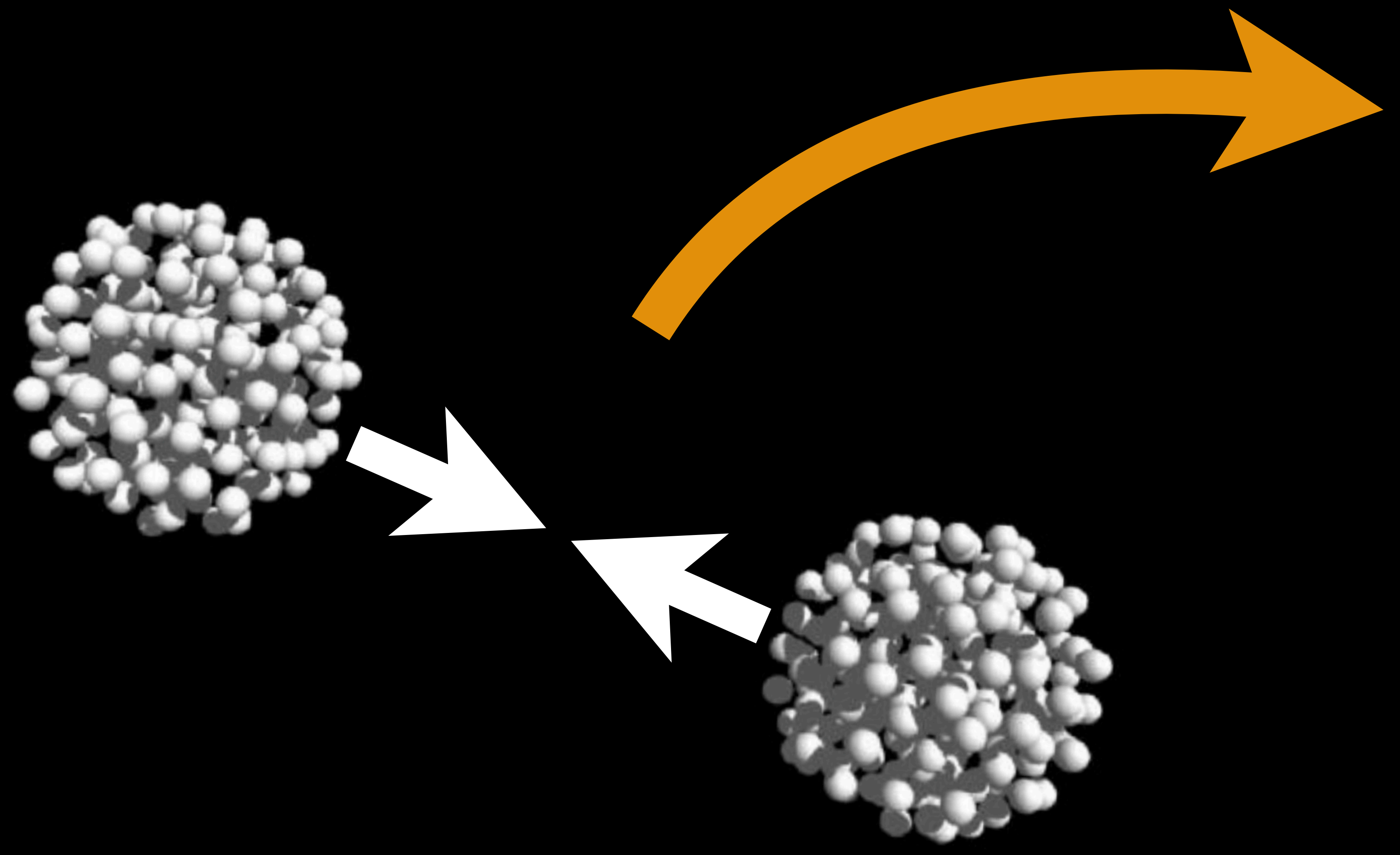
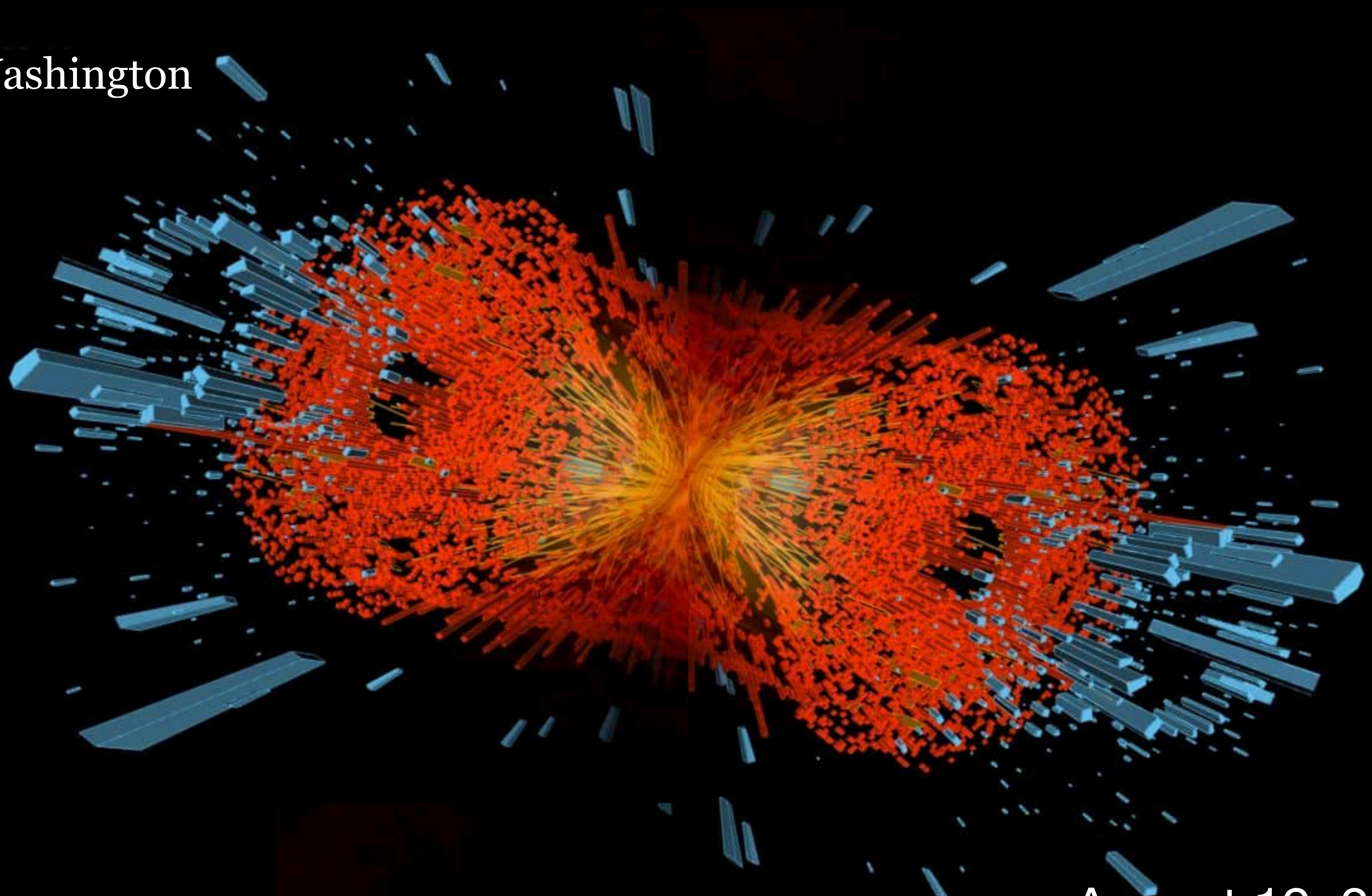
Extracting properties of dense nuclear matter from heavy-ion collisions

Agnieszka Sorensen

Institute for Nuclear Theory, University of Washington

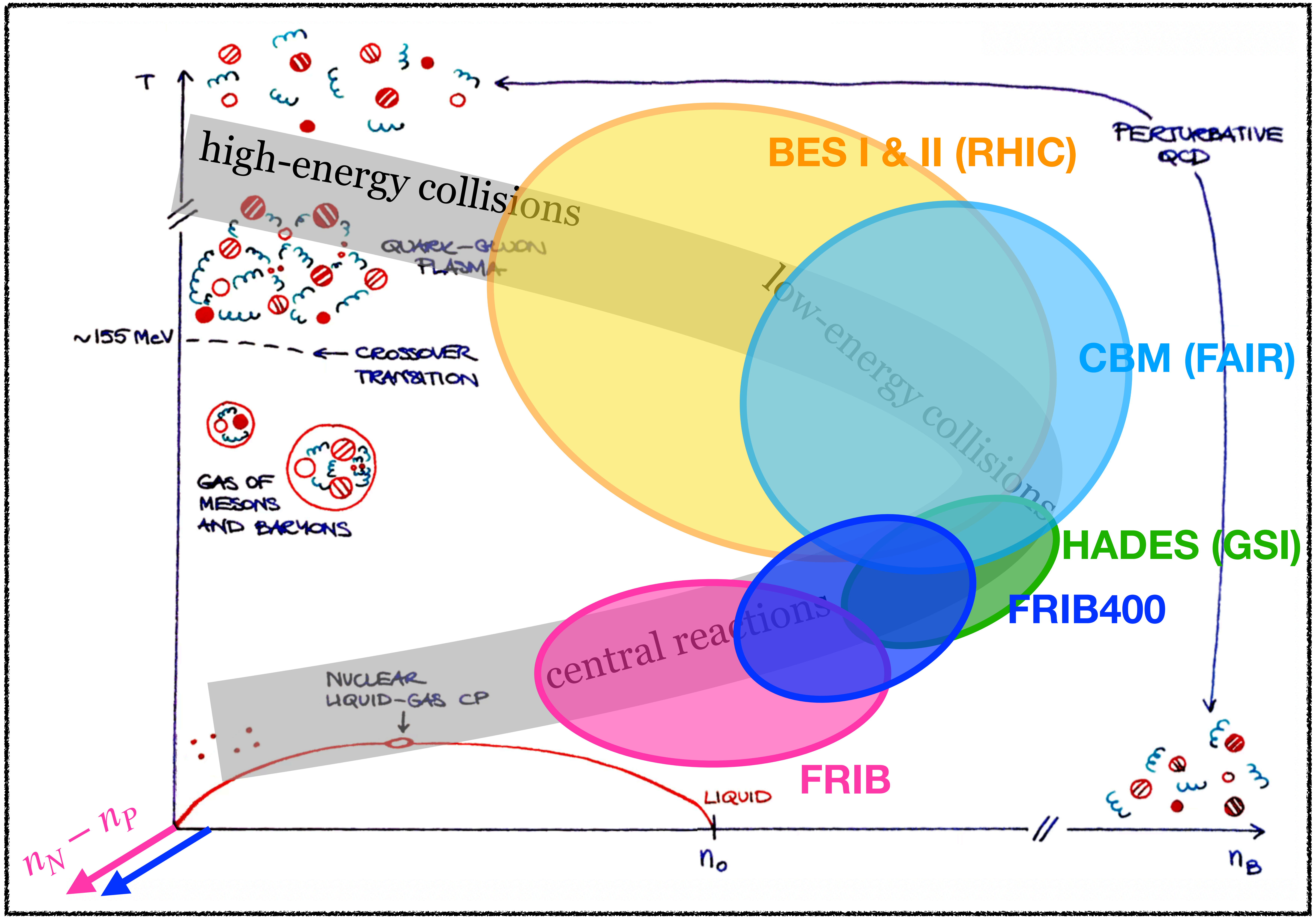




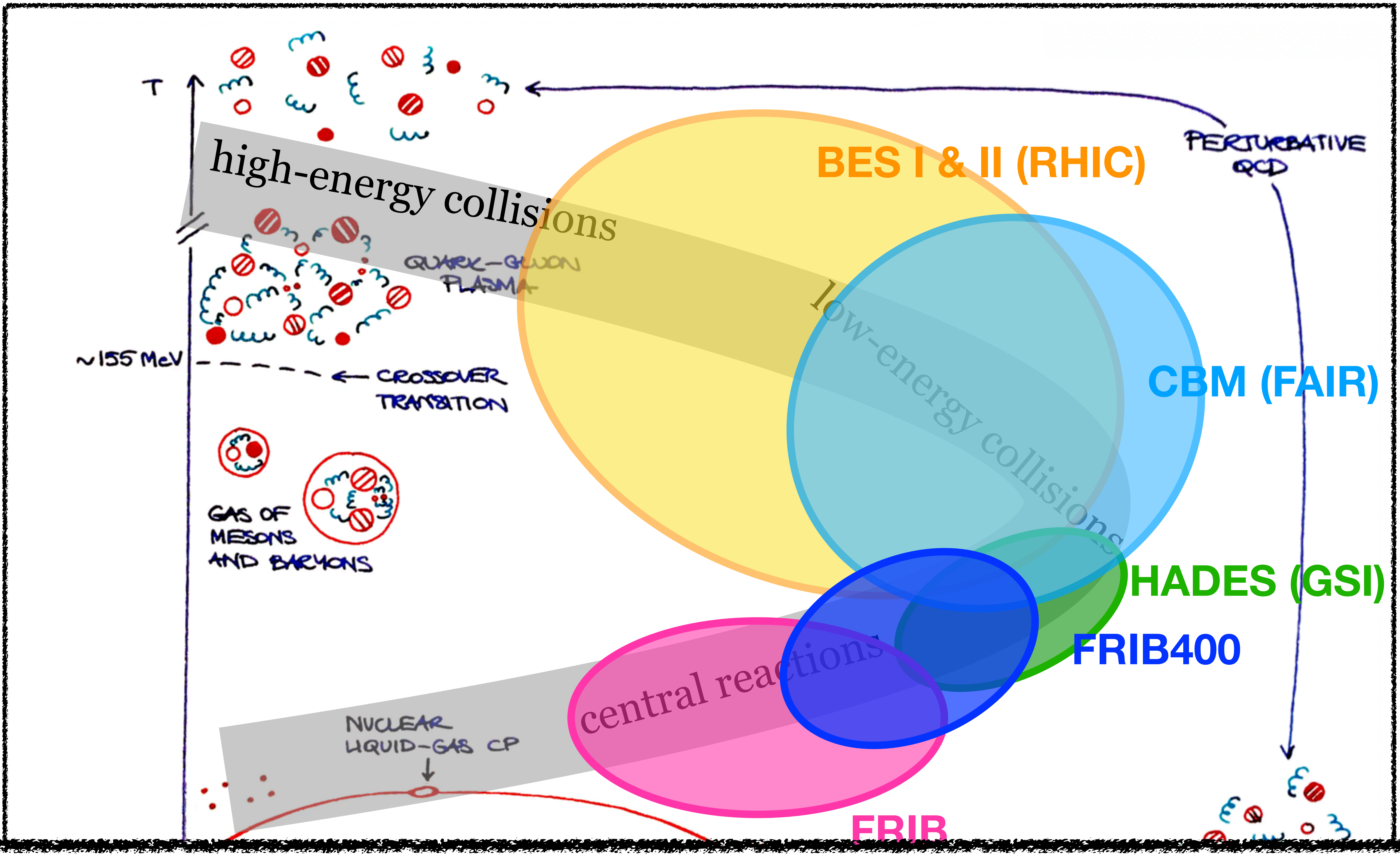
August 19, 2024

14th International Conference on Nucleus-Nucleus Collisions

Heavy-ion collisions = window on properties of dense nuclear matter



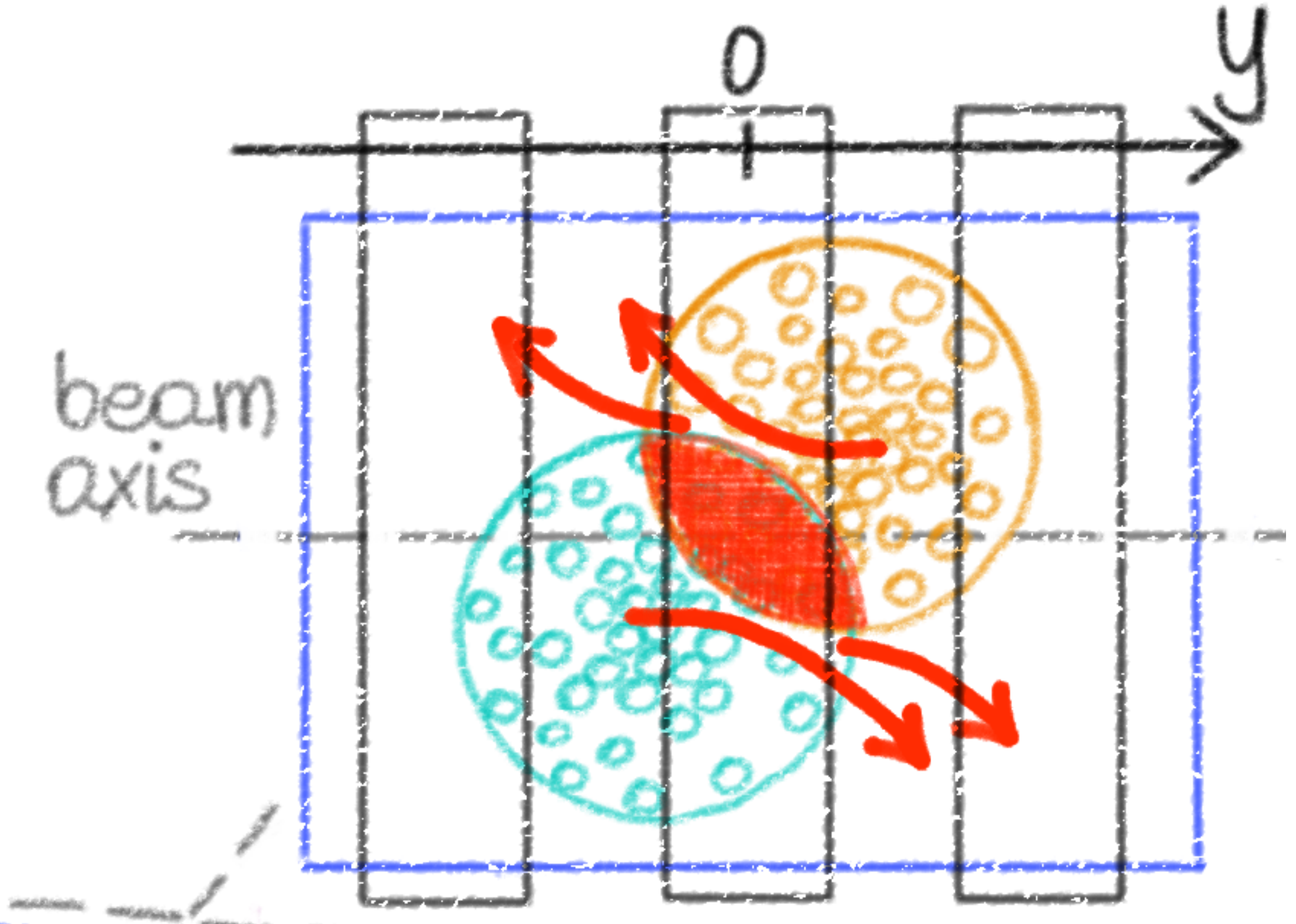
Heavy-ion collisions = window on properties of dense nuclear matter

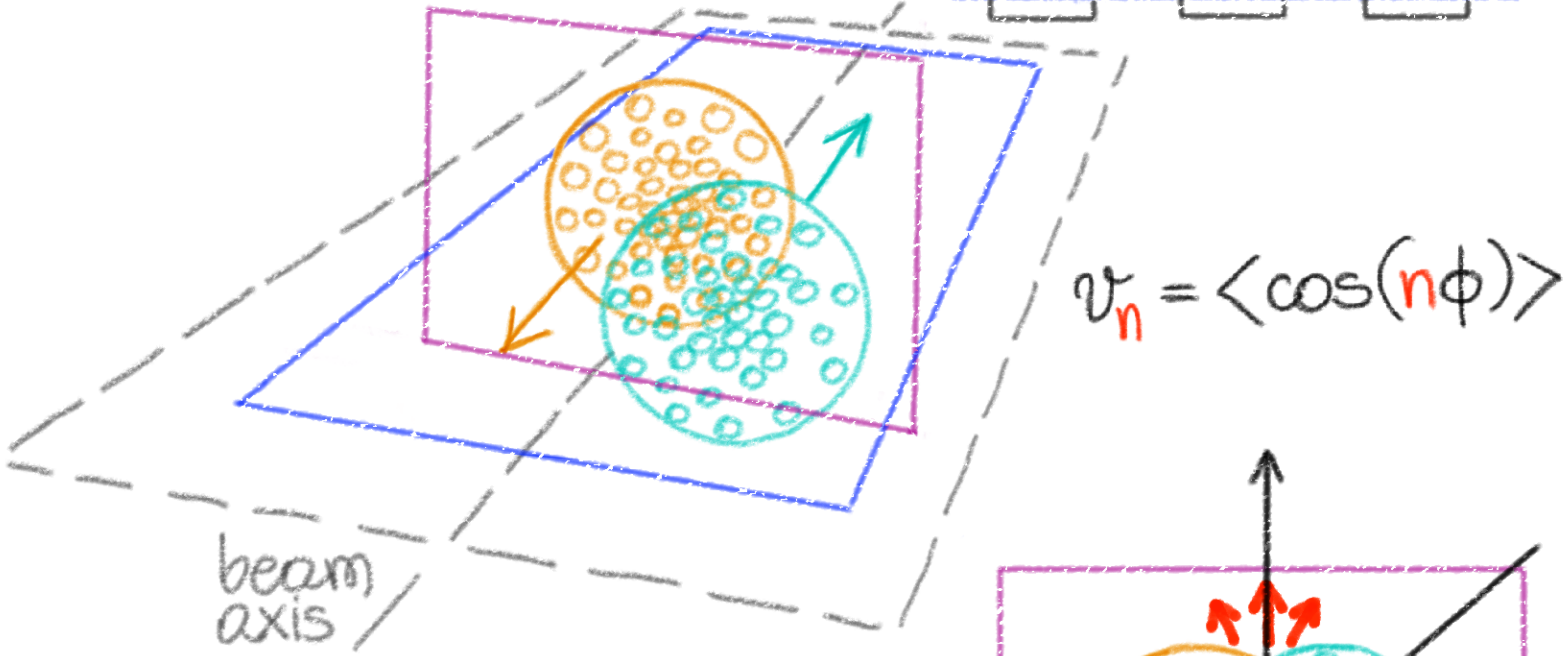


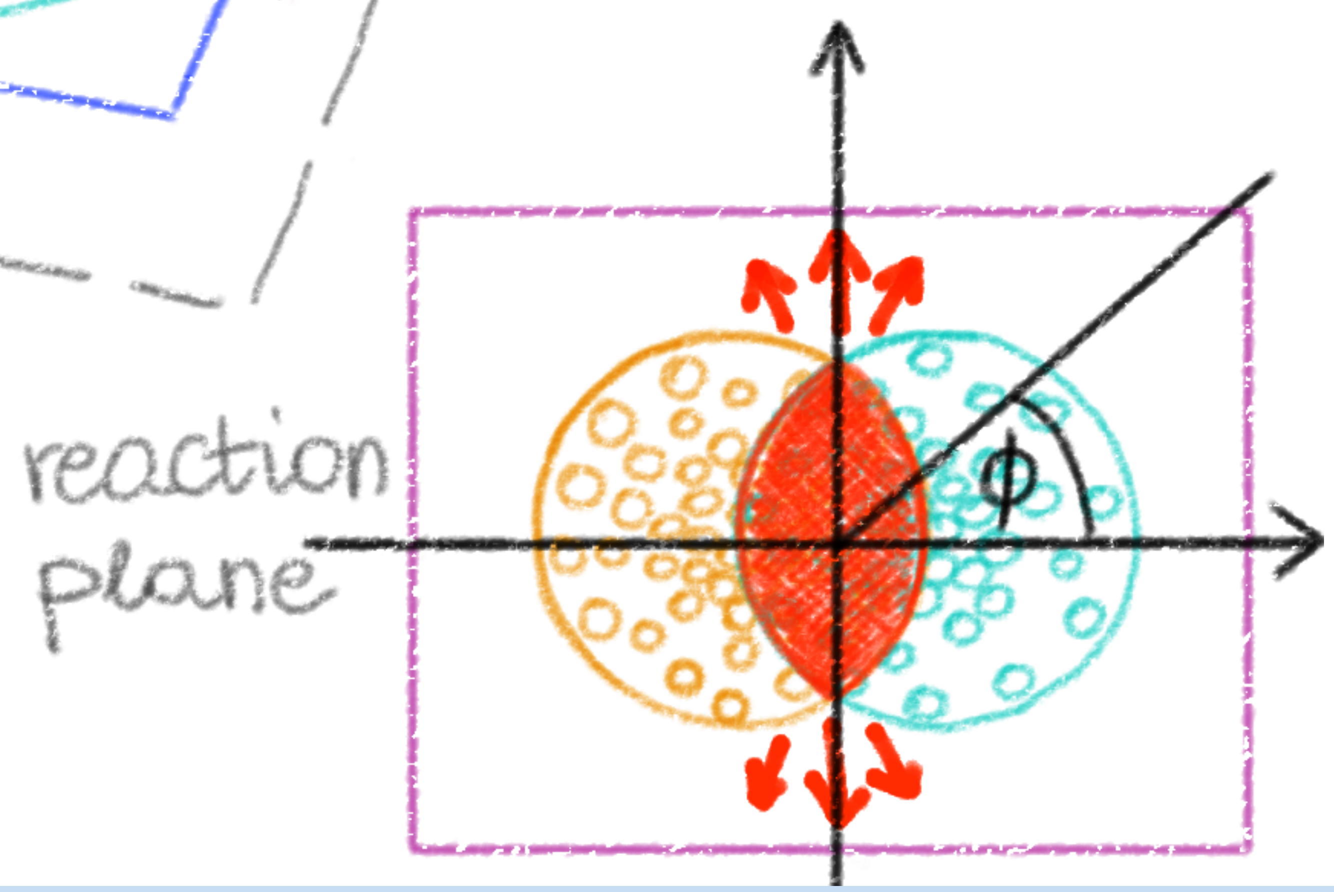
- HICs = the **only** means to probe densities above n_0 in controlled terrestrial experiments

Sketch of a heavy-ion collision evolution and development of flow

** the sketch is informative but not highly realistic*







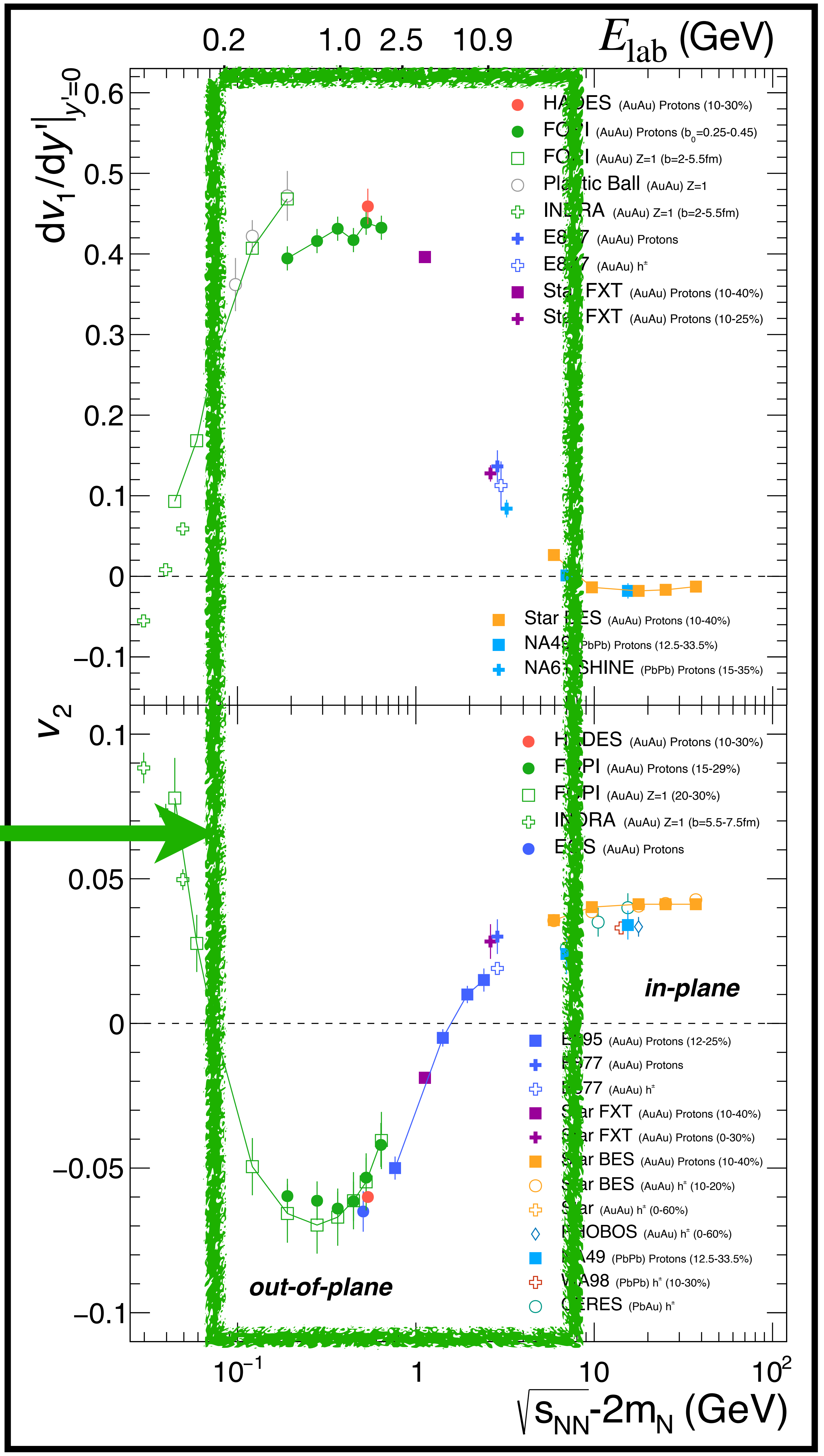
L. Du, **A. Sorensen**, M. Stephanov, Int. J. Mod. Phys. E (available online), arXiv: 2402.10183

J. Adamczewski-Musch *et al.* (HADES), Eur.Phys.J.A 59 (2023) 4, 80, arXiv:2208.02740

v_1 = directed flow

v_2 = elliptic flow

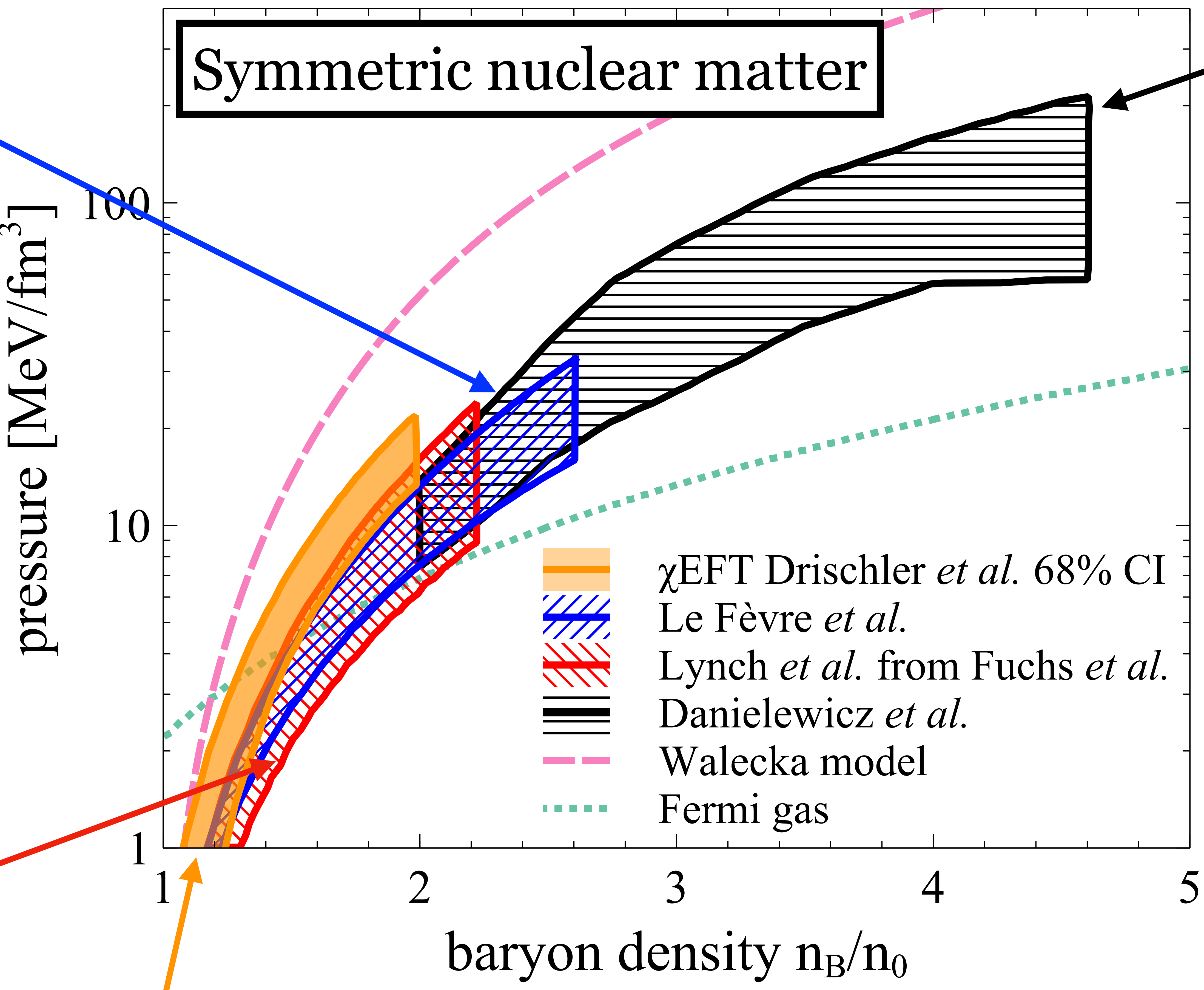
Experiments:
FRIB & FRIB400,
BES FXT,
HADES, CBM, …



Constraints on the EOS come from comparisons to transport models

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

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



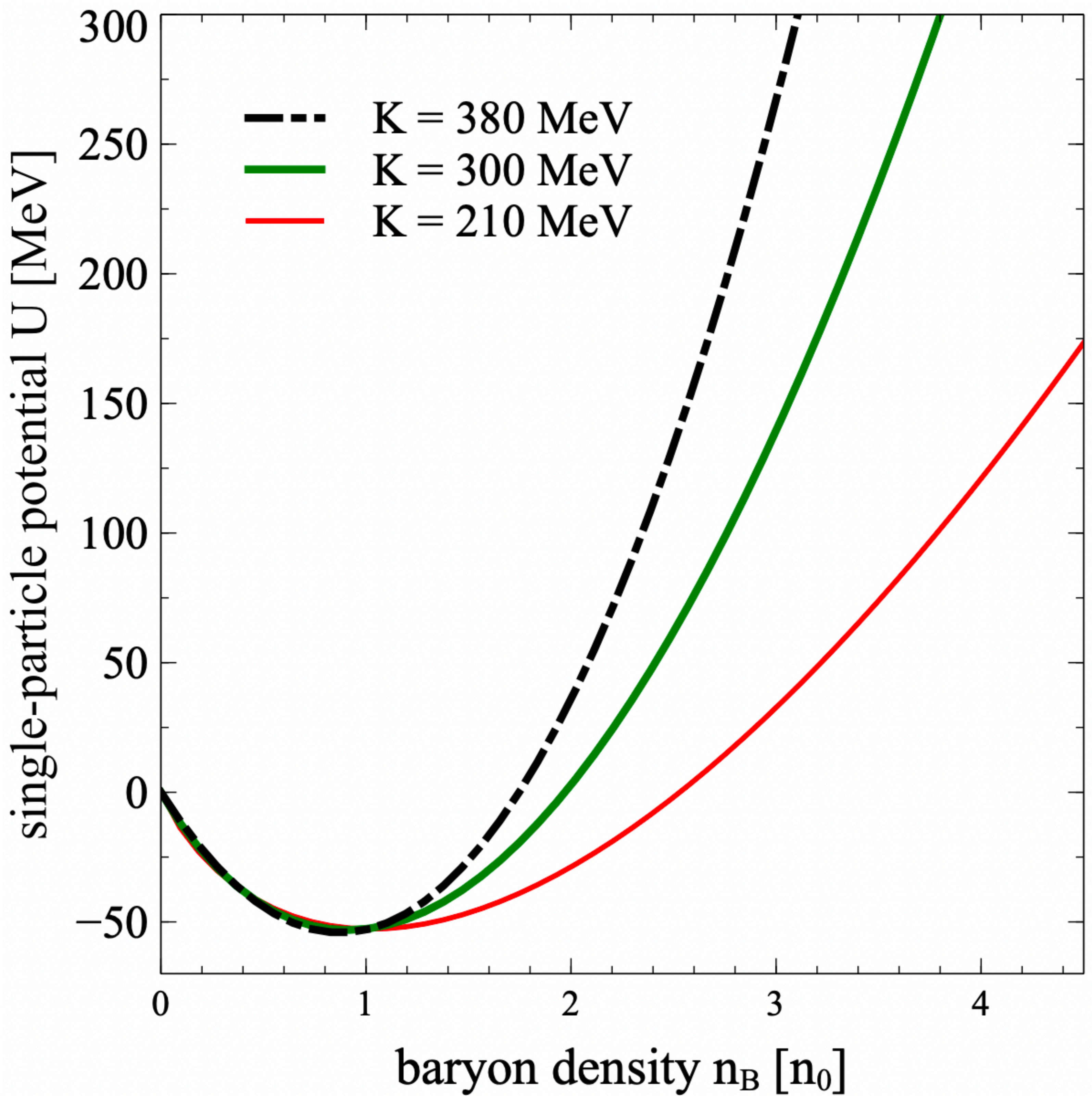
197Au+197Au @ 0.15—10 GeV/u
($\sqrt{s_{NN}}$ = 1.95 — 4.72 GeV)
observables: proton flow
(Plastic Ball, EOS, E877, E895)
model used: **pBUU** w/ nucleons, Δ, N*(1440), pions;
EOS parametrized by K_0;
momentum dependence
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024)
arXiv:2301.13253

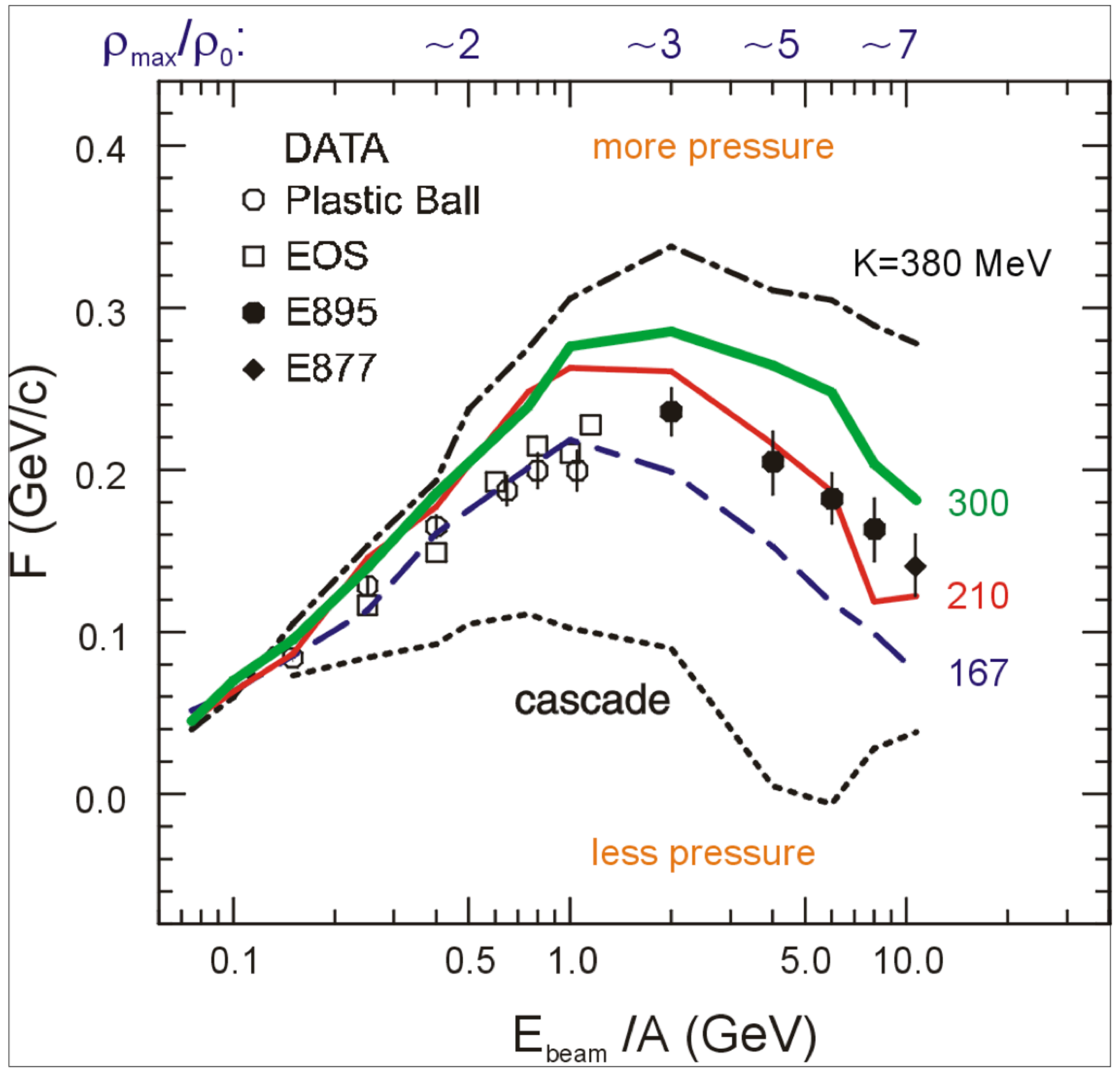
*χ*EFT
C. Drischler *et al.*, Phys. Rev. C **102** 5, 054315 (2020)
arXiv:2004.07805

Standard way of modeling the EOS: Skyrme potential

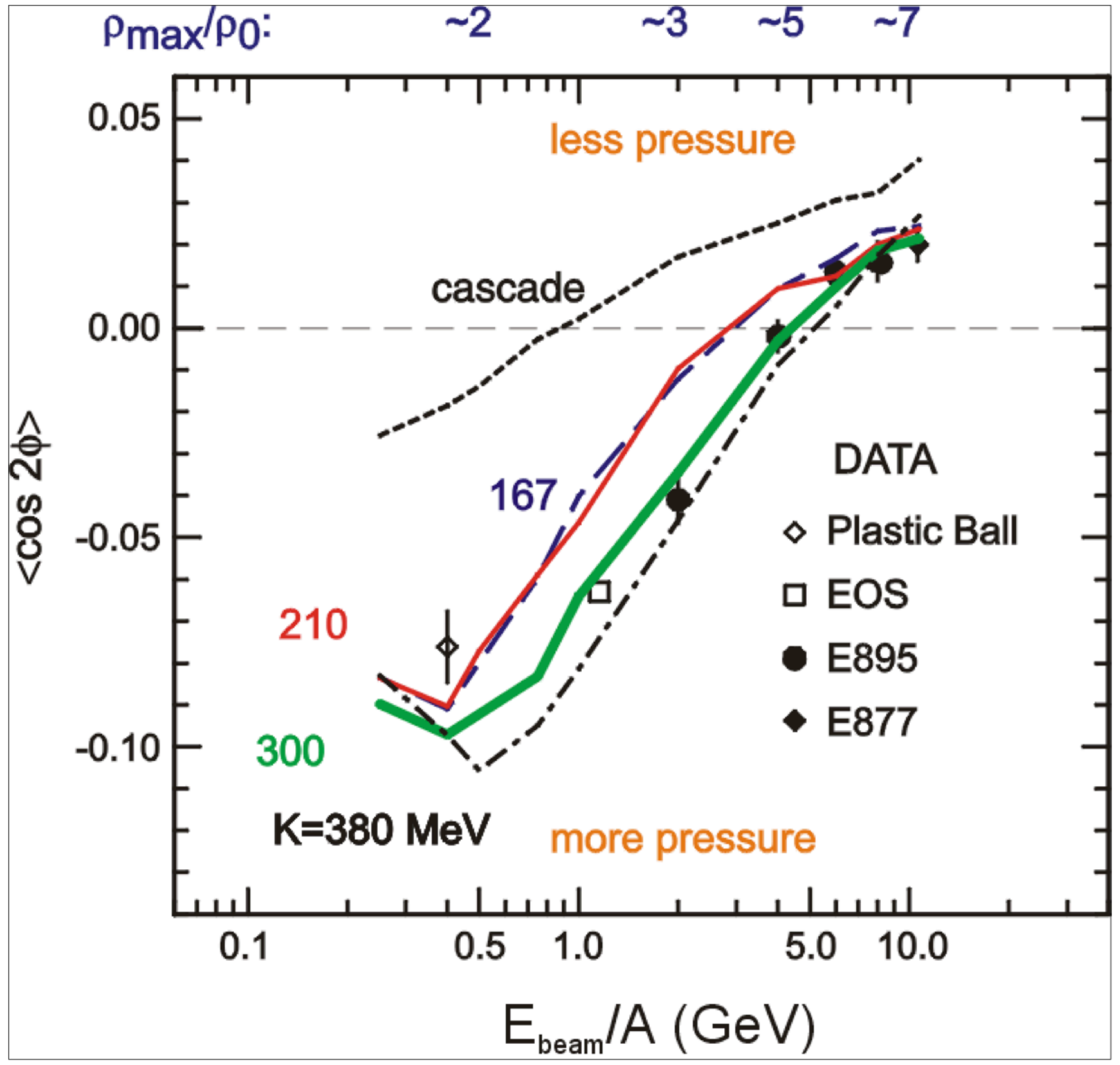
The most common form of the EOS is the "Skyrme potential": $U(n_B) = A\left(\frac{n_B}{n_0}\right) + B\left(\frac{n_B}{n_0}\right)^{\tau}$



$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{\mathrm{cm}})}\right|_{y/y_{\mathrm{cm}}=1} \sim \frac{dv_1}{dy}$$



v_2



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

Standard way of modeling the EOS: Skyrme potential

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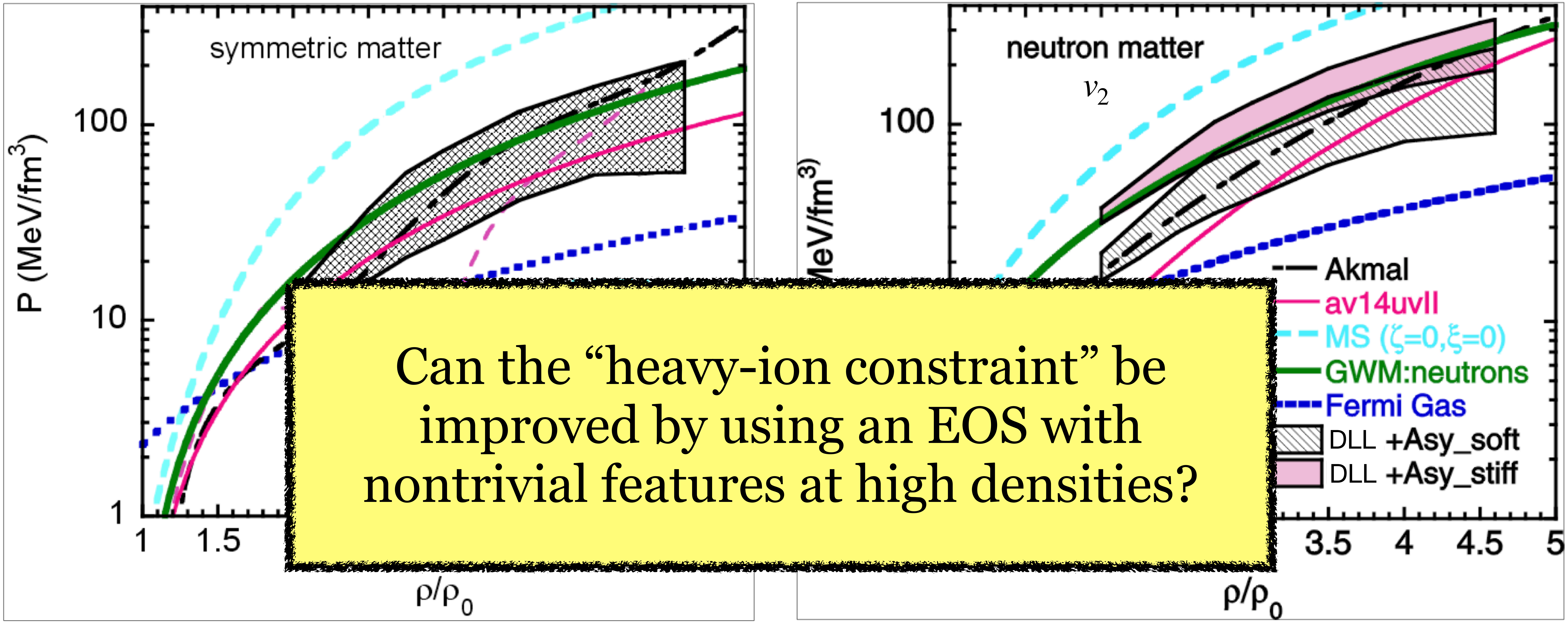
Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

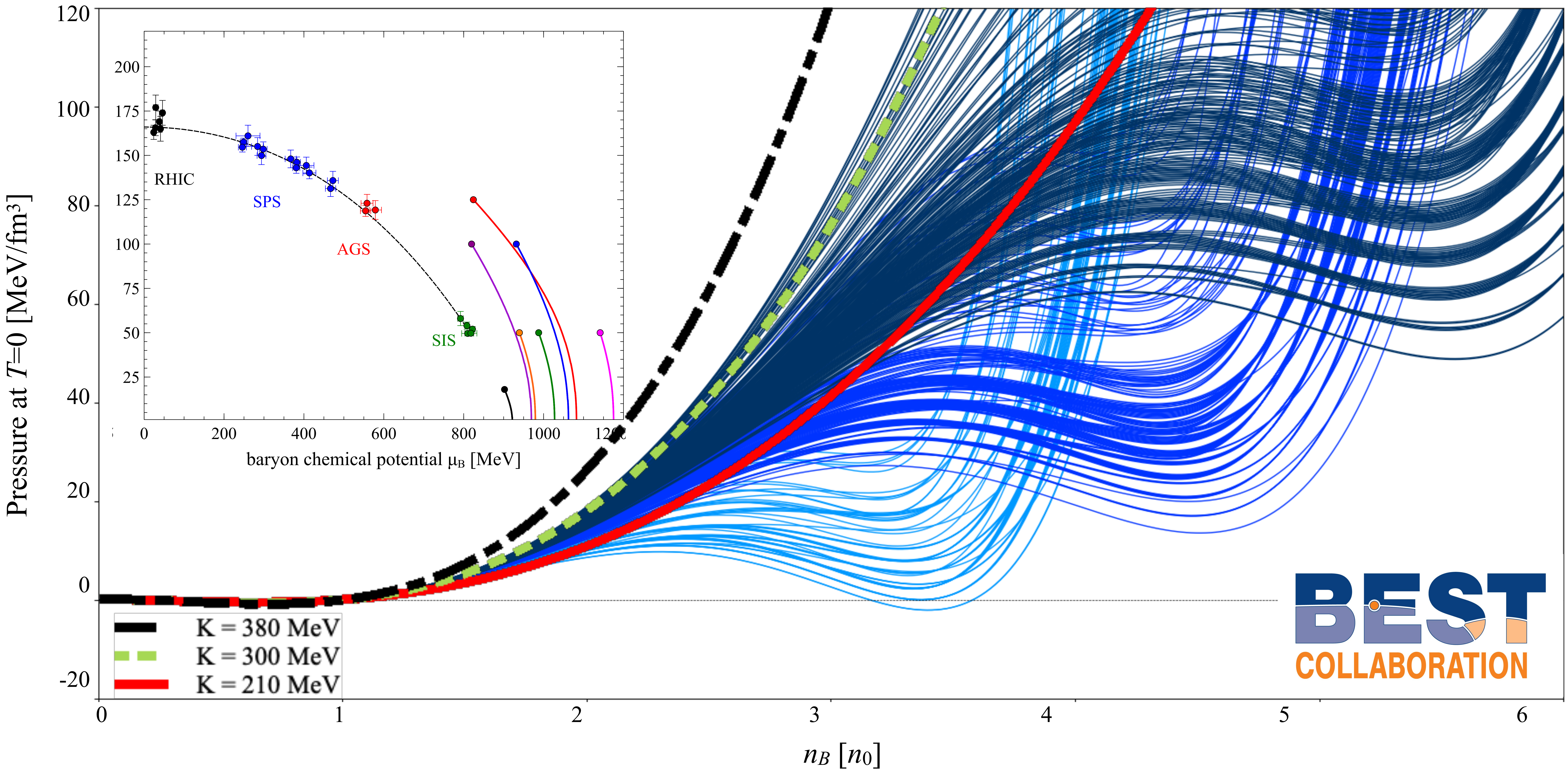
"the heavy-ion constraint"



Can the "heavy-ion constraint" be improved by using an EOS with nontrivial features at high densities?

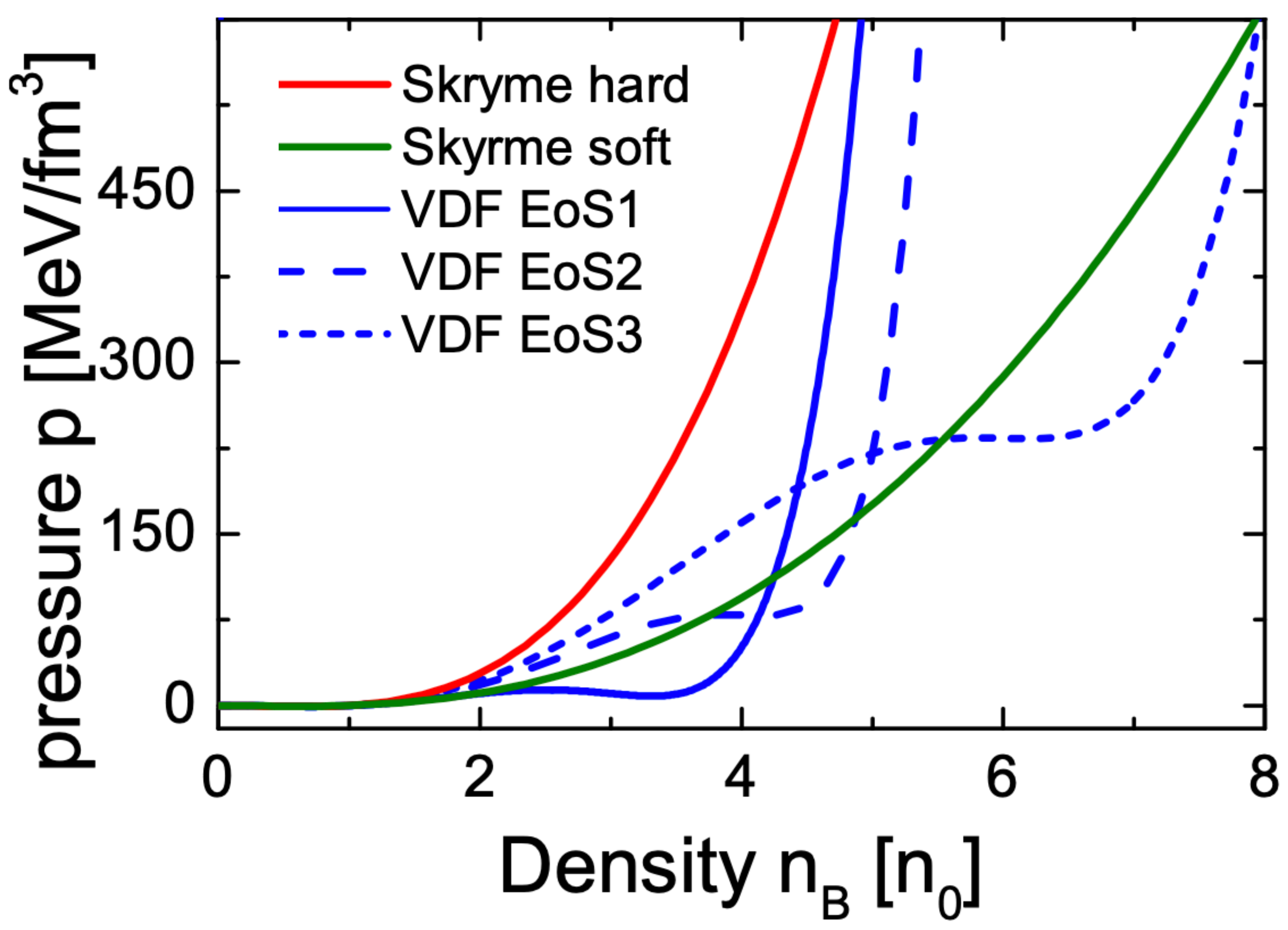
VDF model: relativistic potentials with two 1st order phase transitions

A. Sorensen, V. Koch, Phys. Rev. C **104** (2021) 3, 034904, arXiv:2011.06635



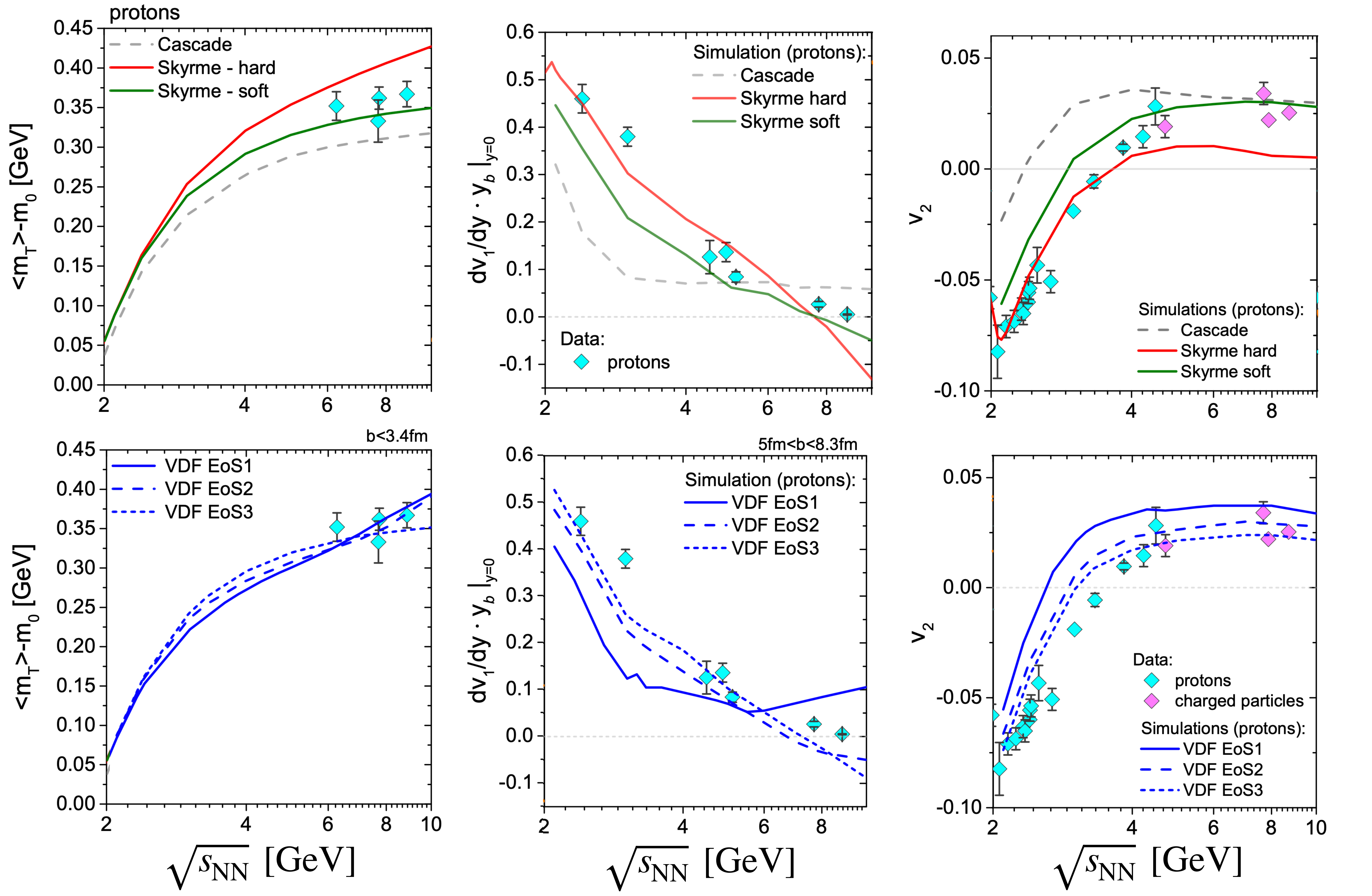
Results from UrQMD with (non-relativistic) VDF

J. Steinheimer, A. Motornenko, **A. Sorensen**, Y. Nara, V. Koch, M. Bleicher,
Eur. Phys. J. C **82**, 10, 911 (2022) arXiv:2208.12091



EoS	$T_c^{(N)}$[MeV]	$n_c^{(Q)}[n_0]$	$T_c^{(Q)}$[MeV]	K_0[MeV]
VDF1	18	3.0	100	261
VDF2	18	4.0	50	279
VDF3	22	6.0	50	356

Very soft EOS at $n_B \in (2,3)n_0$
not supported in VDF+UrQMD



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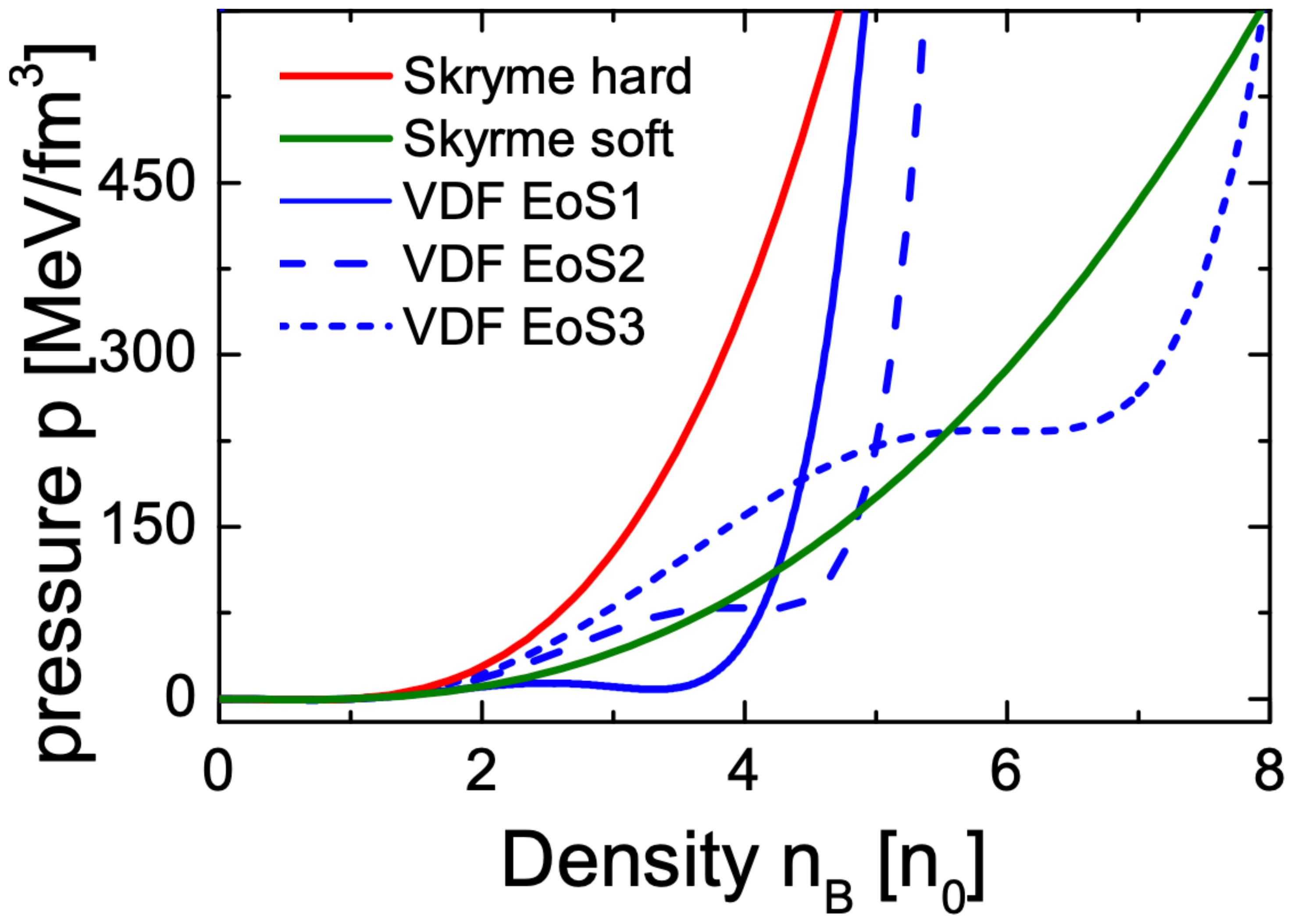

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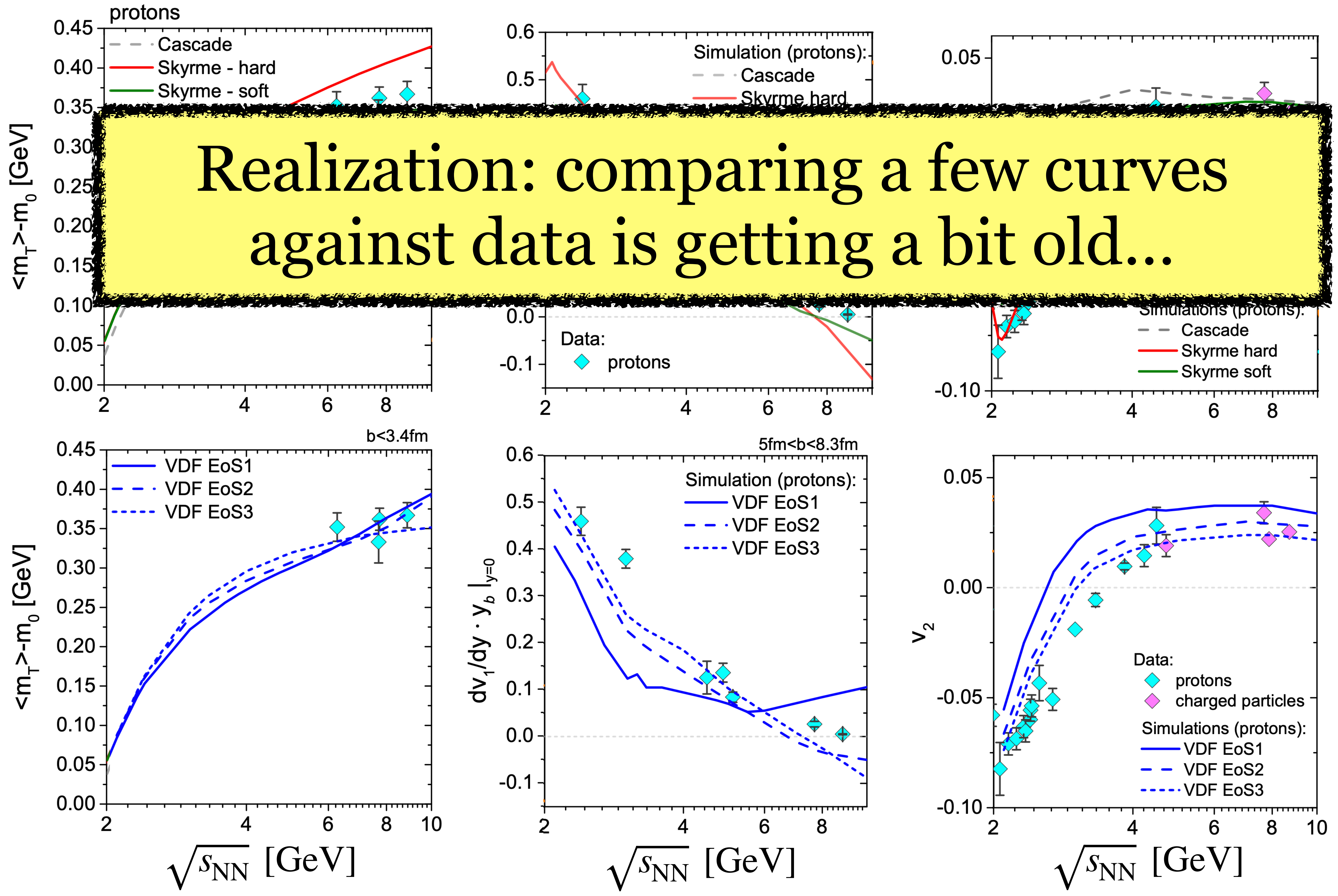
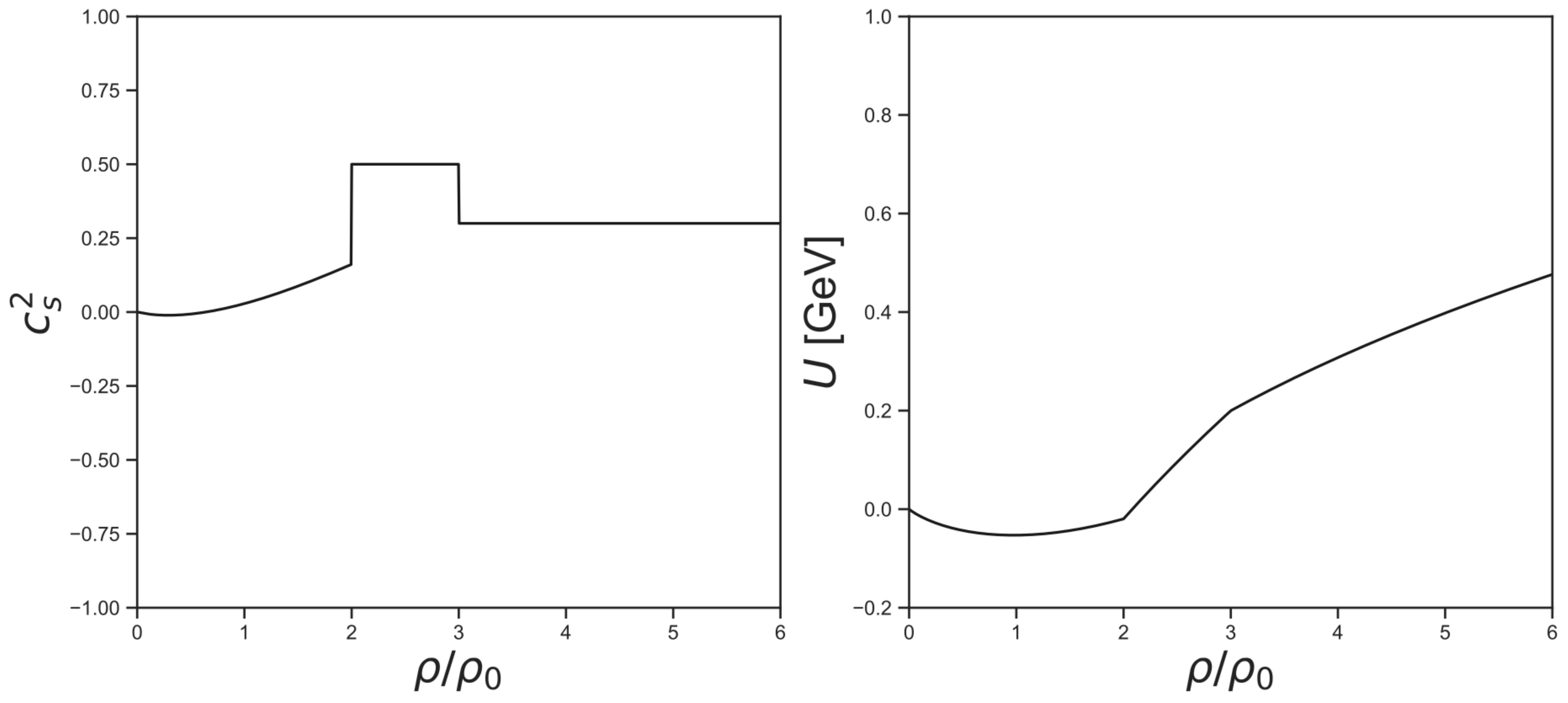


Realization: comparing a few curves against data is getting a bit old…

Bayesian analysis: piecewise parametrization of c_s^2

Piecewise parametrization of $c_s^2(n_B)$:

$$c_s^2(n_B) = \begin{cases} c_s^2(\text{Skyrme}), & n_B < n_1 = 2n_0 \\ c_1^2, & n_1 < n_B < n_2 \\ c_2^2, & n_2 < n_B < n_3 \\ \dots & \\ c_m^2, & n_m < n_B \end{cases}$$



1-to-1 relation to the single-particle potential $U(n_B)$:

$$U(n_B) = \begin{cases} U_{\text{Sk}}(n_B) & n_B < n_1 = 2n_0 \\ U_1(n_B) & n_1 < n_B < n_2 \\ \dots & \\ U_k(n_B) & n_k < n_B < n_{k+1} \end{cases}$$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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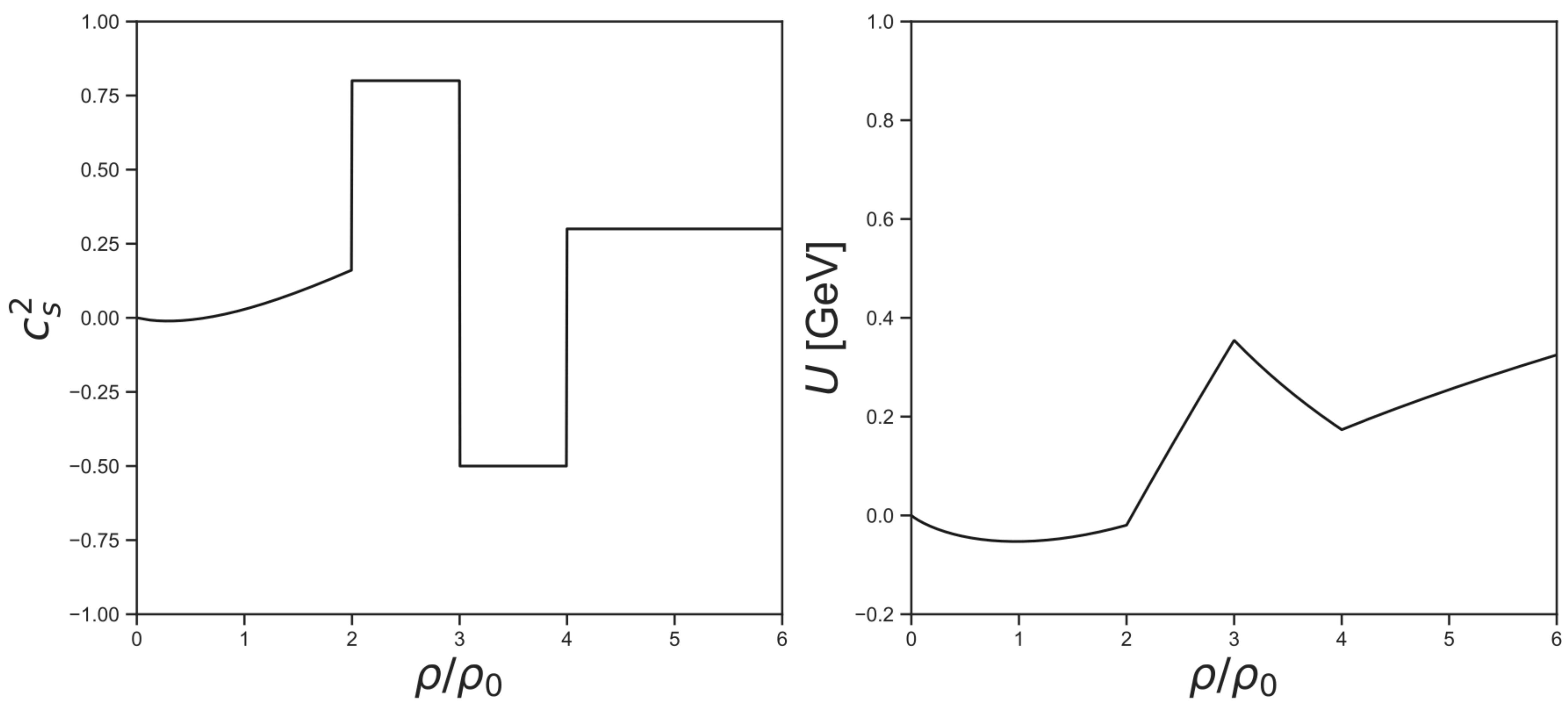

1-to-1 relation to the single-particle potential $U(n_B)$:

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Gradients of $U(n_B)$ enter the EOMs
= directly affect the evolution in simulations

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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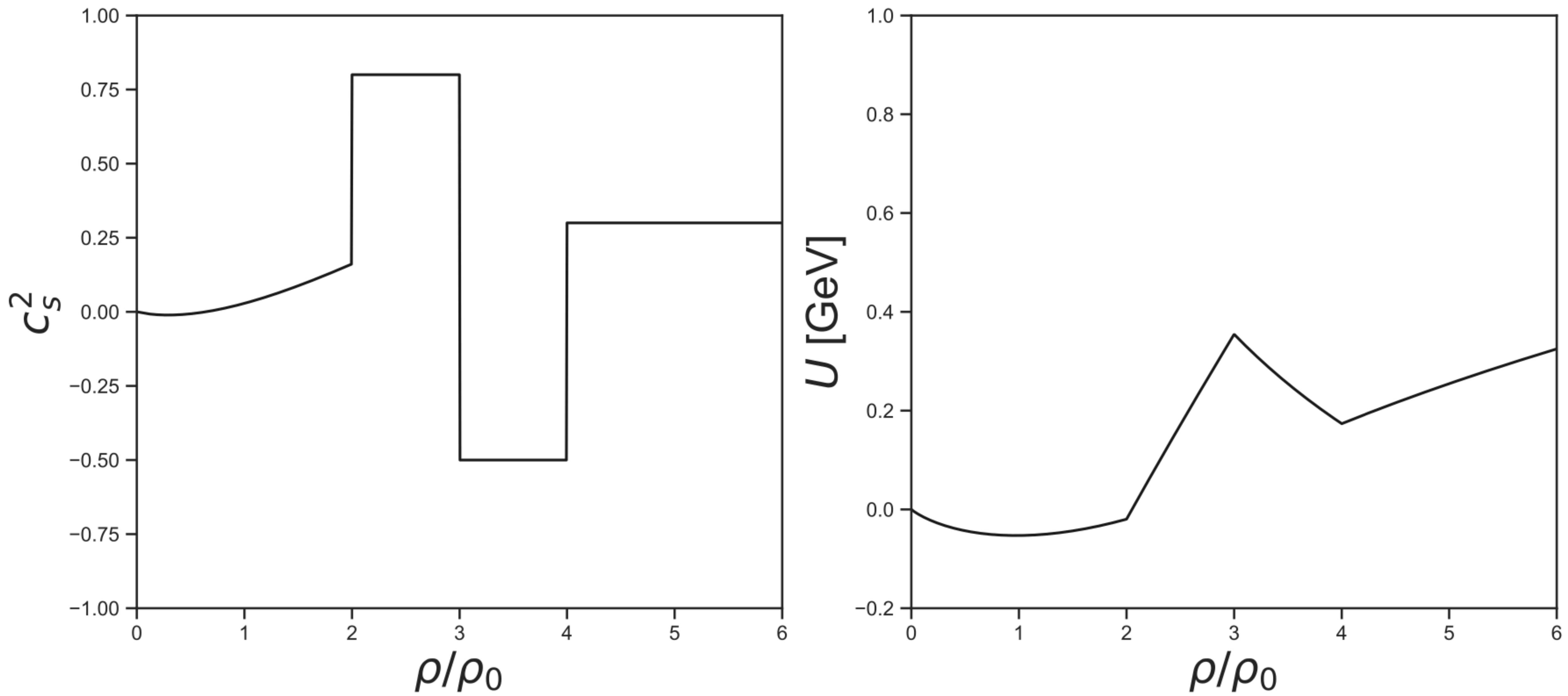

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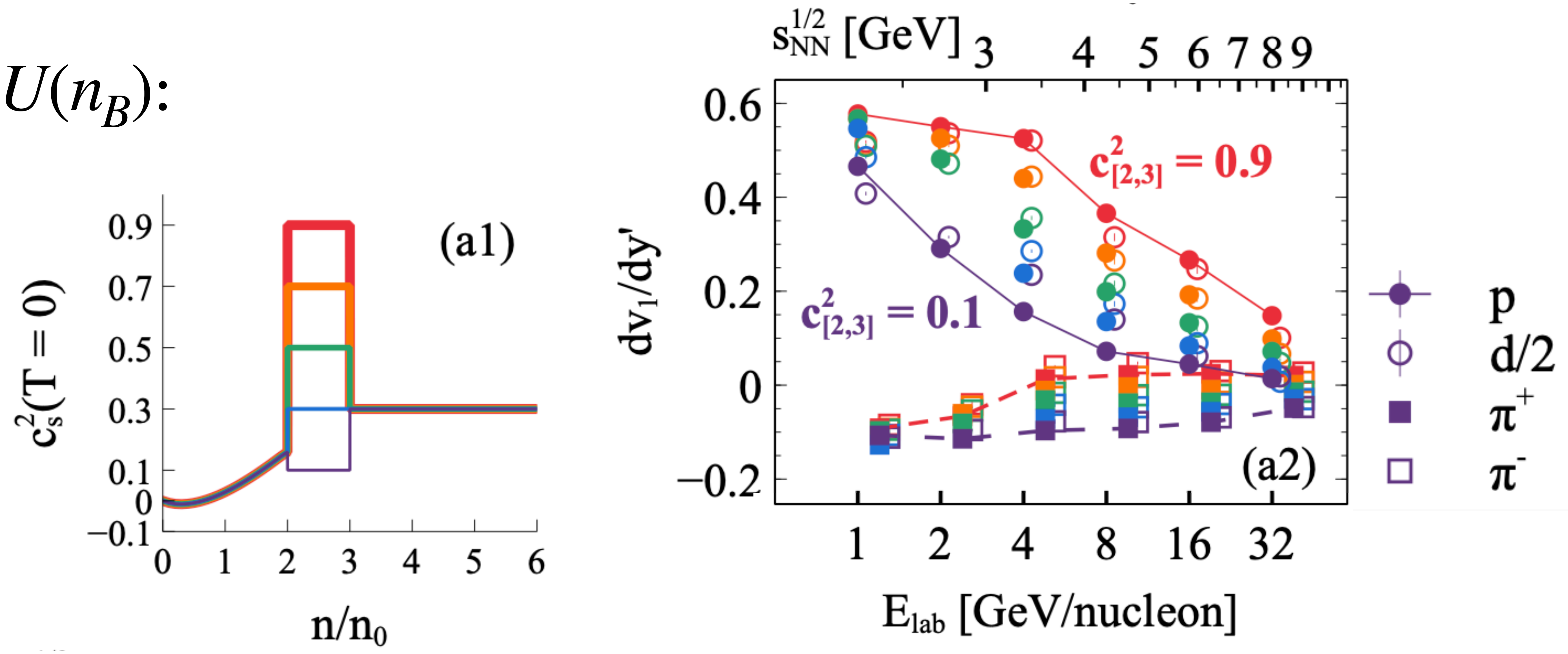
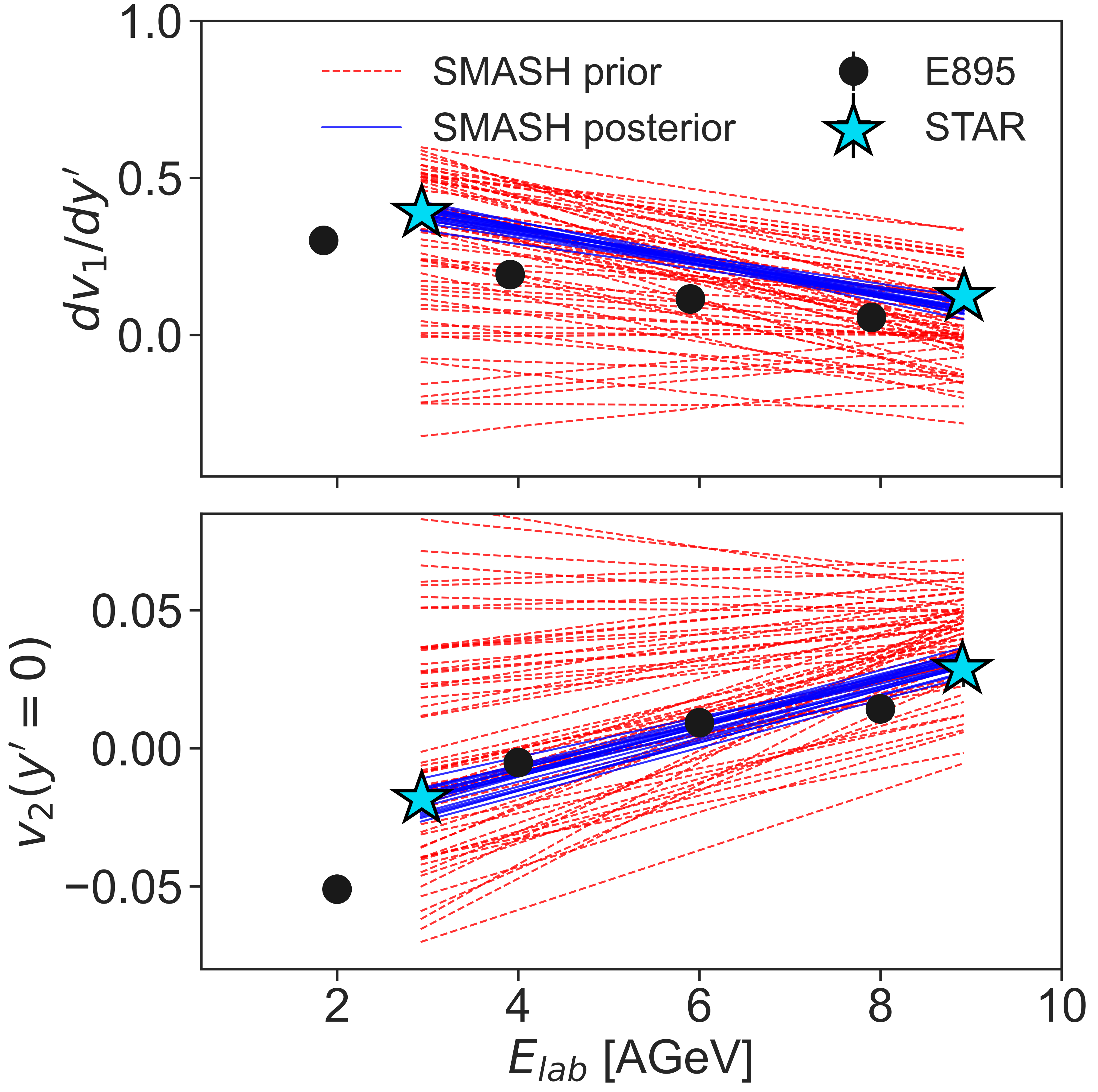
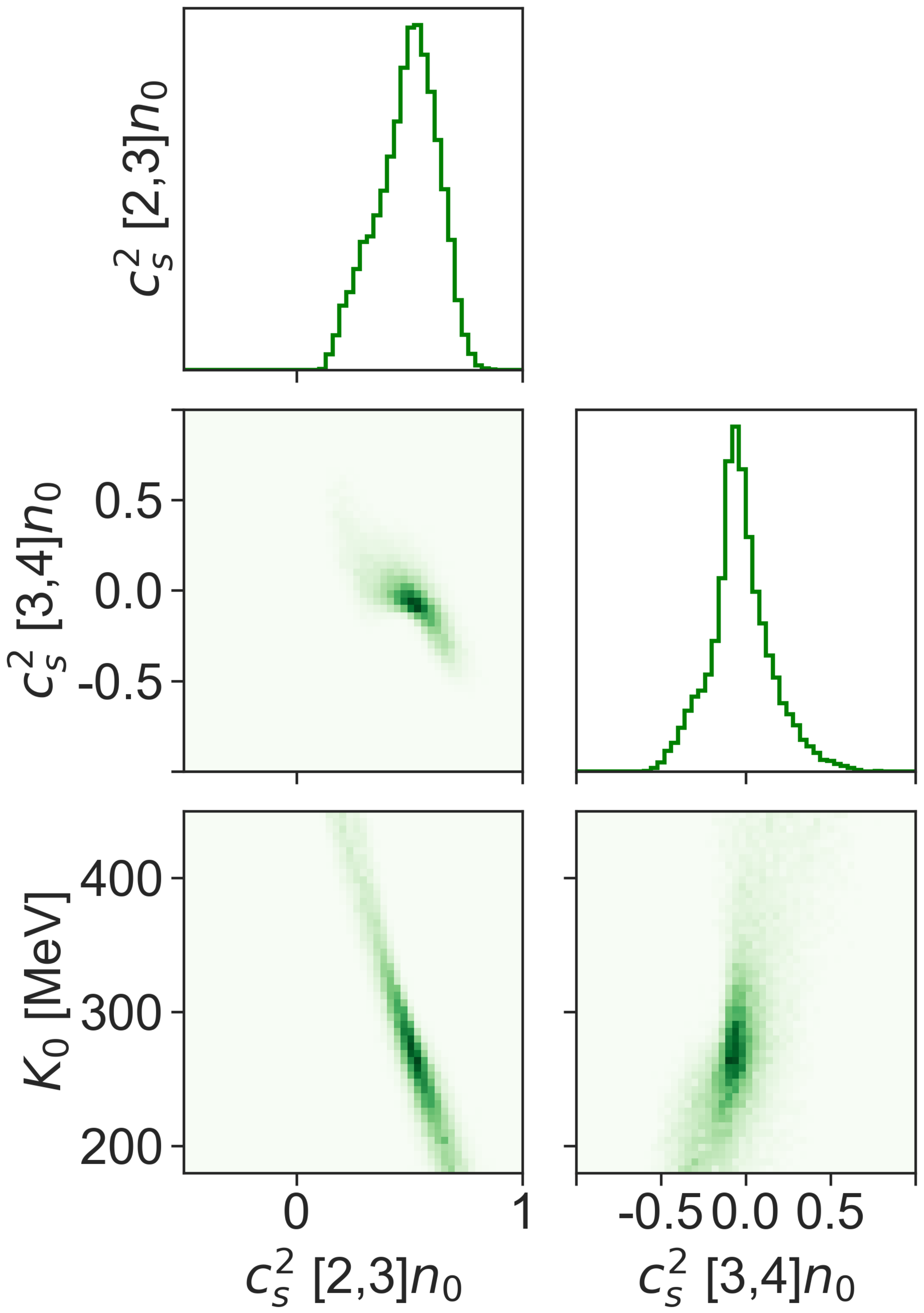
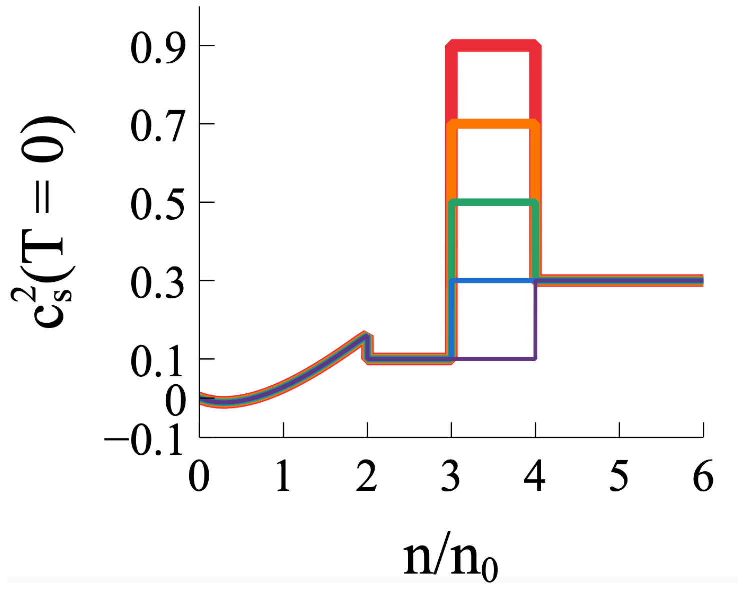


D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Bayesian analysis of BES flow in BUU with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$







The maximum a posteriori probability (MAP) parameters are
$K_0 = 285 \pm 67$ MeV, $c^2_{[2,3]n_0} = 0.49 \pm 0.13$, $c^2_{[3,4]n_0} = -0.03 \pm 0.15$

D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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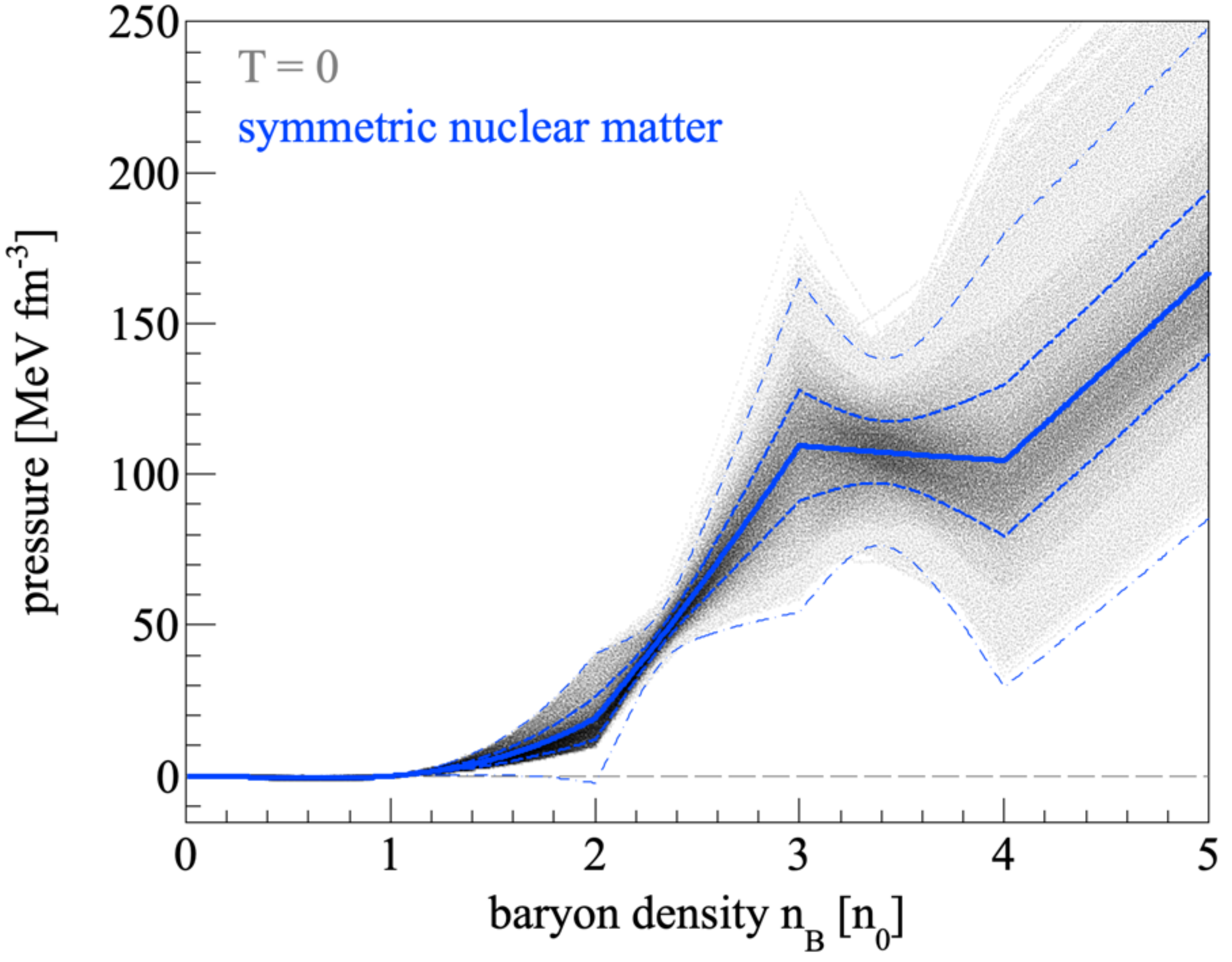
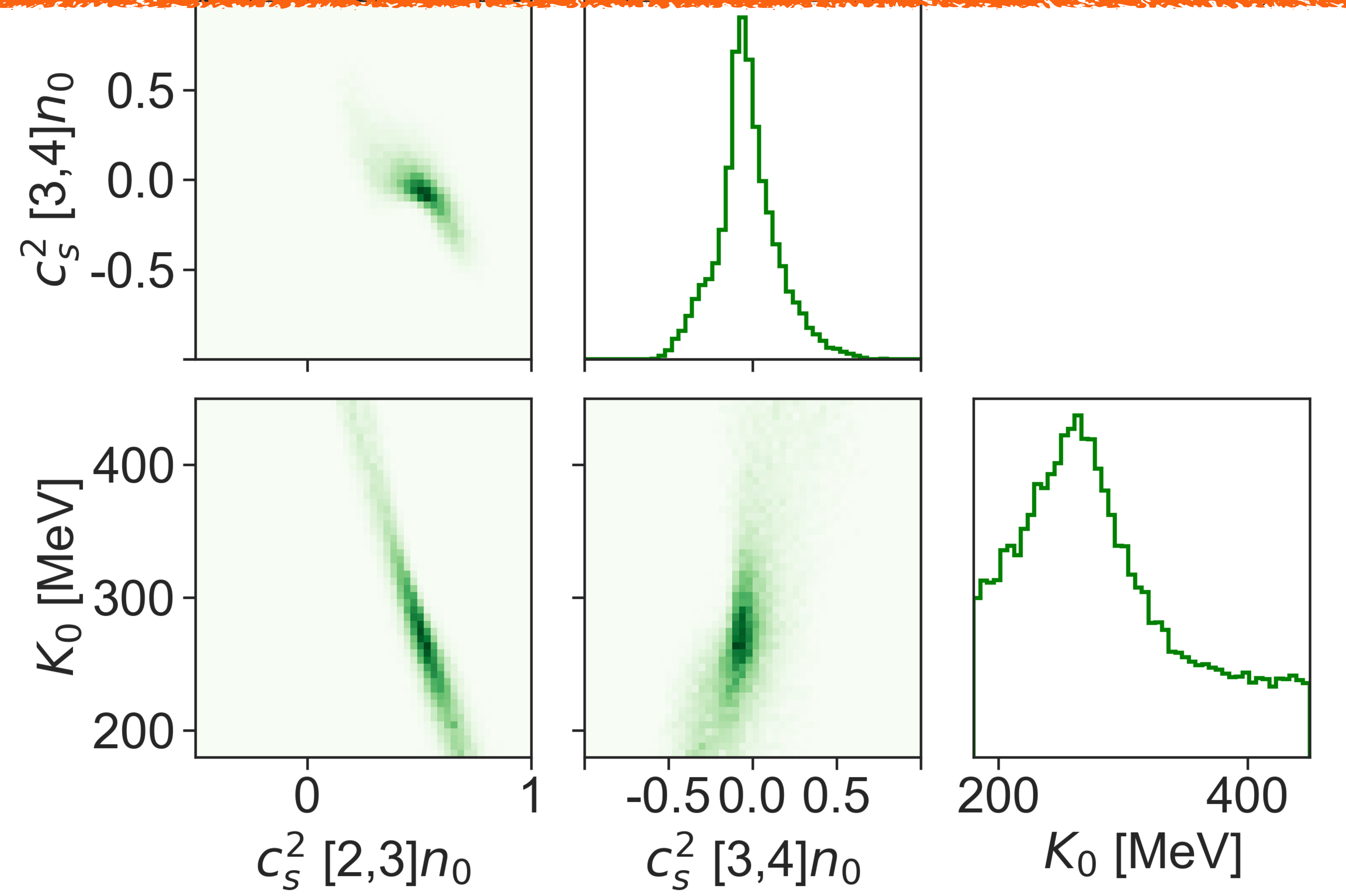


The constrained EOS is very stiff at $n_B \in (2,3)n_0$ and very soft at $n_B \in (3,4)n_0$



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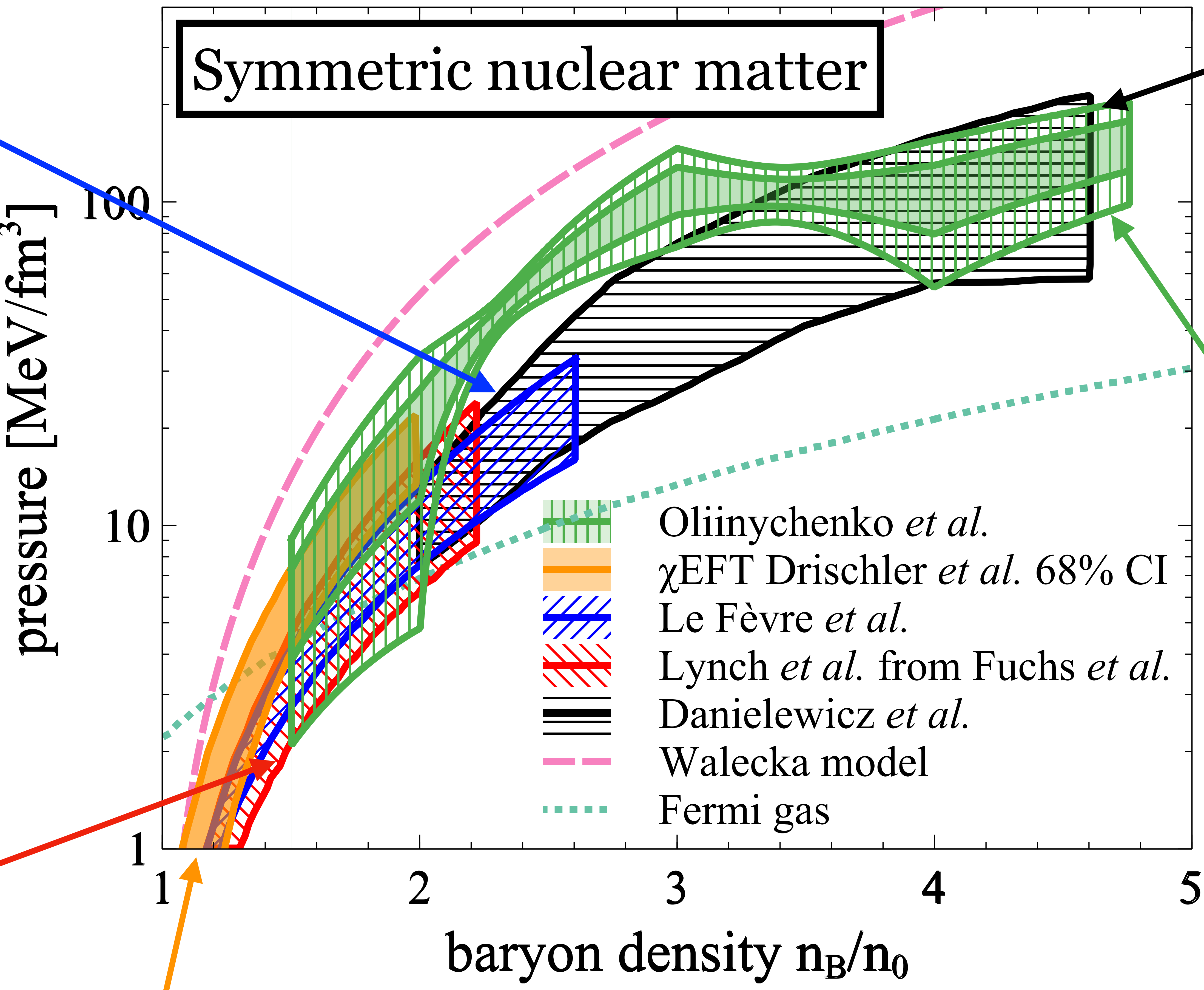
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

EOS of symmetric nuclear matter: selected (*few*) results

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

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



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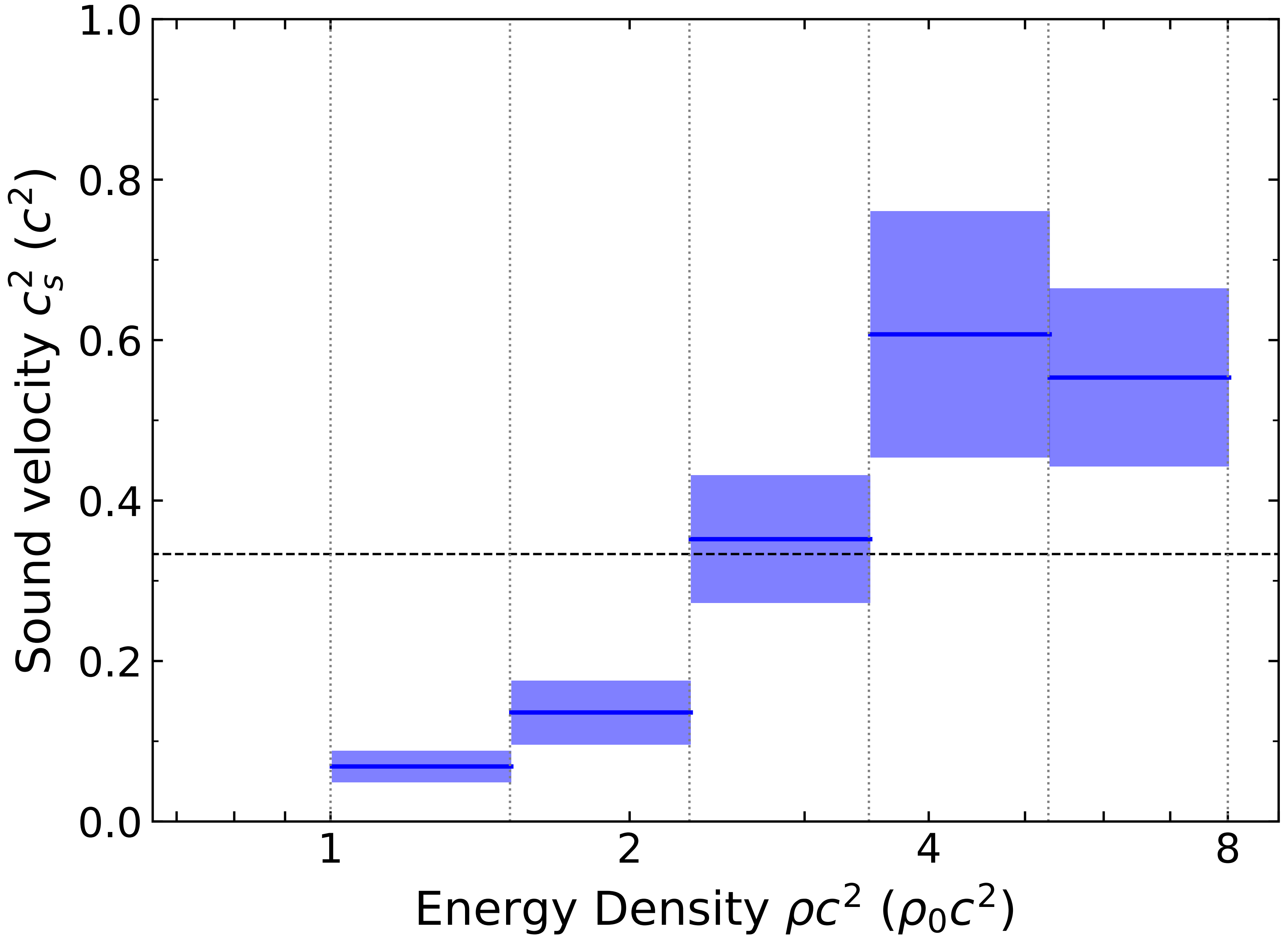
C. Drischler *et al.*, Phys. Rev. C **102** 5, 054315 (2020) arXiv:2004.07805

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
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

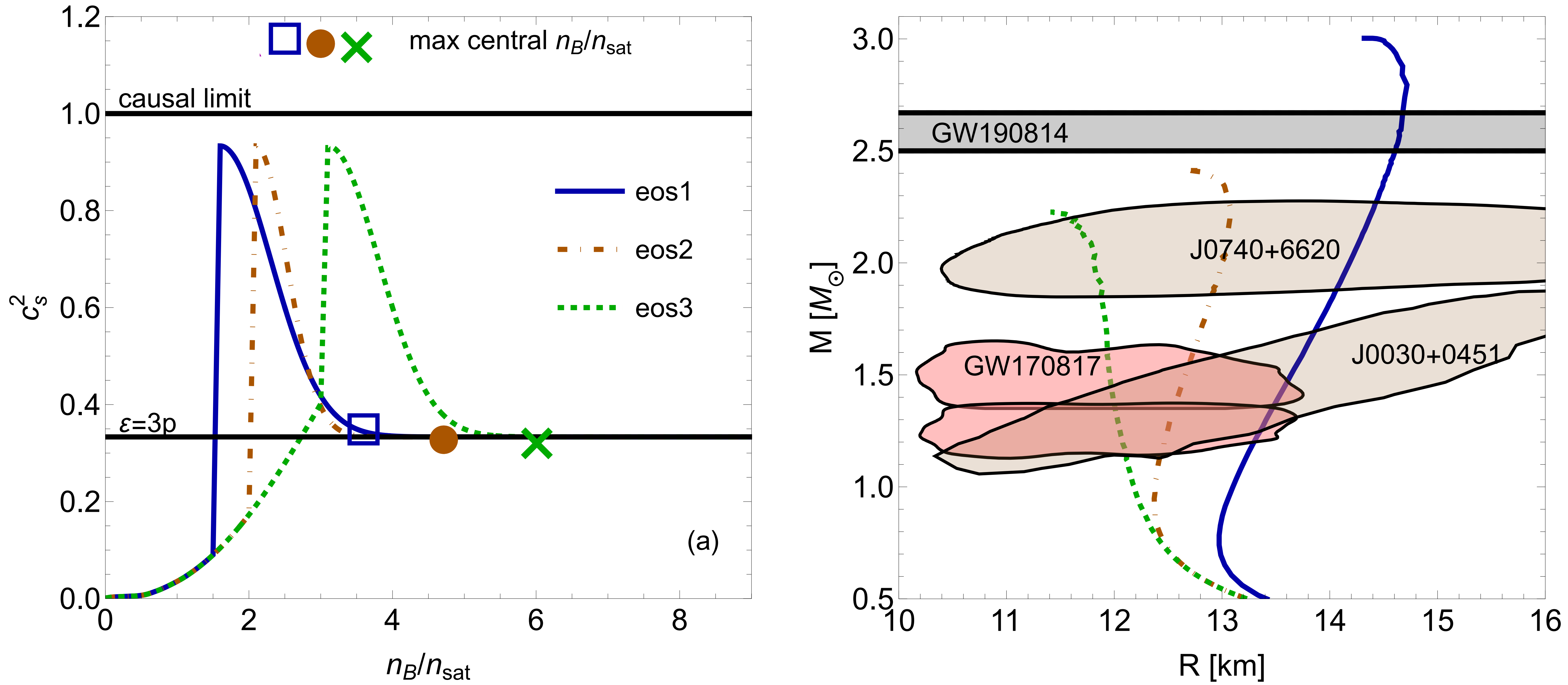
197Au+197Au @ 2.9—9 GeV/u
($\sqrt{s_{NN}}$ = 3 — 4.5 GeV)
observables: proton flow (STAR)
model used: SMASH w/ over 120 hadronic species, including deuterons;
relativistic EOS parametrized independently in different density regions;
NO momentum dependence
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Intriguing results from analyses of astrophysical observations

Recent astrophysical measurements suggest NS EOS may have a nontrivial density-dependence



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



N. Yao, **A. Sorensen,** V. Dexheimer, J. Noronha-Hostler, arXiv:2311.18819
H. Tan, T. Dore, V. Dexheimer, J. Noronha-Hostler, N. Yunes, Phys. Rev. D **105** 2, 023018 (2022)

Which of the allowed NS EOSs are compatible with heavy-ion collision measurements?

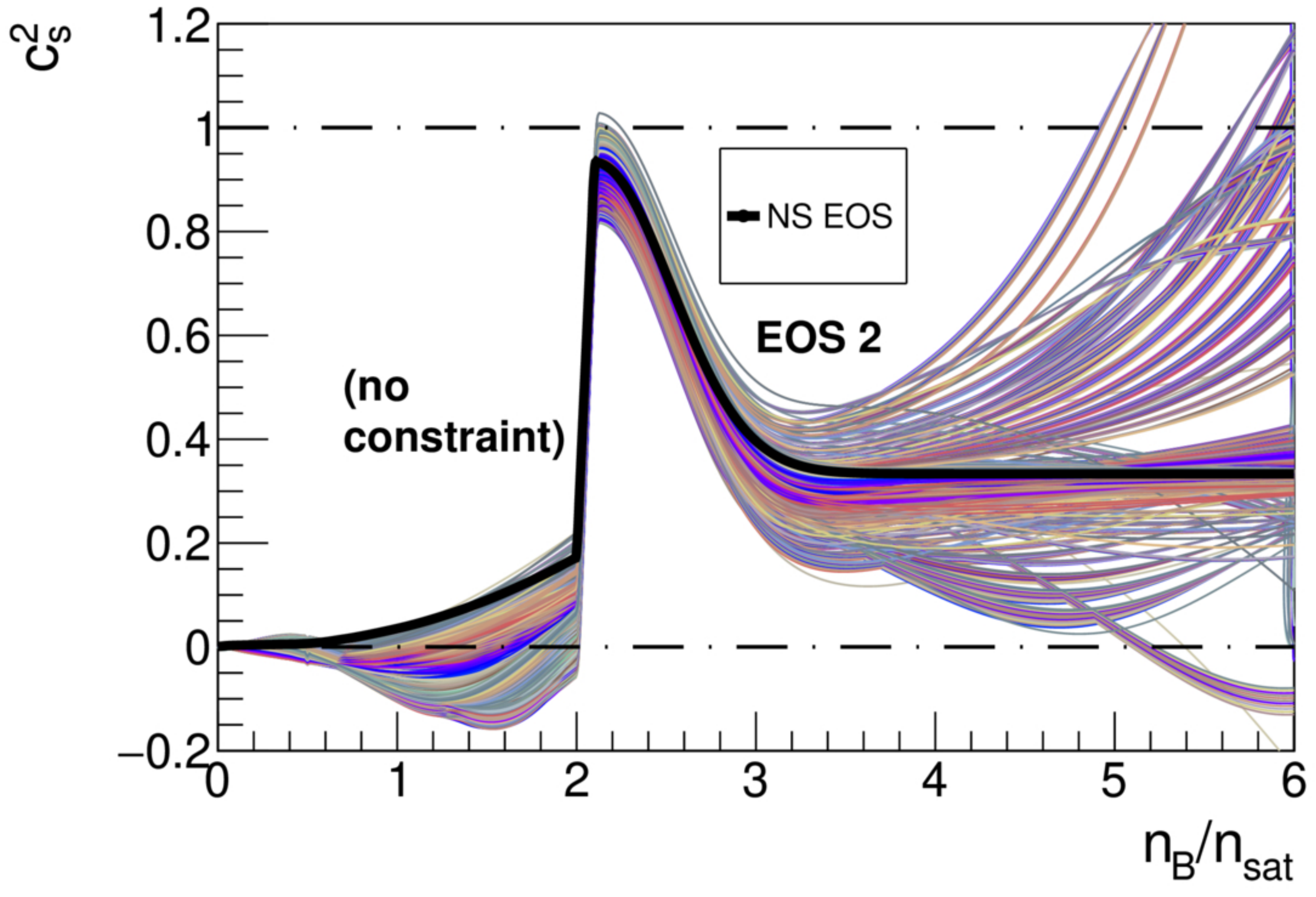
EOS from neutron stars to heavy-ion collisions

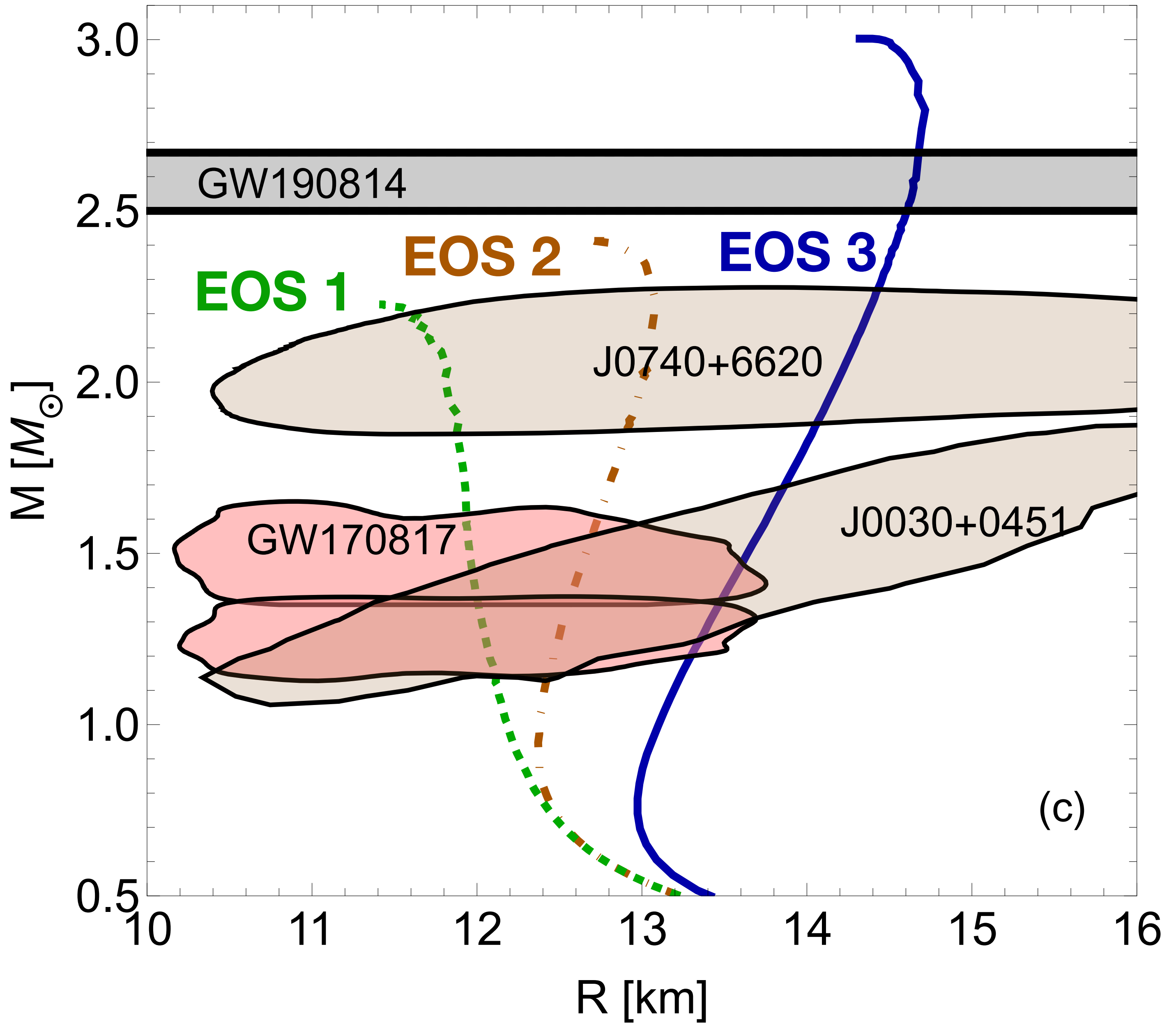
Use symmetry energy parameters exploring the allowed parameter space:

N. Yao, **A. Sorensen**, V. Dexheimer, J. Noronha-Hostler, arXiv:2311.18819

$$\mathcal{E}_{\rm HIC} = \mathcal{E}_{\rm NS} - n_B \underbrace{\left[E_{\rm sym} + \frac{L_{\rm sym}}{3}\left(\frac{n_B}{n_0} - 1\right) + \frac{K_{\rm sym}}{18}\left(\frac{n_B}{n_0} - 1\right)^2 + \frac{J_{\rm sym}}{162}\left(\frac{n_B}{n_0} - 1\right)^3 \right]}_{\approx \text{ symmetry energy } S(n_B)} \delta^2 , \qquad \delta \equiv \frac{n_N - n_P}{n_N + n_P}$$

Coefficient	Range	Step size
$E_{\rm sym,sat}$	27 – 40	1 MeV
$L_{\rm sym,sat}$	30 – 130	10 MeV
$K_{\rm sym,sat}$	-220 – 180	50 MeV
$J_{\rm sym,sat}$	-200 – 800	100 MeV





H. Tan, T. Dore, V. Dexheimer, J. Noronha-Hostler, N. Yunes, Phys. Rev. D **105** 2, 023018 (2022)

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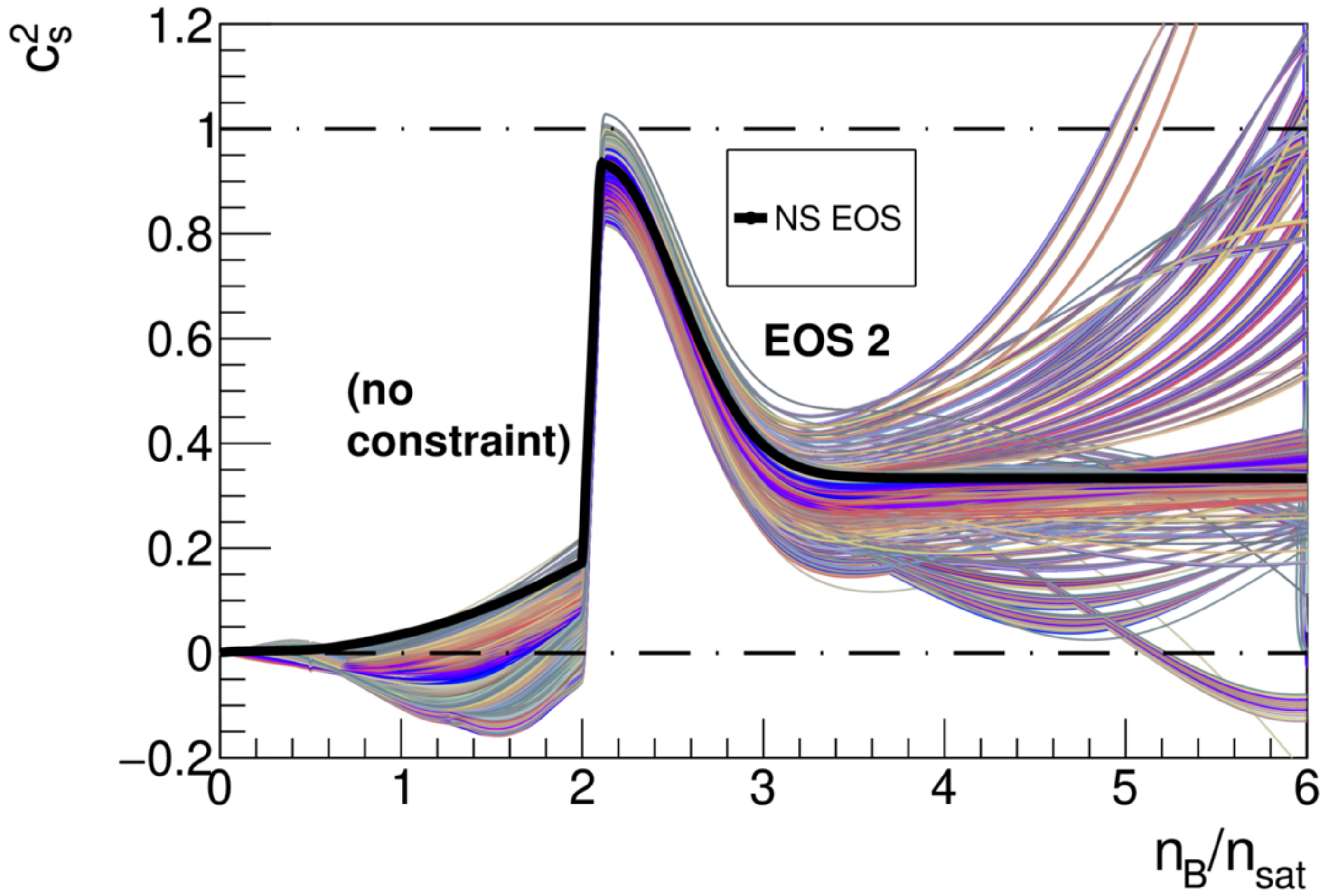
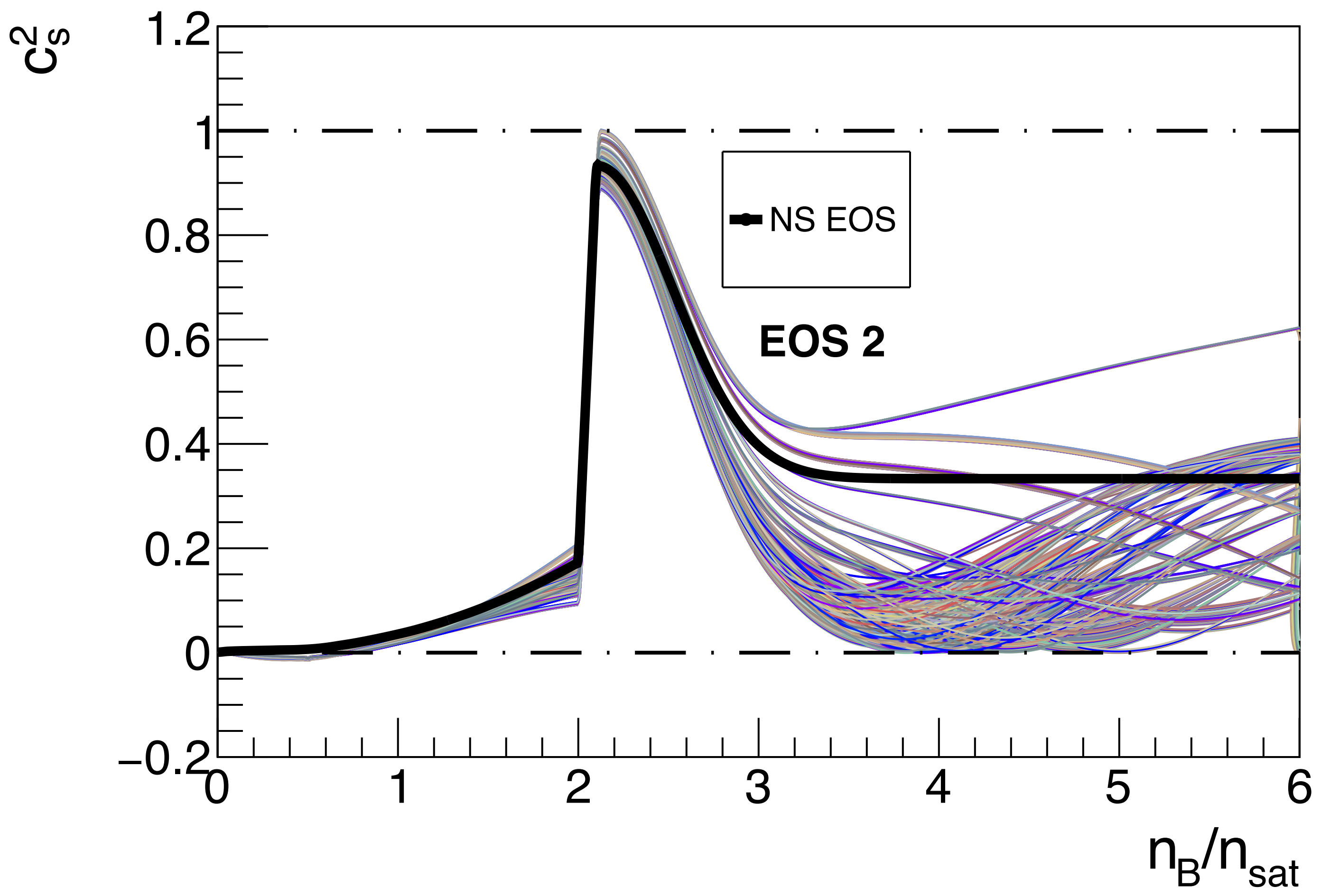
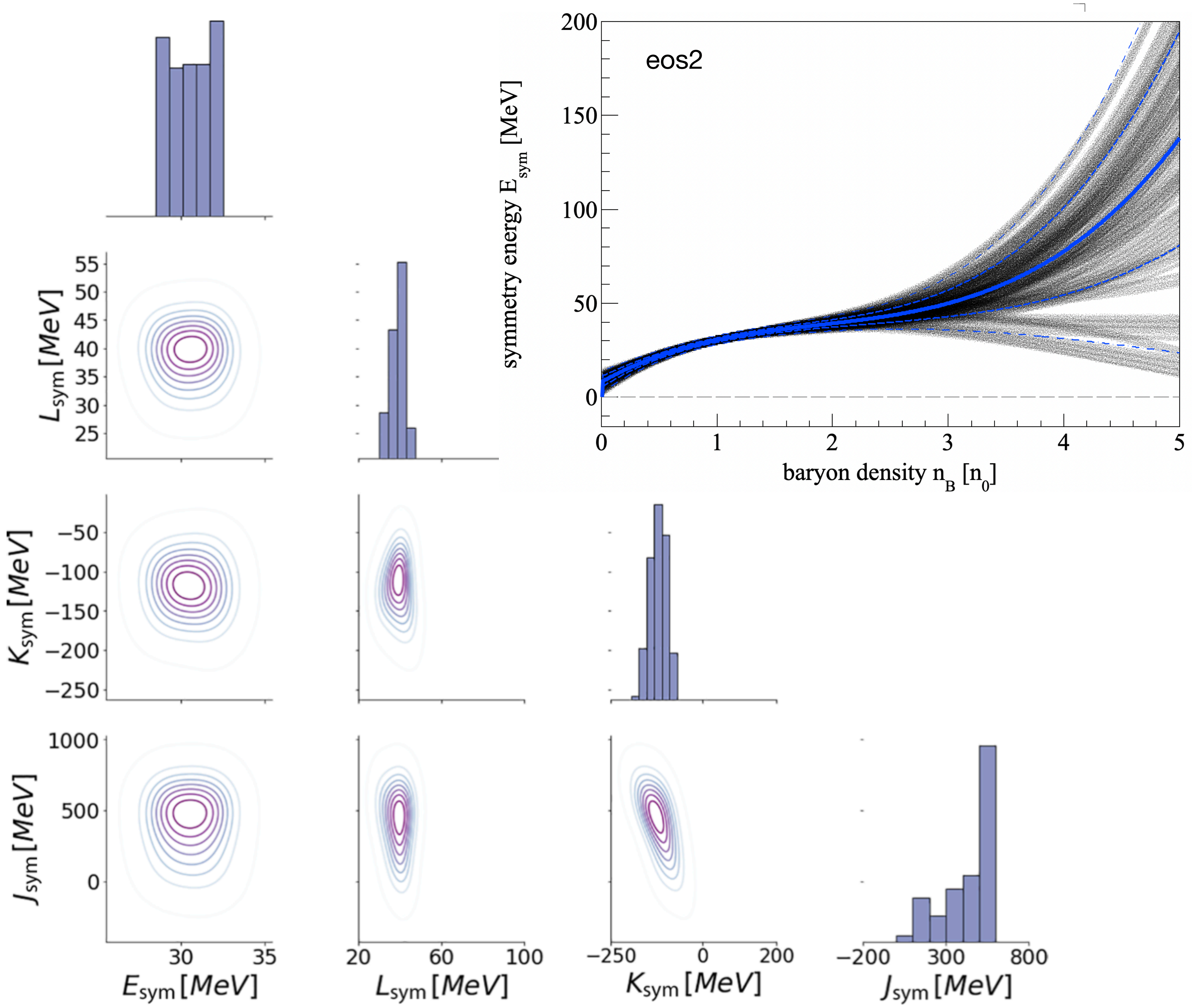


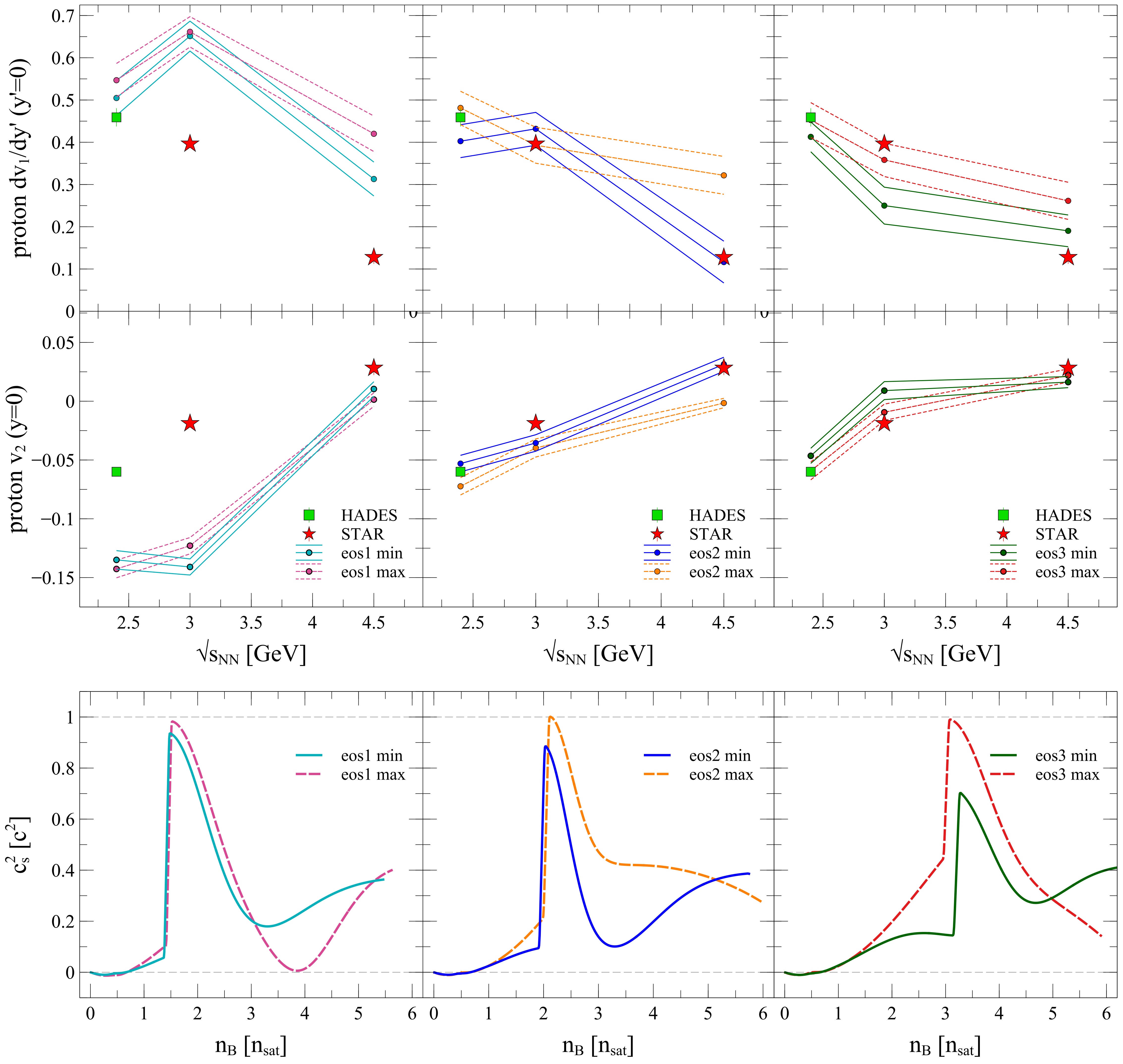




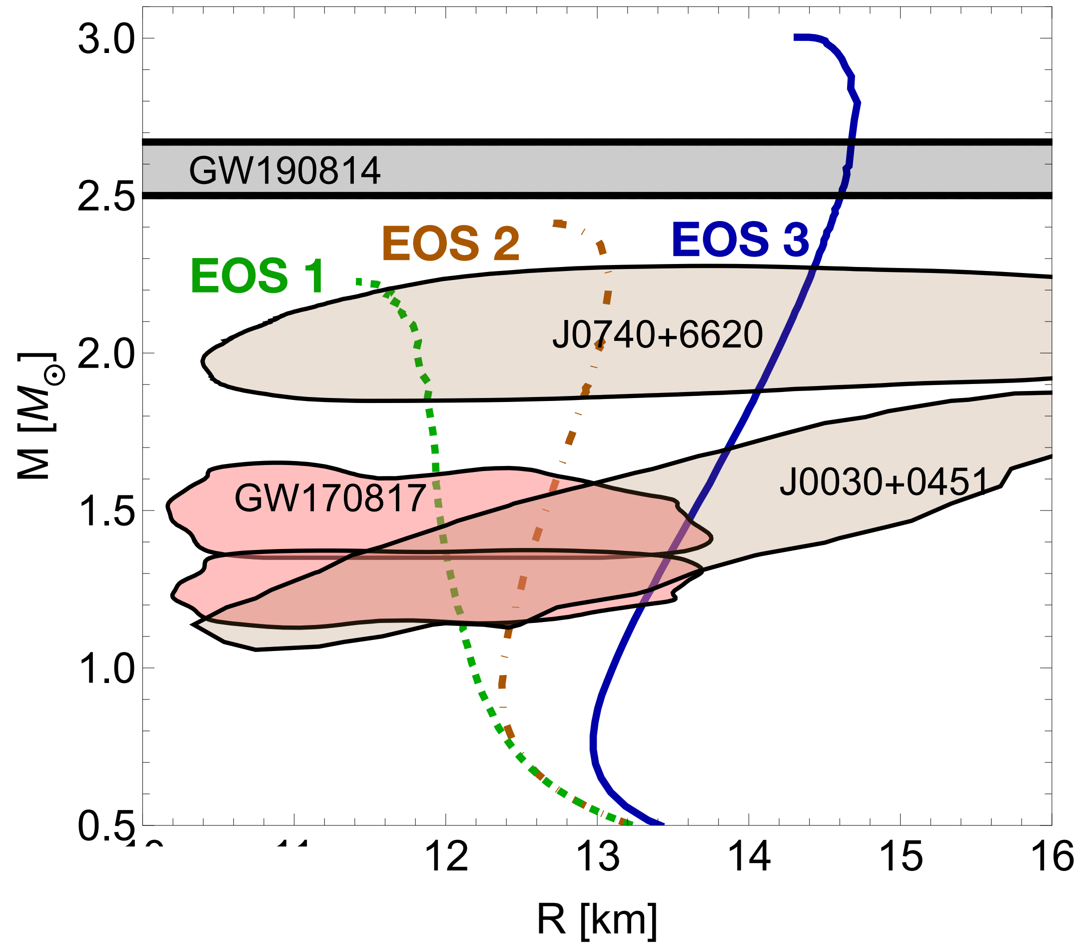
Enforcing nuclear matter properties, causality, and stability above $n_B \approx n_0$ leads to constraints on $E_{\rm sym}$, $L_{\rm sym}$, $K_{\rm sym}$, $J_{\rm sym}$

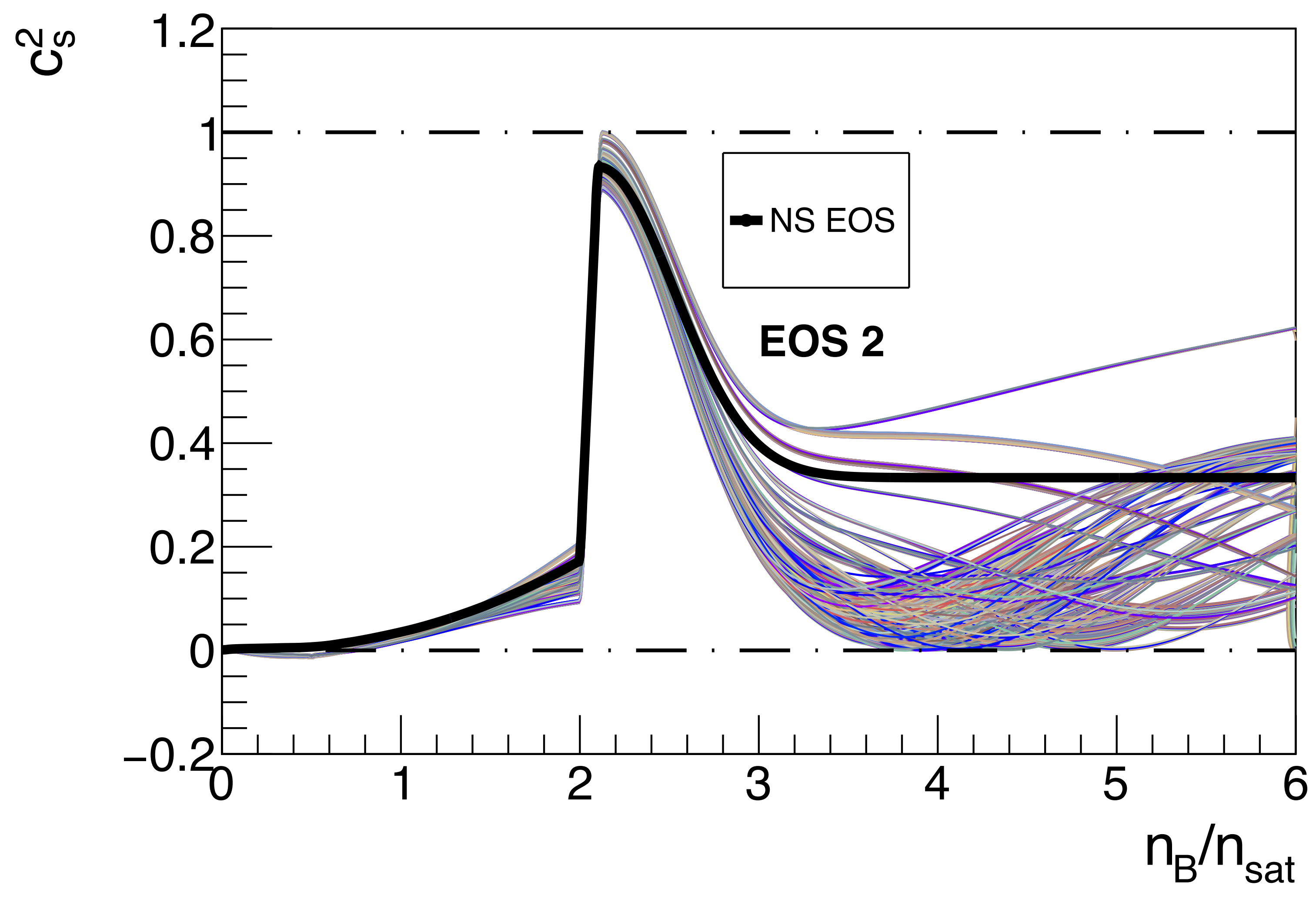
EOS from neutron stars to heavy-ion collisions

"Minimal" and "maximal" EOSs from each family tested against heavy-ion measurements:



EOS	$n_{\rm sat}$ [fm^{-3}]	B [MeV]	K_0 [MeV]	$c_s^2(n_B = n_{\rm sat})$
eos1 min	0.175	-14.6	200.5	0.024
eos1 max	0.171	-17.8	325.9	0.039
eos2 min	0.167	-14.6	206.7	0.025
eos2 max	0.161	-16.9	214.8	0.026
eos3 min	0.153	-14.8	220.2	0.027
eos3 max	0.162	-16.5	201.7	0.024

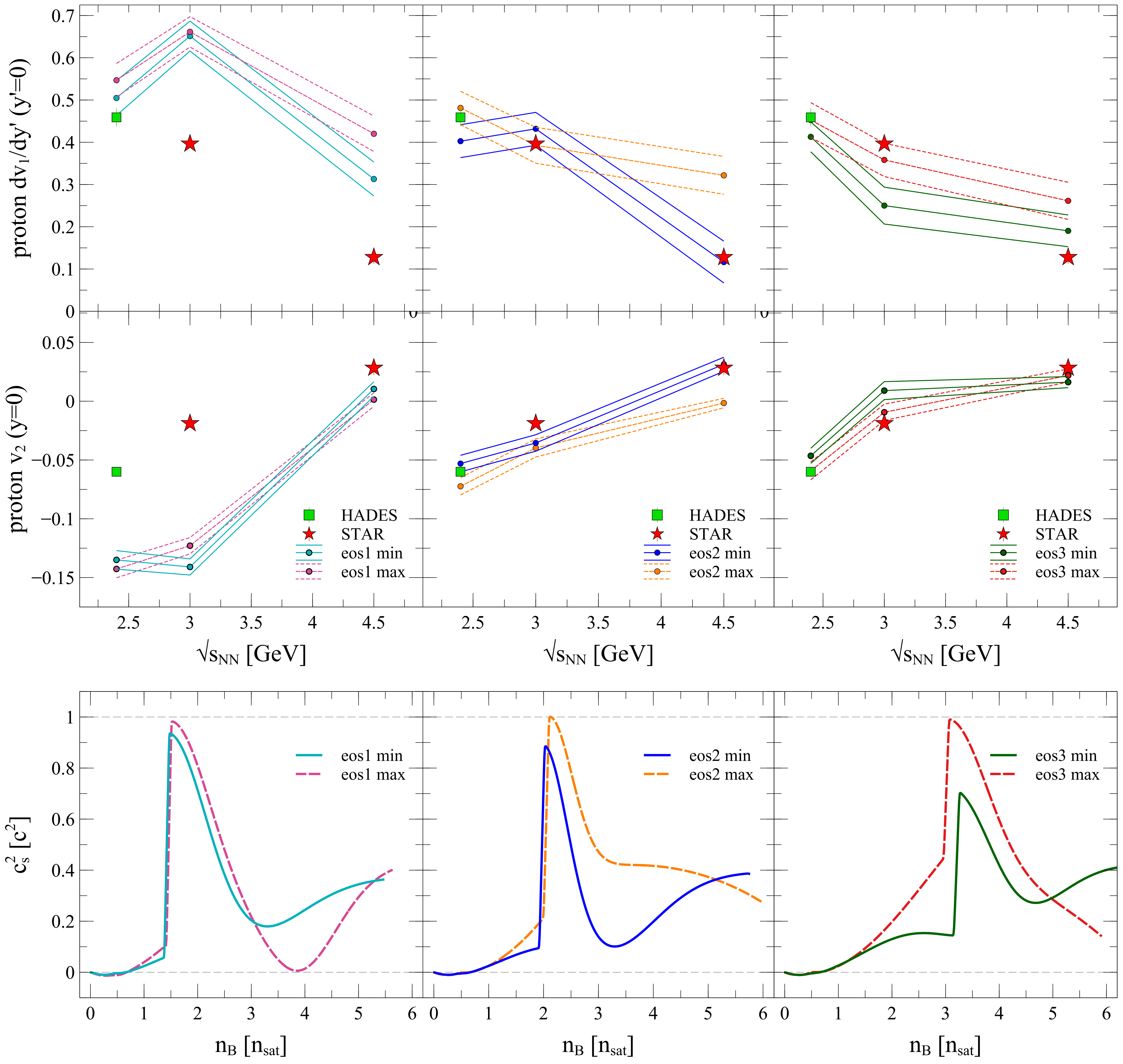




N. Yao, **A. Sorensen**, V. Dexheimer, J. Noronha-Hostler, arXiv:2311.18819

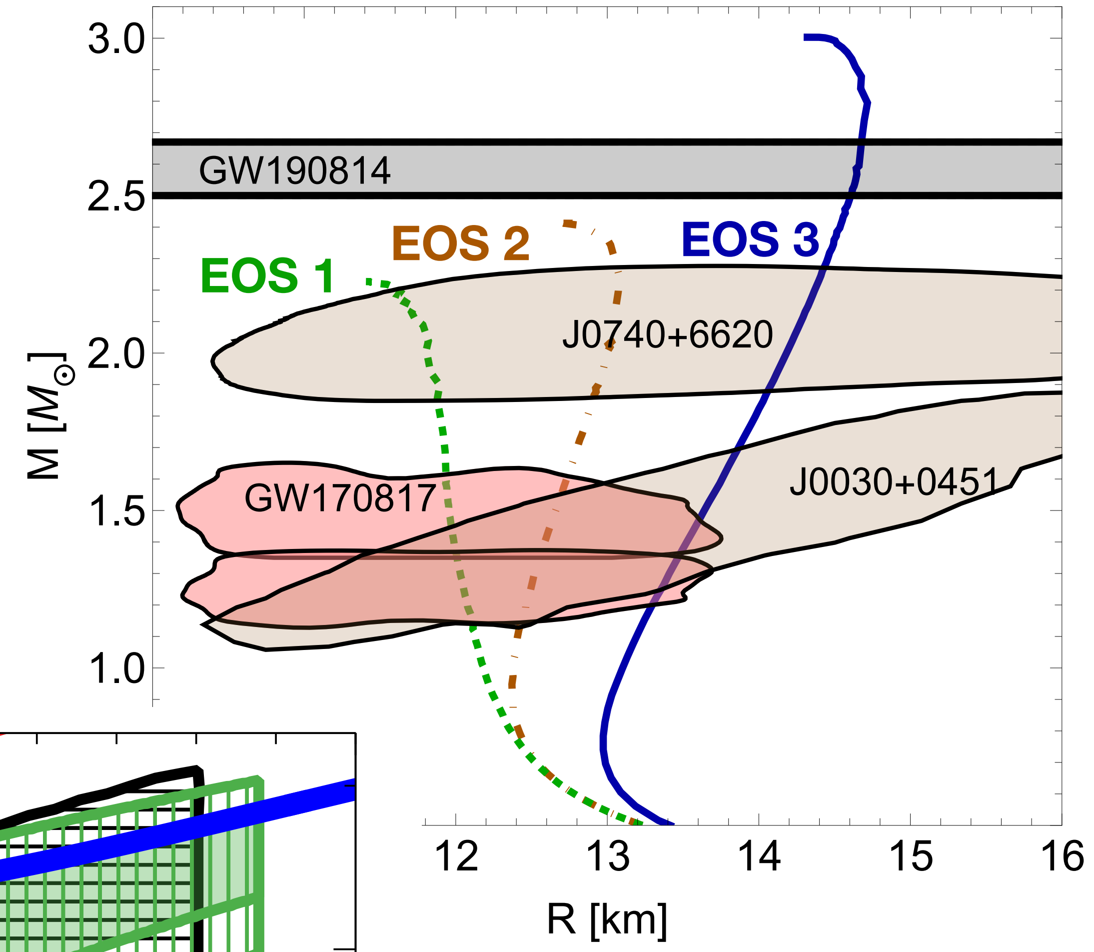
EOS from neutron stars to heavy-ion collisions

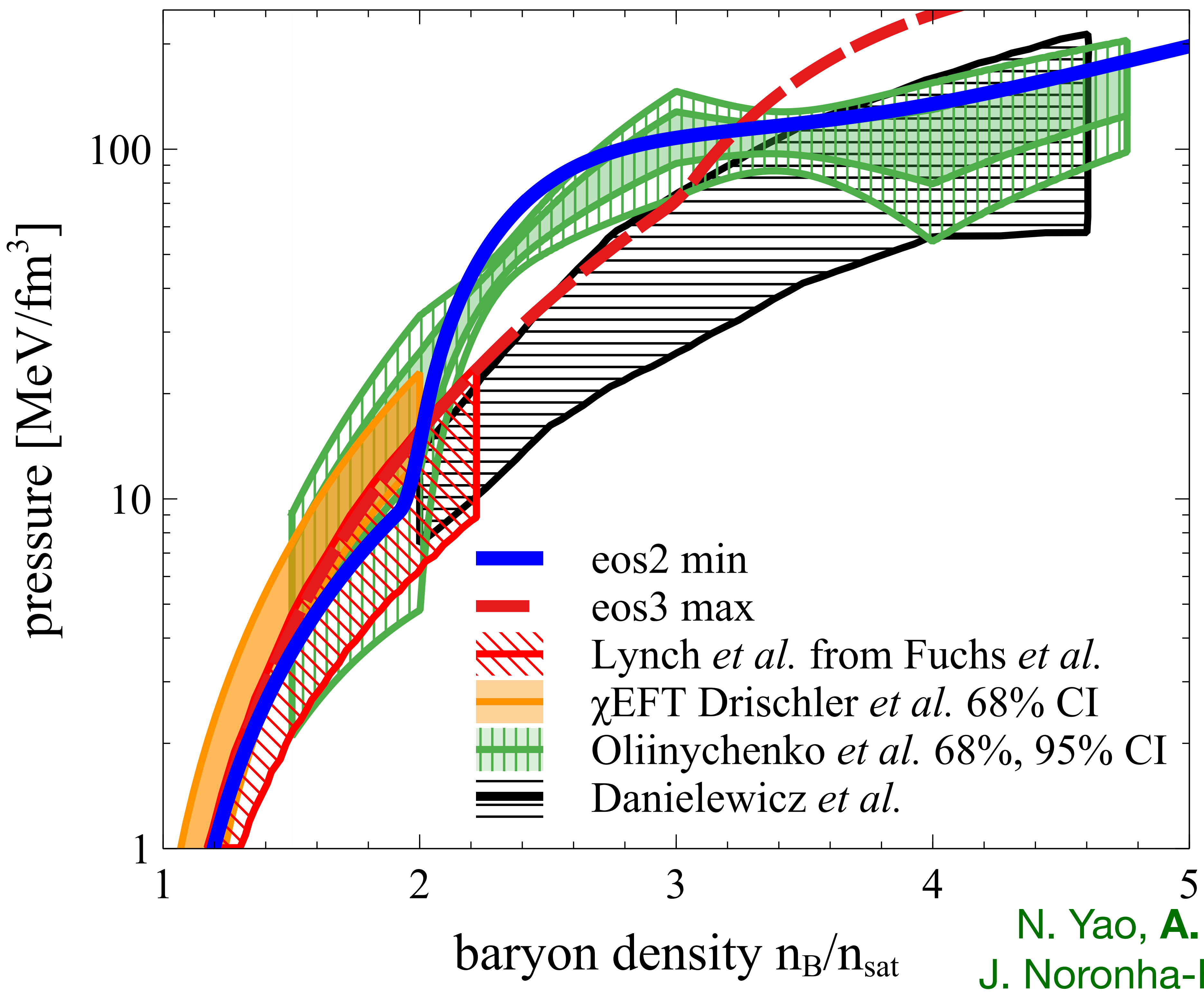
"Minimal" and "maximal" EOSs from each family tested against heavy-ion measurements:



EOS	n_{sat} [fm^{-3}]	B [MeV]	K_0 [MeV]	$c_s^2(n_B = n_{sat})$
eos…				
eos…				
eos…				
eos…				
eos…				
eos3 max	0.162	-16.5	201.7	0.024

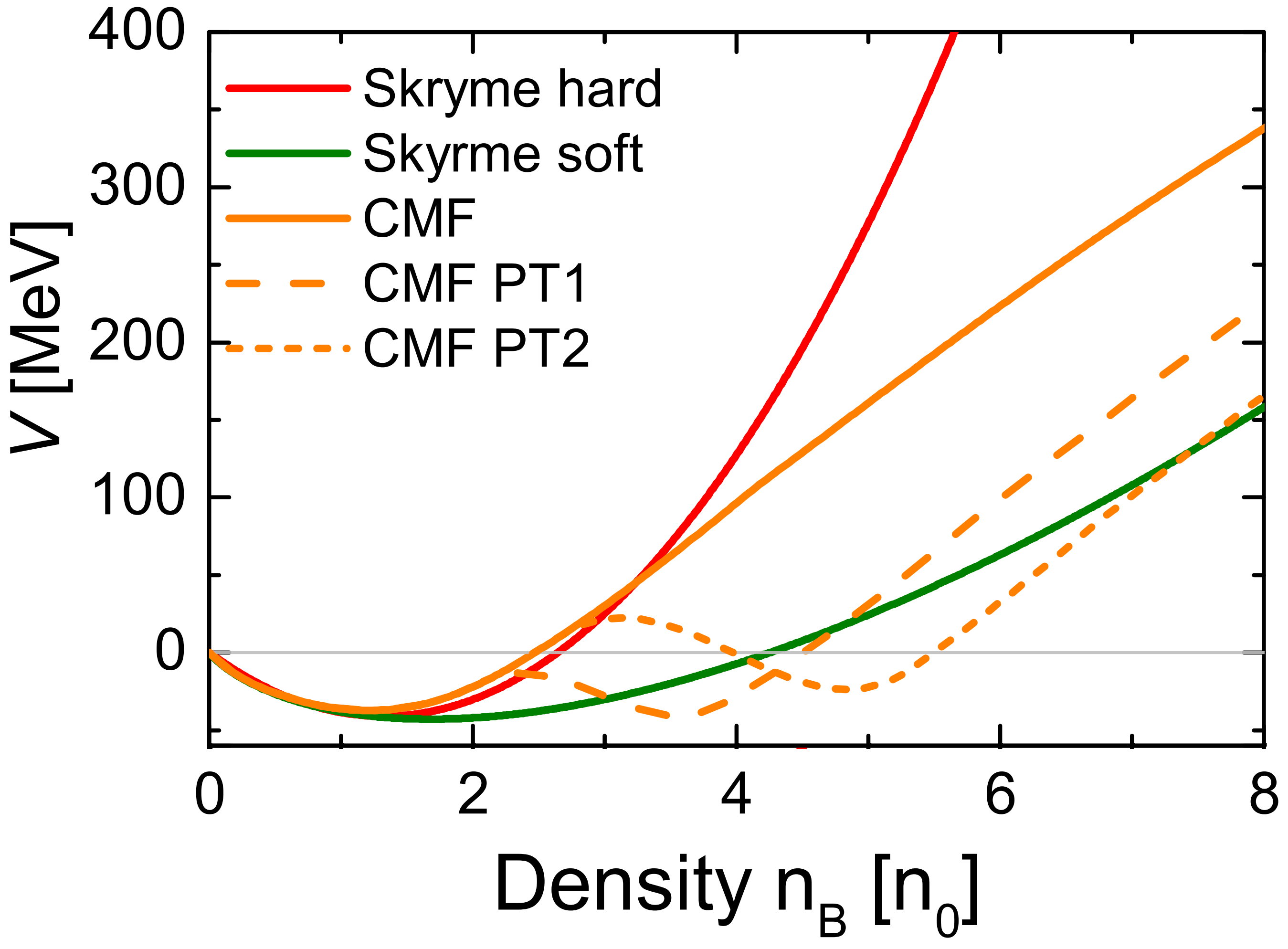
Massive neutron stars and heavy-ion collision data can be described with one EOS

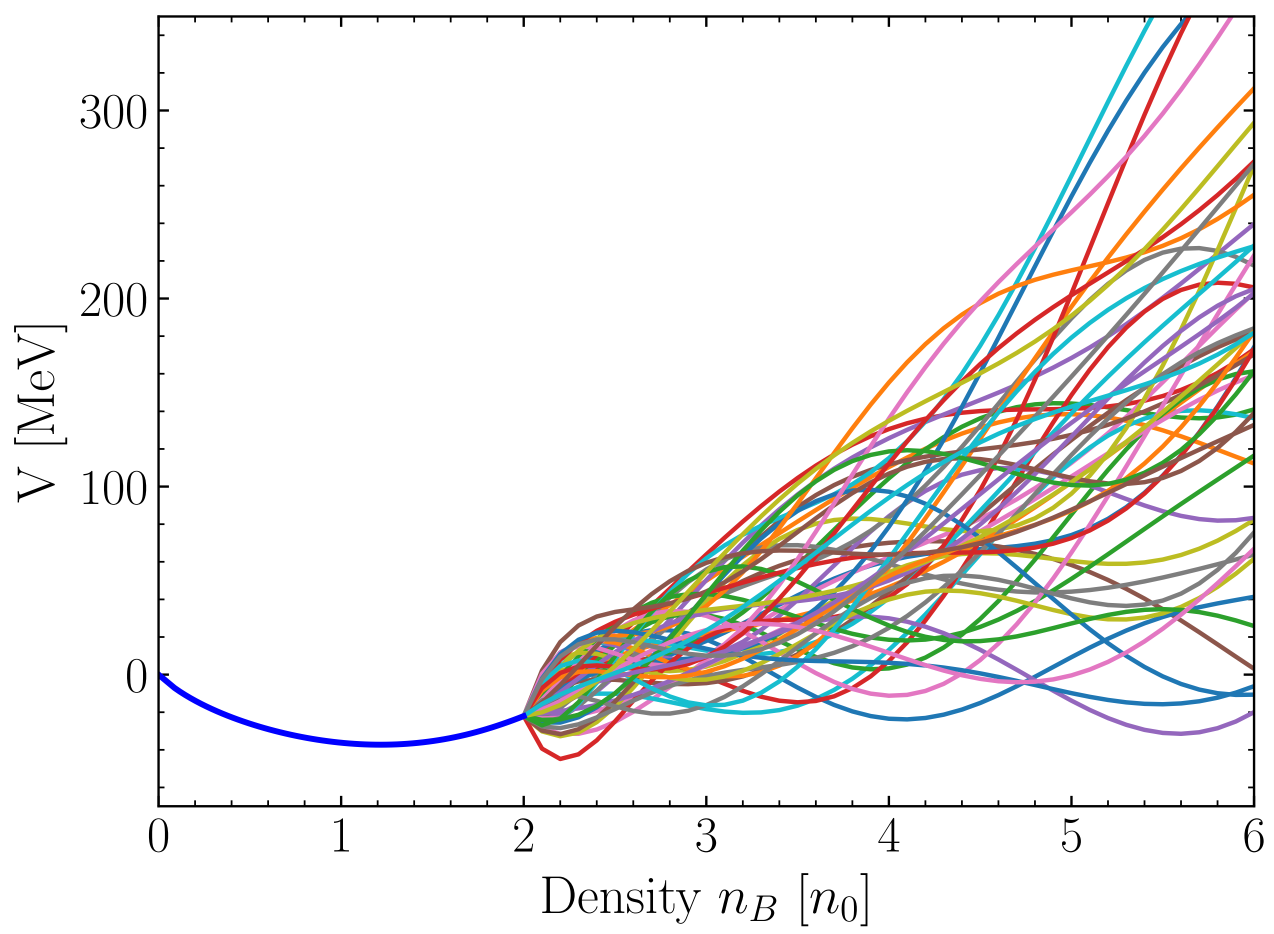




N. Yao, **A. Sorensen**, V. Dexheimer, J. Noronha-Hostler, arXiv:2311.18819

Bayesian analysis of flow data in UrQMD





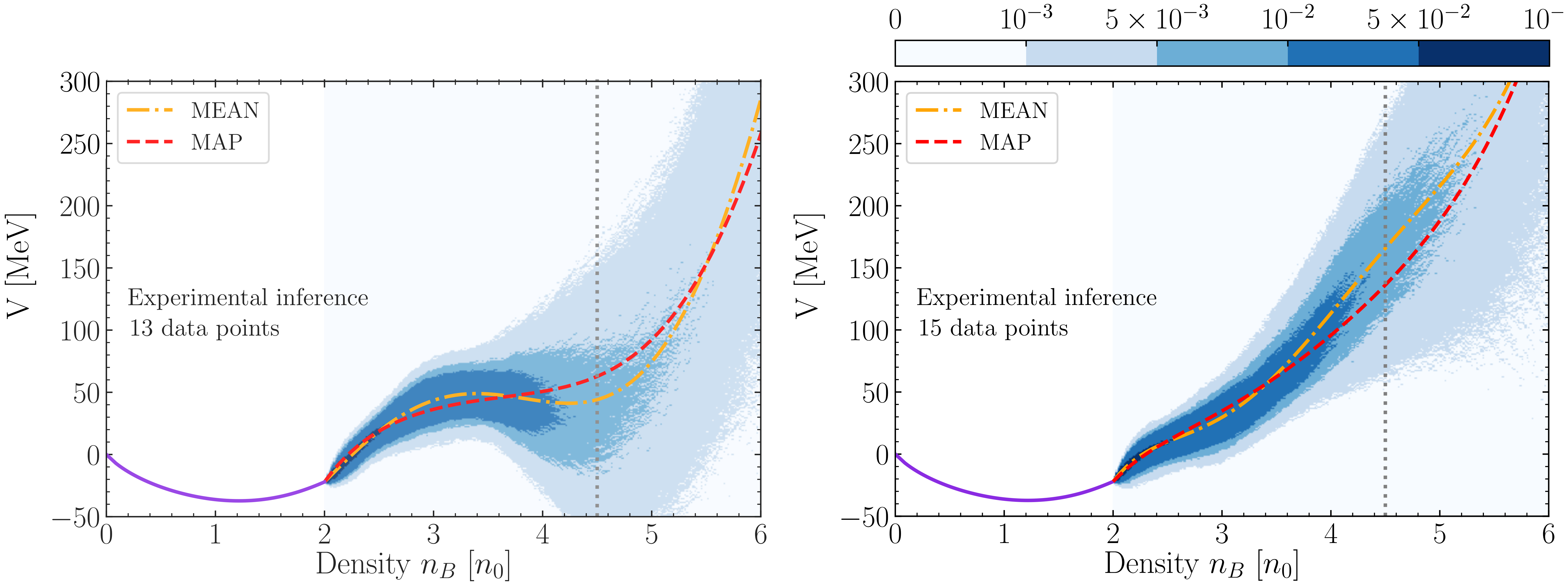
M. Omana Kuttan, J. Steinheimer, K. Zhou, H. Stoecker,
Phys. Rev. Lett. **131** 20, 202303 (2023)
arXiv:2211.11670

$$V(n_B) = \begin{cases} V_{\rm CMF} & n_B \leq 2n_0 \\ \sum_{i=1}^{7} \theta_i \left(\frac{n_B}{n_0} - 1\right)^i + C & n_B > 2n_0 \end{cases}$$

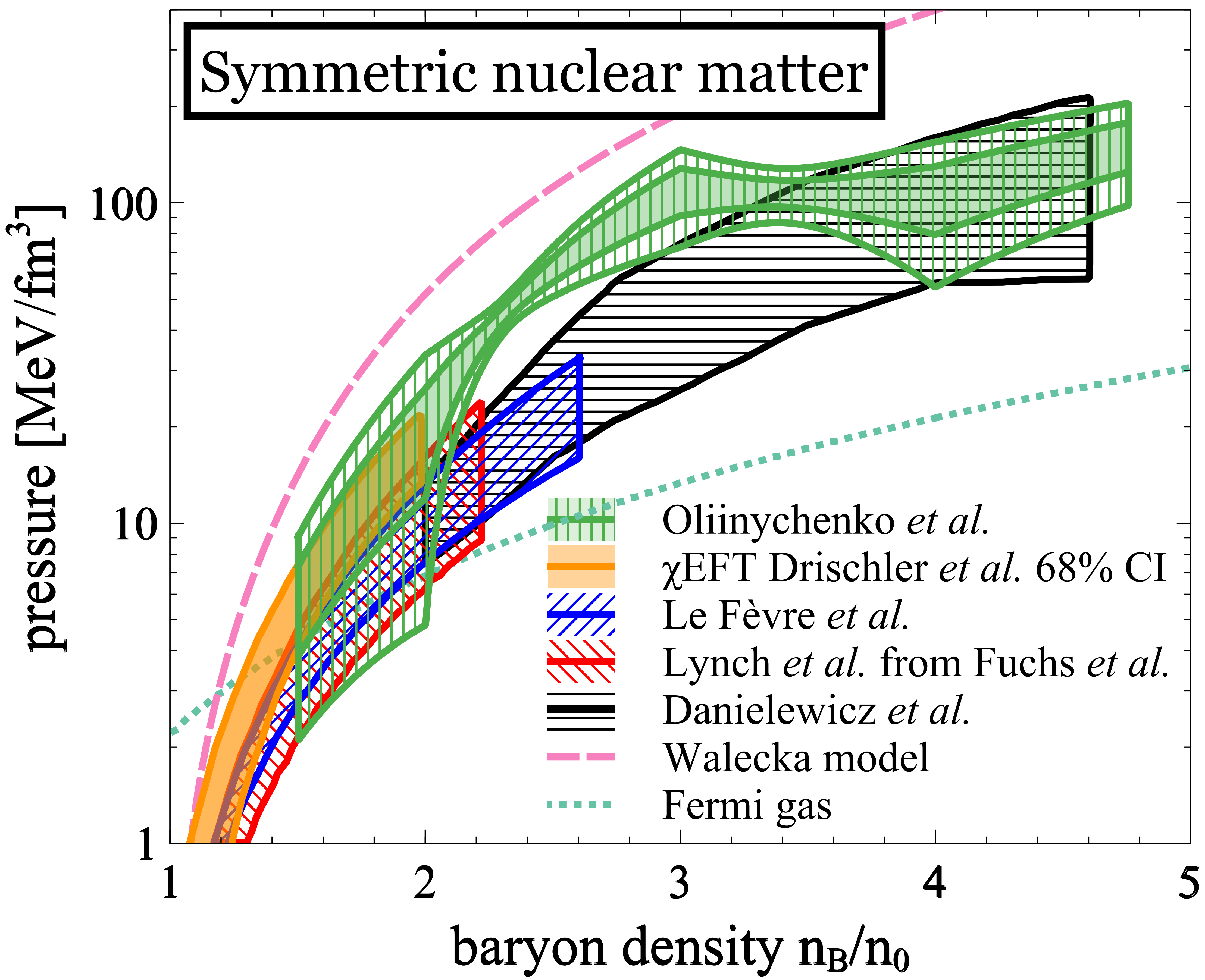
proton mean transverse kinetic energy $\langle m_T \rangle - m_0$:
$\sqrt{s_{\rm NN}} \in [3.83,\ 8.86]$ GeV

proton elliptic flow v_2 at midrapidity:
$\sqrt{s_{\rm NN}} \in [2.24,\ 4.72]$ GeV

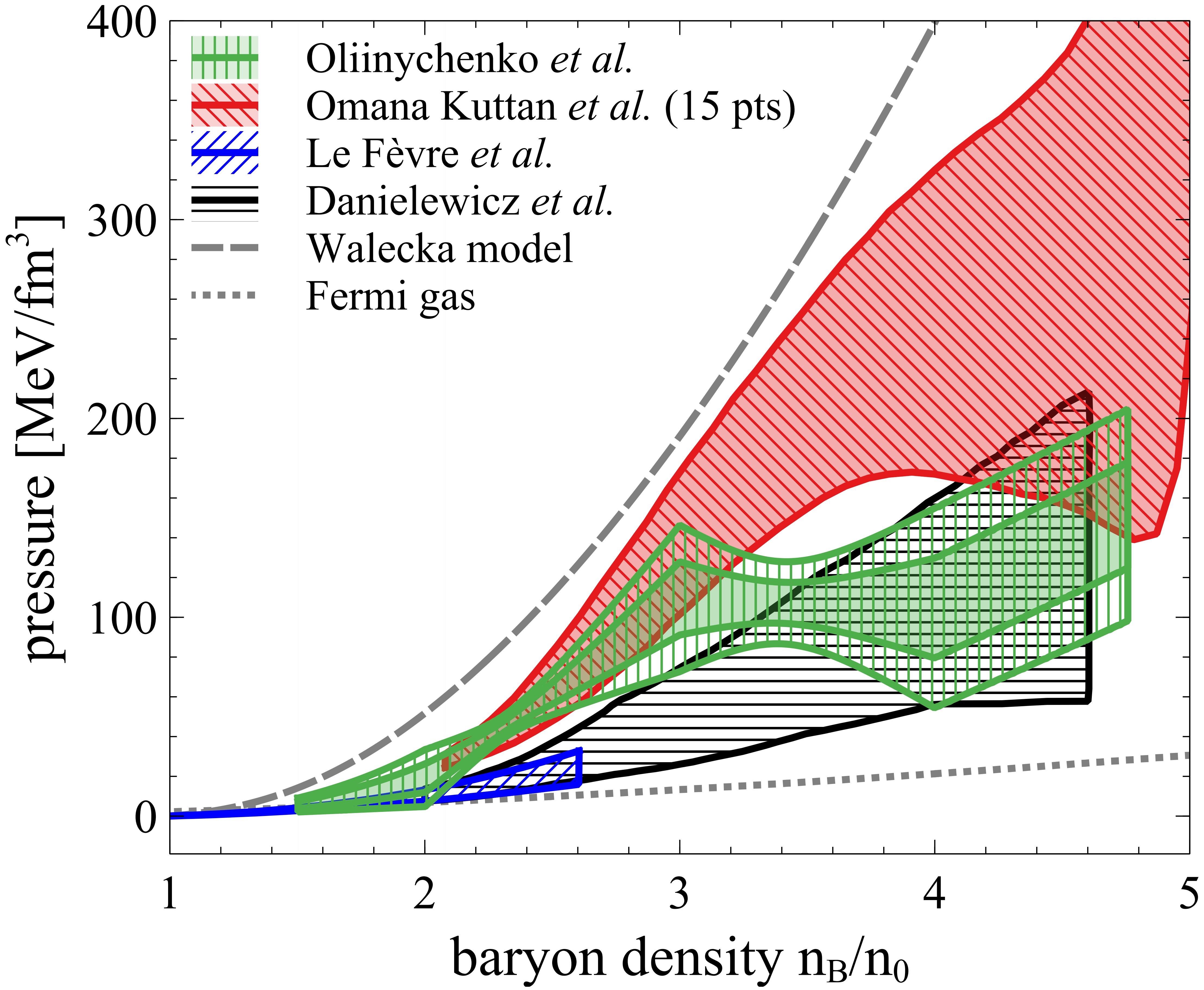
13 points = excluding $\langle m_T \rangle - m_0$
at the two lowest collision energies
$\sqrt{s_{\rm NN}} = 3.83,\ 4.29$ GeV



EOS of symmetric nuclear matter: selected (*few*) results



A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024) arXiv:2301.13253



L. Du, **A. Sorensen**, M. Stephanov, Int. J. Mod. Phys. E (available online), arXiv: 2402.10183

Bayesian analysis of heavy-ion collision and astronomical data

Determination of the equation of state from nuclear experiments and neutron star observations

C.-Y. Tsang, M. B. Tsang, W. G. Lynch, R. Kumar, C. J. Horowitz,
Nature Astron. **8** 3, 328-336 (2024) arXiv:2310.11588

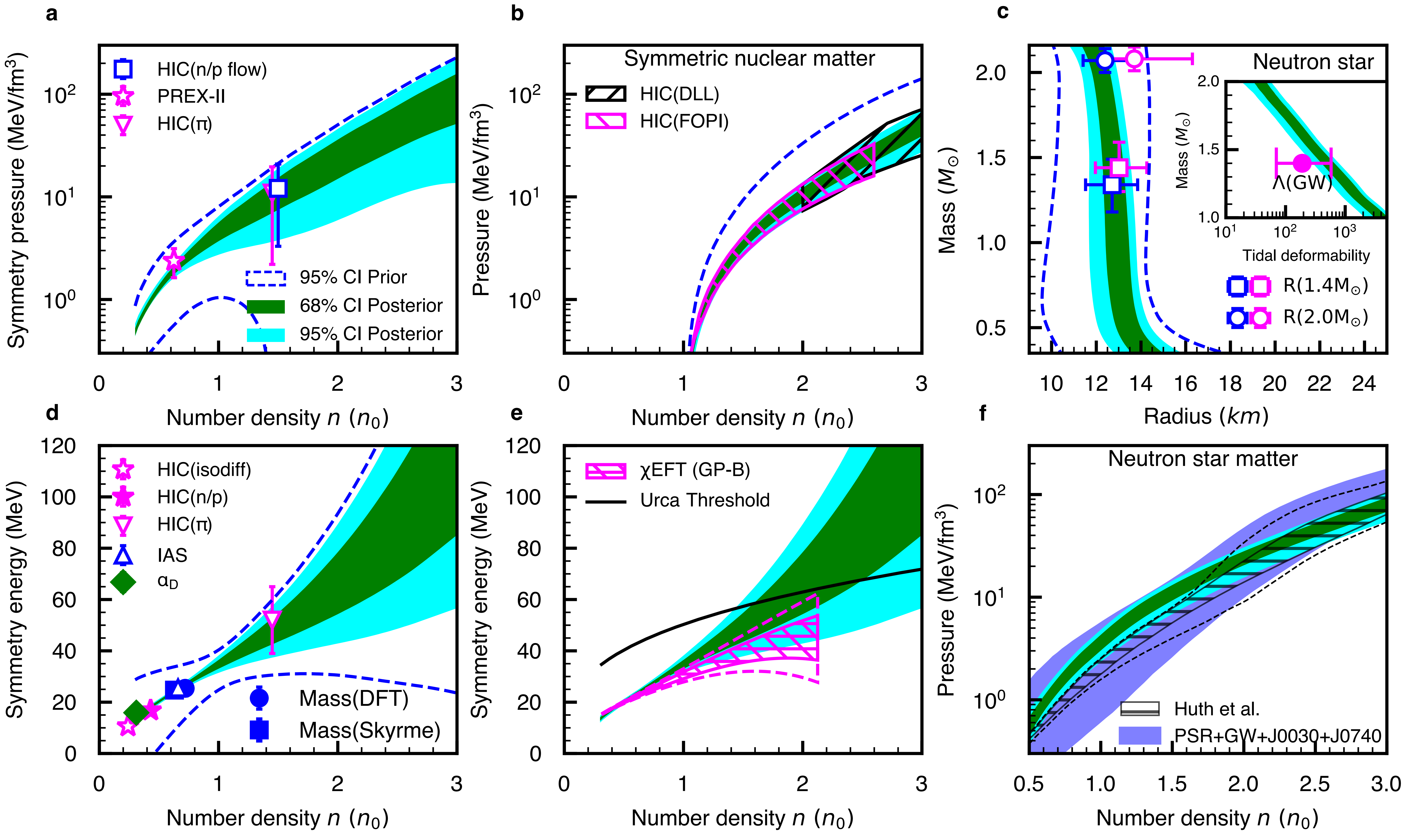
Chun Yuen Tsang, ManYee Betty Tsang, William G. Lynch, Rohit Kumar & Charles J. Horowitz

Symmetric matter Constraints
HIC(DLL)
HIC(FOPI)
GMR

Asymmetric matter Constraints
Nuclear structure
α_D
PREX-II
Nuclear masses
Mass(Skyrme)
Mass(DFT)
IAS
Heavy-ion collisions
HIC(Isodiff)
HIC(n/p ratio)
HIC(π)
HIC(n/p flow)

Astronomical Constraints
LIGO
*Riley PSR J0030+0451
*Miller PSR J0030+0451
*Riley PSR J0740+6620
*Miller PSR J0740+6620

see talk by B. Tsang
Tue 12:00 pm plenary



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Symmetric matter
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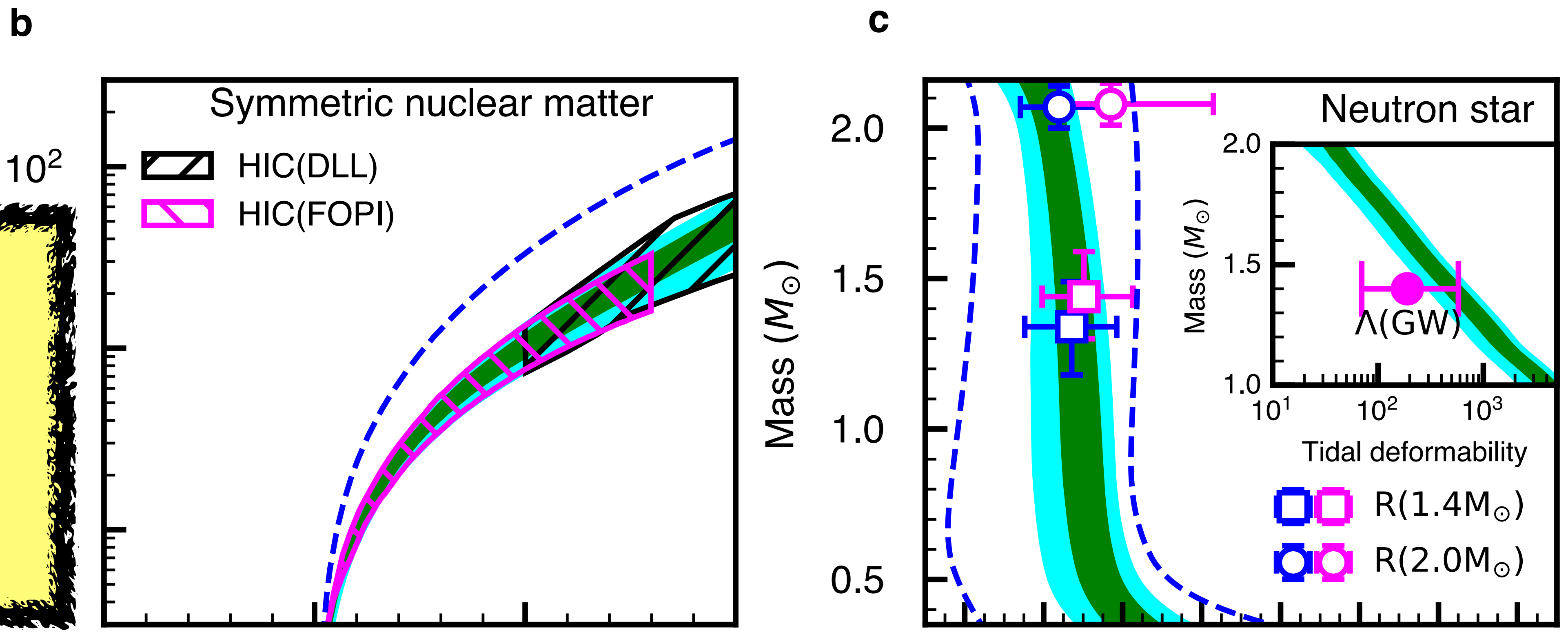


How would the result change if new constraints were used as the input?

DLL is still the state-of-the-art result…

- momentum-dependence
- in-medium cross-sections

also:

- cluster production
- meson potentials
- initial state (e.g., short-range correlations)
- …

… for now :)

Summary

- Heavy-ion collisions at low energies probe multiple fundamental properties of nuclear matter
  - density, isospin, and momentum dependence of nuclear interactions
  - in-medium cross sections
  - cluster production mechanisms
  - ...

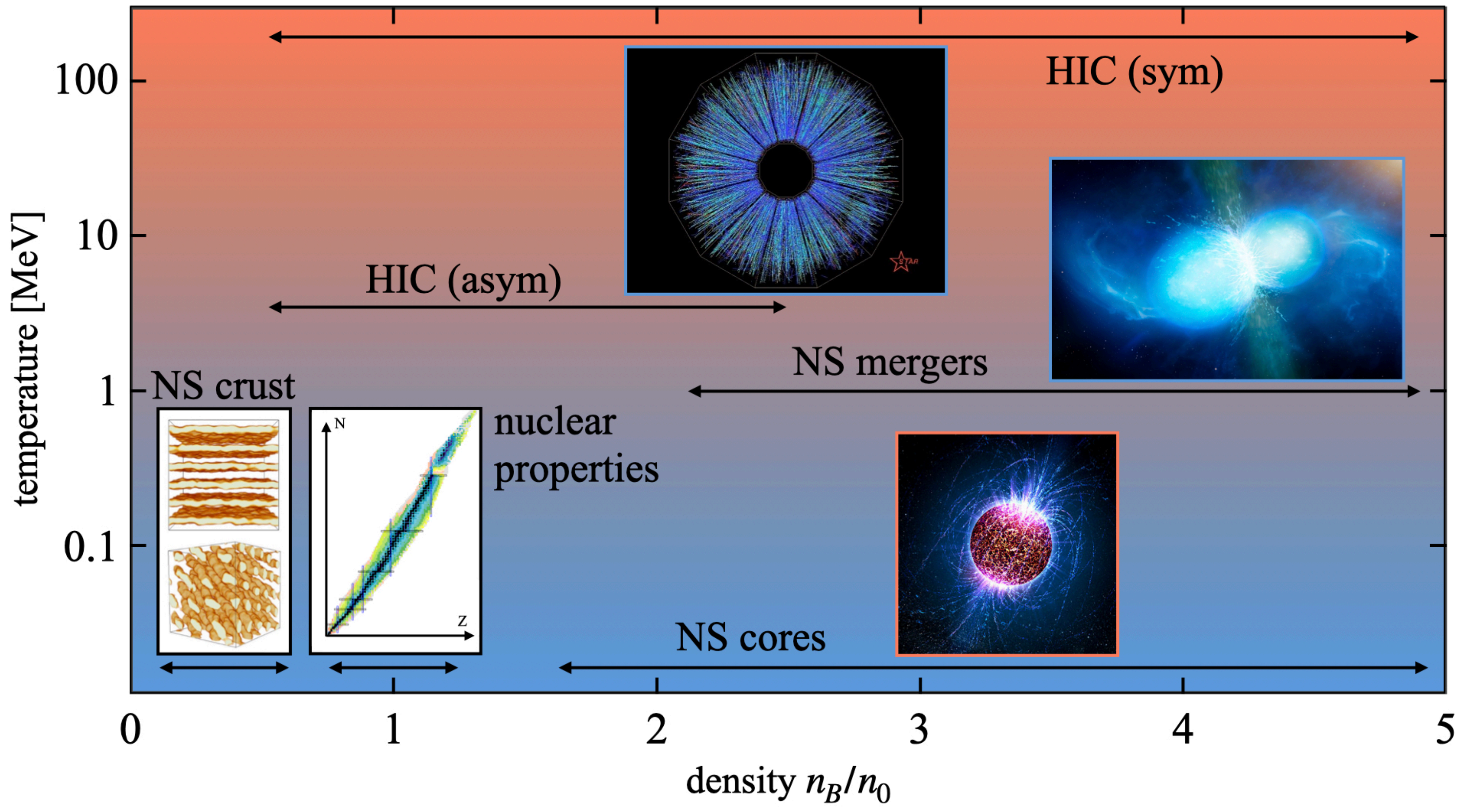
- Transport models needed for interpreting experiments (STAR FXT, HADES, FRIB, CBM, FRIB400)

- How to reconcile various effects affecting the extraction of the EOS?
  (momentum dependence, in-medium cross sections, cluster production, ...)
  Can we move away from phenomenology and toward guidance from theory?
  (needed *also* to ease the computational cost)
  Some ideas in

A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024) arXiv:2301.13253

Dense Nuclear Matter Equation of State from Heavy-Ion Collisions *

Agnieszka Sorensen[1], Kshitij Agarwal[2], Kyle W. Brown[3,4], Zbigniew Chajecki[5], Paweł Danielewicz[3,6], Christian Drischler[7], Stefano Gandolfi[8], Jeremy W. Holt[9,10], Matthias Kaminski[11], Che-Ming Ko[9,10], Rohit Kumar[3], Bao-An Li[12], William G. Lynch[3,6], Alan B. McIntosh[10], William G. Newton[12], Scott Pratt[3,6], Oleh Savchuk[3,13], Maria Stefaniak[14], Ingo Tews[8], ManYee Betty Tsang[3,6], Ramona Vogt[15,16], Hermann Wolter[17], Hanna Zbroszczyk[18]



- Besides the extraction of the EOS, how can low-energy heavy-ion collisions inform other sub-fields in nuclear physics? (e.g., strangeness interactions important for physics of neutron stars)

Thank you for your attention!