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y Radiastronomía

Non-thermal radiation from bow-shocks of massive runaway stars

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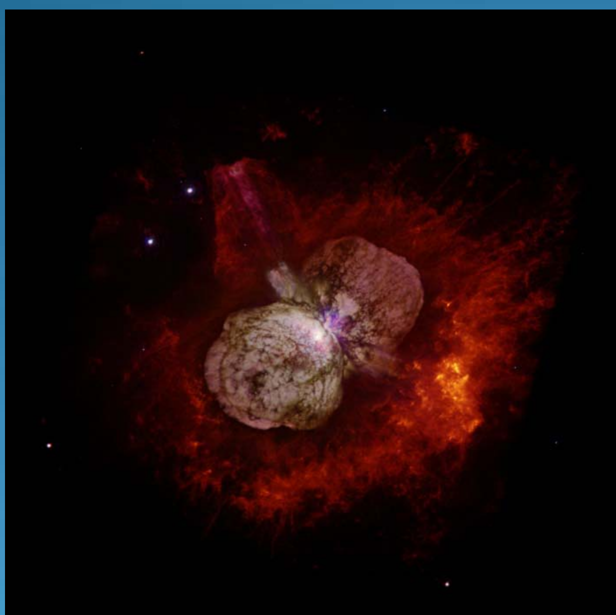
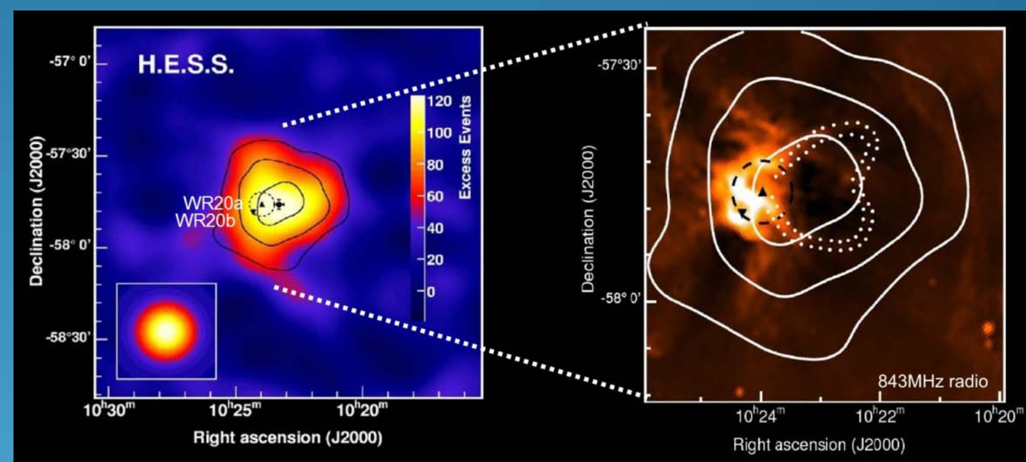
Gamma rays from massive stars: not a new idea (Cassé & Paula 1980, Völk & Forman 1982)

Detection, however, has remained elusive, except in the case of colliding wind binaries and collective effects





Westerlund 2; Aharonian et al. 2007

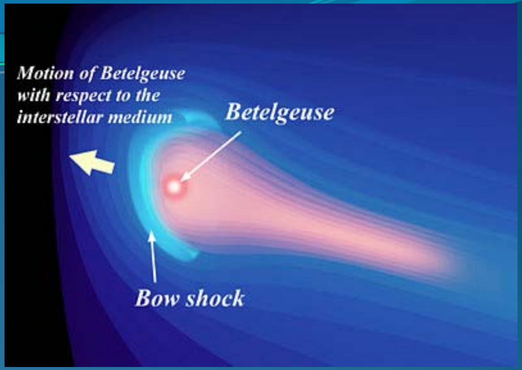
Eta Carinae; Tavani et al. 2009, Abdo et al. 2010

Runaway massive stars

- $v >$ 30 km/s > sound speed
- Origin: binary supernovae / direct encounters in clusters …
- *Rare*: GOSC (Maíz Apellániz+04): 8% of ~400 stars
- Strong stellar winds sweep IS matter

Bow shocks

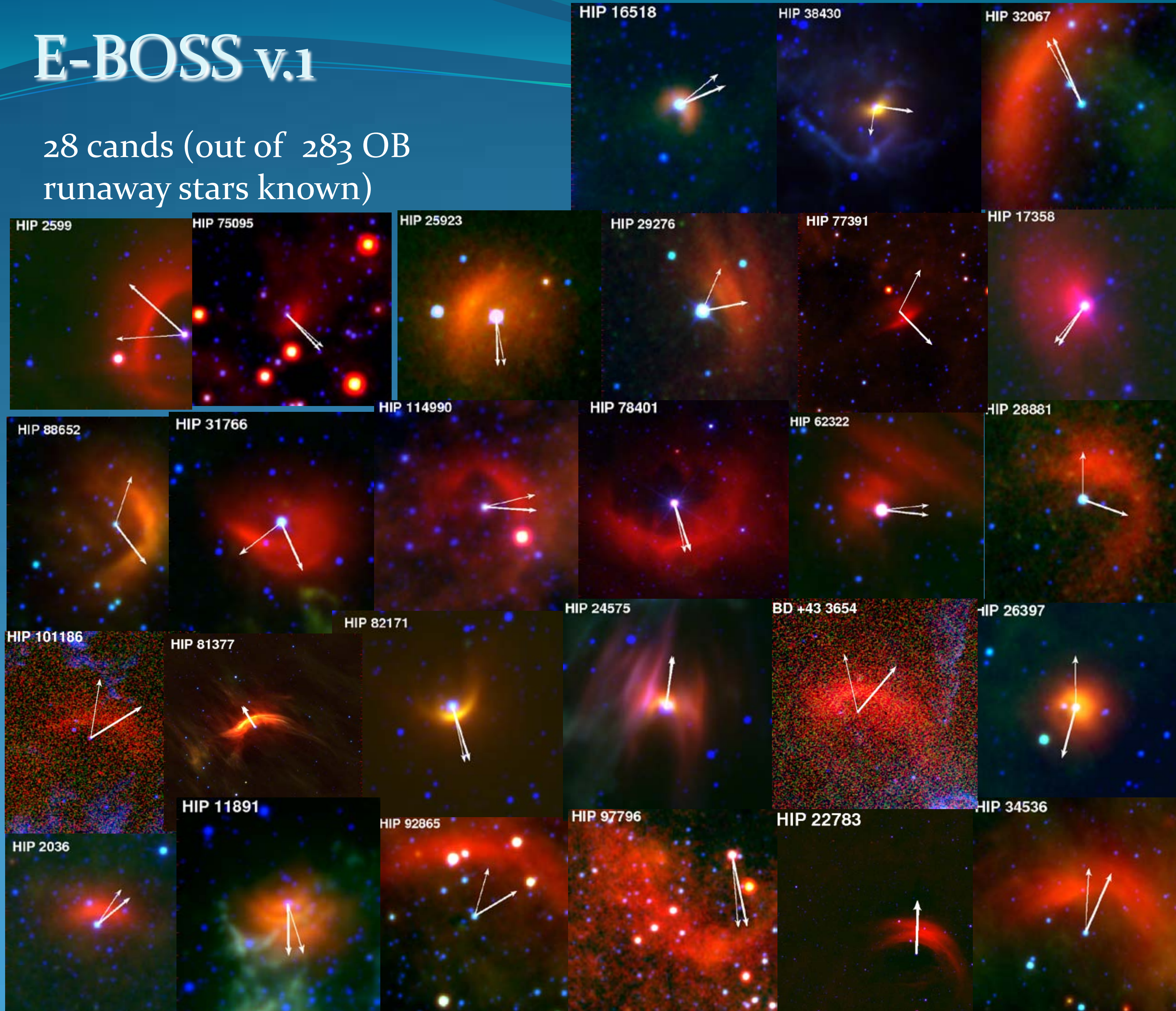
Stellar bow shocks



- Arc-shaped features of piled-up material
- Same direction as stellar velocity
- Winds confined by ISM ram pressure
- Distance to star by momentum balance
- Radiation from shocked gas heats swept dust
- Dust re-radiates as MIR and FIR excess

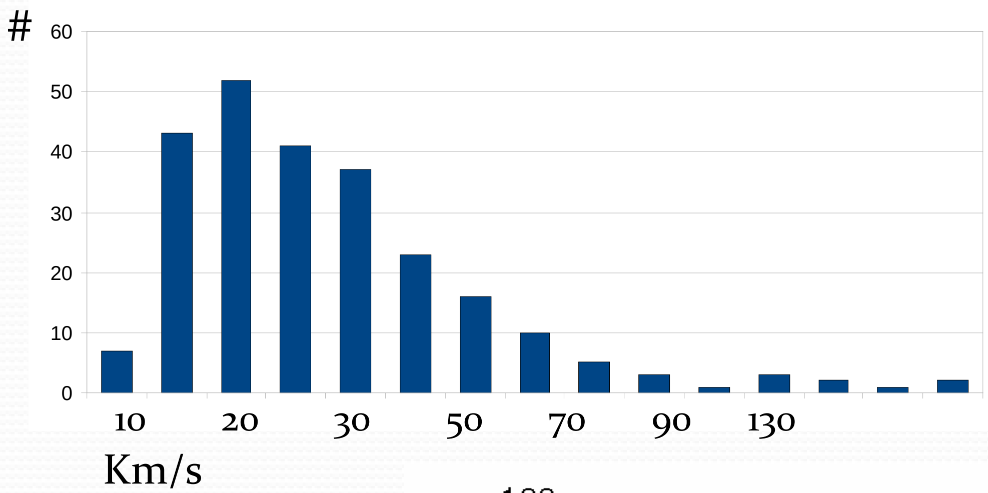
E-BOSS v.1

28 cands (out of 283 OB runaway stars known)



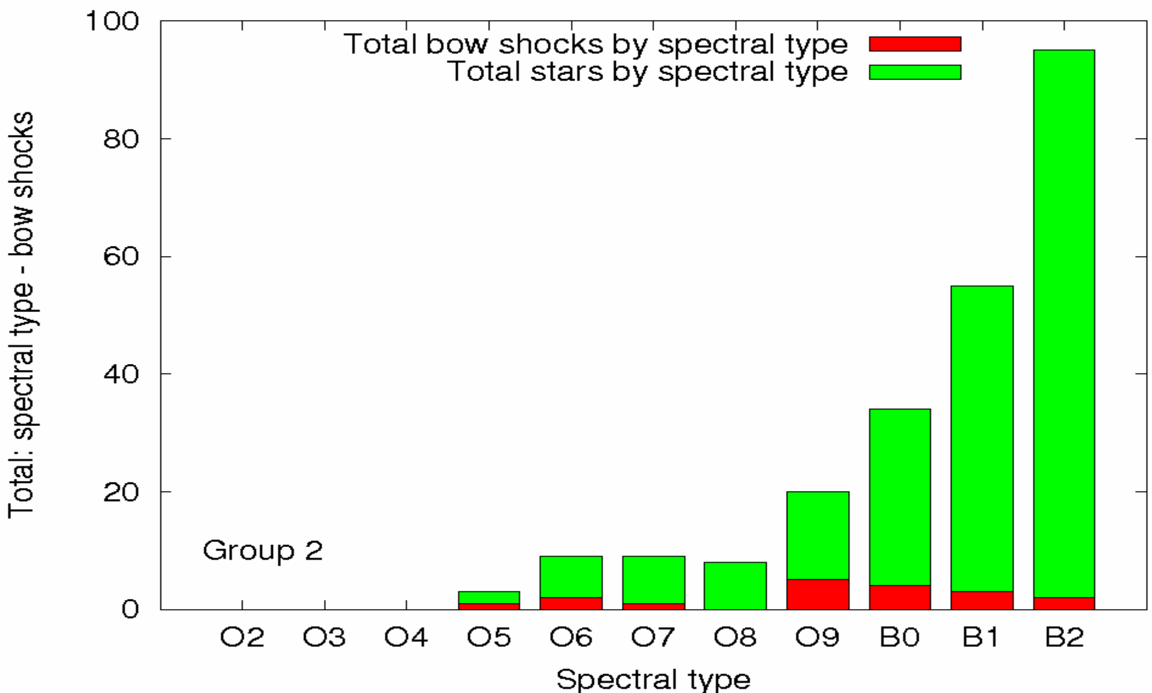
Peri, Benaglia, Brookes, Stevens, Isequilla 2012, A&A

Distributions



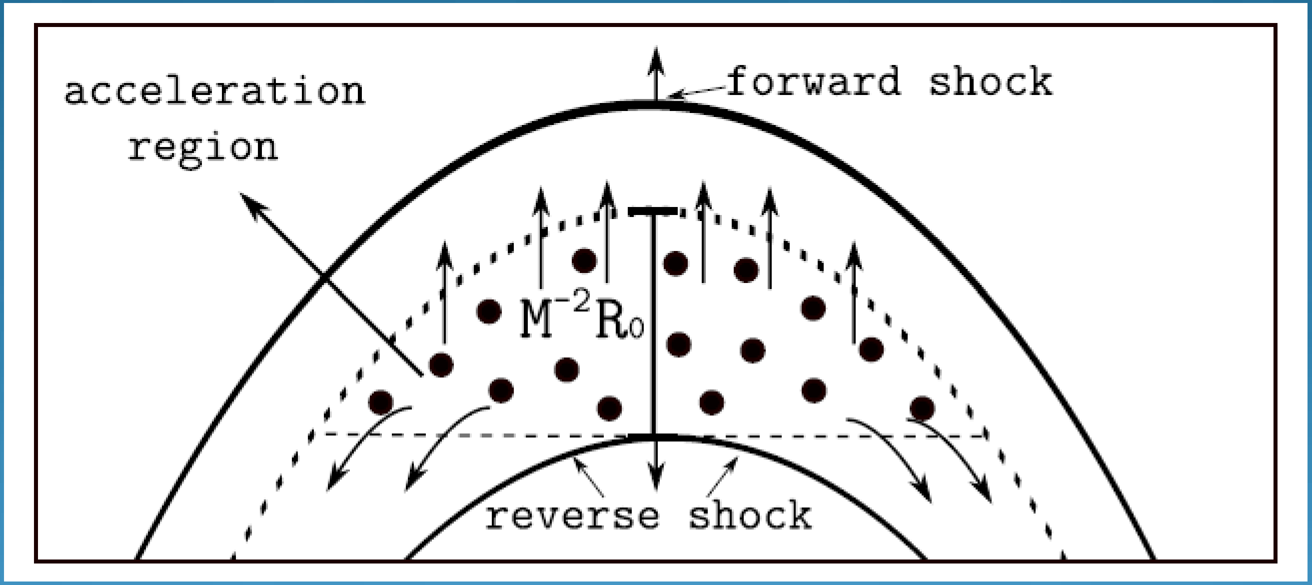
Number of stars vs. Spatial velocity

Tetzlaff + 2010



Peri, Benaglia, et al. 2012, A&A

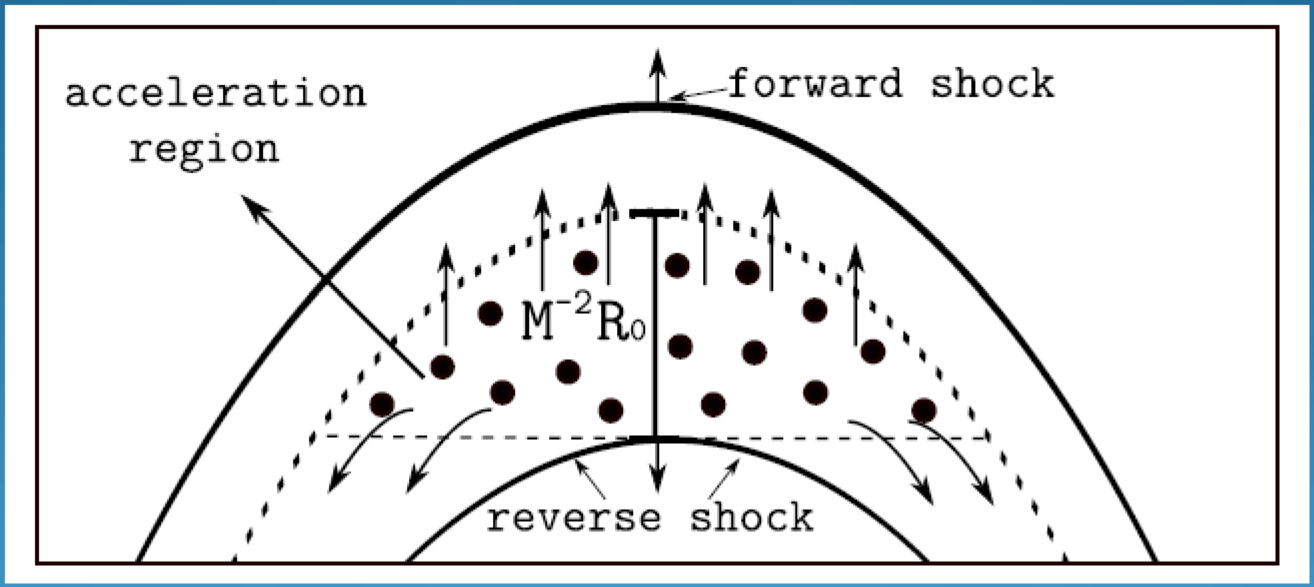
Modeling bow-schocks and their emission



$$R_0 = \sqrt{\frac{\dot{M}_{\rm w} V_{\rm w}}{4\pi \rho_{\rm a} V_\star^2}}.$$

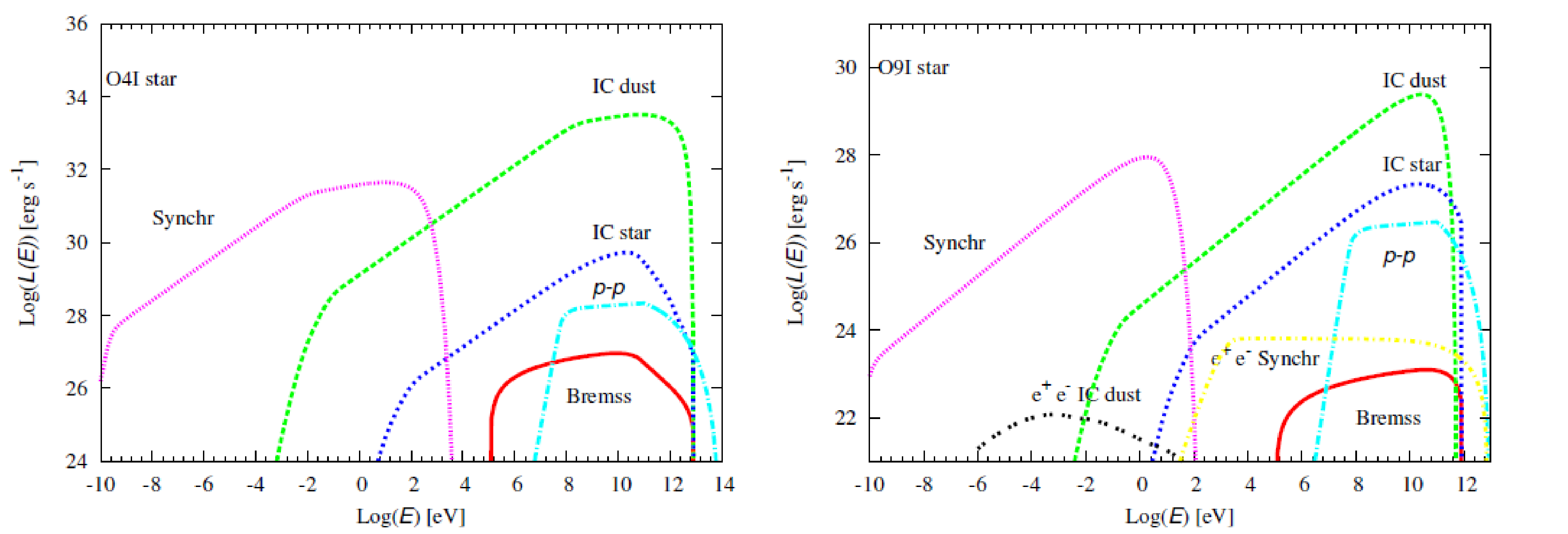
Relativistic particles are accelerated at the reverse adiabatic shock in the stellar wind

Modeling bow-schocks and their emission



$$\frac{\partial}{\partial E}\left[\frac{\mathrm{d}E}{\mathrm{d}t}\bigg|_{\mathrm{loss}} N(E)\right] + \frac{N(E)}{t_{\mathrm{esc}}} = Q(E),$$

Spectral energy distributions for O4I and O9I stars



del Valle & Romero 2012, A&A

The star BD+43°3654

IRAS bow shock candidates (Noriega-C. et al. 1997)

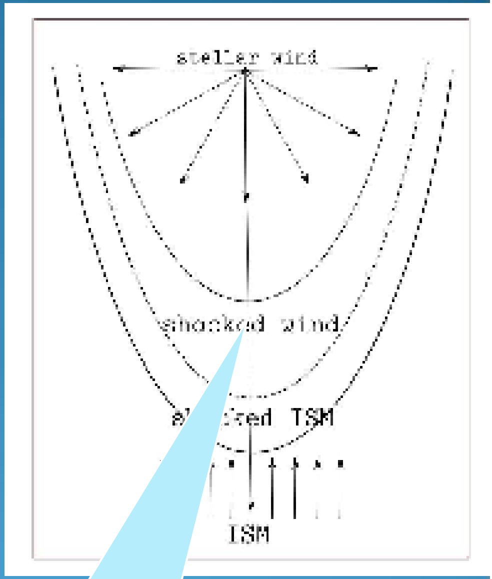
Comerón & Pasquali 2007:

- Bow shock at MSX-D, E bands
- Runaway from Cyg OB2, 1.4 kpc
- O4 If ; 70 M_{o} ; 1.6 Myr; [v_{w} = 3200 km/s]

Kobulnicky et al. 2010:

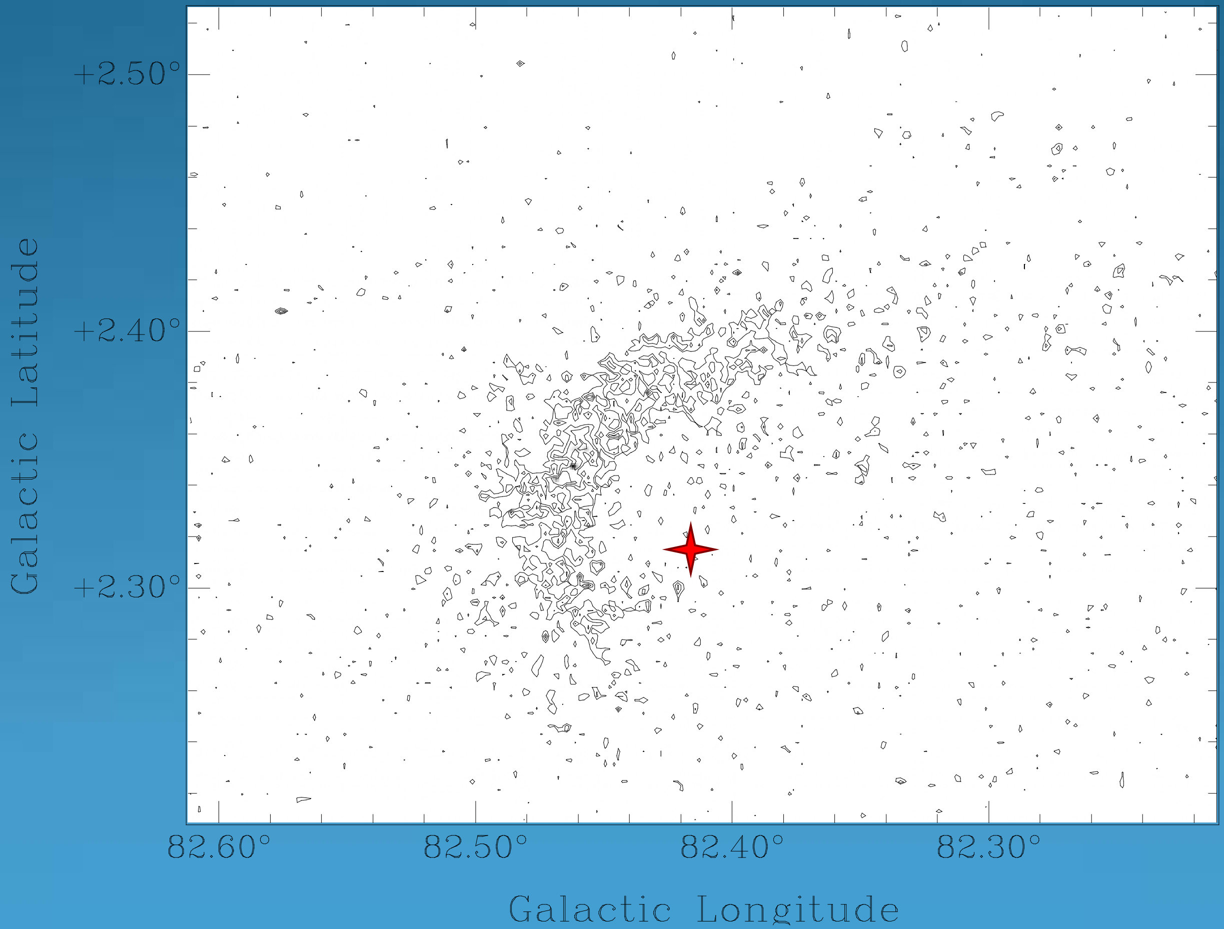
- v ~ 80km/s, dM/dt ~ 2 x 10^{-4} M_{o}/yr

Ambient density: 6 to 100 cm^{-3}



A non-thermal emitter?

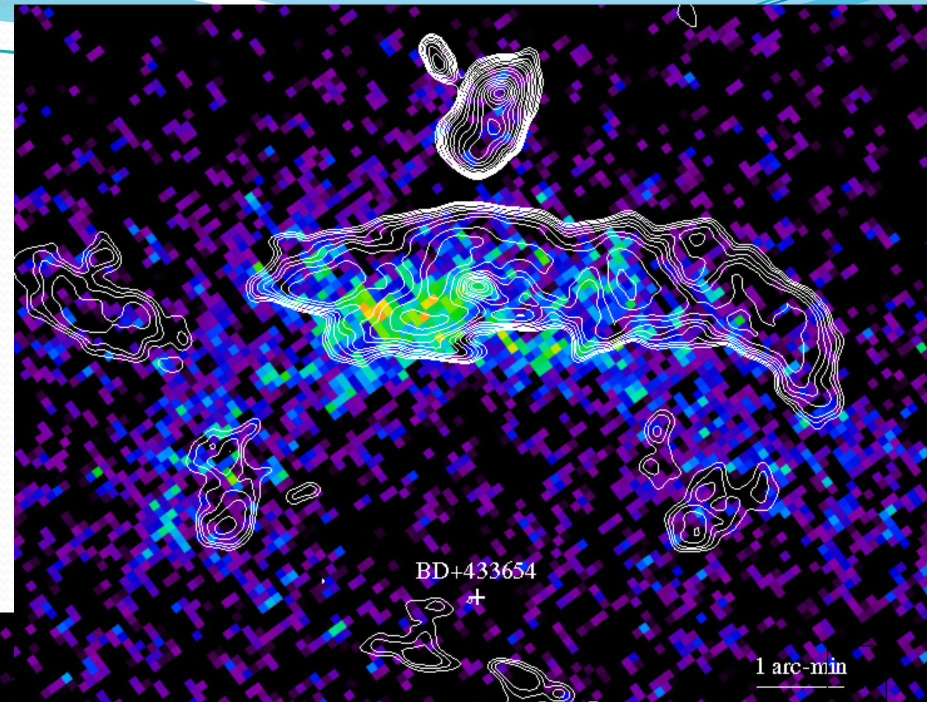
MSX emission toward BD+43^0 3654



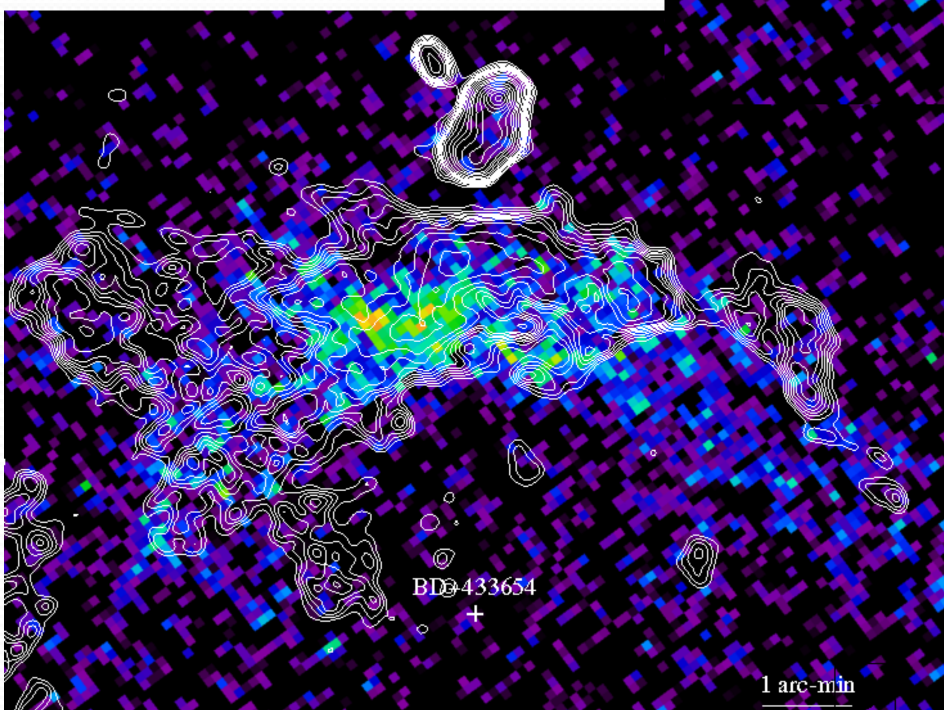
D-band image (14.65 μm)

VLA + MSX images

Benaglia, Romero, et al 2010, A&A



C band

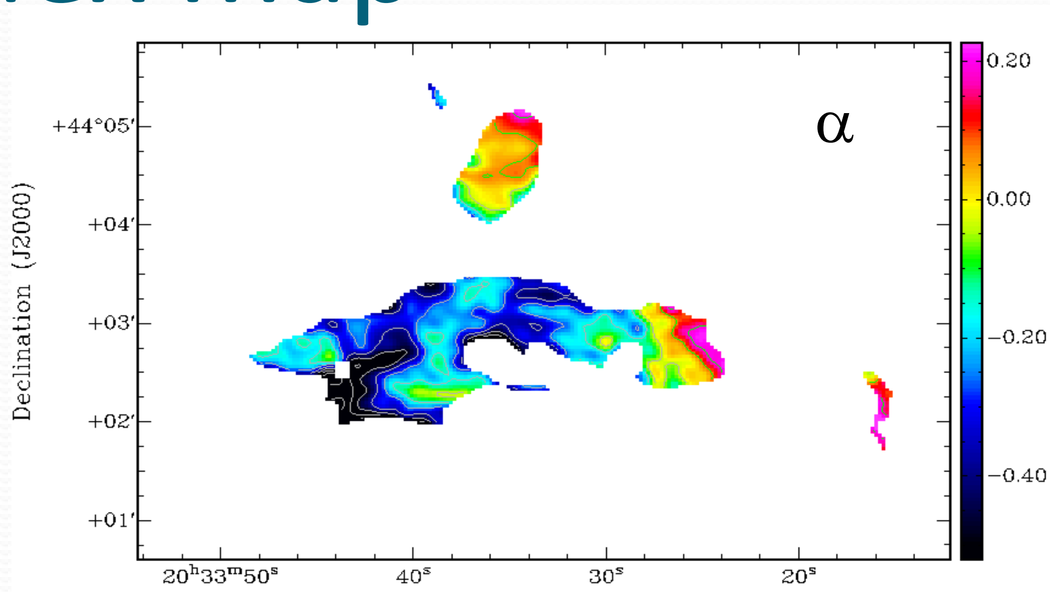


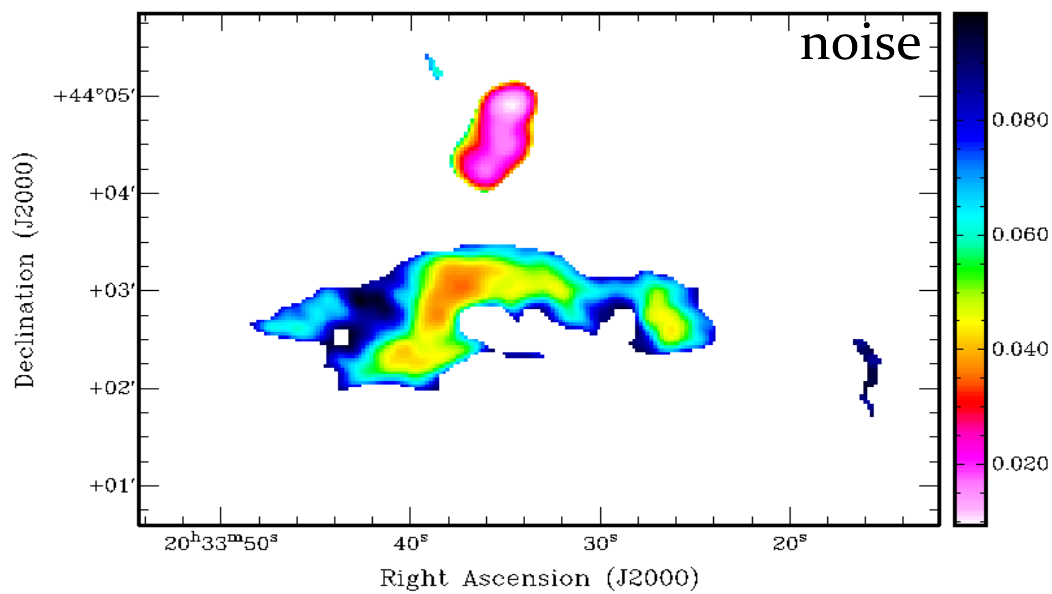
L band

Spectral index map

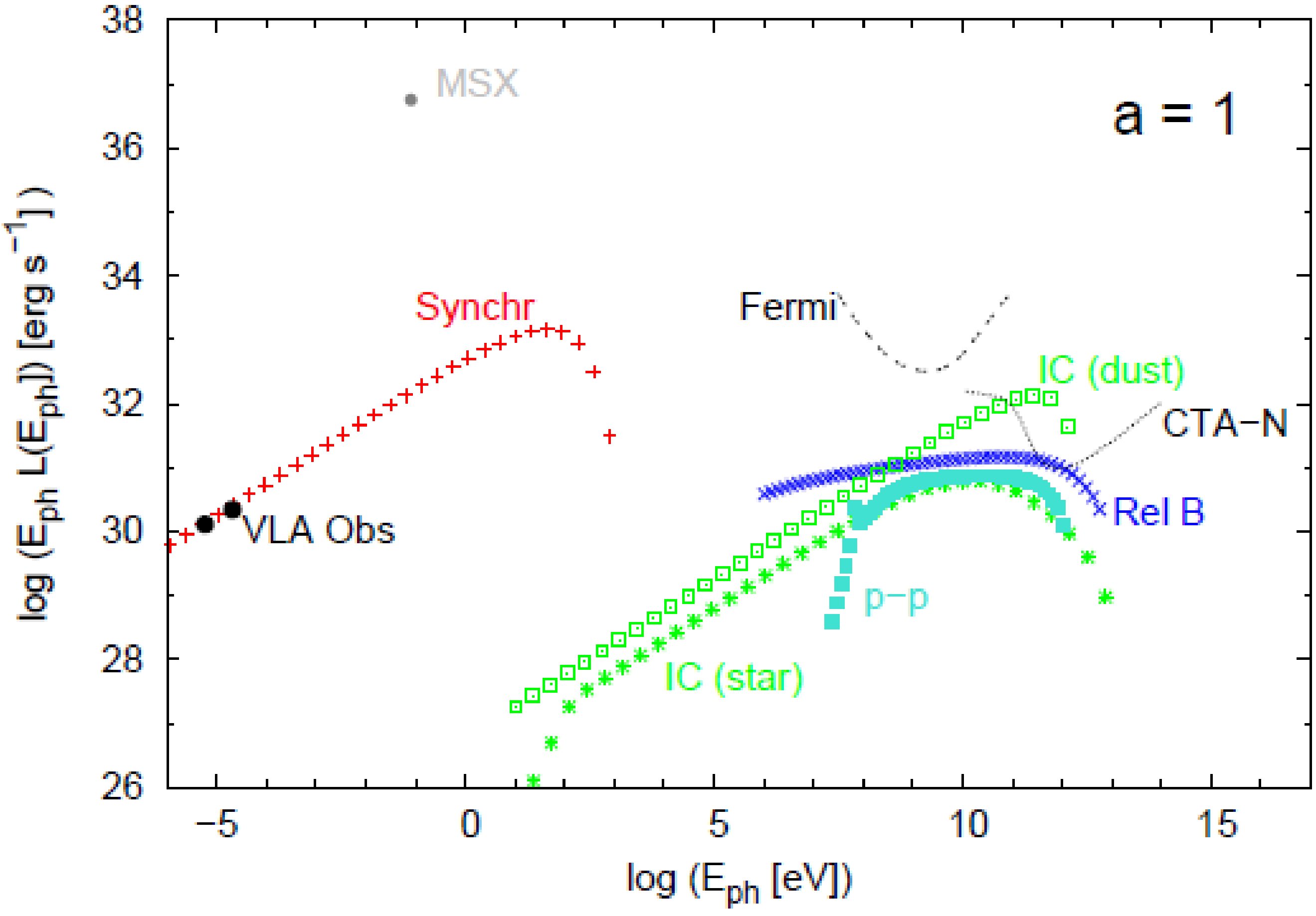
- $S(\nu) \sim k\ \nu^{\alpha}$
- s/n (cont) ≥ 4
- s/n (α) ≥ 10
- $-0.8 \leq \alpha \leq 0.3$.
- $\langle\alpha\rangle$ -0.4

Benaglia, Romero, et al 2010, A&A





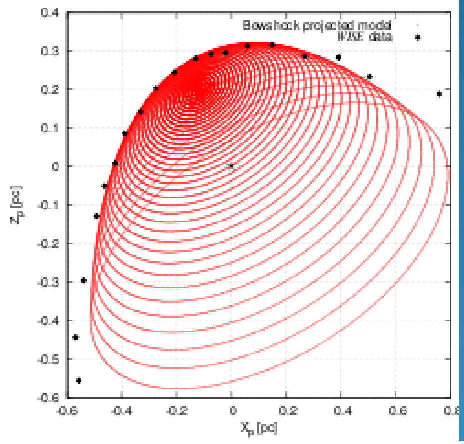
SED

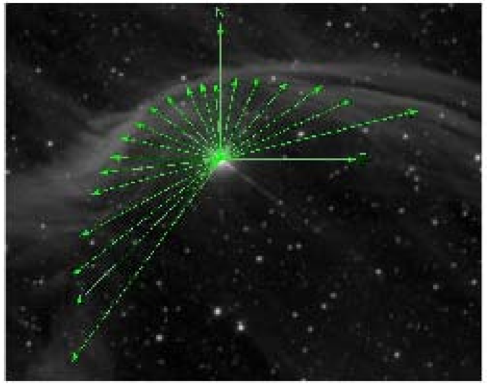


Benaglia, Romero, et al 2010, A&A

ζ Oph bow-shock

del Valle & Romero 2012, A&A





Computed BS & WISE image

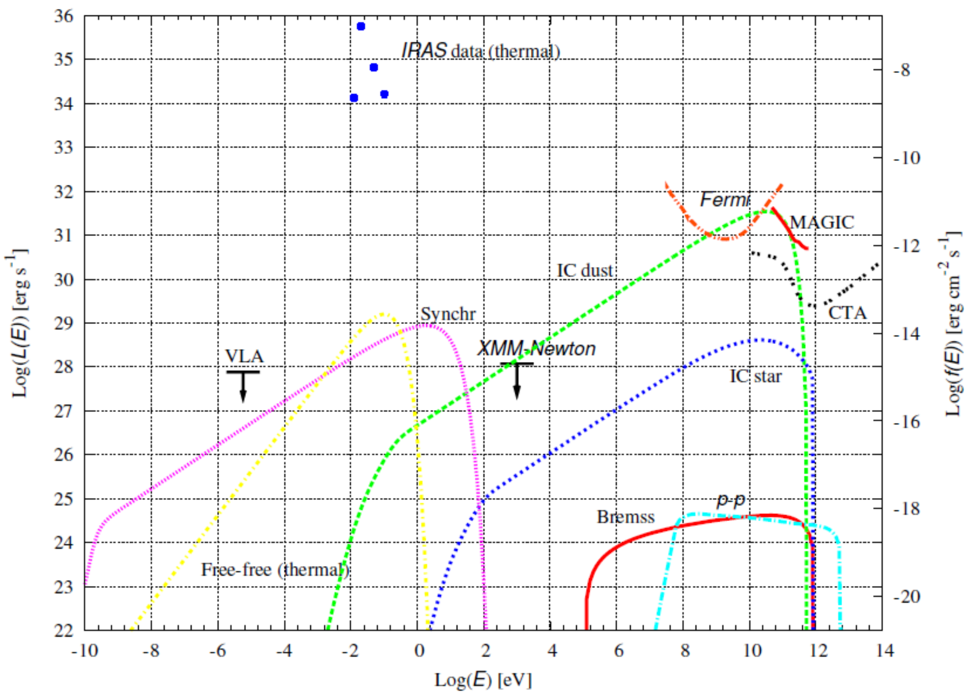
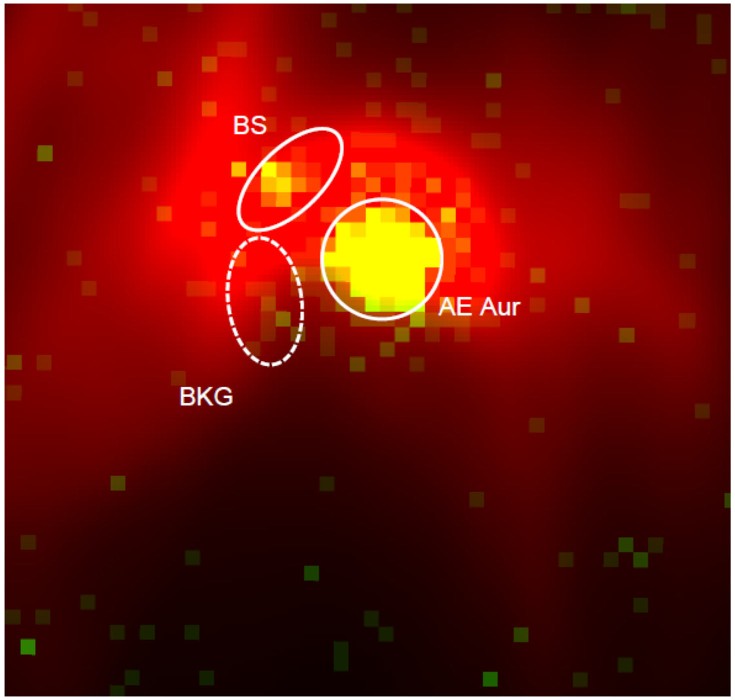


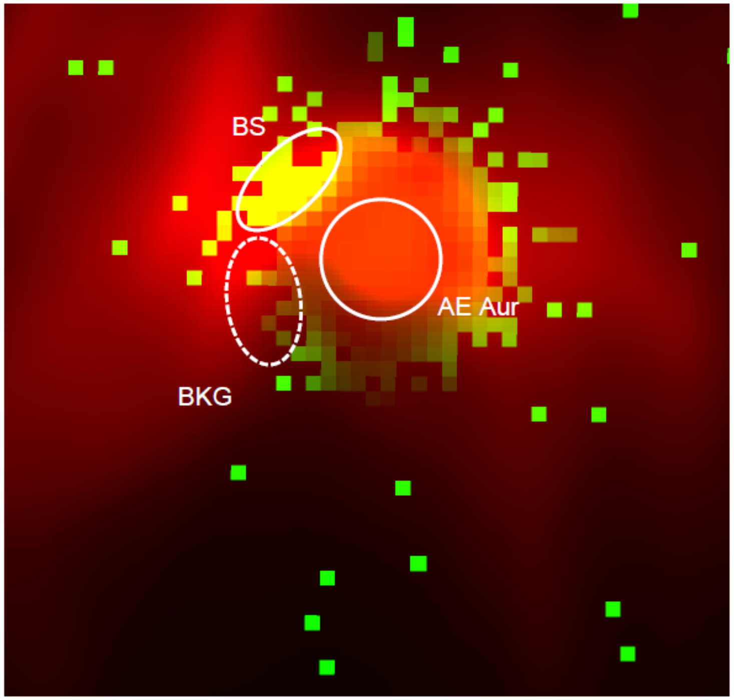
Fig. 11. Computed SED for ζ Oph bowshock, at d ∼ 222 pc. The sensitivity for CTA, *Fermi*, MAGIC, *XMM-Newton* and VLA. *IRAS* data are also shown.

SED and sensitivities

AE Auriage

López-Santiago, Miceli, del Valle, Romero, et al. 2012



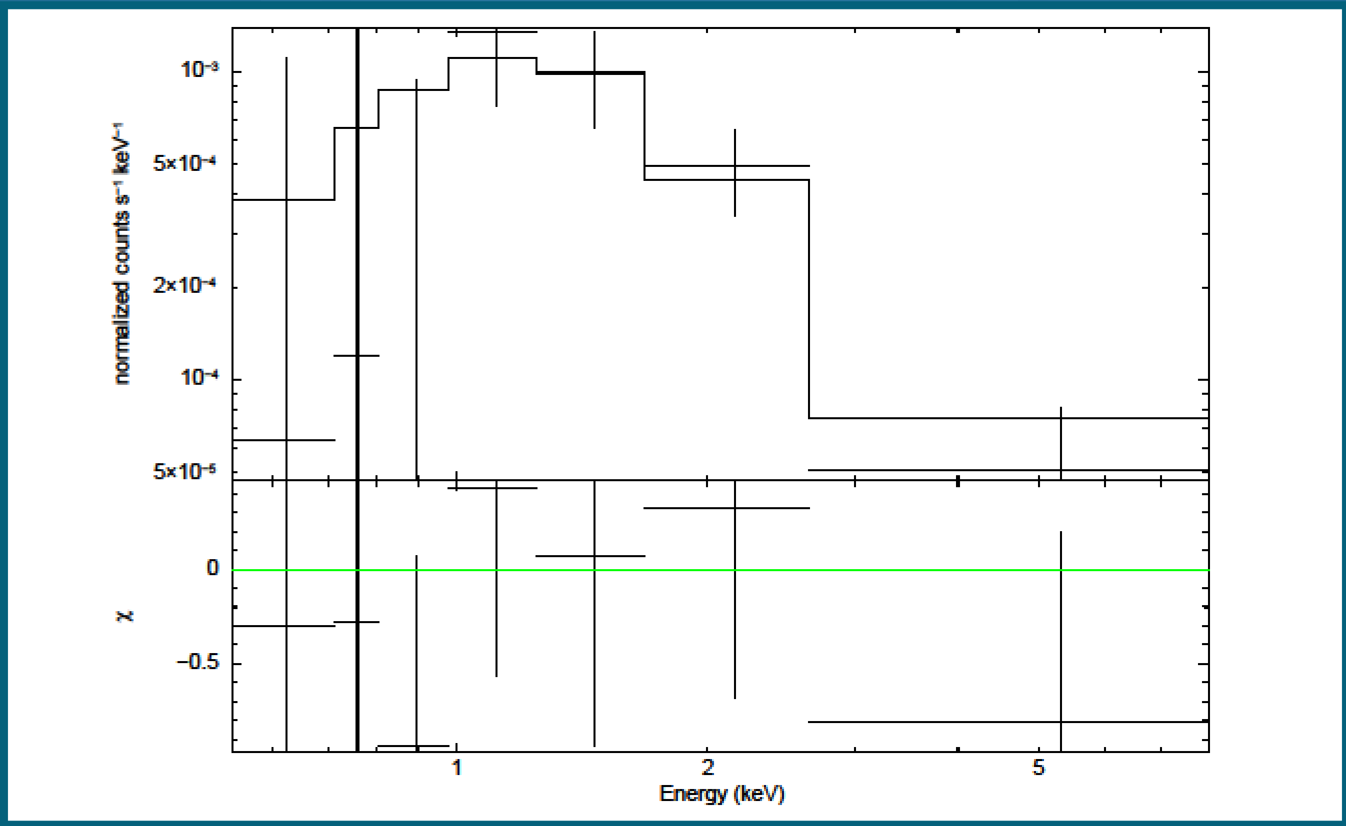


WISE + 1-8 keV EPIC map

Energy map

AE Auriage

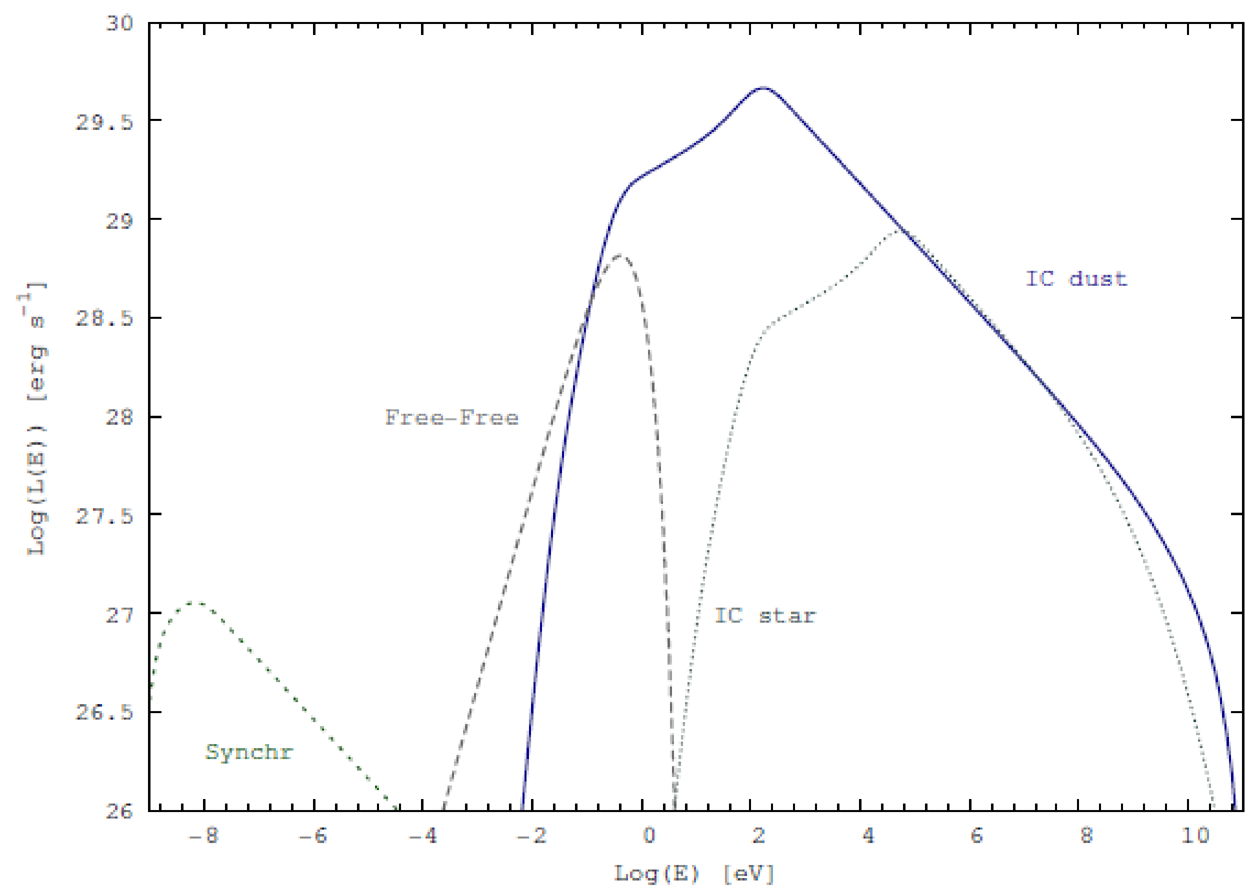
López-Santiago, Miceli, del Valle, Romero, et al. 2012



Absorbed X-ray power law ~ -2.5

AE Auriage

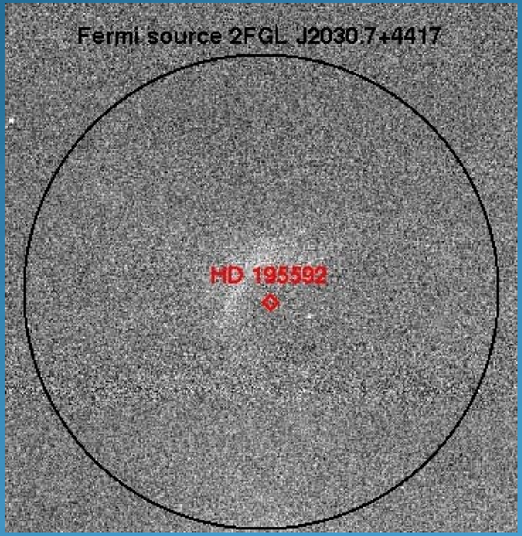
López-Santiago, Miceli, del Valle, Romero, et al. 2012



Eemax~1 TeV

Is HD 195592 a Fermi source?

del Valle, Romero, & De Becker 2012



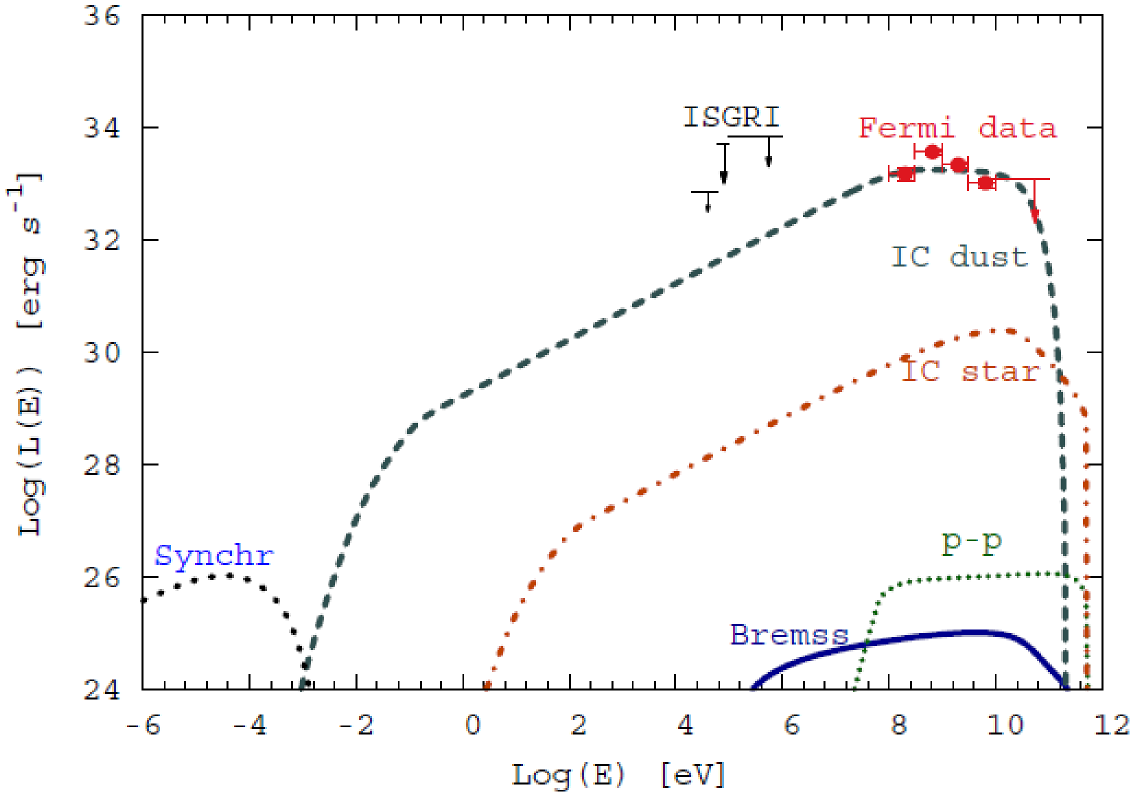


Fig. 2. Computed SED for HD 195592 bowshock, at d ∼ 1 kpc. *Fermi* data of 2FGL J2030.7+4417 and hard X-rays upper limits are also shown.

Conclusions

•Runaway massive stars can produce relativistic particles in their bowshocks.

•They have strong infrared fields so IC losses should be important in many cases.

•Some nearby runaway O stars can be detected in gamma-rays by Fermi and in the future by CTA.

• Others stars, although not reaching the GeV energy range, can be non-thermal X-ray sources.

In any case, nearby runaway massive stars and their associated bowshocks are a potentital class of new high-energy source.

Thanks!

Gamma rays from massive stars: not a new idea

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LOCAL GAMMA RAYS AND COSMIC-RAY ACCELERATION BY SUPERSONIC STELLAR WINDS

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COSMIC RAYS AND GAMMA-RAYS FROM OB STARS

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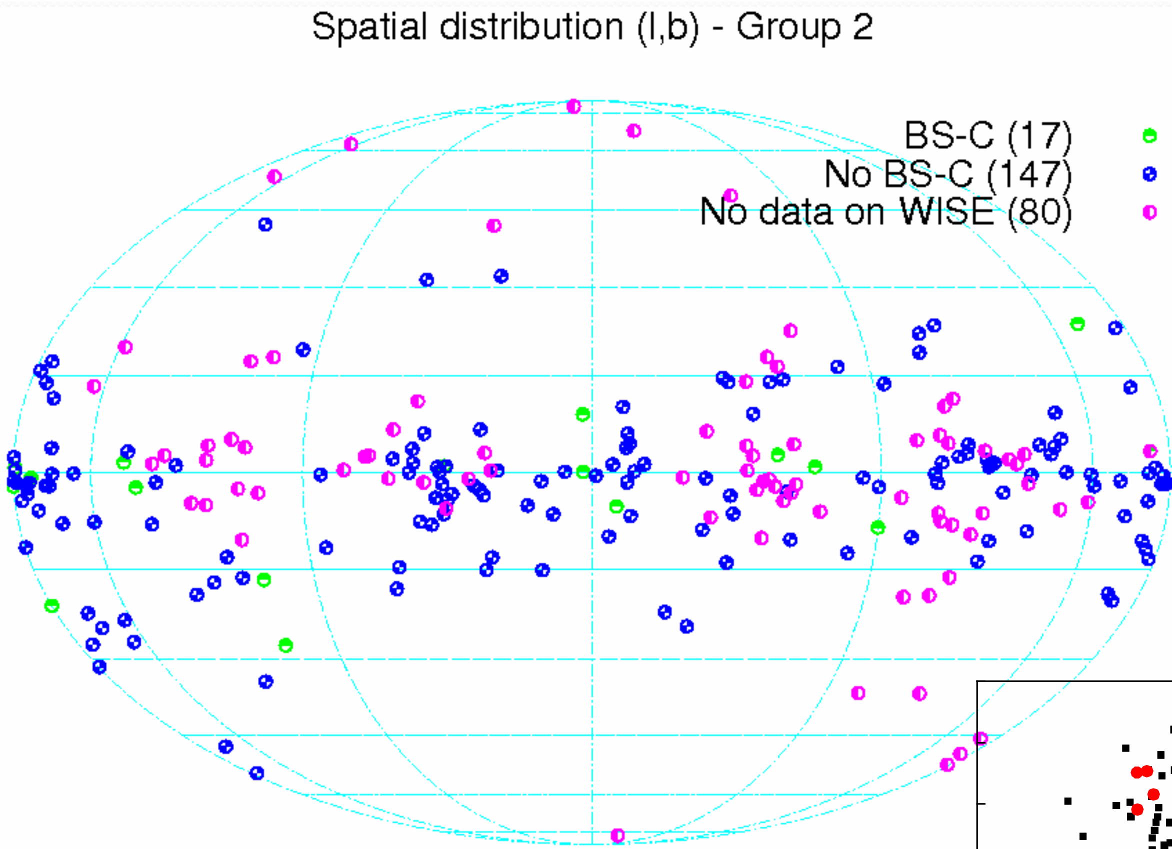
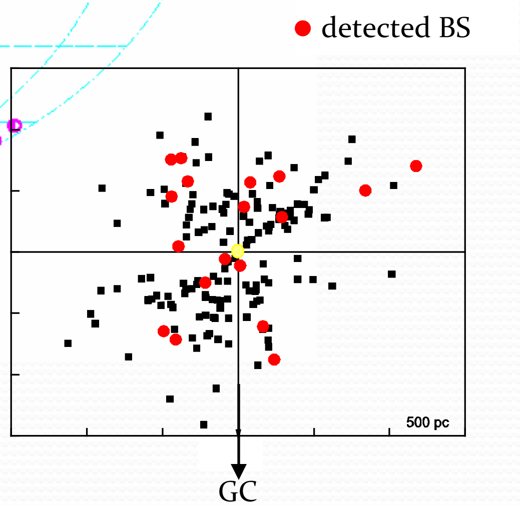
Table 3. List of the E-BOSS bow shock candidates and corresponding stellar parameters.

Star	Group	l [°]	b [°]	Spectral type	d [pc]	v_∞ [km s^{-1}]	$\dot{M} \times 10^6$ [$M_\odot$ yr^{-1}]	v_{tg} [km s^{-1}]	v_r [km s^{-1}]	$\mu_\alpha \cos\delta$ [mas yr^{-1}]	μ_δ [mas yr^{-1}]
HIP 2036	2	120.9137	+09.0357	O9.5III+B1V	757±161[a]	[1200]	0.48	15.2	−5	−1.66	1.90
HIP 2599	1,2	120.8361	+00.1351	B1 Iae	1457±300[a]	1105	0.12	26.2	−2.3	3.65	−2.07
HIP 11891	2	134.7692	+01.0144	O5 V((f))	(900)	2810	1.10	11.9	−48	0.03	−2.16
HIP 16518	2	156.3159	-16.7535	B1 V	(650)	[500]	0.006	47.3	25	−8.28	3.44
HIP 17358	1	150.2834	-05.7684	B5 III	(150)	[500]	<0.001	[35]	4	25.58	−43.06
HIP 22783	1	144.0656	+14.0424	O9.5 Ia	1607±275[a]	1590	0.25	[52]	6.1	−0.13	6.89
HIP 24575	2	172.0813	-02.2592	O9.5 V	548±68[a]	[1200]	0.1	140.0	59.1	−3.58	43.73
HIP 25923	2	210.4356	-20.9830	B0 V	(900)	[1000]	0.06	16.8	17.4	−0.10	−4.87
HIP 26397	2	174.0618	+01.5808	B0.5 V	(350)	[750]	0.014	11.9	−19	0.88	−3.61
HIP 28881	1	164.9727	+12.8935	O8 Vn	1500[b]	2070	0.03	[17]	5	−0.82	−1.49
HIP 29276	1,2	263.3029	-27.6837	B1/2 III	(400)	[600]	<0.001	9.2	30.6	−4.90	7.41
HIP 31766	2	210.0349	-02.1105	O9.7 Ib	1414±28[a]	1590	1.07	6.7	58.4	−0.34	−0.83
HIP 32067	1,2	206.2096	+00.7982	O5.5V((f))+...	2117±367[a]	2960	0.13	23.4	31	0.84	2.55
HIP 34536	1,2	224.1685	-00.7784	O6.5V((f))+...	1293±206[a]	2456	0.19	14.3	58	−1.96	4.40
HIP 38430	1	243.1553	+00.3630	O6Vn+...	(900)	[2570]	0.7	[13]	28	−3.04	−0.38
HIP 62322	2	302.4492	-05.2412	B2.5 V	(150)	[300]	0.006	4.5	42	−41.97	−8.89
HIP 72510	1,2	318.7681	+02.7685	O6.5III(n)(f)	(350)	[2545]	0.27	7.4	−74	−7.49	−5.15
HIP 75095	2	322.6802	+00.9060	B1Iab/Ib	(800)	[1065]	0.14	28.6	4	−8.42	−9.18
HIP 77391	1	330.4212	+04.5928	O9 I	(800)	[1990]	0.25	[19]	15	−4.63	−1.84
HIP 78401	1	350.0969	+22.4904	B0.2 IVe	224±24[a]	[1100]	0.14	[38]	−7	-10.21	-35.41
HIP 81377	1,2	006.2812	+23.5877	O9.5 Vnn	222±22[a]	[1500]	0.02	24.4	−15	15.26	24.79
HIP 82171	2	329.9790	-08.4736	B0.5 Ia	845±120[a]	1345	0.09	65.7	−53.3	−4.64	−20.28
HIP 88652	2	015.1187	+03.3349	B0 Ia	(650)	[1535]	0.5	8.2	30	−1.05	−1.38
HIP 92865	1	041.7070	+03.3784	O8 Vnn	(350)	[1755]	0.04	[2]	−41	−0.78	0.46
HIP 97796	1	056.4824	-04.3314	O7.5 Iabf	2200[c]	[1980]	0.50	[110]	9	−2.03	−10.30
HIP 101186	1	082.3557	+02.9571	O9.7 Ia	1486±402[a]	[1735]	0.23	22.3	−28	−2.37	1.37
BD+43 3654	1	082.4100	+02.3254	O4 If	1450[d]	[2325]	6.5	[14]	−66.2	−0.44	1.3
HIP 114990	1	112.8862	+03.0998	B0 II	1400[e]	[1400]	0.6	[52]	−125.3	−7.86	−0.71

Notes. Galactic coordinates: taken from Simbad. Spectral types: for B-type stars from the Simbad database, for O-type stars GOS Catalog. References for the distance values: (a) Megier et al. (2009), (b) Mason et al. (1998), (c) Schilbach & Roeser (2008), (d) Hanson (2003), (e) Thorburn et al. (2003); distances in brackets: derived from Hipparcos (van Leeuwen 2007) parallaxes. Terminal velocities in square brackets: from Howarth et al. (1997), otherwise inter- or extrapolated from Prinja et al. (1990). Mass-loss rates: derived from Vink et al. (2001). Tangential velocities in brackets derived from proper motions (van Leeuwen 2007), otherwise from Tetzlaff et al. (2010). Radial velocities are from the Second Catalog of Radial Velocities with Astrometric Data (Kharchenko et al. 2007).

Distributions



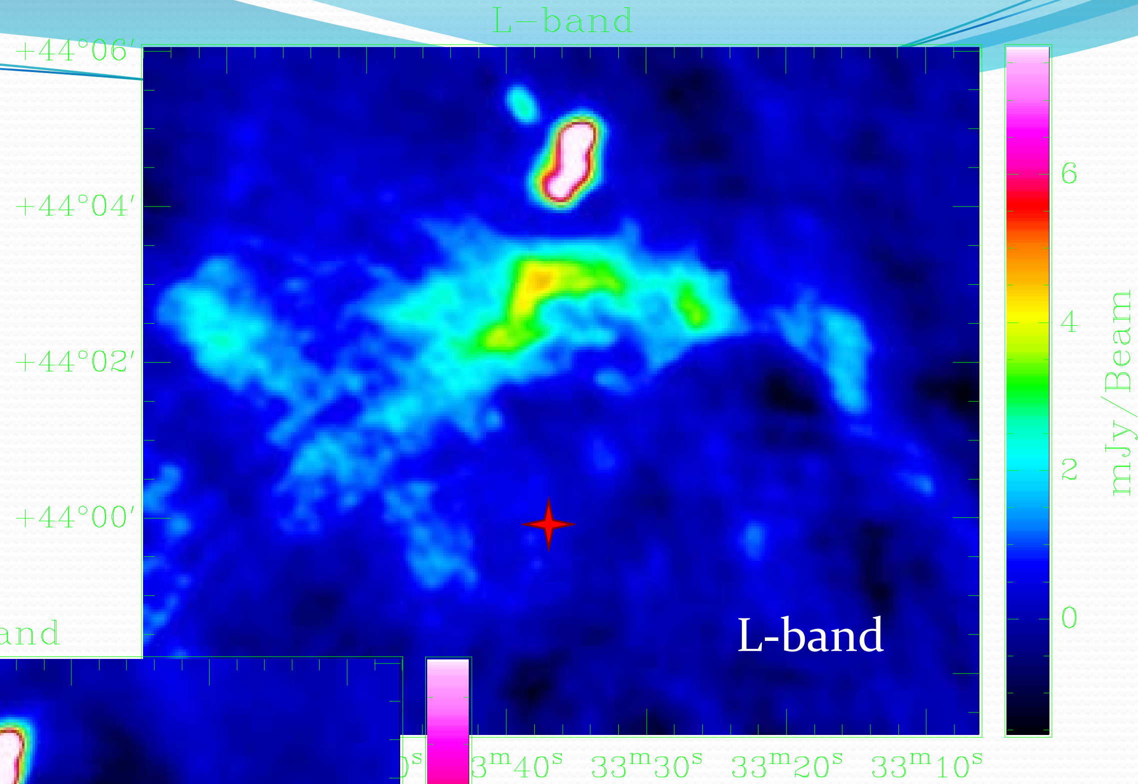


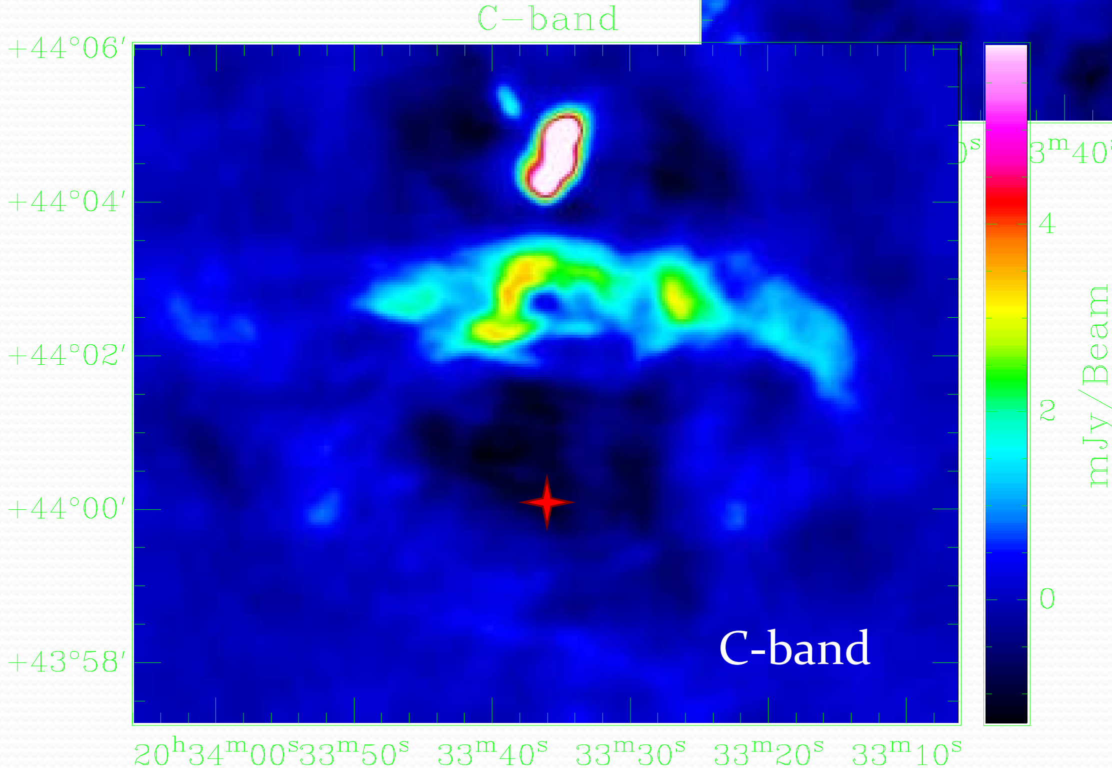
Peri, Benaglia, et al. 2012, A&A

del Valle & Romero: Non-thermal processes in bowshocks of runaway stars

Parameter	O4	O9
R_0 Standoff radius [pc]	8.3	0.2
$V_\star$ Spatial velocity [km s^{-1}]	100	30
$V_{\rm w}^{\rm a}$ Wind velocity [km s^{-1}]	2.2×10^3	0.8×10^3
$\dot{M}_{\rm w}^{\rm a}$ Wind mass loss rate [$M_\odot$ yr^{-1}]	10^{-4}	10^{-6}
$n_{\rm a}$ Ambient density [cm^{-3}]	1	100
$B^{\rm b}$ Magnetic field [G]	$\sim 3.0\times10^{-5}$	$\sim 10^{-5}$
η Acceleration efficiency	$\sim 2.0\times10^{-5}$	$\sim 2.7\times10^{-6}$
L Available power [erg s^{-1}]	$\sim 3.2\times10^{36}$	$\sim 4.3\times10^{33}$
a Hadron-to-lepton energy ratio	1	100
$q_{\rm rel}$ Jet content of relativistic particles	10%	10%
α Injection index	2	2
Δ Thickness of shocked wind [R_0]	~ 0.3	~ 0.3
Vol$_{\rm acc}$ Acceleration region volume [cm^{-3}]	$\sim 7\times10^{56}$	$\sim 10^{51}$
$L_\star{}^{\rm c}$ Star luminosity [$L_\odot$]	$\sim 7\times10^5$	$\sim 5\times10^4$
$T_{\rm IR}$ Dust temperature [K]	~ 24	~ 54

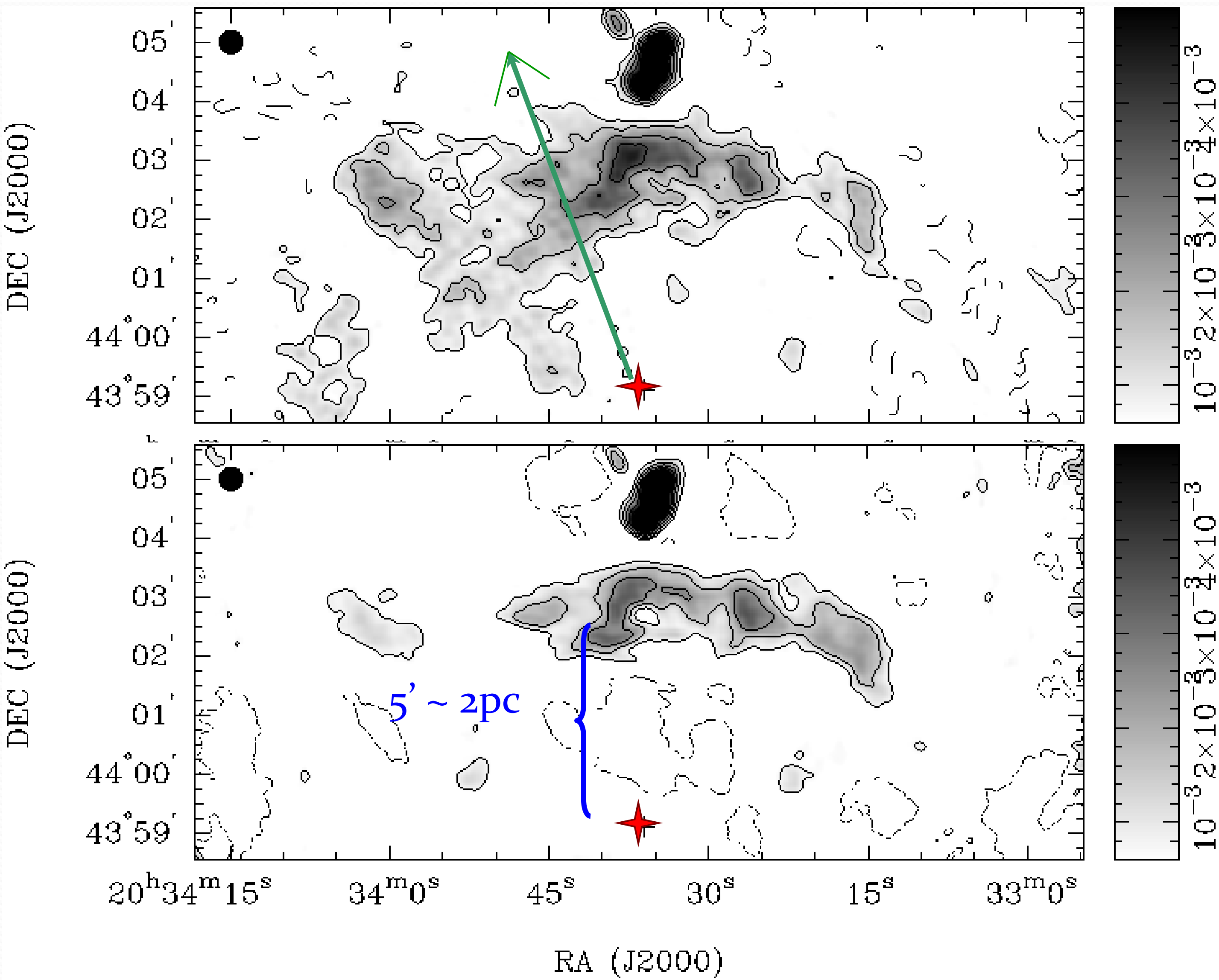
VLA obs





Benaglia, Romero, et al 2010, A&A

Images



Benaglia, Romero, et al 2010, A&A

Is all emmission coming from the BOW SHOCK?

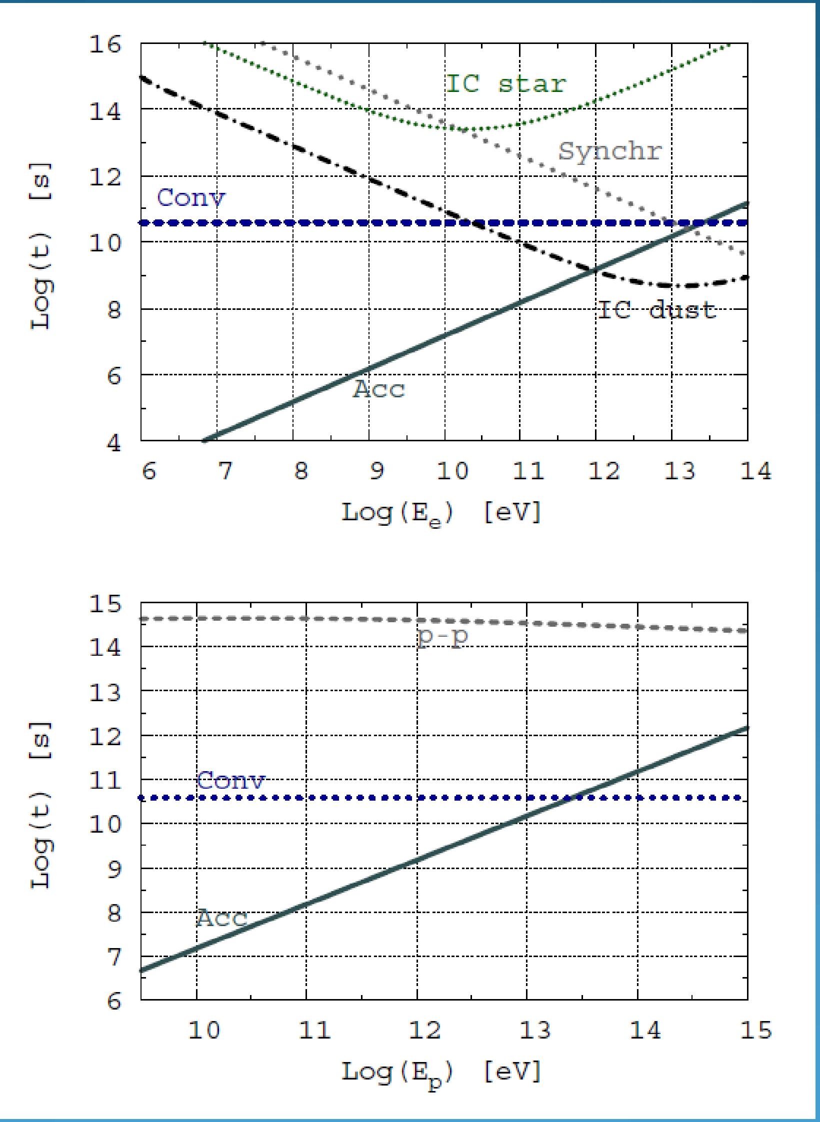
TABLE 1
PARAMETERS FOR THE NON-THERMAL RADIATIVE MODEL FOR AE AUR

Parameter		value
R_0	Standoff radius	1.7×10^4 AU
$\dot{M}_{\rm w}$	Wind mass loss rate	10^{-7} M$_\odot$ yr^{-1}
a	Hadron-to-lepton energy ratio	1
$q_{\rm rel}$	Content of relativistic particles	0.007
α	Particle injection index	2.6
$V_{\rm w}$	Wind velocity	1.5×10^8 cm s^{-1}
L	Available power	4×10^{33} erg s^{-1}
B	Magnetic field	1.1×10^{-4} G
$V_\star$	Star velocity	150 km s^{-1}

Table 1. Parameters for HD 195592

Parameter		value
R_0	Standoff radius	1.73 pc
$\dot{M}_{\mathrm{w}}{}^{(a)}$	Wind mass loss rate	3.3×10^{-7} $M_\odot$ yr^{-1}
α	Particle injection index	2
$V_{\mathrm{w}}^{(a)}$	Wind velocity	2.9×10^{8} cm s^{-1}
χ	Subequipartition factor	5×10^{-2}
B	Magnetic field	$\sim 2\times10^{-6}$ G
$T_\star^{(b)}$	Star temperature	2.8×10^{4} K
$L_\star^{(b)}$	Star luminosity	3.1×10^{5} $L_\odot$
T_{IR}	Dust temperature	~ 40 K

[a] Values from Muijres et al. (2012). [b] Values from Martins, Schaerer & Hillier (2005).


IC star
Synchr
Conv
IC dust
Acc
Log(t) [s]
Log(E_e) [eV]
p-p
Conv
Acc
Log(t) [s]
Log(E_p) [eV]