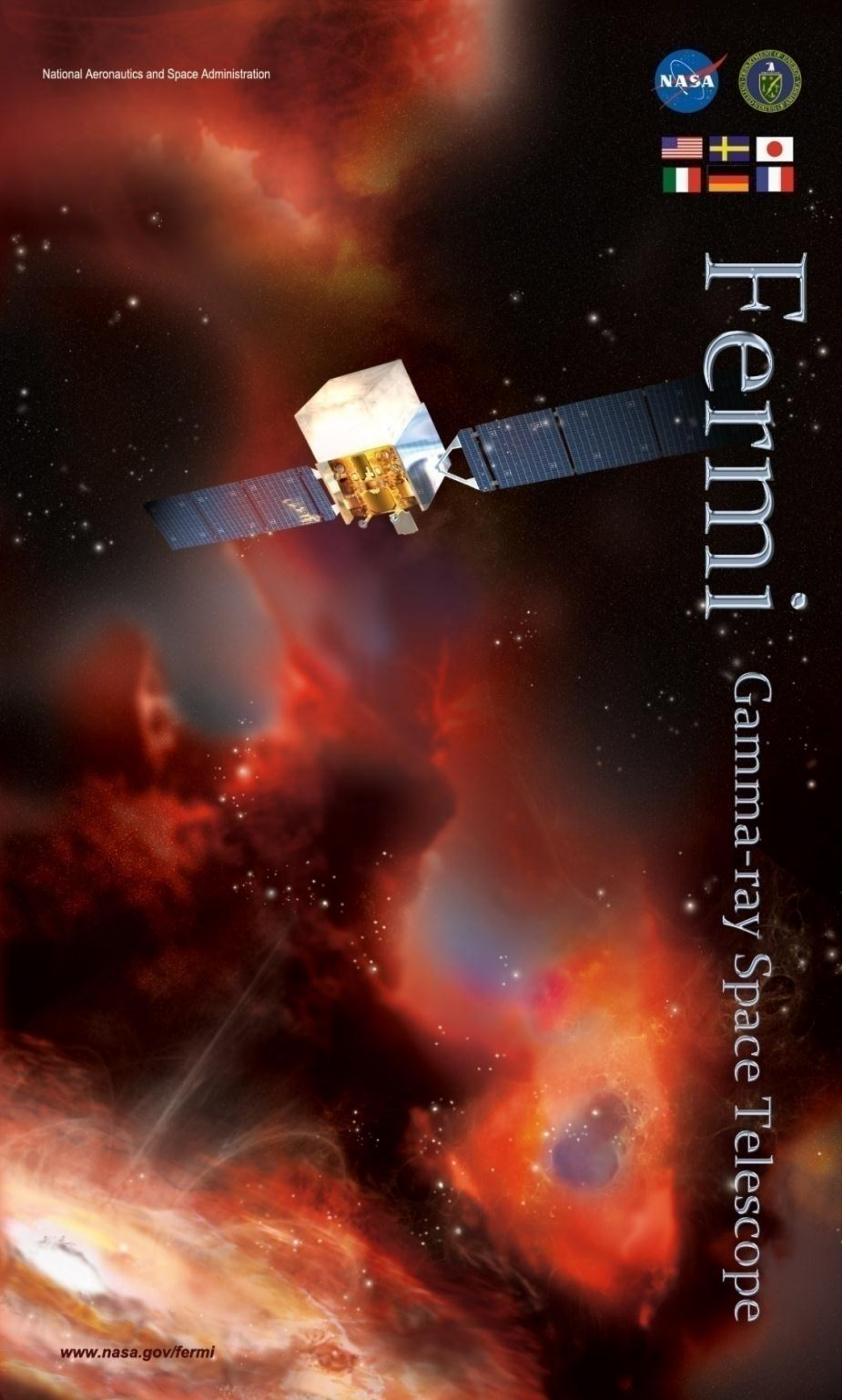
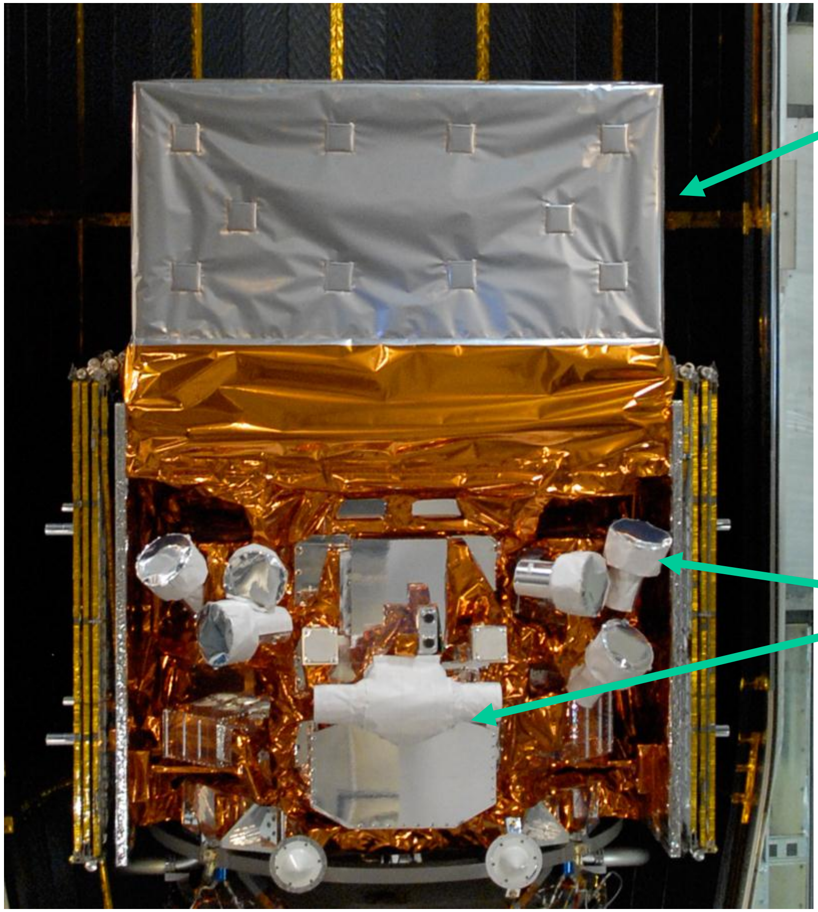


The γ-ray sky after two years of the *Fermi* satellite

Jean Ballet
(AIM, CEA/DSM/IRFU/SAp)
on behalf of the Fermi LAT Collaboration

Marseille, April 4, 2011

The Fermi Observatory



Large Area Telescope (LAT):

• 20 MeV - >300 GeV (including unexplored region 10-100 GeV)

• 2.4 sr FoV (scans entire sky every ~3hrs)

• 1 m^2 geometric area

Gamma-ray Burst Monitor (GBM)

• 8 keV - 40 MeV

• views entire unocculted sky

- **Large leap in all key capabilities, transforming our knowledge of the gamma-ray universe. Great discovery potential.**

Launch!

Cape Canaveral

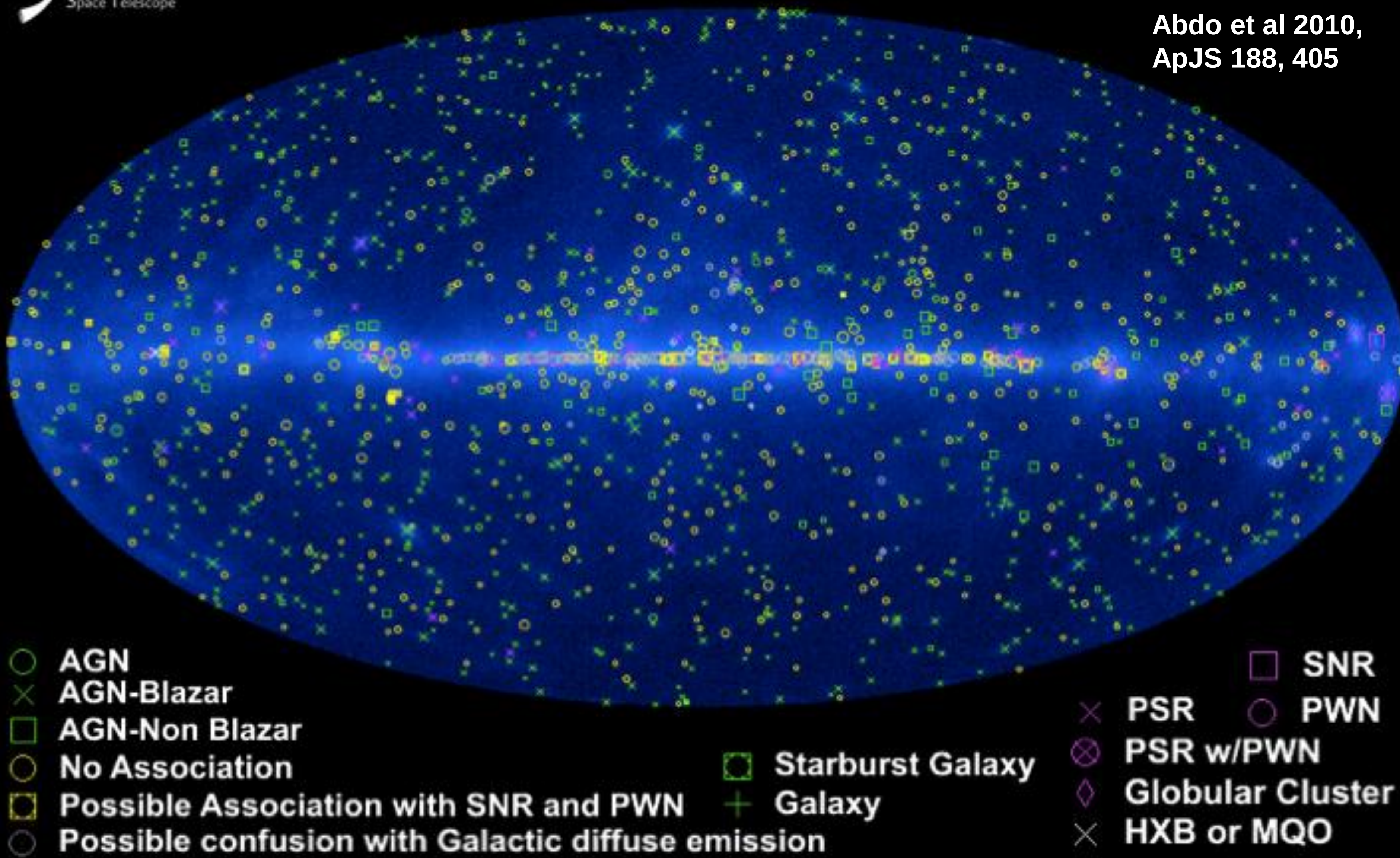
11 June 2008 at 12:05PM EDT

26 August 2008
NASA renames GLAST to Fermi

Operations guaranteed until 2013
NASA review every 2 years after that

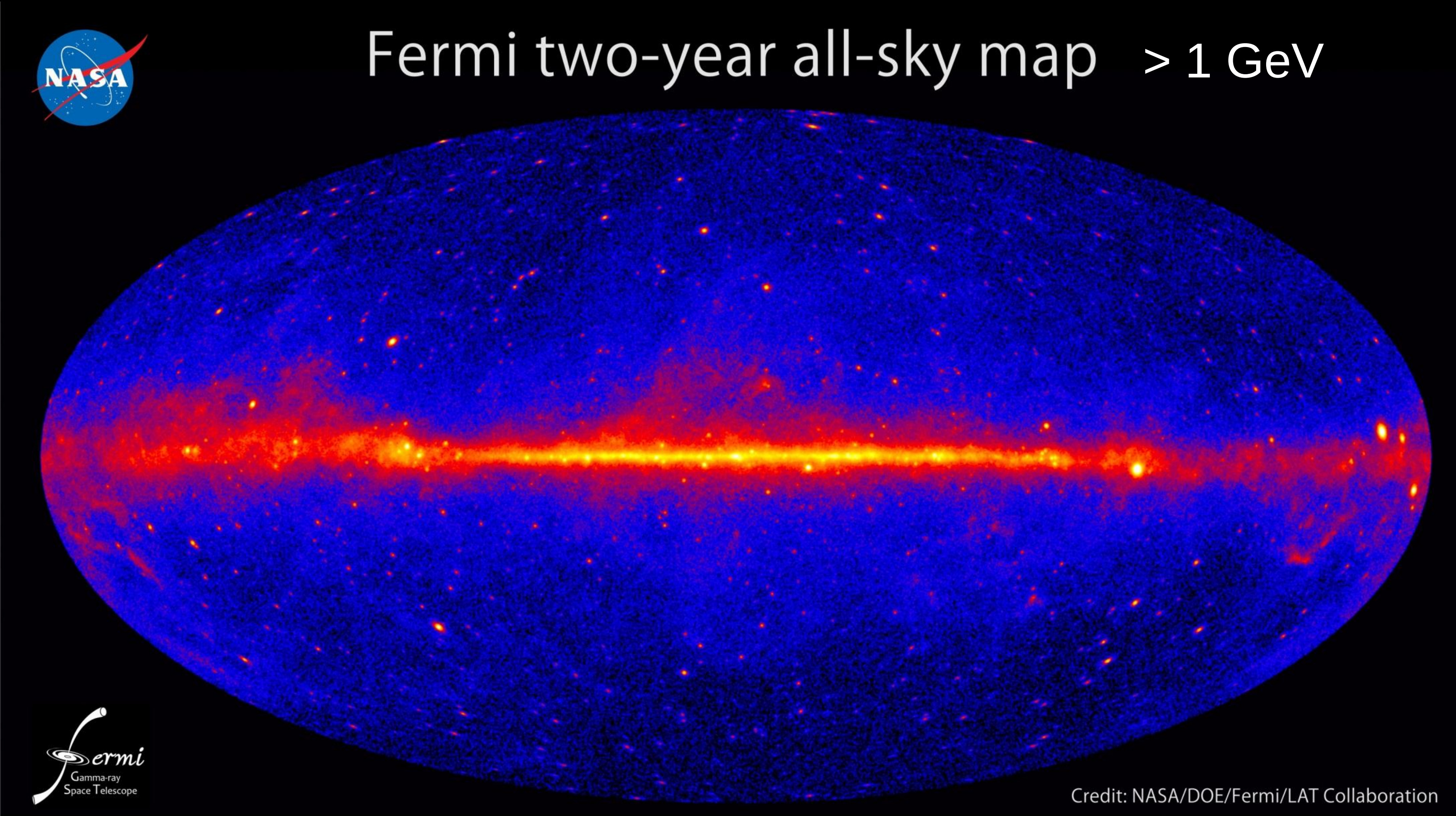
The Fermi LAT 1FGL Source Catalog

Abdo et al 2010, ApJS 188, 405

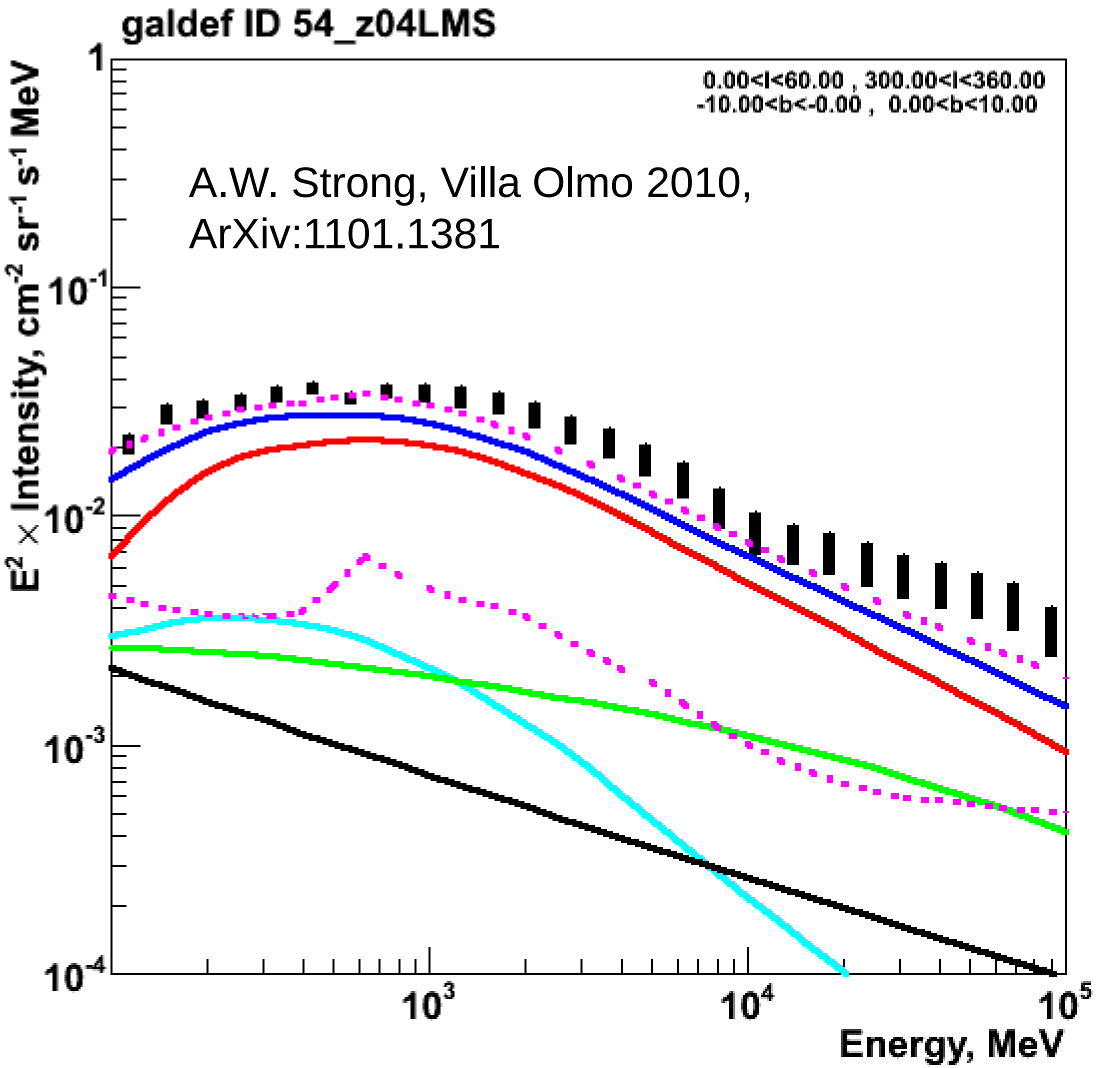


Credit: *Fermi* Large Area Telescope Collaboration

Preparing the 2FGL source catalog



Modeling our Galaxy



Emission toward the **Galactic Ridge** can be modeled as a combination of:

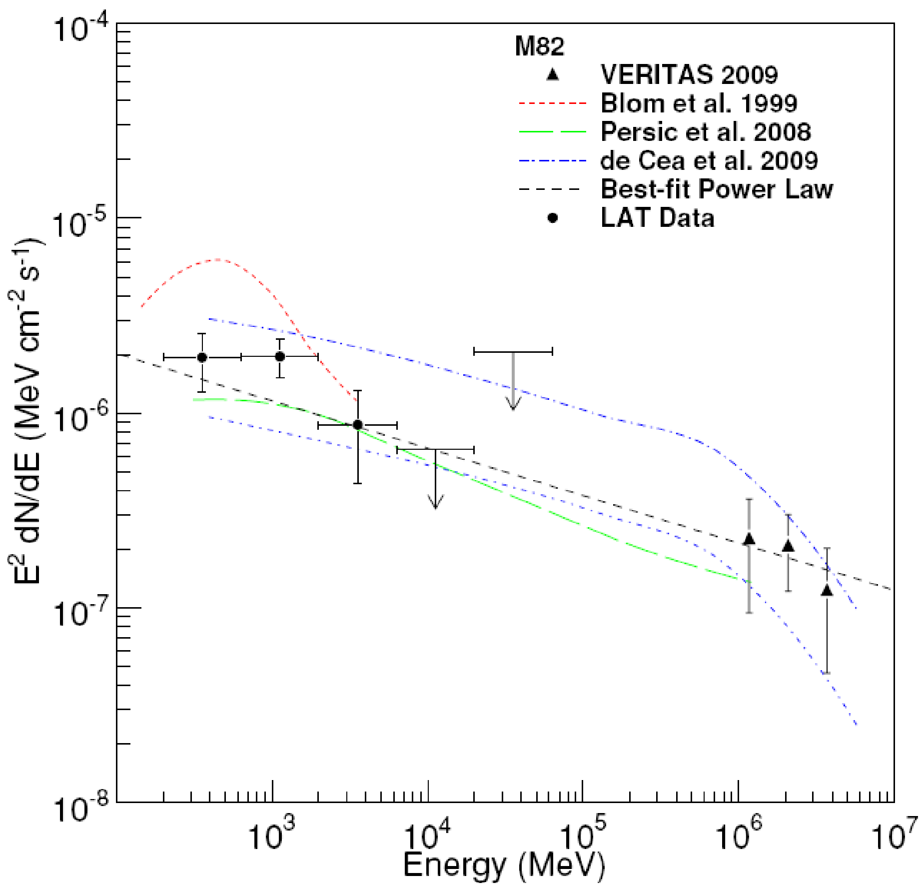
- **Pion-decay** from cosmic-ray hadrons (red line)
- **Bremsstrahlung** from cosmic-ray electrons (cyan line)
- **Inverse Compton** from cosmic-ray electrons (green)
- **Isotropic** emission (black)
- **Sources** (purple dotted)

Definitely emits **neutrinos**, but not very hard

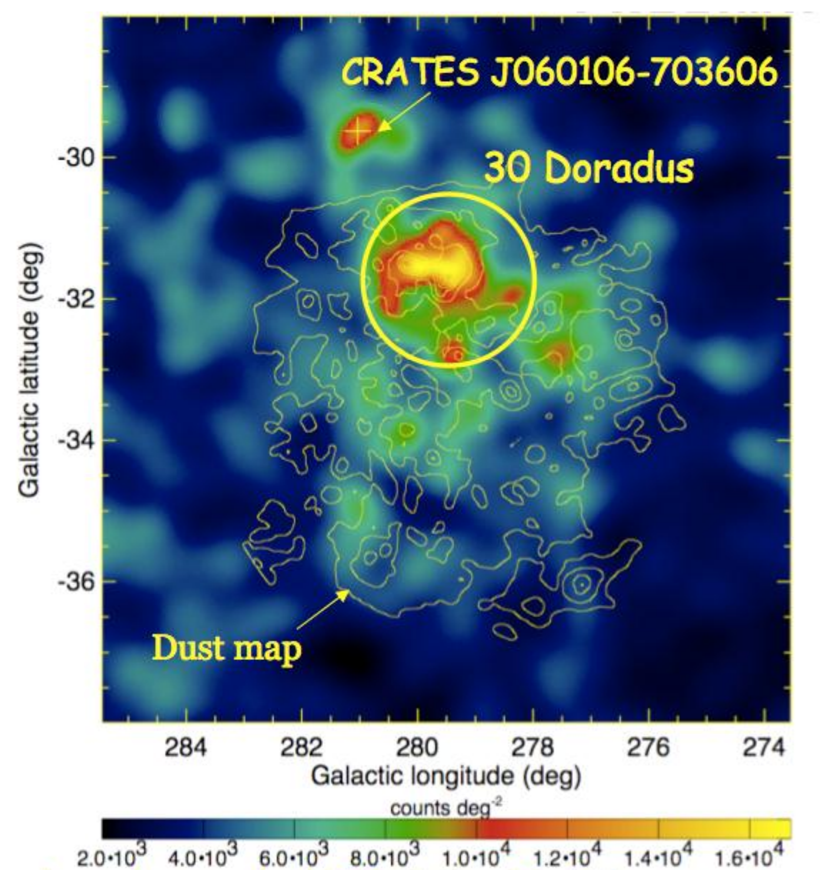
Other galaxies

Starburst: lots of **gas** + lots of **SNe** and **winds** (➔ large CR density) ➔ **large π^0 production**

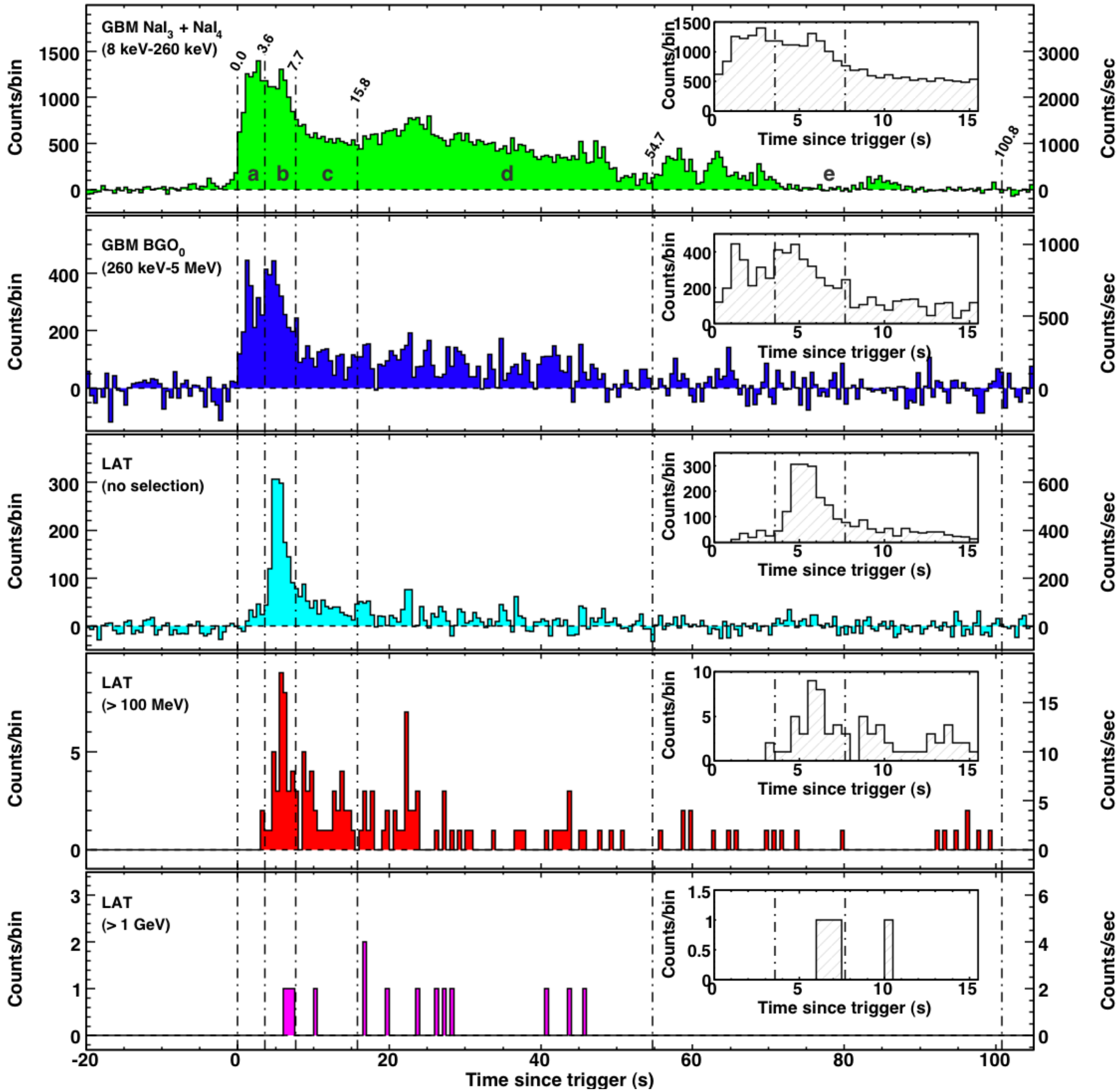
M82: Abdo et al 2010, ApJ 709, L152



LMC: Abdo et al 2010, A&A 512, 7



Temporal properties of GRBs



GRB 080916C
Abdo et al. 2009, Science 323, 1688

- 18 LAT GRBs > 100 MeV
- Delayed GeV emission with respect to MeV
- Long-lived (100 – 1000 s)
- Clear evidence of spectral evolution
- No obvious high-energy break (γ-γ attenuation) implies large Lorentz factor > several hundred
- GeV/MeV fluence ratio larger in short GRBs

Limits on Lorentz Invariance Violation

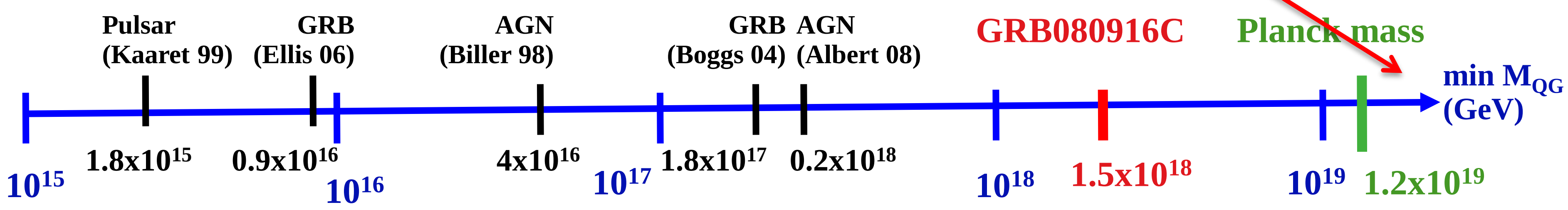
- GRB080916C
  - Highest energy, ~ 13.2 GeV photon, detected 16.5 s after GBM trigger
  - lower limit on the quantum gravity mass (assuming linear energy scaling and high energy photons emitted after GRB trigger):

$$M_{QG} > 1.50 \times 10^{18}\ \mathrm{GeV}/c^2$$

- GRB090510
  - Highest Energy, ~ 31 GeV photon detected 858 ms after onset of GBM emission

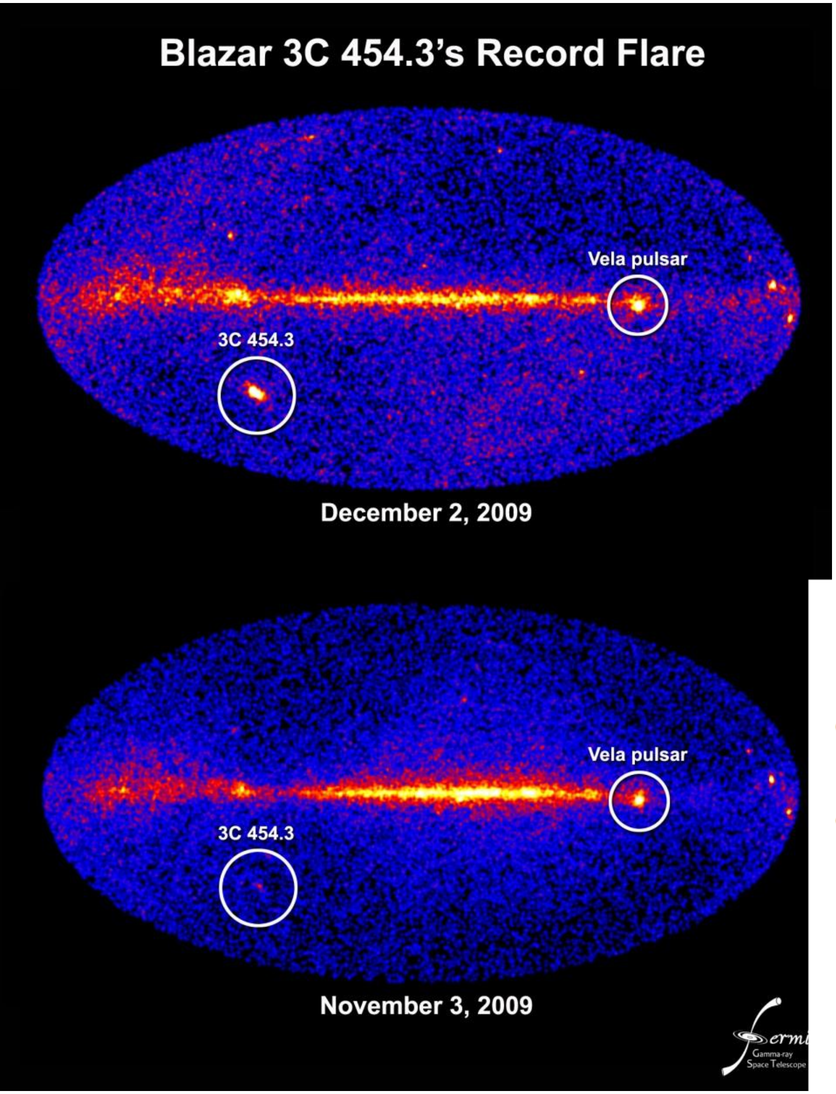
$$M_{QG} > 1.42 \times 10^{19}\ \mathrm{GeV}/c^2\ (>1.19\ M_{Planck}!)$$

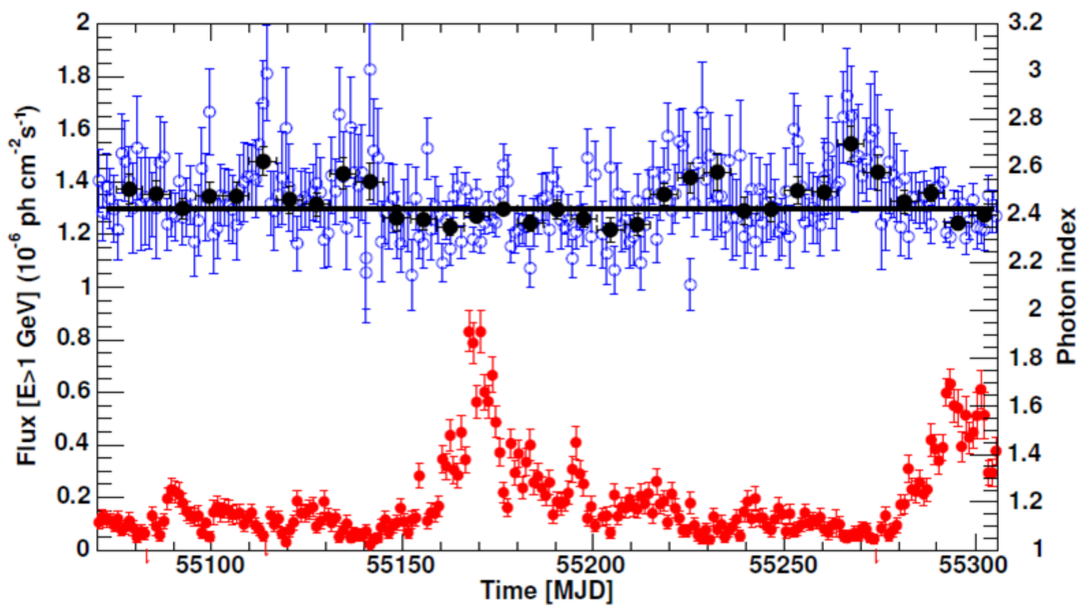
  - rules out many n=1 scenarios



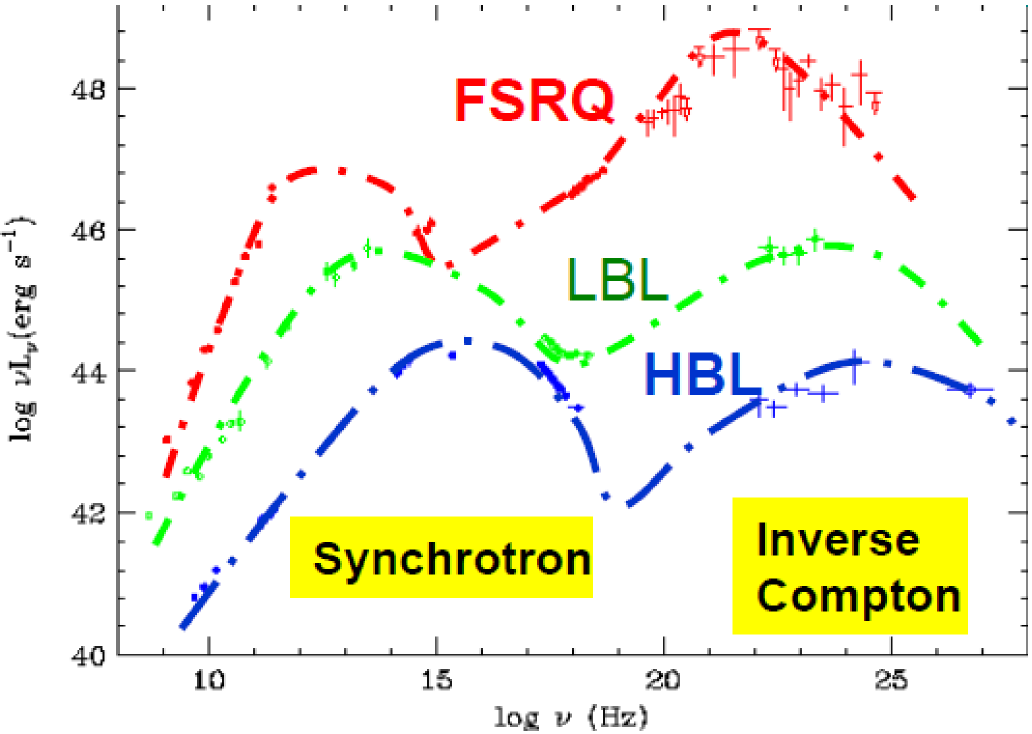
Rapid variability

- **Automated search for flaring sources on 6 hour, 1 day and 1 week timescales.**
  - **LAT scientists perform follow-up analyses, produce ATels, and propose ToOs**
- **>100 Astronomers telegrams**
  - **Discovery of new gamma-ray blazars**
  - **Flares from known gamma-ray blazars**





Blazars



Almost all galaxies contain a massive black hole

- 99% of them are (almost) silent (e.g. our Galaxy)

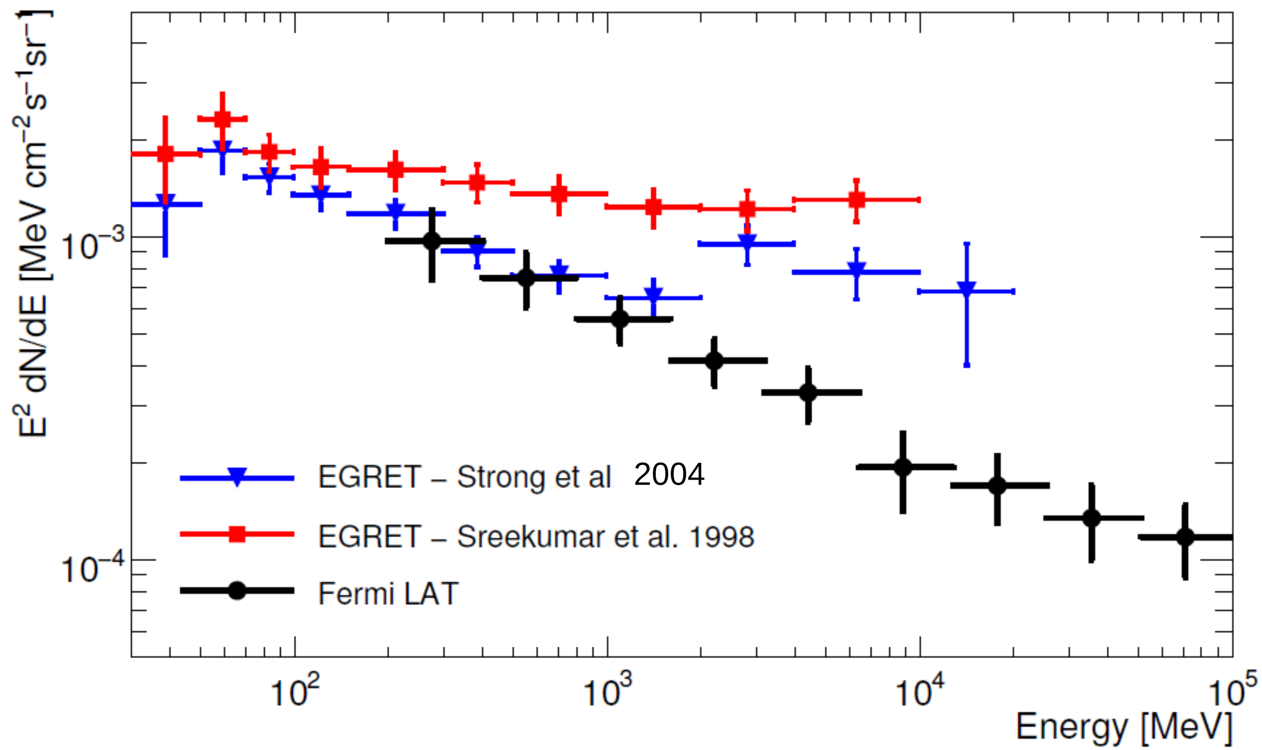
- 1% per cent is active (mostly radio-quiet AGNs): BH+disk: most of the emission in the UV-X-ray band

- 0.1% is radio loud: jets mostly visible in the radio

M_{BH} of $10^7 – 10^9$ M_o

- > **700** Fermi AGN
- Large association fraction thanks to good radio catalogs, known redshift for many
- About half **BL Lacs** (nearby, hard, jet-dominated) and half **FSRQs** (faraway, bright, softer, disk-dominated)
- Very **variable**
- Several MW campaigns to identify correlated variability
- Mainstream model: **Inverse Compton** on synchrotron or disk/torus photons
- Constraints on **Extragalactic Background Light** in optical/UV (also from GRBs)

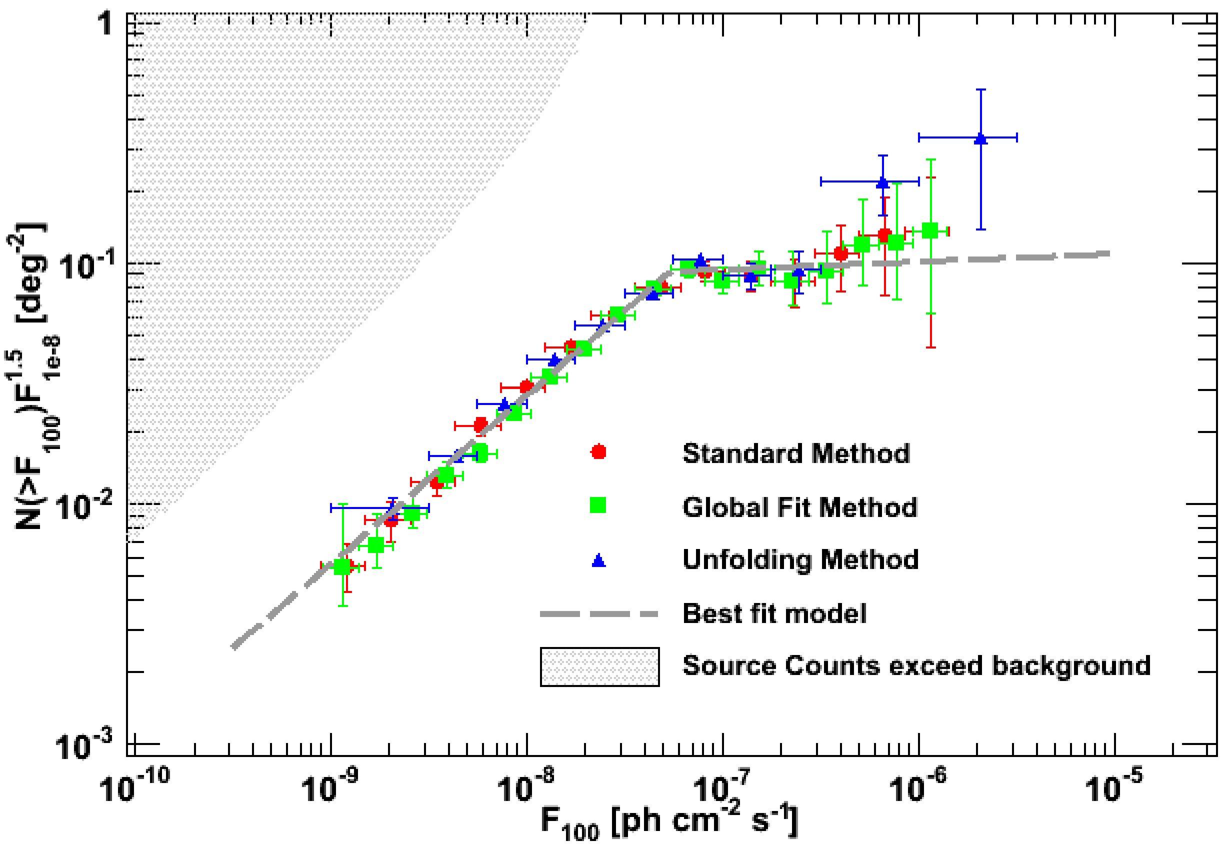
Extragalactic "diffuse" emission



- **Considerably steeper** than the EGRET spectrum by Sreekumar et al.
- **No spectral features** around a few GeV seen in re-analysis by Strong et al.

	Flux, E>100 MeV	spectral index
LAT (this analysis)	**1.03 +/- 0.17**	**2.41 +/- 0.05**
EGRET (Sreekumar et al., 1998)	1.45 +/- 0.05	2.13 +/- 0.03
EGRET (Strong et al. 2004)	1.11 +/- 0.10	
LAT + resolved sources below EGRET sensitivity	1.19 +/- 0.18	2.37 +/- 0.05
	x 10^{-5} cm^{-2} s^{-1} sr^{-1}	

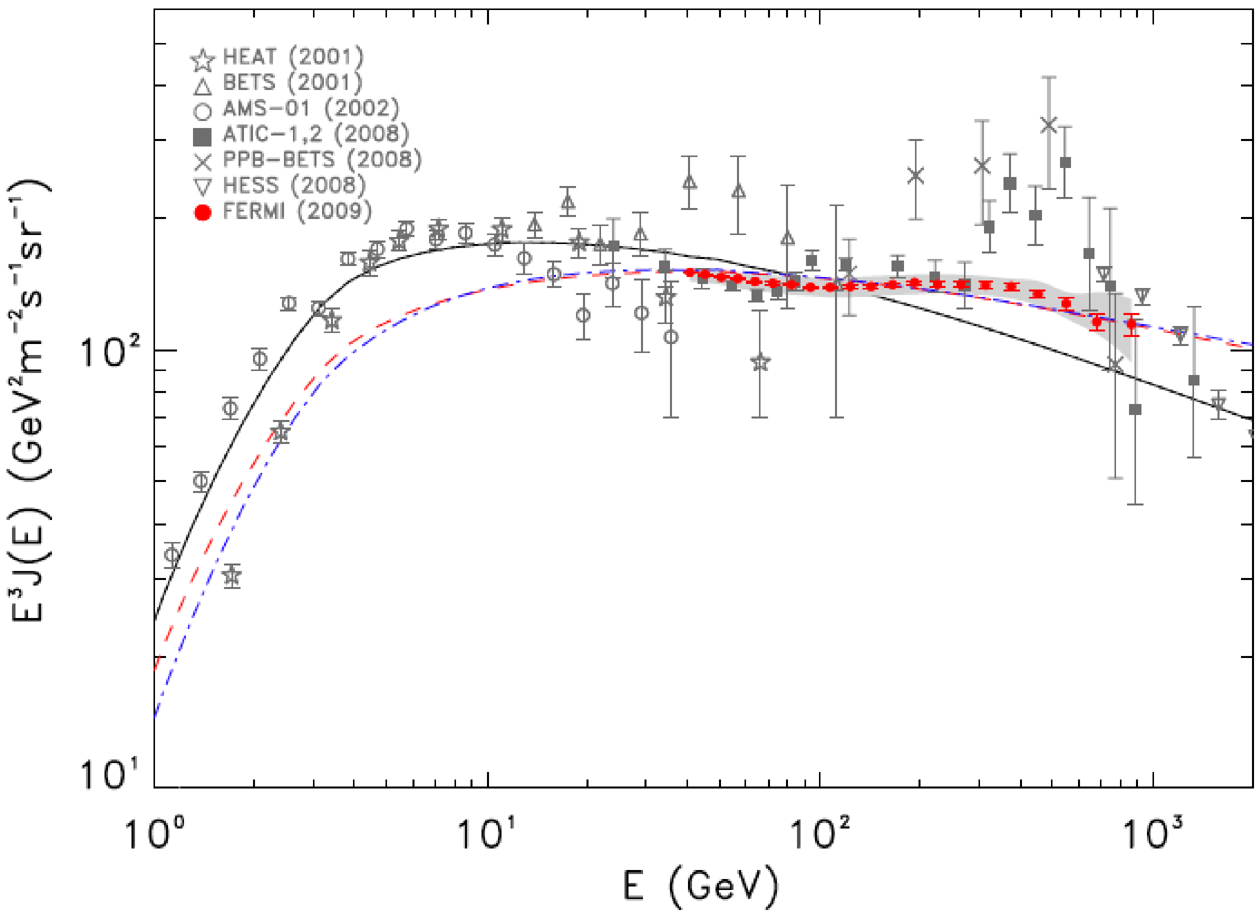
AGN logN logS



- Careful correction for spectral dependence of detection threshold
- Distinct **break** around F_{100} = 5 10^{-8} ph/cm^2/s
- Total AGN contribution falls way short of explaining the isotropic emission
- Other sources, like starburst galaxies, undoubtedly contribute

Abdo et al 2010, ApJ 720, 435

Fermi-LAT electron-positron spectrum



Harder spectrum than conventional cosmic-ray model (GALPROP) but no very large peak below 1 TeV

Abdo et al. 2009
PRL 102, 181101

Being pushed down to 7 GeV

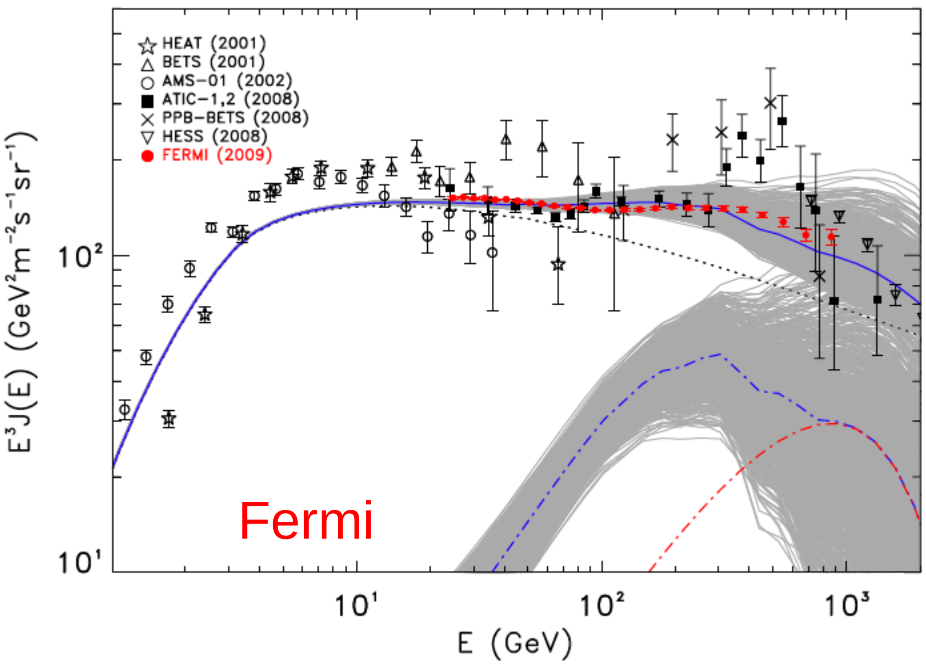
Total statistics collected for 6 months of Fermi LAT observations

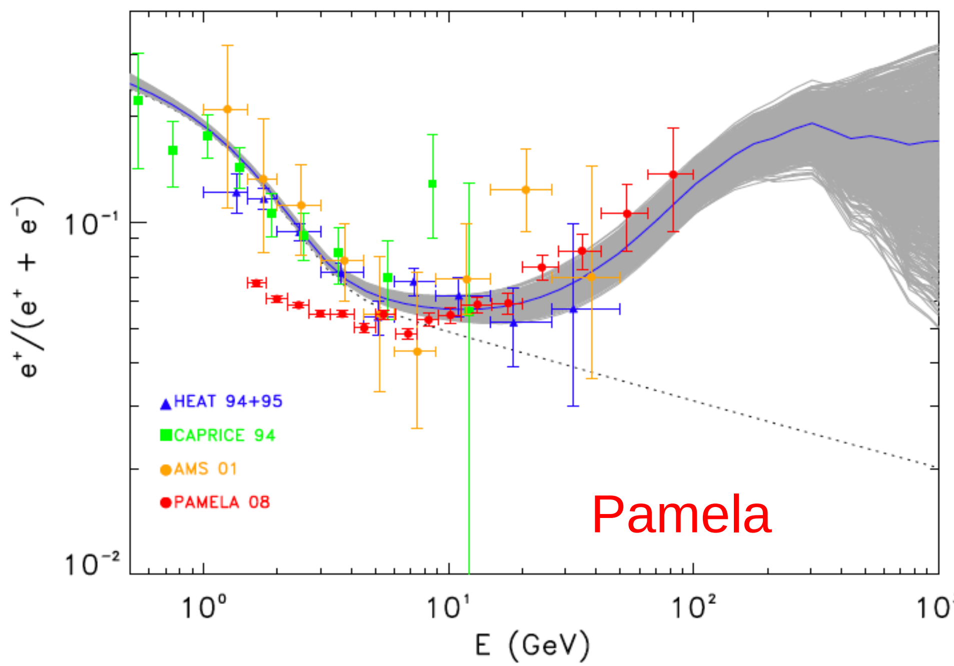
- **~4.5 million candidate electrons above 20 GeV**
- **544 candidate electrons in last energy bin (770-1000 GeV)**

Pulsar origin of the bump?

Random variations of the **pulsar parameters** relevant for **e+e- production**

[*injection spectrum, e+e- production efficiency, PWN “trapping” time*]





Electron/positron **emission** from **pulsars** offers a **viable interpretation** of **Fermi** CRE data also **consistent** with the **HESS** and **Pamela** results

But not the only one

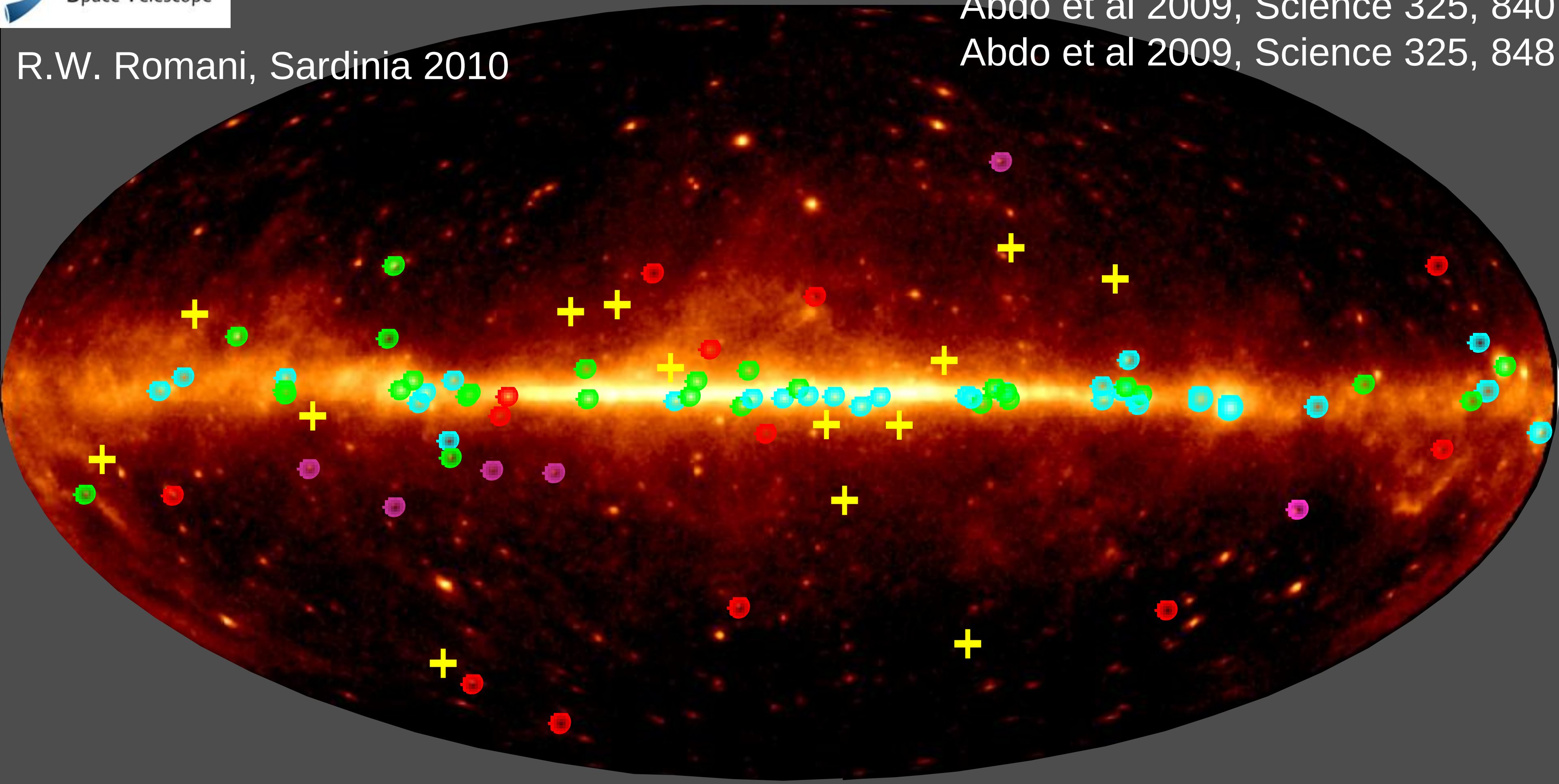
Grasso et al. 2009
Astropart. Phys. 32, 140

The LAT Pulsar Sky

Pulses at 1/10th Real Rate

R.W. Romani, Sardinia 2010

Abdo et al 2009, Science 325, 840
Abdo et al 2009, Science 325, 848



30 Young Radio-selected

13 MSP Radio-selected

25 Young γ-selected

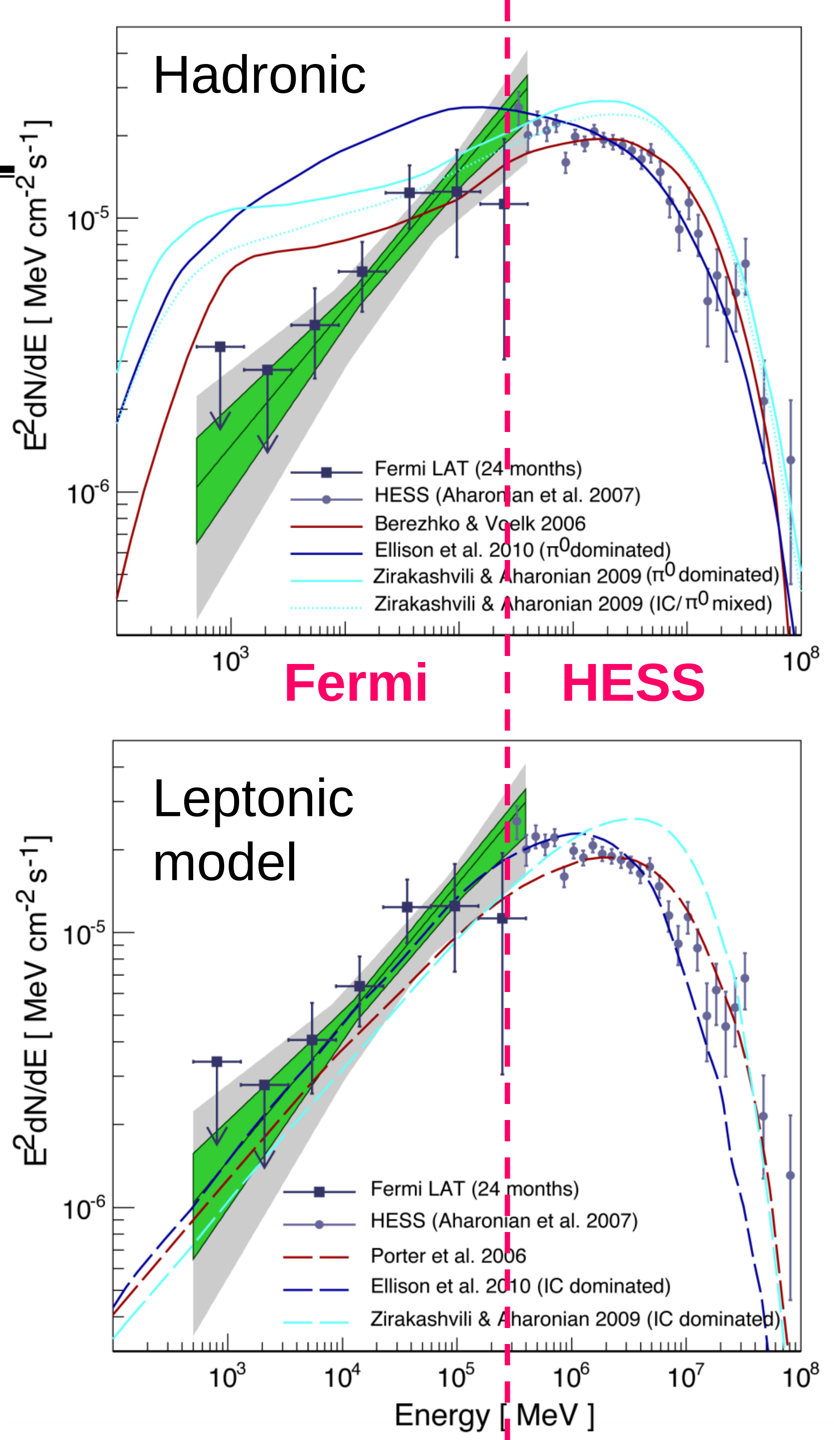
6 γ-sel MSP γ/R pulse

14 γ-sel MSP R pulse

RX J1713.7-3946

Abdo et al 2011, accepted in ApJ
ArXiv: 1103.5727

- Brightest TeV SNR
- **Very faint** Fermi source in a complicated region of the Galactic plane
- **Very hard** (Γ = 1.5 +/- 0.1), not detected below 5 GeV
- **Extended**, compatible with HESS image
- Clearly below the extrapolation of hadronic models, in line with **leptonic** models
- Does not mean that protons are absent, but that **density is low** (as indicated by absence of thermal X-rays). Molecular gas is nearby but not hit by the shock yet (no maser).
- Other young SNRs (like Cas A) are not as hard and could be hadronic.



IC 443 and old SNRs

Older SNR, between 3 and 30 kyr

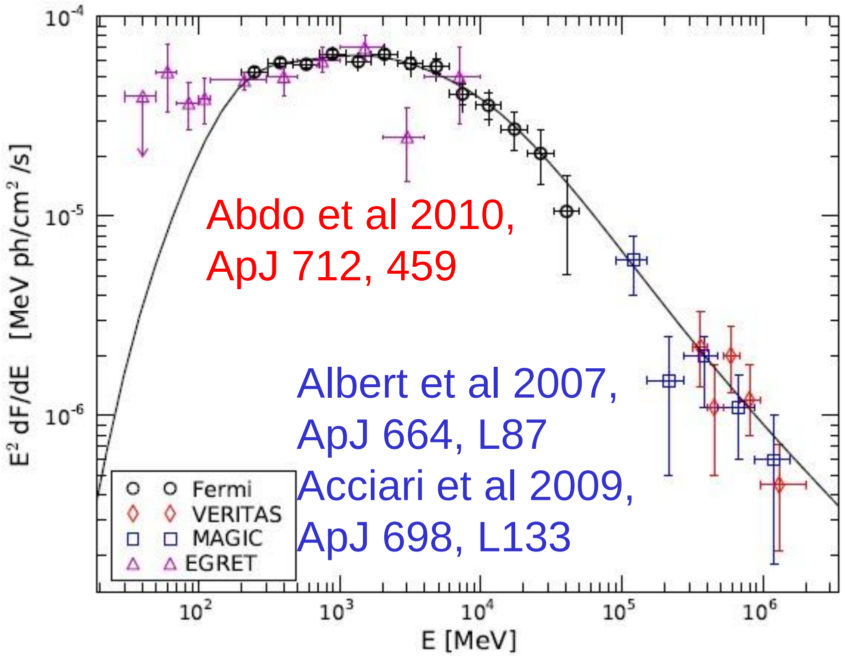
Extended, emission where **molecular clouds** interact with the SNR, does not follow radio contours

Break frequency at ~ 3 GeV, corresponding to **20 GeV** on proton spectrum.

Probably reflects the maximum energy reached by freshly accelerated particles

Clearly **hadronic**, but soft (Γ = 2.9 at TeV)

Requires $E_p \approx 10^{49}$ ergs for n_{gas} = 100 cm^{-3}



W 51C (Abdo et al 2009, ApJ 706, L1; HESS detection)
W 28 (Abdo et al 2010, ApJ 718, 348; Aharonian et al 2008, A&A 481, 401)
W 44 (Abdo et al 2010, Science 327, 1103; no TeV)
W 49 B (Abdo et al 2010, ApJ 722, 1303; recent HESS detection)
3C 391, CTB 37 A, G349.7+0.2, G8.7-0.1 (Castro & Slane 2010, ApJ 717, 372)
Cygnus Loop (submitted)

Summary

- **Sky survey** every 3 hours until 2013, possibly further
- 1451 sources in 1FGL catalog, 2FGL in the works
- Some 700 **blazars**, from BL Lacs to FSRQs
- γ–ray background made up of AGN, galaxies and ?
- 4 very bright **γ-ray bursts**, several fainter ones
- > 70 γ–ray **pulsars** (up from 6), 20 ms pulsars in unidentified sources
- Hadrons in several old **SNRs** (W28, W44, W49B, W51C, IC443)
- 4 **X-ray binaries** (LSI +61 303, LS 5039, Cyg X-3, 1FGL J1018.6-5856)
- Dark matter constraints on lines and dwarf spheroidals
- About 100 papers published at March 2011
- ***More at 3rd Fermi Symposium, May 9-12 in Rome***

Pulsar emission model

In the simplest model, the emission should depend on 4 parameters: spin period, magnetic field, magnetic dipole inclination, and viewing angle

- luminosity derived from rotational energy

  $E_{rot} = ½\, I\, \Omega^2$

  $\dot{E} = -B^2 R^6 \Omega^4 / c^3$

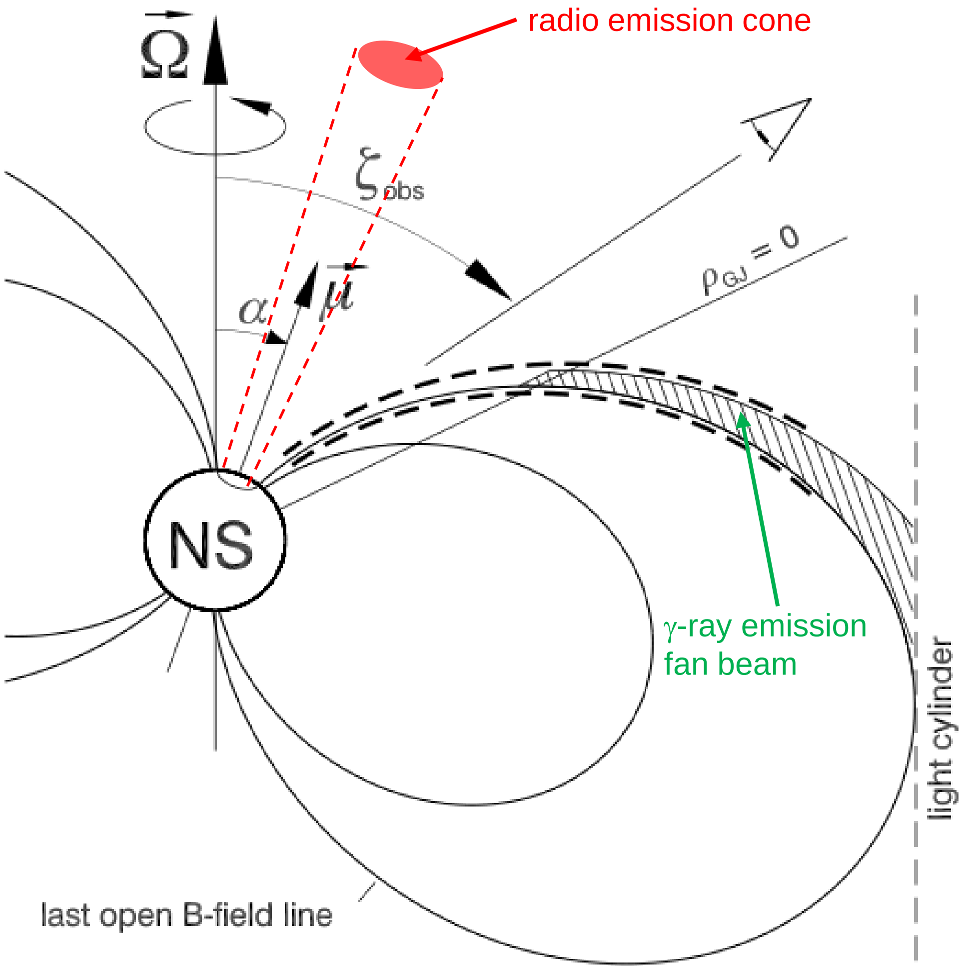
- derived parameters:

  rotational age : $\tau = \Omega / 2\dot{\Omega}$

  B field: $B = 3.2\text{x}10^{19}\, (P\dot{P})^{1/2}$ G

  spin-down power: $L = I\Omega\dot{\Omega}$

  Young pulsars
  P ≈ 0.1 s
  B ≈ 10^{12} G

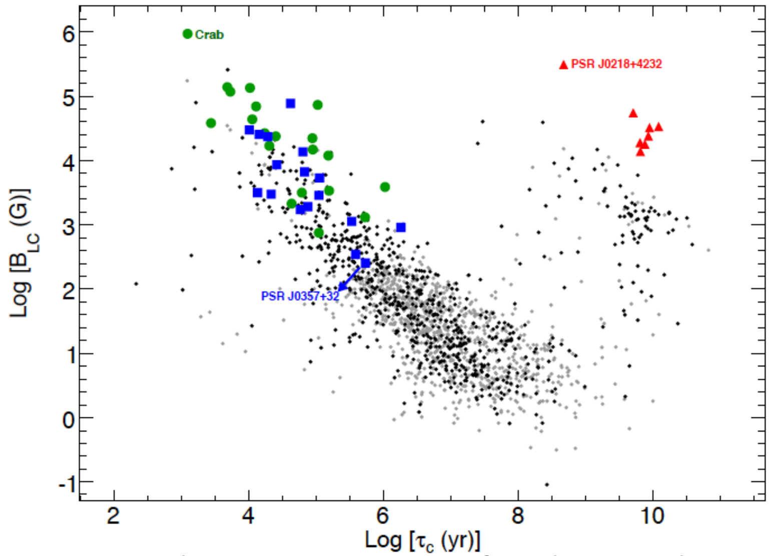


What do we learn ?

As for EGRET, the detected pulsars are relatively close and highly energetic.

The detected pulsars also have the highest values of magnetic field at the light cylinder, B_{LC}.

Both detected normal PSRs and MSPs have comparable B_{LC} values. Similar emission mechanisms operating?



B_{LC} vs. characteristic age for the catalog PSRs

Pulsar catalog: arXiv:0910.1608

Cas A spectrum

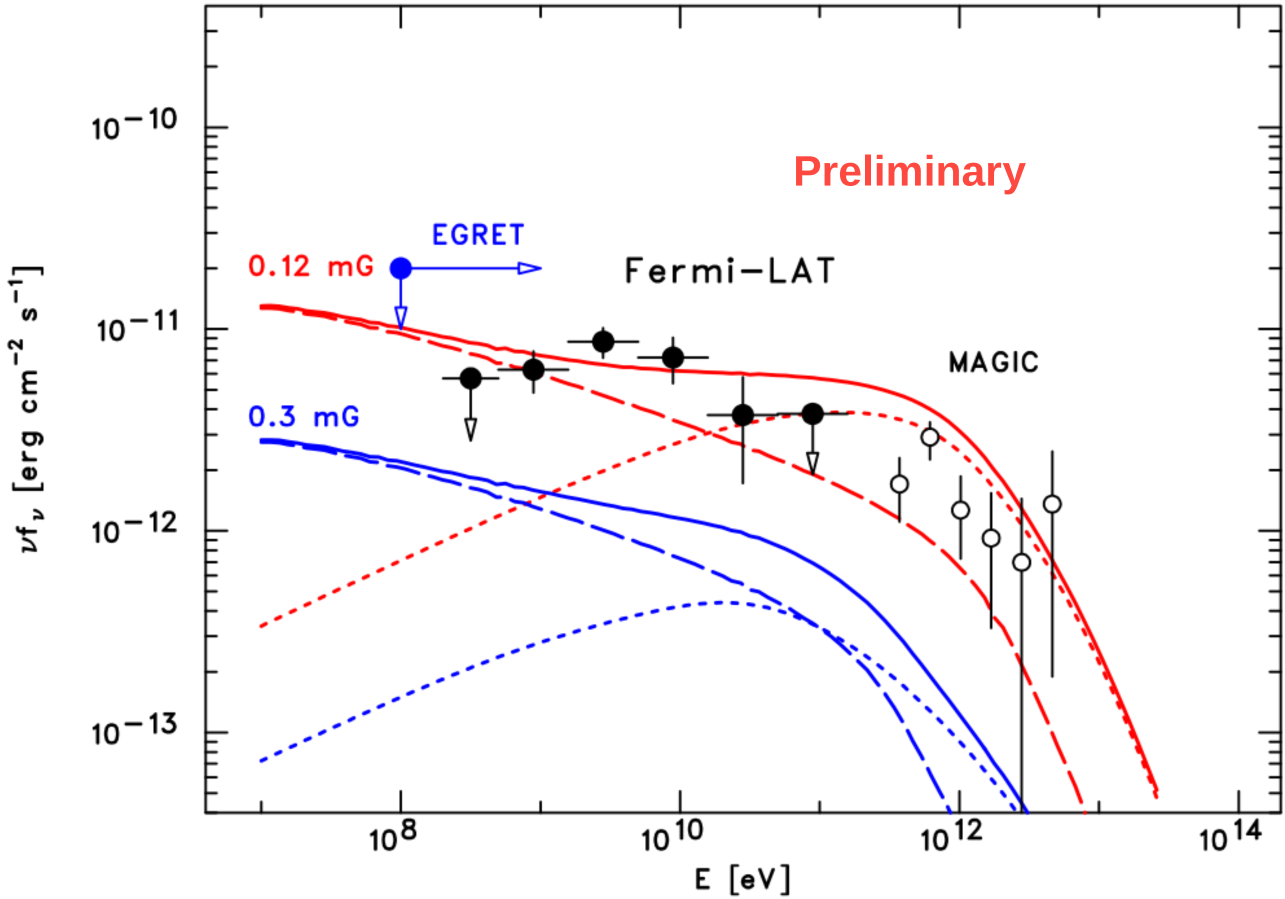
Young SNR (330 yrs)

LAT spectrum connects well with MAGIC TeV γ-rays

No sign for a cutoff (as in pulsars)

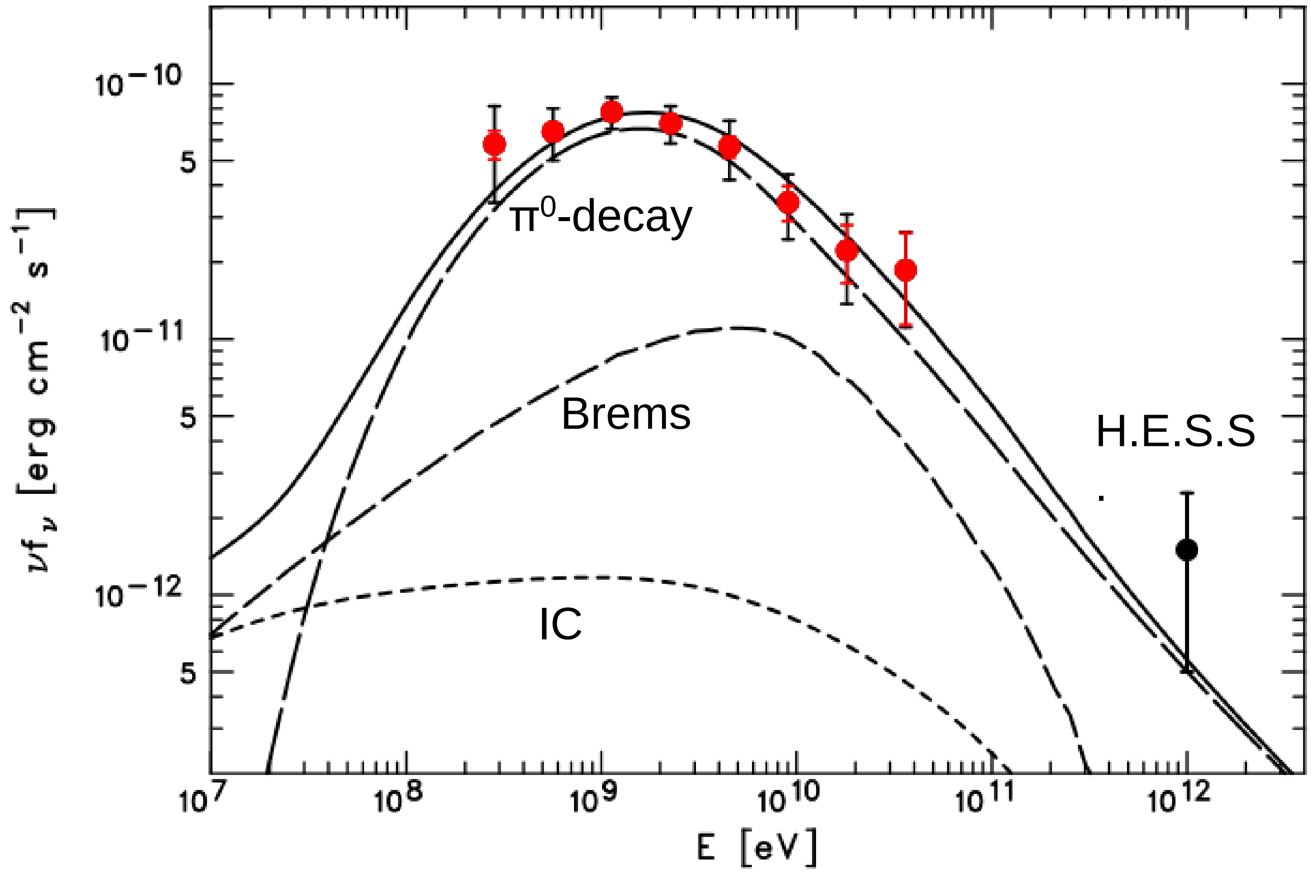
Bremsstrahlung + Inverse Compton (Atoyan et al 2000)

Can also be fitted by pion decay (Berezhko et al 2003)



W51C spectrum

π^0-decay dominant case



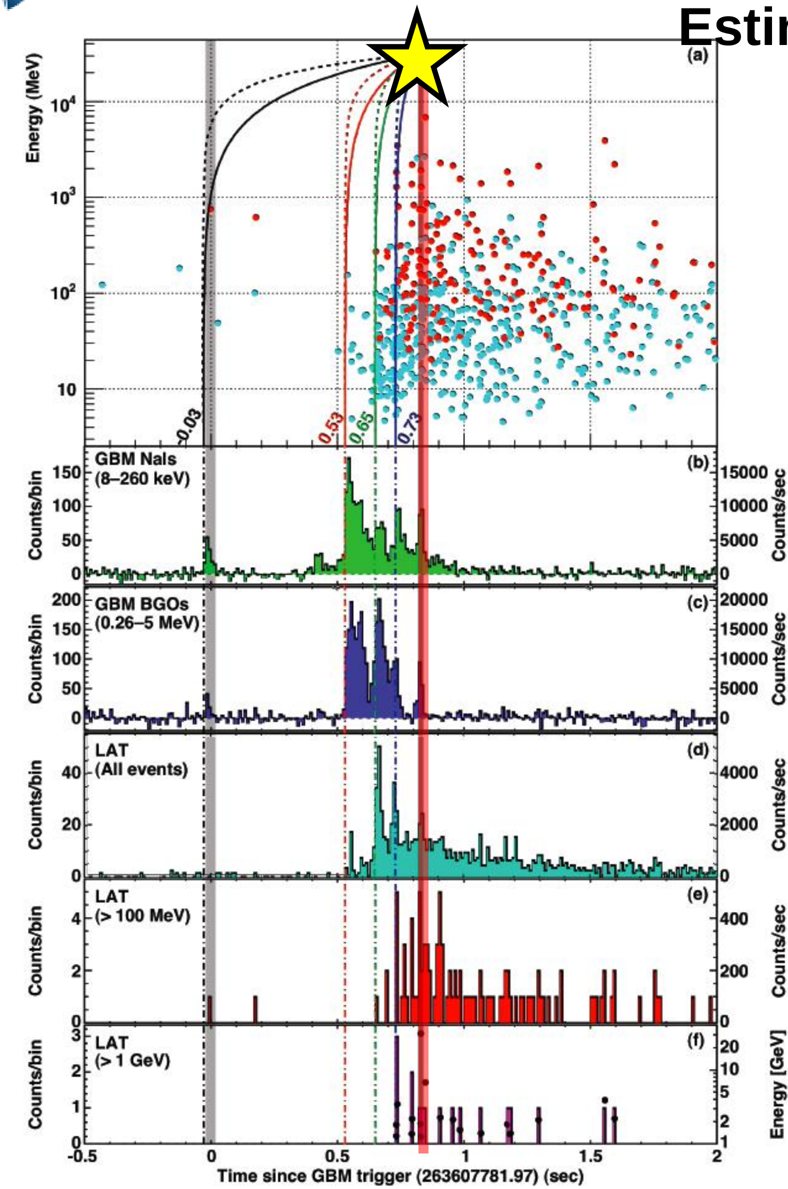
One of the most luminous gamma-ray sources $L = 1 \times 10^{36}$ (D/6 kpc)^2 erg s^{-1}

Spectral steepening in the LAT range

π^0-decay model can reasonably explain the data, requires proton break at ~ 20 GeV

Leptonic scenarios require large amounts of electrons

GRB090510 : first time M_{QG}>M_{planck}



Estimate lower limit of $M_{QG,1}$ for various ⊿t, ⊿E

◆Most conservative case :

31GeV photon starts from any <1MeV emission ⊿t < 859 ms,

$M_{QG,1}/M_{plank}$ > 1.19

◆Least conservative case:

31 GeV photon associates with < 1 MeV spike ⊿t < 10ms,

$M_{QG,1}/M_{plank}$ > 102

Our new limit : $M_{QG,1}/M_{plank}$> several is much stronger than the previous result ($M_{QG,1}/M_{plank}$ > 0.1 : GRB080916C ;Abdo+09)

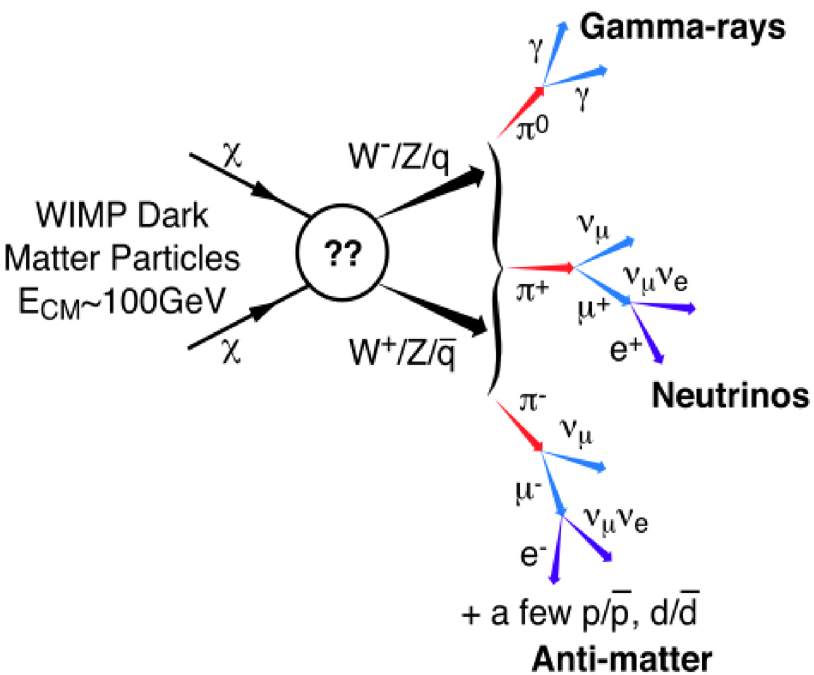
Greatly constrain the quantum gravity model (n=1)

z = 0.9, short GRB

Abdo et al. 2009, Nature 462, 331

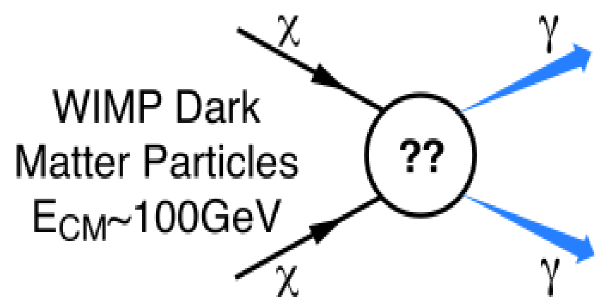
Dark matter: γ from WIMP annihilation

Continuum spectrum with cutoff at Mχ



Spectral line at Mχ (for γγ)

- ✓ Detection of prompt annihilation into γγ (γZ^0) would provide smoking gun for dark matter annihilation
- ✓ Requires best energy resolution
- ✓ However, annihilation fraction in the range 10^{-3}-10^{-4} (depending on the model)



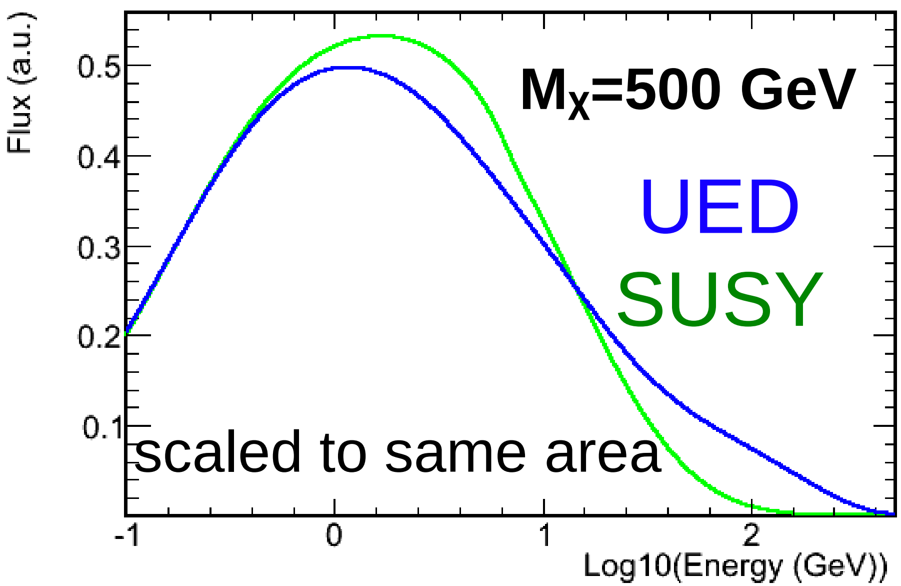
Depends on DM density squared

Two different scenarios: UED vs SUSY

Consider the photon spectrum from 500 GeV WIMP annihilation in SUSY and in UED:

✓UED: photons mostly from lepton bremsstrahlung

✓SUSY: photons mostly from b quark hadronization and then decay, energy spread through many final states lower photon energy. p-wave dominated cross-section yields lower photon fluxes for equal masses



➡ **Spectra can look very different in these scenarios**

mSUGRA parameters:

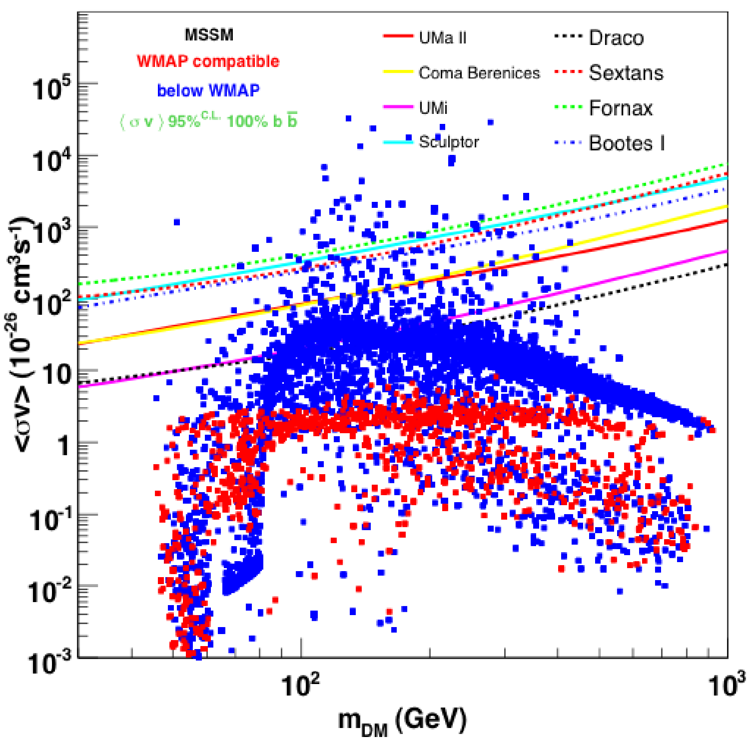
$$m_0 = 500\ \text{GeV}$$
$$m_{1/2} = 1160\ \text{GeV}$$
$$A_0 = 0, \quad \tan\beta = 10$$

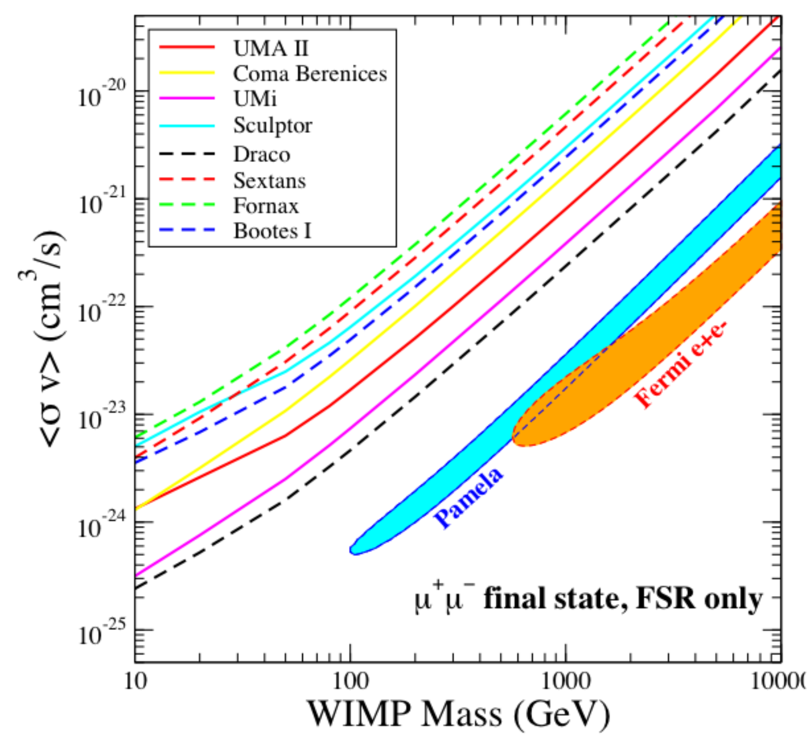
Search for DM in dwarf Spheroidals

Accepted for publication, ApJ
arXiv preprint: 1001.4531

Exclusion regions cutting into interesting parameter space for some WIMP models

WIMPs with large annihilation cross-sections into leptonic final states have been invoked to partially explain cosmic-ray data as the by-product of dark matter annihilation





More on TeV connections

- Milagro (TeV) observations: 14/34 Galactic BSL sources with 3 sigma Milagro excess.
- 9/14 are gamma-ray pulsars
- All 6 previously known Milagro sources associated with Fermi Pulsars.