

GRHayL

An Open-source, Modular, Extensible GRMHD Library

Leo Werneck

In collaboration with Samuel Cupp, Terrence Pierre Jacques, and Zach Etienne



Astrophysical neutrinos and the origin of the elements

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Preamble: IllinoisGRMHD

Our starting point is **IllinoisGRMHD** (Etienne+2015, CQG 32 175009)

- A rewrite of the original GRMHD code from the Illinois NR group
- Leaner and faster, yet round-off agreement with original code
- GRMHD for fully dynamical spacetimes
- Open source and part of the Einstein Toolkit
- “Field tested” to model many systems
 - ✓ Single and binary neutron stars
 - ✓ Black hole accretion disks
 - ✓ Black hole—neutron star binary
 - ✓ White dwarfs

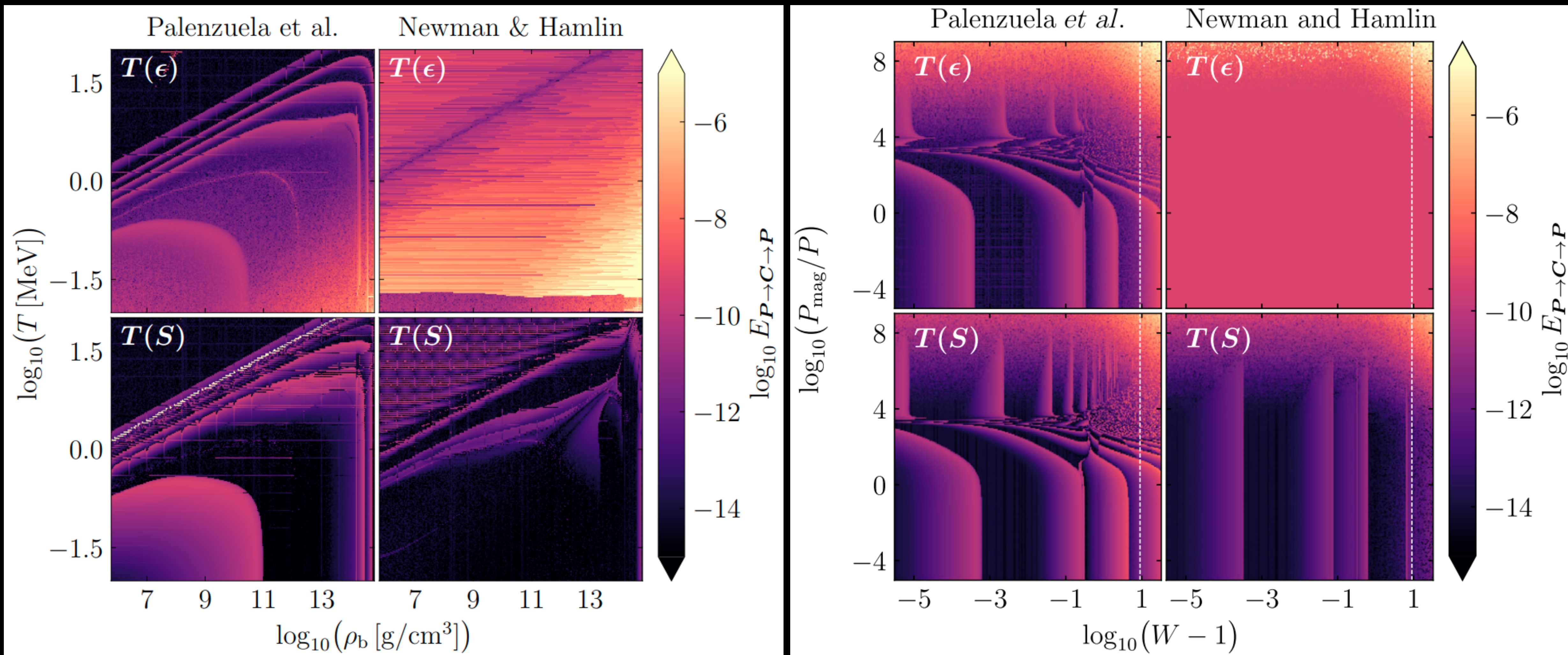


Preamble: IllinoisGRMHD

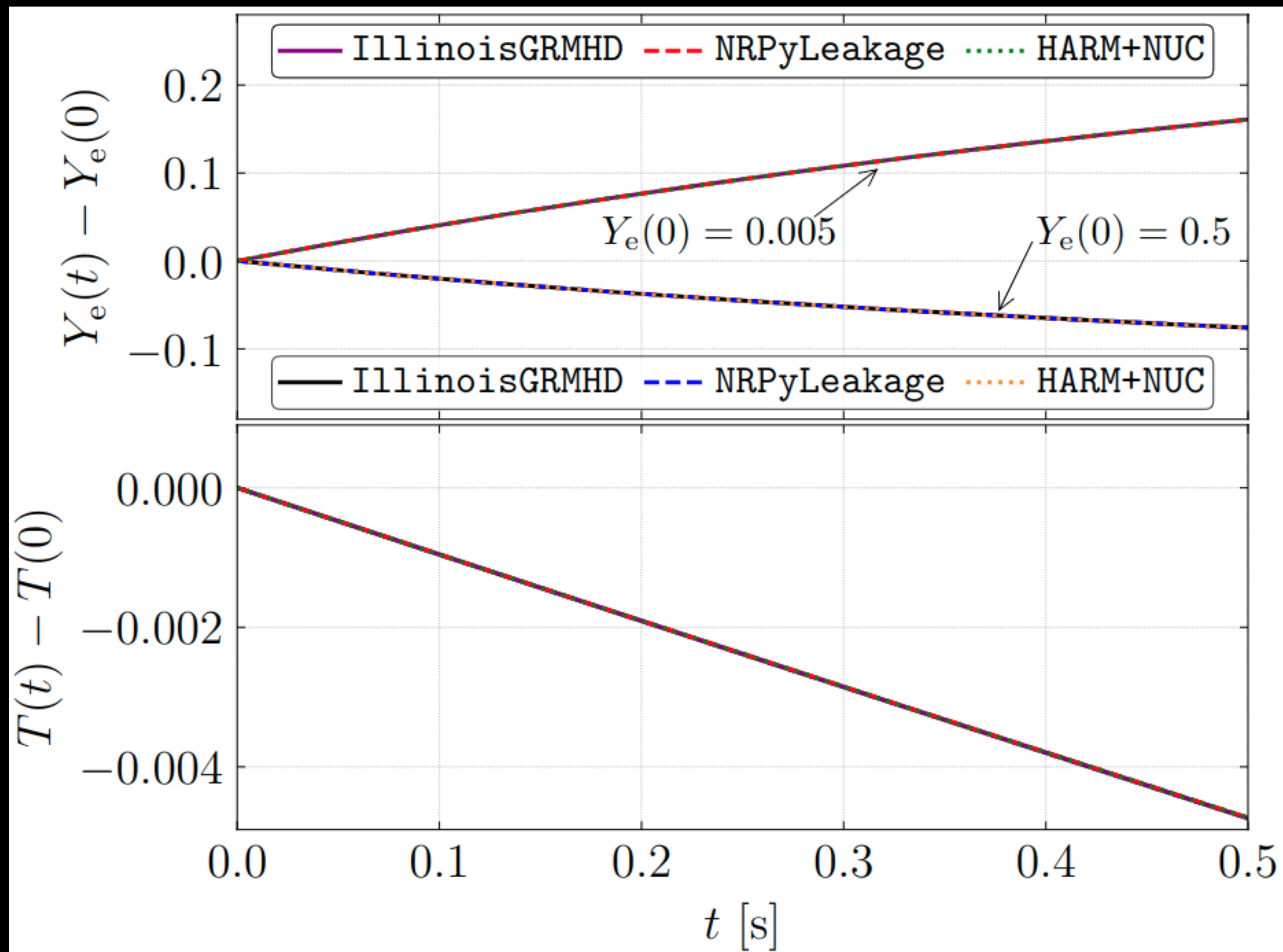
Latest features ([LW+TCAN+2023](#), PRD 107 044037)

- Support for microphysical equations of state tables
- New conservative-to-primitive infrastructure
- Basic neutrino physics via a leakage scheme

Preamble: IllinoisGRMHD

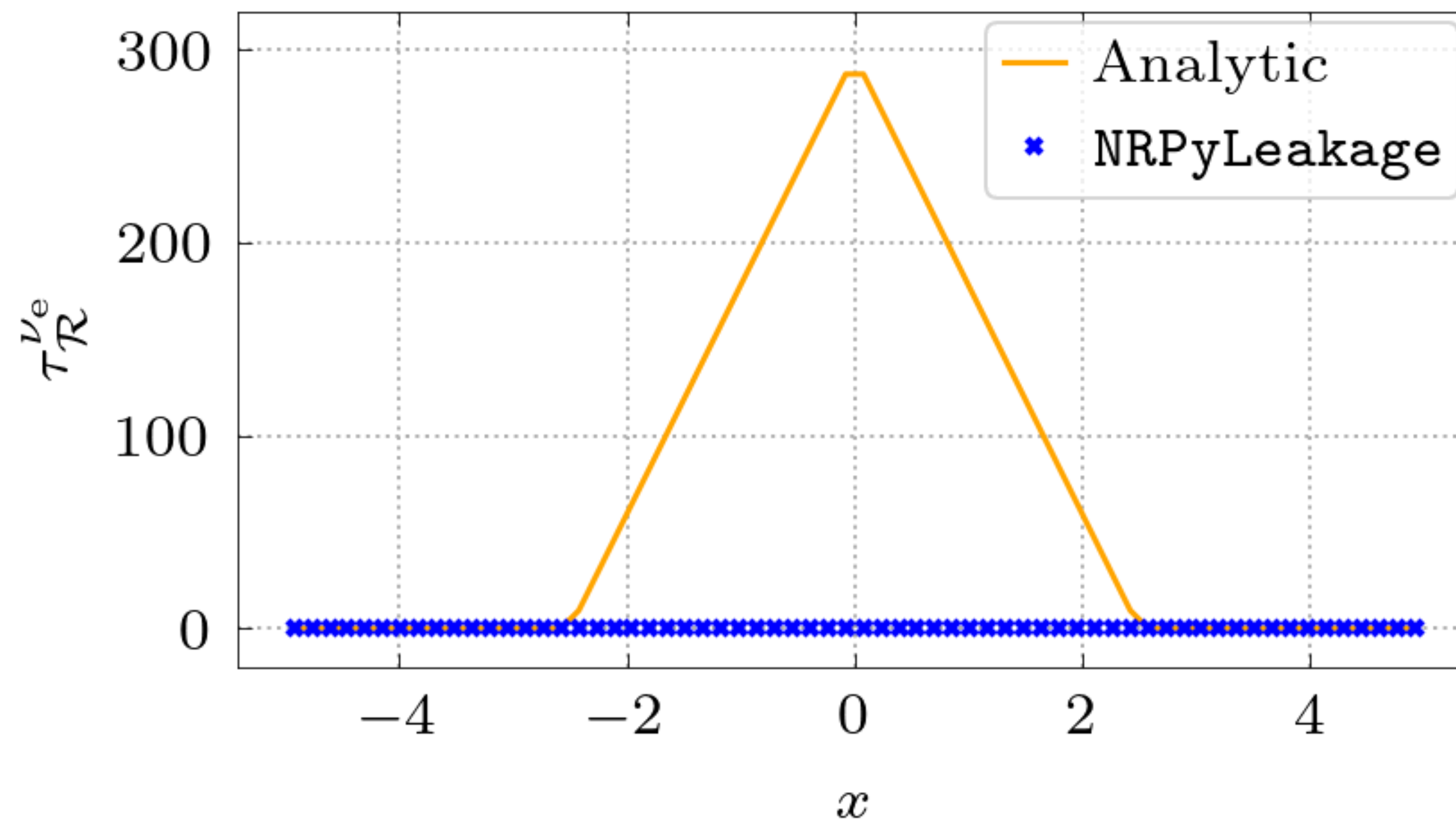


Preamble: IllinoisGRMHD



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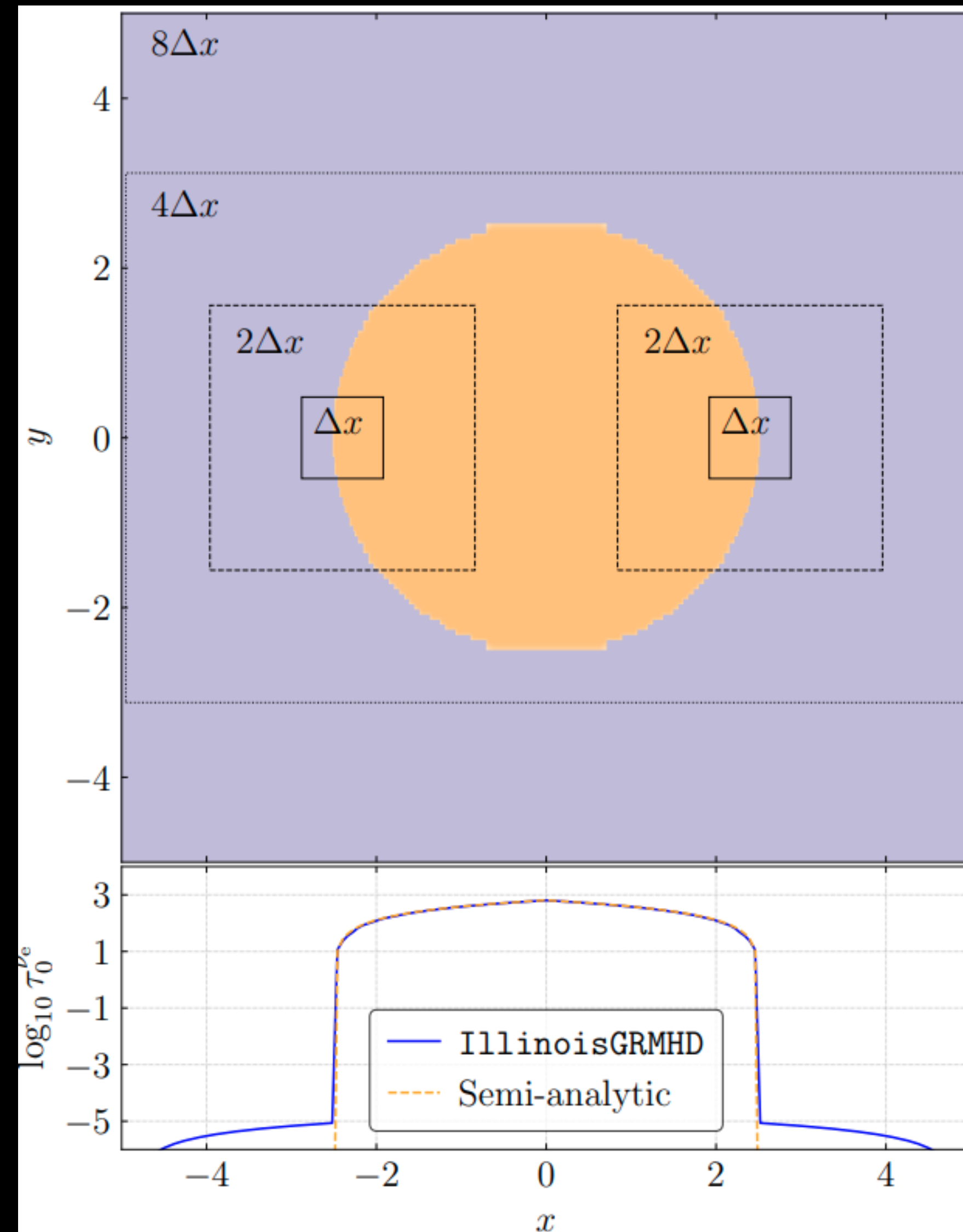
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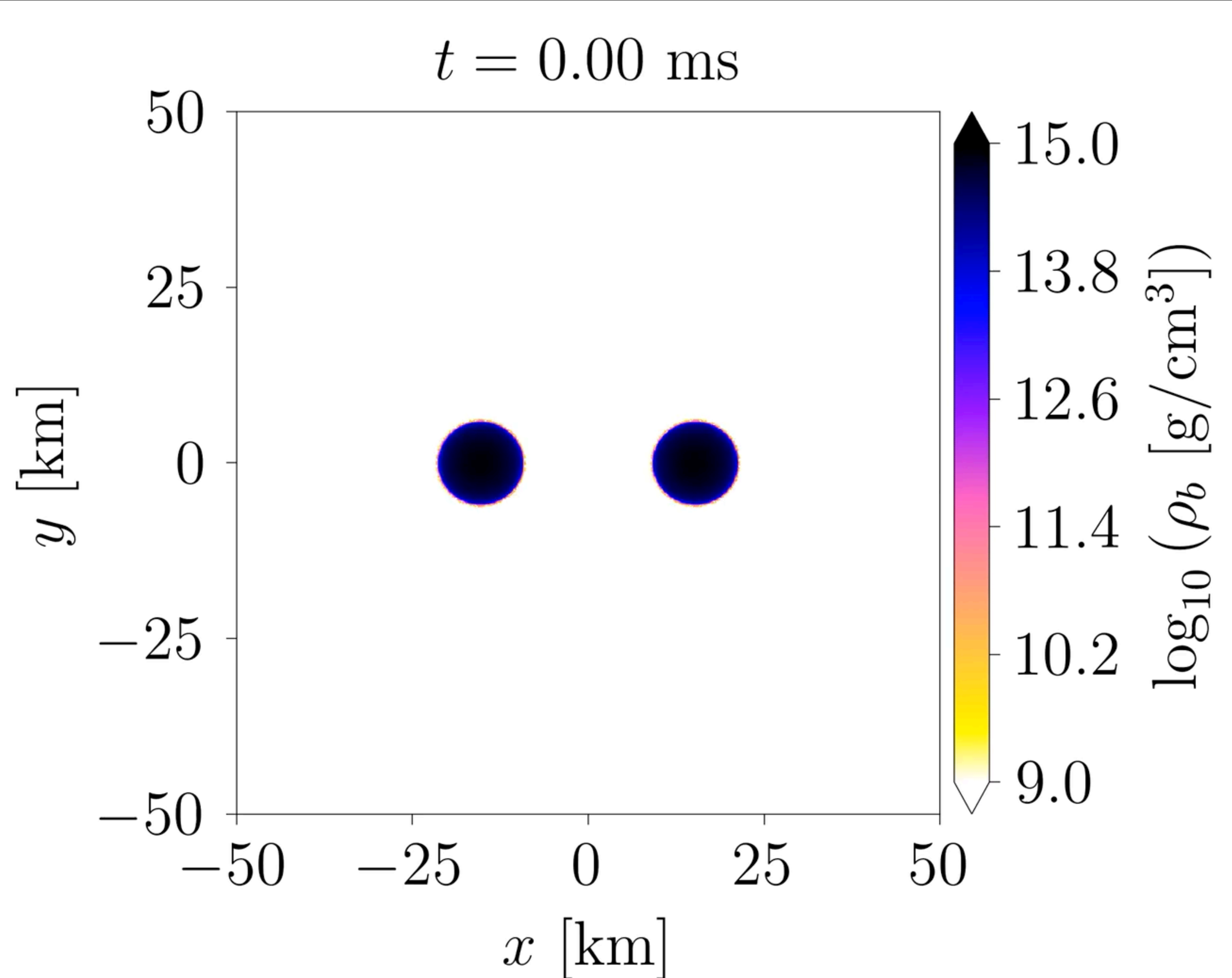
NRPyLeakage

- Based on Ruffert+1996, Burrows+2006, and O'Connor & Ott 2011
- Optical depths are computed using nearest neighbor approach of Nielsen+2011
- Works on systems with or without symmetries

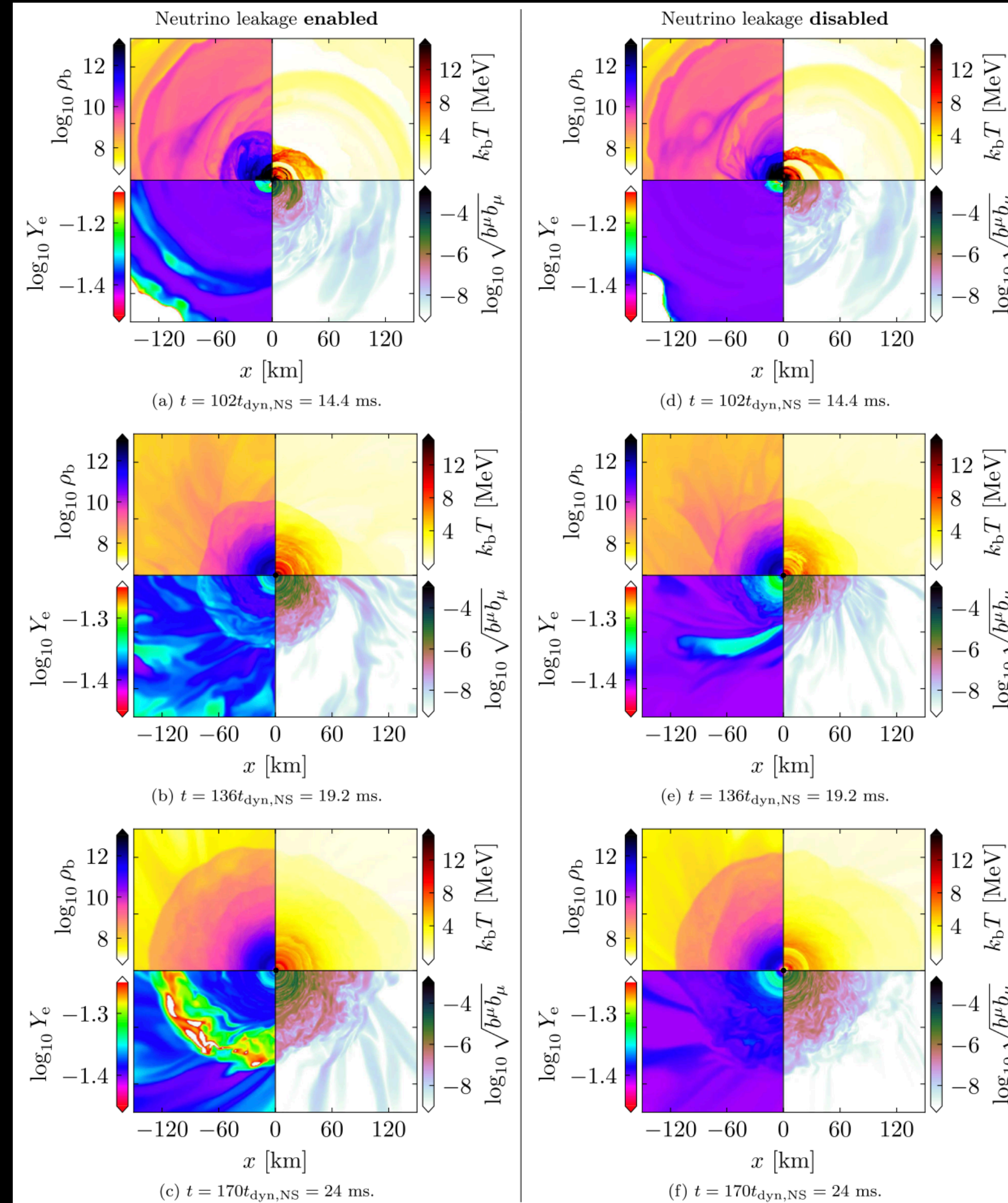
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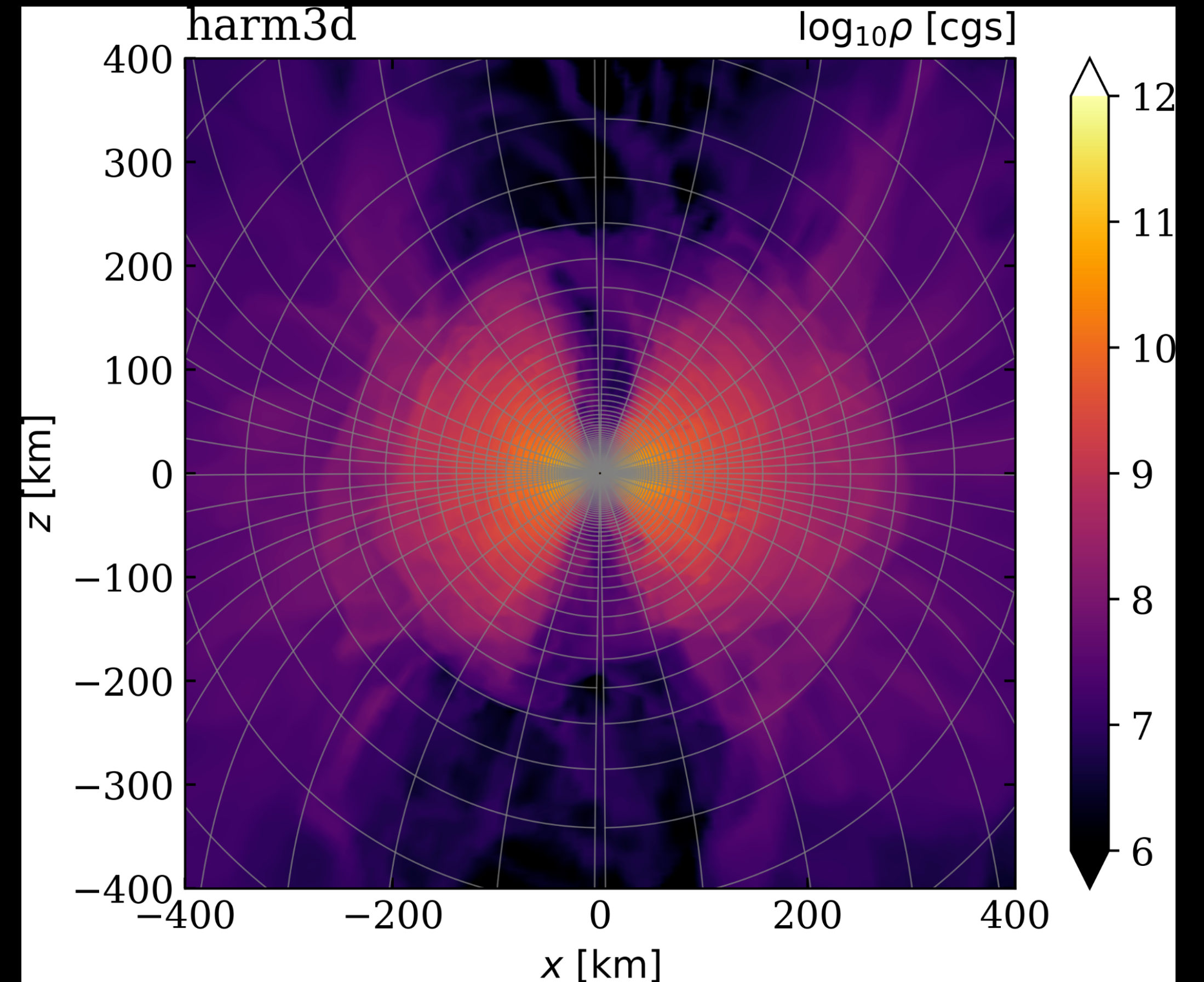
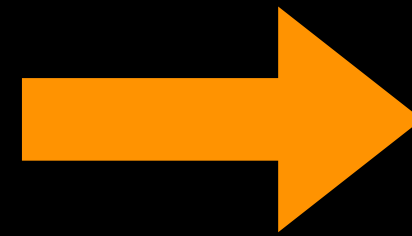
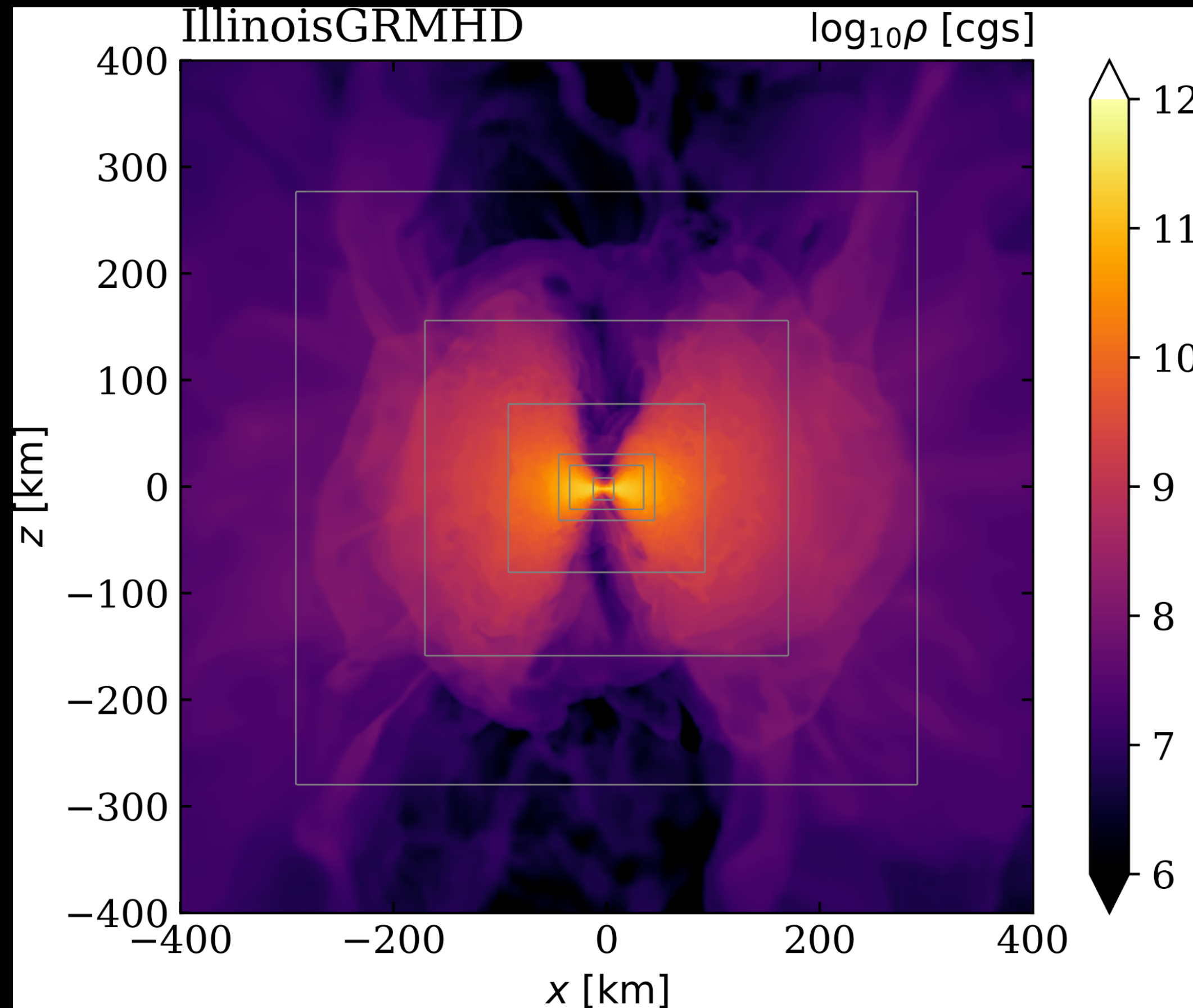
Preamble: IllinoisGRMHD



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Armengol+TCAN+2022

Preamble: IllinoisGRMHD

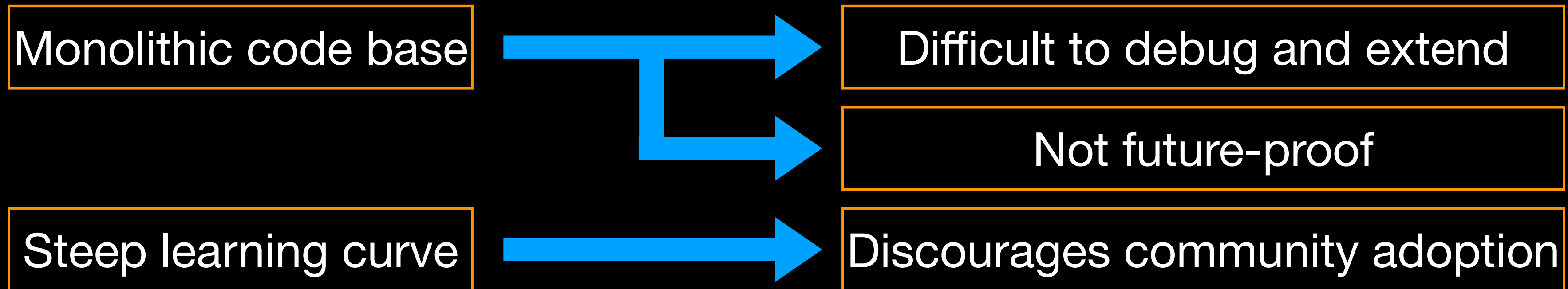
The good

- Field tested
- Open source
- Support for microphysical EOS
- Some neutrino physics support

The not so good

- Tied to a single infrastructure
- Steep learning curve
- Relatively small, but still difficult to modify
- Documentation could be better

GRHayL: Motivation



GRHayL: Motivation



<https://www.teepublic.com/tapestry/3141846-tangled-octopus>

GRHayL: General Relativistic Hydrodynamics Library

- Refactors **IllinoisGRMHD** into modular components
- GRHayL is the **future** of IllinoisGRMHD
 - ★ Better documentation
 - ★ Easier to learn
 - ★ Easier to contribute/extend
 - ★ Infrastructure agnostic

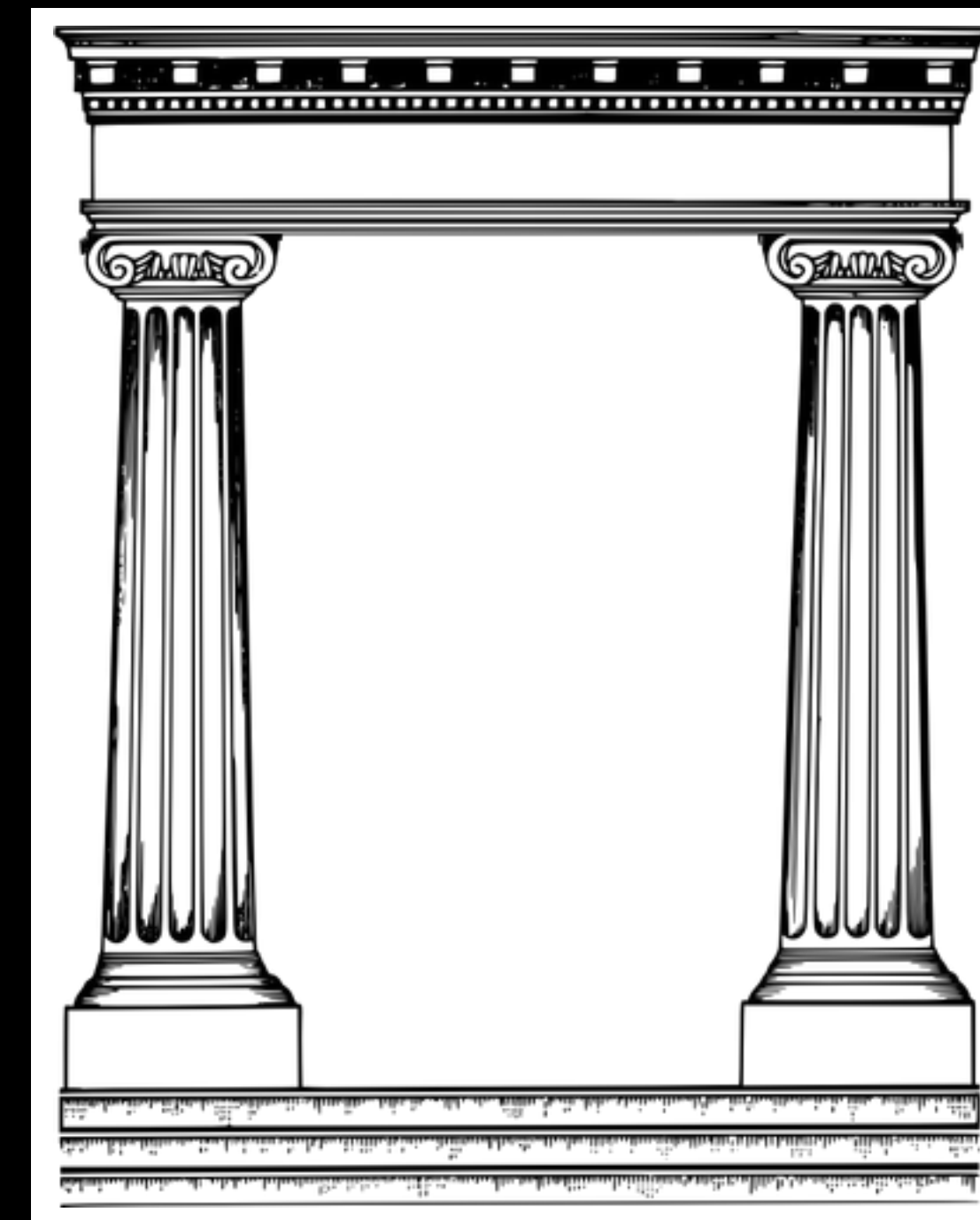
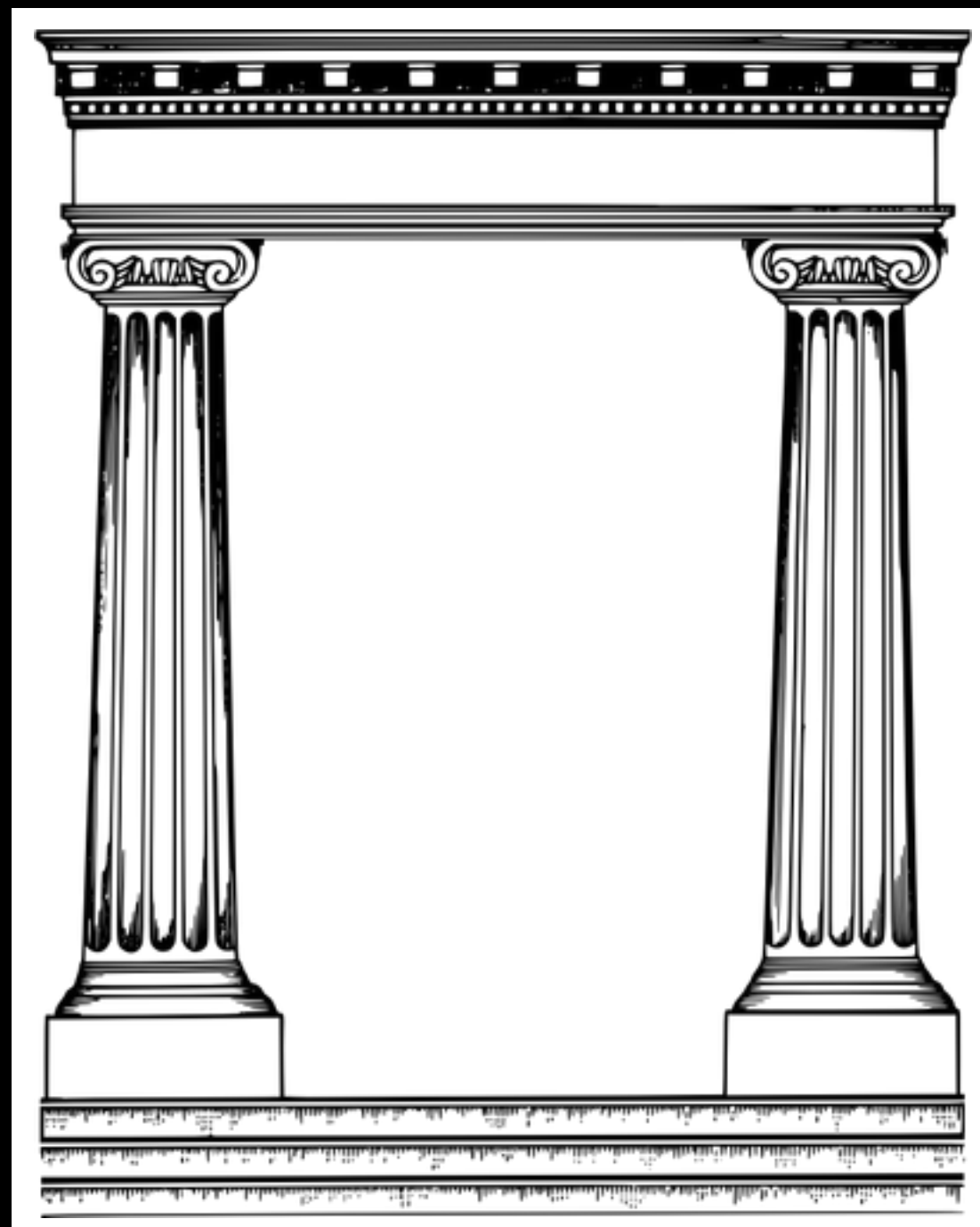
GRHayL: Design Philosophy

Streamlined new user pipeline

Extensive documentation

Modularity

Infrastructure agnosticism



GRHayL: Streamlined new user pipeline & documentation

New students must learn:

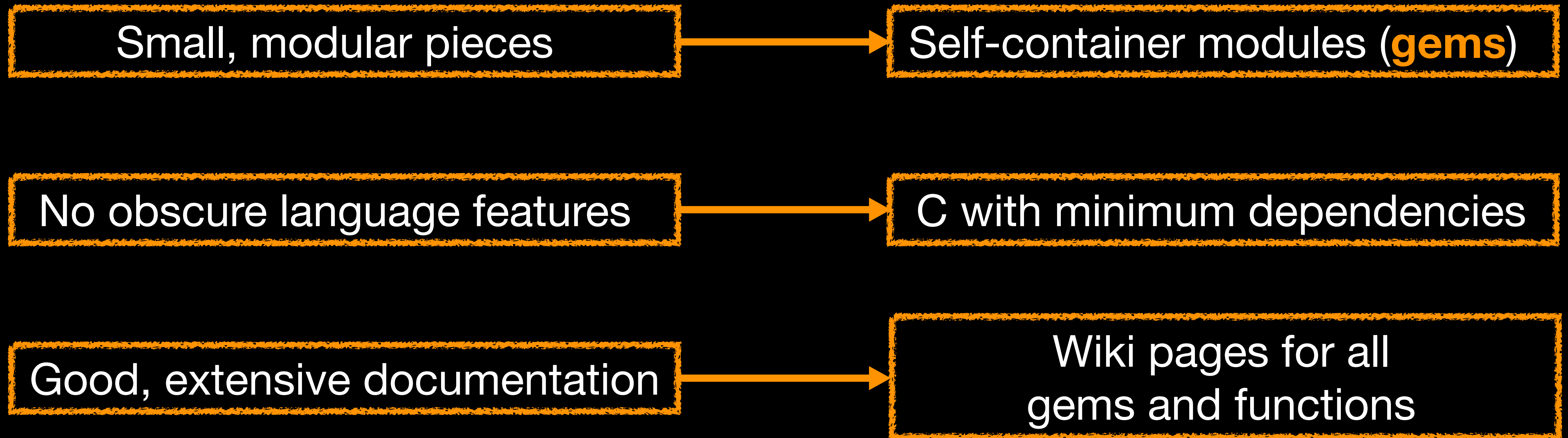
- Physics
- Mathematics
- **Computer science**
- Astronomy

Weakest link!

Solution:

- Small, modular code pieces
- No obscure language features
- **Extensive documentation**

GRHayL: Streamlined new user pipeline & documentation



GRHayL: modularity and infrastructure agnosticism



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<https://www.deviantart.com/sylviaritter/art/Cosmic-Cuttlefish-766515479>

GRHayL: modularity and infrastructure agnosticism



Core Code Infrastructure

Cactus/Einstein Toolkit
NRPy+/BlackHoles@Home
Your Infrastructure/Code

C structs pass data between
infrastructure & gems

Conservatives-to-
Primitives Routines

Reconstruction

GRHD Fluxes and
Sources

Induction Equation

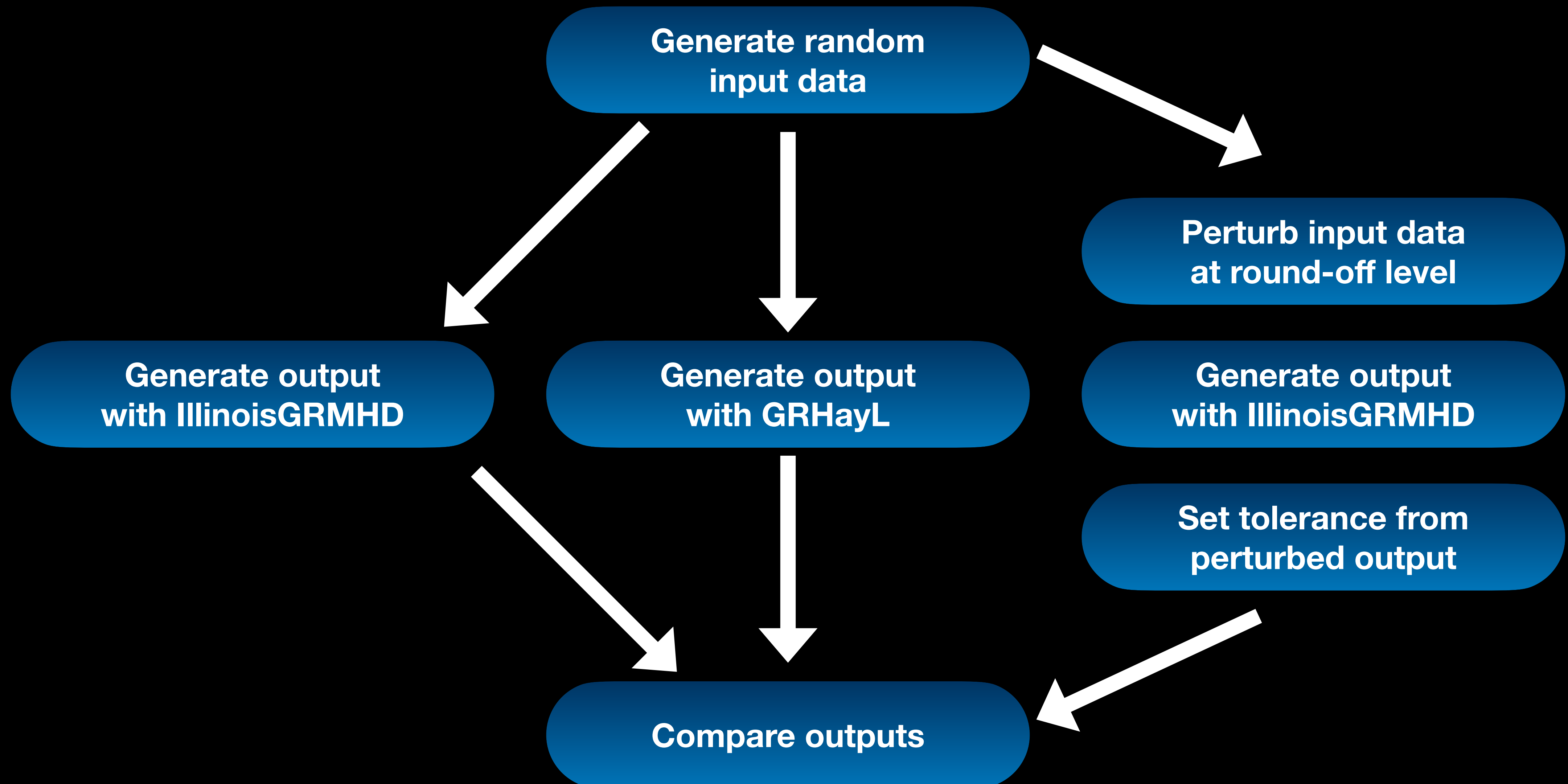
Equation of State

Neutrino Physics

Other Physics

GRHayL: code validation

How do we **validate** GRHayL?

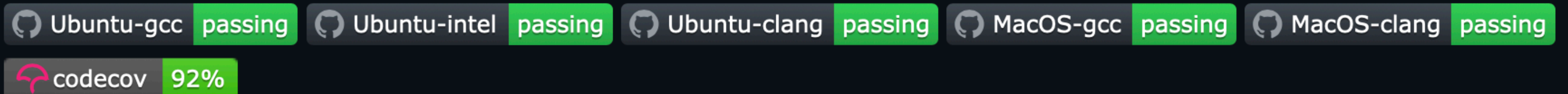


GRHayL: code validation

Automated continuous integration (CI) with GitHub Actions

- Multiple OS/compiler combinations
- Uses trusted output to validate test output
- Core functions have individual unit tests

GRHayL



<https://github.com/GRHayL/GRHayL>

GRHayL: implementations/infrastructures

The GRHayL **library** is mostly oblivious to the grid structure

- Knows nothing about AMR, unigrid, patches, etc
- Many functions also oblivious to coordinate system
- Core functions are also GPU-friendly

GRHayL **implementations** provide needed connective tissue

- Loops
- Gridfunction access
- Function scheduling
- Memory management
- MPI/OpenMP/charm++ parallelization
- I/O

GRHayL: implementations/infrastructures

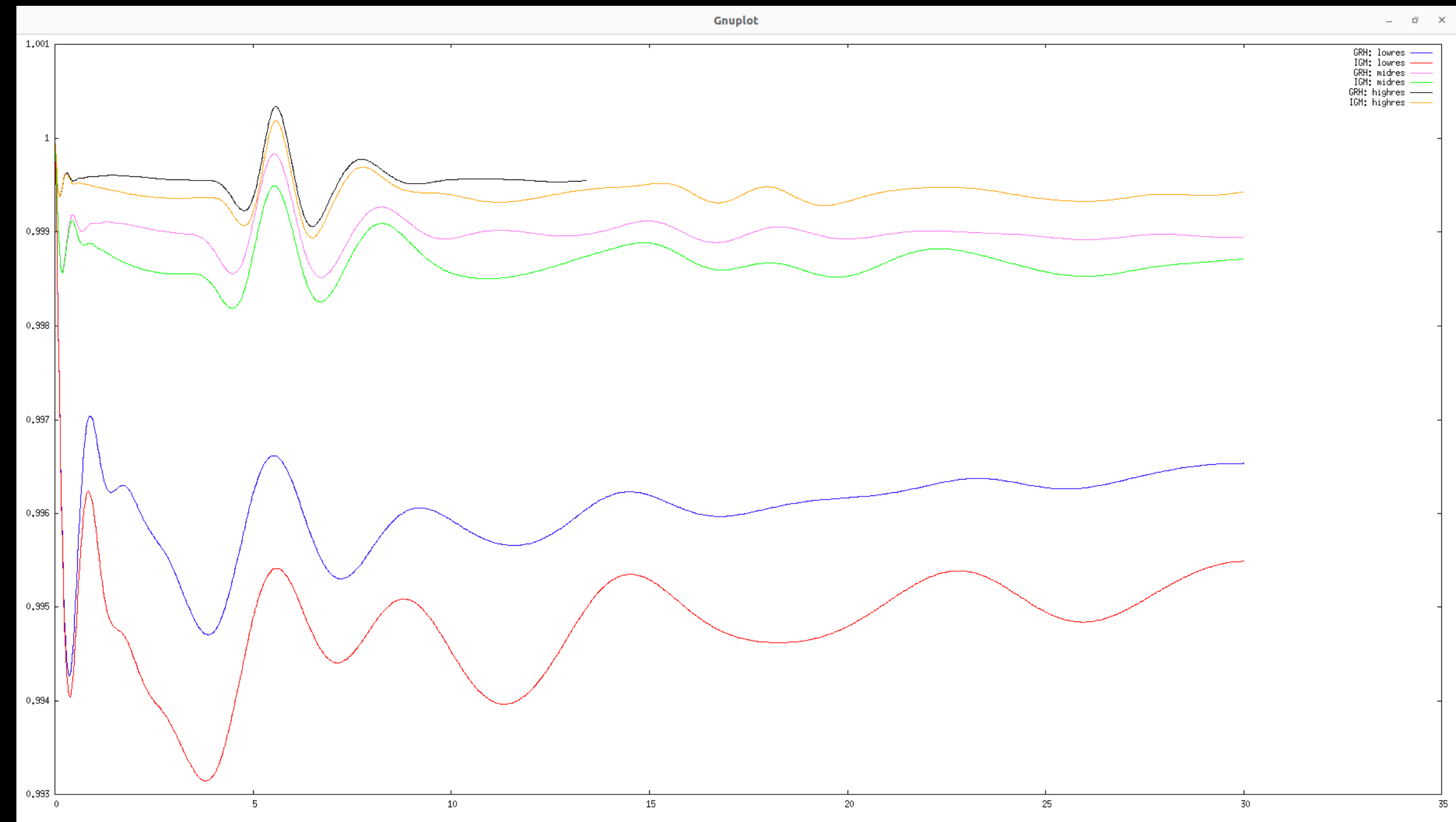
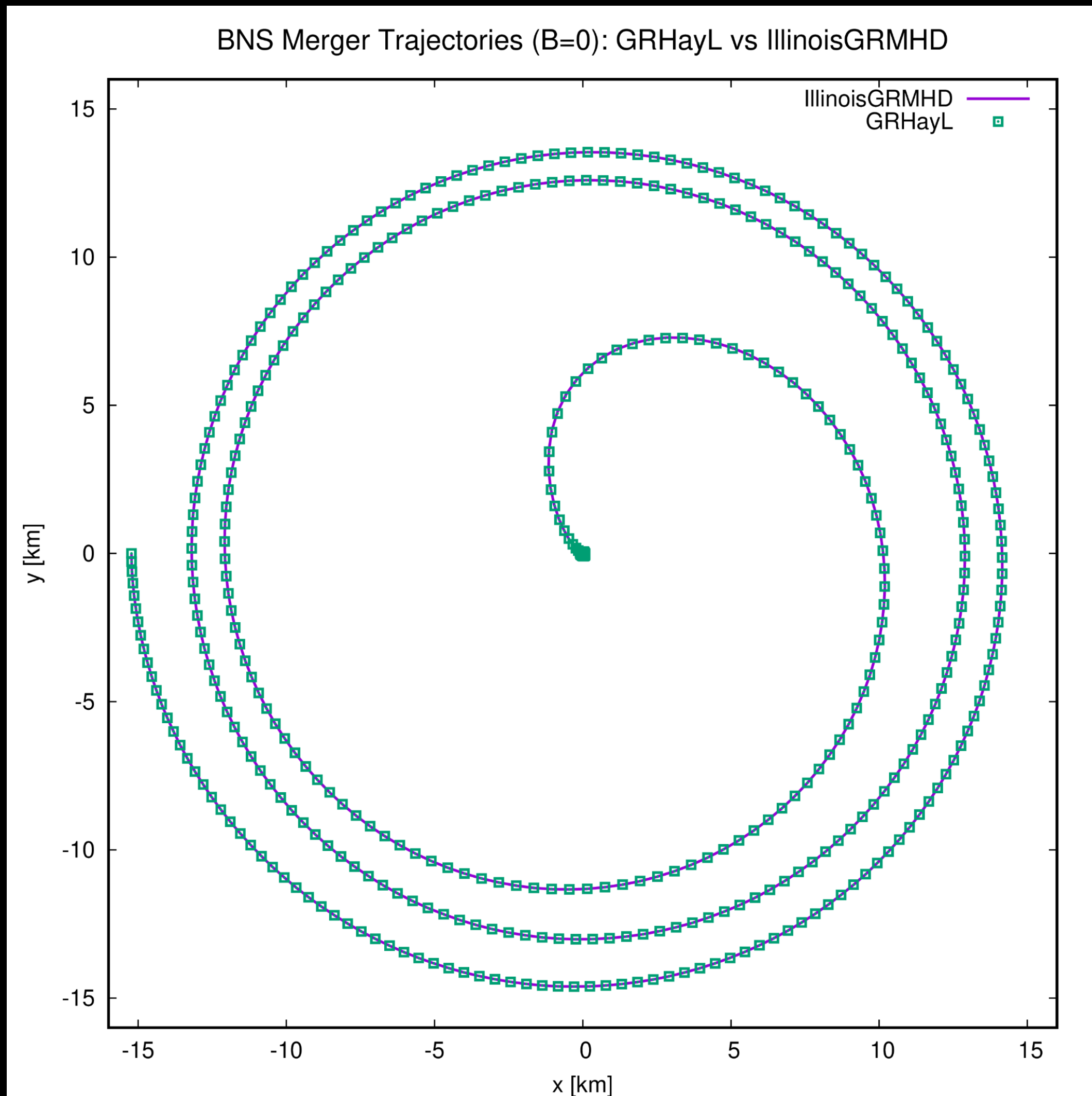
Current implementations (infrastructures)

- IllinoisGRMHD (Carpet/CarpetX)
- GRHayLHD (Carpet/CarpetX/NRPy+)

Future infrastructures

- ChaNGa/MaNga
- GRChombo
- DendroGR
- BlackHoles@Home
- Your infrastructure

GRHayL: implementations/infrastructures



Cupp+ (in preparation)

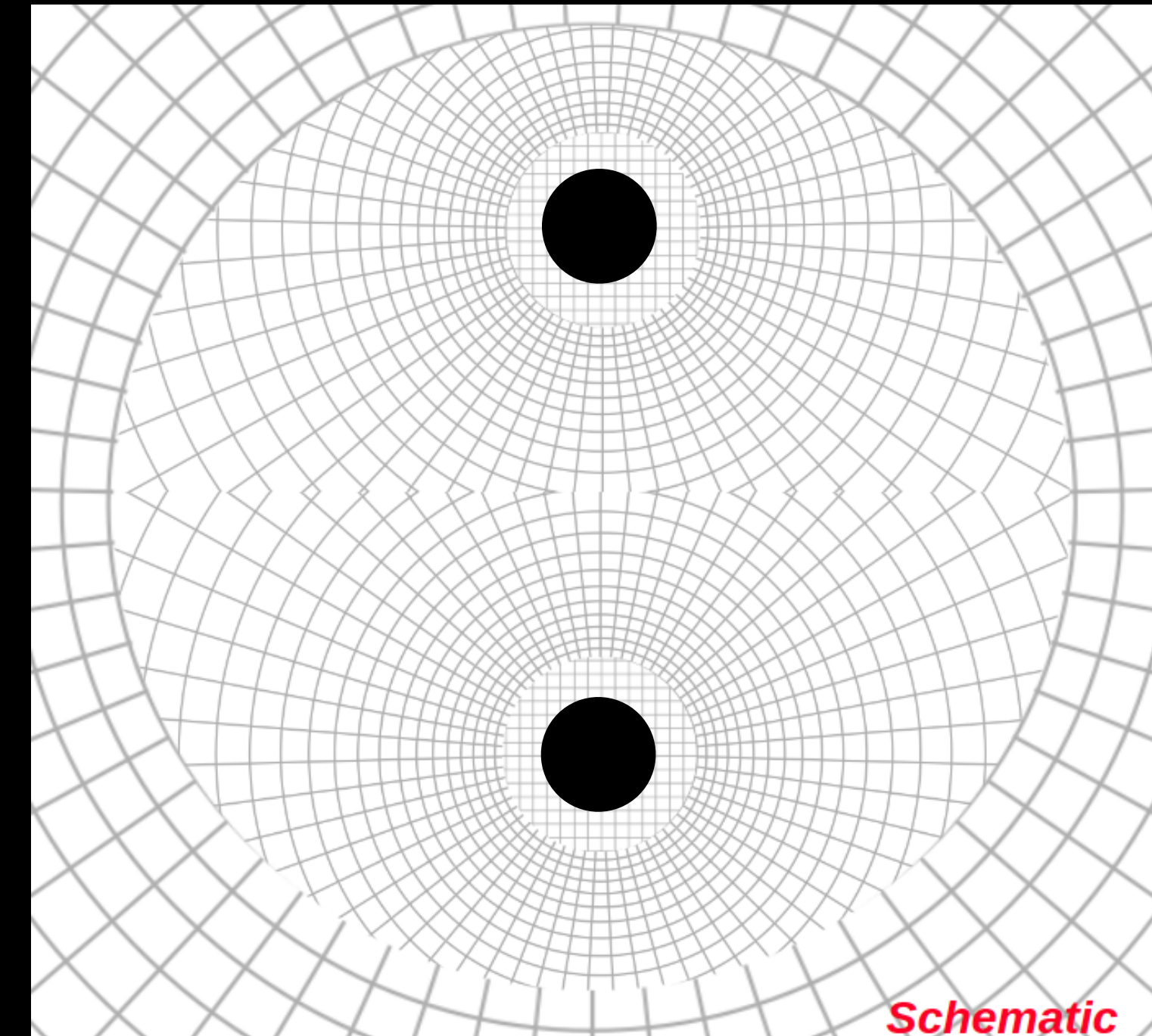
GRHayL: summary and future developments

GRHayL summary:

- GRHayL is the future of IllinoisGRMHD
- Minimal dependencies, highly extensible
- Well documented and modular
- Provide GRMHD for many different infrastructures

Future developments

- Better neutrino physics
- Hand-off support between different infrastructures
- More efficient simulations with curvilinear coordinates
- Full GPU support



Courtesy Zach Etienne

Questions?
