GRHayL

An Open-source, Modular, Extensible GRMHD Library

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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)

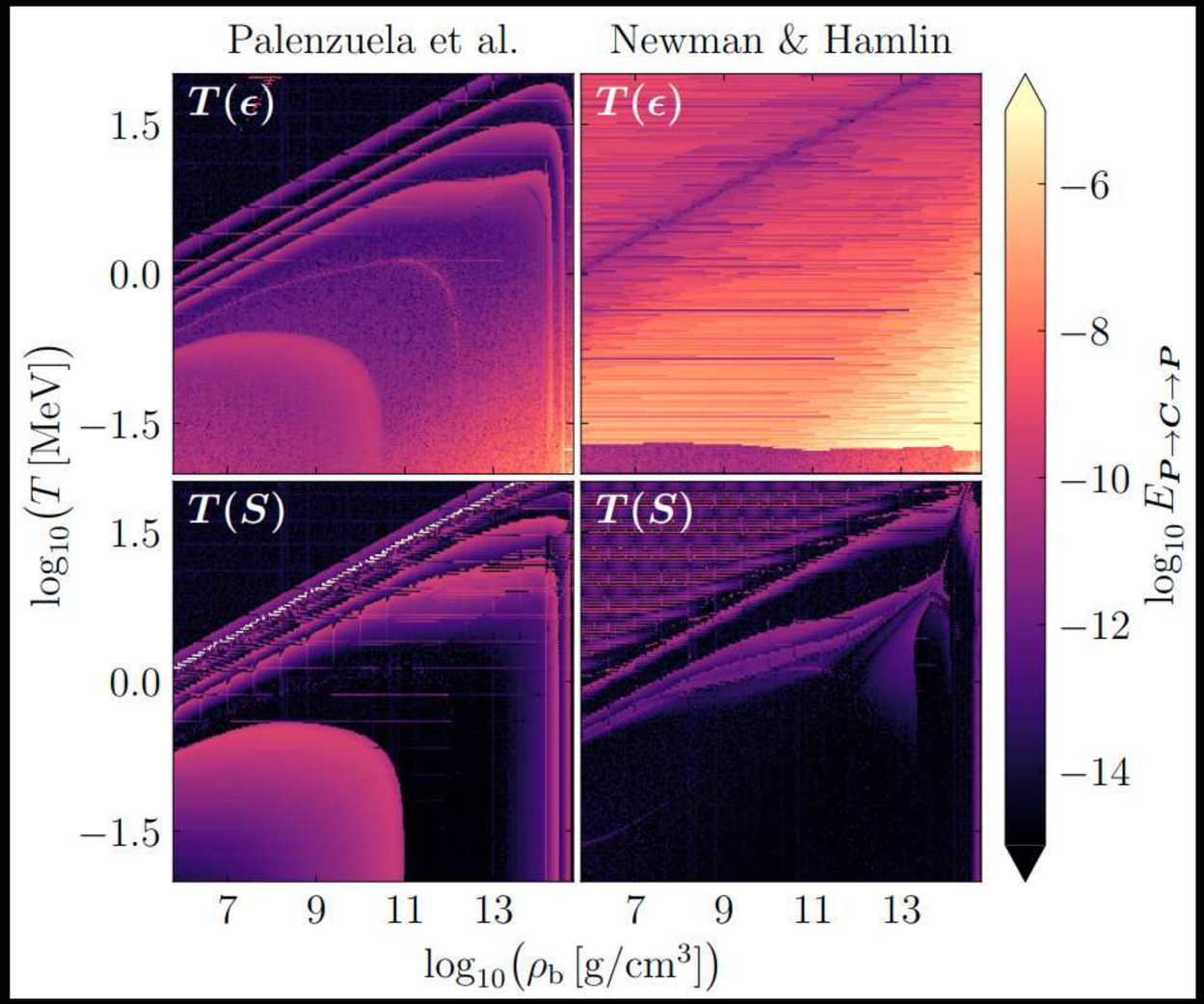
- A rewrite of the original GRMHD code from the Illinois NR group
- Leaner and faster, yet round-off agreement with original code
- GRMHD for fully dynamical spacetimes
- Open source and part of the Einstein Toolkit
- “Field tested” to model many systems
  - ✓ Single and binary neutron stars
  - ✓ Black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

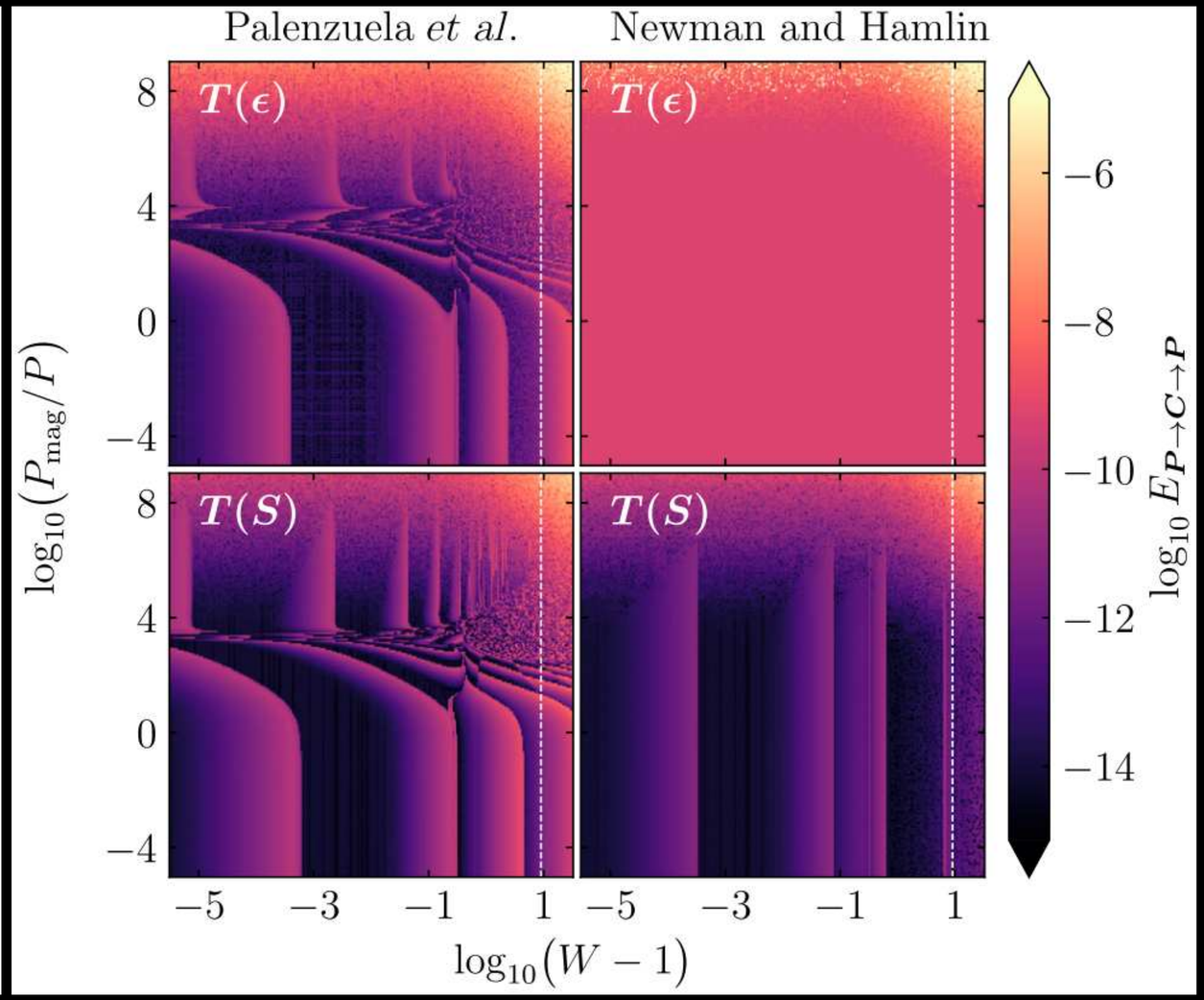
Preamble: IllinoisGRMHD

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

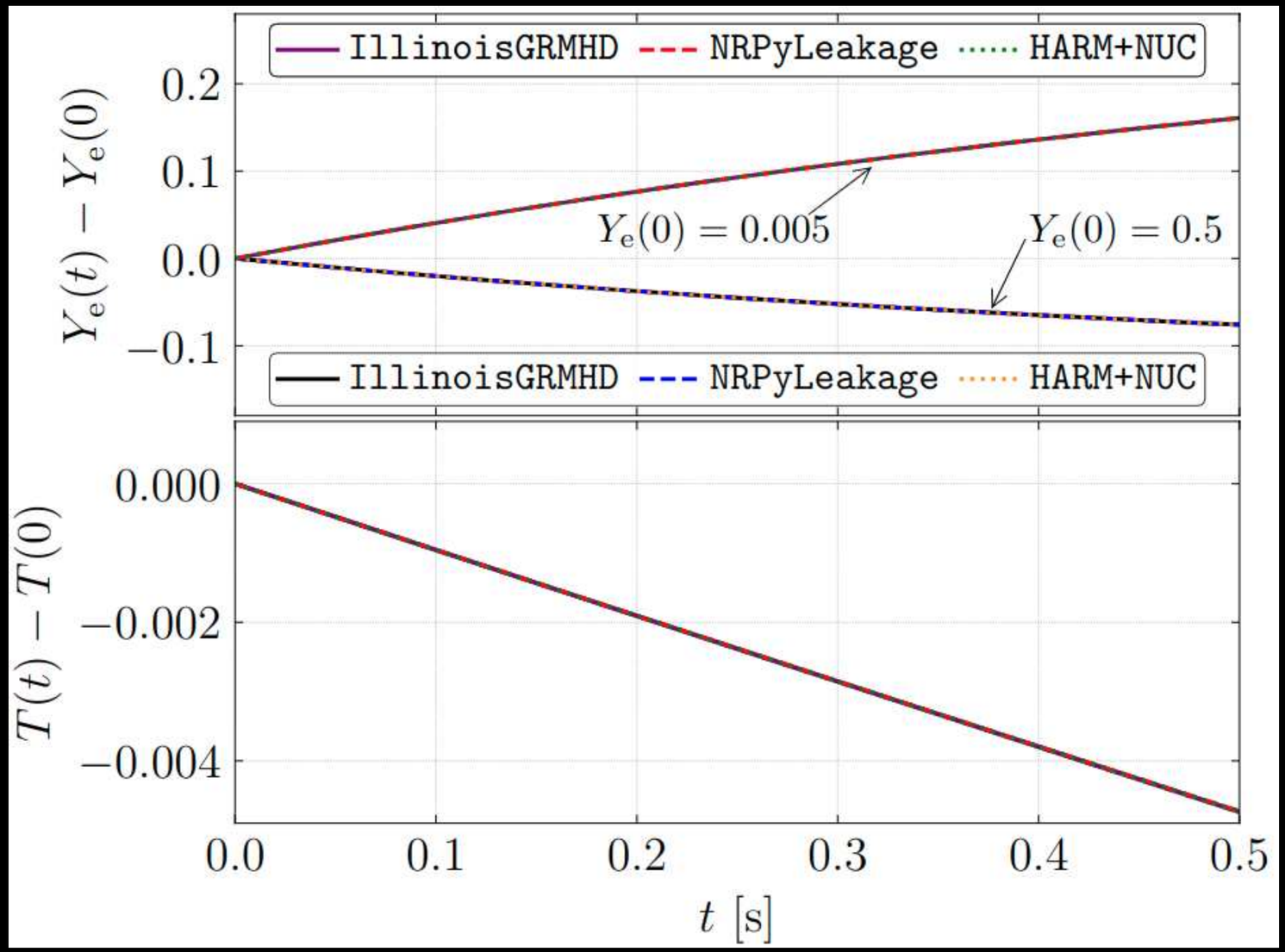
Preamble: IllinoisGRMHD





LW+TCAN+2023

Preamble: IllinoisGRMHD



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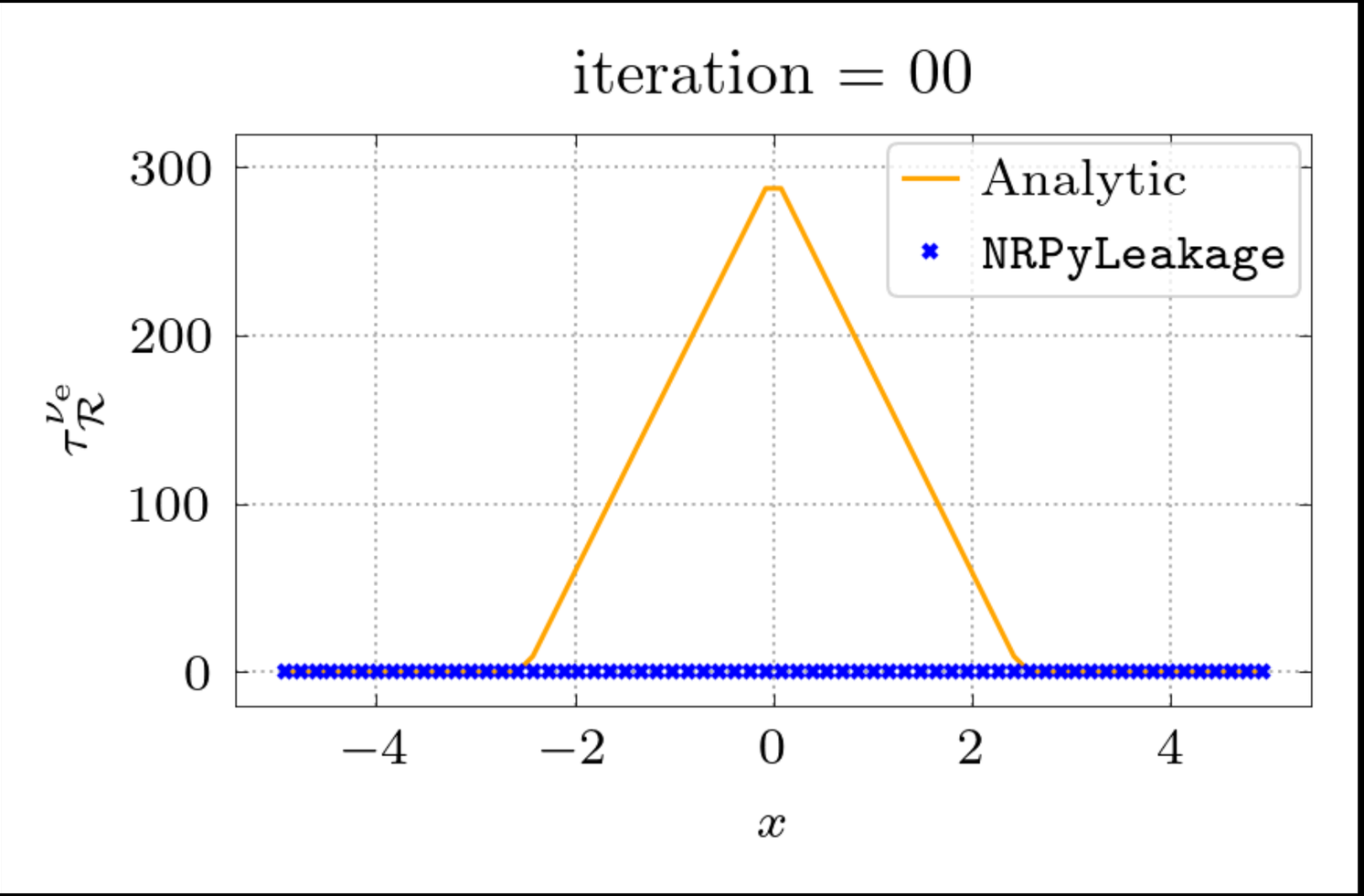
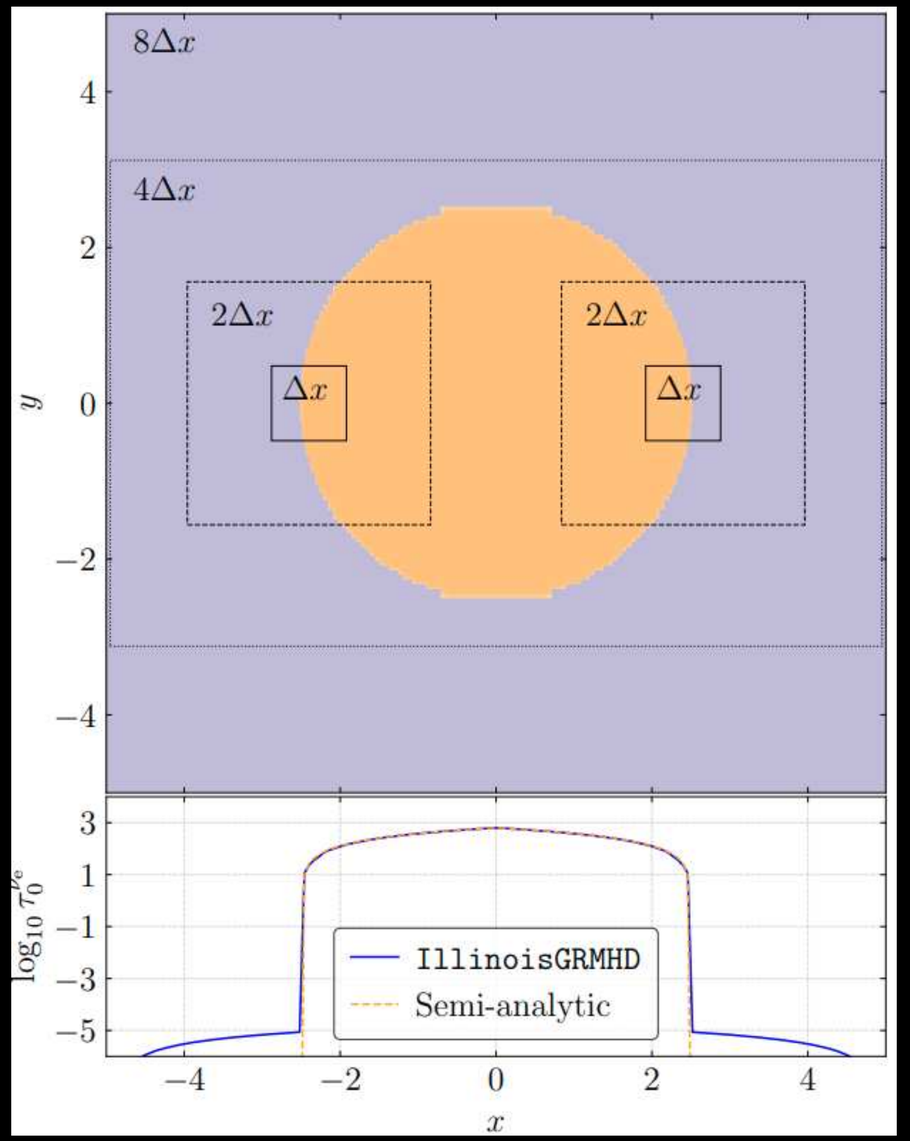


NRPyLeakage

- 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

Preamble: IllinoisGRMHD



LW+TCAN+2023

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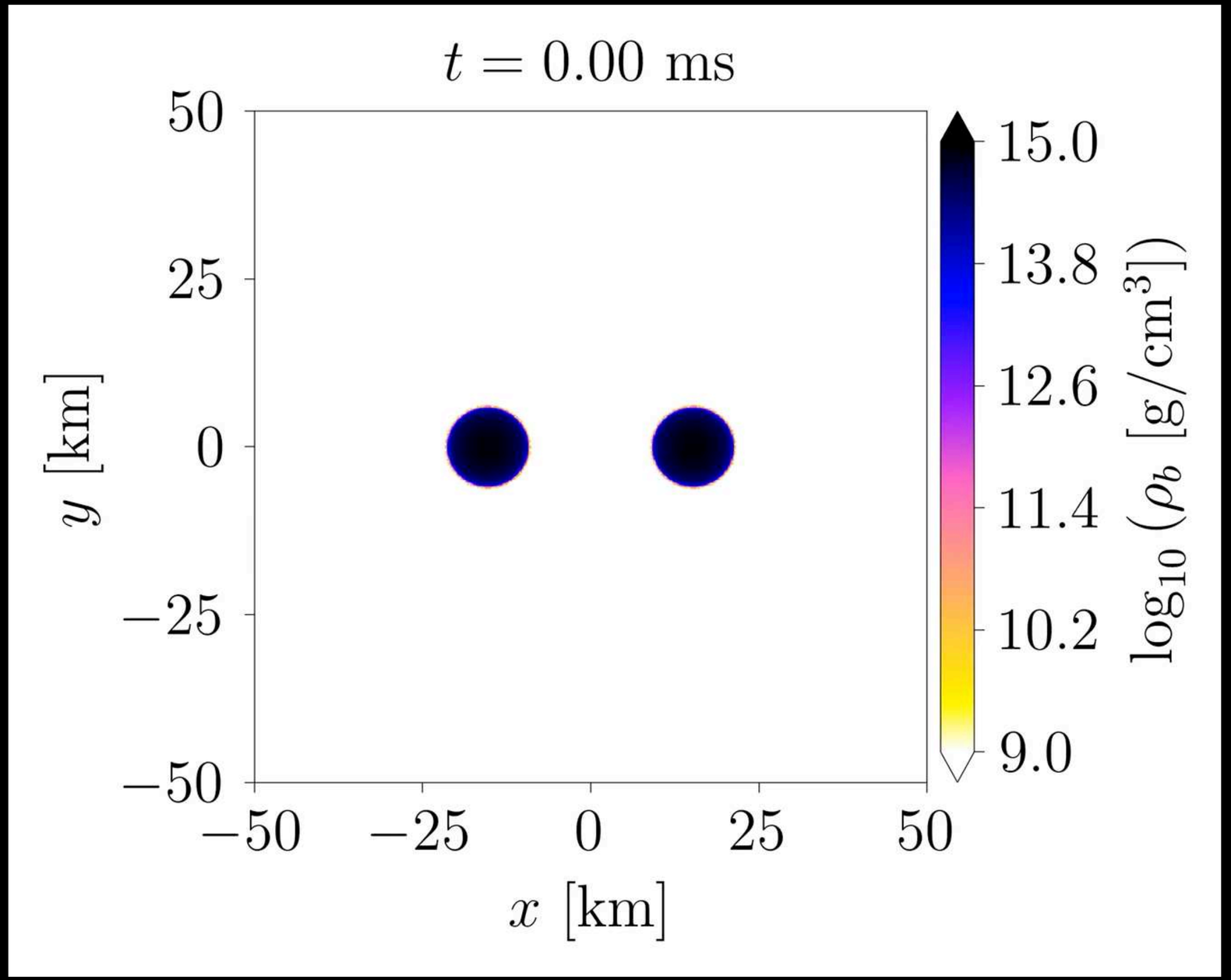

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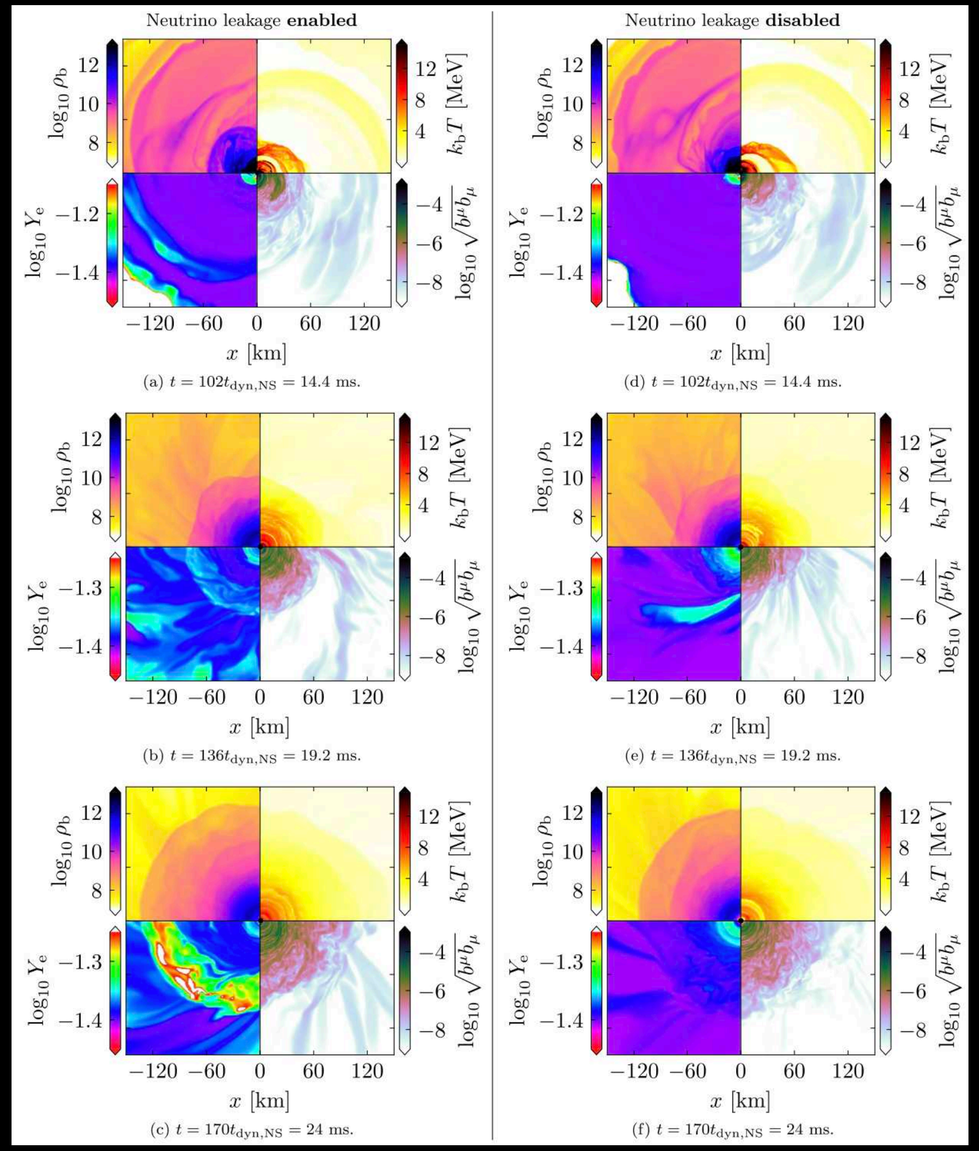

LW+TCAN+2023

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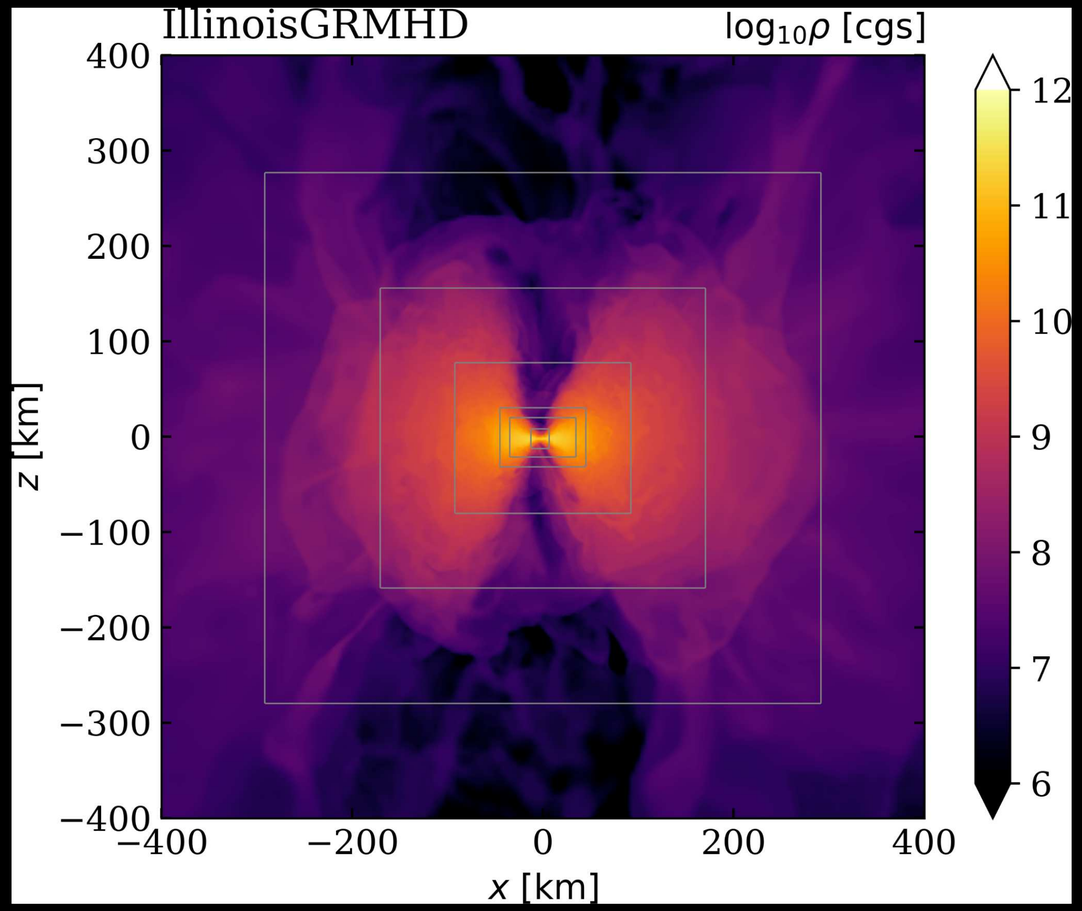
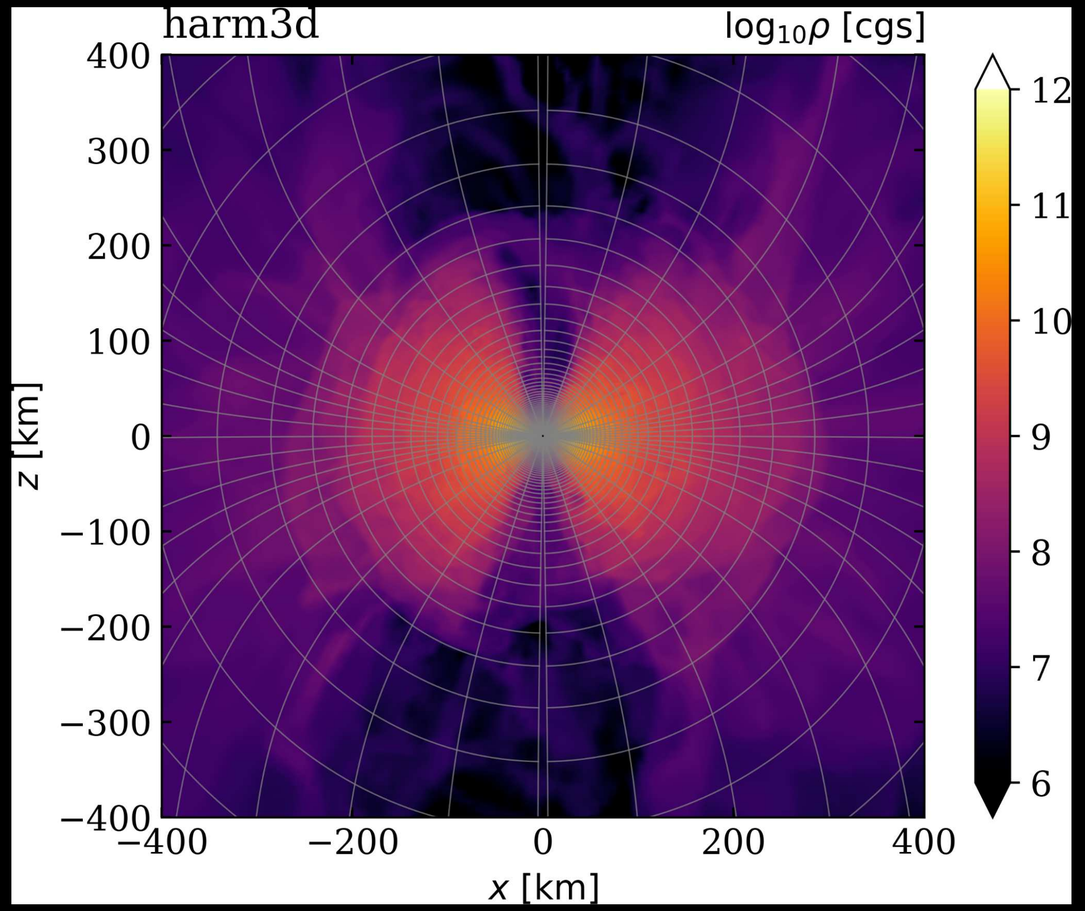




Armengol+TCAN+2022

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

Monolithic code base → Difficult to debug and extend

Monolithic code base → Not future-proof

Steep learning curve → Discourages community adoption

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

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

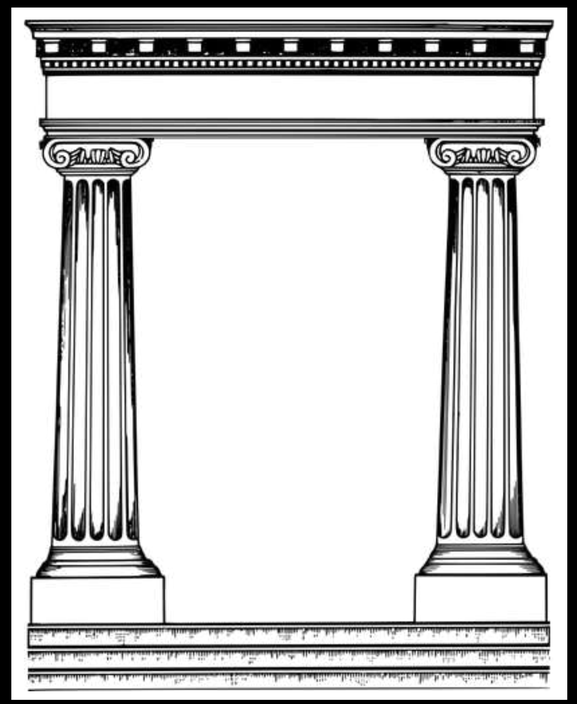
GRHayL: Design Philosophy

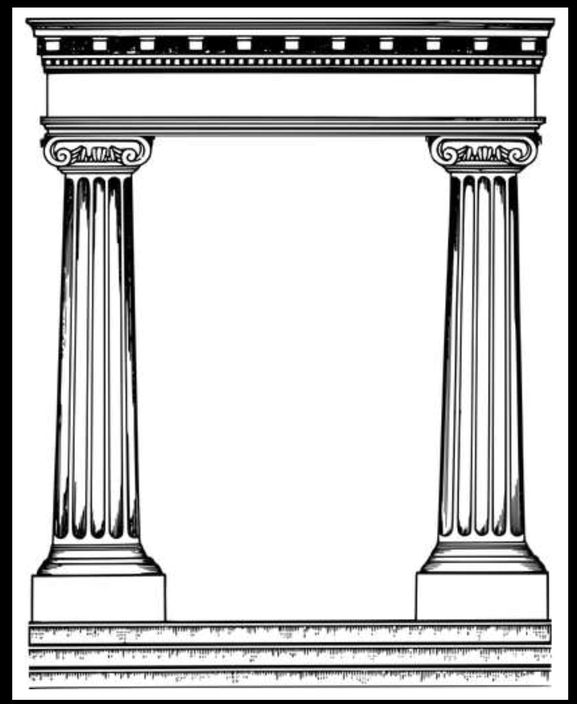
Streamlined new user pipeline

Modularity

Extensive documentation

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

Small, modular pieces → Self-container modules (**gems**)

No obscure language features → C with minimum dependencies

Good, extensive documentation → Wiki pages for all gems and functions

GRHayL: modularity and infrastructure agnosticism

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

GRHayL: modularity and infrastructure agnosticism

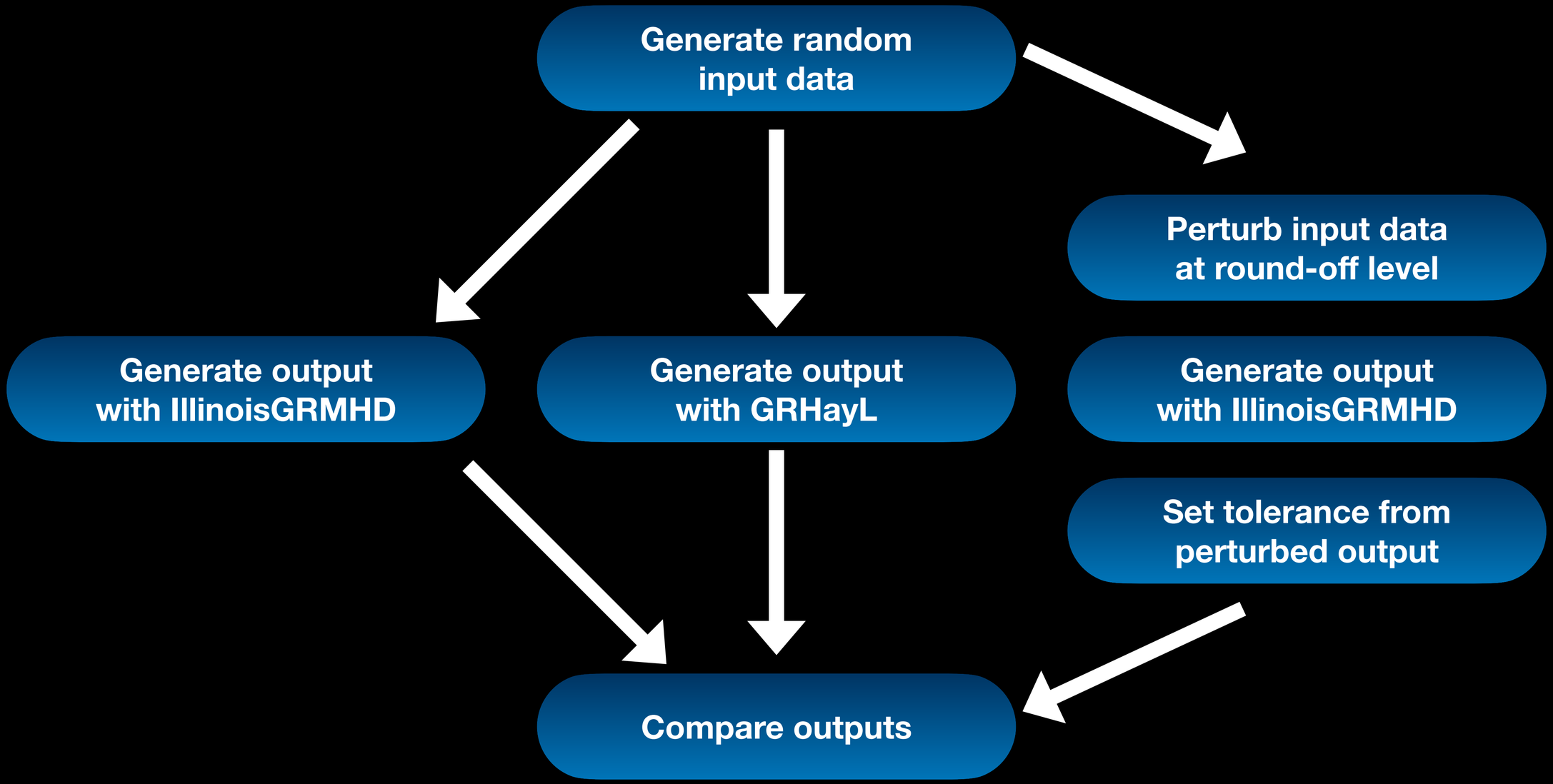
Core Code Infrastructure
Cactus/Einstein Toolkit
NRPy+/BlackHoles@Home
Your Infrastructure/Code

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

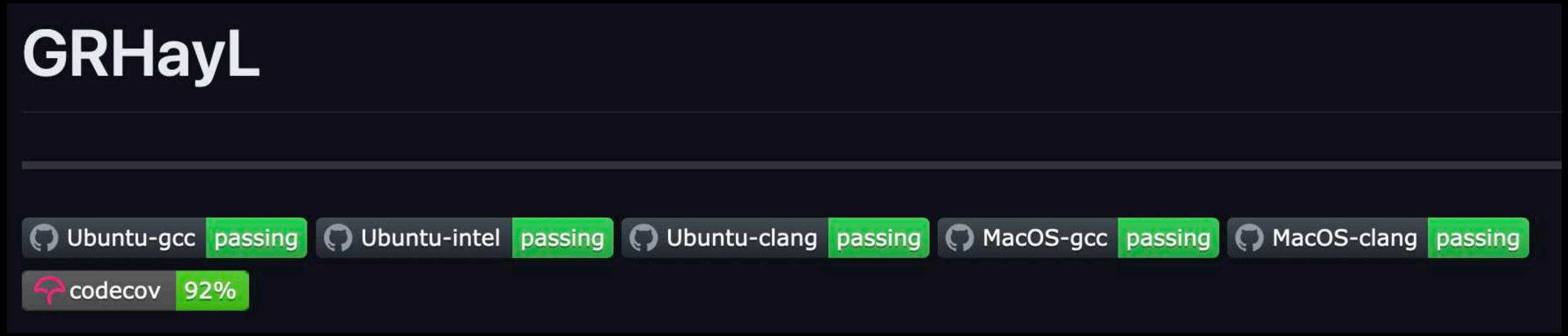
How do we **validate** GRHayL?



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



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

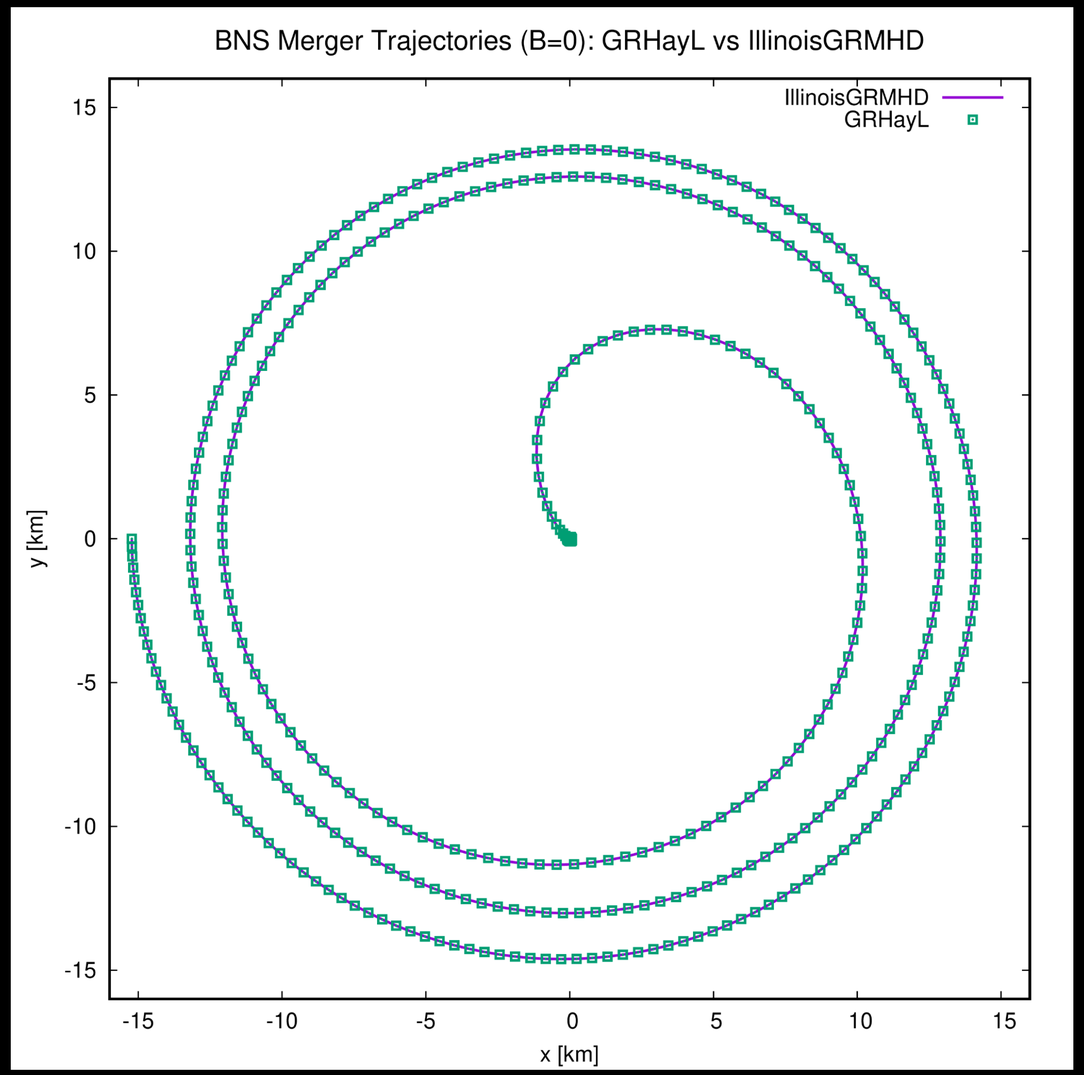
Current implementations (infrastructures)

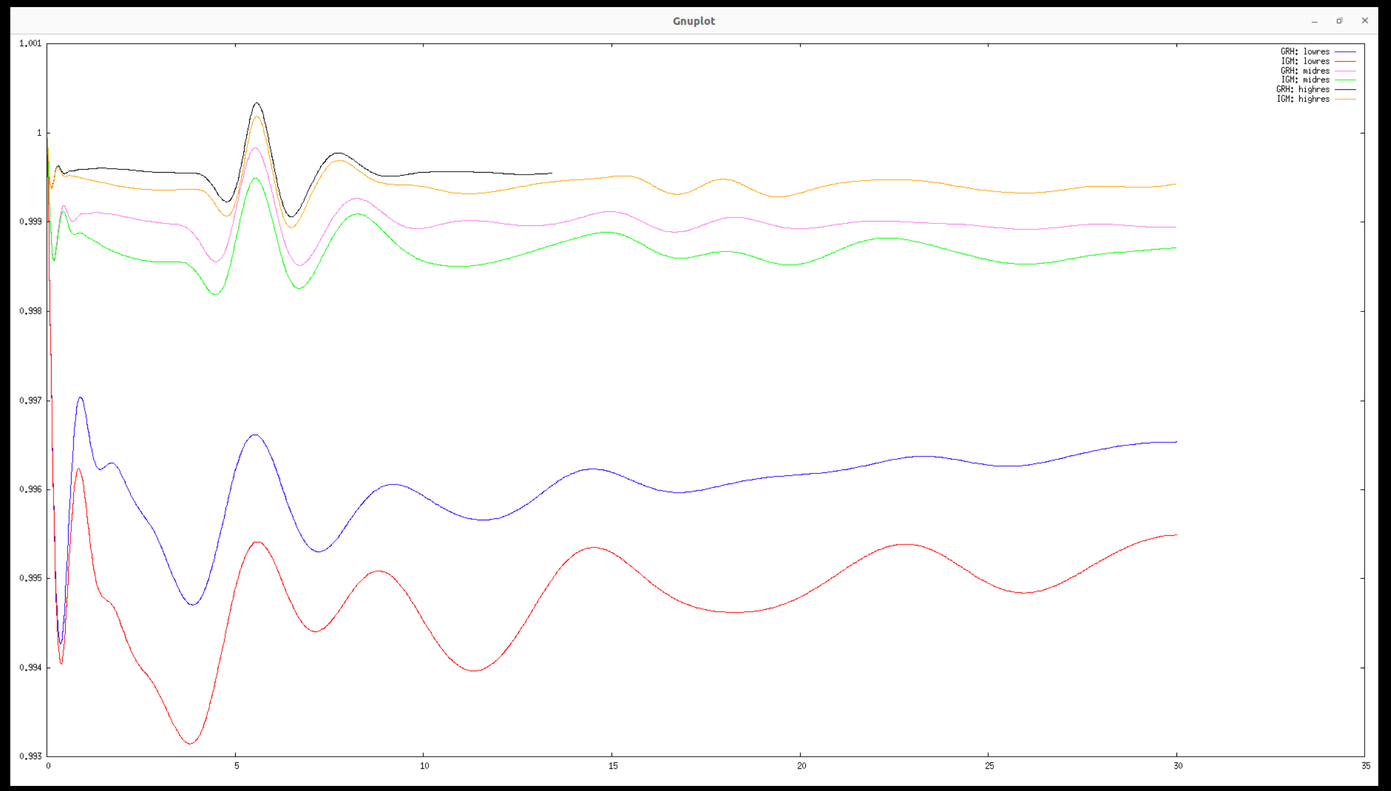
- IllinoisGRMHD (Carpet/CarpetX)
- GRHayLHD (Carpet/CarpetX/NRPy+)

Future infrastructures

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

GRHayL: implementations/infrastructures





Cupp+ (in preparation)

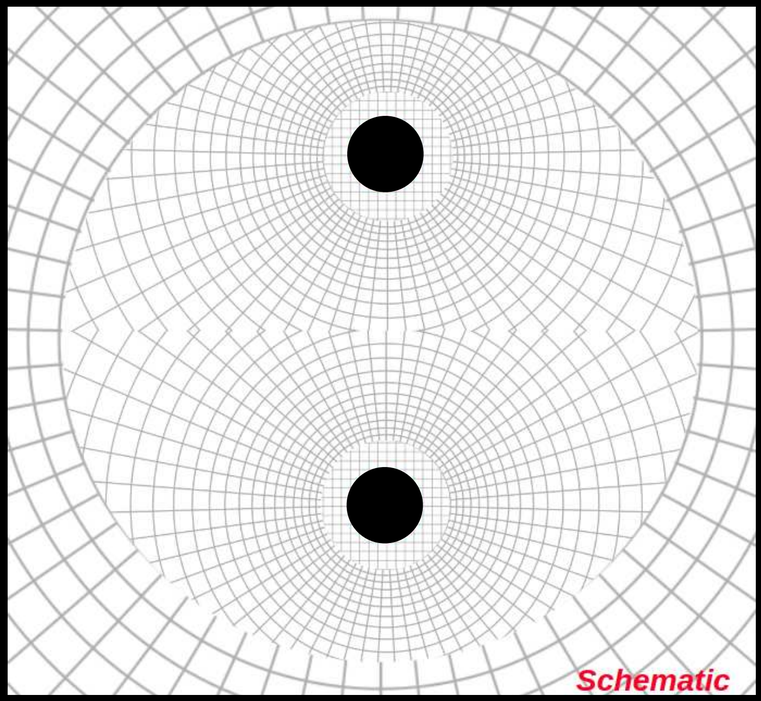
GRHayL: summary and future developments

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?