MUSES – AN OVERVIEW

The nuclear phase diagram puzzle from neutron stars to heavy-ion collisions

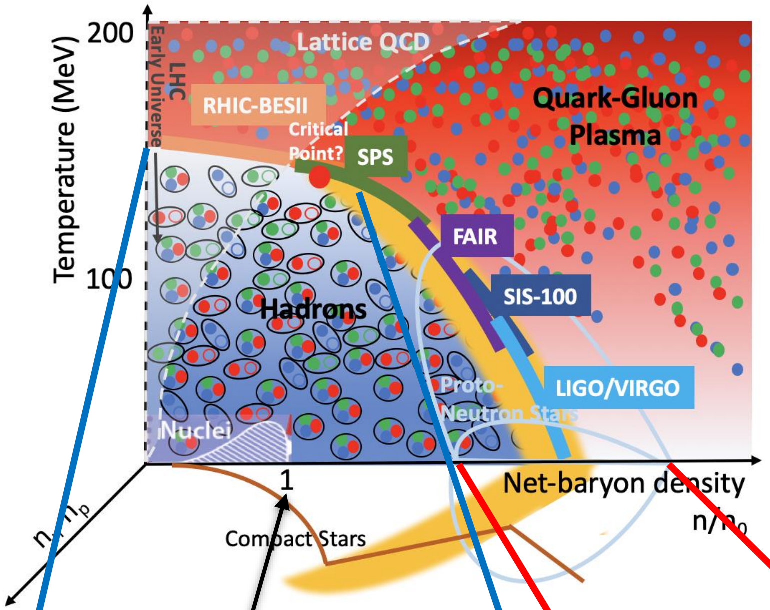
IRL-NPA FRIB
November 1st, 2024

Dr. Johannes Jahan
University of Houston

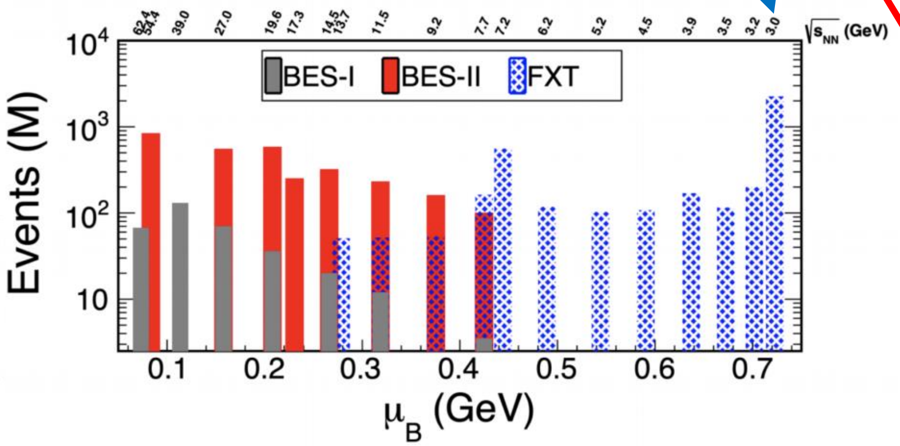
muses

MOTIVATING SCIENCE GOALS

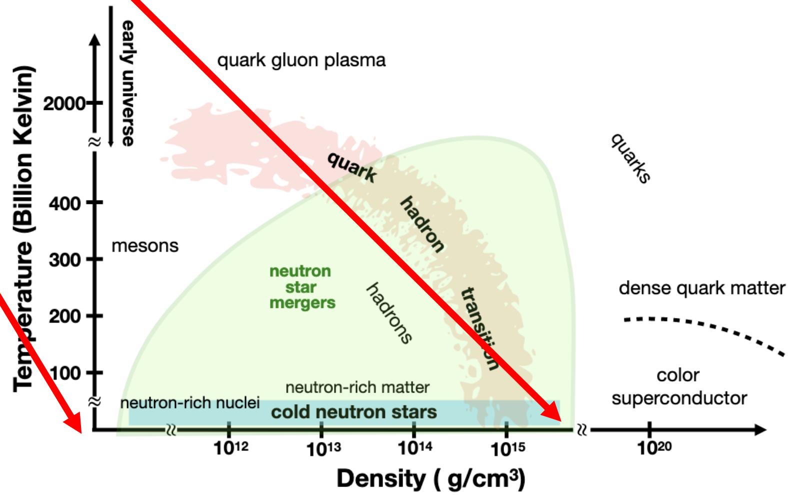
- Where is the transition line at high density?
- Is there a critical point in the QCD phase diagram?
- What are the degrees of freedom in the vicinity of the phase transition?
- What are the phases of QCD at high density?
- How are heavy nuclei created and what is the site of the r-process?



"Normal" matter



- 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

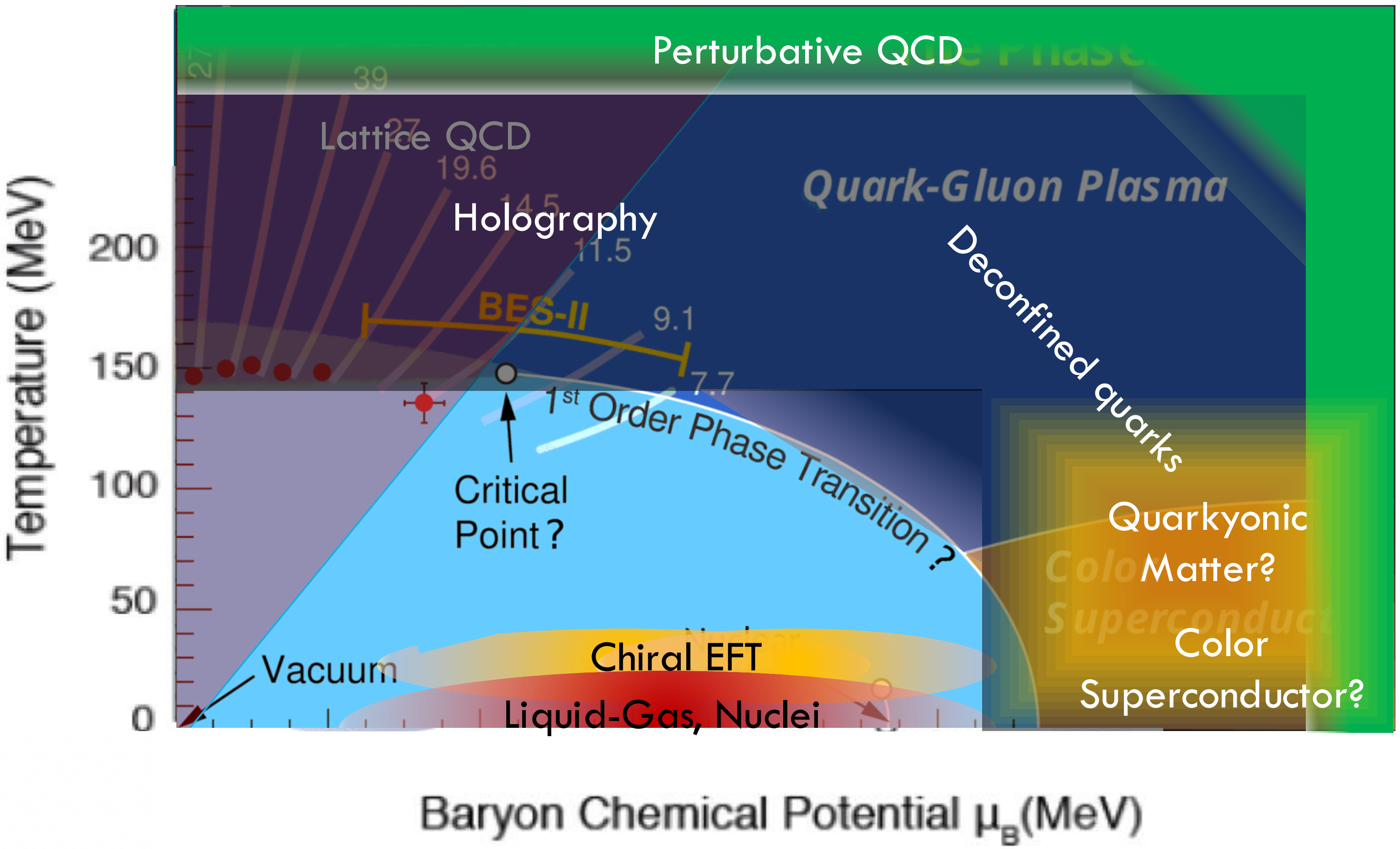


WHAT HAPPENS AT FINITE DENSITIES?

From 1st principles calculation, lattice QCD only allows to compute thermodynamics at μ_B = 0 (matter/antimatter=1).

- Expansion methods can be used, but still restricted to low density regions
- We need to merge the lattice QCD EoS with other effective theories
- Careful study of their respective range of validity

Could we try to merge them together to ensure full coverage of the phase diagram ?



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: Ratti et al., PRD (2006), Dexheimer et al., PRC (2009); Baym et al., Astr. J. (2019)

Quarkyonic: McLerran et al. (2007), Vovchenko et al. (2023)

CSC: Alford et al., PLB (1998); Rapp et al., PRL (1998); S. Rossner, C. R. et al, PRD (2007).

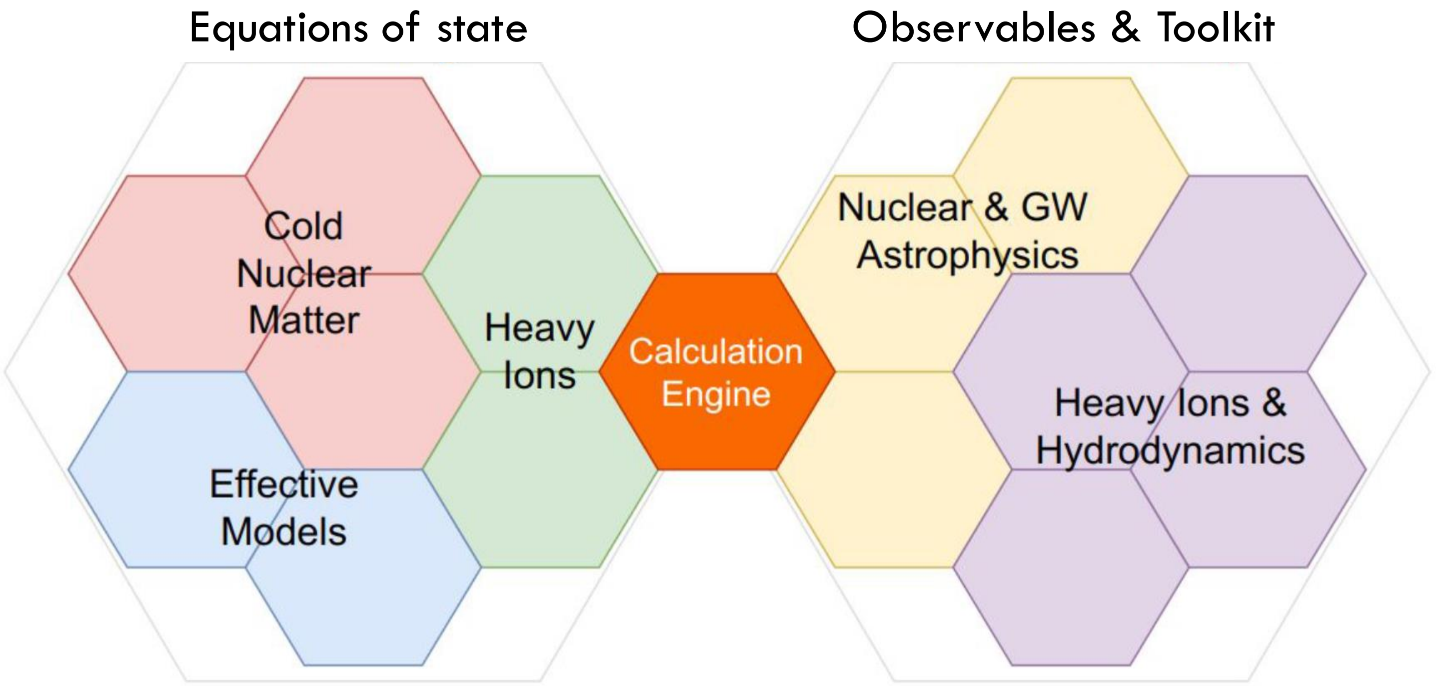
MUSES – MODULAR UNIFIED SOLVER OF THE EQUATION OF STATE

"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, Chiral EFT…)

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
  - **Observables & toolkit package** to compute observables and provide tools to facilitate comparison with experiments
  - **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



This is the list that appeared in the proposal, BUT:
1st MUSES collaboration paper was signed by 58 authors
→ We are growing!

PARTICIPANTS

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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

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FIRST MUSES-WIDE PUBLICATION

Published in
Living Reviews in Relativity

Living Rev.Rel. 27 (2024)
(arXiv:2303.17021)

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)

PUBLIC RELEASE: NOV. 2024

DETAILS

- 1st set of modules will be released very soon *(just a few more weeks to wait…)*
- They will be publicly available & open-source
- We invite people to test these modules and give us feedback!
- The modules to be released will be marked by RELEASE during this talk


NASA Scientific Visualization Studio

EOS FOR NEUTRON STARS

NEUTRON STARS & MERGERS: DETAILS AND NEEDS

DETAILS

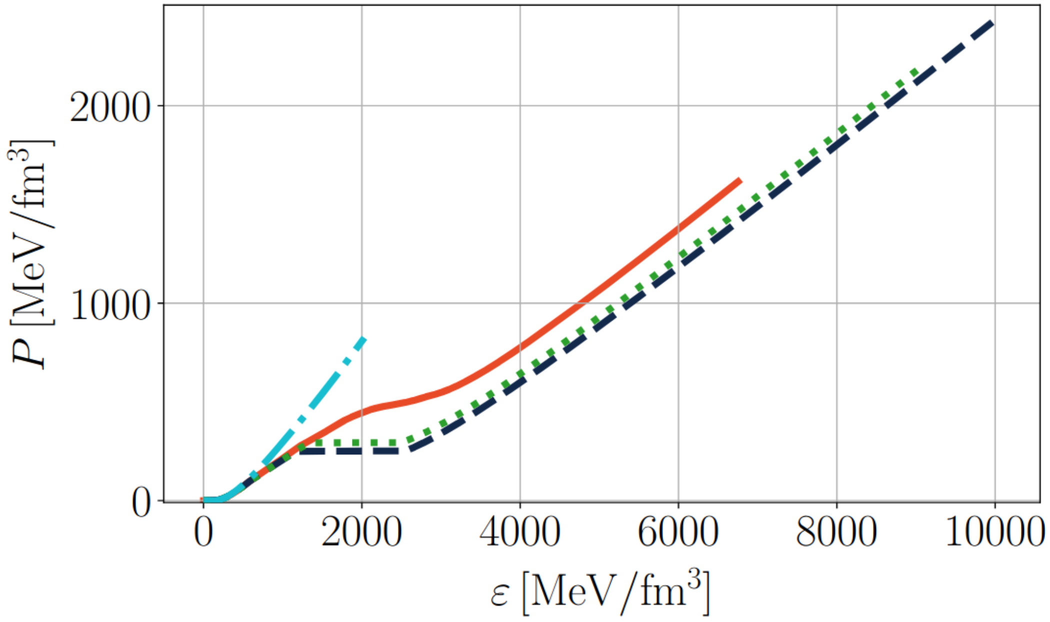
- Long lifetime
- Weak interaction must be considered
- Flavor is driven out of equilibrium temporarily (mergers)
- Electrically neutral for stability $\langle \rho_Q \rangle = 0$

NEEDS

- Standard EoS: (p, s, ε, ρ_B, c_s^2, μ_i, Y_i)
- T=0 EoS for mergers and neutron stars
- Finite-T EoS for mergers
- Lepton EoS
- Flavor equilibration tied to microscopic EOS models

MULTI-PHASE EQUATION OF STATE FOR NEUTRON STARS

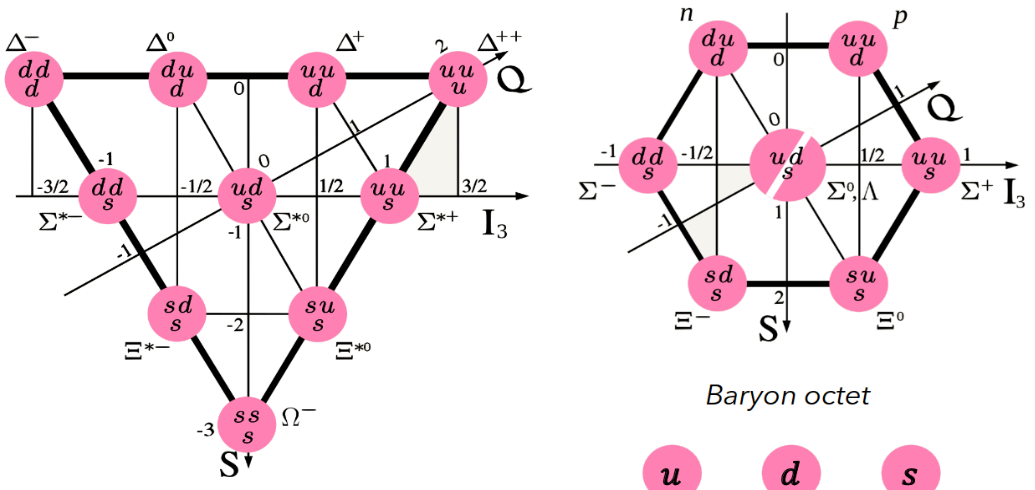
Range: T ~ 0 MeV ; μ_B < 1600 MeV / n_B < ~$10n_s$



- **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 and different parametrizations of vector meson self-interaction term
  - Reproduces nuclear & astrophysics constraints, and matches pQCD in relevant regimes

V. Dexheimer, S. Schramm, PRC 81 (2009)
N. Cruz-Camacho, V. Dexheimer et al., *arXiv:2409.06837*

RELEASE



Baryon decuplet

Baryon octet

SU(3) quarks

Outlooks:
- Add finite-T extension *(T < 160 MeV)*
- Add magnetic field
- Thermal meson interactions
- Study sensitivity of parameters

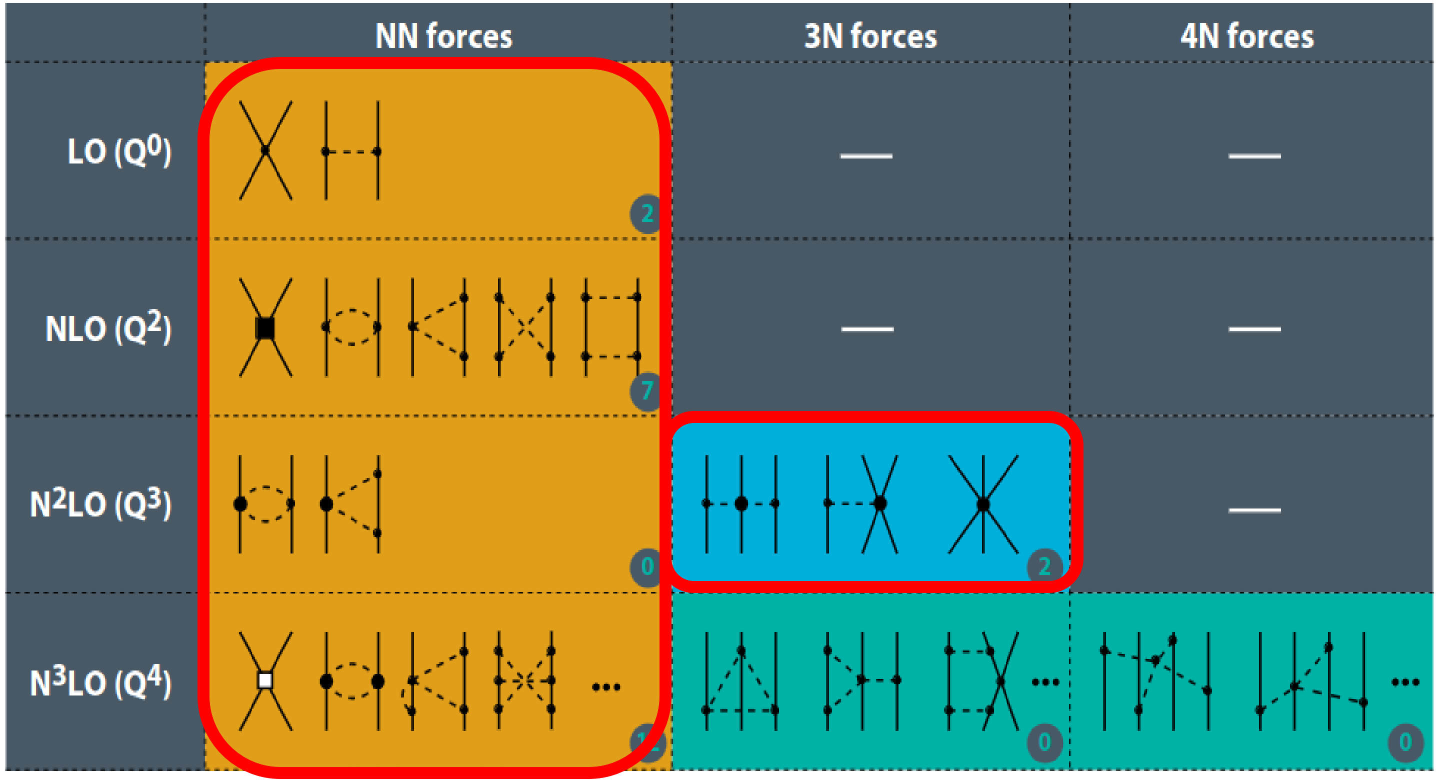
HADRONIC EQUATIONS OF STATE FOR NEUTRON STARS

Range: T ~ 0 MeV ; n_B < ~$2n_s$

- **Chiral effective field theory (ChiEFT)**
  - Interacting nucleons and pions within chiral effective field theory
  - Fitted to nucleon scattering data and boundstate potentials
  - Can compute both symmetric and asymmetric EoS: $0 < Y_p < 0.5$

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

RELEASE



Outlooks:
- Add extension at finite-T *(up to 30 MeV)*
- Include a wider variety of ChiEFT potentials
- Provide uncertainty quantification

HADRONIC EQUATIONS OF STATE FOR NEUTRON STARS

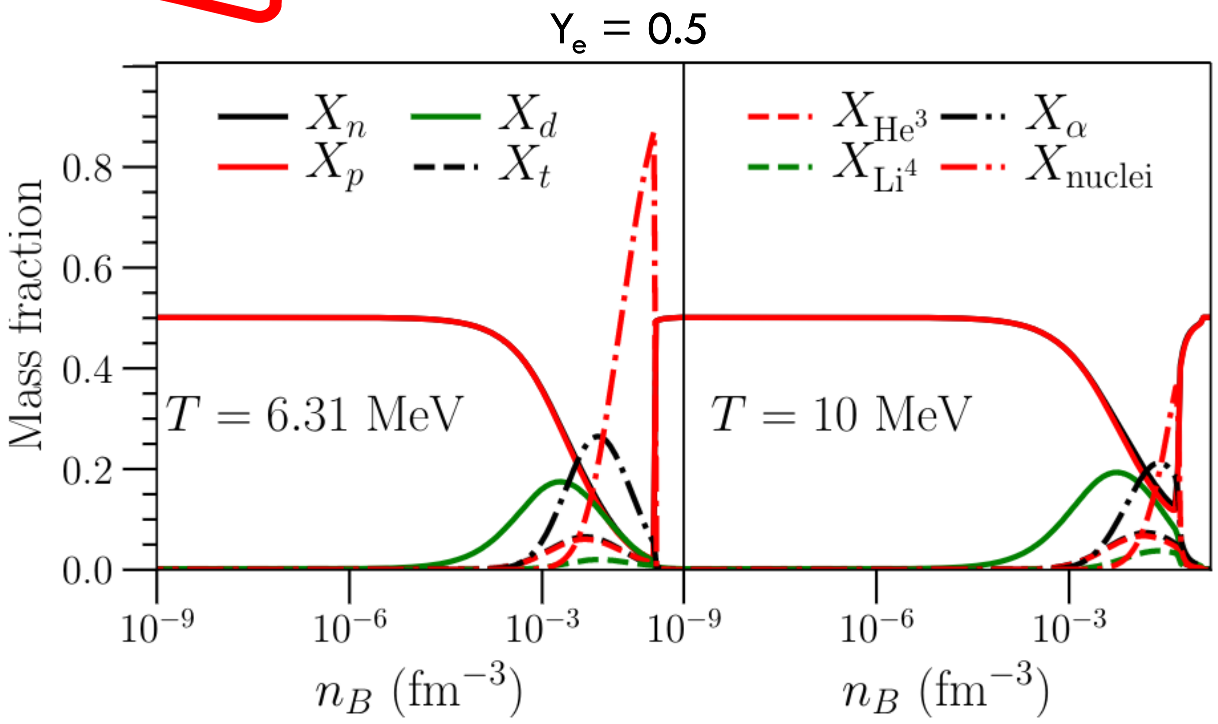
Range: $T \sim 0$ MeV ; $10^{-12} < n_B < 2$ fm^3

RELEASE

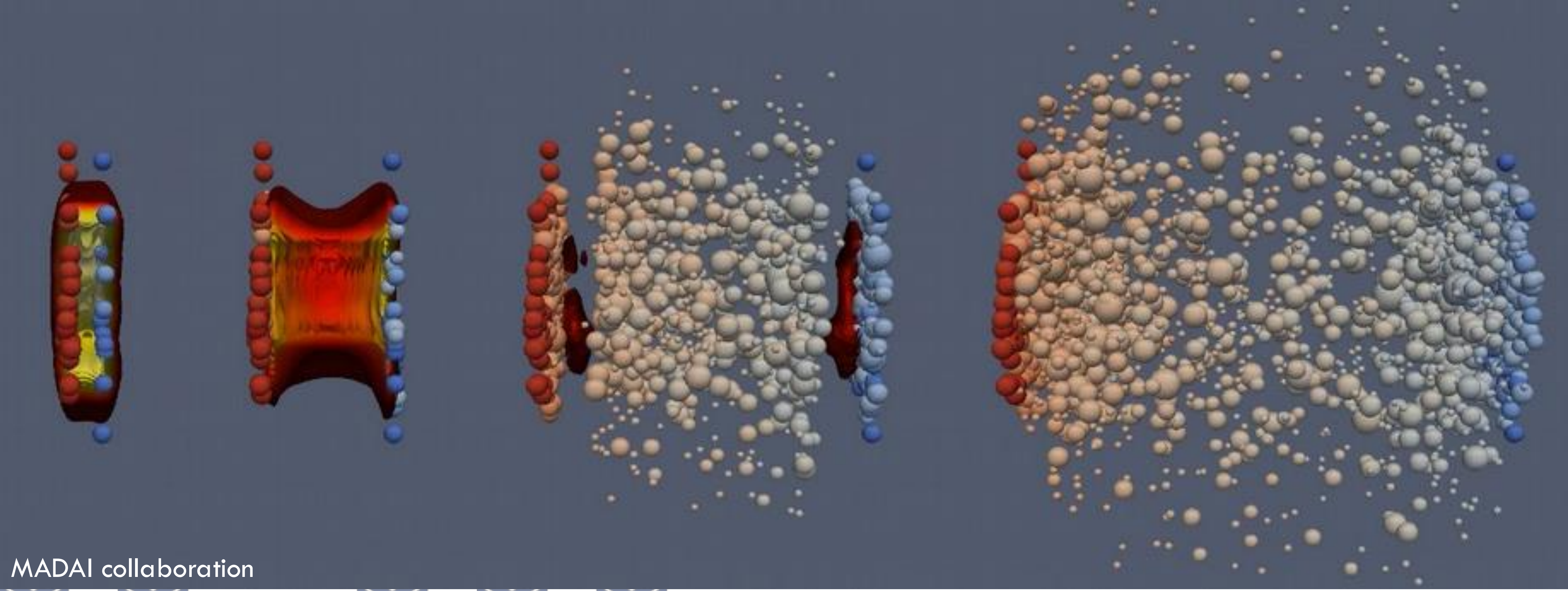
- **University of Tennessee in Knoxville (UTK) EoS**
  - Includes nucleonic degrees of freedom based on a phenomenological fit of free energy density to
    - nuclear experiments
    - astronomical observations

    \+ guided by many-body theory calculations
  - Defined for both symmetric and asymmetric matter for $0.01 < Y_p < 0.5$

  X. Du, A. Steiner, J. Holt, PRC (2019)
  X. Du, A. Steiner, J Holt, PRC 110 (2022)



Outlooks:
- Addition of finite T equations of state
- Extension to strangeness degrees of freedom
- Machine learned emulator



EOS FOR HEAVY IONS

HEAVY ION COLLISIONS: DETAILS AND NEEDS

DETAILS

- System is described in terms of hydrodynamic simulations and/or microscopic transport
- System is not in finite-sized, short lifetime
- Strangeness neutrality $\langle n_S \rangle = 0$ + locally conserved
- Charge: p vs. n in ions → $\langle n_Q \rangle = 0.4 \langle n_B \rangle$

NEEDS

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

EQUATION OF STATE FROM HOLOGRAPHY

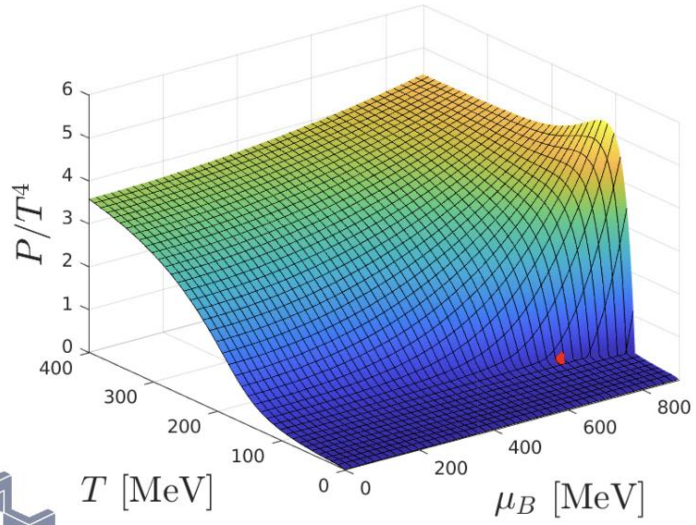
Range: 30 MeV < T < 400 MeV ; μ_B < 1100 MeV

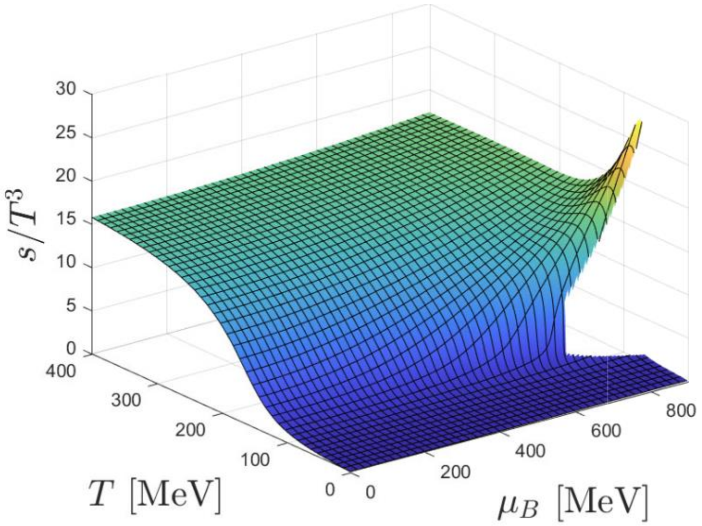
RELEASE

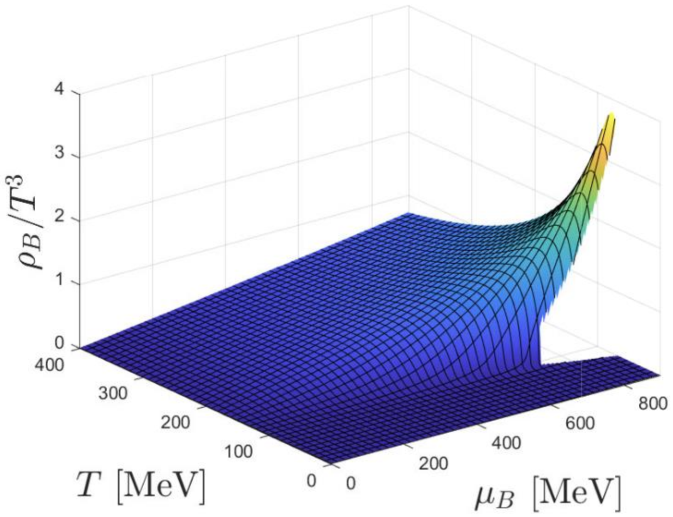
- Use gauge/gravity correspondence to obtain QCD thermodynamics from an Einstein-Maxell-Dilaton Holographic model
- Fix the parameters to reproduce everything we know from the lattice
- Calculate equation of state at finite density, but only for finite μ_B
- Currently includes a critical point (T^{CEP} = ~100 MeV ; μ_B^{CEP} = ~600 MeV)

Outlooks:
- Extension to multiple conserved charges

J. Grefa, C. Ratti et al., PRD (2021)
J. Grefa, C. Ratti et al. *subm. To PRD* (2023)







Ratti's group

4D EQUATION OF STATE FROM L-QCD (BQS-EOS)

RELEASE

Range: 30 MeV < T < 600 MeV ; $\mu_{B/Q/S}$ < 450 MeV

- Full Taylor expansion needed to study different $\mu_{B/Q/S}$ scenarios

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

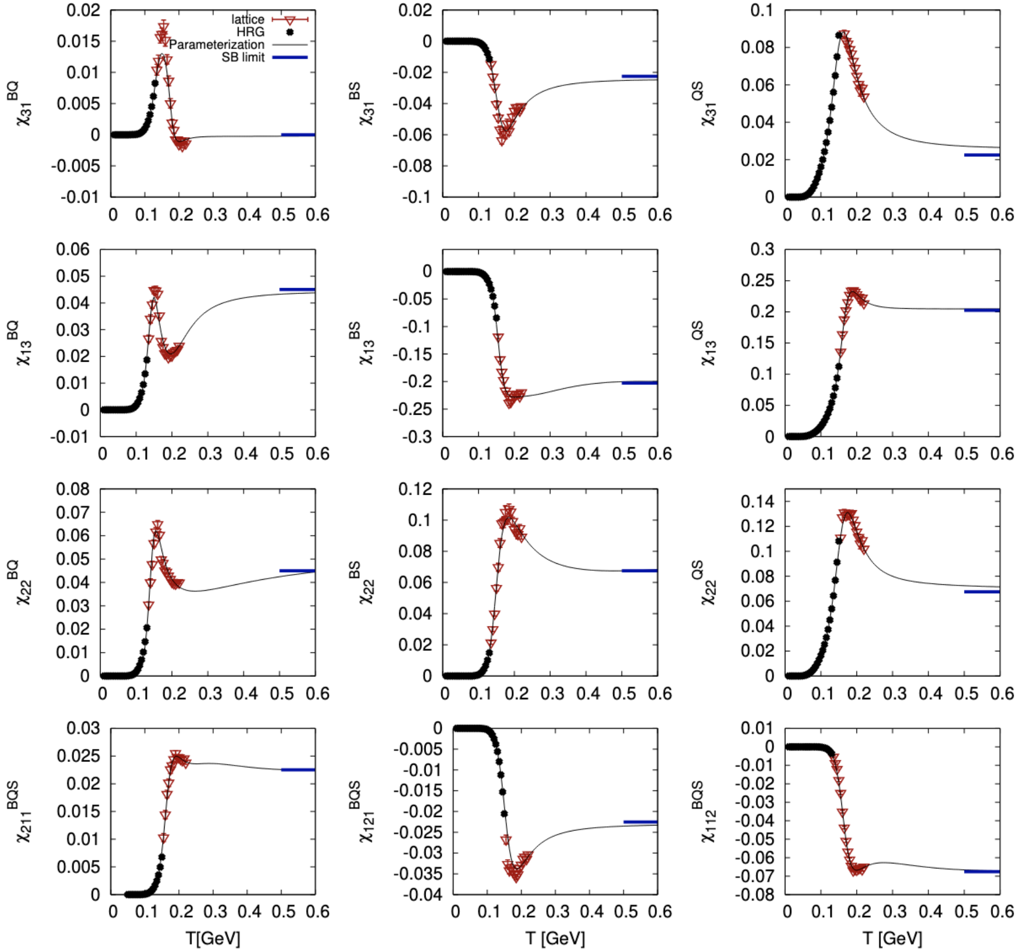
- Parametrized susceptibilities fitted on lattice QCD + HRG

$$\chi_{ijk}^{BQS}(T) = \frac{\sum_{n=0}^{9} a_n^{ijk}/t^n}{\sum_{n=0}^{9} b_n^{ijk}/t^n} + c_0^{ijk} \qquad \text{where } t = T/154\,\mathrm{MeV}$$

$$\chi_2^B(T)) = e^{-h_1/t'-h_2/t'} \times f_3\left(1+\tanh(f_4 t' + f_5)\right) \qquad \text{where } t' = T/200\,\mathrm{MeV}$$

- Coefficients are available from lattice-QCD up to global order 4 (μ/T < 2.5)

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



2D ISING-T.EX.S EQUATION OF STATE FROM L-QCD

RELEASE

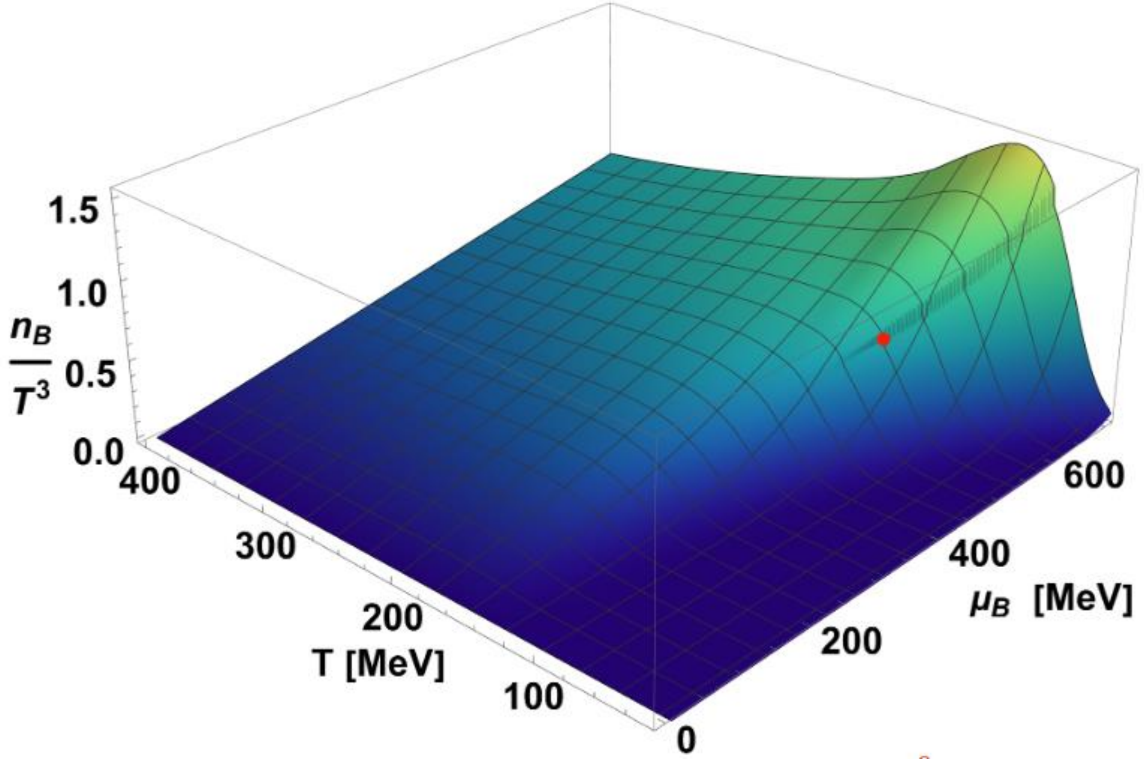
Range: 30 MeV < T < 800 MeV ; μ_B < 700 MeV

- Novel T'-Expansion Scheme (TExS) allows to extend lattice-based EoS up to $\mu_B/T \sim 3.5$ (EoS available at $\mu_S=\mu_Q=0$)

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

- Includes a parametrized critical point from 3D-Ising universality class, with free location along a transition line parametrized according to physical constraints

  M. Kahangirwe, J.J., C. Ratti et al., PRD (2024)



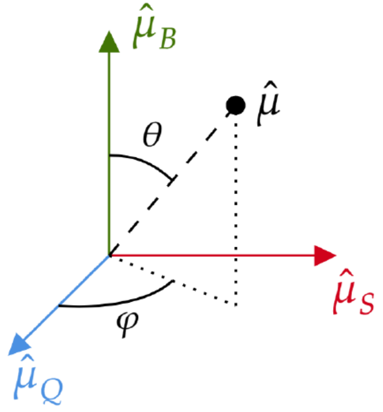
Outlooks:
- Extend it to the case $\langle n_S\rangle=0$ & $\langle n_Q\rangle=0.4\langle n_B\rangle$, relevant for HICs
- Provide adaptive grid to better resolve CP

4D-T.EX.S EQUATION OF STATE FROM L-QCD

In development

Range: T < 800 MeV ; $\mu_{B/Q/S}$ <? 700 MeV

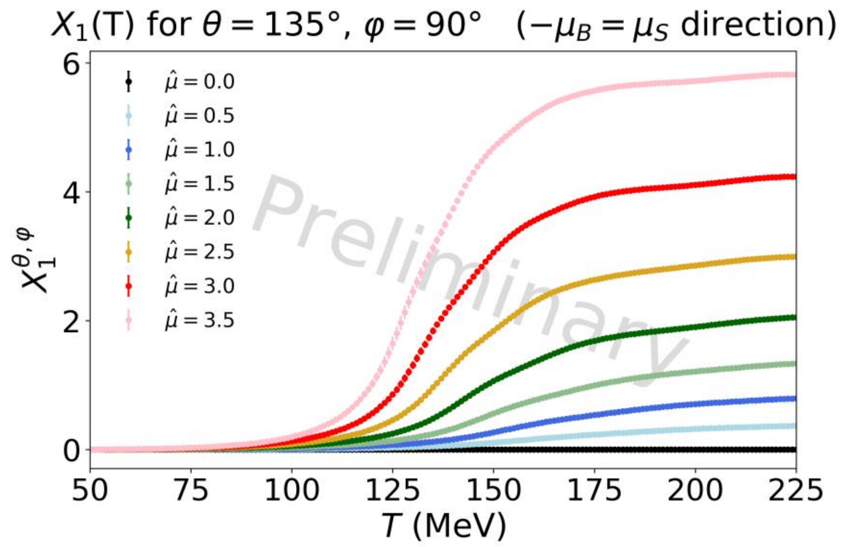
- Generalization of the previous 2D T'-Expansion Scheme to 3 conserved charges by projecting the "cartesian" (μ_B, μ_Q, μ_S) coordinates to spherical ones

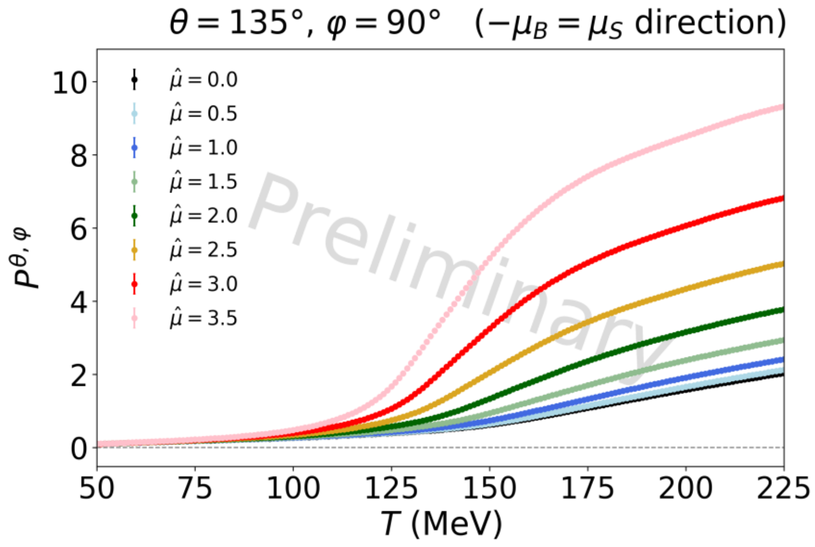


$$\hat{\mu} = \sqrt{\hat{\mu}_B^2 + \hat{\mu}_Q^2 + \hat{\mu}_S^2}$$

$$\hat{\mu}_B = \hat{\mu} \,.\, \cos(\theta)$$
$$\hat{\mu}_Q = \hat{\mu} \,.\, \sin(\theta)\cos(\varphi)$$
$$\hat{\mu}_S = \hat{\mu} \,.\, \sin(\theta)\sin(\varphi)$$

⟶ still a 2D-TExS expansion, along a constant μ/T line





J.J., P. Parotto, C. Ratti et al., (*in preparation*)

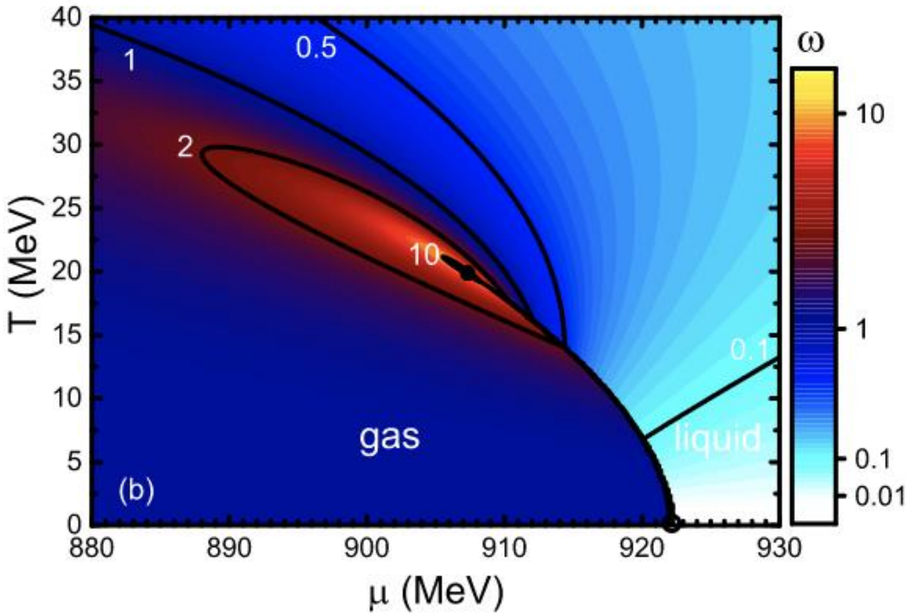
HADRON RESONANCE GAS (HRG) MODEL

Range: $0 < T < 160$ MeV ; $\mu_B < 930$ MeV

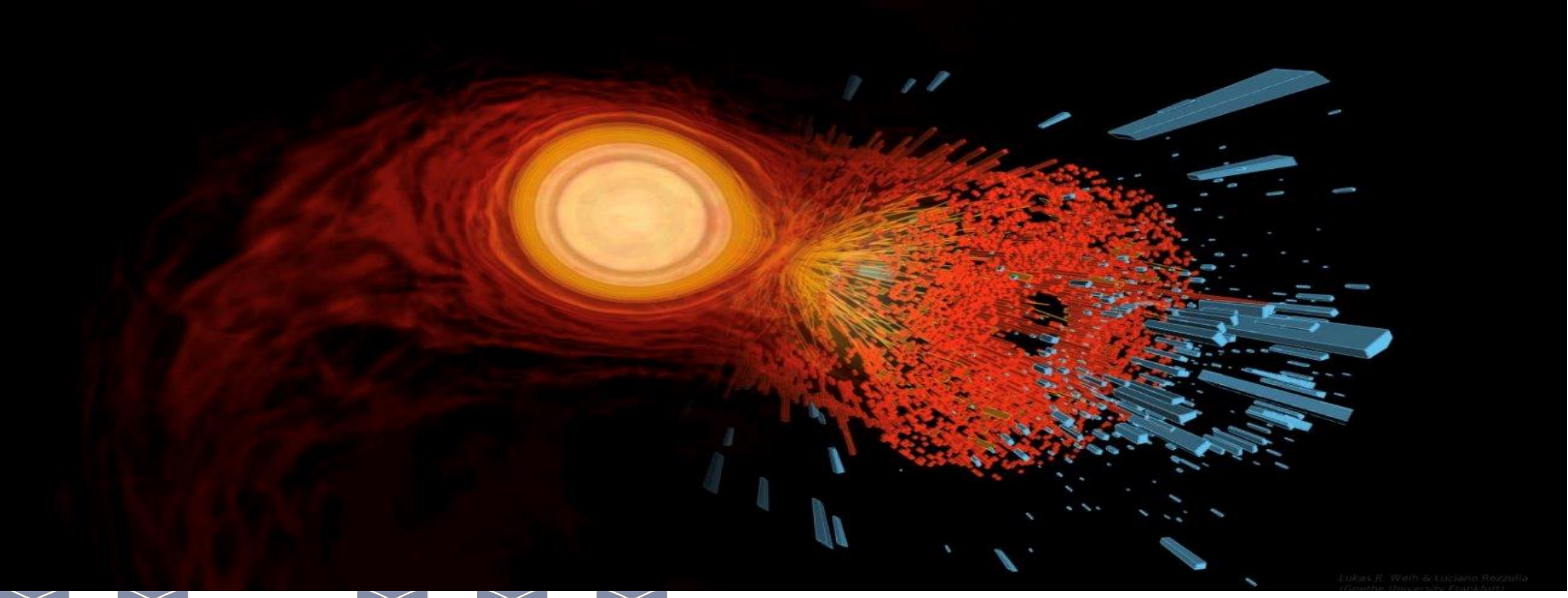
In development

- HRG model provides a well-established and realistic EoS at low temperatures
- **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 (van Der Waals)**
- Describes the liquid-gas phase transition

Goals:
- Implementing FIST into module for thermodynamics results
- Give flexibiliy on the particle list as input
- Extend hadronic spectrum to the most updated PDG list

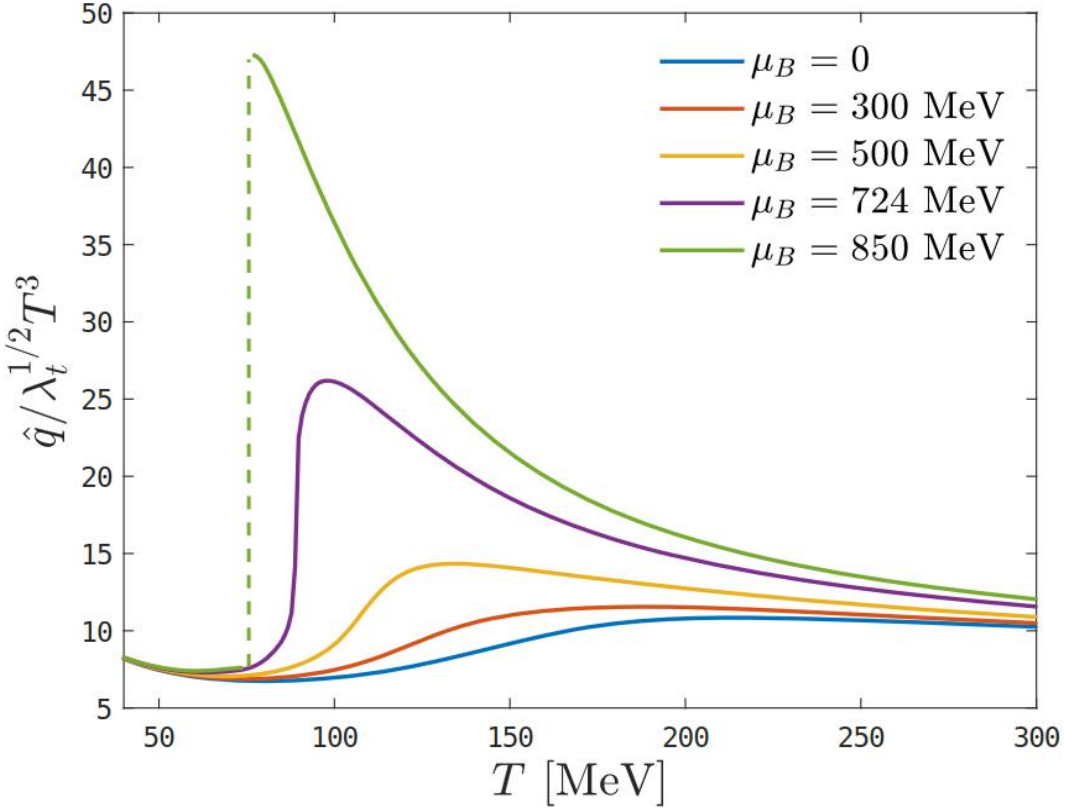


V. Vovchenko, H. Stoecker & M. Gorenstein., PRL (2017)
V. Vovchenko, H. Stoecker, Comput. Phys. Com. (2019)



OBSERVABLES & TOOLS

OBSERVABLES FOR HEAVY-IONS



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

  J. Grefa, C. Ratti et al., PRD (2022)

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

  V. Vovchenko et al., PRC (2016)

ADDITIONAL TOOLKIT 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

A. Nava, J.J., C. Ratti et al. (*in preparation*)

- **PDG21+ list**
  - Add up all resonances from PDG (from * to *****)
  - Create decay channels through radiation for unknown higher energy baryons

J. Salinas San Martin, R. Hirayama, et al. (2016)

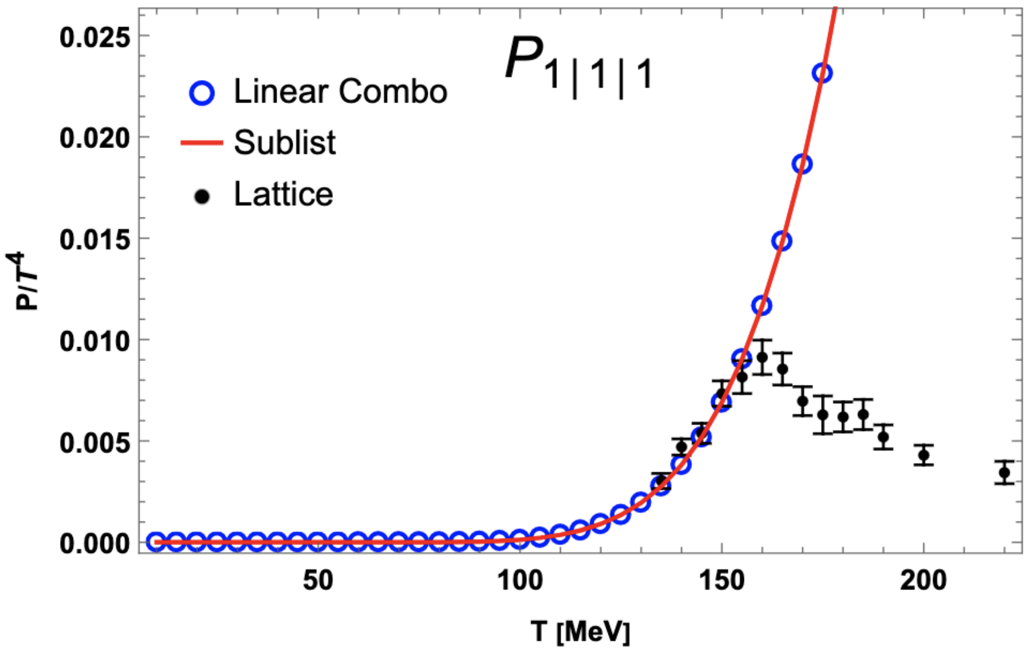


Figure 5.11: $P_{1|1|1} = -\frac{1}{4}\chi_{13}^{SQ} + \frac{1}{4}\chi_{22}^{SQ} - \frac{1}{4}\chi_{112}^{BSQ} + \frac{1}{4}\chi_{121}^{BSQ}$

TOOLKIT FOR NEUTRON STARS

- **Lepton module**
  - Takes in nuclear EoS
  - Compute the charged lepton densities necessary to ensure having charge neutrality

Outlooks:
- include neutrinos
- include photons

RELEASE

- **Flavour equilibration**
  - β-equilibrium (by balancing rates)
  - Given an EoS, computes:
    - Urca rates
      ($n \to p + e + \bar{\nu}_e$ / $p + e \to n + \nu_e$)
    - Equilibrium charge fractions
    - Relaxation rates
    - Damping time
    - Susceptibilities
    - Bulk viscosity

RELEASE

M. Alford, A. Haber et al., Universe (2021)
M. Alford, A. Haber et al., PRC (2024)

- **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

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OBSERVABLES FOR NEUTRON STARS

- **QLIMR module**

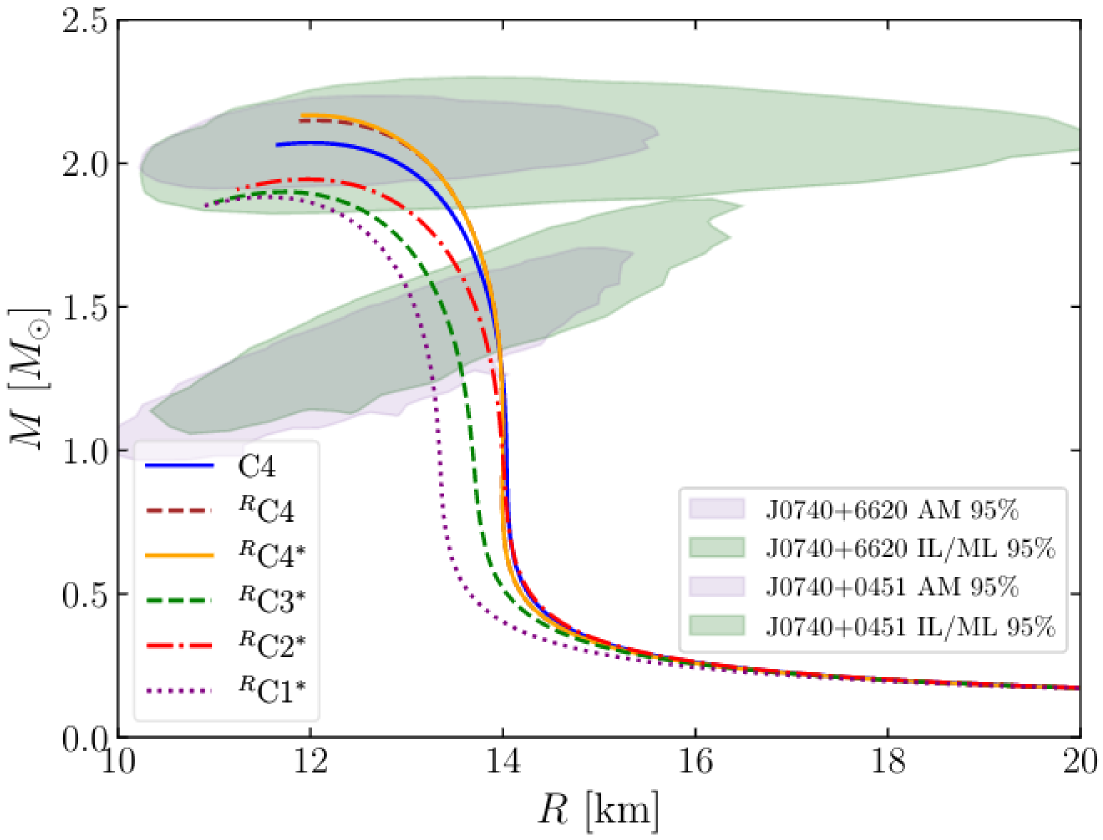
  Given an EoS, solves the Tolmann-Oppenheimer-Volkoff (TOV) equations

$$\frac{dP}{dr} = -\frac{G\epsilon(r)m(r)}{c^2r^2}\left[1+\frac{P(r)}{\epsilon(r)}\right]\left[1+\frac{4\pi r^3 P(r)}{m(r)c^2}\right]\left[1-\frac{2Gm(r)}{c^2 r}\right]^{-1}$$

  and computes:

  - Q: quadrupole moment Q of NS
  - L: tidal Love number (tidal force deformability)
  - I: moment of inertia
  - M: mass of NS (+Δm to correct for rotation)
  - R: radius of NS (+ΔR to correct for HRG too)
  - Local function p(R), m(R)…

RELEASE



R. Kumar, V. Dexheimer et al., PRD 109 (2024) muses Docs Login

muses // Calculation Engine

Getting started

- Read the Quick Start guide to setup your account and learn how to run workflows.
- Ask for help and join the discussion on our community support forum.

What is the Calculation Engine?

The Calculation Engine (CE) 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. **You can also run the CE yourself, either on a single machine using Docker Compose or on a Kubernetes cluster using our Helm chart!**

What are MUSES modules?

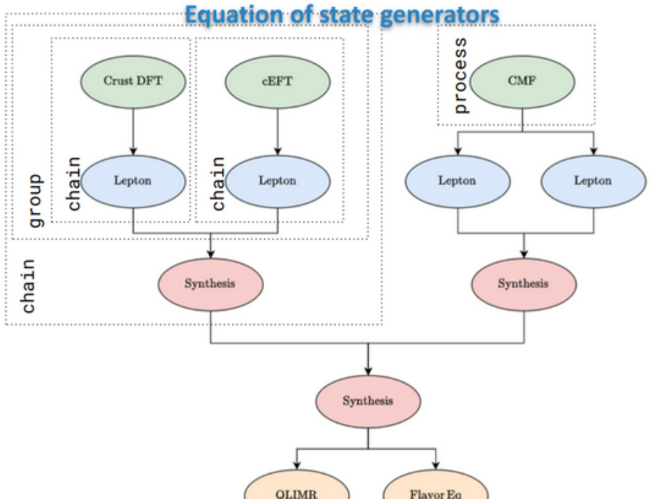
Modules are the atomic processing units of a MUSES workflow. There are several types of modules, including those that calculate equations of state (EoS) and those that derive observable quantities from the EoS.

The equation of state modules include:

- **Chiral EFT** – `chiral_eft (v0.9.0)`
- **Chiral Mean Field** – `cmf_solver (v0.9.3)`

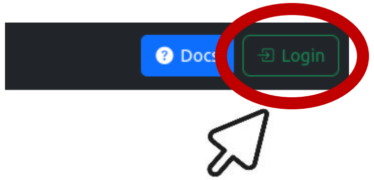
What are workflows?

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 generates reproducible results to download and analyze. Learn more about MUSES workflows here.



PUBLIC RELEASE

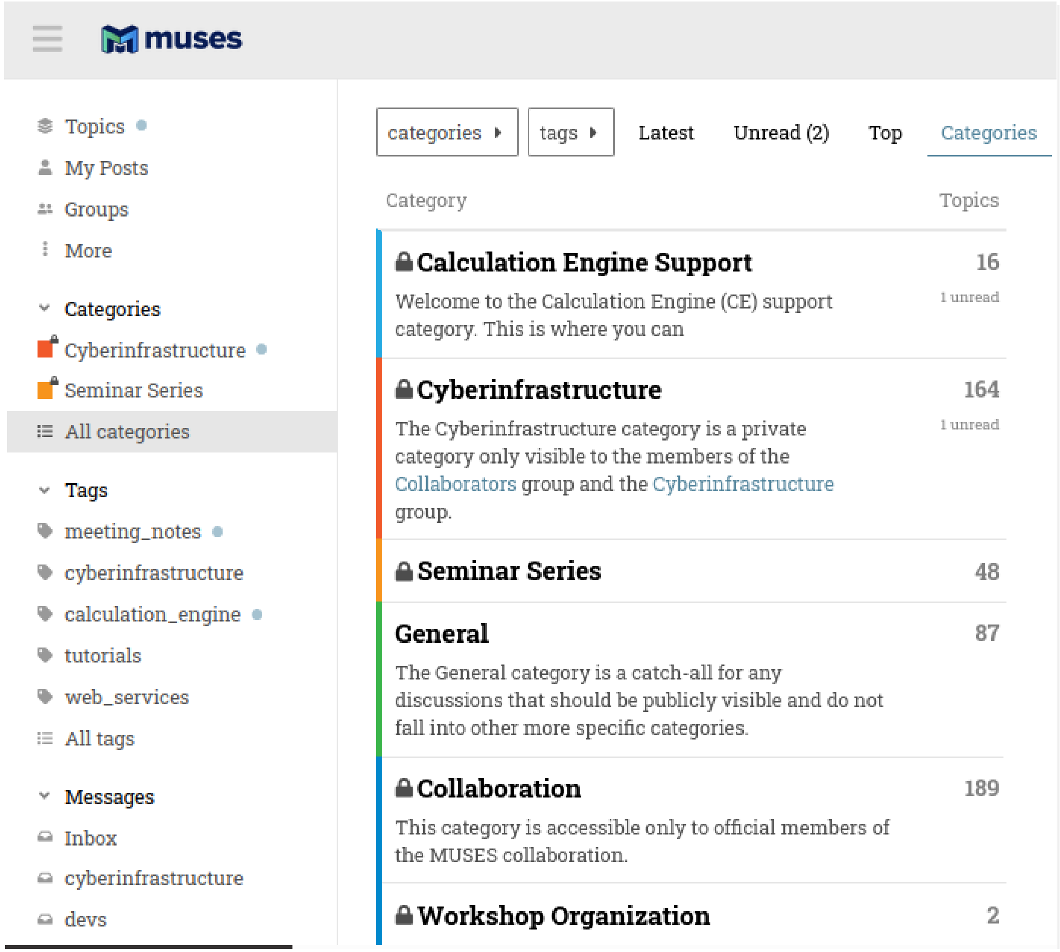
USING THE MUSES CALCULATION ENGINE



What is the Calculation Engine?

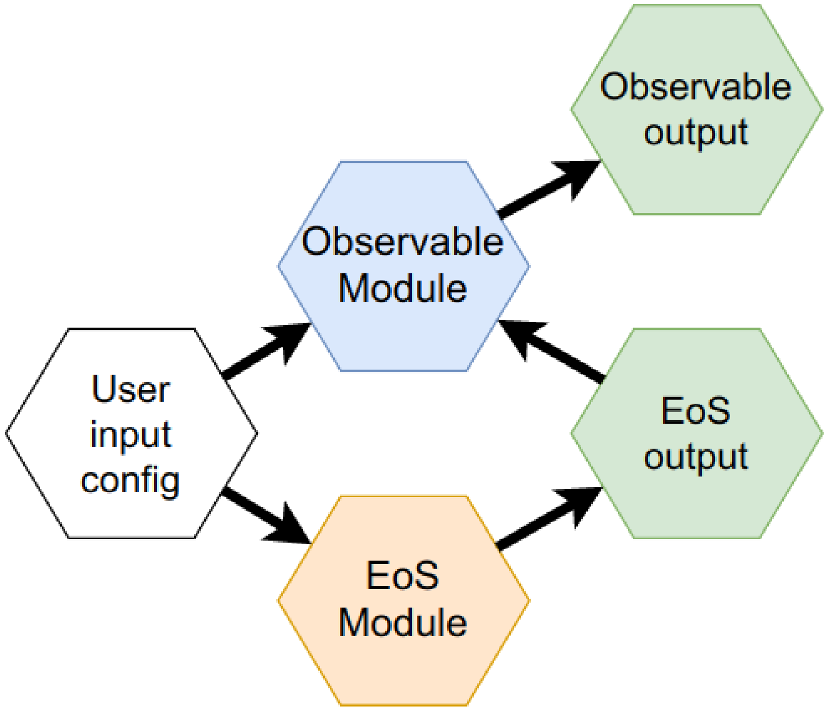
The Calculation Engine (CE) is an application that lets you **run scientific calculations as composable workflows**, constructed from a growing library of MUSES modules.

- Modules can be run on a dedicated cluster (access given via login)
- Online documentation on the use of the CE, the different modules, etc.
- Forum as a platform for users-developers exchanges about support, feedback…

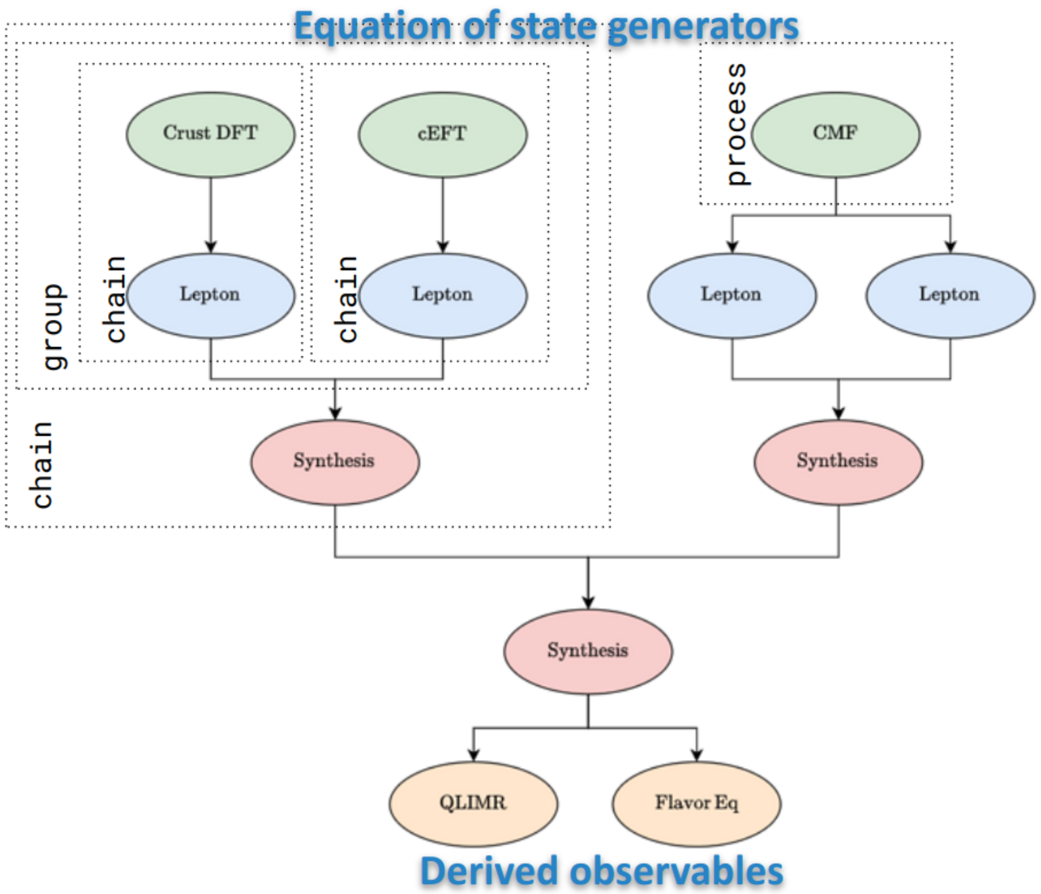


WORKFLOWS IN MUSES

- Example of a typical workflow within MUSES, implying EoS generation + observable calculation



- More complex workflows can also be defined



CONCLUSIONS

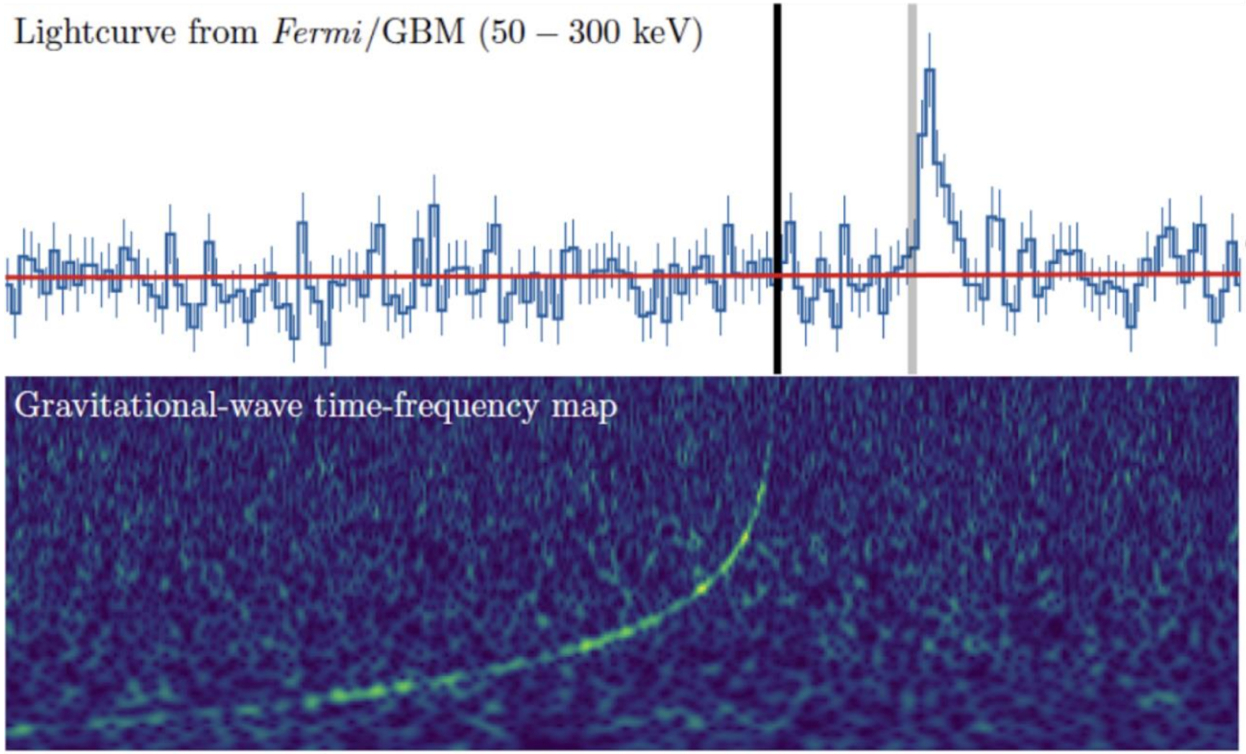
- MUSES will provide a public-accessible framework with a single friendly-user interface, to compute EoSs and related observables from different approaches
- Public release planned for Nov. 2024: open access soon!
  - 3 modules for NS EoS
  - 3 modules for HI EoS
  - 2 toolkit modules / 1 observable modules
- Most modules have plans for improvement (→ 1.1.0)

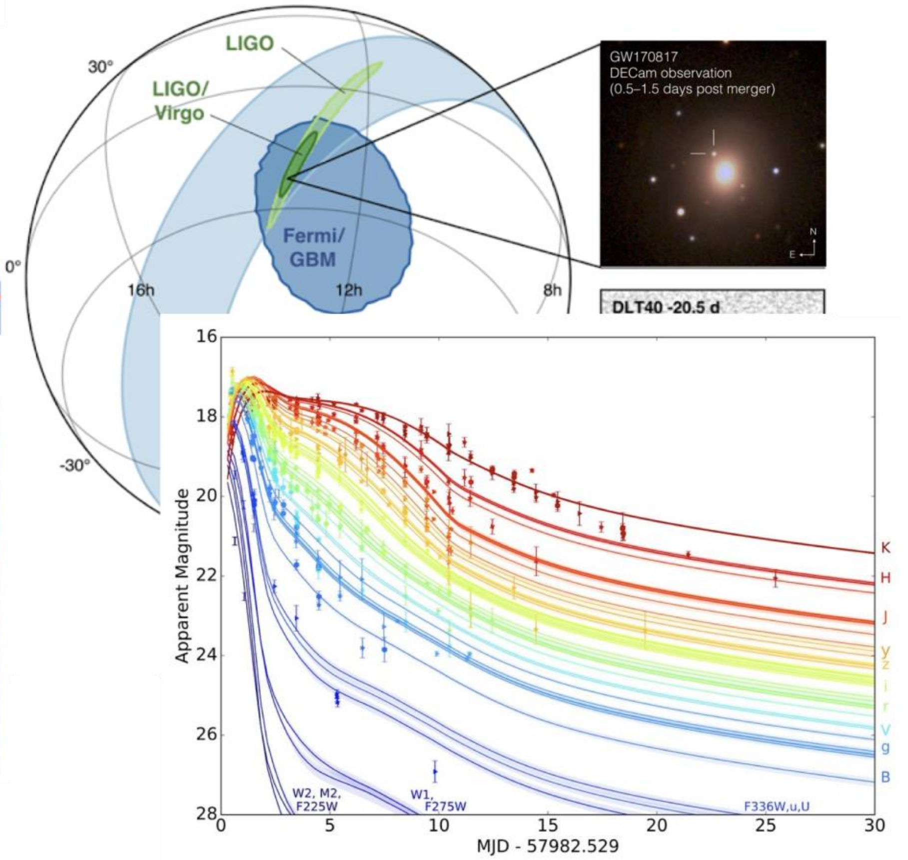
Suggestions, feedback and new collaborators are welcome!

Backup slides

GW170817

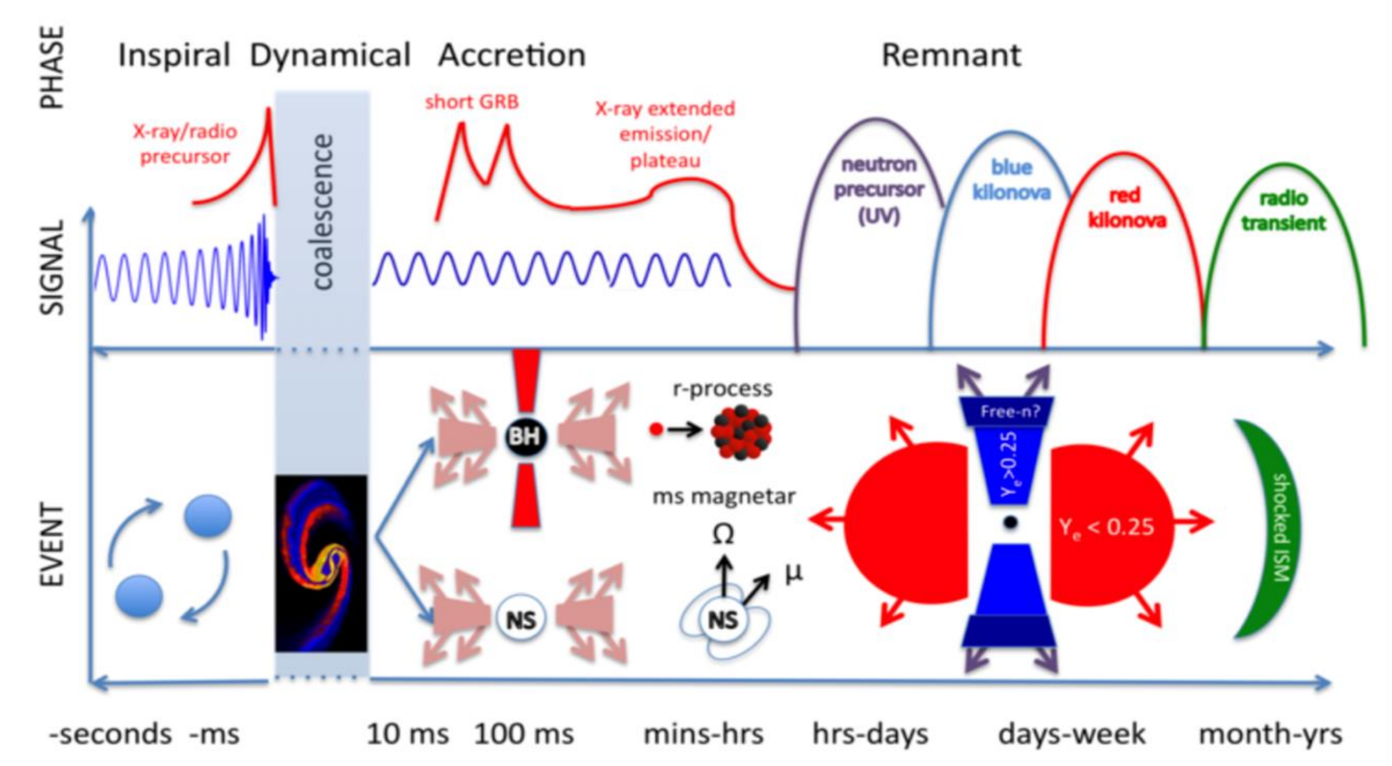
Demonstrated the ability of mergers to advance nuclear physics



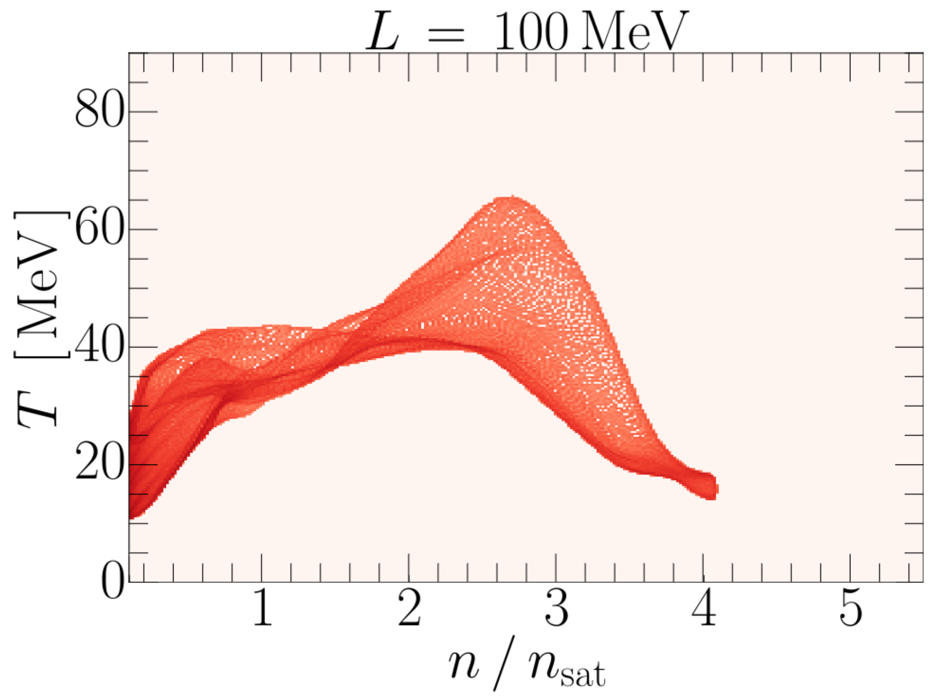


LIGO/Virgo PRL (2017)
P.S. Cowperthwaite et al., Astrophys. J. Lett. (2017)

ANATOMY OF A NEUTRON STAR MERGER

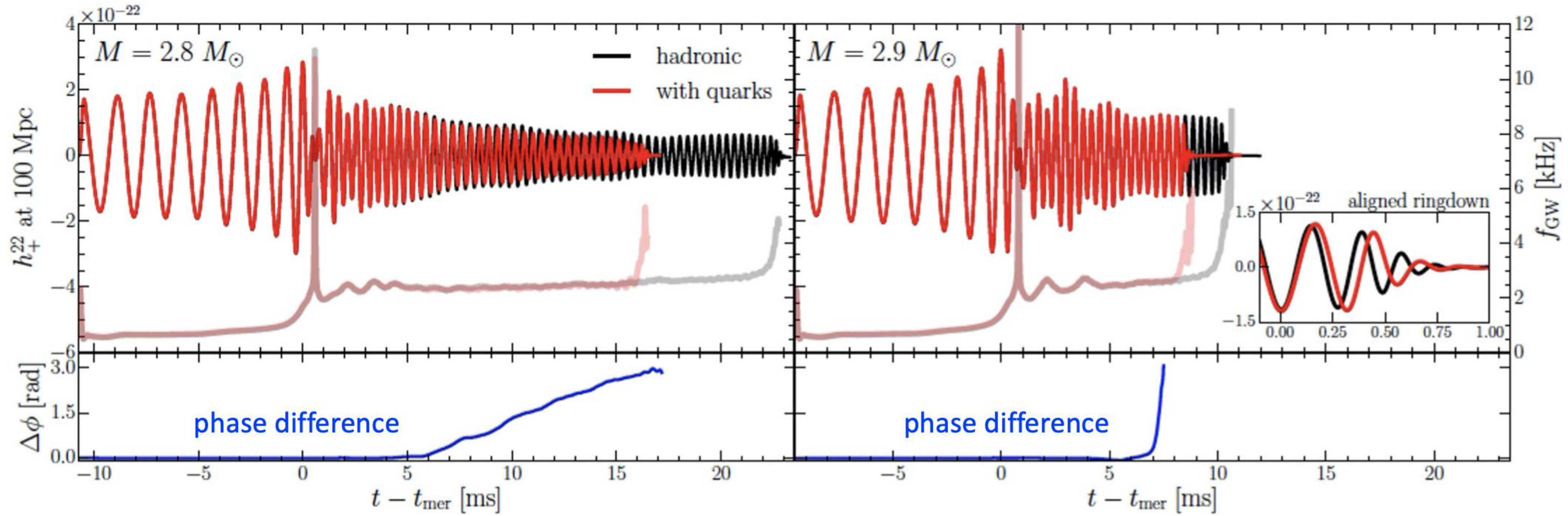


Fernandez & Metzger (2016)



E.R. Most, C.A. Raithel, PRD 104 (2021)

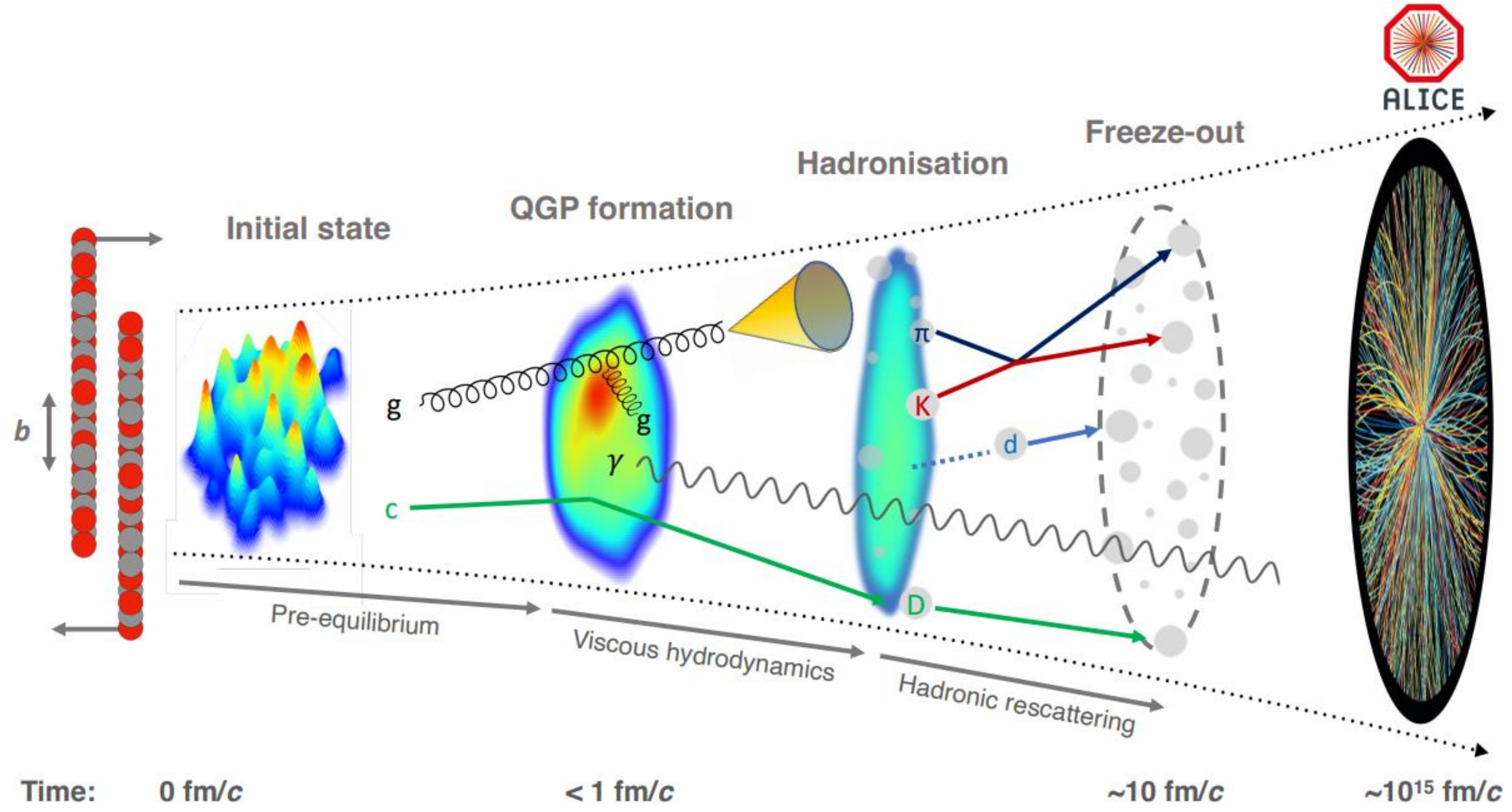
NEUTRON STAR MERGER AND THE EOS

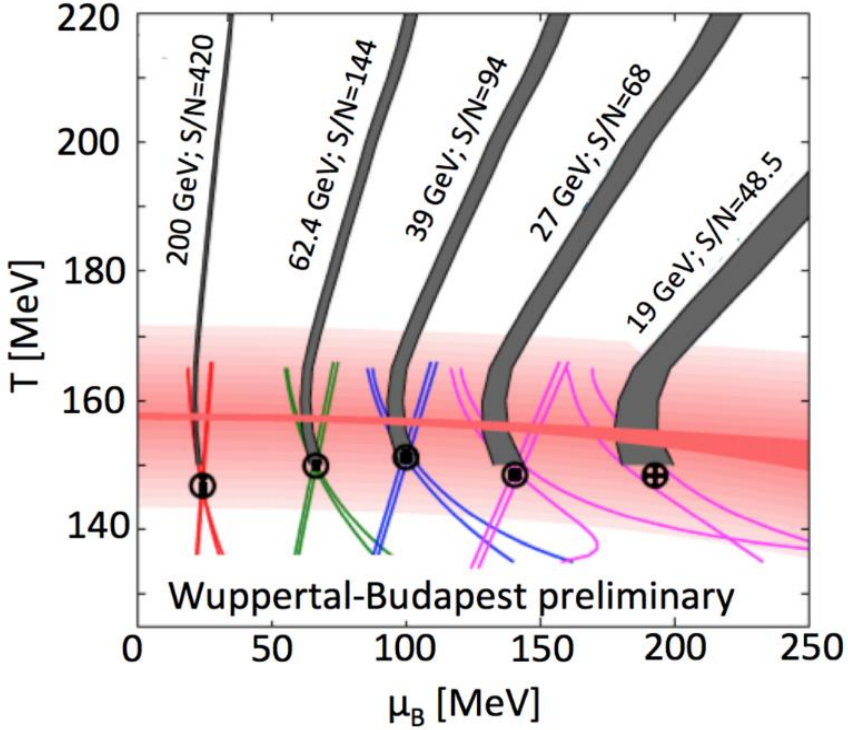


E.R. Most, V. Dexheimer et al., PRL (2019)

- 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

ANATOMY OF A HEAVY-ION COLLISION





The ALICE experiment: A journey through QCD, CERN-EP-2022-227 (2022)

THERMODYNAMICS RELATIONS

$$dp = sdT + nd\mu$$

$$n = \left(\frac{\partial p}{\partial \mu}\right)_T \qquad s = \left(\frac{\partial p}{\partial T}\right)_\mu$$

$$c_s^2 = \left(\frac{\partial p}{\partial \epsilon}\right)_{s/n} = \frac{n^2 \frac{\partial^2 p}{\partial T^2} - 2sn \frac{\partial^2 p}{\partial T \partial \mu} + s^2 \frac{\partial^2 p}{\partial \mu^2}}{(\epsilon + p)\left(\frac{\partial^2 p}{\partial T^2}\frac{\partial^2 p}{\partial \mu^2} - \frac{\partial^2 p}{\partial T \partial \mu}\frac{\partial^2 p}{\partial T \partial \mu}\right)}$$

$$c_V = \frac{T}{V}\left(\frac{\partial S}{\partial T}\right)_{V,N} = T\left(\frac{\partial s}{\partial T}\right)_n = \frac{T\left(\frac{\partial^2 p}{\partial T^2}\frac{\partial^2 p}{\partial \mu^2} - \frac{\partial^2 p}{\partial T \partial \mu}\frac{\partial^2 p}{\partial T \partial \mu}\right)}{\frac{\partial^2 p}{\partial \mu^2}}$$

EQUATION OF STATE FROM HOLOGRAPHY

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

RELEASE

String theory/Classical gravity in 5D	⟷	Quantum Field Theory in 4D

By solving the equations of motion (EoM) for a 5D Einstein-Maxwell-Dilaton (EMD) model defined by the following action:

$$S = \frac{1}{2\kappa_5^2}\int_{M_5} d^5x\,\sqrt{-g}\left[R - \frac{(\partial_\mu\phi)^2}{2} - V(\phi) - \frac{f(\phi)F_{\mu\nu}^2}{4}\right]$$

(simplest action reproducing a realistic 4D QCD EFT)

...one can obtain the following thermodynamic quantities by

- using the UV behavior of the EMD fields
- fixing free parameters Λ, κ_5 and the functional form of $V(\phi)$ and $f(\phi)$ by matching with lQCD results at $\mu_B = 0$

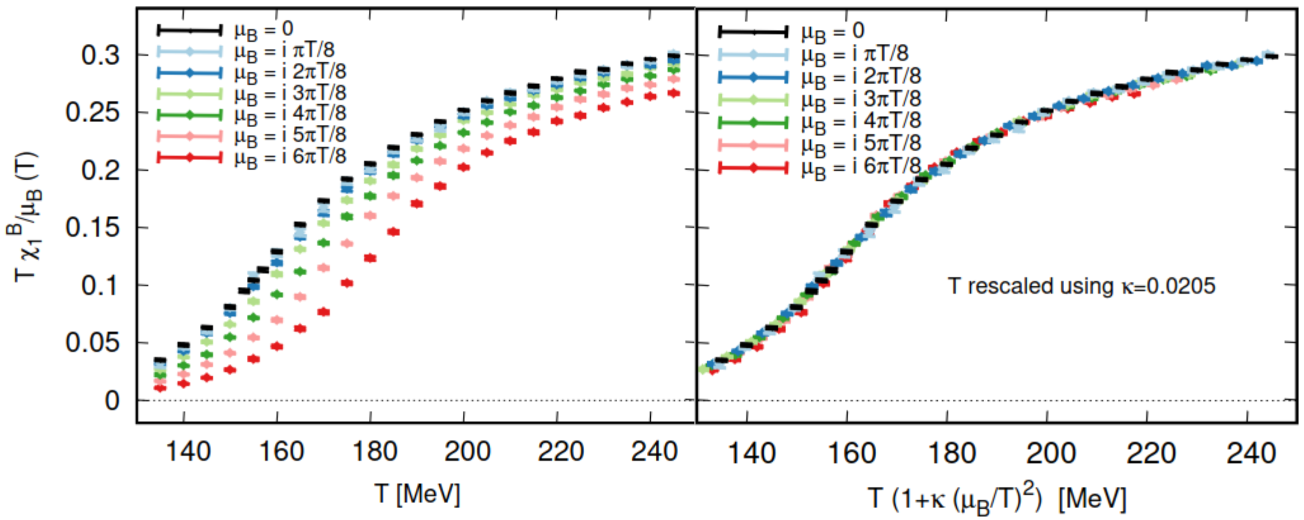
$$T = \frac{1}{4\pi\phi_A^{1/\nu}\sqrt{h_0^{far}}}\Lambda \qquad s = \frac{2\pi}{\kappa_5^2\phi_A^{3/\nu}}\Lambda^3$$

$$\mu_B = \frac{\Phi_0^{far}}{\phi_A^{1/\nu}\sqrt{h_0^{far}}}\Lambda \qquad \rho_B = -\frac{\Phi_2^{far}}{\kappa_5^2\phi_A^{3/\nu}\sqrt{h_0^{far}}}\Lambda^3$$

2D ISING-T.EX.S EQUATION OF STATE FROM L-QCD

RELEASE

Range: 30 MeV < T < 800 MeV ; $\mu_{B/Q/S}$ < 700 MeV



Empirical observation:

- all 1st order susceptibilities scale when defining a μ_B-dependent temperature $T'(T, \mu_B)$
- scales like: $$\boxed{\frac{\chi_1^B(T,\hat{\mu}_B)}{\hat{\mu}_B} = \chi_2^B(T',0)}$$

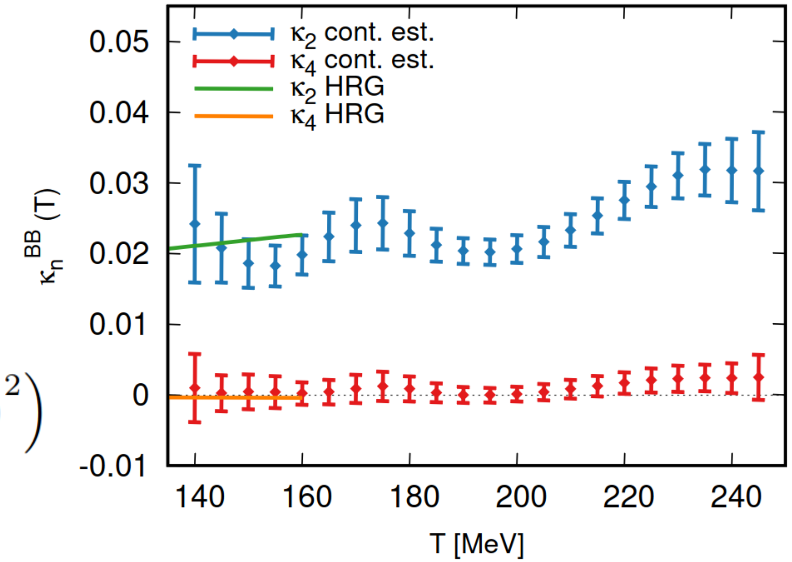
<u>*Main identity*</u>

one can thus redefine temperature and use an alternative expansion scheme:

$$T'(T,\hat{\mu}_B) = T\left(1+\kappa_2^{BB}(T)\hat{\mu}_B^2+\kappa_4^{BB}(T)\hat{\mu}_B^4+\mathcal{O}(\hat{\mu}_B^6)\right)$$

with alternative expansion coefficients *κ*, related to susceptibilities:

$$\kappa_2^{BB}(T) = \frac{1}{6T}\frac{\chi_4^B(T)}{\chi_2^{B\prime}(T)} \qquad \kappa_4^{BB}(T) = \frac{1}{360\chi_2^{B\prime}(T)^3}\left(3\chi_2^{B\prime}(T)^2\chi_6^B(T) - 5\chi_2^{B\prime\prime}(T)\chi_4^B(T)^2\right)$$



M. Kahangirwe, J.J., C. Ratti et al., PRD (2024); arXiv:2402.08636

2D ISING-T.EX.S EQUATION OF STATE FROM L-QCD

α-RELEASE

Range: 30 MeV < T < 800 MeV ; $\mu_{B/Q/S}$ < 700 MeV

Implement scaling behavior of 3D-Ising model EoS:

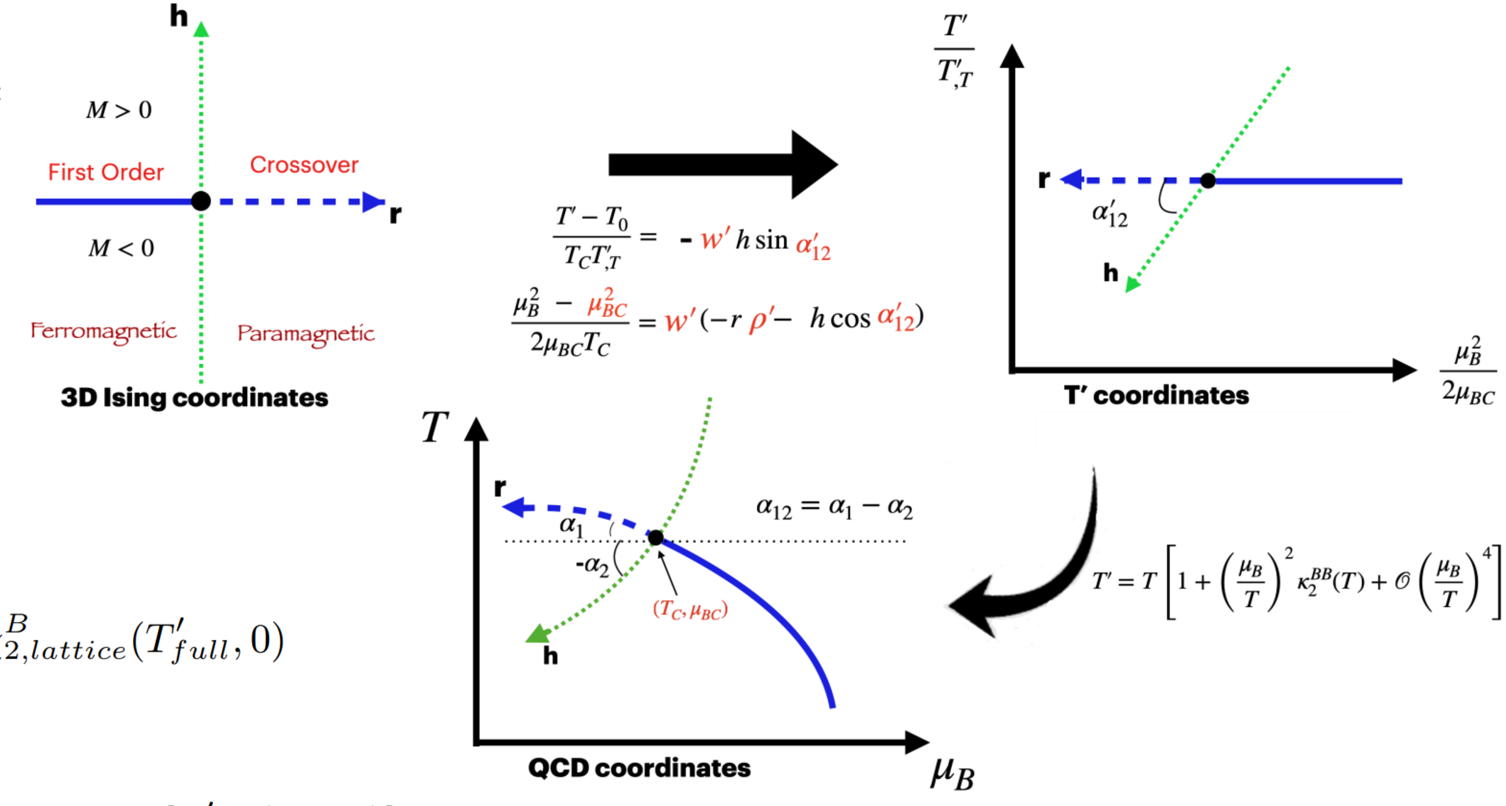
- Define map from 3D-Ising model to QCD

- Estimate contribution to Taylor coefficients from 3D-Ising model critical point

- Reconstruct full baryon density $\frac{n_B^{full}(T,\mu_B)}{(\mu_B/T)T^3} = \chi^B_{2,lattice}(T'_{full},0)$

with

$$T'_{full}(T,\mu_B) = \underbrace{T'_{lattice}(T,\mu_B)}_{\text{lowest orders in } (\mu_B/T)} + \underbrace{T'_{crit}(T,\mu_B) - Taylor[T'_{crit}(T,\mu_B)]}_{\text{higher order in } (\mu_B/T)}$$

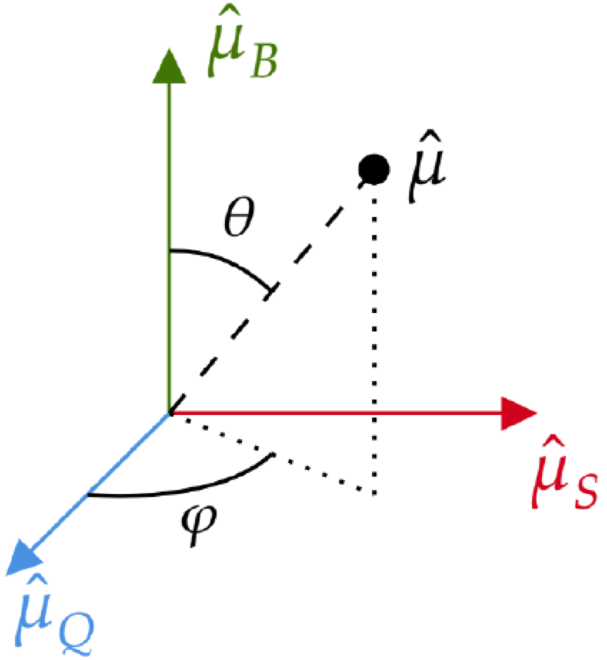


$$T'_{crit}(T,\mu_B) \approx \left(\frac{\partial \chi^B_{2,lat}(T,0)}{\partial T}\Big|_{T_0}\right)^{-1} \frac{n_B^{crit}(T,\mu_B)}{(\mu_B/T)}$$

M. Kahangirwe, J.J., C. Ratti et al., PRD (2024); arXiv:2402.08636

4D-T.EX.S EQUATION OF STATE FROM L-QCD

Range: T < 800 MeV ; $\mu_{B/Q/S}$ <? 700 MeV



- Generalization of the previous 2D T'-Expansion Scheme to 3 conserved charges by projecting the "cartesian" (μ_B, μ_Q, μ_S) coordinates to spherical ones

$$\hat{\mu} = \sqrt{\hat{\mu}_B^2 + \hat{\mu}_Q^2 + \hat{\mu}_S^2}$$

$$\begin{aligned} \hat{\mu}_B &= \hat{\mu}\,.\cos(\theta) \\ \hat{\mu}_Q &= \hat{\mu}\,.\sin(\theta)\cos(\varphi) \\ \hat{\mu}_S &= \hat{\mu}\,.\sin(\theta)\sin(\varphi) \end{aligned}$$

$\longrightarrow$ still a 2D-TExS expansion, along a constant μ/T line

- Calculate expansion coefficient λ_2 based on so-called "generalized susceptibilities" $X_{2/4}$ *(linear combinations of lattice QCD susceptibilities)* + their Stefan-Boltzmann limits

$$\lambda_2^{\theta,\varphi}(T) = \frac{1}{6T}\frac{1}{X_2'^{\theta,\varphi}(T)} \times \left(X_4^{\theta,\varphi}(T) - \frac{\overline{X}_4^{\theta,\varphi}(0)}{\overline{X}_2^{\theta,\varphi}(0)} X_2^{\theta,\varphi}(T) \right)$$

$$X_2^{\theta,\varphi}(T) = c_\theta^2 \cdot \chi_2^B(T) + s_\theta^2 c_\varphi^2 \cdot \chi_2^Q(T) + s_\theta^2 s_\varphi^2 \cdot \chi_2^S(T) + \dots$$

$$X_4^{\theta,\varphi}(T) = c_\theta^4 \cdot \chi_4^B(T) + s_\theta^4 c_\varphi^4 \cdot \chi_4^Q(T) + s_\theta^4 s_\varphi^4 \cdot \chi_4^S(T) + \dots$$

4D-T.EX.S EQUATION OF STATE FROM L-QCD

Range: T < 800 MeV ; $\mu_{B/Q/S}$ <? 700 MeV

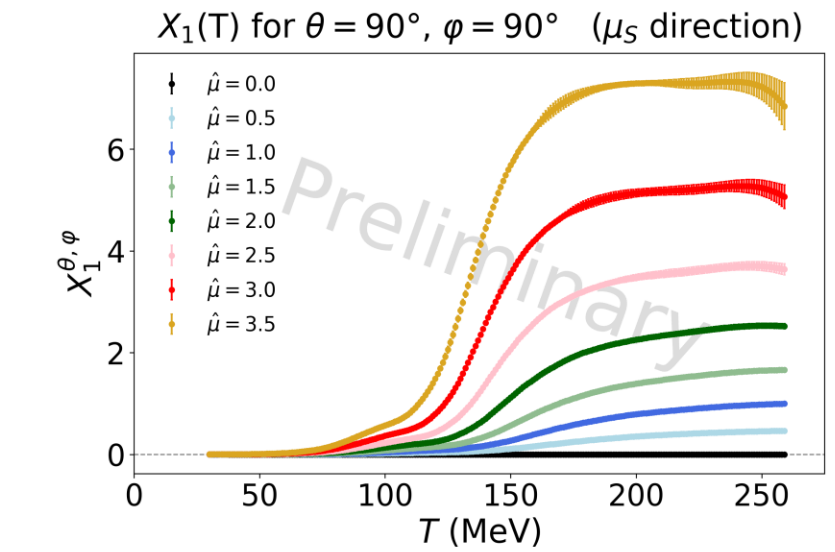
- Compute the "generalized charge density" X_1 along the projected line using the expanded temperature T' and the T.Ex.S main identity (modified to match with Stefan-Boltzmann limit at $T \longrightarrow \infty$)

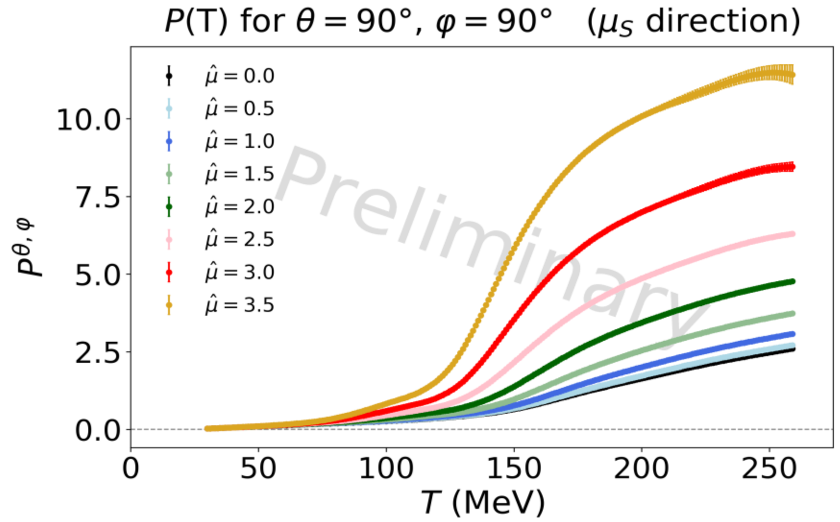
$$\boxed{X_1^{\theta,\varphi}(T,\hat{\mu}) = \frac{\overline{X}_1^{\theta,\varphi}(\hat{\mu})}{\overline{X}_2^{\theta,\varphi}(0)} \times X_2^{\theta,\varphi}\left(T'^{\theta,\varphi}(T,\hat{\mu}),0\right)}$$

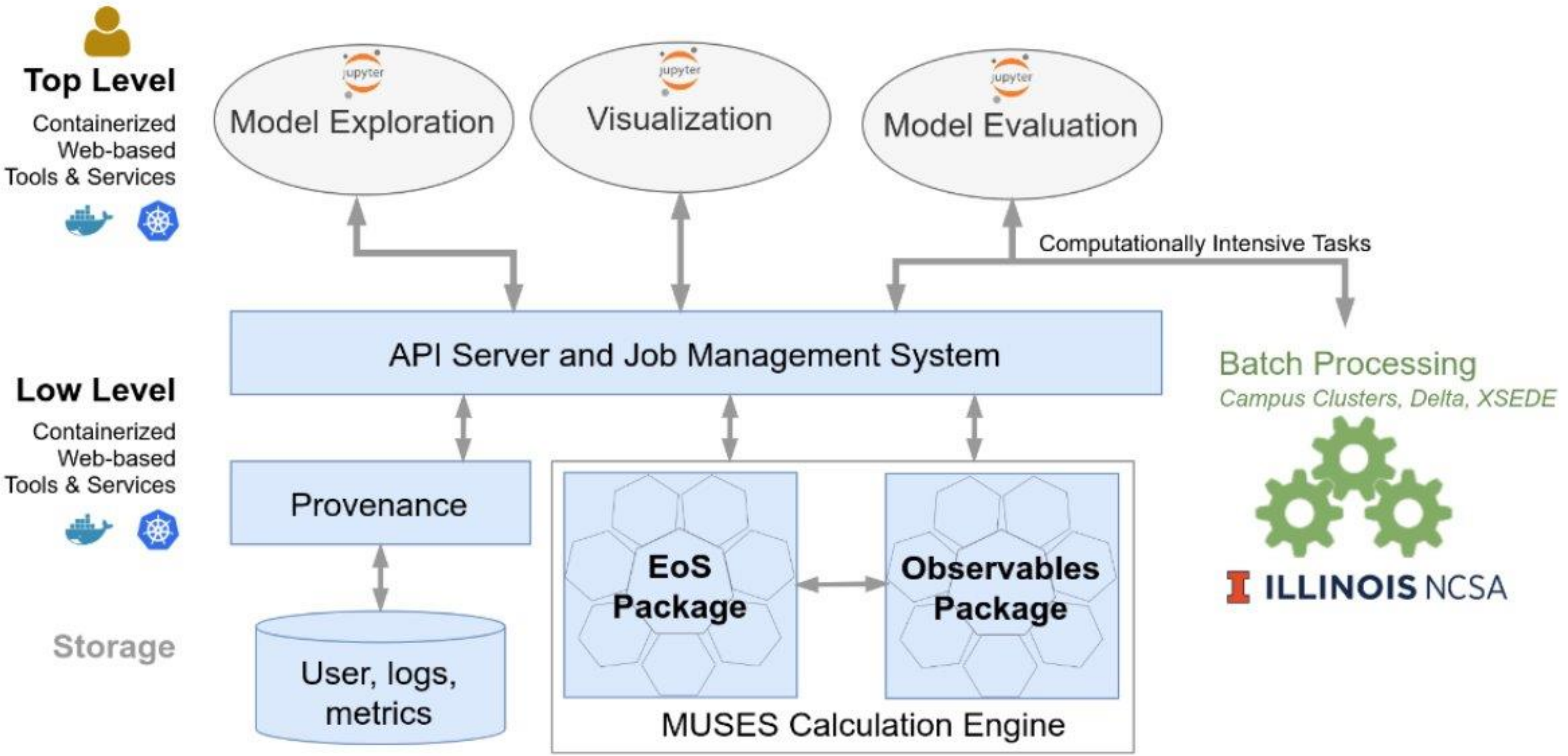
with $$T'^{\theta,\varphi}(T,\hat{\mu}) = T\left(1+\lambda_2^{\theta,\varphi}(T)\hat{\mu}_B^2\right)$$

- Obtain pressure by integrating X_1, allowing then to compute all thermodynamics

$$P^{\theta,\varphi}(T,\hat{\mu}) = P(T,0) + \int_0^{\hat{\mu}} X_1^{\theta,\varphi}(T,\hat{\mu}')d\hat{\mu}'$$



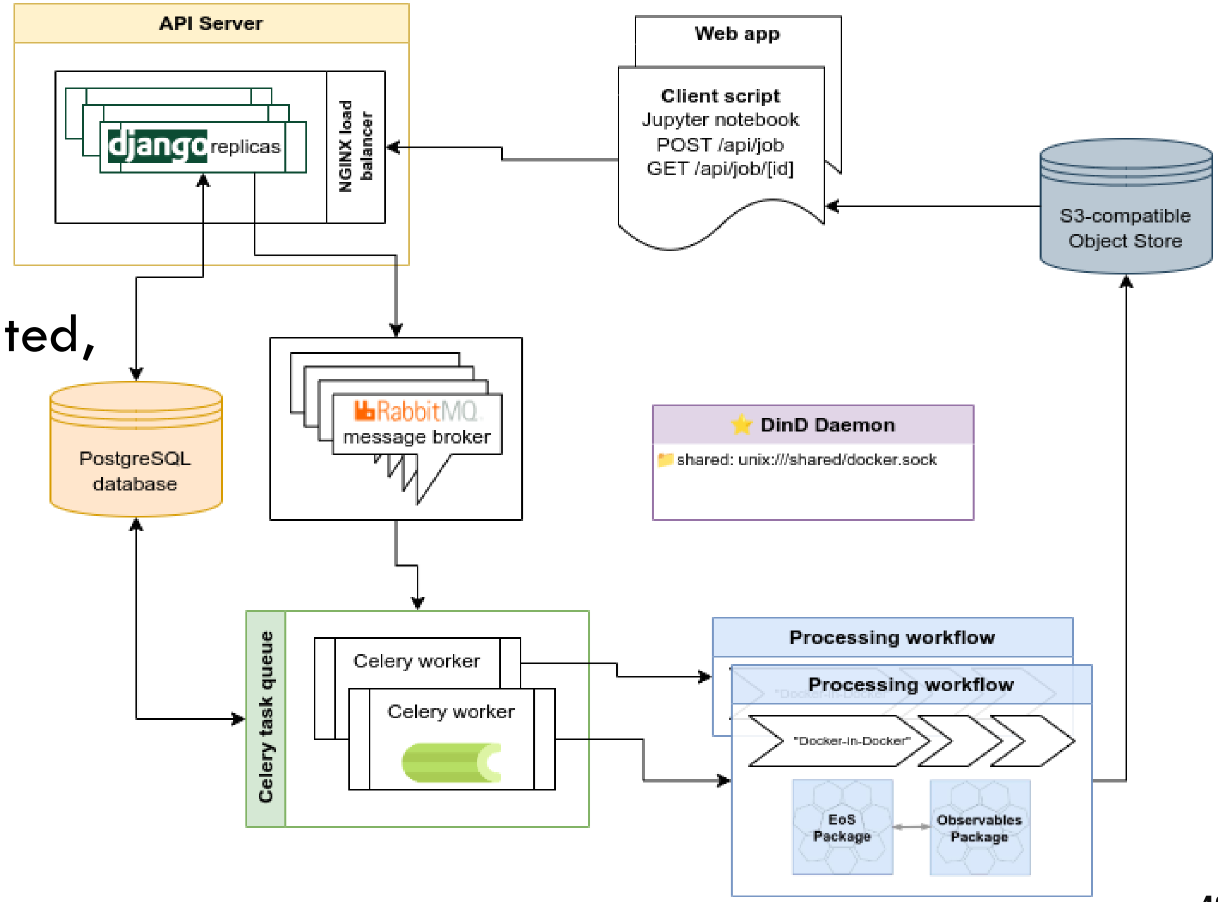




CYBERINFRASTRUCTURE

LOW-LEVEL SERVICES

- The client-facing API will handle communication with client applications through a webpage
- 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



TYPICAL MODULE DESIGN