TECHNION Israel Institute of Technology | Department of Physics

Point symmetries in core-collapse supernovae

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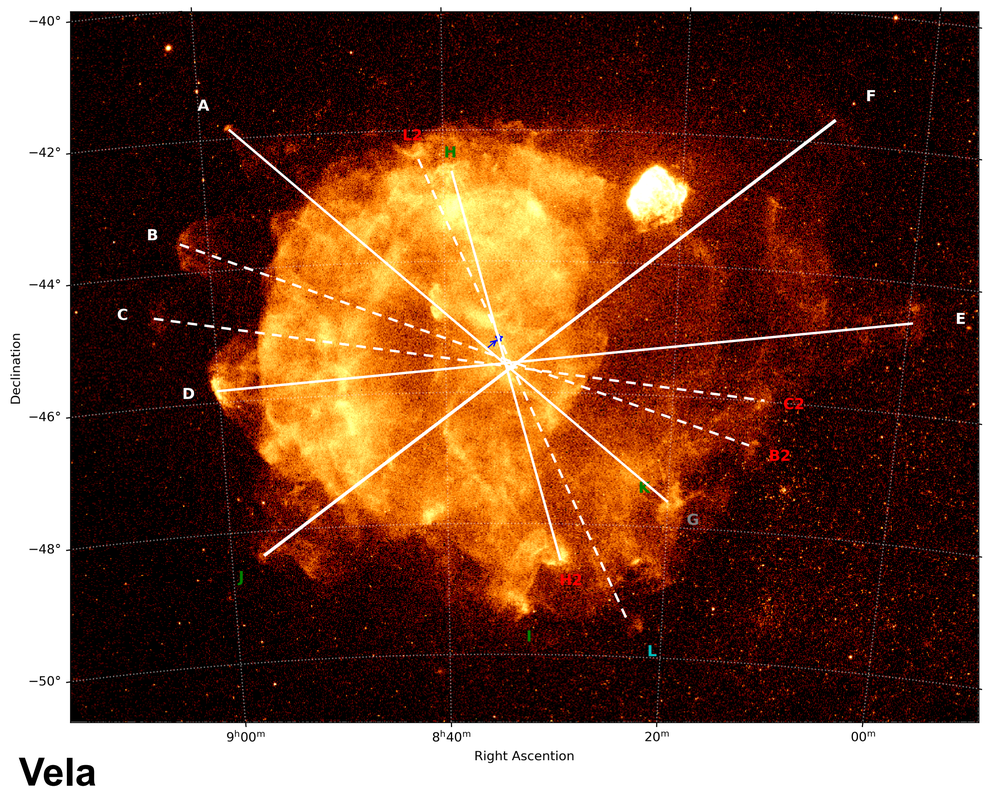


Vela

X-ray counts image, 0.2-2.3 keV, log scaled (DR1 eROSITA-DE data)
See Figures from Soker, N. and **SD**,
"The vela supernova remnant: The unique morphological features of jittering jets",
2025. *RAA*, 25, 035008, doi:10.1088/1674-4527/adb4cc

- **Famous for many clumps (/projectiles/bullets):**

Aschenbach, B. et al. 1995. Nature, Volume 373, Issue 6515, pp. 587-590 doi:10.1038/373587a0

Garcia, F. et al. 2017. A&A, Volume 604, id.L5, 5 pp. doi: 10.1051/0004-6361/201731418

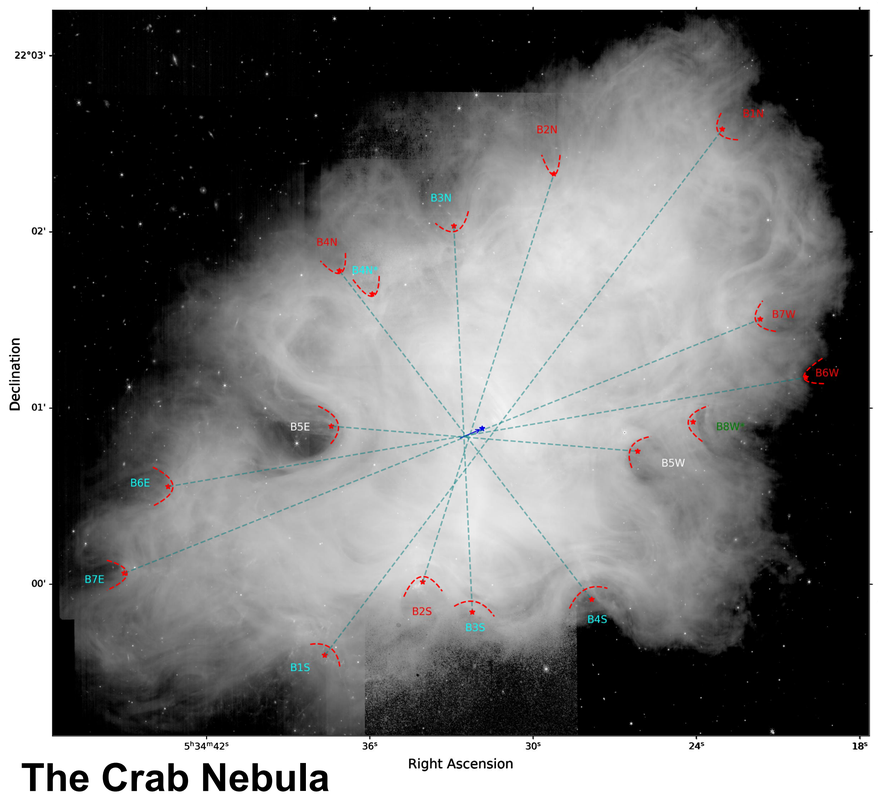
Sapienza, V. et al. 2021. A&A, Volume 649, id.A56, 10 pp. doi: 10.1051/0004-6361/202140412

Mayer, M. et al. 2023. A&A, Volume 676, id.A68, 28 pp. doi: 10.1051/0004-6361/202346691

Soker, N. 2024. OJoA, Vol 7, id.49. doi: 10.33232/001c.120279

Soker, N. and Shishkin, D., 2025. RAA, 25, 035008, doi:10.1088/1674-4527/adb4cc.

- **These clumps can be paired to form a point-symmetrical structure. Possible evidence for many pairs of jets.**



The Crab Nebula

Infrared F480M image, log-norm scaled (JWST, Temim, T. et al. 2024)
See Figures from **SD**, and Soker, N.,
"Et tu, Brute?: The Crab Nebula also exploded by jittering jets",
2025. submitted, doi:10.48550/arXiv.2411.07938

- **A weak explosion with a powerful pulsar wind nebula (PWN; an inner nebula powered by the rotating neutron star) in the center, fueling heated gas outflow.**
- **Many indentations (bays) are revealed by this outflow:**

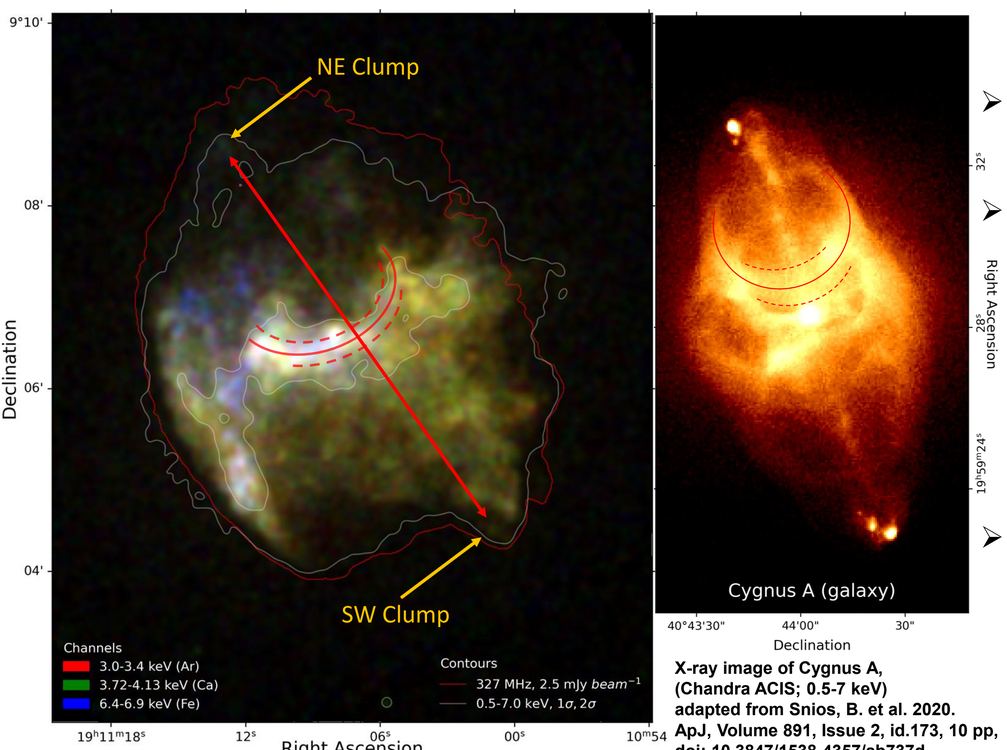
(Long acknowledged, as early as:)
Roberts, I. 1892. MNRAS Vol 52, p 502 doi: 10.1093/mnras/52.7.502

(NW bay, as early as:)
Fesen, R. et al. 1992. ApJ, Volume 399, p 599 doi: 10.1086/171951

Temim, T. et al. 2014. ApJL, Volume 968, Issue 2, id.L18, 25 pp doi: 10.3847/2041-8213/ad50d1

Shishkin, D. and Soker, N. 2025. submitted doi: 10.48550/arXiv.2411.07938

- **These bays indicate the locations of clumps, their point-symmetric formation again points to many pairs of jets.**

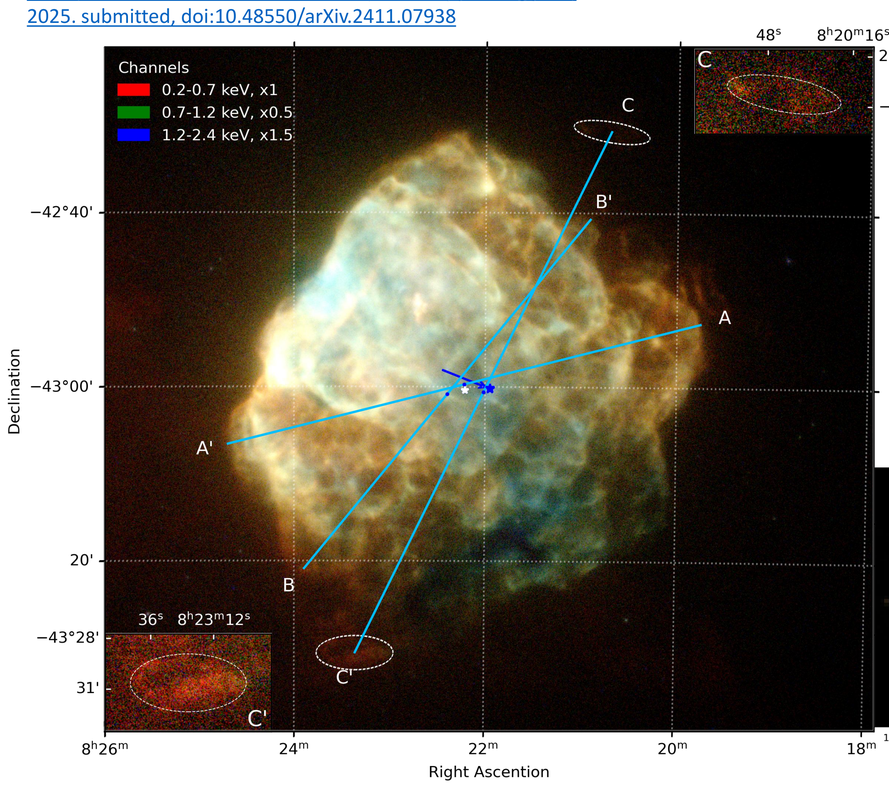


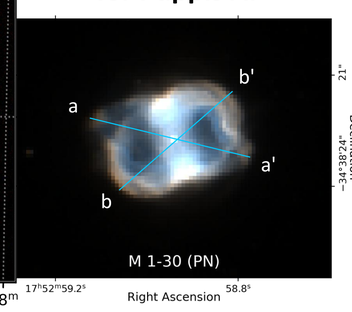
W49B

X-ray image, 3.0-3.4 keV (red) , 3.72-4.13 keV (green) , 6.4-6.9 keV (blue) (Chandra ACIS; Lopez et. al. 2013),
Total counts 0.5-7 keV at $1{,}2\sigma$ (white contours). 327 MHz radio at $2.5\ \mathrm{mJy\ beam^{-1}}$ (red contour, VLA; Lacey et. al. 2001).
See Figures from Soker, N. and **SD**,
"The main jet axis of the W49B supernova remnant",
2025. *PASA*, 42, e048, doi: 10.1017/pasa.2025.39

- **Bright in X-ray, with a slightly extended shape.**
- **Exhibits both a complex inner structure (arc) and an H-shaped abundances map. Coupled with two potential clumps hints at a main jet axis.**
- **Comparison against an X-ray image of the Cygnus A galaxy that has an active jet reveals striking resemblance.**

X-ray image of Cygnus A, (Chandra ACIS; 0.5-7 keV) adapted from Snios, B. et al. 2020. ApJ, Volume 891, Issue 2, id.173, 10 pp, doi: 10.3847/1538-4357/ab737d



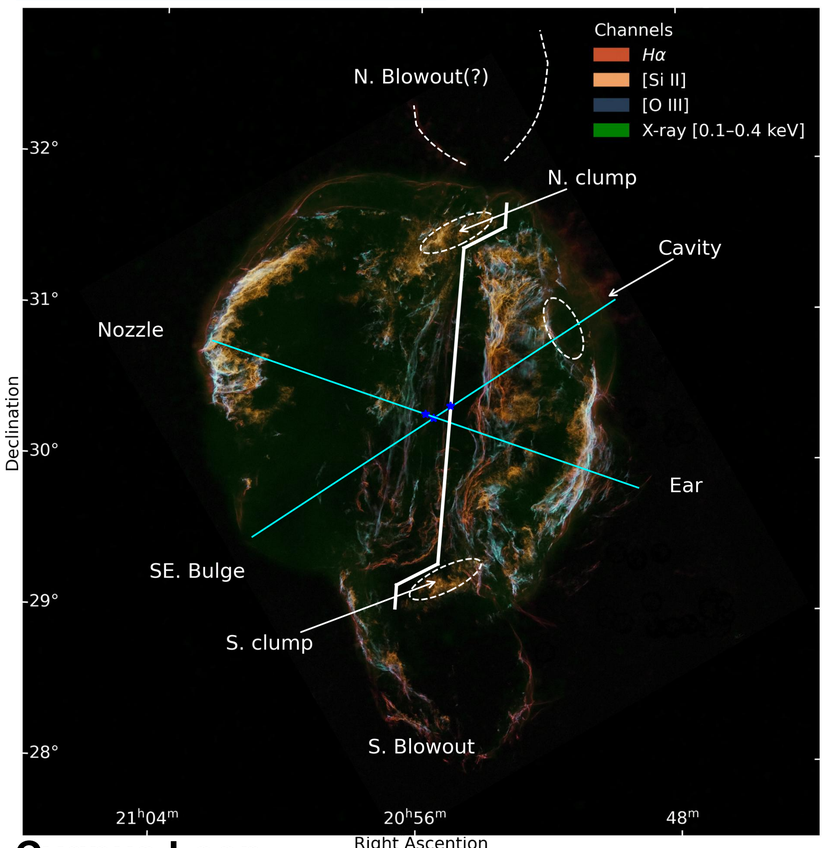


Visible image of M1-30, (HST; F658N/F658N) Prop ID. 8345, PI: Sahai, R. Markings by Hsia et al. (2014)

Puppis A

X-ray counts image, 0.2-2.4 keV, log scaled (EDR eROSITA-DE data)
See Figures from Ealeal, B., **SD**, and Soker, N.,
"The Puppis A supernova remnant: an early jet-driven neutron star kick followed by jittering jets",
2025. *RAA*, 25, 045008, doi: 10.1088/1674-4527/adc24e

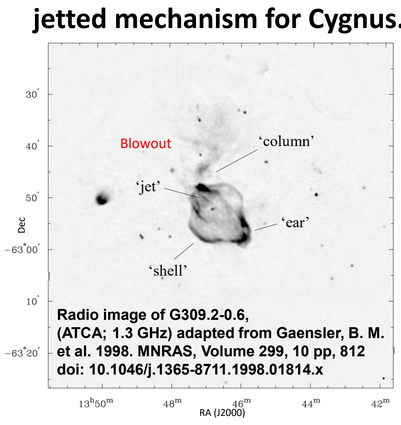
- **The "spaghetti" nebula, famous for its messy filamentous structure in the visible.**
- **Inner structure bright in X-ray emission.**
- **Controversial age – estimates ranging from 20kyr to 200kyr and even 600kyr.**
- **Two very prominent inflated structures at the east and west, with a possible sub-structure hinting at two pairs of jets contributing to their overall shape.**
- **Coupled with the X-ray emission axis, the NS kick direction can be explained by several asymmetrical jet-launching episodes applying kicks with the kick-BEAP mechanism [kick-by-early asymmetric pair(s) of jets].**



Cygnus Loop

Optical (Hα, [O III], [Si II]) image by Min Xie (Raymond, J. C., et al. 2023)
X-ray image 0.1-0.4 keV (over-exposed, alpha=0.08, green) (ROSAT; B. Aschenbach 1993)
See Figures from **SD**, Kaye, R. and Soker, N.
"Identifying Jittering Jet-shaped Ejecta in the Cygnus Loop Supernova Remnant",
2024. *ApJ*, 975, 2, 181, 9 pp, doi: 10.3847/1538-4357/ad8138

- **Middle aged (~20,000 yr) SNR, visible in both (soft) X-ray and visible lines.**
- **Many complex morphological features include well studied outwards propagating shocks (red filaments on the image) and a prominent blowout region at the south.**
- **Identifying and matching features seen in X-ray and/or visible enables the construction of a point-symmetric wind rose.**
- **Comparison against other blowout structures suspected to be jet shaped strengthens a jetted mechanism for Cygnus.**



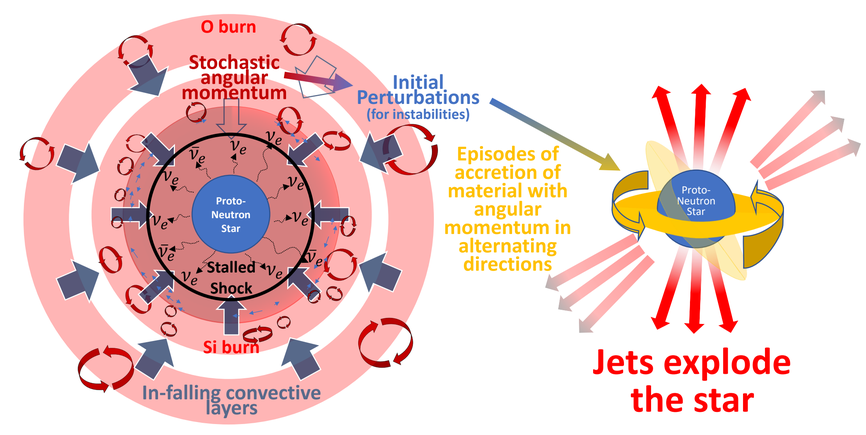
Radio image of G309.2-0.6, (ATCA; 1.3 GHz) adapted from Gaensler, B. M. et al. 1998. MNRAS, Volume 299, 10 pp, 812 doi: 10.1046/j.1365-8711.1998.01814.x

Simeis 147

Optical ([O III]: blue and green, Hα: red hue).
Image by Mr. Christian Koll.

X-ray; 0.3-0.6 keV (red), 0.6 – 1.0 keV (green), 1.0 – 1.5 keV (blue); In the image: yellow.
Image from Michailidis et. al. 2024.

See Figures from **SD**, Ealeal, B. and Soker, N.
"Natal kick by early-asymmetrical pairs of jets to the neutron star of supernova remnant S147"
2025. submitted. doi: 10.48550/arXiv:2506.21548



The jittering jets explosion mechanism (JJEM) for core-collapse supernovae explains explosion to take place by many pairs of bipolar jets in varying (jittering) directions. While most of the jet's energy is invested into exploding the star and ejecting the envelope, some of the last pairs of jets can influence the morphology of the supernova remnant.
This will manifest in point symmetrical structures throughout the remnant, as clumps, projectiles, inflated ears, nozzle-rim pairs, blowouts or other typical jet signatures.

See also: Poster by Noam Soker