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# Fermi acceleration along the orbit of $\eta$ Carinae

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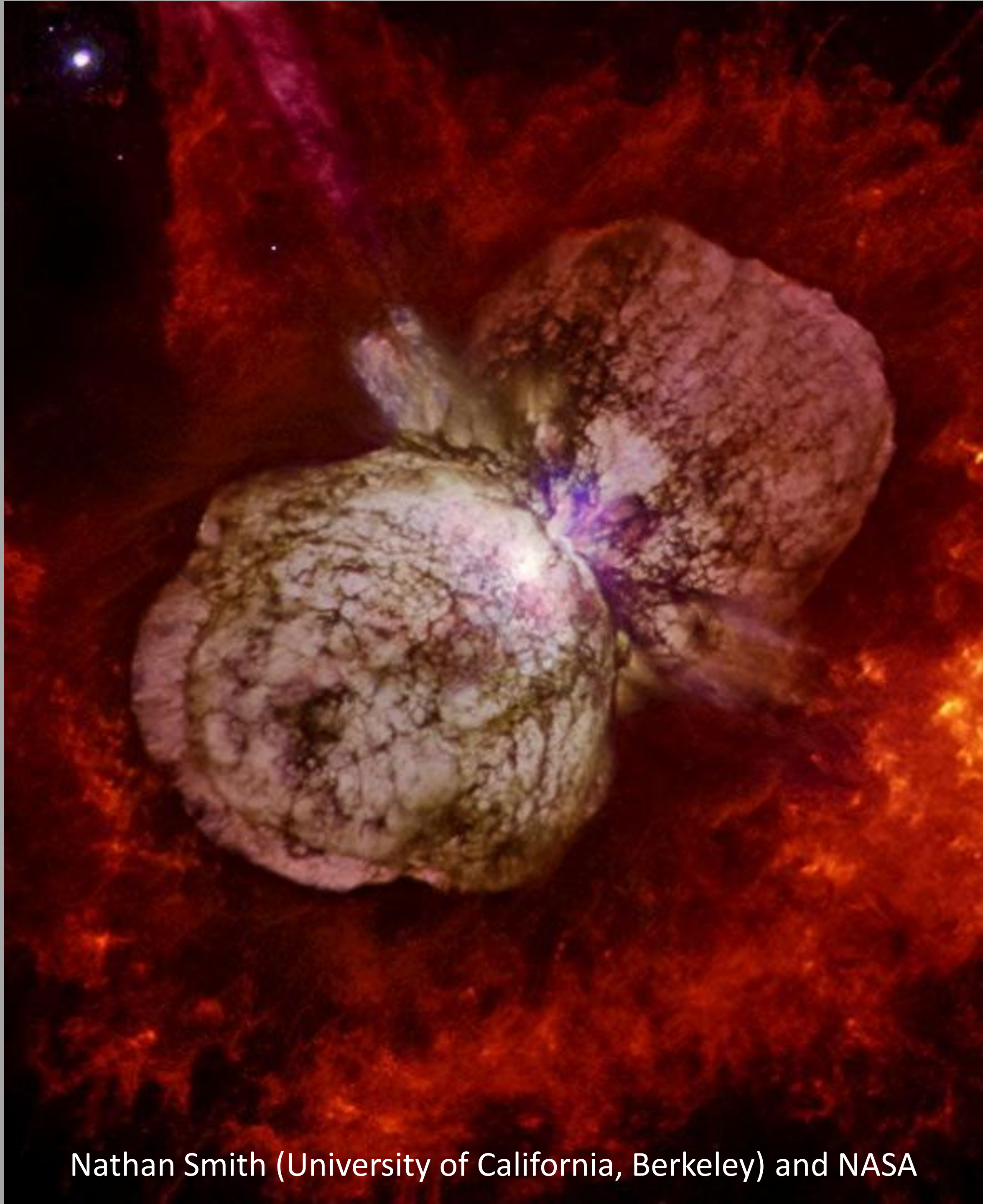
# η Carinae

- Unsurprisingly, η Carinae is one of the most studied systems.
- A simple ADS search for 'eta carinae' in the title yields 548 refereed papers
- But the question remains: Can a system this unique teach us about massive binaries in general?
  *"η Carinae, Rosetta Stone or white elephant?"* prof. Stanley P. Owocki



Nathan Smith (University of California, Berkeley) and NASA

# Simulations of the colliding binary winds

- Smooth Particle Hydrodynamics allowed for first 3D simulations of the colliding winds (See publications by *Madura, Gull, Okazaki et al.)*

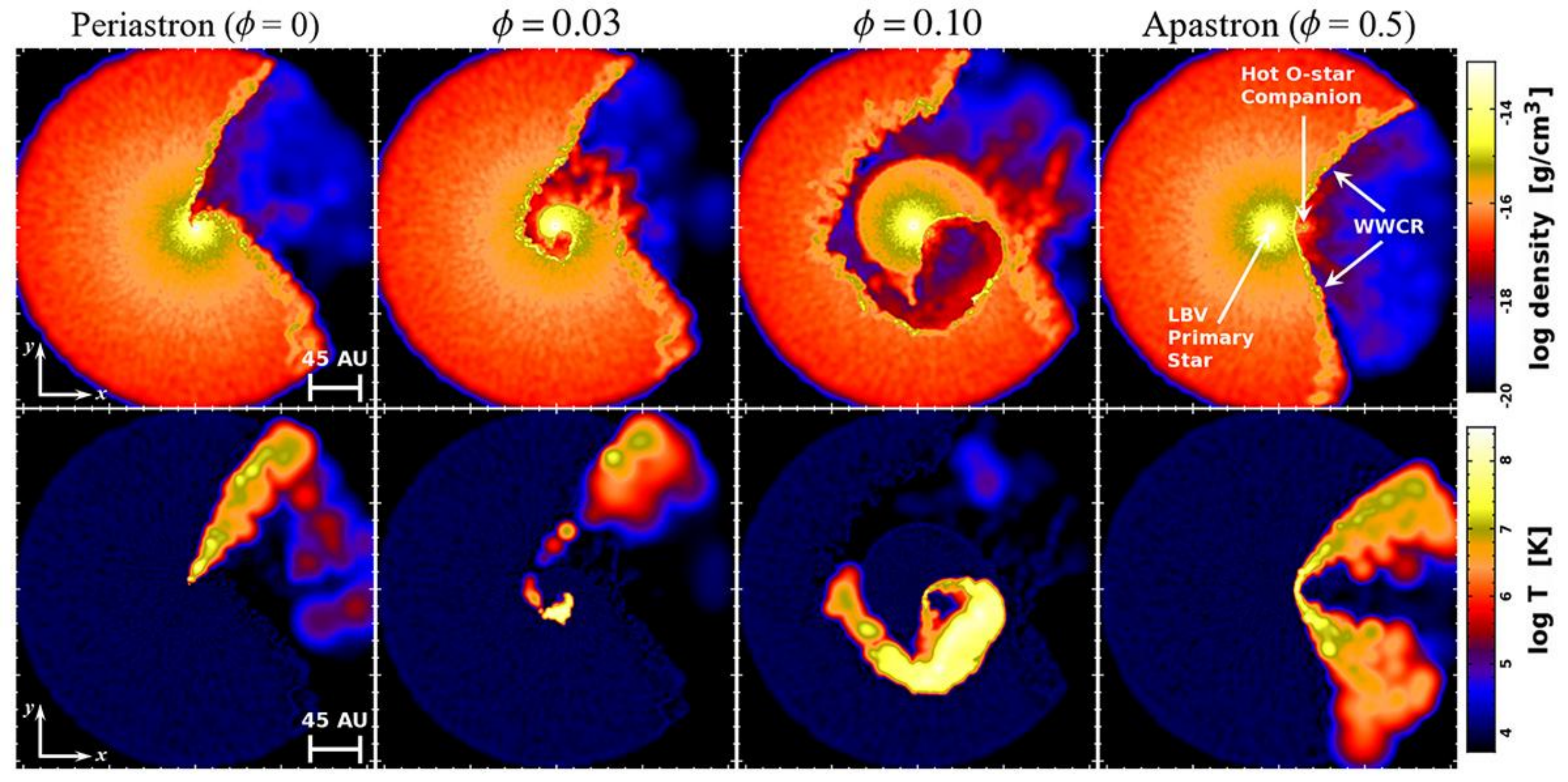



Image Credit Dr. T. Madura

# Simulations of the colliding binary winds

- Improved computational facilities made it possible to simulate the colliding wind shocks with grid MHD, including radiative driving force and gravity (See publications by Parkin & Pittard)

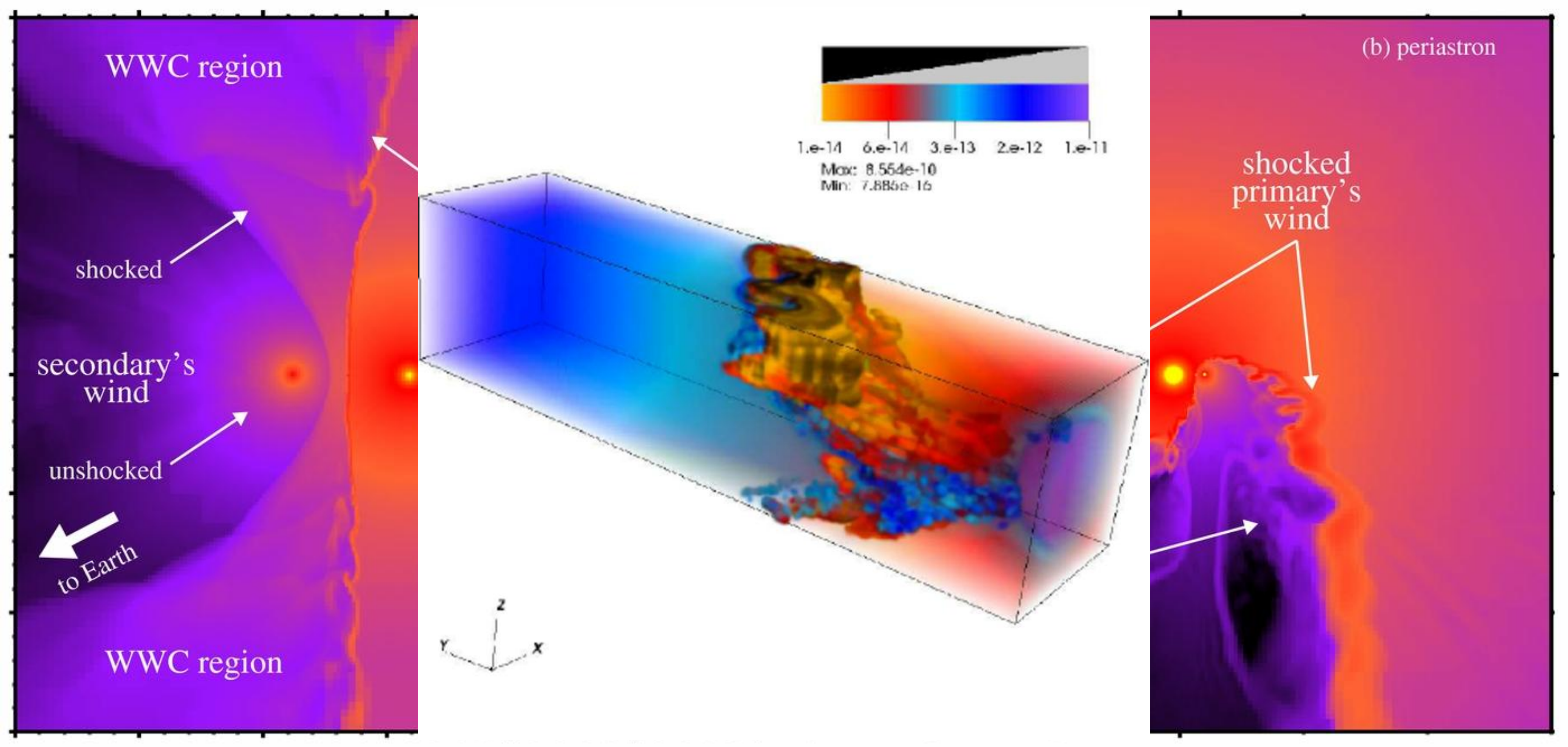



Image Credit Dr. T.R. Parkin

# Part of the physics is missing

- No numerical model of a colliding wind binary accounts for energy loss through particle acceleration
- However
  - These are high Mach shocks ($M_S$~ 10-100)
  - Many stellar wind shocks are radiative:
    - high compression, potentially high B-field compression/amplification
    - Diffusive shock acceleration (Fermi acceleration) may well be important
- Unfortunately, including actual particle physics in the simulations was/is not practical
- There are parametrisations for particle acceleration in stellar wind shocks but they don't include the magnetic field amplification in the shock

# Balbo & Walter 2017: Fermi LAT observations

# Combining observations and theory

**Observations**

- 7 years of Fermi-LAT observations
- Low & high energy light curves
- Gamma-ray luminosity as function of orbital phase

**Theory**

- Start from T.R. Parkin's simulations
- Use simulation result as input for particle acceleration model
- Predict gamma-ray emission

Compare observations to predictions of diffusive shock acceleration

# Initial assessment

- LAT observations in two bands:
  - 0.3-10 GeV
  - 10-300 GeV
- Total emission lines up well with η-Carinae

M. Balbo and R. Walter: Fermi acceleration along the orbit of $\eta$ Carinae

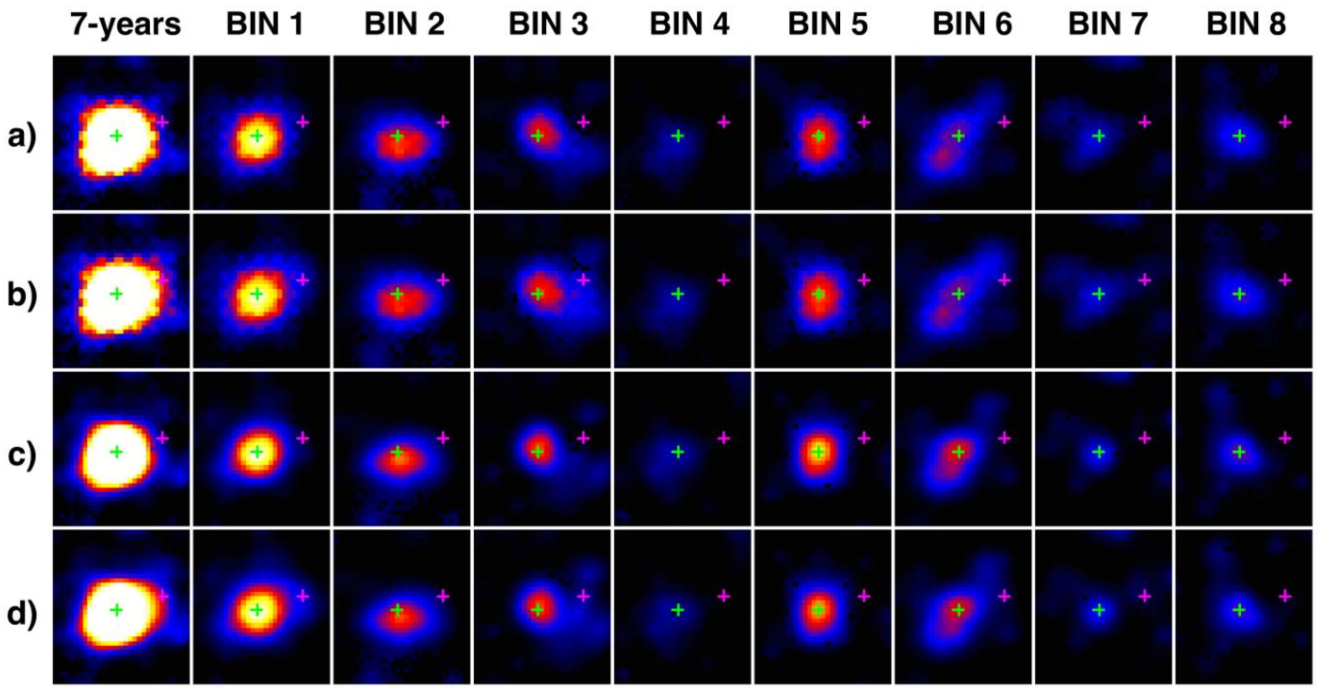



Fig. 2: High-energy TS maps for each of the time intervals, corrected for the small differences of exposure times between the 8 phase bins such that the images illustrate the source variability. Each image has the same width (0.77°). Rows a) and b) show TS maps obtained from the binned analysis, respectively including and excluding J1043 from the model. Rows c) and d) represent the same as a) and b) but from the unbinned analysis. The linear colour map spans TS from 0 to 100. The green and purple crosses are the positions of $\eta$ Carinae and J1043.

# High energy lightcurve

- X-ray lightcurve shows orbital phase dependence
- HE gamma-ray emission appears to lacks similar correlation
    - Some increase during first periastron
    - No significant increase during second periastron

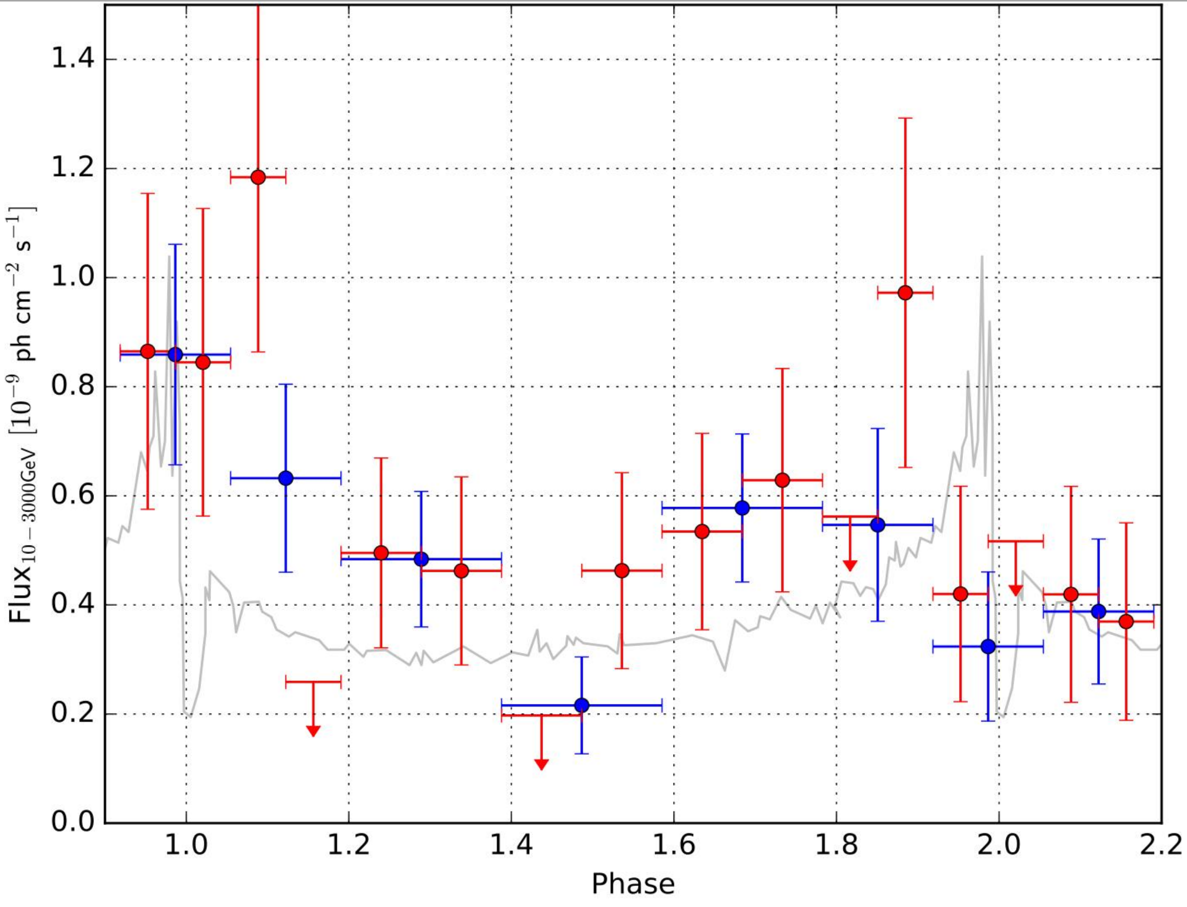



Fig. 1: Seven-year high-energy flux light curve of $\eta$ Carinae obtained from the binned analysis, using the binning as reported in Table 1 (blue points) and with a smaller binning (red points). Error bars are $1\sigma$ and superposed upper limits are 95%. For comparison we plotted an arbitrarily rescaled X-ray light curve (grey line).

# Low energy lightcurve

- Better photon statistics
- Poor spatial resolution
- Clear indication of orbital dependence

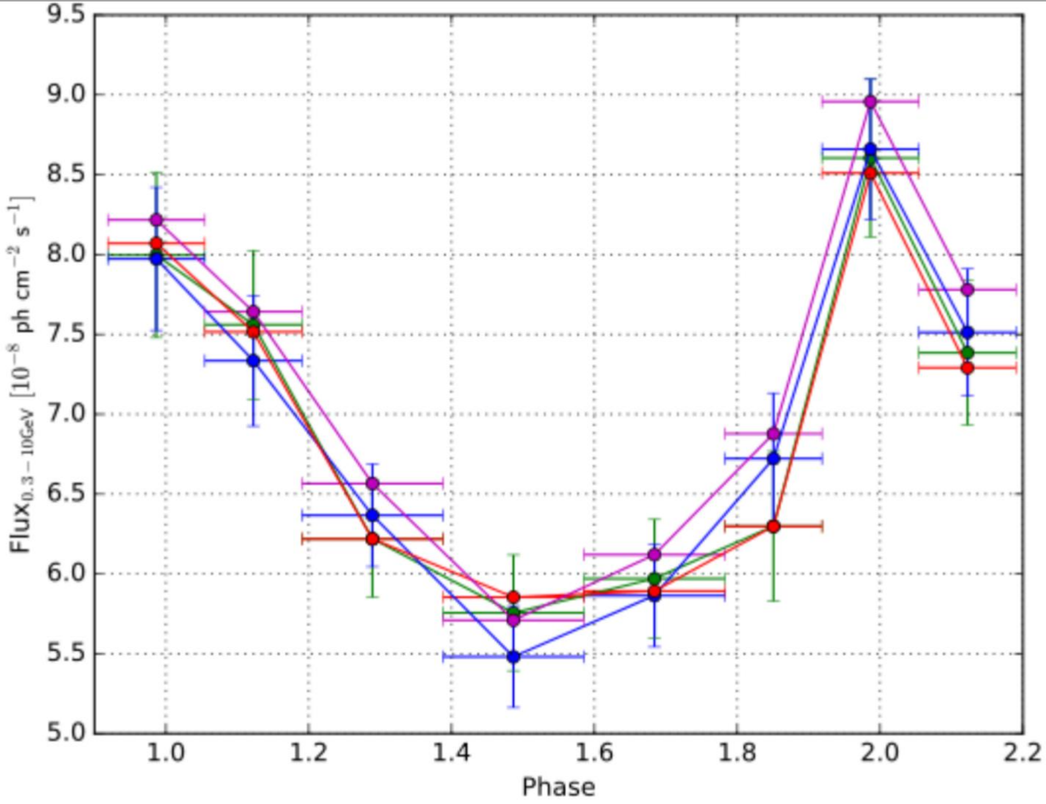



Fig. 4: Integrated flux light curve of $\eta$ Carinae assuming different spectral models: PLEC with three (green) or two (blue) free parameters and BPL with three (red) or two (magenta) free parameters. Error bars are $1\sigma$.

# From high energy particles to high energy photons

**Inverse Compton**

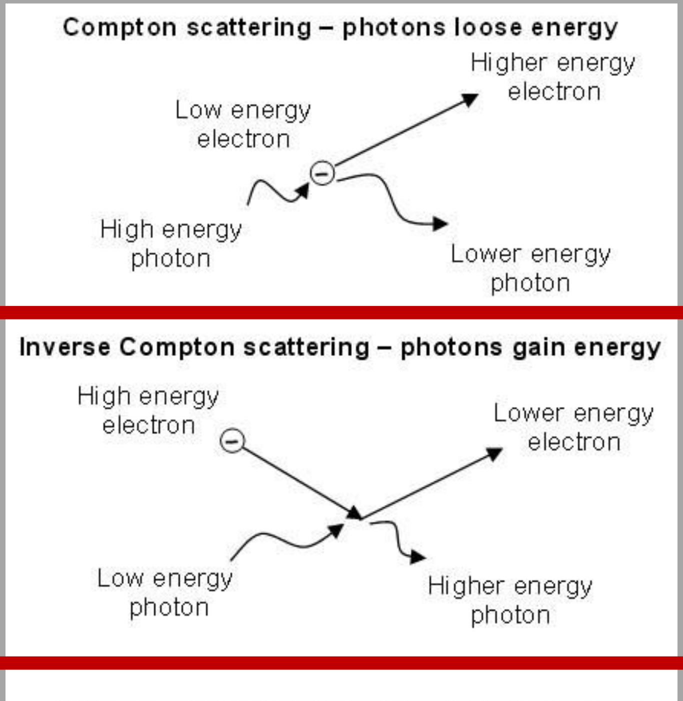
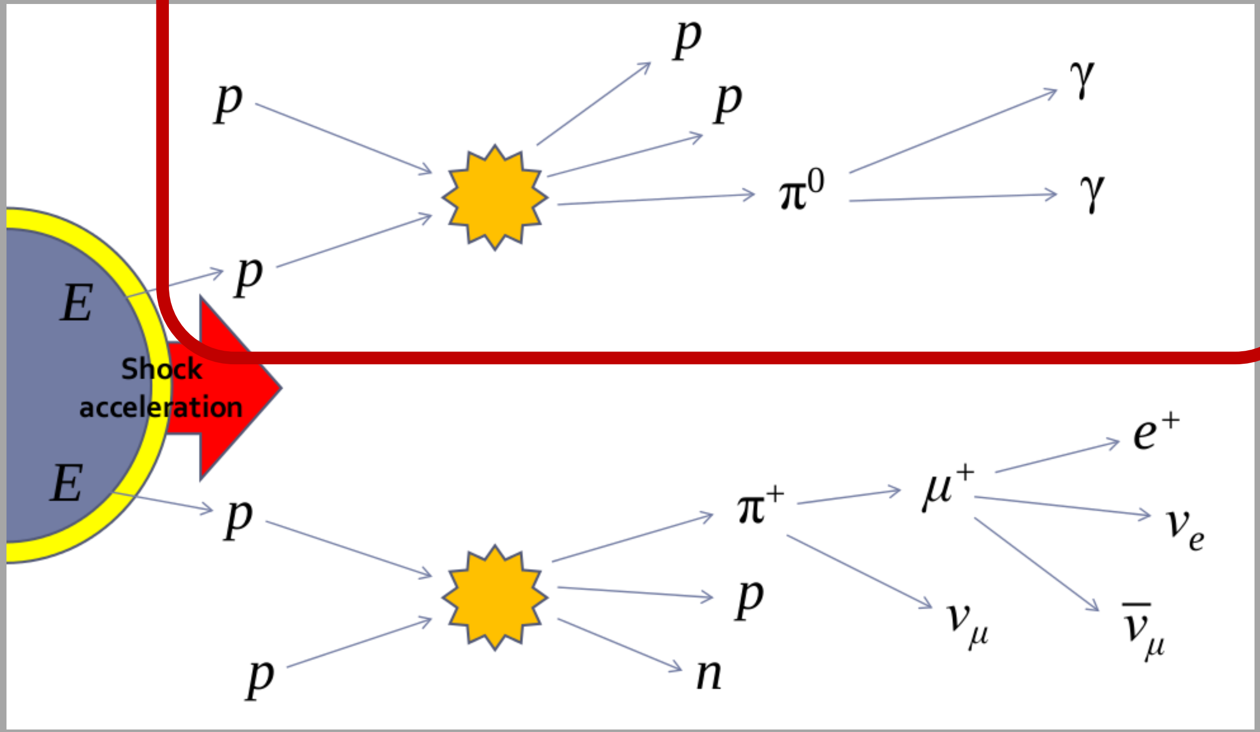



**Figure 6:** The two Compton scattering processes result in radiation being shifted to lower energies (Compton scattering) or higher energies (inverse Compton scattering). The essential factor differentiating these two processes is the kinetic energy of the electron involved.

**Pion decay**



# Simulation

- Low energy emission (inverse-Compton $e^-$ cooling) seems in reasonable agreement with observations
- Pion decay (high energy) matches more poorly
- Magnetic field at 400-500 G seems to produce best results

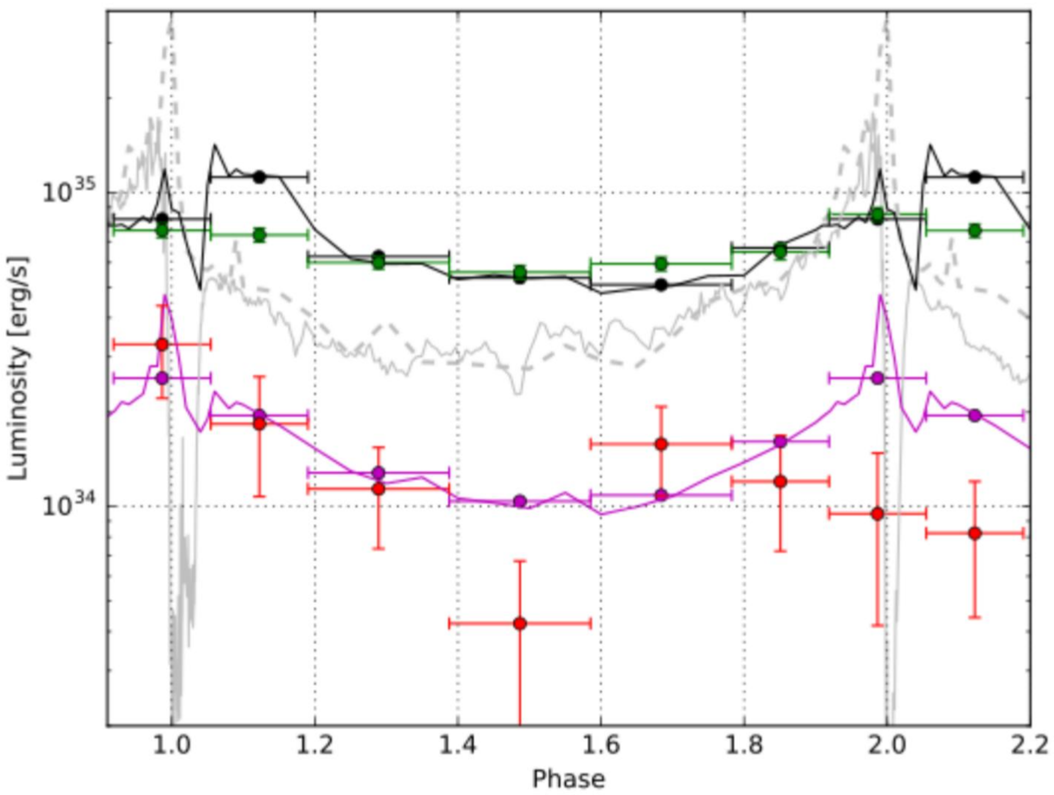



Fig. 5: Simulated and observed X-ray and γ-ray light curves of η Carinae. The black and purple lines and bins show the predicted inverse-Compton and neutral pion decay light curves. The green and red points show the observed Fermi-LAT light curves at low (0.3-10 GeV) and high (10-300 GeV) energies. The dim grey light curves show the observed (continuous) and predicted (dash, without obscuration) thermal X-ray light curves. Error bars are 1σ.

# Contribution to cosmic ray SED

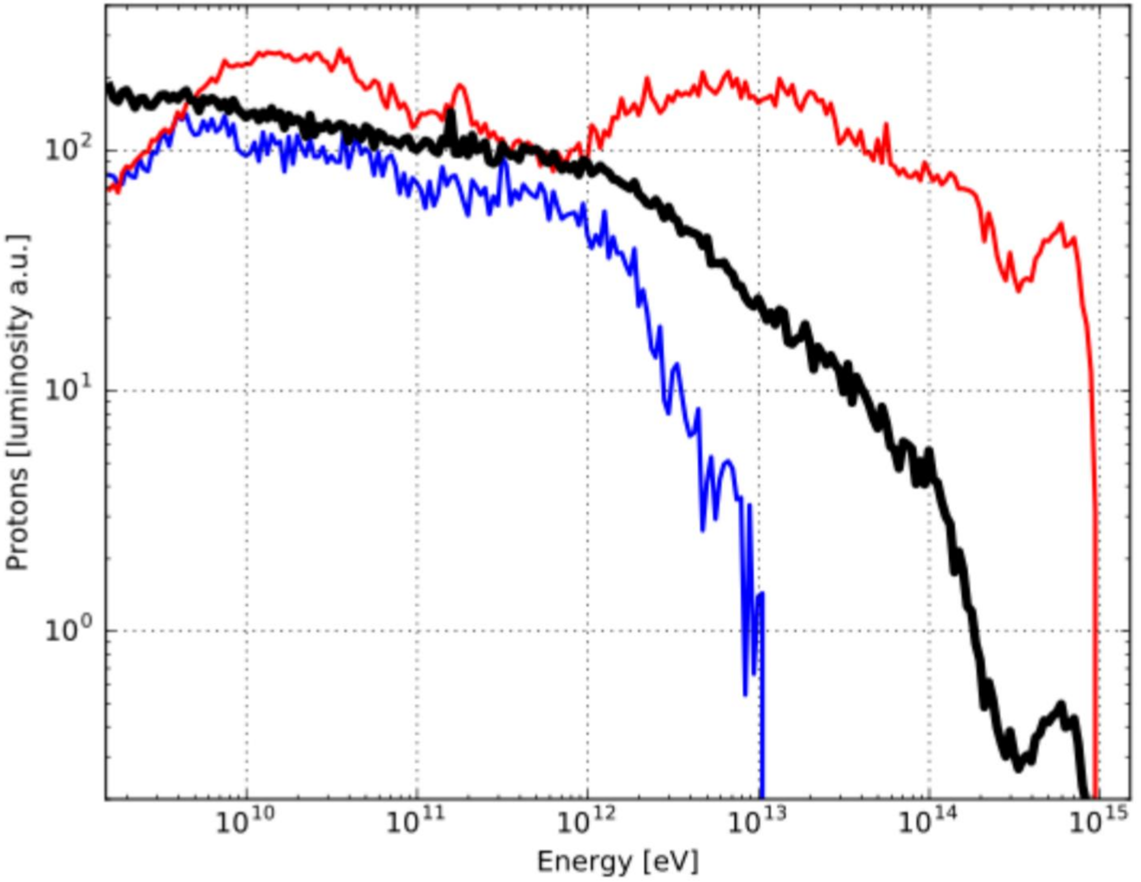



Fig. 8: Protons luminosity spectra (arbitrary units) at periastron (red; phase 1.0), apastron (blue; phase 0.5) and accelerated on average along the orbit (black).

- Can accelerate protons up to the knee
  - $10^{14}$eV average
  - $10^{15}$eV max
- Depends on magnetic field
- There is no magnetic field amplification in this model

# Conclusions

- Low energy gamma-rays caused by inverse Compton scattering
  - show orbital modulation, due to increased thermal radiation at periastron
- High energy gamma-rays caused by pion decay
  - Observations don’t show clear orbital modulation, even though the simulation predicts it. Possible because:
    - The observational statistics are insufficient
    - Local variation in the wind-shock situation
- Magnetic field of η Car A estimated at 400 G