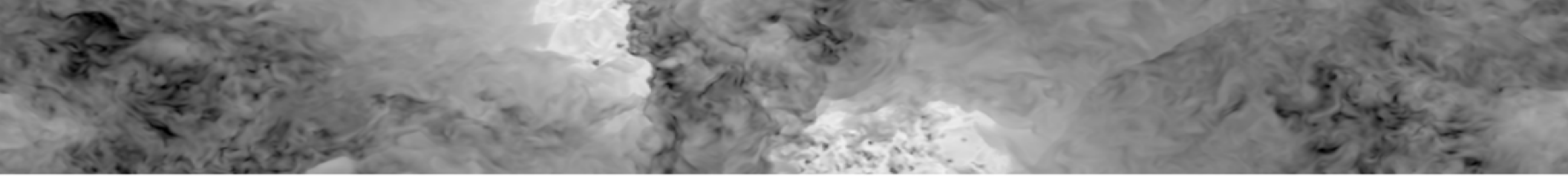


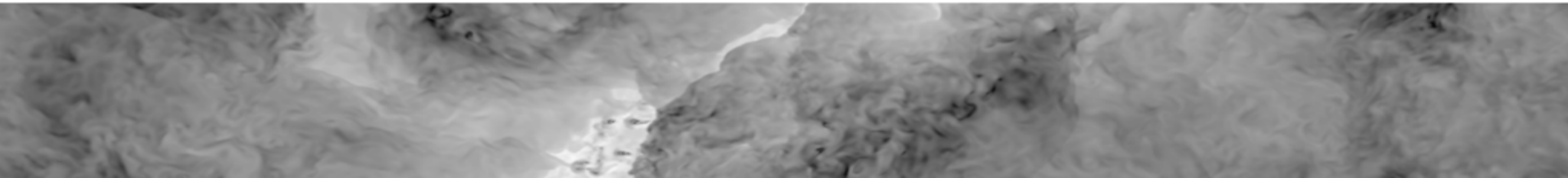
The WhiskyTHC Code

Einstein Toolkit Meeting, Stockholm, 2015

David Radice

CALIFORNIA INSTITUTE OF TECHNOLOGY 1891

Collaborators: E.Abdikamalov, S.Bernuzzi, S.Couch, F.Galeazzi, R.Haas, W.Kastaun, C.Ott, L.Rezzolla, E.Schnetter



Outline

1. The WhiskyTHC Code

2. Applications
    A. Relativistic Turbulence
    B. Binary Neutron Stars
        - Inspiral
        - Post-Merger Physics
    C. Core-Collapse Supernovae

3. Conclusions

WhiskyTHC = Whisky + THC

- Equation of state
- ~~GR sources~~
- Analysis routines

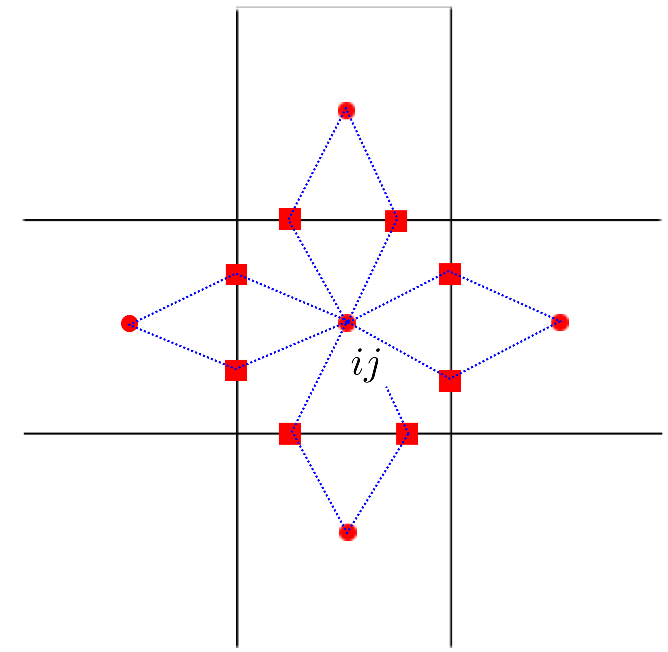
- High-Order FD / FV Methods
- Modular design
- Neutrino leakage (as in Neilsen et al. 2014)

Numerical Methods

Finite Volumes

- Complex to implement
- Large comp. costs
- Conservative
- General grids
- Simple physical interp.

$$\frac{\mathrm{d}\langle \mathbf{U}\rangle_{ij}}{\mathrm{d}t} = -\frac{1}{V_{ij}}\int_{\partial V_{ij}} \mathbf{F}\cdot \mathrm{d}\mathbf{S}$$

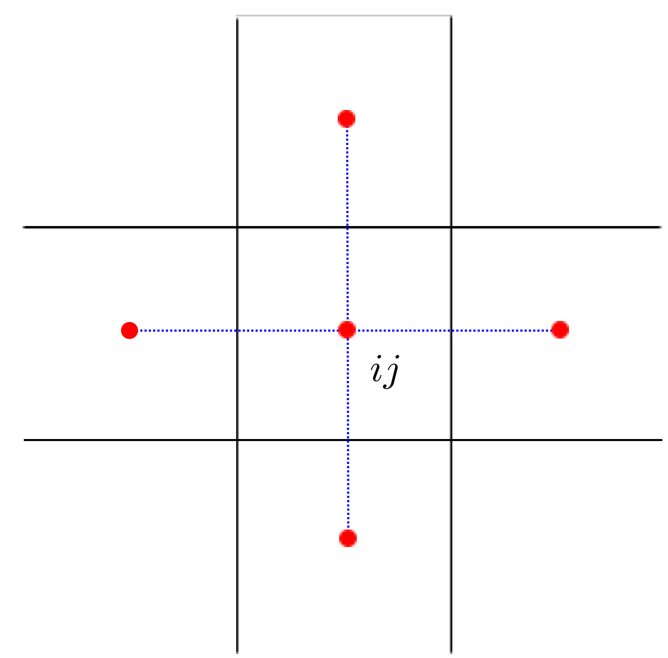


$$\partial_t \mathbf{u} + \nabla\cdot \mathbf{f}(\mathbf{u}) = 0$$

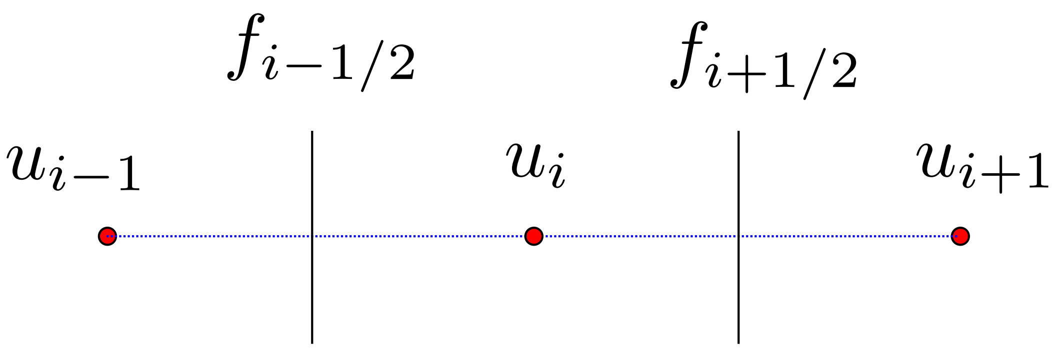
Finite Differences

- Simple to implement
- Low comp. costs
- Discrete conservation
- Tensor product grids

$$\frac{\mathrm{d}\mathbf{U}_{ij}}{\mathrm{d}t} = -\left[D\cdot \mathbf{F}\right]_{ij}$$



Positivity-Preserving Limiter



$$\frac{u_i^{n+1} - u_i^n}{\Delta t} = \frac{f_{i-1/2} - f_{i+1/2}}{\Delta x}$$

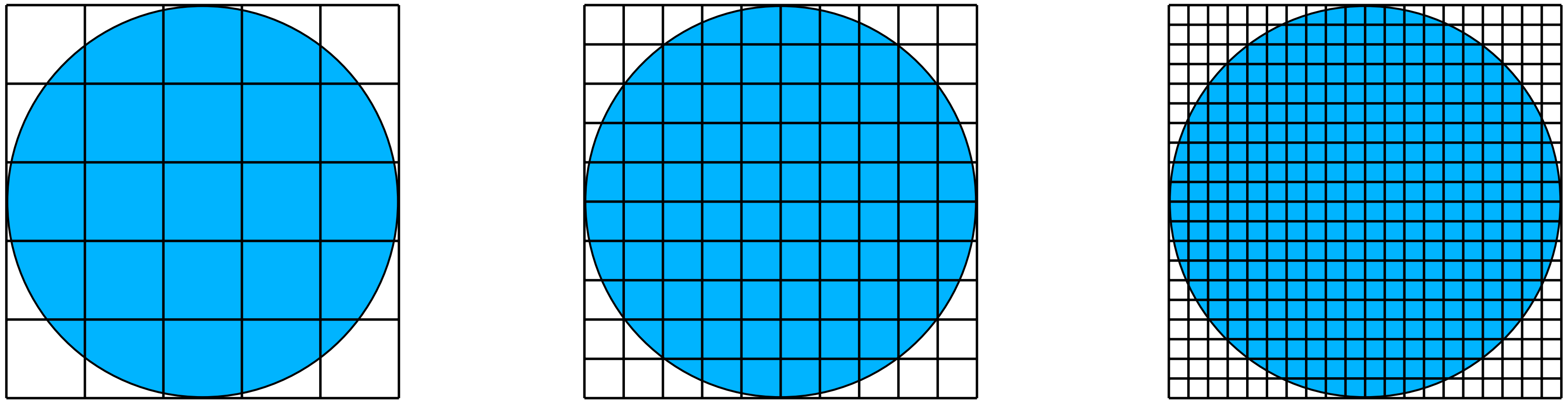
$$u_i^{n+1} = \frac{1}{2}\Bigg[\underbrace{\left(u_i^n + 2\frac{\Delta t}{\Delta x} f_{i-1/2}\right)}_{u_i^-} + \underbrace{\left(u_i^n - 2\frac{\Delta t}{\Delta x} f_{i+1/2}\right)}_{u_i^+}\Bigg]$$

Hu, Adams & Shu (2013)

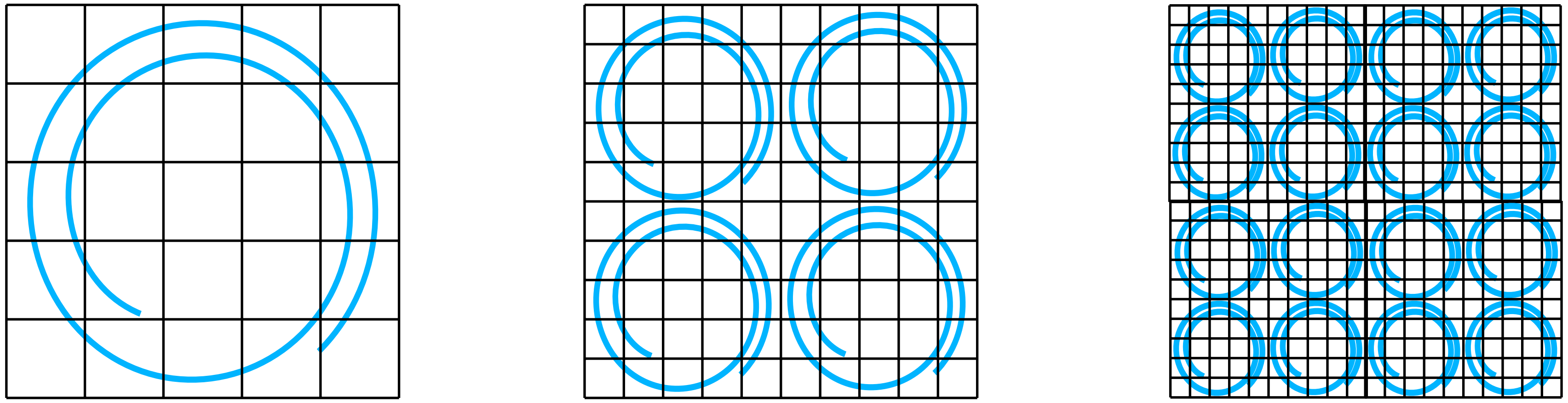
$$u_i^{n+1} = \frac{1}{2}\left(u_i^- + u_i^+\right)$$

The Meaning of Convergence

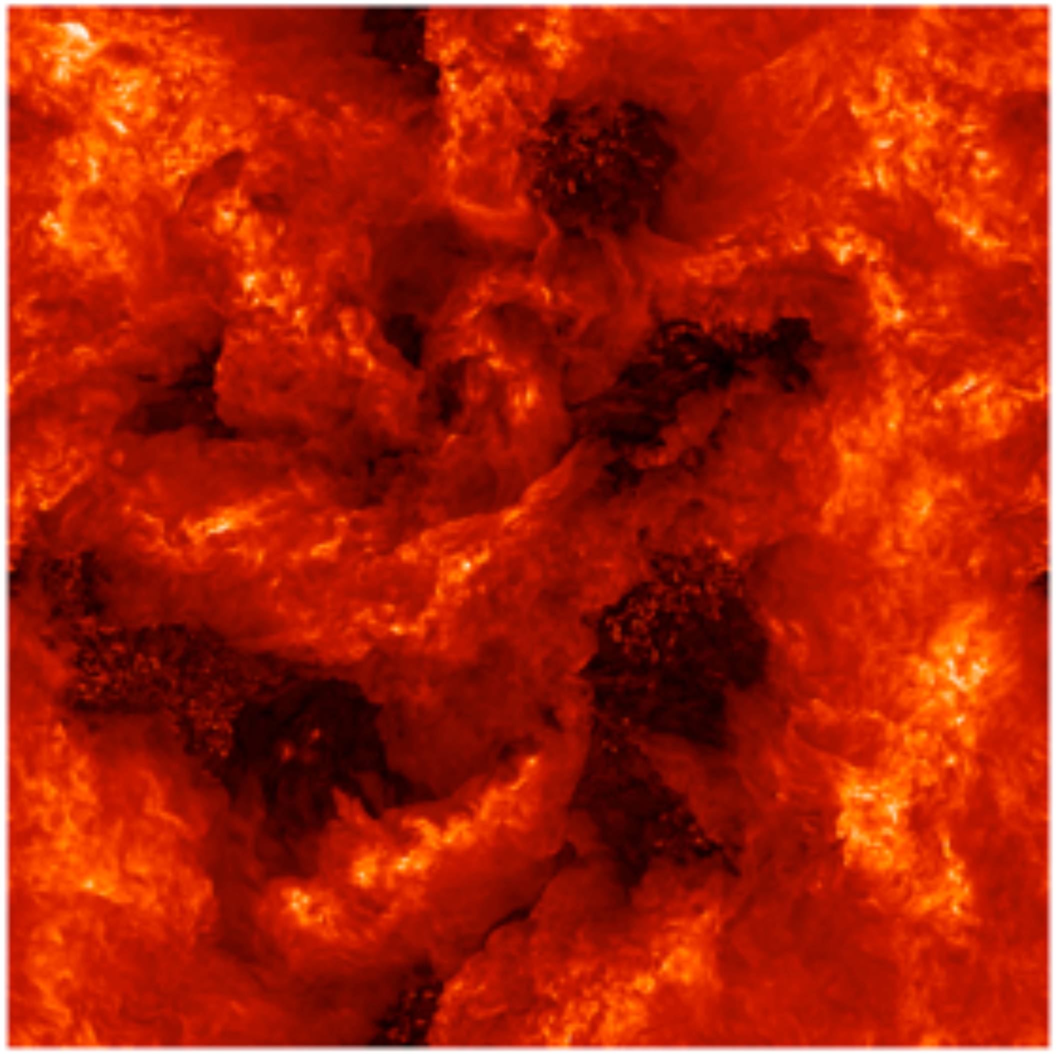
Global simulations:



Local simulations:

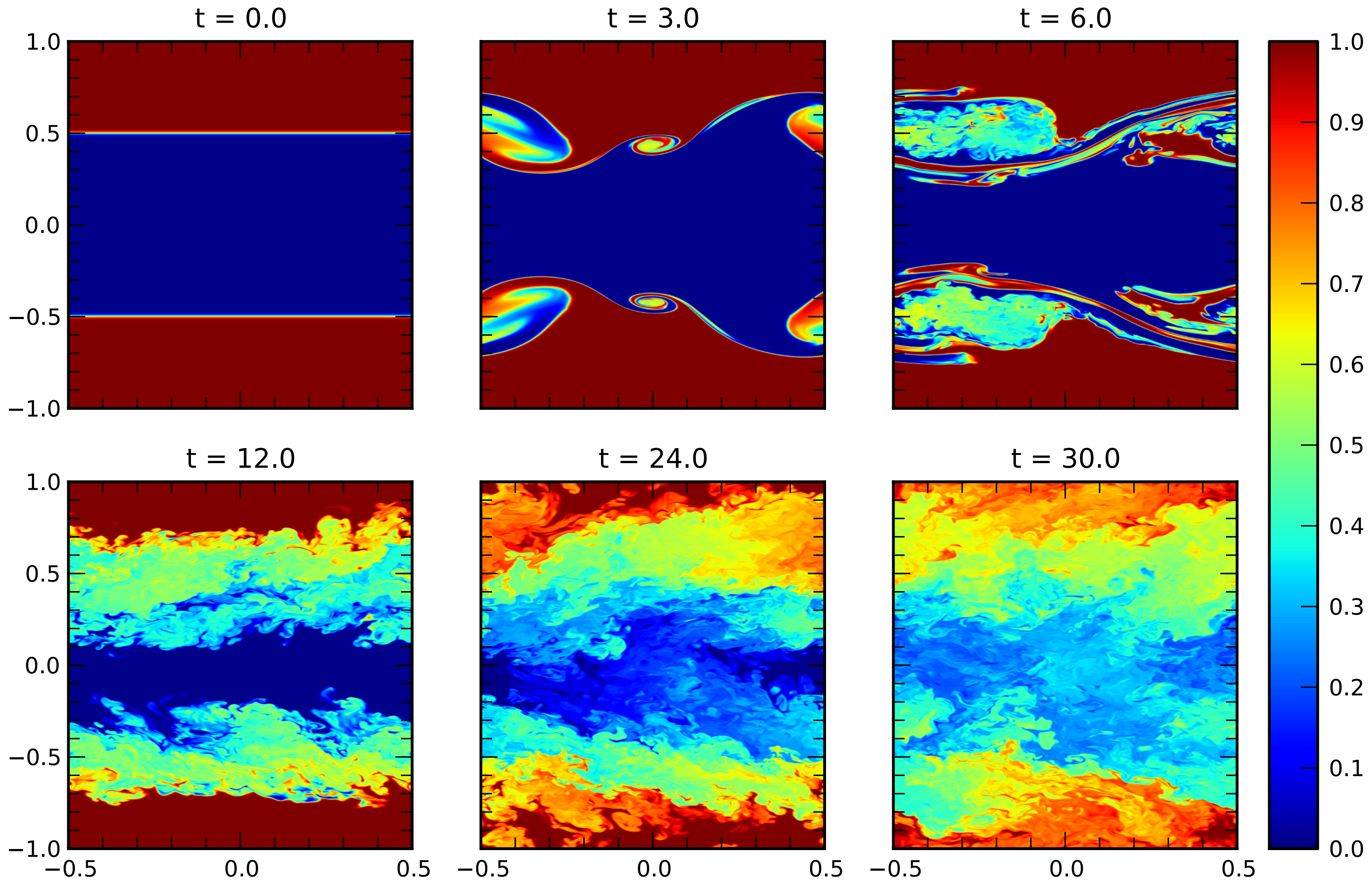


Relativistic Turbulence

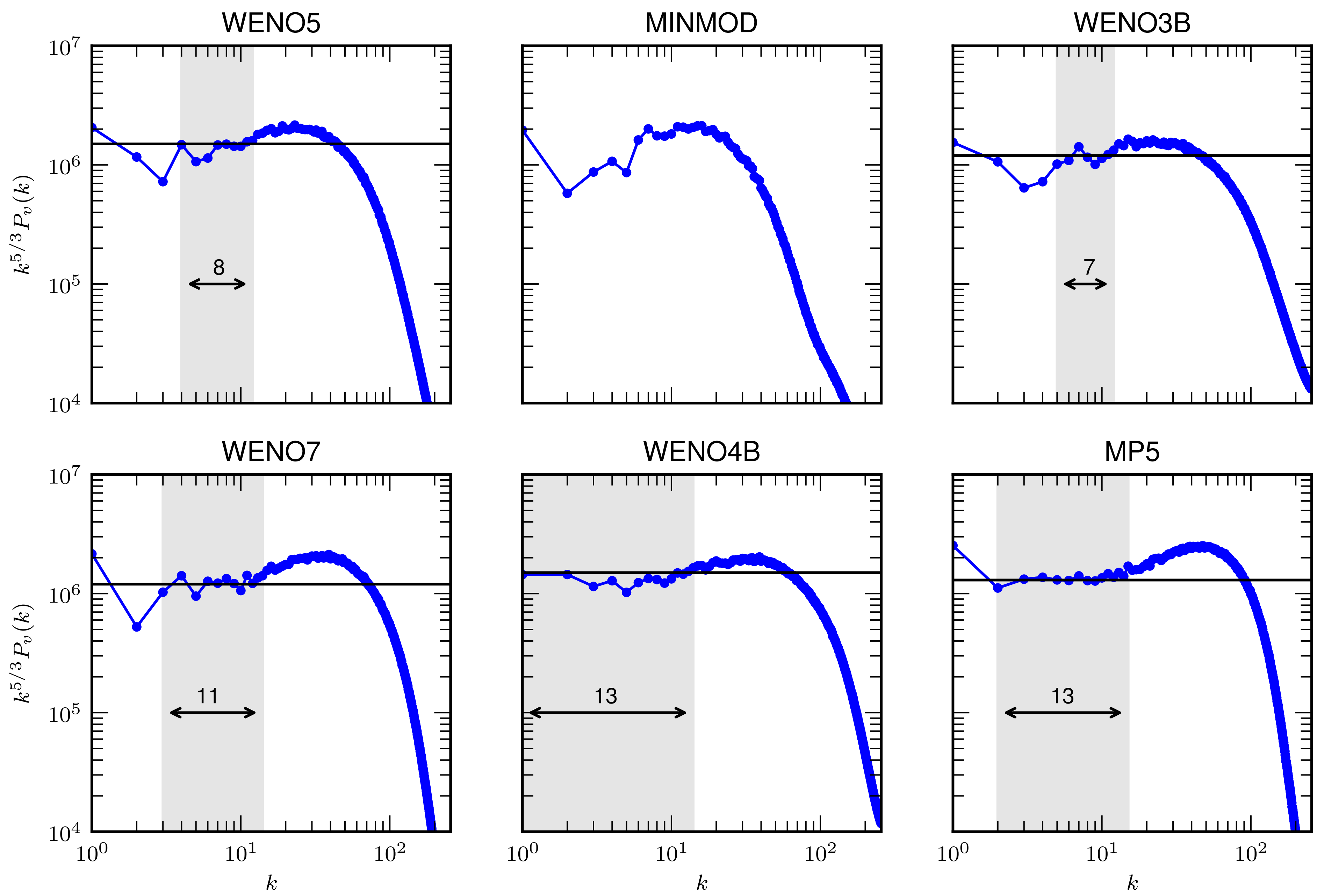


- First application of (Whisky)THC
- GRB jets
- Binary neutron star mergers
- …

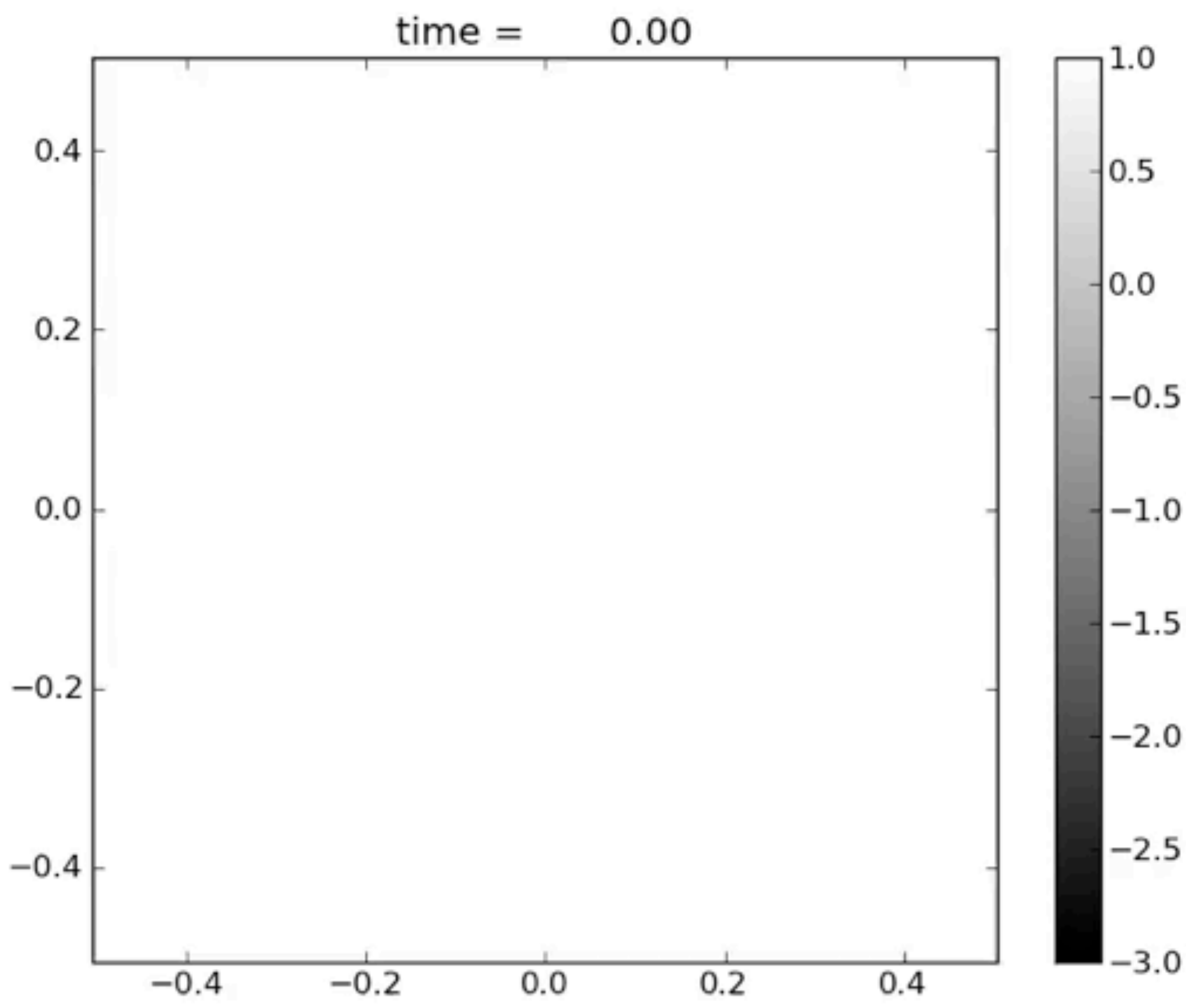
Relat. Kelvin Helmholtz (I)



Relat. Kelvin Helmholtz (II)



Driven Turbulence (I)



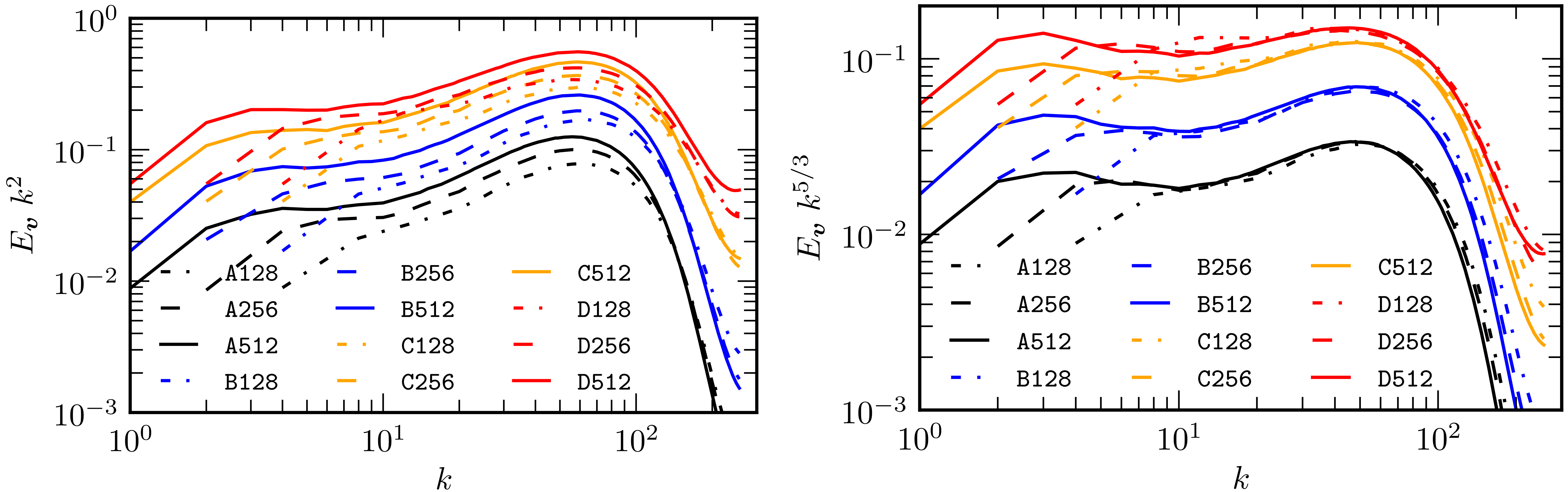
$\log_{10}(\Gamma - 1)$

- Conformal fluid, initially at rest
- Evolve with pseudo-random forcing

$$\nabla_\nu T^{\mu\nu} = F^\mu$$

- Wait until stationarity
- Studied statistical properties

Driven Turbulence (II)

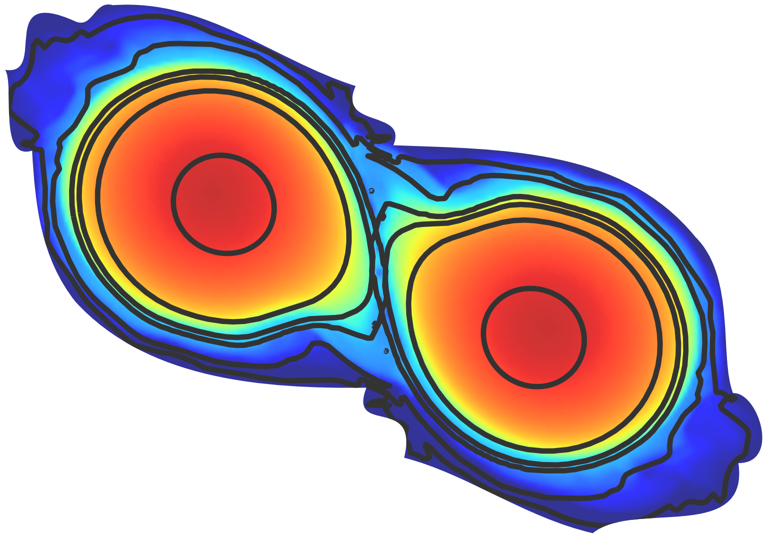


- Studied the power spectrum of the three-velocity
- Data consistent with Kolmogorov (-5/3) slope!

Binary Neutron Stars

Motivations

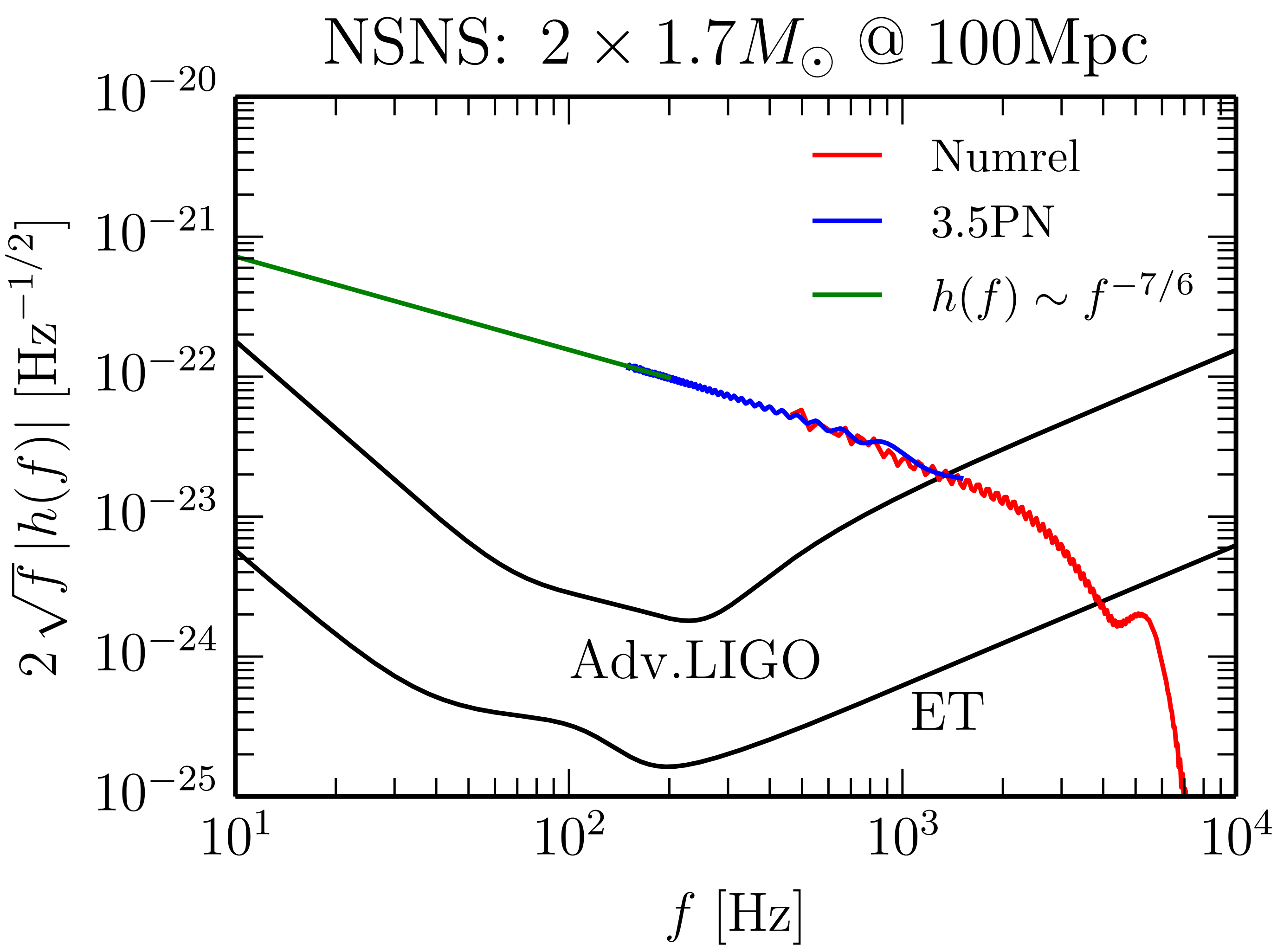
- Gravitational waves
- Short gamma ray burst



Dynamics

- Inspiral
- Merger
- Hypermassive NS?
- Black-hole + torus
- Ultra-relativistic jet?

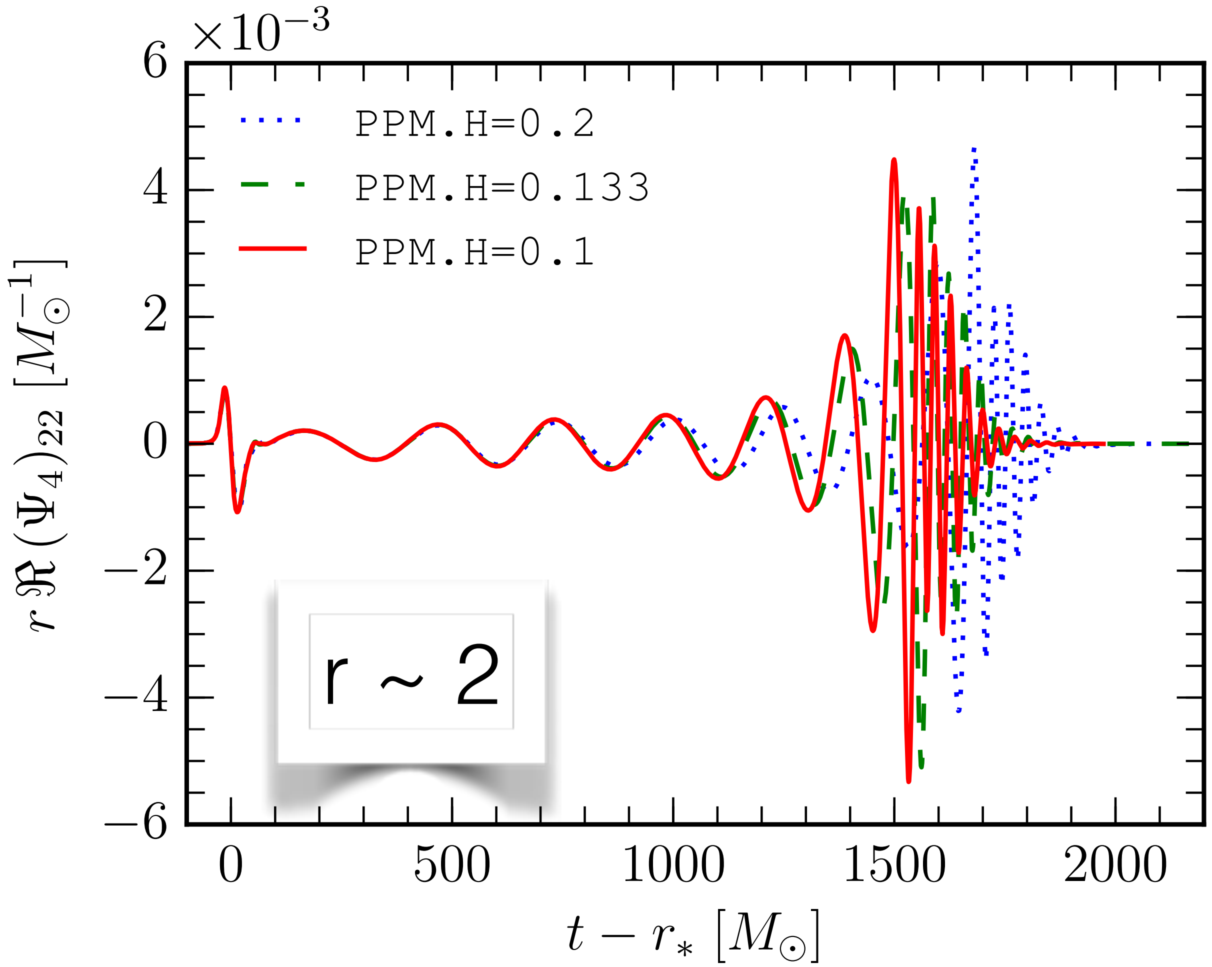
GWs from BNS

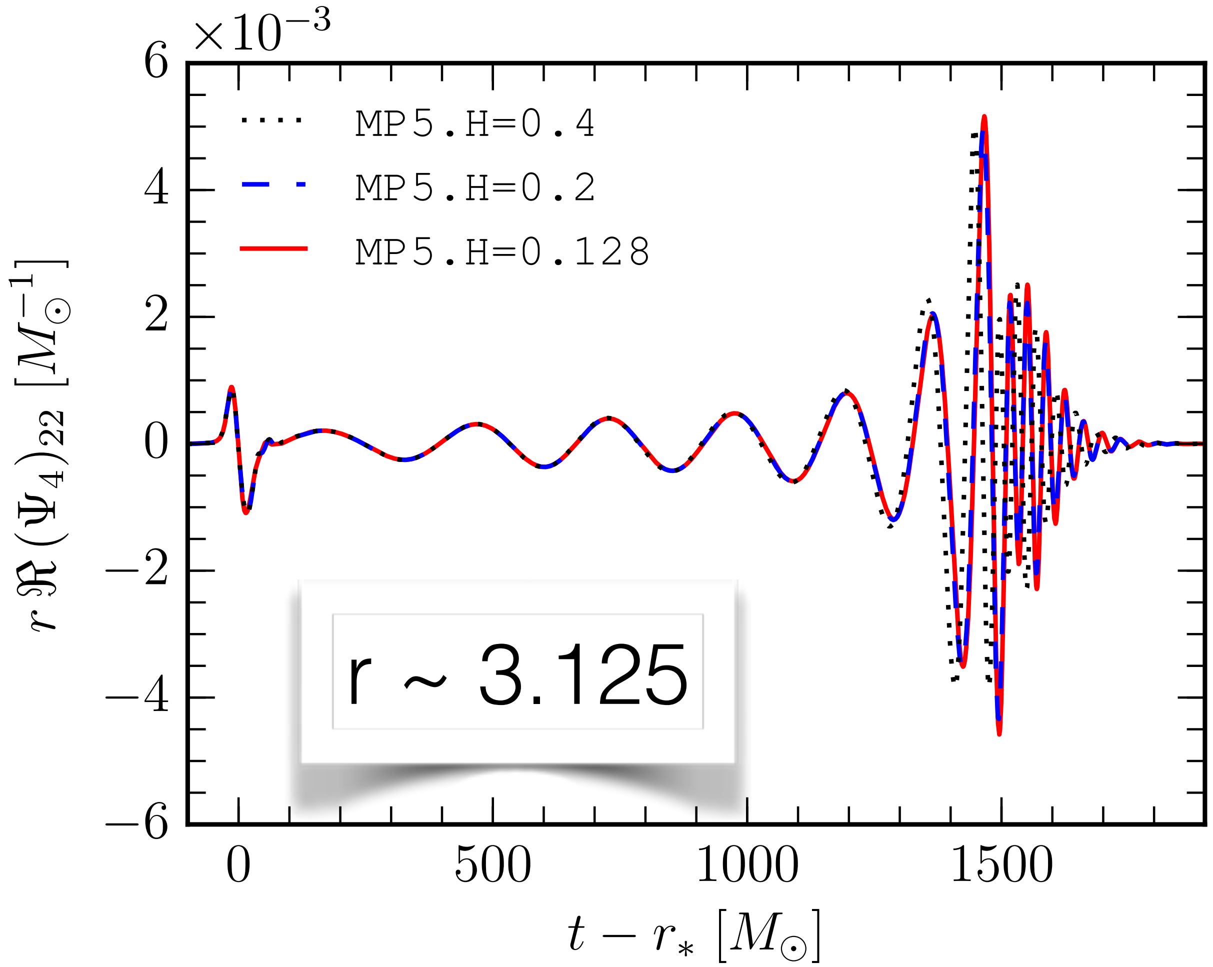


- **Early inspiral:** approximate analytic waveforms
- **Inspiral:** post-Newtonian and effective one-body
- **Late-inspiral and merger:** numerical relativity

Synergy between analytic and numerical relativity

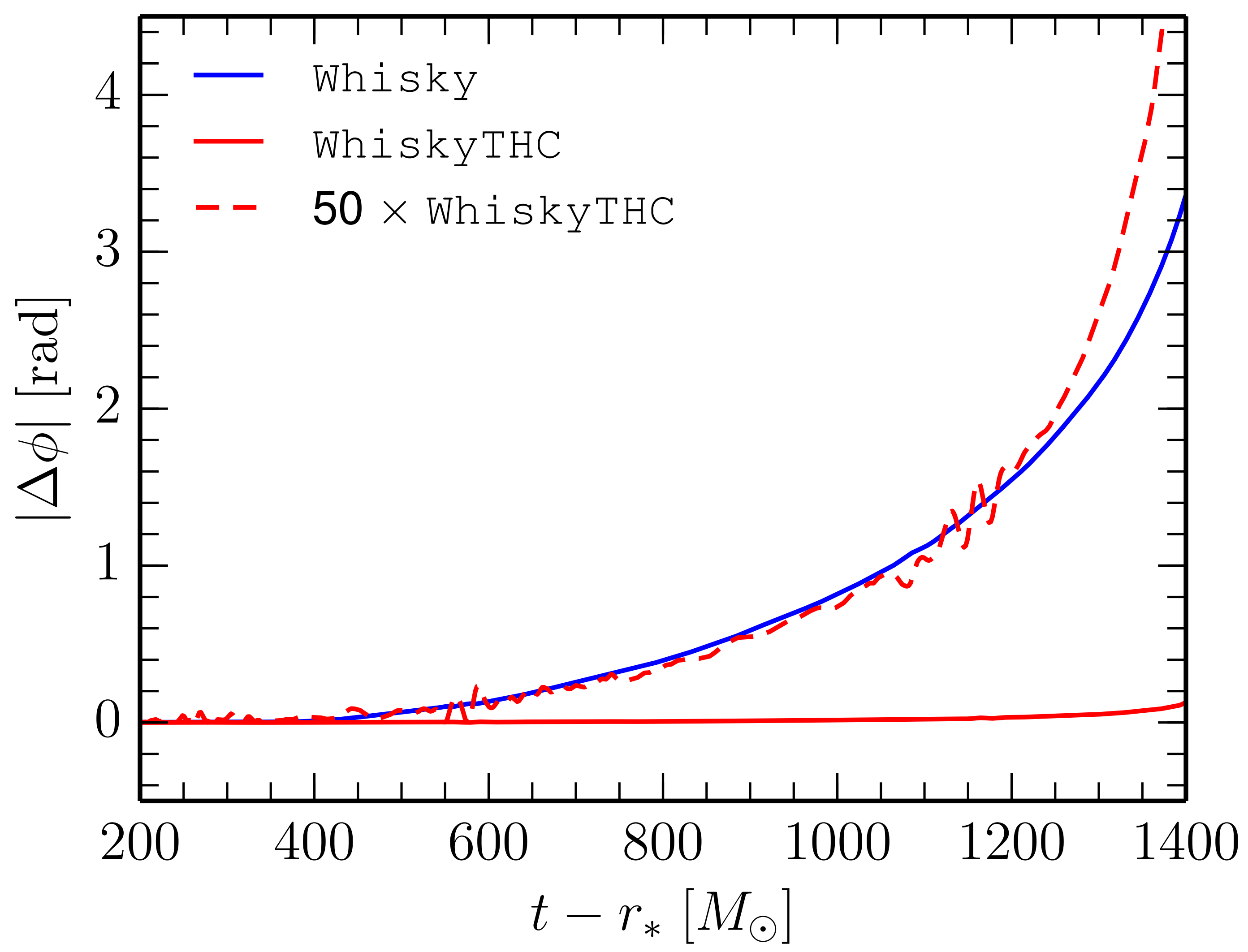
High Order vs 2nd Order (I)





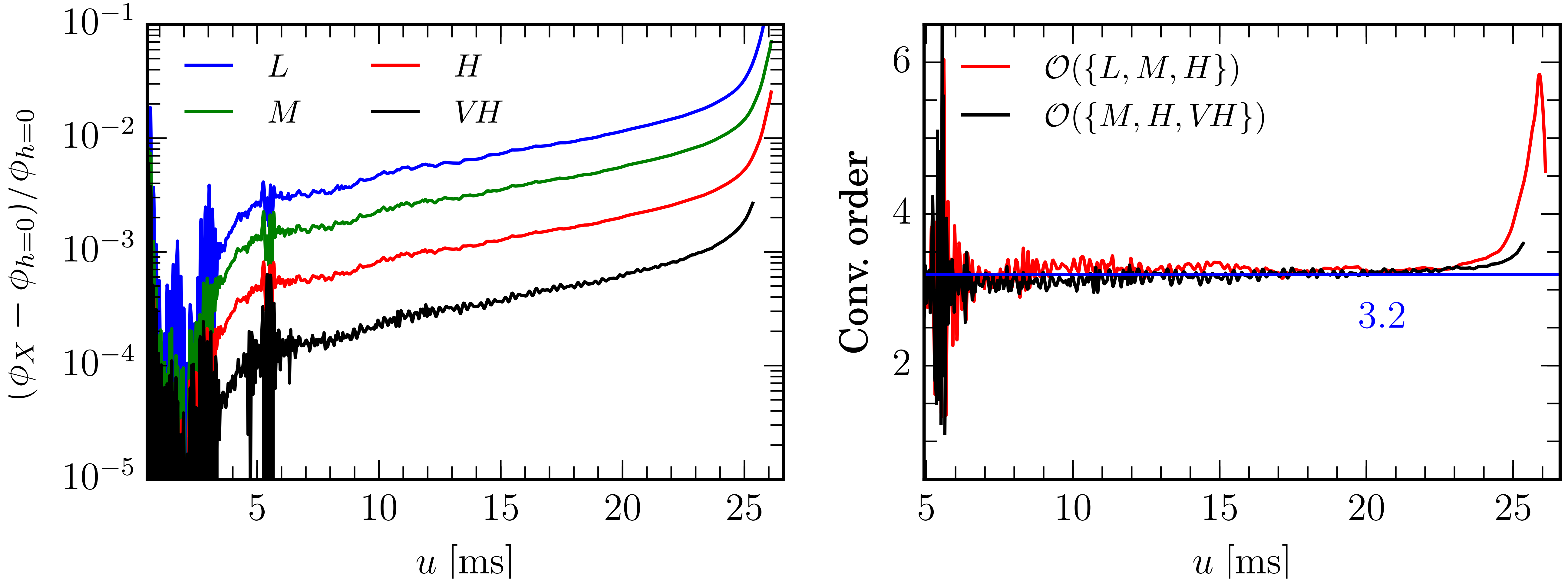
- Better accuracy at lower resolutions
- Smaller de-phasing between different resolutions

High Order vs 2nd Order (II)



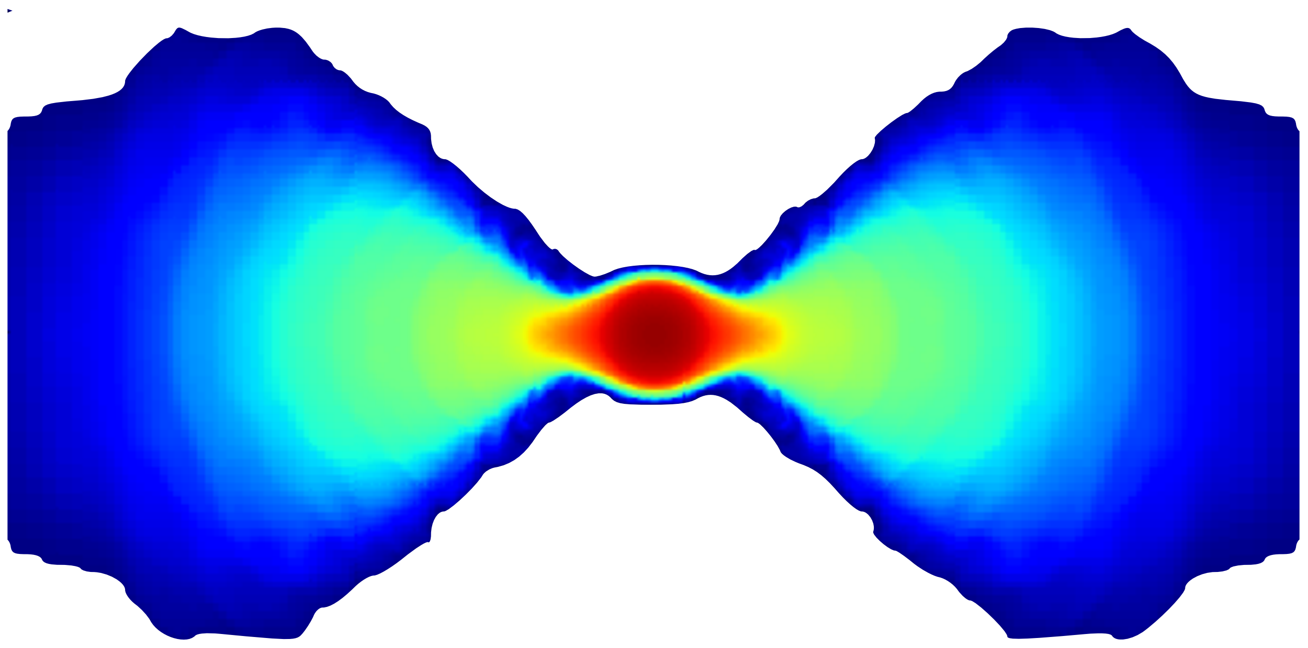
Gain a factor ~50 in phase accuracy at moderate resolution

Phase Accuracy: "Long" Inspiral



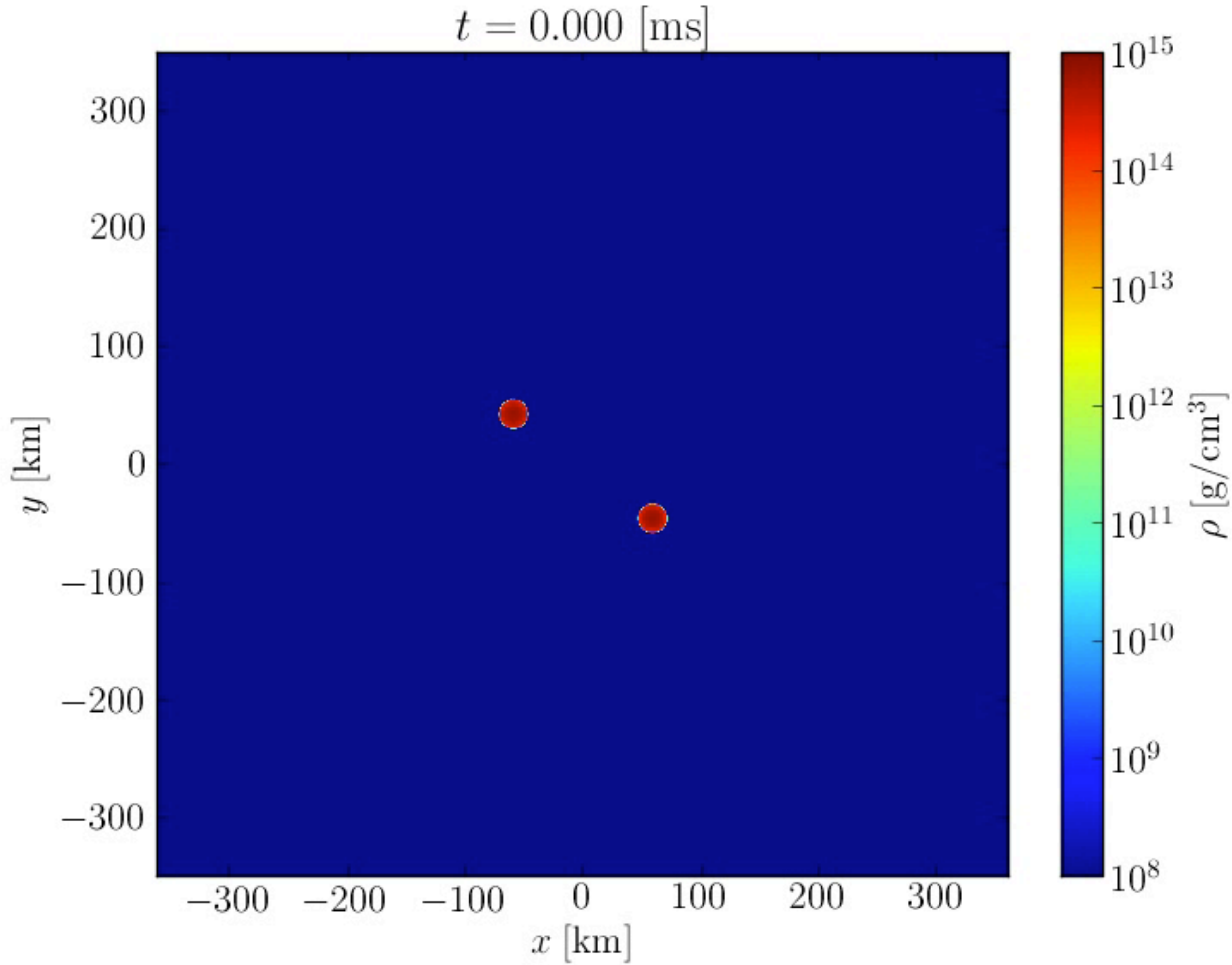
Phase convergence: 8 orbits

Post-Merger Physics



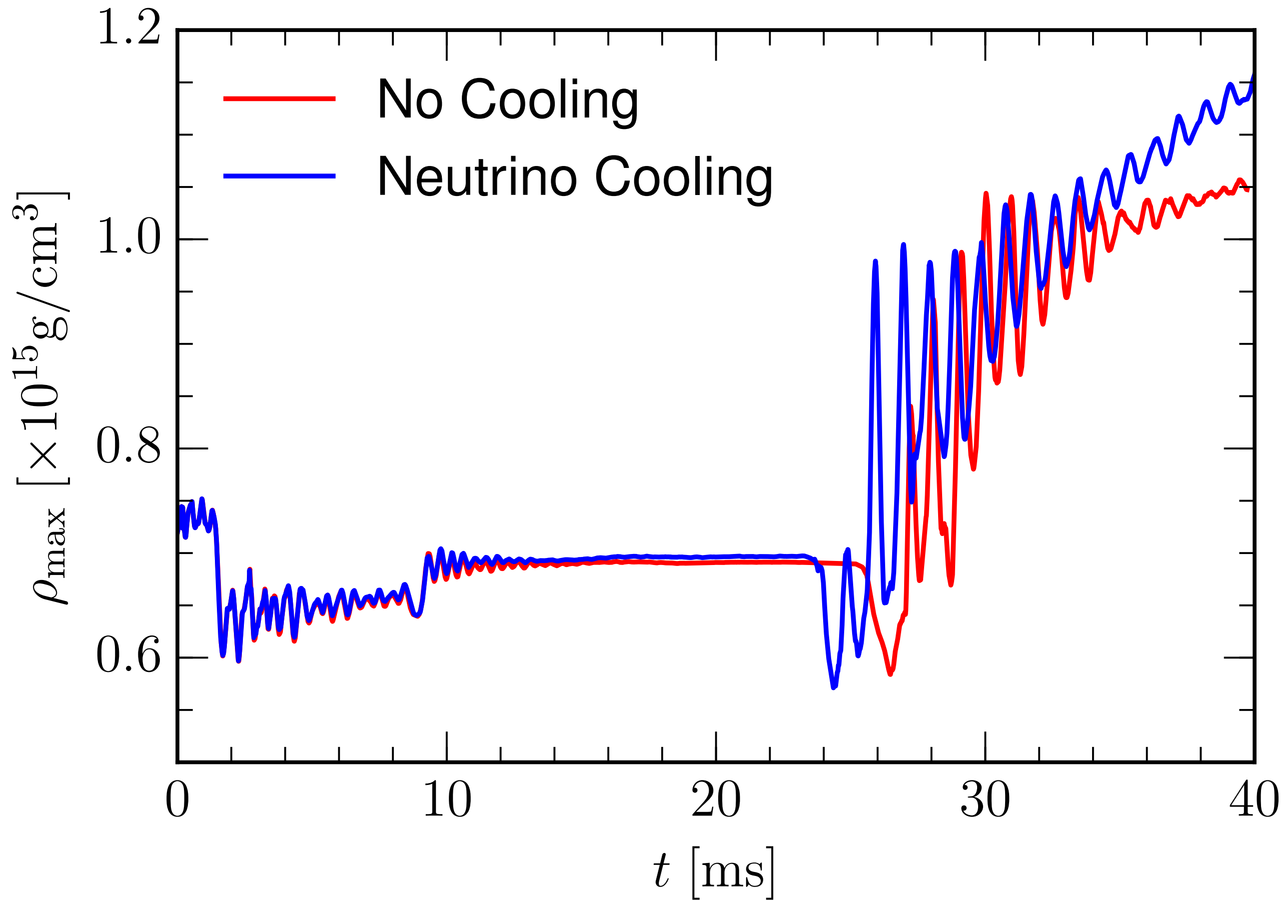
- Thermal effects
- Neutrino cooling
- Magnetic fields
- Turbulence

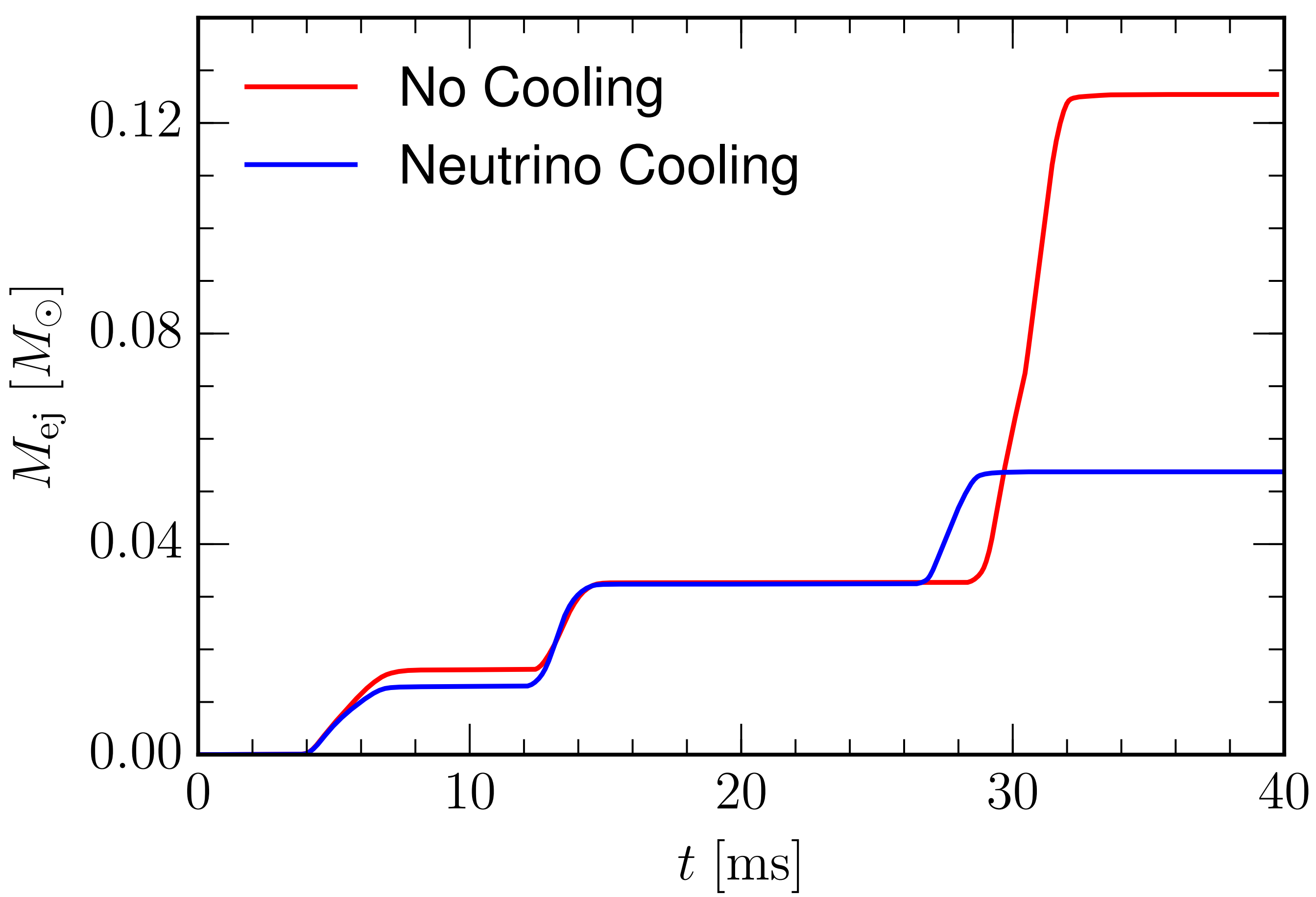
- Dynamical ejecta: r-processes, EM counterparts
- Short gamma-ray bursts progenitor: BH formation, torus evolution, …



$t = 0.000$ [ms]
y [km]
300
200
100
0
−100
−200
−300
x [km]
−300
−200
−100
0
100
200
300
10^{15}
10^{14}
10^{13}
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
ρ [g/cm^3]

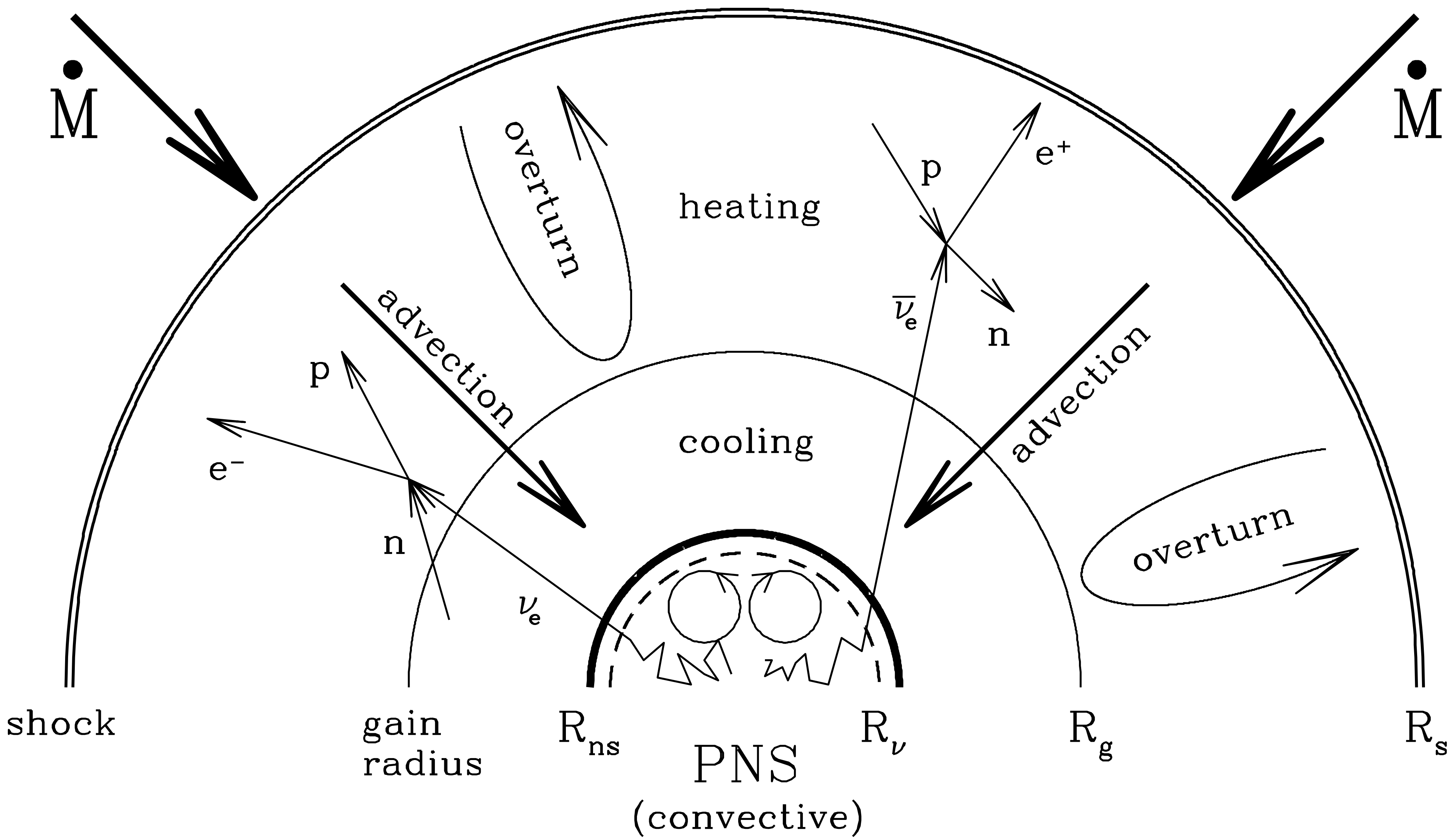
Neutrino Cooling Effects



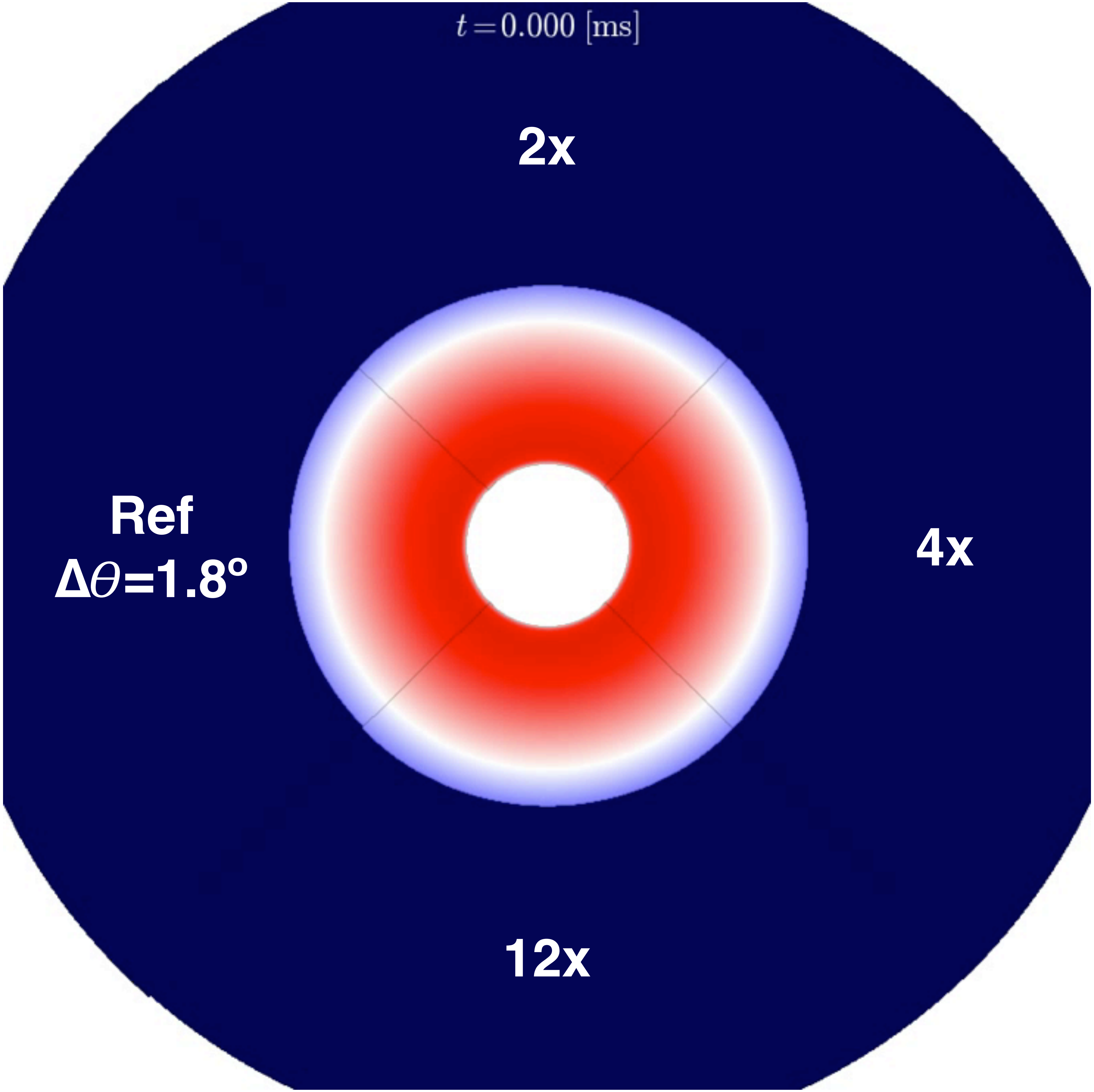


- Anticipates third encounter
- Mass ejected, overall compactness of the system

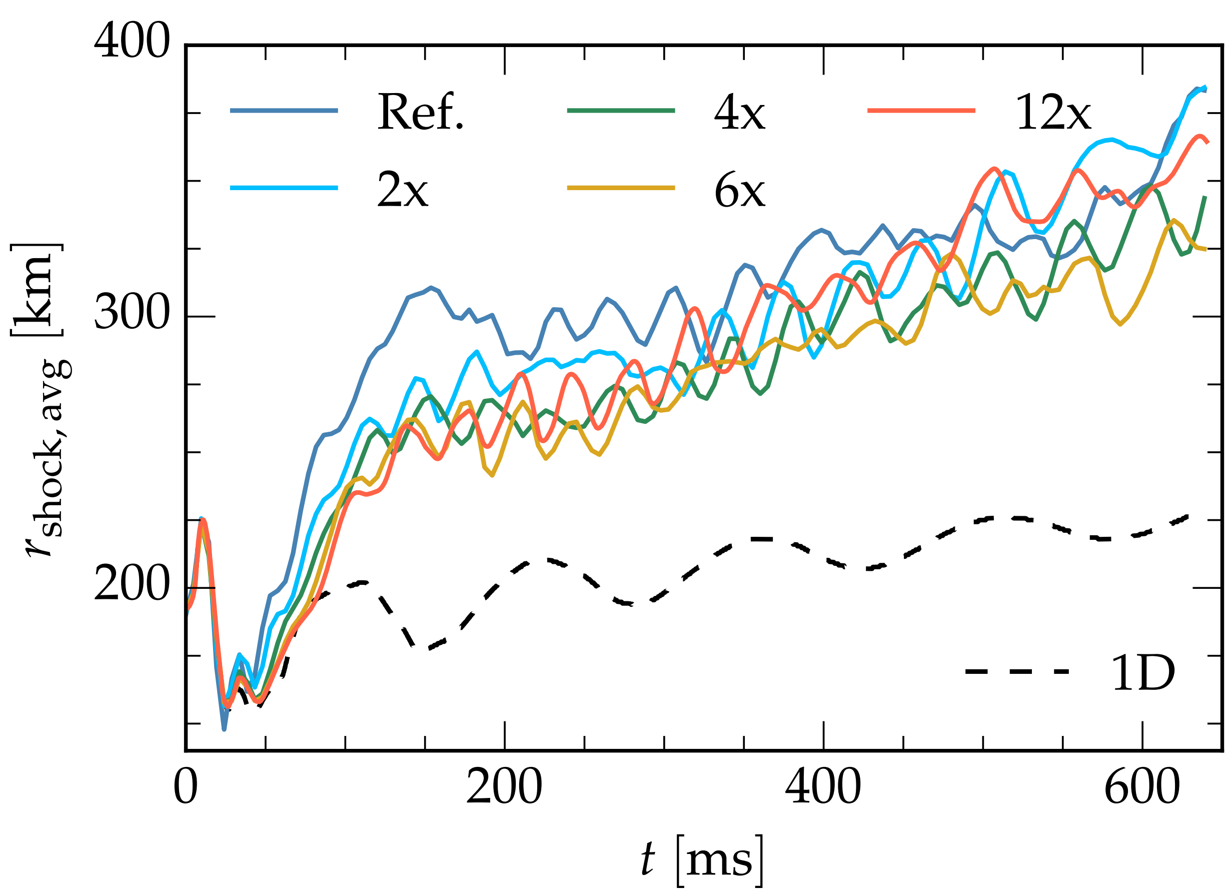
Core-Collapse Supernovae

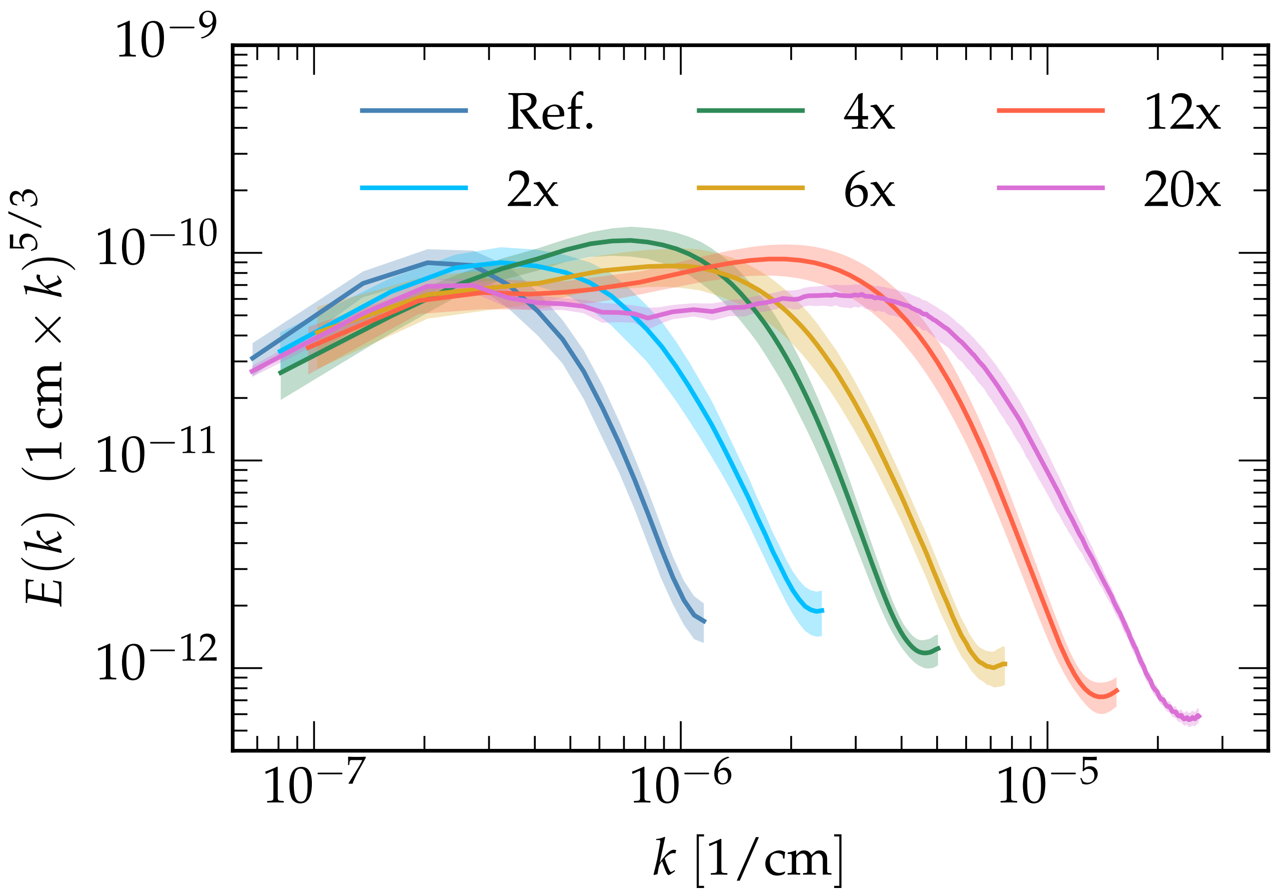


From Janka 2001


$t = 0.000$ [ms]
2x
Ref
$\Delta\theta$=1.8°
4x
12x

Semi-Global Simulation Results





- Global quantities: good “convergence” among resolutions
- Local quantities: inertial range only at prohibitive resolutions

Conclusions

- WhiskyTHC: a modular GRHD code
- Applications: relativistic turbulence, binary neutron star mergers & core-collapse supernovae
- Future work: refluxing, neutrino radiation-transport, GRMHD, DG, …