EOS from the User Perspective

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Overview

- Use case GW data analysis
- Use case BNS merger simulations
- The `RePrimAnd` library

Use case GW data analysis

Example: GW170817 LVK model selection study

- Model GW170817 assuming 24 different EOS
- Direct use of tabulated nuclear physics EOS
- Not using parametrized EOS
- Compute Bayes factors from GW signal
- Predict remnant properties (total baryonic mass)

LIGO Scientific Collaboration, Virgo Collaboration, *Model comparison from LIGO–Virgo data on GW170817's binary components and consequences for the merger remnant*, **CQG 37, 045006 (2020)**

Use case GW data analysis

Example: GW170817 LVK model selection study

- Mostly hadronic, cold, beta-equilibrium EOS
- Main requirement: sequences of non-rotating NSs
  - **Tidal deformability**
  - Gravitational mass
  - Baryonic mass
- Also useful
  - Central density (to interpret EOS constraints)
  - Radius (for computing radius posteriors)
  - Moment of inertia
  - Uniformly rotating sequences at Kepler limit

Use case GW data analysis

First problem: getting and using tables

- Tables provided in different formats
  - CompOSE, Arizona collection, generator code, ..
- Each tool has its own formats and conventions
  - RNS, Lorene, TOV solvers, LIGO's LAL suite, ..
- Inofficial tables in each format
- Metadata scattered in different places
- Sources are simple webpages
  - Data might change, bad for reproducability
  - Can cite only EOS papers, not data
- Ambiguous naming, different variants

Use case GW data analysis

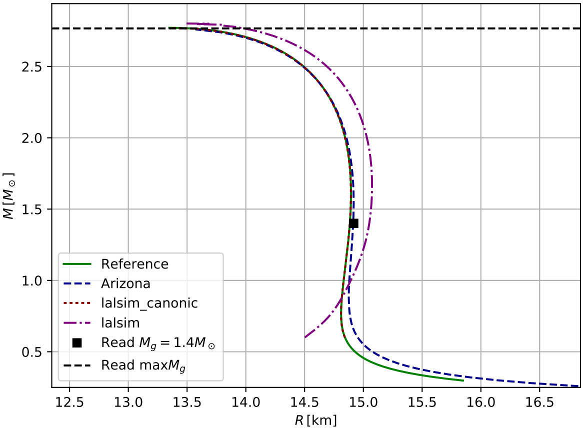
Second problem: ensure quality

- Many tables include causality-violating parts
- Some EOS not even causal up to maximum mass NS
- Raw sources sometimes sampled too coarsely
- May contain isolated points that are faulty
- Wildly varying low density cutoffs
- Need to extend to zero density to determine NS surface

Use case GW data analysis

Second problem: ensure quality

- Need to interpolate EOS
- Need to preserve monotonicity+adiabaticity
- Radius and tidal deformability can become ambiguous



Use case BNS merger simulations

- Need barotropic EOS for initial data (typically cold + beta-equilibrium)
- Require thermal and composition for GR(M)HD simulation
- Additional microphysics when including neutrinos

Use case BNS merger simulations

- Evolving mass, energy, and momentum densities
- Need EOS in terms of (ρ, ϵ, Y_e)
- All schemes need P and c_{snd}
- Some schemes also $\partial P / \partial \rho, \partial P / \partial \epsilon$
  - Derivatives problematic for many primitive recovery schemes
  - New scheme in RePrimAnd library not using derivatives
- Hybrid EOS
  - Semi-analytic ad-hoc construct $P(\rho, \epsilon)$
  - Entropy and temperature ambiguous, rarely used
  - Composition relevant even without neutrino physics

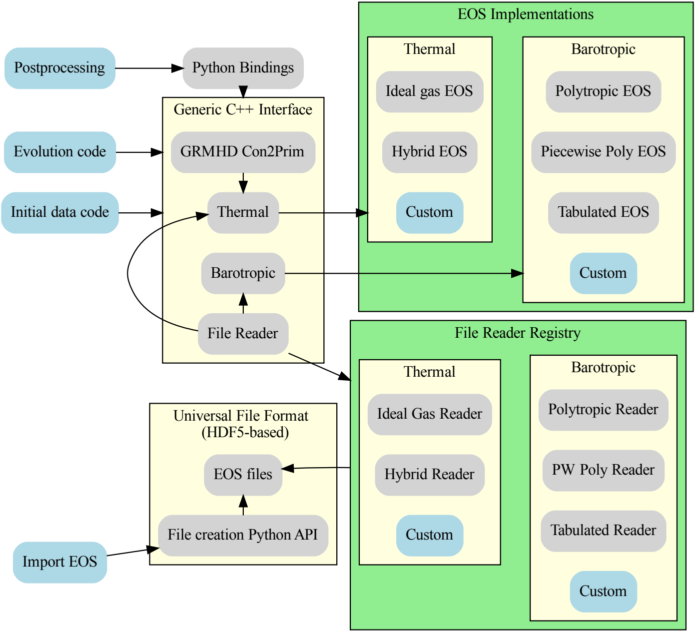
Use case BNS merger simulations

- Available tables use (ρ, T, Y_e)
- Direct use requires inefficient conversion $T \leftrightarrow \epsilon$
- Need EOS to include zero temperature
- Violating causality has consequences, e.g.,
  - Cauchy initial value problem not well-posed
  - Some expressions in numerical evolution can become NAN
  - Uniqueness proof for Con2Prim breaks down
- Need to get rid of isolated faulty points

The RePrimAnd library

- Support library for numerical relativity
- Primitive variable recovery for GRMHD
- Generic EOS framework
  - Barotropic EOS
  - EOS with thermal + composition
- Standalone C++ library
- New: Python language bindings
- Public release
  `https://github.com/wokast/RePrimAnd/tree/v1.0`
- Code archived on Zenodo and citeable via DOI
  `http://doi.org/10.5281/zenodo.4075317`
- Does NOT include EOS collection

The RePrimAnd library



The RePrimAnd library

- Thermal EOS interface
  - Independent variables (ρ, ϵ, Y_e)
  - Provides validity range
  - Provides $P, c_{\mathrm{snd}}, \partial P / \partial \rho, \partial P / \partial \epsilon$
  - Optionally, may provide s, T
  - Optionally, also allow independent variables (ρ, T, Y_e)
- Geared towards numerical relativity simulations
- Python interface supports postprocessing

The RePrimAnd library

Barotropic EOS interface

- Geared towards initial data and evolution
- Mandatory validity down to zero density
- Two parametrizations using ρ and H

$$\log(H) \equiv \int_0^P \frac{dP'}{\rho(P')h(P')} \qquad \text{Pseudo enthalpy}$$

- H useful for initial data codes
- Provides $P, \epsilon, h, c_{\mathrm{snd}},\ H(\rho), \rho(H)$
- Optionally T, Y_e
- Metadata: isentropic ? cold ?
- Python interface supports analysis and postprocessing

The RePrimAnd library

EOS types already in public repository

- Polytropic
- Piecewise polytropic
- Tabulated barotropic
- Hybrid thermal part (any barotropic EOS as cold part)
- Classical ideal gas (for testing)

The RePrimAnd library

Ongoing development

- Fully tabulated 3-parametric EOS
- Extend interface?
- EinsteinToolkit integration
- Include TOV solver (+tidal deformability)
- Include pure-hydro primitive recovery
- More unit tests
- Spectral cold EOS
- Automatic HTML EOS overview creation