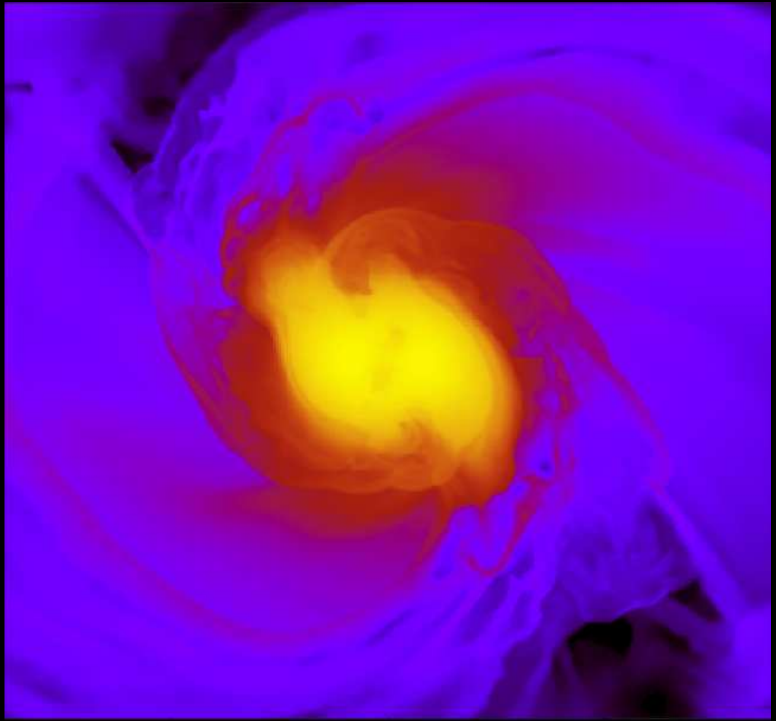
An update on the **IllinoisGRMHD** (“IGM”) code

& accurate, long-term evolutions with the **HandOff+HARMNUC** codes

Leo Werneck
In collaboration with Z.B. Etienne,
F.L. Armengol, A. Murguia-Berthier, S.C. Noble, T. Gupte
& the TCAN-80NSSC18K1488 BNS collaboration

2022 North American Einstein Toolkit School
University of Idaho, Moscow, ID



Baryonic density from a magnetized, equal-mass BNS simulation performed with **IllinoisGRMHD** using the LS220 **tabulated EOS**, shortly after merger

TCAN-80NSSC18K1488 on Binary Neutron Stars Collaboration


Zach Etienne
[BlackHoles@Home]


Thiago Assumpção
[NRPyElliptic]


Manuela Campaneli
[Overview of NR]


Fede Armengol


Josh Faber


Tanmayee Gupte


Scott Noble


Ari Murguia-Berthier

University of Idaho
West Virginia University

Rochester Institute of Technology
RIT
1829

Johns Hopkins University

NASA
Goddard Space Flight Center

Funding acknowledgement NASA-TCAN-80NSSC18K1488

https://compact-binaries.org

Overview

- Introduction & motivation

- An overview of **IllinoisGRMHD**

- Updates:
  - New primitive recovery infrastructure
  - Microphysical finite-temperature equation of state (EOS) support
  - **NRPyEOS**: NRPy+-based microphysics equation of state (EOS) table interpolator
  - **NRPyLeakage**: NRPy+-based neutrino leakage (**NRPyLeakageET**)

- Latest results

- Recap and future work

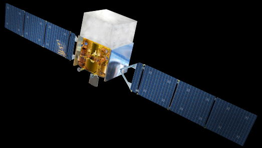
Introduction & motivation

In August 2017…

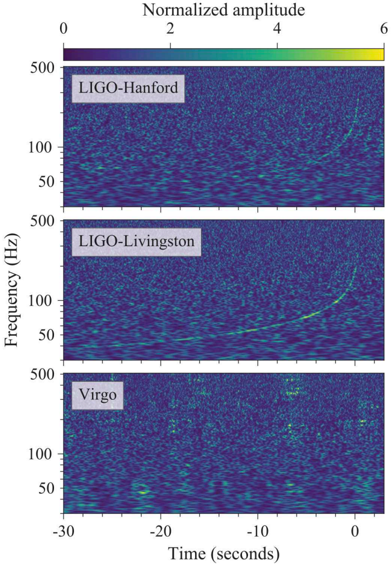
LIGO-Hanford

LIGO-Livingston

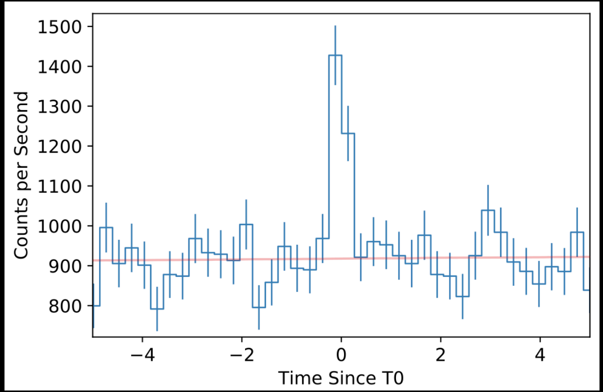
Virgo



Fermi Gamma-ray Burst Monitor



LIGO/Virgo Collaboration, PRL 119 161101 (2017)



Goldstein *et al.*, APJL 848:L14 (2017)

Introduction & motivation

Model BNS systems

Evolve metric quantities

Baikal, ML_BSSN, Lean, …

GRMHD evolution

IllinoisGRMHD, GRHydro, Spritz, …

Realistic equations of state

NRPyEOS, EOS_Omni, …

Neutrino physics

NRPyLeakage, ZelmaniLeak, ZelmaniM1, …

Adaptive Mesh Refinement

Carpet, CarpetX, …

I/O

1D, 2D, 3D data, checkpoints, …

Diagnostics

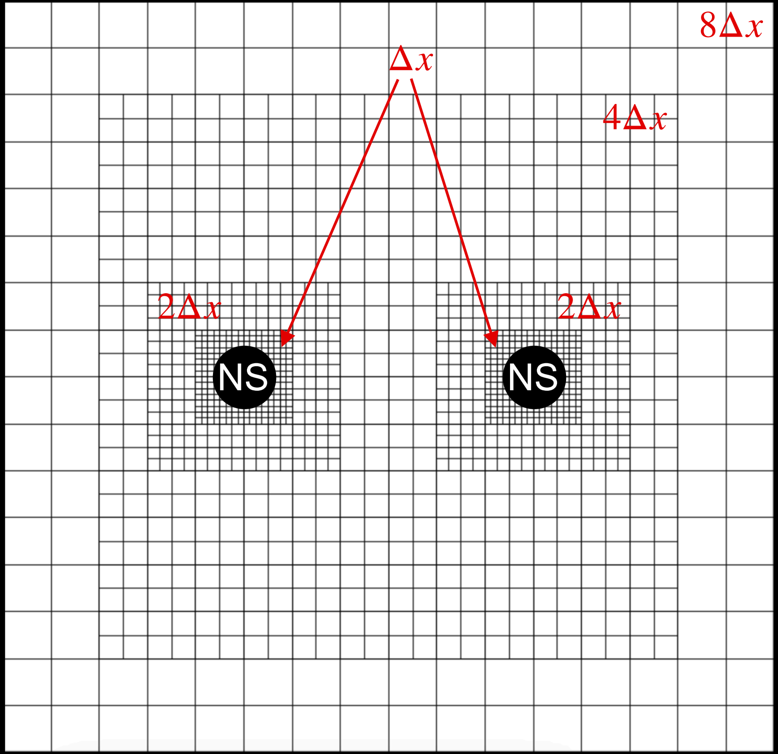
Gravitational waves, volume integrals, …

Introduction & motivation

- We must be capable of accurately and reliably model these systems
- From a computational point of view, we must do it as efficiently as possible
- For typical separations and masses, simulating the full inspiral + merger + postmerger can take months on high-end supercomputers!
- Caveat: we are only modeling O(100 ms), but really need O(seconds)
- Just keep the code running for O(years)?
- Or we could try thinking outside of the box!

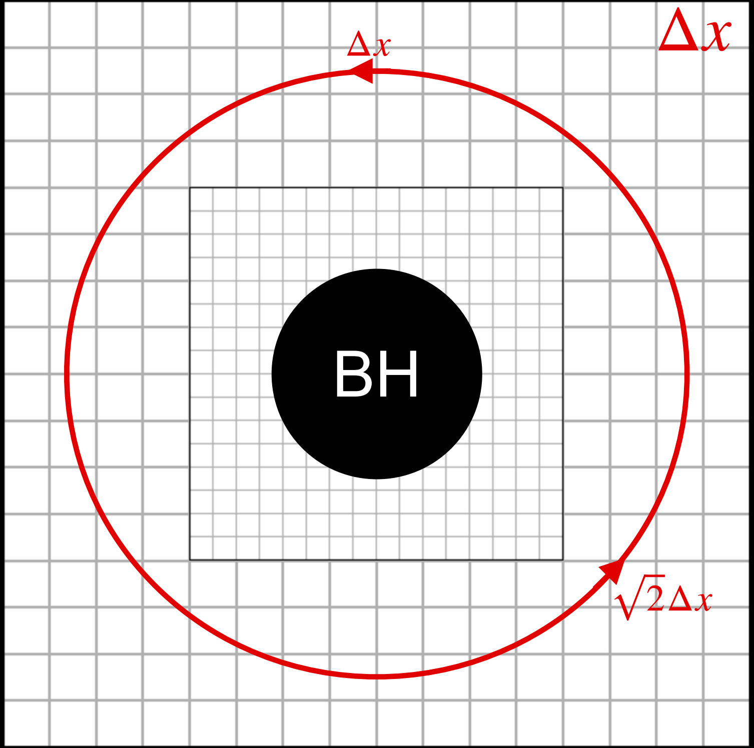
Introduction & motivation

Cartesian AMR



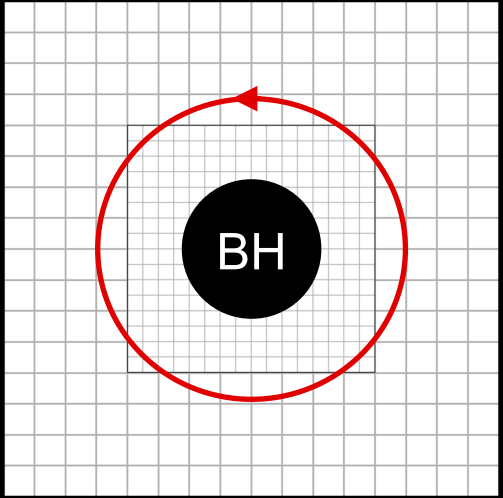
Introduction & motivation

AMR in the postmerger



Courtesy Zach Etienne

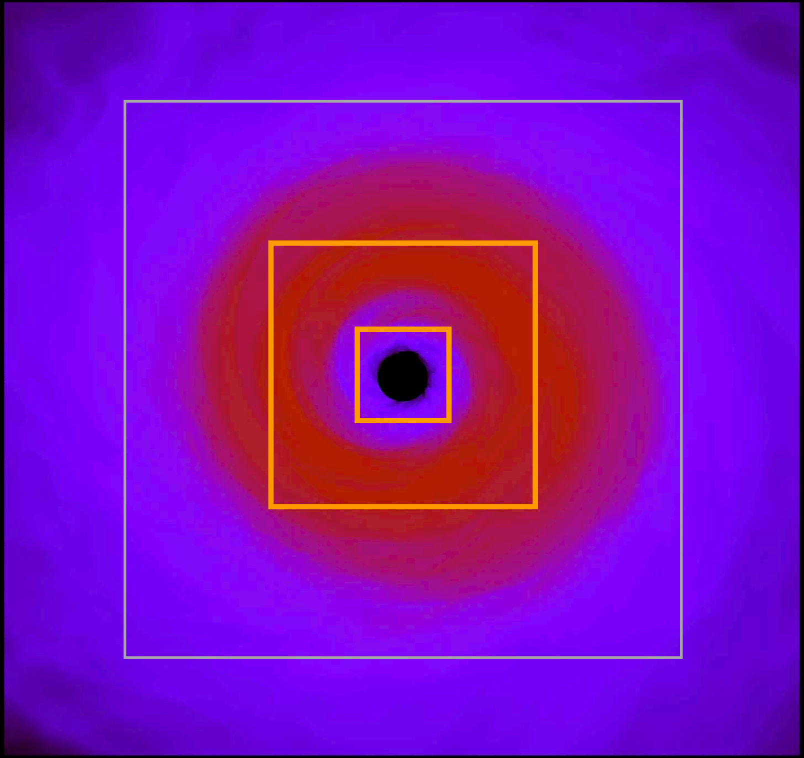
~15x more inefficient
Than spherical grids!



Inefficiencies:

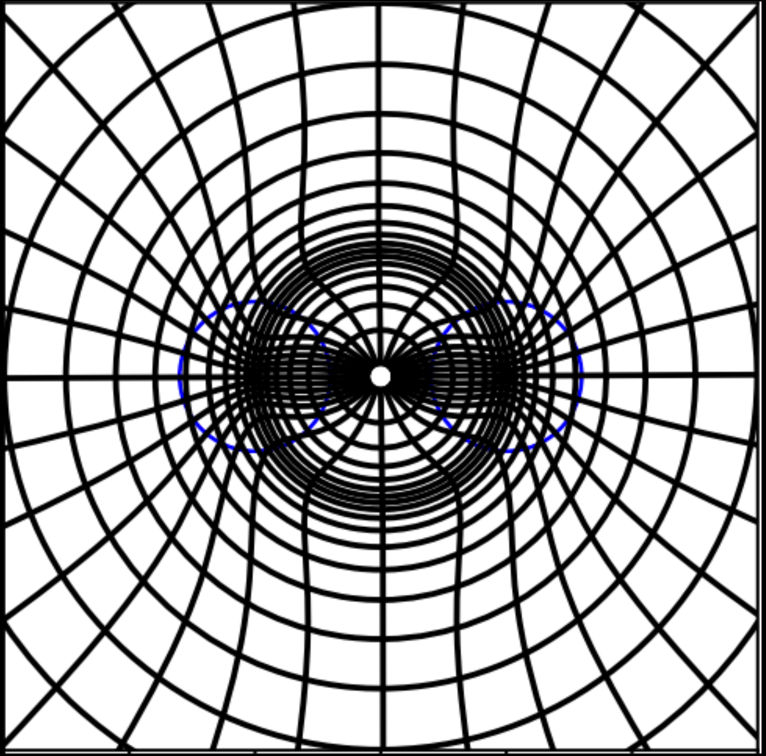
- Changes in resolution: ~2x
- Jumps in radial resolution: ~2x
- Sharp AMR corners *wasted*: ~2x
- Coarse grid under fine grid: ~1.2x
- Fine grids' wide AMR boundary: ~1.5x

Introduction & motivation



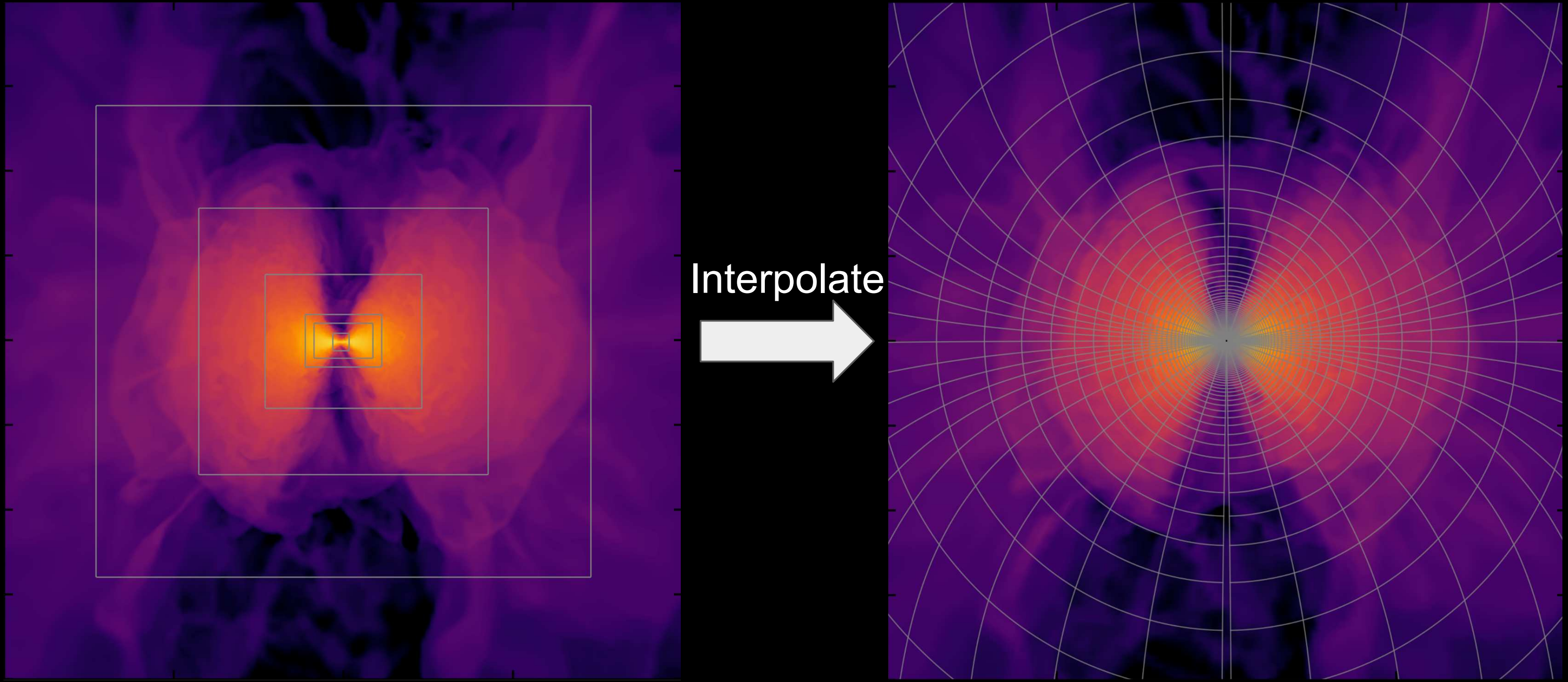
Can we do better?

Yes!



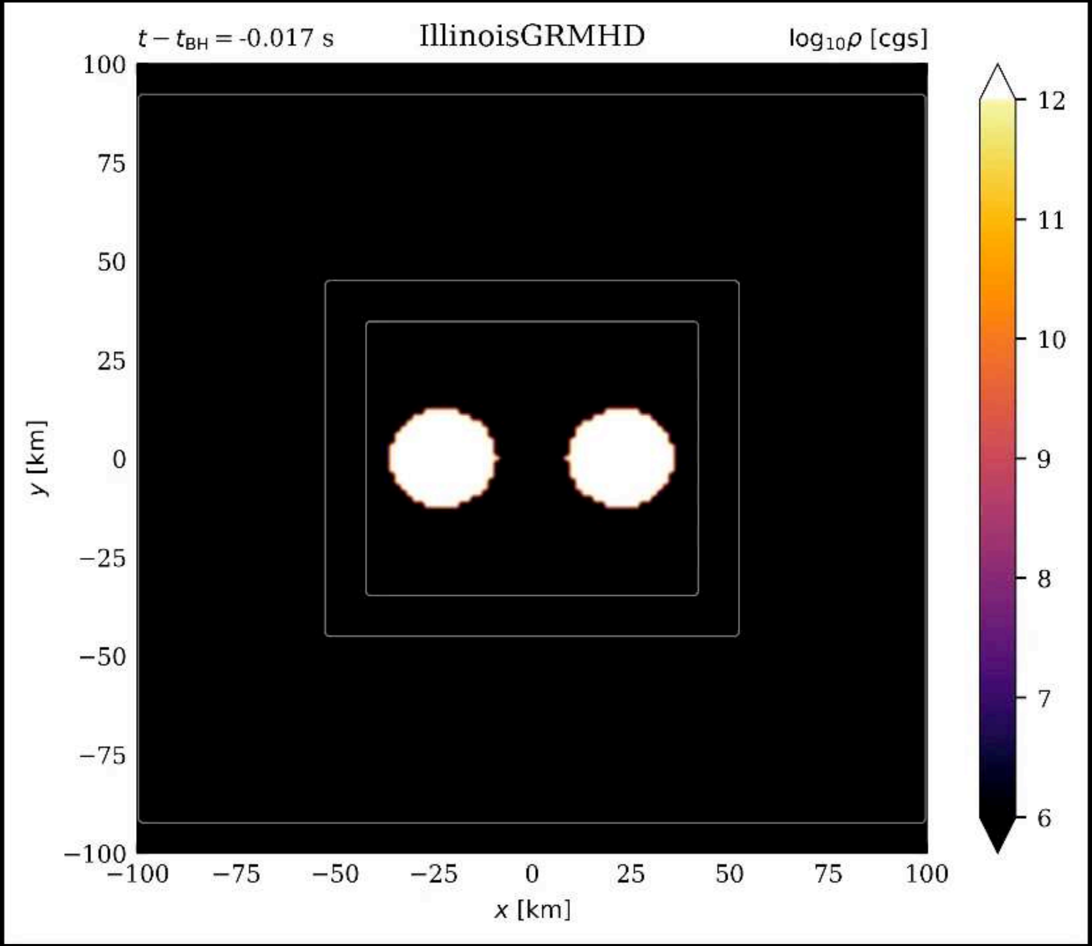
Bowen++ (2019)

The HandOff package



F.L.Armengol++TCAN (arXiv: 2112.09817)

The HandOff package



F.L.Armengol++TCAN
(arXiv: 2112.09817)

The **HandOff** — What physics can we include?

Feature	**IllinoisGRMHD**	**HARM+NUC**	**Production HandOff**
Equation of state: Gamma-law	✓	✓	F.L.Armengol++TCAN (arXiv:2112.09817)
Equation of state: Tabulated	✓	✓	Coming soon!
Neutrino physics (leakage)	✓	✓	

This talk!

L.W., Z. Etienne++TCAN, In Preparation

A.Murguia-Berthier++TCAN *ApJ* **919** 95 (2021)

IllinoisGRMHD

- A rewrite of the original GRMHD code of the Illinois NR Group (arXiv:1501.07276)

- Roundoff agreement with the original code; faster and concise

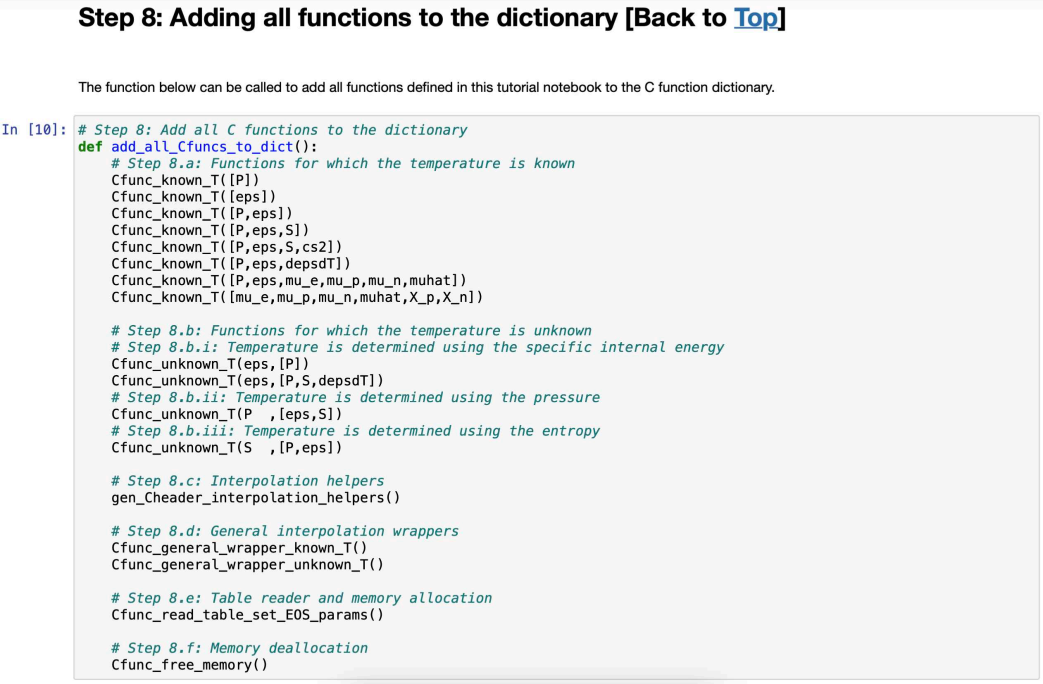
- Open-sourced and available as part of the Einstein Toolkit

- GRMHD for dynamical spacetimes:
  - Single and binary neutron stars with and without magnetic fields
  - Black hole accretion disks;
  - White dwarves;
  - Hypermassive neutron stars;
  - And many more!

- Latest improvements:
  - Hybrid EOS support (including piecewise polytropes)
  - Microphysical finite-temperature equation of state (EOS) support
  - Electron fraction and temperature evolution
  - Neutrino physics via a leakage scheme (**NRPyLeakage**)

NRPyEOS

- New NRPy+-based EOS table interpolation routines, fully documented using Jupyter notebooks
- Clean interface for interpolating finite-temperature EOS tables
- Avoids unnecessary interpolations by generating specialized functions
- NRPy+-version is fully open-source and ET-version will be released soon

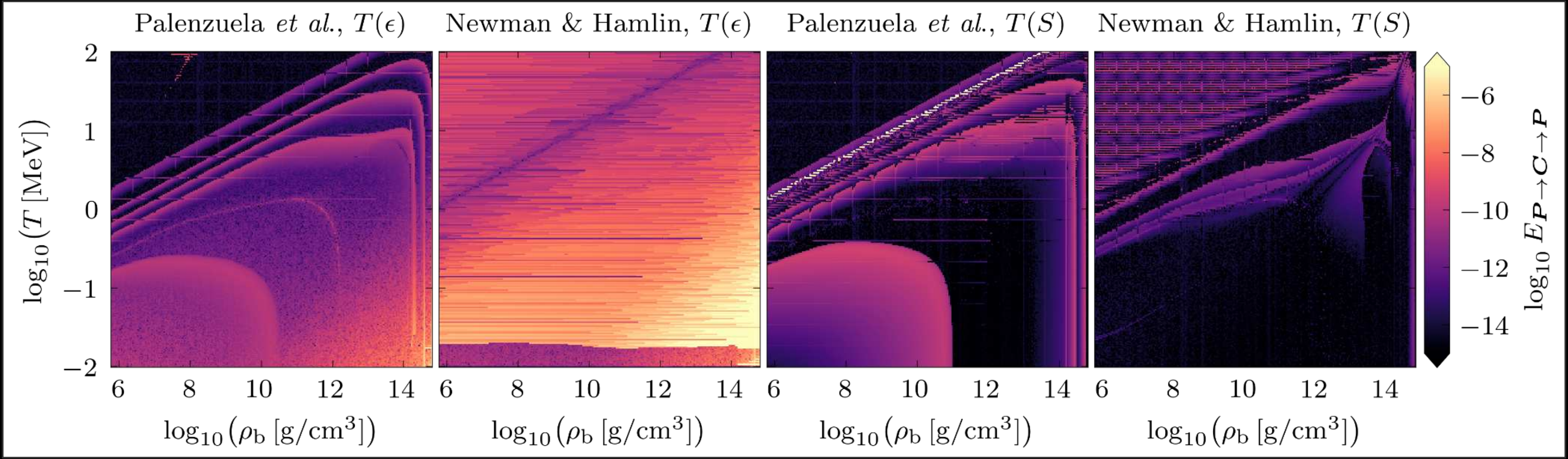


Step 8: Adding all functions to the dictionary [Back to Top]

The function below can be called to add all functions defined in this tutorial notebook to the C function dictionary.

In [10]:
```
# Step 8: Add all C functions to the dictionary
def add_all_Cfuncs_to_dict():
    # Step 8.a: Functions for which the temperature is known
    Cfunc_known_T([P])
    Cfunc_known_T([eps])
    Cfunc_known_T([P,eps])
    Cfunc_known_T([P,eps,S])
    Cfunc_known_T([P,eps,S,cs2])
    Cfunc_known_T([P,eps,depsdT])
    Cfunc_known_T([P,eps,mu_e,mu_p,mu_n,muhat])
    Cfunc_known_T([mu_e,mu_p,mu_n,muhat,X_p,X_n])

    # Step 8.b: Functions for which the temperature is unknown
    # Step 8.b.i: Temperature is determined using the specific internal energy
    Cfunc_unknown_T(eps,[P])
    Cfunc_unknown_T(eps,[P,S,depsdT])
    # Step 8.b.ii: Temperature is determined using the pressure
    Cfunc_unknown_T(P  ,[eps,S])
    # Step 8.b.iii: Temperature is determined using the entropy
    Cfunc_unknown_T(S  ,[P,eps])

    # Step 8.c: Interpolation helpers
    gen_Cheader_interpolation_helpers()

    # Step 8.d: General interpolation wrappers
    Cfunc_general_wrapper_known_T()
    Cfunc_general_wrapper_unknown_T()

    # Step 8.e: Table reader and memory allocation
    Cfunc_read_table_set_EOS_params()

    # Step 8.f: Memory deallocation
    Cfunc_free_memory()
```

New conservative-to-primitive infrastructure



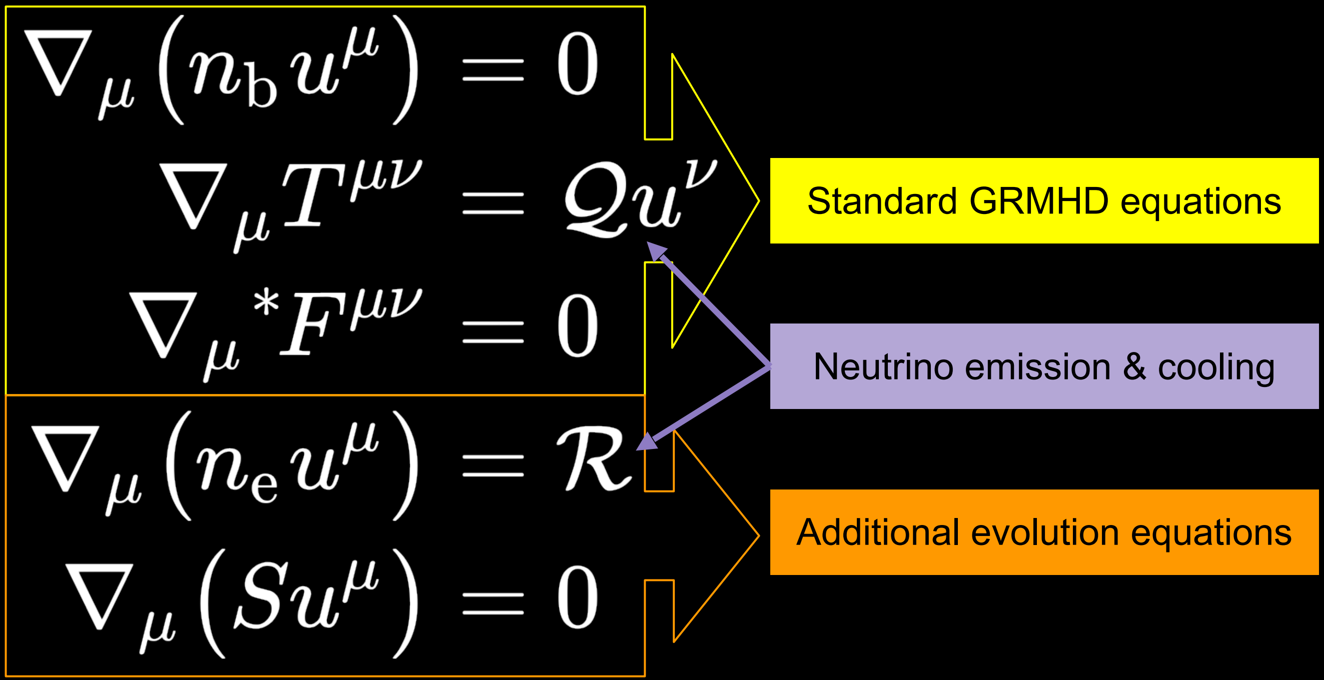
L.W., Z. Etienne++TCAN, In Preparation

Based on: Palenzuela *et al.* (2015), Newman & Hamlin (2014), and the implementation by Siegel *et al.* (2018)

Adapted routines to use the entropy equation as a backup, if desired

RePrimAnd support will be available once it supports tabulated EOS

GRMHD with neutrino leakage



$$\nabla_\mu \left(n_\mathrm{b} u^\mu\right) = 0$$

$$\nabla_\mu T^{\mu\nu} = Q u^\nu$$

$$\nabla_\mu {}^*F^{\mu\nu} = 0$$

$$\nabla_\mu \left(n_\mathrm{e} u^\mu\right) = \mathcal{R}$$

$$\nabla_\mu \left(S u^\mu\right) = 0$$

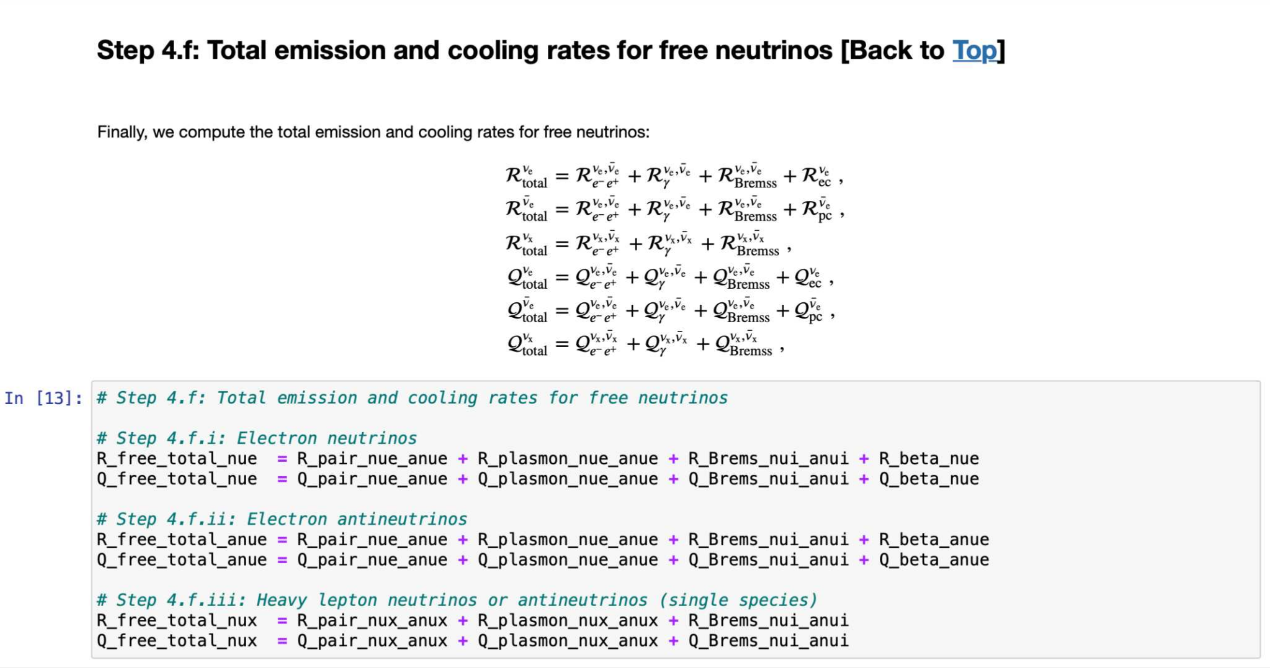
Standard GRMHD equations

Neutrino emission & cooling

Additional evolution equations

NRPyLeakage

- New NRPy+-based neutrino leakage code, fully documented using Jupyter notebooks
- Fast & efficient C code for computing neutrino emission and cooling rates, as well as opacities
- Local “path of least resistance” algorithm for computing the optical depths [Neilsen *et al.* (2011)]
- Cartesian AMR-compatible Einstein Toolkit thorn—**NRPyLeakageET**



Step 4.f: Total emission and cooling rates for free neutrinos [Back to Top]

Finally, we compute the total emission and cooling rates for free neutrinos:

$$
\begin{aligned}
\mathcal{R}^{\nu_{\rm e}}_{\rm total} &= \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{e^{-}e^{+}} + \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\gamma} + \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\rm Bremss} + \mathcal{R}^{\nu_{\rm e}}_{\rm ec}\ ,\\
\mathcal{R}^{\bar{\nu}_{\rm e}}_{\rm total} &= \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{e^{-}e^{+}} + \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\gamma} + \mathcal{R}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\rm Bremss} + \mathcal{R}^{\bar{\nu}_{\rm e}}_{\rm pc}\ ,\\
\mathcal{R}^{\nu_{\rm x}}_{\rm total} &= \mathcal{R}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{e^{-}e^{+}} + \mathcal{R}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{\gamma} + \mathcal{R}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{\rm Bremss}\ ,\\
\mathcal{Q}^{\nu_{\rm e}}_{\rm total} &= \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{e^{-}e^{+}} + \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\gamma} + \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\rm Bremss} + \mathcal{Q}^{\nu_{\rm e}}_{\rm ec}\ ,\\
\mathcal{Q}^{\bar{\nu}_{\rm e}}_{\rm total} &= \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{e^{-}e^{+}} + \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\gamma} + \mathcal{Q}^{\nu_{\rm e},\bar{\nu}_{\rm e}}_{\rm Bremss} + \mathcal{Q}^{\bar{\nu}_{\rm e}}_{\rm pc}\ ,\\
\mathcal{Q}^{\nu_{\rm x}}_{\rm total} &= \mathcal{Q}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{e^{-}e^{+}} + \mathcal{Q}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{\gamma} + \mathcal{Q}^{\nu_{\rm x},\bar{\nu}_{\rm x}}_{\rm Bremss}\ ,
\end{aligned}
$$

In [13]:

```
# Step 4.f: Total emission and cooling rates for free neutrinos

# Step 4.f.i: Electron neutrinos
R_free_total_nue  = R_pair_nue_anue + R_plasmon_nue_anue + R_Brems_nui_anui + R_beta_nue
Q_free_total_nue  = Q_pair_nue_anue + Q_plasmon_nue_anue + Q_Brems_nui_anui + Q_beta_nue

# Step 4.f.ii: Electron antineutrinos
R_free_total_anue = R_pair_nue_anue + R_plasmon_nue_anue + R_Brems_nui_anui + R_beta_anue
Q_free_total_anue = Q_pair_nue_anue + Q_plasmon_nue_anue + Q_Brems_nui_anui + Q_beta_anue

# Step 4.f.iii: Heavy lepton neutrinos or antineutrinos (single species)
R_free_total_nux  = R_pair_nux_anux + R_plasmon_nux_anux + R_Brems_nui_anui
Q_free_total_nux  = Q_pair_nux_anux + Q_plasmon_nux_anux + Q_Brems_nui_anui
```

Neutrino emission and cooling

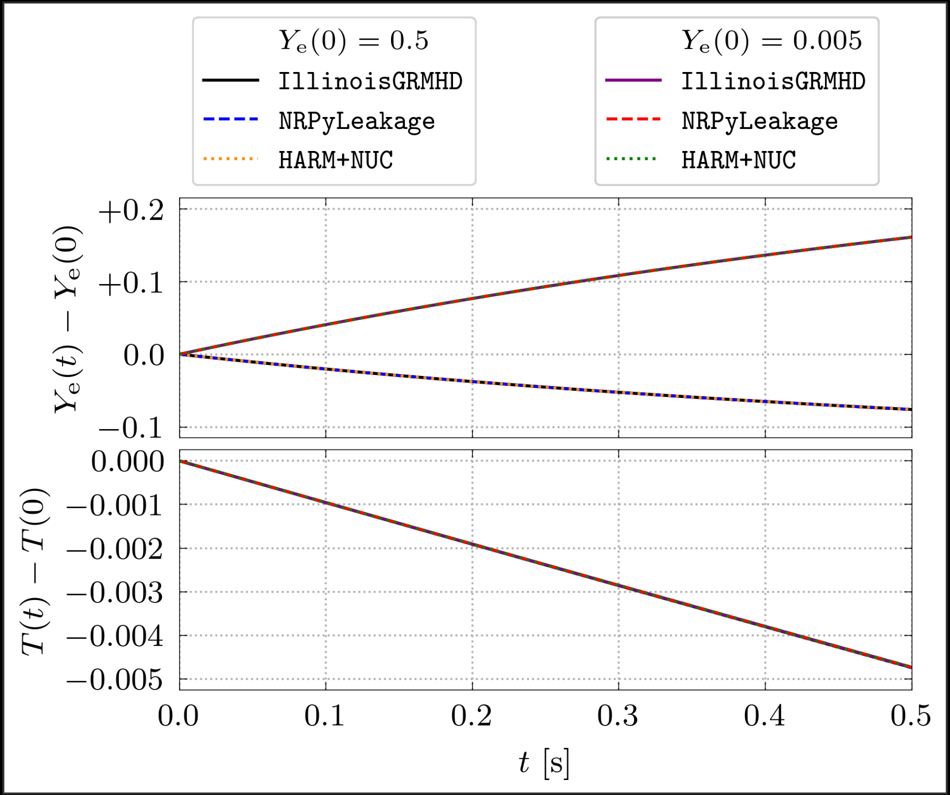
$$\begin{aligned} e^- + p &\rightarrow n + \nu_\mathrm{e} \\ e^+ + n &\rightarrow p + \bar{\nu}_\mathrm{e} \\ e^- + e^+ &\rightarrow \nu_i + \bar{\nu}_i \\ \tilde{\gamma} &\rightarrow \nu_i + \bar{\nu}_i \end{aligned}$$

Based on Ruffert *et al.* (1996):

- Electron absorption by protons
- Positron absorption by neutrons
- Pair annihilation
- Transverse plasmon decay

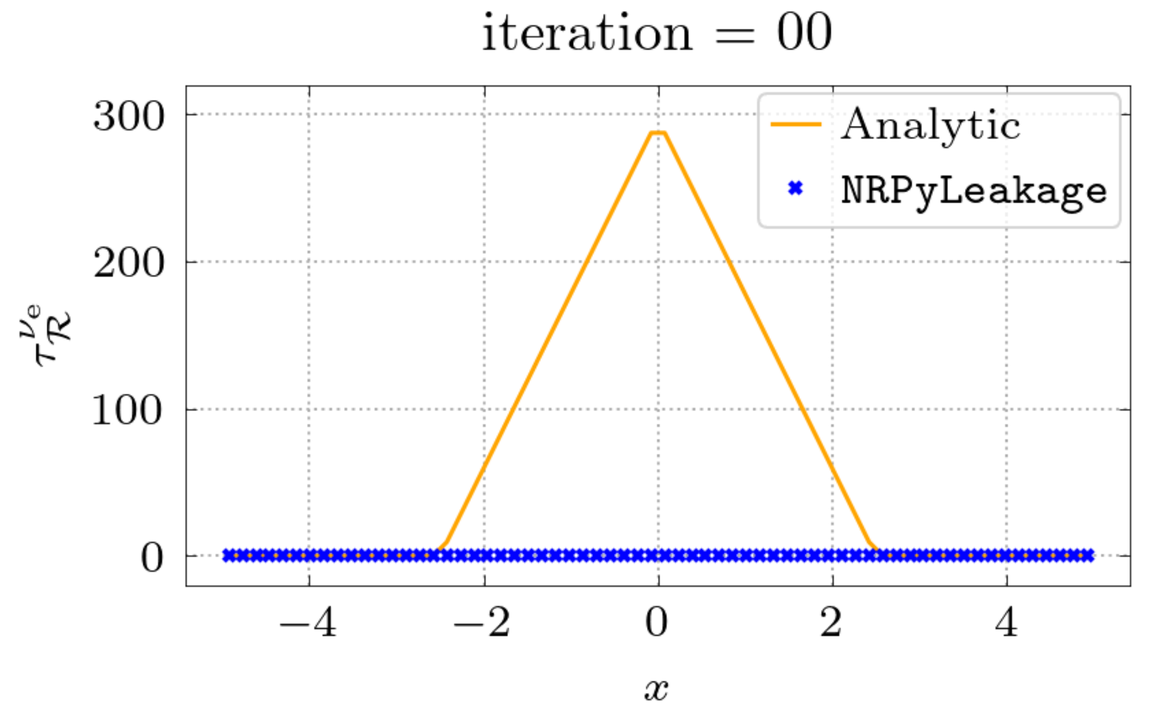
$$N + N \rightarrow N + N + \nu_i + \bar{\nu}_i$$

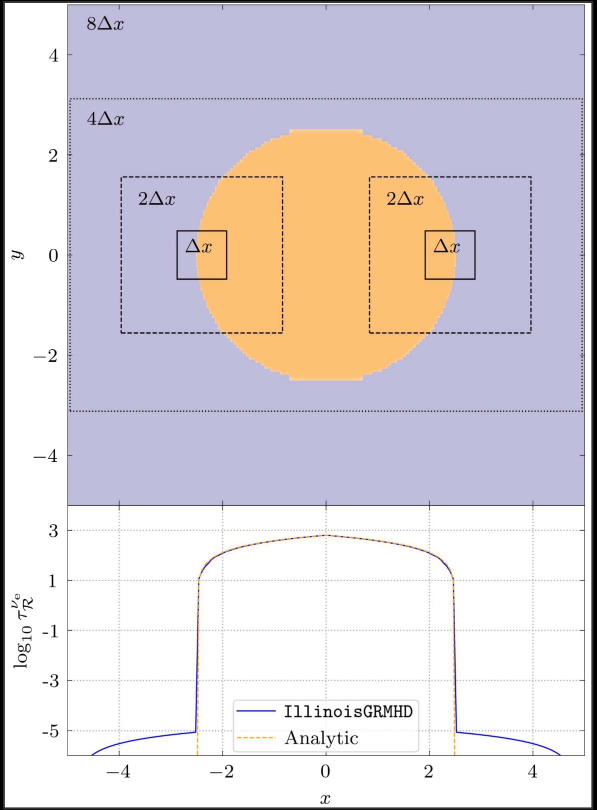
Nucleon-nucleon Bremmstrahlung following Burrows *et al.* (2006) and O'Connor & Ott (2011)



L.W., Z. Etienne++TCAN, In Preparation

Neutrino opacities & optical depths

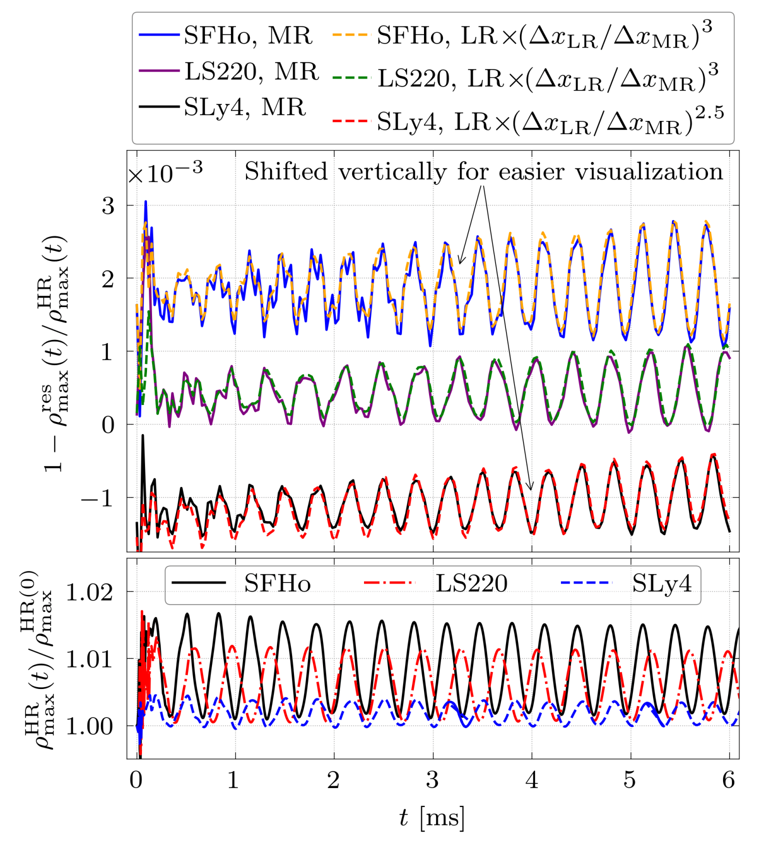




Based on Ruffert *et al.* (1996) and Neilsen *et al.* (2011)

L.W., Z. Etienne++TCAN, In Preparation

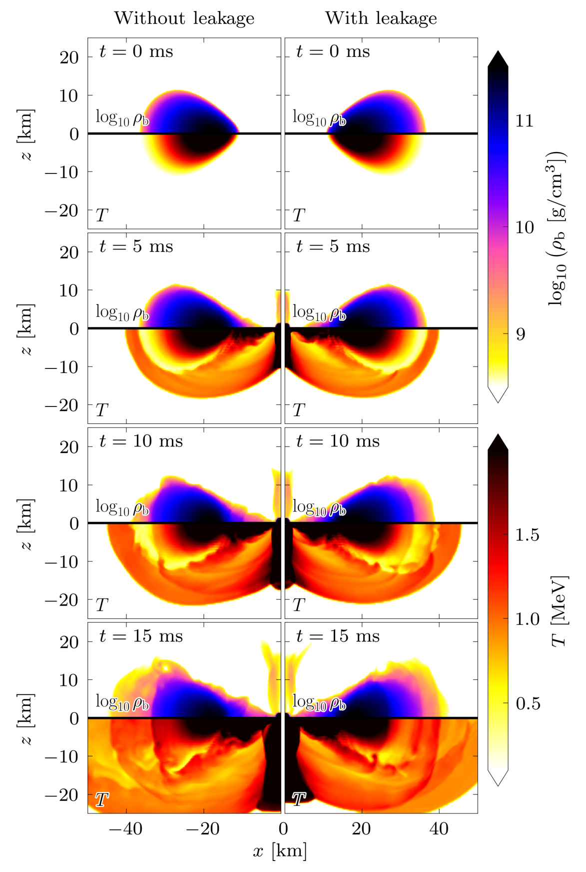
Single neutron stars: convergence test



L.W., Z. Etienne++TCAN, In Preparation

- $M_{\mathrm{TOV}} = 1.4M_{\odot}$
- Unmagnetized
- Fully dynamical spacetime
- Finite resolution induces oscillations
- Should converge away with resolution

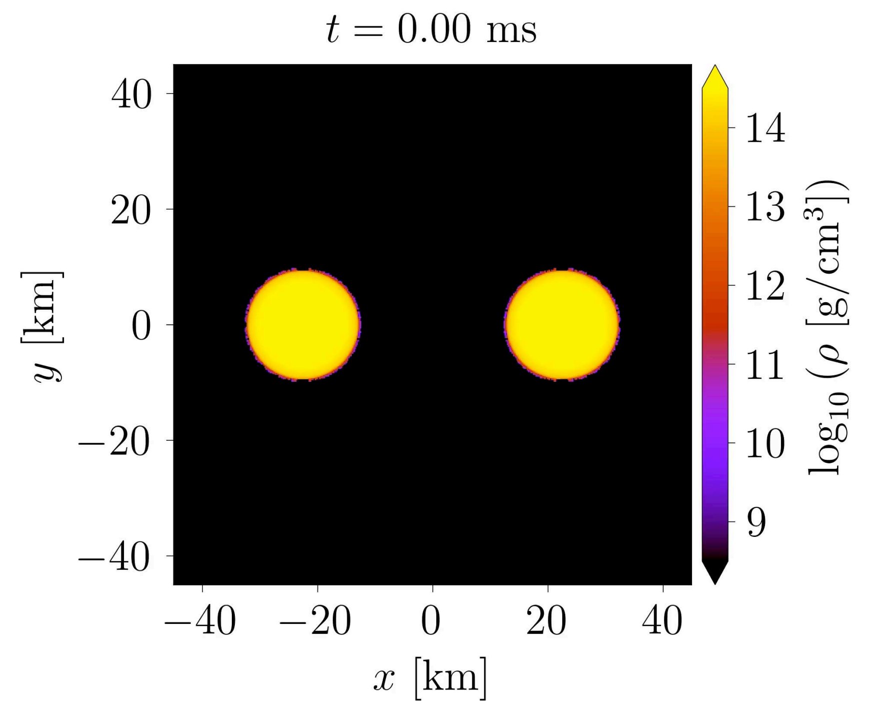
BH accretion disks: Fishbone–Moncrief

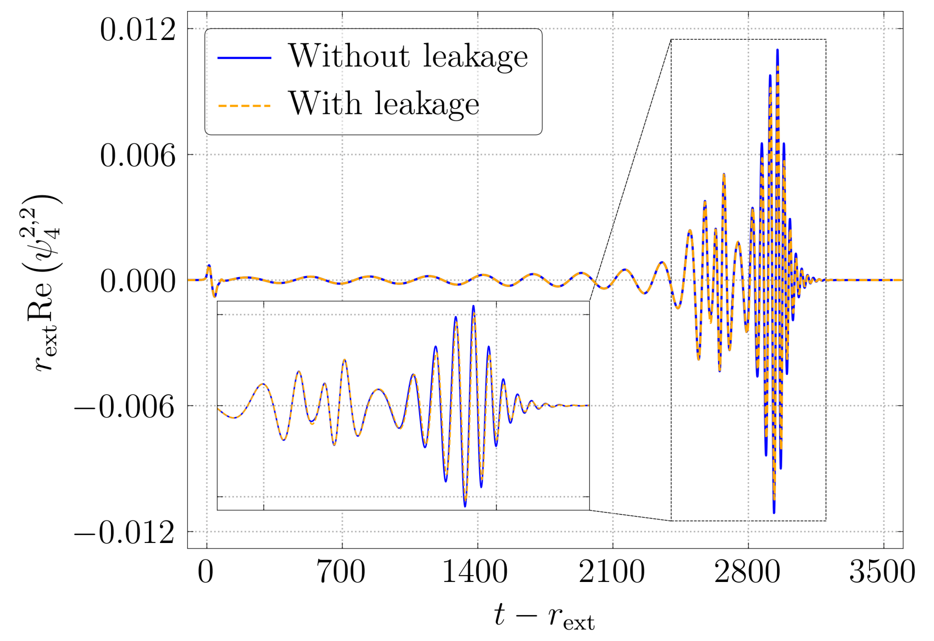


- Unmagnetized
- Fully dynamical spacetime
- Disk structure is reasonably well preserved
- Neutrinos lead to slightly cooler system

L.W., Z. Etienne++TCAN, In Preparation

Magnetized, equal-mass BNS with tabulated EOS + neutrino leakage





L.W., Z. Etienne++TCAN, In Preparation

- Equal-mass (1.39 solar masses)
- Magnetized
- Microphysical, tabulated EOS (O'Connor & Ott LS220 EOS)
- Neutrino leakage enabled (**NRPyLeakageET**)
- Initial data produced by Tanmayee Gupte using LORENE

FRONTERA

INL Idaho National Laboratory

Recap

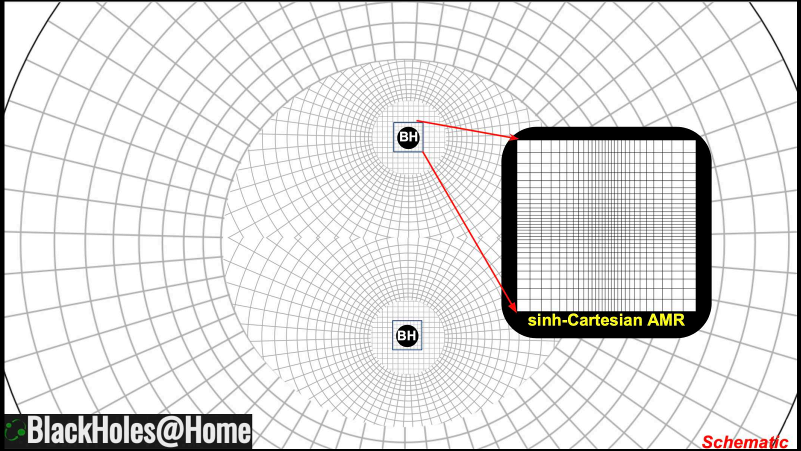
- Goal: Reliably and accurately evolve the remnant black hole for astrophysically relevant (very very long) time scales

- Infrastructure to **HandOff** data from **IllinoisGRMHD** to **HARM+NUC** is ready!

- **IllinoisGRMHD** has been updated with:
  - New conservative-to-primitive infrastructure
  - Microphysical finite-temperature equation of state (EOS) support
  - Electron fraction and temperature evolution
  - Neutrino physics via a leakage scheme (**NRPyLeakage**)

Future work

• CarpetX	(Lorenzo Ennogi/Erik Schnetter’s Talk)
	(S. Brandt’s Tutorial)
• GPU support	(F. Armengol/L. Ennogi/J. Kalinani’s Tutorial)
• “Curvi-IllinoisGRMHD”	(T. Pierre Jacques’s Talk)
• BlackHoles@Home grids	(Z. Etienne’s Talk)
• Open source the code	
• Include in future ET release	



Thank you