# Binary Neutron Star simulations using SpEC

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Workshop on Binary Neutron Star Mergers
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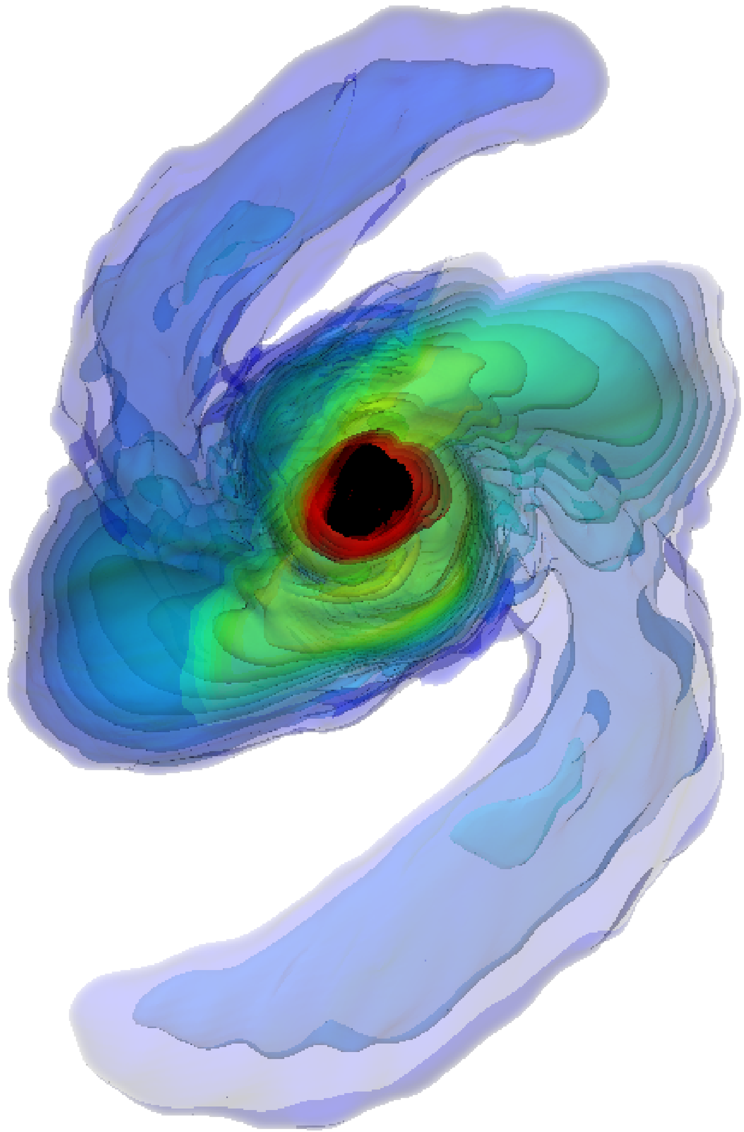
# Binary Neutron Star Mergers

- binary neutron star inspirals among most promising sources of gravitational waves for LIGO
- gravitational wave signal at merger encodes information about the equation of state of neutron star matter
- compact object mergers are possible progenitors for short gamma ray bursts
- outflows are possible sites of r-process nucleosynthesis



# BBH Physics, BNS Physics

### Binary black hole mergers

- mass ratio
- spins

### Binary NS mergers

- mass ratio
- spins
- total mass
- magnetic fields
- equation of state
- neutrino physics
- post-merger disk
- post-merger remnant

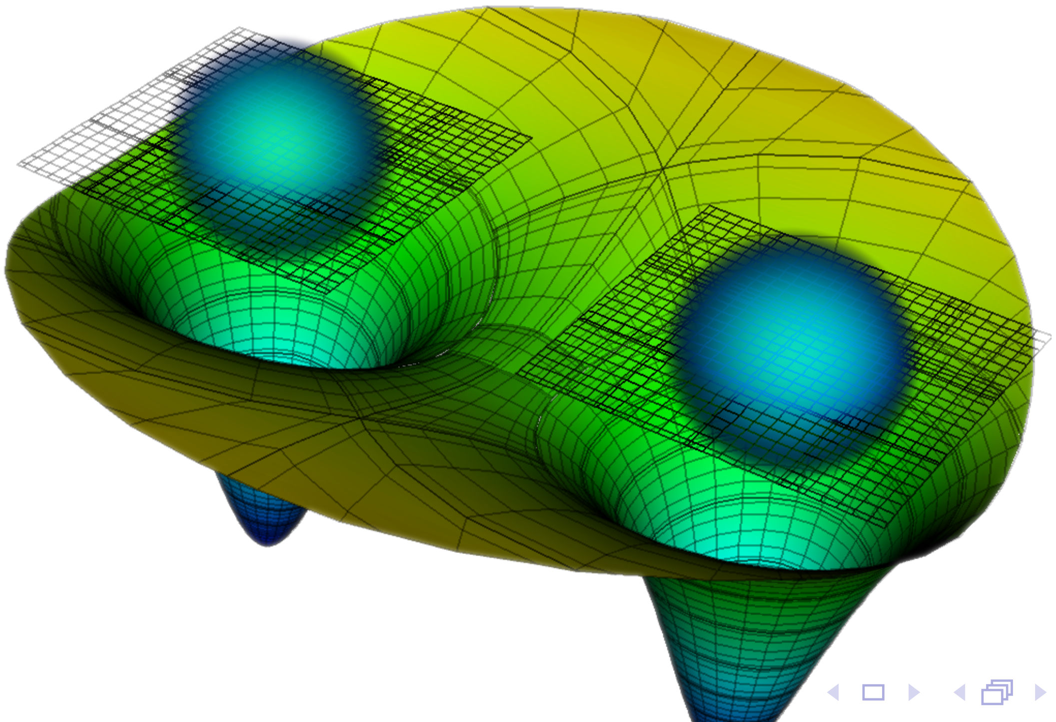
# Hydrodynamics in SpEC

## Spectral domain

- use spectral methods for smooth spacetime evolution
- extents many gravitational wavelenghts into wavezone
- highly efficient

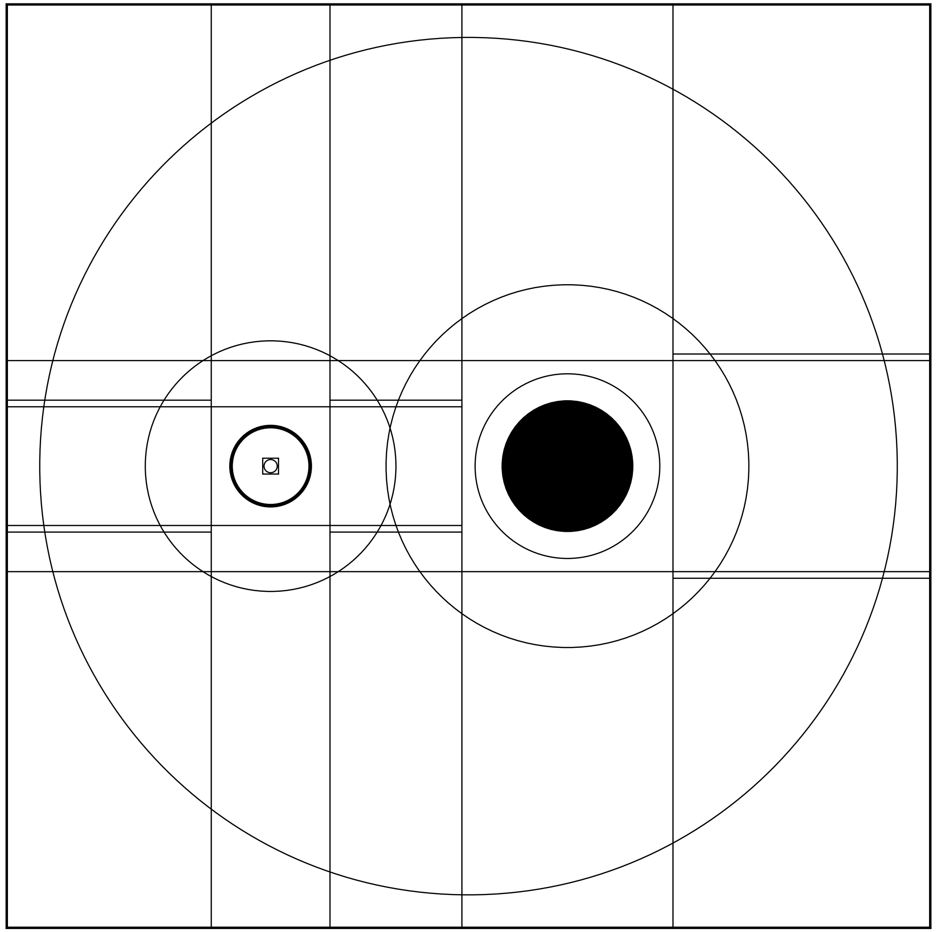
## Finite volume domain

- shock capturing
- coordinate mapping to follow stars and distort grids
- small in-grid velocities
- bulk of CPU time spend here



# Initial data in SpEC

- SpEC contains its own initial data solver Spells
- can produce initial data for BBH, BHNS, NSNS systems
- support multiple EOS eg. from stellarcollapse.org: LS220, SFHo, H-Shen, G-ShenFSU2.1, Hempel-DD2
- support for spinning NS (Tacick et al. in preparation)
- support for near extremal BH (Lovelace et al. CQG 2015)
- eccentricity reduction same as for BBH (Pfeiffer et al. CQG 2007)

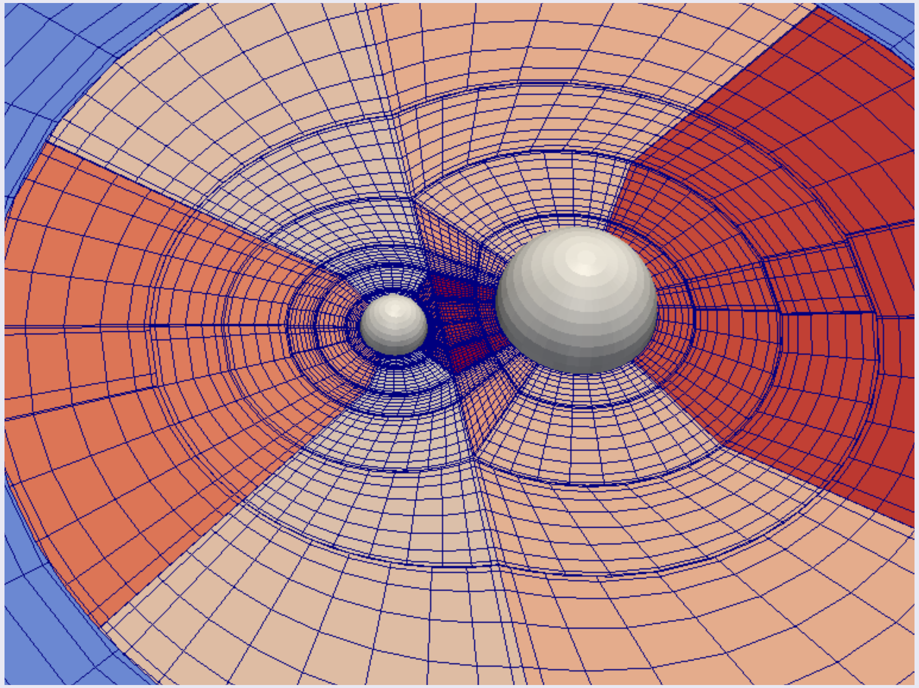


Henrikson et al. PRD 2014

# Mesh refinement in SpEC

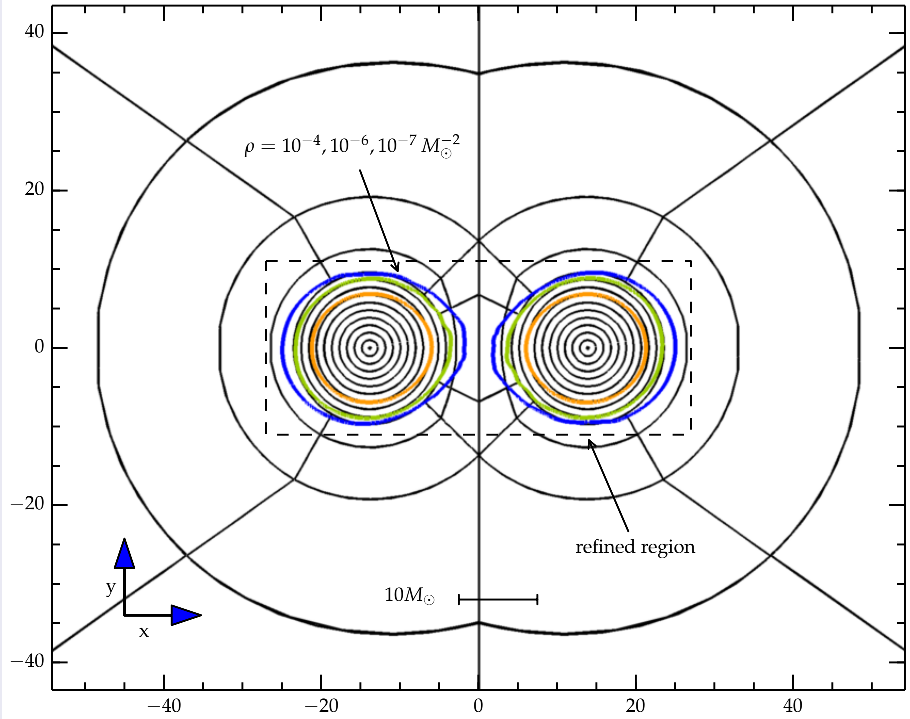
## Spectral domain

- fully h-p adaptive mesh refinement
- measures local truncation error in each grid subdomain
- crucial for BBH plunge phase



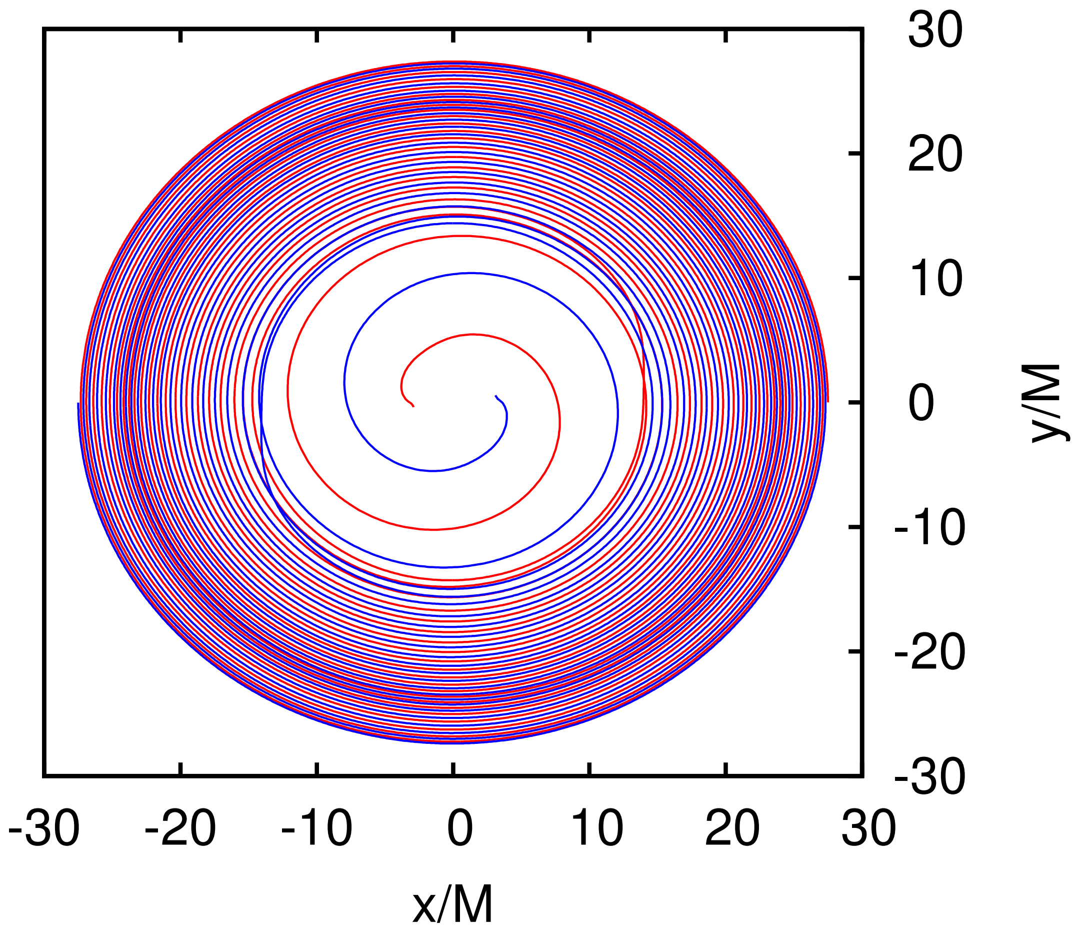
## Finite volume domain

- fixed mesh refinement
- moves with stars
- alternative to non-uniform coordinates to contain disk and outflows

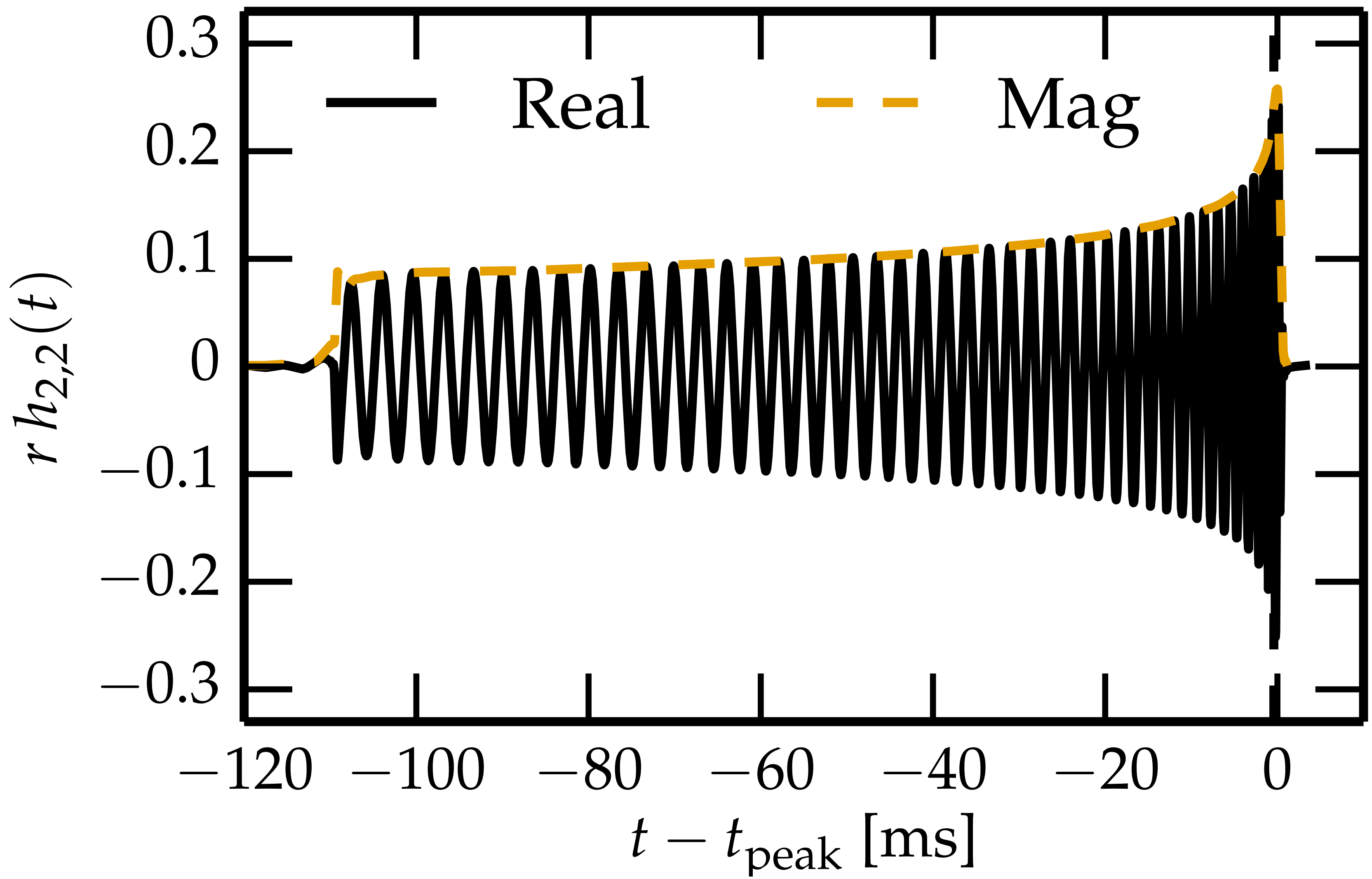


# System parameters

- equal mass neutron stars, $M_b = 1.779\,M_\odot$, $R = 12.2\,\mathrm{km}$, $\mathcal{C} = 0.16$, $\Gamma = 2$
- thin-sandwich, irrotational initial data by Spells
- initial separation $d = 55\,M_\odot$, $81.4\,\mathrm{km}$
- $\gtrsim 20$ orbits to merger
- low initial eccentricity of $\lesssim 10^{-3}$
- inspiral resolution $0.13\,M_\odot$, near merger $0.078\,M_\odot$

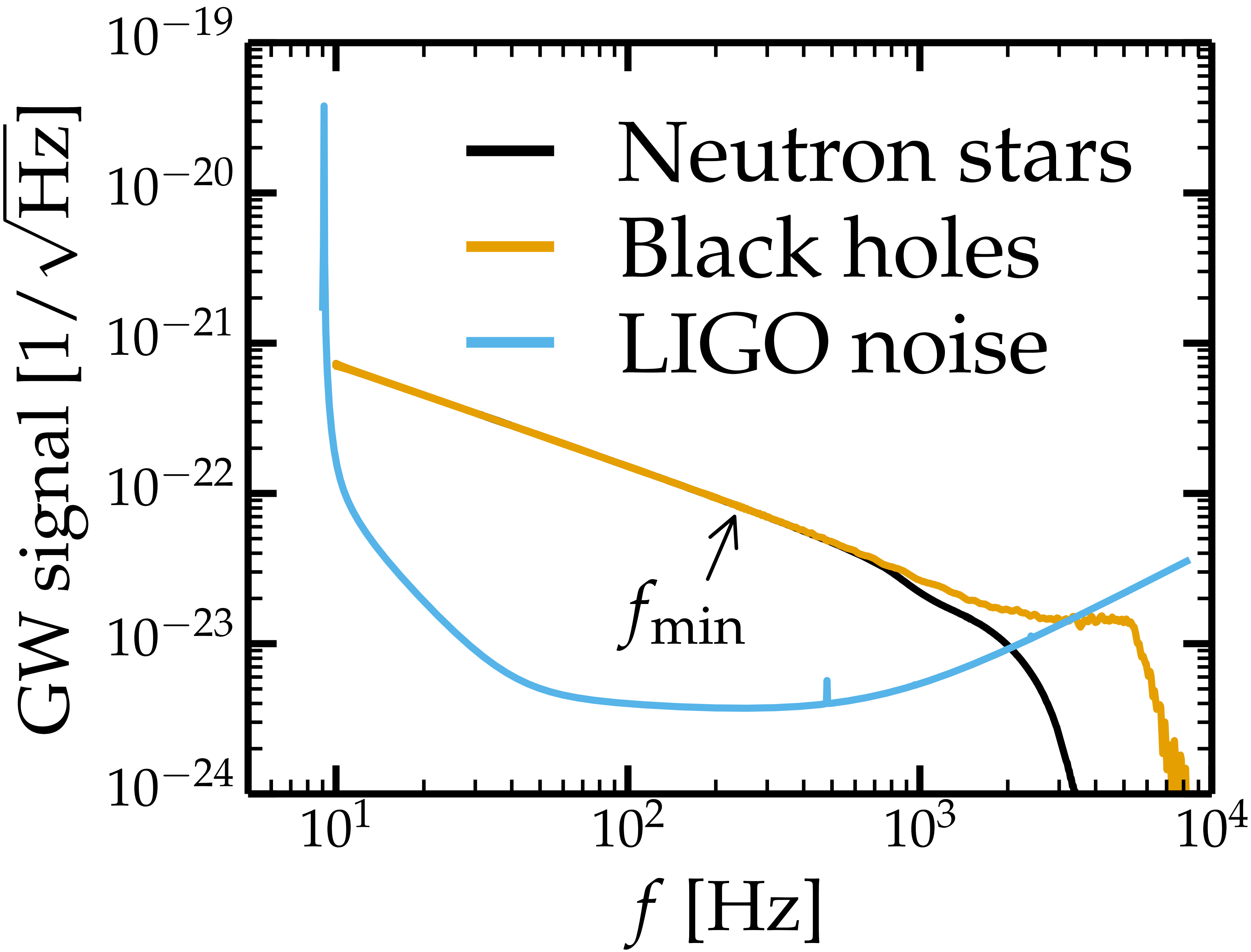


# Gravitational waves during inspiral



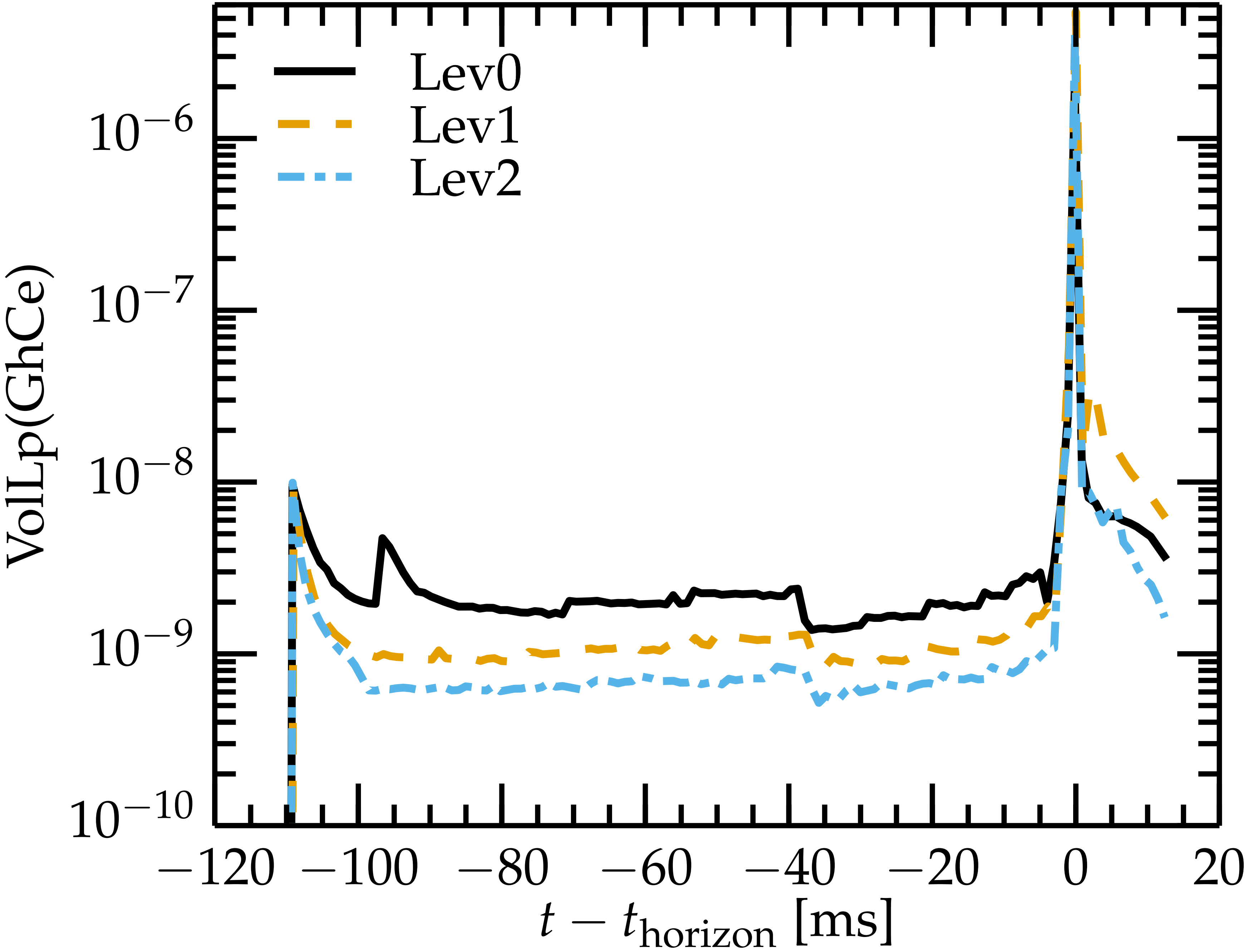

- apparent horizon forms at $t \approx 110\,\text{ms}$
- starting gravitational wave frequency $f_{\text{min}} \approx 280\,\text{Hz}$

# LIGO signal

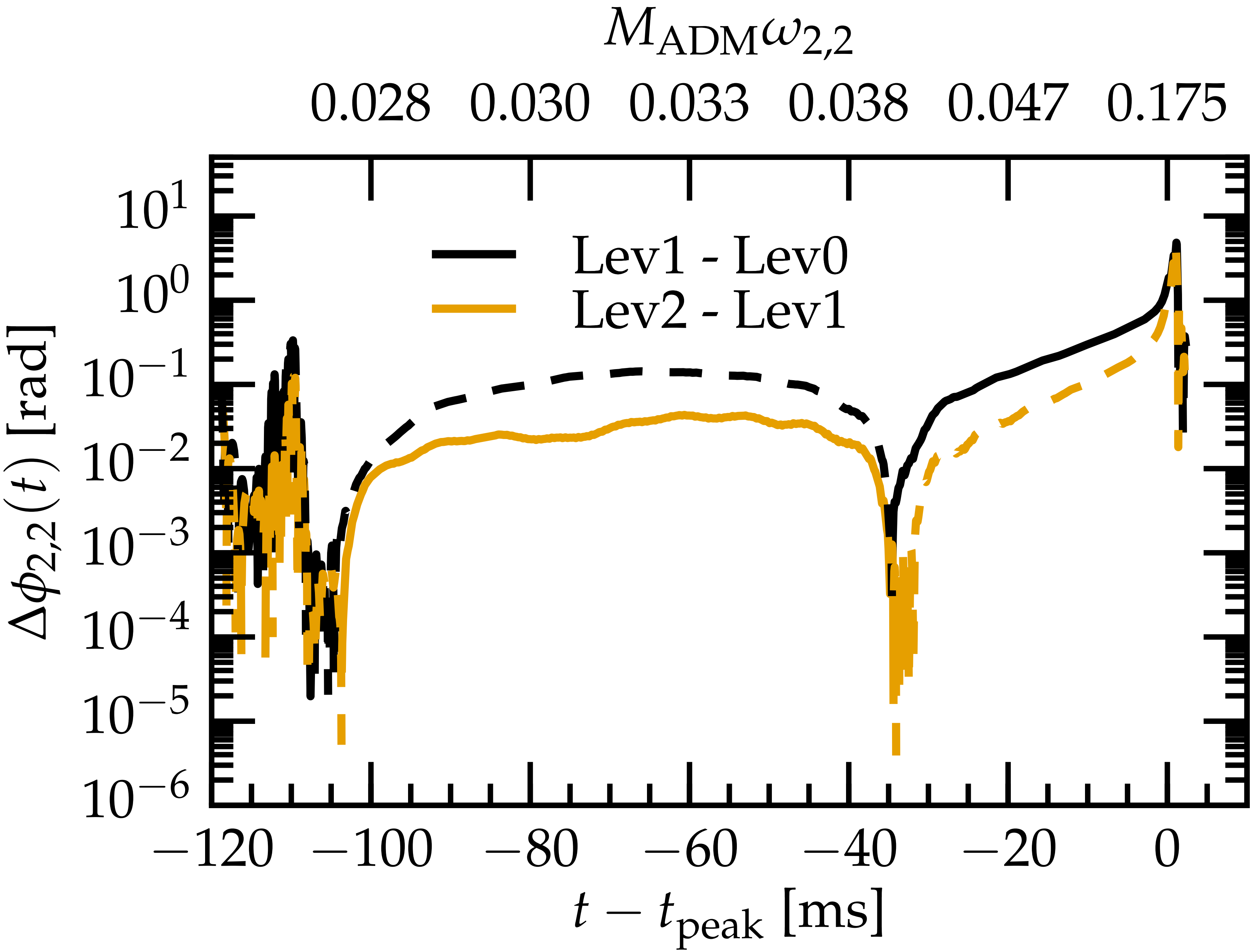


Neutron stars
Black holes
LIGO noise
$f_{\rm min}$
GW signal [1 / $\sqrt{\rm Hz}$]
$10^{-19}$
$10^{-20}$
$10^{-21}$
$10^{-22}$
$10^{-23}$
$10^{-24}$
$10^1$
$10^2$
$10^3$
$10^4$
$f$ [Hz]

# Convergence of constraints



# Convergence of GW phase



# Conclusions

- long NSNS simulations possible
- difficulty in to continue to merger
- assessing numerical errors and convergence complicated by adaptivity
- large initial separation simplifies specifying physical initial data
- coordinate based mesh adaptivity conserves rest mass over long inspiral simulation