Pulsar Wind Nebulae as seen by Fermi-Large Area Telescope

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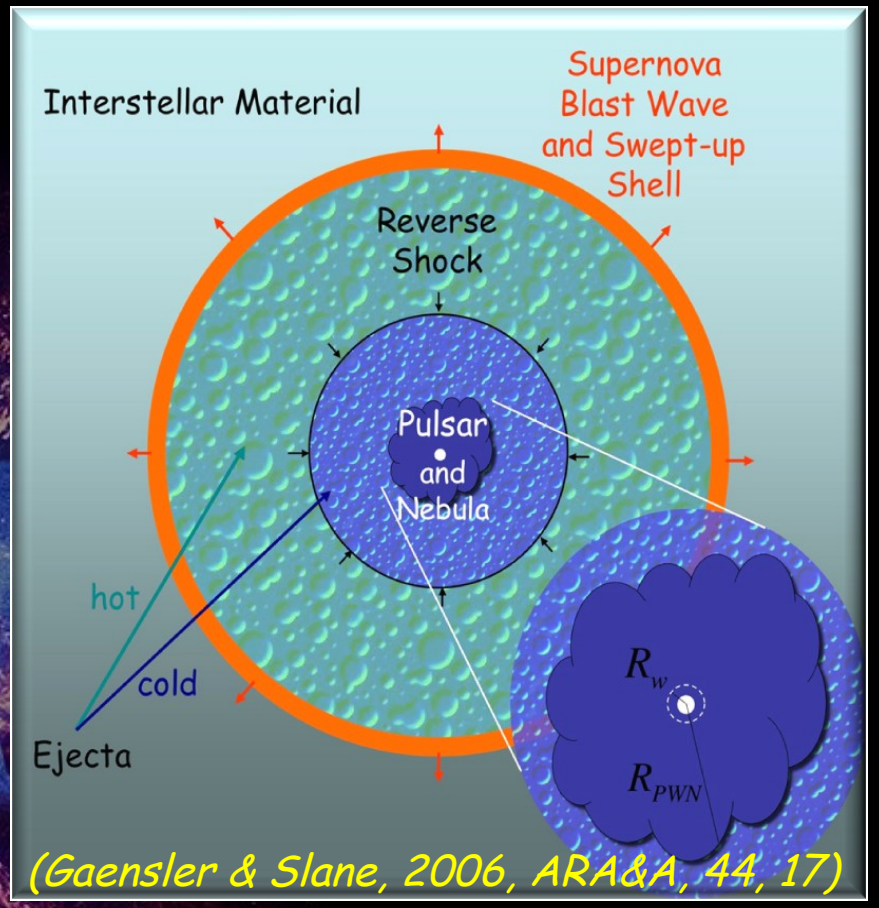
Pulsar Wind Nebulae (PWNe)

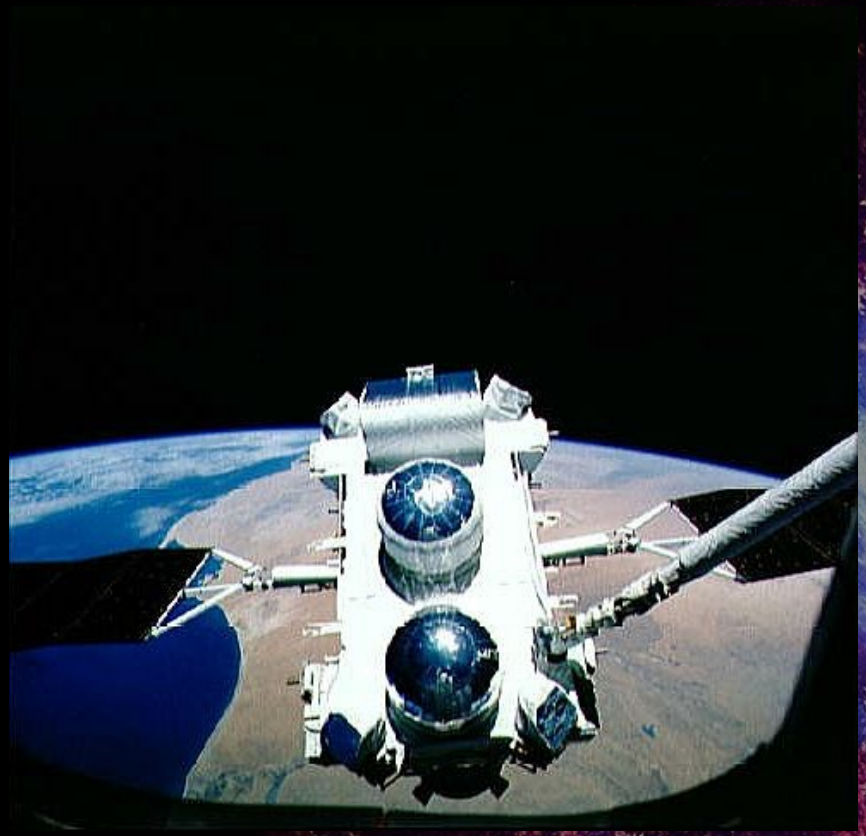
- Pulsar Wind Nebulae :
  - Relativistic particles ($e^{\pm}$) injected by the central pulsar
  - Ejecta of the supernova sweeps up
  - Flow decelerated at the shock
  - Particles accelerated at the shock (Diffusive Shock Acceleration)
  - Non-thermal photons emitted by :
    - ✓ Synchrotron
    - ✓ Bremsstrahlung
    - ✓ Inverse Compton scattering (leptonic scenario)
    - ✓ Pion decay (hadronic scenario)



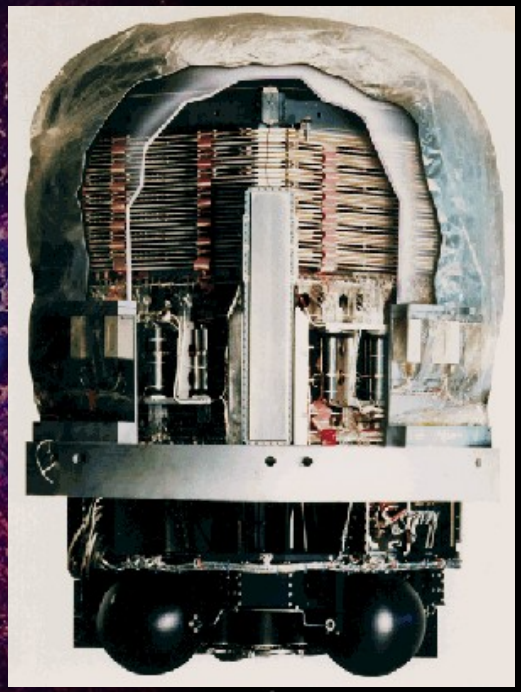
(Gaensler & Slane, 2006, ARA&A, 44, 17)

- High energy observations can help constraining the properties of the PWN (age, injection spectrum, maximum particle energy and breaks, nebular magnetic field, ambient photon field, etc.)

CGRO-EGRET (1991-2000)

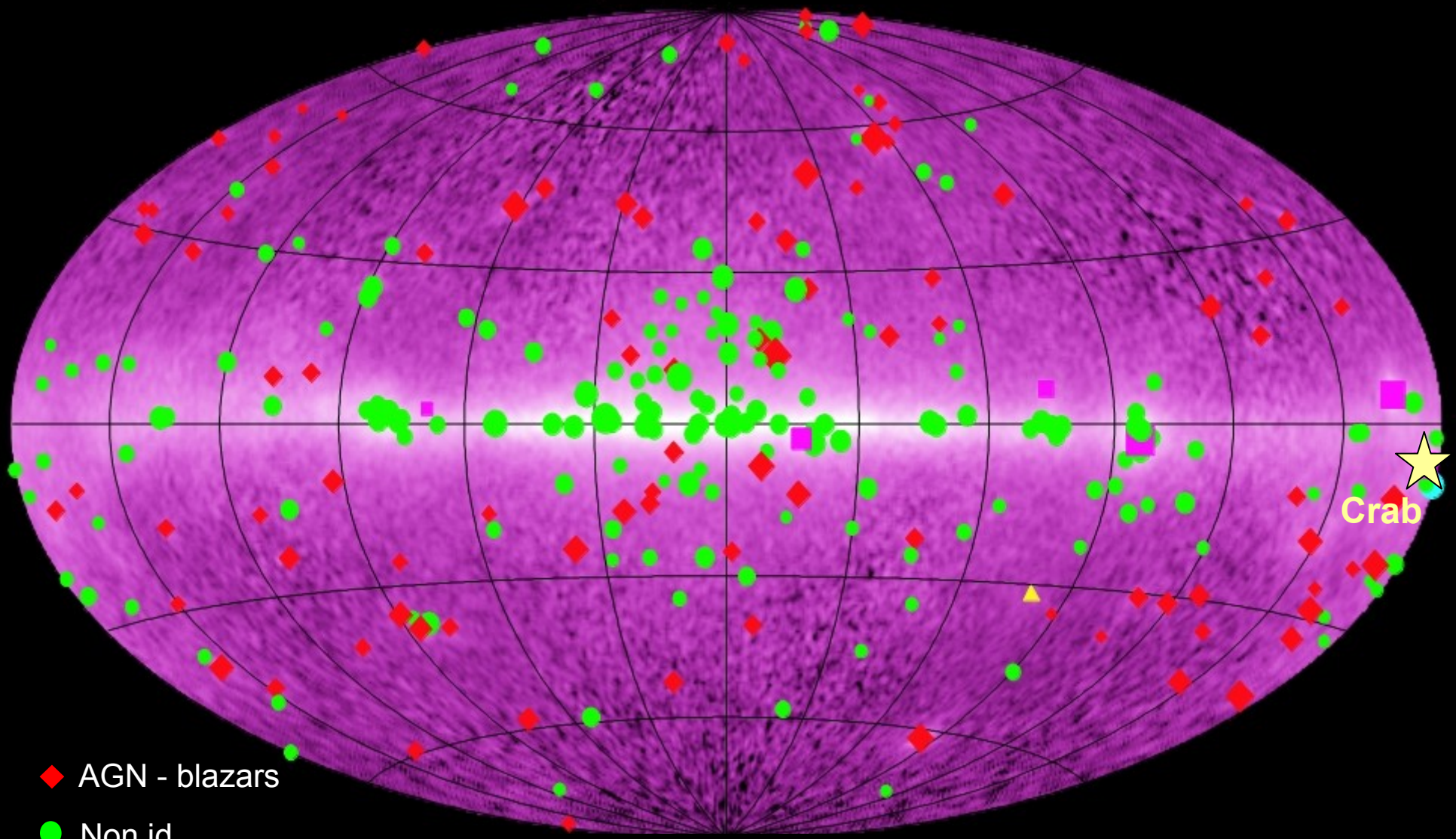


Compton Gamma-Ray Observatory (CGRO)
(Credit: NASA)



Energetic Gamma-Ray Experiment Telescope (CGRO-EGRET)
20 MeV-30 GeV
(Credit : NASA)

The γ-ray sky before *Fermi*



- AGN - blazars
- Non id.
- pulsars
- LMC

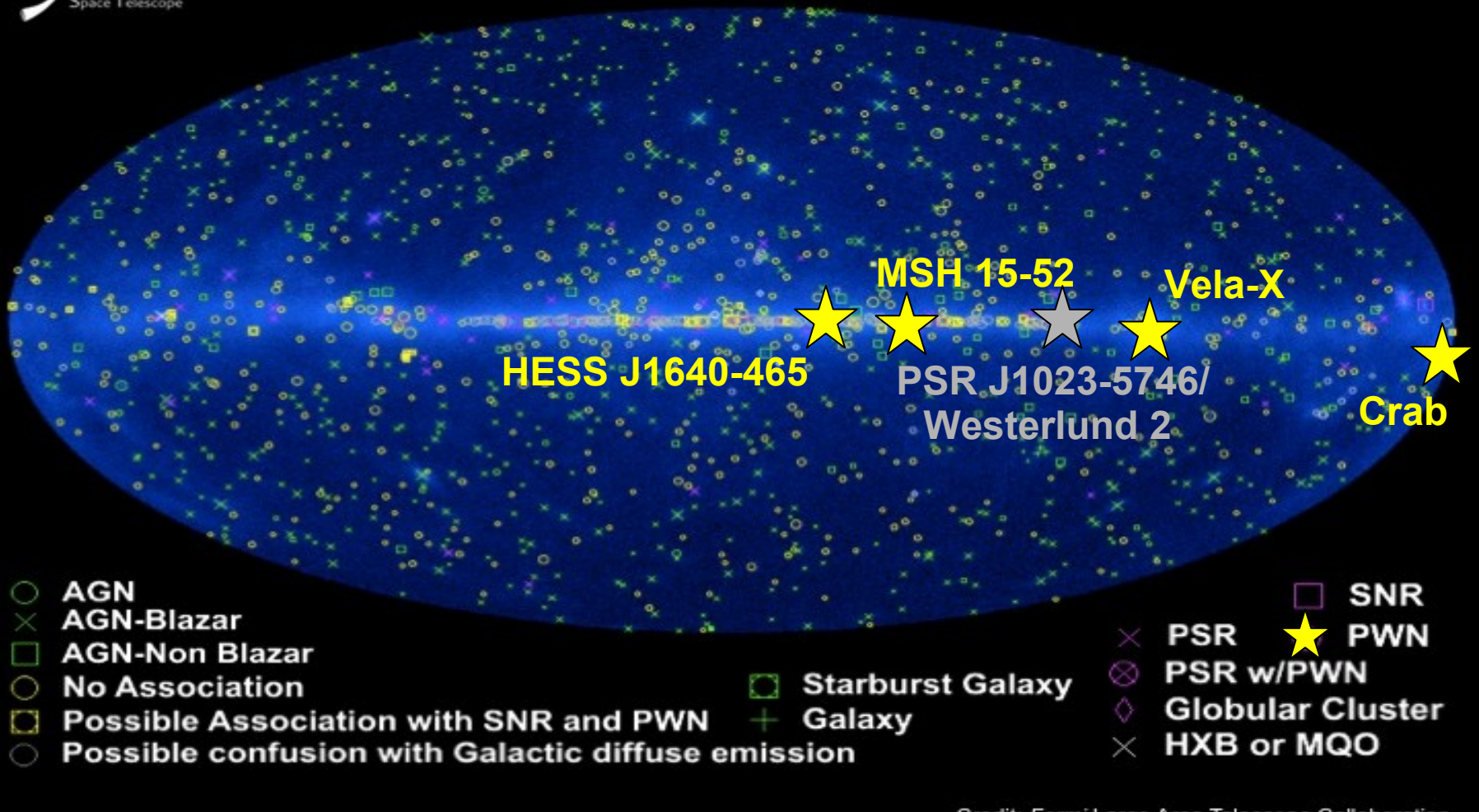
EGRET All-sky Gamma-Ray Survey above 100 MeV

(de Jager et al, 1996, ApJ, 457, 253)

Fermi-LAT 1-year catalog

(Abdo et al, 2010, ApJS, submitted, arXiv:1002.280)

4 firmly identified PWNe and a PWN candidate !



1451 sources detected between 100 MeV and 100 GeV with TS > 25

(http://fermi.gsfc.nasa.gov/ssc/data/access/lat/1yr_catalog/)

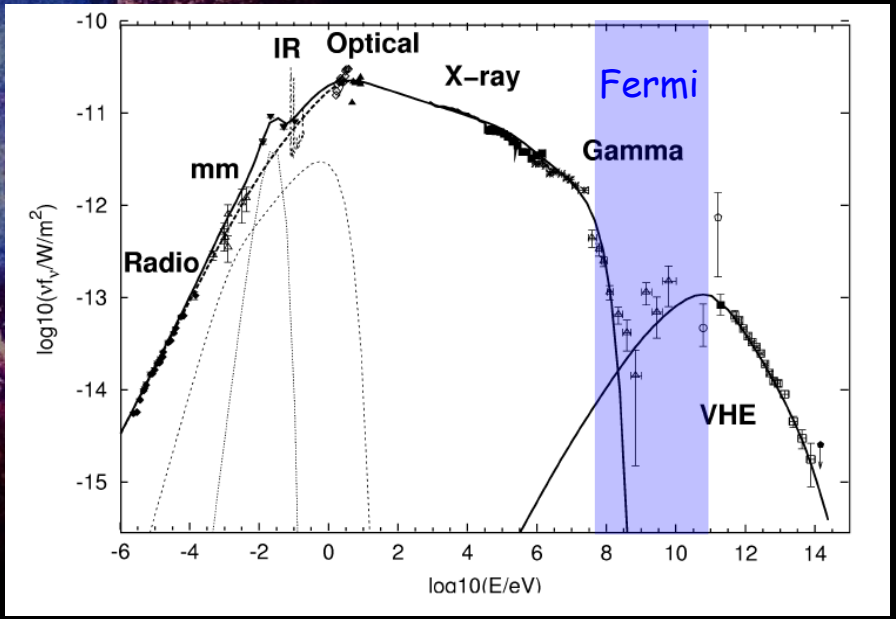
The Crab Nebula

- Pulsar Wind Nebula G184.6-5.8 aka Crab Nebula, powered by the Crab Pulsar (B0531+21, $dE/dt = 4.6 \times 10^{38}$ erg/s)
- No SNR shell detected
- Distance = (2.0 ± 0.2) kpc, characteristic pulsar age = 1240 yr
- Spectrum of the nebula spanning 21 decades in frequency, from radio to ~80 TeV, emission predominantly by non-thermal processes

Earlier γ-ray observations of the Crab Nebula

- EGRET observations of the synchrotron/Inverse Compton spectrum in the 70 MeV – 30 GeV energy band *(De Jager et al., 1996, ApJ, 457, 253)*:
  - Large uncertainties on the spectrum shapes for both components
  - Variability observed at 3.1σ level below 150 MeV
  - no cut-off detected for the inverse Compton component

- MAGIC observations above 60 GeV *(Albert et al, ApJ, 674, 1037, 2008)*:
  Inverse Compton peak energy estimated at (77 ± 35) GeV



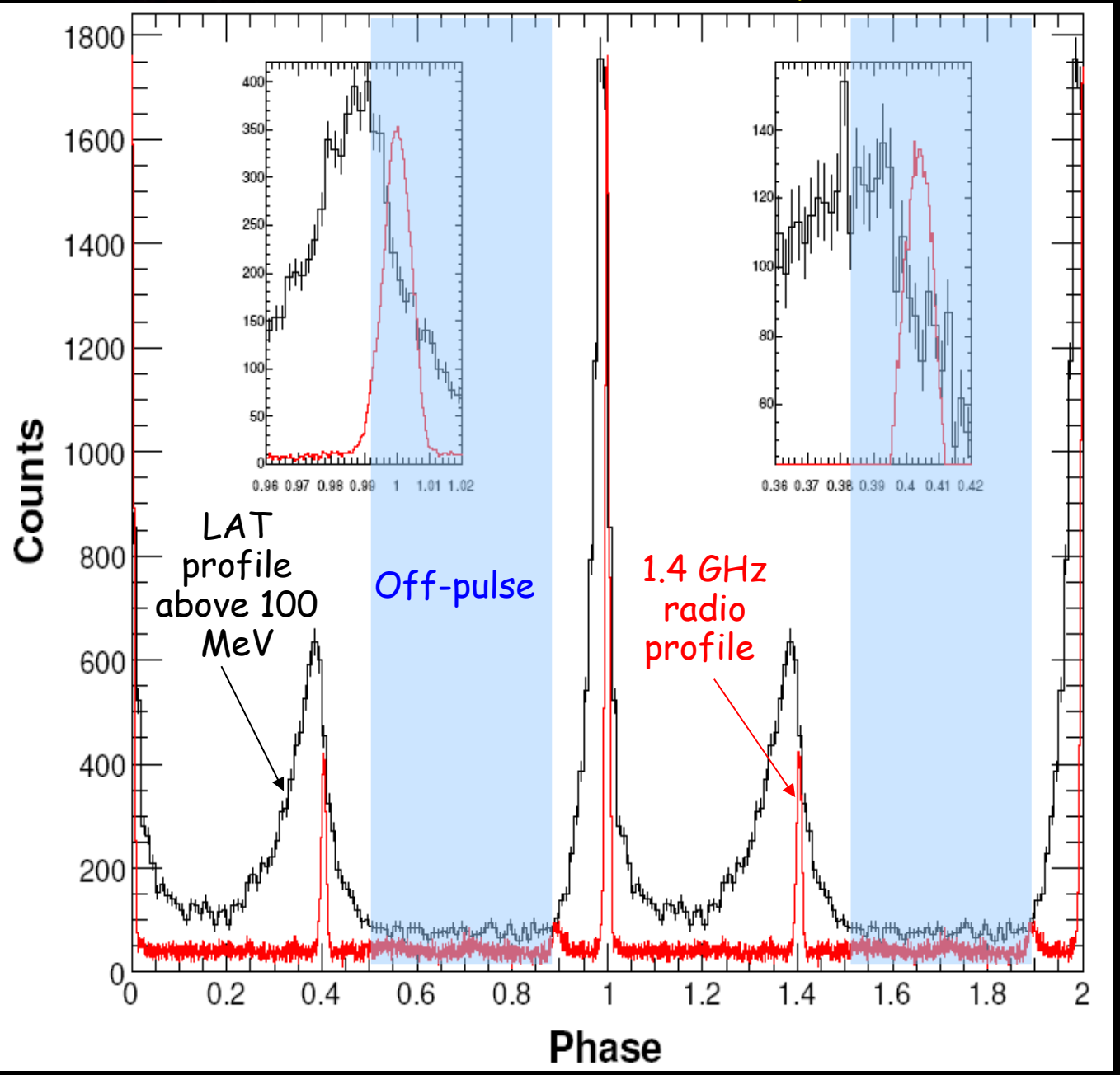
Spectral energy distribution of the Crab Nebula (Horns & Aharonian, ESAPS 552:439, 2004)

LAT Observations of the Crab Pulsar and Nebula

(Abdo et al., 2010, ApJ, 708, 1254)

The following studies were performed with 8 months of data in survey mode

Light curve of the Crab Pulsar. Two cycle are shown.

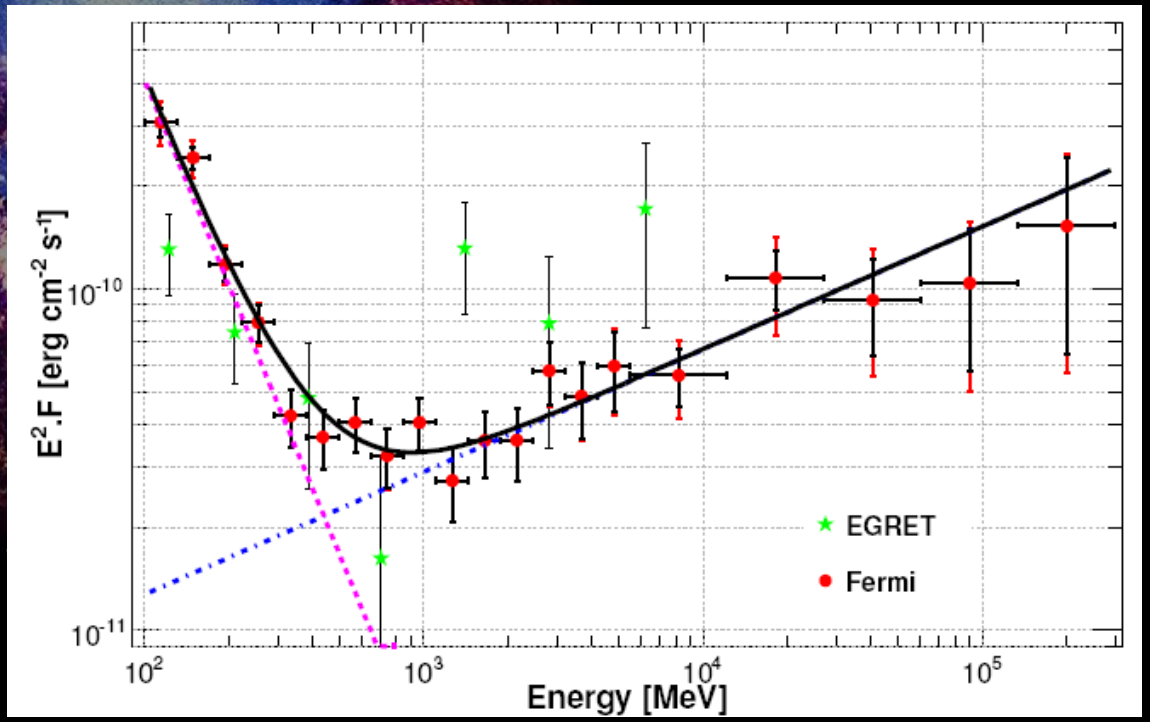


LAT Observations of the Crab Pulsar and Nebula

(Abdo et al., 2010, ApJ, 708, 1254)

- Spectral analysis of the nebula :
  - Performed in the off-pulse window
  - Synchrotron and inverse Compton (IC) components are resolved :
    - Spectral index (sync) = (3.99 ± 0.12 ± 0.08)
    - Spectral index (IC) = (1.64 ± 0.05 ± 0.07)
    - Flux above 100 MeV = $(9.8 \pm 0.7 \pm 1.0) \times 10^{-7}$ cm^{-2} s^{-1}
  - No significant cut-off and variability can be observed, neither for the synchrotron nor for the IC component with 8 month of data in survey mode

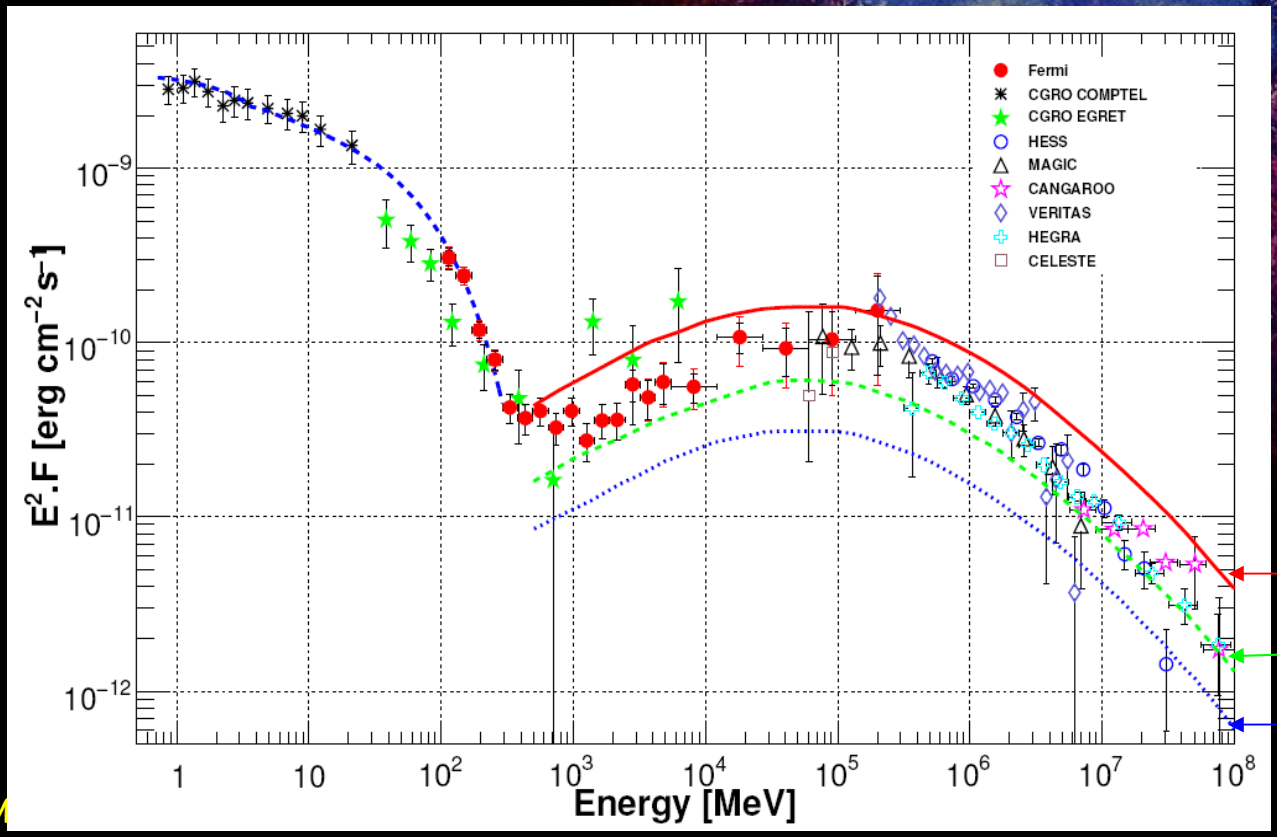
Spectral energy distribution of the Crab Nebula



LAT Observations of the Crab Pulsar and Nebula

(Abdo et al., 2010, ApJ, 708, 1254)

- Synchrotron component fit with COMPTEL + LAT => cut-off at ~100 MeV
- No cut-off seen with LAT data only for the IC component
- LAT high energy and Cherenkov spectra link up naturally
- Overlaying predictions of *Atoyan & Aharonian (1996, MNRAS, 278, 525)* for different mean magnetic fields, the results obtained by the LAT and ground based telescopes are consistent with 100 μG < B < 200 μG, indicating a magnetic field well beyond the equipartition field in the Crab nebula (300 μG)



Spectral enery distribution of the Crab Nebula.

100 µG

200 µG

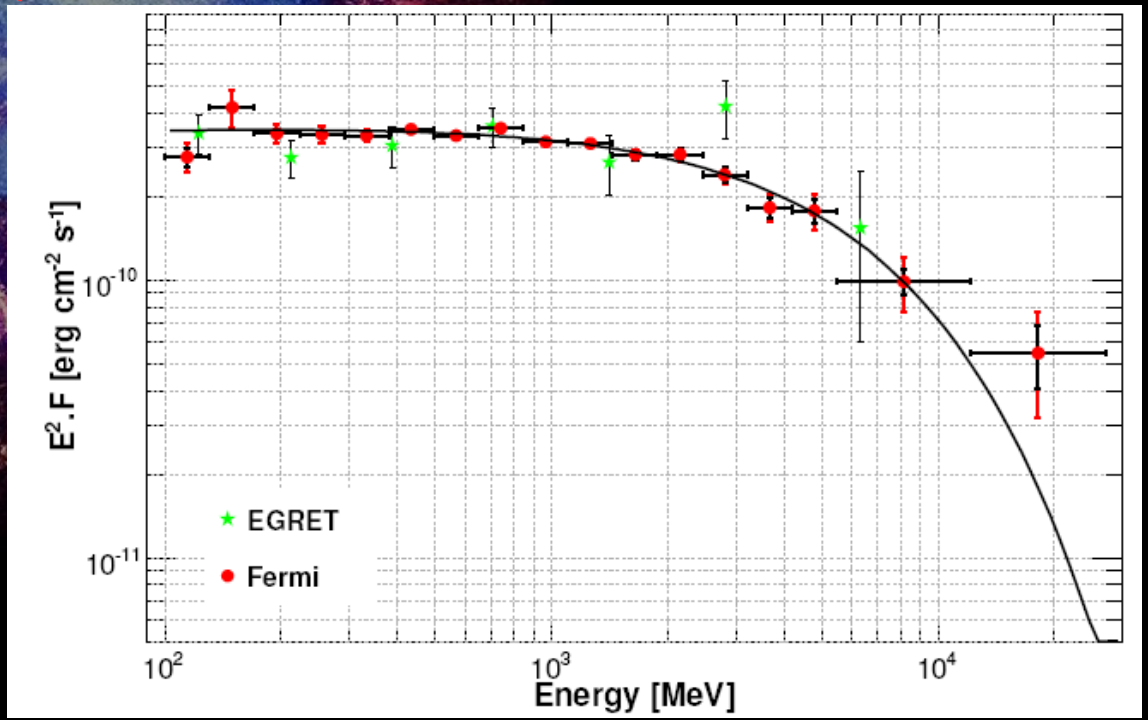
300 µG

LAT Observations of the Crab Pulsar and Nebula

(Abdo et al., 2010, ApJ, 708, 1254)

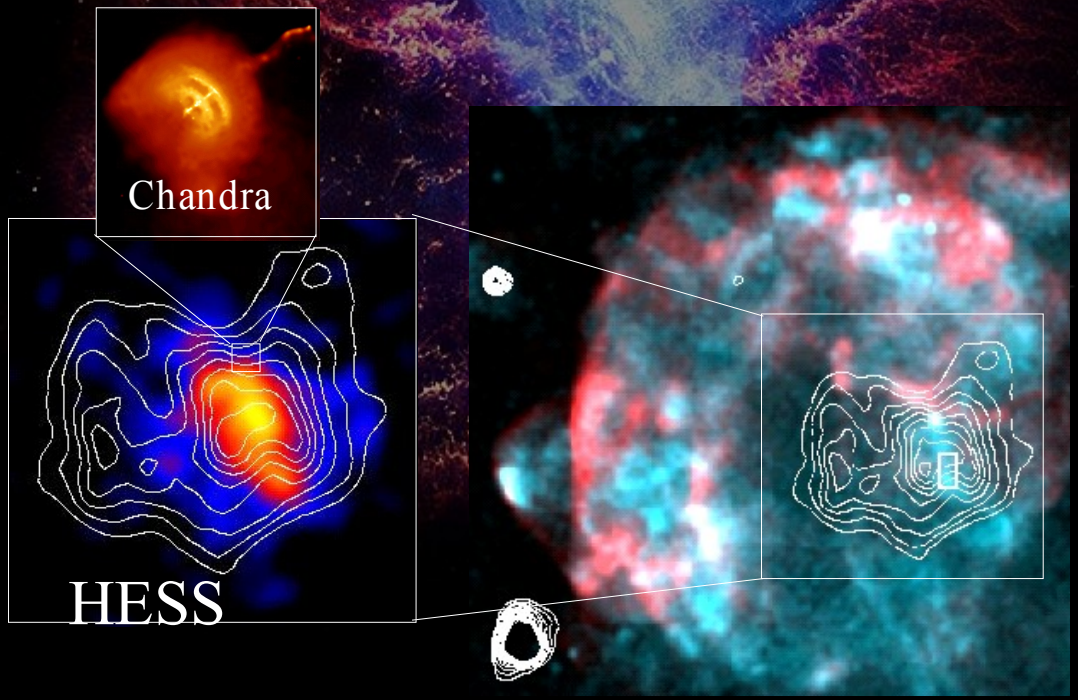
- Spectral analysis of the pulsar :
  - Performed on the whole pulse phase interval
  - Best fit above 100 MeV obtained with a power-law with an exponential cut-off :
    - Spectral Index = (1.97 ± 0.02 ± 0.06)
    - Cut-off energy = (5.8 ± 0.5 ± 1.2) GeV
    - Flux above 100 MeV = $(2.09 \pm 0.03 \pm 0.18) \times 10^{-6}$ cm^{-2} s^{-1}
  - Pulsed photons observed up to ~20 GeV : consistent with an emitting region well above the NS surface

Spectral energy distribution of the Crab Pulsar



Multi-wavelength observations of Vela X

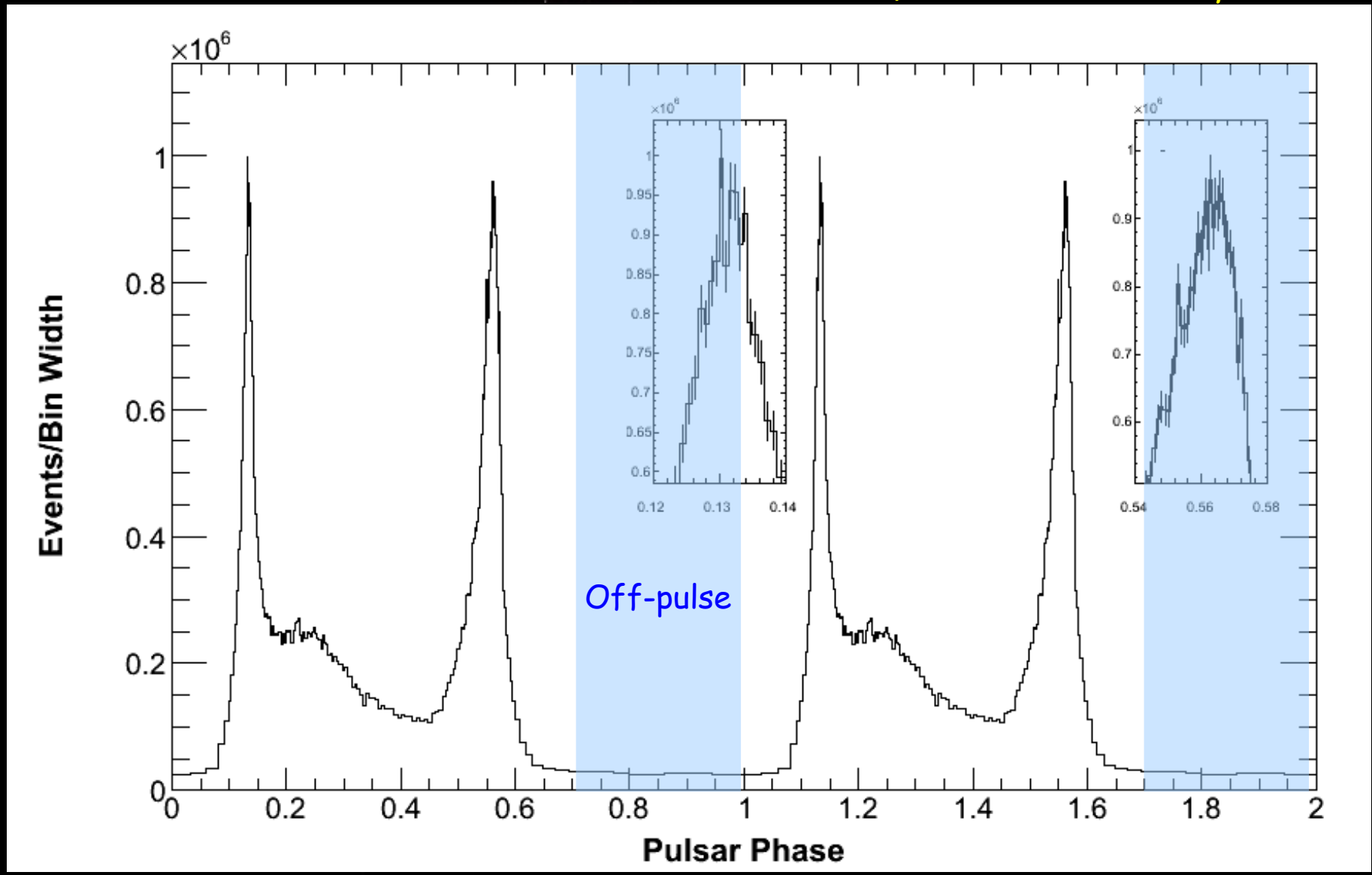
- Elongated cocoon-like hard X-ray structure extends southward of pulsar:
  - clearly identified by HESS as an extended VHE structure
  - this is not the pulsar jet (which is known to be directed to NW); presumably the result of reverse shock interaction
- Extended area (halo) of size 2°x3° (including the cocoon area) seen in radio
- An upper limit, assuming a point source at the position of Vela PSR, was reported using the first 75 days of Fermi data: $F(>100\ \mathrm{MeV}) < 4.5\times10^{-7}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ *(Abdo et al., 2009, ApJ, 696, 1084)*



Composite ROSAT-RASS image of Vela SNR with 8.4 GHz Parkes radio contours overlaid (LaMassa et al, 2008, ApJ, 689, L121)

The Vela Pulsar: Results from the First Year of *Fermi* LAT Observations

(Abdo et al., 2010, ApJ, 713, 154)

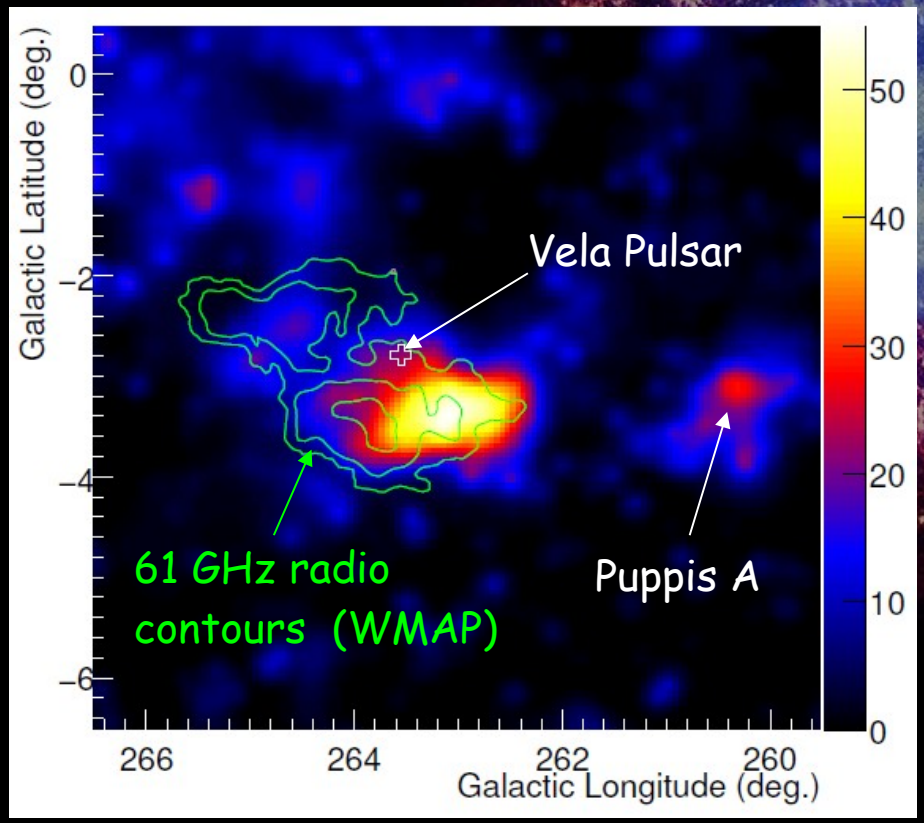


Fermi LAT light curve of Vela above 20 MeV. Two cycles are shown.

LAT Observations of Vela X (morphology)

(Abdo et al., 2010, ApJ, 713, 146)

- Study performed with 11 months of data in survey mode
- Bright emission South of the Vela pulsar + fainter emission to the East
- Gamma-ray complex lies within Vela-X (as seen in radio)
- Significantly extended : best fit above 800 MeV obtained with a uniform disk of radius 0.88°± 0.12°
- Additional source coincident with the SNR Puppis A



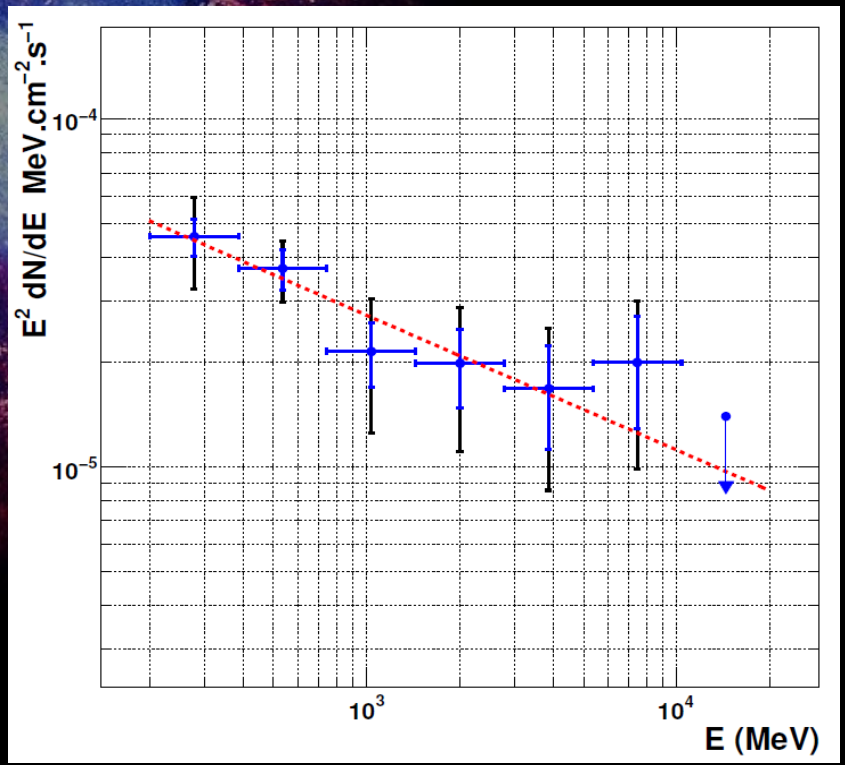
TS map of the off-pulse window above 800 MeV.

LAT Observations of Vela X (spectrum)

(Abdo et al., 2010, ApJ, 713, 146)

- Analysis in the off-pulse window, performed for 200 MeV < E < 20 GeV
- Spatial template used: uniform disk
- Vela-X spectral parameters (renormalized to the total phase):
  - Spectral index = $2.41 \pm 0.09_{stat} \pm 0.15_{syst}$ (soft spectrum)
  - Flux above 100 MeV = $(4.73 \pm 0.63_{stat} \pm 1.32_{syst}) \times 10^{-7}$ cm^{-2} s^{-1}
- No indication of a spectral cut-off at high energy

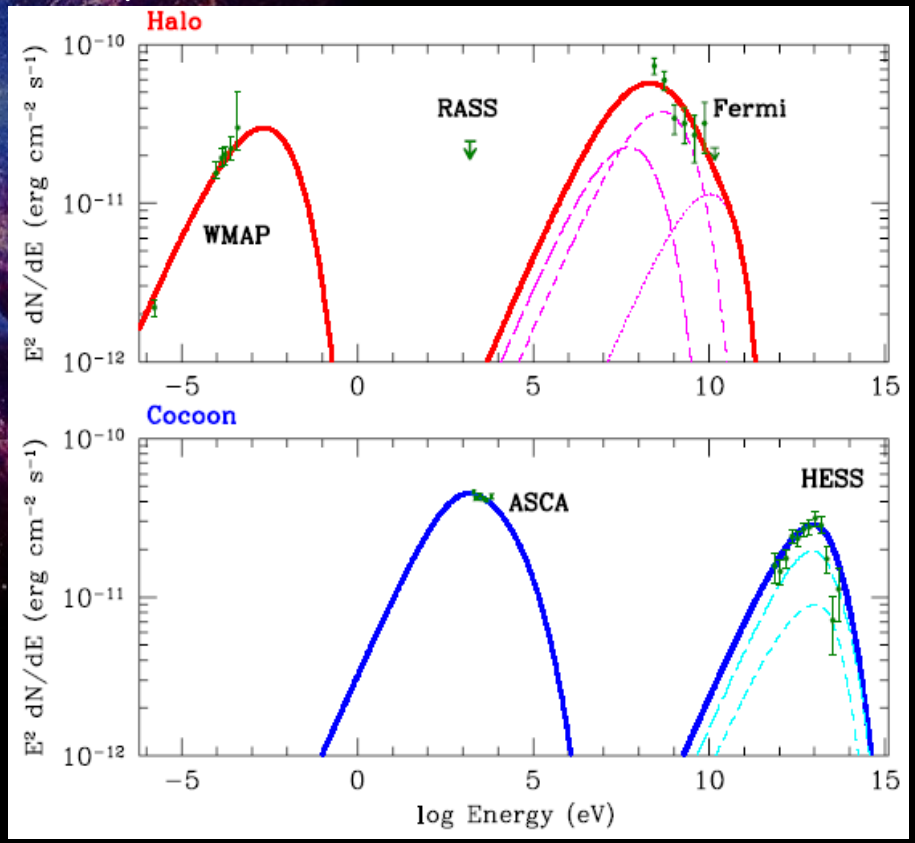
Spectral energy distribution of Vela X



LAT Observations of Vela X (spectrum)

(Abdo et al., 2010, ApJ, 713, 146)

- As noted by *de Jager et al. (2008, ApJ, 689, L125)*, the SED strongly favors a two-component leptonic model
- Hadronic model is disfavoured
- SEDs were computed from evolving power-law electron populations, one each for the X-ray/VHE-peak *cocoon* and radio/MeV-peak *halo:*
  - Halo : This region requires a 130 GeV exponential cut-off controlled by the cut-off of the injected spectrum
  - Cocoon :
    - Synchrotron/Compton peak ratio of the cocoon implies a B=4μG with small uncertainty
    - This region requires a 600 TeV exponential cut-off controlled by the cooling break



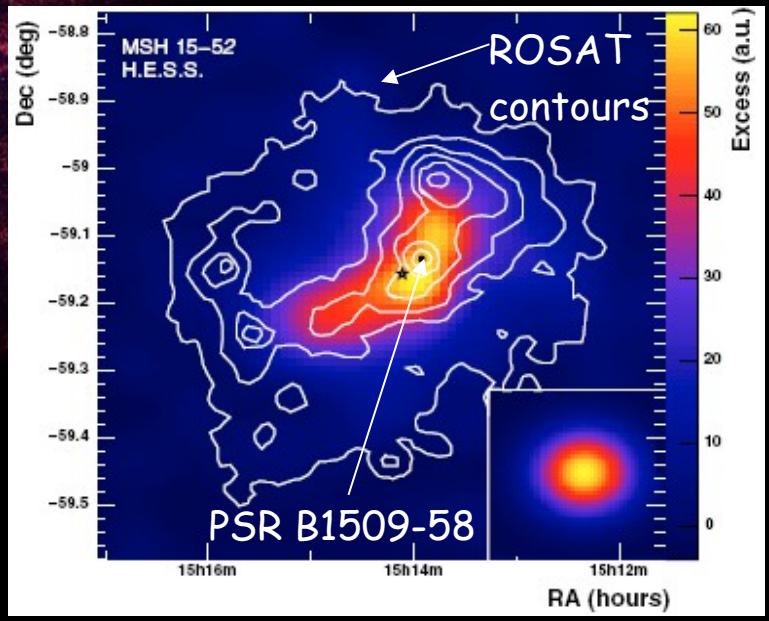
Multiwavelength spectrum of Vela X

The PWN in MSH 15-52

- young composite supernova remnant associated to the radio loud pulsar PSR B1509-58
- bright X-ray and TeV pulsar wind nebula (PWN) powered by PSR B1509-58, significantly extended:
  - in X-rays (ROSAT, 10'*6')
  - at TeV energies (H.E.S.S., 6.4'*2.3')
- pulsations were reported in gamma-rays by CGRO COMPTEL in the 0.75-30 MeV energy range *(Kuiper et al., 1999, A&A, 351, 119)* and by AGILE above 100 MeV *(Pellizzoni et al., 2009, ApJ 695, L115).*

Left : A young pulsar shows its hand (Chandra)

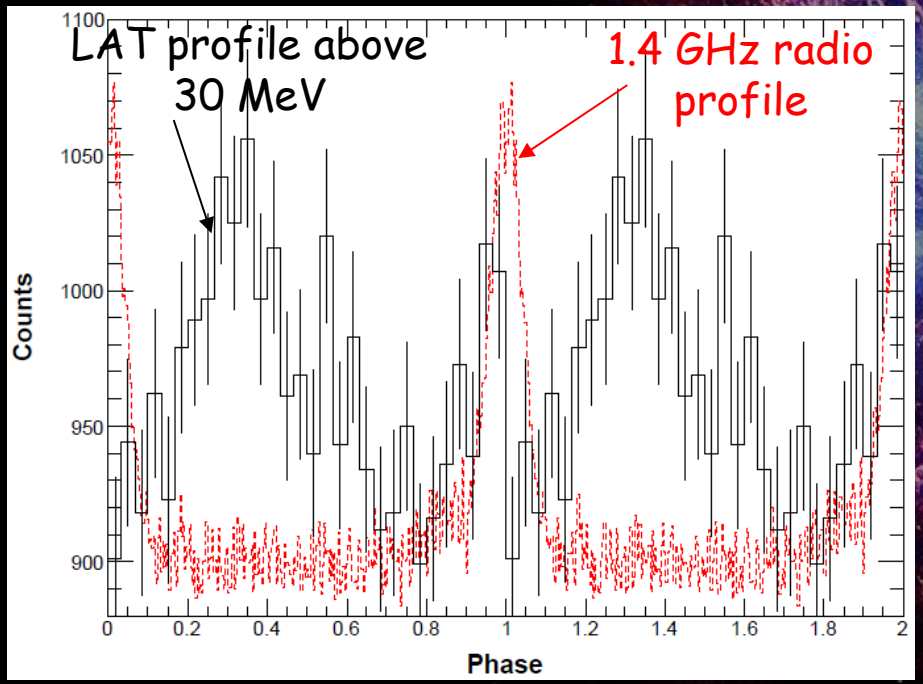
Right : H.E.S.S. Smoothed excess map (Aharonian et al., 2005, A&A, 435, L17)

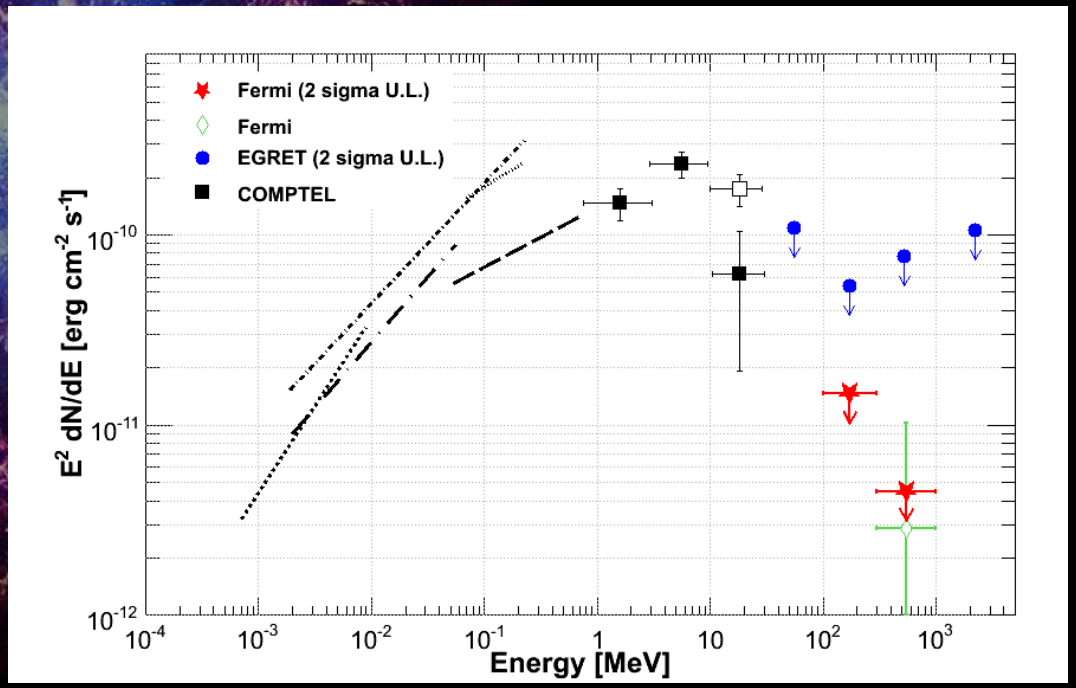


LAT detection of PSR B1509-58

(Abdo et al., 2010, ApJ, 714, 927)

- Detection of PSR B1509-58 at 4.5 σ level above 30 MeV
  - No pulsed signal detected above 1 GeV
  - Second peak at 0.34±0.02 almost aligned with COMPTEL
  - First peak at 0.96 ± 0.02 (not detected by COMPTEL) : harder component ?
  - Spectral energy distribution : consistent with the break at a few tens of MeV as described by *Kuiper et al. (1999, A&A, 351, 119)*



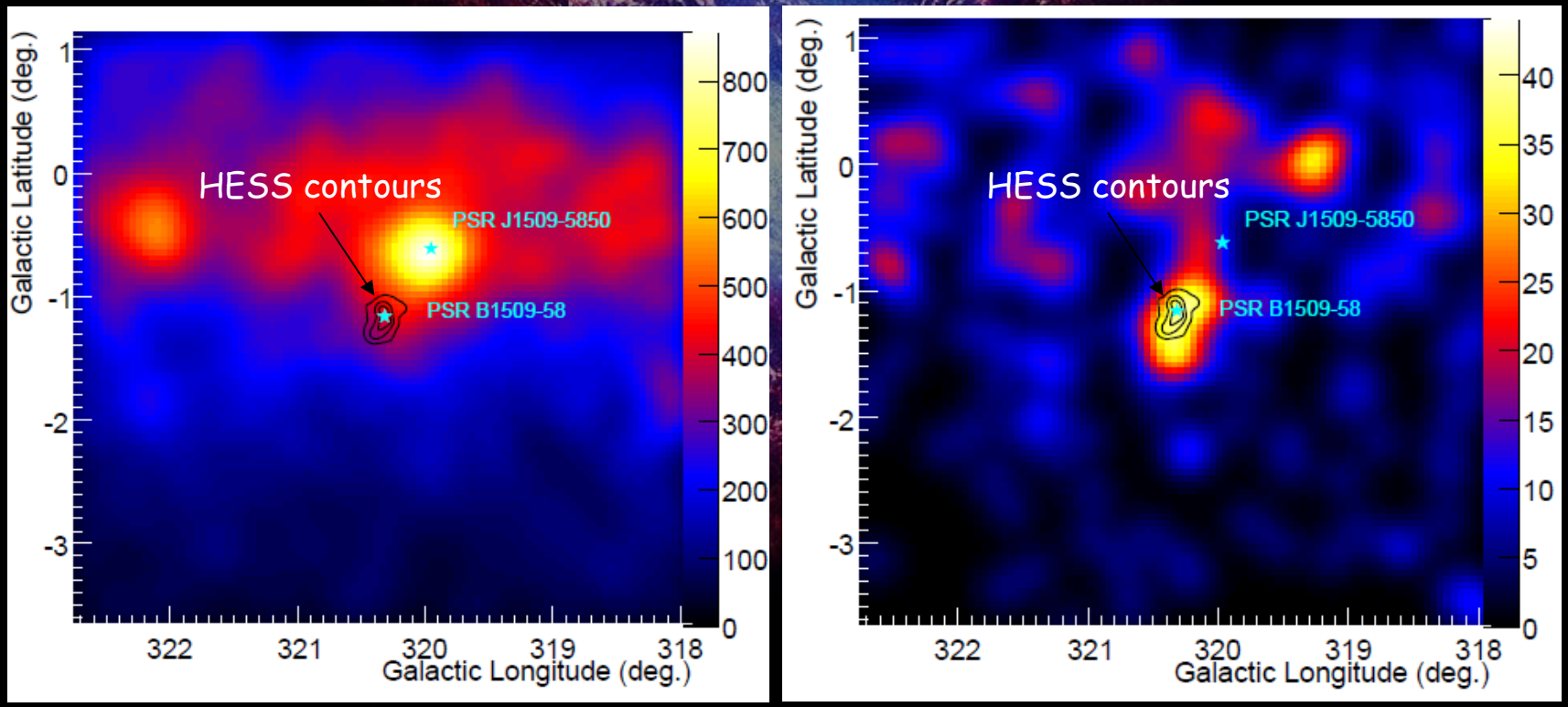


Light curve (left) and spectral energy distribution (right) of PSR B1509-58

LAT Observations of the PWN in MSH 15-52

(Abdo et al., 2010, ApJ, 714, 927)

- Gamma-ray emission dominated by the nearby pulsar PSR J1509-5850 below 3-4 GeV
- Source spatially coincident with the PWN in MSH 15-52 (as seen in X-rays and at TeV energies) detected at a ~8 σ level above 1 GeV
- Source significantly extended : $R_{disk} = (0.25 \pm 0.05)°$

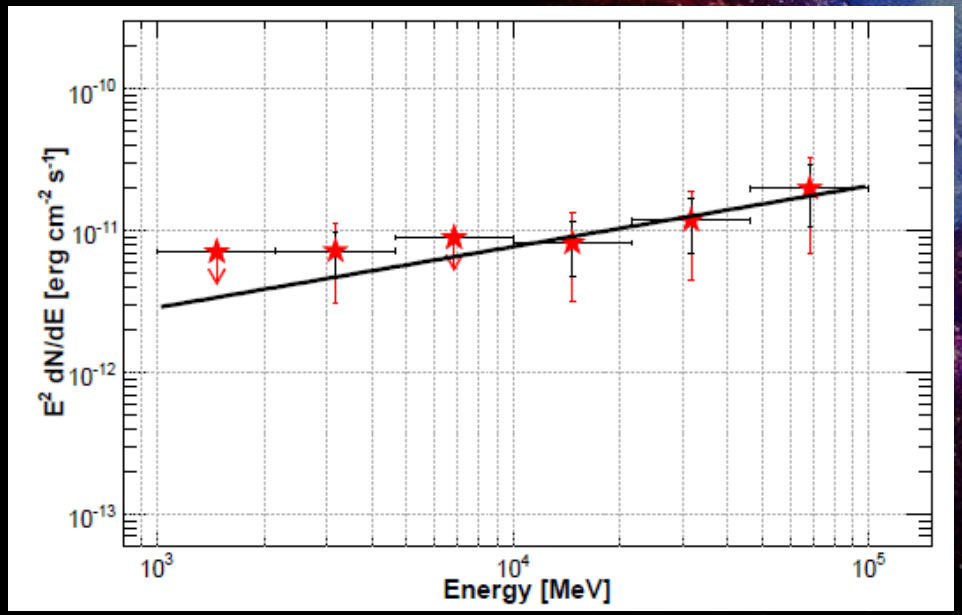


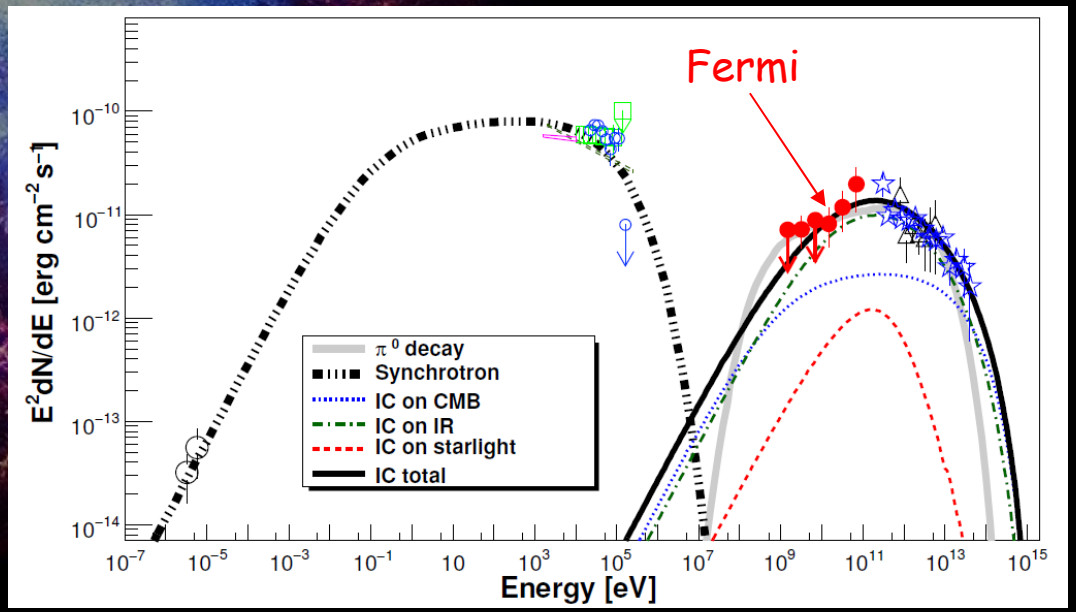
Counts maps above 1 GeV (left) and 10 GeV (right)

LAT Observations of the PWN in MSH 15-52

(Abdo et al., 2010, ApJ, 714, 927)

- Hard spectrum observed above 1 GeV :
  - Flux above 1 GeV : (2.91 ± 0.79 ± 1.35) 10^{-9} cm^{-2} s^{-1}
  - Spectral index : (1.57 ± 0.17 ± 0.13)
- Multiwavelength spectrum :
  - hadronic scenario is disfavoured (energetic point of view)
  - high energy emission can be explained by Inverse Compton scattering (mostly on FIR photon field)





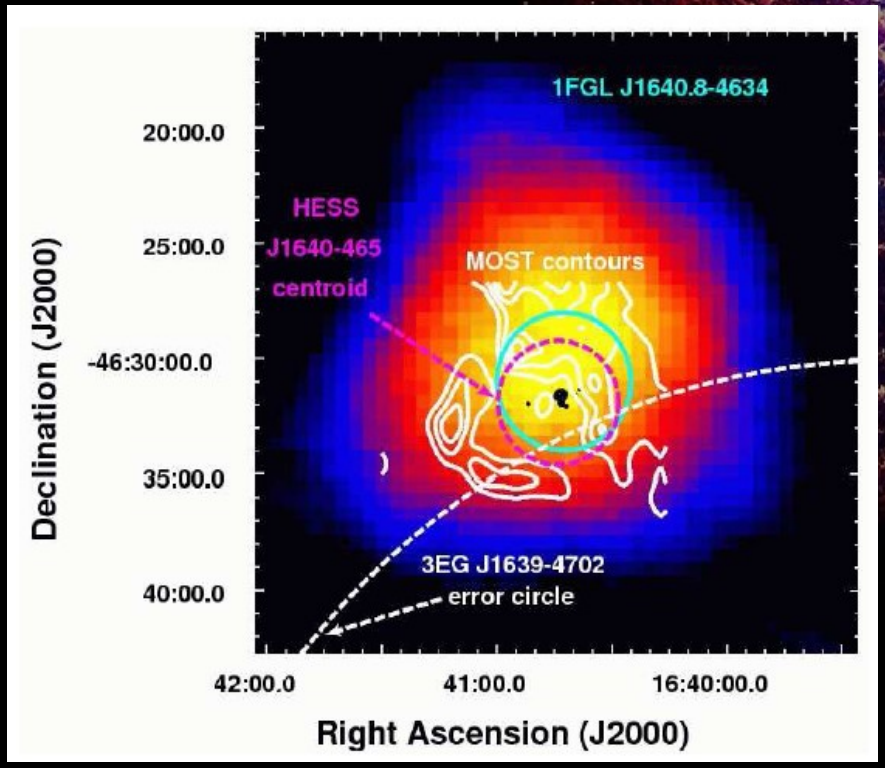
Spectral energy distribution of the PWN powered by PSR B1509-58
Left : in the LAT energy range. Right: from radio to TeV energies

Fermi detection of HESS J1640-465

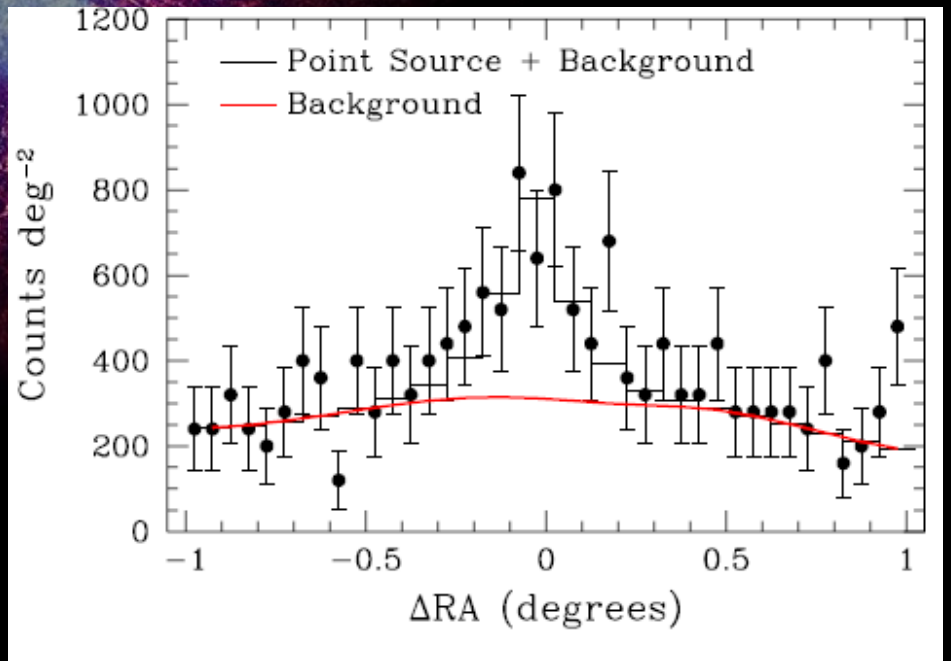
(Slane et al, 2010, arXiv:1004.2936)

- Source discovered at TeV energies by H.E.S.S. *(Aharonian et al, 2006, A&A, 636, 777)*
- Significantly extended in VHE *(Funk et al, 2007, ApJ, 667, 517)* and X-rays *(Lemière et al, 2009, ApJ, 706, 1269)*
- Associated to SNR G338.3–0.0 (distance > 8 kpc)
- No known pulsar but a point source detected by XMM-Newton

- Recent detection at a 17 σ level by Fermi using 15 monts of survey data : no significant extension wrt the LAT PSF



Left : Fermi-LAT counts map above 2 GeV of HESS J1640-465
Below : Profile along RA



Fermi detection of HESS J1640-465

(Slane et al, 2010, arXiv:1004.2936)

- Spectrum in the 0.2 – 50 GeV energy range :
  - modeled by a power-law : $\gamma = 2.30 \pm 0.09$, $F(>100\ \mathrm{MeV}) = 2.8 \pm 0.4\ \mathrm{cm^{-2}\ s^{-1}}$
  - no evidence of a cut-off or break

→ emission not directly from the powering pulsar

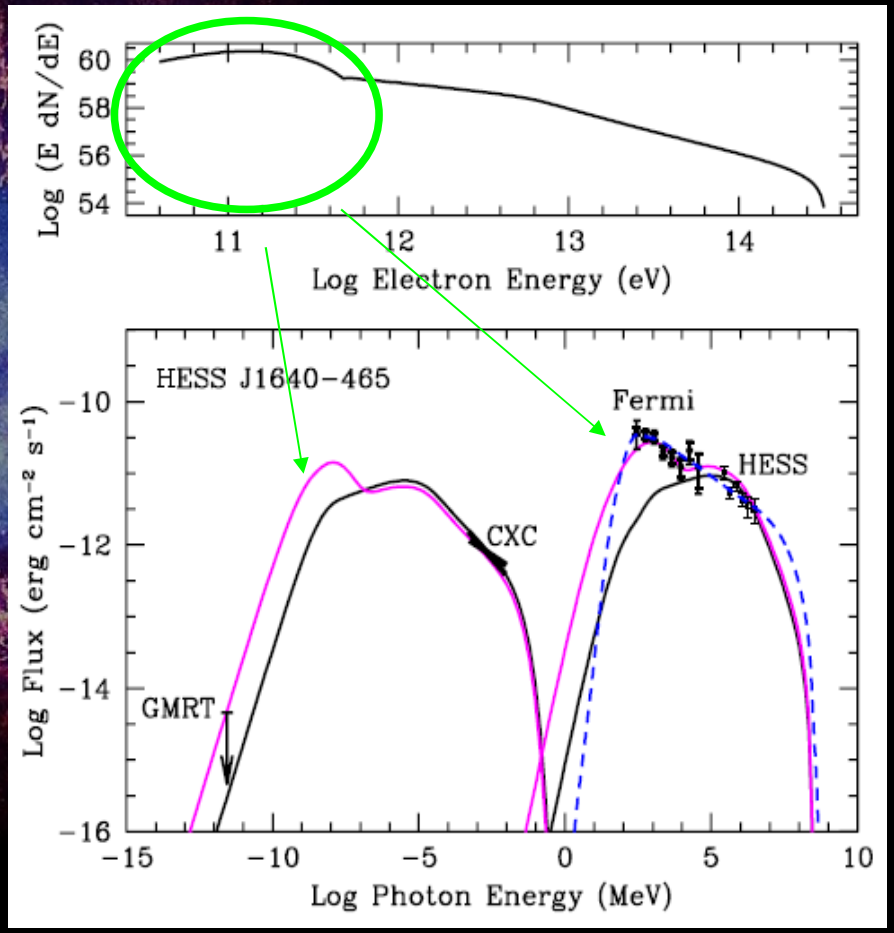
- Multi-wavelength studies :

→ imply a age of ~10 kyr and a magnetic field of ~4 μG

→ γ-ray emission underestimated by a simple synchrotron/IC scenario (black lines)

→ Proton-proton interaction in the SNR (blue dashed curve) unlikely, due to the too high ambient density required

→ Requires an enhancement of the low energy electron population injected in the PWN (magenta line in the case of a maxwellian distribution)



Top : Injection spectrum of the leptonic population
Bottom : multi-wavelength spectrum of HESS J1640-465

The region of Westerlund 2

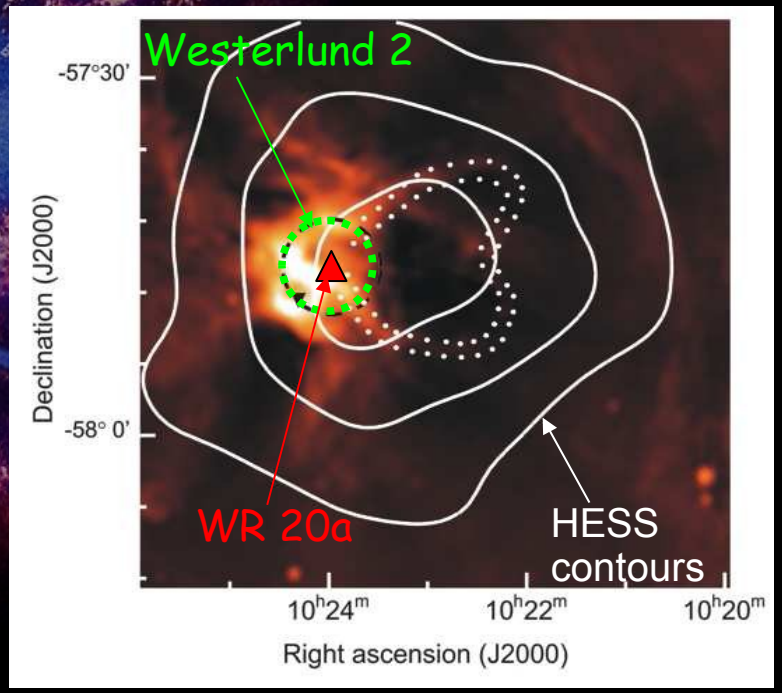
- An extended TeV source, HESS J1023-575, was detected *(Aharonian, F., et al. 2007, A&A, 467, 1075)* in the region of Westerlund 2

- Several scenarii to explain this VHE emission :
  - massive WR binary system WR 20a
  - young stellar cluster Westerlund 2
  - cosmic rays accelerated at their termination shock and interacting with their environment

- The HESS emission slightly offset from WR 20a and Westerlund 2

- The HESS emission is extended

→ disfavors the binary system and stellar cluster hypotheses

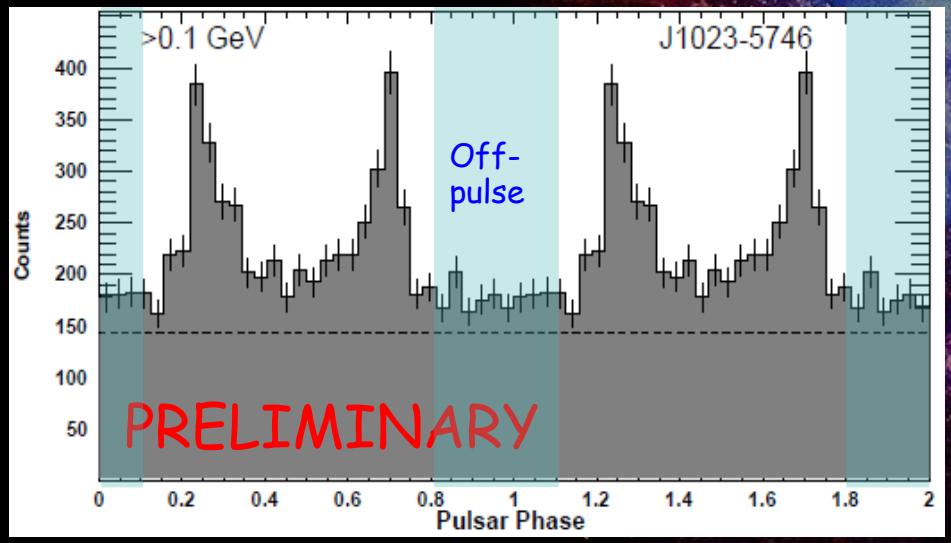


843 MHz image of the region of Westerlund 2 (Aharonian, F., et al. 2007, A&A, 467, 1075)

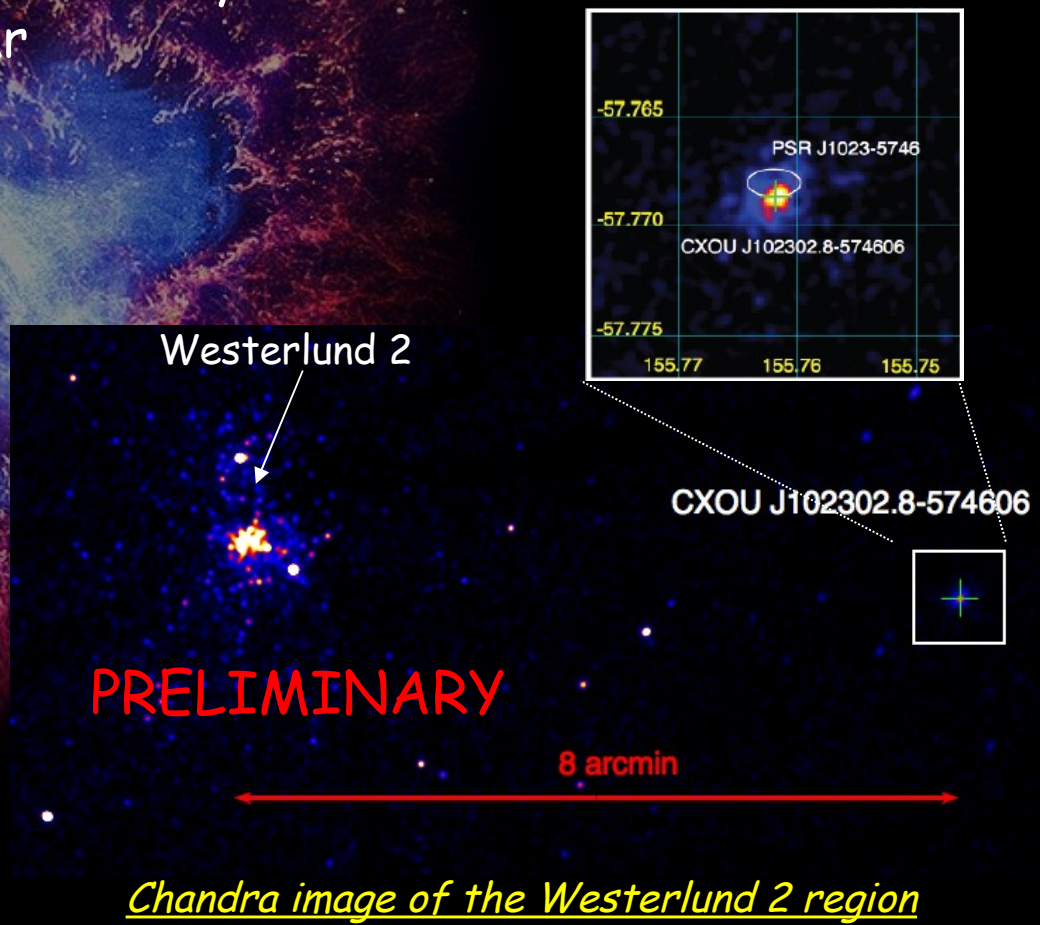
Fermi observations of the region of Westerlund 2

(Saz Parkinson et al., 2010, ApJ, submitted)

- The pulsar PSR J1023-5746 was discovered in blind frequency searches of Fermi LAT data
- An analysis of Chandra data (0.1 – 10 keV) of the region revealed a faint source, CXOU J102302.8-574606, ~8' away from Westerlund 2 core and coincident with the gamma-ray pulsar



Light curve of the pulsar PSR J1023-5746 above 100 MeV



Chandra image of the Westerlund 2 region

A new PWN associated to PSR J1023-5746 ?

(Abdo et al, 2010, in prep.)

- Analysis of the off-pulse windows of PSR J1023-5746 :
  → detection of a significant emission above 10 GeV (morphological studies are on-going)

1. The LAT off-pulse emission is :
   - spatially coincident with the energetic pulsar PSR J1023-5746
   - spatially coincident with the source HESS J1023-575
   - characterized by a hard spectrum which links up nicely with the HESS spectral points

- The pulsar PSR J1023-5746 is young and energetic (spin-down power of ~10^{37} erg/s)
- The HESS source is extended

→ These elements strongly point towards an identification of the off-pulse emission seen by the LAT and the HESS source as the PWN associated to the young pulsar PSR J1023-5746.

Conclusions

- 4 PWNe firmly identified in the LAT energy range :
  - Crab Nebula :
    - synchrotron and inverse Compton components are resolved
    - LAT and Cherenkov spectra link up very nicely
    - constraints on physical parameters (magnetic field, etc)
  - Vela X :
    - detection of a gamma-ray source significantly extended and spatially coincident with the halo seen in radio
    - favors a two-component leptonic model
  - MSH 15-52 :
    - detection of a gamma-ray source significantly extended and spatially coincident with the X-ray and TeV PWN above 1 GeV
    - favors a leptonic scenario
    - constraints on parameters (magnetic field, injection spectrum, etc)
  - HESS J1640-465 :
    - Constraints on physical properties (age, magnetic field, etc)
    - γ-ray spectrum requires an enhancement of the low energy electron population
- A PWN candidate spatially coincident with the blind search pulsar PSR J1023-5746 and the source HESS J1023-575