Fermi-LAT observations of Supernova remnants

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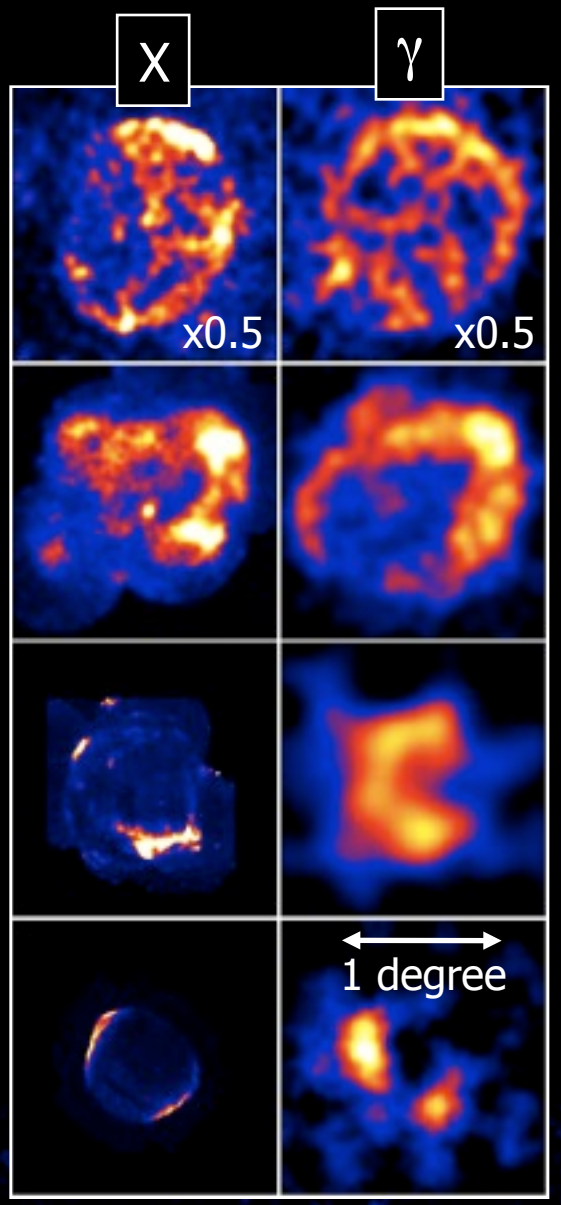
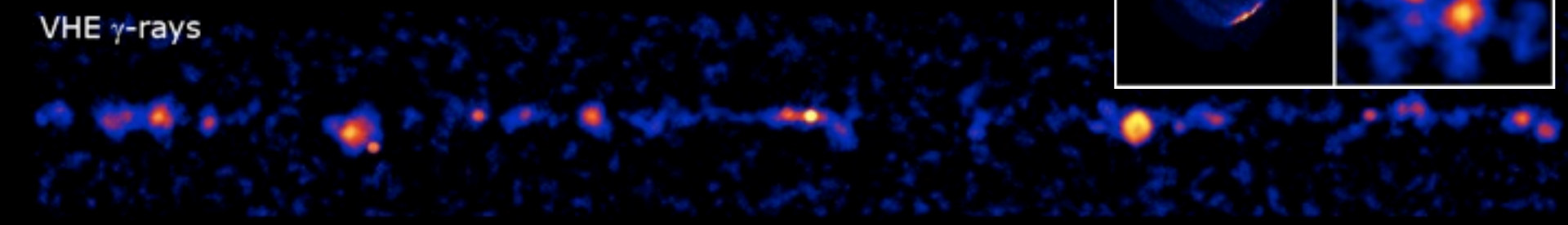
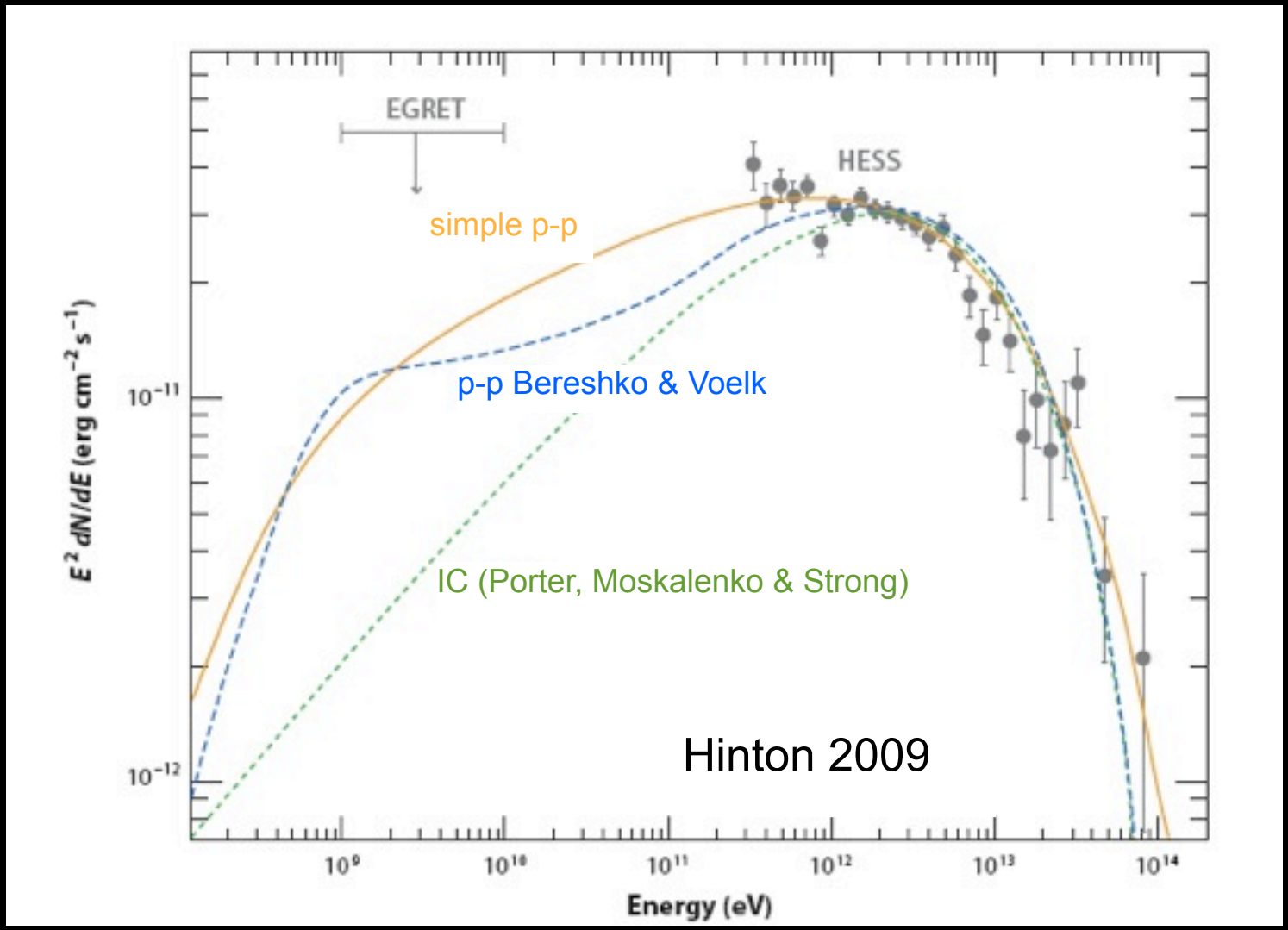
TeV gamma-ray observations

- 4 shell-like objects, detected in TeV gamma-rays
- Young historical SNRs
  - RX J1713.7-3946
  - Vela Junior
  - RCW 86
  - SN 1006
- All show rather clear correlation with non-thermal X-ray emission
- Also detection of Cas A, upper limits for Tycho, Kepler, …





Protons or Electrons?

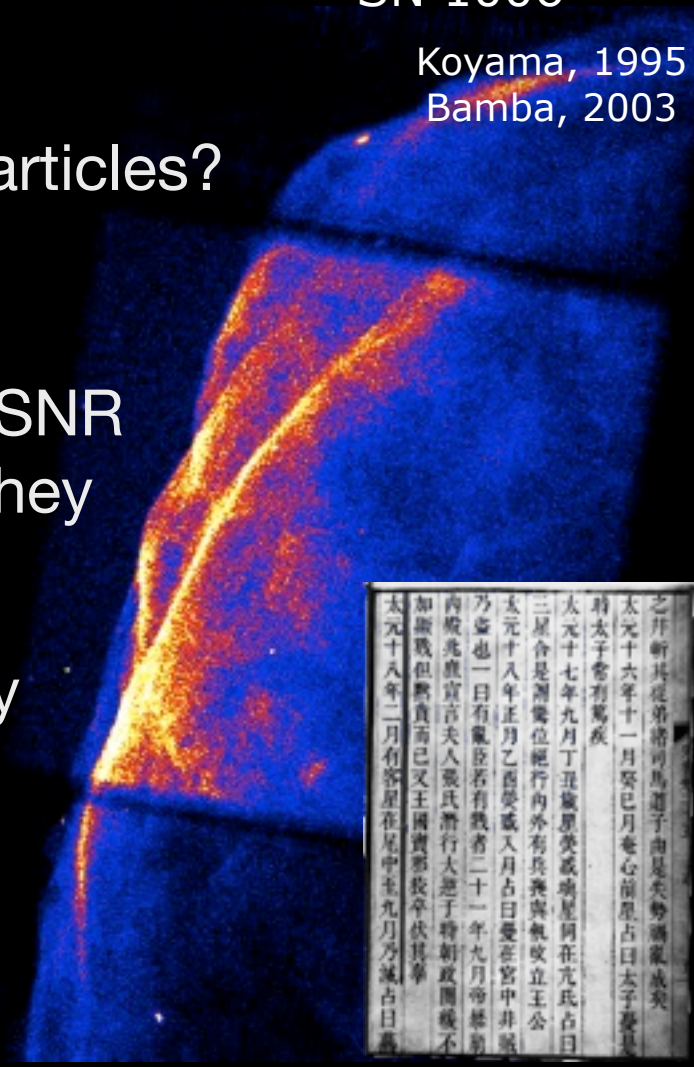


Some of the relevant questions:

- What is the p/e ratio in accelerated particles?
- What is the acceleration rate / time?
- Where does acceleration cut off? Do SNR accelerate CRs up to the knee – are they Pevatrons?
- How efficiently is shock kinetic energy converted to CR energy?

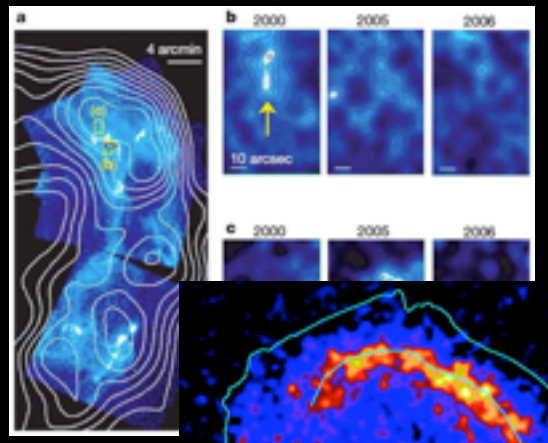
SN 1006

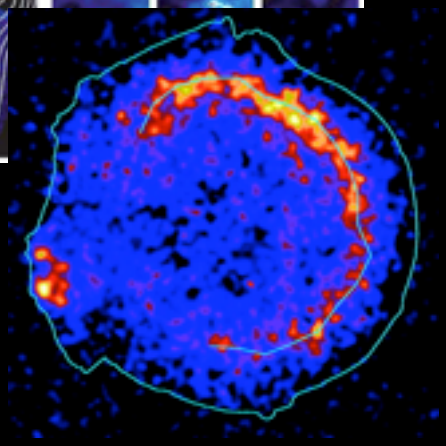
Koyama, 1995
Bamba, 2003

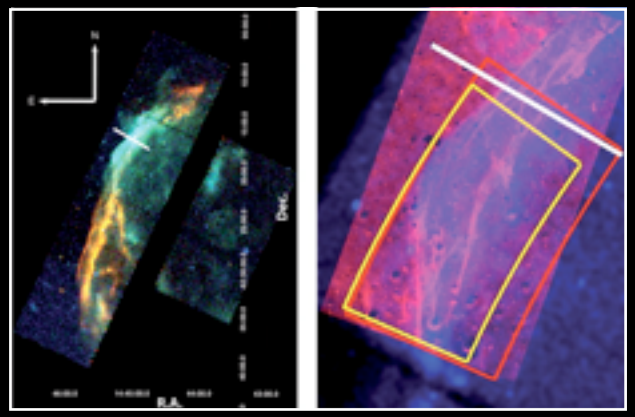


Magnetic fields in SNR shells

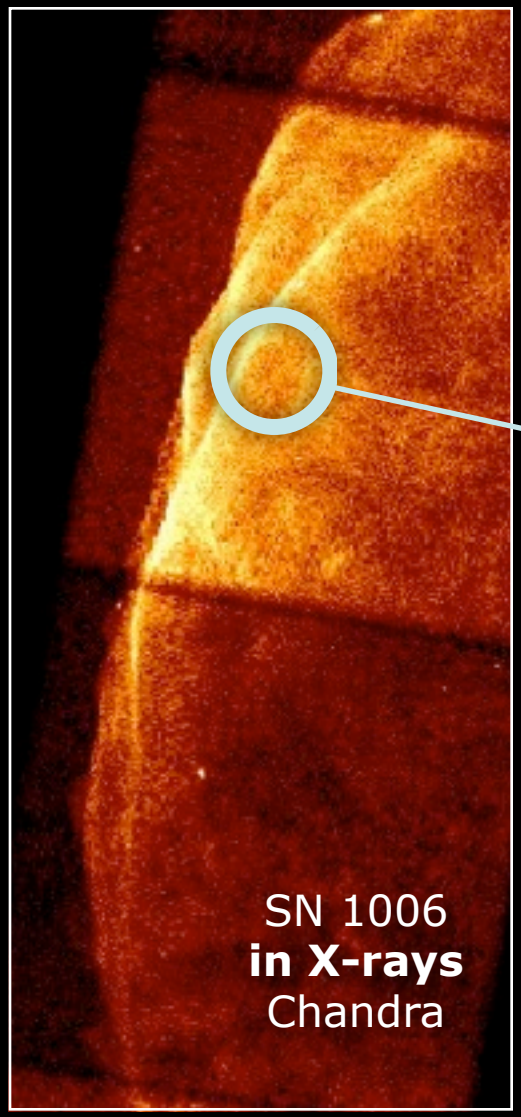
- Mounting evidence that
  - B-fields amplified in SNR shocks
    1. X-ray Filaments
    2. X-ray Variability
  - Cosmic ray pressure is significant
    1. position of CD
    2. post-shock temperature
    3. high B-fields

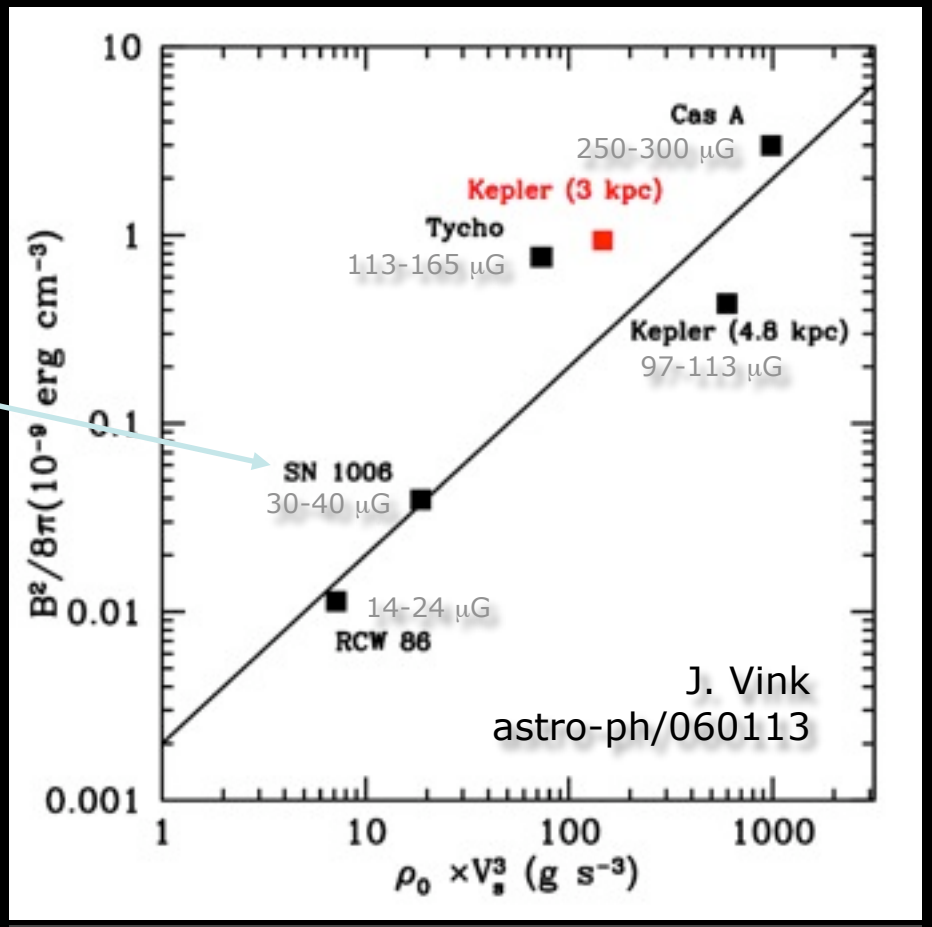






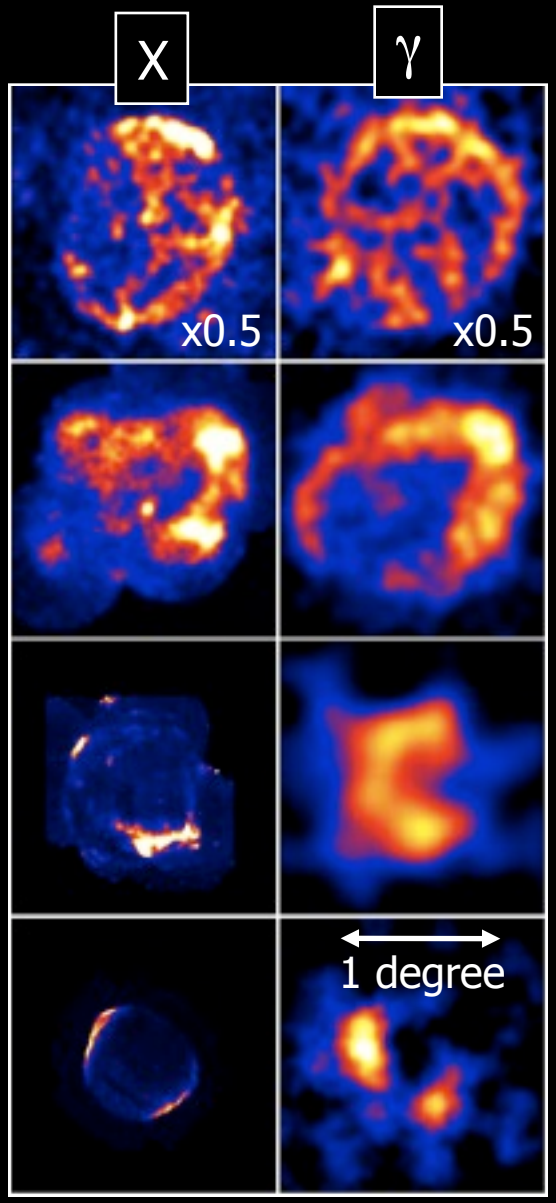
Magnetic fields in SNR shells





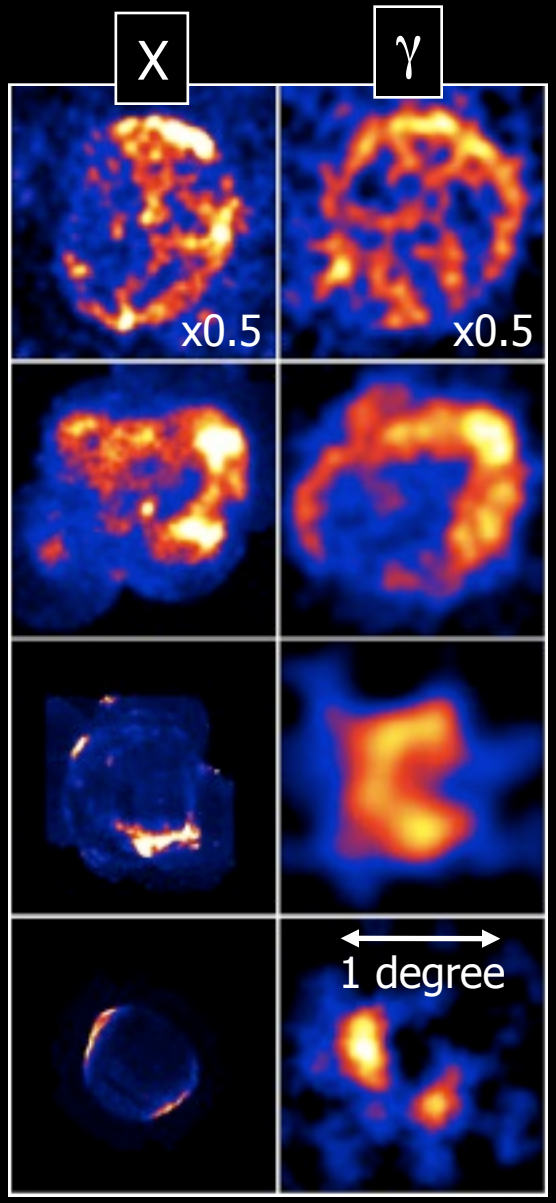
If this is true ...

- TeV gamma-ray emission in young SNRs should be hadronic
- Fermi-LAT sensitivity sufficient to detect these sources in a hadronic scenario in ~1 year of data

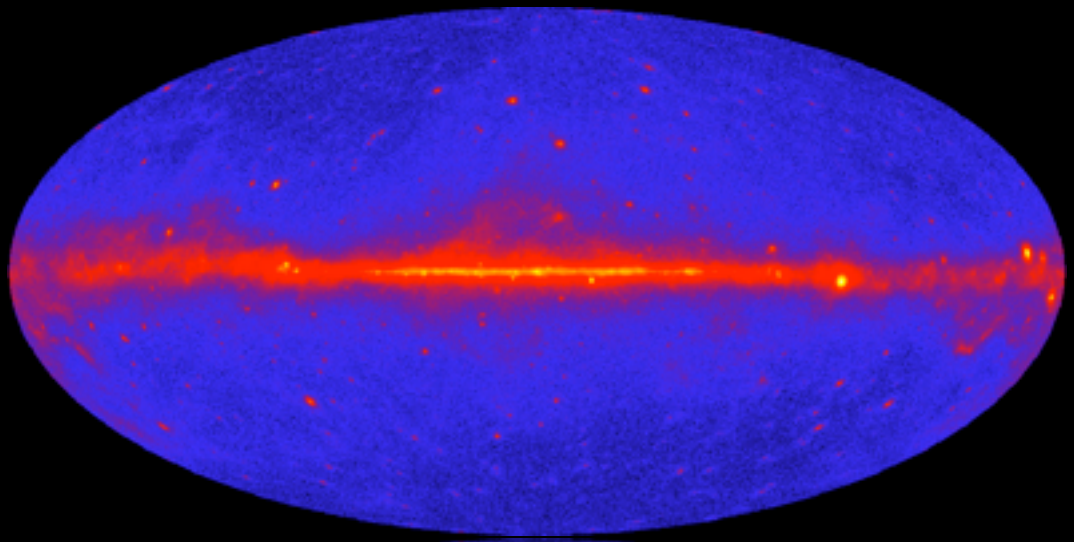


If this is true ...

- TeV gamma-ray emission in young SNRs should be hadronic
- Fermi-LAT sensitivity sufficient to detect these sources in a hadronic scenario in ~1 year of data
- DISCLAIMER: unfortunately, I will not be able to tell you about young SNRs with Fermi today ...



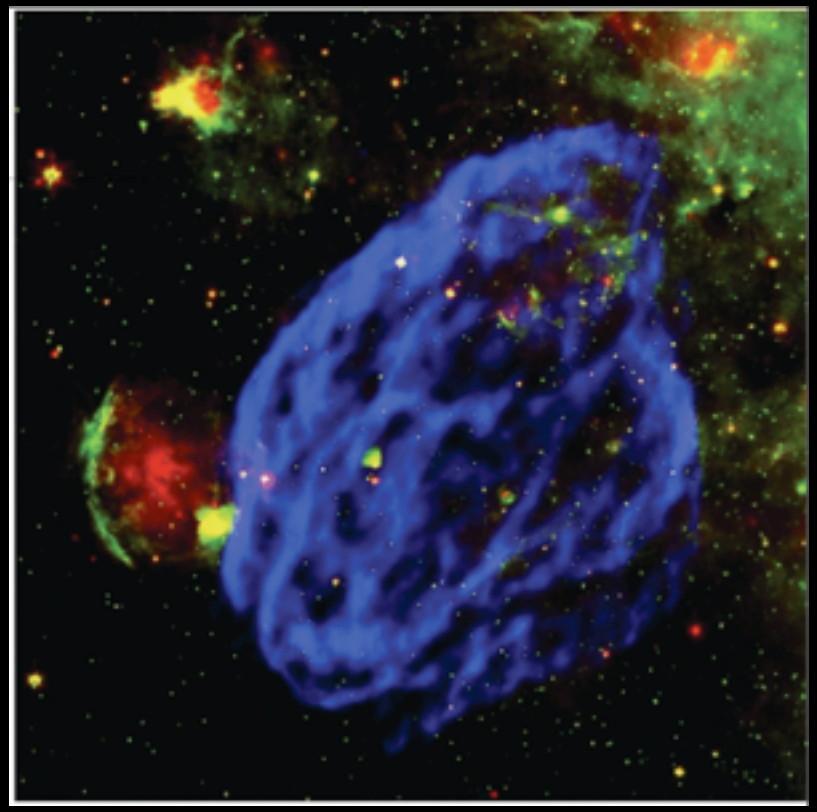
Fermi-LAT early results ...



- … on Supernova remnants and Pulsar Wind Nebulae

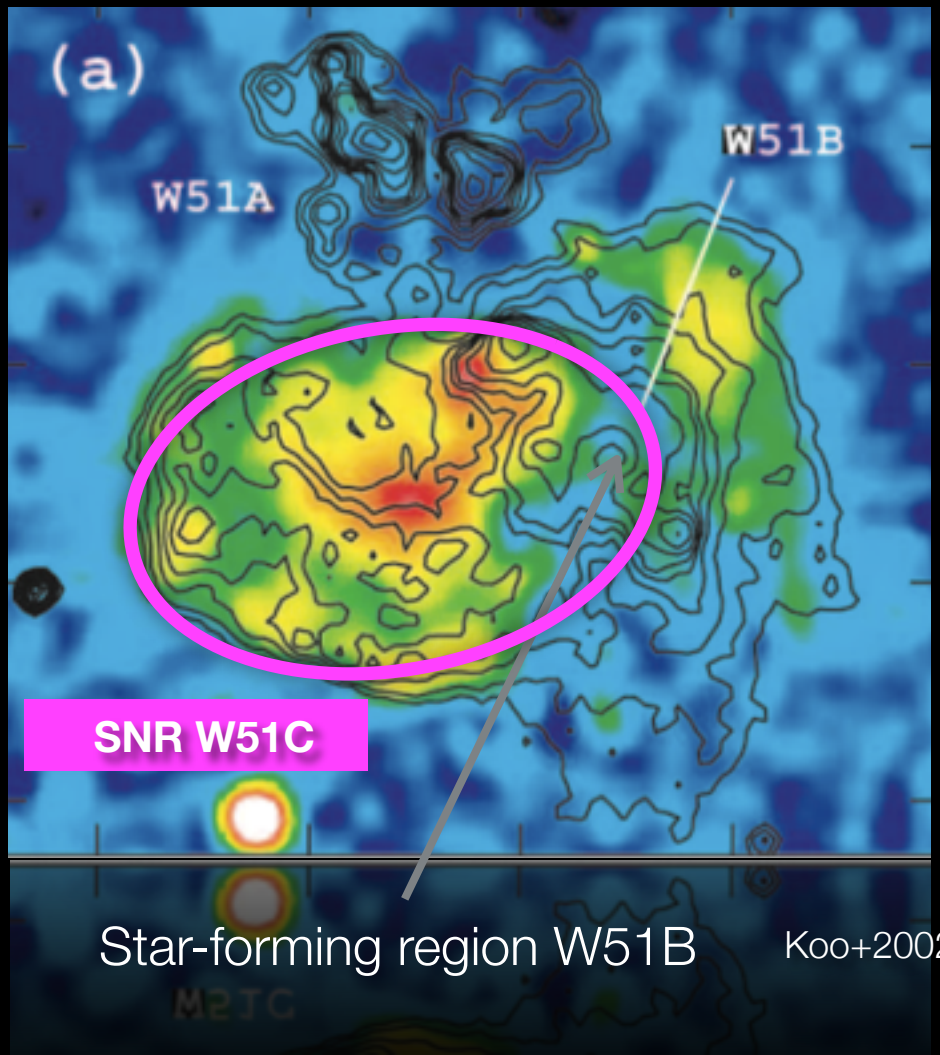
General comments

- Any positional coincidence with an SNR must be tested vs pulsars
- Clear detection of bright GeV gamma-ray sources coinciding with mid-aged SNRs interacting with molecular clouds
  - W51C, W44 and W28
  - IC 443

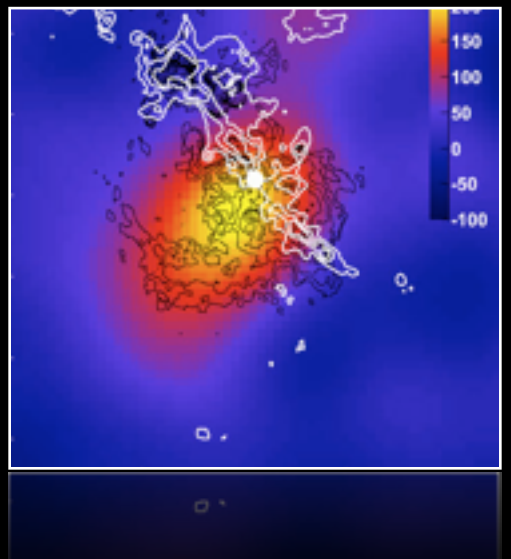


Supernova remnant W51C

ROSAT X-ray (color), VLA (contours)

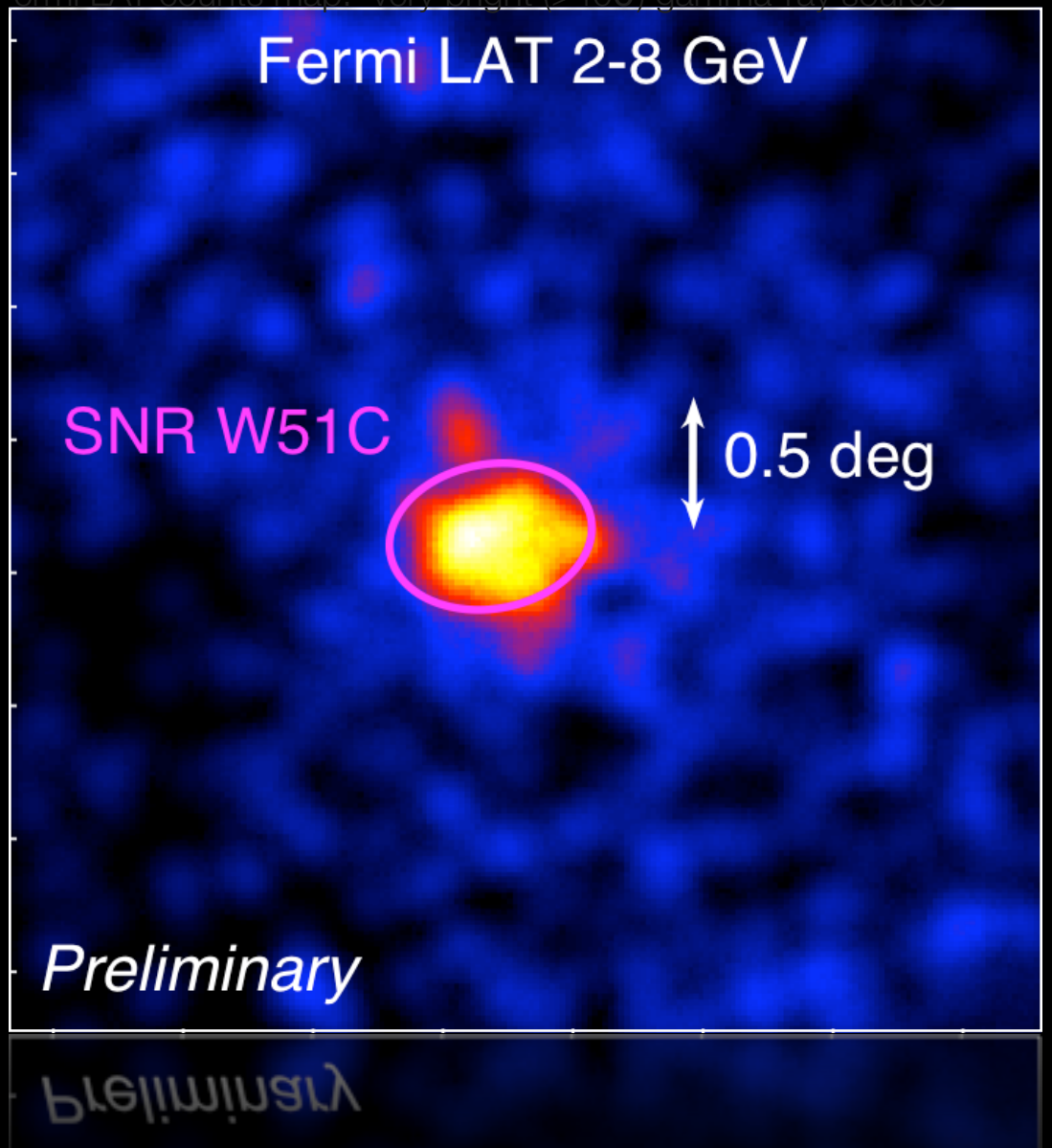


- D ~ 6 kpc, Age ~ 20 kyears
- Molecular cloud interaction
- SNR diameter ~ 30’
- Physical size rather large (90pc x 70 pc
- + recent H.E.S.S. discovery

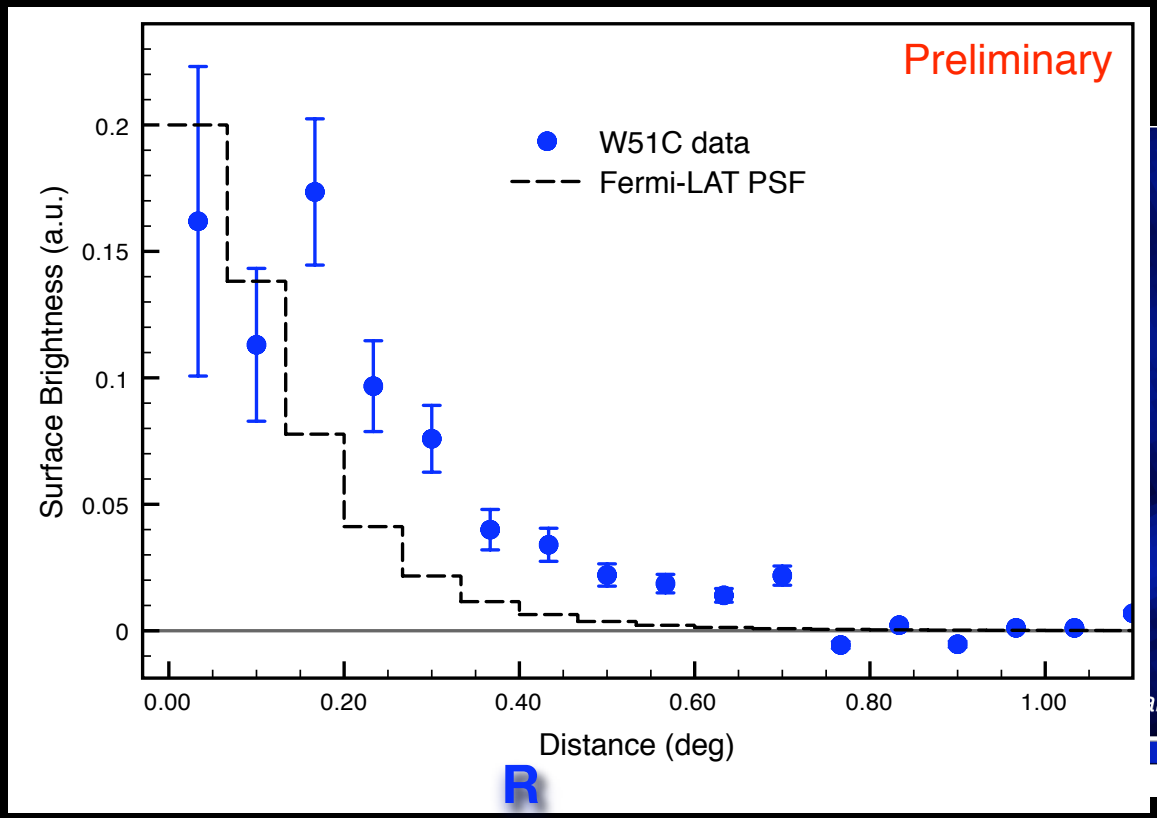


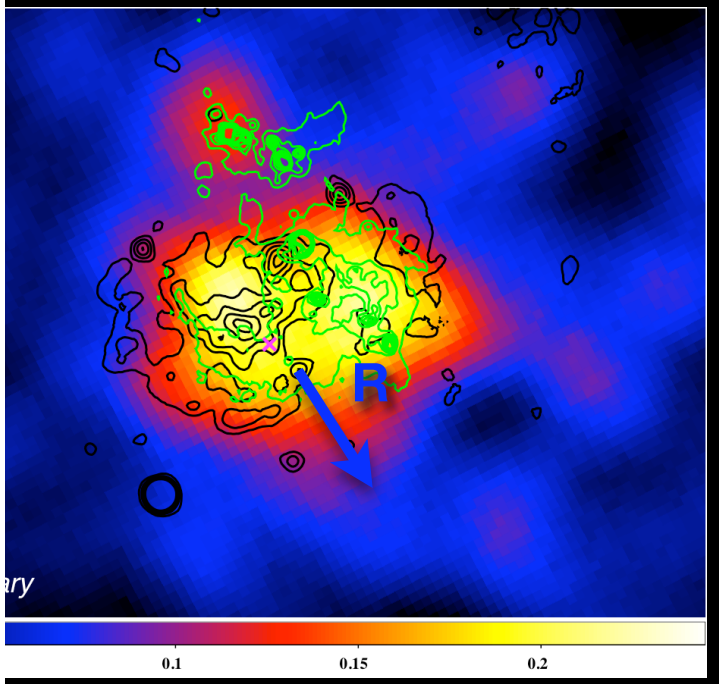
Fermi View on W51C Region

Fermi LAT counts map: very bright (>40σ) gamma-ray source



The W51C source is extended

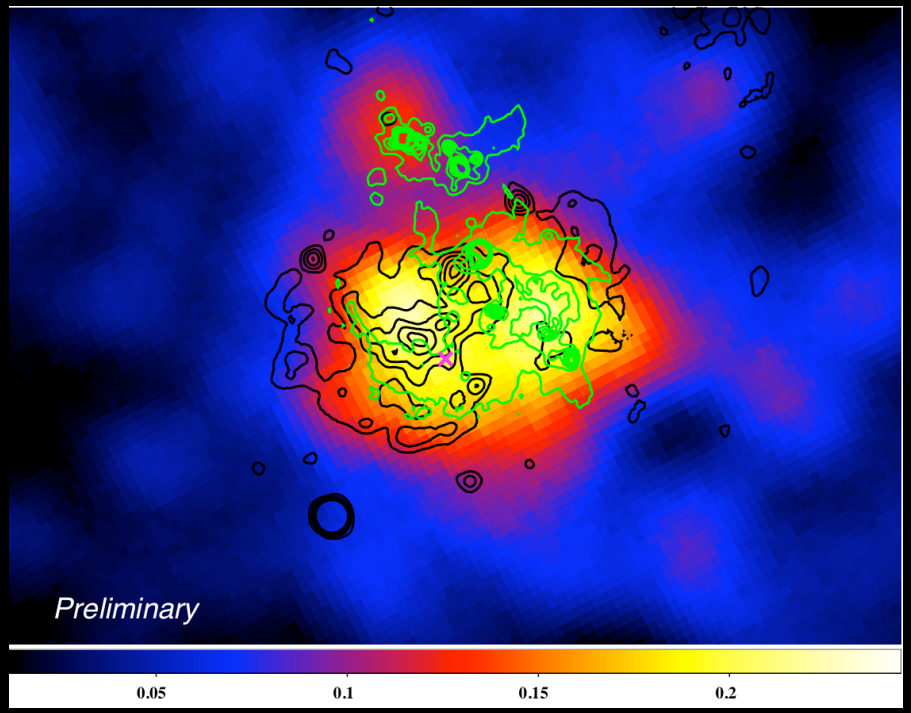




- Mean surface brightness (2-8 Gev) as a function of distance from the SNR center vs. Fermi-LAT PSF

Close-up View on W51C Region

Color: Fermi LAT counts map (2-8 GeV)
Black: ROSAT X-ray map (0.1-2.4 keV)
Green: VLA 1.4 GHz

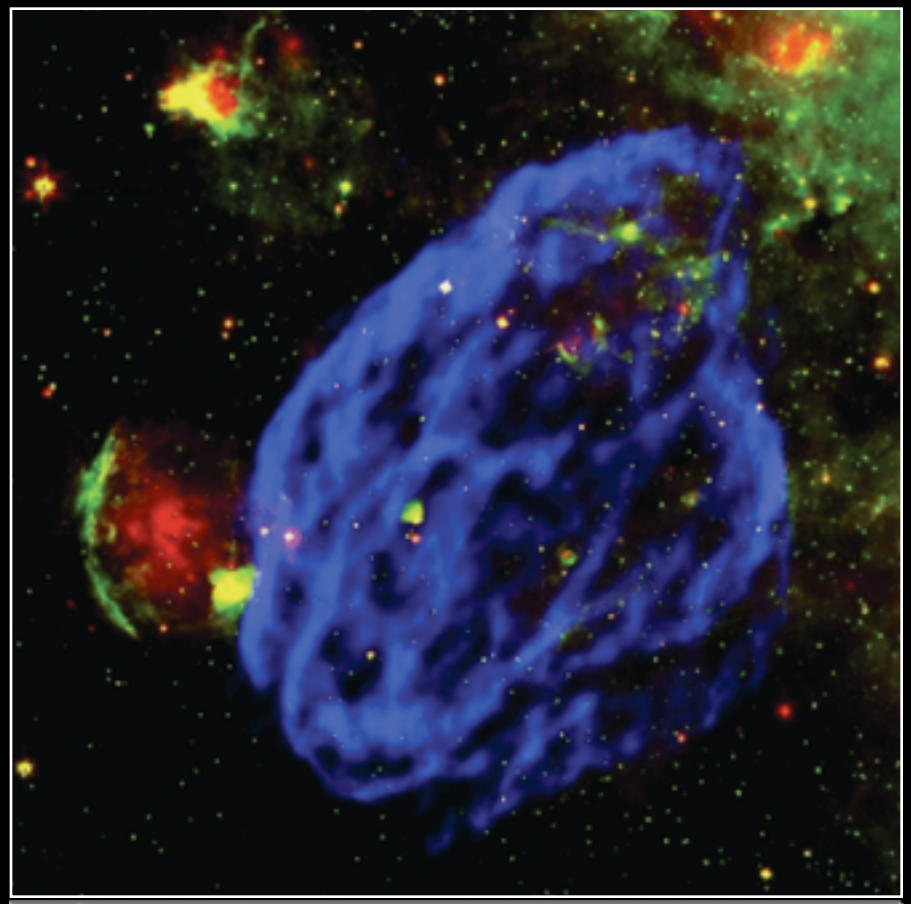


X : CXOJ192318.5+140305 (neutron star?)

- **X-rays:**
  - Thermal emission by shock-heated plasma (kT=0.2 eV)
- **Radio**:
  - Peaks are HII regions
  - Synchrotron radiation of SNR W51C well matched to thermal X-rays

Supernova remnant W44

Blue: VLA (324 MHz)
Green + Red: Spitzer



- Middle-aged (~ 2.0×10^4 yr)
- mixed-morphology SNR
  Distance: ~ 3kpc
- Spatial extent: ~ 35’ × 26’
- Spatially coincident with 3EG J1856+0114
- Cloud-shell interactions
  - CO (Seta et al. 2004),
  - OH maser (1720 MHz: Hoffman et al. 2005)
  - mid-IR(traces shocked H_2; Reach et al. 2006)

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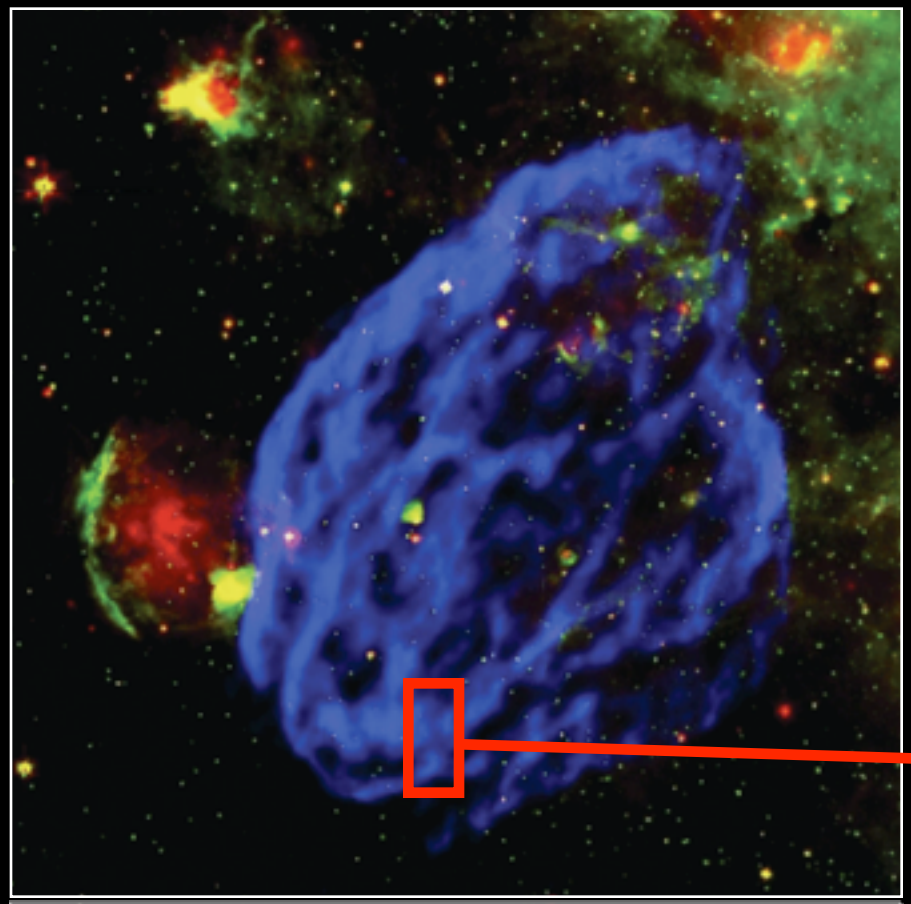
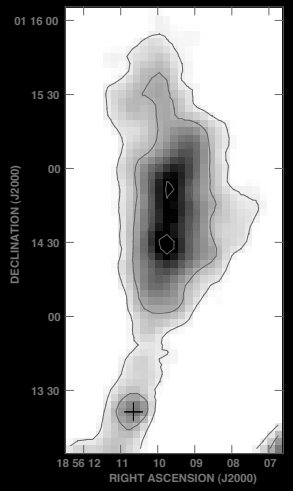


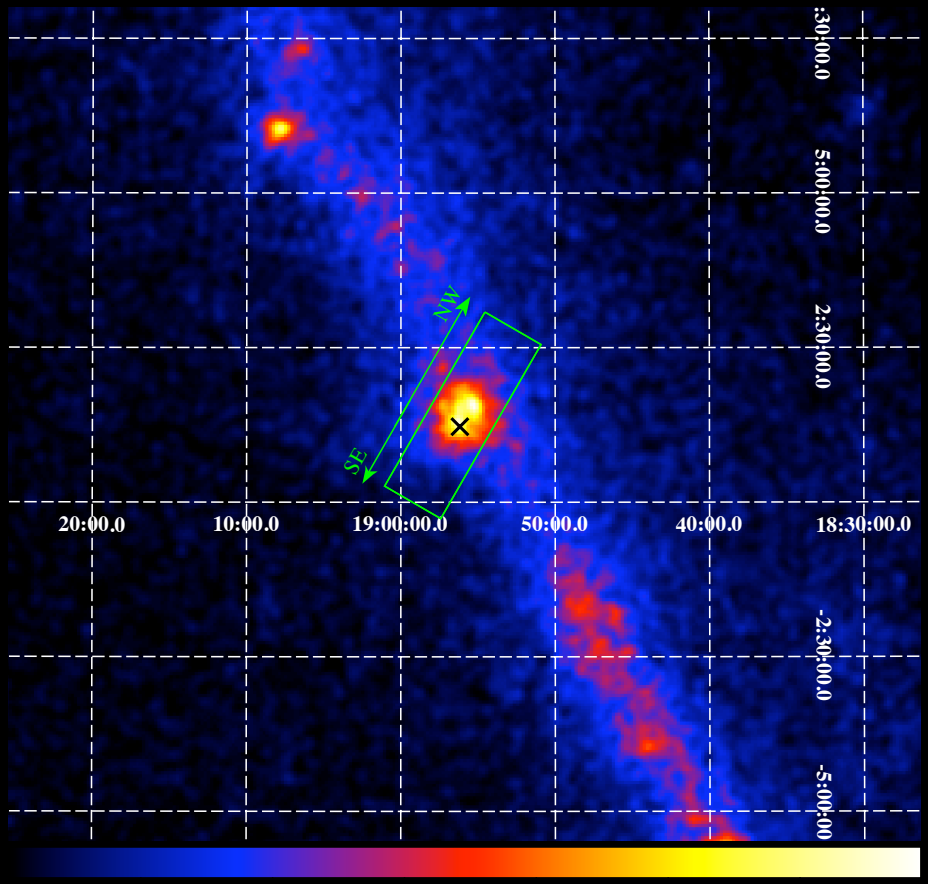
- Pulsar: PSR B1853+01 (Wolszczan et al. 1991)
- Char. age: ~ 2× 10^4 yr
- PWN: Observed in Radio & X-ray (~ 2 arcmin in radio (Frail et al. 1996, Harrus et al. 1996, Petre et al. 2002)



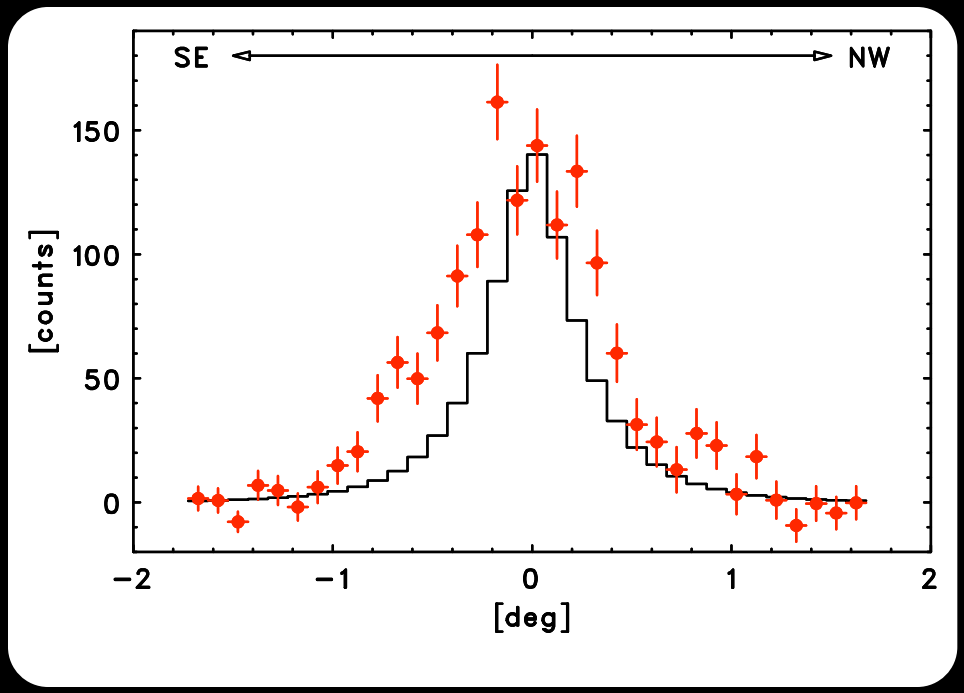
Castalletti+, 2007

Also Extended ….

Smoothed Counts > 1 GeV



- Profile along rectangle
- Red: observed, black: PSF
- Contribution from diffuse background and nearby sources subtracted



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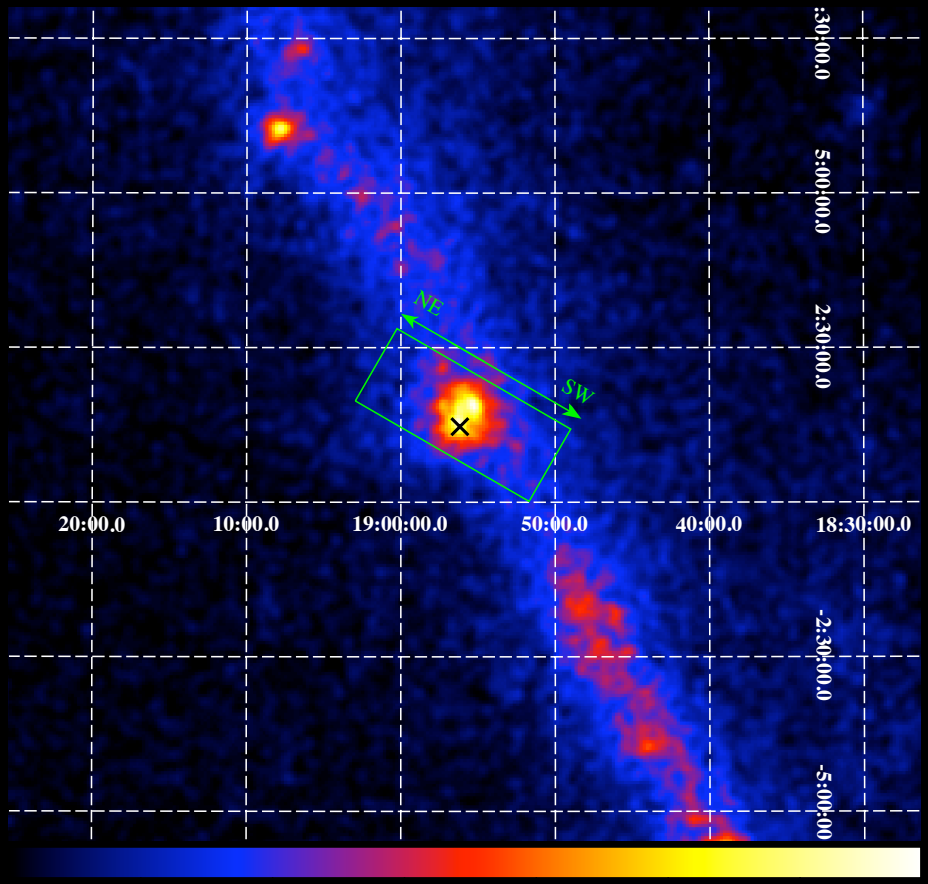

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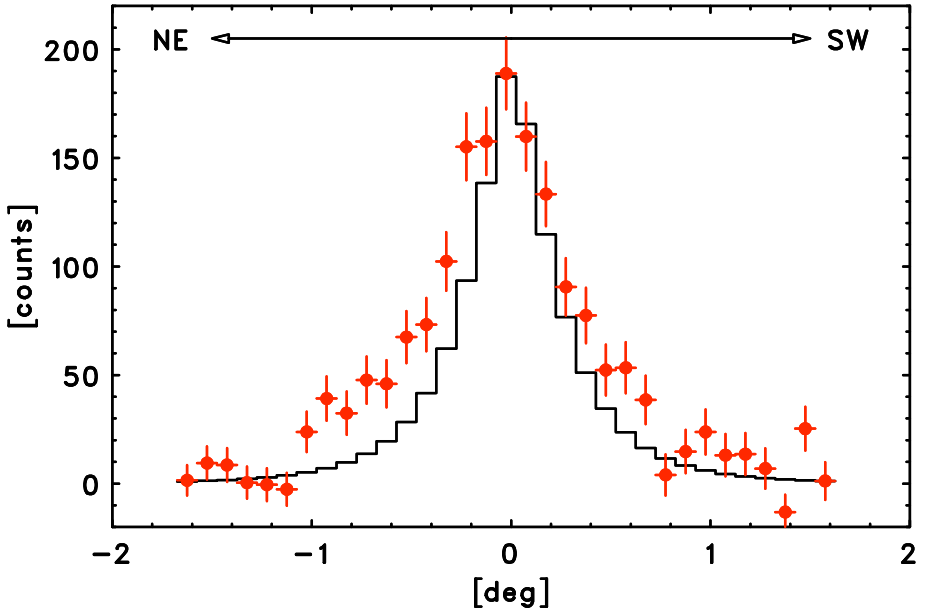

W 28 Region

- Mixed-morphology SNR
- TeV detected by HESS (steep spectrum)
- Distance 1.8-3.3 kpc
- Age: ~35000-150000yr
- South TeV source is star forming region

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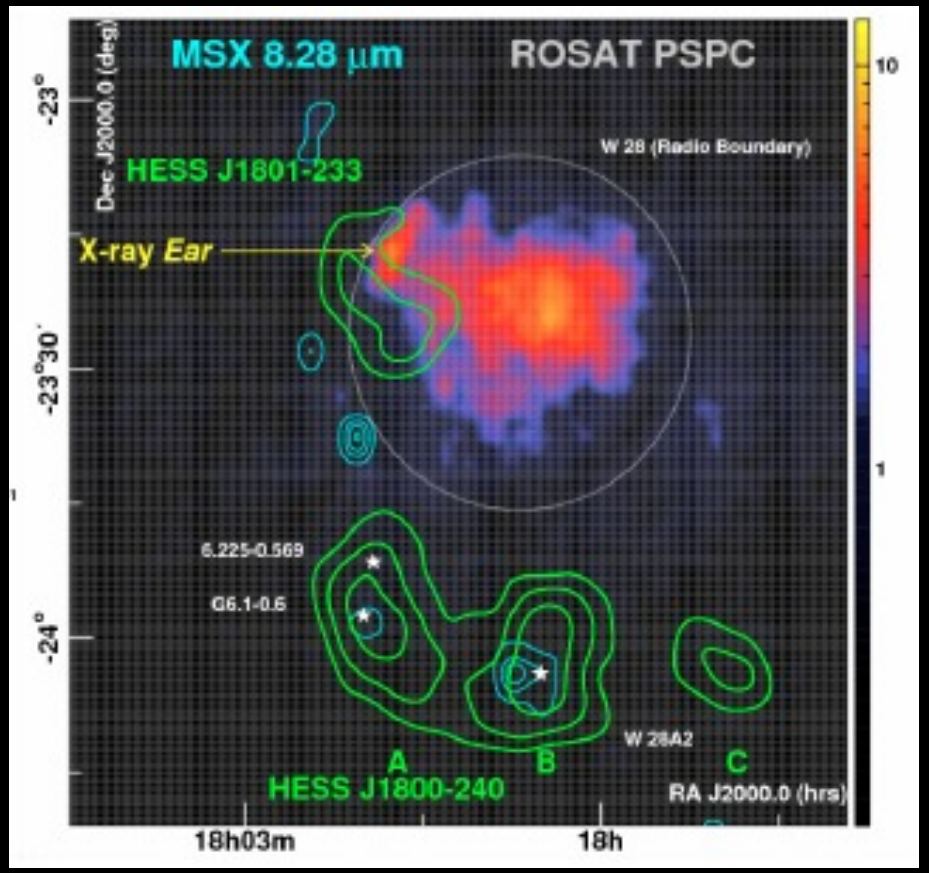
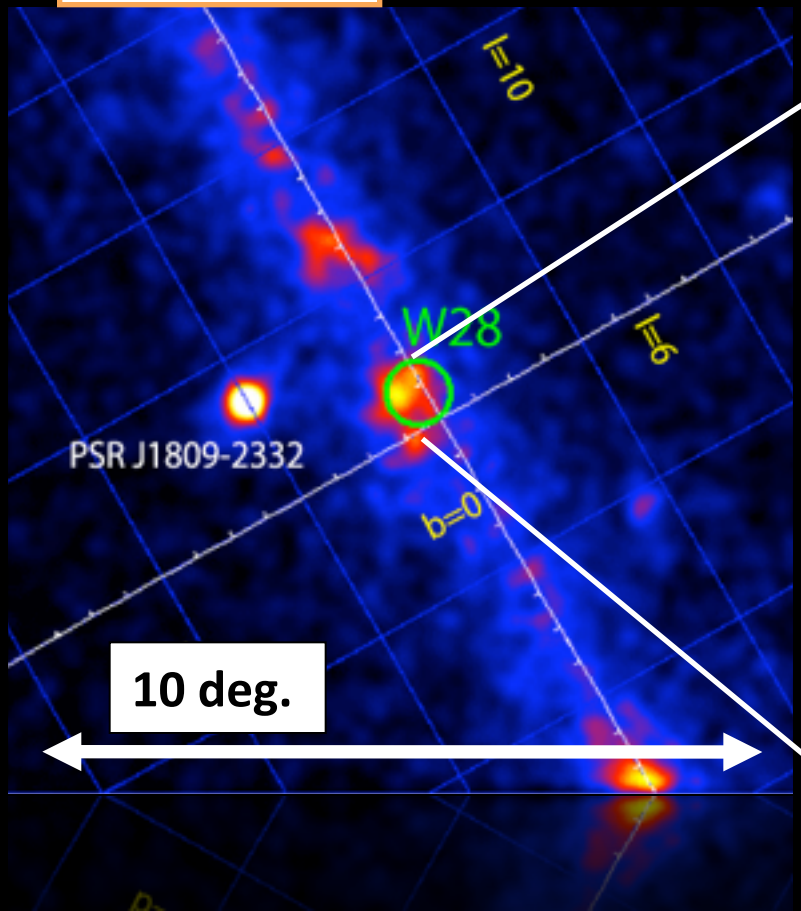
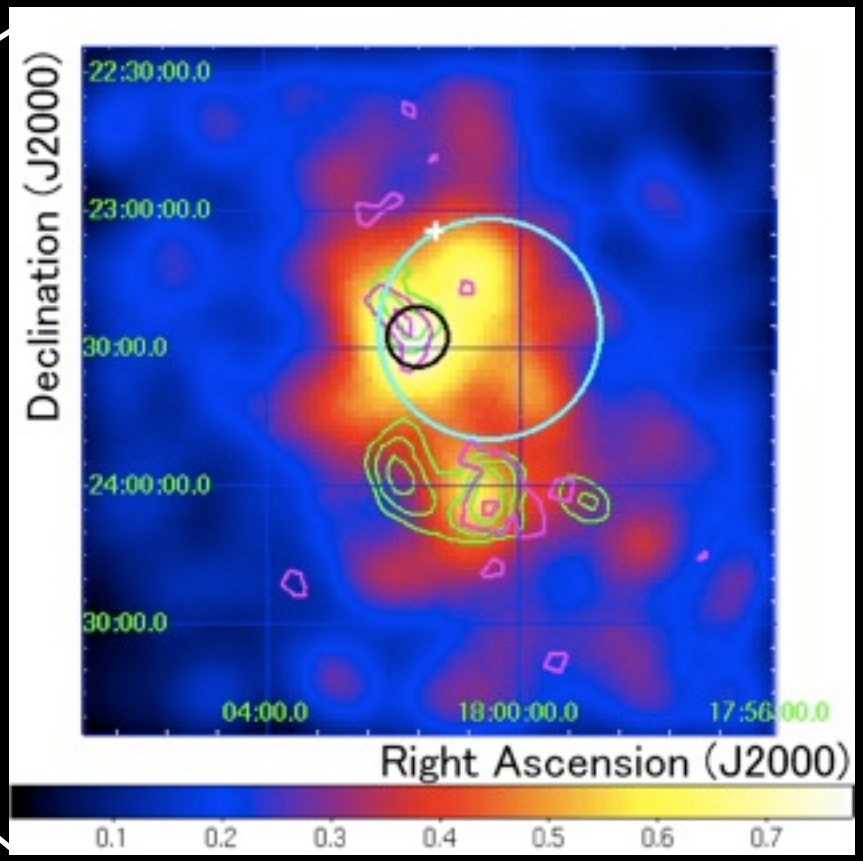


Fermi-LAT count map of W28

Green: H.E.S.S.
Black: Fermi 95% confidence region
Magenta: NANTEN (CO J=1-0)

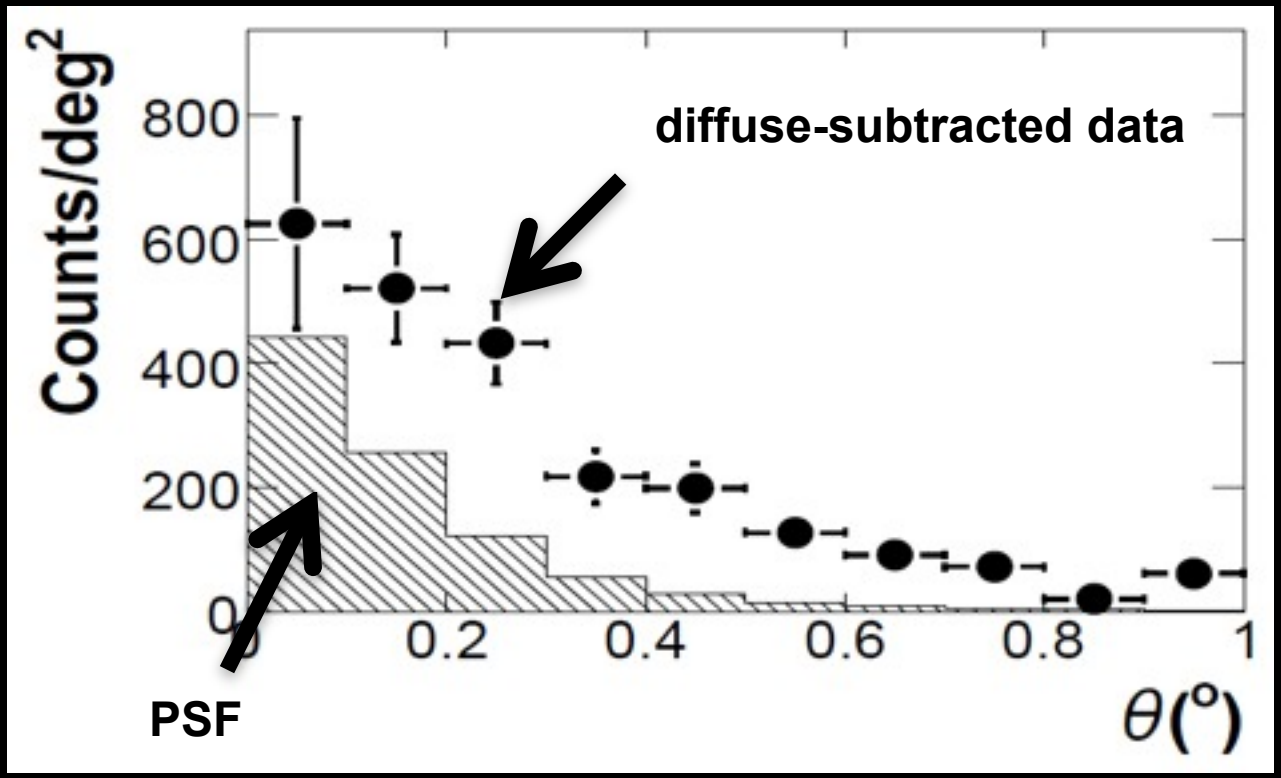
2-10GeV





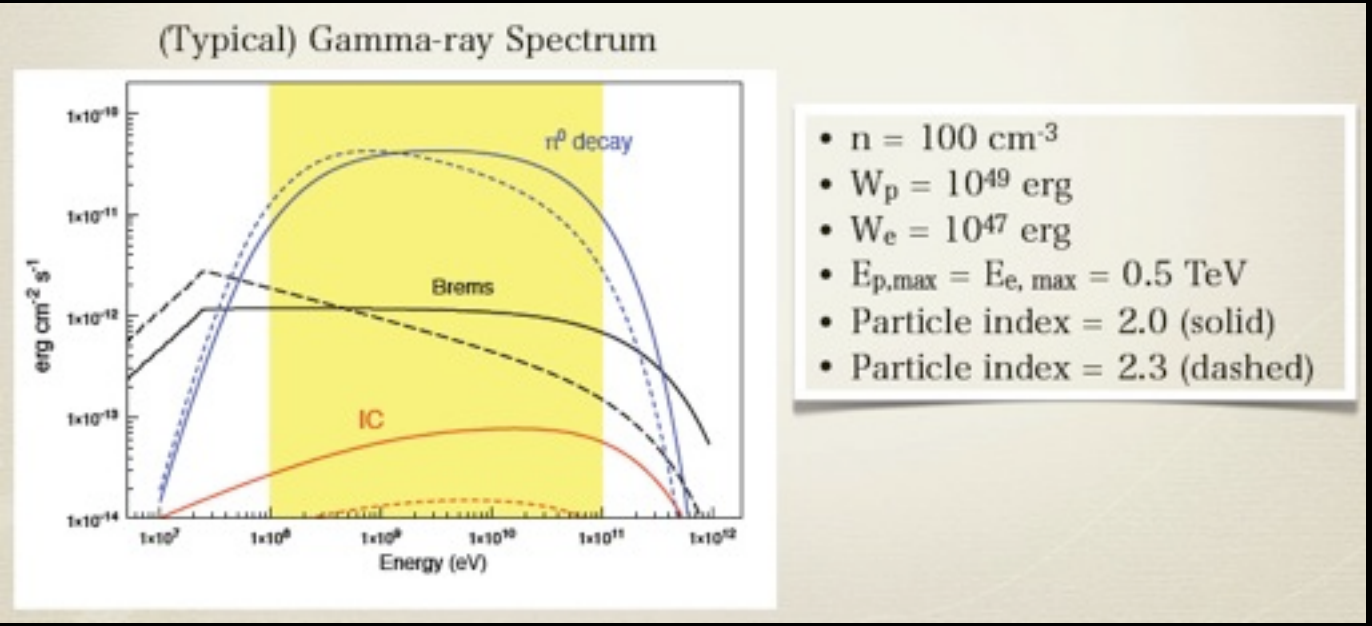
Extension

2.15-4.64GeV



- … again, clearly extended emission

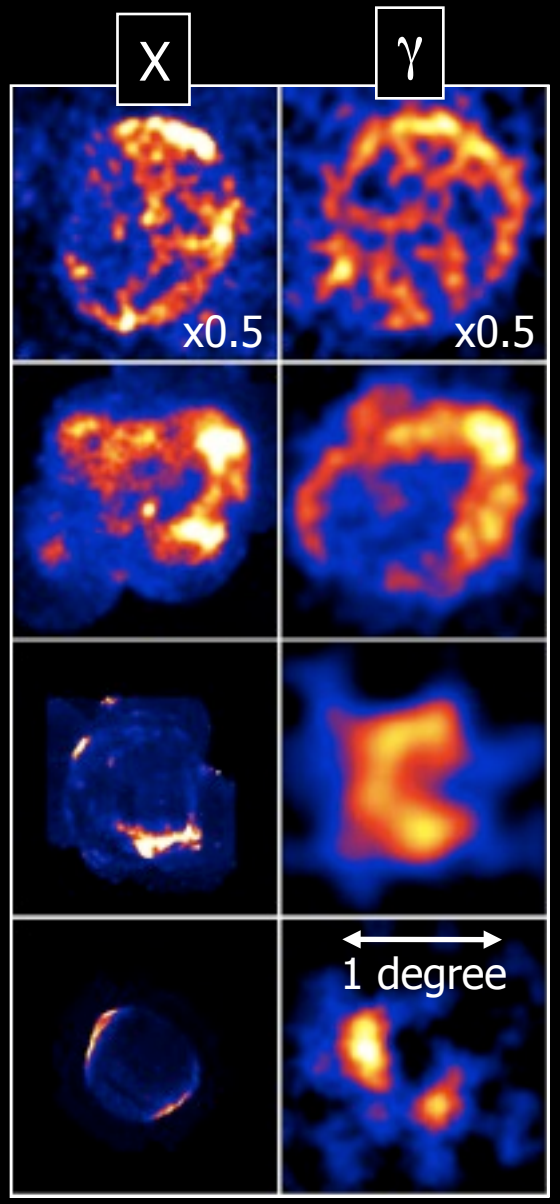
Origin of the GeV γ-rays



- Extended emission matching the radio extent
- Very large luminosity (W51: ~4×10^{35} erg/s at 6 kpc)
- Very faint in TeV (W51: 1% Crab, cf. 70% for RX J1713)
- Mid-aged SNR interacting with molecular cloud
- Similar pictures for W51C, W44, IC 443 and W28

… what do we learn from this?

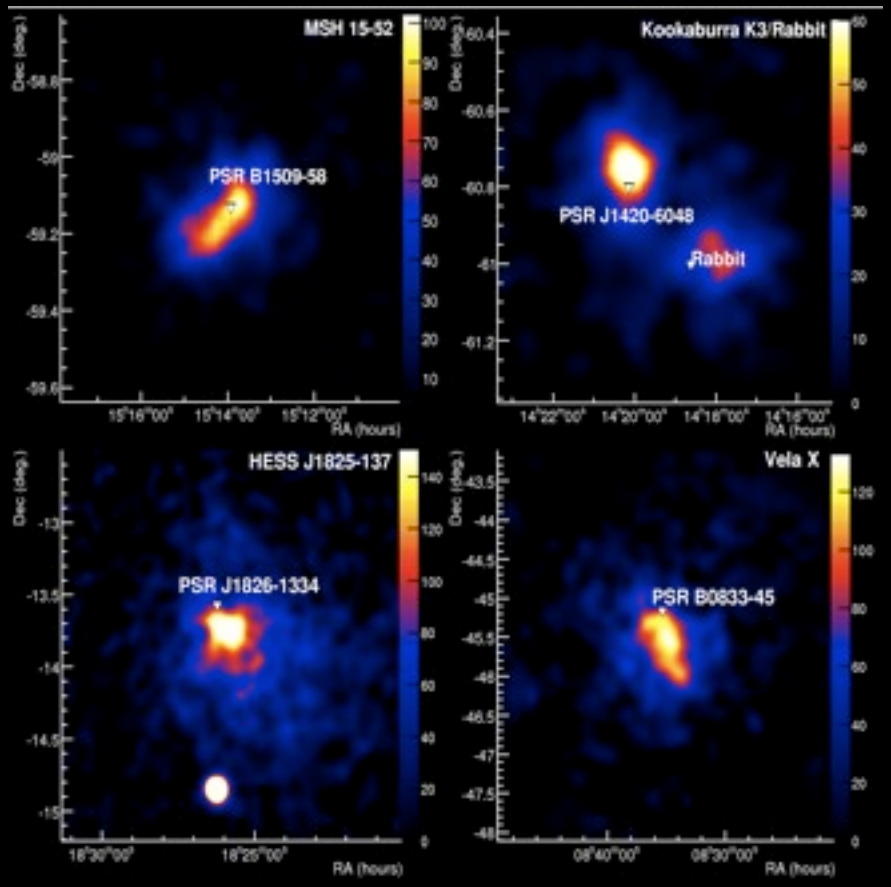
- Completely different picture to TeV gamma-rays:
  - Young SNRs are not bright Fermi-LAT GeV sources
  - Mid-aged SNRs interacting with molecular clouds can be extremely bright
    - Origin?



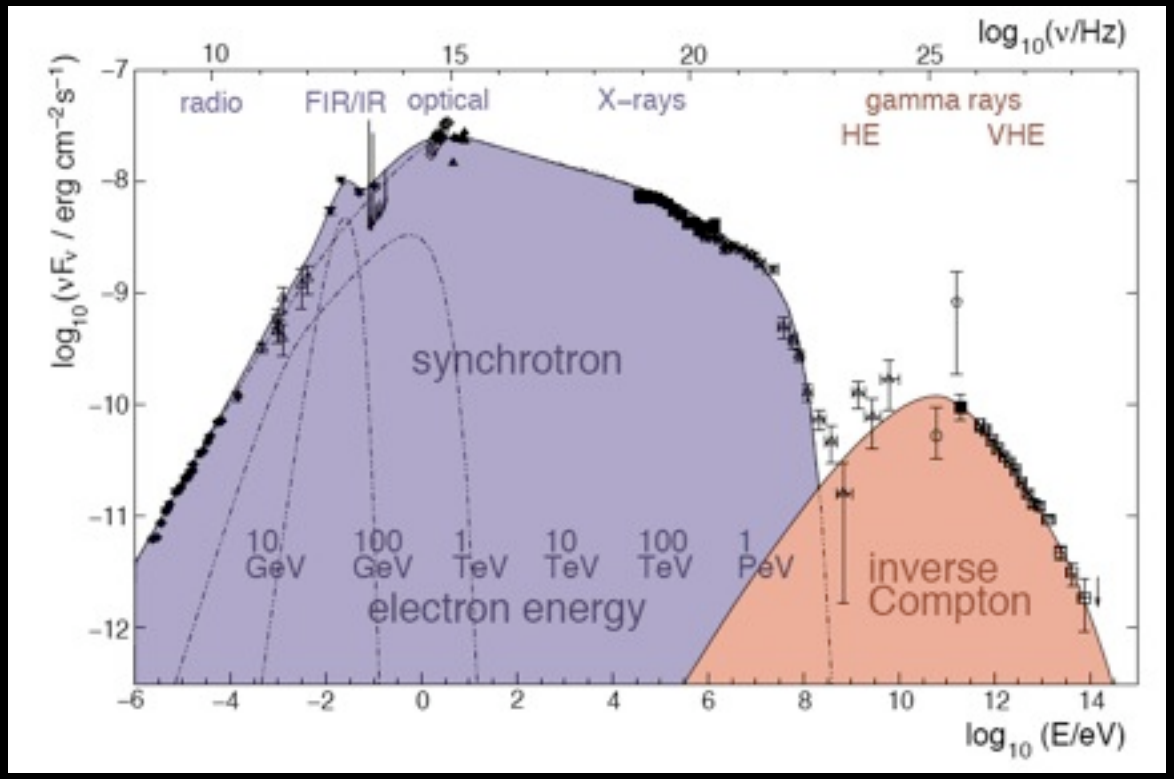
Pulsar Wind Nebulae

- Largest population of Galactic TeV sources
- Dominated by IC of relativistic electrons
- Prototypes:
  - Crab Nebula
  - Vela-X Nebula
  - MSH 15-52

Funk, 2007

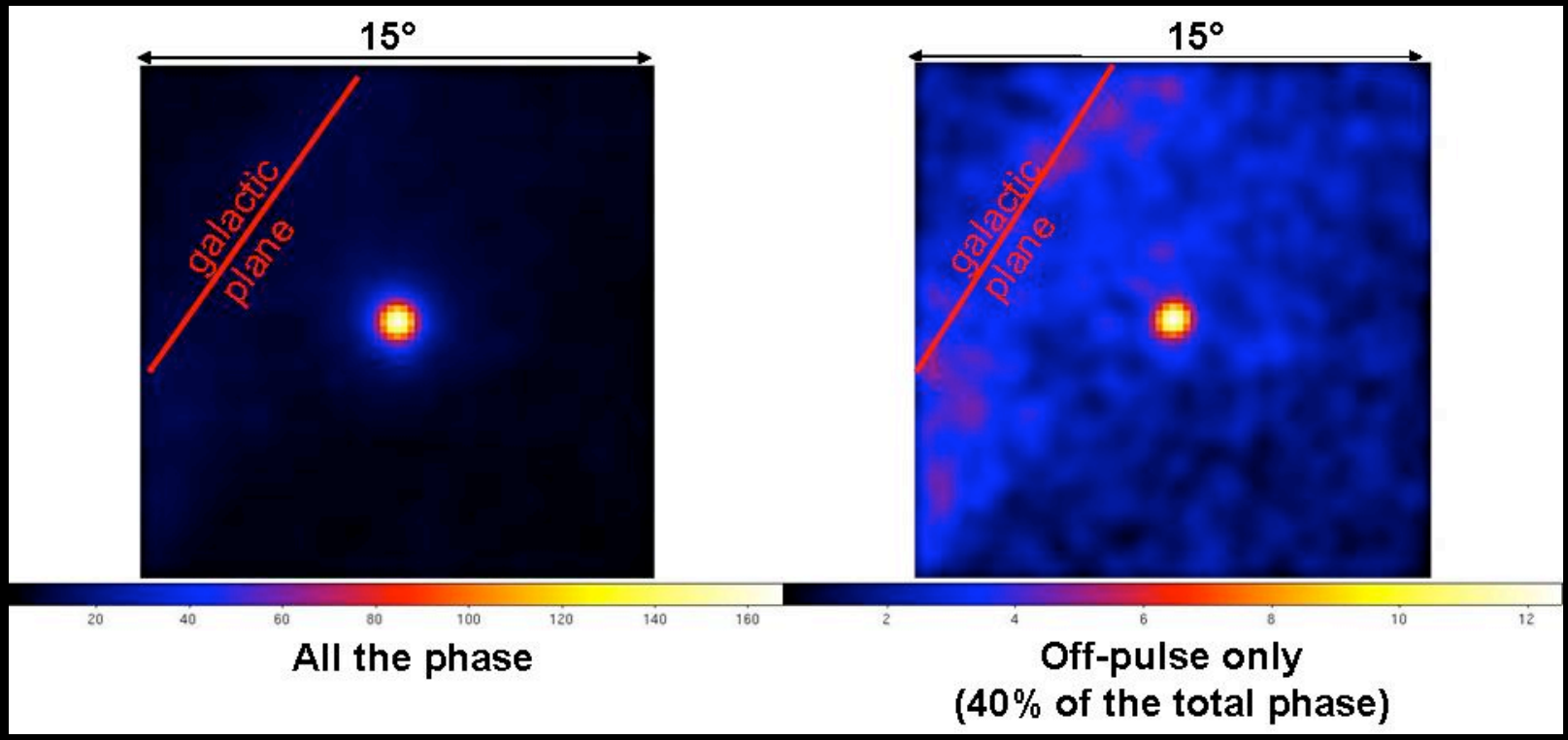


What do we expect?



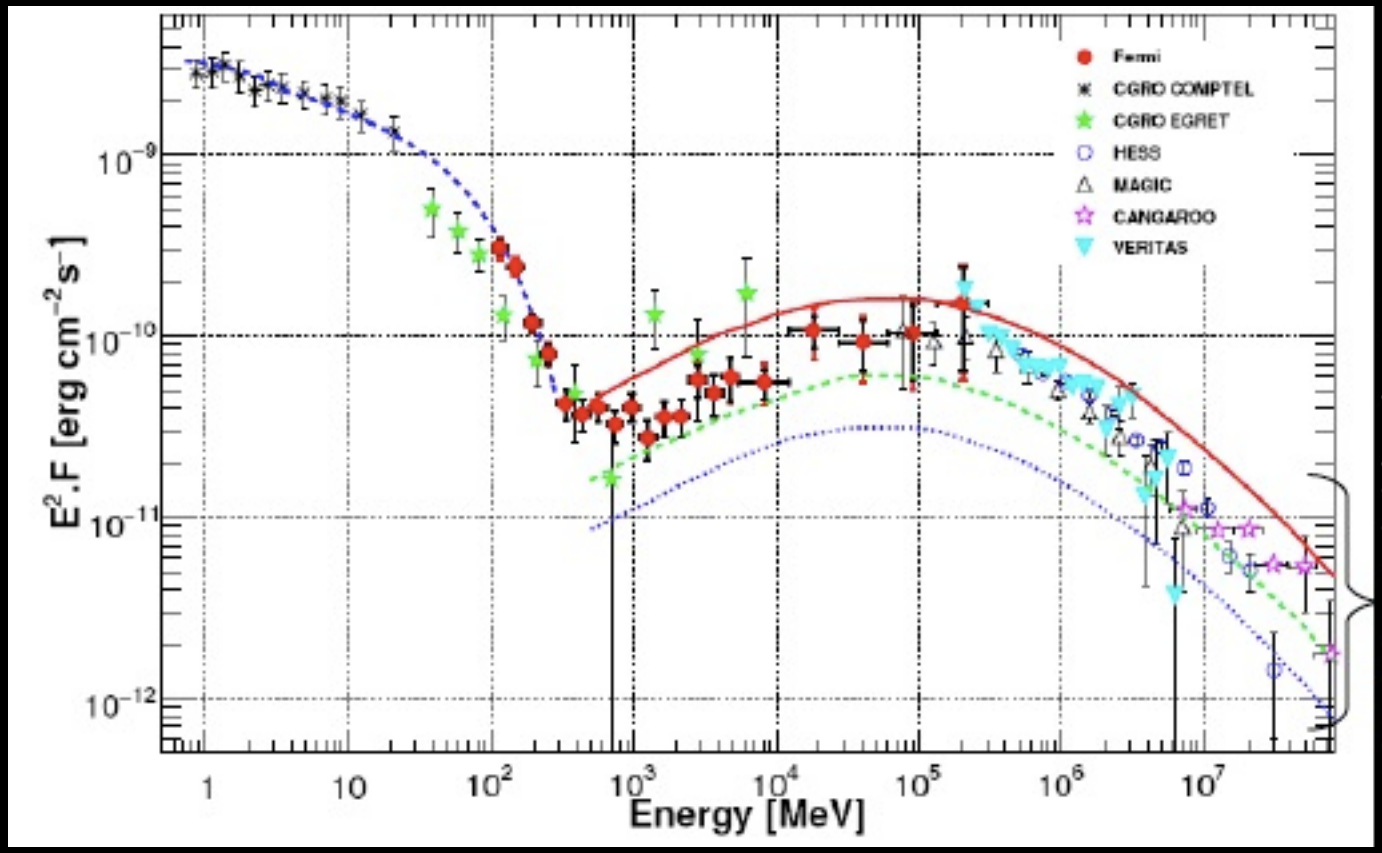
- TeV PWN might be harder to detect since IC component drops significantly when going to lower energies

The Crab Nebula



- Emission clearly detected in the off-pulsar phase

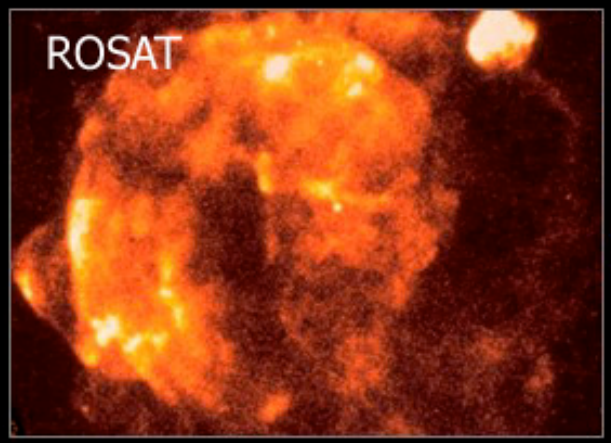
The Crab Nebula

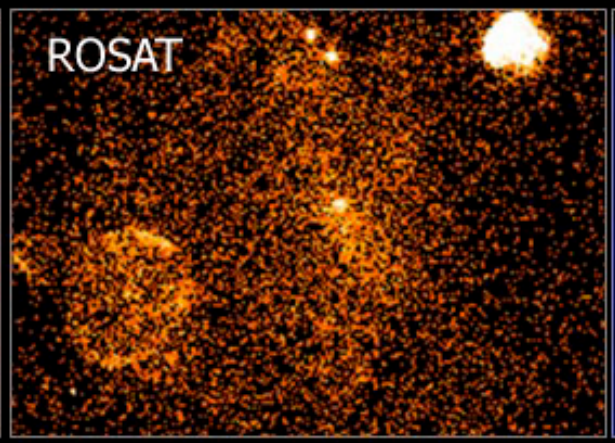


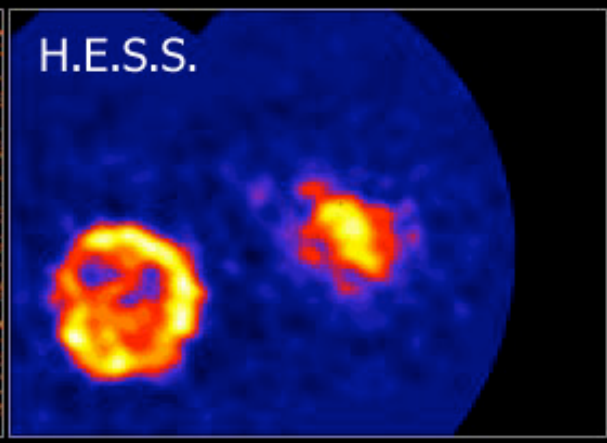
Predictions of Atoyan & Aharonian, MNRAS 1996,
100 μG
200 μG
300 μG

- Synchrotron cutoff at 100 MeV (Comptel + LAT)
- IC component suggests B-field 100-200 μG well below the equipartition field (300 μG)

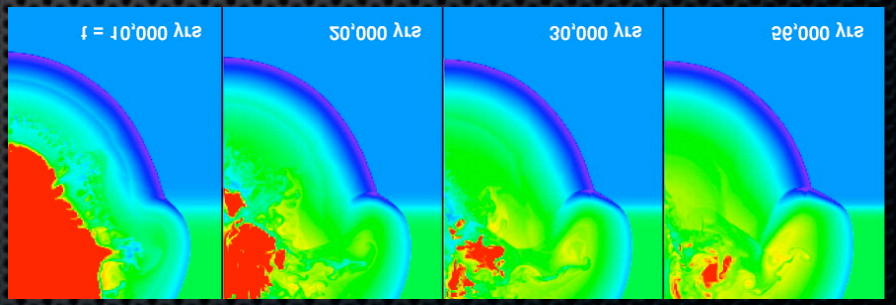
The prototype: Vela X







- Prototype crushed and evolved PWN (south of pulsar)
- Mid-aged Pulsar, very energetic
- X-ray emission (cocoon) matching the TeV emission



Blondin, 2001

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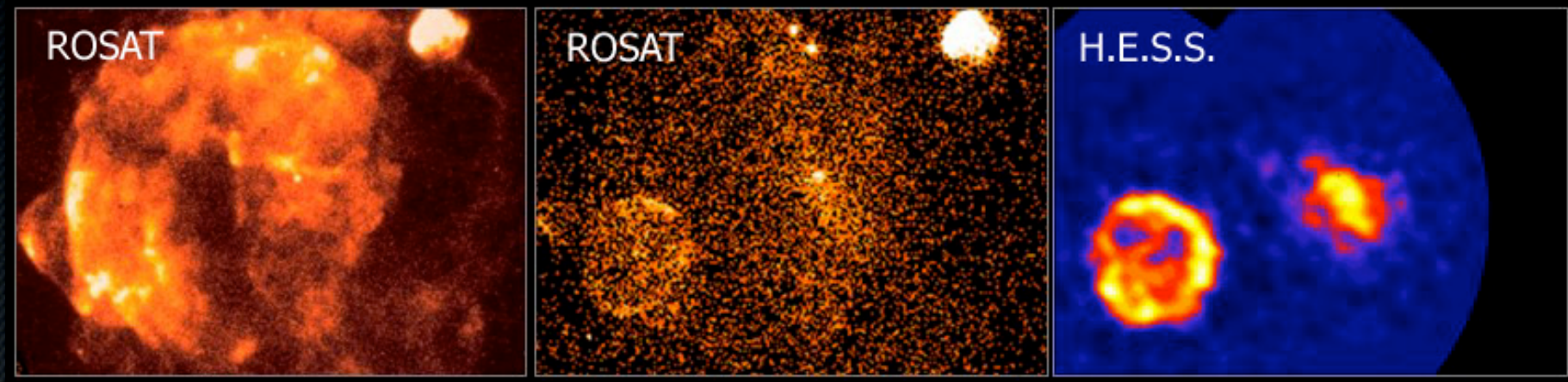
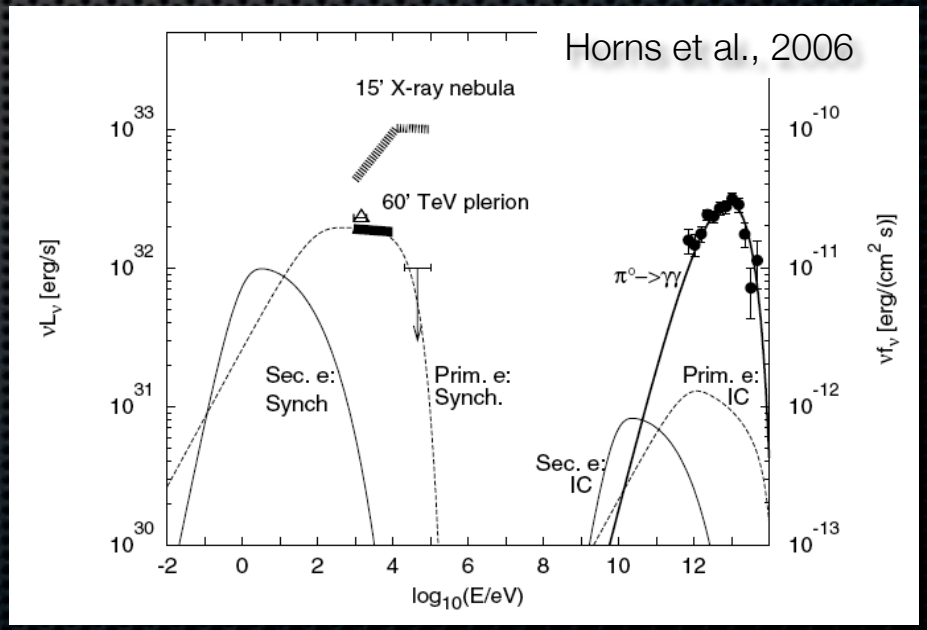


- Ions in the relativistic wind?
  - When looking only at the cocoon:
  - Only 10^{-3} of energy output of pulsar … where is missing energy?
  - Horns et al. 2005, gamma-ray flux hadronic?



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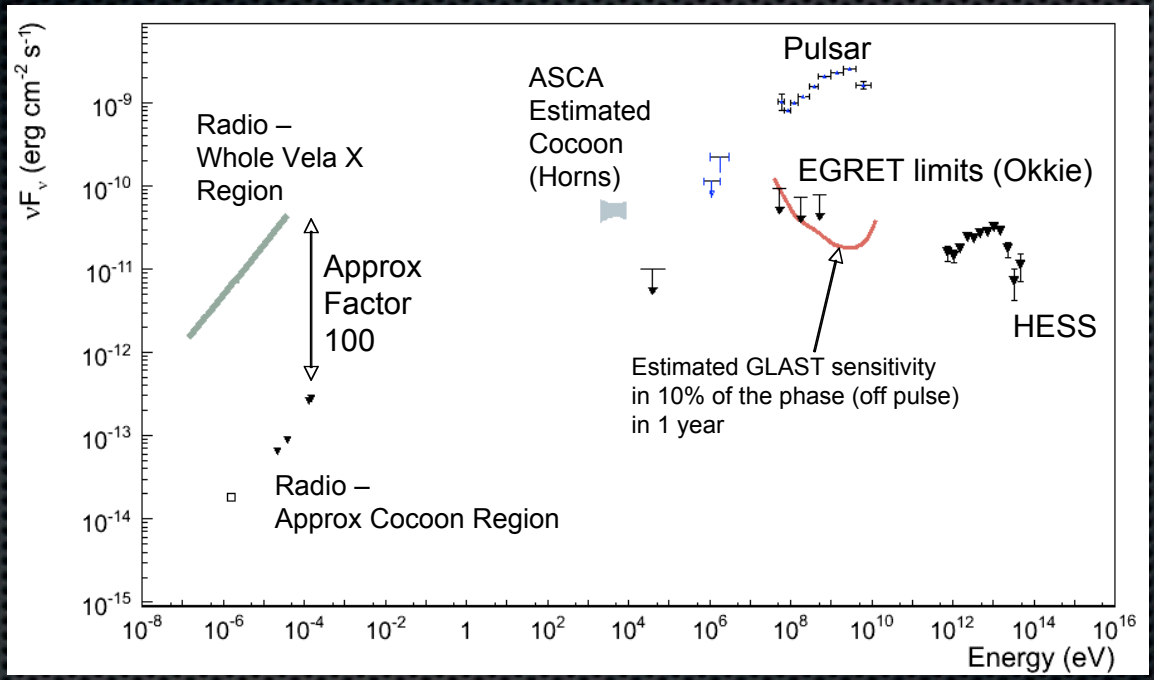

- SED well measured - need two population of electrons
- Cocoon: recently injected electrons (cooling feature)
- Larger radio PWN: older electrons related to higher-spin power of pulsar

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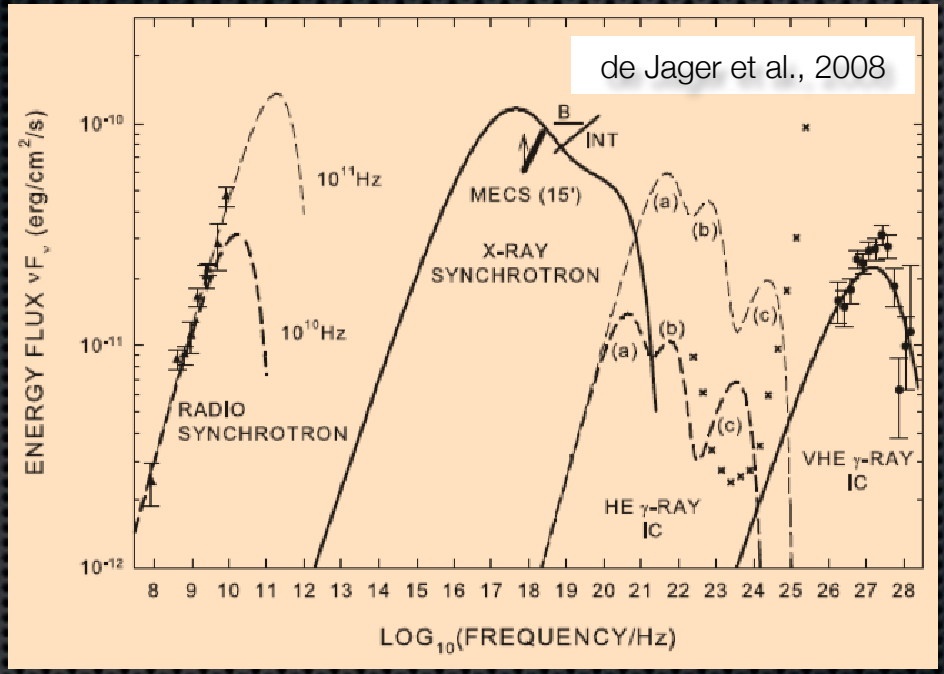

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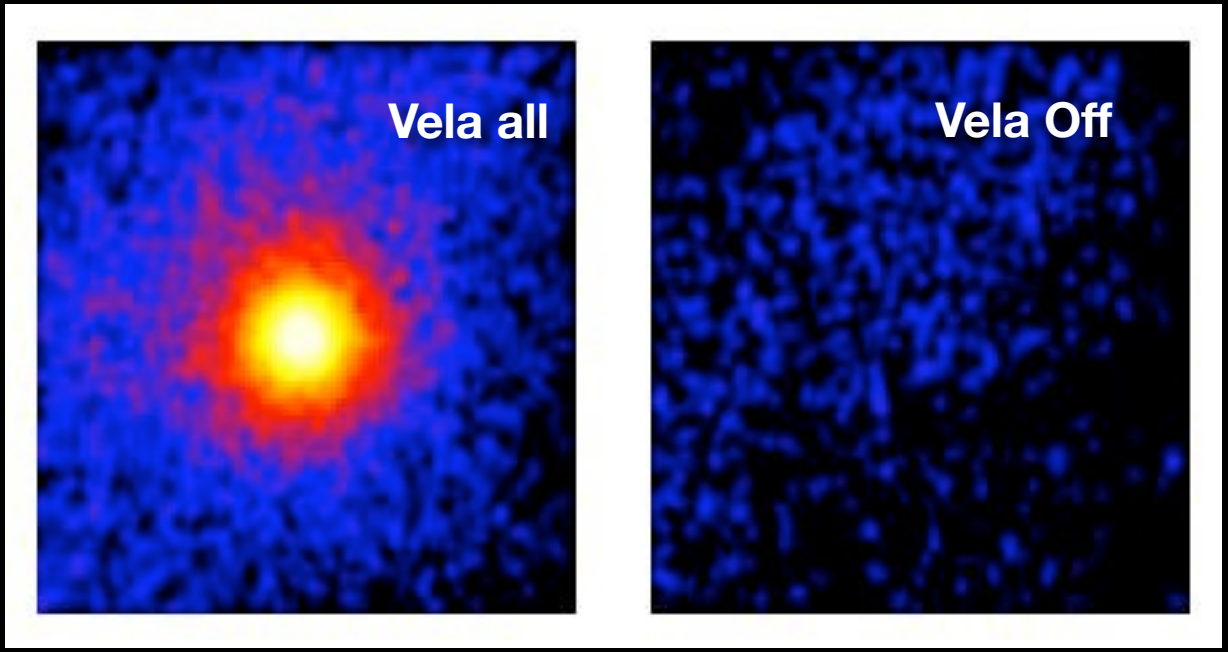
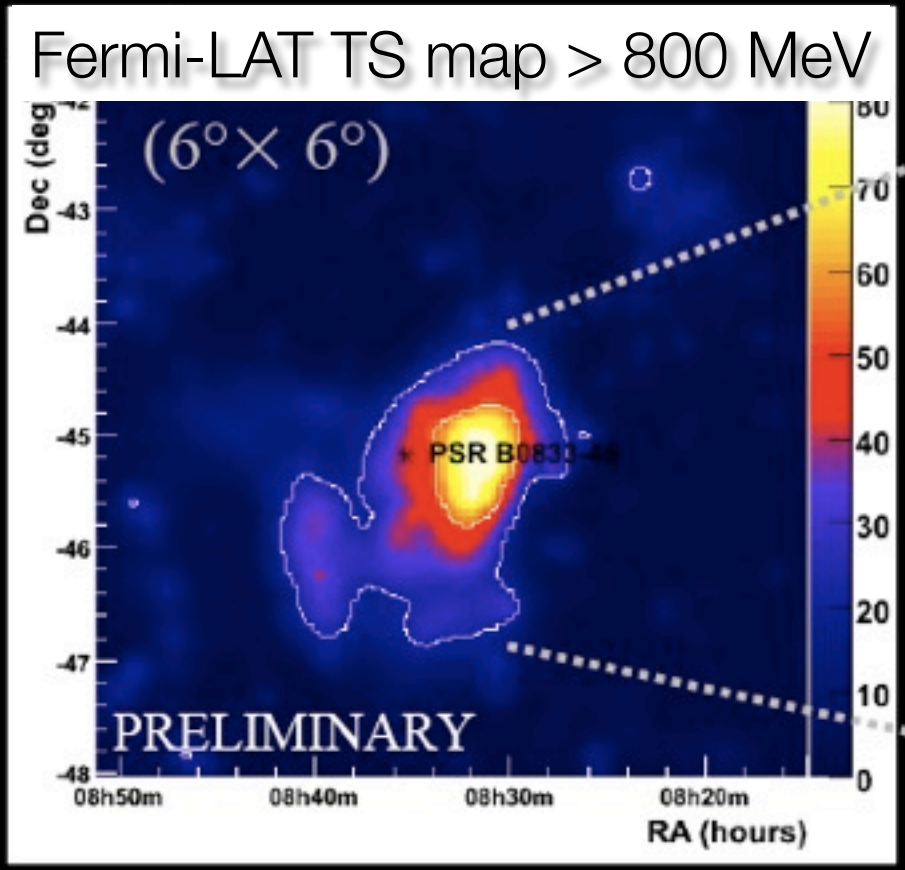
Vela X

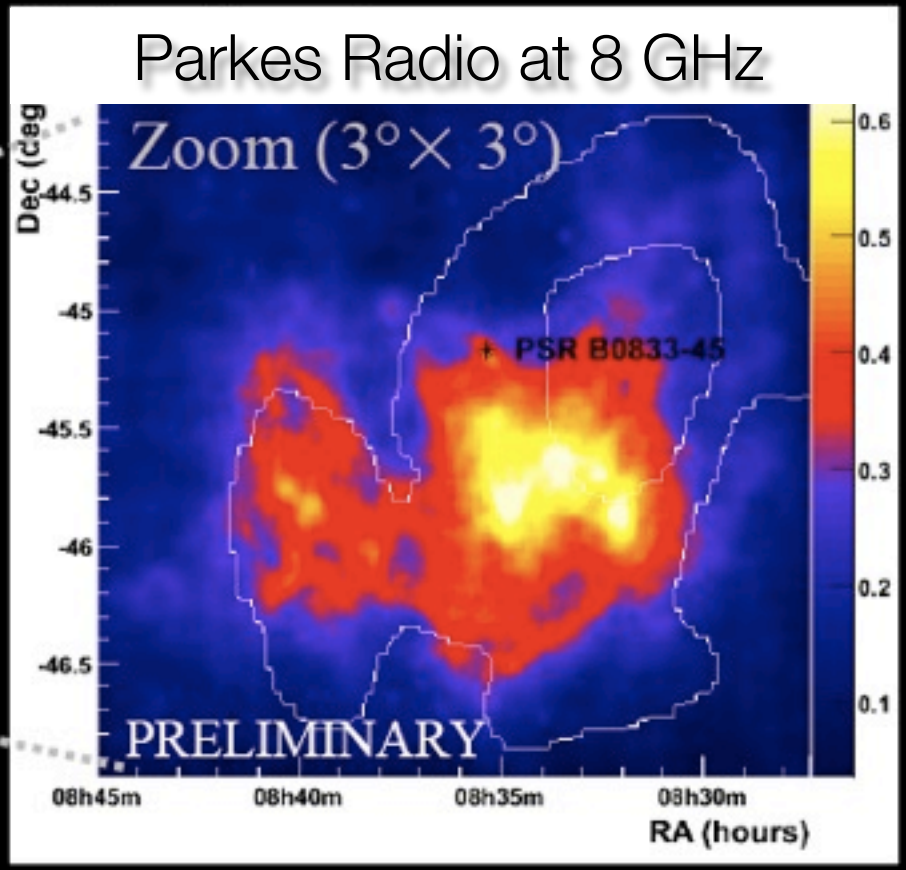


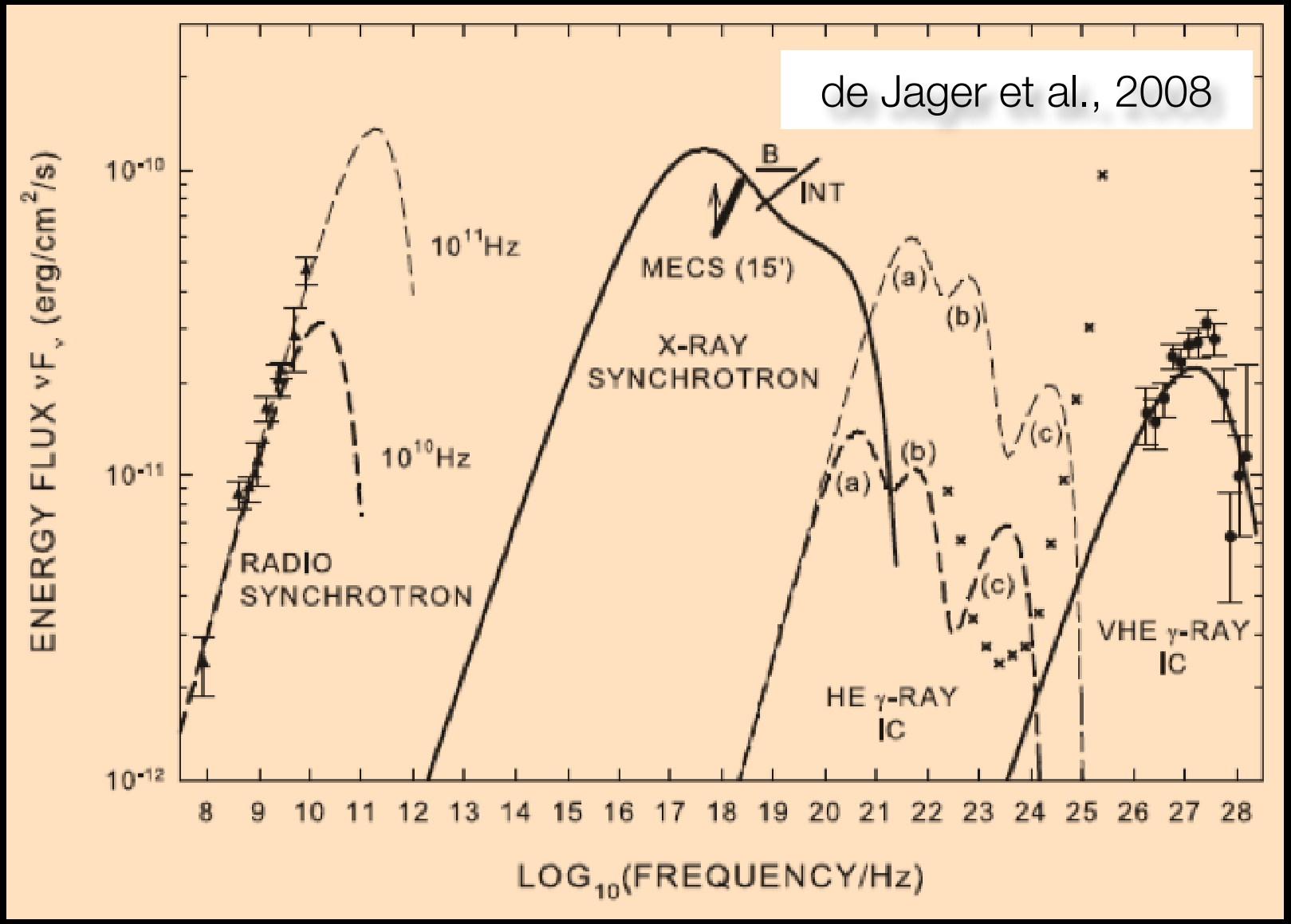
- Off-pulse emission of the brightest persistent GeV source
- In the original 3-month Vela publication we reported an upper limit

Vela X

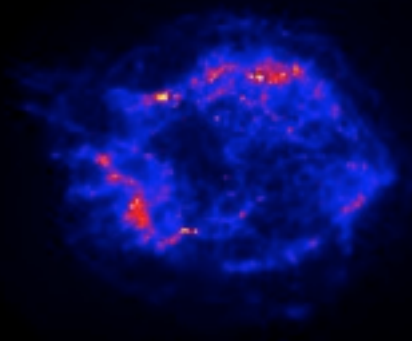
- After 9 months of data, extended source coinciding with radio emission clearly detected in the off data






de Jager et al., 2008
ENERGY FLUX νF_ν (erg/cm²/s)
10^-10
10^-11
10^-12
10^11Hz
10^10Hz
RADIO SYNCHROTRON
B
INT
MECS (15')
X-RAY SYNCHROTRON
(a)
(b)
(c)
(a)
(b)
(c)
HE γ-RAY IC
VHE γ-RAY IC
8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28
LOG10(FREQUENCY/Hz)

Summary



- Fermi-LAT starts to release results on extended sources in the Galactic plane coinciding with SNRs and PWNe
  - These are amongst the hardest sources to analyse with the Fermi-LAT
- Having GeV to TeV coverage plus radio and X-ray will severely constrain models of emitting particle populations
- Mid-aged SNRs interacting with molecular clouds are bright GeV gamma-ray sources.