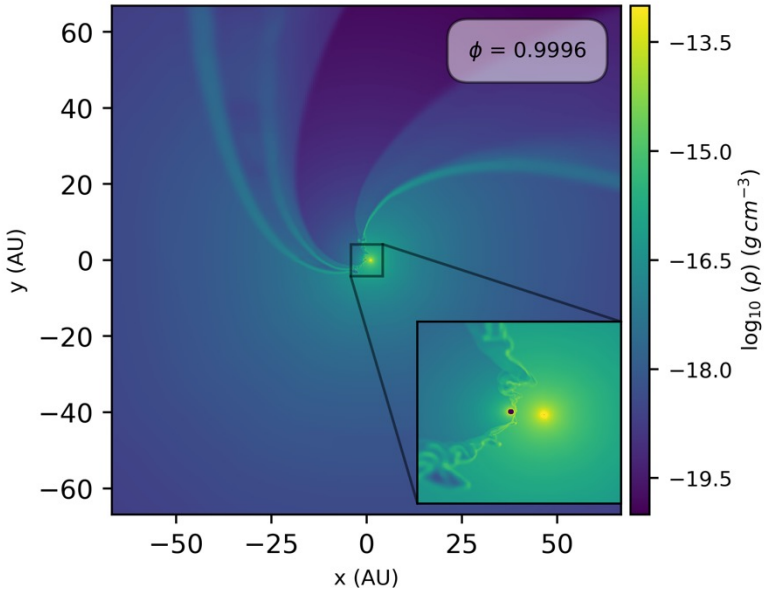
Massive stars in binary systems and star clusters

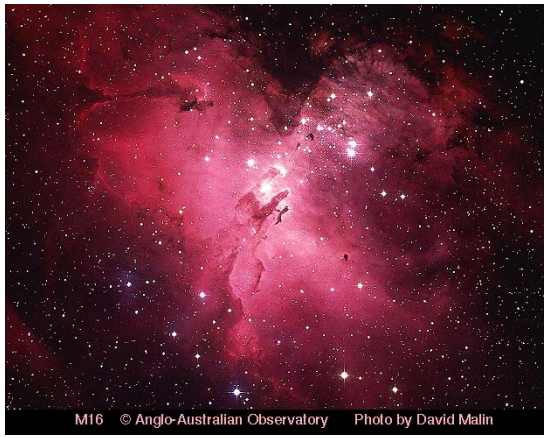
Jonathan Mackey
Dublin Institute for Advanced Studies

Roma International Conference on
AstroParticle Physics (RICAP-24)
26th September 2024



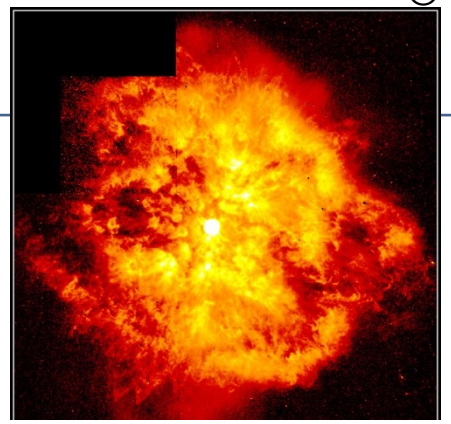
dias.ie

Single Massive Stars



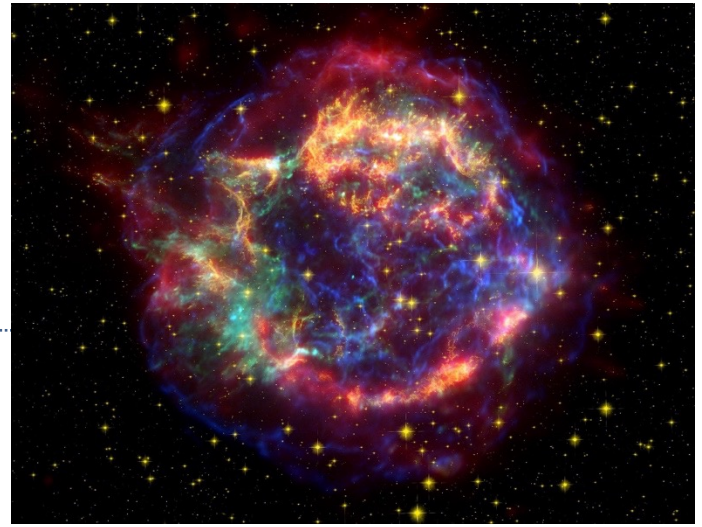
- Born in molecular clouds
- Usually with other OB stars
- Ejected by grav. dynamics

- Stellar wind – ISM interaction produces bow shock
- Particle acceleration in wind termination shock (and forward shock)



- Nebulae due to mass loss
- Can contain a few $M_{\odot}$

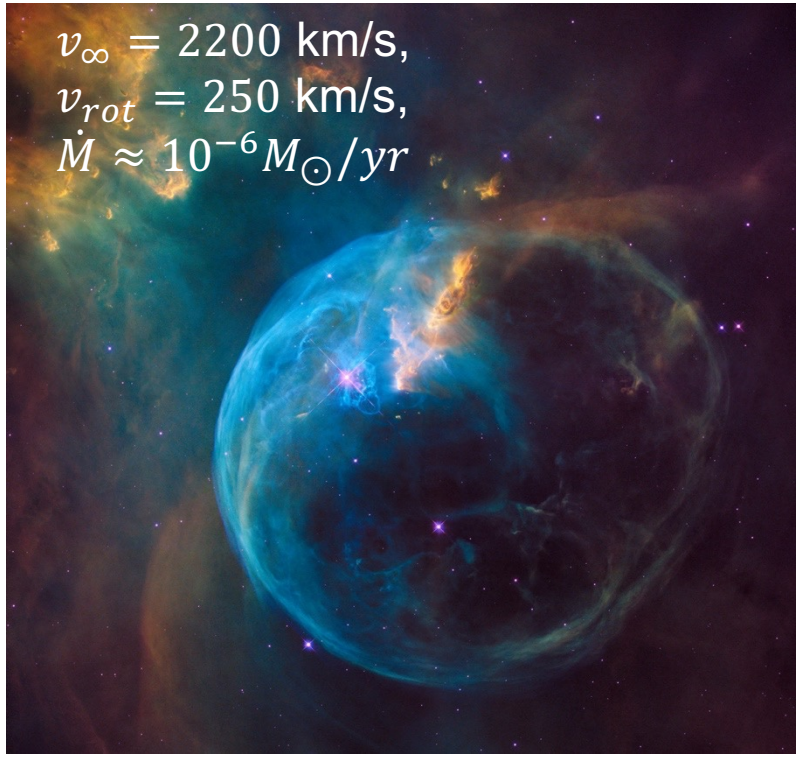
- Supernova explodes into circumstellar matter



- **Caveat:** most single massive stars used to be in a binary/triple system

Bow shocks of hot stars

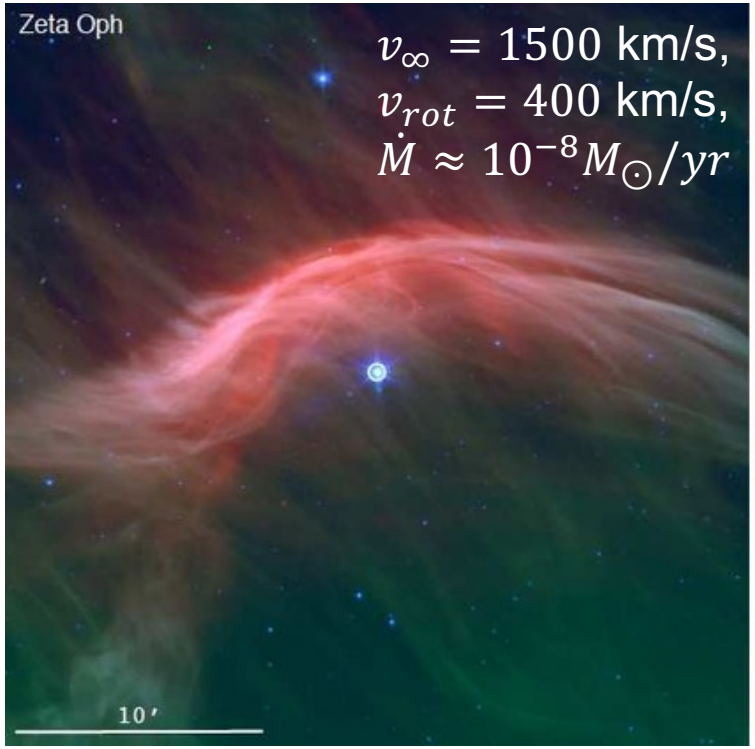
NGC 7635



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

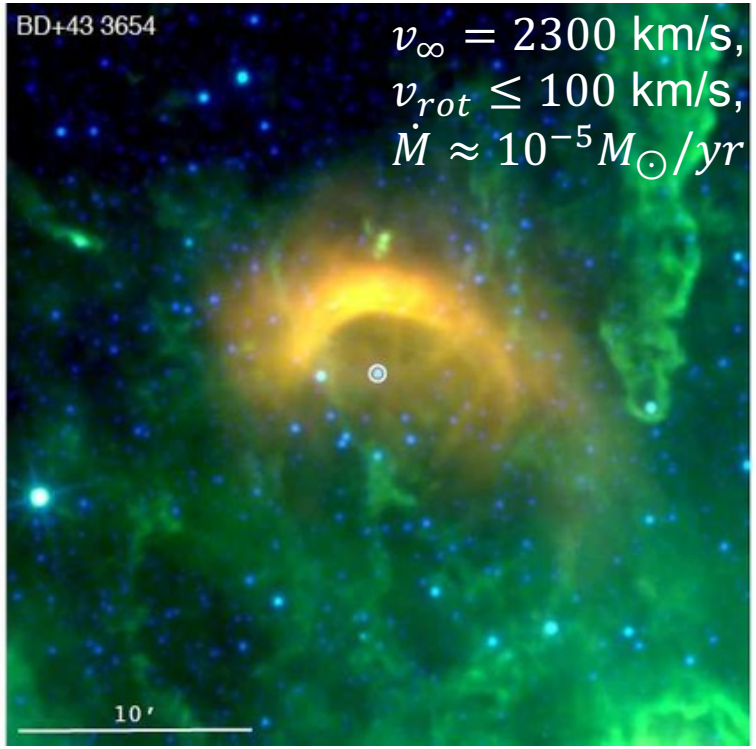
(HST optical image)

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

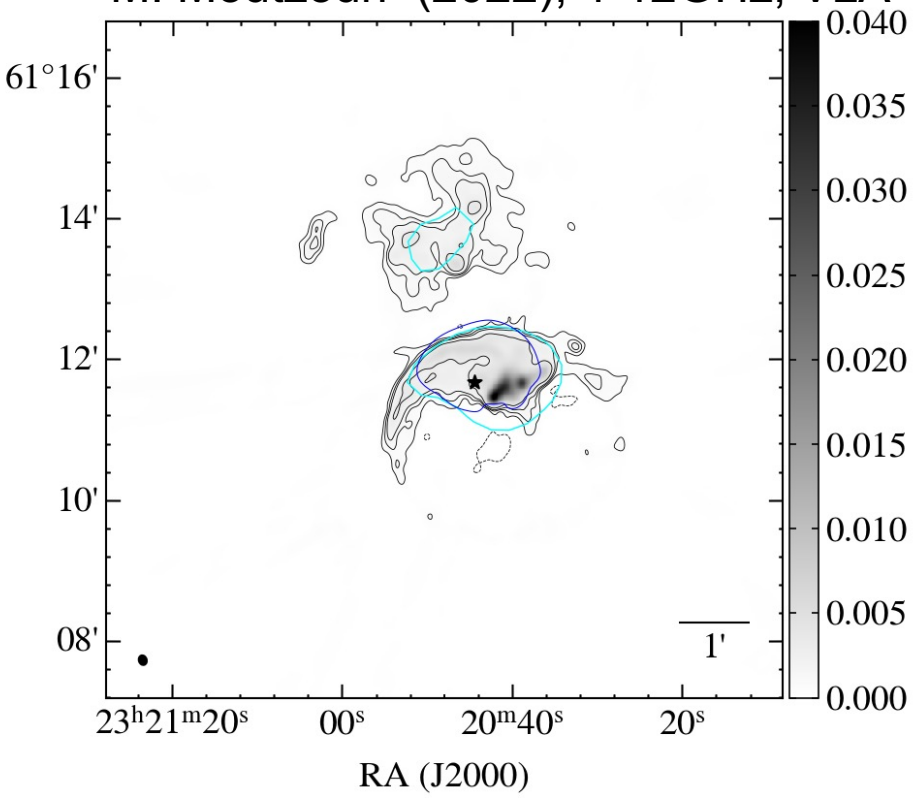


Bow shock of **BD+43 3654**: 60-70 $M_\odot$ supergiant star, ~40,000 K, moving with ~40? km/s in ISM with $n \sim 15\ \mathrm{cm}^{-3}$, in Cygnus region.

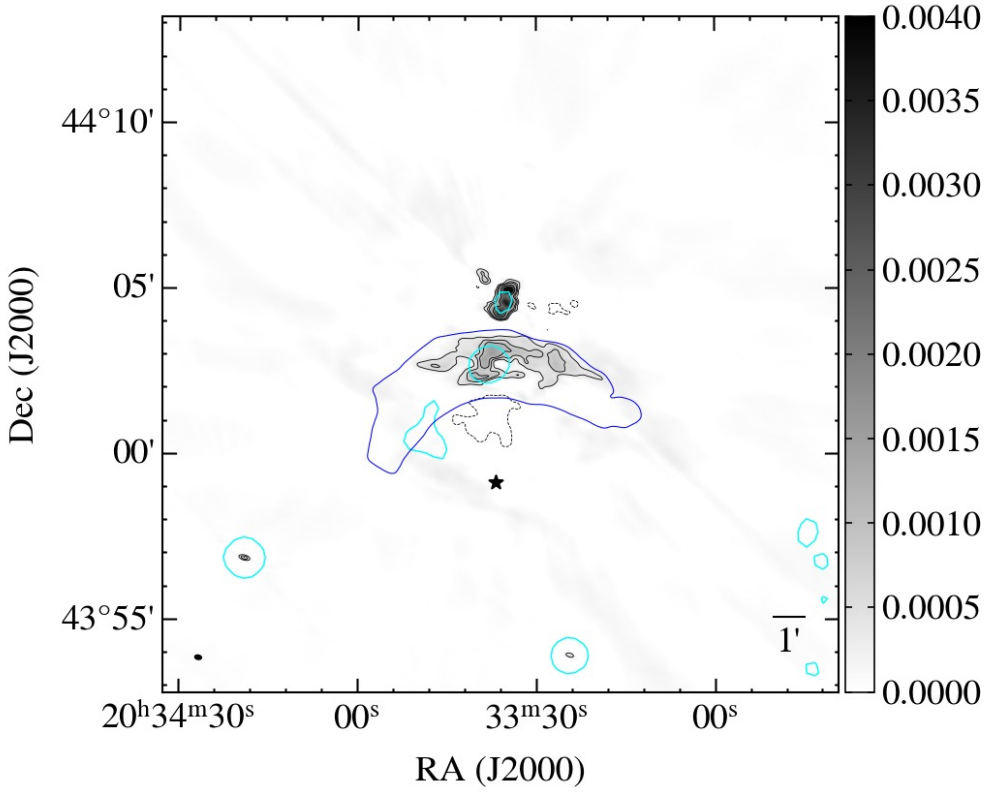
Spitzer Space Telescope IR images from Toala et al. (2016)

Radio observations of bow shocks

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



Detect synchrotron emission based on radio spectral index



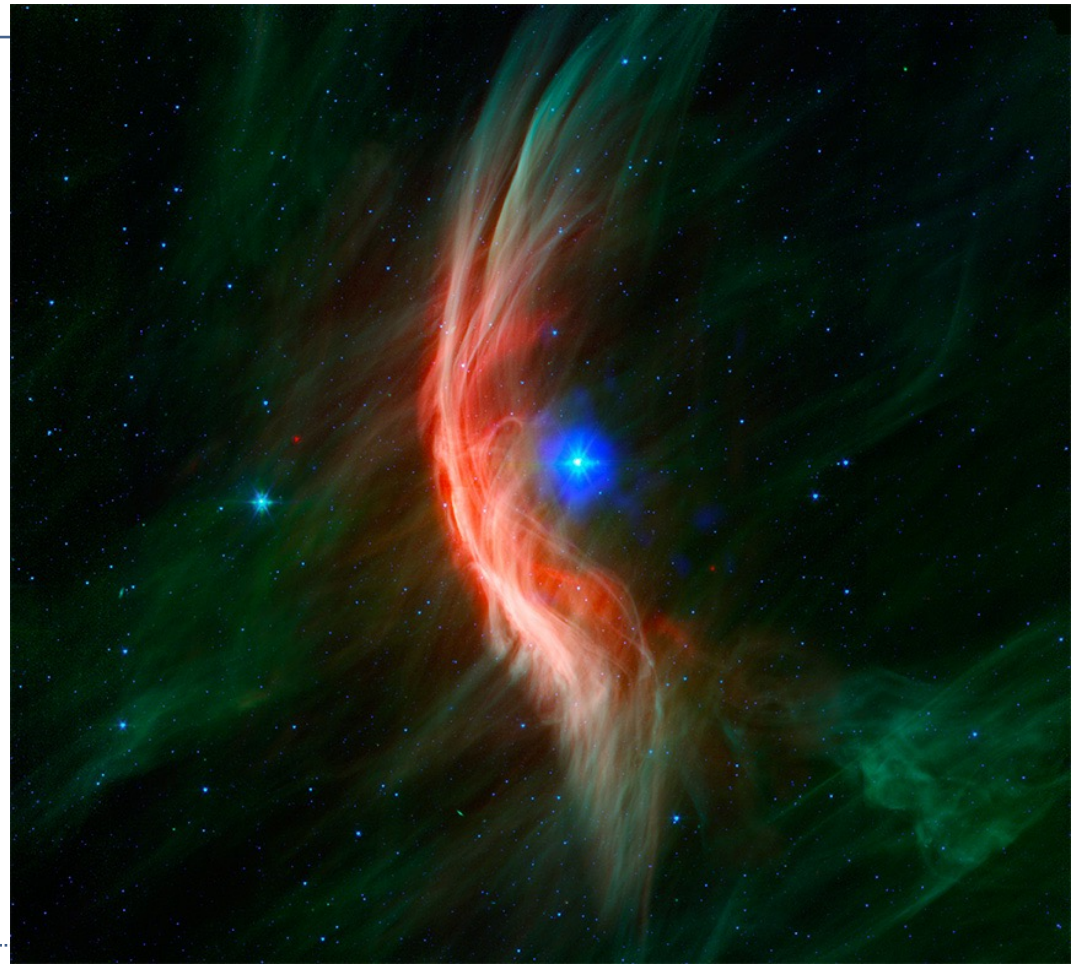
Moutzouri, Mackey, et al. (2022,A&A,663,A80)
https://arxiv.org/abs/2204.11913

No detection at X-ray or Gamma-rays. Would not expect a detection of leptonic emission with current instruments

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

Non-thermal radiation?

- Radio synchrotron emission detected from bow shocks (e.g. Benaglia+,2010,2021)
- Only upper limits at X-ray (Toala+,2017), GeV (Schulz+,2014), TeV (H.E.S.S. Collaboration, 2018)
- Multi-zone model (Del Palacio+,2018) shows that HE/VHE emission difficult to detect even with next-generation facilities.
- Radio suveys with ASKAP, MeerKAT show very promising results (e.g. van den Eijnden+,2024).
- Wolf-Rayet bubbles have no NTE, so far (except WR102 – Prajapati+,2019)

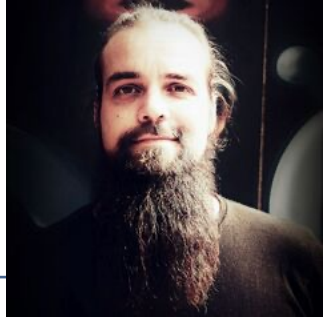


Supernovae and their remnants dominate energy input to ISM and CR production, for all but the most massive stars (e.g. Drury, 2012).

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

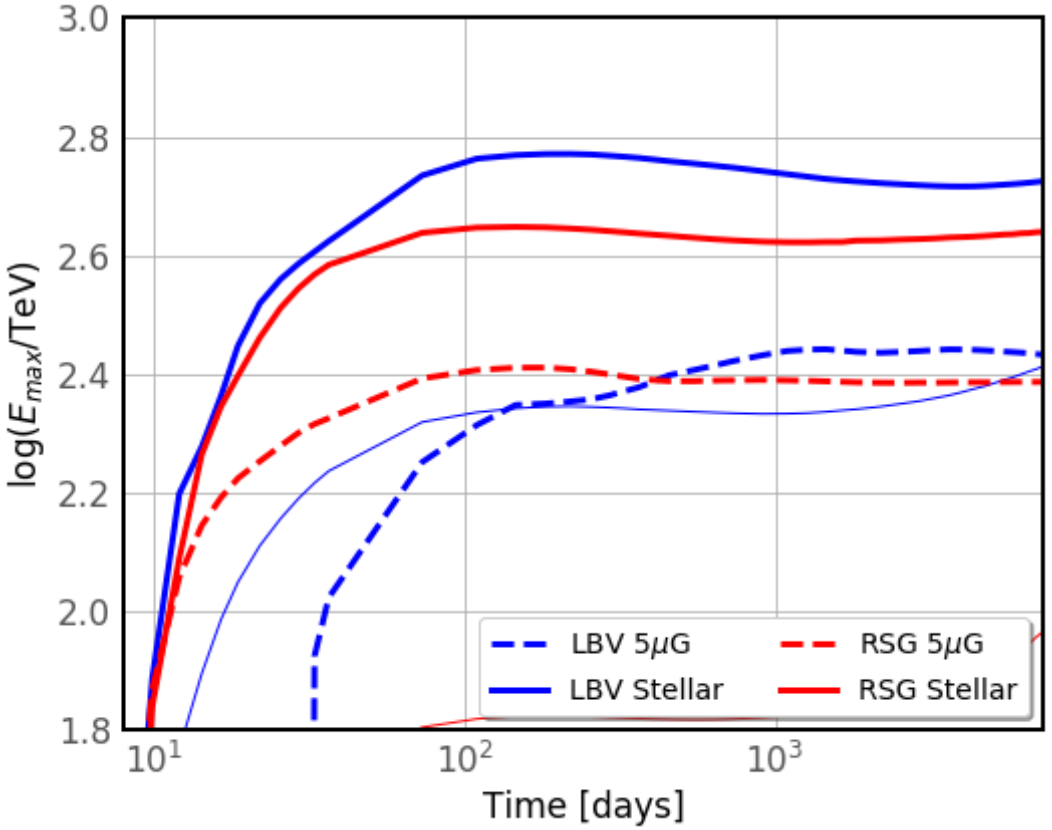
Image credit: X-ray: NASA/CXC/Dublin Inst. Advanced Studies/S. Green et al.; Infrared: NASA/JPL/Spitzer
https://www.nasa.gov/mission_pages/chandra/images/embracing-a-rejected-star.html

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 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)

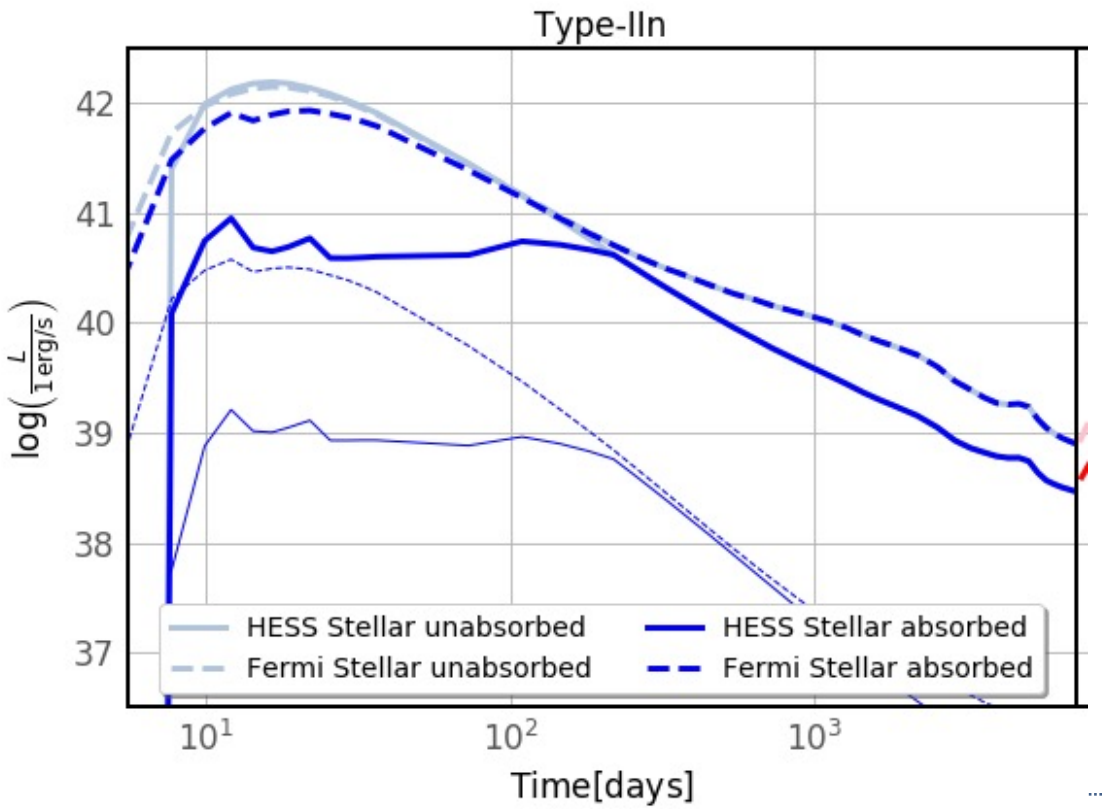


DIAS
Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

Core-collapse Supernovae

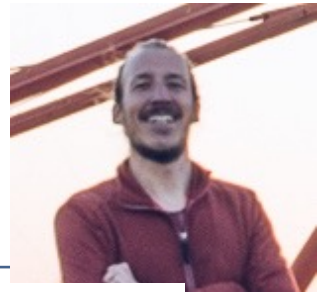
- Suggestions that early months/years of SN evolution provide most efficient acceleration to VHE (Murase+,2011; Bell+,2013)
- High-density environment also conducive to efficient acceleration (recent papers: Marcowith+, Cristofari+)
- We used RATPaC code for coupling hydrodynamics and DSA, transport 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)



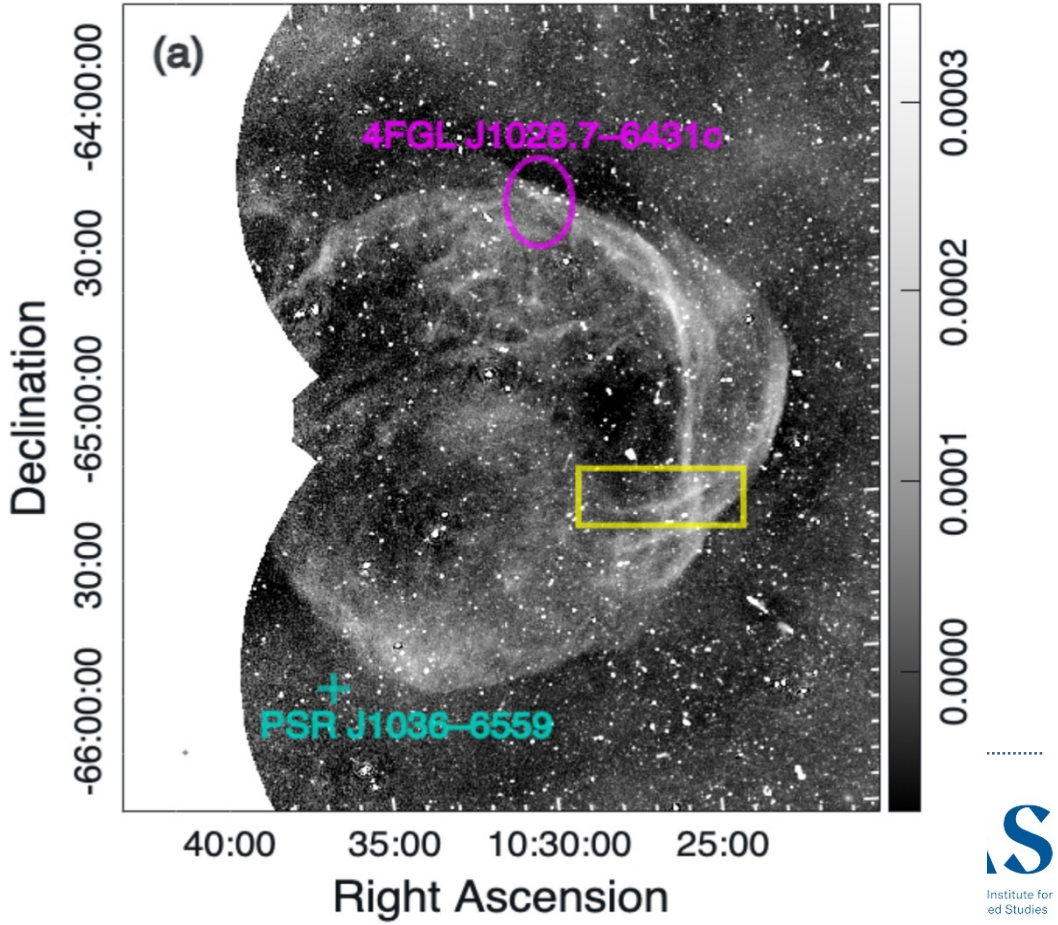
DIAS
Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

Supernova Remnants



- Newly discovered SNR G288.8–6.3 (Filipovic+,2023)
  - Detected with ASKAP EMU survey
  - Far from Galactic Plane, low surface brightness
  - Quite old ($\sim 10^4$ yr), still emitting synchrotron
- Searched for γ-rays with Fermi-LAT
  - Detected an extended source →
  - Similar source size to radio remnant
  - Soft γ-ray spectrum indicates particle escape
- Targeted searches informed by new radio surveys can give new γ-ray discoveries

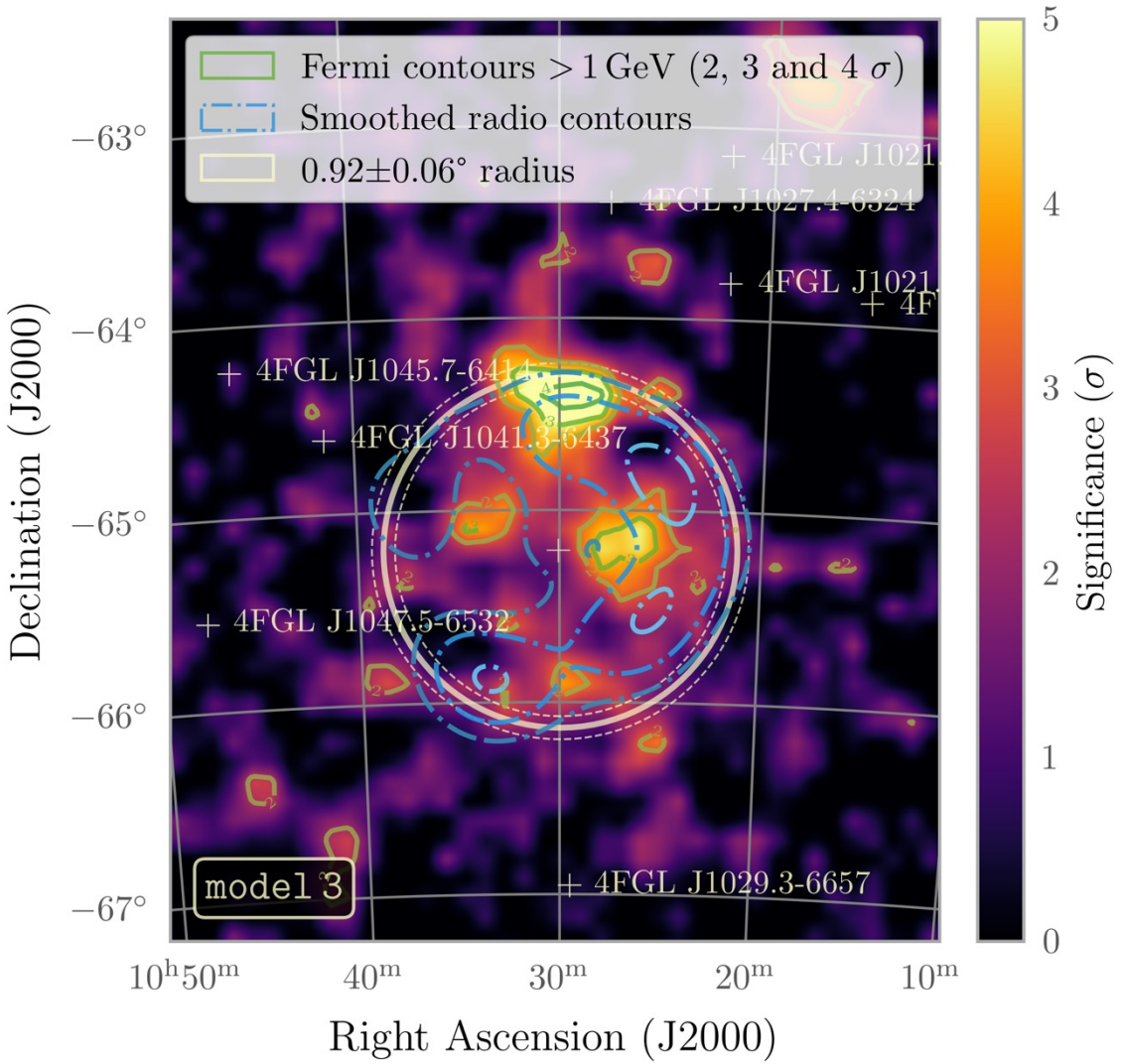
SNR G288.8-6.3 (Filipovic+,2023)



Burger-Scheidlin et al. (2024, A&A, 684, A150)
https://arxiv.org/abs/2310.14431

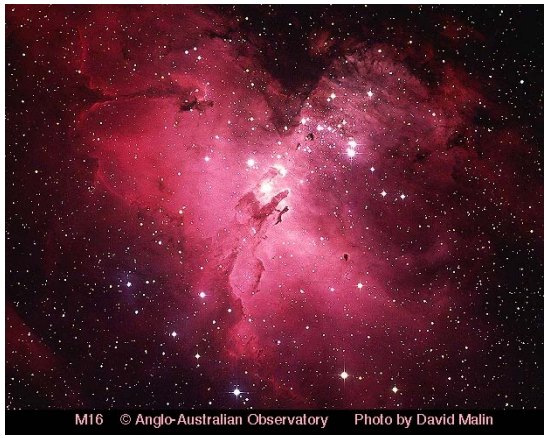
Supernova Remnants

- Newly discovered SNR G288.8–6.3 (Filipovic+,2023)
  - Detected with ASKAP EMU survey
  - Far from Galactic Plane, low surface brightness
  - Quite old ($\sim 10^4$ yr), still emitting synchrotron
- Searched for γ-rays with Fermi-LAT
  - Detected an extended source →
  - Similar source size to radio remnant
  - Soft γ-ray spectrum indicates particle escape
- Targeted searches informed by new radio surveys can give new γ-ray discoveries

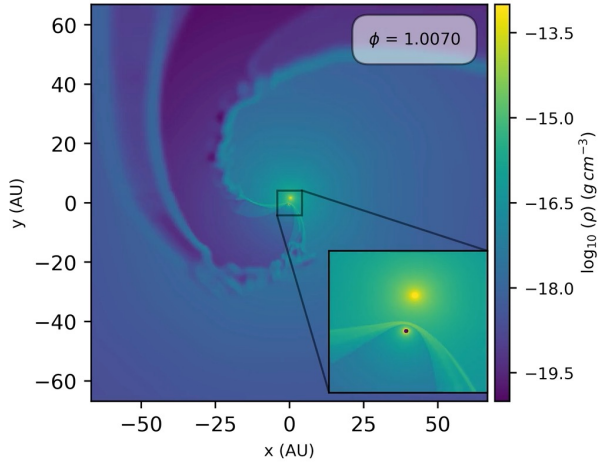


Burger-Scheidlin et al. (2024, A&A, 684, A150)
https://arxiv.org/abs/2310.14431

Binary Systems

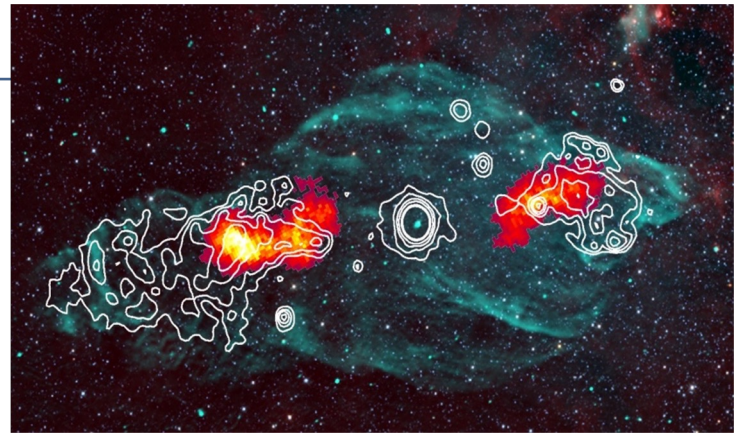


- Almost all massive stars born in binary/triple systems
- Live in their star cluster/association
- Can be ejected dynamically

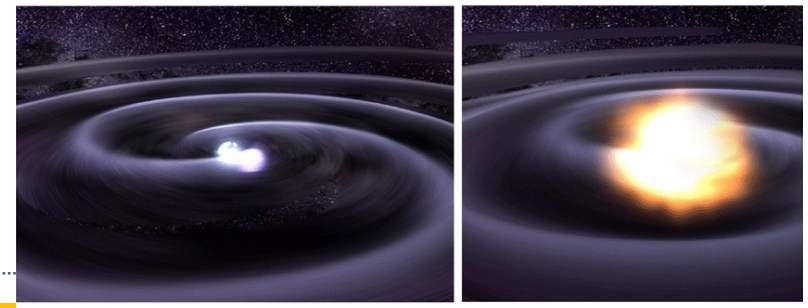


- Wind-wind interaction has efficient particle acceleration (e.g. Reimer+2006)
- Detect NTE radio, X-ray, GeV, TeV from some systems

- When one star dies, HMXB may be produced, e.g. microquasar



- Both stars explode, can result in binary BH system



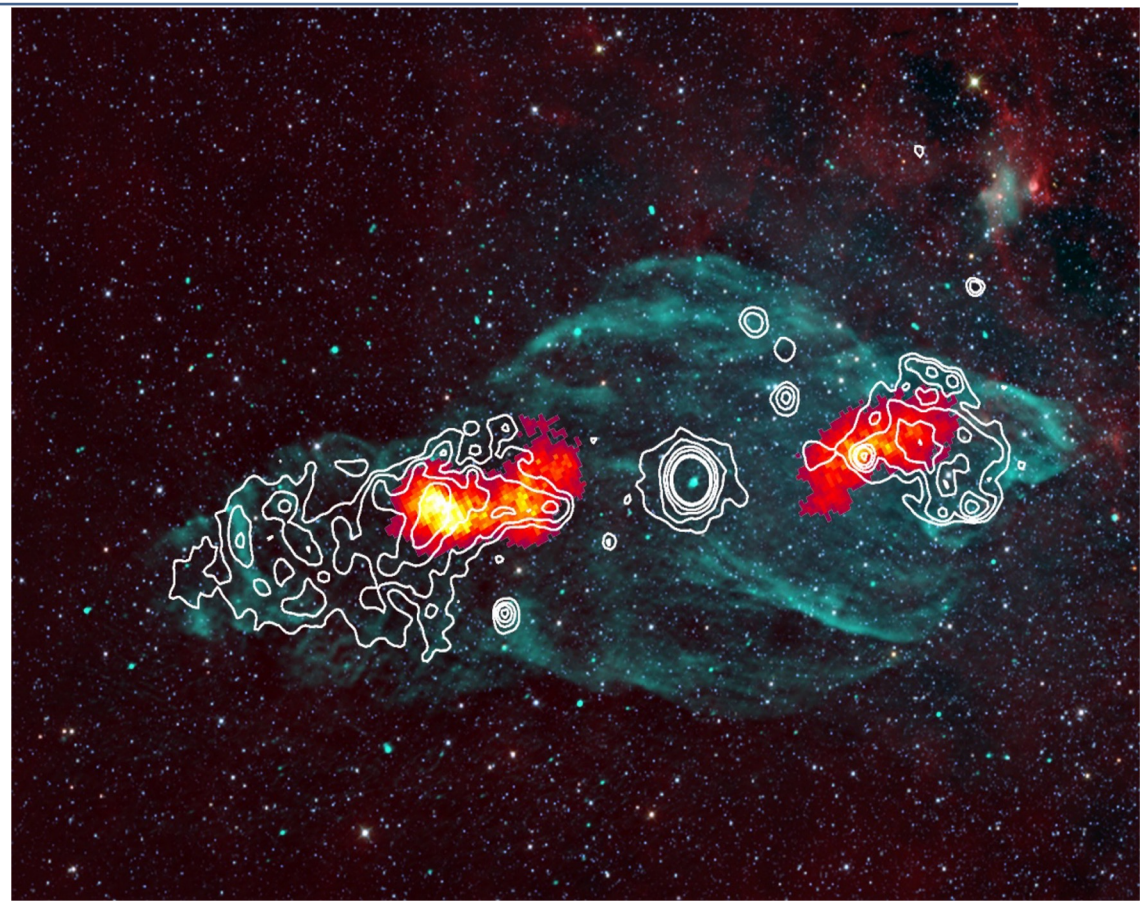
Bright non-thermal emitters from main-sequence to stellar death.
Compact-object binaries extremely efficient accelerators.

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

Microquasar SS433

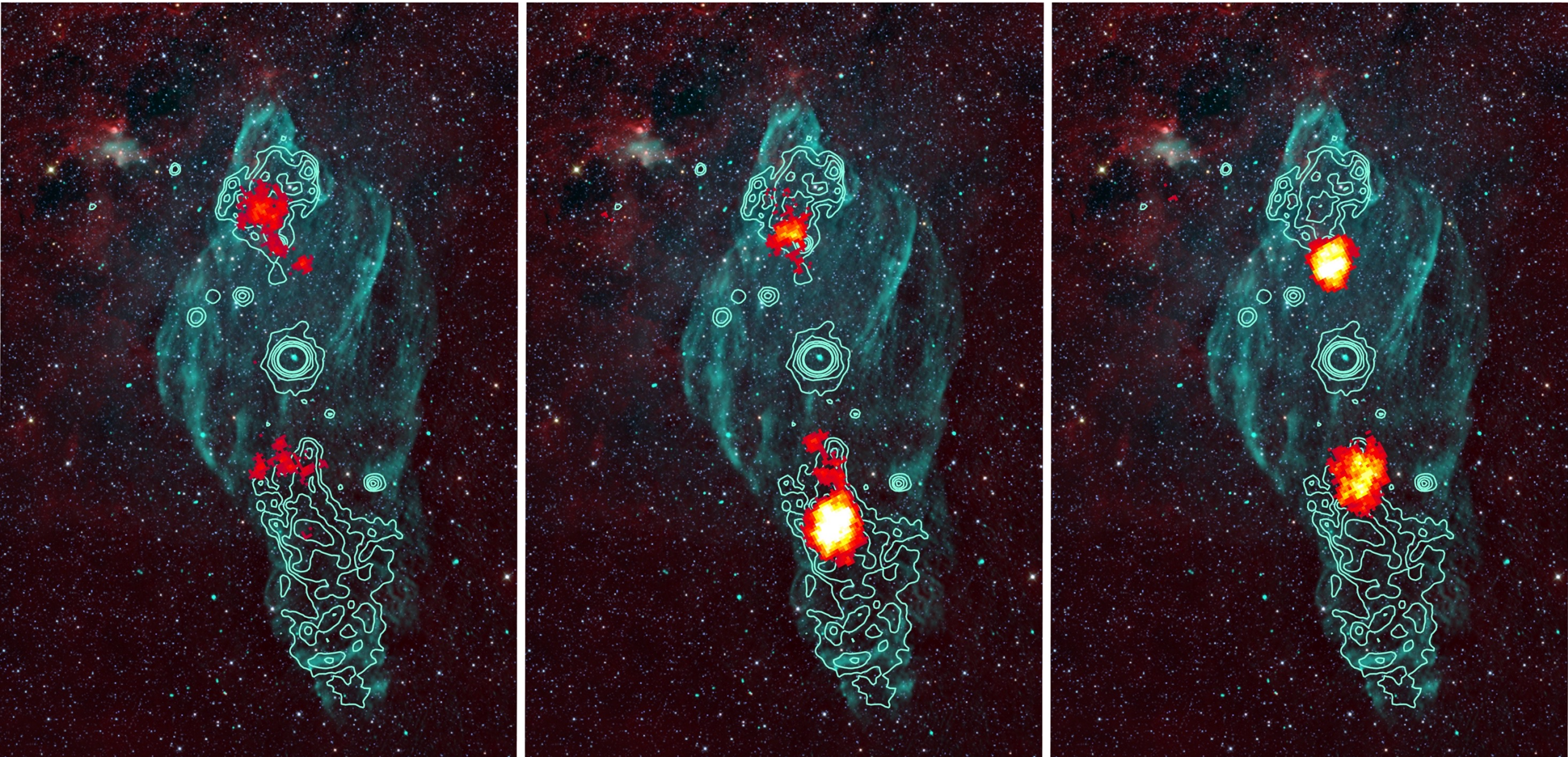
HESS Collaboration (2024, Science, 383, 402)

- HMXB with massive star + black hole
- Roche-lobe overflow → rapid accretion → disk + precessing jets (timescale $10^3 - 10^4$ yr)
- Large-scale emission from elongated SNR
- H.E.S.S. 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



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

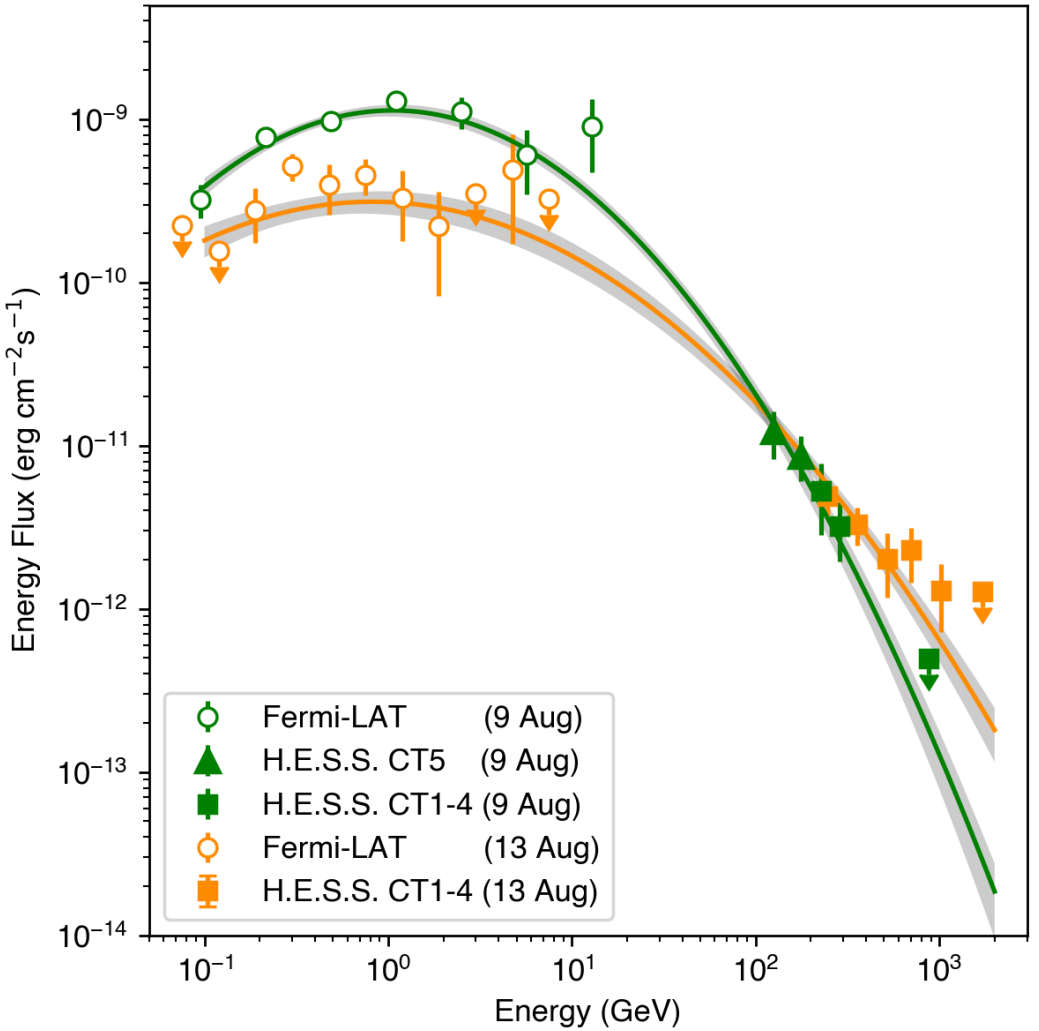
First observation of energy-dependent morphology in TeV emission of a jet!



Recent H.E.S.S. Results

- Binaries also have eruptions (e.g. novae) and variable emission across orbit.
- H.E.S.S. Collaboration (2024) detected time-dependent particle acceleration in nova RS Oph
- H.E.S.S. Collaboration (2024) studied 2021 periastron passage of PSR B1259/LS 2883
  - X-ray – TeV correlation in light-curve (GeV uncorrelated)
- η Car 2020 periastron passage observed with H.E.S.S. (Steinmassl+,2023,ICRC) paper in prep.
  - Detect sub-TeV gamma-rays consistent with extension of FERMI-LAT spectrum.
- Refer to Olaf Reimer's talk in Plenary Session on Tuesday morning for further details.

HESS Collaboration (2022, Science, 376, 77)



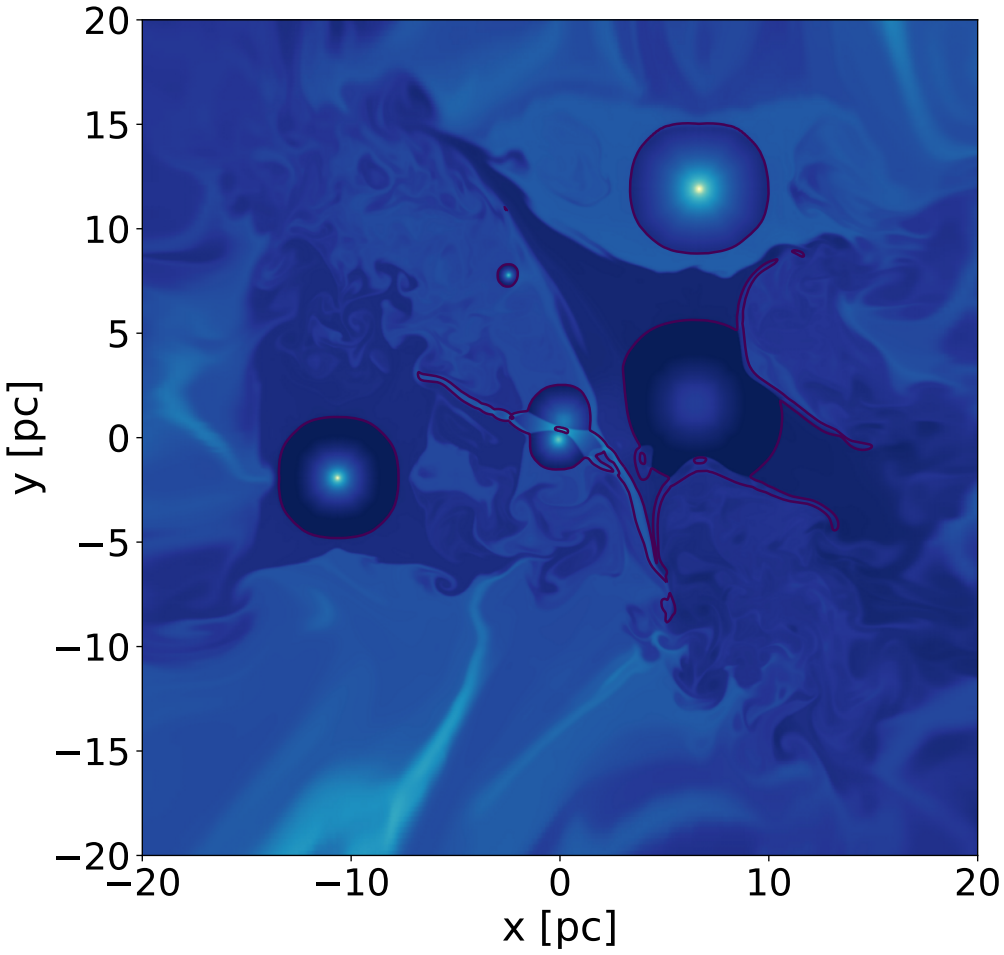
Bright non-thermal emitters from main-sequence to stellar death.
Compact-object binaries extremely efficient accelerators.

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

Star Clusters

- Winds from single and binary stars collide, potentially very efficient accelerators (e.g. Parizot+,2004; Morlino+,2021; Vieu+,2023)
- H.E.S.S. detections of Westerlund 1 (H.E.S.S. Coll, 2022) and R136 (H.E.S.S. Coll, 2024)
- Relative contributions of winds vs. supernovae not so clear because SN dominate the energy budget.
- Cygnus, Wd1, R136 regions all contain older populations → many supernovae have occurred.
- If winds are important, find YMCs before 1st SN:
  - Peron+(2024) found these at GeV energies with Fermi-LAT (talk this session)
  - Recent work: Celli+,2024; Mitchell+,2024)

From Vieu+(2024): 3D hdyro simulations of Cygnus OB2, complex wind/shock structure.



Young Massive Clusters are an important class of gamma-ray emitting sources. Combination of simulation, modelling, and data enabling rapid progress.

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

Westerlund 1

- Richest Galactic population of WR and RSG/BSG stars
  - Uncertain distance and age (3-8 Myr)
- Muno+(2006) estimate up to 100 SN occurred already in Wd1, by extrapolating the IMF.
- Frequency of SN approx. 1 per 10^4 yr
- Expect some HMXB activity, possible microquasar phases.
- Spectacular ring of TeV emission around Wd1, but not clear what powered it
  - Cluster wind – but where is the superbubble?
  - Hadronic emission – but where is the gas?

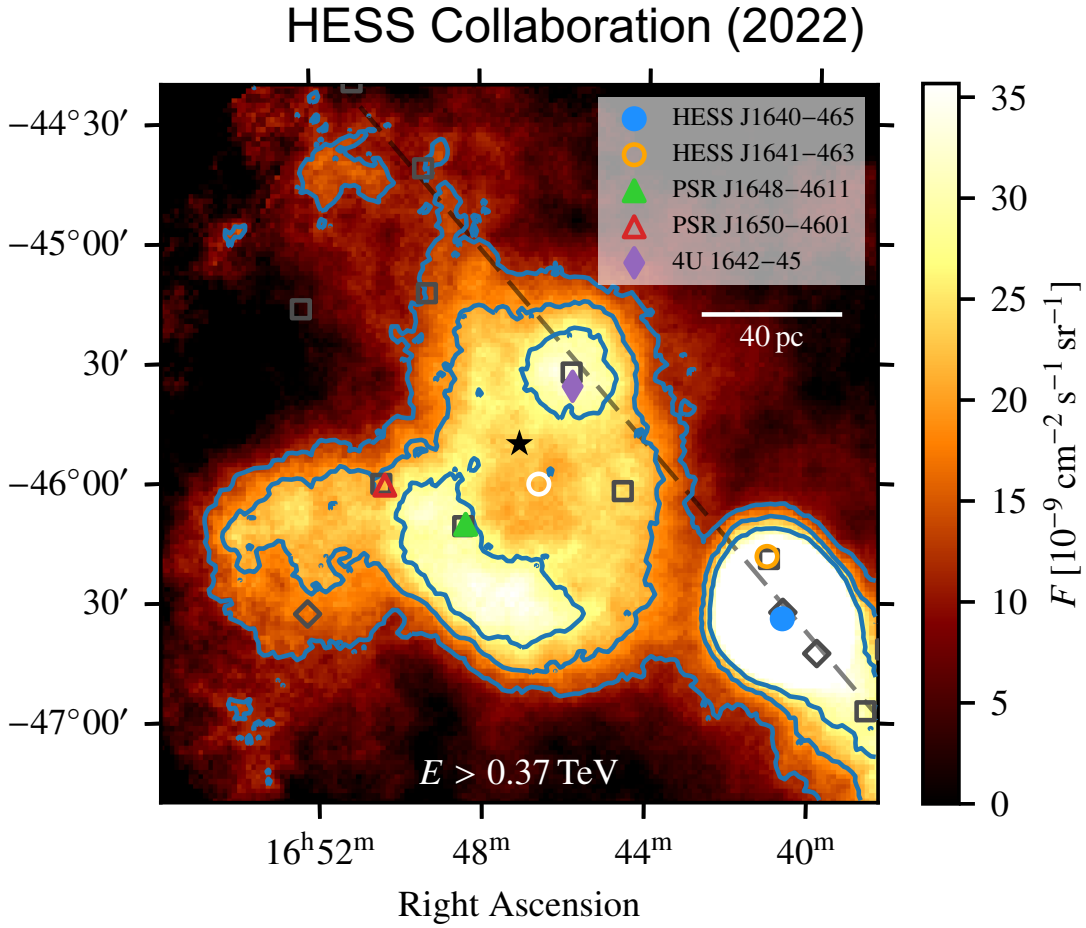
https://esahubble.org/images/potw1710a/

HST image of Wd1 core showing bright WR, RSG and main-sequence stars (**Credit:**ESA/Hubble & NASA)

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

Westerlund 1

- Richest Galactic population of WR and RSG/BSG stars
  - Uncertain distance and age (3-8 Myr)
- Muno+(2006) estimate up to 100 SN occurred already in Wd1, by extrapolating the IMF.
- Frequency of SN approx. 1 per 10^4 yr
- Expect some HMXB activity, possible microquasar phases.
- Spectacular ring of TeV emission around Wd1, but not clear what powered it
  - Cluster wind – but where is the superbubble?
  - Hadronic emission – but where is the gas?



H.E.S.S. Collaboration (2022,A&A): TeV emission from region around Wd1

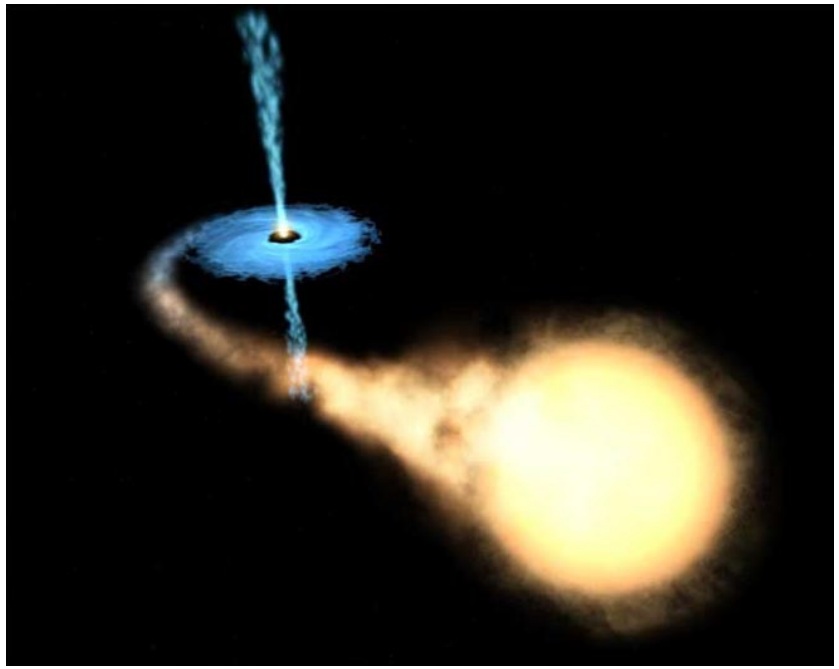
DIAS
Institiúid Ard-Léinn Bhaile Átha Cliath | Dublin Institute for Advanced Studies

Summary and Outlook

- Nebulae around single stars are rather faint non-thermal sources
- Supernovae dominate the total energy budget by far
- Binaries are bright non-thermal emitters (radio to gamma) throughout their lives and deaths
  - Compact-object binaries (HMXB, GRLB) are the most efficient accelerators and emitters
  - Short-lived microquasar phase extremely luminous, but rare
- Star clusters have emerged as important class of bright, hard-spectrum Galactic sources
  - At least some are bright because of acceleration in colliding stellar winds
  - Expect rapid progress in this field in the next few years.

DIAS-CDY Workshop on Gamma-ray Loud Binaries
https://cdy-institute.ie/dias-cdy-workshop/

- 7 – 10 October 2024
  Dublin Institute for Advanced Studies, Ireland
- In-person registration now closed, but virtual participation available for €50 – see link below.
- Scientific topics:
  - gamma-ray observations, from GeV to PeV energies of gamma-ray loud binaries
  - Microquasars
  - Novae
  - colliding wind binaries
  - Theoretical and phenomenological modelling



Zoom participation: https://dias-cdy-workshop.eventbrite.ie/

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