TCAN Workshop on
BNS and BHNS 2021
July 12-16– zoom

The TCAN project on BNS simulations

Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds and Jets in Neutron Star Mergers

Manuela Campanelli

RIT College of Science
Center for Computational Relativity and Gravitation

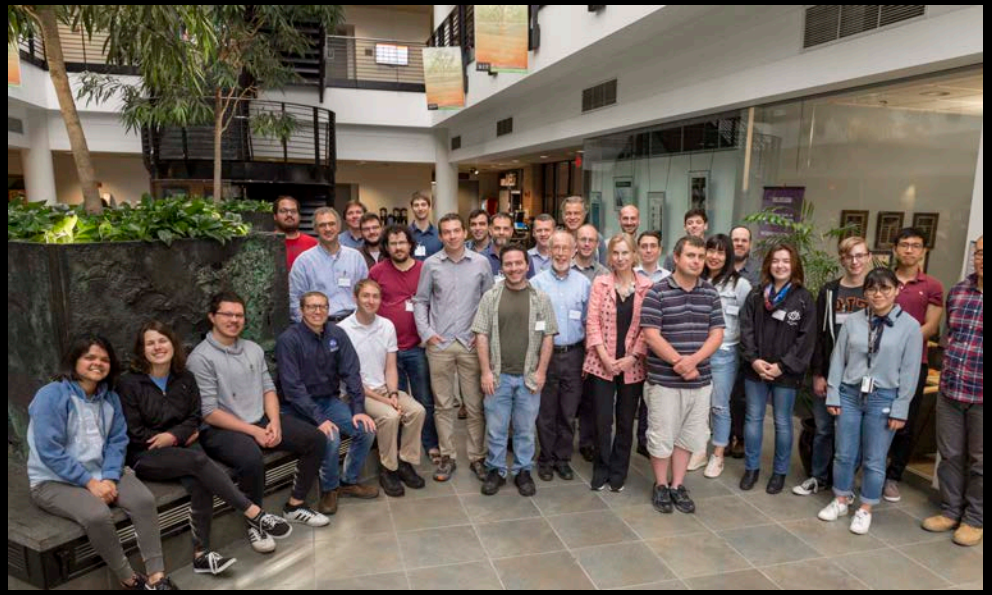
ASPIRE - Astrophysics and Space Physics
Institute for Research Excellence

compact-binaries.org

NASA's TCAN grant
No. 80NSSC18K1488

Who we are …

- Four site PI institutions (RIT, JHU, GSFC, WVU/Idaho) and multiple international collaborators (Berkeley, UCSC, Penn State, INFN, ORNL, LANL, U.Milan, Technion, IAR-Ar, etc);
- Large (now 40+ in total) team structured by working groups.
- Coordinated scheduling to avoid development bottlenecks.
- Weekly group video conferences to keep everyone informed and on-schedule.
- Annual (when possible, in-person) all-team + annual external workshops.
- Build a compact-binaries community bringing additional expertise, larger workforce.



TCAN: compact-binaries.org

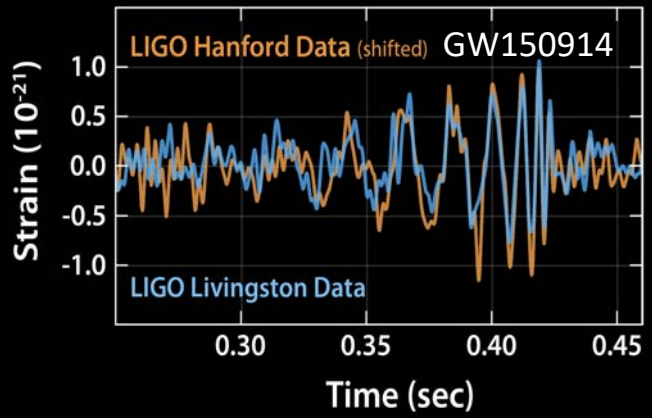
NASA TCAN 80NSSC18K1488 (2019-2022) and other satellite NSF grants

FRONTERA

LSCP AST20021

Windows onto the Universe!

Recent gravitational-wave discoveries by LIGO …



… have opened an unprecedented observational window into binary black holes and neutron stars!

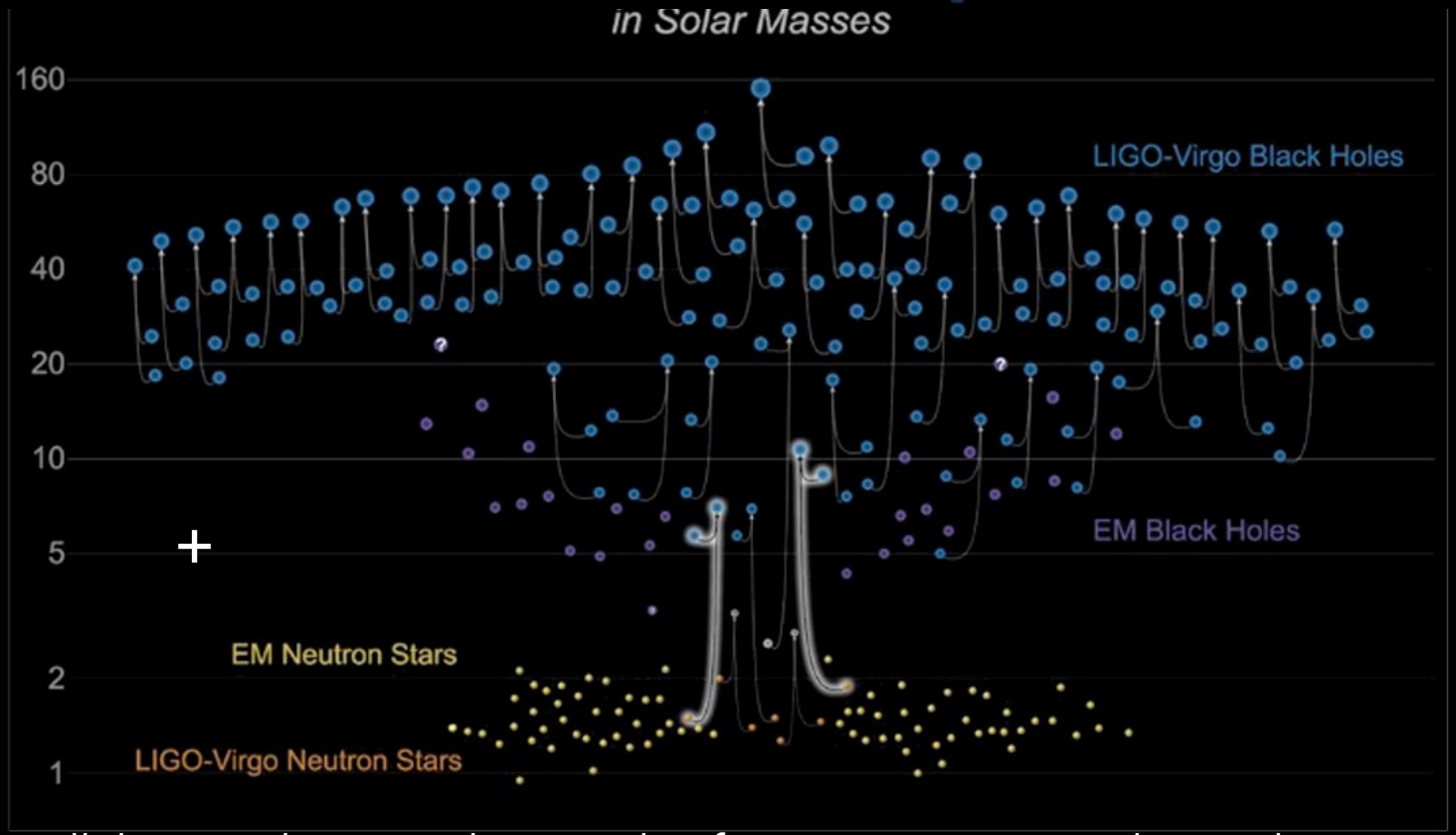
… as well as recent progress in X-ray, gamma ray and radio observations …

+

Aug 2017

GW170817 GRB 170817A

The Window is Expanding!



See Talk by Jacob Lange later today for an overview on these observations!

Theory and Computational Astrophysics Network on BNS and BH-NS Mergers

Long, accurate, simulations in full **3d** requires:

NR + GRMHD
Nuclear and Neutrino Physics, EOS
Neutrino/photon transport
R-processes/nucleosynthesis

They are challenging because they inherently **multi-physics, multi-scale**!

What is the central engine of a sGRB?
How is the jet launched?
What is the nature of the remnant?

Need to simulate ~1 sec after the onset of the merger with resolutions of the scale of the MRI!

TCAN: Building an Integrated set of Computational Tools for the entire BNS merger

Advancing Computational Methods to Understand the Dynamics of Ejection, Accretion, Winds and Jets in Neutron Star Mergers

- Building an initial data pipeline for both neutron stars' structures + surrounding spacetime

- Perform merger proper and long lived postmerger simulations for a variety of BNS and BH-NS scenarios:

  - gravitational wave radiation + MHD
  - prompt ejecta dynamics
  - orbiting bound matter dynamics and radial profile
  - jet-launching and propagation through ejecta
  - nuclear evolution in ejecta and disk
  - outflows: thermodynamics, nuclear evolution, photon spectrum

TCAN: Pioneering a new approach to complex simulations

- Divide the problem according to physical characteristics; different codes for different regimes.

- Then develop self-consistent ``hand-off' tools to transition from one code to another.

- Implementing the most advanced physics in ALL our GRMHD codes (EOS, neutrinos) with the needed consistency for stable data hand-off from one code to another.

- Then develop self-consistent ``hand-off' tools to transition from one code to another.
- Solve "Hand-Off" algorithmic differences e.g. atmosphere treatment, common EOS, neutrino physics, and treatment of MHD.

- Now complete and postmerger simulations are underway on TACC's Frontera supercomputer.

Science Goals

- Produce physically realistic simulations that take a BNS (or BHNS) system up to ~**1sec after merger**.

- Consider a range of cases:
  - BNS merger that lead directly into a BH with a light accretion disk.
  - BNS merger that produce a disk orbiting an HMNS that soon collapses to a BH.
  - BNS merger that lasts a few times longer and leaves behind heavy disk around an HMNS.
  - BNS merger that produces a stable NS with a heavy disk.
  - BHNS merger that produces a light disk.

- Consider also target of opportunity based on LIGO/EM observations.

- Proceed by steps, add spins, realistic magnetic fields to NS, 10^8-10^{14}G.

- Perform accurate simulations with a numerical resolutions 80 m or better.

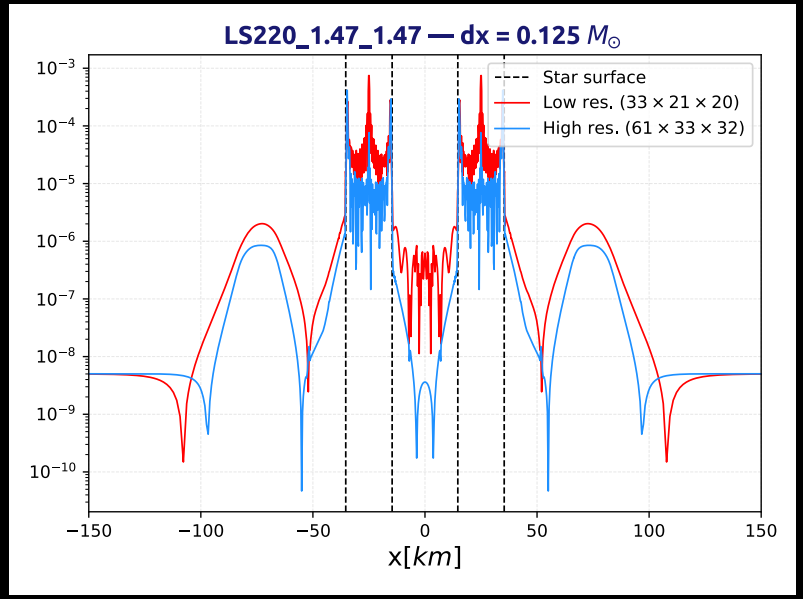
Our Code Repertoire

- LORENE+ (Gupte, Faber) – An open source Initial Data Pipeline for BNS and BHNS extended with parameter-driven interface.
- IllinoisGRMHD (Etienne, Werneck) – GRMHD with tabulaled EOS, Cartesian-AMR grids, staggered A-field, neutrino leakage, etc
- Spritz (Giacomazzo, Ciolfi, Cipolletta, Ennoggi, Kalinani, Pavan) – an independent GRMHD code.
- Harm3D (Noble) + NUC (Murguia Berthier) – A mature accretion disk MHD code, which can handle arbitrary coordinate systems, in prescribed dynamical spacetimes.
- The ``Hand-Off" Toolkit (Lopez Armengol+) for transitioning from Cartesian AMR grids to spherical grids.
- PatchworkMHD (Avara+) – A novel "multipatch" infrastructure capable of coordinating independent programs communicating via boundary condition exchange.
- SphericalNR (Mewes, Zlochower+) – A new GRMHD code based on GRHydro/ETK, spherical coordinates, AMR grids, A-field,
- Paramo (Rueda-Becerril)– A particle acceleration code for relativistic jets Pandurata (Schnittman) – a novel Montecarlo code for neutrino transport.
- Skynet (Zenati)– post-processing nucleosinthesis code
- Pandurata + PTRANSX (Schnittman+) – a novel Montecarlo code for neutrino and radiation transport + reprocessing with atomic features - Friday

Public Repository of Initial data – LORENE

Talk by Tanmayee Gupte

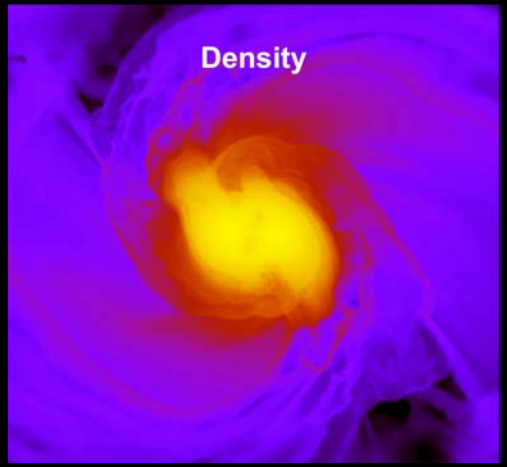
- Modified LORENE to compute unequal mass binary neutron star initial data (ID) with higher mass.
- Developed general formalism to get ID for Tabulated EOS and proved convergence of hamiltonian constraint violations.
- Maintained a public repository for ID with different piecewise polytropic and tabulated equation of state – compact-binaries.org



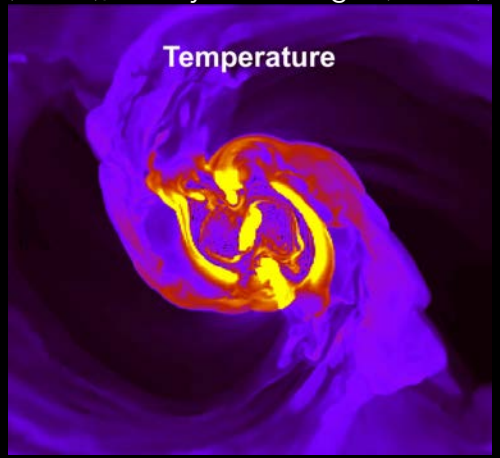
Hamiltonian constraint violations for tabulated EOS

Enhanced IllinoisGRMHD
Talk by Leonardo Werneck

- IllinoisGRMHD's equation of state (EOS) support has been extended to include tabulated EOS.
- Evolution of the entropy and the electron fraction have been added.
- Updated conservative-to-primitive infrastructure to minimize spurious heating of NSs when using tabulated EOS.
- Neutrino leakage implementation is the subject of ongoing work.
- Incorporated "Hand-Off" Tools (e.g. higher order accurate interpolators).
- Wernek+TCAN collaboration 2021, in prep.

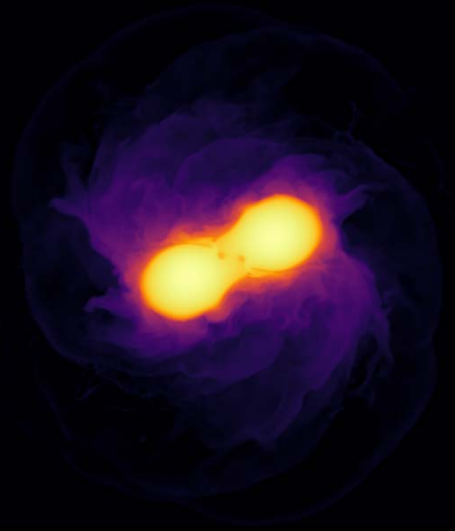


Magnetized, equal-mass BNS simulation performed with IllinoisGRMHD using a tabulated EOS (LS220), shortly after merger (HMNS)



A new GRMHD code – Spritz

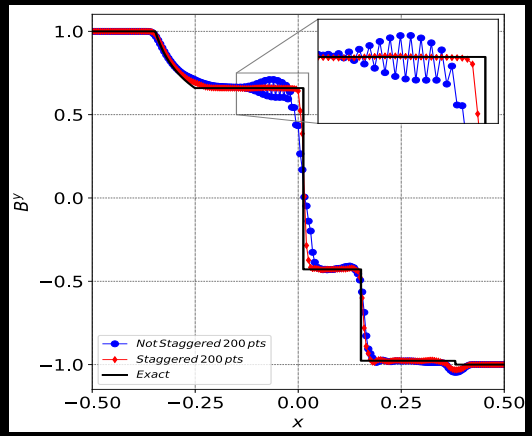
Talk by Lorenzo Ennoggi



- Developing Spritz a new staggered A-field Cartesian-AMR GRMHD code with neutrinos and Tabulated EOS (Cipolletta+2020, Cipoletta+2021).

- Currently Spritz supports both ideal fluid/polytropic and tabulated EOS + Y_e advection and neutrino leakage (through ZelmaniLeak).

- Currently testing different implementations of the generalized Lorenz gauge.



"Hand-Off" Framework to BNS post-merger

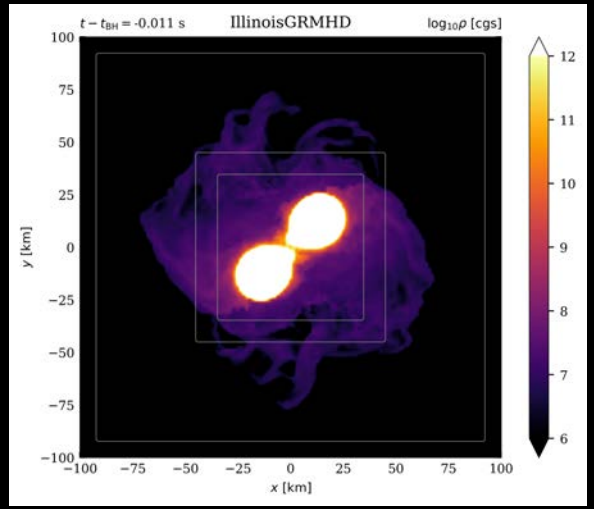
Talk by Federico Lopez Armengol

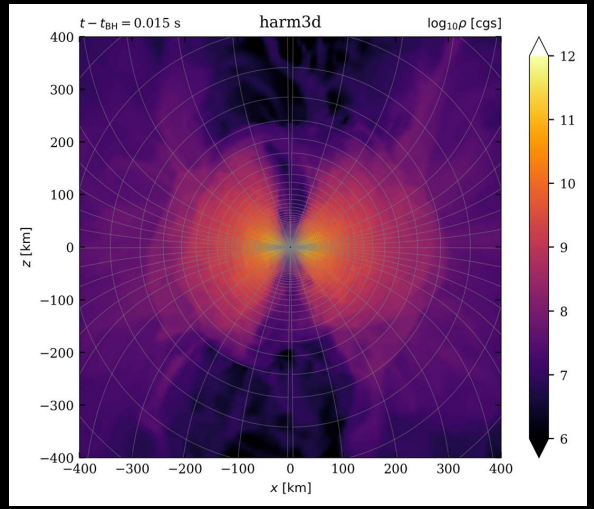
- We developed *Hand-Off* tools for transitioning from a BNS/BH-NS merger simulation using Cartesian-AMR grids to a spherical flexible grid adapted to the geometry of the post-merger (Lopez Armengol in prep 2021).

- This allow us to increase the resolution in desired regions, moving outer boundary farther away.

- Currently, we have tested the *Hand-Off* from IllinoisGRMHD and Spritz to Harm3D-NUC (Murguia Berthier+2021).

- First post-merger simulations now underway on Frontera at TACC for both polytropic and LS220 EOS!





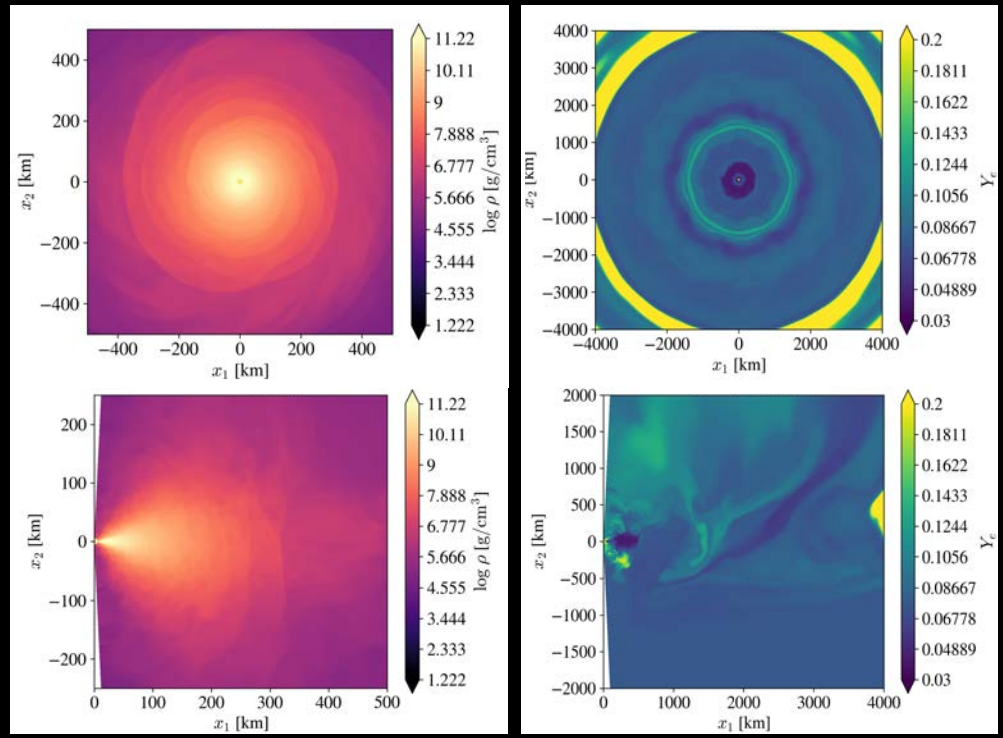
Postmerger Evolutions with HARM3D+NUC

Talk by Ariadna Murguia Berthier

- We have implemented a tabulated EOS and an approximate neutrino transport (leakage scheme) in the well-tested, flexible GRMHD code HARM3D – (Murguia-Berthier +2021).

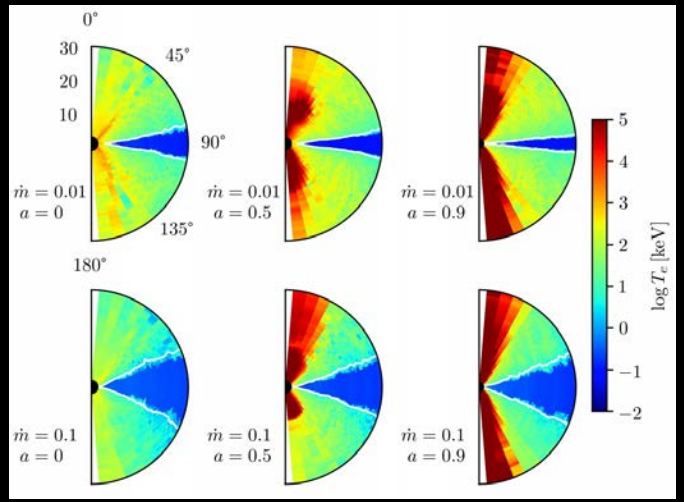
- The new code, called HARM3D+NUC has been formally tested in the paper, and we also use the code to simulate the evolution of a magnetized torus.

- With the new implementation, we are ready to simulate the post-merger simulation after the ``Hand-Off''.



Neutrino + Radiation Transfer - "Pandurata+PTRANSX"
Talk by Jeremy Schnittman

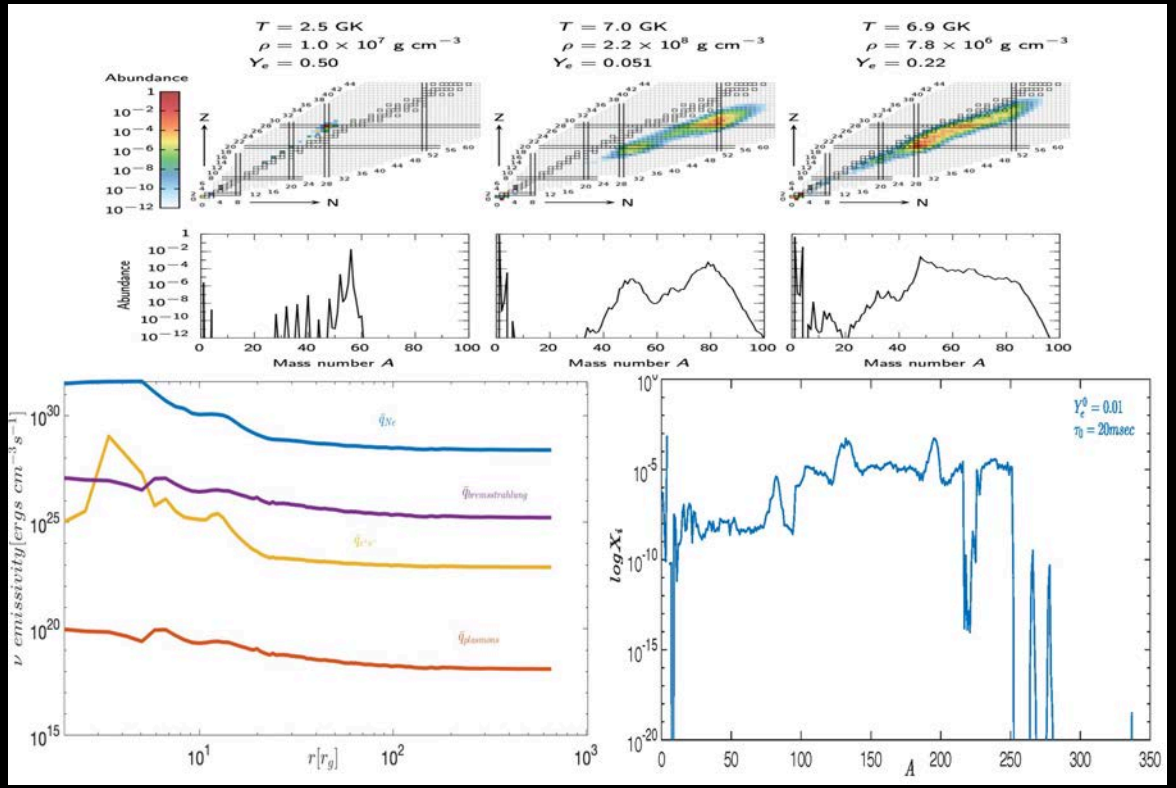
- Pandurata+PTRANSX couples to Harm3d to implement a physical cooling function for the low-density corona, and also solves the ionization balance equations in the optically thick disk.
- The resulting electron temperature map is used in post-processing the Harm3d simulations with Pandurata, generating a broad-band X-ray spectrum, including the thermal emission, inverse-Compton power-law, iron K-alpha line, and the reflection hump around 20 keV.
- The Monte Carlo nature of Pandurata makes it ideally suited for problems with complicated, 3d, time-dependent accretion geometries including both optically thick and optically thin regions.
- We are able to reproduce observations of "low-hard" and "high-soft" states of X-ray binaries by varying the accretion rate in the Harm3d simulations.
- Now extending to include neutrinos!



Series of contour plots of the electron temperature in the disk/corona/jet region, for BH spins parameters a=0, 0.5, and 0.9, and two different accretion rates: 1% and 10% L_{edd} (Kinch+2021). .

Nucleosynthesis – Skynet

Talk by Yossef Zenati



- BNS: post-merger simulation.
- Nucleosynthesis in the debris wind of BNS mergers.
- The neutrinos emissivity in BNS and the final elements using SkyNet code.

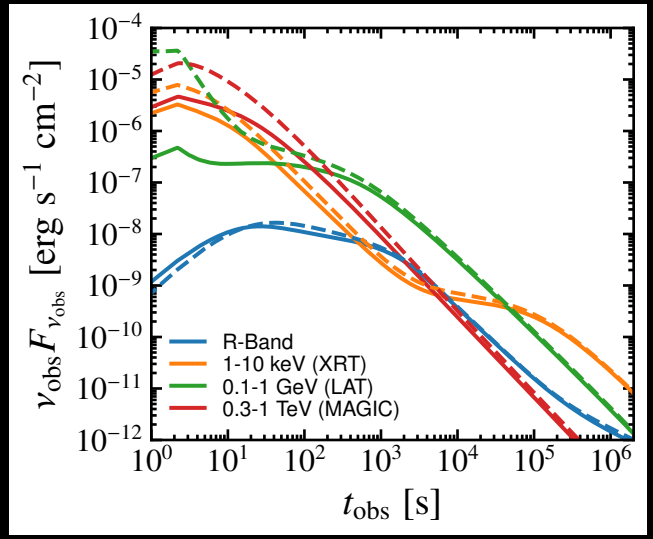
Particle Acceleration in Jets - "Paramo"

Talk by Jesús M. Rueda-Becerril

- A numerical code, named **Paramo**, has been developed with several features capable of evolving energy distributions of particles in relativistic outflows, the evolution of their spectral signature, and the dynamical interaction between them - Rueda-Becerril 2021.

- Paramo can be used in hydrodynamic models of spherical and jetted blast-waves, and in numerical simulations.

- With **Paramo** we will be able to estimate the light curves and spectra from, e.g., the BNS post-merger jet.

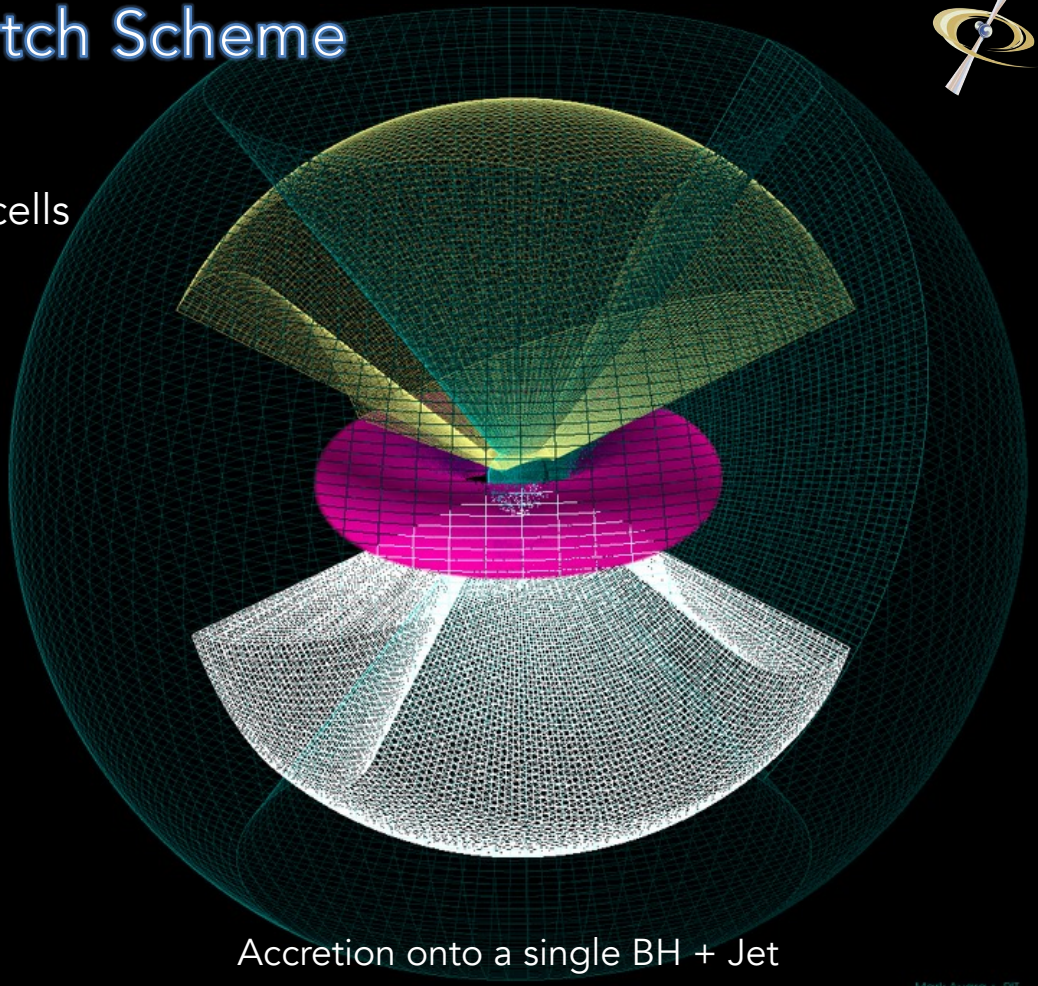


Light curves of a gamma-ray burst afterglow (GRB190114C) at different wave-bands, showing two different radiative cooling prescriptions of accelerated particles

PWMHD - A new Multi-Patch Scheme
Talk by Mark Avara

How do we efficiently simulate 10^7-10^8 cells for 10^6-10^7 steps?

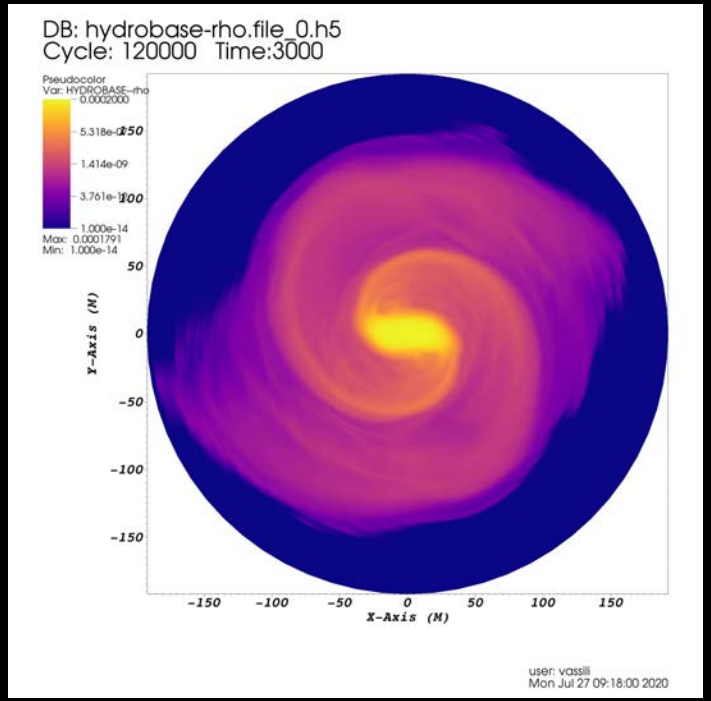
- **PatchworkMHD** – Avara+ 2020 in prep New software infrastructure for problems of discrepant physical, temporal, scales and multiple geometries.
- Early development (hydrodynamics only) – Shiokawa+ 2018
- Accreting supermassive black hole inspiral simulations now up to 30 times more efficient!

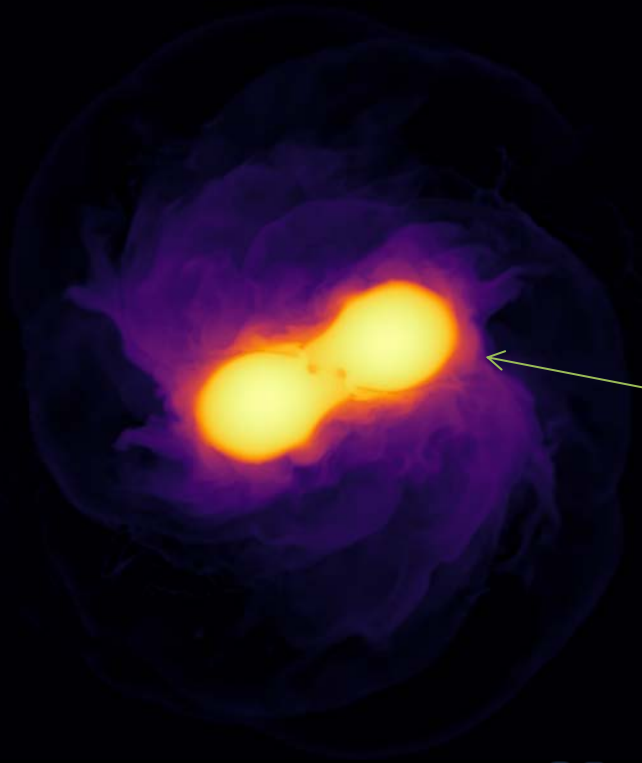


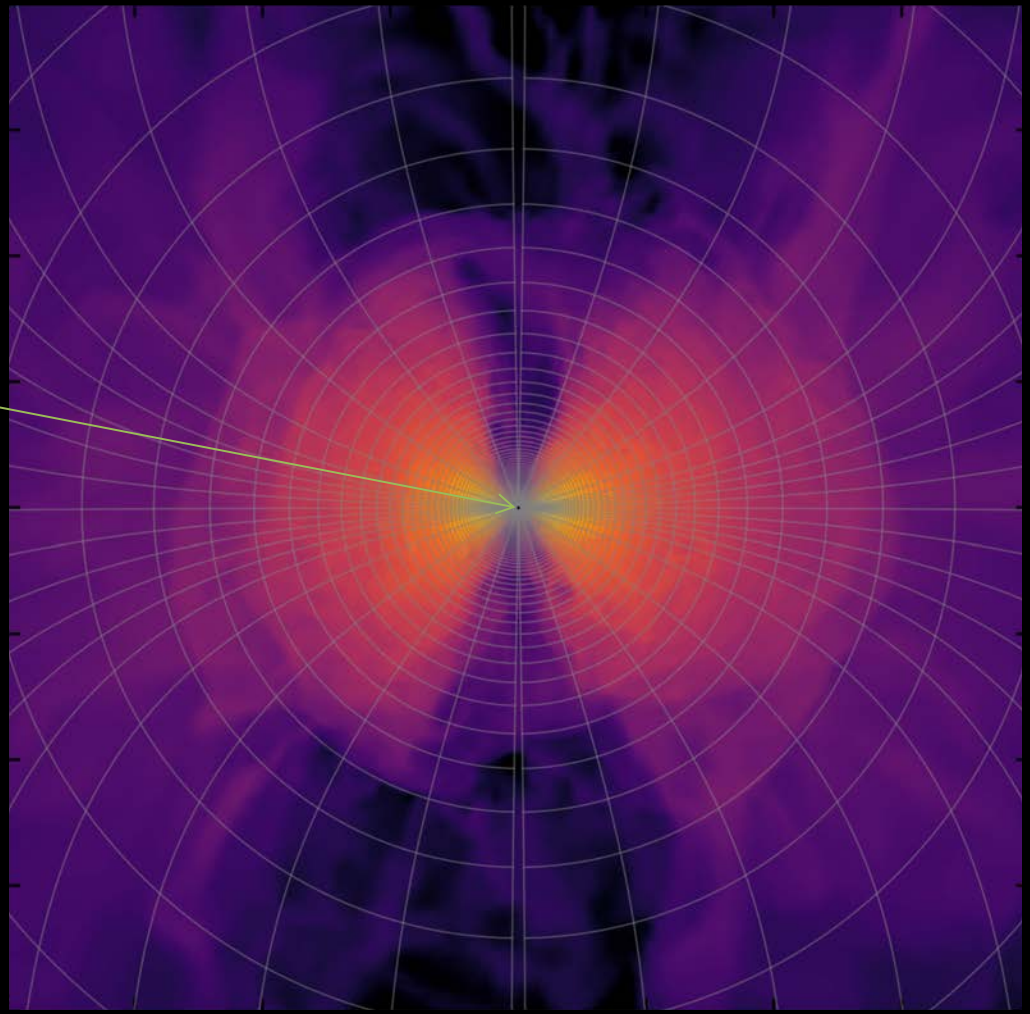
Accretion onto a single BH + Jet

SphericalNR
Talk by Vassilios Mewes

- Adding soon SphericalNR (Mewes+2019,2020) for handling the HMNS cases
- Build on top of the Einstein Toolkit SphericalNR supports curvilinear coordinates using the reference metric approach.
- Currently, cell-centered A-field, high-order GRMHD, finite difference-finite volume code.
- Courant limitation ameliorating via filtering (Zlochower+2021).
- Support NS and vacuum evolutions in full NR!







Stay Tuned!

July 12-16, 2021

Workshop Information

- Zoom link: https://rit.zoom.us/j/98985951339?pwd=N0x6aUFQWWtzY05KK0R2WUhZUW9JQT09
- Workshop schedule: https://compact-binaries.org/node/2856
- Mailing list: workshops@ccrg.rit.edu
- Slack: bnsworkshop2021.slack.com
- Social Media:
  - Twitter handle @CBinaries,
  - Facebook page Compact Binaries,
  - YouTube channel https://www.youtube.com/channel/UCI2xVl2lp5G25_dHIuMkY0g
- Google discussion link: https://docs.google.com/document/d/1-IQm192izfTTi-qVTFhmpuSqd5_-vzT4X5JIob17pXw/edit

Contact Information

Local Organizing Committee:

- Manuela Campanelli (RIT) - Director
- Jim Healy (RIT) - General Technical Support
- Jesus Rueda-Becerril (RIT) - Social Media Coordinator
- Tim Moon (RIT) – Program Coordinator
- Qin Ye (RIT) - General Staff Support
- Yosef Zlochower (RIT) - General Technical Support

Scientific Organizing Committee:

- Dr Federico Lopez Armengol (RIT)
- Dr Manuela Campanelli (RIT)
- Dr Ariadna Murguia Berthier (UCSC/Northwestern University)
- Dr Julian Krolik (John Hopkins University)

Diversity and Inclusion

We are committed to creating a respectful and inclusive community environment that invites participation from everyone, regardless of gender, sexual orientation, disability, physical appearance, body size, race, nationality, or religion.

Our community is based on mutual respect, tolerance, and encouragement, and we are working to help each other live up to these principles. We want our community to be more diverse: whoever you are, and whatever your background, we welcome you.

Additionally, we aim to always be respectful of our environment and strive to be environmentally friendly in all of our events.