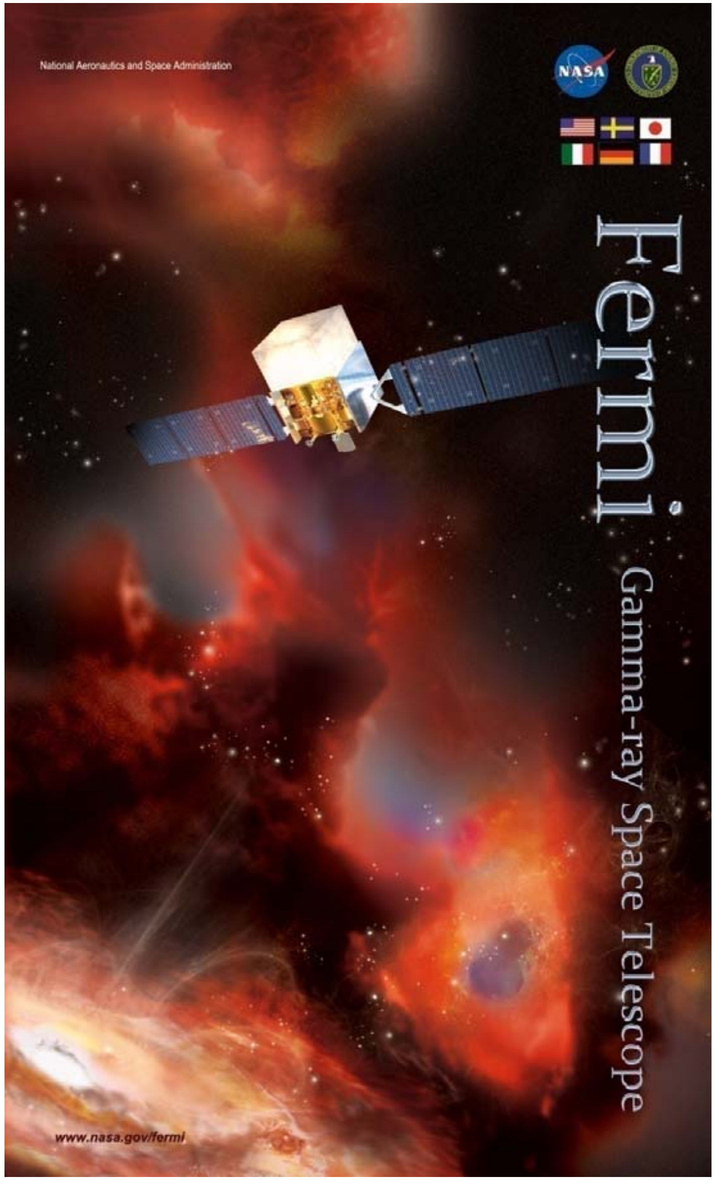


Fermi observations of Galactic sources

Takeshi Nakamori (Waseda U)

on behalf of the Fermi LAT collaboration

Formations of Compact Objects: from the cradle to the grave

Waseda University, Mar 9 2012

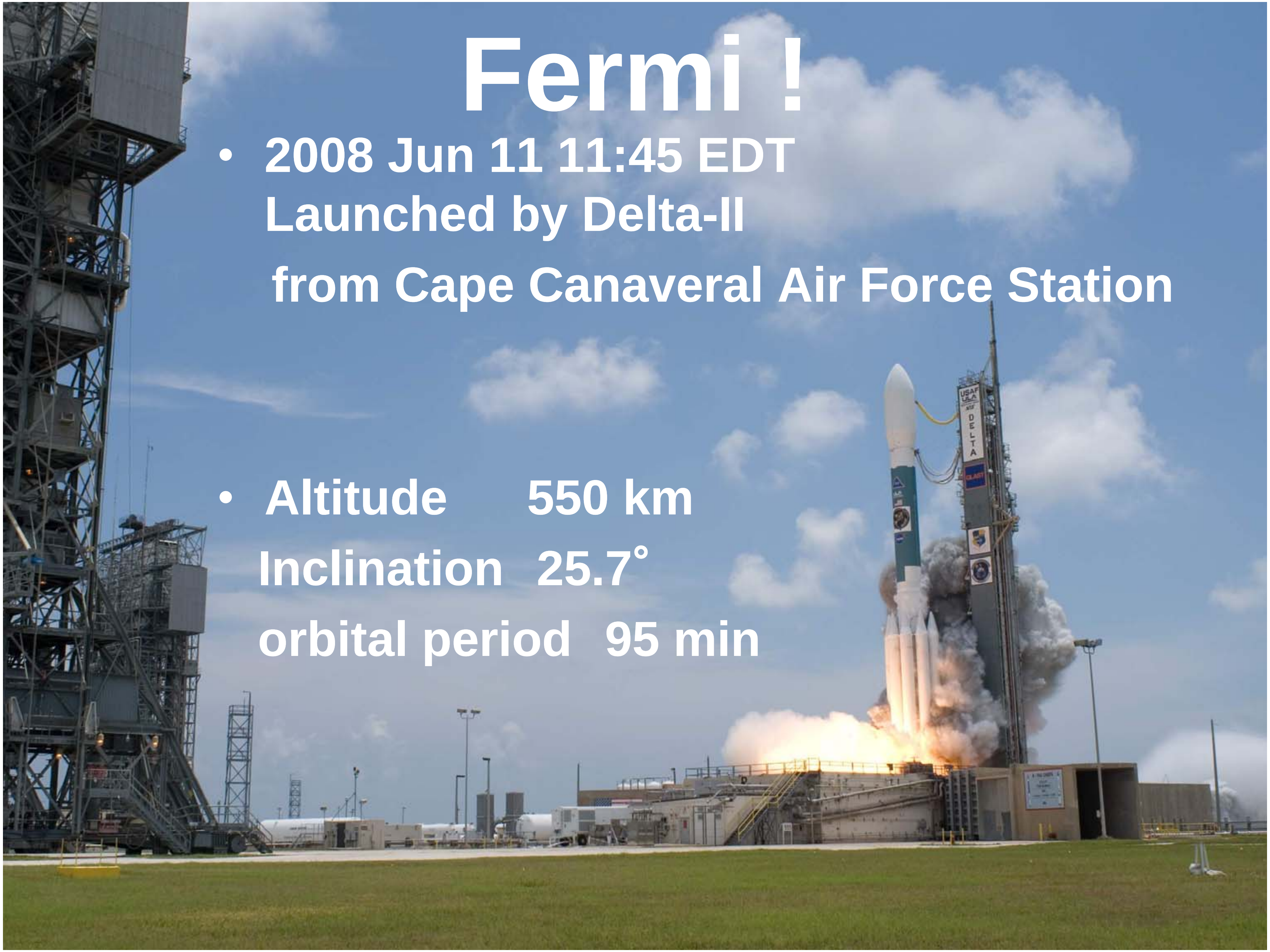
Contents

- Introduction
- Hunting unassociated sources
  – MW follow-ups by Waseda team
- SNRs with Fermi
  – Young SNRs
  – Interaction with MCs
- Summary

Fermi !

- **2008 Jun 11 11:45 EDT**
  Launched by Delta-II
  from Cape Canaveral Air Force Station

- **Altitude 550 km**
  Inclination 25.7°
  orbital period 95 min



Large Area Telescope

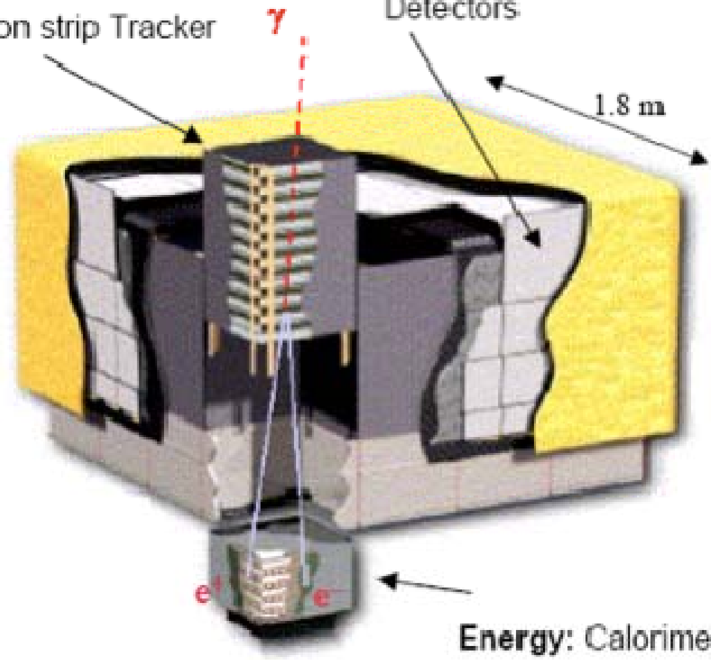
<u>Pair conversion telescope</u>

- **Tracker : silicon strip detector**
  → gamma-ray direction
- **Calorimeter : CsI(Tl)**
  → gamma-ray energy
- **Anticoincidence shield**
  → background rejection

20 MeV – 300 GeV

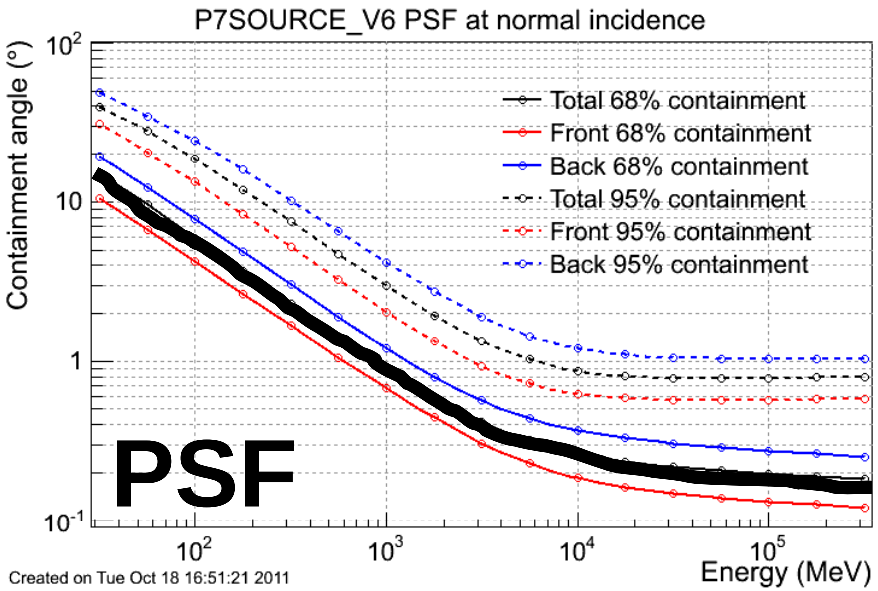
Large FoV (2.4 str)

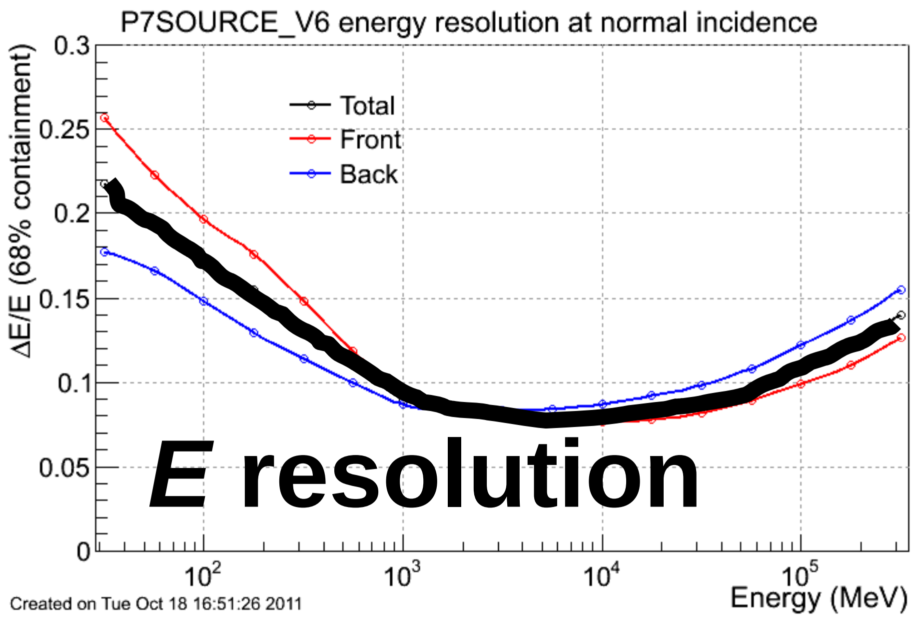
All sky survey every 3 hours



Fermi LAT performance

- **Data are promptly public**
- **Dataset and response updated in 2011 (Pass7)**
  - **Improved effective area in low energies**
  - **In-orbit calibration of PSF**

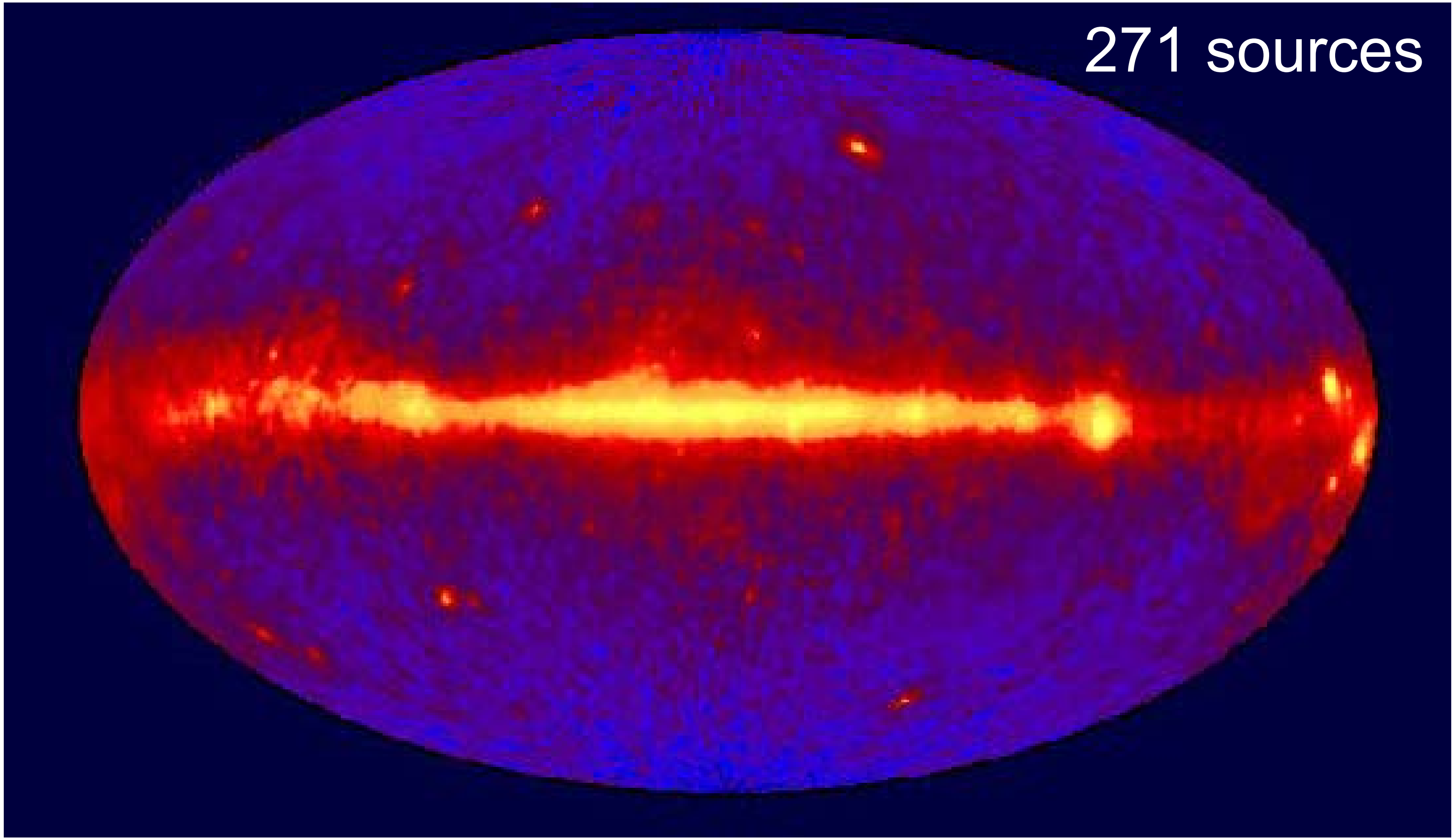




http://www.slac.stanford.edu/exp/glast/groups/canda/lat_Performance.htm

Integral sensitivity for 1 year (E > 10 GeV) : ~ 0.05 Crab (Atwood+09)

EGRET all sky

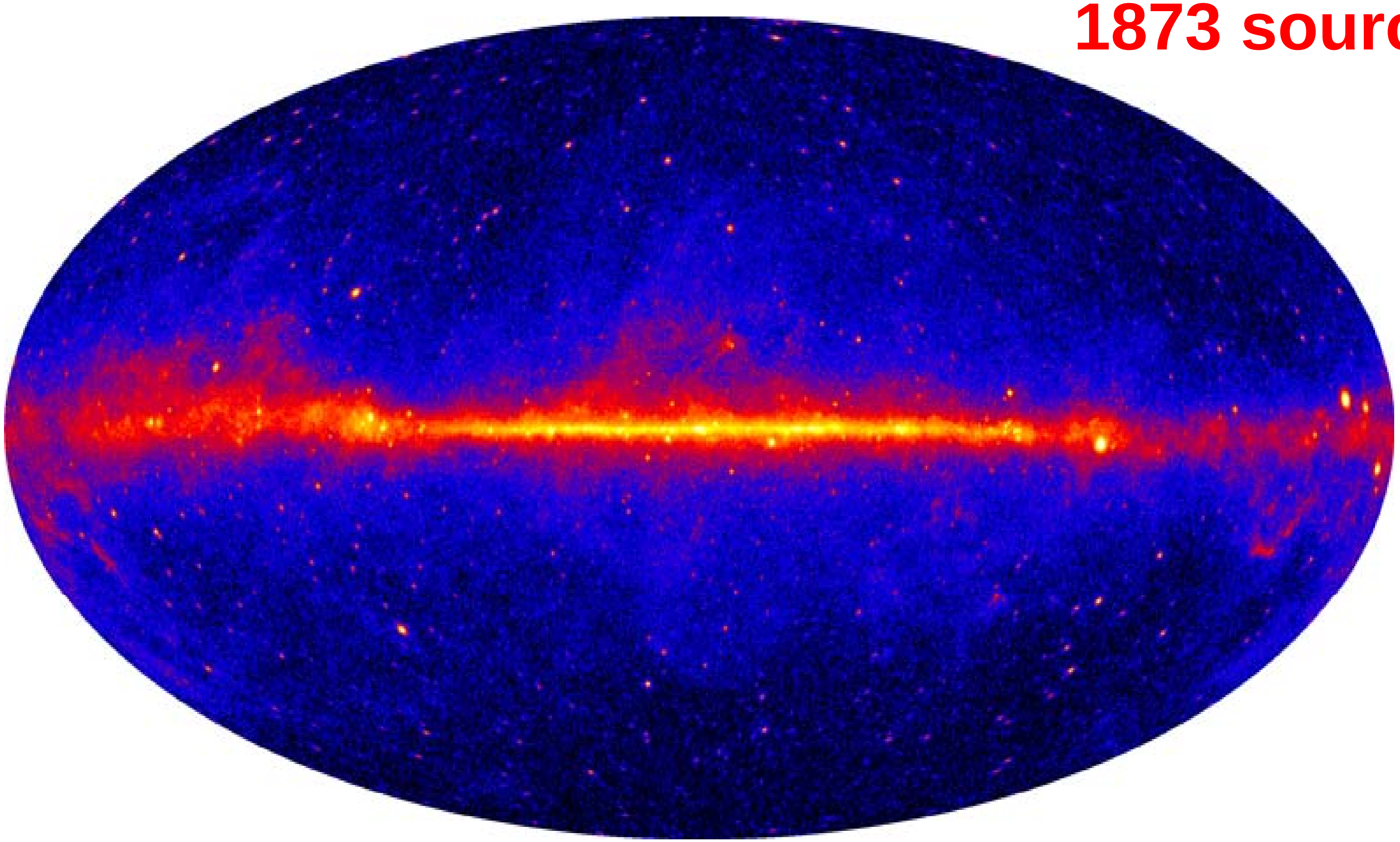


EGRET All-Sky Gamma-Ray Survey (> 100MeV)

Credit: EGRET team

Fermi 2 years

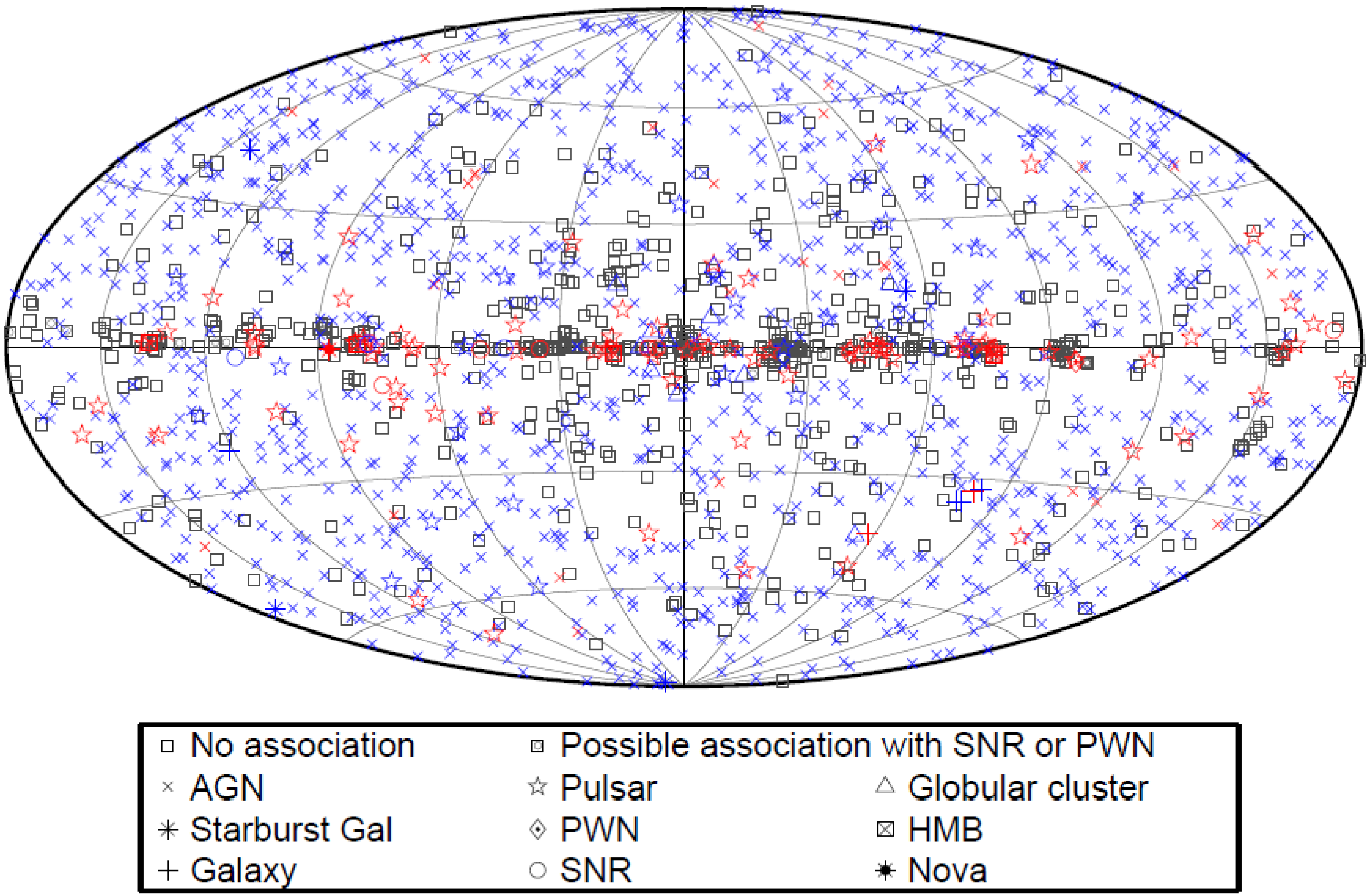
1873 sources



Credit: NASA/DOE/International LAT Team

2FGL catalog

- **1873 source (> 4σ significance)**

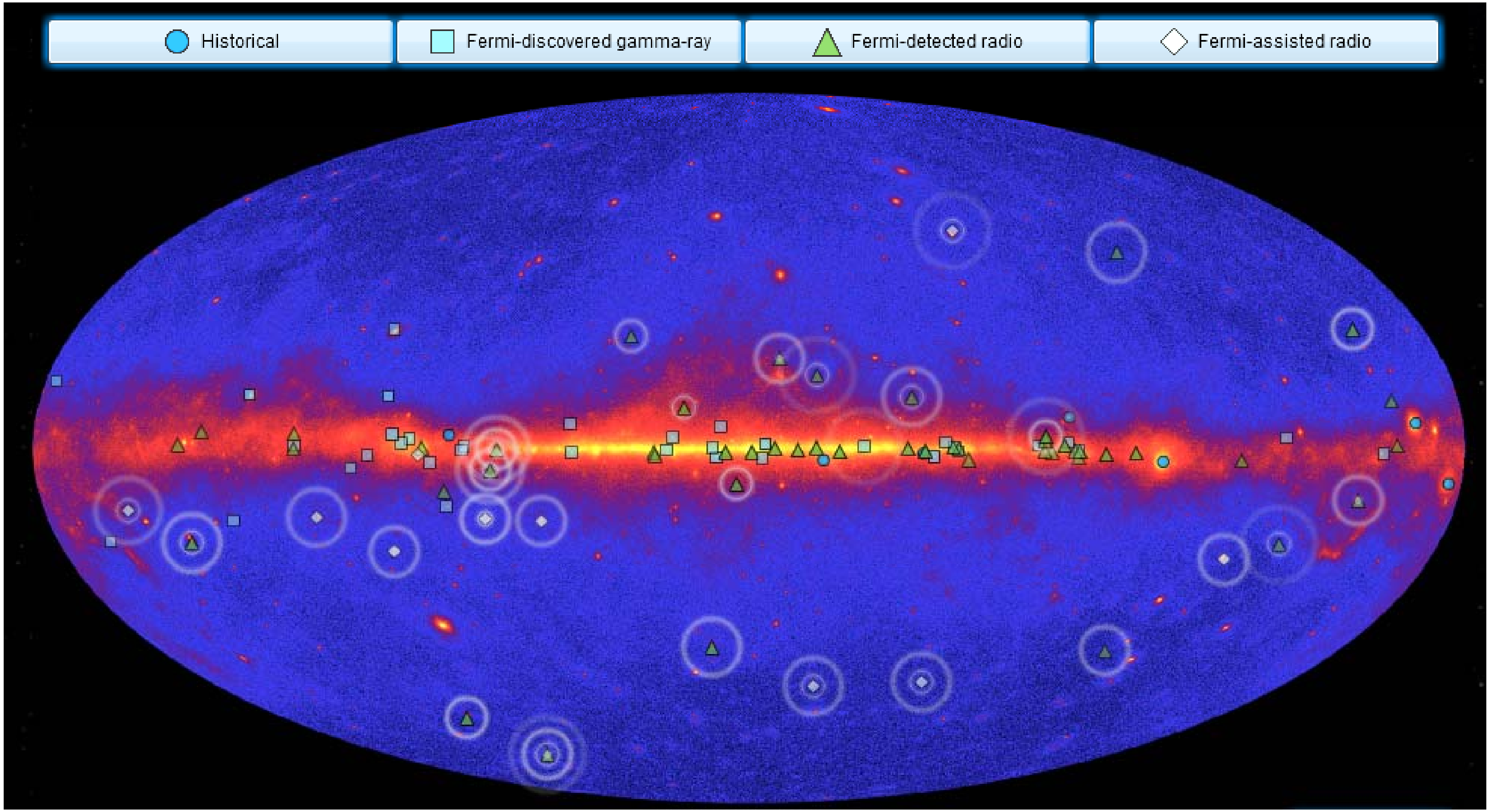


arXiv:1108.1435

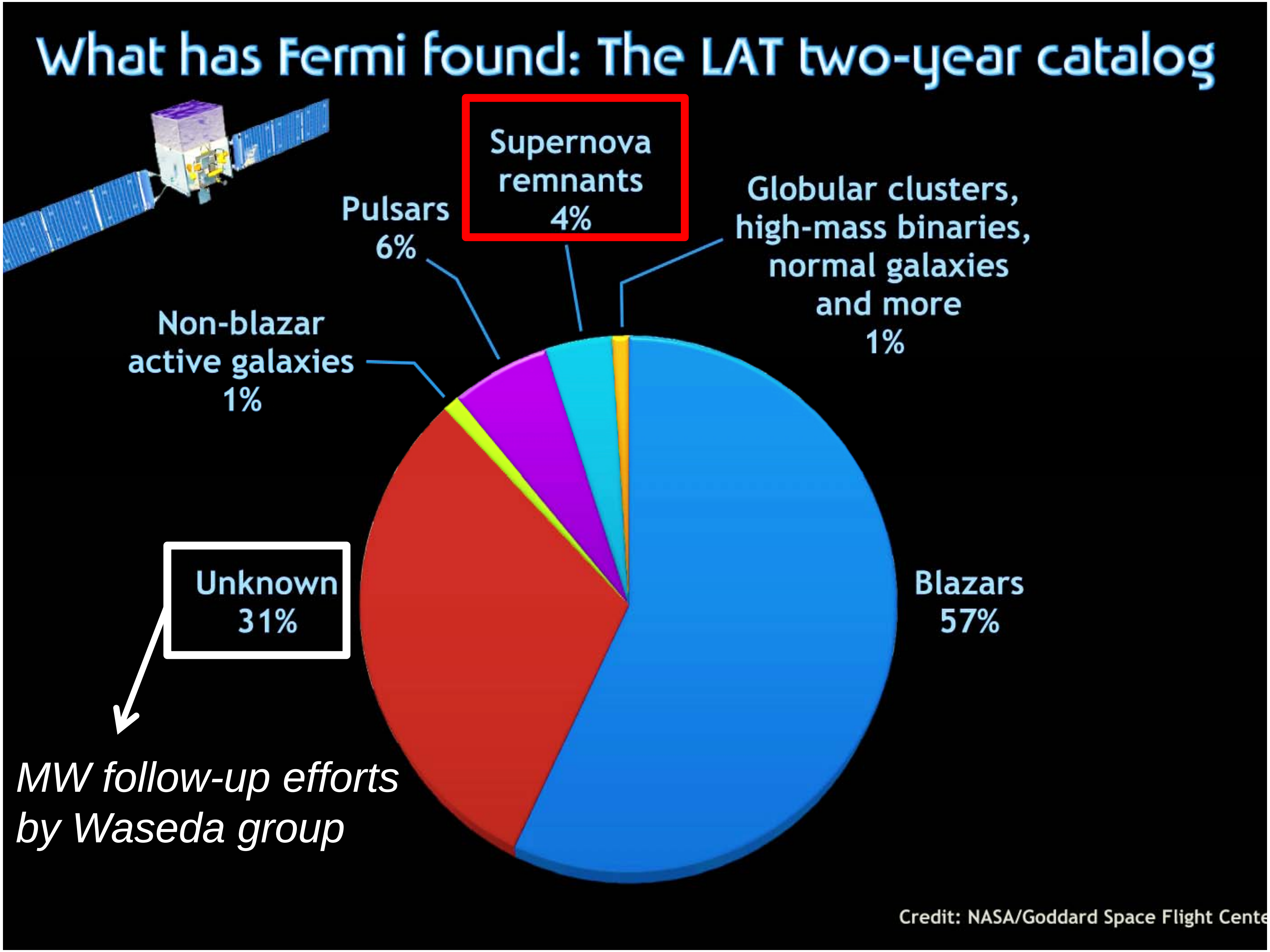
Abdo+, ApJS submitted

Over 100 gamma-ray pulsars

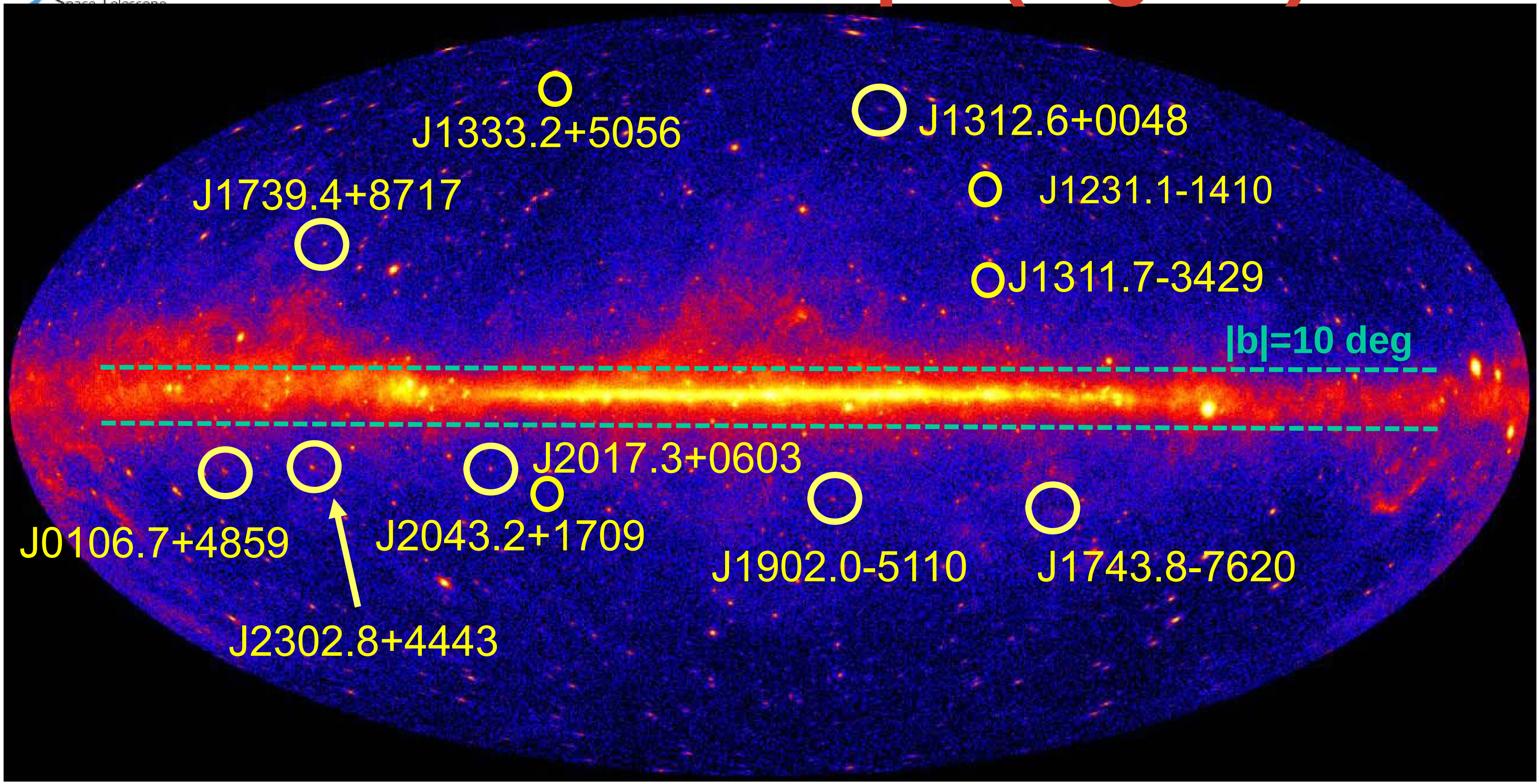
CGRO psrs   Gamma-selected   radio-selected   MSPs



http://www.nasa.gov/externalflash/fermipulsar/


What has Fermi found: The LAT two-year catalog
Supernova remnants 4%
Pulsars 6%
Globular clusters, high-mass binaries, normal galaxies and more 1%
Non-blazar active galaxies 1%
Unknown 31%
Blazars 57%
MW follow-up efforts by Waseda group
Credit: NASA/Goddard Space Flight Cente

Suzaku follow-ups (high-b)

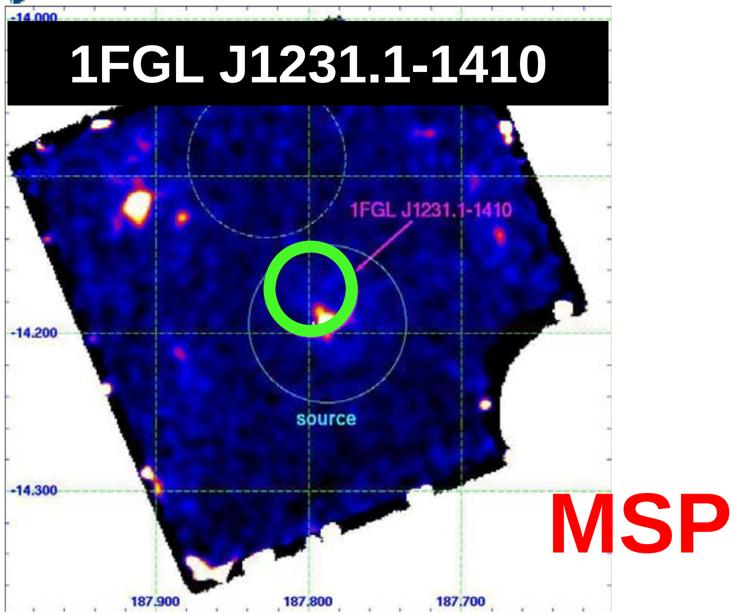


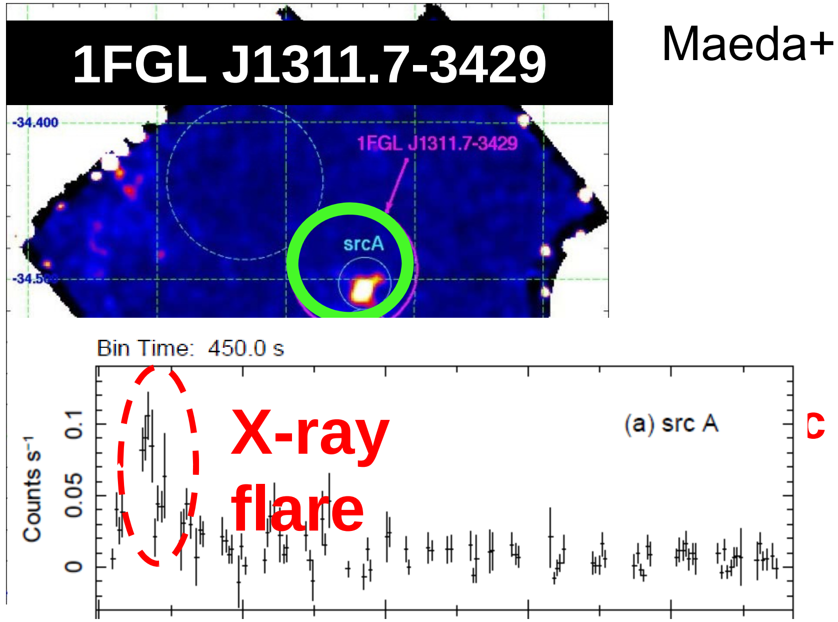
Selection Criteria

- Unassociated objects
- More than 10 degrees away from the galactic plane
- High significance >> 10 σ

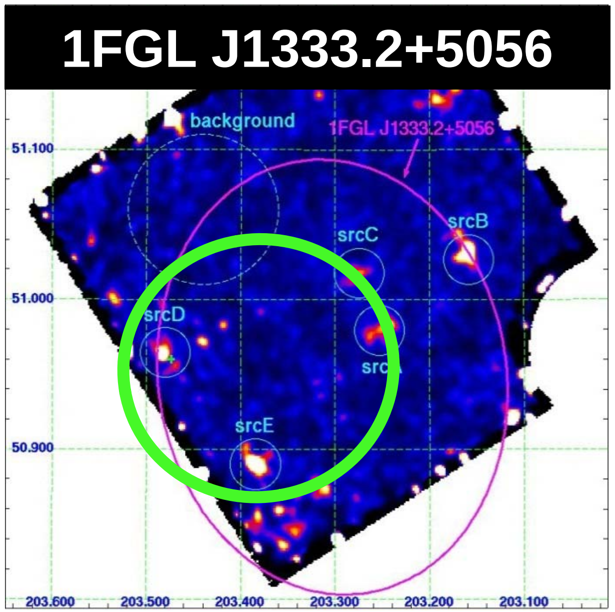
Maeda+ 11
Takahashi+12

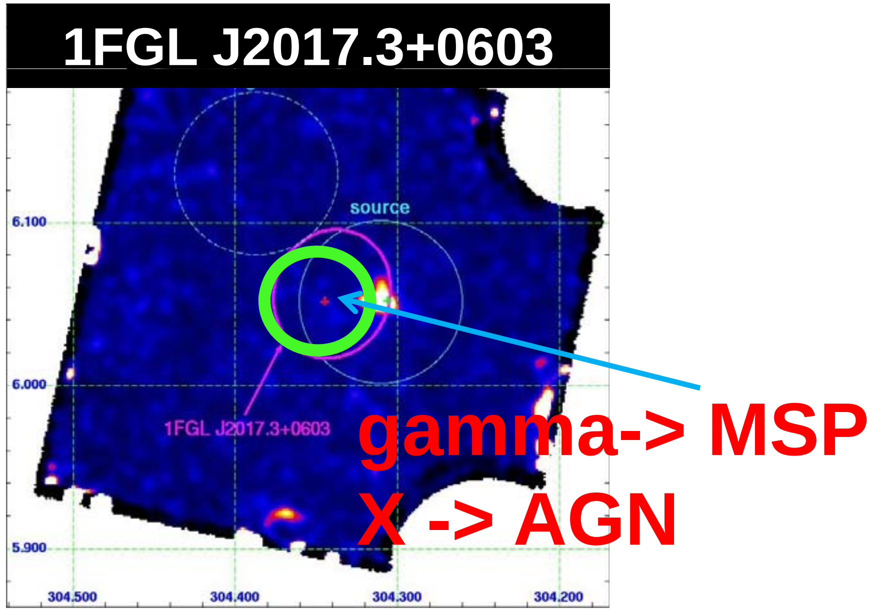
1st Year Results



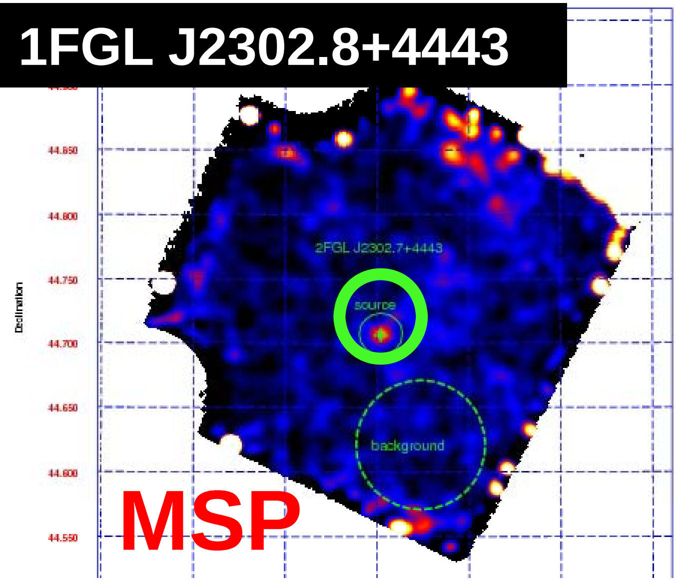


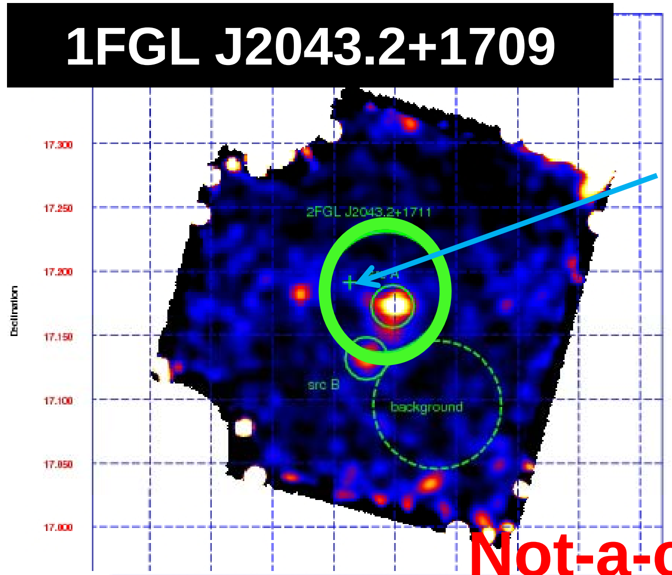
Maeda+11

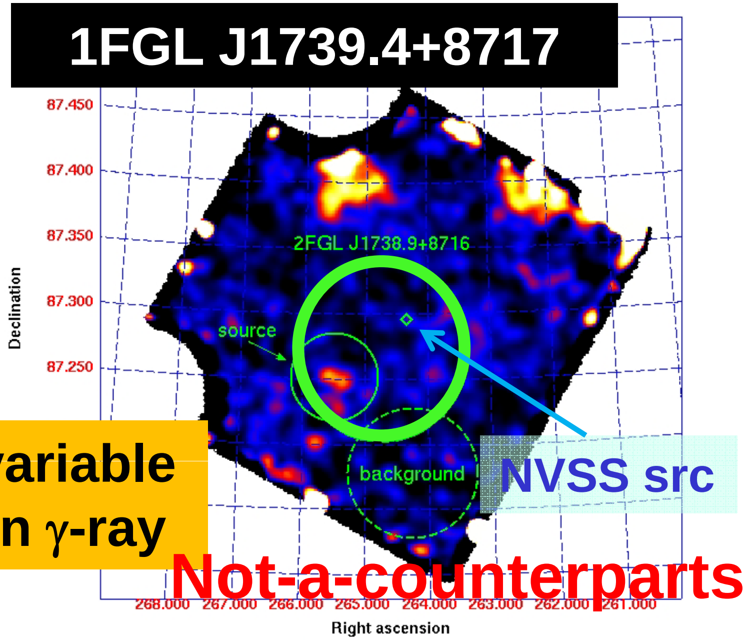


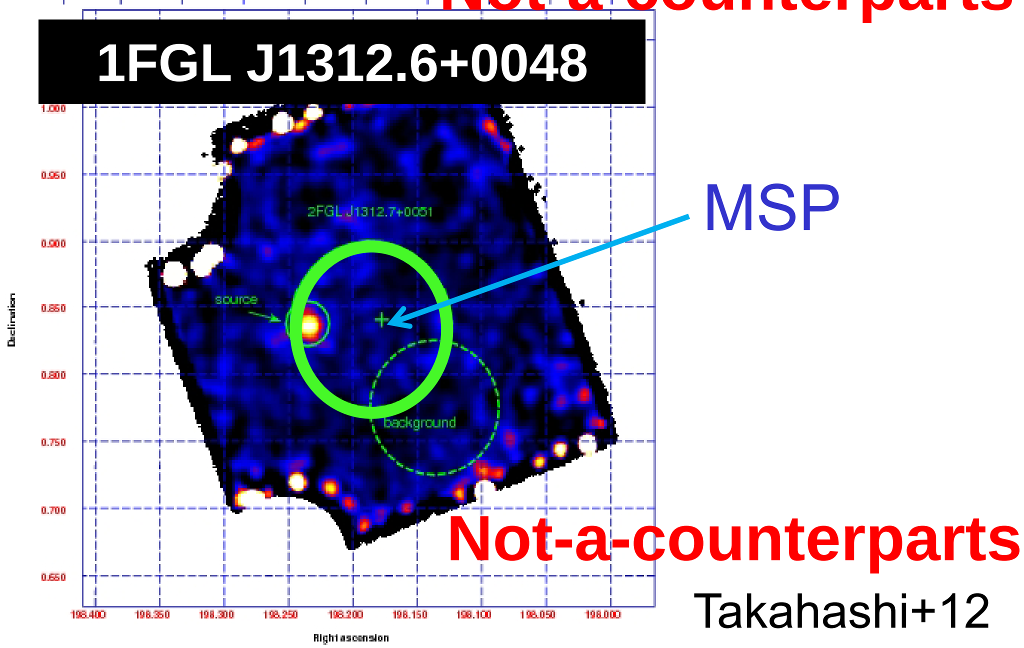


2nd year results





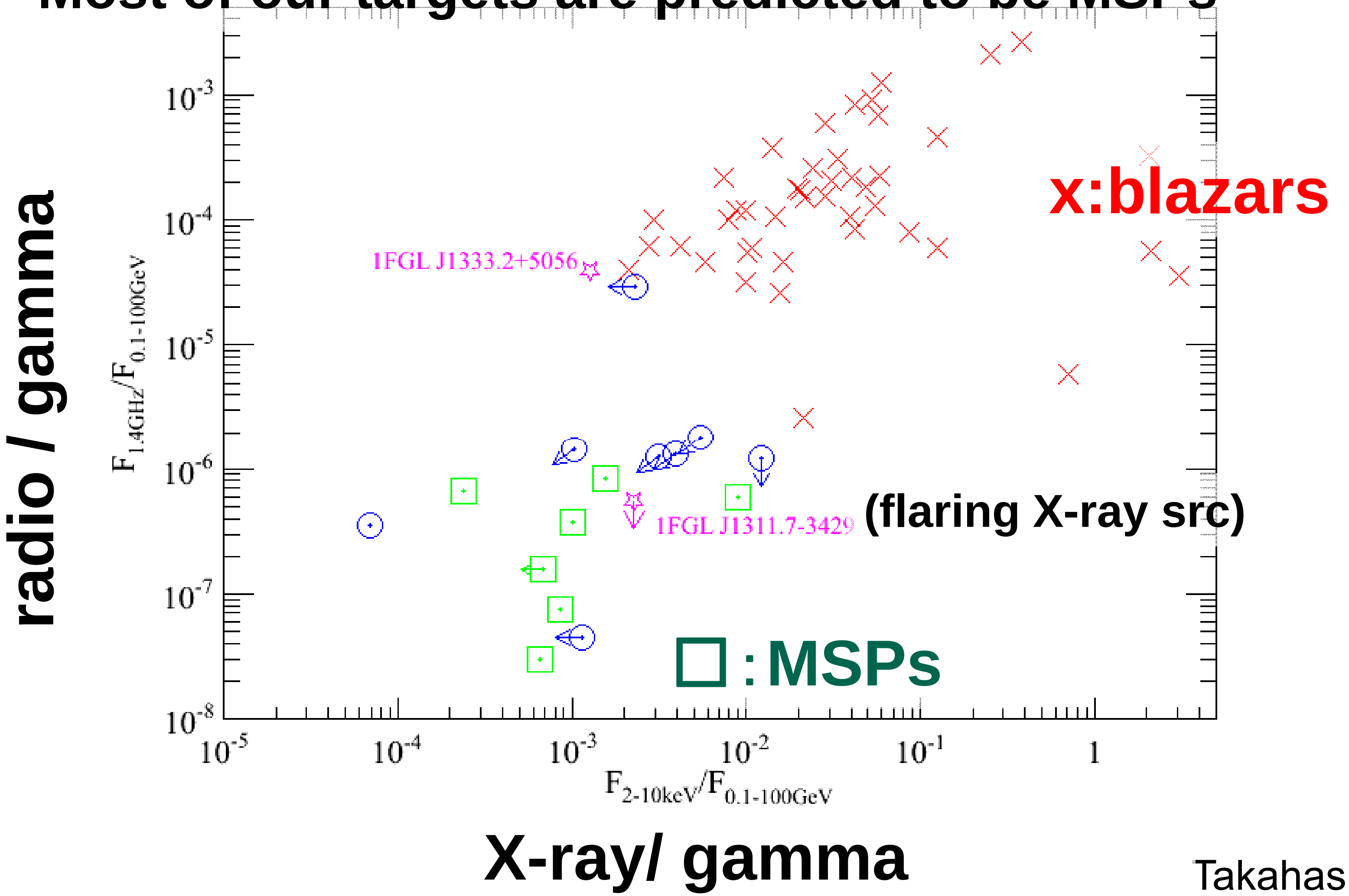




Takahashi+12

Flux ratio population

- Clear separation between blazars and MSPs
- Can be a good indicator of source classes
- Most of our targets are predicted to be MSPs



Takahashi+12

3rd year “hot” results

- **Will be presented at the upcoming ASJ meeting**
- **Papers are also in preparation**

MW observations of 1FGL J2339.7-0531

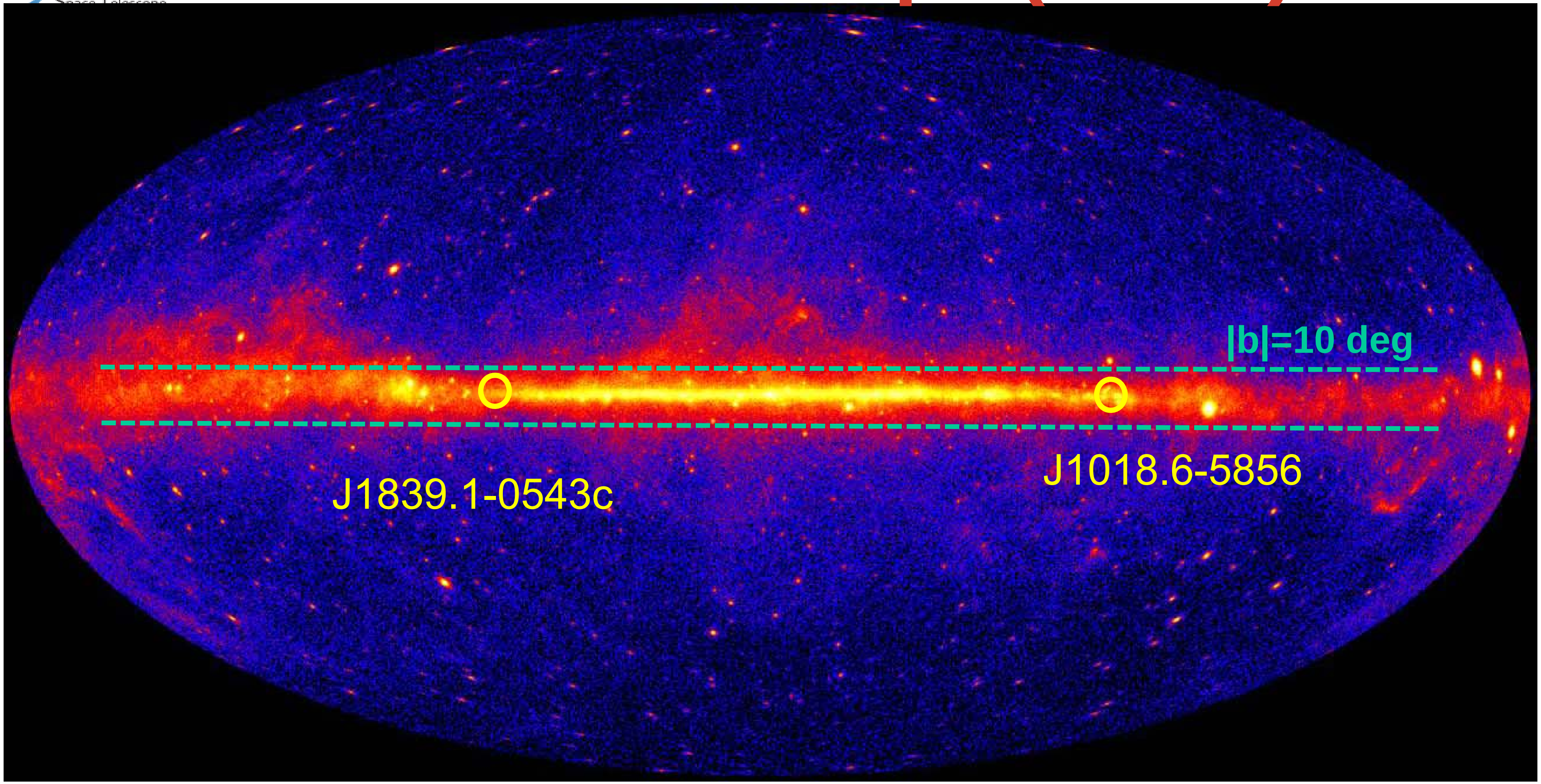
– a candidate of black-widow like pulsar

(Takahashi+, Yatsu+)

See also Kong+12, ApJL, 747, 3

Systematic X-ray study of Fermi unassociated sources at high Galactic latitudes (Maeda+)

Suzaku follow-ups (low-b)

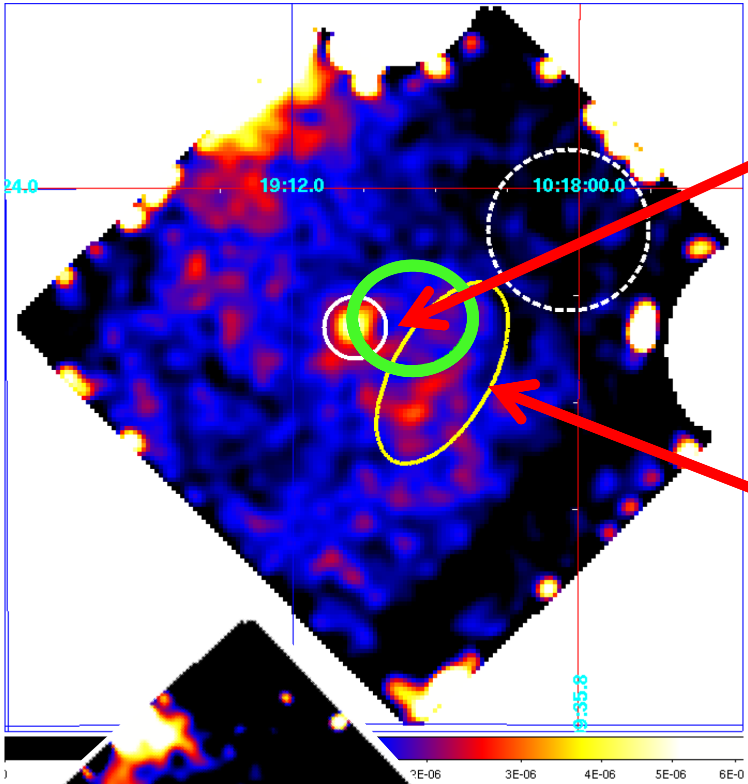


Selection Criteria

- Unassociated objects
- Less than 10 degrees away from the galactic plane
- High significance >> 10 σ

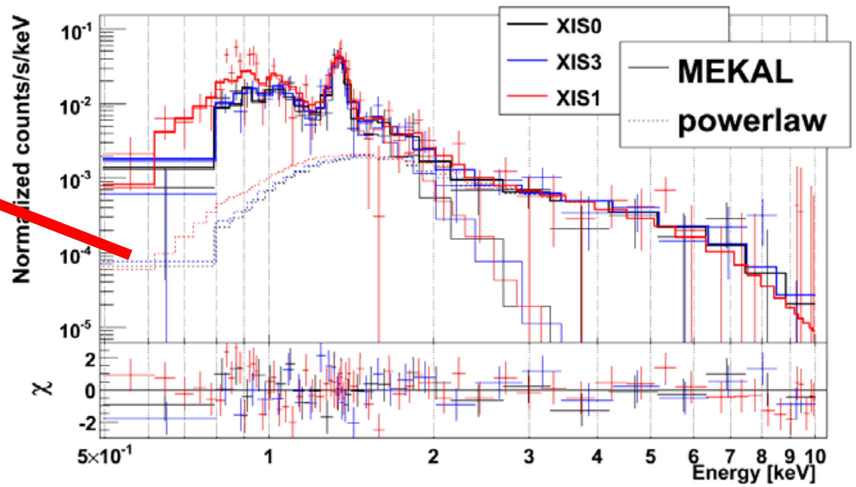
TN+11,
Fermi Symposium

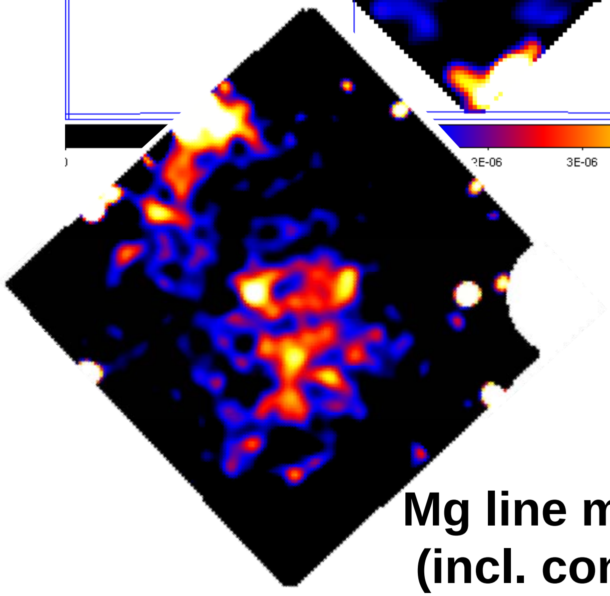
1FGL J1018.6-5856



Non-thermal point source
Photon index ~ 1.7

pulsar ?





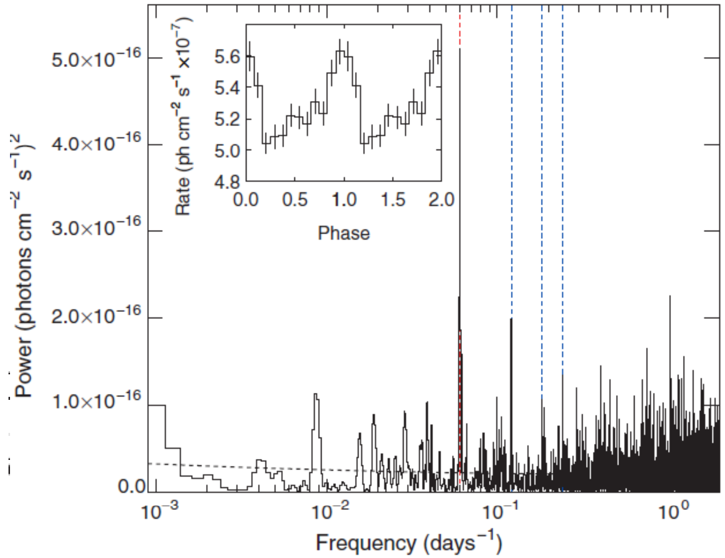
Mg line map
(incl. continuum)

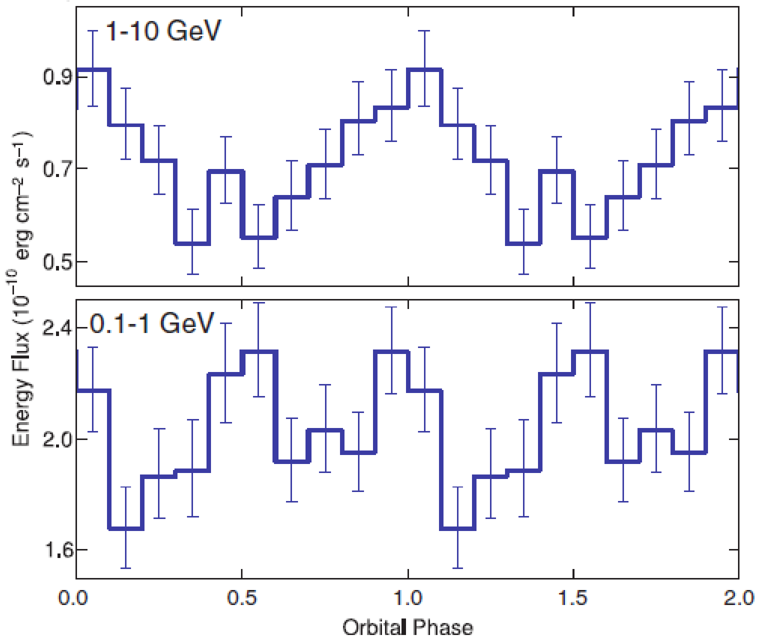
Diffuse emission from thin thermal plasma
Significant He-like Mg line emission
An additional power-law is highly favored

Type II SN ?

TN+11,
Fermi Symposium

New gamma-ray binary





REPORTS

Periodic Emission from the Gamma-Ray Binary 1FGL J1018.6–5856

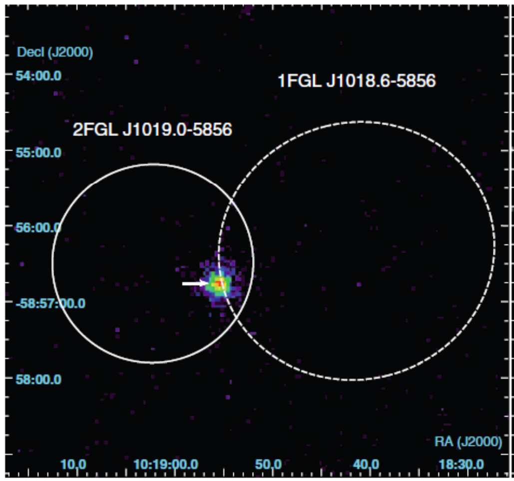
The Fermi LAT Collaboration*

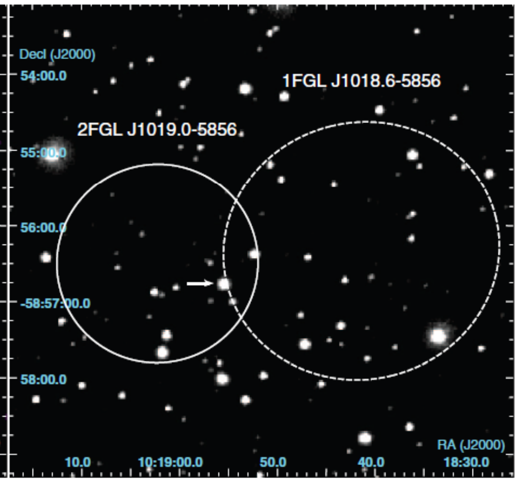
Gamma-ray binaries are stellar systems containing a neutron star or black hole, with gamma-ray emission produced by an interaction between the components. These systems are rare, even though binary evolution models predict dozens in our Galaxy. A search for gamma-ray binaries with the Fermi Large Area Telescope (LAT) shows that 1FGL J1018.6–5856 exhibits intensity and spectral modulation with a 16.6-day period. We identified a variable x-ray counterpart, which shows a sharp maximum coinciding with maximum gamma-ray emission, as well as an O6V((f)) star optical counterpart and a radio counterpart that is also apparently modulated on the orbital period. 1FGL J1018.6–5856 is thus a gamma-ray binary, and its detection suggests the presence of other fainter binaries in the Galaxy.

photons cm^{-2} s^{-1}, making it one of the brighter LAT sources. The source's location at right ascension (R.A.) = 10^h 18.7^m, declination (decl.) = −58° 56.30′ (J2000; ±1.8′, 95% uncertainty) means that it lies close to the galactic plane ($b = -1.7°$), marking it as a good candidate for a binary system. 1FGL J1018.6–5856 has been noted to be positionally coincident with the supernova remnant G284.3–1.8 (*12*) and the TeV source HESS J1018–589 (*14*), although it has not been shown that these sources are actually related.

The modulation at a period of 16.6 days has a power more than 25 times the mean value of the power spectrum and has a false-alarm probability of 3×10^{-8}, taking into account the number of statistically independent frequency bins. From both the power spectrum itself (*15*) and

CA:R.Corbet, Science, 335, 189 (2012)

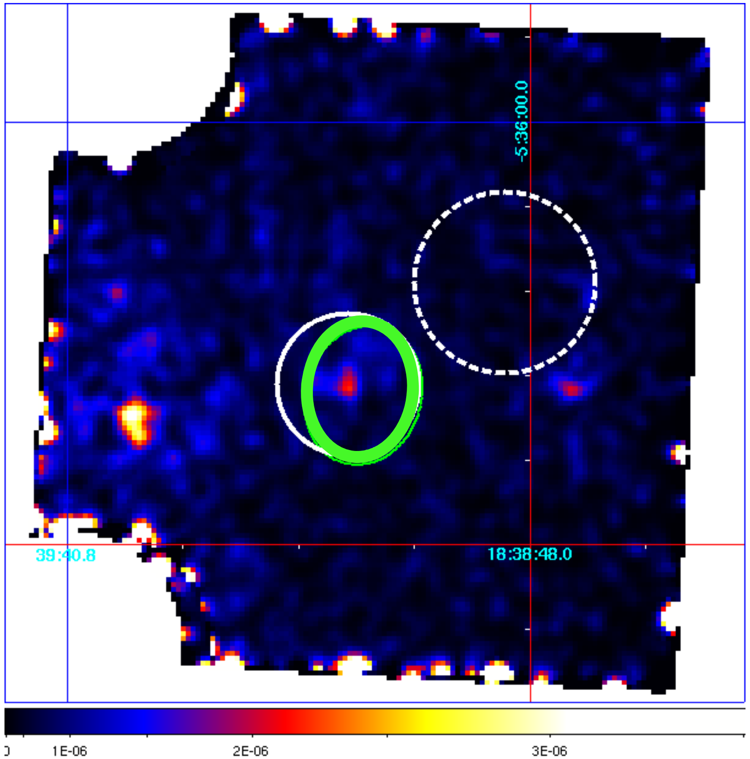




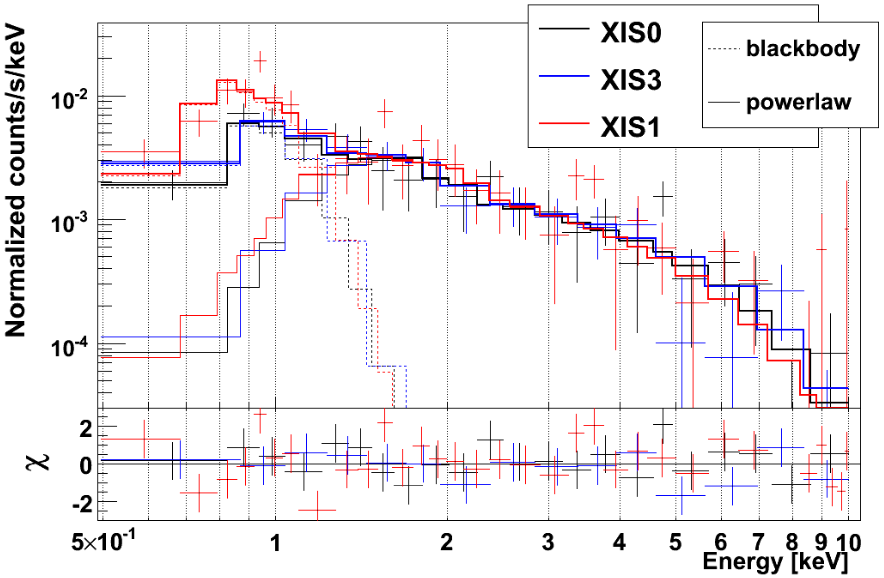
Swift/XRT **Swift/UVOT**

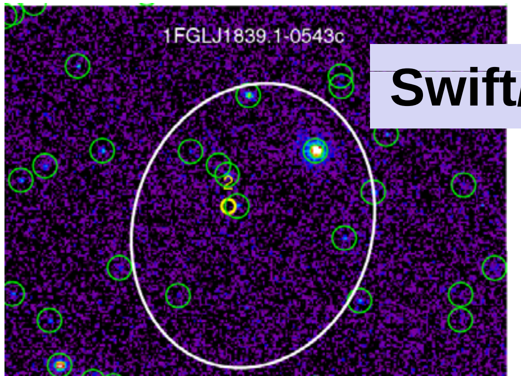
16.6 days period
Companion O6V star

1FGL J1839.1-0543c



Blackbody (0.07keV)
+ power-law ~ 2.3





Swift/UVOT (B2)

mag. 20.78 +/- 0.16

pulsar candidate ?

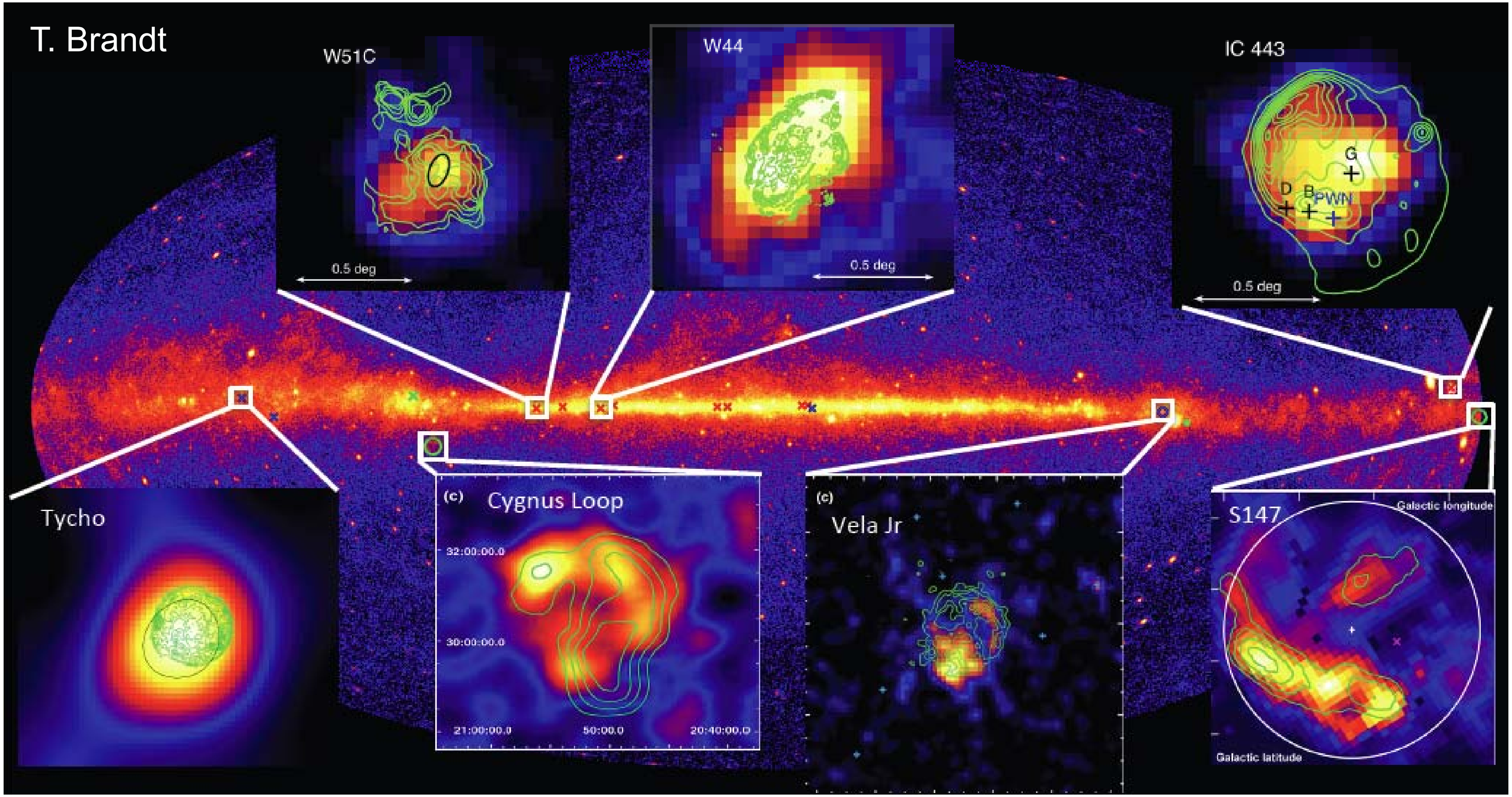
Yet periodicity has not been identified in any WL

TN+11,
Fermi Symposium

Fermi LAT detection of SNRs

16 SNRs including –
- 4 young SNRs
- 9 interacting with MC

+ 43 2FGL candidates

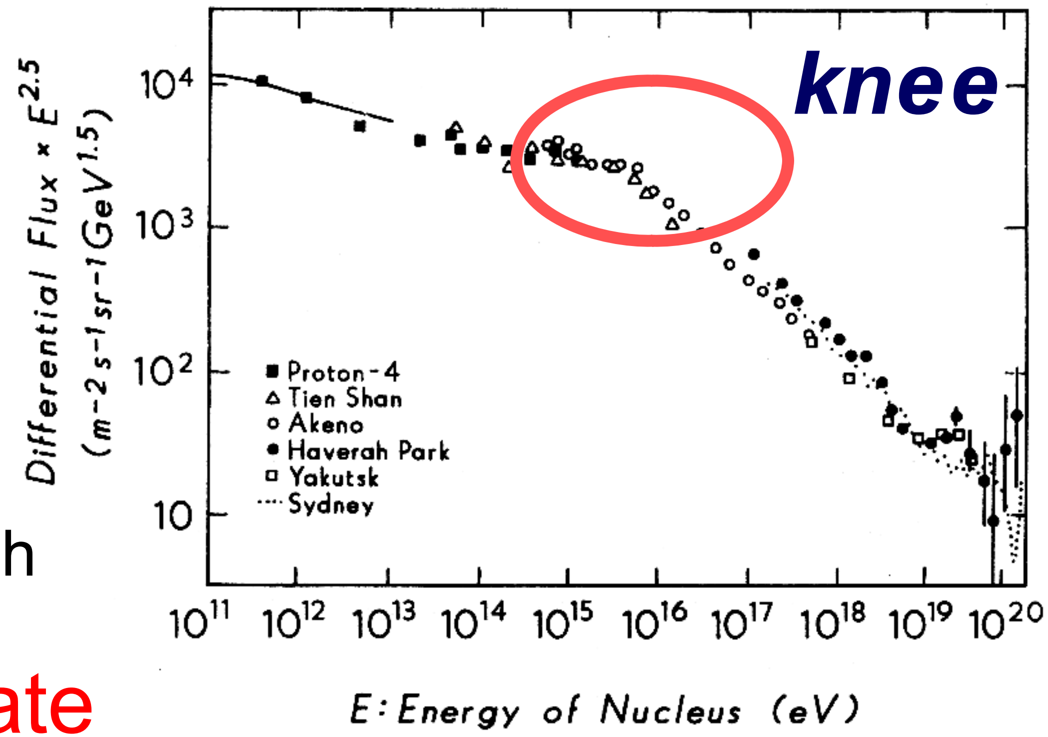


Cosmic ray origin

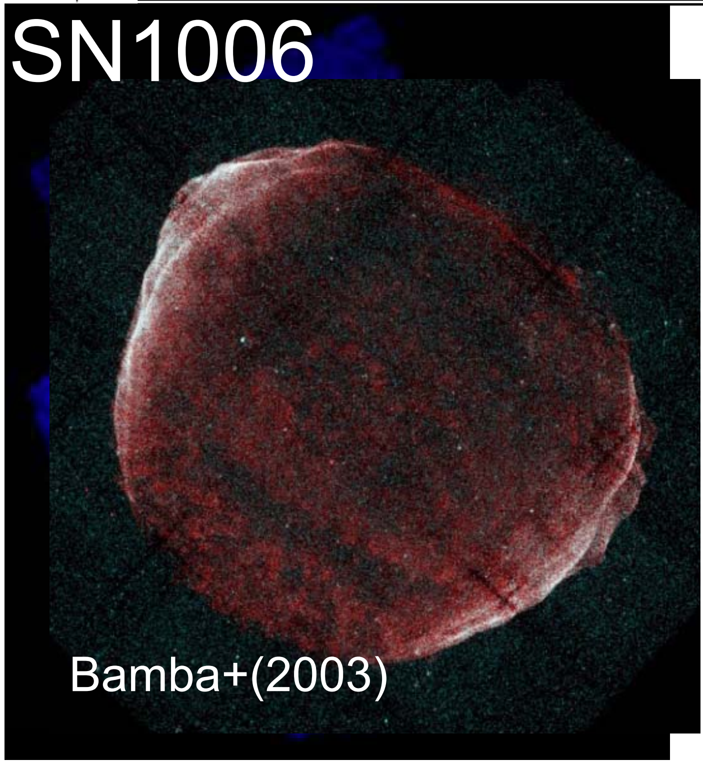
- **Cosmic rays**
  - energy density 1 eV/cc
  - averaged confinement time 2E+7 yrs (1E+14 s）
  - Galactic disc：30 kpc × 300 pc
  - **1E+40 erg/s**
- **Supernovae**
  - 1E+51erg
  - 1 SN/30 yrs
  - **1E+42 erg/s**

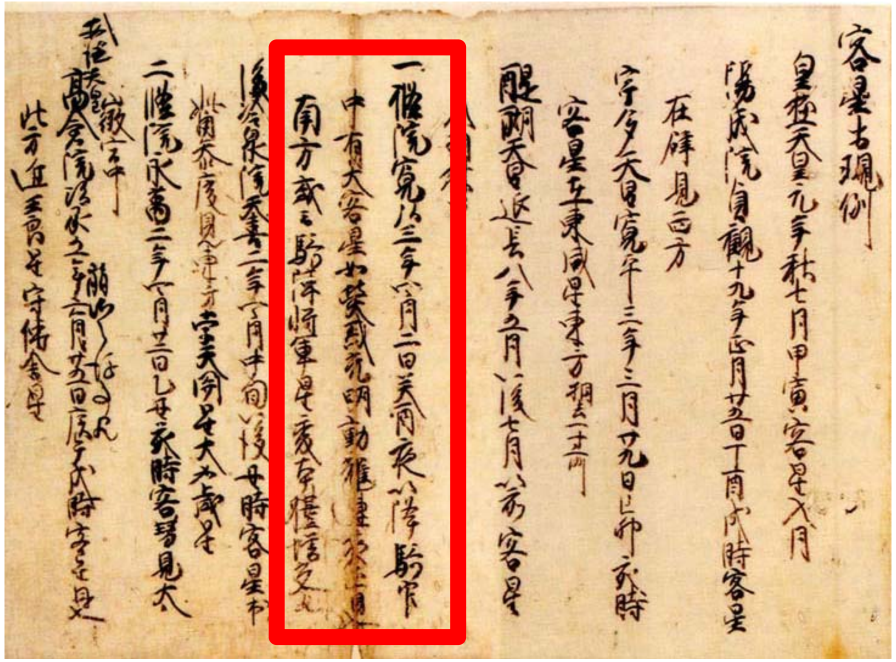
a few % of SNe are enough

Promissing candidate



Accelerated electrons





Fujiwara (1230)

Discovery of an electron-accelerating SNR (Koyama+95)

Inner region: thermal emission from ejecta

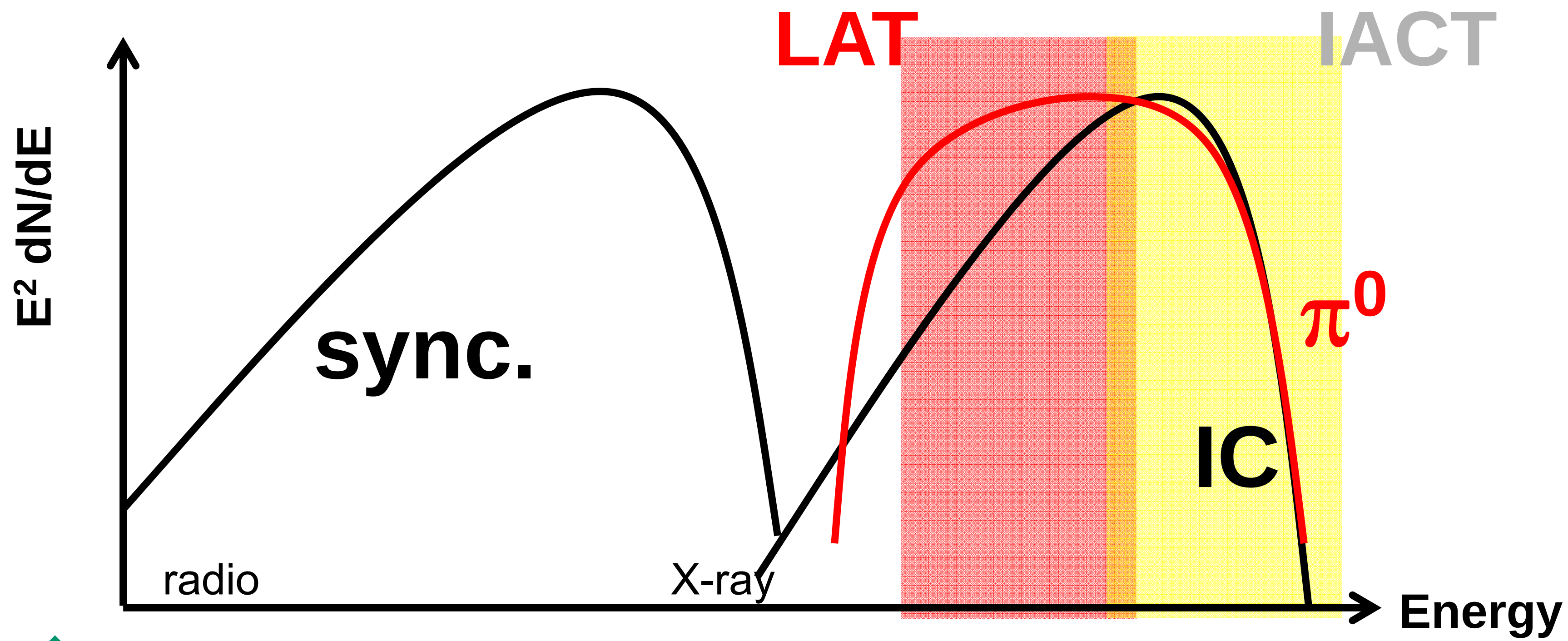
Outer shell : synchrotron emission = e- up to 100 TeV

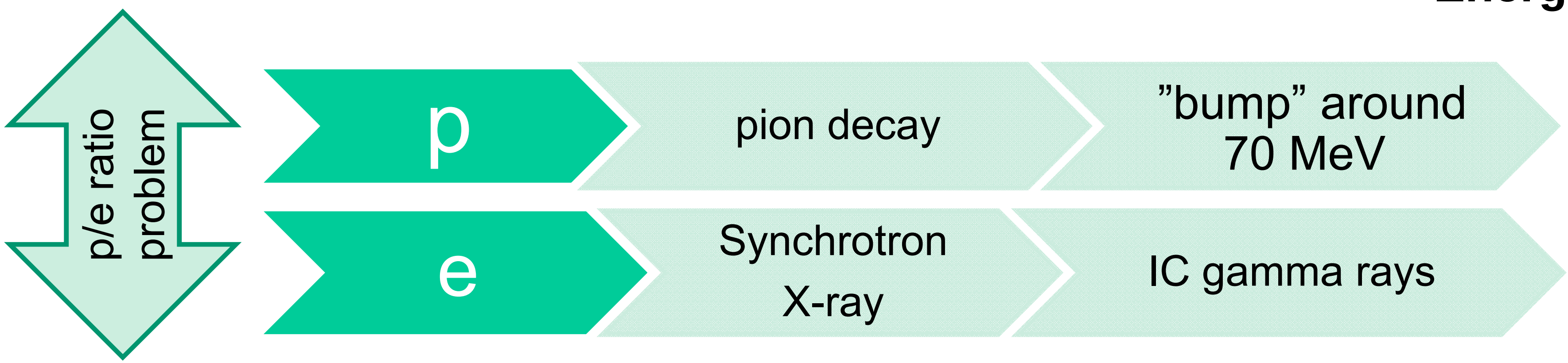
Accl. sites are very thin filaments at the shell (Bamba+03)

Common in young SNRs

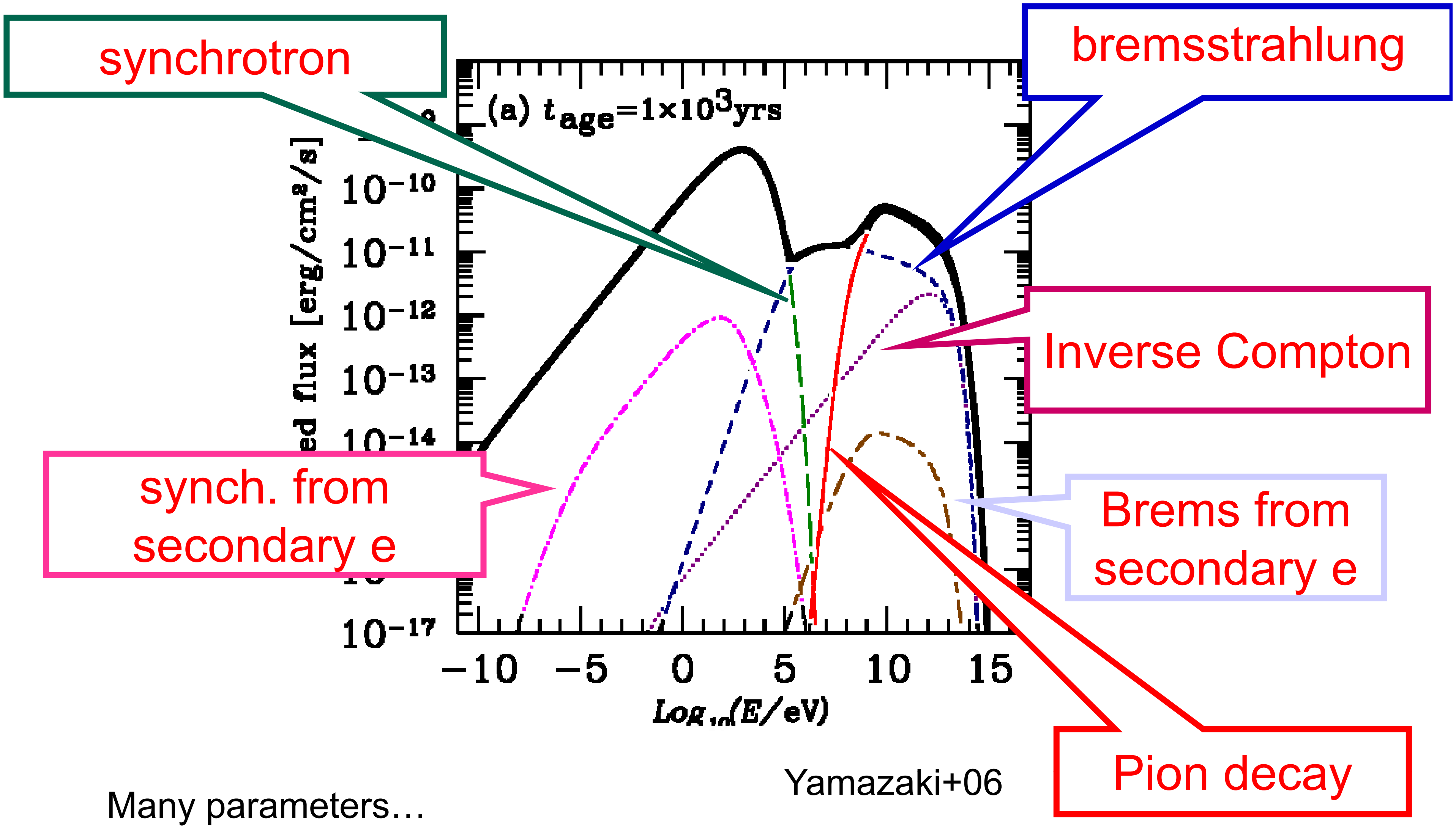
RX J1713-3946, RX J0852-4622, Cas A, RCW 86, etc. etc.

Gammas simply expected





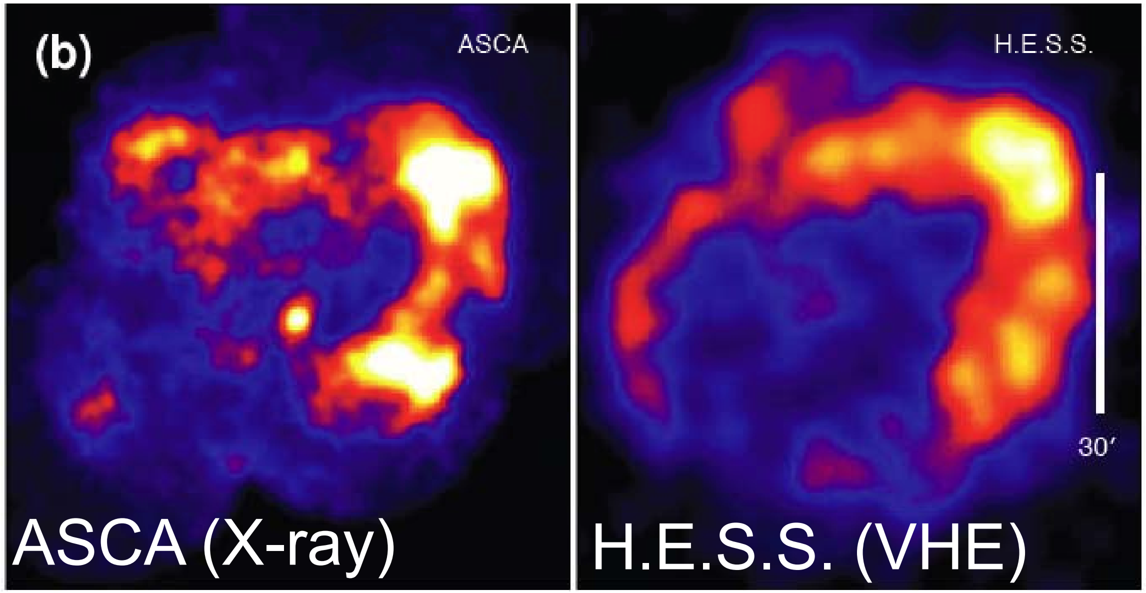
Nature should be more complex..



Yamazaki+06

Many parameters…
And time evolutions…

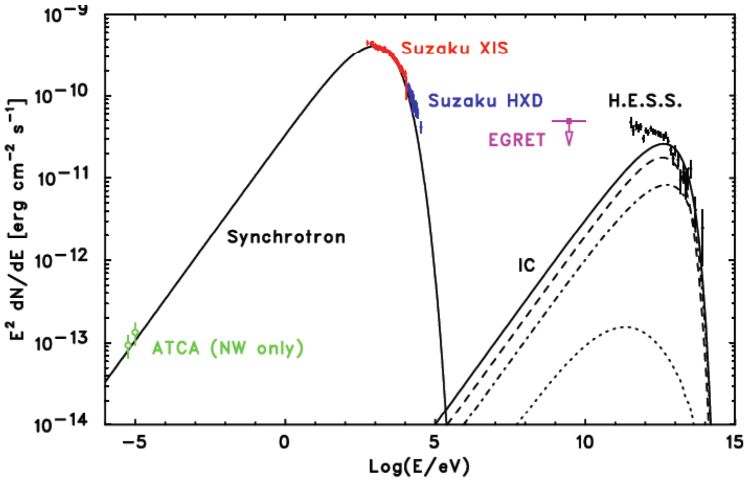
RX J1713.7-3946



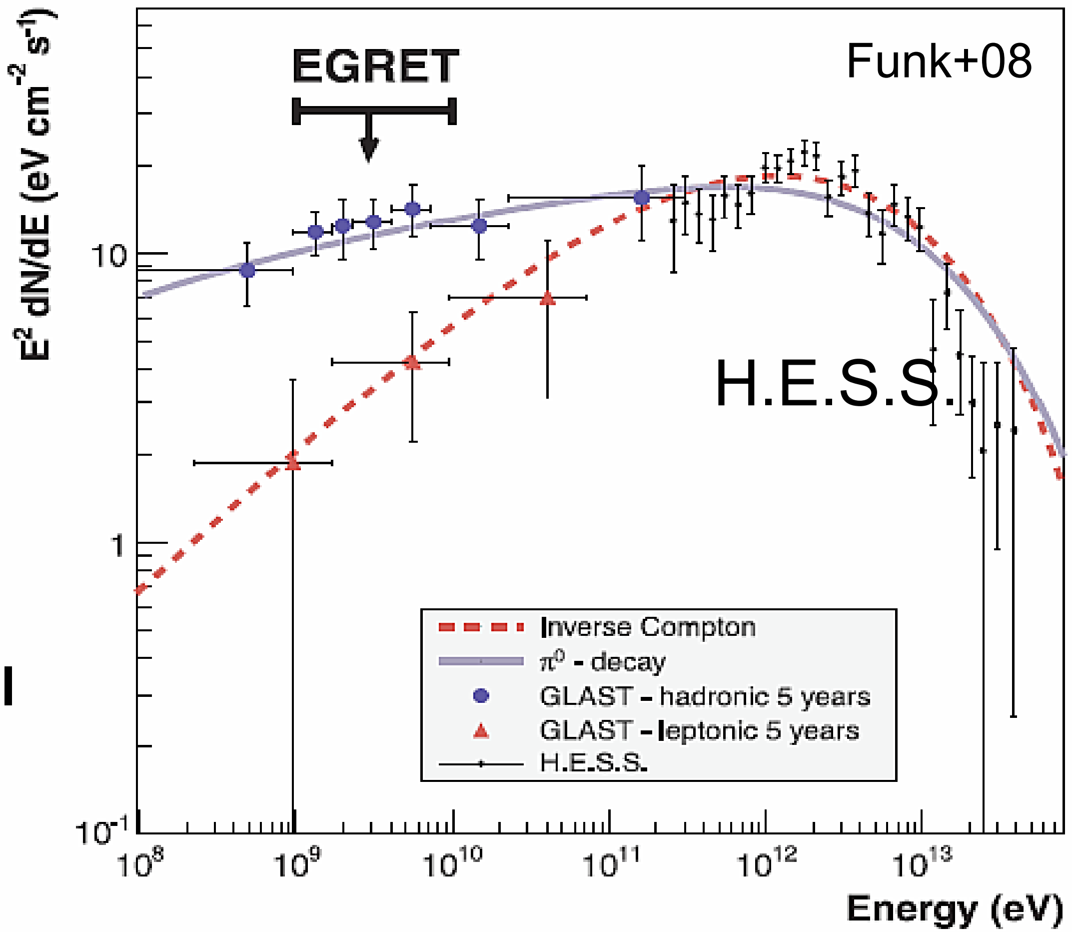
- **Age ~ 1600 yrs, D ~ 1 kpc**
- **2nd example of SN1006**
  - Non-thermal X-ray dominated (Koyama+96)
- **Detection of VHE gamma-rays**
  - CANGAROO, H.E.S.S.
- **Morphologies are quite similar between X-ray and VHE, supporting leptonic scenario**

Expectation for Fermi

Pre-launch simulation



Tanaka+08

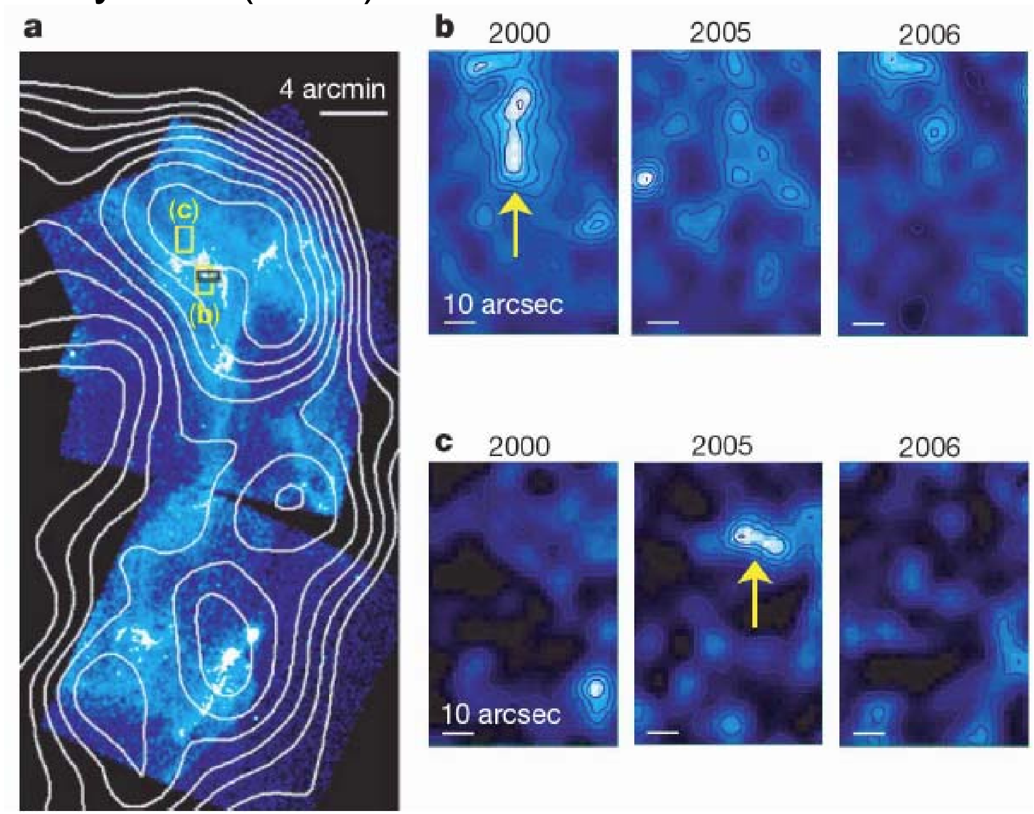


Hard to explain leptonic model with Suzaku data

LAT covers crucial energies to constrain the modeling

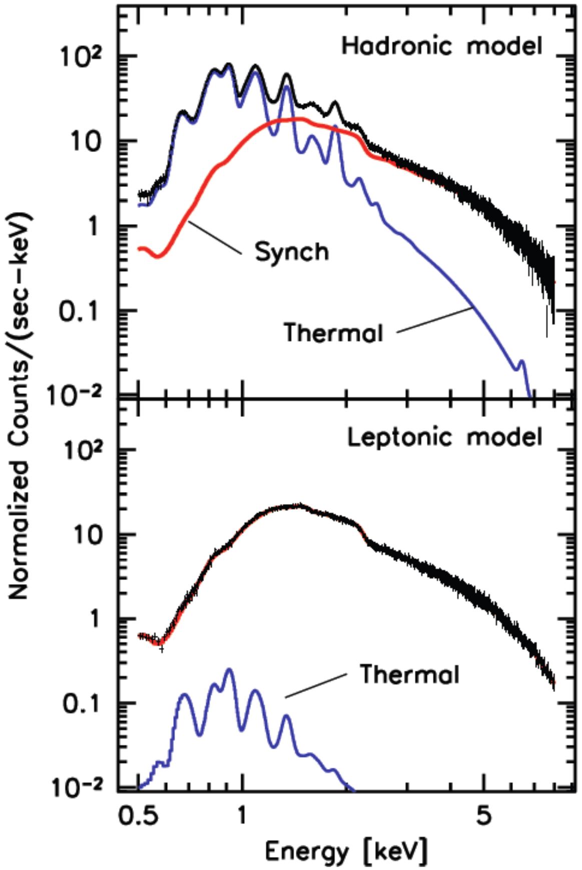
Arguments

Uchiyama+(2007) *Chandra*



Variation in ~1yr time scale
→ Need > 1mG ! (locally)
→ Protons produce TeV gamma-rays ?

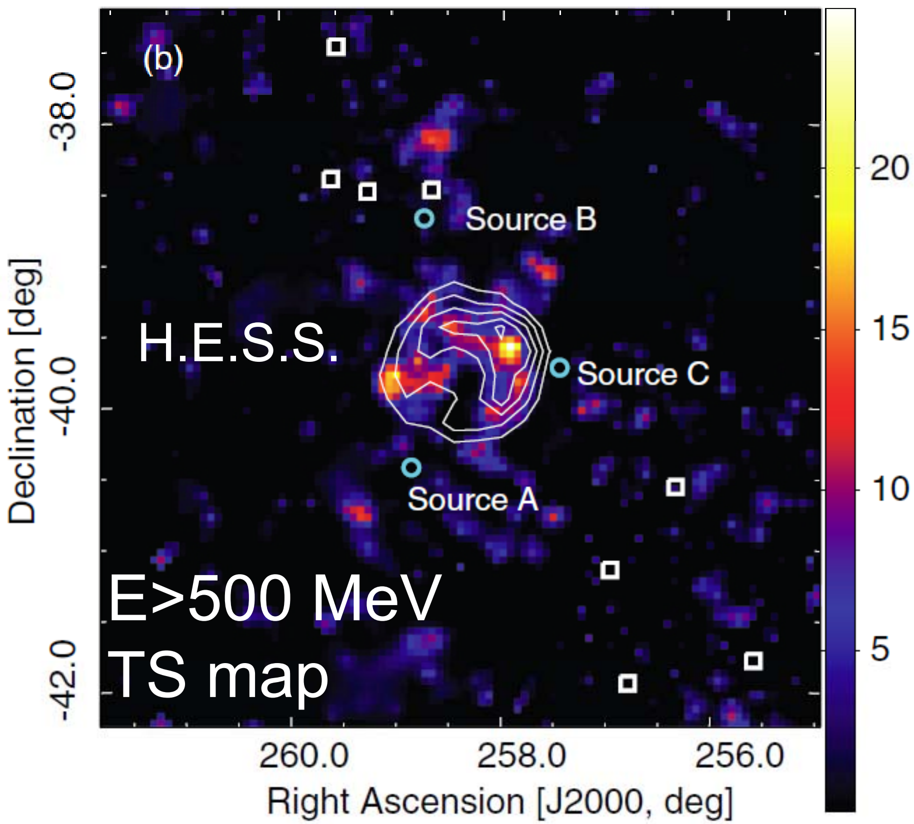
Ellison+(2010)

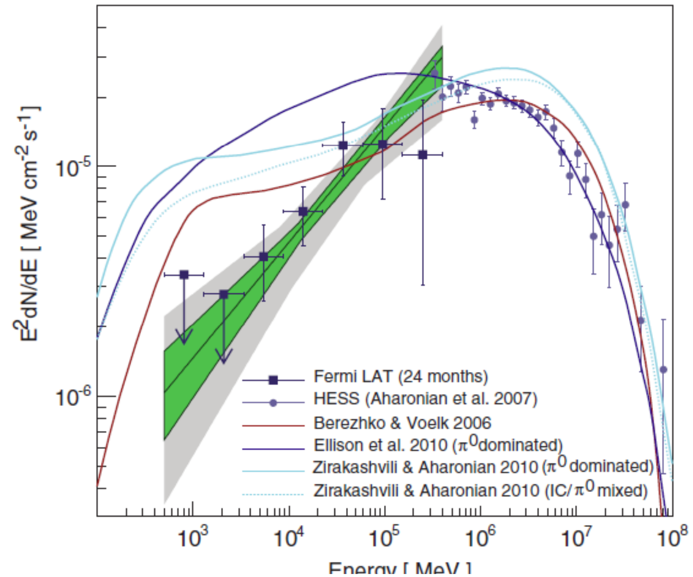


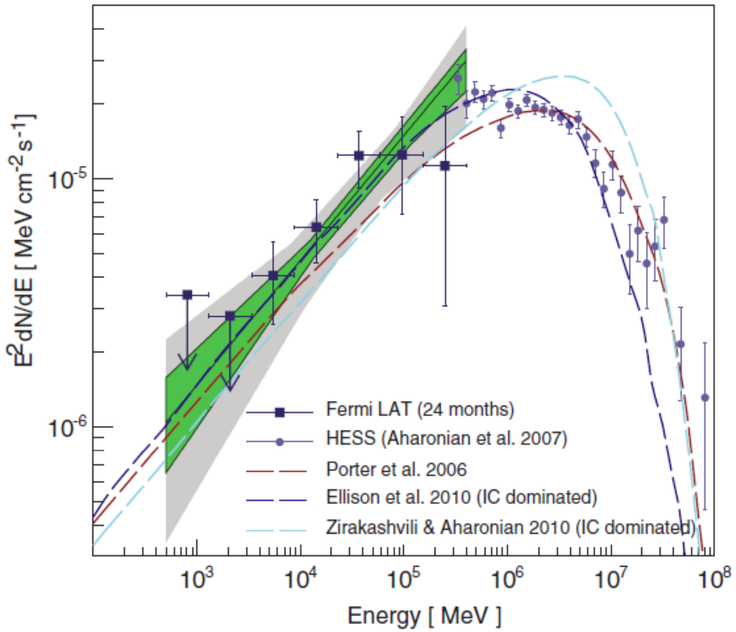
Suzaku would have detected thermal emission in the hadronic case

LAT observation

Abdo+11



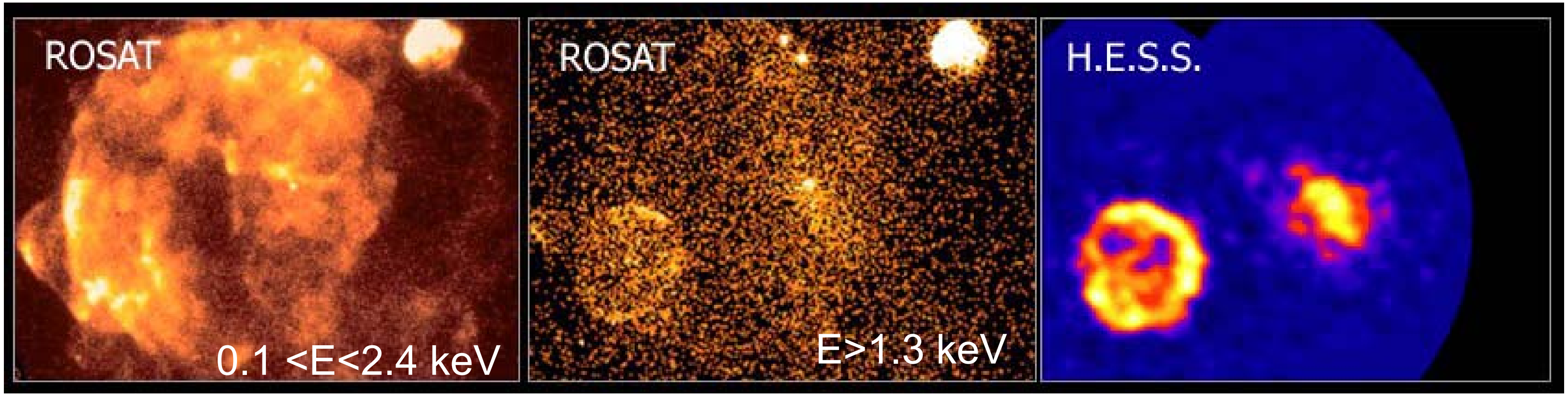




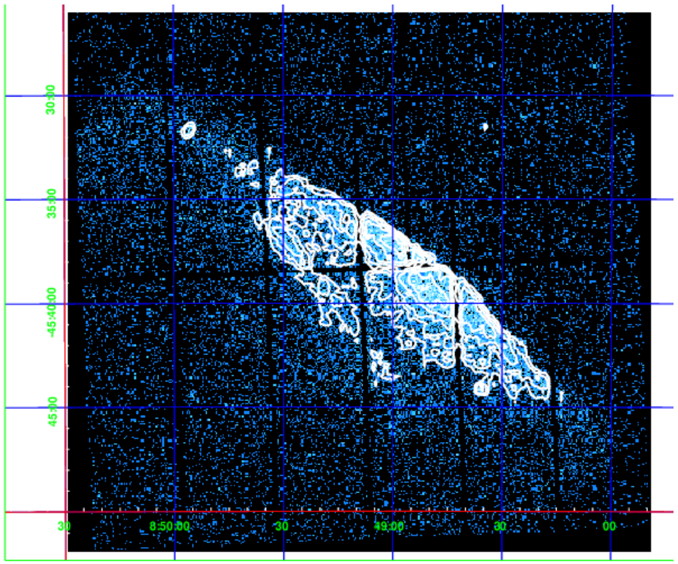
Disk / HESS-template are statistically favored
Hard spectrum (Γ ~ 1.5)
Well fit with leptonic models (B ~ 10uG)

How to reconcile with the strong *B*-field ?
Efficient proton acceleration possible ?

RX J0852.0-4622 (Vela Jr.)

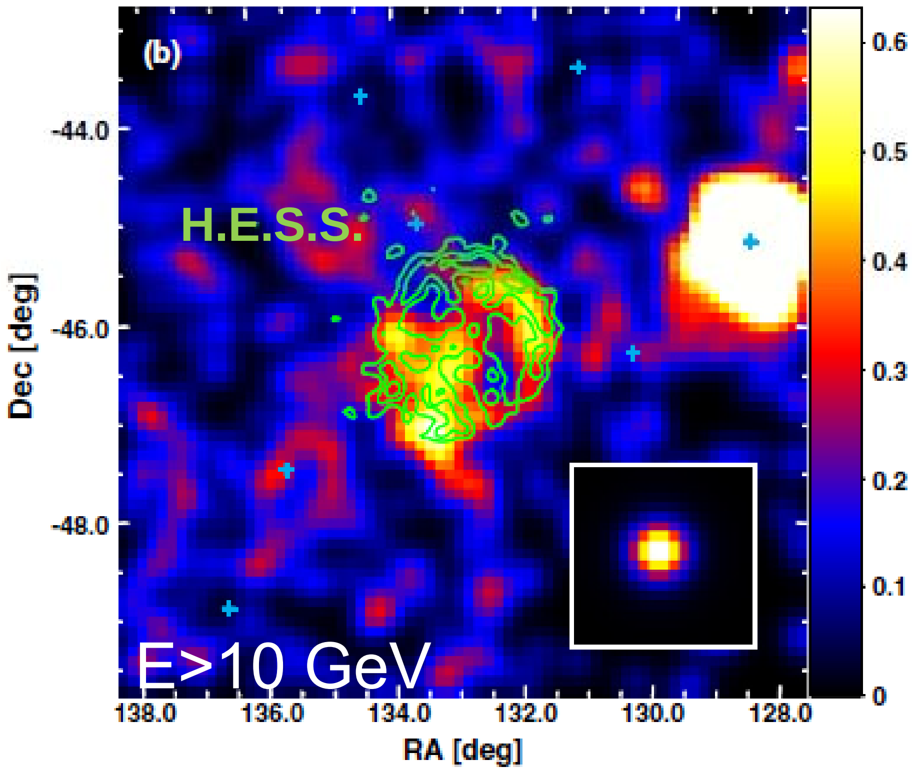


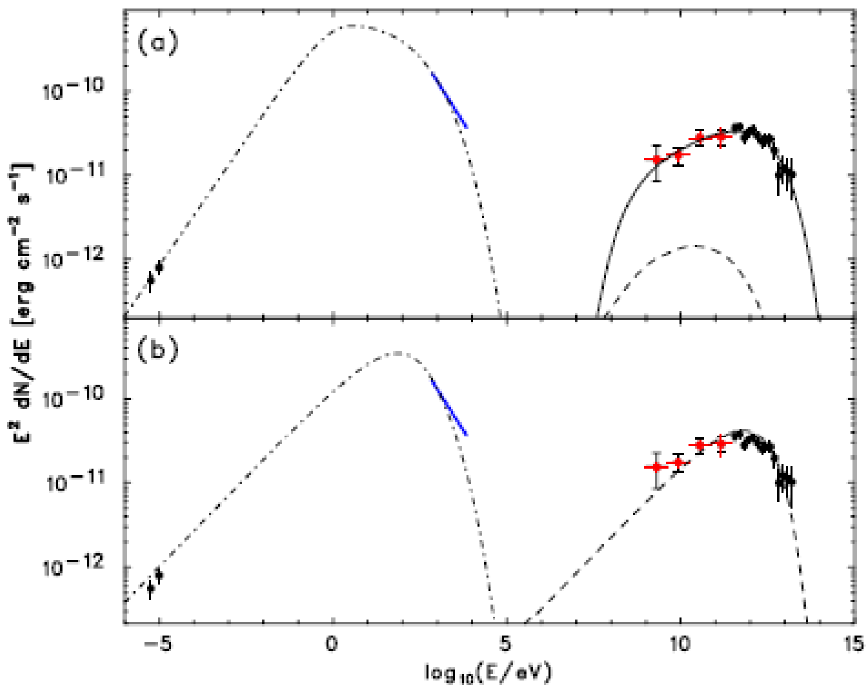
- **Age 1700— 4300 yrs**
- **D ~ 750 pc** (further than Vela SNR)
- **R ~ 1 degree**
- **Discovered in *ROSAT* hard image**
- **Non-thermal X-rays**
  - **filamentary structure with *XMM***
- **Detection of VHE gamma rays**
  - **CANGAROO, H.E.S.S.**



Vela Jr. with LAT

Tanaka+11





Hard spectrum : Γ = 1.87 ± 0.08 (stat) ± 0.17 (sys)

Hadronic model :

a large amount of protons (5E+50 erg for n = 0.1 /cc)

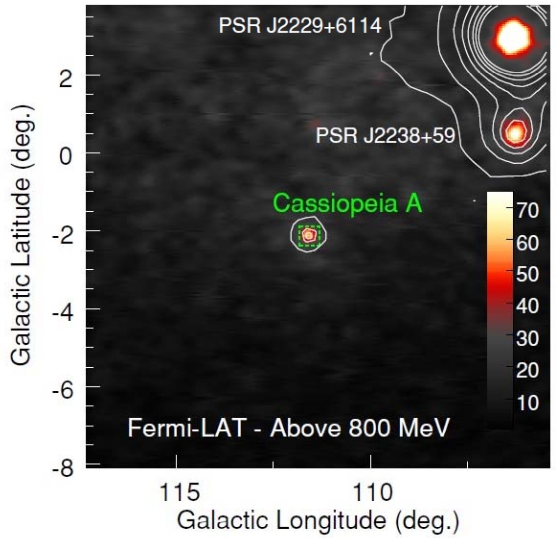
Leptonic model :

weak magnetic field (12uG) against X-ray filaments

Young SNRs with hadronic scenario

Abdo+10

Giordano+12

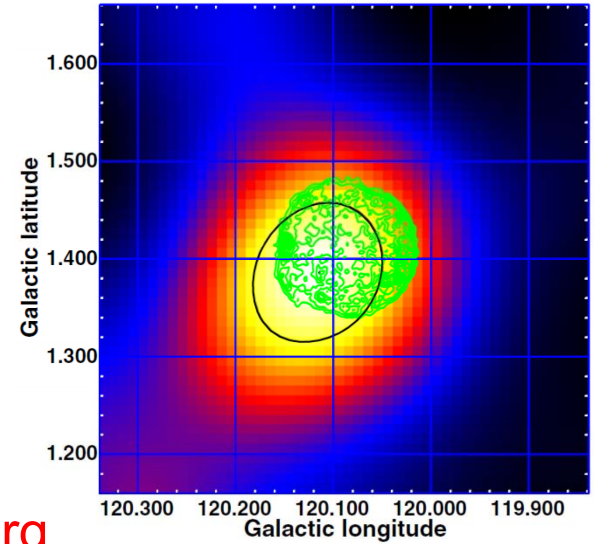


Cas A

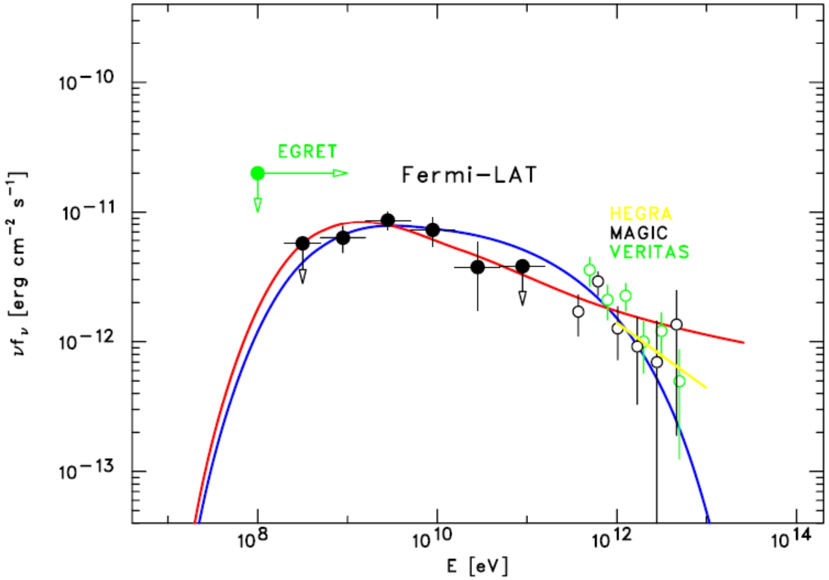
D~3.4 kpc
Age~330 yrs

Tycho

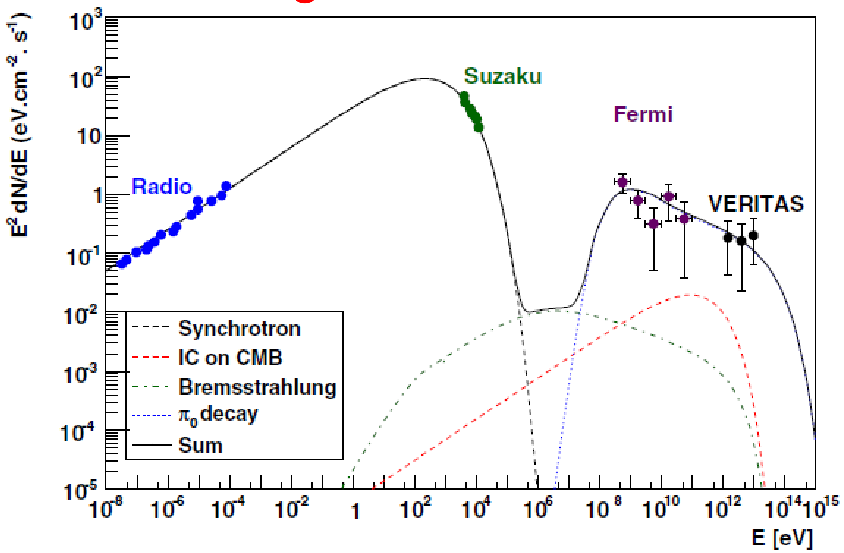
Type Ia
D~3 kpc
Age~440 yrs



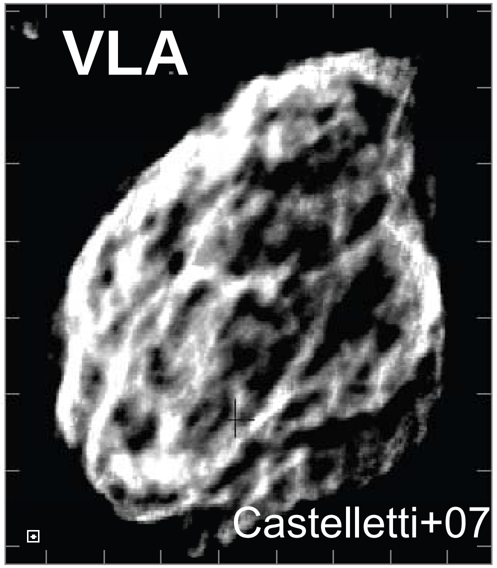
W~1E49 erg



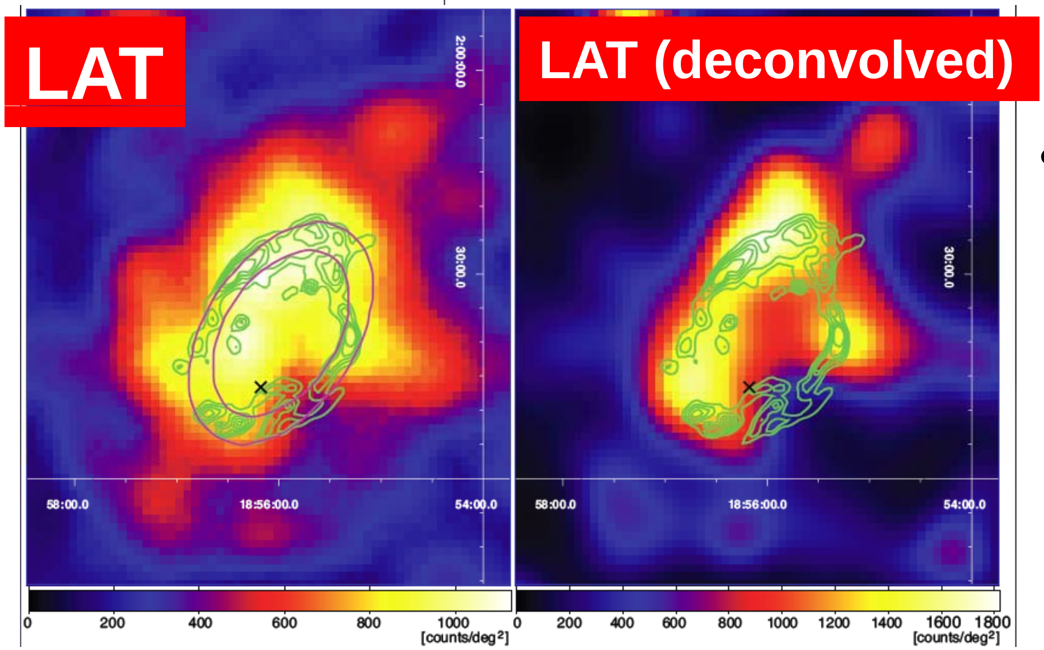
W~1E50 erg



Mid-aged SNR + MC : W44



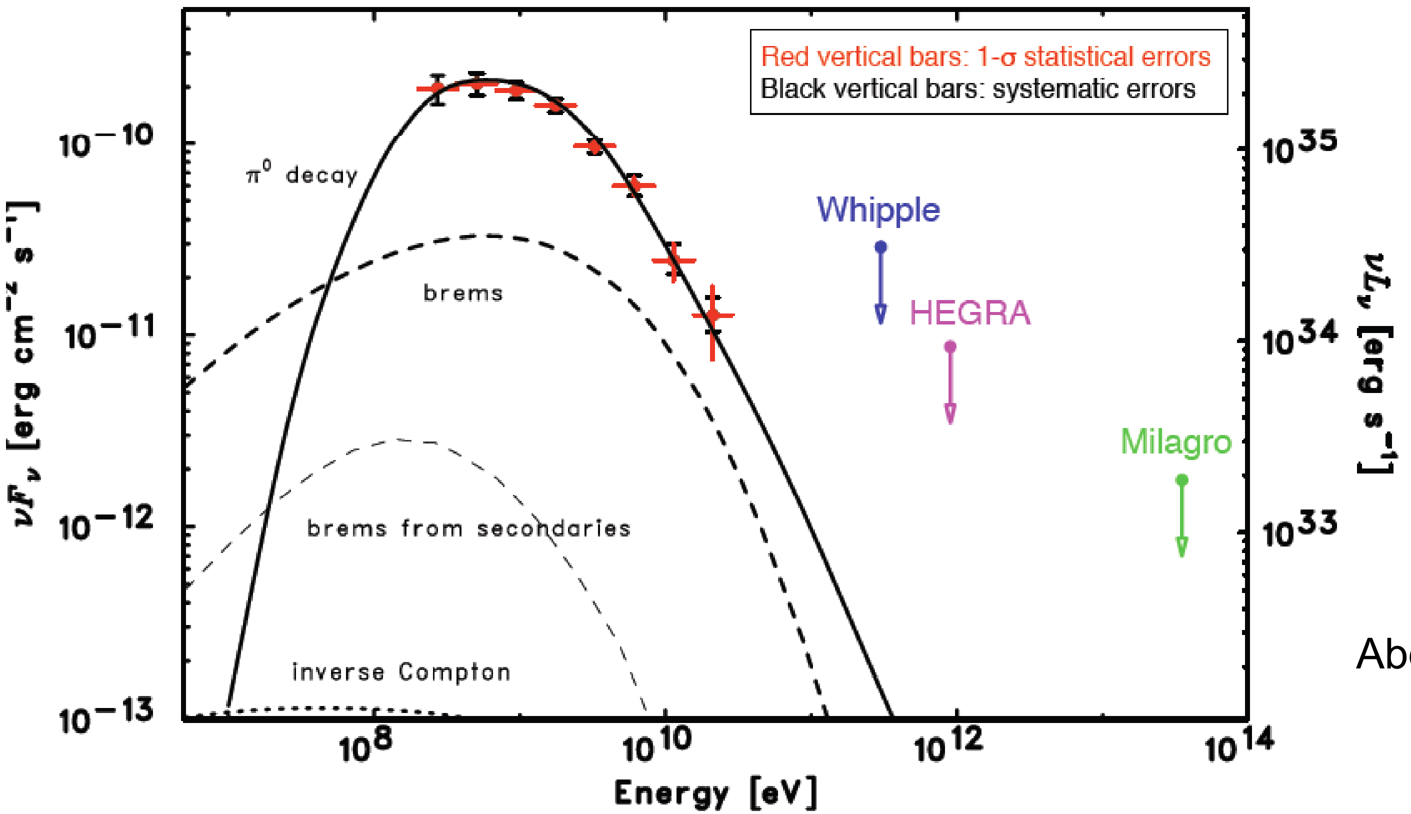
- **Age 20000 yrs**
- **D ~ 3 kpc**
- **35’x26’**
- **Cloud-shell interactions**
  - CO
  - OH maser
  - Mid-IR (shocked H2)



- **LAT detection**
  - Extended emission
  - Ring-like morphology
  - PSR B1853 negligible

Abdo+10

W44 spectrum



Abdo+10

Spectral break/steepening around a few GeV

Hadronic model : works well

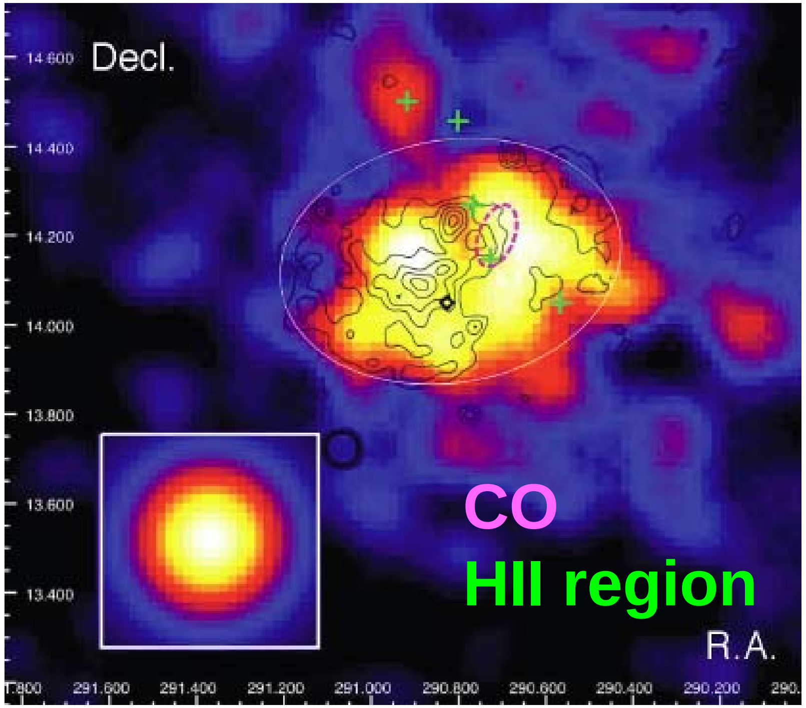
Leptonic model :

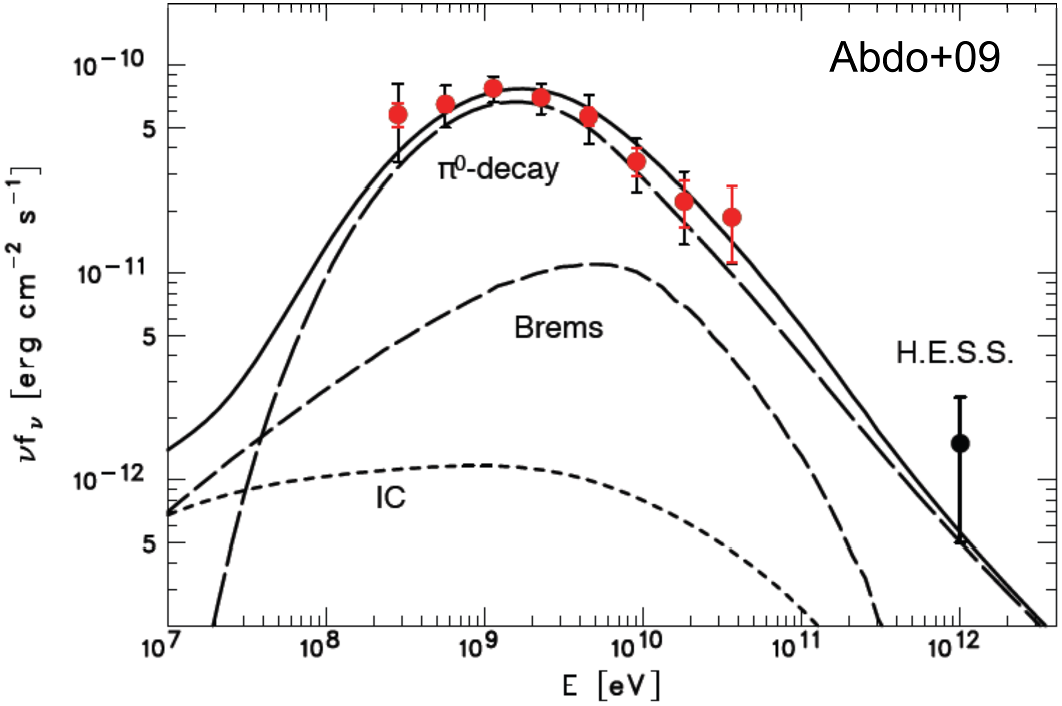
− bremsstrahlung can't reproduce radio

− IC requires 1E+51 erg electrons

W51C

- **Age 30000 yrs**
- **D ~ 6 kpc**



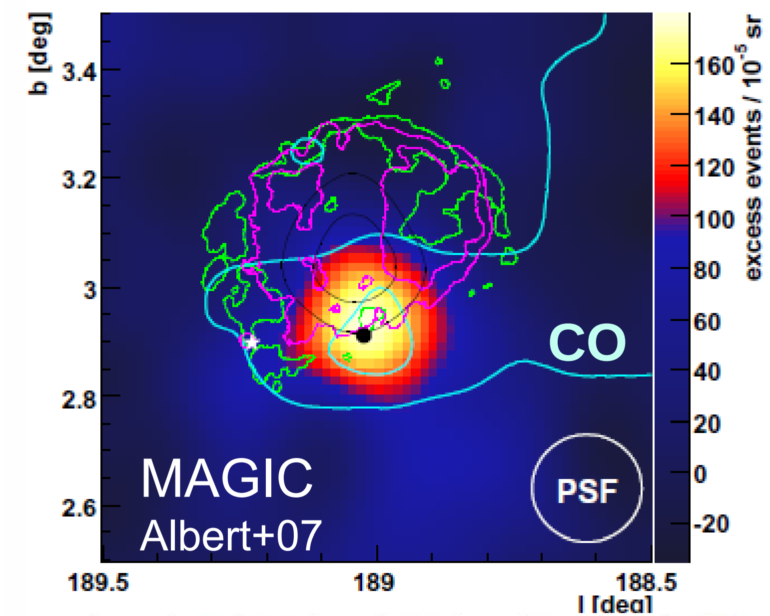


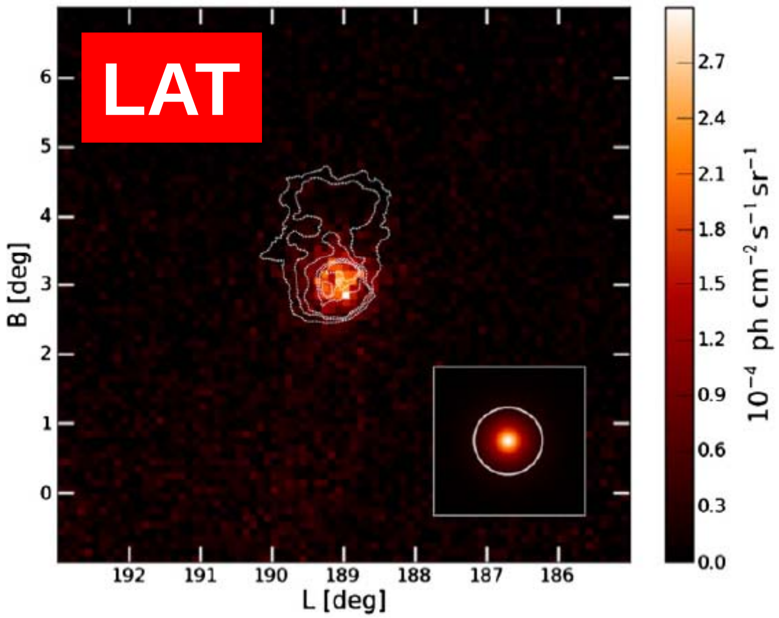
Spectral steepening

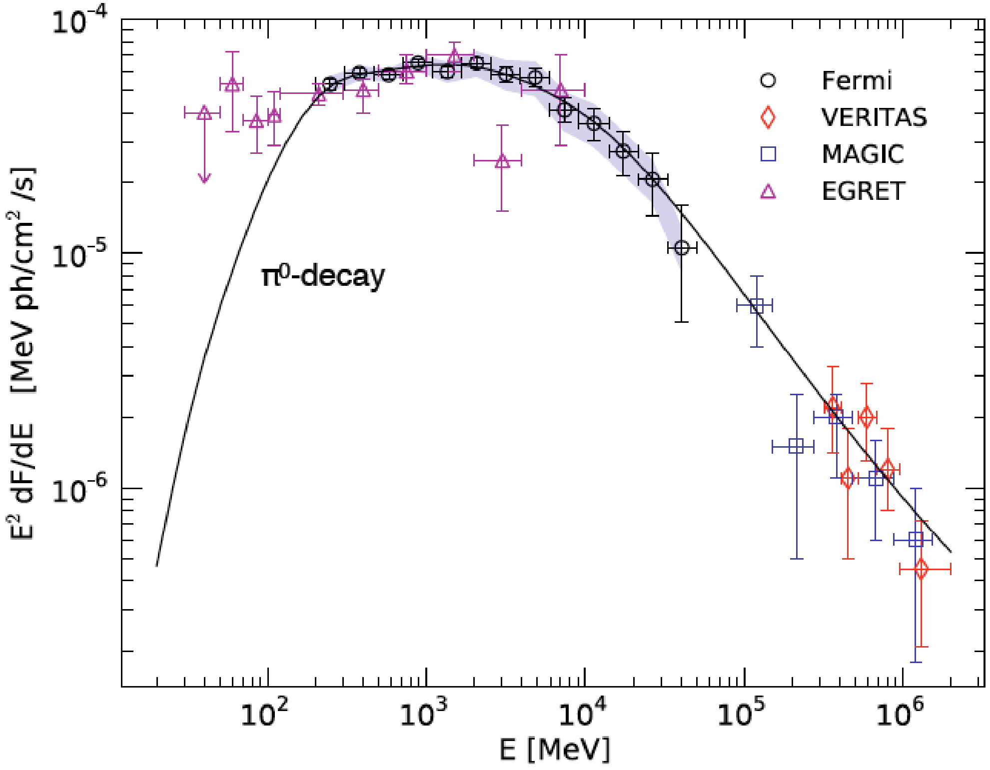
Hadronic model : works well

Leptonic model : not favored as well as W44

IC 443







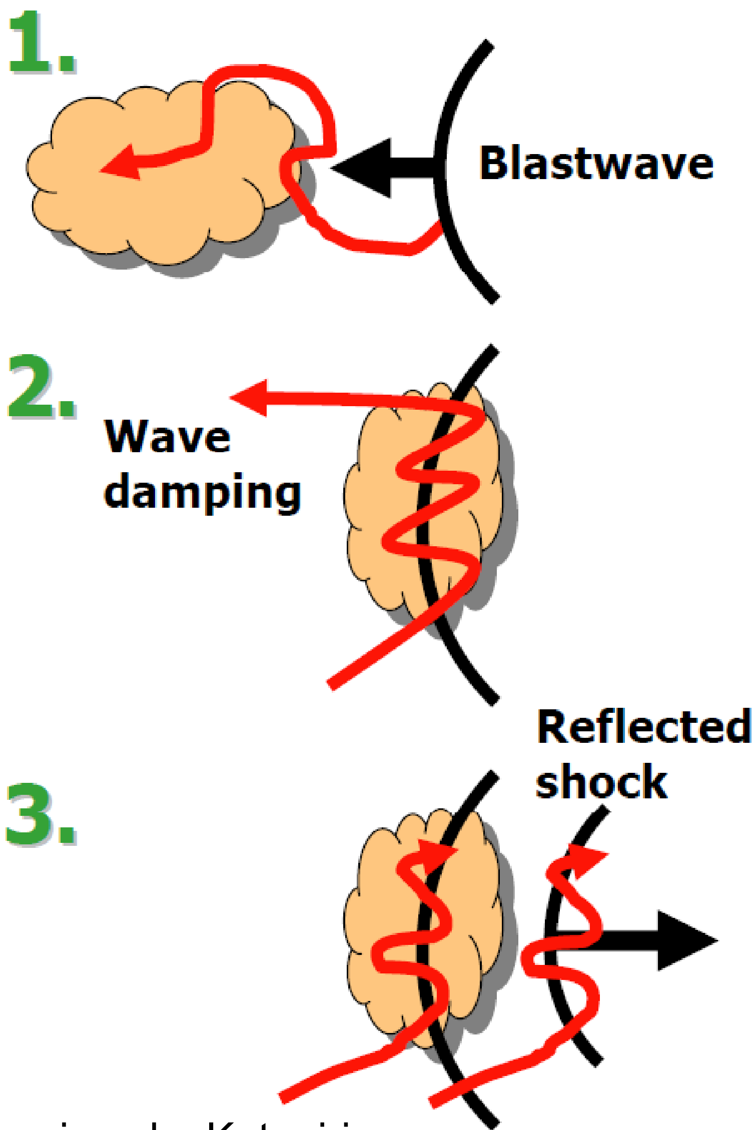
Spectral steepening

Hadronic model : works well

Abdo+10

Spectral steepening is a common feature among mid-aged SNRs interacting with MC

Origin of spectral steepening



Drawings by Katagiri

Possible explanations:

1. **CR diffusion to dense clouds : Runaway CRs** (e.g., Ohira+10)

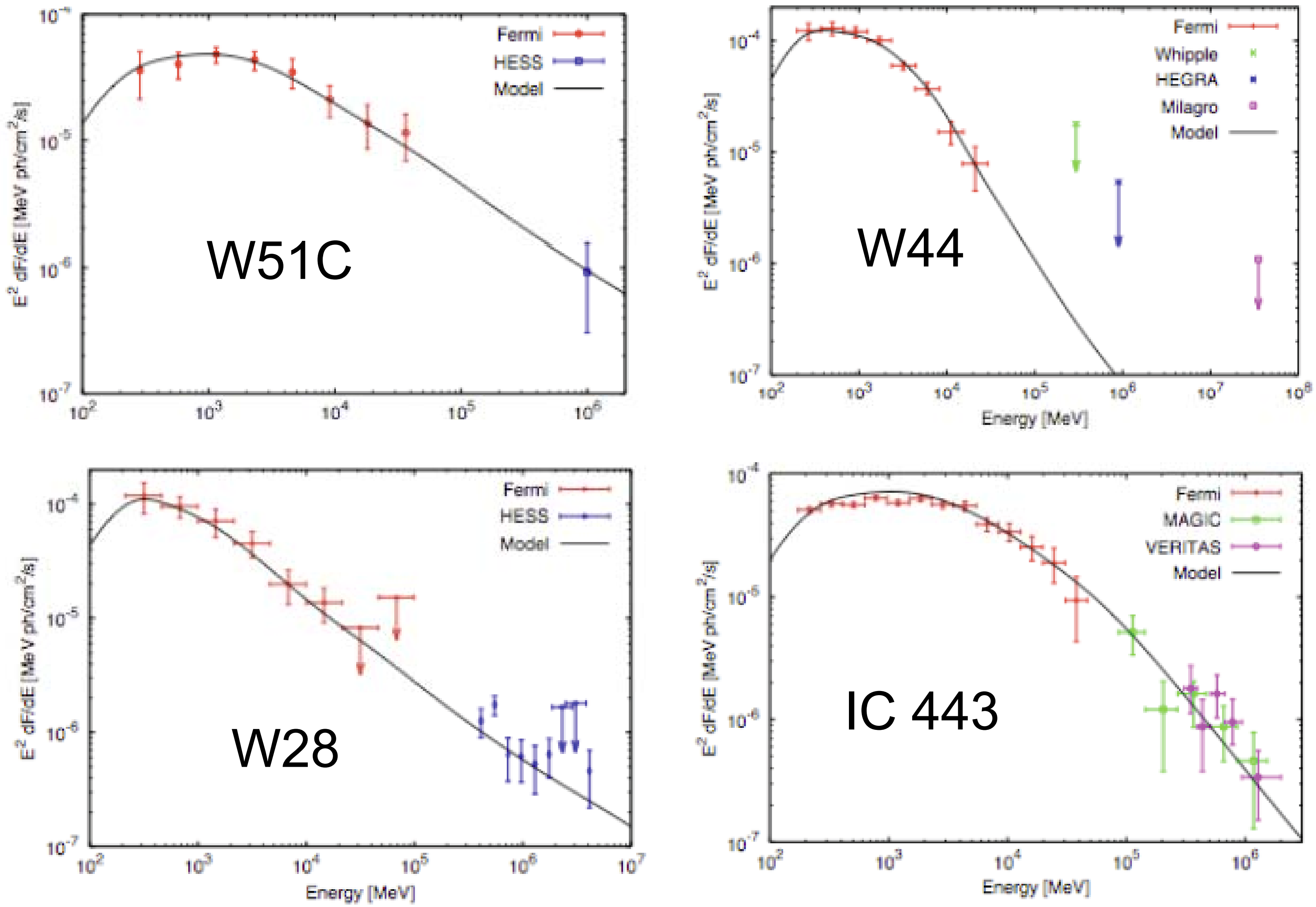
2. **Re-acceleration at a radiative cloud shock with wave damping** due to strong ion-neutral collisions : **Crushed cloud model** (Uchiyama+10).

3. **Further accelerations at multiple reflected shocks** (Inoue+10)

Studying SNRs with large apparent sizes can help to disentangle the origin of the spectral features from the difference of gamma-ray bright regions among the models

Runaway CR model

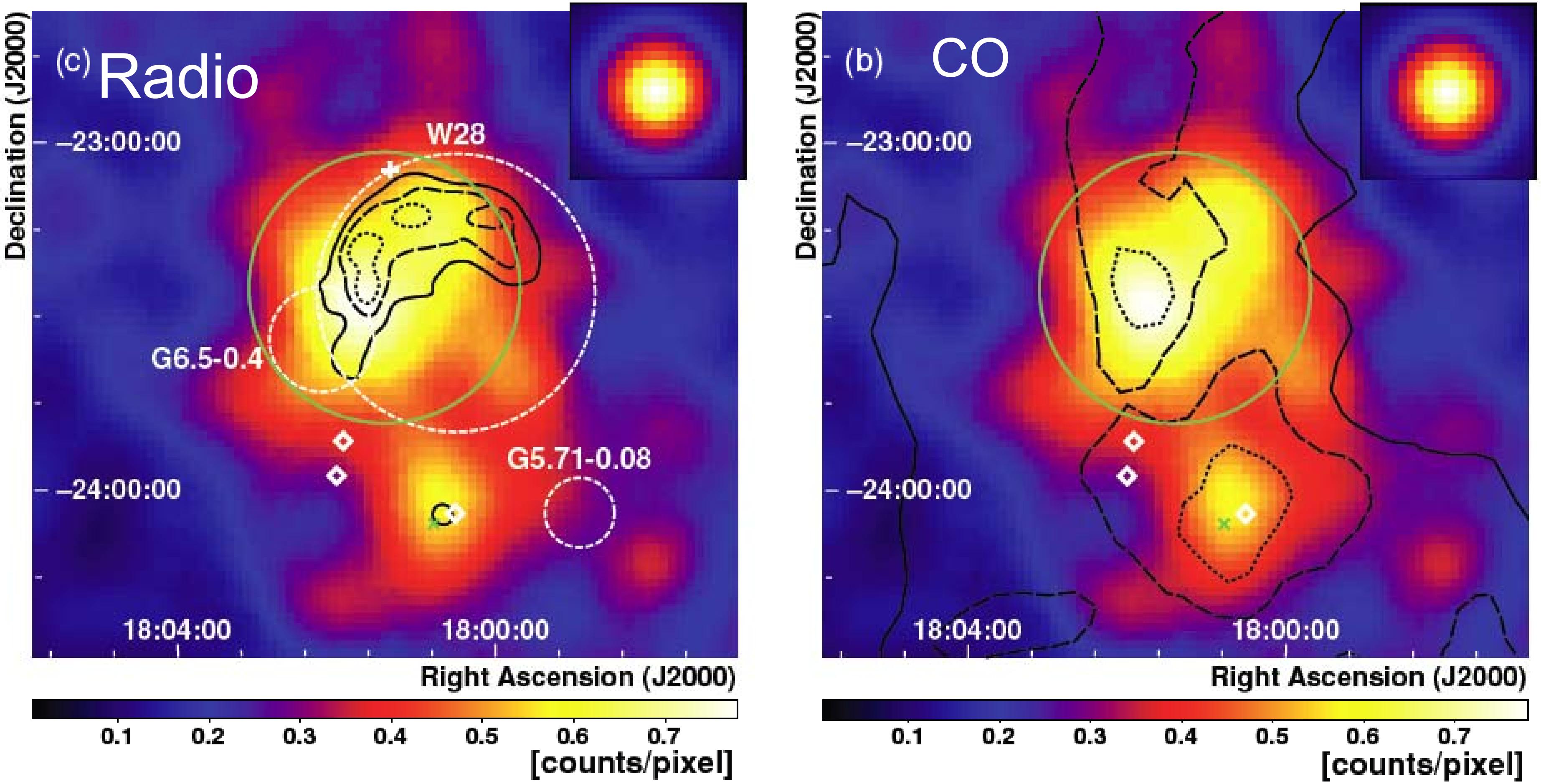
Ohira+10



Works well, but do they fully explain radio brightness ?

W28 could be the case

Abdo+11

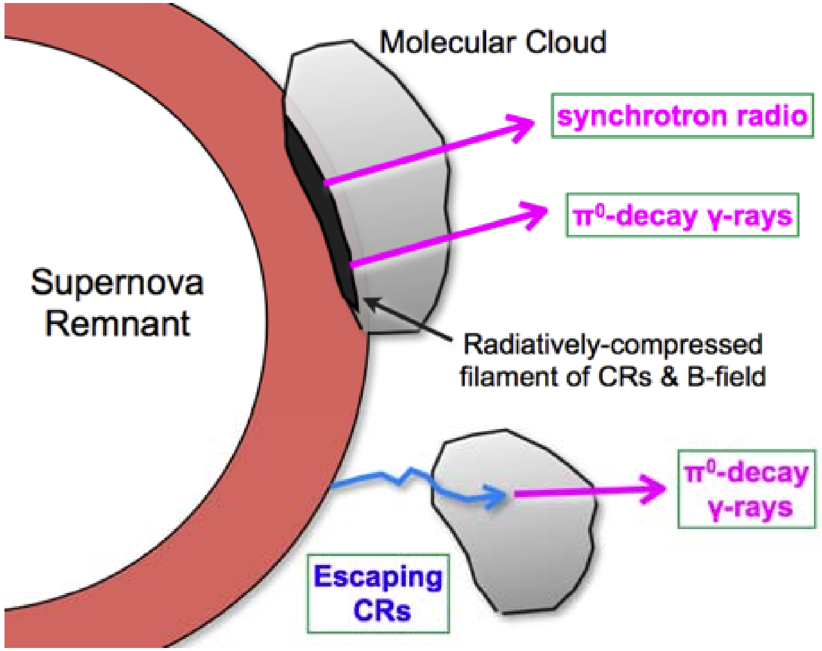


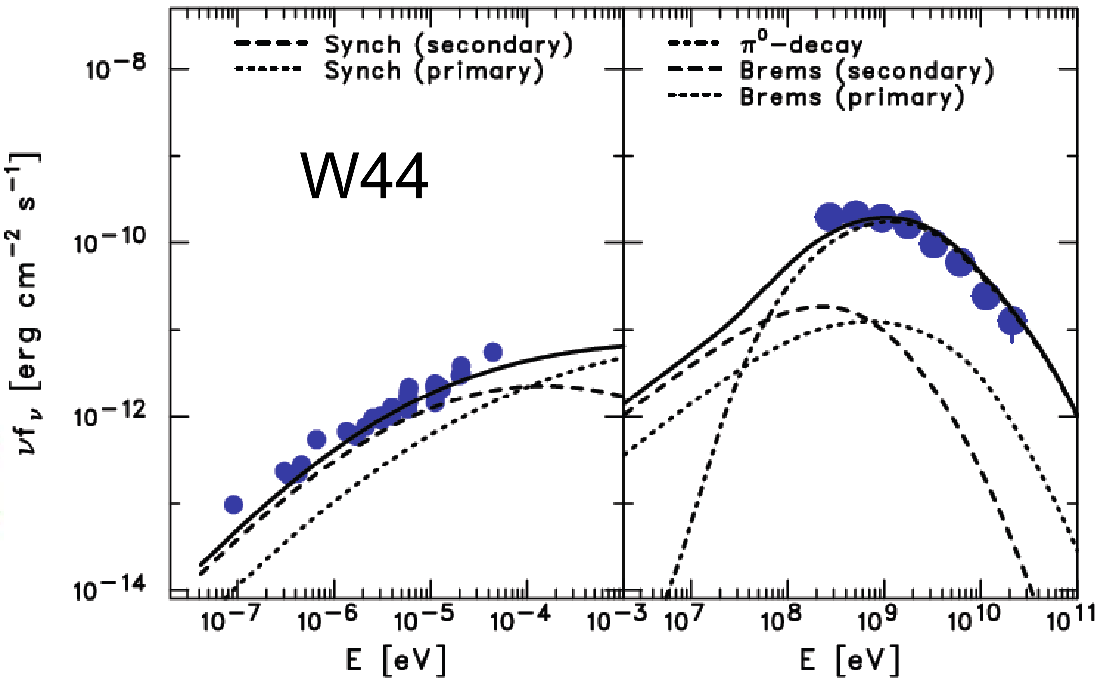
Southern excess correlates not with the radio shell but with MC

Though we don't know whether the distance is consistent

Crushed Cloud Model

Uchiyama+10



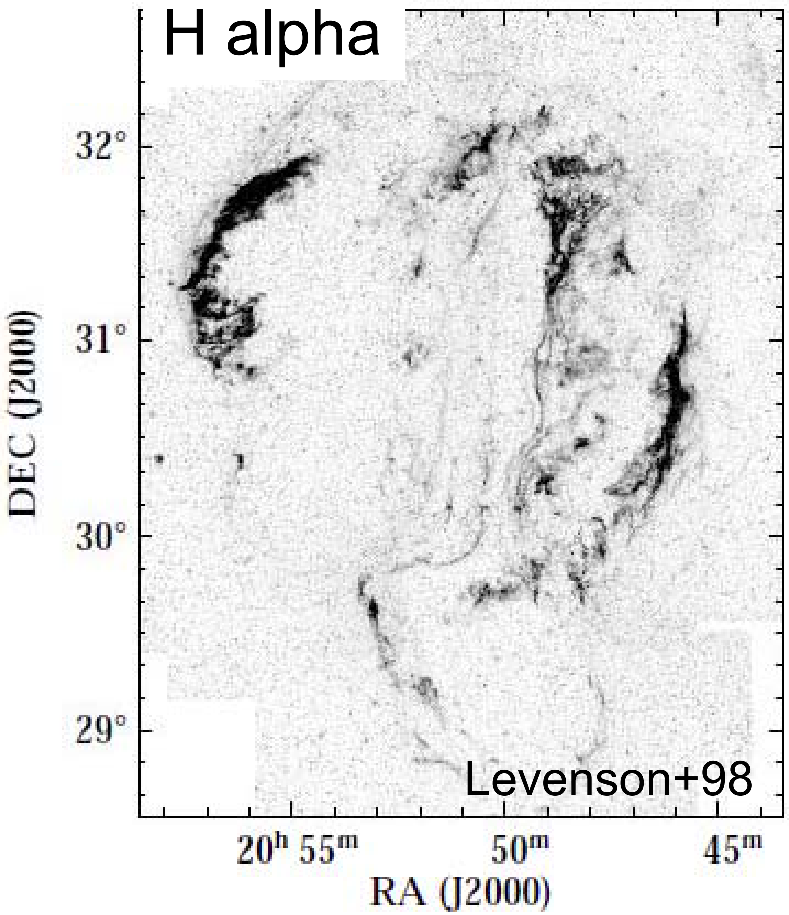


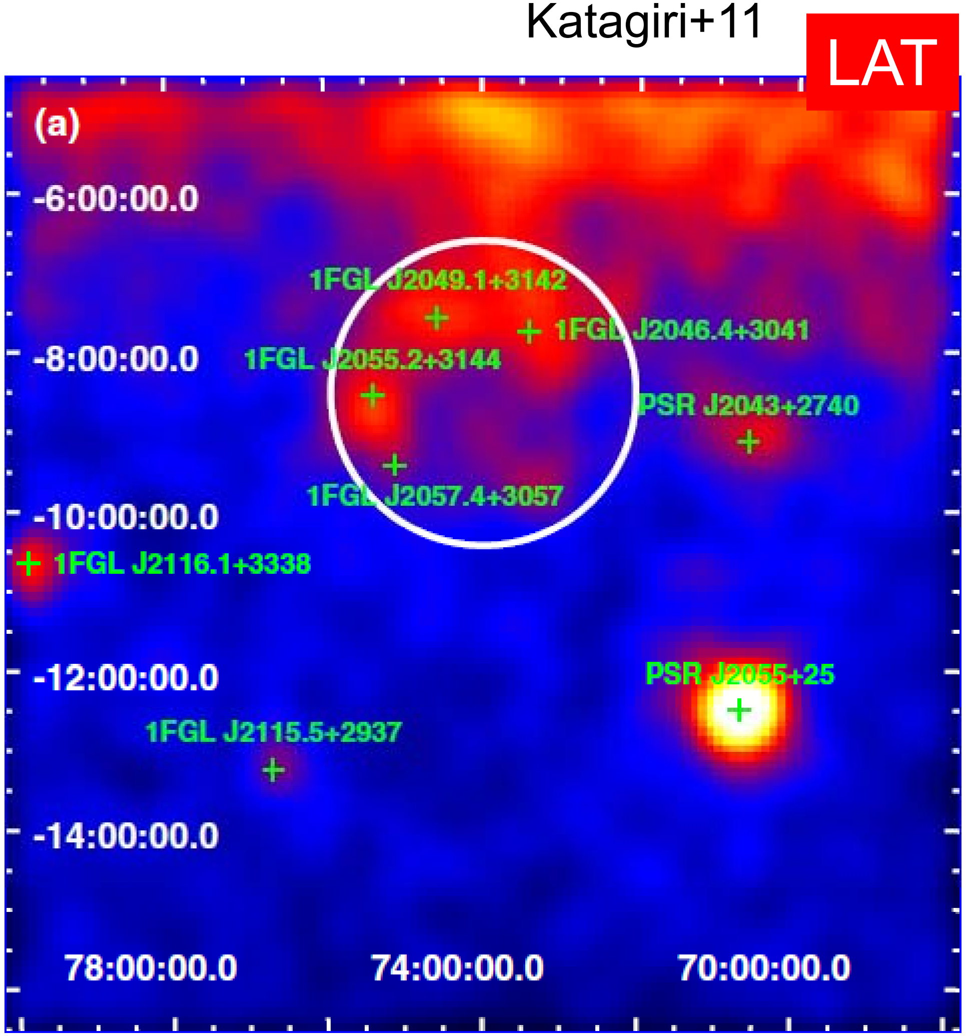
Re-acceleration of Galactic cosmic-rays at cloud shocks explains both radio and gamma-ray fluxes

GeV break may be related to Alfven wave evanescense

Cygnus Loop

Katagiri+11

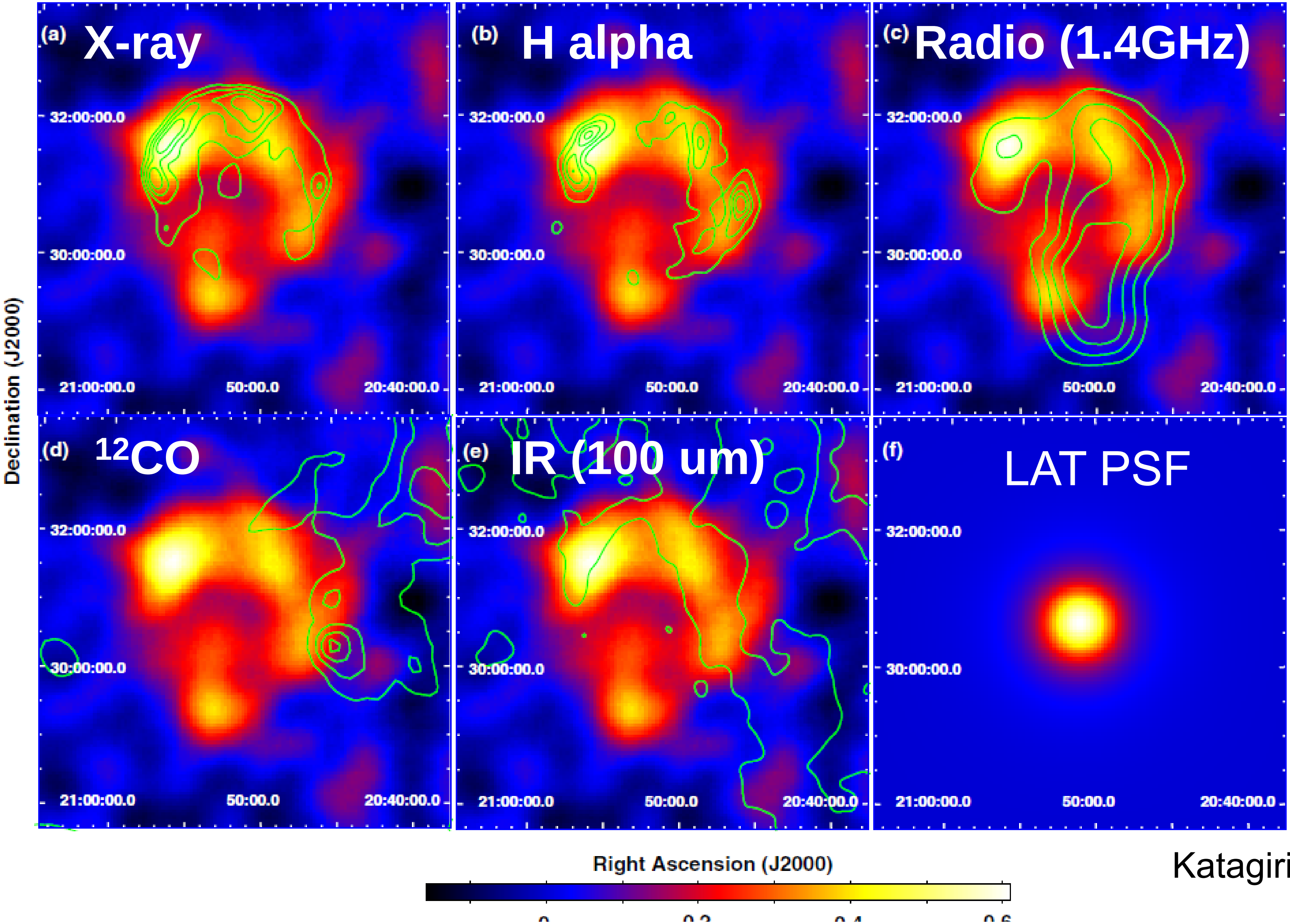




- **Age 20000 yrs**
- **R ~ 1.5 degree**
- **No MC correlation**

- **4 point sources are cataloged**
- **Offset from the Galactic plain**

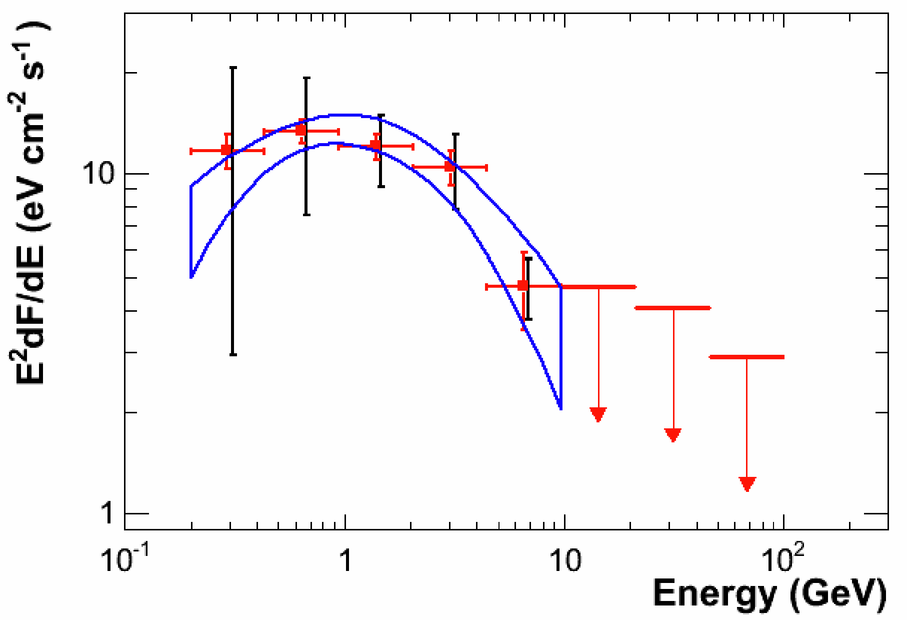
Comparison with MW images

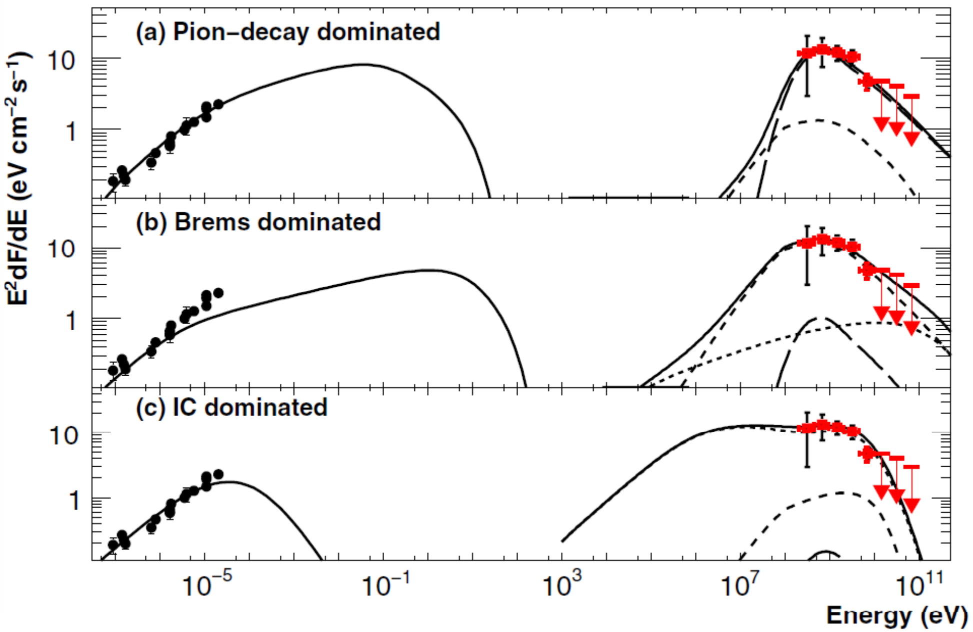


Katagiri+11

Cygnus loop spectrum

Katagiri+11





Spectral steepening as well

Hadronic model : interaction with ISM (n ~ 5 /cc) naturally reproduce the observatons

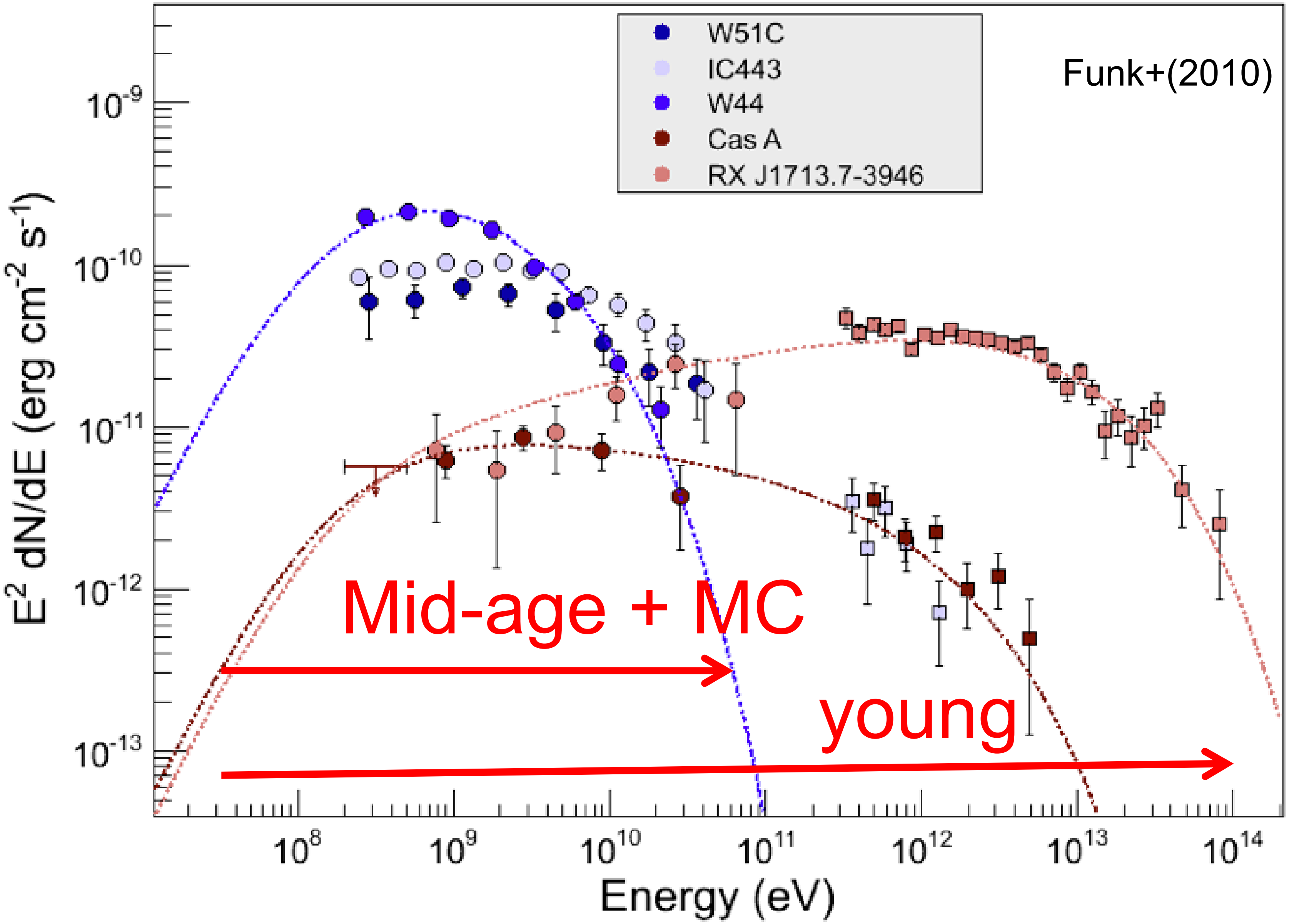
Leptonic model : IC requires n~0.02 and B~2 uG

Emission region and scenarios

Katagiri+11

- **Correspondence among gamma rays, H alpha and X-rays**
  – CRs responsible for gamma-ray emission are localized near the acceleration site
- **Lack of association with dense MCs**
  – CRs are localized near the acceleration sites without significant diffusion
    – Runaway model excluded by morphology
  – Multiple reflected shock model (Inoue+11) might operate since such shocks observed in X/Opt despite dense MC
  – Crushed cloud model may work, though expected fillamental structure is not resolved in gamma-rays

Spectra comparison



SNR detection summary

Young

Middle-aged

Probable Molecular Cloud Interaction

Fermi-detected SNRs	Index [1]	Index 2	E_{Break} (GeV)	Age (yrs)
Casssiopeia A	−2.1 ±0.1	-2.4 ± 0.2**	>100	330
Tycho	−2.3 ± 0.1	-2.0 ± 0.5**	---	438
Vela Jr.	-1.9 ± 0.2	-2.1 ± 0.2**	---	680
RX J1713	-1.5 ± 0.1	-2.2 ± 0.1**	---	1600
Puppis A	-2.0 ± 0.1	---	---	3700
W49B	−2.18 ± 0.04	−2.9 ± 0.2	4.8 ± 1.6	1k-4k
CTB 37A	−2.28 ± 0.1	-2.3 ± 0.3**	---	1500?
3C391	−2.35 ± 0.16	---	---	7k
G349.7+0.2	−2.0 ± 0.1	---	---	14k
Cygnus Loop	-1.83 ± 0.06	-3.23 ± 0.2	2.4 ± 0.3	20k
IC 443	−1.93 ± 0.03	−2.56 ± 0.1	3.3 ± 0.6	3-4k or 20-30k
W30	−2.1 ± 0.1	−2.7 ± 0.1	2.4 ± 1.2	25k
W44	−2.1 ± 0.1	−3.0 ± 0.2	1.9 ± 0.5	20-40k
W51C	−1.97 ± 0.08	-2.44 ± 0.09	1.9 ± 0.2	~30k
S147	−1.4 ± 0.5	-2.5 ± 0.2	1.8 ± 0.8	30k
W28 (N) (and G6.5-0.4)	−2.09 ± 0.36	−2.74 ± 0.15	1.0 ± 0.2	35-150k (40k)

[1] for Power Law or i_1 for Broken Power Law **from VHE measurement

T. Brandt

Summary

- Fermi LAT is operating well over 3 years
- 30% of 2FGL catalog sources remain their nature uncertain
- MW observations is really a powerful tool to probe such objects
  - Several interesting sources do exist !
- LAT has identified 16 SNRs
  - LAT observation triggered theoretical studies
  - “Spectral shape” is not enough
- Pion bump should critically constrain the modelings.
  - We’ll soon explore E<100 MeV with reliable analysis.