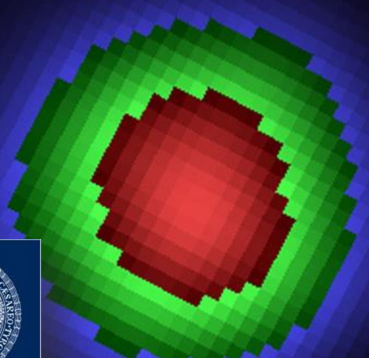
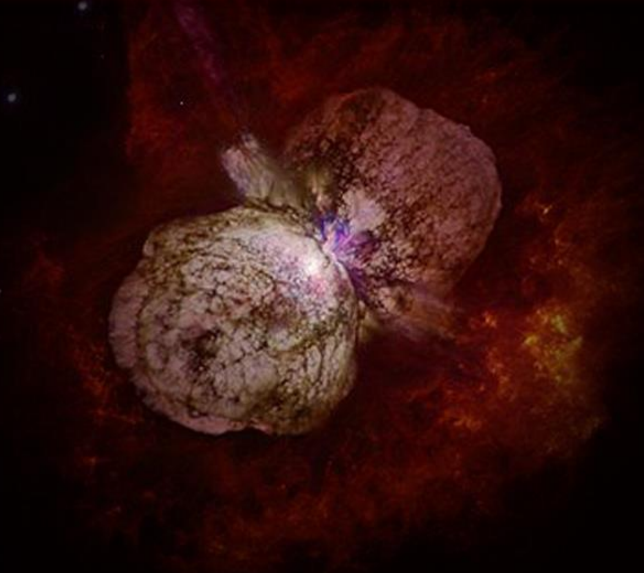
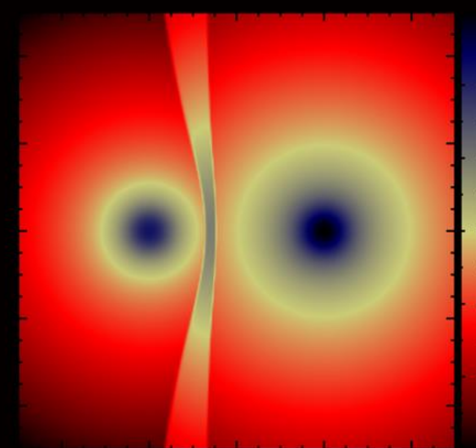
NUMERICAL 3D-HYDRODYNAMIC MODELLING OF COLLIDING WINDS IN MASSIVE STAR BINARIES:

particle acceleration & γ-ray emission







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* A brief introduction

Colliding wind binaries (CWBs) consist of high-mass stars: (OB,WR,LBV)

powerful stellar winds (high mass-loss, high-velocity)

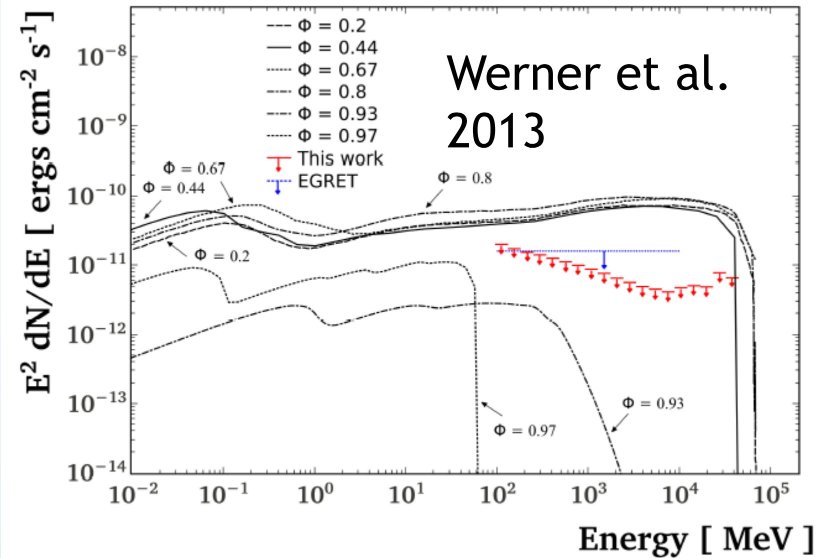
The winds collide …
Diffusive shock acceleration of e^- and nucleons at the shock front

Accelerated particles advect downstream with the wind and lose energy (inverse Compton (IC) cooling, synchrotron losses, collisions, etc.)

These loss-processes cause γ-ray emission!
(inverse Compton scattering, bremstrahlung, π^0-decay)

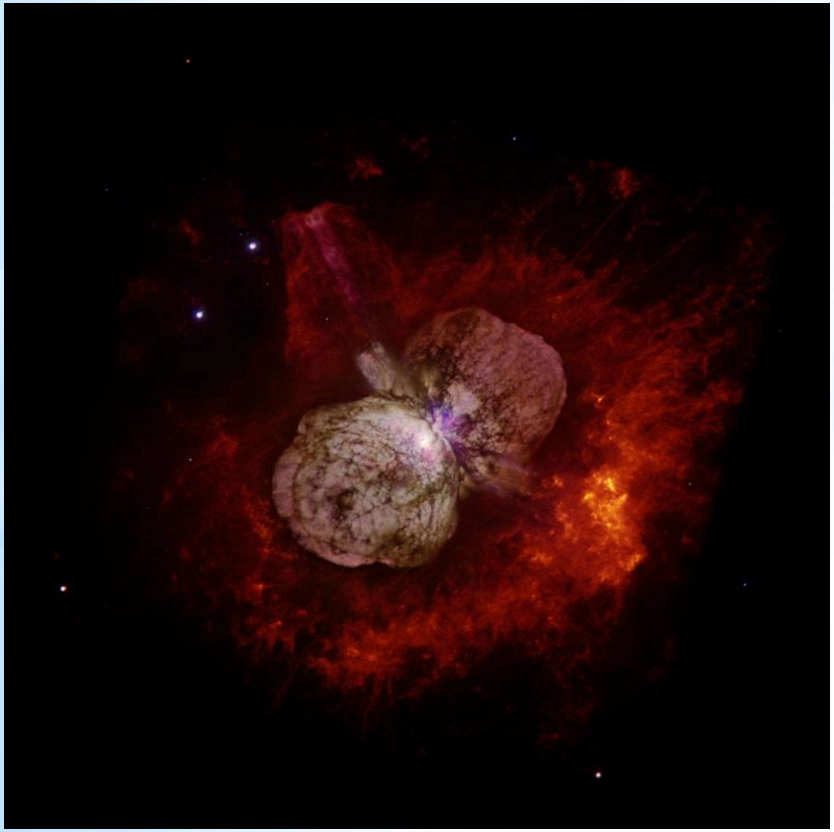
Unfulfilled predictions

- **Detection** in high-energy (HE) γ-ray band with current instruments has been **predicted** (Reimer et al. 2006; Pittard et al. 2006)
- **However:**
    - **COS-B**: four γ-ray sources spatially consistent with the location of the CWB-candidates WR 140, WR 125, WR 98, and WR 105 (Pollock, 1987)
    - **EGRET:** point-like γ -ray source in positional coincidence with WR140 (Romero et al., 1999)
    - **Fermi-LAT:** **no detection** of CWBs (WR 140, WR 147, etc. Werner et al. 2013) – so far latest word



Differential flux upper limits (red lines) of WR 140 compared to theoretical modelling for different orbital phase angles.

Nevertheless, a maverick



η **Carinae as seen by the HST**
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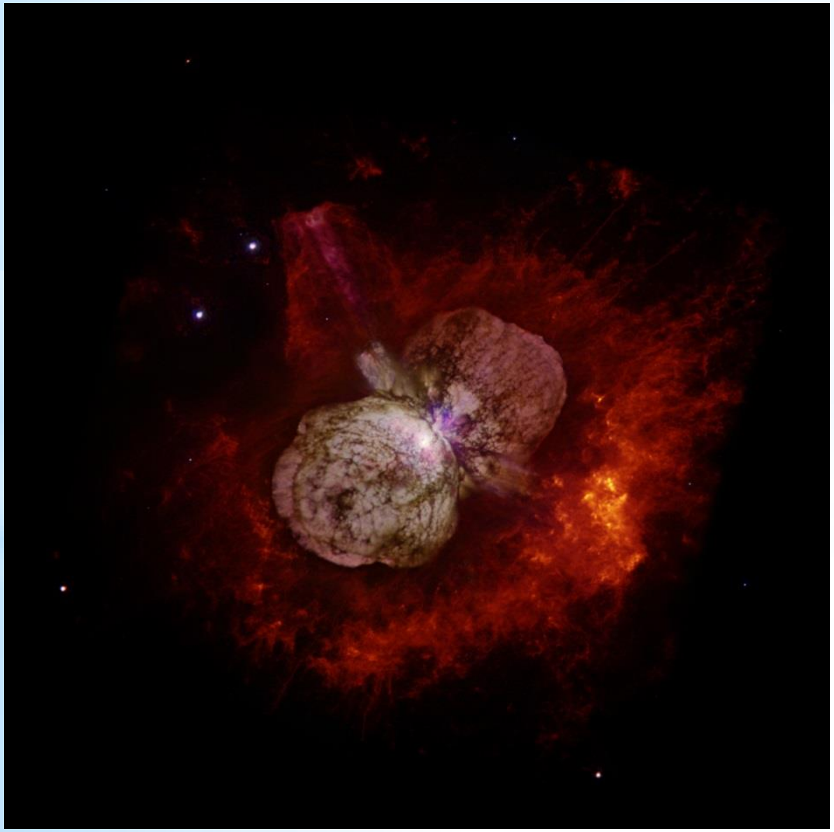
A strong γ -ray source!

Papers on η Car's γ -ray counterpart:

- *Tavani et al. 2009:*
  AGILE detection paper
- *Abdo et al. 2010:*
  Fermi-LAT detection paper
- *Ohm et al. 2010:*
  Connection to eruption of 1843
- *Farnier et al. 2011:*
  hadronic particle accelerator?
- *Reitberger et al. 2012:*
  Fermi-LAT flux modulation paper

Nevertheless, a maverick



η **Carinae as seen by the HST**
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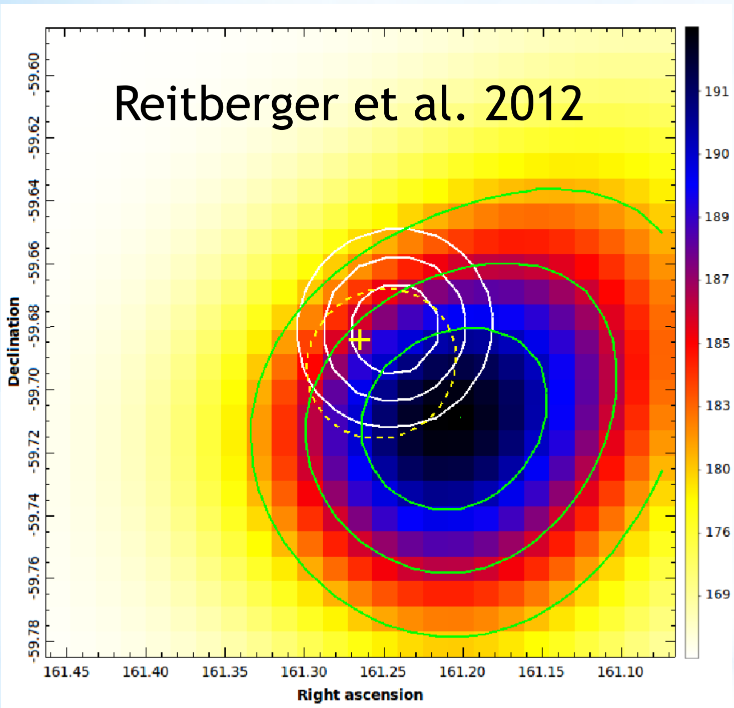
A strong γ -ray source!

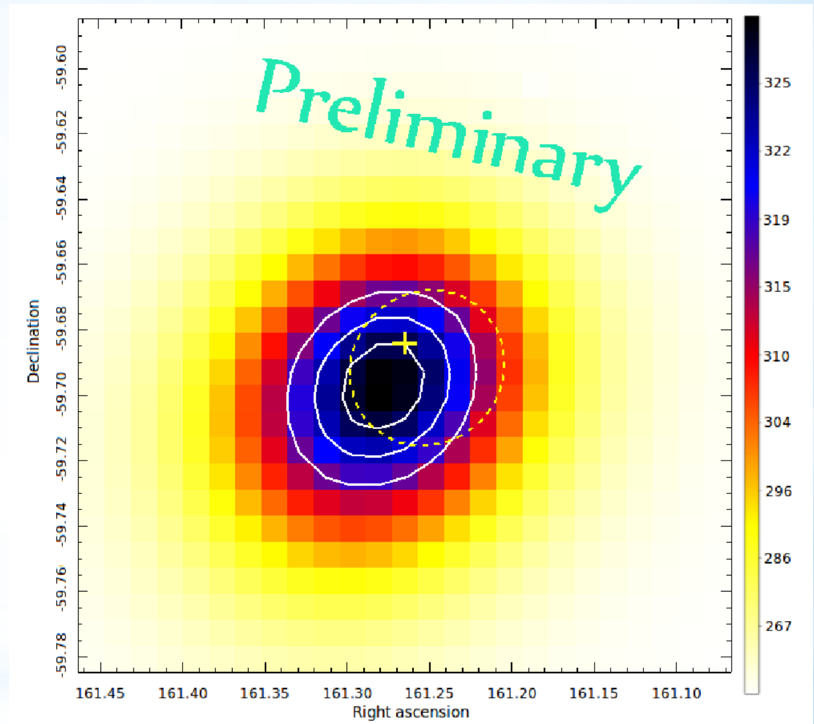
- orbital period:
  2024$\pm$2 days (Corcoran et al. 2005)
- start of Fermi-era:
  Aug 4th 2008 15:43:36.0 UTC
- full orbit on **Feb 18th 2014**
  15:43.36.0 $\pm$2

Spatial consistency!

Test statistics (TS) maps of the celestial region around the nominal position of η Carinae (yellow cross). The TS-value corresponds to the likelihood of the source being located in a specific grid point.

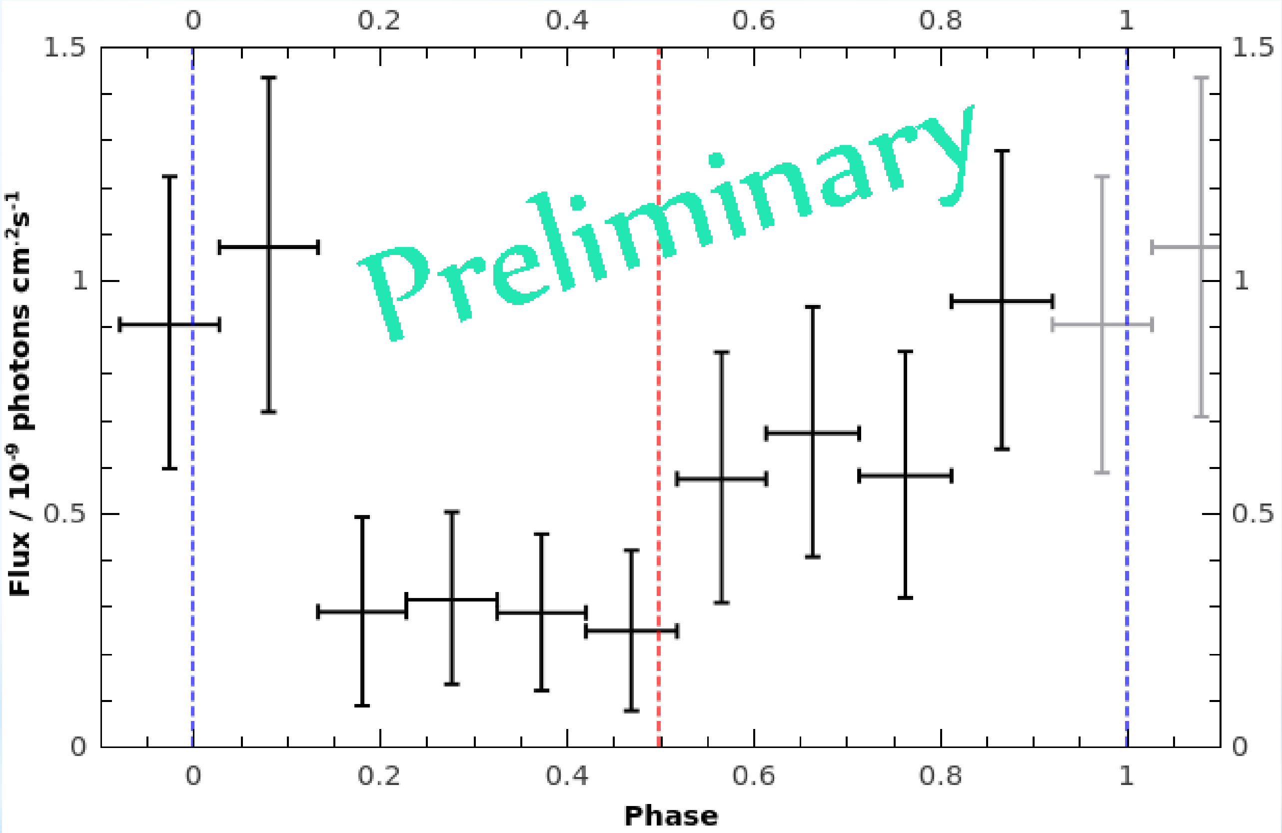


35 months of data at 10 to 300 with green contours representing the 1,2 and 3 sigma error regions for the underlying TS map.



Full-orbit data sample at 10 to 300 GeV with white contours representing the 1,2 and 3 sigma error regions for the underlying TS map.

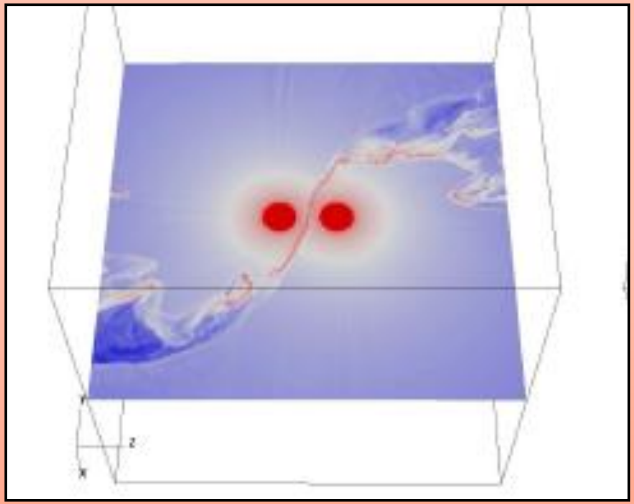
Variabilty in concordance with orbital period



Flux time history of the γ -ray source at the position of η Carinae at energies 10 to 300 GeV. The black data points represent a full-orbit data-sample of 5.5 years. The grey data points on the right are the phase-shifted counterparts of the first two data points on the right. The dashed vertical lines mark the periastron (blue) and apastron (red) passages of the η Car binary system.

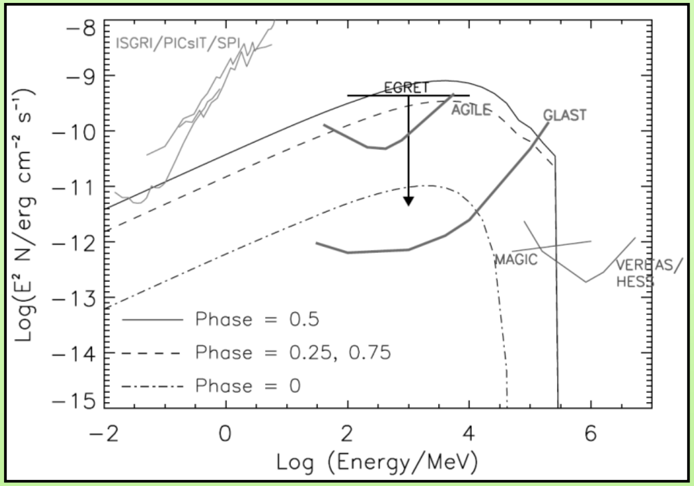
Modelling γ-ray emission in CWBs

a combination of two approaches



* *numerical* hydrodynamic models simulating the dynamics of wind acceleration and collision in course of orbital cycle.

(e.g., Pittard 2009)



* *analytical* models solving a transport eq. for accelerating particles and subsequently computing γ-ray fluxes.

(e.g., Reimer et al. 2006)

Our new simulation procedure **combines both approaches** in a numerical framework.

Modelling

A detailed description is given in **Reitberger et al. 2014a (ApJ)**

- hydrodynamics
- wind acceleration
- transport equation
- 3D distribution of high-energy particles
- effects of orbital motion

and **Reitberger et al. 2014b (ApJ, in press)**

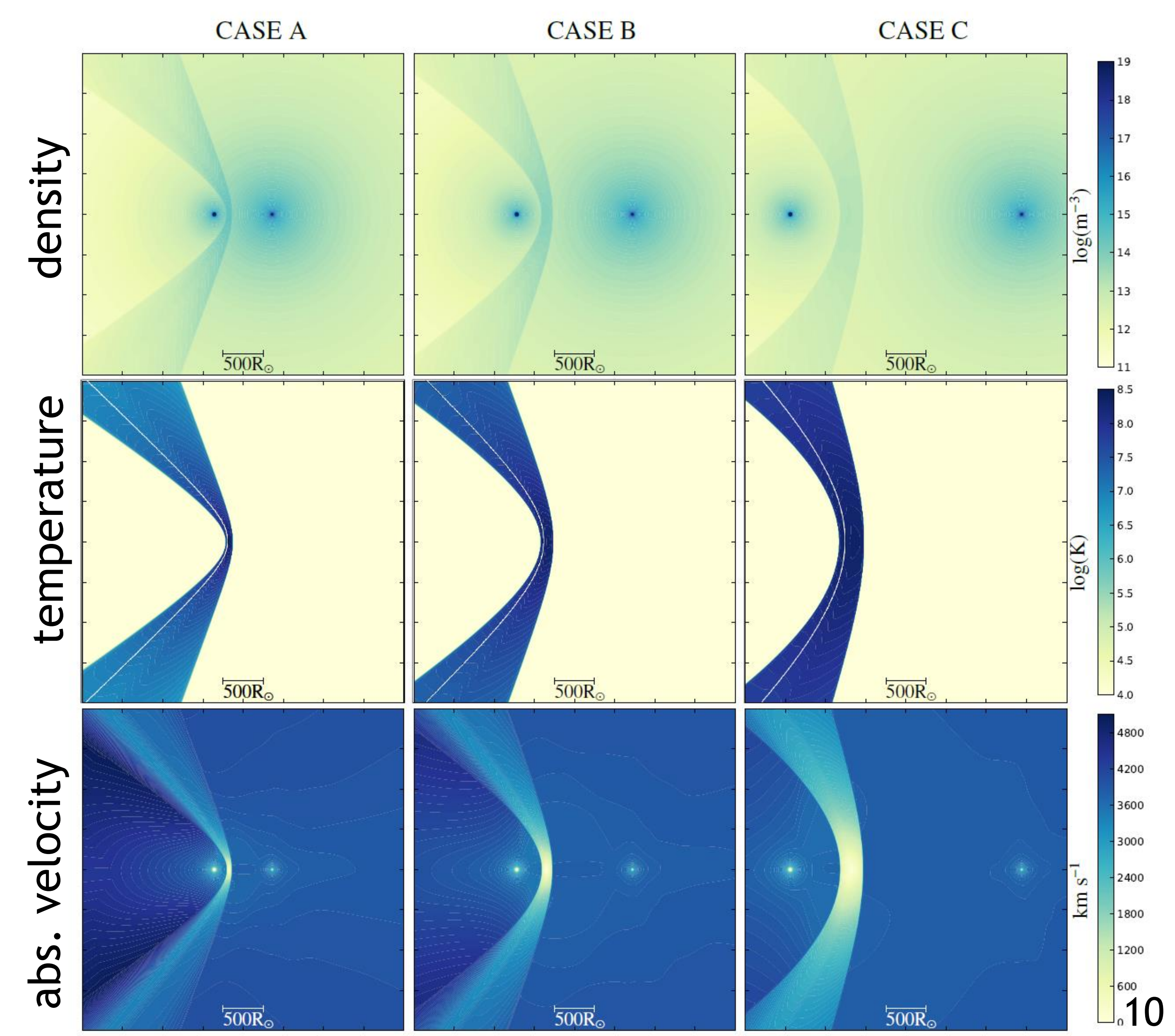
- γ-ray emission channels (IC, bremsstrahlung, neutral pion decay)
- photon photon opacity in stellar radiation fields
- 2D projections of γ-ray emission , SEDs, integrated flux values
- variations with changing stellar separation and viewing angle

both study a binary system with typical parameters – NOT η Carinae

Step I: The wind

The properties of the wind collision region change drastically with stellar separation

This relates directly to changes in high-energy particle distributions and γ-ray emission

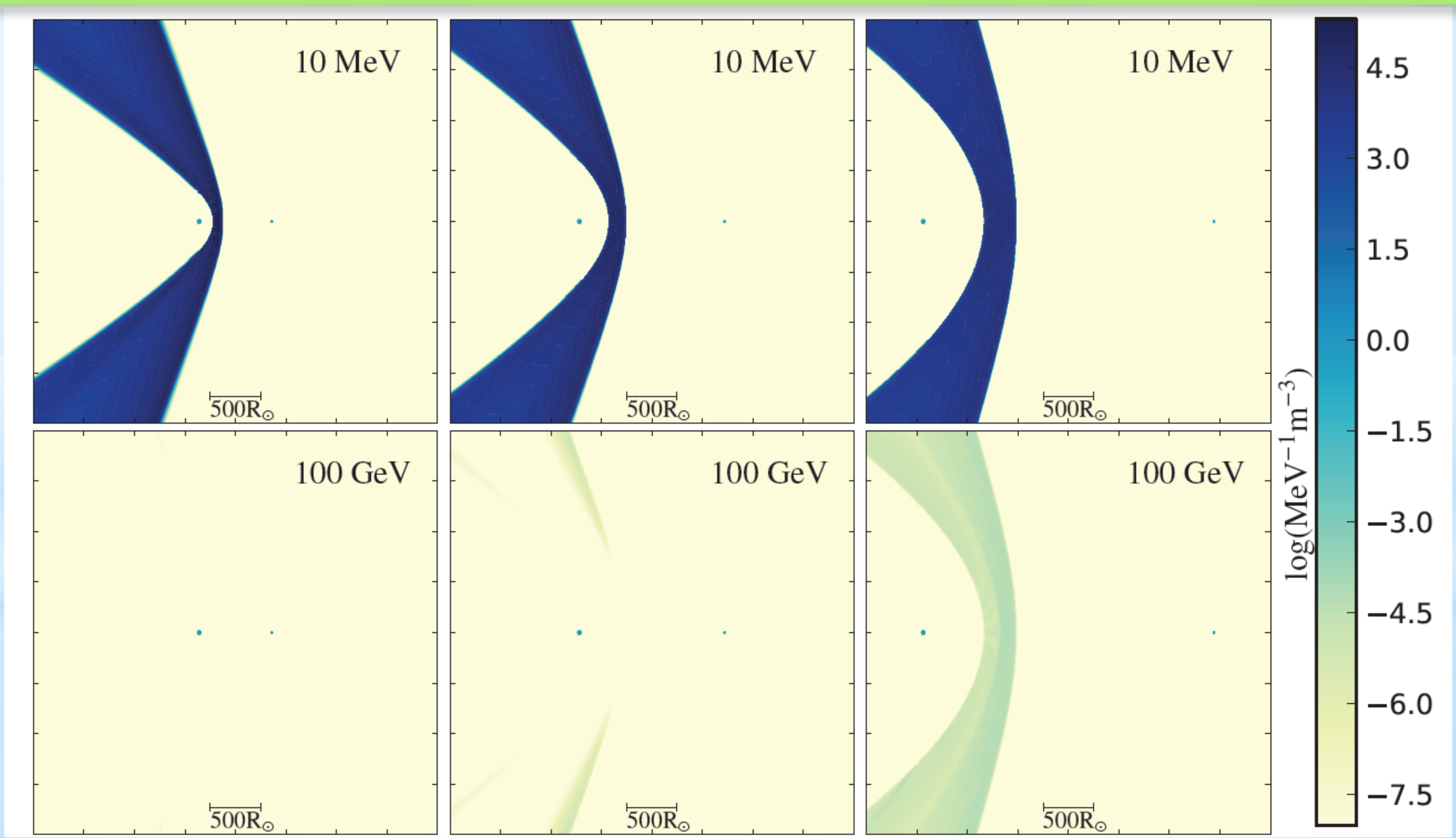


Step 2: Particle Transport

governed by transport equation

$$\frac{\partial N(E)}{\partial t} + \nabla \cdot [\boldsymbol{v} N(E)] + \frac{\partial}{\partial E}\left[\dot{E} N(E)\right] + \frac{N(E)}{\tau} = Q\delta(\mathrm{E} - \mathrm{E}_0)$$

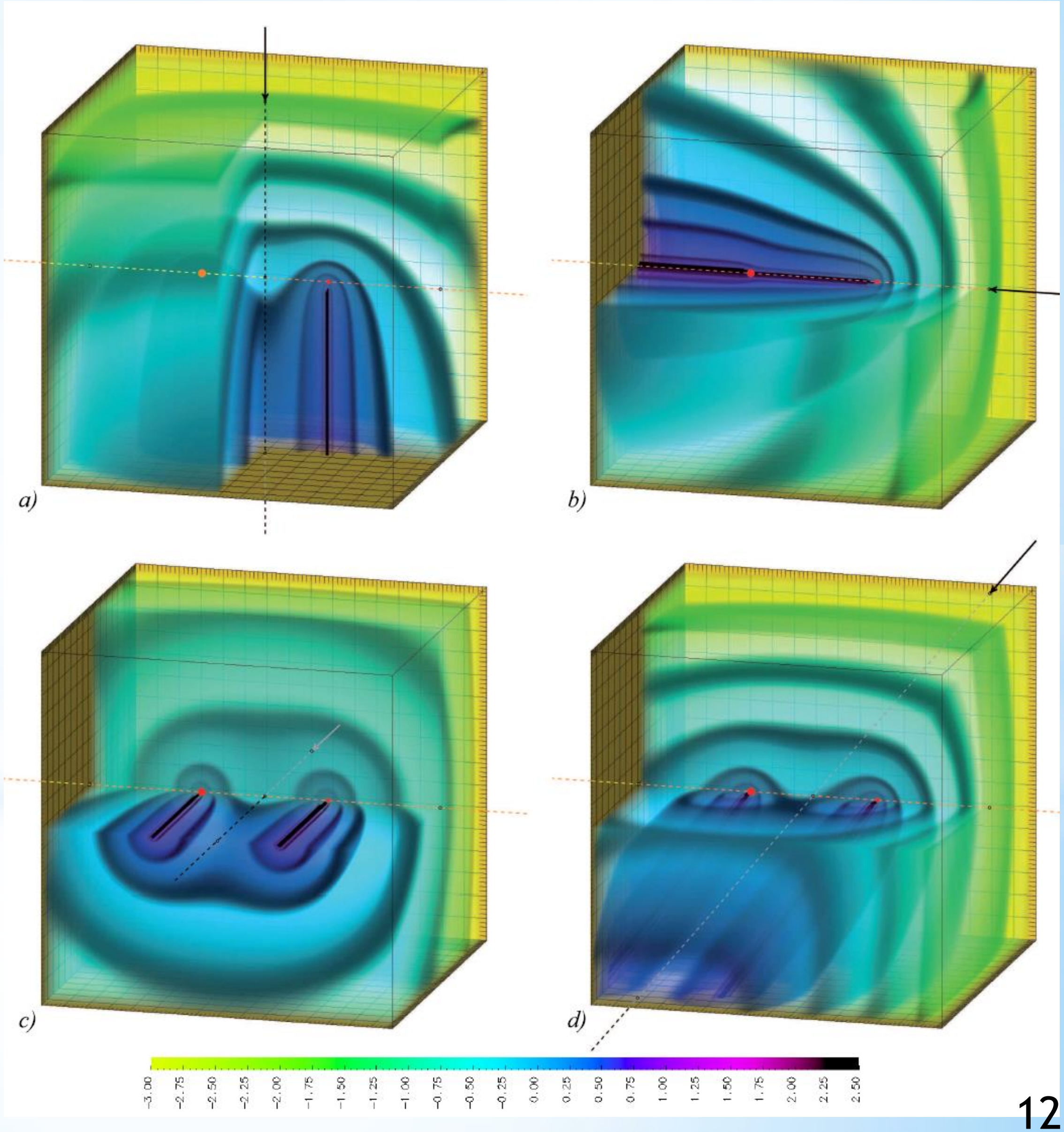
electrons



number density of electrons at different energy bins for different stellar separations

photon-photon opacity

optical depth in $log(\tau)$ for different viewing angles

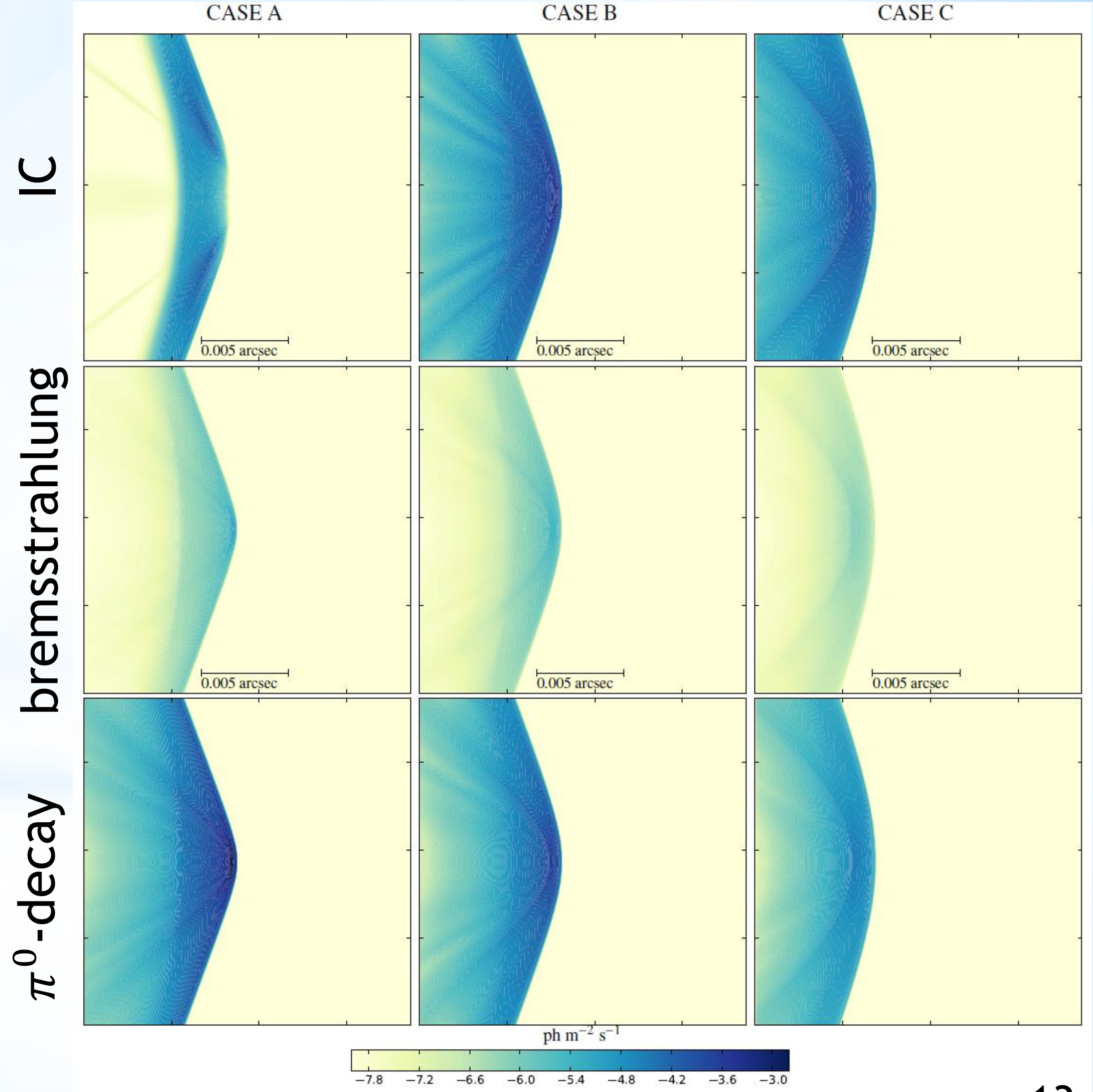


effects of photon-photon opacity along with dependence of IC-emission on scattering angle lead to variations with different viewing angles and orbital phase.

Step III: γ-ray emission

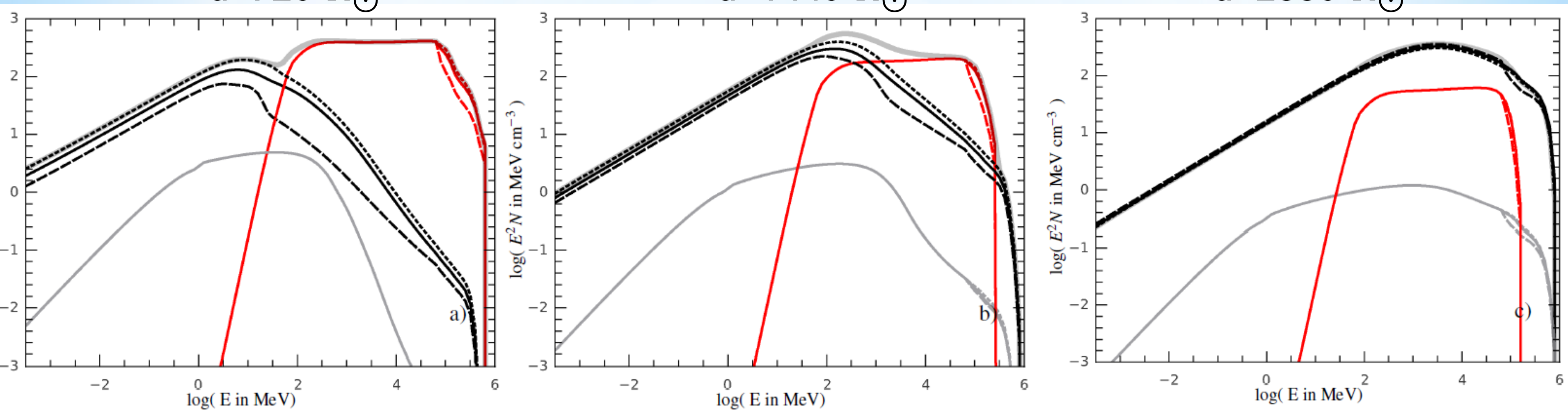
We compute projected emission maps showing how the system would look like with infinite resolution for a given viewing angle.

Flux for E > 100 MeV with inclination i = 0° (face-on) for inverse Compton emission, relativistic bremsstrahlung and neutral pion decay and for three different stellar separations.



SEDs

d=720 $R_\odot$ *d*=1440 $R_\odot$ *d*=2880 $R_\odot$

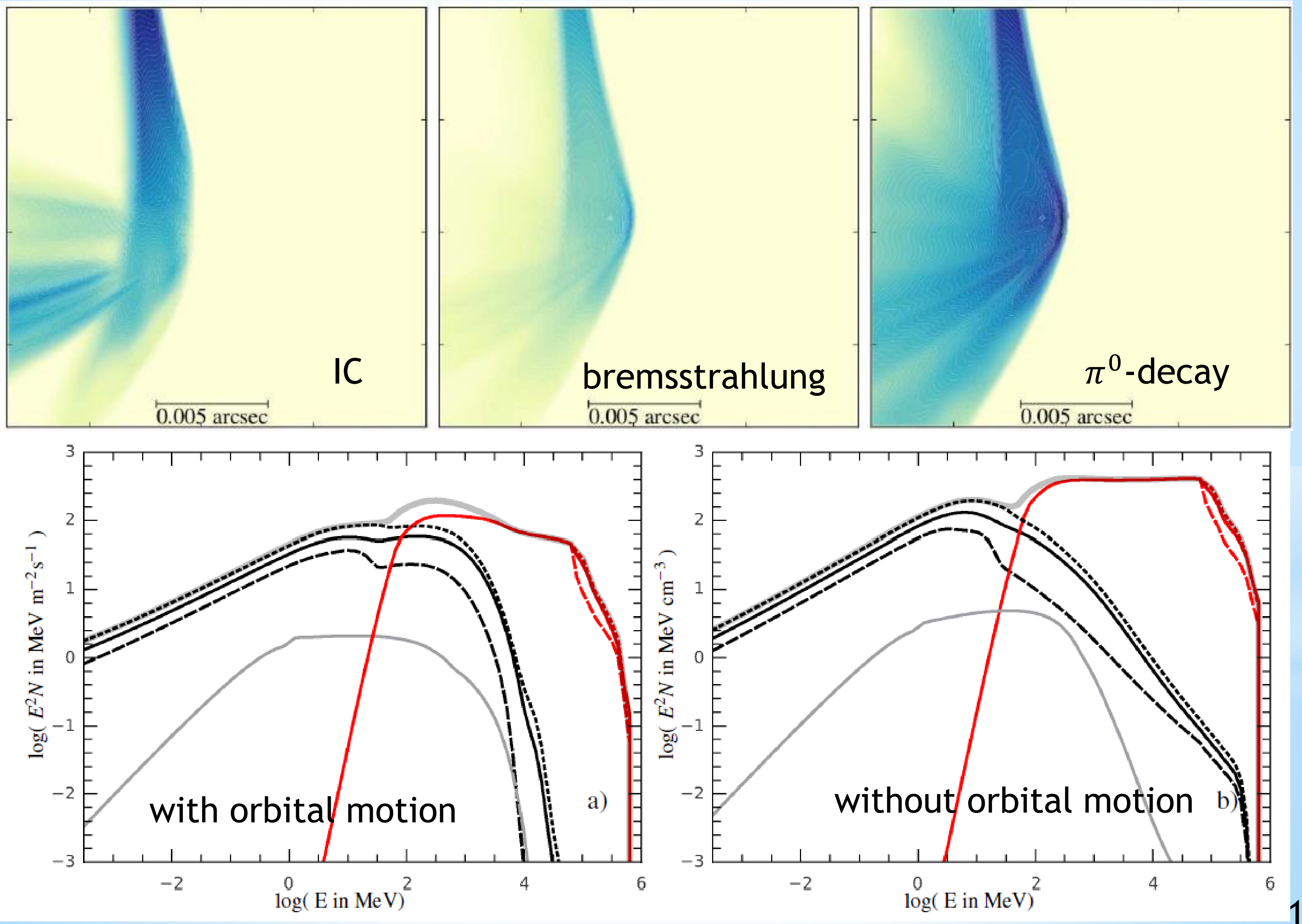


black: inverse Compton / grey: bremsstrahlung / red: neutral pion decay
solid: face-on / dashed: edge on with WR star in front / dotted: edge on with B star in front

Spectra show strong variations for different stellar separations and minor variations for different viewing angles. Effects of photon-photon opacity are also visible at E>100 GeV.

Variations with orbital orientation are expected to be much more prominent for certain different sets of parameters for which the difference of the stellar radiation field is more pronounced.

effects of orbital motion



Conclusions

- **Analytical modelling of high-energy processes in binaries** (e.g., Reimer et al 2006, Bednarek & Pabich 2011) **made transition into HD-based modelling**

- Our models predict significant variations with stellar separation and viewing angle.

- Application to a specific binary system with known stellar and orbital parameters is the next consequent step. We‘ll try to choose parameters resembling the η Car system.

The next generation

- one orbit is not enough!

  Measuring a second or third orbit of η Carinae in high-energy γ rays will provide a crucial test of the hitherto observed variability pattern.

- detection of CWBs with IACT instruments?

  The detection of η Carinae up to 300 GeV with the Fermi-LAT (Reitberger et al. 2012) strongly suggests its detectability with current and future IACT instruments as H.E.S.S 2 and CTA.

- **further observation of CWB systems in conjunction with refined modelling** (also of the still undetected archetypal CWBs) **will allow to constrain important model parameters** (as diffusion coefficient, magnetic field strength, electron-proton injection ratio, etc.)