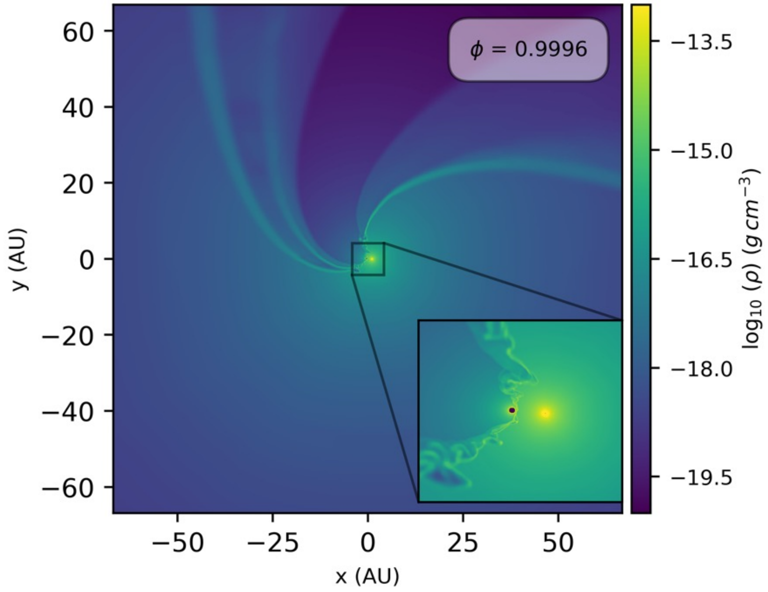
Massive Stars at High Energy

Jonathan Mackey
Dublin Institute for Advanced Studies



CDY seminar, online, 6th March 2024

dias.ie

Outline

- Stellar wind bubbles and bow shocks
- Colliding-wind binaries
- Combined winds+SNe in star clusters
- Dead stars
    - High-mass X-ray/γ-ray binaries
    - Novae
    - Supernovae interacting with stellar winds
- Summary

* **Disclaimer**: observational results will be very biased towards H.E.S.S., especially from the Stellar Sources + SNRPP Working Groups.

H.E.S.S. experiment in Namibia

High-Energy Stereoscopic System

- Array of Imaging Atmospheric Cherenkov Telescopes, sensitive to VHE gamma-rays ~0.1-100 TeV
- Operating since 2003, international collaboration of institutions, including DIAS
- Most sensitive TeV observatory, with 28m optical telescope
- Only one in Southern Hemisphere
- Will not be superseded by the Cherenkov Telescope Array (CTA) until >2028
- I am Working Group Convenor for Stellar Sources
    - γ-ray binaries, pulsars, colliding wind binaries, novae, supernovae, star clusters

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

Expanding wind bubbles

- Matthews (1966): cavity maintained by strong and fast stellar wind of early-type stars.
- Dyson & de Vries (1972): model for expansion of wind bubbles of O stars
- Weaver, McCray + (1977): a comprehensive model for evolution of wind bubbles
- Bubble size (from dimensional analysis):
  - $R(t) \propto \frac{\left(0.5\,\dot{M}\,v_\infty^2\right)^{1/5}}{\rho^{1/5}} t^{3/5}$ in adiabatic limit
  - $R(t) \propto \frac{(\dot{M} v_\infty)^{1/4}}{\rho^{1/4}} t^{1/2}$ in radiative limit
- Stellar motion leads to distorted bubbles.

The Rosette Nebula around NGC2244)

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Credit: John Corban & the ESA/ESO/NASA Photoshop FITS Liberator
https://esahubble.org/projects/fits_liberator/fitsimages/john_corban_12/

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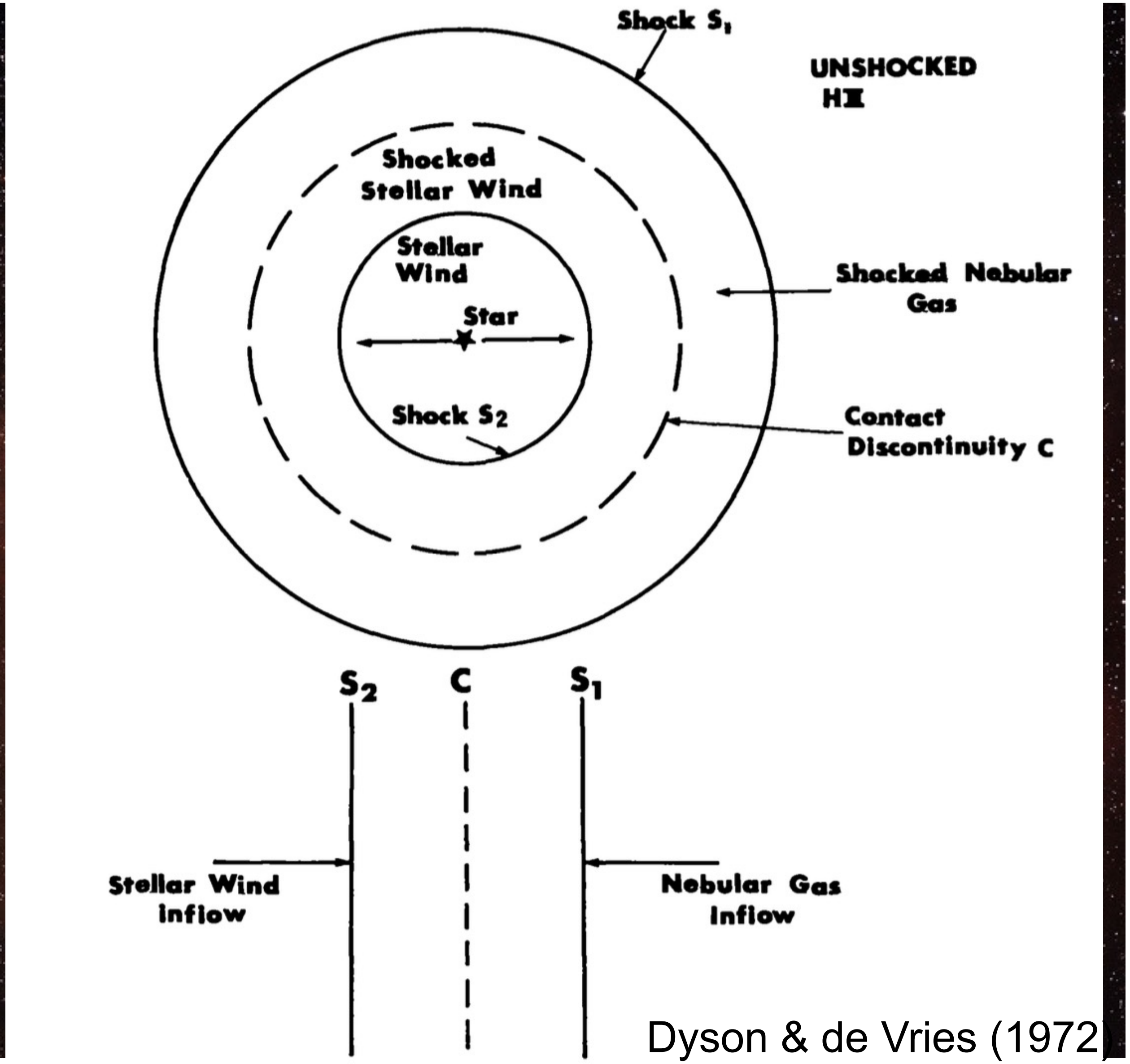
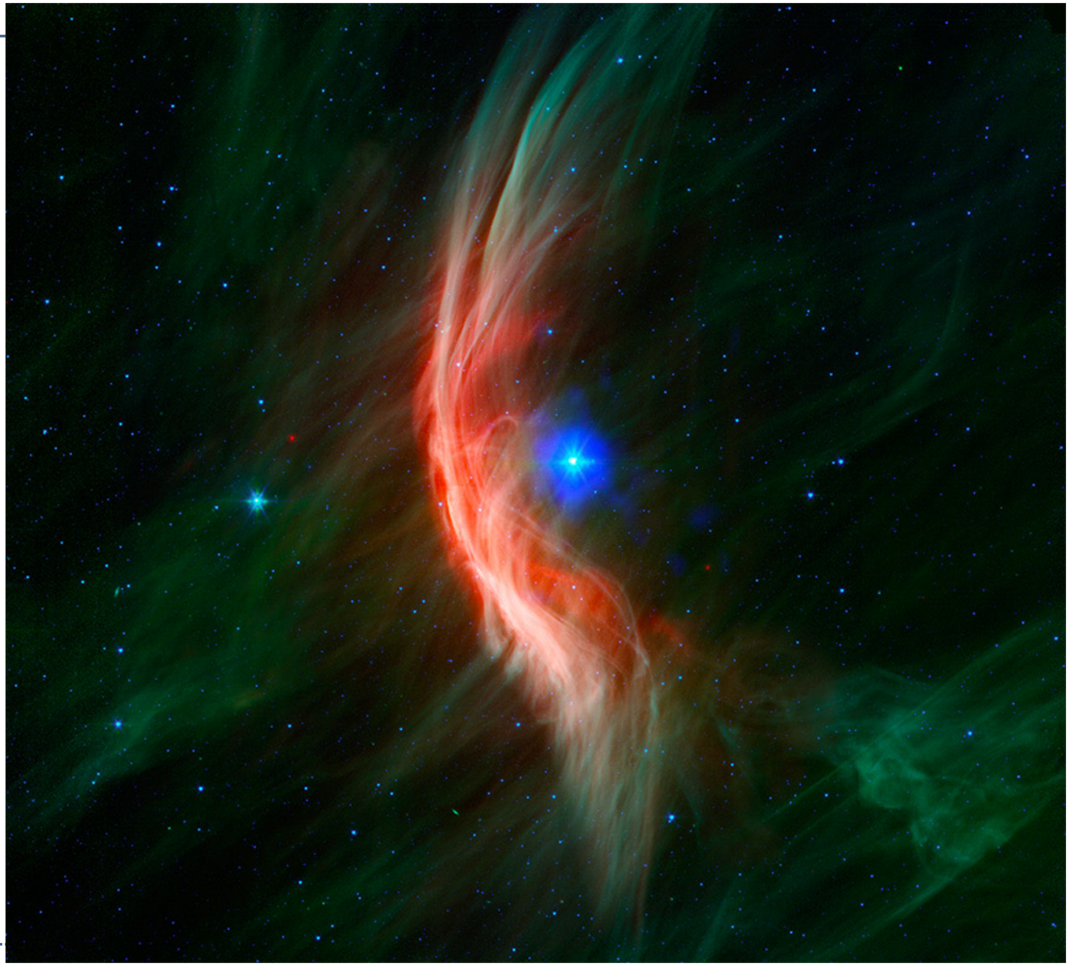


Fig. 1. The idealized flow pattern

Bow shocks – Astrospheres of exiled stars

- There are not many (any?) perfect stellar-wind bubbles:
  - Turbulent ISM, large density fluctuations
  - Stellar motion, Other nearby stars
- Moving stars that produce bow shocks:
  - Shock compression → easier to observe
  - In lower-density (and less structured) ISM → simpler to model
- Pressure balance gives characteristic size (e.g. Baranov+,1971):

$$R_{SO} = \sqrt{\frac{\dot{M} v_\infty}{4\pi\rho_0(v_*^2 + a^2)}}$$



The bow shock of Zeta Ophiuchi, from Spitzer Space Telescope, with Chandra X-rays overlaid in blue

Image credit: X-ray: NASA/CXC/Dublin Inst. Advanced Studies/S. Green et al.; Infrared: NASA/JPL/Spitzer
https://www.nasa.gov/mission_pages/chandra/images/embracing-a-rejected-star.html

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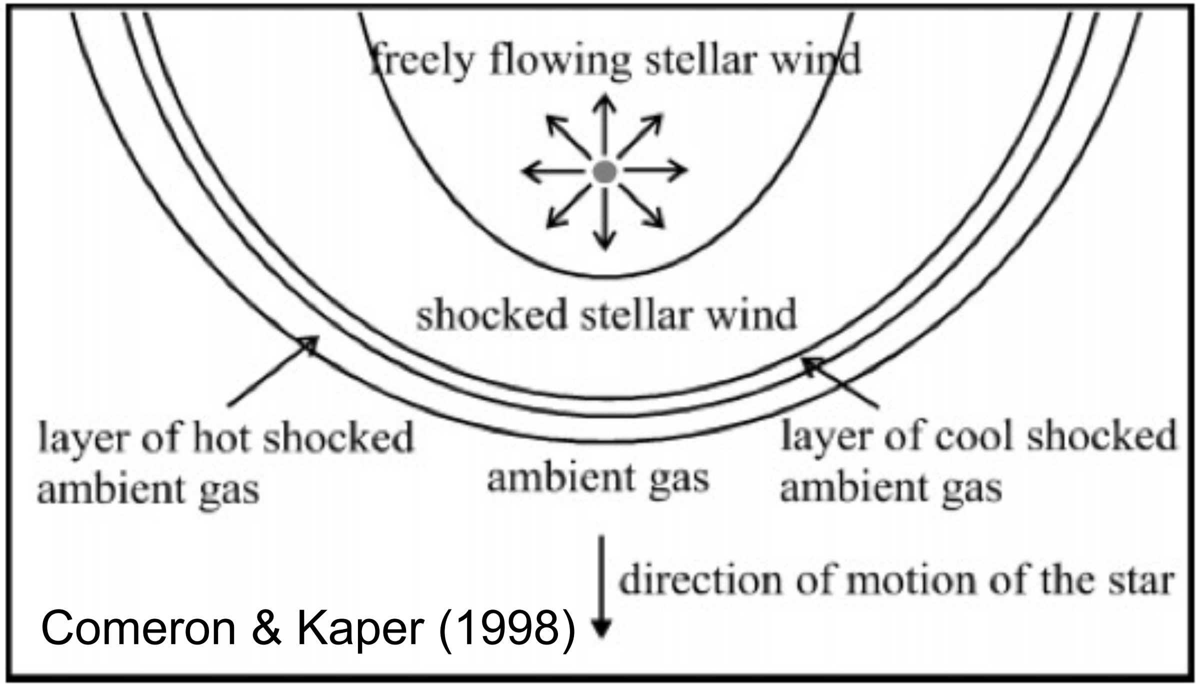

Fig. 1. Sketch of the different regions making up a wind bow shock around a supersonically moving star in the interstellar medium.

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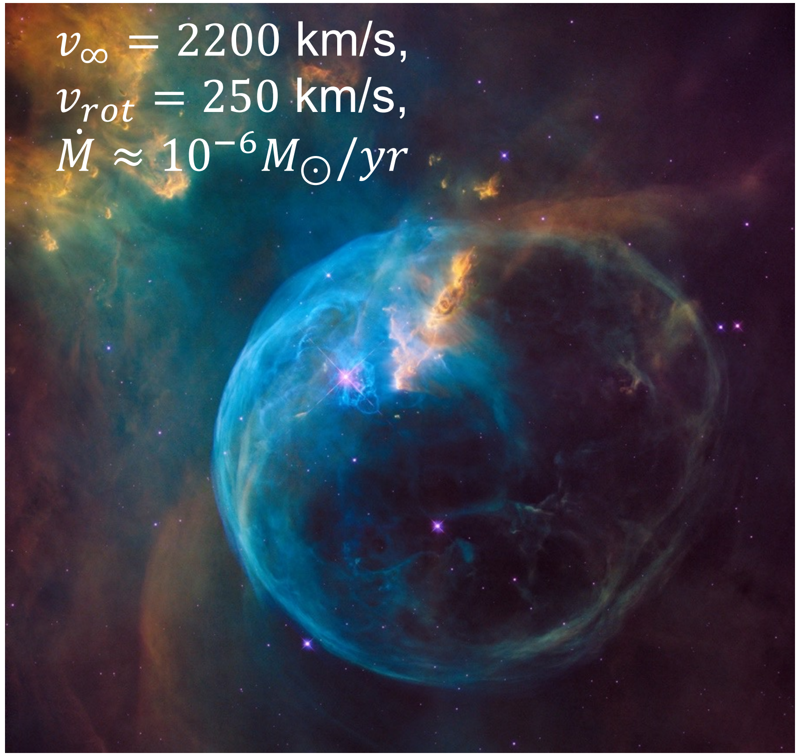
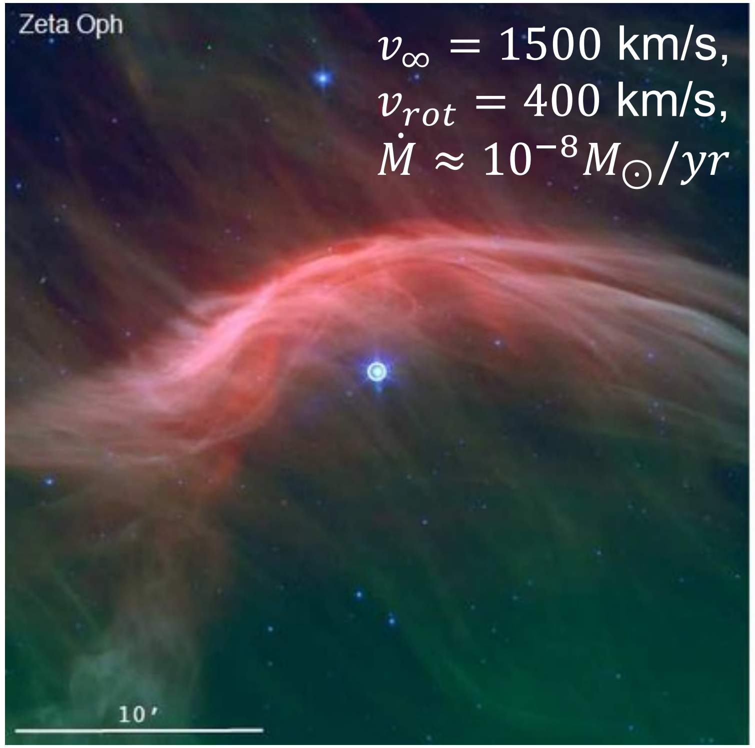
Bow shocks of hot stars

NGC 7635



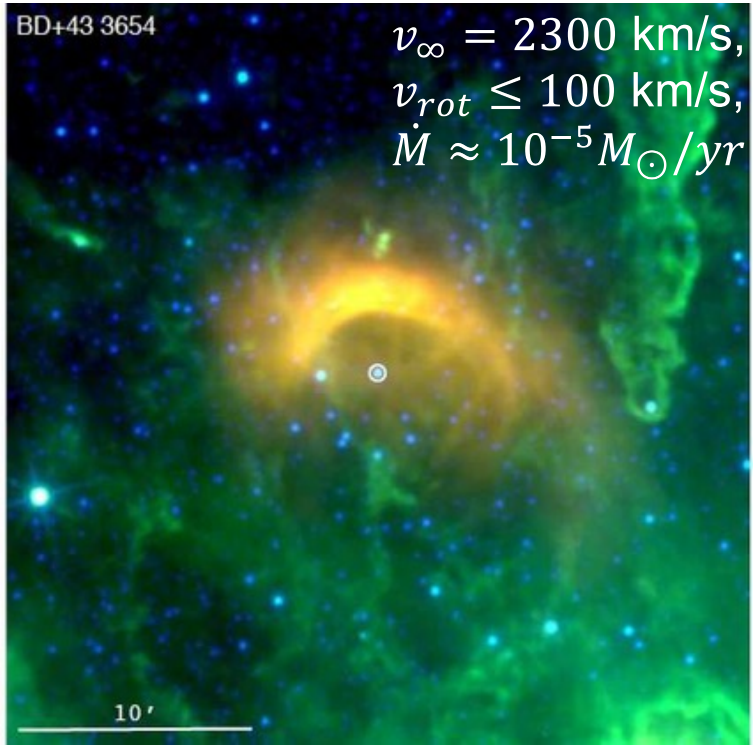
Bubble Nebula, driven by **BD+60 2522**, 40 $M_\odot$ star, ~37,500 K, moving with ~30 km/s into dense ISM, $n \sim 50\ \mathrm{cm}^{-3}$
(HST optical image)

Zeta Ophiuchi



Bow shock of **Zeta Ophiuchi**, driven by a 20 $M_\odot$ star, ~31,000 K, moving with ~30 km/s into ISM $n \sim (3 - 10)\ \mathrm{cm}^{-3}$

BD+43 3654

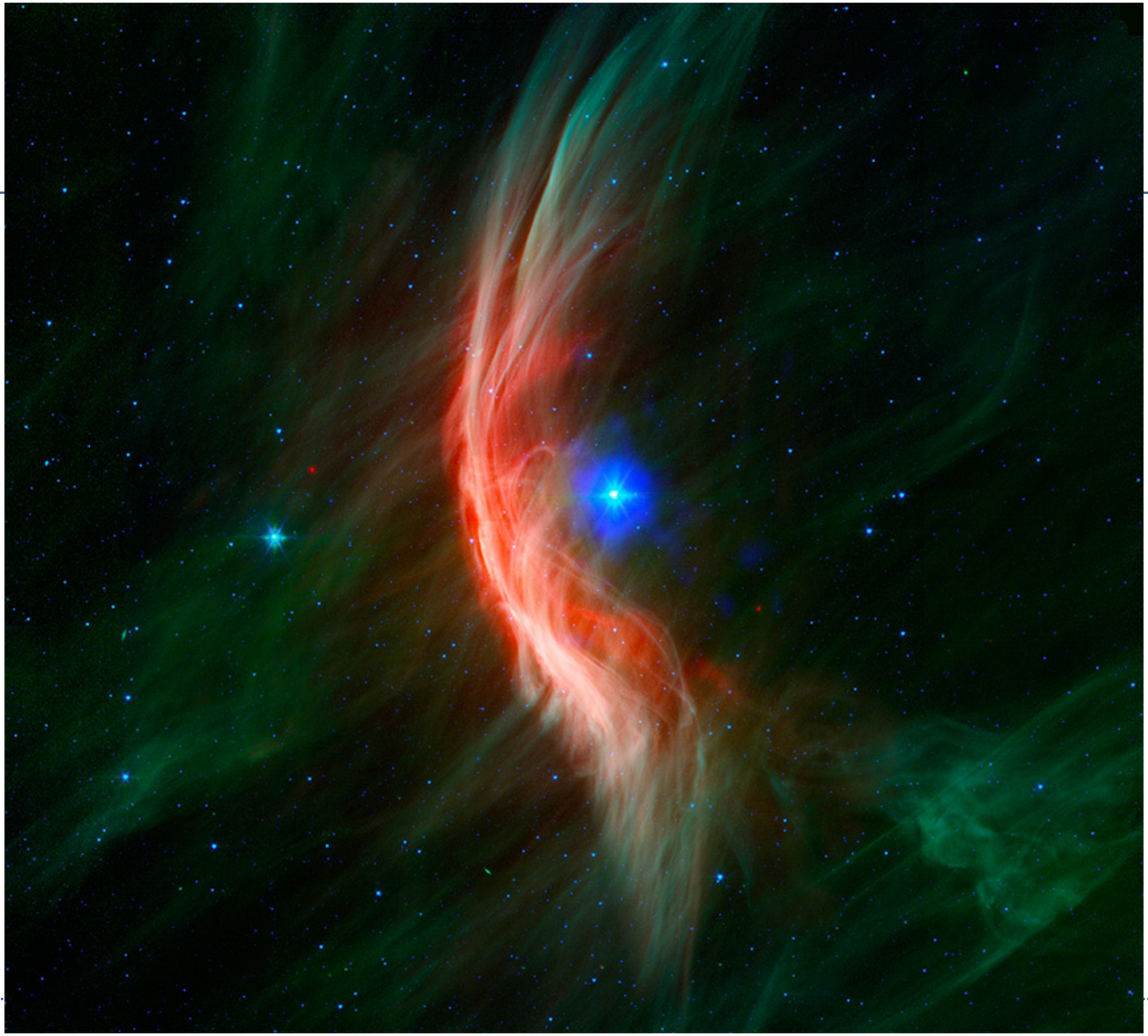


Bow shock of **BD+43 3654**: 60-70 $M_\odot$ supergiant star, ~40,000 K, moving with ~40? km/s in ISM with $n \sim 15\ \mathrm{cm}^{-3}$, in Cygnus region.

Spitzer Space Telescope IR images from Toala et al. (2016)

Zeta Ophiuchi

- Only 135 pc from Earth
- Closest O-type star
- Closest such bow shock
- Gal. lat. +25 deg



The bow shock of Zeta Ophiuchi, from Spitzer Space Telescope, with Chandra X-rays overlaid in blue

Image credit: X-ray: NASA/CXC/Dublin Inst. Advanced Studies/S. Green et al.; Infrared: NASA/JPL/Spitzer
https://www.nasa.gov/mission_pages/chandra/images/embracing-a-rejected-star.html

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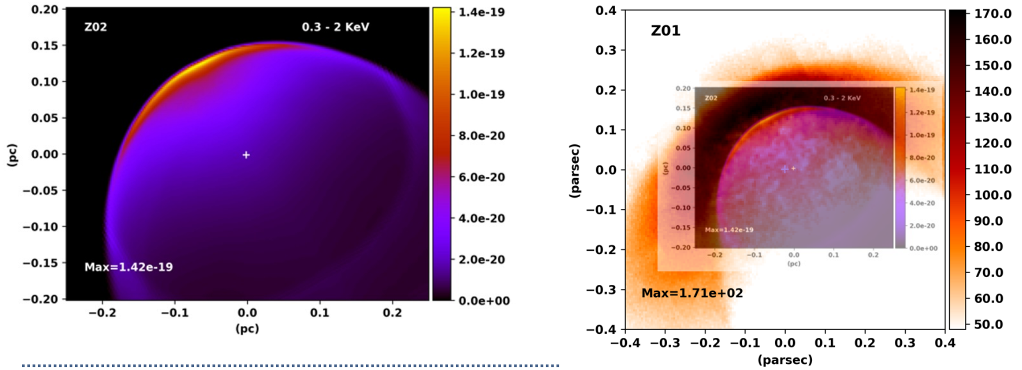
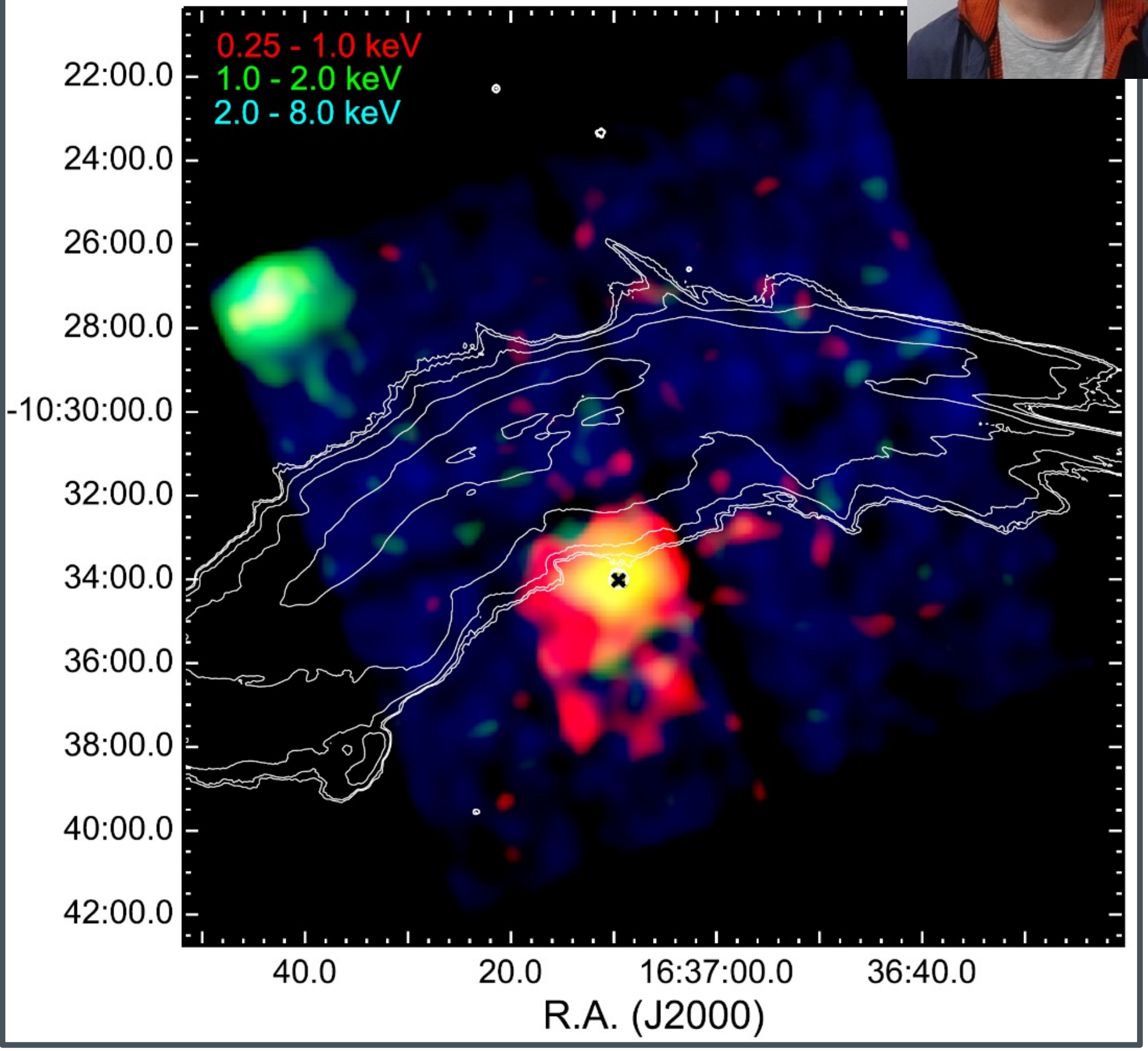
Diffuse X-rays from Zeta Ophiuchi

- Toala+(2016) detected diffuse X-rays from around Zeta Ophiuchi with *Chandra* data.
- Sam Green (PhD 2021) investigated thermal X-ray emission from simulated bow shocks.
- In Green+(2022) we re-analysed the observations, confirming the detection
- First 3D MHD simulations of the bow shock



Synthetic X-ray (left) and IR (right) images of the bow shock.

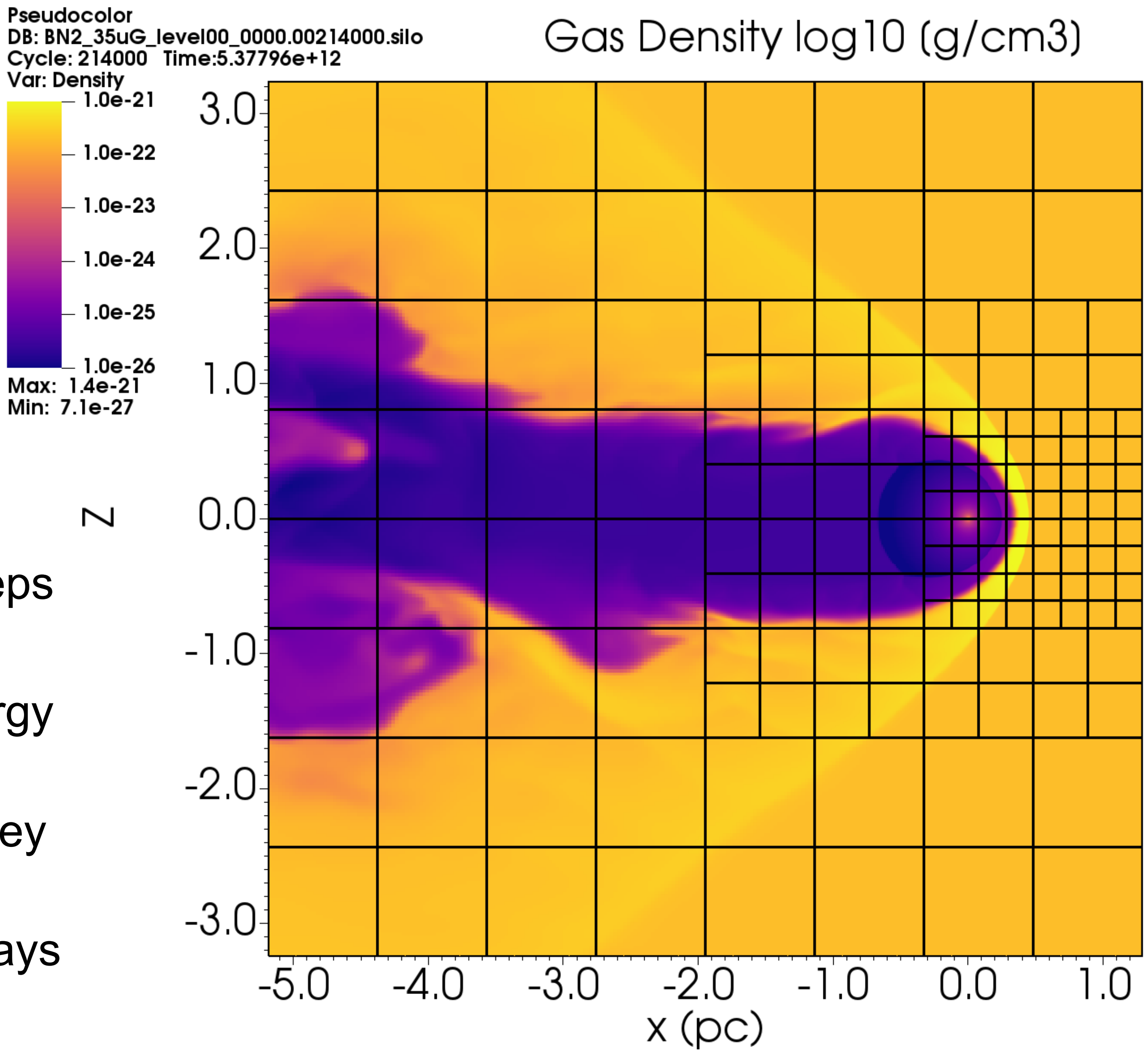


Toala et al., 2016, *Chandra X-ray Observatory*

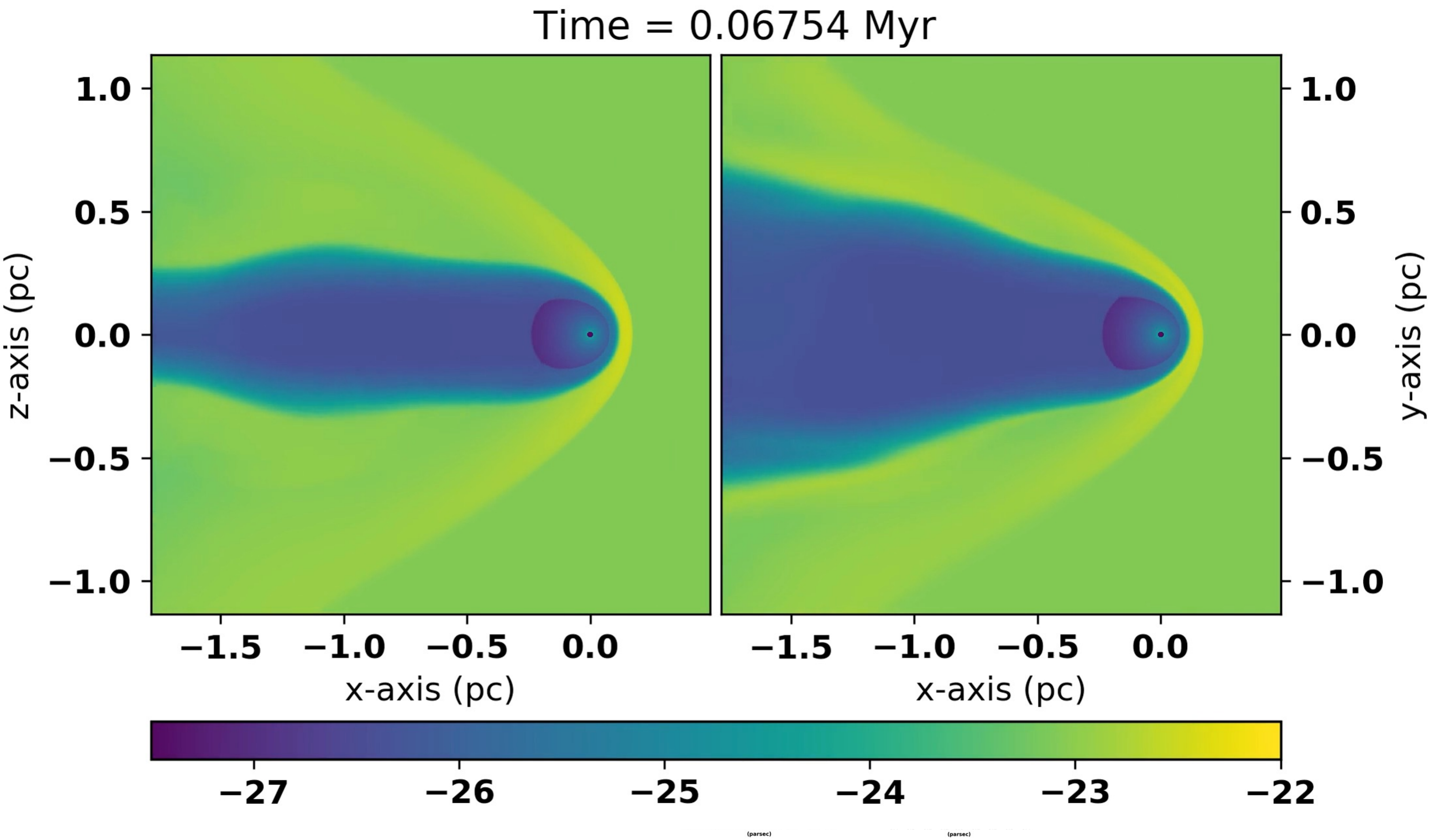
PION MHD code

- Developed to model MHD of photoionized and wind-driven nebulae around massive stars.
- Finite-volume method
- 1D spherical / 2D cylindrical / 3D Cartesian
- Euler or ideal-MHD equations
- Statically refined, nested grid, adaptive timesteps
- MPI+OpenMP parallelized
- Radiative transfer from point sources with energy deposition and ionization
- Methods paper and public code release (Mackey *et al.* 2021, MNRAS)
- pyPION module: read snapshots to numpy arrays

https://www.pion.ie
https://git.dias.ie/massive-stars-software/pion
https://git.dias.ie/massive-stars-software/pypion



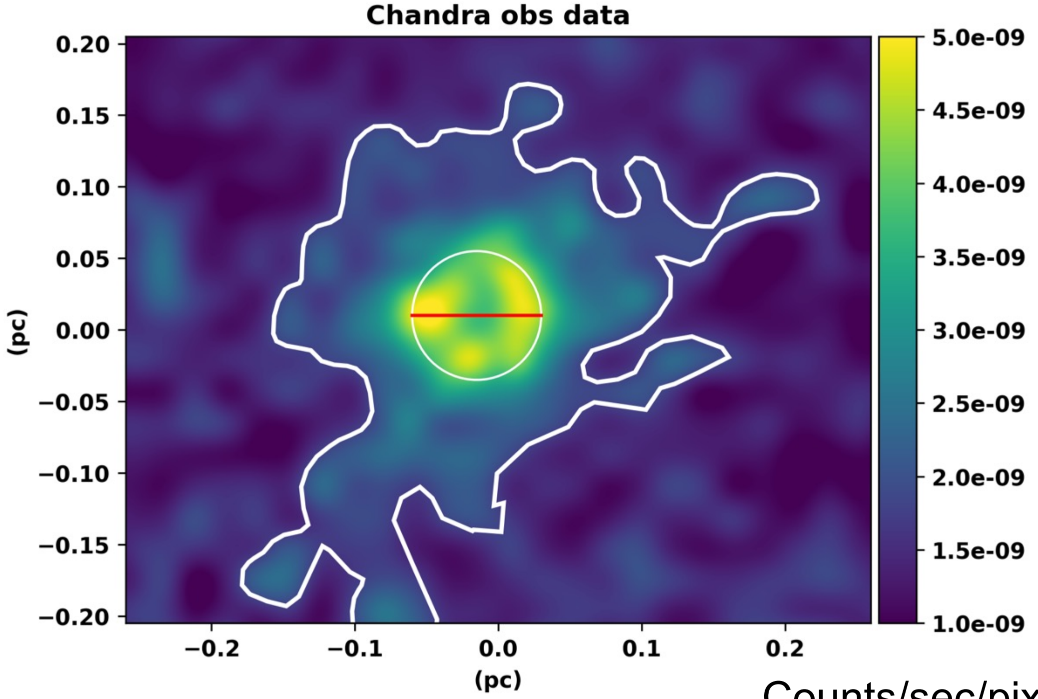
3D Simulation by S. Green of a bow shock from a runaway O star. 256^3 with 3 levels of refinement.

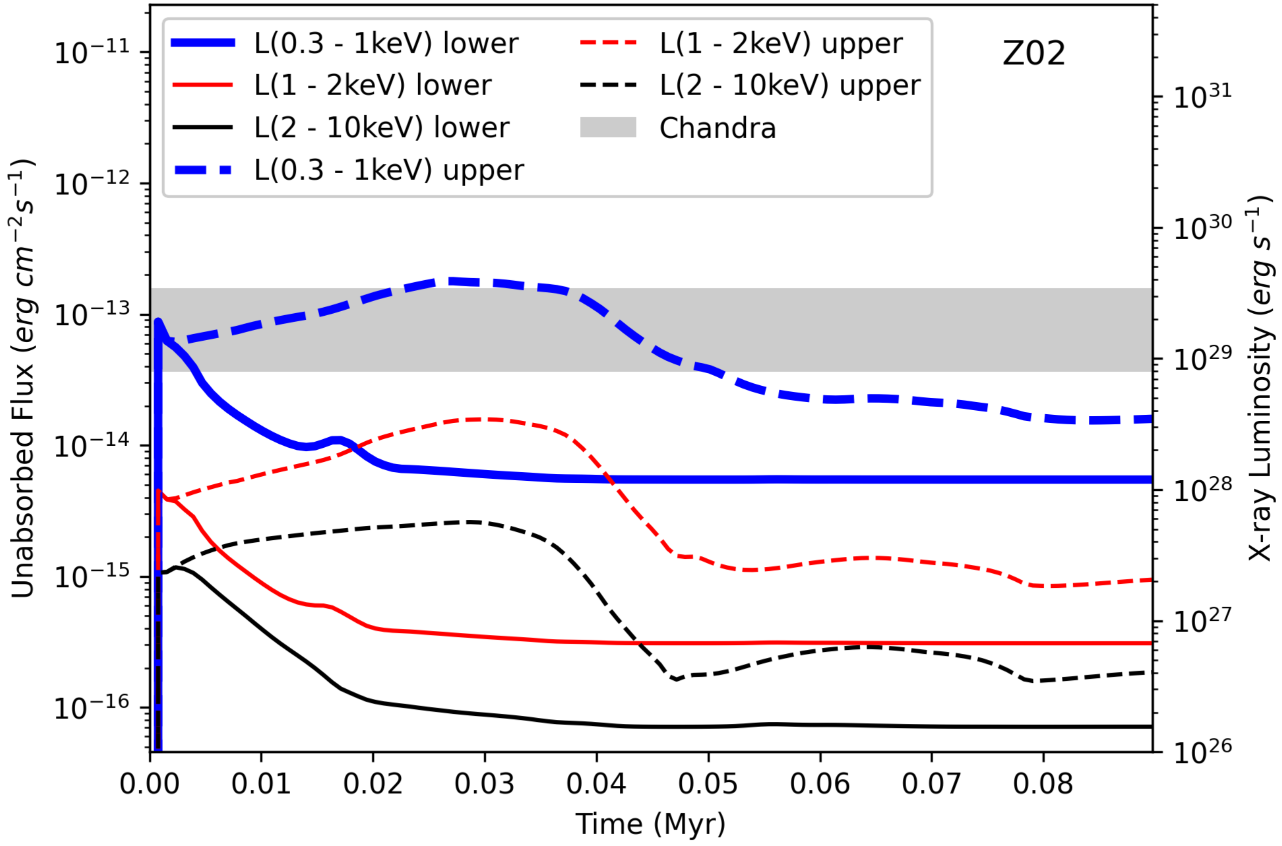


Time = 0.06754 Myr
1.0
0.5
0.0
−0.5
−1.0
z-axis (pc)
y-axis (pc)
−1.5
−1.0
−0.5
0.0
x-axis (pc)
x-axis (pc)
−27
−26
−25
−24
−23
−22
(parsec)
(parsec)

Diffuse X-rays from Zeta Oph – too faint

- 3D MHD results: simulations vs. observations
  - matches IR emission quite well
  - X-rays from simulation are **too faint**
  - X-ray morphology also not the same
  - Likely a resolution issue…





Green, Mackey, et al. (2022,A&A,665,A35)
https://arxiv.org/abs/2203.06331

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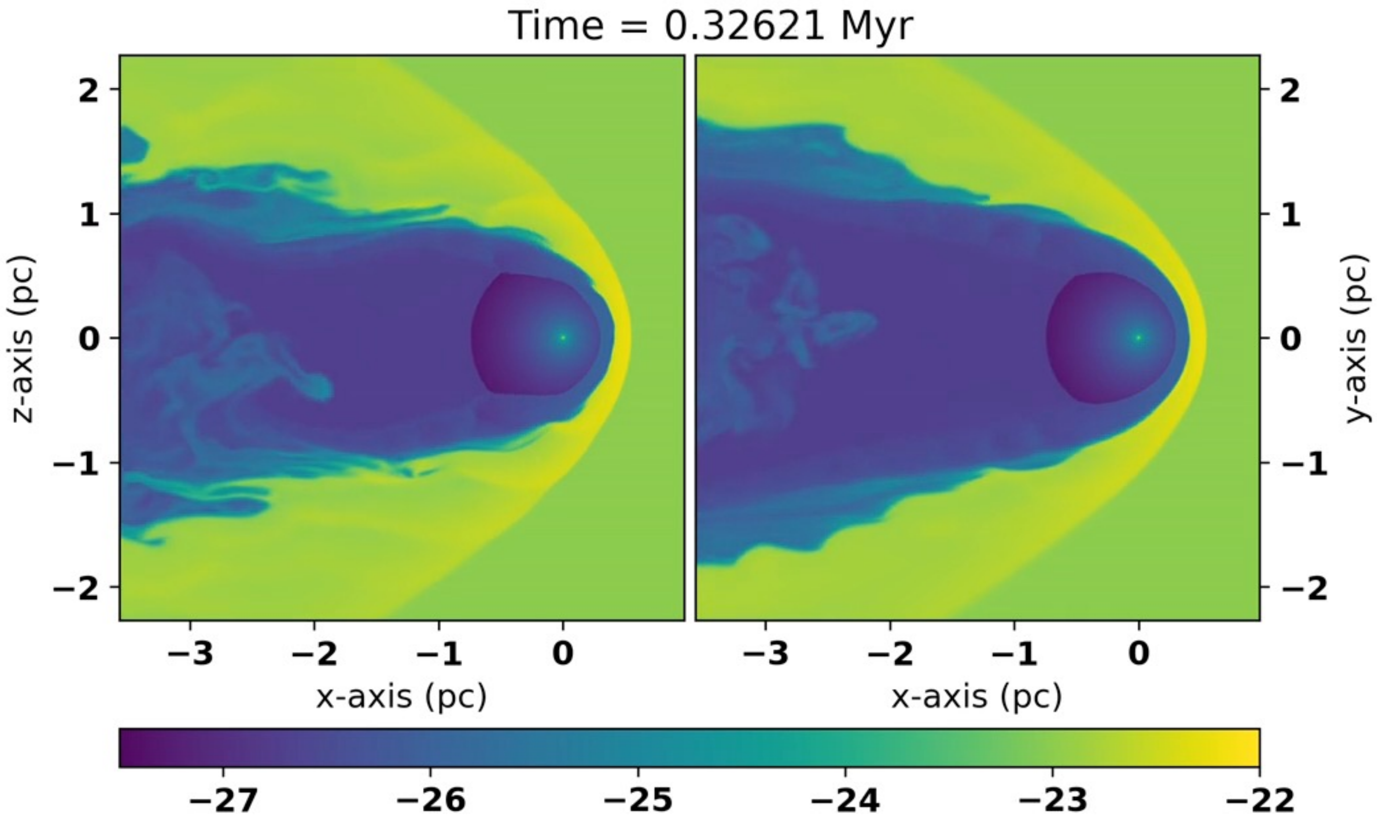
Higher-resolution simulations

- New generation of MHD simulations
- Better MHD solver, higher spatial resolution
  - CD becomes dynamically unstable
  - Bright and variable X-rays from turbulent wake
  - Working on calculating synchrotron emission
- Mainly aimed at modelling thermal plasma
- Not much to say yet about high-energy emission



Mackey, et al. (in prep)

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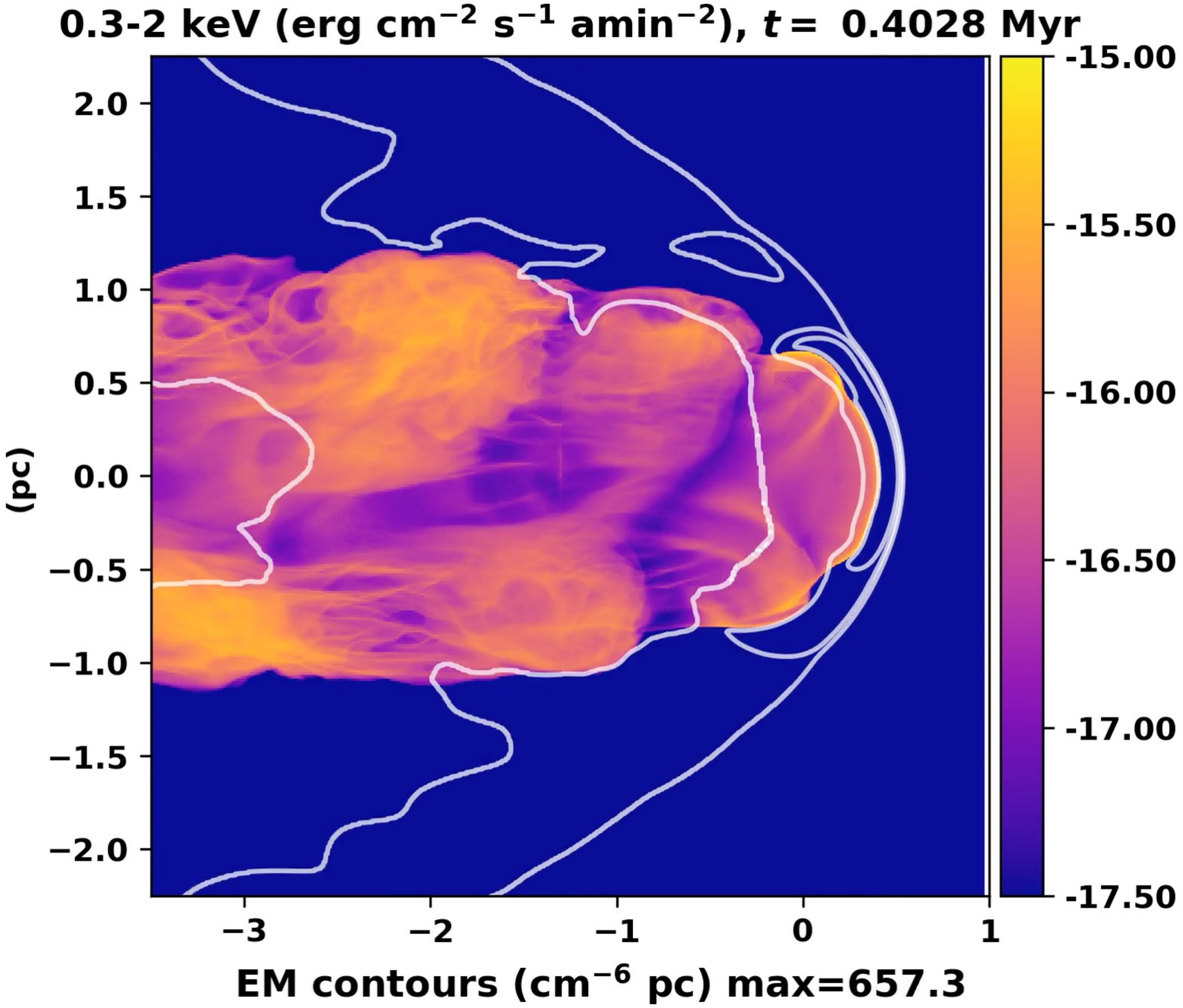
- Working on synchrotron emission modelling

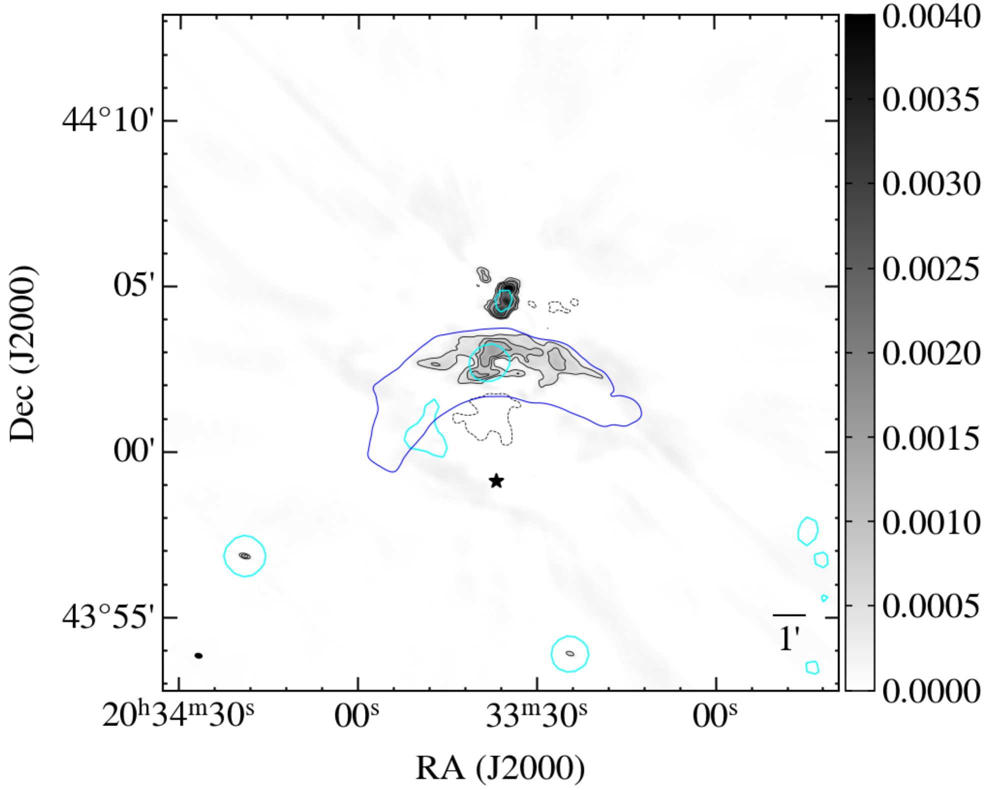


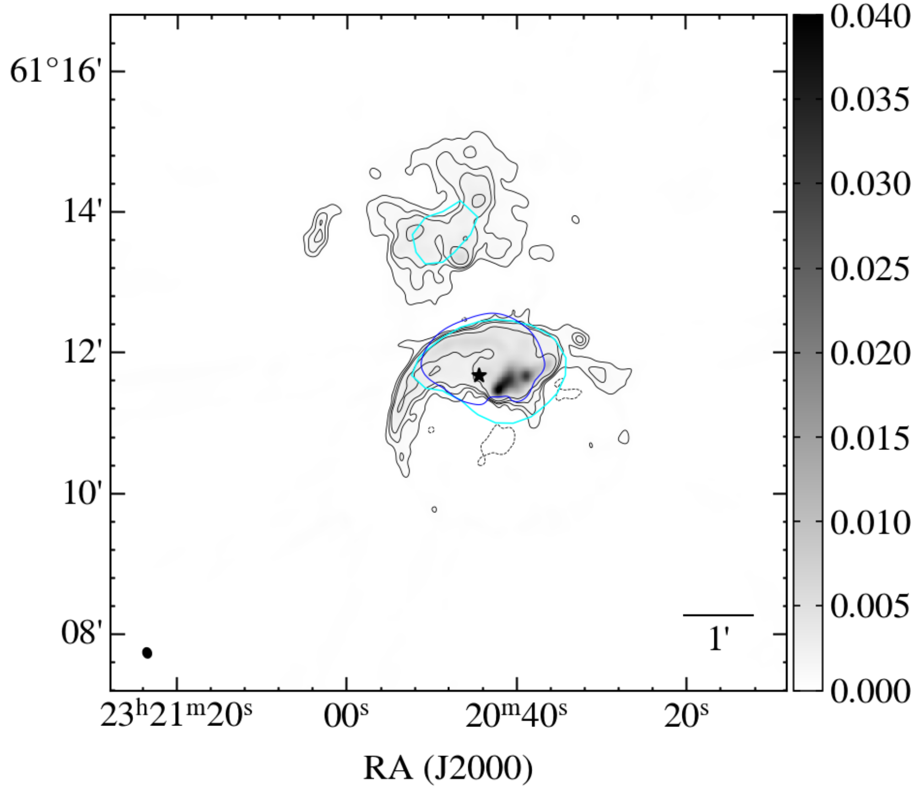
Mackey, et al. (in prep)

Radio observations of bow shocks

Bow shocks of BD+43 3654 (left) and BD+60 2522 (Bubble Nebula, right), M. Moutzouri+(2022), 4-12GHz, VLA

- Apparently synchrotron emission (but difficult to be sure, uv plane sampling)





Moutzouri, Mackey, et al. (2022,A&A,663,A80)
https://arxiv.org/abs/2204.11913

Radio spectral index indicates synchrotron emission

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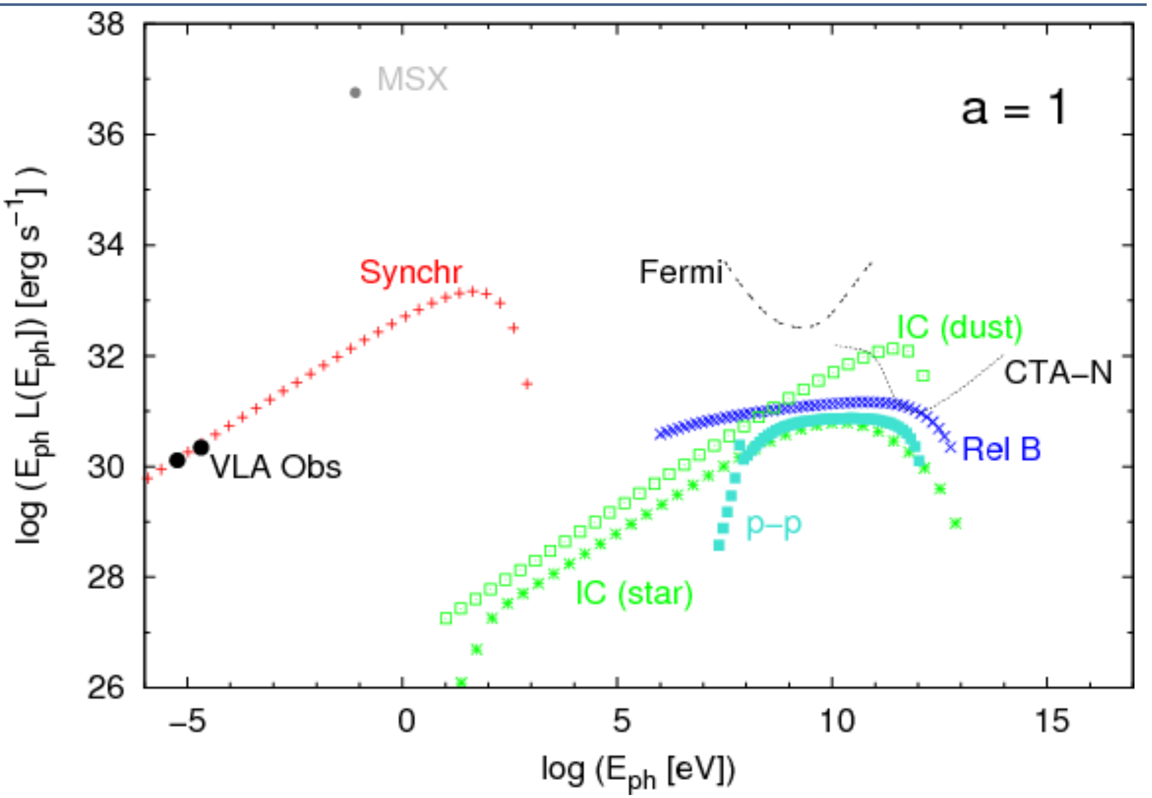
Bow shocks: non-thermal emission

Evidence for/against:

- Radio observations of bow shocks
  - Benaglia+ (2010, 2021)
  - Moutzouri+ (2022)
  - Van den Eijnden+ (2021,2022)
- No detections in X-rays (Toala+,2017)
  - Not really unexpected from shock velocity
- No detections in γ-rays:
  - Search using FERMI-LAT (Schulz+2014)
  - HESS collaboration (2018) upper limits at level 0.1-1% of wind kinetic power.



Radio data from Benaglia+(2010) with one-zone model for high-energy emission

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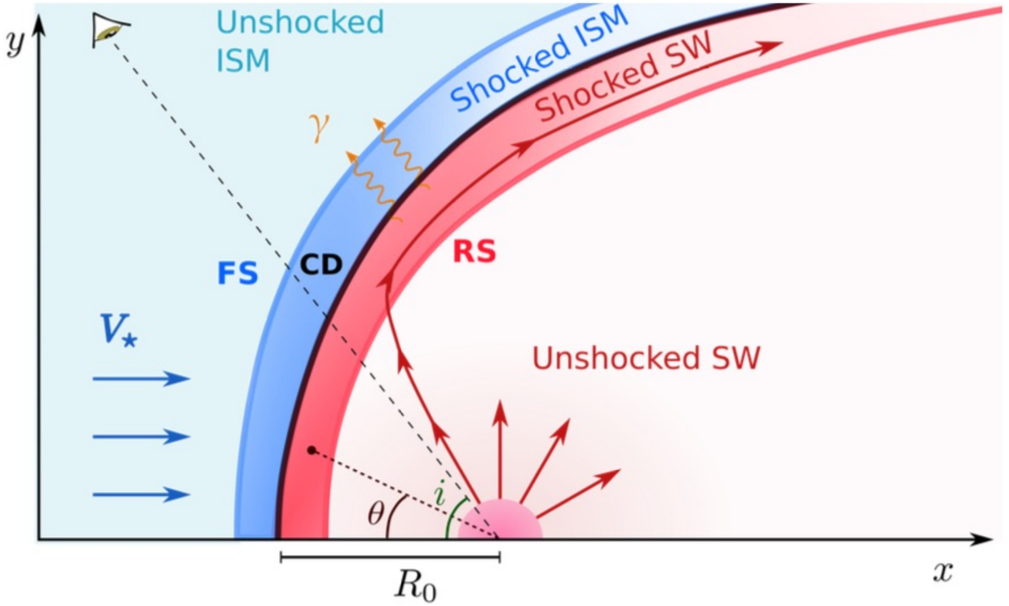
Bow shocks: non-thermal emission

Theoretical predictions

- Del Valle & Romero (2012): quite optimistic for HE detection - $L \sim 10^{30} - 10^{34}\ erg/s$
- Multi-zone model by del Palacio+(2018)
  - Varying shock properties with angle
  - Advection, expansion, B-field estimates



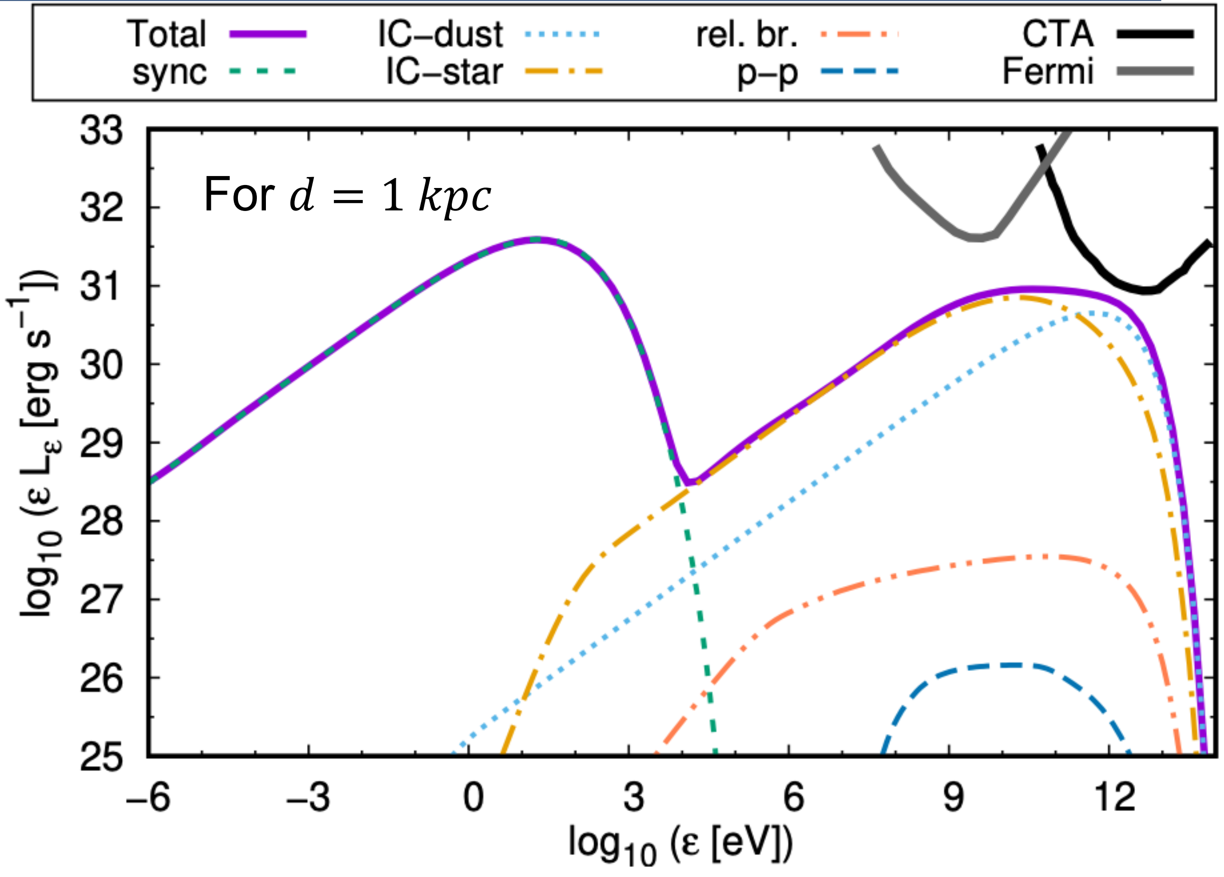


Fig. 7. Comparison of the SEDs of the generic scenario with the parameters specified in Table 1 using a one-zone model (*top panel*) and a multi-zone model (*bottom panel*). The ten-year sensitivity curve of the *Fermi* satellite is taken from http://fermi.gsfc.nasa.gov, and that of the 100-h CTA from Funk et al. (2013).

Bow shocks: non-thermal emission

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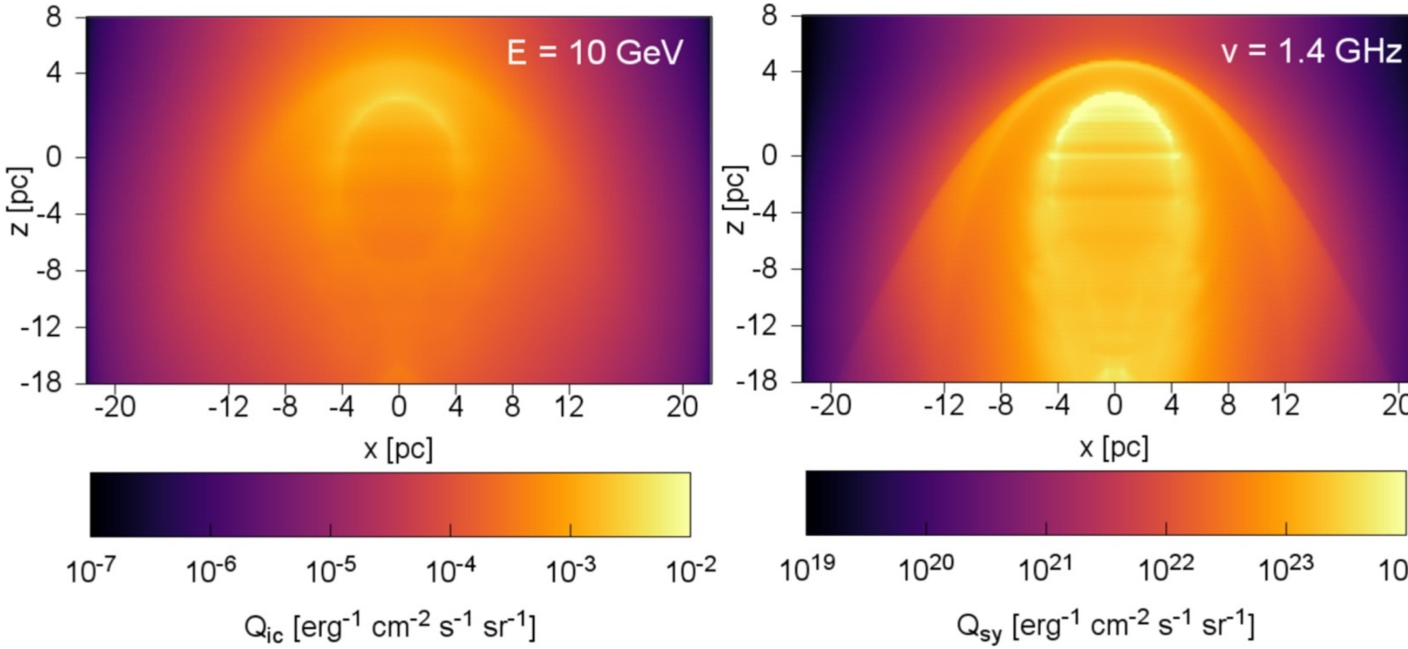
- Multi-zone model by del Palacio+(2018)
  - Varying shock properties with angle
  - Advection, expansion, B-field estimates
- Postprocessing of 2D simulations (del Valle & Pohl (2018)
  - Injection at termination shock, advection + diffusion
  - $\sim [2-8] \times 10^{-5}$ of wind power in $\boldsymbol{\gamma}$-rays
  - HE $L \sim 10^{30} - 10^{31}\ erg/s$



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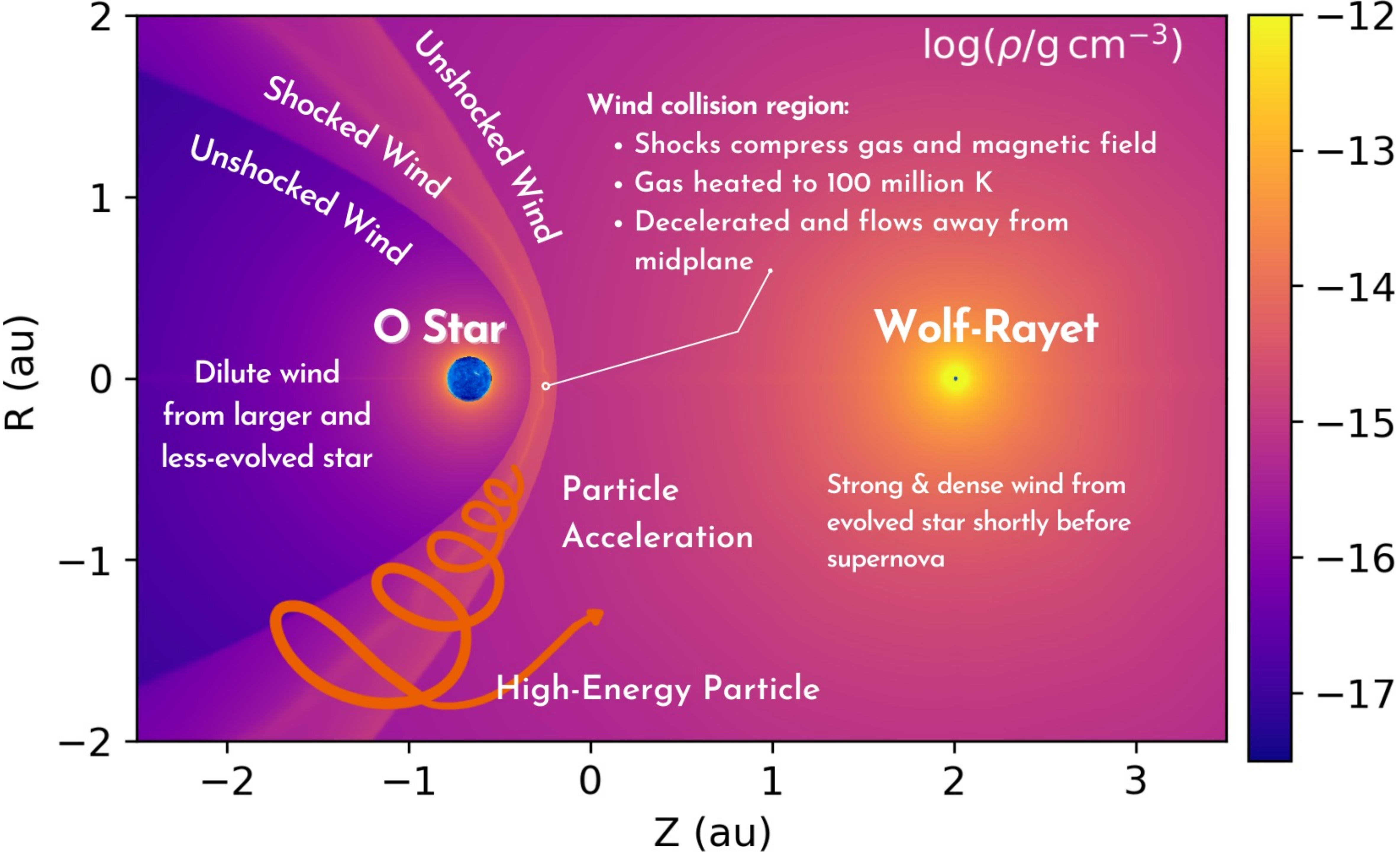
Summary: bow shocks

- 3D MHD simulations now possible, including stellar + ISM magnetic fields
  - Can predict observables related to thermal plasma: radio, IR dust, optical lines, X-ray
  - With some assumptions can also model the non-thermal electrons + their emission
  - Significant uncertainty in stellar magnetic field (mostly upper limits)
- Only evidence for non-thermal emission is from radio measurements
- X-ray upper limits are not very constraining (models predict a minimum at 1 keV)
- Gamma-ray upper limits can exclude optimistic theoretical scenarios
  - Energy densities are relatively low → radiative processes are inefficient
  - Almost all accelerated protons escape the system to the ISM (del Palacio+2018)
  - Accelerated electrons should emit IC radiation to TeV, may be hard to detect
- Zeta Ophiuchi may be best candidate ($d = 135\ pc$), but it has a very weak wind

Colliding-Wind Binary Systems

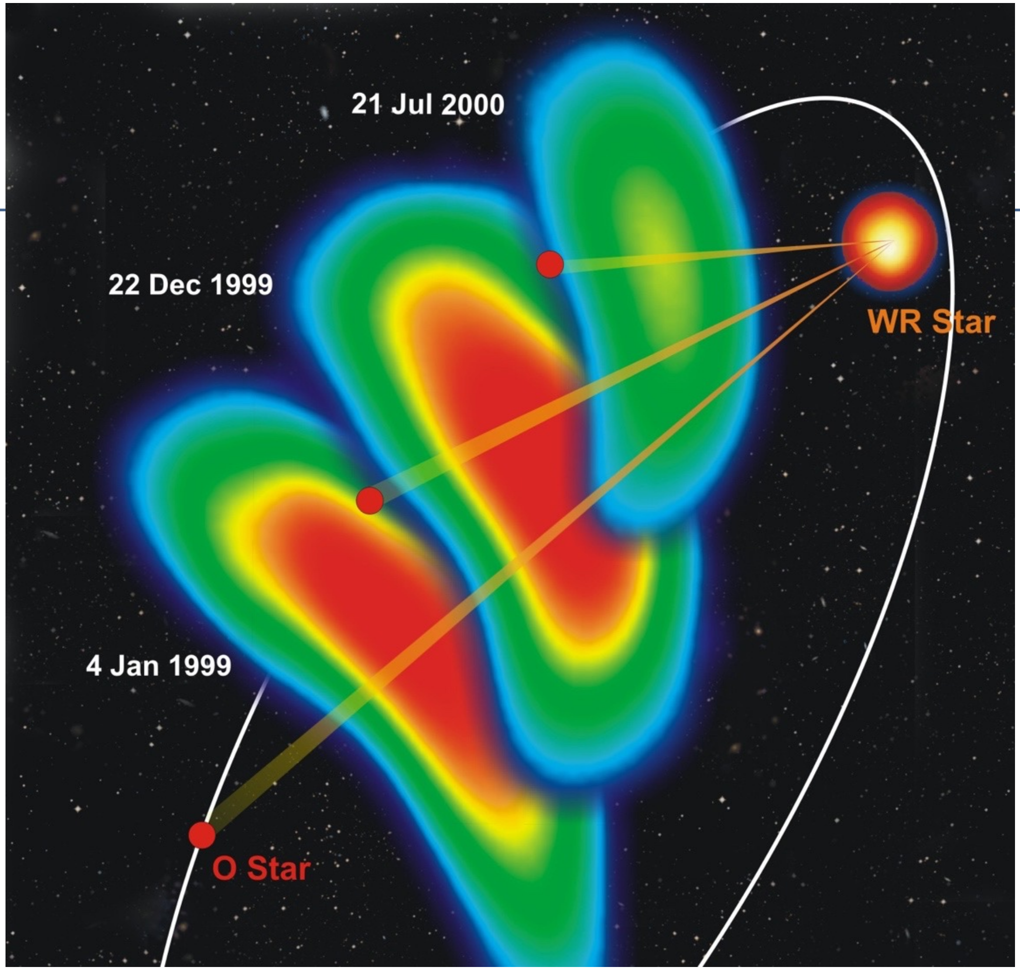
Brighter than isolated stars because of proximity to companion – shocks at high density, short timescales



log(ρ/g cm−3)
Unshocked Wind
Shocked Wind
Unshocked Wind
Wind collision region:
• Shocks compress gas and magnetic field
• Gas heated to 100 million K
• Decelerated and flows away from midplane
O Star
Wolf-Rayet
Dilute wind from larger and less-evolved star
Particle Acceleration
Strong & dense wind from evolved star shortly before supernova
High-Energy Particle
R (au)
Z (au)

Colliding-wind binaries

- CWBs probe winds of both stars:
  - Eccentric orbits → predictable time-varying shock conditions
  - Constrain winds of massive stars
    - Wind clumping, acceleration, mass-loss rates
    - Final pre-supernova evolutionary stage
  - Intense dust production
  - Particle acceleration in shocks
  - Progenitor systems for NS/NS, NS/BH, BH/BH mergers.



Synchrotron radio observations of WR140
Dougherty et al. (2006)

Inner dust nebula of WR104
Credit: Peter Tuthill.
http://www.physics.usyd.edu.au/~gekko/wr104.html

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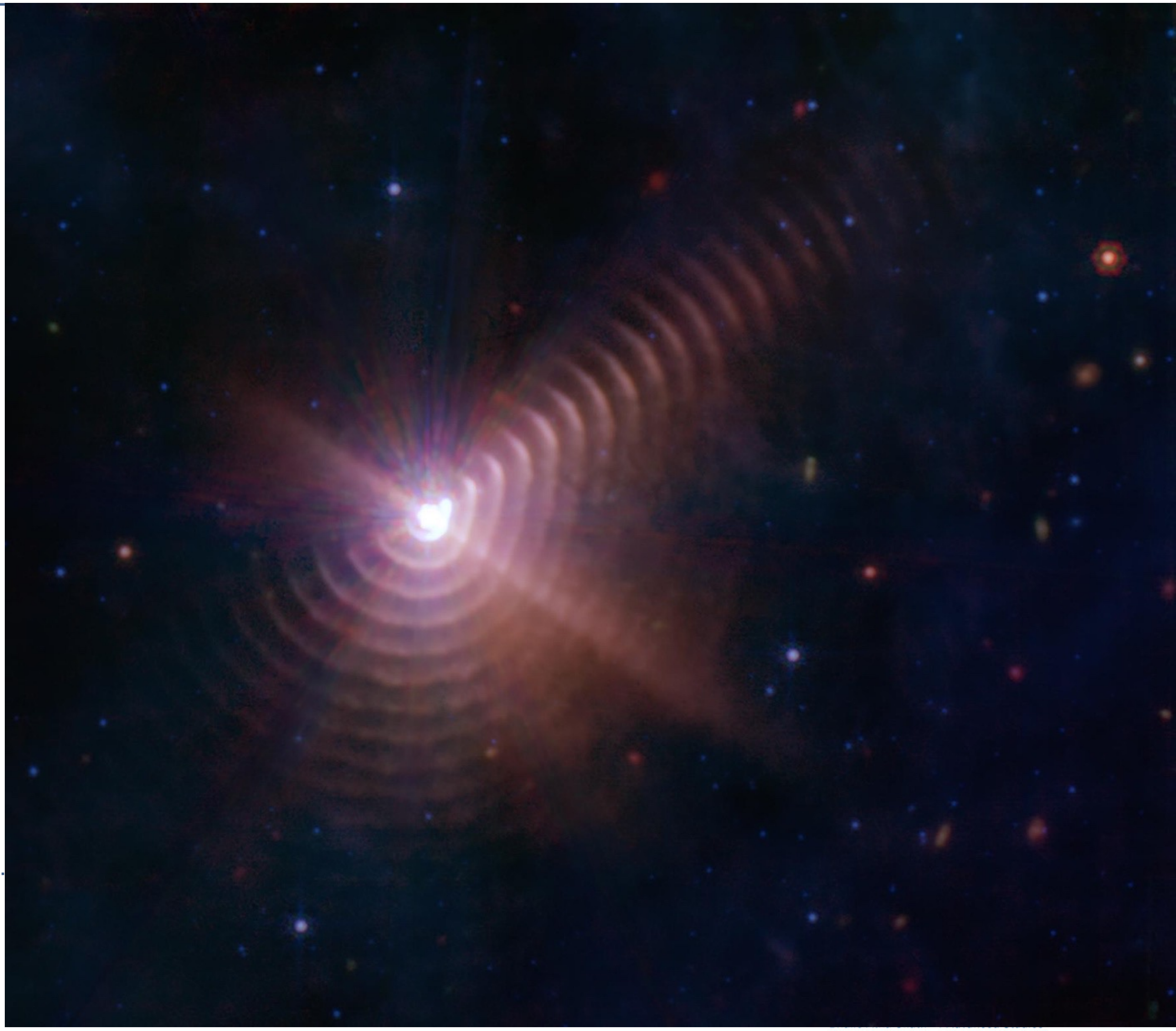
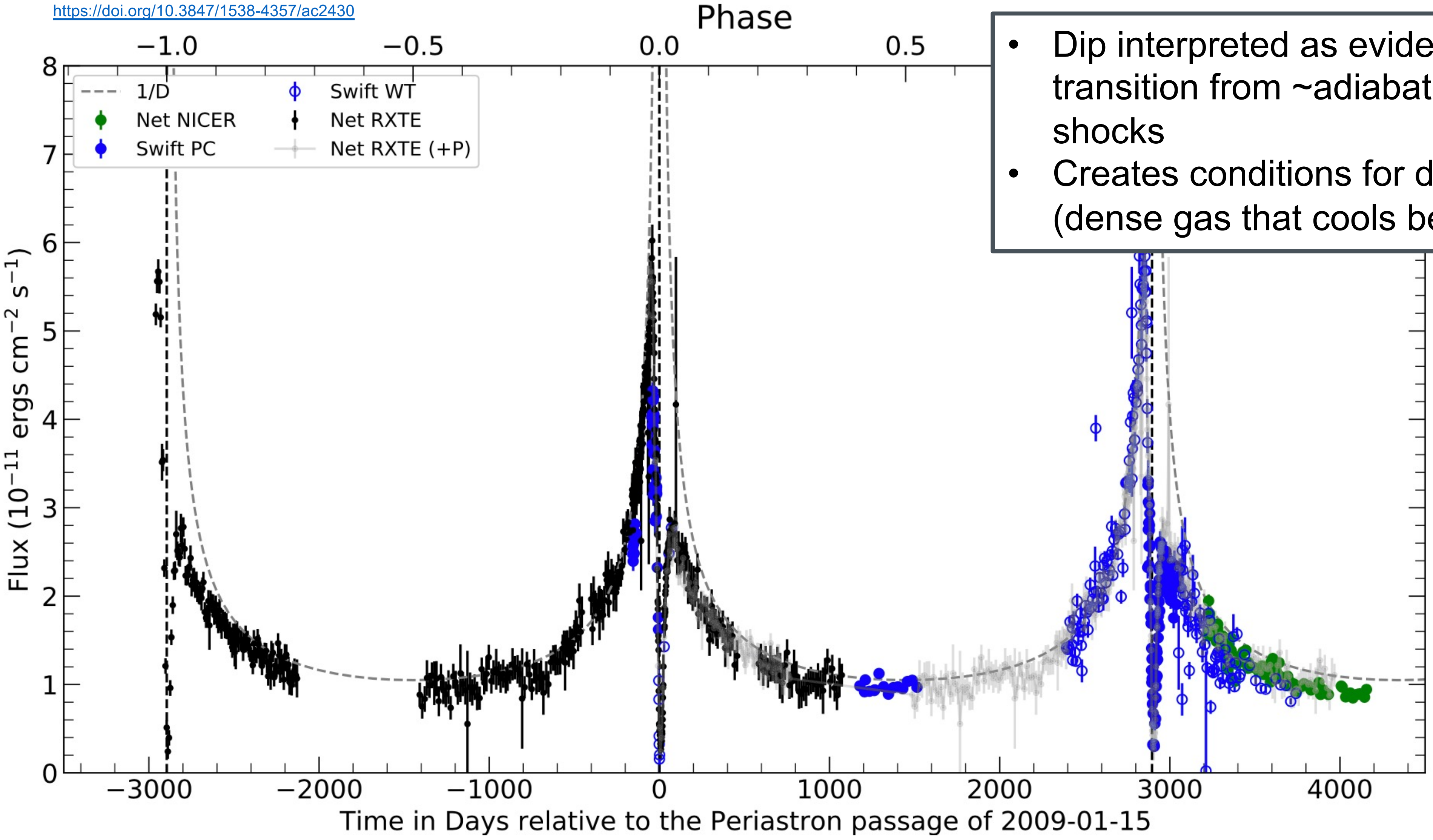
Concentric dust rings in WR 140 from successive periastron passages (JWST, Lau+2022)



X-ray lightcurve of WR140 (Pollock+,2021)

https://doi.org/10.3847/1538-4357/ac2430



- Dip interpreted as evidence for transition from ~adiabatic to radiative shocks
- Creates conditions for dust formation (dense gas that cools below 10^4 K)

Figure 2. The RXTE, Swift, and NICER light curve of WR 140, 2000–2020. The time zero-point corresponds to the periastron passage JD 2,454,846.727 = 2009 January 15 05:26. The gray points are the RXTE fluxes advanced by one period. The black dashed vertical lines are the times of periastron passage, while the gray dashed curves show the expected $1/D$ variation in flux for an unobscured adiabatic system of colliding winds.

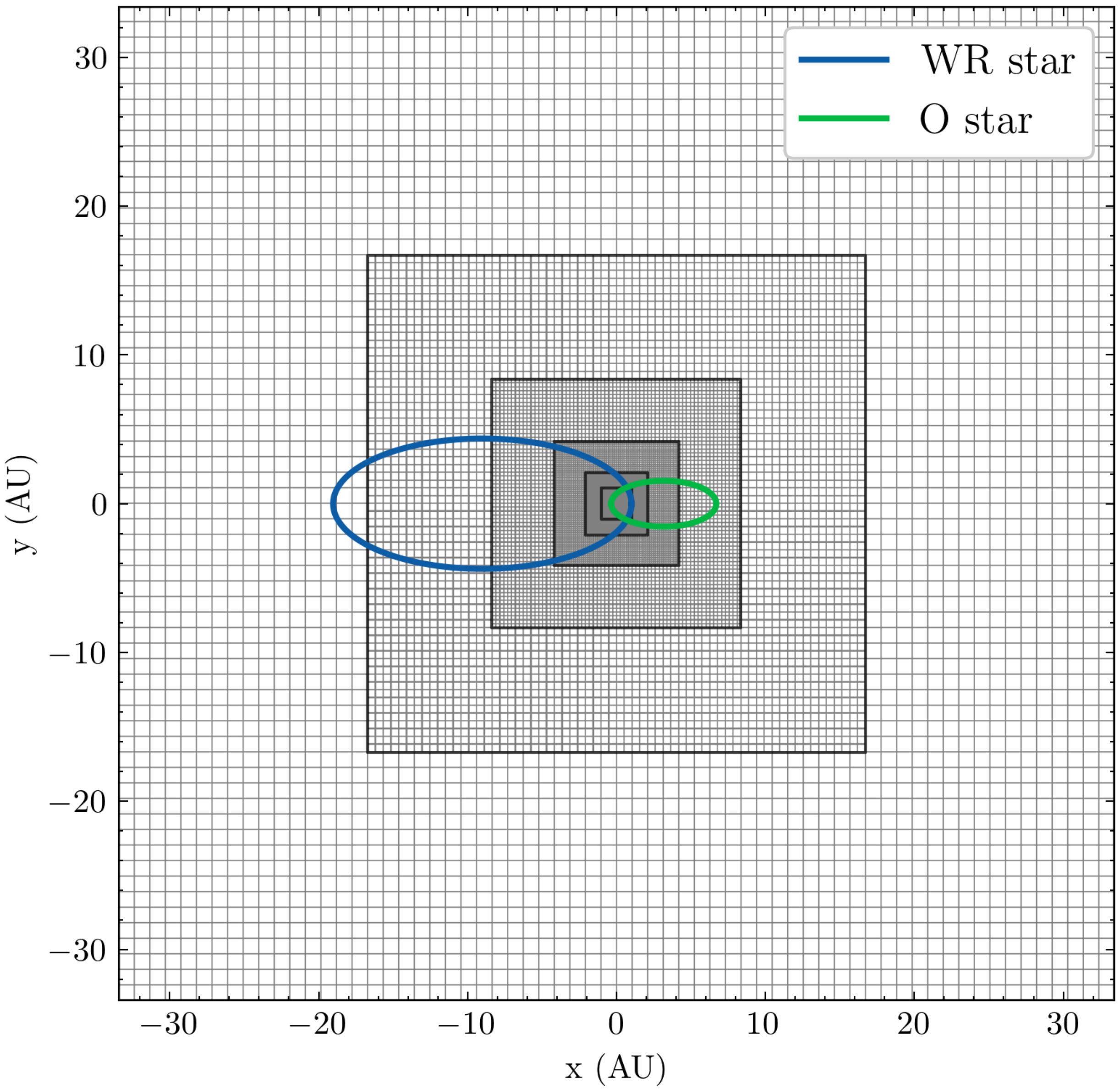
The need for MHD simulations

- Interpretation of radio and gamma-ray observations requires:
  - Where are the shocks and what are their properties?
  - Conditions in the thermal plasma
  - Magnetic field configuration (for acceleration and transport)
  - System timescales (dynamical, thermal, acceleration)
- Phenomenological or one-zone models often inconclusive or inconsistent
- 3D simulations with particle acceleration+transport very challenging
  - Galactic-scale algorithms don't translate to these small scales
  - PIC simulations don't get to system scale
- 1st step: MHD simulations with postprocessing for CRs (test-particle limit)
  - Assume acceleration is inefficient → no back-reaction on MHD flow

3D simulations of WR140 periastron passage

- 3D MHD simulations with static mesh-refinement, $256\times256\times64$ cells per level
- 7 grid levels centred on centre of mass
- Both stars on finest level at periastron
- *First 3D MHD simulations of CWBs with orbital motion, stellar rotation, IC cooling in the literature*
- Start 140 days before periastron and finish similar time after periastron

Mackey et al. (2023, MNRAS, **526**, 3099)
https://arxiv.org/abs/2301.13716



Inverse-Compton Cooling

of thermal electrons

- Relevance for CWBs proposed by Cherepashchuk (1976), also Myasnikov & Zhekov (1993)
- Mostly ignored for the past 30 years
- IC cooling rate for non-relativistic electrons in radiation field with energy density U_γ is:

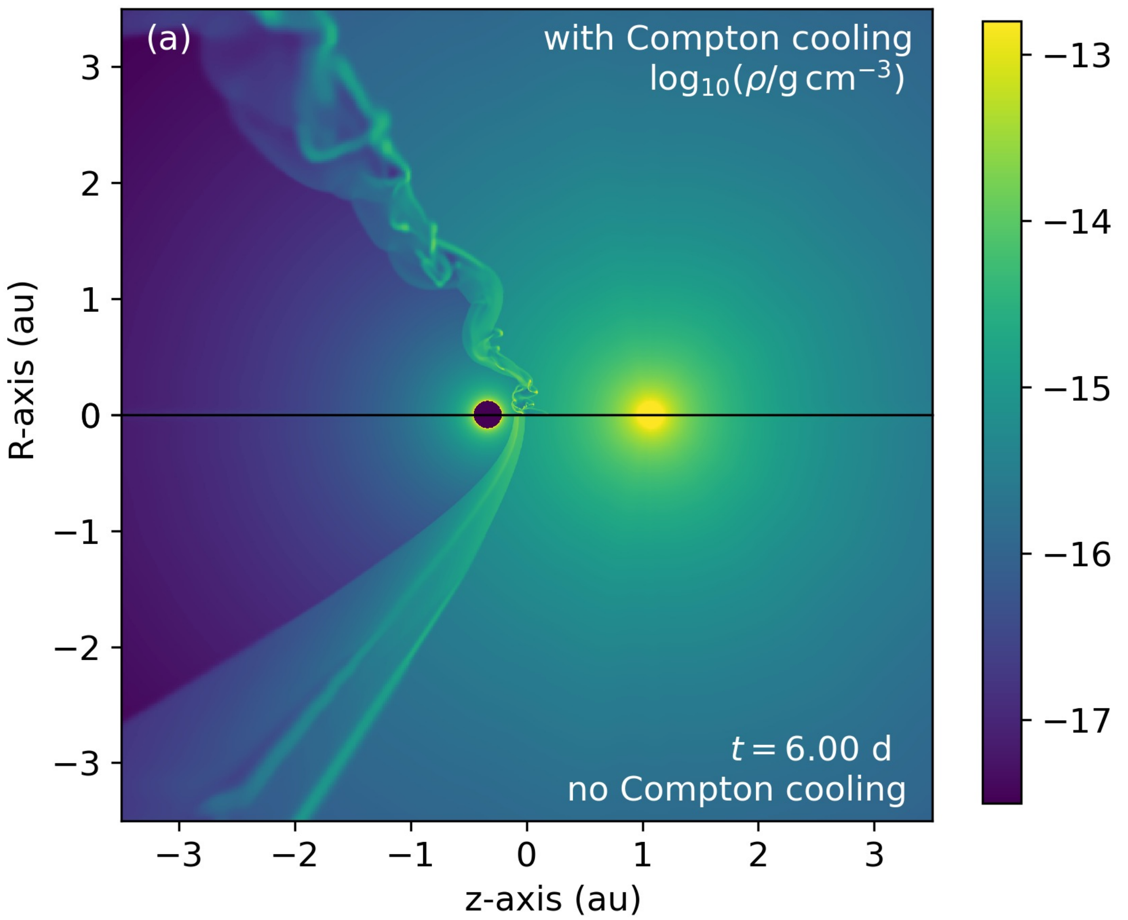
$$\dot{E}_{IC} = \frac{4n_e kT}{m_e c} \sigma_T U_\gamma$$

- Cooling time depends only on U_γ :

$$\tau_{IC} = \frac{3\mu_e m_e c}{8\mu\sigma_T} U_\gamma^{-1}$$

- We show this can be the shortest timescale for some CWBs

2D hydrodynamic simulation of WR140 at periastron



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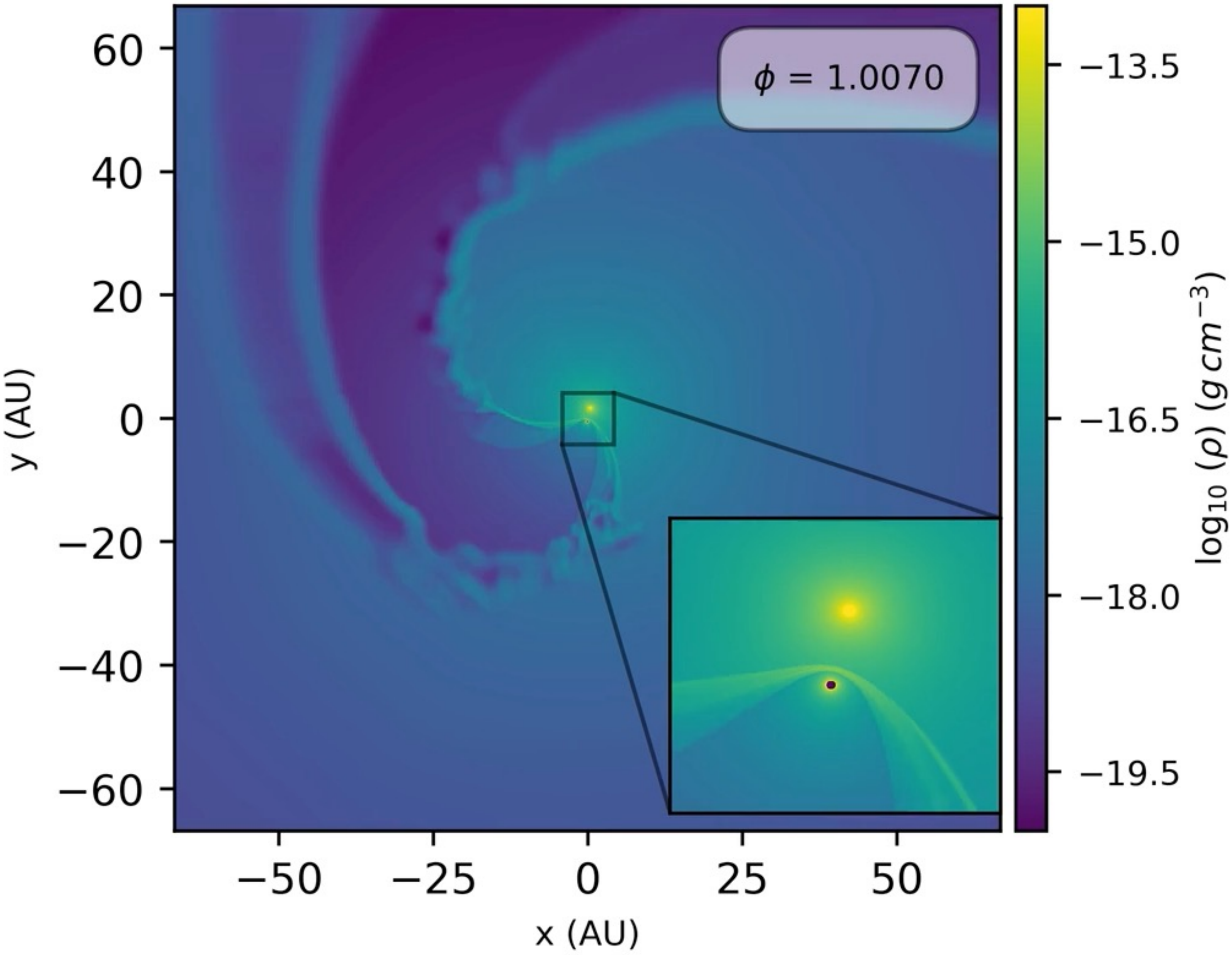

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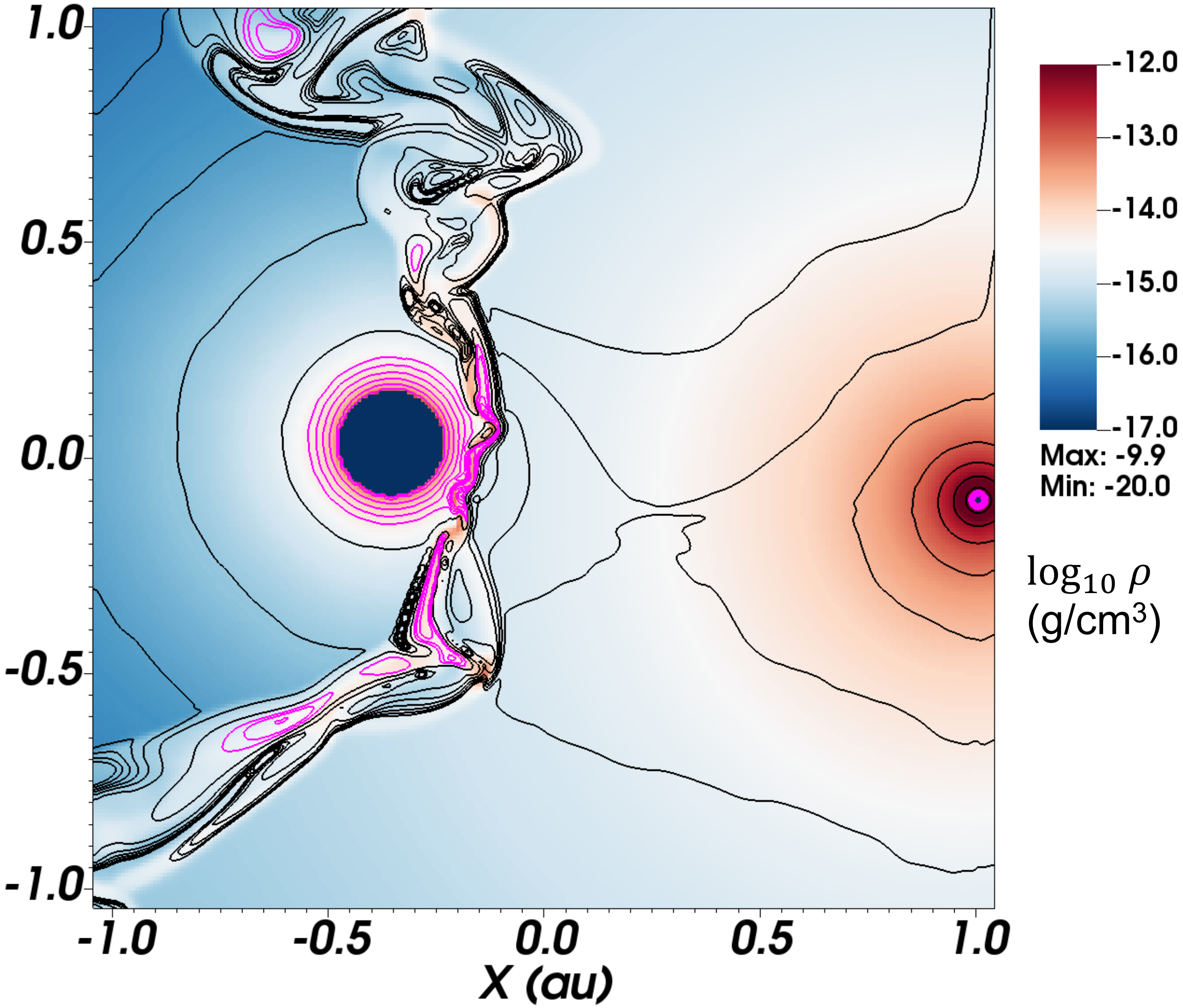
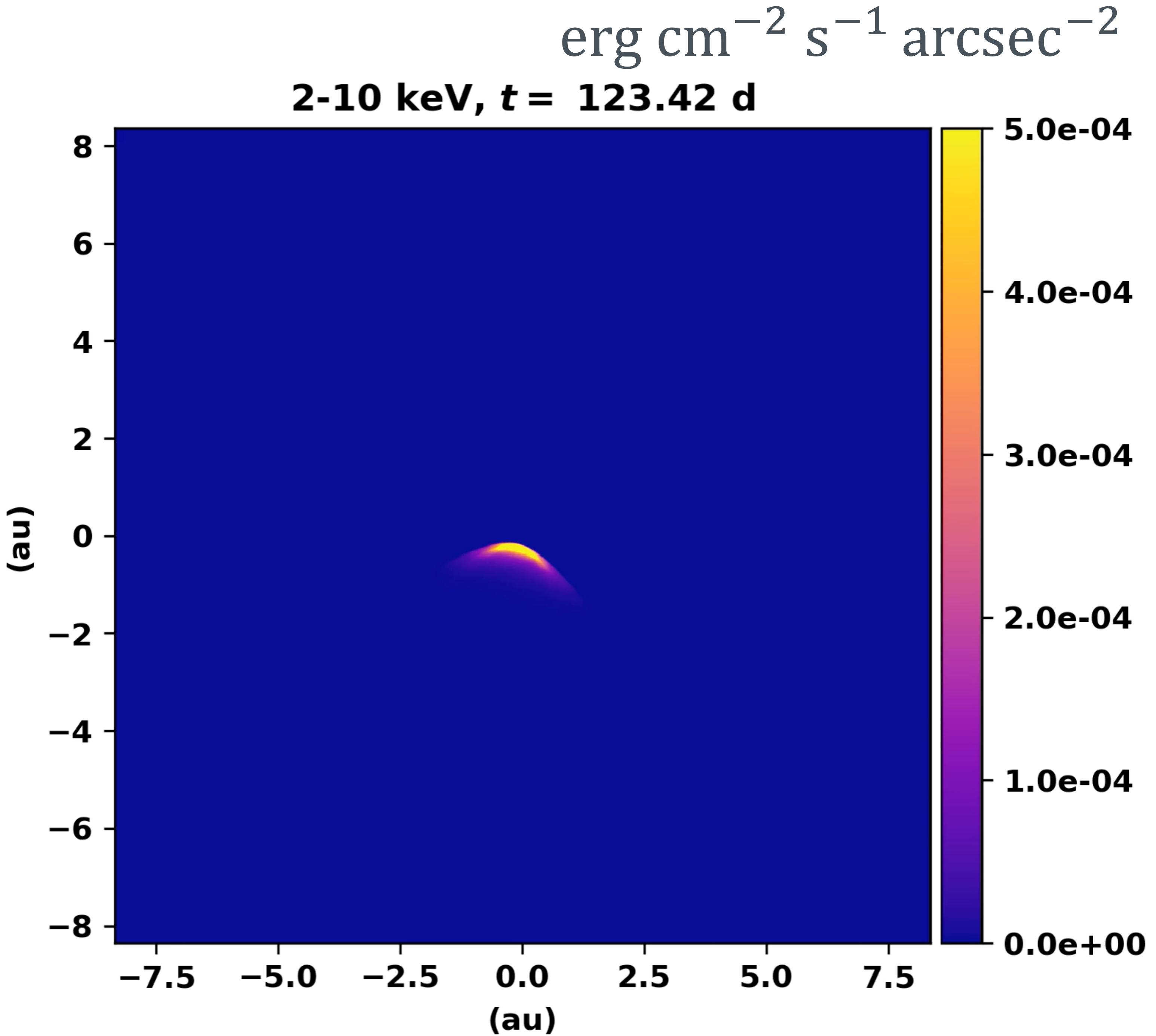
3D simulations of WR140 periastron passage

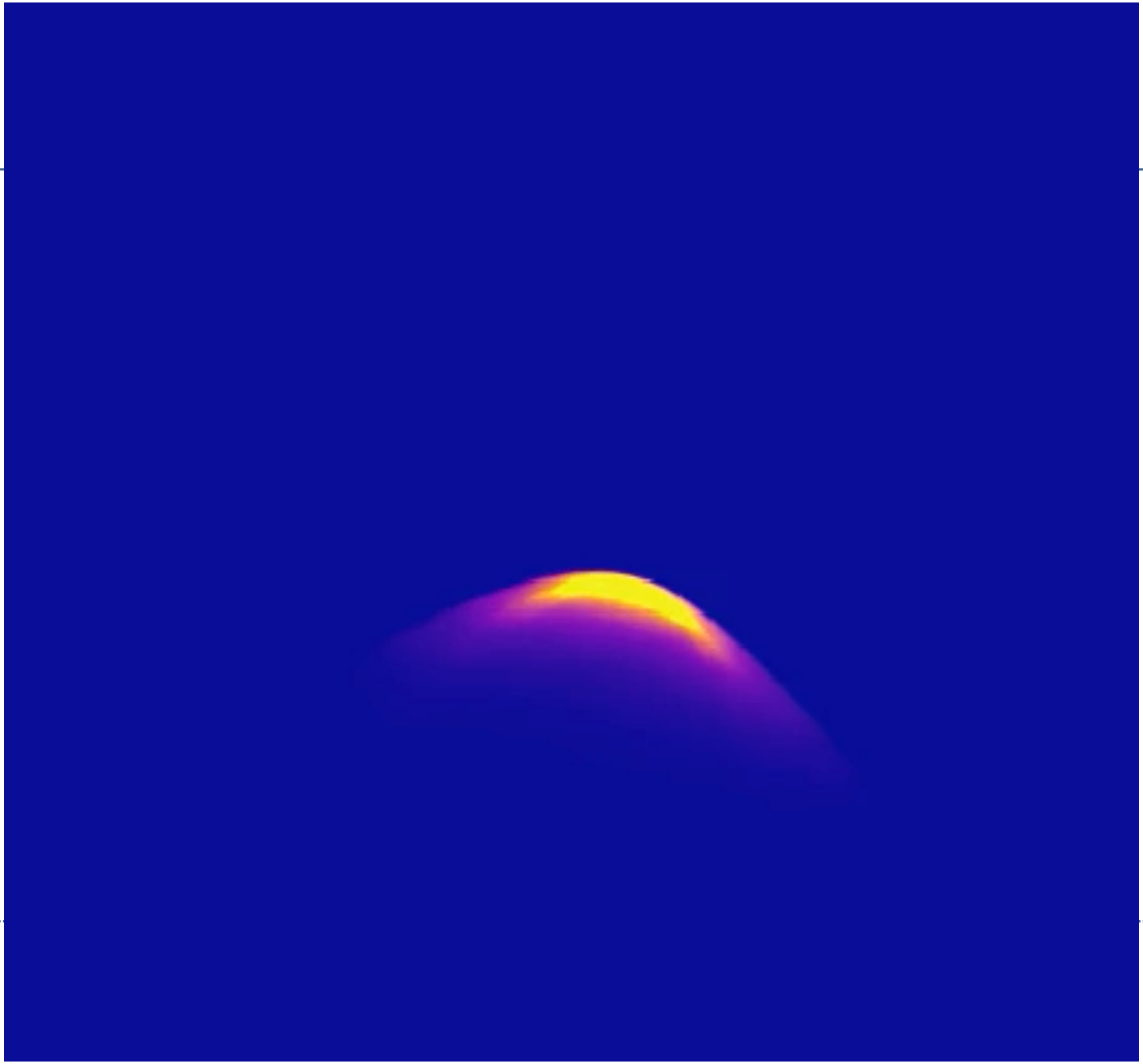
- Gas density on colour scale
- Contours = Alfvén Mach number of flow:
  - Black contours, $M_A \in [100,700]$ steps of 100
  - Pink contours, $M_A \in [20,70]$ steps of 10
- Input stellar field field:
  - O star: 1G surface field, split-monopole
  - WR star: 100G, split monopole
  - Field swept into Parker spiral by stellar rotation (at large distance from star)



Slice in orbital plane (z=0) of 3D simulation, gas density

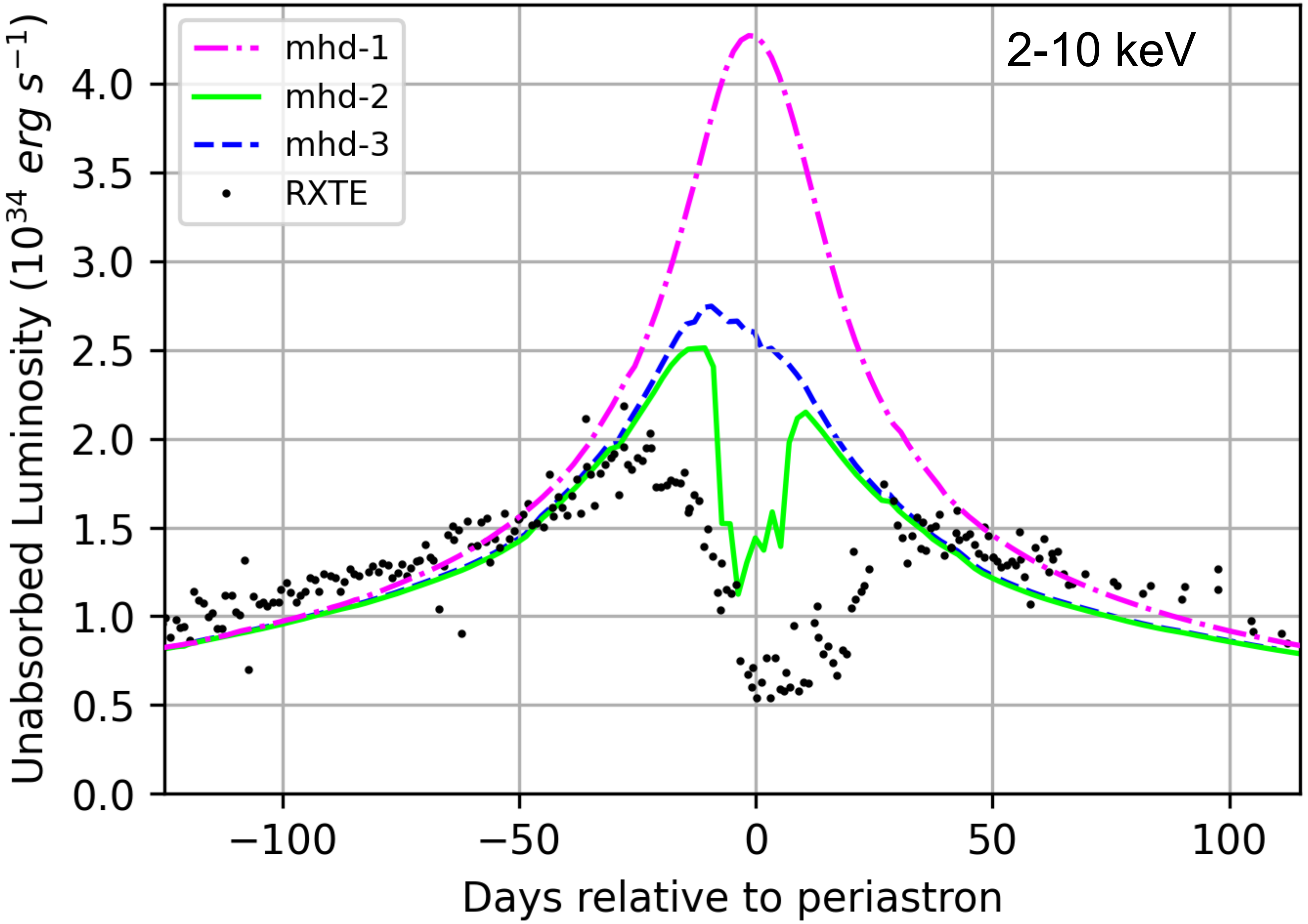
- Hard X-ray emission maps
- Looking down on orbital plane
- Absorption not included.





Hard X-ray emission from the wind-wind collision

- Synthetic X-ray luminosity calculated from simulation snapshots + XSPEC tables
- **`mhd-1`**: instantaneous wind acceleration, no IC cooling
- **`mhd-3`**: wind acceleration, no IC cooling
- **`mhd-2`**: wind acceleration, IC cooling
- RXTE data from Pollock+(2021)
- Used mass-loss rates derived from X-ray observations (Sugawara+,2015)
- Dip in lightcurve triggered by IC cooling
- Again, working on synchrotron emission from postprocessing…



These models can/will be used as a basis for investigating DSA and high-energy radiation

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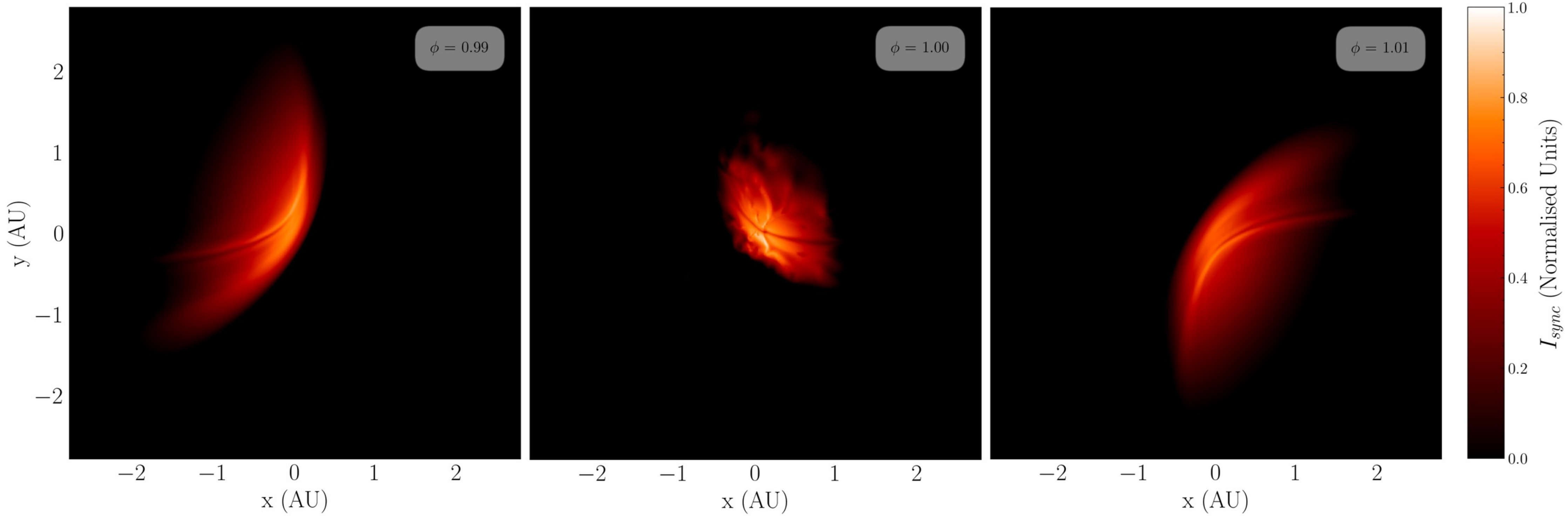
1st attempt at radio synchrotron emission



Produced by T. Jones for BSc project (2023) using method of Jun & Norman (1996)
So far omits free-free absorption, so lacking in predictive power.

Non-thermal emission from CWBs

- Quite a few systems have bright radio synchrotron emission De Becker+(2013)
- Predictions for particle acceleration and HE radiation seem promising
  - Eichler(1993), Reimer+(2006), del Palacio+(2016)
- Only γ^2 **Vel** and **η Car** have detected HE/VHE emission (Pshirkov+2016)
  - γ^2 **Vel**: Marti-Devesa+(2020)
  - **η Car**: Reitberger+(2015), HESS Collaboration (2020)
  - **Apep**: upper limits (Marti-Devesa+2021)
- γ^2 Vel is pretty faint considering $d = 333$ pc
- Only η Car is an efficient HE+VHE emitter (White+2020)

Spectrum of Gamma[2] Velorum from FERMI-LAT (Marti-Devesa+,2020)

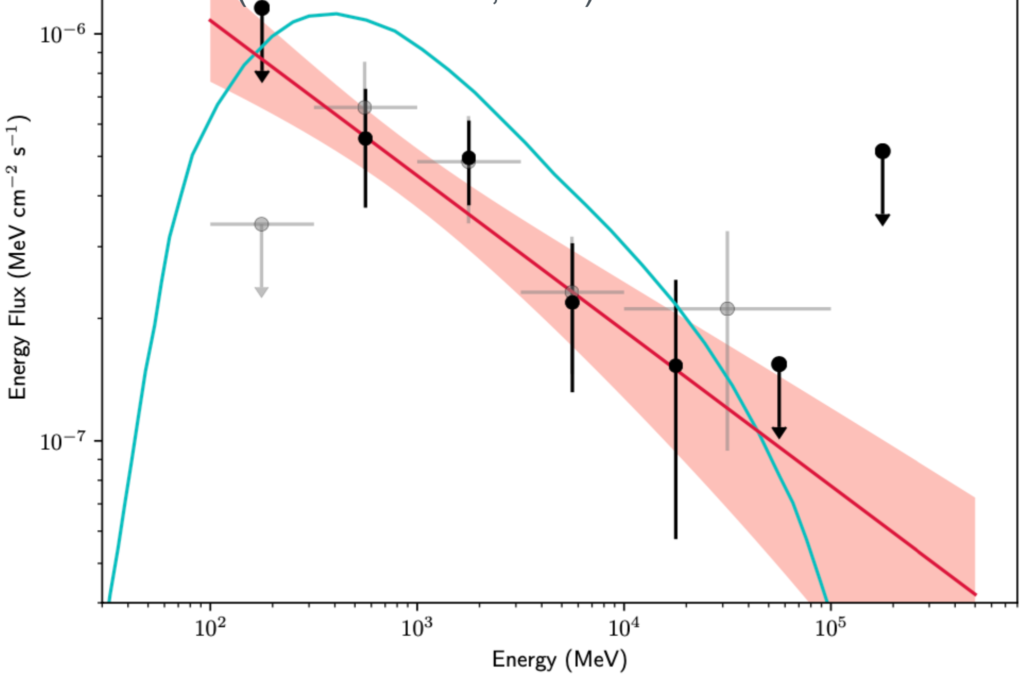


Fig. 5. Spectrum from γ^2 Velorum. The red line corresponds to the best-fit PL spectral shape and has an uncertainty of 1σ. The 95% confidence level upper limits are used for energy bins with less than 2σ detection. Data from Pshirkov (2016) are shown in grey. Emission from Reitberger et al. (2017) at apastron is shown in blue. The spectrum was obtained assuming $\Gamma = 2.0$ per each energy bin by default with *fermipy* ($\Gamma = 2.39$ provides fully compatible results).

Non-thermal emission from η Car

- Probably the most extreme CWB in the Galaxy
- LBV + O/WR system with 5.5 year period
- No non-thermal radio detected so far (absorbed?)
- Non-thermal and variable X-rays detected (Hamaguchi+2018)
- Detected by AGILE and FERMI-LAT
- Observed with HESS around 2014 and 2020 periastron passages
  - 2014 results in HESS Collaboration (2020) →
  - 2020 results presented at ICRC 2023 by Simon Steinmassl (MPIK) for HESS Coll.

FERMI-LAT +HESS spectrum of Eta Car during 2014 periastron passage (HESS Collaboration,2020)

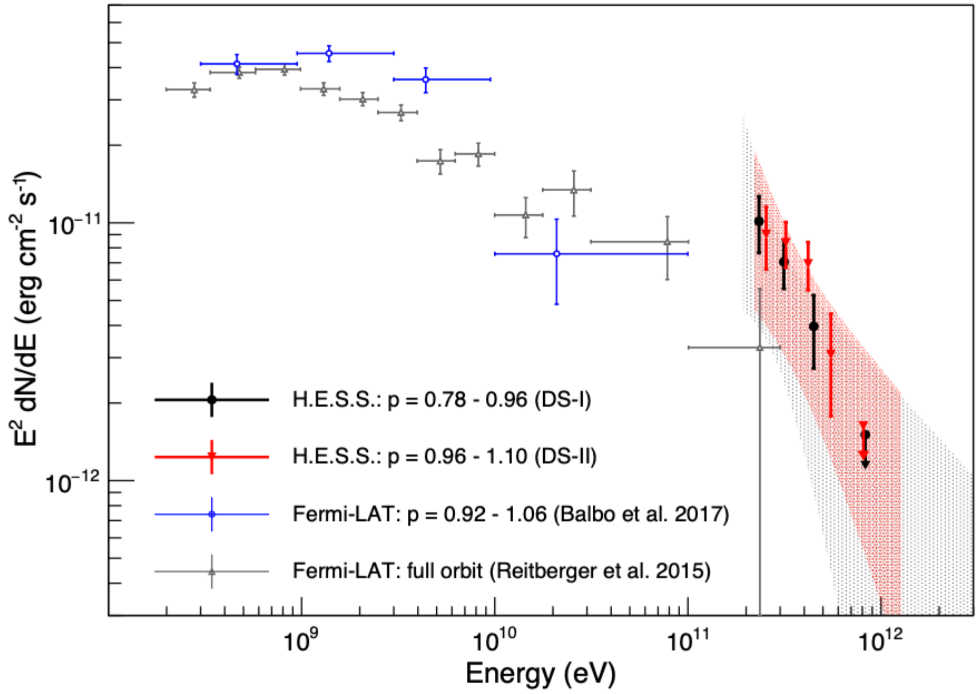
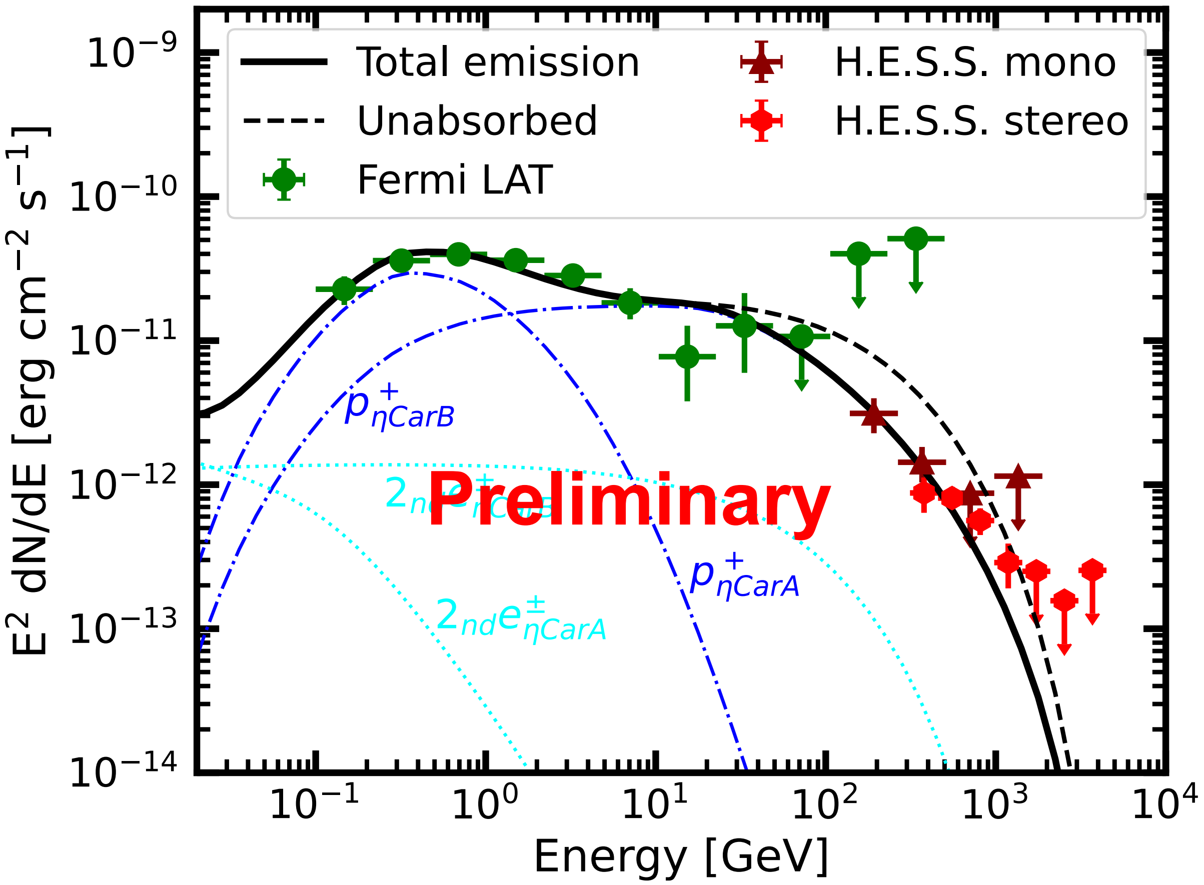


Fig. 3. Spectral energy distribution of η Car for DS-I (black) and DS-II (red). H.E.S.S. points show 1σ statistical errors. The shaded regions indicate the combined statistical and systematic errors (as given in the main text and Table 3). *Fermi*–LAT spectra from Reitberger et al. (2015) for the full orbit (grey) and for the last periastron passage from Balbo & Walter (2017) (blue) are also shown.

Non-thermal emission from η Car

- Around 100 h of observations in 2020 around periastron, with all 5 telescopes
- Difficult analysis b/c of v. bright nebula
- η Car detected at energies > 0.14 TeV during 2020 periastron passage
- Soft spectrum in continuation of high energy Fermi-LAT component, $\Gamma \sim 3.3$.
- No significant variability during periastron passage
- Look out for the paper in the next few months

Steinmassl+HESS (ICRC 2023)
Model adapted from White+(2020)



Summary: Colliding-Wind Binaries

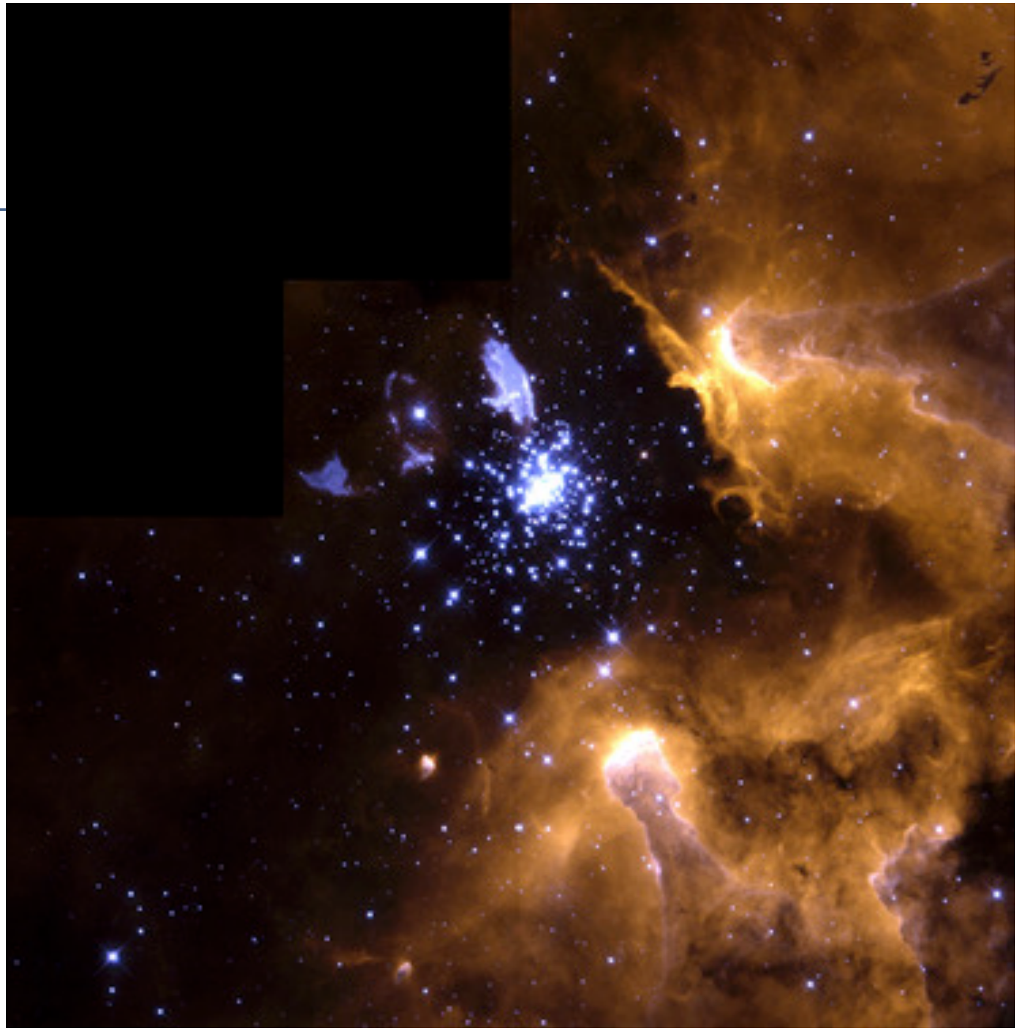
- 3D MHD simulations are possible, with simplifying assumptions for wind acceleration and magnetization
- These can accurately model the thermal plasma for the first time (with high resolution)
- Can test+extend one-zone and multi-zone models for particle acceleration and radiation
- A surprise that only two HE (and one VHE) CWB systems have been detected
- Both are interpreted as hadronic emission
  - For γ^2 Vel it is argued that electrons only reach 100 MeV and pp emission absorbed at >100 GeV (Reitberger+,2017)
  - For η Car efficient acceleration of protons to >20 TeV is inferred (White+2020) and $\gamma\gamma$ absorption is ineffective.
- What about other systems? Based on non-detection of Apep, Marti-Devesa+(2023) argue that synchrotron emission is a poor predictor of HE/VHE emission.
- WR140 could be a good target for TeV, although not detected by FERMI

Star Clusters

Brighter than isolated stars by superposition of many sources:
multiple shocks and larger volume → CRs confined longer and to higher energy

Star Clusters

- Winds from massive stars (esp. WR) in clusters may contribute to gamma-ray sky (Cesarsky+,1983)
- Measurements from clusters and associations supports this (Aharonian+,2019), especially contribution at highest energies
- Popular model of Morlino+(2021) of efficient acceleration in termination shock of "cluster wind"
- Superbubble model Vieu+('22,'23) → 1-100 PeV
- Very recent paper (Peron+2024) detects embedded SCs with FERMI-LAT
  - Argues for significant contribution of winds to CR pop.
  - Efficient acceleration of ~10% of wind energy



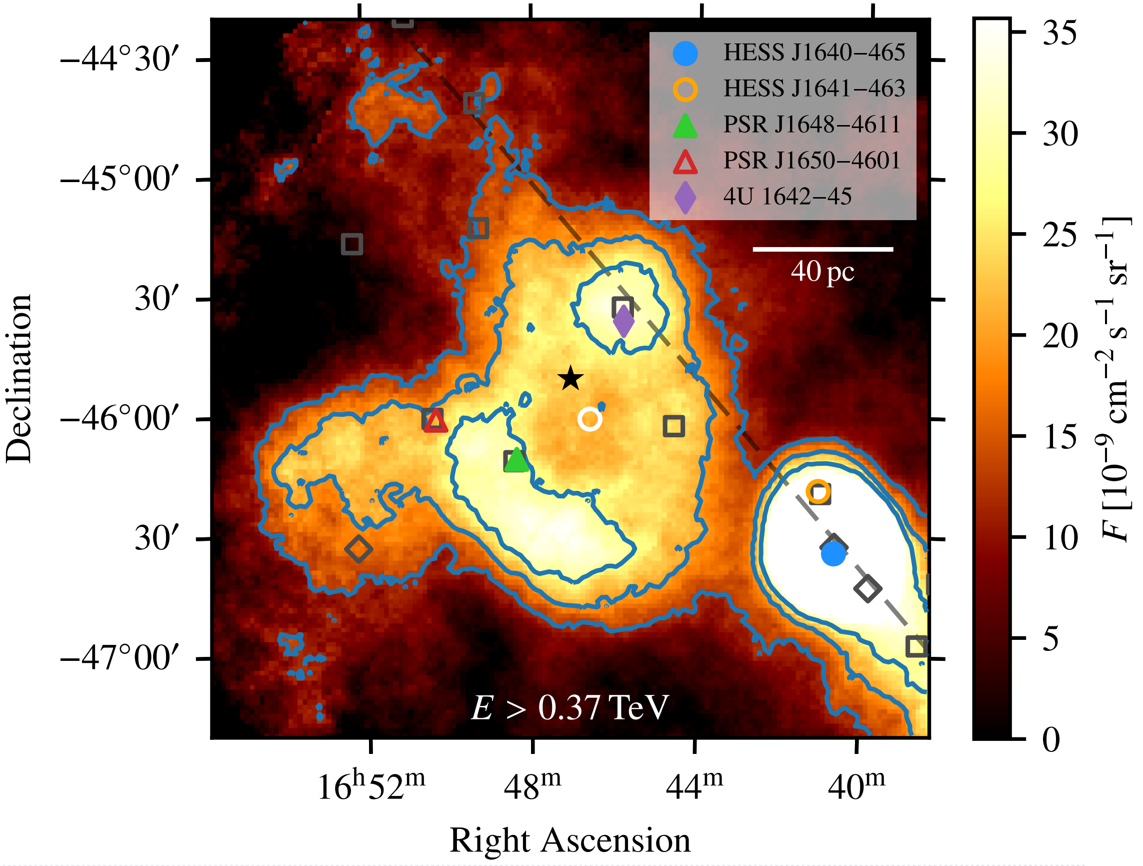
NGC3603 - HST

1. Contribution of stellar winds to CR population?
2. Contribution of star clusters (Wind+Binaries+SN)?

Star Clusters – Westerlund 1

- Detection at TeV (HESS Collaboration, 2012)
- Detailed analysis (HESS Collaboration, 2022)
- HESS flux map →
  - shows bright shell of emission around Wd1
  - 1-2 degree diameter, bit offset from Wd1
  - No energy-dependent morphology
- Hard spectrum ($\Gamma \sim 2.3$) extends to tens of TeV
- Hadronic and leptonic models possible
  - Not clear that dense gas is present at peaks for hadronic
  - Leptonic model works if there is a cluster TS at the shell
- Where did the CRs come from?
  - Wd1 likely had many supernovae in past 1-2 Myr
  - Strong stellar winds from richest population of WR stars

HESS Collaboration (2022)



Star Clusters – Westerlund 2

- Wd2 younger than Wd1, not clear if it already had SN explosions
- Near Westerlund 2: "interstellar weather vanes" →
  - Source S1 indicates wind of $\sim 300\ km/s$ expanding from Wd2 (for $n \sim 1\ cm^{-3}$)
  - Evidence of cluster wind
- Bright TeV source near not conclusively associated with cluster Wd2 (HESS Collaboration 2011)
- New results presented at ICRC 2023, interpretation ongoing.

Povich+(2008): bow shocks reveal cluster wind

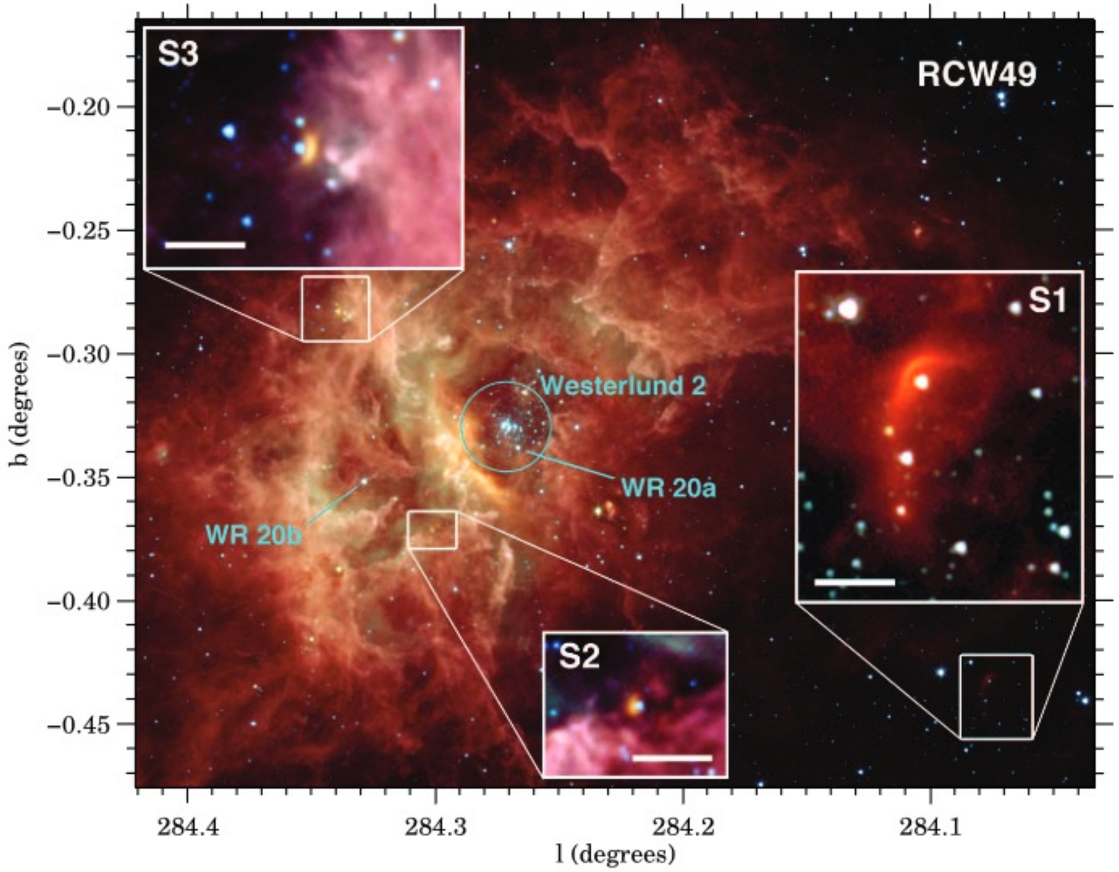
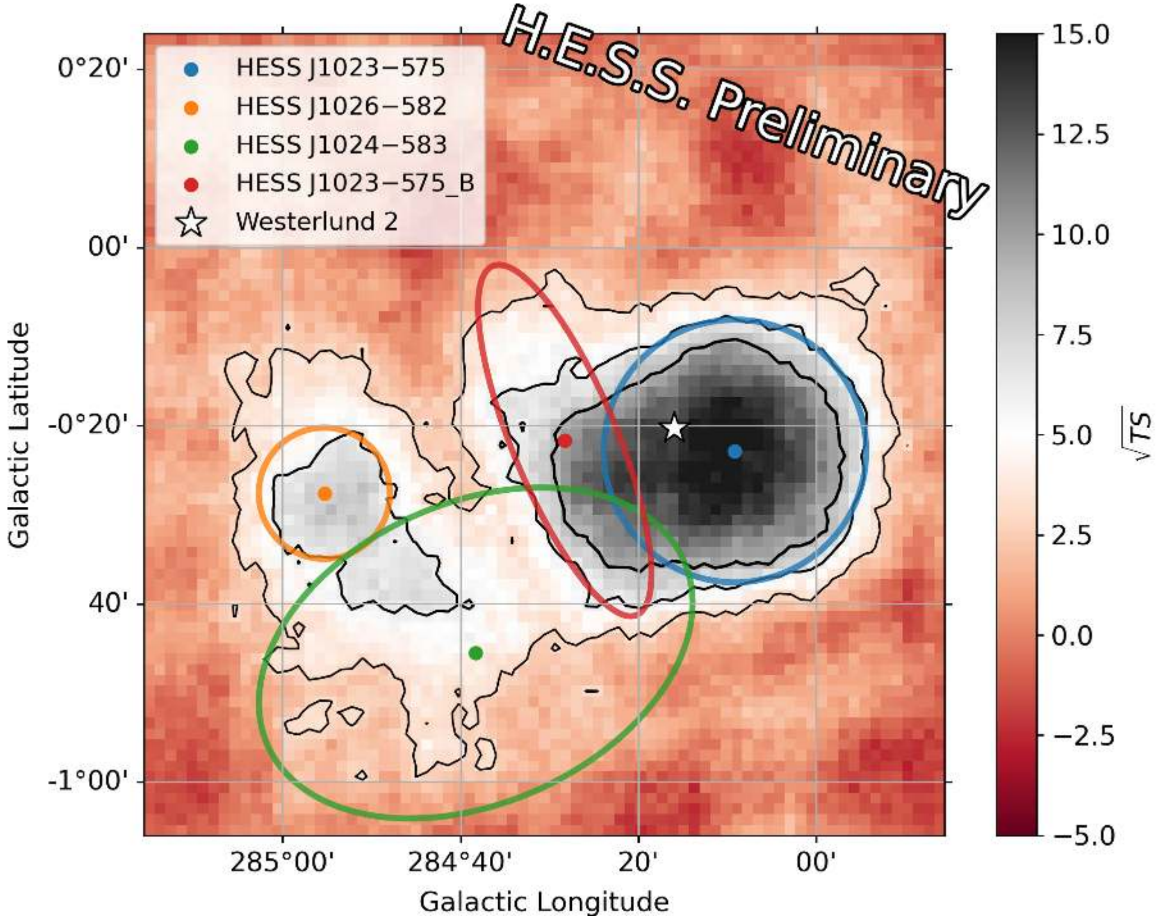


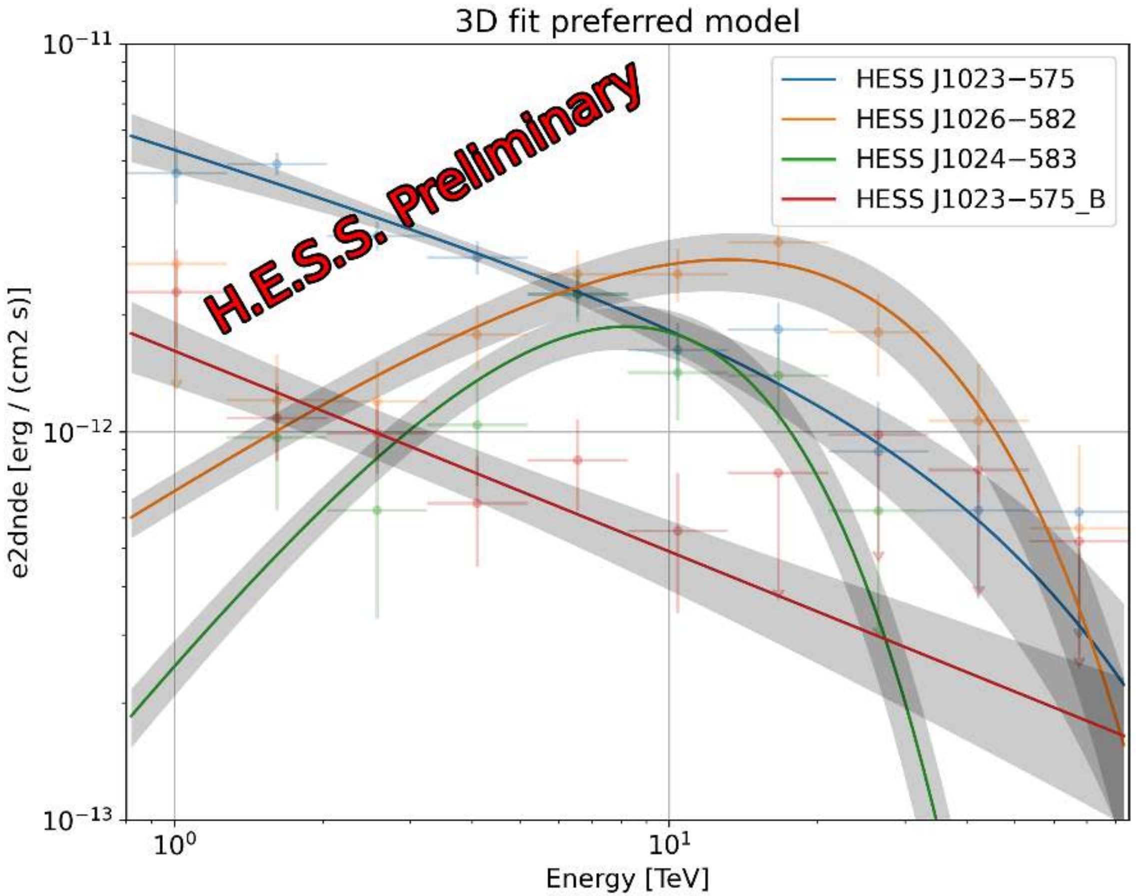
FIG. 2.—GLIMPSE full-color image of RCW 49 (*blue*: [3.6]; *green*: [4.5]; *orange*: [5.8]; *red*: [8.0]). The bow shocks RCW 49-S1, RCW 49-S2, and RCW 49-S3 are enlarged in three separate insets (scale bars are $30'' \approx 0.6$ pc at 4.2 kpc). Three energy sources that could drive large-scale interstellar flows are also indicated: the Westerlund 2 cluster (*circled*), and the Wolf-Rayet stars WR 20a and WR 20b.

Preferred model components

For Wd2

- Results presented at ICRC 2023 by T.L. Holch on behalf of HESS collaboration
- PoS(ICRC2023)778

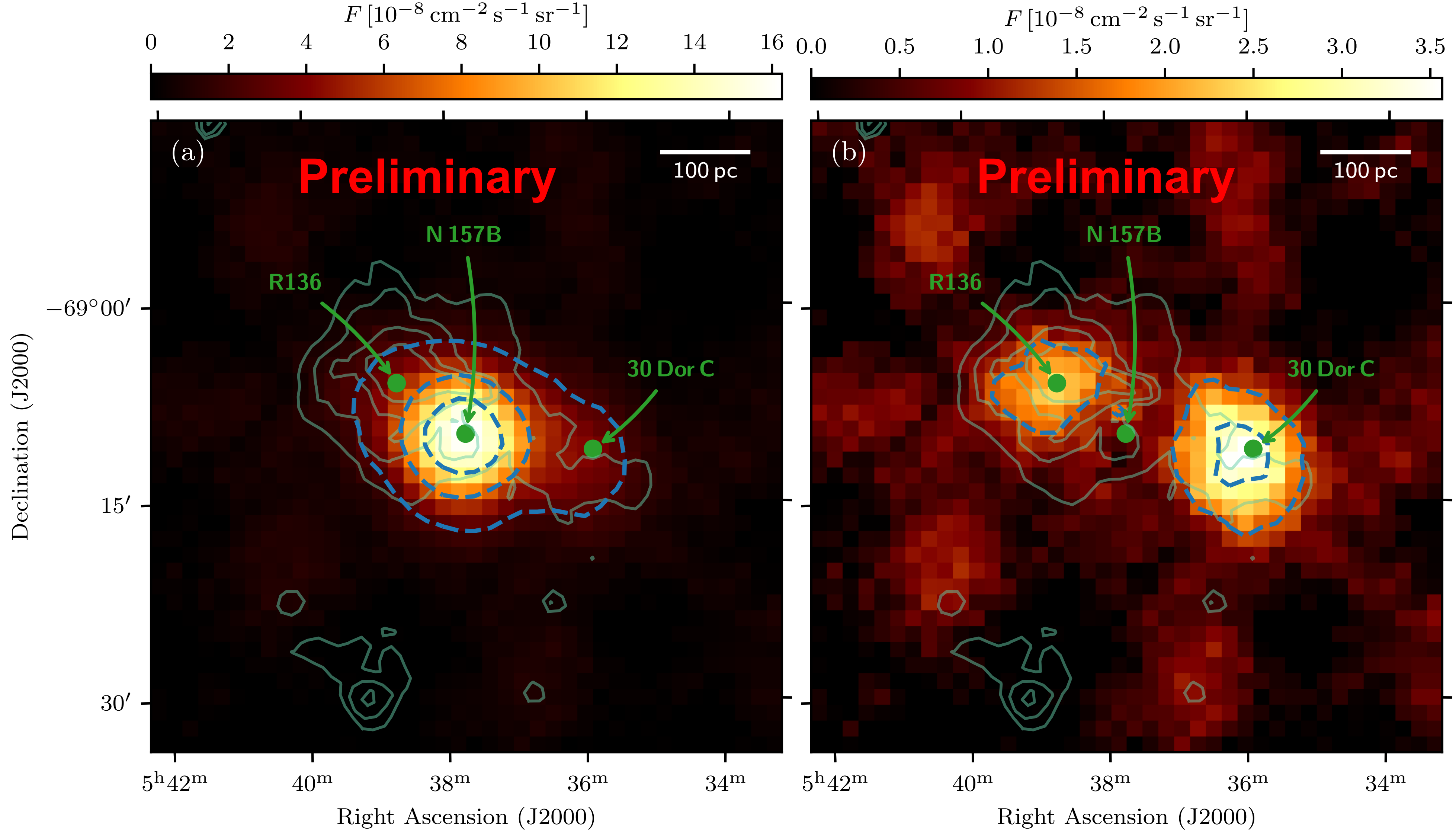




Star Clusters – R136

- Central cluster of the Tarantula region
- Most massive star cluster in Local Group
- Contains stars with initial mass $> 200M_{\odot}$
- TeV results presented by L. Mohrmann at TeVPA 2023 on behalf of HESS Collaboration
- TeV gamma-rays detected from region
- Appears spatially extended
- More $\boldsymbol{\gamma}$-ray luminous than Wd1
- Paper coming soon

Flux maps (TeVPA 2023)



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Summary: Star Clusters

- Exciting field in gamma-ray Astronomy – new discoveries with existing instruments
- Detections at GeV and TeV show that star clusters are effective accelerators to VHE
- Brightest objects (Wd1, R136) have had many supernovae – what produced the CRs?
- Younger clusters are key for testing if stellar winds effectively accelerate
- New results suggest that they do! (Peron+2024)

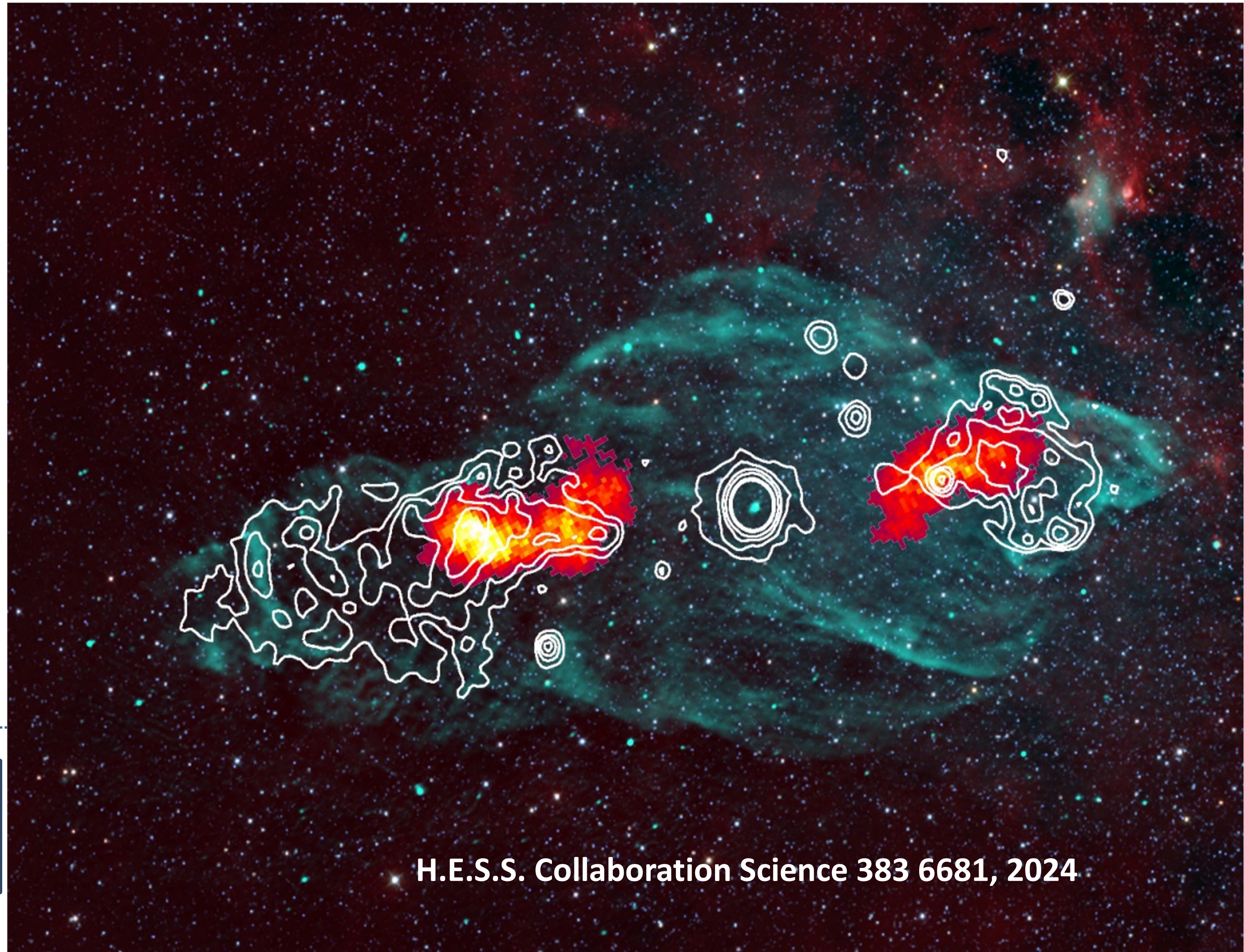
Dead Stars – the final chapter

Dead Stars: the best accelerators?

- Novae:
  - High velocity shocks ~5,000 km/s
  - Dense circumstellar environment (disk/wind)
- Core-collapse SN explosions in first weeks to years
  - Higher velocity shocks ~10,000 km/s
  - Fast and efficient accleration
- High-mass X-ray Binaries (HMXB)
  - Massive Star + Black Hole
  - Massive Star + Neutron Star
  - Relativistic plasma before acceleration even starts → easier to get to HE/VHE
  - Subset of gamma-ray-loud HMXBs are very prominent Galactic sources

Potentially time-dependent acceleration and emission

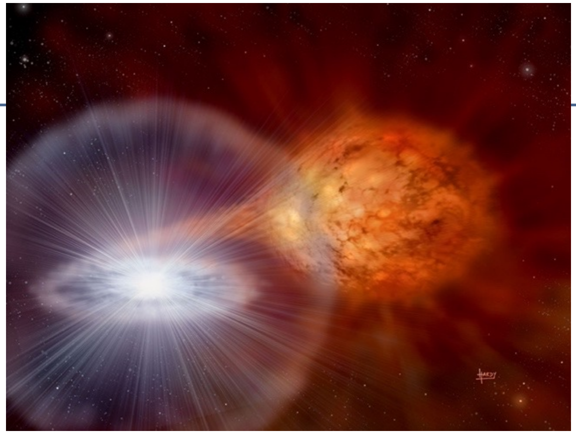
Blue/green = radio/IR, white contours = X-ray, red/yellow = HESS

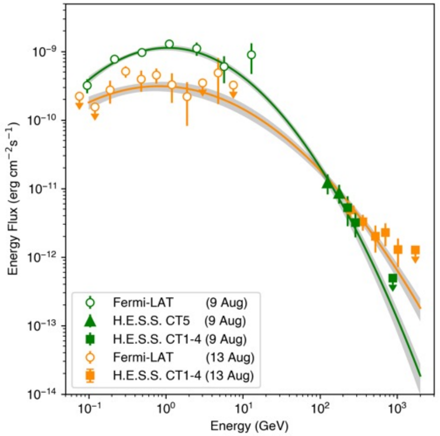


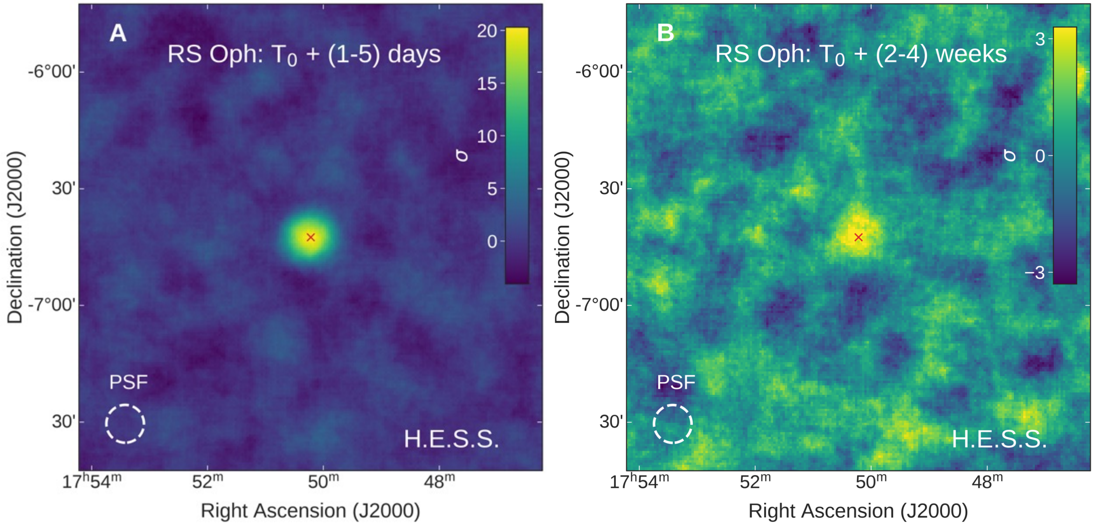
Nova RS Ophiuchi

Science Paper led by Alison Mitchell (FAU)

- Recurrent nova from binary system with Red Giant and White Dwarf
- WD near Chandrasekhar mass
- Eruption 08.08.2021
- Detected by HESS on first night after trigger 09.08.2021
- Peak TeV flux later than GeV → **time-dependent particle acceleration**







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REPORT | GAMMA-RAY ASTRONOMY

Time-resolved hadronic particle acceleration in the recurrent nova RS Ophiuchi

H.E.S.S. COLLABORATION Authors Info & Affiliations

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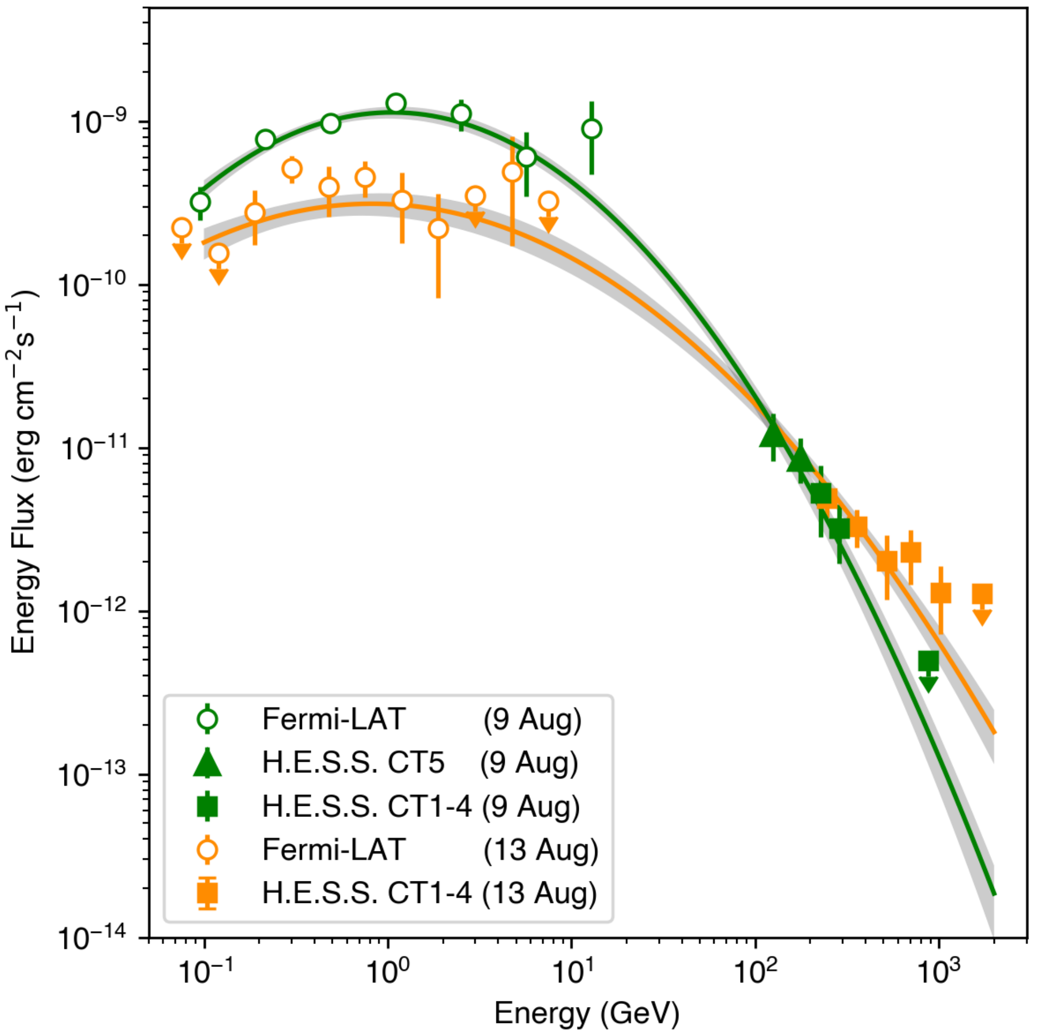
Nova RS Ophiuchi

- Peak TeV flux later than Gev → **time-dependent particle acceleration**
- Model:
    - 4500 km/s shock expands into wind of Red Giant (RG)
    - Particle acceleration at forward shock
    - Hadronic emission from interaction with RG wind
- Results sensitive to wind density (and magnetic field) distribution.
- More detailed modelling required

HESS Collaboration (2022, Science, 376, 77)



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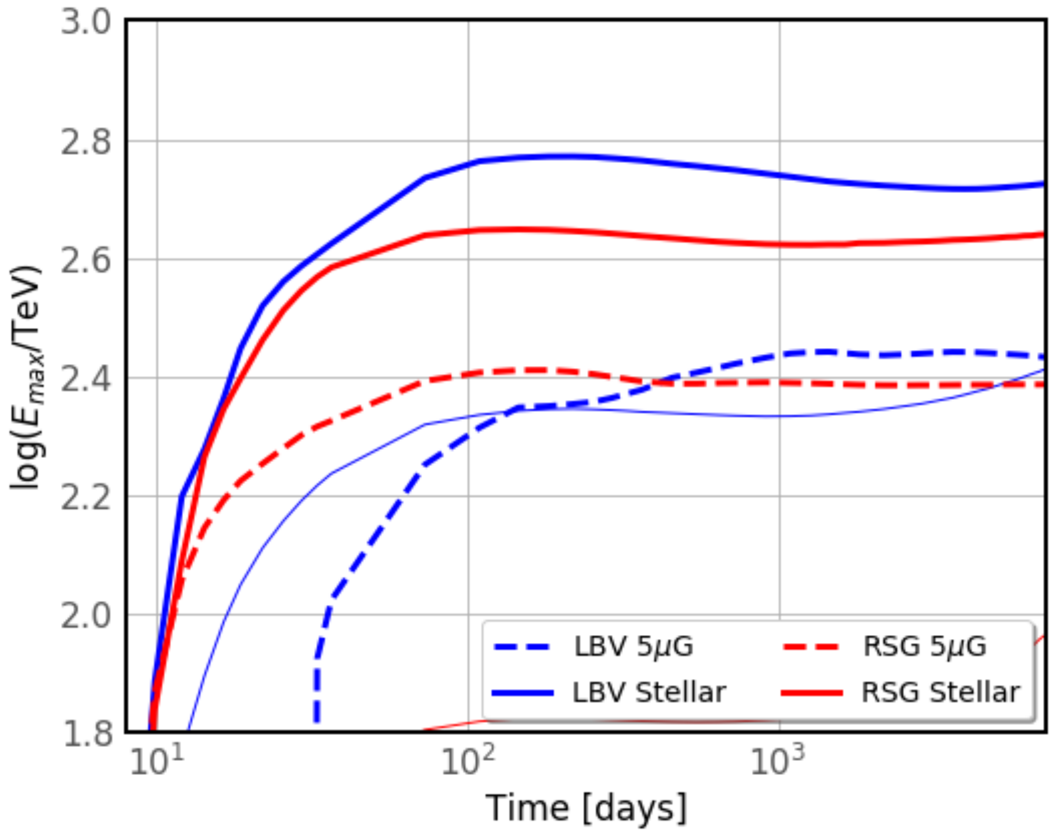
Core-collapse Supernovae

- Suggestions that early months/years of SN evolution provide most efficient acceleration to VHE (Murase+,2011; Bell+,2013)
- High-density environment also conducive to efficient acceleration (recent papers: Marcowith+, Cristofari+)
- We used RATPaC code for coupling hydrodynamics and DSA, transport and radiation, to study CCSN
  - Explosion into dense stellar wind
  - Find max. energy of protons 200-600 TeV
  - GeV/TeV emission strongly absorbed for first ~100 days post-explosion

Brose, Susch + Mackey (2022)



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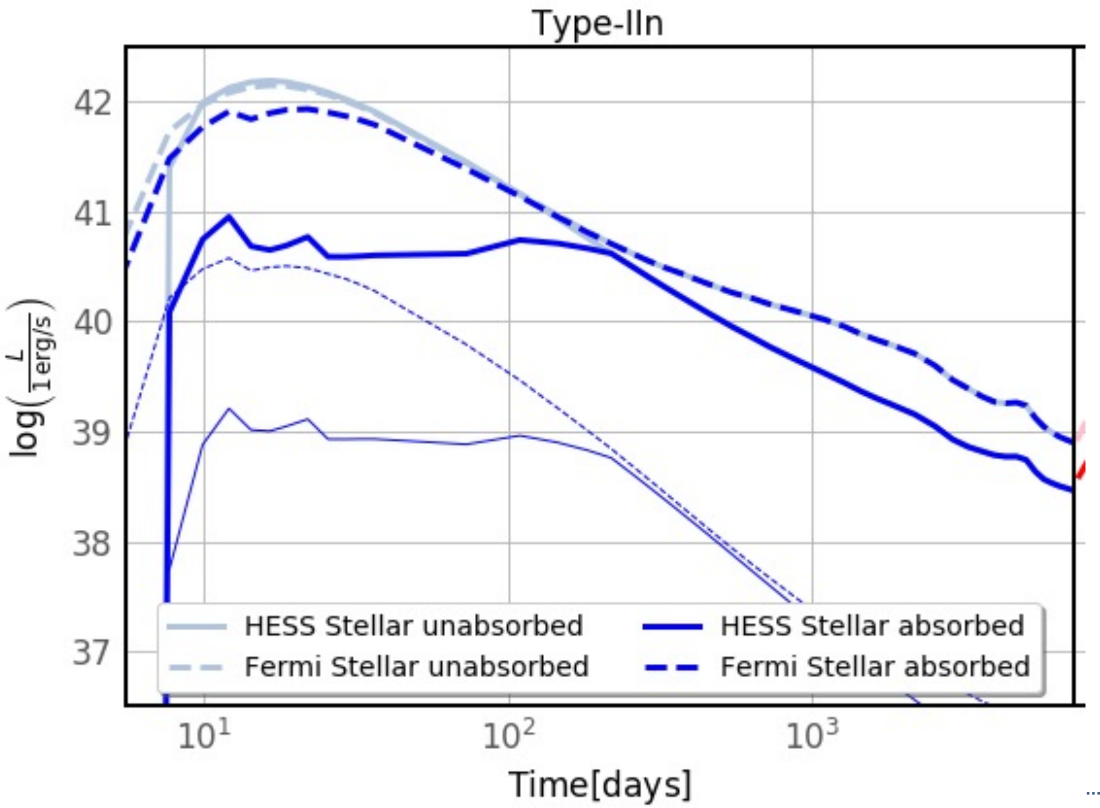

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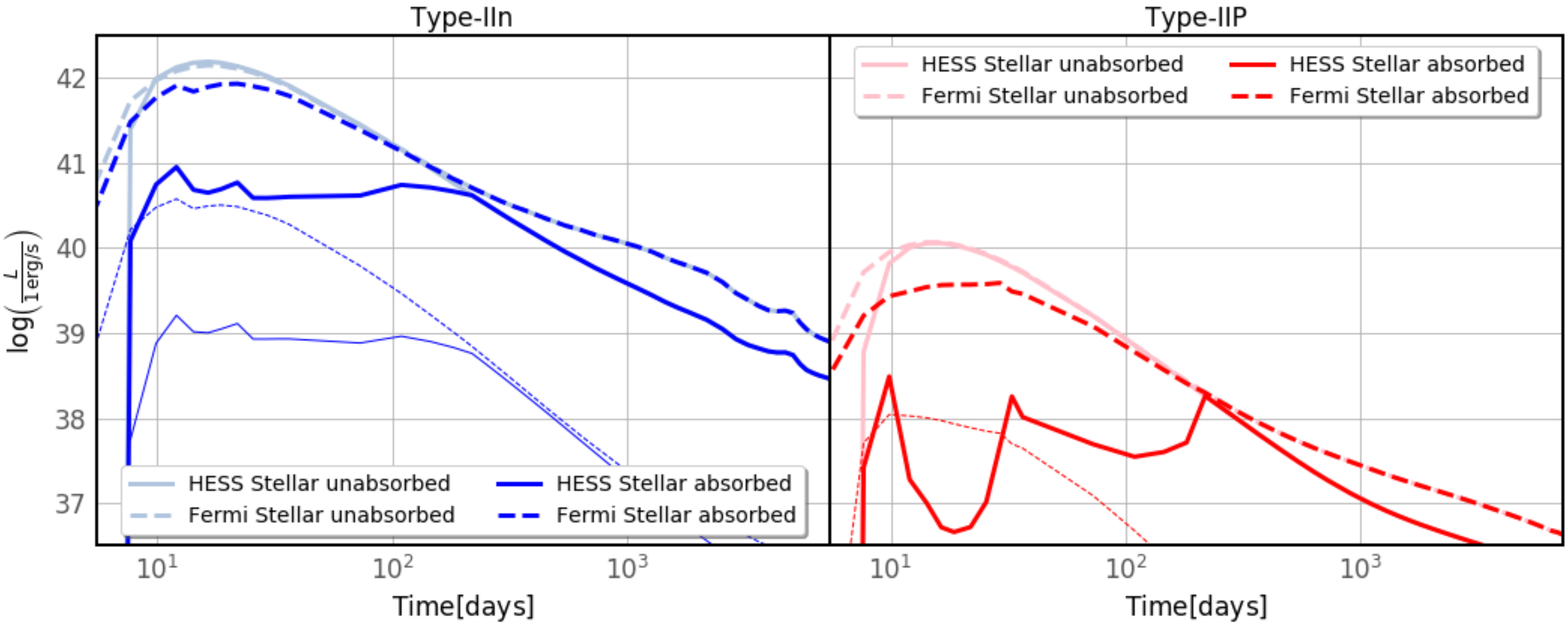
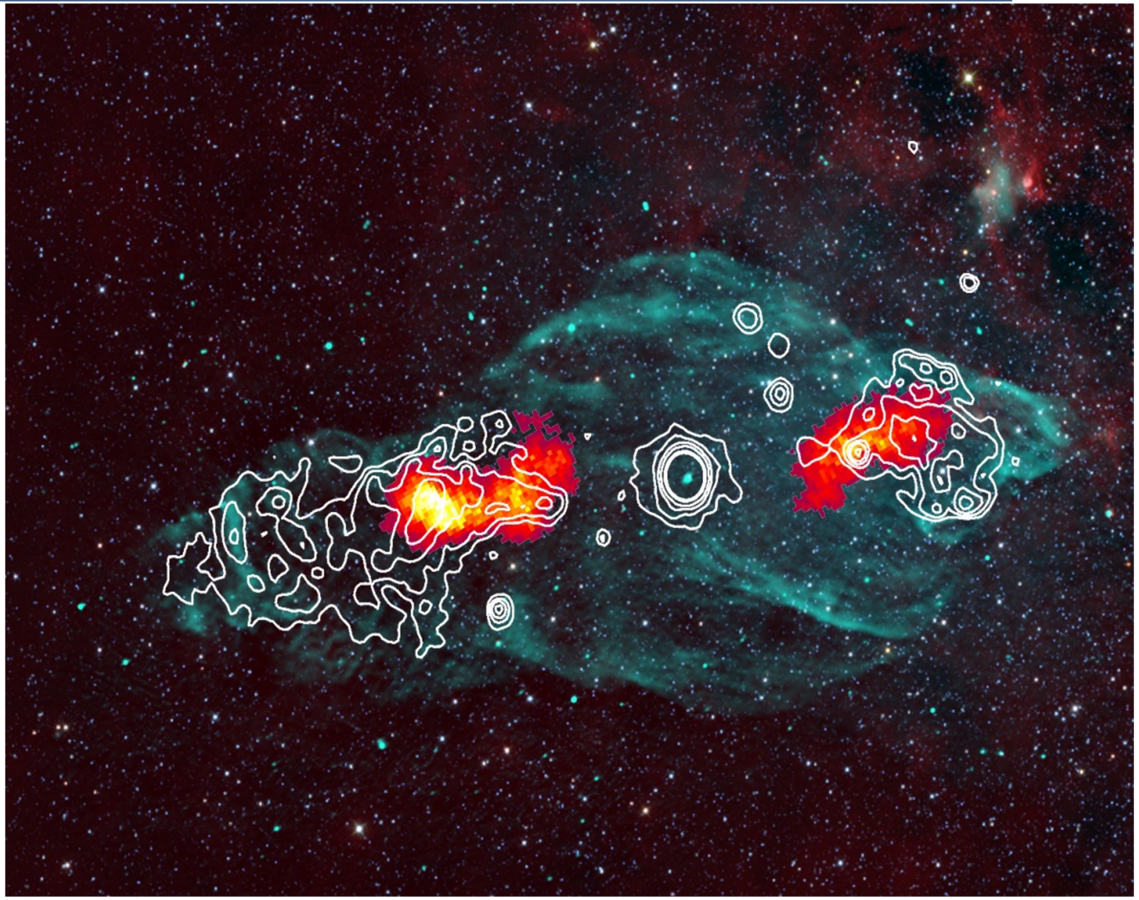


- CCSNe are detectable sources of transient gamma-rays in the very local Universe
- Our model can produce close to PeV particles on 100-1000 day timescales
- Preliminary indications that interaction with dense shells boosts to a few PeV (Brose+, in prep)

Microquasar SS433

HESS Collaboration (2024, Science, 383, 402)

- HMXB with massive star + black hole
- Roche-lobe overflow → rapid accretion → disk + precessing jets
- Large-scale emission from elongated SNR
- HESS Collaboration (2024):
  - Detection of large-scale jets on both E+W sides
  - Sensitivity gains through new ABRIR method (Olivera-Nieto+2022)
  - Efficient shock acceleration of electrons at base of outer jets
  - Leptonic emission
  - Energy-dependent morphology detected, from cooling electrons



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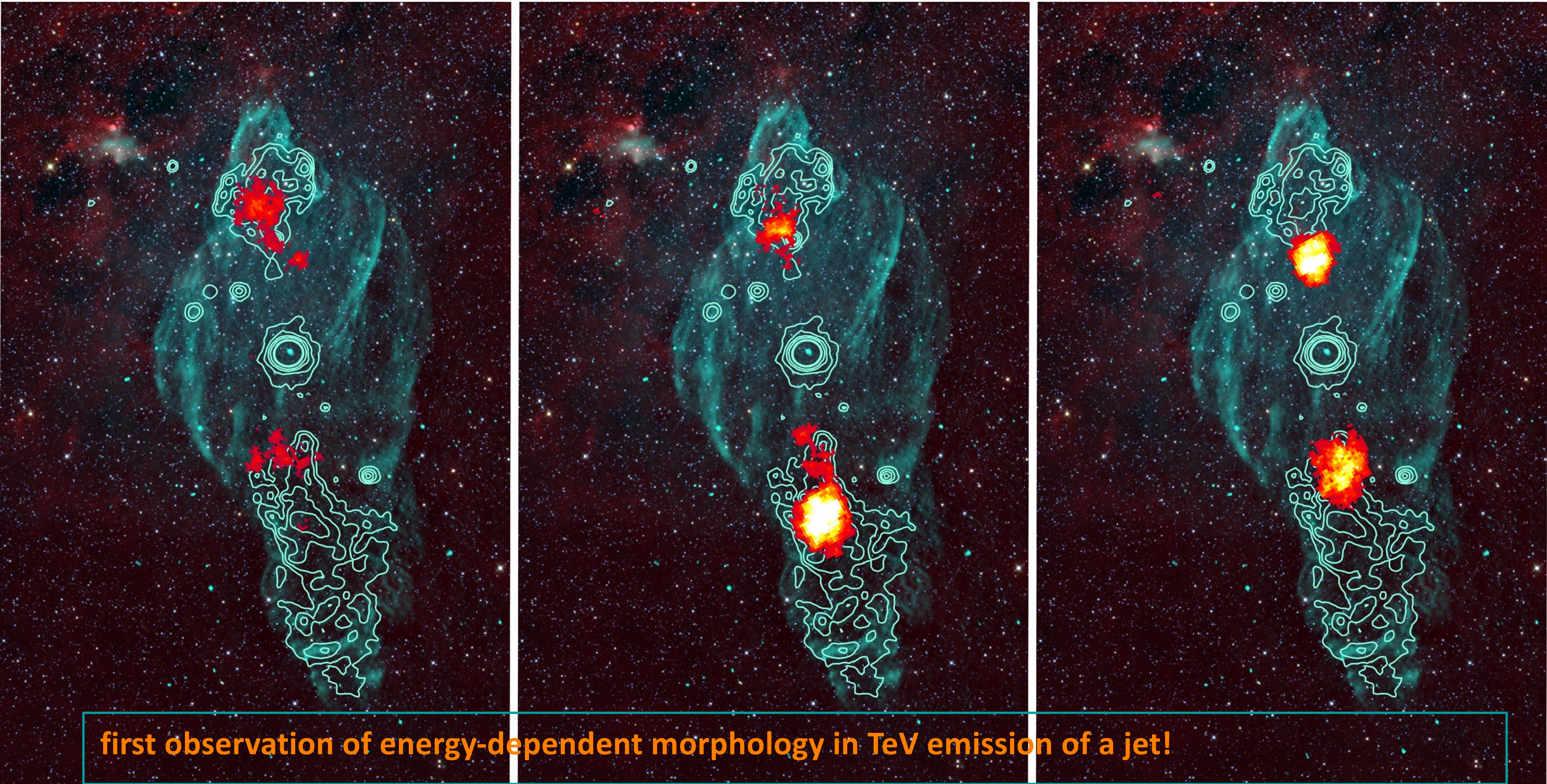
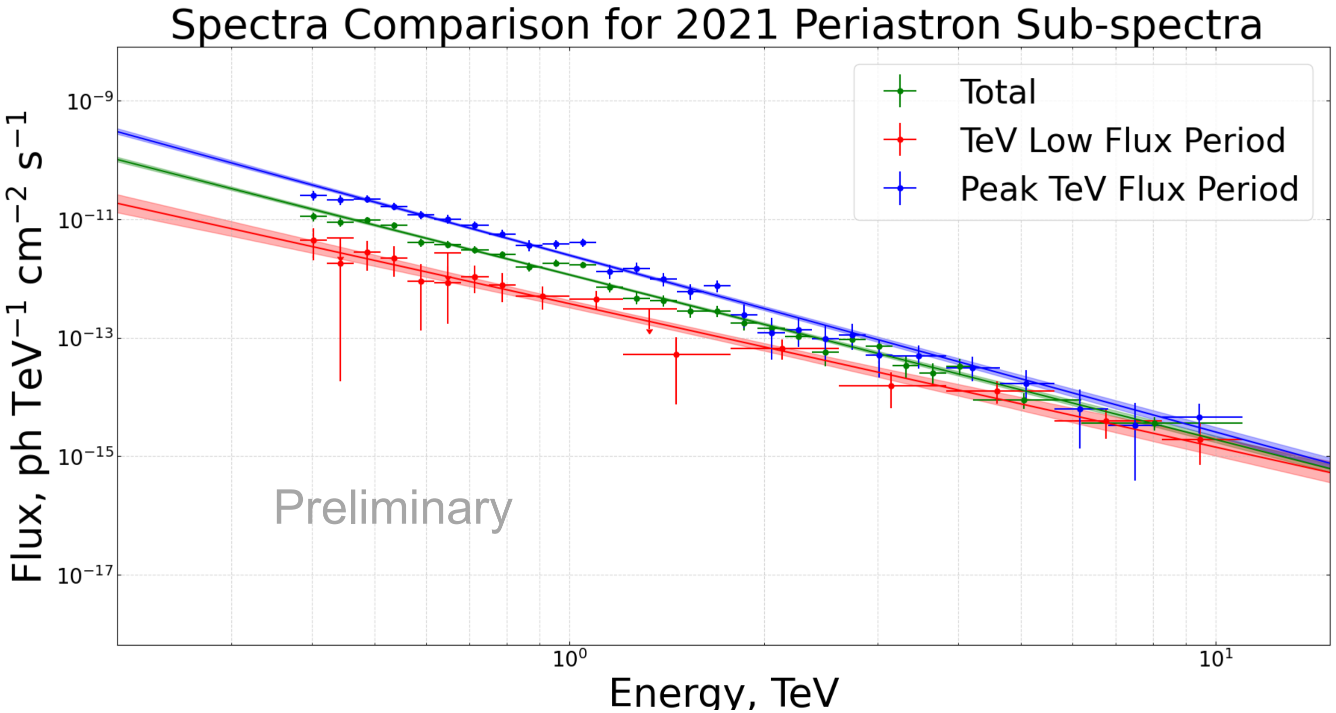
0.8 to 2.5 TeV	2.5 to 10 TeV	above 10 TeV



first observation of energy-dependent morphology in TeV emission of a jet!

γ-Ray Binary PSR B1259-63/LS2883

- HMXB with Oe massive stars and a pulsar
- Highly eccentric orbit – pulsar passes through decretion disk of Oe star pre/post periastron
- HESS papers in 2005, 2009, 2012, 2020 on the periastrons of 2004, 2007, 2011, 2014+2017
- Re-observed during 2020 periastron:
  - Results presented at ICRC2023 by C. Thorpe-Morgan on behalf of HESS Coll. →
  - Detected in range 0.3-30 TeV
  - Measure spectral variation during periastron for 1st time
    $\Gamma \sim 2.4$ to 3.0 from low to high flux state



Summary

- Wind bubbles / bow shocks: weak non-thermal emitters. May be good accelerators, but not clear
  - Unfortunately the closest ones have weak winds
  - Can learn a lot about hot thermal plasma. The non-thermal plasma: not so clear
- Colliding-wind binaries: bright non-thermal radio sources, but only two detected at HE/VHE: the closest to Earth + the most extreme in the Galaxy
  - MHD modelling not very advanced → one-zone or multi-zone models
  - Impact of $\gamma\gamma$ absorption vs. cooling/advection timescales on max. energy still uncertain
- Star clusters: bright high-energy sources and effective accelerators to VHE
  - Relative contribution of winds vs. SN and HMXBs?
  - Significant advances ongoing, great prospects for next-generation observatories
- Dead stars are the brightest! Novae, CCSNe, HMXBs, Microquasars