Modeling Multimessenger Magnetized Compact Object Mergers

Astrophysical neutrinos and the origin of the elements
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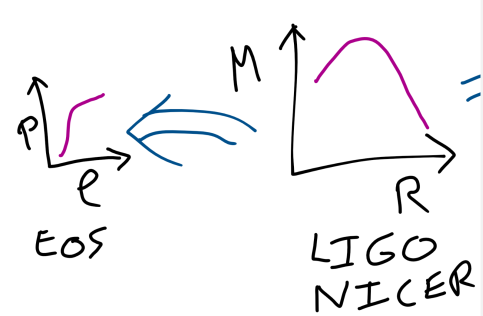
Motivation

- Realistic simulations of compact object mergers...
  - Fully nonlinear general relativity
  - Realistic, temperature-dependent equations of state
  - Neutrino processes
  - Relativistic magnetohydrodynamics, resistive MHD, forcefree, hybrid
  - Magnetic field instabilities...resolve, multiscale, ?
- ...for **multi-messenger astronomy**...
  - GW: LVK, future third-generation detectors
  - Neutrinos: direct-detection unlikely, but ejecta composition important for kilonova properties
  - EM: GRBs, kilonovae, other [precursors, flares, FRBs(?), etc]
- ...with efficient use of modern computers:
  - good scaling to solve big problems in reasonable time
  - w/ distributed AMR to resolve range of scales
  - efficient power usage (GFLOPS/W)? GPU/accelerator?

Some Preliminary (and possibly provocative) Thoughts/Questions

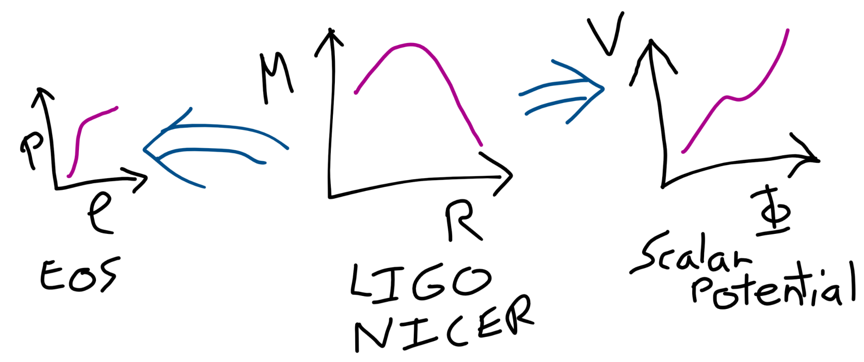
- Lots of CCSN observed, but only one definitive BNS merger
- Which ν effects are the biggest (biggest bang for the buck)?:
  - Muons
  - Flavor change/quantum kinetics
  - Leakage→(M1 or MC)→hybrid→full direct Boltzmann
  - All ν species and lepton number conservation
  - Other?
- How do above effects compare to BNS numerical errors for ejecta?
  - atmosphere & stellar surface discontinuity
  - Unresolved scales and instabilities
  - Choices: Initial data, EoS, environment (magnetosphere, dark matter, etc)
- What constitutes "exotic physics"?
  - Phase transitions (not so exotic?)
  - Axion Like Particles (ALPs) & Alternative Gravity
  - Cosmic strings/PBHs/etc
- Degeneracies

Inverting M vs R curve



- "Inverse Structure Problem for Neutron-Star Binaries" [Lindblom,1807.02538
- "The Relativistic Inverse Stellar Structure Problem" [Lindblom,1402.0035] [Lindblom,Indik,1207.3744]

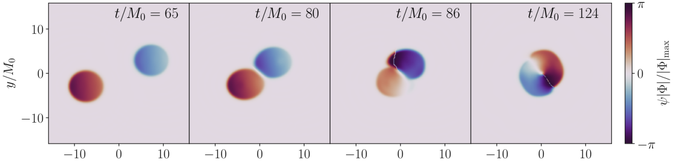
Inverting M vs R curve



NSs–vs–Boson Stars [w/Rigel Mummers, unpublished Nov. 2022]

- Tidal deformabilities determined by **EoS**
- Stability can be read-off **M-vs-R curve**
- Formation mechanism understood from **stellar collapse**
- **hard** surface

- Tidal deformabilities determined by **scalar potential**
- Stability can be read-off **M-vs-R curve**
- Formation mechanism understood from **scalar condensation**
- **no** surface

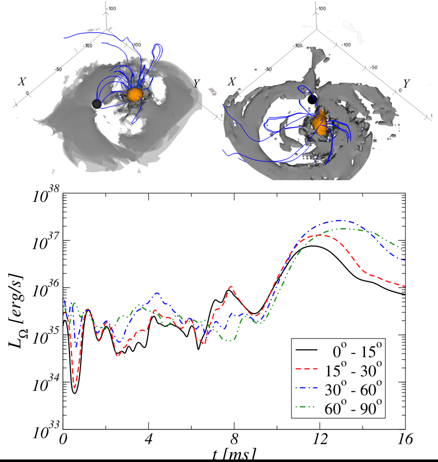


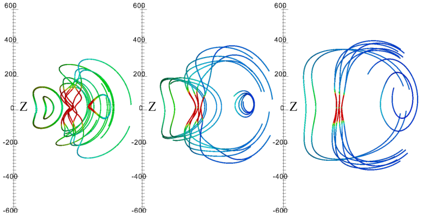
Now stable with rotation! [Siemonsen, East, 2302.06627]

Multimessenger Signals from BH-NS [East,Lehner,SLL,Palenzuela,2101.12214]

- EM observations may be key to distinguishing some BHNS from BNS
- Precursor signals do not beneft from GW sky-localization and so must be EM loud
- 5:1 mass ratio ($7\ M_\odot$ and $M_{\rm NS} = 1.33 M_\odot$)
- Magnetized NS with $\Gamma = 2$ and surface field strength $B_* = 3 \times 10^9$ G
- Studied previously: BH acts as a battery in Unipolar Induction (UI) model [Hansen,Lyutikov 2012] [McWilliams,Levin 2011] [Prio, 2012] [Lai 2012] [D'Orazio+ 2016] and BNS precursor flaring [Most,Philippov,2205.09643, 2001.06037]
- Evolved with HAD resistive MHD with current prescribed such that:
  - Inside the star: approaches ideal MHD
  - Outside the star: approaches force-free limit

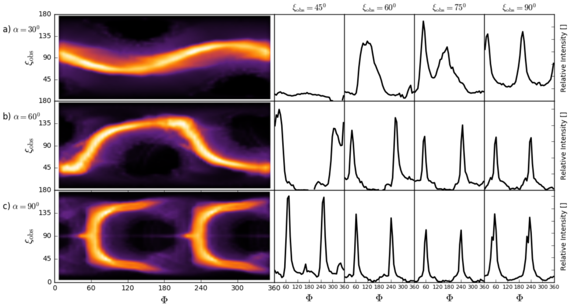
Multimessenger Signals from BH-NS [East,Lehner,SLL,Palenzuela,2101.12214]





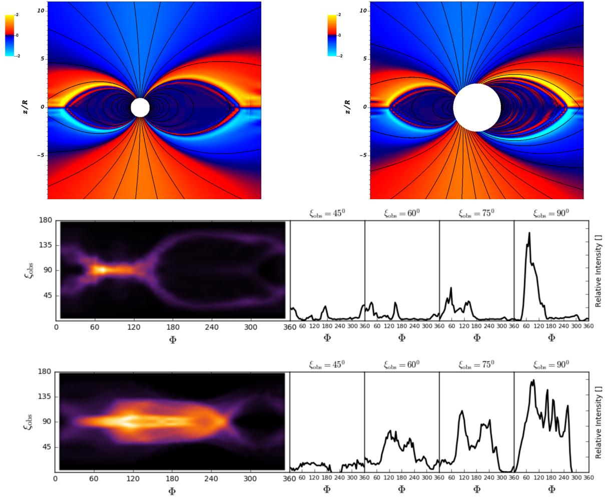
- EM power peaks a bit after GW peak
- (non-spinning) BH leaves a small current sheet in its wake
- Plasmoids ejected with some columnation soon after merger

Gamma-radiation sky maps from compact binaries [Ortiz+ 2107.07020]



- Poynting flux only simple proxy for EM signals
- Use the Separatrix Layer model for gamma-ray emission of `[Bai,Spitkovsky 0910.5741]`
- Generalize to more complicated configurations:
  - Test with inclined dipole (ie pulsar)
  - Magnetic twists and offset dipole
  - Binaries with `enclosing surface approximation`
    - Perfectly conducting surface
    - Enclosing either two dipoles (BNS) or single dipole (BHNS)

Gamma-radiation sky maps from compact binaries [Ortiz+ 2107.07020]

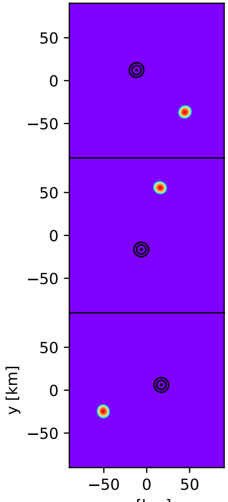


- *Enclosing surface approximation* matches well orbiting NS (left top)
- Generate skymap and lightcurves for our BHNS evolution (left middle)
- Enclosing surface approximation (left bottom)

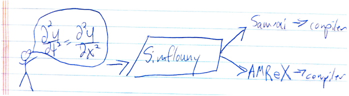
BH-NS Mergers w/ MHDuet

Carlos Palenzuela (UIB Spain)
& Miguel Bezares (U.Nottingham UK)

- Work in progress...
- Study magnetic effects with LES subgrid
- Extend to realistic EoS w/ M1 neutrino transport



MHDuet and MHDueX

- Developed as successor to HAD
- Written w/in `Simflowny` which generates the code using a range of infrastructures 

- Code can be generated using either:
  - `SAMRAI` infrastructure from LLNL which reaches exascale for some problems
  - `AMReX` massively parallel AMR from LBNL/NREL/ANL via DOE
    - Promises scaling to higher numbers of cores
    - Supports GPUs via CUDA, HIP, SYCL, OpenACC

MHDuet

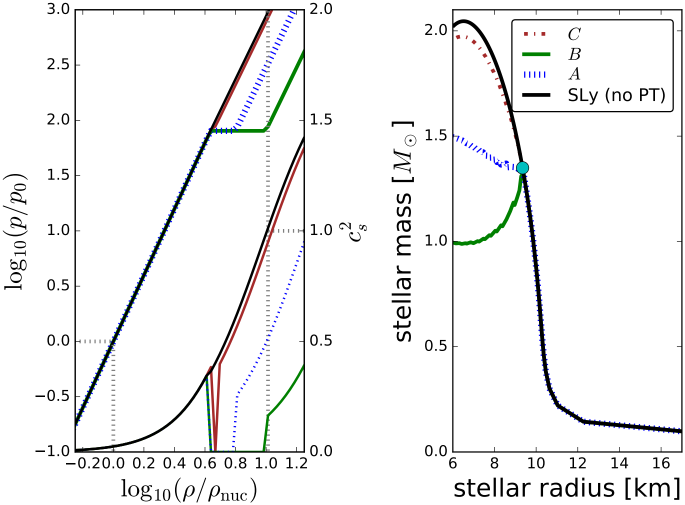
- Past work with MHDuet:
  - Magnetized NS & BNS mergers with phase transitions [SLL,Palenzuela,Lehner 2010.12567]
  - BNS mergers compared to HAD [SLL,Palenzuela,Lehner 2002.07554]
  - Related codes: boson star mergers [Bezares+ 2201.06113]
- Initial data via Lorene or FUKA
  - BH-NS binaries in quasi-circular orbits
  - NS-NS binaries in quasi-circular orbits
- MHDuet open-source `mhduet.liu.edu`—more documentation to come

Phase Transitions: EoS Variations [SLL,Palenzuela,Lehner,2010.12567]

Variations of SLy defined as piecewise polytrope:

- Onset density, ρ_1
- "size" of PT (e.g. "latent heat") $\Delta\rho$
- Γ in post-PT regime (e.g. slope)

Affects stability of solutions

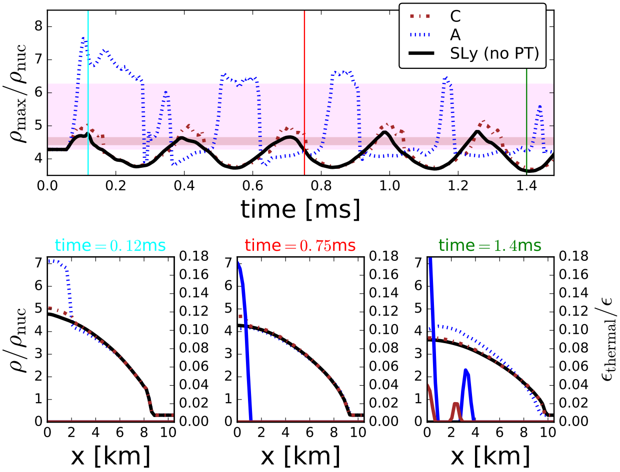


Phase Transitions: Star Dynamics [SLL,Palenzuela,Lehner,2010.12567]

Non-rotating, non-magnetic, perturbed by accretion (large atmosphere):

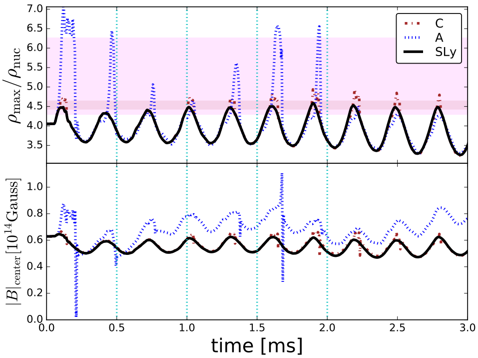
- Oscillations drive NS through PT
- If hybrid stable, oscillations tends to dampen
- If hybrid unstable, collapse ensues

similar to "reverse phase transitions" in BNS of [Ujevic+ 2211.04662]

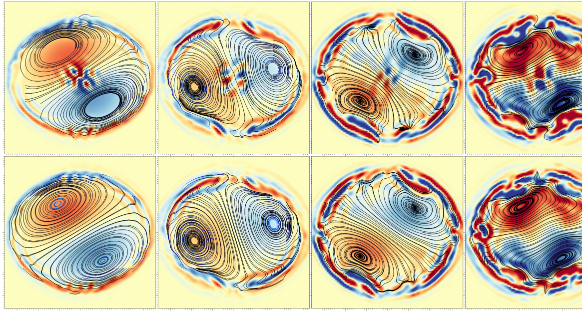


Phase Transitions: Rotating Magnetized Stars

[SLL,Palenzuela,Lehner,2010.12567]



Magnetic field changes core with PT but not likely to change EM signals

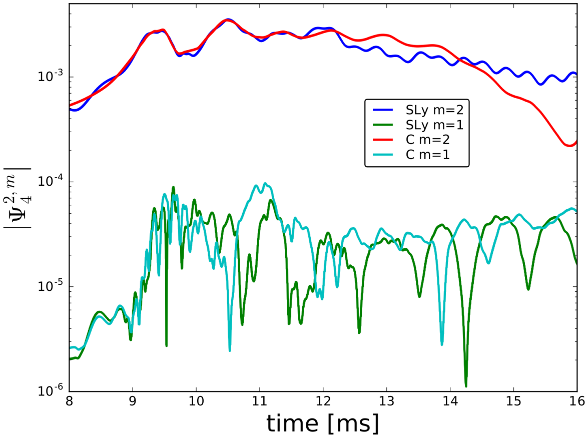


Phase Transitions: $m = 1$ in $q = 0.92$ BNS Merger w/ PT [SLL,Palenzuela,Lehner,2010.12567]

[Espino+,2301.03619] finds PT damps $m = 1$ instability

Here, no significant damping of $m = 1$ mode by PT

Although PT in this case isn't that strong



Why Trust Large Eddy Simulation (LES) Method w/ Gradient Sub-Grid Scale (SGS) Model

- Tests:
  - a priori: filter/coarsen a resolved solution, SGS τ correlates very well with SFS
  - a posteriori: LES solution compares will w/ well-resolved non-LES solution
- Spectral scalings agree with expectations
- No free parameters (besides $\mathcal{C}_i$) and no calibration
- Used (ie *trusted*) in a variety of fields
- Gradient model allows both direct and inverse cascades

...a well motivated subscale model

[Palenzuela,SLL,Minano,2204.02721]

General Relativity and Quantum Cosmology

arXiv:2204.02721 (gr-qc)

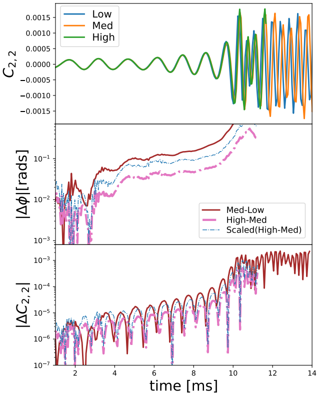
[Submitted on 6 Apr 2022]

Large Eddy Simulations of Magnetized Mergers of Neutron Stars with Neutrinos

C.Palenzuela, S.L.Liebling, B.Micano

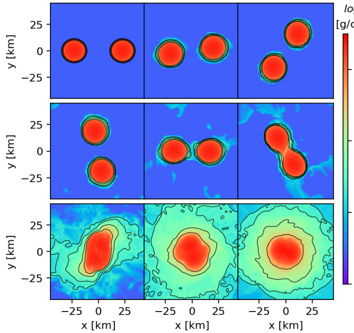
- Extend LES to realistic equations of state
- Implement leakage scheme within MHDuet
- Improve local optical depth calculation

Binary Convergence



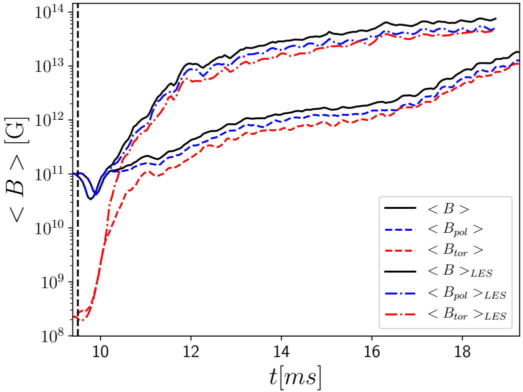
SH EoS, $M_B = 1.49 M_o dot$ (Total
$M_{\rm ADM} = 2.74 M_\odot$, $T = 0.01$ MeV
Initial separation 45 km

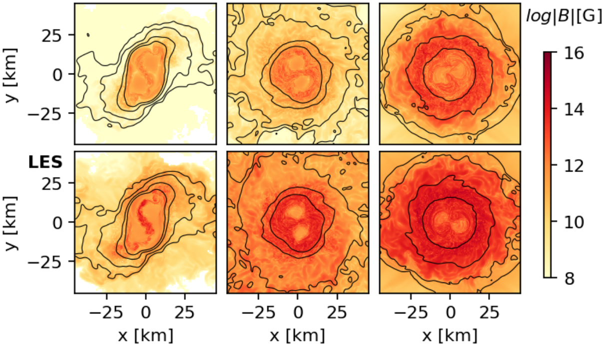
Convergence of GW involves
most all of the code:
EOM, AMR, extraction, EoS



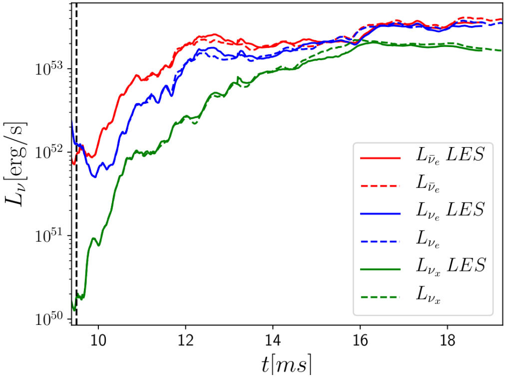
Waveforms converge to at least $3^{\rm rd}$ order

LES Amplifies Magnetic Field





LES Amplifies Magnetic Field But Not Much Affect on ν luminosities



Latest Work: Study GW170817-like BNS mergers

- Work with Carlos Palenzuela (@UIB Spain)
- Chirp mass consistent with GW170817: 1.186 $M_\odot$
- EoSs consistent with current constraints, spanning range: SLy and DD2

E.g.: [Radice,et al,1711.03647]

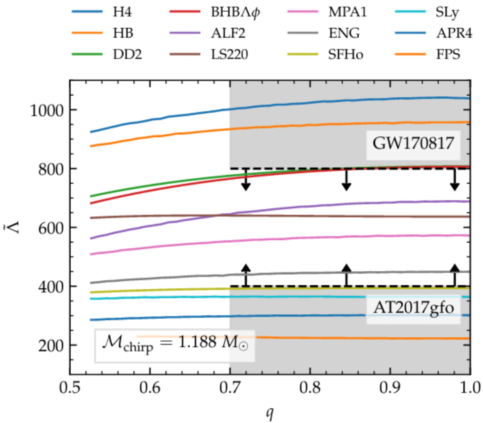


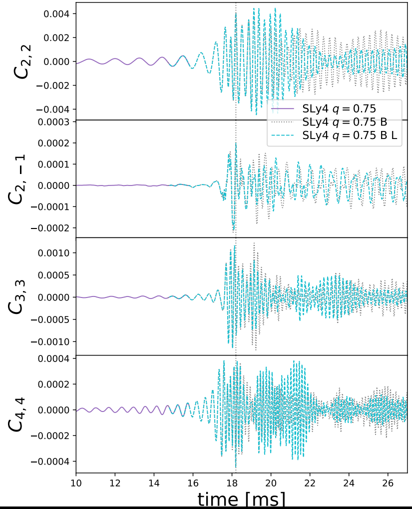
Figure 2. Tidal parameter $\tilde\Lambda$ (Eq. 1) as a function of the mass ratio q for a fixed chirp mass $\mathcal{M}_{\rm chirp} = 1.188\ M_\odot$. The shaded region shows the region excluded with 90% confidence level by the LIGO-Virgo observations (Abbott et al. 2017b), with the additional constraint of $\tilde\Lambda \geq 400$ derived from the simulations and the EM observations. EOSs whose curves enter this region are disfa-

BNS Mergers

- Realistic, temperature dependent EoS
- Large-Eddy-Simulation techniques for magnetic field
- Leakage (and M1 neutrino transport soon...see [Izquierdo,Pareschi,Minano,Masso,Palenzuela,2211.00027])

EoS	q	$M_{\rm chirp}$ ($M_\odot$)	$M_{\rm ADM}$ ($M_\odot$)	R_1 (km)	R_2 (km)	C_1	C_2	$\lvert B_{\rm initial}\rvert^{\rm max}$ (10^{14} G)	$t_{\rm peak}$ (ms)	$t_{\rm collapse} - t_{\rm pea}$ (ms)
DD2	0.75	1.186	2.759	10.2	10.5	0.16	0.15	8.2	14.6	
DD2	0.87	1.186	2.733	10.4	10.5	0.20	0.19	4.6	15.4	
DD2	1.00	1.186	2.725	10.4	10.4	0.18	0.18	3.0	15.3	
SLy	0.75	1.186	2.759	8.7	9.3	0.26	0.20	2.2	18.2	8.8/8.7
SLy	0.87	1.186	2.733	8.9	9.2	0.23	0.19	1.5	18.0	12.8/15.2
SLy	1.00	1.186	2.725	9.1	9.1	0.24	0.24	1.9	15.0	11.5/8.9

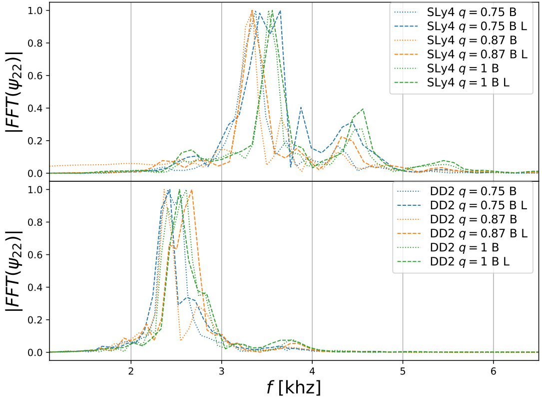
Gravitational Waves



Leakage damps oscillations

Assymmetric mass ratios collapse sooner (consistent with `[Just+,2302.10928]`) modulo some ambiguity in when to start the clock

Postmerger Gravitational Waves



[Dhani,Radice+,2306.06177] find that high frequency content indicative of collapse

Here, SLy4 collapses (with HF bump) versus DD2 which does not collapse (without HF bump)

Conclusion & Continuing Work

- The scalar potential may allow for boson star to mimick NS requiring multimessenger to distinguish
- Magnetized NS in BHNS may potentially power EM signal in the absence of significant disruption
- Examined phase transitions in NS: magnetized stars, $m = 1$, "reverse PT"
- Future: analyzing runs consistent with GW170817:
  - Two EoSs that span consistent range
  - Mass ratio spanning $q = 0.75 - 1$
  - Magnetized stars with LES subgrid model
  - Neutrino scheme: leakage (and soon M1 transport)
  - Looking at ejecta properties, kilonovae predictions, and r-process yields
- Have begun studying BH-NS mergers
- Have an AMReX-enabled version of the code, MHDUEX:
  - Can run on GPUs
  - Needs more testing