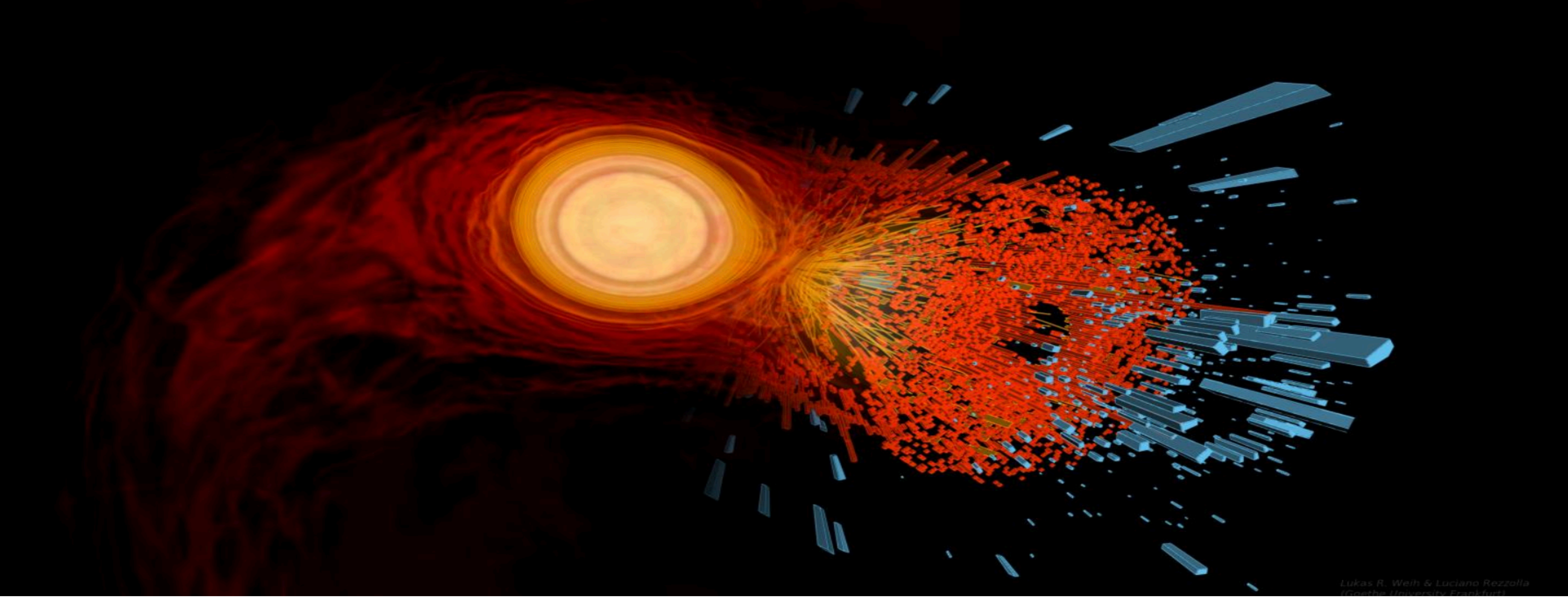


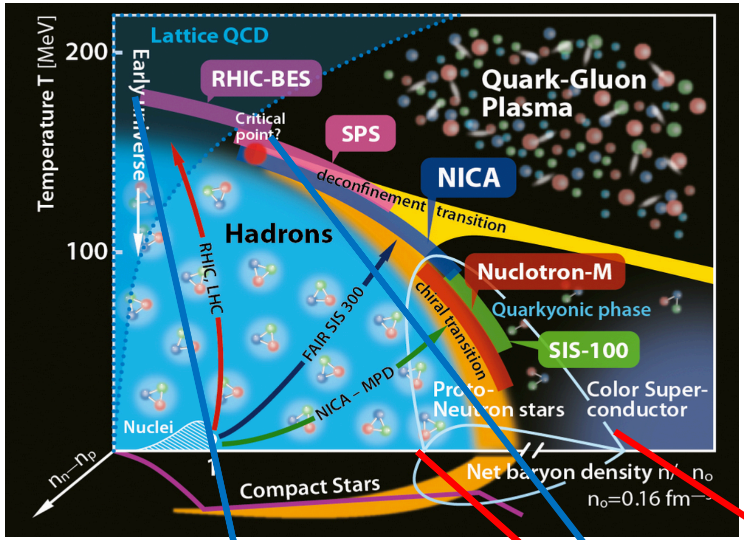
Lukas R. Weih & Luciano Rezzolla (Goethe University Frankfurt)

THE MUSES COLLABORATION

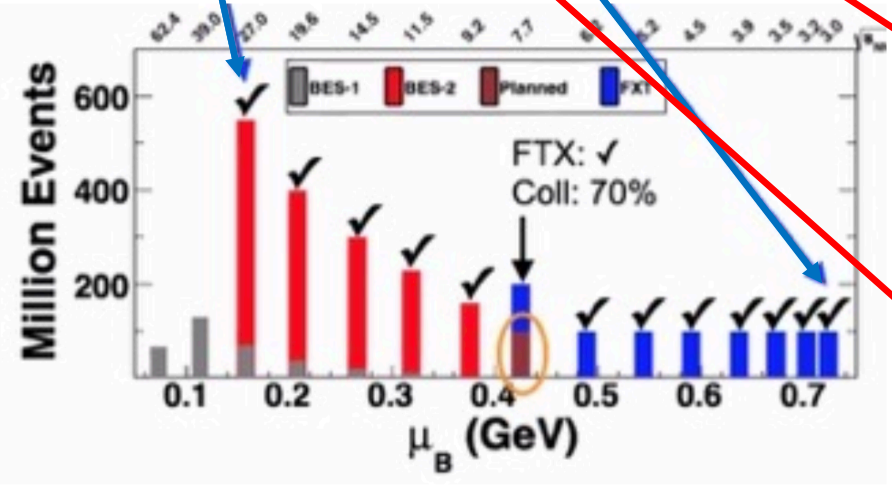
Claudia Ratti
University of Houston

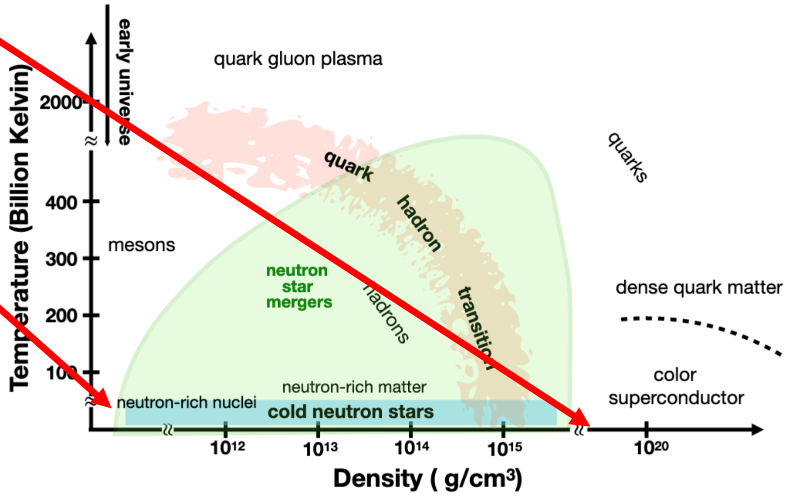
MOTIVATING SCIENCE GOALS

- Is there a critical point in the QCD phase diagram?
- Where is the transition line at high density?
- What are the phases of QCD at high density?
- Are we creating a thermal medium in experiments?
- What is the nature of neutron-rich nuclei? How are heavy nuclei created and what is the site of the r-process?



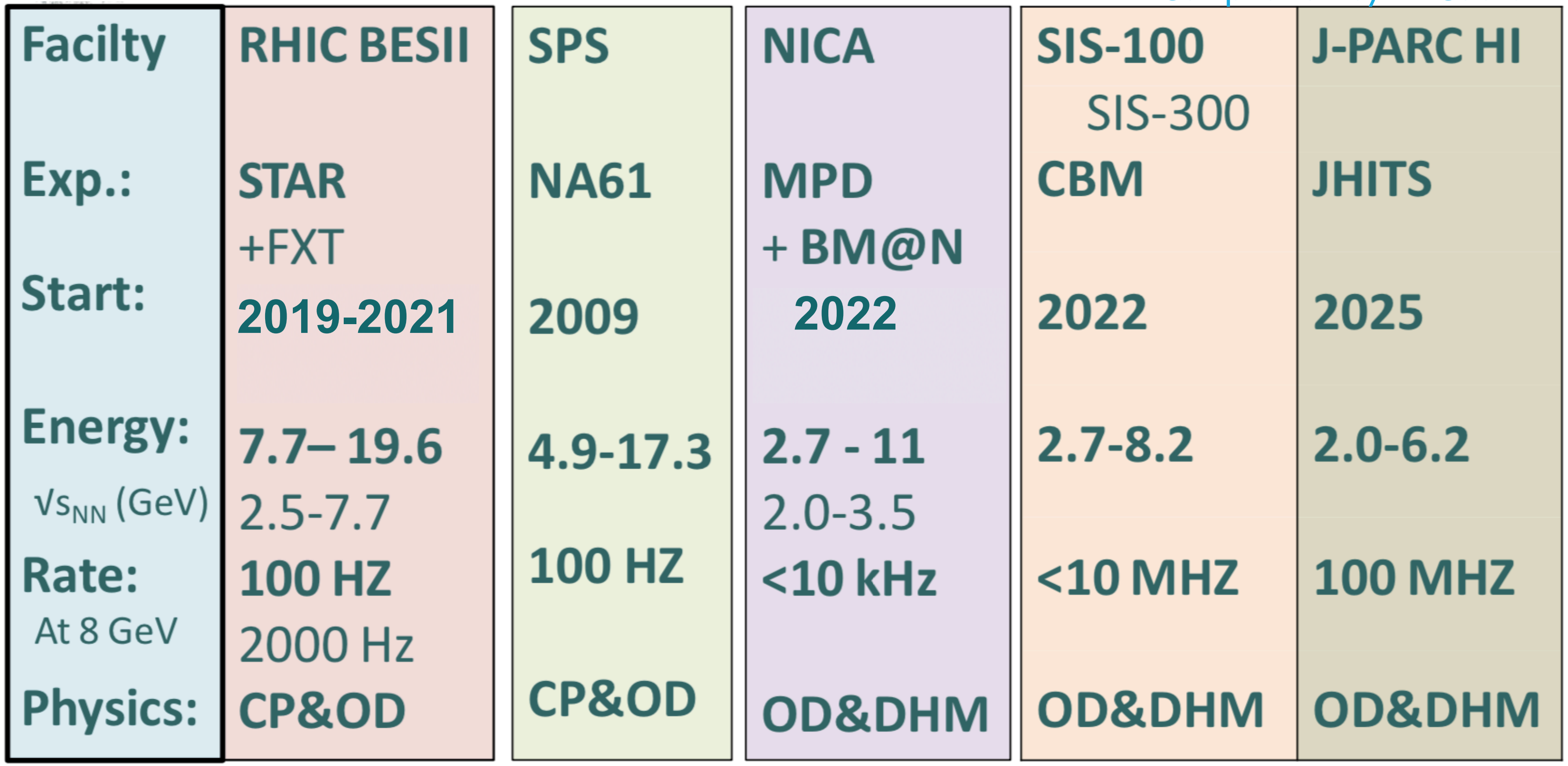
- Run 2019:
  - Collider: $\sqrt{s_{NN}}$=14.6, 19.6, 200 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.2 GeV
- Run 2020:
  - Collider: $\sqrt{s_{NN}}$=9.2, 11.5 GeV
  - Fixed target: $\sqrt{s_{NN}}$=3.5, 3.9, 4.5, 5.2, 6.2, 7.2, 7.7 GeV
- Run 2021:
  - Collider: $\sqrt{s_{NN}}$=7.7 GeV





TERRESTRIAL FACILITIES FOR FINITE-DENSITY QCD

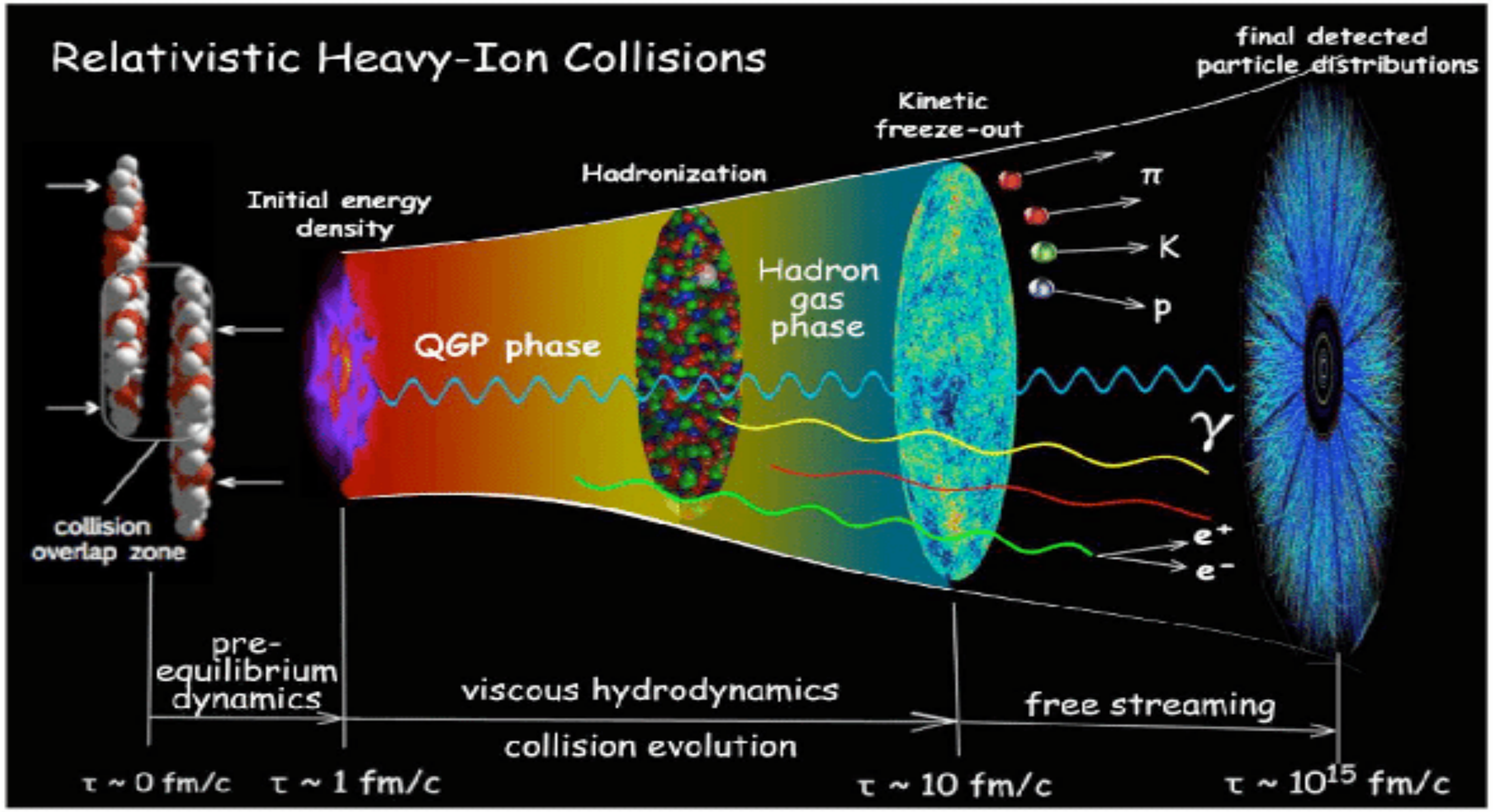
Compilation by D. Cebra

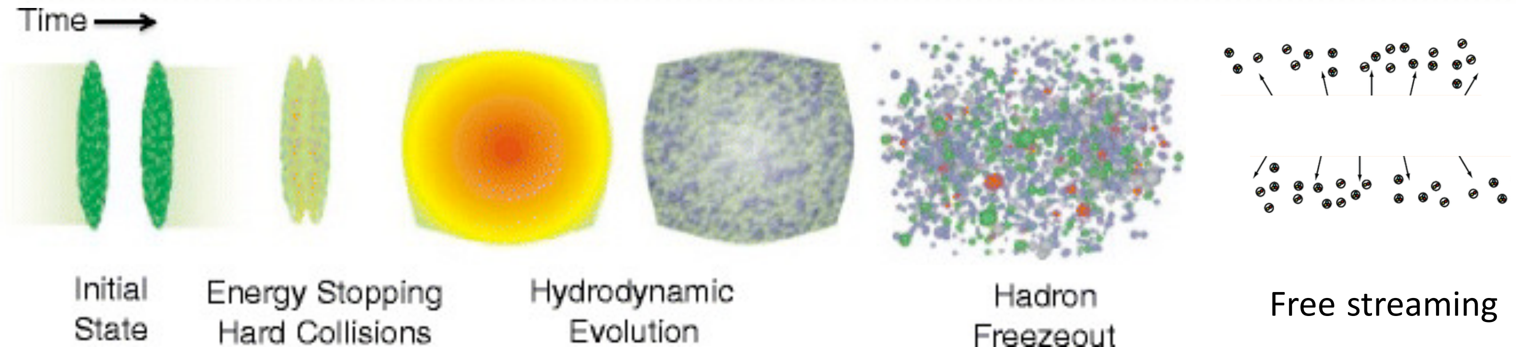


Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-2021	2009	2022	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed target	Fixed target Lighter ion collisions	Collider Fixed target	Fixed target	Fixed target

CP=Critical Point OD= Onset of Deconfinement DHM=Dense Hadronic Matter

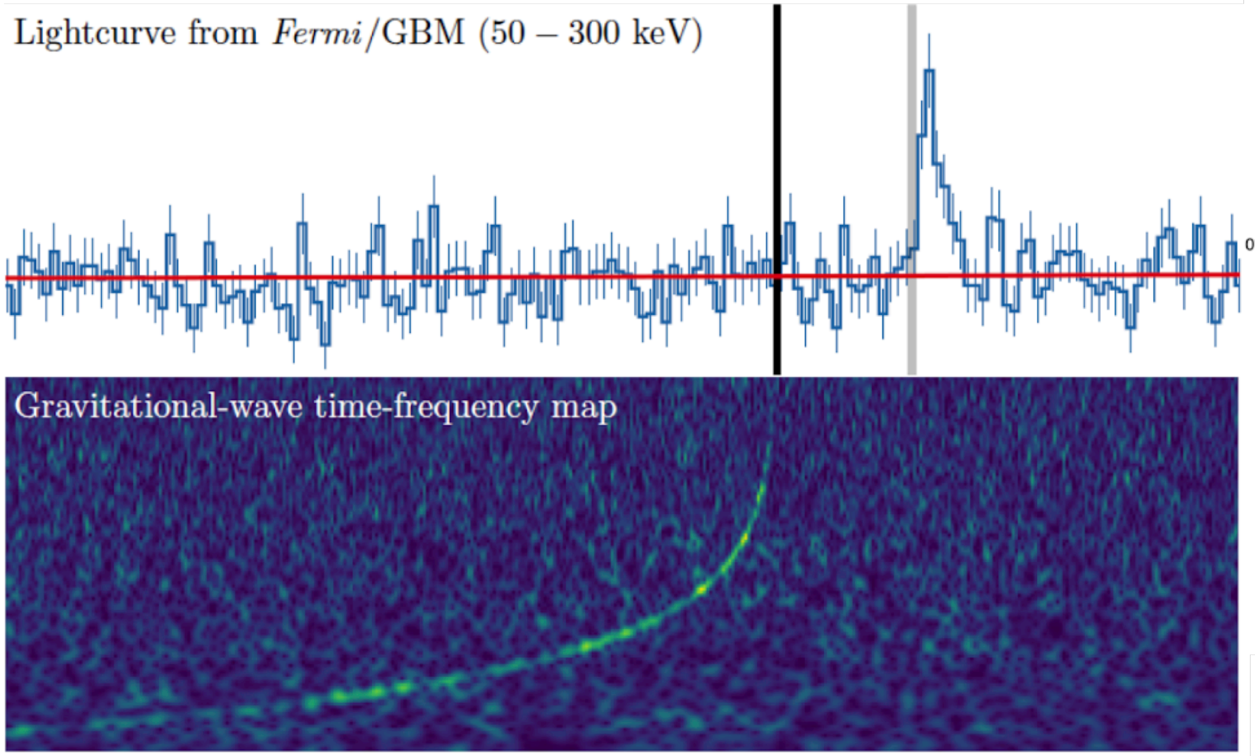
ANATOMY OF A HEAVY-ION COLLISION

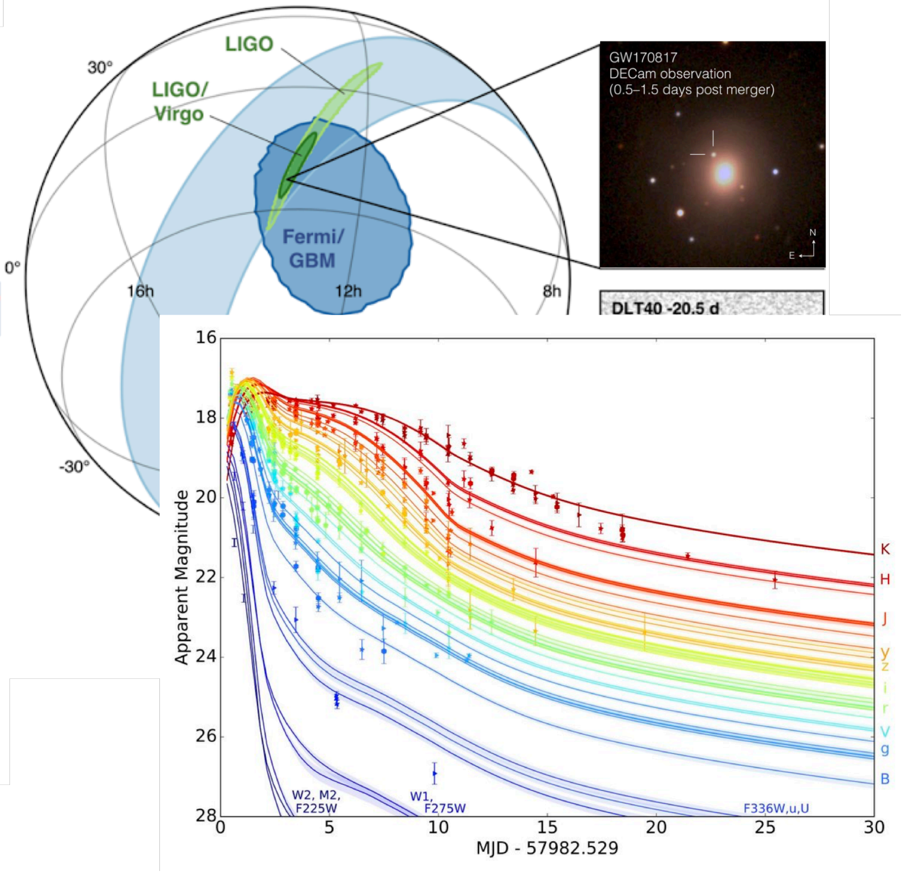




GW170817

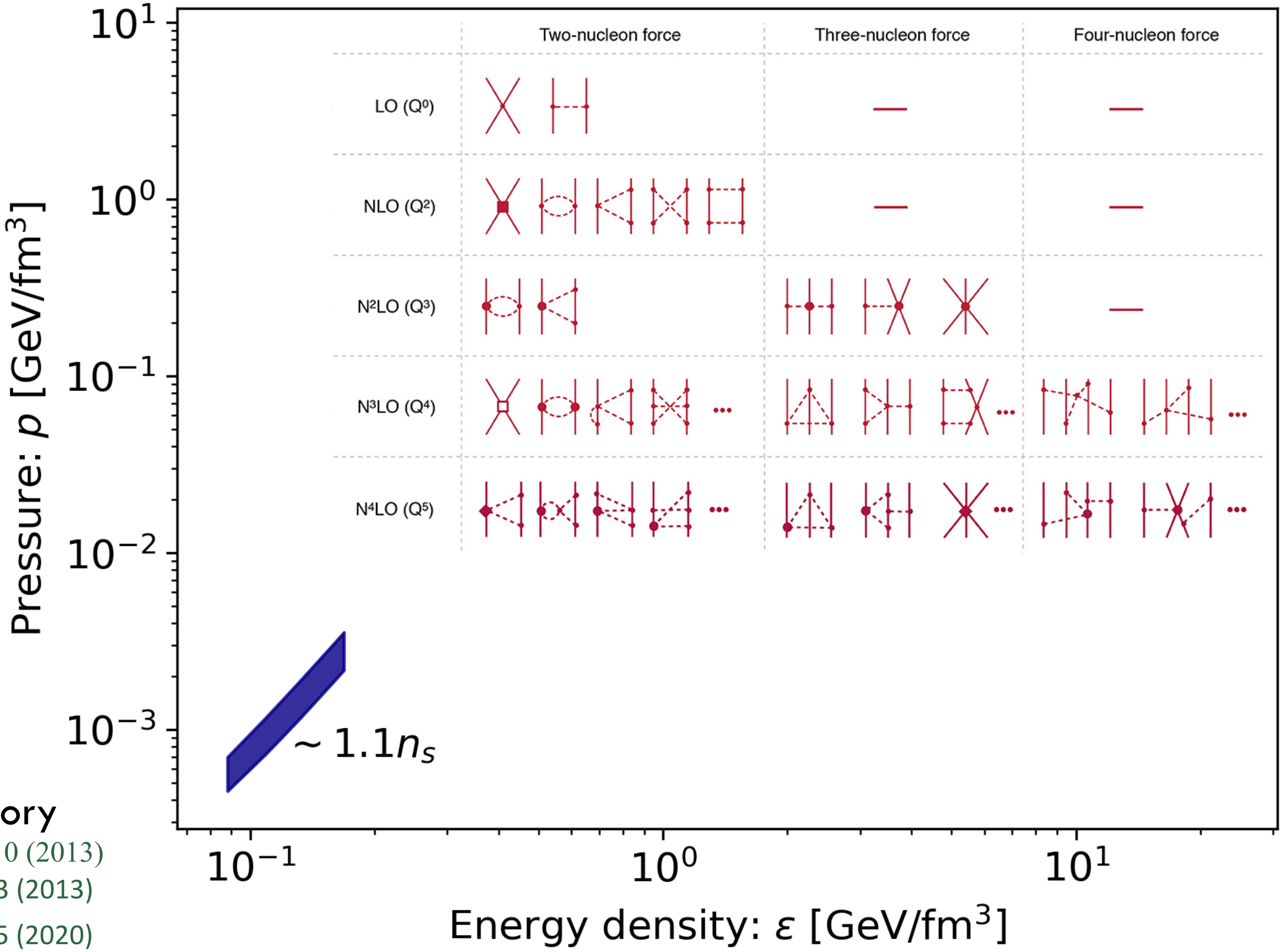
Demonstrated the ability of mergers to advance nuclear physics





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

NEUTRON STARS AND MERGERS



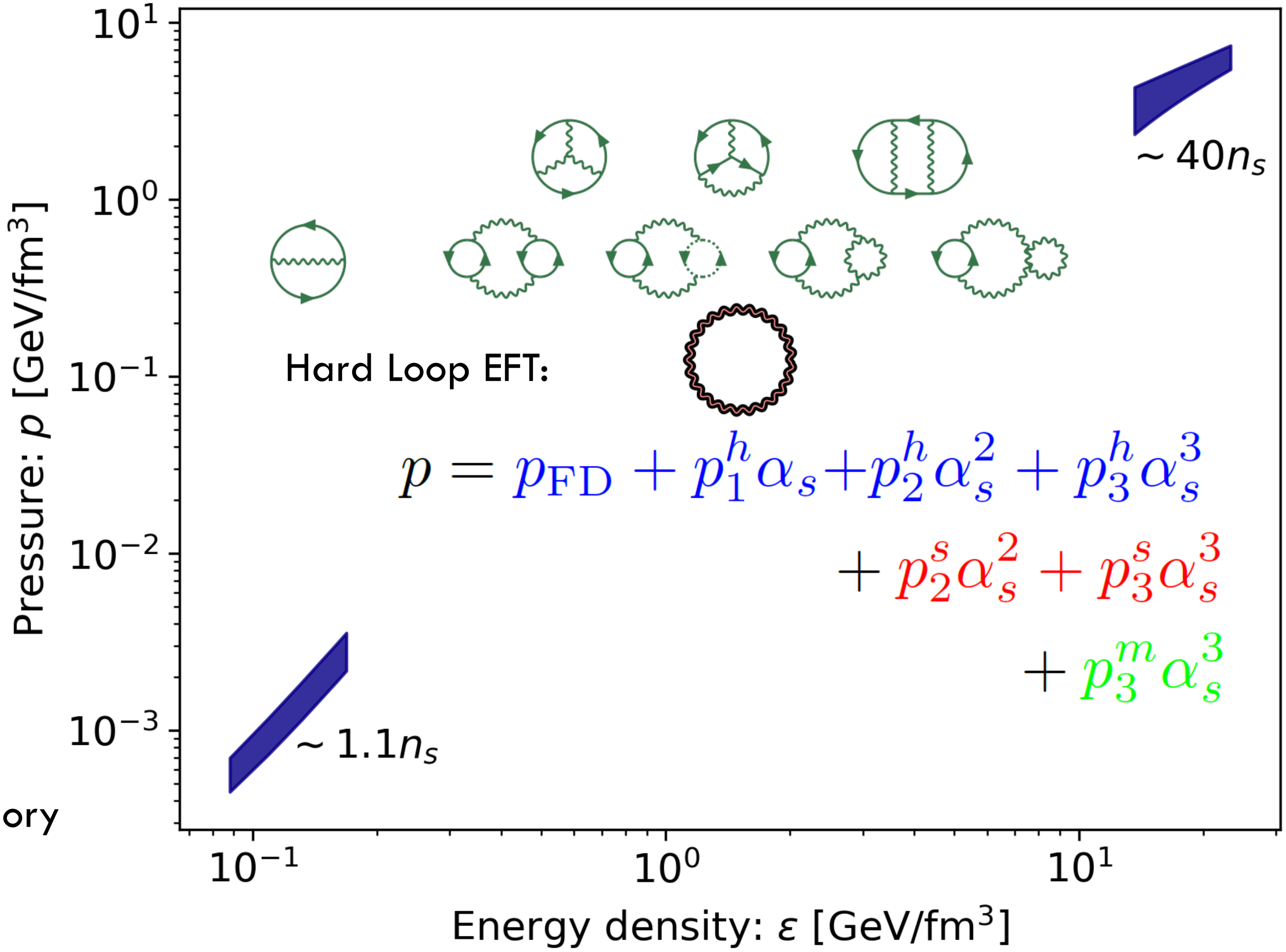
Chiral effective theory

Tews et al. PRL 110 (2013)

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

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

NEUTRON STARS AND MERGERS



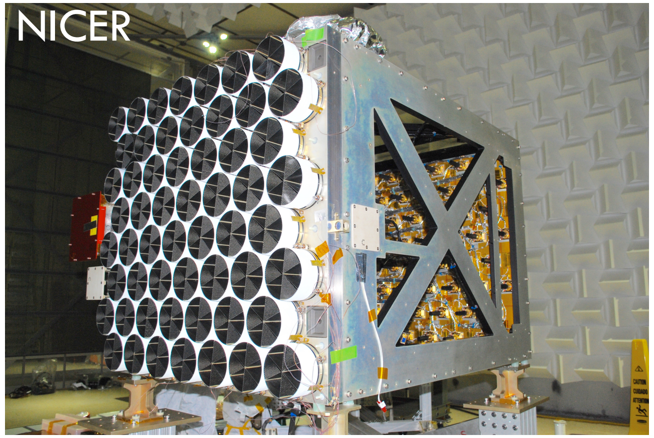
$$p = p_{\rm FD} + p_1^h\alpha_s + p_2^h\alpha_s^2 + p_3^h\alpha_s^3 + p_2^s\alpha_s^2 + p_3^s\alpha_s^3 + p_3^m\alpha_s^3$$

Perturbative QCD

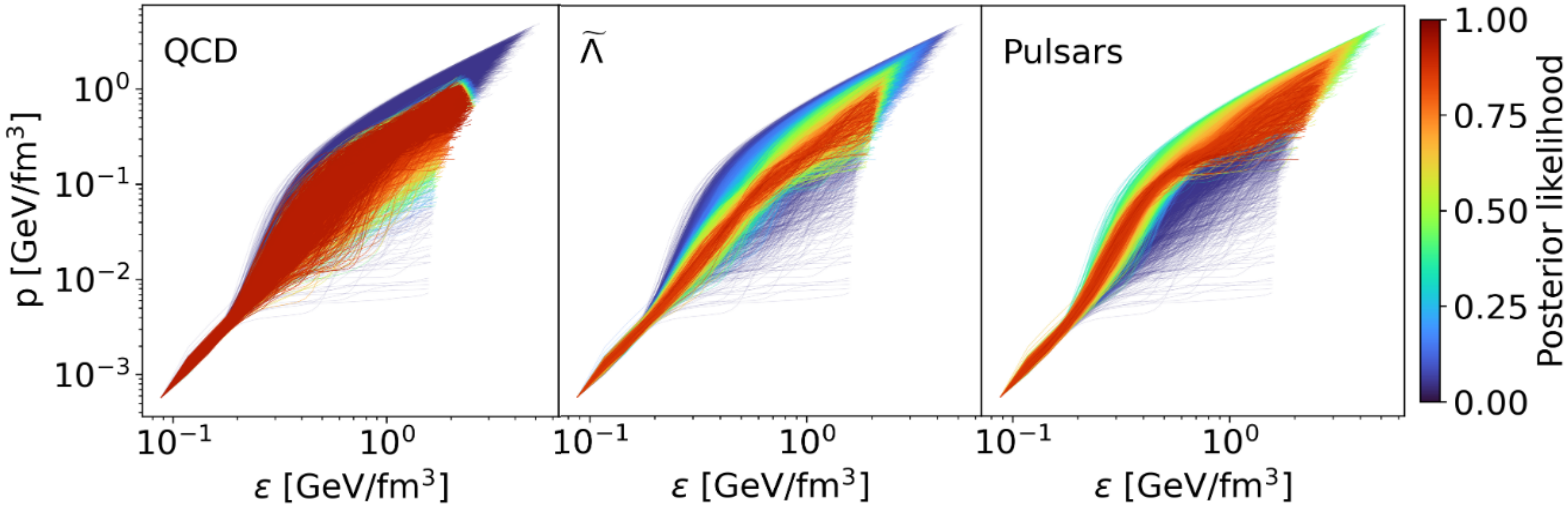
Andersen et al., PRD (2002);
Kurkela, Vuorinen PRL 117 (2016)
Annala et al., Nat. Ph. (2020)

Chiral effective theory

NEUTRON STARS AND MERGERS



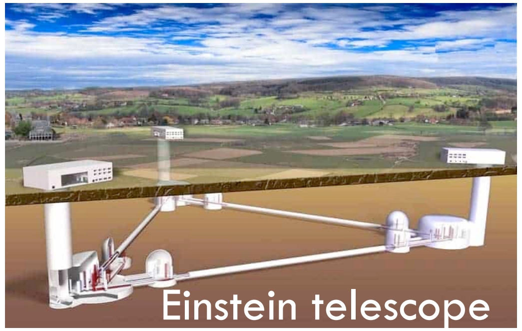
QCD input and NS observations can constrain the interpolation

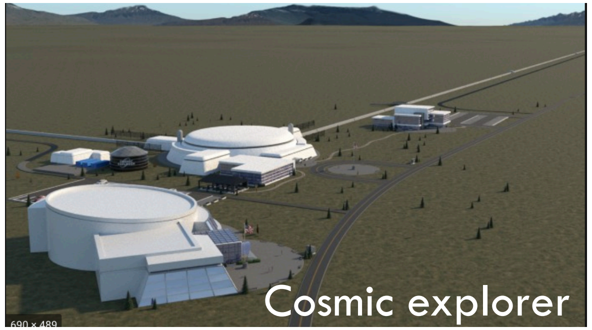


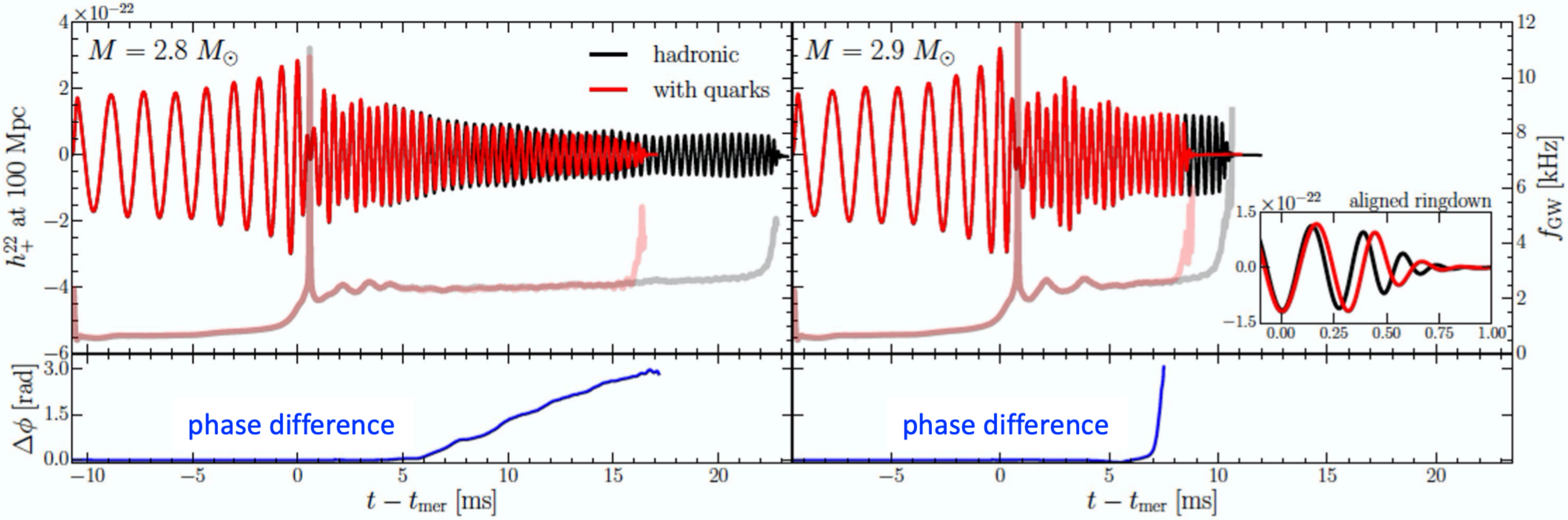
Slide adapted from talk by A. Kurkela

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





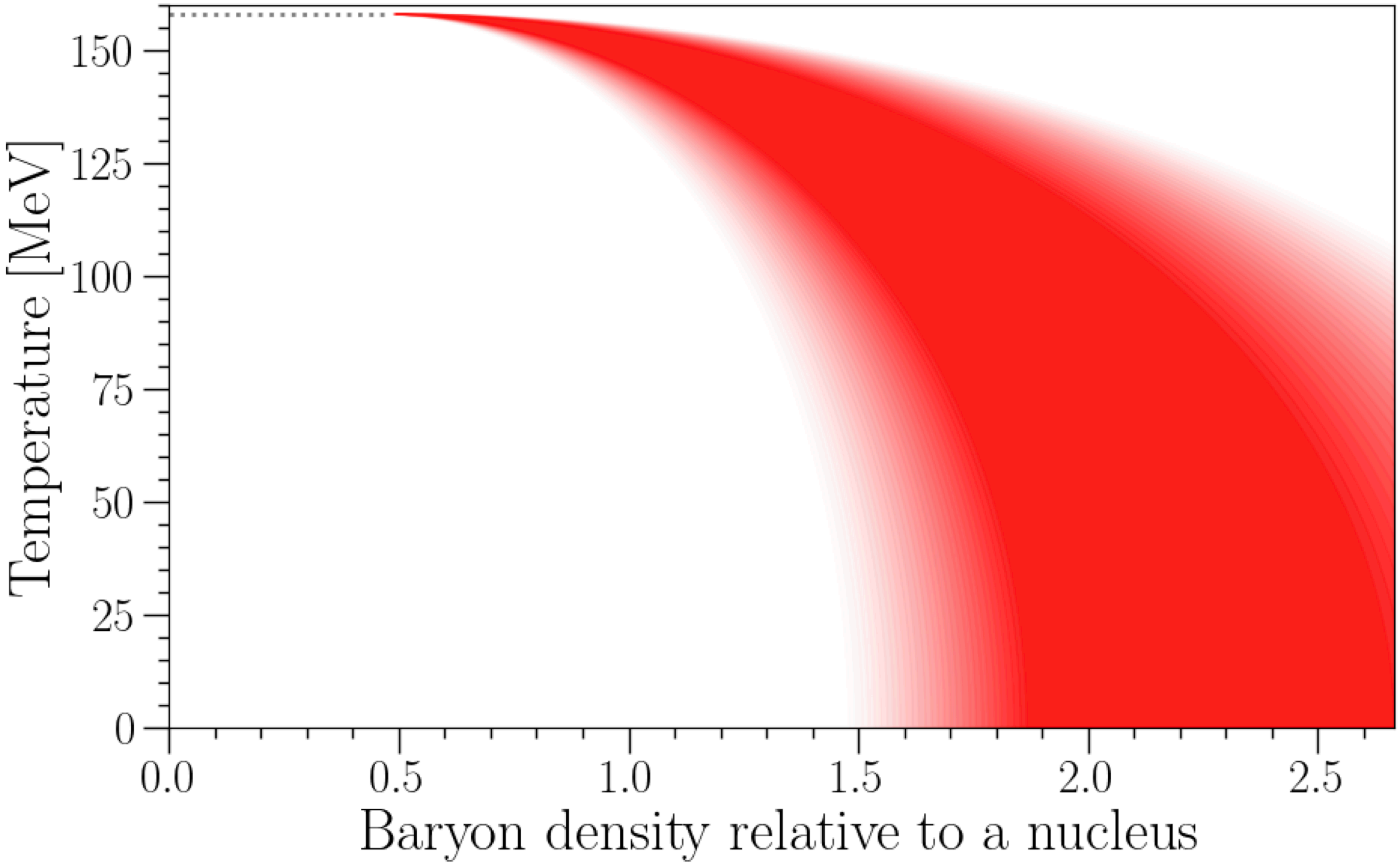


E. Most et al., PRL (2019)

Rich Neutron Star Merger Possibilities

Strong dependence on total system mass

- Multi-messenger observables depend strongly on nuclear physics
- Observation of 3.4 solar mass GW190425 shows not all merging neutron stars look like GW170817
- Larger total mass than GW170817 may lead to prompt collapse to black hole with little ejecta or electromagnetic signal
- Smaller total mass may produce powerful magnetar and electromagnetic signal much more energetic than GW170817
- Need to combine nuclear physics with end to end simulations to map out large and rich merger phase space of observables


Temperature [MeV]
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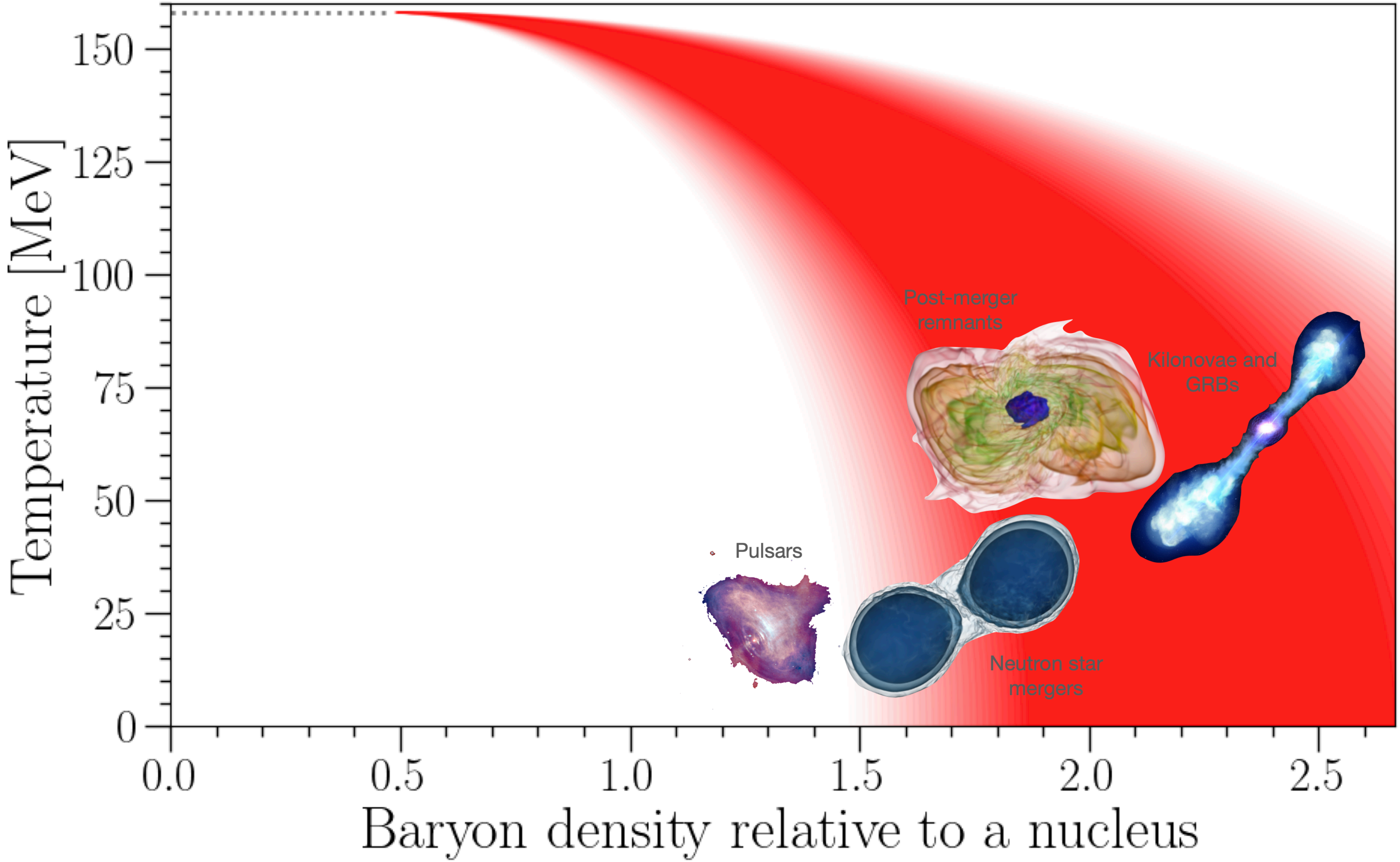
Baryon density relative to a nucleus


Temperature [MeV]
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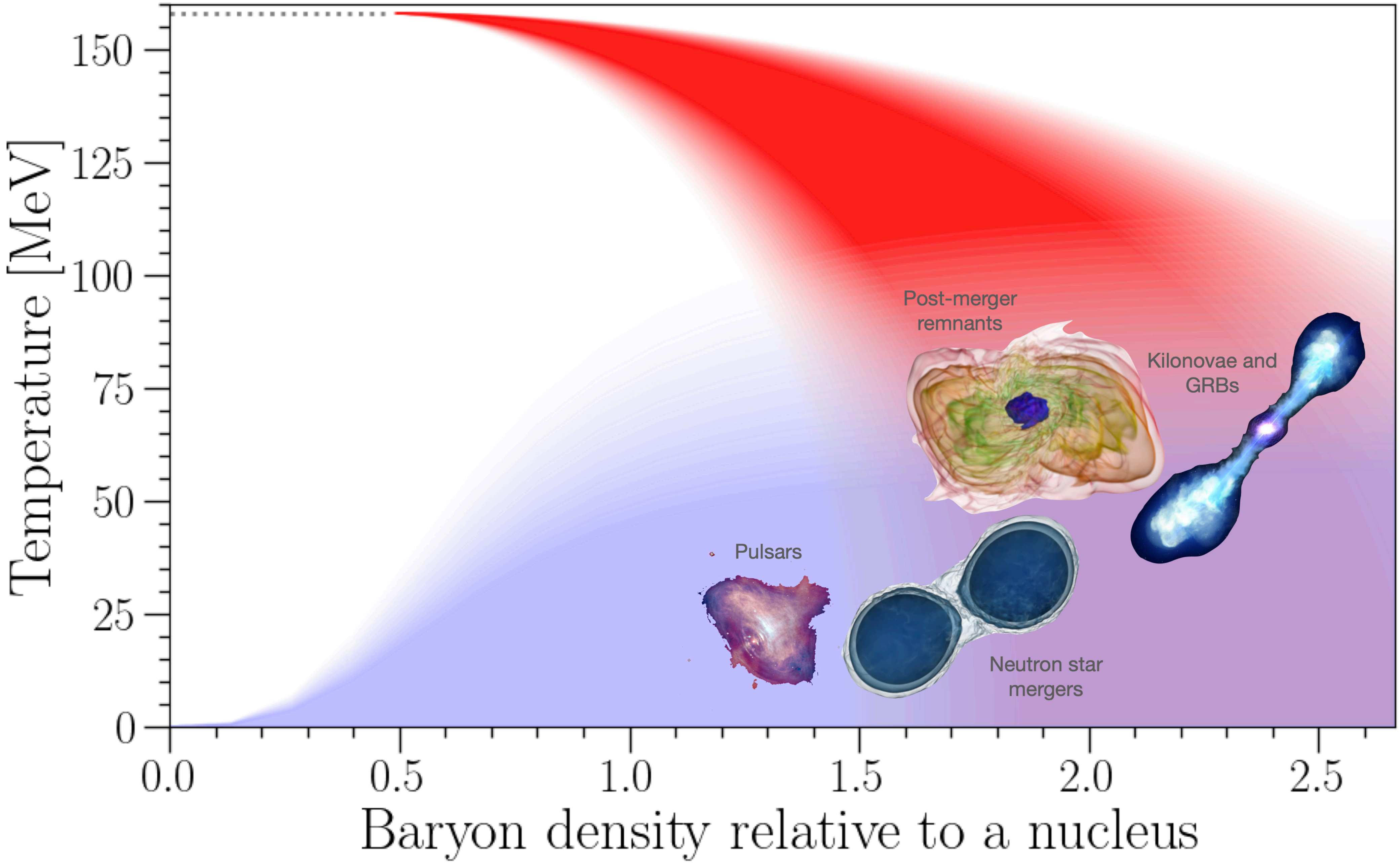
Baryon density relative to a nucleus
Post-merger remnants
Kilonovae and GRBs
Pulsars
Neutron star mergers


Temperature [MeV]
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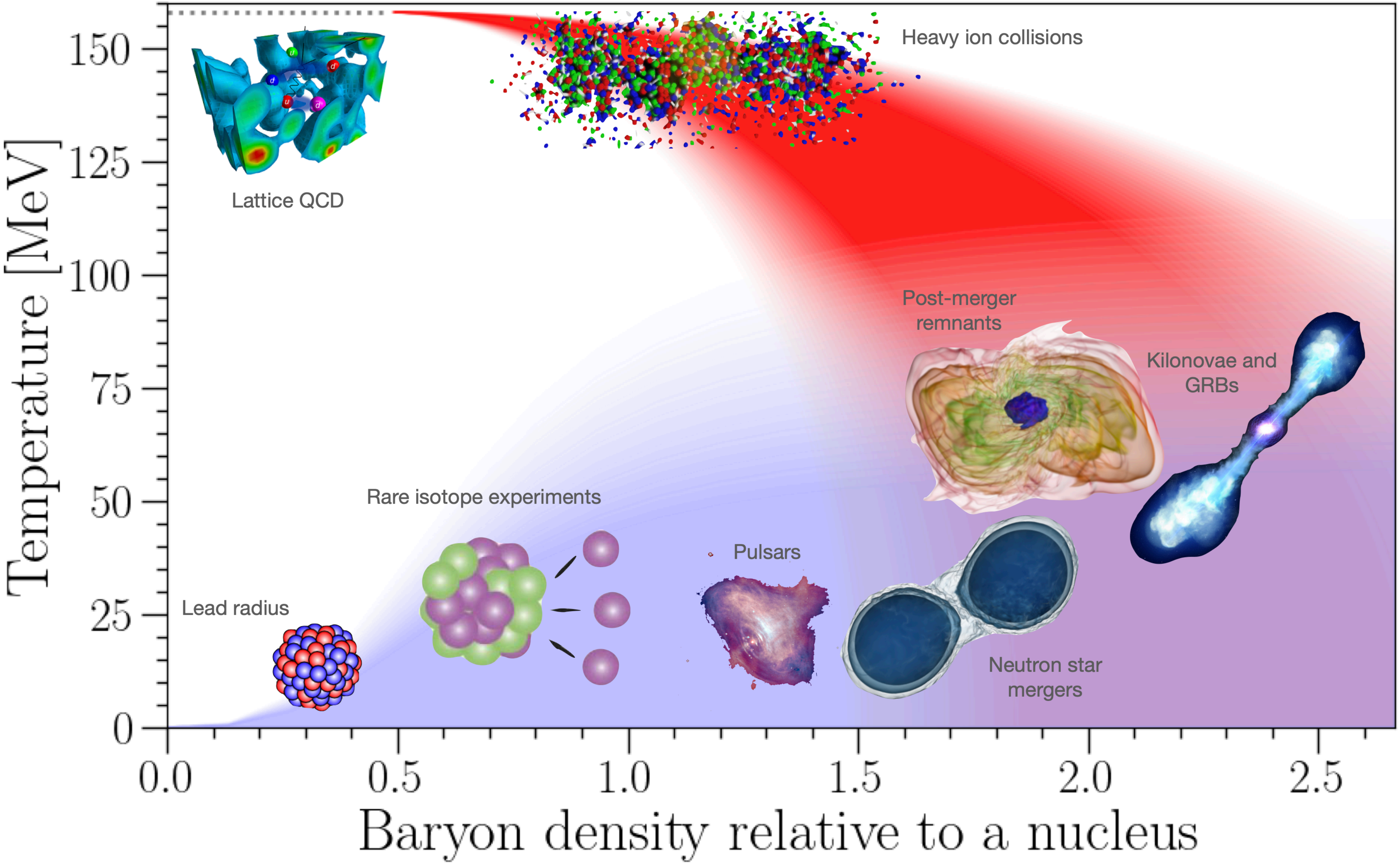
Baryon density relative to a nucleus
Post-merger remnants
Kilonovae and GRBs
Pulsars
Neutron star mergers

x



Temperature [MeV]
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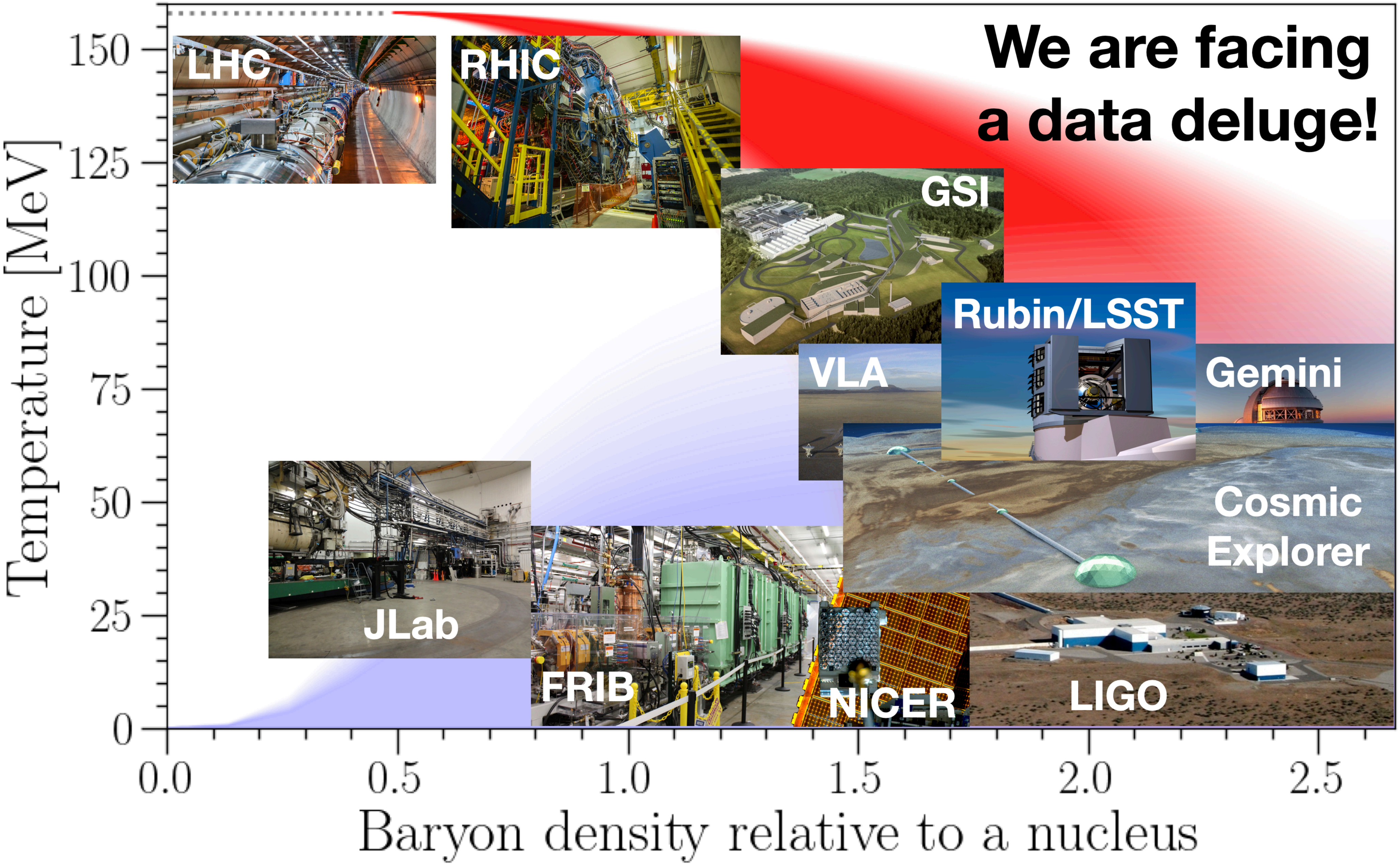
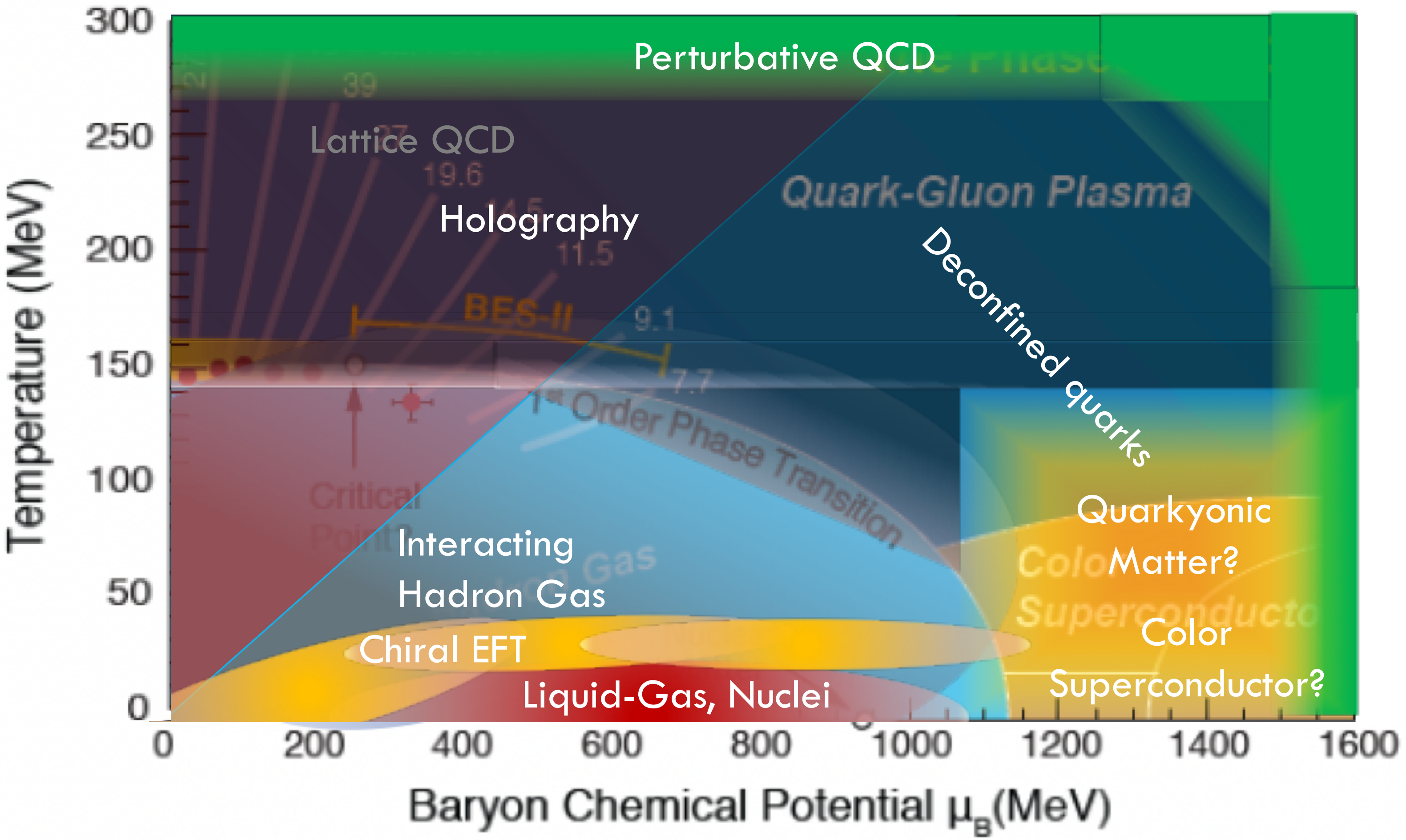
2.5
Baryon density relative to a nucleus
Lattice QCD
Heavy ion collisions
Post-merger remnants
Kilonovae and GRBs
Rare isotope experiments
Pulsars
Lead radius
Neutron star mergers



We are facing a data deluge!

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 – MODULAR UNIFIED SOLVER OF THE EQUATION OF STATE

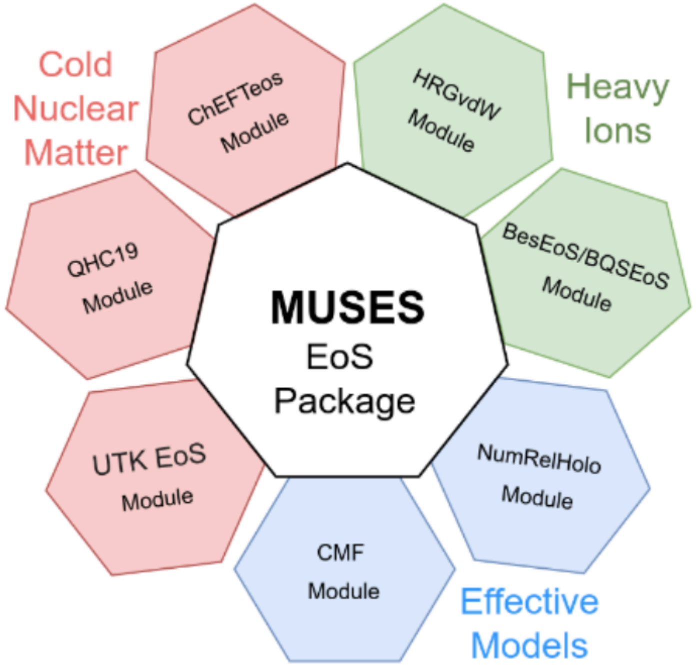
"An open-source cyberinfrastructure fostering a community-driven ecosystem that provides key computational tools to promote, transform and support groundbreaking research in nuclear physics and astrophysics, computational relativistic fluid dynamics, gravitational-wave and computational astrophysics."

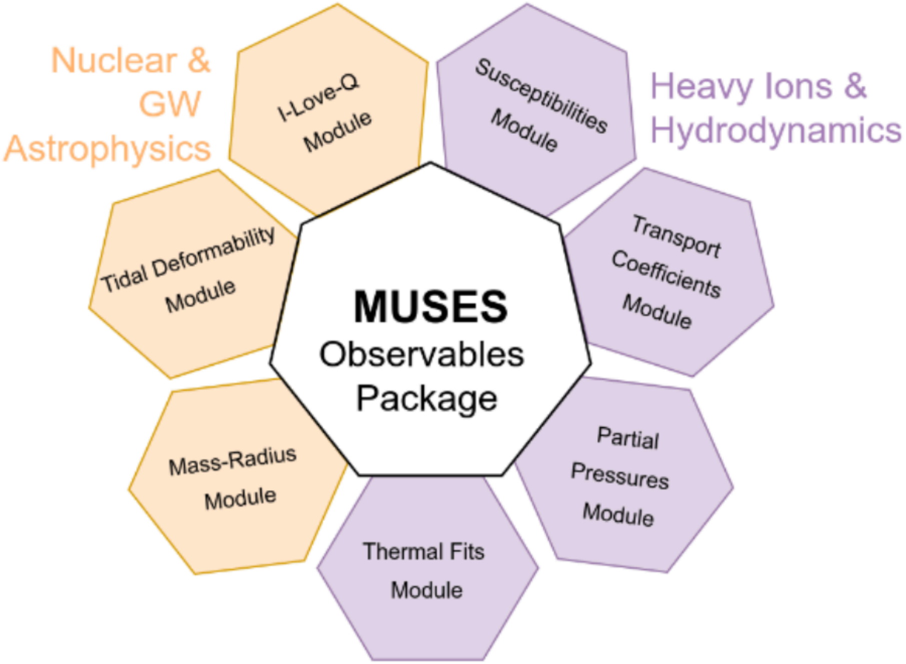
- Modular: while at low densities the equation of state is known from 1st principles, at high μ_B we will implement different models ("modules") that the user will be able to pick

- 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

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

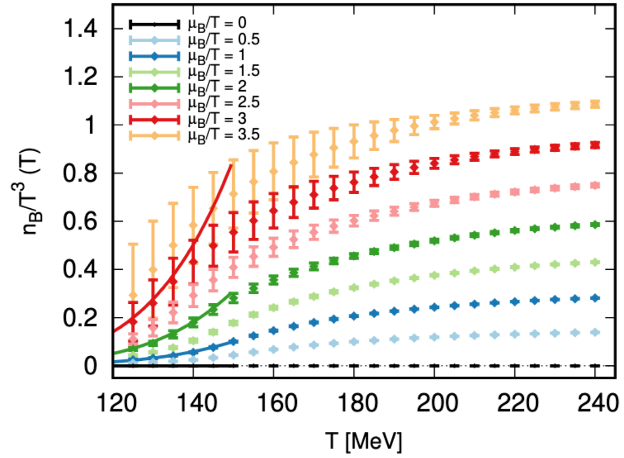
EOS FOR HEAVY IONS

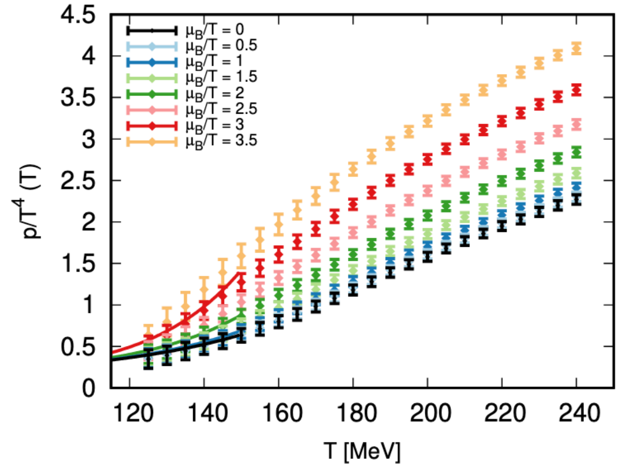
- EoS from first principles
- EoS with 3D Ising critical point
- HRG model
- EoS from Holography

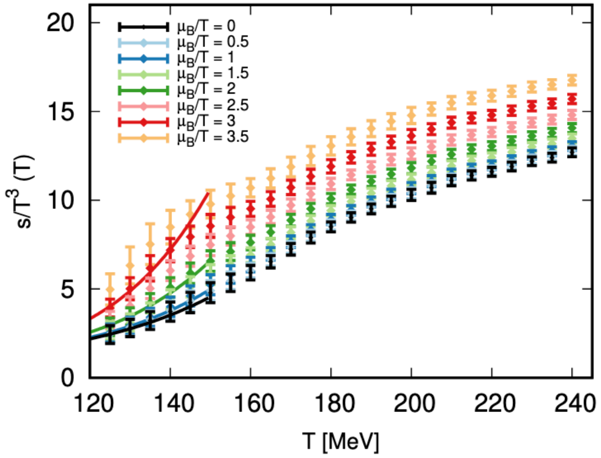
EQUATION OF STATE FROM FIRST PRINCIPLES

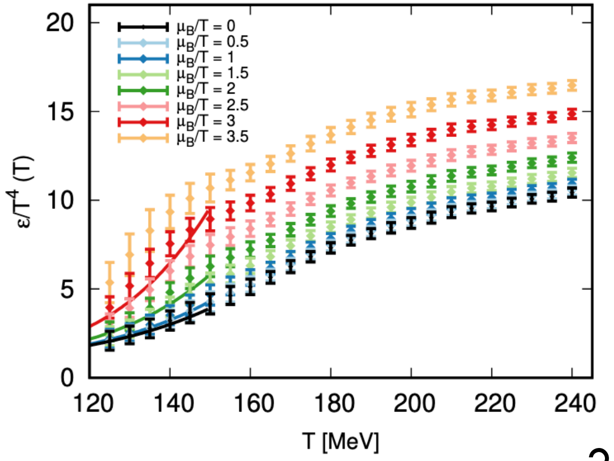
S. Borsanyi, C. R. et al., PRL (2021)
S. Borsanyi, C. R. et al., PRD (2022)

- 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 highest possible μ_B
- Extension to μ_S & $\mu_Q \neq 0$
- Implementation into the MUSES engine

EQUATION OF STATE FROM FIRST PRINCIPLES (BQSEOS)

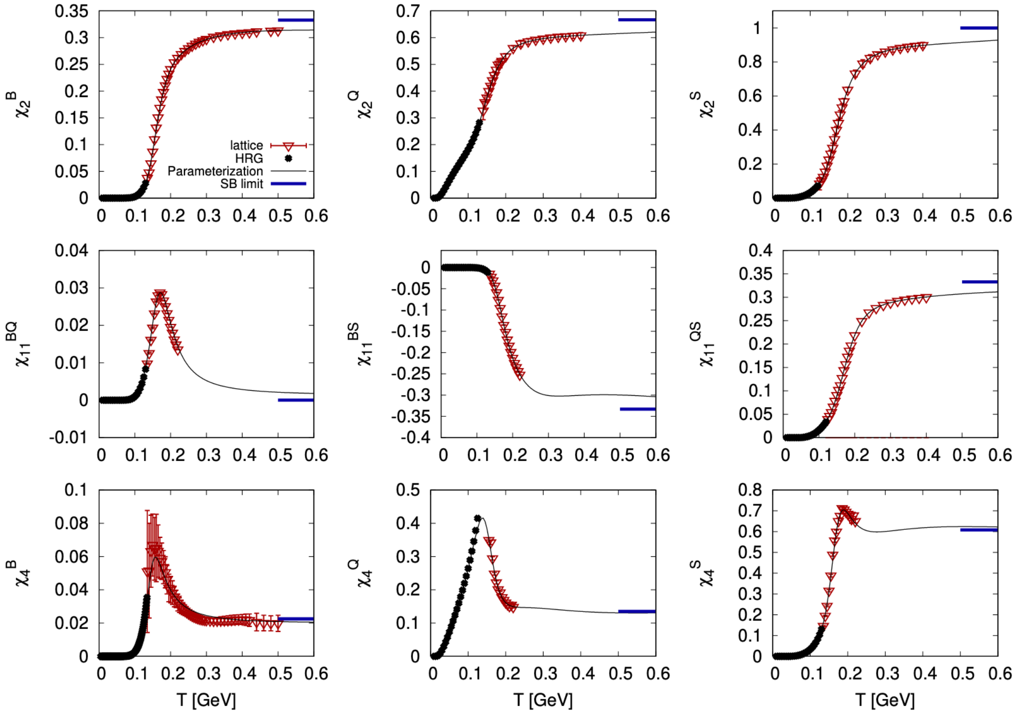
Range: $0<T<600$ MeV; $\mu_B<450$ MeV

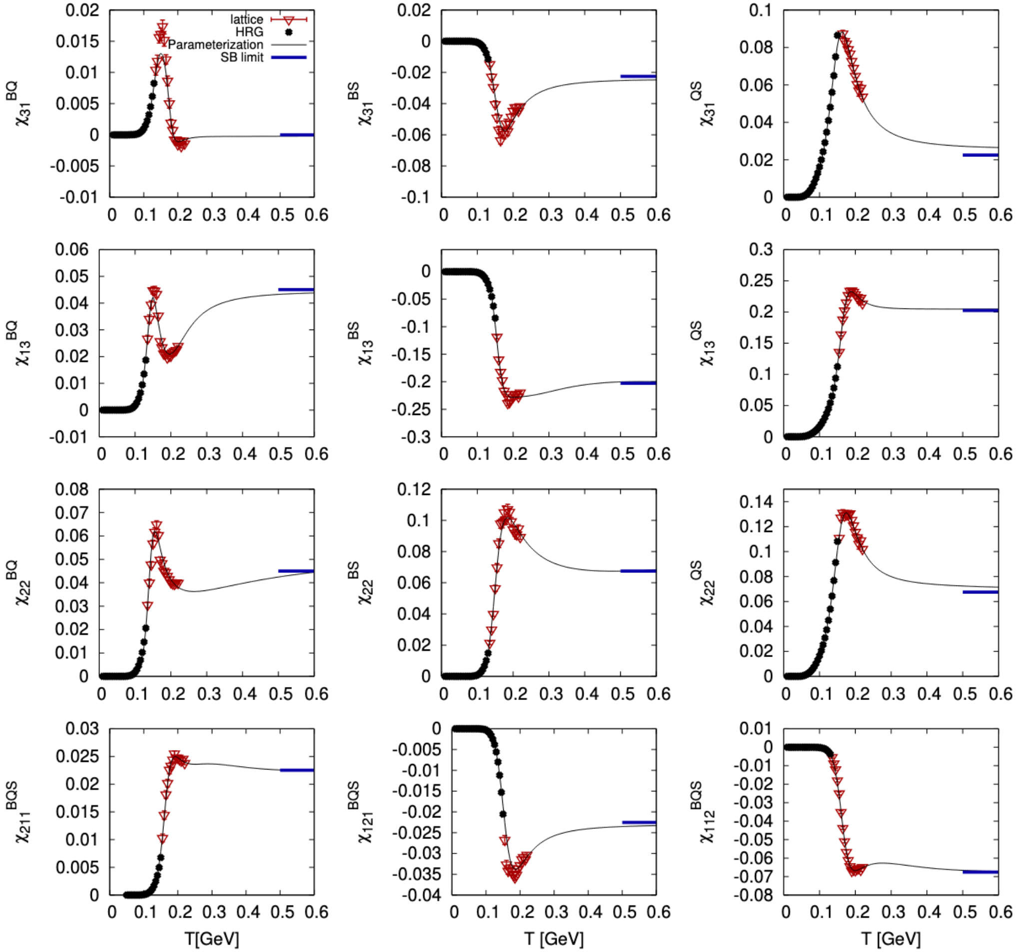
S. Borsanyi, C. R. et al., JHEP (2018)
J. Noronha-Hostler, C. R. et al., PRC (2019)
A. Monnai et al., PRC (2019)

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

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

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



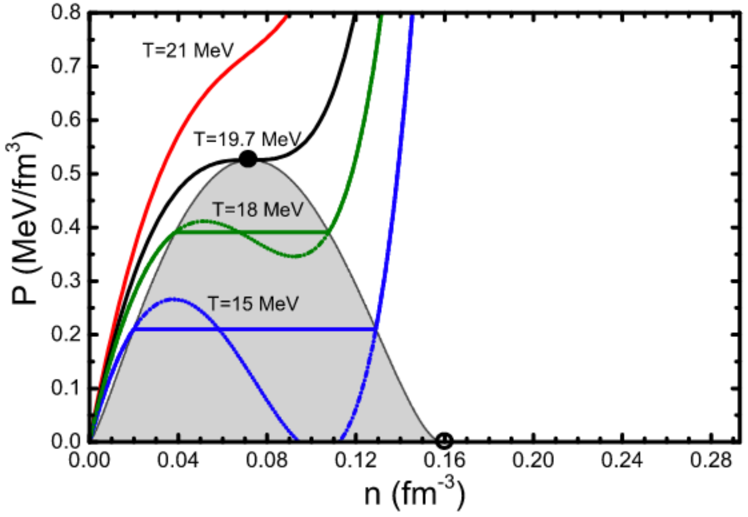


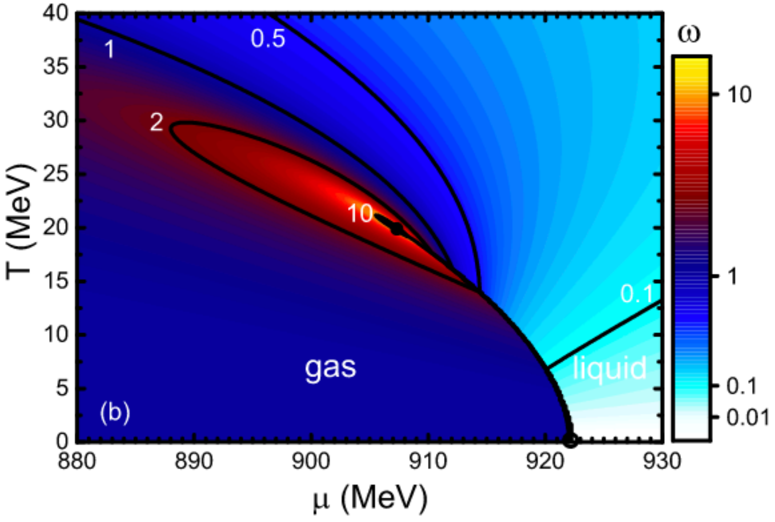
HADRON RESONANCE GAS (HRG) MODEL

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

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

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

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

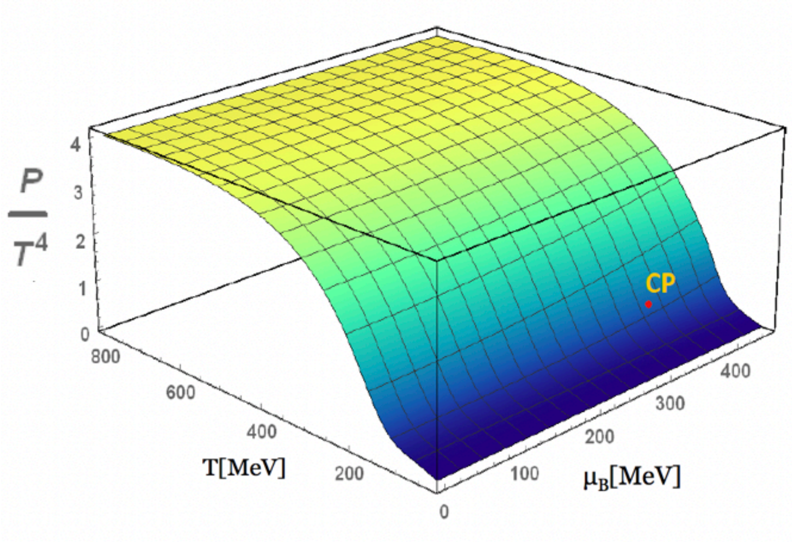
P. Parotto, C. R. et al., PRC (2020)

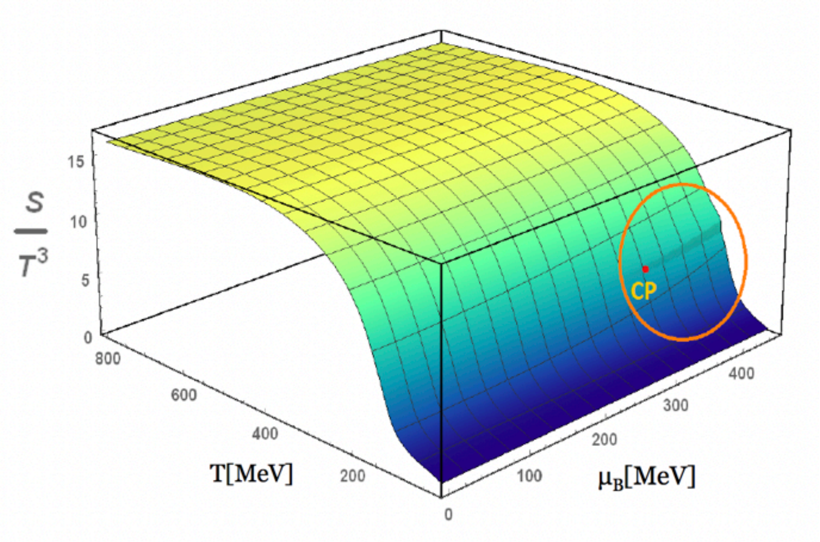
J. Karthein, C. R. et al., EPJ Plus (2021)

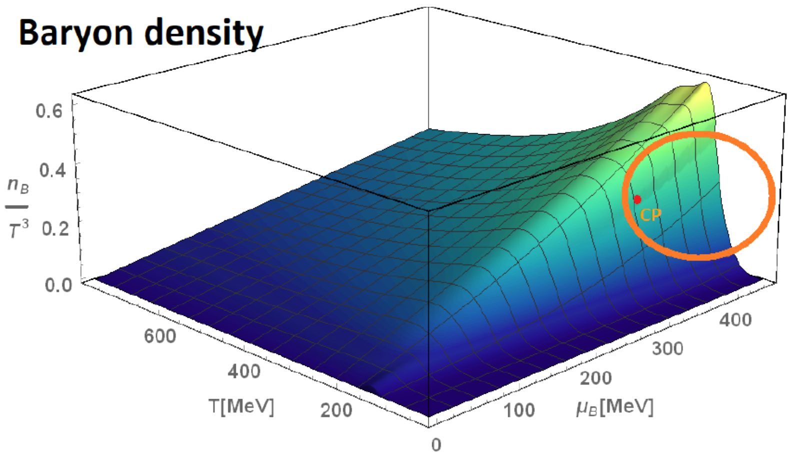
- Implement scaling behavior of 3D-Ising model EoS
- Define map from 3D-Ising model to QCD
- Estimate contribution to Taylor coefficients from 3D-Ising model critical point
- Reconstruct full pressure
- Currently available at $\mu_S=\mu_Q=0$ and for $<n_S>=0$, $<n_Q>=0.4<n_B>$

Goals: See talk by Michael Kahangirwe

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







EQUATION OF STATE FROM HOLOGRAPHY (NUMRELHOLO)

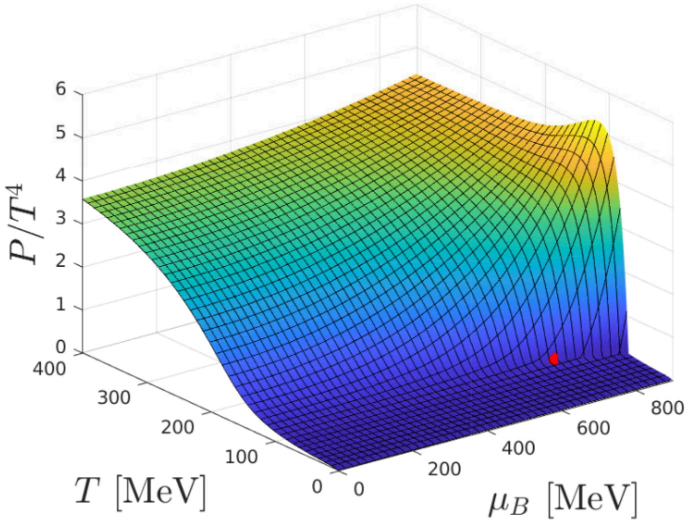
J. Grefa, C. R. et al., PRD (2021)

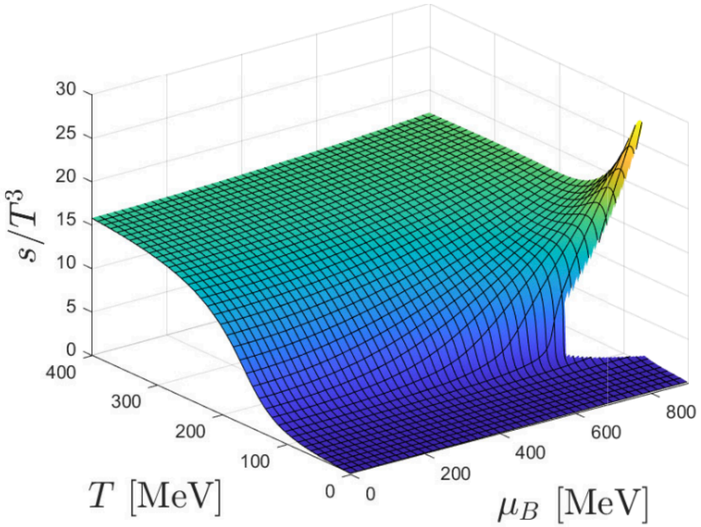
Range: 30 MeV<T<400 MeV; μ_B<1100 MeV

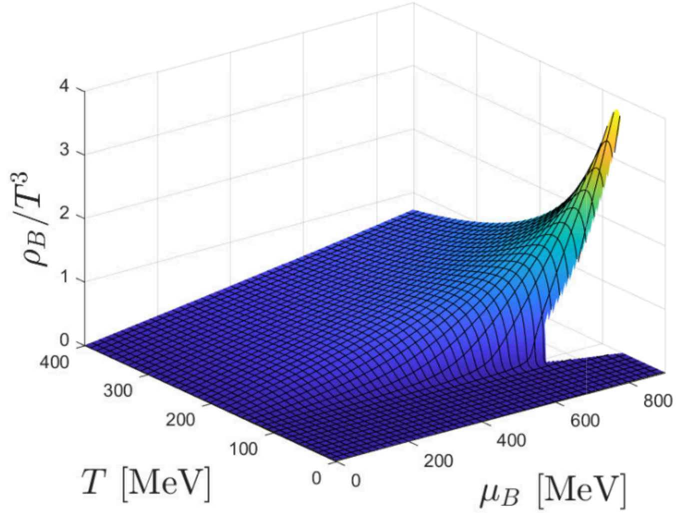
- Use AdS/CFT correspondence
- Fix the parameters to reproduce everything we know from the lattice
- Calculate equation of state at finite density
- Model currently has only baryon number
- Prediction of critical point: T_C= 89 MeV μ_{BC}=723 MeV

Goals: See talk by Mauricio Hippert

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







EOS FOR NEUTRON STARS

- Perturbation Theory
- Chiral Mean Field Model
- QHC19
- UTK EOS
- EoS from Holography

EQUATIONS OF STATE

- Chiral mean field 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

V. Dexheimer, S. Schramm PRC (2009)

- Quark-Hadron Crossover (QHC19)
  - Smooth crossover between hadrons and quarks
  - Hadronic EoS based on 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)

- UTK Equation of state
  - Includes nucleonic degrees of freedom based on a phenomenological fit to nuclear experiment and astronomical observations

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

- Chiral effective field theory
  - Interacting nucleons and pions within chiral effective field theory

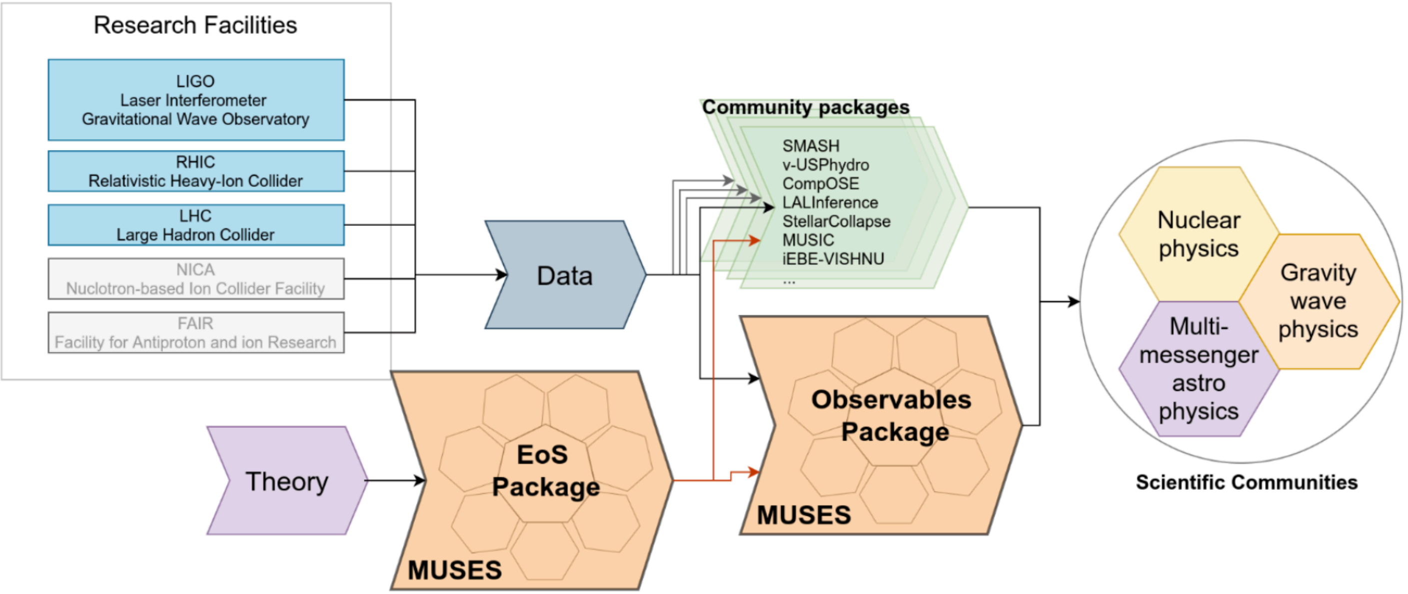
J. Holt & N. Kaiser, PRD (2017)

CYBERINFRASTRUCTURE

- Goals
- Calculation engine
- Web tools
- Low-level services

GOALS

- Connect computer scientists and physicists to provide solutions to numerical method challenges
- Interface MUSES modules
- Develop MUSES web-tools and services
- Create application programming interface
- Design a scalable, high-availability and container-based deployment system



Research Facilities

LIGO
Laser Interferometer
Gravitational Wave Observatory

RHIC
Relativistic Heavy-Ion Collider

LHC
Large Hadron Collider

NICA
Nuclotron-based Ion Collider Facility

FAIR
Facility for Antiproton and ion Research

Data

Theory

EoS
Package
MUSES

Community packages
SMASH
v-USPhydro
CompOSE
LALInference
StellarCollapse
MUSIC
iEBE-VISHNU
...

Observables
Package
MUSES

Nuclear
physics

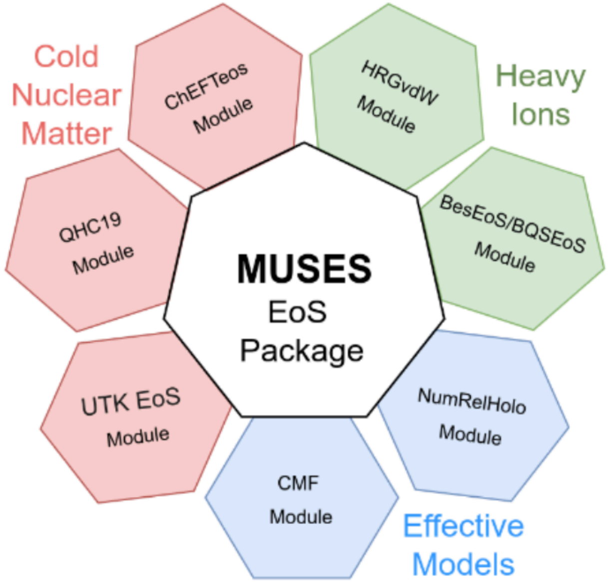
Gravity
wave
physics

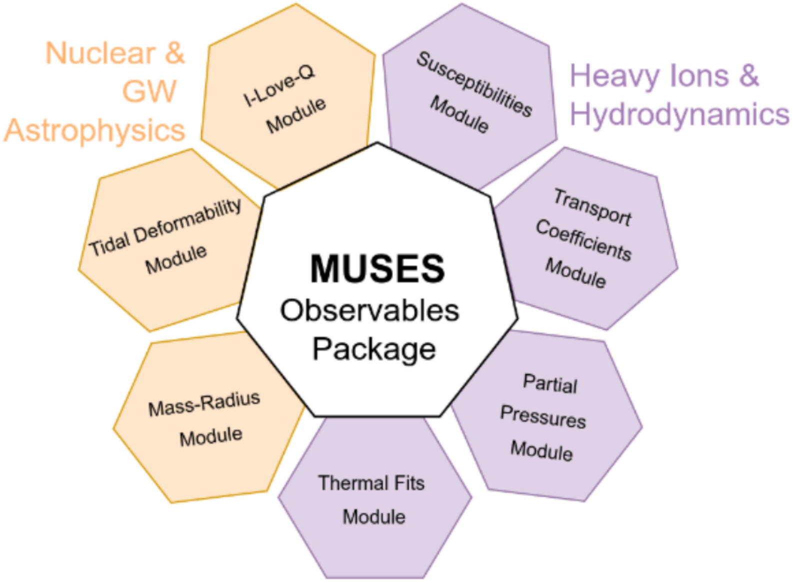
Multi-
messenger
astro
physics

Scientific Communities

CALCULATION ENGINE

- Smooth transitions when connecting modules in the same phase
- Phase matching with crossover or first-order phase transition
- Development of an integrated EoS package
- Observables package





USERS

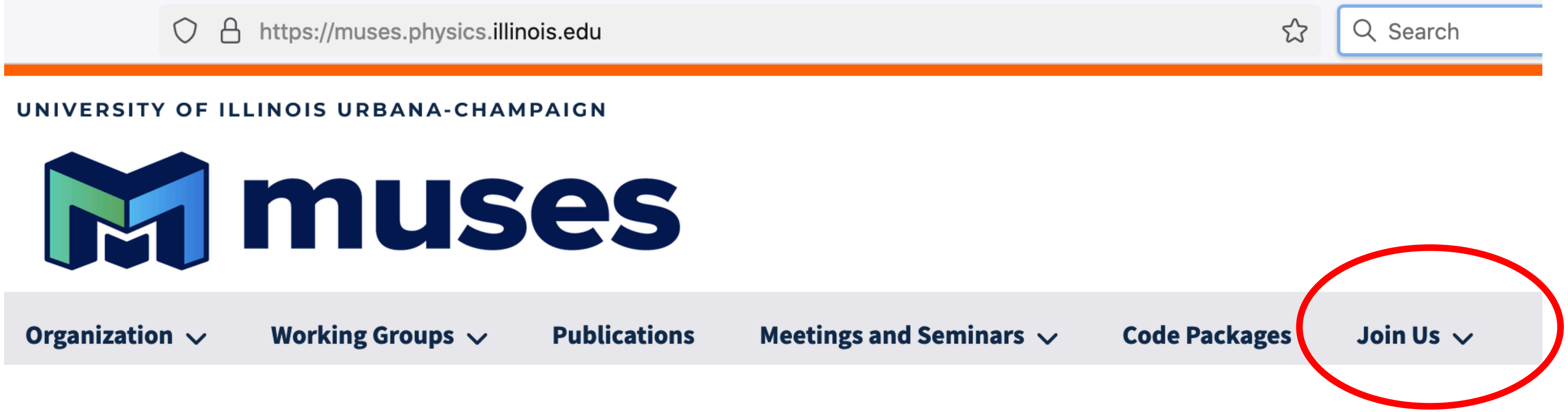
- Goals
- Observables for neutron stars
- Observables for heavy-ions

GOALS

- Mold the output of MUSES to facilitate its adoption in various communities
- Develop a package to compute observables. Test the equation of state
- Observables for neutron stars
  - Mass-radius relationship
  - Gravitational wave observables (tidal deformability, moment of inertia, quadrupole moment)
- Heavy-ion observables
  - Thermal fits
  - Partial pressures
  - Fluctuations of conserved charges
  - Transport coefficients

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 second year
- Some of the modules will become available soon
- Check out our webpage at https://muses.physics.illinois.edu/
- We welcome new users any time



Backup slides

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.”*

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…)*

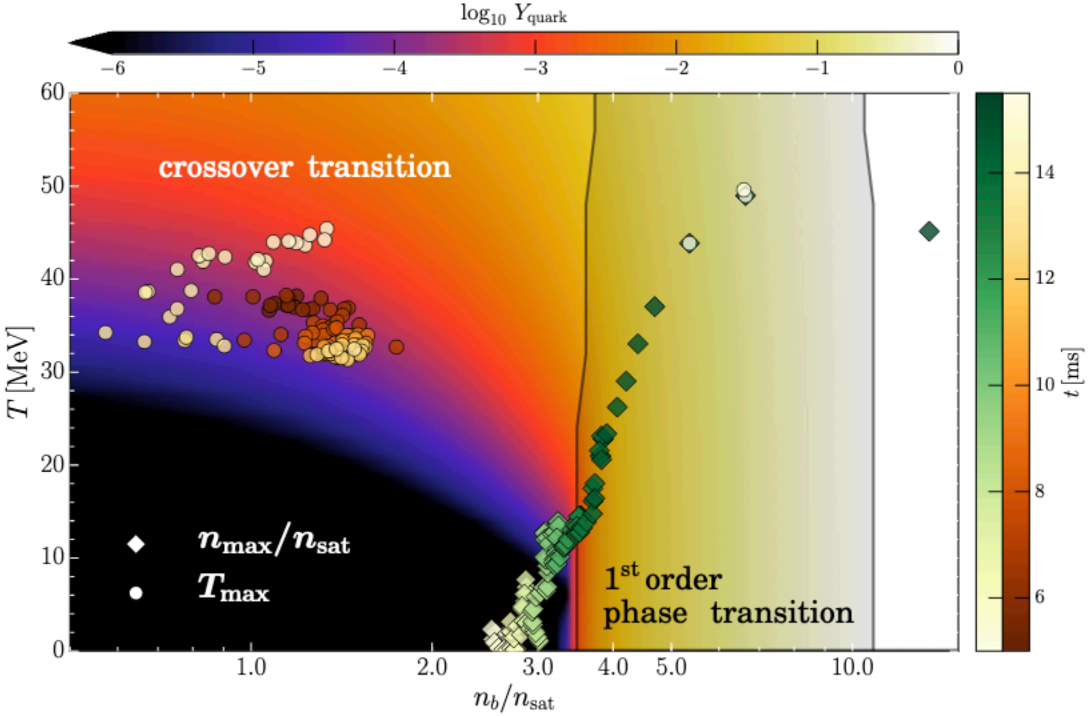
CHIRAL MEAN FIELD MODEL (CMF)

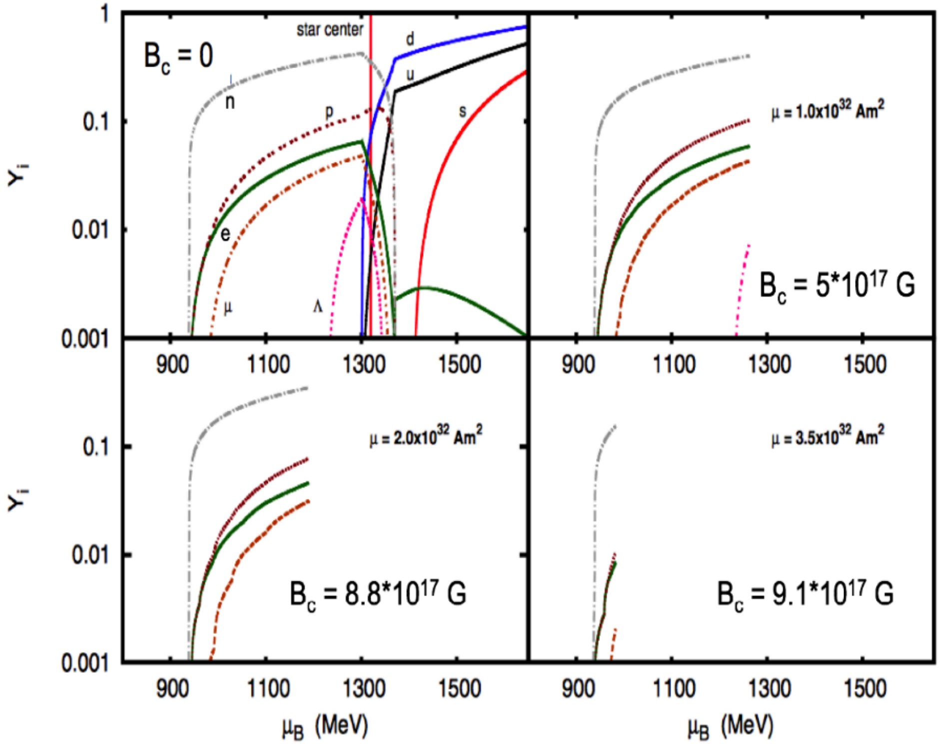
V. Dexheimer, S. Schramm PRC (2009)

- 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)



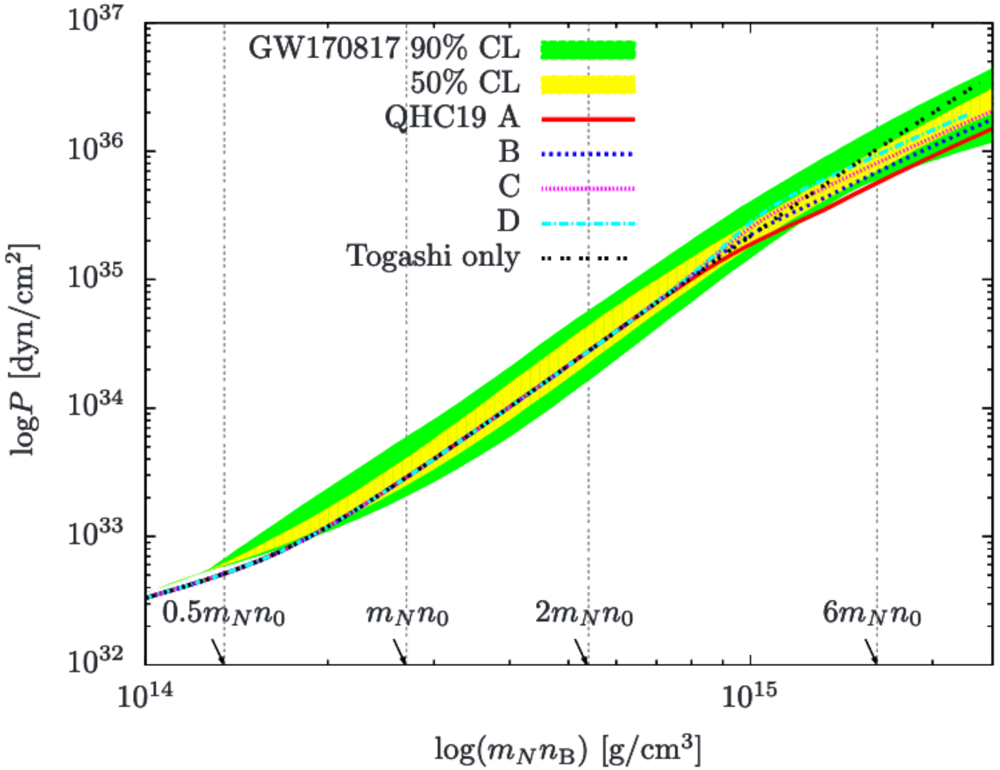


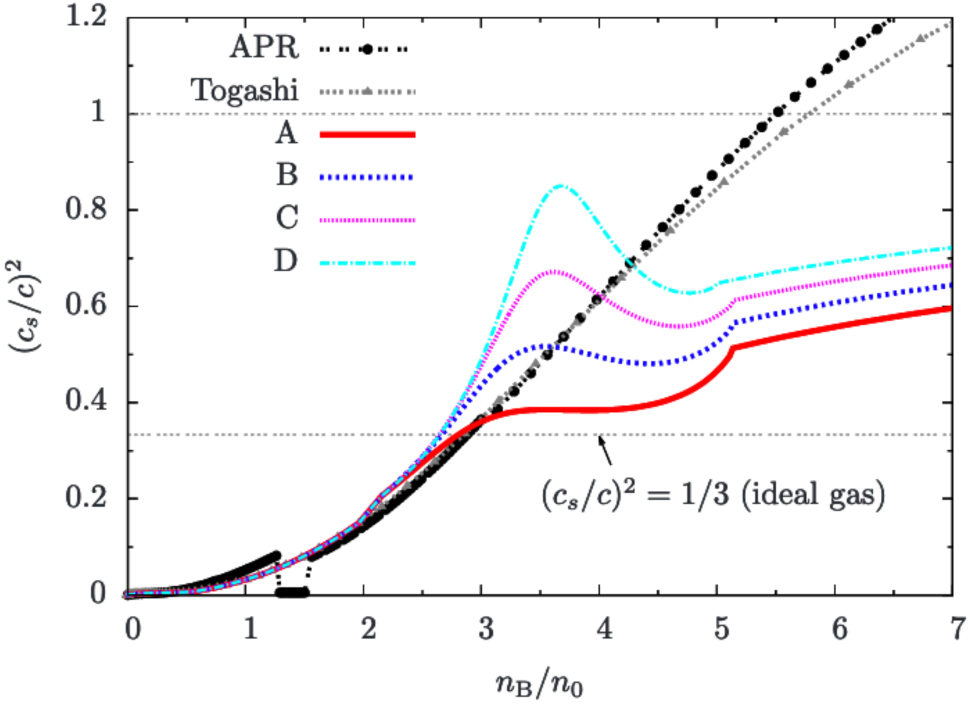
QUARK-HADRON CROSSOVER (QHC19)

- 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

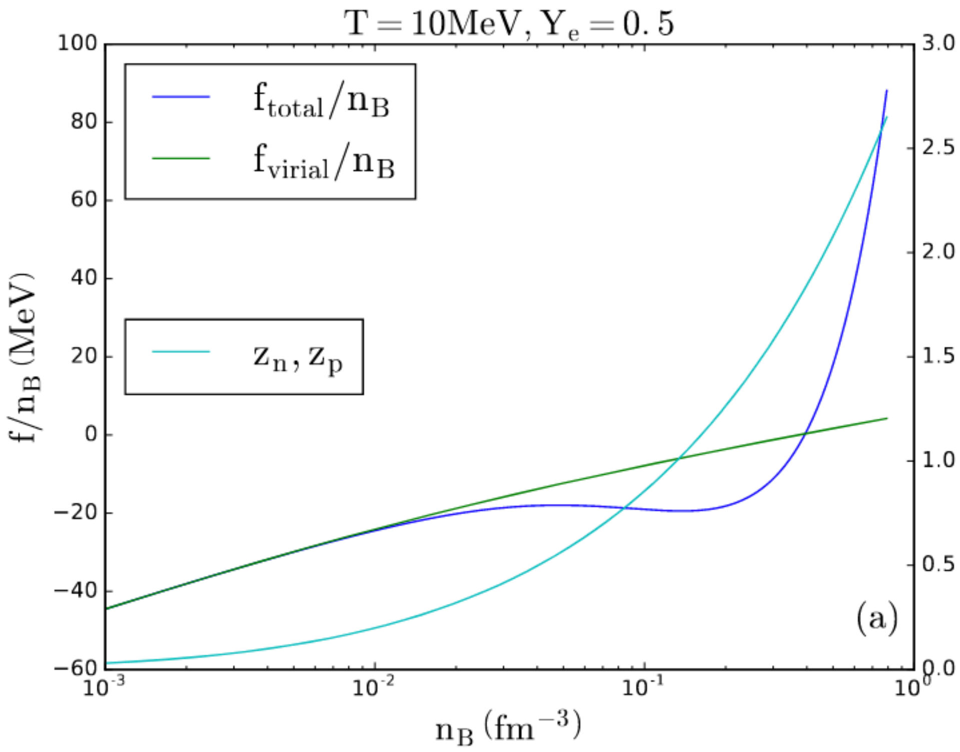


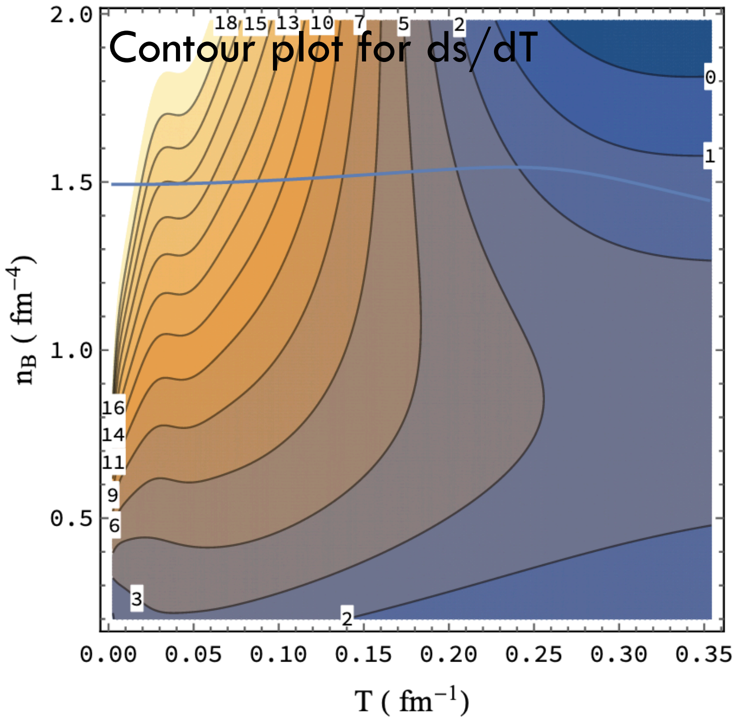


UNIVERSITY OF TENNESSEE KNOXVILLE EOS(UTK EOS)

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




Contour plot for ds/dT

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

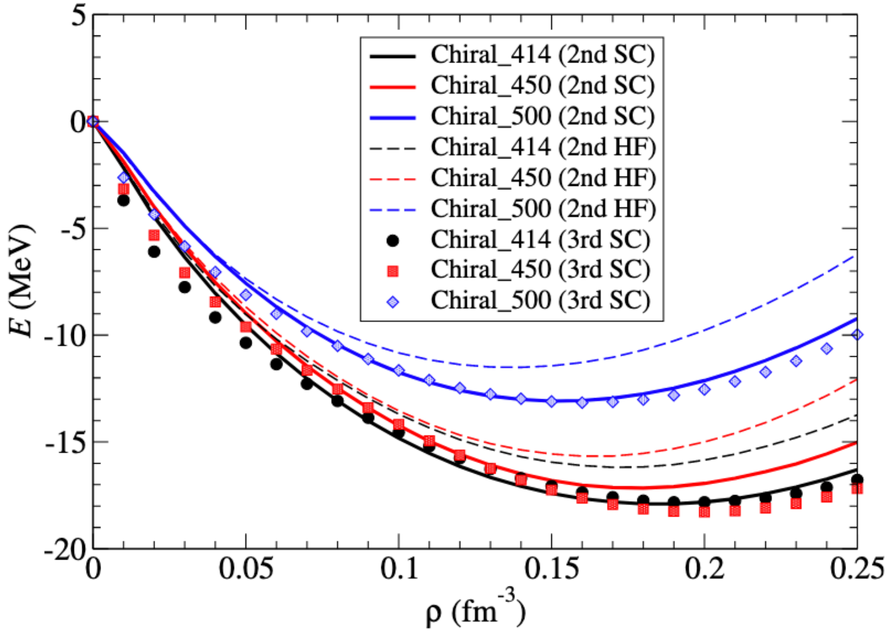
CHIRAL EFFECTIVE FIELD THEORY (CHEFTEOS)

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

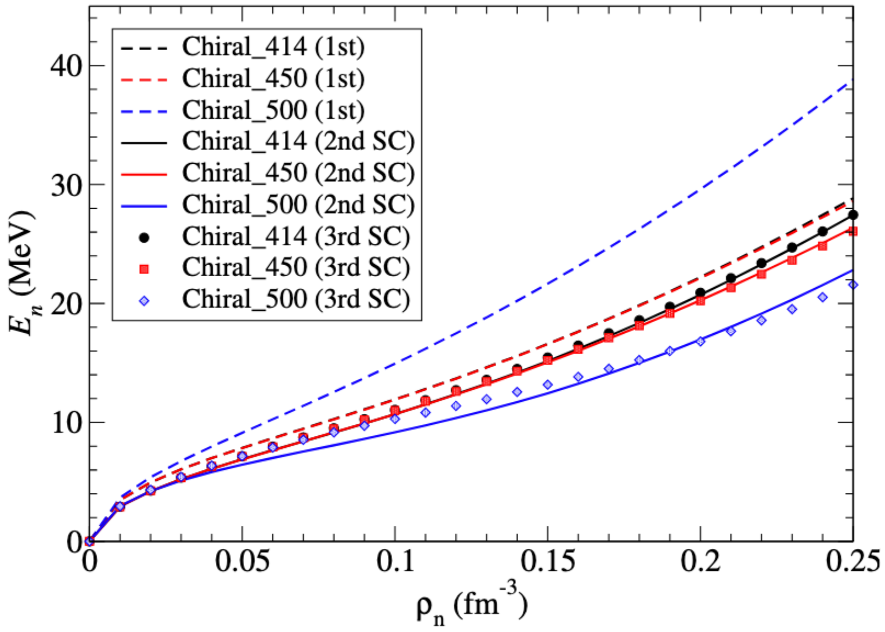
- Describes matter in the range T<25 MeV, 800 MeV<μ_B<1100 MeV
- Interacting nucleons and pions within chiral effective field theory
- Constrains do not exist for asymmetric matter

Goals:

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

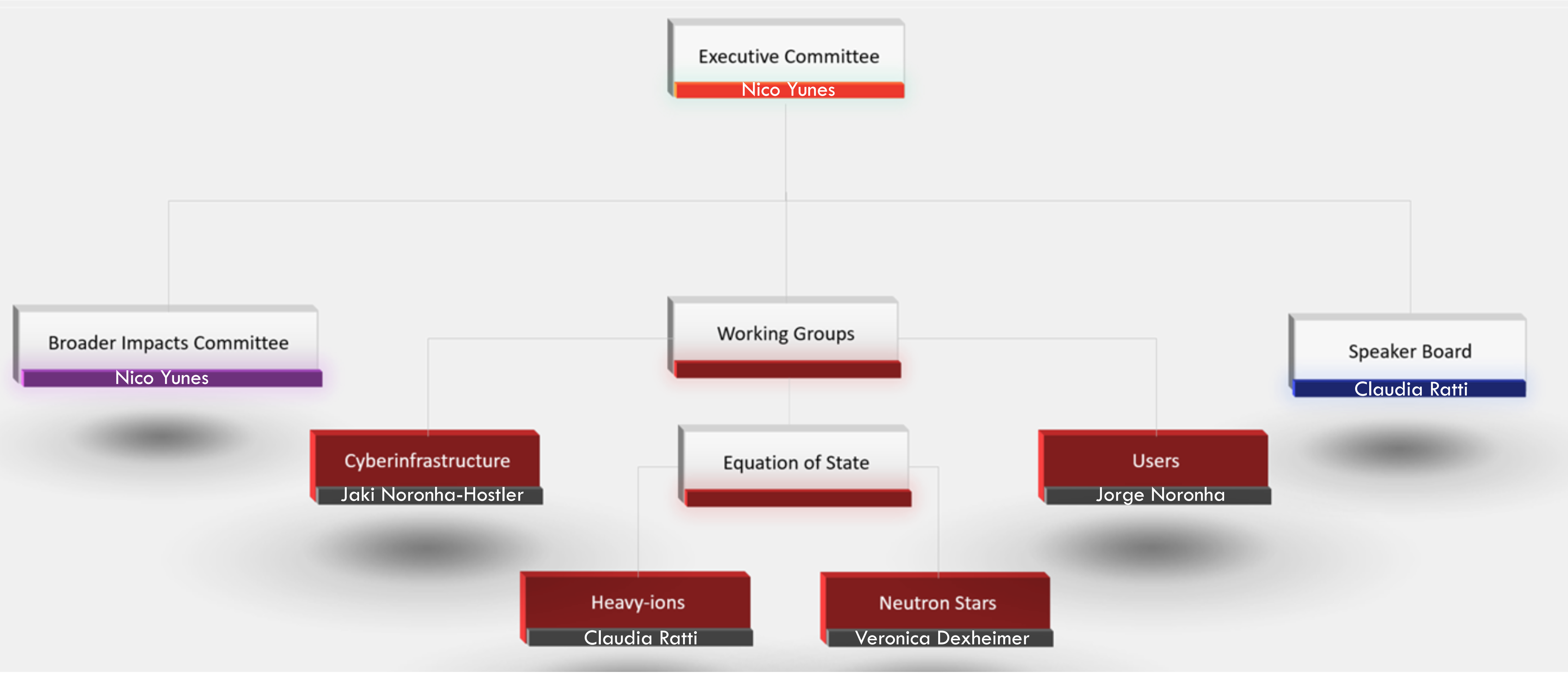


EoS for symmetric nuclear matter



EoS for neutron matter

ORGANIZATION



Executive Committee
Nico Yunes

Broader Impacts Committee
Nico Yunes

Working Groups

Speaker Board
Claudia Ratti

Cyberinfrastructure
Jaki Noronha-Hostler

Equation of State

Users
Jorge Noronha

Heavy-ions
Claudia Ratti

Neutron Stars
Veronica Dexheimer

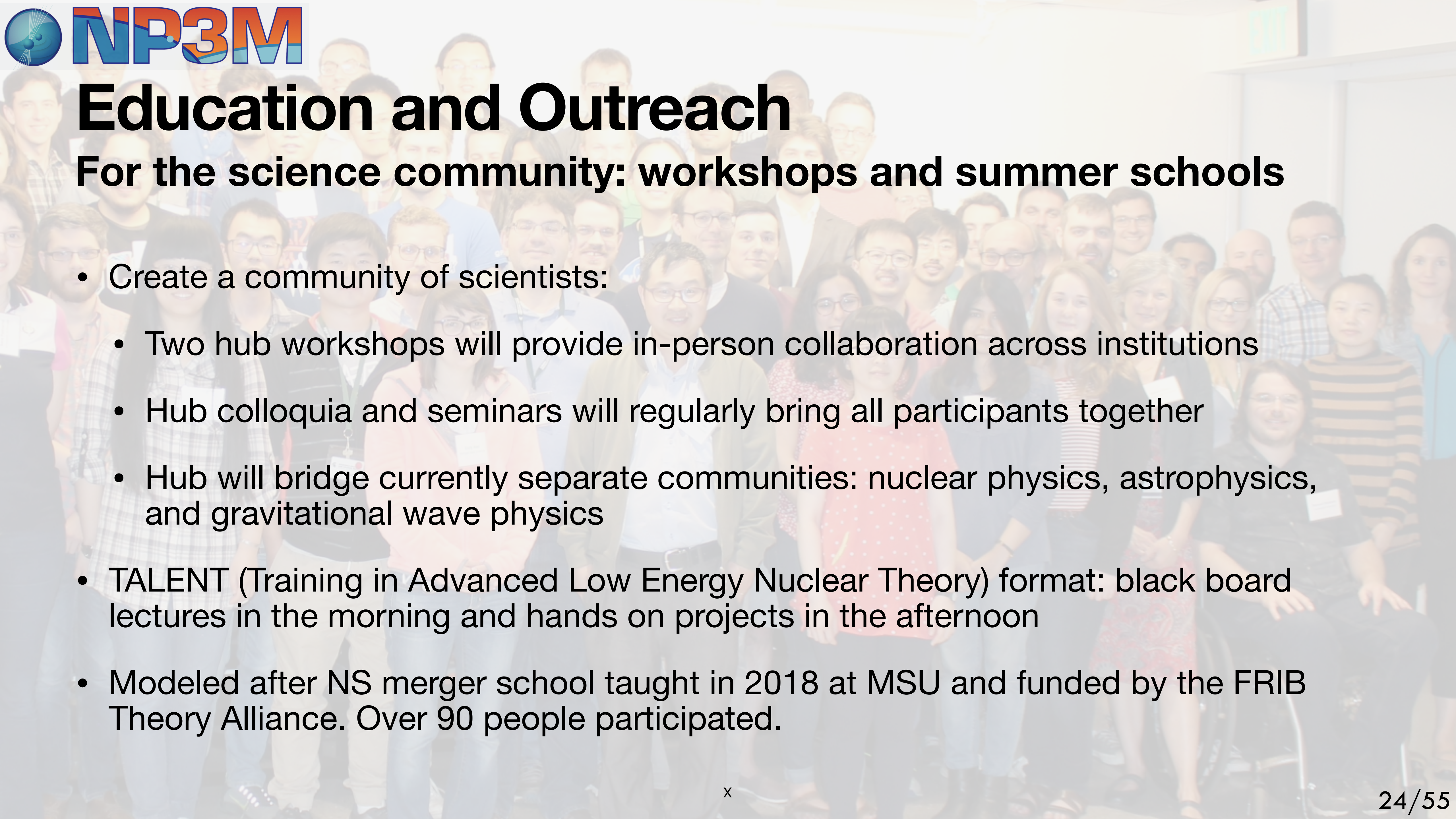
BROADER IMPACT COMMITTEE

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

muses

BROADER IMPACT

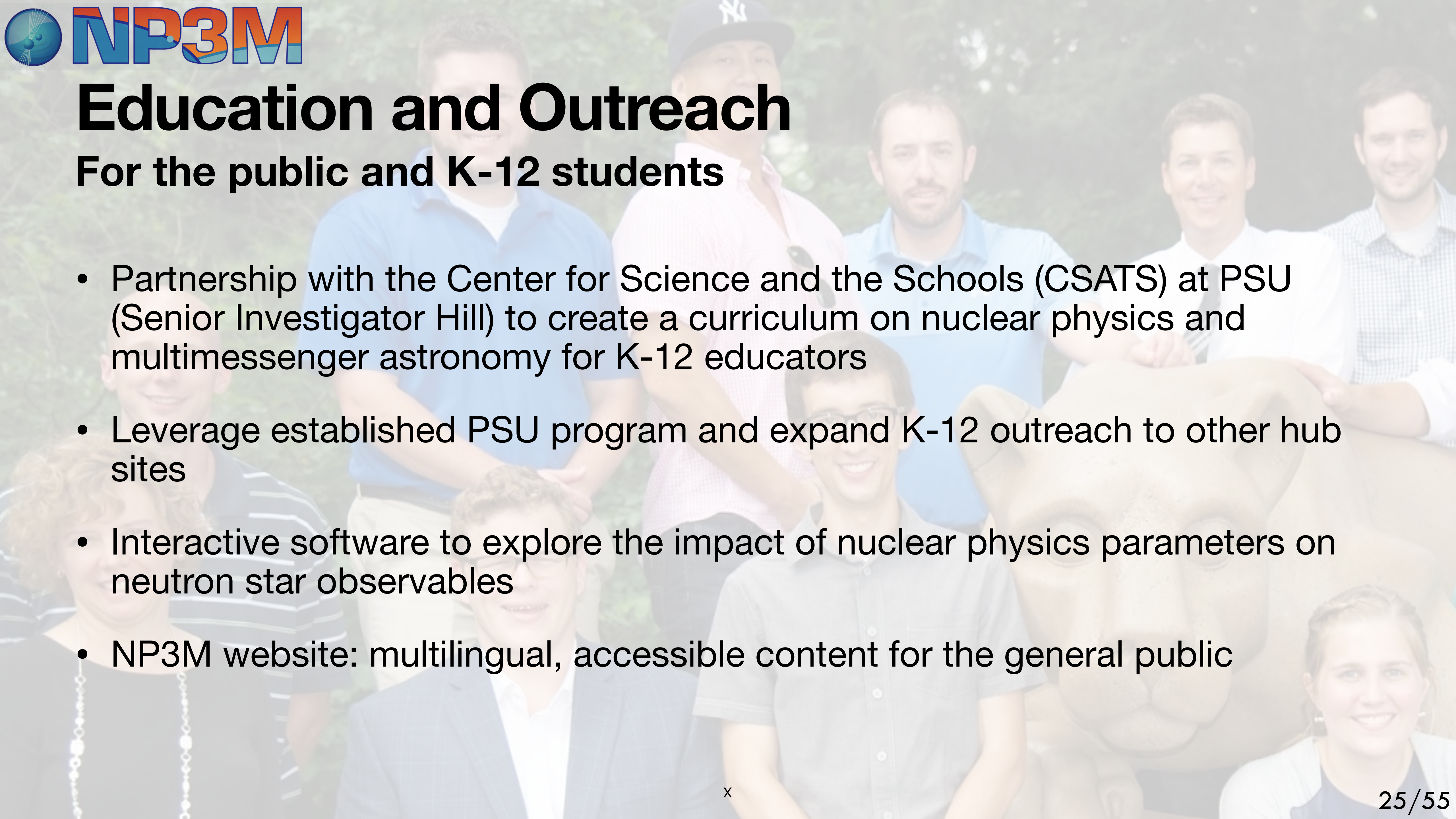
- Annual workshop that combines a training camp and a professional think tank
  - Students and postdocs have the possibility to establish collaborations with more senior scientists
- Bi-weekly seminar series on MUSES-related topics (suggest speakers to Mauricio Hippert Jamie Karthein, Joaquin Grefa, 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



Education and Outreach

For the science community: workshops and summer schools

- Create a community of scientists:
  - Two hub workshops will provide in-person collaboration across institutions
  - Hub colloquia and seminars will regularly bring all participants together
  - Hub will bridge currently separate communities: nuclear physics, astrophysics, and gravitational wave physics
- TALENT (Training in Advanced Low Energy Nuclear Theory) format: black board lectures in the morning and hands on projects in the afternoon
- Modeled after NS merger school taught in 2018 at MSU and funded by the FRIB Theory Alliance. Over 90 people participated.



Education and Outreach

For the public and K-12 students

- Partnership with the Center for Science and the Schools (CSATS) at PSU (Senior Investigator Hill) to create a curriculum on nuclear physics and multimessenger astronomy for K-12 educators
- Leverage established PSU program and expand K-12 outreach to other hub sites
- Interactive software to explore the impact of nuclear physics parameters on neutron star observables
- NP3M website: multilingual, accessible content for the general public

Equity, Diversity, and Inclusion

Creating a more inclusive nuclear physics community

- A multi-institution hub will help to attract and retain excellent postdoctoral scholars from underrepresented groups
- University of Houston and Cal State University Fullerton are minority serving institutions
- Syracuse and Cal State Fullerton have well established bridge programs through NSF PAARE program. PSU is part of the NSF Cal Bridge program. Indiana has an APS bridge program
- Hub postdocs will have the opportunity to mentor these students
- The hub will allow us to unite these programs bringing more research opportunities to the students and enlarging the cohort of peers at all levels

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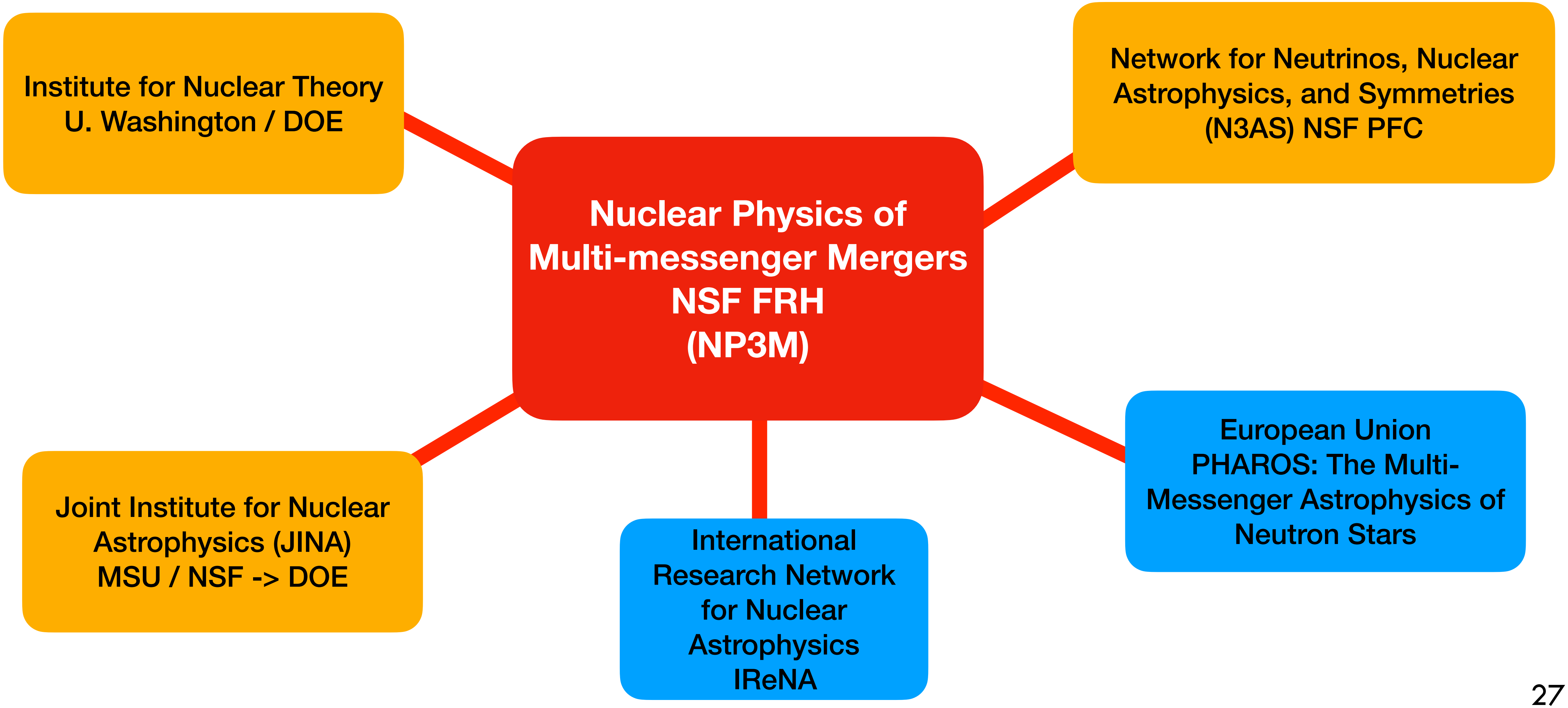
Broader Impact: Nuclear Theory Community

The NP3M Hub as an integral part of nuclear theorists worldwide



Nuclear Physics of
Multi-messenger Mergers
NSF FRH
(NP3M)

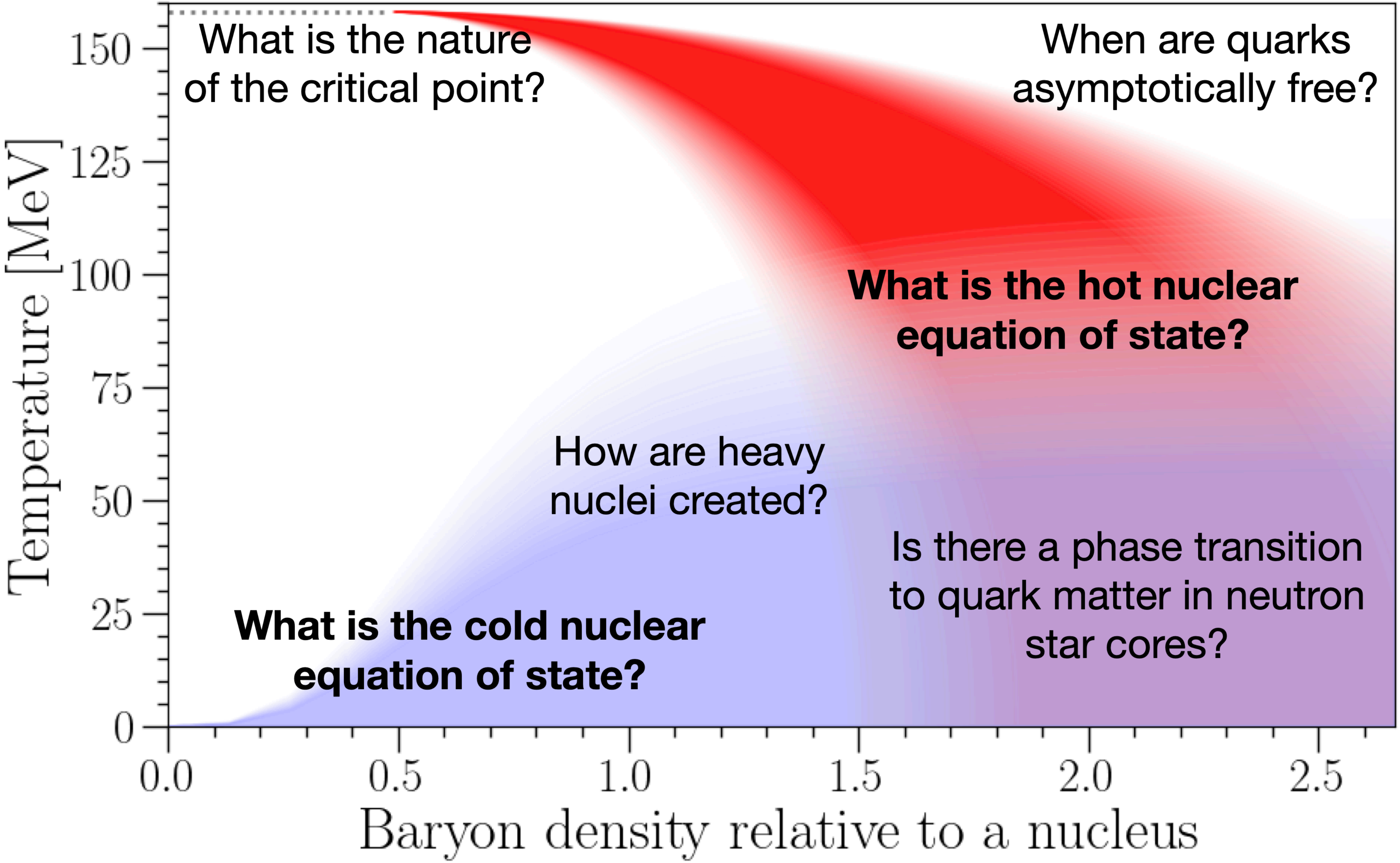
Institute for Nuclear Theory
U. Washington / DOE

Network for Neutrinos, Nuclear Astrophysics, and Symmetries (N3AS) NSF PFC

Joint Institute for Nuclear Astrophysics (JINA)
MSU / NSF -> DOE

International Research Network for Nuclear Astrophysics
IReNA

European Union
PHAROS: The Multi-Messenger Astrophysics of Neutron Stars



What is the nature of the critical point?

When are quarks asymptotically free?

What is the hot nuclear equation of state?

How are heavy nuclei created?

Is there a phase transition to quark matter in neutron star cores?

What is the cold nuclear equation of state?

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

Broader Impact: Adjacent Communities

NP3M has strong connections

- Nuclear experiment:
  - FRIB via SI Nazarewicz and IAC Schatz
  - ISAC/ARIEL via ICO Dillman
  - GSI via ICO Dillman, ICO Galatyuk, and IAC Schwenk
  - RHIC via co-PI Ratti and SI Rapp
  - JLAB via co-PI Horowitz

- Astronomical observations:
  - Electromagnetic observatories through SI Villar
  - Einstein Telescope via CO Sathyaprakash
  - LIGO and Cosmic Explorer co-PI Brown, SI Read, and CO Sathyaprakash
  - Fermi via ICO Allen

- Computational collaborations:
  - NUCLEI SciDAC via co-PI Horowitz and SI Nazarewicz
  - TEAMS SciDAC via PI Steiner, co-PI Radice, and SI Hix
  - Simulating eXtreme Spacetimes via SI Foucart

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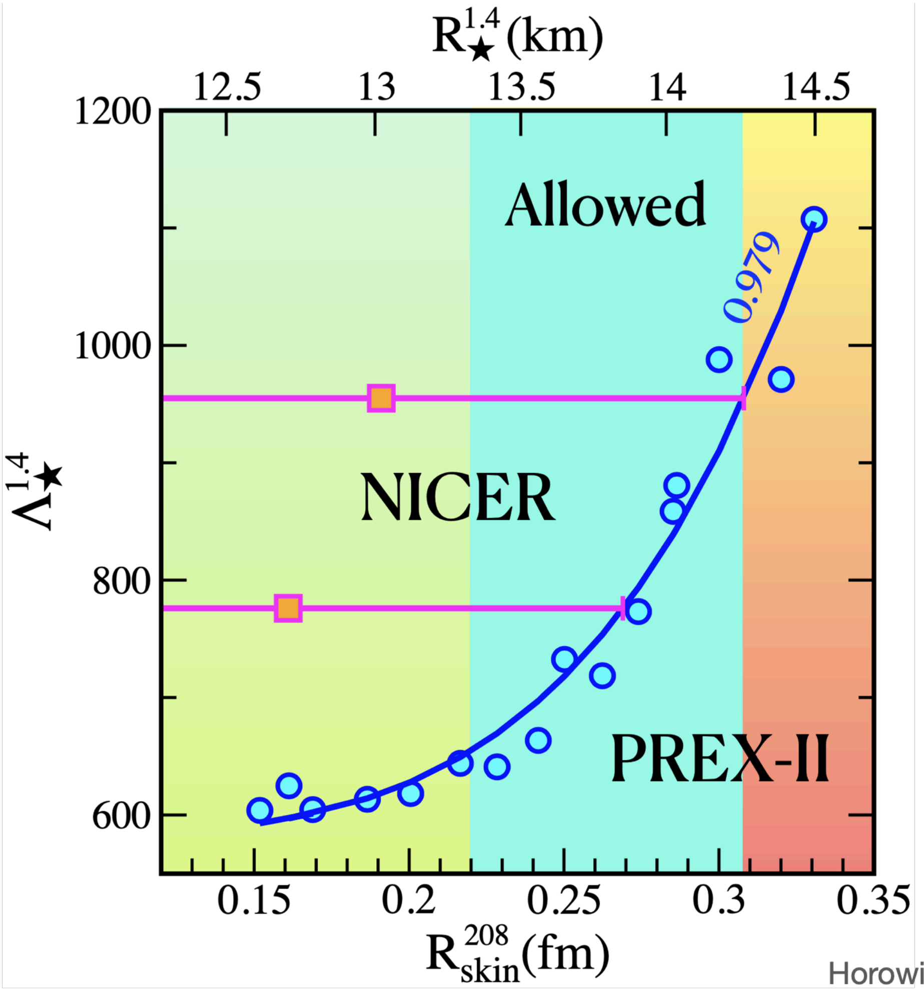
Neutron matter in the lab and in the heavens

Connecting PREX and FRIB to neutron star mergers

- The Hub will build density functionals that include information from PREX, FRIB experiments, astronomical observations, and chiral effective field theory/quantum Monte Carlo
- Integrate density functional theory into merger simulations
- PREX/CREX parity violation experiments measure the neutron skin of ^{208}Pb, ^{48}Ca
- Complementary to FRIB experiments on more neutron-rich nuclei



Horowitz/IU

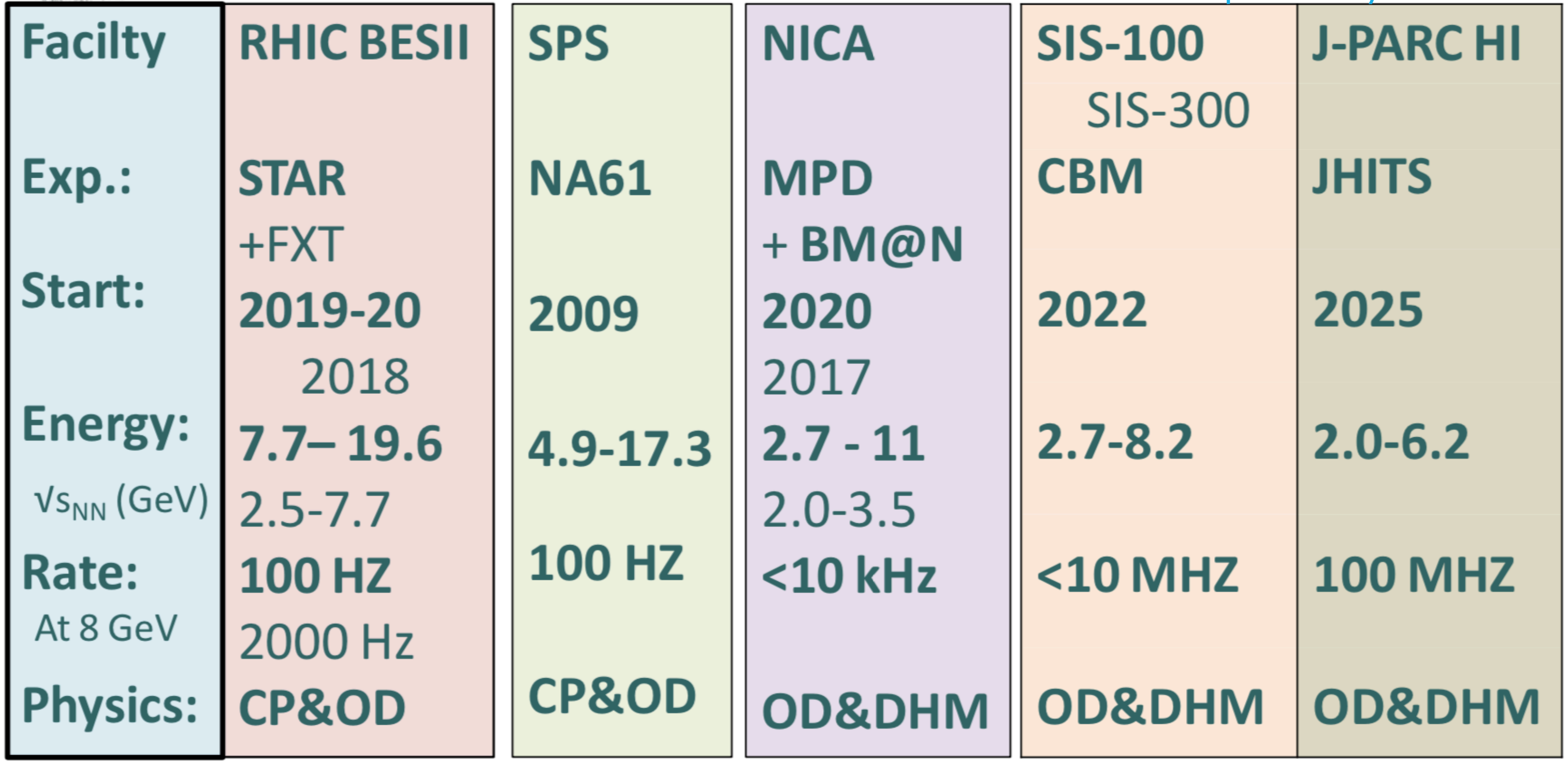
NP3M: Key Deliverables

Using mergers to advance nuclear theory

- Create probability distributions for nuclear physics parameters at high and low temperatures based on new theoretical developments
- High-precision, end-to-end predictions of multi-messenger observables including:
  - Imprint of EOS on tidally interacting neutron stars and post-merger objects
  - Electromagnetic signatures from mergers
  - Explore the parameter space of possible mergers and allowed nuclear theory
  - Integrate uncertainty quantification into analyses
- Update nuclear models with new experimental and observational data

COMPARISON OF THE FACILITIES

Compilation by D. Cebra

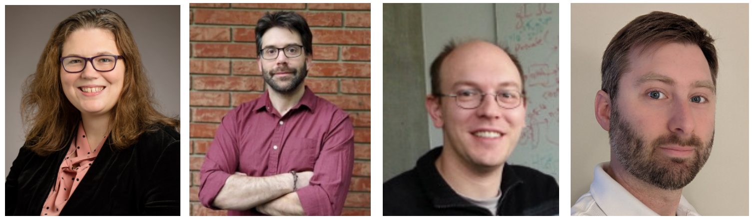


Facilty	RHIC BESII	SPS	NICA	SIS-100 SIS-300	J-PARC HI
Exp.:	STAR +FXT	NA61	MPD + BM@N	CBM	JHITS
Start:	2019-20 2018	2009	2020 2017	2022	2025
Energy: $\sqrt{s_{NN}}$ (GeV)	7.7– 19.6 2.5-7.7	4.9-17.3	2.7 - 11 2.0-3.5	2.7-8.2	2.0-6.2
Rate: At 8 GeV	100 HZ 2000 Hz	100 HZ	<10 kHz	<10 MHZ	100 MHZ
Physics:	CP&OD	CP&OD	OD&DHM	OD&DHM	OD&DHM
	Collider Fixed target	Fixed target Lighter ion collisions	Collider Fixed target	Fixed target	Fixed target

CP=Critical Point OD= Onset of Deconfinement DHM=Dense Hadronic Matter

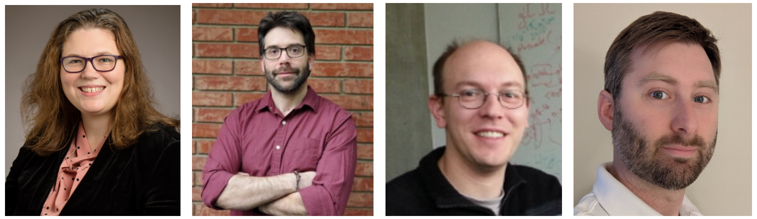
WEBPAGES

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



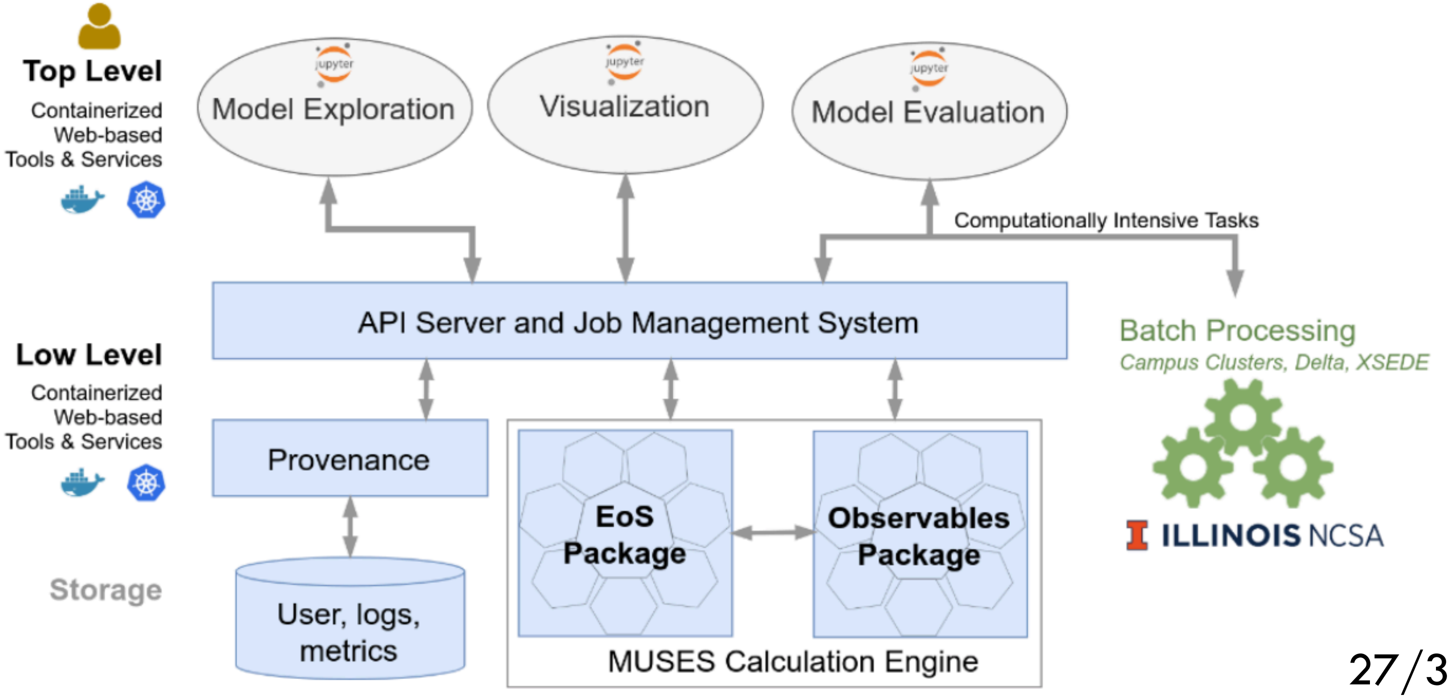
WEB TOOLS

- 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



Top Level
Containerized
Web-based
Tools & Services

Model Exploration
Visualization
Model Evaluation

Computationally Intensive Tasks

API Server and Job Management System

Batch Processing
Campus Clusters, Delta, XSEDE

ILLINOIS NCSA

Low Level
Containerized
Web-based
Tools & Services

Provenance

EoS Package
Observables Package
MUSES Calculation Engine

Storage

User, logs, metrics

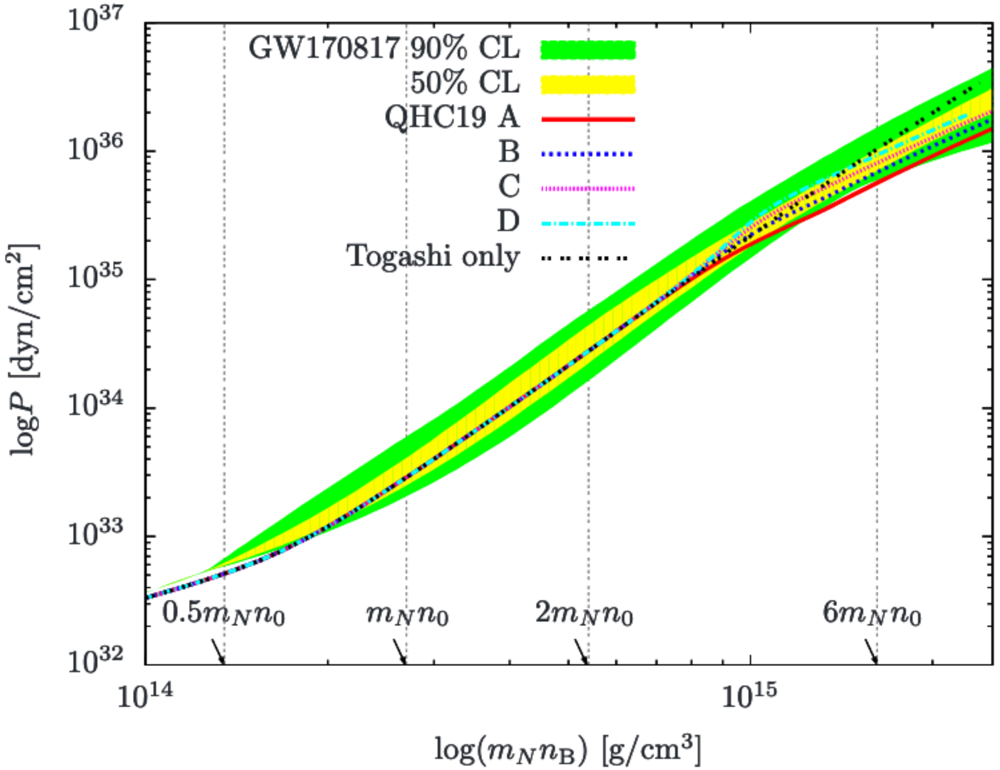
Hajme
Togashi

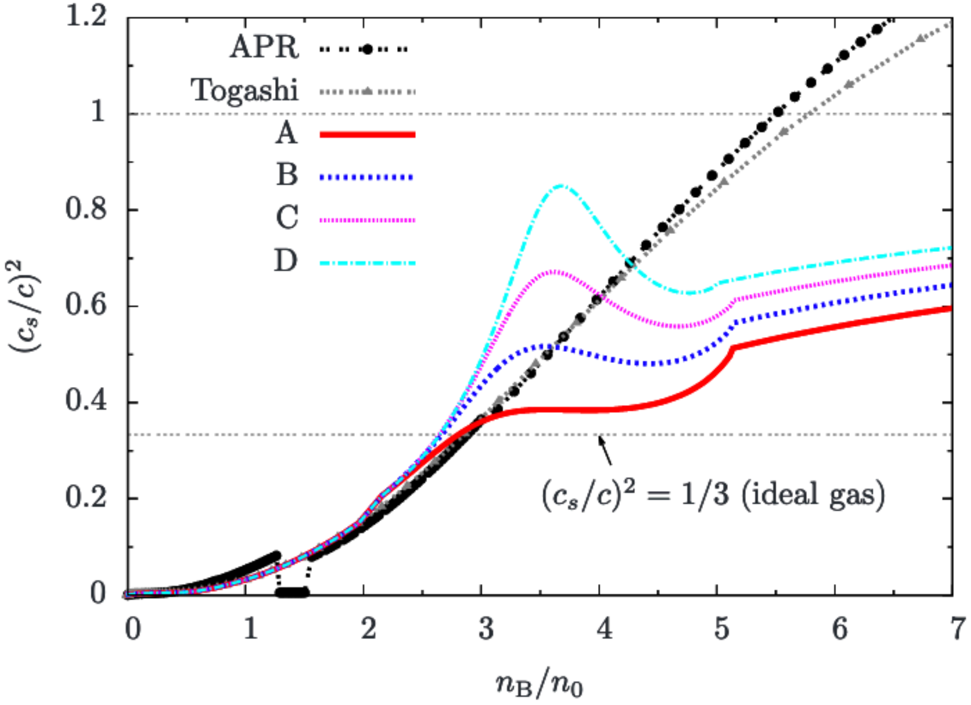
QUARK-HADRON CROSSOVER (QHC19)

- 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)

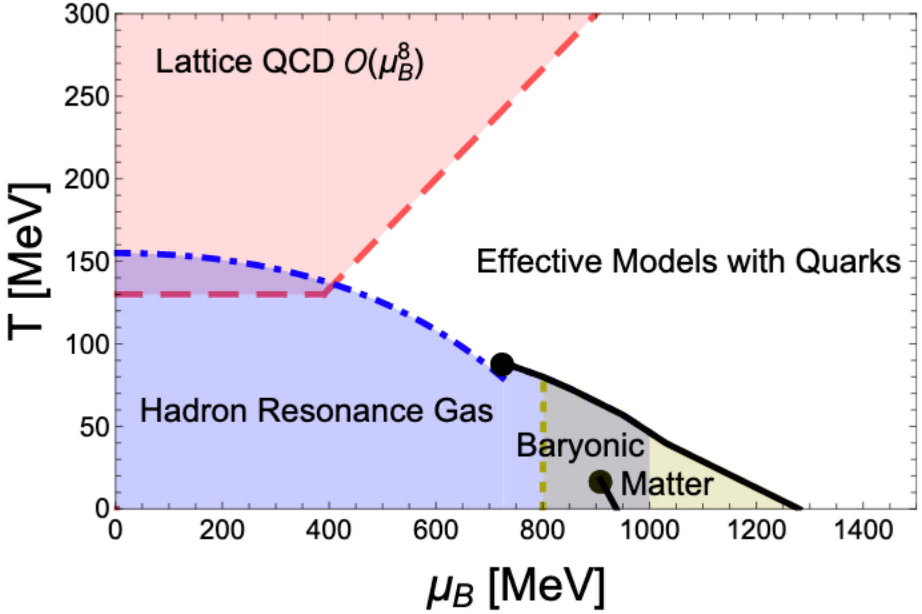
Goals:
- Optimization of the code
- Incorporation into MUSES





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



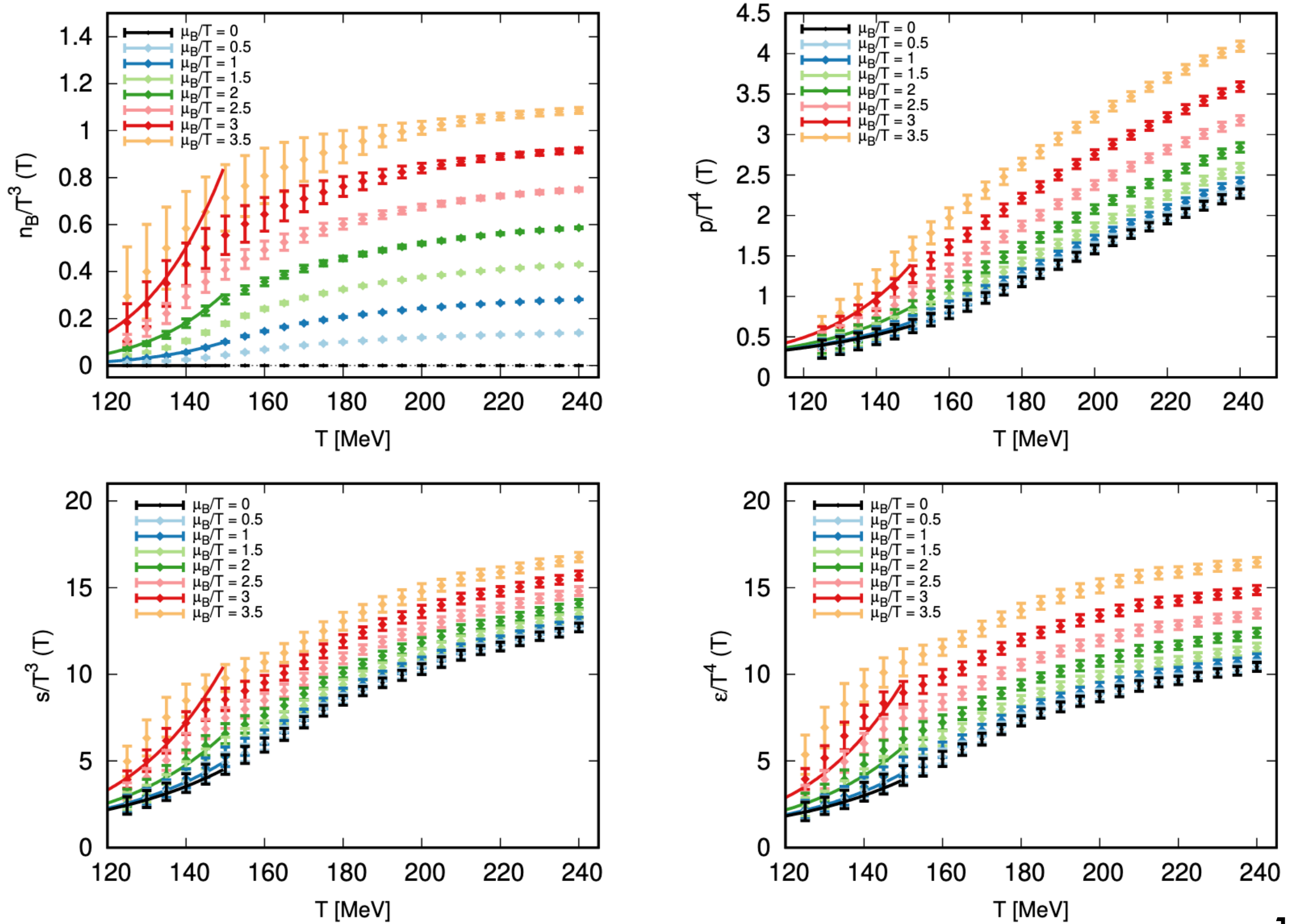
EQUATION OF STATE FROM FIRST PRINCIPLES

- Novel expansion scheme allows to extend to $\mu_B/T \sim 3.5$
- EoS available so far at $\mu_S = \mu_Q = 0$
- Working on the extension 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 highest possible μ_B
- Extension to μ_S & $\mu_Q \neq 0$
- Implementation into the MUSES engine

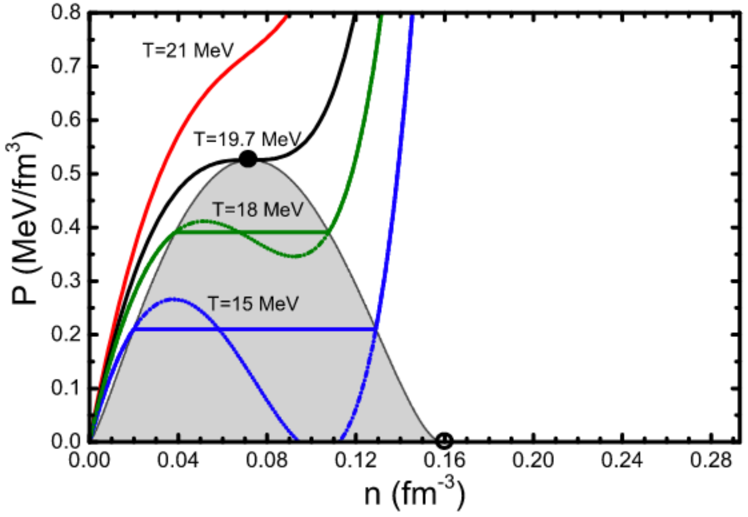
S. Borsanyi, C. R. et al., PRL (2021)

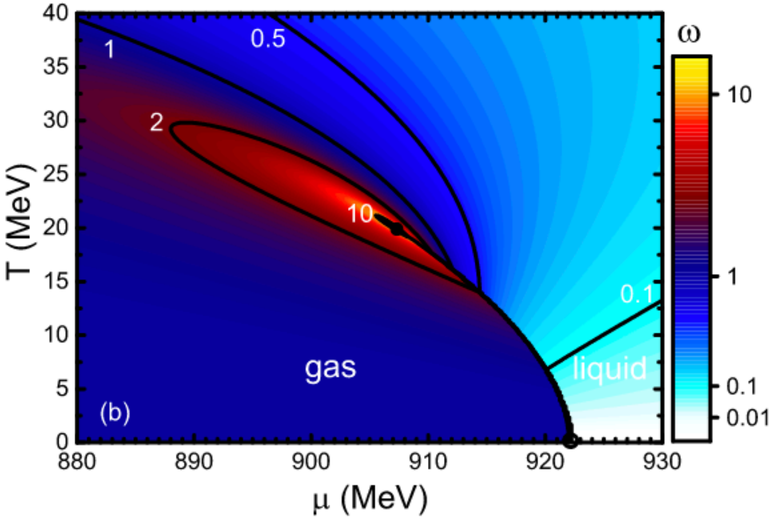


HADRON RESONANCE GAS (HRG) MODEL

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

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)

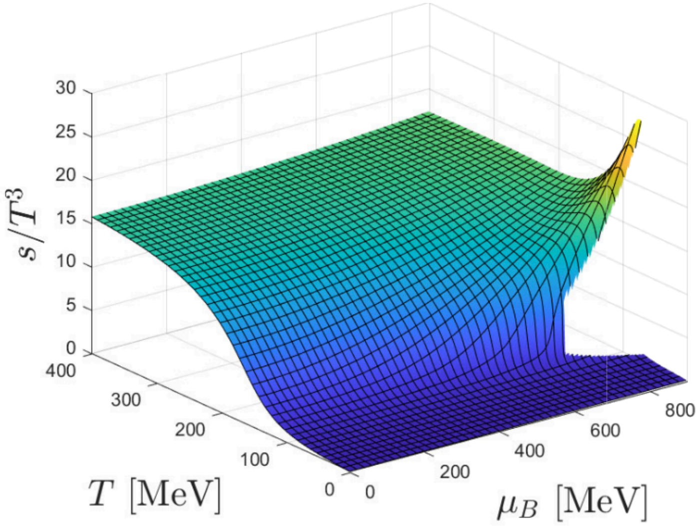
- EoS with 3D Ising model critical point
  - Coverage: 0<T<800 MeV, $0<\mu_B<450$ MeV

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)

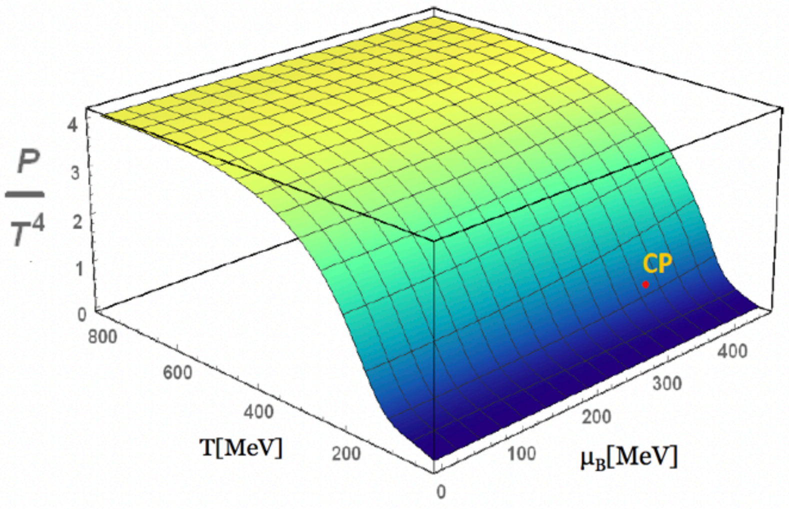
P. Parotto, C. R. et al., PRC (2020)

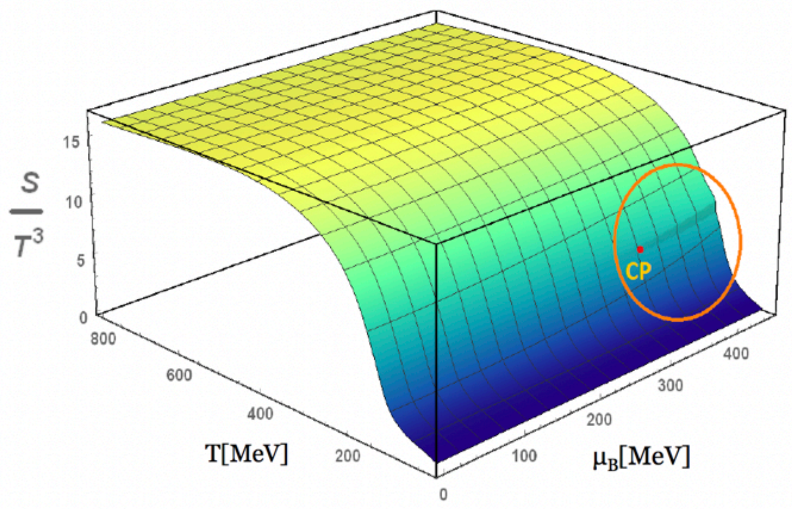
J. Karthein, C. R. et al., EPJ Plus (2021)

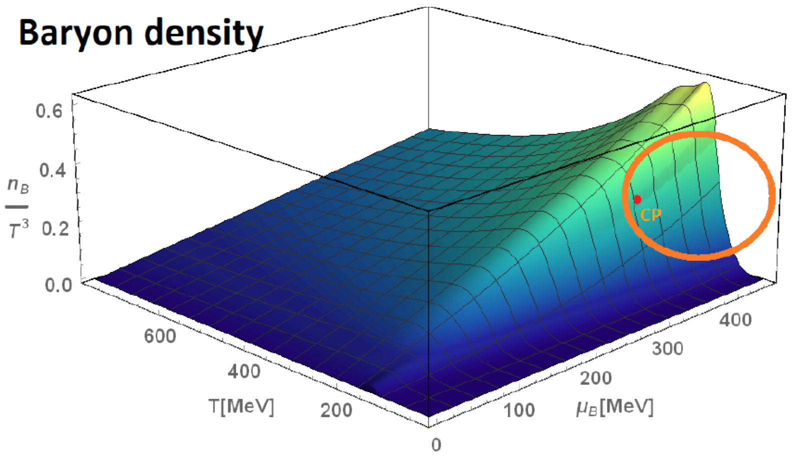
- Implement scaling behavior of 3D-Ising model EoS
- Define map from 3D-Ising model to QCD
- Estimate contribution to Taylor coefficients from 3D-Ising model critical point
- Reconstruct full pressure
- Currently available at $\mu_S=\mu_Q=0$ and for $<n_S>=0$, $<n_Q>=0.4<n_B>$

Goals:

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







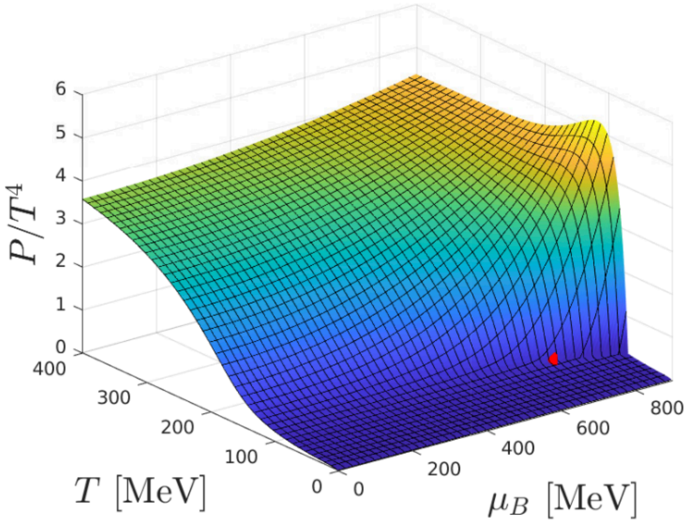
EQUATION OF STATE FROM HOLOGRAPHY (NUMRELHOLO)

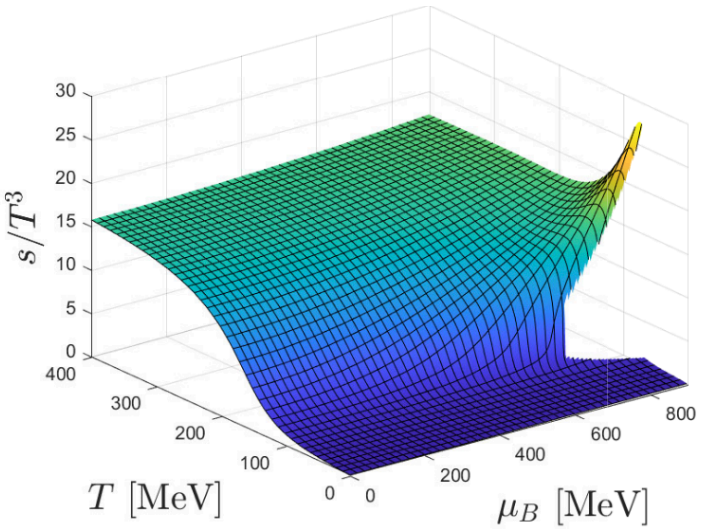
J. Grefa, C. R. et al., PRD (2021)

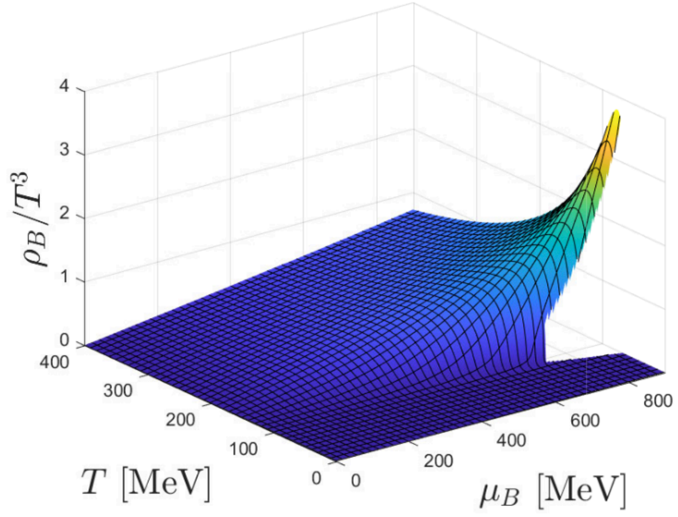
- Use AdS/CFT correspondence
- Fix the parameters to reproduce everything we know from the lattice
- Calculate equation of state at finite density
- Model currently has only baryon number
- Prediction of critical point: T_C= 89 MeV μ_{BC}=723 MeV

Goals:

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



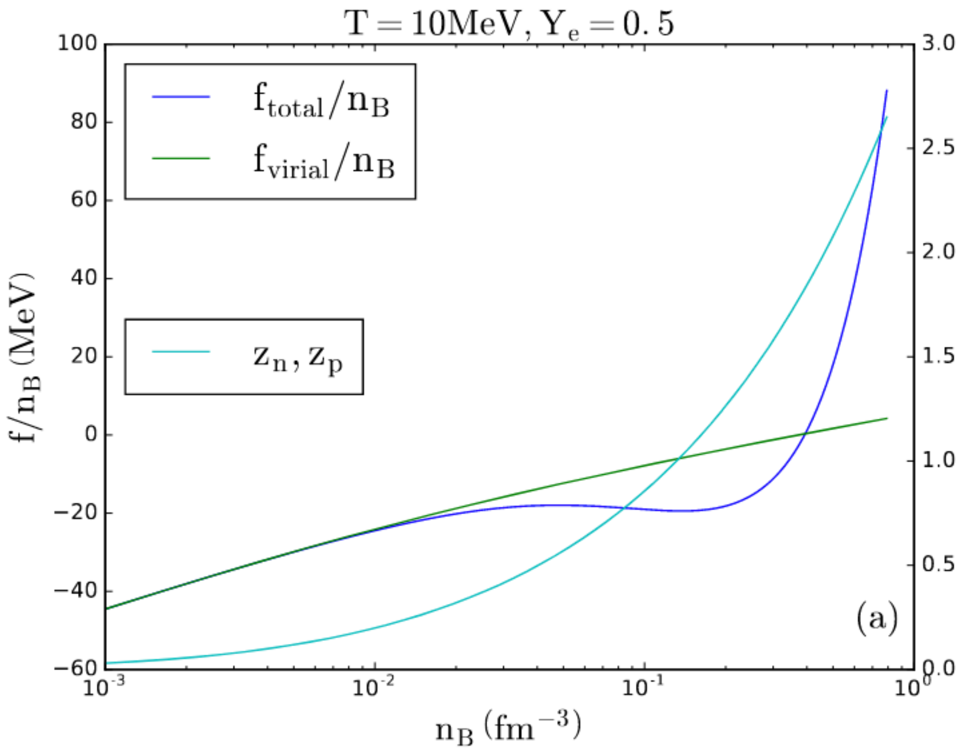


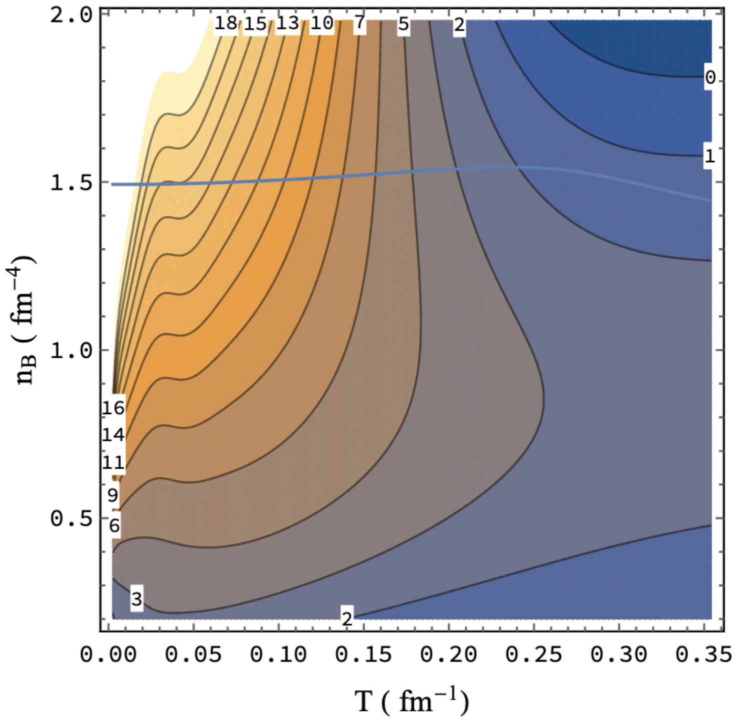


UNIVERSITY OF TENNESSEE KNOXVILLE EOS(UTK EOS)

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





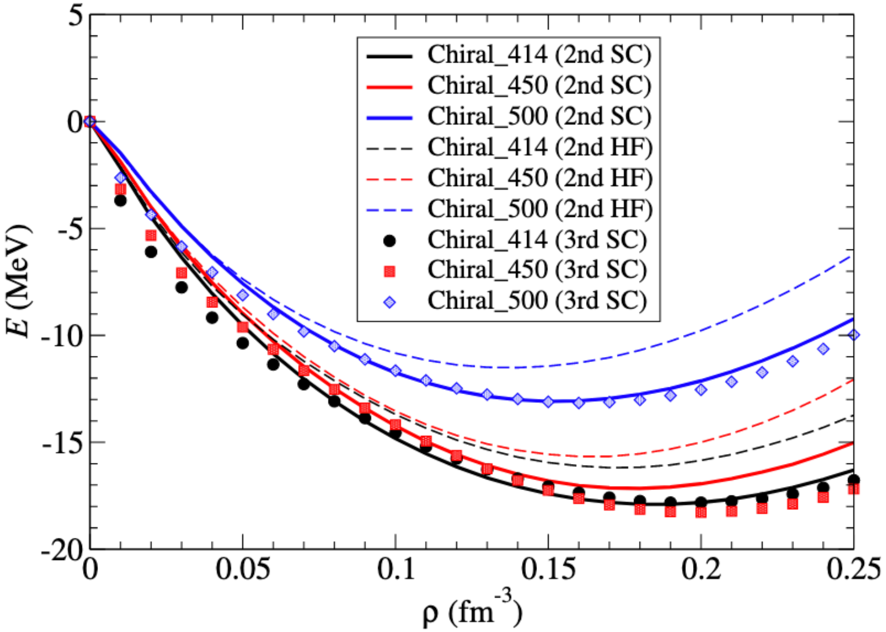
Goals:
- Optimization of the code
- Extension to strangeness degrees of freedom
- Incorporate into MUSES

CHIRAL EFFECTIVE FIELD THEORY (CHEFTEOS)

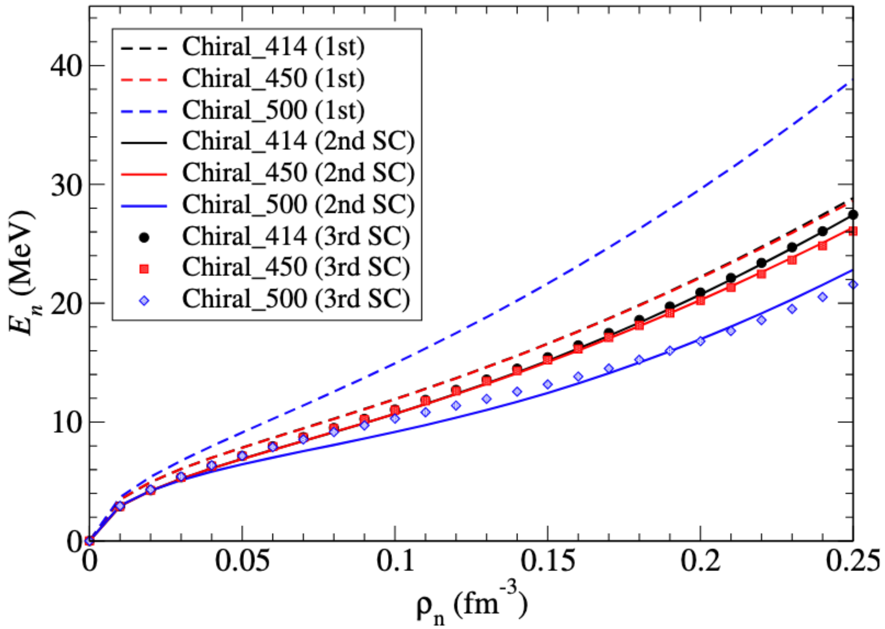
J. Holt & N. Kaiser, PRD (2017)

- 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

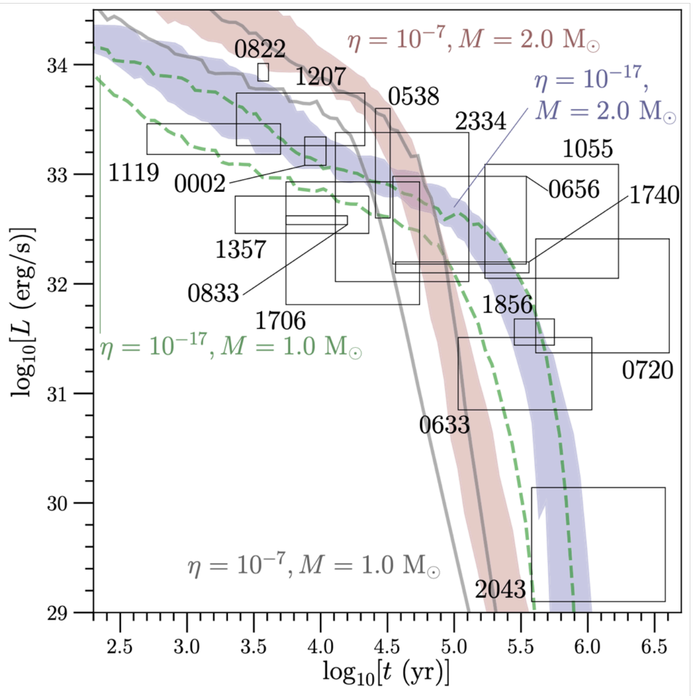
Nucleon-nucleon interactions from neutron star mergers

- 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

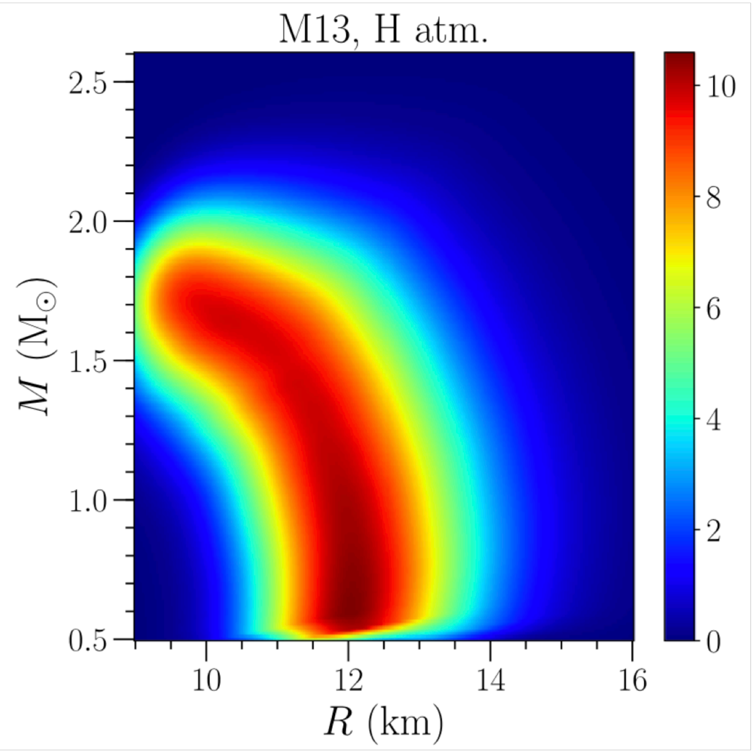
NP3M

Multi-Messenger Inference

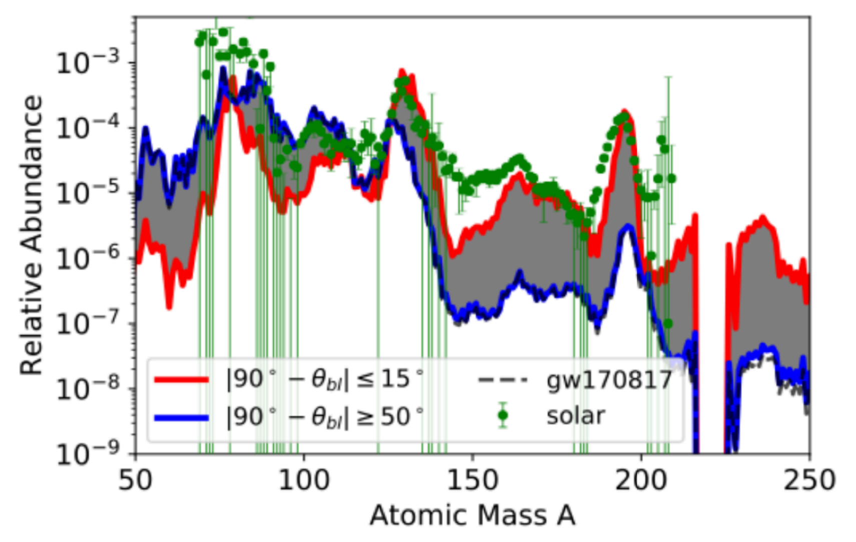
Connecting to observables



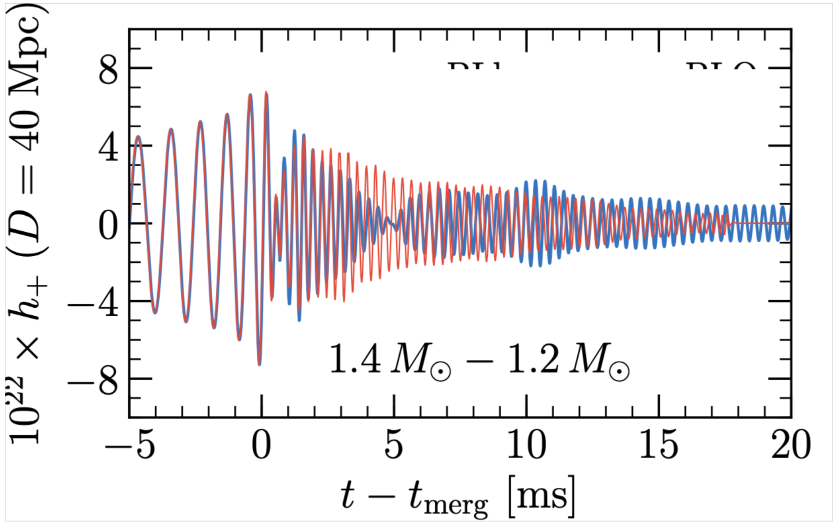
Age-luminosity relations for isolated neutron stars (UTK)



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)