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

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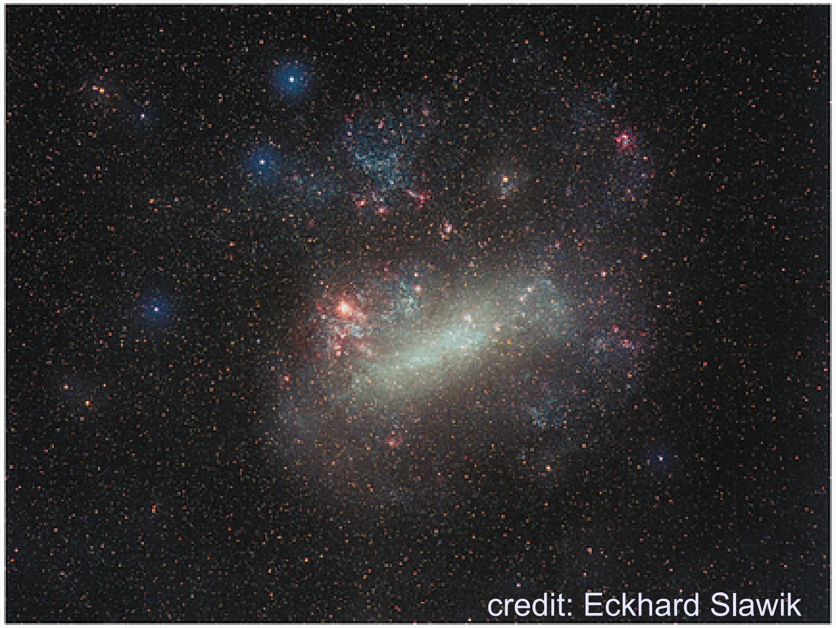
https://www.mpi-hd.mpg.de/hfm/HESS/HESS.shtml

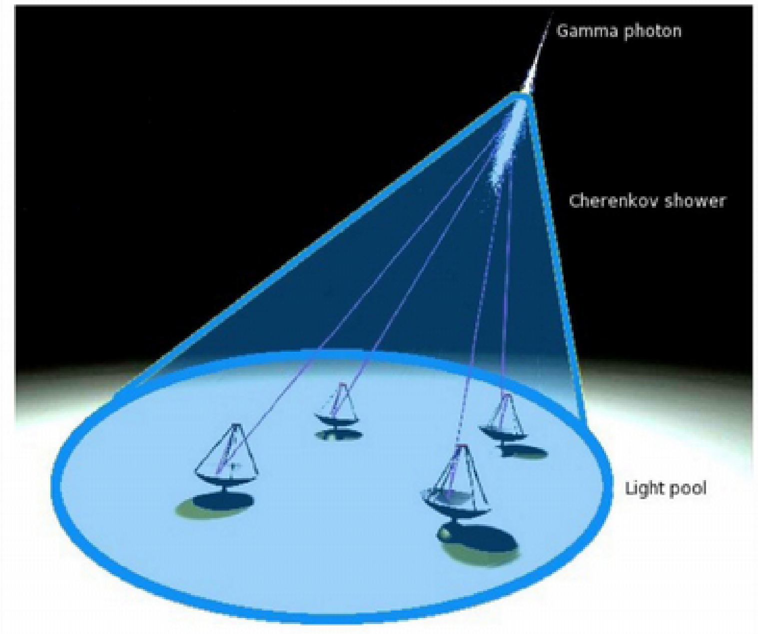
...or 30 years after SN 1987A

- there is no TeV emission from SN 1987A
- motivation for this talk
  - overview of TeV emission from LMC
  - individual TeV sources → most powerful accelerators in LMC
  - sensitivity for SN 1987A



High Energy Stereoscopic System

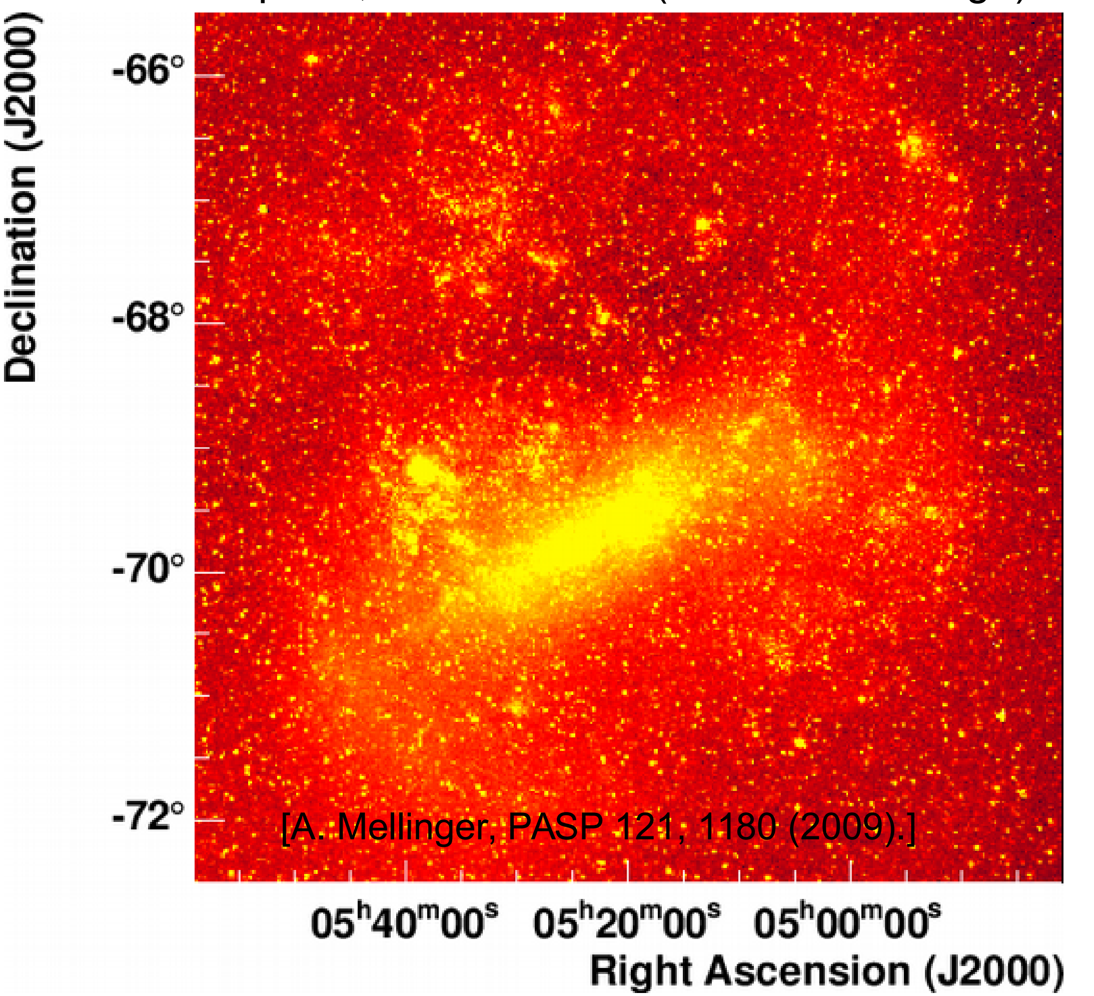
- 5 Imaging Cherenkov Telescopes
- record Cherenkov light of air showers
- 5° field of view (CT 1–4)
- 100 GeV ... tens of TeV
- angular resolution ~0.07°
- Namibia → only instrument for TeV observations of the LMC
- data presented here: only 4 telescopes
  - CT5 ignored when present



H.E.S.S. LMC Observation Campaign

- time line:
  - 2004: start with SN 1987A
  - 2009: 49 h
    - *A&A* 545, L2 (2012)
  - 2013: 210 h
    - *Science* 347:6220, 403 (2015)
  - now: 277 h
- observation conditions
  - large zenith angle (45° - 52°)
  - → energy threshold ~700 GeV
- spatial coverage:
  - mainly around Tarantula nebula
  - some coverage further out

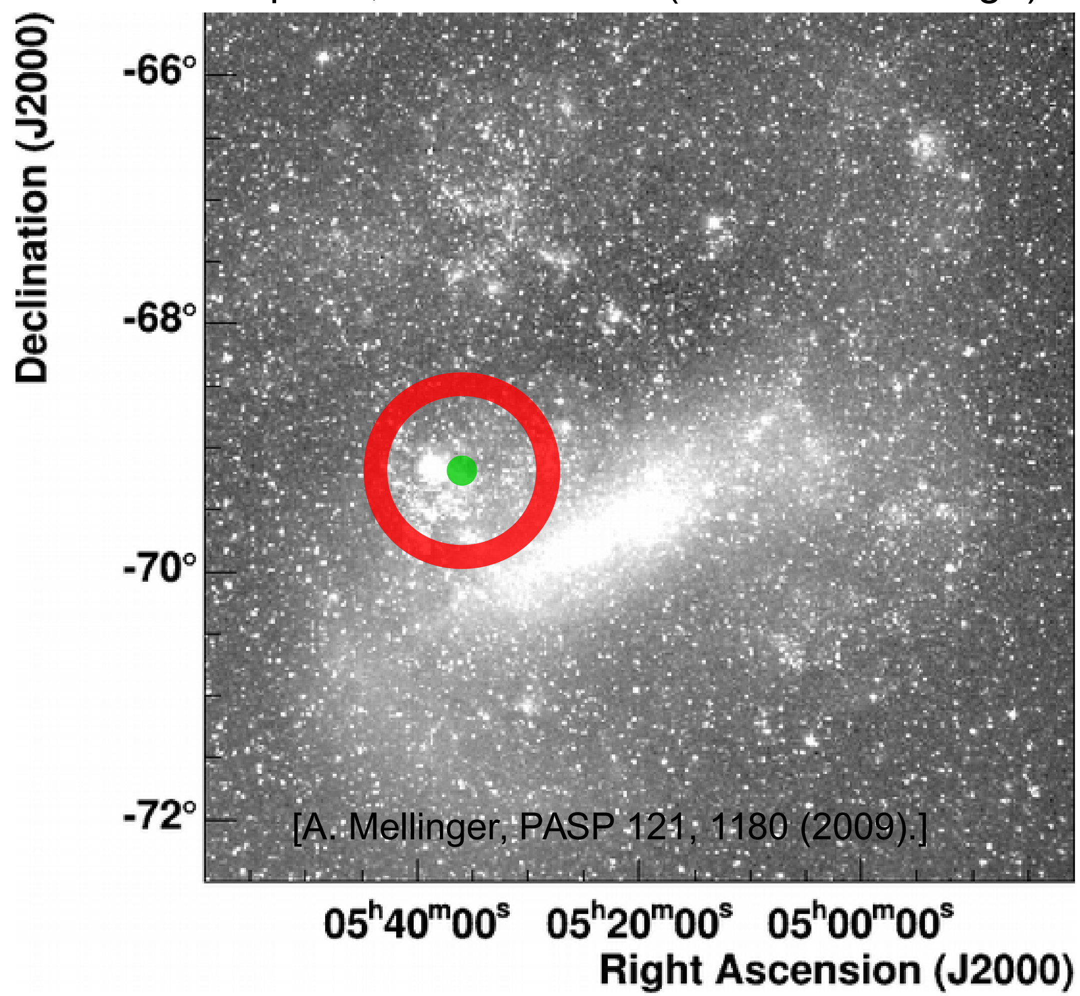
optical, 576 – 788 nm (false colour image)



H.E.S.S. Background Subtraction

- background from ring around target position
  - radius 0.7°
- sensitive to point-like sources only
- not sensitive to diffuse emission
- possible diffuse emission is subtracted

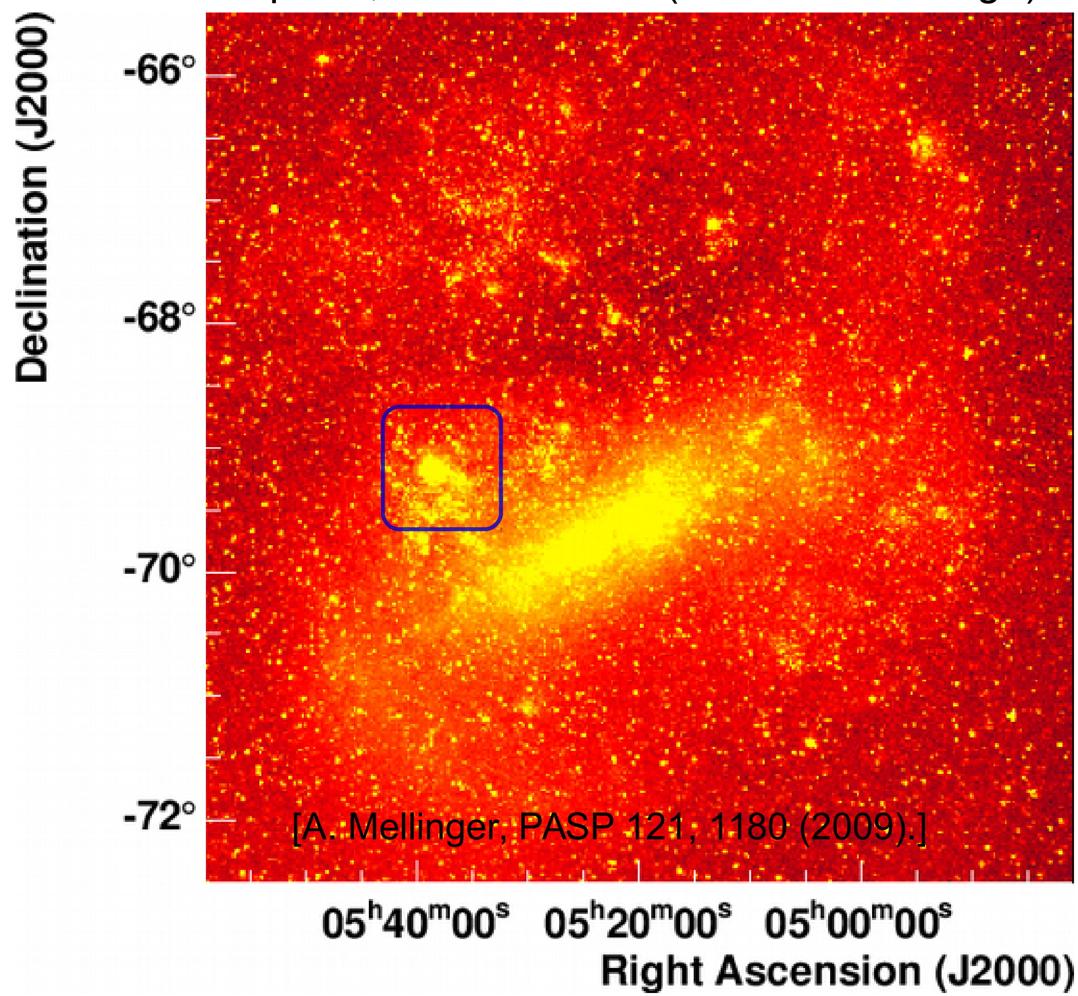
optical, 576 – 788 nm (false colour image)



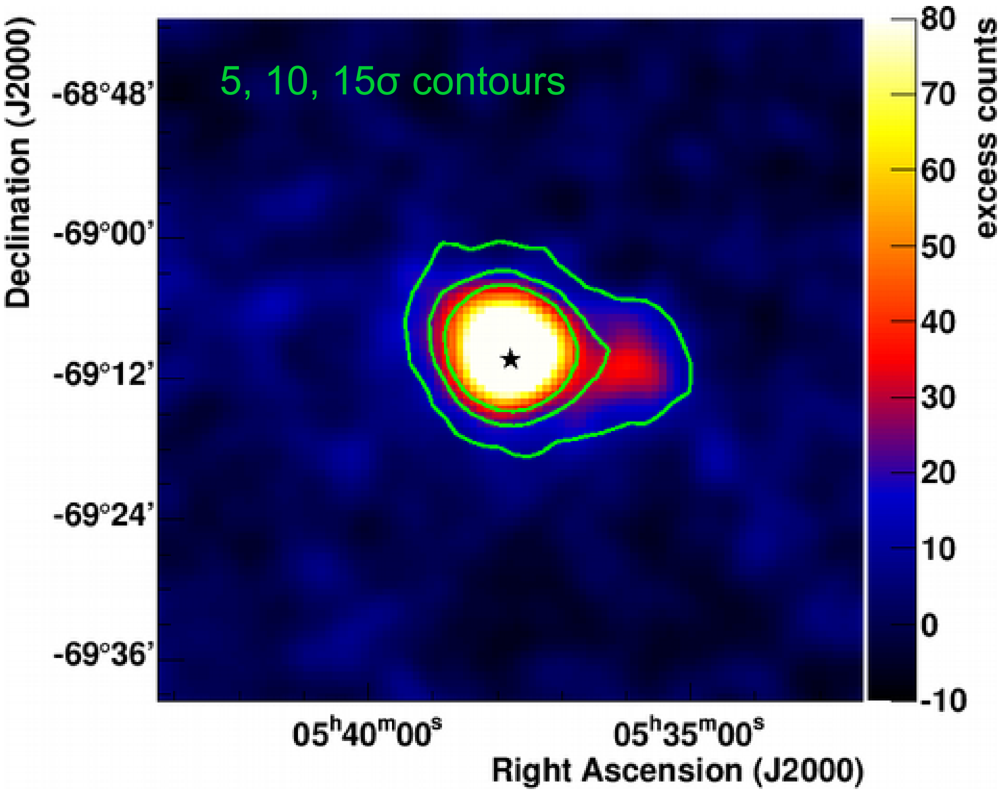
The Tarantula Nebula

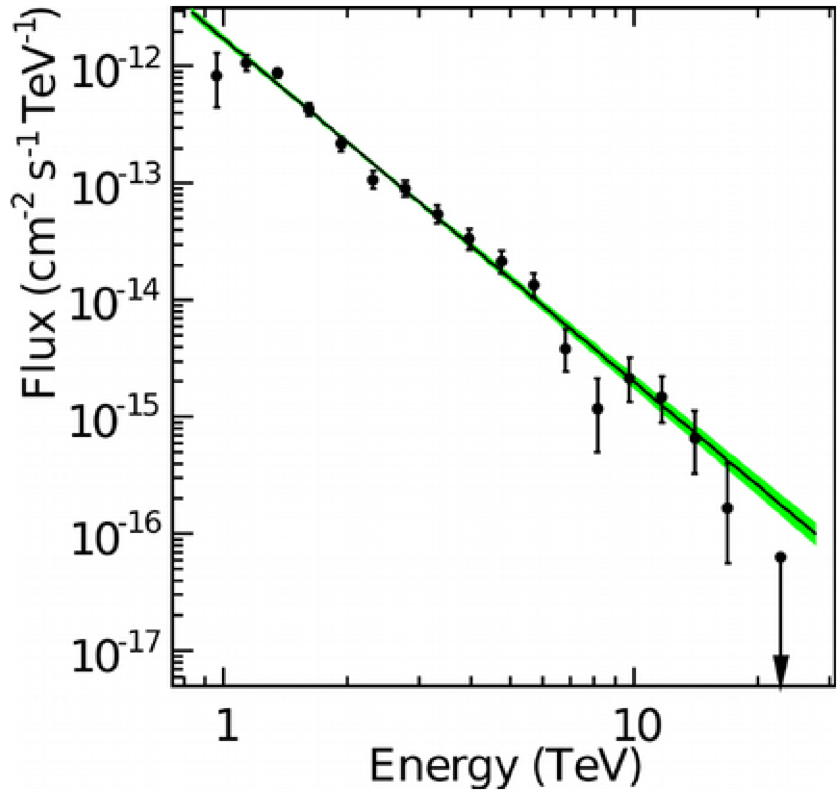
- largest star forming region in Local Group
- objects
  - SN 1987A
  - PSR J0537–6910
    - $\dot{E}$ = 4.9 10^{38} erg/s
  - superbubble 30 Dor C
  - PSR J0540–6919
    - $\dot{E}$ = 1.5 10^{38} erg/s

optical, 576 – 788 nm (false colour image)



The Pulsar Wind Nebula N 157B





- 613 gamma rays, 33 σ
  - as of 2013
- clearly centred on PSR J0537–6910

- spectral index 2.8 ± 0.1
- emission up to > 10 TeV
- no significant spectral cut-off
- $L_{1\text{-}10\ \mathrm{TeV}}$(50 kpc) = (6.8±0.3) 10^{35} erg/s
  - 0.1% $\dot{E}$

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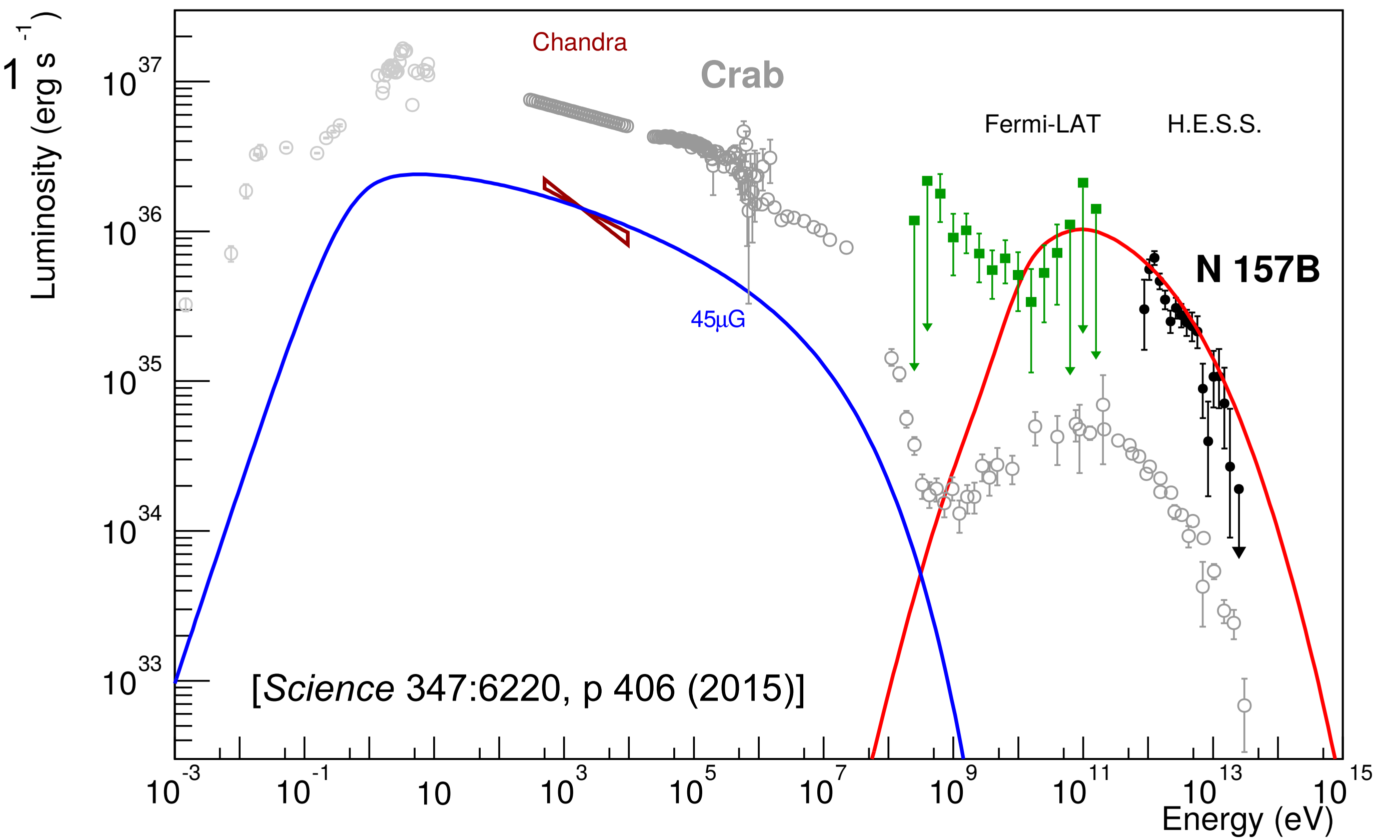
The Pulsar Wind Nebula N 157B

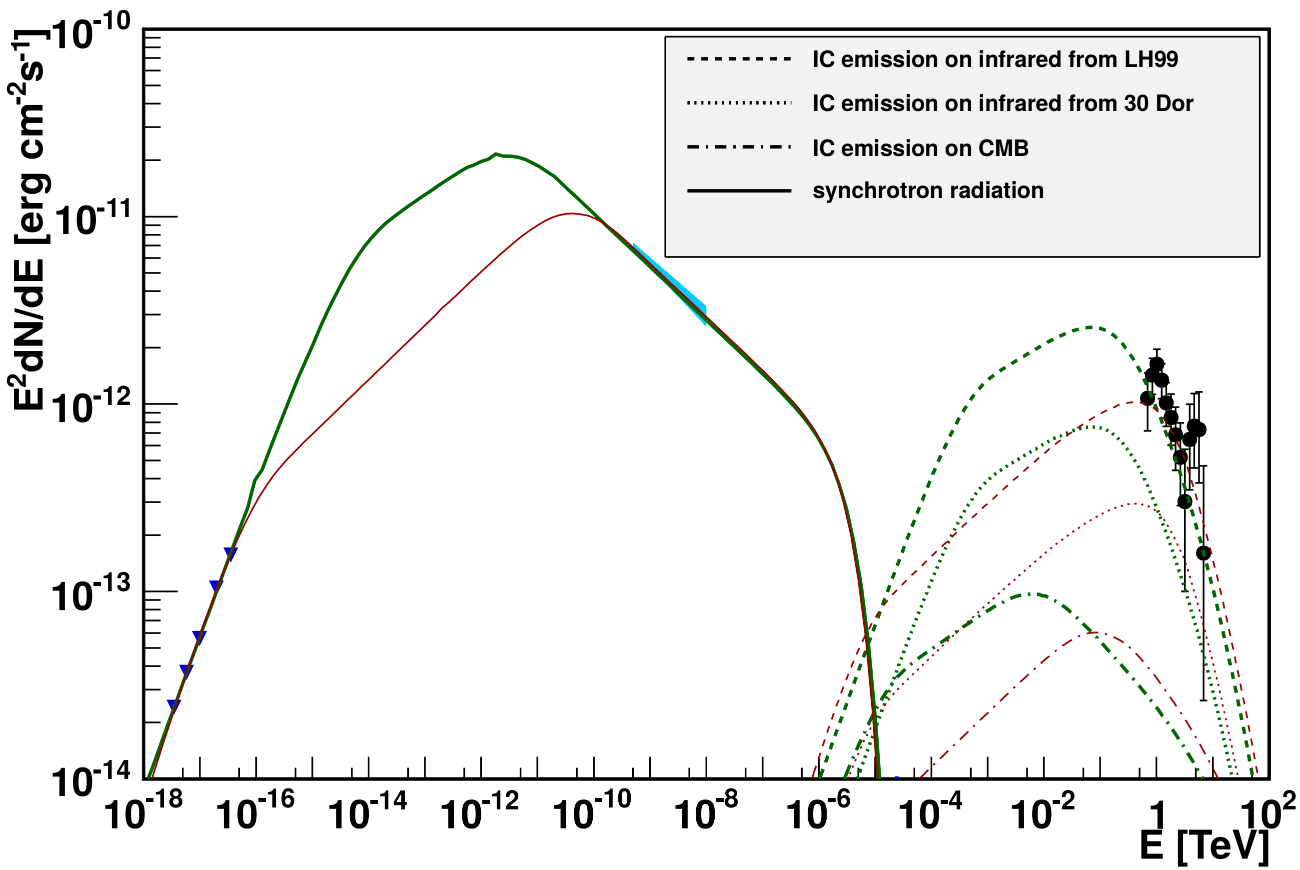
- PWN:
  - inverse Compton on strong infra-red fields → bright in gamma rays
  - X-ray synchrotron emission → low magnetic field of 45 μG
  - constant injection of 11% $\dot{E}$ into electrons >400 GeV
- Fermi/LAT
  - Fermi coll. *A&A* 586, A71 (2016)
  - matches model
  - 2nd component?
- Crab Nebula
  - 123 μG
  - 50% $\dot{E}$
- → N 157B apparently inefficient accelerator



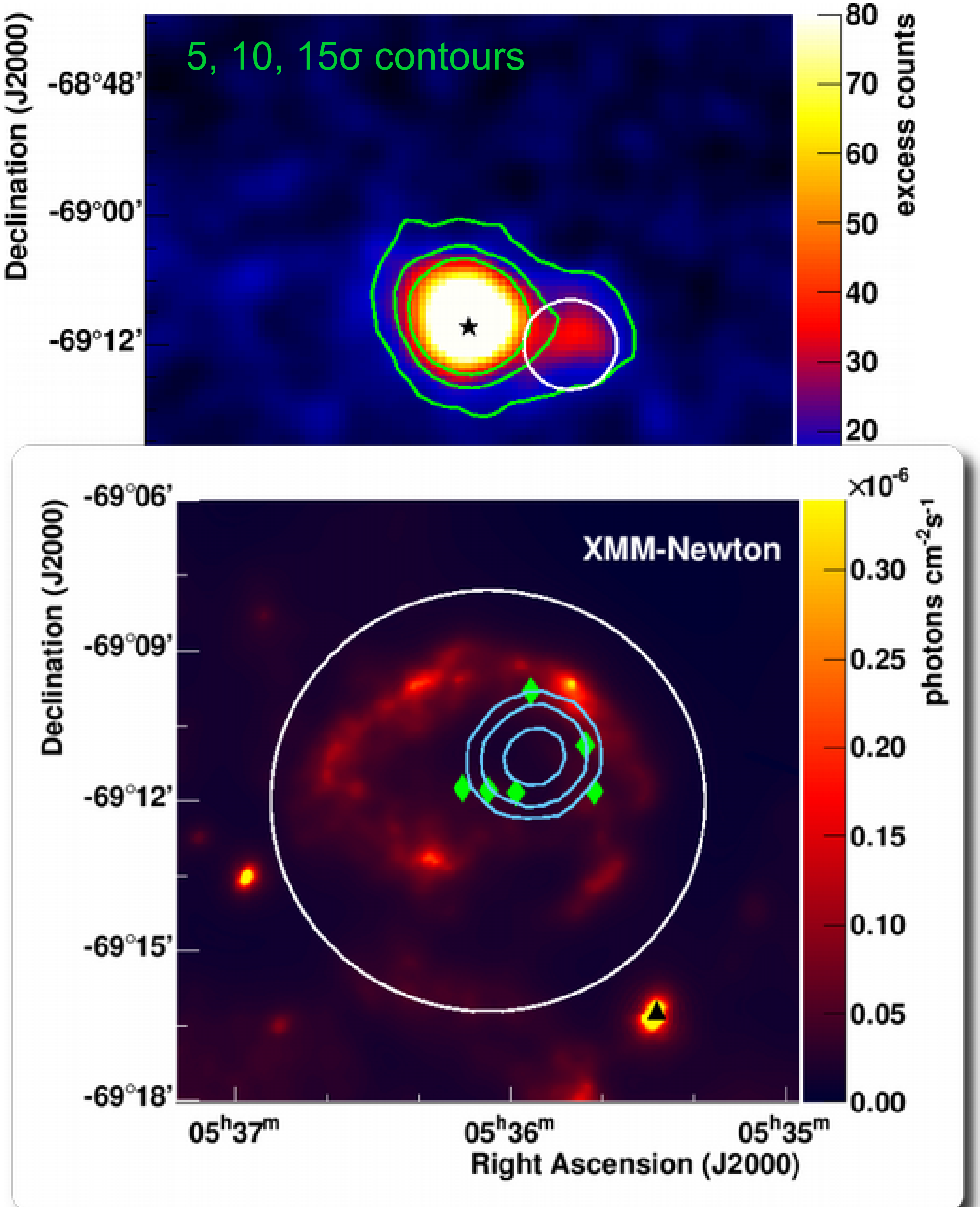
The Birth Period of PSR J0537–6910

- modelling total emission, from radio to TeV [*A&A* 545, L2 (2012)]
- total energy in electrons: 4 x 10^{49} erg
- relate to spin-down
- birth period <10 ms
  - confirming earlier results
  - but independent of
    - age
    - braking index
    - glitch history

$$
\begin{aligned}
W_{\mathrm{tot}} &= \epsilon\eta\left(E_{\mathrm{rot},0} - E_{\mathrm{rot}}\right) \\
&= \epsilon\eta\frac{1}{2}I\left(\left(\frac{2\pi}{P_0}\right)^2 - \left(\frac{2\pi}{P}\right)^2\right) \\
&= 2\times10^{49}\epsilon\eta\frac{I}{10^{45}\,\mathrm{g\,cm^2}}\left(\left(\frac{10\,\mathrm{ms}}{P_0}\right)^2 - \left(\frac{10\,\mathrm{ms}}{P}\right)^2\right)\mathrm{erg}
\end{aligned}
$$

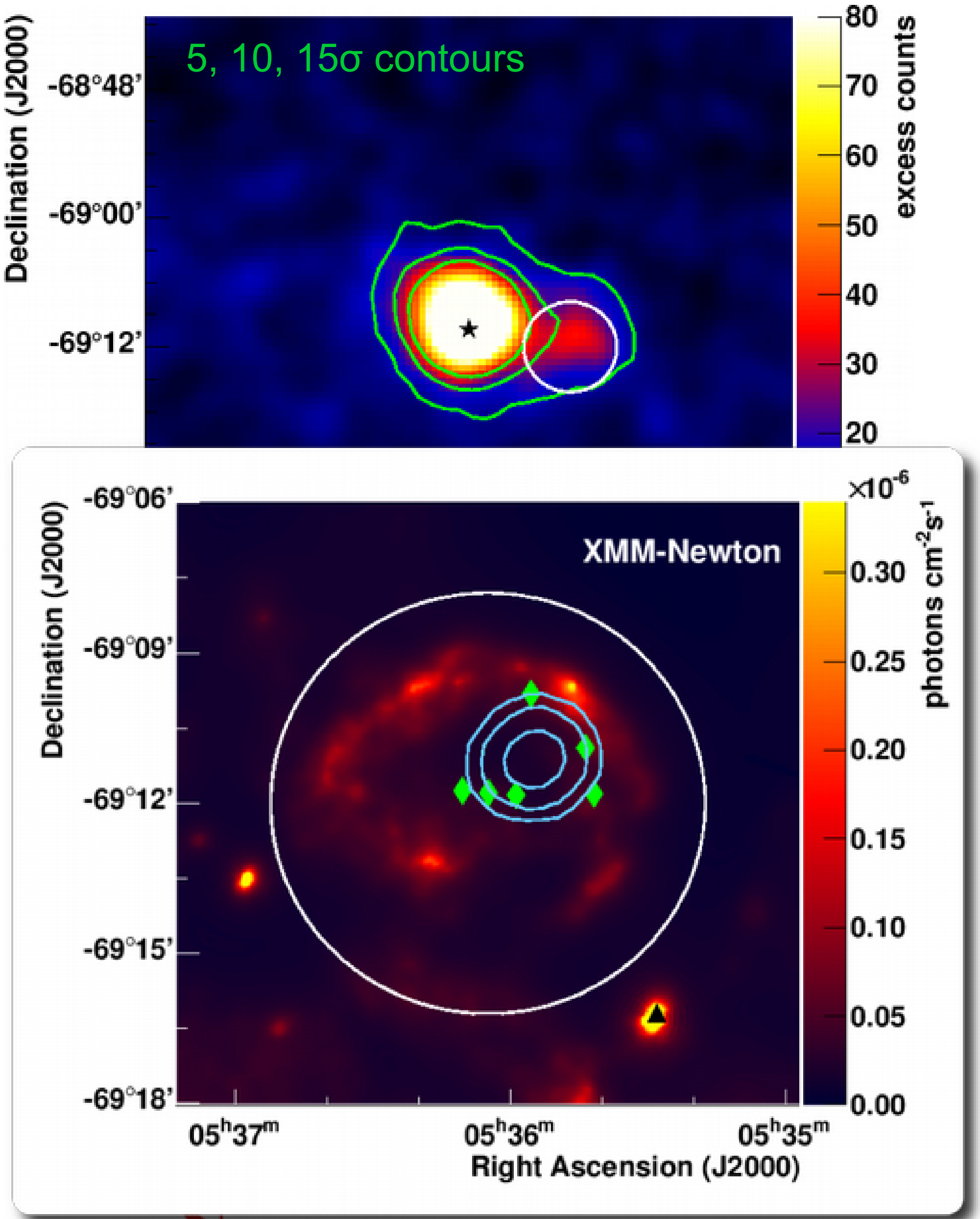


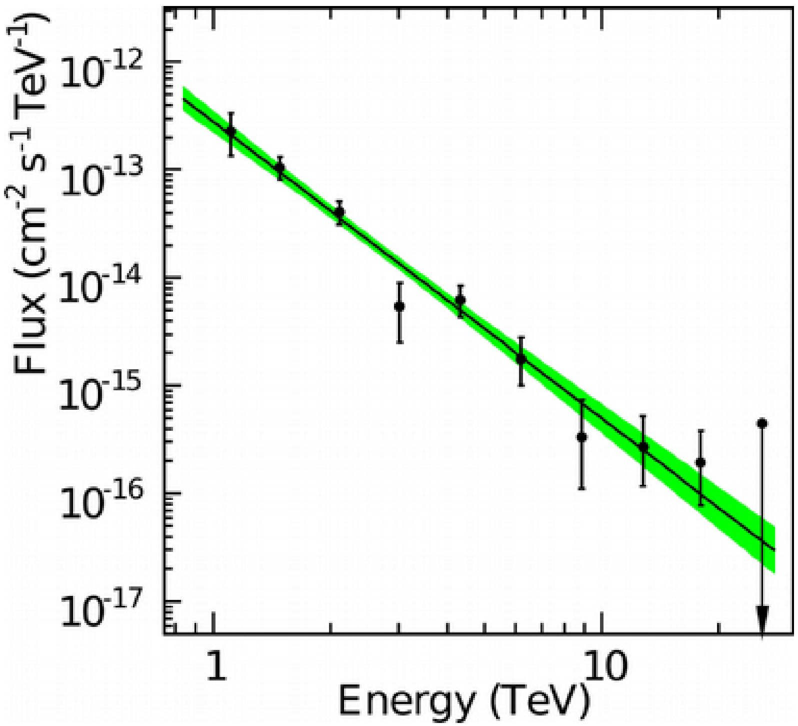
The Superbubble 30 Dor C



- 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
  - non-thermal X-ray 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

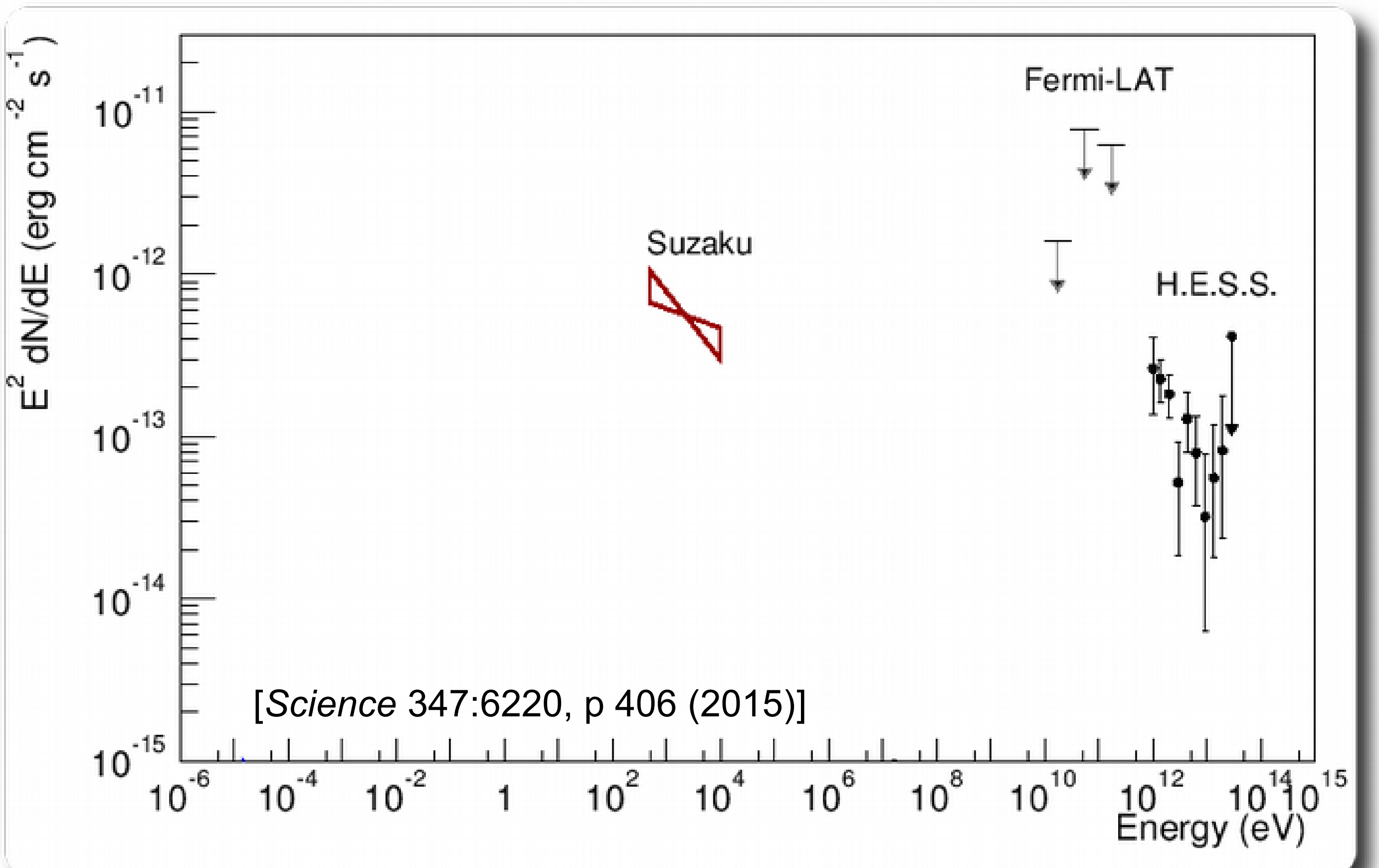
The Superbubble 30 Dor C





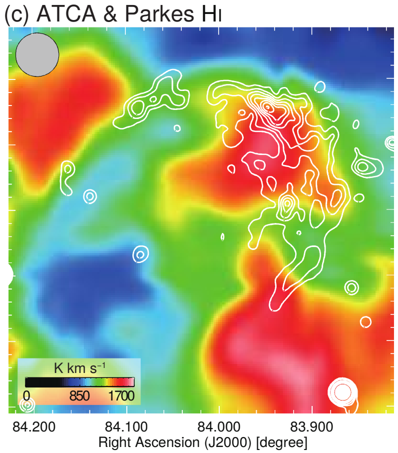
- spectral index 2.6 ± 0.2
- $L_{1\text{-}10\ \mathrm{TeV}}$(50 kpc) = (9 ± 2) 10^{34} erg/s
  - corrected for N 157B spill-over

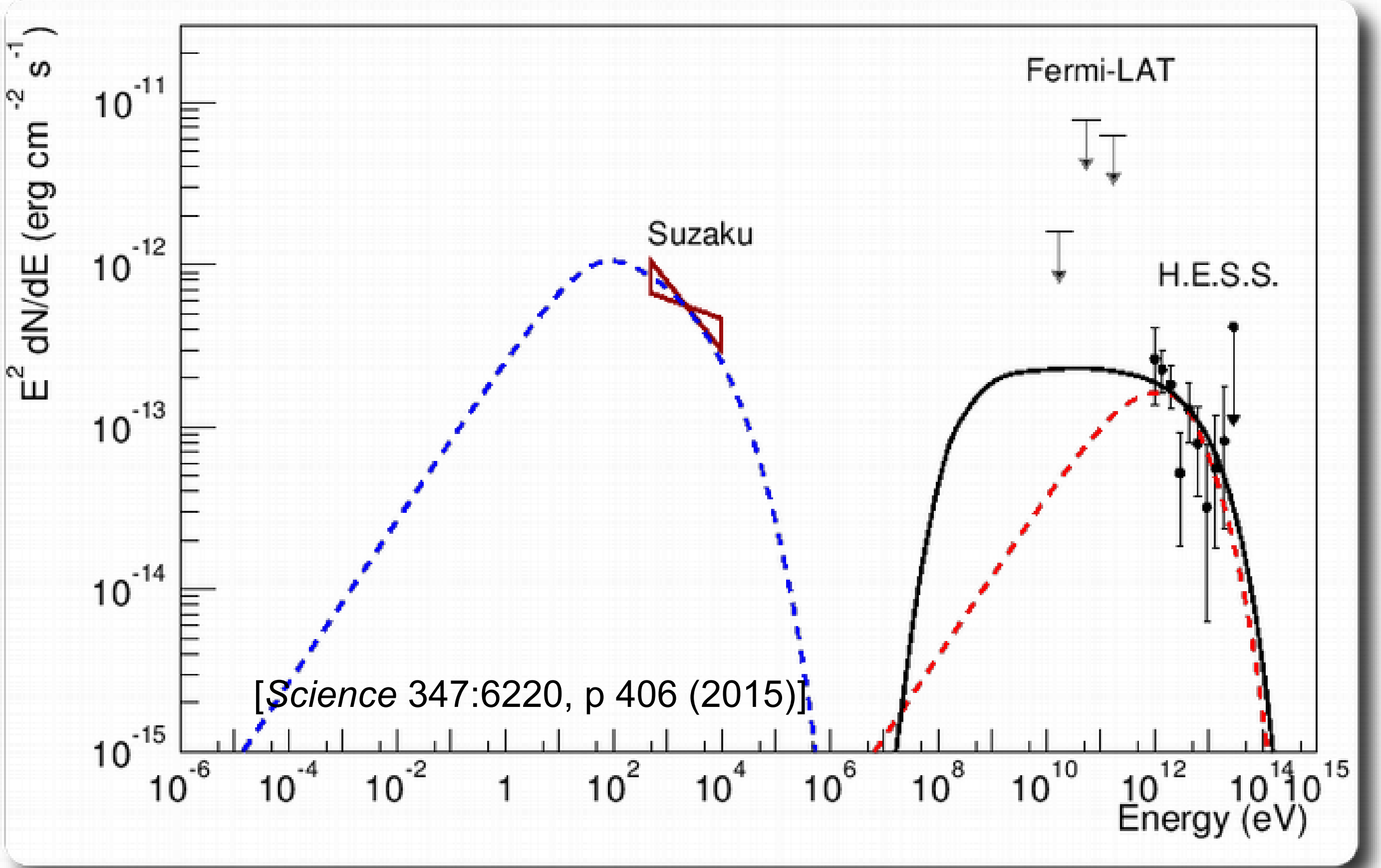
The Superbubble 30 Dor C



The Superbubble 30 Dor C

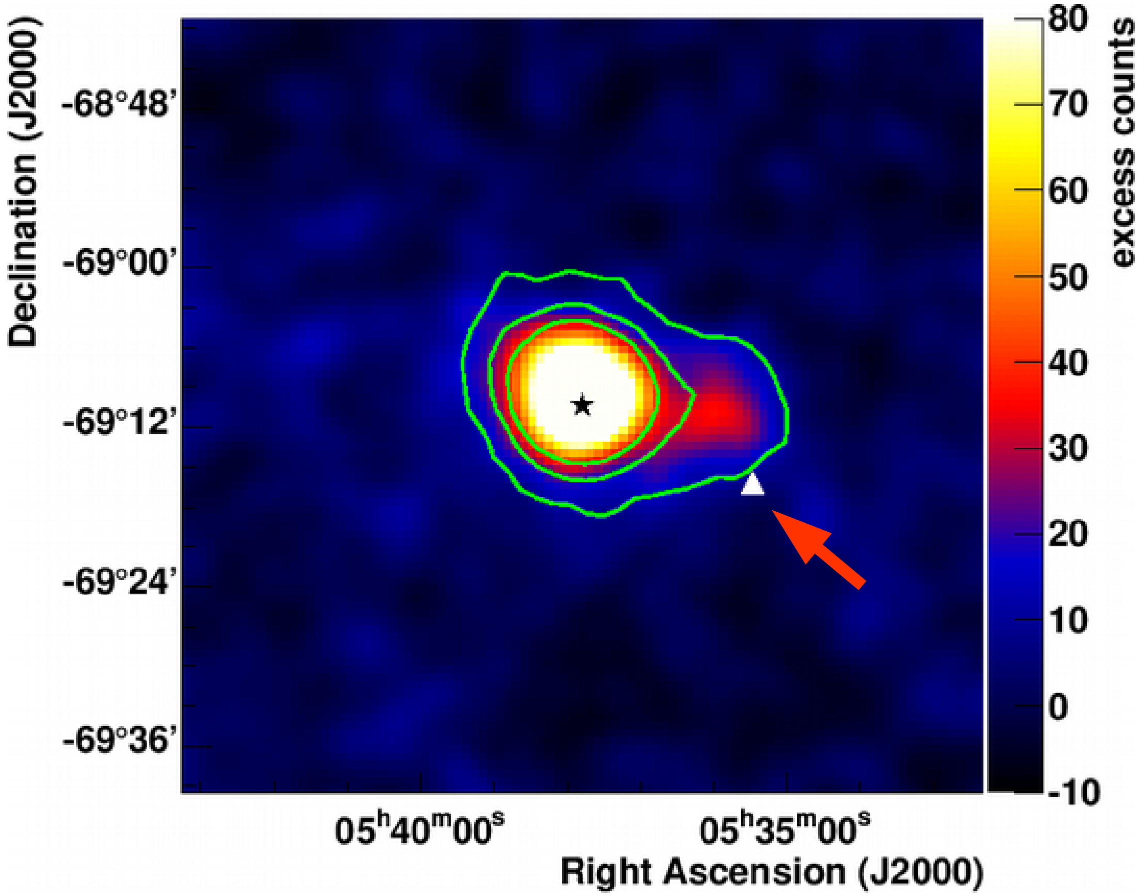
- **hadronic scenario**
- W_{pp} = (0.7 – 25) x 10^{52} (n_H / 1 $cm^{-3})^{-1}$ erg
- high density clouds: n_H ~ 60 cm^{-3} [Sano et al. AIP1792, 040038 (2017)]
- 10^{50}...10^{51} erg in protons
- **leptonic scenario**
- low magnetic field: ~15 μG
- 4 x 10^{48} erg in electrons
- **no model favoured**
- but: evidence for efficient particle acceleration in a superbubble





The Supernova Remnant of SN 1987A

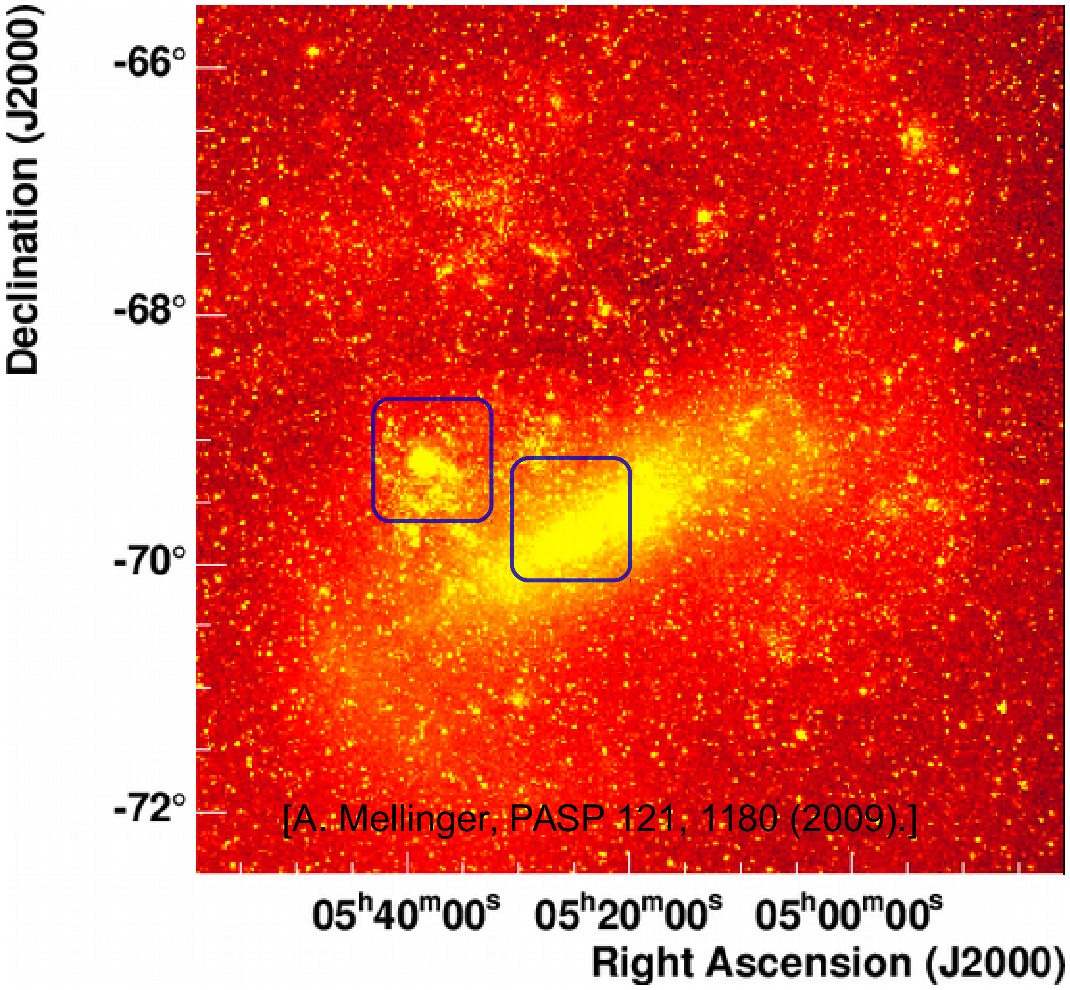
- **not detected**
- gamma ray flux
  F (>1 TeV) < 5 x 10^{-14} $cm^{-2}s^{-1}$
  - 99% confidence level
- gamma ray luminosity
  L (>1 TeV) < 2.2 10^{34} erg/s
- at predicted level
  [Berezhko, Ksenofontov & Völk 2015]



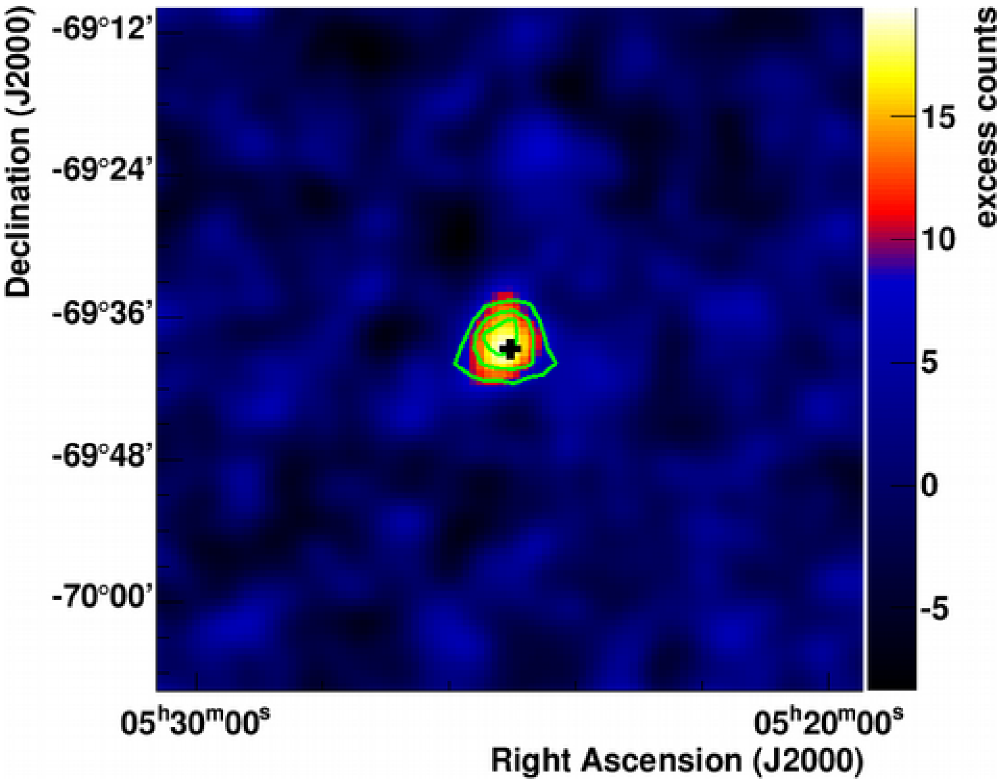
[*Science* 347:6220, p 406 (2015)]

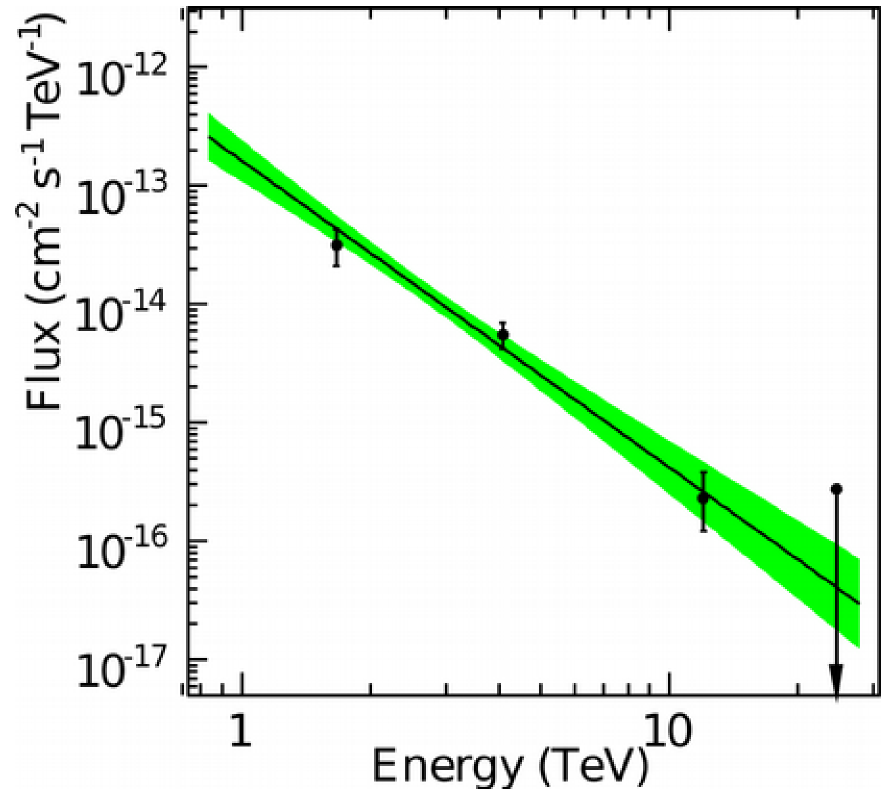
The Large Magellanic Cloud

optical, 576 – 788 nm (false colour image)



The Supernova Remnant N 132D



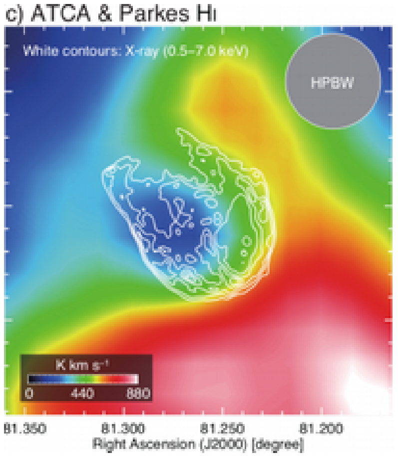


- potential gamma ray emitter [Katz & Waxman, 2008]
- significant detection:
  - 4.7 σ (2013)
  - now >5σ

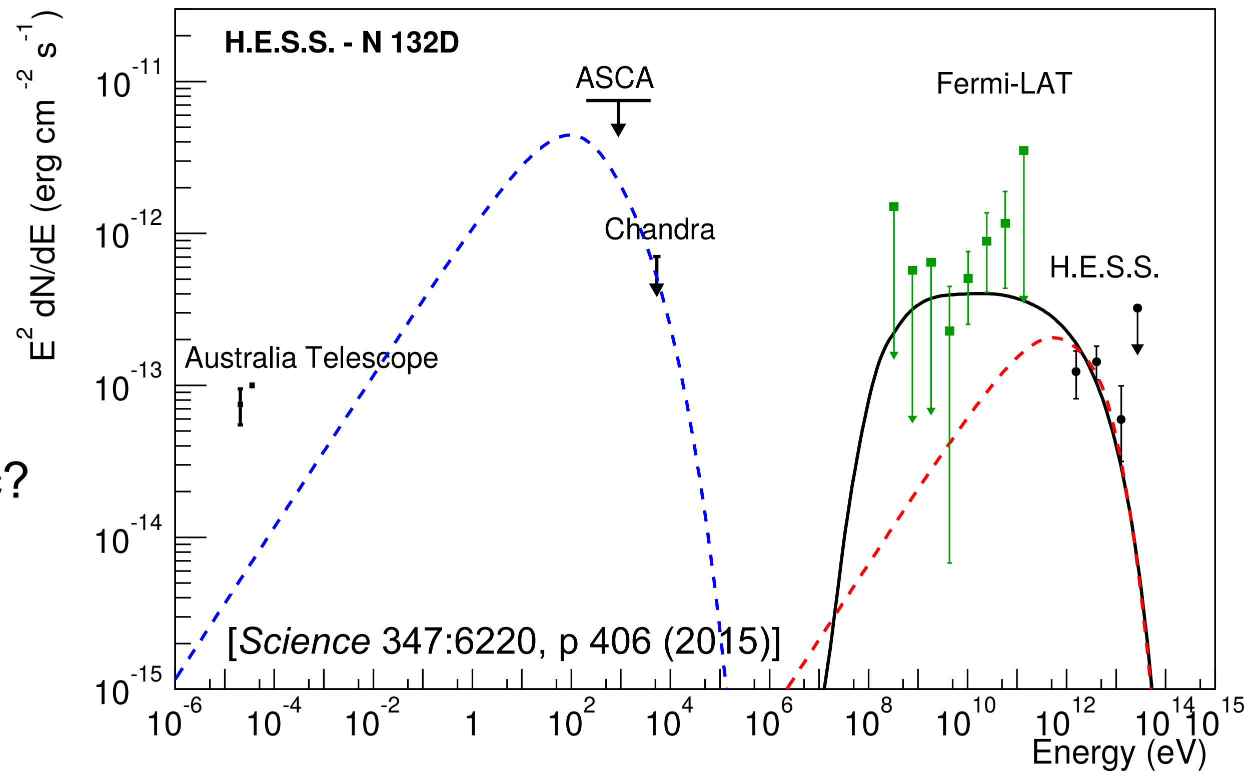
- spectral index 2.4 ± 0.3
- $L_{1\text{-}10\ \mathrm{TeV}}$(50 kpc) = (9 ± 2) 10^{34} erg/s

The Supernova Remnant N 132D

- **hadronic scenario**
  - energy in protons $W_{pp} = 10^{52}\ (n_H/1\mathrm{cm}^{-3})^{-1}$ erg
  - → efficient energy conversion to Cosmic Rays (17%) 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
- Fermi results: hadronic/leptonic?
- N 132D intermediate age
  - how long do SNRs accelerate up to 10^{15} eV

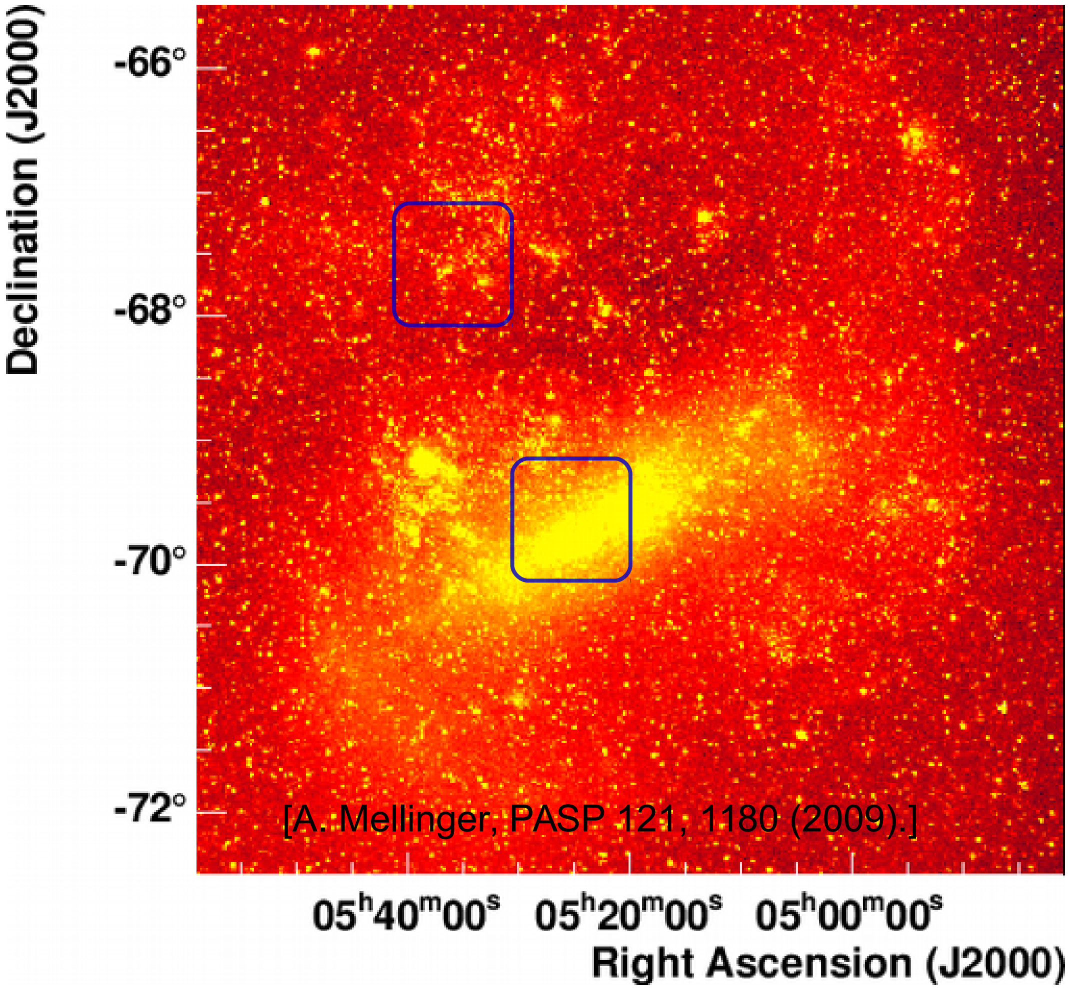


[Sano et al. AIP1792, 040038 (2017)]



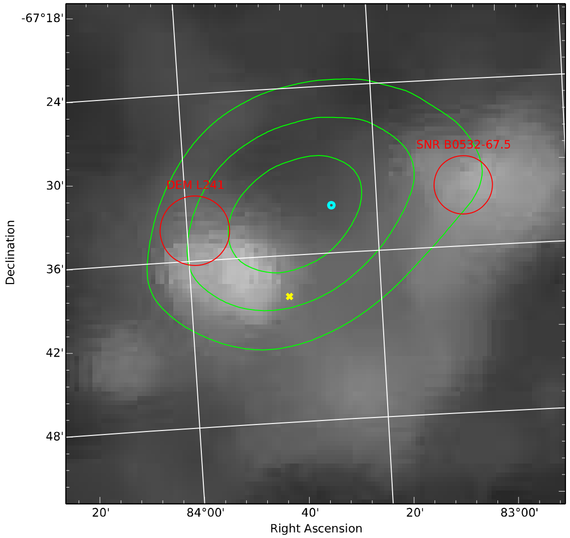
The Large Magellanic Cloud

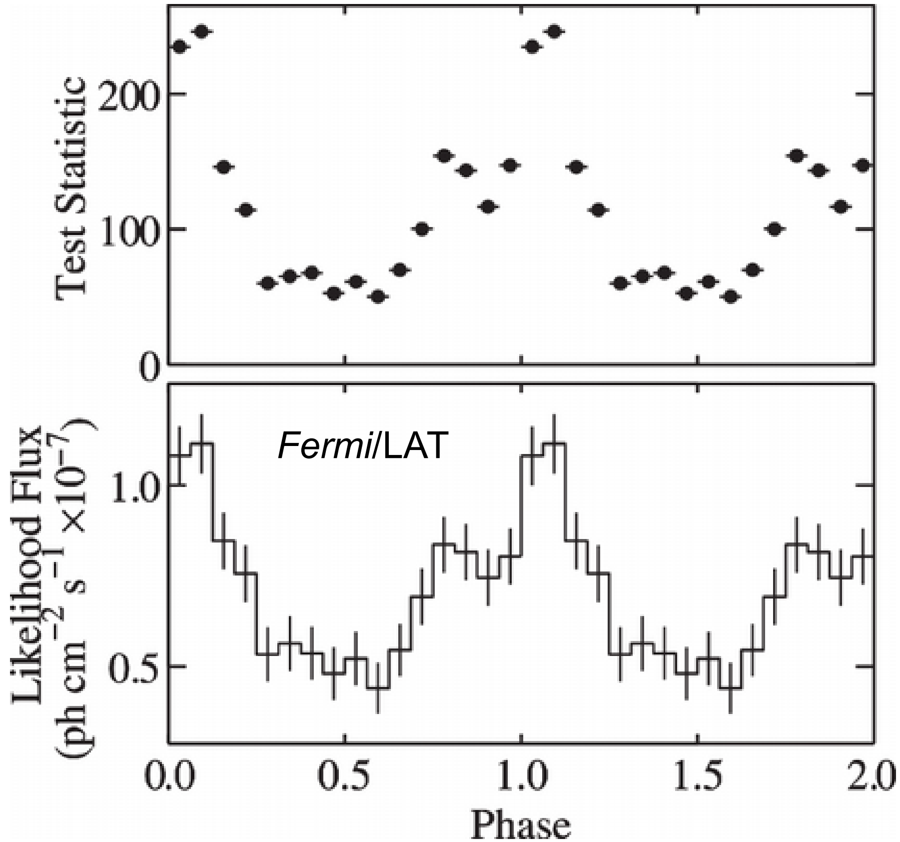
optical, 576 – 788 nm (false colour image)

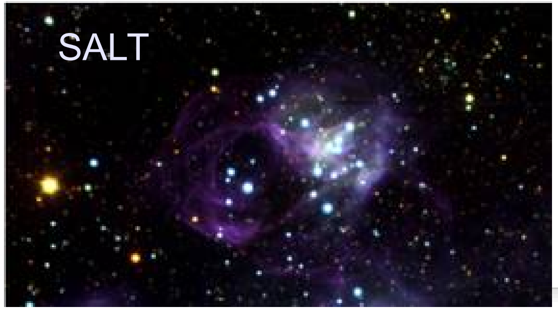


LMC P3 – A New Gamma-Ray Binary

- previously unidentified *Fermi* source
  - [Fermi coll., *A&A* 586, A71 (2016)]
- blind search found periodic emission
  - [Corbet et al., *ApJ*, 829:105 (2016)]
  - period 10.301 ± 0.002 days
  - X-ray and radio in anti-phase
- companion star
  - O5 III(f)
  - similar to gamma-ray binaries
    LS 5039 and 1FGL J1018.6-5856







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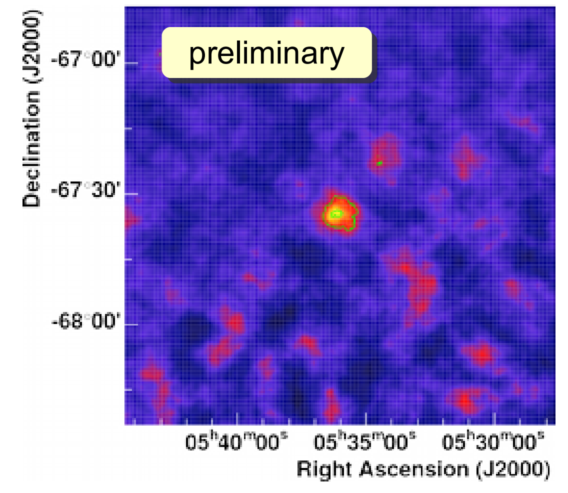
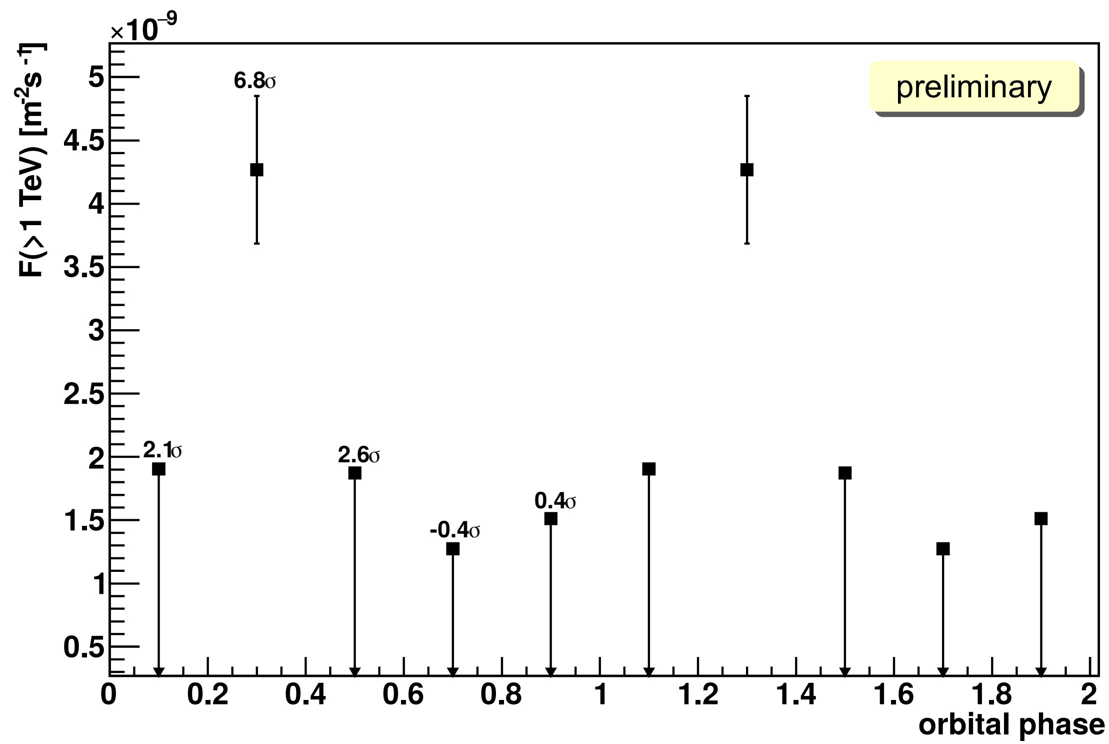
LMC P3 in TeV gamma rays



- 100 h acceptance corrected live-time
- 65 excess events, 5.5 σ → firm detection
- phase-folded light-curve, phase 0 at Fermi maximum
  - roughly equal exposure per phase bin
- emission only between 0.2 and 0.4: 6.8 σ (6.6 σ after 5 trials)
  - clear modulation with orbital period
  - at minimum of GeV emission
- no direct measurement of periodicity
  - Lomb-Scargle test
  - auto-correlation function



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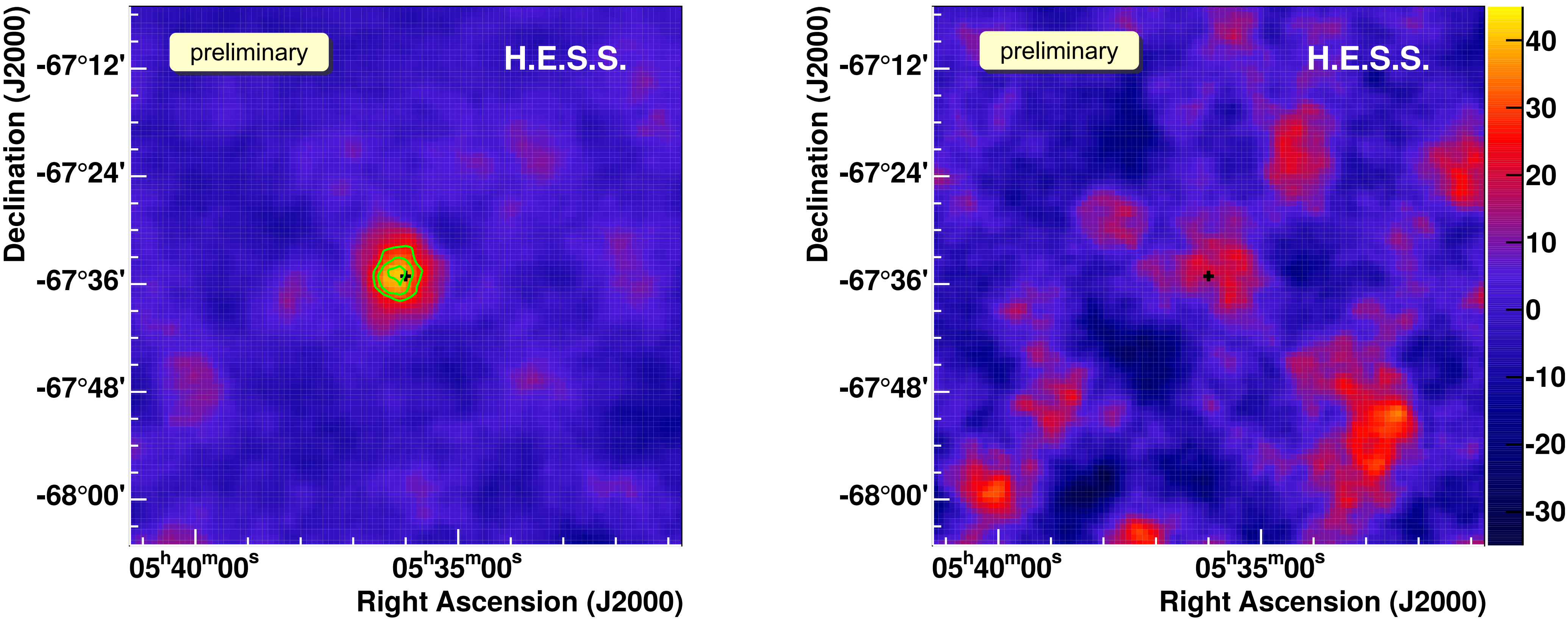
LMC P3 in TeV gamma rays



on peak
0.2 – 0.4
6.8 σ
(11 ± 1) x 10^{35} erg/s

average
5.5 σ
(2.4 ± 0.5) x 10^{35} erg/s

off peak
0.4 – 0.2
2.5 σ
<1.9 x 10^{35} erg/s (99% CL)

all numbers preliminary

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LMC P3 in TeV gamma rays

- 6^{th} TeV gamma-ray binary
- similar to LS 5039 and 1FGL J1018.6-5856
  - companion star: O5III(f), O6V(f), O6.5V(f)
  - orbital period: 10.3 d, 3.9 d, 16.6 d
- most luminous: 10^{35} erg/s (rather than 10^{33}erg/s)
- GeV and TeV emission in anti-phase
- unknown:
  - compact object?
  - orbital parameters: inclination, distance, periastron, ...

Summary

- 4 TeV sources in LMC:
  - PWN N 157B
  - 30 Dor C
  - N 132D
  - binary LMC P3
- 4 different source classes
- first individual cosmic-ray sources in an external galaxy
  - similar to Milky Way 10 years ago

tip of the iceberg?

  - future observations with CTA

optical, 576 – 788 nm (false colour image)