An overview of the muses cyberinfrastructure and what it can do for you

Veronica Dexheimer

Original muses team

PI and co-PIs

1. Nicolas Yunes; University of Illinois at Urbana-Champaign; **PI**
2. Jacquelyn Noronha-Hostler; University of Illinois at Urbana-Champaign; co-PI
3. Jorge Noronha; University of Illinois at Urbana-Champaign; co-PI
4. Claudia Ratti; University of Houston; co-PI and **spokesperson**
5. Veronica Dexheimer; Kent State University; co-PI

Senior investigators

1. Matias Carrasco Kind; National Center for Supercomputing Applications
2. Roland Haas; National Center for Supercomputing Applications
3. Timothy Andrew Manning; National Center for Supercomputing Applications
4. Andrew Steiner; University of Tennessee, Knoxville
5. Jeremy Holt; Texas A&M University
6. Gordon Baym; University of Illinois at Urbana-Champaign
7. Mark Alford; Washington University in Saint Louis
8. Elias Most; Princeton University

Now we have 91+ collaborators

External collaborators

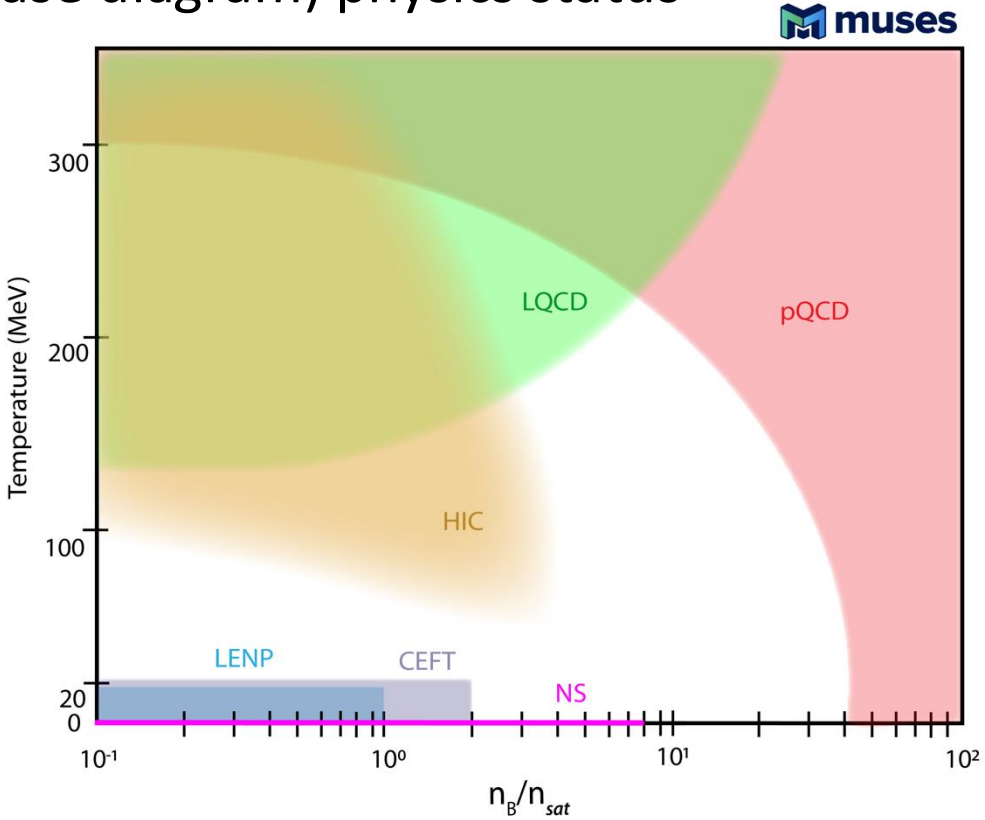
1. Helvi Witek; University of Illinois at Urbana-Champaign
2. Stuart Shapiro; University of Illinois at Urbana-Champaign
3. Katerina Chatziioannou; California Institute of Technology
4. Phillip Landry; California State University Fullerton
5. Reed Essick; Perimeter Institute
6. Rene Bellwied; University of Houston
7. David Curtin; University of Toronto
8. Michael Strickland; Kent State University
9. Matthew Luzum; University of Sao Paulo
10. Hajime Togashi; Kyushu University
11. Toru Kojo; Central China Normal University
12. Hannah Elfner; GSI/Goethe University Frankfurt

High-energy (QCD phase diagram) physics status

- Current input from different (first-principle and effective) theories and experiments

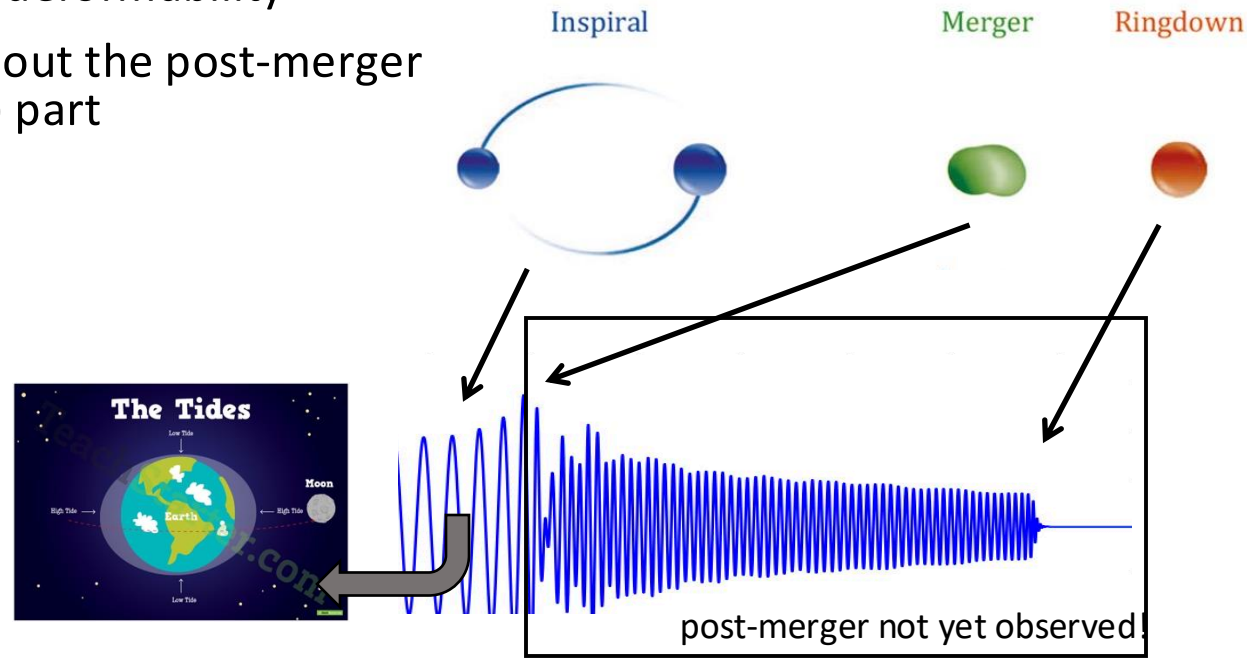
  - lattice QCD
  - perturbative QCD
  - chiral effective field theory
  - heavy-ion collisions
  - low-energy nuclear physics
  - observations of neutron

Living Rev.Rel. 27 (2024) 1, 3
e-Print: 2303.17021 [nucl-th]



Gravitational wave data

- Several measurements from neutron-star mergers but only GW170817 provided electromagnetic counterparts and a relevant measurement of the tidal deformability
- Without the post-merger (hot) part



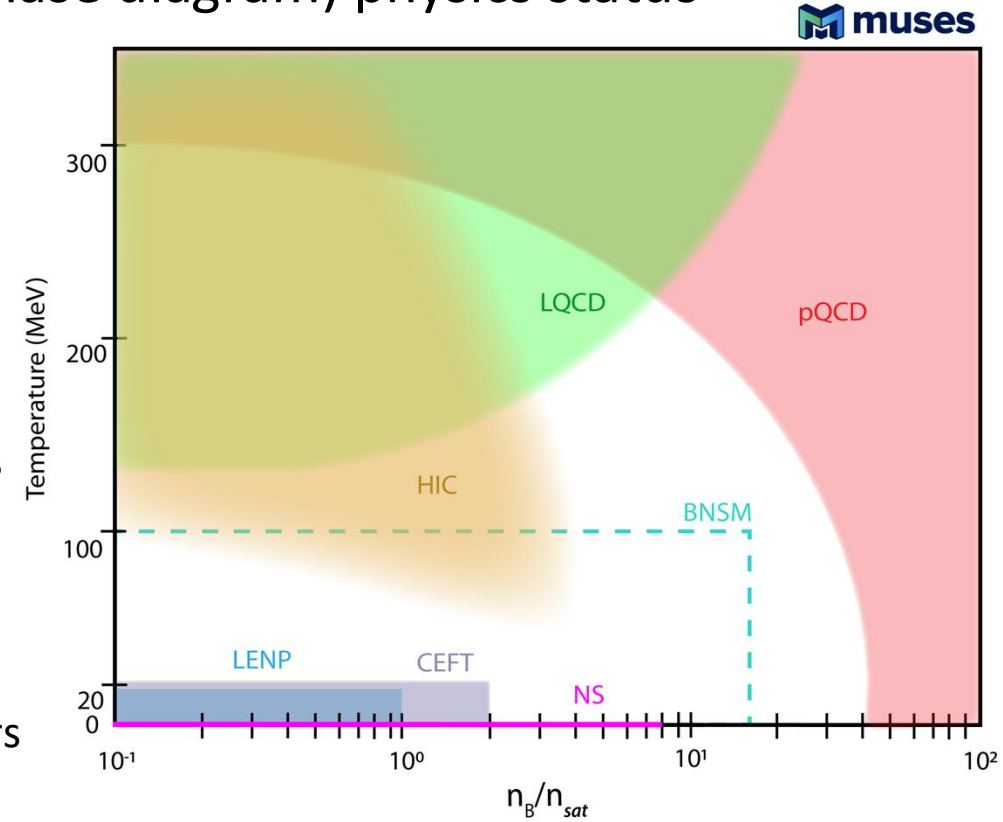
High-energy (QCD phase diagram) physics status

- Current input from different (first-principle and effective) theories and experiments

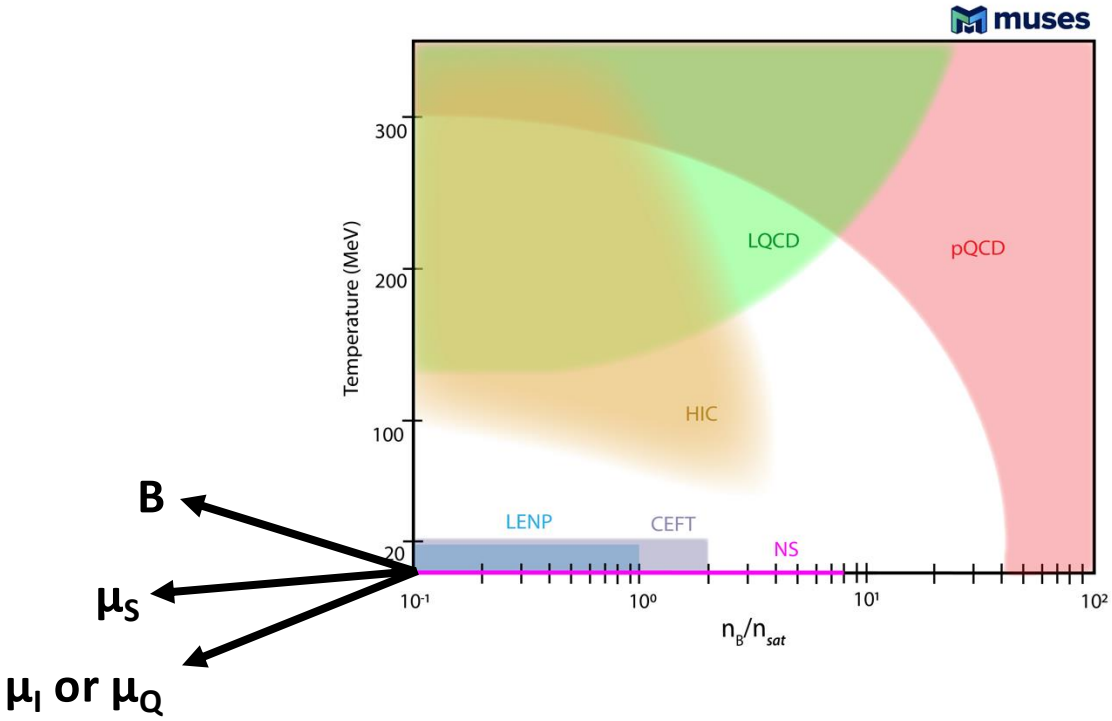
  - lattice QCD
  - perturbative QCD
  - chiral effective field theory
  - heavy-ion collisions
  - low-energy nuclear physics
  - observations of neutron

Living Rev.Rel. 27 (2024) 1, 3
e-Print: 2303.17021 [nucl-th]

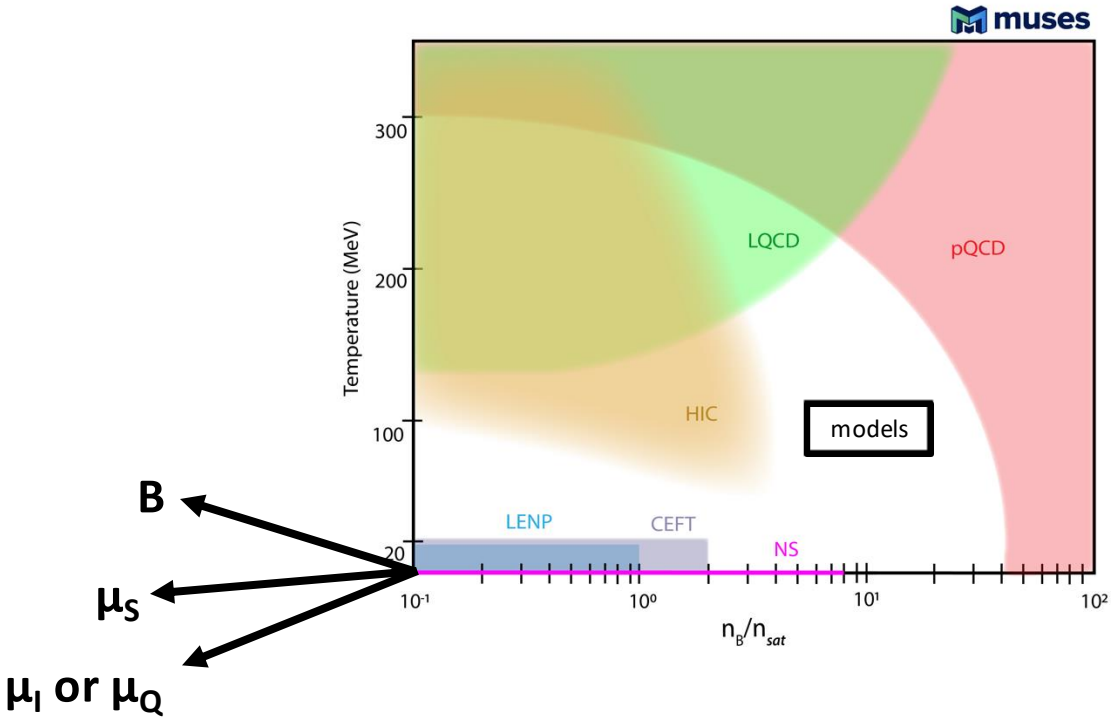
  - binary neutron star mergers coming soon…



What about more physics (or dimensions)?

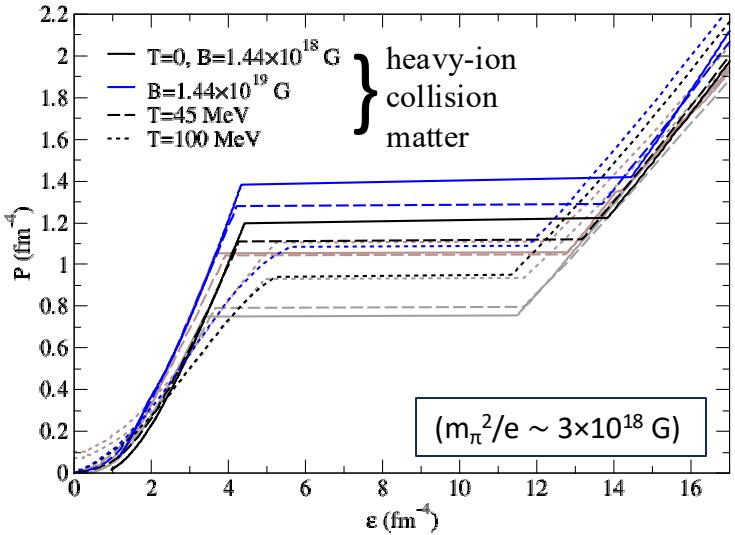


What about more physics (or dimensions)?



5D Chiral Mean Field (CMF) model ~~phase diagram~~ curves

- Equation of state for hadronic and quark matter with 1st order phase transition



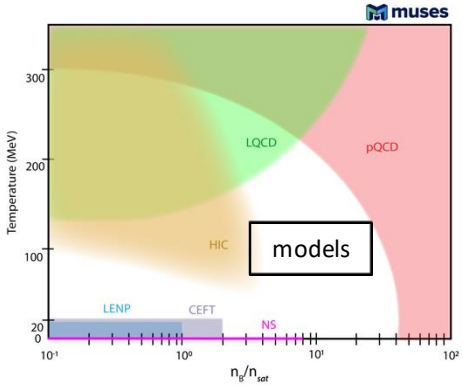
- Neutron-star matter also shown for comparison in different colors

  B=1.44x10^18 G for neutron-star matter

  B=1.44x10^19 G for neutron-star matter

Phys.Rev.D 108 (2023) 6, 063011
e-Print: 2304.02454

muses cyberinfrastructure



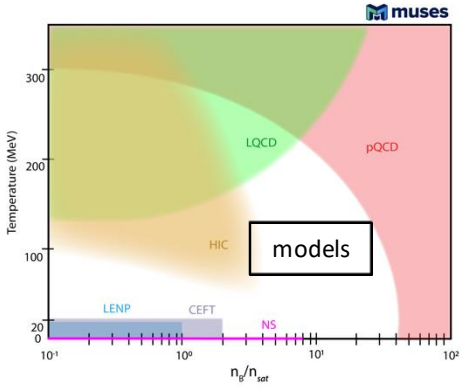
- **M**odular **U**nified **S**olver of the **E**quation of **S**tate (EoS)
- Modular: different theories/models (modules) for the user to pick from **and modify**
- Unified: different modules are combined in different ways to ensure maximal coverage of the phase diagram
- Web-based tools and services that provide interactive interfaces to the Calculation Engine
- Job management system and a deployment system that can be reproduced in other computing environments
- EoS description modules and observable modules that link to experiments
- Developers: physicists + computer scientists working together to develop optimized software in modern programing languages
- Users: interested scientists from different communities, who provide input

★ muses cyberinfrastructure

- “If a MUSES module is a song, the Calculation Engine is not the album containing the song, it is the jukebox playing the songs. ’’

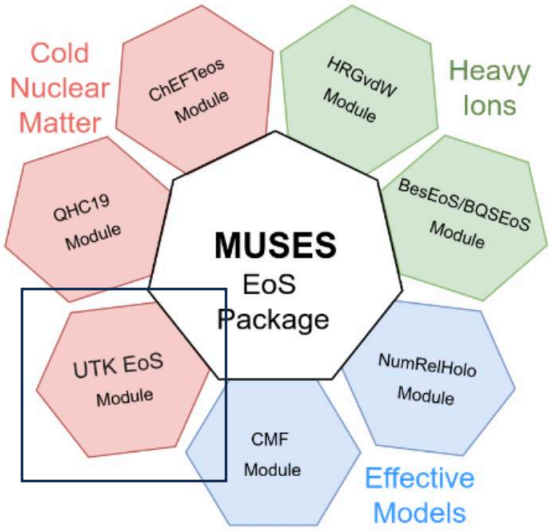
Andrew Manning

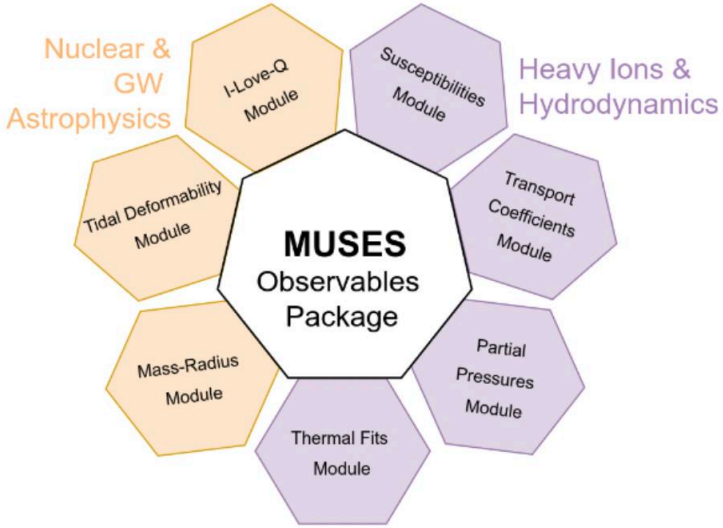
muses cyberinfrastructure



- **M**odular **U**nified **S**olver of the **E**quation of **S**tate (EoS)
- Modular: different theories/models (modules) for the user to pick from **and modify**
- Unified: different modules are combined in different ways to ensure maximal coverage of the phase diagram
- Web-based tools and services that provide interactive interfaces to the Calculation Engine
- Job management system and a deployment system that can be reproduced in other computing environments
- EoS description modules and observable modules that link to experiments
- Developers: physicists + computer scientists working together to develop optimized software in modern programing languages
- Users: interested scientists from different communities, who provide input

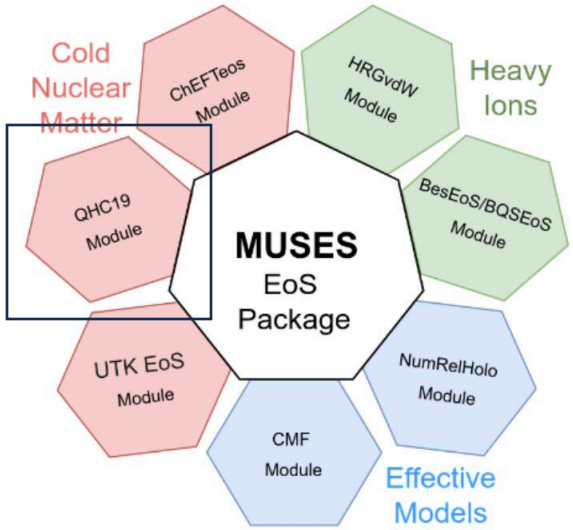
muses modules

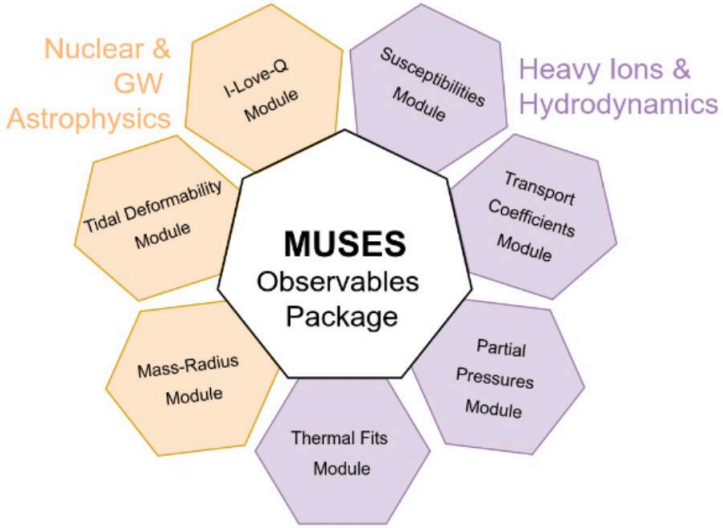




+ Lepton Module, Synthesis Module, Interpolator Module, …

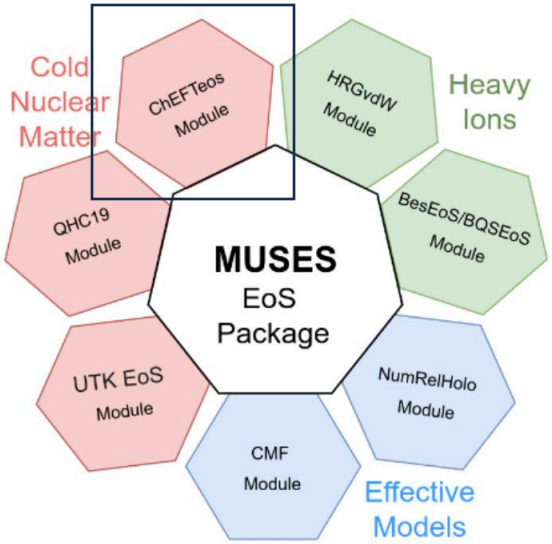
muses modules

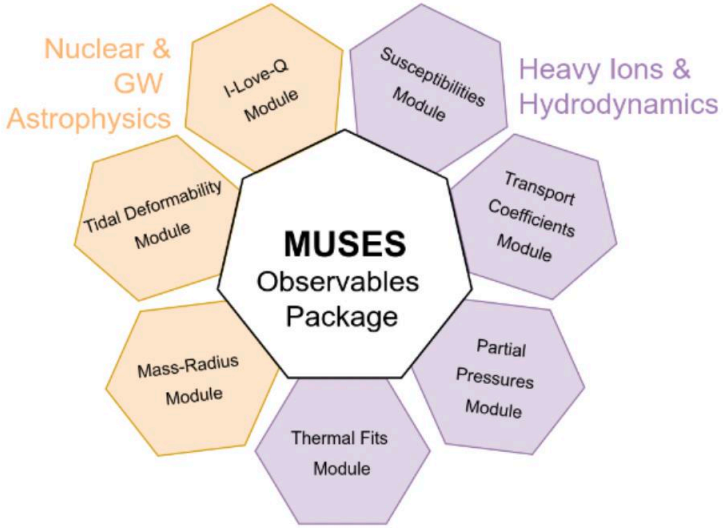




+ Lepton Module, Synthesis Module, Interpolator Module, …

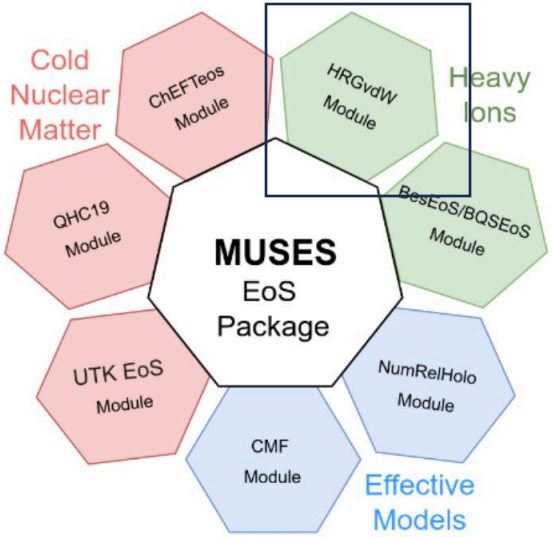
muses modules

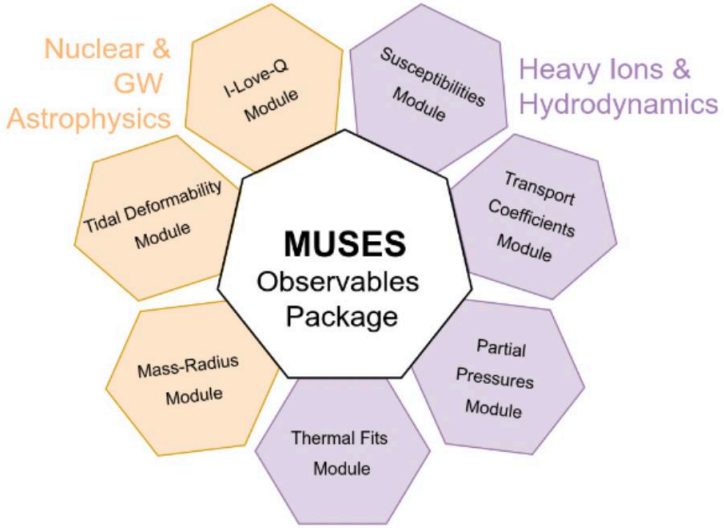




+ Lepton Module, Synthesis Module, Interpolator Module, …

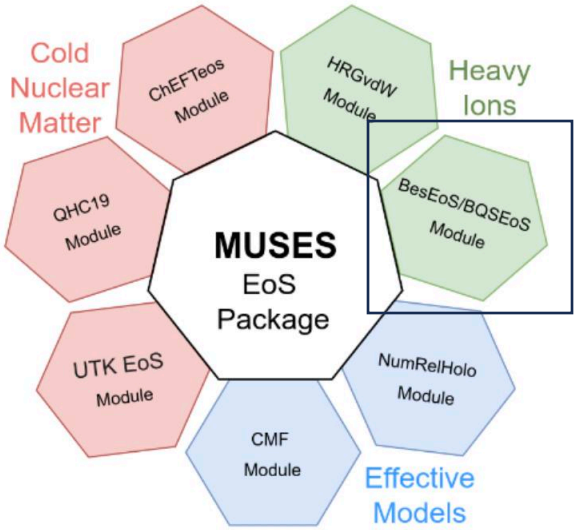
muses modules

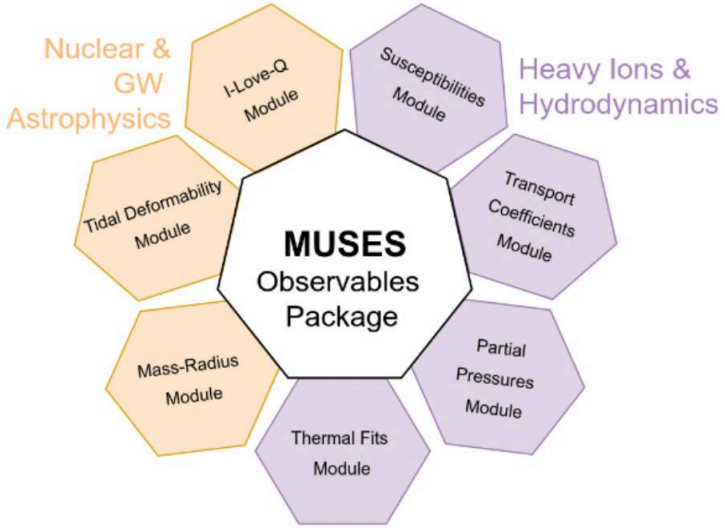




+ Lepton Module, Synthesis Module, Interpolator Module, …

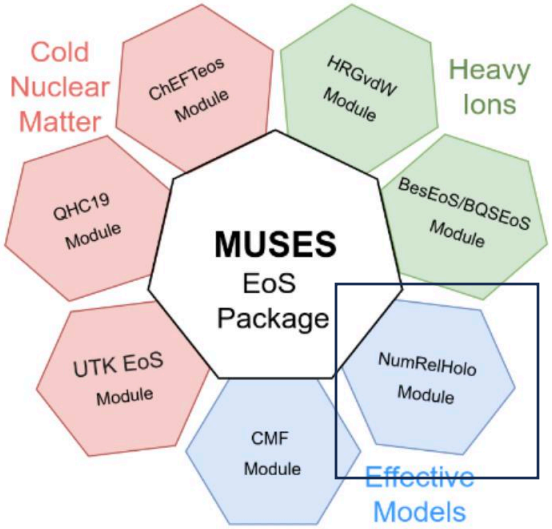
muses modules

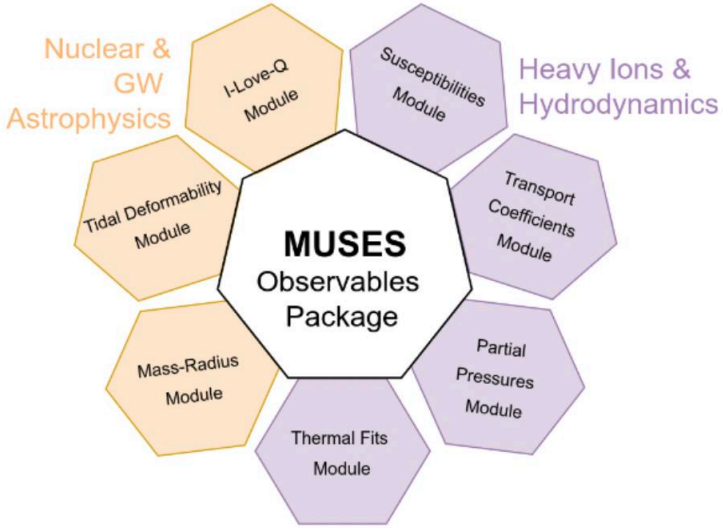




+ Lepton Module, Synthesis Module, Interpolator Module, …

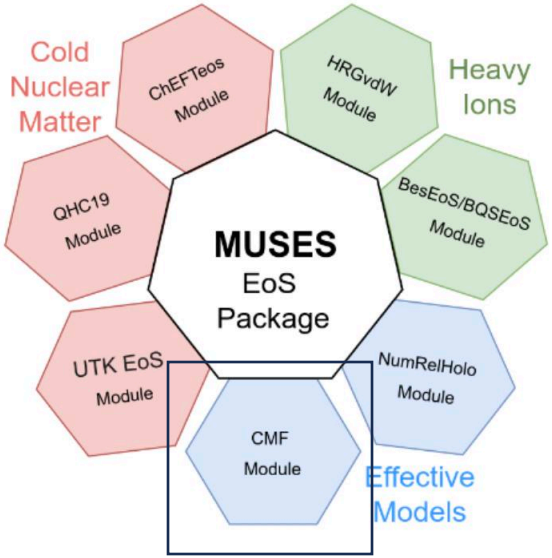
muses modules

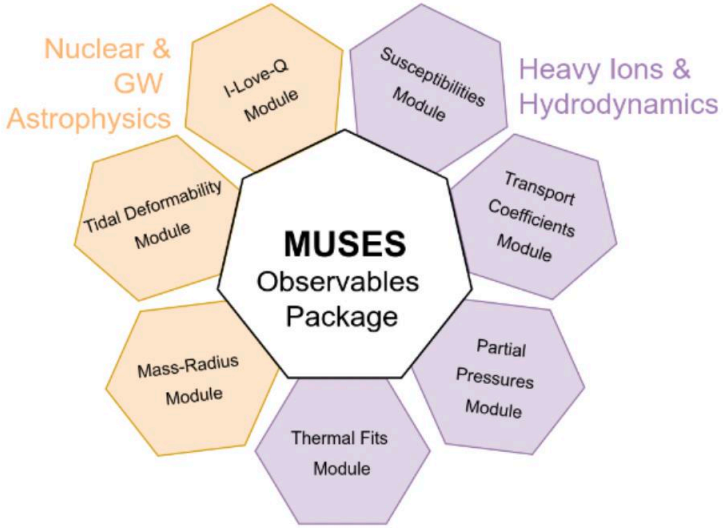




+ Lepton Module, Synthesis Module, Interpolator Module, …

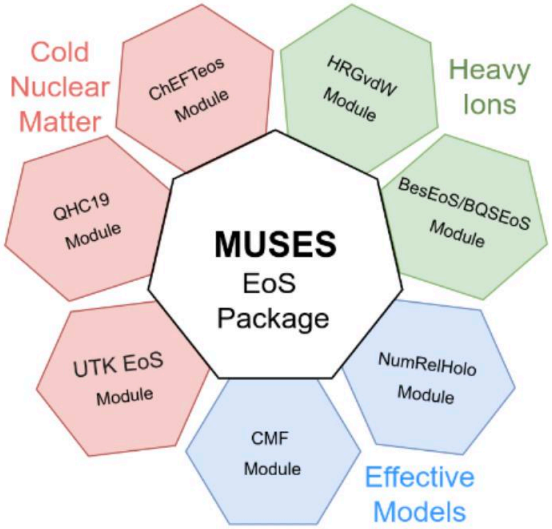
muses modules

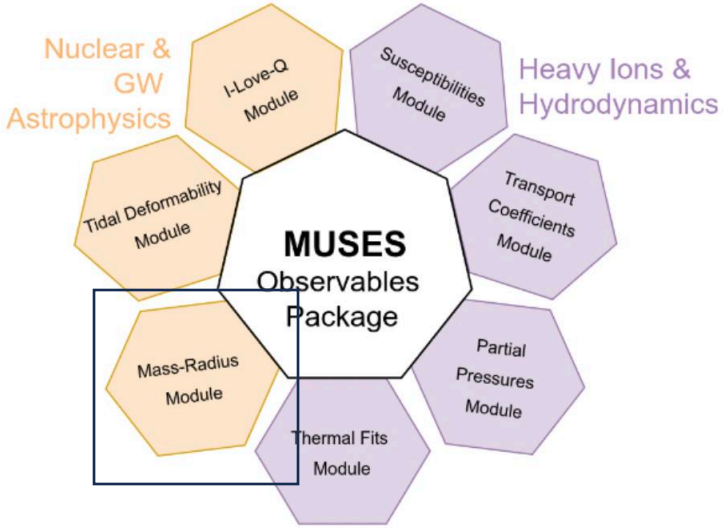




+ Lepton Module, Synthesis Module, Interpolator Module, …

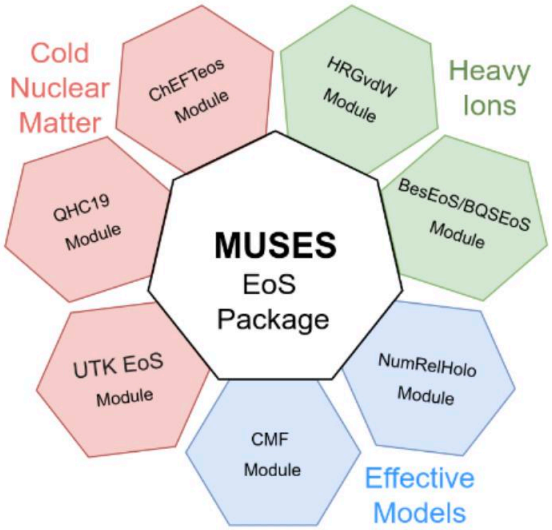
muses modules

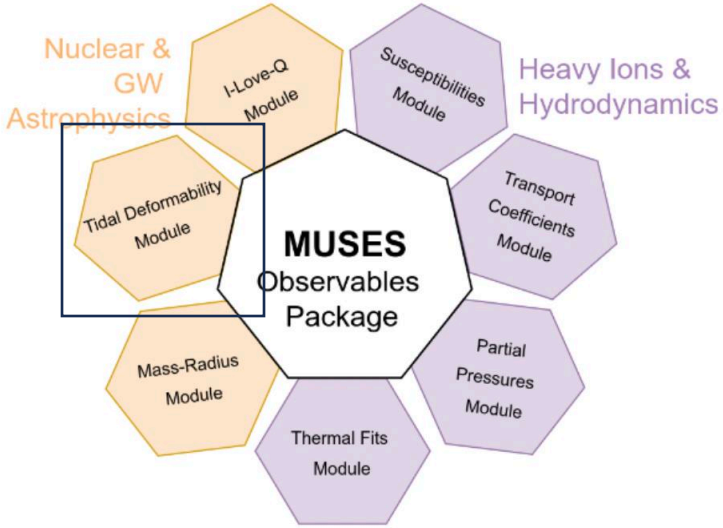




+ Lepton Module, Synthesis Module, Interpolator Module, …

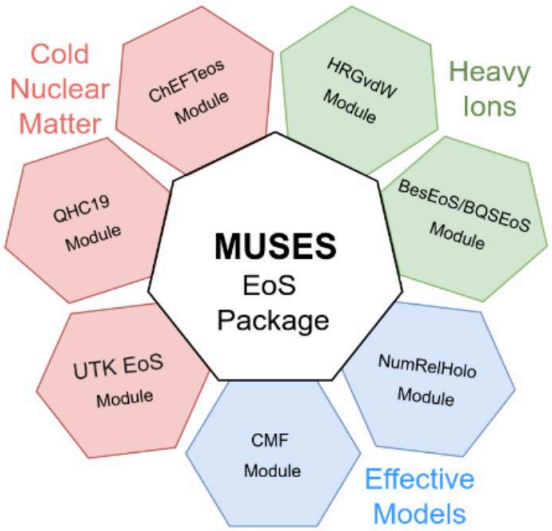
muses modules

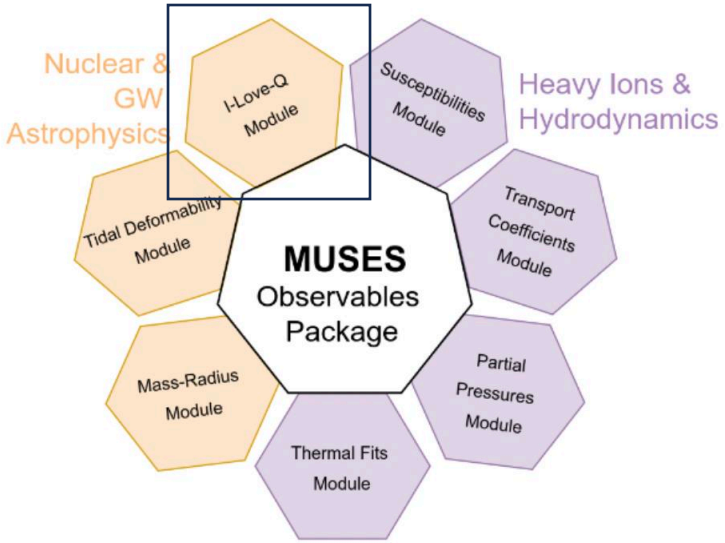




+ Lepton Module, Synthesis Module, Interpolator Module, …

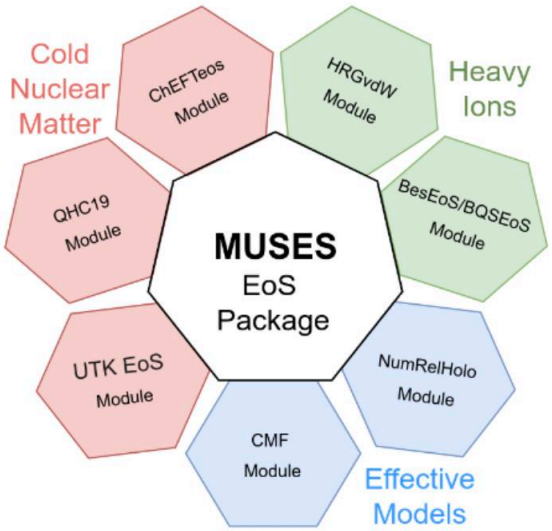
muses modules

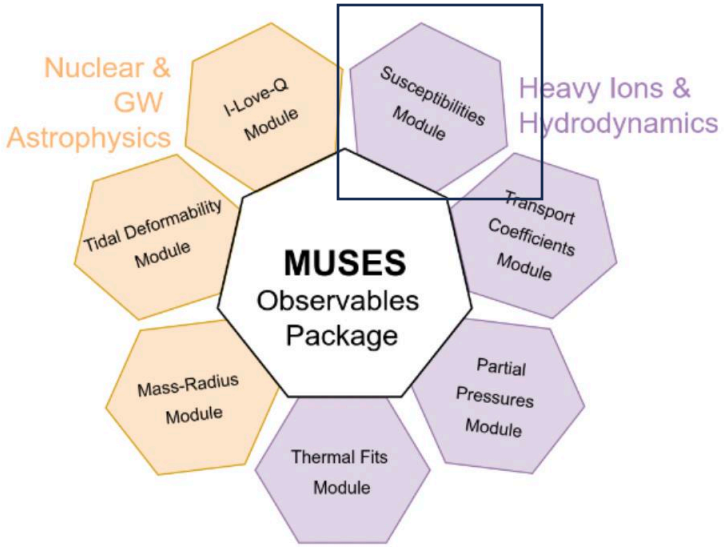




+ Lepton Module, Synthesis Module, Interpolator Module, …

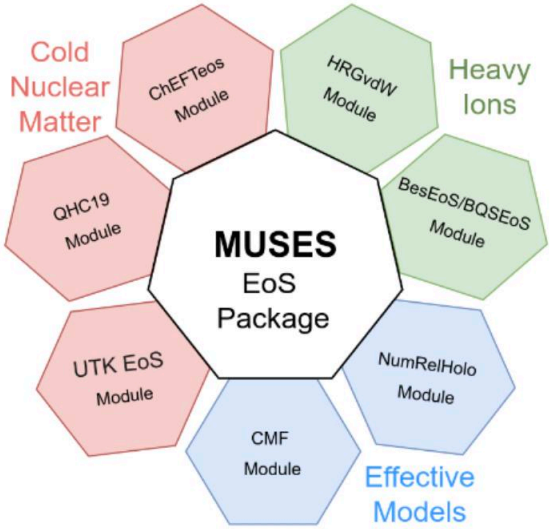
muses modules

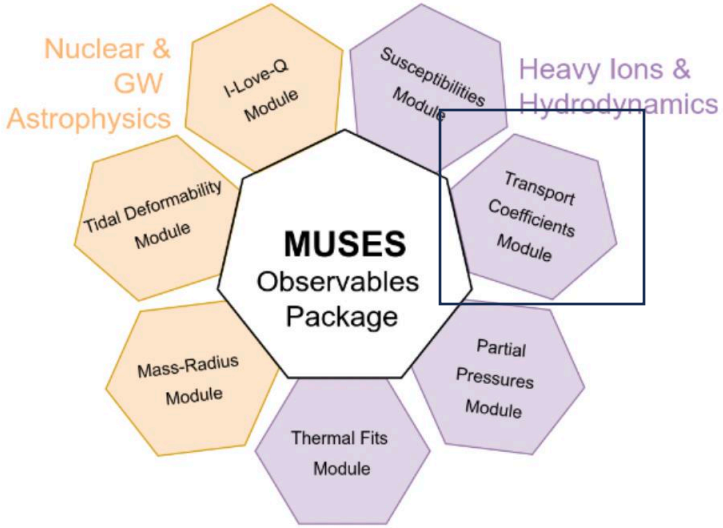




+ Lepton Module, Synthesis Module, Interpolator Module, …

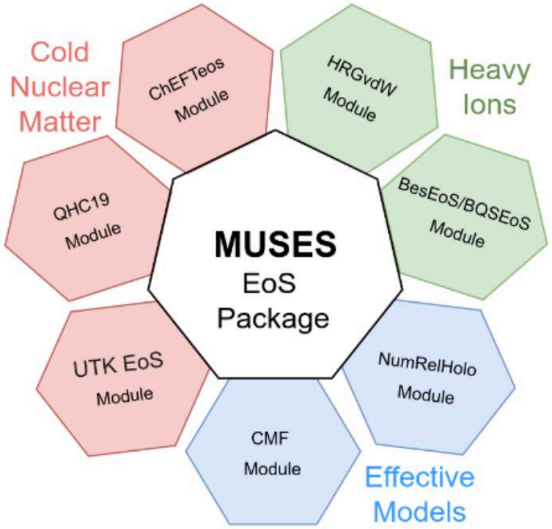
muses modules

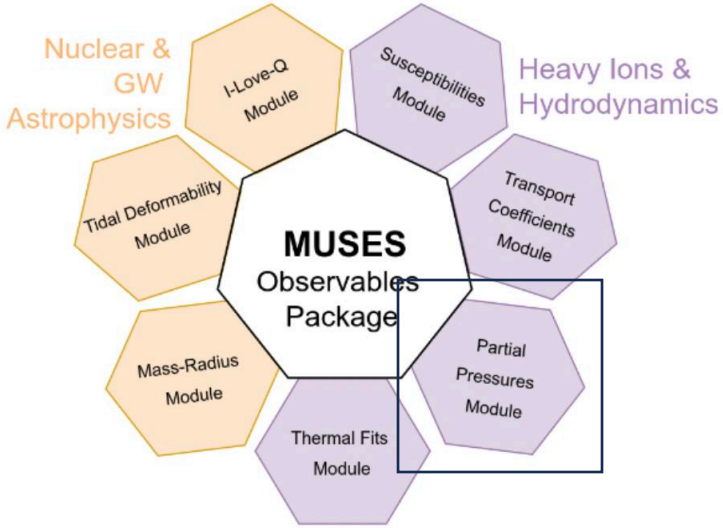




+ Lepton Module, Synthesis Module, Interpolator Module, …

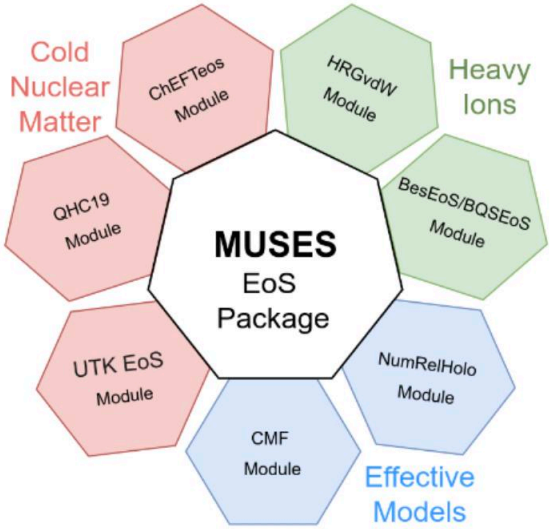
muses modules

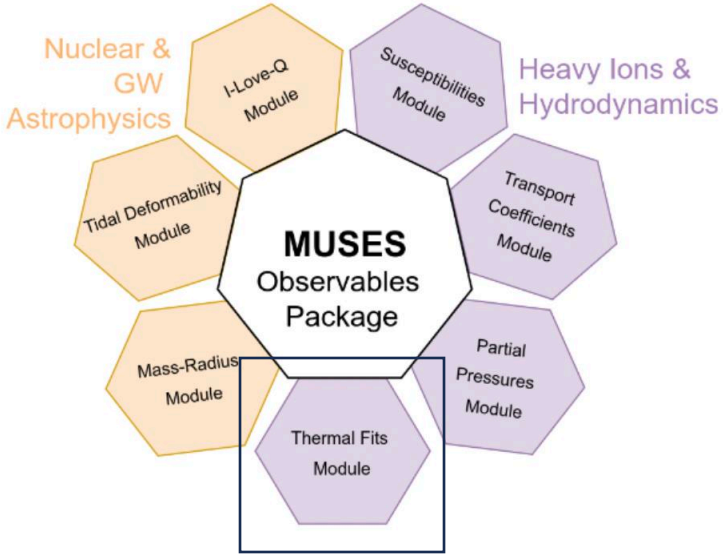




+ Lepton Module, Synthesis Module, Interpolator Module, …

muses modules

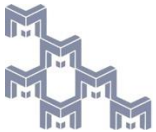




+ Lepton Module, Synthesis Module, Interpolator Module, …

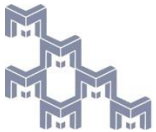
muses alpha release (September 2024)

- We invited a limited number of users to test modules and provide feedback
- Included a first set of EoS and observable modules
- All free and open-source



muses beta release (February 2025)

- We publicly released the alpha release modules
- We invite everyone to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary



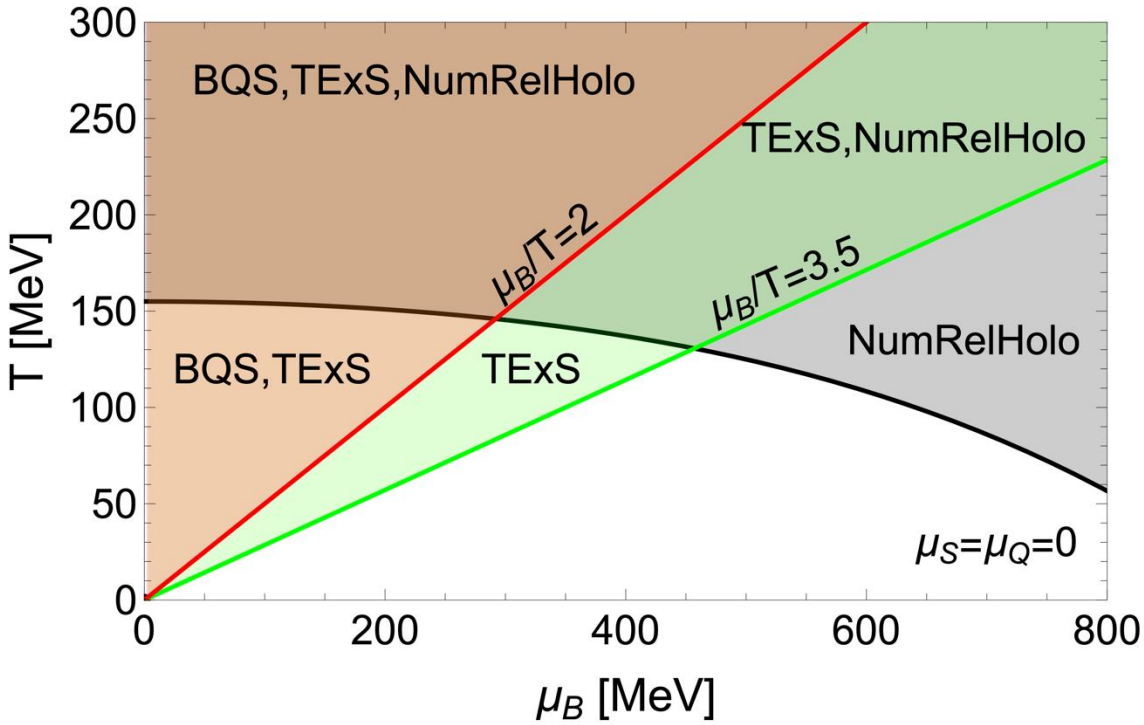
muses beta release (February 2025)

- We publicly released the alpha release modules
- We invite <u>everyone</u> to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary

finite T

- ✓ BQS EOS: 4D lattice QCD with alternative expansion scheme in μ_B
- ✓ ISING-TEXS EOS: 2D Critical behavior into lattice QCD alternative expansion
- ✓ NUMRELHOLO: 2D AdS/CFT correspondence based EoS

muses beta release (February 2025)



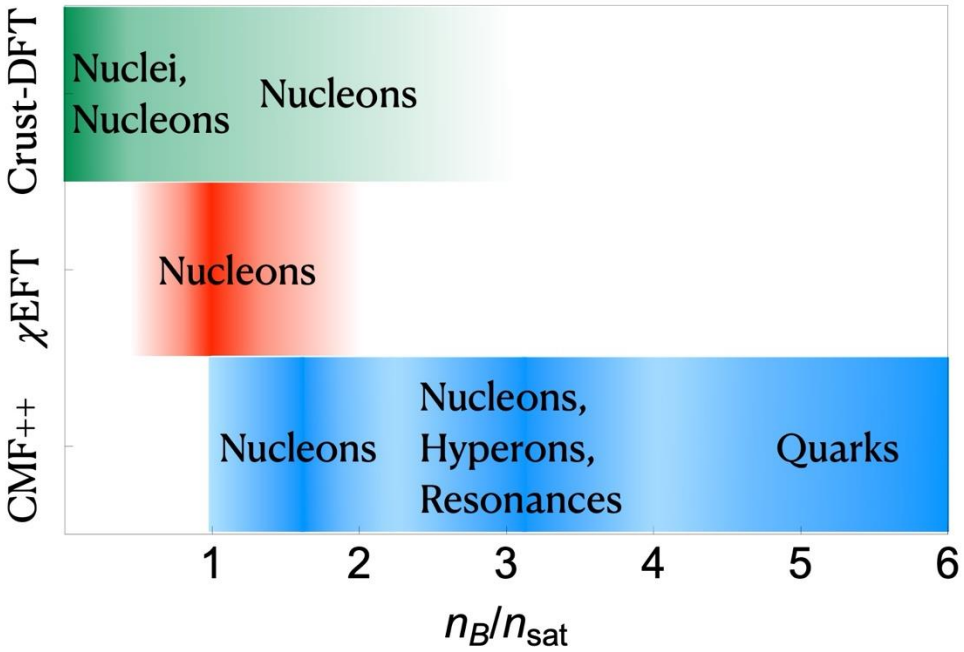
muses beta release (February 2025)

- We publicly released the alpha release modules
- We invite everyone to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary

finite T
- ✓ BQS EOS: 4D lattice QCD with alternative expansion scheme in μ_B
- ✓ ISING-TEXS EOS: 2D Critical behavior into lattice QCD alternative expansion
- ✓ NUMRELHOLO: 2D AdS/CFT correspondence based EoS

T ~ 0
- ✓ CMF: 3D Chiral EoS with different orders for deconfinement
- ✓ CEFT: 2D EoS for interacting nucleons
- ✓ UTK or Crust DFT: 2D EoS including nucleons and nuclei
- ✓ Lepton module, Synthesis module, CompOSE outputs

muses beta release (February 2025)

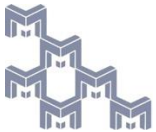


★ muses beta release (February 2025)

- We publicly released the alpha release modules
- We invite <u>everyone</u> to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary

finite T

- ✓ Transport coefficients: thermal conductivity, baryon conductivity & diffusion, shear & bulk viscosities, …



muses beta release (February 2025)

- We publicly released the alpha release modules
- We invite everyone to test these modules and provide feedback
- Includes a first set of modules (free and open-source) but still preliminary

finite T
- ✓ Transport coefficients: thermal conductivity, baryon conductivity & diffusion, shear & bulk viscosities, …

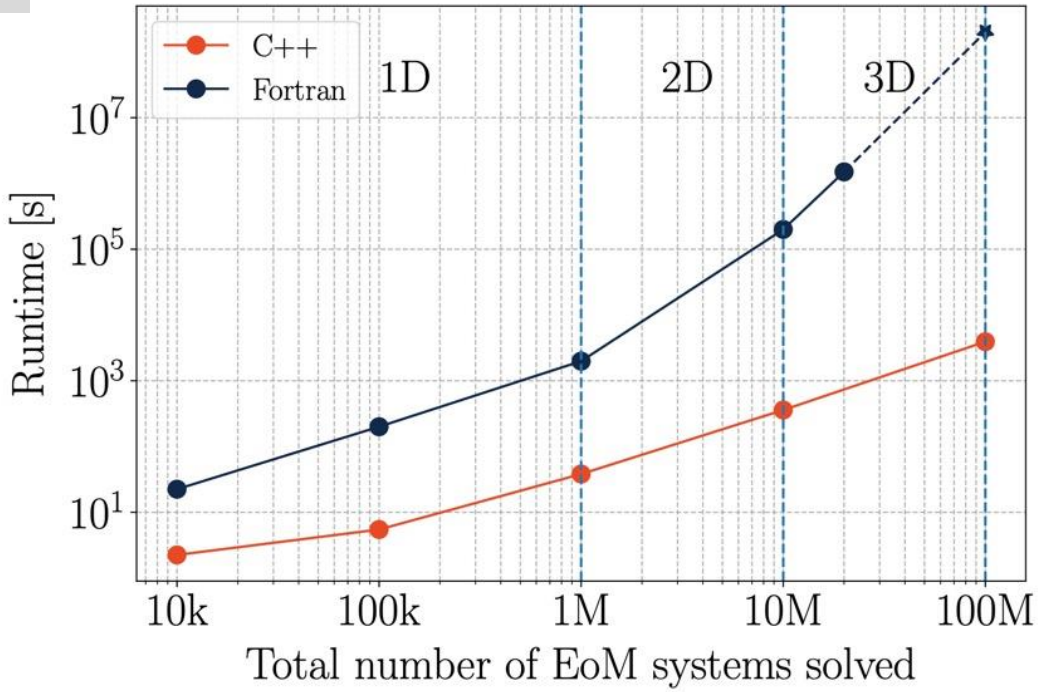
T ~ 0
- ✓ QLIMR module: quadrupole moment, tidal Love number, moment of inertia, mass, and radius of static and slowly rotating neutron stars
- ✓ Flavor equilibration for weak β-equilibrium: Urca rates, relaxation rates, damping time, bulk viscosity

both
- ✓ Susceptibilities

see next talk (Mateus Pelicer) for workflow example

Results for CMF++

e-Print: 2409.06837



Results for CMF++

e-Print: [2409.06837](2409.06837)

a) scalar meson field σ normalized by vacuum

b) deconfinement field **Φ**

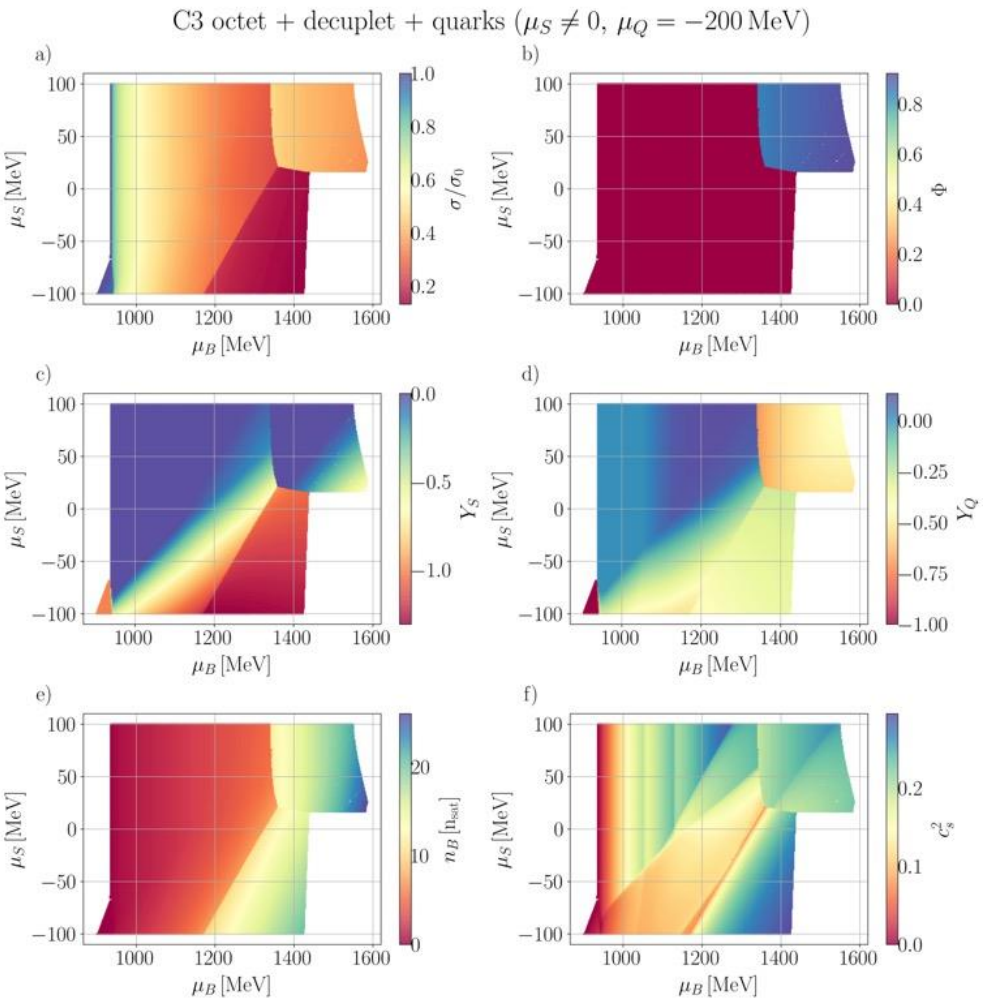
c) strangeness fraction

d) charge fraction

e) baryon density

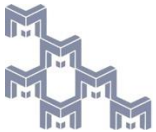
f) speed of sound squared

with high order susceptibilities



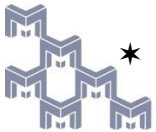
muses conclusions

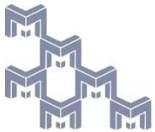
- The MUSES Calculation Engine is an application that lets you run calculations as a composable workflow compose of growing libraries of MUSES modules (see next talk from Mateus Pelicer for workflow example)
- Users and developers can seek support and exchange ideas on the MUSES community forum
- Everyone can run workflows on the dedicated high-performance computing cluster at NCSA operated by the MUSES collaboration for the research community (access given via login) OR self-host their own instance of the Calculation Engine using Docker Compose or Kubernetes
- Online documentation on the use of the CE, the different modules, etc.
- 2 MUSES mini symposia in APS meeting: NSs, HIs



muses outlook

- Extend T~0 modules to finite T
- Combine T~0 modules with finite T ones
- Add strangeness to some T~0 modules
- More interpolating functions
- Interpolate particle properties
- Include pasta phases
- Extend ISING-TEXS lattice QCD EOS to 4D
- Nuclear properties module
- Thermal-FIST module (ideal HRG and VdW)
- Fully parametrized EoS's …



muses links

- MUSES: https://musesframework.io/
- Seminar series: https://musesframework.io/seminar/
- Publications: https://musesframework.io/publications/
- Forum discussions: https://forum.musesframework.io/
- Code documentation and links to module source : https://ce.musesframework.io/docs/