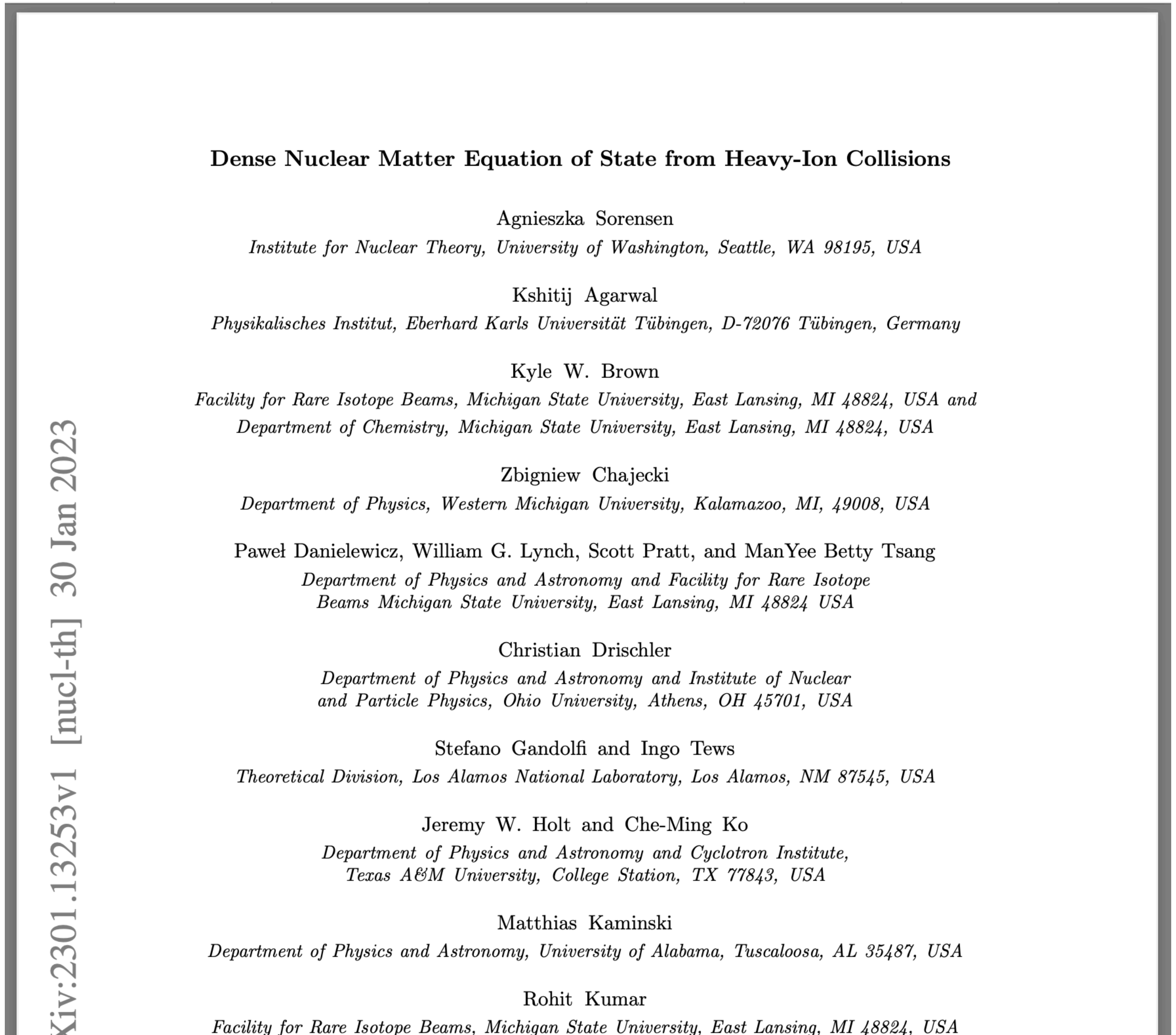
Dense Nuclear Matter Equation of State from Heavy-Ion Collisions

A. Sorensen *et al.*,
arXiv:2301.13253

INSTITUTE for NUCLEAR THEORY

February 13th, 2023



Xiv:2301.13253v1 [nucl-th] 30 Jan 2023

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions

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White paper on the role of HICs in uncovering the EOS

A. Sorensen *et al.*, arXiv:2301.13253

23 primary authors: **AS**, Kshitij Agarwal, Kyle Brown, Zbigniew Chajecki, Paweł Danielewicz, Christian Drischler, Stefano Gandolfi, Jeremy Holt, Matthias Kaminski, Che-Ming Ko, Rohit Kumar, Bao-An Li, William Lynch, Alan McIntosh, William Newton, Scott Pratt, Oleh Savchuk, Maria Stefaniak, Ingo Tews, ManYee Betty Tsang, Ramona Vogt, Hermann Wolter, Hanna Zbroszczyk

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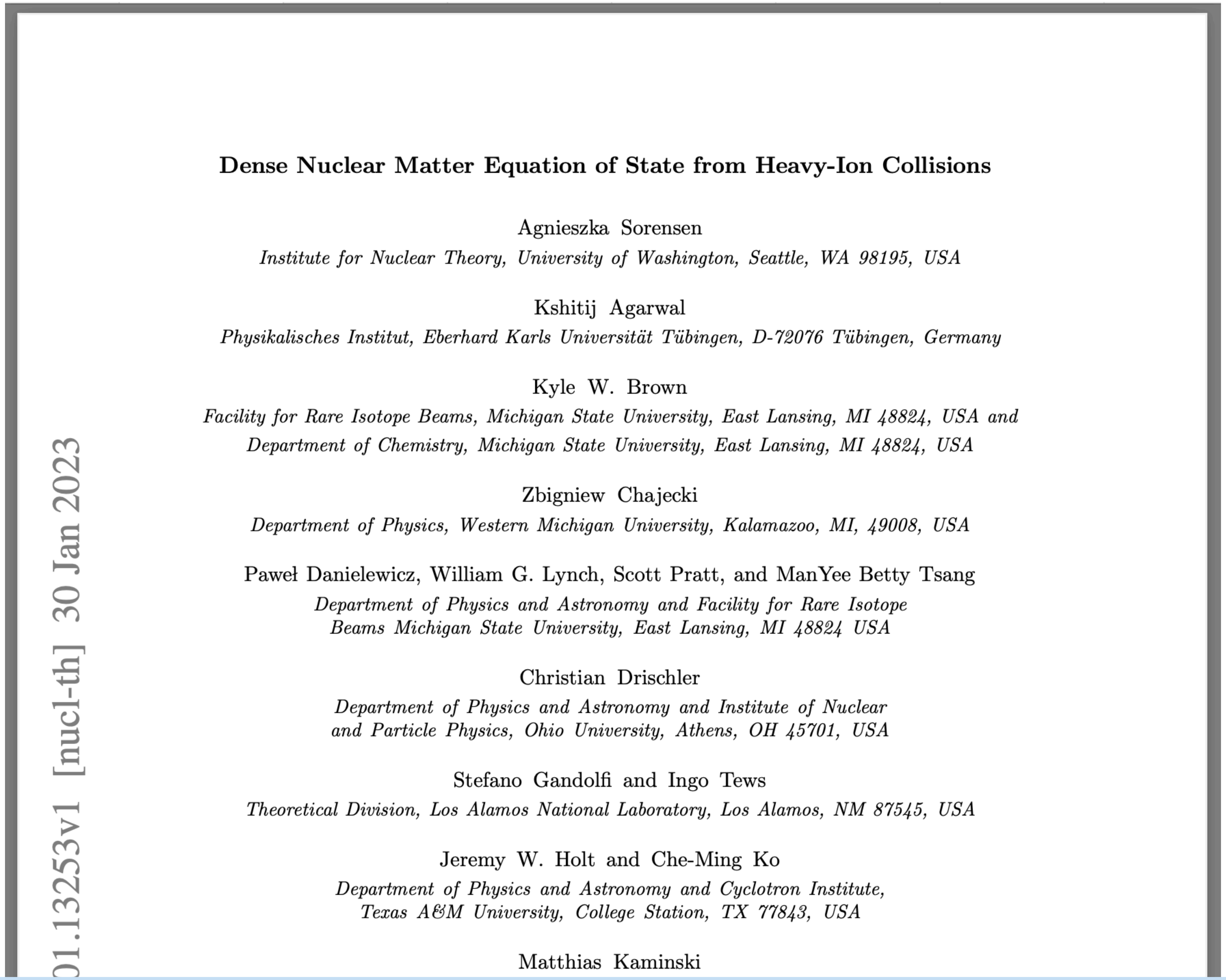
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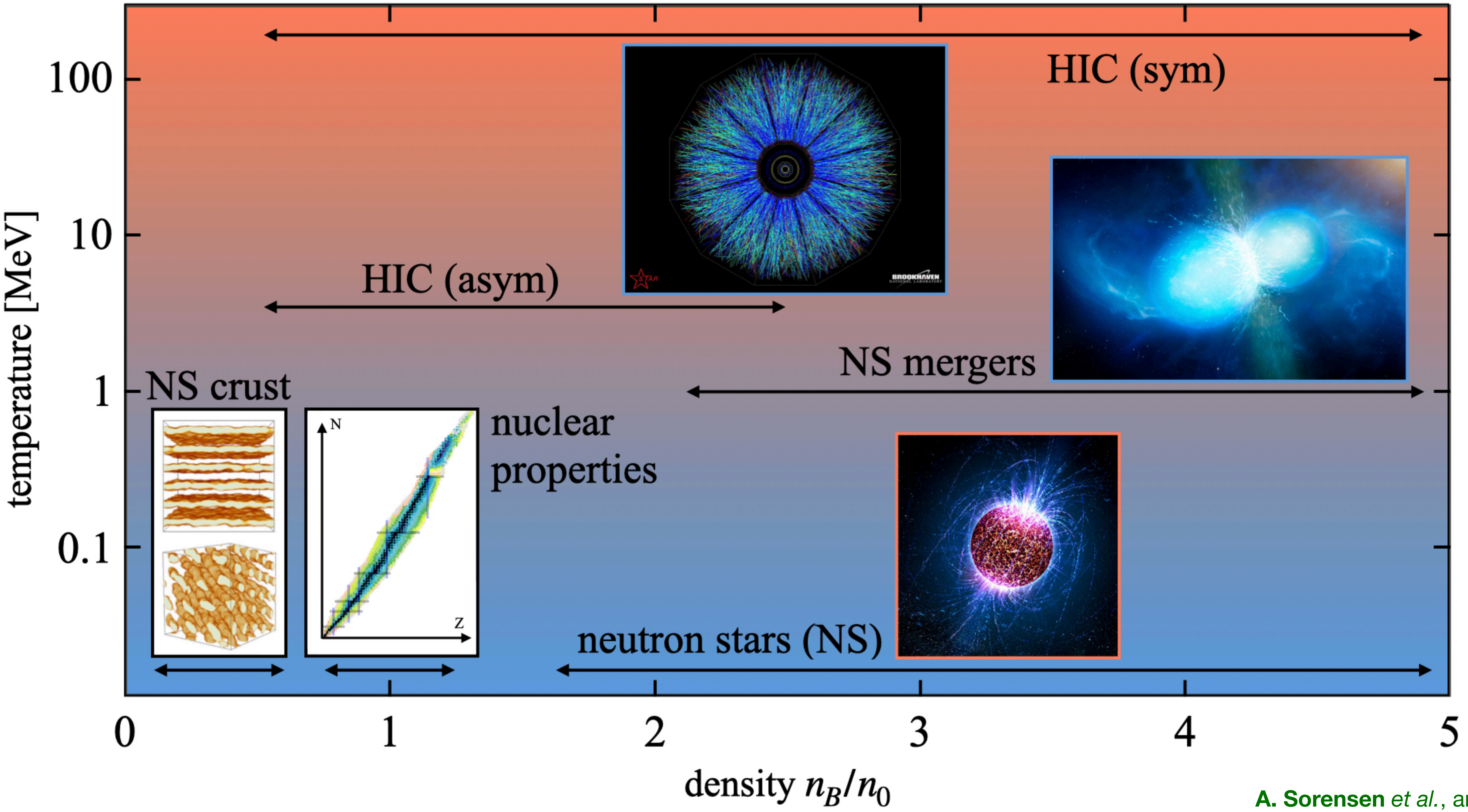
Department of Physics and Astronomy and Cyclotron Institute, Texas A&M University, College Station, TX 77843, USA

Matthias Kaminski

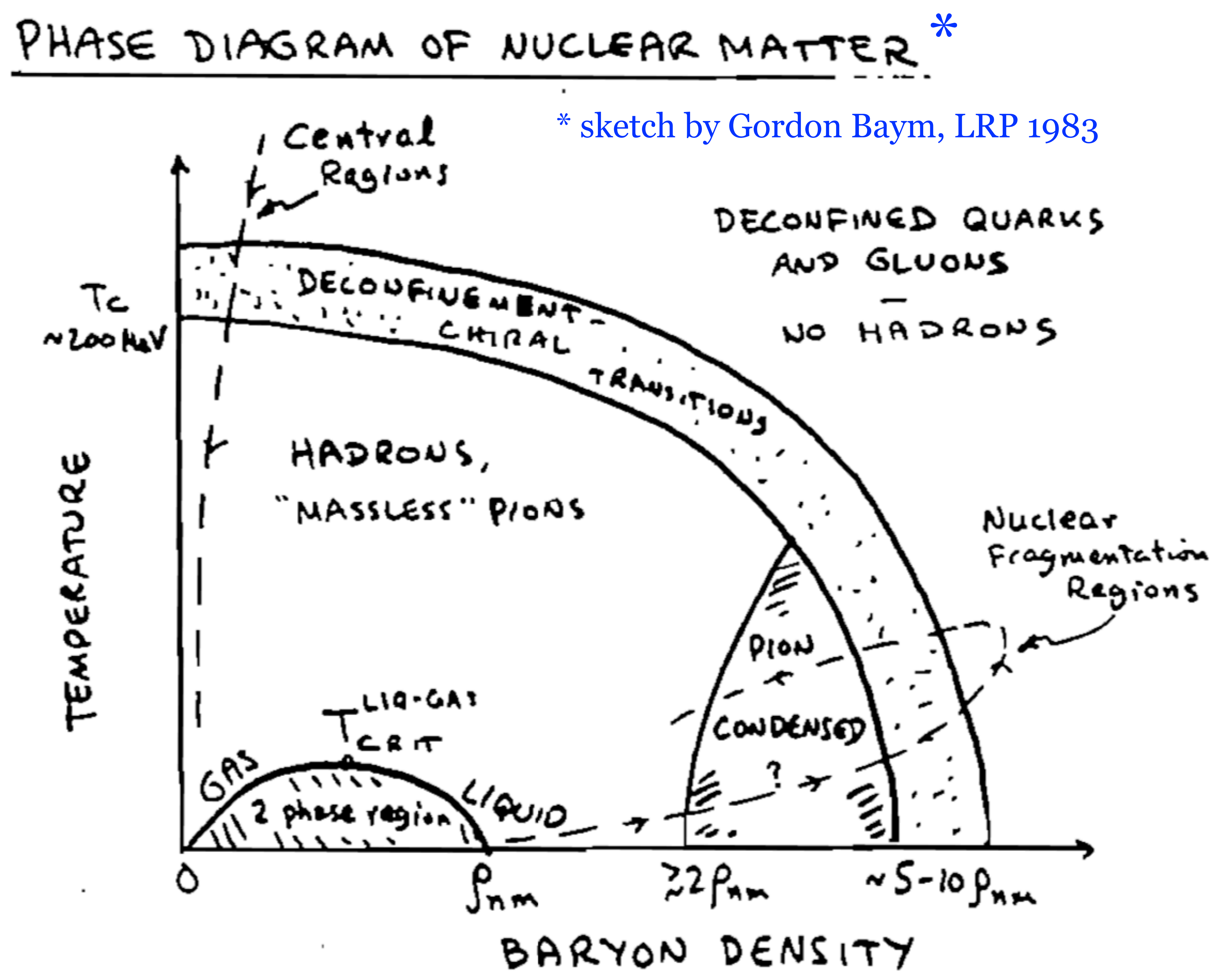
Experiments and astronomical observations sensitive to the EOS



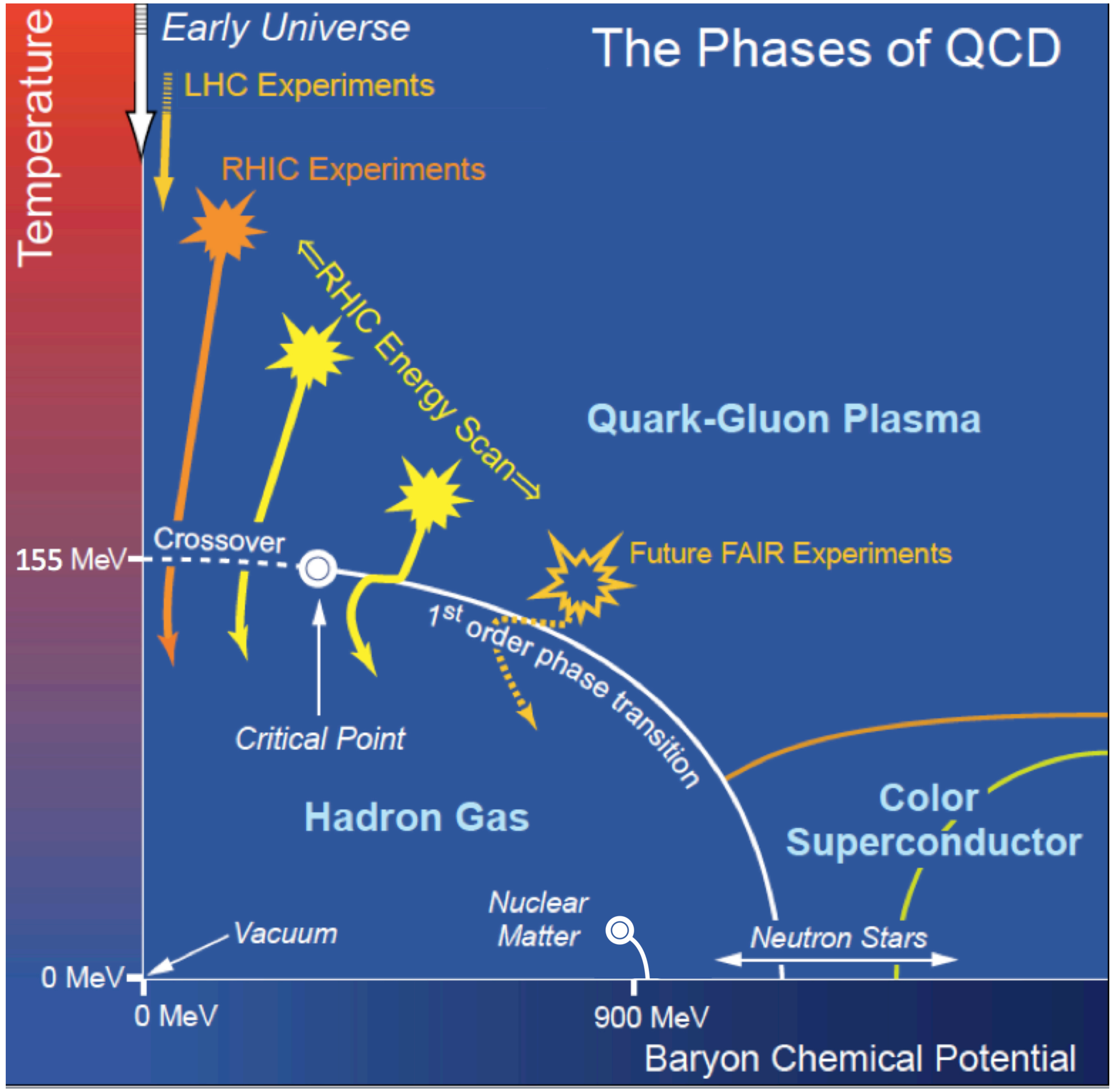
A. Sorensen *et al.*, arXiv:2301.13253

The EOS = key to understanding fundamental properties of QCD matter

1) Uncovering the phase diagram of isospin-symmetric QCD matter:



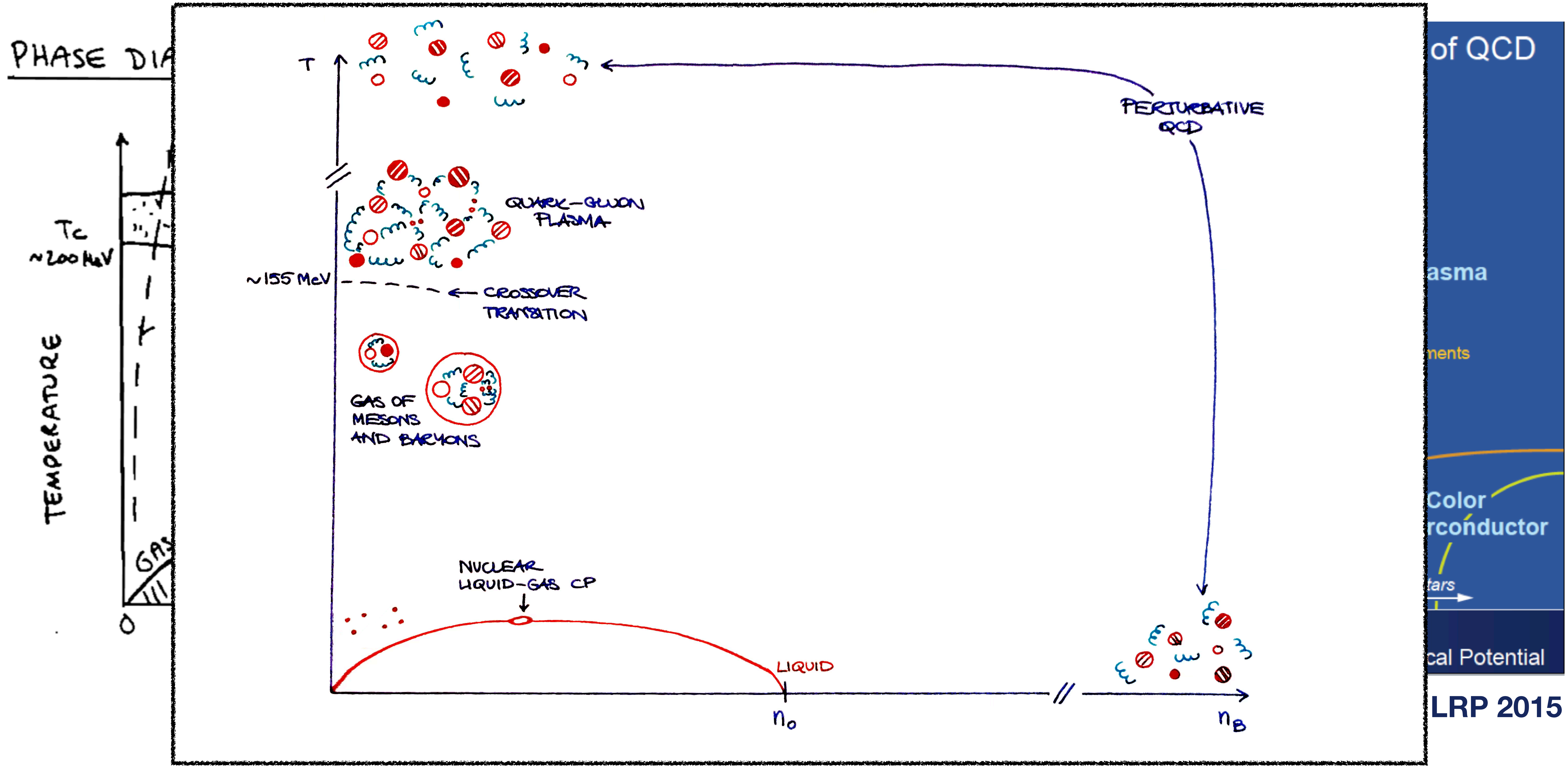
* sketch by Gordon Baym, LRP 1983



LRP 2015

The EOS = key to understanding fundamental properties of QCD matter

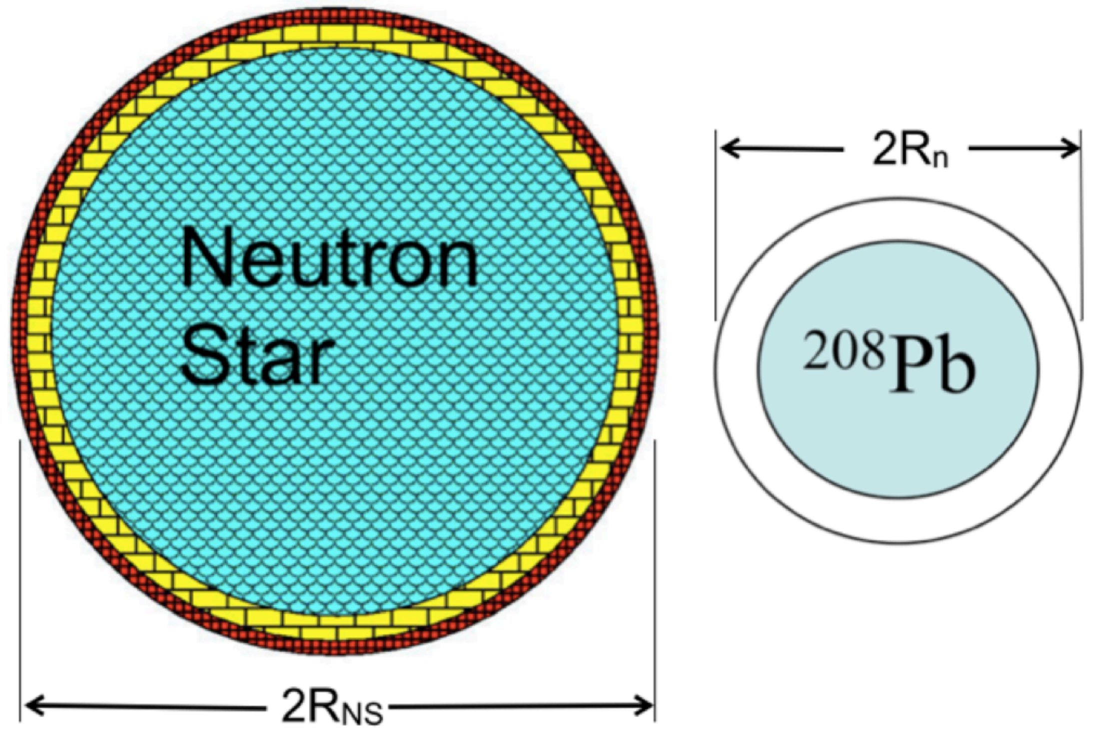
1) Uncovering the phase diagram of isospin-symmetric QCD matter:

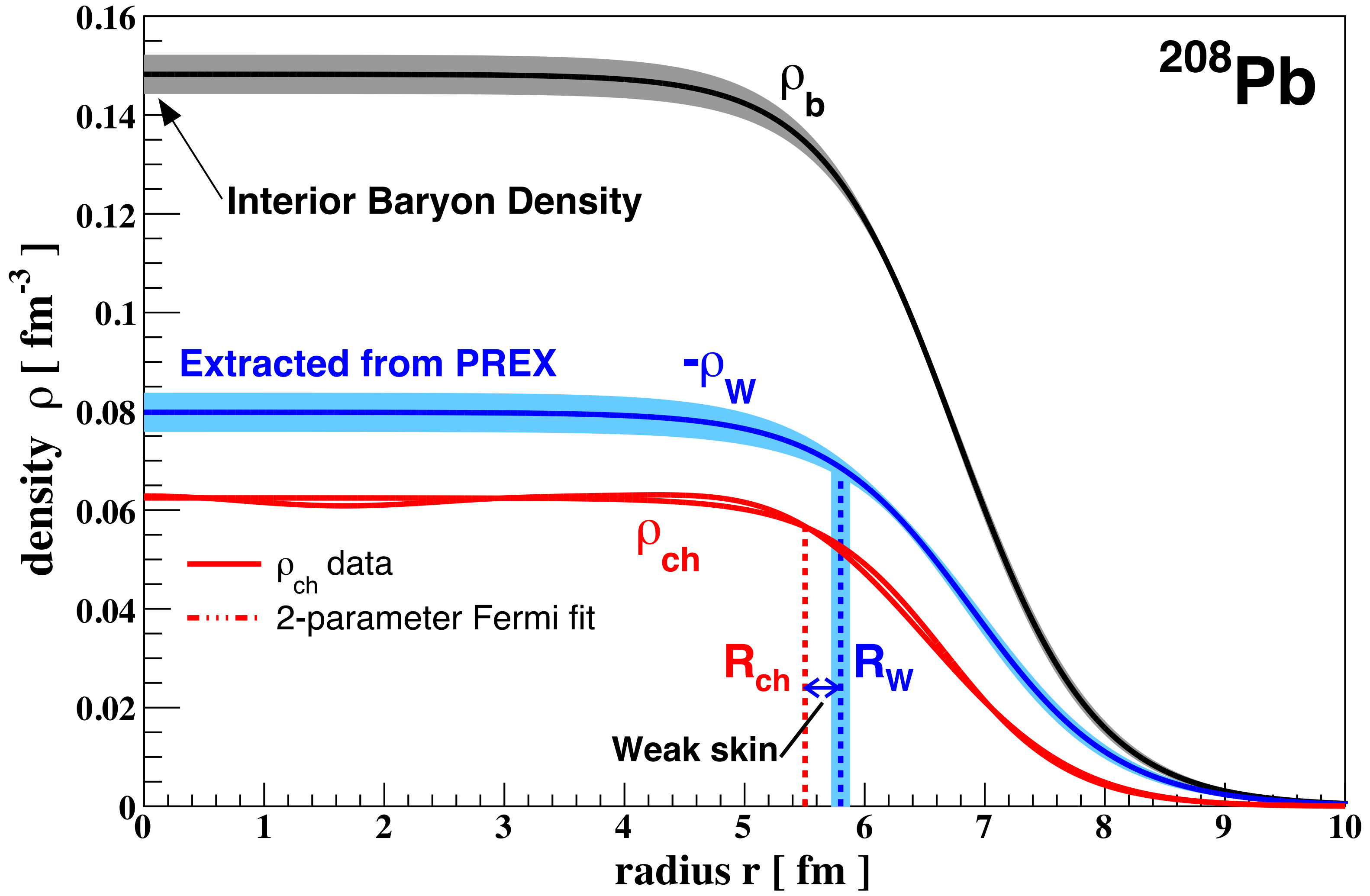


LRP 2015

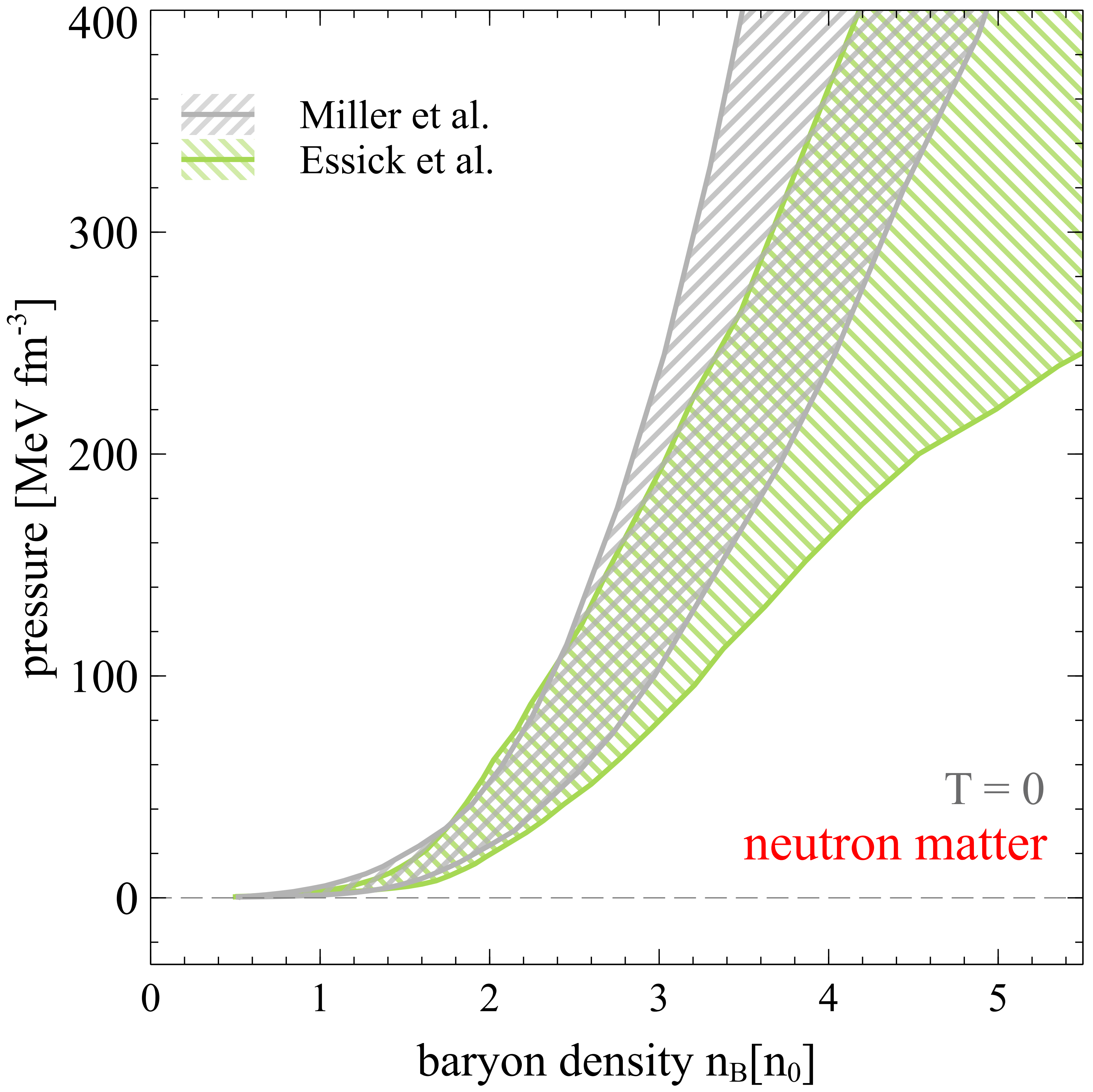
The EOS = key to understanding fundamental properties of QCD matter

2) Uncovering the isospin-dependence of strong interactions



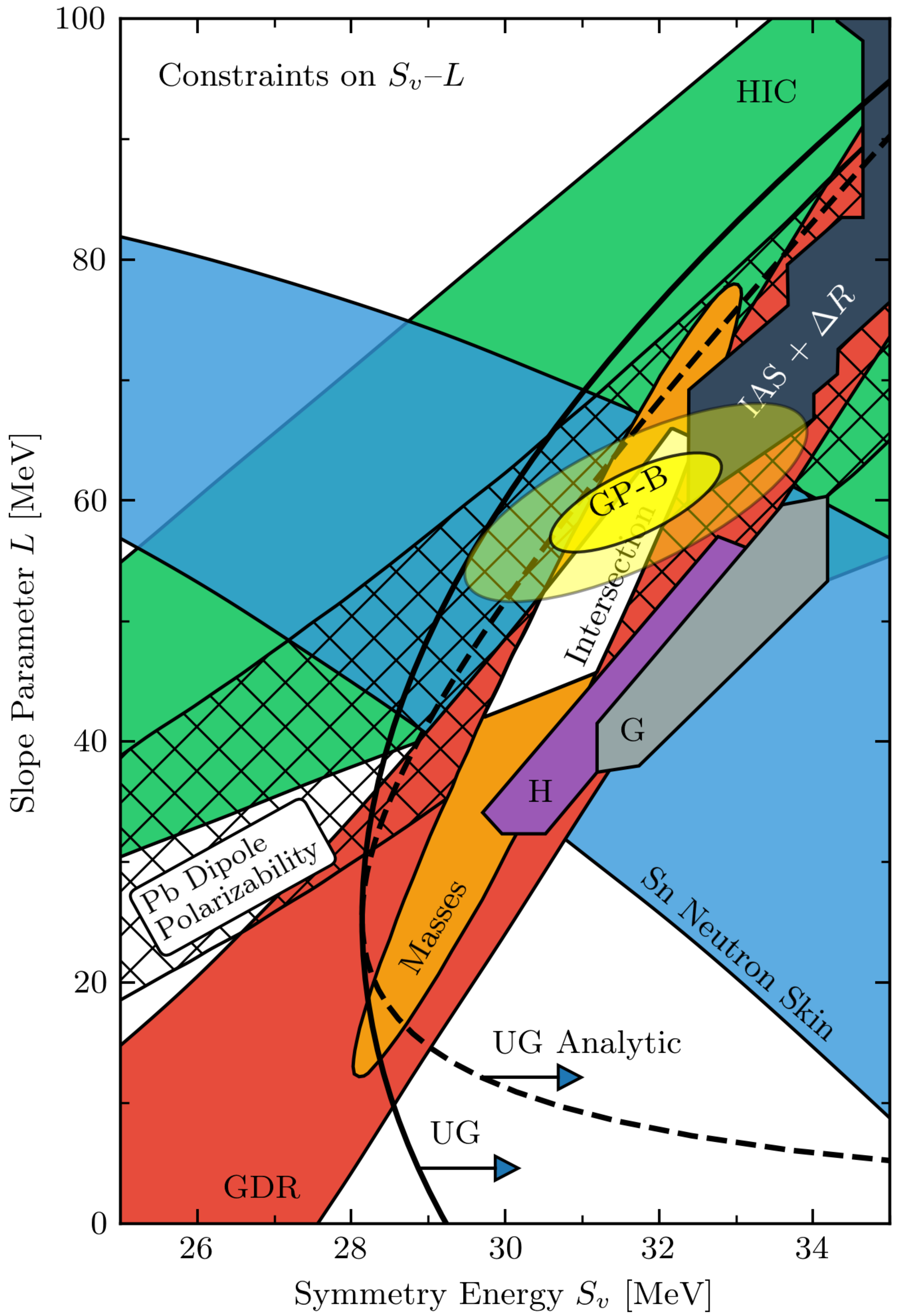


D. Adhikari *et al*. (PREX Collaboration), Phys. Rev. Lett. **126** 17, 172502 (2021), arXiv:2102.10767



M. C. Miller *et al*., Astrophys. J. Lett. **918**, L28 (2021), arXiv:2105.06979

R. Essick, I. Tews, P. Landry, S. Reddy, D. E. Holz, Phys. Rev. C **102**, 055803 (2020), arXiv:2004.07744

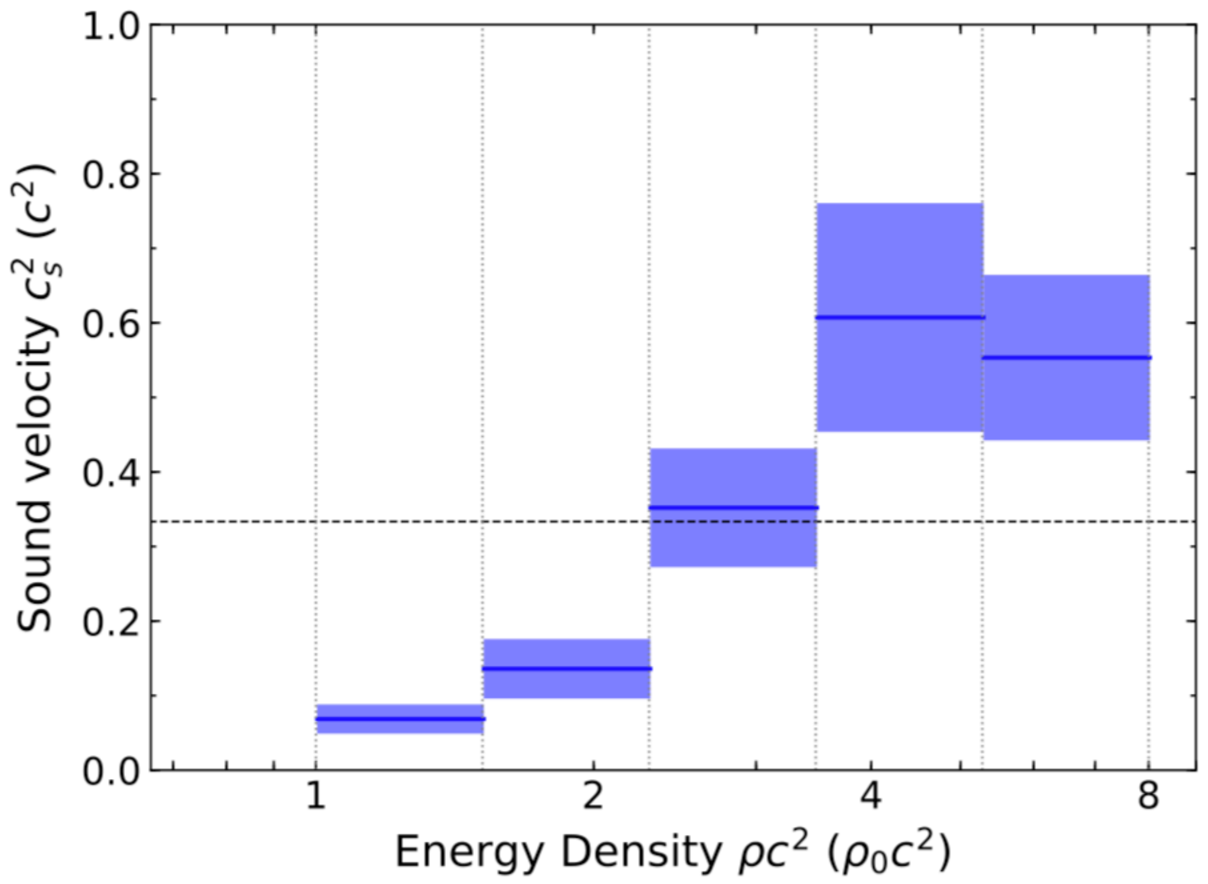


C. Drischler, R. J. Furnstahl, J. A. Melendez, D. R. Phillips, Phys. Rev. Lett. **125** 20, 202702 (2020), arXiv2004.07232

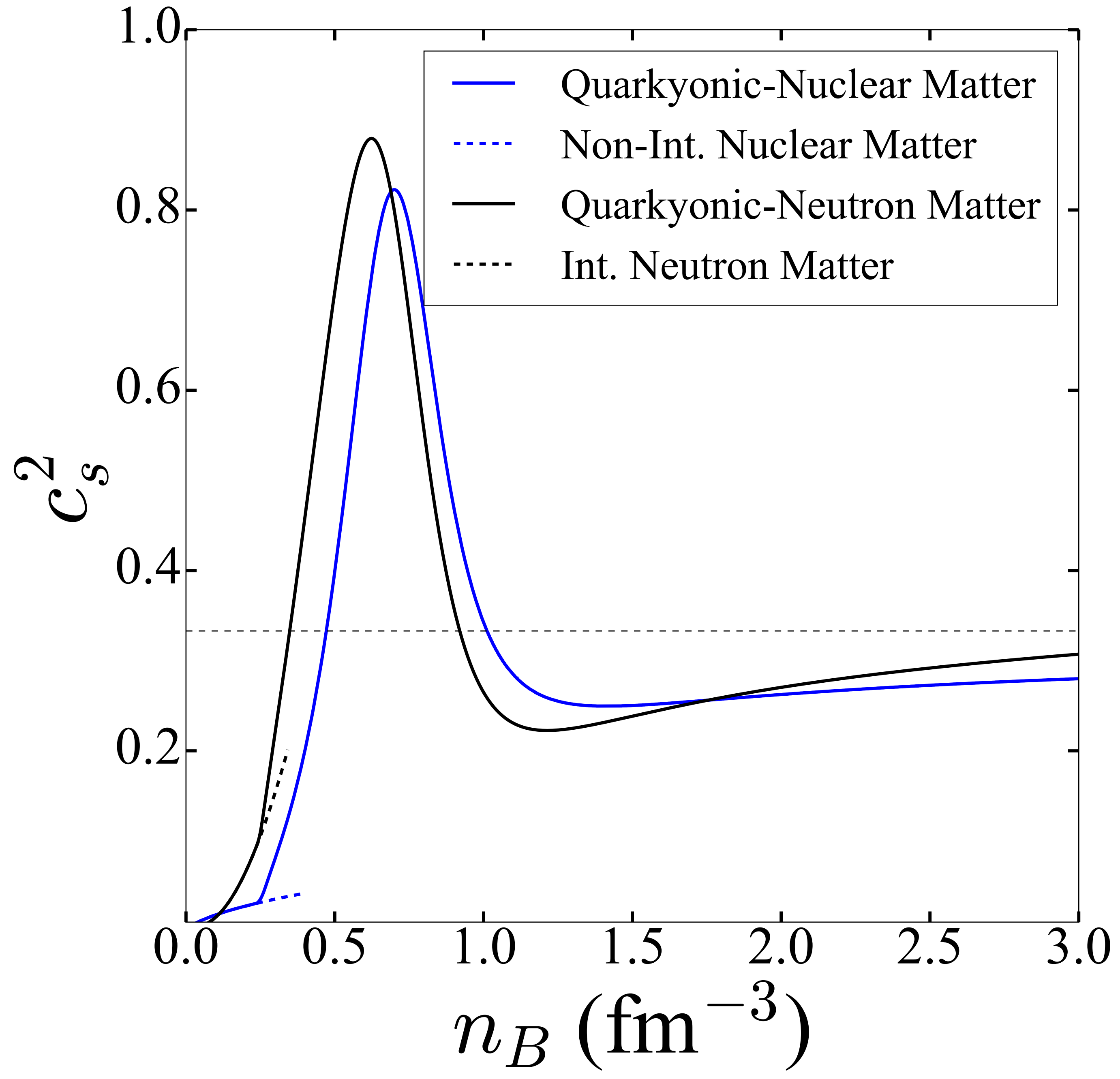
The EOS = key to understanding fundamental properties of QCD matter

3) Understanding extreme behavior at high baryon densities: is $c_s^2 > 1/3$ for symmetric matter?

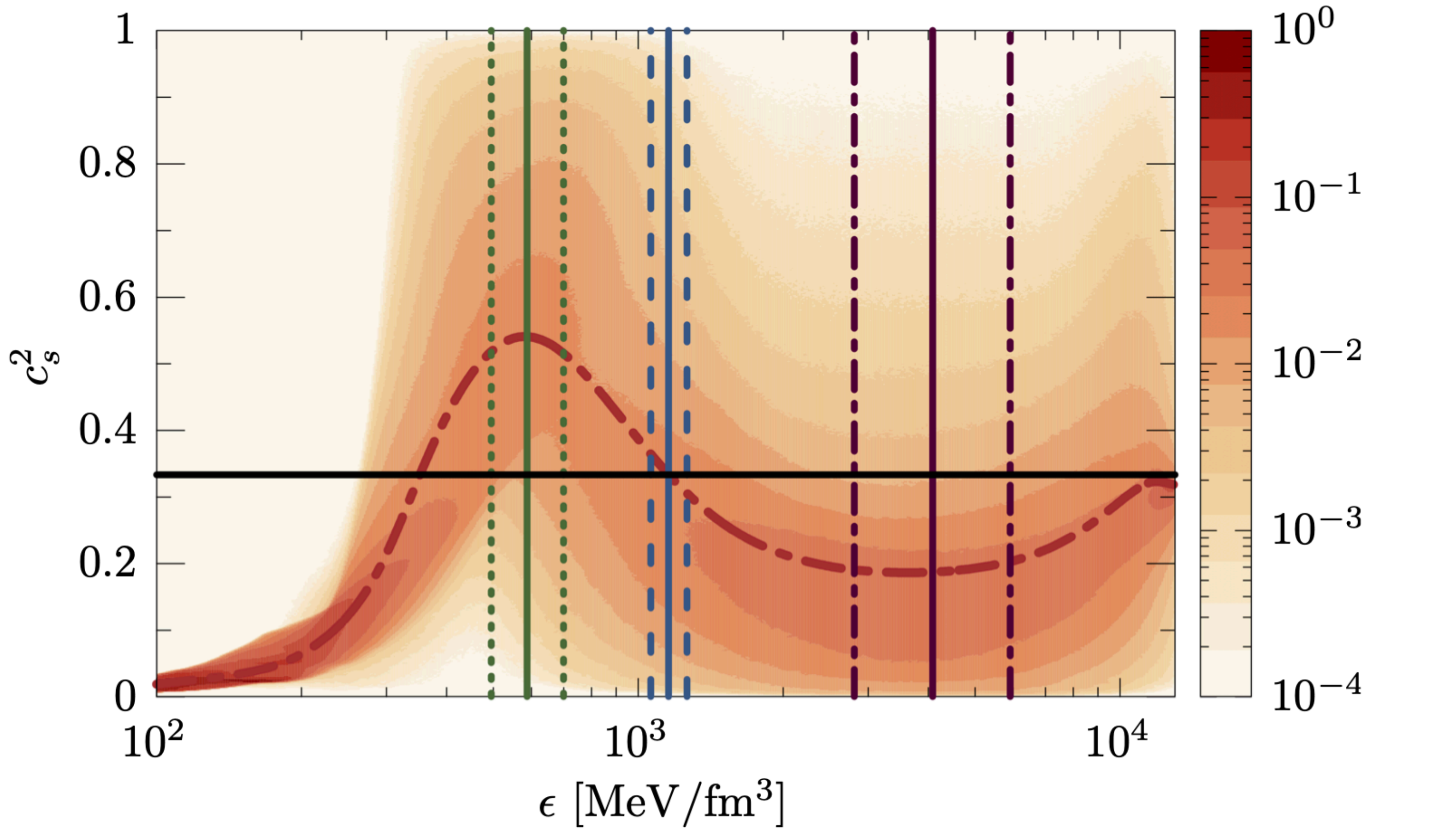
P. Bedaque and A. W. Steiner, Phys. Rev. Lett. **114**, no.3, 031103 (2015), arXiv: 1408.5116
I. Tews, J. Carlson, S. Gandolfi and S. Reddy, Astrophys. J. **860**, no.2, 149 (2018), arXiv:1801.01923



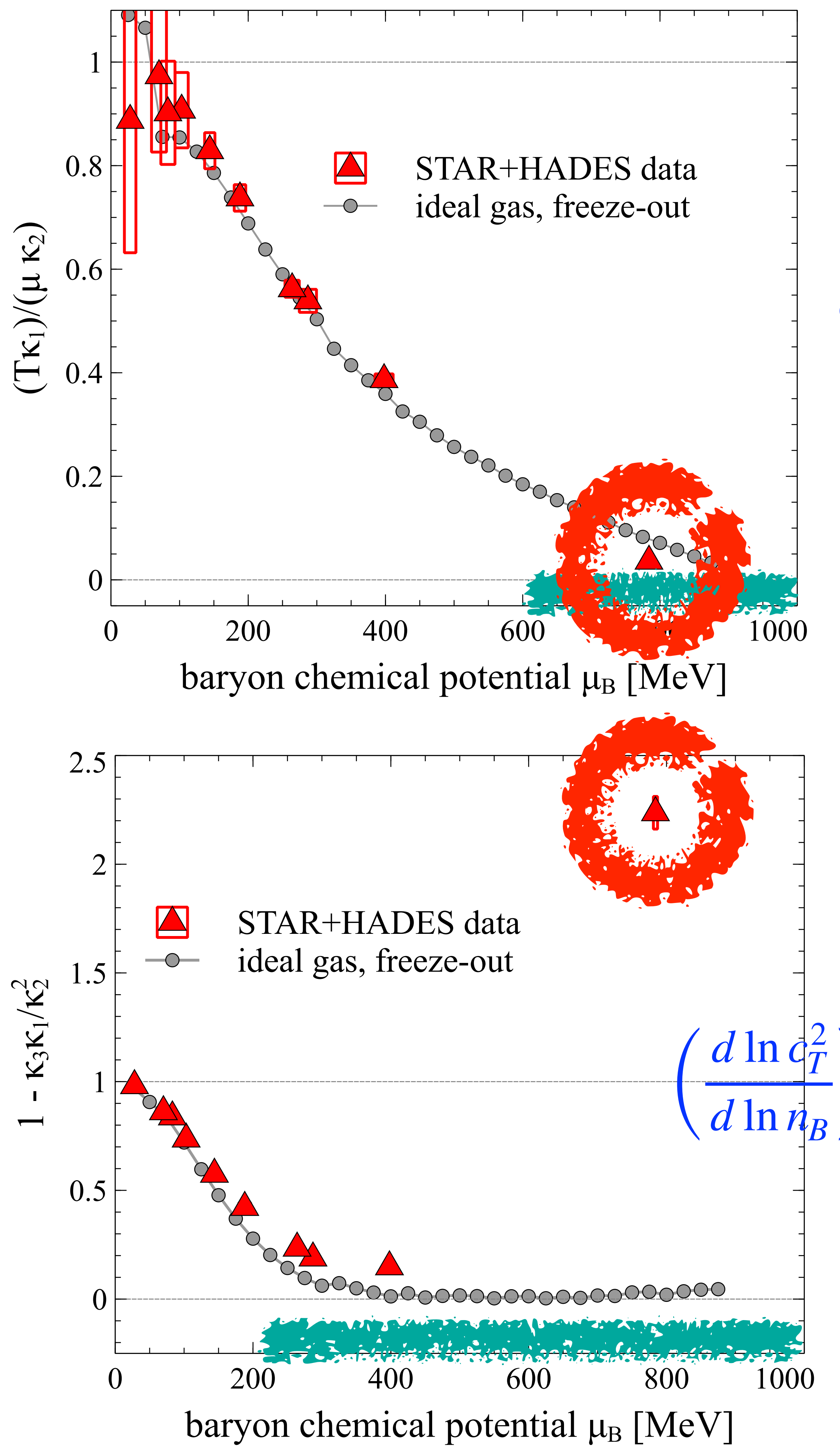
Y. Fujimoto, K. Fukushima and K. Murase,
Phys. Rev. D **101** (2020) 5, 054016, arXiv:1903.03400



L. McLerran and S. Reddy,
Phys. Rev. Lett. **122**, no.12, 122701 (2019), arXiv:1811.12503



M. Marczenko, L. McLerran, K. Redlich, C. Sasaki,
Phys. Rev. C **107**, 2, 025802 (2023) arXiv:2207.13059



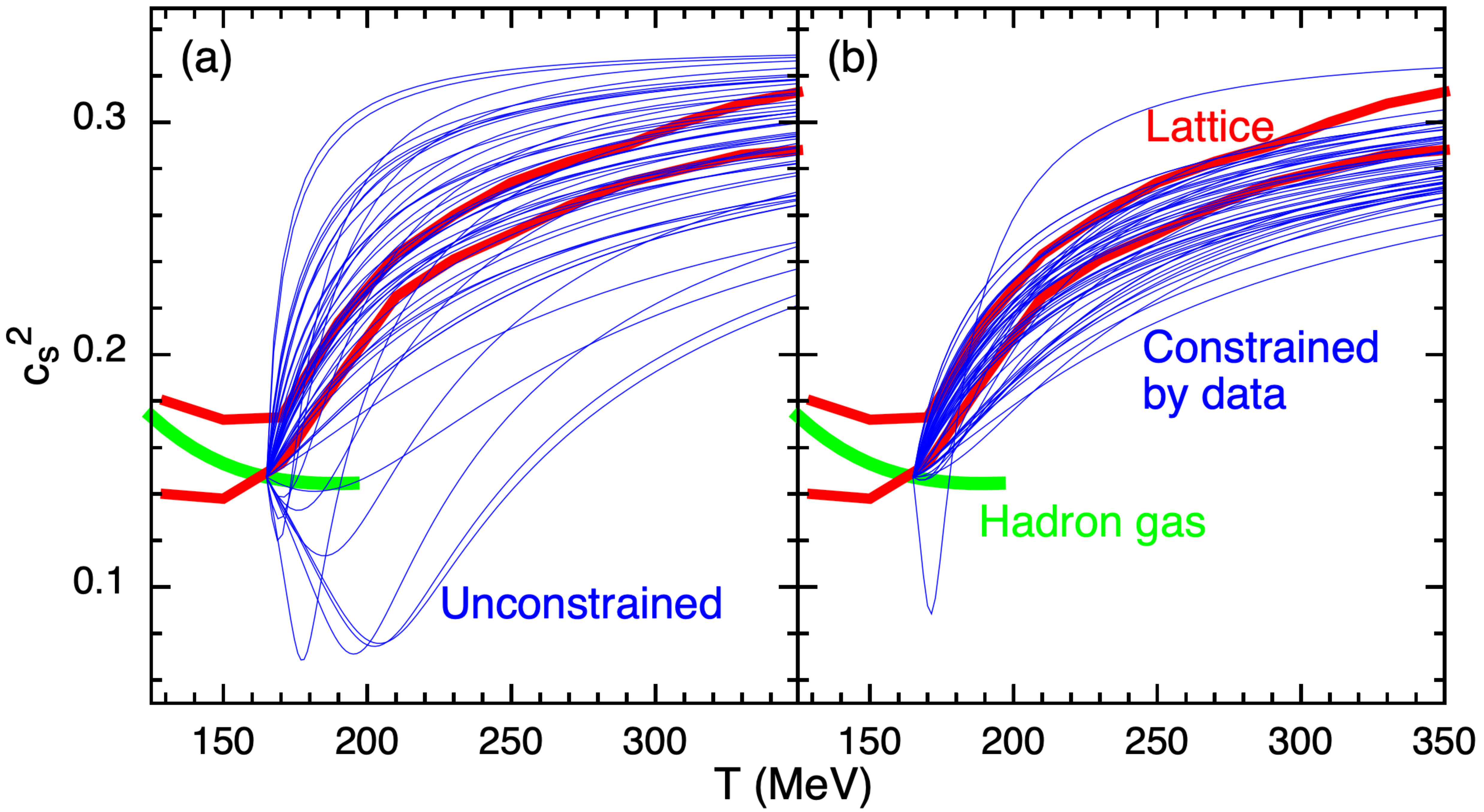
$$c^2_{T=0} \approx \frac{T}{\mu_B}\frac{\kappa_1}{\kappa_2}$$

$$\left(\frac{d\ln c_T^2}{d\ln n_B}\right)_{T=0} + c^2_{T=0} \approx 1 - \frac{\kappa_3\kappa_1}{\kappa_2^2}$$

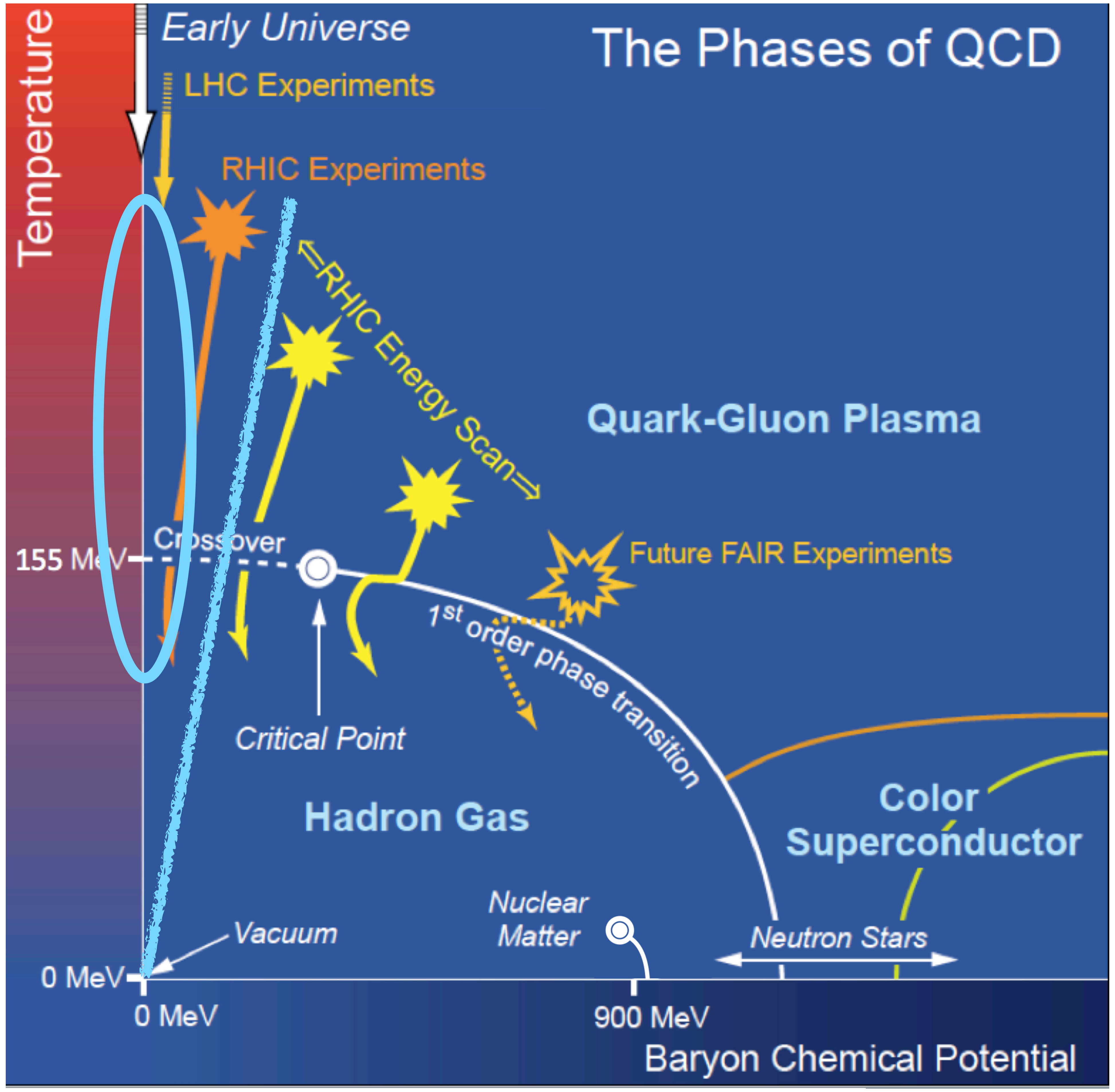
A. Sorensen, D. Oliinychenko, V. Koch, L. McLerran,
Phys. Rev. Lett. **127** (2021) 042303, arXiv:2103.07365

The QCD phase diagram from heavy-ion collisions

Bayesian analysis of experimental data using relativistic viscous hydrodynamics



S. Pratt, E. Sangaline, P. Sorensen, H. Wang,
Phys. Rev. Lett. **114** (2015) 202301
arXiv:1501.04042



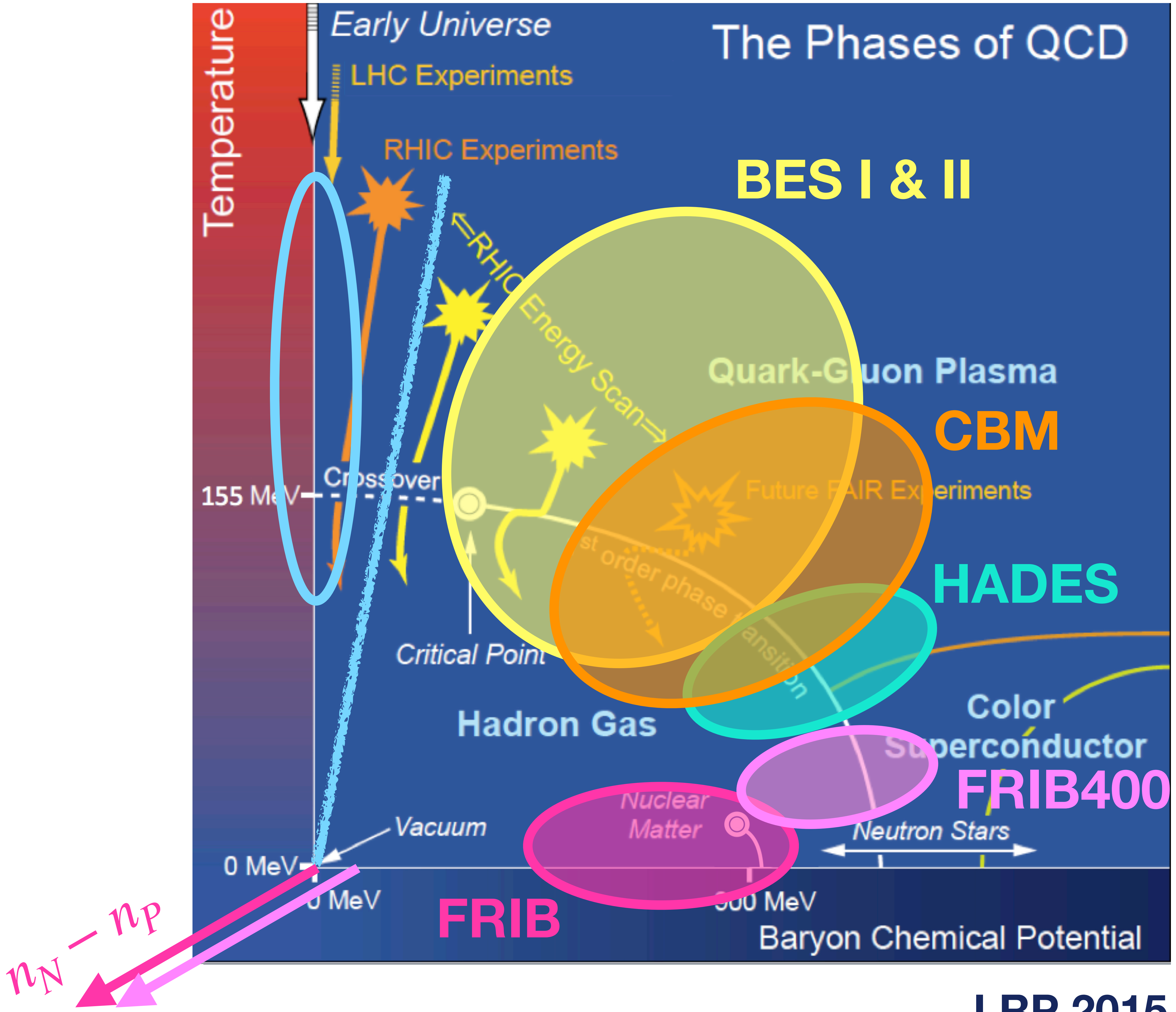
LRP 2015

LQCD EOS ($\mu_B = 0$)
finite m_q = crossover
pseudocritical temperature $T_{pc} \simeq 155$ MeV

HotQCD, Phys. Lett. B **795** (2019) 15-21
arXiv:1812.08235

S. Borsanyi *et al*, Phys. Rev. Lett. **125** (2020) 5, 052001", arXiv:2002.02821

The QCD phase diagram: enormous interest in behavior at high n_B

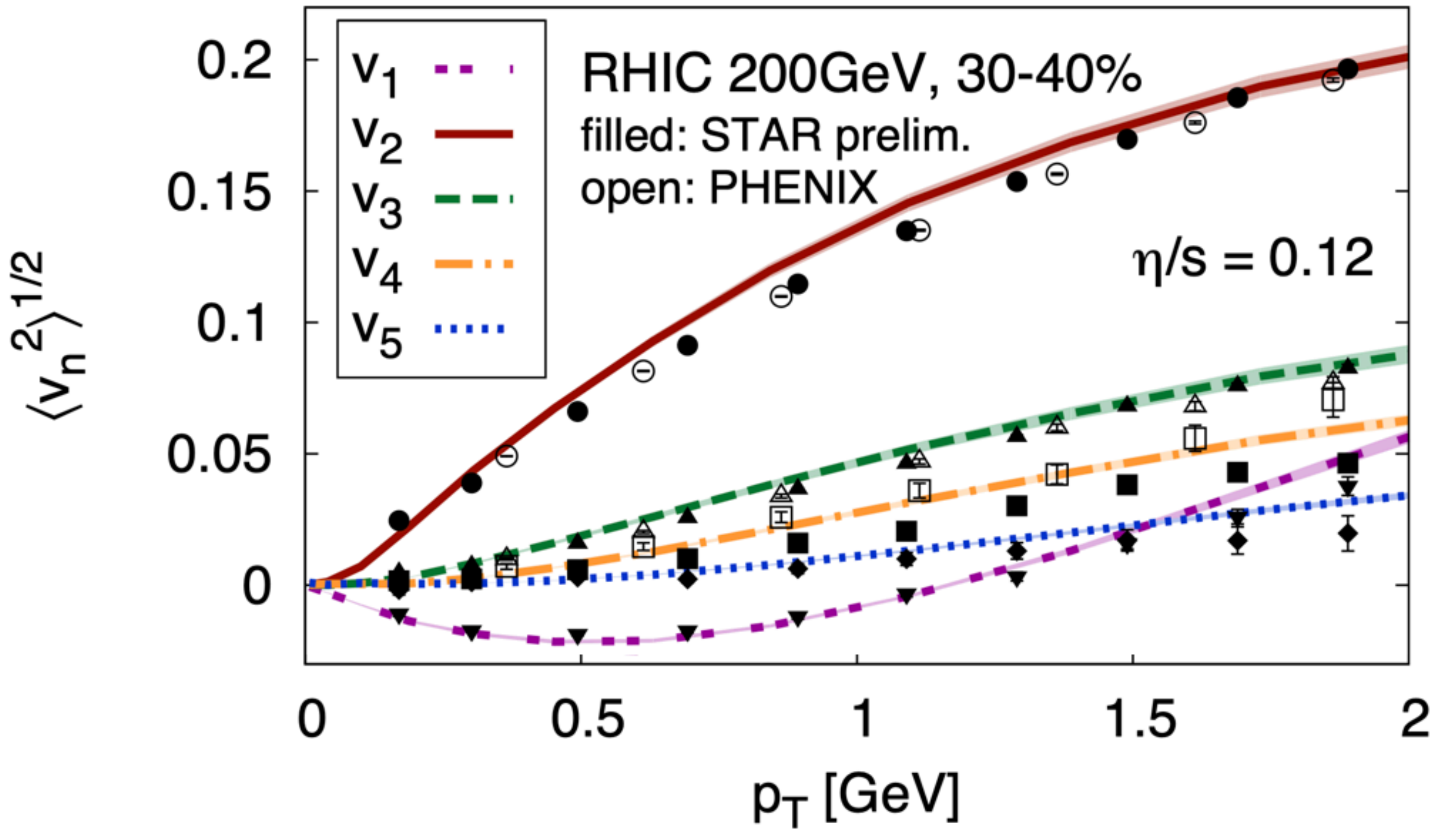


LRP 2015

Models predict a 1st order phase transition at large μ_B ~ large n_B

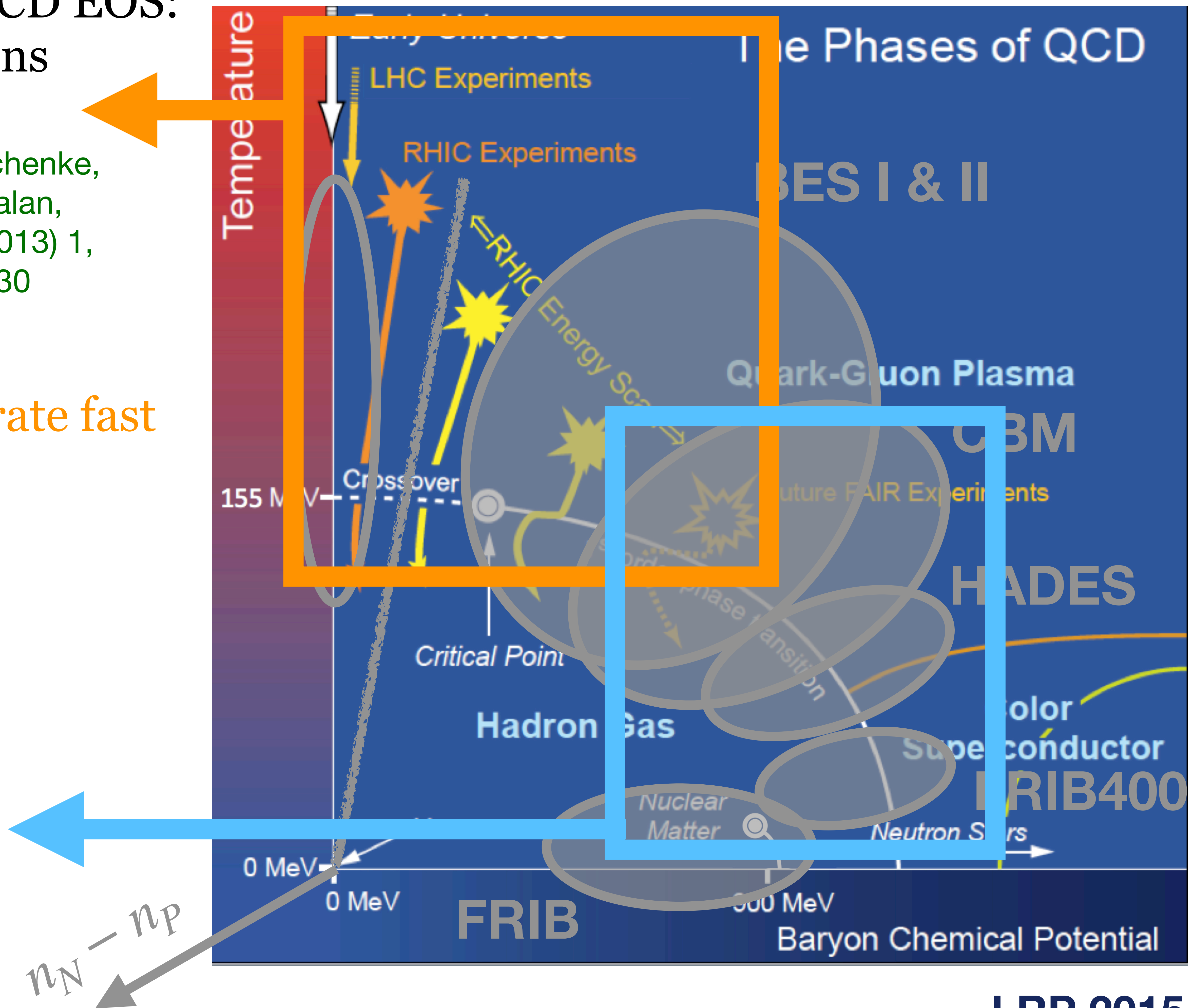
The EOS of dense nuclear matter in heavy-ion collisions

Relativistic viscous hydrodynamic simulations with LQCD EOS: amazing agreement with data from high-energy collisions



C. Gale, S. Jeon, B. Schenke, P. Tribedy, R. Venugopalan, Phys. Rev. Lett. **110** (2013) 1, 012302, arXiv:1209.6330

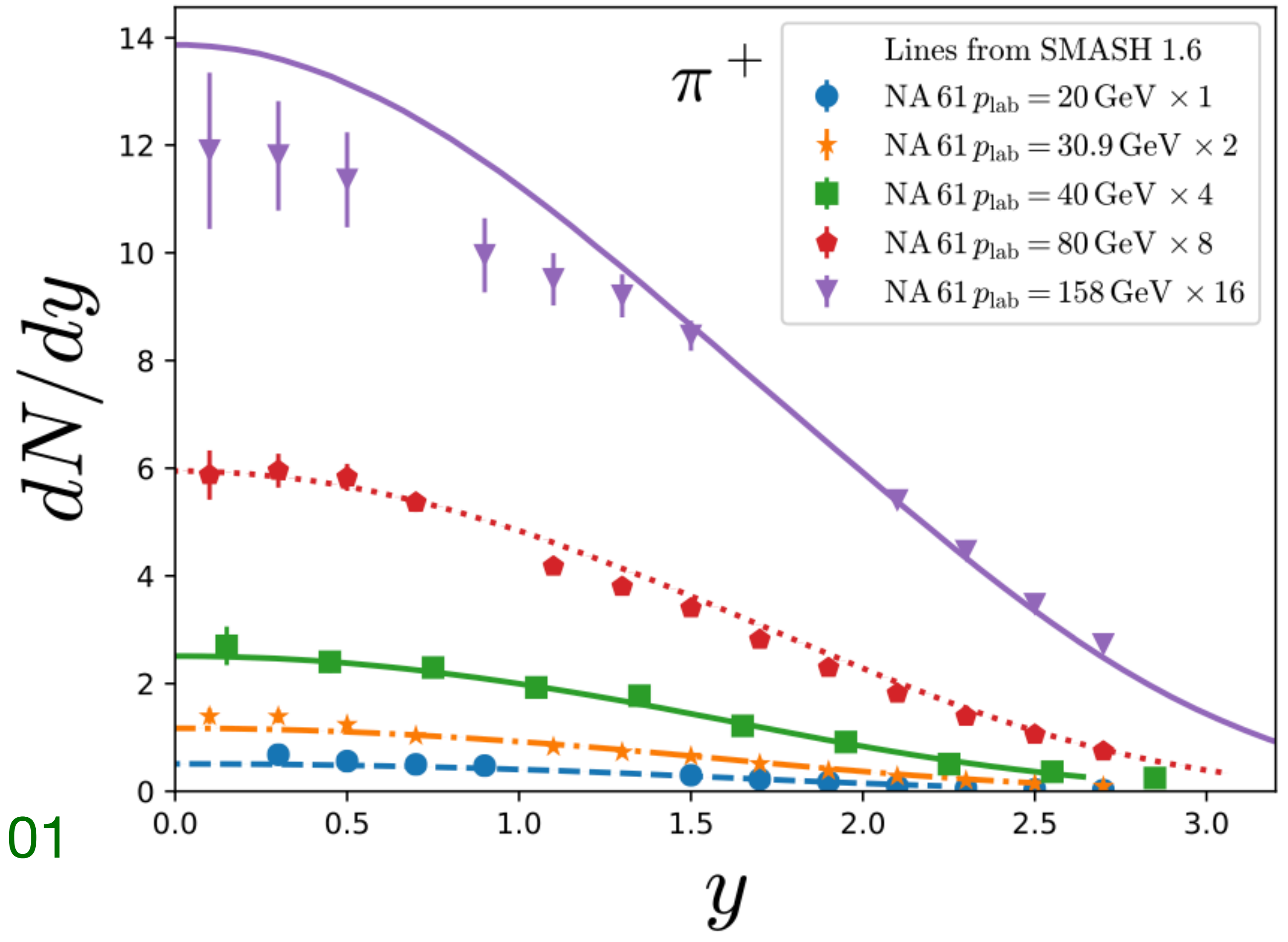
systems equilibrate fast = hydro applies



LRP 2015

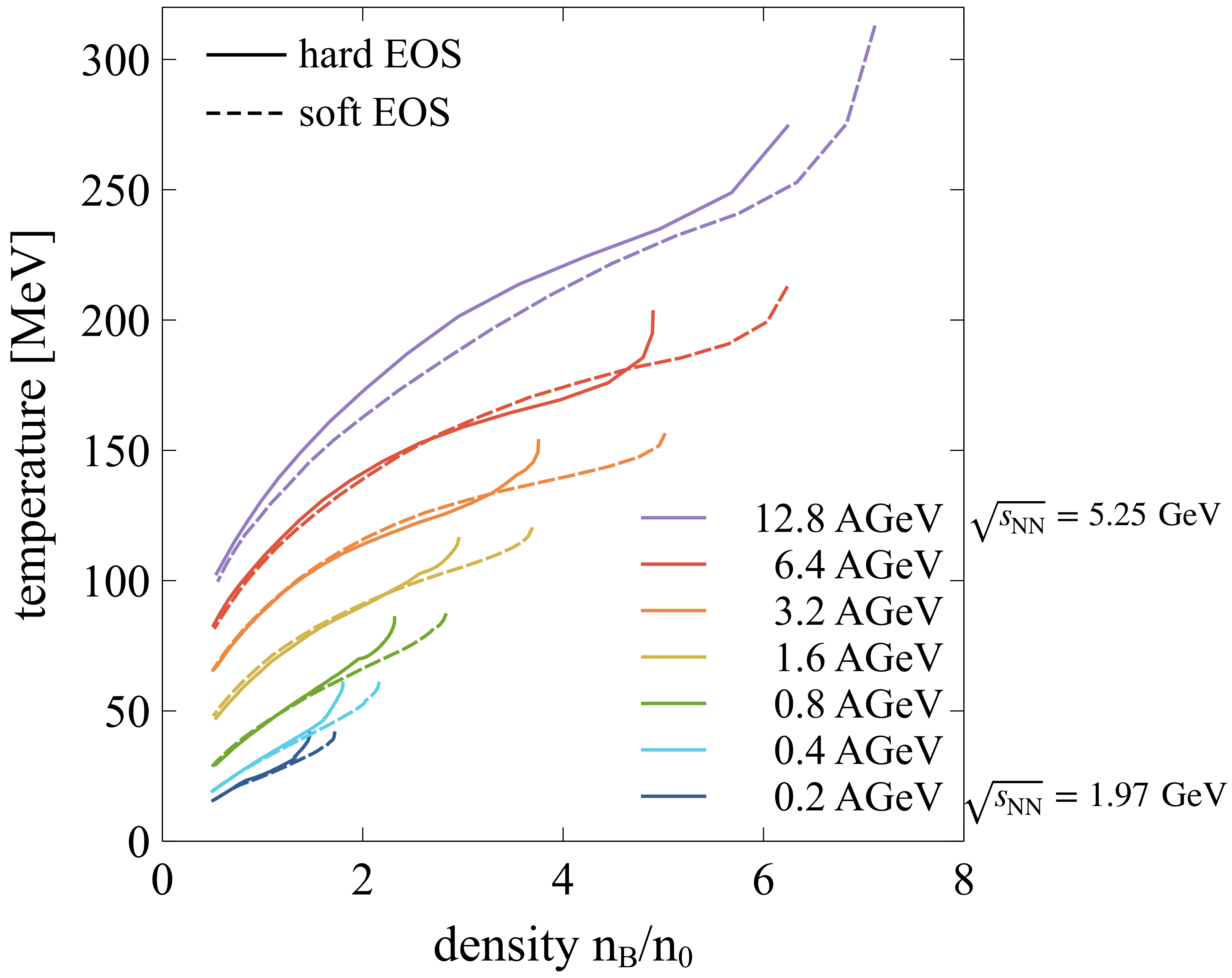
Hadronic transport simulations:

systems out of equilibrium = microscopic approach needed

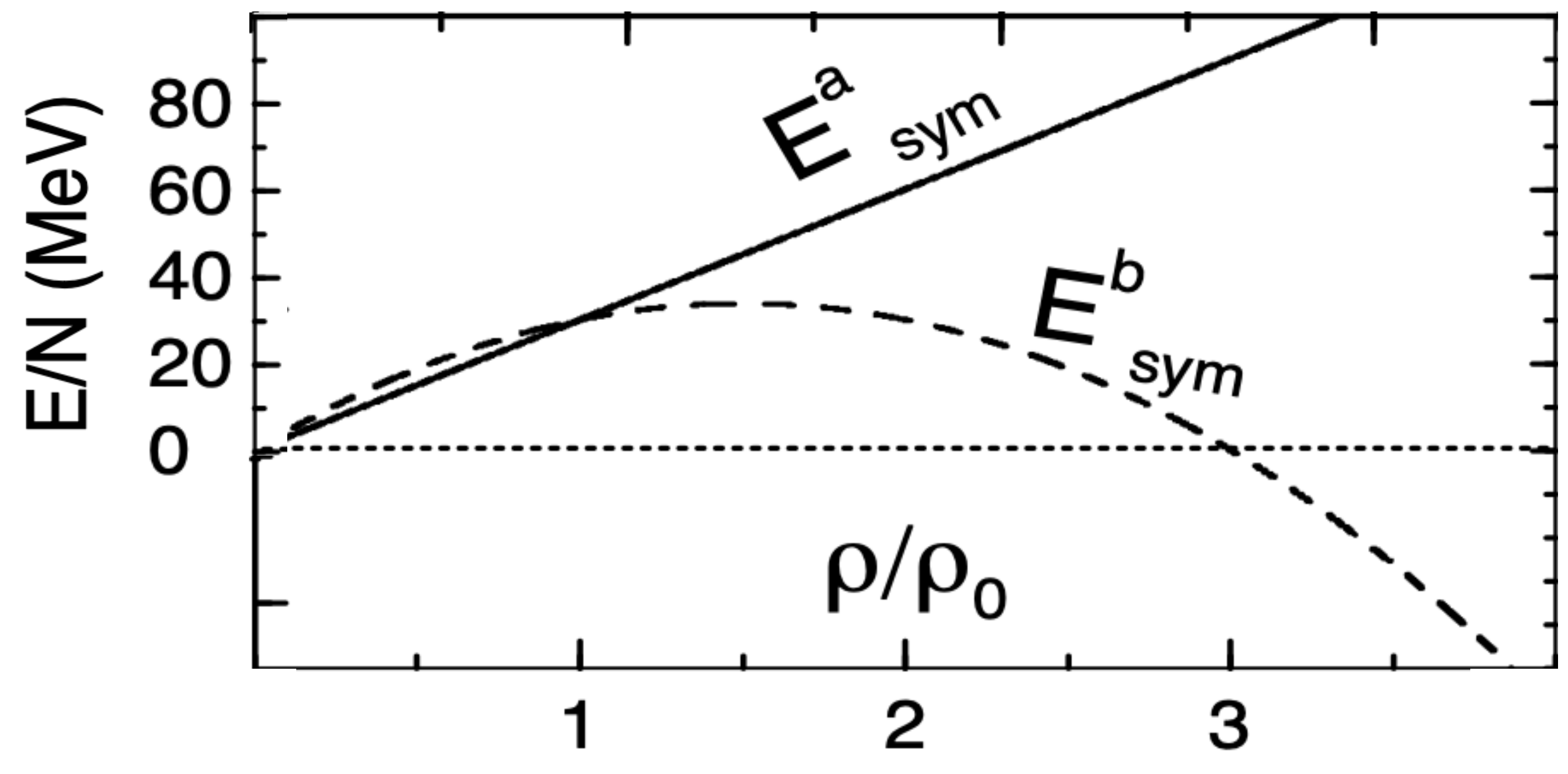


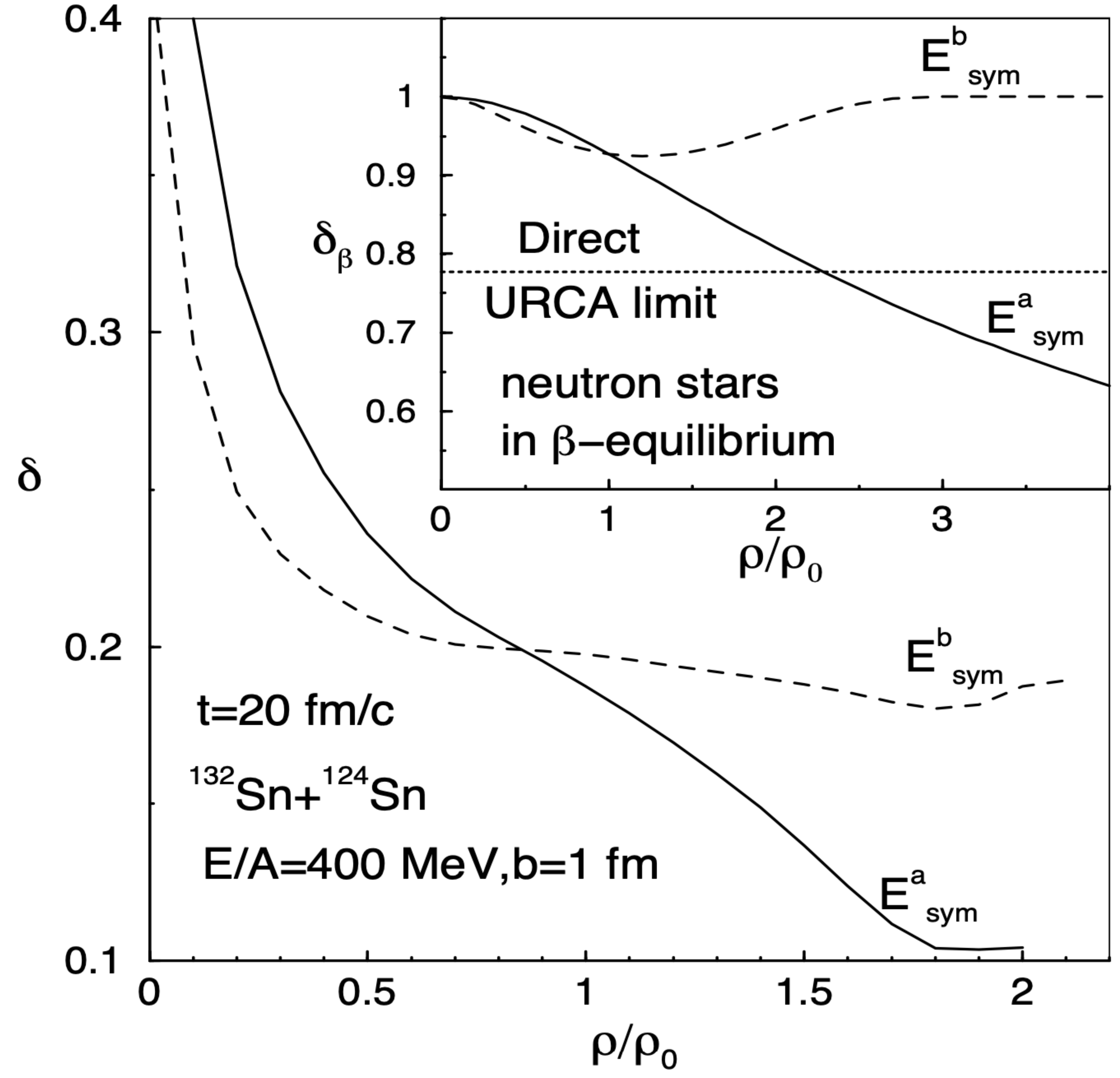
J. Mohs, S. Ryu, H. Elfner, J. Phys. G **47** (2020) 6, 065101 arXiv:1909.05586

Intermediate-energy heavy-ion collisions probe wide ranges of density and temperature



A. Sorensen *et al.*, arXiv:2301.13253





B.-A. Li, Phys. Rev. Lett. **88**, 192701 (2002) arXiv:nucl-th/0205002

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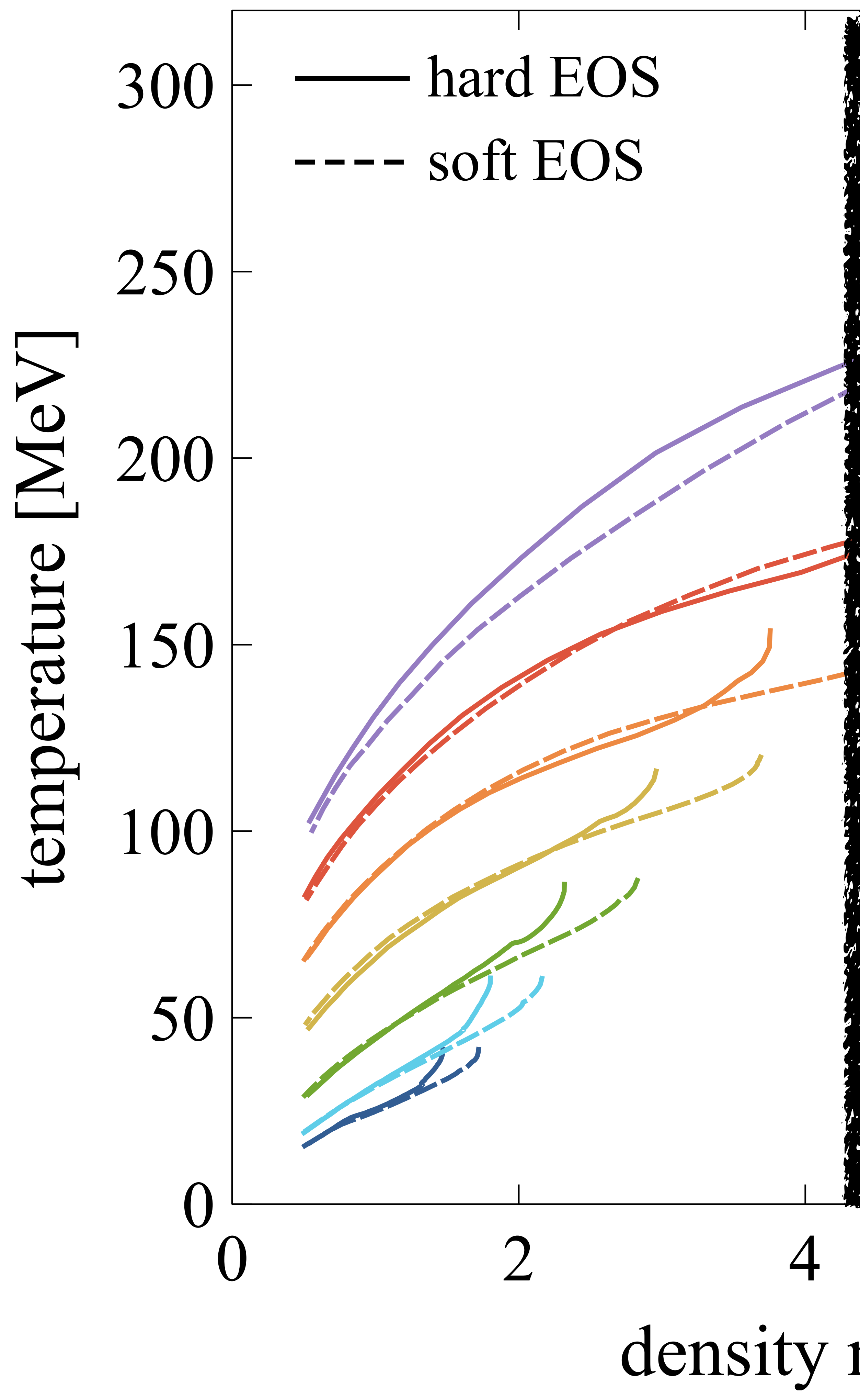
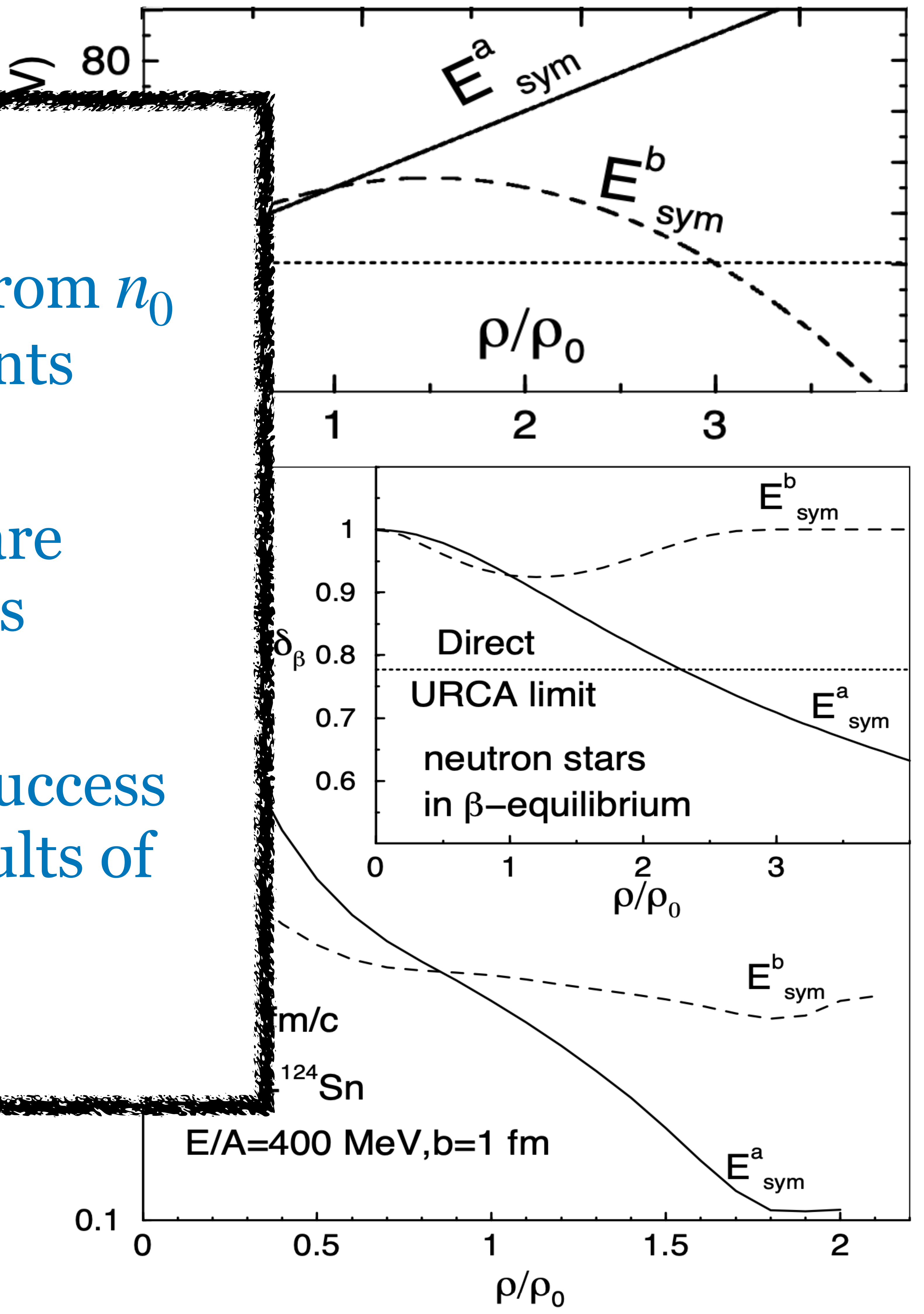


A. **Sorensen** *et al.*, arXiv:2301.13253

The only means to probe (far) away from n_0 in controlled terrestrial experiments

Hadronic transport simulations are necessary to interpret the results

Unique opportunity to build on the success of using simulations to interpret results of HICs at high energies



B.-A. Li, Phys. Rev. Lett. **88**, 192701 (2002) arXiv:nucl-th/0205002

Why another white paper?

A. Sorensen *et al.*, arXiv:2301.13253

Executive summary:

- Profound questions challenging our understanding of strong interactions remain unanswered:
  - the phase diagram of QCD at high n_B is unknown
  - the density-dependence of the symmetry energy is not well constrained
- Among controlled terrestrial experiments, collisions of heavy nuclei at intermediate beam energies (from a few tens of MeV/nucleon to about 25 GeV/nucleon in the fixed-target frame) probe the widest ranges of baryon density and temperature.
- Hadronic transport simulations are currently the only means of interpreting observables measured in heavy-ion collision experiments at intermediate beam energies:
  state-of-the-art hadronic transport simulations needed for physics at RHIC, GSI, FAIR, FRIB

- US PIs with expertise in hadronic transport theory research *(to the best of my knowledge)*:
  - members of the TMEP collaboration: Paweł Danielewicz, Che-Ming Ko, Bao-An Li, Betty Tsang, Bill Lynch
  - Volker Koch, Steffen Bass, Zi-Wei Lin, Jorge A. Lopez
  (emeritus positions: Jørgen Randrup, George Bertsch)

Transport model simulations of heavy-ion collisions (Section II A)

- Boltzmann-Uehling-Uhlenbeck (BUU)-type codes:

  - solve coupled Boltzmann equations $\forall i: \quad \frac{\partial f_i}{\partial t} + \frac{d\mathbf{x}_i}{dt}\frac{\partial f_i}{\partial \mathbf{x}_i} + \frac{d\mathbf{p}_i}{dt}\frac{\partial f_i}{\partial \mathbf{p}_i} = I_{\mathrm{coll}}^{(i)}$

  with the method of test particles: the distribution is *over*sampled with a *large* number of discrete test-particles, which are evolved according to the single-particle EOMs
  (test particles probe the evolution in the phase space)

  - forces from single-particle energies (mean-fields: needs a robust density calculation!)

  - collision term based on measured cross-sections for scatterings and decays

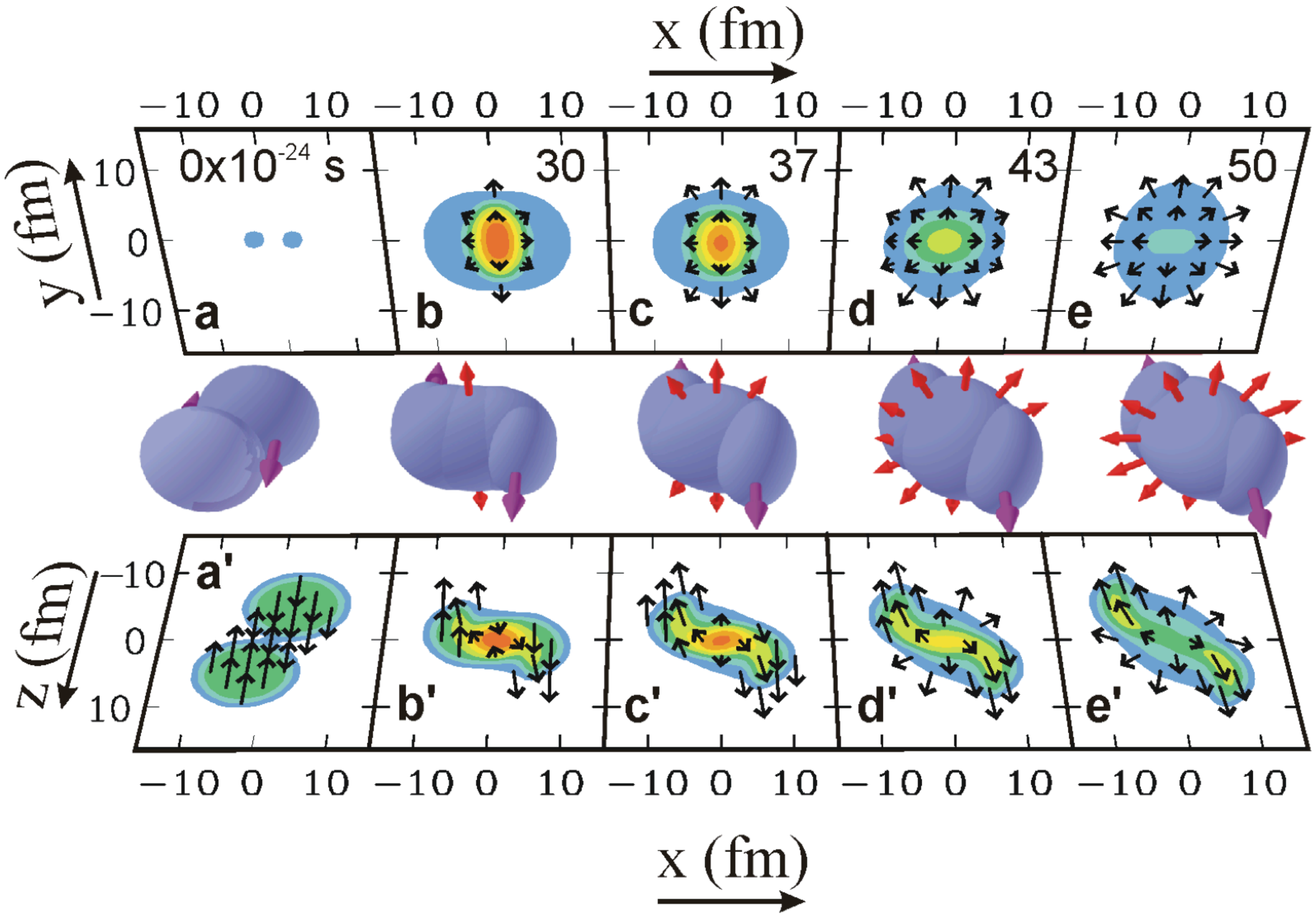
- Quantum Molecular Dynamics (QMD)-type codes
  - solve molecular dynamics problem (evolve nucleons according to their EOMs)

  - forces: in principle distance-dependent particle-particle interactions, in practice: often mean-fields!

  - collisions based on measured cross-sections for scatterings and decays

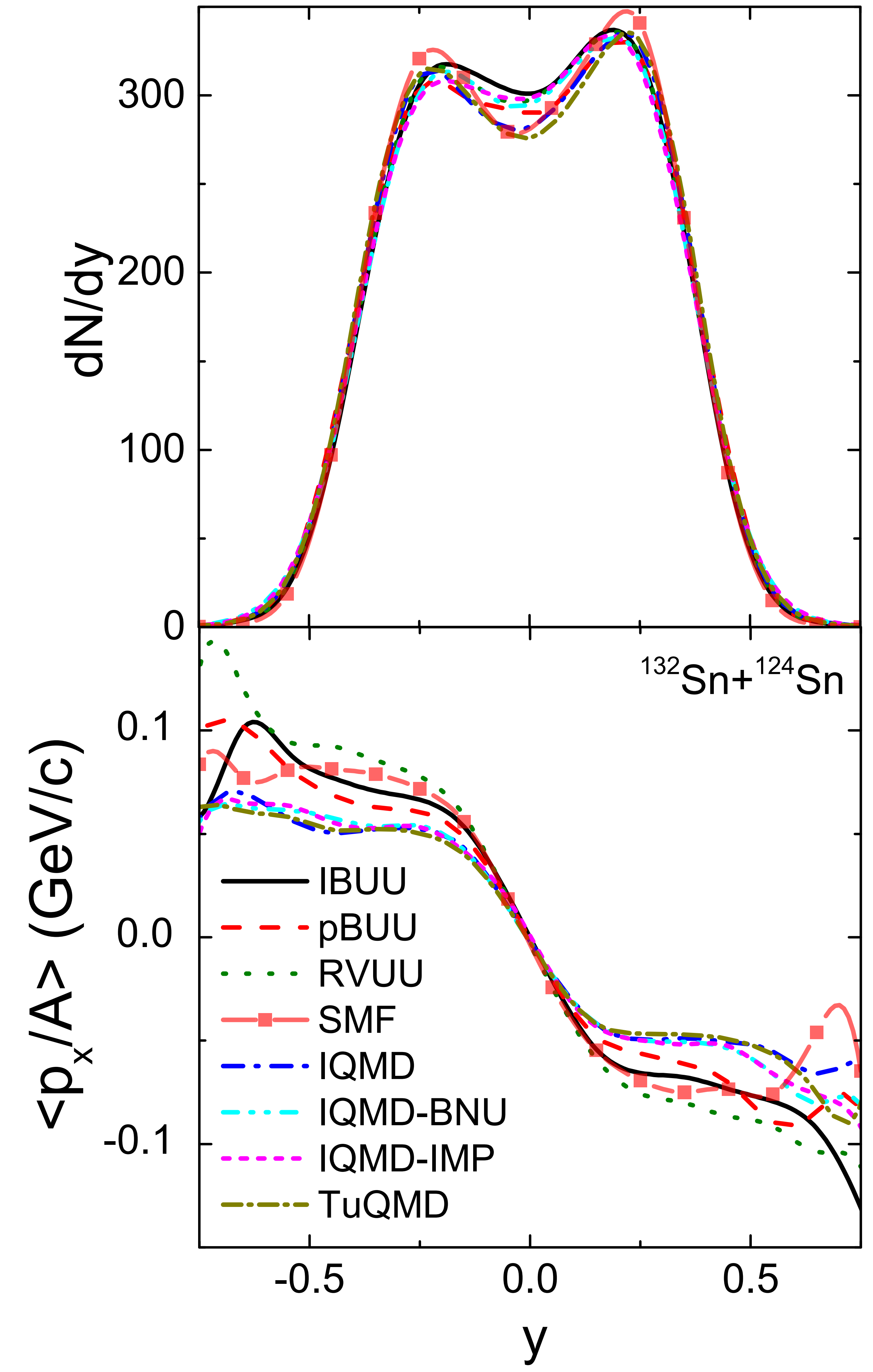
Transport model simulations of heavy-ion collisions (Section II A)

Flow observables are the canonical observables for extracting the EOS



P. Danielewicz, R. Lacey, W. G. Lynch,
Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

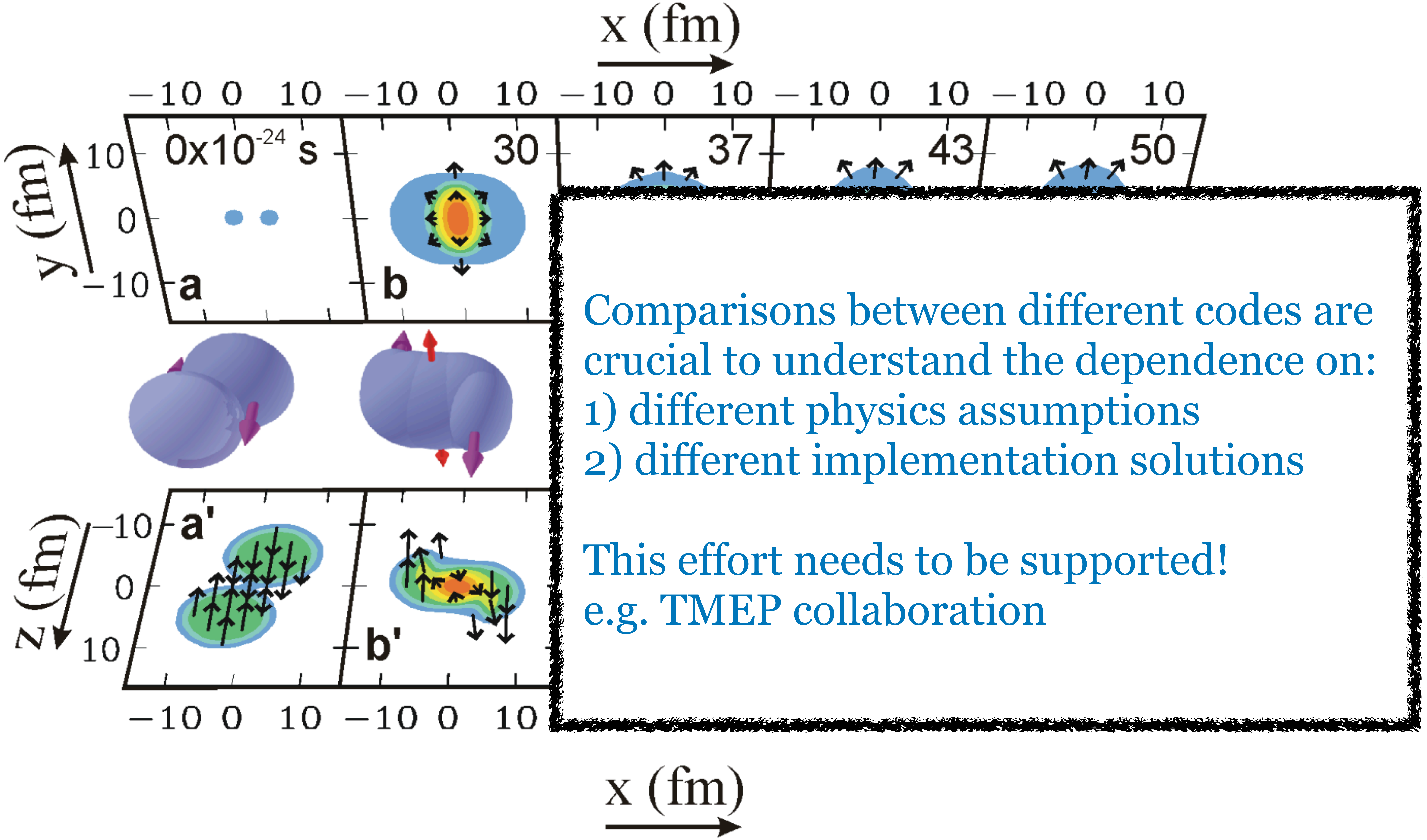
There is code-dependence:



J. Xu *et al.* (TMEP Collaboration), *in preparation*

Transport model simulations of heavy-ion collisions (Section II A)

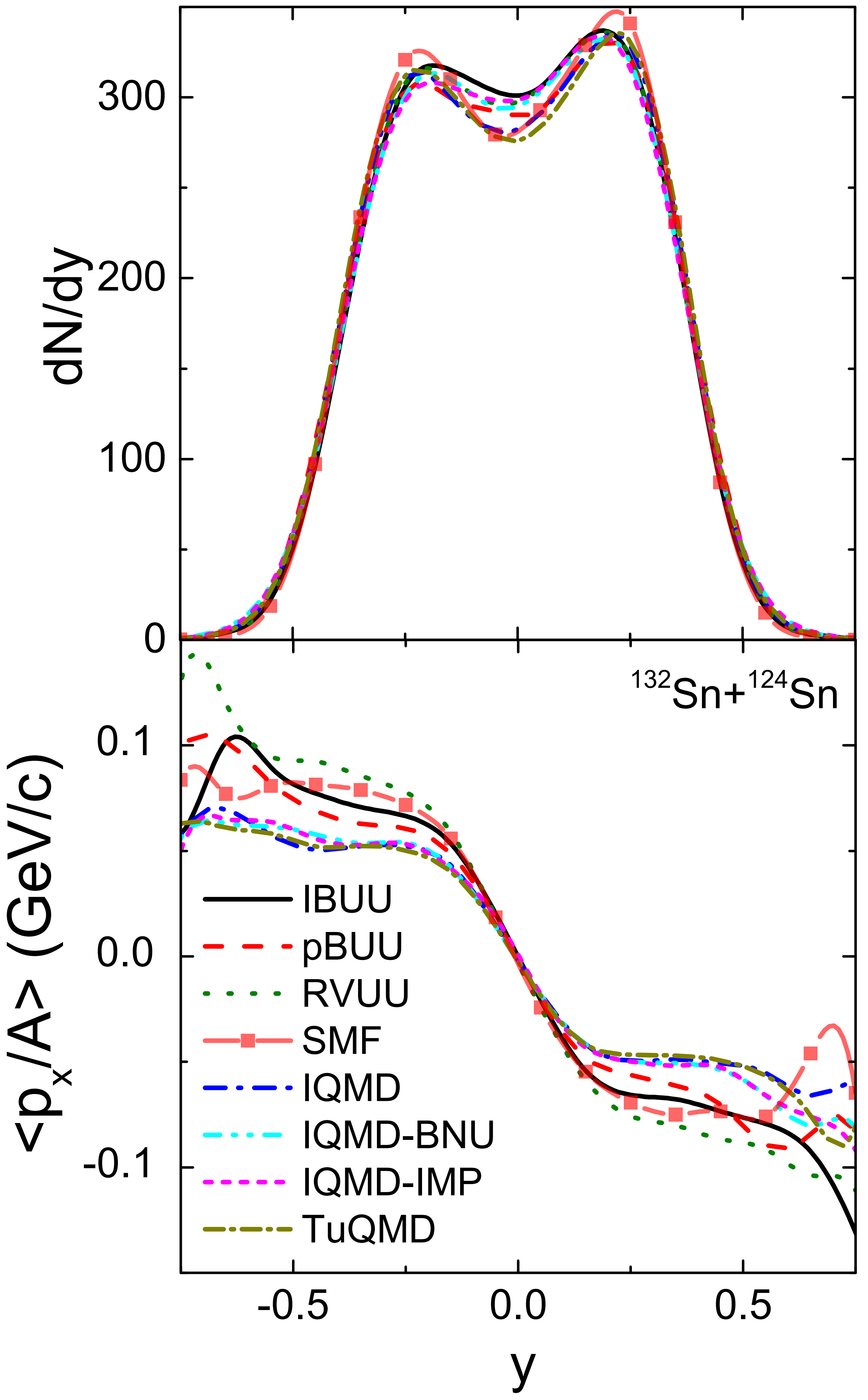
Flow observables are the canonical observables for extracting the EOS



Comparisons between different codes are crucial to understand the dependence on:
1) different physics assumptions
2) different implementation solutions

This effort needs to be supported!
e.g. TMEP collaboration

There is code-dependence:



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Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

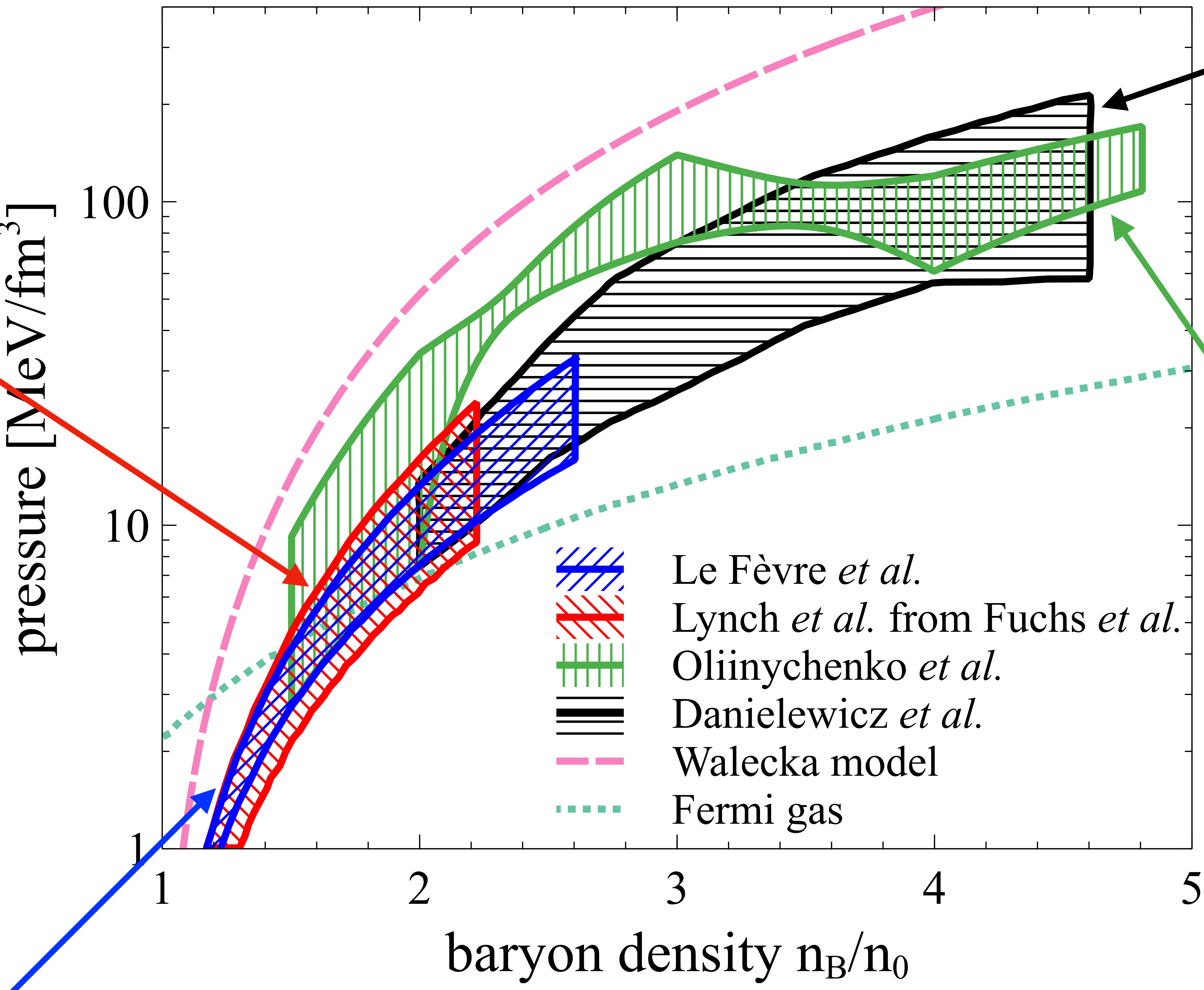
J. Xu *et al.* (TMEP Collaboration), *in preparation*

Transport model simulations of heavy-ion collisions (Section II A)

Symmetric nuclear matter:

197Au+197Au & 12C+12C @ < 1.5 GeV/u
($\sqrt{s_{NN}}$ < 2.5 GeV)
observables: subthreshold kaon production (KaoS)
model used: QMD w/ nucleons, Δ, N*(1440), pions, kaons;
EOS parametrized by K_0;
kaon potentials, momentum dependence
C. Fuchs *et al.*, Prog. Part. Nucl. Phys. **53**, 113–124 (2004) arXiv:nucl-th/0312052

197Au+197Au @ 0.4—1.5 GeV/u
($\sqrt{s_{NN}}$ = 2.07 — 2.52 GeV)
observables: proton flow (FOPI)
model used: isospin QMD (IQMD) w/ nucleons, Δ, N*(1440), deuterons, tritons;
EOS parametrized by K_0;
momentum dependence
A. Le Fèvre, Y. Leifels, W. Reisdorf, J. Aichelin, C. Hartnack, Nucl. Phys. A 945, 112 (2016), arXiv:1501.05246



A. Sorensen *et al.*, arXiv:2301.13253

197Au+197Au @ 0.15—10 GeV/u
($\sqrt{s_{NN}}$ = 1.95 — 4.72 GeV)
observables: proton flow (Plastic Ball, EOS, E877, E895)
model used: pBUU w/ nucleons, Δ, N*(1440), pions;
EOS parametrized by K_0;
momentum dependence
Danielewicz, Lacey, Lynch, Science **298**,1592–1596 (2002)

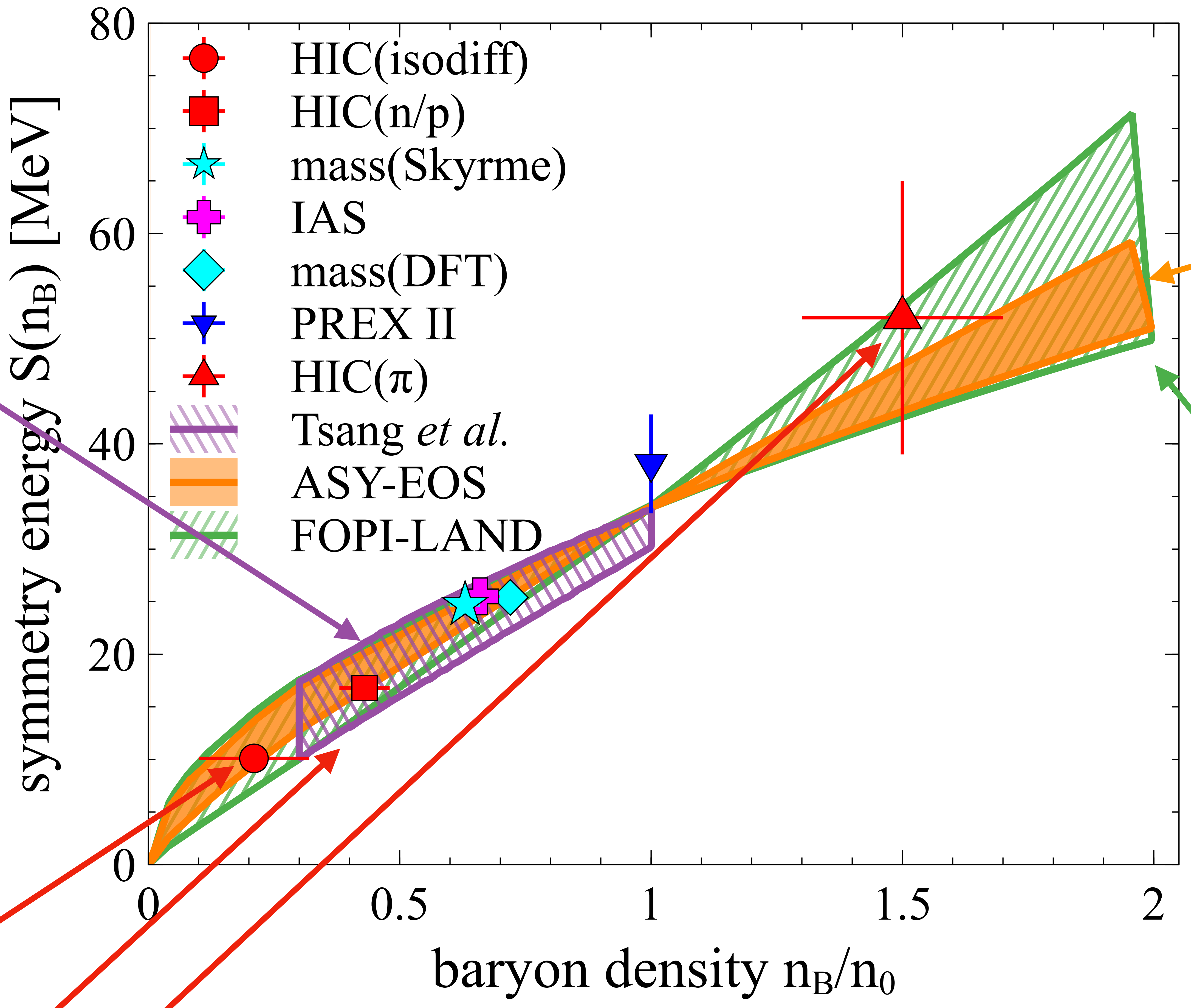
197Au+197Au @ 2.9—9 GeV/u
($\sqrt{s_{NN}}$ = 3 — 4.5 GeV)
observables: proton flow (STAR)
model used: SMASH w/ over 120 hadronic species, including deuterons;
relativistic EOS parametrized independently in different density regions;
[NO momentum dependence]
D. Oliinychenko, AS, V. Koch, L. McLerran, arXiv:2208.11996

Transport model simulations of heavy-ion collisions (Section II A)

Symmetry energy:

112Sn+124Sn @ = 0.05 GeV/u
($\sqrt{s_{NN}}$ = 1.97 GeV)
observables: isospin diffusion, ratio of neutron to proton spectra
model used: ImQMD
M. B. Tsang, Y. Zhang, P. Danielewicz, M. Famiano, Z. Li, W. G. Lynch, A. W. Steiner, Phys. Rev. Lett. **102**, 122701 (2009), arXiv:0811.3107

Sn systems @ < 0.27 GeV/u
($\sqrt{s_{NN}}$ < 2.01 GeV)
observables: isospin diffusion, neutron to proton energy spectra, pion ratios (SPIRIT)
model used: ImQMD, dcQMD, momentum dependence
W. G. Lynch and M. B. Tsang, Phys. Lett. B 830, 137098 (2022), arXiv:2106.10119

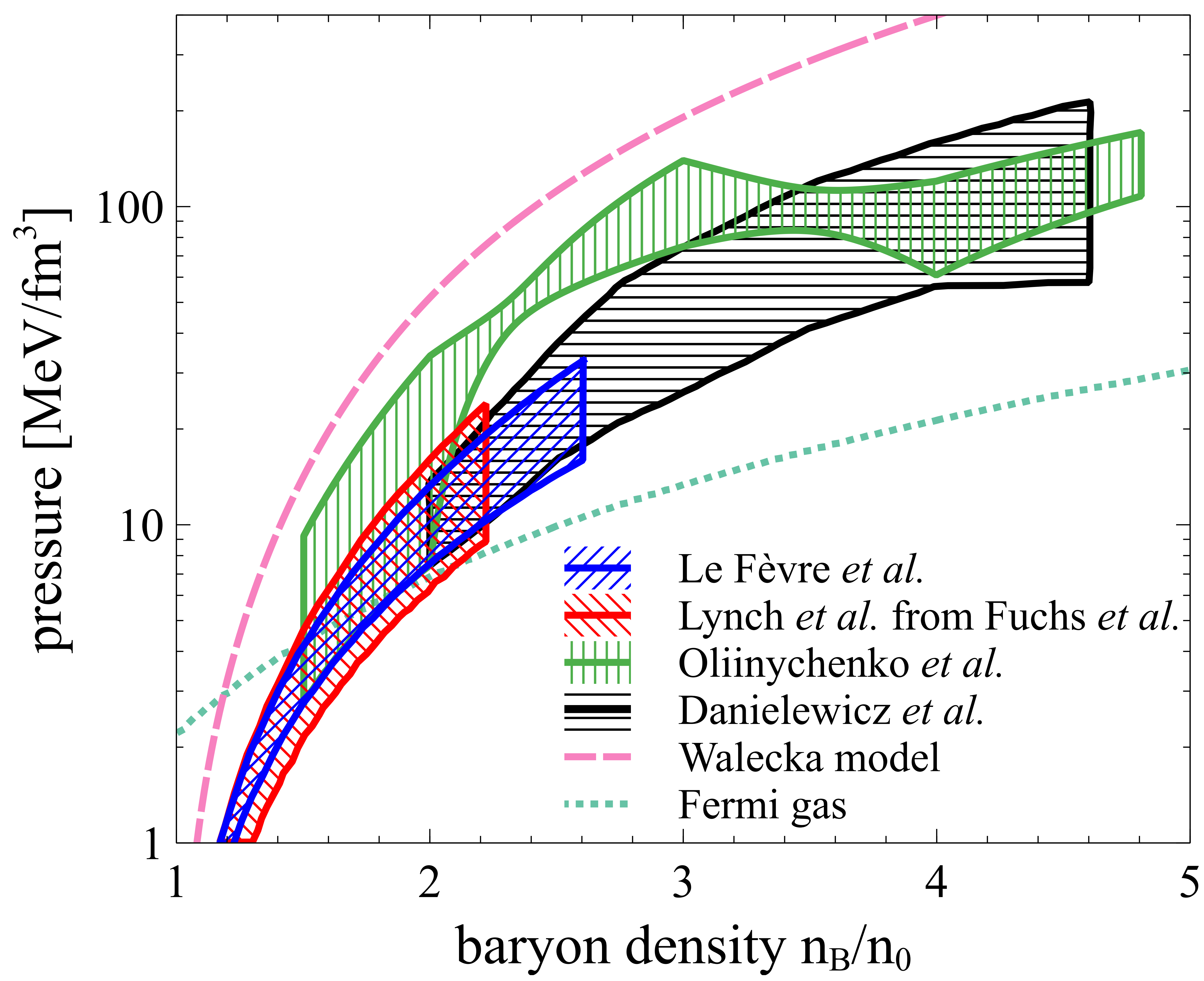


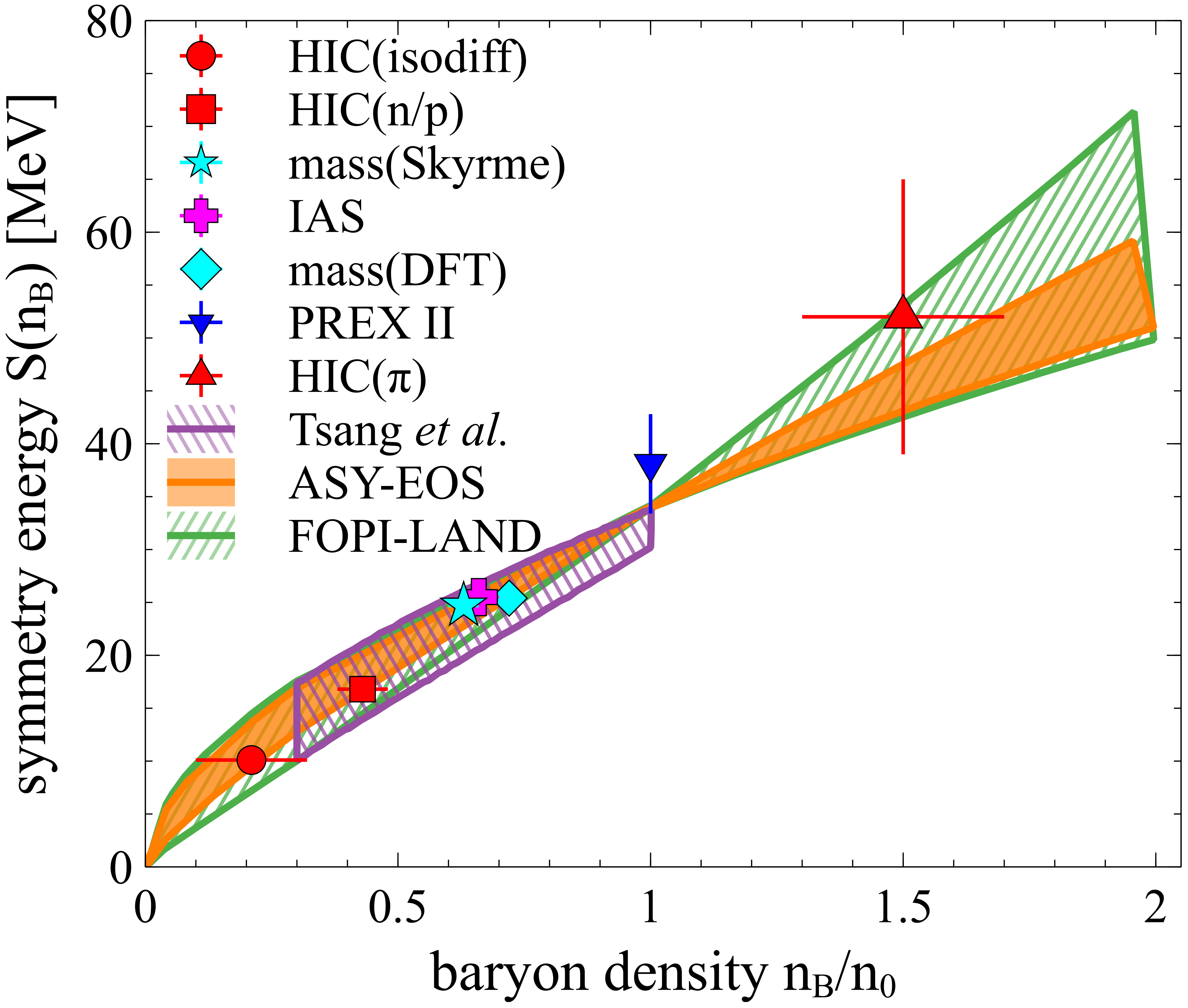
A. Sorensen *et al.*, arXiv:2301.13253

197Au+197Au @ 0.4 GeV/u
($\sqrt{s_{NN}}$ = 2.07 GeV)
observables: ratio of neutron to charged fragments (ASY-EOS)
model used: UrQMD, momentum dependence
P. Russotto *et al.*, Phys. Rev. C **94**, 034608 (2016), arXiv:1608.04332

197Au+197Au @ 0.4 GeV/u
($\sqrt{s_{NN}}$ = 2.07 GeV)
observables: ratio of elliptic flow of neutrons and hydrogen nuclei (FOPI-LAND)
model used: UrQMD, momentum dependence
P. Russotto *et al.*, Phys. Lett. B **697**, 471 (2011), arXiv:1101.2361

Transport model simulations of heavy-ion collisions (Section II A)

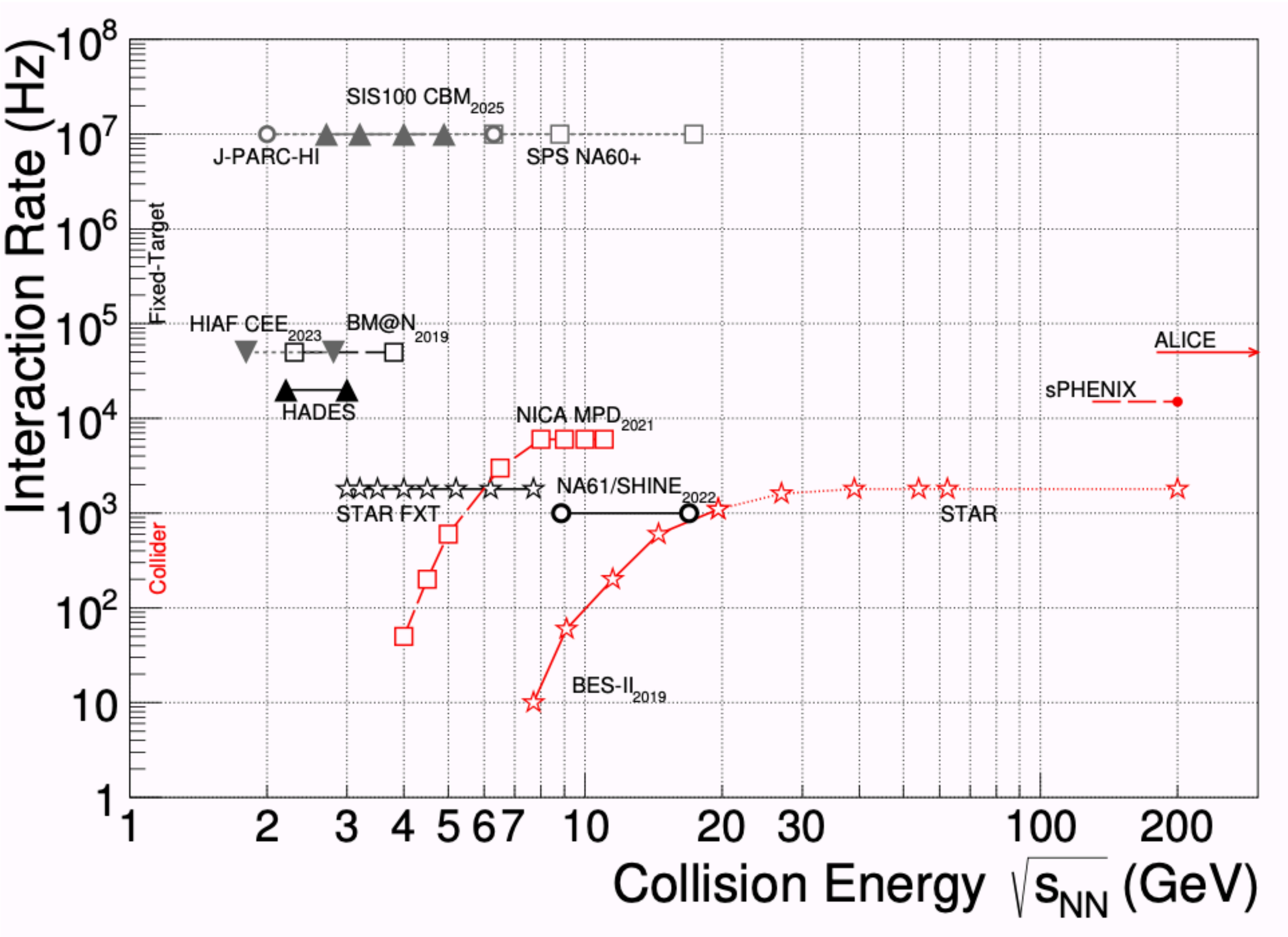




Error bars are due to differences between models and the data!

A. Sorensen *et al.*, arXiv:2301.13253

Precision era of heavy-ion collisions

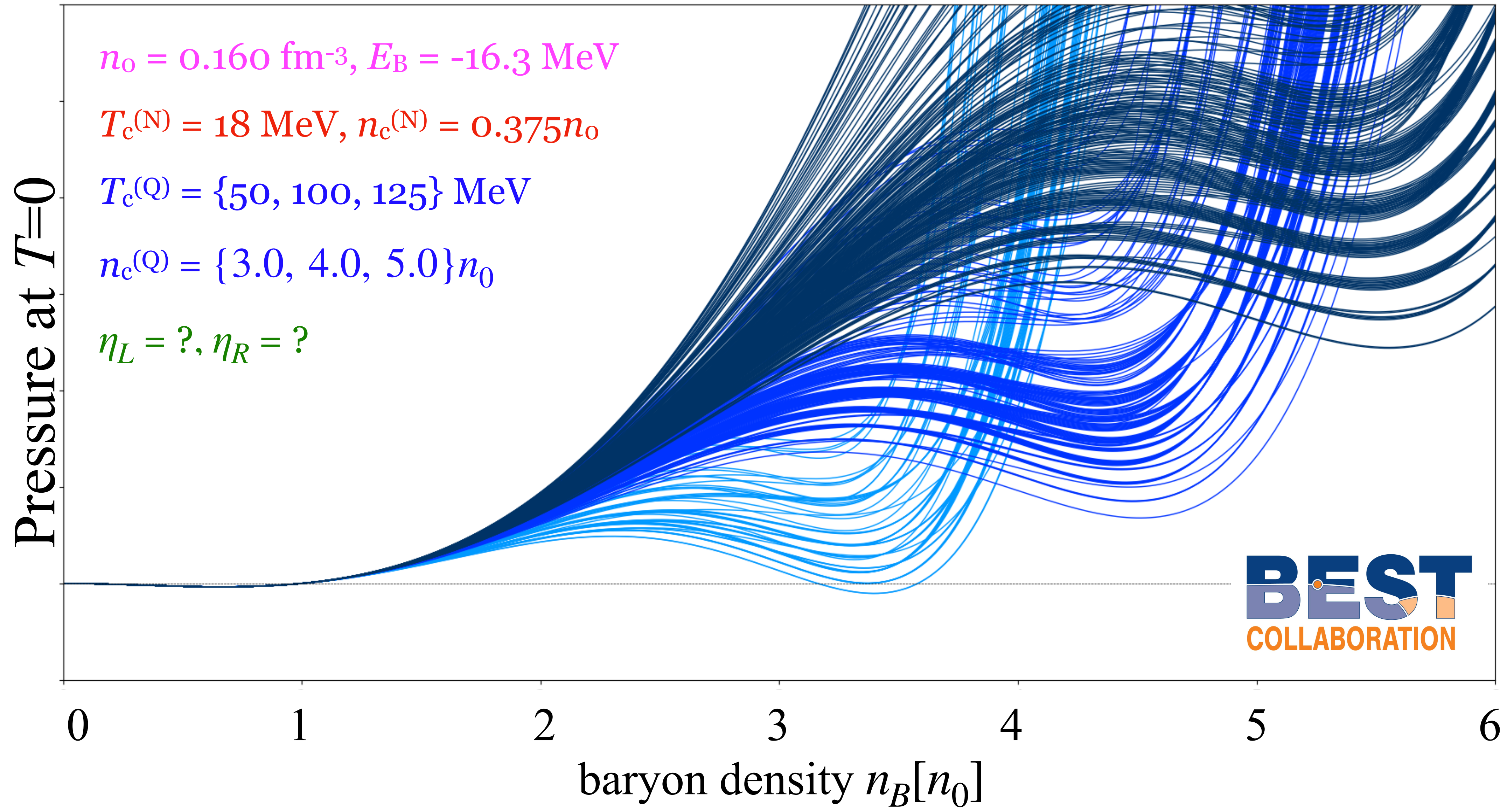


Precision experiments
NEED precision simulations

Program to improve transport model simulations (Section II A)

1. More flexible EOS: flexible density (no more parametrization by K_0!), momentum, isospin dependence

Vector density functional (VDF) model:
relativistic EOS based on a polynomial with an arbitrary number of terms proportional to powers of j_B^μ

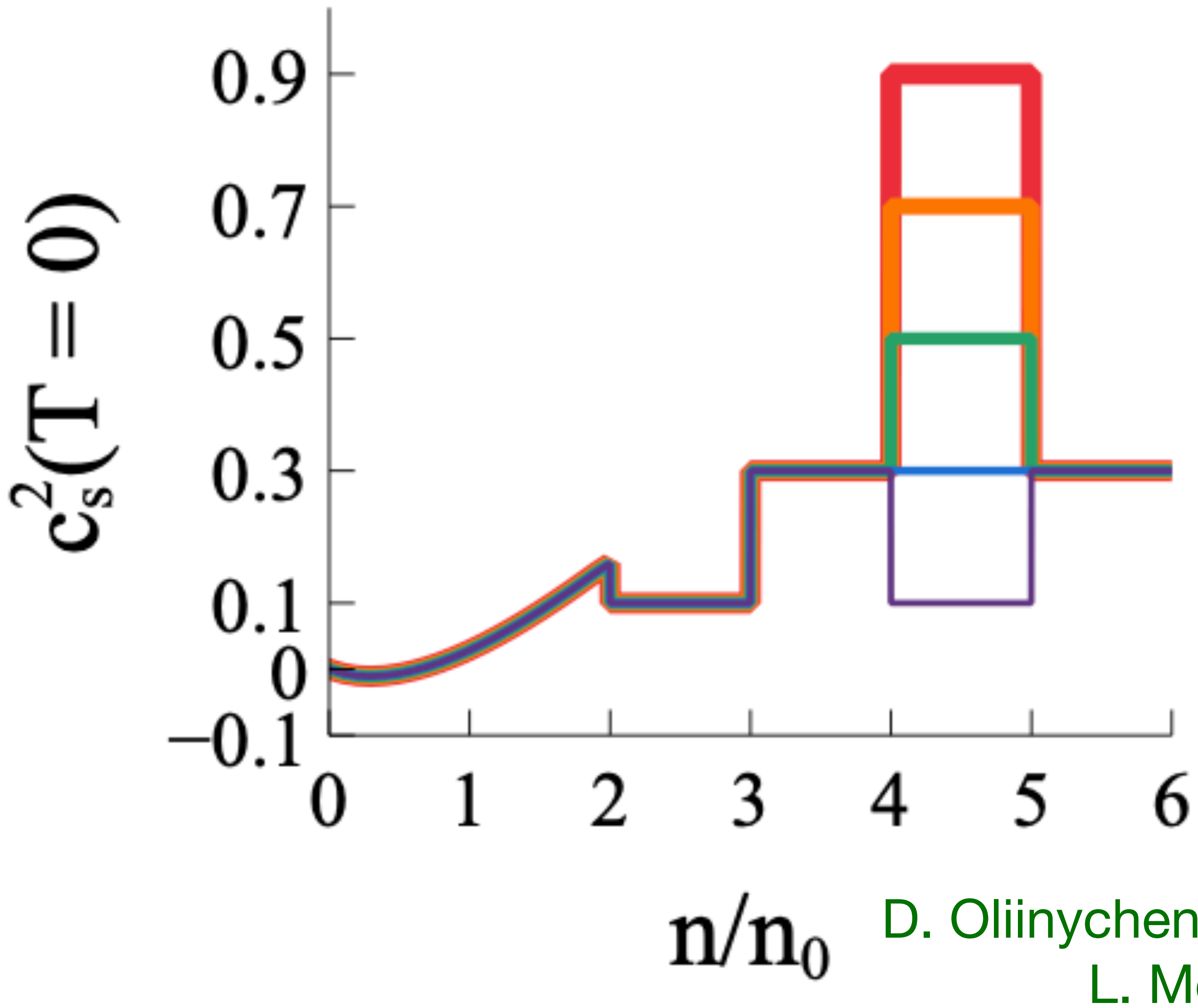


A. Sorensen, V. Koch, Phys. Rev. C **104** no. 3 (2021) 034904, arXiv:2011.06635

A. Sorensen, arXiv:2109.08105 (dissertation)

flexible momentum dependence

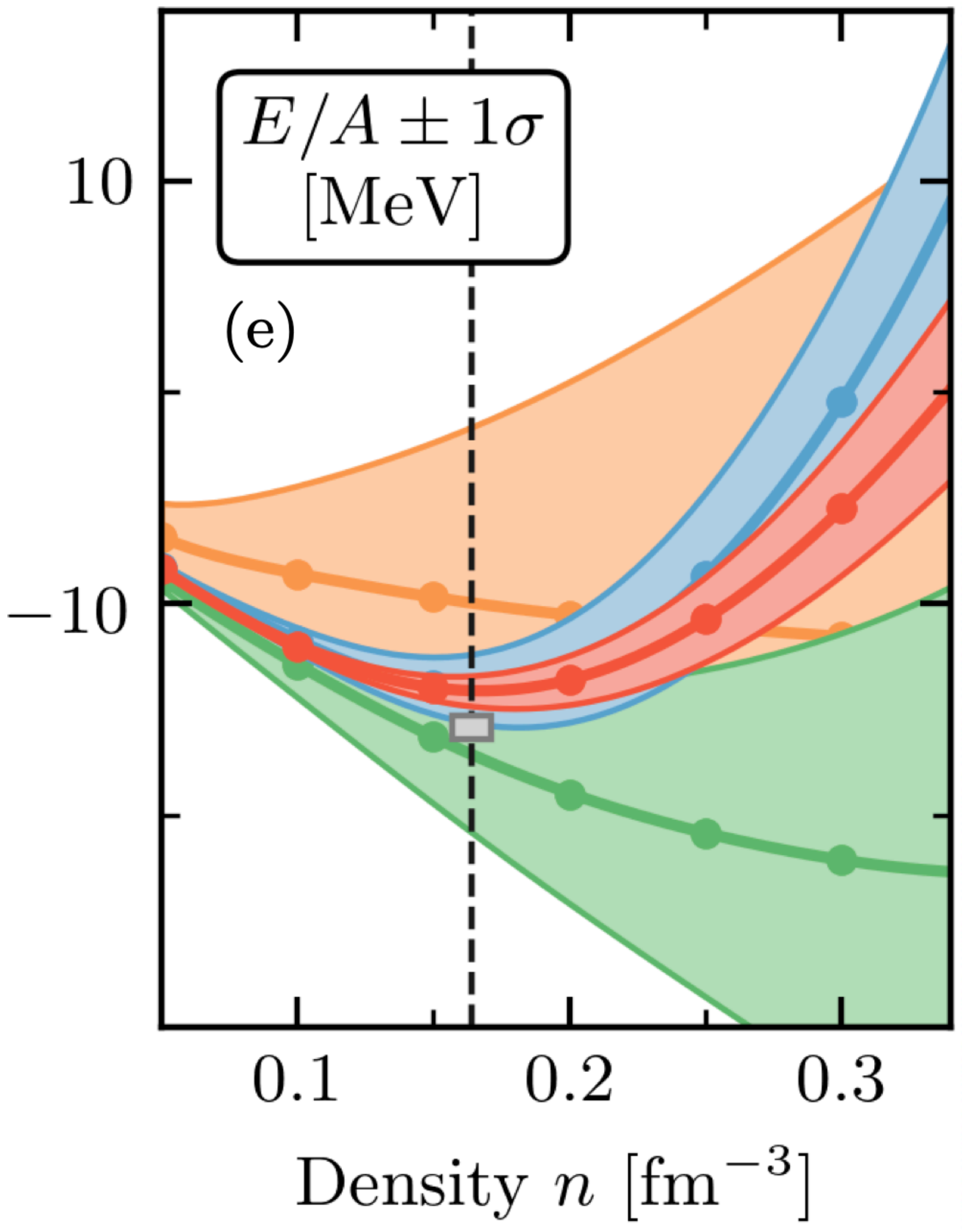
generalized VDF:
parametrization of the mean-field by varying the speed of sound *independently* in chosen density regions



D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996

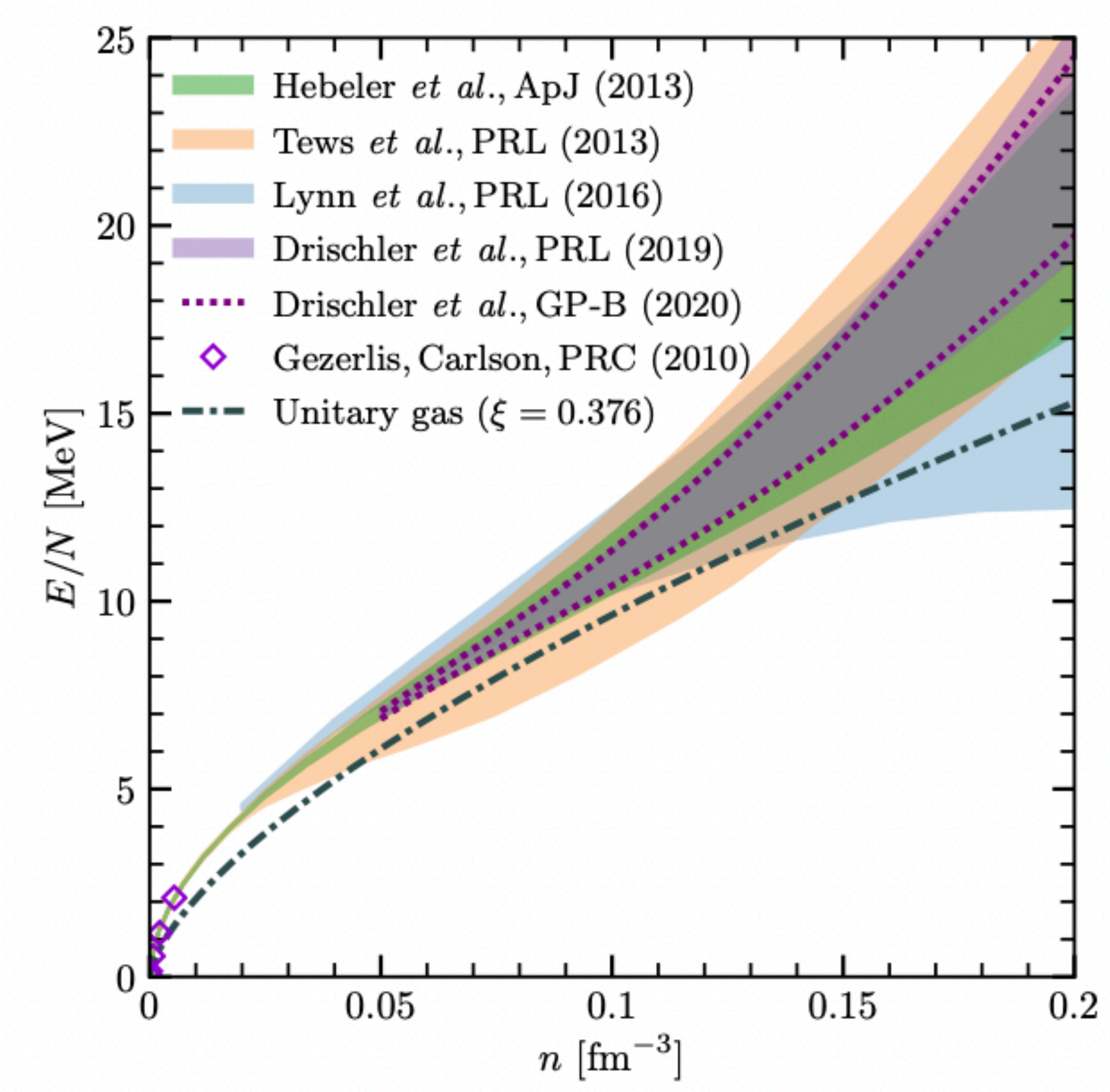
2. Better microscopic input to the EOS

- needed: single-particle potentials, in-medium interactions
- could possibly be used for consistency between the mean-field and the effective in-medium collision cross-sections



C. Drischler, R. J. Furnstahl, J. A. Melendez, D. R. Phillips, Phys. Rev. Lett. **125** 20, 202702 (2020), arXiv:2004.07232

χEFT (Section II B)



S. Huth, C. Wellenhofer, A. Schwenk, Phys. Rev. C **103** 2, 025803 (2021), arXiv:2009.08885

Program to improve transport model simulations (Section II A)

3. Treatment of fluctuations

- BUU: Langevin extension of the BUU equation
- importance for intermediate mass fragments (produced in, e.g., spinodal fluctuations)

4. Treatment of correlations (beyond mean-field)

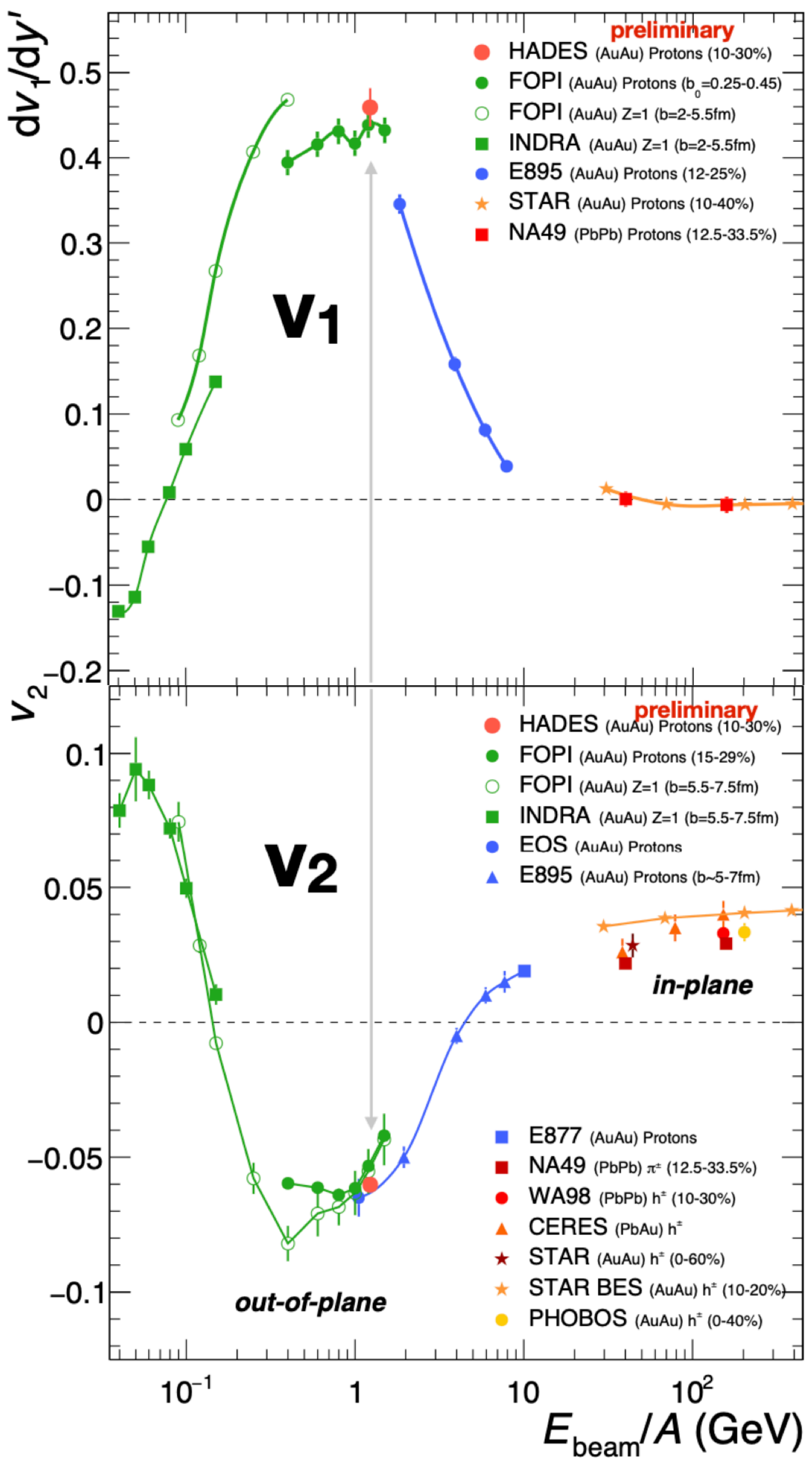
- Light clusters (LCs): deuterons, tritons, helium nuclei…
- in-medium properties of LCs are not well known
- e.g., in SMASH production occurs through a fictitious d' resonance
  $NN \leftrightarrow d'$, $Nd' \leftrightarrow Nd$ (effectively nucleon catalysis $N\,N\,N \leftrightarrow N\,d$)
  $NN \leftrightarrow d'$, $\pi d' \leftrightarrow \pi d$ (effectively pion catalysis $\pi N\,N \leftrightarrow \pi d$)
  $N\,N \leftrightarrow \pi d$

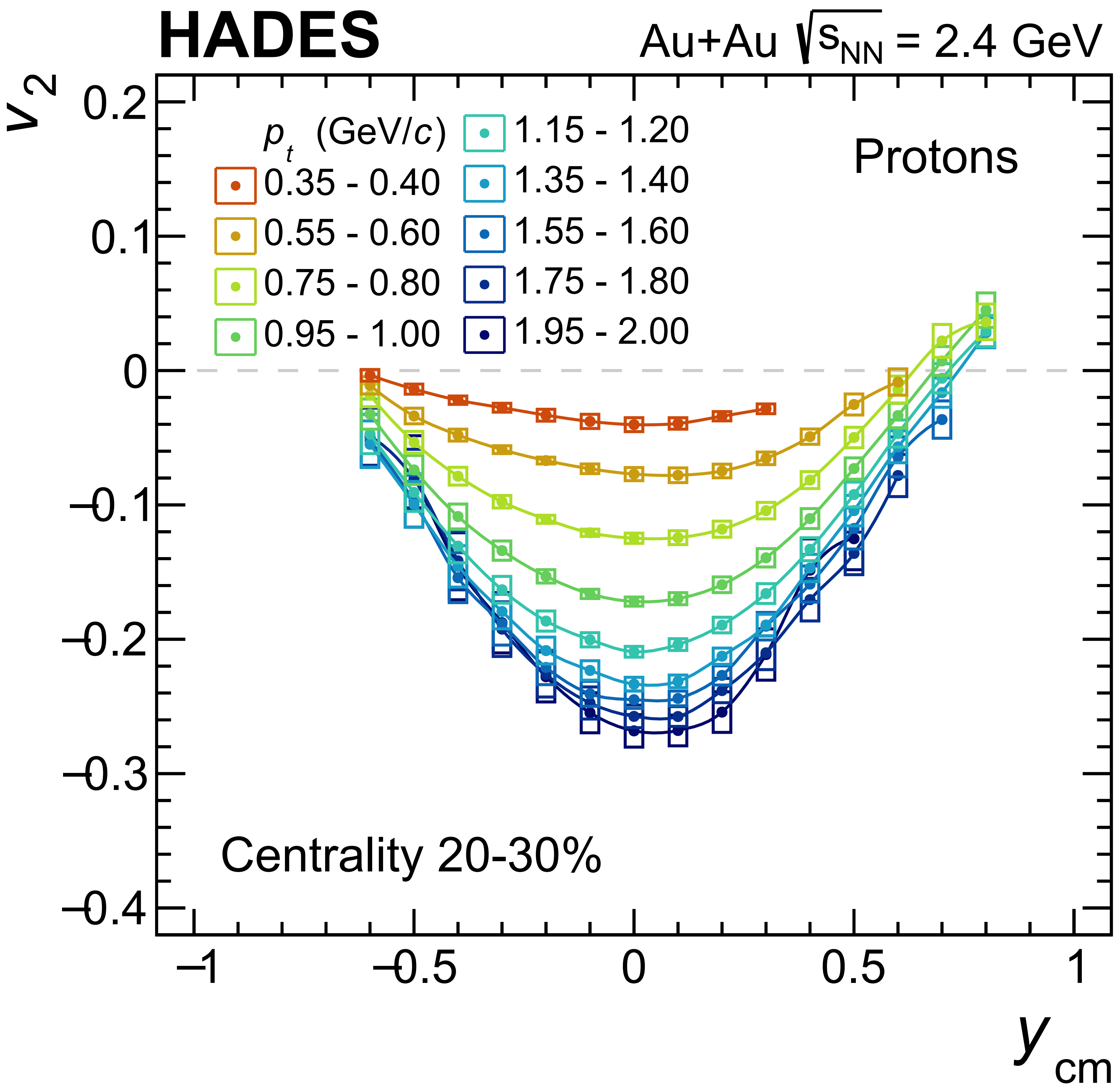
Program to improve transport model simulations (Section II A)

5. New observables, e.g:

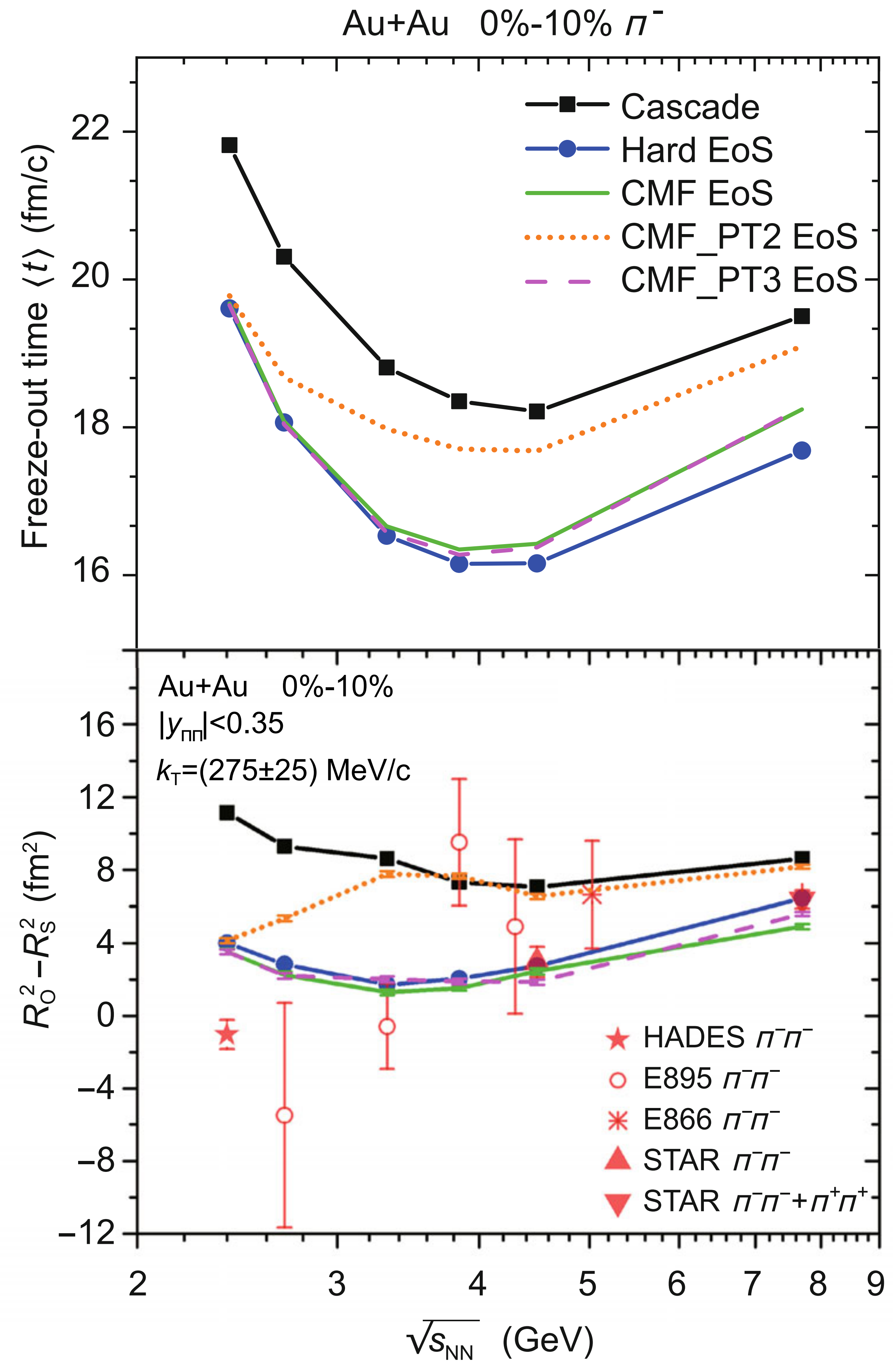
(also Sections III A,B)

- triple-differential flow observables
- HBT correlations





J. Adamczewski-Musch *et al*. (HADES), arXiv:2208.02740



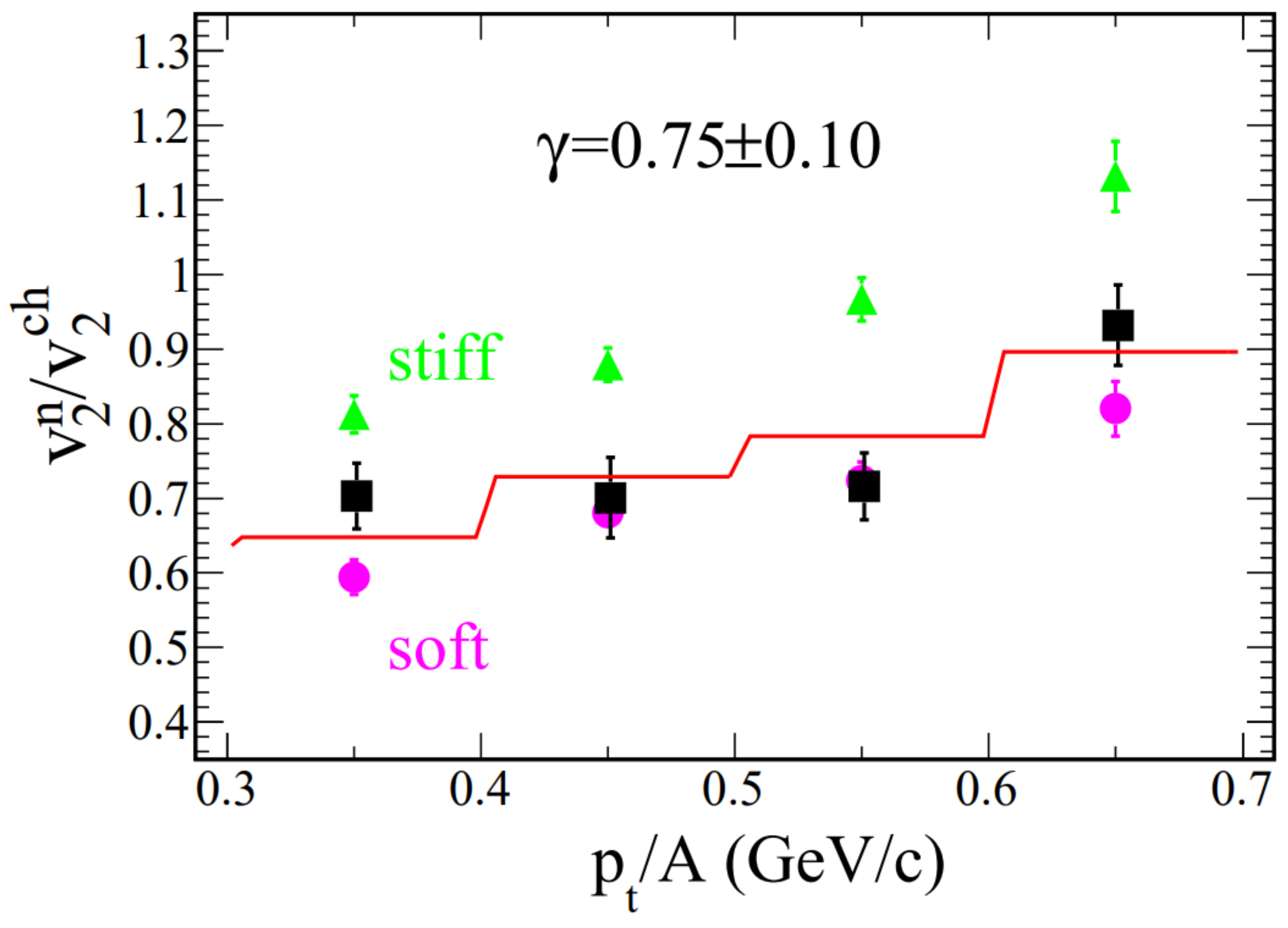
P. Li, J. Steinheimer, T. Reichert, A. Kittiratpattana, M. Bleicher, and Q. Li, Sci. China Phys. Mech. Astron. 66, 232011 (2023), arXiv:2209.01413

Program to improve transport model simulations (Section II A)

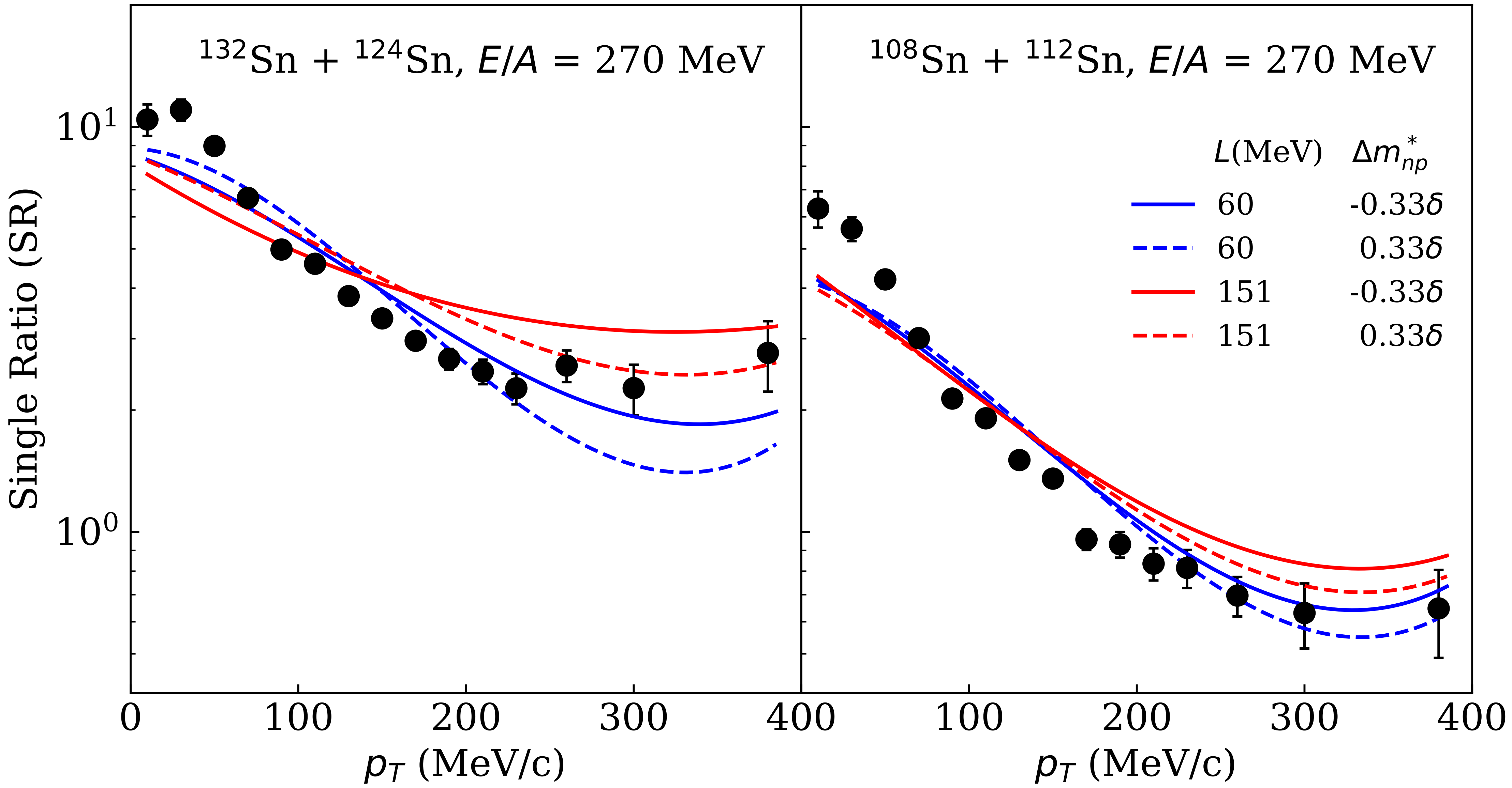
5. New observables, e.g:

(also Sections III A,B)

- larger isospin asymmetries available at FRIB
- new observables at high energies?

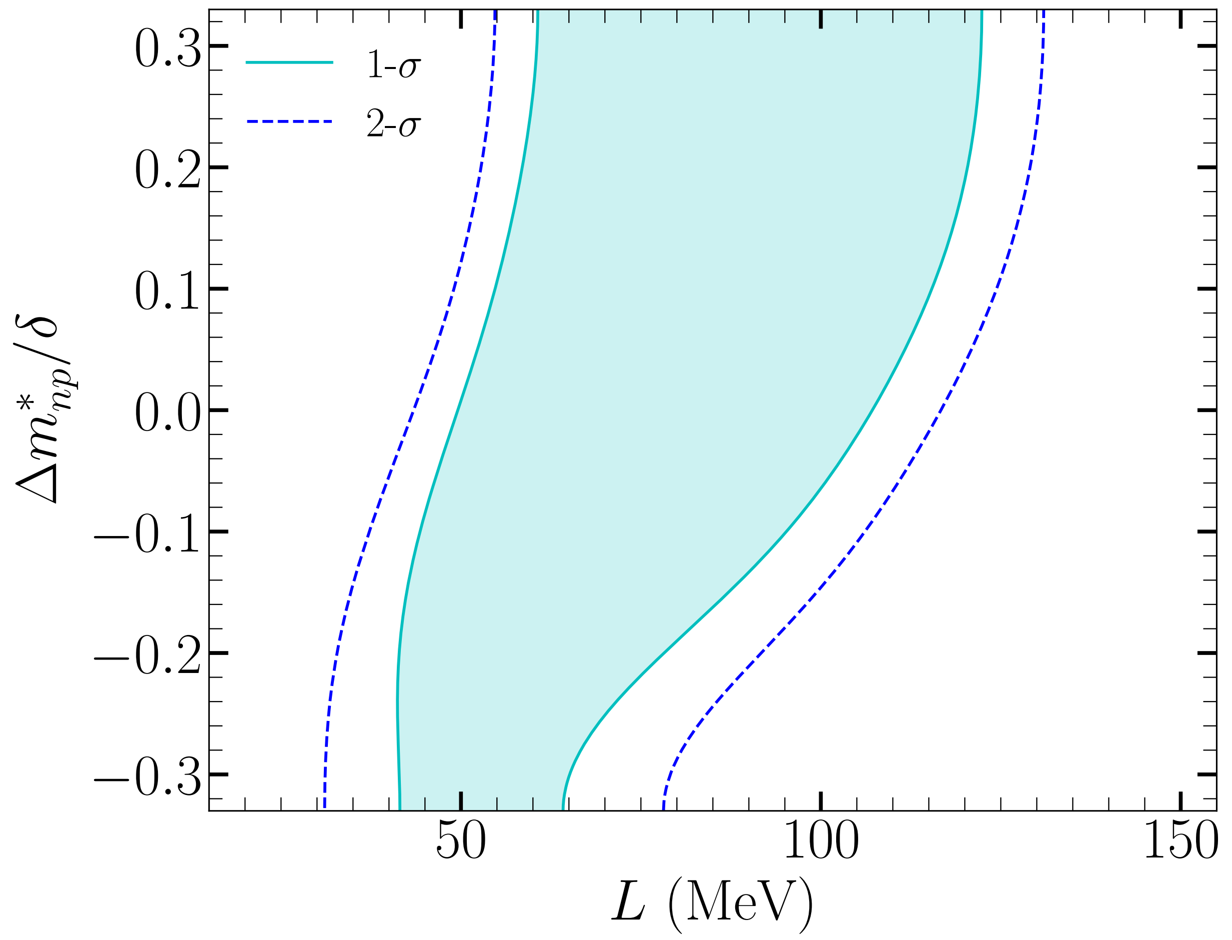


P. Russotto *et al.*, Phys. Rev. C **94**, 034608 (2016), arXiv:1608.04332



M. D. Cozma and M. B. Tsang, Eur. Phys. J. A **57**, 309 (2021), arXiv:2101.08679

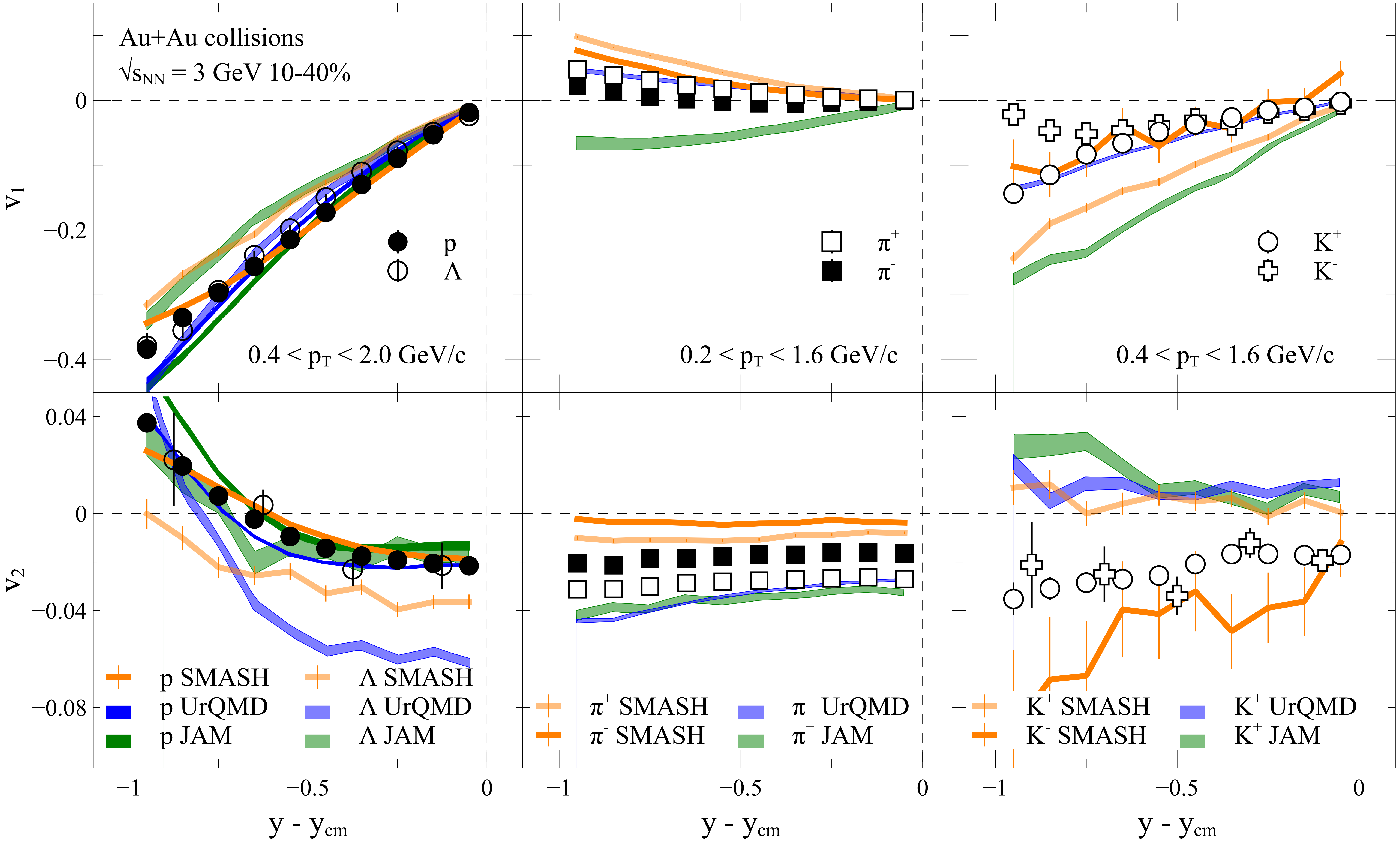
J. Estee et al. (SπRIT), Phys. Rev. Lett. **126**, 162701 (2021), arXiv:2103.06861



Program to improve transport model simulations (Section II A)

6. Describing *multiple* observables at the same time

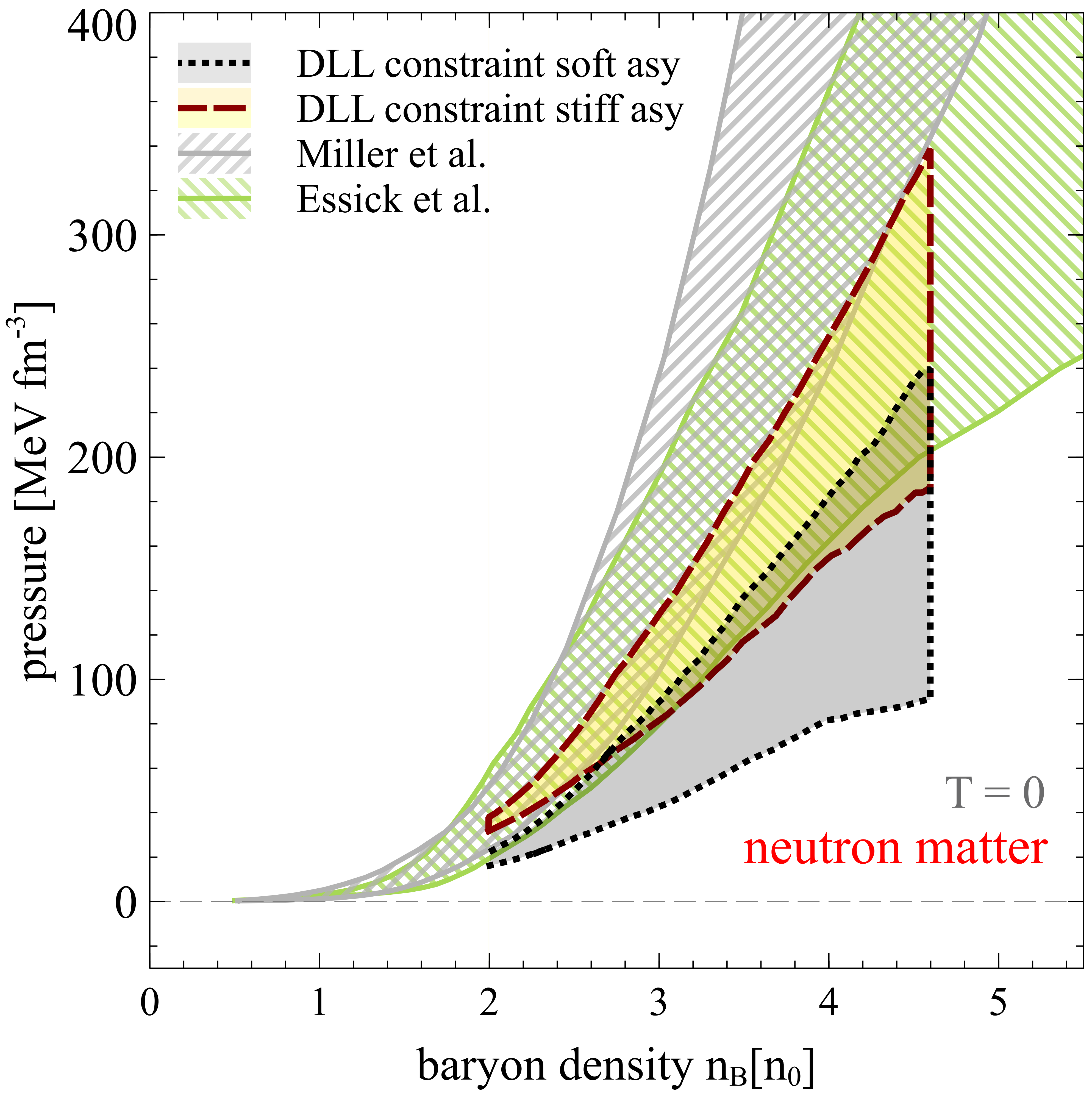
(also Section III A)



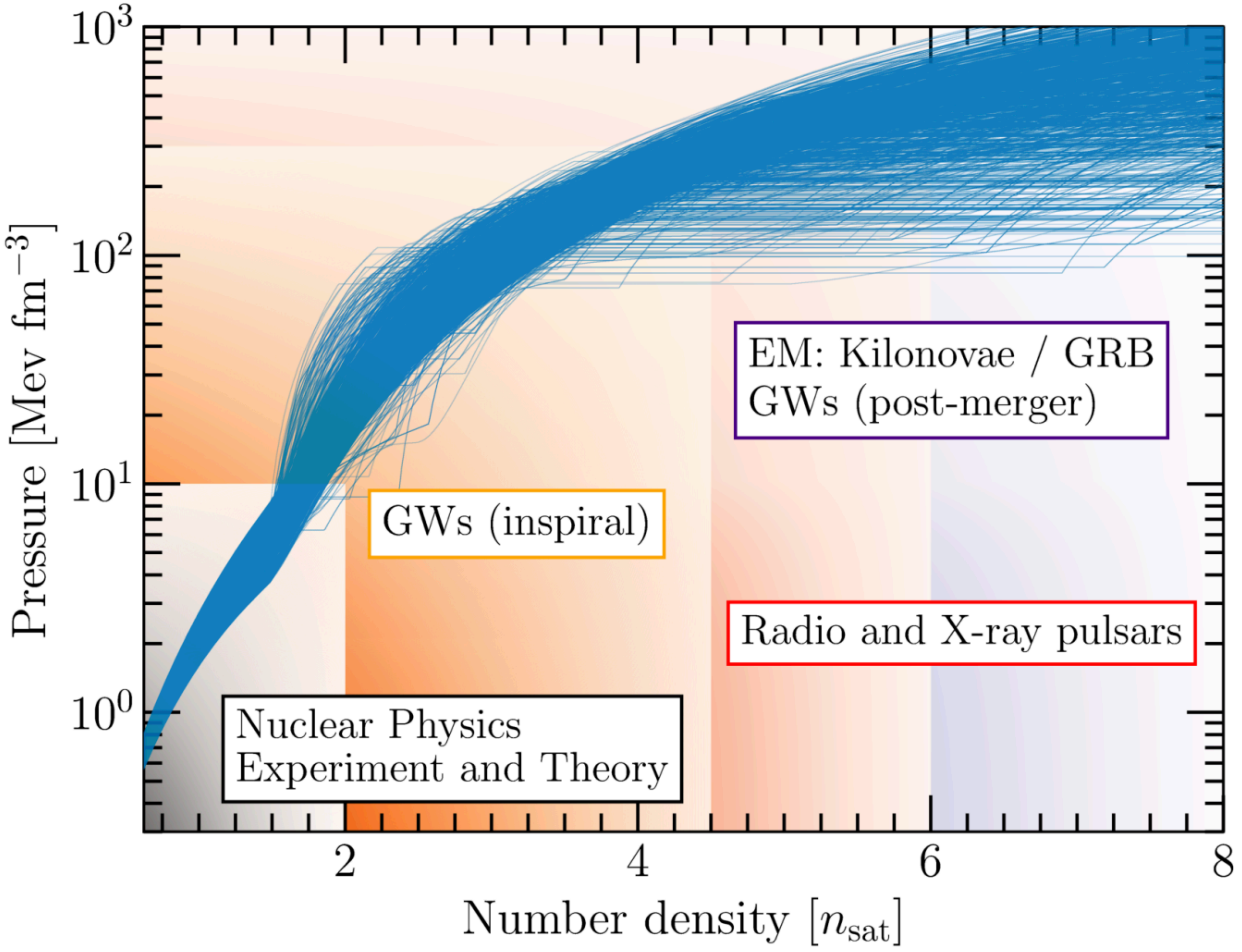
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996

A. Sorensen *et al.*, arXiv:2301.13253

Common interest with neutron star studies (Section II C)



P. Danielewicz, R. Lacey, and W. G. Lynch,
Science **298**, 1592 (2002), arXiv:nucl-th/0208016



P. T. H. Pang et al., (2022), arXiv:2205.08513

Significant potential in exploring global analyses (Section IV)

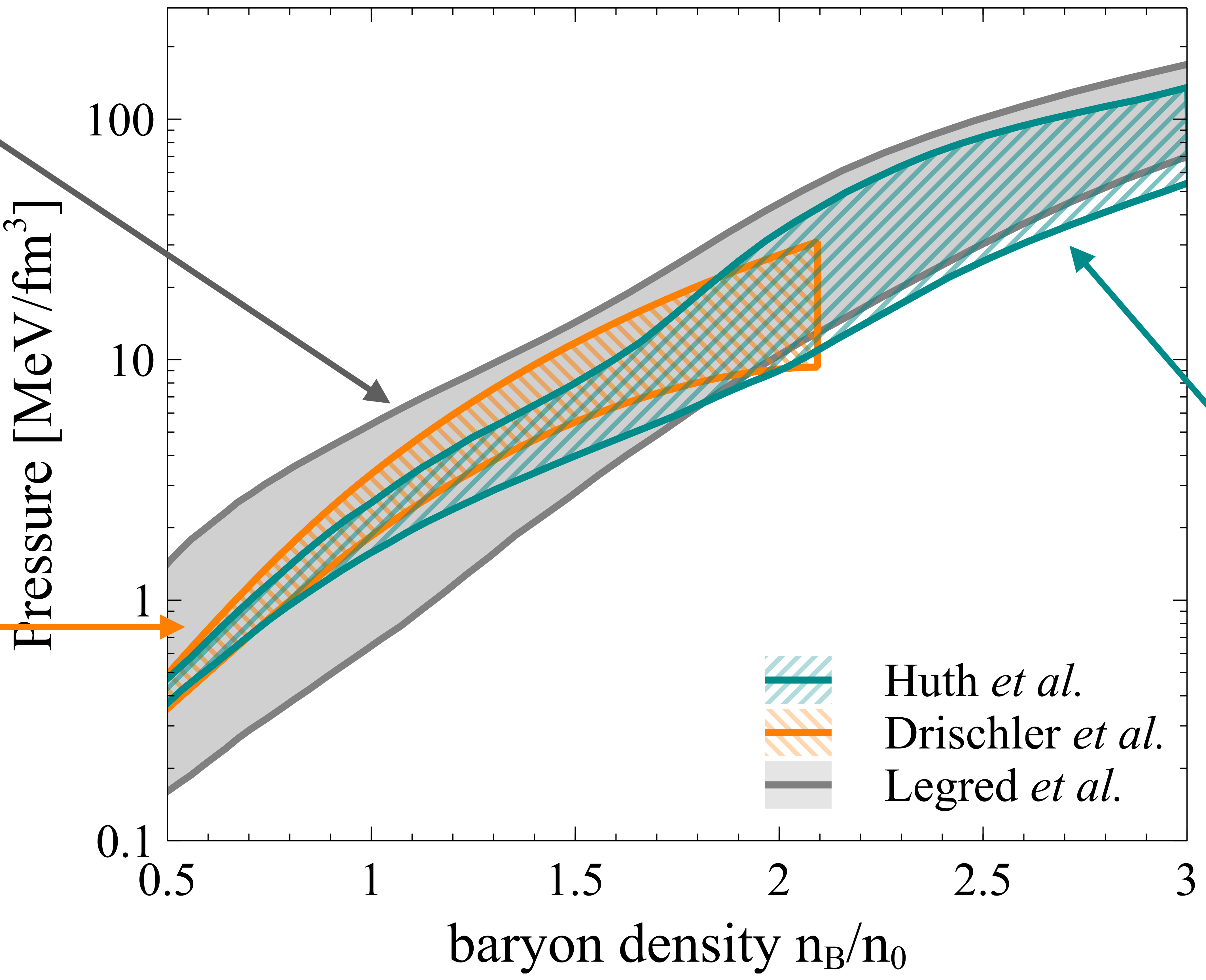
Constraints using multiple inputs (nuclear structure, heavy-ion collisions, neutron stars) are tight

nonparametric EOS inference based on Gaussian processes
combines information from X-ray, radio, and gravitational wave observations of neutron stars.

I. Legred, K. Chatziioannou, R. Essick, S. Han, and P. Landry, Phys. Rev. D **104**, 063003 (2021), arXiv:2106.05313

Bayesian analysis of correlated effective field theory truncation errors based on order-by-order calculations up to next-to-next-to-next-to-leading order in the χEFT expansion

C. Drischler, S. Han, J. M. Lattimer, M. Prakash, S. Reddy, and T. Zhao, Phys. Rev. C **103**, 045808 (2021), arXiv:2009.06441



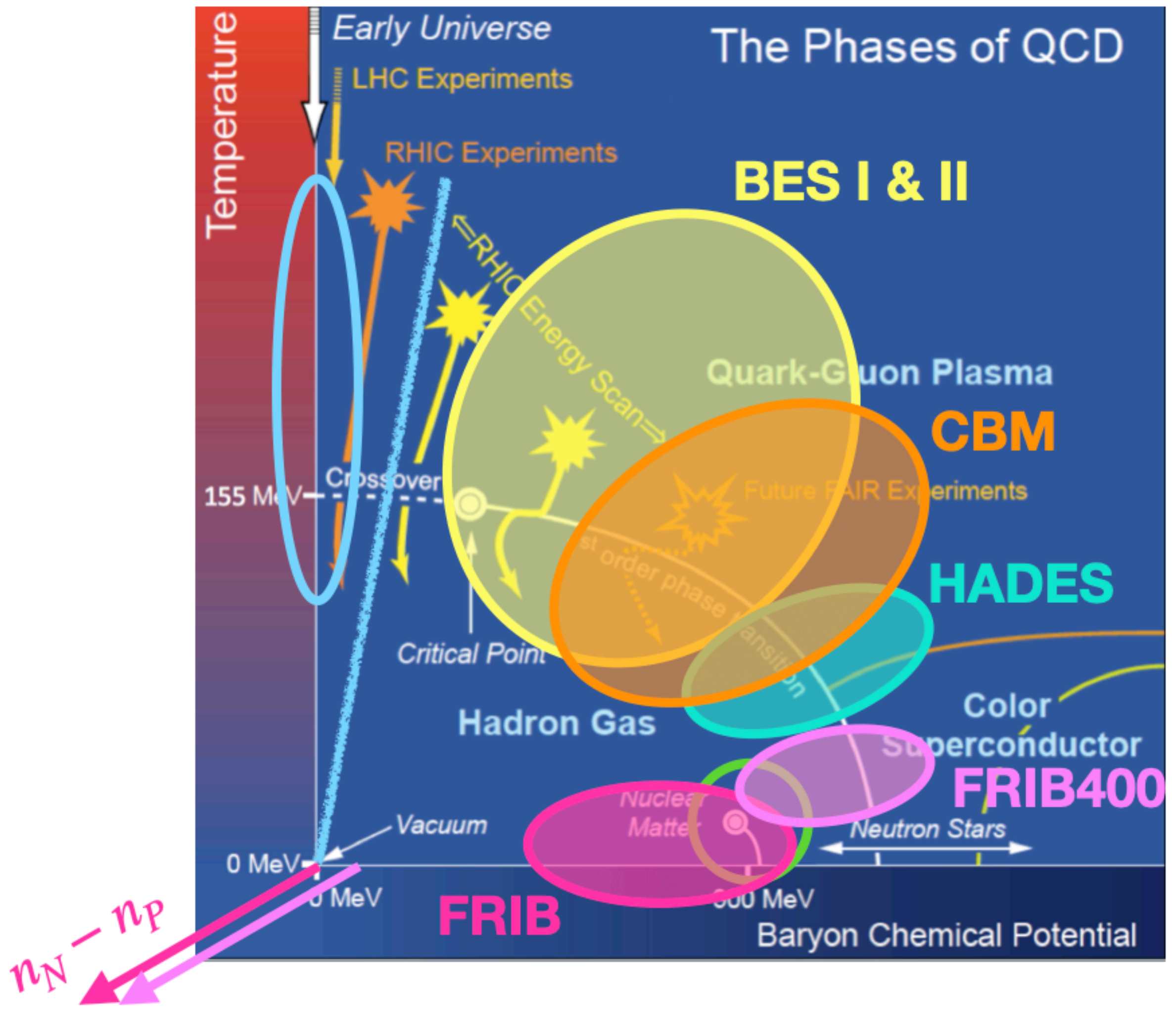
A. Sorensen *et al.*, arXiv:2301.13253

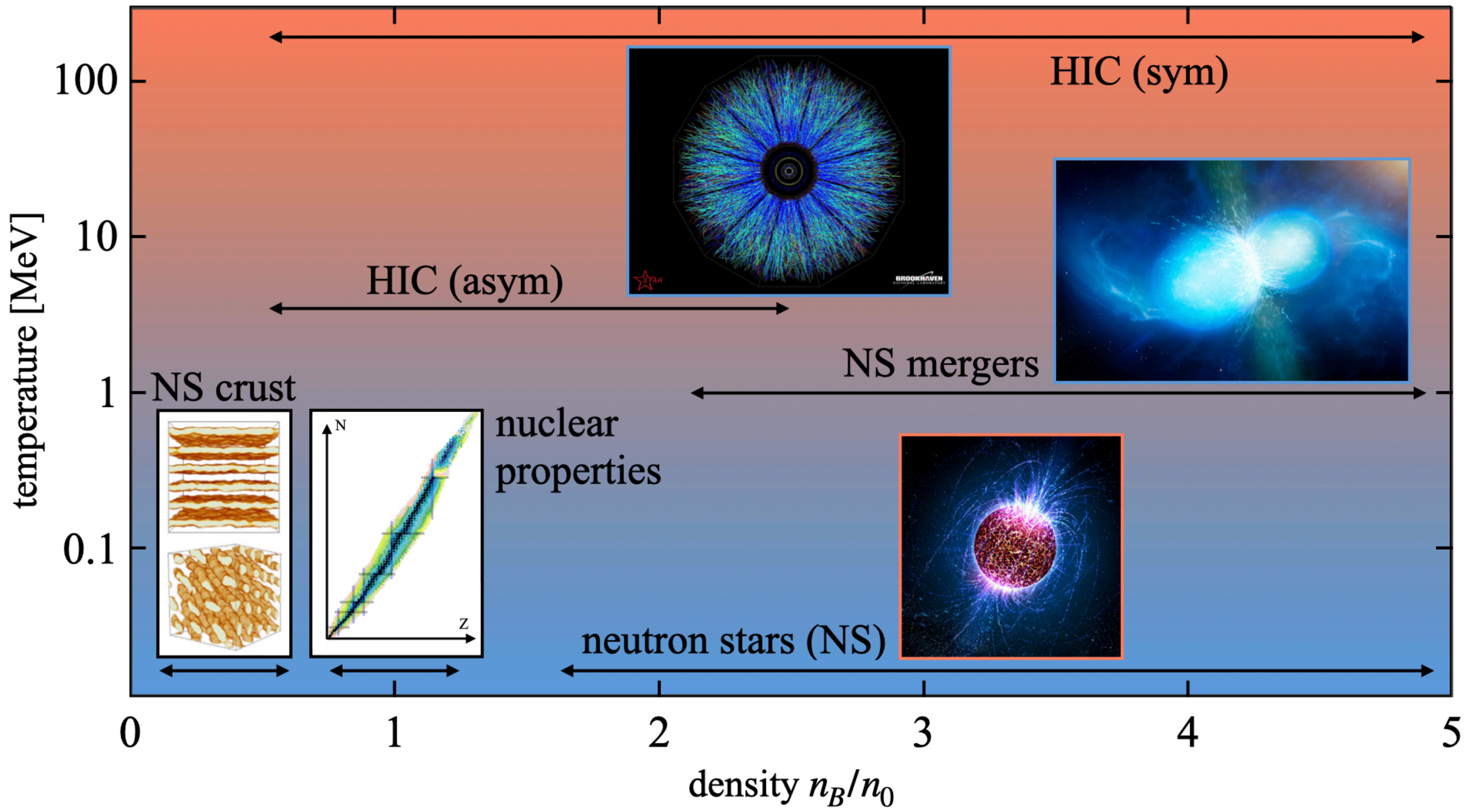
combined nuclear theory via χEFT calculations (constraining the EOS below 1.5n0), EOS inferences from heavy-ion collisions from FOPI and ASY-EOS experiments, and astrophysical data on bulk neutron star properties

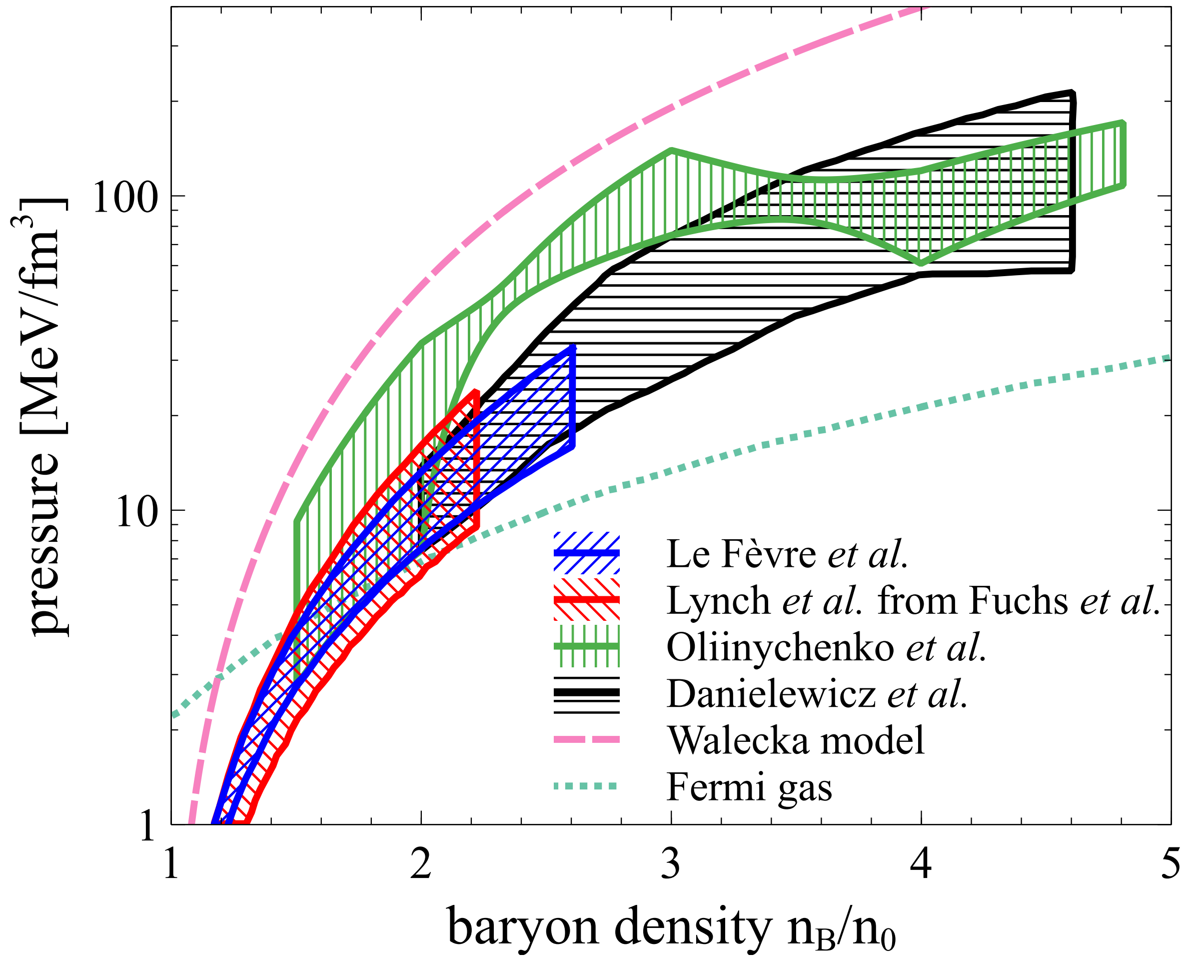
S. Huth et al., Nature **606**, 276 (2022), arXiv:2107.06229

Summary

- Analyses of hadronic transport simulations of heavy-ion collisions at intermediate energies can put tight constraints on the dense nuclear matter EOS
- Improvements are needed for the treatment of microscopic interactions, fluctuations, threshold effects, … etc. Tests of models are necessary!
- BES-II, HADES, CBM, FRIB, FRIB400, … *need* state-of-the-art hadronic transport to fully utilize their potential to constrain the EOS







Thank you for your attention