Non-thermal emission from stellar bow shocks

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Stellar winds

Powerful, supersonic winds

Mechanical energy into the ISM

$$\dot{M} \sim 10^{-7} - 10^{-5} M_{\odot}/y$$

$$v_{\infty} \sim 500 - 3000 \mathrm{km/s}$$

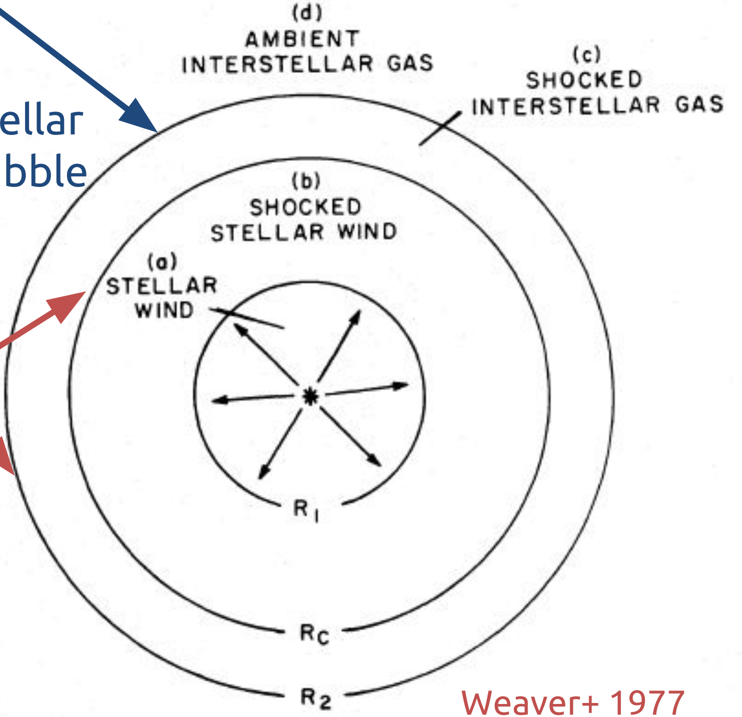
$$L_{kin} \sim 10^{36} \mathrm{erg/s}$$

Strong shocks can accelerate **relativistic particles** (a.k.a. *cosmic rays*)

Systems involving massive stars **are sources of Galactic CRs** → **How much do they contribute to the observed CR spectrum?**

Stellar bubble

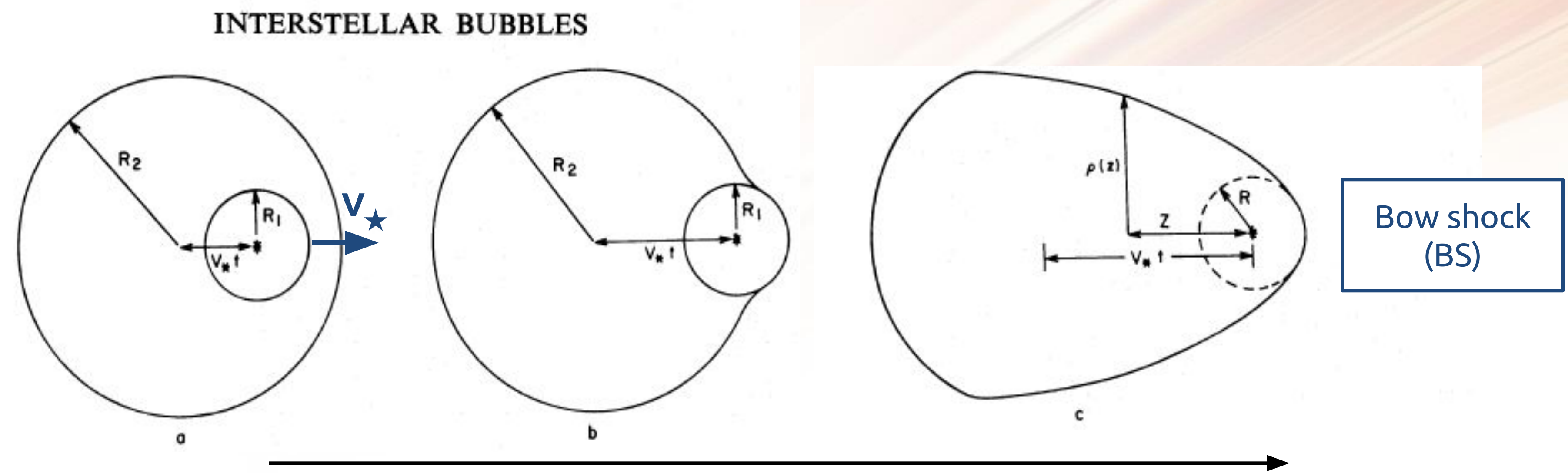
Two shock fronts



Weaver+ 1977

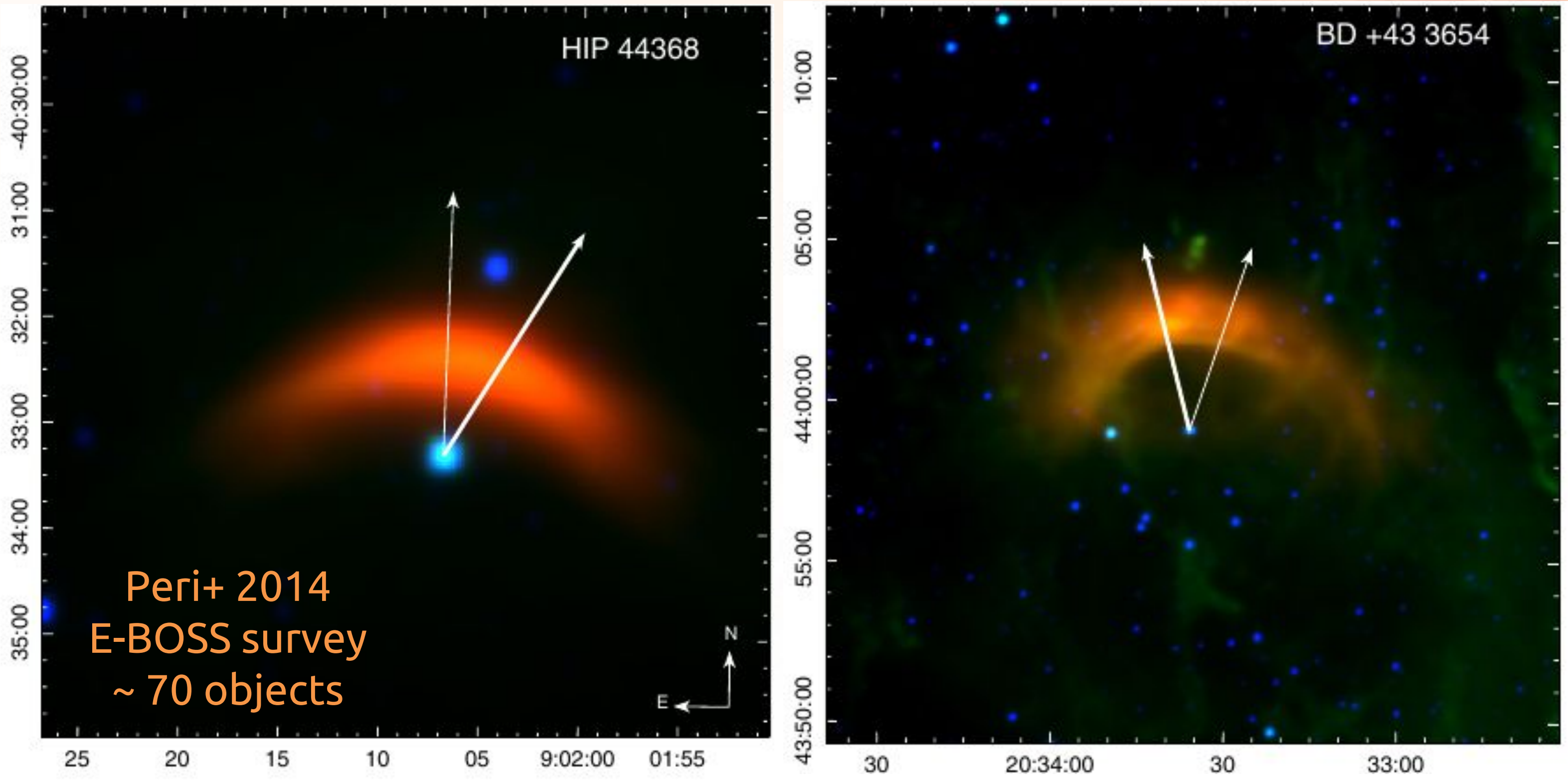
Runaway massive stars

Runaway stars have high peculiar spatial velocities (w.r.t. their surrounding medium), $V_\star$ > 30-40 km/s . Close to %30-50 of the runaway stars are massive stars (Stone 1991). Observations show that ~**10-20% of O stars are runaway stars** (Maíz Apellániz+ 2018).



Weaver+ 1977

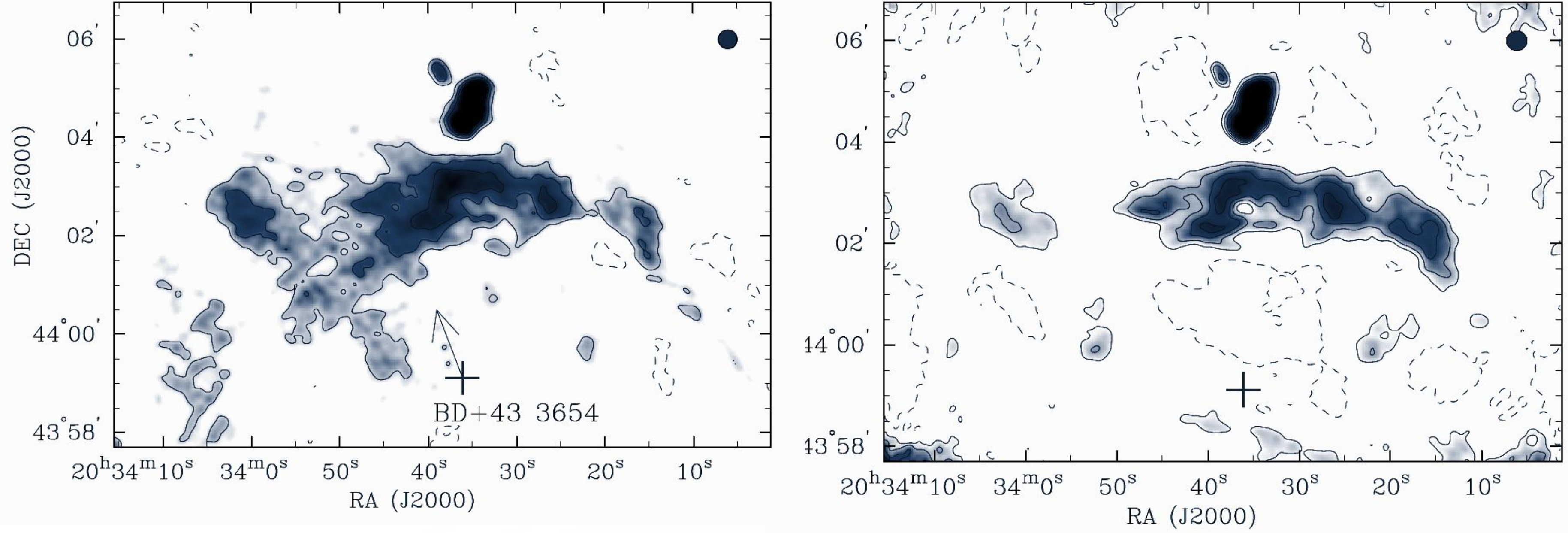
Thermal emission



Peri+ 2014
E-BOSS survey
~ 70 objects

Thick vectors = proper motions, thin vectors = proper motions w.r.t. the surrounding ISM.
The catalogue has been extended by Kobulnicky+ 2016 to ~ 700 objects.

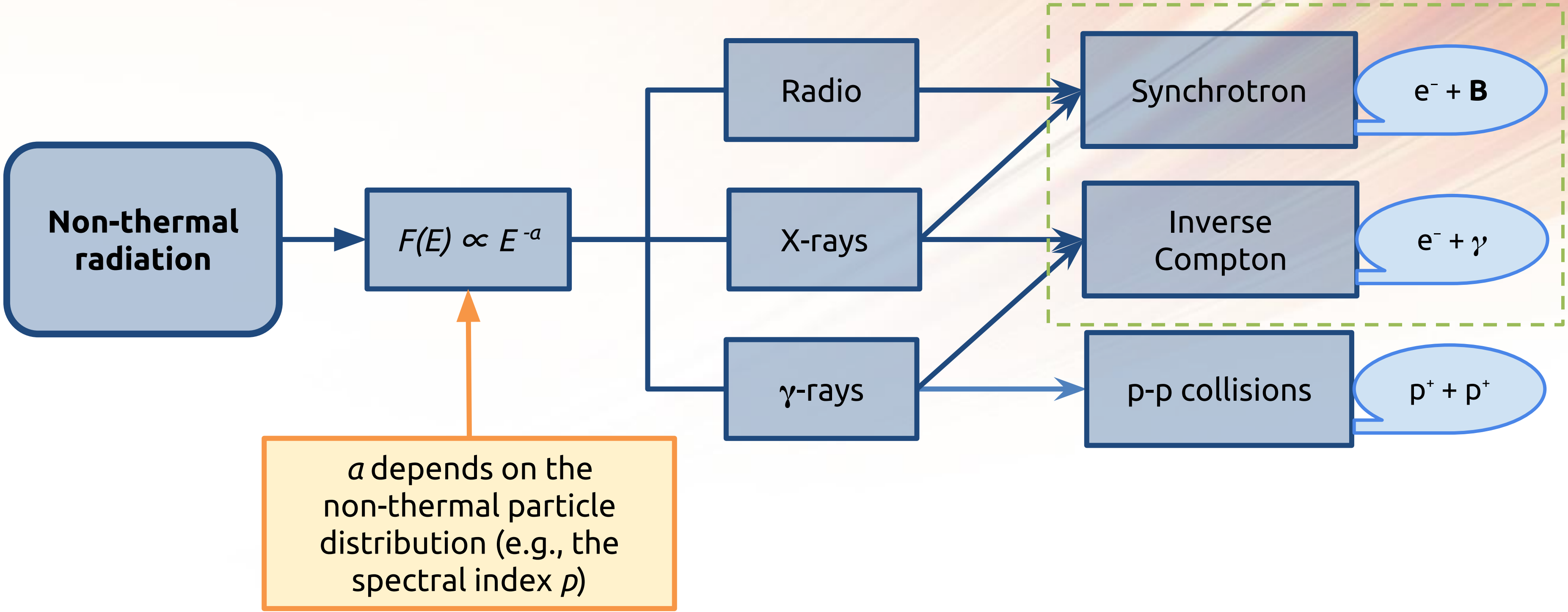
Non-thermal emission



Continuum emission at 1.42 GHz (*left*), and at 4.86 GHz (*right*) from VLA observations (Benaglia+ 2010). Total flux: $S_{1.4}$ = 660 mJy, $S_{4.8}$ = 370 mJy → **$\langle\alpha\rangle$ = -0.5.**

This is the only reliable evidence of non-thermal emission in a stellar bow shock

Non-thermal emission



Non-thermal radiation

$F(E) \propto E^{-a}$

a depends on the non-thermal particle distribution (e.g., the spectral index *p*)

Radio

X-rays

γ-rays

Synchrotron

Inverse Compton

p-p collisions

$e^- + \mathbf{B}$

$e^- + \gamma$

$p^+ + p^+$

Non-thermal emission

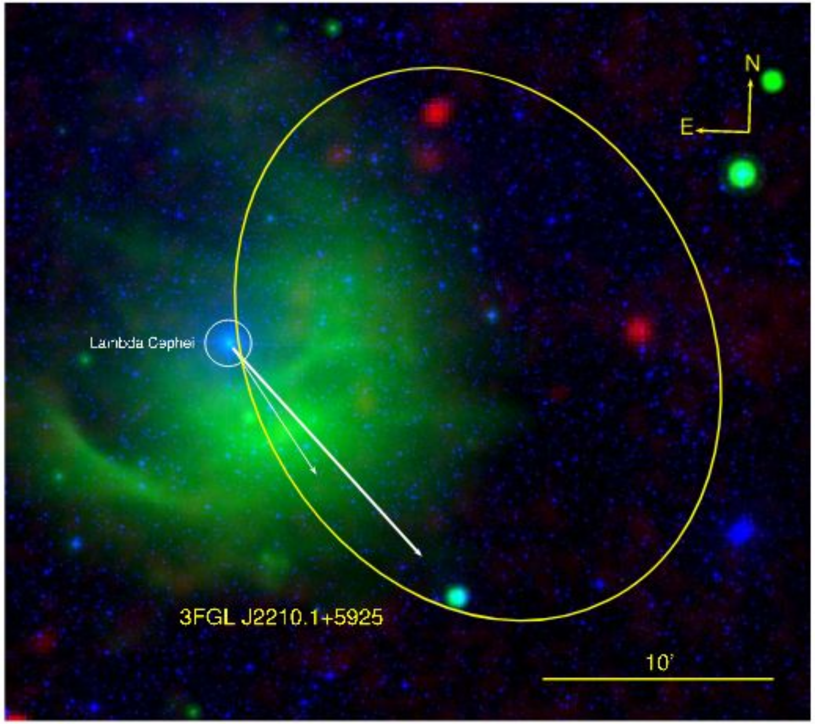
Attempts to detect high-energy (X-ray / γ-ray) emission from stellar BSs (predictions by del Valle+12):

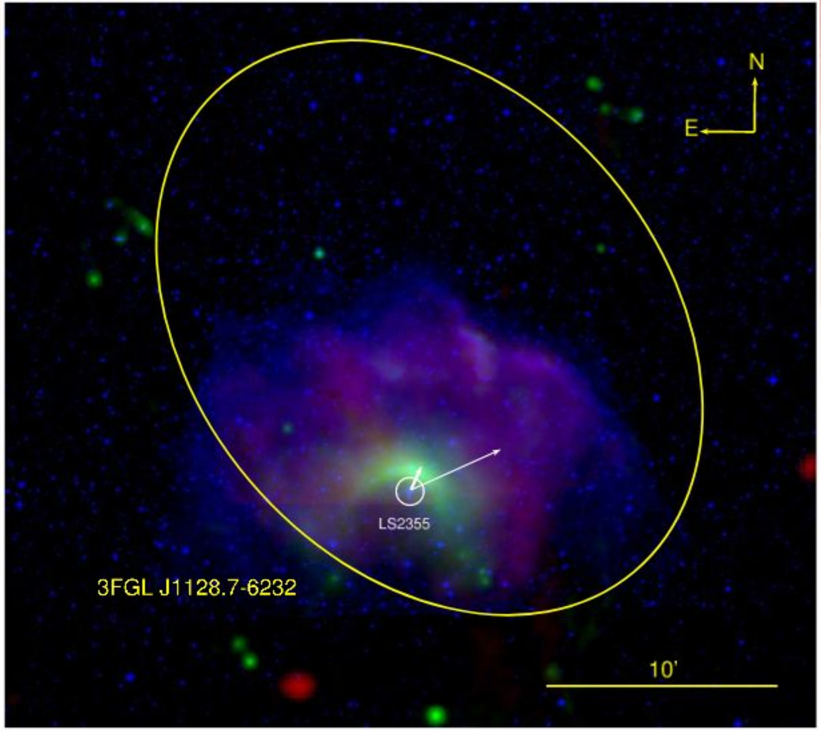
- ➢ Schulz+2014 → No stellar BS were detected with *Fermi* at 0.1-300 GeV energies in a sample of 27 objects.
- ➢ H.E.S.S. Coll. 2017 → No stellar BS were detected at TeV energies from 32 candidates. Upper-limits: L_{TeV} < 0.1-1% L_{wind}
- ➢ De Becker+ 2017 → No stellar BS detected with *XMM-Newton* in X-Rays from 5 candidates. Estimate that $P_{IC} \sim 10^{-5}\, P_w$
- ➢ Toalá+ 2016 → No stellar BS detected with *XMM-Newton* in X-Rays for 2 BSs (including BD+43)
- ➢ Toalá+ 2017 → No stellar BS detected with *XMM-Newton* in X-Rays (even refuted a previous false-positive).

Is it just a sensitivity issue?

Gamma-ray emission?

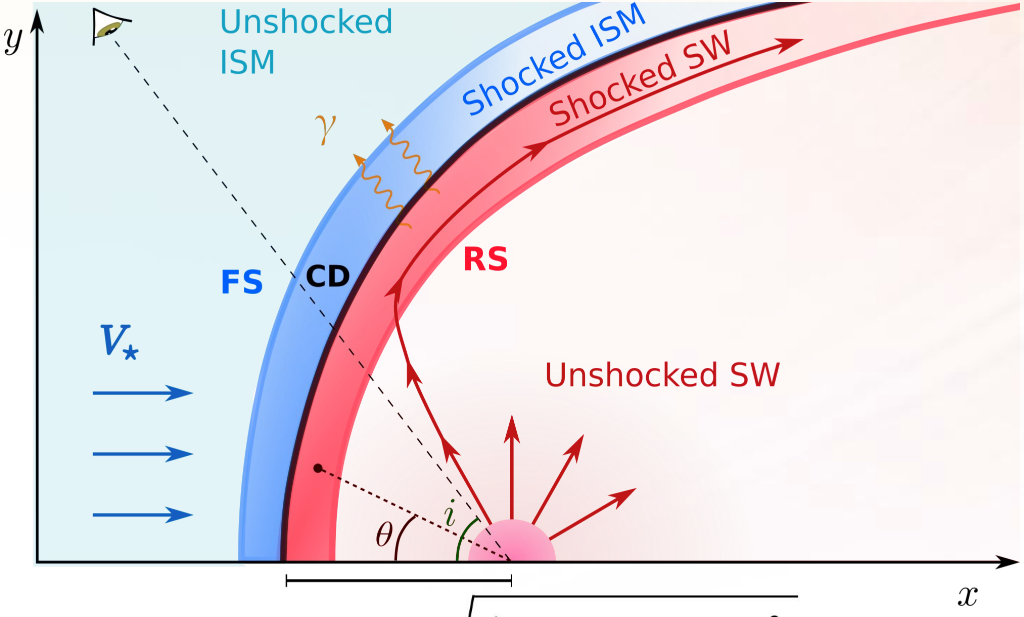
Sánchez-Ayaso+2018 recently suggested the possible association of two stellar BSs with unidentified *Fermi* sources





Extended Model: Geometry

Relativistic particles are **accelerated** in the BS and are carried away (**convected**) by the shocked wind. Relativistic electrons produce **synchrotron** and **IC emission**.



$$R_0 = \sqrt{\dot{M}_{\rm w} v_{\rm w}/(4\pi\rho_{\rm ISM} V_\star{}^2)}$$

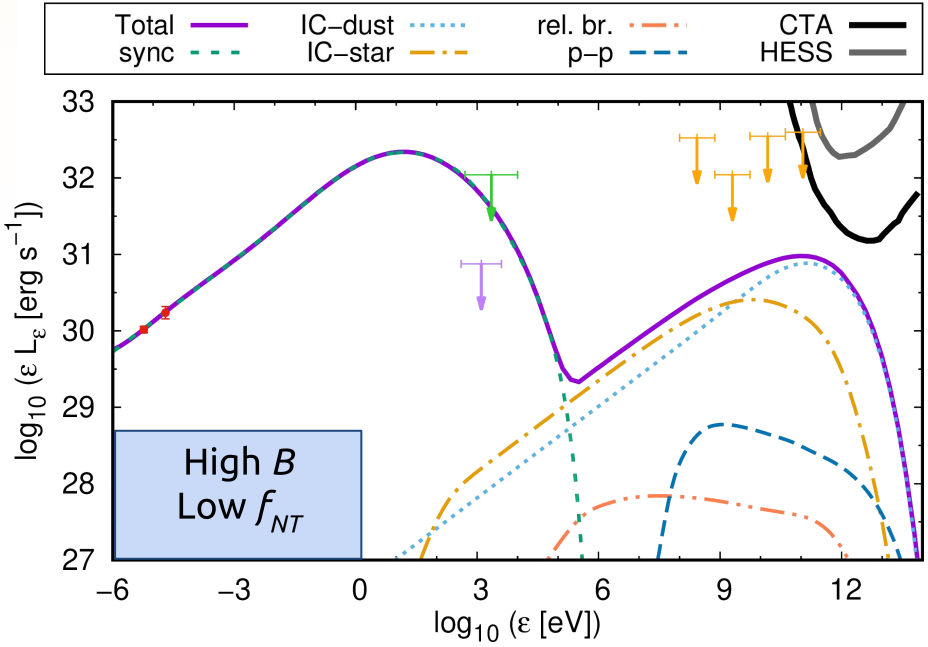
del Palacio, S., Bosch-Ramon, V., Müller, A., & Romero, G.E. (2018)

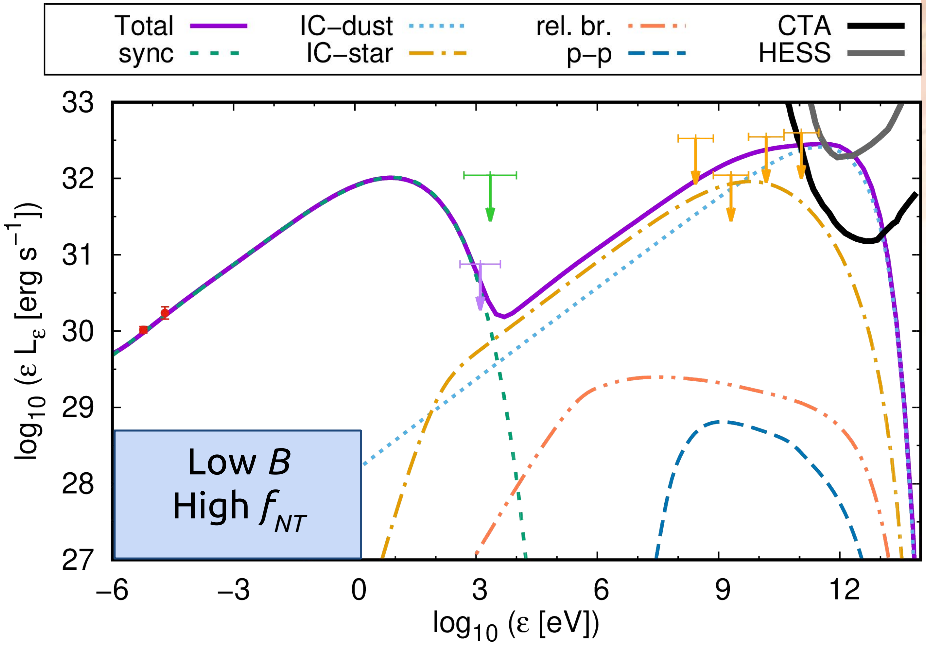
- BS = axisymmetric (2-D) shell.
- Adiabatic RS + laminar flow
- Analytical prescriptions for the thermodynamical quantities in the shocked SW + Bohm diffusion.
- Free parameters: The <u>magnetic field strength</u> (*B*) and the <u>fraction of energy injected in relativistic particles</u> (f_{NT}).

Particle escape is dominant: electrons radiate only ~1% of their energy, whereas protons essentially escape into the ISM as CRs

Non-thermal emission

Model application to **BD+43 3654**: *i)* We can discard a combination of a high *B* and fast (Bohm) diffusion; *ii)* the expected γ-ray luminosity depends on B.

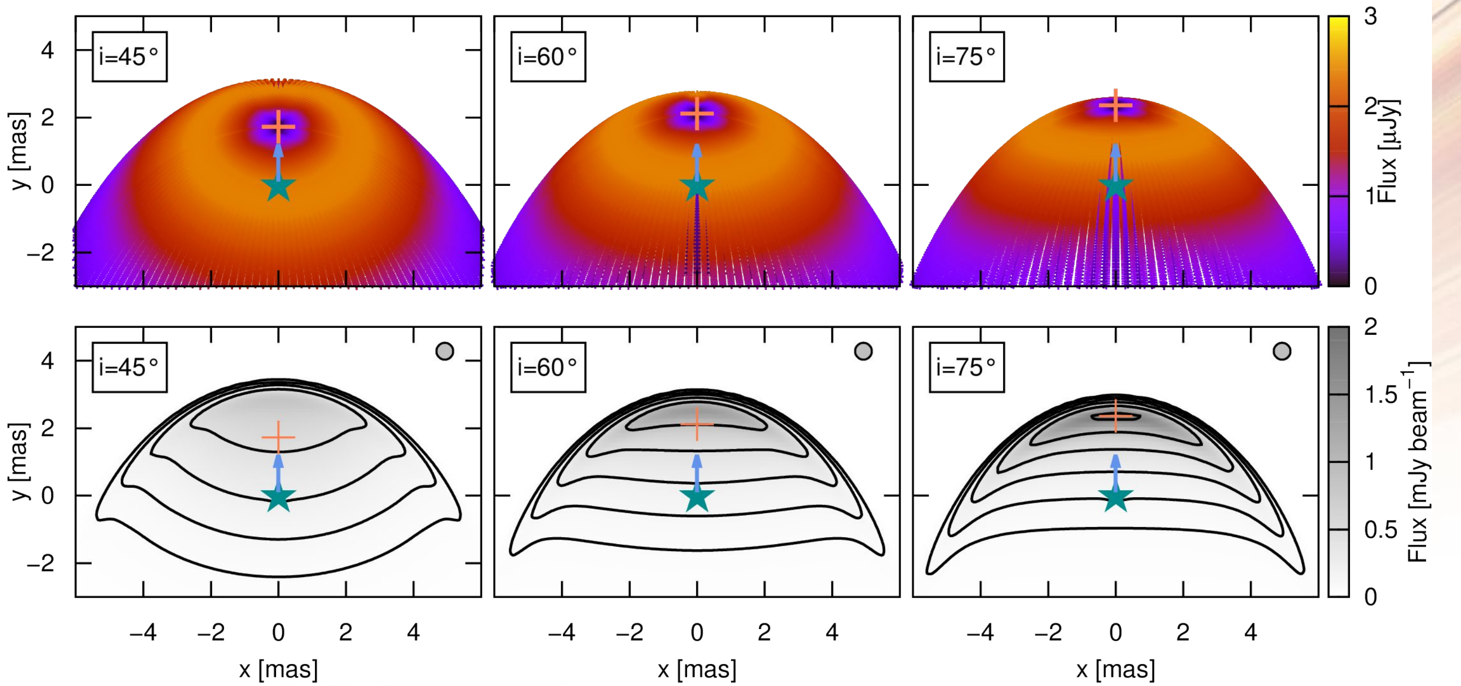




(See del Valle+ 2018 for a detailed analysis on the impact of diffusion)

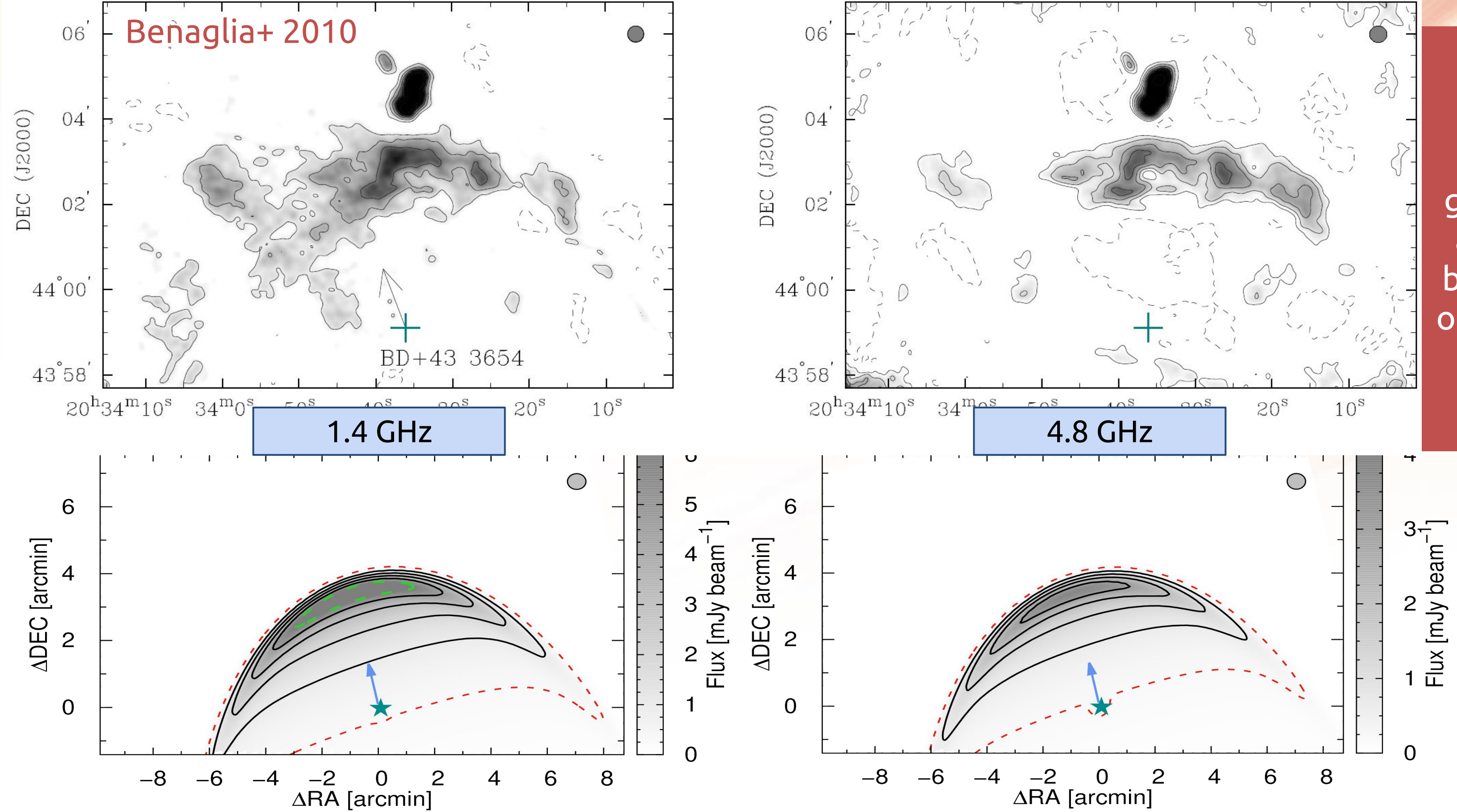
Extended Model: Emission maps

Face-on ⟷ Edge-on



Synthetic radio emission maps before (*top*) and after (*bottom*) convolution with a gaussian beam for different inclinations

Extended Model: BD+43° 3654



i ~ *75°*
(almost edge-on)
gives a good agreement between the observed and synthetic maps

Luminosity Scaling

Selection criteria for observational campaigns: Useful scaling relations for the expected luminosity w.r.t. the system parameters show that **the best candidates are defined by the stellar wind properties** rather than the medium or peculiar motion

Radio emission →

$$\boxed{L_{\rm sy} \sim L_{\rm NT,e} \times (t_{\rm conv}/t_{\rm sy}) \propto \dot{M}^{1.5}\, v_{\rm w}^{1.5}\, n_{\rm ISM}^{0.5}\, v_\star}$$

HE γ-ray emission →

$$\boxed{L_{{\rm IC},\star} \propto L_{\rm NT,e}(t_{\rm conv}/t_{{\rm IC},\star}) \propto \dot{M}^{2}\, v_{\rm w}\, n_{\rm ISM}^{0.5}\, v_\star}$$

Best NT radio emitters ≠ best γ-ray emitters →

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

Conclusions

- ★ Numerical models → **Constrain** unknown parameters such as **the magnetic field strength**, the **amount of energy injected in relativistic particles and acceleration efficiency**. **Deep observations in X-rays** are useful.
- ★ Assess future **observational campaigns in the radio and γ-ray band** in determining the most promising targets → The NT luminosity is strongly dependent on the mass-loss rate.
- ★ **Multi-zone models** → Study the emitting structure by means of **synthetic emission maps.**
- ★ Our model reproduces the radio observations from **BD+43°3654** and predicts that the system **γ-ray emission could be detectable** with current or forthcoming instruments.
- ★ **Stellar BSs can be efficient particle accelerators** (although not radiatively efficient).
- ★ **Estimate surface stellar magnetic fields** (or infer magnetic field amplification in the BS):

$$B_\star = 0.25\, B(\theta)\, (R(\theta)/R_\star)\, (v_\infty/v_{\rm rot})$$

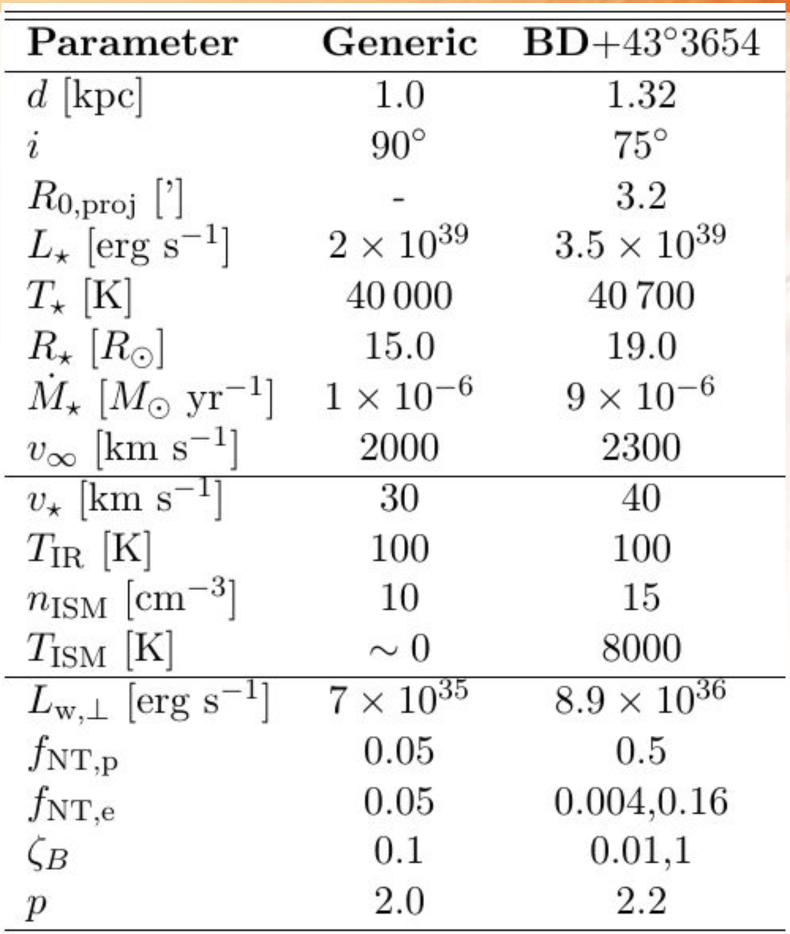
Work in progress

We obtained a **deep** observation with **JVLA** (PI: P. Benaglia) to perform a **polarimetric study of BD+43°3654**:

- **Improve previous** spectral index **maps** and detect fainter emission farther from the apex: 10 times better sensitivity + spectral index error < 10%.
- **Trace the magnetic field topology** and strength around the shock: detect down to 5% fractional linear polarization (synchrotron emission is intrinsically polarized) at 5σ within a total intensity contour at 0.5 mJy beam^{-1} → **Implications for particle acceleration theory.**

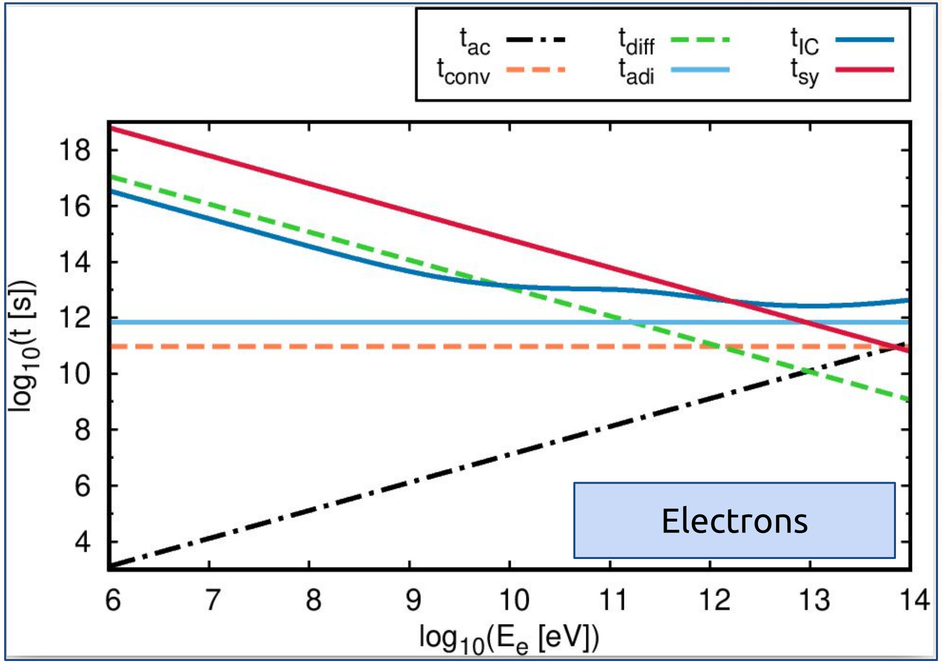
Thank You

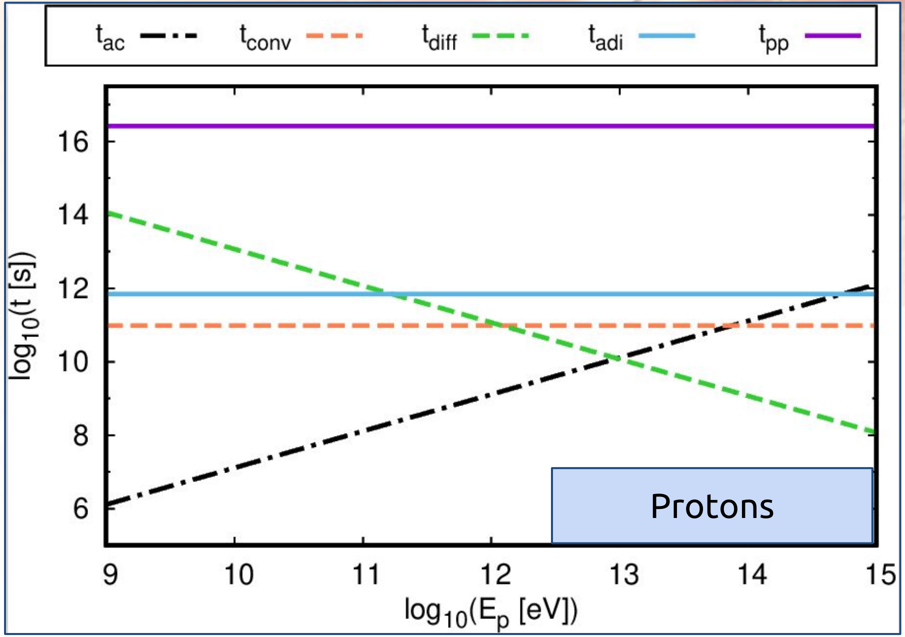
Parameters



Parameter	Generic	BD+43°3654
d [kpc]	1.0	1.32
i	90°	75°
$R_{0,\mathrm{proj}}$ [']	-	3.2
$L_\star$ [erg s^{-1}]	2×10^{39}	3.5×10^{39}
$T_\star$ [K]	40 000	40 700
$R_\star$ [$R_\odot$]	15.0	19.0
$\dot{M}_\star$ [$M_\odot$ yr^{-1}]	1×10^{-6}	9×10^{-6}
v_∞ [km s^{-1}]	2000	2300
$v_\star$ [km s^{-1}]	30	40
T_{IR} [K]	100	100
n_{ISM} [cm^{-3}]	10	15
T_{ISM} [K]	~ 0	8000
$L_{\mathrm{w},\perp}$ [erg s^{-1}]	7×10^{35}	8.9×10^{36}
$f_{\mathrm{NT,p}}$	0.05	0.5
$f_{\mathrm{NT,e}}$	0.05	0.004,0.16
ζ_B	0.1	0.01,1
p	2.0	2.2

Extended Model: Particle distribution



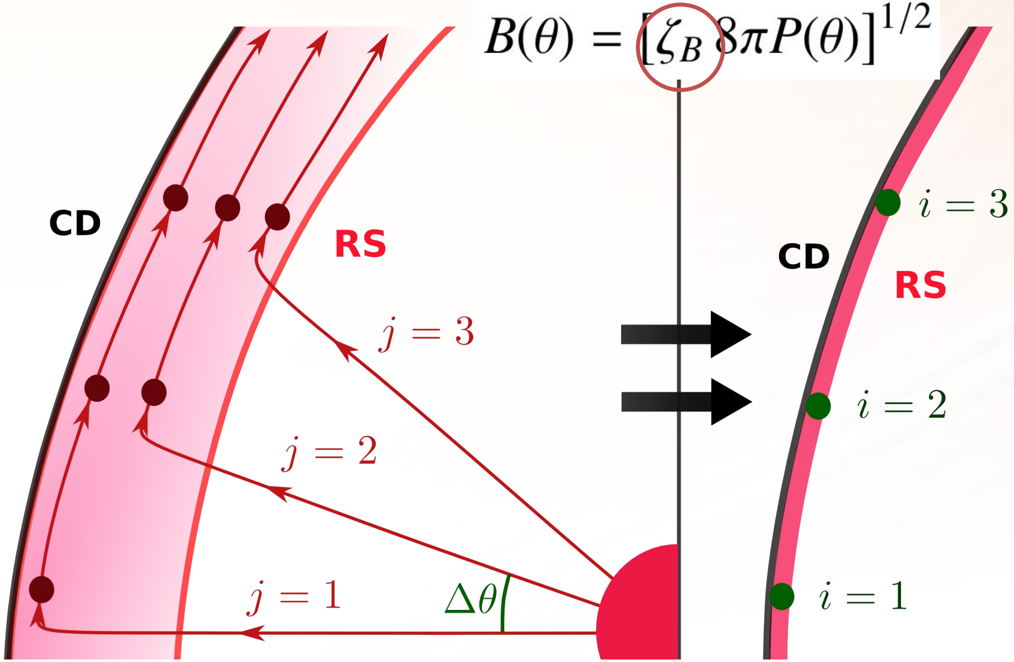


Particle escape is dominant: electrons radiate only ~1% of their energy, whereas protons esencially escape into the ISM as CRs

Extended Model

$$\Delta L_{\mathrm{NT}}(\theta_i) = \boxed{f_{\mathrm{NT}}}\; L_{\mathrm{w},\perp}(\theta_i)\,\frac{\Delta\Omega(\theta_i)}{4\pi}$$

$$B(\theta) = \left[\boxed{\zeta_B}\, 8\pi P(\theta)\right]^{1/2}$$



- Relativistic particles are accelerated once the fluid line enters the RS region, and flow together with the shocked fluid.
- The BS radiation is produced by a sum of 1D emitters symmetrically distributed around the direction of motion of the star.
- The hydrodynamics and particle distribution have azimuthal symmetry. Emission or absorption processes can depend on the line of sight (thus in the azimuthal angle)