Fermi at Five

Some highlights from *Fermi* Large Area Telescope

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For the *Fermi* LAT Collaboration

16th Lomonosov Conference
Moscow, August 24, 2013

For deeper insight into each topic see the 4th Fermi Symposium

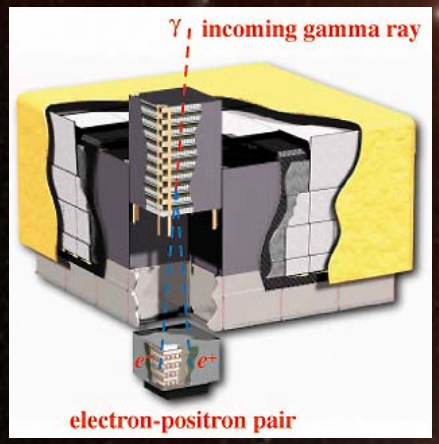
http://fermi.gsfc.nasa.gov/science/mtgs/symposia/2012/

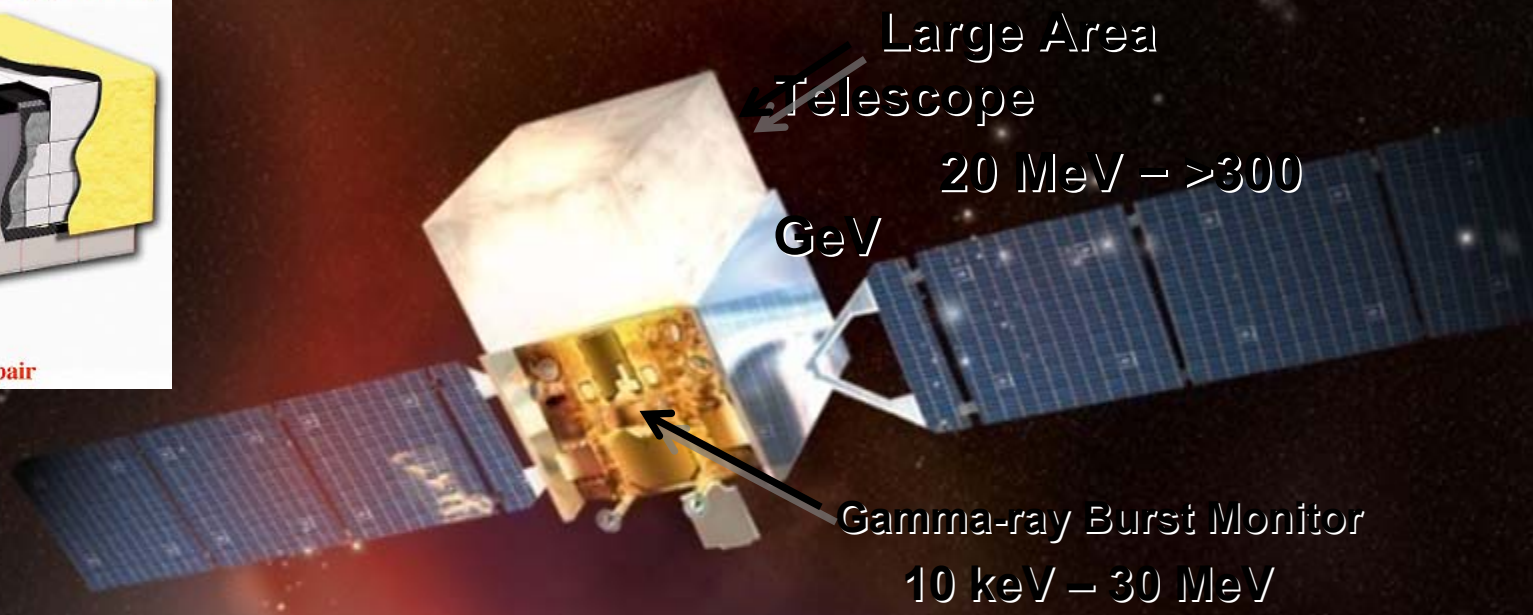
The 5th Fermi Symposium:
October 20-25, 2014
Nagoya, Japan


Peter Michelson
Bill Atwood
Pre-launch test


June 11, 2008
12:05 pm (EDT)

Fermi Gamma-ray Space Telescope



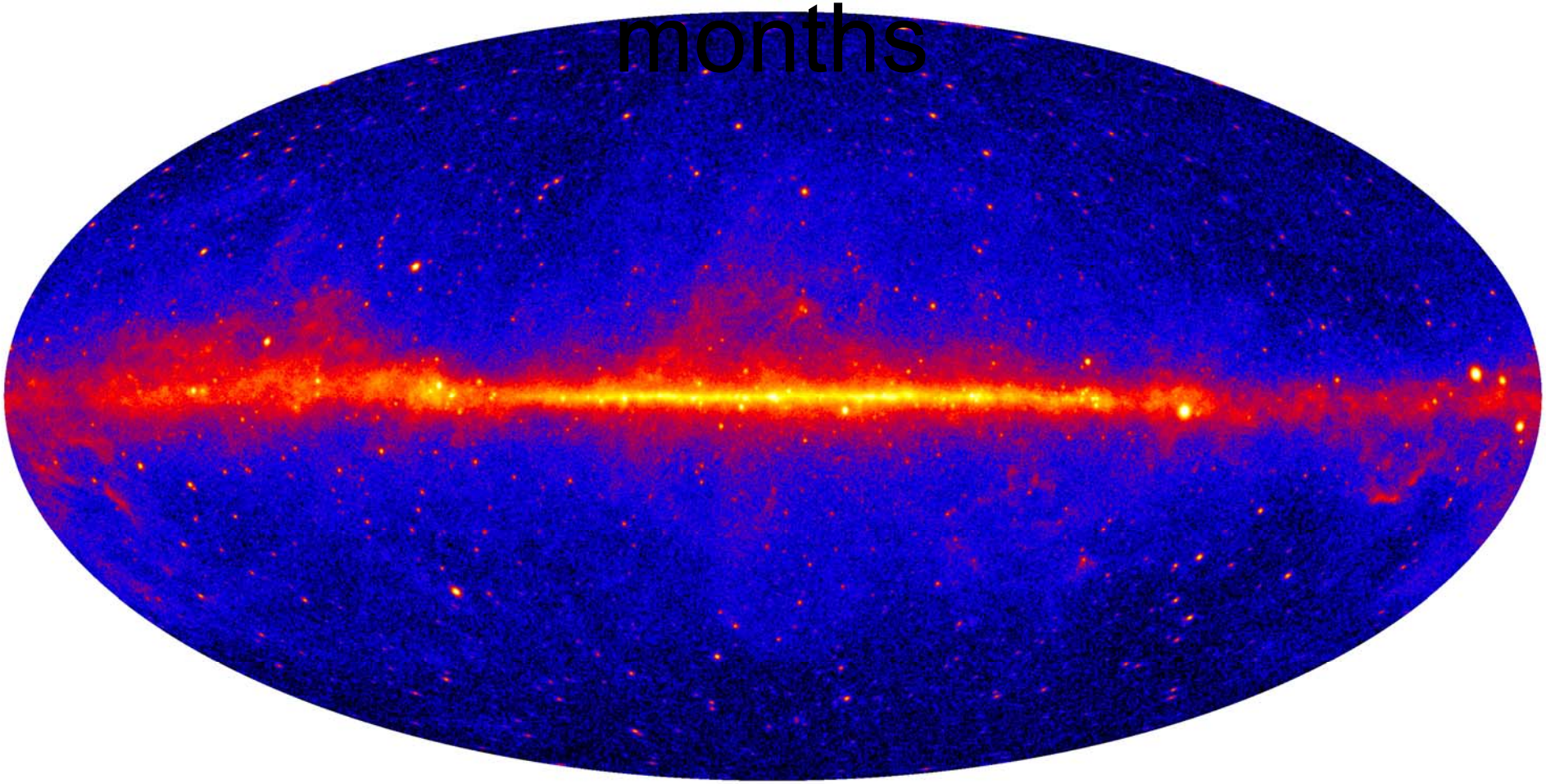


- The LAT is a unique resource providing
  - *Broad energy coverage, overlap with ACTs*
  - *Large FoV: all-sky coverage every 3 hours – transients*

- Observatory is operating smoothly
  - *Instruments and spacecraft operate as designed, no degradation in science performance since launch*

Fermi-LAT skymap >1 GeV

months

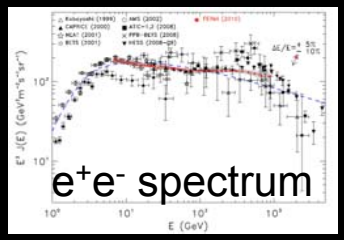


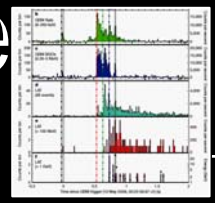
4-year sky map, >1 GeV, front converting (best psf) (4.52M events)

Fermi's skymap of particle interactions

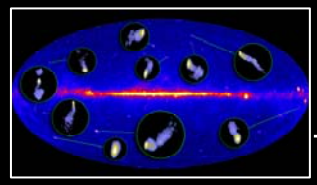
- >100 MeV, 36 months
- shows where accelerated particles meet target (gas, photons)
- ~80% of the emission is diffuse
- many transients in the γ-ray sky

Fermi Highlights and Discoveries

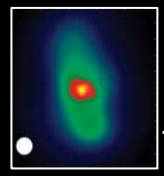




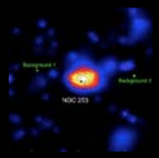
GRBs



Blazars

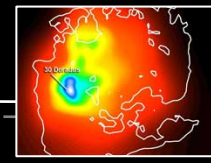


Radio Galaxies

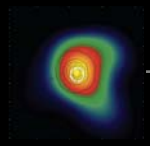


Starburst Galaxies

LMC & SMC

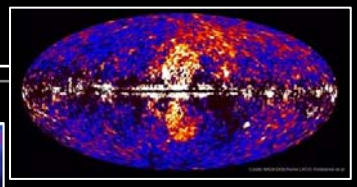


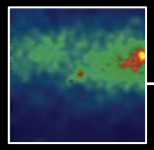
Extragalactic



Globular Clusters

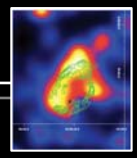
Fermi Bubbles

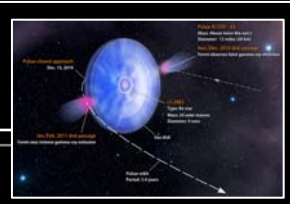




Nova

SNRs & PWN

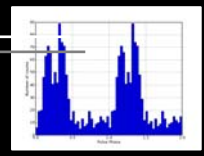




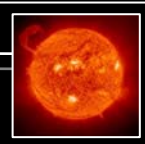
Galactic

γ-ray Binaries

Pulsars: isolated, binaries, & MSPs



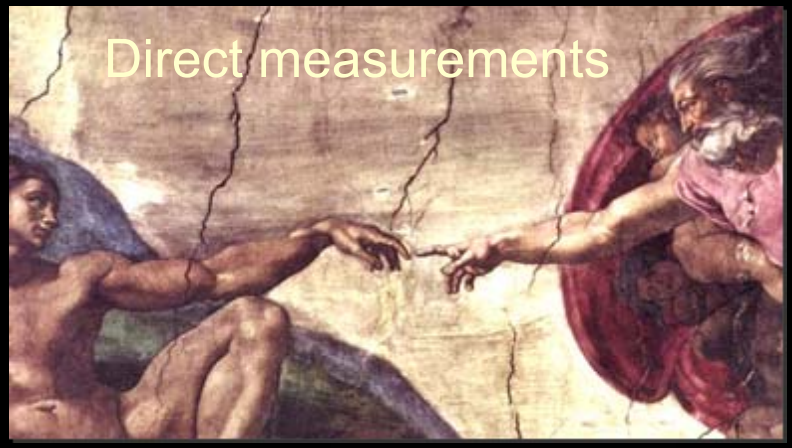
Sun: flares & CR interactions

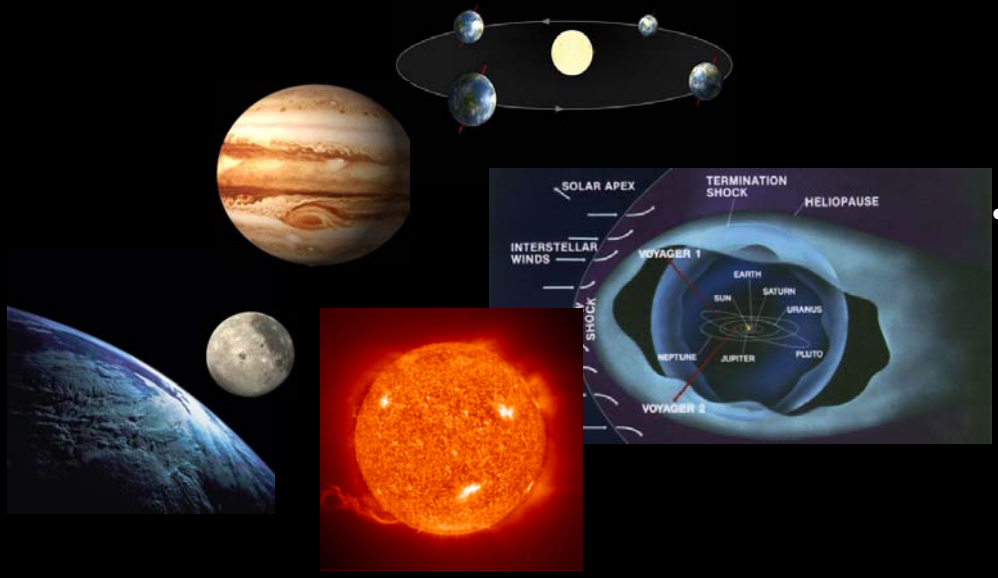


Terrestrial γ-ray Flashes

Unidentified Sources
(577/1873)

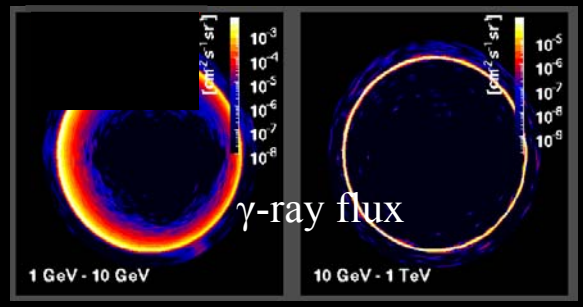
Solar System

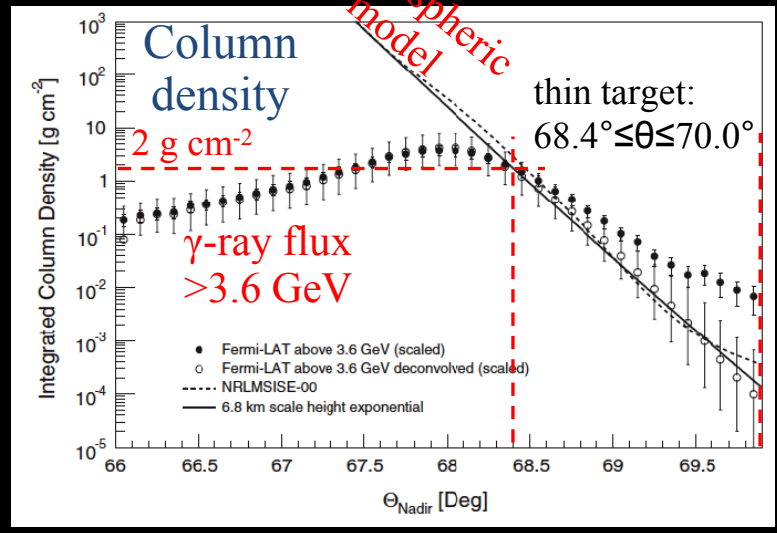


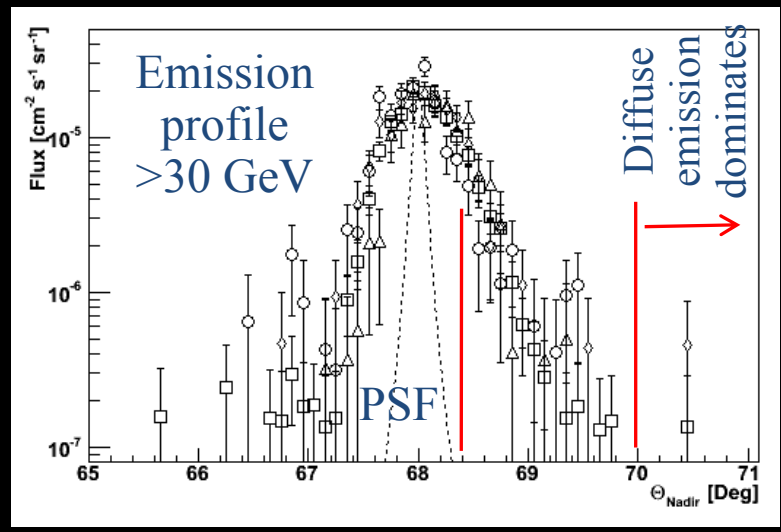


- Allows to reconcile direct & indirect observations
  - Test models of interactions
  - Calibration of the instrument
- Detected sources:
  - The Earth (PRD 80, 122004, 2009)
    - The limb
    - Terrestrial γ-ray flashes
  - The Moon (ApJ 758, 140, 2012)
  - The steady Sun (ApJ 734, 116, 2011)
  - Solar flares
- Potential sources (in progress):
  - Main Belt rocks & dust
  - Jovian & Neptunian Trojans
  - Kuiper Belt rocks & dust
  - Oort Cloud

Fermi-LAT observations of the Earth's limb



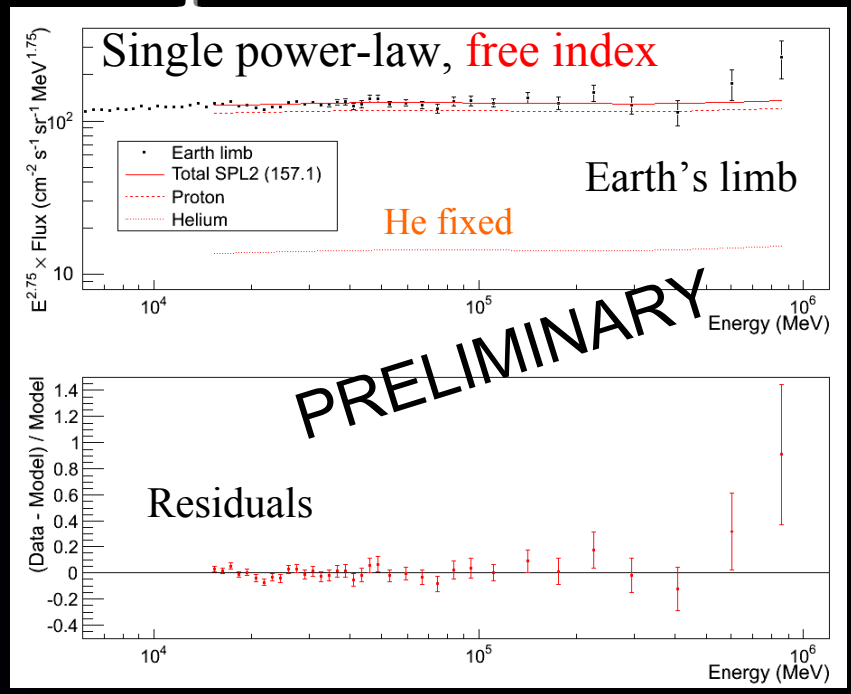


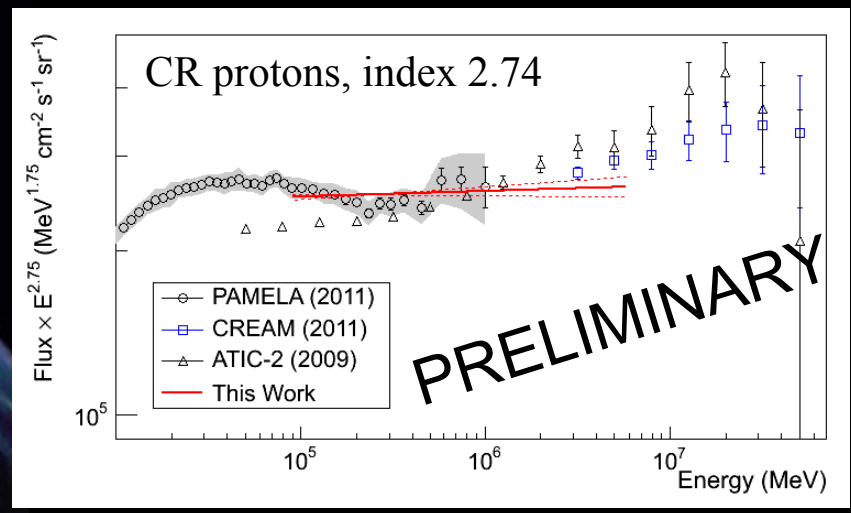


- Due to its proximity, the Earth is the brightest γ-ray source on the sky
- The emission is produced by the CR cascades in the atmosphere
- Most energetic γ-rays are produced by CRs hitting the top of the atmosphere at tangential directions (thin target)

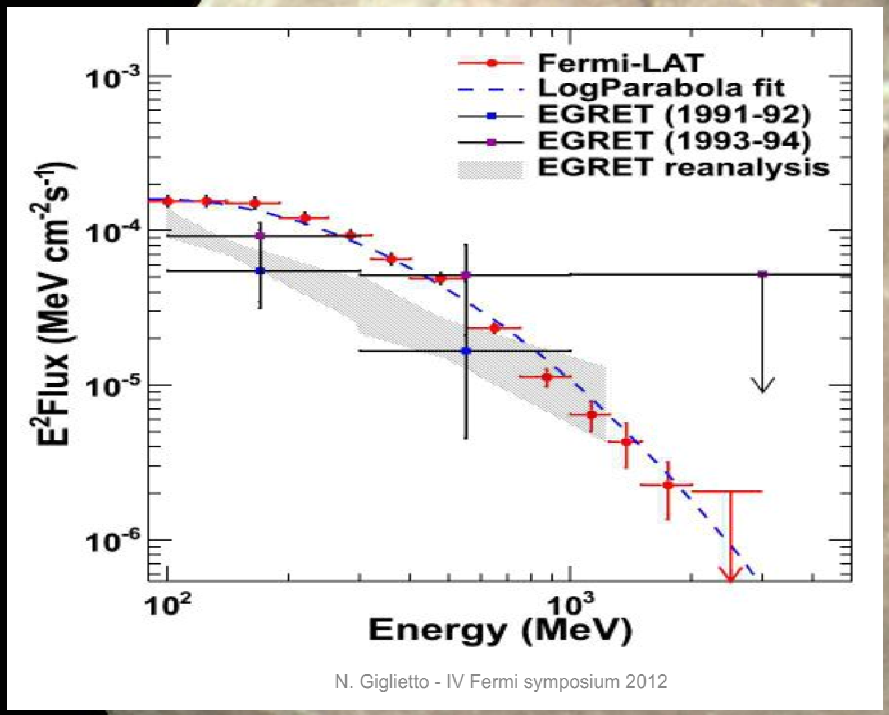
Inferring the CR spectrum

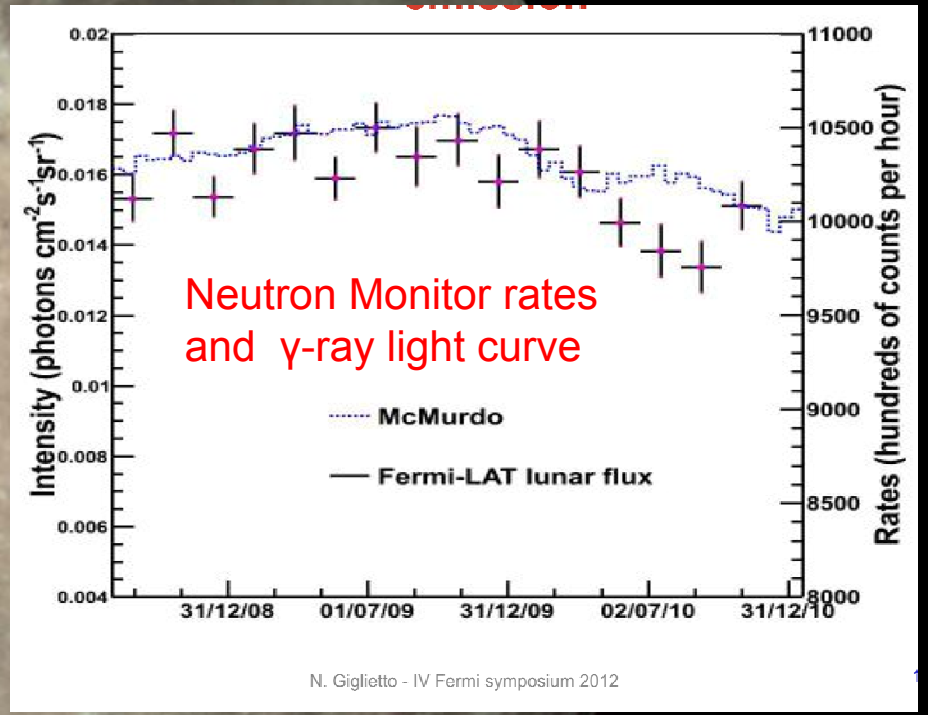
- A fit with a single power-law with free index yields index 2.74
- A broken power-law provides a comparable quality fit
- Fermi-LAT continues to collect data: more statistics, and extension to higher energies





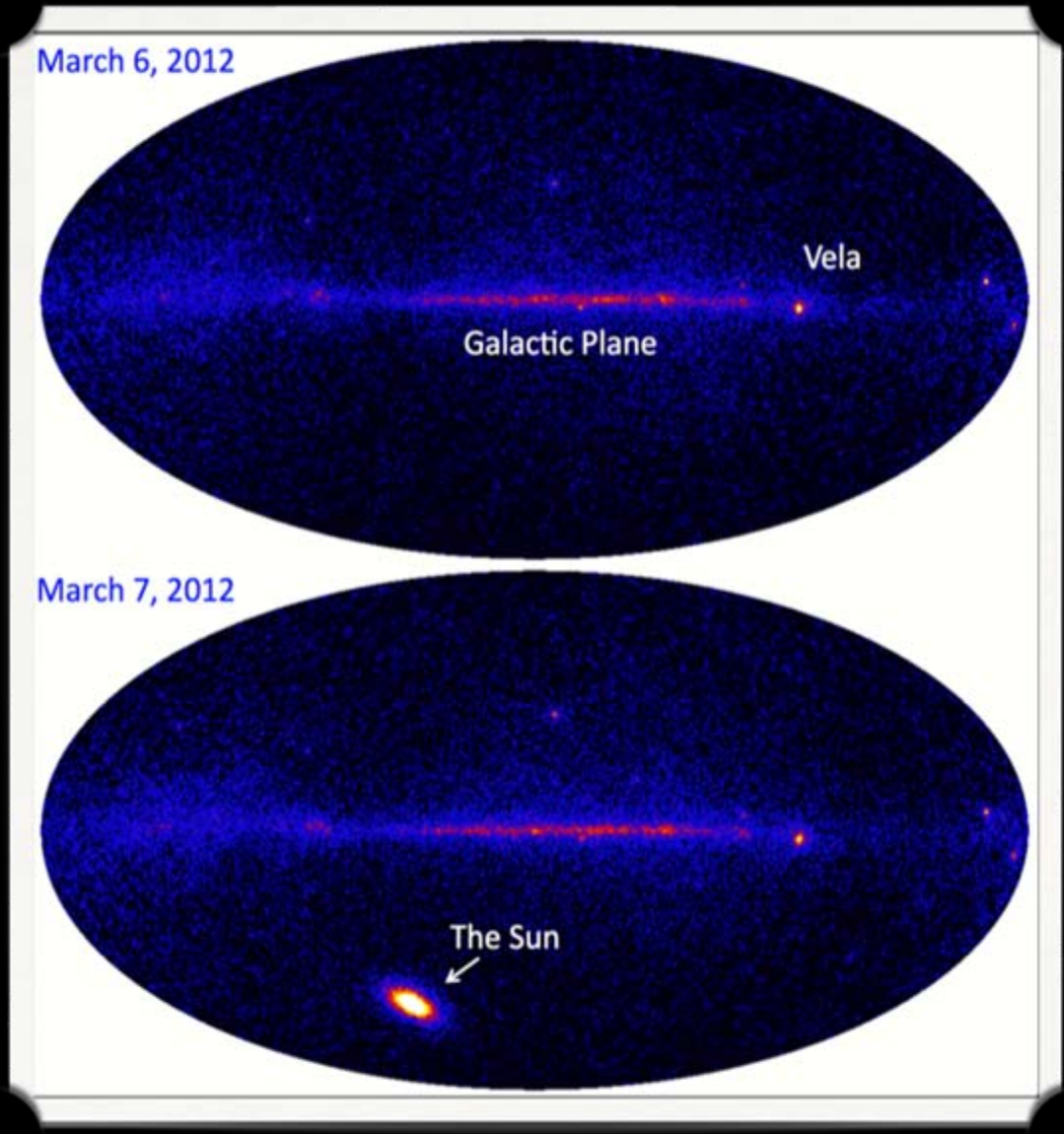
Fermi LAT observation of the Moon (3 years)





- Emits γ-rays due to the cosmic ray interactions with the surface material
- The spectrum is softer than predicted – effect of the surface roughness?
- Independent method to monitor cosmic ray flux outside of the geomagnetic field

Solar Flares

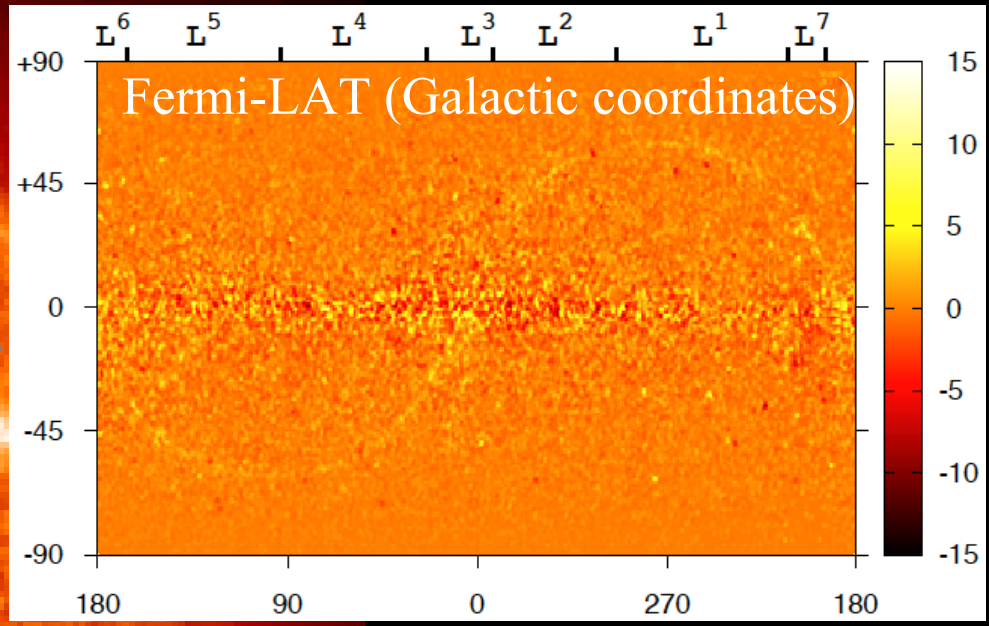


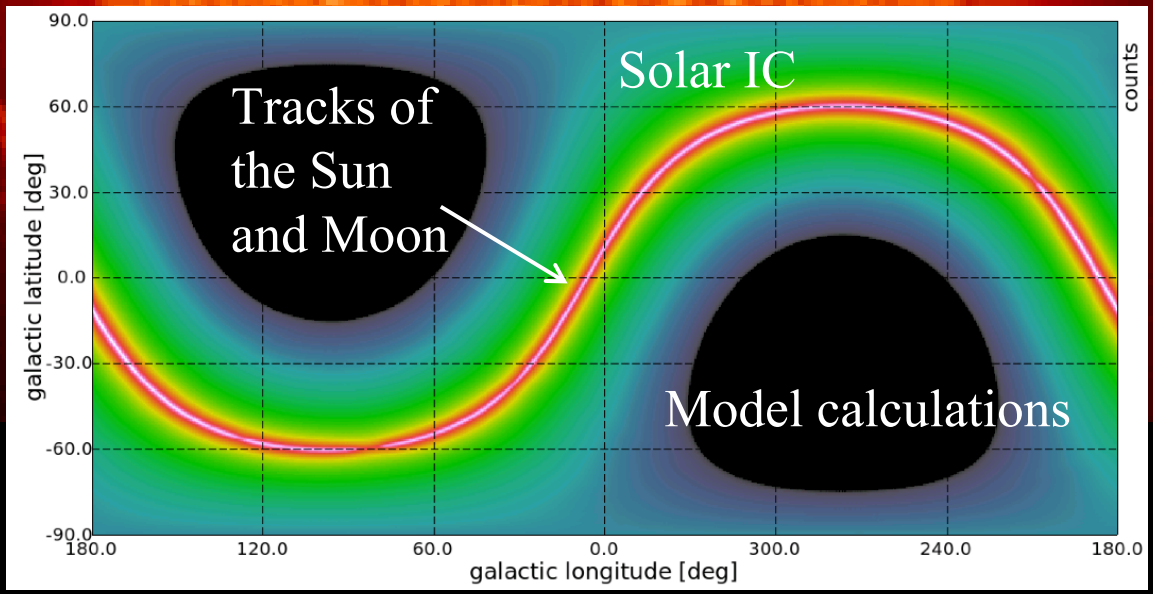
The March 7, 2012, X5.4 solar flare was the second most intense in 5 years. Fermi observed gamma-ray flux at >100 MeV:

- ✧1,000 times brighter than the steady Sun
- ✧100 times brighter than the Vela pulsar
- ✧50 times brighter than the Crab "*superflare*" of April 2011
- ✧Highest-energy photon (4 GeV) ever detected from a solar flare!
- ✧The high-energy emission lasted about 20 hours – the longest ever seen from a solar flare.

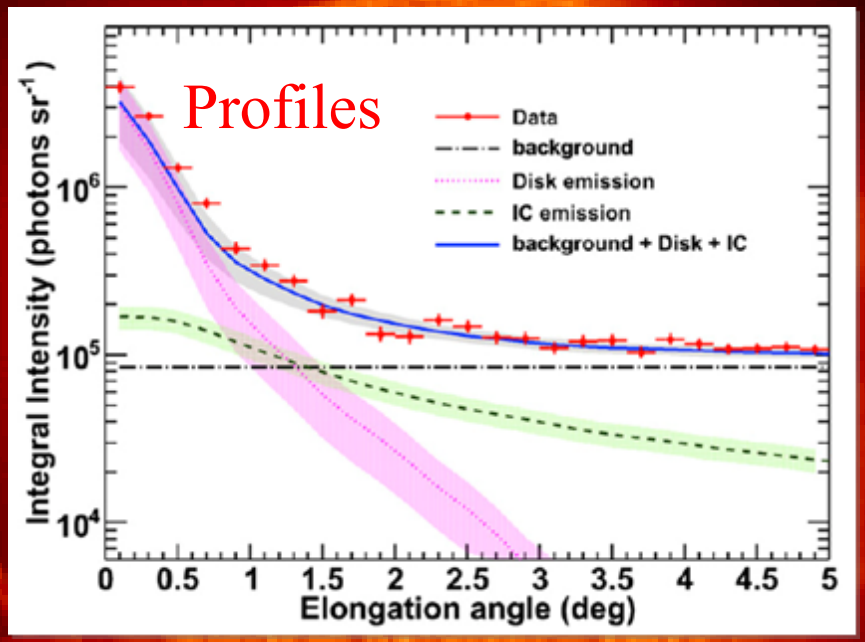
Solar system

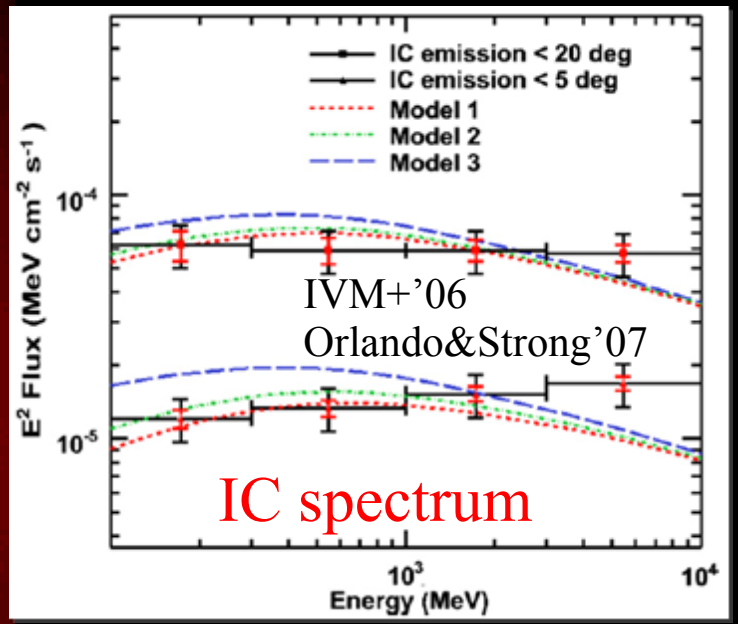
- Raw data sliced by 2 months interval, background removed; ➔ the solar track is clearly visible

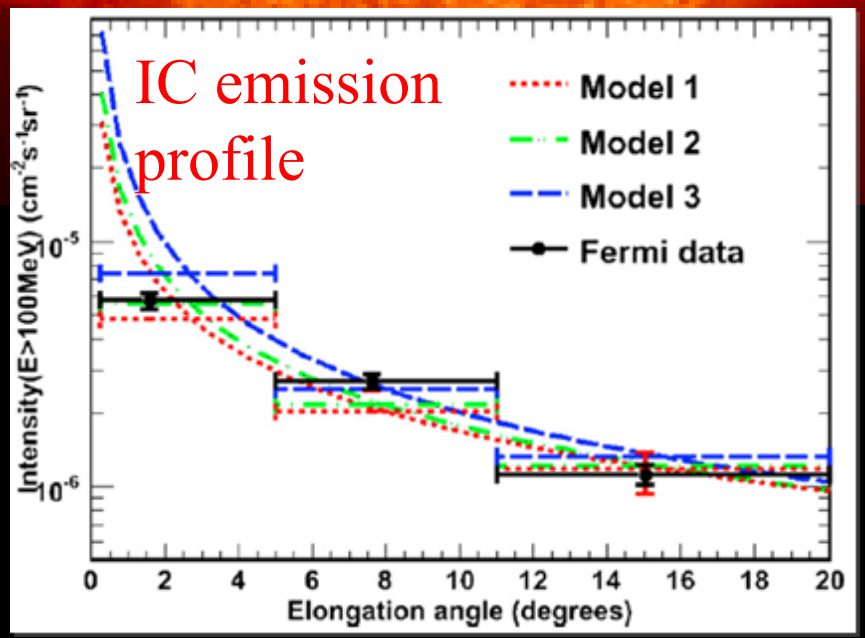


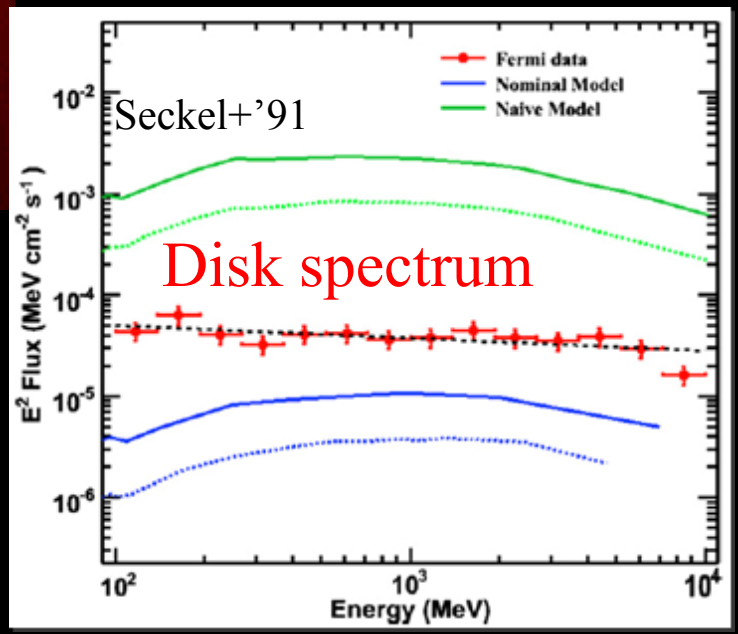


Fermi-LAT observations of the Sun

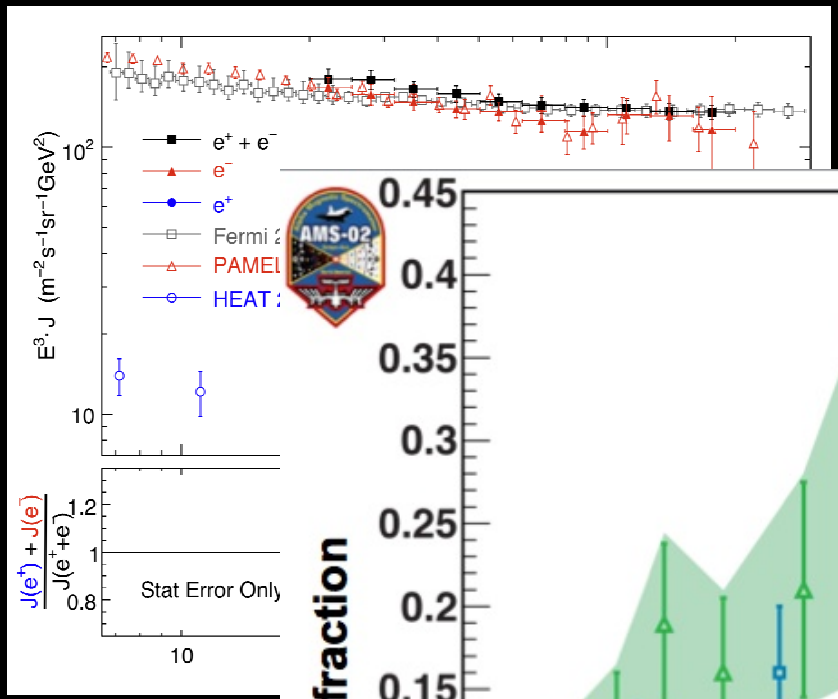


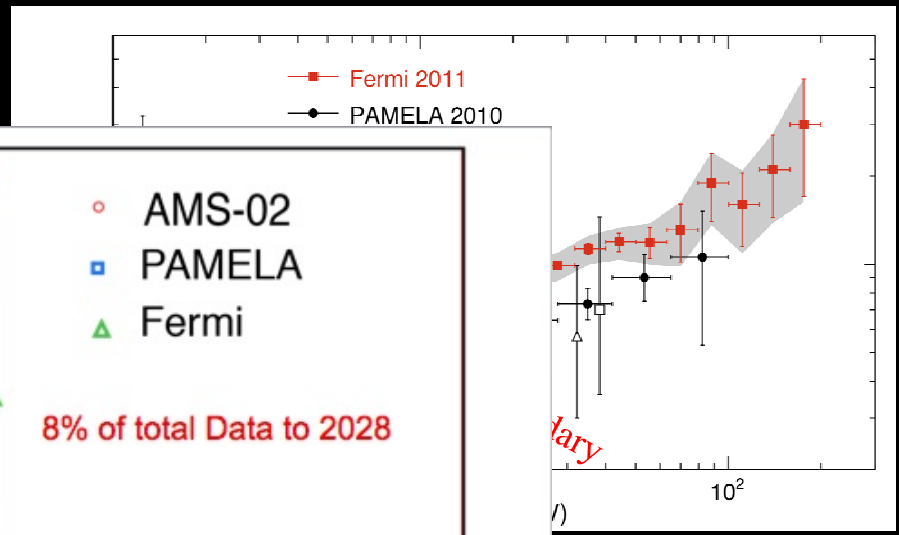


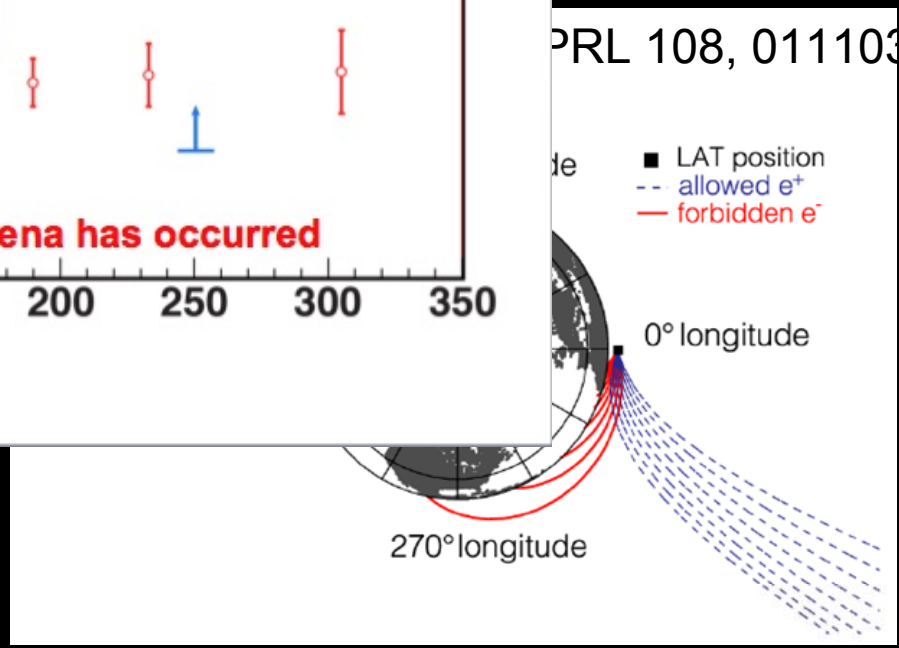




Fermi-LAT: e^+ & e^- fluxes and positron fraction

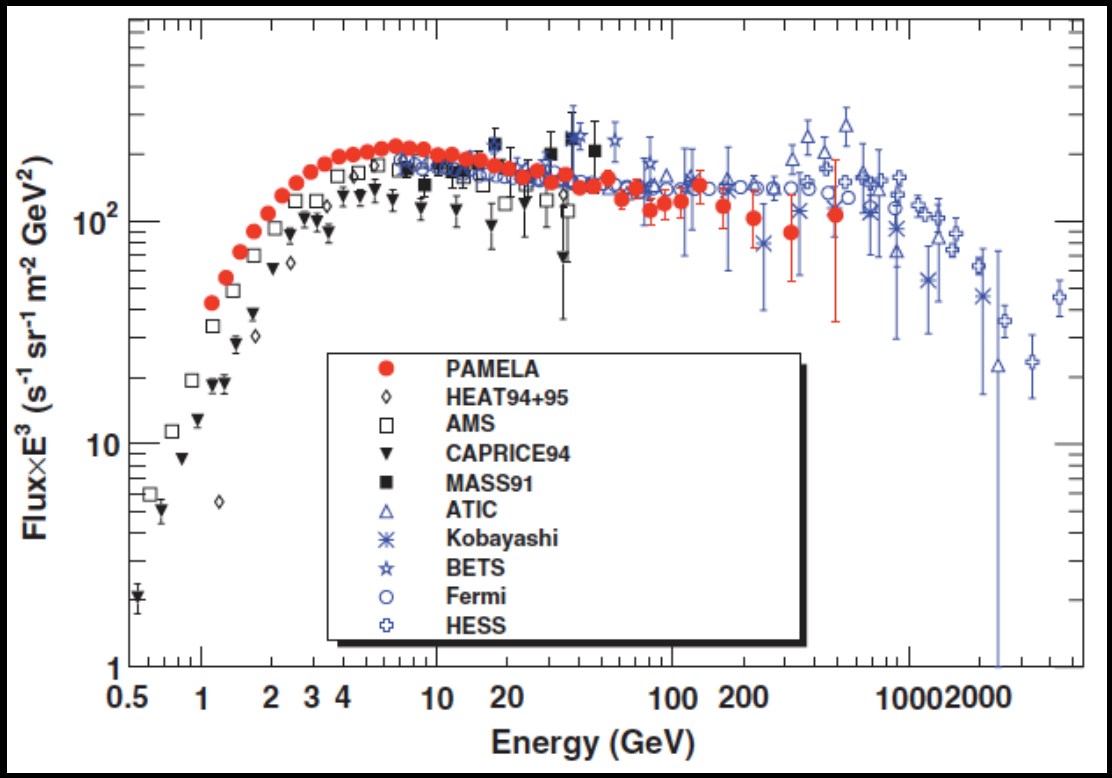


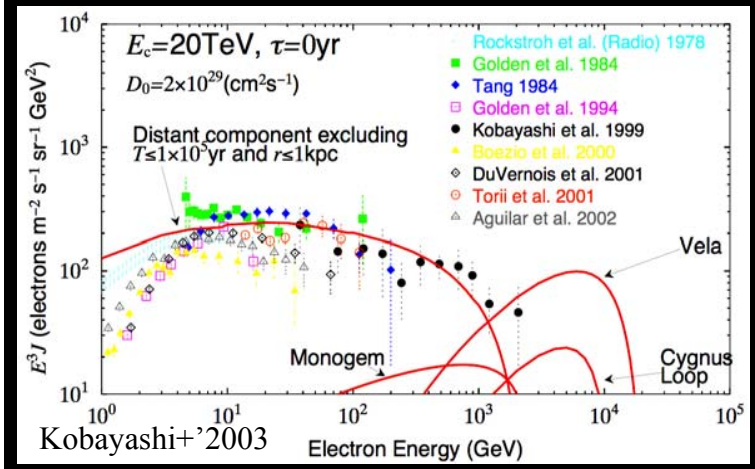




- State-of-th
  have a mag
  field
- Measured a
- Fraction = $\Phi(e^+) / [\Phi(e^+) + \Phi(e^-)]$
- Confirmed rise in the positron fraction
- Extended measurements up to 200 GeV

All-electron spectrum



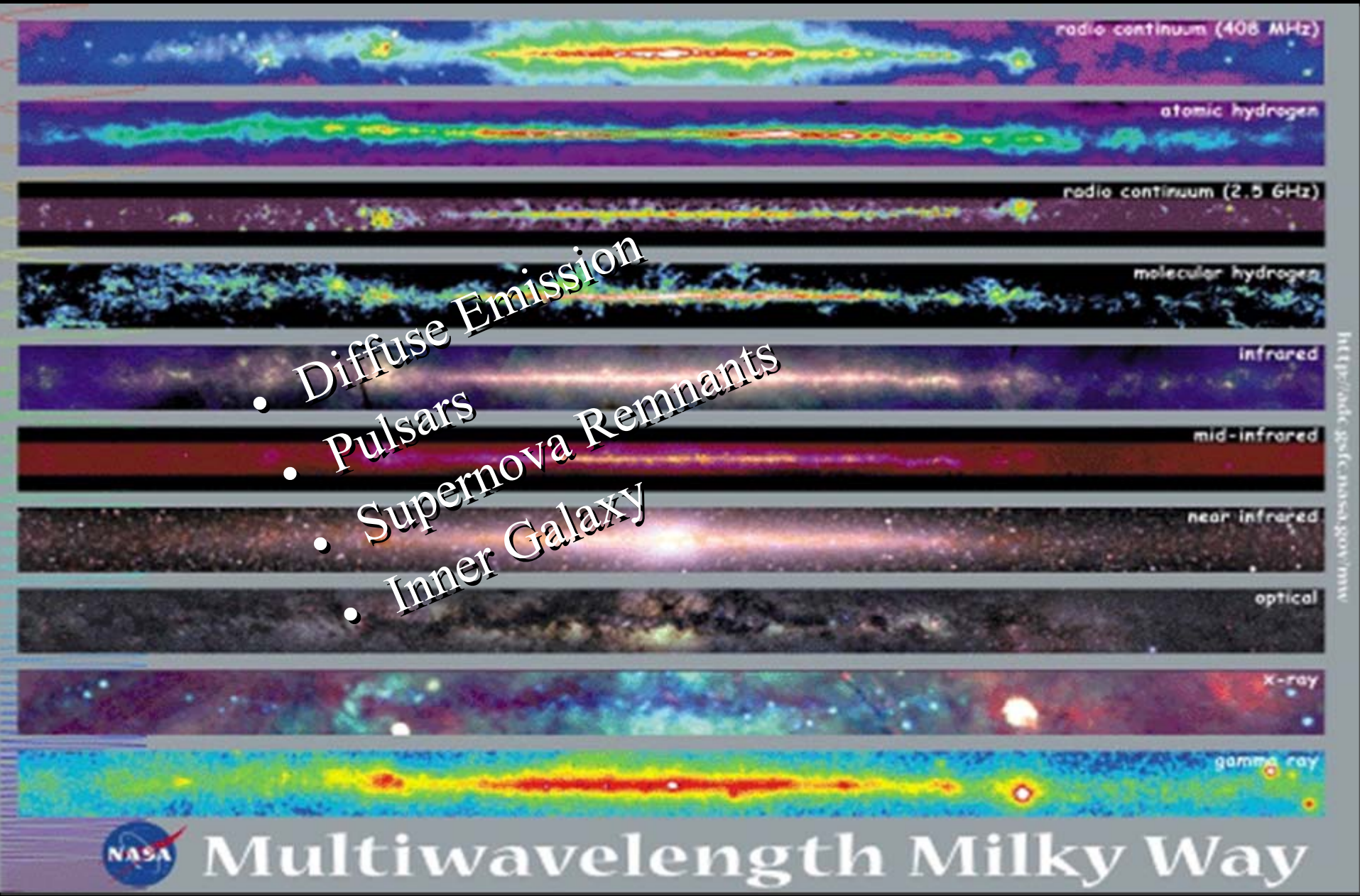


Kobayashi+'2003

- Fermi-LAT and PAMELA data agree well
- Shows some structure (breaks and bumps)
- Flatter than extrapolated from low energies
- Sharp cutoff at 1 TeV (HESS), as expected

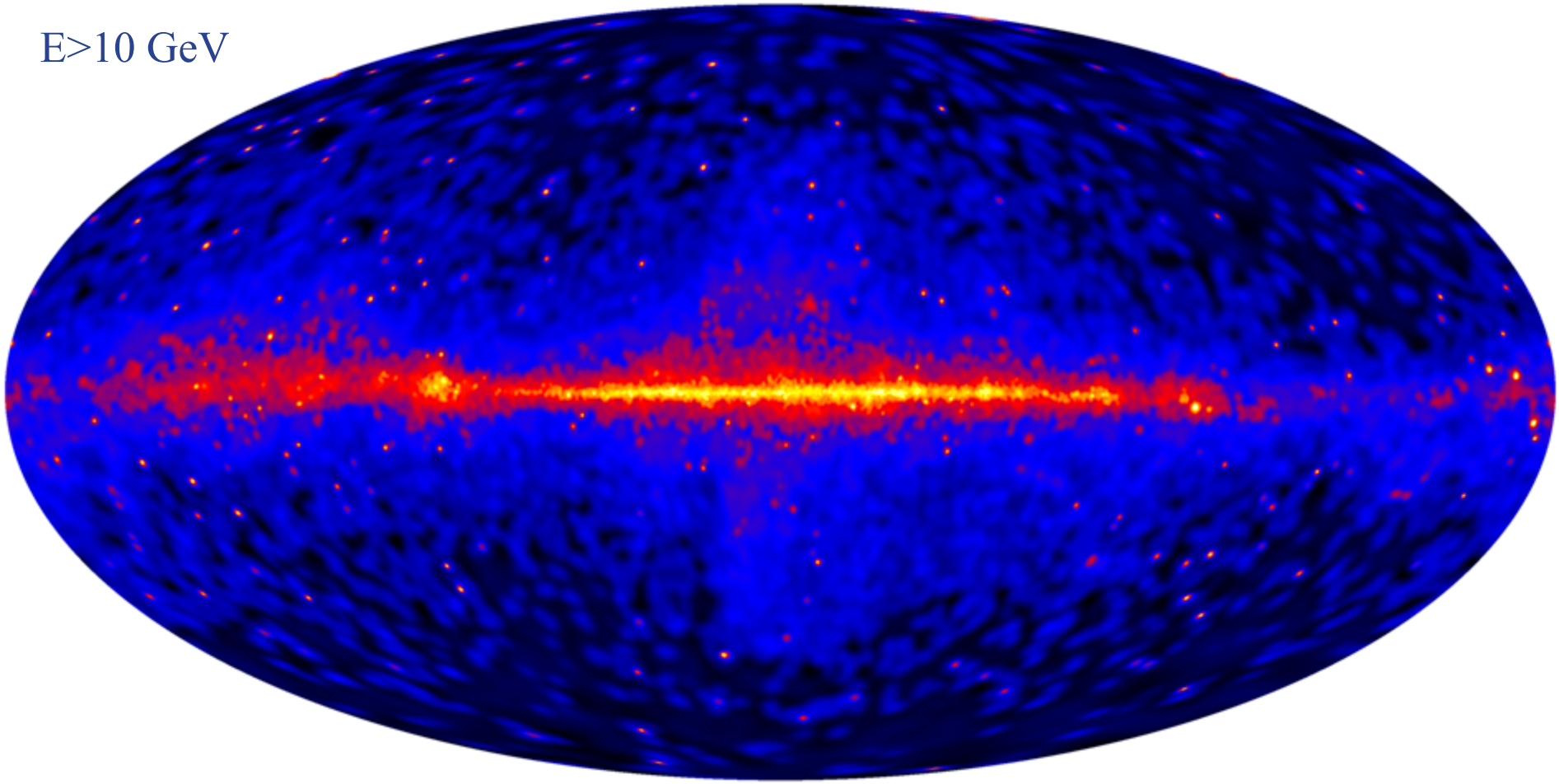
- Cannot be reproduced with a single power-law injection spectrum
- Origin
  - Local sources?
  - perhaps needs a second component with hard spectrum (positrons?)

The Milky Way galaxy



- Diffuse Emission
- Pulsars
- Supernova Remnants
- Inner Galaxy

Fermi-LAT skymaps, 48 months

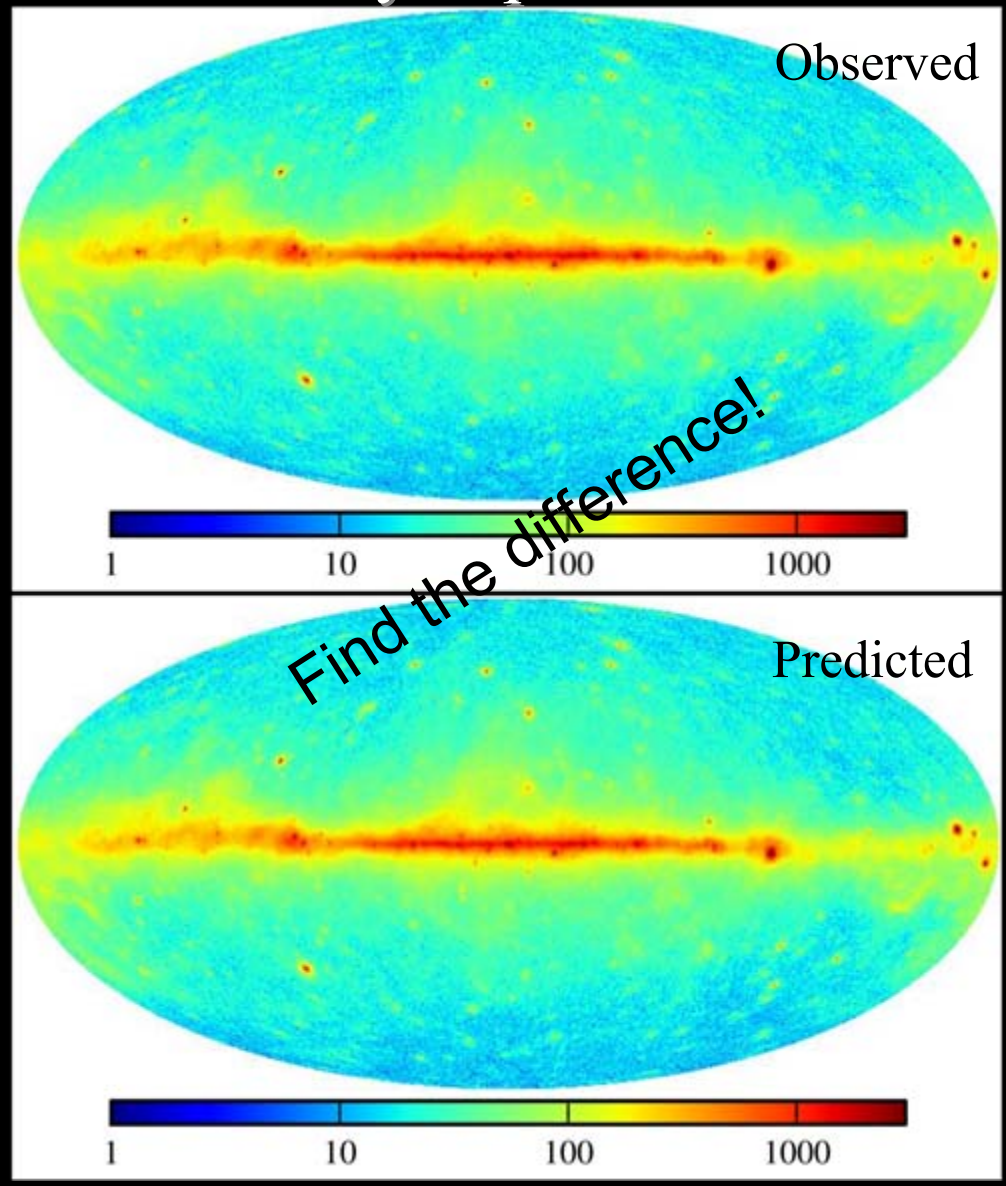


- ~80% of the emission is diffuse – a lot of statistics
- Fewer sources at high energies
- Pion-decay emission at high latitudes is “local”

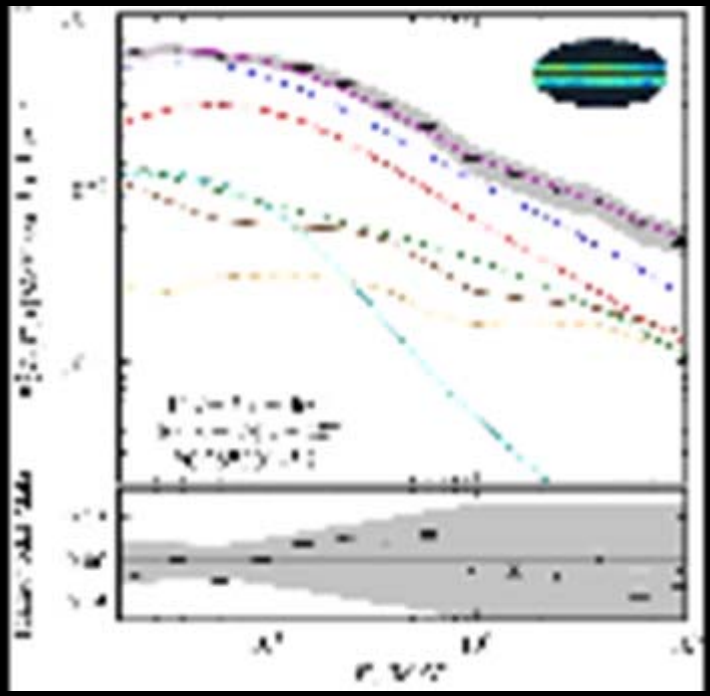
Diffuse emission skymaps

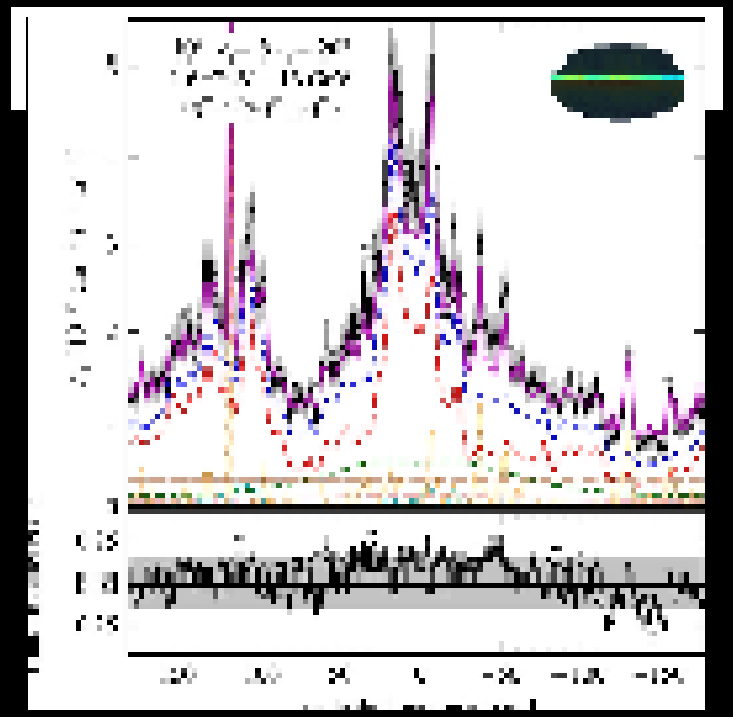
- Observed Fermi-LAT counts in the energy range 200 MeV to 100 GeV

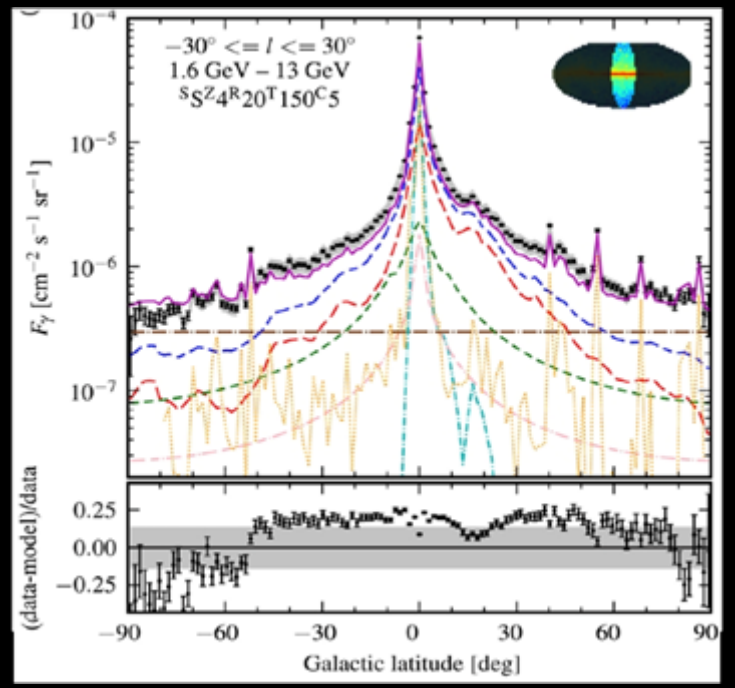
- Predicted counts calculated using GALPROP model tuned to CR data
- Grid of 128 models covering plausible confinement volume, CR source distributions, etc.
- A massive Fermi-LAT study – ApJ 750 (2012) 3



Spectrum and profiles

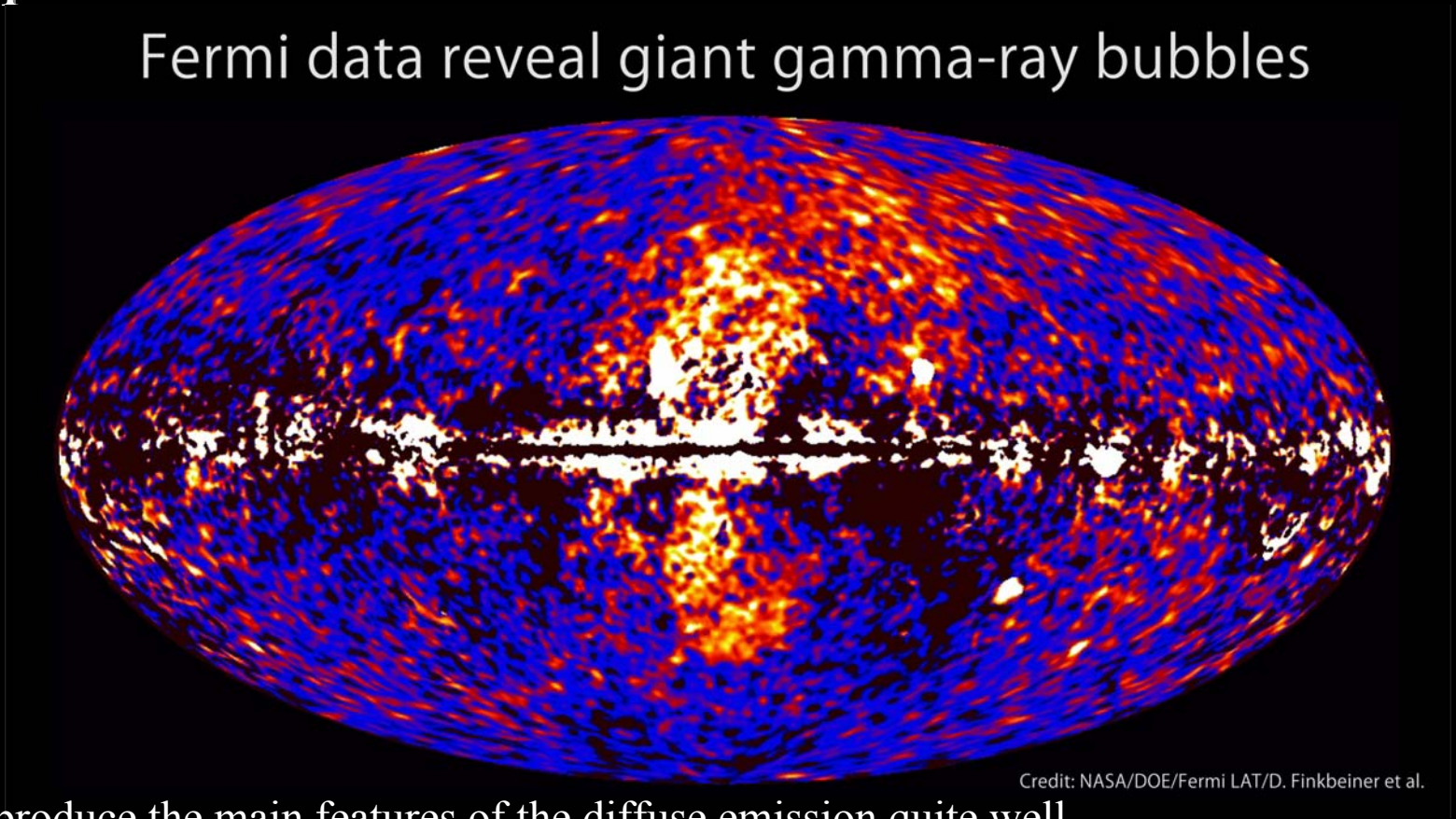






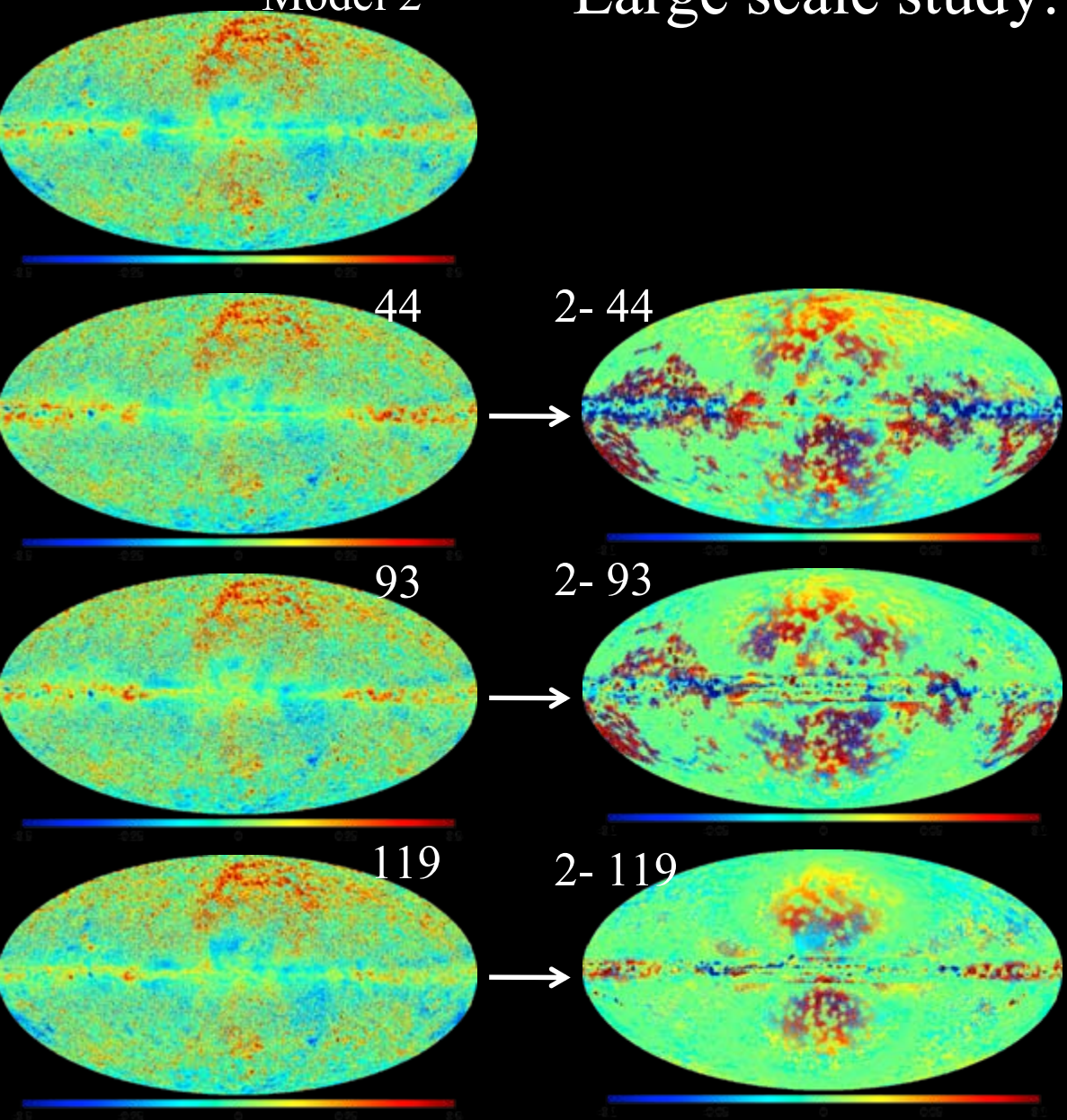
- Components of the model
  - Neutral pion emission from gas H_2, HI, HII
  - Inverse Compton
  - Bremsstrahlung
  - Detected sources
  - Isotropic emission

NASA press release



- ✧ Models reproduce the main features of the diffuse emission quite well
- ✧ Discrepancies between the physical model and high-resolution data (residuals) are the gold mines of new phenomena!
- ✧ Every extended source and/or process that is not included into the model pops up and exposes itself as a residual

Large scale study: residuals



- Agreement for models is overall good, but features are visible in residuals at ~% level
- Difference between illustrative models shown in right maps : structure due to variations of model parameters

- Models details:

  2: $SNR^{Z}4^{R}20^{T}150^{C}5$

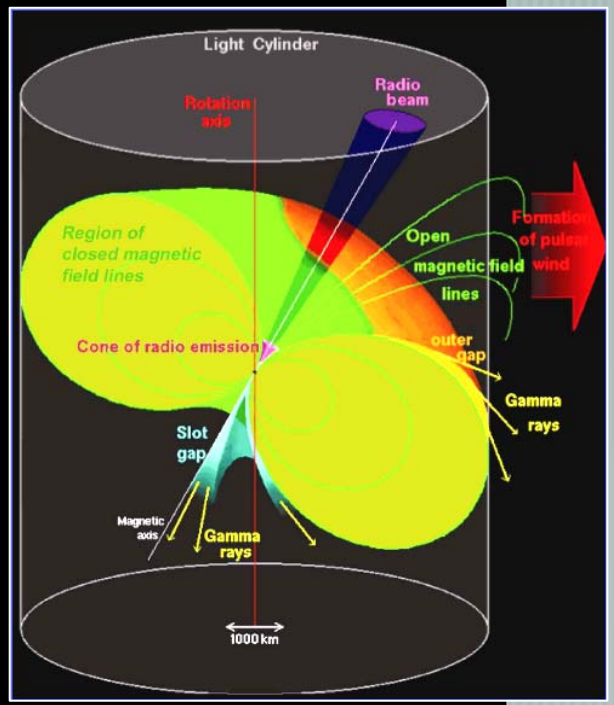
  44: $Lorimer^{Z}6^{R}20^{T}\infty^{C}5$

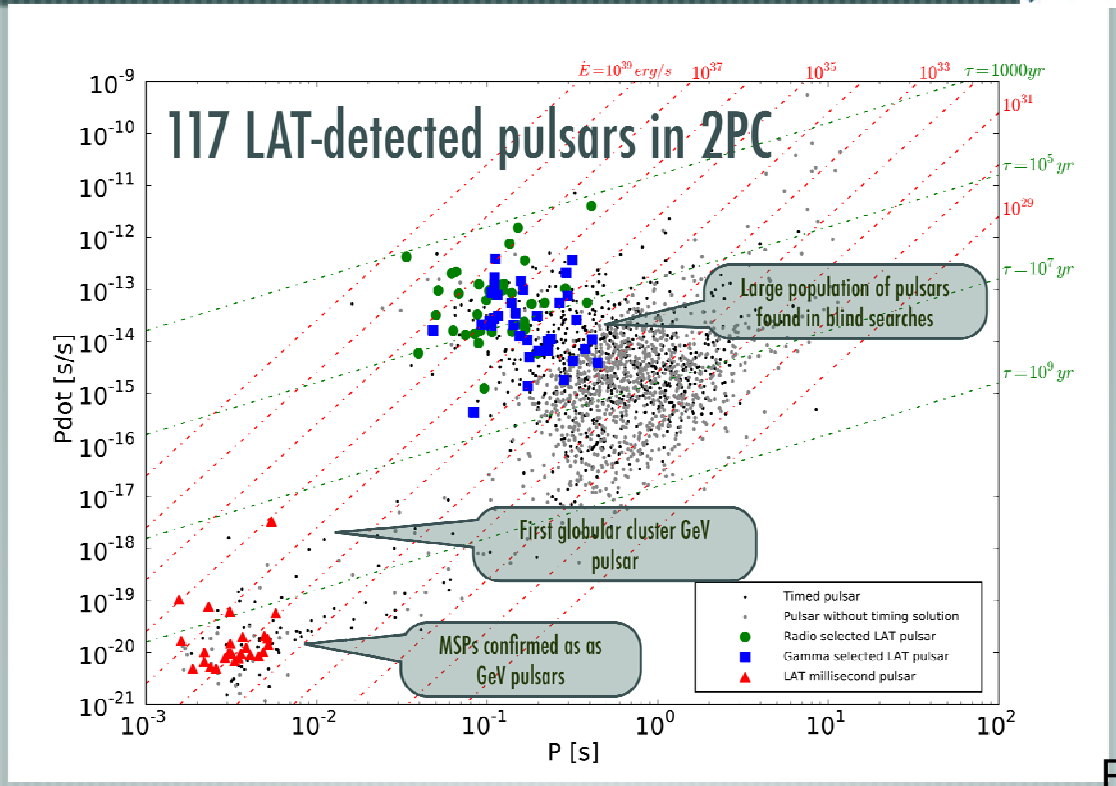
  93: $Yusifov^{Z}10^{R}30^{T}150^{C}2$

  119: $OB^{Z}8^{R}30^{T}\infty^{C}2$

Pulsars

LAT Pulsar Population Explosion





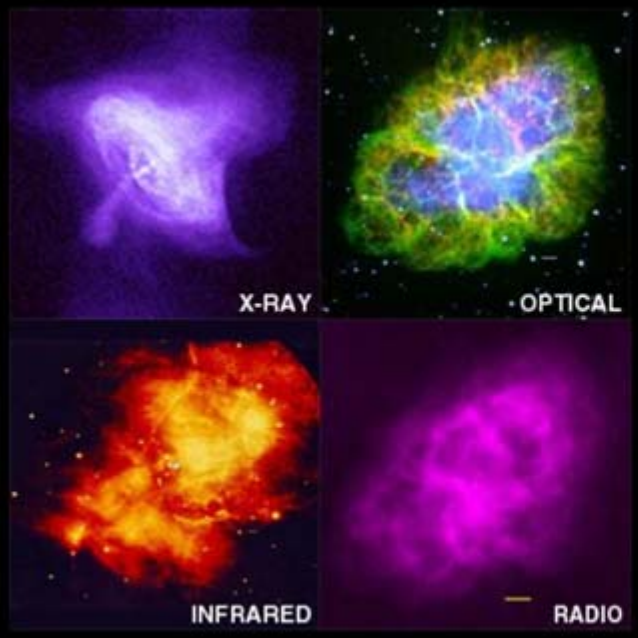
P.Ray

- Number is still increasing rapidly >200 soon
- First blind search MSP announced recently: Pletsch et al. found PSR J1311-3430
  - Optical observations (Romani 2012) constrained the search somewhat
  - Most compact MSP known (1.56 h) & M_{pulsar} >2.1 M_{Sun} (Romani et al.)

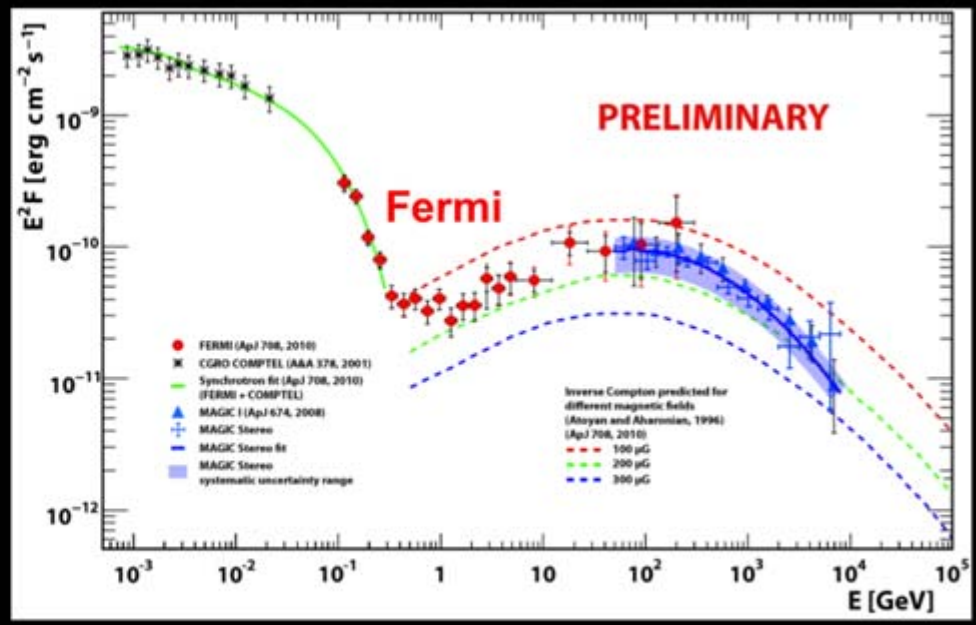
The Crab Nebula, the brightest VHE source...

The brightest VHE galactic «steady» source, observed by every Cherenkov experiment & Fermi (Abdo et al, 2010, 708, 1254):

- γ-ray emission below 500 MeV due to synchrotron emission
  - → electrons accelerated up to ~1 PeV
- high energy component due to IC (mainly on synchrotron photons)
  - → fit of the IC peak at ~60 GeV (using Fermi and IACT results)
  - → magnetic field constraint in the 100 – 200 μG range



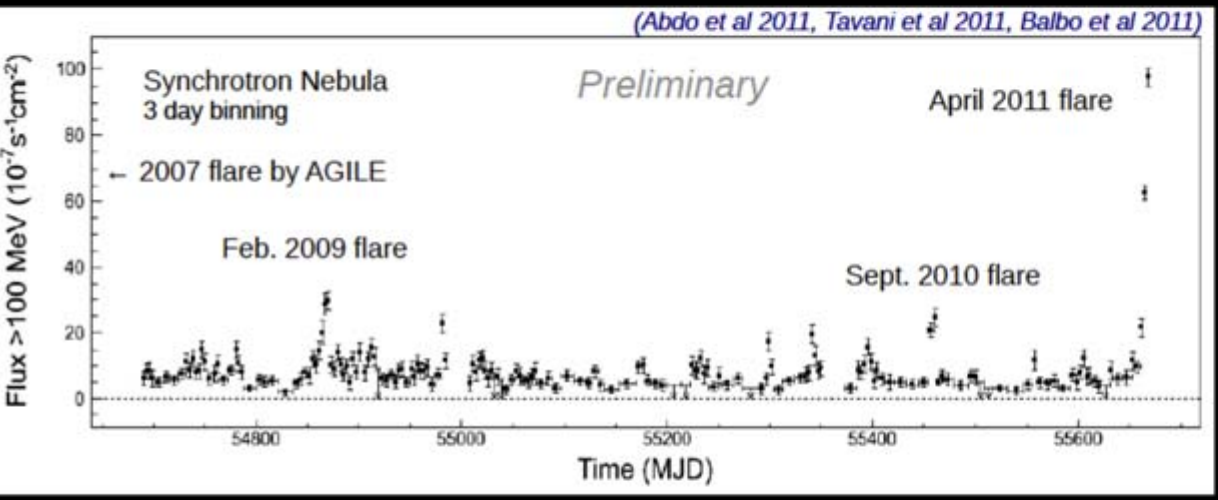
E. de Cea del Pozo, ICRC 2011

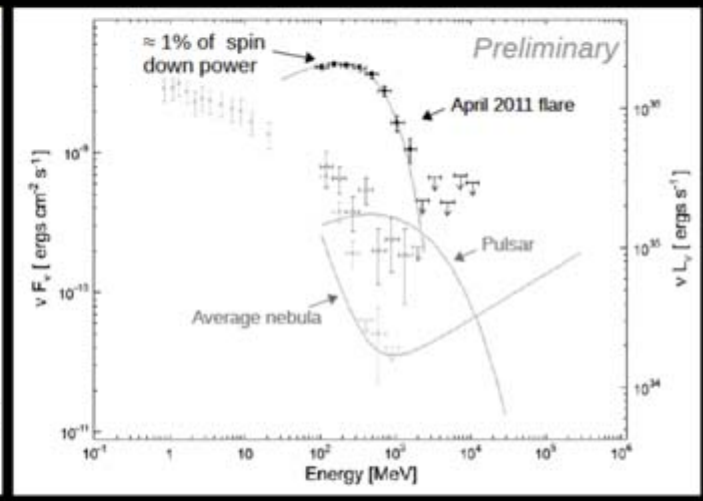


... but no more a standard candle

Recent flares of the synchrotron component (Oct. 2007, Feb. 2009, Sept. 2010, Apr. 2011) :

R. Buehler, Fermi Symposium 2011





Three day Crab synchrotron curve

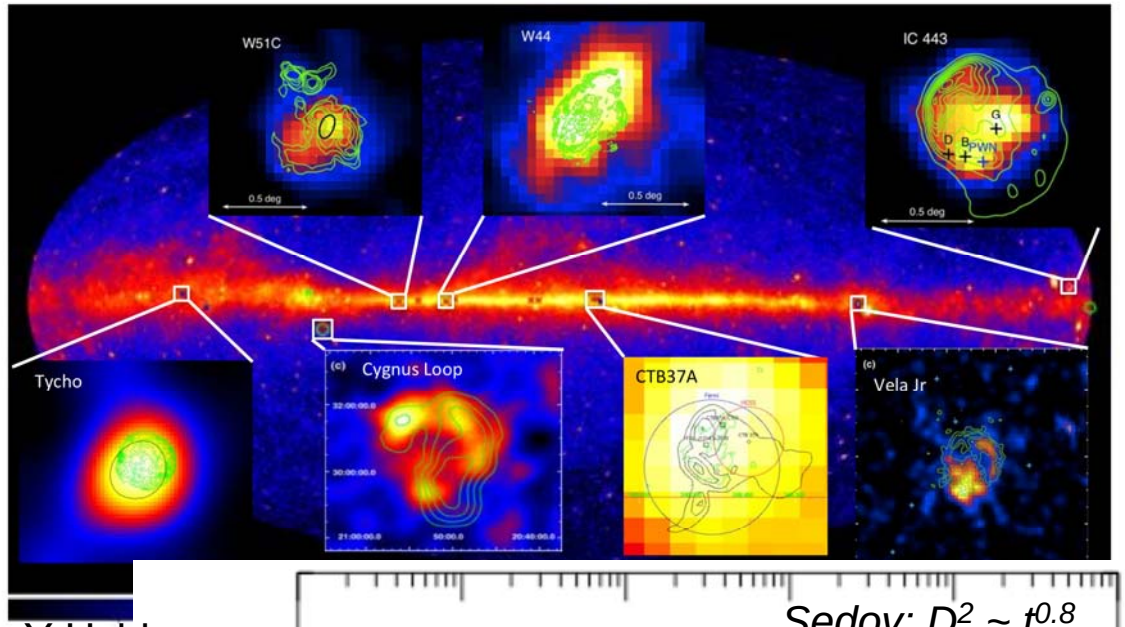
- Average flux ~6e-7 ph/cm2/s above 100 MeV, whith three flares as extremes of persistent variability

- Flux increase by ~5 during 2009 and 2010 flares, by ~30 during 2011 flare !

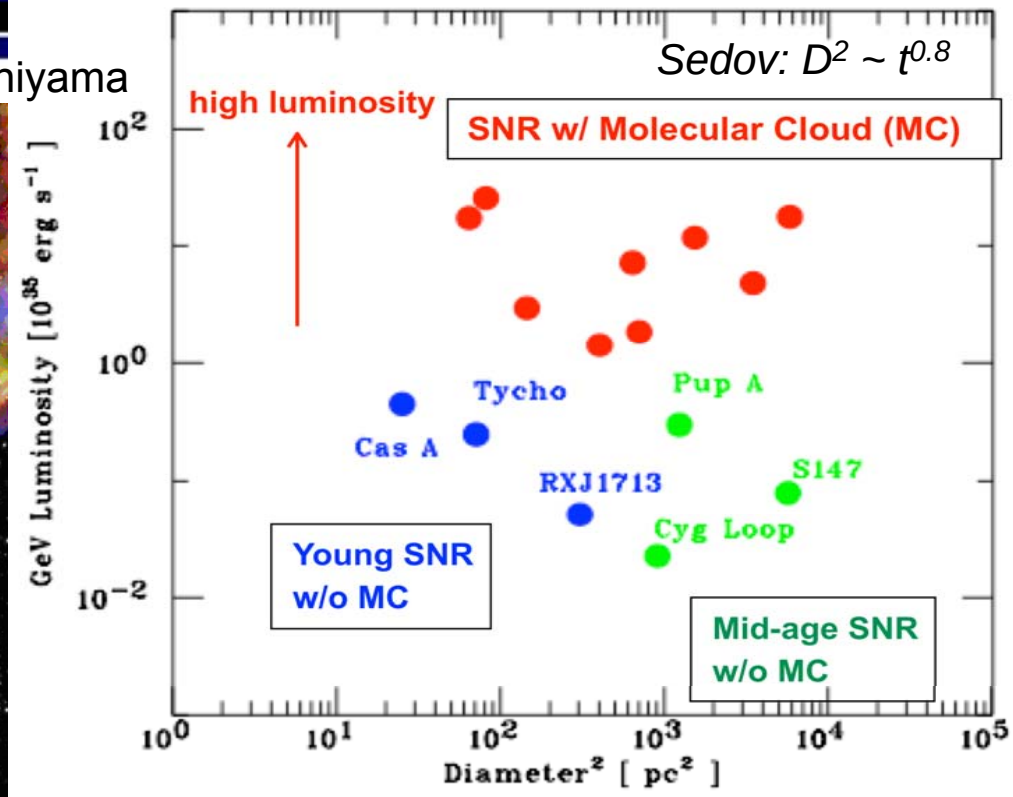
- - *Compact emission region < 0.0004 pc ~ 0.04" (for D<4)* → *Emission from the inner nebula*

Supernova Remnants

- 13 identified SNRs
  - *9 interacting*
  - *4 young SNRs*



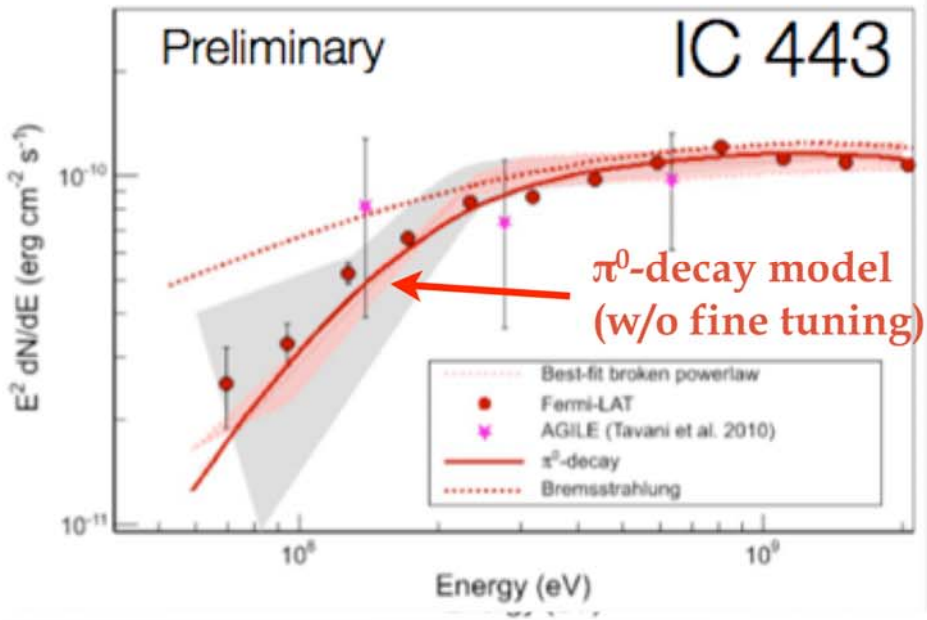
Y.Uchiyama

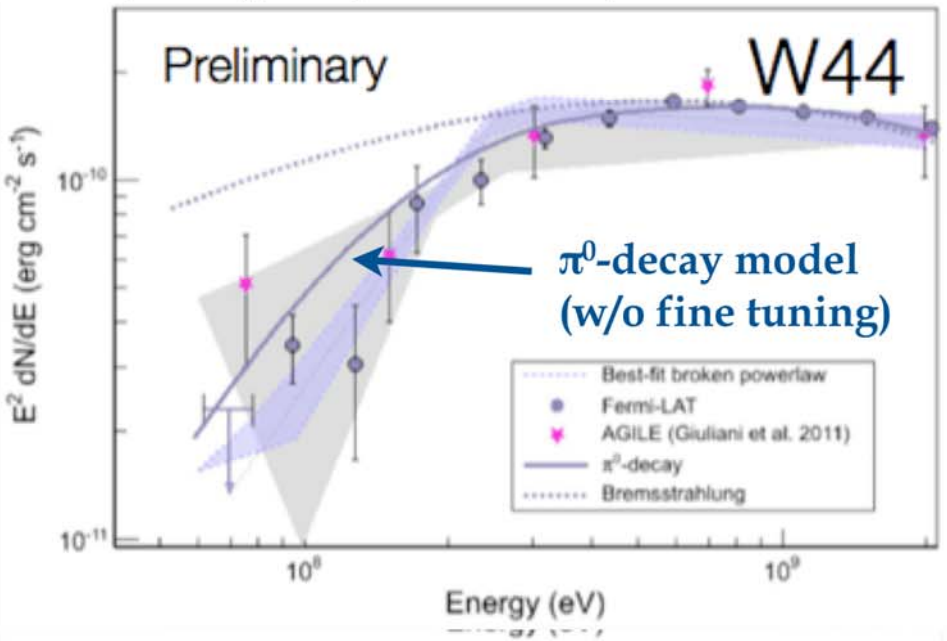


from Thompson, Baldini, & Uchiyama (2012)

Fermi LAT Spectra of SNRs W44 & IC443: Signature of π^0-decay γ-rays

Fermi-LAT Collaboration 2012 (Funk, Tanaka, Uchiyama) Science in press





- ☑ Our previous papers reported spectra only >200 MeV.
- ☑ Here we report spectra down to 60 MeV thanks to:
  - ✱ Recent update ("Pass-7") of event reconstruction, which largely improved effective area at low energies.
  - ✱ Increased exposure time: 1 yr ➜ 4 yr

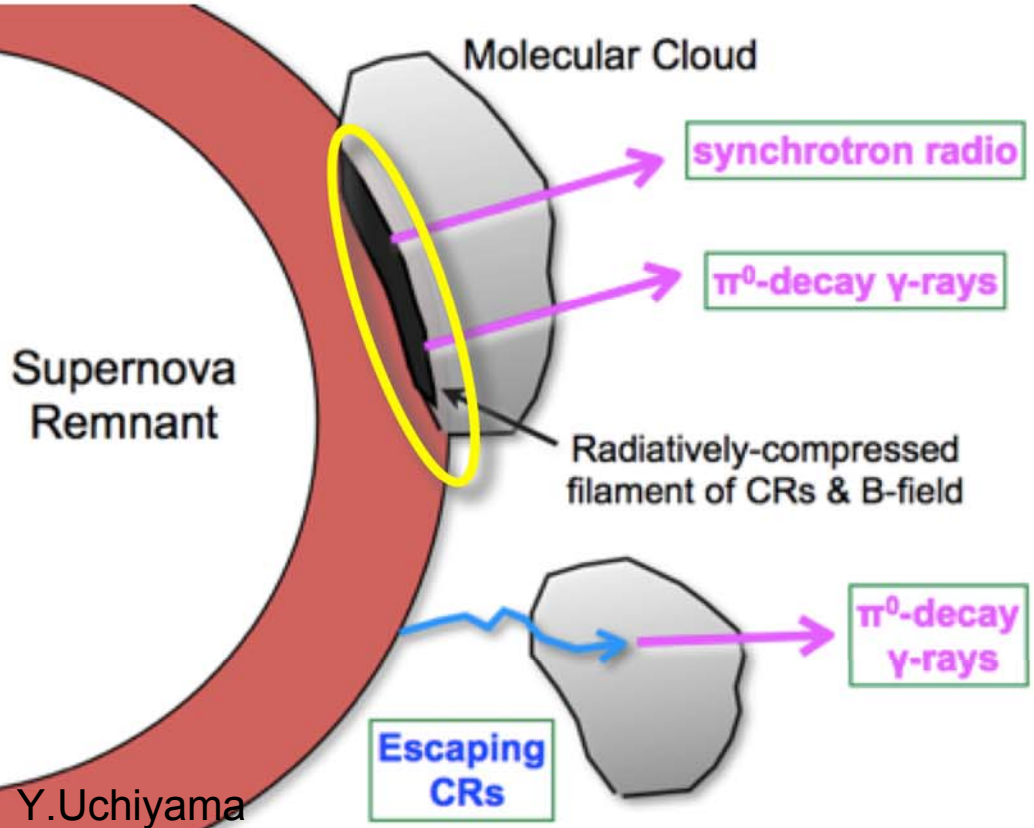
Sub-GeV spectra of IC443/W44 agree well with π^0-decay spectra.

Y.Uchiyama

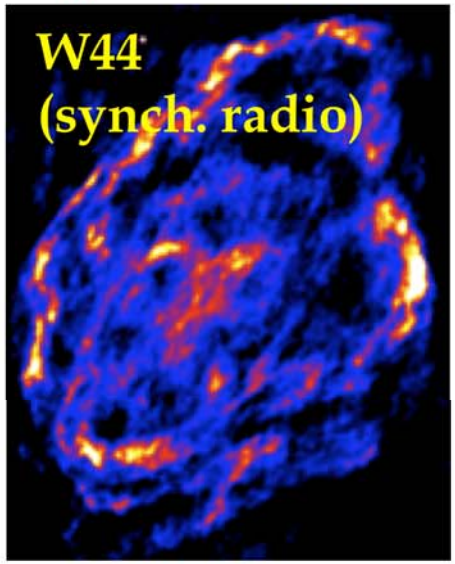
Crushed Cloud Model

Blandford & Cowie (1982)
Uchiyama et al. (2010)

- The π^0-decay γ-rays come from shocked molecular clouds
  - Radiative shock ➜ high compression ➜ high CR & gas density
  - Shock: slow (~100 km/s), partially ionized ➜ Maximum energy < TeV
  - Thin filaments or sheets ➜ Hard to confine CRs at high energies
  - Reacceleration of pre-existing CRs may be important



- The Case of W44:
  - Shocked MC mass of 5000 $M_\odot$
  - Synchrotron radiation correlated with shocked H_2 gas (infrared lines)

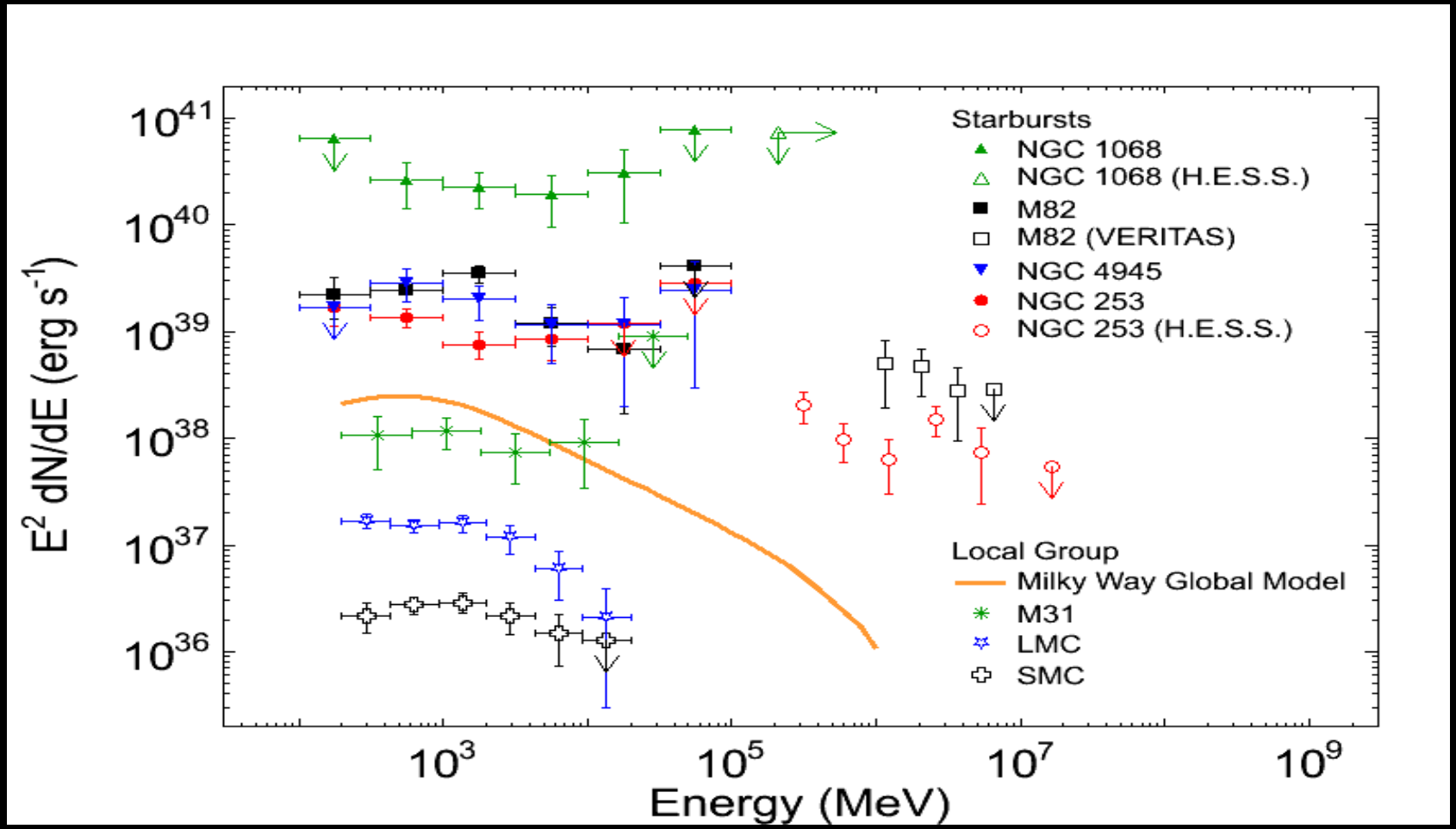


Y.Uchiyama

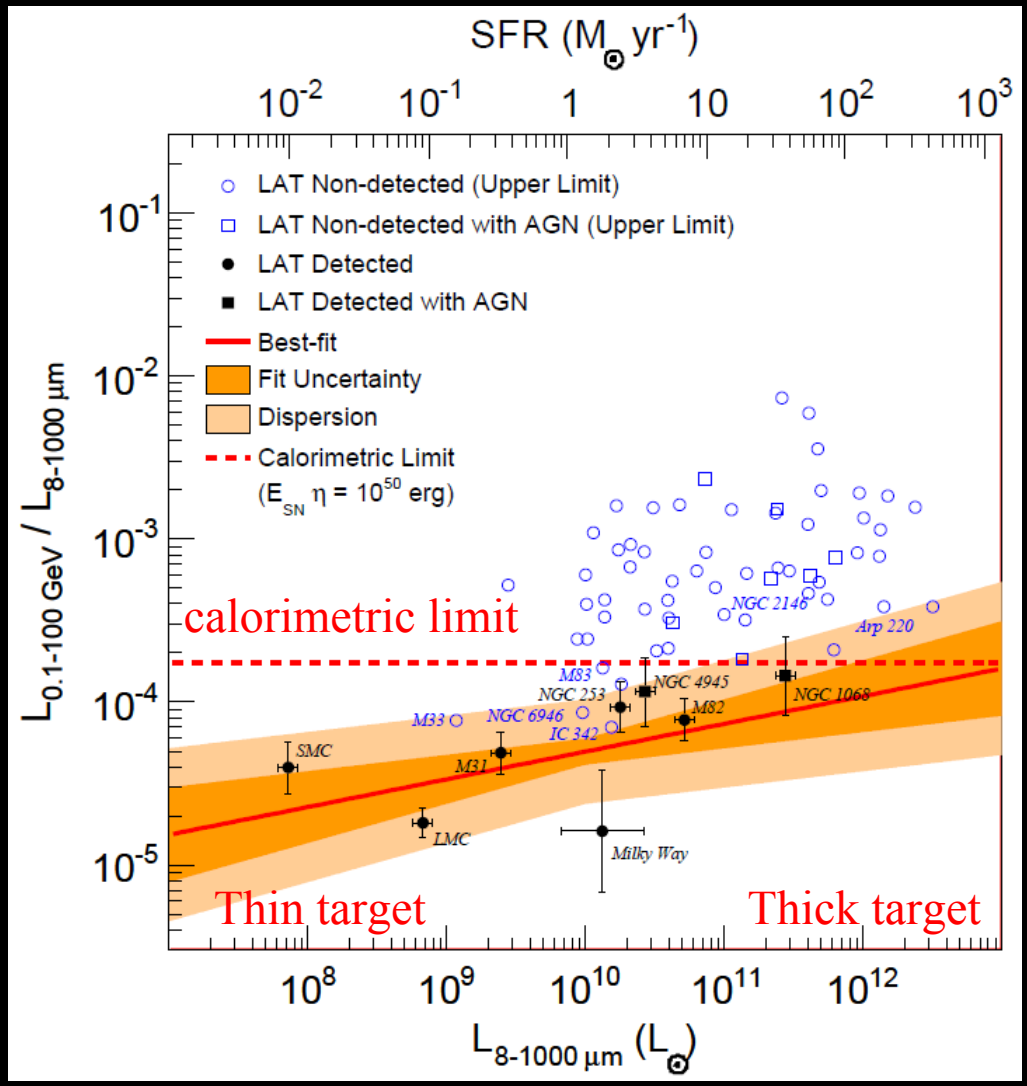
Extragalactic Sources

- Active Galaxies
- Gamma-Ray Bursts
- Starforming Galaxies
- Isotropic background

Starforming Galaxies



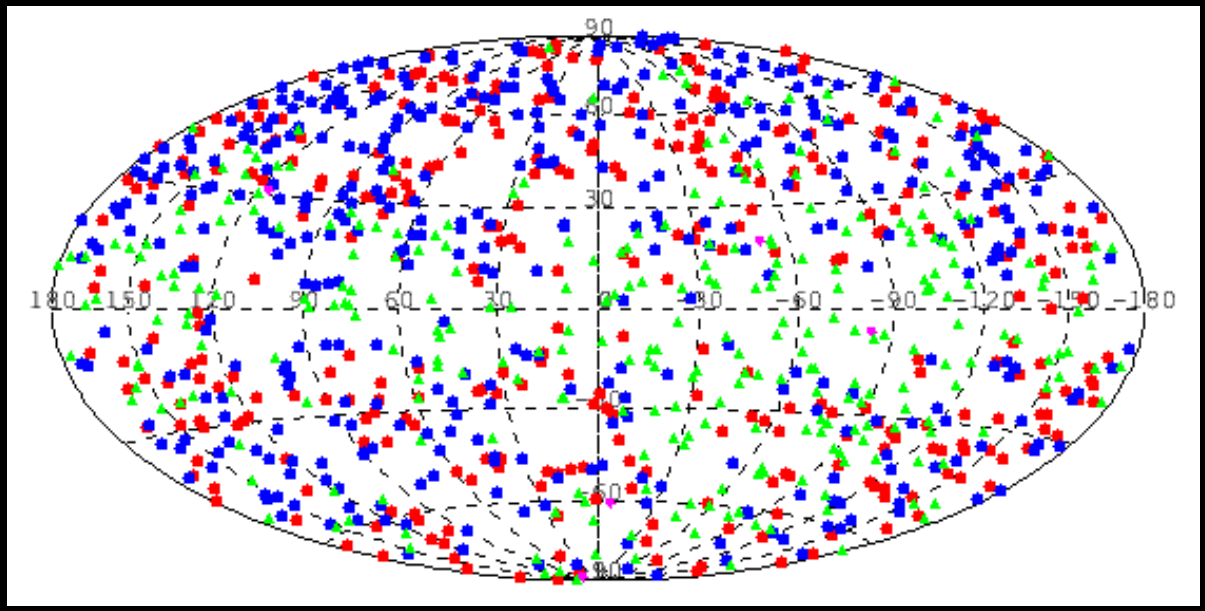
Cosmic Rays as a Universal Phenomenon



- γ-ray luminosity vs. IR luminosity for normal galaxies detected with Fermi-LAT
- The γ-ray luminosity scales linearly (index ~1.1) with the total emission of hot stars reprocessed by dust – a tracer of star formation
- The ratio approaches the calorimetric limit in star-burst galaxies
- An evidence of the SNR-CR connection in normal star-forming galaxies

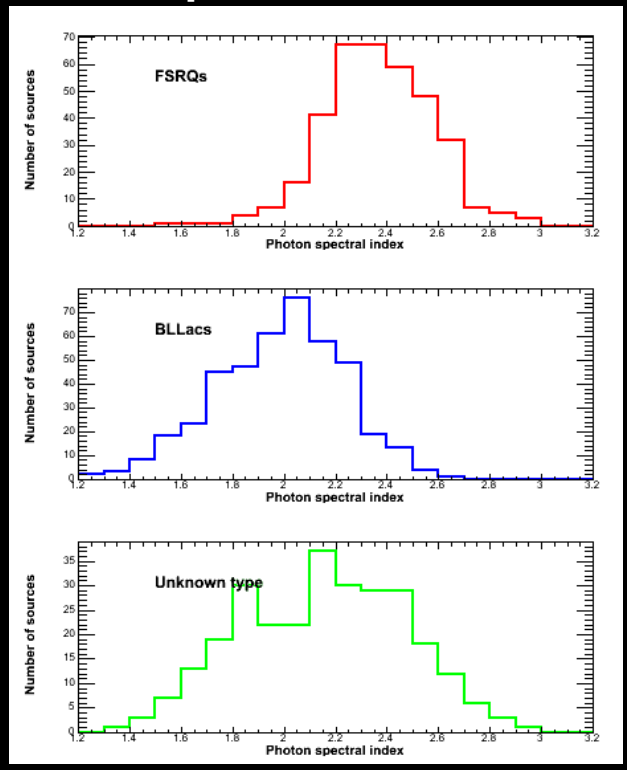
2nd LAT AGN Catalog

1,016 sources



FSRQs:360
BL Lacs:423
Other AGN (including radio and starburst): 30
Unknown: 203

Spectral Index



Look for spatial association between 2FGL sources and known AGN

Less sensitivity near galactic plane (foreground confusion & survey bias)

Fermi GRB detections by August 1, 2011

~682 GBM GRB (since Aug 2008)

32 LAT GRB (9 LAT LLE-only GRB)

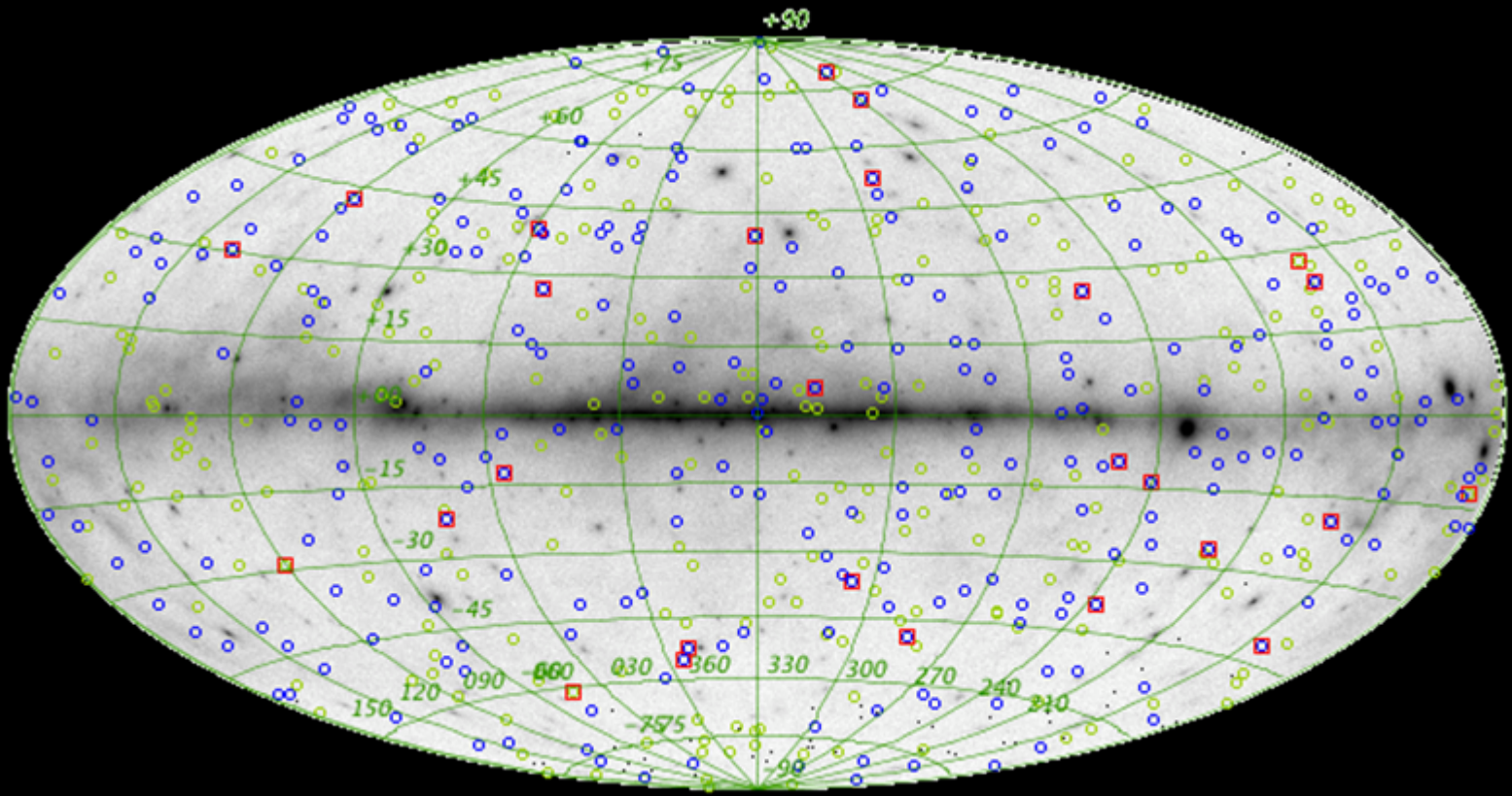
Circles:

In Field-of-view of LAT (<70˚): 345

Out of the FOV

Squares:

LAT detections



The Brightest and Most Distant GRBs

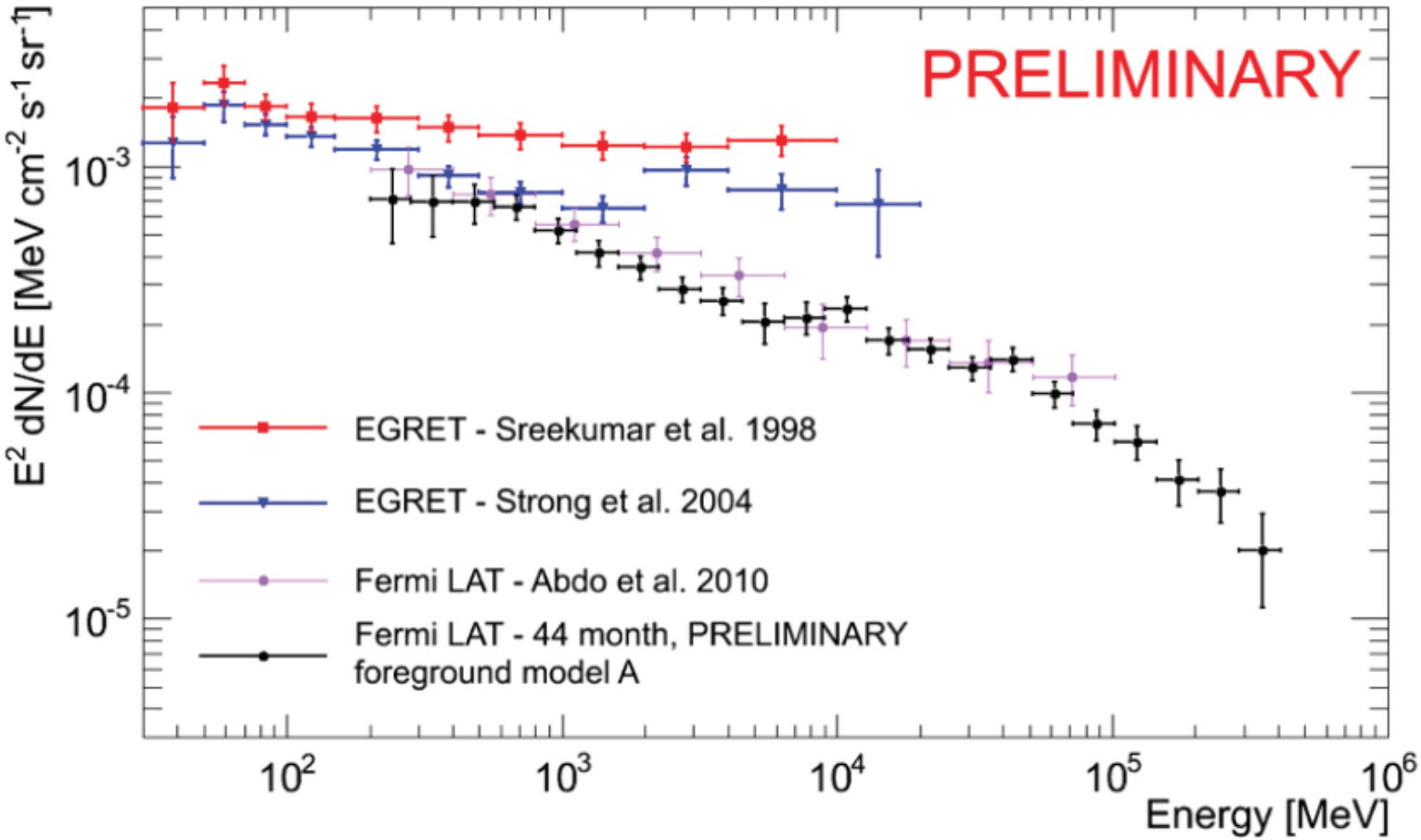
GRB Name	GBM T90	N Pred. Events (>100MeV, Trans.)	HE Delayed Onset?	Long Lived HE Emission?	Maximum Energy (GeV)	Arrival time of the highest events (seconds since trigger)	Redshift
GRB080825C	Long	10	√	√	0.6	28.3	-
GRB080916C	Long	188	√	√	13.2	16.5	4.35
GRB081006	Long	13	√	√	0.8	1.8	-
GRB081024B	Short	11	√	√	3.1	0.6	-
GRB081207	Long	LLE	-	-	-	-	-
GRB090217	Long	17	√	√	1.2	179.1	-
GRB090227B	Short	3	-	-	0.0	0.0	-
GRB090323	Long	30	√	√	7.5	195.4	3.57
GRB090328	Long	50	√	√	24.5	261.7	0.736
GRB090510	Short	186	√	√	31.3	0.8	0.903
GRB090531B	Short	LLE	-	-	1.6	115.2	-
GRB090626	Long	LLE	√	√	2.1	111.6	-
GRB090902B	Long	314	√	√	33.4	81.8	1.822
GRB090926	Long	249	√	√	19.6	24.8	2.106
GRB091003	Long	3231	√	√	2.8	6.5	0.897
GRB091031	Long	15	√	√	1.2	79.8	-
GRB100116A	Long	14	-	√	13.1	296.4	-
GRB100225A	Long	LLE	-	-	-	-	-
GRB100325A	Long	6	-	√	1.9	71.4	-
GRB100414A	Long	27	√	√	4.7	288.3	1.368
GRB100724B	Long	22	-	-	0.2	61.8	-
GRB100728A	Long	4	-	-	0.1	81.2	-
GRB100728A	Long	LLE	-	-	0.1	81.2	-
GRB101014A	Long	LLE	-	-	-	-	-
GRB101123A	Long	LLE	-	-	-	-	-
GRB110120A	Long	5	-	-	1.8	72.5	-
GRB110328B	Long	LLE	-	-	1.6	514.7	-
GRB110428A	Long	17	√	√	2.6	14.8	-
GRB110529A	Short	LLE	-	-	-	-	-
GRB110625A	Long	12	-	√	2.4	272.4	-
GRB110721A	Long	29	-	√	1.7	0.7	0.38
GRB110731A	Long	65	√	√	3.4	436.0	2.83

PRELIMINARY

- ~30 GRB have been seen by LAT above 100 MeV;
- Both long (>2 sec) and short (<2 sec) bursts have been seen;
- Some bursts are only visible in LAT Low Energy events;
- Most of the bursts show high-energy emission afterglow and delayed high-energy onset;
- Constraint: lower limit of bulk Lorentz factor of the colliding shells: ~1000;
- Some bursts have an extra spectral component (a different mechanism at high energy?);

- These short, distant and bright flashes can be used as tools to probe basic physics…

Comparison to older measurements.



- In agreement with published spectrum.
- Error bars predominantly systematic. Visible structures in the spectrum are **not significant**.
- Possible spectral softening at high energies ?

Conclusions

- Fermi is still young – just finished its planned 5 year primary mission phase and going for an extended mission
- Will stay in orbit until, at least, 2016
- Pass 8 will extend the energy range toward low energies, more events will be recovered
- Keep tuned

Thanks!