Black hole-neutron star mergers with GPU-accelerated codes

Talk by Oliver Steppohn

Collaborators: Sebastiano Bernuzzi, David Radice

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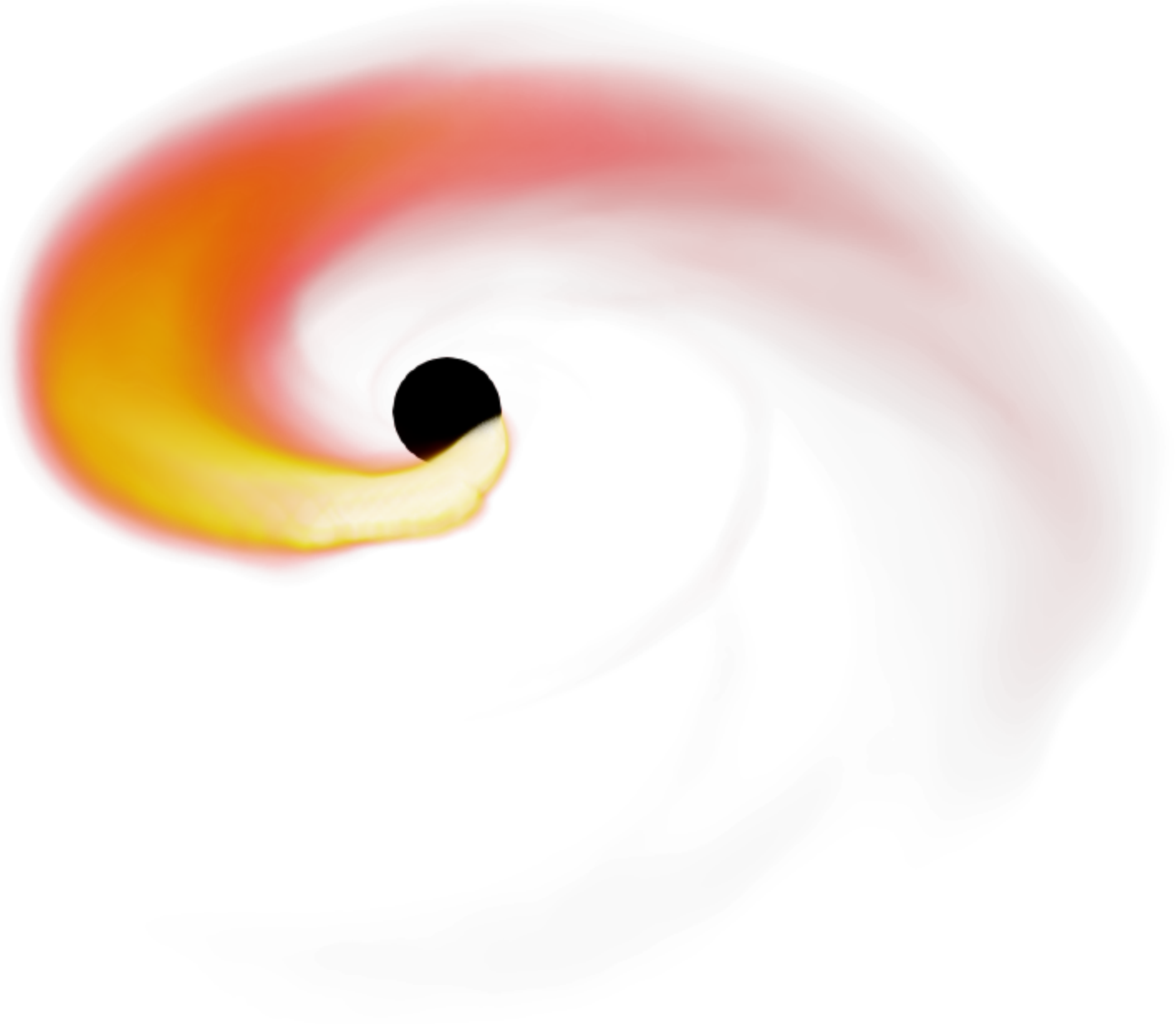

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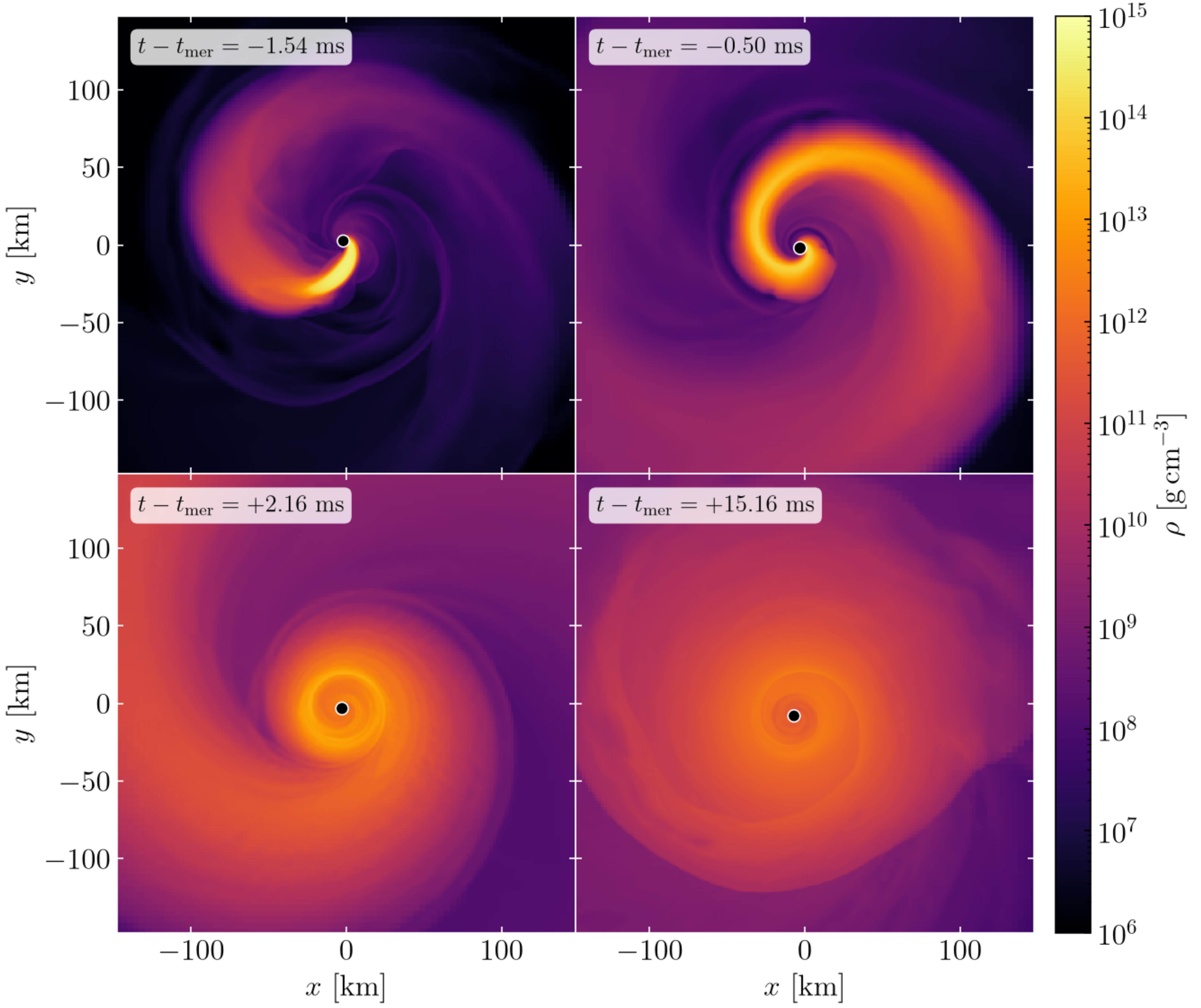
NSF

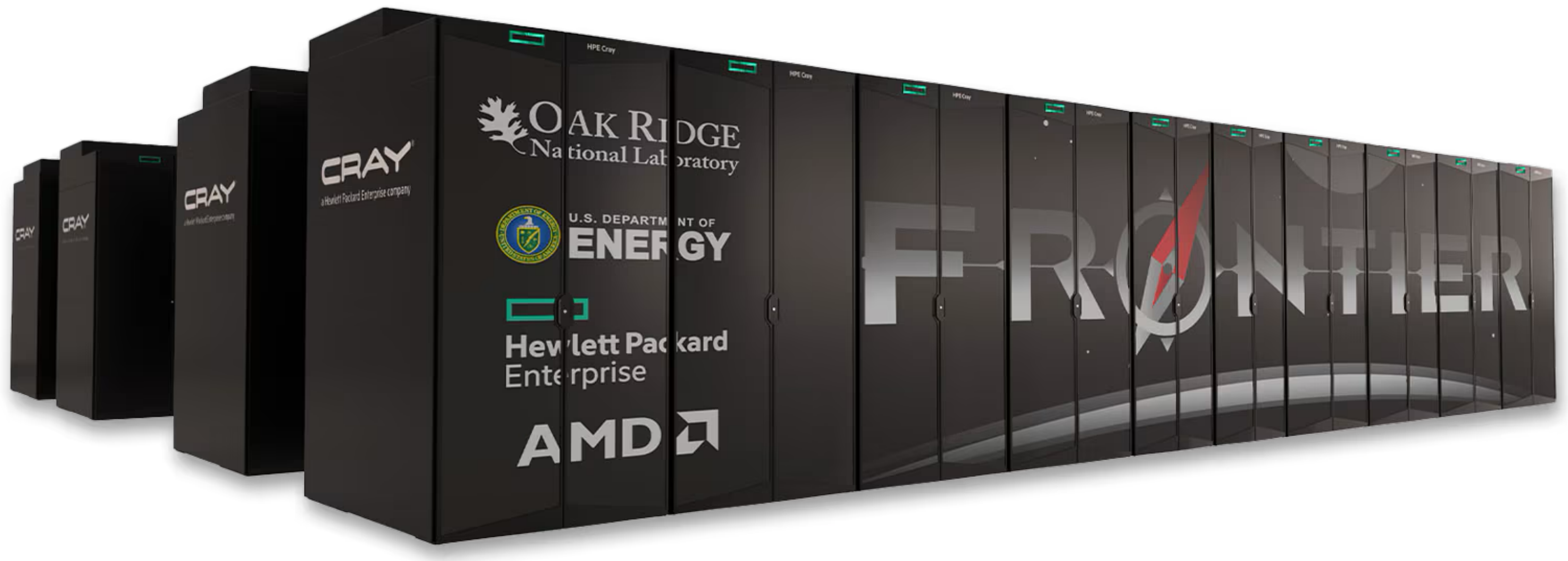
Black hole-neutron star mergers

- Two observations of BHNS without electromagnetic counterpart - GW200105 and GW200115 [Abbott et al. 2021]
- Electromagnetic counterpart predicted by simulations if binary parameters suitable for tidal disruption, i.e. small mass ratio or larger black hole spin
- Disk formation, mass ejection and r-process nucleosynthesis accompany the disruption with high-luminosity kilonovae from radioactively decaying material
- Rapidly spinning remnant surrounded by magnetized disk could power short-hard GRBs



The exascale era

- Majority of scientific supercomputing facilities listed on the Top500 list are equipped with GPU computing nodes (Frontier, Aurora, JUPITER, …)
- **Challenge:** need for performance scalability of legacy codes or development of new GPU-accelerated codes
- **Opportunity:** complex problems can be solved faster, more efficient and in larger quantities
- Usage of performance portable ecosystems such as Kokkos* can make heterogeneous integration of scientific codes on various architectures simpler



Europe

EuroHPC Joint Undertaking

Finnland: LUMI

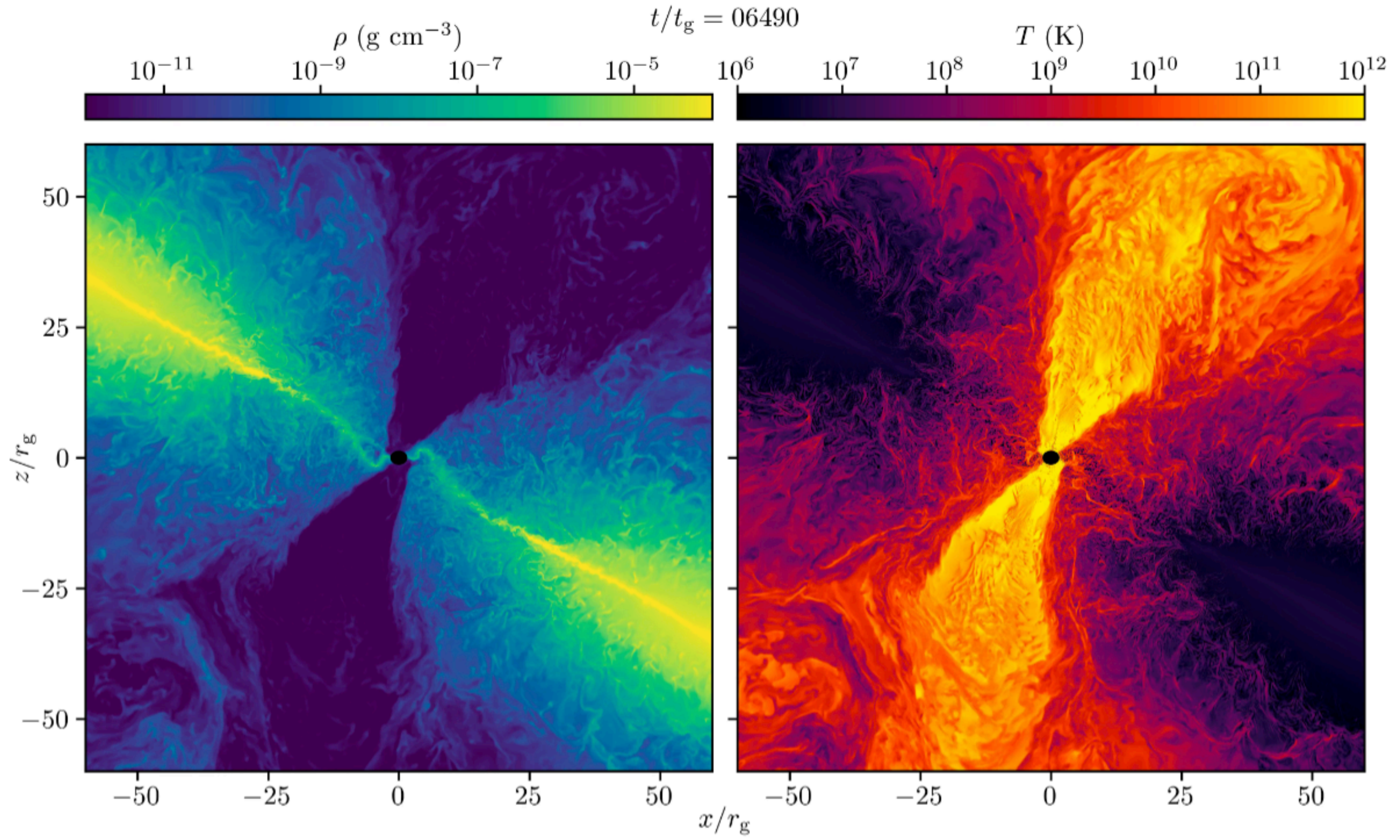
Germany: JUPITER

Italy: LEONARDO CINECA

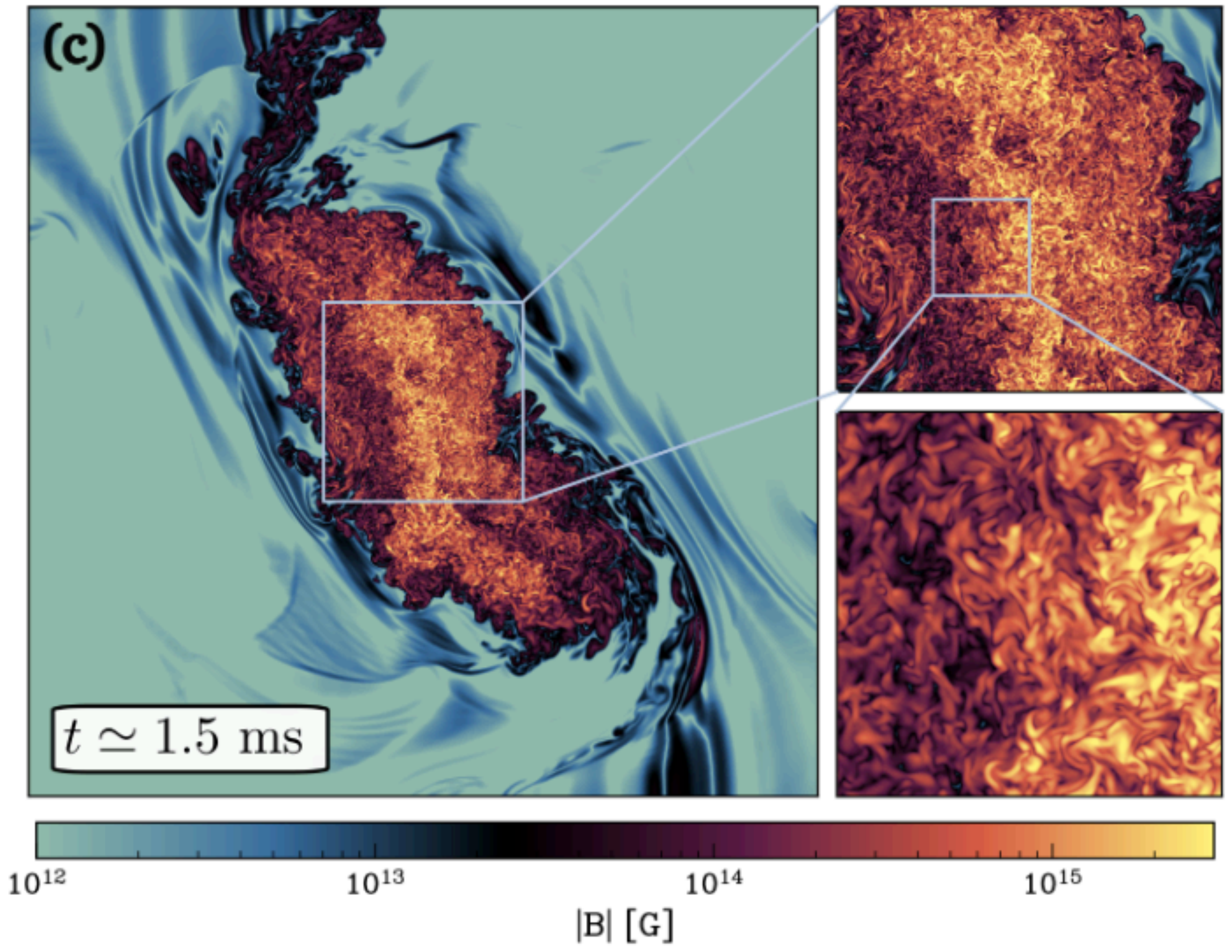
*https://kokkos.org/

AthenaK

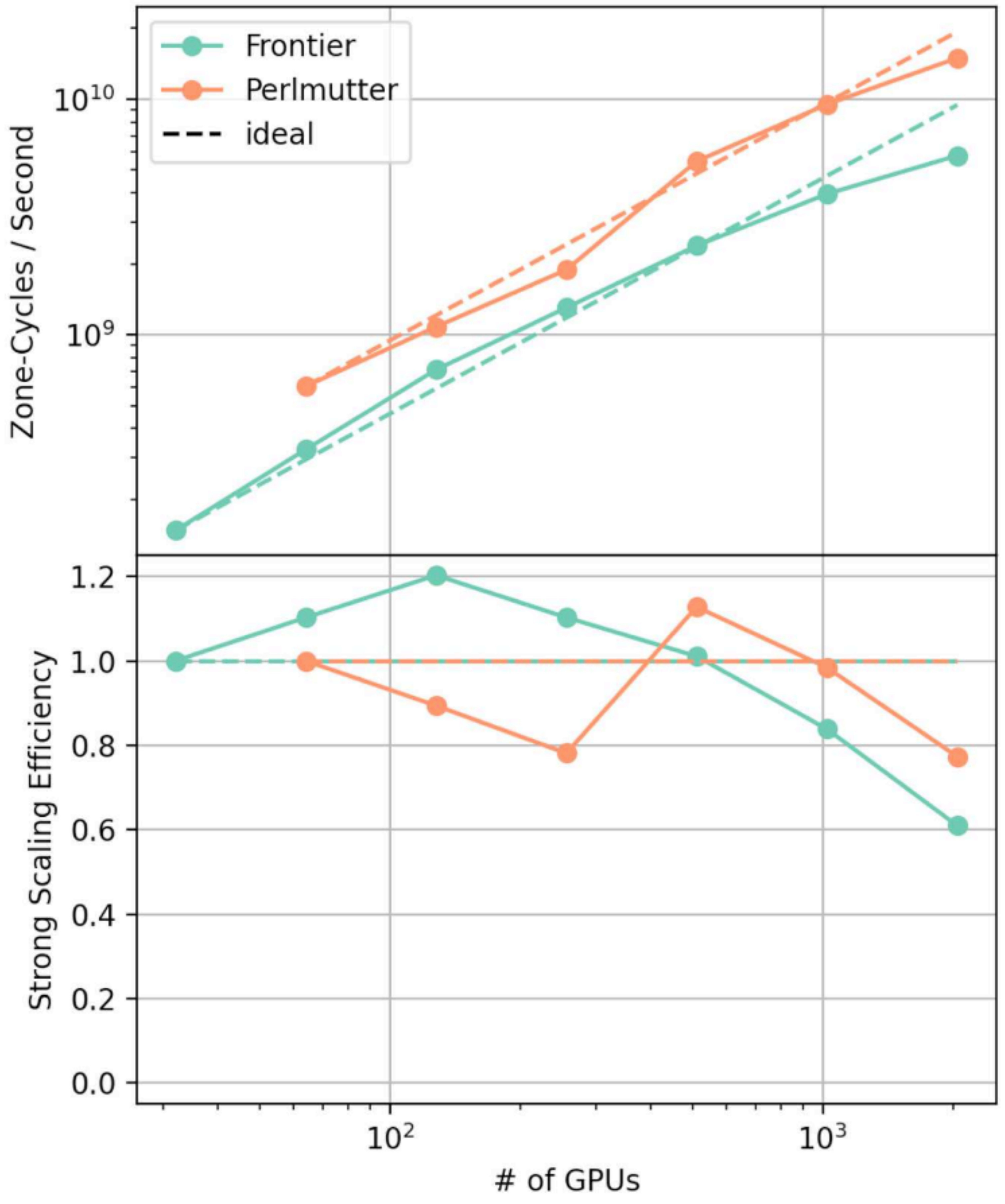
- Rewrite of Athena++ block-based AMR framework interfacing Kokkos for performance portability on heterogeneous architectures [Stone et al. 2024]
- Z4c numerical relativity module for binary black hole evolutions [Zhu et al. 2024]
- GRMHD extension with first-order flux correction [Fields et al. 2024]
- Applications: neutron star mergers, turbulence, accretion disks etc.



Taken from [Stone et al. 2024]



Adapted from [Gutiérrez et al. 2026]



Taken from [Zhu et al. 2024]

Setup

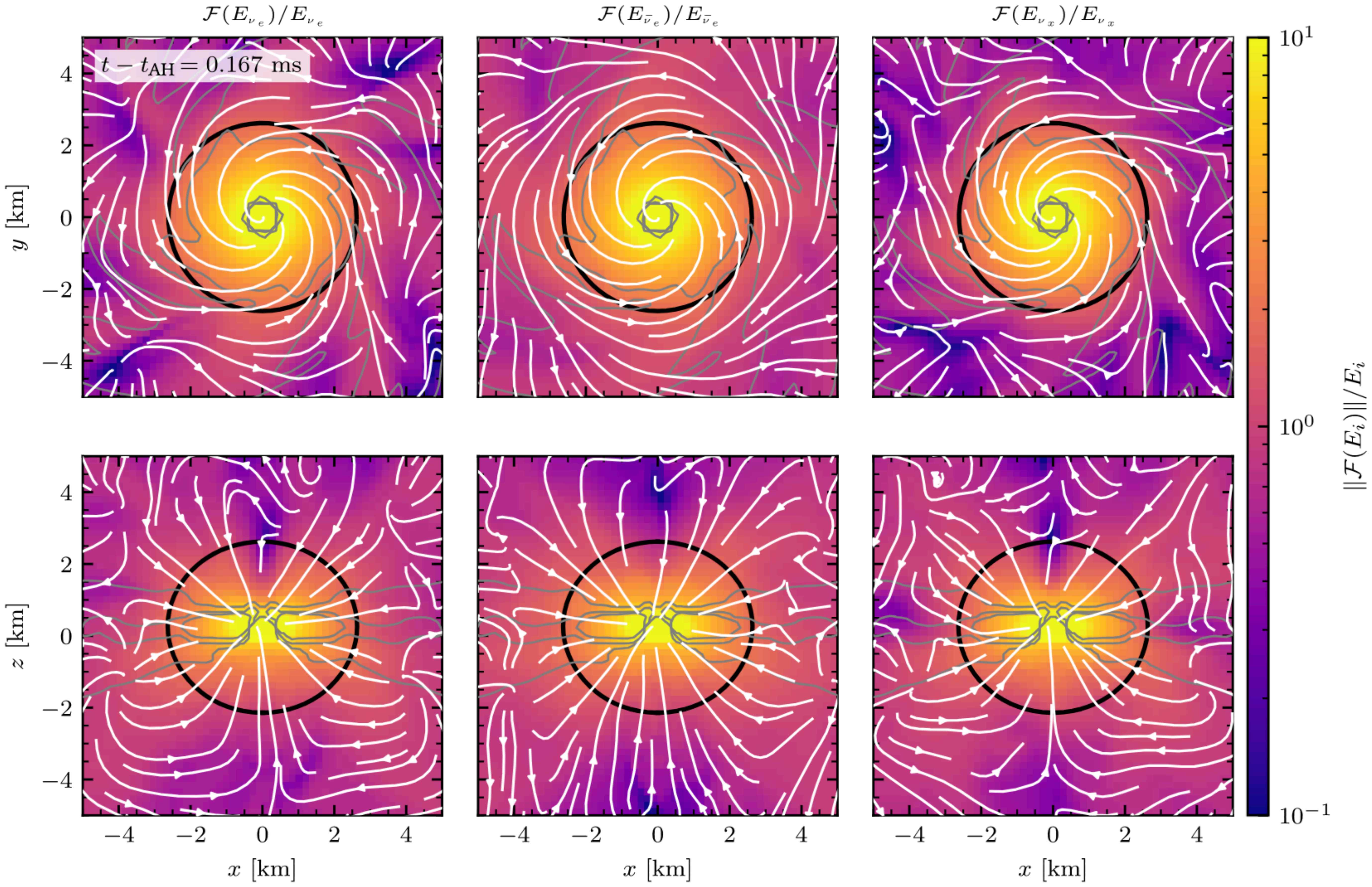
Verification: black hole-neutron star evolutions up to 100ms with/without magnetic fields and full microphysics

Initial data

- BHNS with $q \simeq 3.3$ and $\chi_{\rm BH} = 0.75$ using $\rm Elliptica$ [Rashti et al. 2022]
- Internal dipole magnetic field with $B_{\rm max} = 3e15G$
- Lowest resolution: 360m (currently ongoing 240m)

Black hole treatment

- Fastflow horizon finder [Gundlach 1998]
- Smooth excision formulation similar to [Daszuta et al. 2026]



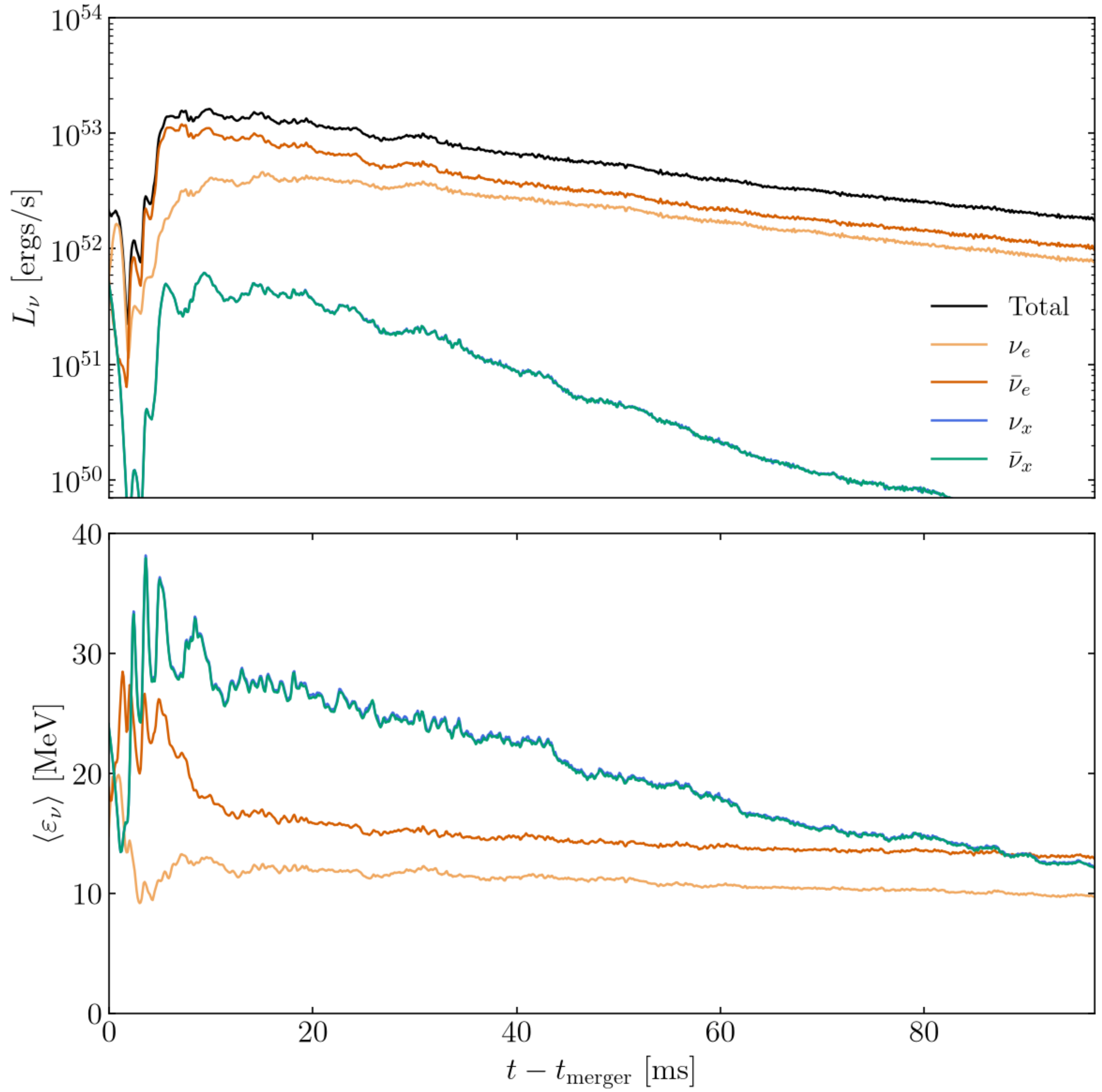
Taken from [Daszuta et al. 2026]

Setup

Verification: black hole-neutron star evolutions up to 100ms with/without magnetic fields and full microphysics

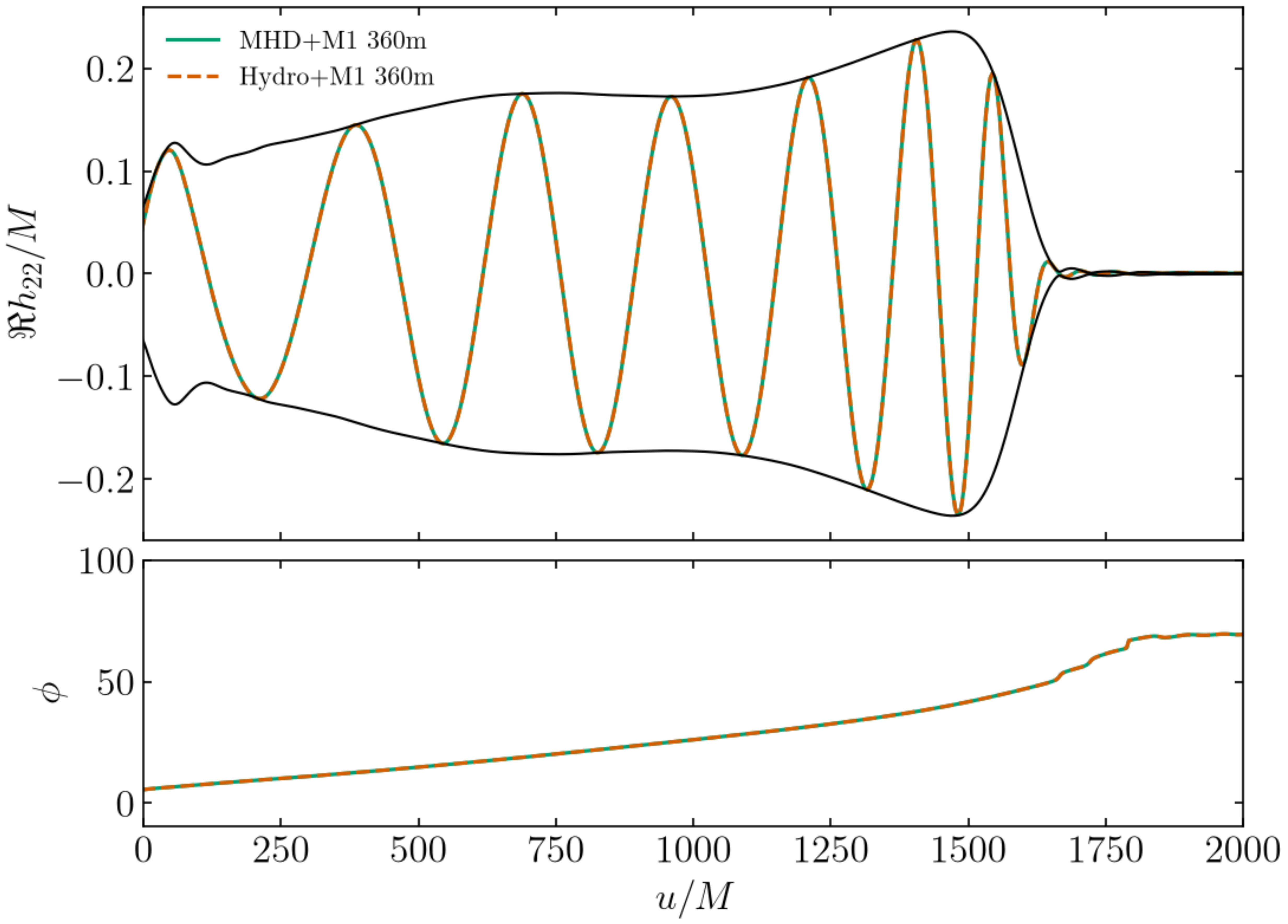
Neutrino treatment

- M1 implementation from THC [Radice et al. 2022]
- Online opacity calculation with BNSNurates library [Chiesa et al. 2024]
- Reactions: β-processes, $e^- - e^+$ annihilation, nucleon-nucleon bremsstrahlung, isoenergetic scattering off nucleons, (inelastic scattering off e^- and e^+)
- Equilibrium distribution function with corrections in optically thin limit

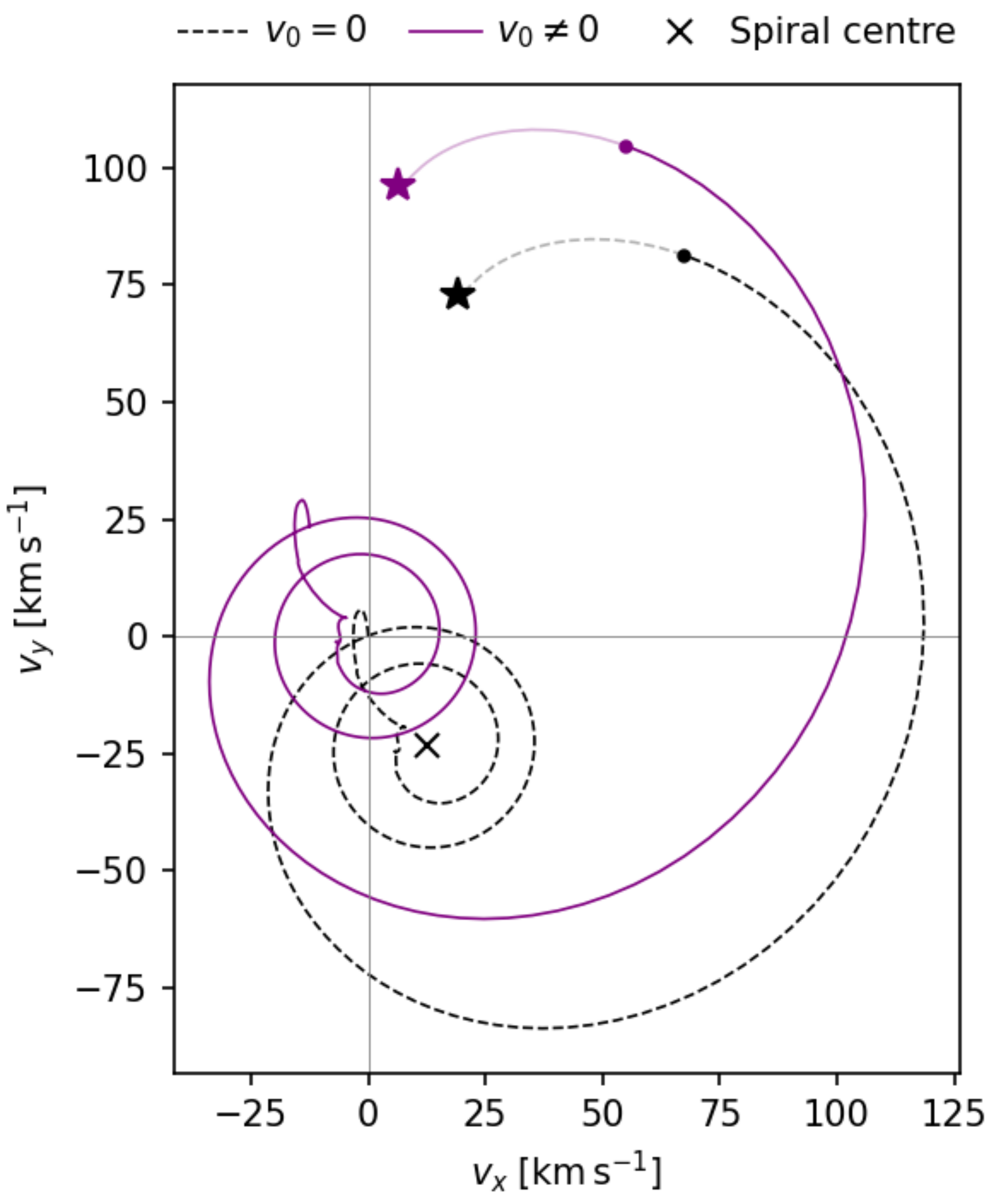


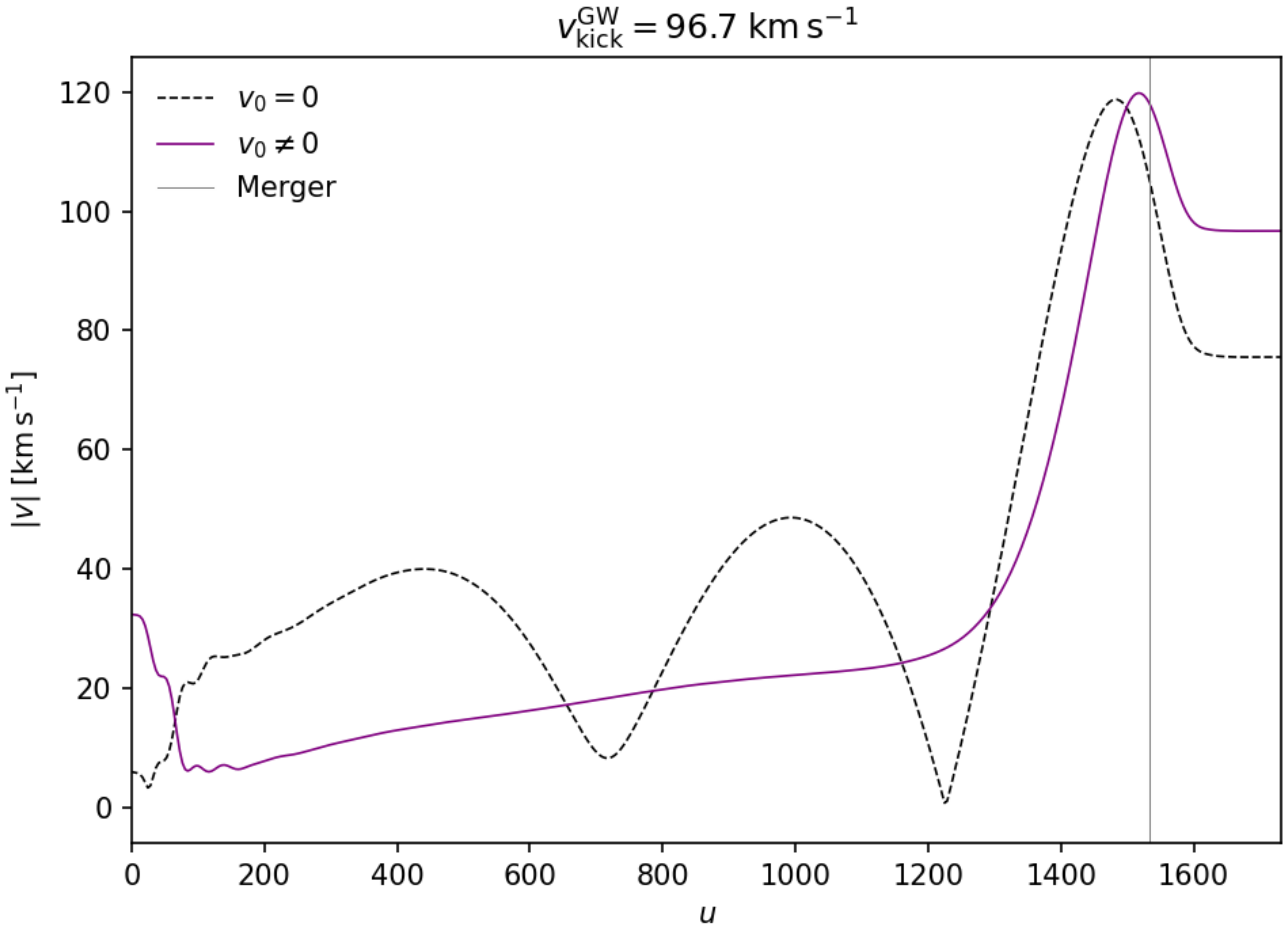
Waveforms

- Newman-Penrose gravitational wave extraction at r = 400 code units
- Residual eccentricity from the phenomenological fits of [Dietrich et al. 2015] around 0.0392
- Good agreement with waveform catalogs
- Black hole kick due to gravitational waves estimated at about 100 km/s with method of [Gonzalez et al. 2025]
- Ringdown is suppressed in this configuration



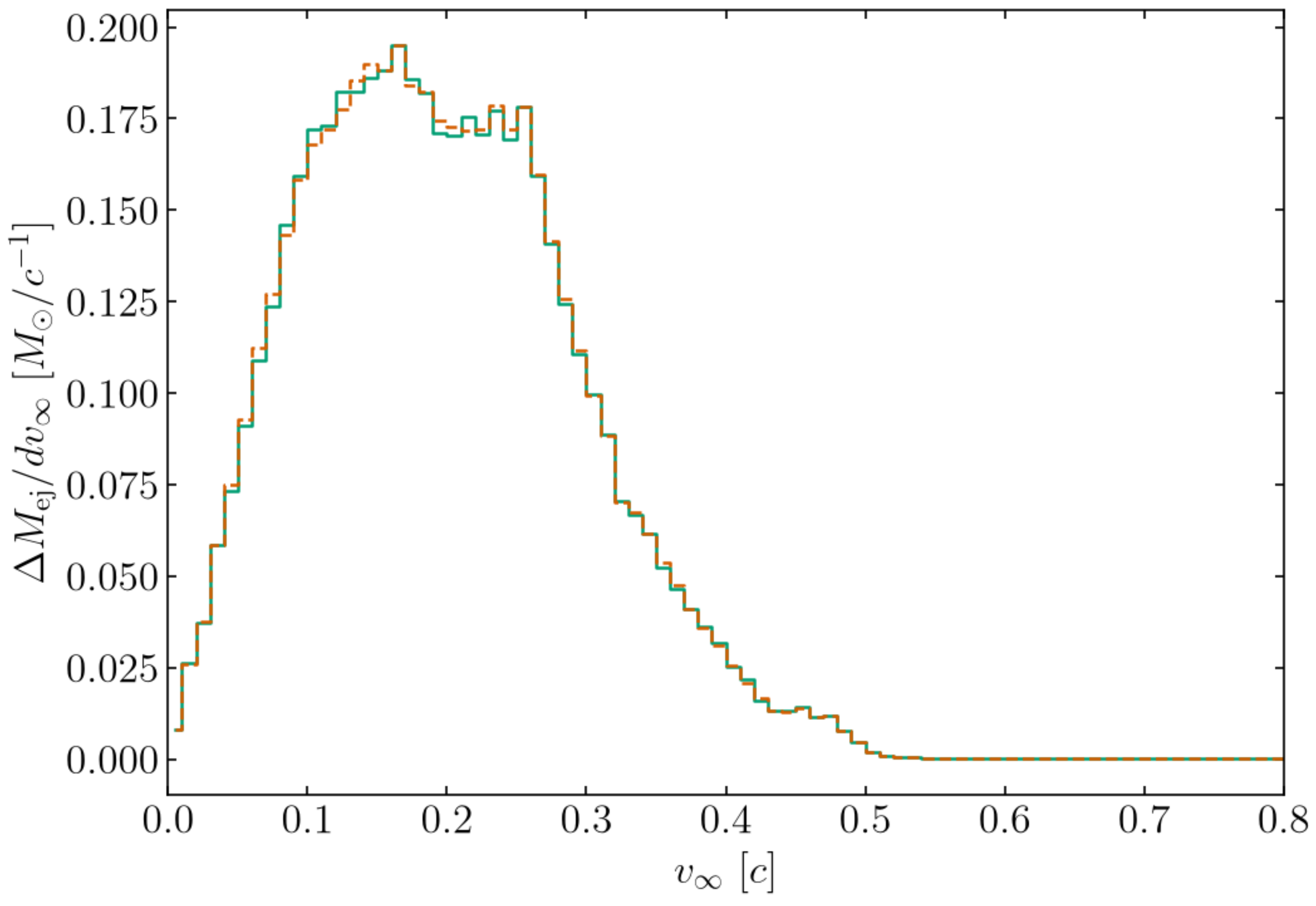
Black hole kick

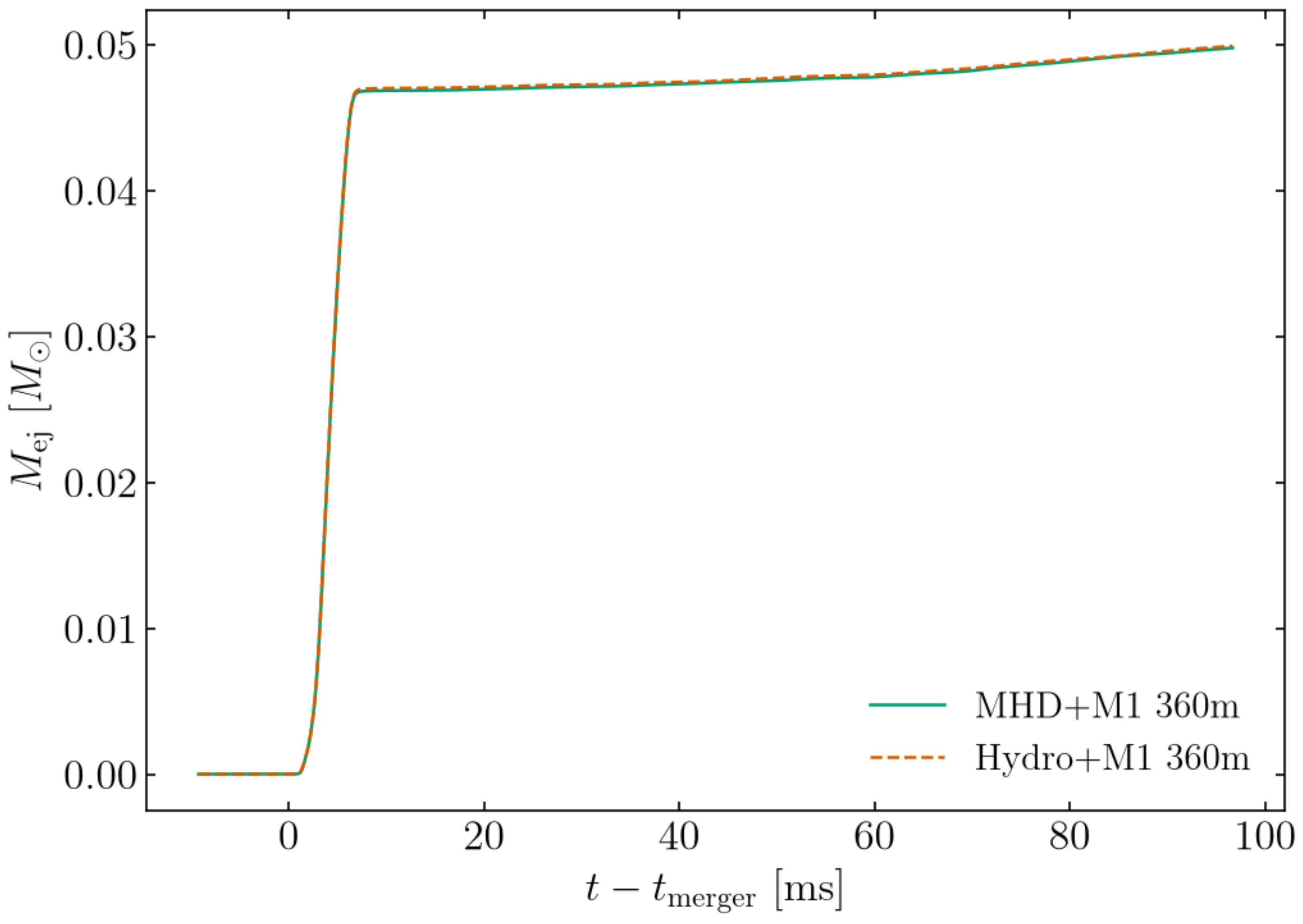


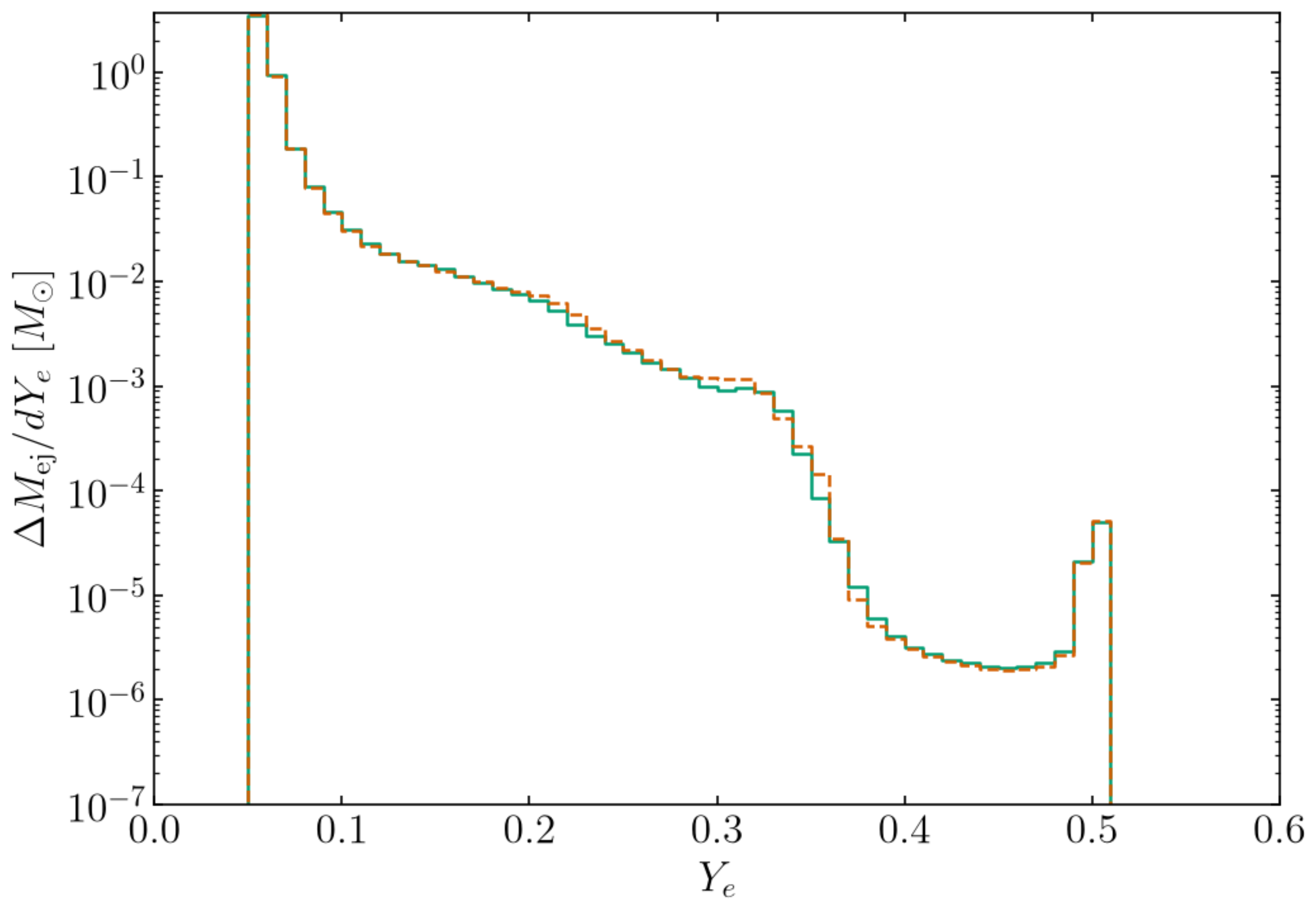


Ejecta

- MRI at this resolution unresolved - no effects on the outflow properties
- Longer timescales required to see a difference
- Benchmark of expected results
- Black hole kick due to ejecta estimated between 200 - 300 km/s using the ejecta mass/velocity - larger than the kick from GW (as expected from the literature)



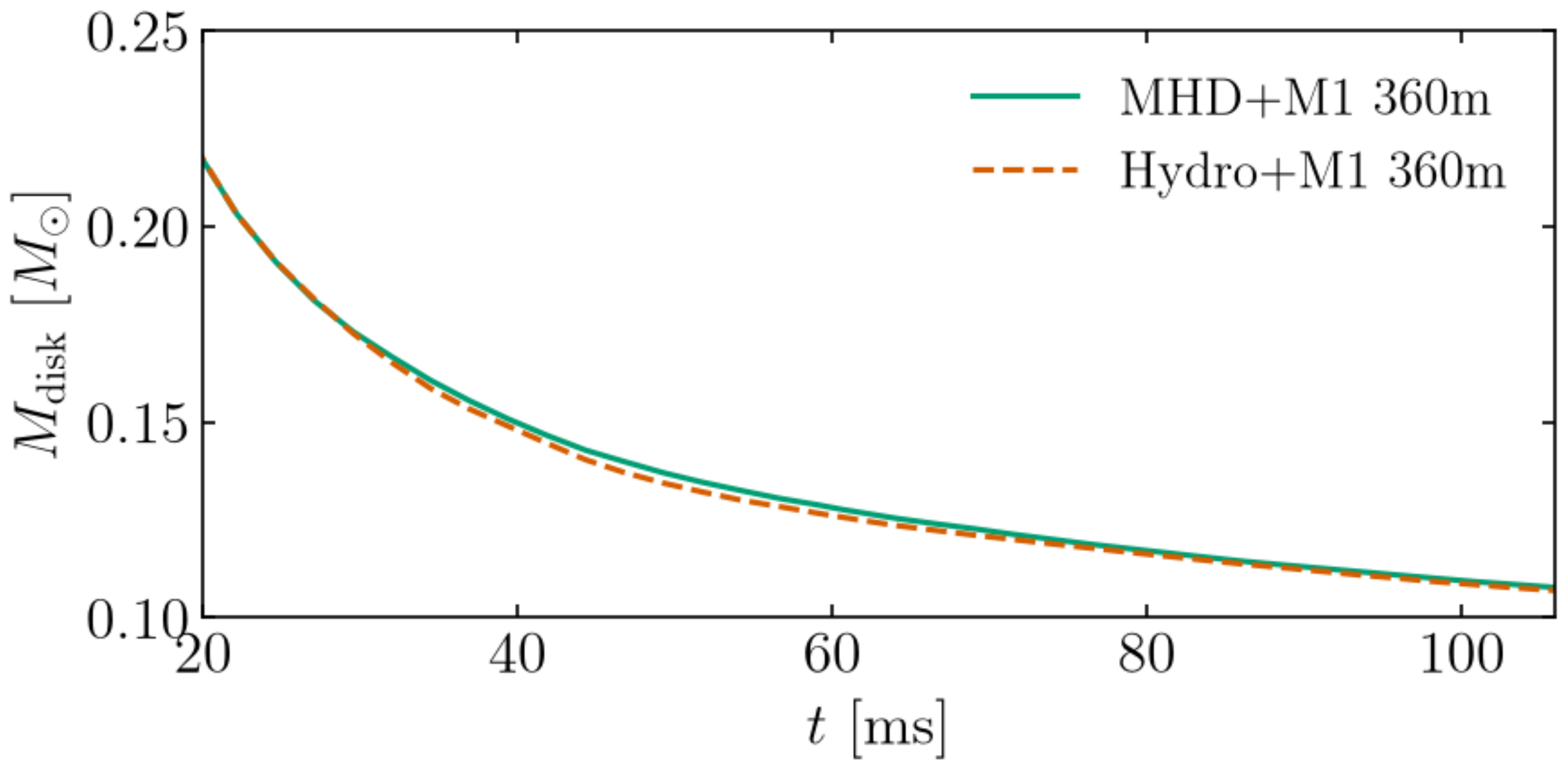


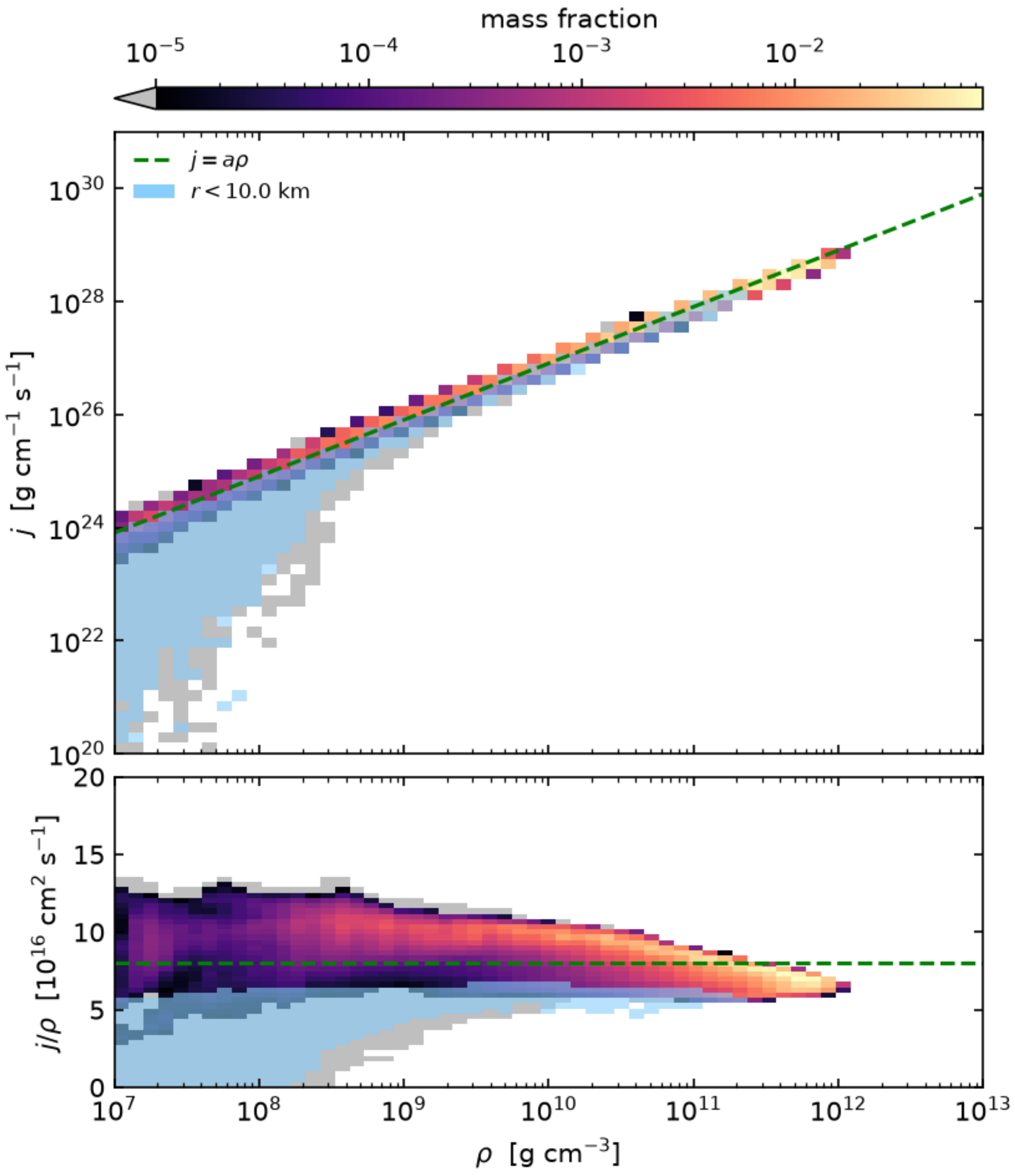


Disk

- Disks follow the linear trend between angular momentum density and rest-mass density [Camilletti et al. 2024]

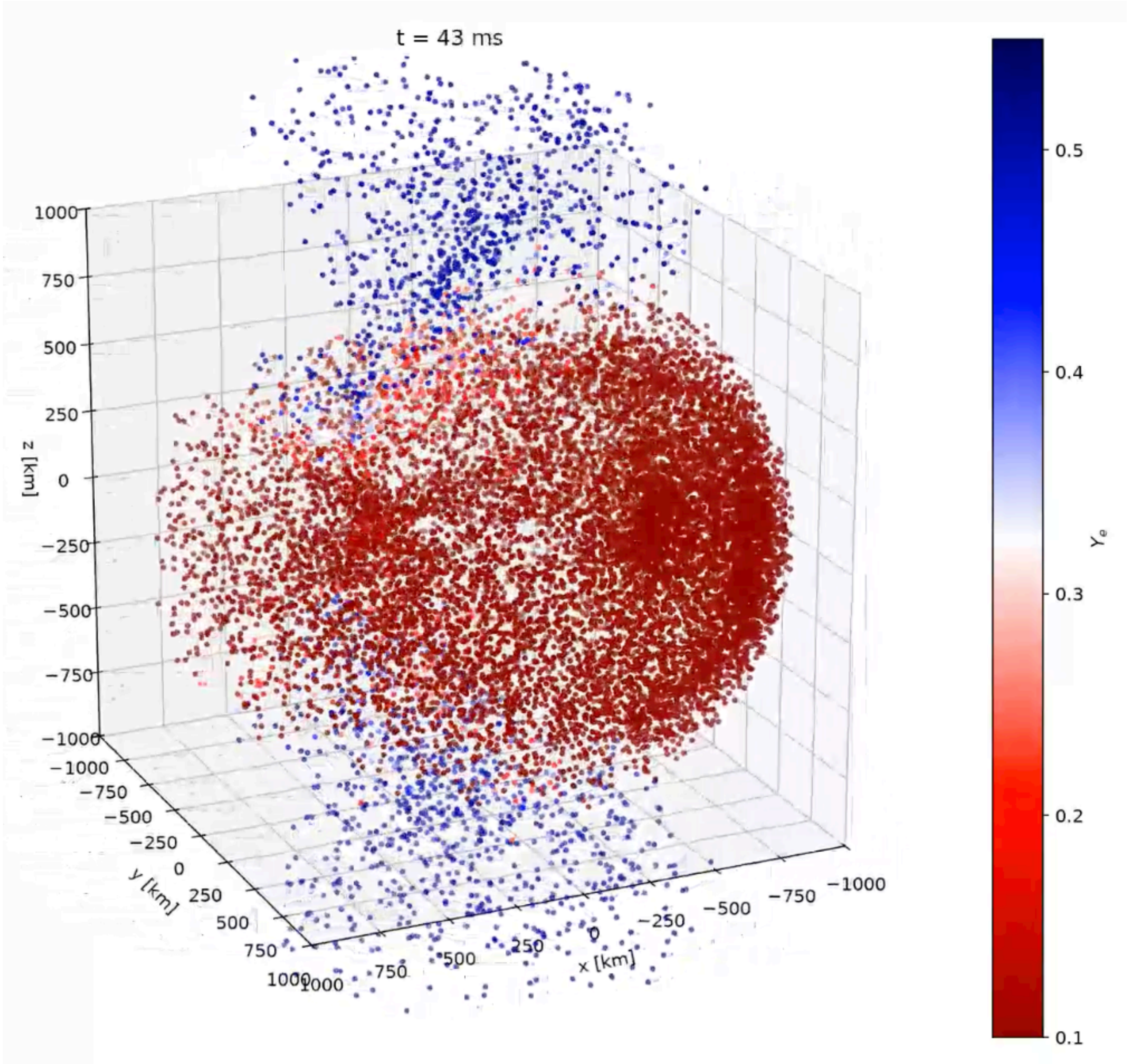
- Slope is a factor of ~2 higher than for BNS disks

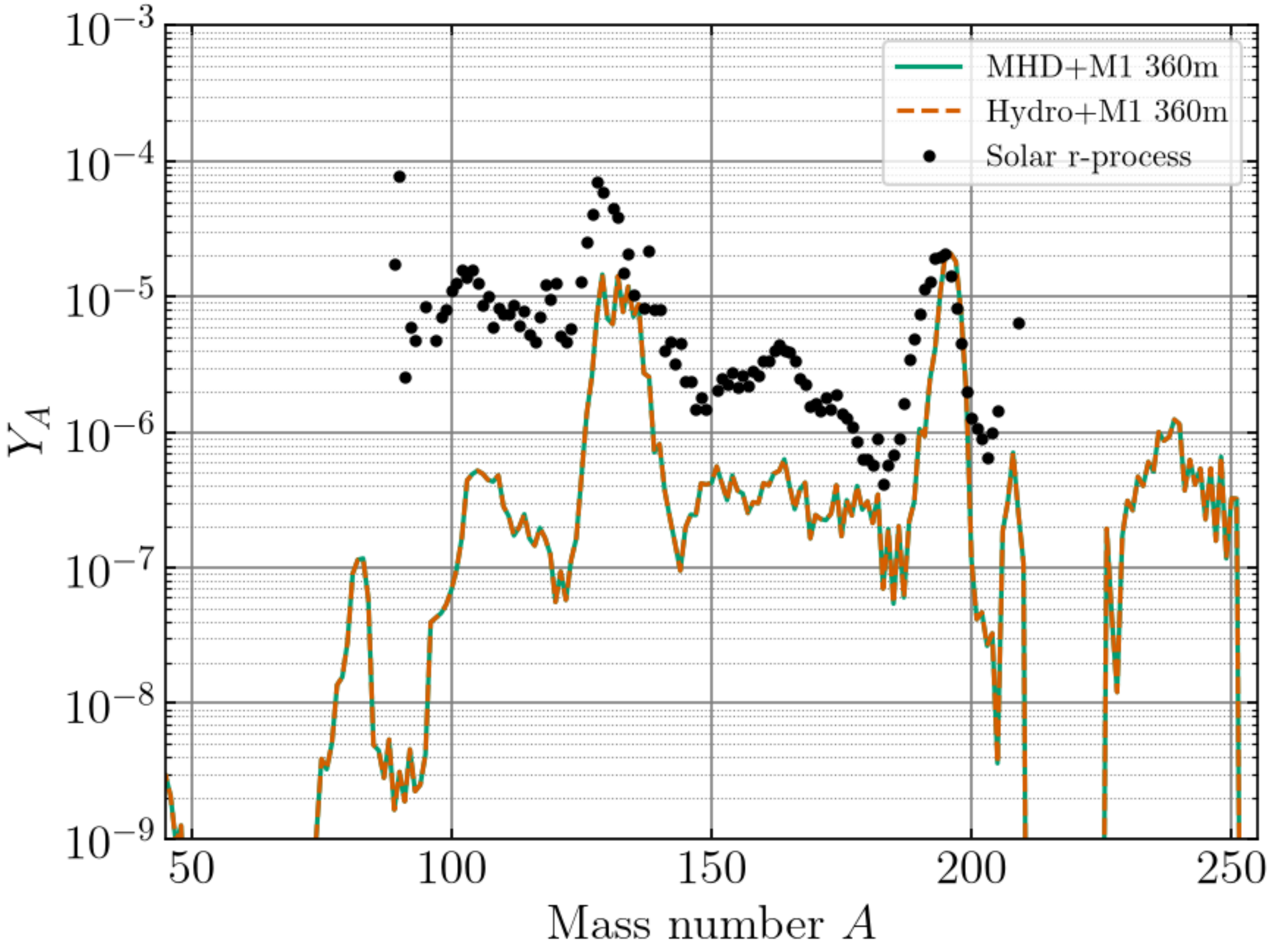




Nucleosynthesis

- Nucleosynthesis yields following [Camilletti et al. 2022] under assumption of homologous expansion
- Tracer particles for more accurate trajectories





Conclusions

Performance

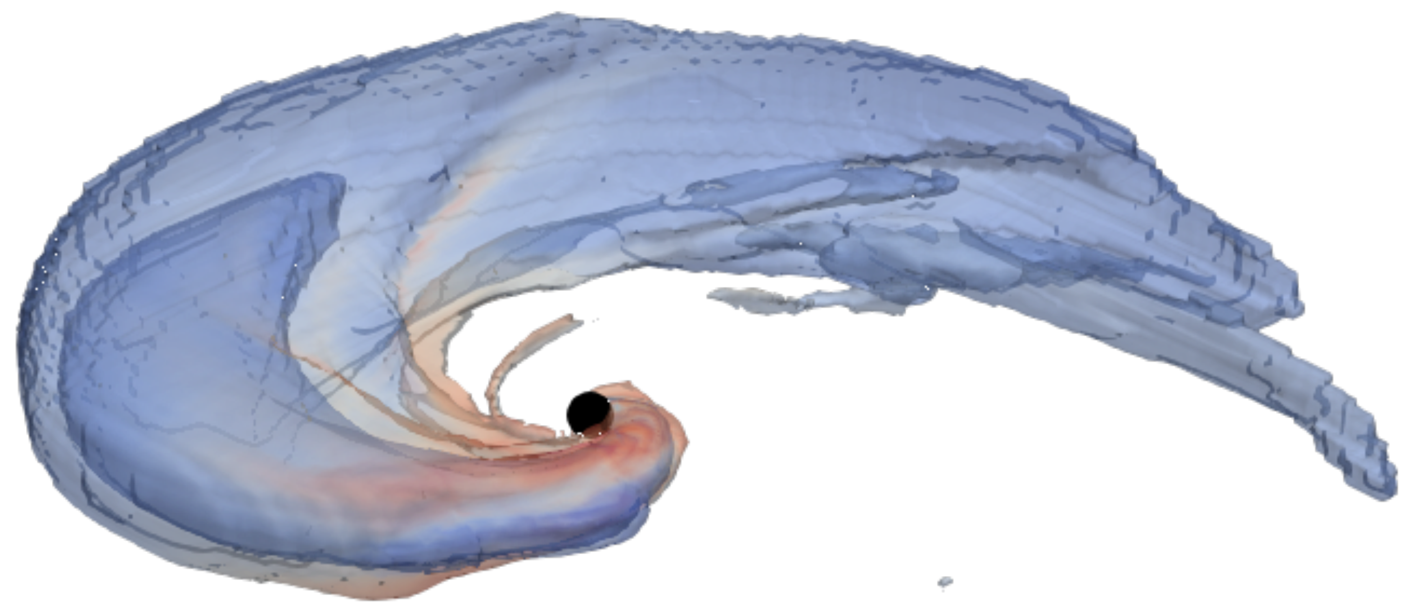
LEONARDO: 360m with MHD+M1 up to 100ms on 48 GPUs — **~ 48 hours**

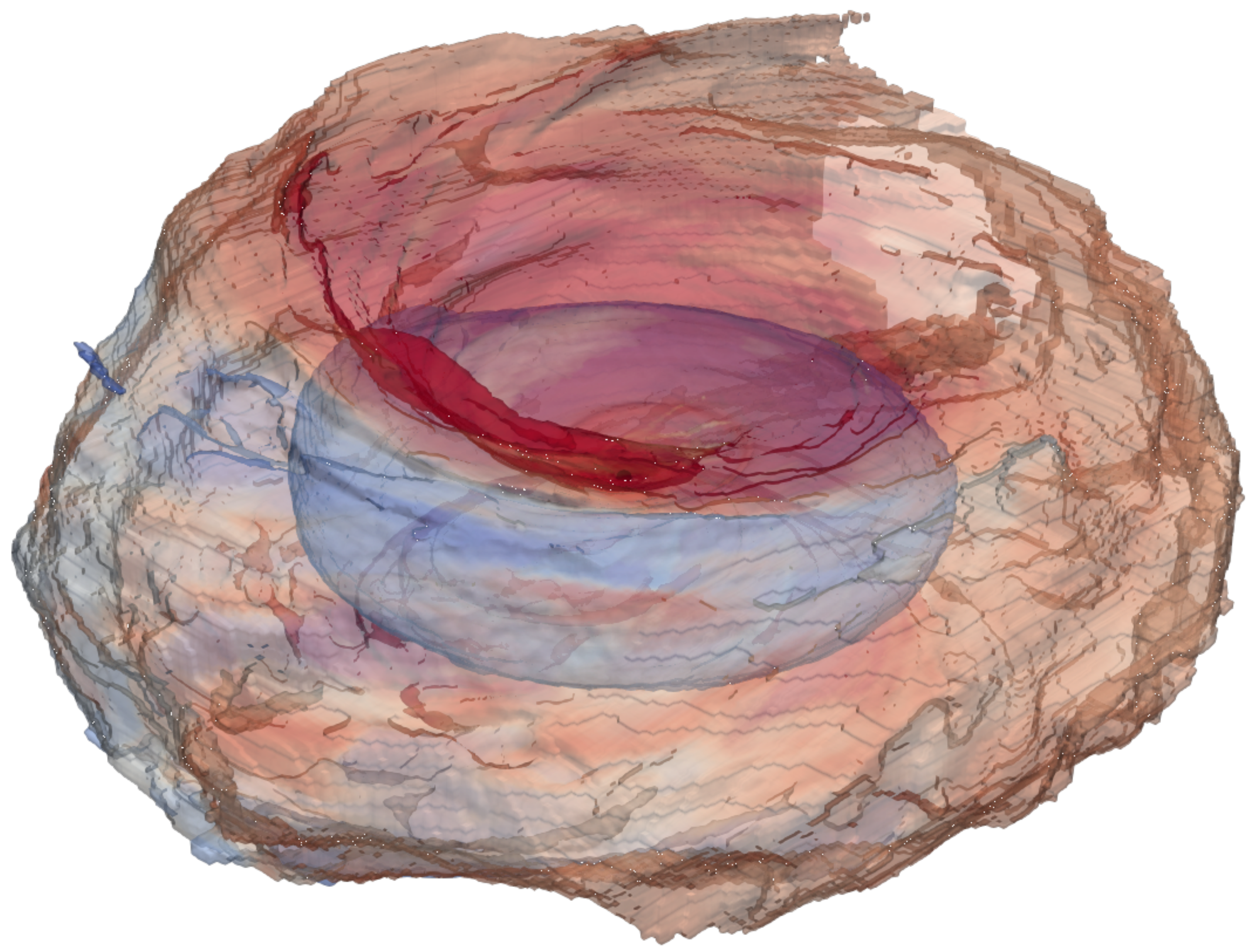
Summary

- **Exascale** era opens new possibilities for numerical relativity and scientific computing
- AthenaK has shown reproducibility of results from legacy codes with full microphysics

Outlook

- Large-scale neutron star merger simulation campaign
- MHD “convergence” series for BHNS
- Highest resolutions possible?





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[Dietrich et al. 2015] - Dietrich, Tim, et al. "Binary neutron stars with generic spin, eccentricity, mass ratio, and compactness: Quasi-equilibrium sequences and first evolutions." *Physical Review D* 92.12 (2015): 124007.

[Abbott et al. 2021] - Abbott, Richard, et al. "Observation of gravitational waves from two neutron star–black hole coalescences." *The Astrophysical journal letters* 915.1 (2021): L5.

[Rashti et al. 2022] - Rashti, Alireza. ELLIPTICA: A New Pseudospectral Code for the Construction of Initial Data. Diss. Florida Atlantic University, 2022.

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[Hayashi et al. 2023] - Hayashi, Kota, et al. "General-relativistic neutrino-radiation magnetohydrodynamics simulation of seconds-long black hole-neutron star mergers: Dependence on the initial magnetic field strength, configuration, and neutron-star equation of state." *Physical Review D* 107.12 (2023): 123001.

[Stone et al. 2024] - Stone, James M., et al. "AthenaK: a performance-portable version of the Athena++ AMR framework." *arXiv preprint arXiv:2409.16053* (2024).

[Zhu et al. 2024] - Zhu, Hengrui, et al. "Performance-portable numerical relativity with AthenaK." *The Astrophysical Journal Supplement Series* 278.2 (2025): 50.

[Fields et al. 2024] - Fields, Jacob, et al. "Performance-portable binary neutron star mergers with AthenaK." *The Astrophysical Journal Supplement Series* 276.2 (2025): 35.

[Chiesa et al. 2024] - Chiesa, Leonardo, et al. "Open-source library for performance-portable neutrino reaction rates: Application to neutron star mergers." *Physical Review D* 111.6 (2025): 063053.

[Camilletti et al. 2024] - Camilletti, Alessandro, et al. "Geometric and thermodynamic characterization of binary neutron star accretion discs." *Physical Review D* 109.6 (2024): 063023.

[Gonzalez et al. 2025] - Gonzalez, Alejandra, et al. "Black-hole–neutron-star mergers: New numerical-relativity simulations and multipolar effective-one-body model with spin precession and eccentricity." *Physical Review D* 113.12 (2026): 124032.

[Gutiérrez et al. 2026] - Gutiérrez, Eduardo M., et al. "Turbulent Dynamo Action in Binary Neutron Star Mergers." *arXiv preprint arXiv:2601.20953* (2026).

[Daszuta et al. 2026] - Daszuta, Boris, et al. "GR-Athena++: Binary Neutron Star Merger Simulations with Neutrino Transport." *arXiv preprint arXiv:2602.18290* (2026).

Resources

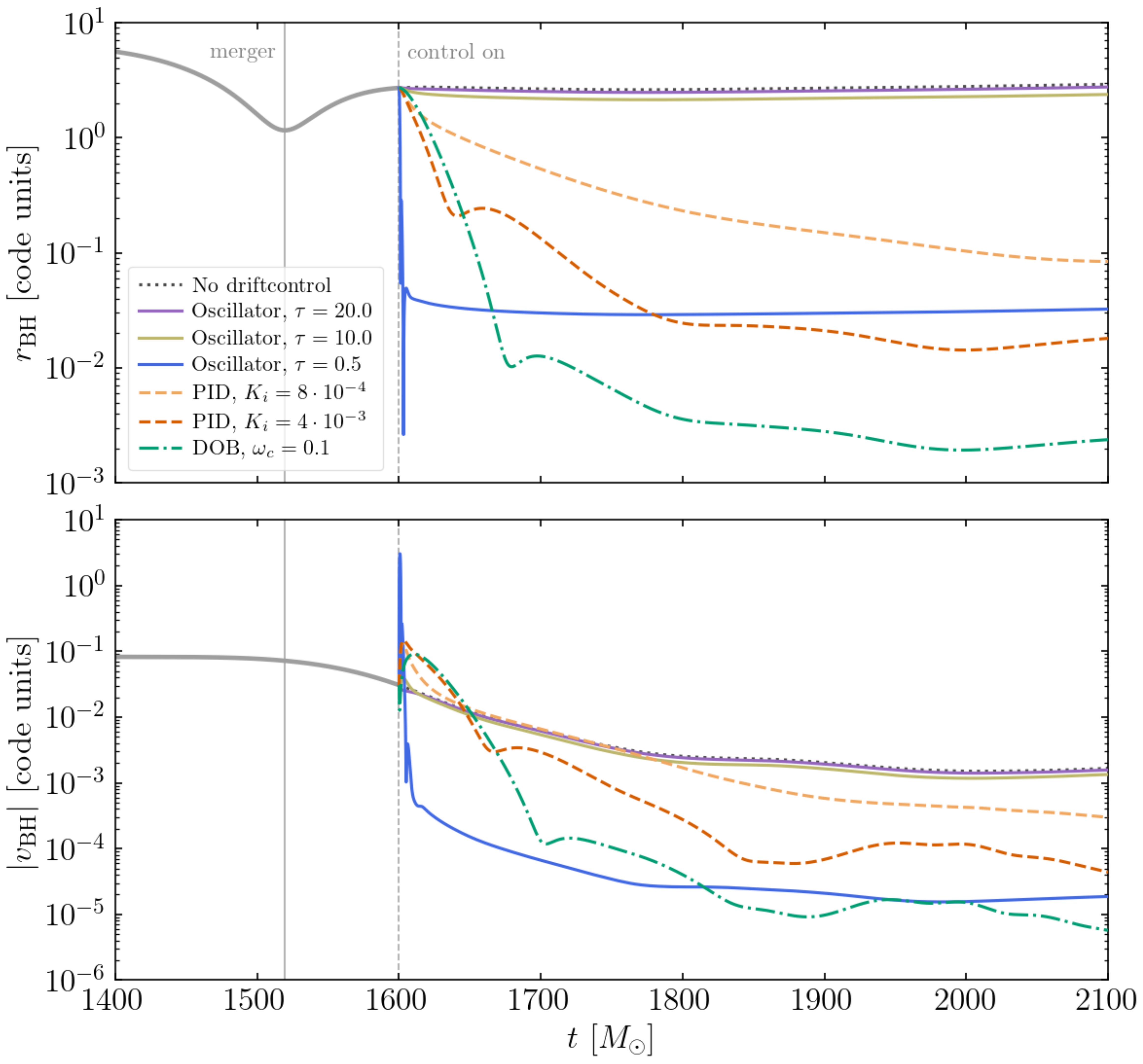
Logos:

1. NSF: https://mediahub.nsf.gov/portals/dnmqqhzz/NSFBrandIdentityPortal/c/6153bea4-c792-4c28-9c4e-d46c7ccdb600/s/ef5d598d-788b-4487-81a4-d1aa83ec640e
2. DFG: https://www.dfg.de/de/service/logo-corporate-design
3. PennState: https://science.psu.edu/
4. Core: http://www.computational-relativity.org/

HPC:

1. Aurora: https://www.heise.de/news/Aurora-Exaflops-Supercomputer-mit-Intel-Technik-kommt-2021-4340094.html
2. Frontier: https://www.hpe.com/de/de/products/compute/hpc/cray/oak-ridge-national-laboratory.html
3. Leonardo: https://www.hpc.cineca.it/projects/leonardo-2/
4. Lumi: https://lumi-ai-factory.eu/
5. Jupiter: https://www.ai.rwth-aachen.de/cms/ki/partnerschaften/wissenschaft/~boibss/jupiter-ai-factory-jaif-/?lidx=1
6. EuroHPC: https://www.eurohpc-ju.europa.eu/about/contact_en
7. Kokkos: https://github.com/kokkos

Driftcontrol



Implementation

- Driftcontrol methods for mitigating the black hole kick

1. Oscillator: $u = \dfrac{e}{\tau^2} + \dfrac{2\zeta v}{\tau}$
2. PID: $u = K_p e + K_d v + K_i \int e dt$
3. DOB: $\hat{f} = p + \omega_0 v,$

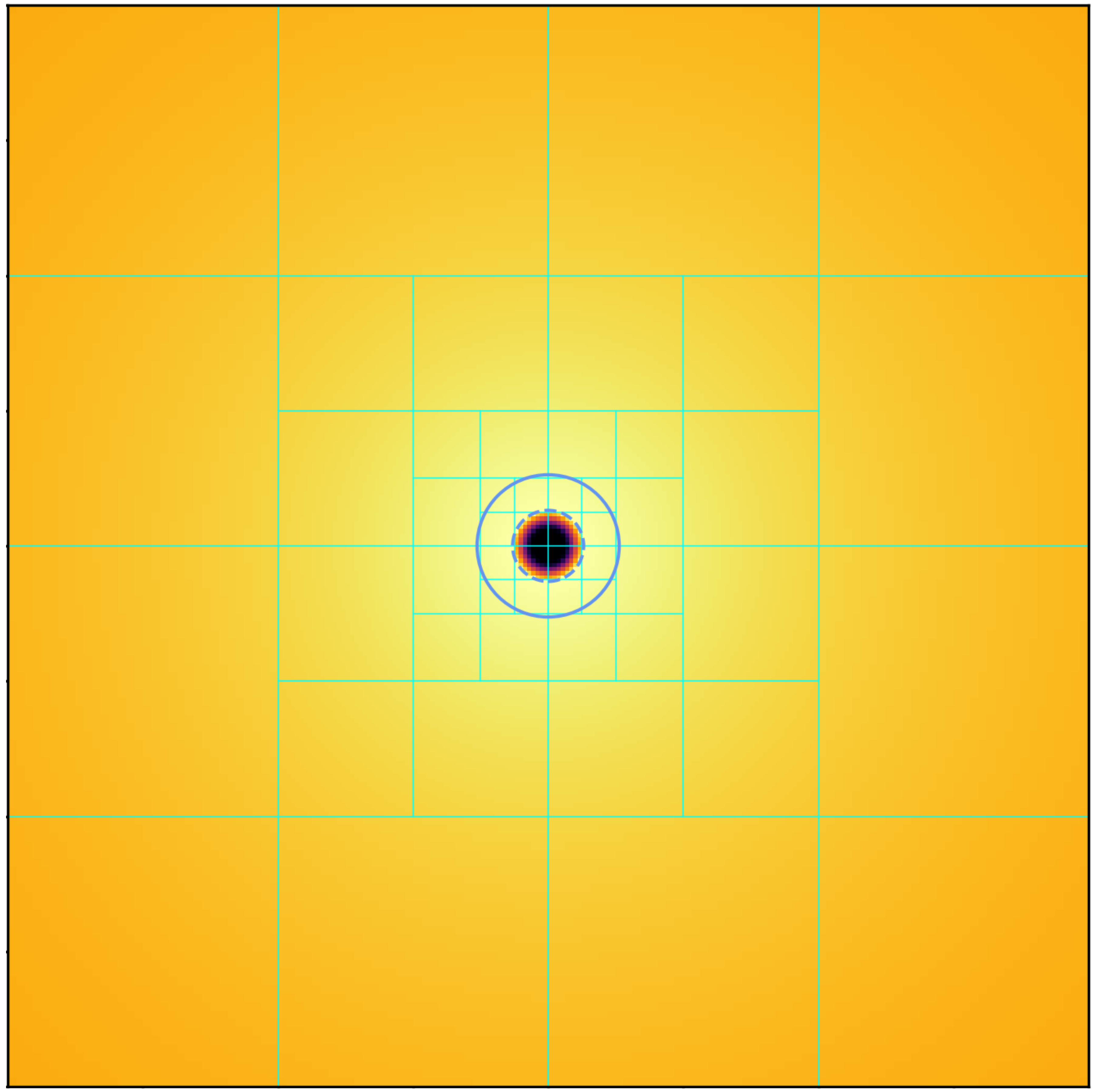
$$u = \omega_c^2 e + 2\zeta\omega_c v + \hat{f},$$

$$\dot{p} = \omega_0(\omega_c^2 e + 2\zeta\omega_c v)$$

$$\dot{x}^i_{\rm BH} = -\beta^i$$

$$\ddot{x}^i_{\rm BH} = -\partial_t \beta^i = -gu + f$$

Smooth excision



Implementation

- Smooth excision formulation similar to [Daszuta et al. 2026]:

$$\partial_t \tilde{D} = \ldots - w(\tilde{D} - \tilde{\rho}_{\rm ex})/t_{\rm damp}$$
$$\partial_t \tilde{S}_i = \ldots - w\tilde{S}_i/t_{\rm damp}$$
$$\partial_t \tilde{\tau} = \ldots - w(\tilde{\tau} - \tilde{\tau}_{\rm ex})/t_{\rm damp}$$
$$\partial_t(\tilde{D}Y_e) = \ldots - w(\tilde{D} - \tilde{\rho}_{\rm ex})Y_e/t_{\rm damp}$$