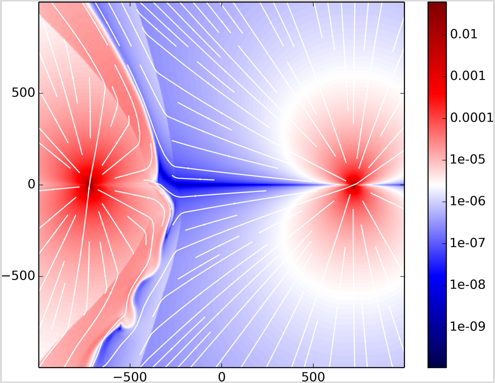
Particle Acceleration

in Colliding-Wind Binaries



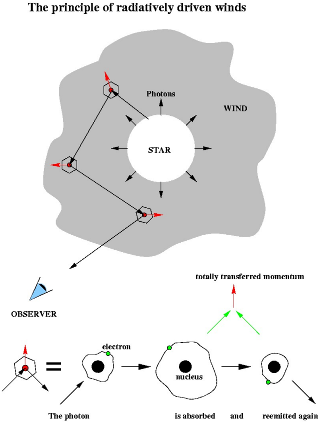
R. Kissmann, K. Reitberger, A. Reimer, O. Reimer

Astrophysical Shocks, Potsdam 2018

Binary System

- Two Massive Stars. . .

Line-driven Winds



(Sketch by R. Kudritzki)

Binary System

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- ...each with line-driven wind outflow

Colliding Wind Binaries

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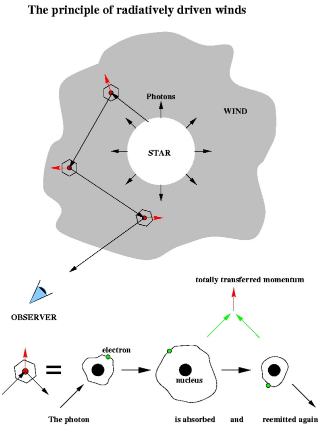

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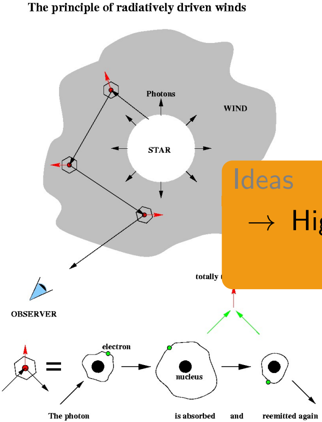
Results

- Supersonic massive wind outflows
- Interaction $\rightarrow$ wind-collision region

Line-driven Winds



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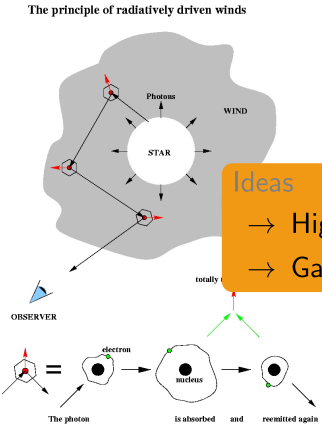

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→ High-energy particles?

→ Gamma-ray emission?

Most Recent Detection?

Pshirkov 2016

- Fermi-LAT gamma-ray data for 7 binary candidates
- 7 years of Fermi-LAT data
- spatial agreement & detection only for WR 11

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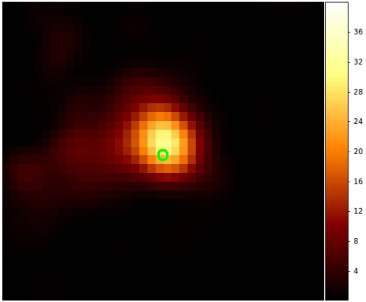
TS map (2 x 2) deg



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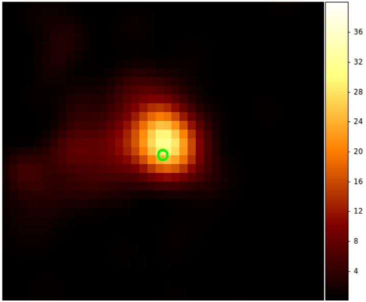

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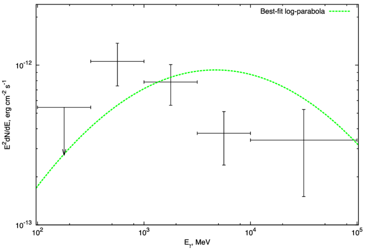

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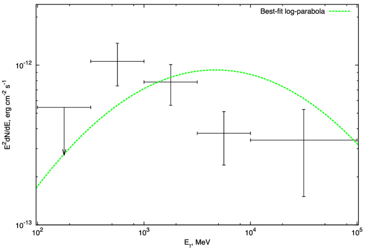

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Problem

- Theoretical Predictions
- Why only WR 11?

Emissivity of Different CWBs

	WR 11	η Carinae	WR 140	units
spectral type	WC8 + O7.4	WR? + LBV	WC7 + O8	
total kinetic power of winds	0.6[1]	2.8[2]	6.1[2]	10^{30} J s^{-1}
γ-ray flux (0.1 to 100 GeV)	1.8±0.6[1]	184±30[3]	$<$ 1.1[1] / $<$ 9.6[4]	$10^{-5}\,\frac{\mathrm{ph}}{\mathrm{m}^{-2}\mathrm{s}^{-1}}$
orbital modulation	no[1]	yes[5]	-	
high-energy γ-ray luminosity	0.0037[1]	7.8[3]	-	10^{27} J s^{-1}
nonthermal radio luminosity	1.5[2]	-	26[2]	10^{22} J s^{-1}

1 *Pshirkov (2016)*
2 *De Becker et al. (2013)*
3 *Ferme LAT 4-Year Point Source Cataloque*
4 *Werner et al. (2013)*
5 *Reitberger et al. (2015)*

Physical Parameters of Different CWBs

	WR 11	η Carinae	WR 140	units
period	$\sim$80[1]	$\sim$2024[2]	$\sim$2900[3]	d
eccentricity	$\sim$0.3[4]	$\sim$0.9[5]	$\sim$0.9[3]	
distance	$\sim$340[4]	$\sim$2300[6]	$\sim$ 1800[7]	pc
stellar separation	170-340	330 - 6300	360 - 6700	$R_\odot$
mass loss primary	~ 2[1]	~ 2500[8]	~ 90[1]	10^{-7} M$_\odot$ yr^{-1}
dominant wind	O,WR	LBV,WR	O,WR	

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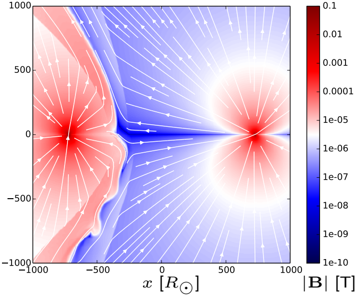
$\rightarrow$ Numerical model

CWBs: Our Modelling Ingredients

1: MHD Solver

- Line-driven winds
- Stellar dipole fields
- Free evolution

Magnetic Field



(RK et al. (2016) ApJ **831**, 121)

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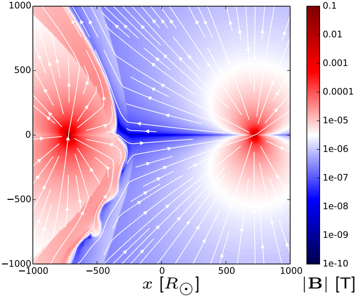

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3: Non-Thermal Emission

- Computation From Particle Spectra
- Postprocessing

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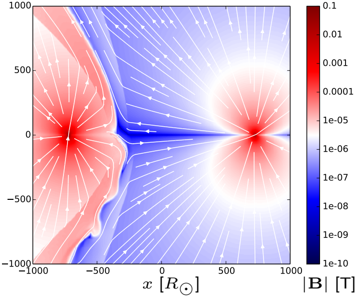

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Stellar Winds

- Example: Hydrodynamics

System of Equations

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

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Maths Behind Stellar Winds

Stellar Winds

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- Force density $\mathbf{f}$:
  - Gravity of stars
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Line Driving

- Contribution of $> 10^4$ lines
- Wind expansion $\rightarrow$ Doppler shift $\rightarrow$ Expensive

Line Acceleration – CAK Approximation

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Numerical Approximation

- Collective: power law

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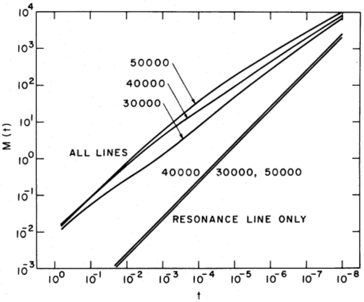

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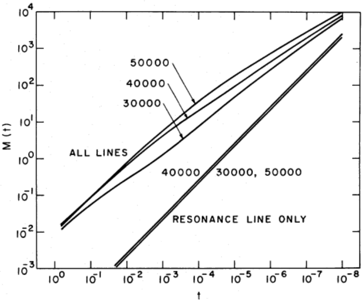

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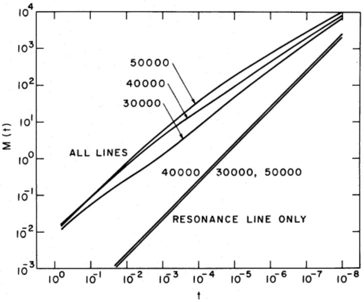

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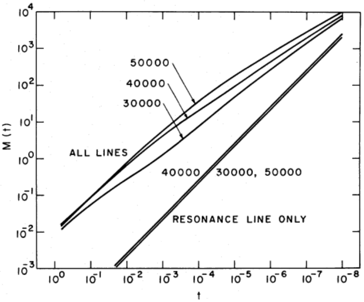

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Situation in WR 11

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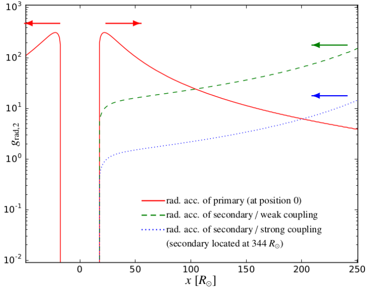

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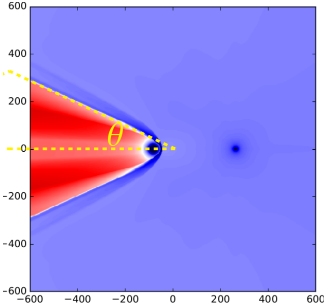

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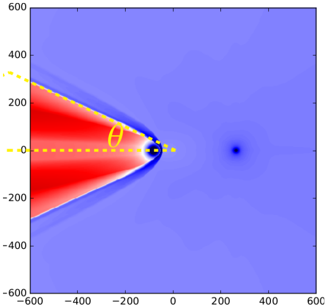

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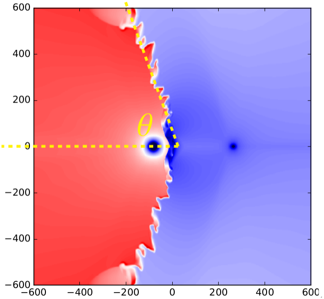

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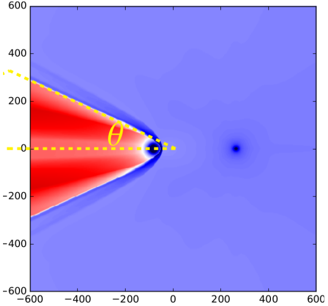

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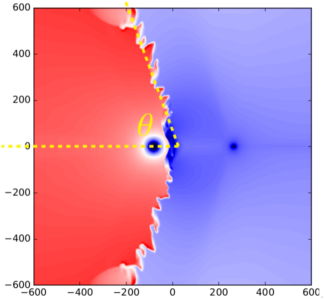

Effects

- Radiative breaking
- Shadowing

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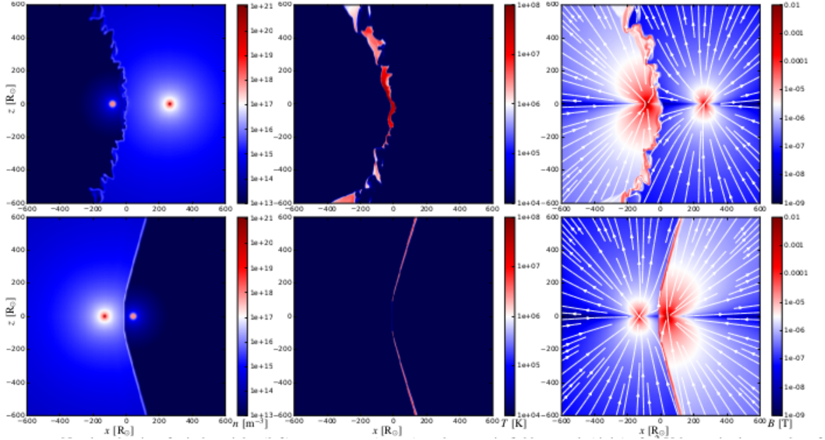

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Specifics: Adding Particles

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Specifics: Adding Particles

Transport Equation

$$\frac{\partial j}{\partial t} - D(E)\nabla^2 j + \nabla \cdot (\mathbf{u} j) - \frac{\partial}{\partial E}\left(\left(\frac{E}{3}\nabla \cdot \mathbf{u} + \dot{E}_{\text{loss}}\right) j\right) = Q_0 \delta(E - E_0)$$

Physical Processes

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Energy loss processes

- Synchrotron (Electrons)
- Inverse Compton (Electrons)
- Thermal bremsstrahlung (Electrons)
- Coulomb losses
- Nucleon-nucleon interaction

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Implementation

- Electrons & Protons
- → Advected scalar fields
- → Semi-Lagrangian solver

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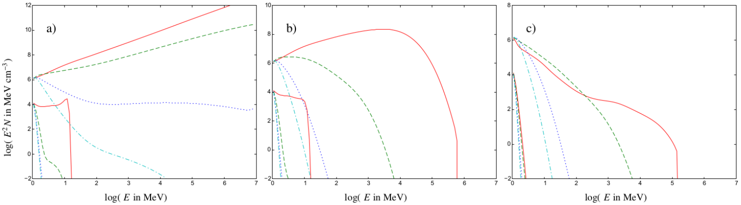
Results

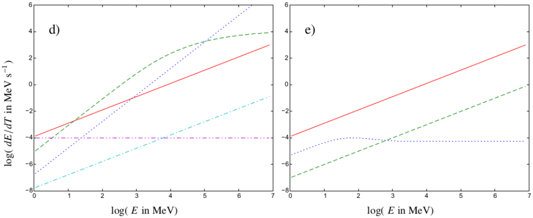
- Position-dependent particle flux
- → Can compute non-thermal emission

The Role of Spatial Diffusion

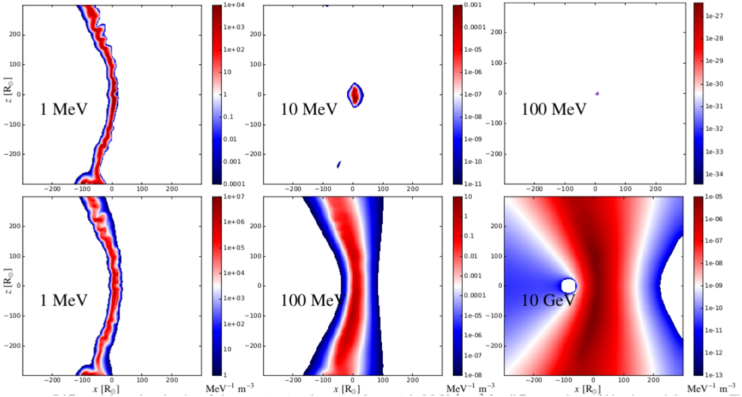
Particle Spectra



Energy-Loss and Acceleration Rates

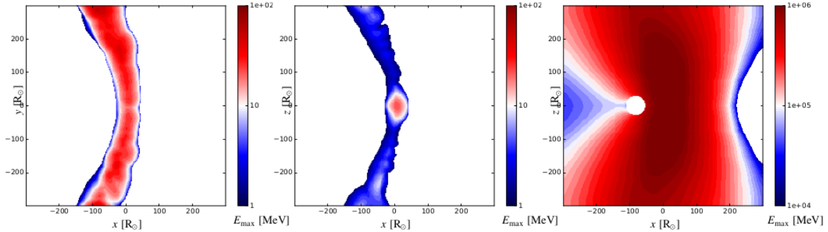


Spatial Distribution



Resulting Particle Distribution

Maximum Particle Energies



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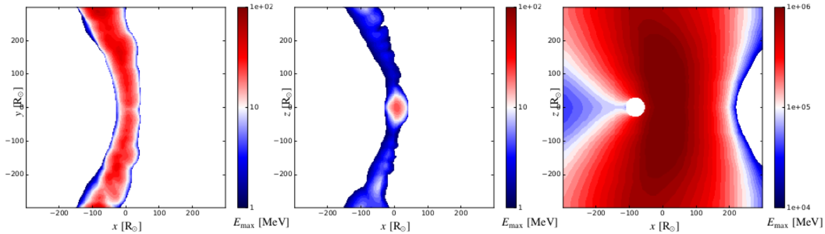
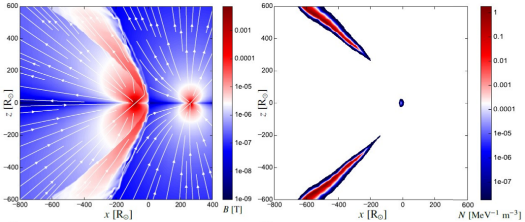


Magnetic Field & Electron Flux



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    - High radiation fields
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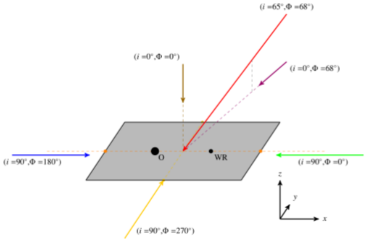

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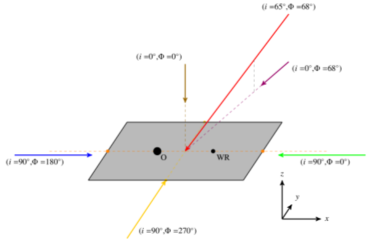
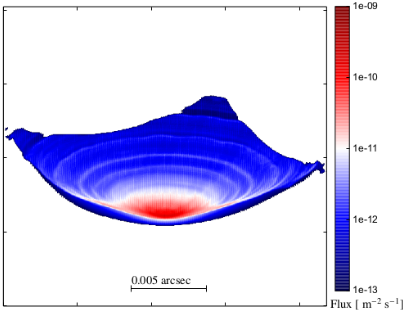
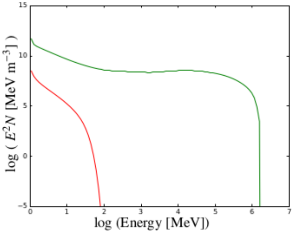


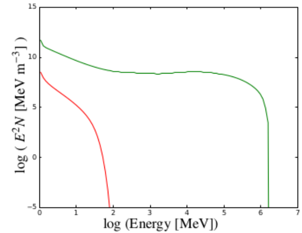
Pion-Decay Emission



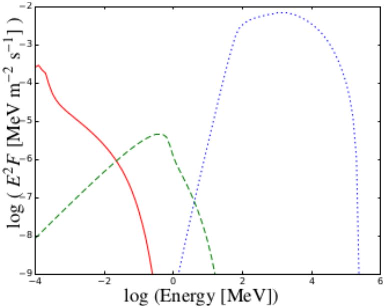
Integrated Particle Spectra



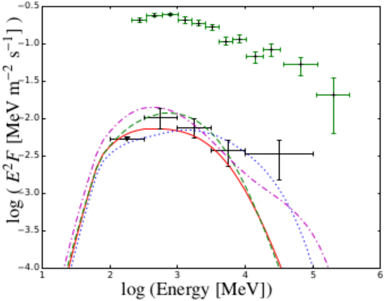
Integrated Particle Spectra



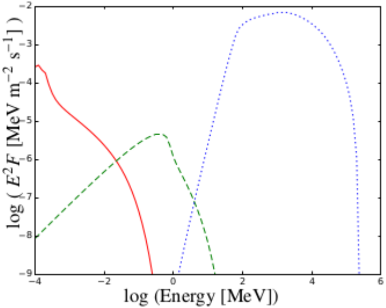
Non-Thermal Radiation



Comparison To Data



Non-Thermal Radiation



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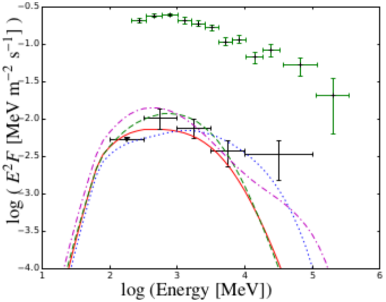

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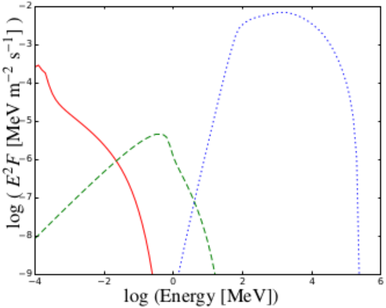
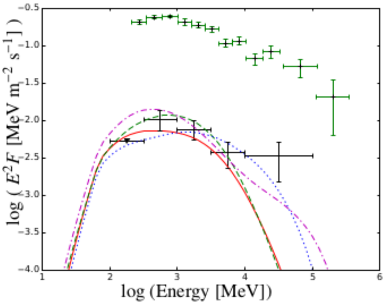


Conclusion

- WR 11: hadron accelerator
- Fit to data possible

Comparison To Data



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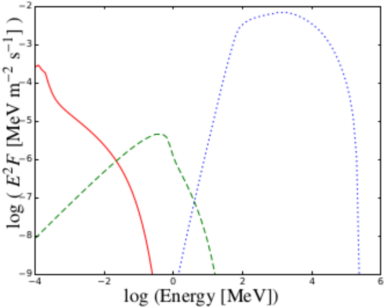

Ongoing / Outlook

- Investigation of WR 140, WR 147, & η Carinae
- New application: gamma-ray binaries