GRHayL & IllinoisGRMHD: cross-infrastructure GRMHD code development

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In collaboration with
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and Zachariah Etienne

einstein toolkit

NRPy

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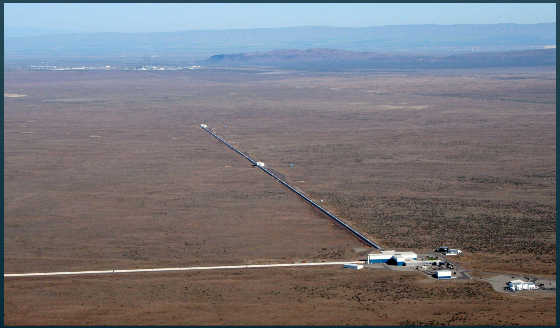
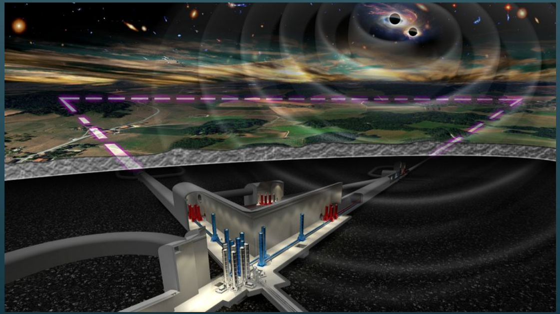
West Virginia University
DEPARTMENT OF PHYSICS AND ASTRONOMY

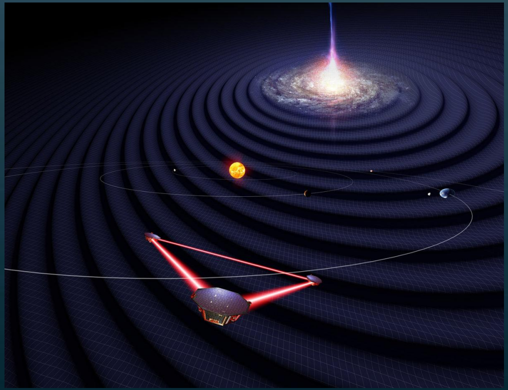
Challenges in Numerical Relativity

Improved gravitational wave detectors
New land- and space-based detectors

→ Higher accuracy requirements







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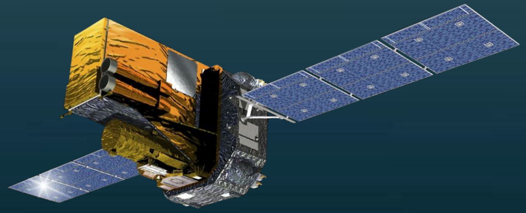
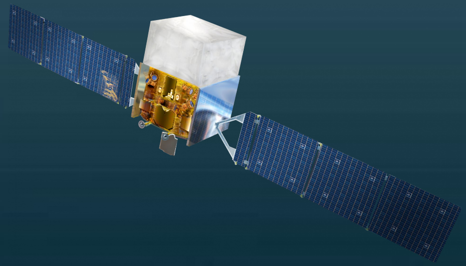
Multi-messenger astronomy → Additional physics (e.g. neutrinos)





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Higher computational cost!

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Rapidly changing HPC landscape
CPU→GPU
→ Requires infrastructure changes

Challenges in Numerical Relativity

Additional physics

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Infrastructure changes

GRMHD codes must rapidly adapt to changing infrastructures and community needs

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- Additional physics
- Higher accuracy requirements
- Infrastructure changes

GRMHD codes must rapidly adapt to changing infrastructures and community needs

Our solution: a modular, extensible GRMHD code library

What is *IllinoisGRMHD*?

- Numerical relativity code for simulating general relativistic magneto-hydrodynamics (GRMHD)
- Well-tested GRMHD evolution thorn in the Einstein Toolkit

- Refactored from closed-source code from the Illinois NR group
- Agrees with old code to round-off level
- Designed to be cleaner, better documented

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Internal Illinois Group code
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IllinoisGRMHD
Espino *et al.* (2023)

Frankfort/IllinoisGRMHD (FIL)
Most *et al.* (2019)

Tabulated IllinoisGRMHD
Werneck *et al.* (2023)

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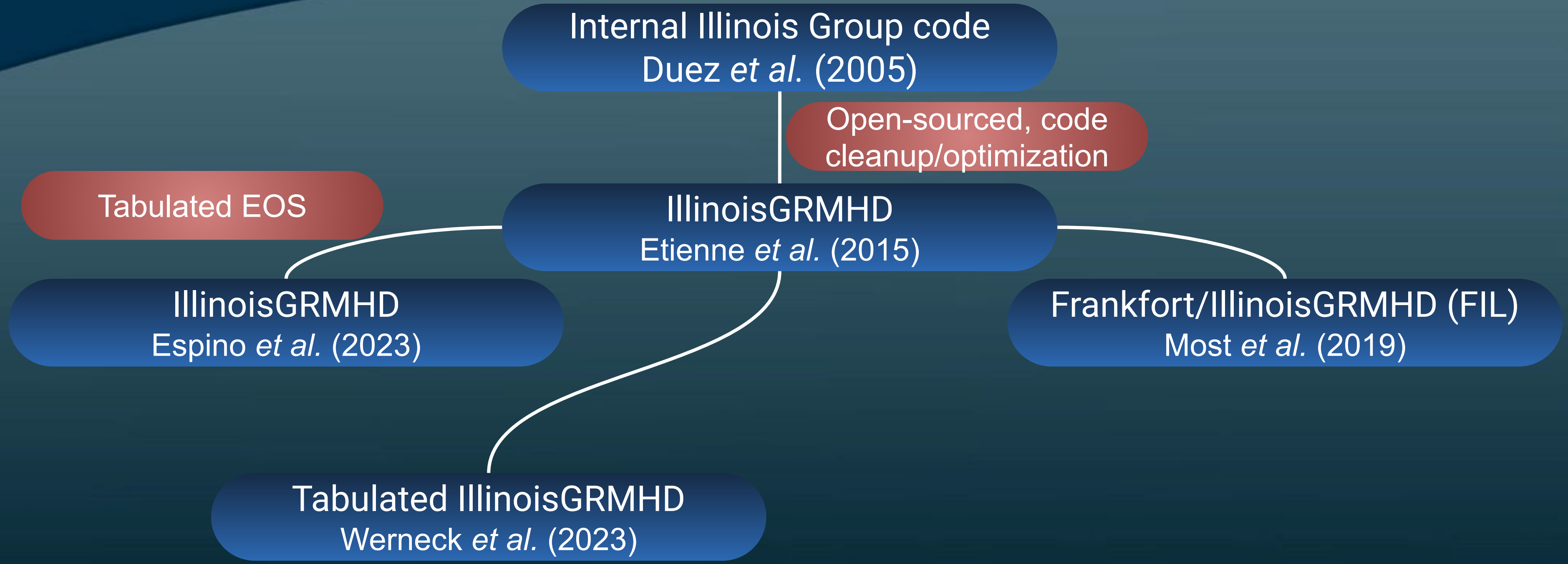

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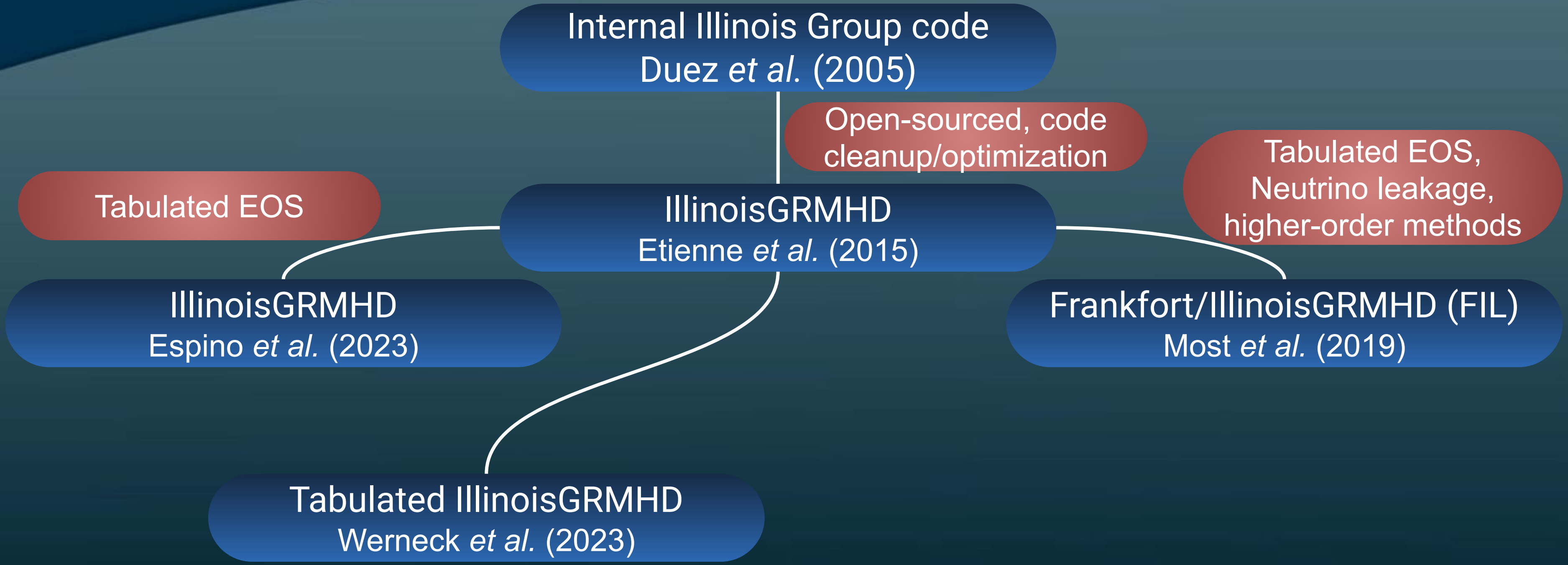

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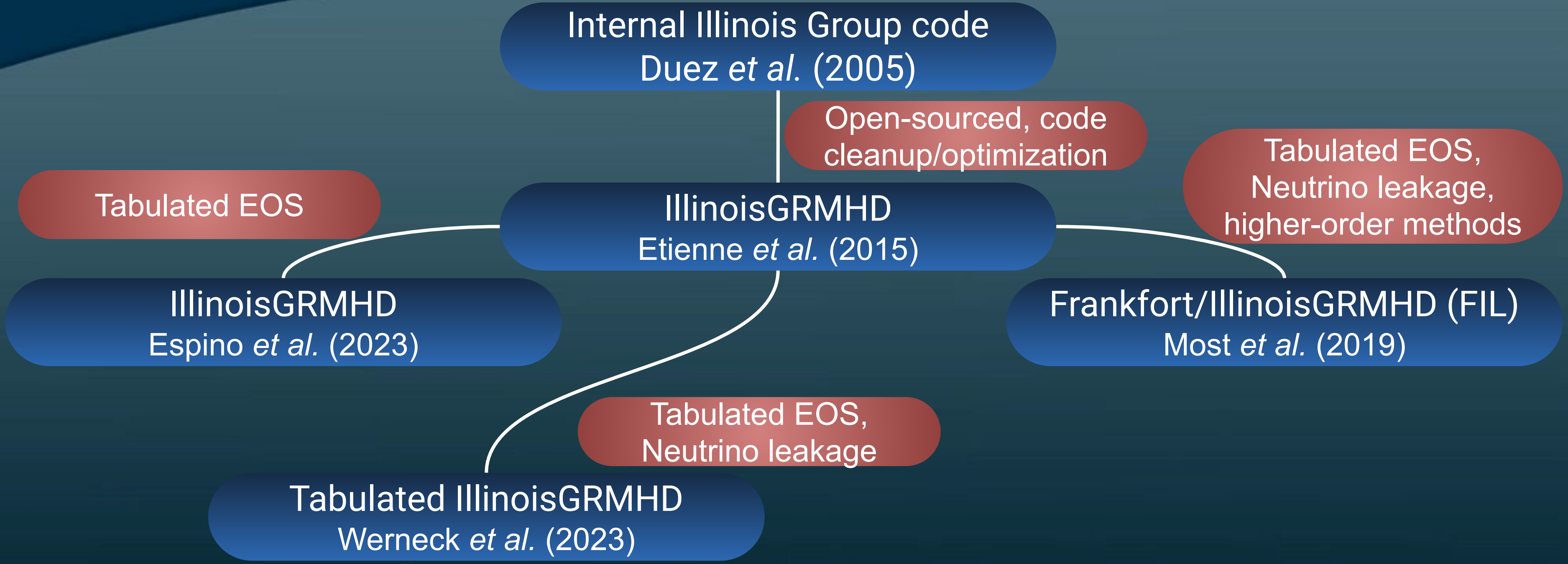

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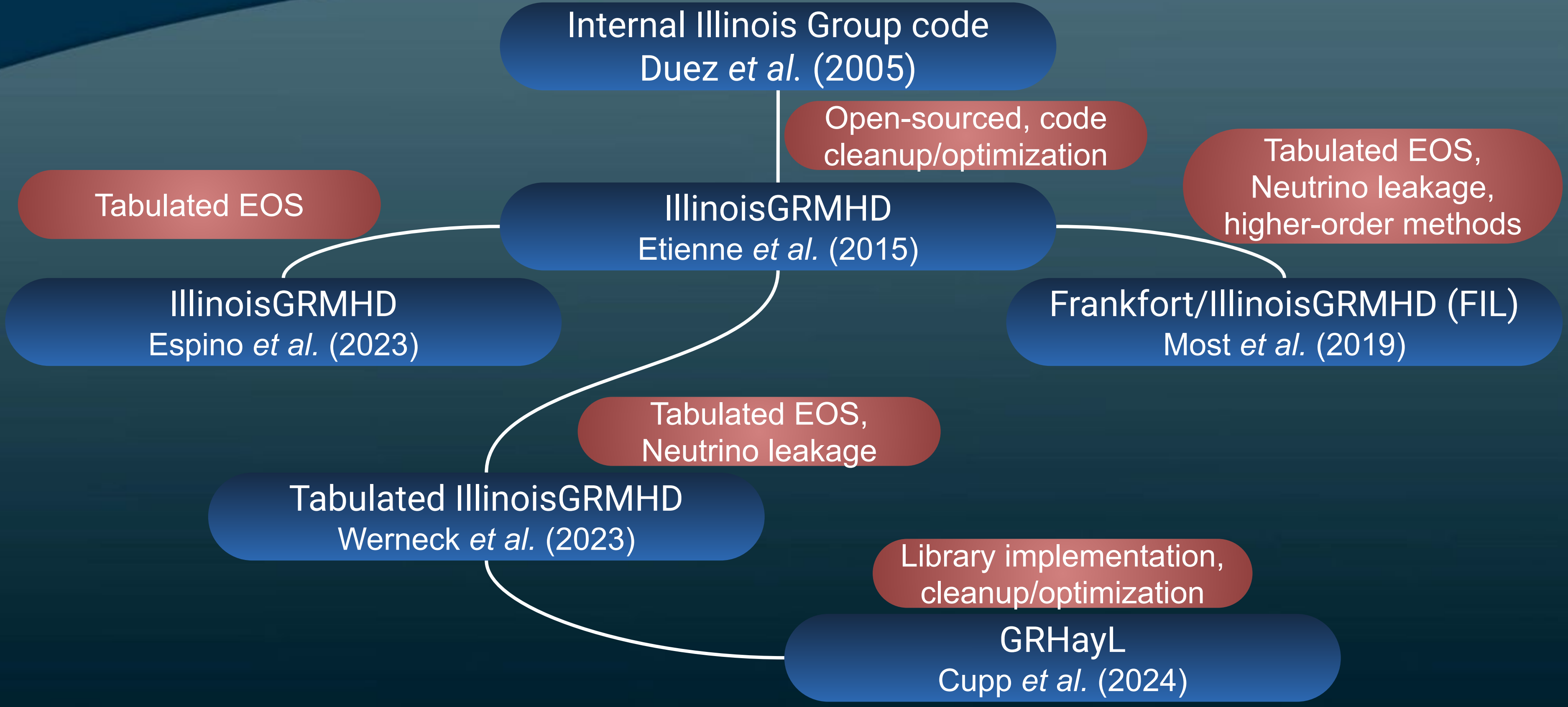

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General Relativistic Hydrodynamics Library (GRHayL)

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- Library functions are purely pointwise or stencil-wise, ensuring infrastructure-agnosticism

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- Better documentation
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Automated continuous integration (CI) testing

- Validates output against old IllinoisGRMHD when possible
- Unit tests cover 97% of the GRHayL codebase

Modularity and Extensibility

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

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

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

Modularity and Extensibility

Core Code Infrastructure

Cactus/Einstein Toolkit

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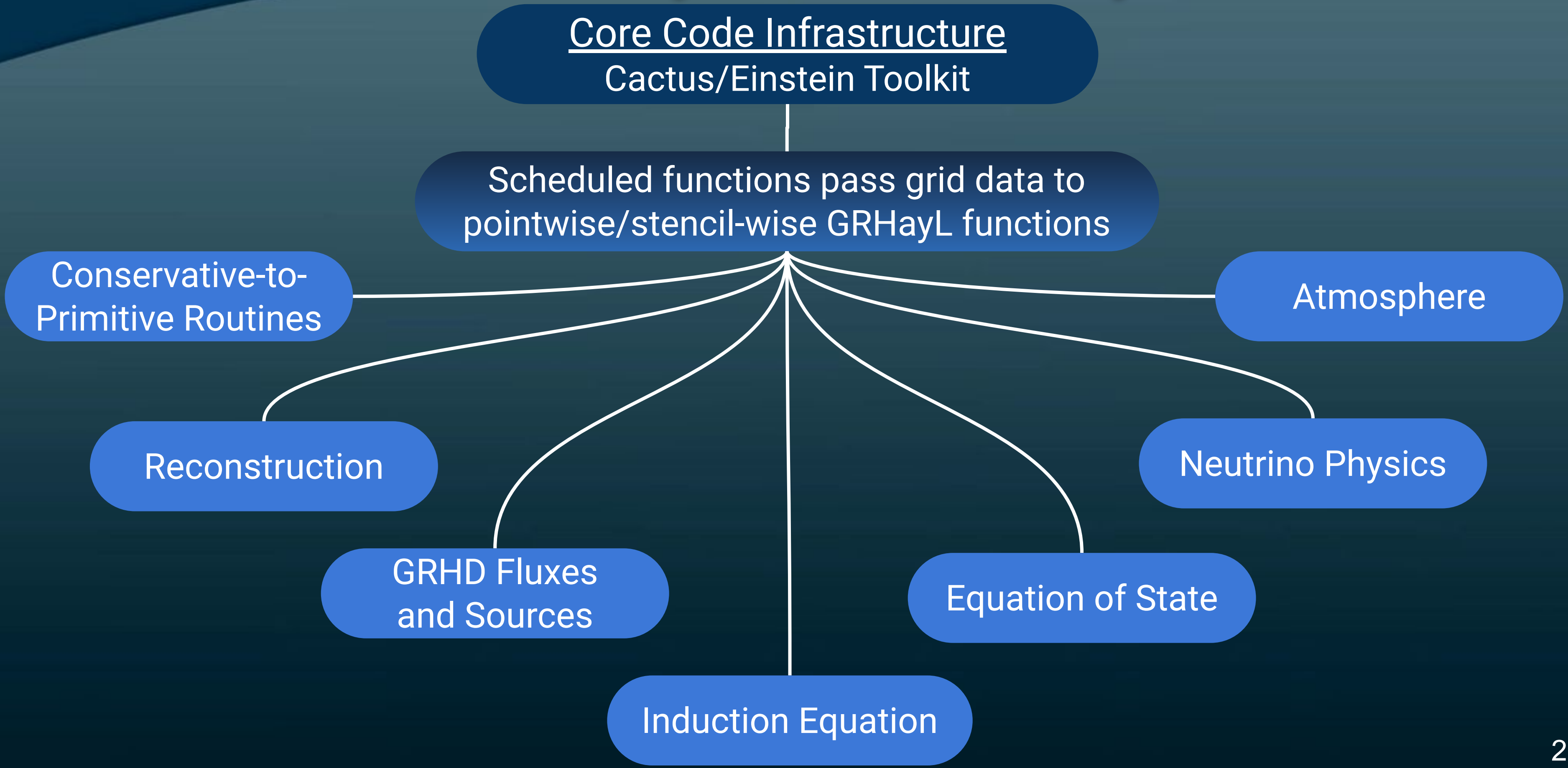
Scheduled functions pass grid data to pointwise/stencil-wise GRHayL functions

Modularity and Extensibility



Modularity and Extensibility

GRHayL Features

- *Atmosphere* module currently only provides constant atmosphere prescription
- Radial falloff prescription is in progress

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- Neutrino M1-closure scheme planned, as well as photon transport schemes

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- *Flux_Source* module provides functions for computing
- Characteristic speeds
- Source terms and fluxes for conservative variables, including entropy and electron fraction

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- *EOS* module provides simple Gamma-law, hybrid piecewise polytrope, and tabulated equations of state
- Function calls abstracted to allow for swapping of functions for more modularity

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- Up to 3 backups can be selected for use by built-in backup routine

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- *Induction* module provides function to facilitate computing the right-hand sides for evolving the staggered vector potential and scalar potential

GRHayL Features

- *Reconstruction* module provides methods for computing the face values of cell-centered quantities
- Currently includes minmod, mc, superbee, and PPM methods

GRHayL in the Toolkit: GRHayLib

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- Works for Carpet and CarpetX, but functions currently only available on the host

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- Code improvements removed ~40% of grid functions

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- GRHayLHDX implements an identical evolution code for CarpetX
- Currently only runs on the host
- Once GRHayL supports GPUs, this thorn can immediately turn on GPU capability

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  - 1D sound wave, shock tube, and Balsara tests
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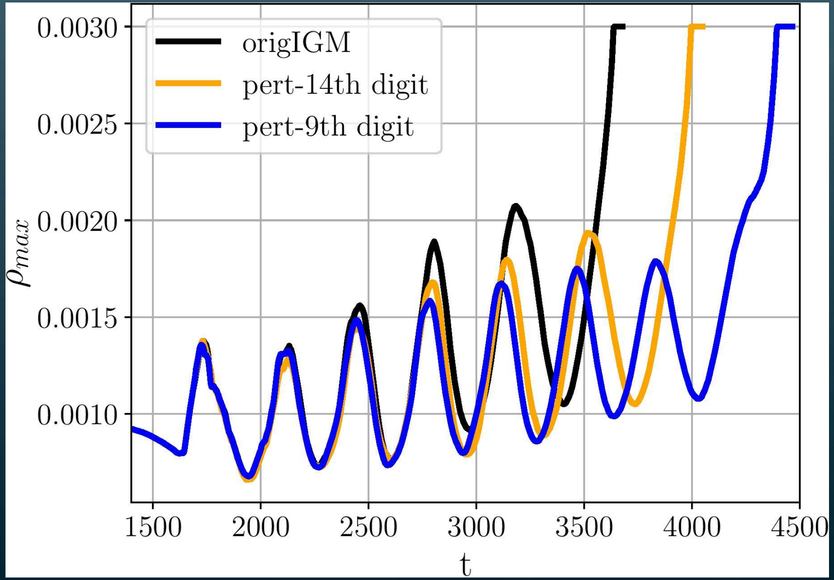
- GRHayLIDX provides the same features for CarpetX

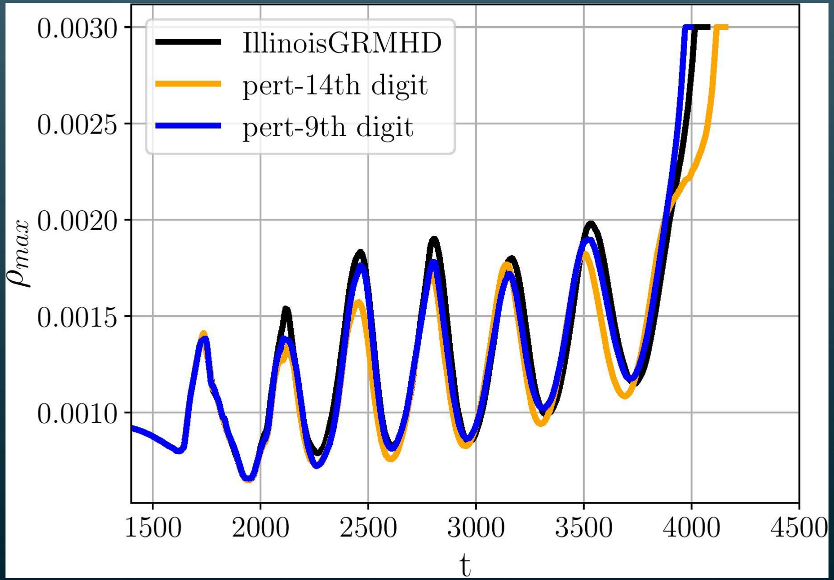
Hybrid EOS BNS comparison: central density

Effects of perturbing the initial data

Old IllinoisGRMHD



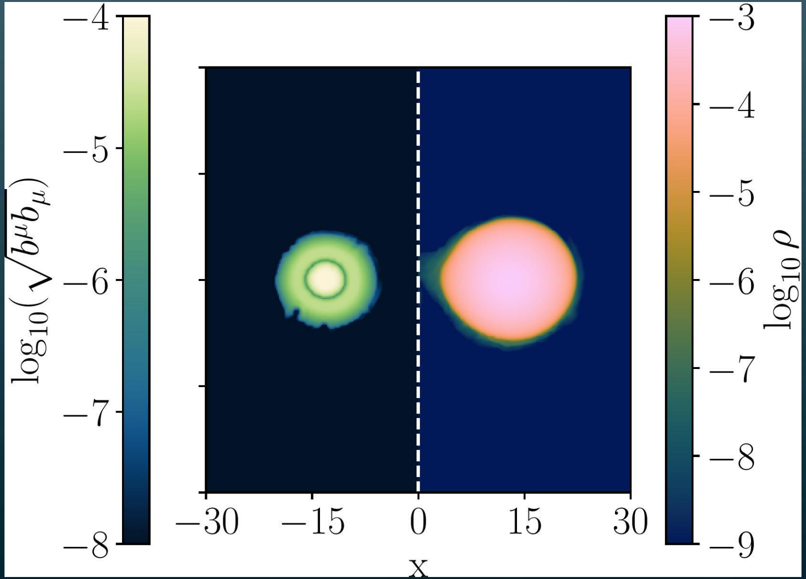
New (GRHayL-based) IllinoisGRMHD



Hybrid EOS BNS comparison: density and magnetic field strength

Slice of z=0 plane during inspiral at t=944 (two full orbits)

Old IllinoisGRMHD



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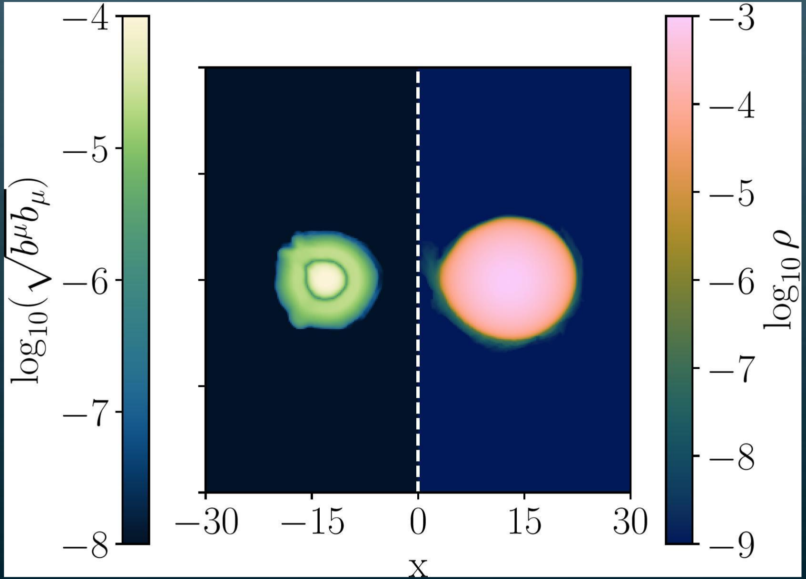
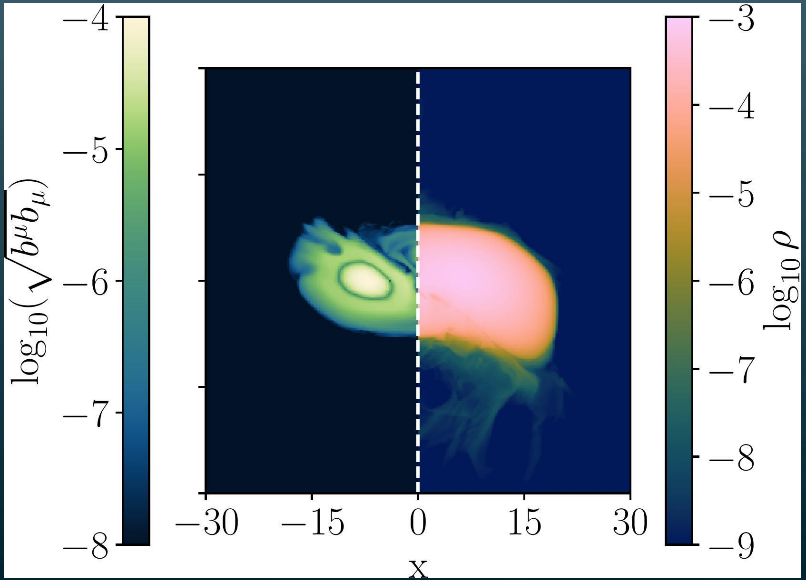


Hybrid EOS BNS comparison: density and magnetic field strength

Slice of z=0 plane during inspiral at t=1632 (first touch)

Old IllinoisGRMHD



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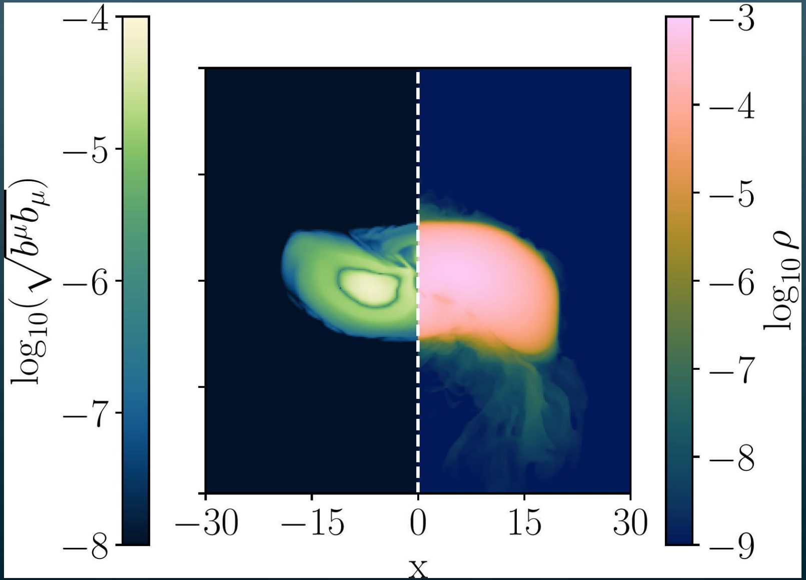
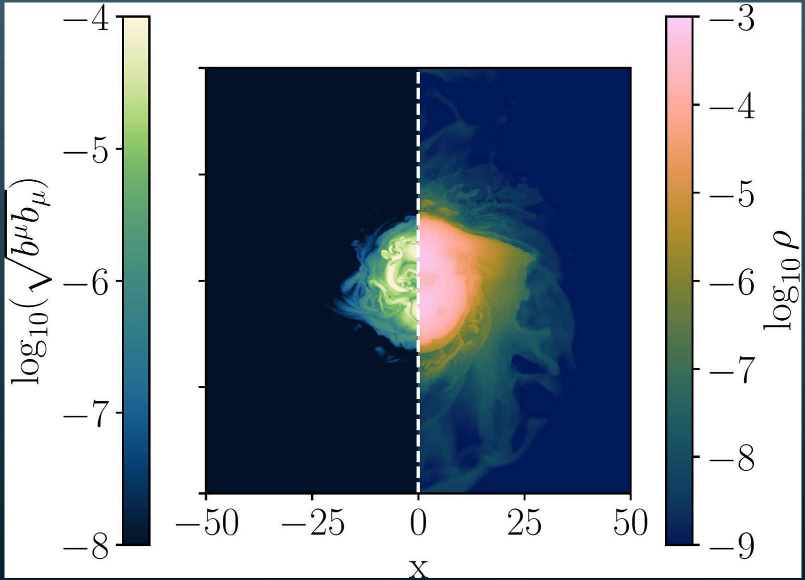


Hybrid EOS BNS comparison: density and magnetic field strength

Slice of z=0 plane at t=1920 (hypermassive neutron star)

Old IllinoisGRMHD



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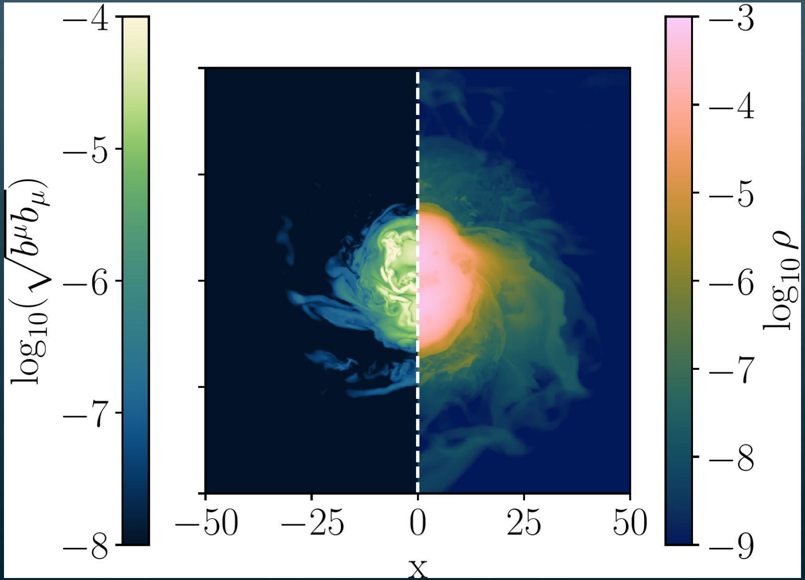
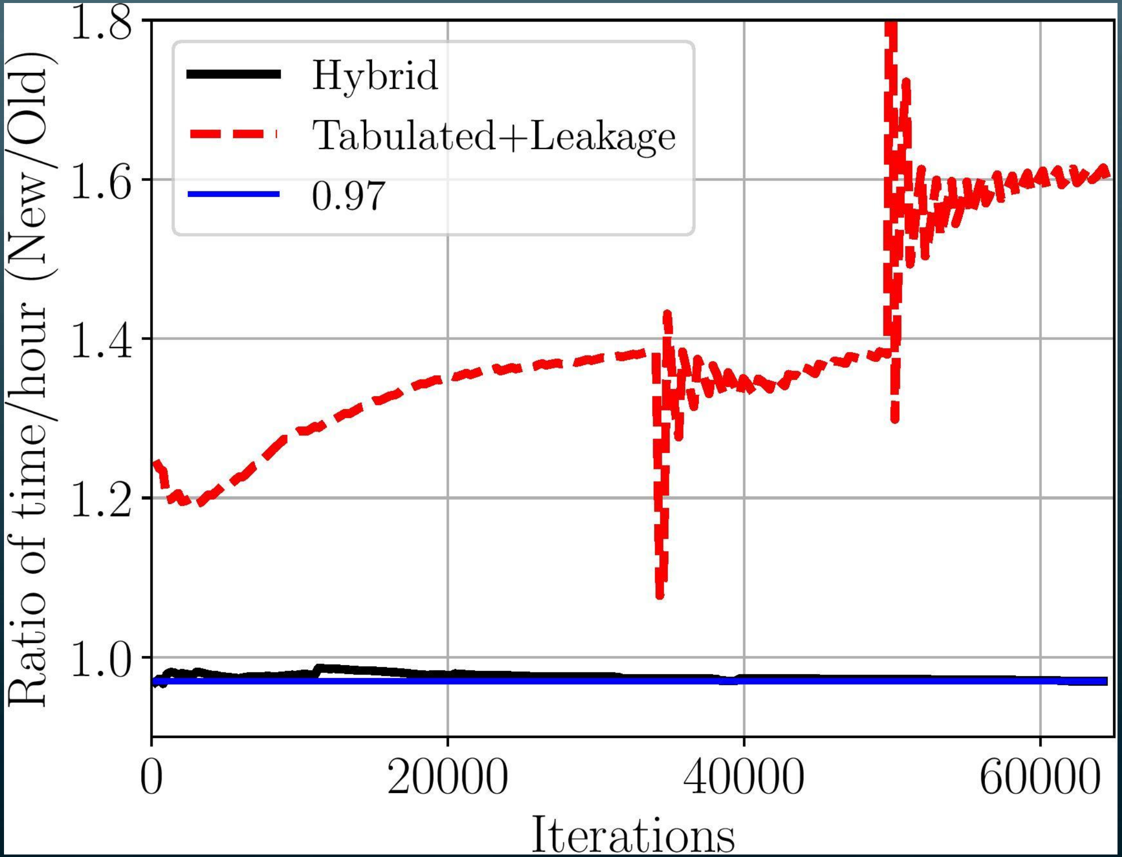


BNS comparison: simulation runtimes

- Ratio of new/old simulation time per hour
- Hybrid code is slower by ~2.5% → 30 day simulation gains ~1 day
- Tabulated code is faster by 20-60%
- Spikes are from checkpoint/restarts



GRHayLib Parameter Setup

GRHayLib::con2prim_routine = “Noble2D”

GRHayLib::con2prim_backup_routines[0] = “Palenzuela1D”

GRHayLib::Lorenz_damping_factor = 0.1

GRHayLib::Psi6threshold = 1e+100

GRHayLib::rho_b_atm = 1.0e-10

GRHayLib::rho_b_min = 1.0e-10

GRHayLib::rho_b_max = 0.003

GRHayLib Parameter Setup: Hybrid EOS

GRHayLib::EOS_type = “Hybrid”

GRHayLib::Gamma_ppoly_in[0] = 2

GRHayLib::Gamma_th = 2

GRHayLib::k_ppoly0 = 1

GRHayLib::neos = 1

GRHayLib Parameter Setup: piecewise polytrope (SLy)

```
GRHayLib::EOS_type            = "Hybrid"
GRHayLib::Gamma_th            = 2
GRHayLib::neos                = 7
GRHayLib::k_ppoly0            = 168.57487497864866555
GRHayLib::rho_ppoly_in[0]     = 3.9514374600825099344e-11
GRHayLib::rho_ppoly_in[1]     = 6.1264330975269766832e-07
GRHayLib::rho_ppoly_in[2]     = 4.2549756827347083401e-06
GRHayLib::rho_ppoly_in[3]     = 0.00023677859688909009043
GRHayLib::rho_ppoly_in[4]     = 0.00081153036440410962048
GRHayLib::rho_ppoly_in[5]     = 0.0016192159535484849844
GRHayLib::Gamma_ppoly_in[0] = 1.5842499999999999361
GRHayLib::Gamma_ppoly_in[1] = 1.2873300000000000853
GRHayLib::Gamma_ppoly_in[2] = 0.62222999999999999498
GRHayLib::Gamma_ppoly_in[3] = 1.3569199999999999904
GRHayLib::Gamma_ppoly_in[4] = 3.0049999999999998934
GRHayLib::Gamma_ppoly_in[5] = 2.9879999999999999893
GRHayLib::Gamma_ppoly_in[6] = 2.8509999999999999787
```

GRHayLib Parameter Setup: Tabulated EOS

```
GRHayLib::EOS_tablepath = “path_to_table.h5”
GRHayLib::EOS_type = “tabulated”
GRHayLib::evolve_entropy = “yes”
GRHayLib::evolve_temperature = “yes”
GRHayLib::rho_b_atm = 1.29e-10
GRHayLib::rho_b_max = 0.004
GRHayLib::rho_b_min = 1.29e-10
GRHayLib::T_atm = 0.01
GRHayLib::T_max = 90
GRHayLib::T_min = 0.01
GRHayLib::Y_e_atm = 0.5
GRHayLib::Y_e_max = 0.5
```

Converting an IllinoisGRMHD parfile

1. Remove ID_converter_ILGRMHD and Convert_to_HydroBase thorns
2. If using ID_converter_ILGRMHD::pure_hydro_run, switch to using GRHayLHD
3. Change the following parameters:
   - ID_converter_ILGRMHD::Gamma_Initial→GRHayLib::Gamma_ppoly_in[0]
   - ID_converter_ILGRMHD::random_seed→IllinoisGRMHD::random_seed
   - ID_converter_ILGRMHD::random_pert→IllinoisGRMHD::random_pert
   - ID_converter_ILGRMHD::K_Initial→GRHayLib::k_ppoly0
   - Convert_to_HydroBase::Convert_to_HydroBase_every
     →IllinoisGRMHD::Convert_to_HydroBase_every
4. If you want to perturb the initial data, add
   IllinoisGRMHD::perturb_initial_data = yes
5. Remove the deprecated parameters IllinoisGRMHD::tau_atm and IllinoisGRMHD::conserv_to_prims_debug

Converting an IllinoisGRMHD parfile

6. Change the following parameters
   - IllinoisGRMHD::GAMMA_SPEED_LIMIT→GRHayLib::max_Lorentz_factor
   - IllinoisGRMHD::K_poly→GRHayLib::k_ppoly0
   - IllinoisGRMHD::rho_b_atm→GRHayLib::rho_b_atm
   - IllinoisGRMHD::rho_b_max→GRHayLib::rho_b_max
   - IllinoisGRMHD::Psi6threshold→GRHayLib::Psi6threshold
   - IllinoisGRMHD::neos→GRHayLib::neos
   - IllinoisGRMHD::gamma_th→GRHayLib::Gamma_th
   - IllinoisGRMHD::damp_lorenz→GRHayLib::Lorenz_damping_factor

Thanks for attending!

Questions?