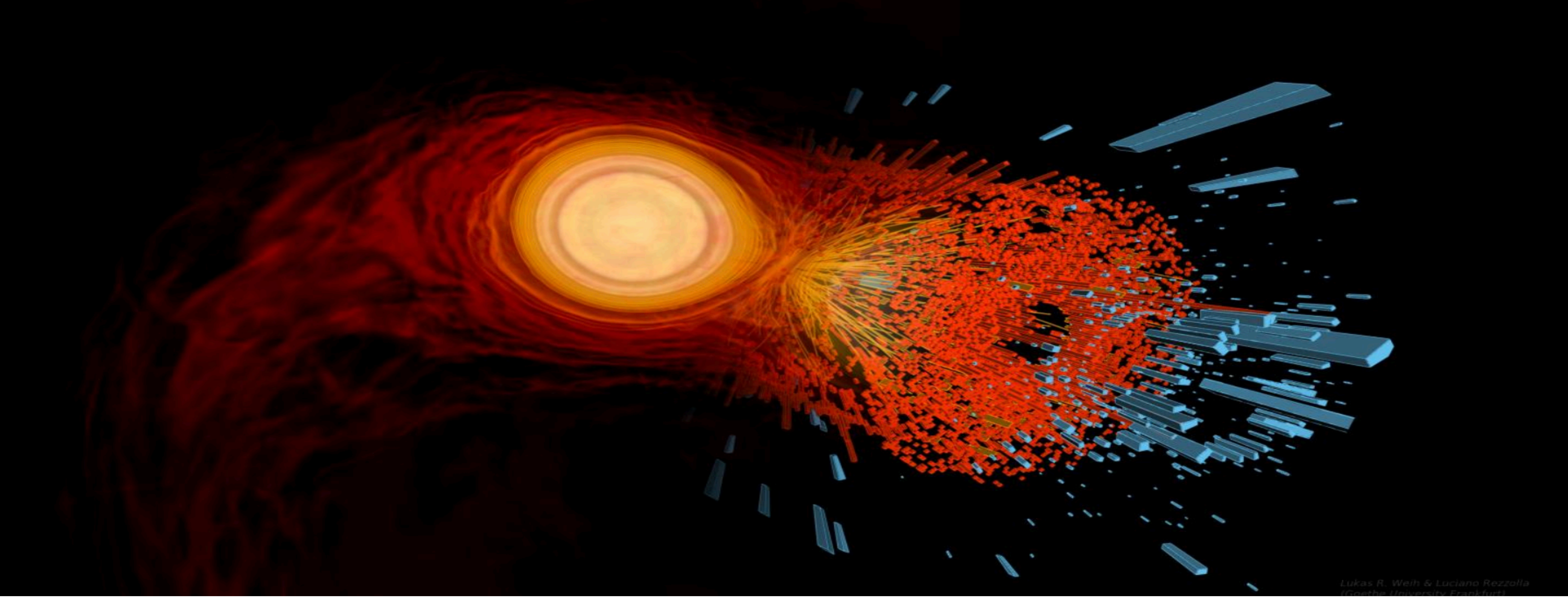


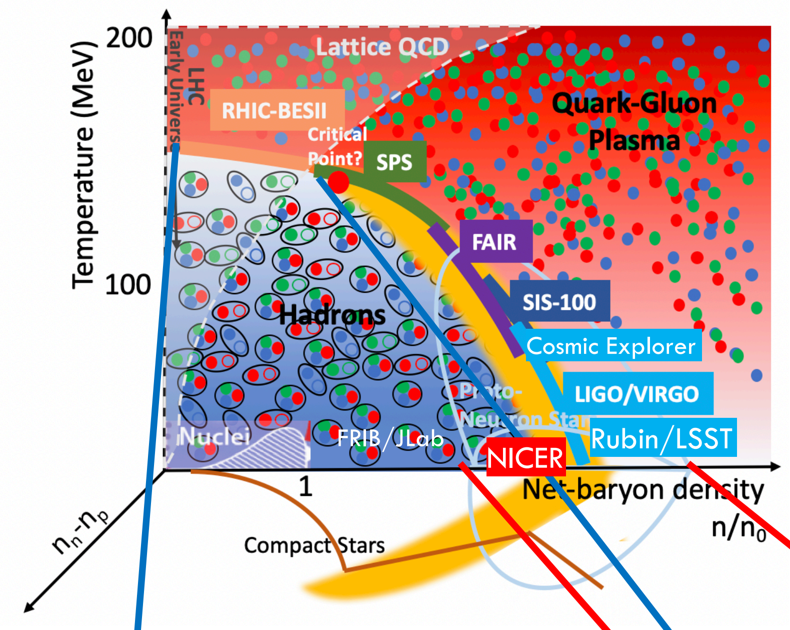
STATUS OF THE MUSES COLLABORATION

Claudia Ratti
University of Houston

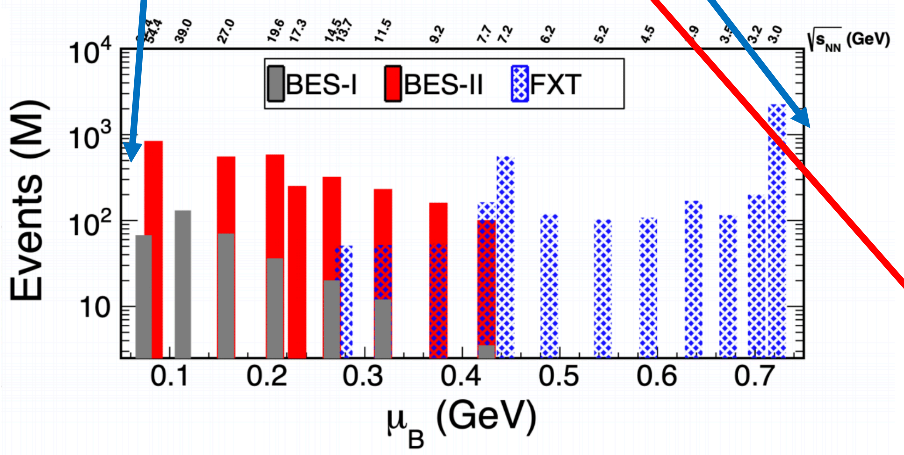
muses NP3M NuSTEAM
Nuclear Science in Texas to Enhance and Advance Minorities

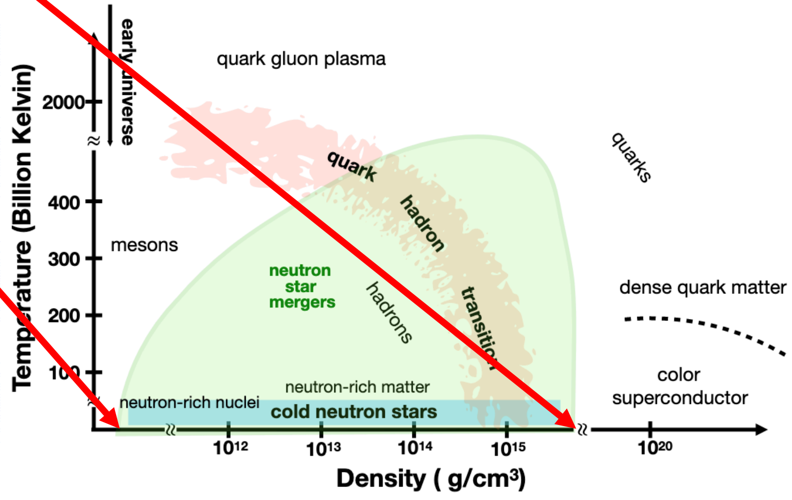
MOTIVATING SCIENCE GOALS

- Is there a critical point in the QCD phase diagram?
- What are the degrees of freedom in the vicinity of the phase transition?
- Where is the transition line at high density?
- What are the phases of QCD at high density?
- What is the nature of matter in the core of neutron stars?



- Run 2019:
  - Collider: $\sqrt{s_{NN}}$=14.6, 19.6, 200 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.2 GeV
- Run 2020:
  - Collider: $\sqrt{s_{NN}}$=9.2, 11.5 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7 GeV
- Run 2021:
  - Collider: $\sqrt{s_{NN}}$=7.7, 17.3 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.0, 9.2, 11.5, 13.7 GeV





TERRESTRIAL FACILITIES FOR FINITE-DENSITY QCD

Compilation by D. Cebra

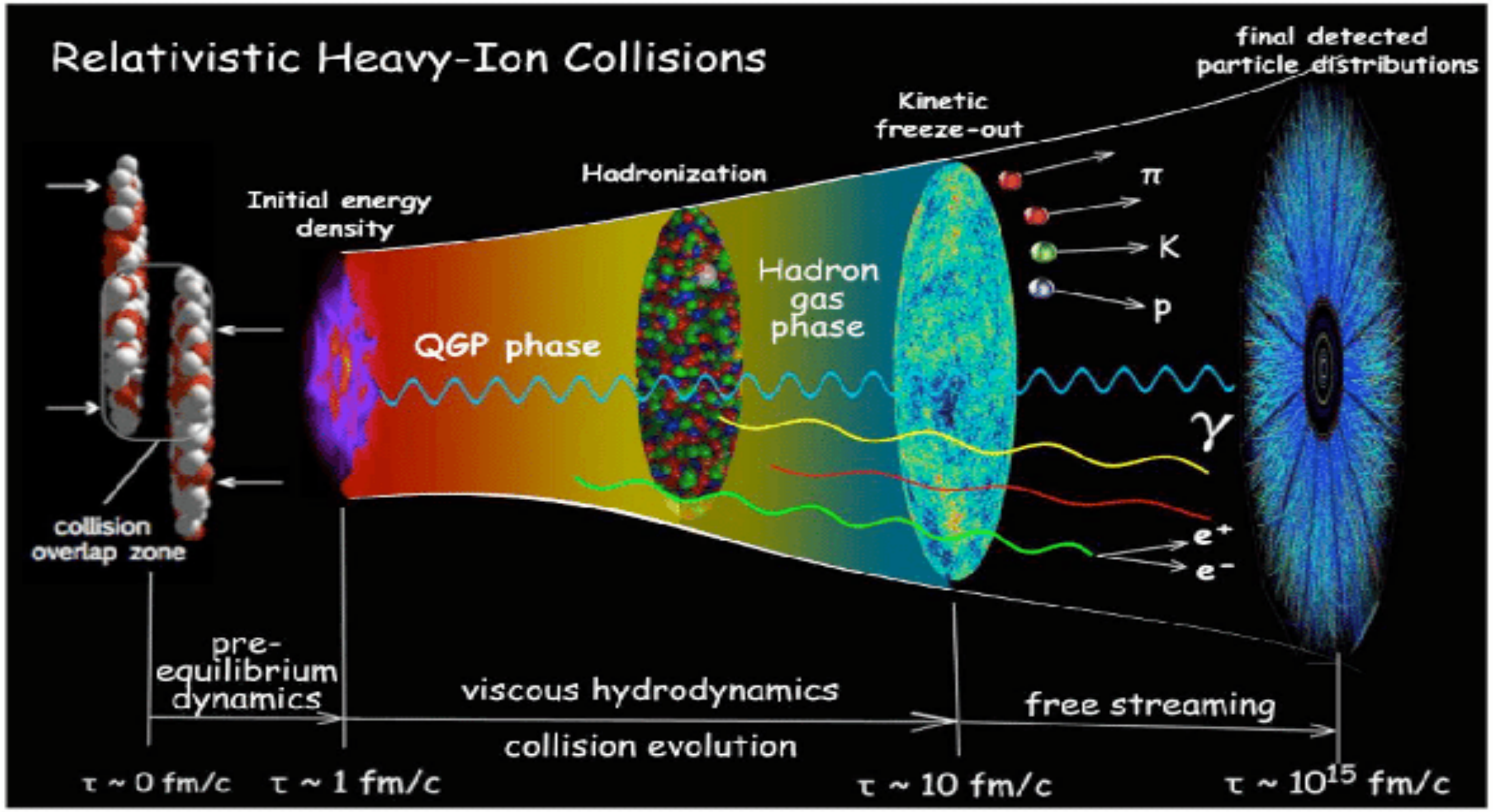
CP=Critical Point

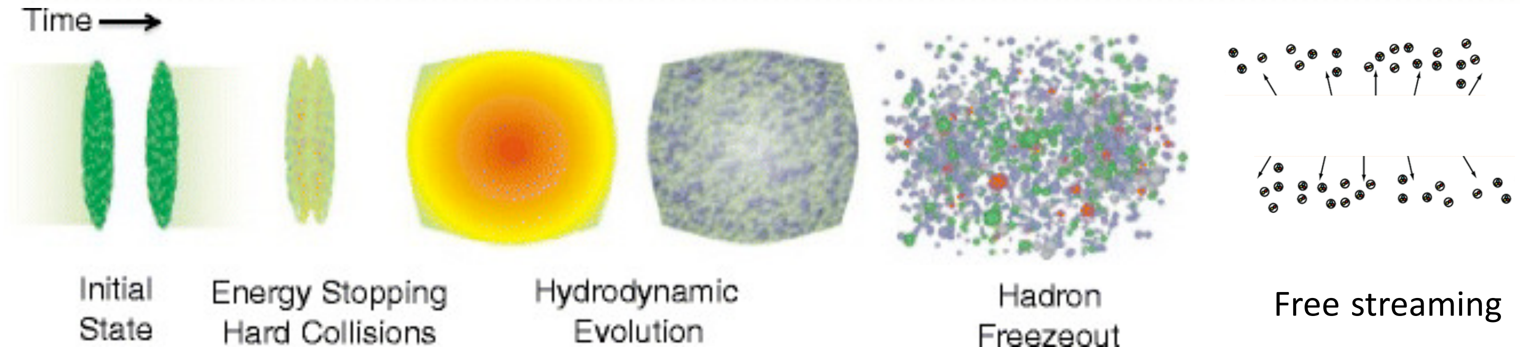
OD= Onset of Deconfinement

DHM=Dense Hadronic Matter

Facilty	RHIC BESII	SPS	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	CBM	JHITS
Start:	2019-2021	2009	2025	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM
	Collider Fixed target	Fixed target Lighter ion collisions	Fixed target	Fixed target

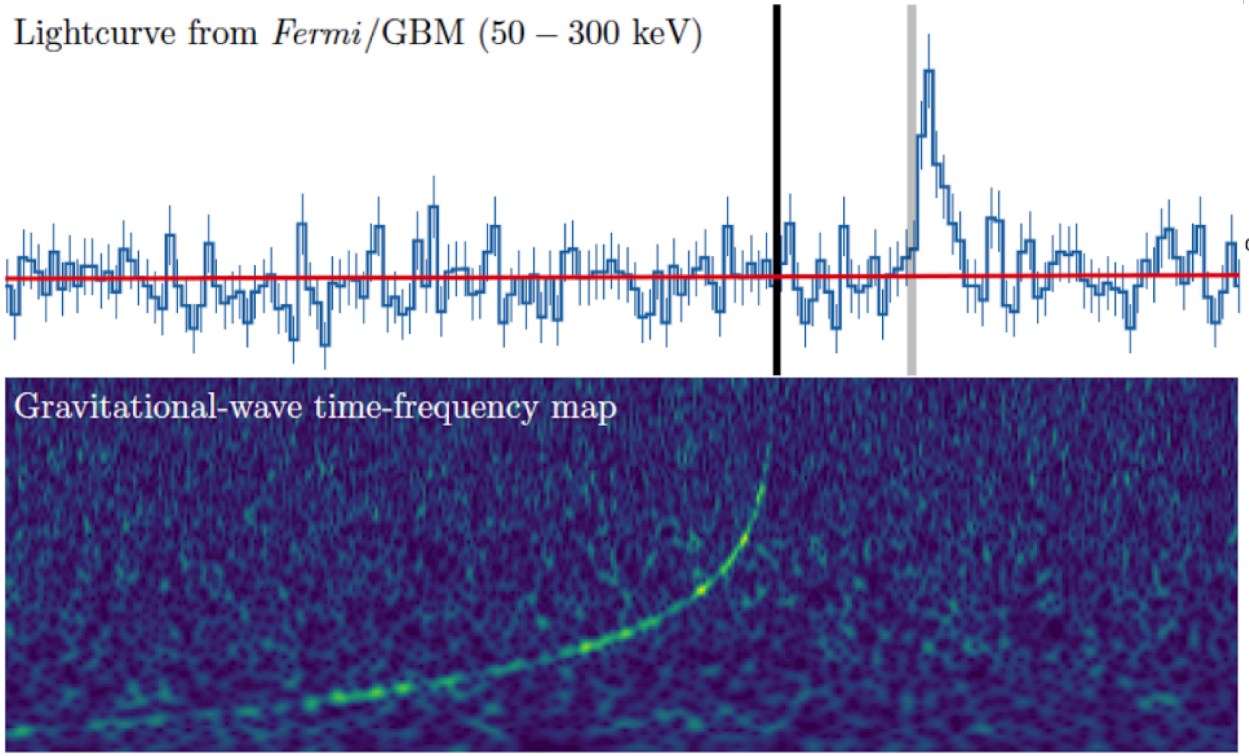
ANATOMY OF A HEAVY-ION COLLISION

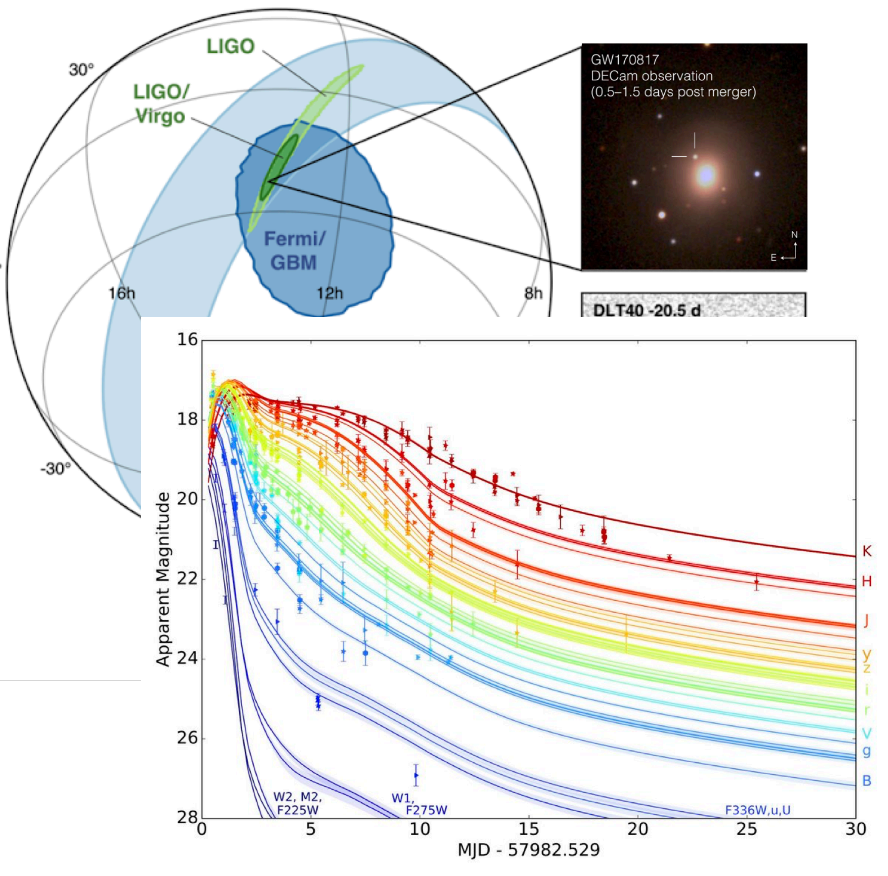




GW170817

Demonstrated the ability of mergers to advance nuclear physics

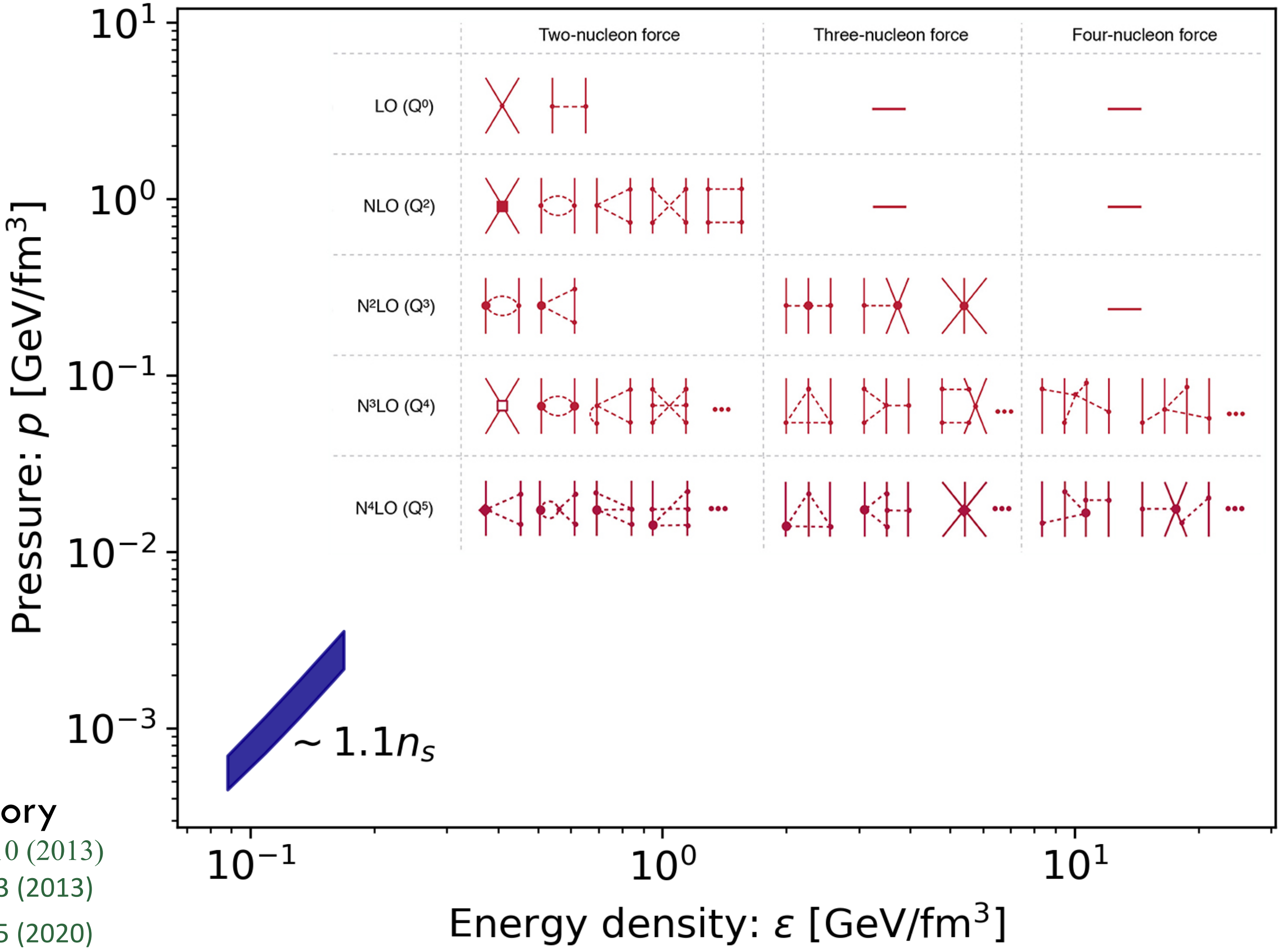




LIGO/Virgo PRL (2017)

P.S. Cowperthwaite et al., Astrophys. J. Lett. (2017)

NEUTRON STARS AND MERGERS



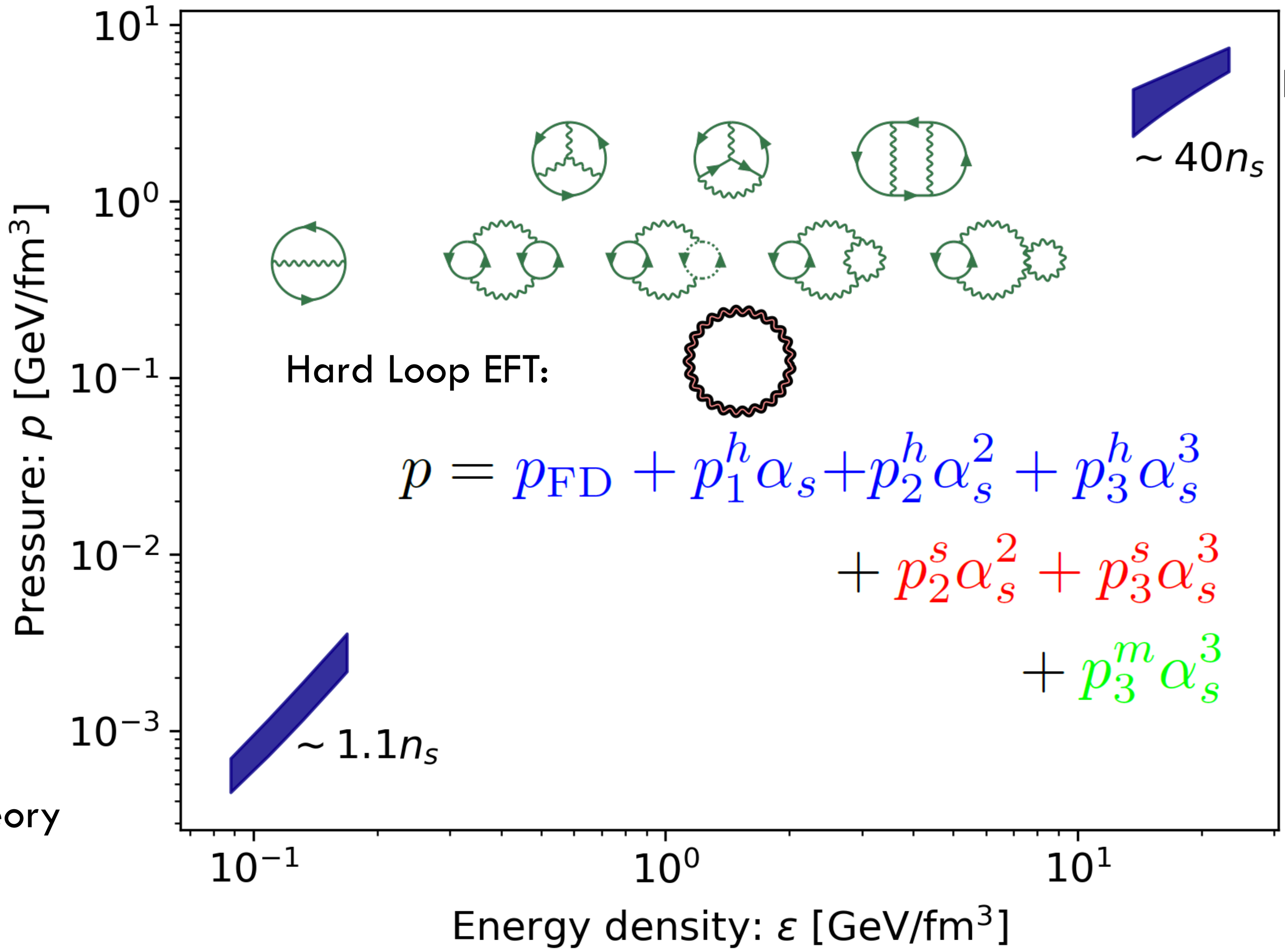
Chiral effective theory

Tews et al. PRL 110 (2013)

Hebeler, Lattimer et.al. APJ 773 (2013)

Drischler, Furnstahl et.al. PRL 125 (2020)

NEUTRON STARS AND MERGERS

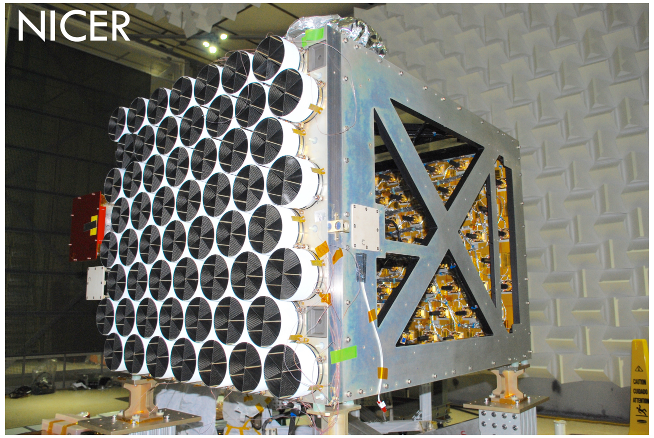


Perturbative QCD

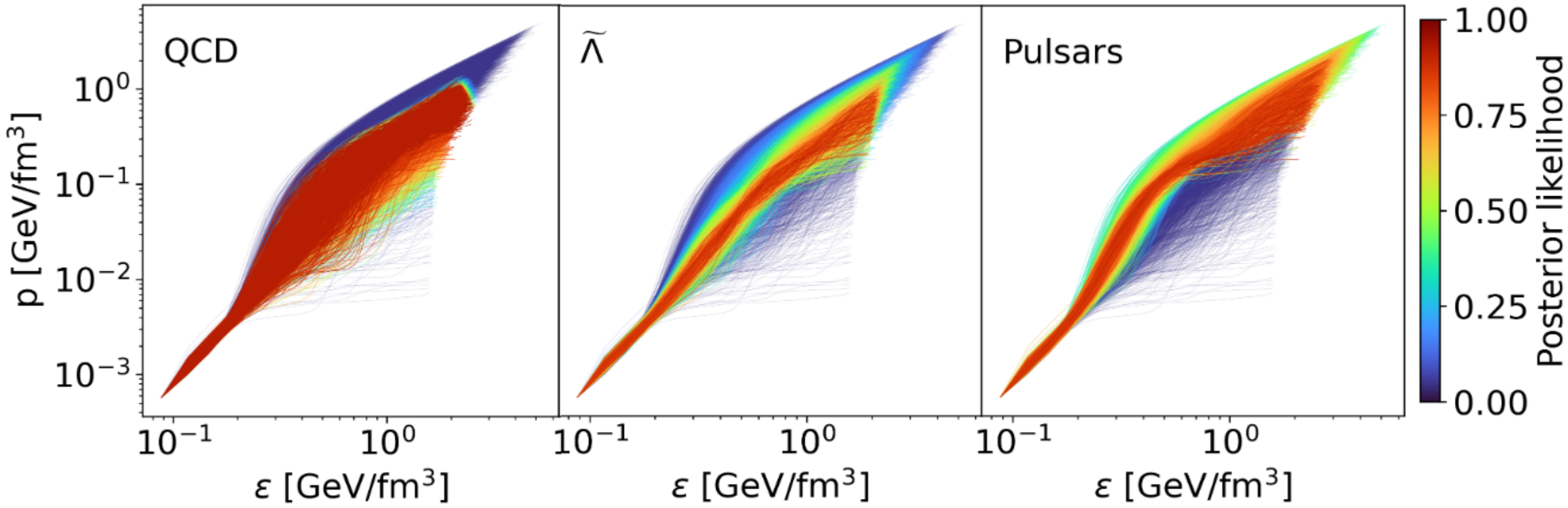
Andersen et al., PRD (2002);
Kurkela, Vuorinen PRL 117 (2016)
Annala et al., Nat. Ph. (2020)

Chiral effective theory

NEUTRON STARS AND MERGERS



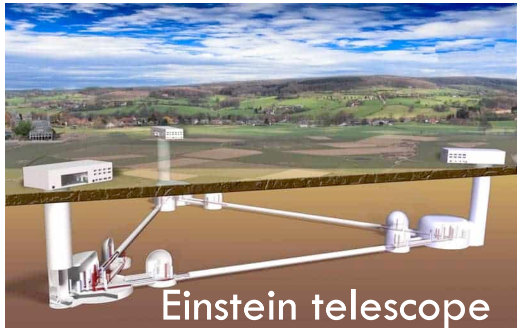
QCD input and NS observations can constrain the interpolation

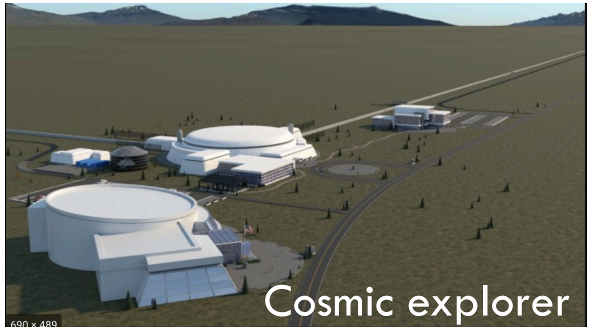


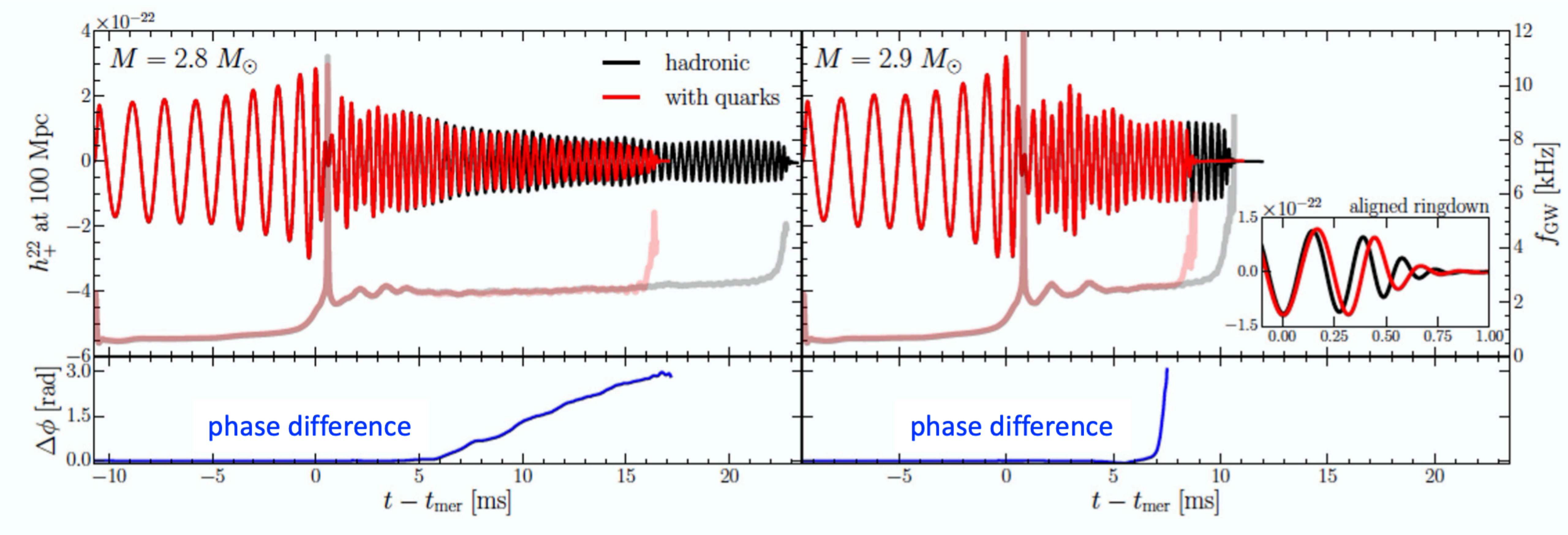
Slide adapted from talk by A. Kurkela

NEUTRON STARS AND MERGERS

- Post-merger signal sensitive to order of the phase transition
- Next generation observatories will be able to detect it!
- Need to combine the nuclear physics input and simulations



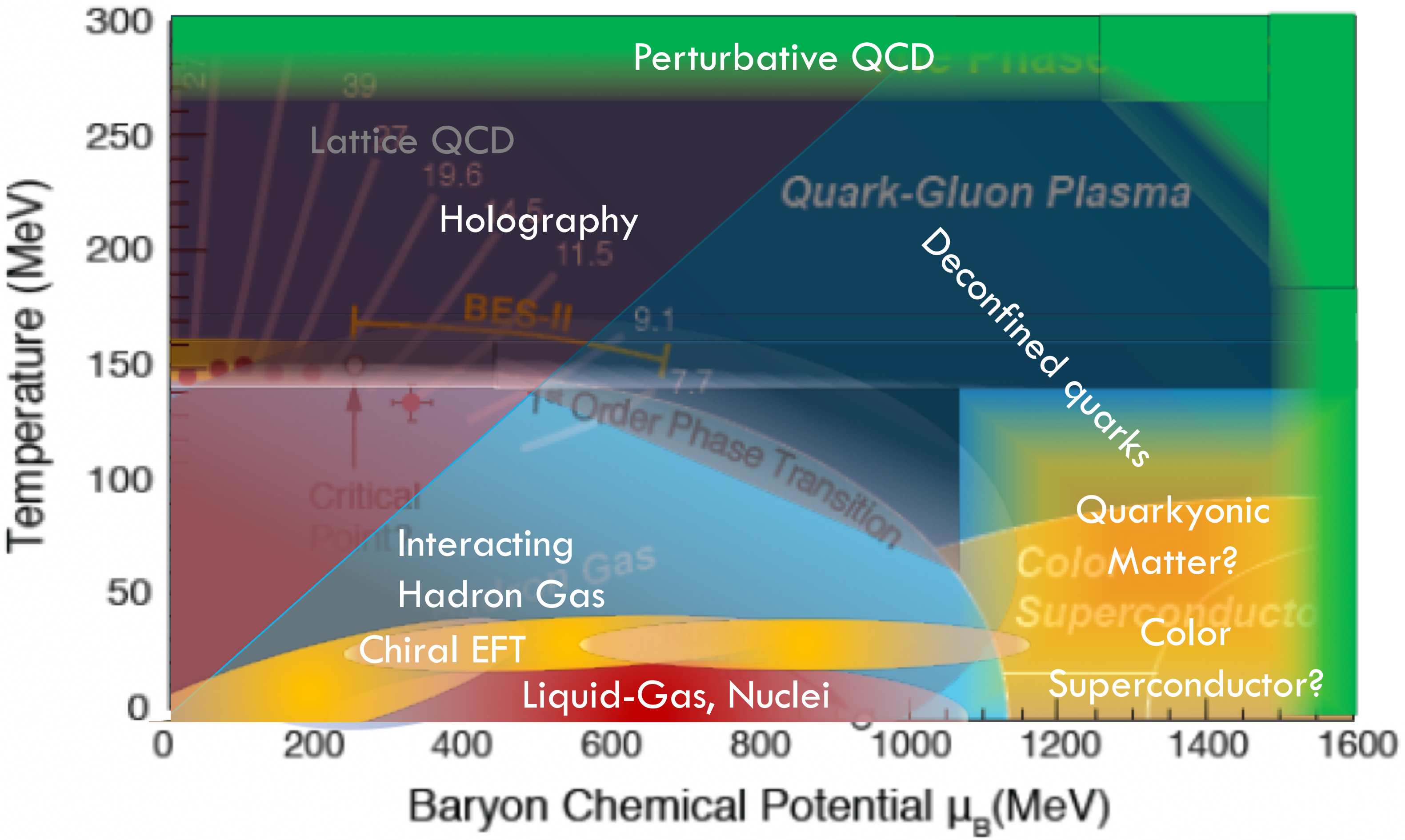




E. Most et al., PRL (2019)

WHAT HAPPENS AT LARGE DENSITIES?

- We need to merge the lattice QCD equation of state with other effective theories
- Careful study of their respective range of validity
- Constrain the parameters to reproduce known limits
- Test different possibilities and validate/exclude them



Lattice QCD: S. Borsanyi, C. R. et al, PRL (2021)
Interacting HRG: V. Vovchenko et al., PRL (2017)
Liquid-gas, Nuclei: see e.g. Du et al. PRC (2019)
Chiral EFT: see e.g. Holt, Kaiser, PRD (2017)
Holography: R. Critelli, C. R. et al., PRD (2017)

pQCD: Andersen et al., PRD (2002); Annala et al., Nat. Ph. (2020)
quarks: C. R. et al., PRD (2006), Dexheimer et al., PRC (2009); Baym et al., Astr. J. (2019)
quarkyonic: McLerran, Pisarski NPA (2007)
CSC: Alford et al., PLB (1998); Rapp et al., PRL (1998), S. Rossner, C. R. et al, PRD (2007), .

muses

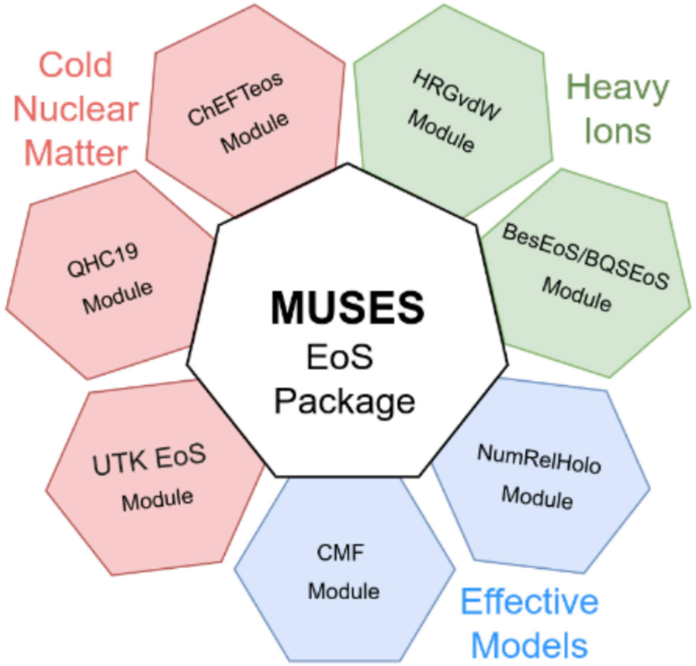
MUSES – MODULAR UNIFIED SOLVER OF THE EQUATION OF STATE

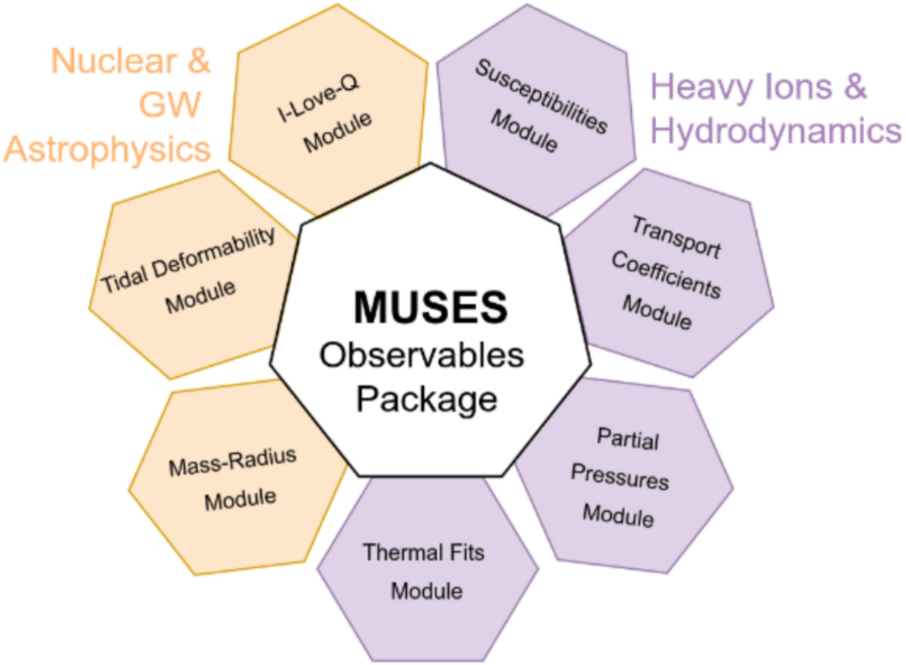
"An open-source cyberinfrastructure fostering a community-driven ecosystem that provides key computational tools to promote, transform and support groundbreaking research in nuclear physics and astrophysics, computational relativistic fluid dynamics, gravitational-wave and computational astrophysics."

- Modular: while at low densities the equation of state is known from 1st principles, at high μ_B we will implement different models ("modules") that the user will be able to pick
- Unified: the different modules will be smoothly merged together to ensure maximal coverage of the phase diagram, while respecting established limiting cases (lattice, perturbative QCD, ChPT…)

MUSES GOALS AND MILESTONES

- CyberInfrastructure of interoperating tools and services within a replicable and flexible deployment system
  - Upgrade of existing calculation tools to modern programming languages
  - **Equation of State (EoS) package** that combines all the EoS modules using smooth transition functions
  - **Web-based tools and services** that provide interactive interfaces to the calculation engine
  - **Job management system** that executes client-requested calculations using the best available processing system
  - Scalable, high-availability **deployment system** that can be reproduced in other computing environments





DEVELOPERS & USERS

- The team which we put together consists of
  - Developers: physicists + computer scientists will work together to develop the software that generates the equations of state over a range of temperature and chemical potentials to cover the whole phase diagram
  - Users: a variety of scientists from different communities, who have expressed an interest in the output of the framework

muses

This is the list that appeared in the proposal
BUT: Muses collaboration paper was signed by 58 authors
→ We are growing!

PARTICIPANTS

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

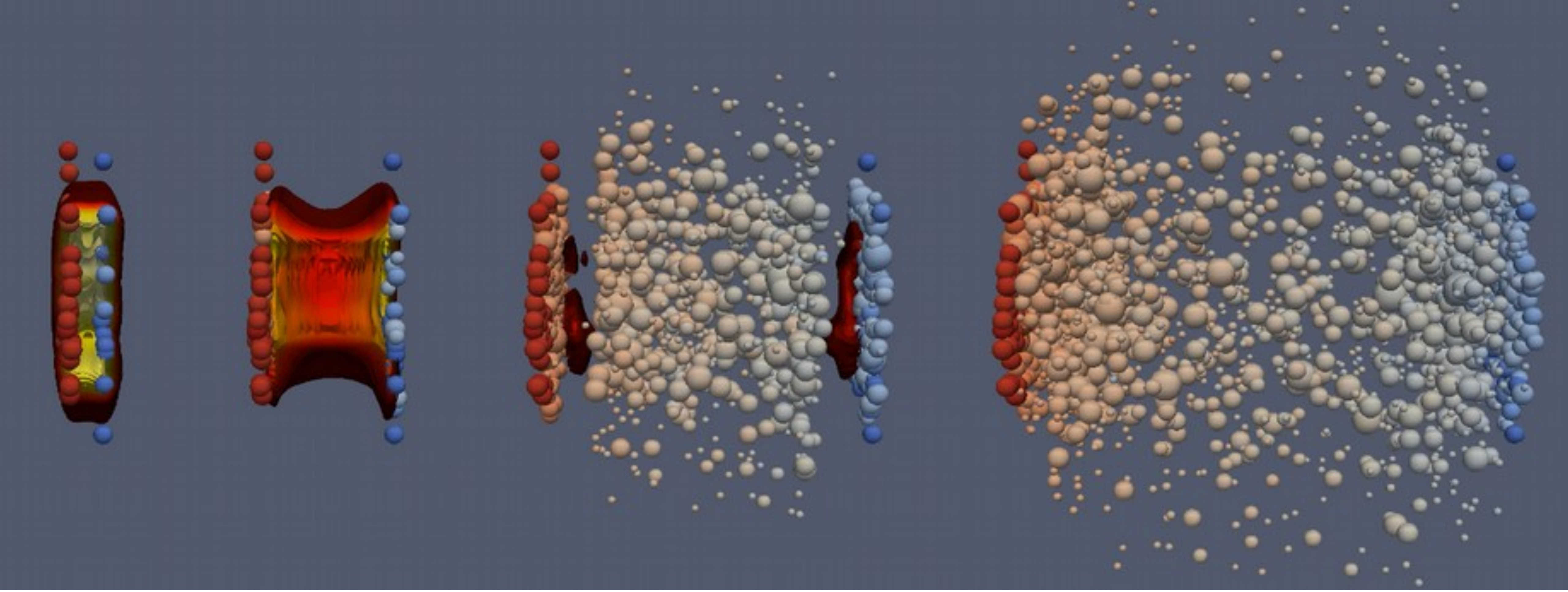
External collaborators

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

ALPHA-RELEASE: MAY 1ST 2024

DETAILS

- A first set of modules will be released on this date
- They will be open-source, but still preliminary
- We invite interested people to test these modules and give us their feedback
- The modules to be released will be marked as α-RELEASE during my talk



EOS FOR HEAVY IONS

- EoS from first principles
- EoS with 3D Ising critical point
- HRG model
- EoS from Holography

HEAVY ION COLLISIONS: DETAILS AND NEEDS

DETAILS

- System is described in terms of hydrodynamic simulations
- Strangeness neutrality $<\rho_S>=0$
- Short lifetime, strangeness conserved
- Charge: p vs. n in ions: $<\rho_Q>=0.4<\rho_B>$
- System is not in equilibrium

NEEDS

- To take into account local fluctuations, 4D Equation of State is needed
- Free parameters: T, μ_B, μ_S, μ_Q
- Thermodynamic variables (p, s, ε, ρ_B, c_s^2)
- 1st and 2nd order derivatives of pressure with respect to chemical potentials
- Inclusion of critical point
- Transport coefficients

MUSES EoS Package

Heavy Ions

BesEoS/BQSEoS Module

α-RELEASE

See talk by Johannes Jahan

EQUATION OF STATE FROM FIRST PRINCIPLES (BQSEOS)

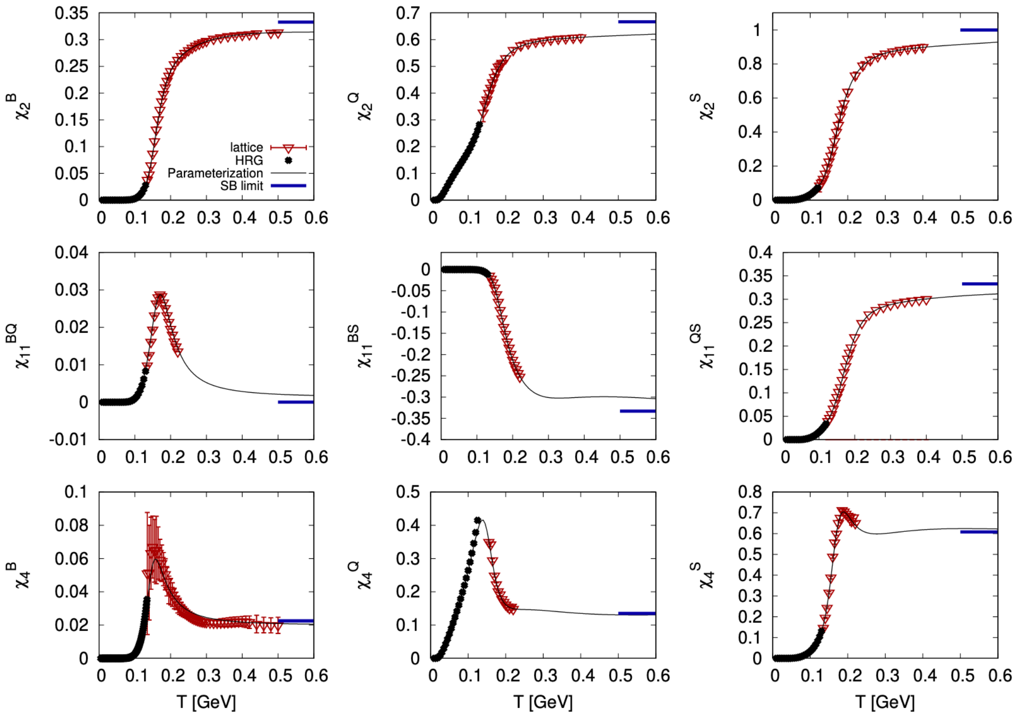
Range: $0<T<600$ MeV; $\mu_B<450$ MeV

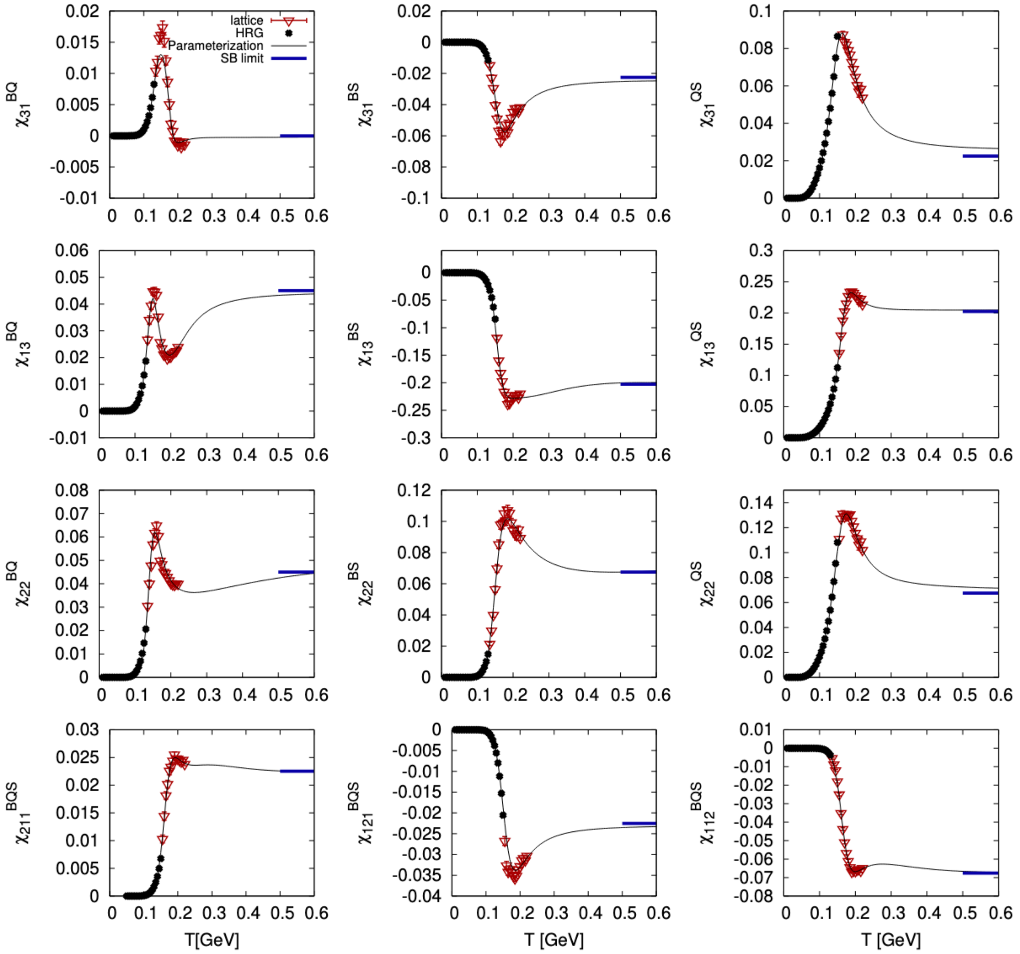
S. Borsanyi, C. R. et al., JHEP (2018)
J. Noronha-Hostler, C. R. et al., PRC (2019)
A. Monnai et al., PRC (2019)

- Full Taylor expansion needed to study different μ_S and μ_Q scenarios

$$\frac{p(T,\mu_B,\mu_Q,\mu_S)}{T^4} = \sum_{i,j,k} \frac{1}{i!j!k!} \chi_{ijk}^{BQS} \left(\frac{\mu_B}{T}\right)^i \left(\frac{\mu_Q}{T}\right)^j \left(\frac{\mu_S}{T}\right)^k$$

- Coefficients are available up to global order 4 ($\mu/T<2$)





Heavy Ions
BesEoS/BQSEoS Module
MUSES EoS Package

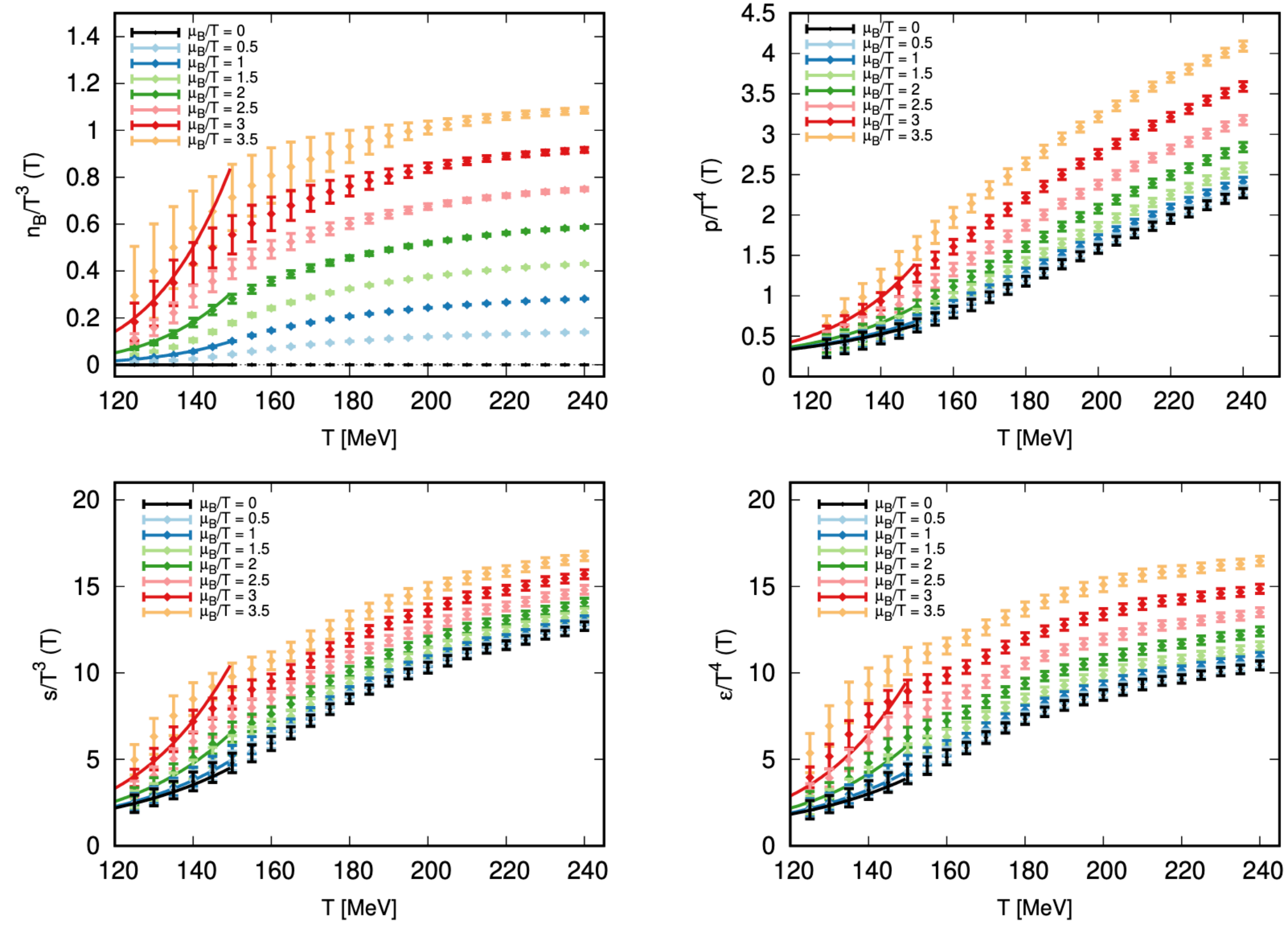
See talk by Johannes Jahan

UPDATE: NEW EXPANSION SCHEME (4D-TEXS)

S. Borsanyi, C. R. et al., PRL (2021)
S. Borsanyi, C. R. et al., PRD (2022)

- Novel expansion scheme allows to extend to $\mu_B/T \sim 3.5$
- EoS available at $\mu_S=\mu_Q=0$
- It was recently extended to the case $\langle n_S\rangle=0$, $\langle n_Q\rangle=0.4\langle n_B\rangle$ of relevance for heavy-ion collisions

Goals:
- Extension to μ_S & $\mu_Q \neq 0$ (4D)
- Implementation into the MUSES engine



α-RELEASE

ISING-TEXS EOS

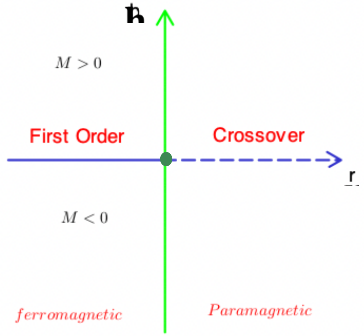
Purpose: To put 3DIsing model Critical behavior into Lattice QCD Alternative Expansion EoS for $\mu_B \in [0,700] MeV$ and $T \in [10,800] MeV$

Physics:

$$n_B(T,\mu_B) = \frac{\mu_B}{T}\chi_2^B(T',0)$$

$$T'[T,\mu_B] = T\left[1 + \kappa_2^{BB}(T)\left(\frac{\mu_B}{T}\right)^2 + \kappa_4^{BB}(T)\left(\frac{\mu_B}{T}\right)^4 + \mathcal{O}\left(\frac{\mu_B}{T}\right)^6\right]$$

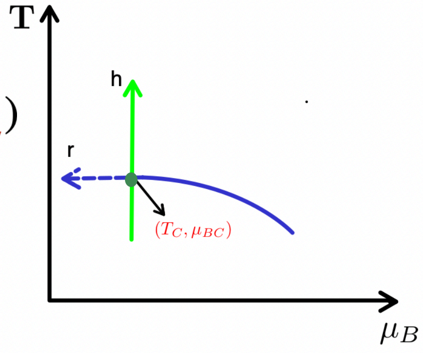
See talk by Micheal Kahangirwe arXiv: 2402.08636



3D-Ising Co-ordinates

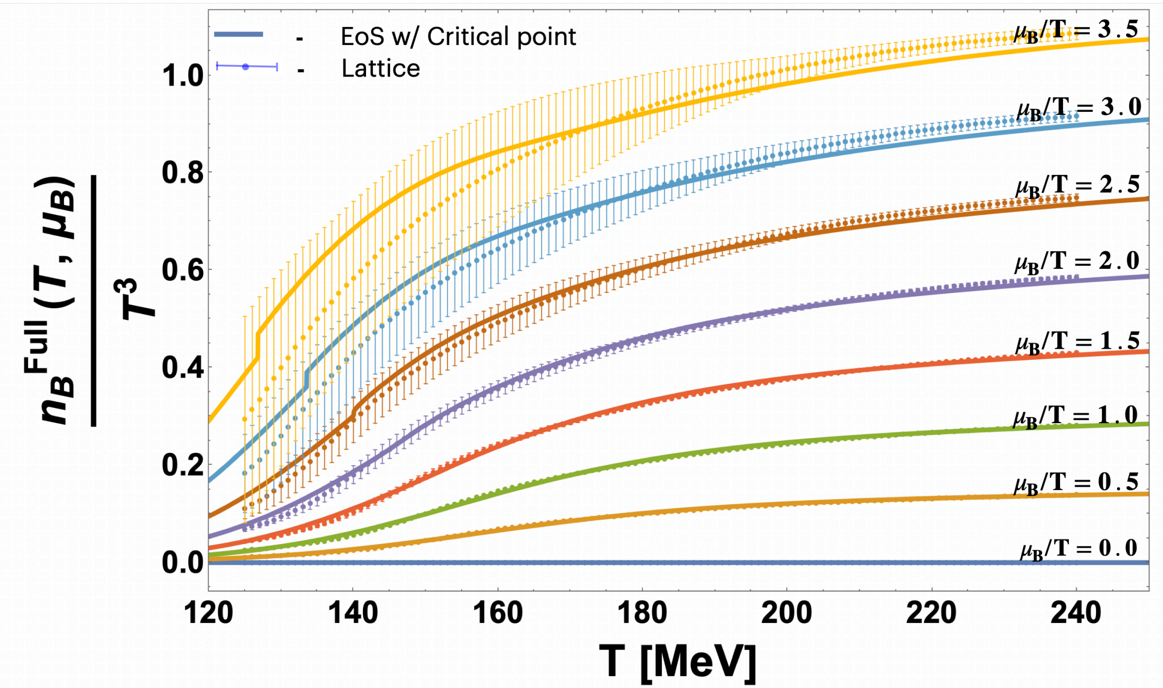
$$\frac{T' - T_0}{T_0} = w\, h \sin \alpha_{12}$$

$$\frac{\mu_B^2 - \mu_{BC}^2}{T_0^2} = w(-r\rho - h \cos \alpha_{12})$$



QCD - Co-ordinates

User Input $\mu_{BC},\ w,\ \rho,\ \alpha_{12}$



Status: Available on GitHub

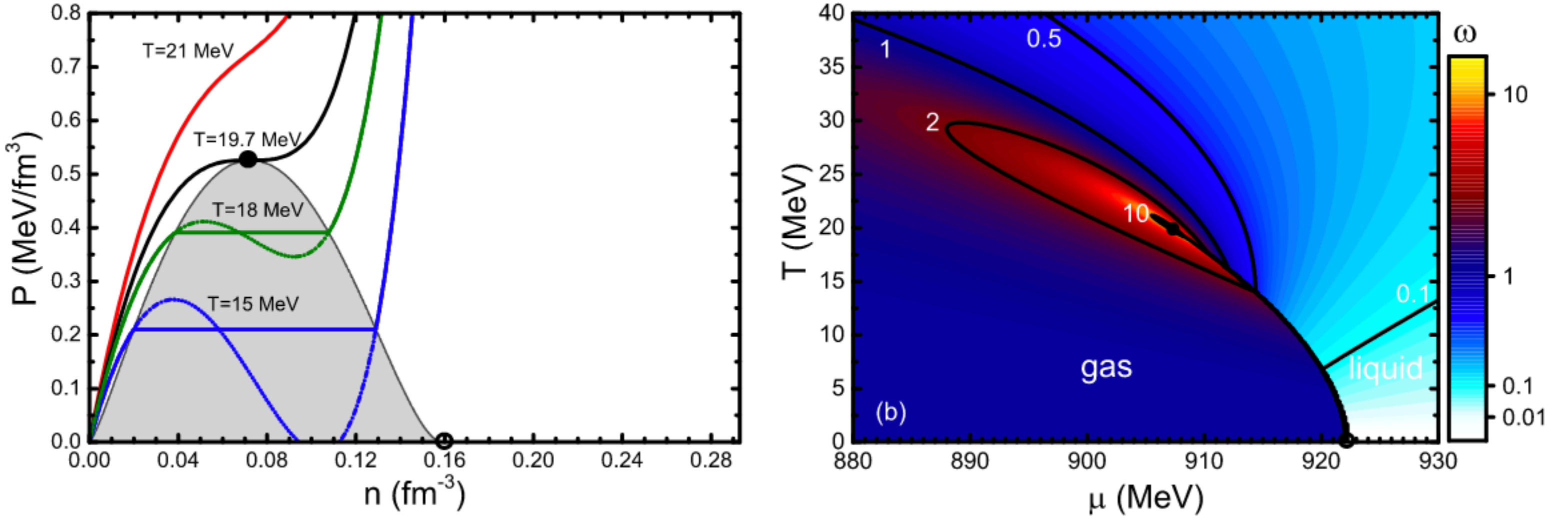
Remaining Work :

- Defining the YAML specifications & manifest + Python wrappers to ensure input/output compatibility requirements
- Create the Docker container

HADRON RESONANCE GAS (HRG) MODEL

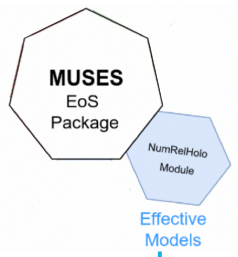
Range: $0<T<160$ MeV; $\mu_B<1$ GeV

- The HRG model provides a well-established and realistic Equation of State at low temperatures
- Its ideal version is based on the assumption that an **interacting gas of hadrons** in the ground state can be well-approximated by an **ideal gas of resonances**
- At large density we need to incorporate additional interactions such as van Der Waals
- It describes the liquid-gas phase transition



Goals:

- Fix the parameters to describe the liquid-gas critical point
- Thermal FIST already does this
- Incorporation into MUSES
- Extend hadronic spectrum to the most updated PDG list



α-RELEASE

EQUATION OF STATE FROM HOLOGRAPHY (NUMRELHOLO)

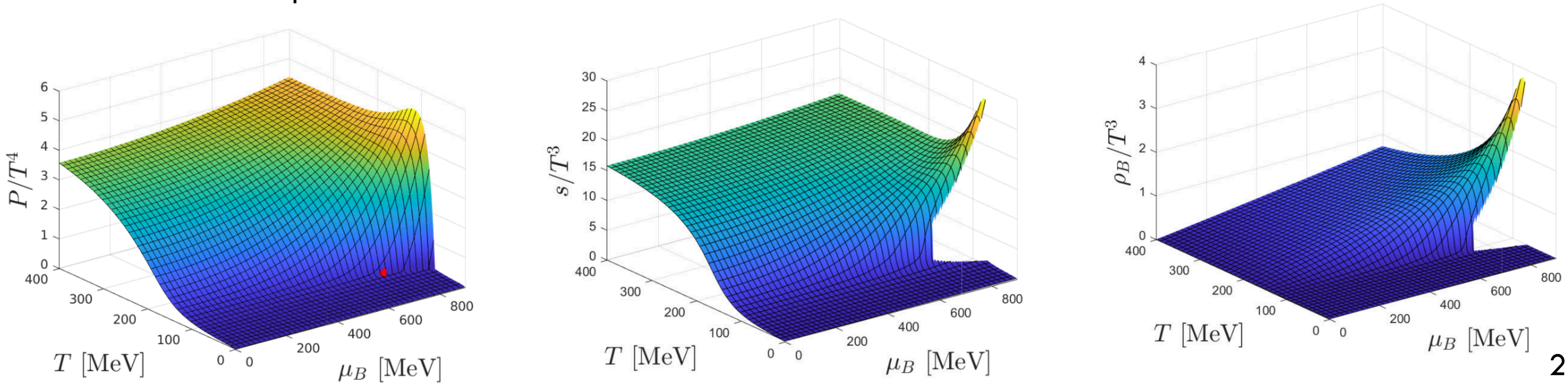
J. Grefa, C. R. et al., PRD (2021), PRD (2022)

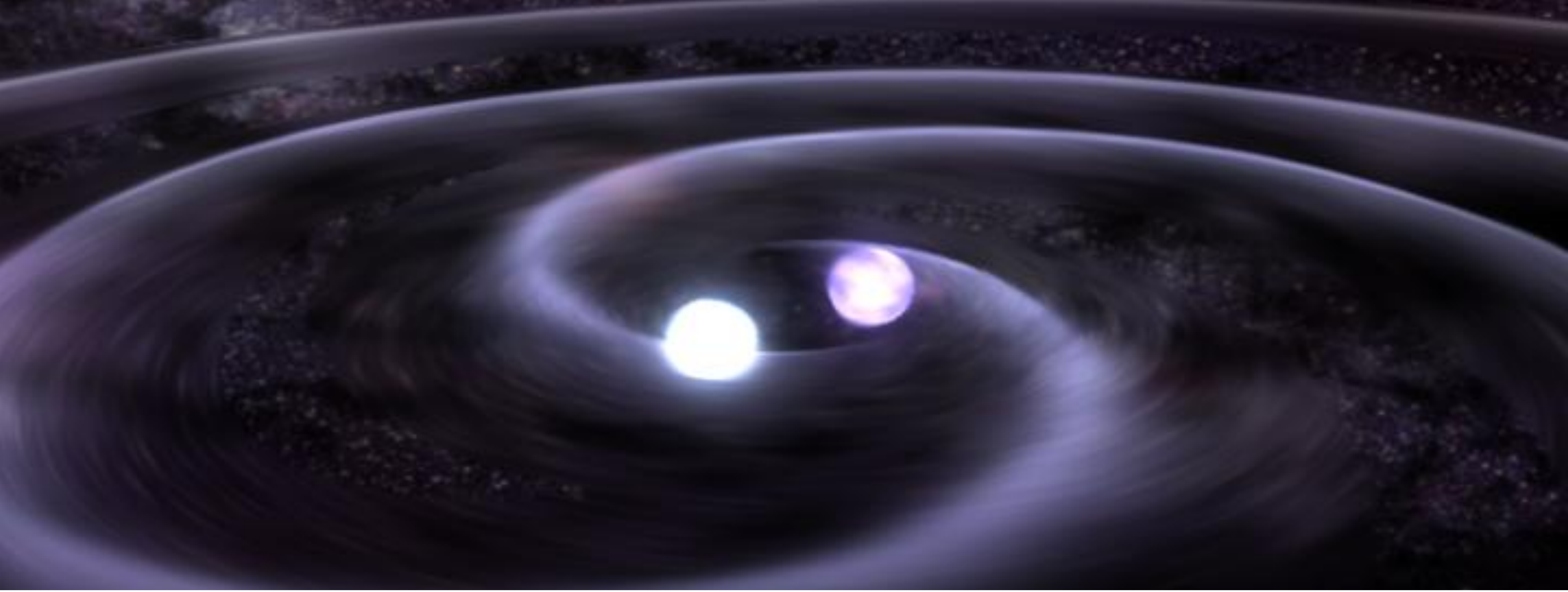
Range: 30 MeV<T<400 MeV; μ_B<1100 MeV

See talk by Joaquin Grefa

- Use AdS/CFT correspondence
- Fix the parameters to reproduce everything we know from the lattice
- Calculate equation of state at finite density
- Model currently has only baryon number
- Model has a critical point

Outlooks:
- Extension to multiple conserved charges





EOS FOR NEUTRON STARS

- Chiral Mean Field Model
- QHC19
- UTK EOS
- Chiral effective theory

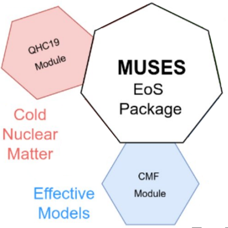
NEUTRON STARS & MERGERS: DETAILS AND NEEDS

DETAILS

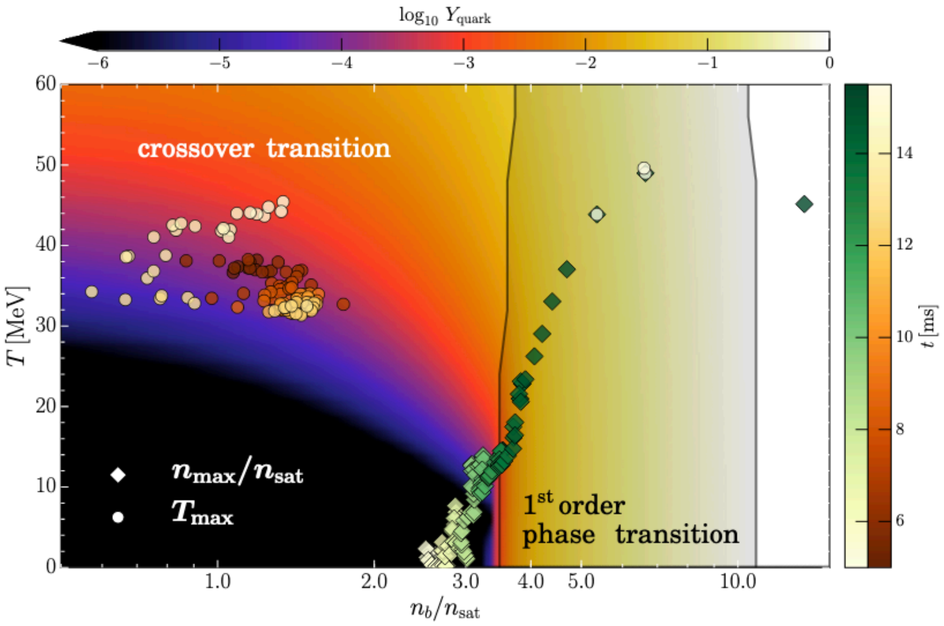
- Long lifetime
- Weak decay: s--> u+W^-
- Strangeness most likely *not* in equilibrium
- Electrically neutral for stability $<\rho_Q>=0$

NEEDS

- Standard EOS: (p, s, ε, ρ_B, c_s^2, μ_i, Y_i)
- Finite-T EOS for mergers
- Ranges: $0<\rho_B<(4\text{-}5)\rho_0$, $0<T<100$ MeV
- T=0 EOS for mergers and neutron stars
- Lepton EOS
- Variable proton fraction



MULTI-PHASE EQUATIONS OF STATE FOR NEUTRON STARS



- **Chiral Mean Field (CMF) model**
  - Crossover at low density and first-order phase transition at high density
  - Based on non-linear sigma model with the addition of deconfined quarks
  - Reproduces nuclear & astrophysics constraints, and matches pQCD in relevant regimes

V. Dexheimer, S. Schramm, PRC (2009)
E. Most, V. Dexheimer et al., PRL (2019)

α-RELEASE

- **Quark-Hadron Crossover (QHC19)**
  - EoS with smooth crossover between hadrons and quarks
  - Hadronic EoS is based on the Togashi model, which describes non-uniform and uniform matter, and beta-equilibrium
  - Quark matter is described in the NJL model with vector interaction

G. Baym et al., Astrophys. J (2019)

Goals:
- Optimization of the code
- Incorporation into MUSES (NJL part only at 1st)

HADRONIC EQUATIONS OF STATE FOR NEUTRON STARS

- **Chiral effective field theory (ChiEFT)**
  - Interacting nucleons and pions within chiral effective field theory
  - Describes matter in the range $T < 30$ MeV ; $800 \text{ MeV} < \mu_B < 1100$ MeV
  - Proton fraction: $0 < Y_p < 0.6$

  J. Holt & N. Kaiser, PRC (2017)

α-RELEASE

- **University of Tennessee in Knoxville (UTK) EoS**
  - Includes nucleonic degrees of freedom based on a phenomenological fit to nuclear experiments & astronomical observations
  - Covers densities from 10^{-12} to 2 fm^{-3}, and $T \rightarrow 100$ MeV

  X. Du, A. Steiner, J. Holt, PRC (2019)

α-RELEASE

Outlooks:
- Extension to strangeness degrees of freedom

USERS

- Observables for heavy-ions
- Observables for neutron stars
- Flavor Equilibration
- Compatibility with existing codes/repositories

OBSERVABLES FOR HEAVY-IONS

- **Susceptibilities & hadronic species contributions**
  - Susceptibilities from lattice QCD will be computable
  - using HRG, one can study the breakdown of different hadron families:
    - we will provide combinations for hadronic contributions to total pressure
    - we will provide analogous relations for susceptibilities

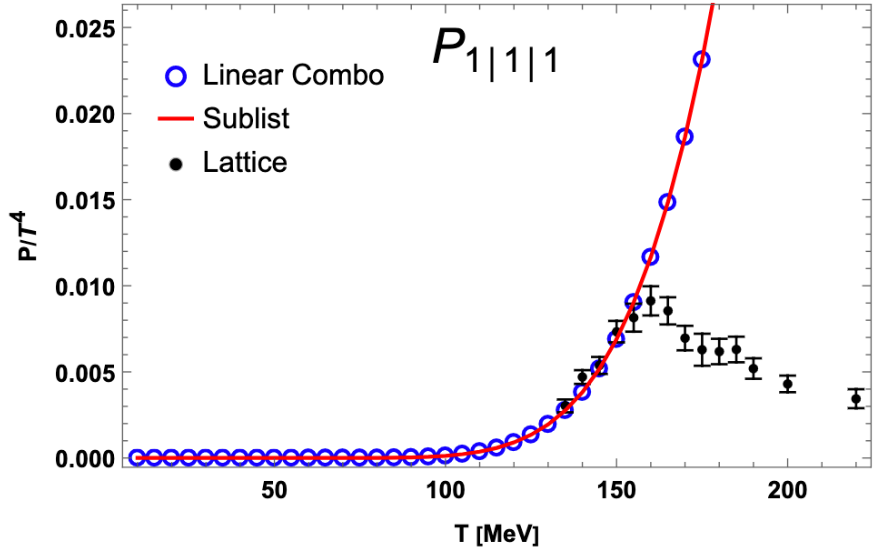


Figure 5.11: $P_{1|1|1} = -\frac{1}{4}\chi_{13}^{SQ} + \frac{1}{4}\chi_{22}^{SQ} - \frac{1}{4}\chi_{112}^{BSQ} + \frac{1}{4}\chi_{121}^{BSQ}$

- **Transport coefficients from Holographic module**
  - Thermal conductivity
  - Baryon conductivity & diffusion
  - Shear & bulk viscosities
  - HQ drag force & Langevin diffusion coefficients
  - Jet quenching parameter

α-RELEASE

- **Freeze-out physics**
  - T and μ_B at chemical freeze-out can be fitted from experimental data with HRG
  - will be incorporated with Thermal-FIST

OBSERVABLES FOR NEUTRONS STARS & MERGERS

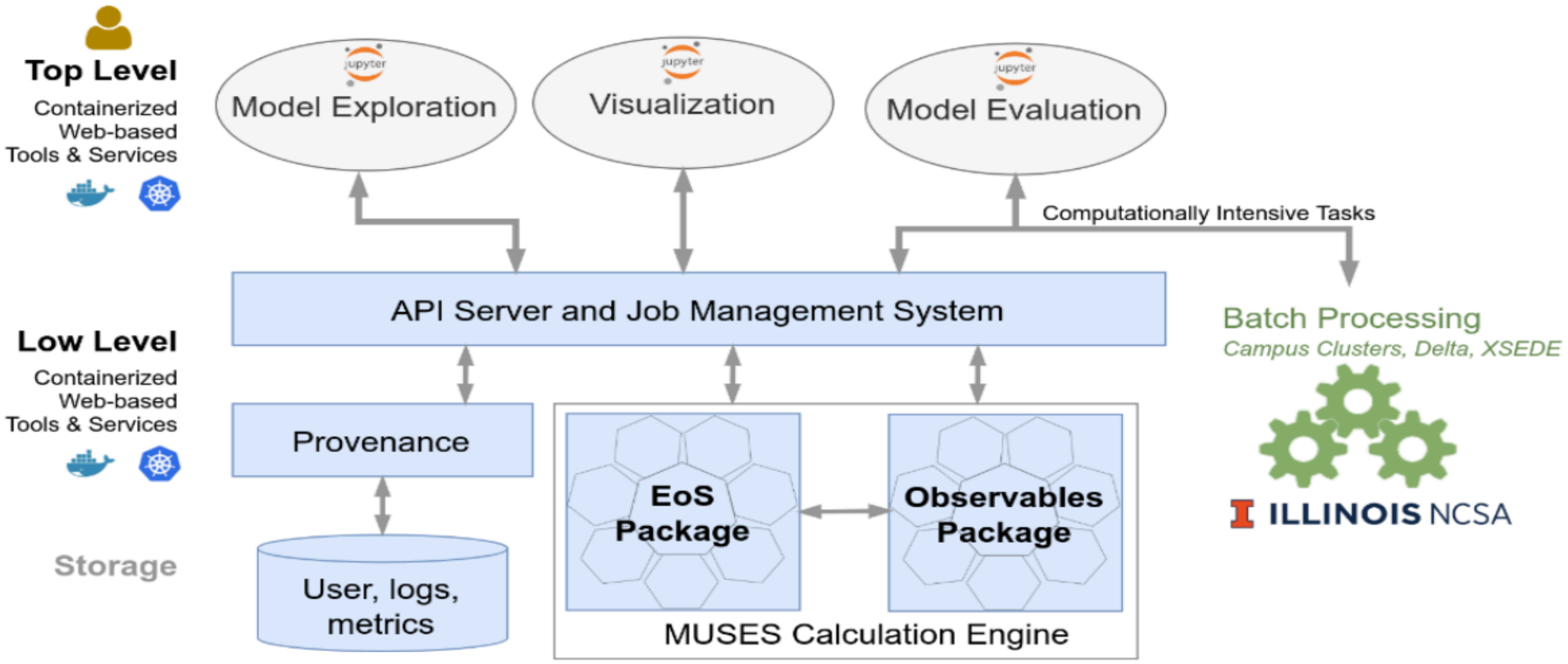
- **QLIMR module**
  - Given an EoS, solves the Tolmann-Oppenheimer-Volkoff (TOV) equations and computes:
    - Q: quadrupole moment Q of NS
    - L: tidal Love number (tidal force deformability)
    - I: moment of inertia
    - M: mass of NS
    - R: radius of NS

α-RELEASE

- **Flavor equilibration**
  - β-equilibrium: $\mu_n - \mu_p - \mu_e = 0$
  - Given an EoS, computes:
    - Urca rates
      ($n \rightarrow p + e + \bar{\nu}_e$ / $p + e \rightarrow n + \nu_e$)
    - Equilibrium charge fractions
    - Relaxation rates
    - Damping time
    - Susceptibilities
    - Bulk viscosity

α-RELEASE

- **Adapter modules for NS & mergers simulation tools**
  - Ensuring compatibility with CompStar Online Supernovae Equations of State (CompOSE), a standard format, with the aim to provide thousands of 1D/2D/3D EoS tables for NS
  - Ensuring compatibility with merger simulations



CYBERINFRASTRUCTURE

CYBERINFRASTRUCTURE BINDS US ALL

- Connect computer scientists and physicists to provide solutions to numerical method challenges
- We need multidimensional EoS interpolators, root-finders, etc.
- Make sure code is compatible with heavy-ion and neutron-star simulations
- We need to learn how to merge different equations of state

- Another important part of the work is to ensure user-friendly interface and usability

We expect soon the first few modules to be deployed!

FIRST MUSES-WIDE PUBLICATION!

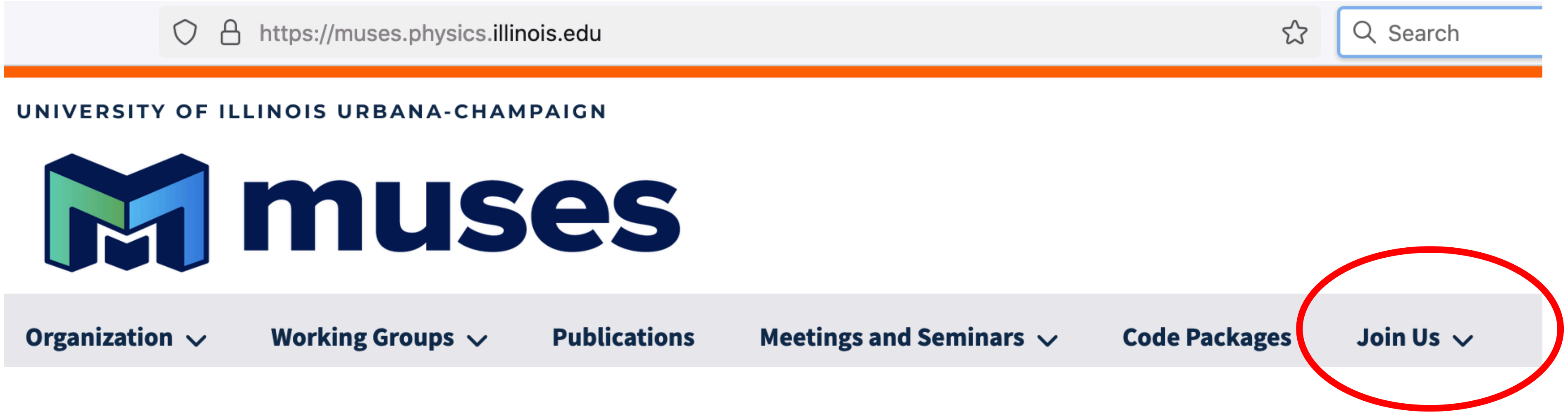
Theoretical and Experimental Constraints for the Equation of State of Dense and Hot Matter

Rajesh Kumar,[1,*] Veronica Dexheimer,[1,†] Johannes Jahan,[2] Jorge Noronha,[3] Jacquelyn Noronha-Hostler,[3] Claudia Ratti,[2] Nico Yunes,[3] Angel Rodrigo Nava Acuna,[2] Mark Alford,[4] Mahmudul Hasan Anik,[5] Katerina Chatziioannou,[6,7] Hsin-Yu Chen,[8,9] Alexander Clevinger,[1] Carlos Conde,[3] Nikolas Cruz Camacho,[3] Travis Dore,[10] Christian Drischler,[11] Hannah Elfner,[12] Reed Essick,[13] David Friedenberg,[14] Suprovo Ghosh,[15] Joaquin Grefa,[2] Roland Haas,[3] Jan Hammelmann,[16] Steven Harris,[17] Carl-Johan Haster,[18,19] Tetsuo Hatsuda,[20] Mauricio Hippert,[3] Renan Hirayama,[16] Jeremy W. Holt,[14] Micheal Kahangirwe,[2] Jamie Karthein,[21] Toru Kojo,[22] Philippe Landry,[23] Zidu Lin,[5] Matthew Luzum,[24] T. Andrew Manning,[3] Jordi Salinas San Martin,[3] Cole Miller,[25] Elias Roland Most,[26,27,28] Debora Mroczek,[3] Azwinndini Muronga,[29] Nicolas Patino,[3] Jeffrey Peterson,[1] Christopher Plumberg,[30] Damien Price,[2] Constanca Providencia,[31] Romulo Rougemont,[32] Satyajit Roy,[5] Hitansh Shah,[2] Stuart Shapiro,[3] Andrew W. Steiner,[5,33] Michael Strickland,[1] Hung Tan,[3] Hajime Togashi,[22] Israel Portillo Vazquez,[2] Pengsheng Wen,[14] and Ziyuan Zhang[4]

(MUSES Collaboration)

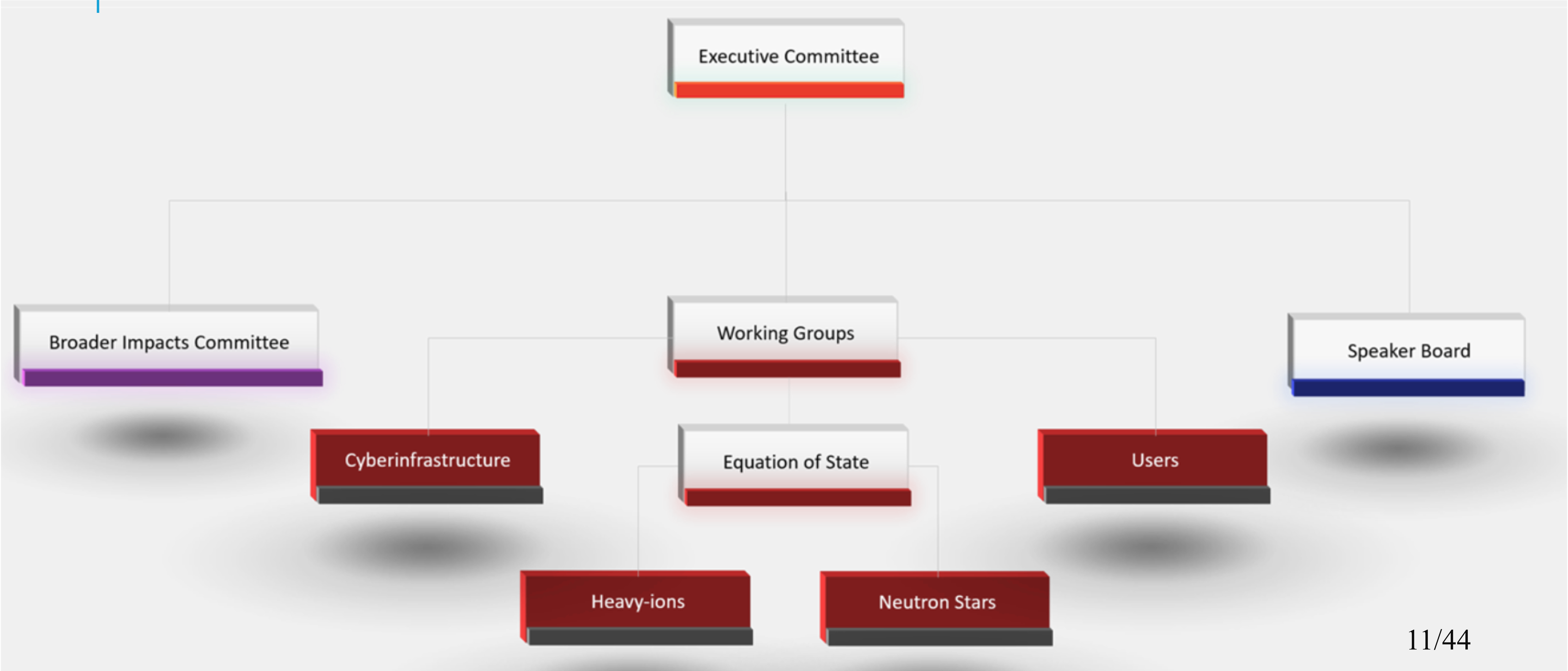
CONCLUSIONS

- MUSES will provide a modular unified solver for the equation of state and calculate observables of relevance for the heavy-ion and astrophysics communities
- We are currently in our third year
- Watch out for the alpha release
- Check out our webpage at https://muses.physics.illinois.edu/
- We welcome new users any time



Backup slides

MUSES ORGANIZATION



NSF CSSI

- Cyberinfrastructure for Sustained Scientific Innovation

“The Cyberinfrastructure for Sustained Scientific Innovation (CSSI) umbrella program seeks to enable funding opportunities that are flexible and responsive to the evolving and emerging needs in cyberinfrastructure.”

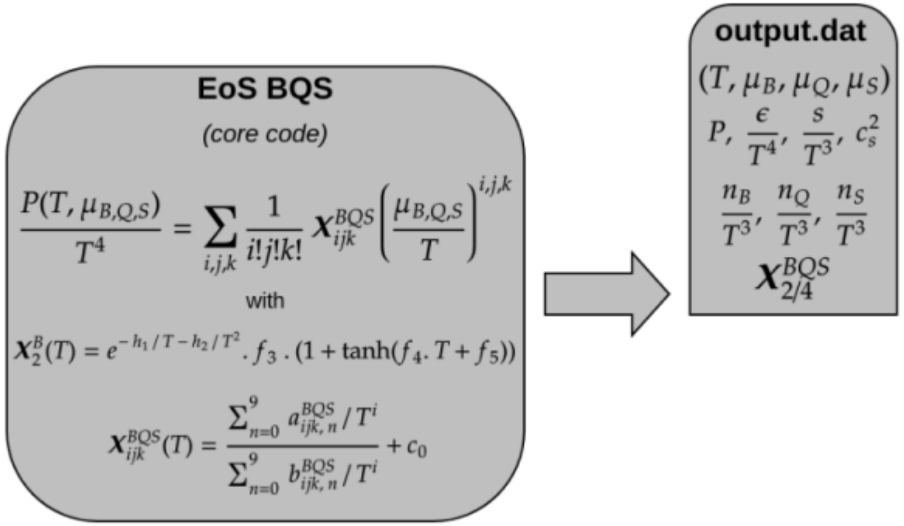
*“**Framework Implementations:** These awards target larger, interdisciplinary teams organized around the development and application of services aimed at solving common research problems faced by NSF researchers in one or more areas of science and engineering, and resulting in a sustainable community framework providing CI services to a diverse community or communities.”*

MODULE - BQS EOS

Developers: Hitansh S. + Johannes J. + Claudia R. (*UH*)

Purpose : provide calculation of a Taylor expanded EoS in 4D (T, μ_B, μ_S, μ_Q) in the ranges $T \in [30,800]$ MeV and $\mu_i \in [0,450]$ MeV

Ratti group:
See talk by Johannes Jahan



J. Noronha-Hostler et al., Phys.Rev.C (2019)

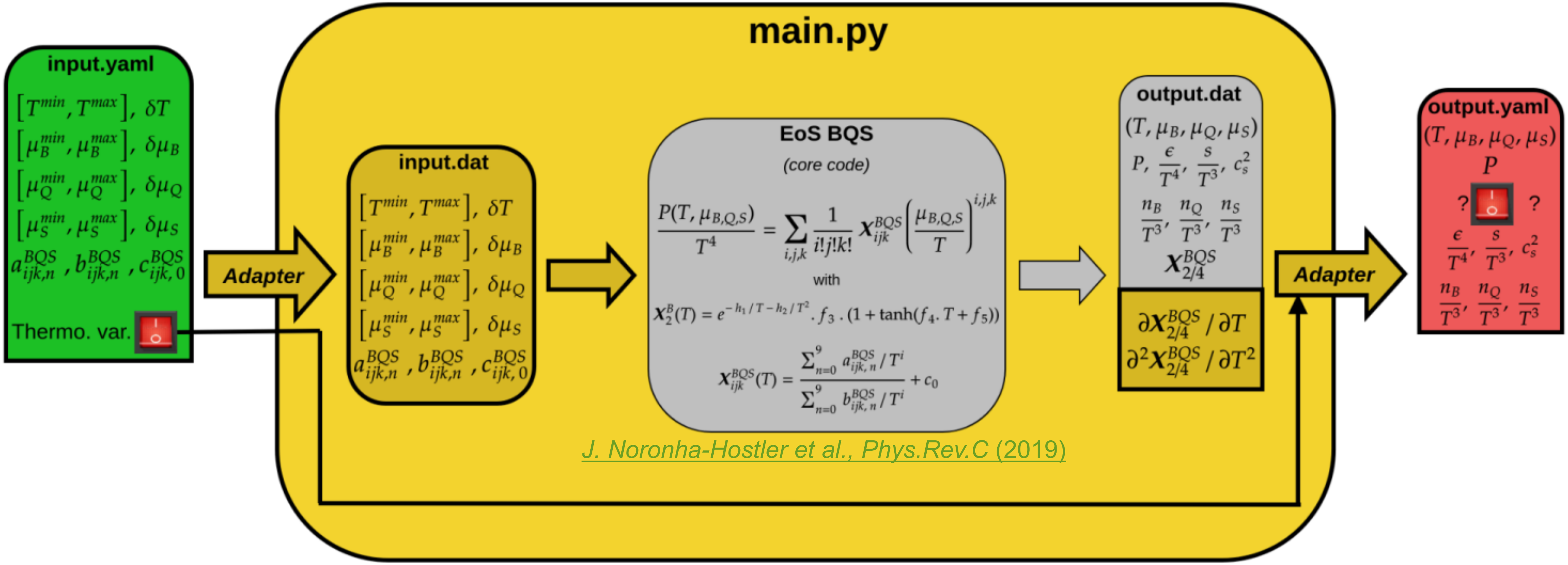
Previous status

MODULE - BQS EOS

Developers: Hitansh S. + Johannes J. + Claudia R. (*UH*)

Purpose : provide calculation of a Taylor expanded EoS in 4D (T, μ_B, μ_S, μ_Q) in the ranges $T \in [30,800]$ MeV and $\mu_i \in [0,450]$ MeV

Ratti group:
See talk by Johannes Jahan



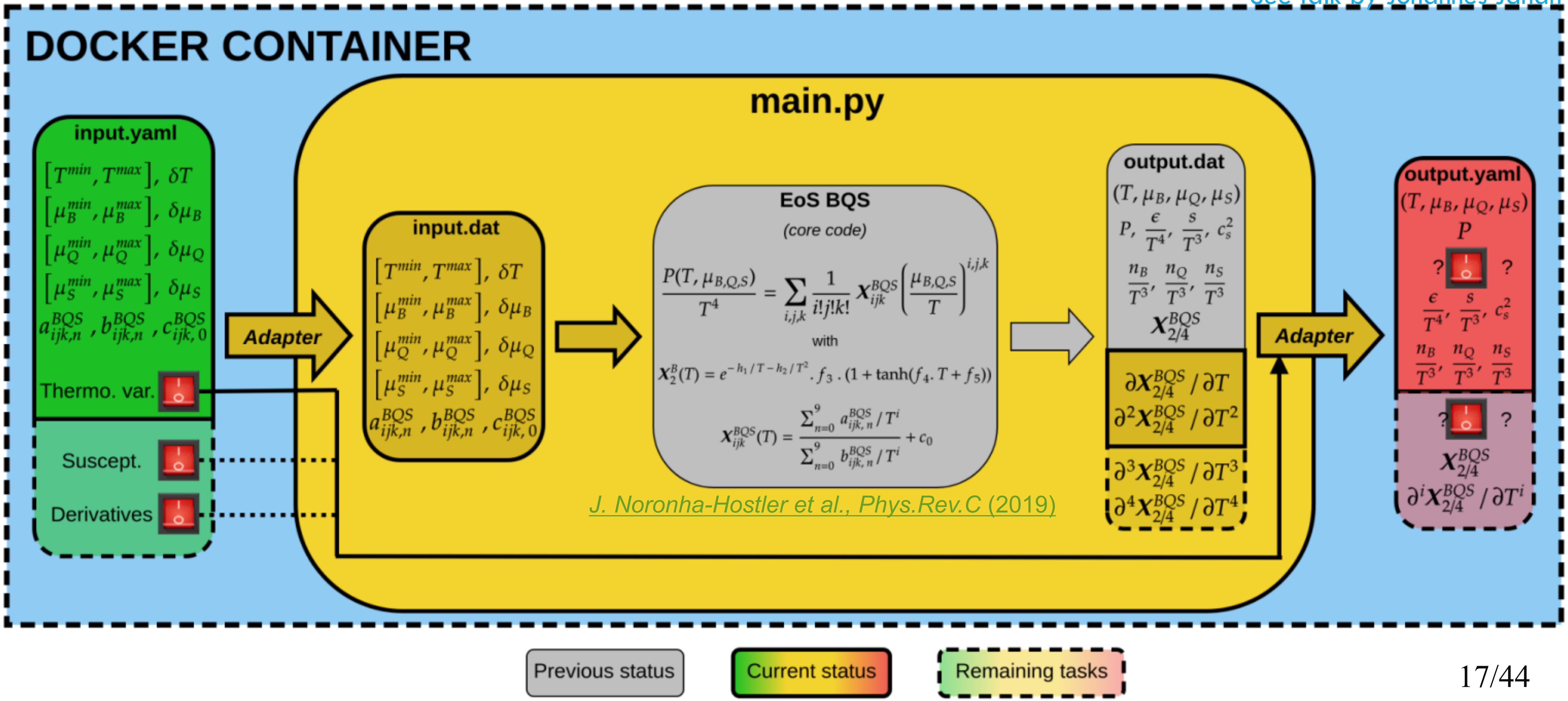
Previous status Current status

MODULE - BQS EOS

Developers: Hitansh S. + Johannes J. + Claudia R. (*UH*)

Purpose : provide calculation of a Taylor expanded EoS in 4D (T, μ_B, μ_S, μ_Q) in the ranges $T \in [30,800]$ MeV and $\mu_i \in [0,450]$ MeV

Ratti group:
See talk by Johannes Jahan



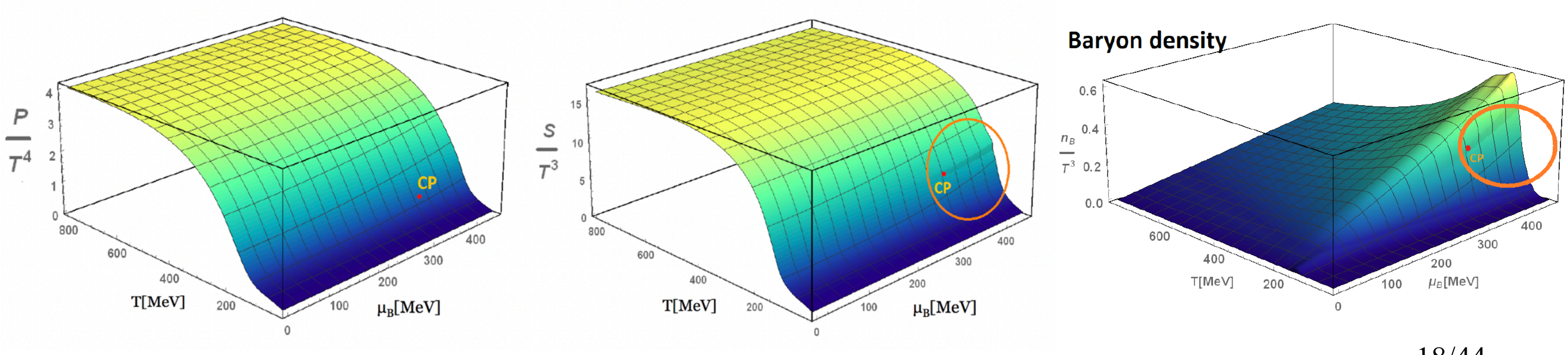
EQUATION OF STATE WITH 3D-ISING CRITICAL POINT (BESEOS)

Range: $0<T<800$ MeV; $\mu_B<450$ MeV

Ratti group:
See talk by Micheal Kahangirwe
P. Parotto, C. R. et al., PRC (2020)
J. Karthein, C. R. et al., EPJ Plus (2021)

- Implement scaling behavior of 3D-Ising model EoS
- Define map from 3D-Ising model to QCD
- Estimate contribution to Taylor coefficients from 3D-Ising model critical point
- Reconstruct full pressure
- Currently available at $\mu_S=\mu_Q=0$ and for $<n_S>=0$, $<n_Q>=0.4<n_B>$

Goals:
- Extension of range in μB
- Extension to three conserved charges
- Incorporation into MUSES



MUSES
EoS
Package
NumRelHolo
Module
Effective
Models

EQUATION OF STATE FROM HOLOGRAPHY (NUMRELHOLO)

J. Grefa, C. R. et al., PRD (2021)

Range: 30 MeV<T<400 MeV; μ_B<1100 MeV

Noronha-Ratti groups:
See talk by Mauricio Hippert

Before MUSES

- Slow Matlab code
- Noisy results
- Filters needed
- No documentation
- Artisanal fit

Current status

- Fast, stable C++ EoS
- Bayesian analysis almost done
- Partial documentation
- Transport coefs. (Matlab)

Purpose

- Optimized C++ code for Holographic EoS
- Transport coefs.
- Inclusion of strangeness and electric charge

To do

- Standardized tests
- Final version of EoS
- CE integration
- C++ transport coefs.
- Strangeness and electric charge

Dexheimer/Noronha-Hostler groups:
See talk by Nicholas Cruz Camacho

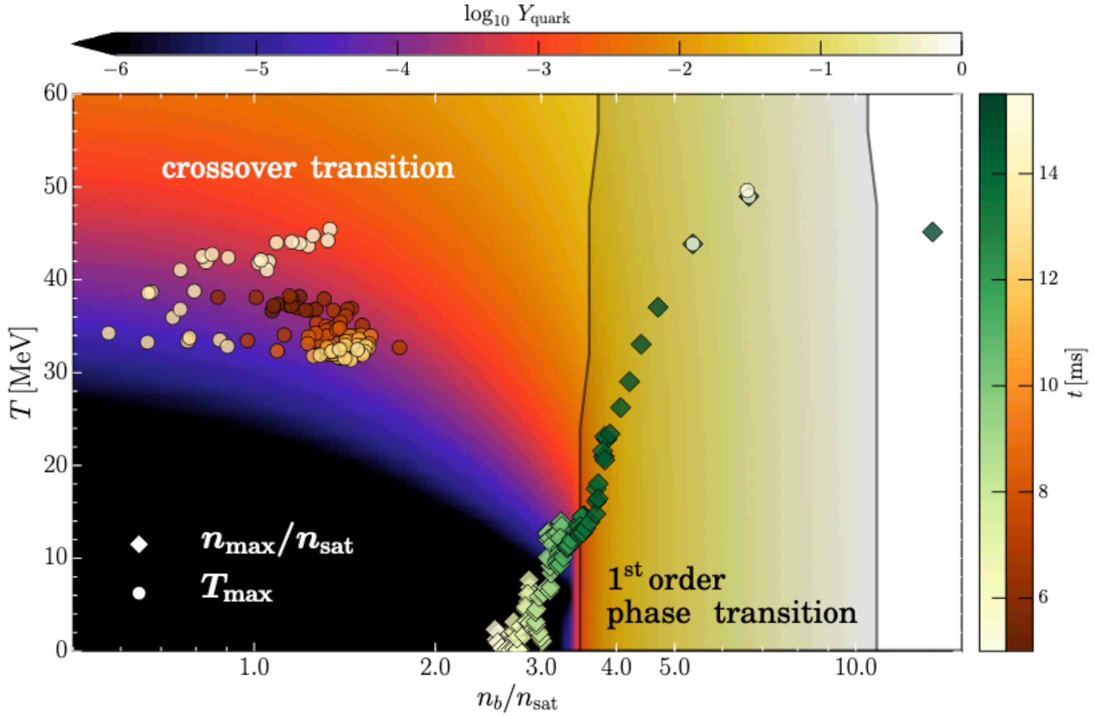
CHIRAL MEAN FIELD MODEL (CMF)

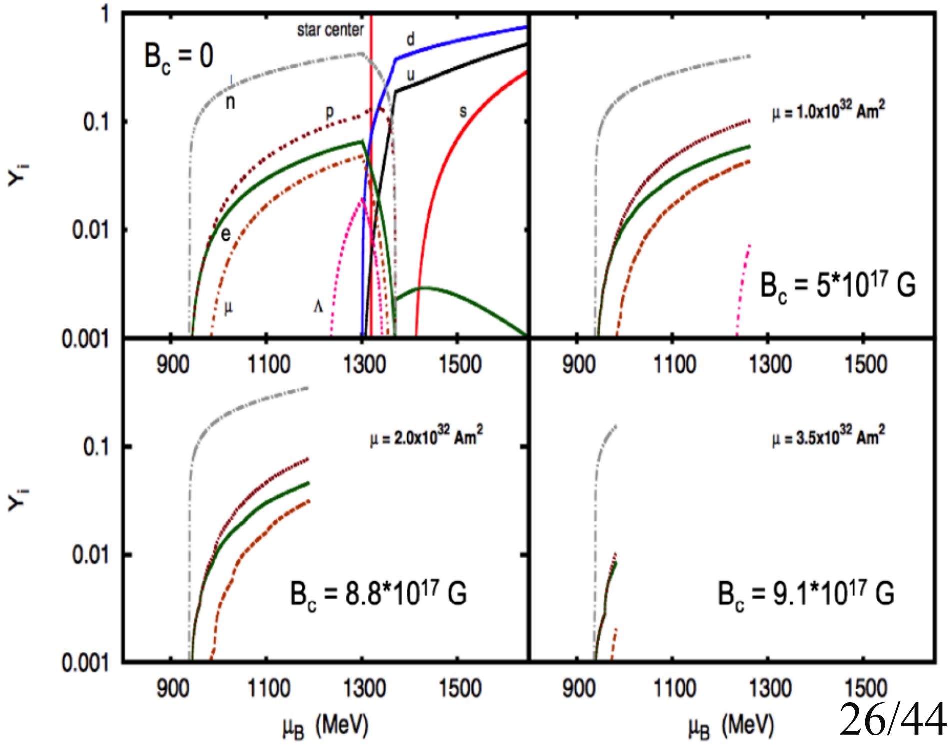
V. Dexheimer, S. Schramm PRC (2009)

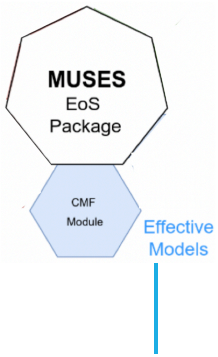
- Crossover at low density and first-order phase transition at high density
- Based on non-linear sigma model with the addition of deconfined quarks
- Reproduces nuclear and astrophysical constraints
- Matches perturbative QCD in the relevant regime

Goals:
- Optimization of the code
- Parameter fit to new lattice data
- Incorporate into MUSES

E. Most, V. Dexheimer et al., PRL (2019)







CMF
CHIRAL MEAN FIELD

Dexheimer/Noronha-Hostler groups:
See talk by Nicholas Cruz Camacho

Purpose

- Create an open-source optimized modular modern C++ code within the MUSES calculation engine to compute multidimensional EoS tables using the CMF model.

Status before MUSES

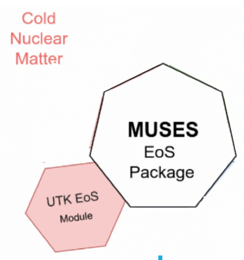
- Fortran 77 proprietary code
- Spaghetti code between non- and magnetic cases, not properly documented
- Antique root solving and integration routines

Current status

- High resolution zero temperature nonmagnetic case that agrees with the previous code for all particles ✓
- Dockerfile available and registered into the calculation engine 0.10.0 ✓
- Offline coupled to QLIMR ✓

Outlook

- Couple to flavor equilibration module Ziyuan Zhang
- Zero temperature magnetic case
- Finite temperature non- and magnetic case
- Add thermal meson interactions
- Introduce normalization that breaks the mass degeneracy between vector mesons Rajesh Kumar

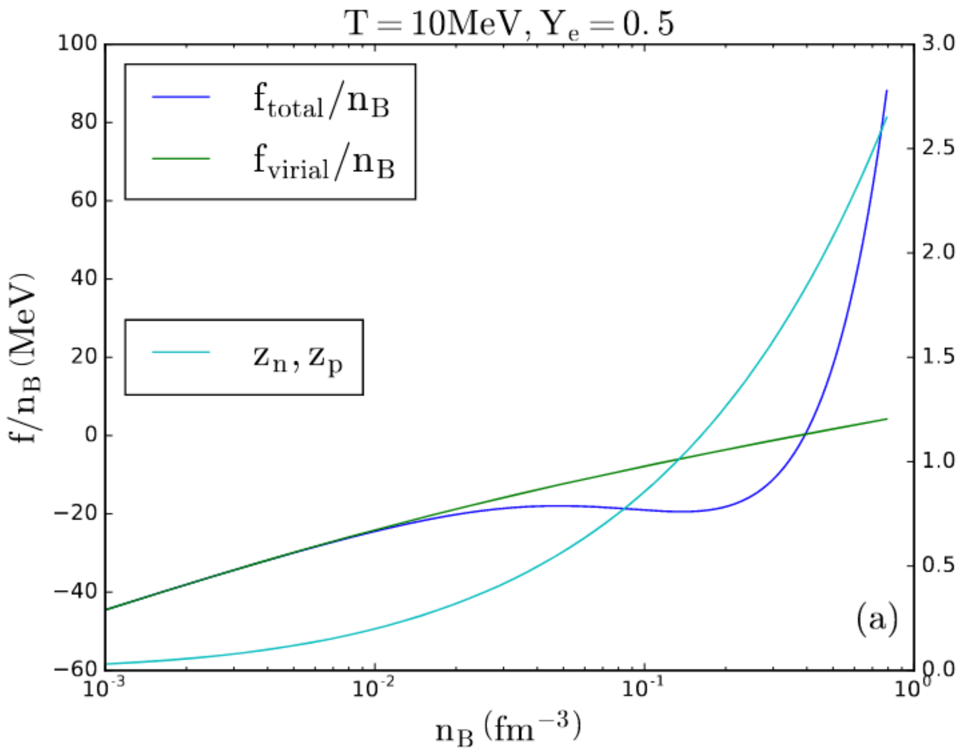


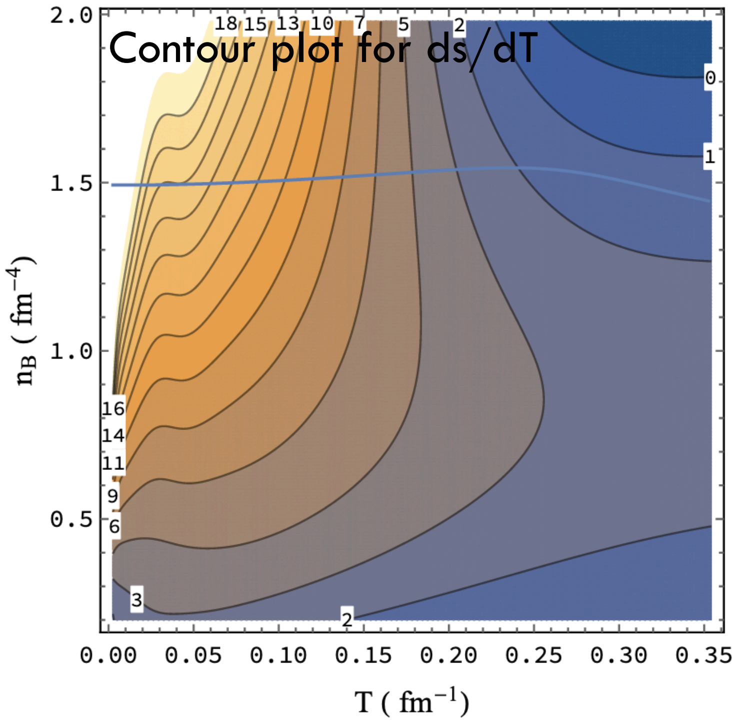
A. Steiner group: See talk by Satyajit Roy

UNIVERSITY OF TENNESSEE KNOXVILLE EOS(UTK EOS)

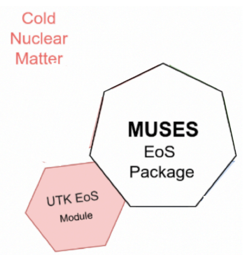
X. Du, A. Steiner, J. Holt, PRC (2019)

- Includes nucleonic degrees of freedom based on a phenomenological fit to nuclear experiment and astronomical observations
- Covers densities from 10^{-12} to 2 fm^{-3} and temperatures up to 100 MeV





Goals:
- Optimization of the code
- Extension to strangeness degrees of freedom
- Incorporate into MUSES



A. Steiner group: See talk by Satyajit Roy

UNIVERSITY OF TENNESSEE KNOXVILLE EOS(UTK EOS)

X. Du, A. Steiner, J. Holt, PRC (2019)

Purpose:

- Include strangeness
- Use machine learning to improve the EOS calculation

Status:

STRANGENESS

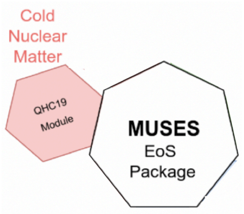
- Built code infrastructure
- Three density regimes: non-degenerate, near saturation (with nuclei), high-density matter
- Non-degenerate strangeness being implemented with hadronic resonances
- Strangeness with nuclei? Some ideas

MACHINE LEARNING

- Working on neural network and Gaussian process interpolators

Outlook:

- Finalize testing of non-degenerate strangeness
- Include pion-nucleon interactions
- Improve EOS for crust
- Implement CMF or NJL for high density
- Slow code: plan to also create tables
- Neutrino opacities



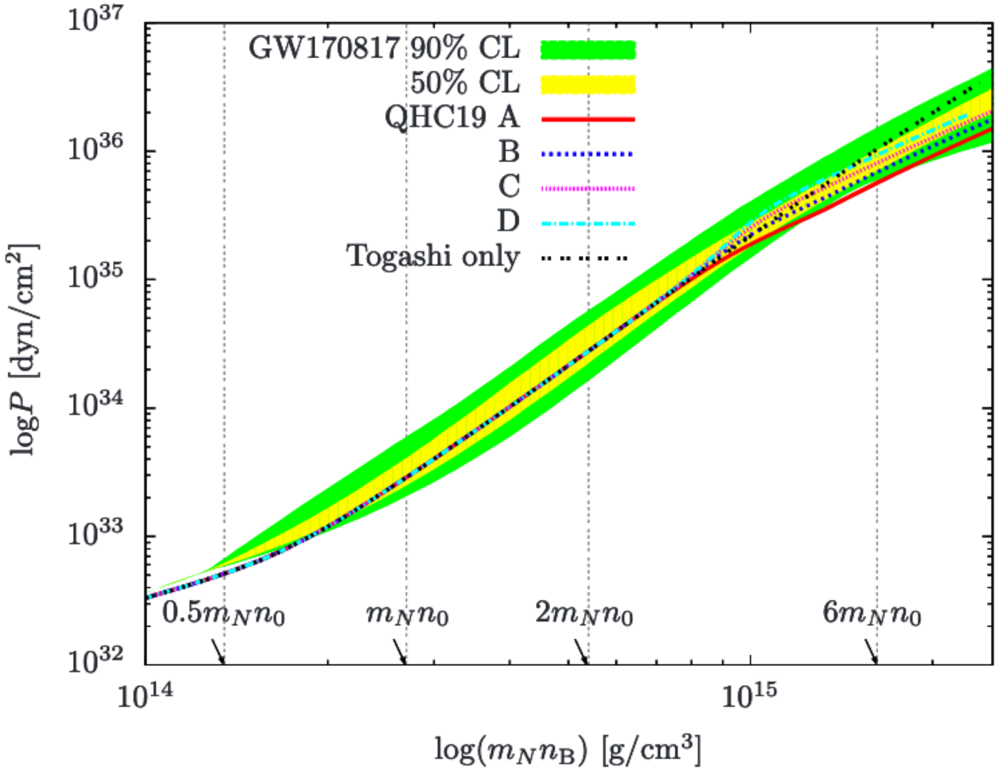
G. Baym/T. Koju groups: See talk by Toru Koju

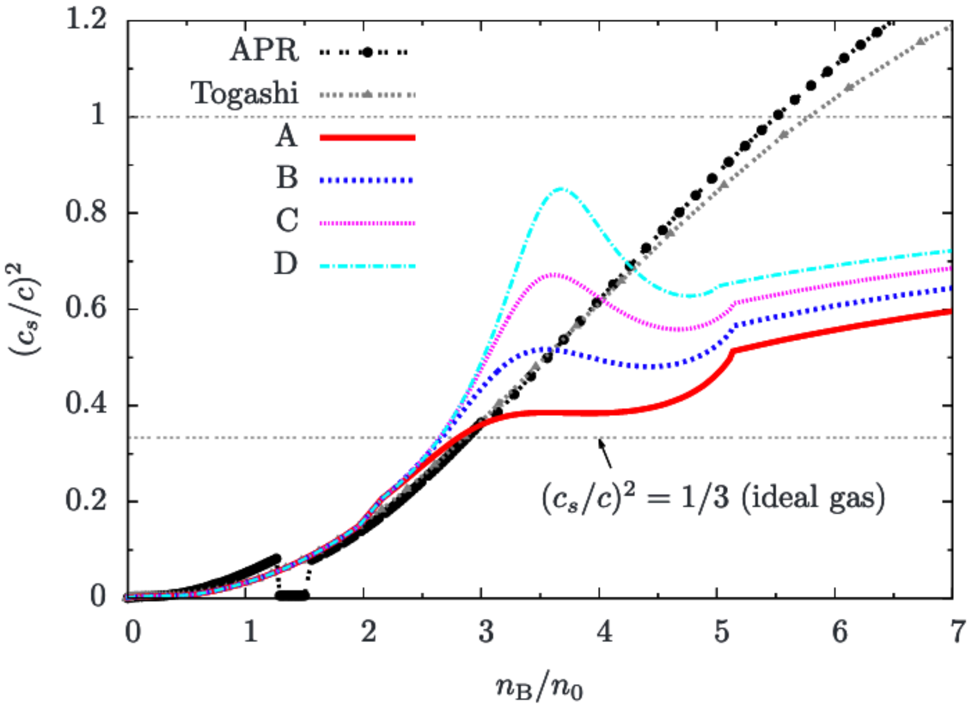
QUARK-HADRON CROSSOVER (QHC19)

G. Baym et al., Astrophys. J (2019)

- Equation of state with smooth crossover between hadrons and quarks
- Hadronic EoS is based on the Togashi model, which describes non-uniform and uniform matter, and beta-equilibrium
- Quark matter is described in the NJL model with vector interaction

Goals:
- Optimization of the code
- Incorporation into MUSES
- Current goal: NJL only





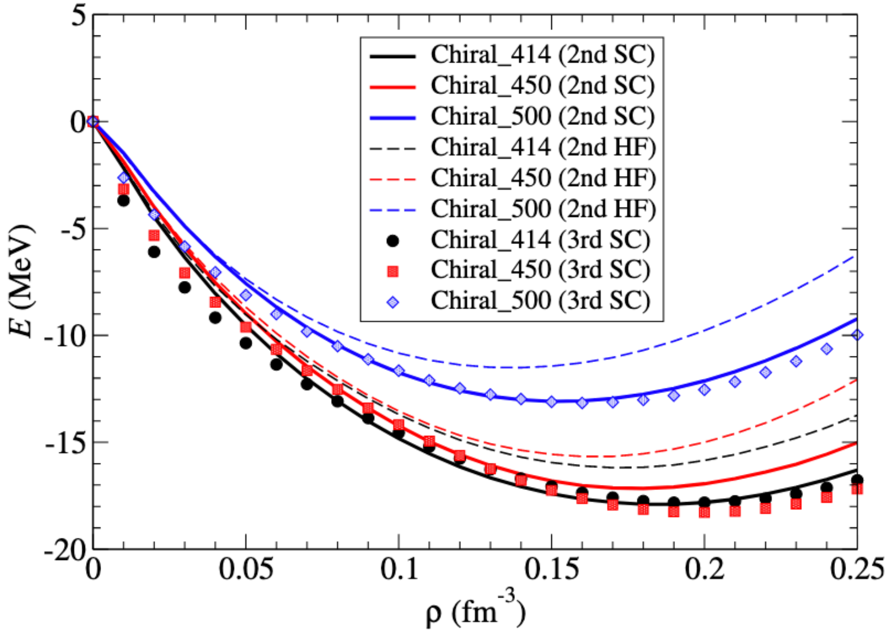
J. Holt group: See talk by David Friedenberg

CHIRAL EFFECTIVE FIELD THEORY (CHEFTEOS)

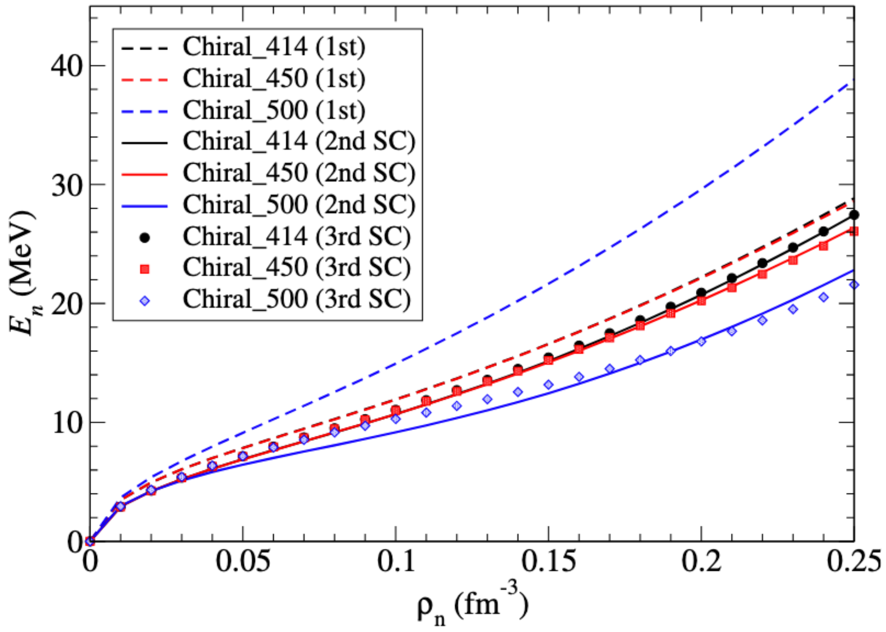
J. Holt & N. Kaiser, PRD (2017)

- Describes matter in the range T<30 MeV, 800 MeV<μ_B<1100 MeV
- Proton fraction: 0<Y_p<0.6
- Interacting nucleons and pions within chiral effective field theory
- Constrains do not exist for asymmetric matter

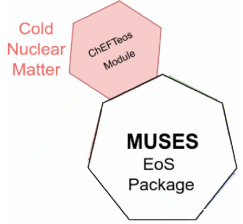
Goals:
- Optimization of the code
- Optimization of root-finding techniques
- Incorporate into MUSES



EoS for symmetric nuclear matter



EoS for neutron matter



J. Holt group: See talk by David Friedenberg

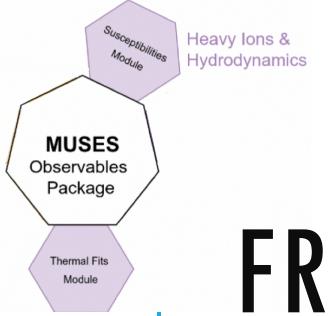
CHIRAL EFFECTIVE FIELD THEORY (CHEFTEOS)

J. Holt & N. Kaiser, PRD (2017)

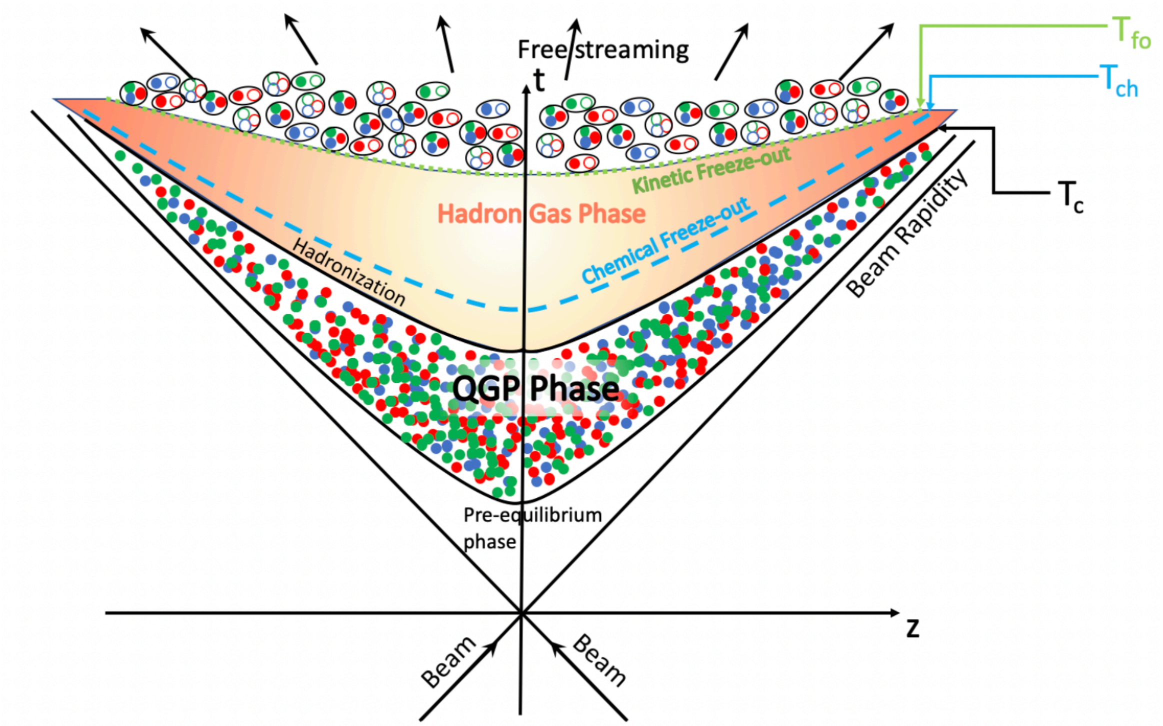
Purpose:
- Calculate first and second order contributions to the free energy at arbitrary density and temperature

Status:
- First order and second order codes
- Calculate free energy and Grand Canonical potential

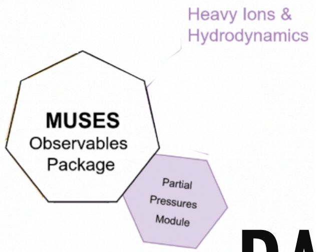
Outlook:
- Interface with MUSES cyberinfrastructure
- Docker container
- Extend phase space into third dimension
- Self-energy corrections to second order



FREEZE-OUT PHYSICS: FLUCTUATIONS & THERMAL FITS



- Chemical freeze-out: inelastic reactions cease: the chemical composition of the system is fixed (particle yields and fluctuations)
- Experimental results are available for these observables
- By fitting them with the HRG model, we can obtain the temperature and chemical potential of the chemical freeze-out
- Thermal FIST already does this
- Goal: incorporate it into MUSES engine



C. Ratti group: See talk by Angel Nava

PARTIAL PRESSURES

- Lattice QCD calculates full pressure
- There is no way of identifying the degrees of freedom that produced it
- We want to find a way of isolating the contribution of family of hadrons, grouped according to their quantum numbers
- Exploit the functional form of the HRG model EOS
- Build the partial pressures as linear combinations of susceptibilities
- There are 13 such partial pressures
- Goal: needs to be discussed

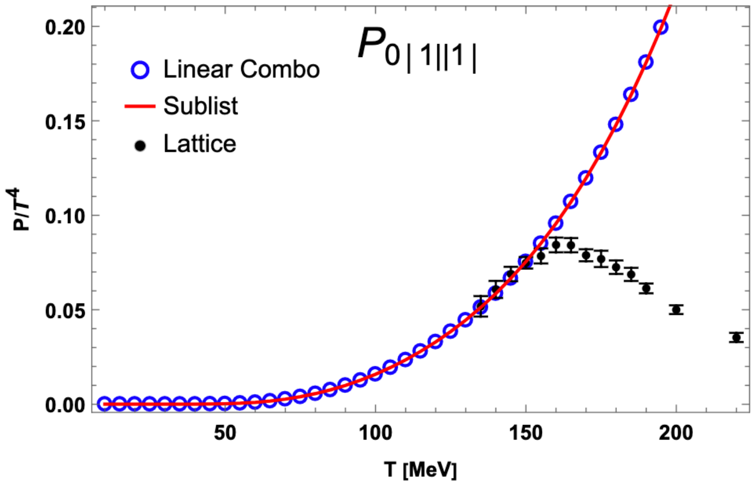


Figure 5.6: $P_{0|1||1|} = \frac{1}{8}\chi_2^Q - \frac{1}{8}\chi_4^Q + \frac{1}{3}\chi_{13}^{SQ} - \frac{1}{12}\chi_2^S + \chi_{22}^{SQ} - \frac{1}{3}\chi_{31}^{SQ} + \frac{1}{12}\chi_4^S + \frac{1}{4}\chi_{13}^{BQ} + \chi_{112}^{BSQ} + \frac{1}{6}\chi_{13}^{BS} - \frac{1}{4}\chi_{31}^{BQ} - \frac{1}{6}\chi_{31}^{BS}$

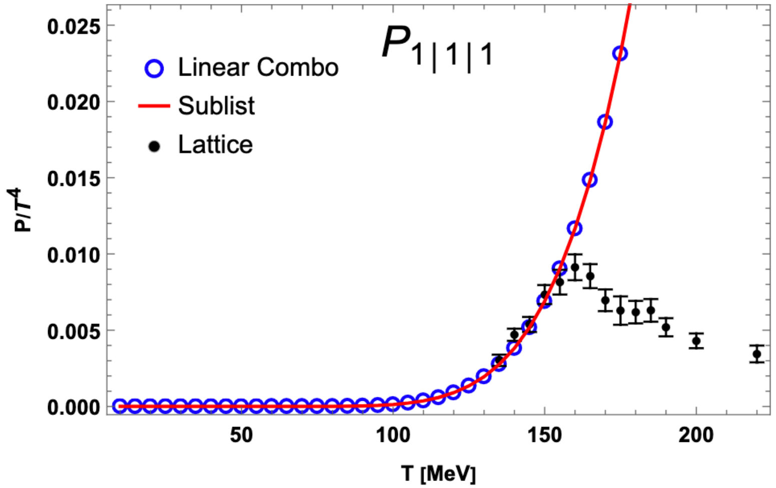
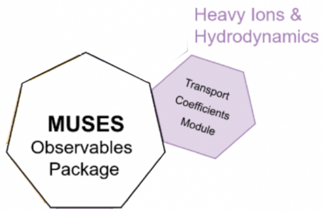


Figure 5.11: $P_{1|1|1} = -\frac{1}{4}\chi_{13}^{SQ} + \frac{1}{4}\chi_{22}^{SQ} - \frac{1}{4}\chi_{112}^{BSQ} + \frac{1}{4}\chi_{121}^{BSQ}$



Ratti/Noronha groups: J. Grefa et al., PRD (2022)

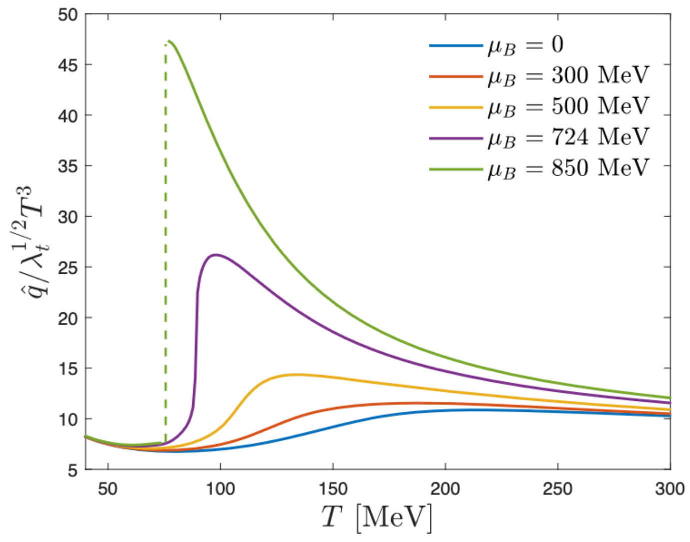
TRANSPORT COEFFICIENTS

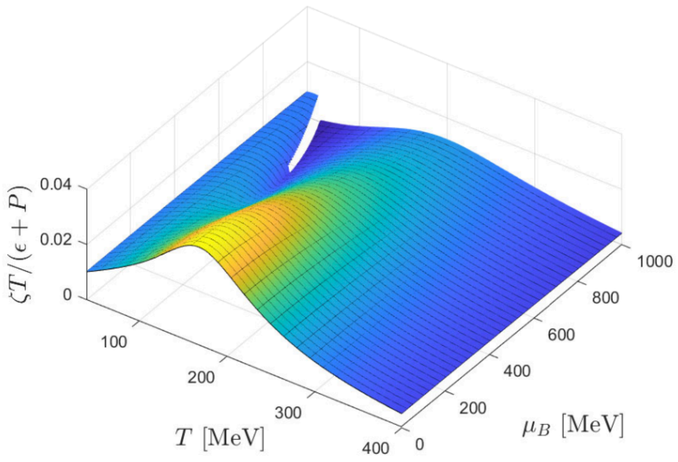
- Calculated in the holographic model

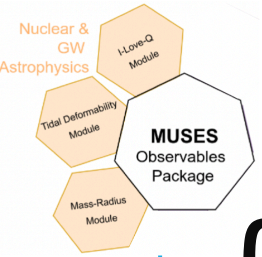
- Provide the following:
  - Baryon conductivity & diffusion
  - Thermal conductivity
  - Heavy quark drag force & Langevin diffusion coefficients
  - Jet quenching parameter
  - Shear viscosity
  - Bulk viscosity

- Status: we published the coefficients

- Need to start working on the code







N. Yunes group: See talk by Carlos Conde Ocazionez

QLIMR MODULE

Purpose

Given a barotropic EoS table, the main purpose of this module is to compute the radius $R_\star$, the mass $M_\star$, the moment of inertia I, the tidal Love number λ and the quadrupole moment Q of a NS for a given set of central energy densities ε_c.

Status before MUSES

A Mathematica code was developed by Hung Tan which achieves the main purpose of this module. It also contains additional functions to compute binary love relations.

Current status

- Computes $R_\star$, $M_\star$, I and λ using `.yaml` files and python adaptors for I/O data.
- Works effectively in docker.
- Locally running using CMF module EoSs.

What remains to be done

- Finish code parallelization.
- Solve $l = 0$ equations at $\mathcal{O}(\Omega^2)$.
- Output all local functions as `.csv` files.
- Integrate into calculation engine.
- Compute Q and binary Love relations.

M. Alford group: See talk by Ziyuan Zhang

FLAVOR EQUILIBRATION

Purpose:

- Provide code to calculate Urca rates and related dense matter properties

Status:

- Completed Python code that can calculate Urca rates, equilibrium charge fraction, relaxation rates, susceptibilities, bulk viscosity, damping time.
- Containerized the module using Docker. Working on integration to the calculation engine.
- Writing a paper on flavor equilibration using the module code.
- Investigated Gaussian process regression as a better interpolator.

Outlook:

- Possible expansions of the functionality. (npeμ matter, neutrino-trapped regime, Urca rates with arbitrary neutrino distribution function, etc.)
- Possible usage of Gaussian process interpolation for MUSES

COMPATIBILITY WITH COMPOSE

- CompStar Online Supernovae Equations of State
  https://compose.obspm.fr
- Provides hundreds of 1D, 2D and 3D EoS tables in a common format for astrophysical applications
- The goal is to make MUSES compatible with CompOSE standard files
- Work on this will begin summer 2023, starting with the CMF and lepton modules.

COUPLING TO NUMERICAL RELATIVITY

- Start date: Late 2023 – 2024
- Goals:
  - Ensure MUSES can be used in neutron star merger simulations
  - Various formats and table sampling
  - Ensure sufficient performance (interpolation!)
  - Initial exploration of impact of nuclear parameters

- Related work:
  - First simulation of effective bulk viscosity in mergers (with Alford, Haber, Harris, Noronha, Zhang)
  - Exploration of nuclear symmetry energy (with Raithel / not MUSES)

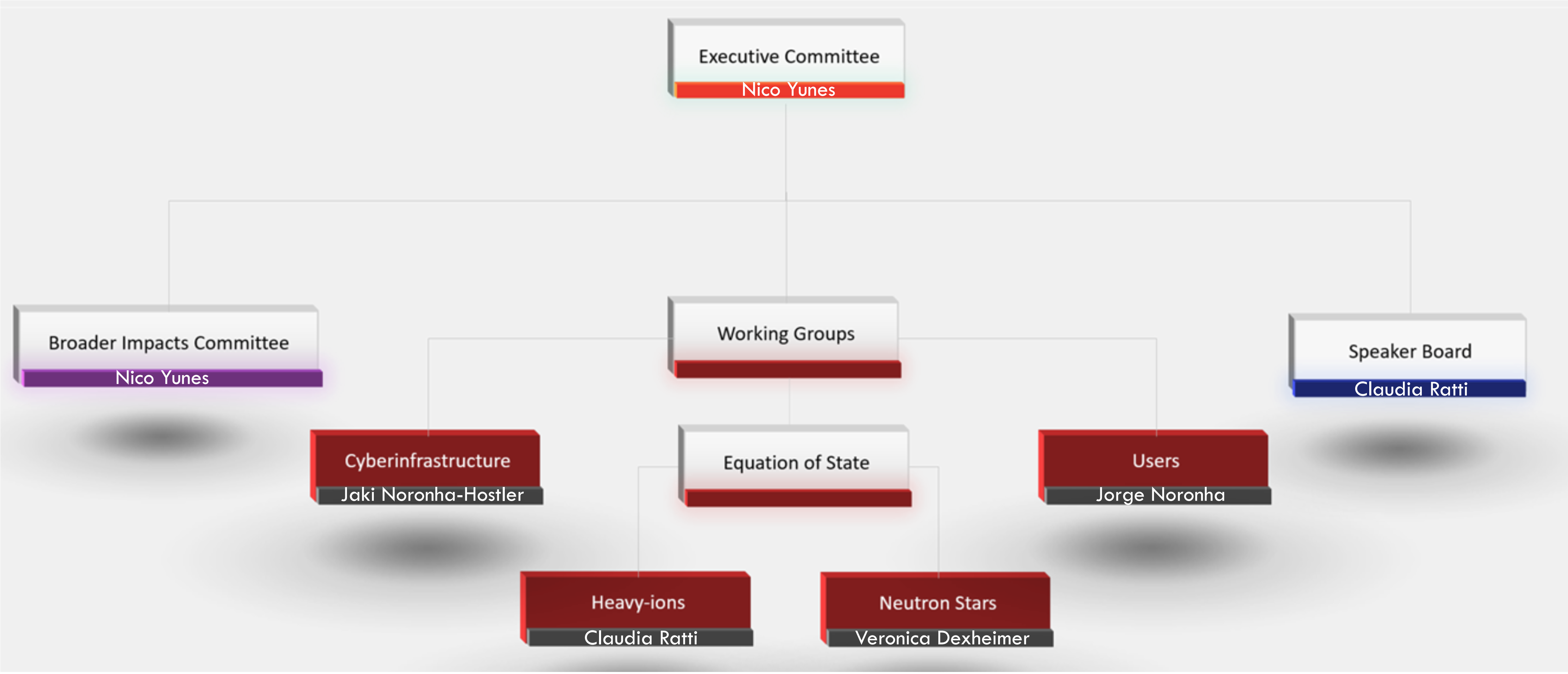
COMMUNITY-DRIVEN

- *We held a workshop "From heavy-ion collisions to neutron stars" in August 2020*

COMMUNITY-DRIVEN

- *We held a workshop "From heavy-ion collisions to neutron stars" in August 2020*
- *~100 registered participants from heavy-ion and neutron-star communities*
- *Talks + panel discussions on what is really needed to move forward*
  - *Realistic, flexible equation of state in which the users can pick and choose different options (degrees of freedom, first-order vs smooth crossover, exotic quark flavors, values of electric charge and strangeness chemical potentials…)*

ORGANIZATION



BROADER IMPACT COMMITTEE

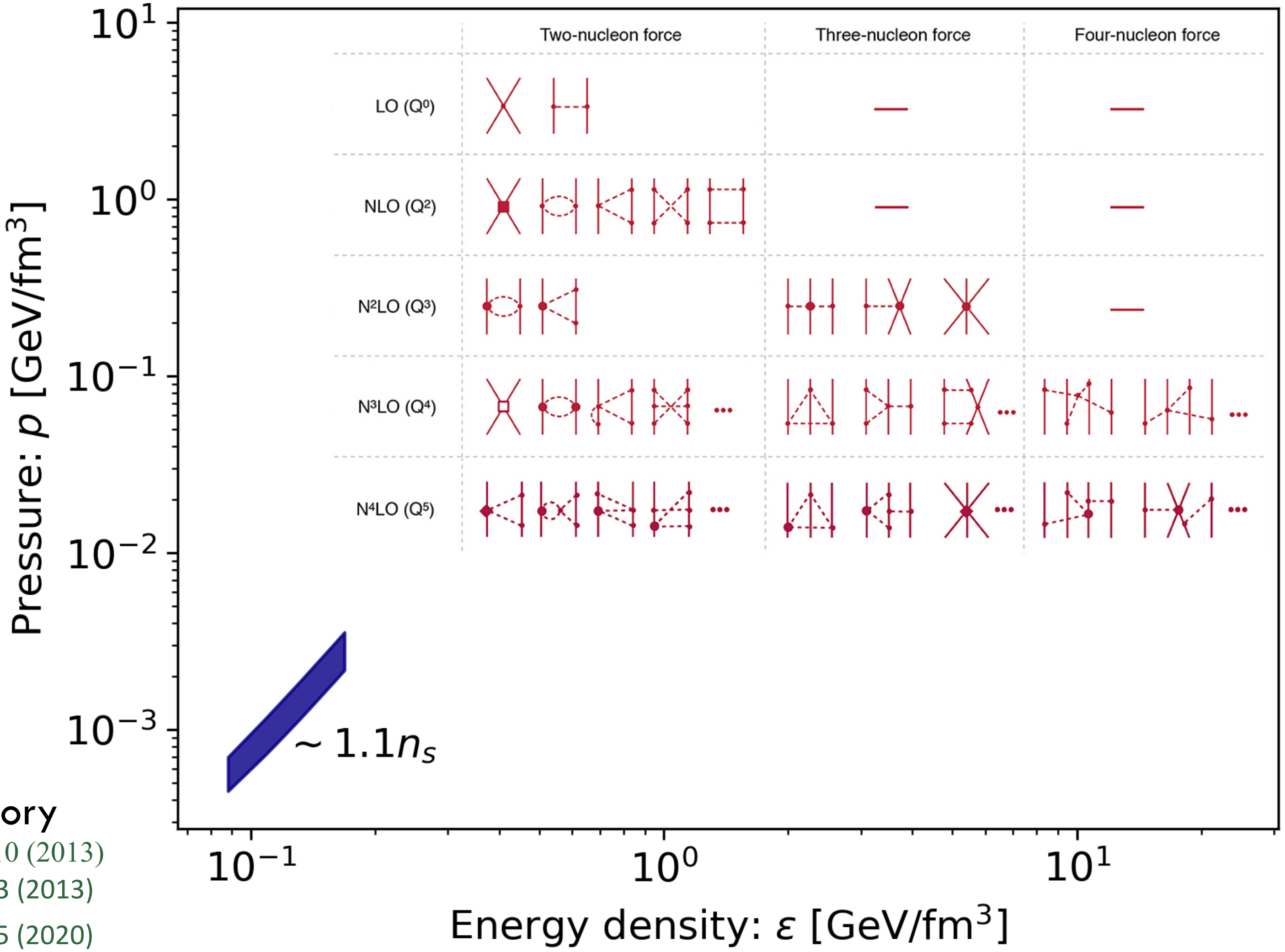
- Seminar series
- Schools
- Hybrid workshops
- Tutorial system
- Diversity

BROADER IMPACT

- Annual workshop that combines a training camp and a professional think tank
  - Students and postdocs have the possibility to establish collaborations with more senior scientists
- Bi-weekly seminar series on MUSES-related topics (suggest speakers to Mauricio Hippert Jamie Karthein, Joaquin Grefa, Hung Tan, Peter Jeffery)
- Tutorial: Web-based teaching system to provide the community with a self-learning tool
- Diversity: recruitment, support, training of underrepresented students and postdocs (REU, CuWiP, UH); creation of a multi-lingual “for the public” section on the webpage

NEUTRON STARS AND MERGERS



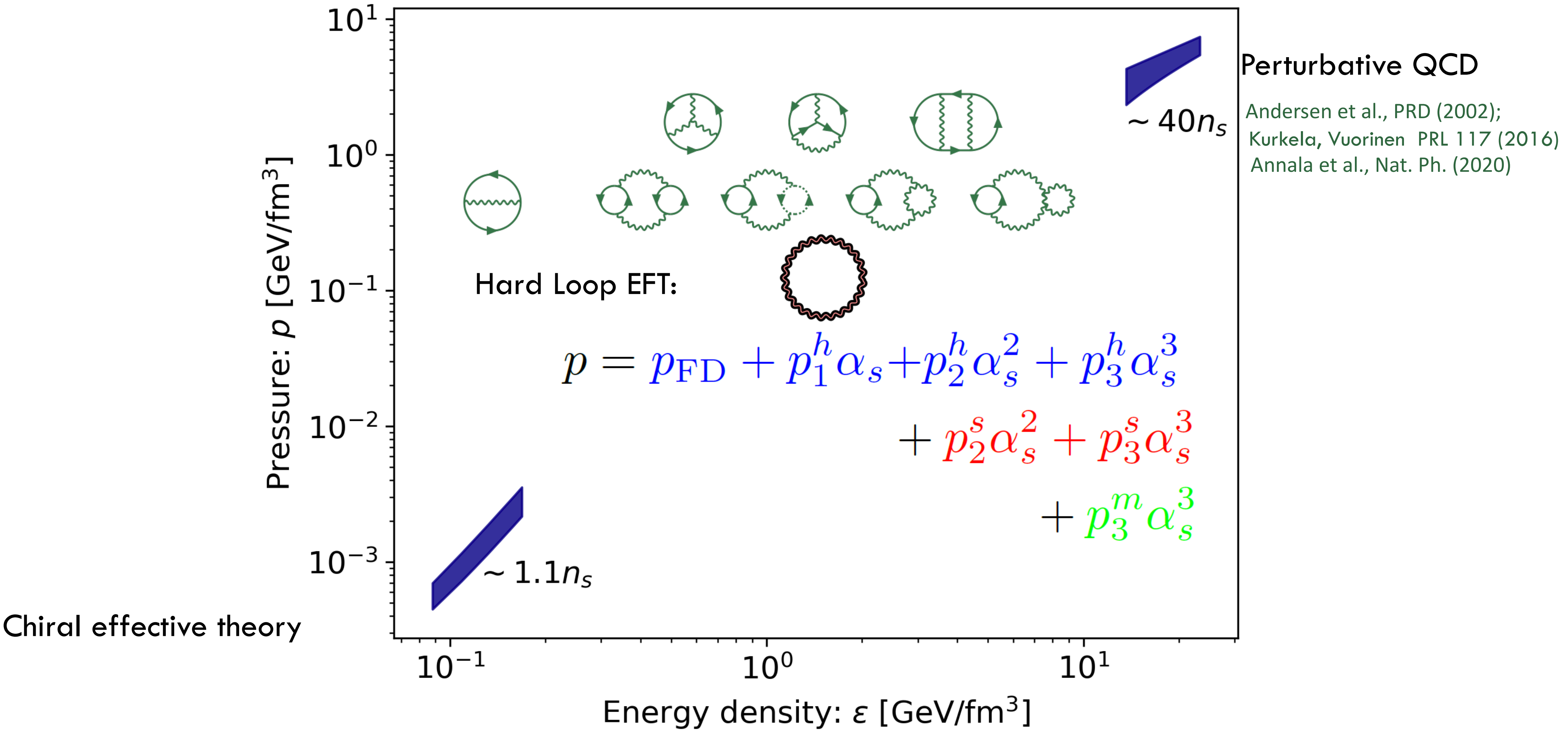
Chiral effective theory

Tews et al. PRL 110 (2013)

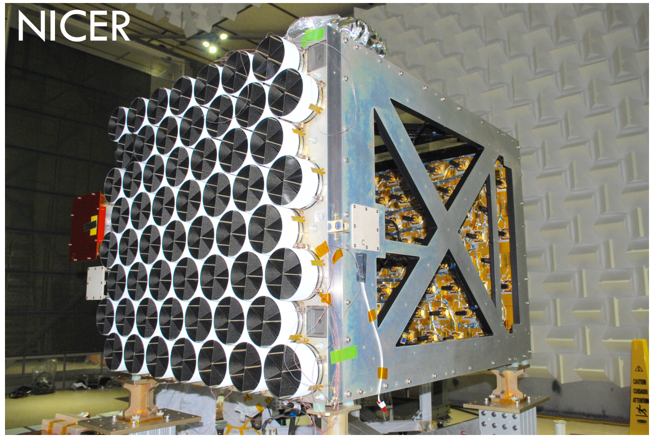
Hebeler, Lattimer et.al. APJ 773 (2013)

Drischler, Furnstahl et.al. PRL 125 (2020)

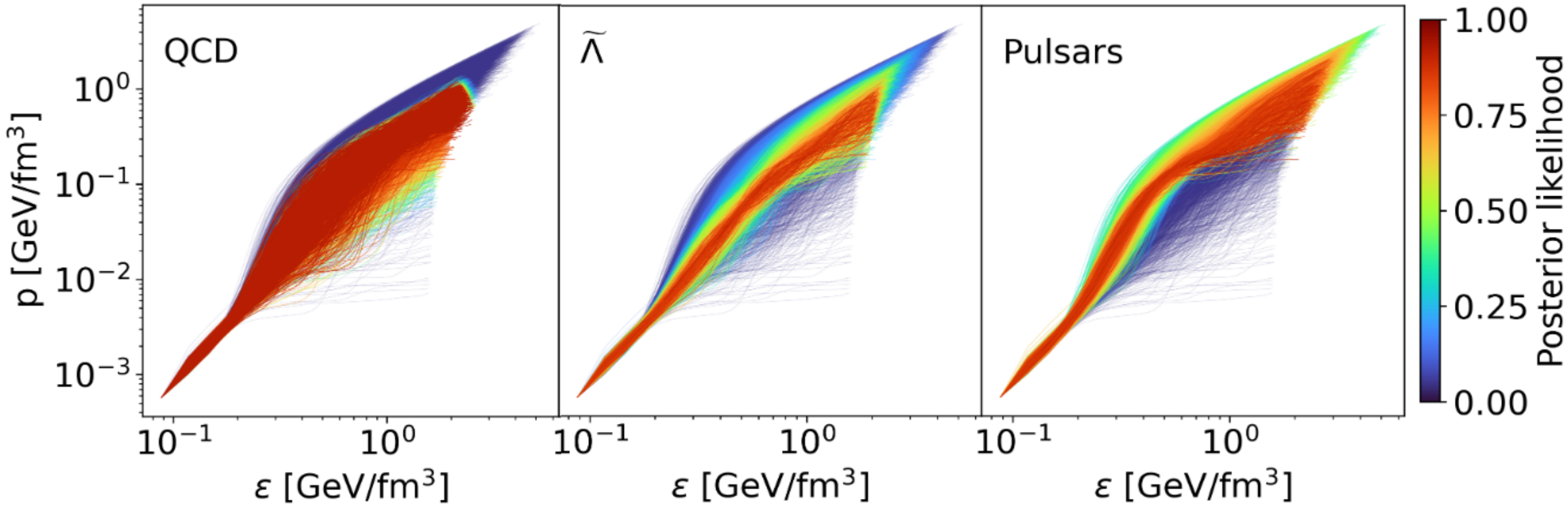
NEUTRON STARS AND MERGERS



NEUTRON STARS AND MERGERS



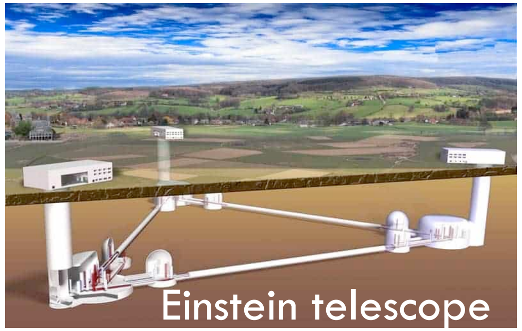
QCD input and NS observations can constrain the interpolation

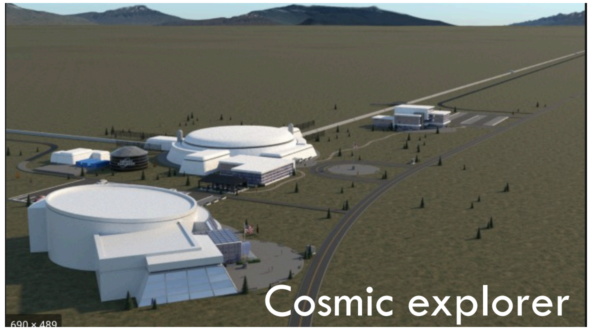


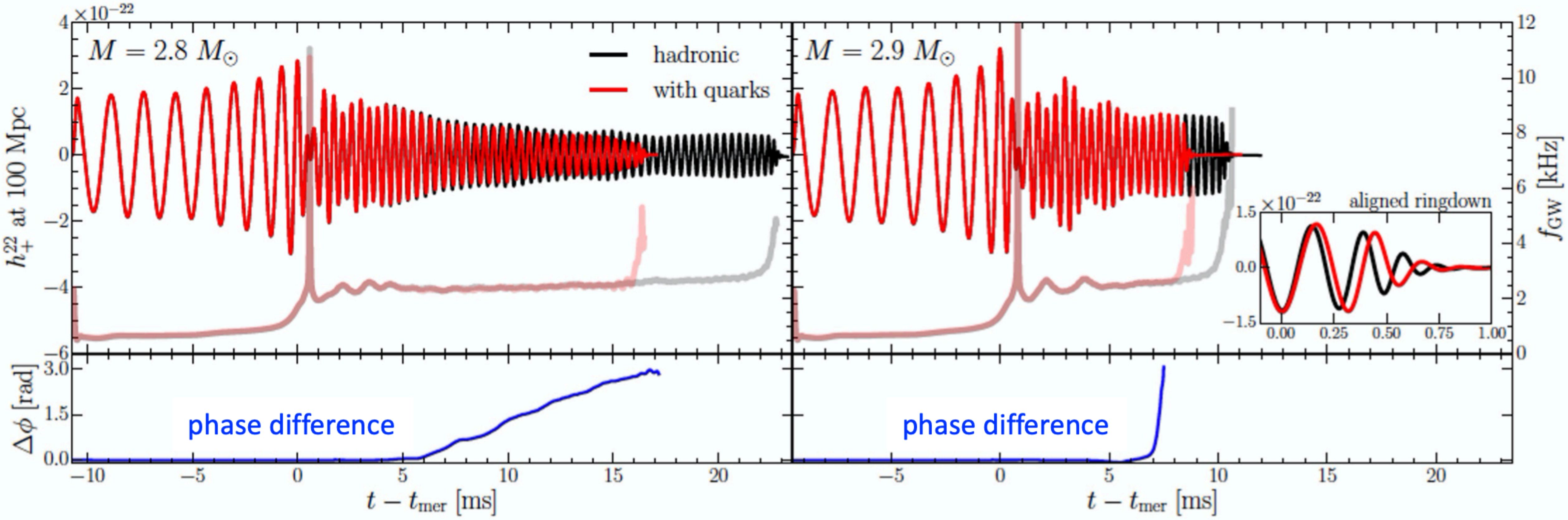
Slide adapted from talk by A. Kurkela

NEUTRON STARS AND MERGERS

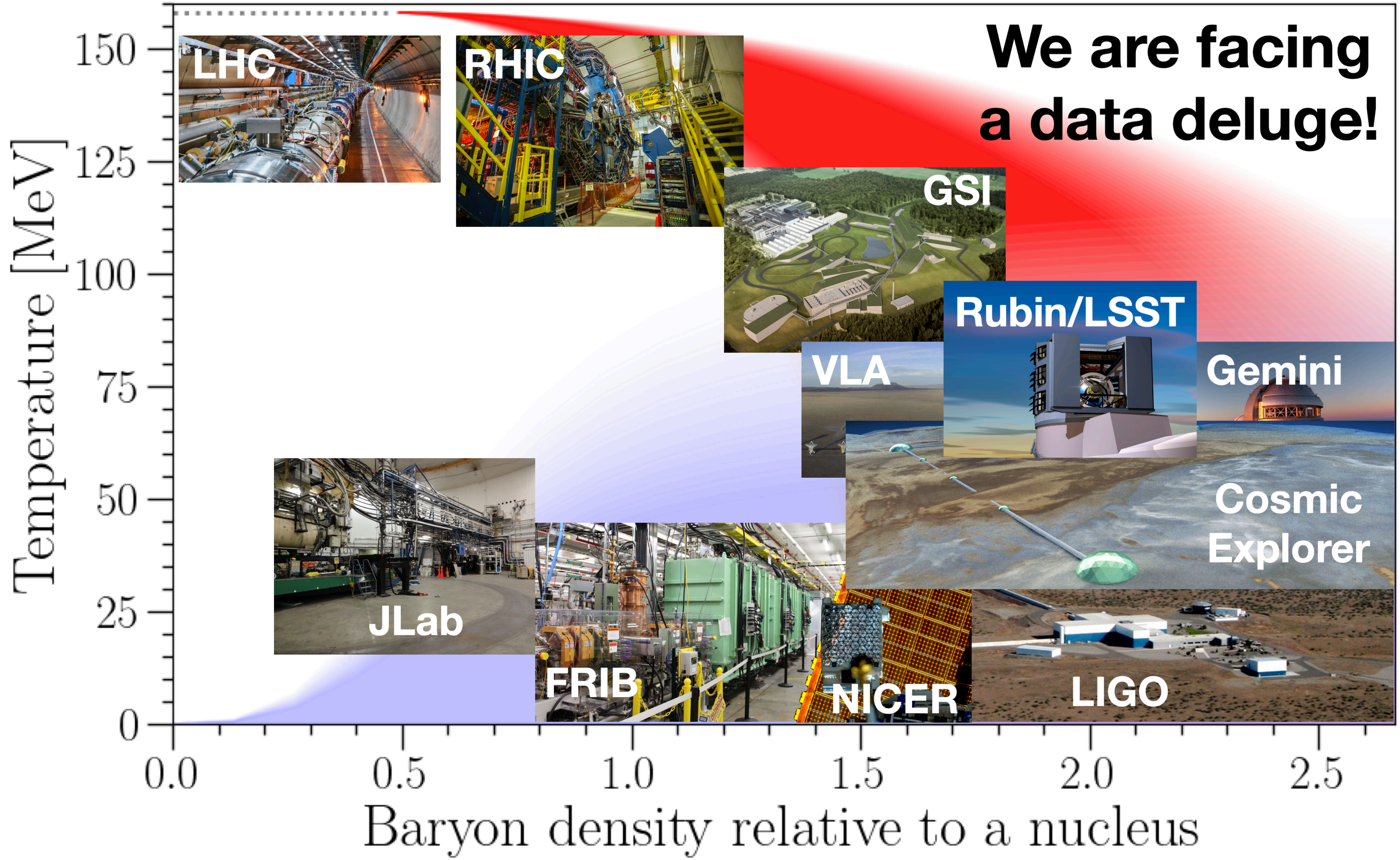
- Post-merger signal sensitive to order of the phase transition
- Next generation observatories will be able to detect it!
- Need to combine the nuclear physics input and simulations







E. Most et al., PRL (2019)



We are facing
a data deluge!
LHC
RHIC
GSI
Rubin/LSST
VLA
Gemini
Cosmic
Explorer
JLab
FRIB
NICER
LIGO
Temperature [MeV]
150
125
100
75
50
25
0
0.0
0.5
1.0
1.5
2.0
2.5
Baryon density relative to a nucleus

x

muses




EQUATIONS OF STATE

- Chiral mean field model — V. Dexheimer, S. Schramm PRC (2009)
  - Crossover at low density and first-order phase transition at high density
  - Based on non-linear sigma model with the addition of deconfined quarks
- Quark-Hadron Crossover (QHC19) — G. Baym et al., Astrophys. J (2019)
  - Smooth crossover between hadrons and quarks
- UTK Equation of state — X. Du, A. Steiner, J. Holt, PRC (2019)
  - Includes nucleonic degrees of freedom based on a phenomenological fit to nuclear experiment and astronomical observations
- Chiral effective field theory — J. Holt & N. Kaiser, PRD (2017)
  - Interacting nucleons and pions within chiral effective field theory

WEBPAGES

- Static webpage
- Computational tools
- Forum
- More resources (JupyterHub, Community chat, Collaborative documents, Collaboration Cloud storage)



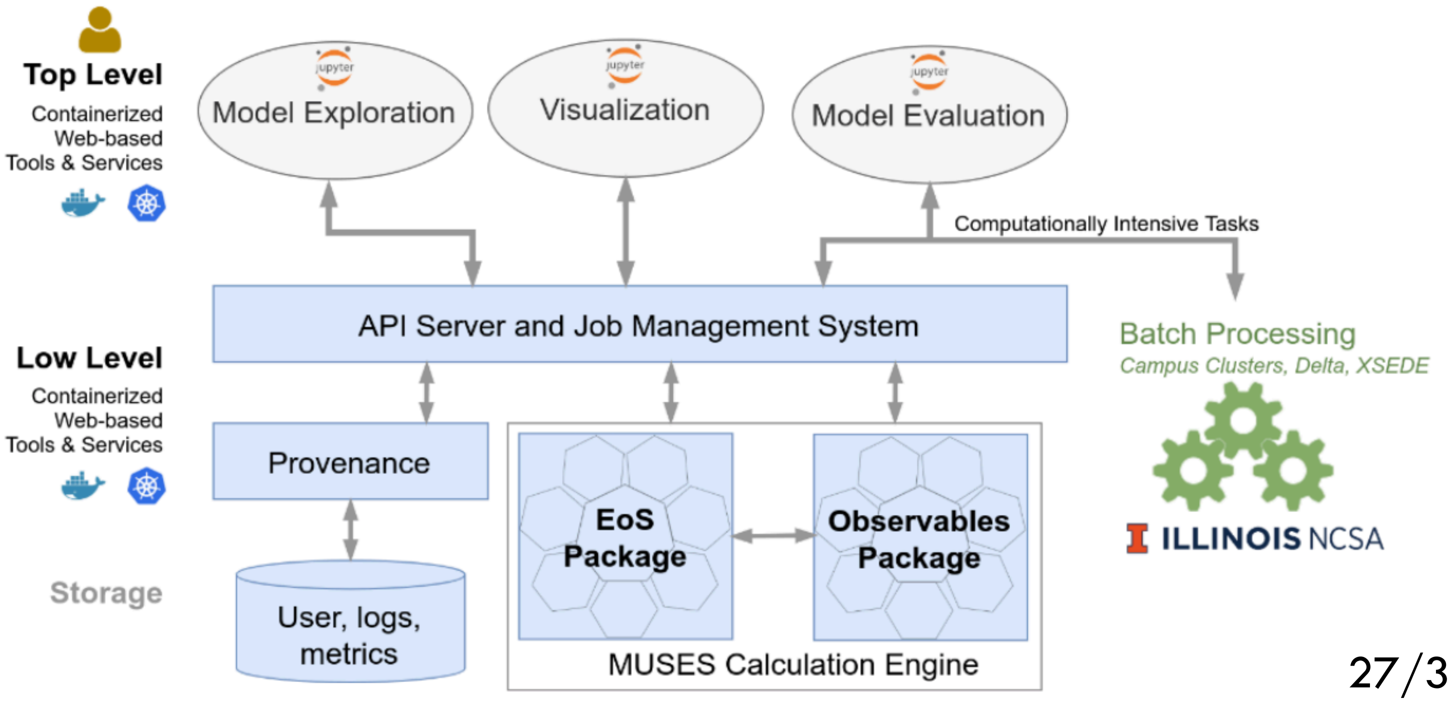

WEB TOOLS

- Web interface allows access, interaction with the parameters, models, packages, and the computing nodes to perform the calculations
- Users can register and get access to documentation, manage their submitted jobs, download all input/output of their calculation
- New users can access a model exploration component, that allows them to understand MUSES as a whole
- The model evaluation component will be used for interactive, real-time evaluation of models
- The visualization component will provide tools to visualize the parameter space and the model in an intuitive way
- Computationally-intensive tasks will be submitted using a bash processing system and results will be retrieved when ready




LOW-LEVEL SERVICES

- The client-facing API will handle communication with client applications
- Direct communication with the Batch and Provenance for storage
- Provenance will record all useful information: user activity, workflows executed, models evaluated, inputs/outputs, details of computational jobs (all only accessible internally)
- Storage will consist of a collection of services that store and serve data



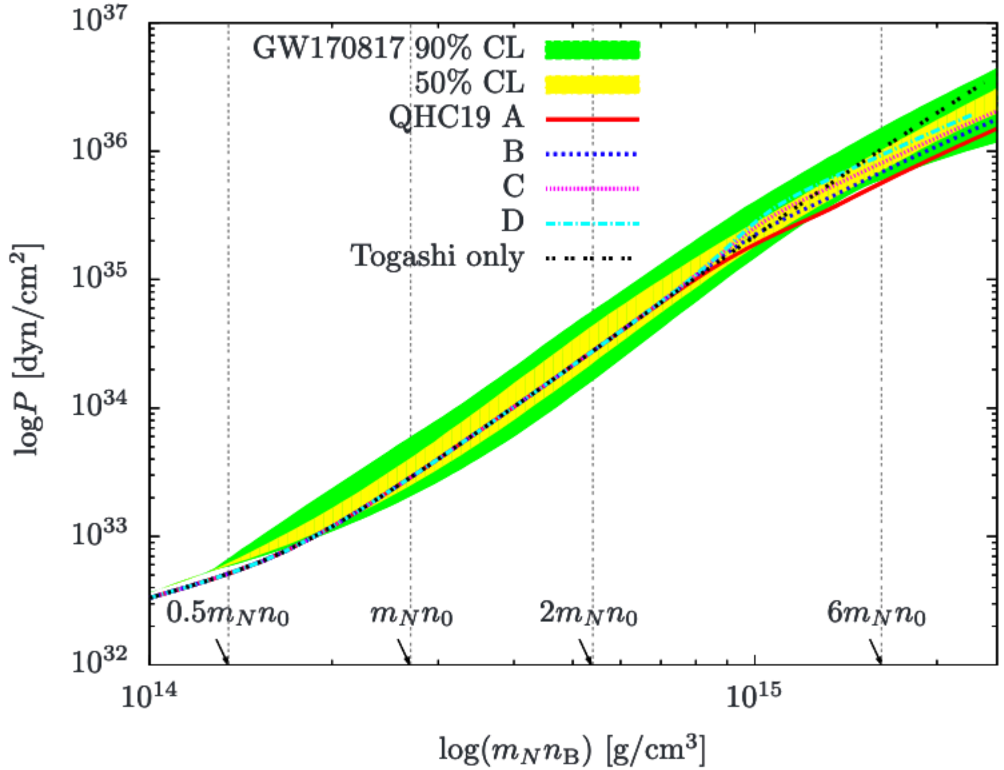
Hajme Togashi

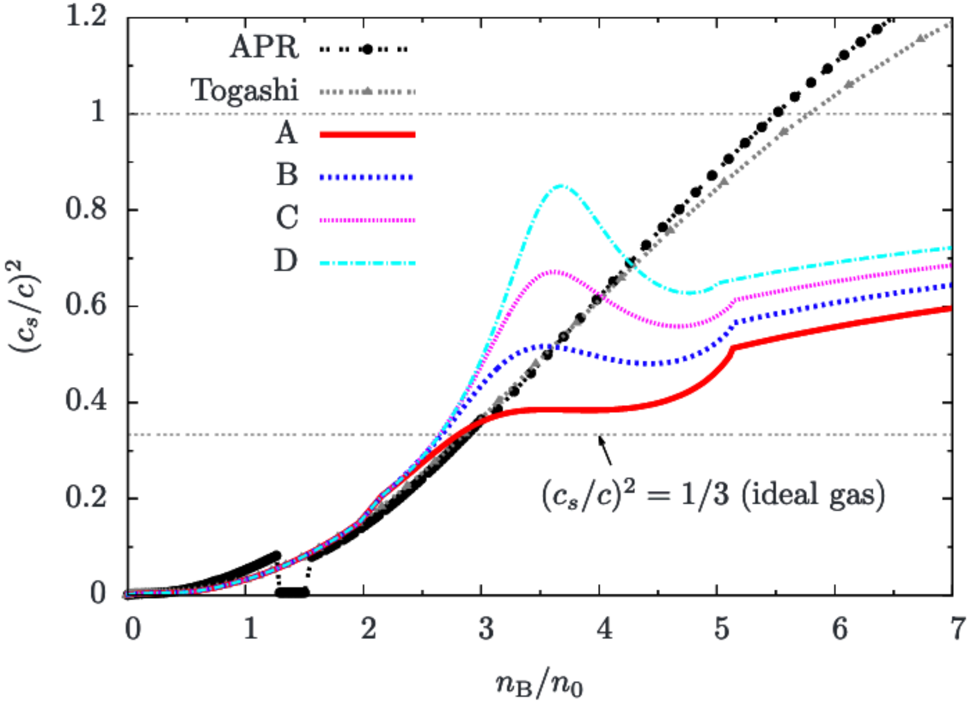
QUARK-HADRON CROSSOVER (QHC19)

- Equation of state with smooth crossover between hadrons and quarks
- Hadronic EoS is based on the Togashi model, which describes non-uniform and uniform matter, and beta-equilibrium
- Quark matter is described in the NJL model with vector interaction

G. Baym et al., Astrophys. J (2019)

Goals:
- Optimization of the code
- Incorporation into MUSES





FERMIONIC SIGN PROBLEM

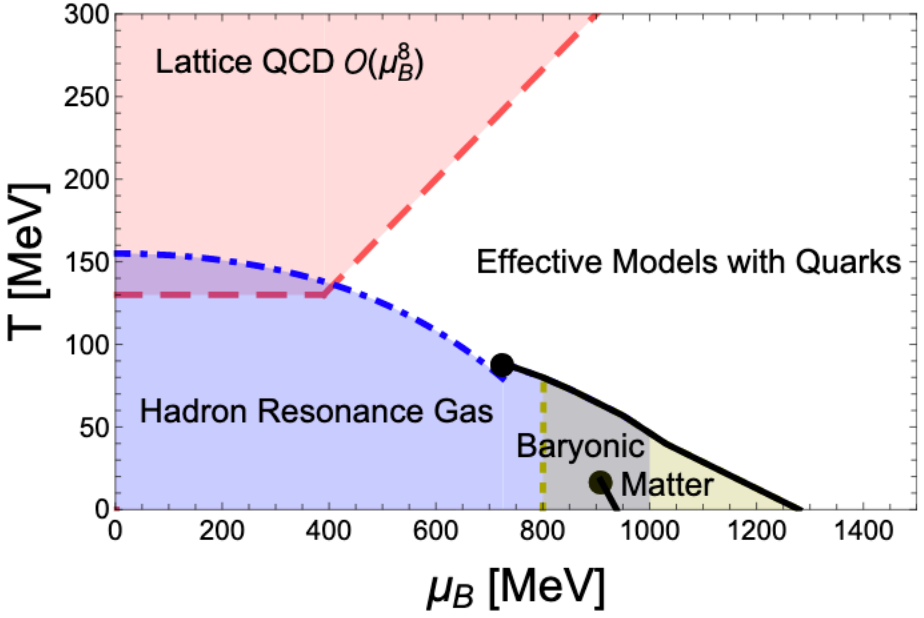
- QCD can only be solved numerically in the range of temperature and density relevant to study the phase transition

- This numerical technique is lattice QCD and it is based on Monte Carlo importance sampling

- Importance sampling cannot be applied at finite density, because the weight becomes complex

- For this reason, we do not know the equation of state and phase diagram at all temperatures and densities from first principles

- We need to rely on models to explore the regions which lattice QCD cannot reach



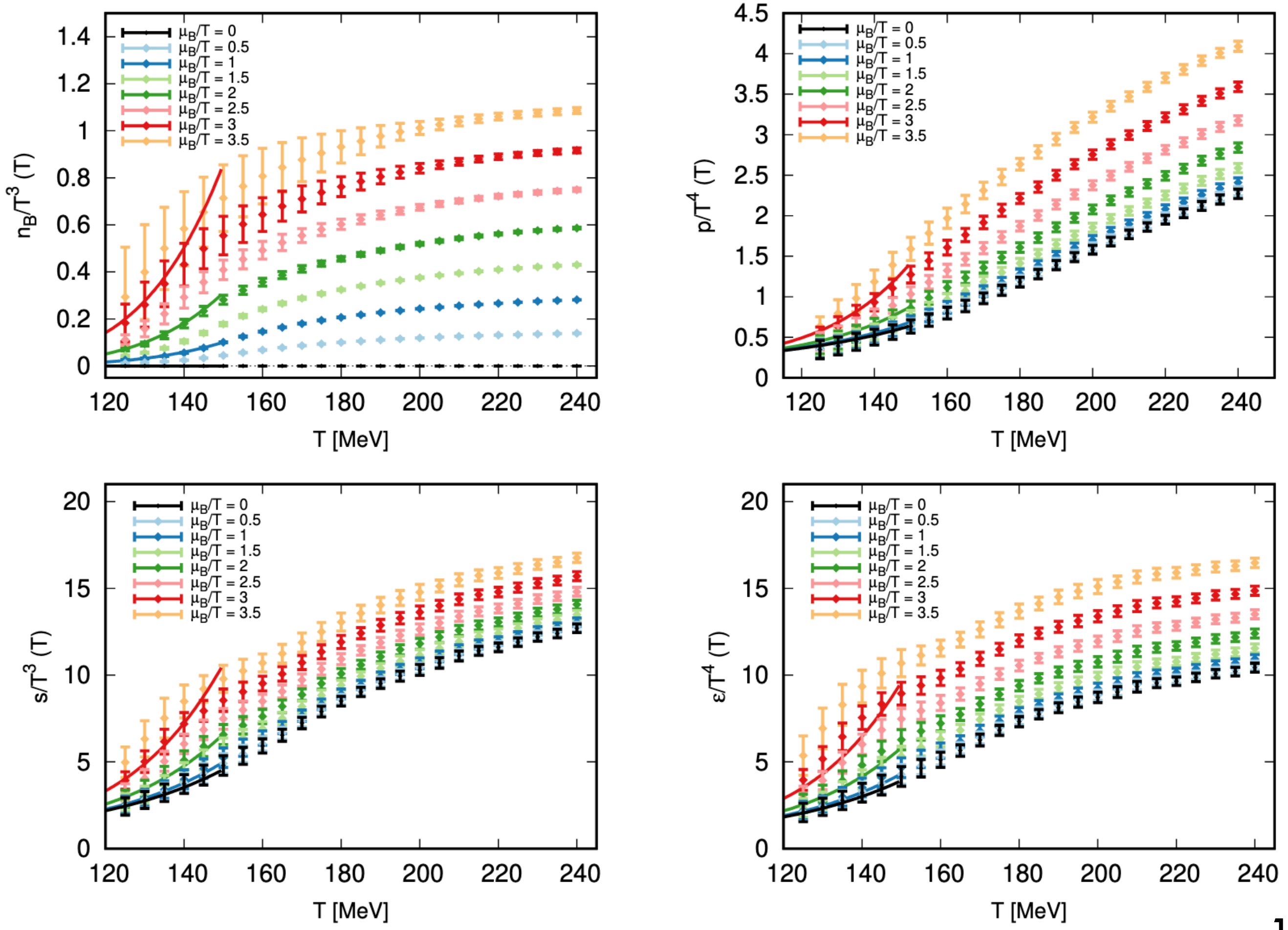
EQUATION OF STATE FROM FIRST PRINCIPLES

- Novel expansion scheme allows to extend to $\mu_B/T\sim3.5$
- EoS available so far at $\mu_S=\mu_Q=0$
- Working on the extension to the case $<n_S>=0$, $<n_Q>=0.4<n_B>$ of relevance for heavy-ion collisions

Goals:

- Extension to highest possible μ_B
- Extension to μ_S & $\mu_Q\neq0$
- Implementation into the MUSES engine

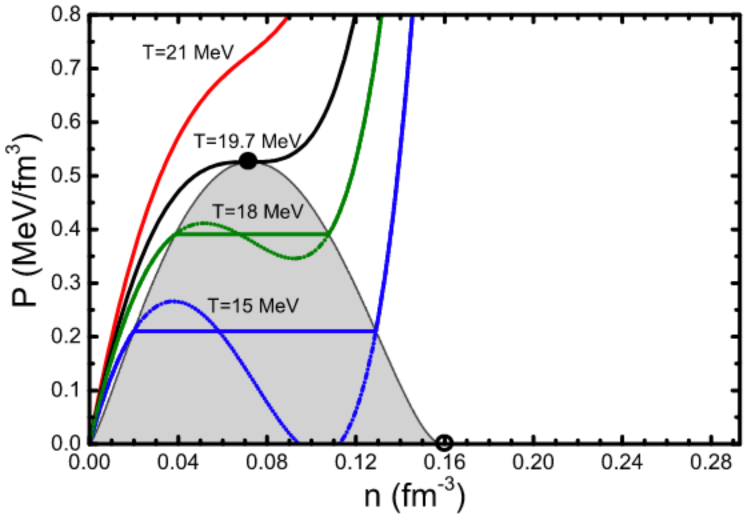
S. Borsanyi, C. R. et al., PRL (2021)

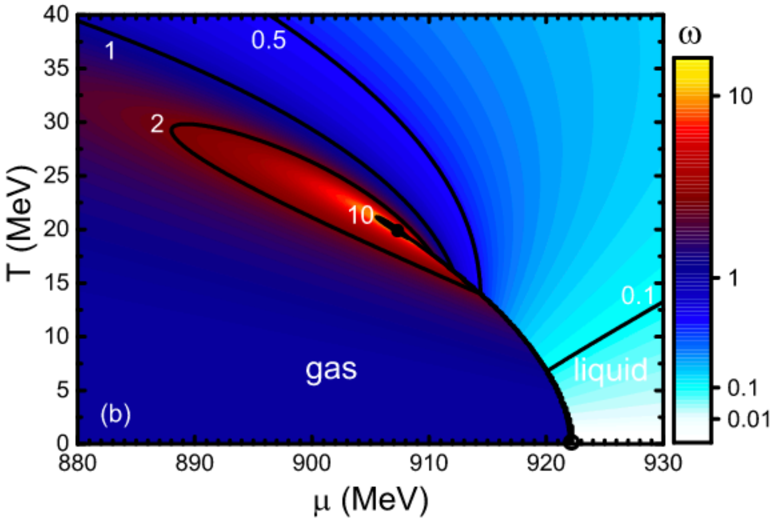



HADRON RESONANCE GAS (HRG) MODEL

V. Vovchenko et al., PRC (2015)

- The HRG model provides a well-established and realistic Equation of State at low temperatures
- Its ideal version is based on the assumption that an **interacting gas of hadrons** in the ground state can be well-approximated by an **ideal gas of resonances**
- At large density we need to incorporate additional interactions such as van Der Waals
- It describes the liquid-gas phase transition





Goals:
- Optimization of the code
- Fix the parameters to describe the liquid-gas critical point
- Incorporation into MUSES

muses

EQUATIONS OF STATE

- Taylor expansion from lattice QCD at finite T, μ_B, μ_S, μ_Q
  - Coverage: $120<T<800$ MeV, $0<\mu_B/T<2.5$

S. Borsanyi, C. R. et al., JHEP (2018)
J. Noronha-Hostler, C. R. et al., PRC (2019)
A. Monnai et al., PRC (2019)

- HRG model with van der Waals interactions
  - Coverage: $0<T<150$ MeV, $0<\mu_B<1000$ MeV

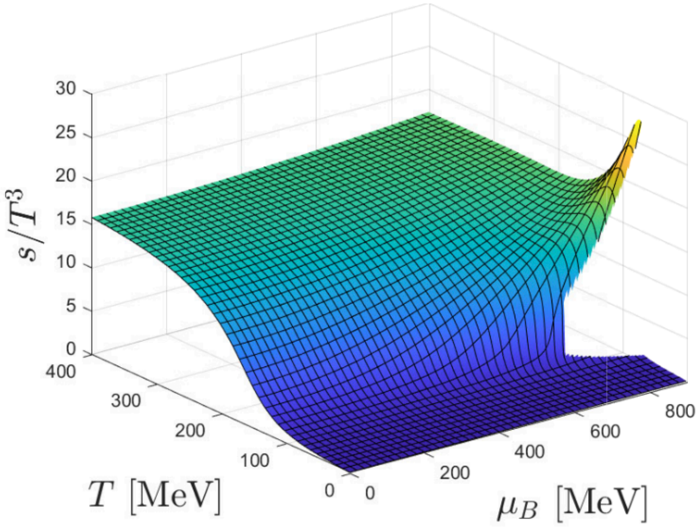
V. Vovchenko et al., PRC (2015)

- EoS with 3D Ising model critical point
  - Coverage: $0<T<800$ MeV, $0<\mu_B<450$ MeV

P. Parotto, C. R. et al., PRC (2020)
J. Karthein, C. R. et al., EPJ Plus (2021)

- Equation of state from holography
  - Coverage: $100<T<800$ MeV, $0<\mu_B<1100$ MeV

J. Grefa, C. R. et al., PRD (2021)




EQUATION OF STATE WITH 3D-ISING CRITICAL POINT (BESEOS)

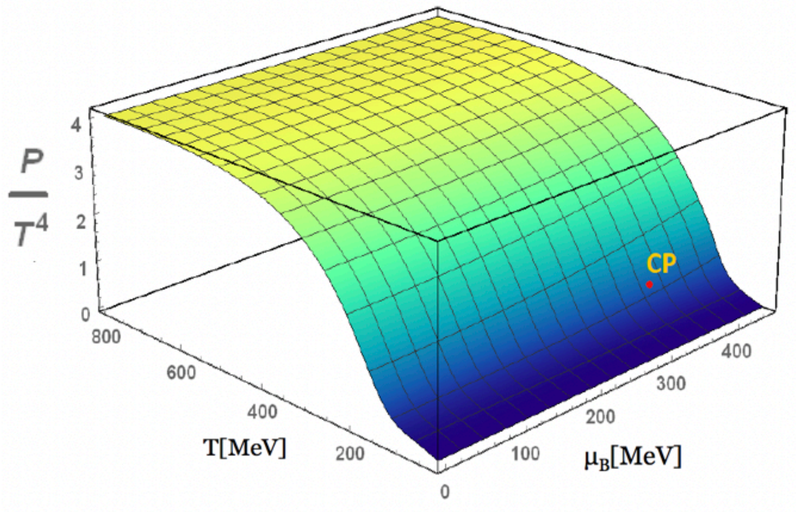
P. Parotto, C. R. et al., PRC (2020)

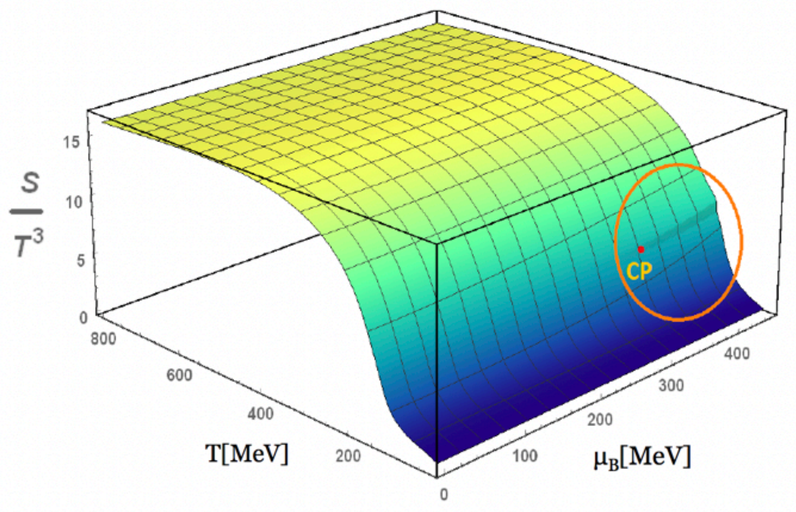
J. Karthein, C. R. et al., EPJ Plus (2021)

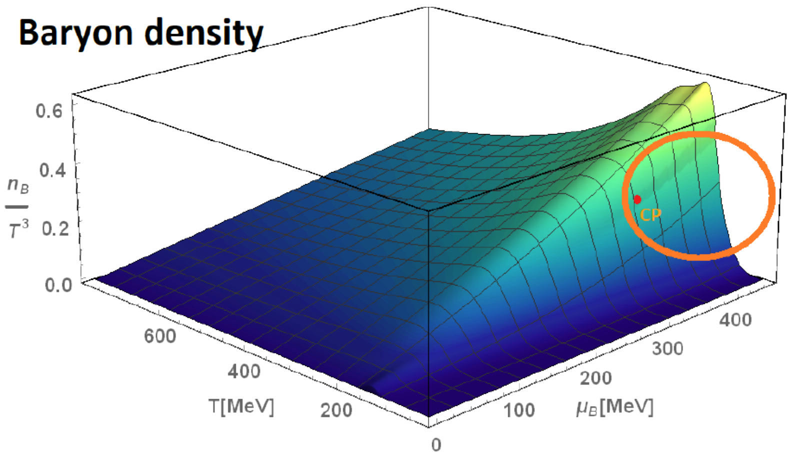
- Implement scaling behavior of 3D-Ising model EoS
- Define map from 3D-Ising model to QCD
- Estimate contribution to Taylor coefficients from 3D-Ising model critical point
- Reconstruct full pressure
- Currently available at $\mu_S=\mu_Q=0$ and for $\langle n_S \rangle=0$, $\langle n_Q \rangle=0.4\langle n_B \rangle$

Goals:

- Extension of range in µB
- Extension to three conserved charges
- Incorporation into MUSES





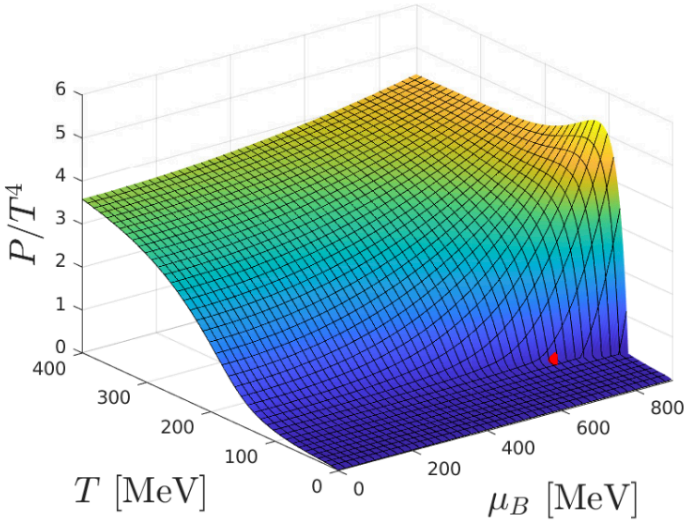


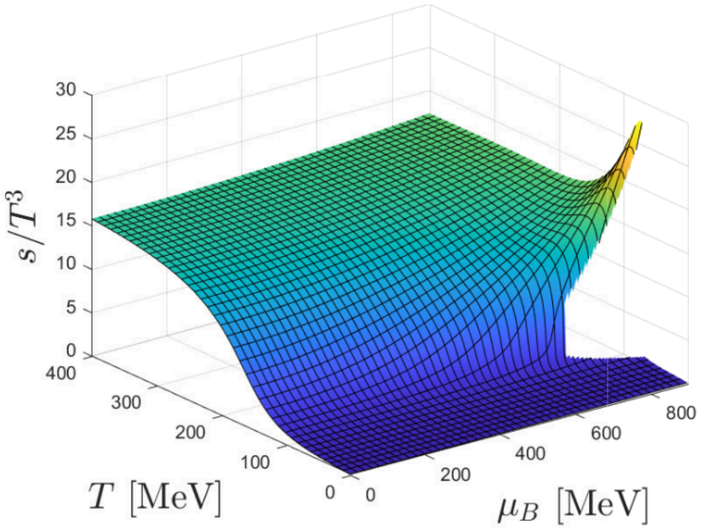

EQUATION OF STATE FROM HOLOGRAPHY (NUMRELHOLO)

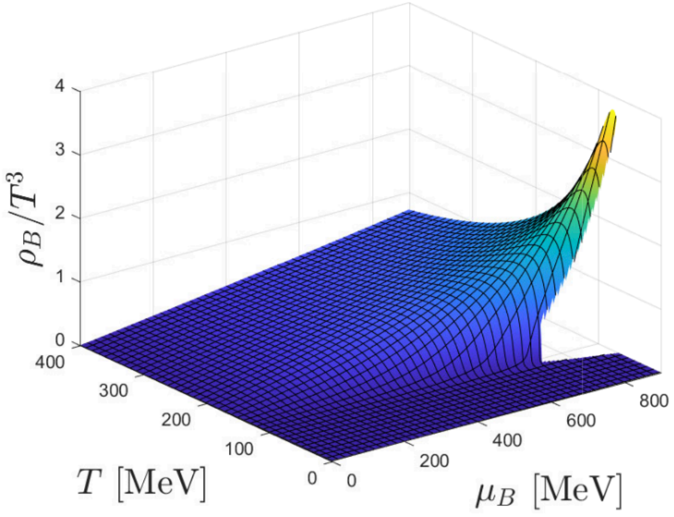
J. Grefa, C. R. et al., PRD (2021)

- Use AdS/CFT correspondence
- Fix the parameters to reproduce everything we know from the lattice
- Calculate equation of state at finite density
- Model currently has only baryon number
- Prediction of critical point: T_C= 89 MeV μ_{BC}=723 MeV

Goals:
- Optimization of the code
- Inclusion of more than one conserved charge
- Incorporation into MUSES



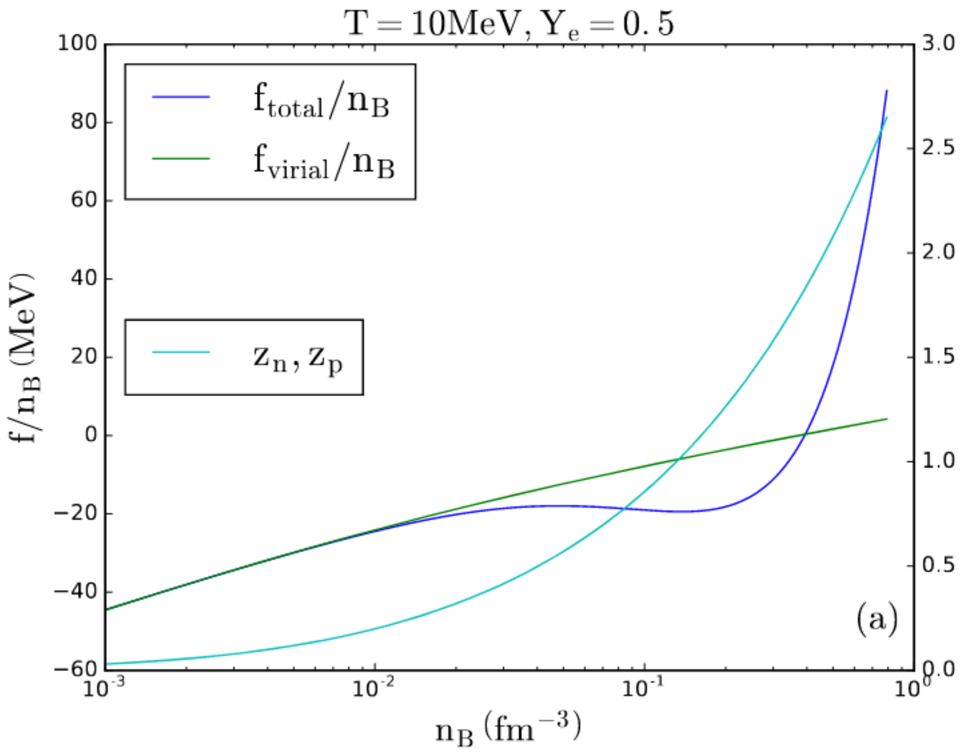


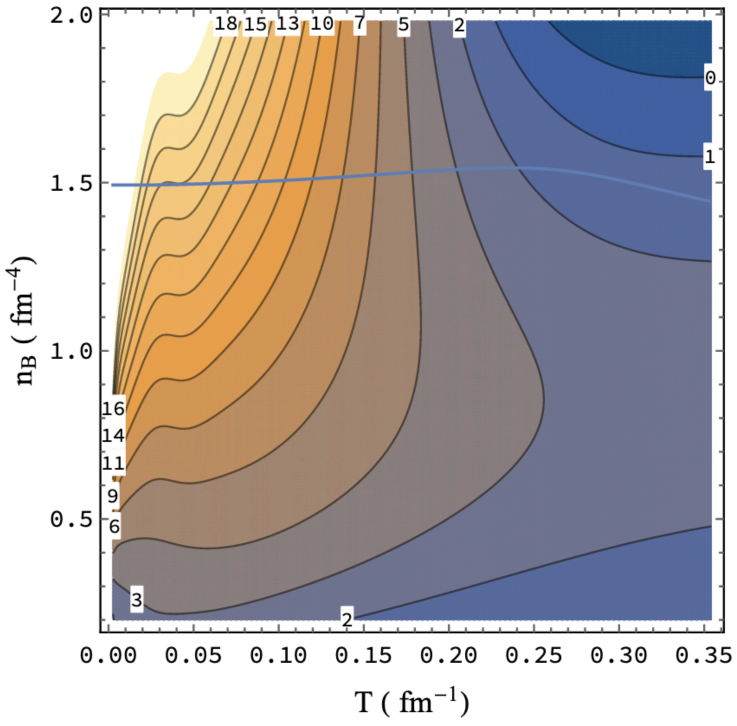


UNIVERSITY OF TENNESSEE KNOXVILLE EOS(UTK EOS)

- Includes nucleonic degrees of freedom based on a phenomenological fit to nuclear experiment and astronomical observations
- Covers densities from 10^{-12} to 2 fm^{-3} and temperatures up to 100 MeV

X. Du, A. Steiner, J. Holt, PRC (2019)





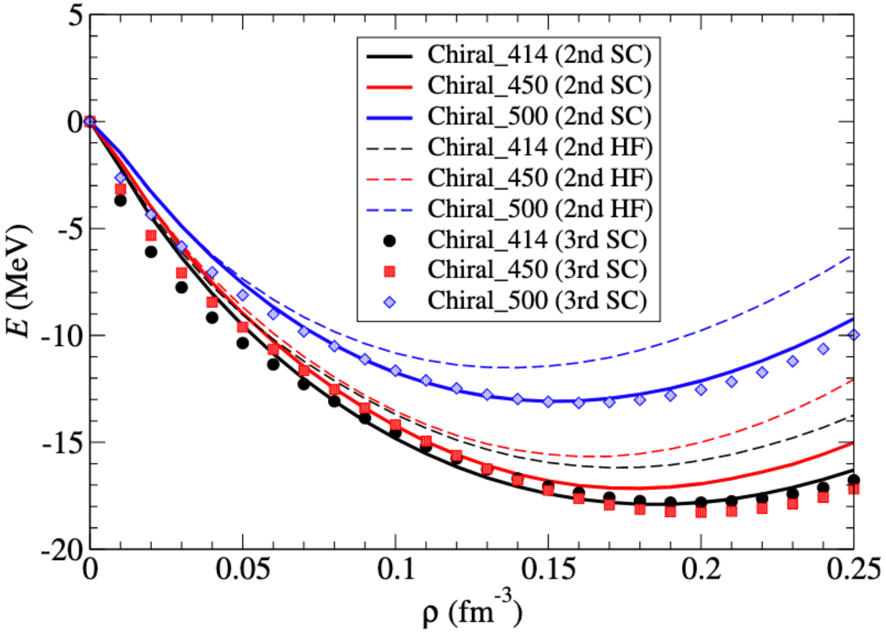
Goals:
- Optimization of the code
- Extension to strangeness degrees of freedom
- Incorporate into MUSES

CHIRAL EFFECTIVE FIELD THEORY (CHEFTEOS)

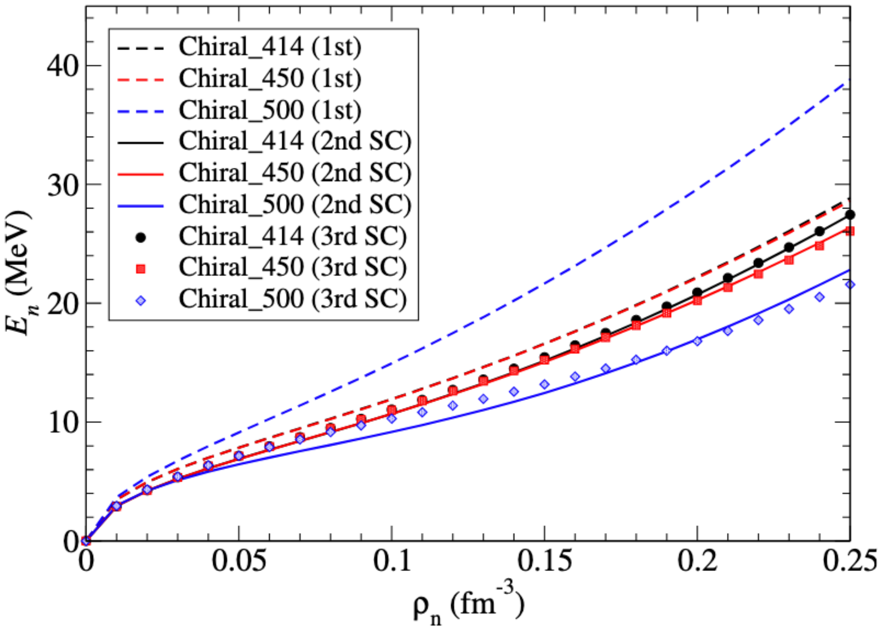
J. Holt & N. Kaiser, PRD (2017)

- Describes matter in the range T<25 MeV, 800 MeV<μ_B<1100 MeV
- Interacting nucleons and pions within chiral effective field theory
- Constrains do not exist for asymmetric matter

Goals:
- Optimization of the code
- Optimization of root-finding techniques
- Incorporate into MUSES



EoS for symmetric nuclear matter



EoS for neutron matter

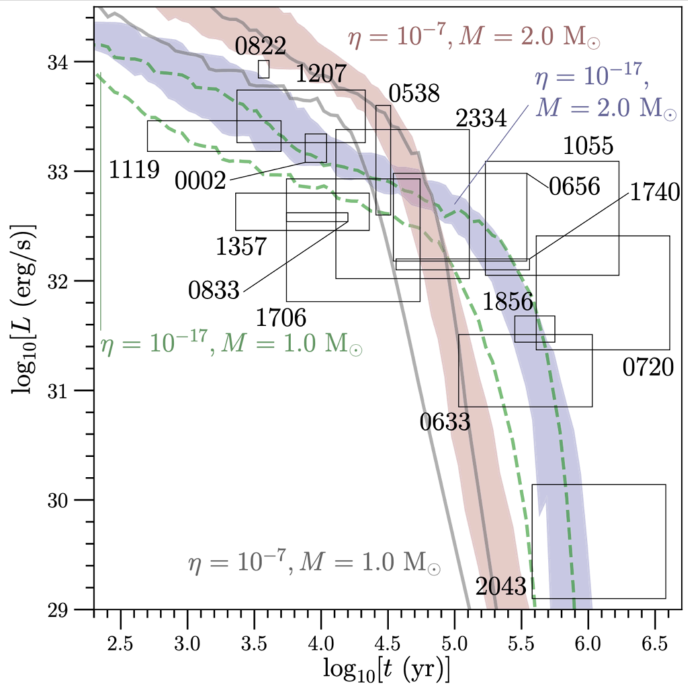
From Observables to Nuclear Physics

Nucleon-nucleon interactions from neutron star mergers

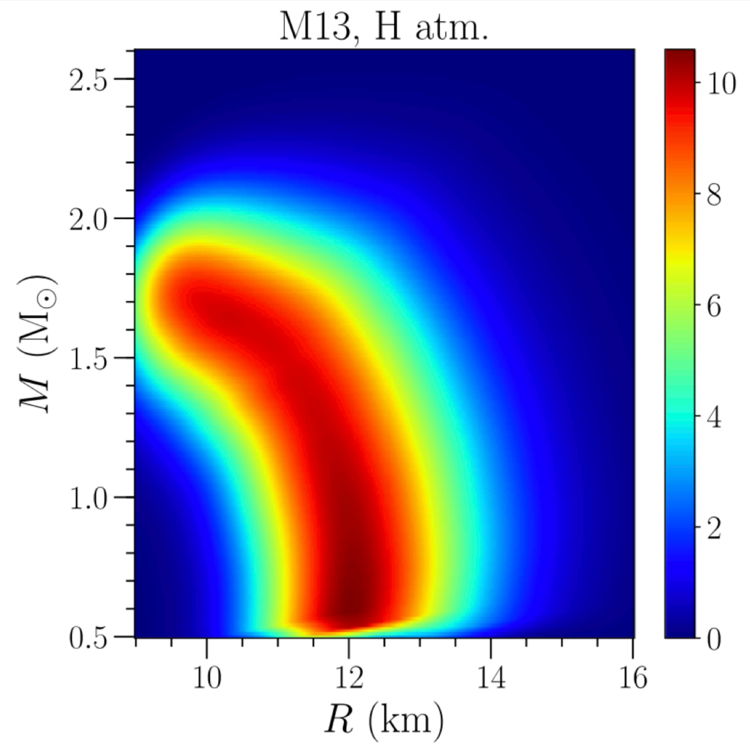
- Goal of the hub is to go beyond the "obvious" observable parameters and understand nuclear physics, but…
- We will not understand mergers work until we understand the nuclear theory
- We cannot constrain nuclear theories without understanding mergers
- Develop models that constrain the underlying nuclear theory using multi-messenger observables
- Start with reasonable prior choices, use observations to tune nuclear theory, improve models, revisit observations, make predictions

Multi-Messenger Inference

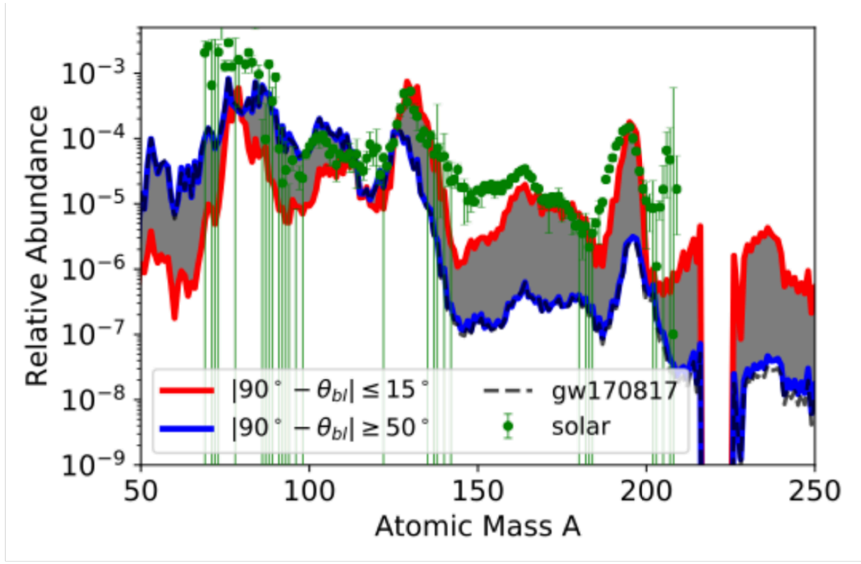
Connecting to observables



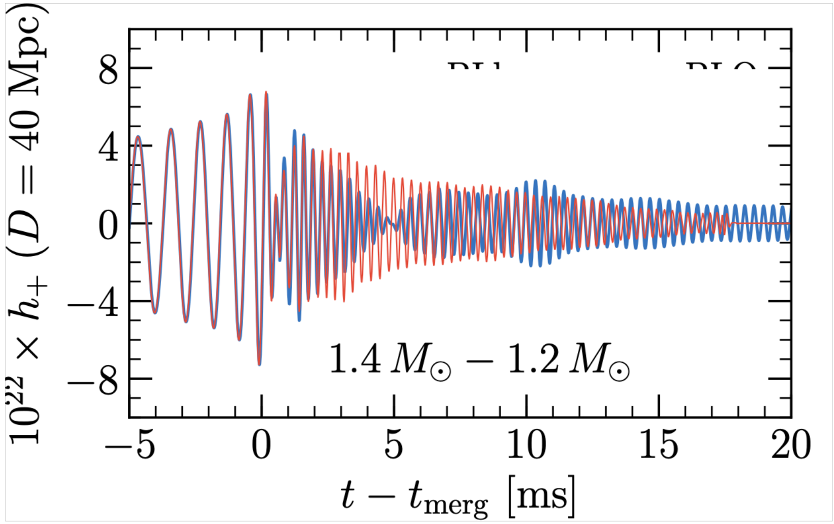
Age-luminosity relations for isolated neutron stars (UTK)



X-ray spectra of Quiescent low-mass X-ray binaries (UTK)



r-process abundances (PSU, UNH and UTK)



Predictions for multi-messenger observations (SU, CSUF, PSU)