Accurate, long-term binary neutron stars simulations with **IllinoisGRMHD** and **HARM+NUC**

Leo Werneck

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

APS April Meeting 2022
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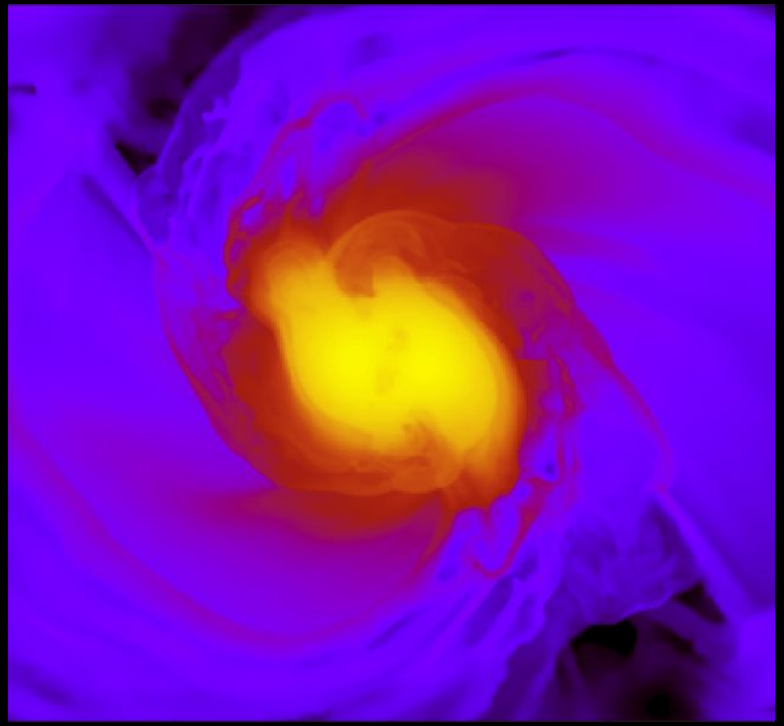

Baryonic density from a magnetized, equal-mass BNS simulation performed with **IllinoisGRMHD** using the LS220 **tabulated EOS**, shortly after merger

TCAN-80NSSC18K1488 on Binary Neutron Stars collaboration


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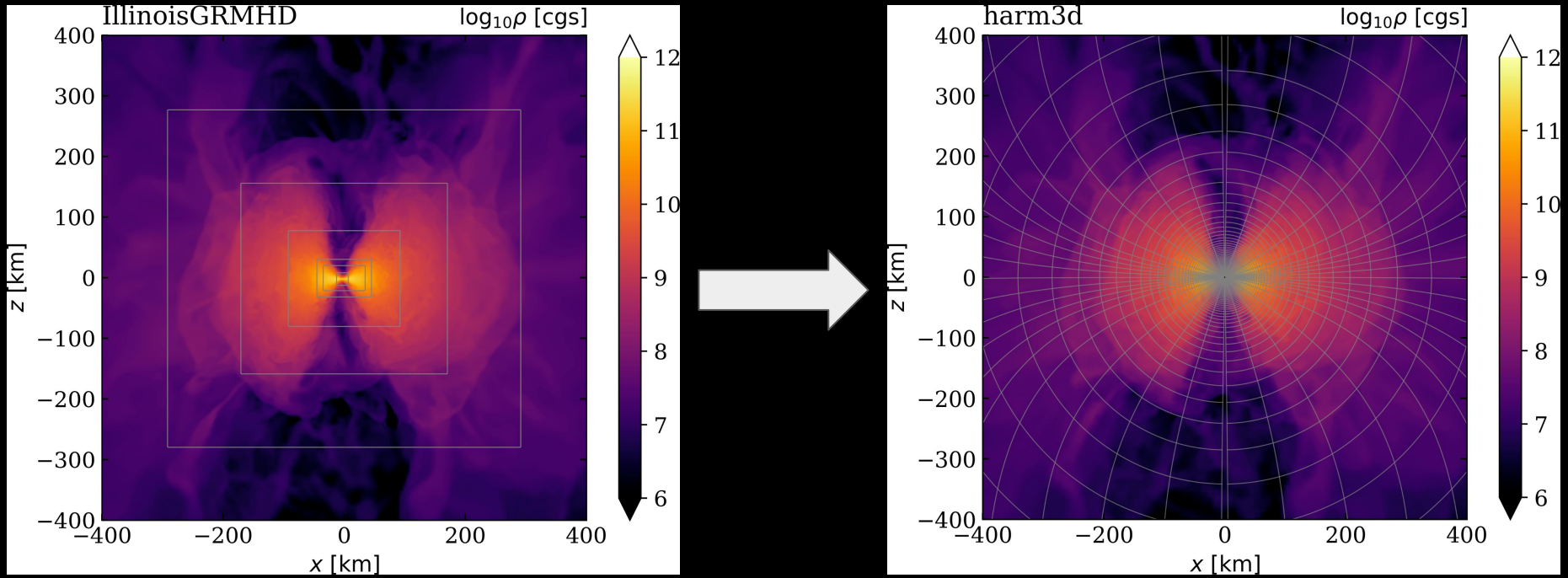
https://compact-binaries.org

The HandOff package

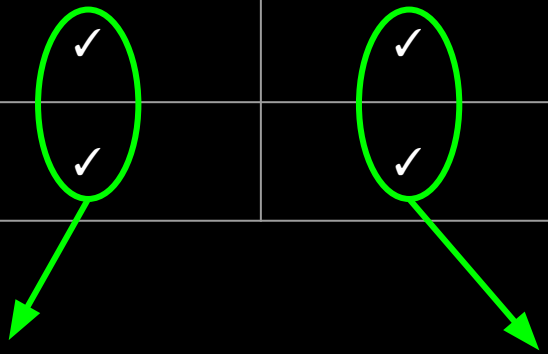


F.L.Armengol++TCAN (arXiv: 2112.09817)

See Fede's talk after this one for details! (K16.00002)

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!

- A.Murguia-Berthier++TCAN *ApJ* **919** 95 (2021)
- See Ari's talk later today for details! (K16.00003)

GRMHD with neutrino leakage

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

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

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

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

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

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

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:

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

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

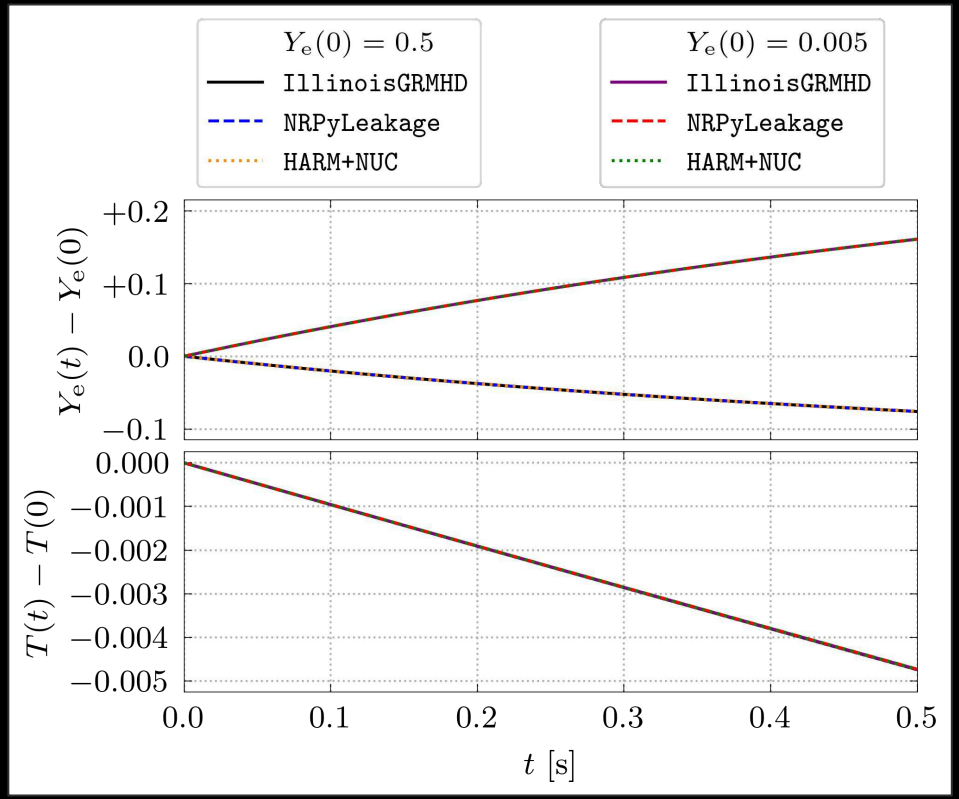
$$
\begin{aligned}
e^- + p &\rightarrow n + \nu_\mathrm{e} \\
e^+ + n &\rightarrow p + \bar{\nu}_\mathrm{e} \\
e^- + e^+ &\rightarrow \nu_i + \bar{\nu}_i \\
\tilde{\gamma} &\rightarrow \nu_i + \bar{\nu}_i
\end{aligned}
$$

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

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

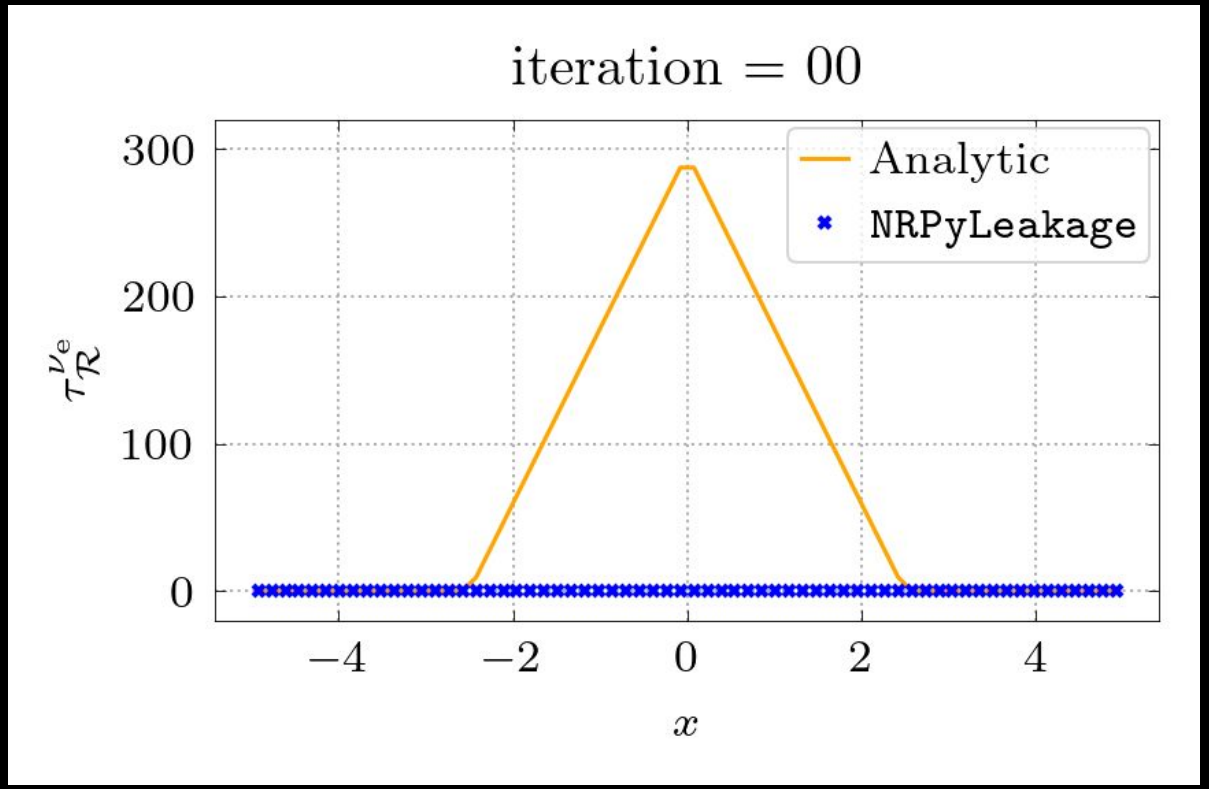
$$N + N \rightarrow N + N + \nu_i + \bar{\nu}_i$$

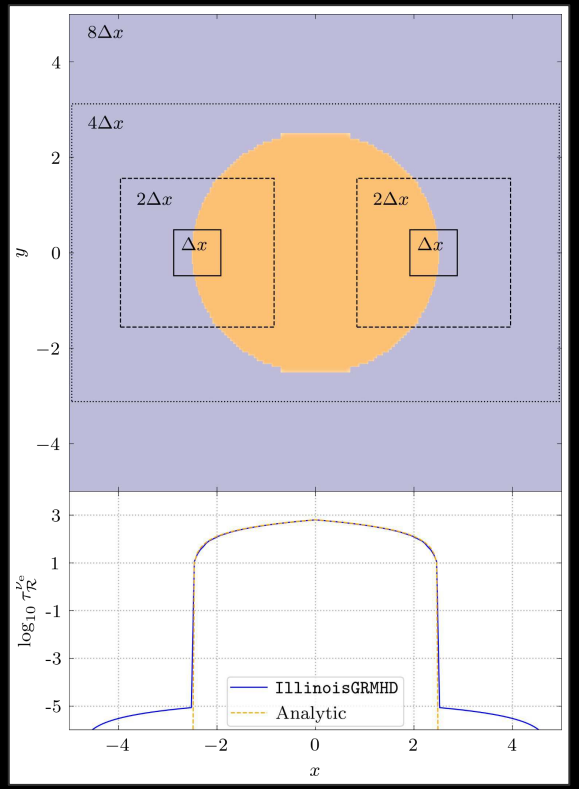
Nucleon-nucleon Bremmstrahlung following Burrows *et al.* (2006) and O'Connor & Ott (2011)



L.W.++TCAN (In preparation)

Neutrino opacities & optical depths

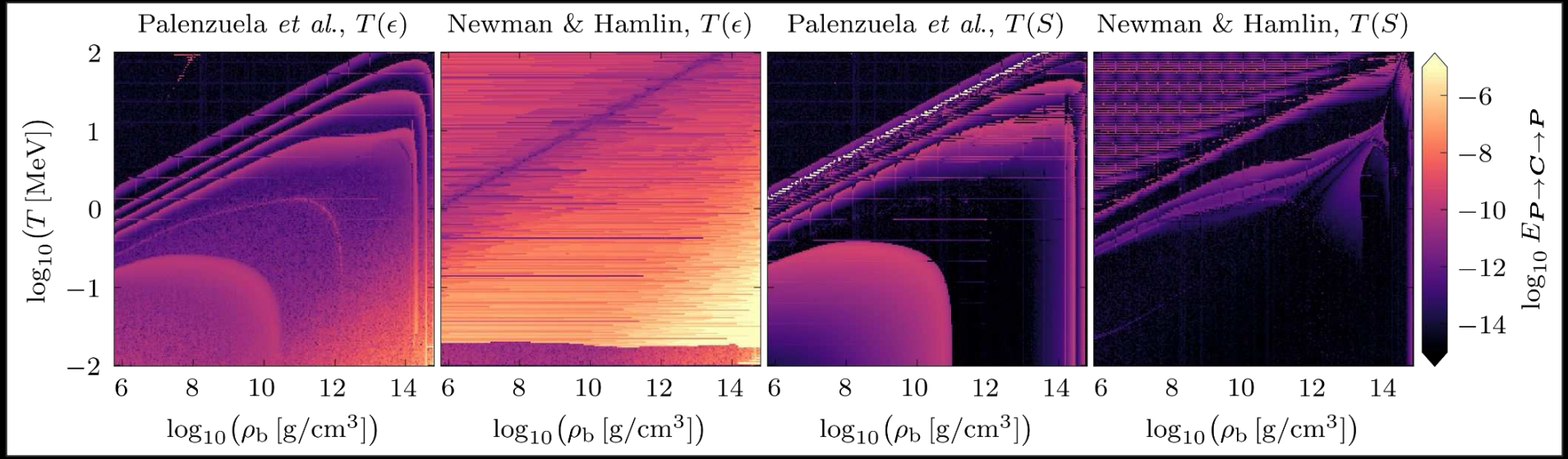




Based on Ruffert *et al.* (1996) and Neilsen *et al.* (2011)

L.W.++TCAN (In preparation)

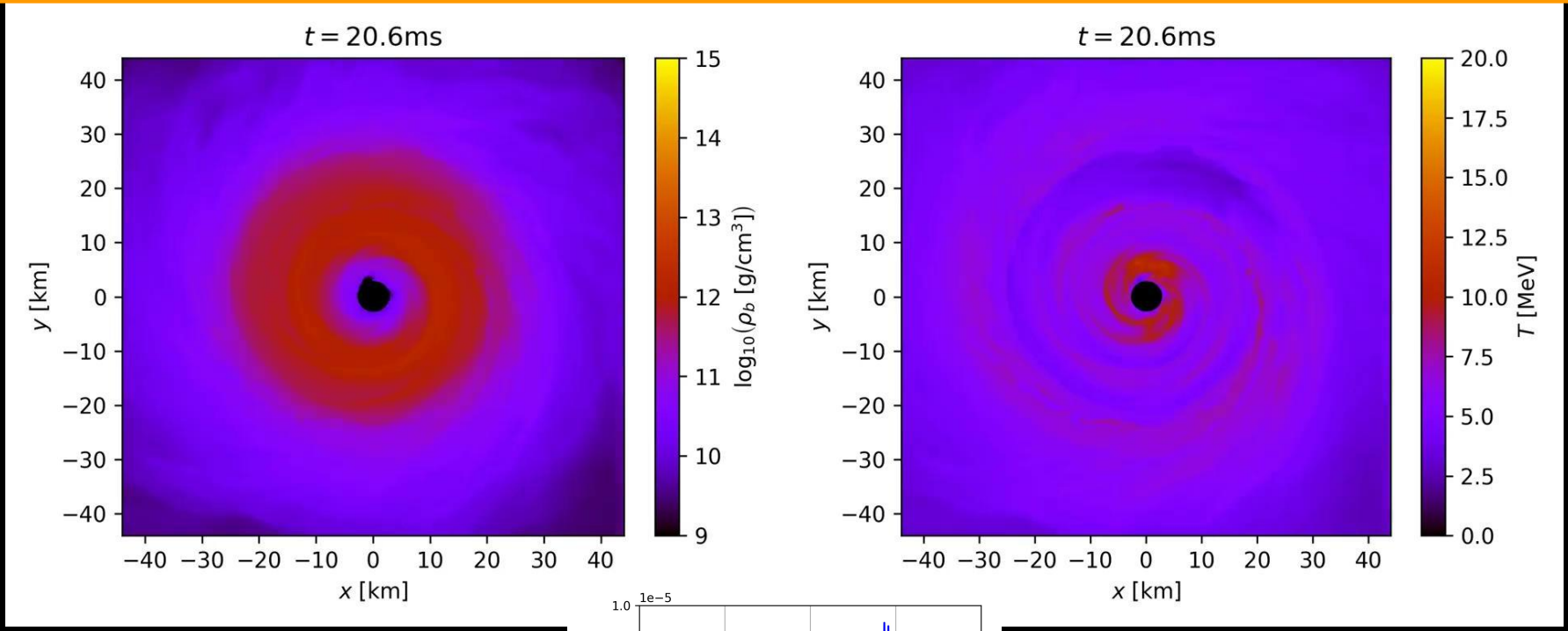
New conservative-to-primitive infrastructure



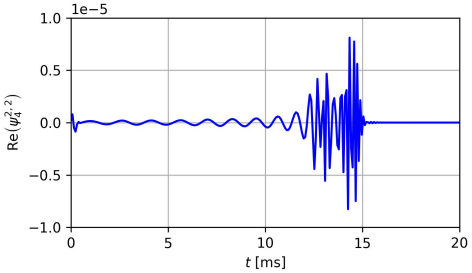
Based on: Palenzuela *et al.* (2015), Newman & Hamlin (2014), and the implementation by Siegel *et al.* (2018)

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

Magnetized, equal-mass BNS results with tabulated EOS



- Equal-mass (1.39 solar masses)
- Magnetized
- Advanced EOS
- [O'Connor & Ott LS220 EOS]



- Initial data produced by Tanmayee Gupte using LORENE (for more details see talks by T. Gupte and Josh Faber from 2021 TCAN Workshop)

FRONTERA

Summary & future work

- Infrastructure to **HandOff** data from **IllinoisGRMHD** to **HARM+NUC** is ready!
- Reliably and accurately evolve the remnant black hole for astrophysically relevant (very very long) time scales
- **IllinoisGRMHD** has been updated with:
  - Tabulated equation of state (EOS) support
  - New conservative-to-primitive infrastructure
  - Neutrino physics (NRPyLeakage)
- Tests with realistic, tabulated EOS and neutrino physics are running at this very moment!
- Stay tuned for Fede's and Ari's talks for more details!