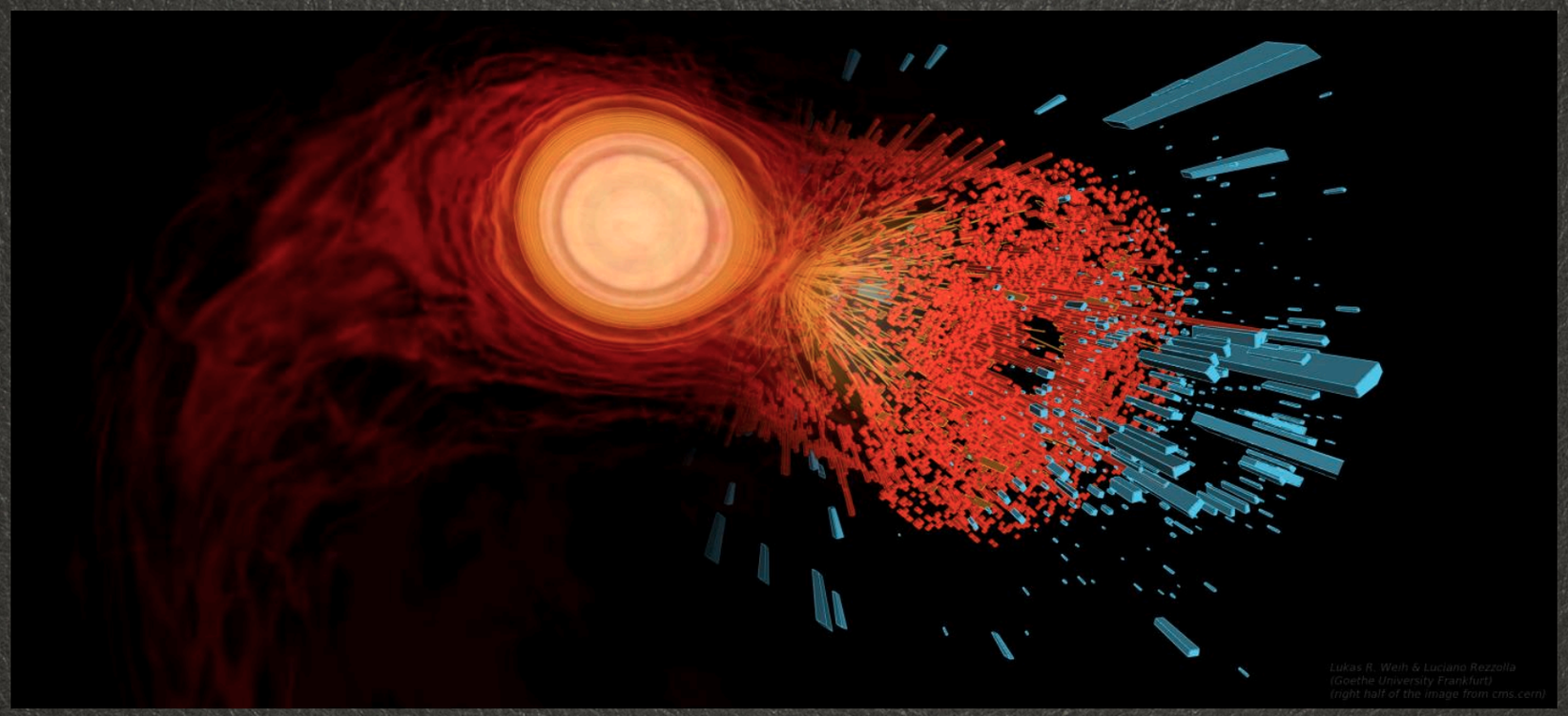
Illinois Center for Advanced Studies of the Universe

muses

BEST COLLABORATION

DNP Town Hall 2022

High Density QCD Theory

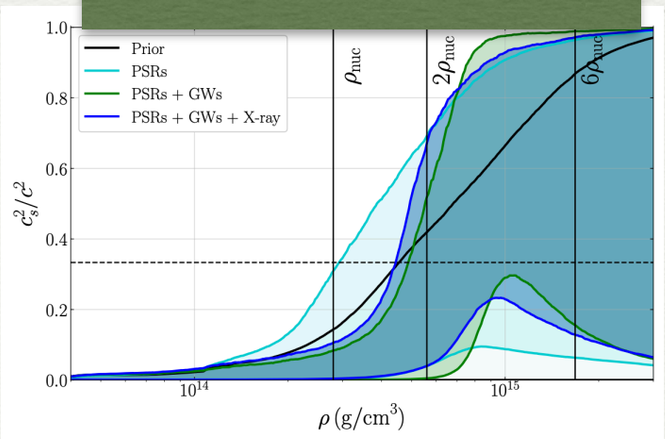


Jacquelyn Noronha-Hostler
University of Illinois at Urbana-Champaign

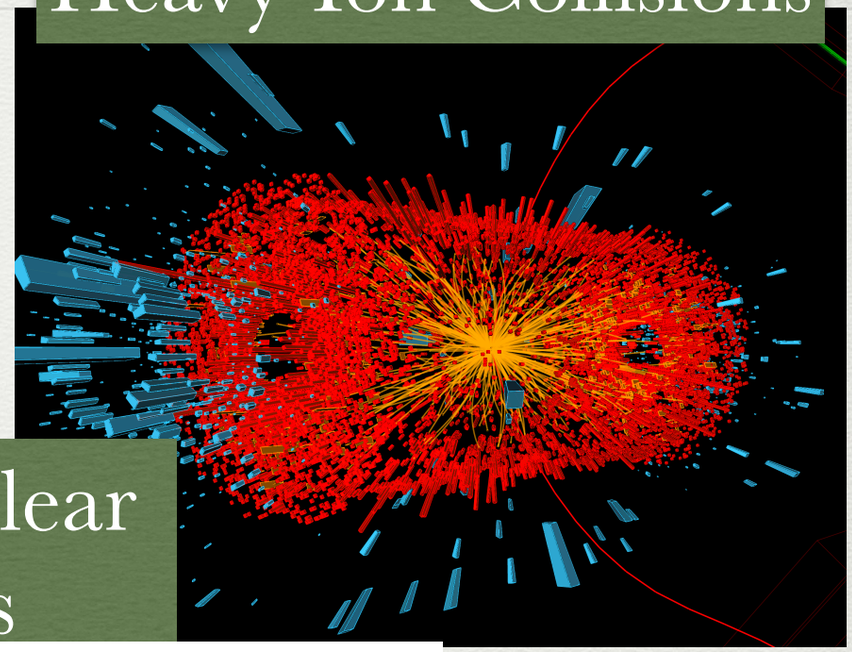
Who works on dense matter?

Numerical Relativity/ Gravitational Waves

Data Scientists



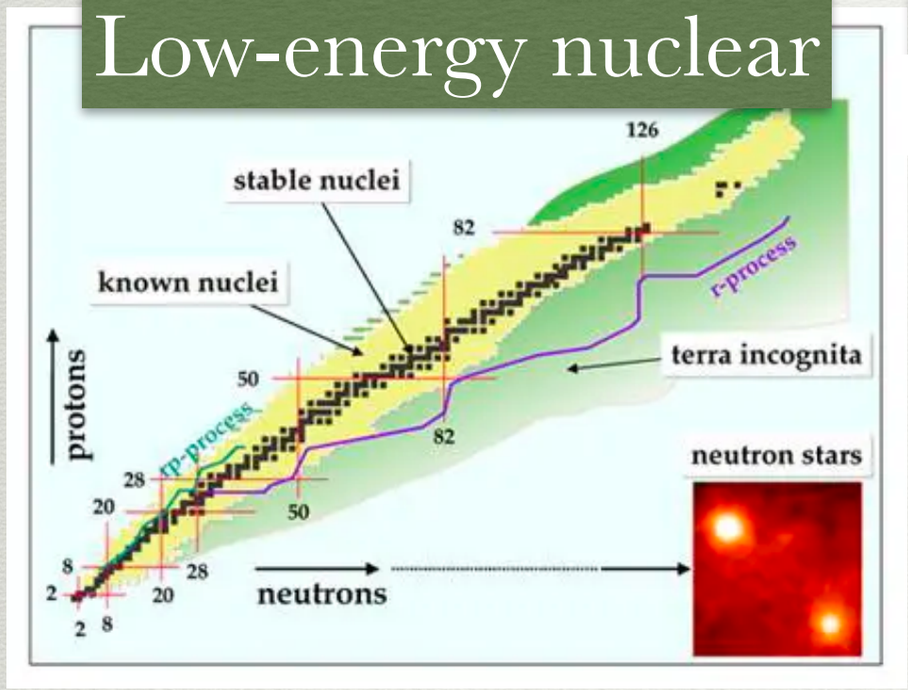
Heavy-Ion Collisions

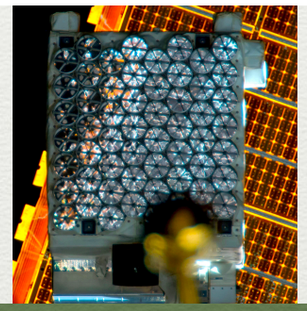


High-energy nuclear astrophysicists

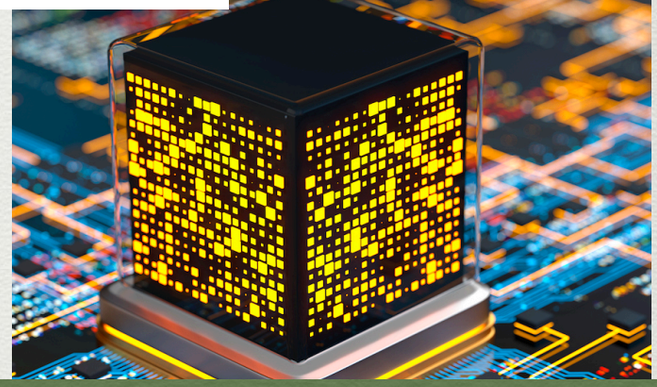
$$L = L_{Kin} + L_{Int} + L_{Self} + L_{SB} - U,$$

Low-energy nuclear





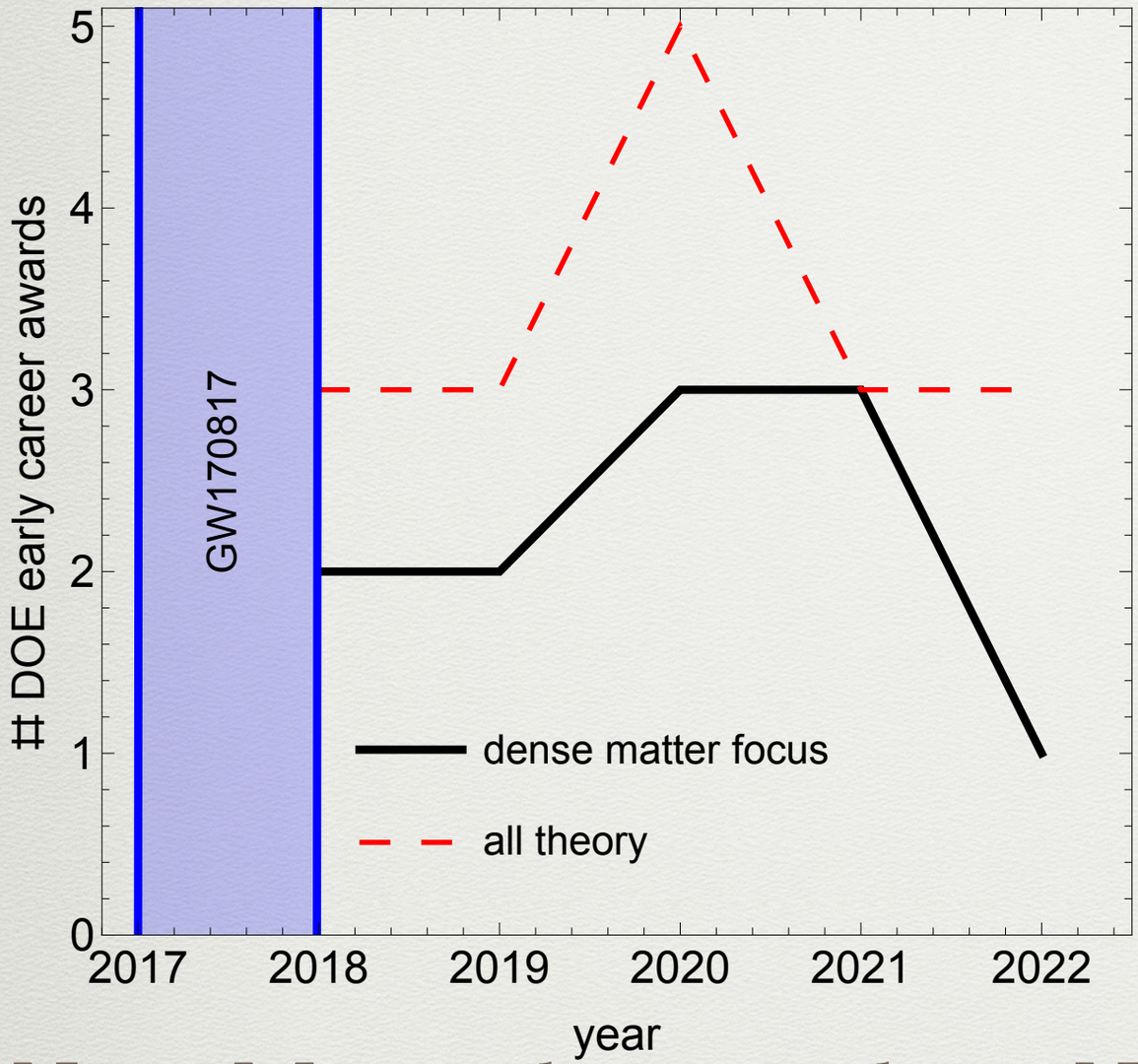
Astrophysicists (NICER)



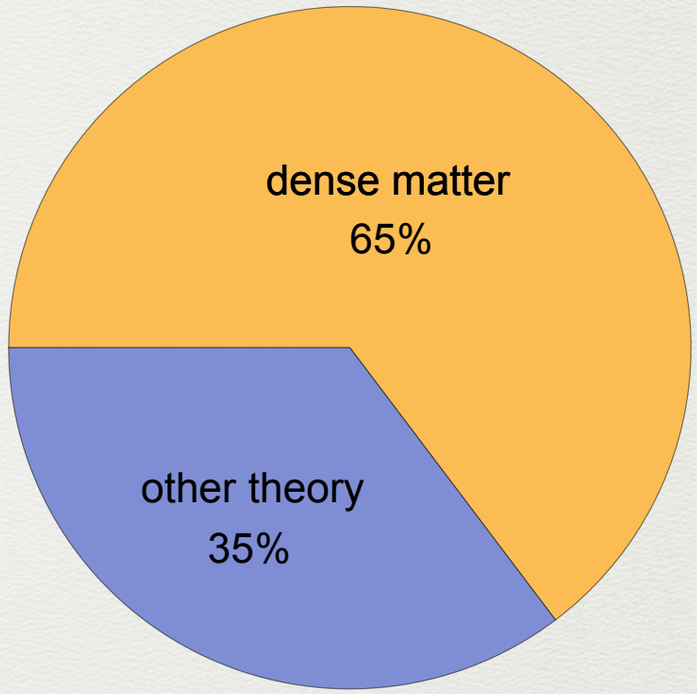
Quantum Computing

How big is the theory community?

Study DOE Early Career Awardees since 2018



Note: Many others out there, NSF CAREER awards, 4+ faculty hires last year, regular DOE/NSF holders



- 2 Heavy-Ions (BES)
- 3 Low-Energy (FRIB)
- 1 High-Energy Astro
- 4 Gravity
- 1 Quantum Computing

Former and Existing Collaborations

BEST COLLABORATION

- DOE topical collaboration: 2016-2020
- BEST EOS (~100 citations) - University of Houston, University of Illinois Urbana-Champaign, University of Illinois Chicago, MIT, and North Carolina State University as well as external collaborators at SUBATECH
- Highlights: Baryon stopping initial conditions, Hydro with baryon conservation, Hadronic afterburner with potentials
- 2 bridge hires+5 postdocs → faculty positions
- 2 DOE ECA winners: JNH & Shen
- ~ 200 papers, 500+ talks, 50+ plenaries

NSF funded collaborations

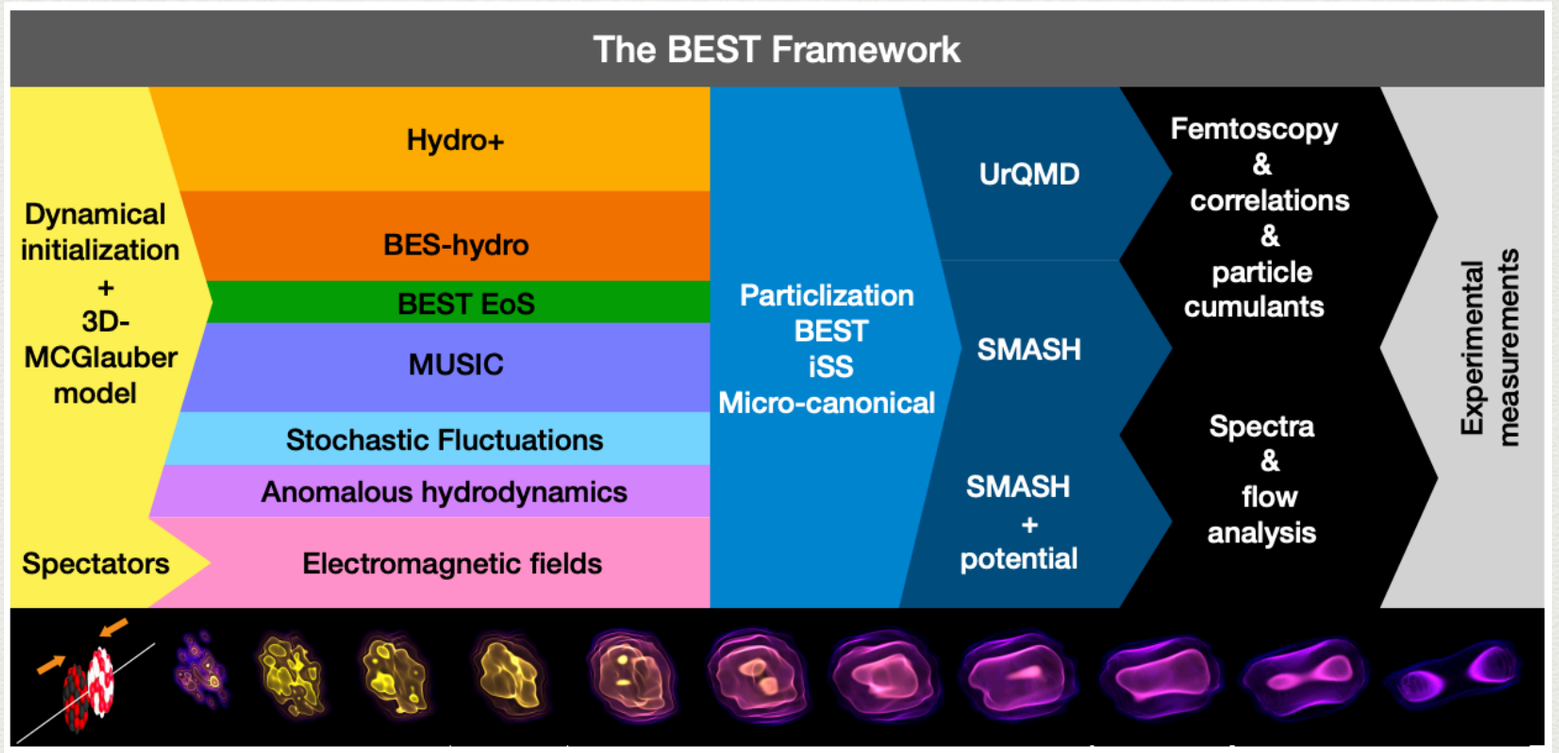
- MUSES (Cyberinfrastructure) 2021-2026
  Topics: Open-source equation of state **modules**
- BAND (Cyberinfrastructure) 2020-2025
  Topics: Uncertainty quantification **tools** across all nuclear
- JETSCAPE (Cyberinfrastructure) 2020-2024
  Topics: jets/heavy flavor, hydro+hadron transport
- NP3M (Hub) 2021-2026
  Topics: Neutron star mergers and supernova
- N3AS (PFC) 2020-2025
  Topics: Neutrinos, dark matter, nucleosynthesis, numerical relativity

What is missing?
* Analysis of heavy-ion BESII data
* Connect low/high energy nuclear physics
* Explore synergy between HIC/NS

Where are we now? What is left?

Summary document

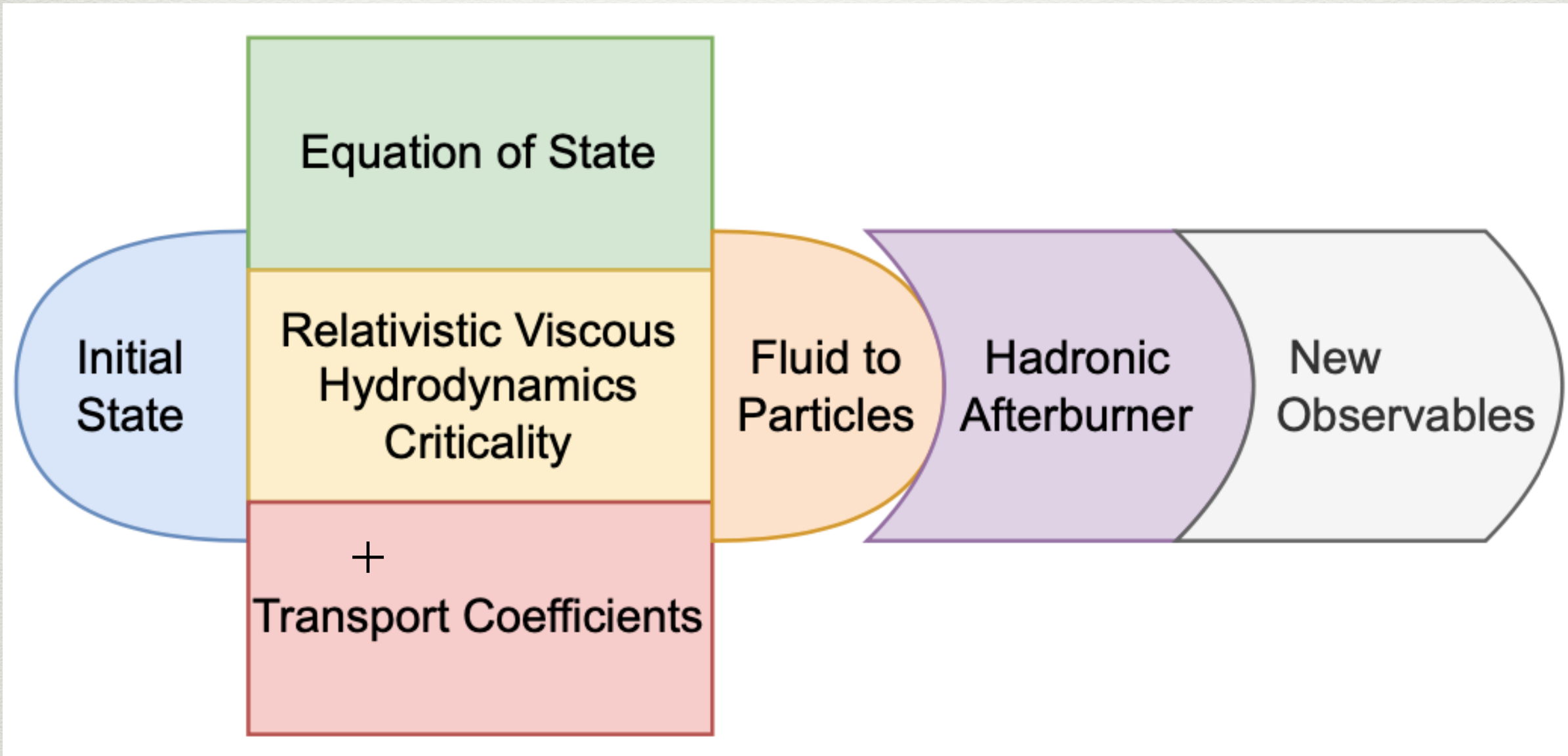
[BEST] Nucl.Phys.A 1017 (2022) 122343, 2108.13867 [nucl-th]



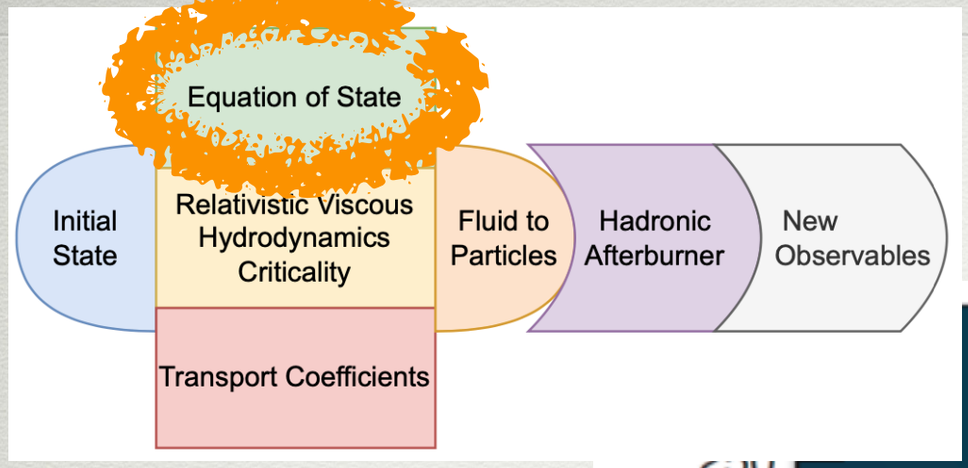
1. Still waiting on BES II data
2. Some tools not yet finished, some not fully coupled together
3. 1st-order transition needs significant theoretical development
4. Connections to neutron stars (mergers) begging to be made!

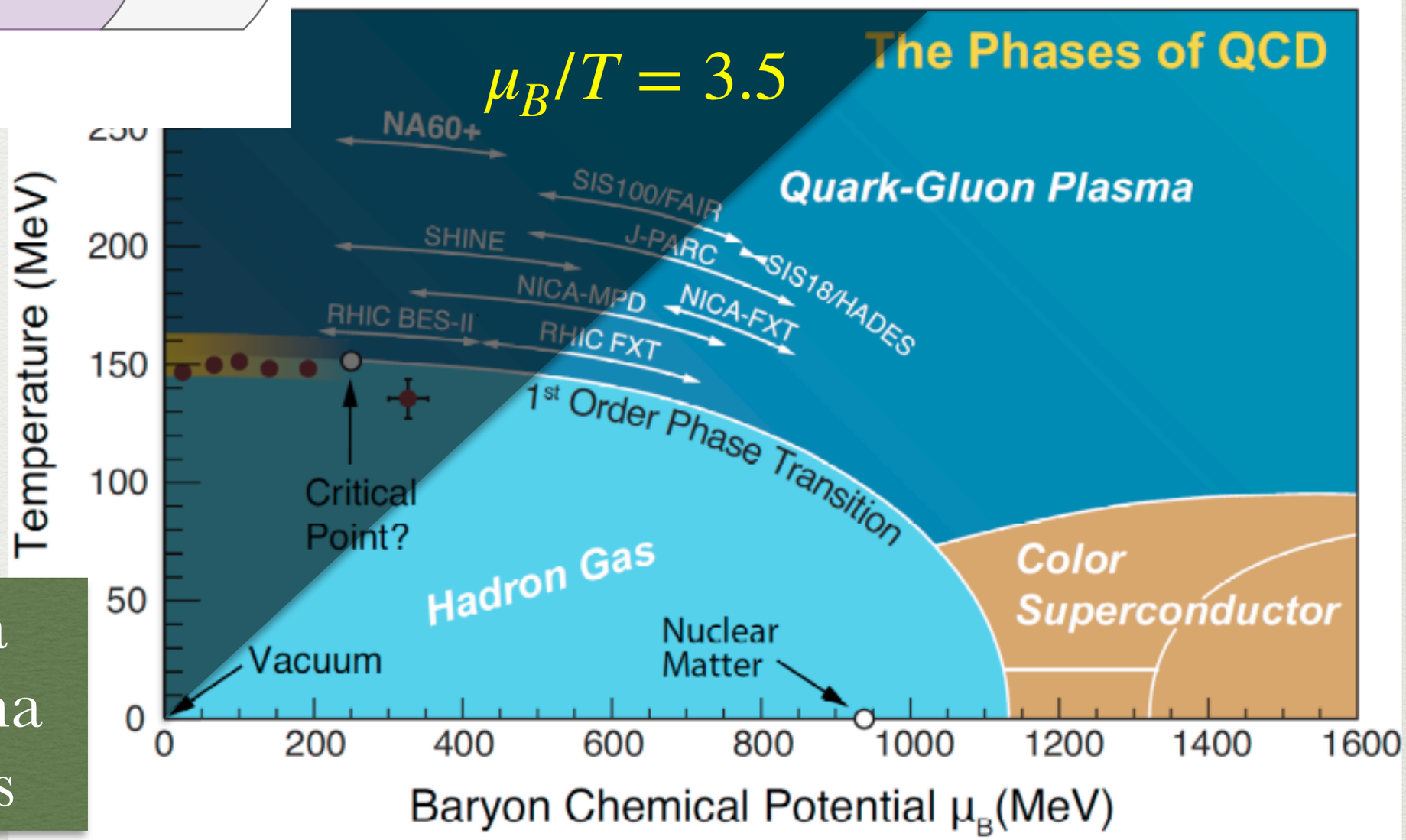
Standard Model of HIC:

It all needs to change at large μ_B!



Beyond Lattice QCD?

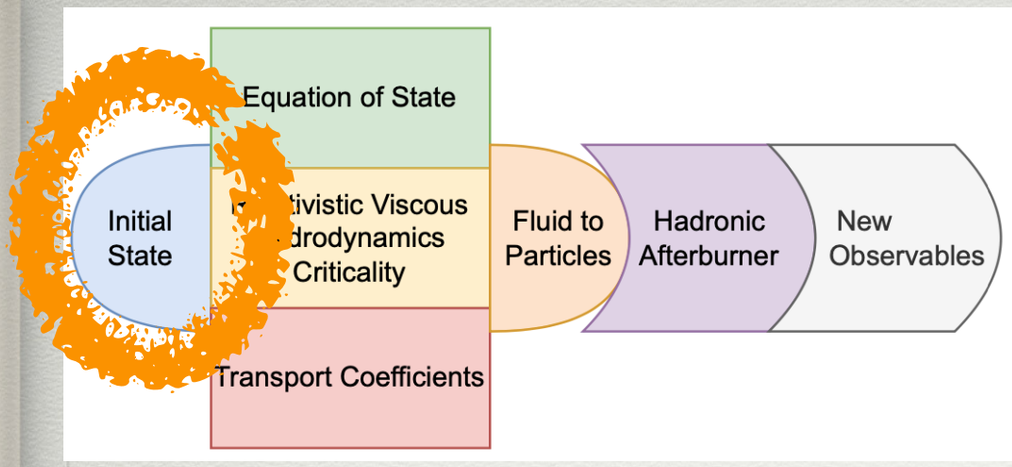




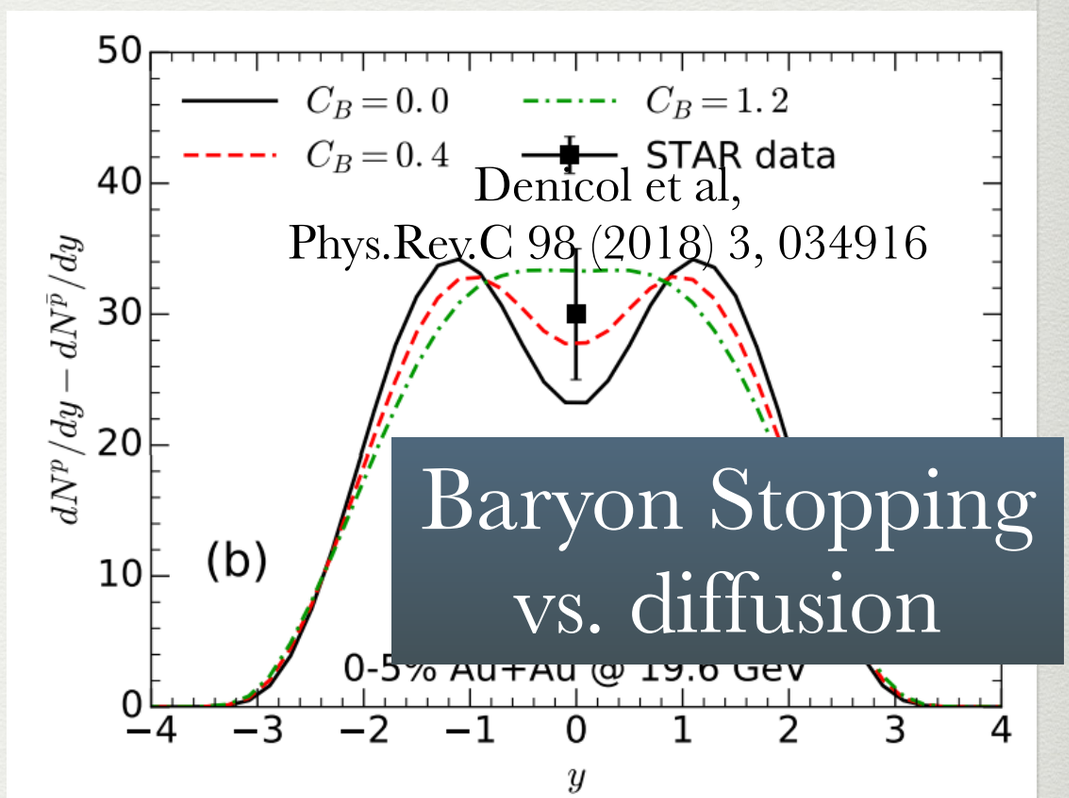
Talks: Claudia Ratti's & Martha Constantinou's

HIC: 4D EOS $\left\{T, \mu_B, \mu_S, \mu_Q\right\}$, NS: 3D EOS $\left\{T, \mu_B, Y_Q\right\}$,

Test with CP & 1st-order PT; 2nd CP; new phases of matter



Need full $T^{\mu\nu}, J^{\mu}$



Denicol et al,
Phys.Rev.C 98 (2018) 3, 034916

Baryon Stopping vs. diffusion

Out-of-equilibrium initial state

Dore et al, Phys.Rev.D 102 (2020) 7, 074017; 2207.04086 [nucl-th]

Fluctuations in Z/A in the IC?

Rapidity dependence?

D.o.f. vs $\sqrt{s_{NN}}$? Initial T, μ_B?

Simple Initial State: ε, n_B

Better Initial State: $\varepsilon, n_B, n_Q, n_S$

+flow: $\varepsilon, n_B, n_Q, n_S, u^\mu$

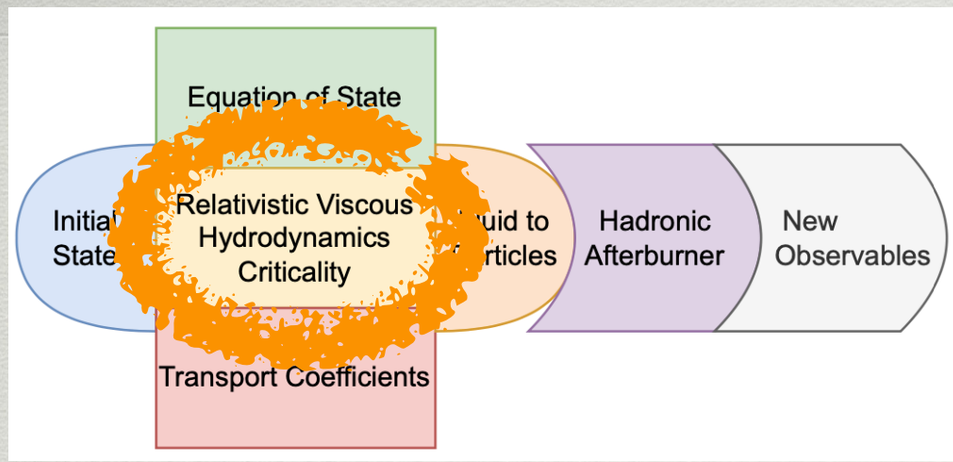
+dissipative: $\varepsilon, B^\mu, S^\mu, Q^\mu, \pi^{\mu\nu}, \Pi$

Shen & Schenk *Phys.Rev.C* 97 (2018) 2, 024907

[ICCING] Carzon et al, *Phys.Rev.C* 105 (2022) 3, 034908
Fluctuations only, no net-n_B

Hadron transport possible [SMASH, URQMD, etc.],
not used in practice

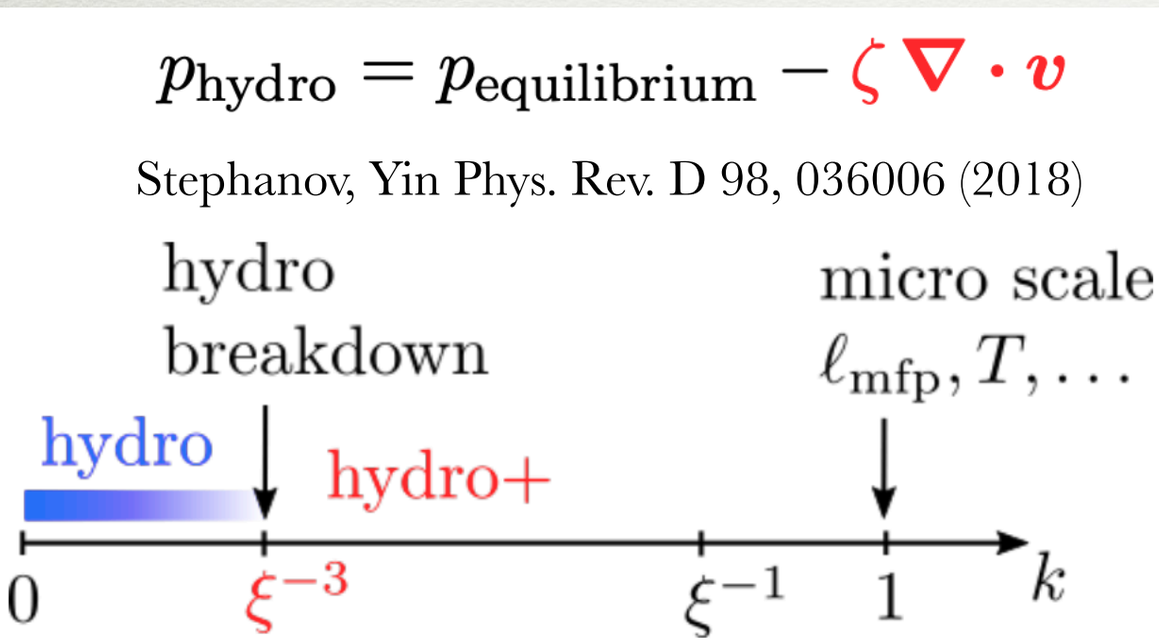
Far-from-equilibrium hydro @ BESII



Hydro should break down at the CP

$$p_{\text{hydro}} = p_{\text{equilibrium}} - \zeta \nabla \cdot v$$

Stephanov, Yin Phys. Rev. D 98, 036006 (2018)



Critical fluctuations: theory? Slow modes?

- Hydro approach:
- Causality/stability

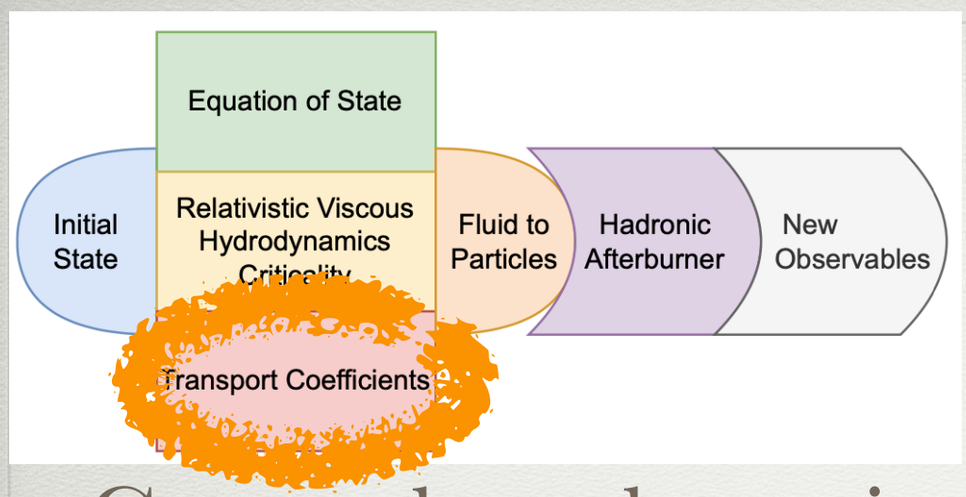
$$\varepsilon + p \geq \frac{(\delta^q_{n\pi})^2}{2\beta_\pi(2\beta_\pi\beta_n^{qq'} - (\delta^q_{n\pi})^2)}$$

Almaalol et al, 2209.11210 [hep-th]

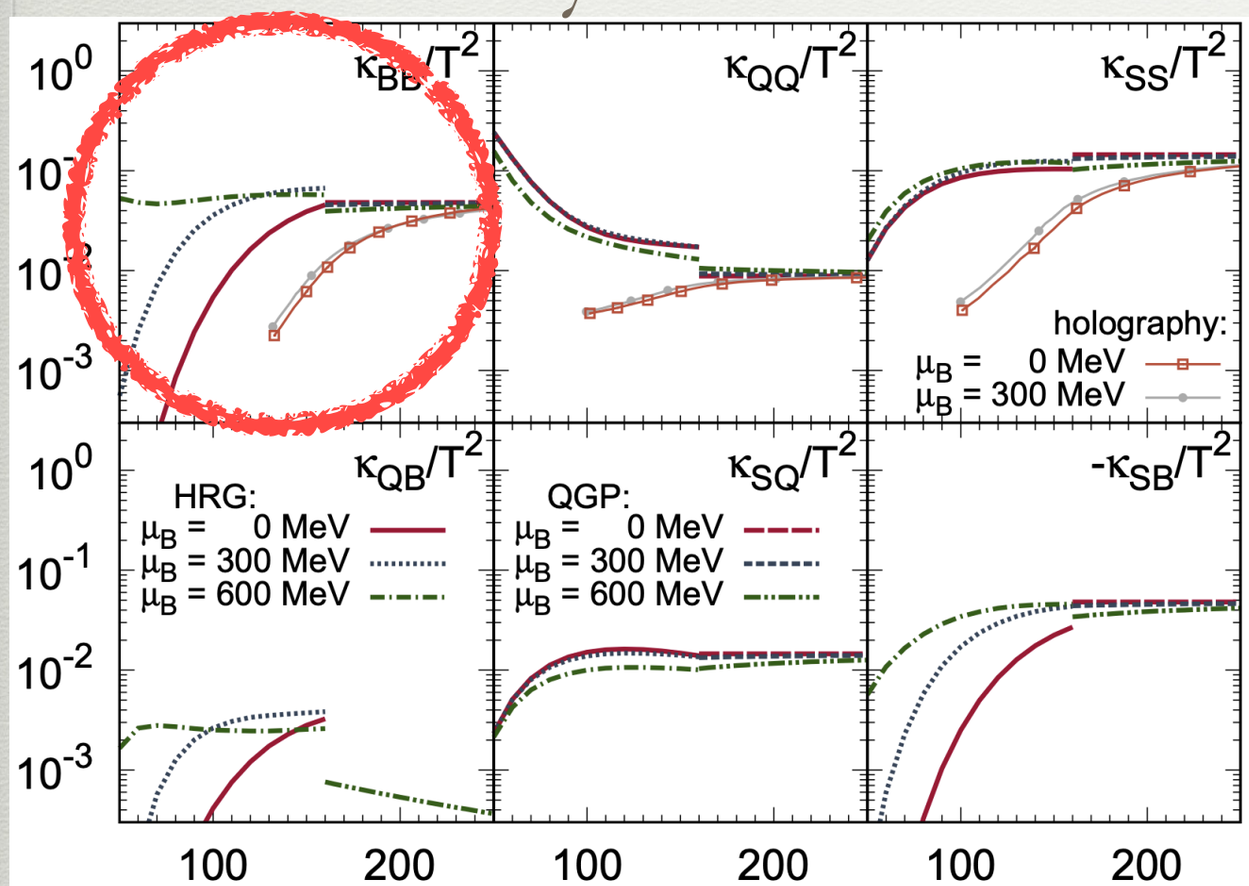
- Attractors
- Israel-Stewart, DNMR, BDNK?

Implement in hydro, run tests, compare to data/theory constraints+metastable?

Unique feature of QCD: BSQ Diffusion κ_{ij}

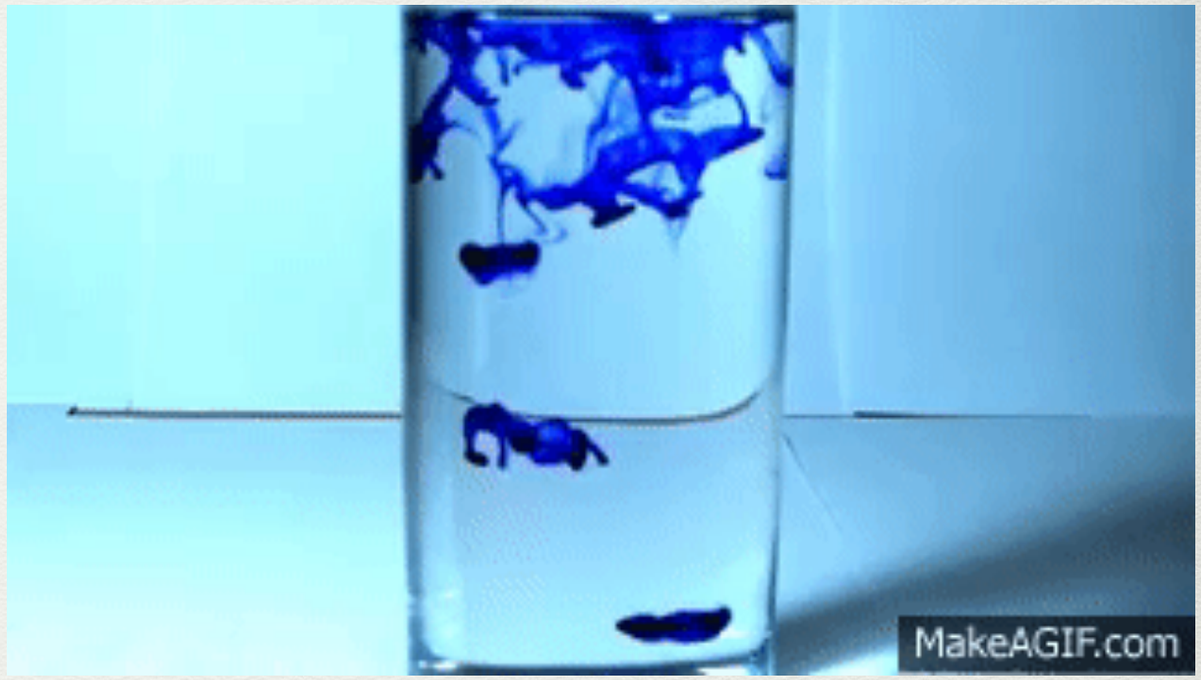


Currently, only κ_{BB} in 2+1/3+1 hydro codes

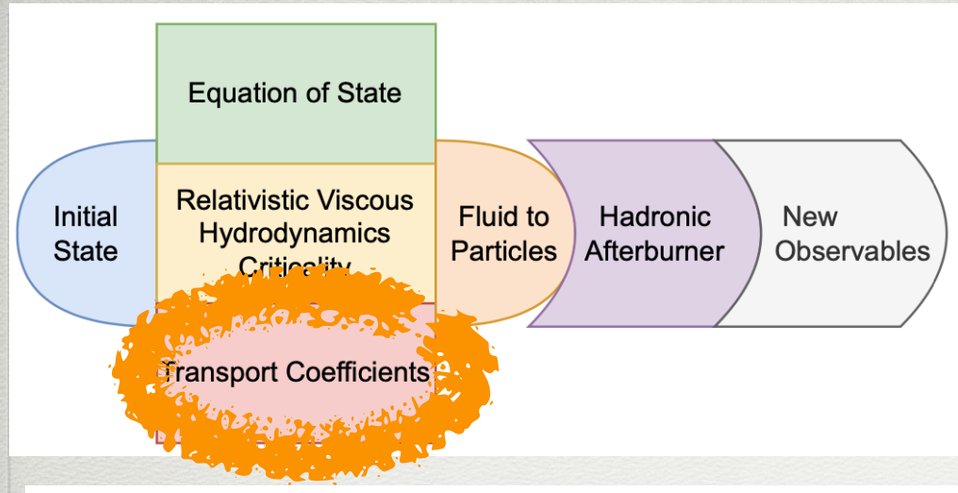


Greif et al, Phys.Rev.Lett. 120 (2018) no.24, 242301

Rougemont et al, Phys.Rev. D96 (2017) no.1, 014032

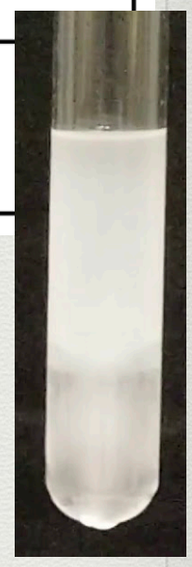


- BSQ diffusion generates fluctuations in charge
  Fotakis et al *Phys.Rev.D* 101 (2020) 7, 076007
- Requires BSQ EOS, initial conditions, particalization



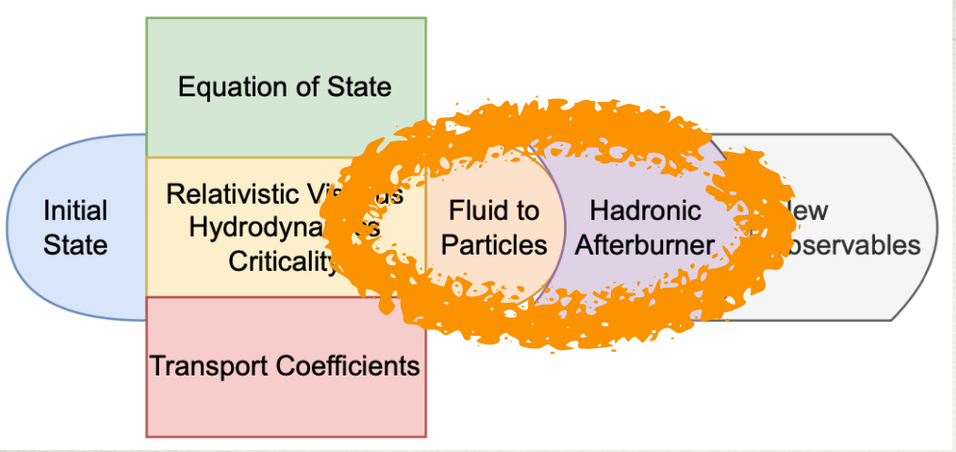
What will transport coefficients teach us about phase transitions?

Transport Coefficient	Critical Point	1st-order	Comments
Shear viscosity	Critical scaling negligable	jump	HRG may ↑ with nB, QGP may ↓ with nB
Bulk viscosity	Diverges (peak)	jump	Complicated with cs2->1
Baryon Diffusion	Opalesence (=0)	jump	HRG may ↑ with nB, QGP may ↓ with nB
BSQ diffusion	???	jump	Models give different results



Need full scale Bayesian analysis in 3+1 model

Holography Grefa et al, *Phys.Rev.D* 106 (2022) 3, 034024; Critical Scaling *Phys.Rev.C* 95 (2017) 3, 034902 ; Bulk/shear Dore et al, 2207.04086 [nucl-th]; Shear viscosity across 1-st order phase transition Soloveva et al, *Phys.Rev.C* 103 (2021) 5, 054901



How is hadron transport affected at large n_B?

Out-of-equilibrium corrections to distribution function

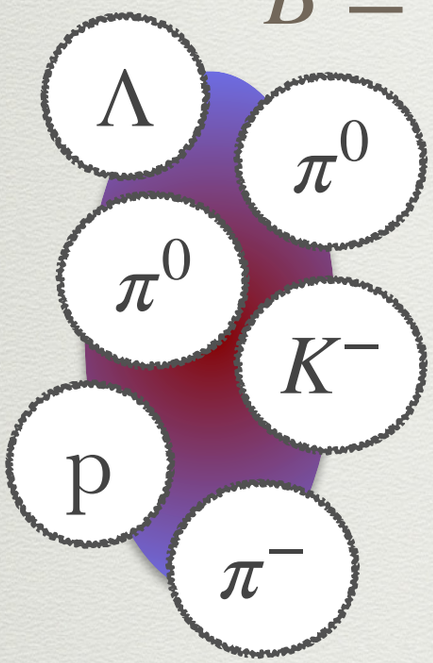
$$f = f_{ideal} + \delta f_{bulk} + \delta f_{shear} + \delta f_{B,S,Q}$$

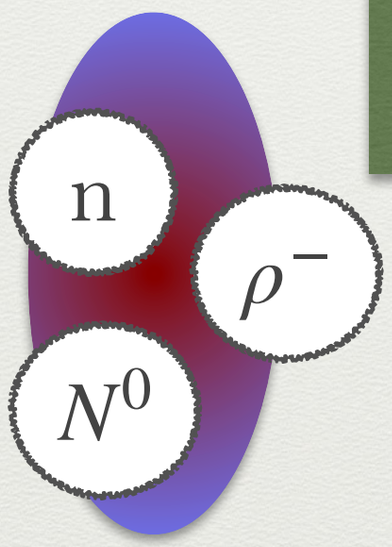
Criticality at FO: Pradeep et al, *PRD* 106 (2022) 3, 036017

Sampling routine to conserve BSQ

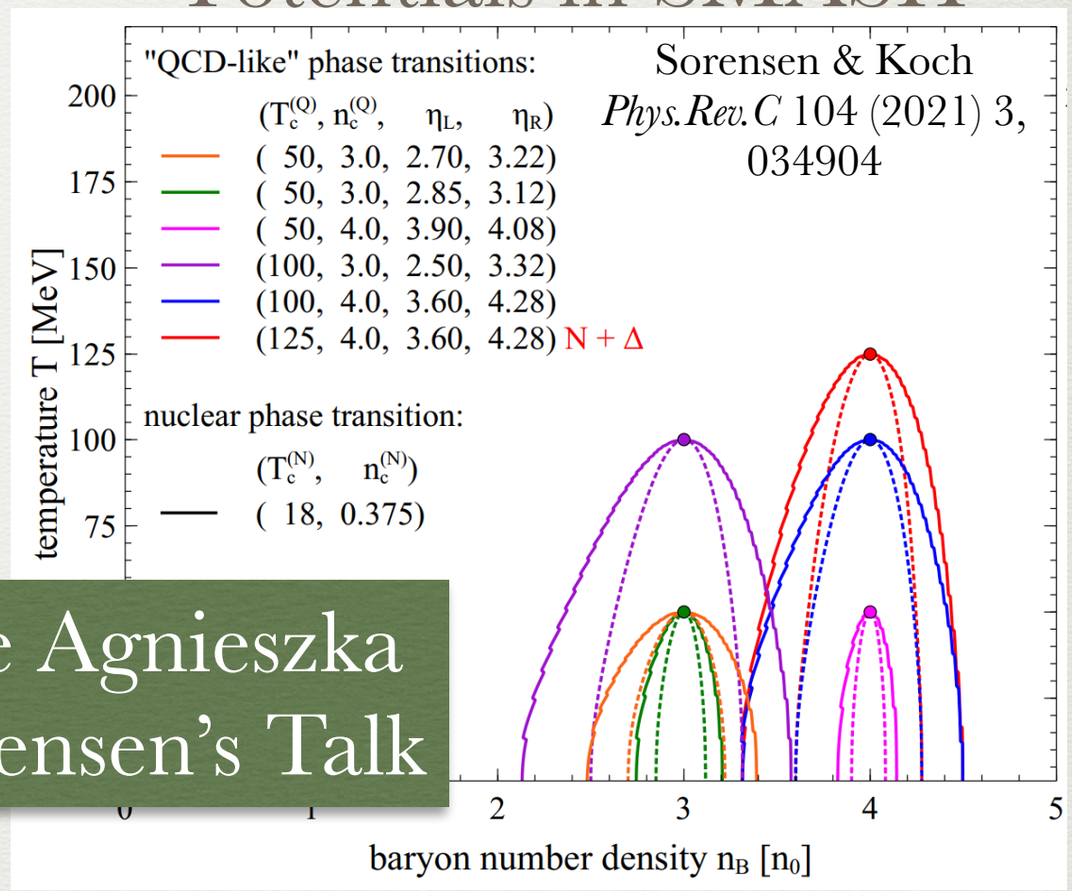
Oliinychenko & Koch Phys.Rev.Lett. 123 (2019) 18, 182302

$$B = 2, S = 0, Q = -1$$





Potentials in SMASH



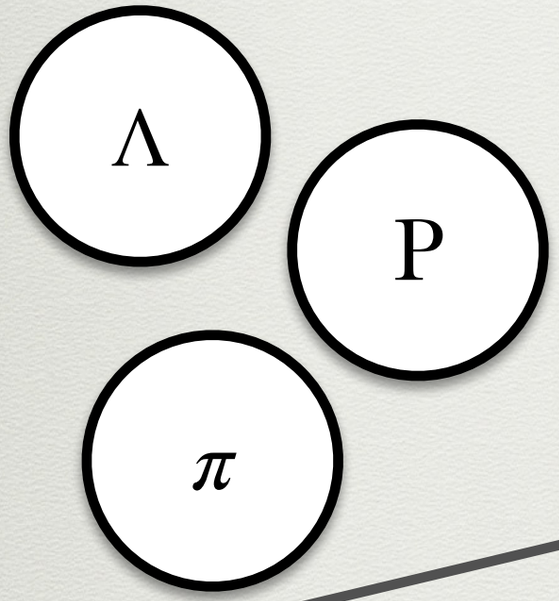
See Agnieszka Sorensen's Talk

Still must couple BSQ hydro+sampling+transport with potentials

Degrees of freedom at low $\sqrt{s_{NN}}$

Dynamics below $\sqrt{s_{NN}} < 7.7$ GeV?

Hydro+Transport
works well above
$\sqrt{s_{NN}} > 7.7$ GeV



Hydro vs. Transport
mixed results
$\sqrt{s_{NN}} < 7.7$ GeV

What if we don't find the CP?

Remaining questions: applicability of BSQ hydrodynamics, BSQ transport coefficients and initial state, vorticity, sign problem etc

See Rob Pisarski's Talk

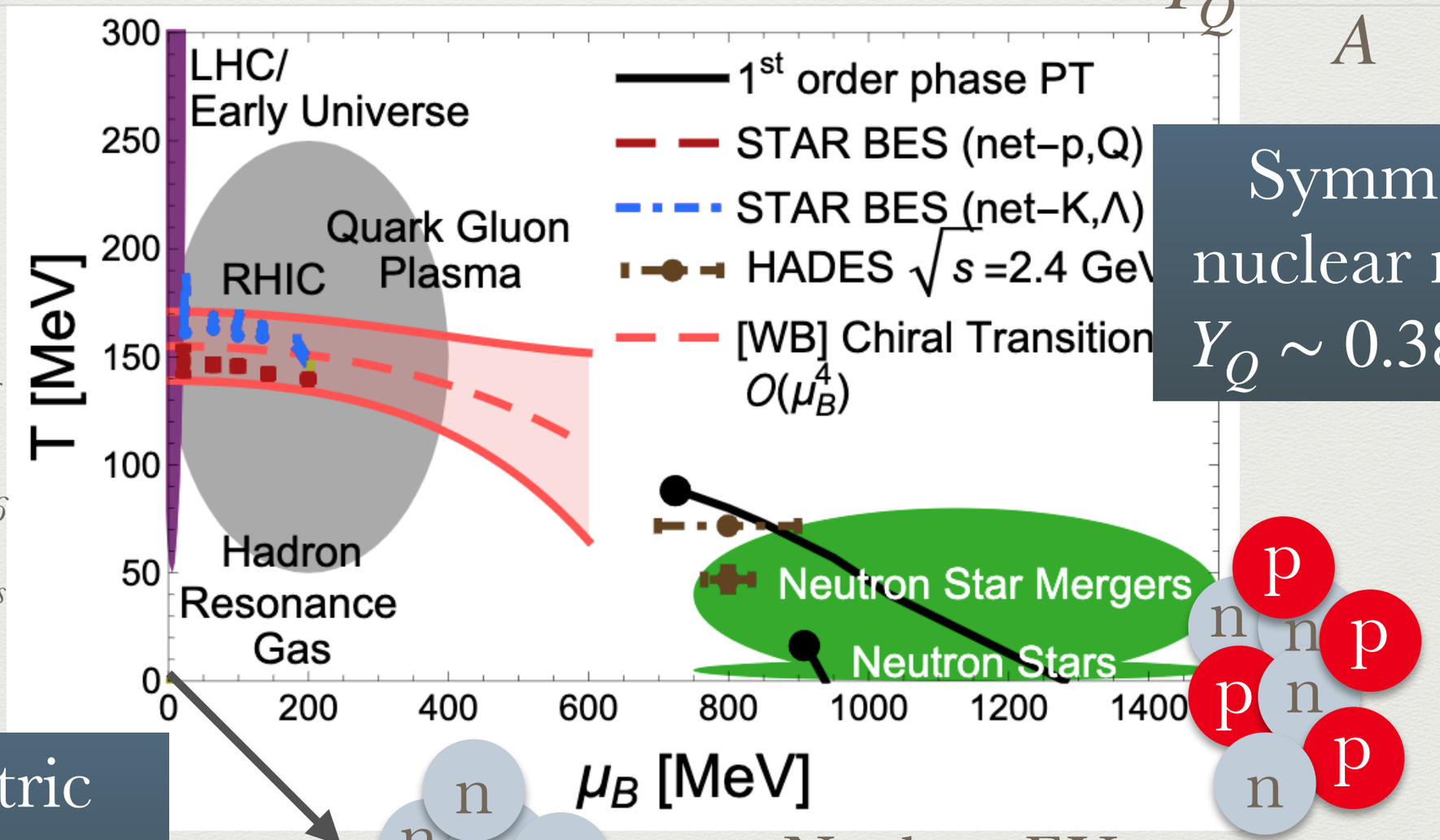
Other phases of matter: pion/kaon condensates, moat regimes, color superconductivity in NS, etc

Connections to NS: quarkyonic matter/bump in c_s^2, isospin dependence of EOS, QCD EOS with and without leptons/weak interactions…

How do we connect NS and HIC in the phase diagram?

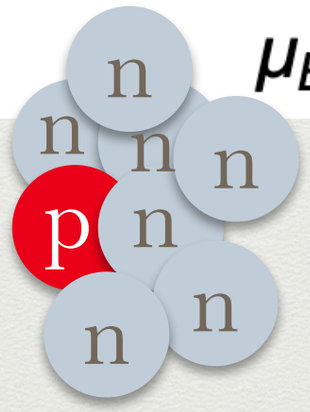
$$Y_Q = \frac{Z}{A} = \frac{n_Q^{QCD}}{n_B}$$

Light transition *Phys.Lett. B738 (2014) 305-310;*
Strange Transition *Bellwied, JNH, Parotto, Vazquez, Ratti, Stafford, arXiv:1805.00088 ;*
Neutron Star (mergers) *V. Dexheimer ariXiv:1708.08342;*
Holography *Critelli, JNH, et al, Phys.Rev. D96 (2017) no.9, 096026;*
[HADES] *Nature Physics volume 15, pages 1040–1045(2019);*



Symmetric nuclear matter
$Y_Q \sim 0.38 - 0.5$

Asymmetric nuclear matter
$Y_Q \sim 0.01 - 0.2$

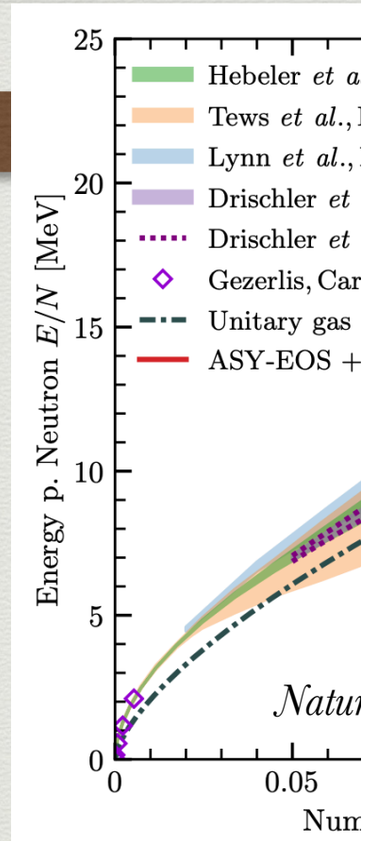


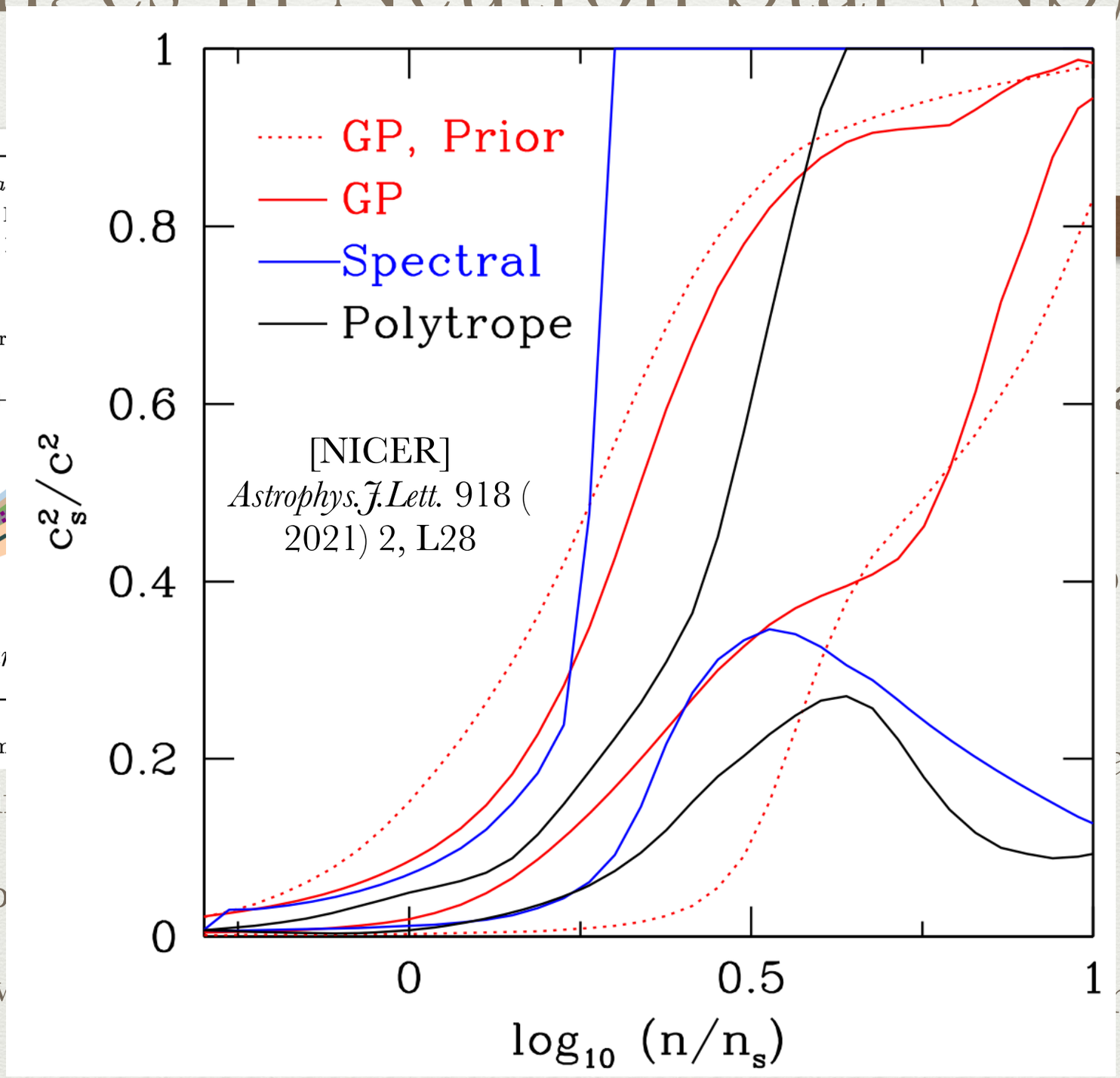
Nuclear EX measure coefficients to connect HIC to NS (PREXII/isobars/FRIB400)

Challenges in Neutron Star (NS) EOS

Low n_B

High n_B





dense QCD
ansitions (in
m)

aryon

ave observables

roblem

- Uncertainty quanti
- Finite T and transp
- Collaborations betv needed

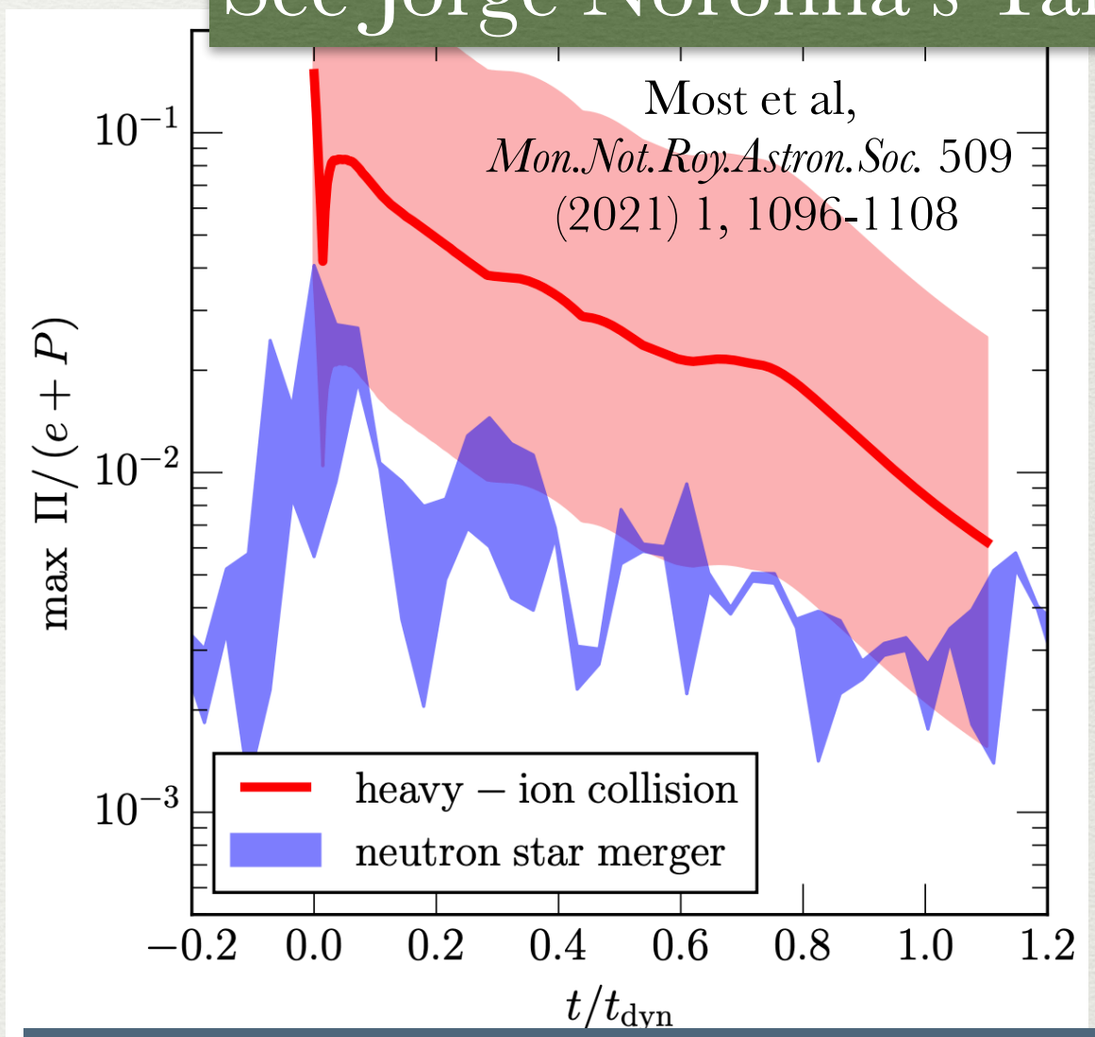
Neutron stars out-of-equilibrium

See Jorge Noronha's Talk

Delayed β-equilibrium in mergers

$$n \to p + e^- + \bar{\nu}_e$$
$$p + e^- \to n + \nu_e$$
$$n + X \to p + X + e^- + \bar{\nu}_e$$
$$p + e^- + X \to n + X + \nu_e$$

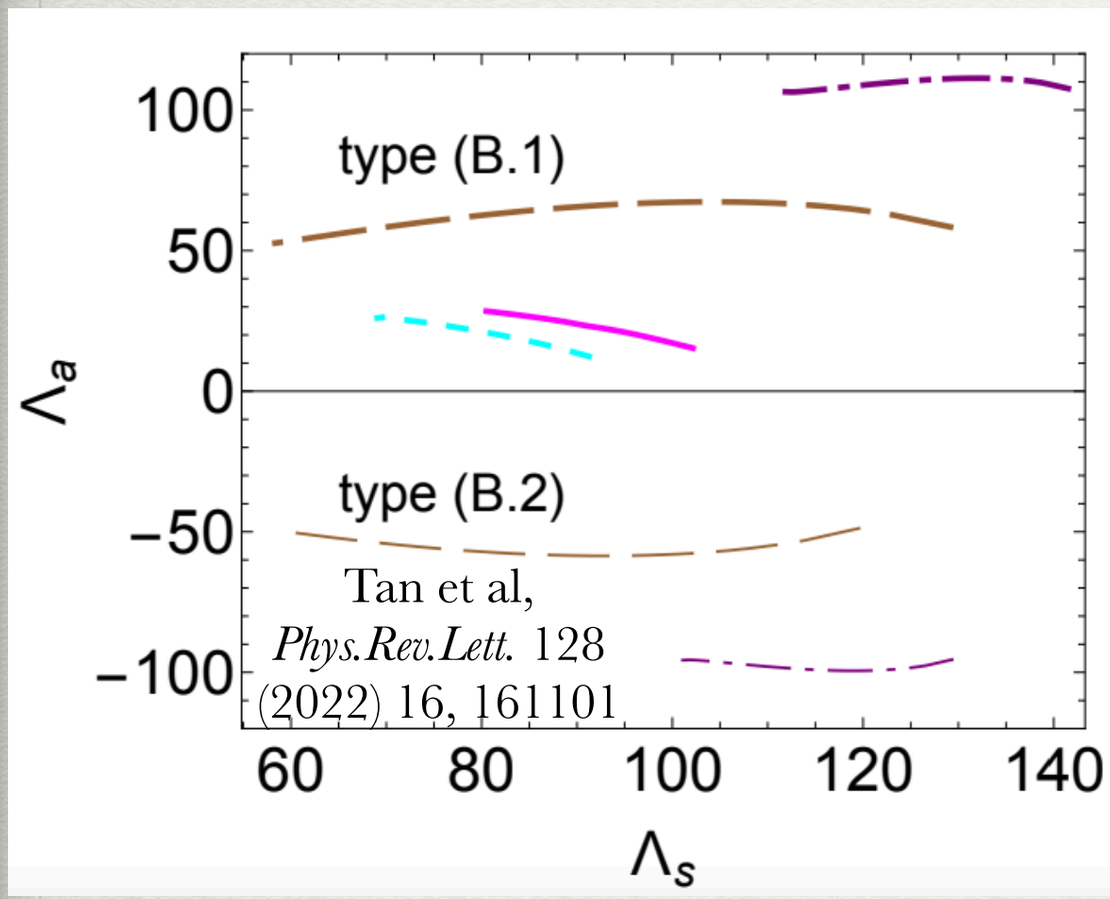
- Sensitivity to T, different degrees of freedom, phase transitions
- Requires collaborations between nuclear physicists and numerical relativity
- Signatures in gravitational waves?

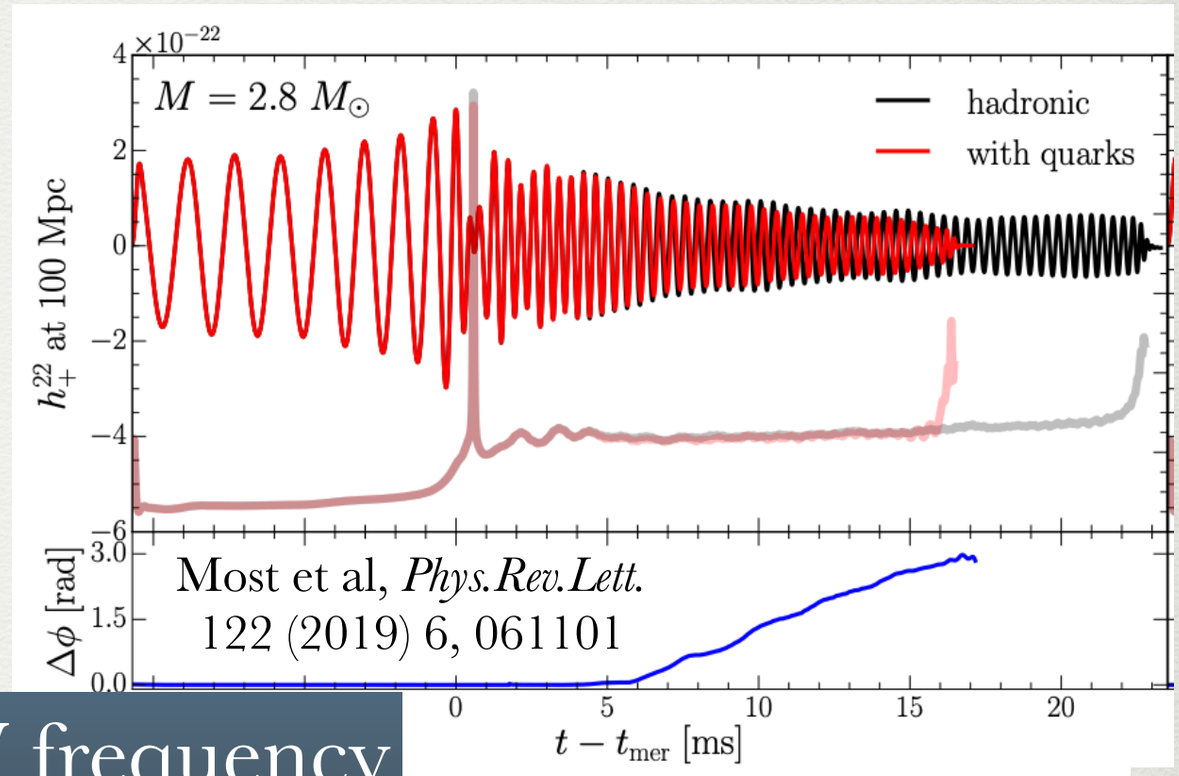


Opportunity to understand rel. viscous fluids in General Relativity

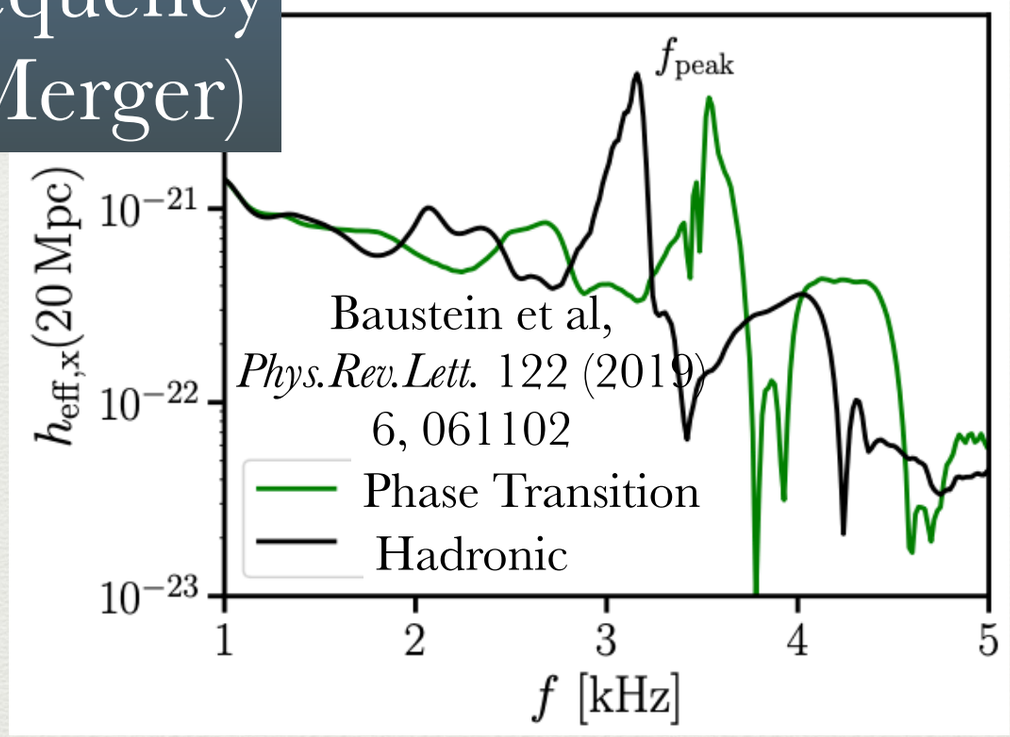
Interdisciplinary collaborations

Binary love relation (inspiral)





GW frequency (Post-Merger)

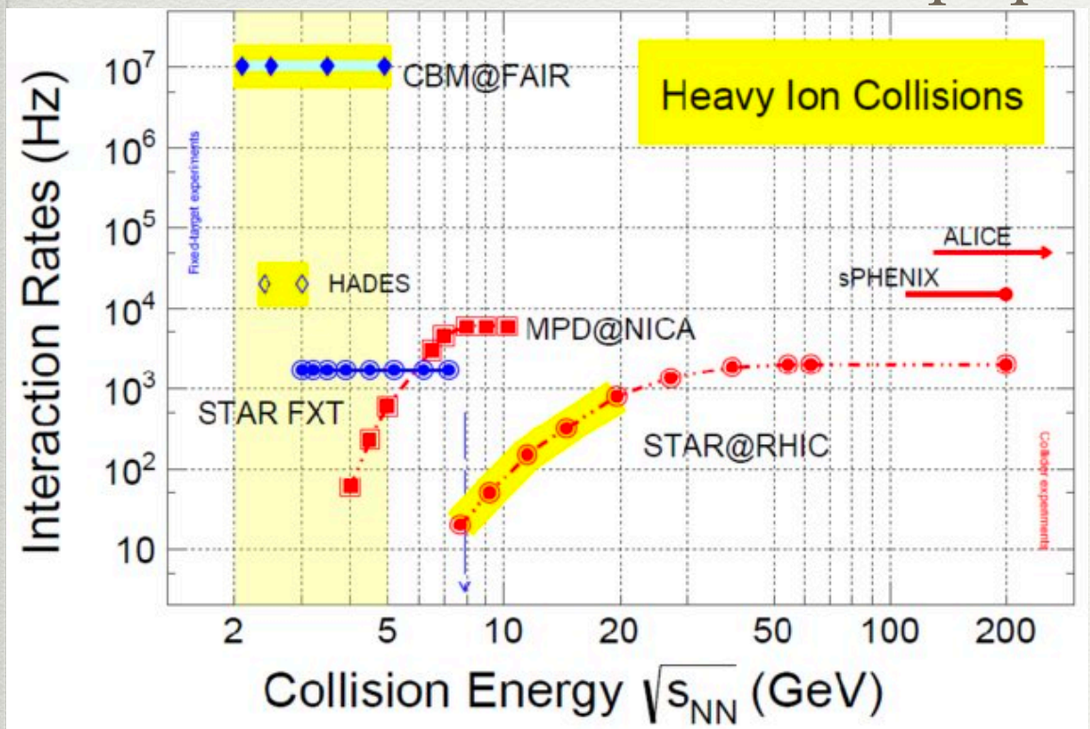


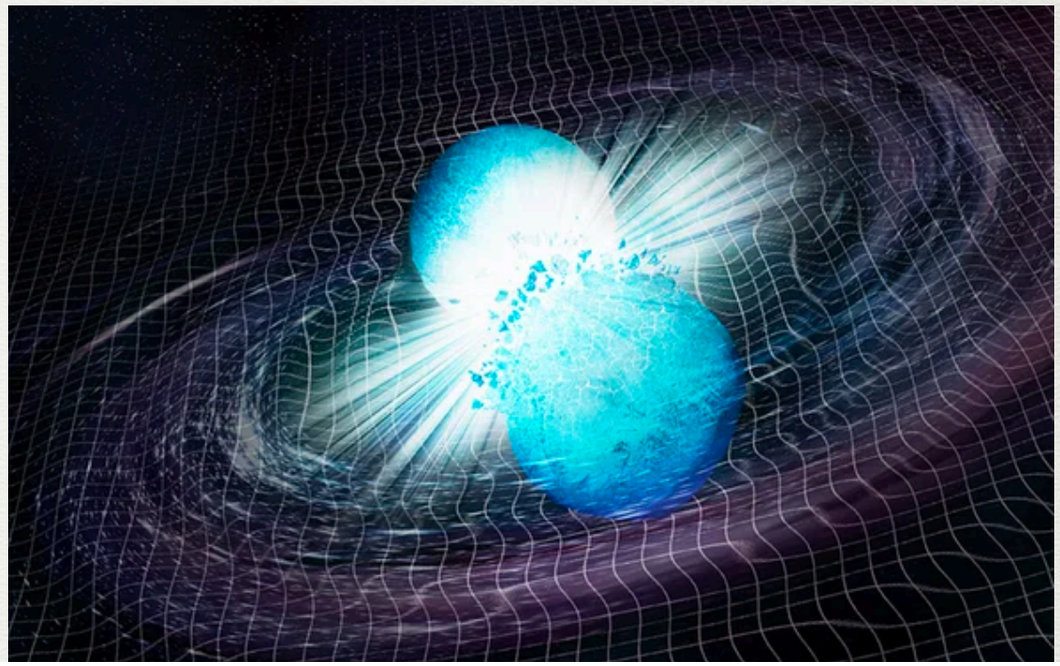
Gravity-nuclear collaborations extremely fruitful to identifying new observables: funding mechanism?

See Nu Xu's Talk

Why CBM? Astro Observations?

CBM US contribute white paper: https://arxiv.org/pdf/2209.05009.pdf





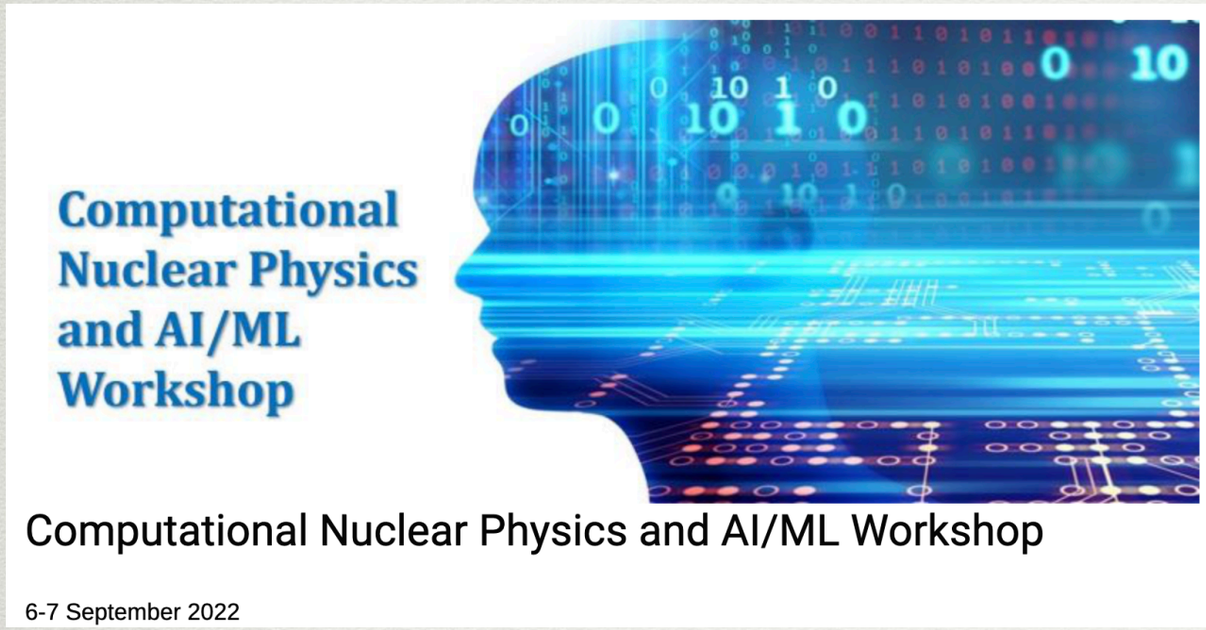
- Resolve unanswered questions from BESII/ fixed target (new observables)
- Isopin/species dependences (crucial for HIC to NS)
- Hypernuclei (strangeness information!)
- Large US theory community, very EX driven (needs talk between theory/experiment)

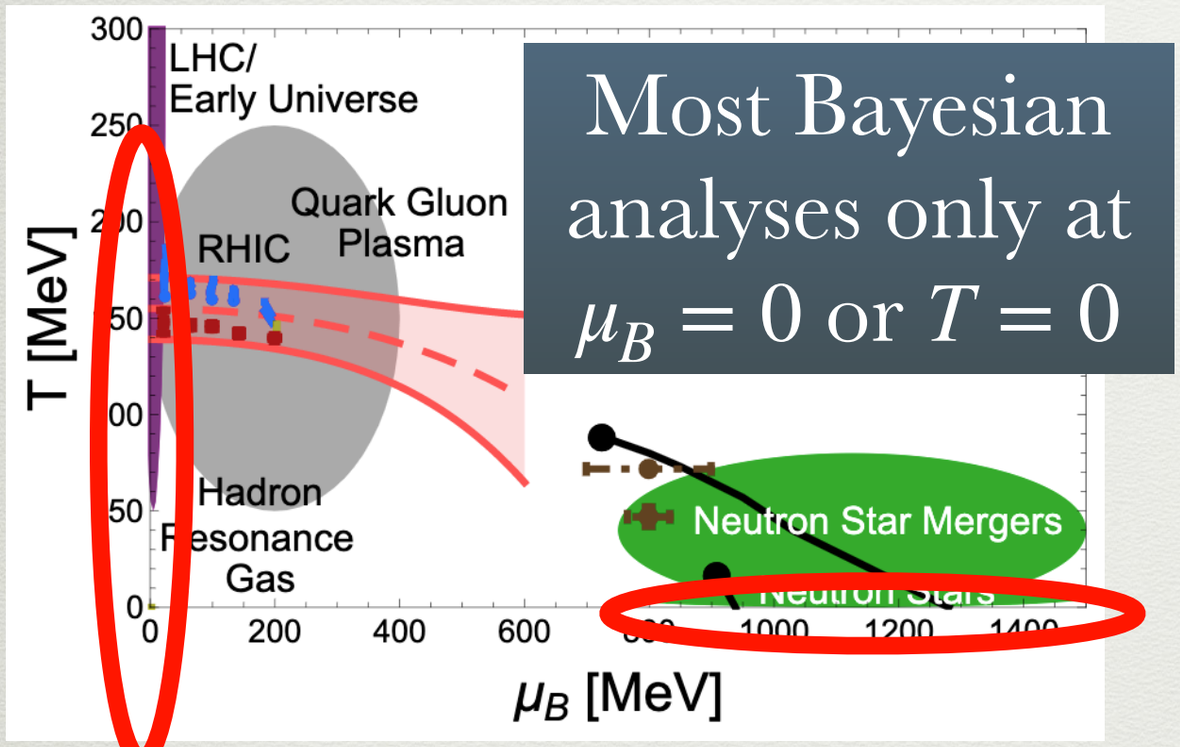
Run	Years	% err (GW170817)	New physics
O2/3	done	~100%	GW170817, NS-BH
O4	23-24	~40%	Λ, post-merger
O5	26-29	~20%	Localization
3G	30-50	~3%	All NS in universe

Details https://arxiv.org/pdf/1903.03909.pdf

NICER renewed for 3 years!

Computational opportunities





Bayesian Analysis needed at low $\sqrt{s_{NN}}$ with BES theory

* Location of CP/first-order
* ML/AI for identifying new features/phases
* Functional form of EOS/ transport coefficients
* Connecting the EOS in HIC to NS (both from data and theory constraints)
* Input from experimentalists on best constraints
* Hydro vs transport

Physics motivation: low $\sqrt{s_{NN}}$ heavy-ions

- Existence, location, properties of the QCD critical point
- Dynamic vs static universality of QCD critical point.

See Jinfeng Liao's Talk

- Can we understand Λ polarization/spin hydrodynamics at large densities?
- How are baryons stopped in relativistic collisions? What roles does electric charge/isospin play?
- Hadron vs quark degrees of freedom at low $\sqrt{s_{NN}}$? Extract dense matter EOS, relevant for neutron stars
- Other phases of matter at large μ_B?

Physics motivation: neutron stars

From HIC to NS Workshop 2020 Summary: J.Phys.G 48 (2021) 7, 073001 Snowmass 2022: 2209.07412 [astro-ph.HE]

- Phase(s) of matter at large density: detectability? Properties in and out-of-equilibrium?
- What is the interplay between strong and weak interactions (neutrinos), E&M, and gravity? What new things can be found in neutron star mergers?
- Do QCD phases remain the same once the charge fraction is changed? Symmetric vs. asymmetric matter
- New ideas on constraining neutron skin?

Nuclear structure+HIC white paper: 2209.11042 [nucl-ex]

See Jiangyong Jia's Talk

- What role does beyond standard model physics play?

Thank you everyone for your input and discussions!

Agnieszka Sorensen, Bjoern Schenke, Christopher Plumberg, Chun Shen, Claudia Ratti, Dekrayat Almaaol, Gordon Baym, Huan Huang, Ingo Tews, Jamie Karthien, Jorge Noronha, Krishna Rajagopal, Mark Alford, Misha Stephanov, Nicolas Yunes, Nu Xu, Pawel Danielewicz, Rob Pisarski, Swagato Mukherjee, Thomas Schaefer, Thomas Schaefer, Veronica Dexheimer

Recommendations for the LRP

- Theoretical nuclear physics is essential for establishing new scientific directions, and meeting the challenges and realizing the full scientific potential of current and future experiments. We recommend increased investment in the base program and expansion of topical programs in nuclear theory.
- Put the pieces together developed by the BEST collaboration to search for the critical point/1st order phase transition at STAR/CBM
  - Theory work needed on equations of motion: critical fluctuations, non-linear causality constraints for BSQ hydrodynamics, metastable region, transport codes+potentials
- Uncertainty analysis for chiral effective field theory to higher-order terms, finite T, transport coefficients; further development/constraints on microscopic models
- Pursue synergy between heavy-ions and neutrons stars on dissipative processes; joint statistical analyses; looking for $c_s^2 \to 1$
- **Crucial time with BESII data coming, CBM@FAIR being built, LIGO upgrades, and new data from NICER to study dense QCD!**