H.E.S.S. Observations of the LMC

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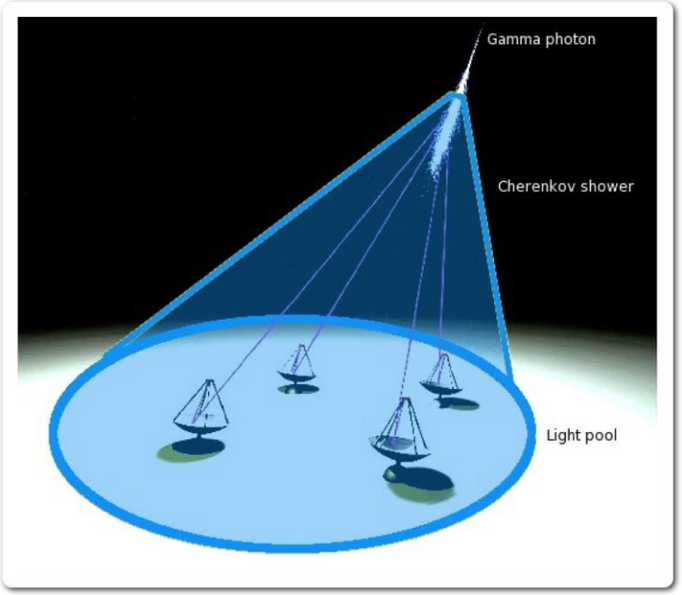
What is the Large Magellanic Cloud?

- a satellite galaxy of the Milky Way
- ~10° diameter (20x full moon)
- extension: 8 kpc
- distance: 50 kpc
- inclination: 31°

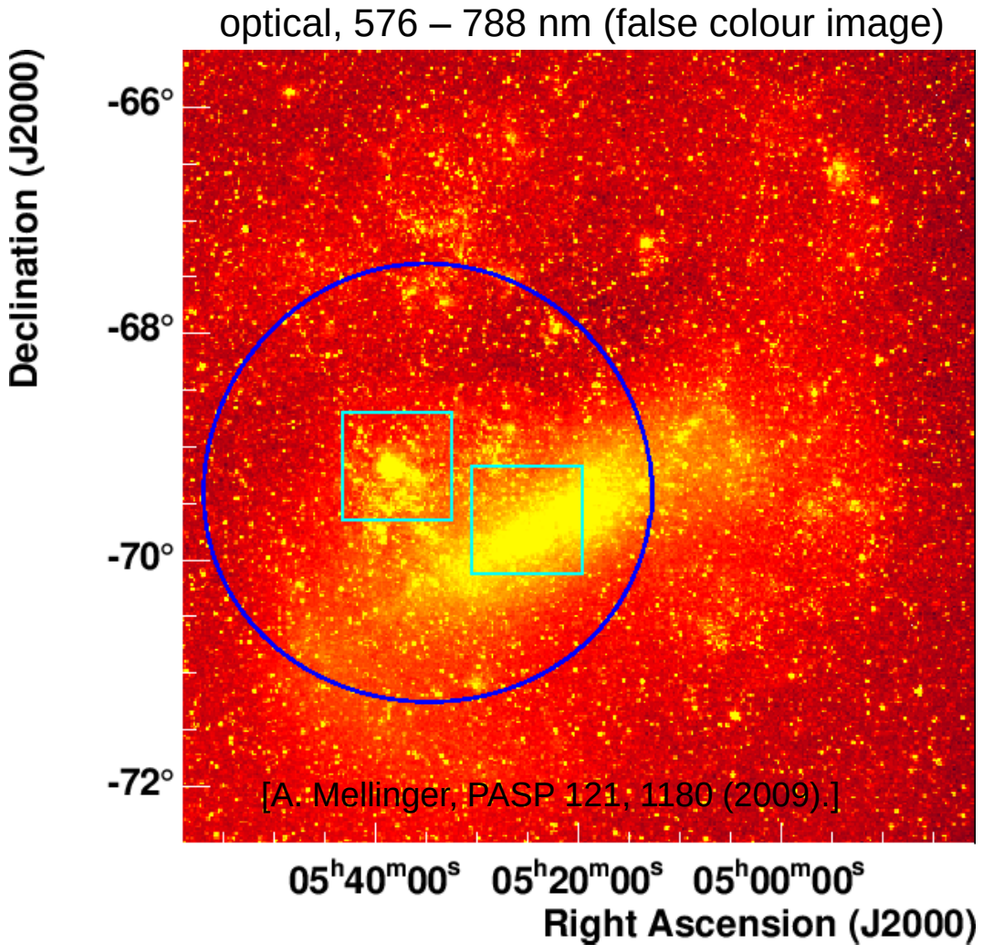
High Energy Stereoscopic System

- 5 Imaging Cherenkov Telescopes
  - record Cherenkov light of air showers
- 5° field of view (CT 1–4)
- 100 GeV ... tens of TeV
- Namibia → only instrument for TeV observations of the LMC
- data presented here: H.E.S.S. phase I → only 4 telescopes

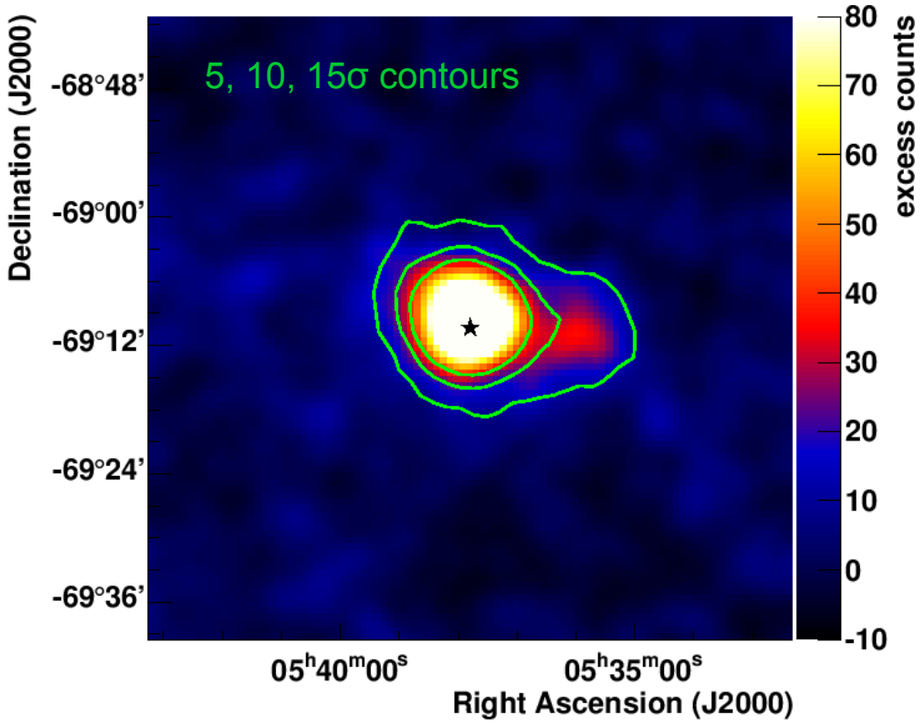


H.E.S.S. LMC Observation Campaign

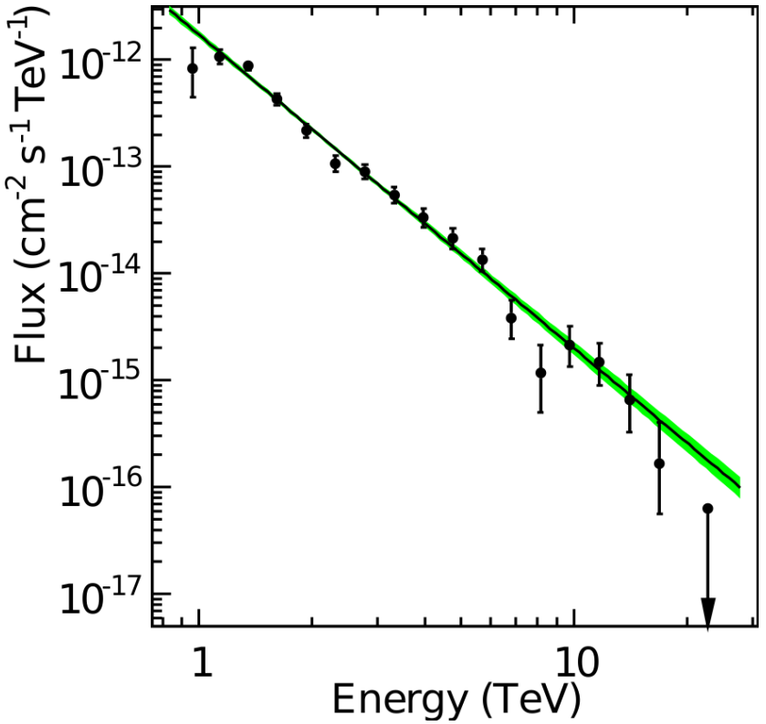
- time line:
  - 2004: start with SN 1987A
  - 2009: 49 h (published 2012)
  - 2013: 210 h (this talk)
- observation conditions
  - large zenith angle (45° - 52°)
  - → energy threshold ~700 GeV
- spatial coverage:
  - roughly: 2° around N 157B
    - contour line: 2° mean camera offset
  - main targets: N 157B, SN 1987A (Tarantula nebula)
  - secondary target: N 132D



The Pulsar Wind Nebula N 157B Revisited



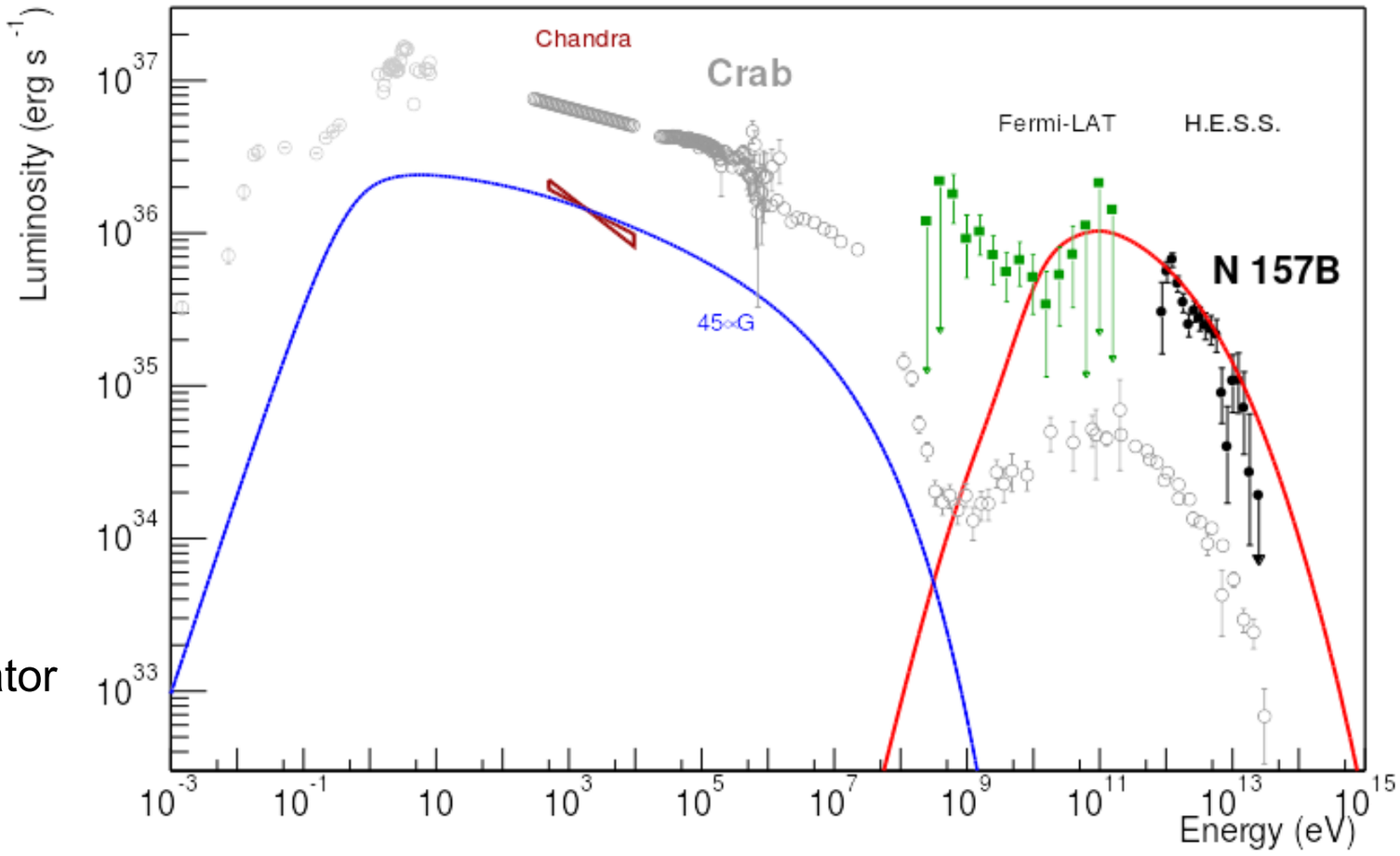
- 613 gamma rays, 33 σ
- confirms previous result [H.E.S.S. *A&A* **545**, L2 (2012)]



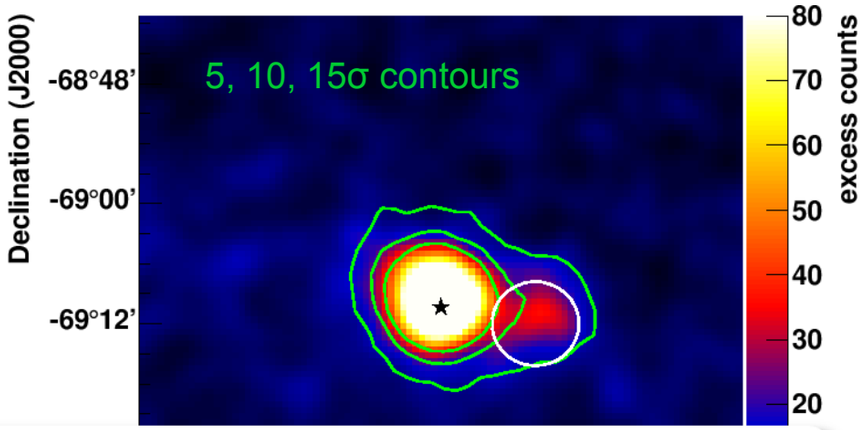
- spectral index 2.8 ± 0.1
- no significant spectral cut-off
- $L_{1\text{-}10\ \mathrm{TeV}}(50\ \mathrm{kpc}) = (6.8 \pm 0.3)\ 10^{35}$ erg/s
- under-estimation of flux in 2012:
  - imperfect modelling of instrument response

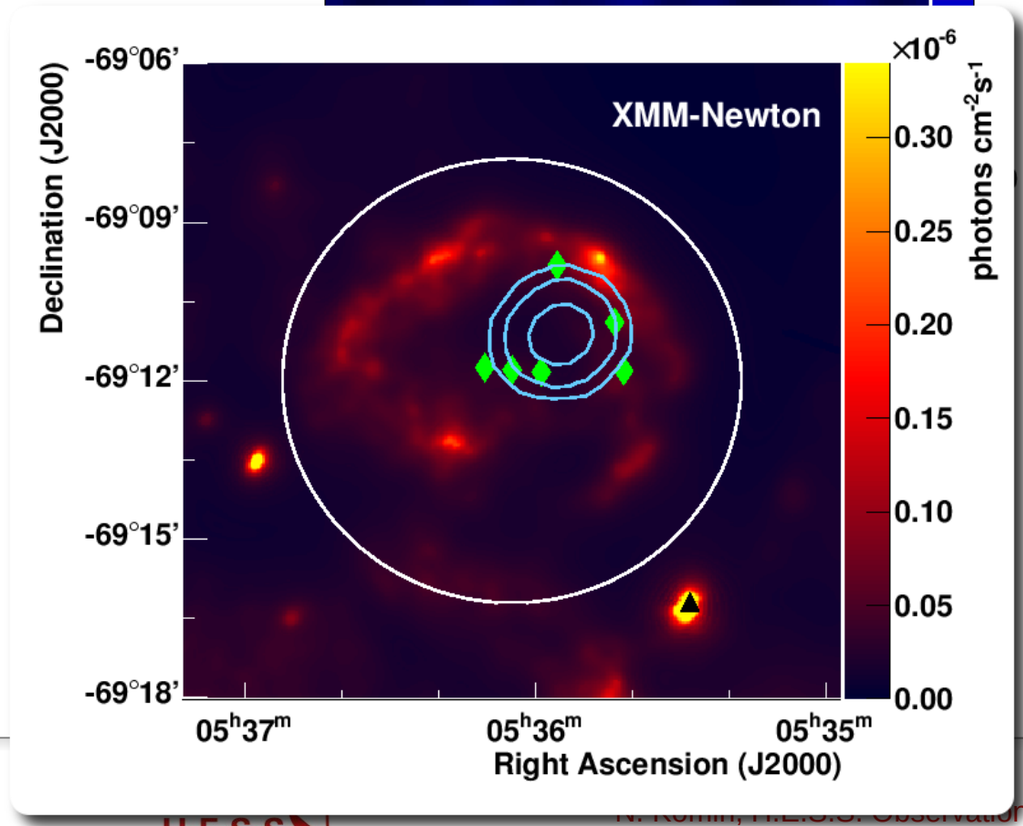
The Pulsar Wind Nebula N 157B Revisited

- pulsar wind nebula powered by PSR J0537–6910 ($\dot{E}$ = 4.9 10^{38} erg/s)
- inverse Compton emission on strong infra-red fields → bright in gamma rays
- X-ray synchrotron emission
  → low magnetic field of 45 μG
- constant injection of 11% $\dot{E}$
  into electrons >400 GeV
- Milky Way counterpart:
  - Crab Nebula
  - $\dot{E}$ = 4.5 10^{38} erg/s
  - same model
    - 123 μG
    - 50% $\dot{E}$
- → N 157B apparently inefficient accelerator
- new *Fermi* results: 2nd component?



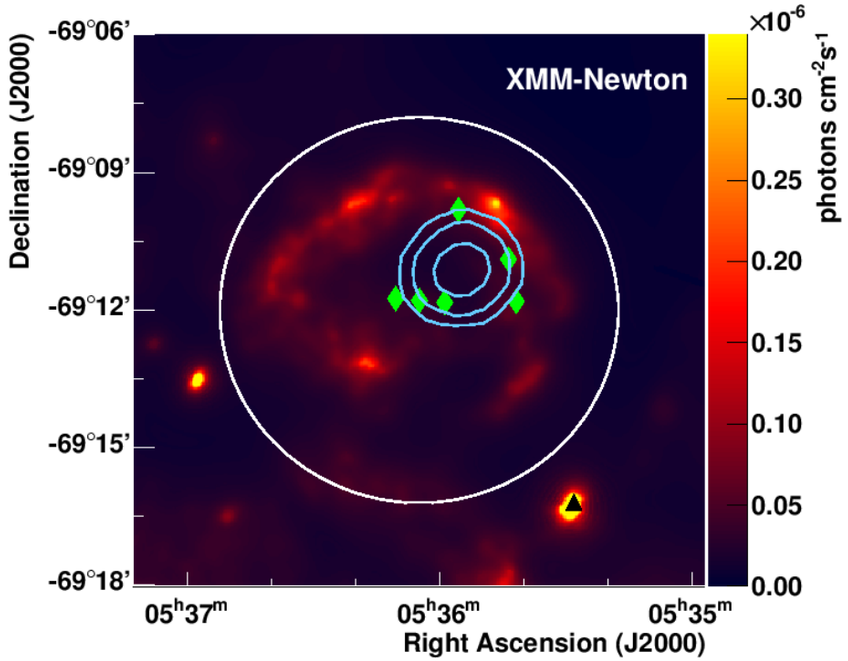
New Source Discovery



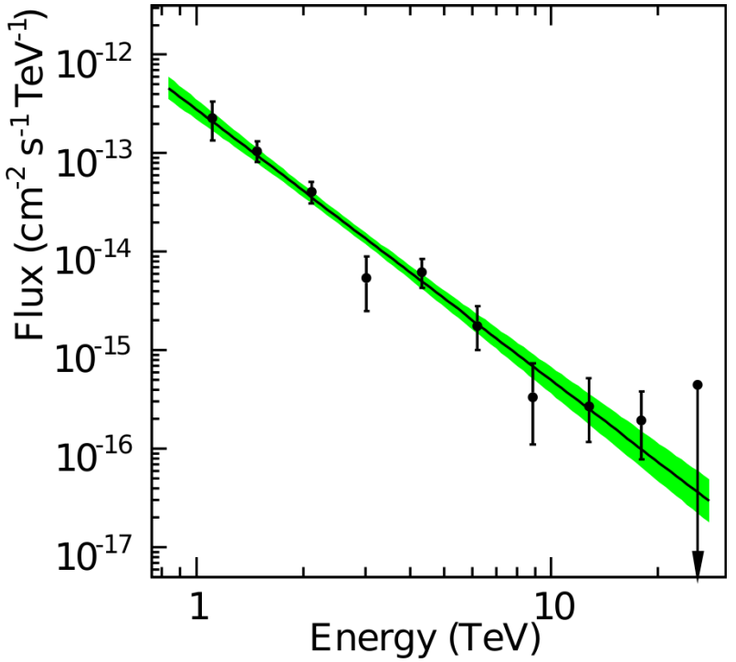


- additional emission SW of PWN
  - 130 pc at 50 kpc
- >5 σ above spill-over
- two-source morphology favoured by 8.8σ
- position (contours) compatible with
  - shell of superbubble 30 Dor C
  - star clusters of LH 90 (·)
- not compatible with SN 1987A (▲)
- note: angular resolution does not allow conclusion on morphology

The Superbubble 30 Dor C

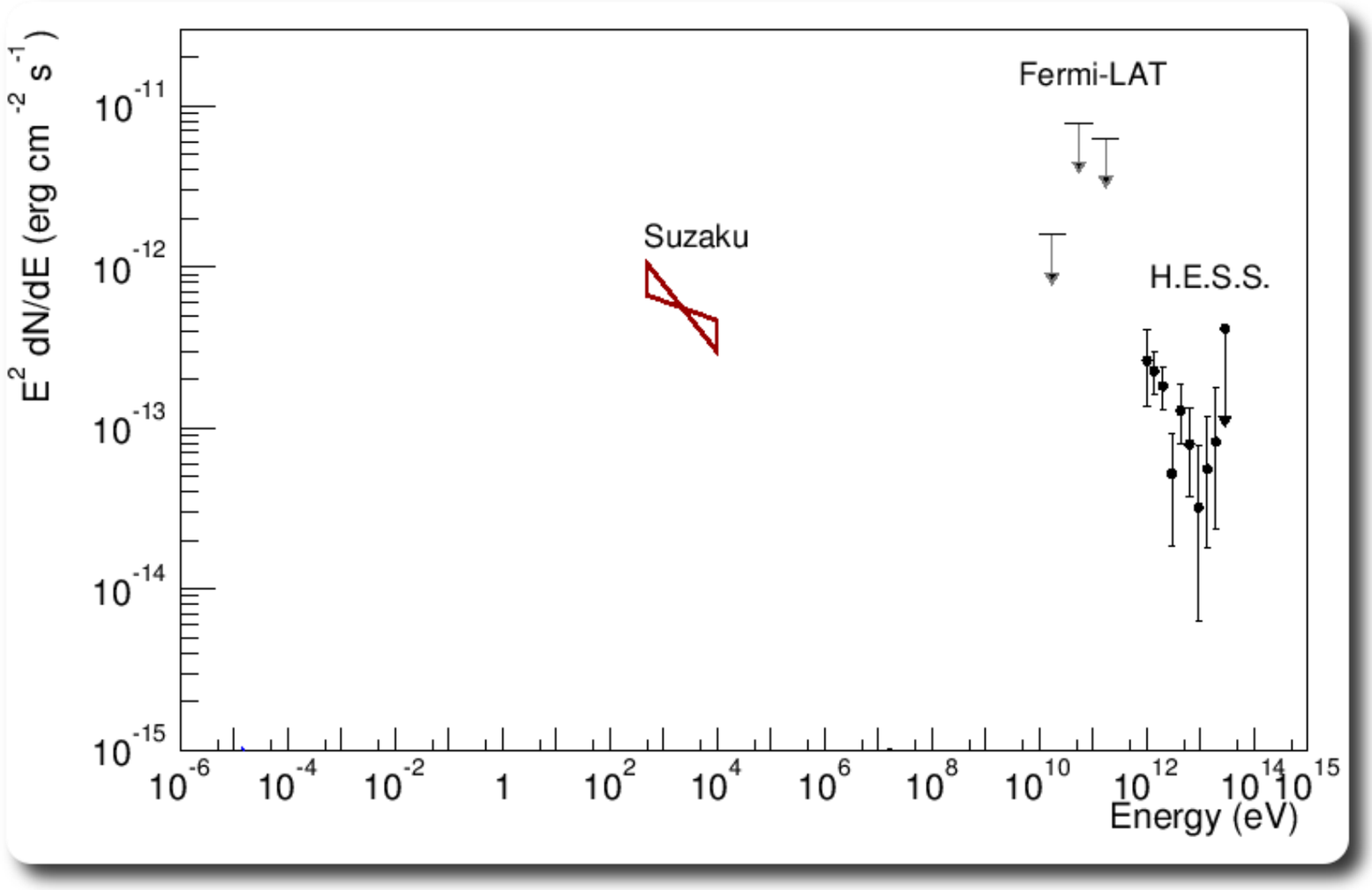


- non-thermal X-rays from shell
- → TeV emission from shell likely
- alternative scenarios
  - SNR
  - unseen pulsars/PWN
  - background AGN



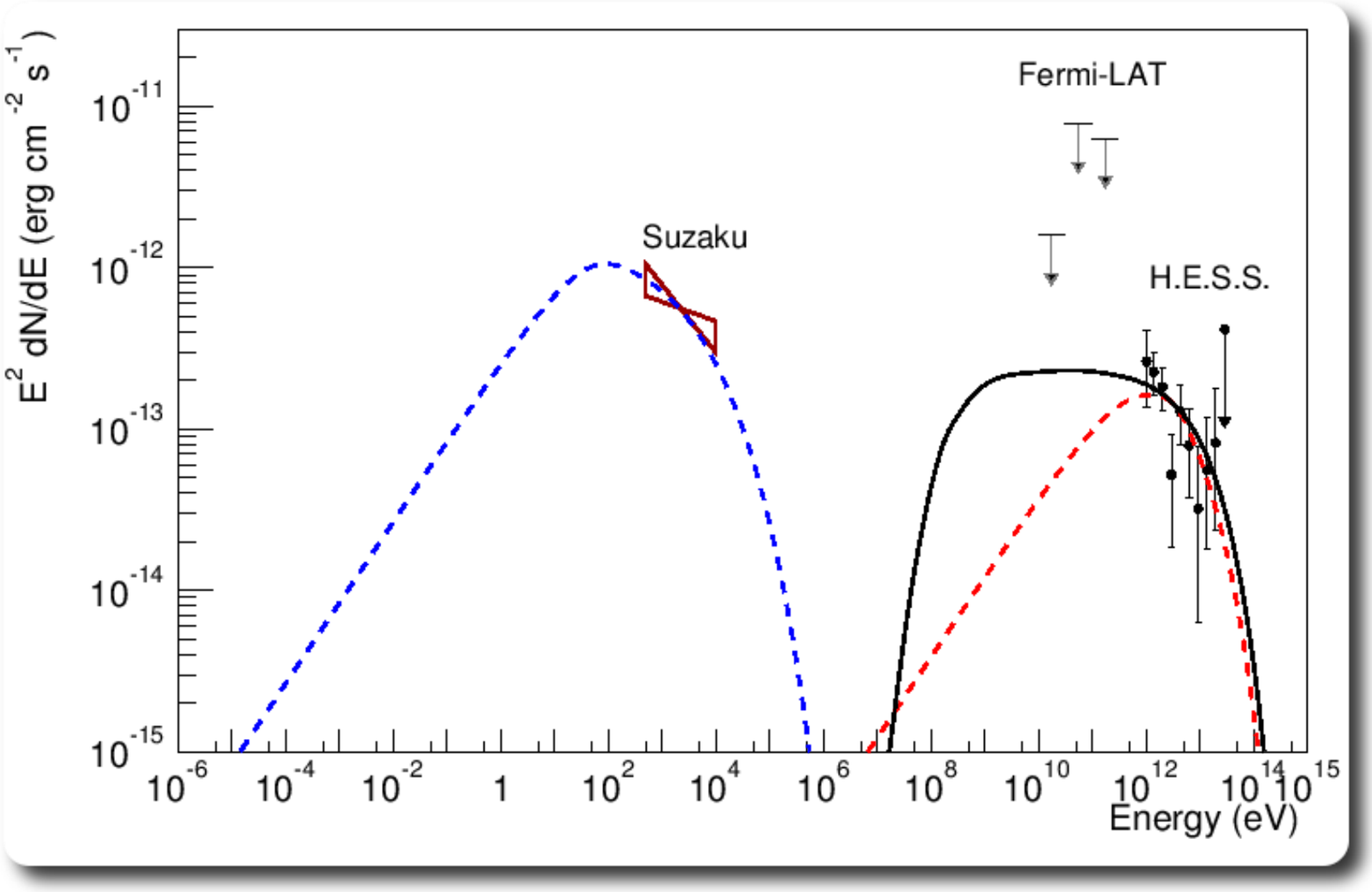
- spectral index 2.6 ± 0.2
- $L_{1\text{-}10\ \mathrm{TeV}}(50\ \mathrm{kpc}) = (9 \pm 2)\ 10^{34}$ erg/s
  - corrected for N 157B spill-over

The Superbubble 30 Dor C



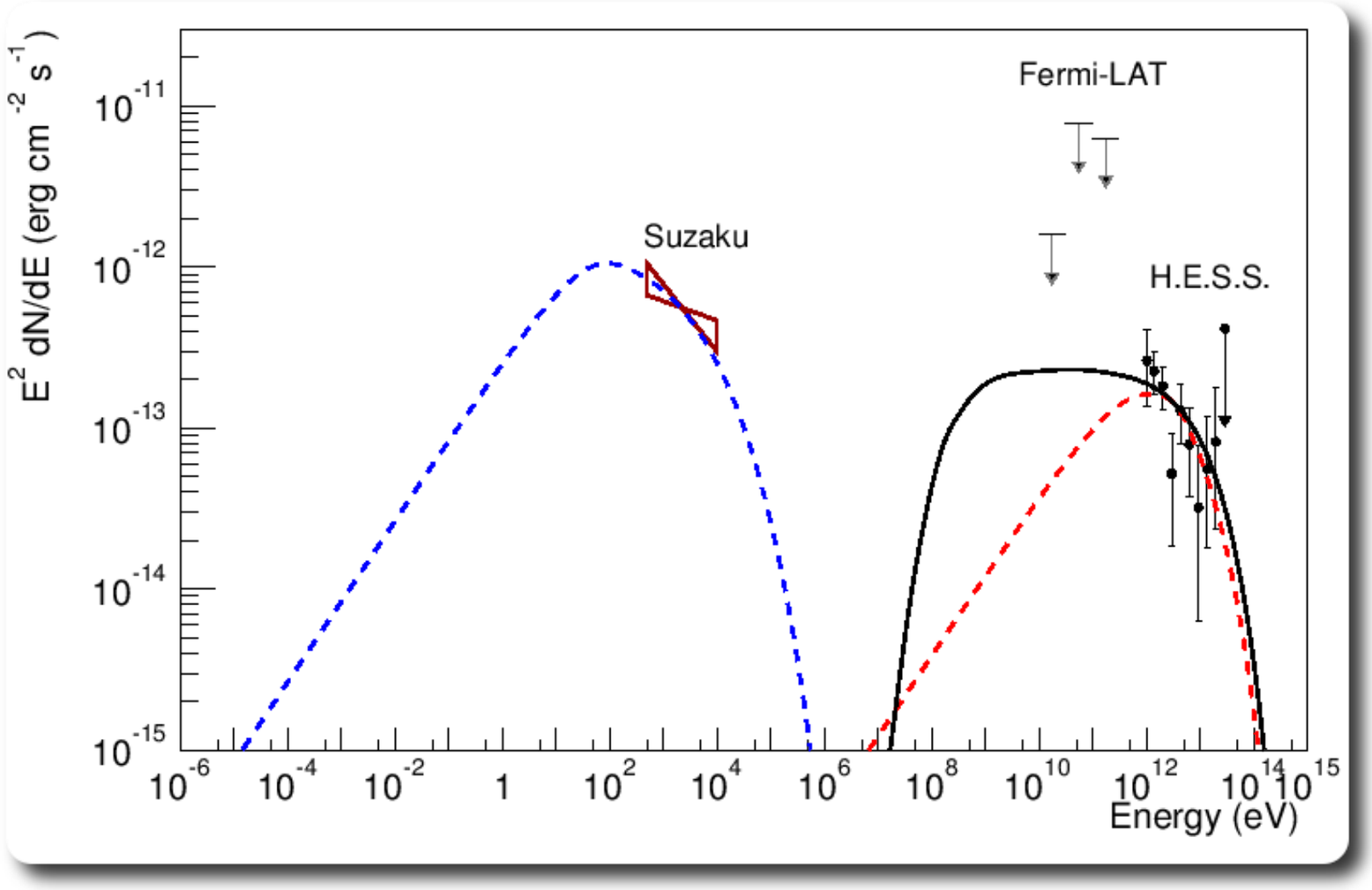
The Superbubble 30 Dor C

- **hadronic scenario**
- energy in protons
  W_{pp} = (0.7 – 25) x 10^{52} (n_H / 1 cm^{-3})$^{-1}$ erg
- even for 5 supernova explosions
  high density needed: n_H > 20 cm^{-3}
  - thermal X-rays indicate low density:
    n_H ~ 0.4 cm^{-3}
    [Bamba et al. 2004]
- **leptonic scenario**
- low magnetic field:
  ~15 μG
- 4 x 10^{48} erg in electrons



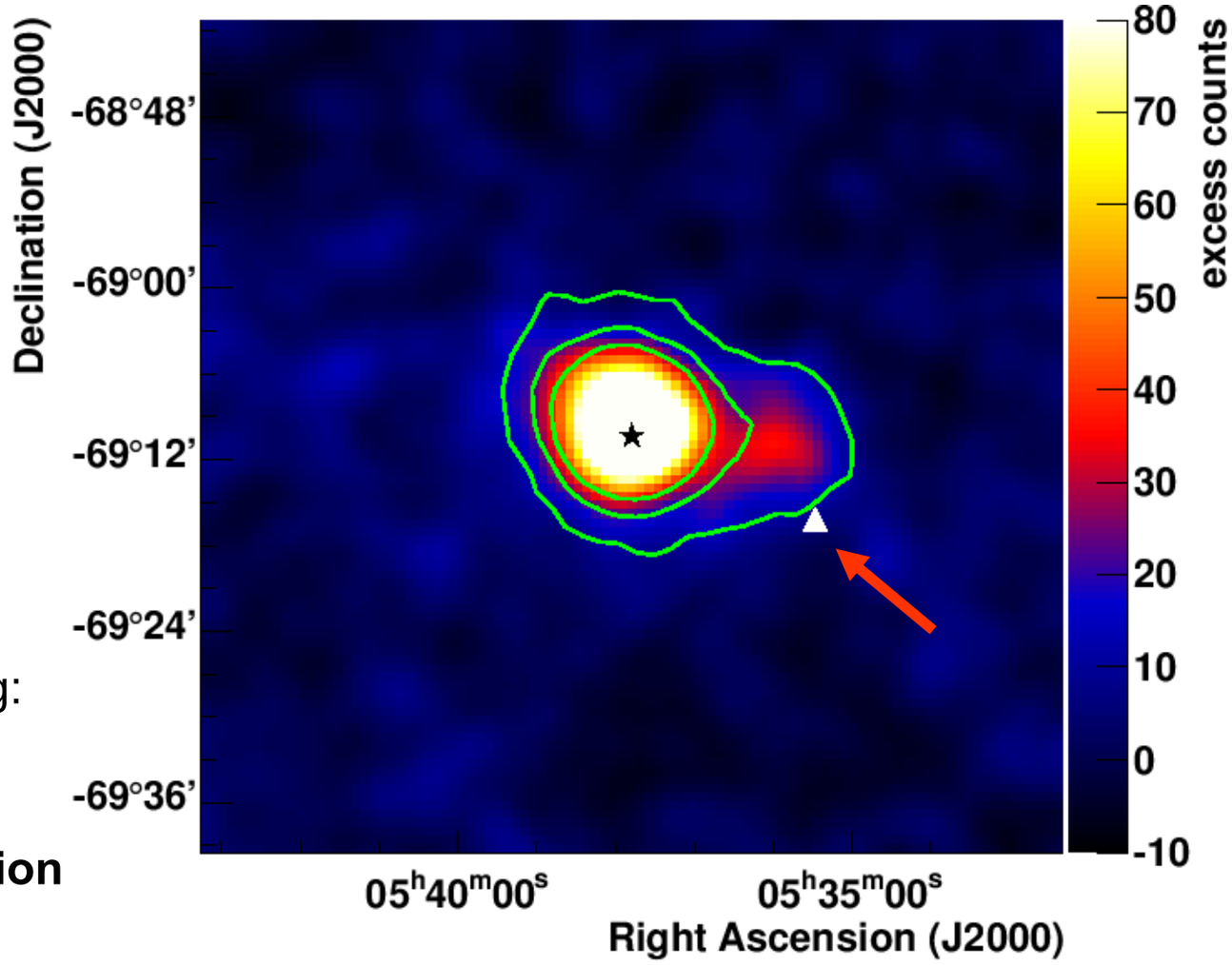
The Superbubble 30 Dor C

- hadronic or leptonic: no model favoured
- but: evidence for efficient particle acceleration in a superbubble
- first unambiguous detection of a superbubble in gamma rays
- Galactic counterpart: Westerlund 1
  - emission from PWN?



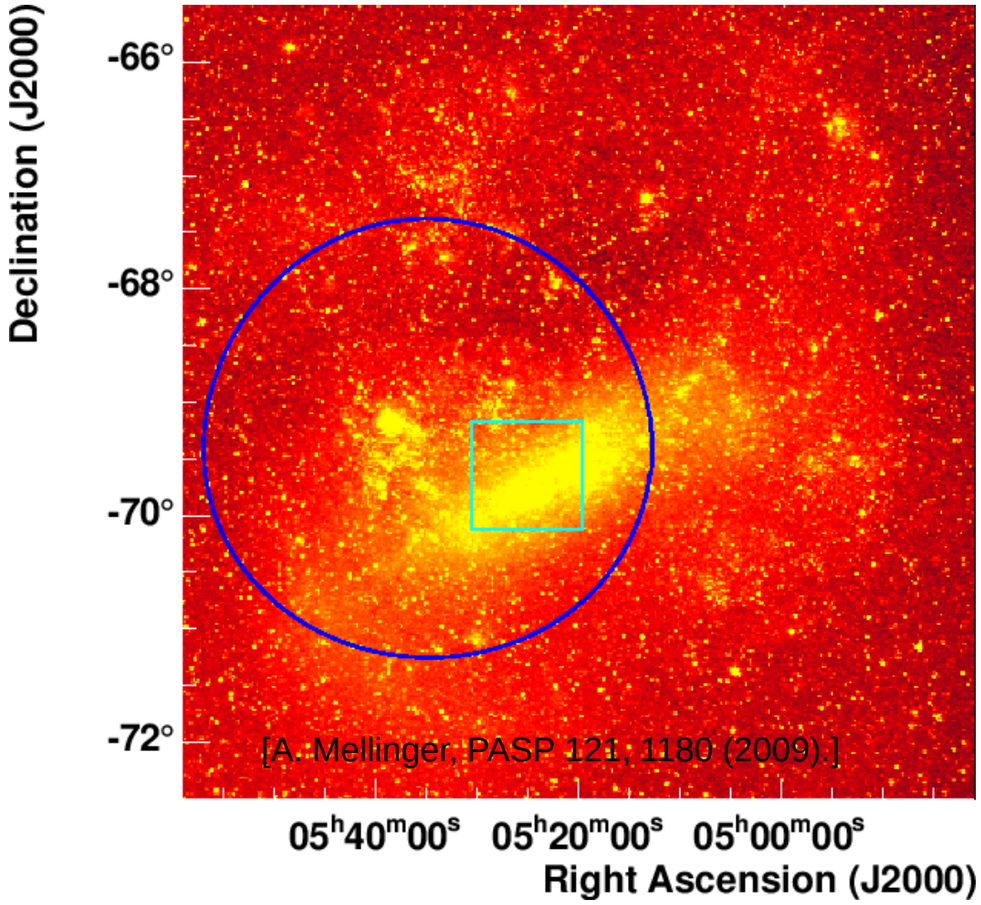
The Supernova Remnant of SN 1987A

- **not detected**
- gamma ray flux F (>1 TeV) < 5 x 10^{-14} $cm^{-2}s^{-1}$
  - 99% confidence level
- gamma ray luminosity L (>1 TeV) < 2.2 10^{34} erg/s
- **hadronic scenario**
  - predicted
    Berezhko, Ksenofontov & Völk 2015
  - shock front has reached equatorial ring with $n_H = 10^3$ ... $3x10^4$ cm^{-3}
  - f is fraction of particles interacting with the ring: $f \sim 0.2$
  - energy in protons: $W_p < 1.4\ f \times 10^{48}$ erg
    → **SN 1987A not enough time for acceleration**

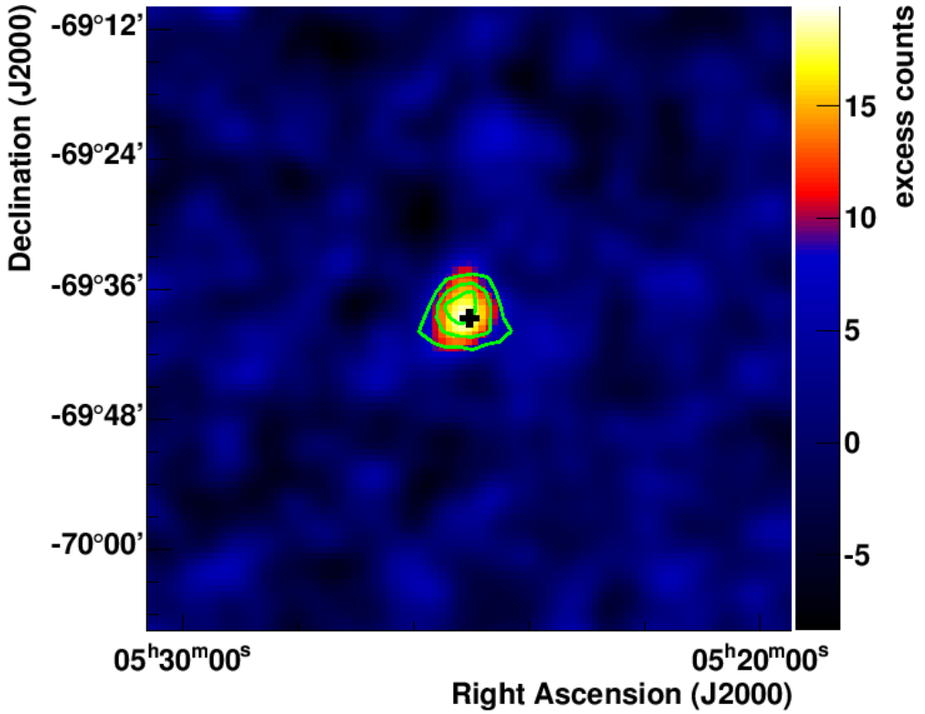


H.E.S.S. LMC Observation Campaign

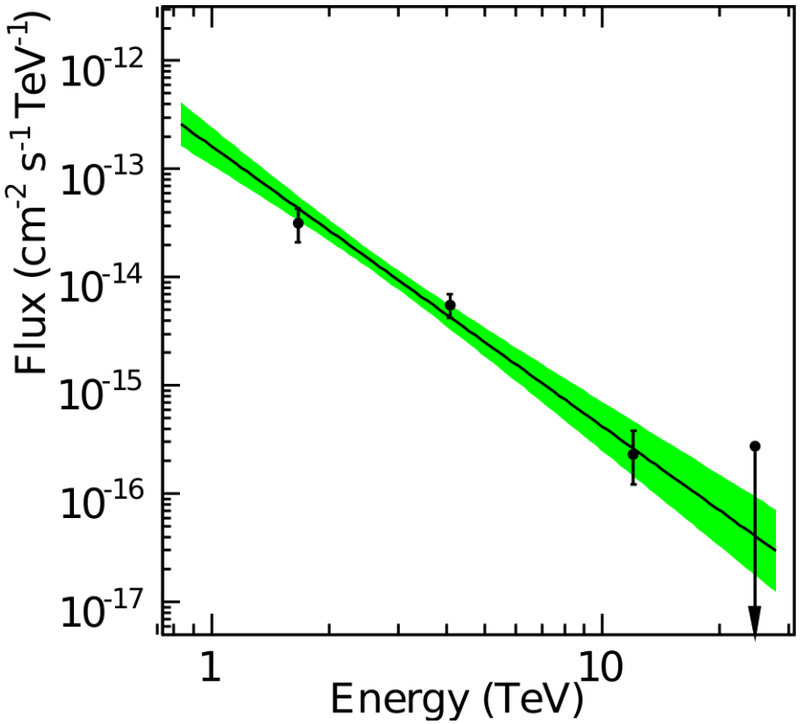
optical, 576 – 788 nm (false colour image)



The Supernova Remnant N 132D



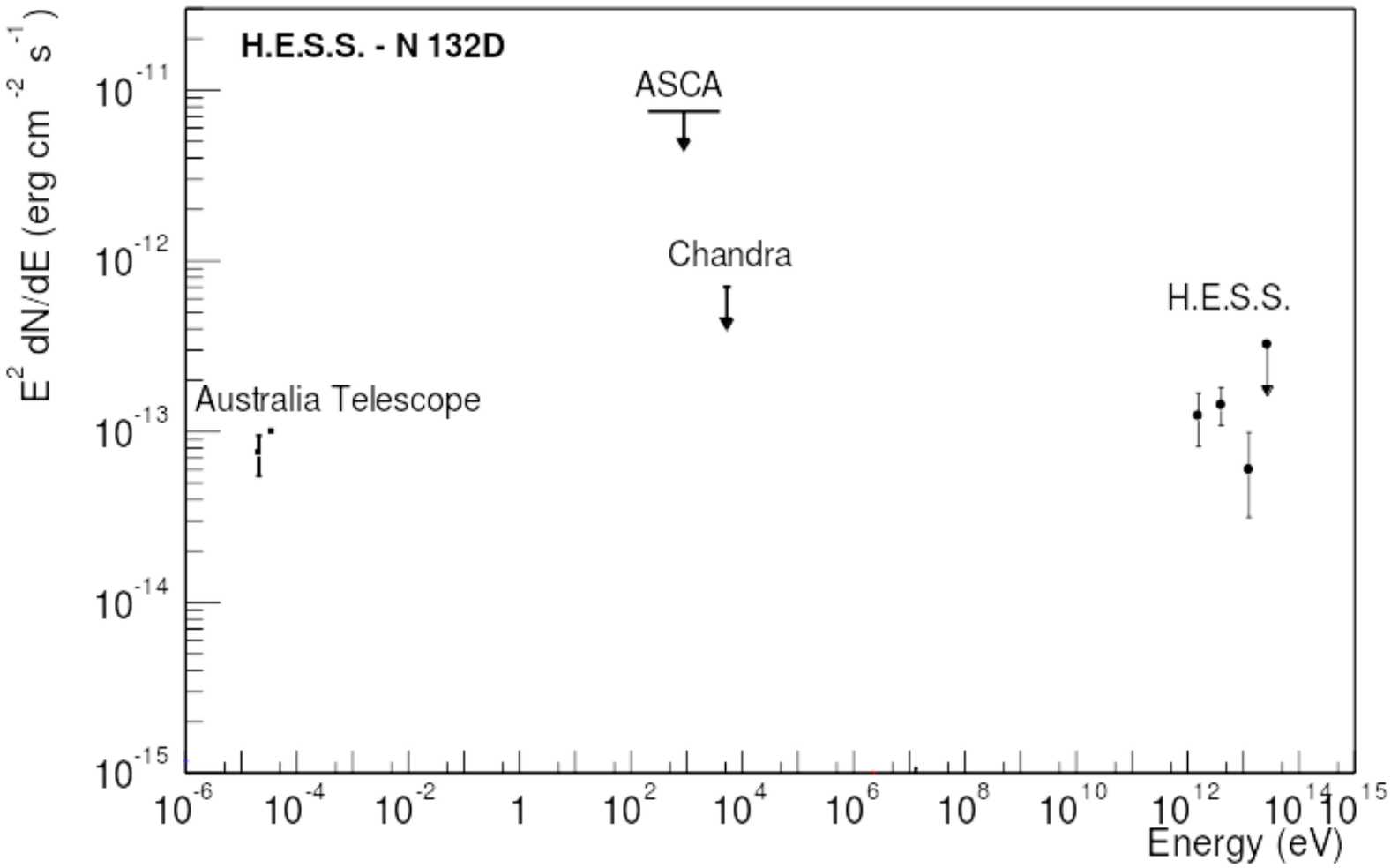
- potential gamma ray emitter [Katz & Waxman, 2008]
- evidence for emission:
  - 4.7 σ at nominal test position
- *Fermi* detection at MeV/GeV



- spectral index 2.4 ± 0.3
- $L_{1\text{-}10\ \mathrm{TeV}}(50\ \mathrm{kpc}) = (9 \pm 2)\ 10^{34}$ erg/s

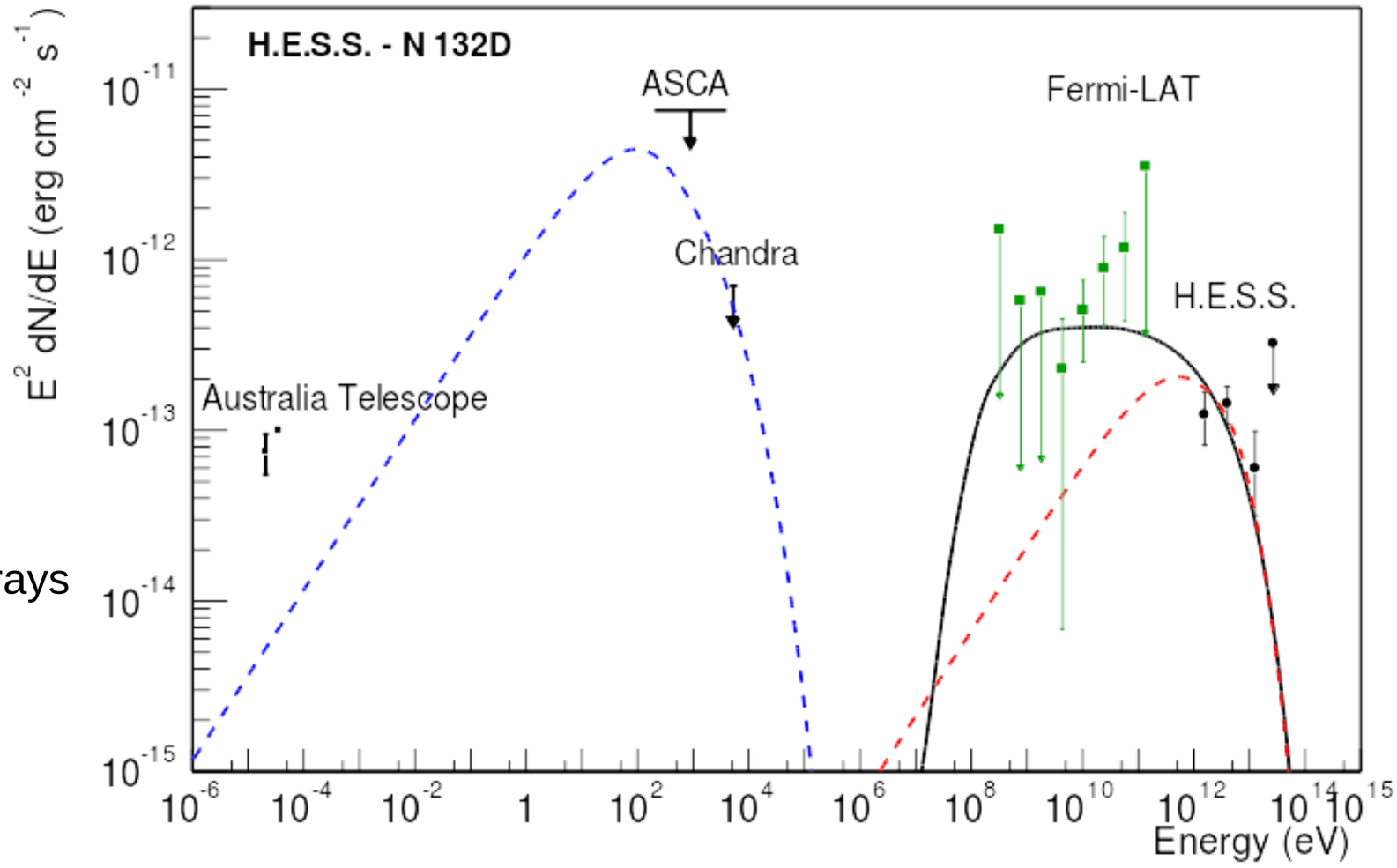
The Supernova Remnant N 132D

- X-ray features
  - strong thermal emission
  - upper limit on non-thermal emission
  - high explosion energy 6 x 10^{51} erg
  - pre-shock density 2.6 cm^{-3}
  - age 6000 years
  - [Hughes et al. 1998]



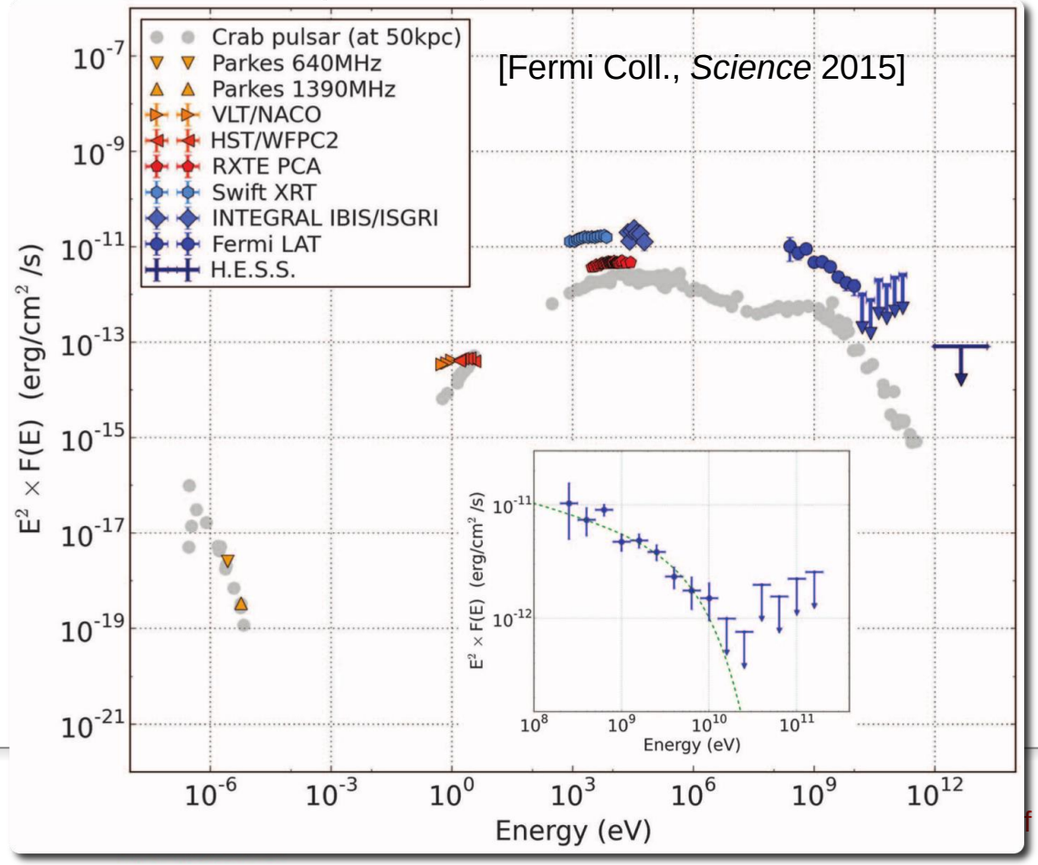
The Supernova Remnant N 132D

- **hadronic scenario**
  - energy in protons
    $W_{pp} = 10^{52}\ (n_H/1\mathrm{cm}^{-3})^{-1}$ erg
  - → efficient accelerator (17% to CR) or high post-shock density
  - possible interaction with interstellar clouds
- **leptonic scenario**
  - infra-red from dust
  - magnetic field ~20 μG
  - depends on level of non-thermal X-rays
- new Fermi results: hadronic/leptonic?
- N 132D intermediate age
  - how long do SNRs accelerate up to 10^{15} eV

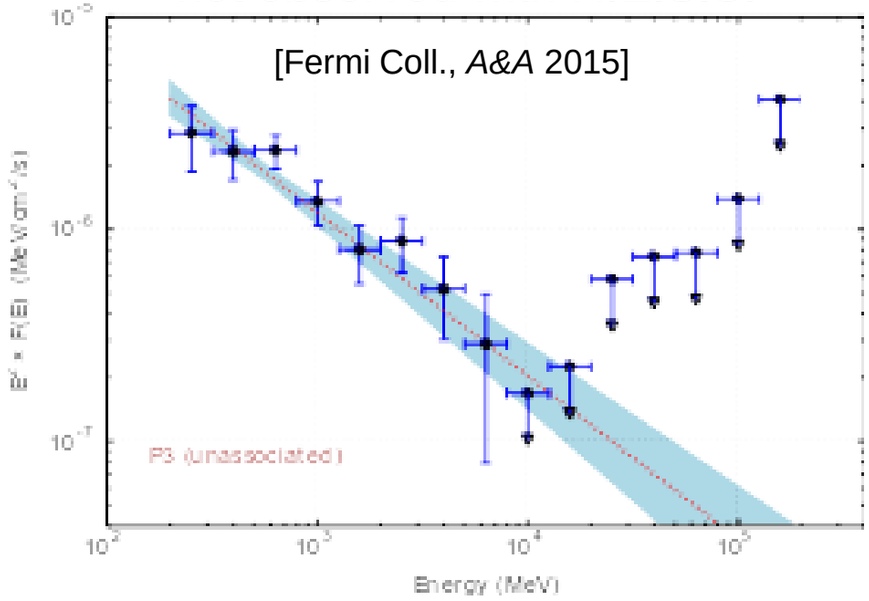


Fermi sources not detected with H.E.S.S.

- PSR J0540–6919: 1st extra-galactic γ-ray pulsar
  - *Fermi* detects pulsed emission
  - X-ray luminous PWN
  - not detected with H.E.S.S.
    - $F(> 1\text{TeV}) < 4.8 \times 10^{-14}\ \text{cm}^{-2}\text{s}^{-1}$



- Unassociated source “P3”
  - HII region NGC 2029 / NGC 2032
  - marginally consistent with
    - SNR DEM L241
    - Seyfert 1 galaxy 2E 1445
  - steep spectrum
  - not observed with H.E.S.S.



Summary

- **deep H.E.S.S. observations → 3 TeV sources in LMC:**
  - PWN N 157B
    - Crab counter-part
    - but low magnetic field and efficiency
  - 30 Dor C
    - first unambiguous detection of a superbubble in gamma rays
  - N 132D
    - one of the oldest TeV emitting SNRs
- first individual cosmic-ray sources in an external galaxy

→ *Science* **347:**6220 (2015)

- tip of the iceberg?
  - future observations with CTA