Non-thermal emission from colliding stellar winds

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PANTERA Stars

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Stellar winds

Massive stars launch **powerful, hypersonic winds**. Non-thermal emission associated with wind shocks in:

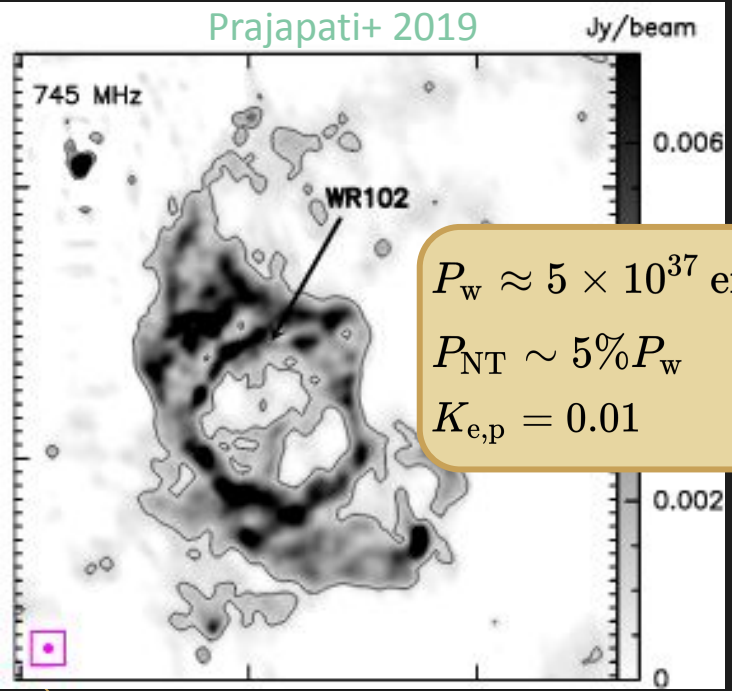
- stellar bubbles
- stellar bow shocks
- **colliding-wind binaries**

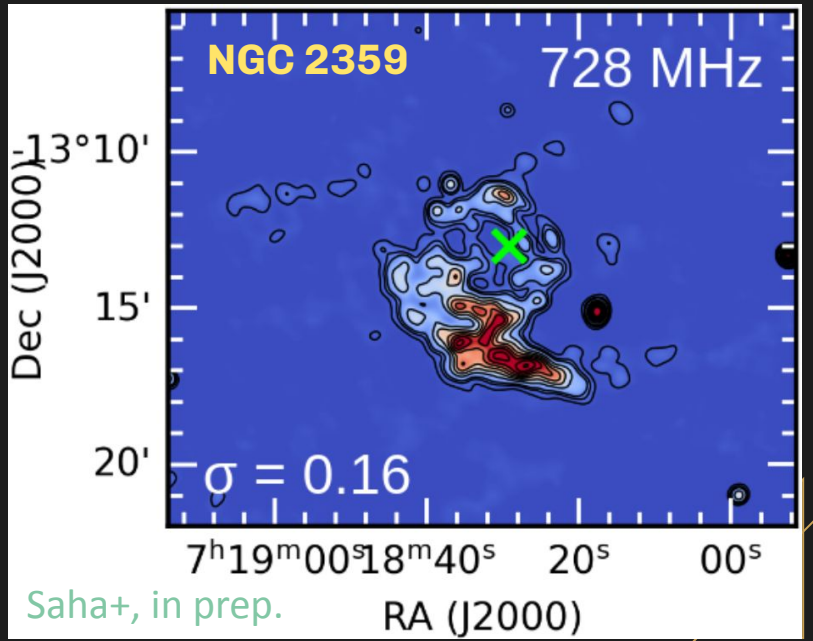
$$\left\{ \begin{array}{l} \dot{M} \sim 10^{-6}\,\mathrm{M_\odot\,yr^{-1}} \\ v_\infty \sim 1000\,\mathrm{km\,s^{-1}} \end{array} \right\}$$

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

Stellar bubbles

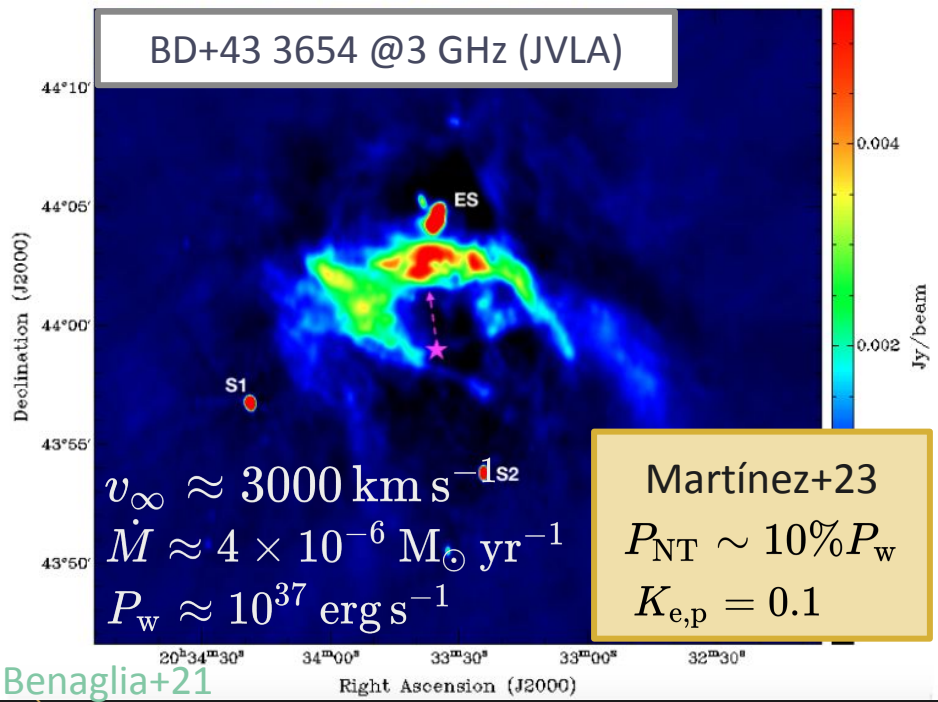
Detection of non-thermal radio emission towards WR bubbles



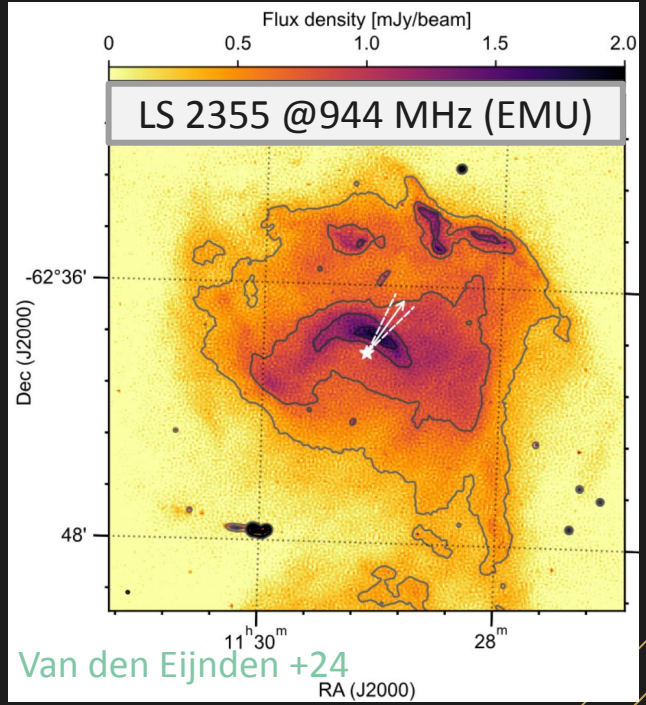


Stellar bowshocks

Detection of non-thermal radio emission from runaway massive stars



Benaglia+21



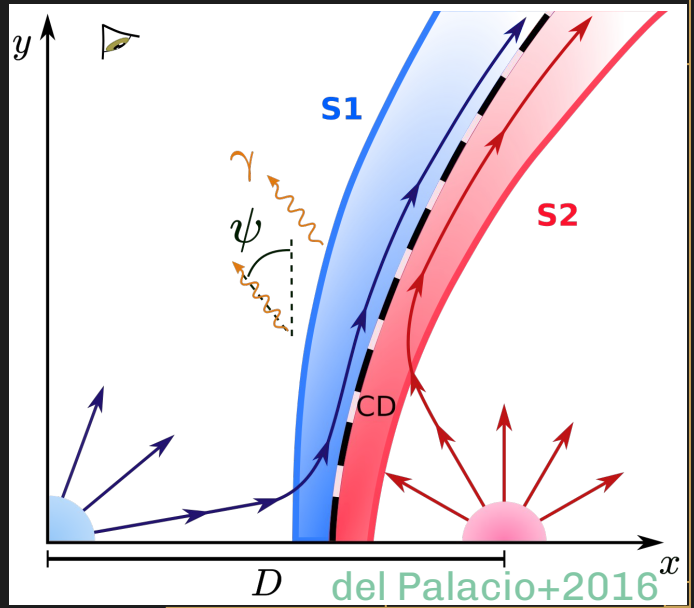
Van den Eijnden +24

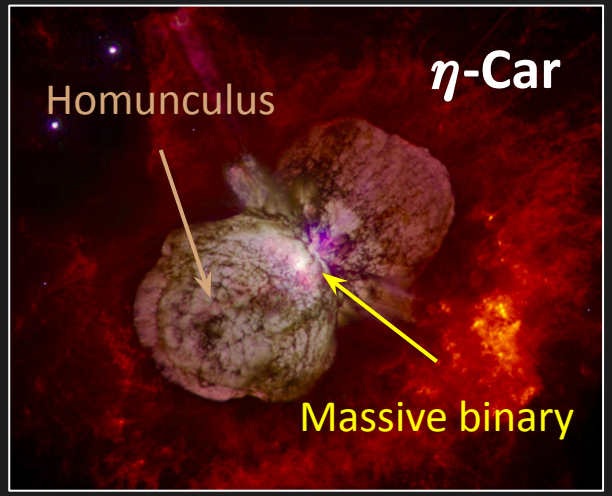
Colliding-wind binaries

More compact systems, higher target densities, higher opacity, orbital variability

1. Wind-collision region = axisymmetric surface
2. Two shock fronts (adiabatic + laminar flow)
3. Relativistic particles accelerated at the shocks
4. Non-thermal emission (sync., IC, p-p) and absorption processes (FFA, γ-γ)
5. Free parameters: B and $f_{\rm NT}$ (...)

$$P_B = \eta_B P_{\rm th} \qquad L_{\rm NT}(i) = f_{\rm NT} L_{\rm w,\perp}(i)$$





$\dot{M}_1 \approx 5 \times 10^{-4}\,\mathrm{M_\odot\,yr^{-1}}$

$v_{\infty,1} \approx 500\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{w},1} \approx 4 \times 10^{37}\,\mathrm{erg\,s^{-1}}$

$\dot{M}_2 \approx 1.4 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$

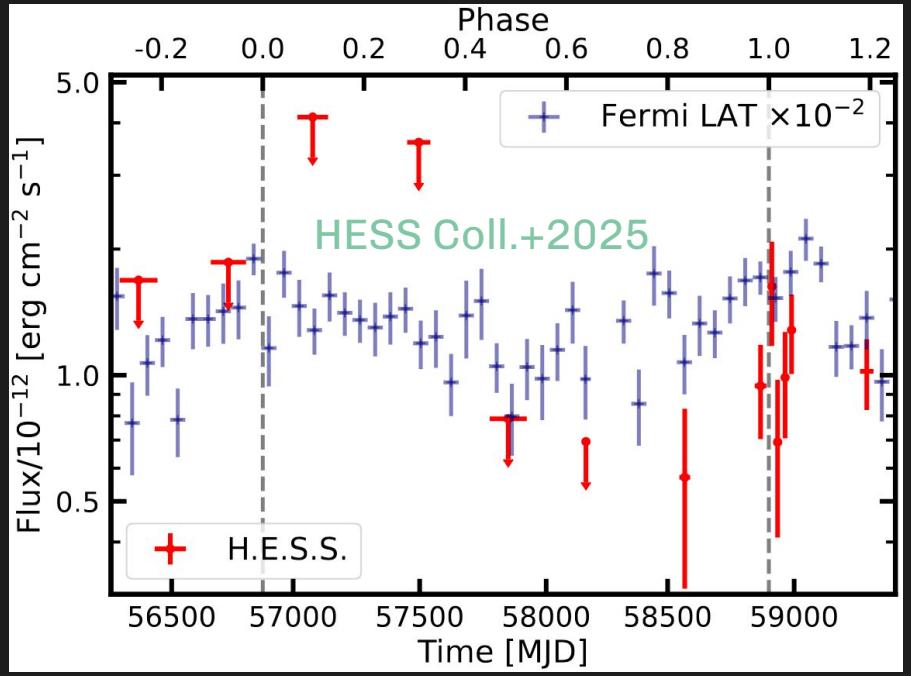
$v_{\infty,2} \approx 3000\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{w},2} \approx 4 \times 10^{37}\,\mathrm{erg\,s^{-1}}$

Orbital period ~5.5 yr. Brightest at periastron (a_p~1.5 AU).

Detected with *Fermi* (Tavani+09, Marti-Devesa+21...) and H.E.S.S. (HESS Coll.+20, +25).

Also detected in hard X-rays.

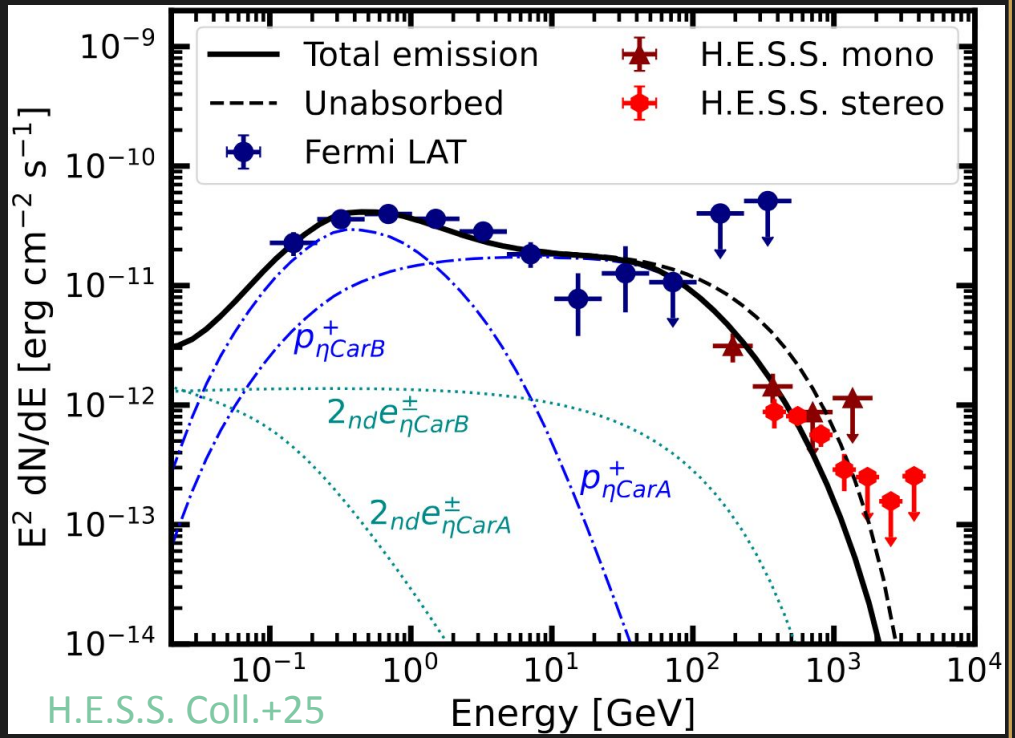


η-Car

- SED fitting:

  $P_{NT} \sim 10\% P_w$

  $P_e/P_p \sim 3\%$.
- The emitter has to be at 10-20 AU, suggesting a larger mixing region.
- Cut-off in the proton spectrum at ~1.5 TeV



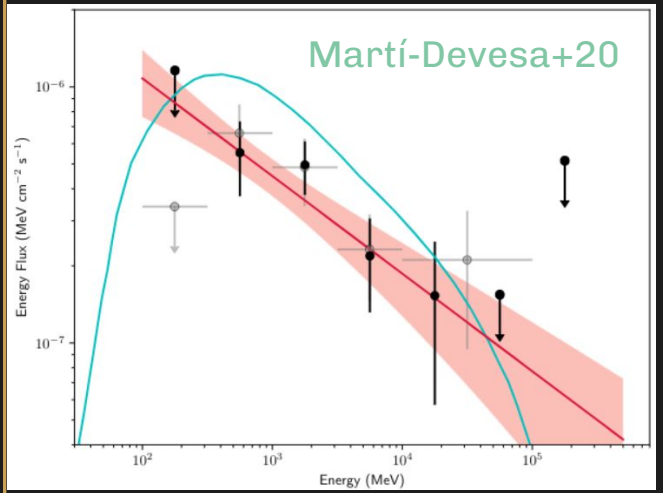
γ^2-Velorum

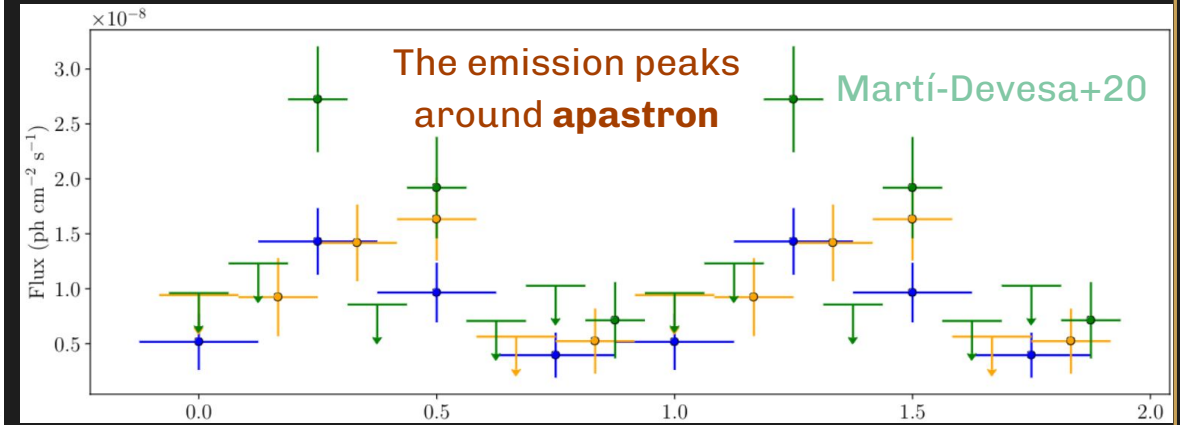
P~80 d, *a*~1 AU. Detected with *Fermi* (Pshirkov+16). The emission is likely hadronic (Reitberger+17).

$\dot{M}_1 \approx 3 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ $\quad$ $\dot{M}_2 \approx 1.8 \times 10^{-7}\,\mathrm{M_\odot\,yr^{-1}}$

$v_{\infty,1} \approx 500\,\mathrm{km\,s^{-1}}$ $\quad$ $v_{\infty,2} \approx 2500\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{w},1} \approx 2 \times 10^{37}\,\mathrm{erg\,s^{-1}}$ $\quad$ $P_{\mathrm{w},2} \approx 4 \times 10^{35}\,\mathrm{erg\,s^{-1}}$



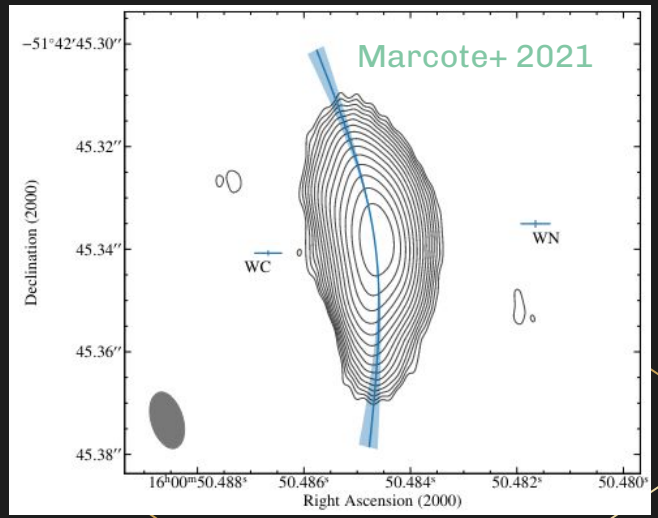


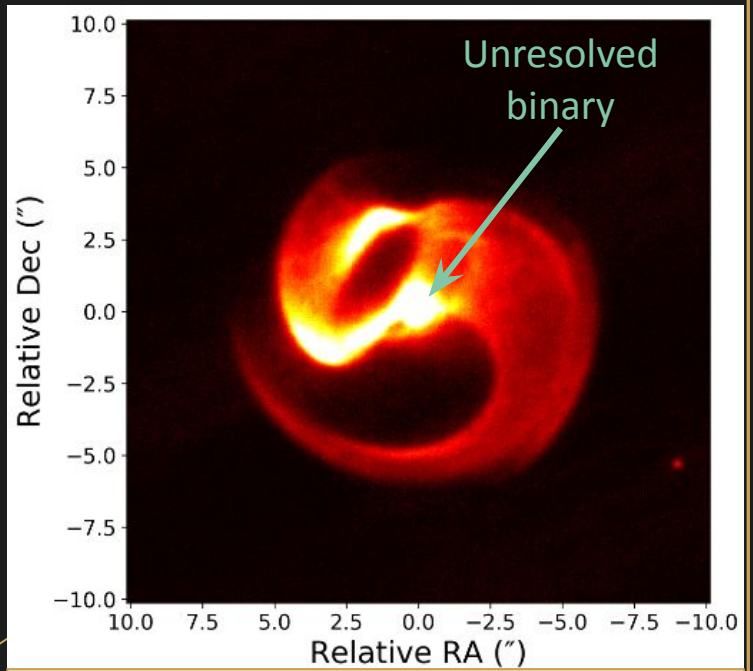
Apep

$\dot{M}_1 \approx 3.5 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ $\dot{M}_2 \approx 1.6 \times 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$

$v_{\infty,1} \approx 3350\,\mathrm{km\,s^{-1}}$ $v_{\infty,2} \approx 2350\,\mathrm{km\,s^{-1}}$

$P_{\mathrm{w},1} \approx 10^{38}\,\mathrm{erg\,s^{-1}}$ $P_{\mathrm{w},2} \approx 3 \times 10^{37}\,\mathrm{erg\,s^{-1}}$





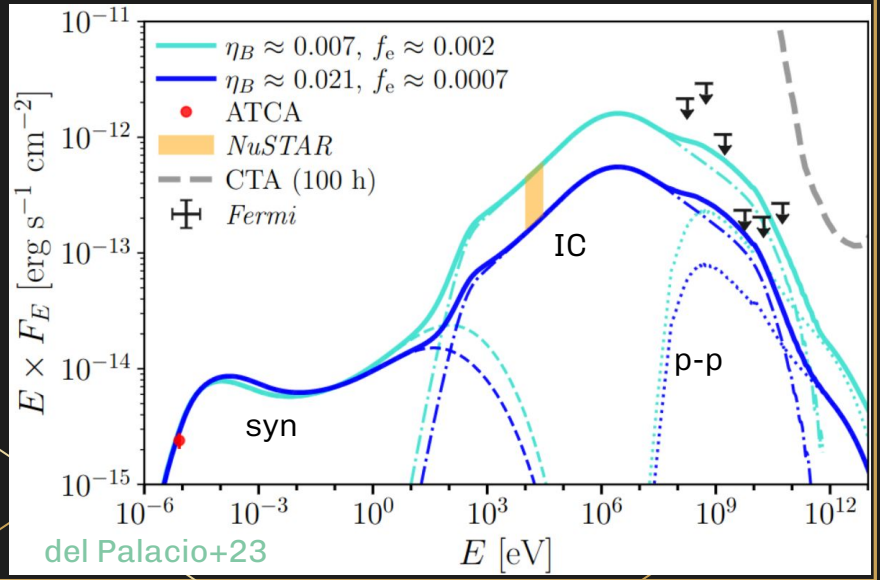
IR emission at 1.3 μm (Han+2020)

Apep

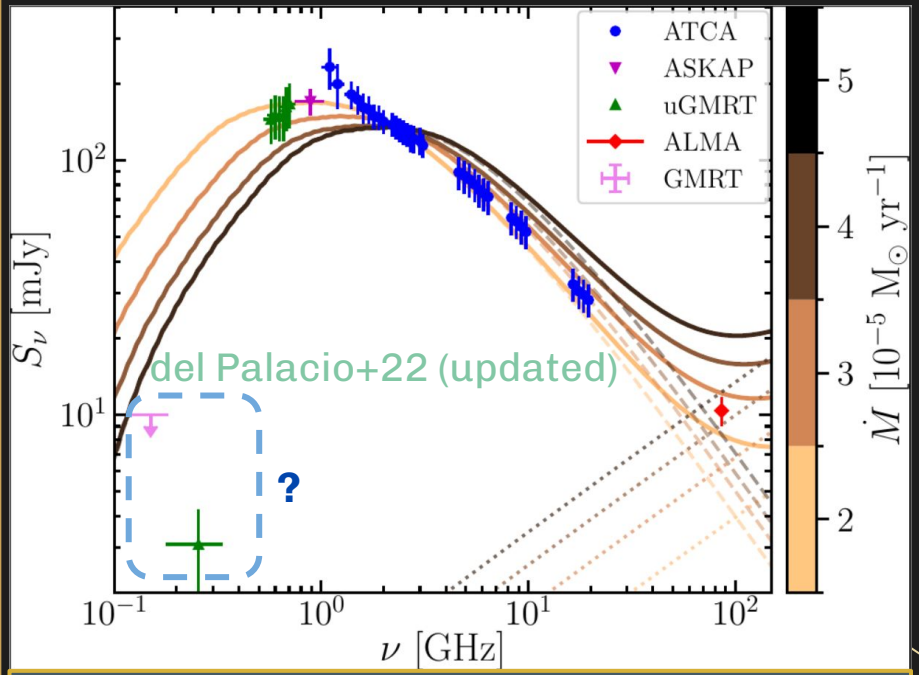
- This is the **brightest synchrotron** CWB: $S_{1.4\ \mathrm{GHz}}$ = 166 mJy, α =-0.71 (Callingham+19)
- Long period orbit. The stars are separated by 47 mas ($D_{\mathrm{proj}} \sim 110$ AU)
- Well-characterised winds (del Palacio+22, Zhekov+25)
- Hard X-ray source (del Palacio+23)

$$P_{\mathrm{NT,e}} \sim 10^{-4} P_{\mathrm{w}}$$
$$P_{\mathrm{NT}} \sim 0.5\% P_{\mathrm{w}}$$
$$K_{\mathrm{e,p}} = 0.04$$

Strong constraints in the SED from the *NuSTAR* detection (del Palacio+23) and the *Fermi* ULs (Martí-Devesa+23)



Apep



The low-frequency turnover due to FFA depends on the density, thus on the wind mass-loss rate

- ALMA data can constrain better the wind mass-loss rate (B6 and B7 observations planned this year)
- How to explain such a steep spectrum at low frequencies?
- We need better observations at < 1 GHz

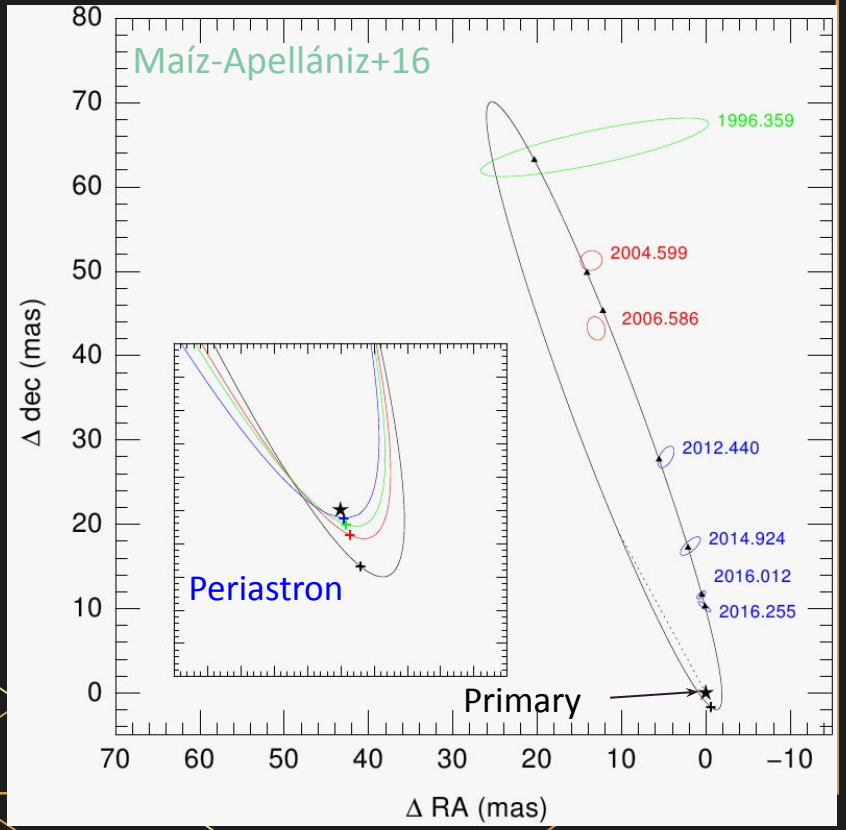
HD 93129A

$\dot{M}_1 \approx 10^{-5}\,\mathrm{M_\odot\,yr^{-1}}$ $\dot{M}_2 \approx 4\times10^{-6}\,\mathrm{M_\odot\,yr^{-1}}$

$v_{\infty,1} \approx 3200\,\mathrm{km\,s^{-1}}$ $v_{\infty,2} \approx 2800\,\mathrm{km\,s^{-1}}$

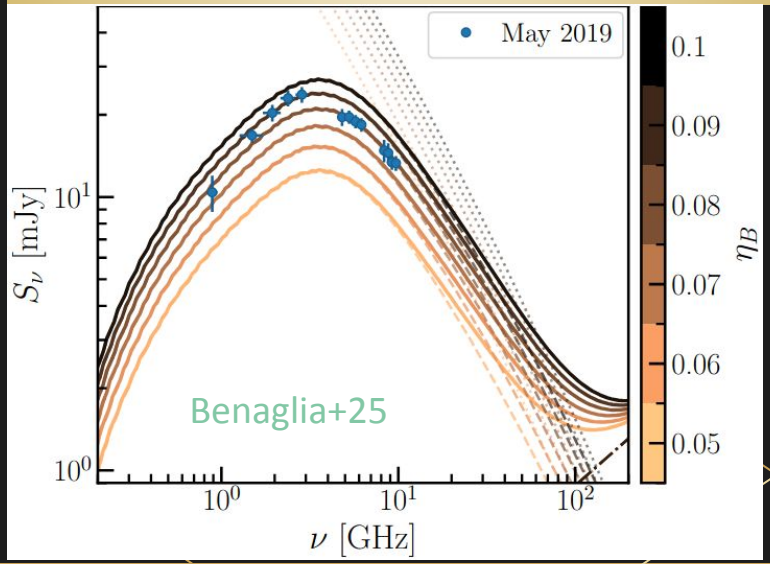
$P_{\mathrm{w},1} \approx 3\times10^{37}\,\mathrm{erg\,s^{-1}}$ $P_{\mathrm{w},2} \approx 10^{37}\,\mathrm{erg\,s^{-1}}$

- ★ Long period orbit: P ~ 100 yr, a_p ~ 10 AU.
- ★ Possibly a triple system
- ★ Non-thermal emission resolved in radio (Benaglia+15).
- ★ Possible hard X-ray source (del Palacio+20), hints of orbital variability (in prep.)



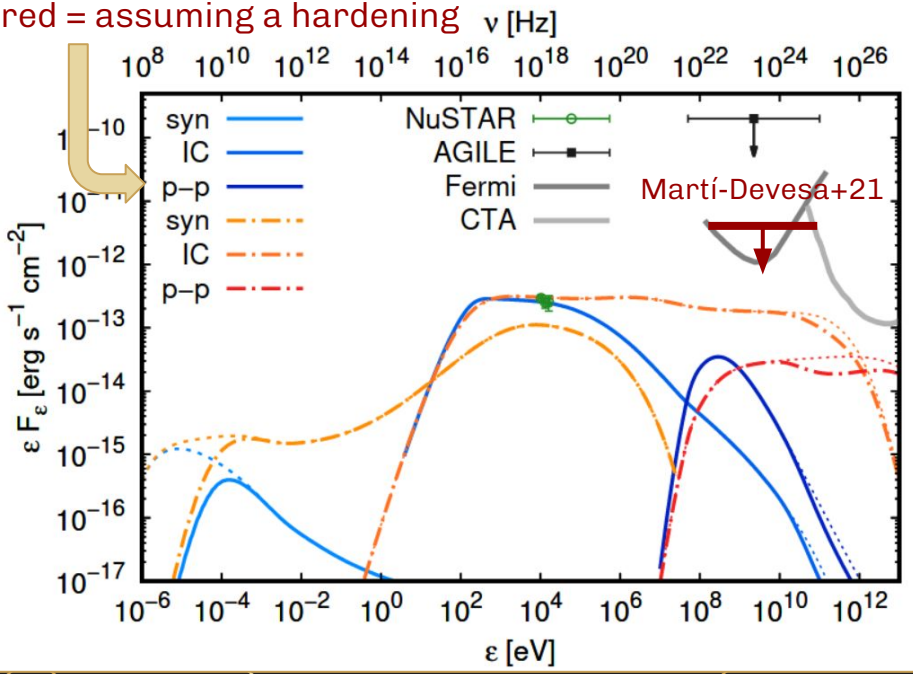
The system HD 93129A

The X-ray observations during periastron (2018) + radio observations (~2019):
$f_{NT,e}$ ~ 0.15% and η_B ~ *0.085* (B_{WCR} ~ 1 G)



blue = soft spectrum (radio)
red = assuming a hardening

del Palacio+20



Summary CWBs

System	d (kpc)	D (AU)	L_{w1}, L_{w2} (erg/s)	Radio	X-rays	γ-rays
γ^2 Vel (WR+O)	0.342	~1.6	2e37, 4e35	no	no	yes
Eta-Car (LBV + O?)	2.35	~1.5	4e37, 4e37	no	yes	**yes**
HD 93129A (O+O…)	2.4	~20	1e37, 1e37	yes	yes?	no
Apep (WR+WR)	2.4	>110	1e38, 3e37	yes!	yes?	no

Conclusions

- We detect non-thermal emission associated with colliding stellar winds
- **CWBs are faint high-energy sources** (very few detections)
- **Radio observations are insufficient** to characterise the non-thermal particle population. Potentially, great **synergy with observations at high-energies** (X-rays and γ-rays). However, bright in radio $\not\leftrightarrow$ bright in γ-rays.
- Multi-wavelength observations + detailed **modelling** can shed light on the **properties of CWBs** (magnetic fields, particle-acceleration efficiency).

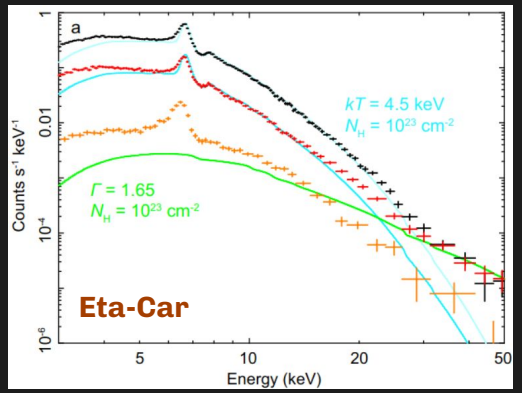
Thank you

Observational status

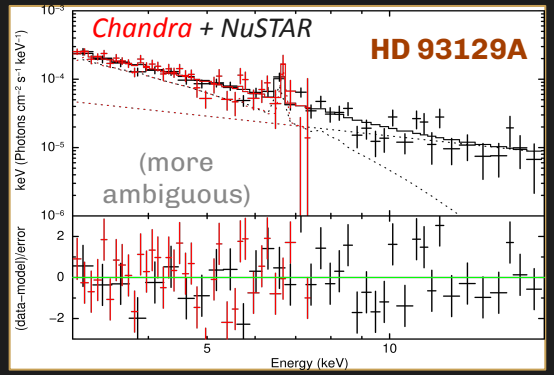
- **+40 CWBs identified in radio**
- **2 CWBs detected in γ-rays**
- **2 (3?) CWBs detected in hard X-rays**

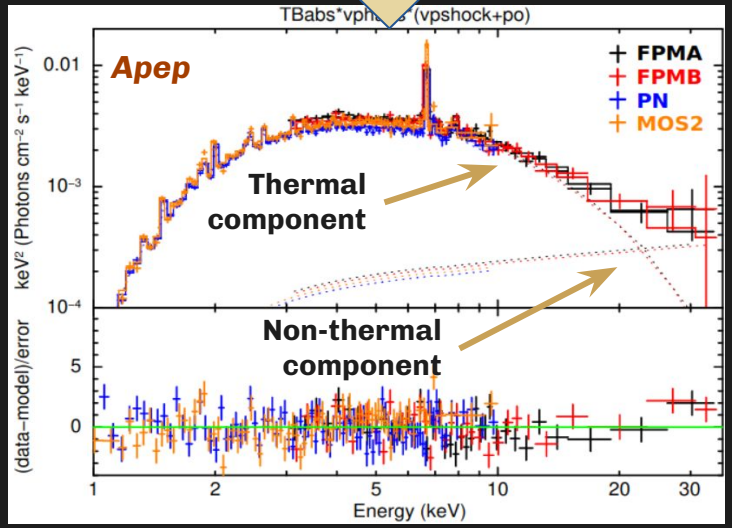
Apep is the first system detected at radio and at high-energies!

Hamaguchi+18



del Palacio+20





del Palacio+23

Transport equation

Stationary and inhomogeneous structure made up of multiple 1-D emitters

For a given 1-D linear emitter we obtain *N(E)* at each position:

- First cell ($j = i_{\rm min}$):

$$N_0(E, i_{\rm min}) \approx Q(E, i_{\rm min}) \min(t_{\rm cell}, t_{\rm cool})$$

$$L_{\rm NT}(i_{\rm min}) = f_{\rm NT} L_{\rm w,\perp}(i_{\rm min})$$

- Next cells ($j > i_{\rm min}$):

$$N(E', i+1) = N(E, i) \frac{|\dot{E}(E, i+1)|}{|\dot{E}(E', i+1)|} \frac{t_{\rm cell}(i+1)}{t_{\rm cell}(i)}$$

del Palacio+22

del Palacio+16