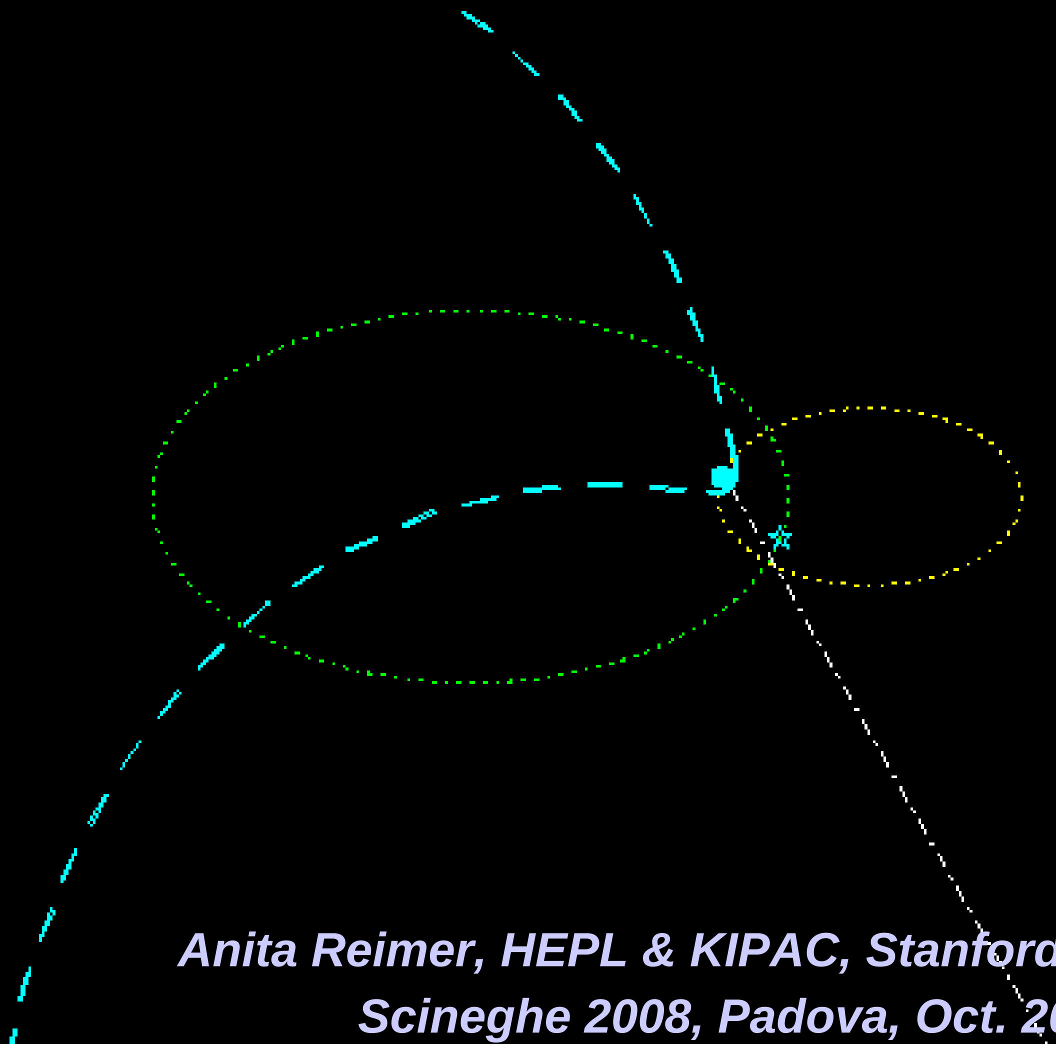
MASSIVE STARS IN COLLIDING WIND SYSTEMS: THE HIGH-ENERGY GAMMA-RAY PERSPECTIVE



Anita Reimer, HEPL & KIPAC, Stanford University

Scineghe 2008, Padova, Oct. 2008

Massive Stars ...

...are **hot** (~3-6·10^4K), **massive** (~20-80 M_o), **luminous** (~$10^{5-6}L_o$)

...show **large mass loss rates** in stellar winds: ~$10^{-6...-3}M_o$/yr

...possess **supersonic winds**: $V(x) \approx V_\infty(1-R_*/x)$, V_∞~1-5·10^3 km/s

evolution ↓

Stage	M_i ($M_\odot$)	L ($L_\odot$)	Δt (Myr)	v_∞ km s^{-1}	$\dot{M}$ ($M_\odot yr^{-1}$)	ΔM ($M_\odot$)	L_w/L	η
O star	40	2 10^5	5	3000	10^{-6}	5	0.004	0.7
FAST wind, long time								
LBV/(RSG)	35	4 10^5	10^{-2}	300	10^{-3}	10	0.02	35
SLOW wind, short time								
WR	25	3 10^5	0.5	2000	3 10^{-5}	15	0.04	10
FAST wind, moderate time								
SN(Ib,c)	10	10^{11}	(10^{-7})	30000	(50)	5	40	700
ULTRAFAST wind, ultrashort time								
BH	5							
~NO wind, ~infinite time								

Notes: Total mass loss during stage, $\Delta M = \dot{M}\Delta t$. $L_w \equiv \dot{M}v_\infty^2/2$, $\eta \equiv \dot{M}v_\infty/(L/c)$. The SN duration, Δt, is the time required to reach $L = L_{max}/2$ and the SN mass-loss rate is simply $\Delta M/\Delta t$.

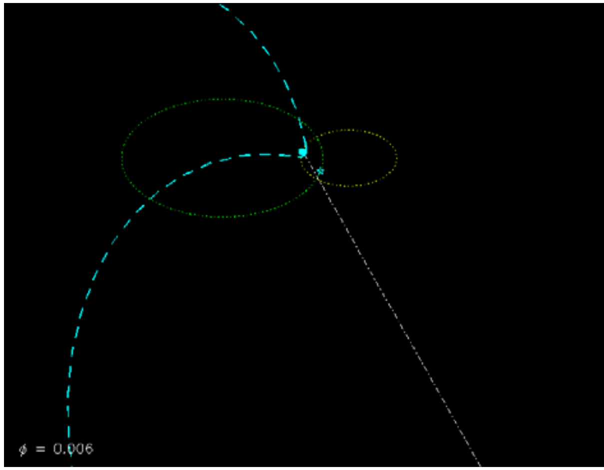
[From: Moffat 2001]

Potential sites of particle acceleration

➡ **various kinds of shocks/instabilities:**

- **Intra-Wind interactions:**

  „clumps“, shocks from line-driven instabilities („chaotic wind model“)



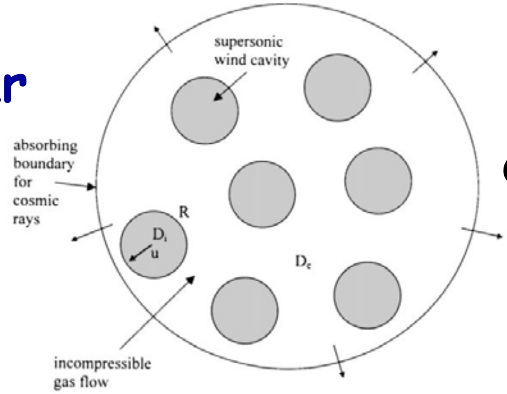
- **Wind-Wind collisions**

- **Wind-ISM collisions**

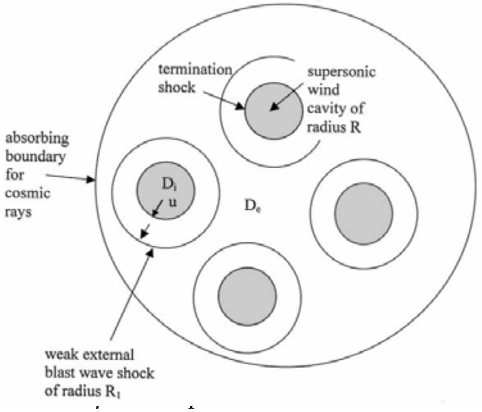
- **Collective effects of stellar winds:**

  large scale shocks at core of association

  (e.g. Bykov et al. 1992)



or:



Broadband characteristics

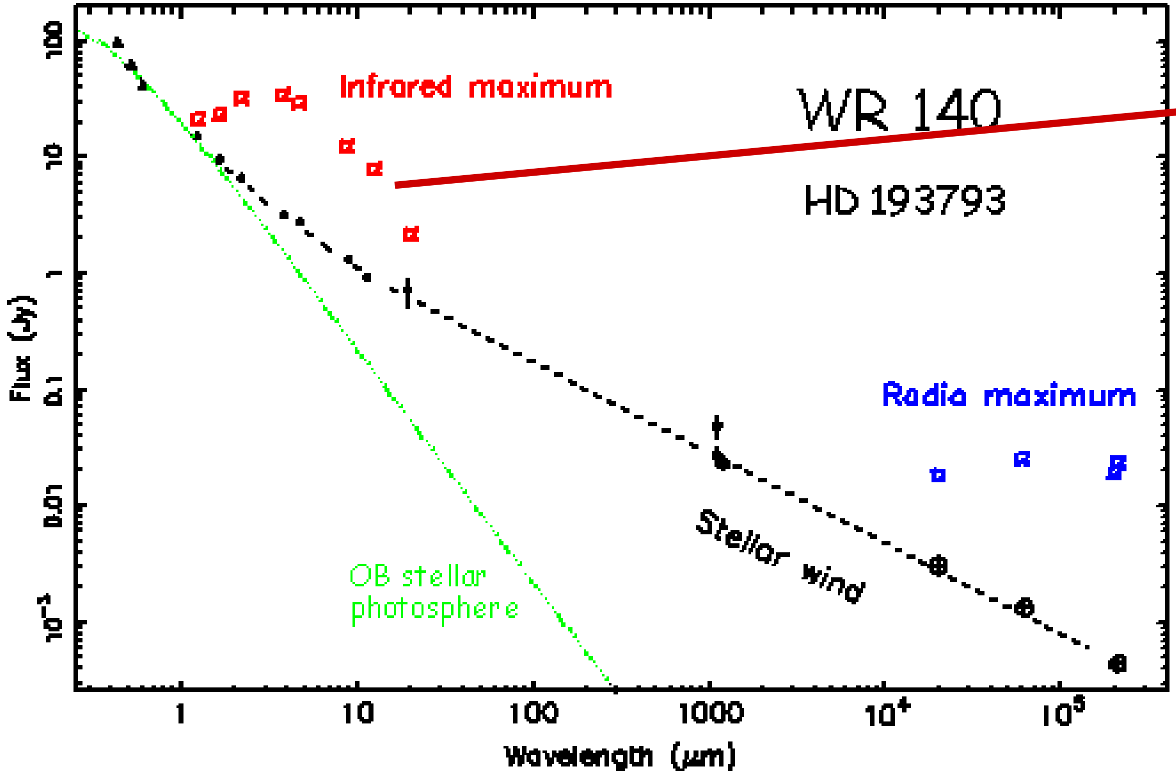
- **Radio band:**

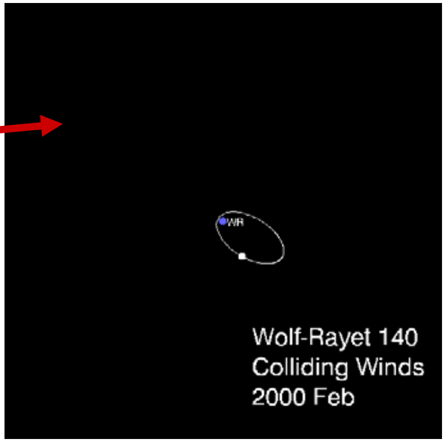
  free-free emission (S ~ $\nu^{0.6}$ for isothermal spherical wind) +

  synchrotron radiation **(„proof" for existence of relativistic electrons!)**

- **IR:**

  thermal (episodic dust formation during periastron in WC-binaries)

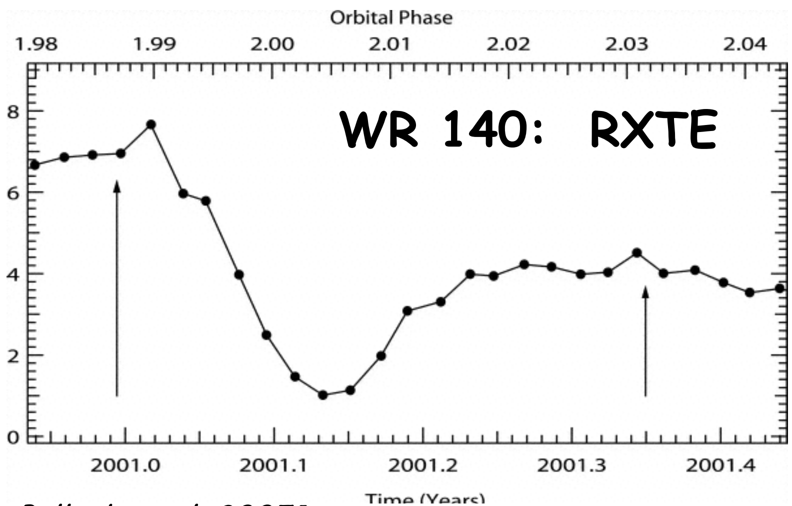




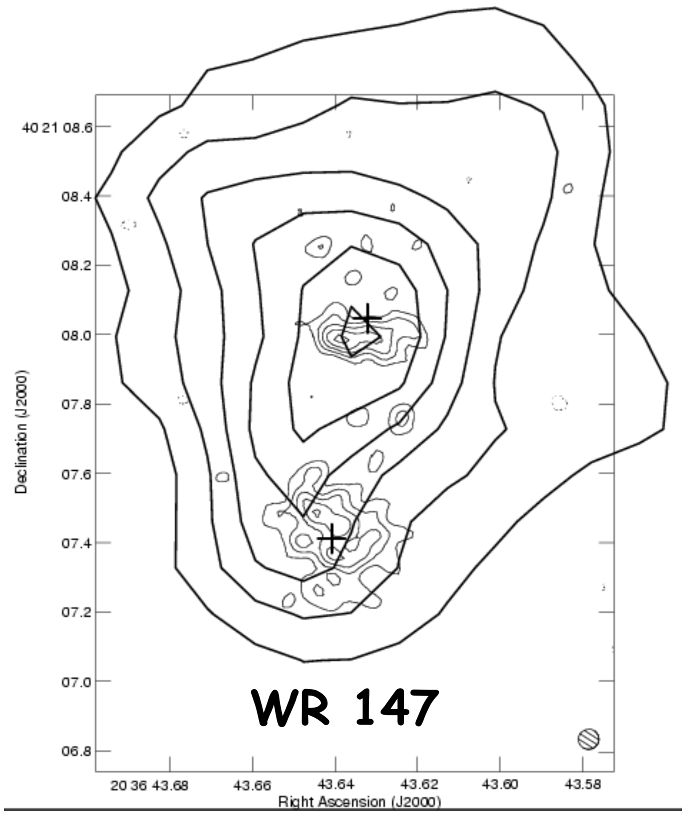
The low-energy SED of WR 140 (WC7 + O4-5).

Broadband characteristics: X-rays

- thermal (shock-heated gas) + non-thermal ?
- $L_x \sim L_{bol}$ for single O-stars; L_x (binary) > L_x (2 x single)
- phase-locked variability in binaries



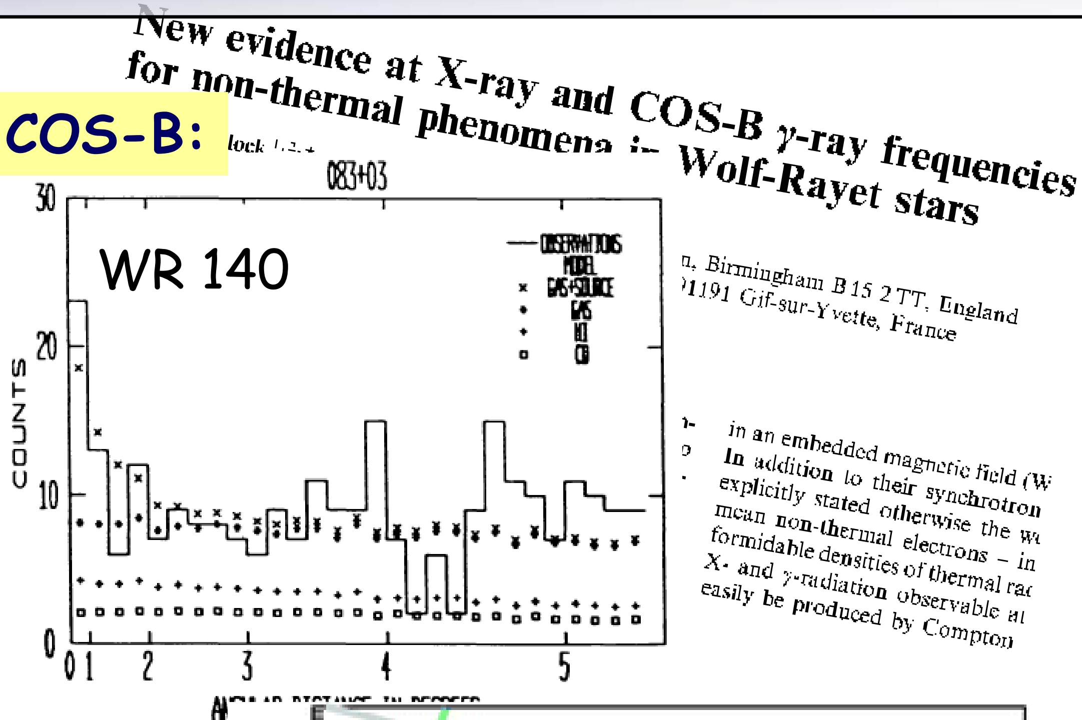
[from: Pollock et al. 2005]



[from: Pittard et al. 2002]

Broadband characteristics: γ-rays

COS-B:

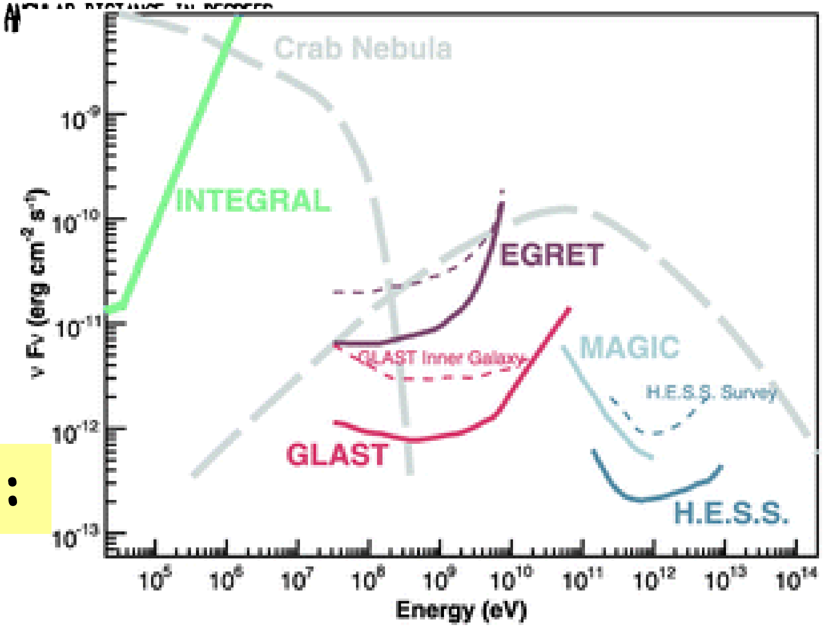


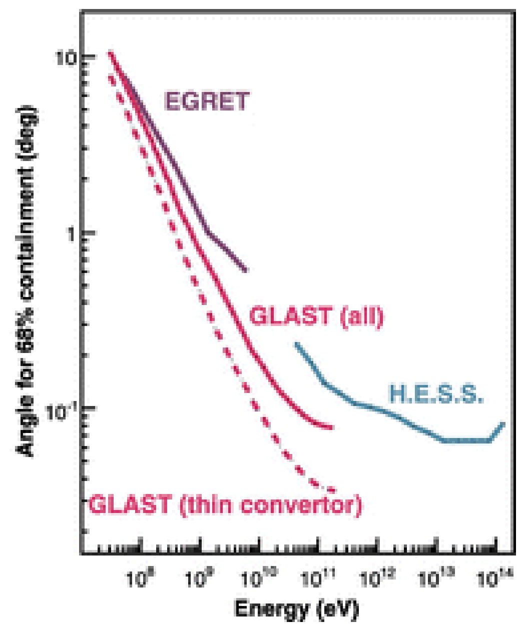
EGRET:

- Population studies imply **correlation of some still unidentified γ-ray sources (Unids) with massive star populations** (OB-associations, WR-, Of-stars)

[Montmerle 1979, Romero et al. 1999, ...]

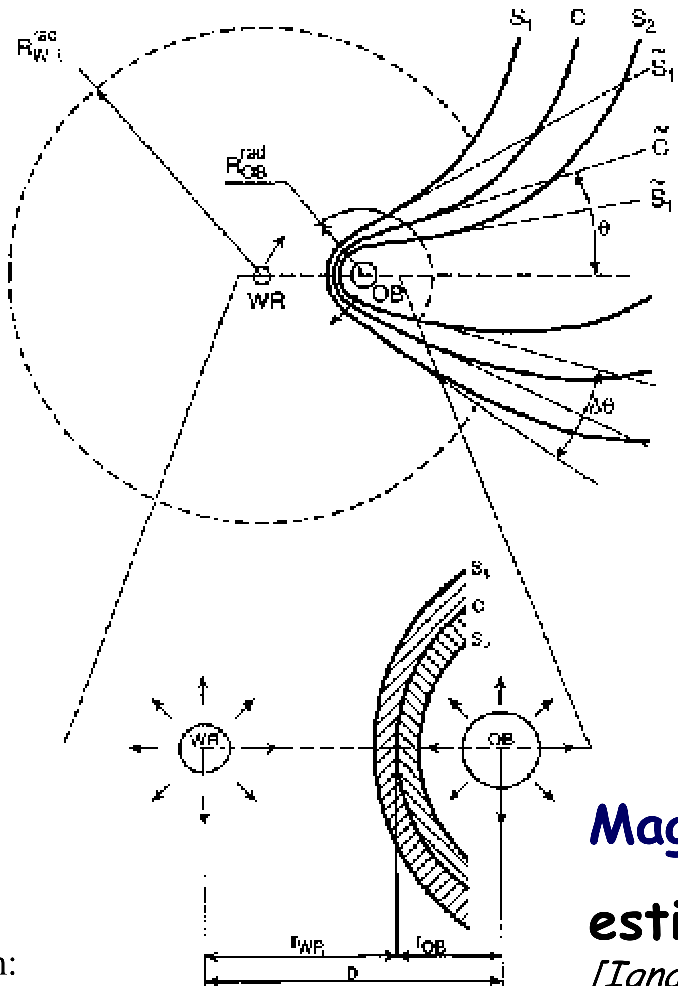
Today:





[from: Funk et al. 2008]

A schematic view on a COLLIDING WIND REGION



from:
Eichler & Usov 1993

Wolf–Rayet period characterization and distribution

Period (d)	Characterization	N_{WN}	N_{WC}
$P<1$	very-short-period binary	3	1
$1<P<10$	short-period binary	15	9
$10<P<100$	medium-period binary	8	5
$100<P<1000$	long-period binary	3	3
$1000<P<10000$	very-long-period binary	2	7
$10000<P$	extremely-long-period binary	1	1

$D \sim 3 \ldots 10^5\ R_o$

Stagnation point (ram pressure balance):

$$r_{OB} = x = \frac{\sqrt{\eta}}{1+\sqrt{\eta}} D \qquad \text{with} \qquad \eta = \frac{\dot{M}_{OB} V_{\infty,OB}}{\dot{M}_{WR} V_{\infty,WR}}$$

→ $\eta \ll 1$ for WR-binaries

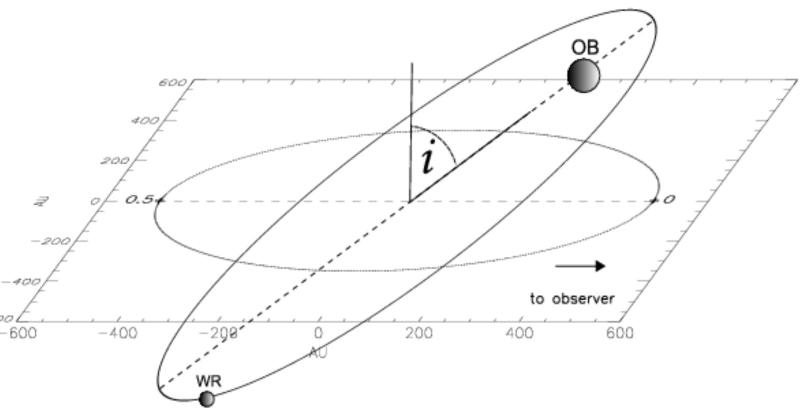
Magnetic field:

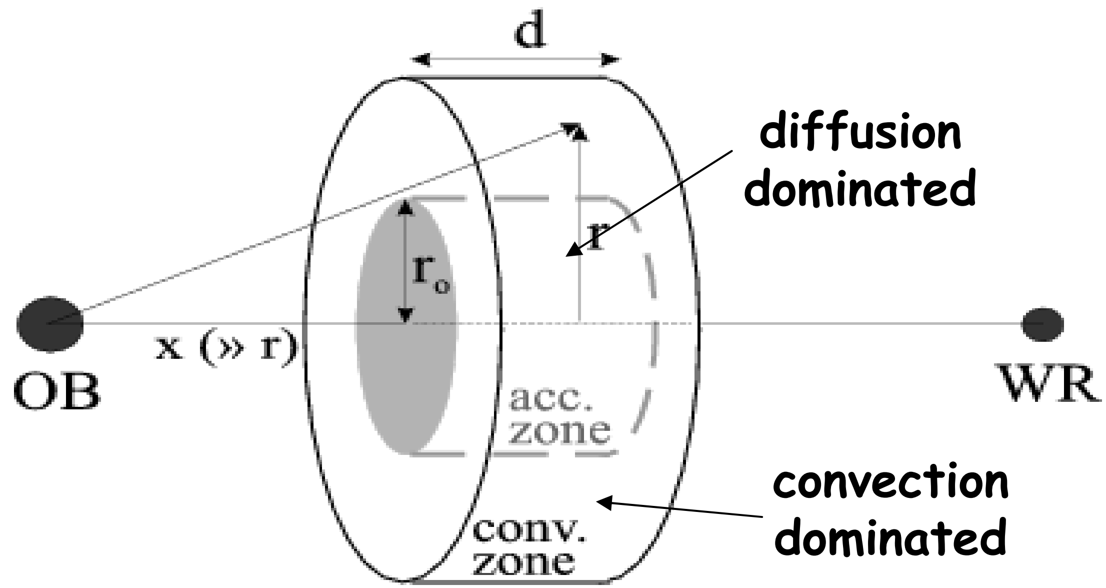
estimated surface magnetic field: B_S~10-10^{4}G
[Ignace et al. 1998; Mathys 1999; Donati et al. 2001,2002]

→ **> mG-fields at tenths of pc**

The Model

[Reimer et al. 2006, ApJ]

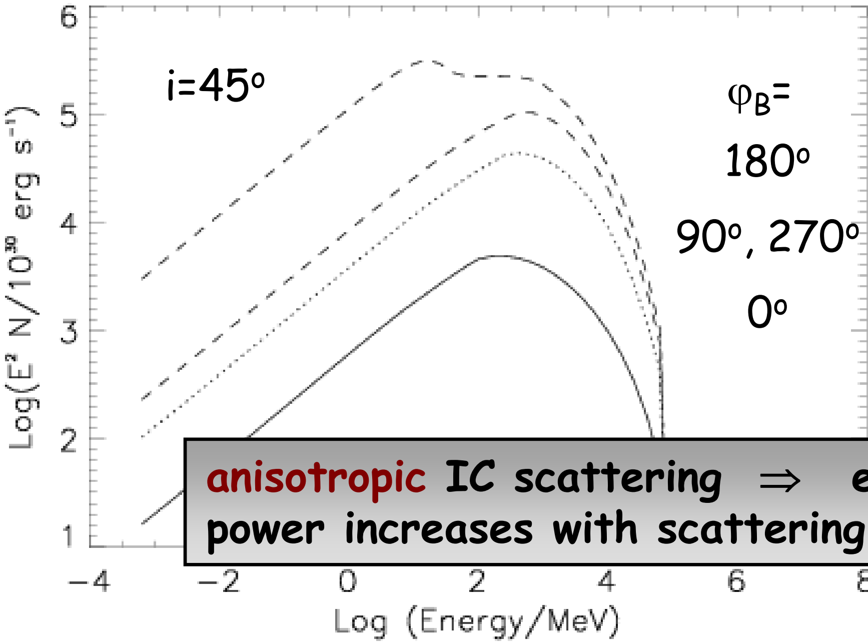




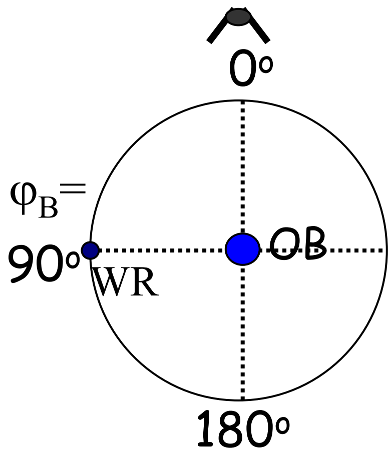
- **uniform wind**
- neglect interaction of stellar radiat. field on wind structure
  $\Rightarrow$ restrict to **wide binaries**
- **cylinder-like** emission region (x»r, emission from large r negligible)
- **photon field** of OB-comp. **monochromatic**: $n(\varepsilon) \sim \delta(\varepsilon-\varepsilon_T)$, ε_T»10eV
  electron distribution **isotropically**
- convection velocity **V = const.**
- magnetic field **B = const.** throughout emission region

Constituting the γ-ray output: Operating processes

- Inverse Compton scattering off stellar photons (anisotropic, KN?)



anisotropic IC scattering ⇒ emitted power increases with scattering angle !

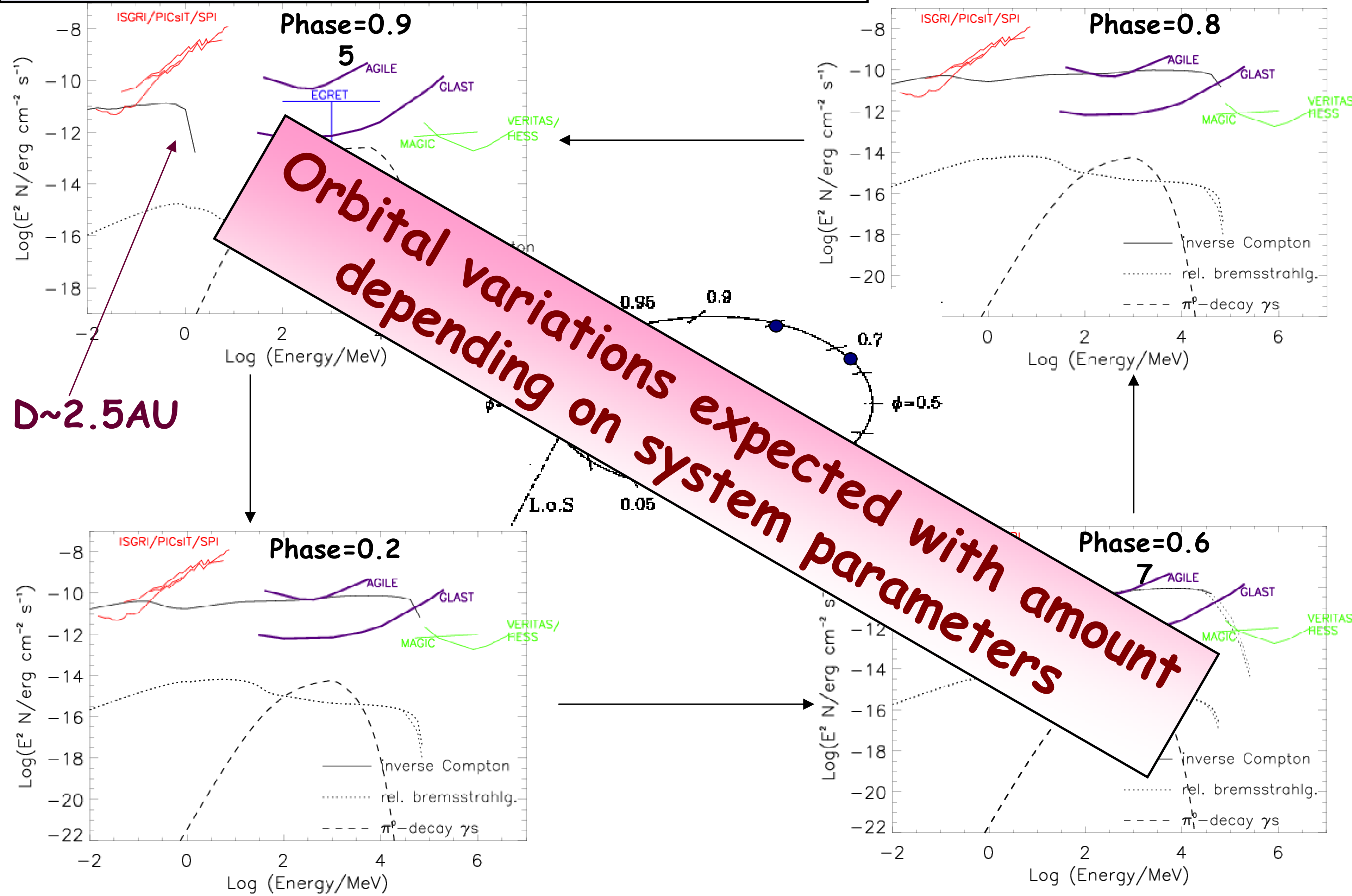


⇒ orbital variation of IC radiation expected

- Relativistic bremsstrahlung
- NN/pp inelastic scattering
- γ-absorption due to γγ-collision: $E_{\gamma,cr}$~66 $(T_4/K)^{-1}$GeV, T_4=T/(5·10^4K)
- propagation (convection, diffusion): *spectral softening in post-shock flow*
- *alternative:* cascade models if ions reach suff.high E *[e.g. Bednarek 05]*

Example: WR 140 (WC7+O4-5V)

[from: Reimer et al. 2006, ApJ]



WR 147 (WN8+B0.5V)

MAGIC:

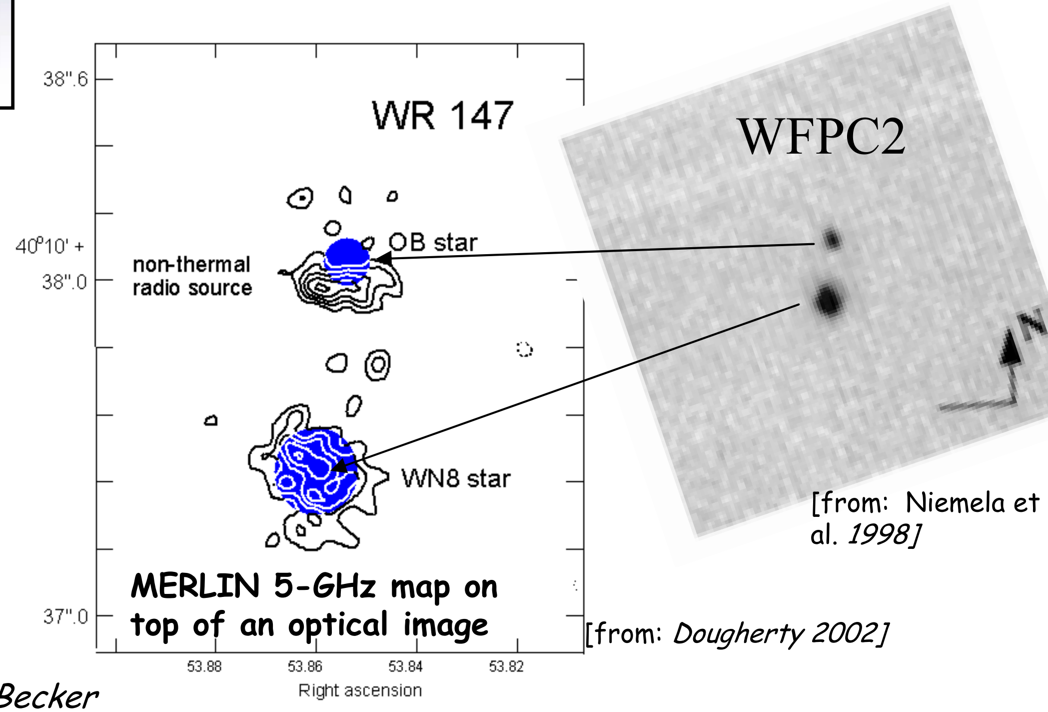
WR 147 OBSERVATION RESULTS[a]

Energy [GeV]	N_{excess} [evts]	S [σ]	U.L. [evts (cm^{-2} s^{-1})]
>80	-196±175	-1.1	150 (1.1×10^{-11})
>200	-92±89	-1.0	84 (3.1×10^{-12})
>600	-20±24	-0.8	28 (7.3×10^{-13})

INTEGRAL:

Energy band (keV)	Count rate (cts s^{-1})	Upper limits (3σ) Photon flux (ph cm^{-2} s^{-1})	Flux (erg cm^{-2} s^{-1})
3EG J2033+4118			
20–60	0.087	1.1×10^{-4}	6.1×10^{-12}
60–100	0.051	3.4×10^{-5}	4.2×10^{-12}
100–1000	0.069	7.9×10^{-5}	4.0×10^{-11}

[from: De Becker etal. 2007]

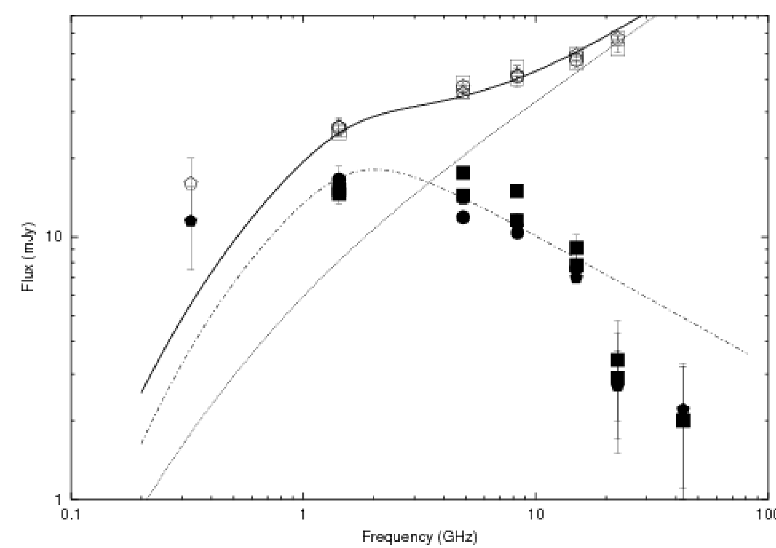


MERLIN 5-GHz map on top of an optical image

[from: *Dougherty 2002]*

[from: Niemela et al. *1998]*

- **distance ~ 650 pc**
- **L_B ~ 1.9·10^{38} erg/s**
- **T_{eff} ~ 28 500 K**
- **WN: V~950km/s, M~2.5·10^{-5}M$_o$/yr**
- **(O)B: V~800km/s, M~4·10^{-7} M$_o$/yr**
- **D ~ 417 AU / cos i**



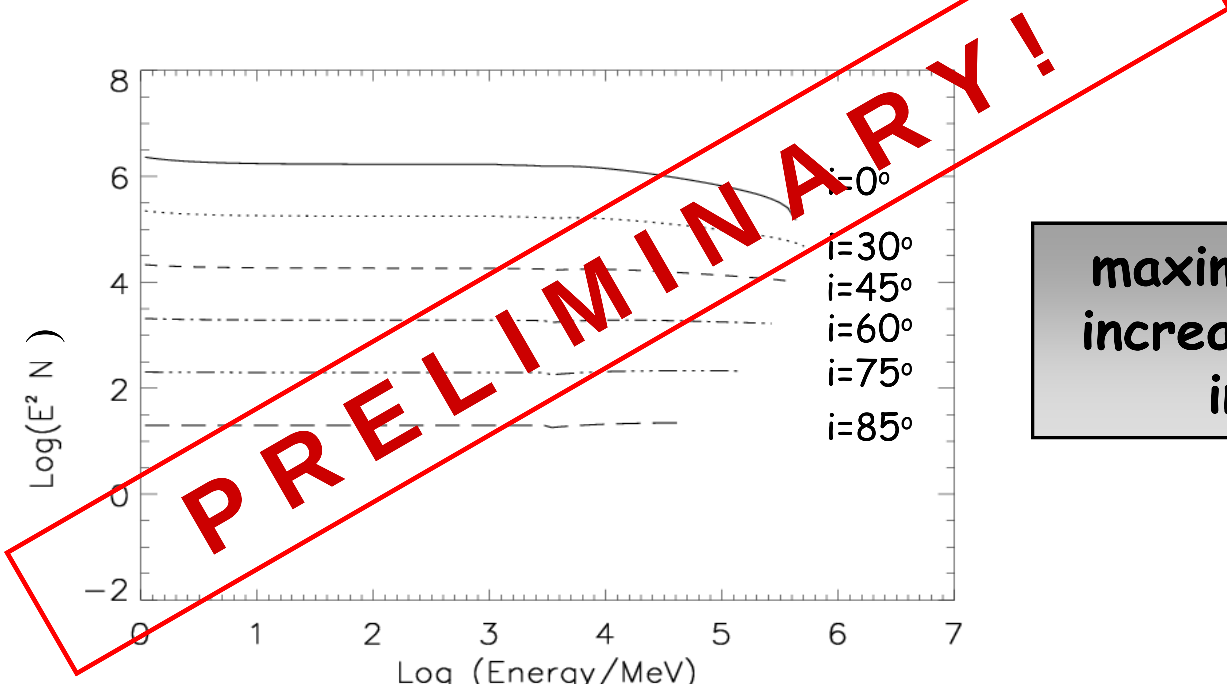
Constraining WR 147's particle spectrum

- *observational constraints:* synchrotron spectrum ($\gamma_{e,max}$, B, norm.), projected stellar separation (⇒ inclination i affects magnetic/photon field density at shock)

- *physics constraints:* acceleration rate to overcome Coulomb losses, Bohm limit for diffusive shock acceleration, energy & particle number conservation

  ⇒ κ_{acc} allows >GeV photon/e^- production within obs./physics constraints

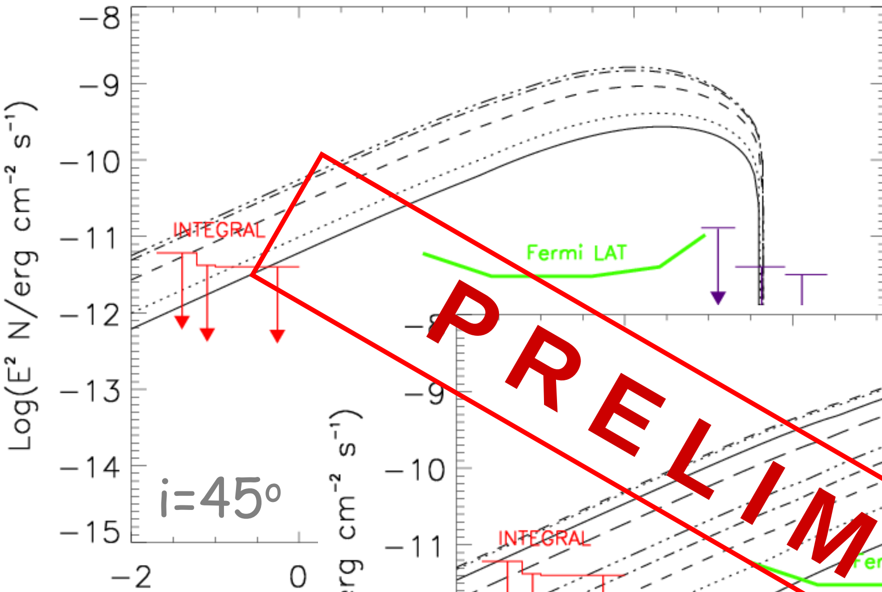
- higher field strengths at shock location for small inclination systems allows particle acceleration to larger particle energy



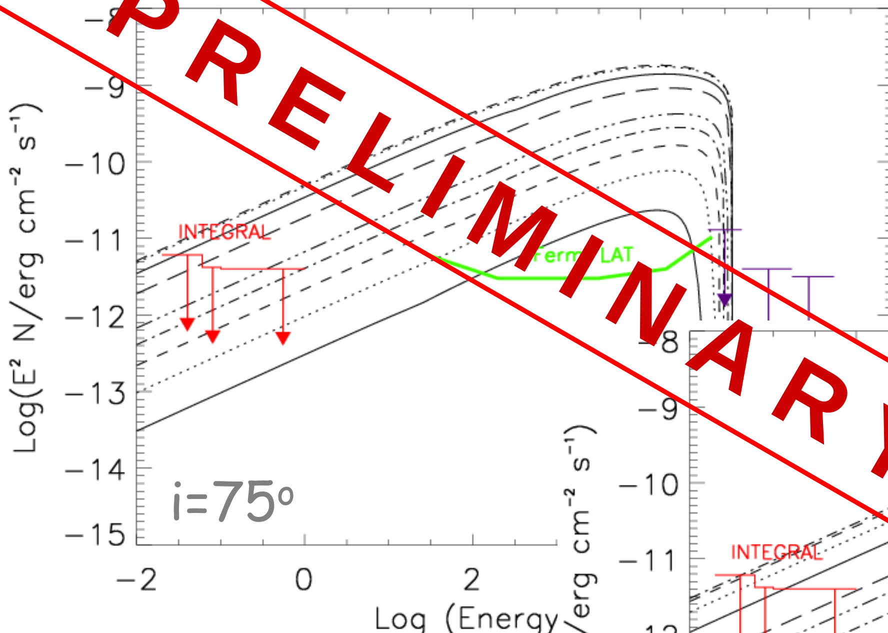
maximum particle energy increases with decreasing inclination angle

[Reimer et al. 2008, submitted]

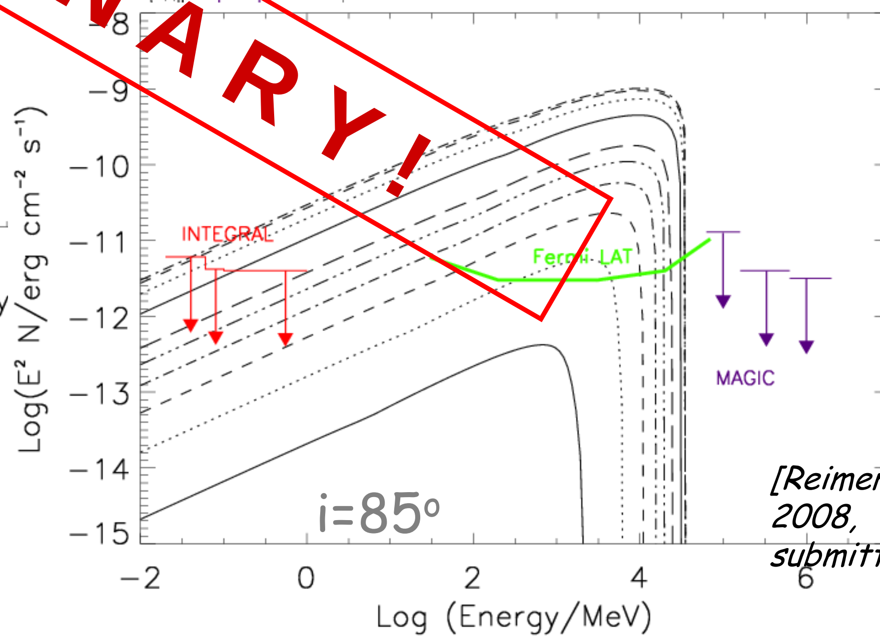
Orbital modulations of IC spectrum



MAGIC/INTEGRAL upper limits rule out this setting



MAGIC/INTEGRAL upper limits constrain star-centered line-of-sight angle $\Theta_L < 50°$



>100GeV observations have no constraining power

[Reimer etal. 2008, submitted]

... in summary:

- High energy flux limits indicate preference for WR 147 to possess large inclination angles i, *OR* particle acceleration is not sufficiently effective to allow GeV photon production.

- Sufficient sensitive γ-ray measurements < 1-10 GeV (e.g. Fermi LAT) have the potential to constrain WR 147's system geometry.

- For geometric well known systems, sufficient sensitive γ-ray measurements allow to constrain particle acceleration efficiency.

The massive binaries population in our Galaxy: How many are detectable at γ-rays at most?

- **227 WR-stars/-systems detected in the Milky Way**

  [v.d. Hucht ´01+´06: 7th cat. Galactic WR-stars + extension]

- **WR-binary frequency** (incl. probable binaries) **~ 40-50%** **88 systems**

  - **distance ≤ 4 kpc** → **- 42 systems**

    [γ-ray flux dilution factor ~ distance^2]

  - **shock location above star's photosph.** → **- 14 systems**

    [*shock location determined by winds' ram pressure balance*]

  - **orbital period/stellar separation known** → **- 11 systems**

    [*required to determine shock location and environment*]

⇒ 21 WR-binaries for *potential* γ-ray detectibility

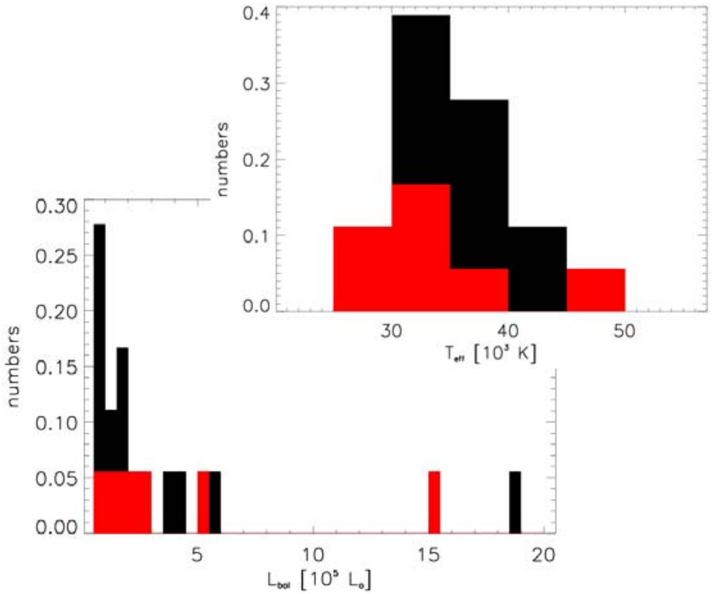
Parameters & Assumptions

- IC component only [likely dominant; Reimer etal. 06 model used]
- max. possible acceleration rate [mechanism not specified]
- system parameters [L_{bol}, $\dot{M}_{OB,WR}$, $M_{OB,WR}$, $V_{\infty,OB,WR}$, T_{eff}, D_{WR-OB}, d_L]:

  van der Hucht `01, Markova et al `05, Nugi & Lamers `00, Schaerer & Maeder `92, Cherepashchuk `01
- e=0 assumed [$\langle e \rangle_{obs}$ low, e_{max}~0.9], i=0° for unknown systems inclination
- B_*=100G + magnetic rotator model *[Weber & Davis 1967]*
- energy (particles) injection: (a) particle number conservation:

  rel. particle flux ≤ wind particle flux enter acc.zone

  (b) energy conservation: $L_{inj} \leq L_{wind}$



→ ε_{target}~T_{eff}, u_{target}~L_{OB}/x^2, $x=D_{WR-OB}\sqrt{\eta}/1+\sqrt{\eta}$, $\eta=(\dot{M}_{OB}V_{OB})/(\dot{M}_{WR}V_{WR})$

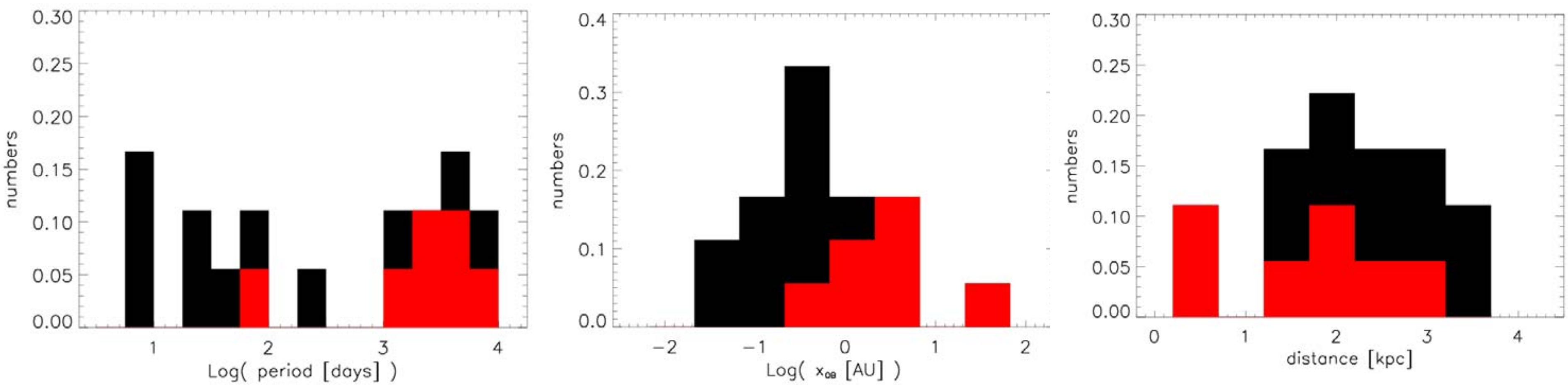
→ $S_{0.1-100GeV}$

Results

LAT-source, if:
- $E_{IC,max} > E_{LAT,\,min}$
- $F_{IC(>100MeV)} > F_{min,LAT(>100MeV)}$ [used: 2×10^{-8} cm^{-2}s^{-1} for 1yr exp. at $|b|<0.5$]

→ $6\text{-}7^{+2}_{-5}$ WR-binaries at most detectable by Fermi LAT

- tend to be very-long-period binaries [otherwise severe IC-losses cause low E cutoff of e^-spectr. → inhibition of GeV-prod. in shorter-period binaries], $x>10^{12}$cm
- all but one turn out to be non-thermal radio emitters
- only most nearby (< 1kpc) WR-systems safely LAT-detectable



γ-ray production >100 GeV?

Cherenkov source, if:

- $E_{IC,max}$ > 100 GeV
- $F_{IC(>100GeV)}$ = ?

⇨ 2^{+1}_{-2} WR-binaries potentially emit > 100 GeV photons

- expected $F_{IC(>100GeV)}$ *very low* even under favourable orbital geometry
- tend to be very-long-period binaries, $x>10^{13}$cm

⇒ individual WR-binary systems are not favourable Cherenkov sources

Stellar clusters possibly more promising (see *Westerlund 2*) ?

Summary

- Massive star-star binary systems are potential γ-ray sources
- Characteristics of observables in the γ-ray band:
    - concentrated towards spiral arms, not spatially extended
    - orbital variations, amplitude depends on system geometry
      (IC anisotropic, modulations of target photon density, wind density at shock and/or size/geometry of emission region, etc.; non-orbital variations from wind clumping?)

- Sensitive γ-ray measurements (e.g. Fermi LAT) have the potential to constrain the system geometry and/or provide information on particle acceleration process for geometric well known systems.

  E.g. WR 147: HE flux limits indicate preference large inclination angles, OR: particle acceleration efficiency does not allow GeV photon production.

- 6^{+2}_{-5} WR-binaries at most detectable by Fermi LAT (1yr):
  ⇒ highest chance for very-long period, nearby systems
  [Most promising candidates: WR 11, 70, 125, 137, 140, 146, 147]

- individual star-star binaries not favourable sources for current Cherenkov telescopes

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