Radio emission from stellar bowshocks in massive runaway stars

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Stellar winds

Massive stars launch **powerful, hypersonic winds**. The study of interactions of stellar winds and shock physics include:

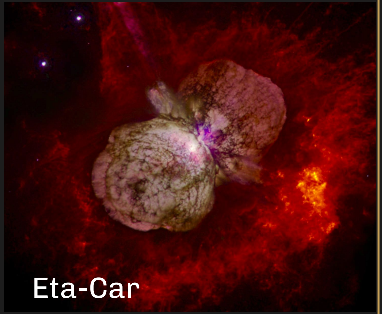
- stellar bubbles
- **stellar bow shocks**
- colliding-wind binaries
- microquasars

$$\left\{ \begin{array}{l} \dot{M} \sim 10^{-6}\,\mathrm{M_\odot\ yr^{-1}} \\ v_\infty \sim 1000\,\mathrm{km\,s^{-1}} \end{array} \right\}$$

$$\Downarrow$$

$$\left\{ \begin{array}{l} P_{\mathrm{kin}} \sim 10^{36}\,\mathrm{erg\,s^{-1}} \\ E \sim 10^{50}\,\mathrm{erg} \end{array} \right\}$$

Zeta Ophiuchi



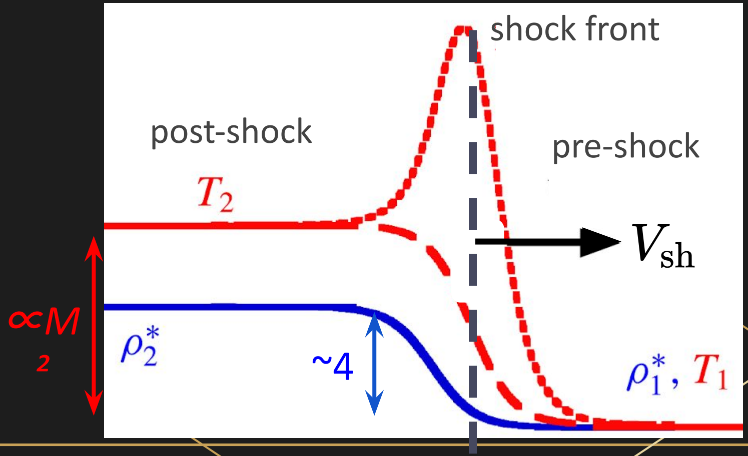
Eta-Car

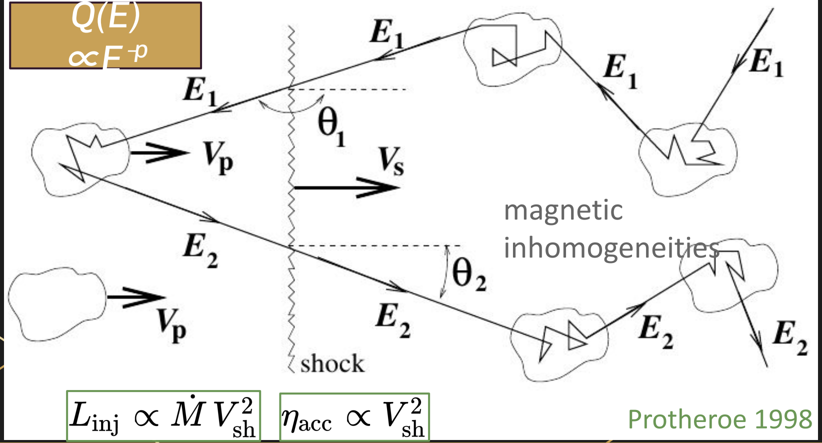
Shocks

A perturbation that propagates with a supersonic speed generates a shock wave. The bulk kinetic energy of the fluid is converted into internal energy in the shocks.

The shock compresses and heats the gas

Diffusive (shock) acceleration of particles





$Q(E) \propto E^{-p}$

$L_{\rm inj} \propto \dot{M}\, V_{\rm sh}^2$

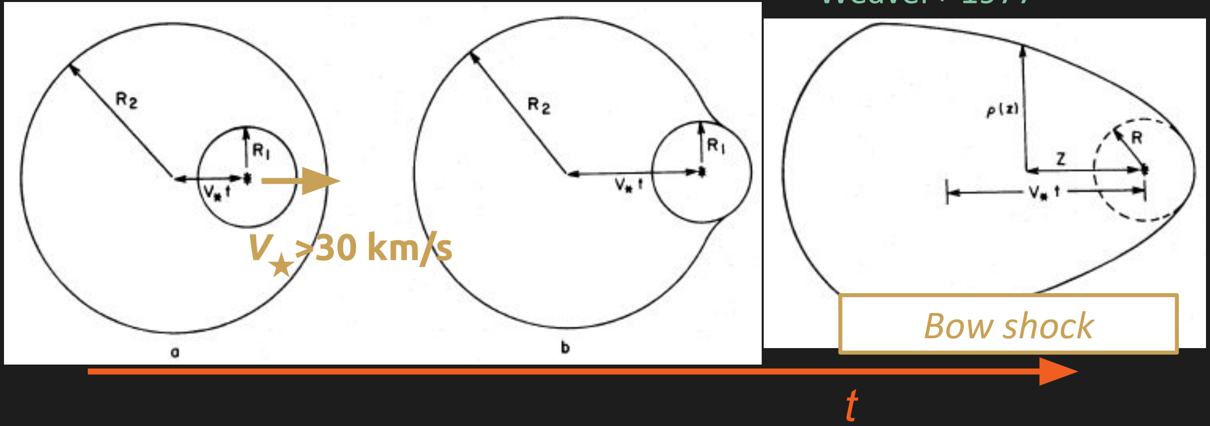
$\eta_{\rm acc} \propto V_{\rm sh}^2$

Protheroe 1998

Stellar bowshocks

Spherical wind + supersonic stellar motion (w.r.t. its environment) = stellar bow shock

Weaver+ 1977



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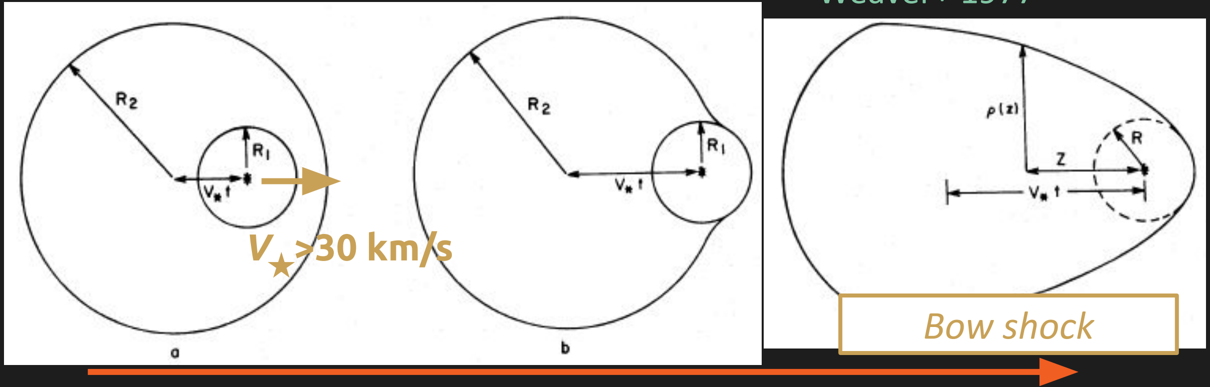
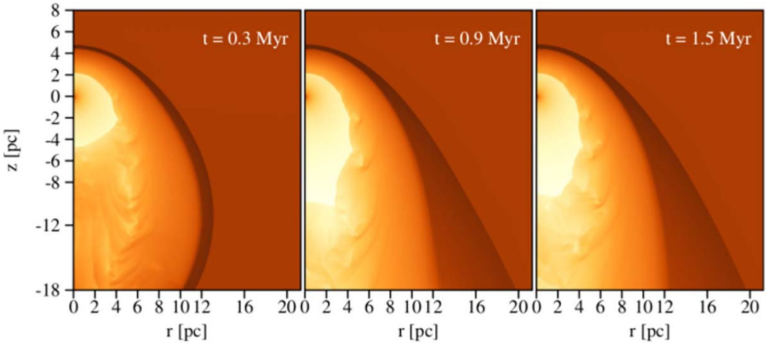


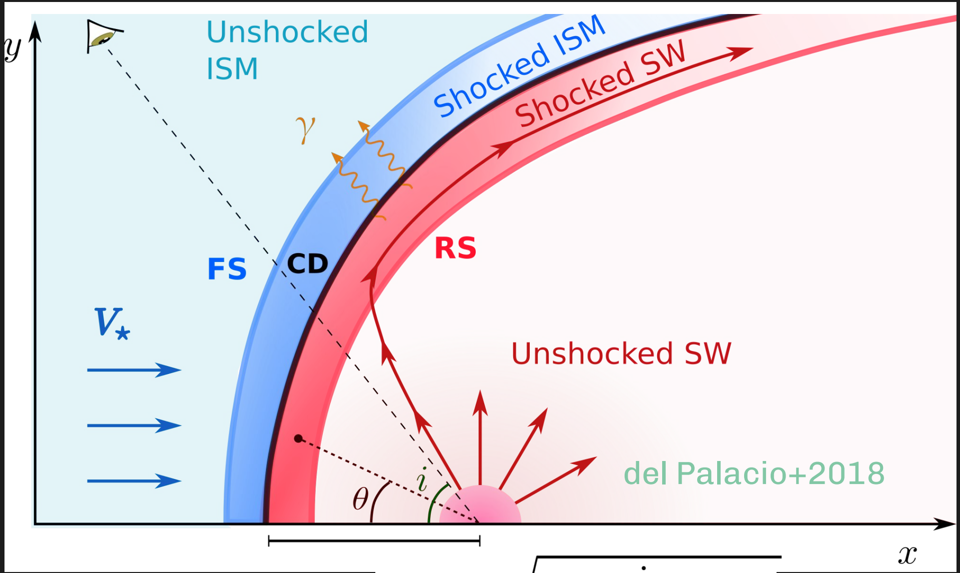


del Valle+ 2018

Stellar bow shocks

- **FS** = slow, dense (f-f, dust, lines)
- **RS** = fast (non-thermal emission, X-rays?)

This structure is embedded within an HII region.



del Palacio+2018

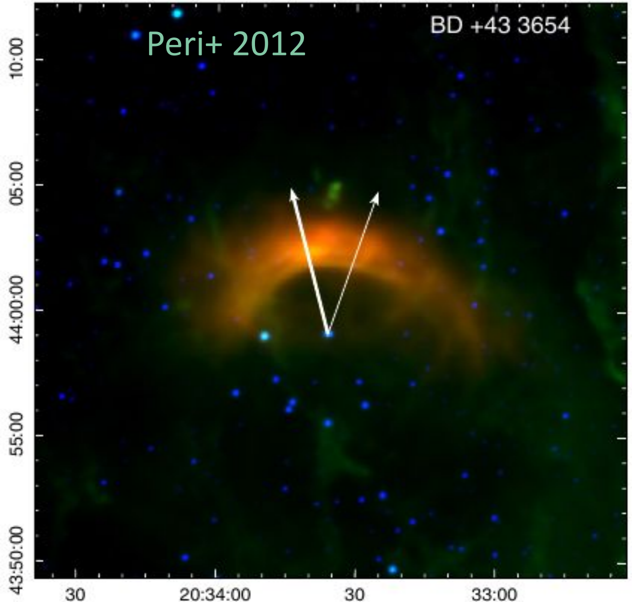
$$R_0 = \sqrt{\frac{\dot{M} v_\infty}{4\pi \rho_{\mathrm{ISM}} \left(V_\star^2 + c_{\mathrm{s}}^2\right)}}$$

Stellar bow shocks

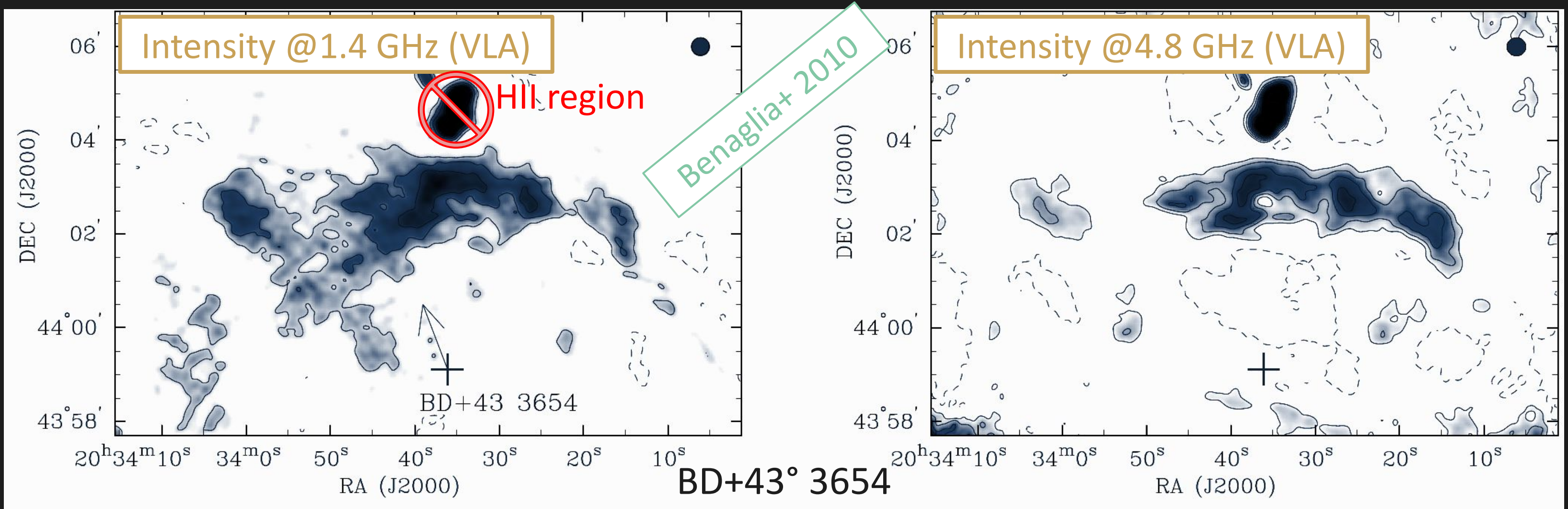
Runaway stars represent a significant fraction (~10-20%) of massive stars of spectral type O (Maíz Apellániz+ 2018).

The main tracer of bow shocks is the IR emission from heated dust (also optical lines, e.g. H_α):

Peri+ 2012 (2015) ⟶ Catalogue of 28 (45) objects.
Kobulnicky+ 2017 ⟶ Catalogue of 709 objects.



Observations

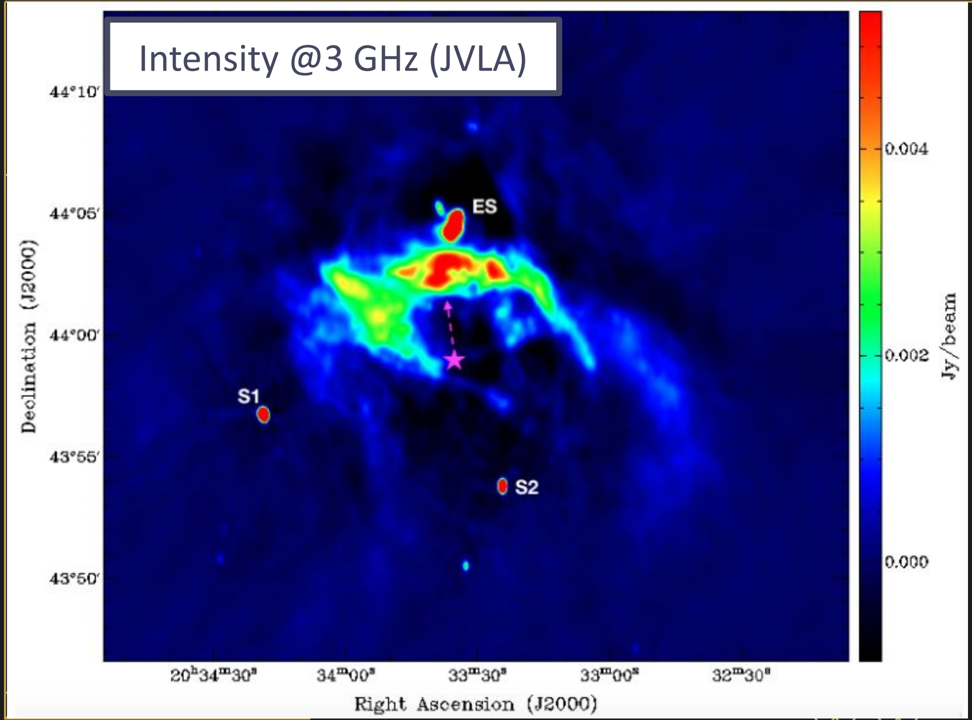


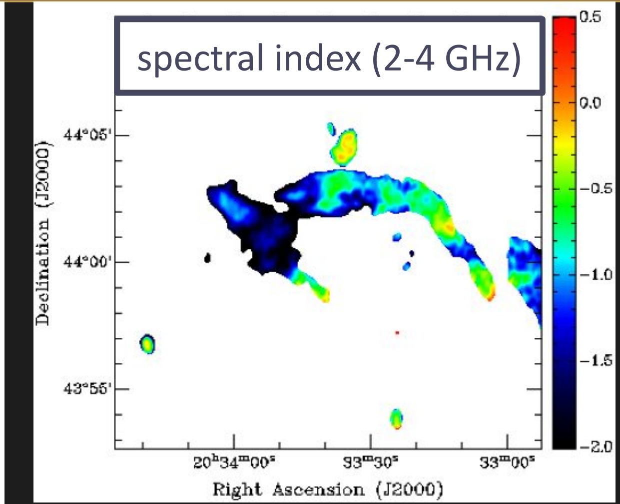
BD+43° 3654

The first stellar bowshock with detected **non-thermal** radio emission: <α> = -0.5.

Issue: missing flux?

Observations


Intensity @3 GHz (JVLA)

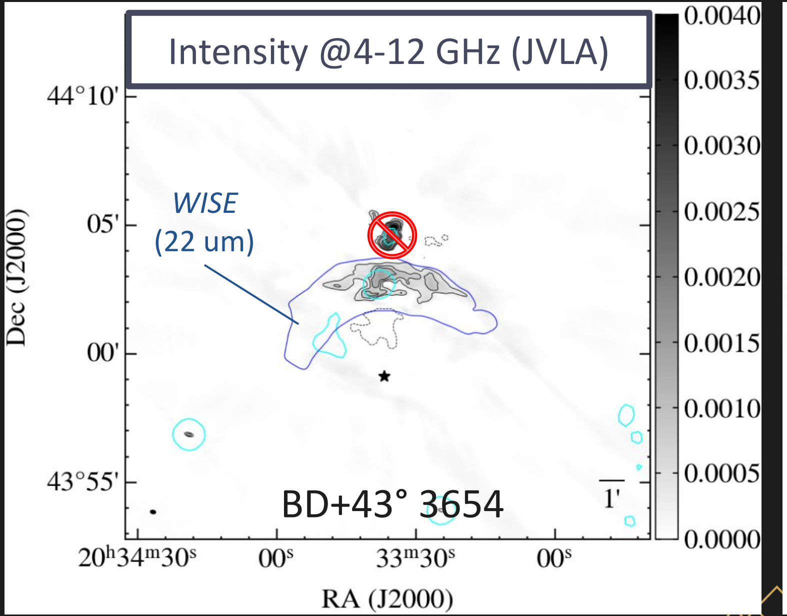

spectral index (2-4 GHz)

Benaglia, del Palacio+ 2021

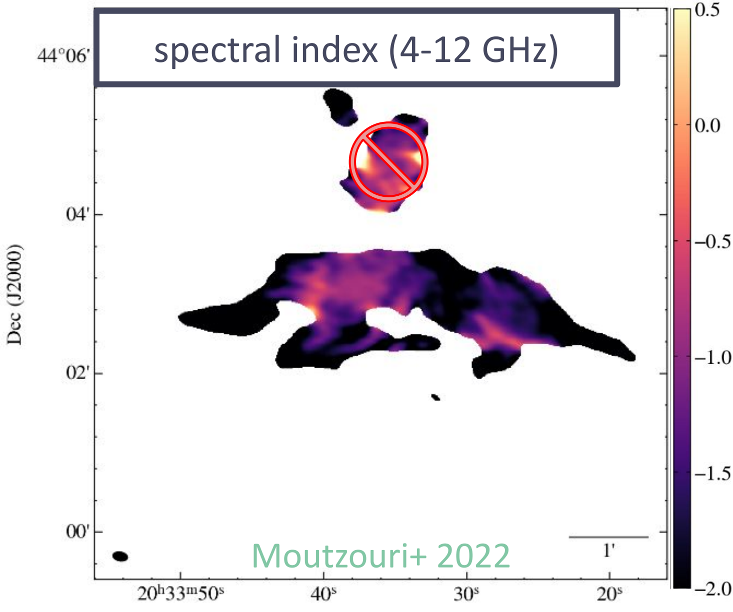
- Significant diffuse and soft (α<-1) emission, previously undetected.
- Lack of polarisation in the synchrotron emission (< 0.5%)

Observations

More observations of BD+43° 3654 (still missing flux)



Intensity @4-12 GHz (JVLA)

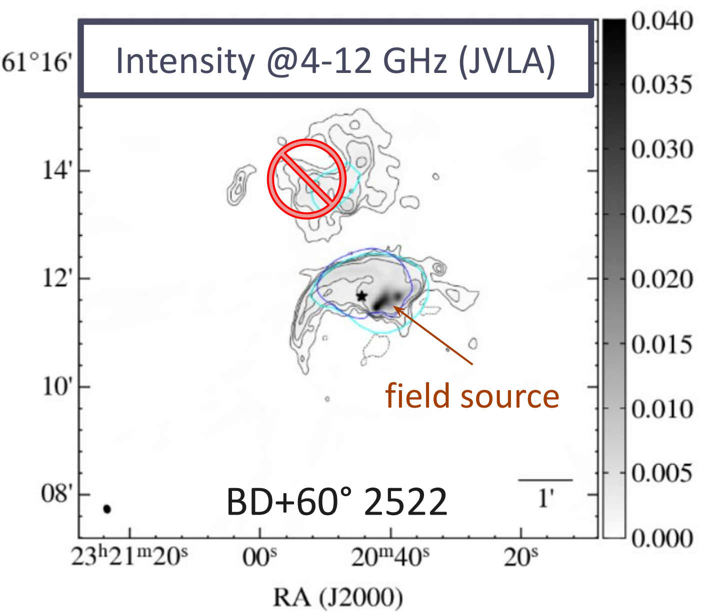


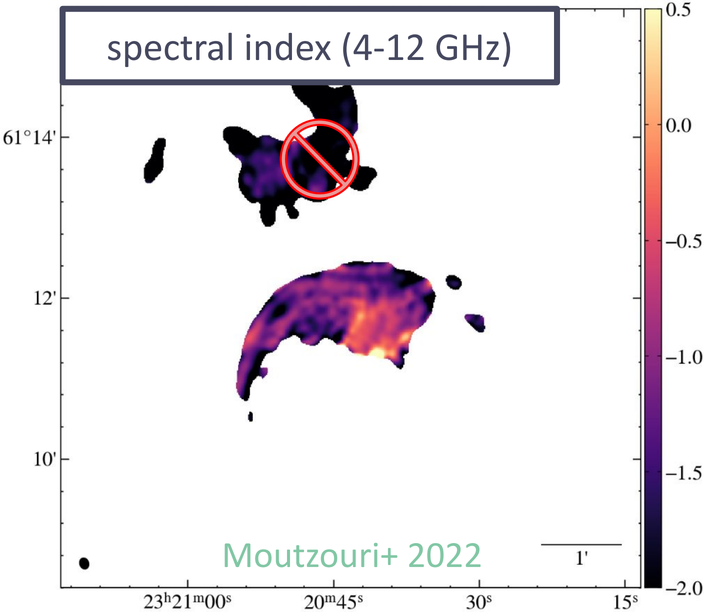
spectral index (4-12 GHz)

Moutzouri+ 2022

Observations

2nd non-thermal bowshock detected

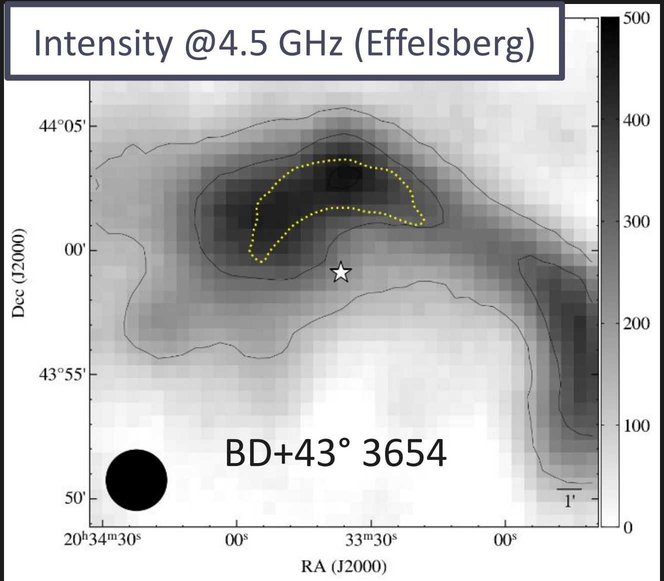

Intensity @4-12 GHz (JVLA)

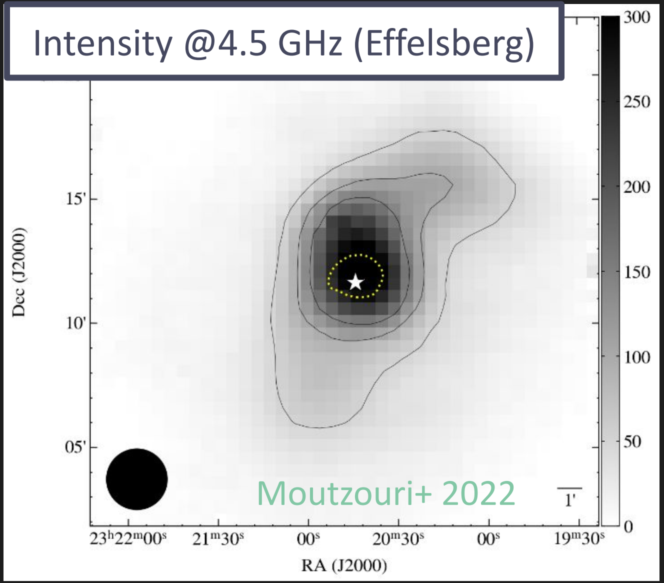

spectral index (4-12 GHz)

Moutzouri+ 2022

Observations

Single-dish observations with Effelsberg. Issue: too much contamination!

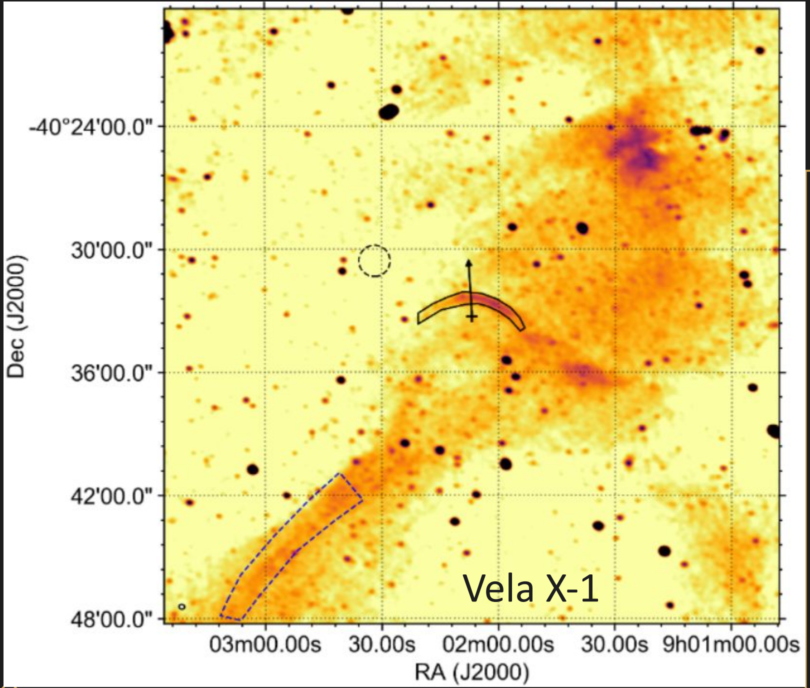




Observations

MeerKAT detection of the bow shock of Vela X-1 at 1.4 GHz (Van den Eijnden+ 2021)

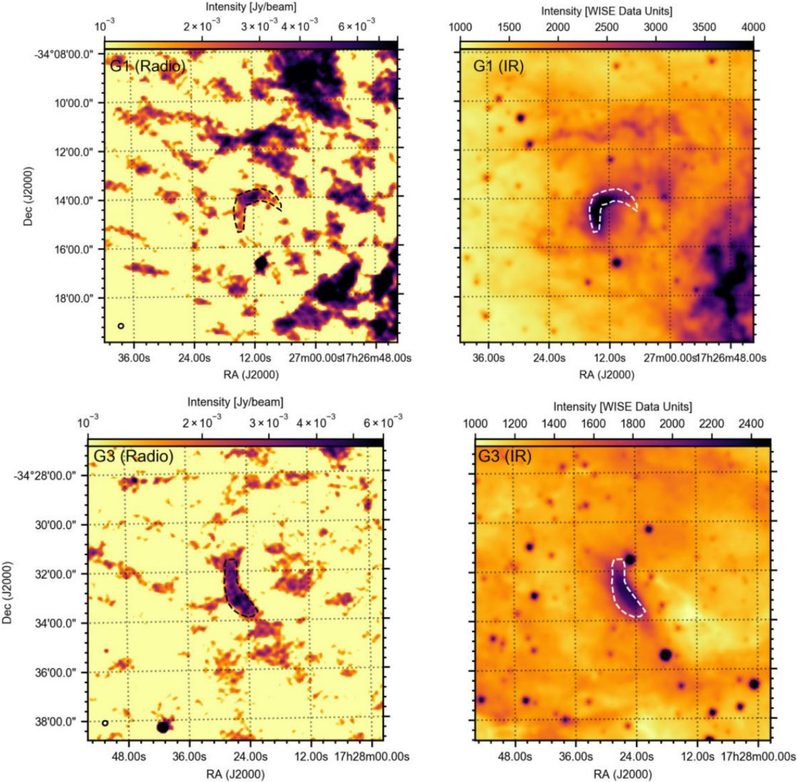
Low S/N, no spectral information
→ Not clear if it is synchrotron emission



Observations

Systematic search for radio counterparts of stellar bow shocks in the RACS survey (ASKAP @887 MHz; Van den Eijnden+ 2022).

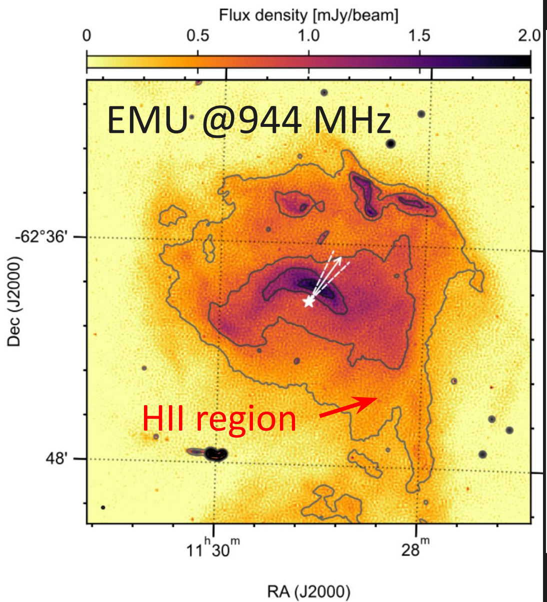
Low S/N, no spectral information
→ Not clear if it is synchrotron emission

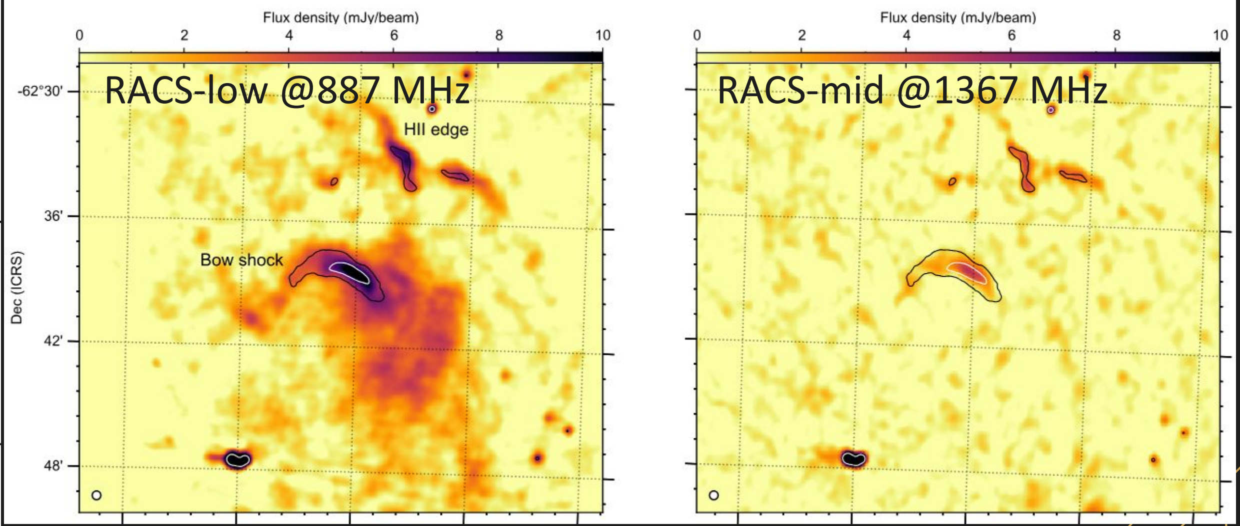


Observations

Van den Eijnden+ 2024: detection of LS 2355 with ASKAP surveys.

Issue: Unreliable spectral indices ($\alpha < -2 \rightarrow$ missing flux, need more short baselines)





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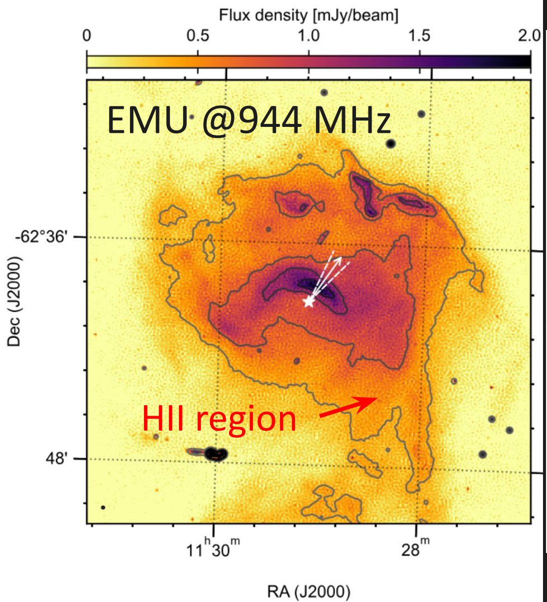
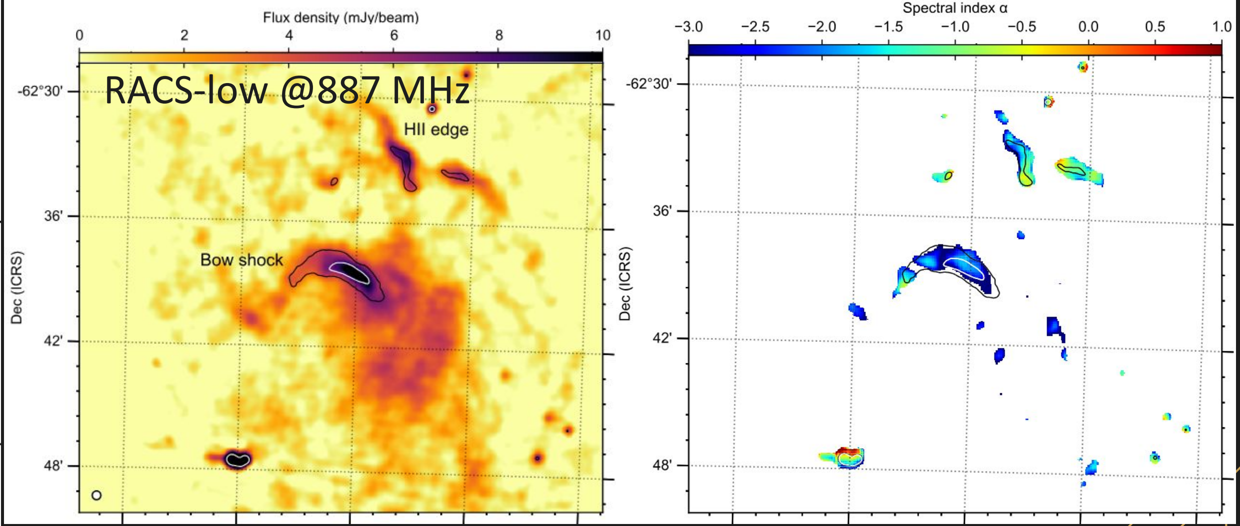


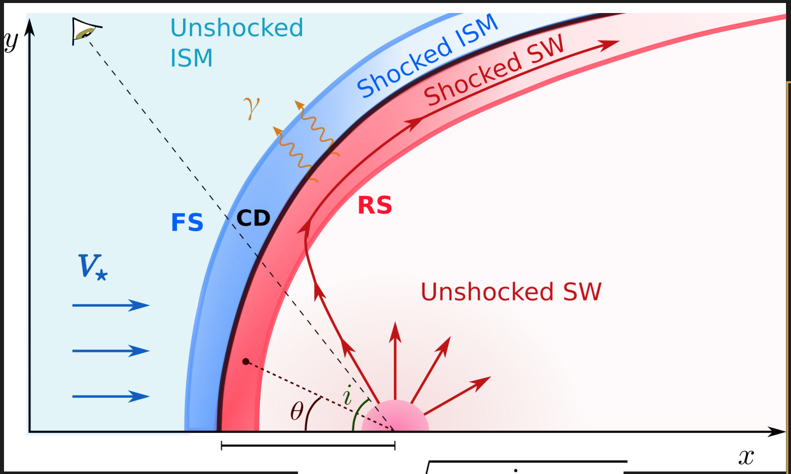


Non-thermal emission model

1. Bowshock = axisymmetric shell
2. **RS** adiabatic and laminar flow
3. NT particles accelerated in the RS → NT emission (sync., IC, p-p)
4. Free parameters: *B*-field intensity and fraction of energy injected in relativistic particles (f_{NT}); projection angle in the sky (i)
5. *B* in the bow shock → *B* in stellar surface:

$$B(\theta) = \left[\zeta_B\, 8\pi P(\theta)\right]^{1/2} \rightarrow B_\star = 0.25\, B(\theta)\,(R(\theta)/R_\star)\,(v_\infty/v_{\rm rot})$$

del Palacio+2018

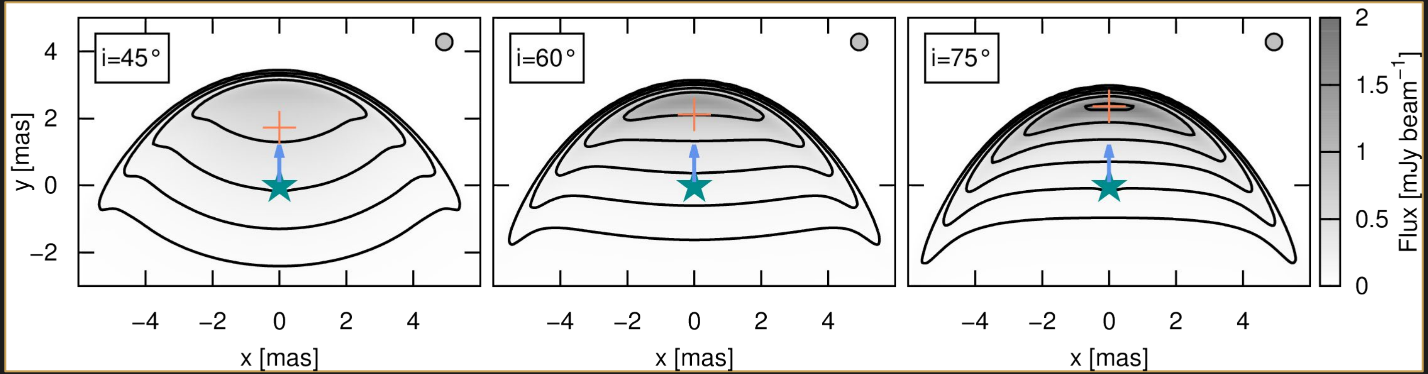


$$R_0 = \sqrt{\frac{\dot{M} v_\infty}{4\pi \rho_{\rm ISM}\,(V_\star^2 + c_s^2)}}$$

Stellar bow shocks

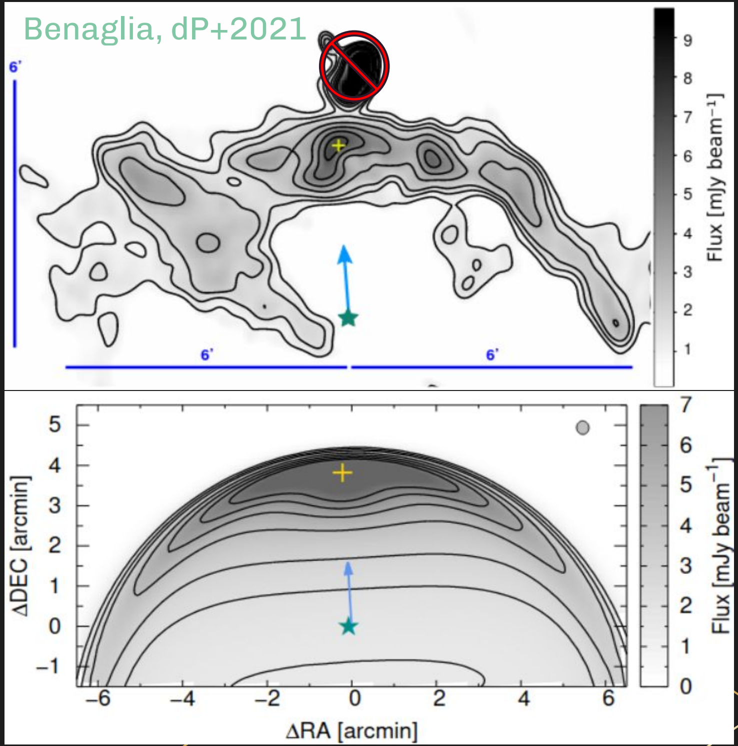
del Palacio+2018

Face on ⟷ Edge on



Synthetic emission maps (convolving with a gaussian beam)

Results


Benaglia, dP+2021

Using our non-thermal emission model we could:

- Estimate the projection angle on the sky (*i* ≅ 60°).
- Constrain the magnetic field intensity and the fraction of power converted to non-thermal particles:

$$B_{\rm WCR} \sim 35 - 100\ \mu{\rm G} \longrightarrow B_\star \leq 360\ {\rm G}$$

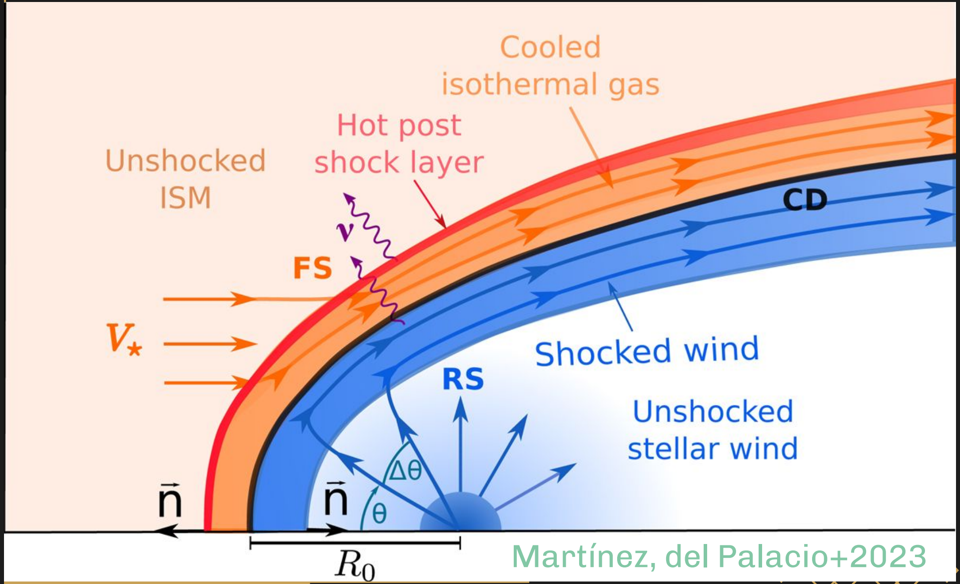
$$f_{\rm NT,e} \approx 1\% - 10\%$$

The degeneracy between these two parameters cannot be solved with radio data alone

We need detections at high energies (X/γ -rays)

Extended emitter model

Upgrades: Inclusion of **free-free emission from the FS** + detailed modelling of the low-frequency emission

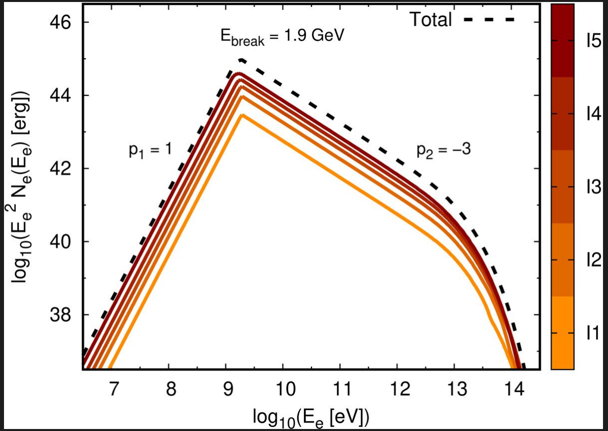


Martínez, del Palacio+2023

Additional free parameters:

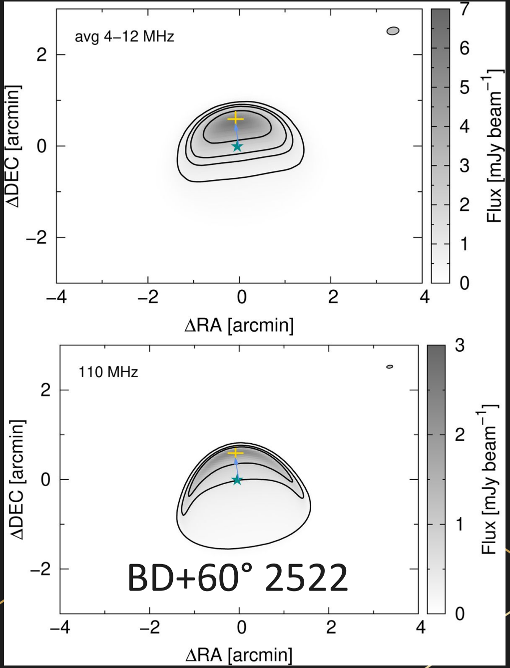
* Thickness of the isothermal layer

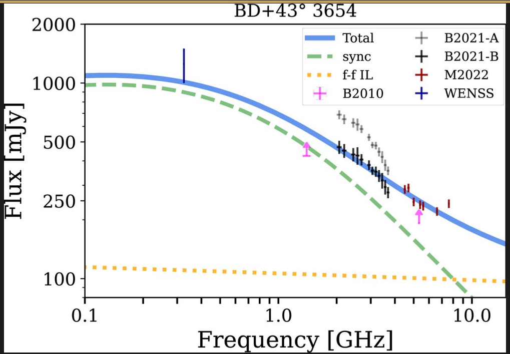
* E_{break} in the electron energy distribution

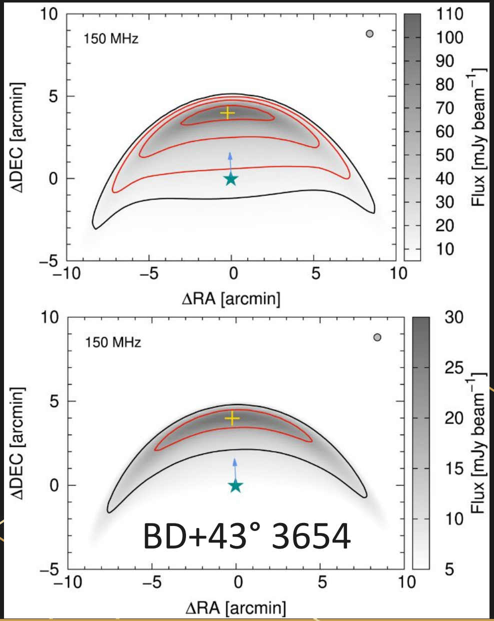


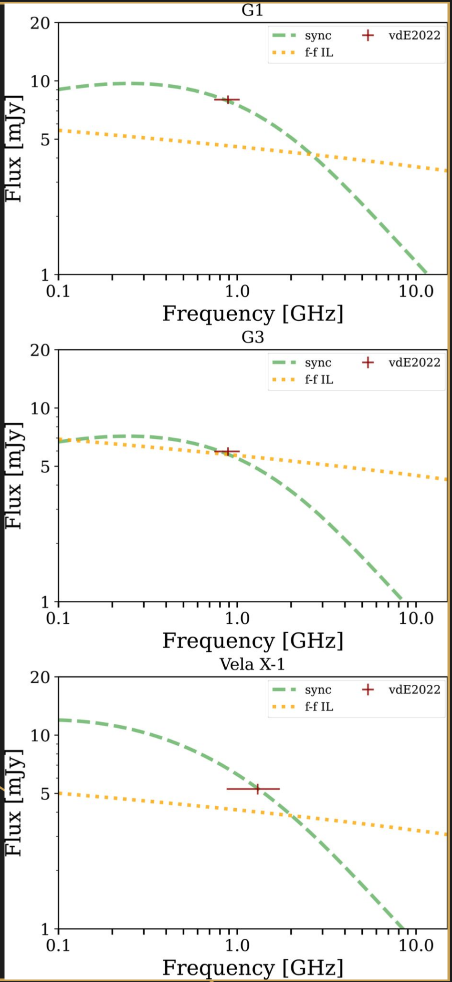
Results

Martínez, del Palacio+2023



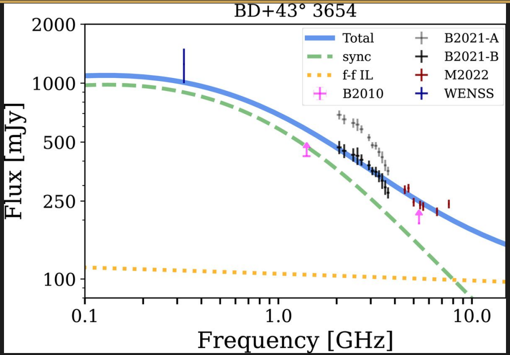


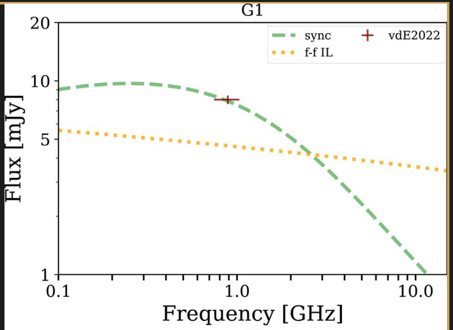


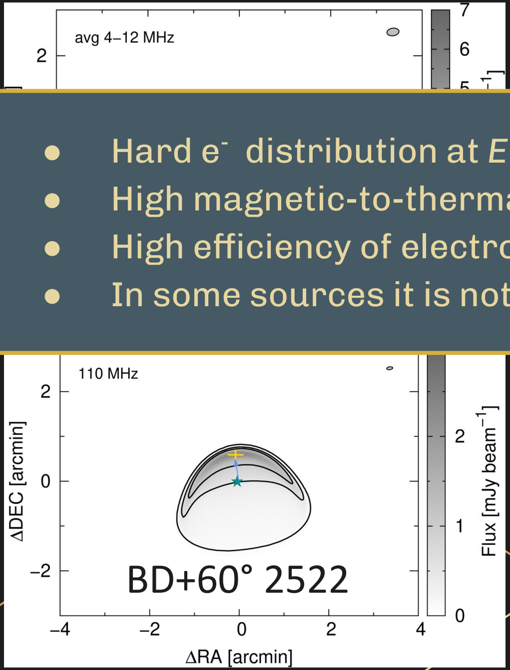


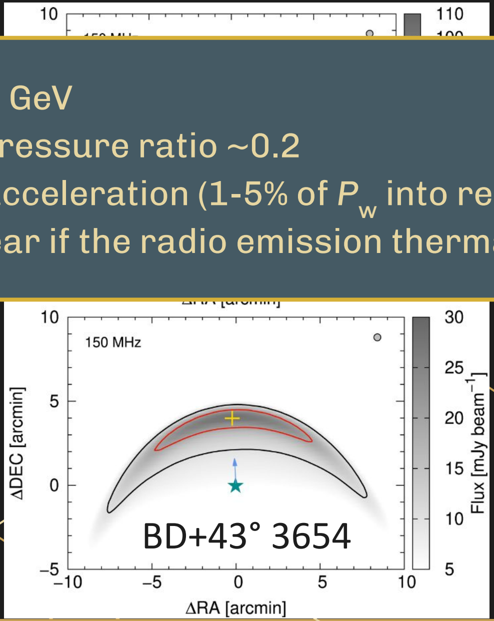
Results

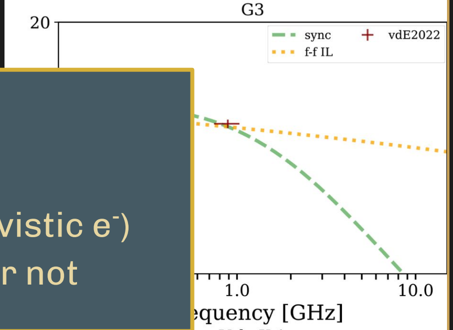
Martínez, del Palacio+2023

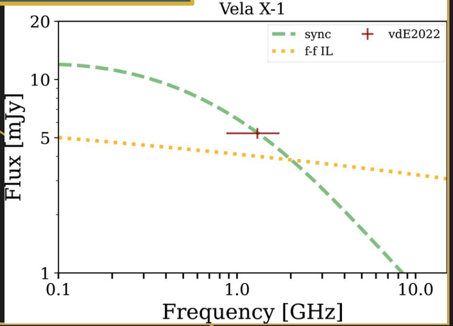












- Hard e$^-$ distribution at $E < 1$ GeV
- High magnetic-to-thermal pressure ratio ~0.2
- High efficiency of electron acceleration (1-5% of P_w into relativistic e$^-$)
- In some sources it is not clear if the radio emission thermal or not

Conclusions

- **Stellar bow shocks** are emerging as a class of **non-thermal sources**.
- **Low-frequency radio observations are ideal** to probe their synchrotron emission. SKA unprecedented sensitivity at different spatial scales can be a game-changer to obtain reliable fluxes and spectral indices in faint sources.
- Detailed **modelling** allow us to characterize the **physical properties of the bow shocks** (kinetic power, magnetic fields, particle-acceleration efficiency...).
- **Synergy between observations at radio and high-energies** (X-rays and γ-rays).

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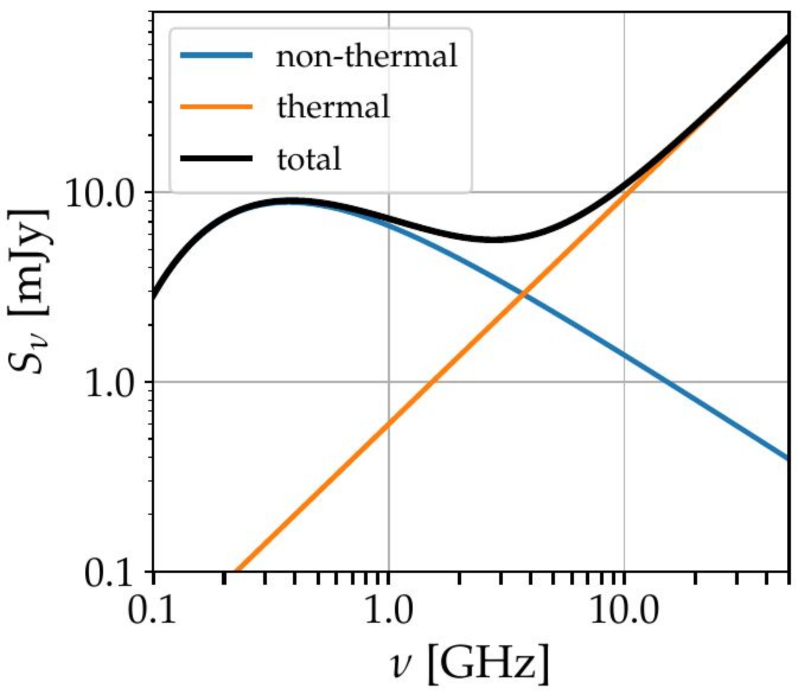
Thanks!

Radio continuum SED

- Plasmas also produce thermal emission → composite spectrum.
- **Non-thermal emission dominates the SED at low frequencies**.
- A wide frequency coverage is important to disentangle the different components.



Typical radio SED of a source

Relativistic particle acceleration

Diffusive shock acceleration

Converts kinetic energy into internal energy. Requires strong shocks.

Magnetic reconnection

Converts magnetic energy into internal energy. Requires strong magnetic fields (+ topology + turbulence...)

Injected spectrum → $Q(E) = Q_0 E^{-p} \times \exp\left(-E/E_{\max}\right)$

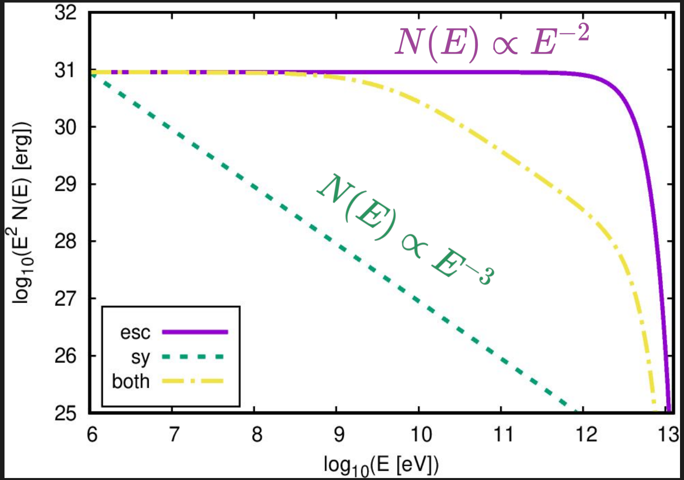
Free parameters:

- Normalisation constant Q_0 (how much power is given to relativistic particles)
- Spectral index ($p \approx 2 - 2.2$)
- Maximum particle energy (acceleration efficiency + cooling/escape processes)

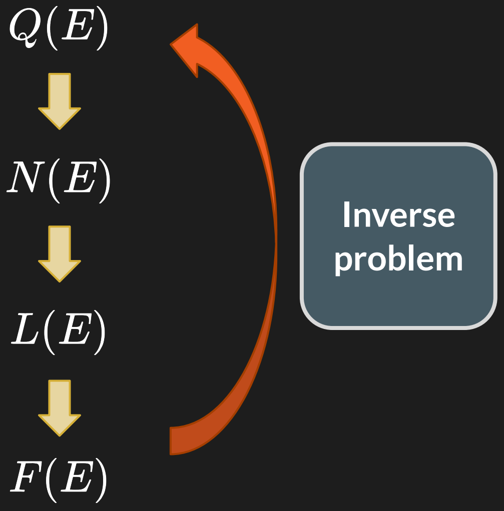
Particle energy distribution

From the injection function *Q(E,**r**,t)* one can obtain the evolution of the particle energy distribution *N(E,**r**,t)* by solving a transport equation that takes into account particle cooling and transport (escape). Typically, *N(E)* is also a power law.

$$Q(E) \propto E^{-2}$$



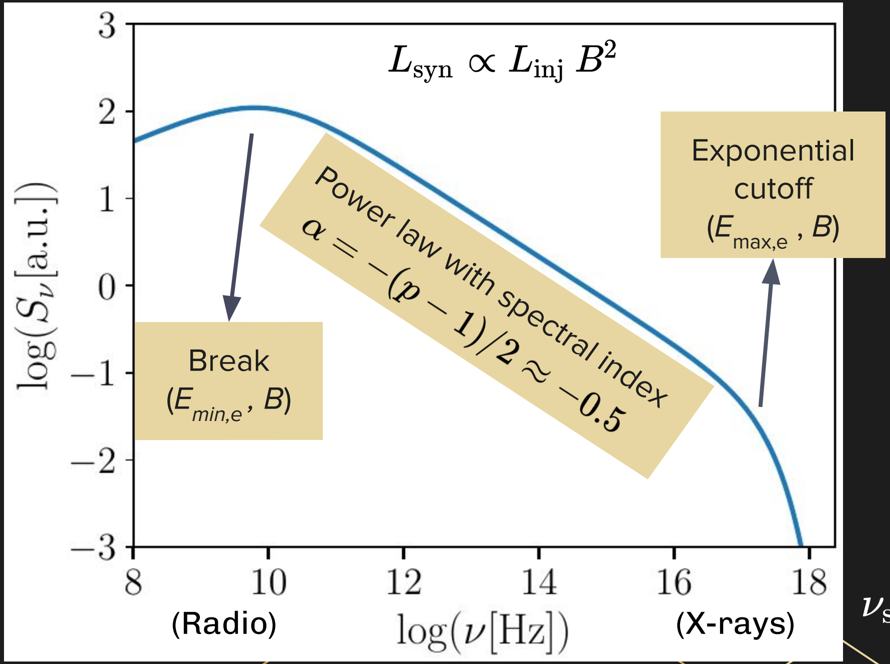
The emitted spectrum depends on *N(E)*, not *Q(E)*



$$Q(E)$$
$$\Downarrow$$
$$N(E)$$
$$\Downarrow$$
$$L(E)$$
$$\Downarrow$$
$$F(E)$$

Inverse problem

Radiative processes: synchrotron



Typical intrinsic synchrotron SED

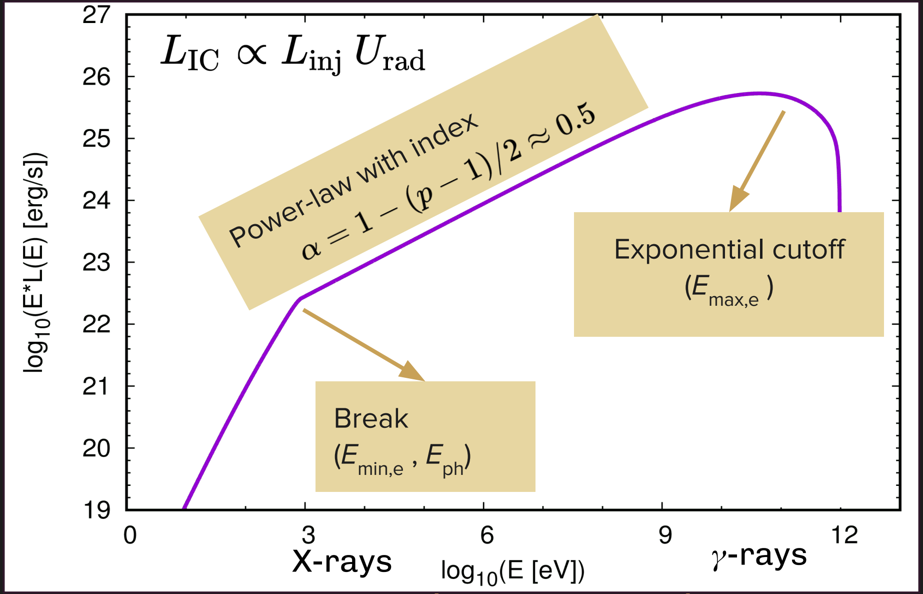
$$\nu_{\mathrm{sy}} \propto B\, E^2$$

Electrons radiate in the presence of a magnetic field. This emission is intrinsically **polarised**.

Studying the synchrotron SED can give insight on the **relativistic particle energy distribution** (*N*(*E*)) and the **magnetic fields** in the source.

Radiative processes: Inverse Compton

A relativistic electron up-scatters a low energy photon (e.g., from a star) to higher energies (hard X-rays/γ-rays)



Results

The dependence of the emitted luminosity w.r.t. the system parameters shows that the best candidates are defined by the stellar wind properties rather than the medium (del Palacio+2018)

Radio emission →

$$L_{\rm sy} \propto \dot{M}_{\rm w}^{1.5}\, v_{\rm w}^{1.5}\, n_{\rm ISM}^{0.5}\, v_\star$$

γ-ray emission →

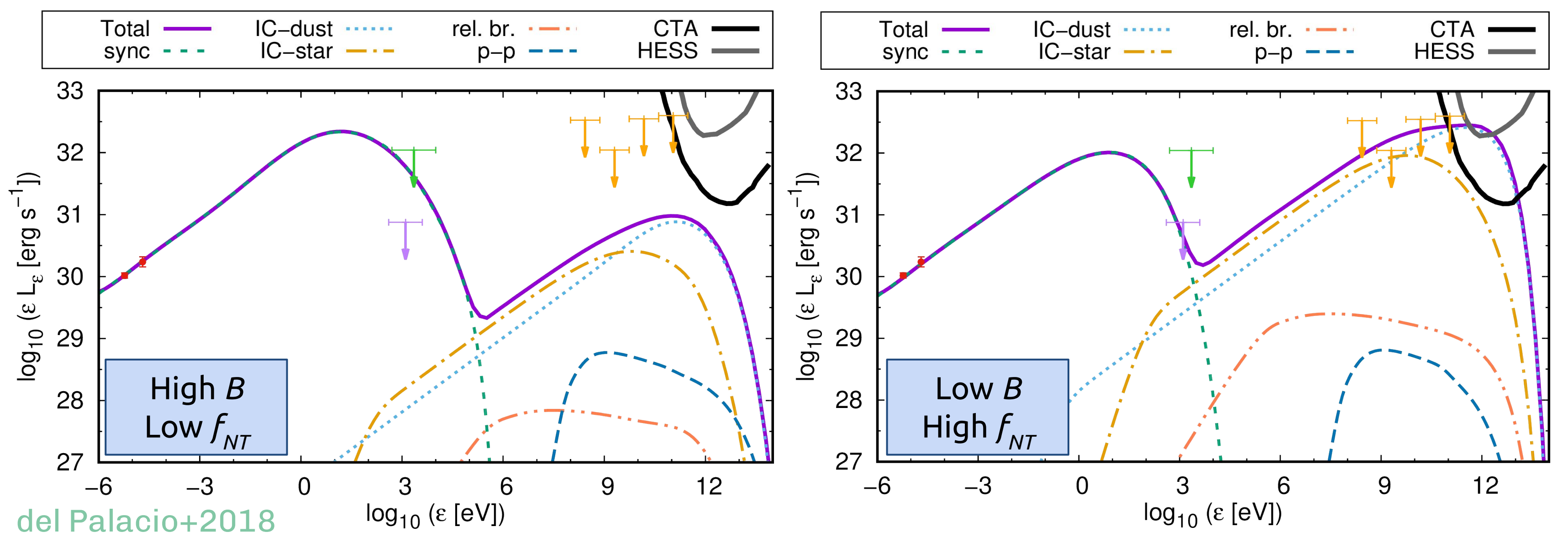
$$L_{\rm IC} \propto \dot{M}_{\rm w}^{2}\, v_{\rm w}\, n_{\rm ISM}^{0.5}\, v_\star$$

Best radio emitters ≠ best γ-ray emitters →

$$\frac{L_{\rm radio}}{L_\gamma} \propto \left(\frac{v_{\rm w}}{\dot{M}_{\rm w}}\right)^{0.5}$$

Results

Breaking the degeneracy: predictions for the high-energy SED

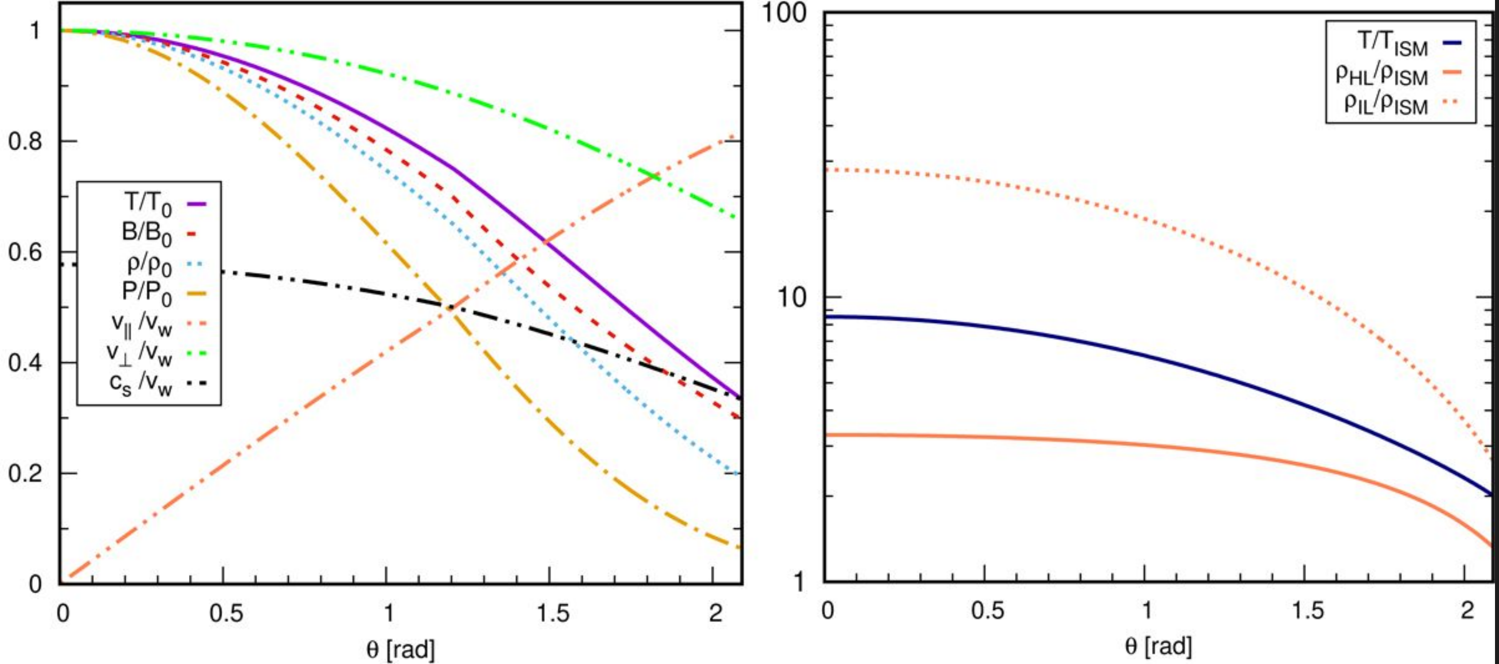


Higher B = less emission at high energies

Results

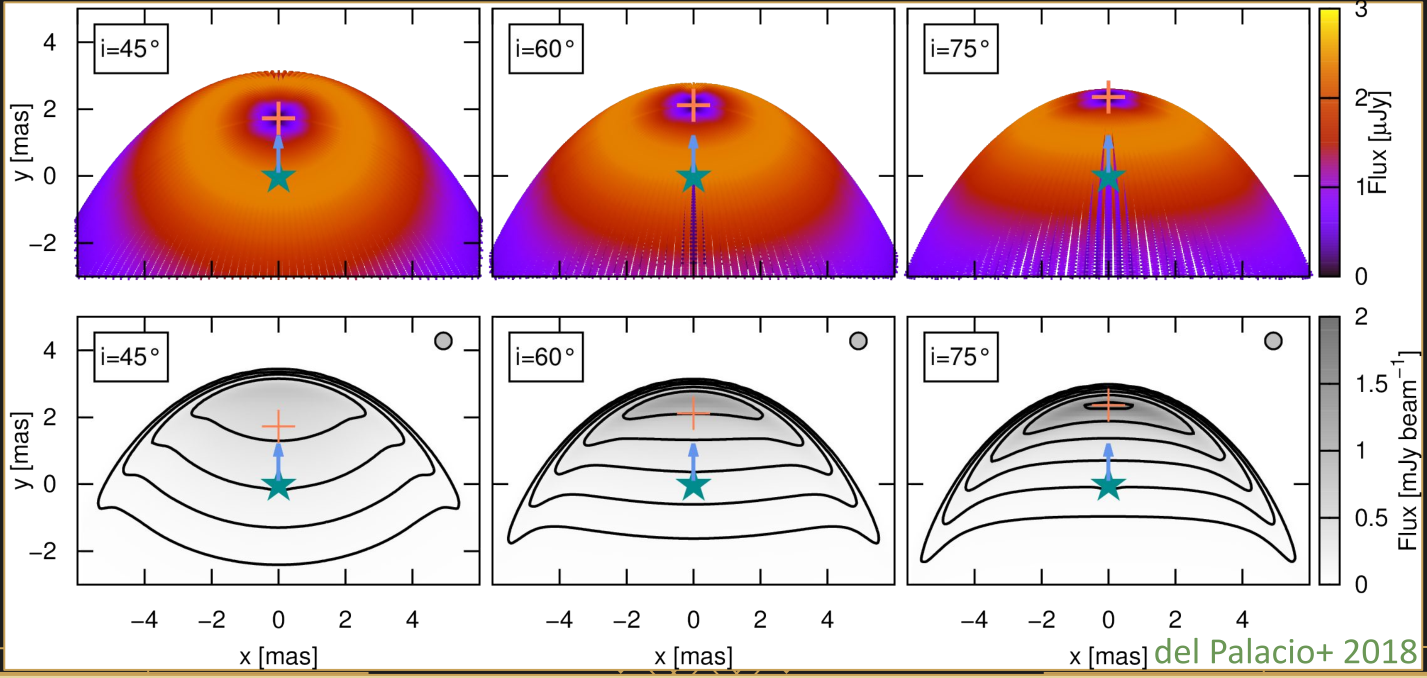
Thermodynamical quantities along the bow shock

(normalized to quantities at the stagnation point, except the velocities which are normalized to v_w)



Stellar bow shocks

Face on ⟷ Edge on



del Palacio+ 2018

Synthetic emission maps before (top) and after (below) convolving with a gaussian beam

Gamma-ray emission?

Sánchez-Ayaso+2018 suggested the possible association of two stellar BSs with unidentified Fermi sources