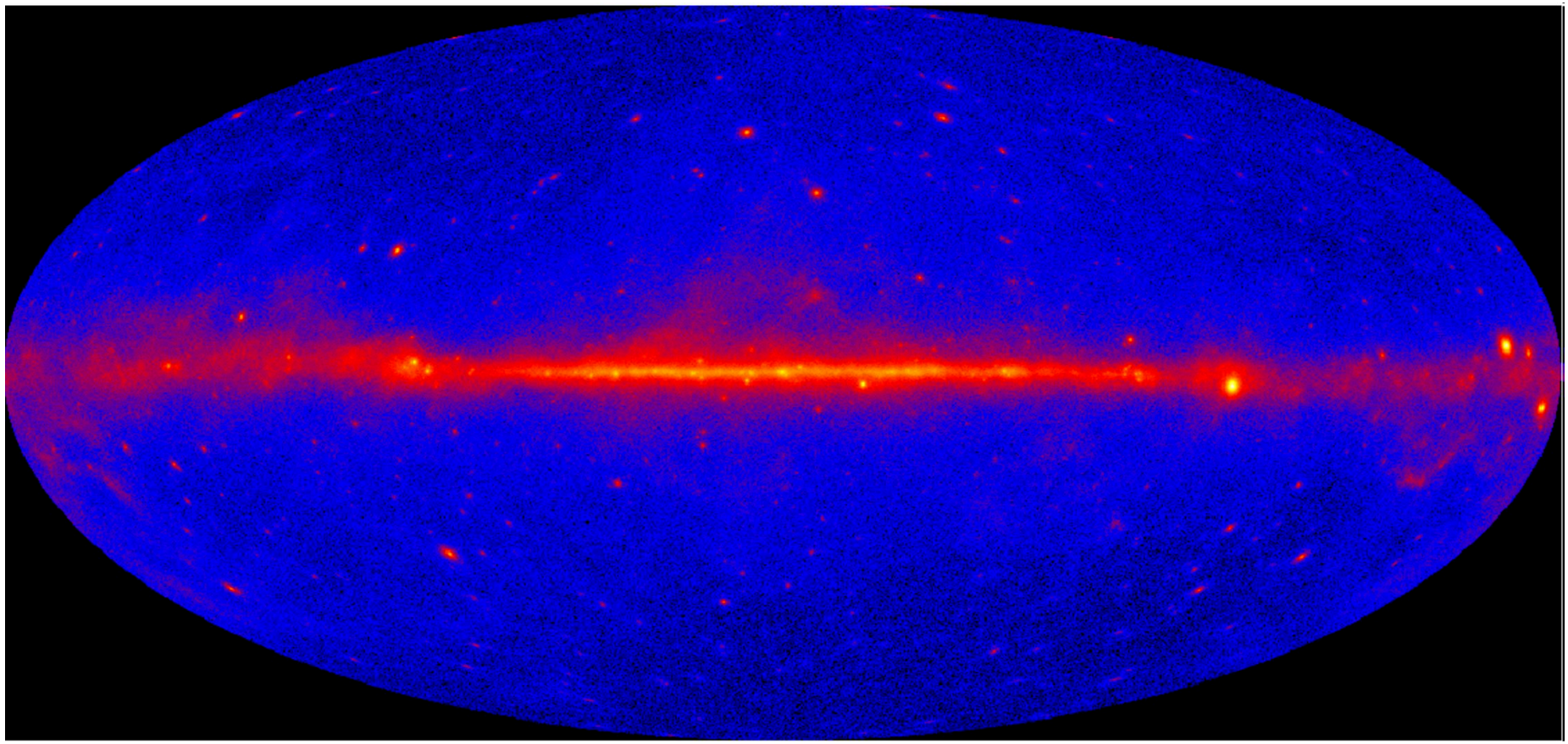
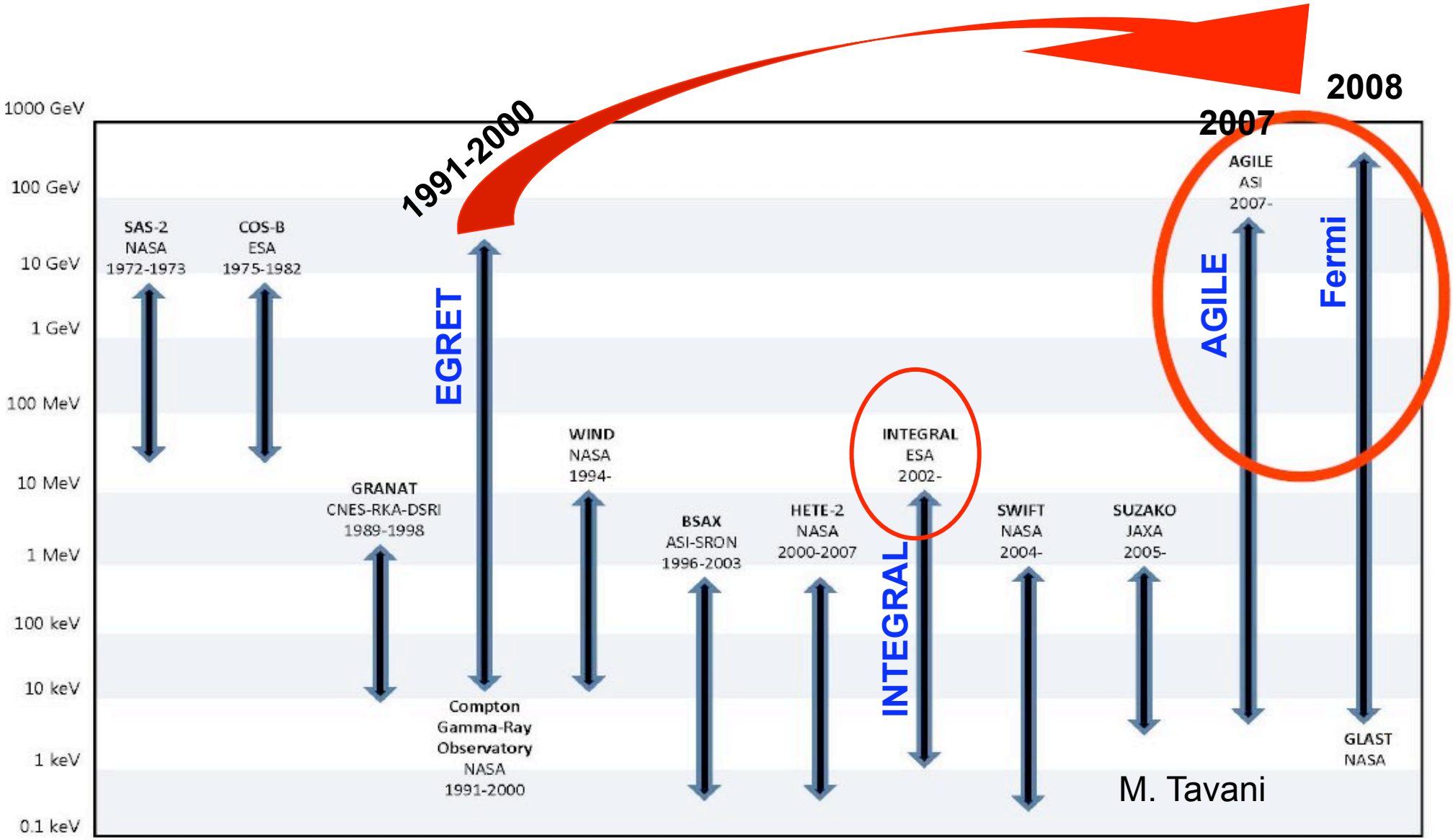
Space based observations of gamma rays



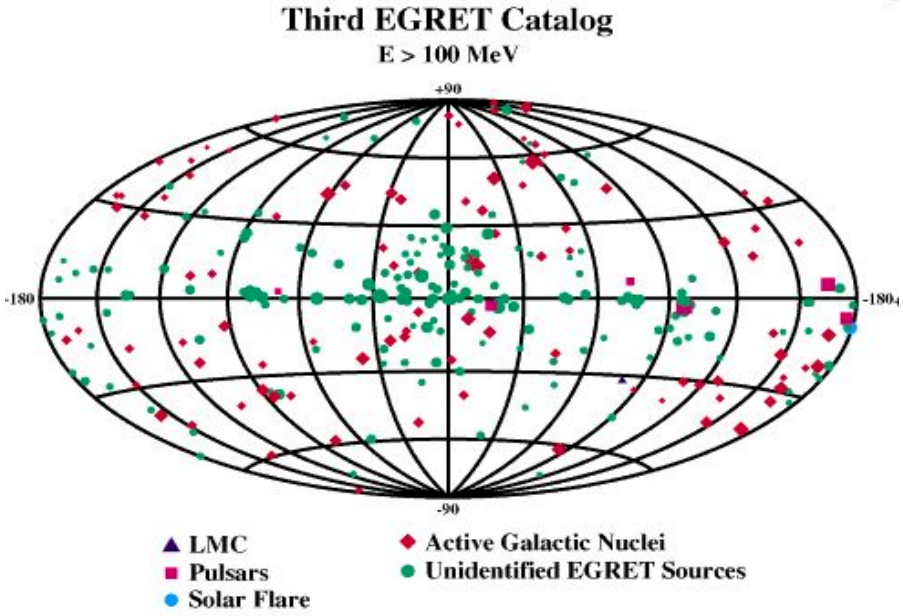
Philippe Bruel
LLR - Ecole polytechnique-IN2P3/CNRS
(Fermi-LAT collaboration)

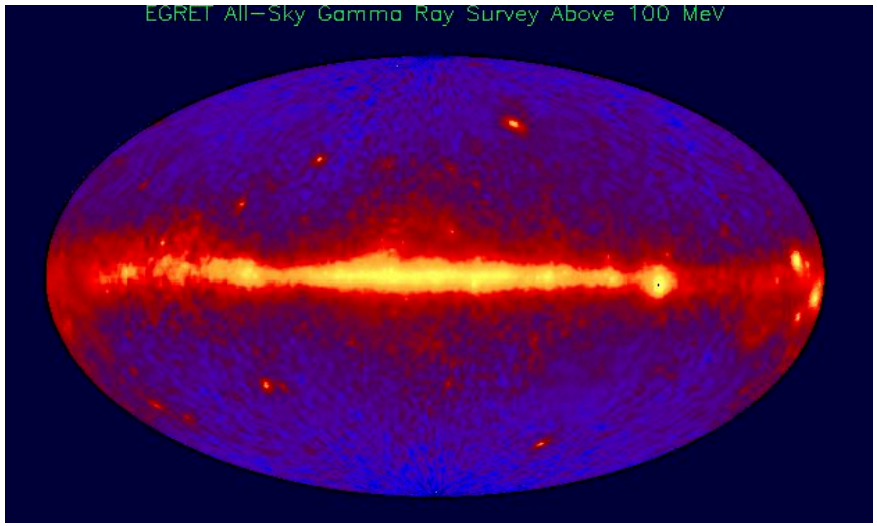
Space gamma rays observations



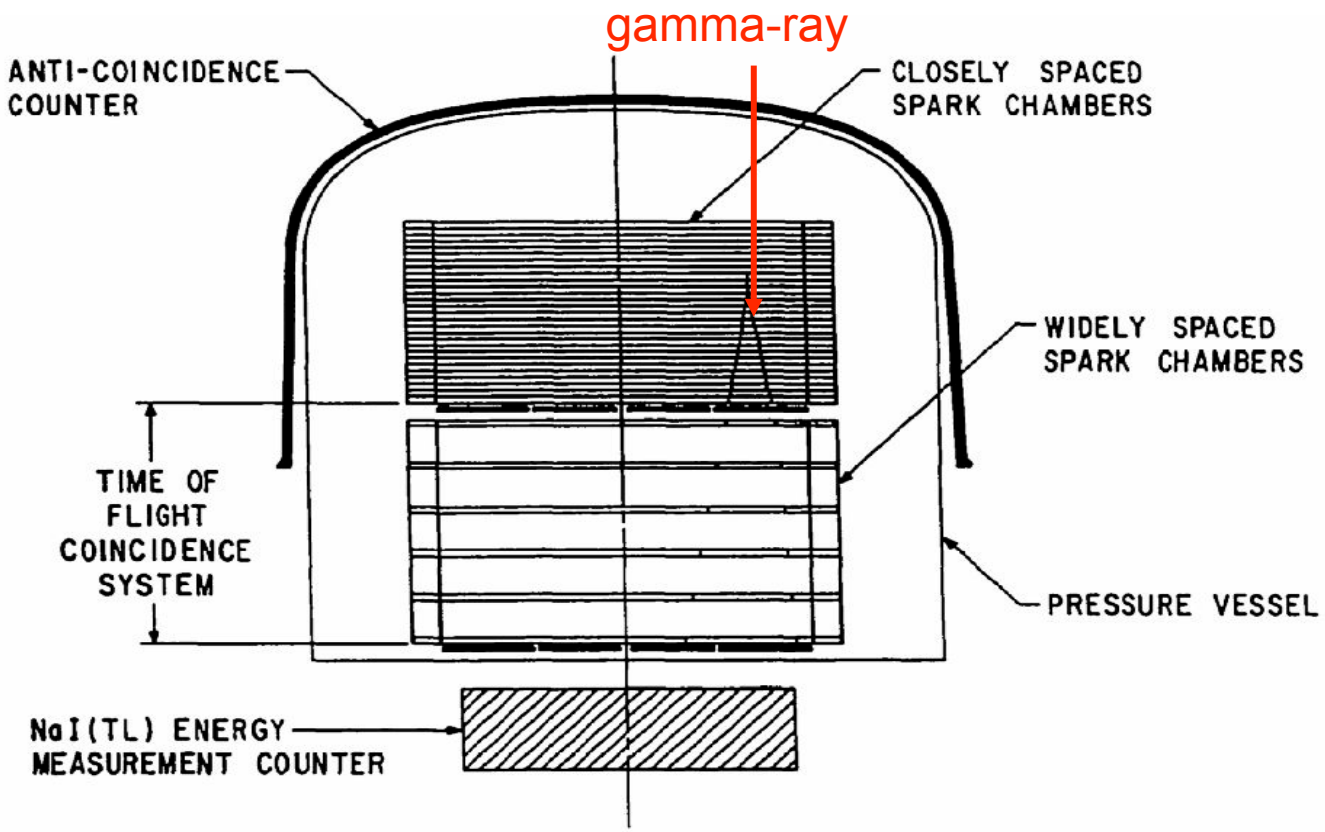
EGRET legacy (1991 -2000)

- 3rd EGRET catalog : 271 sources above 100 MeV
  - 6 pulsars
  - 66+27 blazars (AGNs)
  - 170 unidentified
- Far better than COSB 25 sources (1975-1892)
- But some limitations :
  - Rather poor angular resolution (~6° at 100 MeV) and limited effective area x field of view
  - Localization limitation -> identification limitation
  - Not so many sources
    - To perform **population studies**
    - With high statistics to study in details
  - Limited sensitivity to variability





EGRET : a particle detector in space



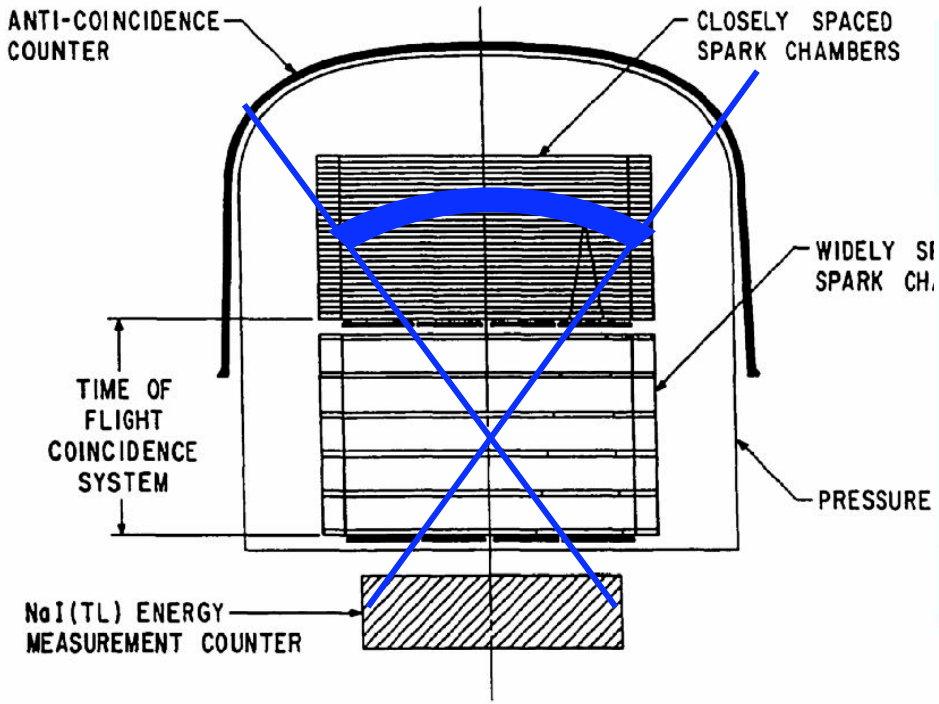
- Angular resolution
  - Limited at low energy by multiple scattering
  - Limited at high energy by position measurement
- Energy measurement
  - Limited by shower containment
  - Can be overcome by longitudinal segmentation

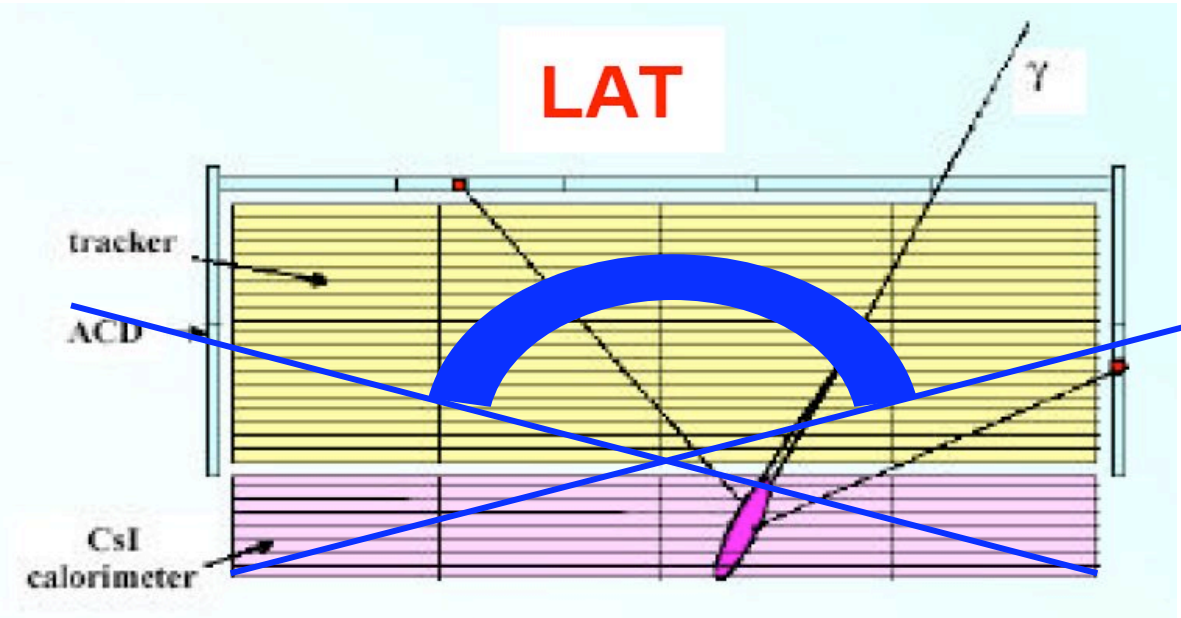
- Basic sub-detectors :
  - Pair production in the tracker -> direction measurement
  - Calorimeter for energy measurement
  - Anti-coincidence detector to tag charge particles

Improving EGRET performance

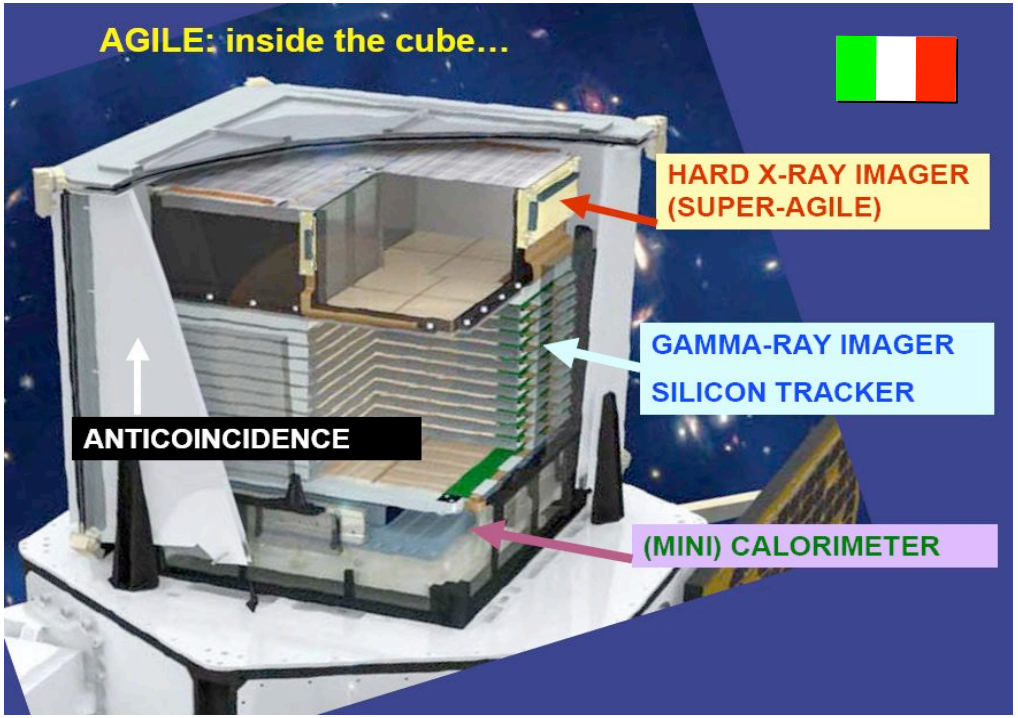
- Limitations :
  - Spark chambers (limited lifetime)
  - Small field of view
  - Monolithic dome (backsplash veto above ~10GeV)
  - Large deadtime

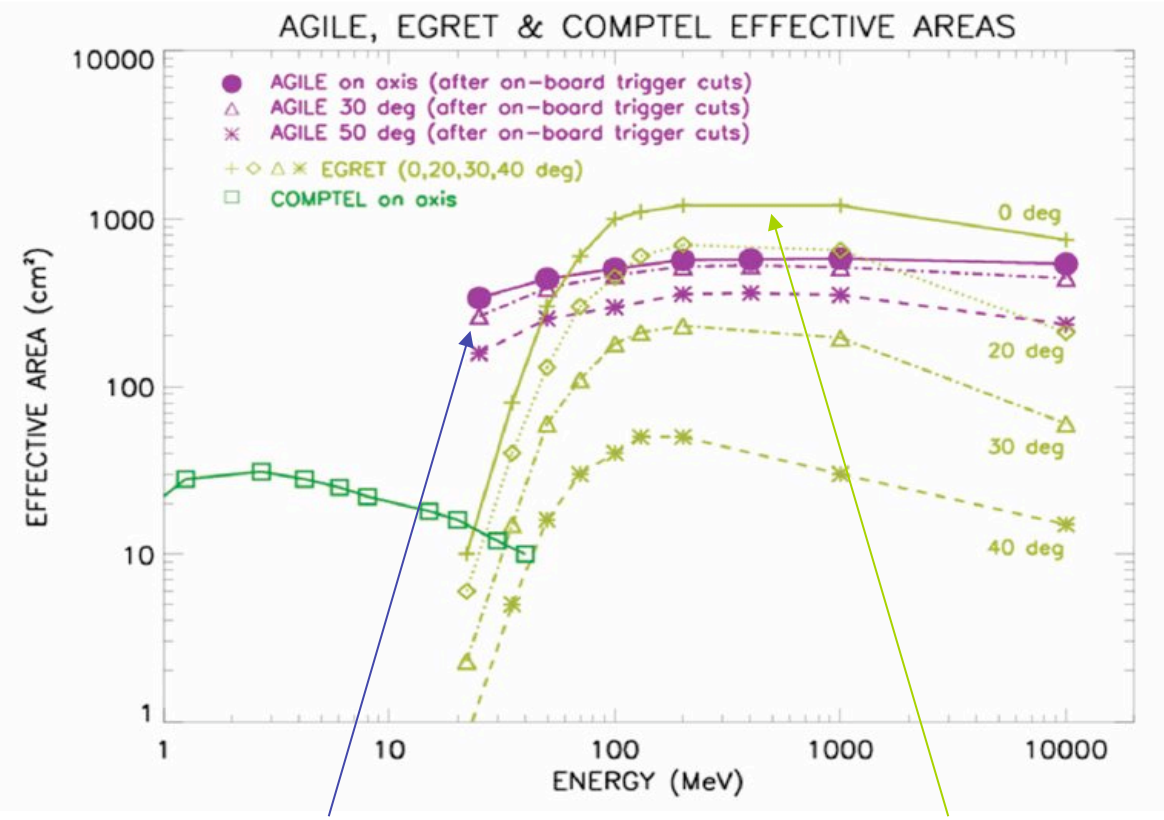
- Improvements :
  - Silicon strips detector
  - Compactness
  - Anti-coincidence detector segmentation
  - Calorimeter segmentation
  - Fast electronics





AGILE in orbit since April 2007





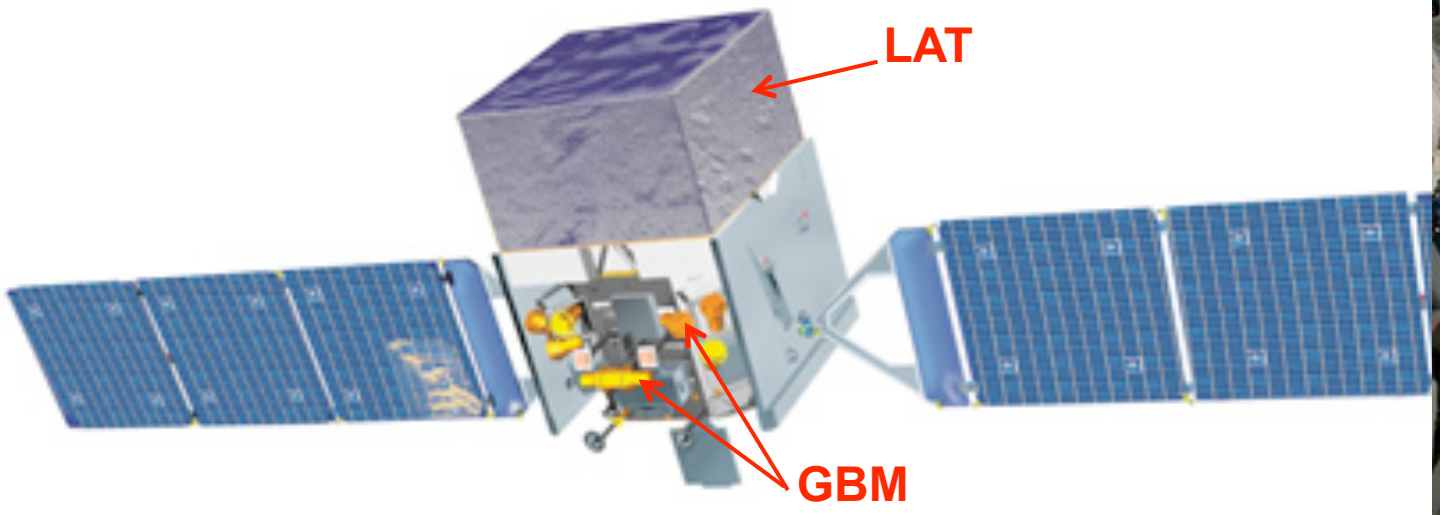
- Light instrument :
  - 100 kg
  - Tracker : 12 (x,y) planes
  - Calorimeter : 1.5 X_0

AGILE
38x38 cm²

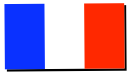
EGRET
80.5x80.5 cm²

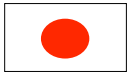
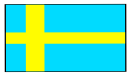
Fermi in orbit since June 2008

- Two instruments:
  - Large Area Telescope (LAT)
    - 20 MeV - >300 GeV
  - Gamma-ray Burst Monitor (GBM)
    - 8 keV - 40 MeV



Fermi Large Area Telescope

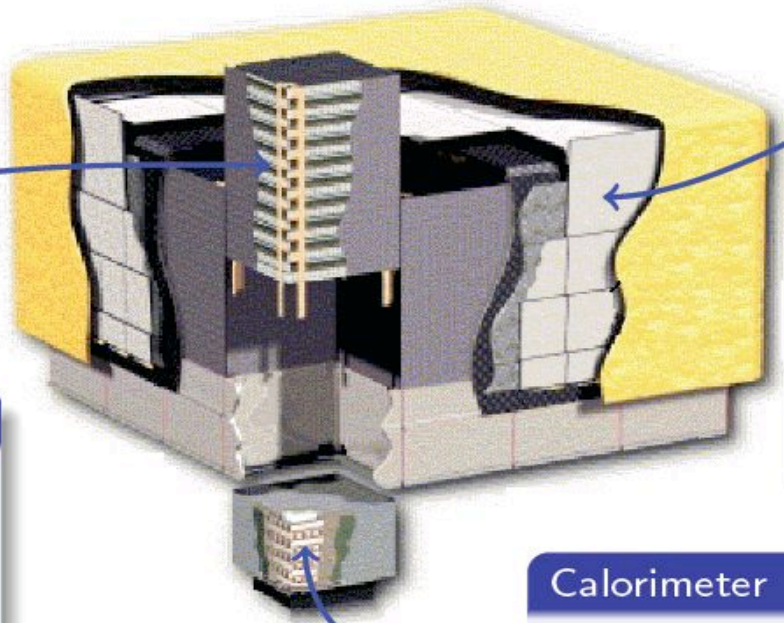


Large Area telescope

- Overall modular design
- 4 × 4 array of identical towers (each one including a tracker and a calorimeter module)
- Tracker surrounded by an Anti-Coincidence Detector (ACD)

~3000kg
160x160 cm^2



Tracker

- Silicon strip detectors, W conversion foils: 1.5 radiation lengths on-axis
- 10k sensors, 80 m^2 of silicon active area, 1M readout channels
- High-precision tracking, short dead time

Anti-Coincidence Detector

- Segmented (89 tiles) as to minimize self-veto at high energy
- 0.9997 average detection efficiency

Calorimeter

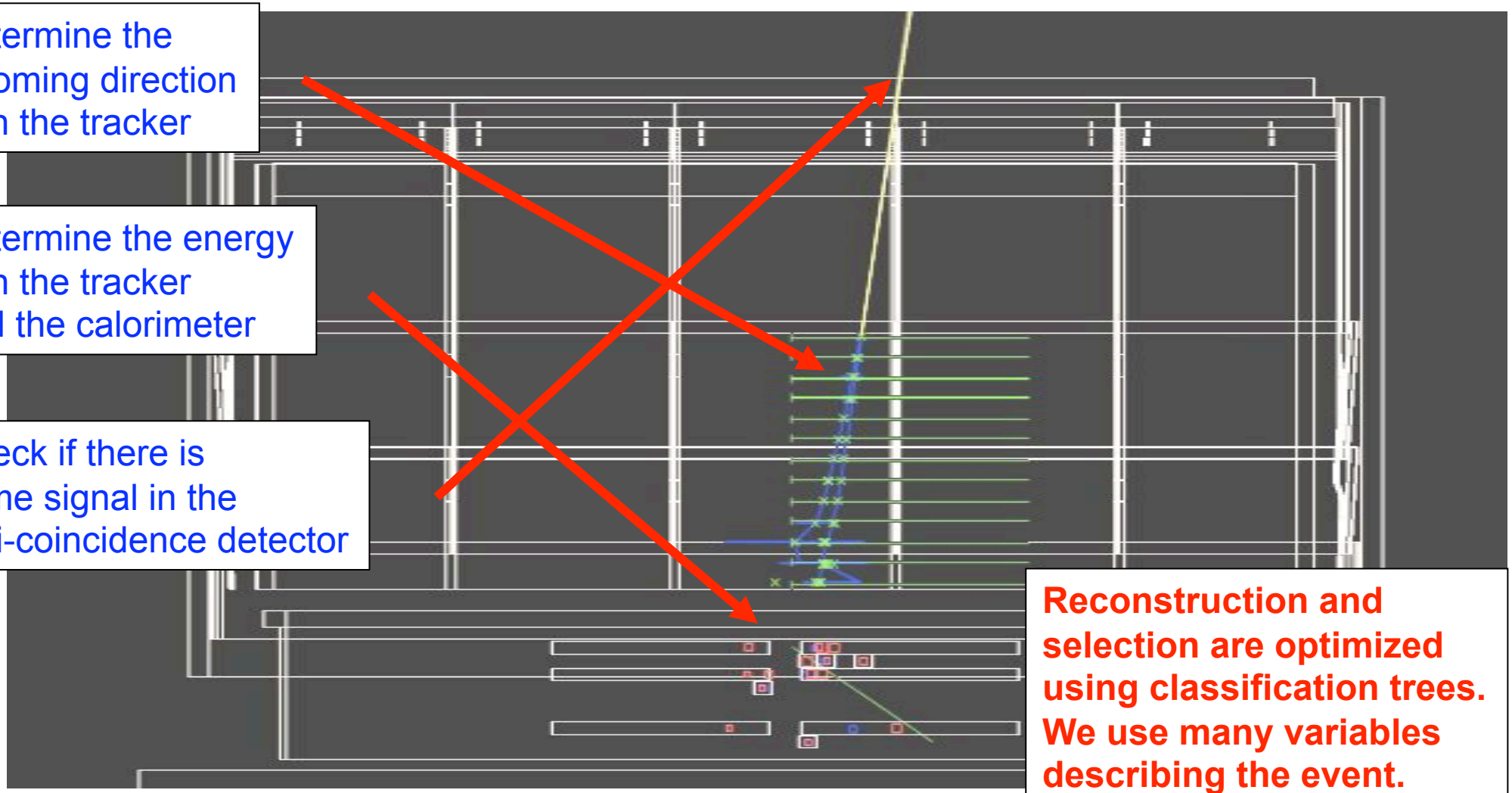
- Hodoscopic tower of 1536 CsI(Tl) crystals: 8.6 radiation lengths on-axis
- 3D shower profile reconstruction for leakage correction and hadron rejection

Event reconstruction

Determine the incoming direction with the tracker

Determine the energy with the tracker and the calorimeter

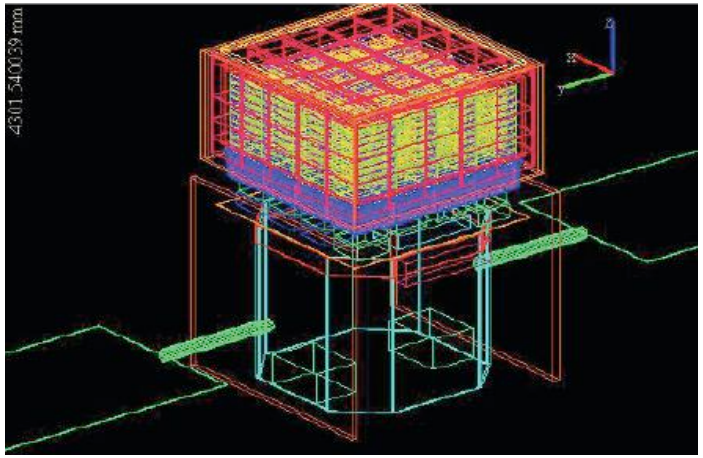
Check if there is some signal in the anti-coincidence detector

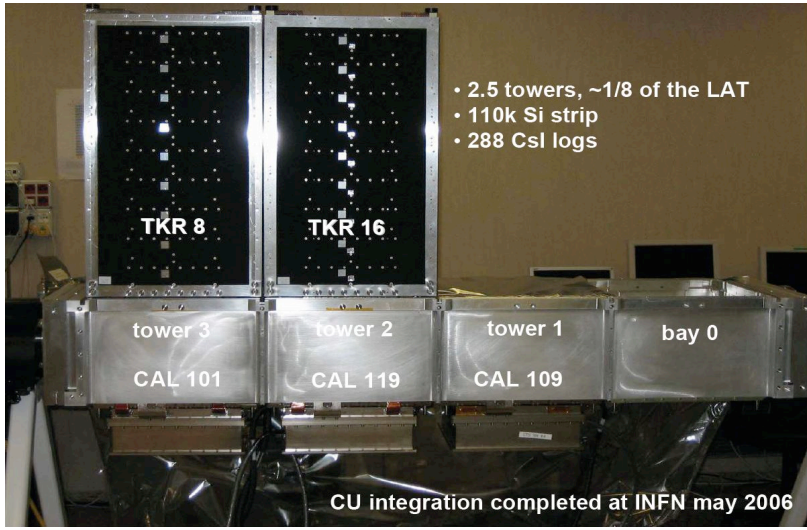


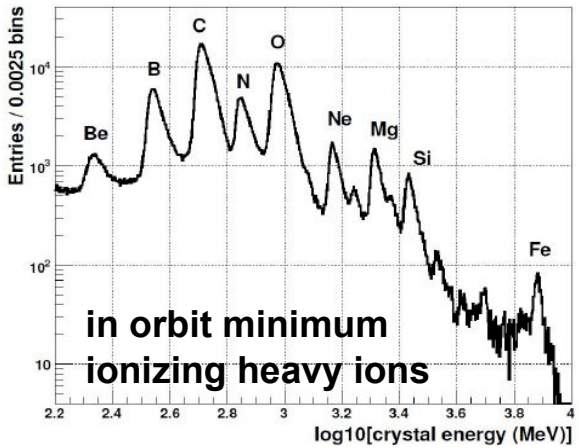
Reconstruction and selection are optimized using classification trees. We use many variables describing the event.

Ensuring the most realistic simulation

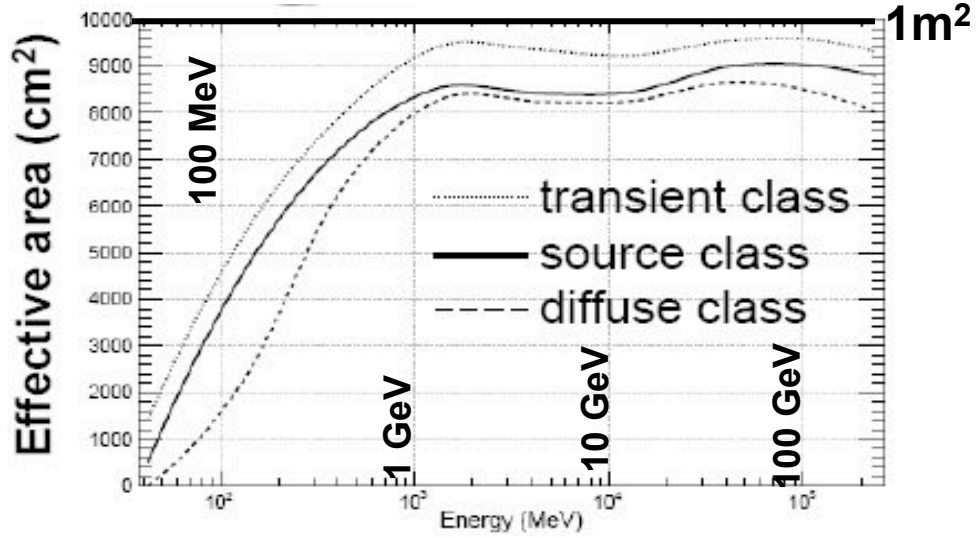
- Detailed instrument simulation with Geant4
  - Reconstruction tuning
  - Event selection and performance
  - Residual background estimation
- Beam tests (the last one at CERN in 2006)
  - Calibration Unit (2.5 towers) with electrons, gammas, protons, pions, from 10 MeV to 300 GeV in many configurations (94M evts)
- Calibrations
  - Using muons (on ground) and protons (in orbit)
  - Intra tower anc[illegible]nent
  - Stability

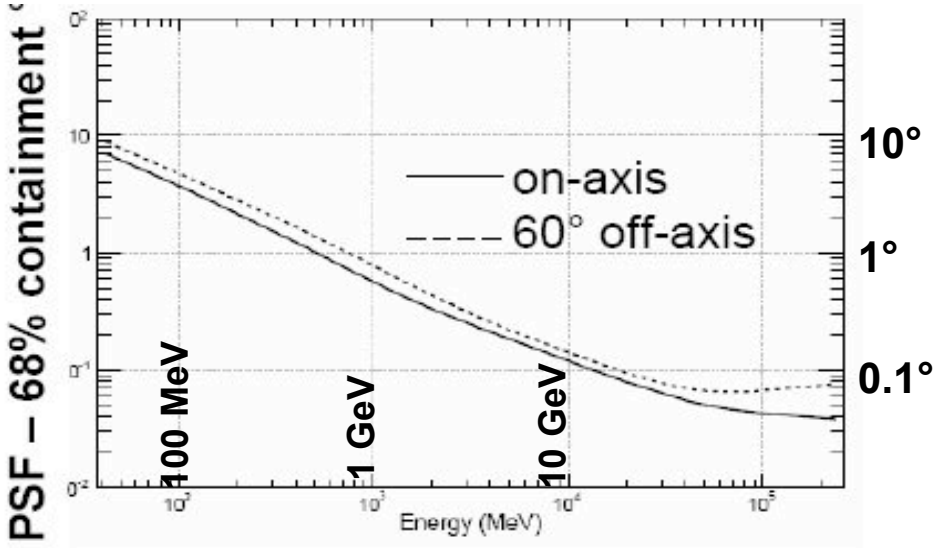


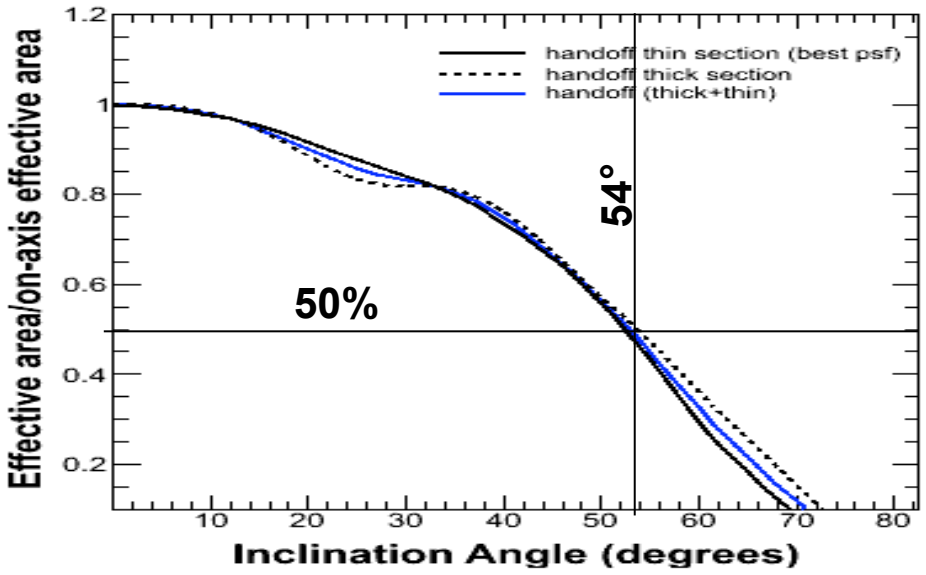


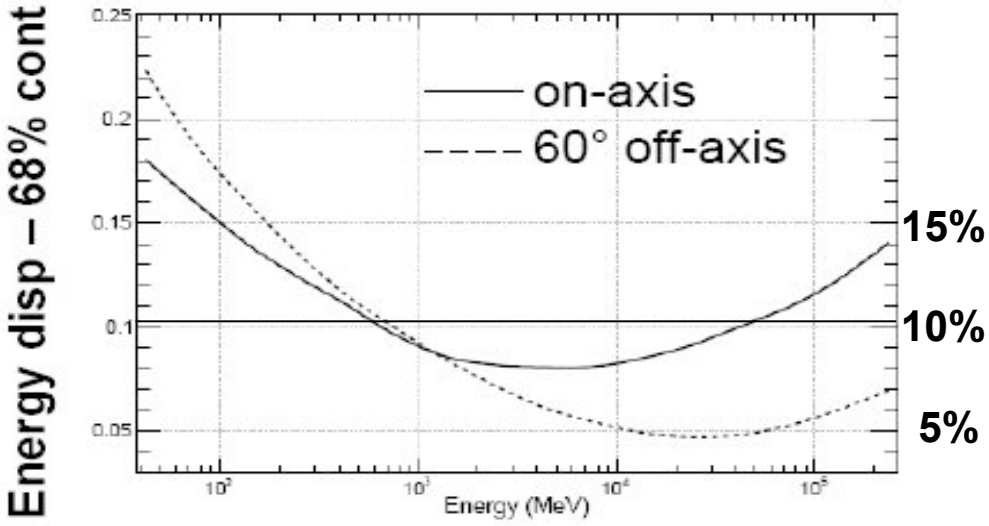


High level performance of Fermi LAT



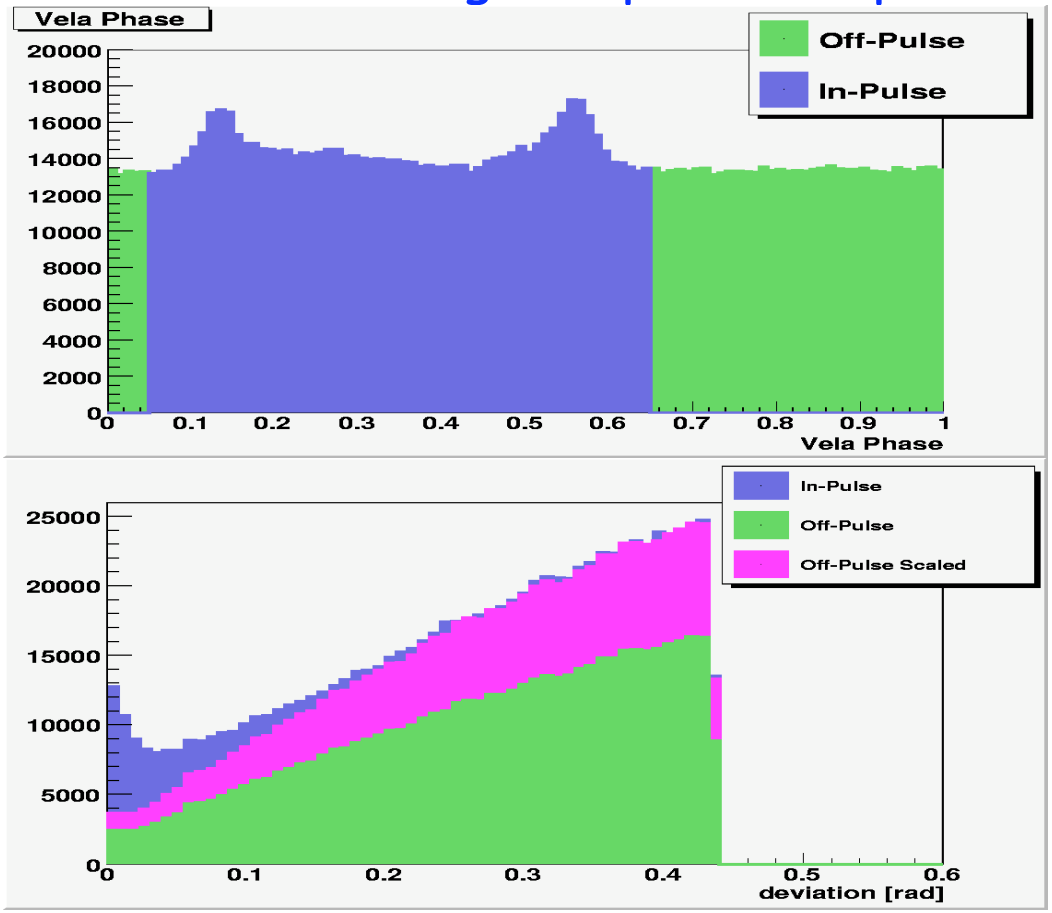


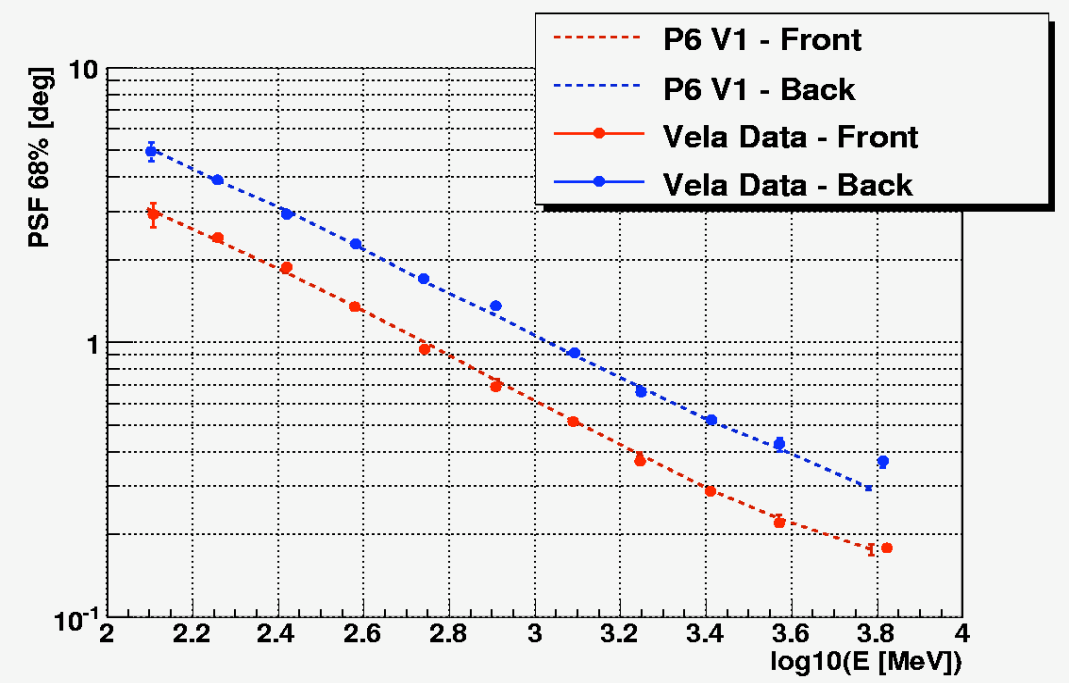




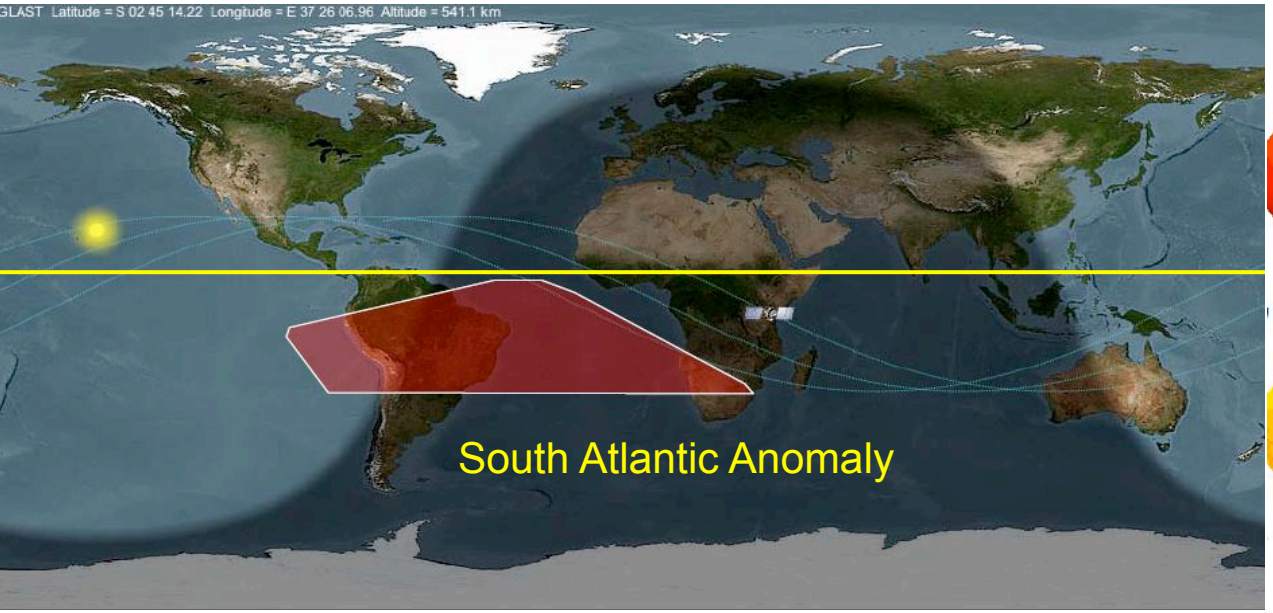
On orbit performance validation

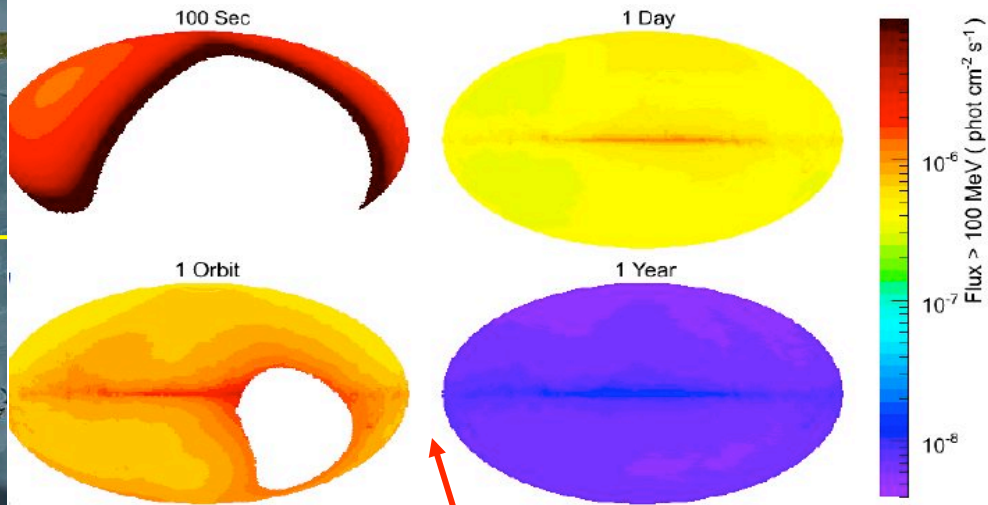
- Main method : using bright pulsars (i.e. Vela)
  - Selecting events in-pulse and off-pulse
  - Subtracting off-pulse component to get a pure gamma signal

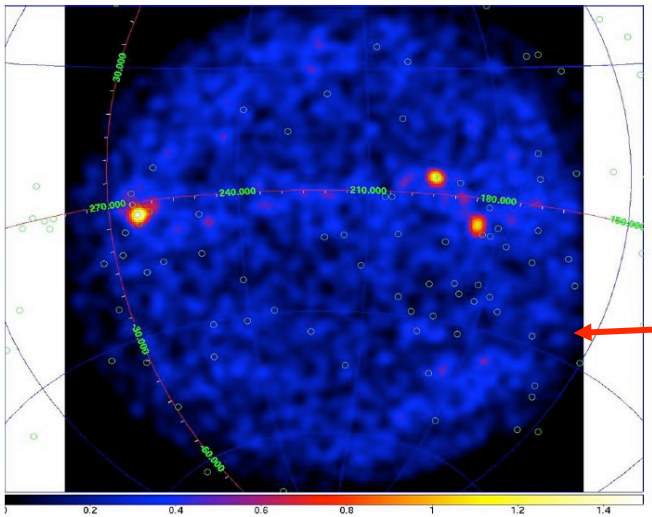




AGILE and Fermi in space : 2 x 2.5 sr



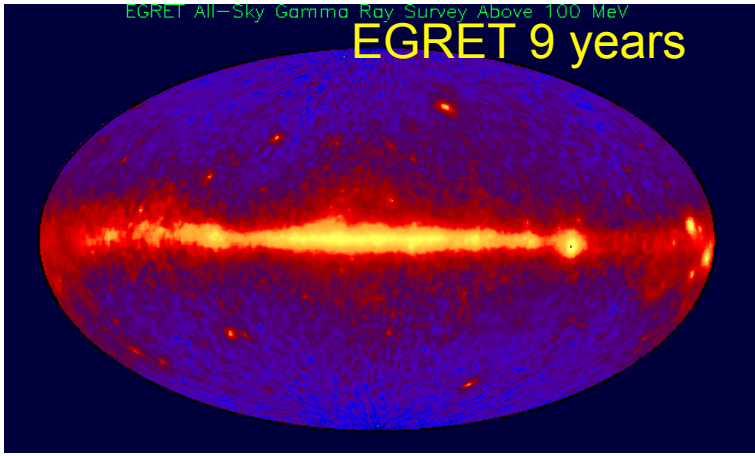


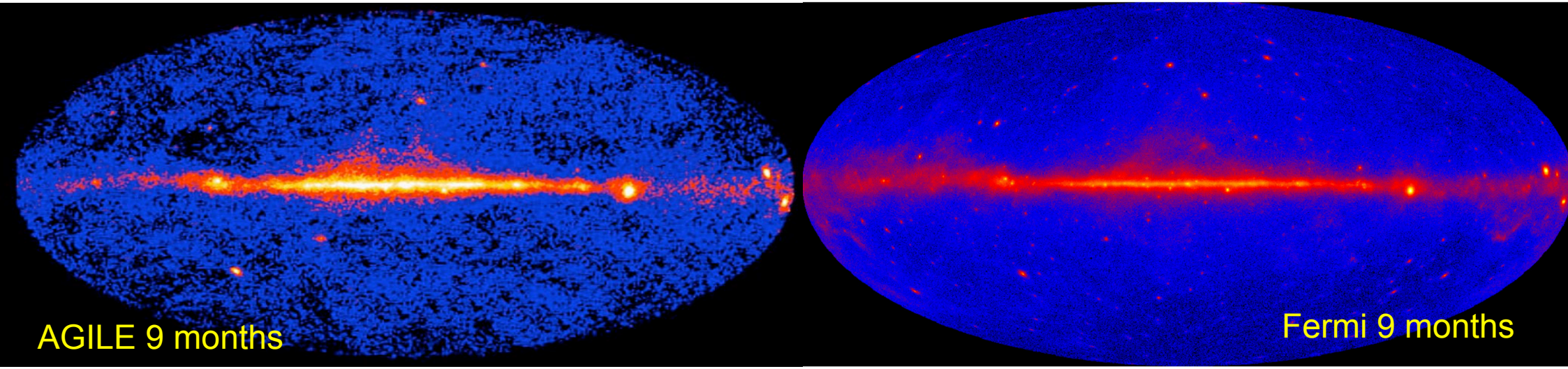


	AGILE	Fermi
Altitude,inclination	535 km, 2.5°	565 km, 25.6°
Period	1.5h	1.5h
Attitude	Pointing	Survey mode Each source is seen ~30min every 3 hours
Lifetime	2+4 years	5+5 years

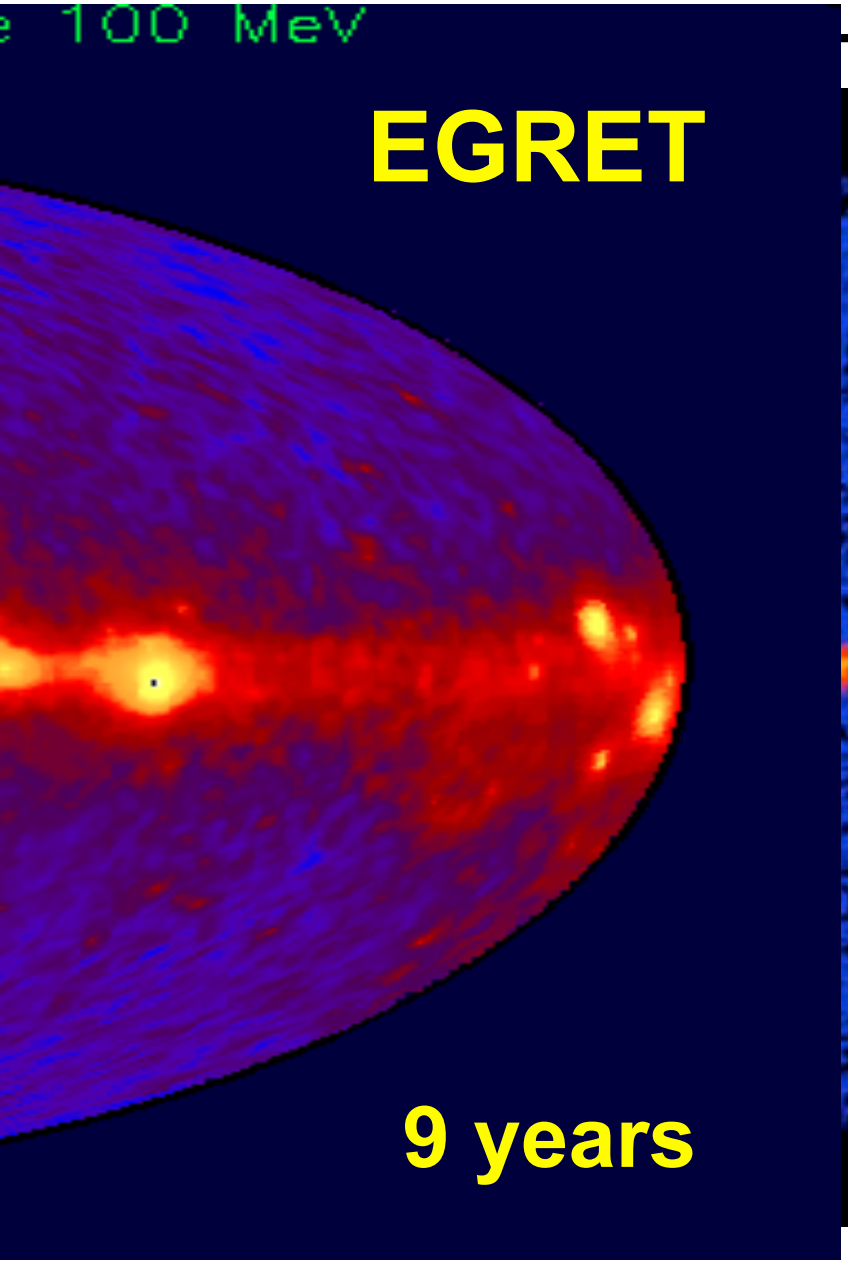
The gamma-ray sky above 100 MeV

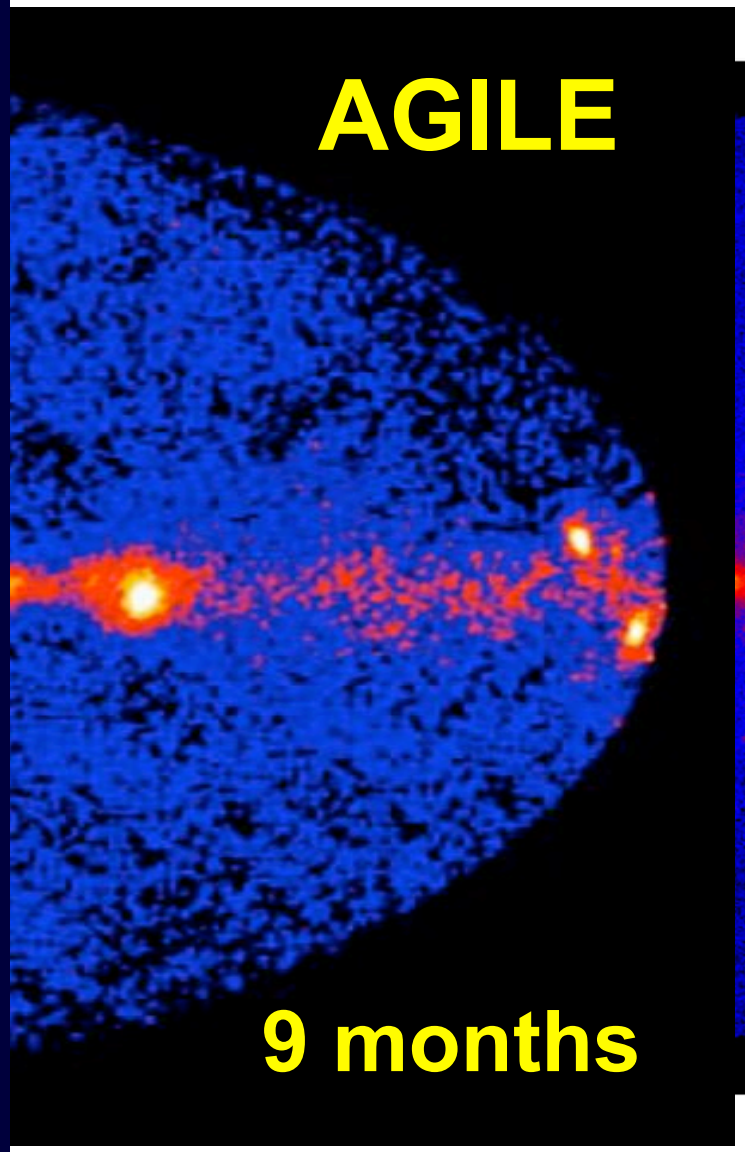
	Ang. Res. (100 MeV)	Ang. Res. (10 GeV)	Eng. Rng. (GeV)	$A_{eff}\,\Omega$ (cm^2 sr)	# γ-rays
EGRET	5.8°	0.5°	0.03–10	750	1.4×10^6
AGILE	~4°	~0.15°	0.02–30	1,500	4×10^6/yr
Fermi	3.5°	0.1°	0.02–300	20,000	80×10^6/yr

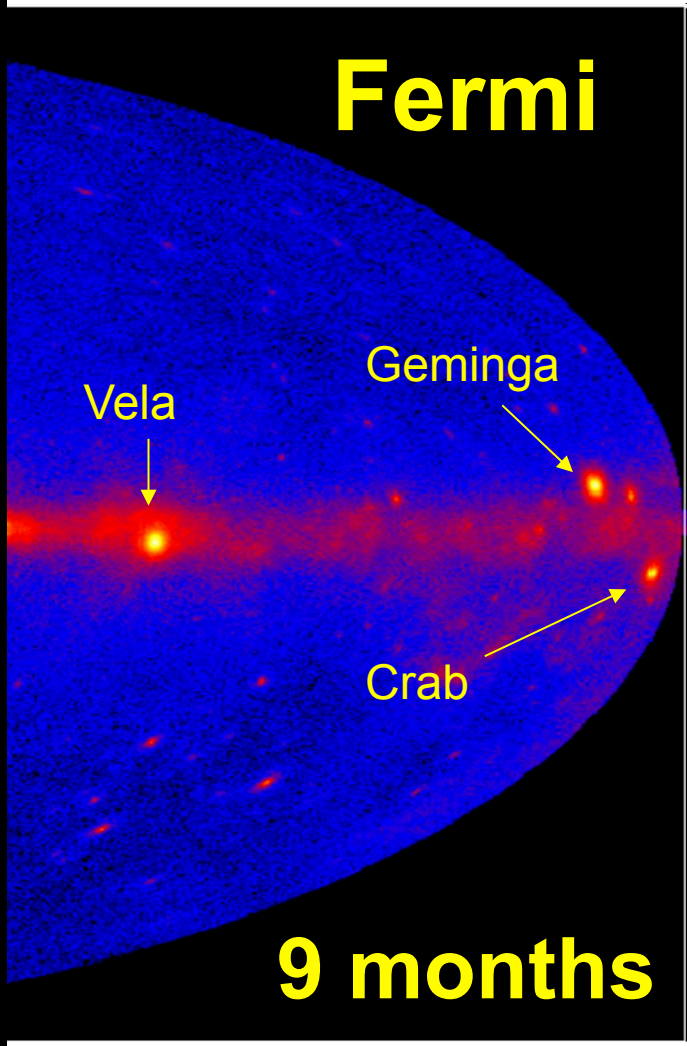




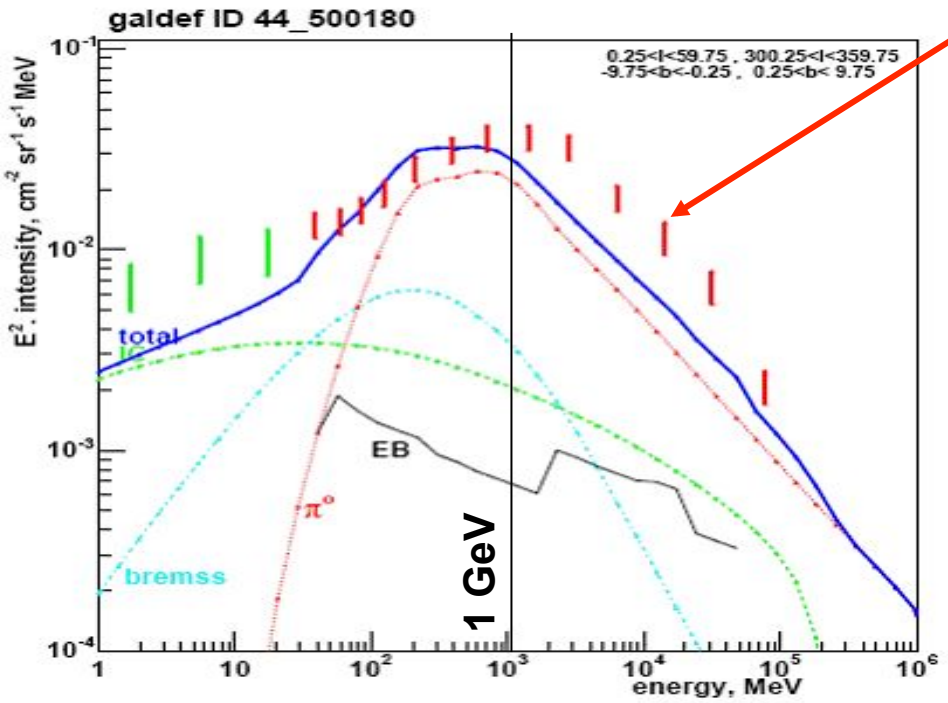
The gamma-ray sky above 100 MeV



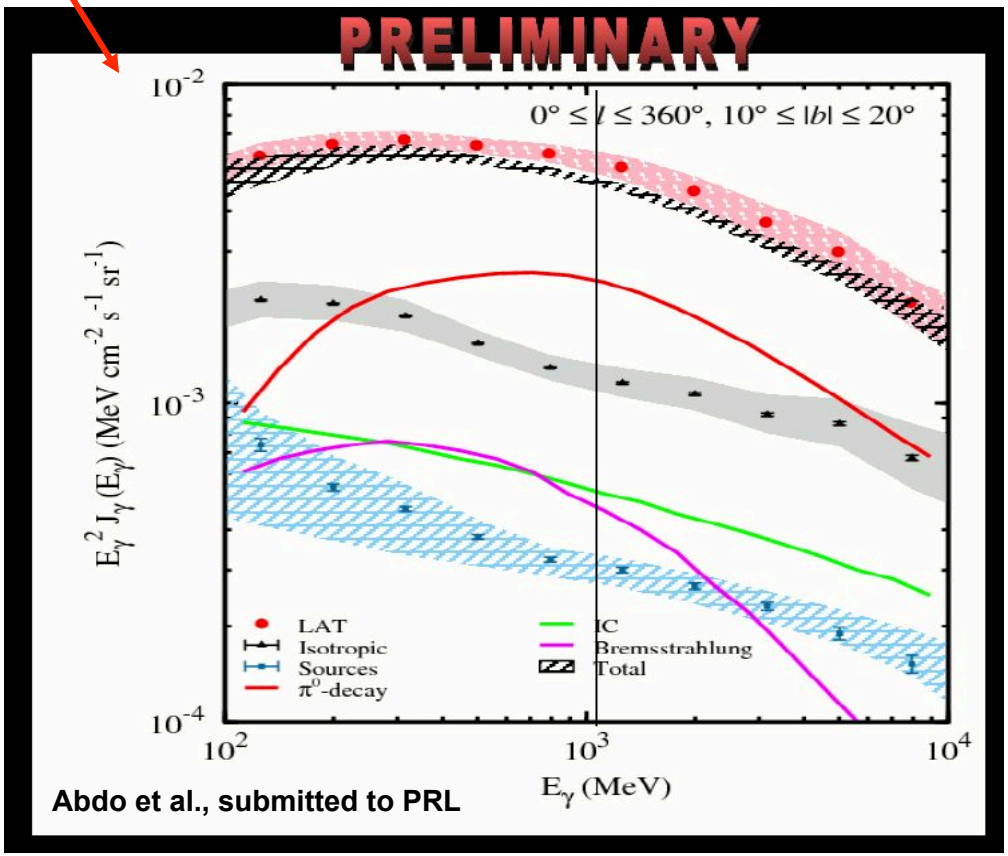




Galactic diffuse emission



- EGRET GeV excess
- Fermi-LAT data averaged over intermediate latitudes 10°<|b|<20° don't confirm the excess



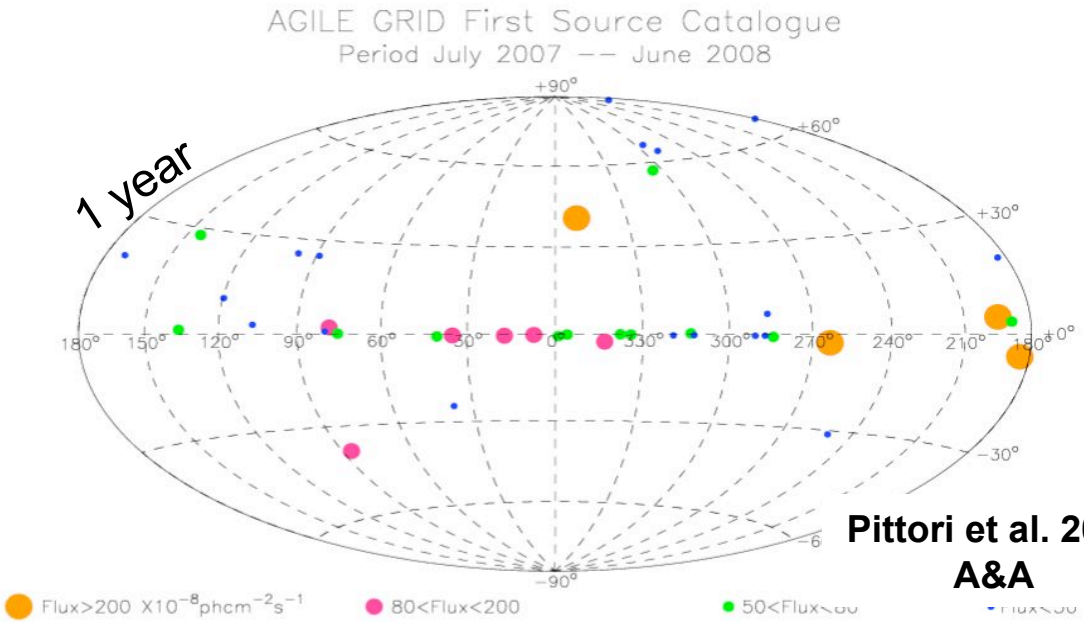
- Model is assumed (based on pre-Fermi data)
  - π° decay
  - BremsStrahlung
  - Inverse Compton

High confidence source lists

- AGILE : 40 sources (>4 σ)

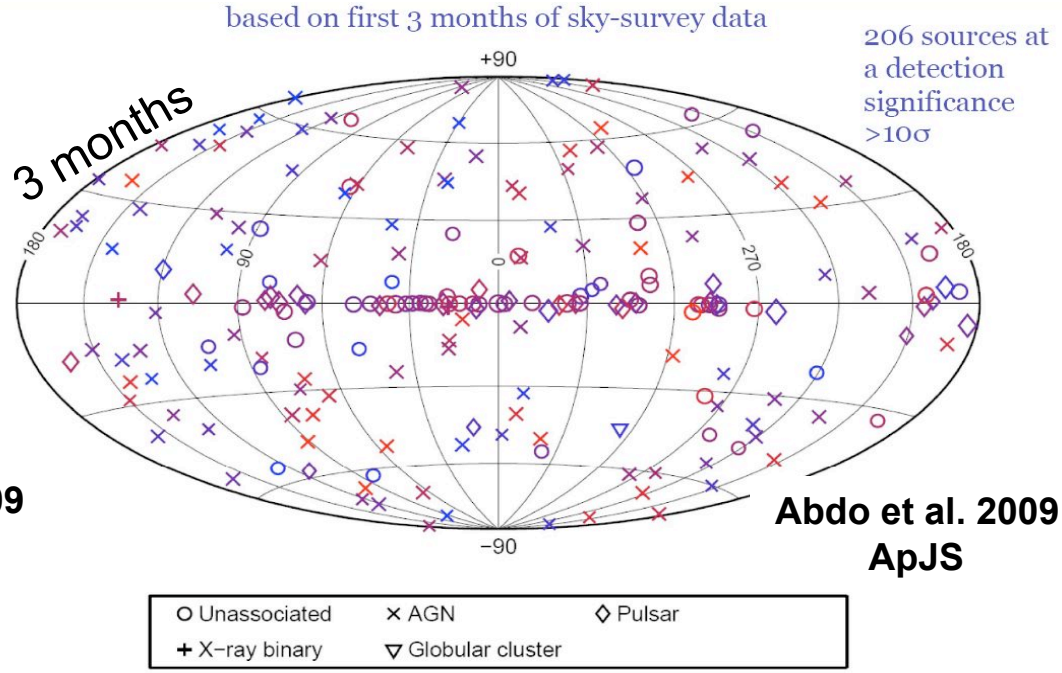
(conservative analysis – low eff.)

  - 7+13 pulsars (50%)
  - 8+5 blazars (33%)
  - 3 unassociated (8%)



Pittori et al. 2009
A&A

- Fermi : 206 sources (>10 σ)
  - 30 pulsars (15%)
  - 119 blazars (58%)
  - 37 unassociated (18%)

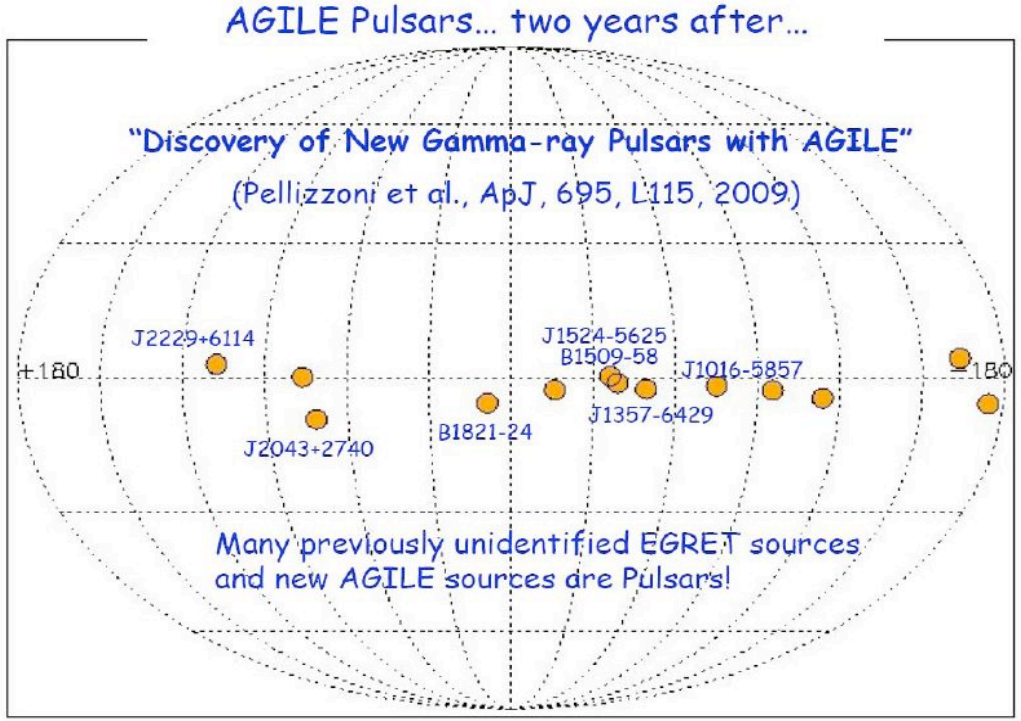


Abdo et al. 2009
ApJS

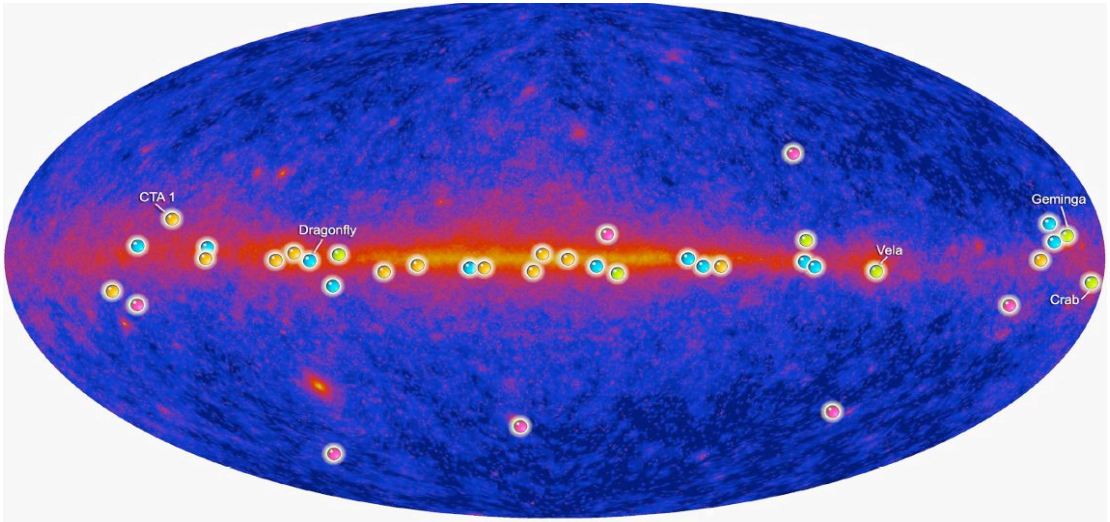
Pulsars

EGRET : 6 pulsars

AGILE : 13 pulsars

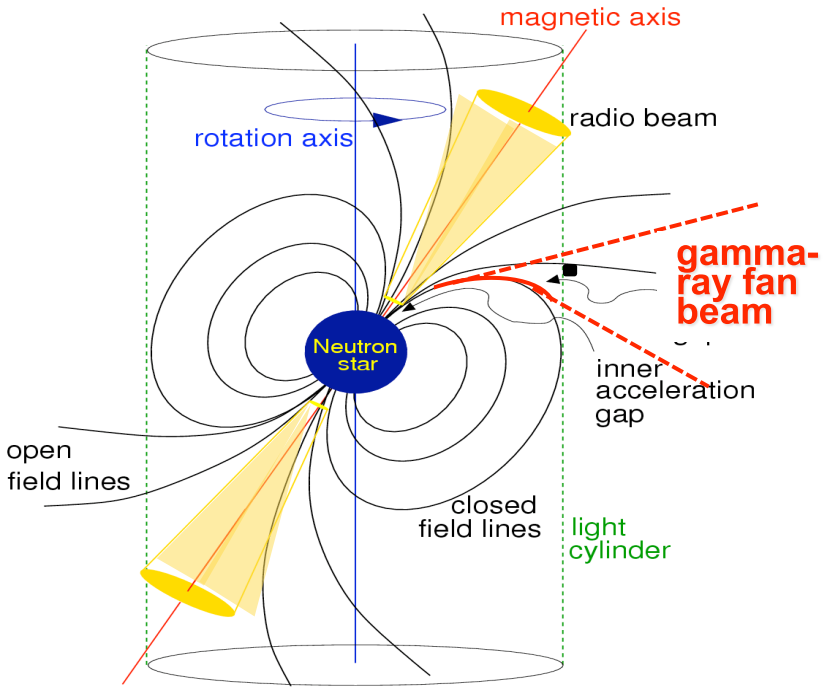


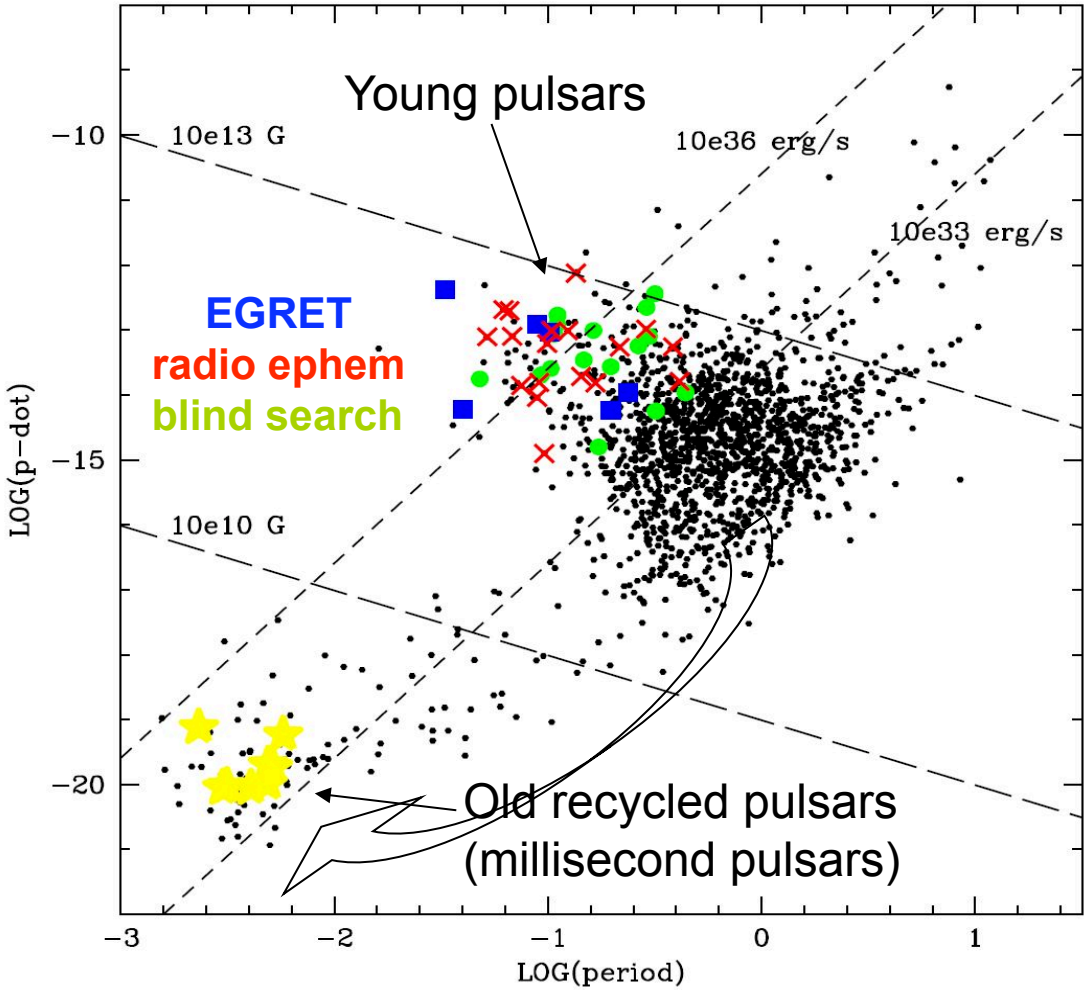
Fermi : 47 pulsars



Different kinds of pulsars ?

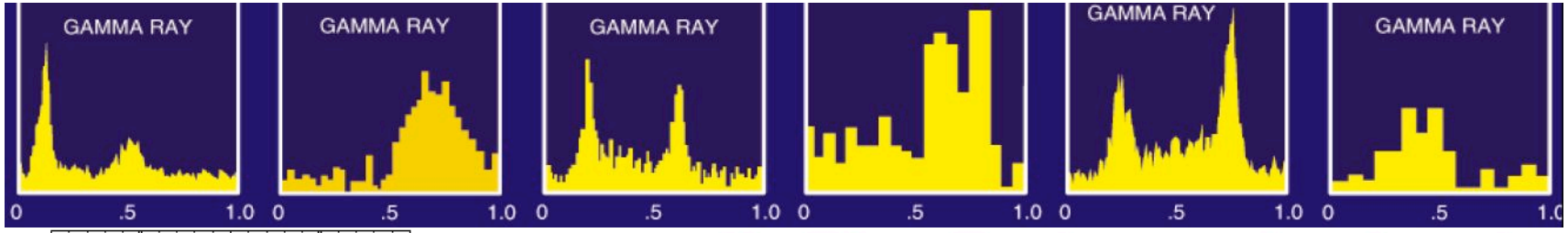
- Fermi 47 pulsars :
  - 6 seen by EGRET
  - 23 young radio pulsars
  - 16 new pulsars discovered in a blind search
  - 8 millisecond pulsars



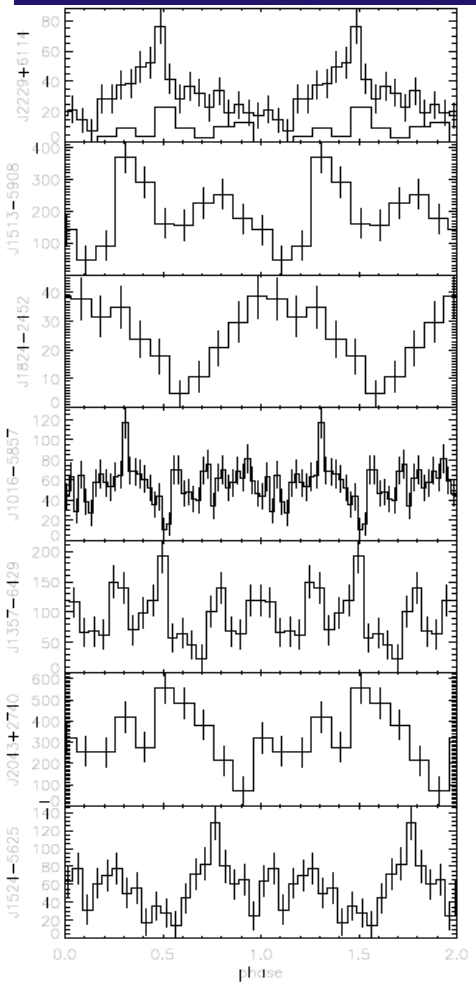


Pulsars characteristics : light curves

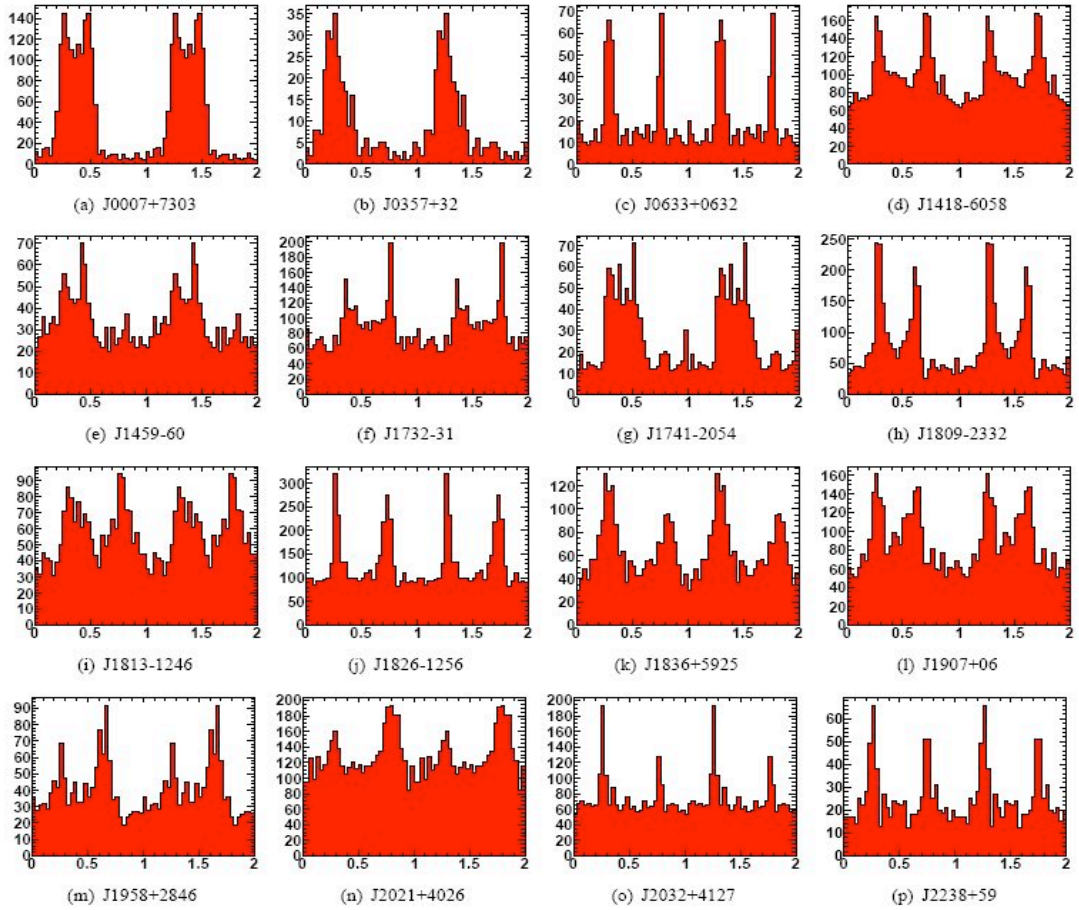
EGRET :



AGILE :

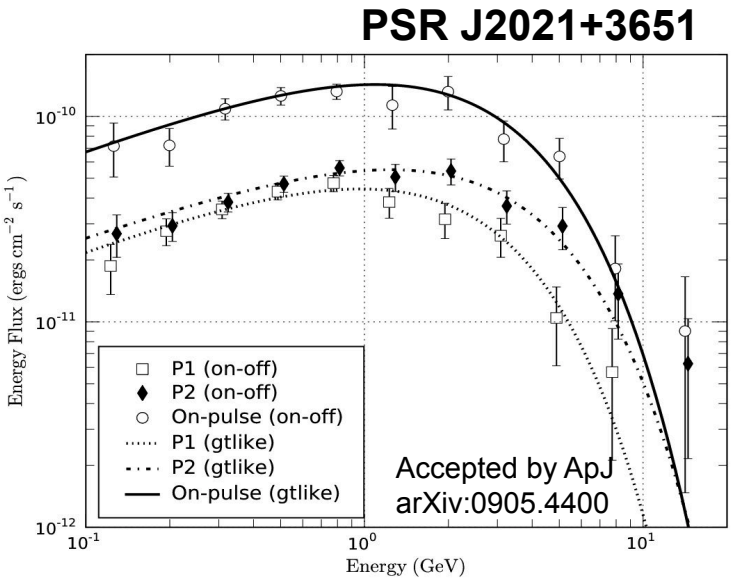


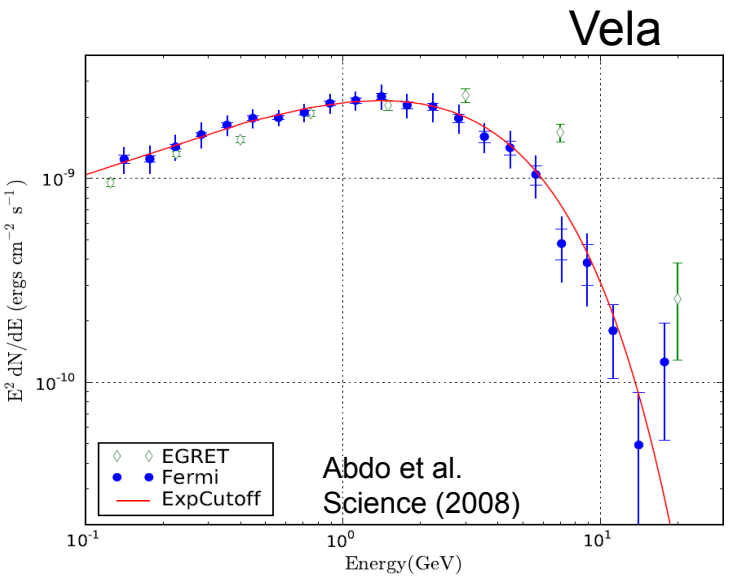
Fermi :



Pulsars characteristics : energy spectra

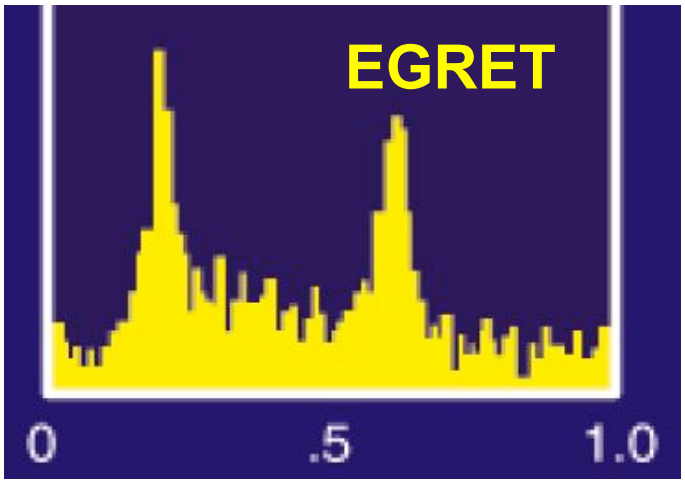
All spectra are power-law with exponential cut-off between ~1 and ~6 GeV





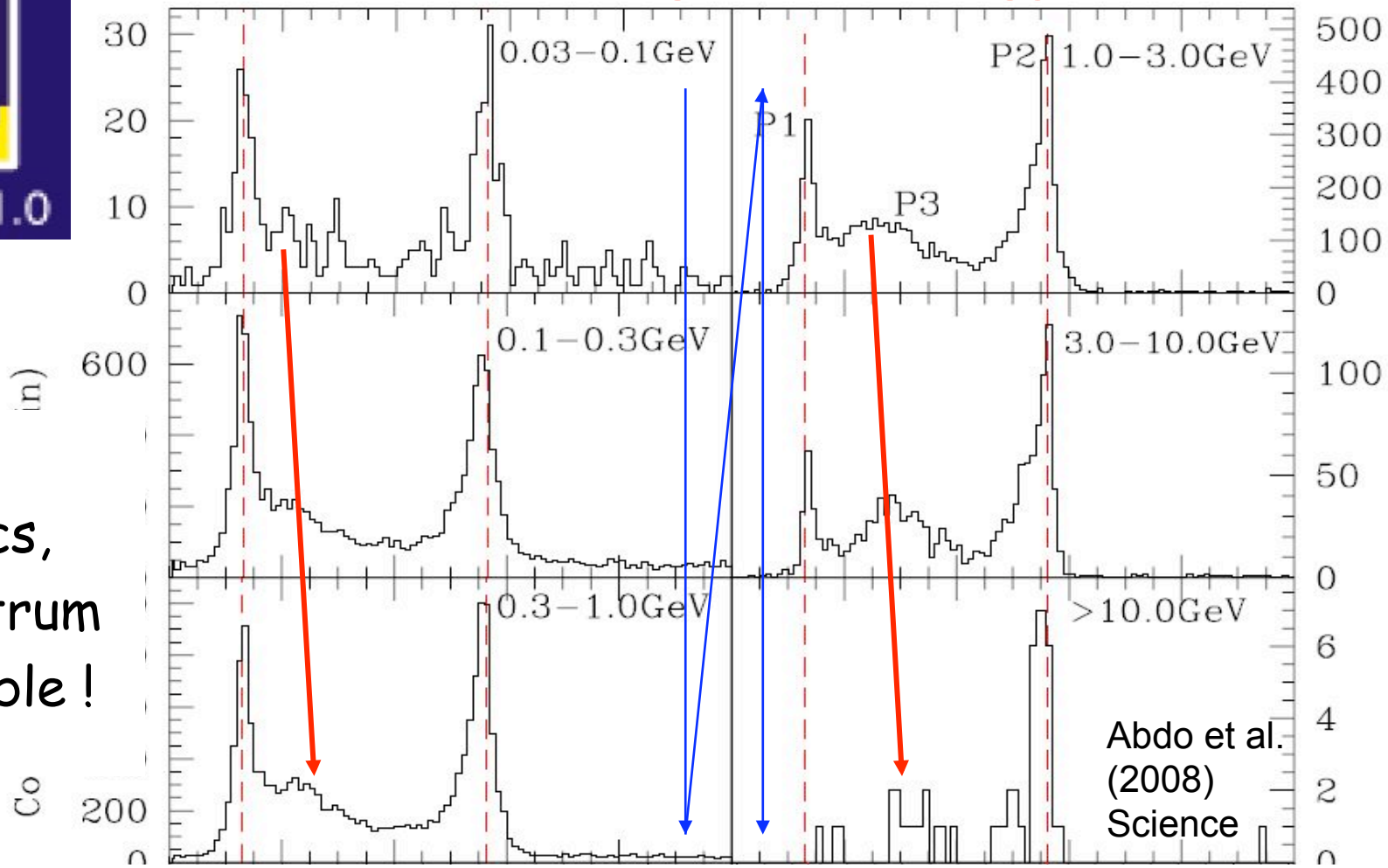
- All kinds of pulsars (radio loud, radio quiet, millisecond pulsars) have the same characteristics (light curve and spectrum) : the emission mechanism is likely the same, taking place in the outer magnetosphere

High statistics pulsar : Vela



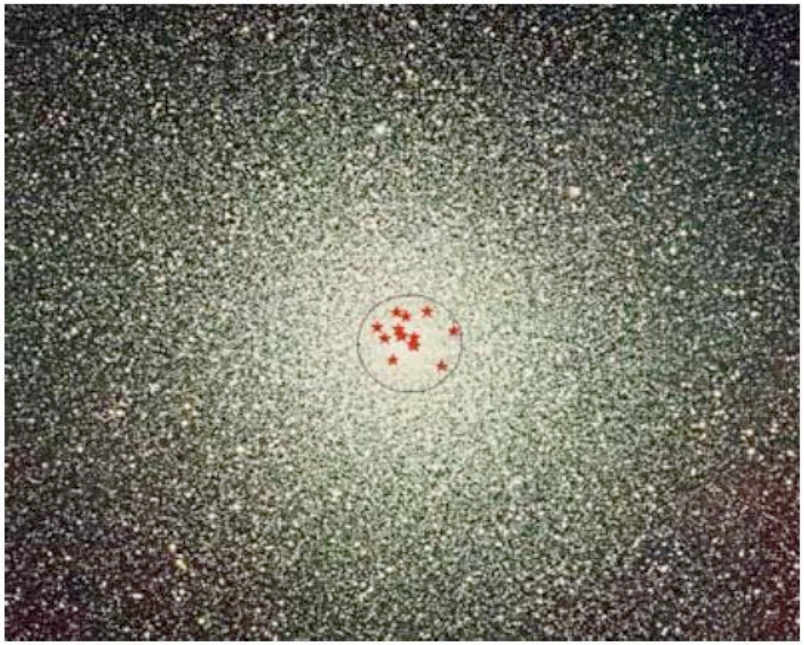
Next to come :
Thanks to statistics,
Phase resolved spectrum
analysis is now possible !

Fermi : a third peak evolving with energy



Globular cluster : 47 Tucanae

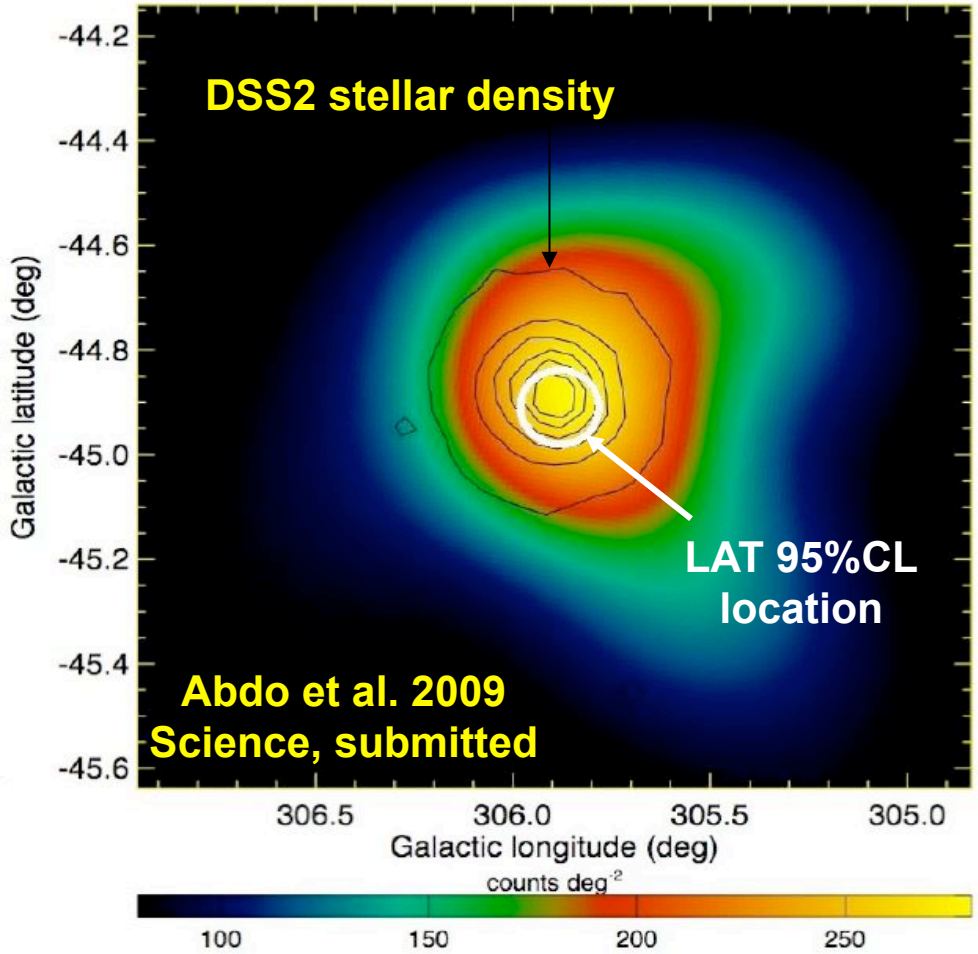
23 MSP in 47 Tucanae



AAO (David Malin)

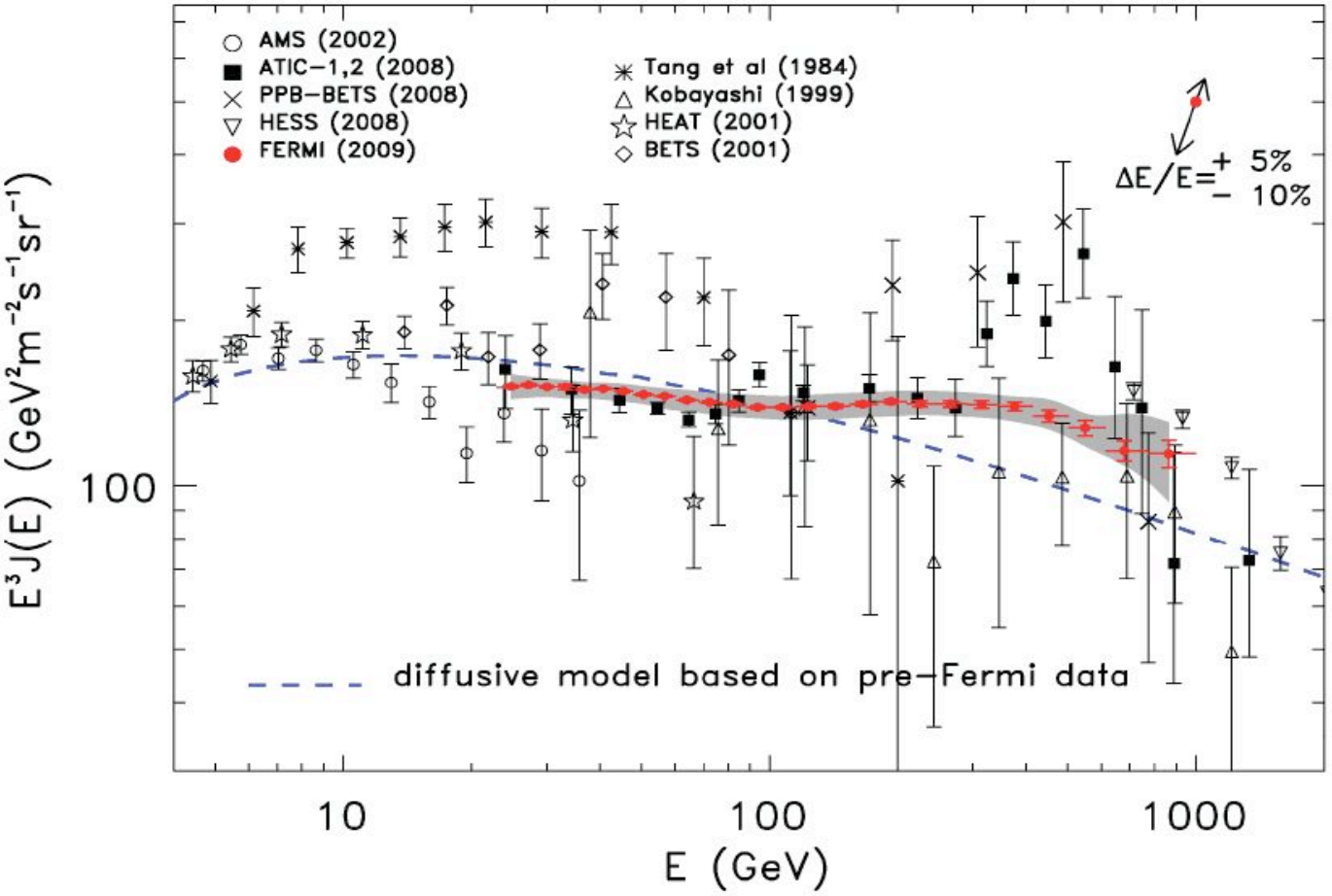
- Long awaited first detection of a globular cluster
- Spectral shape comparable to average of galactic field MSPs
- Luminosity suggests <40 MSPs in 47 Tucanae (radio/X-rays : 30-60)

LAT counts map of 47 Tuc

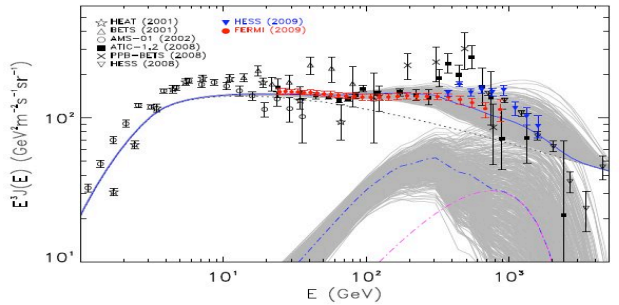


High energy cosmic ray electron spectrum

Fermi is also able to measure the electron+positron spectrum up to 1TeV

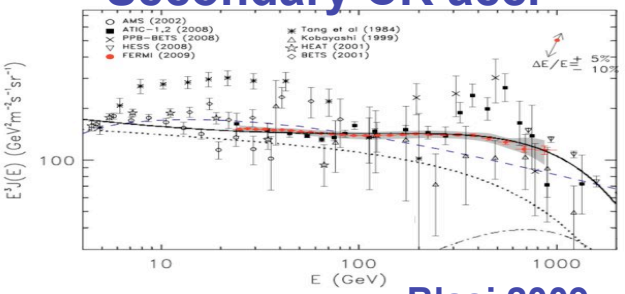


Pulsars



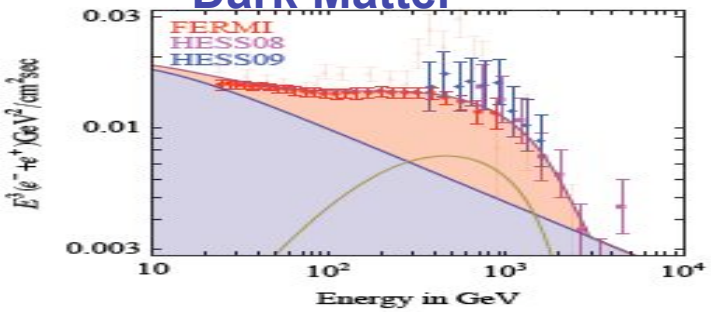
Grasso et al. 2009

Secondary CR acc.



Blasi 2009

Dark Matter



Strumia et al. 2009

Unified picture of AGNs

- Powered by accretion onto a central, supermassive black hole
- Jets: highly collimated outflows with $\Gamma \sim 10$
  - Large brightness temps, superluminal motion, rapid variability in γ-rays
- Unified Model: observer line-of-sight determines source properties, e.g., radio galaxy vs blazar
- Other factors: accretion rate, BH mass and spin
- Open questions: nature of plasma, location of dissipation, gamma-ray emission processes

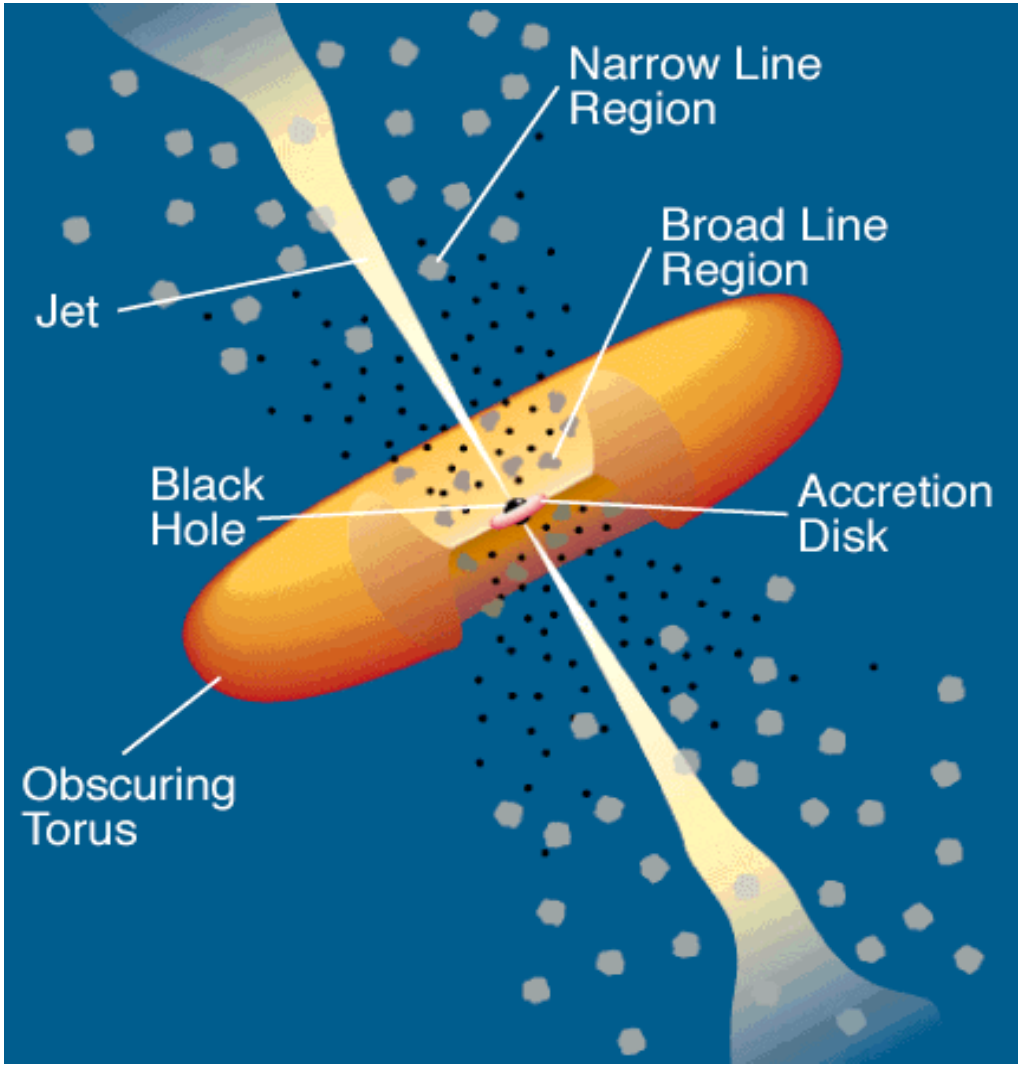
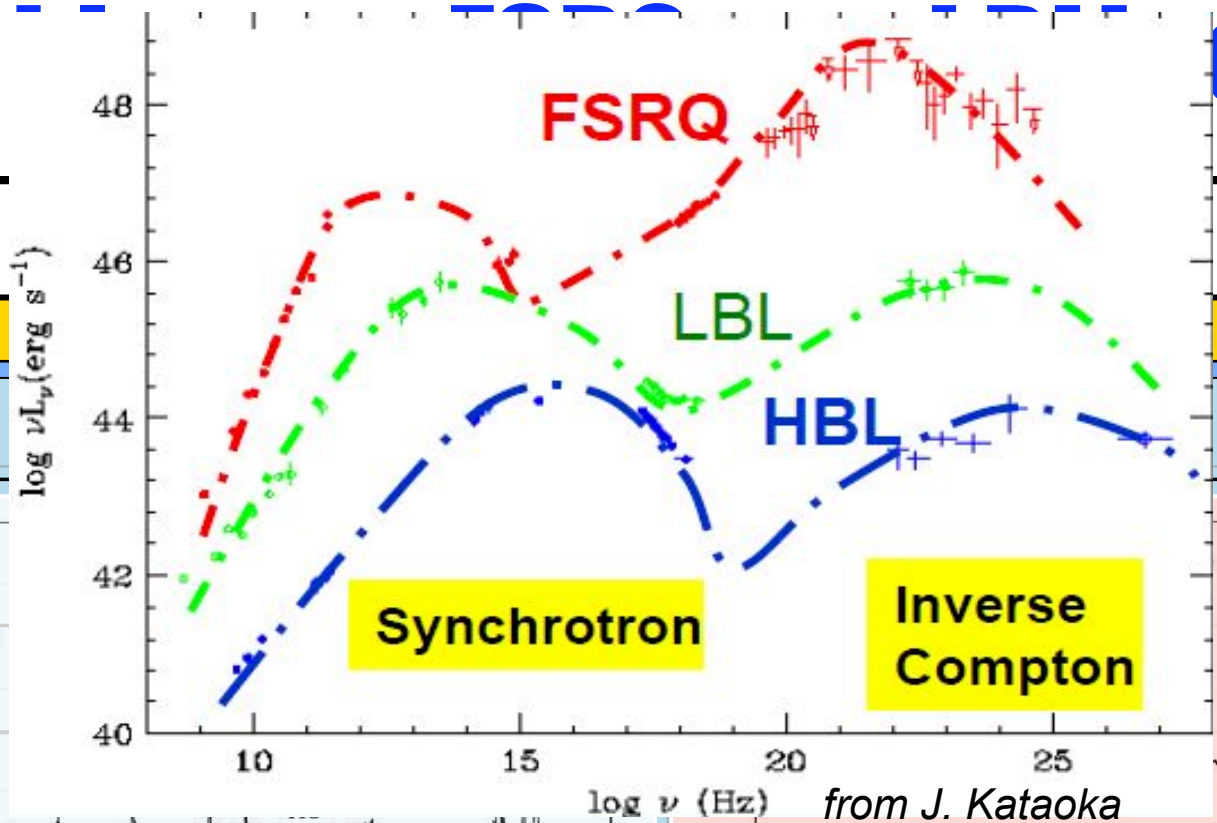


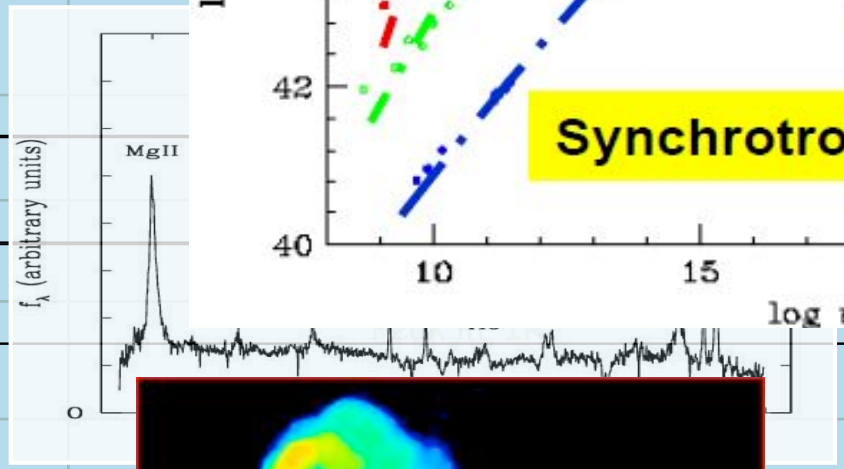
Image Credit: C.M.Urry & P. Padovani

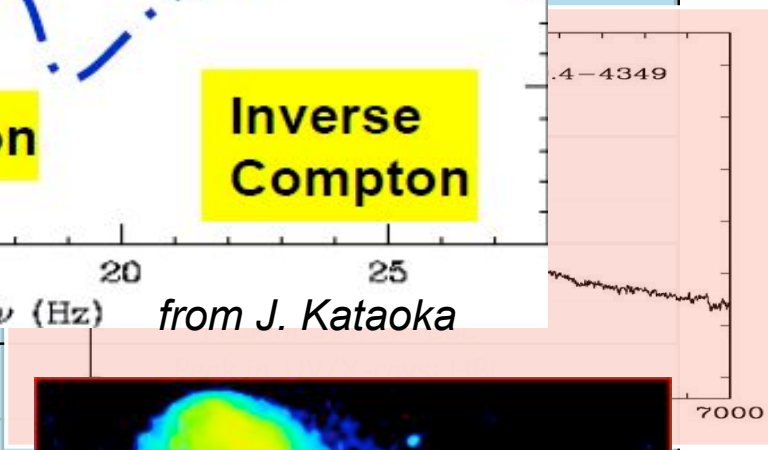
Two flavors of [illegible] cs

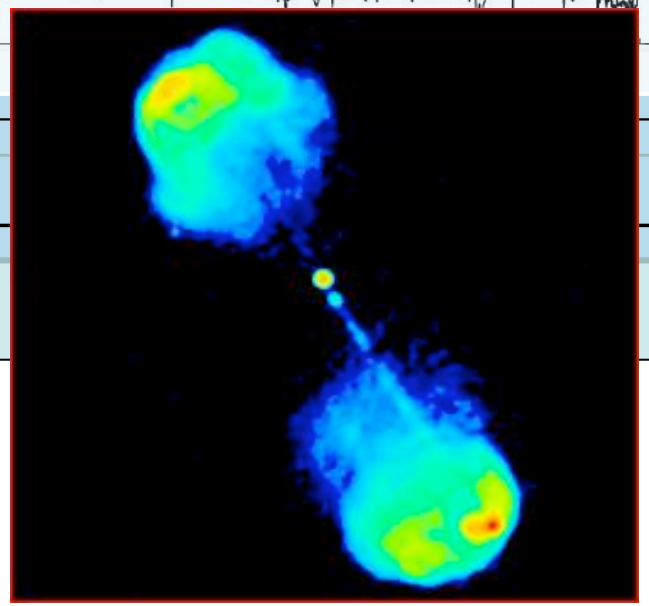
class	
defining property	
environment	
Power	
Parent population	
Synchrotron hump in SED	
EGRET-detected	
Redshift of EGRET sources	

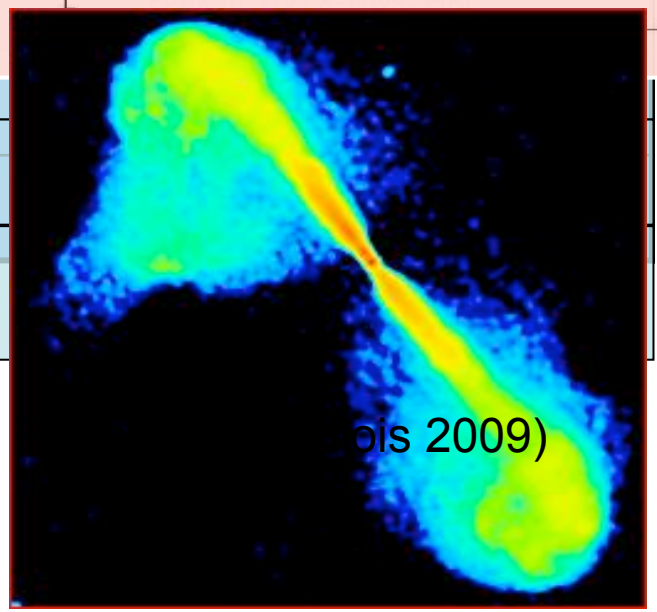


from J. Kataoka





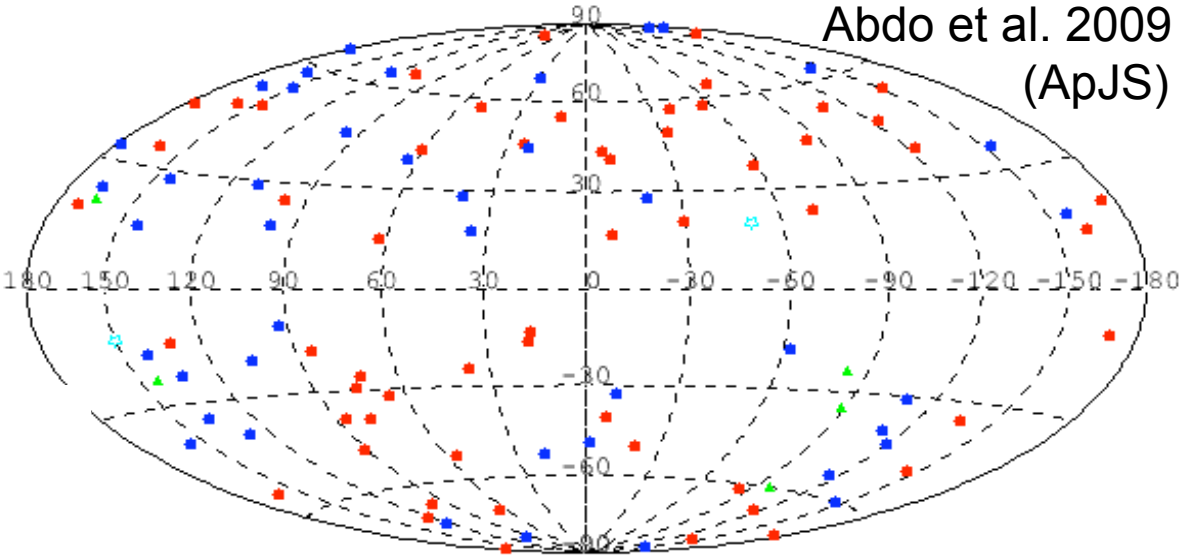




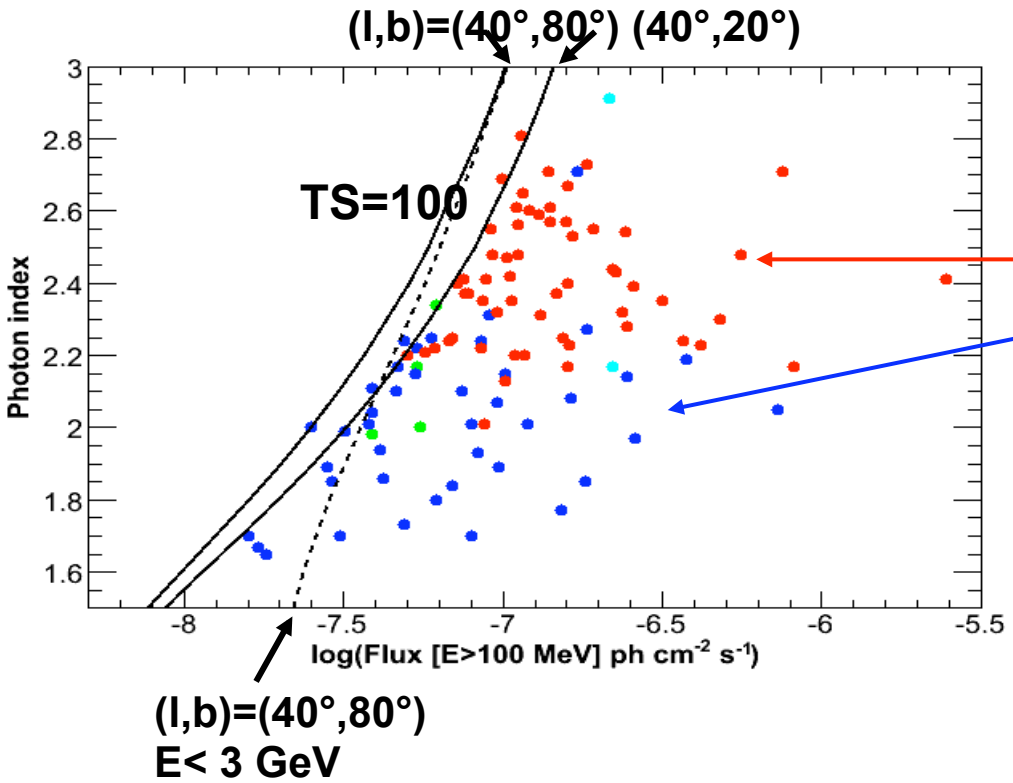
ois 2009)

Fermi bright AGN sample (LBAS)

3-month dataset, >10σ significance: 106 sources at |b|>10° with high-confidence AGN associations, 2/3 of which non-detected by EGRET

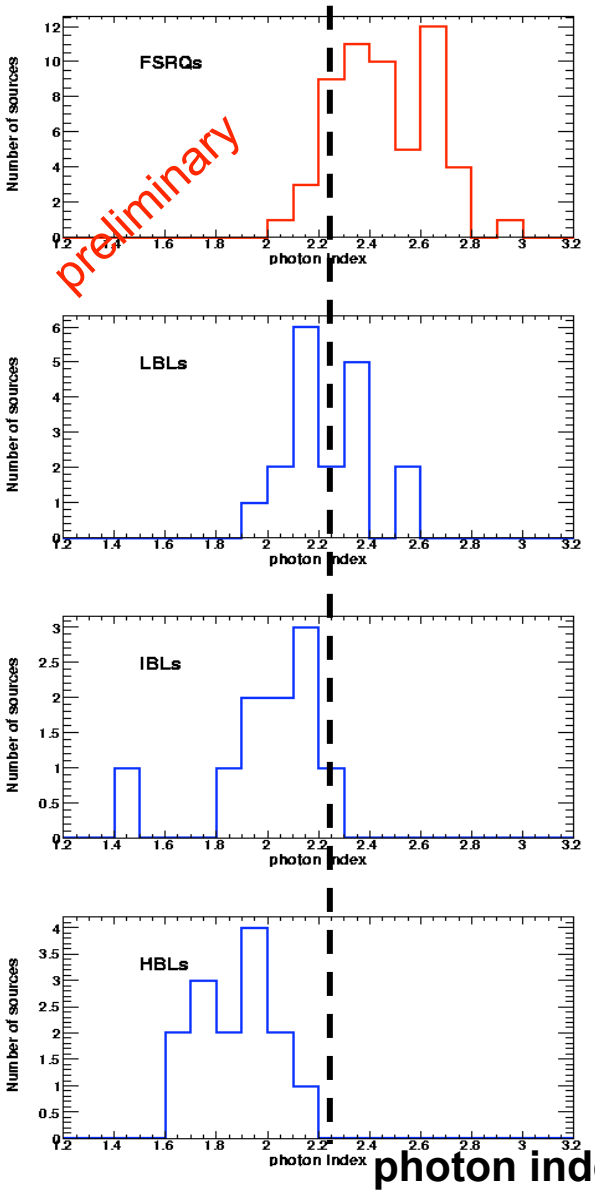


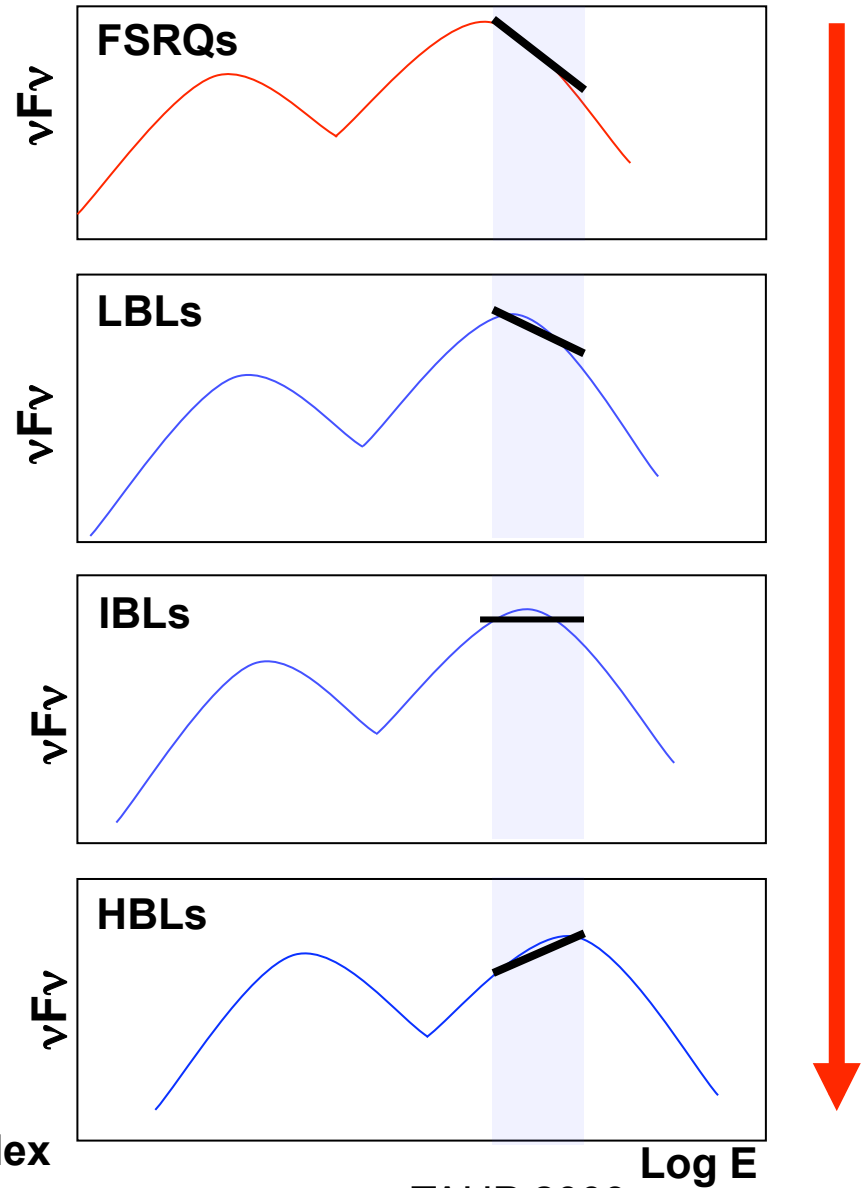
Abdo et al. 2009 (ApJS)



- 57 FSRQs (50%) (EGRET : 77%)
- 42 BLLacs (40%) (EGRET : 23%) including 10 HBLs
- 5 of Unknown type
- 2 Radio Galaxies (Cen A, NGC1275)

Fermi AGNS : photon index distributions



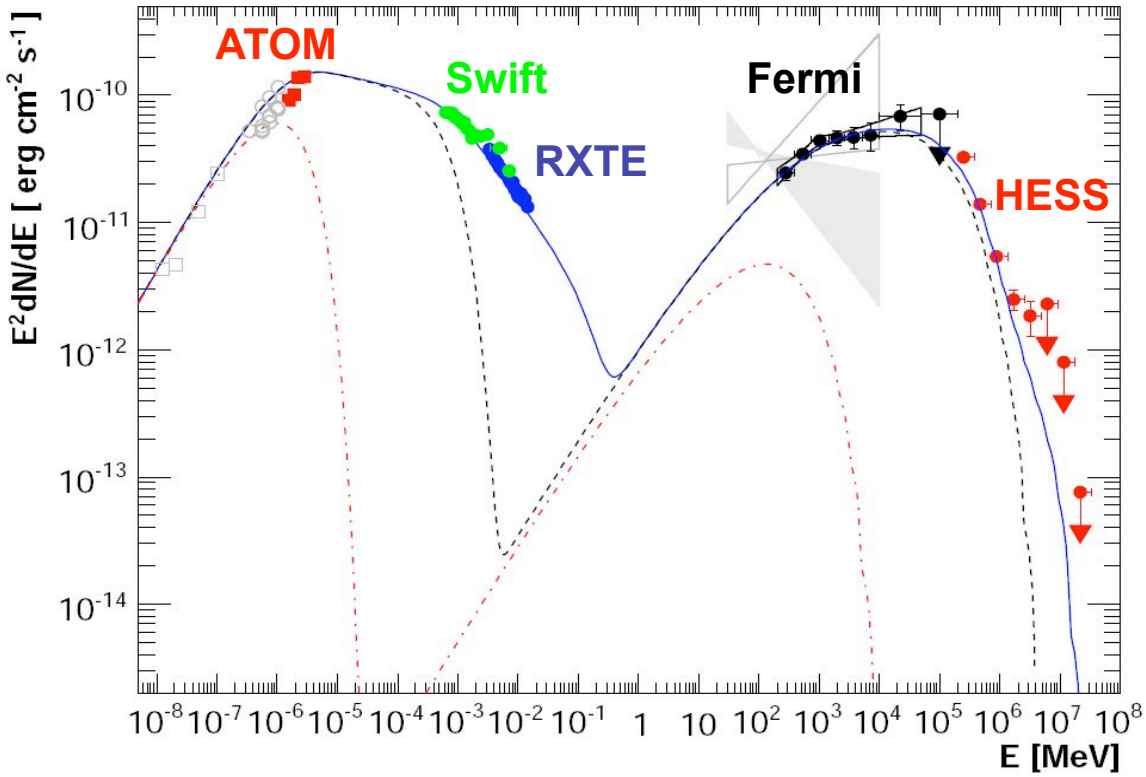


Possible unification scenario (Ghisellini arXiv:0903.2043)

- From FSRQs (young, showing cosmic evolution) with standard accretion of the disk
- to BLLacs ("old", no cosmic evolution) with radiatively inefficient accretion of the disk

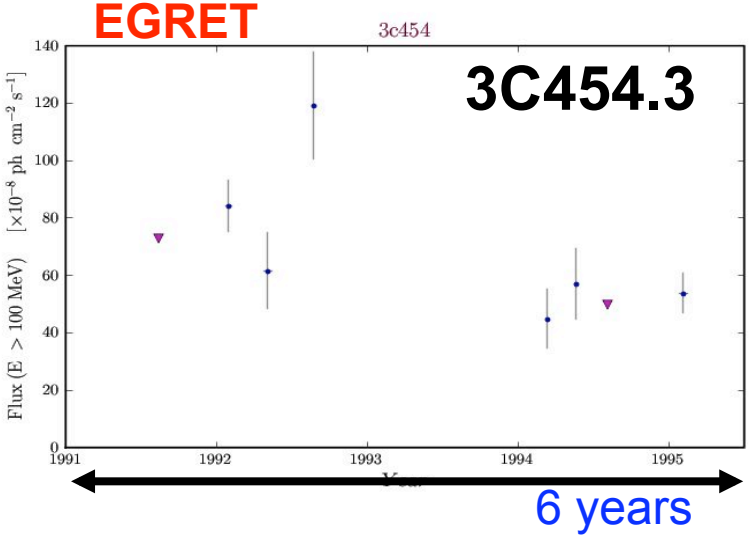
PKS 2155-304: Individual SED analysis

- PKS 2155-304:
  - HBL, z=0.116
- First simultaneous SED including GeV-TeV data
- Unexpected correlations:
  - strong correlation between optical and TeV fluxes
  - X-ray flux varies independently of TeV flux
  - correlation between TeV flux and GeV photon index
- Challenge simple SSC models



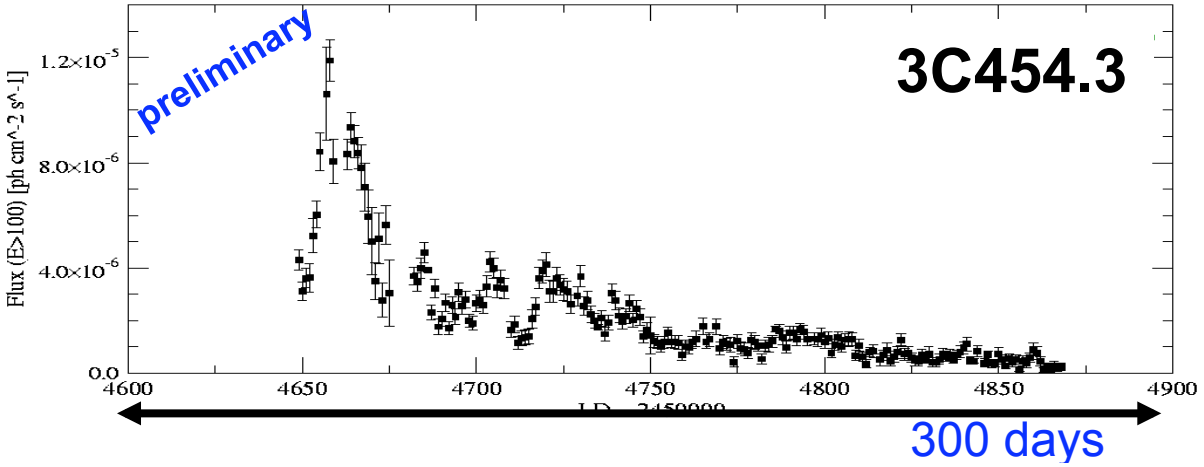
Source monitoring and variability

EGRET

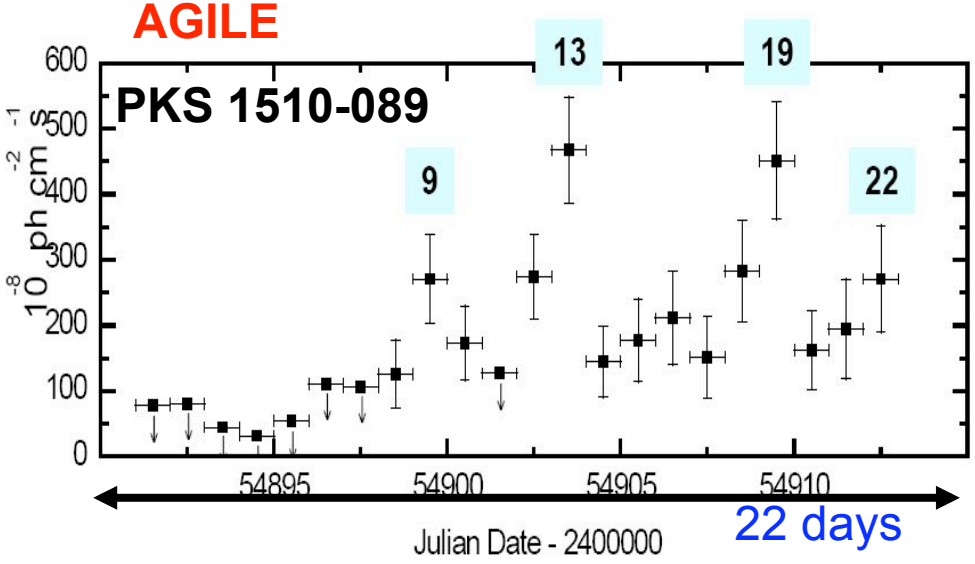


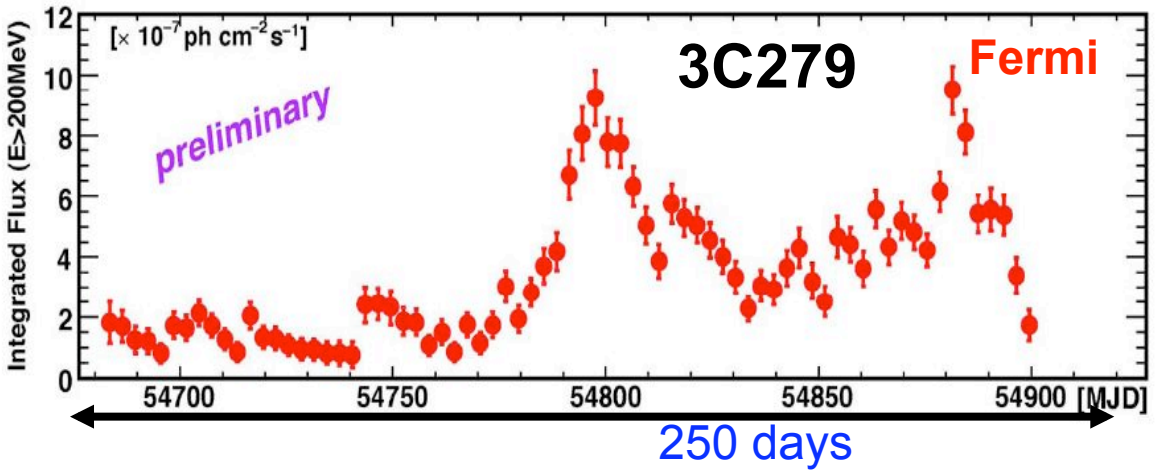
EGRET: sparse 15-day long viewing periods
-> very difficult to establish variability patterns

Fermi



AGILE

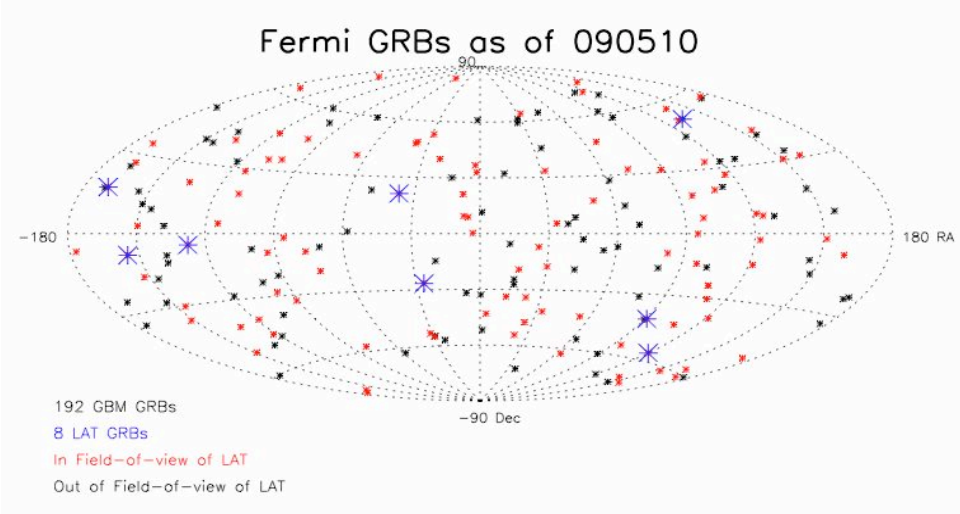




Gamma Ray Bursts

EGRET : 4 GRBs

- **AGILE as of 090510 :**
  - X-ray localizations : 21
  - <50MeV detections : 103
  - 20 MeV-10 GeV : 3
    - 080514B - one evt at 300 MeV
    - 090401B
    - 090510 - >100 MeV short GRB

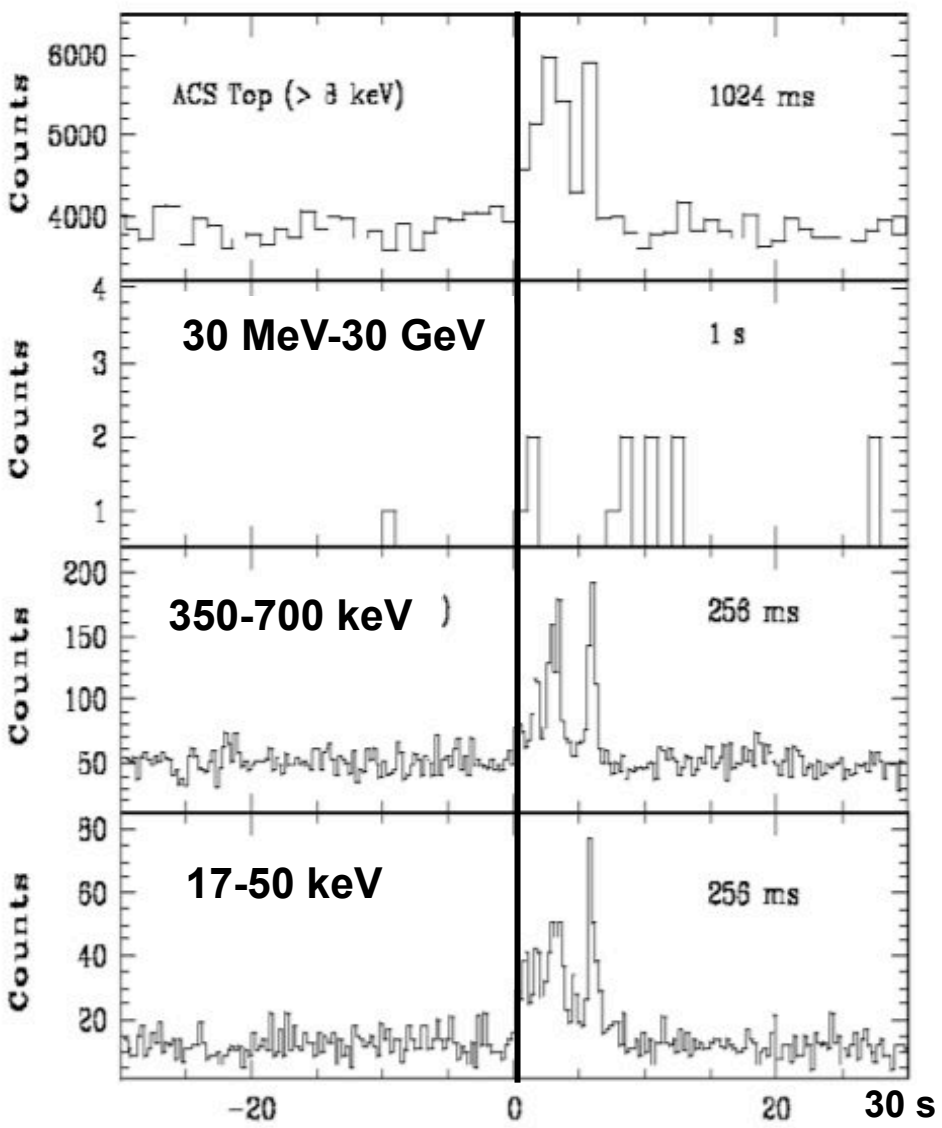


- **Fermi as of 090510 :**
  - GBM (<40 MeV) : 192
  - LAT (>20 MeV) : 8
    - GRB 080825C
    - GRB 080916C – very strong, z=4.35
    - GRB 081024B – short
    - GRB 081215A – LAT rate increase
    - GRB 090217
    - GRB 090323 – ARR, z=3.6
    - GRB 090328 – ARR, z=0.736
    - GRB 090510 – short, intense, 1st LAT GCN notice, z=0.9

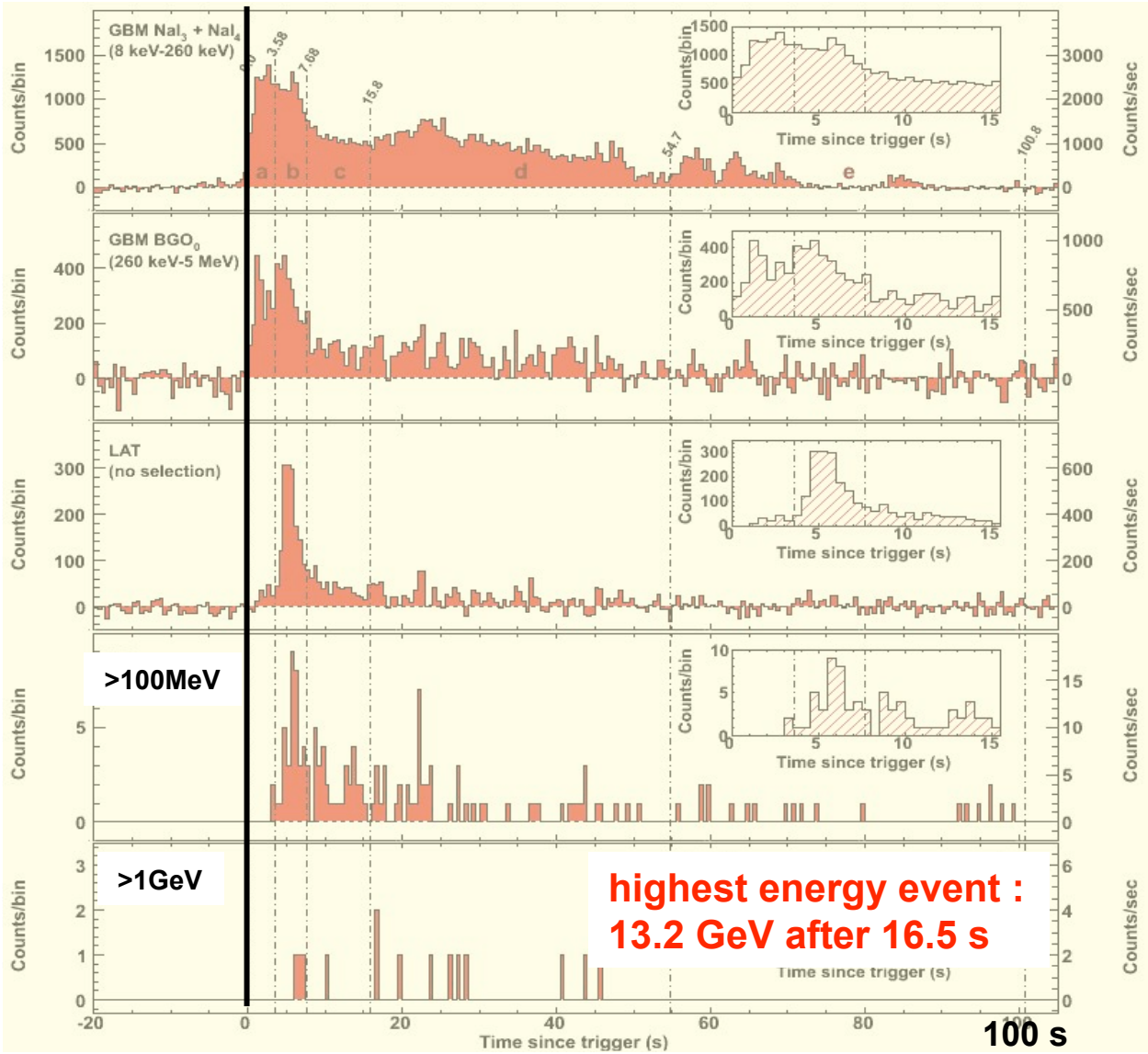
  LAT detected rate : 1 per month

Gamma Ray Bursts

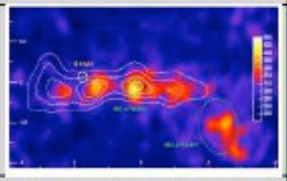
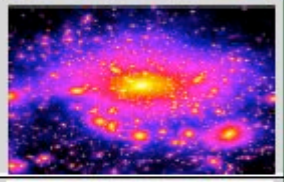
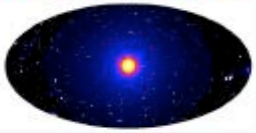
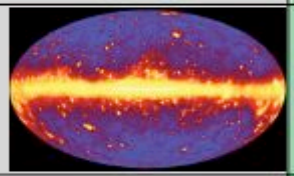
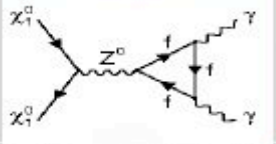
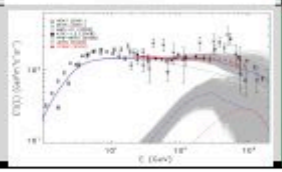
AGILE : GRB080514B



Fermi : GRB 080916C, z=4.35



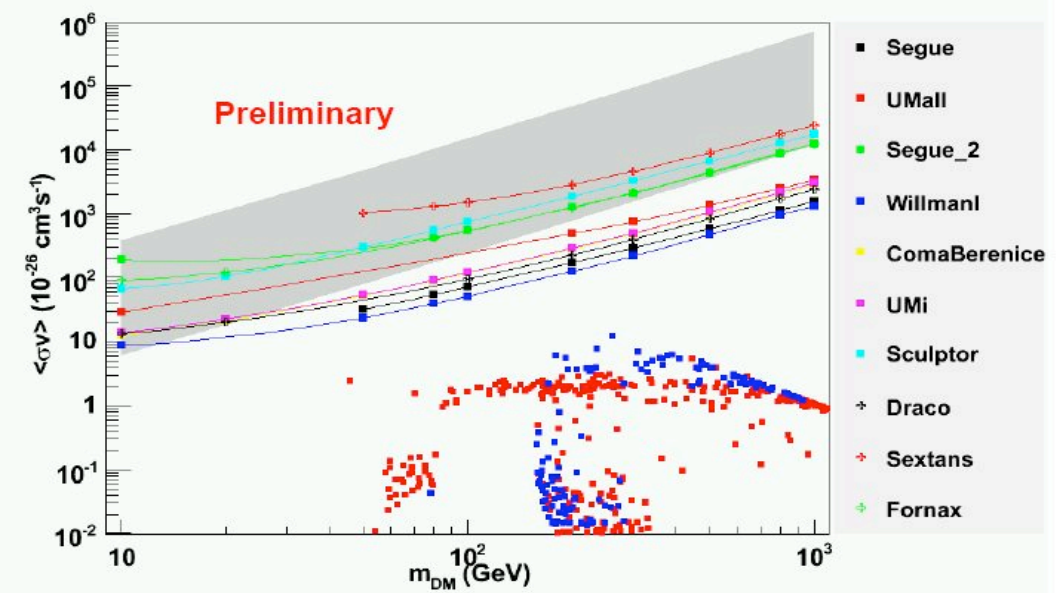
Dark matter

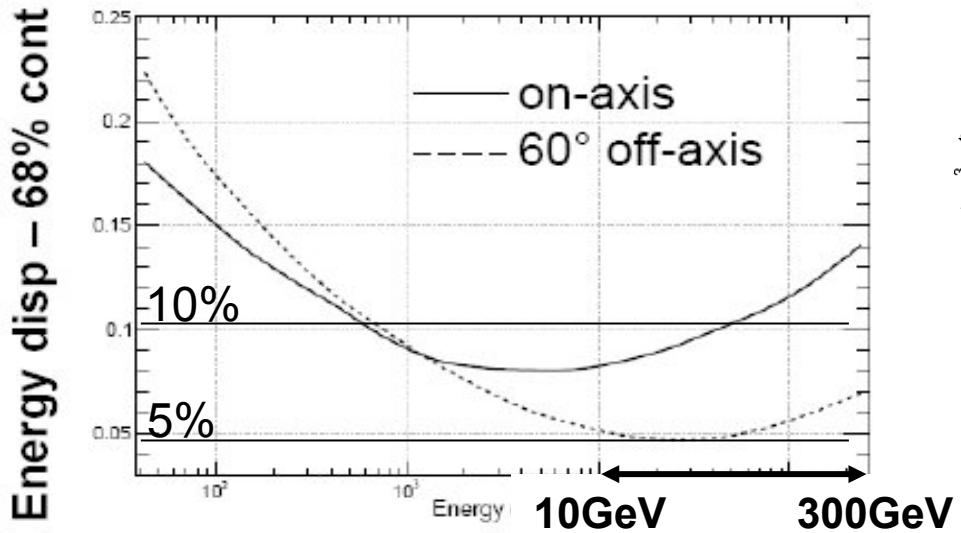
Search Technique		advantages	challenges
Galactic center		Good Statistics	Source confusion/Diffuse background
Satellites, Subhalos, Point Sources		Low background, Good source id	Low statistics
Milky Way halo		Large statistics	Galactic diffuse background
Extra-galactic		Large Statistics	Astrophysics, galactic diffuse background
Spectral lines		No astrophysical uncertainties, good source id	Low statistics
Cosmic-ray electrons		Experimental hints, large stat. + DM models discrimination	Astrophysical background Diffusion models

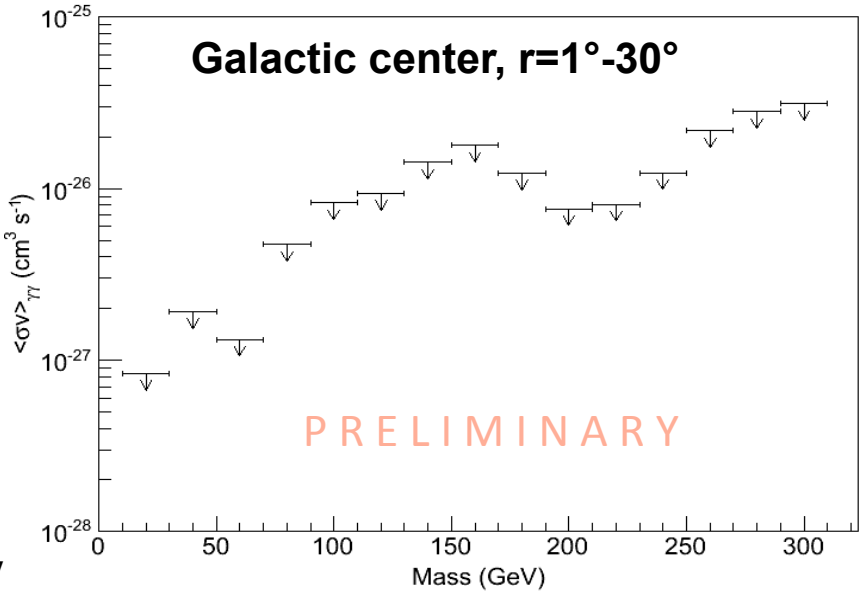
E.A. Baltz et al. JCAP07 (2008) 013, arXiv:08062911

Dark matter results

- Dwarf spheroidal galaxies :
  - Most DM-dominated systems known in the universe (high M/L)
  - Most of them expected to be free from any other astrophysical source (low content of gas and dust)
- Annihilation lines



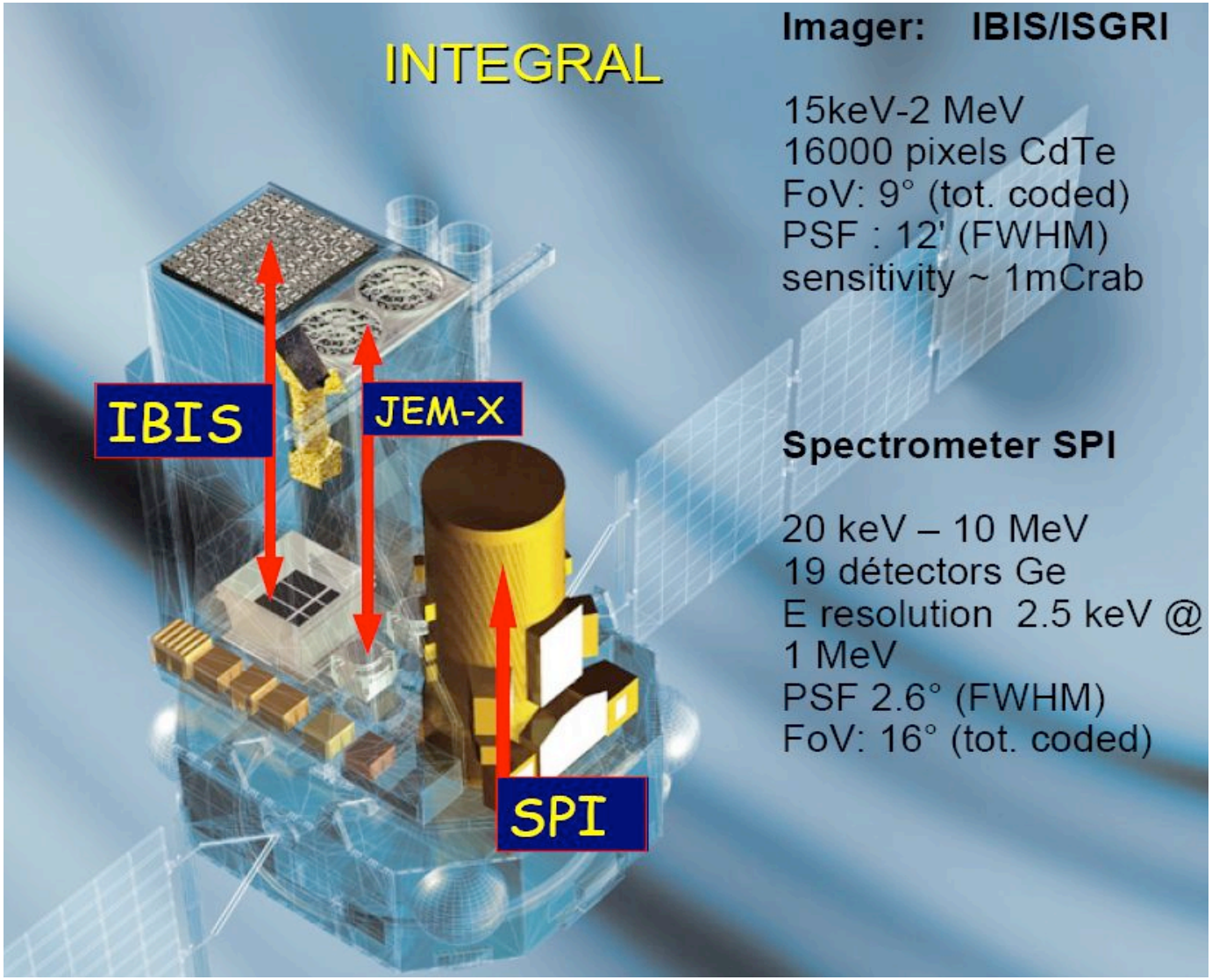




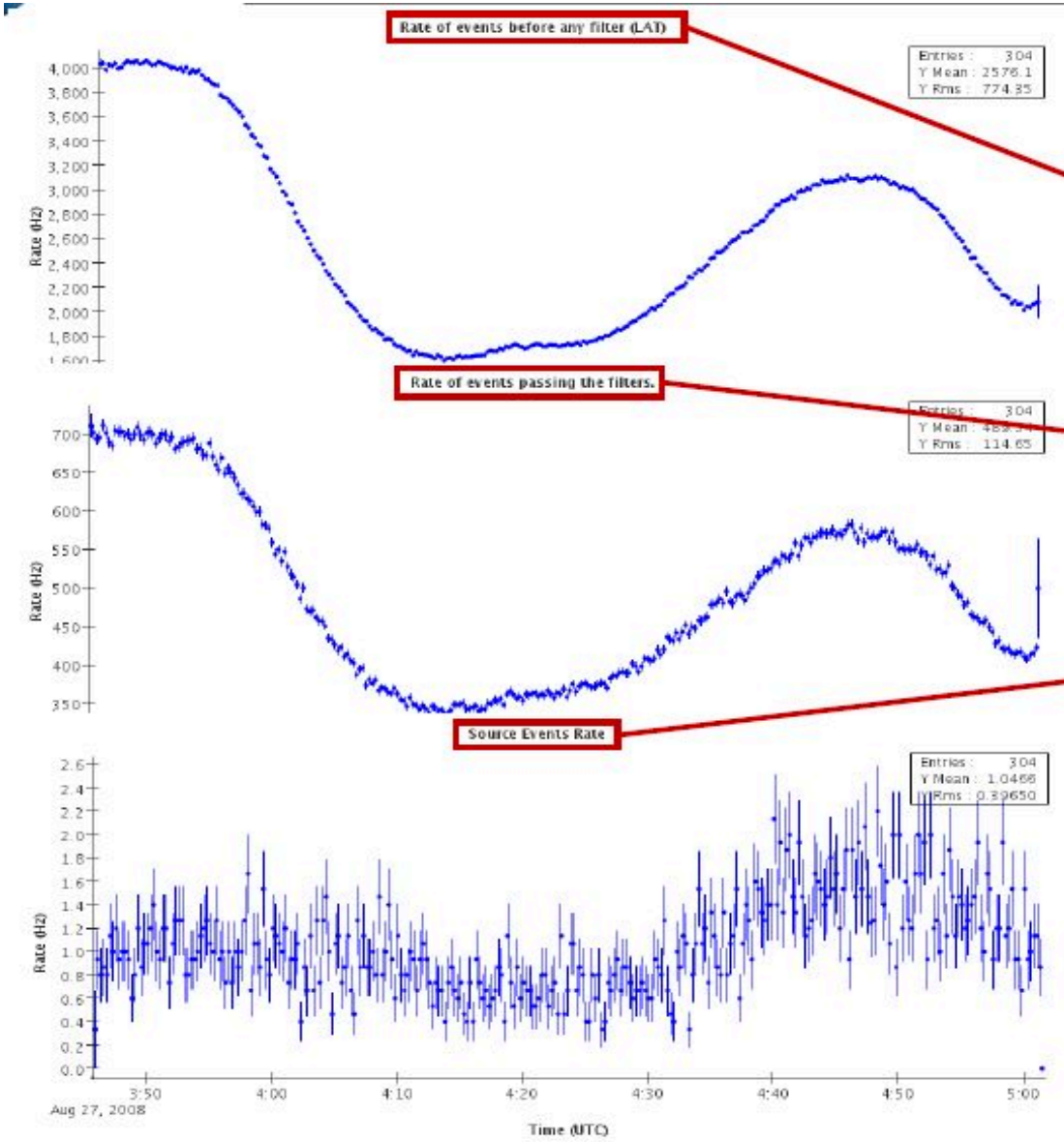
Conclusions

- The success of AGILE and Fermi is due to their very good performance
- We have definitely entered a new era of gamma-ray astronomy !
- As new data come in, we will understand more and more the gamma-ray sky
  - More sources -> population studies
  - The very details of bright objects
- Importance of multi-wavelength effort
  - Campaign, ToO, ATEL, …
- AGILE Guest observer Program
  - http://agile.asdc.asi.it
- Fermi-LAT data will be public very soon (mid August)
  - http://fermi.gsfc.nasa.gov/ssc/data/
  - Since launch, public light curve of ~30 monitored sources

INTEGRAL


INTEGRAL
IBIS
JEM-X
SPI
Imager: IBIS/ISGRI
15keV-2 MeV
16000 pixels CdTe
FoV: 9° (tot. coded)
PSF : 12' (FWHM)
sensitivity ~ 1mCrab
Spectrometer SPI
20 keV – 10 MeV
19 détectors Ge
E resolution 2.5 keV @ 1 MeV
PSF 2.6° (FWHM)
FoV: 16° (tot. coded)

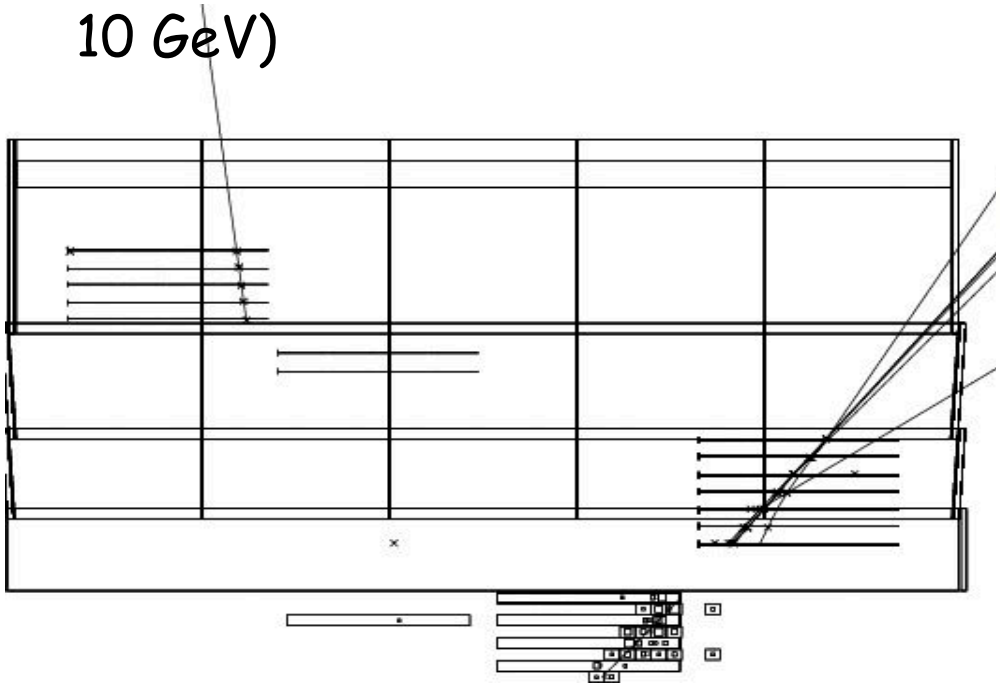
Fermi in orbit rates

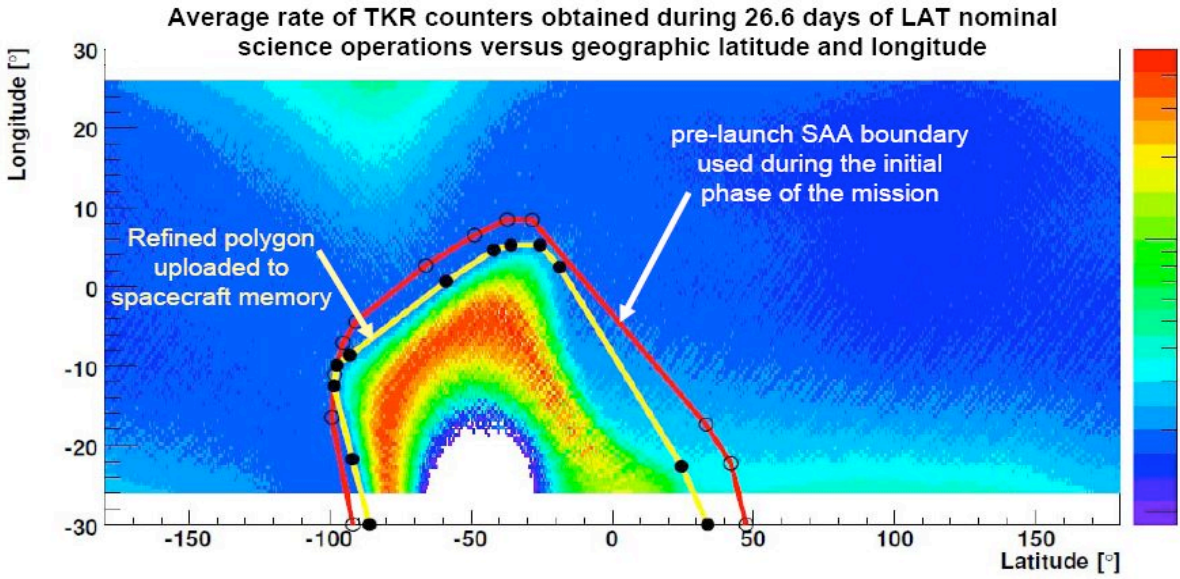


- ✓ Overall trigger rate: ~few KHz
  - ✓ Huge variations due to orbital effects.
- ✓ Downlink rate: ~400—500 Hz
  - ✓ ~90% from GAMMA filter
  - ✓ ~20—30 Hz from DGN filter
  - ✓ ~5 Hz from HIP filter
- ✓ Rate of photons after the standard background rejection cuts for source study: ~1 Hz
- ✓ Most of the downlinked events are in fact background, final ~ 1000:1 rejection is done in ground processing.

On orbit effective area validation

- We have discovered a pure orbit effect that must be taken into account in order to have a realistic effective area : off-time cosmic rays passing through the LAT decrease the effective area (~10% at 200 MeV, 10% at 1 GeV, ~0 at 10 GeV)

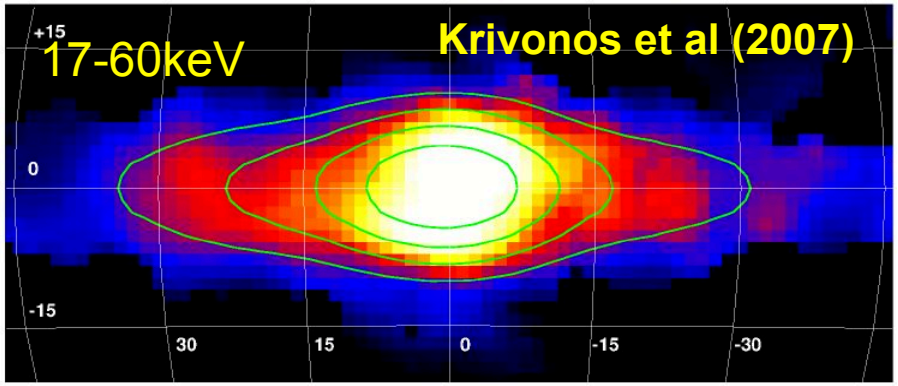


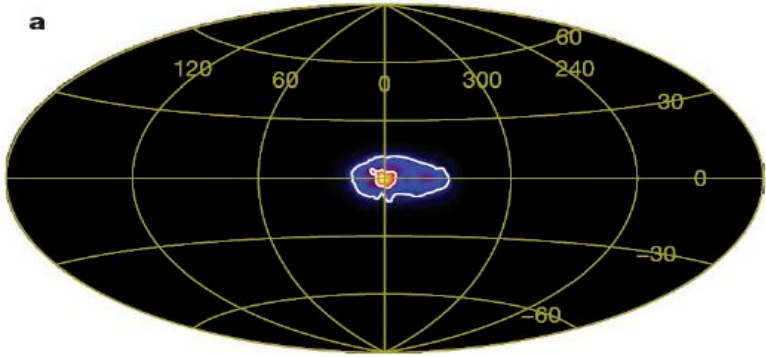


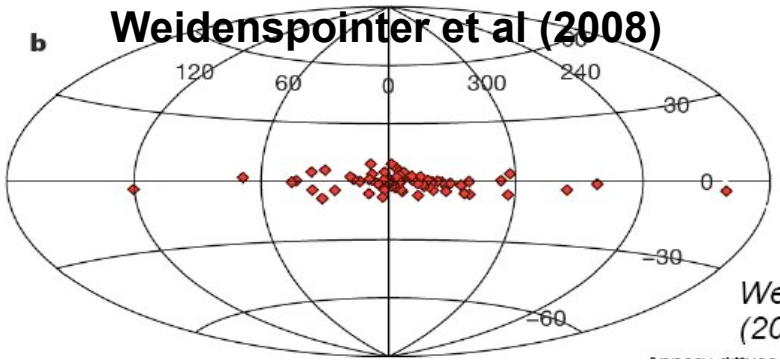
- Using random triggered events, we can simulate this effect and get a good agreement between selection efficiency in data and simulation.
- Systematics : 10% at 100 MeV, 5% at 600 MeV, 20% at 10 GeV

Galactic diffuse emission : low energy part

- E < 100 keV : INTEGRAL showed that more than 80% of the galactic flux is due to point sources.The rest is correlated to DIRBE 4.9 μ m maps, so likely due to unresolved faint sources
- Origin of the 511 keV emission : INTEGRAL detection of an asymmetry in disk distribution, correlated with the Low Mass X-ray Binaries

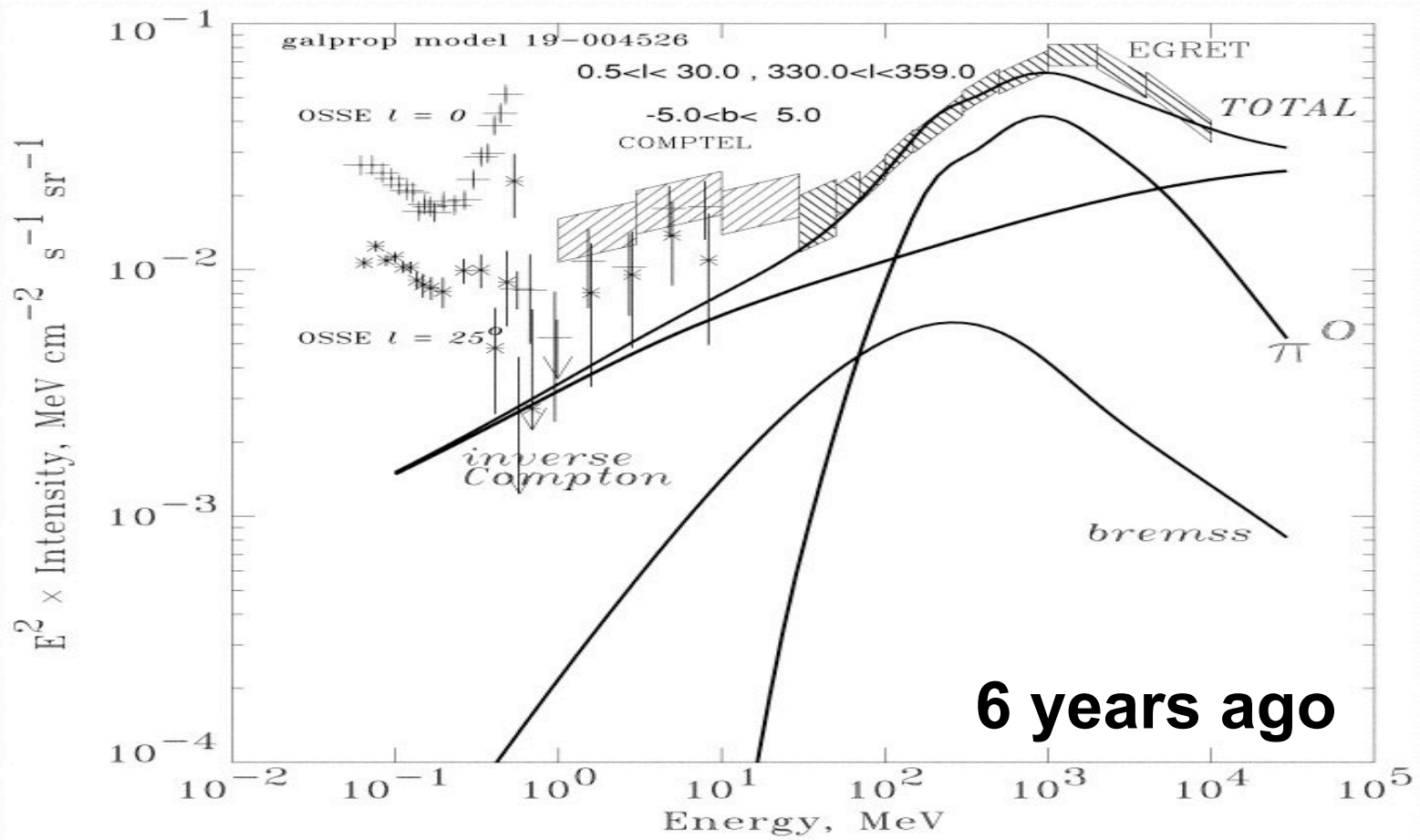






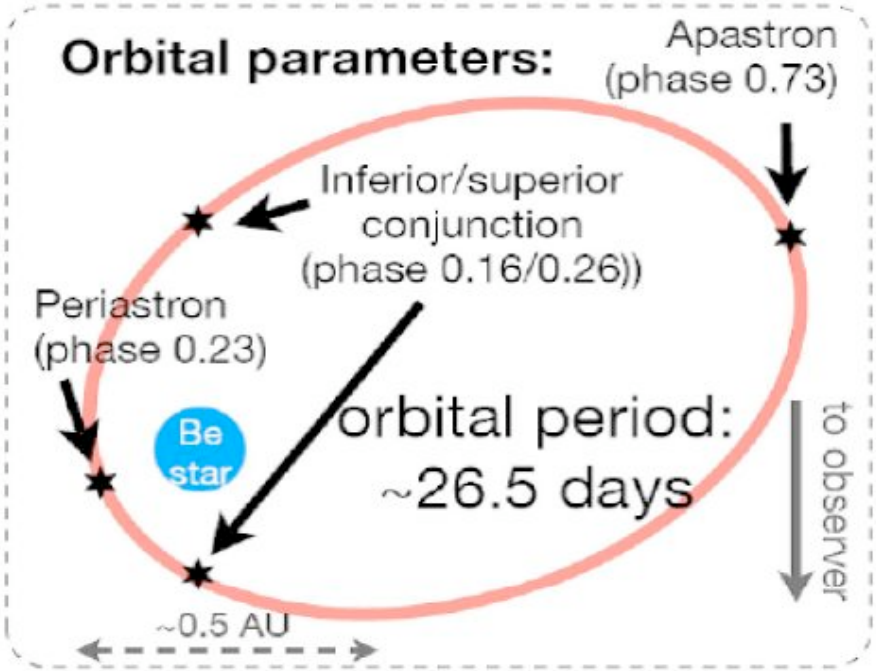
Galactic diffuse emission

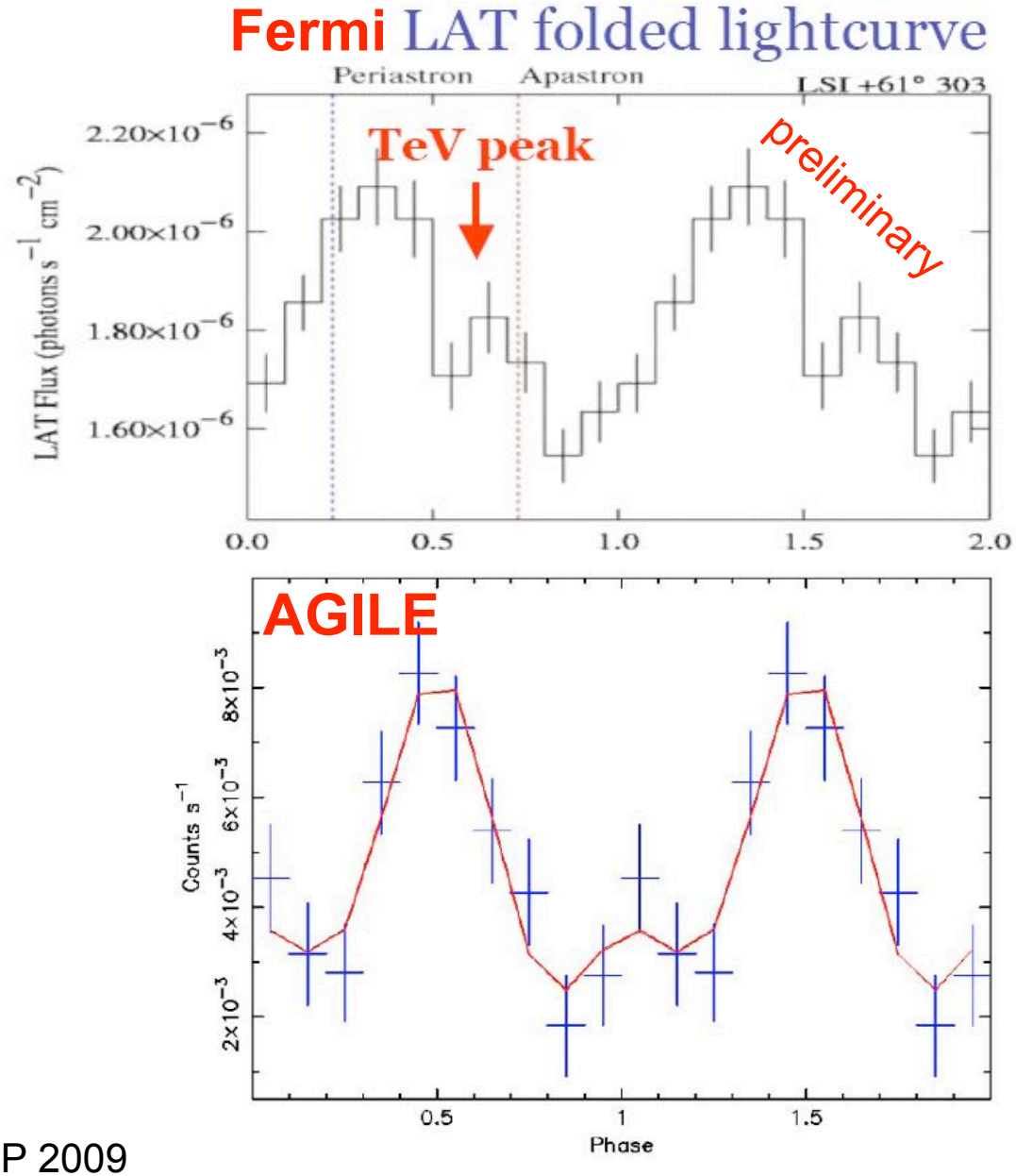
- Understanding the whole spectra : from point sources contribution to production from cosmic rays interaction



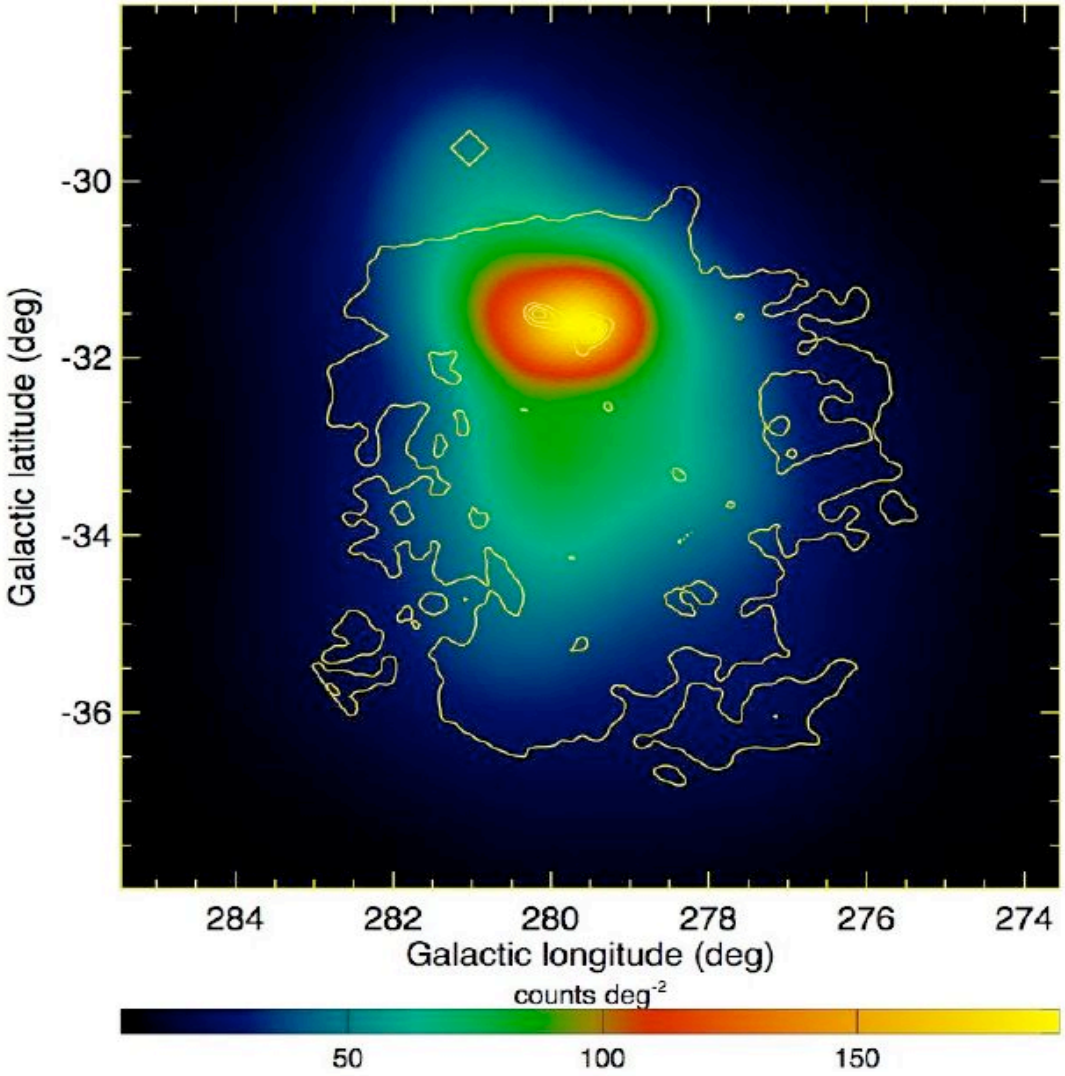
The first GeV Binary : LSI +61°303

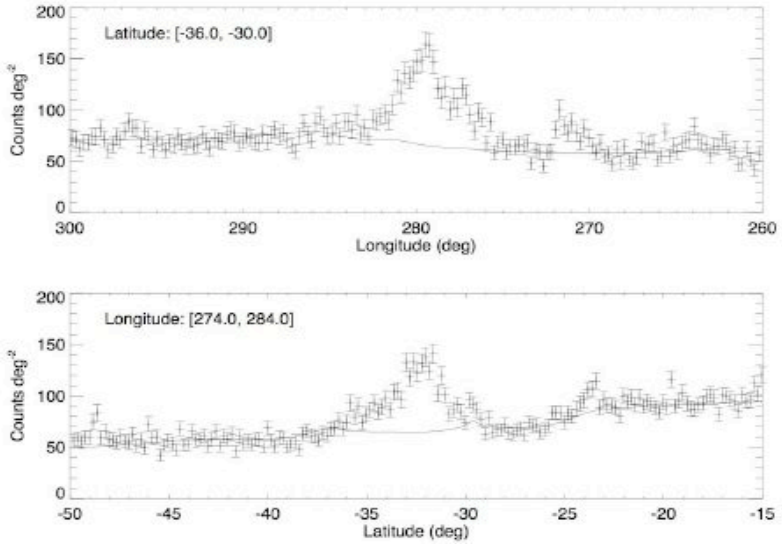
- Be binary : VERITAS and MAGIC see TeV emission modulated on 26.5 days period





Another galaxy : the Large Magelanic Cloud



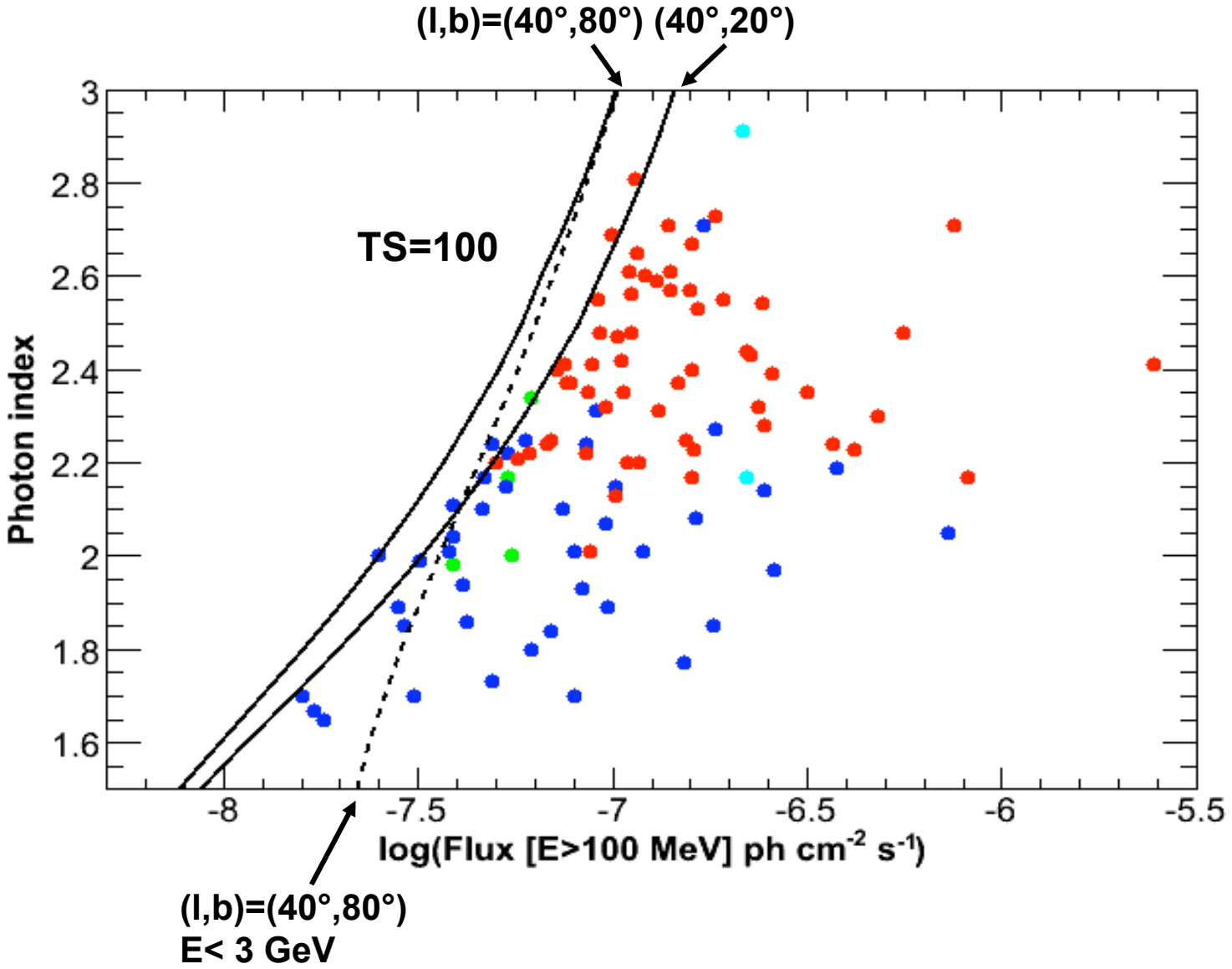


- Fermi clearly resolves the LMC
- Gamma-ray emission maximum near 30 Doradus
- Morphology correlates well with gas distribution
- Question of CR excess in 30 Dor under investigation

Knödlseder et al. 2009
Jaén conference
astro-ph/0905.2498

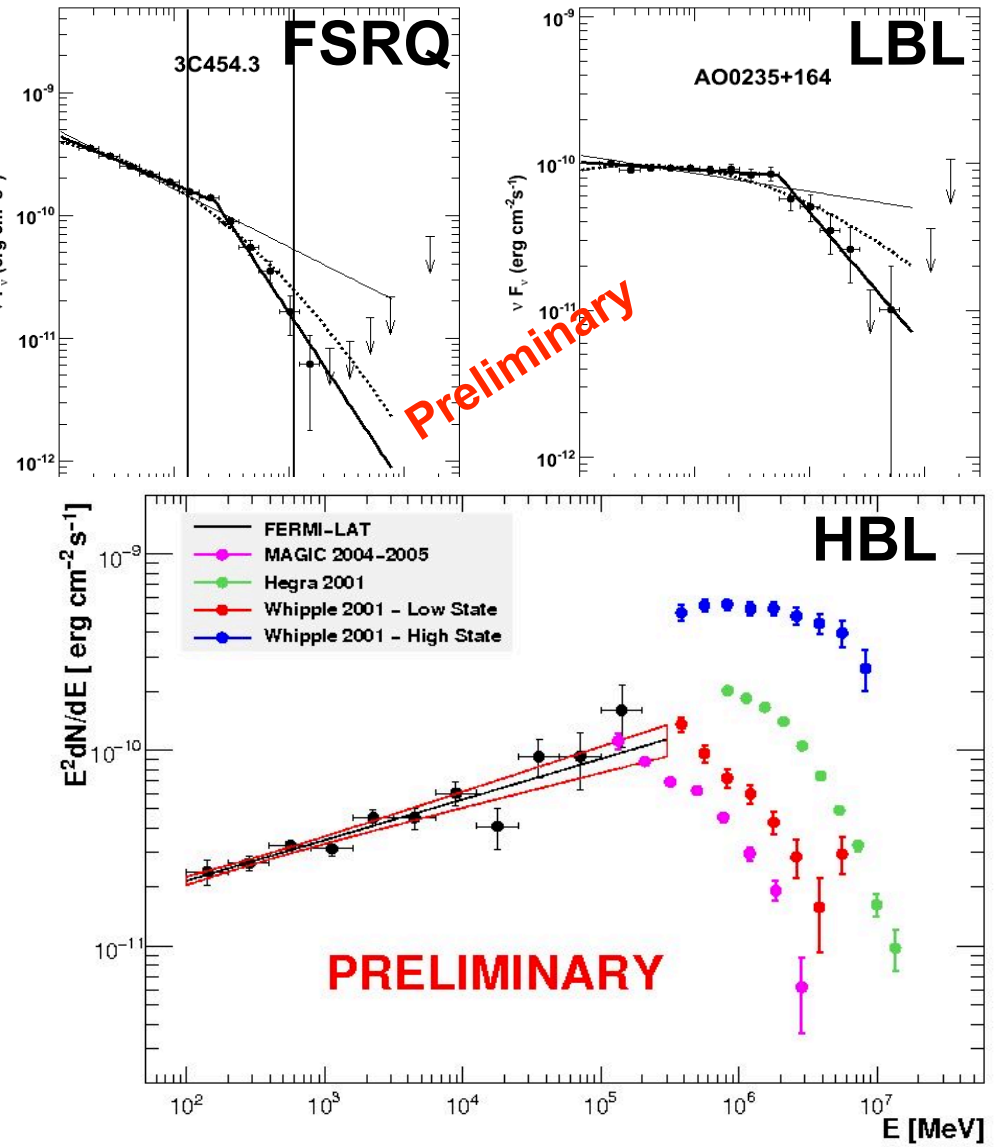
Index vs flux

FSRQ
BLLac
Uncertain
Radio Galaxies

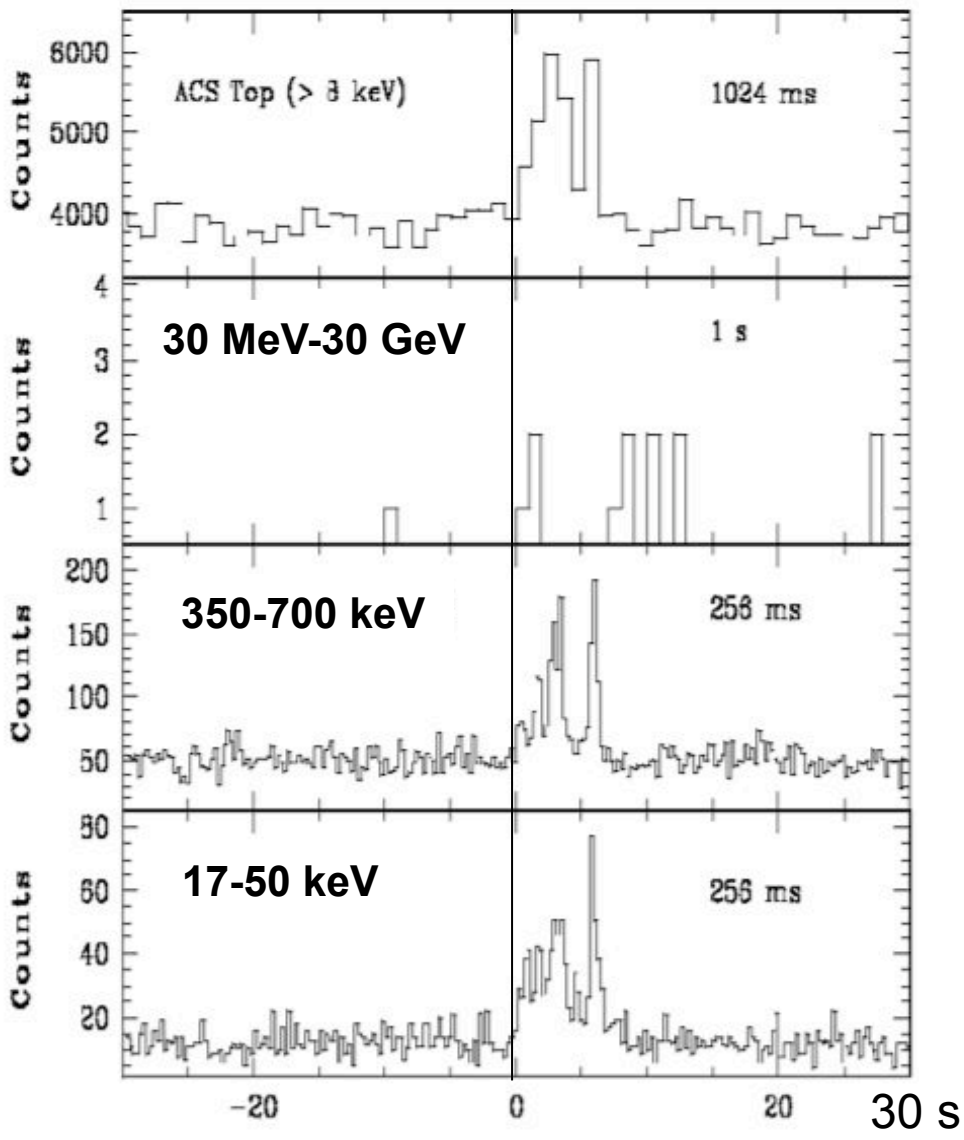


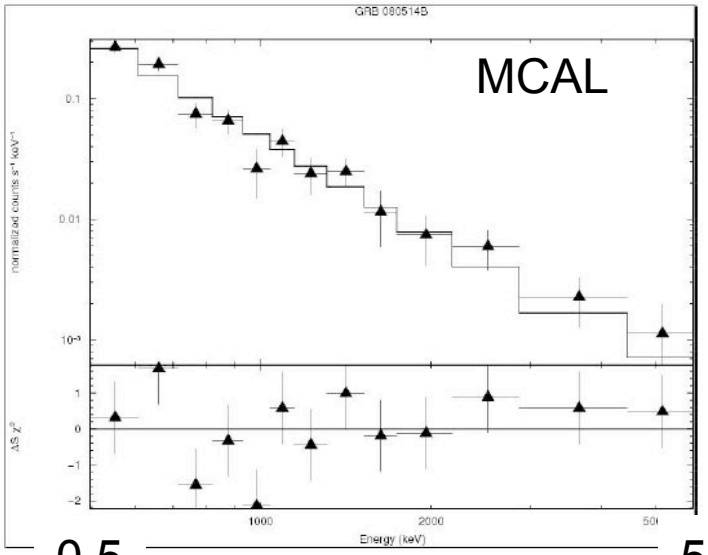
Non power-law spectra

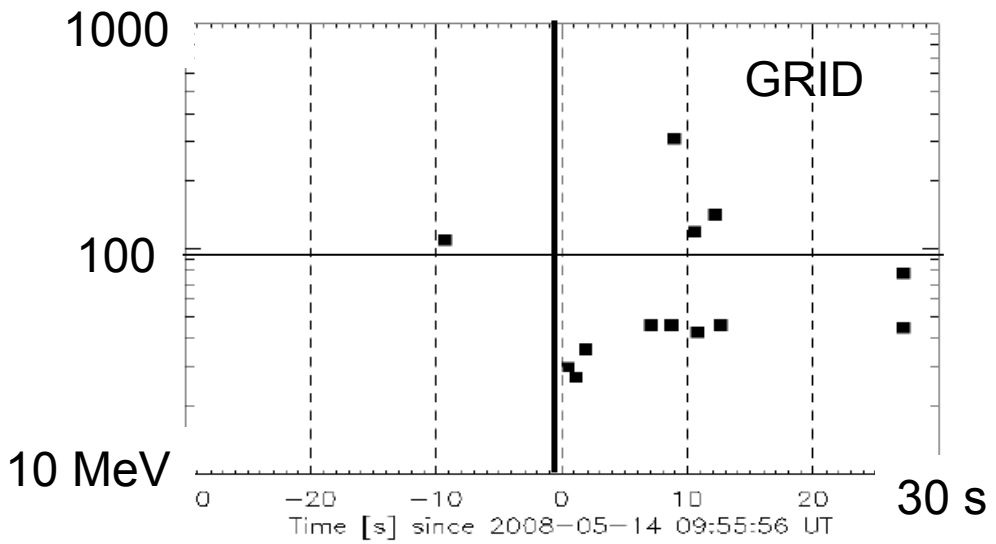
- First definitive evidence of a spectral break above 100 MeV
- General feature in FSRQs and many LBLs
- Absent in HBLs
- Broken power law model seems to be favored
- $\Delta\Gamma = 1.2 > 0.5 \Rightarrow$ not from radiative cooling
- Possible explanations:
  - "intrinsic" absorption via $\gamma\gamma$ opacity from accretion disk or BLR photons
  - feature in the underlying particle distribution
- Implications for EBL studies and blazar contribution to extragalactic diffuse emission



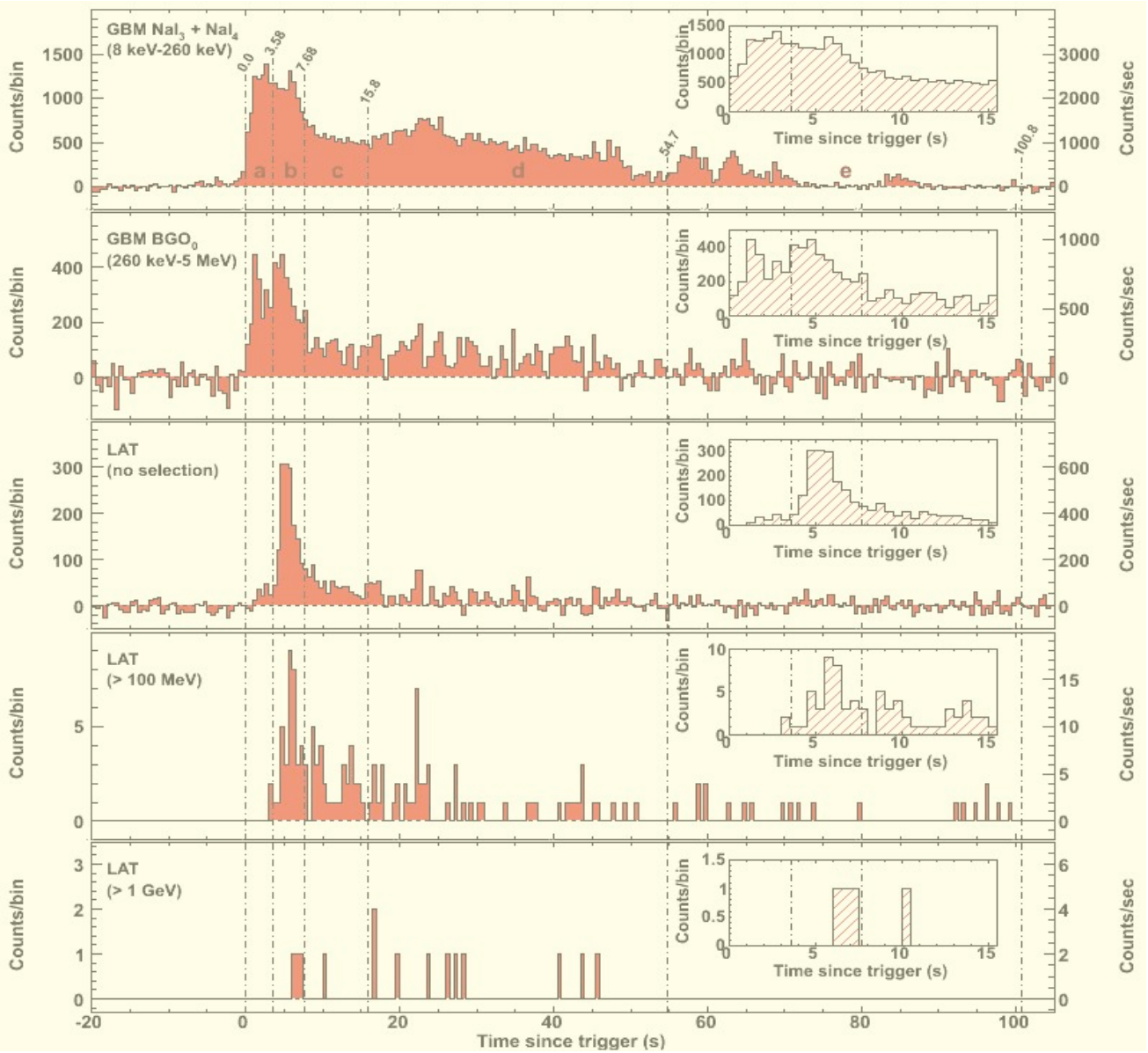
GRB 080514B with AGILE





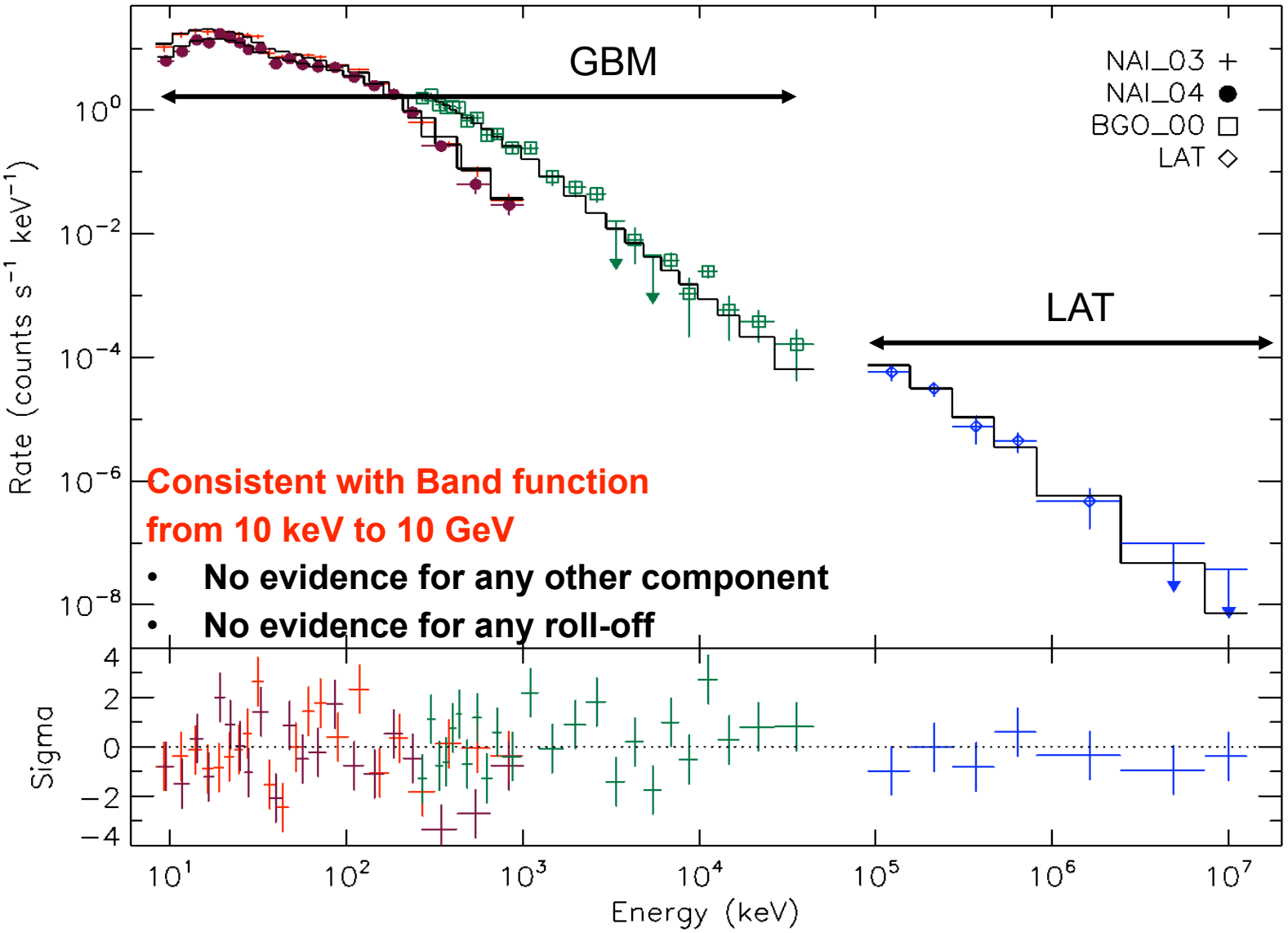


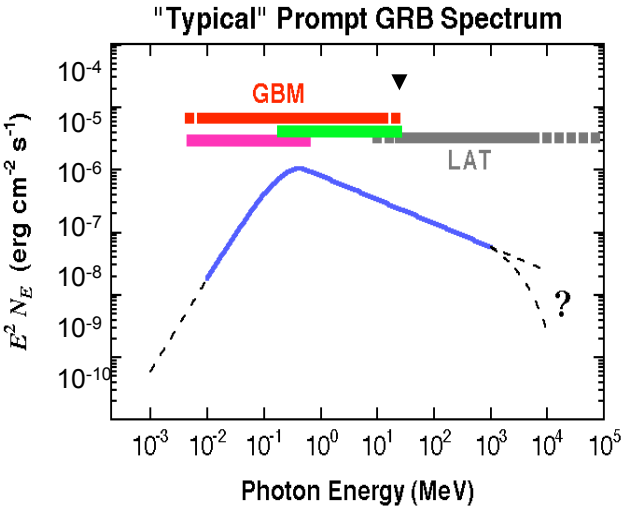
GRB 080916C with Fermi



- Fermi first high-energy GRB (>100 MeV) with known redshift 4.35 =
- The LAT can be used as a counter to maximize the rate and to study time structures above tens of MeV
  - ~4.5 s delay between >100 MeV and 100 keV radiations
- Spectroscopy needs LAT event selection (>100 MeV)
  - Apparent isotropic energy release is 8.8×10^{54} ergs
  - 14 events >1 GeV
  - Highest energy photon (E = 13.2 GeV after 16.5 s) from GRB with z

GRB 080916C spectrum with Fermi

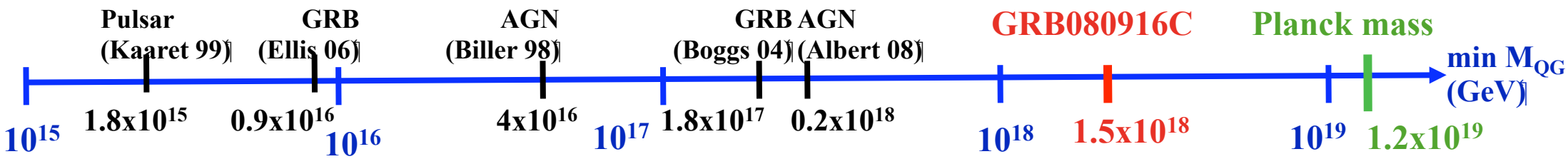




Quantum Gravity mass limit

- Quantum gravity :
  - Highest energy, ~13.2 GeV photon, detected 16.5 sec after GBM trigger
  - Conservative lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):
    $M_{QG} > (1.50 +/- 0.20) \times 10^{18}$ GeV/c^2

(1 order of magnitude higher than the previous best estimate, 1 order of magnitude below the Planck mass)



GRBs

- High-energy GRB observations
  - Evidence (though not significant in all cases) for a delay between keV-MeV and >100 MeV emissions
  - Band function provides good fits over wide energy range with no need for additional components so far
  - All LAT detected GRBs show significant HE emission extending after the low energy emission has (almost) disappeared below detectability
- Consequences
  - Narrow collimated relativistic jet
  - keV-GeV spectrum and variability: unique mechanism, same emission region (leptonic or hadronic origin?)
  - Best constraints ever on Bulk Lorentz factor (> 600 to 900) and MQG >0.1 M_{planck}
  - Opening high-energy window has great promise for emission mechanisms and tests for Lorentz invariance