Modelling Wind Dynamics and Gamma-Ray Emission from LS 5039

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy
Universitat de Barcelona

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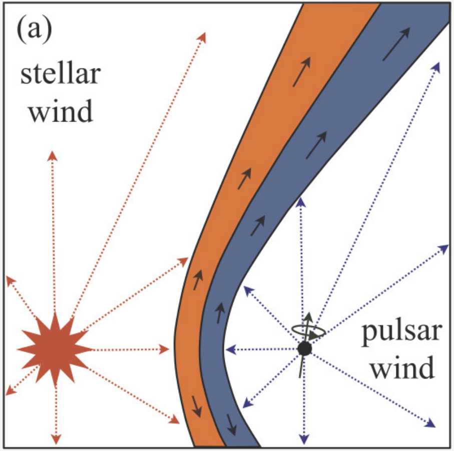
Scenario



(Dubus (2015))

Stellar Wind

- Stellar gas outflow
- Mass-loss rate $\sim 2 \times 10^{-8} M_{\odot}$yr^{-1} $\rightarrow 2.5 \times 10^{27}$W
- Wind speed 2000 km/s

$\rightarrow$ 3D hydrodynamics

A Stellar-Wind Bow Shock

(Image credit: NASA)

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Pulsar Wind

- Pair-plasma outflow
- Spin-down luminosity:
  7.55×10^{28}W
- Wind speed: 99% c

$\rightarrow$ 3D relativistic(!) hydrodynamics

The Crab Pulsar

(Image credit: NASA & ESA)

Stellar Winds

- Relativistic HD

Relativistic Hydrodyamics

$$\frac{\partial D}{\partial t} + \nabla \cdot \left(\frac{1}{\gamma} D \mathbf{u} \right) = 0$$

$$\frac{\partial \mathbf{m}}{\partial t} + \nabla \cdot \left(\frac{1}{\gamma} \mathbf{m} \otimes \mathbf{u} + p \mathbb{1} \right) = \mathbf{f}$$

$$\frac{\partial \tau}{\partial t} + \nabla \cdot \left((\tau + p) \frac{1}{\gamma} \mathbf{u} \right) = S_\tau$$

Equation of state

$$h = h(\rho, p) = 1 + \frac{\Gamma}{\Gamma - 1} \frac{p}{\rho}$$

Stellar Winds

- Relativistic HD
- Conserved Quantities
  - Density $D = \gamma\rho$
  - Momentum
    $m^j = \gamma\rho h u^j = \gamma^2\rho h v^j$
  - Energy density $\tau = \gamma^2\rho h - p - D$

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- Solver: CRONOS MHD / RHD code

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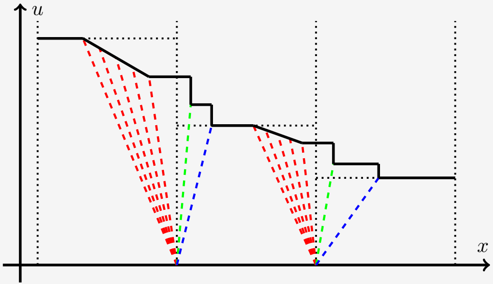
1D Conservation Law – Time Step



Transport Equation

$$\nabla_\mu \left(u^\mu \mathcal{N}'\right) + \frac{\partial}{\partial \gamma'} \left\{ \left(-\frac{\gamma'}{3} \nabla_\mu u^\mu + \dot{\gamma}'_{rad} \right) N' \right\} = 0$$

Physical Processes

- Inject spectrum at shocks
  - Maxwellian
  - Power law
- Transport with fluid flow
- ~~Spatial diffusion~~
- Energy losses

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Energy loss processes

- Adiabatic losses
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Results

- Position- & energy-dependent particle flux → 4D problem

→ Can compute non-thermal emission

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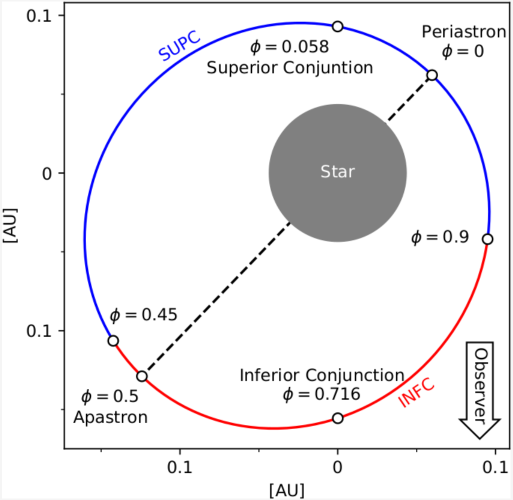
Oribital configuration

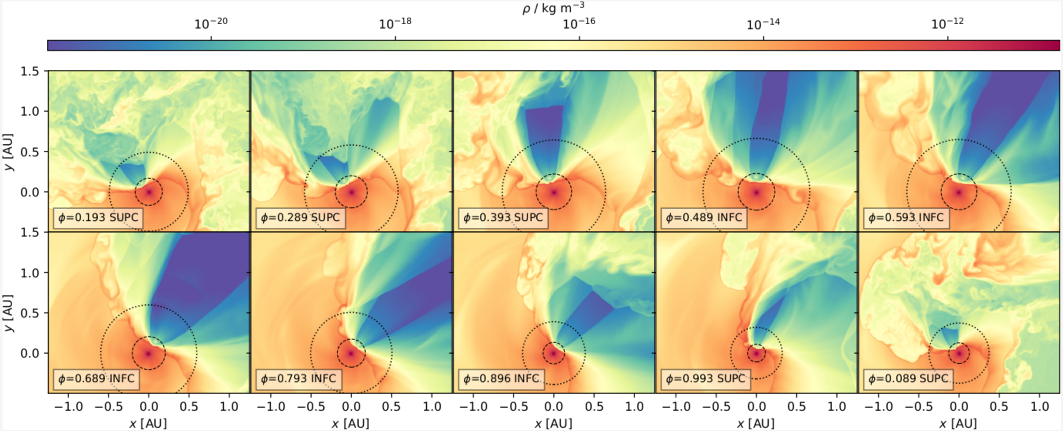


(Huber et al. (2021))

Simulation Setup

- Numerical domain: 2.5×2×1 AU
- Spatial resolution: 640×512×256 cells
- 50 logarithmic energy bins
- Co-rotating frame
- Semi-major axis: $a = 0.145$ AU, excentricity: $e = 0.35$
- Orbital timescale: 3.9 d
- Timestep: $\sim$1 s
- 1000 core first-generation Epyc system

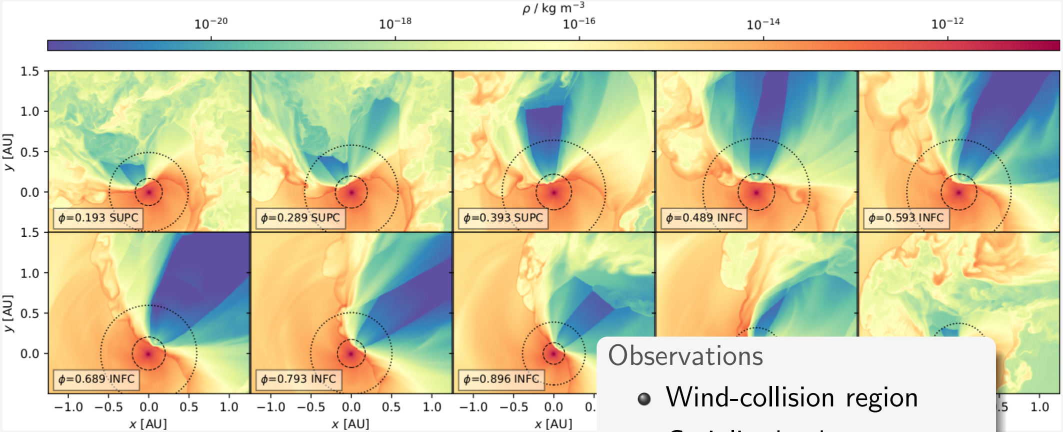
Gas Density



(Huber et al. (2021))

Wind Interaction

Gas Density



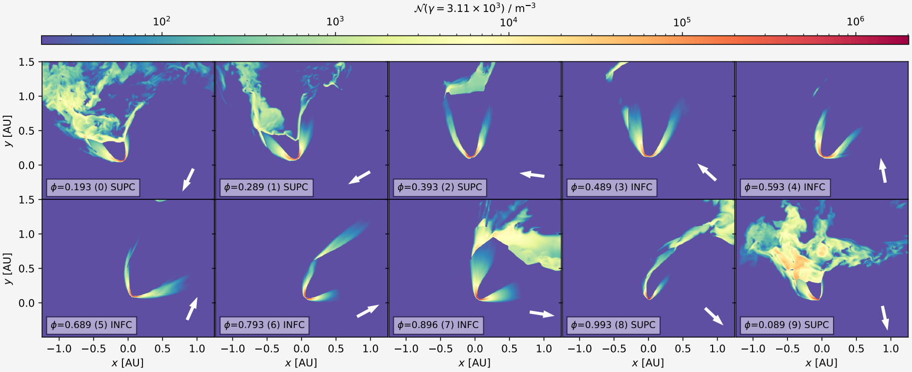
. (2021))

Observations

- Wind-collision region
- Coriolis shock
- Turbulence
- Unshocked pulsar wind

Energetic Particles

Lower Energies ($E = 1.6$ GeV)



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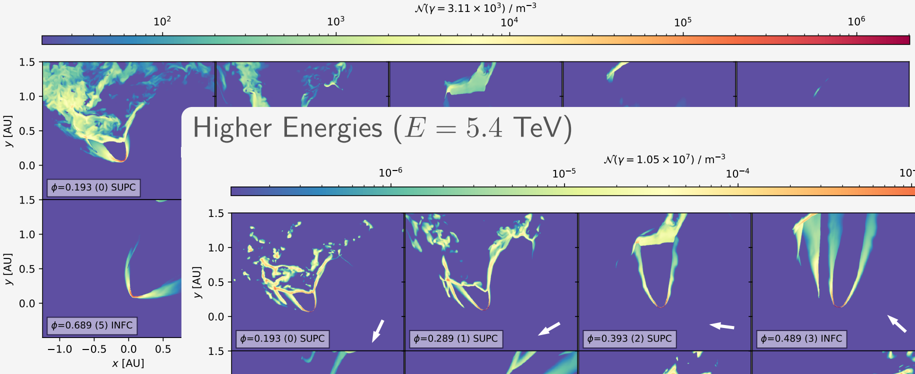
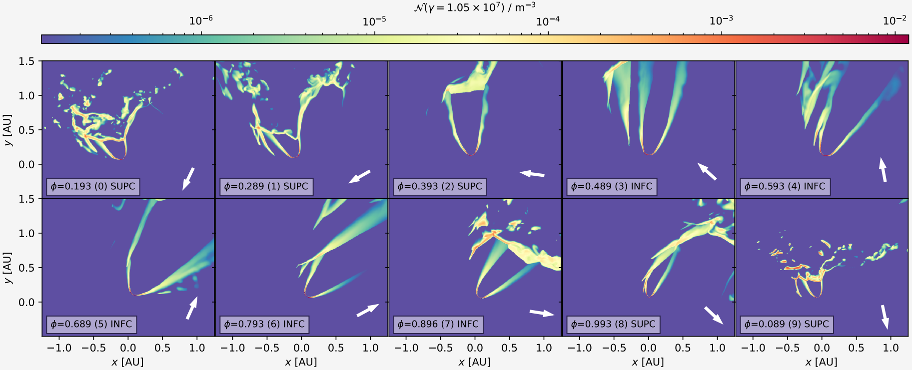


Higher Energies ($E = 5.4$ TeV)



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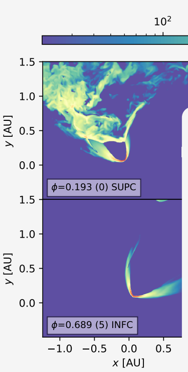

Injection Spectrum

- $\leftrightarrow$ particle density
- $\leftrightarrow$ internal energy
- $\leftrightarrow$ magnetic field

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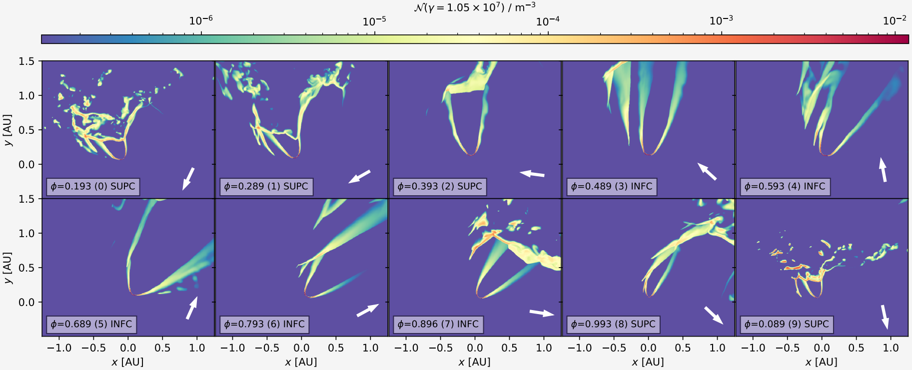

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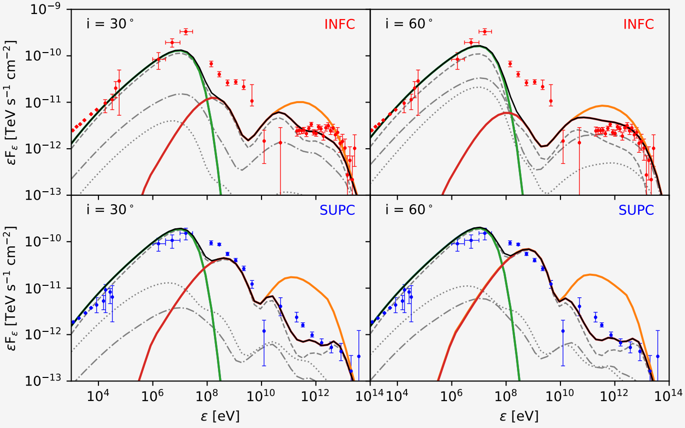
Results on local infrastructure

Phase-Averaged Emission Spectra



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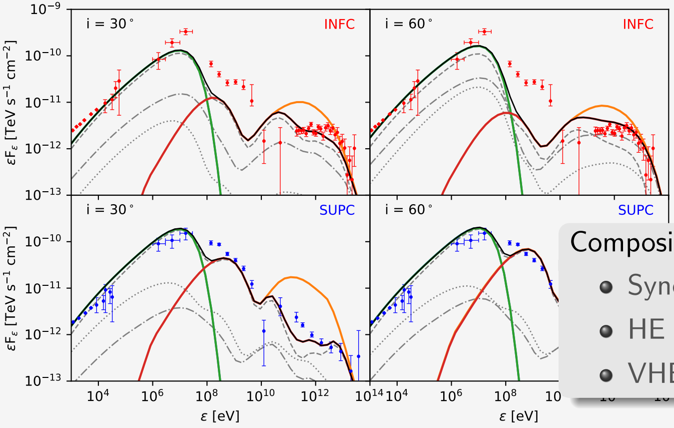


(Huber et al. (2021))

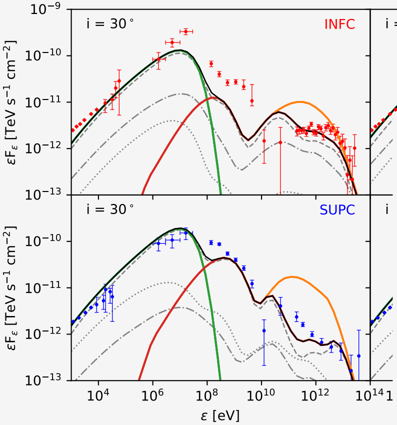
Composition of Spectrum

- Synchrotron up to ~10 MeV
- HE gamma rays: IC of Maxwellian
- VHE gamma rays: IC of power-law

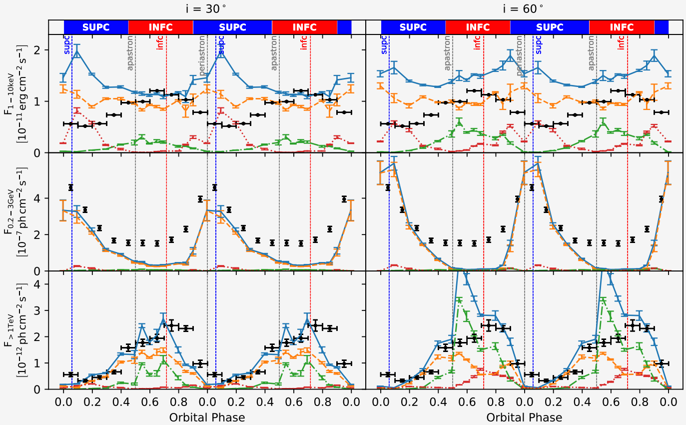
Gamma-Ray Emission

Results on local infrastructure

Phase-Averaged Emission Spectra



Emission Lightcurves



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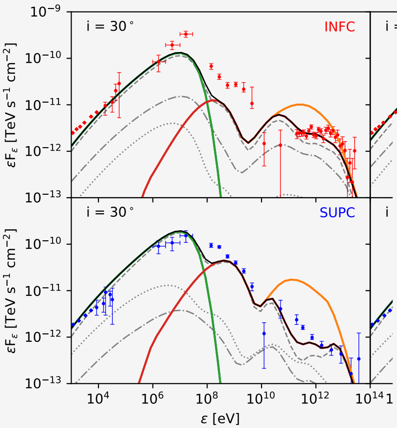
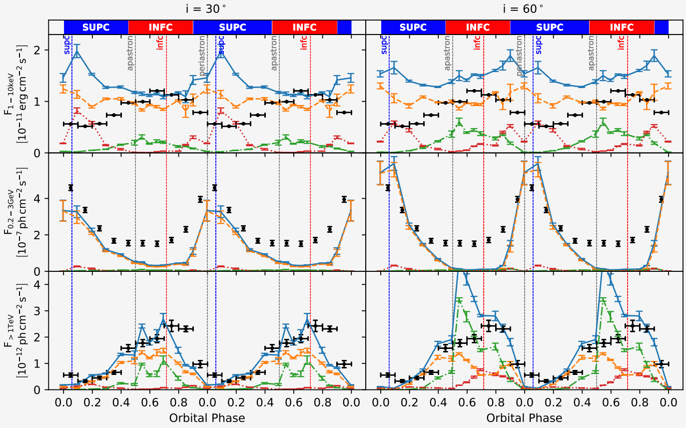


Inclination Dependence

- Anisotropic IC
- $\gamma - \gamma$ absorption
- Relativistic beaming

Emission Lightcurves



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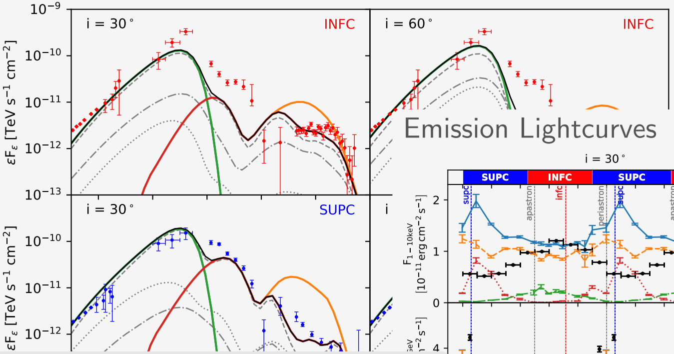

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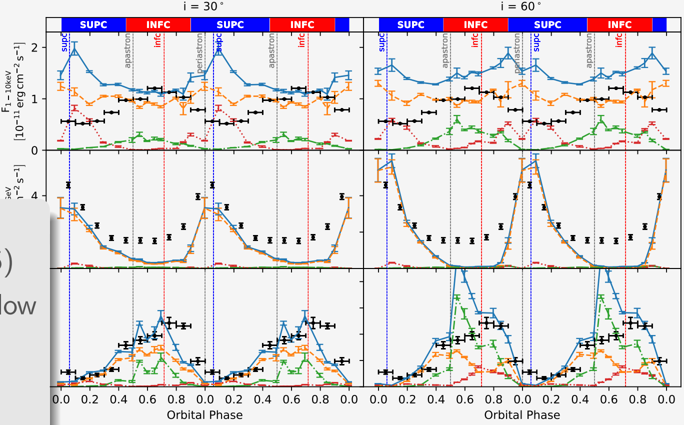


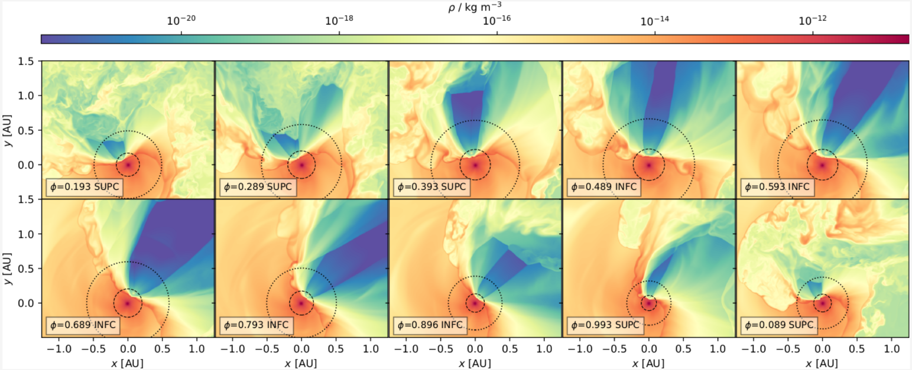
(Huber et al. (2021))

Issues

- Need hard spectral index (1.5)
- Wrong phase dependence at low energies $\rightarrow$ magnetic field?
- Magnetospheric emission?
- Partly missing Coriolis shock

Preliminary: New Simulations (PRACE)

Stellar-Wind Interaction



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Increasing Resolution

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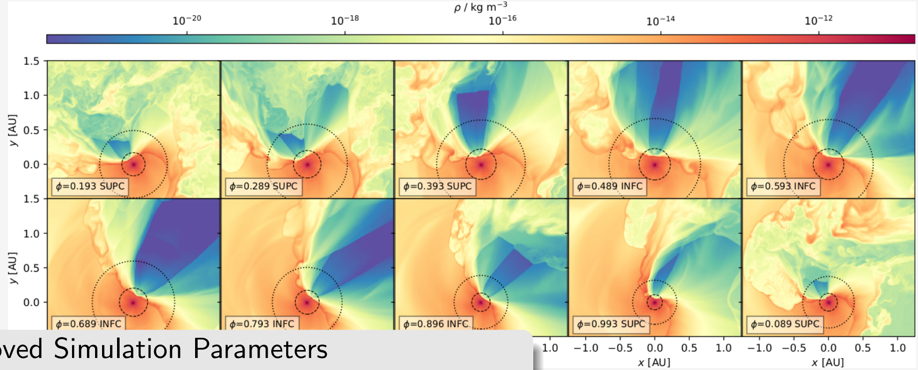

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Improved Simulation Parameters

- Larger domain 4×3×2 AU
- Spatial resolution: 2048×1536×1024 → 40× increase (∼ 3 billion cells)
- Simulation of 3 full orbits (nearly 1 million steps per orbit)

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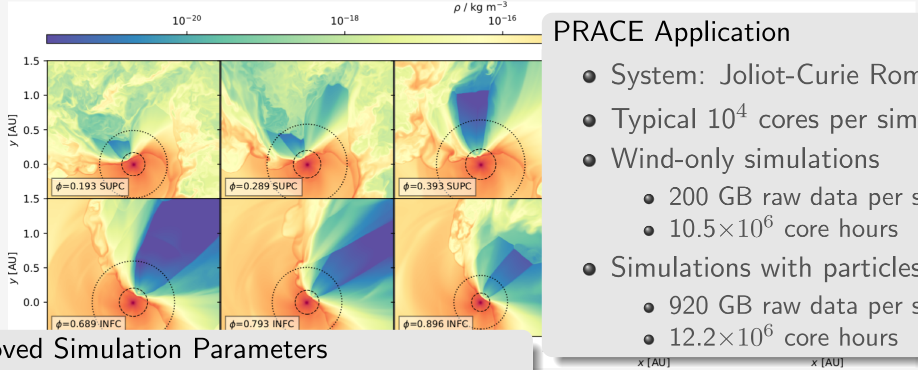

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PRACE Application

- System: Joliot-Curie Rome
- Typical 10^4 cores per simulation
- Wind-only simulations
  - 200 GB raw data per step
  - 10.5×10^6 core hours
- Simulations with particles
  - 920 GB raw data per step
  - 12.2×10^6 core hours

Improved Simulation Parameters

- Larger domain $4\times3\times2$ AU
- Spatial resolution: $2048\times1536\times1024$
  $\rightarrow$ $40\times$ increase ($\sim$ 3 billion cells)
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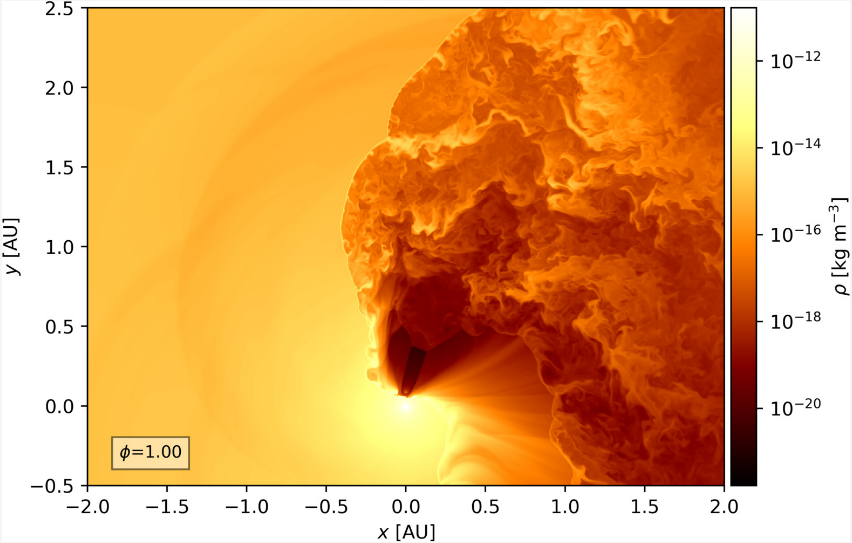
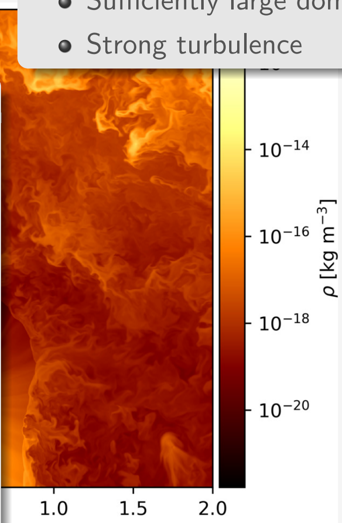

2.5
2.0
1.5
1.0
0.5
0.0
−0.5
y [AU]
−2.0
−1.5
−1.0
−0.5
0.0
0.5
1.0
1.5
2.0
x [AU]
ϕ=1.00
10−12
10−14
10−16
10−18
10−20
ρ [kg m−3]

Dynamics of Stellar Winds (Corotating Frame)

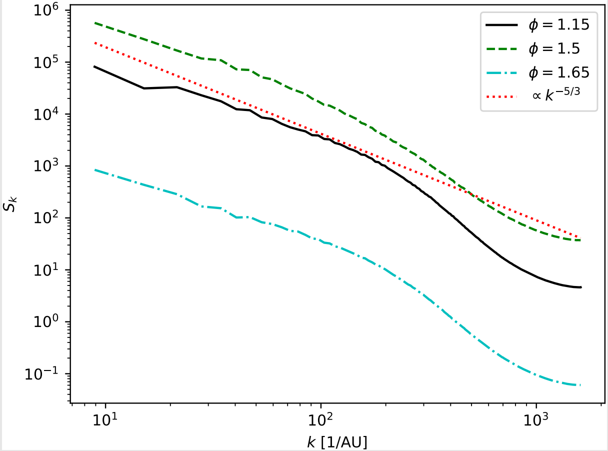
Gas Density



Observation

- Sufficiently large domain ✓
- Strong turbulence

Preliminary: Four-Velocity Power Spectrum

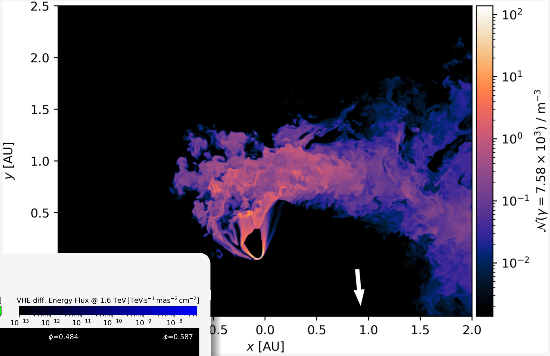


Conclusion

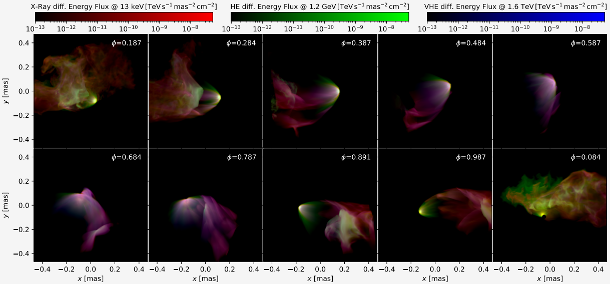
Current Status

- Coupled RHD plus transport
- Pulsar-wind scenario
- Currently: higher-resolution model
  - Post processing
  - Analysis of RHD winds
- Future: Magnetic field!

Energetic Particles



Emission Projections



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