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The investigation of Particle-Accelerating Colliding-Wind Binaries : a multi-wavelength endeavour

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Outline

Massive stars, binaries, and some of their emission processes

The sub-class of particle accelerators : PACWBs

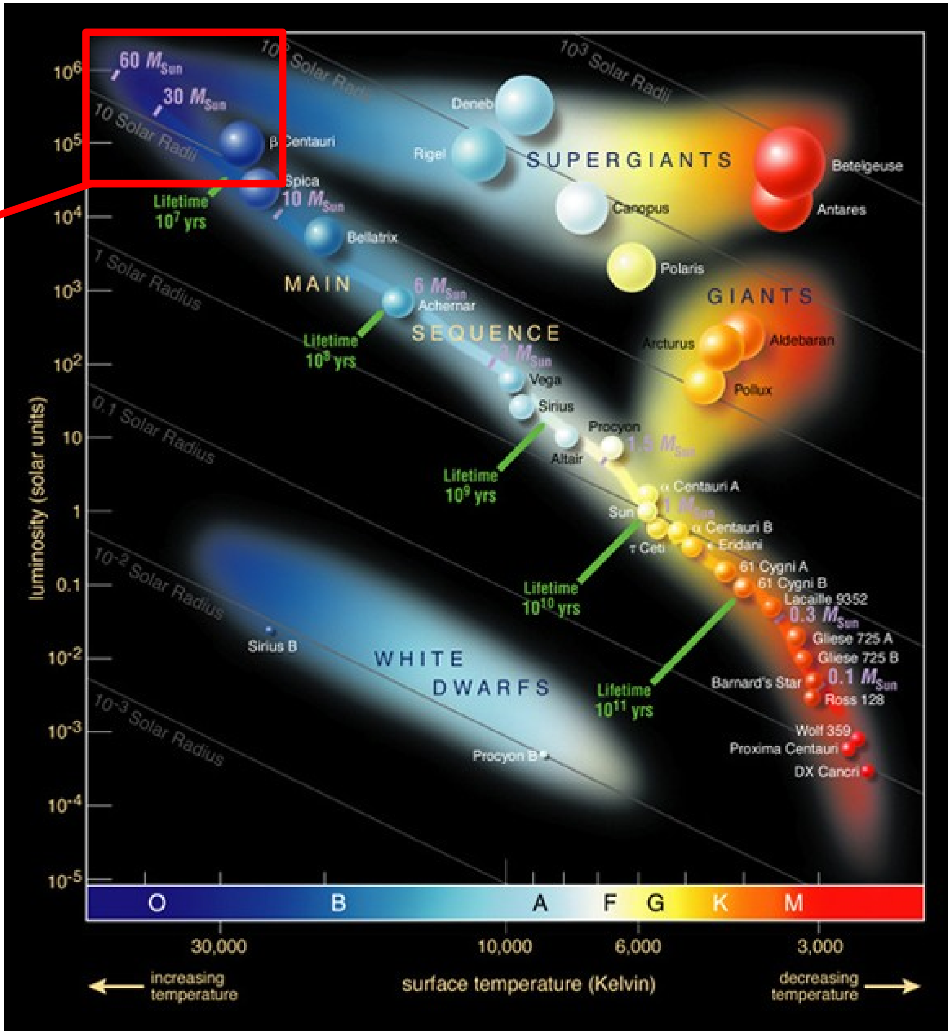
Non-thermal emission from PACWBs

Concluding remarks

Massive stars, binaries, and some of their emission processes

What stars are we talking about?

Hertzsprung-Russel diagram



Most massive stars in the upper left corner

Mass:
Typically larger than 8 – 10 M_{sol}

Luminosity:
Larger than 10^4 L_{sol} (most frequently in the range 10^5 – 10^6 L_{sol})

Temperature:
Larger than 20000 K (up to ~10^5 K)

Evolution time-scale:
A few/several Myr (up to ~10 Myr)

What stars are we talking about?

A crucial feature of massive stars: the **stellar wind**!

Conversion of radiative energy into mechanical energy!

Consequence of the high luminosity
→ **strong radiation pressure**
→ massive stars lose large amounts of material during their evolution time

What stars are we talking about?

A crucial feature of massive stars: the **stellar wind**!

Conversion of radiative energy into mechanical energy!

Consequence of the high luminosity
→ **strong radiation pressure**
→ massive stars lose large amounts of material during their evolution time

- Depending on the spectral type/evolutionary stage, typical **mass loss rates** are in the range **10^{-7} – 10^{-5} M_{sol}/yr**
  (mass loss rate of the solar wind ~10^{-14} M_{sol}/yr)

- Ejected material can reach quite high speeds:
  Terminal velocities typically of the order **1000 – 3000 km/s**

As a result, a huge amount of kinetic power is ejected into the interstellar medium

$$P_{kin} = \frac{1}{2}\dot{M}\,V_{\infty}^2 \longrightarrow P_{kin} \approx 3.16 \times 10^{35}\,\dot{M}_{usual}\,V_{\infty,usual}^2 \quad \text{(erg / s)}$$

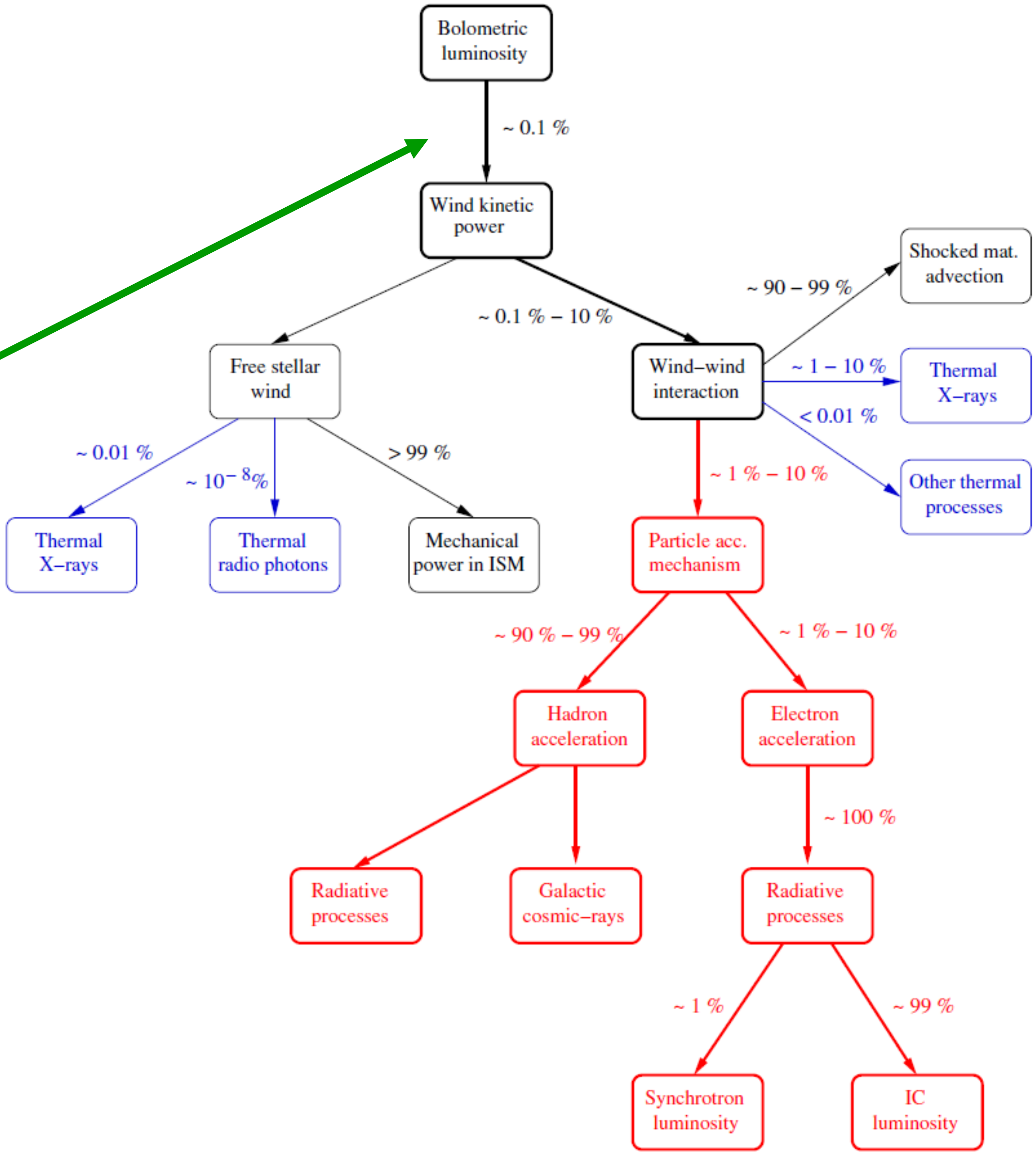
Important for energy budget considerations!

[Usual units are M_{sol}/yr and km/s]

The physics of massive stars can be viewed/discussed in terms of a succession of energy conversion processes

$$P_{\rm kin} = \frac{1}{2}\,\dot{M}\,V_{\infty}^{2}$$

Results from a conversion of radiative energy into kinetic power



Emission processes from individual stellar winds

Thermal radio emission

Stellar winds consist of a plasma, made of ions and electrons, at a typical temperature of a few 10^4 K

→ **Optically thick thermal bremsstrahlung spectrum**

Emission spectrum predicted, and measured, as a power law with a positive spectral index :

$$\boxed{S_\nu \propto \nu^{0.6}}$$

Emission processes from individual stellar winds

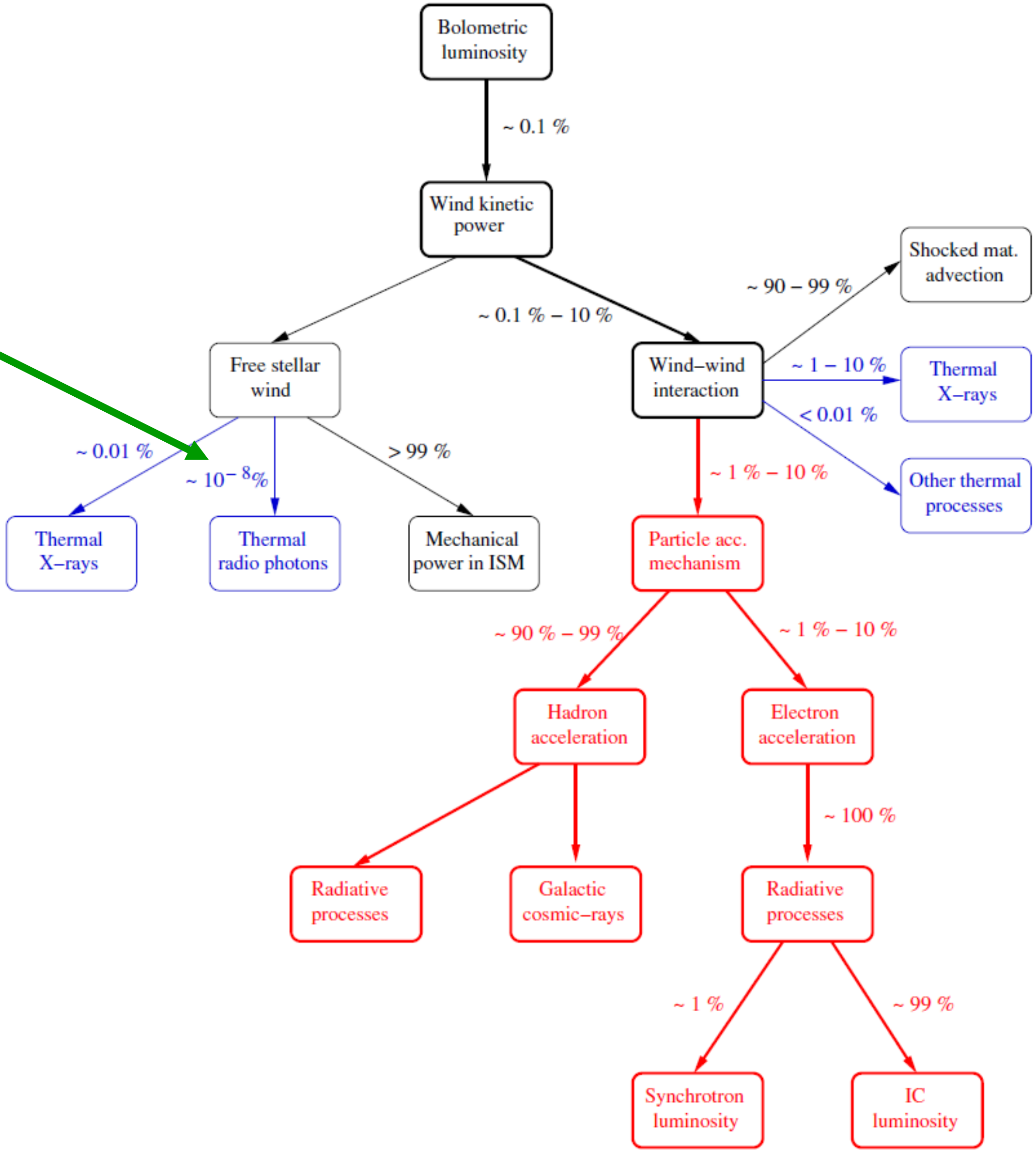
Thermal radio emission

Conversion of a small fraction of the kinetic power into thermal radio emission

$$P_{\rm kin} = \frac{1}{2}\,\dot{M}\,V_\infty^2$$

$$\downarrow$$

$L_{\rm radio}$



Emission processes from individual stellar winds

The smooth wind is thus able to produce thermal bremsstrahlung in the radio and far-infrared domains. Do we expect significant emission processes to operate at other wavelengths?

Let's turn to one of the most important features of stellar winds:

instabilities !

Responsible for a fragmentation of the stellar wind, with different parcels of wind material moving at different velocities

→ fragments moving at different speeds will collide

→ intrinsic hydrodynamic shocks

→ significant heating of the post-shock material

→ thermal energy available to feed thermal emission processes!

Emission processes from individual stellar winds

Shock physics:

Rankine-Hugoniot relations for strong shocks

→ post-shock temperature depends on the pre-shock velocity

$$\mathrm{T_{post-shock}} \approx 13.6 \times \mathrm{V^2_{usual}}$$

Pre-shock velocity for intrinsic shocks ~ 300 – 600 km/s

→ post-shock temperatures of the order of **a few 10^6 K**

→ stellar winds are expected to be thermal X-ray emitters

Some pioneering works exploring the idea that stellar winds of massive stars could produce thermal X-rays:
Lucy & White 1980, ApJ, 241, 300
Lucy 1982, ApJ, 255, 286

Emission processes from individual stellar winds

L_X – L_{bol} relation :

Many observational studies emphasized a likely relation between thermal X-ray luminosity (emerging from the stellar wind) and the bolometric luminosity:

$$L_X / L_{bol} \sim 10^{-7}$$

Results from a competition between X-ray emission and intrinsic free free absorption by the stellar wind material (remember we are talking about soft X-rays, at most at a few keV)

Some theoretical validation: **(Owocki et al. 2013, MNRAS, 429, 3379)**

A linear relation between L_X and L_{bol} should exist over a wide range of stellar wind parameters, with some deviations expected for very high / low density stellar winds.

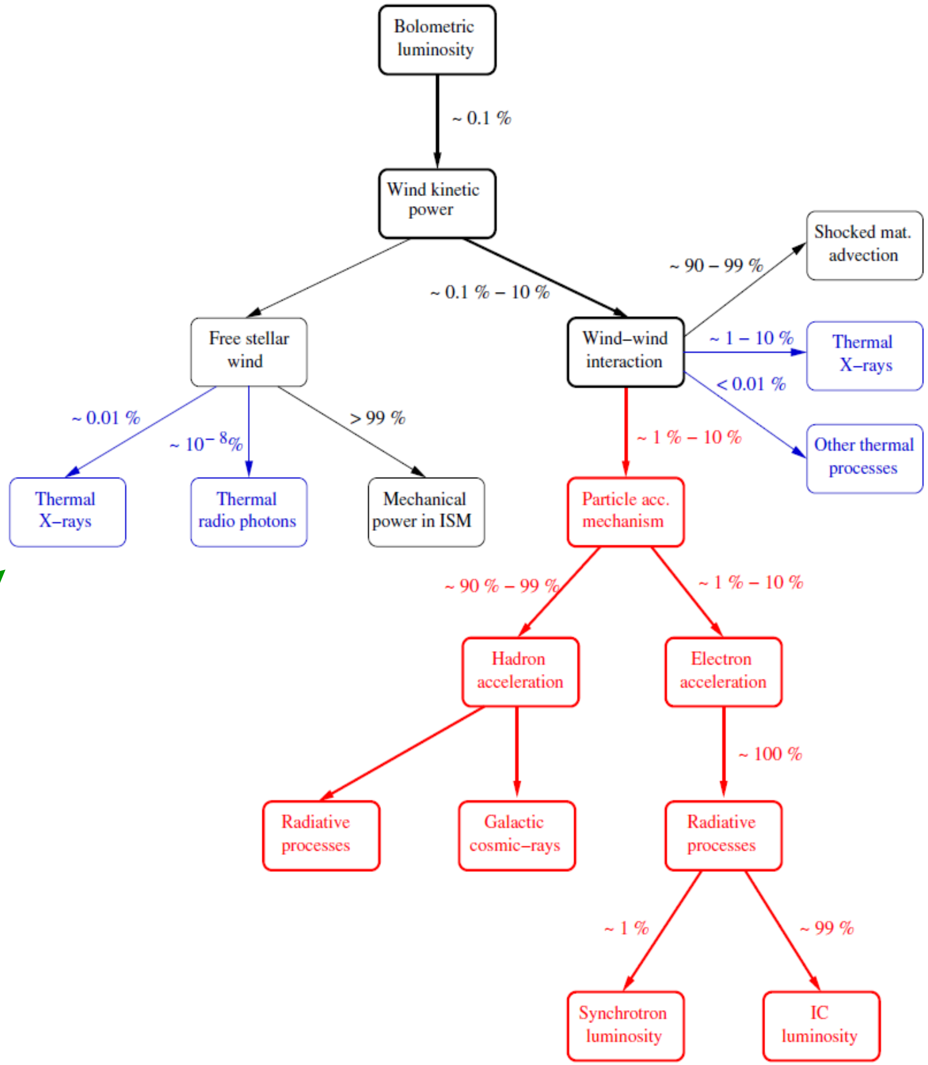
Emission processes from individual stellar winds

Thermal X-ray emission

$$P_{\rm kin} = \frac{1}{2}\dot{\rm M}\,{\rm V}_\infty^2$$

$$\downarrow$$

$$L_X$$



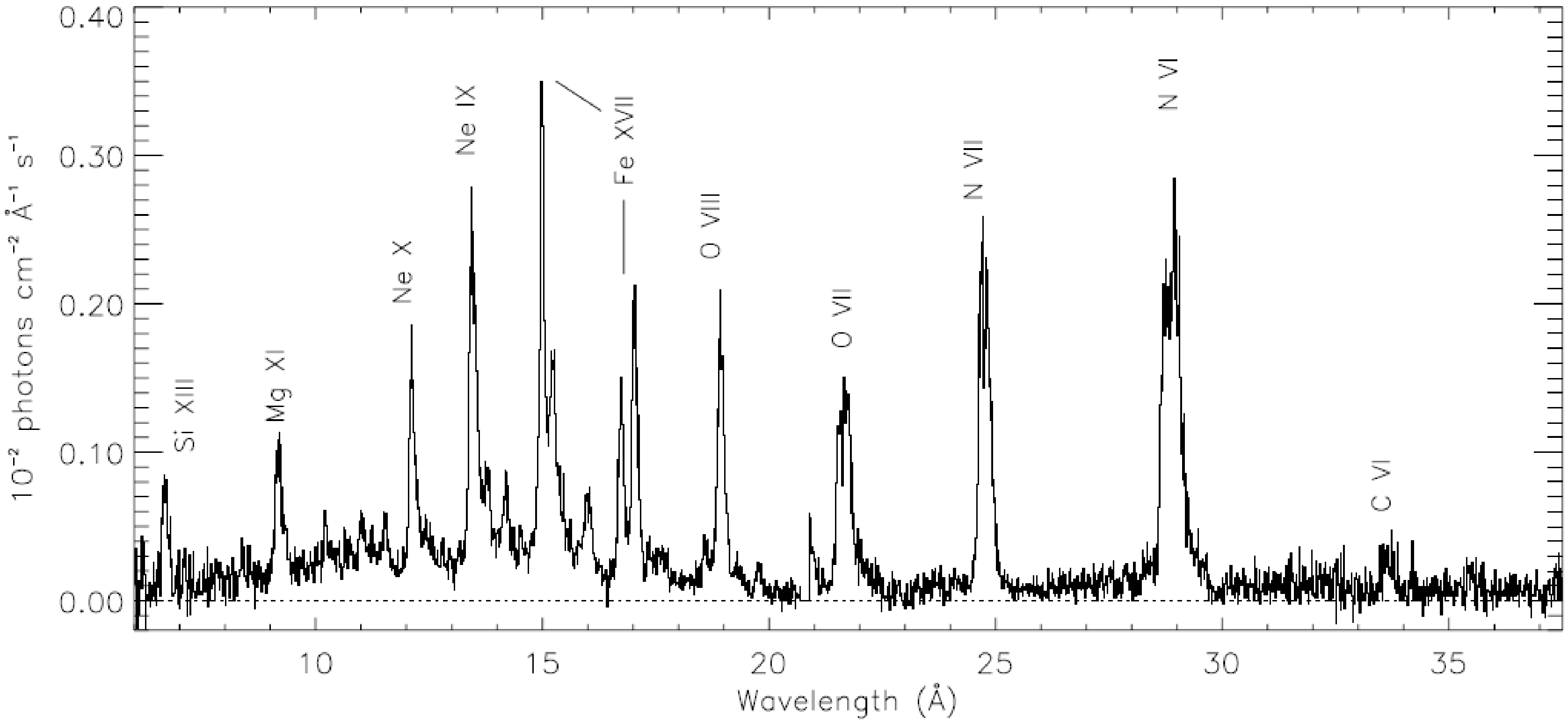
Results from a conversion of the kinetic power into thermal X-rays

Emission processes from individual stellar winds

Thermal X-ray emission

High resolution X-ray spectra
→ XMM-Newton/RGS spectrum of ζ Pup
→ emission line spectrum produced by a hot plasma

(Kahn et al. 2001, A&A, 365, L312)



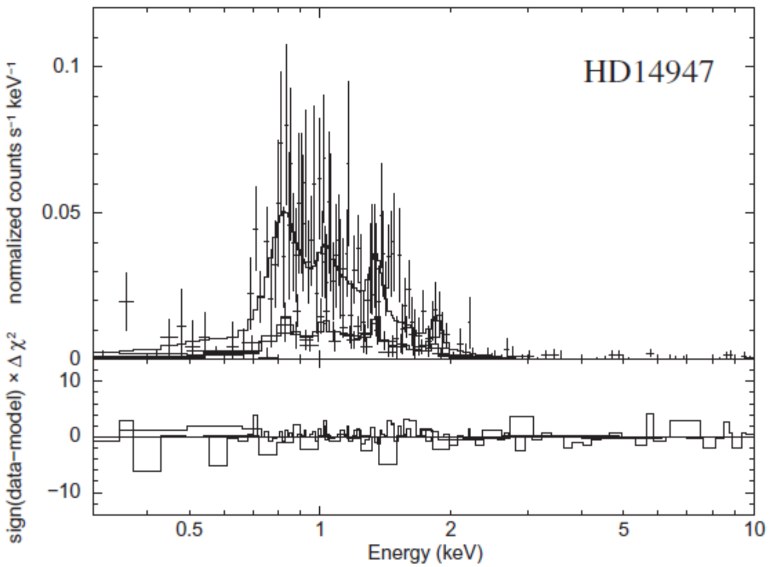
Emission processes from individual stellar winds

Thermal X-ray emission

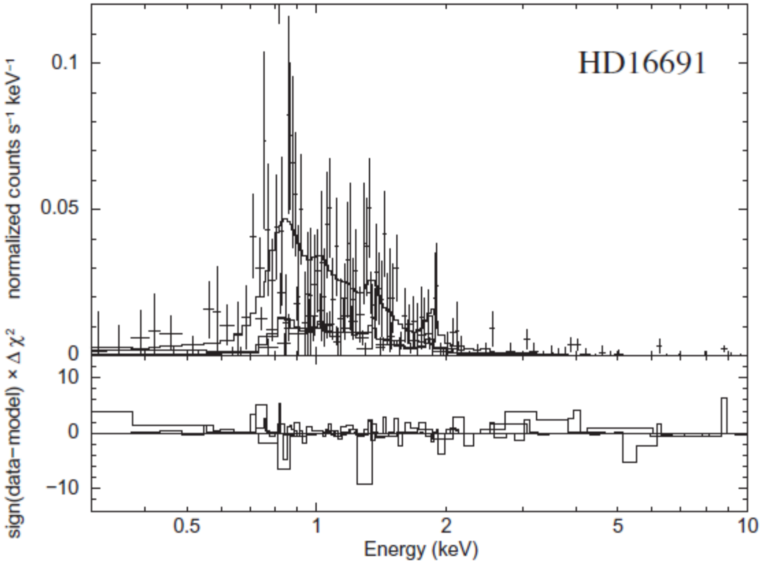
<u>The case of evolved O-type stars :</u>

Denser stellar winds → enhanced intrinsic absorption → reduced L_X / L_{bol} ratio

Ex: HD16691 and HD14947 (OIf$^+$)
“presumably single stars”
(De Becker 2013, NewA, 25, 7)

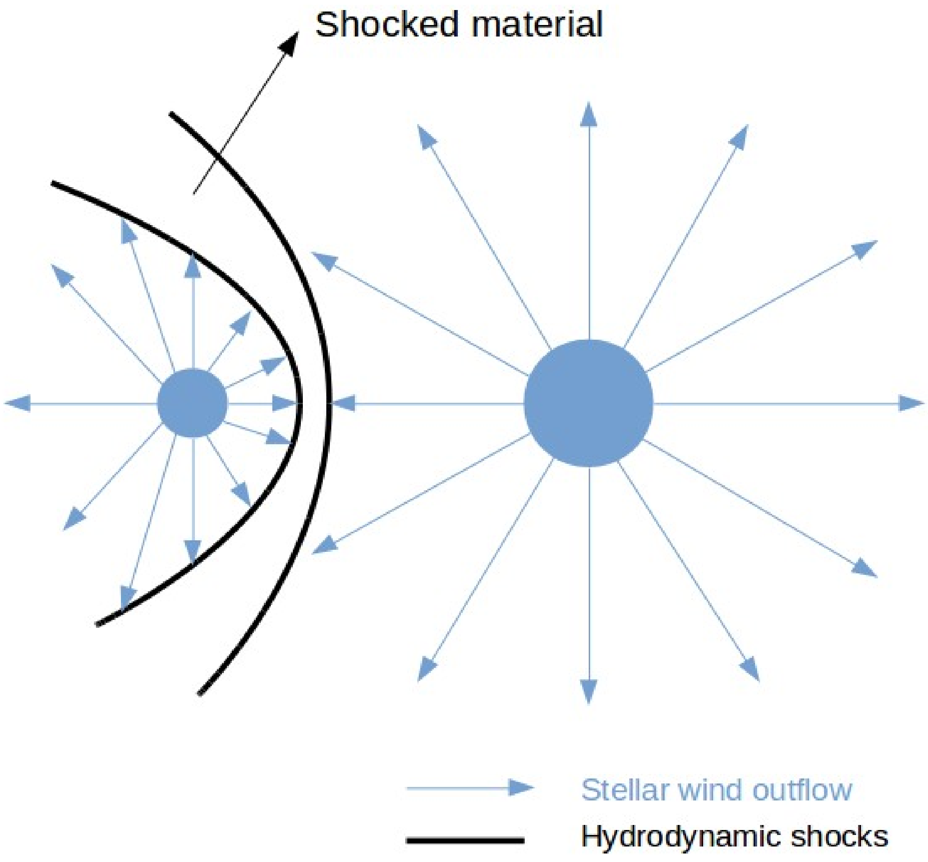


L_X / L_{bol} ~ $10^{-7.4}$ – $10^{-7.5}$



Low resolution XMM/EPIC spectra, fitted with a 1-T thermal model

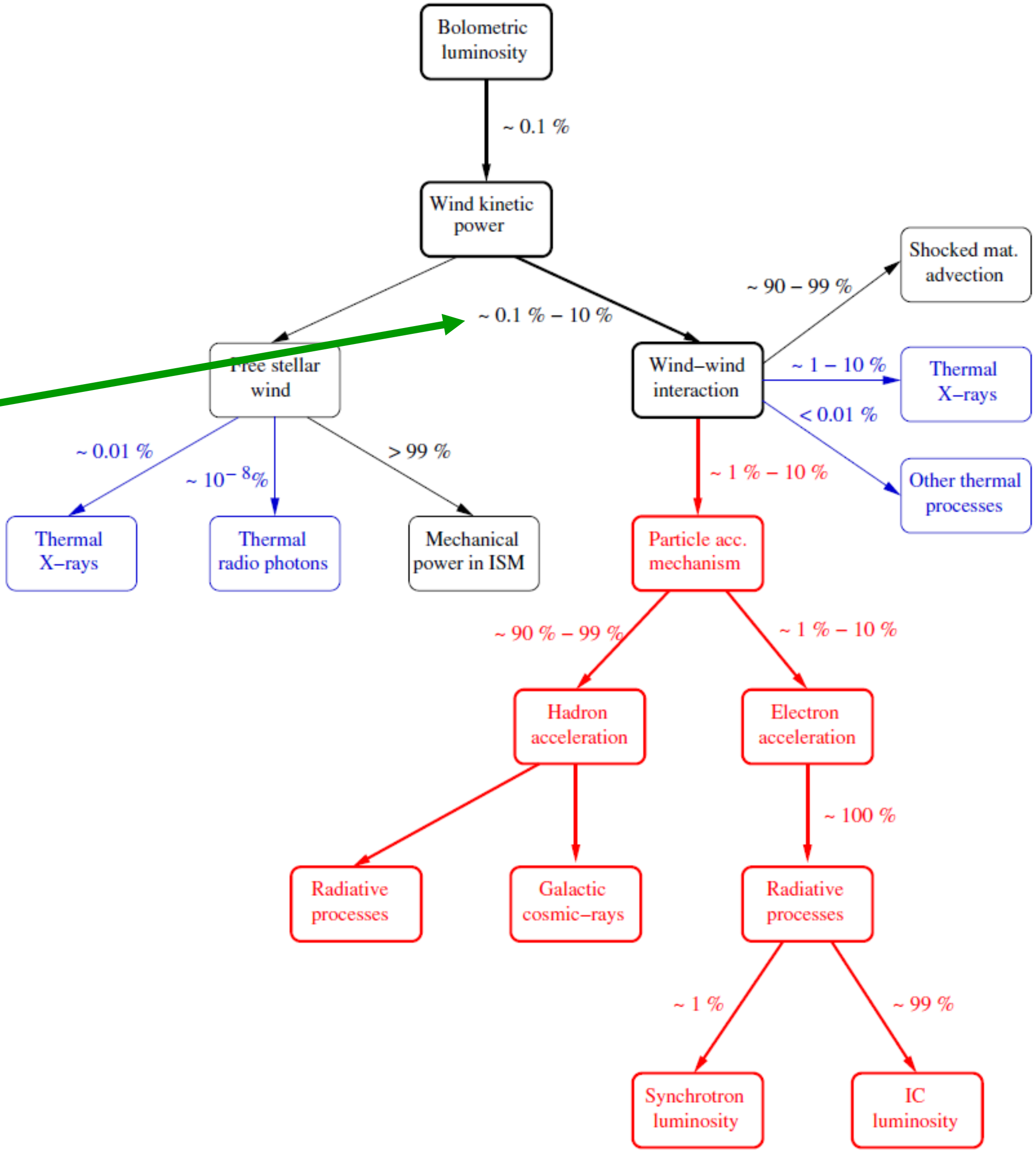
When winds collide...



- Systems made of massive stars (O, B, WR…)
- Multiplicity is a crucial feature (binaries, triple and higher multiplicity…)
- A large fraction of massive stars are in binary systems
- Variability on the orbital time-scale is very important
- Strong stellar winds collide and create strong shocks

When winds collide...

A fraction of the wind kinetic power is injected into the colliding-wind region



Emission processes from colliding winds

Shock physics:

Rankine-Hugoniot relations for strong shocks

→ post-shock temperature depends on the pre-shock velocity

$$\mathrm{T_{post-shock}} \approx 13.6\ \times\ \mathrm{V^2_{\infty,usual}}$$

Pre-shock velocity for CW shocks : V_∞ ~ 2000 – 3000 km/s

→ post-shock temperature of the order of **a few 10^7 K**

→ post-shock plasma expected to be a thermal X-ray emitter

Emission processes from colliding winds

L_X – L_{bol} relation :

Considering the intrinsic emission from the winds in the system

$L_{X,1} / L_{bol,1} \sim 10^{-7}$

$\rightarrow L_{X,1} \sim 10^{-7} L_{bol,1}$

$L_{X,2} / L_{bol,2} \sim 10^{-7}$

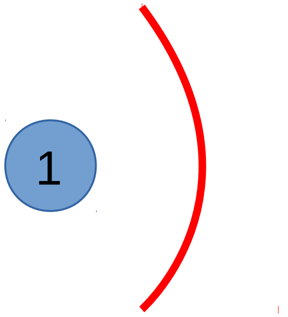
$\rightarrow L_{X,2} \sim 10^{-7} L_{bol,2}$

$$L_{X,tot} = L_{X,1} + L_{X,2} \sim 10^{-7} (L_{bol,1} + L_{bol,2}) = 10^{-7} L_{bol,tot}$$

$$\rightarrow L_{X,tot} / L_{bol,tot} \sim 10^{-7}$$

Emission processes from colliding winds

$L_X - L_{bol}$ relation :



Considering the intrinsic emission from the winds in the system and the contribution from the Colliding-Wind Region (CWR)

$L_{X,1} / L_{bol,1} \sim 10^{-7}$

$\rightarrow L_{X,1} \sim 10^{-7} L_{bol,1}$

$L_{X,2} / L_{bol,2} \sim 10^{-7}$

$\rightarrow L_{X,2} \sim 10^{-7} L_{bol,2}$

$$L_{X,tot} = L_{X,1} + L_{X,2} + L_{CWR} > 10^{-7} (L_{bol,1} + L_{bol,2}) = 10^{-7} L_{bol,tot}$$

$$\rightarrow L_{X,tot} / L_{bol,tot} > 10^{-7}$$

A luminosity ratio larger than 10^{-7} is often considered as an indication of colliding winds contributing to the overall thermal X-ray emission → indirect indication for binarity !

Emission processes from colliding winds

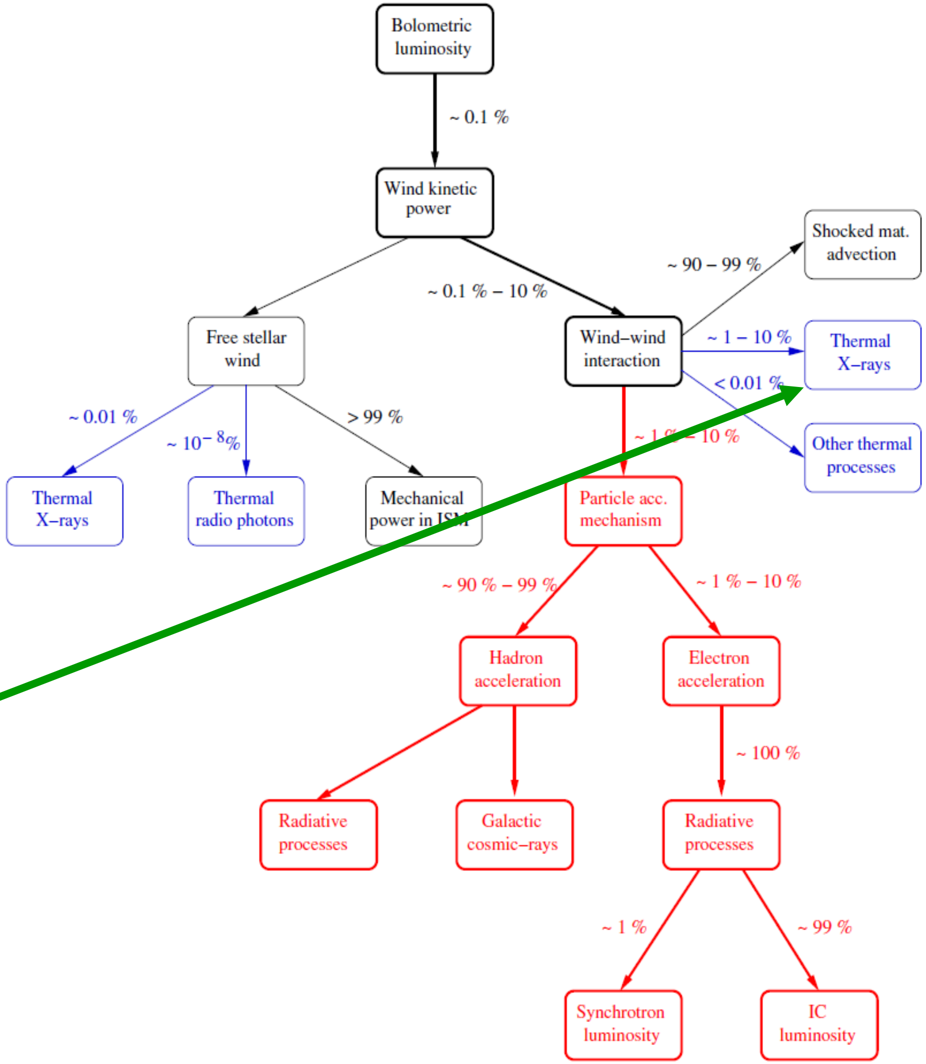
Thermal X-ray emission

$$P_{\mathrm{kin,CWR}} = f_{\mathrm{CWR}}\, P_{\mathrm{kin}}$$

$$\downarrow$$

$$L_{\mathrm{X,CWR}}$$

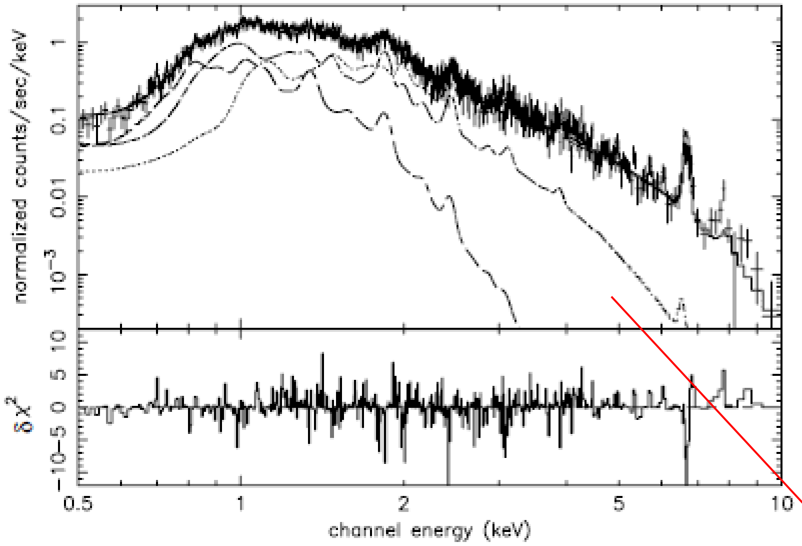
Results from a conversion of the kinetic power injected in the CWR into thermal X-rays



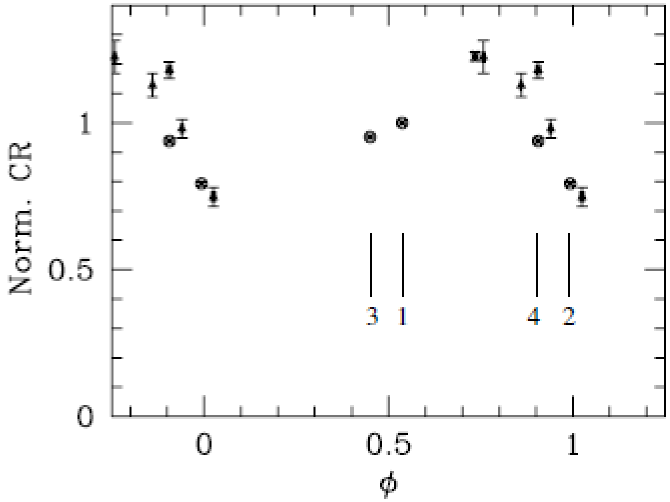
Emission processes from colliding winds

Thermal X-ray emission

Cyg OB2 #8A : O6If + O5.5III(f)


EPIC–pn : observation 1, 3–T MEKAL model

Multi-observatory, phase-folded light curve (P ~22 d)



(ephemeris determined on the basis of visible data)

$L_X / L_{bol} \sim 10^{-5.6} – 10^{-5.5}$
→ high X-ray overluminosity

(De Becker et al. 2006, MNRAS,371, 1280)

Multiple components model

Emission processes from colliding winds

Thermal X-ray emission

HD167971 : (O7.5III + O9.5III) + O9.5 I

P_{AaAb} = 3.32 d (circular orbit, eclipsing)

(Leitherer et al. 1987, A&A, 185, 121)

P_{AB} ~ 21 yr (eccentric orbit)

(Ibanoglu et al. 2013, MNRAS, 436, 750)

How many sources of thermal X-rays in this system?

- Stellar wind of component Aa
- Stellar wind of component Ab
- Stellar wind of component B
- Wind collision region Cwab
- Wind collision region CWAB

Where should a variability come from?

- Wind collision region CWAB
- Potentially, the eclipse if the AaAb system

Emission processes from colliding winds

Thermal X-ray emission

Long period, ~21 yr !

Eccentric orbit → significant variation of the separation between 2002 and 2014

CWAB contributes only to a moderate fraction of the overall X-ray spectrum

→ the spectrum is not dominated by the long period wind collision region

However!

Slight – marginal – variation compatible with an eclipse effect between the two observations in 2002

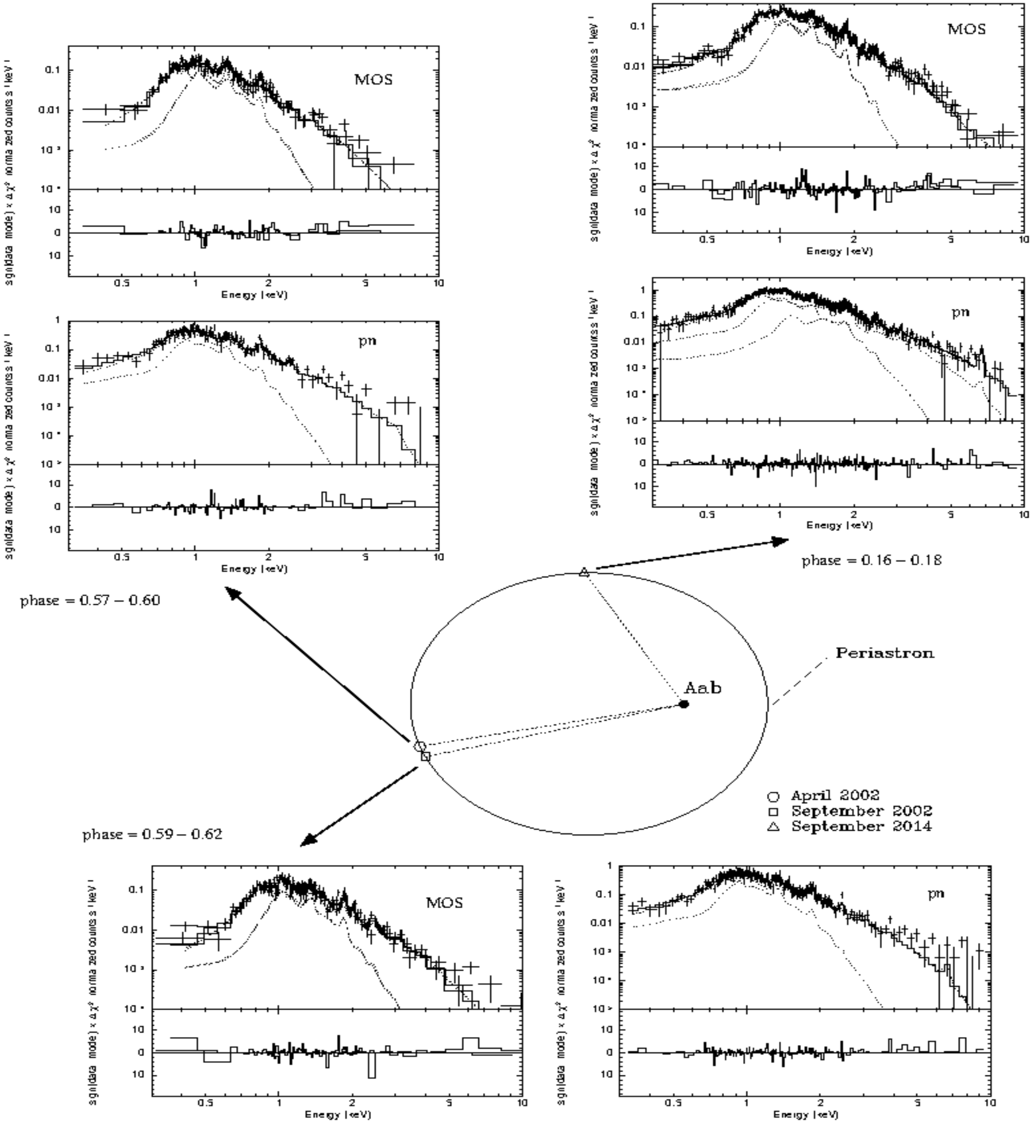
Significant overluminosity:

$L_X / L_{bol} \sim 1.3 - 1.8\ 10^{-6}$

Themal X-ray efficiency ratio:

$L_X / P_{kin} \sim 1.2 - 1.6\ 10^{-3}$

(De Becker 2015, MNRAS, 451, 1070)

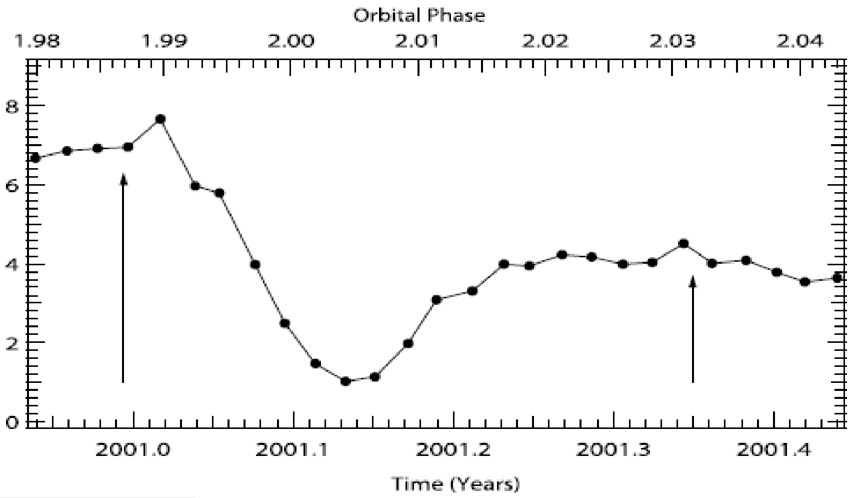


Emission processes from colliding winds

Thermal X-ray emission

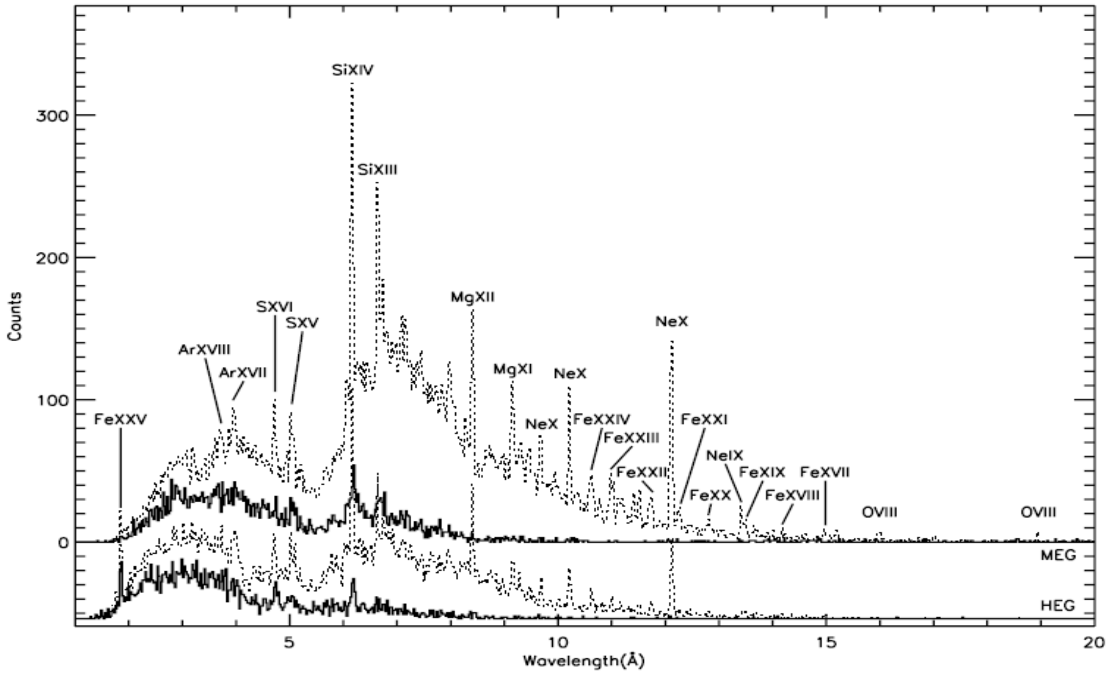
WR140 : WC7pd + O5.5f (III – I)

P ~ 7.9 yr
e ~ 0.9



RXTE X-ray light curve
(2 – 10 keV)

(Pollock et al. 2005, ApJ, 629, 482)



Chandra gratings
spectra

Pre-periastron

Post-periastron

Emission processes from colliding winds

Thermal X-ray emission

Eta Car : LBV ?

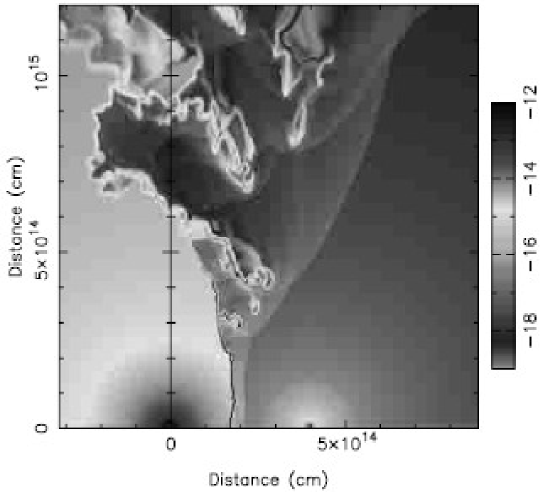
P ~ 5.5 yr

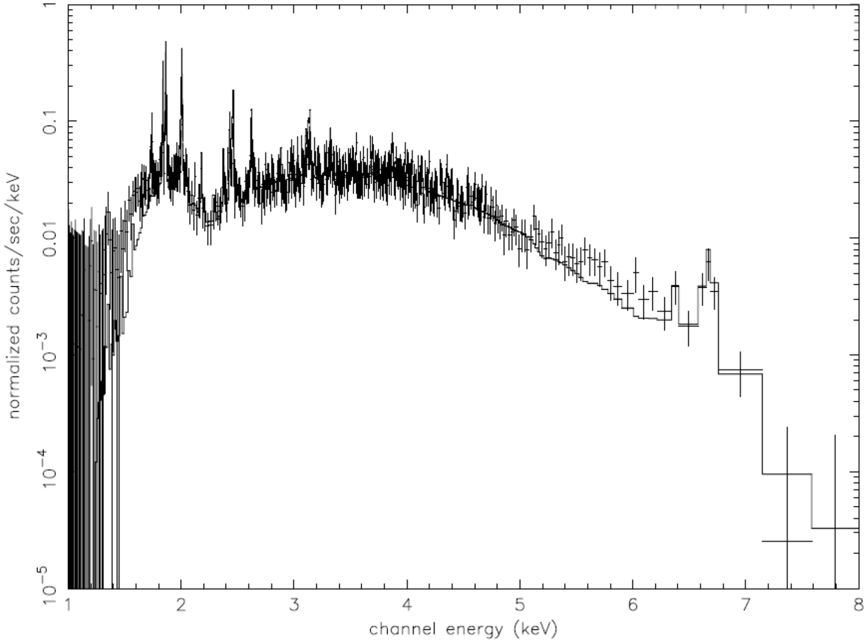
Modelling the X-ray spectrum using a hydro + radiative code depending on wind parameters

→ determination of mass loss rates and terminal velocities:

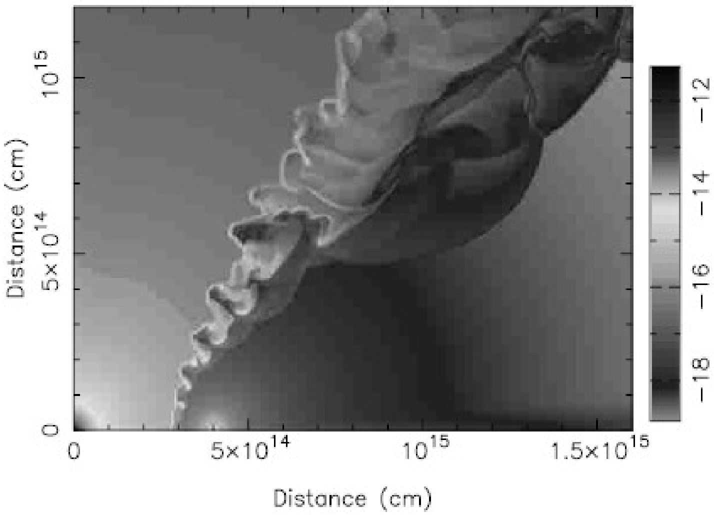
P : 2.5 10^{-4} M_{sol} / yr ; 500 – 700 km/s

S : 10^{-5} M_{sol} / yr ; 3000 km/s





(Pittard & Corcoran 2002, A&A, 383, 636)



So far, we have learned that..

- individual stellar winds can produce **thermal radio emission**

- individual stellar winds can produce **thermal X-ray emission**

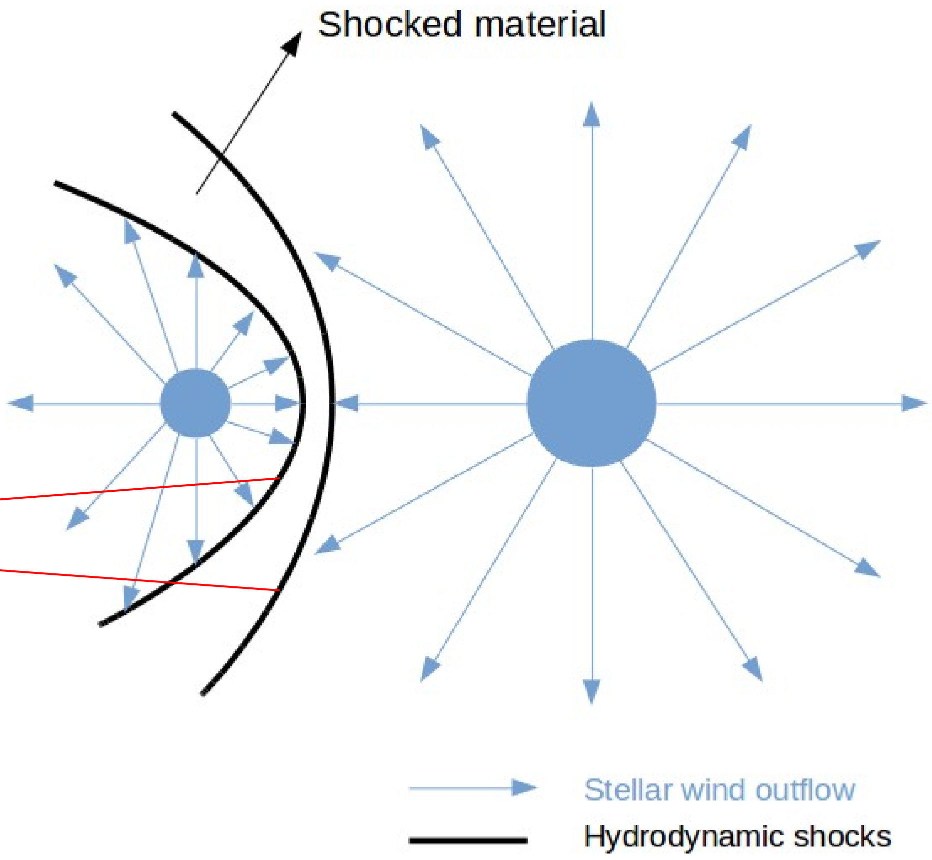
- colliding stellar winds can produce **additional thermal X-ray emission**

Those features are common among Colliding-Wind Binaries (CWB)

The sub-class of particle accelerators : PACWBs

Particle acceleration in CWBs

So-called 'standard scenario' for particle acceleration by massive stars
→ Diffusive Shock Acceleration in the wind collision region in massive binaries



Strong shocks likely
to be active in DSA

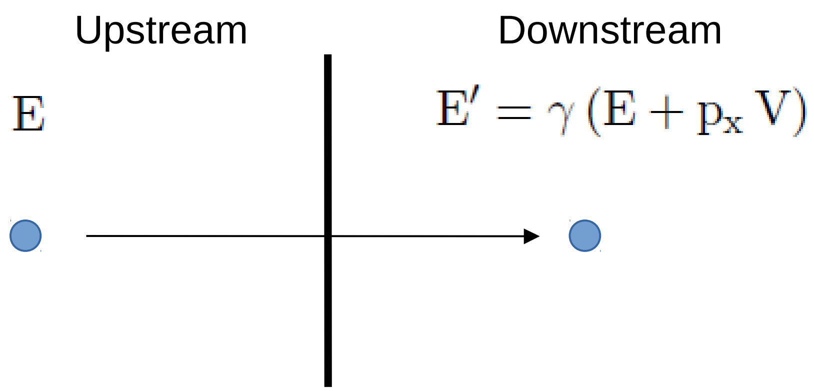
Particle acceleration in CWBs

So-called 'standard scenario' for particle acceleration by massive stars
→ Diffusive Shock Acceleration in the wind collision region in massive binaries

V : shock velocity jump

Energy of the particle calculated using a Lorentz transformation

Requirement : velocity vectors of particles need to be randomized on either side of the shock



E

$$E' = \gamma \, (E + p_x \, V)$$

Relative energy gain :

$$\frac{\Delta E}{E} \propto \frac{V}{c}$$

→

Iterative process with escape probability at every iteration

Power law distribution :

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

Strong shocks: p ~ 2

(e.g. Longair, 1994, High energy astrophysics – 2nd Edition)

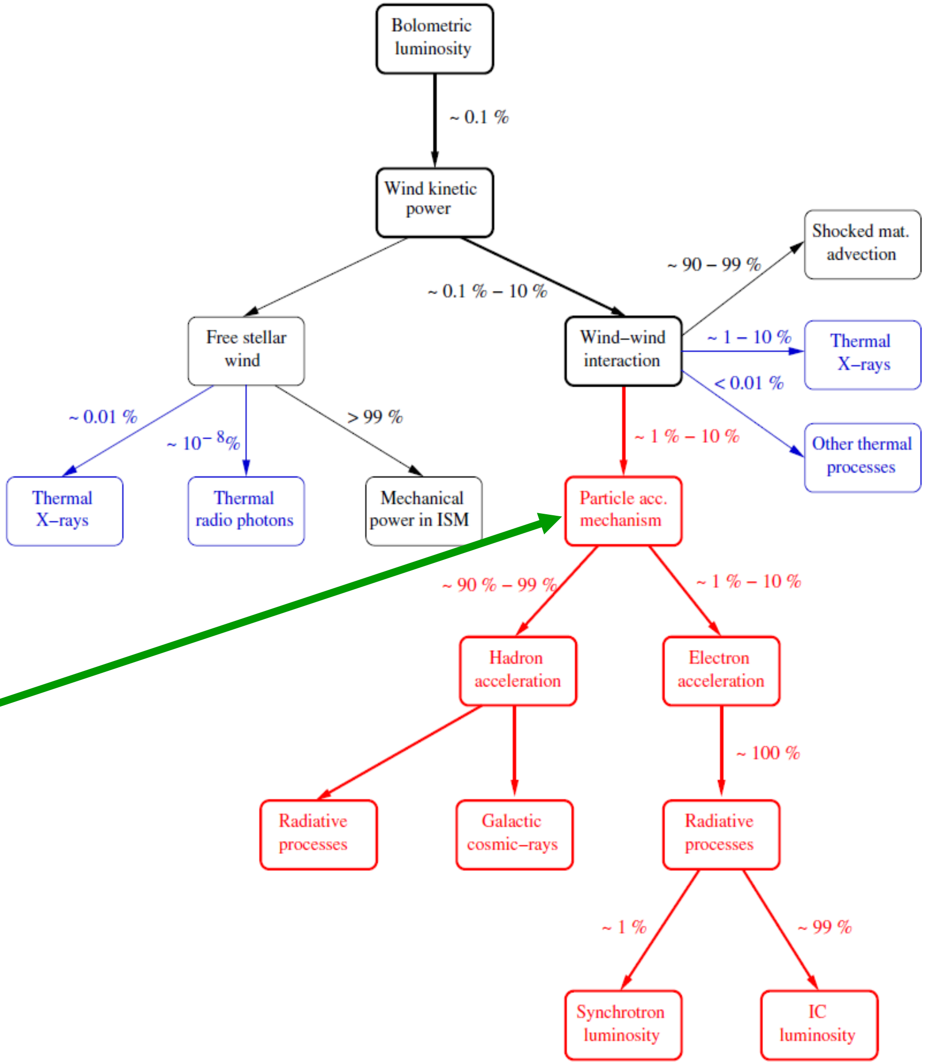
Particle acceleration in CWBs

$$P_{\mathrm{kin,CWR}} = f_{\mathrm{CWR}}\, P_{\mathrm{kin}}$$

$$\downarrow$$

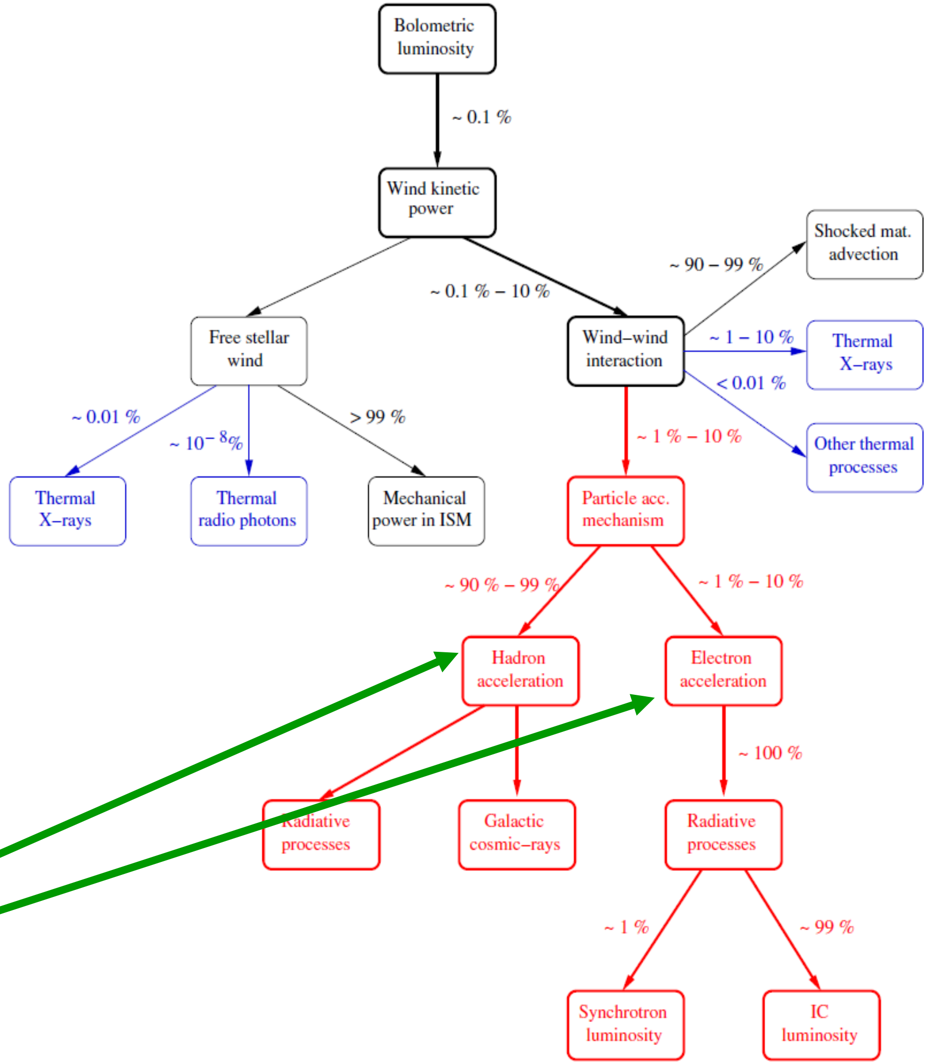
$$P_{\mathrm{NT}} = f_{\mathrm{NT}}\, P_{\mathrm{kin,CWR}}$$

Results from a conversion of the kinetic power injected in the CWR into non-thermal particles



Particle acceleration in CWBs

$$\begin{tikzcd}
 & P_{NT} = f_{NT}\, P_{kin,CWR} \arrow[dl] \arrow[dr] & \\
P_e = f_e\, P_{NT} & & P_h = f_h\, P_{NT}
\end{tikzcd}$$



The power injected in non-thermal particles is distributed between electrons and hadrons

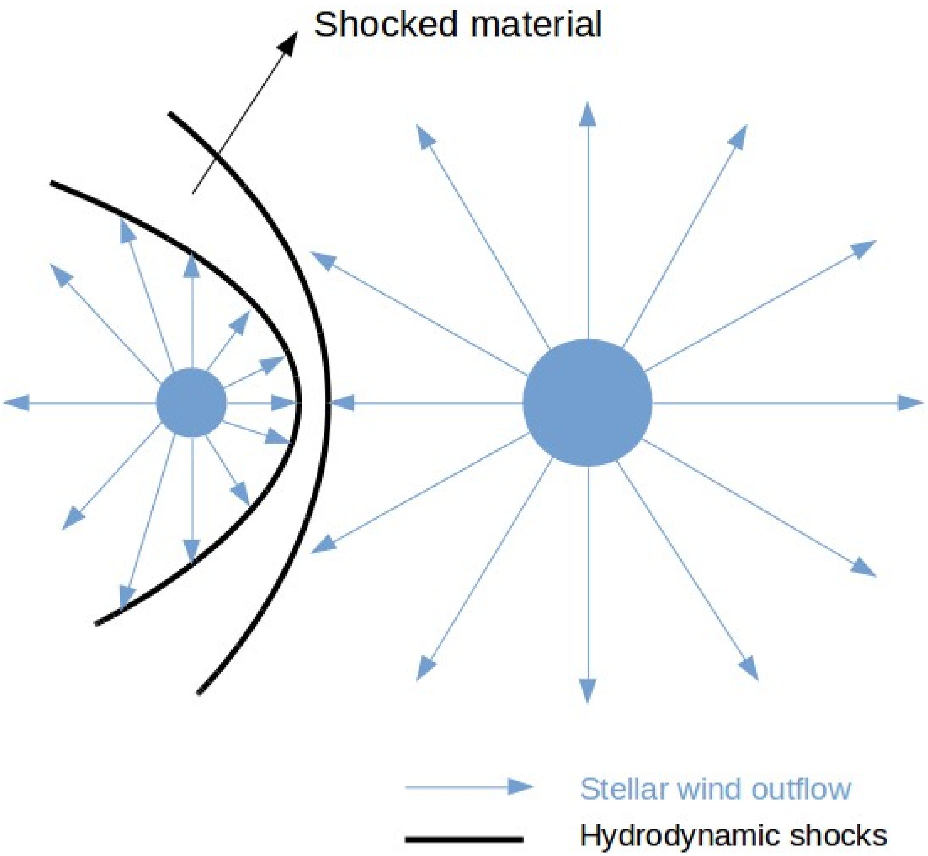
Particle acceleration in CWBs

Radiative processes involving relativistic electrons:

- **Synchrotron radiation**
Interaction with the magnetic field

- **Inverse Compton scattering**
Interaction with the photospheric radiation field

- **Relativistic bremsstrahlung**
Interaction with nuclei in the stellar wind material
(most of the time negligible with respect to other processes)



Particle acceleration in CWBs

Among the class of CWBs, about 40 systems are known to be particle accelerators:

Catalogue of PACWBs :
De Becker & Raucq 2013, A&A, 558, A28

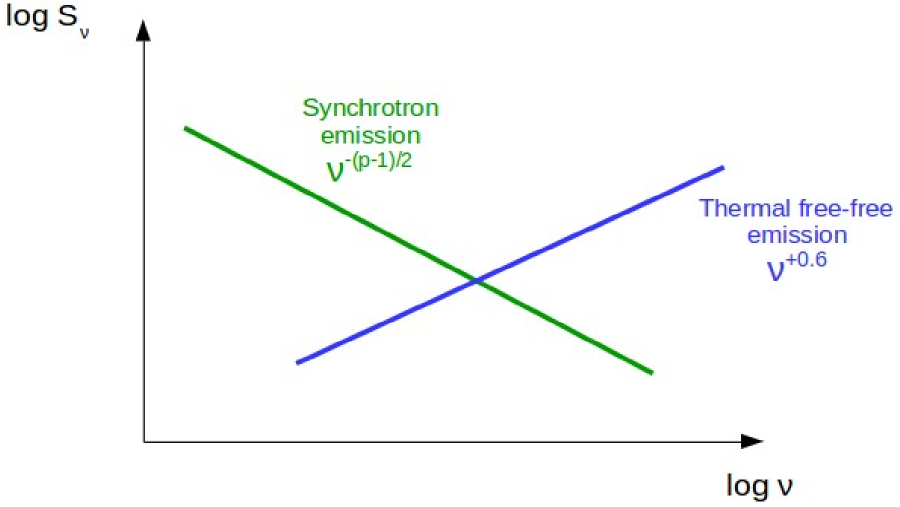
- Most PACWBs are identified thanks to synchrotron radiation in the raido domain (relativistic electrons)
- In one case, there is confirmation of non-thermal X-ray and gamma-ray emission (relativistic electrons and protons)

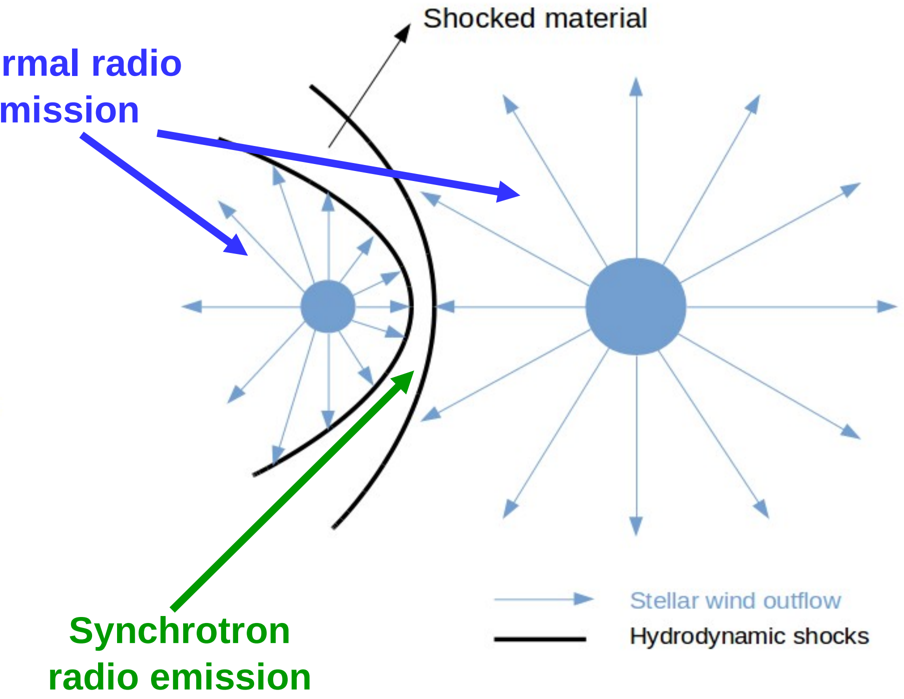
→ **Let's have a look at their non-thermal signatures**

Non-thermal emission from PACWBs

Synchrotron emission from PACWBs

$$S_\nu^{\rm obs} = S_\nu^{\rm th} + S_\nu^{\rm syn} {\rm e}^{-\tau_\nu^{\rm ff}}$$





The radio spectrum is a combination of thermal (optically thick) emission from the stellar winds, and synchrotron emission produced in the colliding wind region (composite spectrum!) → spectral index can be neither typical of pure NT or T emission

$$\alpha = \frac{\ln\left(\frac{S_{\nu,1}}{S_{\nu,2}}\right)}{\ln\left(\frac{\nu_1}{\nu_2}\right)}$$

Synchrotron emission from PACWBs

Synchrotron emission is the most efficient tracer of particle acceleration in massive binaries !
→ valuable probe for non-thermal physics in massive binaries

- Spectral index
- Brightness temp.
- Variability

$\alpha < 0.6$ (for S_ν prop. to ν^α)
→ deviation w.r.t. pure thermal emission

Component with $T_B \sim 10^6 - 10^7$ K

Emission related to the colliding-wind region
- physical conditions are phase dependent
- orientation effect due to free-free absorption

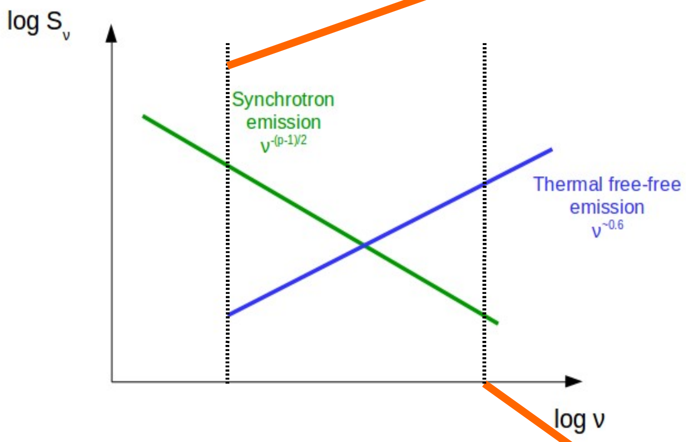
→ Catalogue of ~40 systems **(De Becker & Raucq 2013, A&A, 558, A28)**

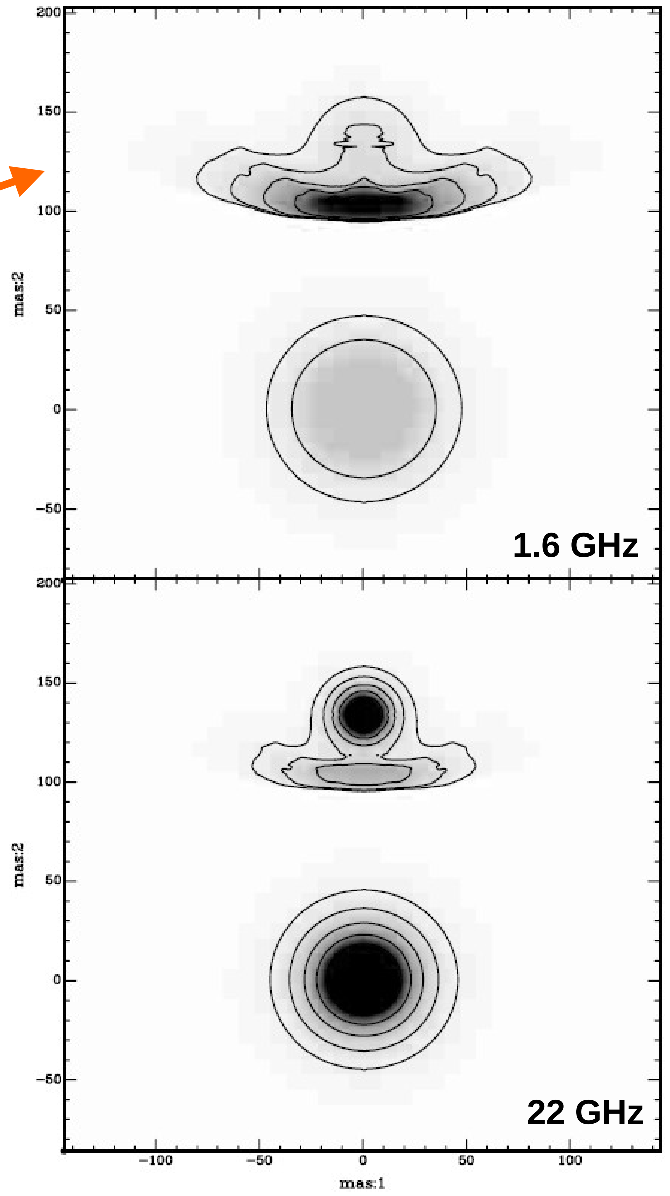
http://www.astro.ulg.ac.be/~debecker/pacwb/

Synchrotron emission from PACWBs

Simulations of radio emission from colliding-wind binaries **(Dougherty et al. 2003, A&A, 409, 217)**

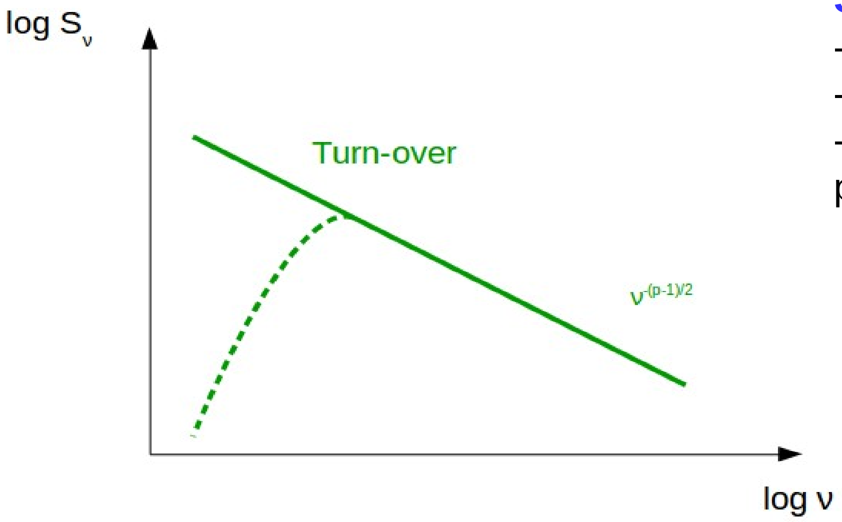
Typical case of a WR + O system





Synchrotron emission from PACWBs

- Turn-over processes



Synchrotron Self-Absorption (SSA)

- optically thick spectrum with $\alpha = 5/2$
- active if the number density of NT e is high enough
- not dominant for PACWBs (may contribute for shorter period systems : De Becker 2018, A&A, 620, A144)

Razin-Tsytovitch effect

- suppression of the effect of beaming for NT electrons embedded in a thermal plasma
- strong suppression of synchrotron emission below a cut-off frequency
- may contribute for PACWBs

Free-free absorption (FFA)

- absorption of radio photons by thermal electrons very abundant in the wind plasma
- highly dependent on stellar separation, system orientation, wind properties… (e.g. Williams et al. 1990, MNRAS, 243, 662 ; Dougherty et al. 2003, A&A, 409, 217)
- very important for PACWBs, origin of a strong phase-locked variability

Synchrotron emission from PACWBs

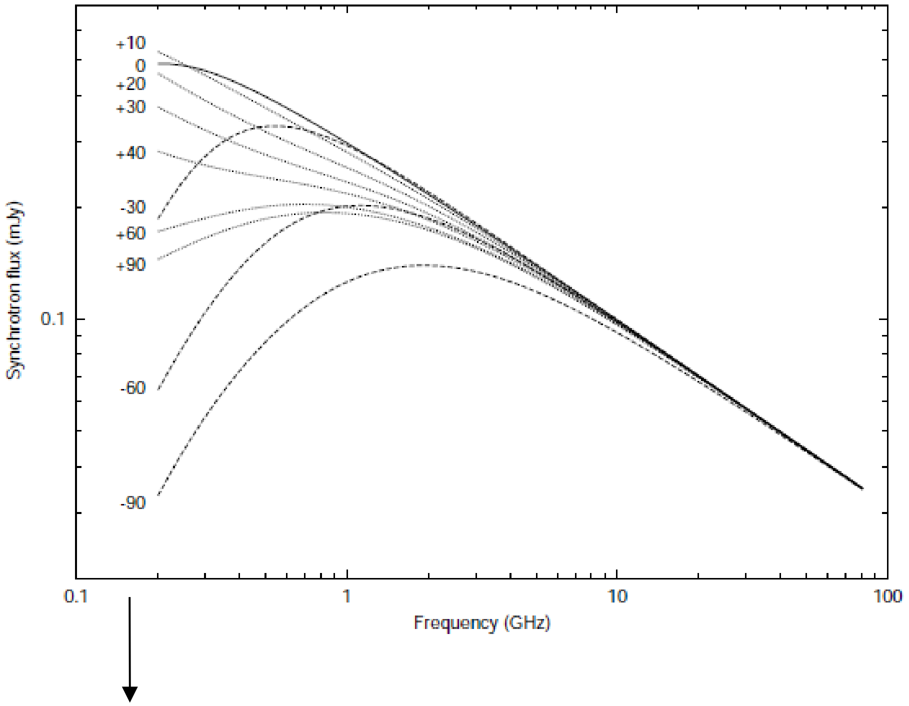
Simulations of radio emission from colliding-wind binaries (Dougherty et al. 2003, A&A, 409, 217)

Effect of FFA on the spectrum, as a function of the inclination of the system

- i < 0° : WR wind in front
- i > 0° : O wind in front

→ orientation effects are very important !

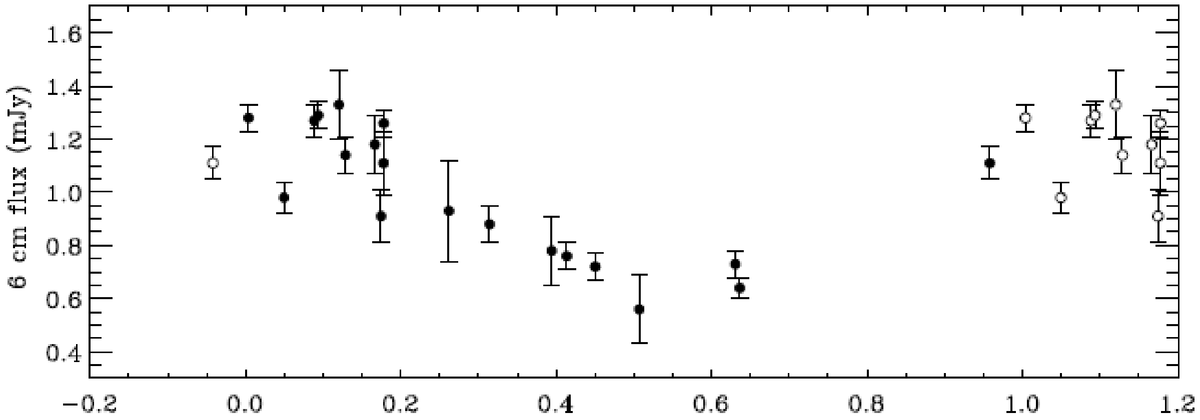
At some lower frequencies, the intrinsic synchrotron emission may be high, but severely attenuated by FFA



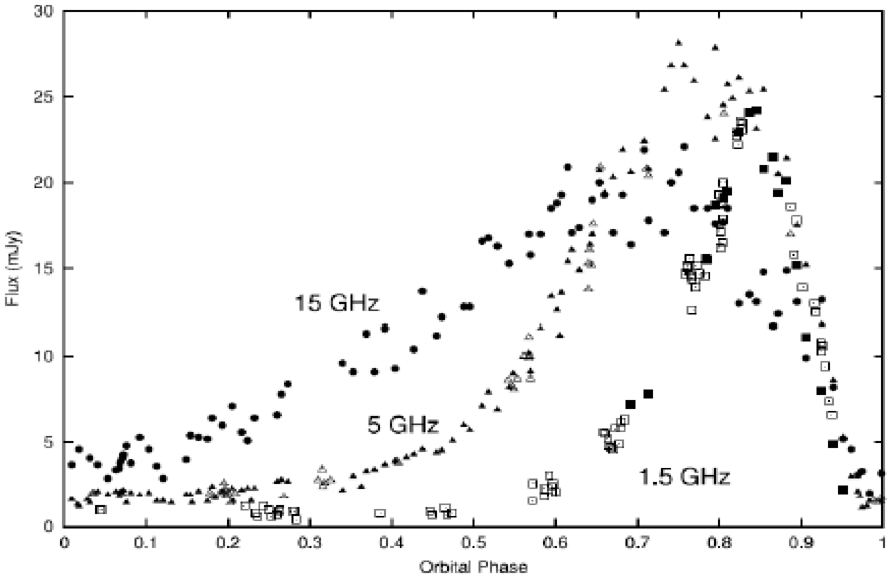
Inclination i

Synchrotron emission from PACWBs

Radio emission variable on the orbital time-scale



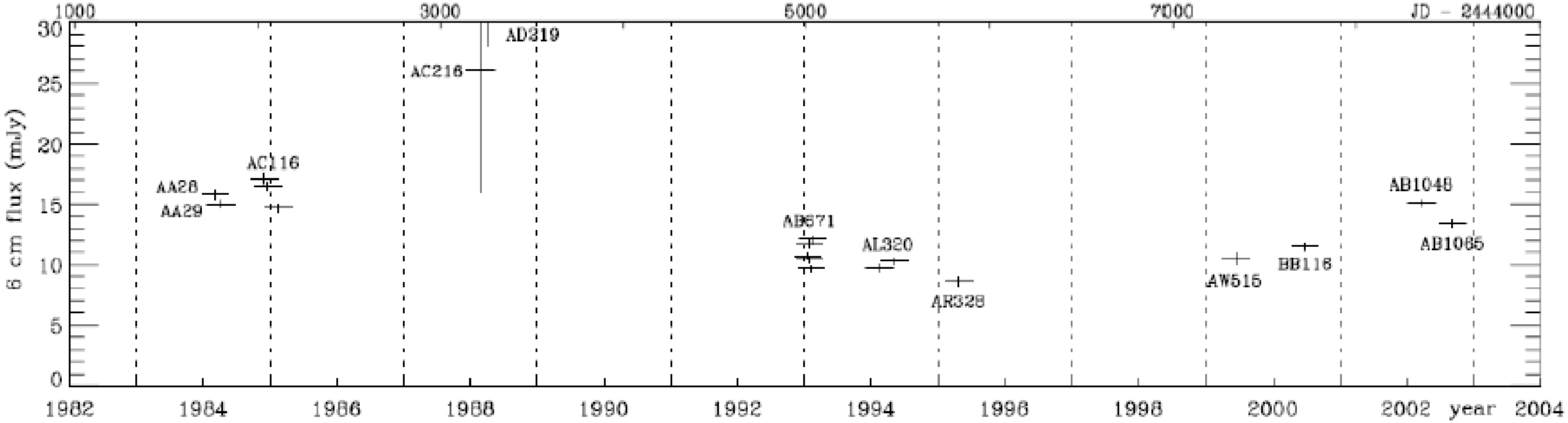
Cyg OB2 #8A: binary system with a period of about 22 d (VLA observations)
(Blomme et al. 2010, A&A, 519, A111)



WR140: a binary system with a period of about 8 yr (VLA observations)
(Dougherty et al. 2005, ApJ, 623, 447)

Synchrotron emission from PACWBs

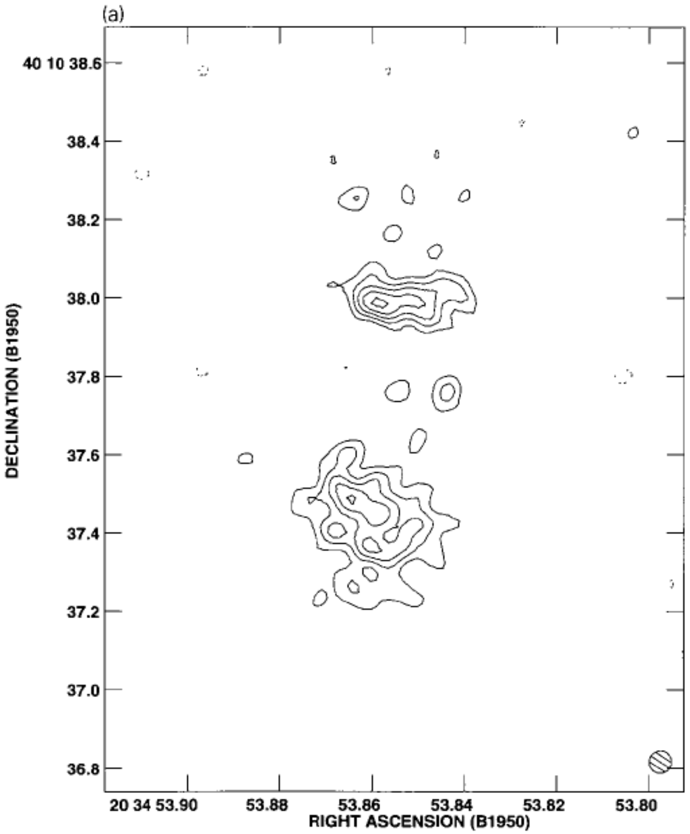
Radio emission variable on the orbital time-scale



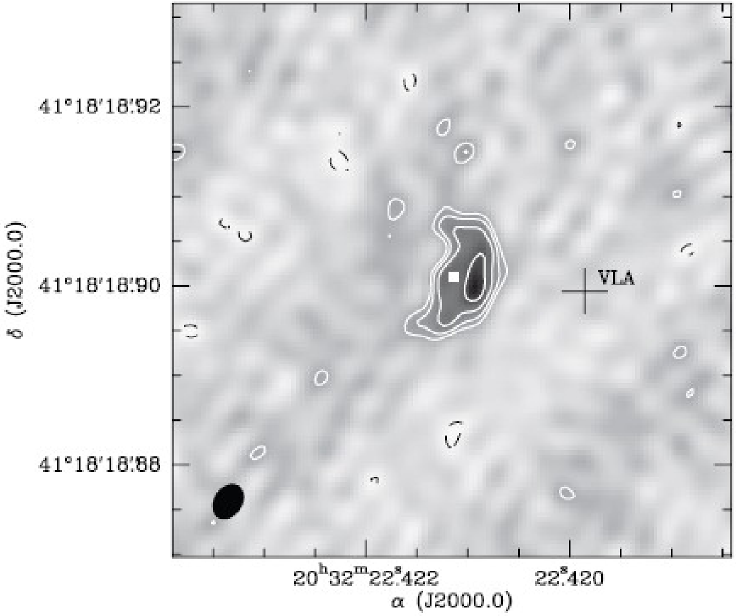
HD167971: triple system with a long period of about 21 yr
(VLA observations)
(Blomme et al. 2007, A&A, 464, 701)

Synchrotron emission from PACWBs

VLBI observations: imaging of the synchrotron emission region



WR147: a system with an very long orbital period!
(MERLIN observations at 5 GHz)
(Williams et al. 1997, MNRAS, 289, 10)

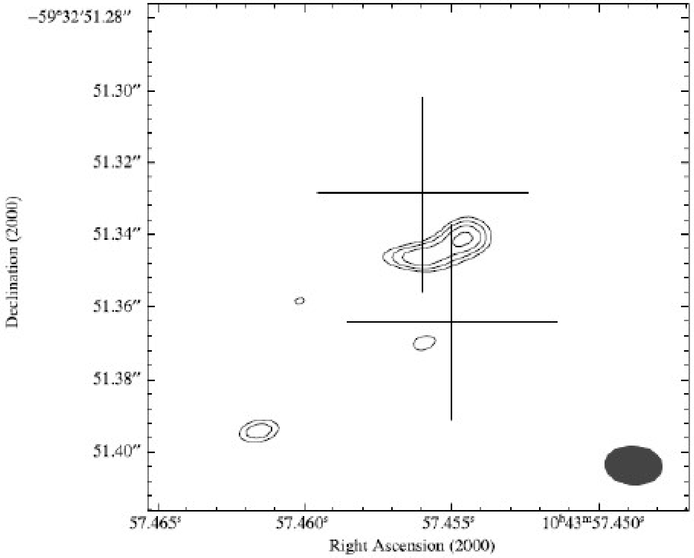


Cyg OB2 #5: a multiple O-type system including notably a 6.7 yr period!
(VLBA observations at 8.4 GHz)
(Ortiz-Leon et al. 2010, ApJS, 737, 30)

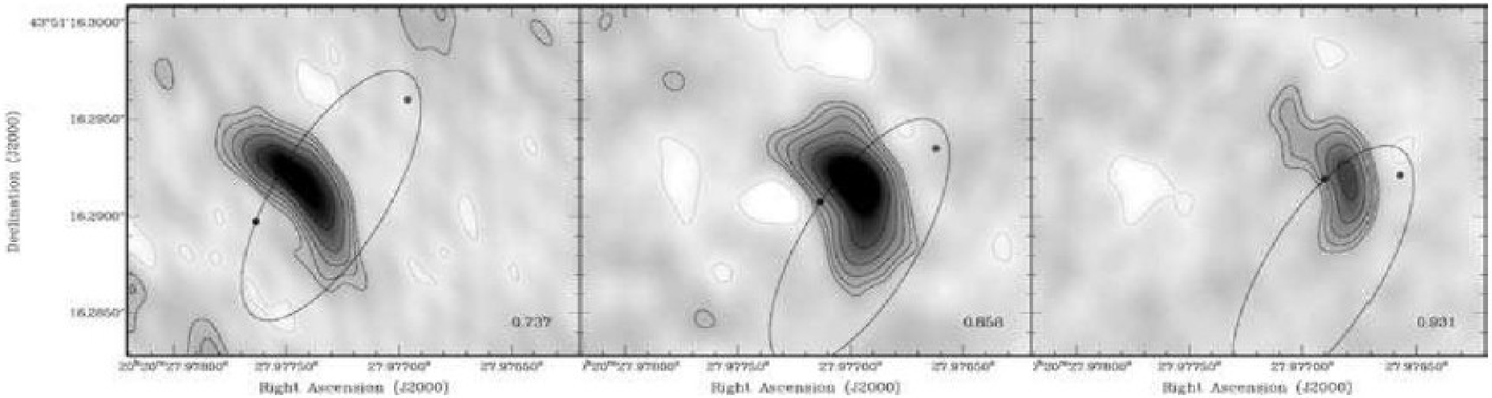
Synchrotron emission from PACWBs

VLBI observations: imaging of the synchrotron emission region

HD93129A: a system with an orbital period of decades!
(LBA observations at 2.3 GHz)
(Benaglia et al. 2015 A&A, 579, A99)



WR140: a binary system with a period of about 8 yr
(VLBA observations at 8.4 GHz)
(Dougherty et al. 2005, ApJ, 623, 447)



High energy NT emission from PACWBs

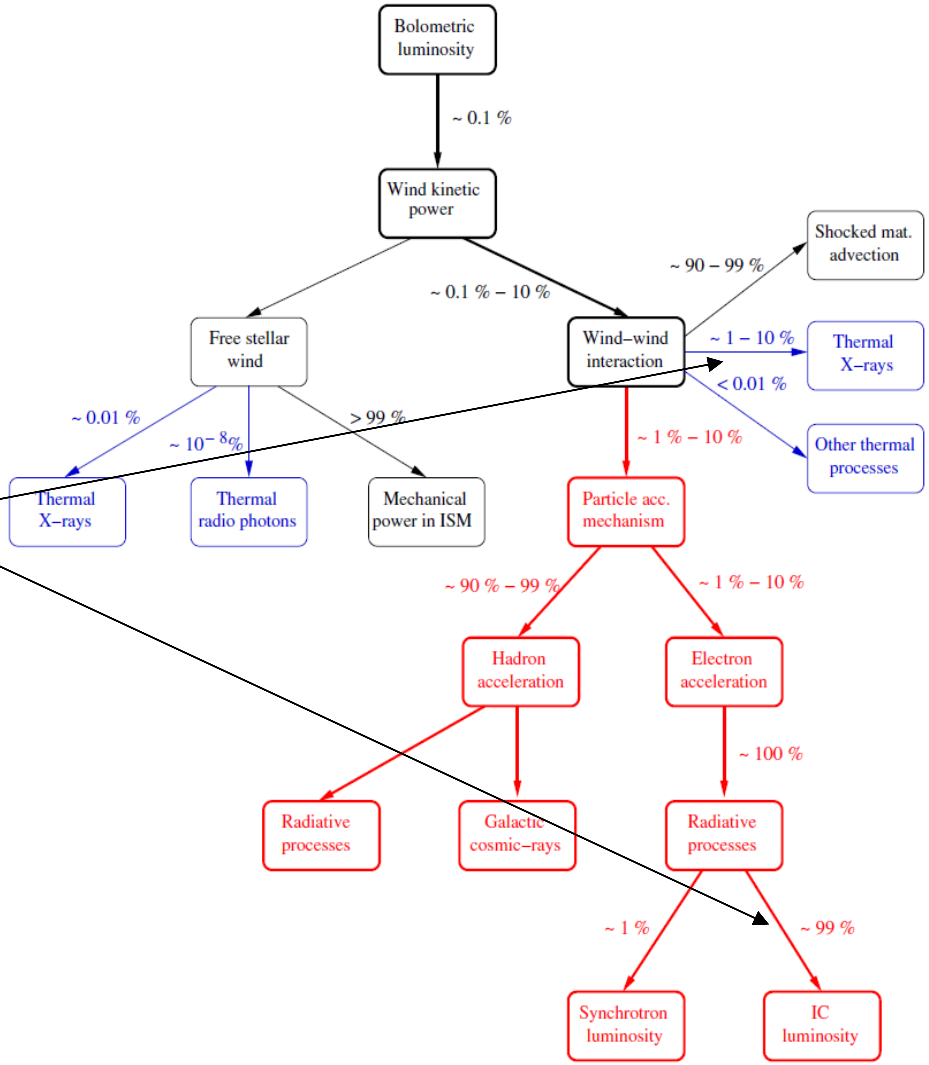
What about the detection of **high energy NT** emission ?

Inverse Compton scattering is expected to be active in CWBs

→ what about soft X-ray observations (below 10 keV) ?

Soft X-ray spectra are dominated by the thermal emission from the colliding winds (and from individual winds)
→ soft X-rays not adequate (no detection of any IC scattering component in XMM spectra so far)
→ strong requirement to explore hard X-rays

(De Becker 2007, A&ARv, 14, 171)



High energy NT emission from PACWBs

Inverse Compton scattering

Condidering the high radiative energy density, IC scattering is the most efficient cooling process for relativistic electrons in a CWR

Energy loss rate:

$$-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{\mathrm{IC}} = \frac{4}{3}\,\sigma_{\mathrm{T}}\,\mathrm{c}\,\mathrm{U}_{\mathrm{rad}}\,\gamma^2\,\beta^2$$

Typical energy of scattered photons:

$$<\nu>=\frac{4}{3}\,\gamma^2\,\nu_{\circ}$$

For a population of relativistic electrons:

$$\left(\frac{\mathrm{dE}}{\mathrm{dV\,dt\,d}\nu}\right)_{\mathrm{IC}} \propto \nu^{-\frac{p-1}{2}}$$

(Blumenthal & Gould 1970, Rev. Mod. Phys., 42, 237)

Comparison to synchrotron radiation:

Energy loss rate:

$$-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{\mathrm{synch}} = \frac{4}{3}\,\sigma_{\mathrm{T}}\,\mathrm{c}\,\mathrm{U}_{\mathrm{mag}}\,\gamma^2\,\beta^2$$

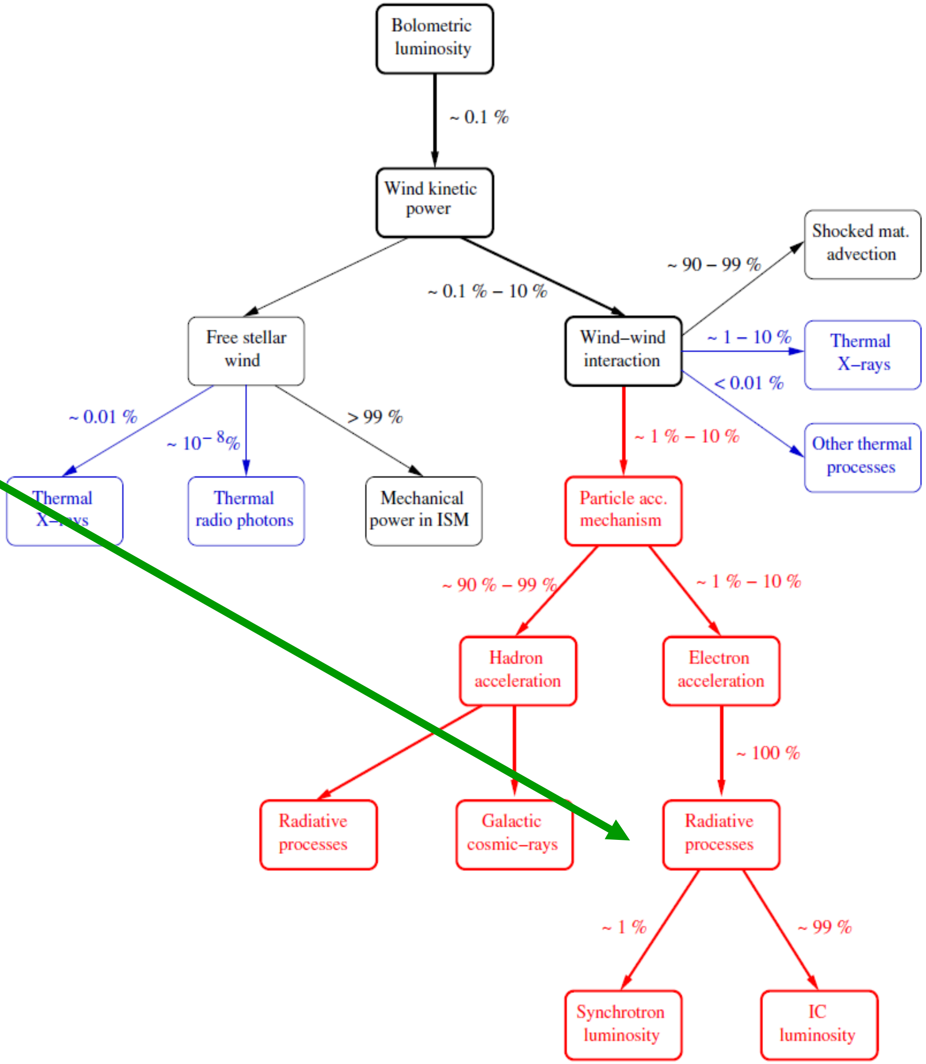
Synchrotron/IC luminosity ratio:

$$\frac{\mathrm{L}_{\mathrm{synch}}}{\mathrm{L}_{\mathrm{IC}}} = \frac{-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{\mathrm{synch}}}{-\left(\frac{\mathrm{dE}}{\mathrm{dt}}\right)_{\mathrm{IC}}} = \frac{\mathrm{U}_{\mathrm{mag}}}{\mathrm{U}_{\mathrm{rad}}}$$

$U_{mag} << U_{rad}$ → IC dominates !

High energy NT emission from PACWBs

Energy injected in relativistic electrons is mainly radiated through IC scattering, because the energy density in the radiation field is larger than that of the local magnetic field



High energy NT emission from PACWBs

What about emission processes involving relativistic protons?

Neutral pion decay from proton-proton collisions

(e.g. Cheng & Romero 2005, ASSL, vol. 304)

$p + p \rightarrow \pi^0 + X$
$\pi^0 \rightarrow \gamma + \gamma$

→ a fraction of relativistic protons can interact with thermal material, and finally produce γ-rays

→ in principle, CWB could be γ-ray emitters up to energies limited by the energy spectrum of relativistic protons

However, the interaction gamma-rays with the intense ambient radiation field yields

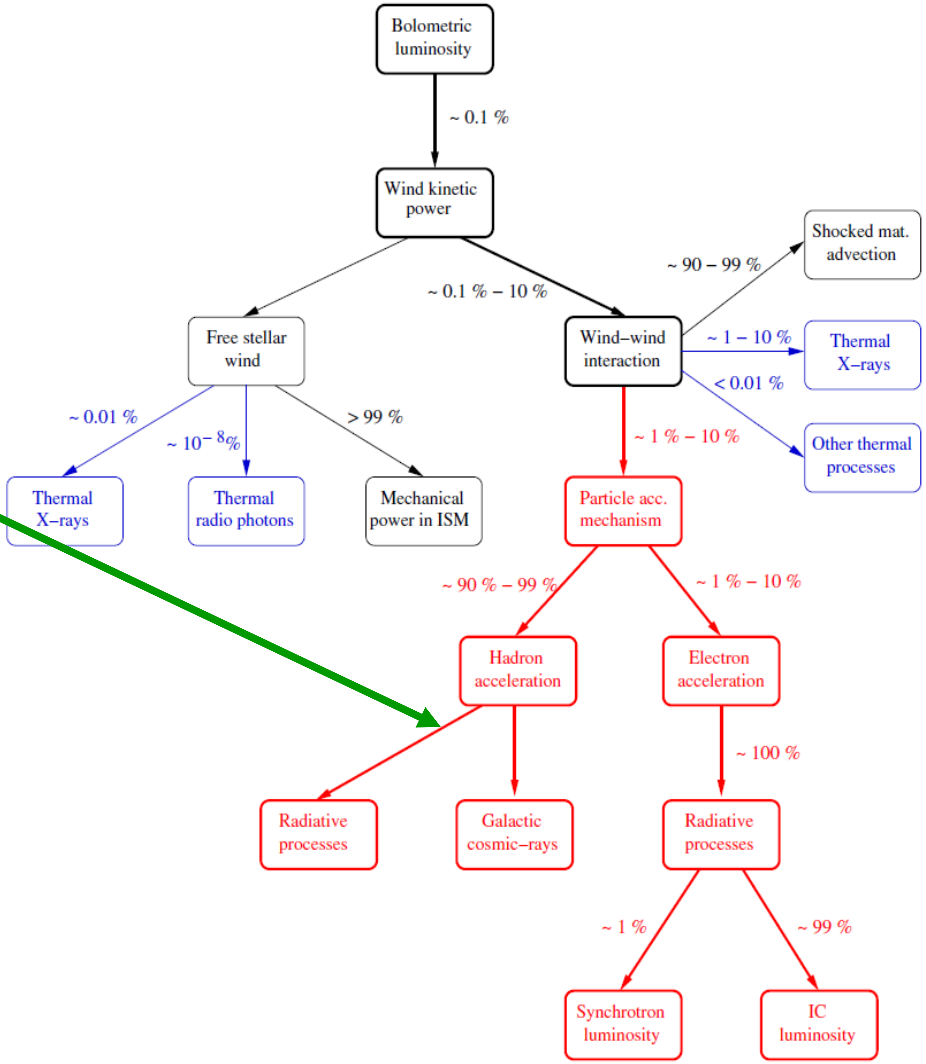
$\gamma + \gamma' \rightarrow e^+ + e^-$ (pair creation)

→ the radiation field produced by massive stars is quite opaque to γ-rays, and a significant attenuation is expected

(Romero et al., 2010, A&A, 518, A12;
Reitberger et al. 2014, ApJ, 789, 87)

High energy NT emission from PACWBs

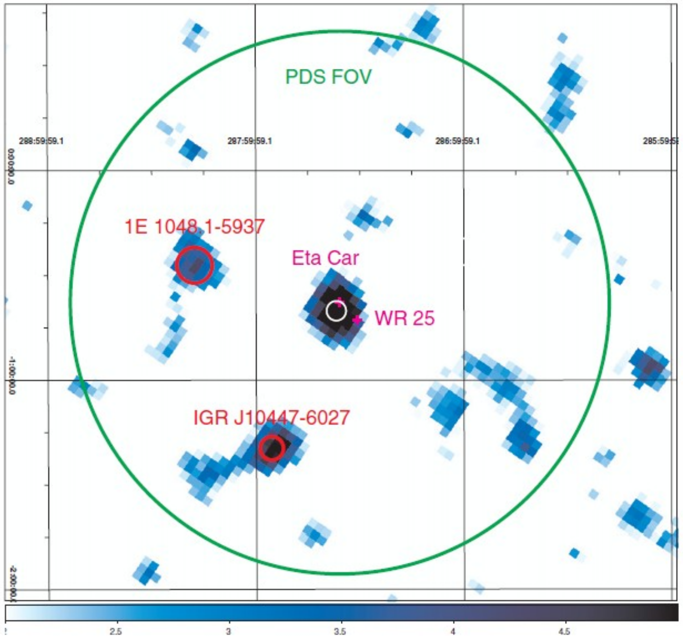
Energy injected into relativistic protons (and potentially heavier nuclei) is expected to be partly radiated through hadronic processes, and the residual energy contributes to the population of Galactic cosmic-rays.



High energy NT emission from PACWBs

Inverse Compton scattering in hard X-rays:

- Several PACWB in the Cygnus region → no detection with INTEGRAL **(De Becker et al. 2007, A&A, 472, 905)**
- Eta Carinae (very massive transition object) → detected with BeppoSax **(Viotti et al. 2004, A&A, 420, 527)**, with INTEGRAL **(Leyder et al. 2008, A&A, 477, L29)**, and with Suzaku **(Sekigushi et al. 2009, PASJ, 61, 629)**
- WR140 potentially detected with Suzaku, but might be a contamination by a background Seyfert galaxy **(Sugawara et al. 2015, PASP, 67, 121)**

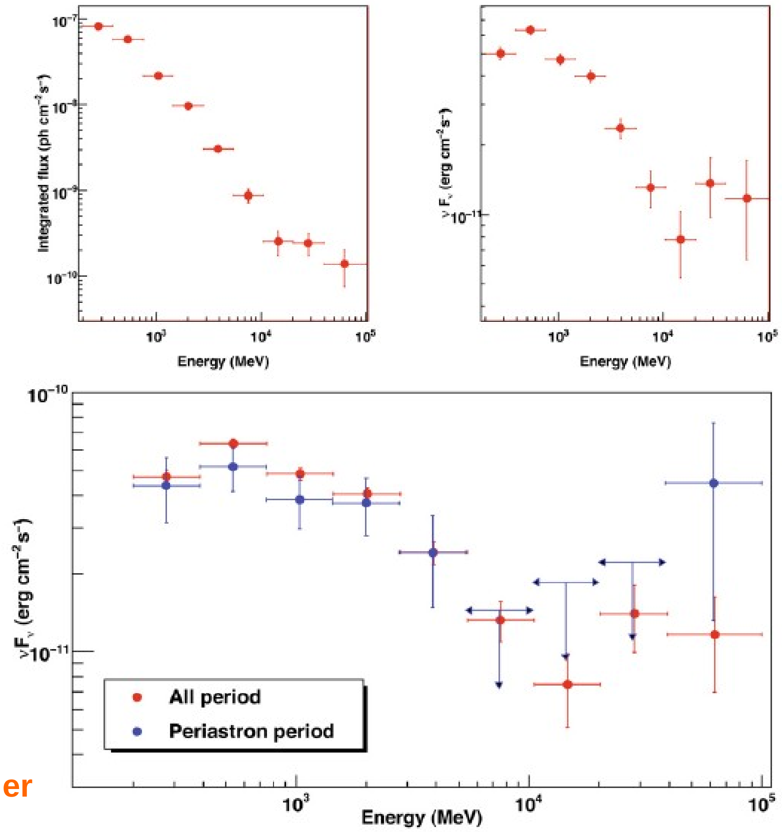


Eta Car: extreme CWB with a P ~ 5.5 yr

High energy NT emission from PACWBs

Detection in γ-rays:

- Eta Carinae → detected with AGILE **(Tavani et al. 2009, ApJ, 698, L142)** and with Fermi **(Abdo et al. 2010, ApJS, 187, 460)**
- WR11 potentially detected with Fermi **(Pshirkov 2016, MNRAS, 457, L99)**
- A sample of WR-type CWB investigated after many years of observations with Fermi → no detection ! **(Werner et al. 2013, A&A, 555, A102)**



Gamma-ray emission from Eta Car **(Farnier et al. 2011, A&A, 526, 57)**

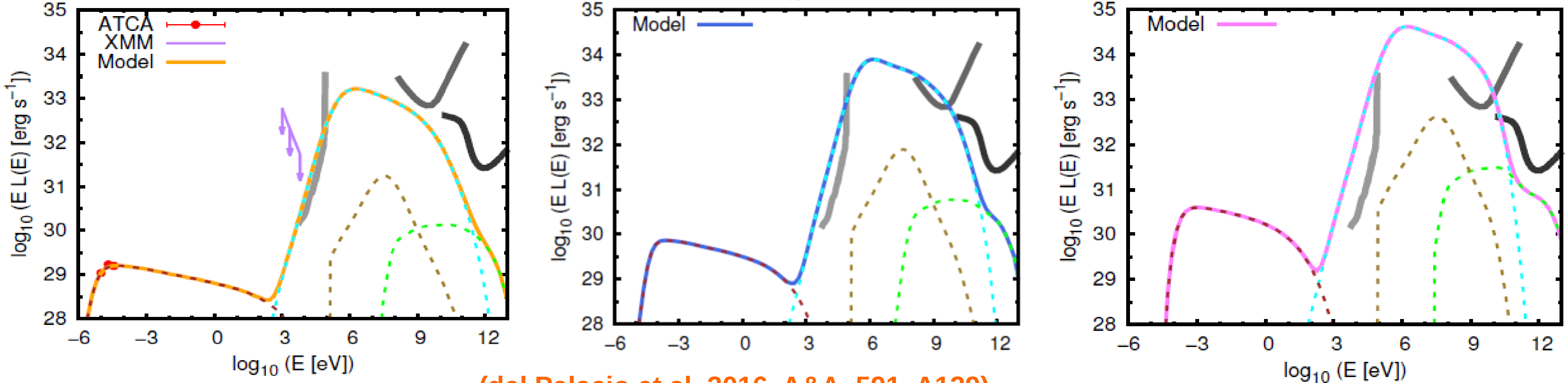
High energy NT emission from PACWBs

Can we make some predictions about the expected emission of PACWBs in the high energy domain (where detections so far are rare)?

→ **yes, we can!**

The long period system HD93129A:
Spectral energy distributions for different situations/orbital phases, confronted to sensitivity curves for various observatories
→ significant variability
→ chances of detection depend on the assumed parameters, and on the orbital phase
→ strong evidence that elusive high energy detections may become more probable if systems are probed at adequate epochs

High importance of models to help to prepare observations!



At the time of the radio observations

Close to the epoch of the study

At the (assumed) periastron passage

(del Palacio et al. 2016, A&A, 591, A139)

Concluding remarks

Concluding remarks

- Colliding-wind massive binaries (CWBs) display a rich and diversified physics
- Many physical processes are at work in various spectral domains, hence the interest of muti-wavelength investigations
- These systems can be particle accelerators, hence the PACWB status
- PACWB are efficient non-thermal emitters in the radio domain, and are very good candidates for high energy non-thermal emission
- These systems offer the opportunity to study the same non-thermal physics as supernova remnants, but in a different part of the parameter space and a different geometry
- A better understanding of their physics, considering their full Galactic population, is relevant in the context of the study of the sources of Galactic cosmic-rays

Thank you !