PION: Simulating bow shocks and circumstellar nebulae around massive stars

Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

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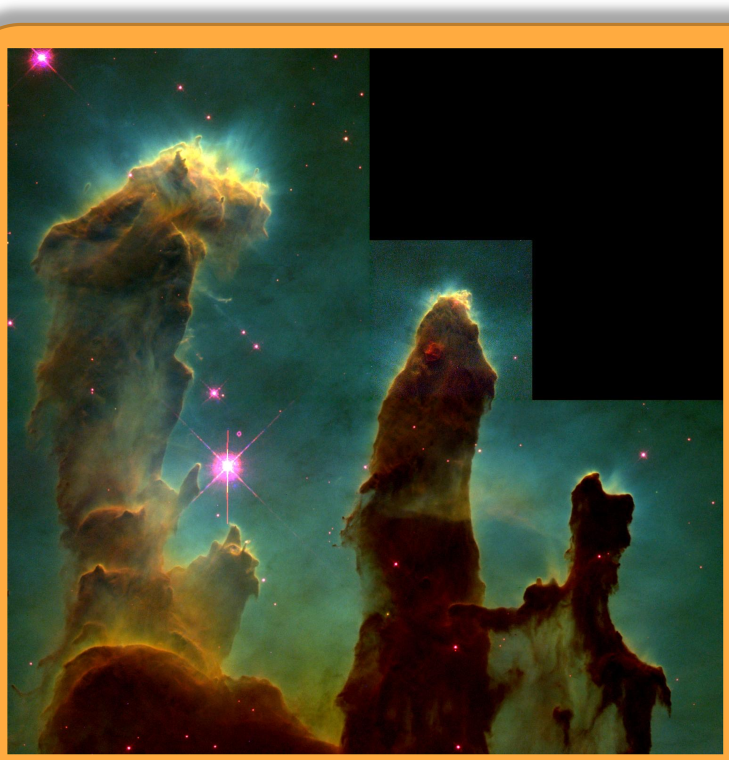


The Pillars of Creation in the Eagle Nebula, NGC 6611. (Credit: HST/NASA: J.Hester, P.Scowen)
https://www.spacetelescope.org/images/opo9544a/

- **Stellar Winds**: enrich space with heavy elements, produce bubbles and nebulae, and set the density field into which supernova explodes.
- **Radiation**: produces photoionized nebulae around hot stars, creates pillars, globules, disperses molecular clouds.
- **Supernovae**: explosive energy input at the end of a star's life. Stirs up interstellar gas, creates shells and supershells, destroys clouds.

PION couples radiation-magnetohydrodynamics with results from stellar evolution calculations to investigate nebulae around massive stars. This poster presents code upgrades with example applications.

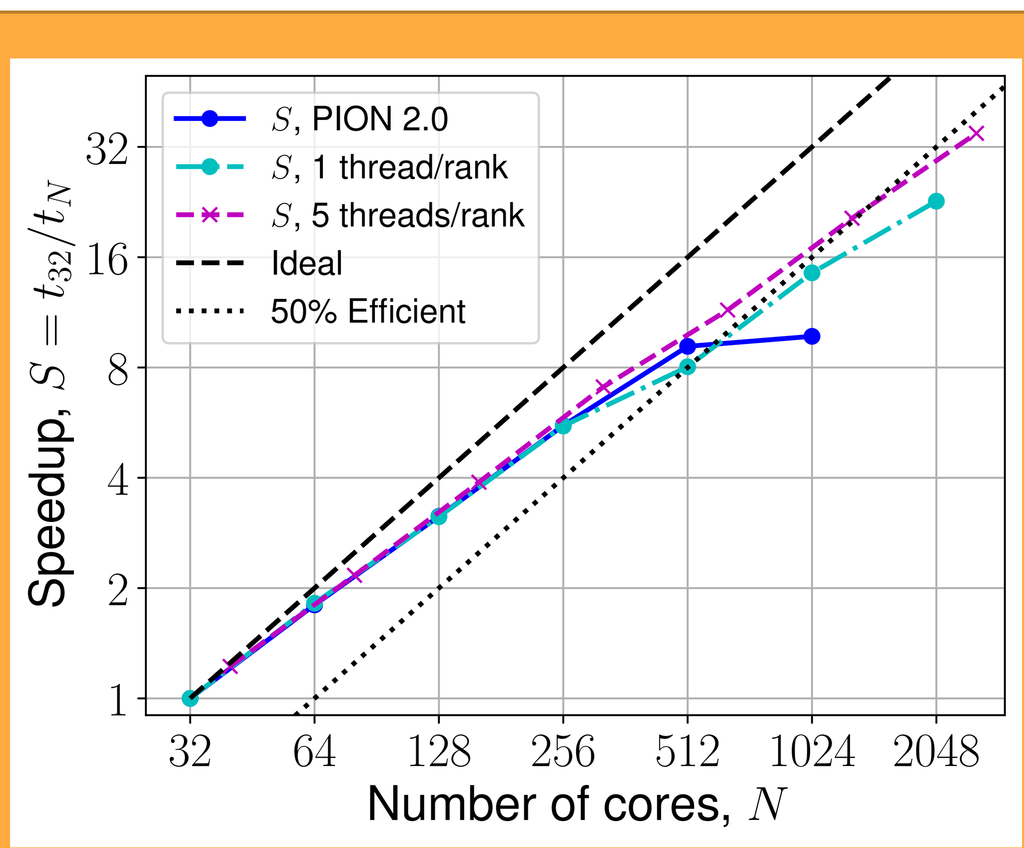
https://www.pion.ie

- **Methods paper: Mackey et al. (2021, MNRAS, 504, 983)**
- **Applied to the bow shock of Zeta Oph with 3D MHD simulations: Green et al. (2022), arXiv:2203.06331, A&A submitted.**

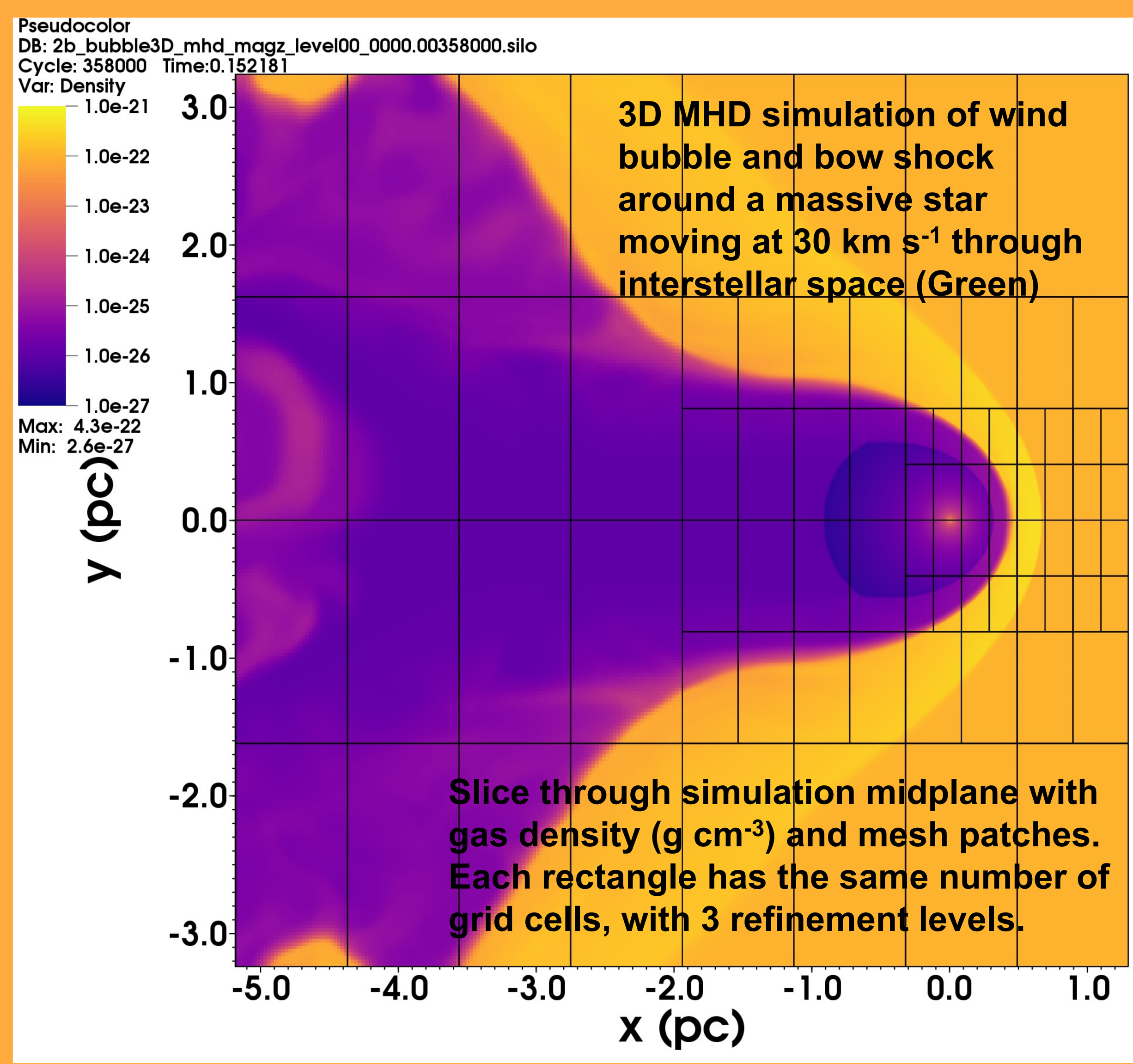
Thor's Helmet: a wind-blown bubble around a Wolf-Rayet Star (Credit: ESO/B. Bailleul)
https://www.eso.org/public/images/eso1238a/

Recent Upgrades

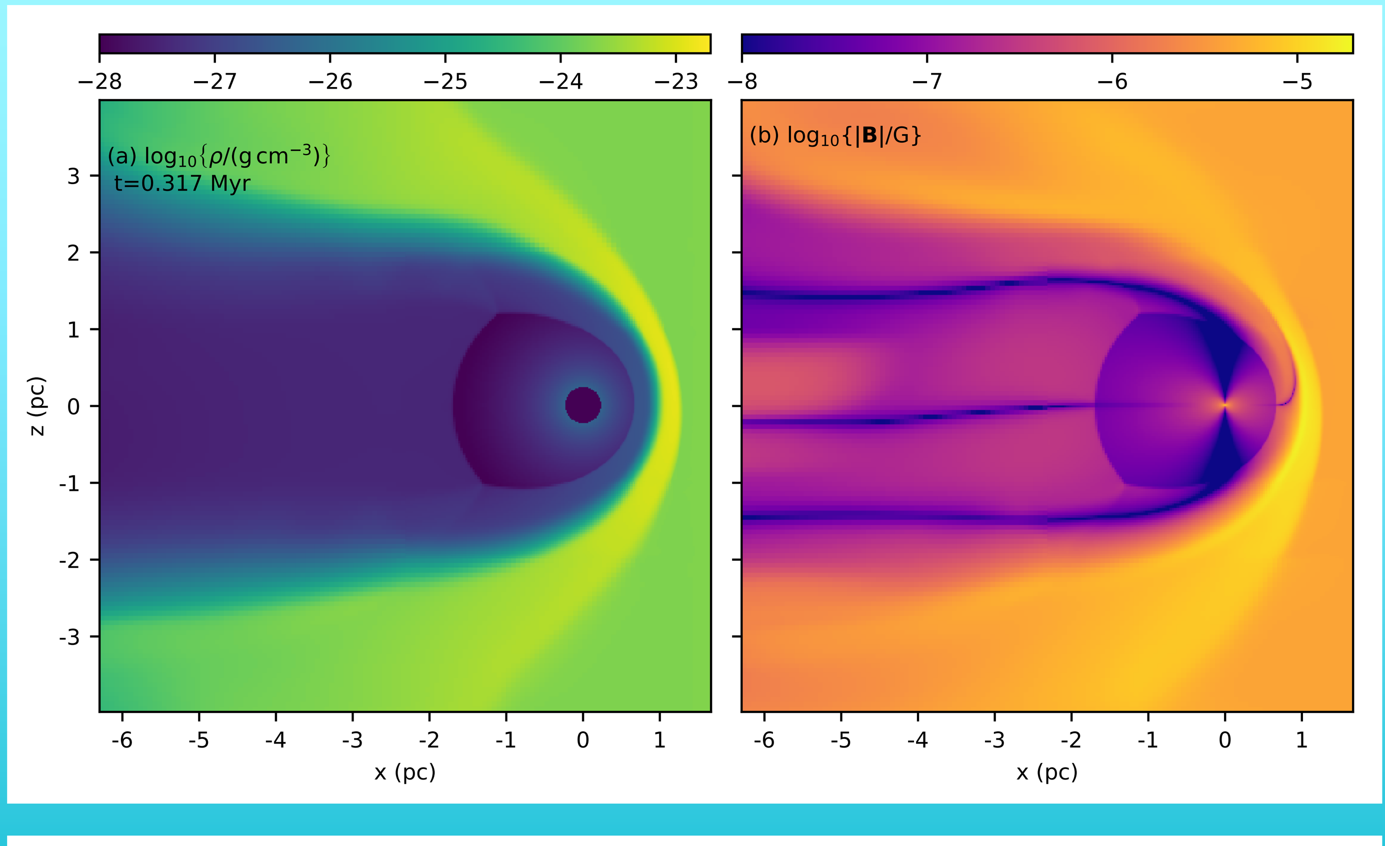
- **Nested Grid**: allows higher resolution near the star, enables higher-resolution 3D simulations
- **Robust MHD solver**: allows MHD simulations of nebulae, and prediction of non-thermal emission
- **Python postprocessing module**: quick visualization and analysis of data, also publication-quality figures
- **Hybrid parallelization (OpenMP+MPI)**, significantly improves scaling compared with only MPI
- **Orbital motion** for colliding-wind binary systems



Strong scaling of PION for a 3D MHD simulation of a bow shock around a runaway massive star. The simulation has 256^3 grid cells per level and 3 levels of refinement. Results from PION v2.0 from Mackey et al. (2021) (blue solid line) are compared with an upgraded version of PION run with 1 (cyan dot-dashed line) and 5 (magenta dashed line) OpenMP threads per MPI process. The speedup, S, is defined as the run duration using N cores, t_N, divided by the run duration using 32 cores, t_{32}.



3D MHD simulations of Bow shocks

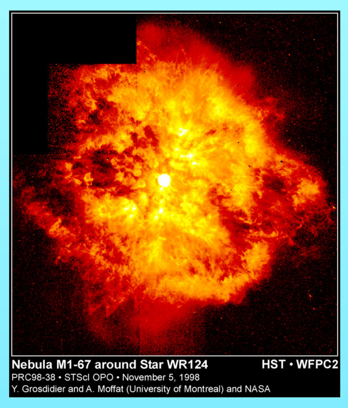


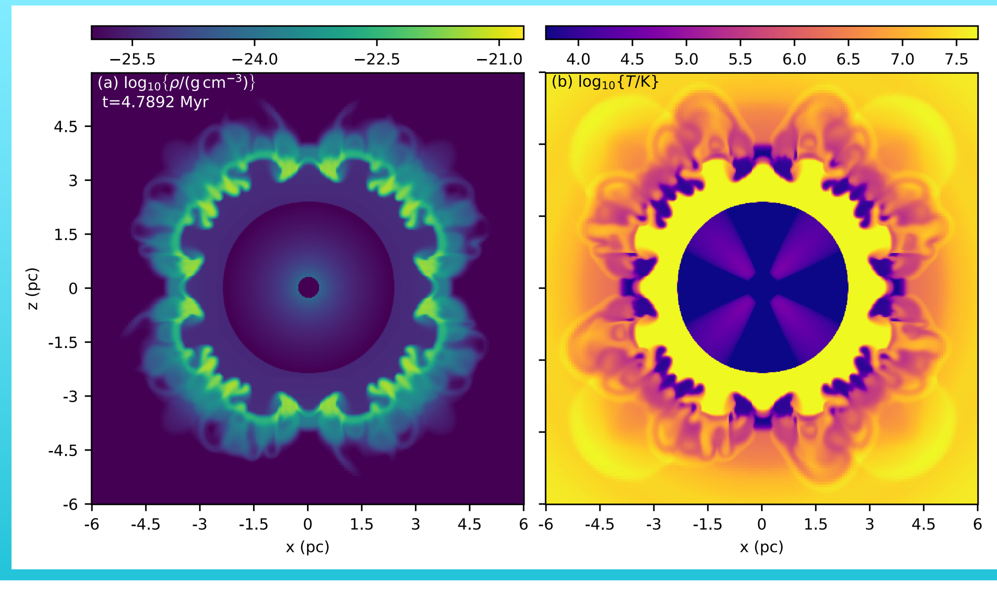
3D MHD simulation of bow shock: log10 of gas density (*left*) and log10 of |B|/G (*right*) (Mackey+2021)

- 3D MHD simulations are now quite straightforward with PION.
- Similar results to previous work (Baalmann *et al.* 2021; Scherer *et al.* 2020; Kissmann *et al.* 2018), and to Heliosphere models, e.g., Pogorelov *et al.* (2004).
- 3D MHD is important for capturing dynamics of unstable bow shocks
- MHD is important for non-thermal radiation properties.

3D Wolf-Rayet Nebula Models

- Radiation-hydrodynamics including photoionization
- Uses evolutionary calculation from Garcia-Segura *et al.* (1996) for 35 $M_\odot$ star: MS→RSG→WR





Log10 of gas density (*left*) and temperature (*right*) From Mackey *et al.* (2021) – 3D R-HD 256^3 4 levels

Funding from a Royal Society-SFI University Research Fellowship, a Royal Society-SFI Research Fellows Enhancement Award, and an IRC Starting Laureate Award. Thanks to the Irish Centre for High-End Computing (ICHEC) for the provision of computing resources and support.

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