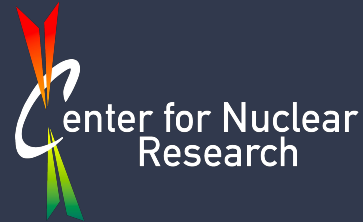


Building Neutron Stars using MUSES Workflows

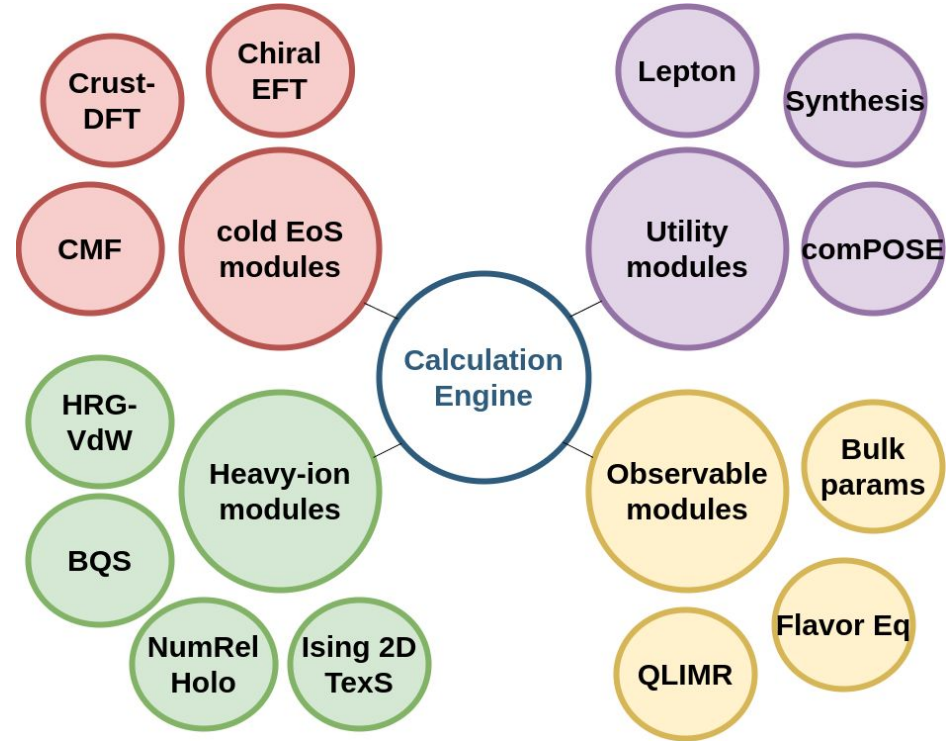
Mateus R. Pelicer

Center for Nuclear Research, Kent State University



Modular Unified Solver of the Equation of State

- Maintainable and open-source codes
- Codes are integrated in the Calculation Engine
 - Run constituent codes in workflows
 - Provide the unified EoSs at any thermodynamic regime
- Connect collaborators and community

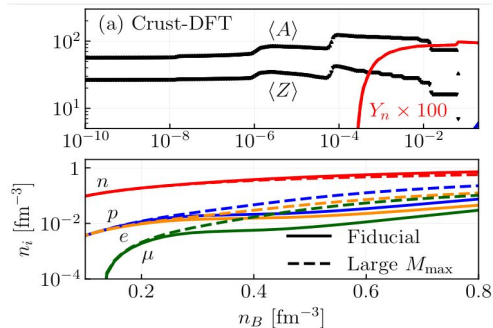


Nuclear models for Neutron Stars

- Most physics-derived EoS do not cover the entire density range of a Neutron Star
- How to build a unified EoS between the crust and the core with different models?

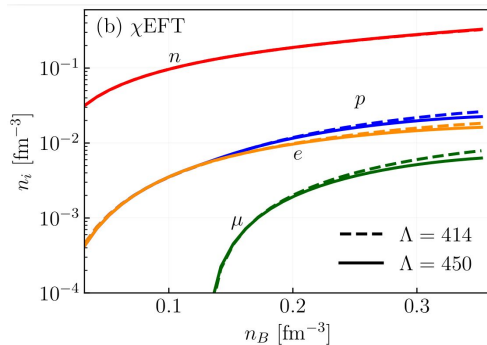
Crust DFT (nuclei + homogeneous)

- Phenomenological EoS
- Nuclei: virial expansion
- Nucleon: free energy expansion
- Independent parameters in different regimes



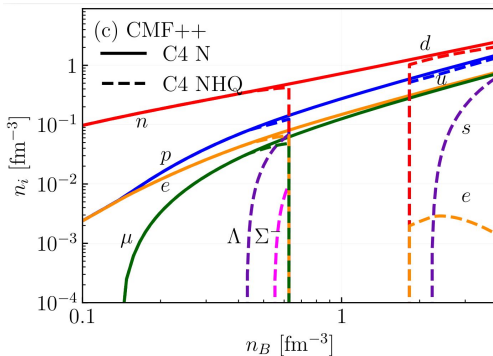
Chiral EFT

- Low-energy limit of QCD
- Long range interaction: pion exchange
- Short range: Contact terms
- Quadratic expansion for asymmetric matter



Chiral Mean Field

- Non-linear realization of chiral symmetry
- Baryon octet + decuplet
- + quarks
- Polyakov inspired variable

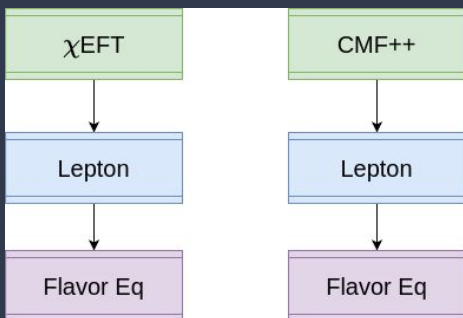


Workflow example: Flavor Equilibrium

A workflow

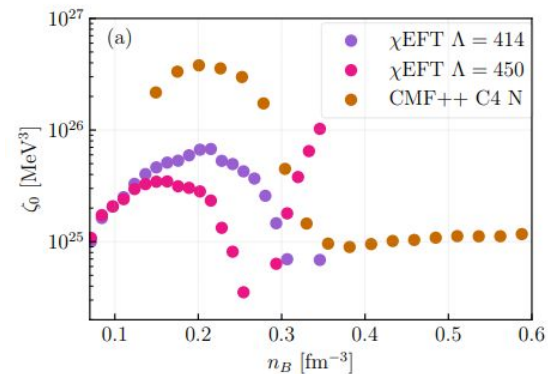
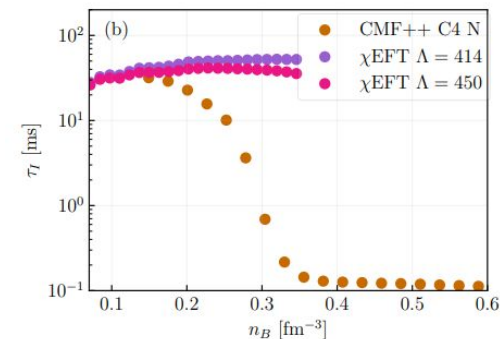
. Out-of-equilibrium quantities due to density oscillations:

- Bulk viscosity
- Relaxation time
-



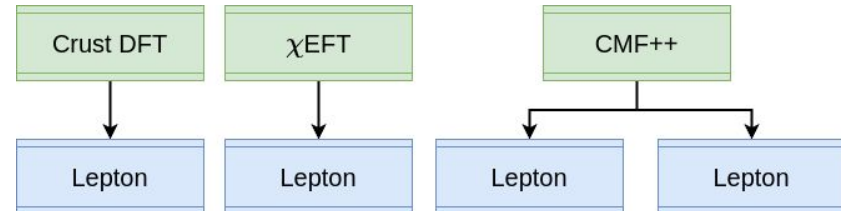
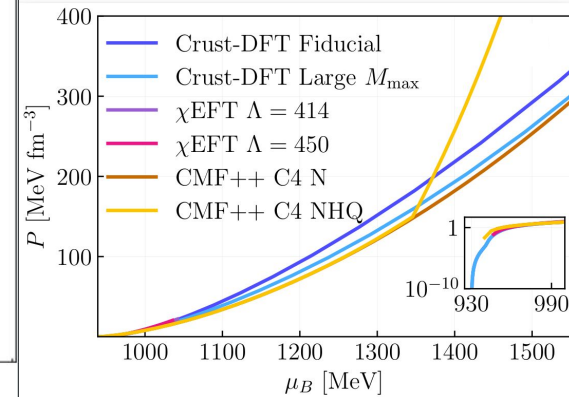
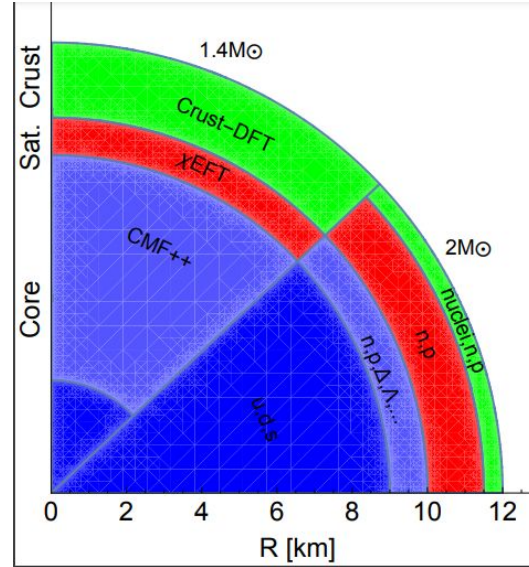
```

processes:
- name: cmf
  module: cmf_solver
  config:
    computational_parameters:
      options:
        vector_potential: 4
      output_files:
        output_flavor_equilibration: true
- name: lepton-cmf
  module: lepton
  config:
    global:
      use_charge_neutrality: true
    output:
      output_flavor_equilibration: true
    particles:
      use_electron: true
      use_muon: false
    pipes:
      input_flavor_equilibration:
        module: cmf_solver
        process: cmf
        label: CMF_for_Flavor_equilibration
- name: flavor-cmf
  module: flavor_equilibration
  config:
    mission: 'getFlavorEquilInfo'
    nBn0_start: 1
    nBn0_end: 5
    nBn0_step: 0.1
    T_start: 2.0
    T_end: 2.1
    T_step: 10.0
    pipes:
      EoS:
        module: lepton
        process: lepton-cmf
        label: flavor_equilibration
components:
- type: chain
  name: workflow
  sequence:
  - cmf
  - lepton-cmf
  - flavor-cmf
  
```



Building Neutron Stars

- Most physics-derived EoS do not cover the entire density range of a Neutron Star
- How to build a unified EoS between the crust and the core?
- Build workflows and connect different EoSs



Phase transitions

First order transition:

- Maxwell

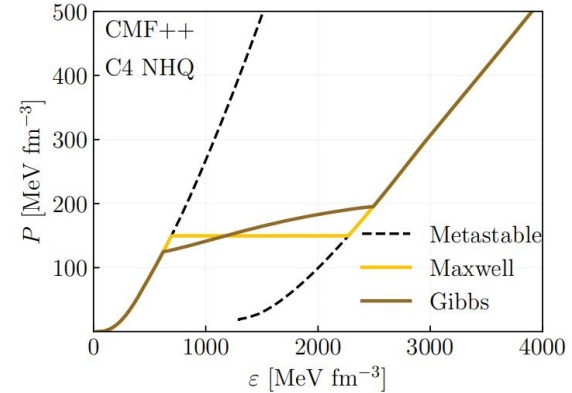
$$P^I = P^{II}, \quad \mu_B^I = \mu_B^{II}$$

- Gibbs

$$\mu_Q^I = \mu_Q^{II} = -\mu_e$$

$$fn_Q^I + (1-f)n_Q^{II} + n_{\text{leptons},Q} = 0$$

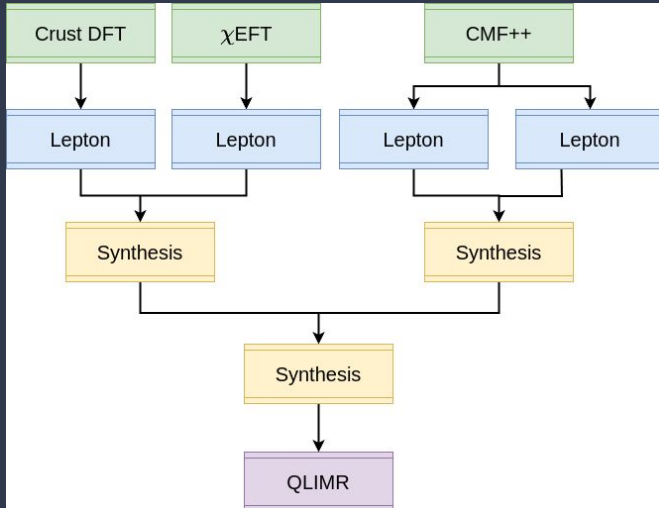
- Attach (artificial transition)



Smooth transition:

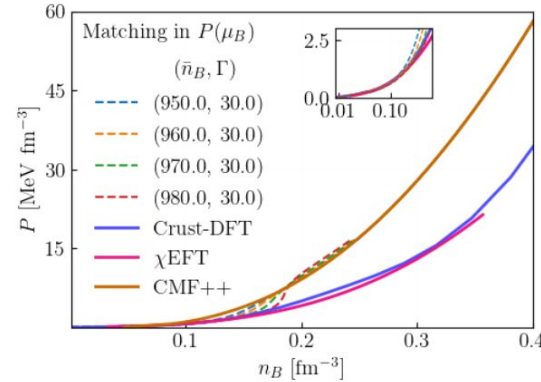
- Hyperbolic tangent interpolation $f_{\pm}(x) = \frac{1}{2} \left(1 \pm \tanh \left[\frac{x - \bar{x}}{\Gamma} \right] \right)$
- Y and x can be chosen
- Each choice has pros and cons

$$Y(x) = Y^I(x)f_-(x) + Y^{II}(x)f_+(x)$$



Smooth matching: $P(\mu_B)$

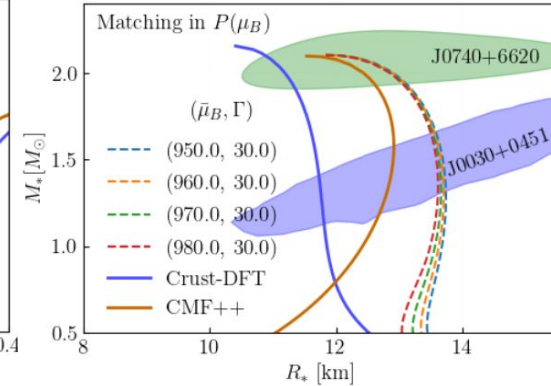
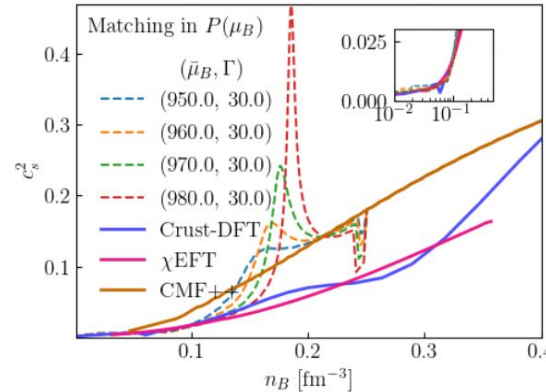
- Crust-DFT + χ EFT: (0.1, 0.02)
- Cannot match the densities
- Large oscillations in speed of sound
- Dip in speed of sound at the end of overlap
- Increase in NS radius



$$n_B(\mu_B) = \frac{dP}{d\mu_B} = f_- n_B^I + f_+ n_B^{II} + \Delta n_B$$

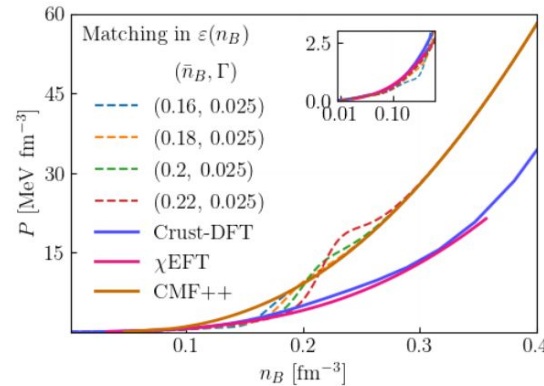
$$\Delta n_B = -g(\mu_B) (P^I - P^{II})$$

$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$



Smooth matching: $\mathcal{E}(n_B)$

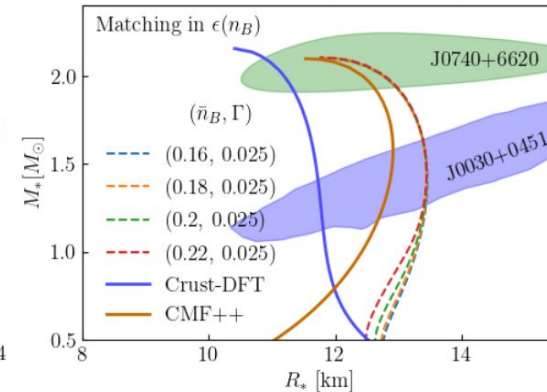
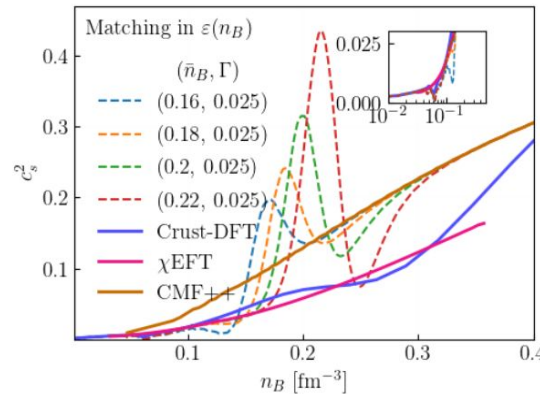
- Crust-DFT + χ EFT: (0.09, 0.03)
- No dip in speed of sound at end of overlap
- Large oscillations in speed of sound
- Parent EoS is recovered
- Increase in NS radius



$$P(n_B) = n_B^2 \frac{d(\epsilon/n_B)}{dn_B} = f_- P^I + f_+ P^{II} + \Delta P.$$

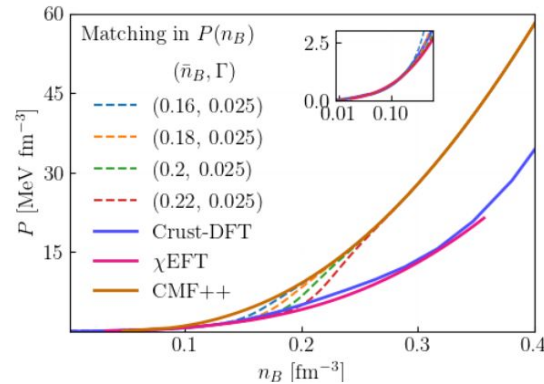
$$\Delta P = -g(n_B) n_B (\epsilon^I - \epsilon^{II})$$

$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$



Smooth matching: $P(n_B)$

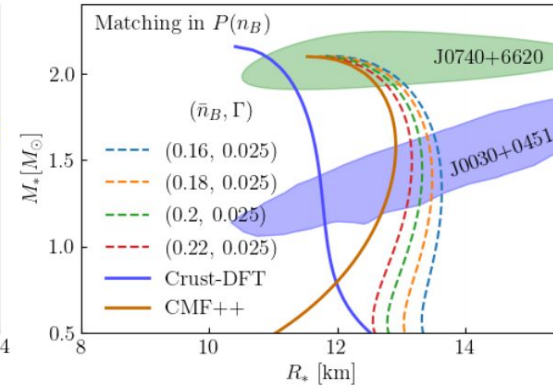
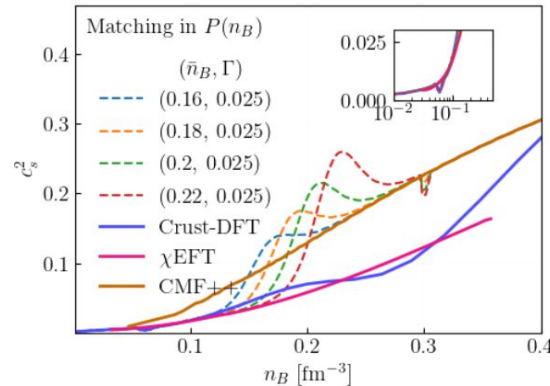
- Crust-DFT + χ EFT: (0.01, 0.02)
- Small dip in speed of sound at end of overlap
- Smaller oscillations
- Parent EoS is recovered
- Increase in NS radius



$$\varepsilon(n_B) = \varepsilon^I f_- + \varepsilon^{II} f_+ + \Delta\varepsilon$$

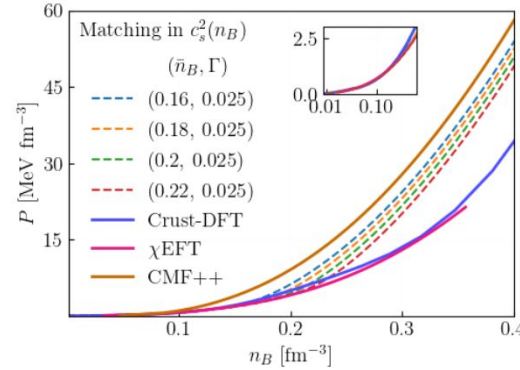
$$\Delta\varepsilon = n_B \int_{\bar{n}_B}^{n_B} \frac{dn'_B}{n'_B} g(n_B) (\varepsilon^I - \varepsilon^{II})$$

$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$



Smooth matching: $c_s^2(n_B)$

- Crust-DFT + χ EFT: (0.065, 0.01)
- Intermediate NS radius for interpolated EoS
- No bumps in speed of sound
- The parent EoS is never recovered



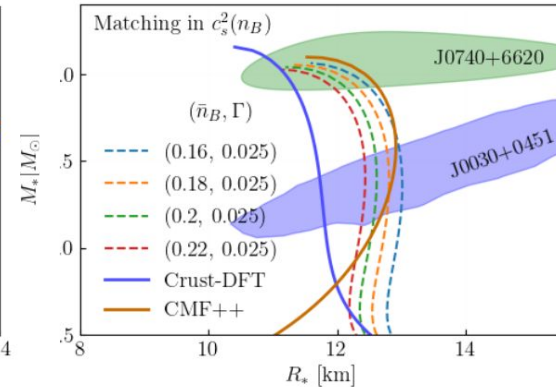
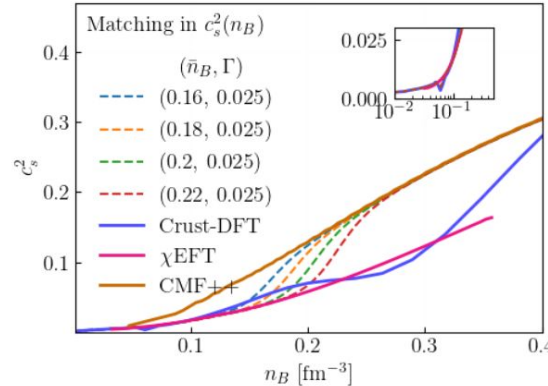
$$\frac{d\varepsilon}{dn_B} = \frac{\varepsilon + P}{n_B},$$

$$\frac{dP}{dn_B} = c_s^2(n_B) \frac{\varepsilon + P}{n_B}$$

$$n_{B,i+1} = n_{B,i} + \Delta n_B,$$

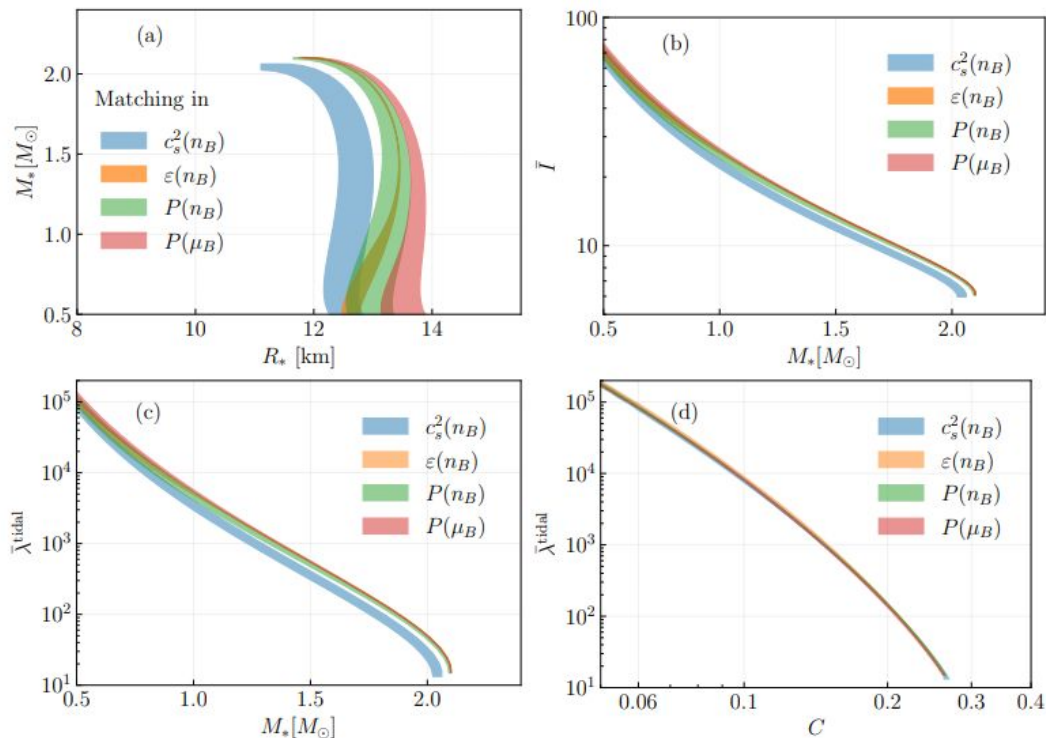
$$\varepsilon_{i+1} = \varepsilon_i + \Delta n_B \left(\frac{\varepsilon_i + P_i}{n_{B,i}} \right),$$

$$P_{i+1} = P_i + c_s^2(n_{B,i}) \Delta n_B \left(\frac{\varepsilon_i + P_i}{n_{B,i}} \right)$$



QLIMR module

- . Quadrupole moment
- . tidal Love number
- . Moment of Inertia
- . Mass
- . Radius



- The module also supports rotating stars
 - Hartle-Thorne perturbative approach

Universal Relations: I-Love-Q

- Universal relations remain robust
- Possible reasons why are they universal:
 - Mostly dependent on low-density EoS
 - As compactness grows, the relation approaches that of a BH

- Dimensionless quantities:

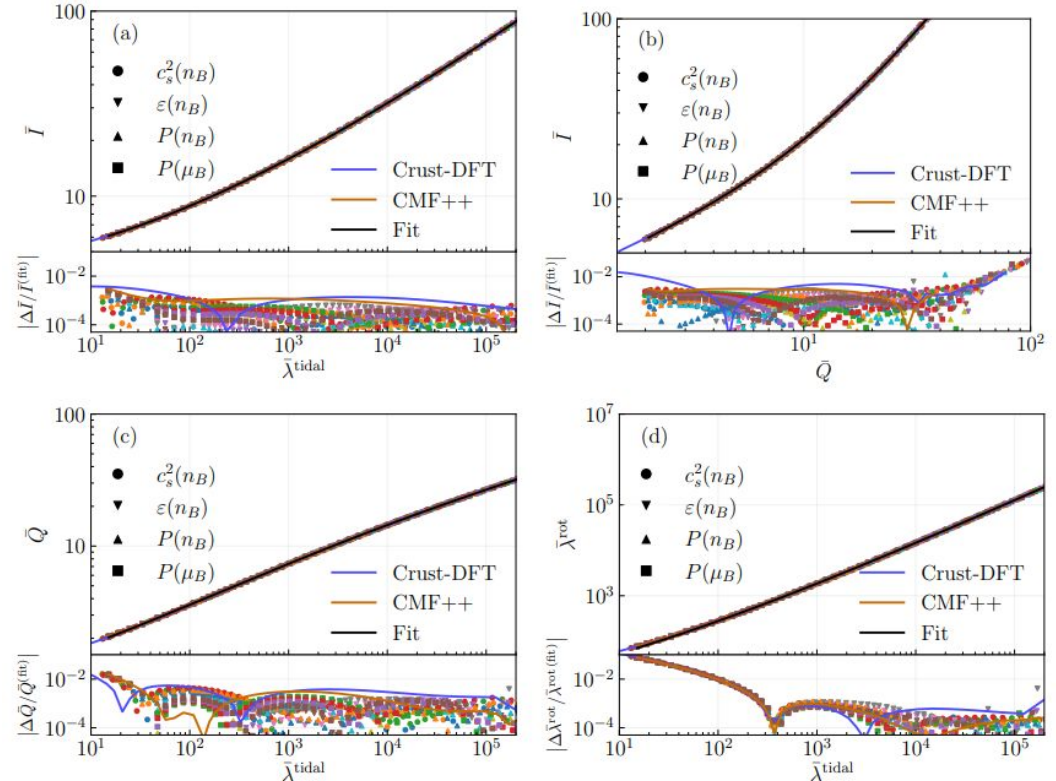
$$\bar{I} \equiv \frac{I}{M_*^3} \quad ; \quad \bar{\lambda}^{\text{tidal}} \equiv \frac{\lambda^{\text{tidal}}}{M_*^5} \quad ; \quad \bar{Q}^{\text{rot}} \equiv -\frac{Q^{\text{rot}} M_*}{J^2}$$

I-Love-Q

Kent Yagi¹ and Nicolás Yunes¹

¹Department of Physics, Montana State University, Bozeman, MT 59717, USA.

(Dated: November 19, 2013)



Summary

- ❑ MUSES is an open-source tool that can be used to
 - ❑ Explore available nuclear models
 - ❑ Join EoSs (e.g. crust-core)
 - ❑ Compute phase transitions
 - ❑ Compute NS observables for your project
 - ❑ Compute out-of-equilibrium quantities
- ❑ Jupyter notebooks showing how to use the CE are available
- ❑ Different ways to merge EoSs lead to different NS properties
- ❑ The merging in the speed of sound is the one that leads to minimal artificial effects
 - ❑ meta and unstable phases
 - ❑ peaks and dips in the speed of sound



MUSES // Calculation Engine

Getting started

- ❑ [Read the Quick Start guide](#) to setup your account and learn how to run workflows.
- 🔗 Join the discussion and ask for help [on our community support forum](#).
- ☰ Learn how to [cite this software in your publications](#).

What is the Calculation Engine?

The Calculation Engine is an application that lets you run scientific calculations as composable workflows, constructed from a growing library of MUSES modules. The service hosted at <https://ce.musesframework.io> provides the research community with scalable, high-performance computing resources to run intensive calculations.

[Ask for help and report bugs here.](#)

The MUSES project is supported by National Science Foundation under Cooperative Agreement OAC-2103680.

What are workflows?

MUSES workflows provide a way to orchestrate a custom execution of MUSES modules, allowing you to generate equations of state, process and synthesize data, and calculate observable quantities. Individual workflow executions are called jobs, which you can run concurrently on our performant compute nodes to generate reproducible results to download and analyze. [Learn more about MUSES workflows here.](#)

