Building Neutron Stars using MUSES Workflows

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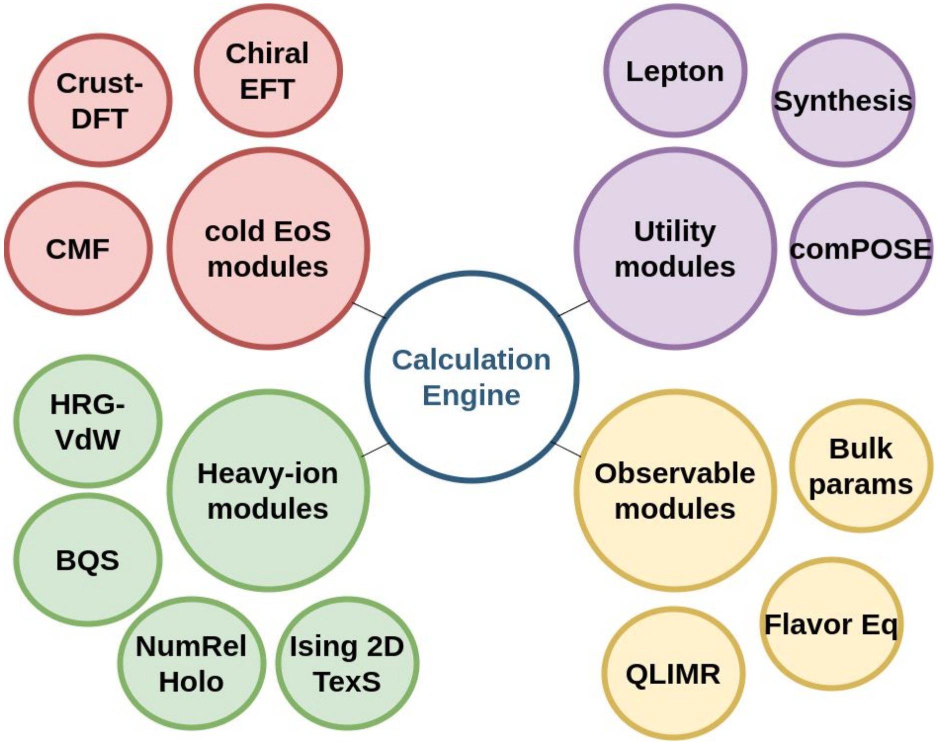
Modular **U**nified **S**olver of the **E**quation of **S**tate

- 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



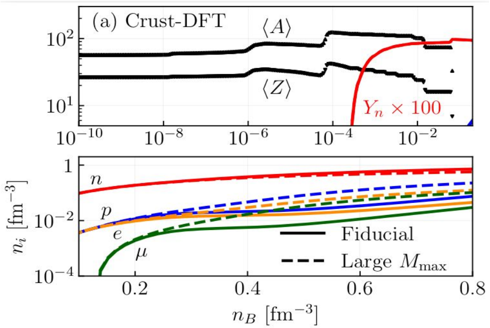
Nuclear models for Neutron Stars

- 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?

muses

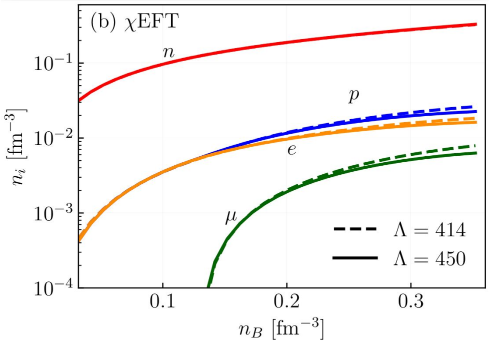
Crust DFT (nuclei + homogeneous)

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



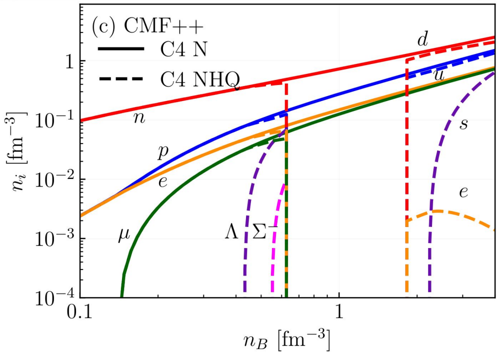
Chiral EFT

- 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

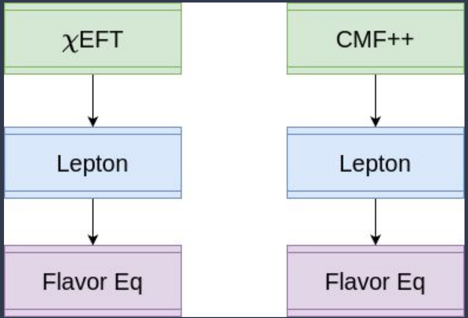


Worklflow example:
Flavor Equilibrium

A workflow

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

- Bulk viscosity
- Relaxation time
-

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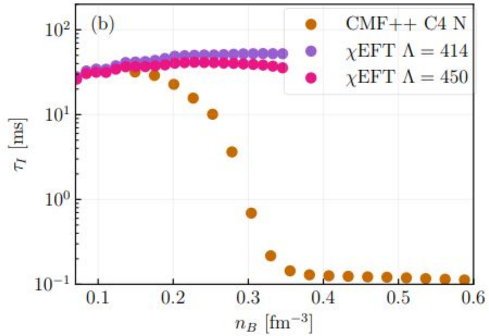
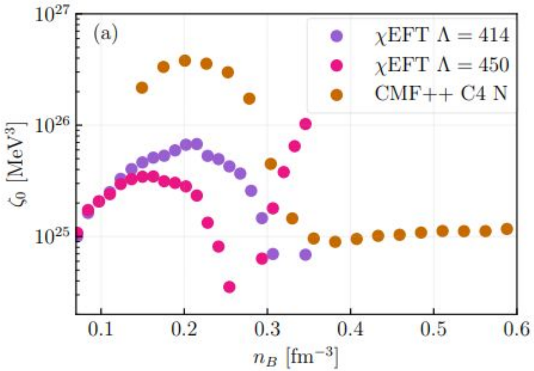
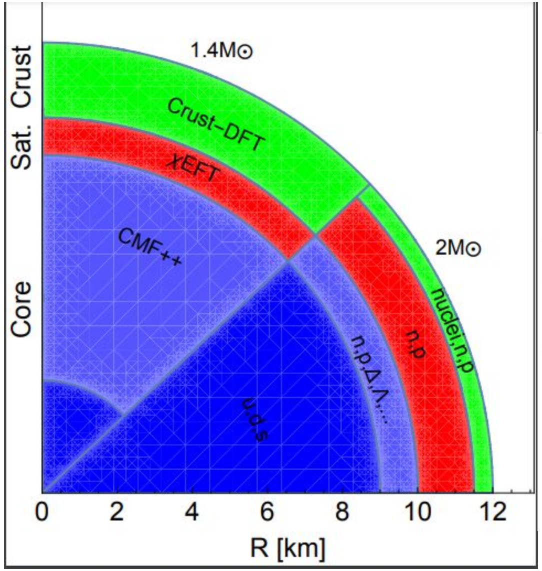
- name: cmf
  module: cmf_solver
  config:
    computational_parameters:
      options:
        vector_potential: 4
      output_files:
        output_flavor_equilibration: true
- name: lepton-cmf
  module: lepton
  config:
    global:
      use_charge_neutrality: true
    output:
      output_flavor_equilibration: 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
```

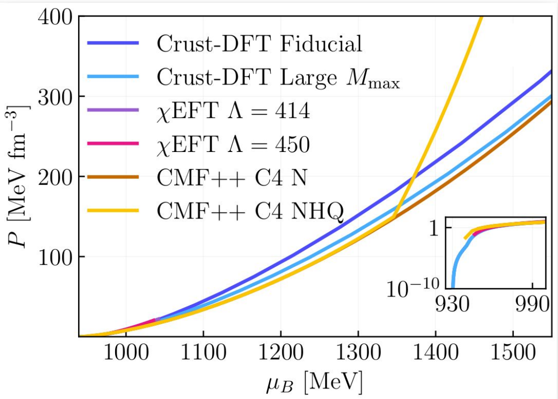


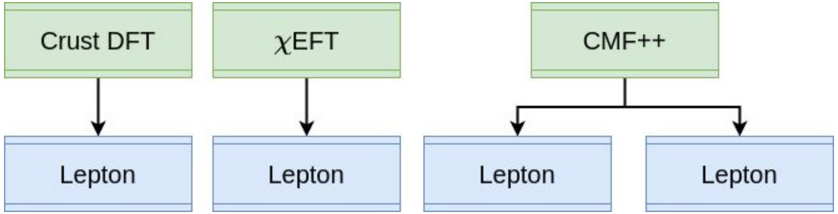


Building Neutron Stars

- 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

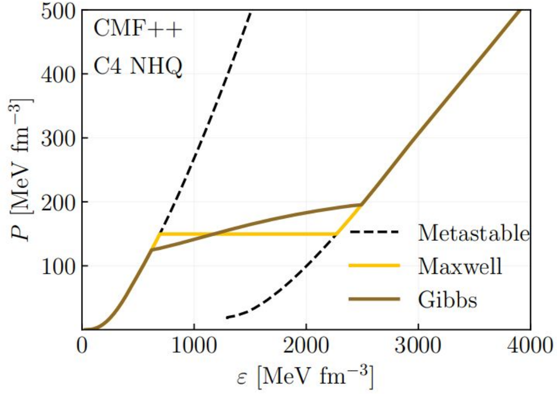
$$P^{I} = P^{II}, \quad \mu_B^{I} = \mu_B^{II}$$

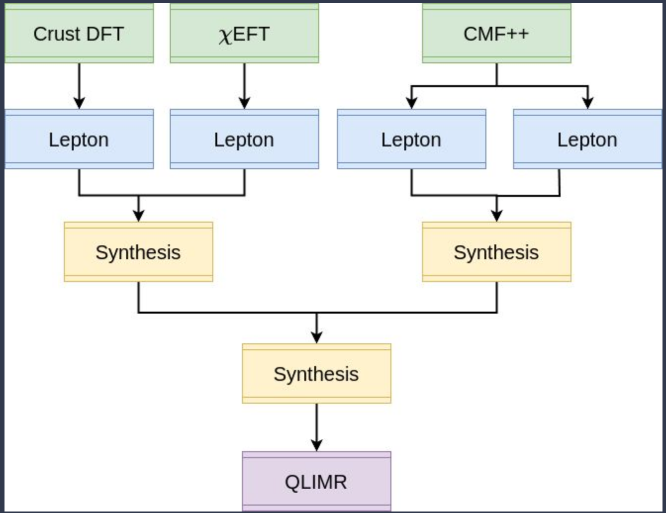
- Gibbs

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

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

- Attach (artificial transition)





Smooth transition:

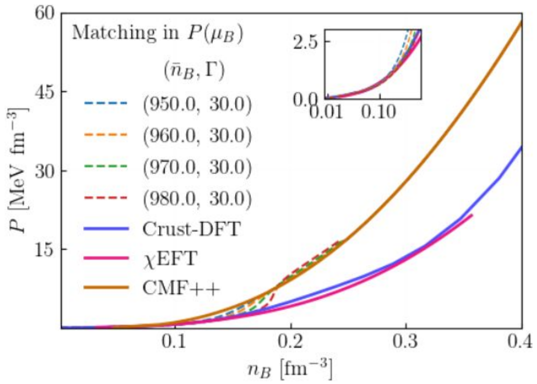
- Hyperbolic tangent interpolation
- Y and x can be chosen
- Each choice has pros and cons

$$f_{\pm}(x) = \frac{1}{2}\left(1 \pm \tanh\left[\frac{x-\bar{x}}{\Gamma}\right]\right)$$

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

Smooth matching: P(μ_B)

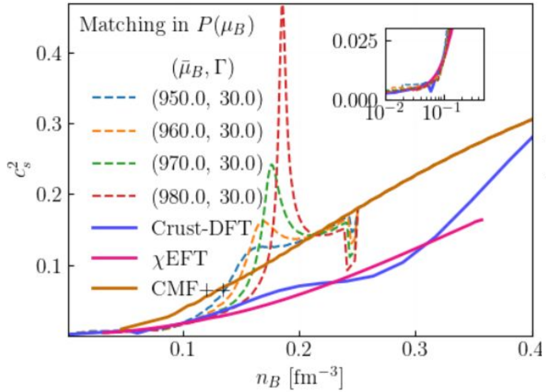
- Crust-DFT + χEFT: (0.1, 0.02)
- Cannot match the densities
- Large oscillations in speed of sound
- Dip in speed of sound at the end of overlap
- Increase in NS radius

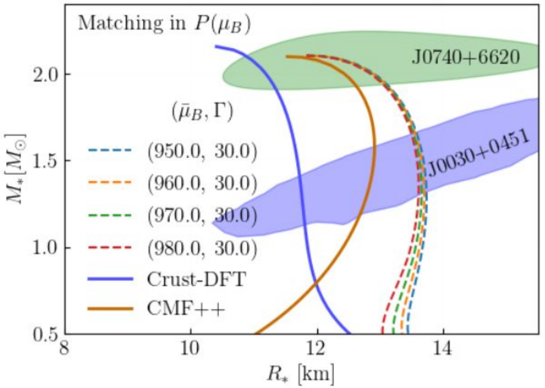


$$n_B(\mu_B) = \frac{dP}{d\mu_B} = f_- n_B^I + f_+ n_B^{II} + \Delta n_B$$

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

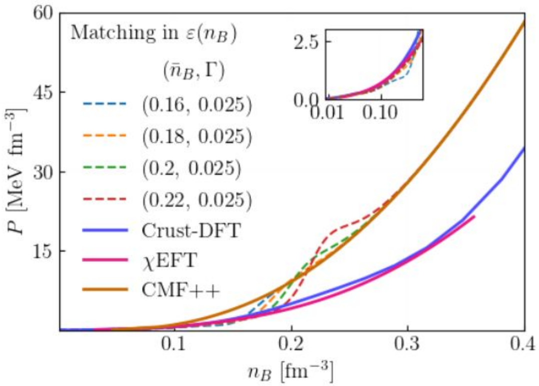
$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$





Smooth matching: $\varepsilon(n_B)$

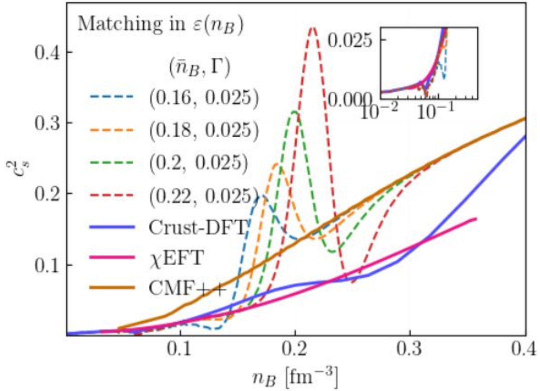
- Crust-DFT + χEFT: (0.09, 0.03)
- No dip in speed of sound at end of overlap
- Large oscillations in speed of sound
- Parent EoS is recovered
- Increase in NS radius

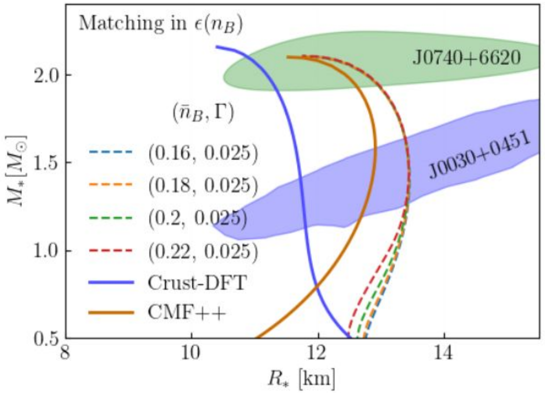


$$P(n_B) = n_B^2 \frac{d(\varepsilon/n_B)}{dn_B} = f_- P^I + f_+ P^{II} + \Delta P$$

$$\Delta P = -g(n_B)\, n_B \left(\varepsilon^I - \varepsilon^{II}\right)$$

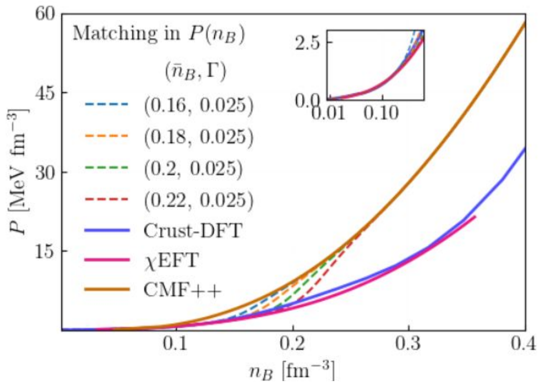
$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$





Smooth matching: P(n_B)

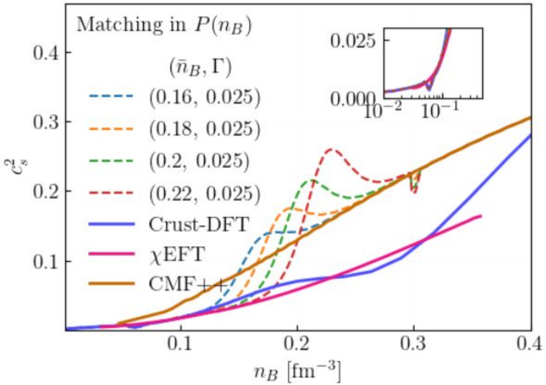
- Crust-DFT + χEFT: (0.01, 0.02)
- Small dip in speed of sound at end of overlap
- Smaller oscillations
- Parent EoS is recovered
- Increase in NS radius

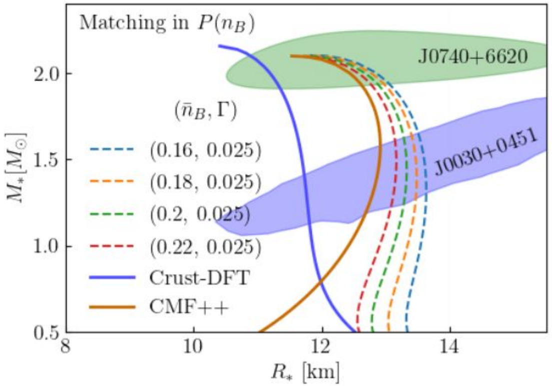


$$\varepsilon(n_B) = \varepsilon^I f_- + \varepsilon^{II} f_+ + \Delta\varepsilon$$

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

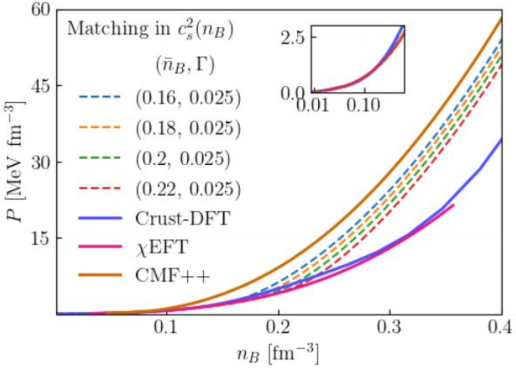
$$g(x) = \frac{df_+}{dx} = -\frac{df_-}{dx}$$





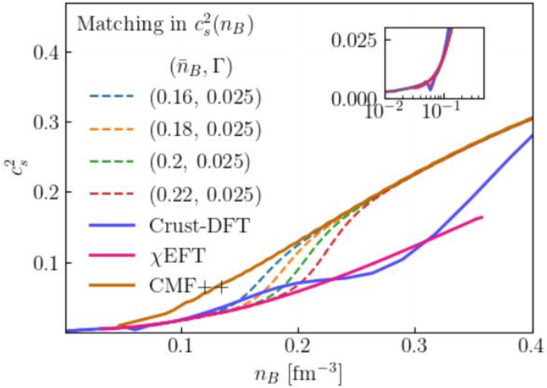
Smooth matching: $c_s^2(n_B)$

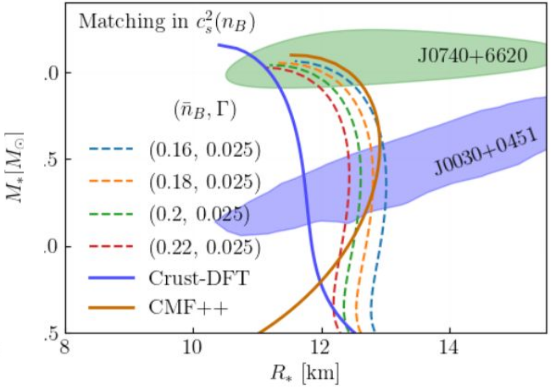
- Crust-DFT + χEFT: (0.065, 0.01)
- Intermediate NS radius for interpolated EoS
- No bumps in speed of sound
- The parent EoS is never recovered



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

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





QLIMR module

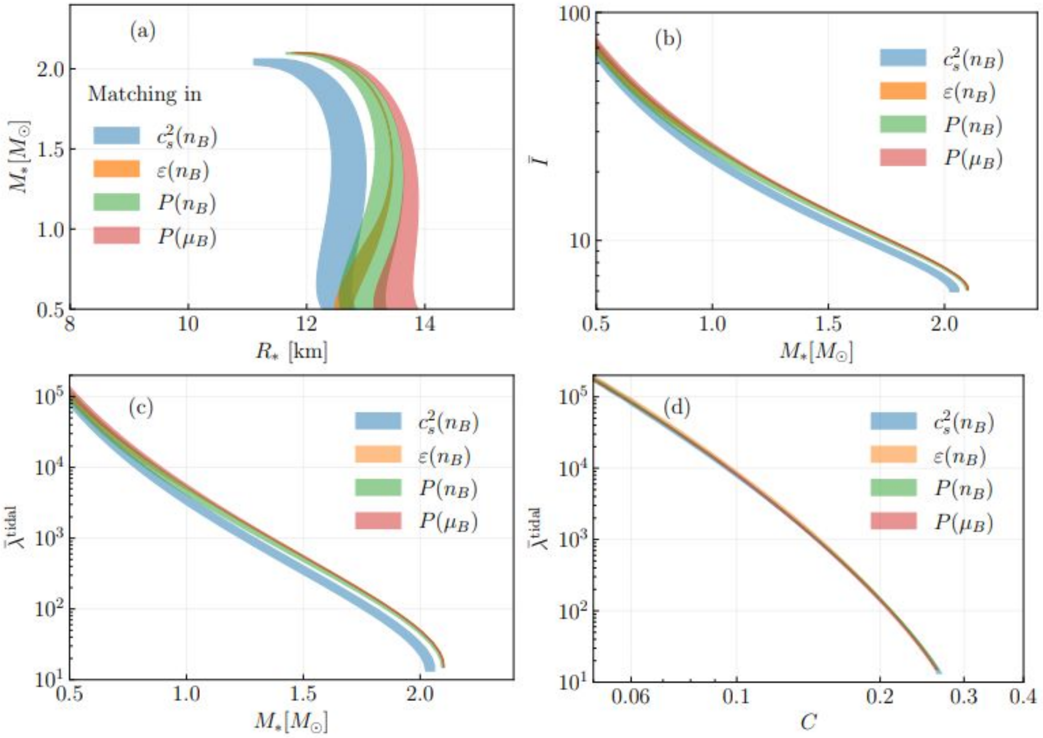
. **Q**uadrupole moment

. tidal **L**ove number

. Moment of **I**nertia

. **M**ass

. **R**adius



- The module also supports rotating stars
  - Hartle-Thorne pertubative 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:

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

I-Love-Q

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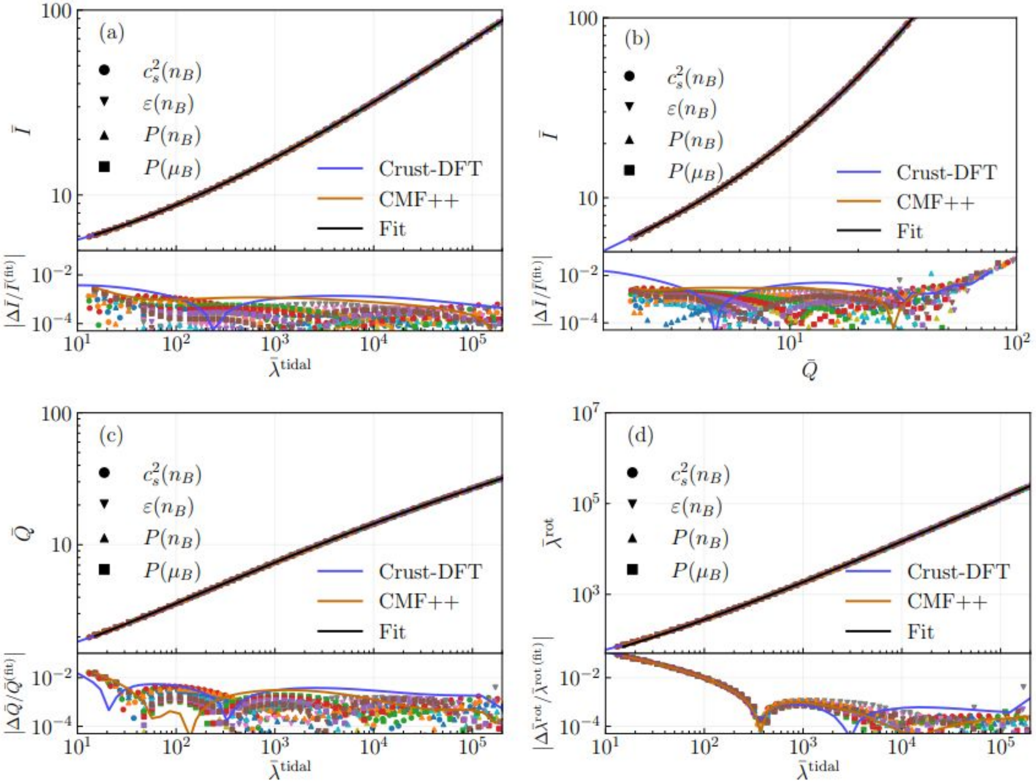
(Dated: November 19, 2013)

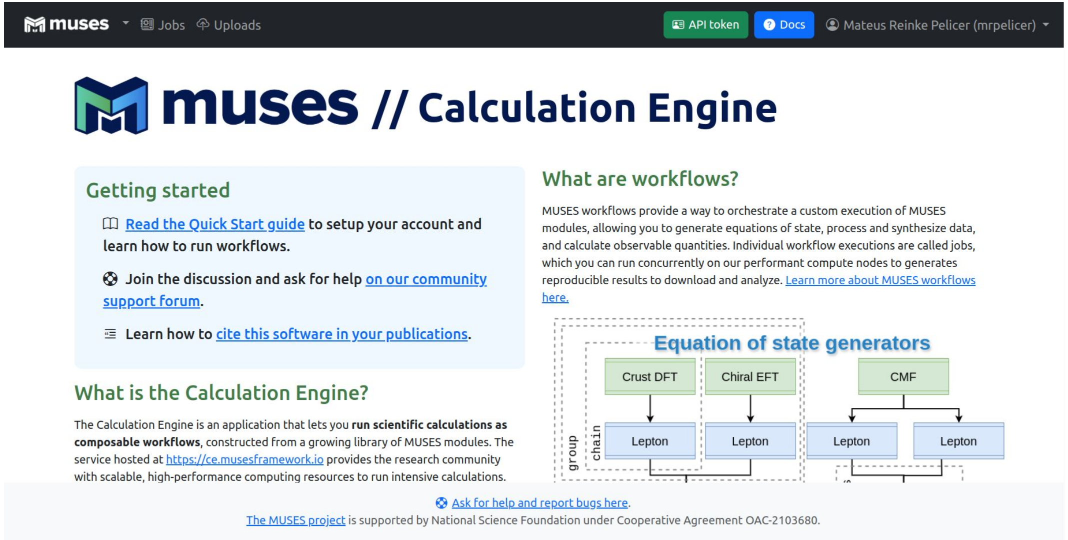


Summary

- 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



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