXiv:0811.1160

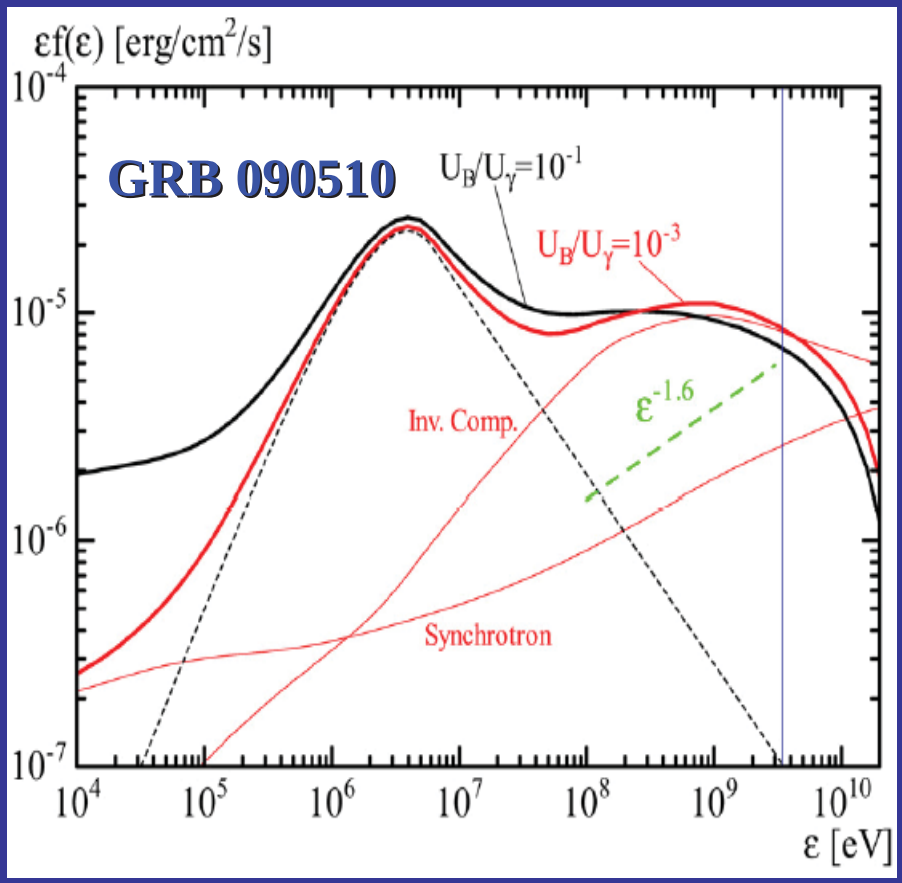
Hadronic model for LAT emission

Proton-synchrotron model



Razzaque, Dermer & Finke 2010

Photo-hadronic model



Asano, Guiriec & Meszaros 2009

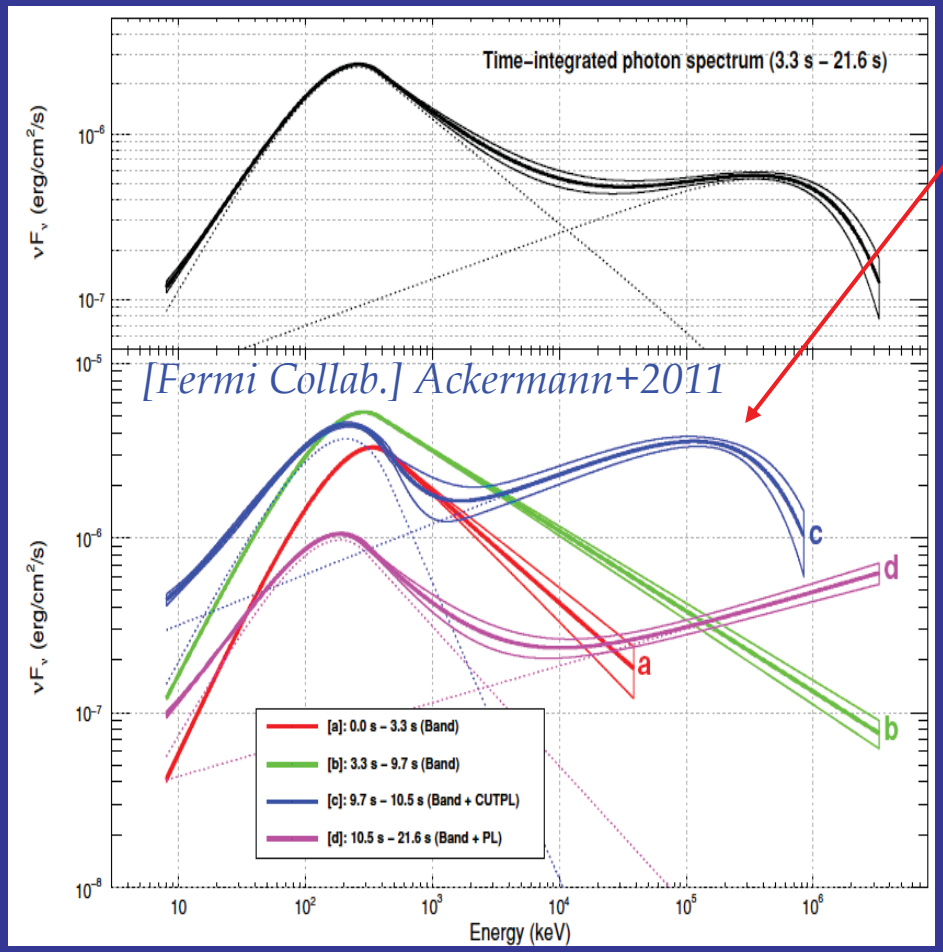
Hadronic models: Require large (~$10^2 \times \gamma$ rays) energy budget

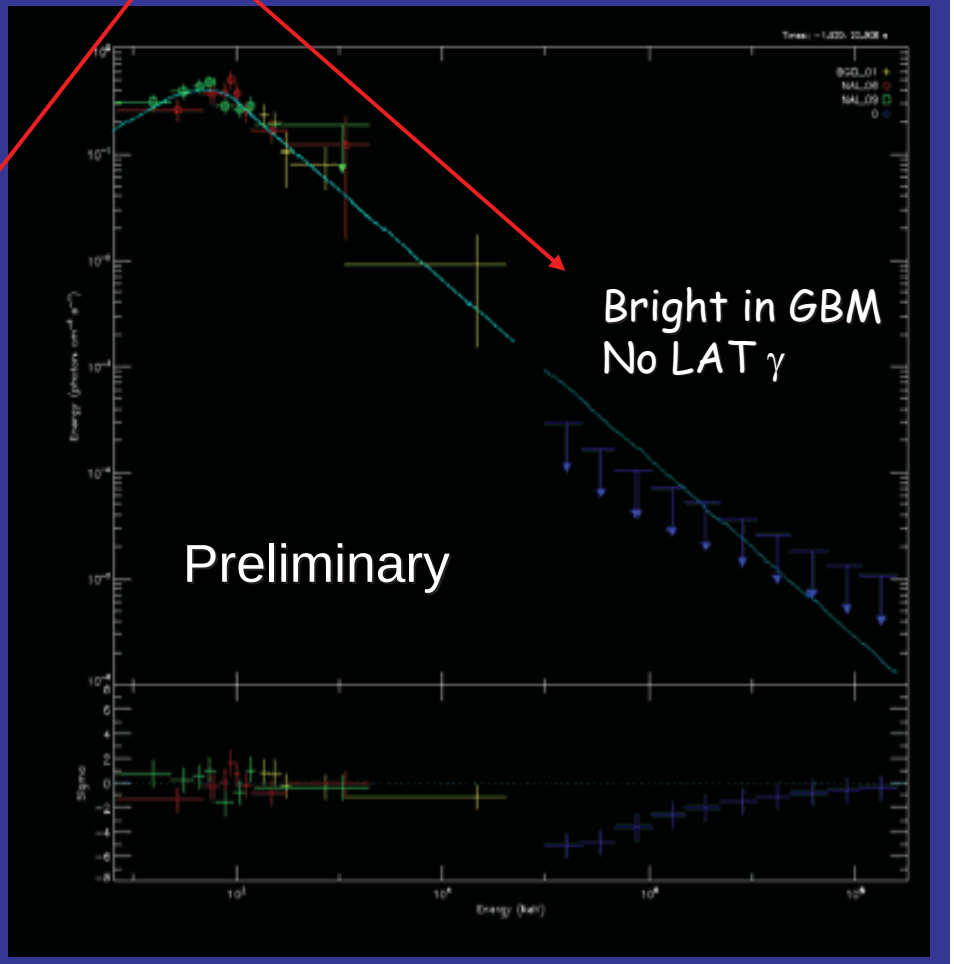
Narrow ($1/\Gamma$) jet opening angle can help by reducing actual energy release

Low Γ GRBs

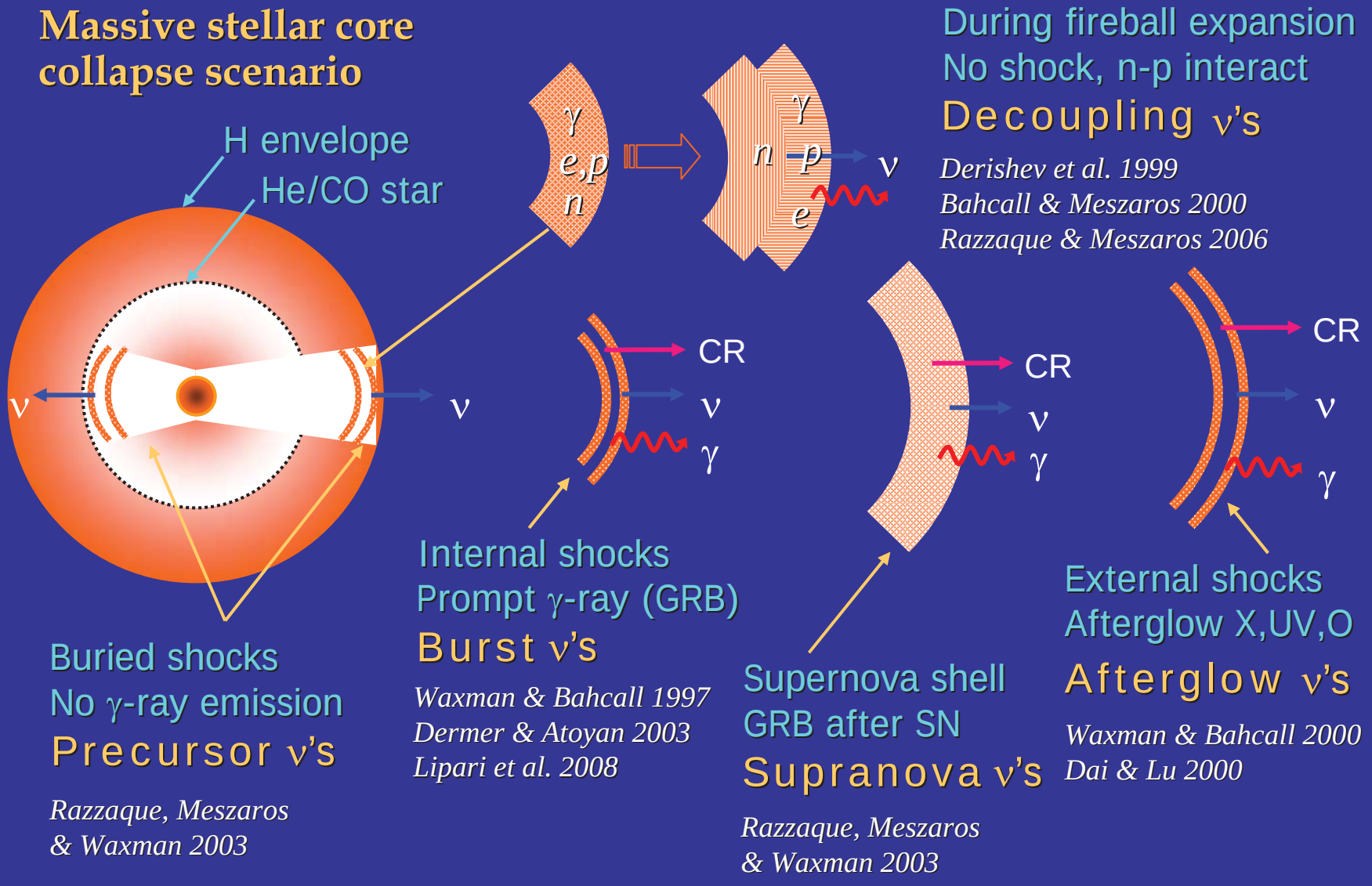
Evidence of a γγ cutoff?

GRB 090926A





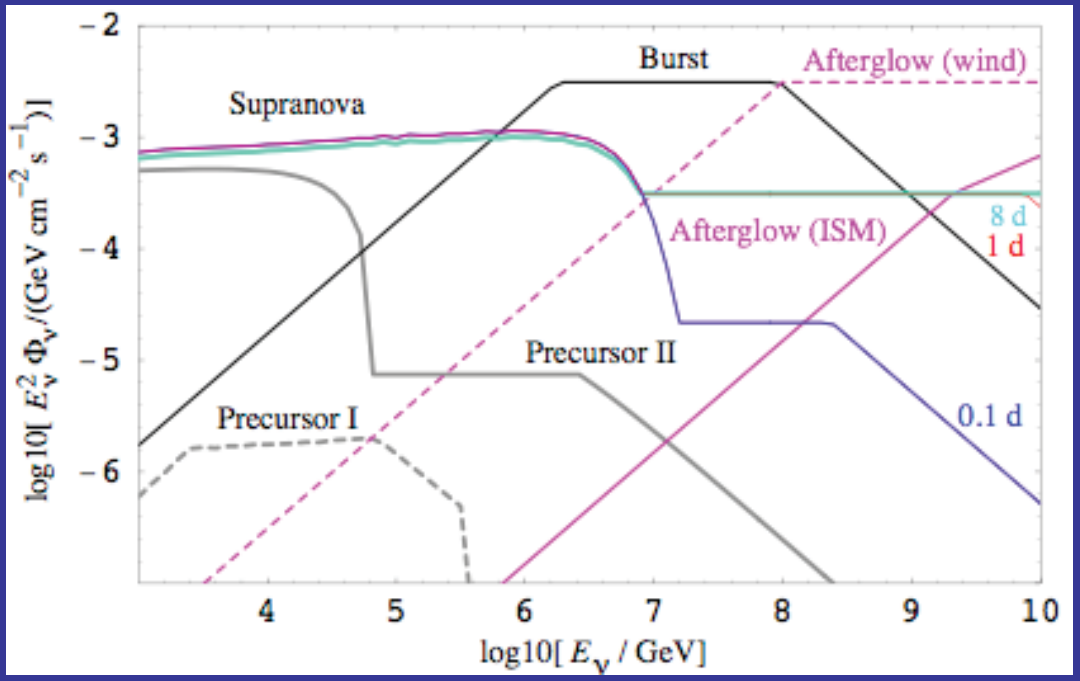
High-energy Neutrinos from GRBs



GRB HE ν Detection Prospects

GRB 030329/SN 2003dh

Typical long duration GRB with bright SN
~10^{51} ergs/s luminosity at redshift z = 0.17



Neutrino flux models:
Dai & Lu 2000 (afterglow wind)
Razzaque, Meszaros & Waxman 2003 (supranova)
Razzaque, Meszaros & Waxman 2003 (precursor)
Waxman & Bahcall 2000 (afterglow ISM)
Waxman & Bahcall 1997 (burst/prompt)

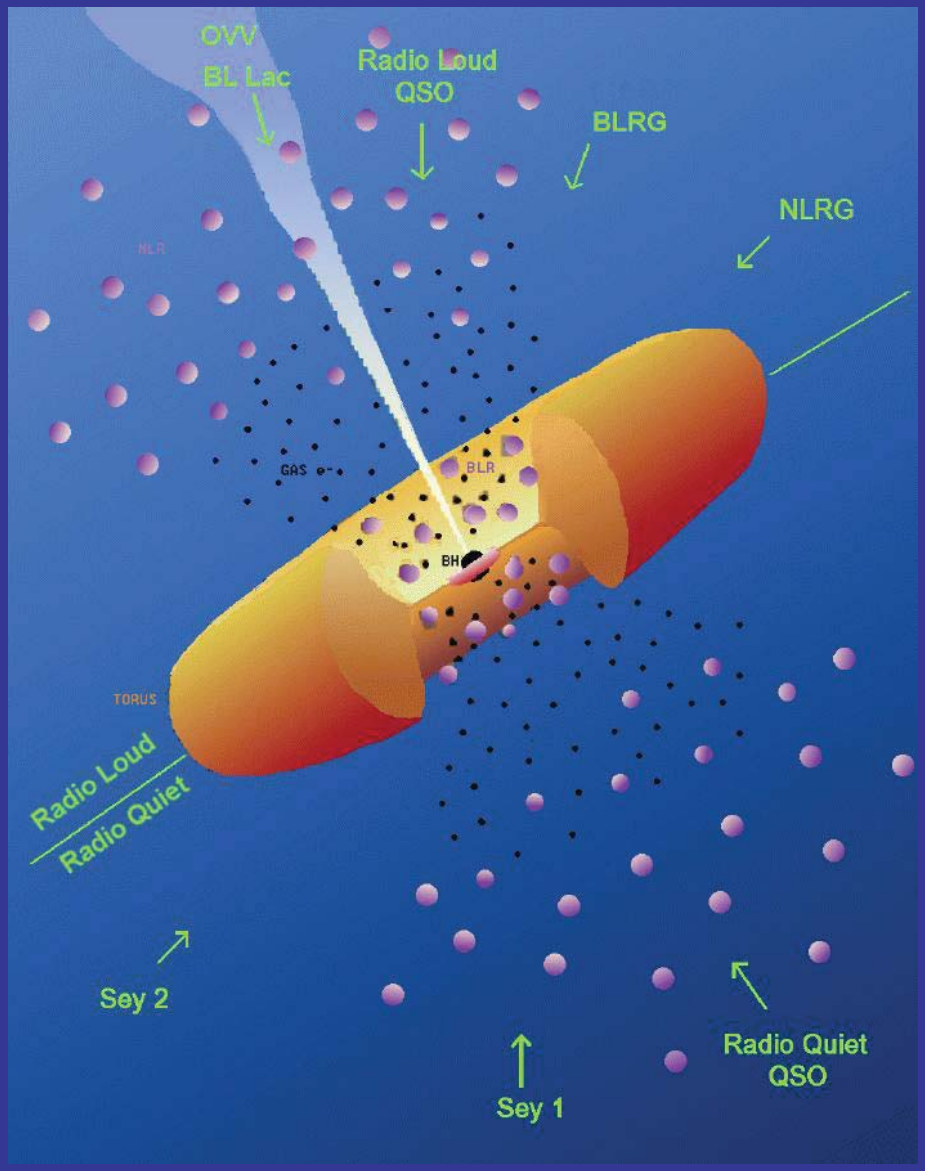
Razzaque, Meszaros & Waxman 2004

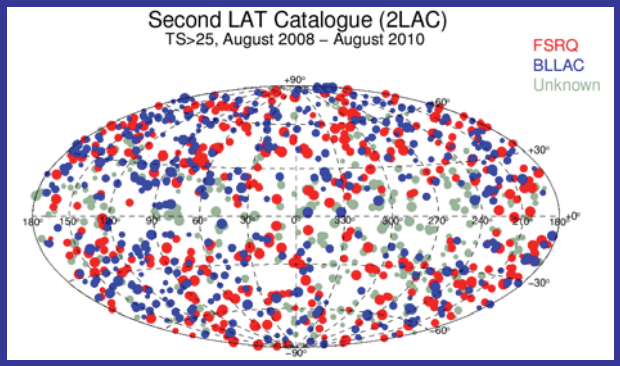
Projected ν events for IceCube		
Flux model	ν_μ	$\nu_e+\nu_\tau$
Precursor II (H)	4.1	1.1
Burst/prompt	3.2	0.3
Afterglow (ISM)	-	-
Afterglow (wind)	0.1	-
Supranova (~1 d)	13	2.4

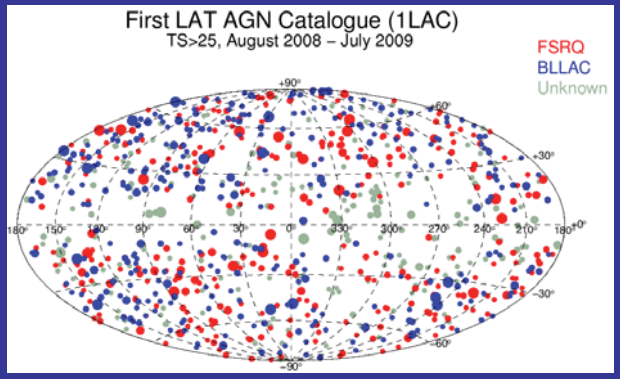
Nearby ($z<0.5$) bright GRBs with high variability (~1 ms) and/or low Γ are the best bet GRB candidates for neutrino telescopes

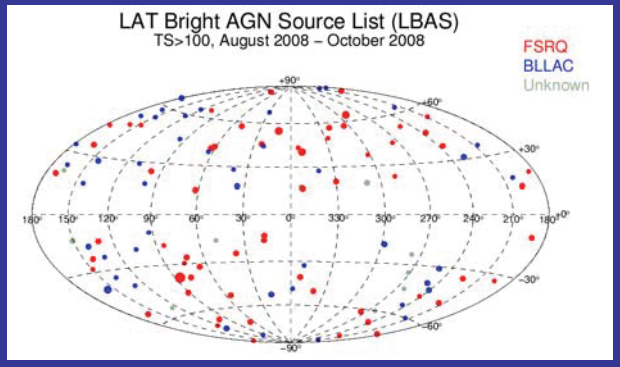
Probably need to wait for sometime …

Fermi LAT view of Active Galaxies





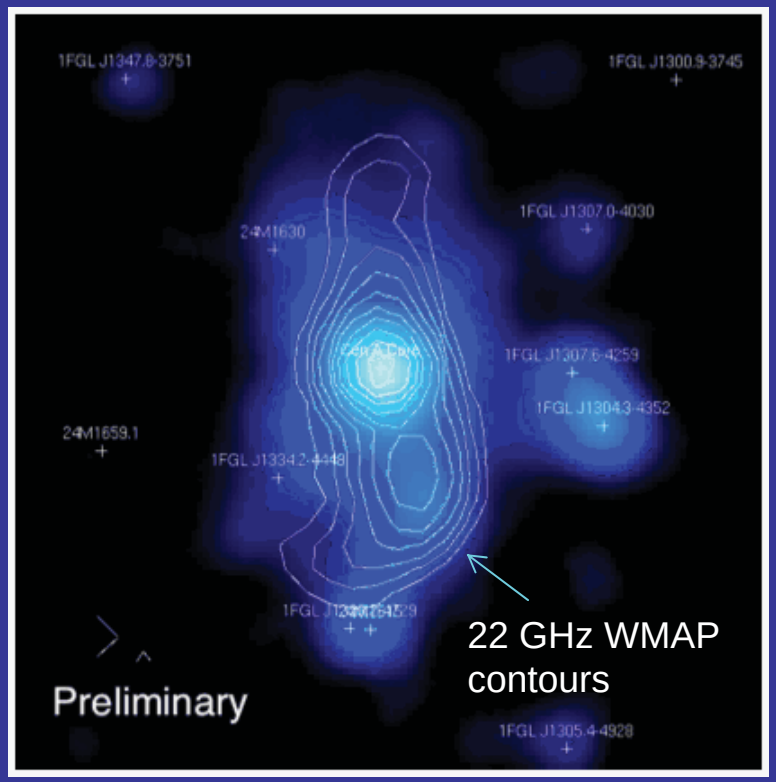




Centaurus A, Nearest Radio Galaxy

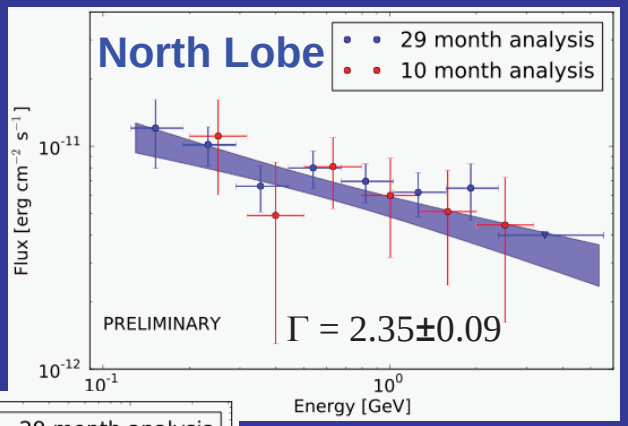
29 months of *Fermi* LAT observation

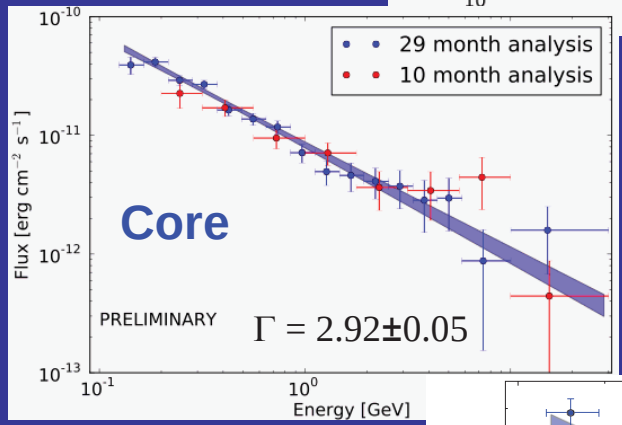
At ~3.7 Mpc, Cen A is widely thought to be an UHECR source



Smoothed γ-ray counts map of the 10°×10° region surrounding Cen A.

Lobe γ-ray emission is most likely Compton-scattered CMB

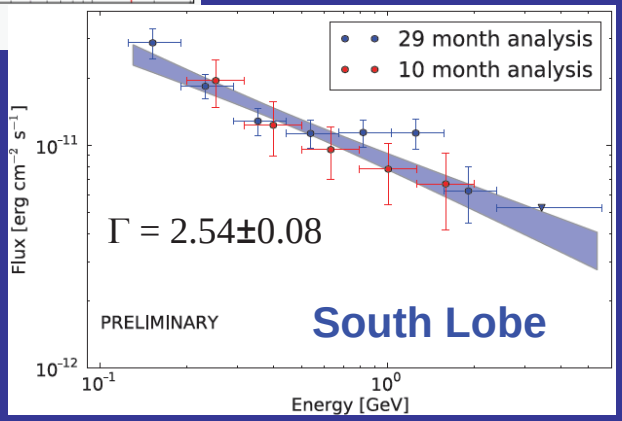




Flux >125 MeV [10^{-7} ph cm^{-2} s^{-1}]

North: 0.56 ± 0.08
Core: 2.27 ± 0.12
South: 1.19 ± 0.11

Core γ-ray emission is most likely inverse Compton from the inner jet

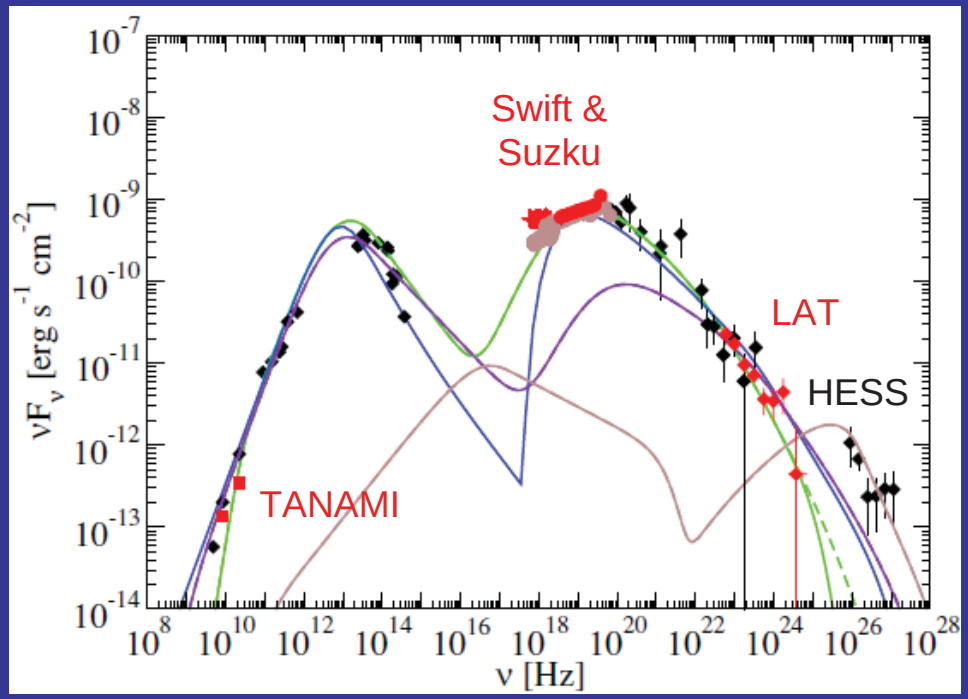


Modeling Cen A Core Emission

Radio galaxies are thought to be misaligned blazars Jet pointing in other direction, compared to blazars with jet pointing in our direction

Broadband SED of *Cen A*

[Fermi Collab.] Abdo+ 2010



One-zone Synchrotron-Self-Compton (SSC) model of the SED

- Extract model parameters: *Jet Doppler factor, bulk Lorentz factor, Magnetic field, jet power*
- Use these parameters to calculate the maximum cosmic ray energy

Hillas condition: $t_{\rm acceleration} = t_{\rm dynamic}$

$$E_{\rm max} \cong 4\times10^{19}\,\frac{Z}{\phi}\left(\frac{B}{6.2\,{\rm G}}\right)\left(\frac{t_v}{10^5\,{\rm s}}\right)\delta_D\left(\frac{\Gamma_j}{7.0}\right)\,{\rm eV}$$

Can accelerate to 10^{20} eV in flares

Escape mechanism from the misaligned jet and point to the Earth:

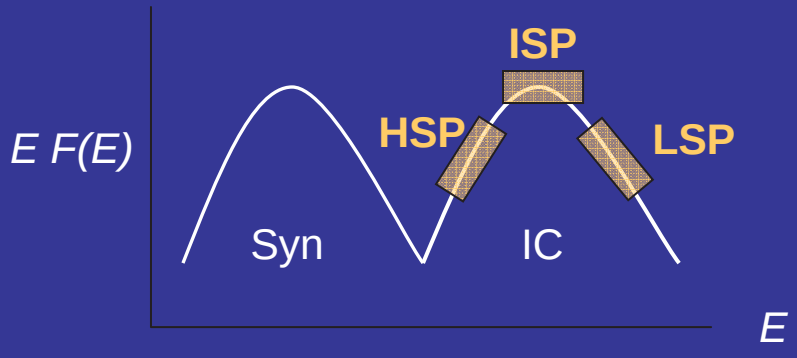
- $p\gamma \rightarrow n$ in the jet
- $n \rightarrow p$ in the ~500 kpc radio lobes
- Deflection in the lobe *B* field (~uG)

Dermer, S.R., Finke & Atoyan 2009

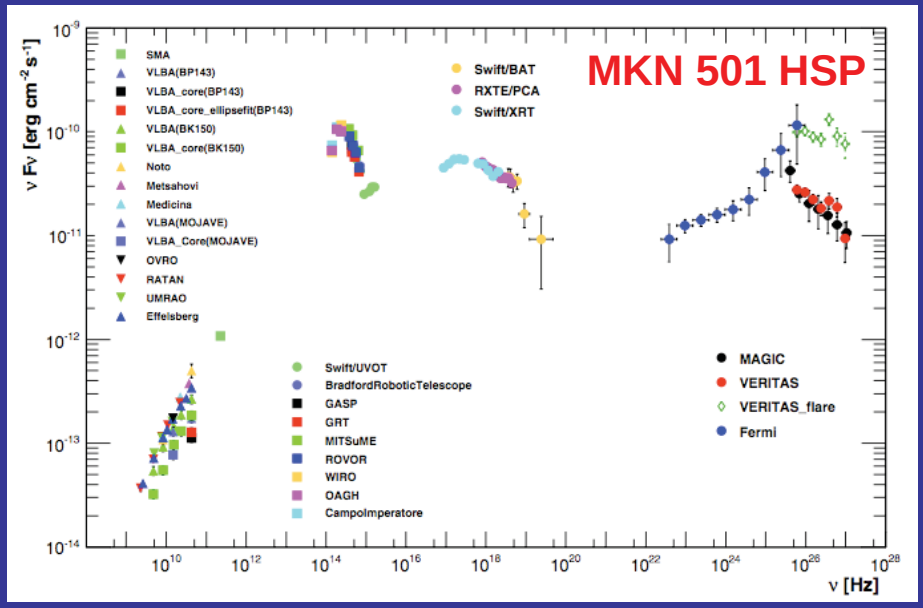
Multiwavelength Observations

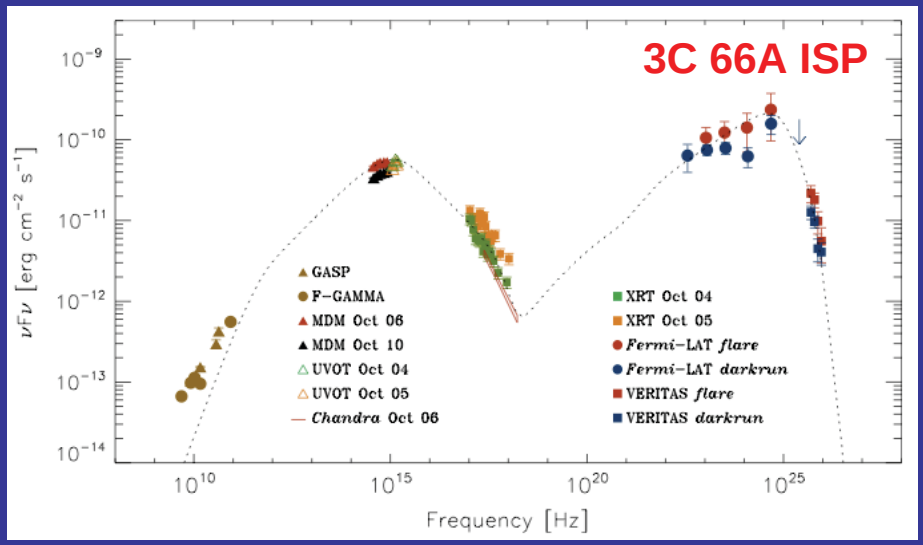
Unprecedentedly long and multiwavelength (Radio to TeV) campaigns capture simultaneous flux help modeling and interpretations

FSRQ IC peak frequency under 100 MeV
BL Lac IC peak frequency spans across the entire LAT energy range



A simple homogeneous one-zone SSC model is not able to reproduce all the variety of SEDs, especially of the LSP type
> Multi-zone Compton model or UHECRs?

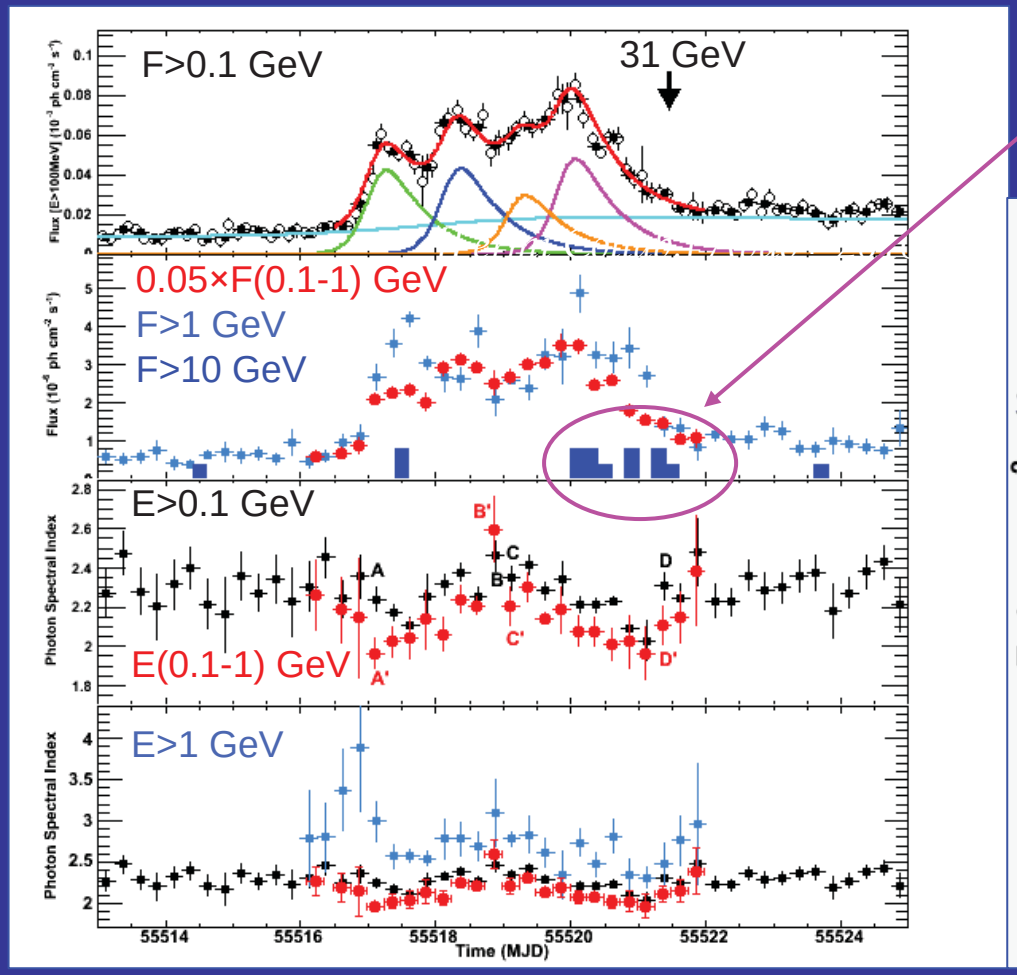




Nov. '10 Giant Flare of 3C454.3

Light Curves of 5 day outburst

[Fermi Collab.] Abdo+ 2011

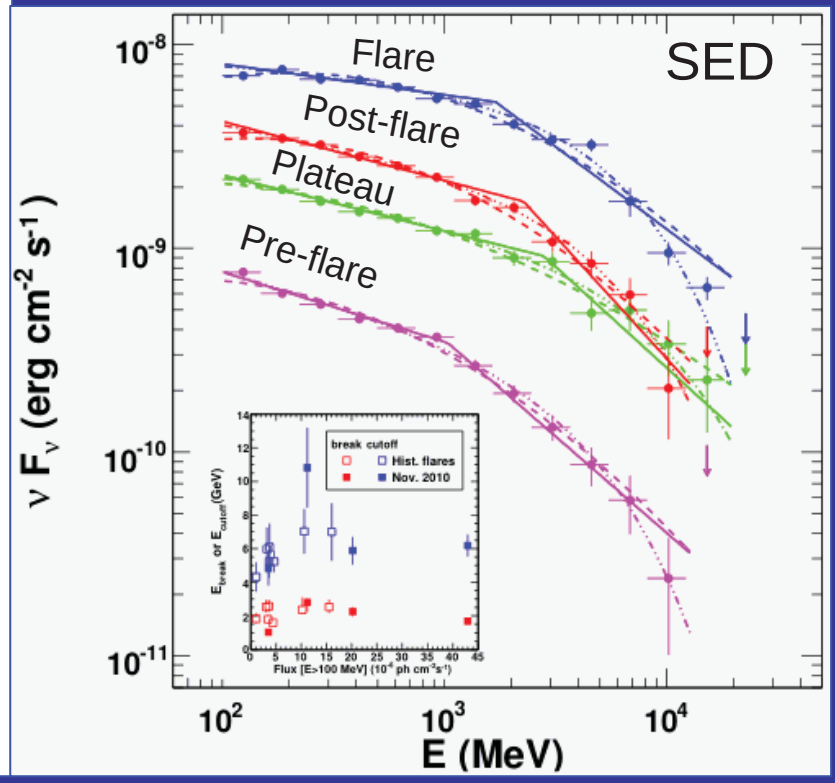


5 times brighter than the Vela pulsar, the brightest γ-ray source

Apparent-isotropic γ-ray luminosity: $(2.1\pm0.2)\times10^{50}$ erg/s !!

Most ≥10 GeV photons arrive late

UHECR acceleration?



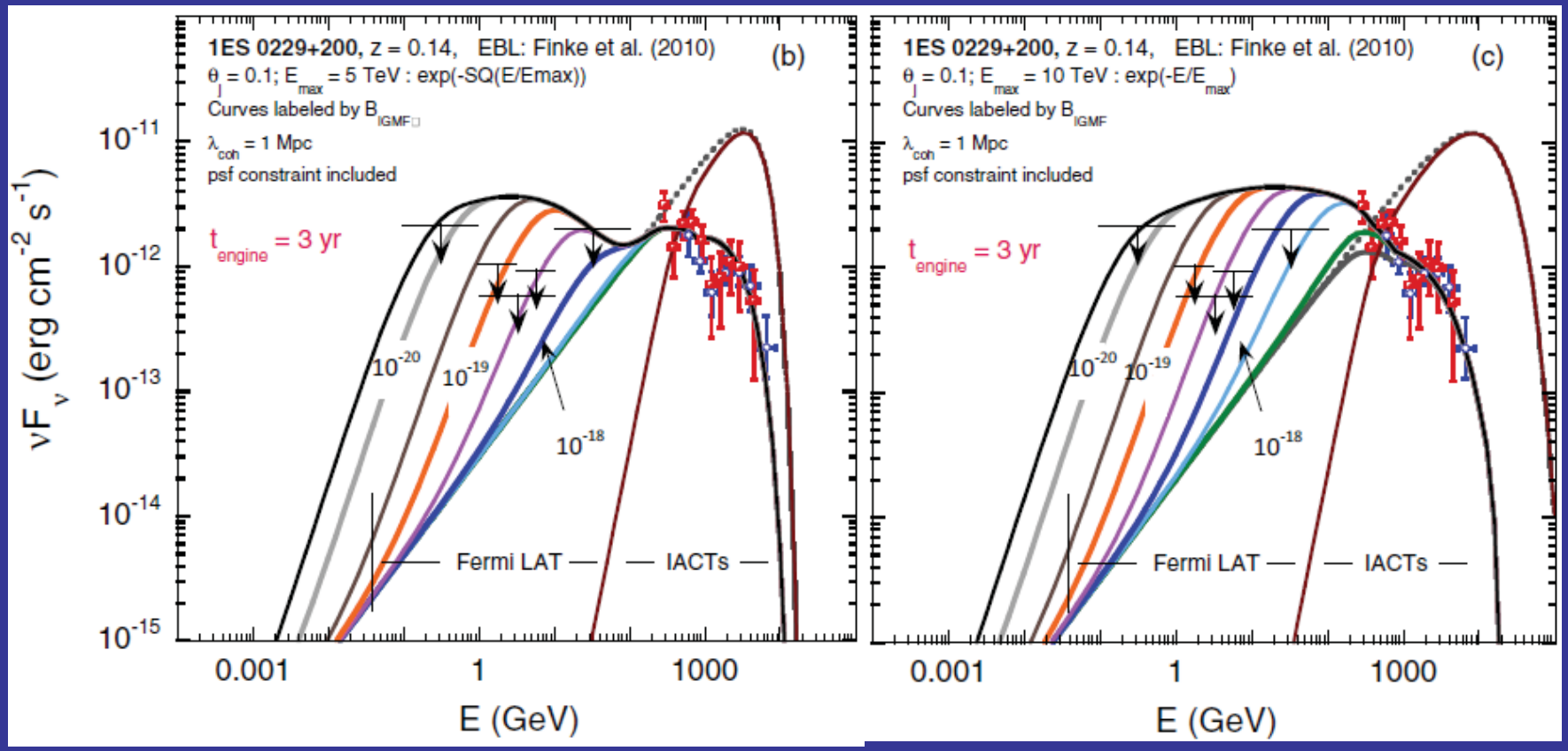
LAT undetected blazars

TeV γ-ray blazar: 1ES 0229+200

Detected by HESS and VERITAS
2σ upper limit from Fermi LAT

TeV γ absorbed by EBL photons, IC cascade
Limit on IGMF $\geq 10^{-18}$ G

Dermer, Cavadini, S.R., Finke, Chiang, Lott 2011



Summary

- Supernova remnants:
  - Both leptonic and hadronic γ-ray models seem to work on source-by-source basis
  - Neutrino detection will distinguish the two
- Gamma Ray Bursts:
  - Fermi LAT GRBs, although the most energetic ones, may not be the best neutrino sources
  - Bright GRBs in Fermi GBM is favored for neutrino production
  - Bright nearby GRBs seem to be rare
- Blazar γ-ray emission is broadly understood in the leptonic models
  - A hadronic emission component could be there

UHECRs might be quietly accelerated at the sources without visible γ-ray signature!

Synchro-Compton: GRB 090510

(Abdo et al., ApJ, 2010)

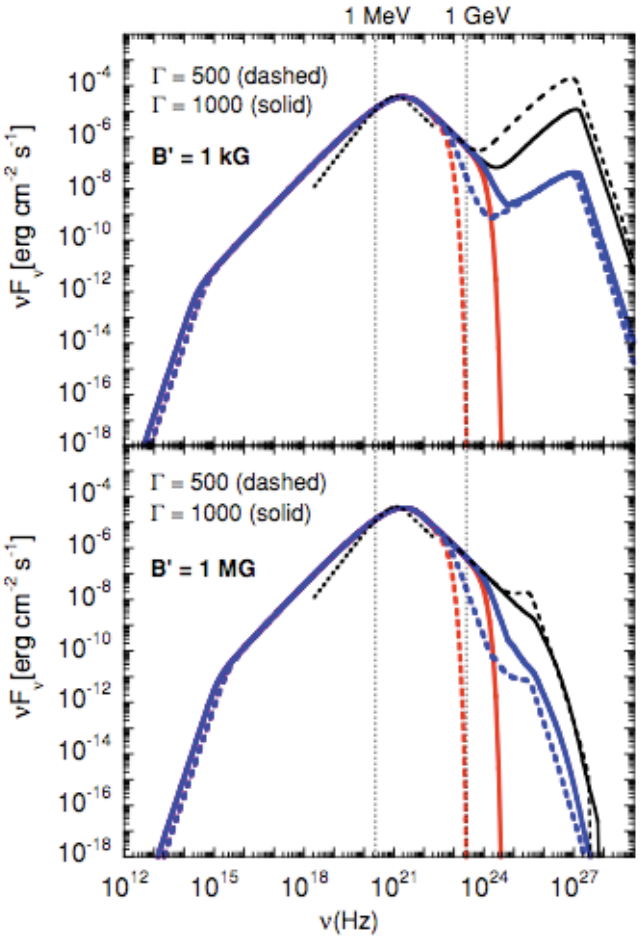
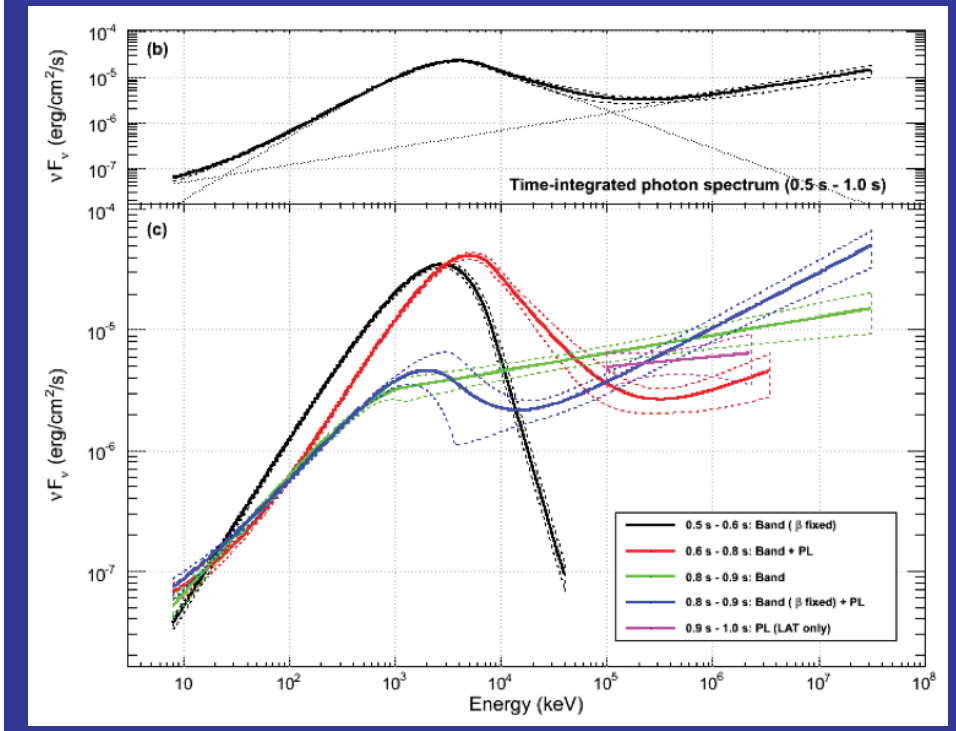


Figure 6. Synchrotron/SSC model for interval b (T_0+0.6 s to T_0+0.8 s) of GRB 090510. Dotted curves show the Band component during this time interval. The magnetic field in the top and bottom panels is 1 kG and 1 MG, respectively. The dashed and solid curves show results for $\Gamma = 500$ and $\Gamma = 1000$, respectively. The upper blue and lower red curves show received fluxes (without EBL corrections) assuming spherical and exponential γ-ray escape probabilities, respectively.



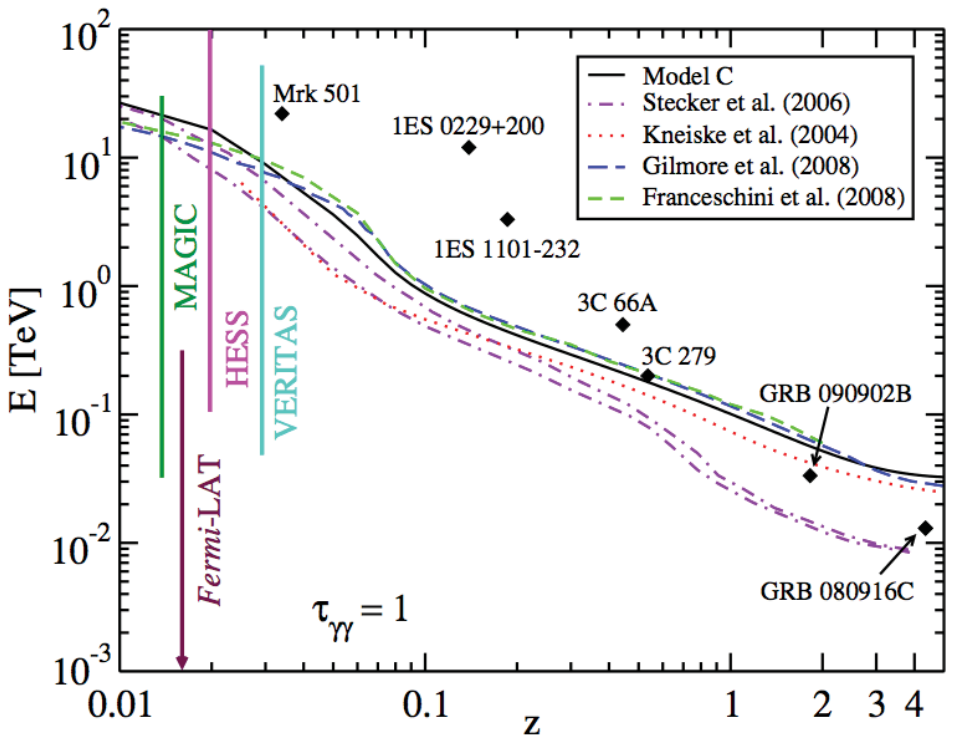
- Can not produce delay longer than the pulse width, ~ 0.01 s - 0.1 s
- Can not produce excess emission at <100 keV
- Energetically efficient

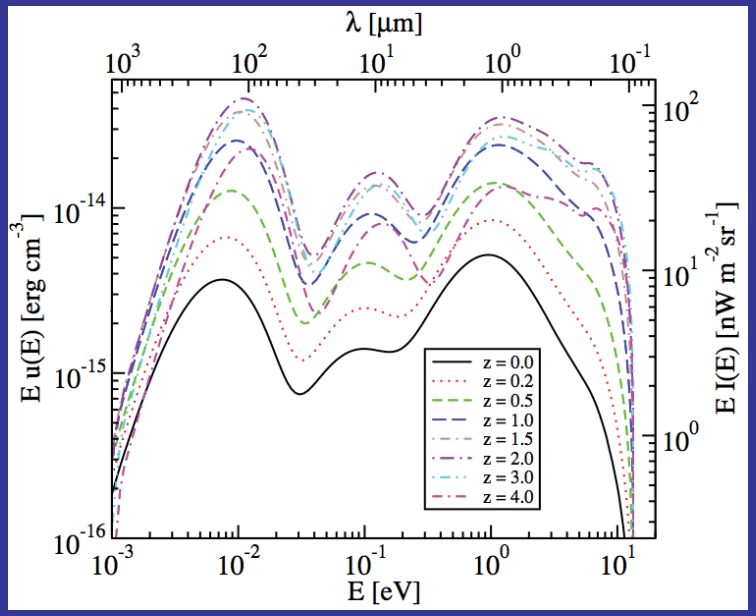
Gamma Ray Opacity of the Universe

High-energy γ rays interact with EBL photons to produce *e*+*e*- pairs

Nishikov 1961; Gould+Schreder 1966; Fazio+Stecker 1970

Very high-energy g detected by Fermi LAT can probe the background radiation field





Modeling of an evolving EBL is necessary to calculate the γ ray opacity $\tau_{\gamma\gamma}(E, z)$ from sources at cosmological distances

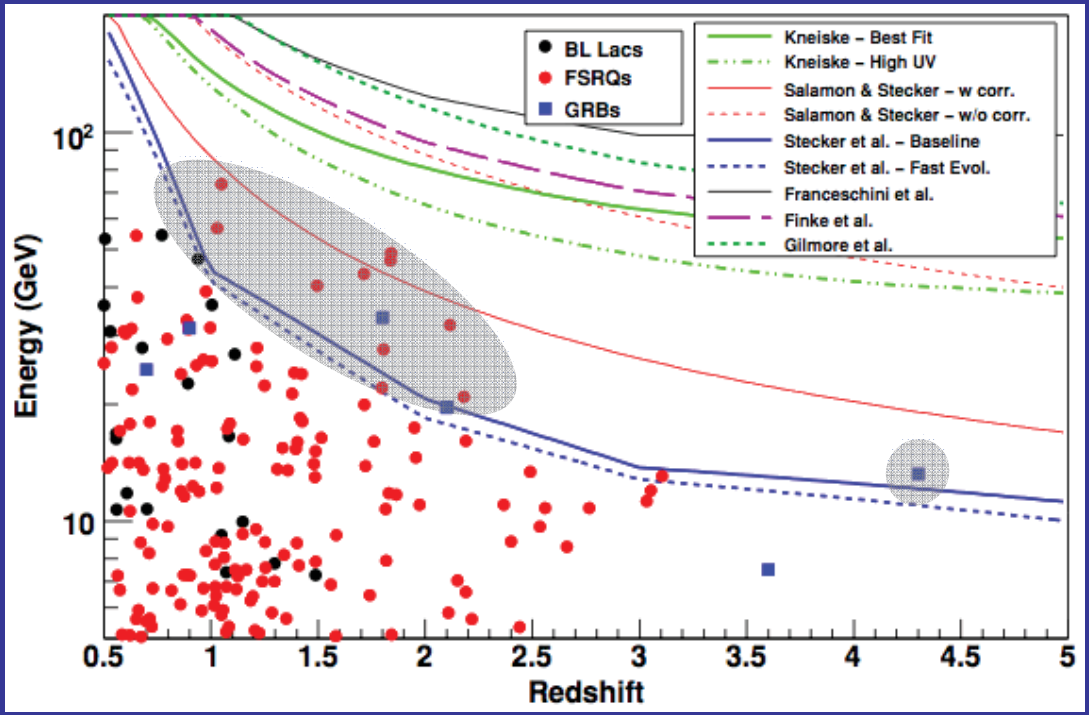
$$E_\gamma \approx \frac{0.26\ \text{TeV}}{(1+z)\,E_{\text{EBL}}(\text{eV})}$$

High Energy High Redshift Sample

Make cuts on energy, > 10 GeV and redshift > 0.5

Clean sample: 200 AGNs (from 11 month 1LAC catalog)
6 GRBs (until Sept. 30, 2009)

[Fermi Collab.] Abdo+ 2010



EBL model prediction for $\tau_{\gamma\gamma}(E, z)=3$

Highest energy photons from constraining sample

Some models predict very small probabilities to find those photons

Use these high-energy photons to constrain EBL models ➔

EBL Model Rejection

Several EBL Models were considered, but only models by Stecker et al. (2006) could be constrained

Model Rejection probability: $P_{\text{rejection}} = P_{\text{bkg}} + P_{\text{HEP}}\,(1 - P_{\text{bkg}})$

[Fermi Collab.] Abdo+ 2010

Table 4

Listed are the Significance of Rejecting the "Baseline" Model (Stecker et al. 2006), Calculated Using the HEP Method Described in Section 3.2.1

Source	z	Energy (GeV)	P_{bkg}	HEP Method Applied to Stecker 06		HEP Rejection
				P_{HEP}	$P_{\text{rejection}}$	Significance
J1147−3812	1.05	73.7	7.0×10^{-4}	1.2×10^{-4}	8.1×10^{-4}	3.2σ
J1504+1029	1.84	48.9	5.6×10^{-3}	6.7×10^{-5}	5.7×10^{-3}	
		35.1	9.8×10^{-3}	6.8×10^{-3}	1.7×10^{-2}	
		23.2	5.6×10^{-3}	1.8×10^{-1}	1.9×10^{-1}	
				Combined $P_{\text{rej}} = 1.7 \times 10^{-5}$		4.1σ
J0808−0751	1.84	46.8	1.5×10^{-3}	1.9×10^{-4}	1.7×10^{-3}	
		33.1	2.7×10^{-3}	3.7×10^{-3}	6.4×10^{-3}	
		20.6	6.9×10^{-3}	2.5×10^{-1}	2.6×10^{-1}	
				Combined $P_{\text{rej}} = 2.8 \times 10^{-6}$		4.5σ
J1016+0513	1.71	43.3	1.1×10^{-3}	5.4×10^{-4}	1.6×10^{-3}	
		16.8	8.2×10^{-3}	4.9×10^{-1}	4.9×10^{-1}	
		16.1	8.2×10^{-3}	6.5×10^{-1}	6.5×10^{-1}	
				Combined $P_{\text{rej}} = 5.3 \times 10^{-4}$		3.3σ
J0229−3643	2.11	31.9	1.7×10^{-3}	8.9×10^{-5}	1.8×10^{-3}	2.9σ
GRB 090902B	1.82	33.4	2×10^{-6}	2.0×10^{-4}	2.0×10^{-4}	3.7σ
GRB 080916C	4.24	13.2	8×10^{-8}	6.5×10^{-4}	6.5×10^{-4}	3.4σ

Upper Limits on the γ ray Opacity

Independent of EBL models

- Opacity

$\tau_{\gamma\gamma}(E,z) = \ln[F_{\rm int}(E>E_{\rm brk})/F_{\rm obs}(E>E_{\rm brk})]$

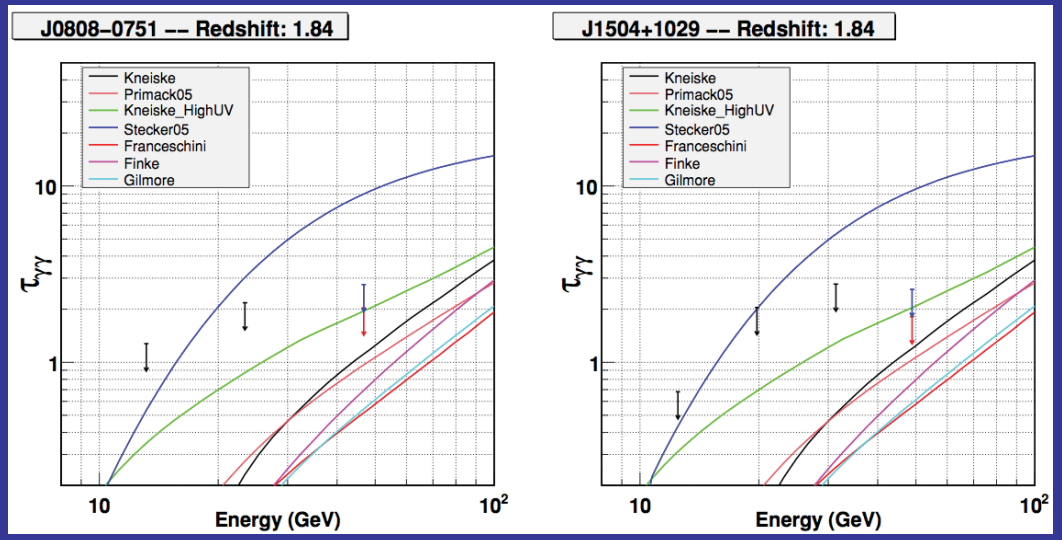
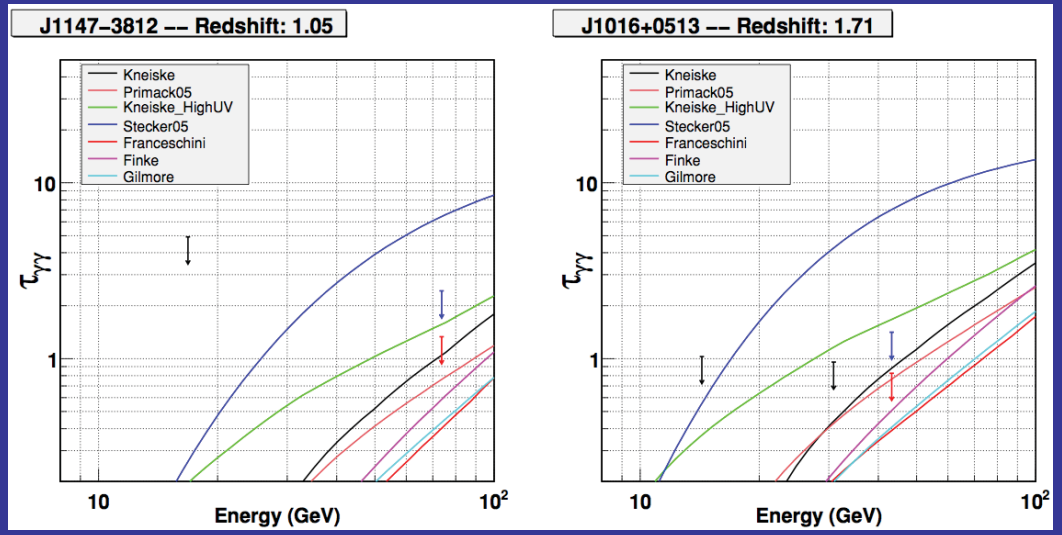
- Propagate errors from fitting $F_{\rm int}(E<E_{\rm brk})$
- Upper limits on $\tau(E,z)$ from $F_{\rm obs}(E>E_{\rm brk})$

$\tau_{\gamma\gamma,\ 95\%\ \rm CL}(E,z) =$

$\ln[F_{\rm int}(E>E_{\rm brk})/F_{\rm obs}(E>E_{\rm brk})] + 2\sigma$

[Fermi Collab.] Abdo+ 2010

Table 7

Upper Limits (95% CL) on the γ-ray Optical Depth for AGNs in Table 4

Source	z	$E_{\rm max}$	$\tau_{\rm UL}(z, E_{\rm max})$	Energy Bins 10 GeV–100 GeV
J1147−3812	1.05	73.7	1.33	2 bins/dec
J1504+1029	1.84	48.9	1.82	5 bins/dec
J0808−0751	1.84	46.8	2.03	4 bins/dec
J1016+0513	1.71	43.3	0.83	2 bins/dec
J0229−3643	2.11	31.9	0.97	2 bins/dec
J1012+2439	1.81	27.6	2.41	2 bins/dec