Max-Planck-Institut für Kernphysik

Detection of the young massive star cluster R136 with H.E.S.S.

Lars Mohrmann, Nukri Komin

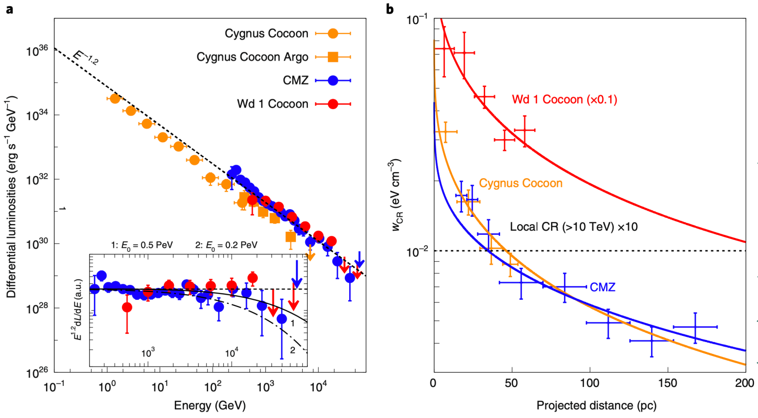
(for the H.E.S.S. Collaboration)

TeVPA 2023 — Naples, Italy — September 11, 2023

Image credit: NASA, ESA, P. Crowther (University of Sheffield)

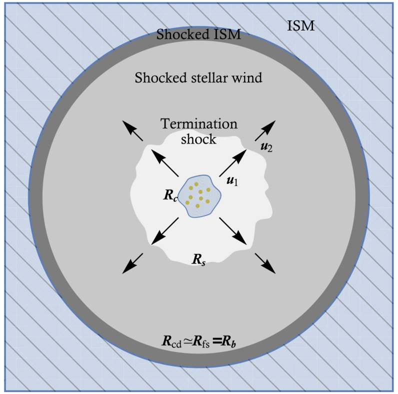
Why young massive star clusters?

- *They could be major factories of Galactic cosmic rays*
  - challenging the "SNR paradigm"
  - especially at the highest energies
    → long-sought "PeVatrons"?

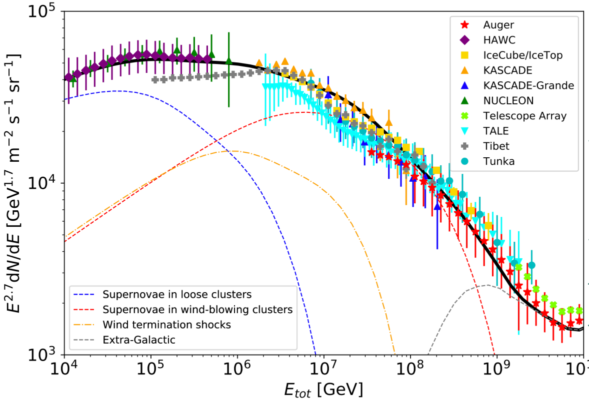


Aharonian et al., Nat. Astron. **3**, 561 (2019)

- <u>But:</u> massive star clusters are "messy" environments!
  - many open questions:
    - do supernovae or stellar winds dominate?
    - what is the preferred acceleration site?
    - etc …



Morlino et al., MNRAS **504**, 6096 (2021)

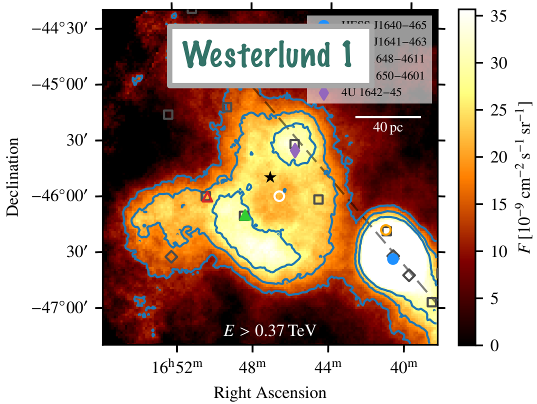


Vieu & Reville, MNRAS **519**, 136 (2023)

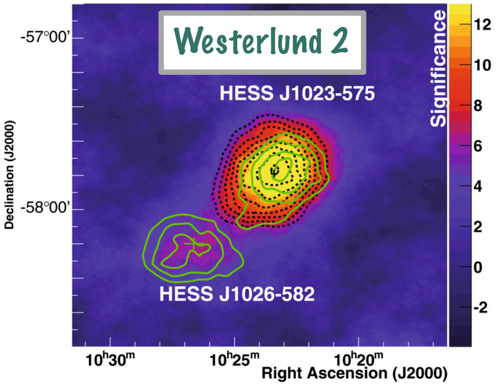
Young massive star clusters at TeV gamma rays

- Only few detections
  - association with star cluster not always firm
- Need more!
  - preferably at different cluster evolutionary stages…

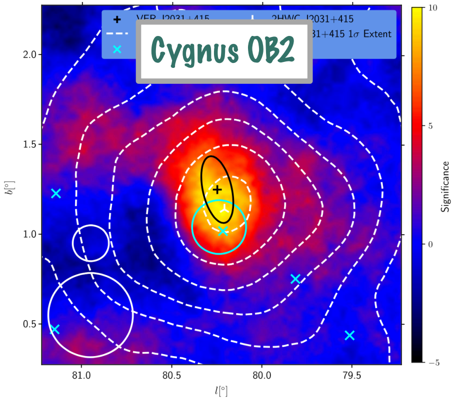
HESS Coll., A&A **666**, A124 (2022)



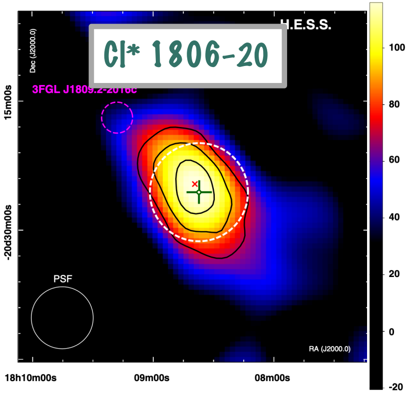
HESS Coll., A&A **525**, A46 (2011)



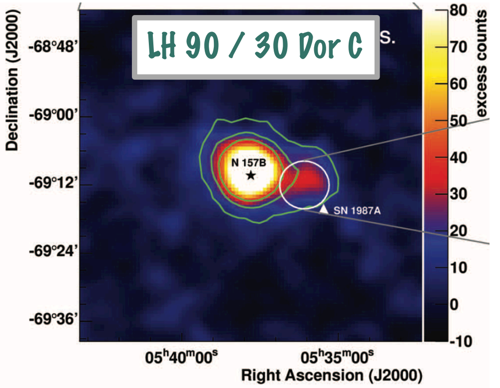
VERITAS Coll., ApJ **861**, 134 (2018)



HESS Coll., A&A **612**, A11 (2018)



HESS Coll., Science **347**, 406 (2015)



The Tarantula Nebula in the LMC

Credit: ESO

- Tarantula nebula
  - most active starburst region in Local Group
  - host to numerous star clusters
  - one of the largest known H-II regions
  - *a place to look for gamma-ray emission from young massive star clusters!*

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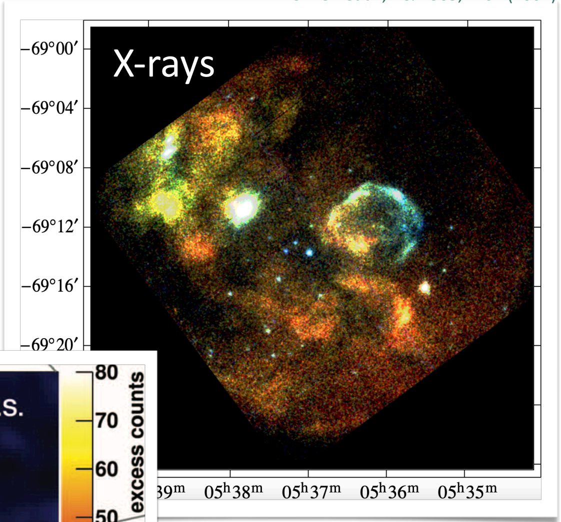
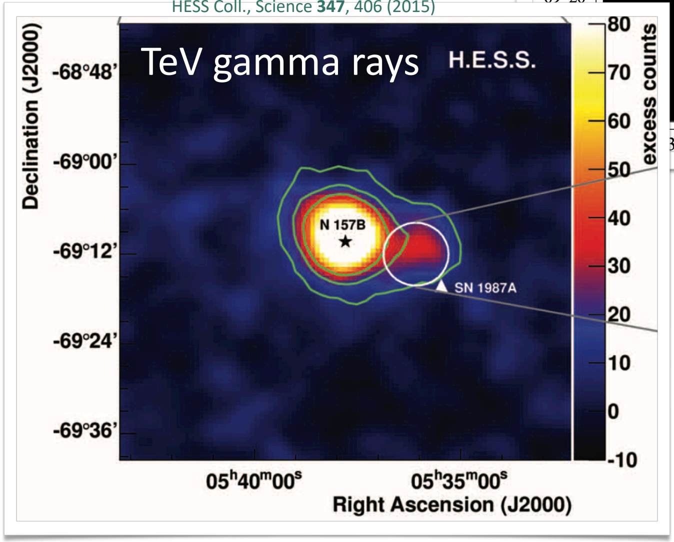
Dennerl et al., A&A **365**, L202 (2001)



HESS Coll., Science **347**, 406 (2015)



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  - **N 157B** — pulsar wind nebula

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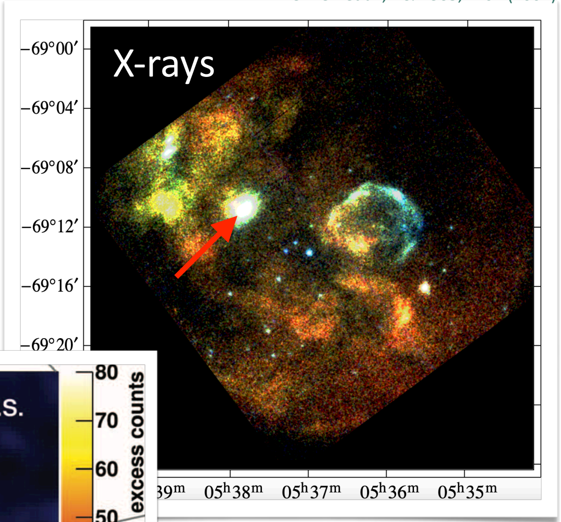
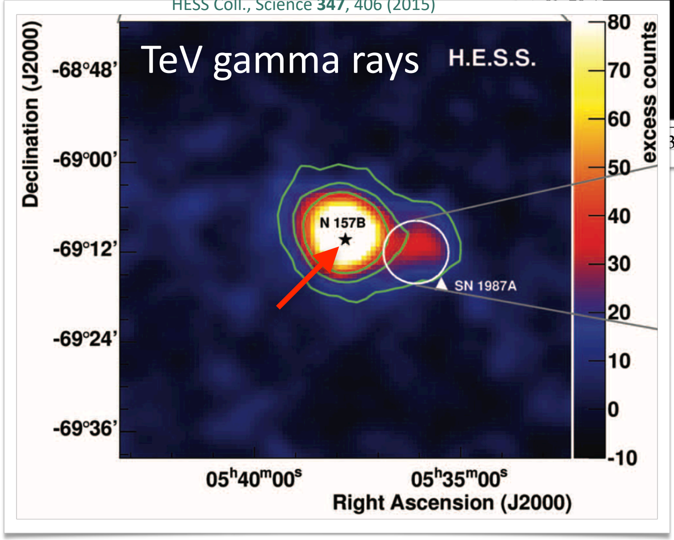


HESS Coll., Science **347**, 406 (2015)



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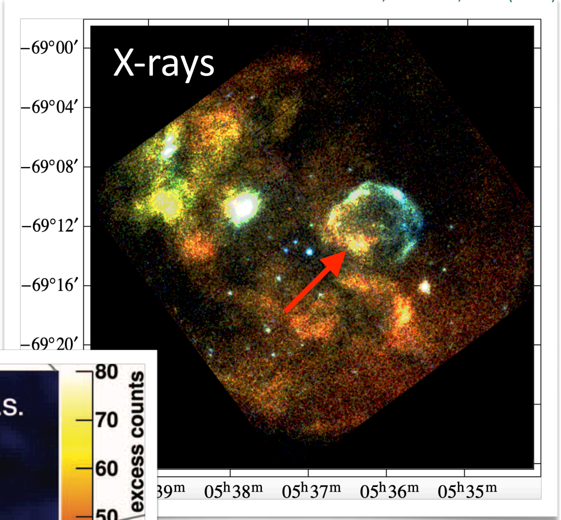
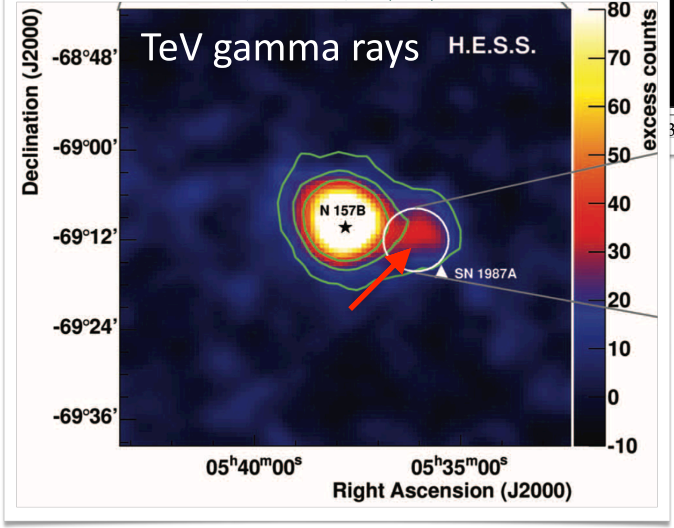


HESS Coll., Science **347**, 406 (2015)



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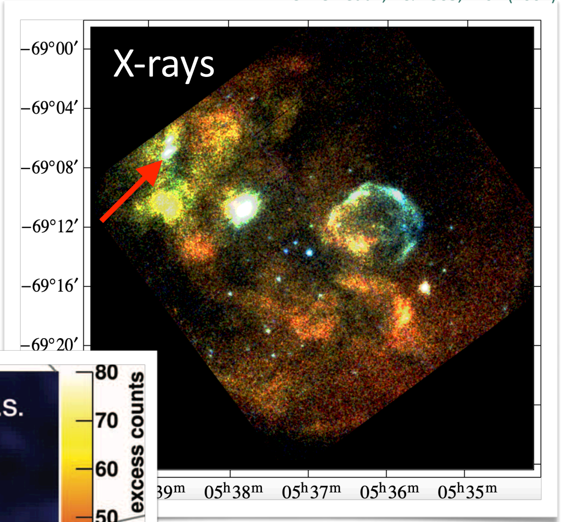
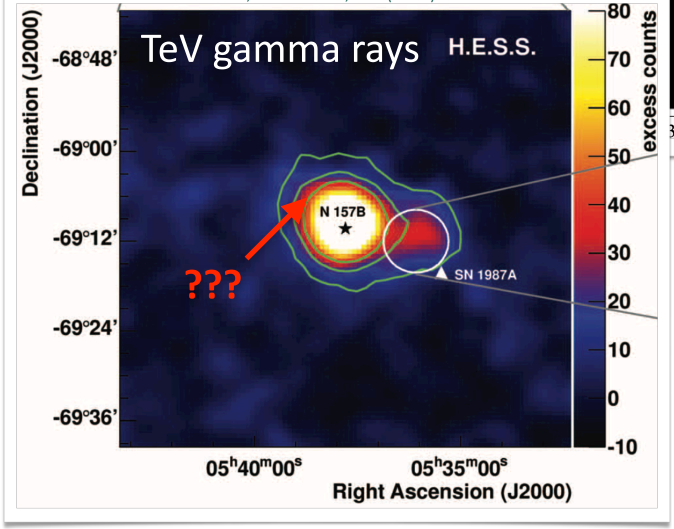
  - **N 157B** — pulsar wind nebula
  - **30 Dor C** — superbubble (around LH90 association of clusters)
  - **R136** — super star cluster (not detected in gamma rays so far)

Dennerl et al., A&A **365**, L202 (2001)



HESS Coll., Science **347**, 406 (2015)

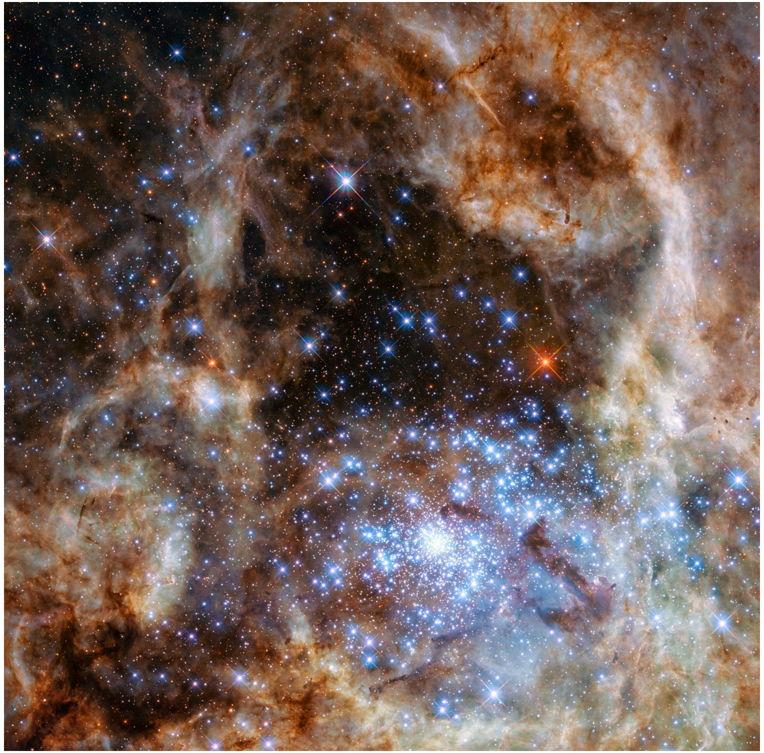


The super star cluster R136

- **Comparatively young:** age $\sim (1.5 \pm 0.5)\,\mathrm{Myr}$
- **Very massive:** total mass $\sim 90{,}000\,M_\odot$
- Multiple stars with $M > 100\,M_\odot$
- Total wind power: $\sim 10^{39}\,\mathrm{erg\,s^{-1}}$ (uncertain!)

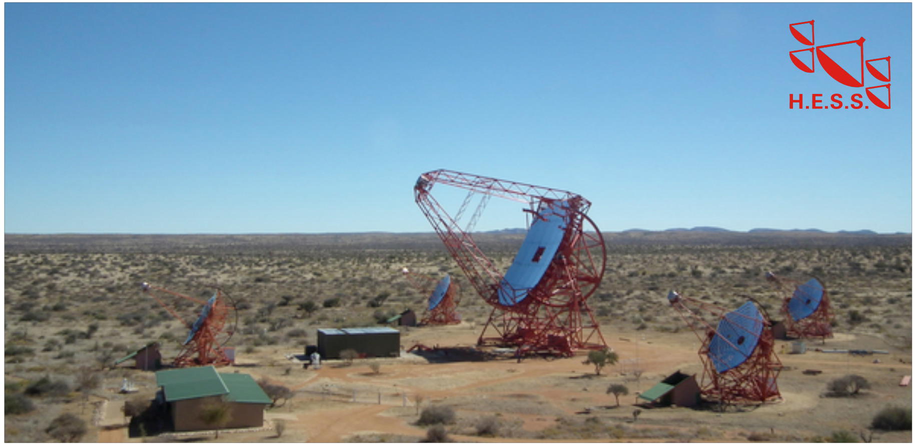
- $\Rightarrow$ a prime candidate for cosmic-ray acceleration, and thus gamma-ray emission

Credit: NASA, ESA, P. Crowther (University of Sheffield)



H.E.S.S.

- High Energy Stereoscopic System
  - array of 5 Cherenkov telescopes
  - Khomas highland, Namibia
  - detects gamma rays with $E \gtrsim 100\,\mathrm{GeV}$
  - angular resolution $\lesssim 0.1^\circ$



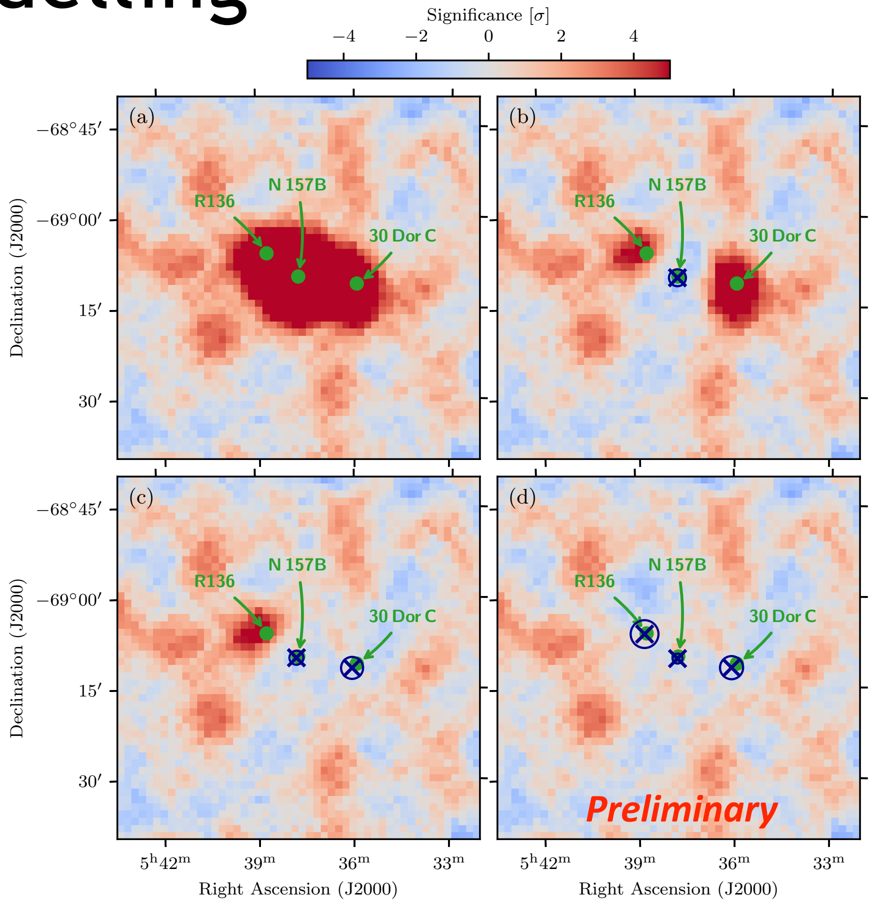
- Analysed data set
  - 360 hours of good quality data
  - taken between 2004-12-30 and 2022-02-02
  - data from four 12-meter telescopes only

Source modelling

- 3D likelihood analysis
  - model spectra & morphologies simultaneously
  - spatial models: 2D Gaussians
  - spectral models: power law / log-parabola
  - add sources until no significant residuals remain

γπ A **Python** package for **gamma-ray** astronomy

Source	Significance
N 157B	51σ
30 Dor C	11σ
R136	6.3σ



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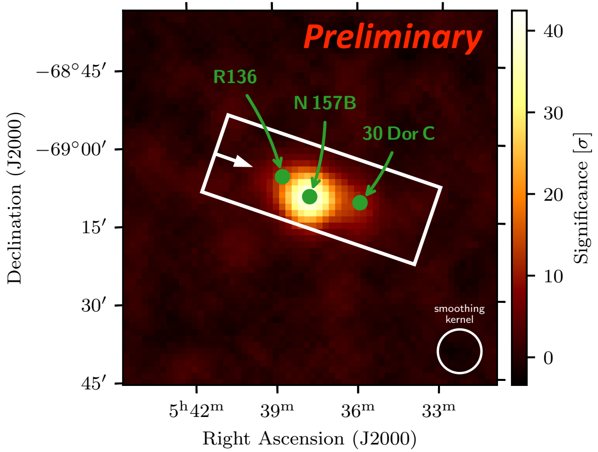
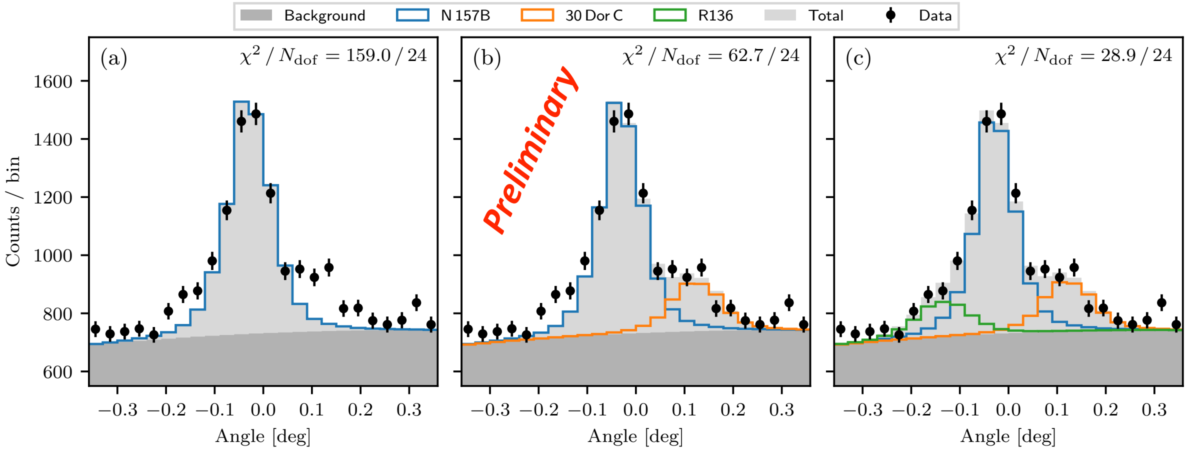
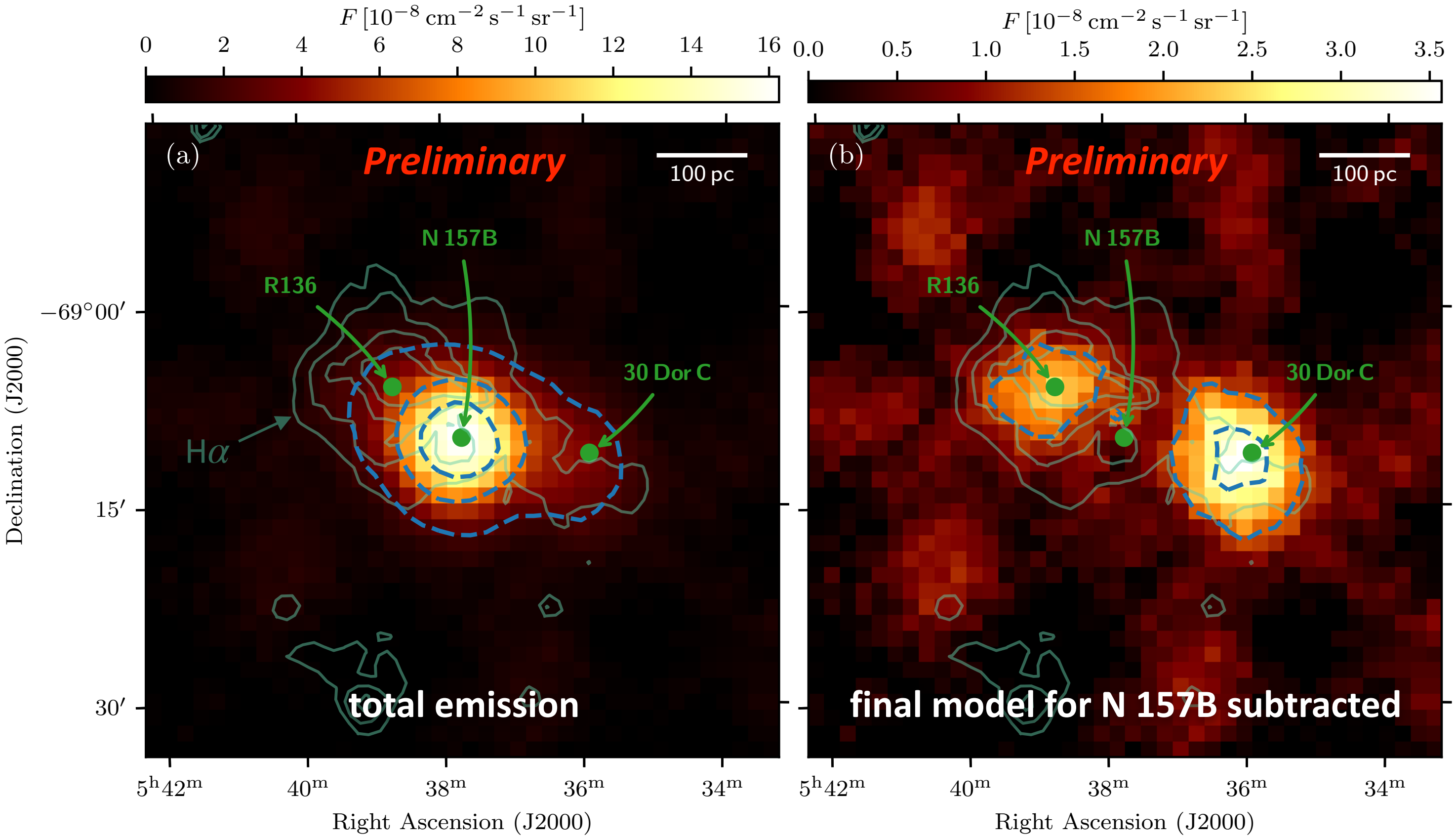


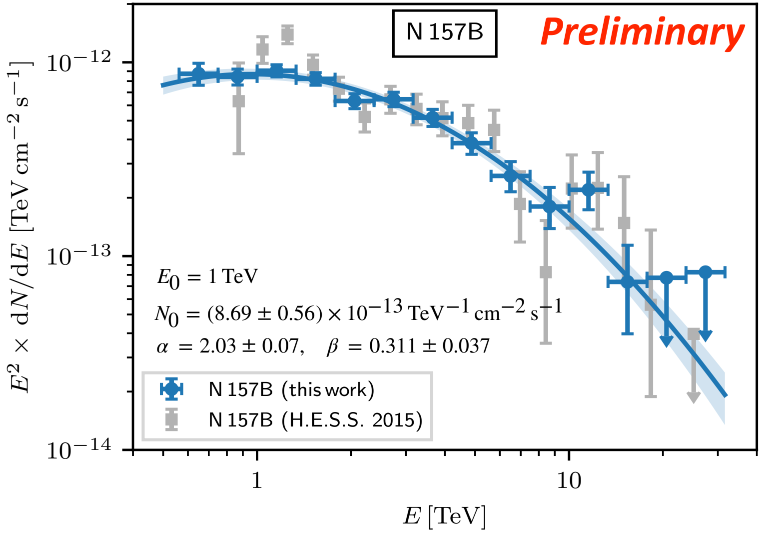


Flux maps

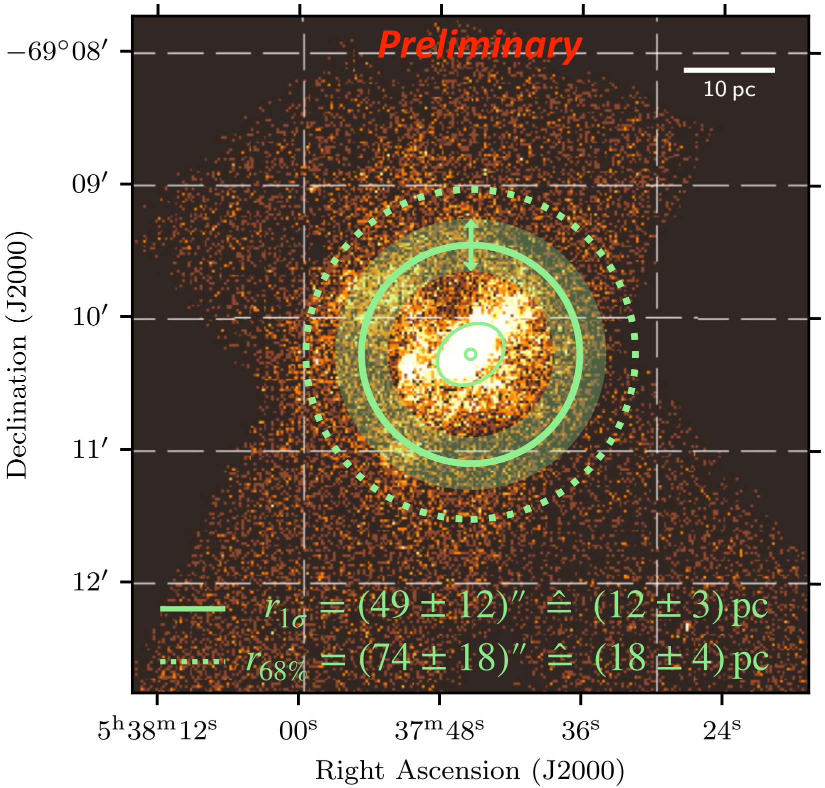

$F\ [10^{-8}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}]$
0 2 4 6 8 10 12 14 16
$F\ [10^{-8}\ \mathrm{cm^{-2}\ s^{-1}\ sr^{-1}}]$
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
(a)
Preliminary
100 pc
N 157B
R136
30 Dor C
Hα
total emission
(b)
Preliminary
100 pc
N 157B
R136
30 Dor C
final model for N 157B subtracted
Declination (J2000)
−69°00′
15′
30′
5h42m 40m 38m 36m 34m
Right Ascension (J2000)
5h42m 40m 38m 36m 34m
Right Ascension (J2000)

N 157B

- Spectrum consistent with published result
- Position and extent match well with *Chandra* X-ray image

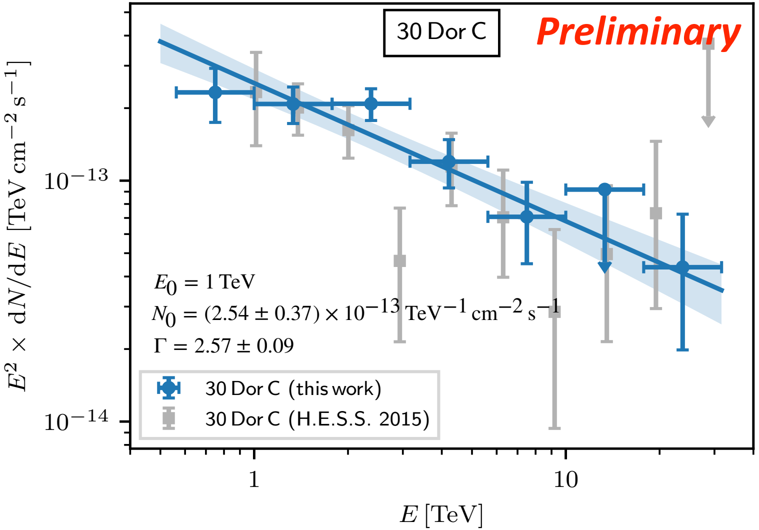


Background image credit: Chen et al., ApJ **651**, 237 (2006)

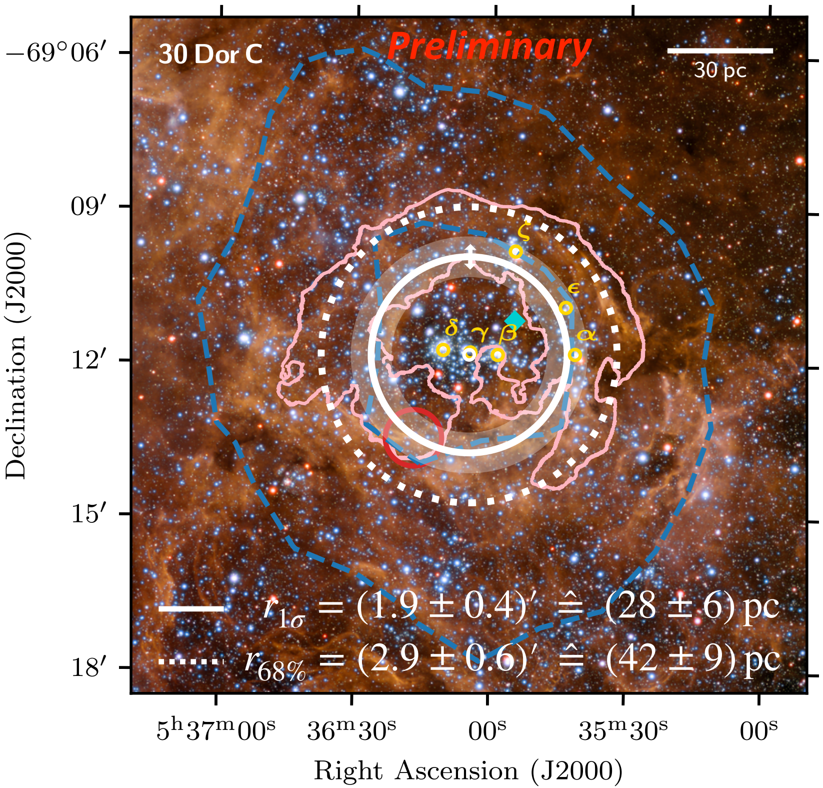


30 Dor C

- Spectrum consistent with published result
- Extension established (3.3σ) for the first time
- Size roughly compatible with X-ray shell

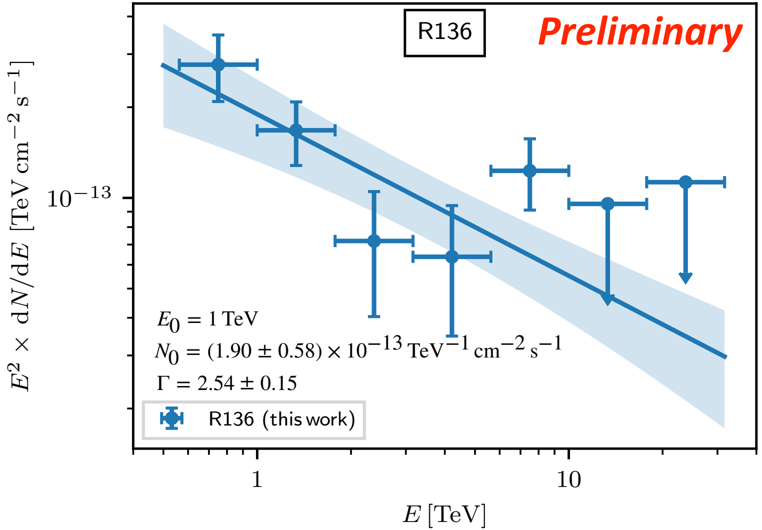


Background image credit: ESO

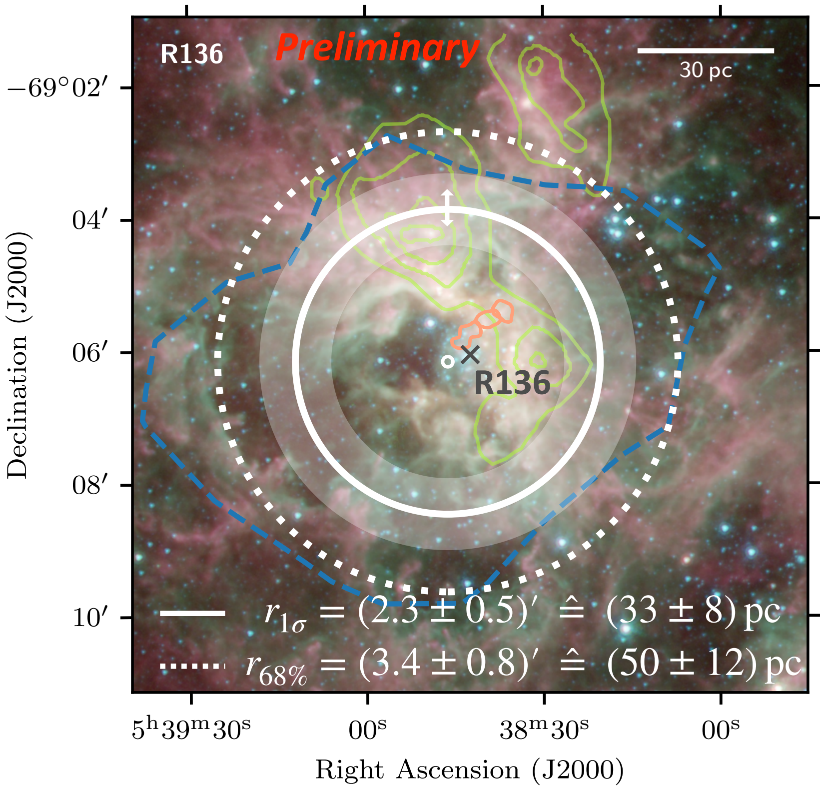


R136

- Position coincides very well with star cluster
- Also observed as extended (3.1σ)



Background image credit: NASA/JPL-Caltech

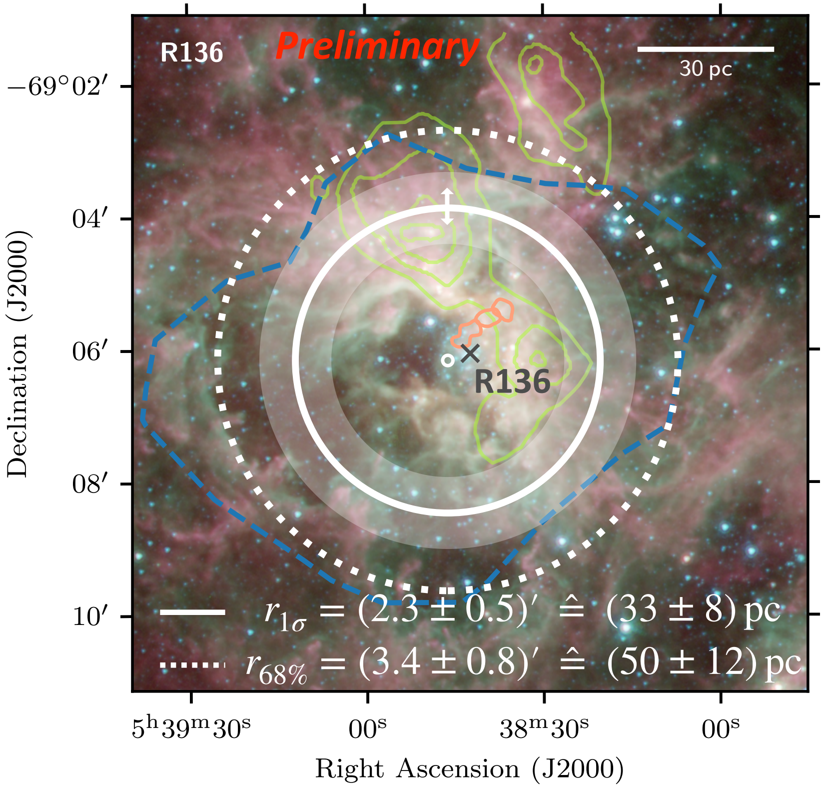


R136

- Position coincides very well with star cluster
- Also observed as extended (3.1σ)

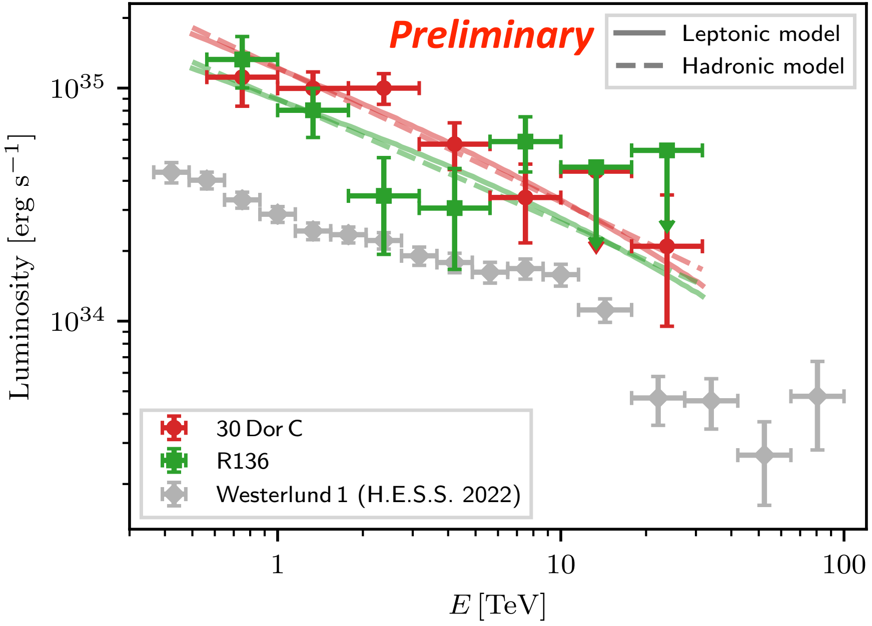
- Compare size with expectation from expanding superbubble:
  - assume cluster wind has $L_w = 10^{39}\,\mathrm{erg\,s^{-1}}$, $v_w = 2{,}000\,\mathrm{km\,s^{-1}}$
  - age: $1.5\,\mathrm{Myr}$
  - following Weaver (1977):
    - superbubble radius $\approx 56\,(n\,/\,100\,\mathrm{cm^{-3}})^{-1/5}\,\mathrm{pc}$
    - termination shock radius $\approx 11\,(n\,/\,100\,\mathrm{cm^{-3}})^{-3/10}\,\mathrm{pc}$

Background image credit: NASA/JPL-Caltech



Energy requirements

- 30 Dor C and R136 are ***twice as luminous*** as Westerlund 1 — the most massive young star cluster in the Milky Way!



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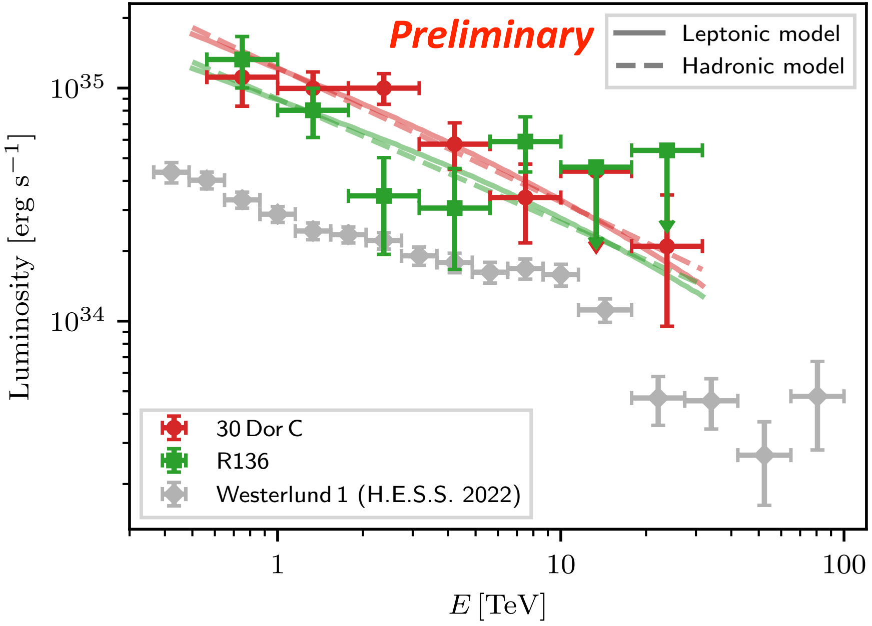
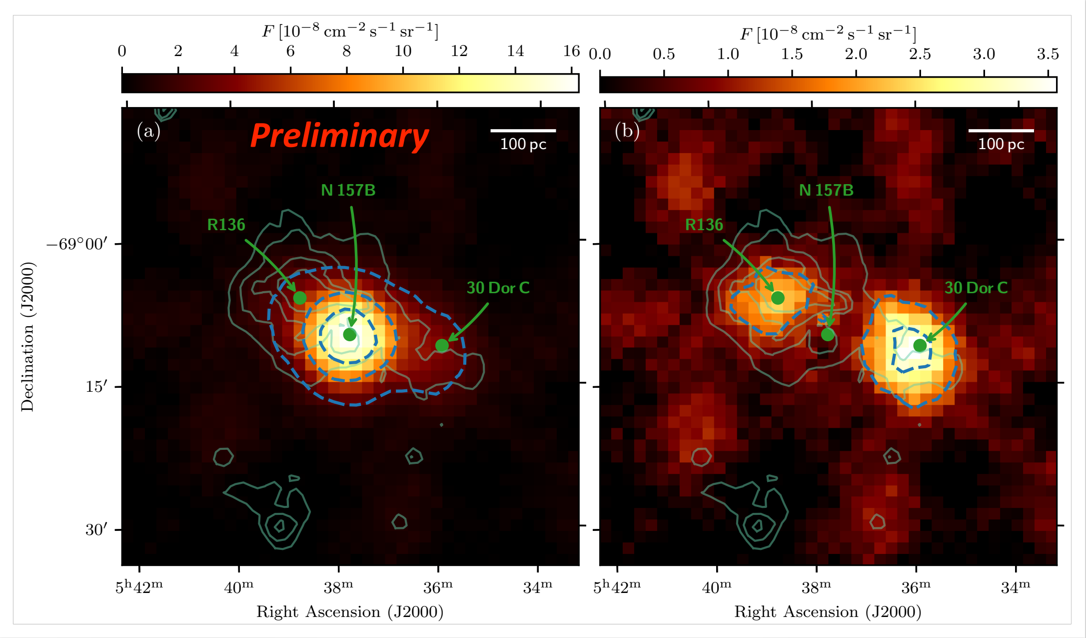
- Fitted physical spectral models with *naima* package (results are for R136)
  - hadronic (*pp*) model
    - $W_p(E_p > 1\,\mathrm{GeV}) \sim 1.1 \times 10^{51}\,(n/100\,\mathrm{cm}^{-3})^{-1}\,\mathrm{erg}$
      → need high gas density
  - leptonic (inverse Compton) model
    - $L_e(E_e > 0.1\,\mathrm{TeV}) \sim 5.3 \times 10^{36}\,\mathrm{erg\,s}^{-1}\ (B = 5\mu G)$
      → affordable, given cluster wind power of $\sim 10^{39}\,\mathrm{erg\,s}^{-1}$



Conclusion

- H.E.S.S. analysis of Tarantula Nebula region in LMC
  - discovery of gamma-ray emission from super star cluster R136
  - new results on superbubble 30 Dor C
  - both sources
    - exceed luminosity of most massive young star cluster in Milky Way
    - appear spatially extended



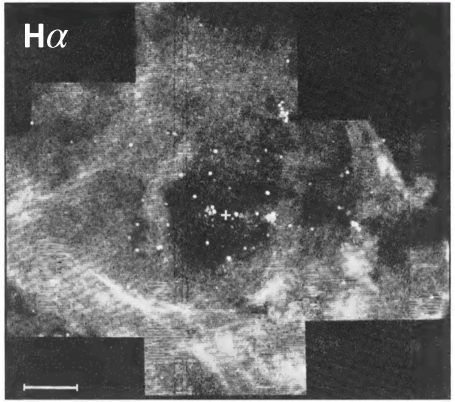
- Paper in preparation — stay tuned!

Backup slides

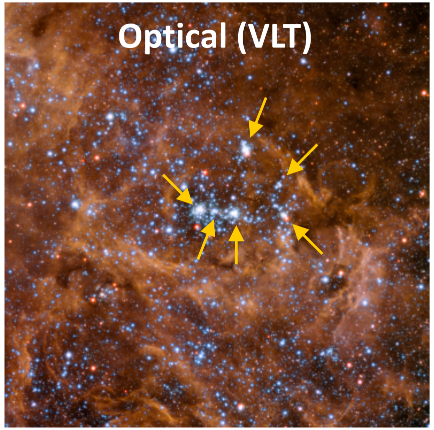
The superbubble 30 Dor C

- Superbubble (seen e.g. in Hα)
- Surrounds "LH 90" association of star clusters
  - age $\sim 4\,\mathrm{Myr}$ (but older sub-populations exist)
  - several WR stars
  - wind power $\sim 2 \times 10^{38}\,\mathrm{erg\,s^{-1}}$ (uncertain!)
- X-ray synchrotron emission
  - not from Hα shell (too slow, $\sim 100\,\mathrm{km\,s^{-1}}$)
  - rather: SNR expanding fast ($\gtrsim 3{,}000\,\mathrm{km\,s^{-1}}$) in low-density superbubble
  - low B-field ($\lesssim 20\,\mu\mathrm{G}$) suggests leptonic origin of TeV emission
- MCSNR J0536–6913: another putative SNR

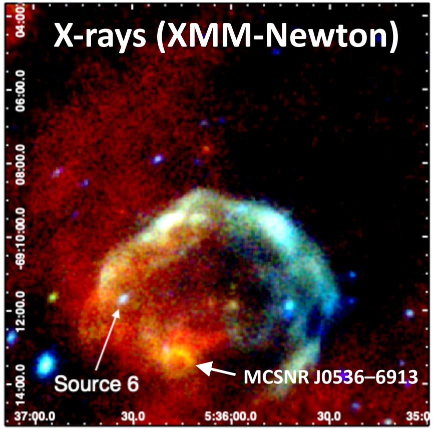
Mathewson et al., ApJS **58**, 197 (1985)



Credit: ESO



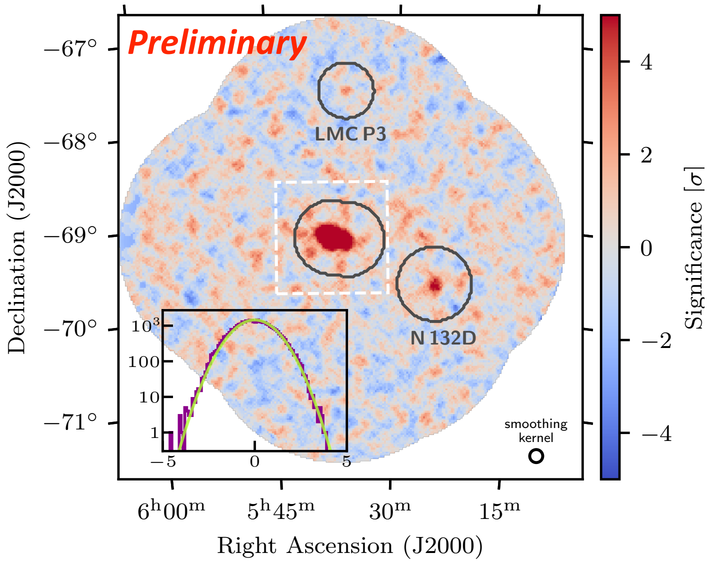
Kavanagh et al., A&A **573**, A73 (2015)



Details of analysis

- 3D likelihood analysis
- First step: adjustment of background model
  - for each observation, fit normalisation & spectral tilt
  - significance distribution outside exclusion regions indicates good description of background
- Iterative modelling procedure
  - add source components until no significant emission remains

ROI center (J2000)	R.A. $5^h35^m28.25^s$ Dec. $-69°16'13.08''$
ROI size	$5° \times 5°$
Spatial pixel size	$0.02° \times 0.02°$
Maximum offset angle	$1.5°$
Energy binning	16 bins / decade
Energy threshold	0.5 TeV



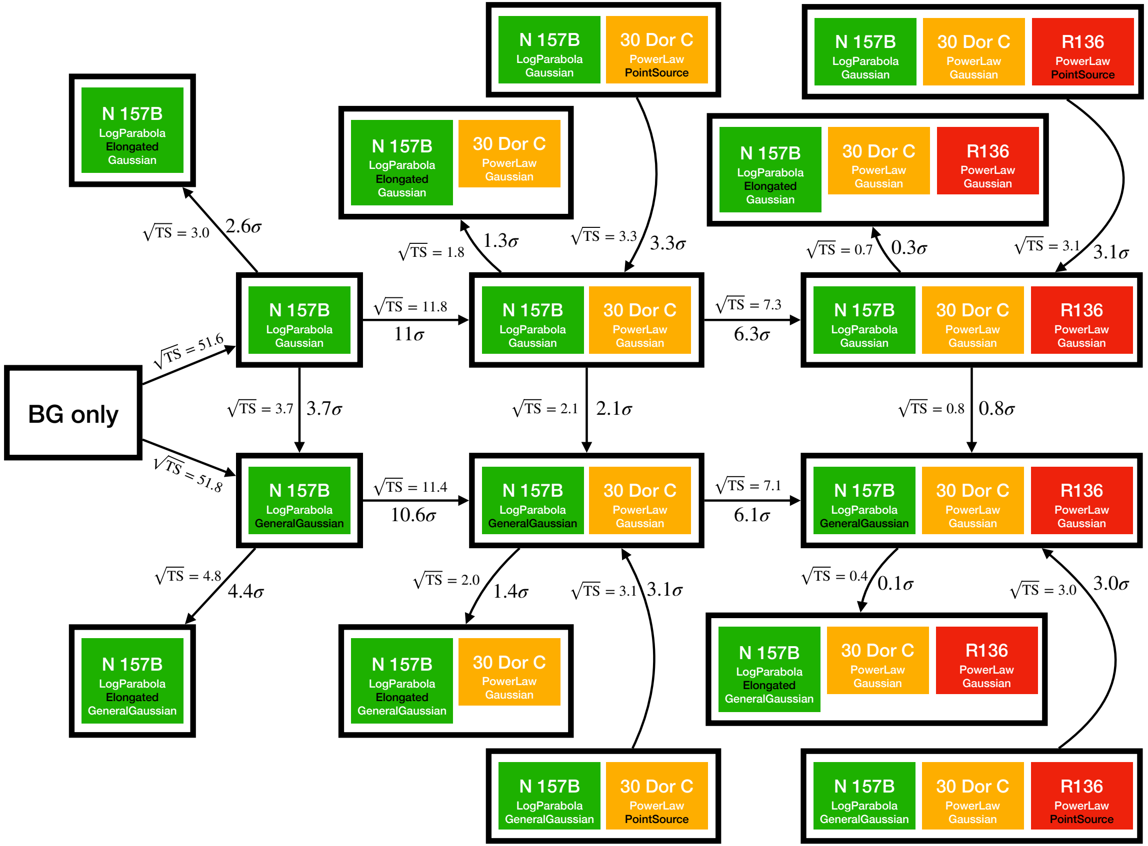
Best-fit model parameters

Preliminary

Parameter	Unit	Value
N 157B / HESS J0537−691		
R.A.	deg	$84.4394 \pm 0.0048_{\rm stat}$ $(5^{\rm h}37^{\rm m}45.5^{\rm s} \pm 1.1^{\rm s}_{\rm stat})$
Dec.	deg	$-69.1713 \pm 0.0016_{\rm stat}$ $(-69°10'17'' \pm 6'')$
σ	deg	$0.0137 \pm 0.0033_{\rm stat} \pm 0.0030_{\rm sys}$
ϕ_0	$10^{-13}\,{\rm TeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}$	$8.69 \pm 0.56_{\rm stat} \pm 0.85_{\rm sys}$
α	—	$2.03 \pm 0.07_{\rm stat} \pm 0.08_{\rm sys}$
β	—	$0.311 \pm 0.037_{\rm stat}$
30 Dor C / HESS J0535−691		
R.A.	deg	$84.021 \pm 0.018_{\rm stat}$ $(5^{\rm h}36^{\rm m}5.0^{\rm s} \pm 4.3^{\rm s}_{\rm stat})$
Dec.	deg	$-69.197 \pm 0.006_{\rm stat}$ $(-69°11'49'' \pm 22'')$
σ	deg	$0.0319 \pm 0.0066_{\rm stat} \pm 0.0034_{\rm sys}$
ϕ_0	$10^{-13}\,{\rm TeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}$	$2.54 \pm 0.37_{\rm stat}\ {}^{+0.44}_{-0.40}\vert_{\rm sys}$
Γ	—	$2.57 \pm 0.09_{\rm stat}$
R136 / HESS J0538−691		
R.A.	deg	$84.692 \pm 0.038_{\rm stat}$ $(5^{\rm h}38^{\rm m}46^{\rm s} \pm 9^{\rm s}_{\rm stat})$
Dec.	deg	$-69.103 \pm 0.013_{\rm stat}$ $(-69°06'11'' \pm 47'')$
σ	deg	$0.0384 \pm 0.0090_{\rm stat}\ {}^{+0.0045}_{-0.0037}\vert_{\rm sys}$
ϕ_0	$10^{-13}\,{\rm TeV}^{-1}\,{\rm cm}^{-2}\,{\rm s}^{-1}$	$1.90 \pm 0.58_{\rm stat}\ {}^{+0.45}_{-0.38}\vert_{\rm sys}$
Γ	—	$2.54 \pm 0.15_{\rm stat}$

Alternative models

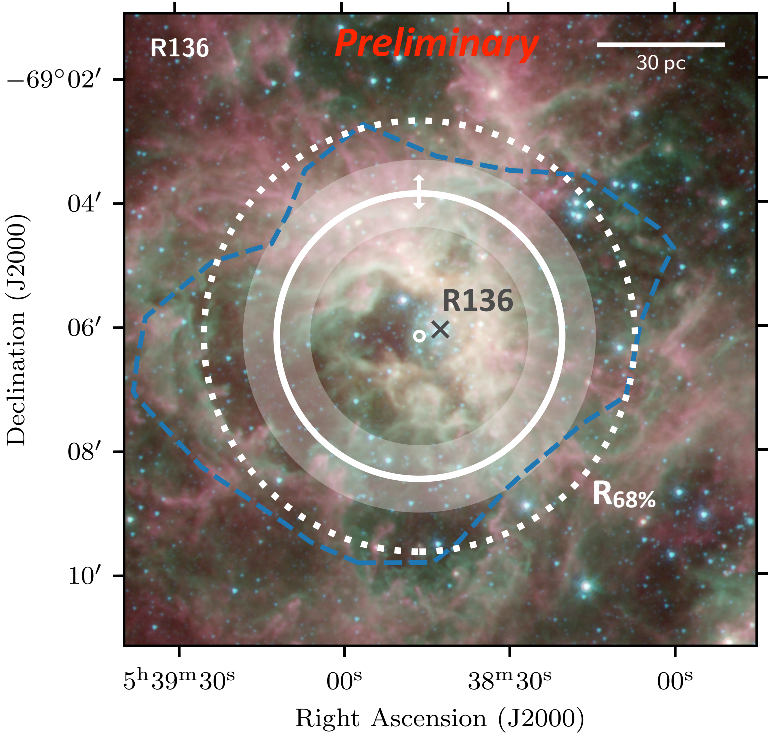
- Many alternatives tested
- In particular, allowed more flexible spatial model for N 157B
  - elongation
  - "generalised Gaussian"
  - → model with 3 sources is always strongly preferred



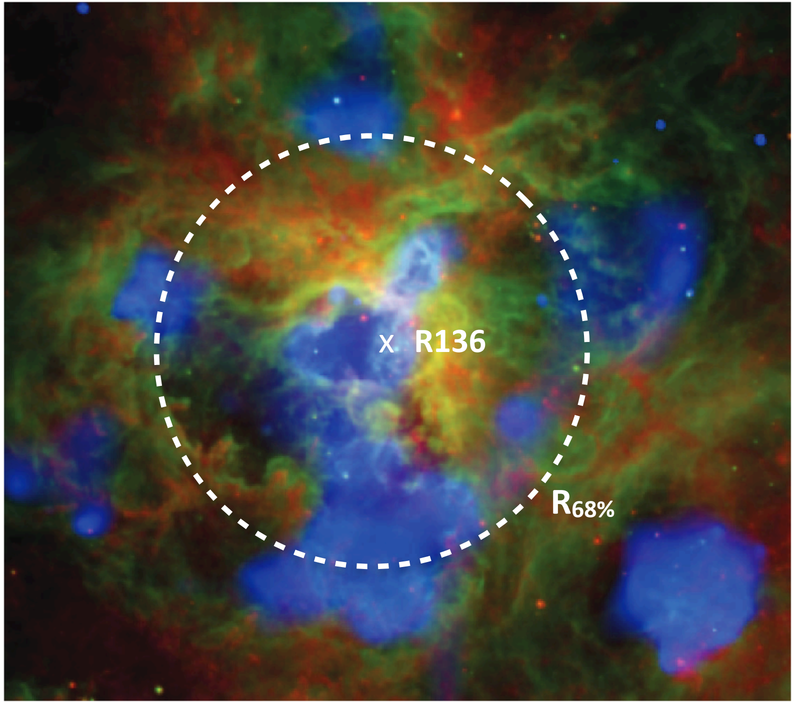
R136 — MWL view

- Size of TeV emission ≈ size of superbubble?

Background image credit: NASA/JPL-Caltech



Townsley et al., AJ **131**, 2140 (2006)

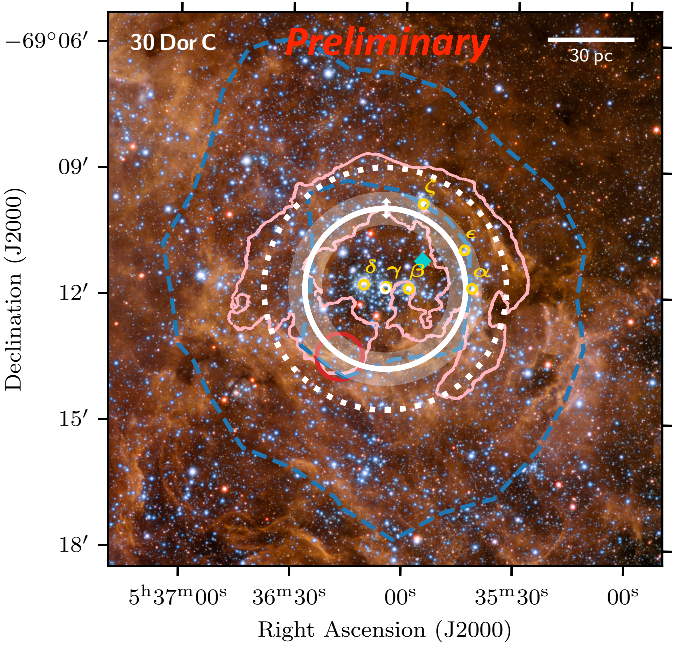


infrared 6.5–9.4 µm Hα X-ray 0.9–2.3 keV

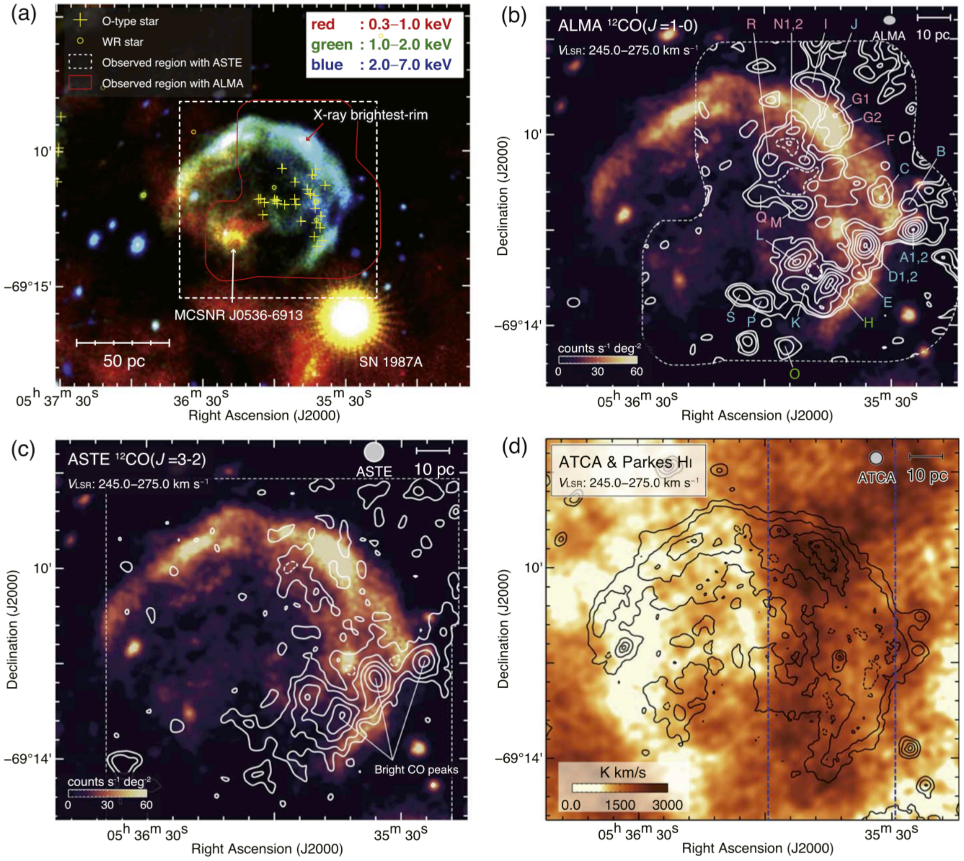
30 Dor C — MWL view

- Dense ($\gtrsim 100\,\mathrm{cm}^{-3}$) molecular clouds, in particular in western part of shell

Background image credit: ESO



Yamane et al., ApJ **918**, 36 (2021)

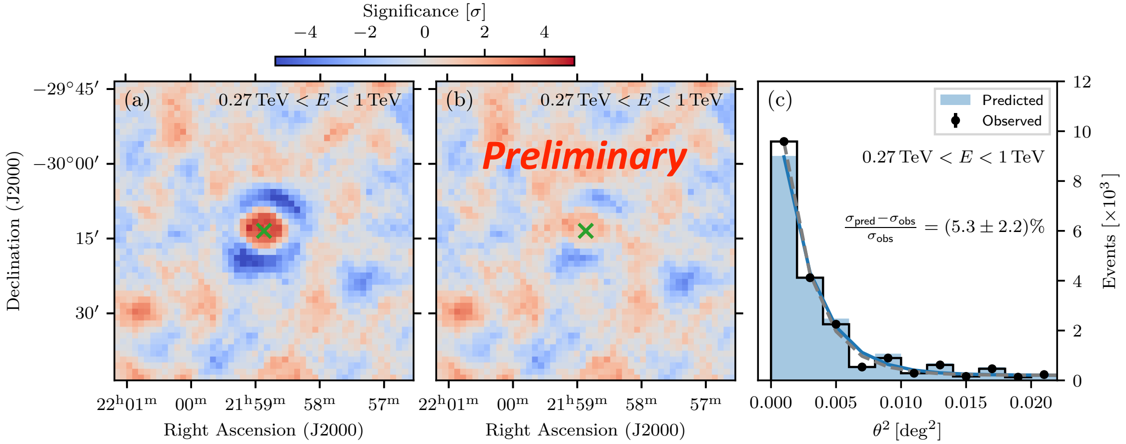


Estimation of systematic uncertainties

- Systematic uncertainties derived with "bracketing" approach
  - vary instrument response functions
  - repeat modelling analysis
  - systematic error = difference to default best-fit parameter value
  - total systematic error is quadratic sum of different contributions
  - do not quote error if negligible compared to statistical one

- Systematic effects considered:
  - background normalisation* ($\pm 0.5\,\%$)
  - energy scale ($\pm 10\,\%$)
  - PSF width ($\pm 5\,\%$)

  (derived from study on PKS 2155–304, see below)



* of the stacked data sets (i.e. not per run!)