Generating Physically Realistic Neutron Star Initial Data

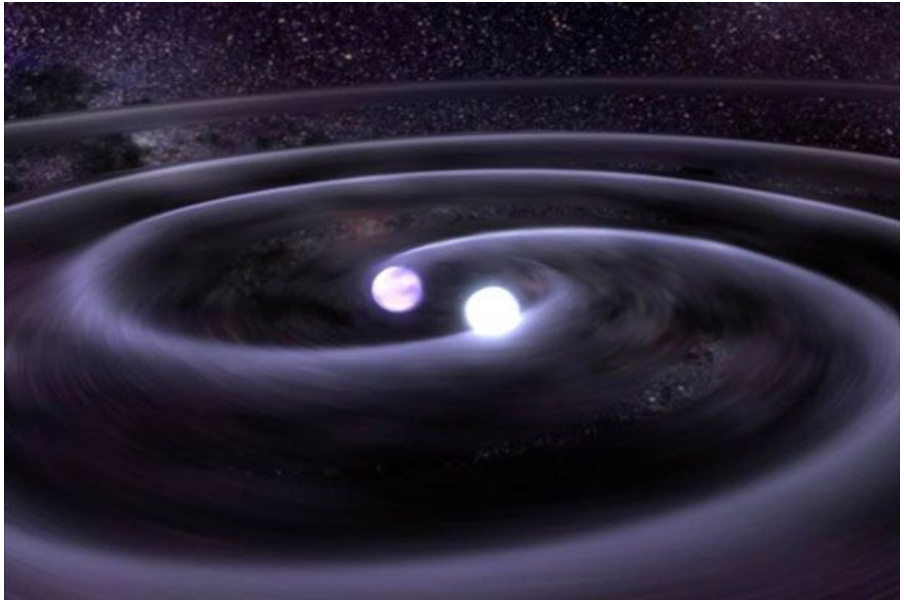
Grace Fiacco, Trung Ha
Advisor: Dr. Joshua Faber
Rochester Institute of Technology

Our Project

- Objective: We will be studying BNS mergers where we vary the masses, mass ratio, and EOS
- Project Status:
  - Compiling a library of BNS initial data using numerical code LORENE
  - Implemented modifications to make Lorene user-friendly and less error prone
  - Working on using Lorene data in Einstein Toolkit
- End Goals:
  - Calculate gravitational waveforms
  - Determine the mass ejecta as a function of various parameters
  - Track the final fate of merger remnants

Background - Why Neutron Stars?

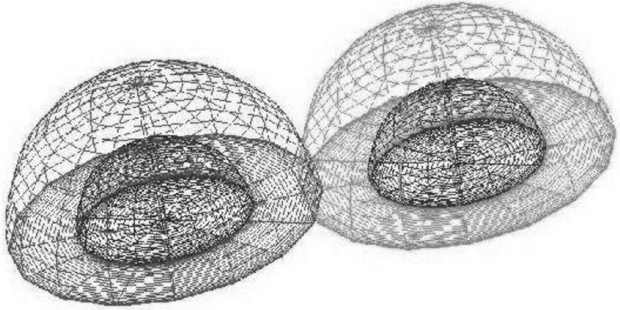
- Binary neutron star (BNS) mergers provide the best joint gravitational wave and electromagnetic sources for multimessenger astrophysics
- Allows us to both test General Relativity and explore nuclear matter equations of state (EOS)
- We require initial data to link observables to physical features of the NS



NASA/Goddard Space Flight Center

Lorene - Overview & History

- Developed in 2001
- Consists of C++ classes that solves partial differential equations through a multi-domain spectral method
- Varying Physical Models
    - Magnetized NS
    - Rotating NS
    - Black holes
    - BH/NS Binaries



Gourgoulhon et al. 2001

Lorene - How it Works

- Uses GR and Tolman-Oppenheimer-Volkov (TOV) Equations to model isolated NS
- Assume quasi-equilibrium
    - Irrotational binary
    - Spatial 3-metric
    - Slow circular inspiral
- Conformal Thin-Sandwich Formalism to solve non-linear elliptic equations
    - Elliptic field equations
    - Elliptic matter equation for the velocity potential

Lorene - How it Works Cont.

Equation of state

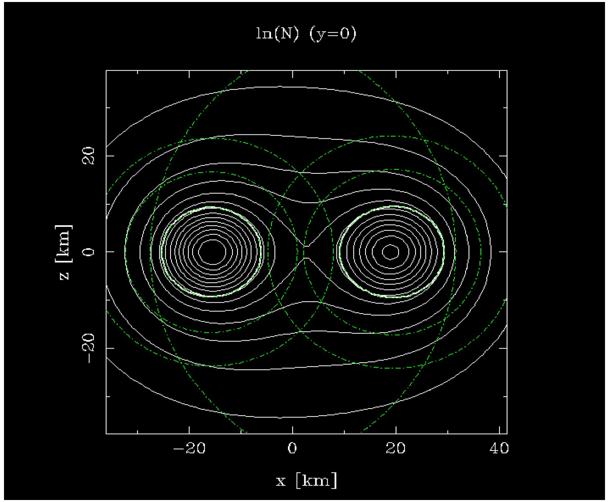
- Polytropes: $P = k\rho^{\gamma}$
- Piecewise Polytropes
- Several well-known "physically motivated" models
  - APR, FPS, SLy

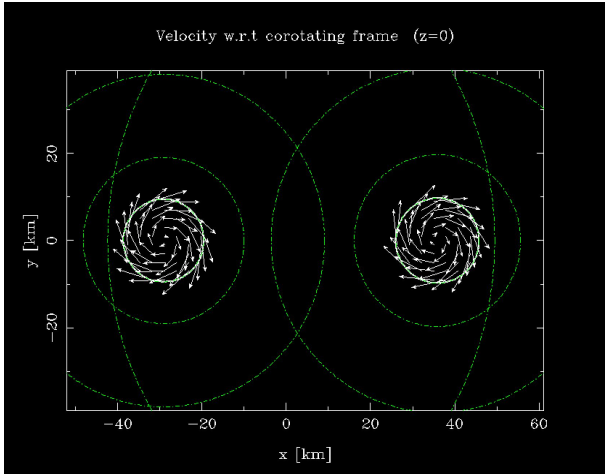
Running Lorene

- Three steps:
  - Generate the initial mass and radius based on enthalpy guesses
  - Input initial and final masses, binary separations, distance steps, etc into the main sequence
  - Run coalescence sequence with the provided values

Lorene Configurations and Uses

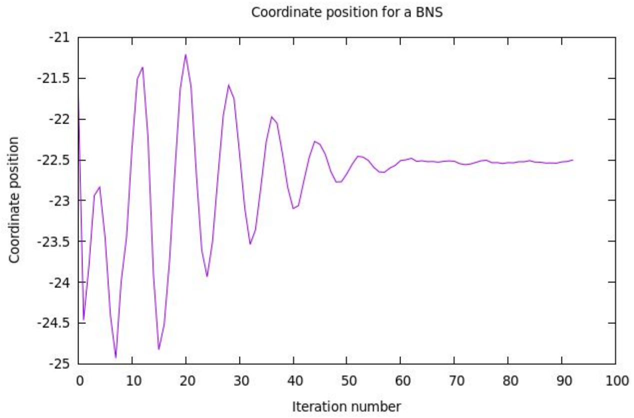
- Has the ability to generate multiple plots with different characteristics
  - Rotational velocity
  - Metric components
- Compatible with Einstein ToolKit Code for dynamical simulations

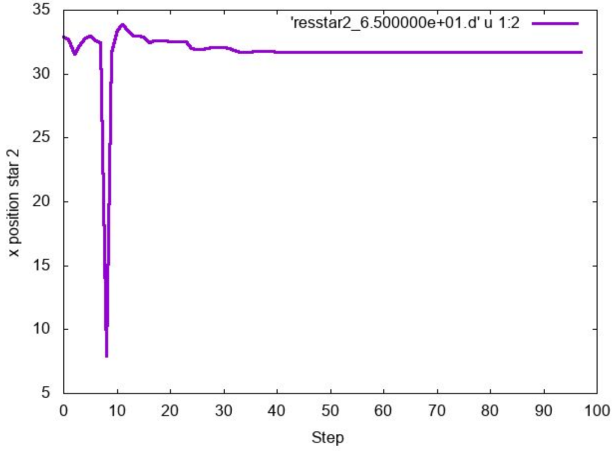




Complications & Modifications

- Secant Method for Unequal Binaries
  - Locates the rotation axis of the system. Potential infinite divergence in the function being set to zero
  - Fix: Take the reciprocal of the function - allows easier convergence
- Center of Mass & Angular Velocity
  - High mass binaries - CoM and angular velocity wanders - crashes code
  - Fix: Created a sequence that can both increase the mass and decrease the separation of the two stars without crashing





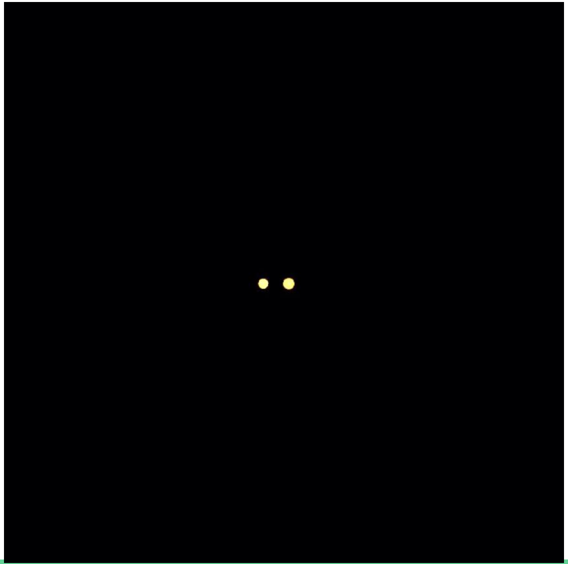
Current Work – Einstein Toolkit (ETK)

- Implementing previously generated initial data from Lorene into dynamical simulation using ETK:
    - Reran datasets by research group at Parma University to make sure our version work correctly (De Pietri, Roberto, et al., 2016).
    - Figure out how to convert units from Lorene to ETK for the neutron star density ρ and constant of proportionality K in the equation of state: $P = k\rho^\gamma$.
    - Perform dynamical simulations with generated datasets, create movies using VisIT visualization software.

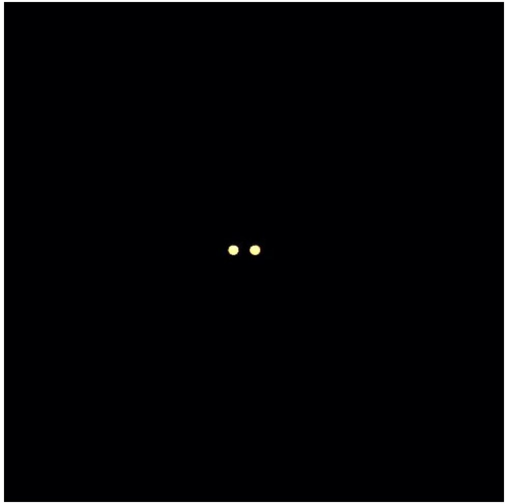
Dynamical Simulations with the Einstein Toolkit

- Preliminary results: dynamical simulations of two configurations, both using AP4 equation of state

Star 1: 1.80 solar masses
Star 2: 1.25 solar masses



Star 1: 1.40 solar masses
Star 2: 1.40 solar masses



Summary & Future Work

Past & Current Work

- Modified the Lorene initial data code
  - Mass and radius stepping sequence
- Compiling a public initial data library
- Launching Lorene runs through ETK and creating visualizations

Future

- Perfecting dynamical simulations of our initial data
- Perform various analyses of the simulations
  - Gravitational waveforms
  - Mass ejecta
  - Fate of merger remnants

Acknowledgements & Questions

- Our advisor, Dr. Joshua Faber at the Rochester Institute of Technology
- Our collaborator, Tanmayee Gupte
- The TCAN Collaboration
  - WVU, John Hopkins University, NASA Goddard

Center for Computational Relativity and Gravitation