Equation of state inference for NS parameter estimations: the CUTER tool

Philip DAVIS
on behalf of the LuTH-Caen group in Virgo :
LPC-Caen, GANIL, LuTH, Observatoire de Strasbourg

In collaboration with : California State University, Fullerton

GW dans le grand ouest - 27 mai 2025

Background Context

Neutron stars (NSs) : dense and compact objects formed from progentors with masses $\geq$ 8-10 Msun :

● Mass : ~ 1-2 Solar masses

● Radii : ~10 – 14 km

● Mean density : ~10^{14} – 10^{15} g/cm^3

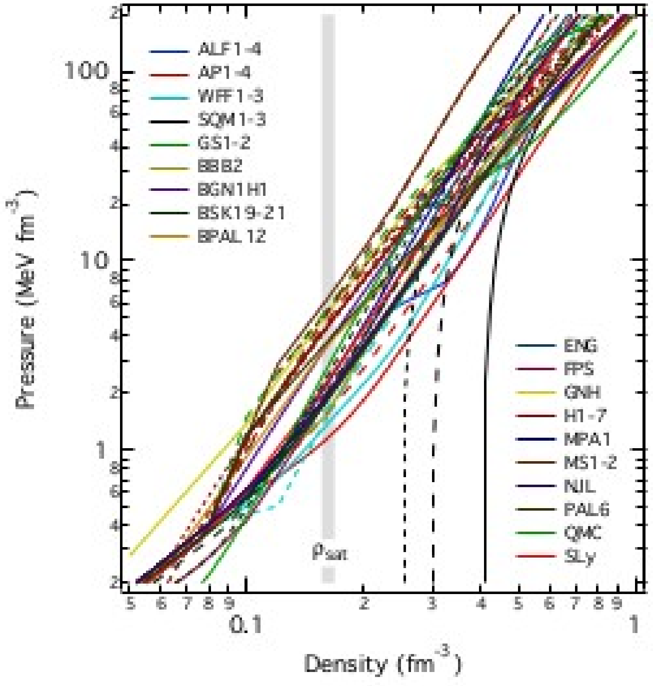
For cold, mature NSs :

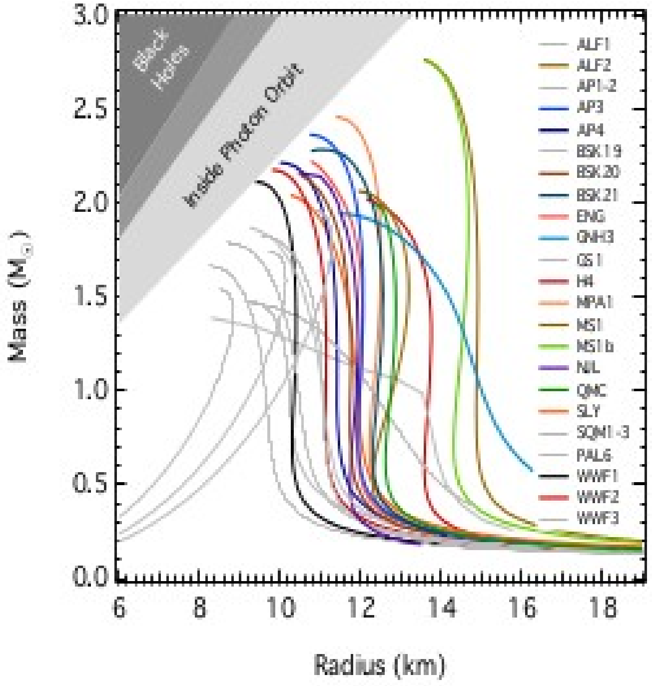
● The equation of state (EoS) describes a relationship between the pressure and the density,

● Once we have the EoS, we can determine the structure of a NS

● Then calculate global NS properties, e.g. mass, radius, tidal deformability.

Credit : Ozel & Freire 2016





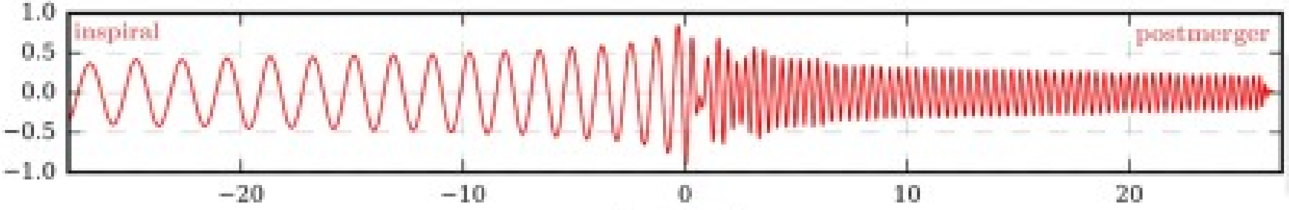
There are many NS EoS,

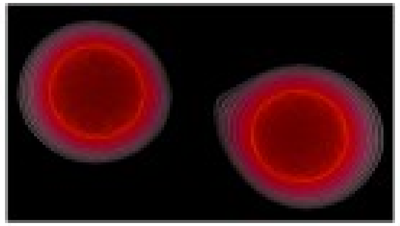
→ Comparison between calculated and observed NS properties can help constrain the EoS.

Background Context (cont.)

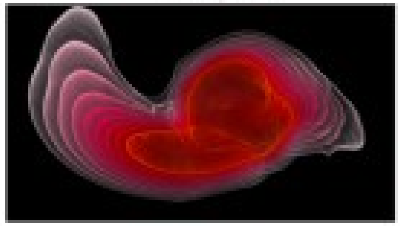
Terrestrial experiments can only probe low-density regimes. For higher densities, require astrophysical constraints, e.g. gravitational waves (GWs) during NS merger events.

Credit : Dietrich et al. 2021

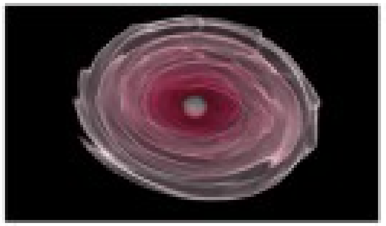




Pre-merger



Merger



Post-merger

The shape of the GW signal (the « waveform ») depends on the property of matter and hence the EoS of the NS.

Comparing observed and simulated waveforms, provides information on the EoS.

Credit : Virgo/ Ligo collaboration

Development of numerical tools for the LIGO-Virgo-Kagra collaboration by members of LuTH-Caen group in Virgo (LPC, LuTH, Strasbourg, GANIL).

Aim of role : raise awareness of good software development practices and data management so that quality numerical tools and data can be used by the scientific community.

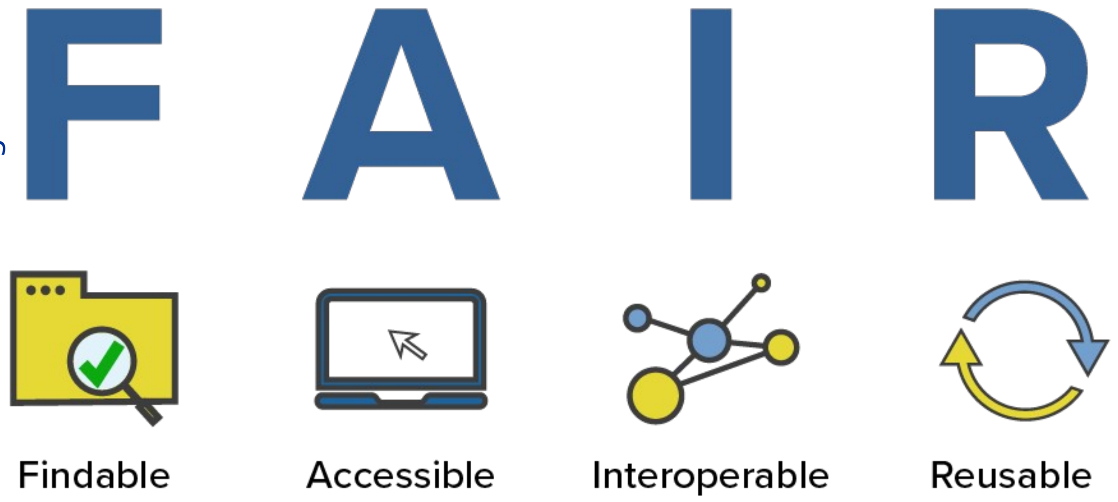
Why is this important ?

Good software and data practices ensure :

- Robustness and reliabability,
- Transparency,
- Traceability,
- Reproducibility.

These are in turn important for the Open Science initiative, which :

- Improves visibility of research,
- Ensures research can be validated,
- Improves collaborations,
- Reduces duplicated effort.



Credit : www.nlm.nih.gov

Challenges for reproducible science

1,500 scientists lift the lid on reproducibility

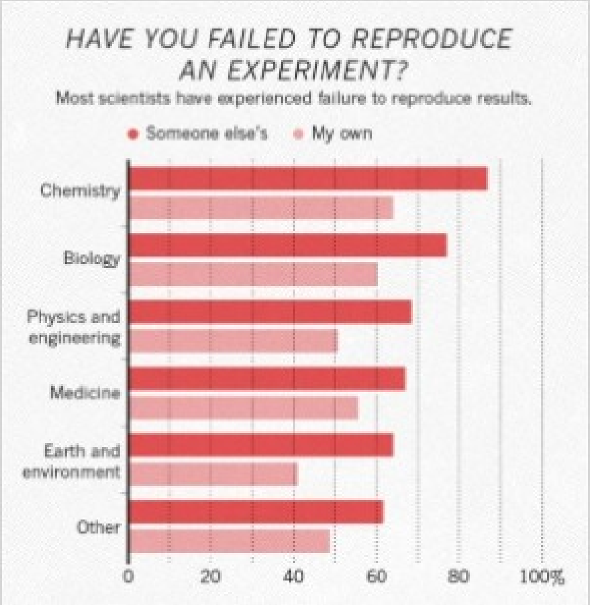
Monya Baker

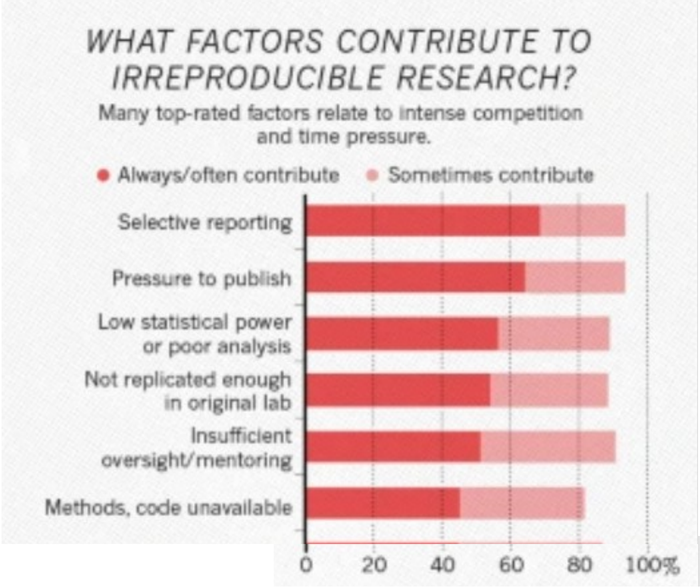
Nature **533**, 452–454 (2016) | Cite this article

2131 Citations | **5236** Altmetric | Metrics

This article has been updated

Survey sheds light on the 'crisis' rocking research.





https://www.nature.com/articles/533452a

Physics/engineering : ~ 70 % of scientists in study have failed to reproduce results,

~ 40 % of respondants said unavailability of codes/ methods always or often contributed.

Also, potential problems with :

- bugs within the code,
- numerical libraries are missing or incompatible with the host machine

By following good coding practices, we can hope to improve our chances of reproducing (numerical) experiments.

Raising awareness of good practices

Created training material covering software development working practices :

- Version control with git and GitLab,
- Design and documentation,
- Tests,
- Code reviews.

Courses given to LuTH-Caen group members,

LPC « permanences » : exchange ideas concerning software working practices and data managements.

Bootcamp, Nov. 2024 for new PhD starters.

Software Development and Testing Tutorial

2. Development working practices

Philip DAVIS
Ingenieur de Recherche
Laboratoire de Physique Corpusculaire

IN2P3

Recap

Code repository: A database, usually located on an external server, where code is stored. GitLab is just one such example.

Version control: A way to track code changes in a organized and logical way.

Code branch: A separate copy of the latest, stable version of the code where we can make changes without interfering with the Master. Changes to the code are saved via **commits.**

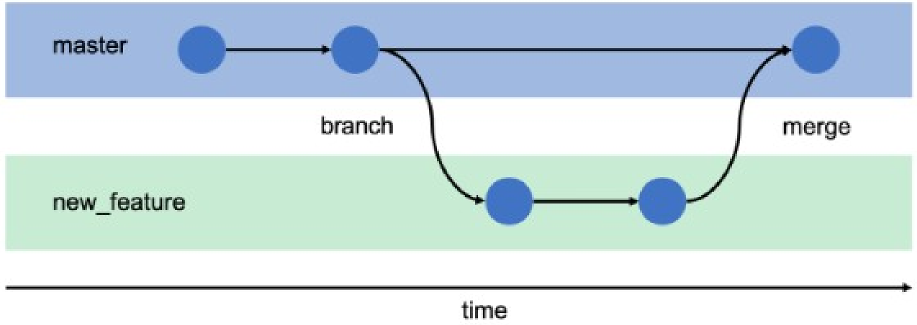
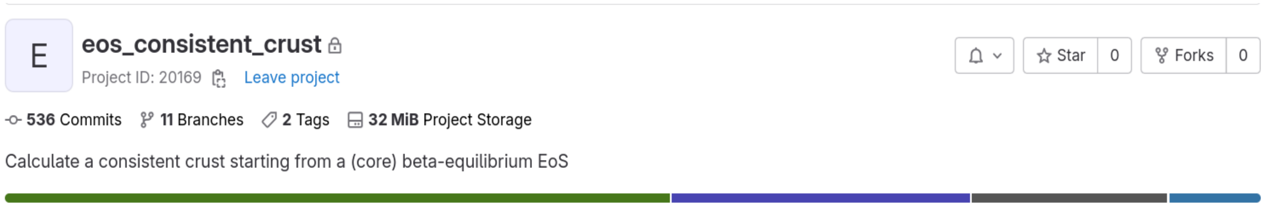


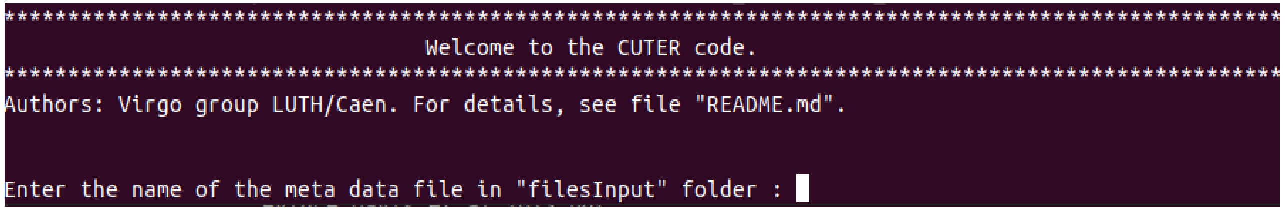
Fig. 1: Illustration of a code branch (credit: gitbookdown.dallasdatascience.com)

CUTER (Crust Unified Tool for Equation-of-State Reconstruction)

- A NS equation of state is needed to relate different global NS properties, for example mass and radius,

- Inconsistent treatment of NS crust (« non-unified ») can introduce biases.





Numerical tool, CUTER, developed for the LIGO-Virgo-Kagra collaboration :

- User provides beta-equilibrated EoS with a few nuclear parameters describing high-density core,

- CUTER computes additional nuclear parameters not necessarily known a priori,

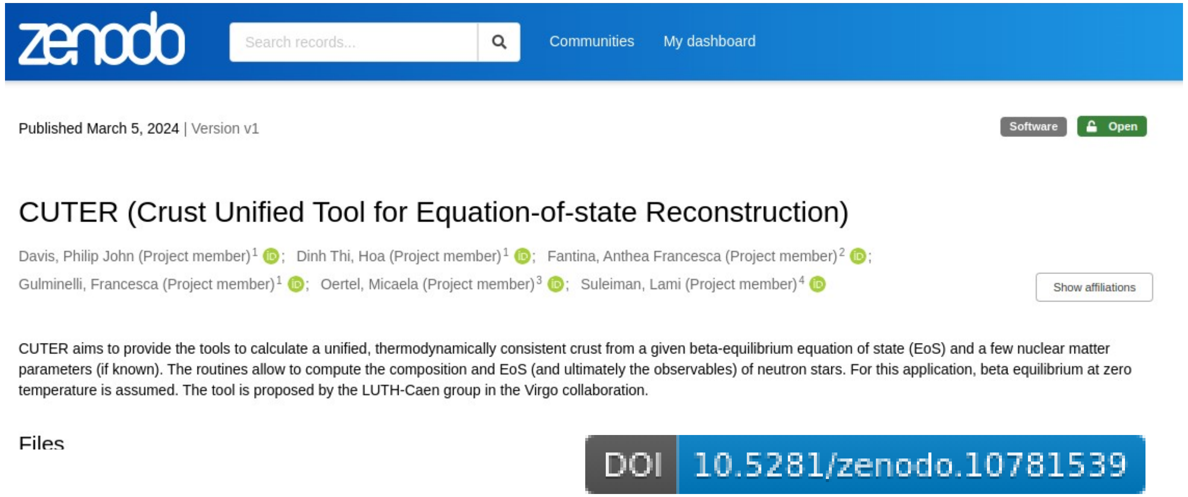
- Crust computed from same parameters and attached to core, hence thermodynamically consistent,

- Aim : reduce errors of inferred global properties of NS. Important for the next generation of gravitational wave detectors (e.g. Einstein Telescope).

CUTER (cont.)

Working practices followed :

- Software development « workflow »
- Hosted on IN2P3 and LIGO GitLab sites,
- Documentation (e.g. README),
- Addition of a License,
- Sign-off by external reviewer,
- `Conda` to manage software environment,
- `Pytest` for automated testing.



zenodo

Communities My dashboard

Published March 5, 2024 | Version v1

Software Open

CUTER (Crust Unified Tool for Equation-of-state Reconstruction)

Davis, Philip John (Project member)[1]; Dinh Thi, Hoa (Project member)[1]; Fantina, Anthea Francesca (Project member)[2]; Gulminelli, Francesca (Project member)[1]; Oertel, Micaela (Project member)[3]; Suleiman, Lami (Project member)[4]

Show affiliations

CUTER aims to provide the tools to calculate a unified, thermodynamically consistent crust from a given beta-equilibrium equation of state (EoS) and a few nuclear matter parameters (if known). The routines allow to compute the composition and EoS (and ultimately the observables) of neutron stars. For this application, beta equilibrium at zero temperature is assumed. The tool is proposed by the LUTH-Caen group in the Virgo collaboration.

Files

DOI 10.5281/zenodo.10781539

`CUTER` opened to LVK May 2023
Corresponding article published in
Davis et al. 2024, A&A.
https://doi.org/10.1051/0004-6361/202348402

Since then :

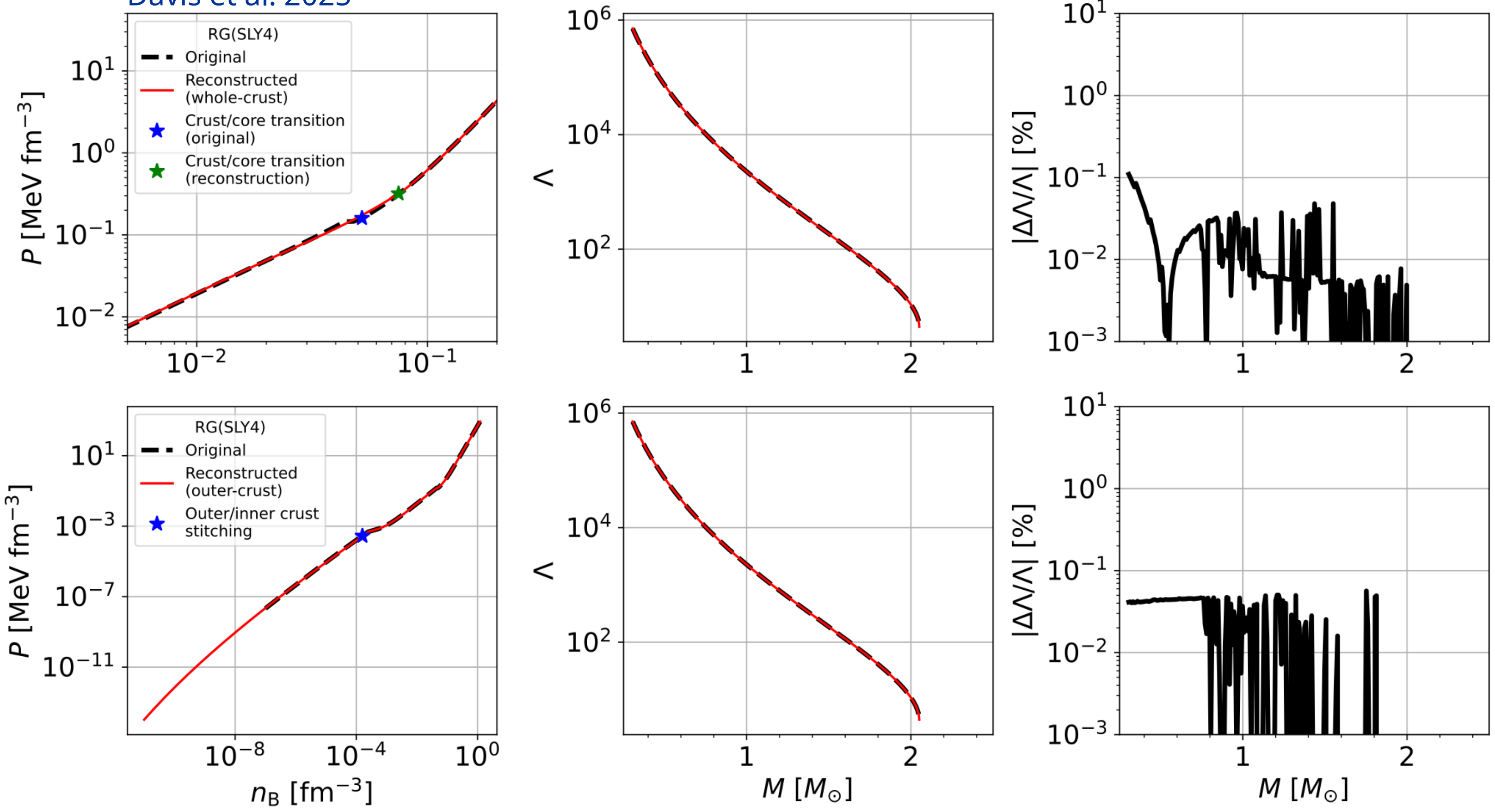
- `CUTER V2`: Outer-crust reconstruction only (baryon densities less than ~10^{-4} fm^{-3})

  - Inclusion of outer crust ensures correct calculation of NS properties,
  - Uses analytical fits of Brussels-Montreal Skyrme (BSk) EoS,
  - Addresses « jumps » due to changes in composition.

CUTER (cont.)

Type of reconstruction depends on the minimum density entry in given EoS table.

Davis et al. 2025



WHOLE CRUST RECONSTRUCTION
(min. baryon density ≥ 10^{-4} fm^{-3})

OUTER CRUST RECONSTRUCTION
(min. baryon density < 10^{-4} fm^{-3})

Typical relative errors in tidal deformability < 0.1 % for each reconstruction functionality.

CUTER V2: Released to LVK August 2024

Paper : Davis et al. 2025, EPJA

https://doi.org/10.1140/epja/s10050-025-01562-0

CUTER (cont.)

Decoding Long-duration Gravitational Waves from Binary Neutron Stars with Machine Learning: Parameter Estimation and Equations of State

Qian Hu,[1,*] Jessica Irwin,[1] Qi Sun,[2] Christopher Messenger,[1] Lami Suleiman,[3] Ik Siong Heng,[1] and John Veitch[1,†]

[1] *Institute for Gravitational Research, School of Physics and Astronomy, University of Glasgow, Glasgow, G12 8QQ, United Kingdom*
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[3] *Nicholas and Lee Begovich Center for Gravitational Wave Physics and Astronomy, California State University Fullerton, Fullerton, California 92831, USA*

(Dated: December 5, 2024)

https://arxiv.org/abs/2412.03454
(in press)

Community contributions :

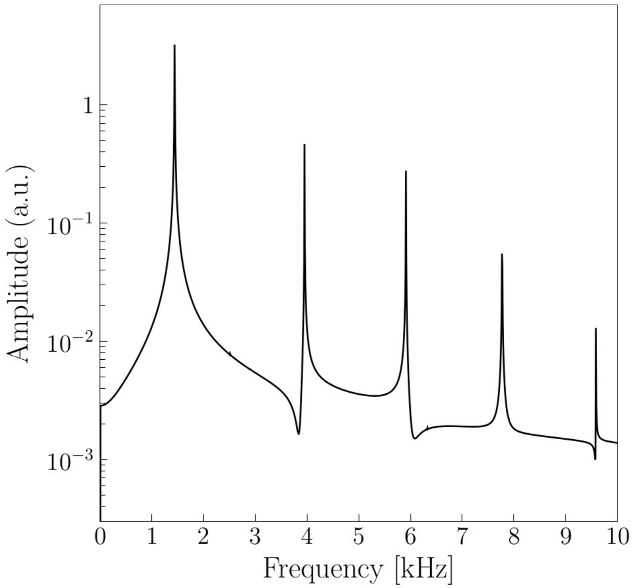
● Consistent EoS data produced by CUTER added to LVK analysis pipelines,

● Ongoing studies on binary NS parameter and EoS estimation from GW detection using third generation detectors (Einstein Telescope, Cosmic Explorer),

● New, consistent EoS tables will be added to the CompOSE database.

Future plans

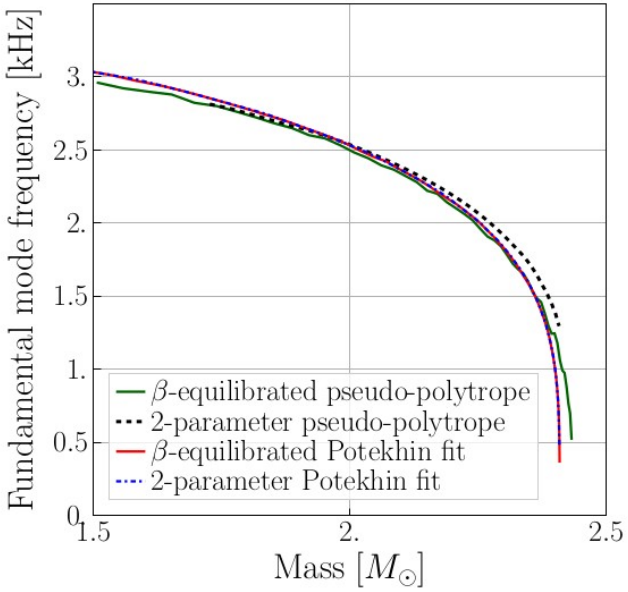
Servignat et al. 2023, Class. Quantum Grav.
DOI : 10.1088/1361-6382/acc828



Medium term (3-4 years)

- Parametric study of NSs with a large set of microphysical inputs, simulating possible GW signals, from a post-merger of NS+NS binary,
- In collaboration with researchers from the Observatoire de Strasbourg, in the framework of the *ANR GW-HNS (2023-2025) project,*
- Development of hydro code to model oscillating NSs and analytical representations of EoS underway.

Servignat (+Davis) et al. 2023, Phys. Rev. D (DOI: https://doi.org/10.1103/PhysRevD.109.103022



Long term (> 5 years)

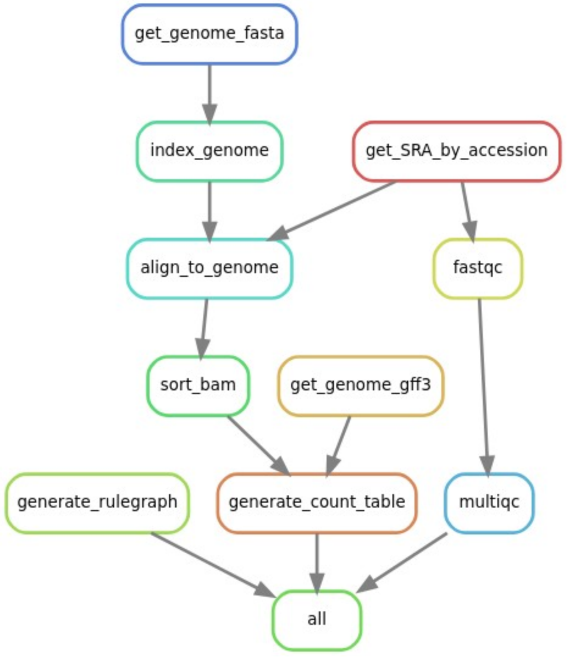
- Provide data (e.g. GW waveforms) for the LIGO-Virgo-Kagra analysis pipelines and other collaborators,

Associated challenges

- Storing, sharing and publication of large datasets,
- Transparency regarding the provenance of data sets (e.g. processing performed, code versions) → meta data ?
- Computationally intensive simulations,
- Managing software environments for multiple langages (`Python, C/C++, Fortran`)
- Managing and automating complex task « workflows ».

Make use of publicly available tools, e.g.

- `Datalad`, `Git/Gitlab` : management of code and data,
- `Docker, Conda` : management of software environments,
- `Snakemake` : automating task workflows.



Credit : nbis-reproducible-research.readthedocs.io

Merci pour votre attention

CUTER (cont.)

Potential future plans for CUTER :

- Aim for 6-month delivery cycles,
- Continuous Integration/Continuous Deployment (CI/CD),
- Documentation on static web-site (e.g. via Sphinx or Doxygen),
- Incorporated into LVK analysis pipelines (LaLSuite)
- Promotion/ training of the code (first hopefully to be organised at CoCoNut meeting, Oct. 2025),
- Improvement and subsequent publication of underlying C library (led by Gabriele Montefusco),
- Incorporation of finite temperature effects.