Transport simulations for extracting the properties of dense nuclear matter

Agnieszka Sorensen

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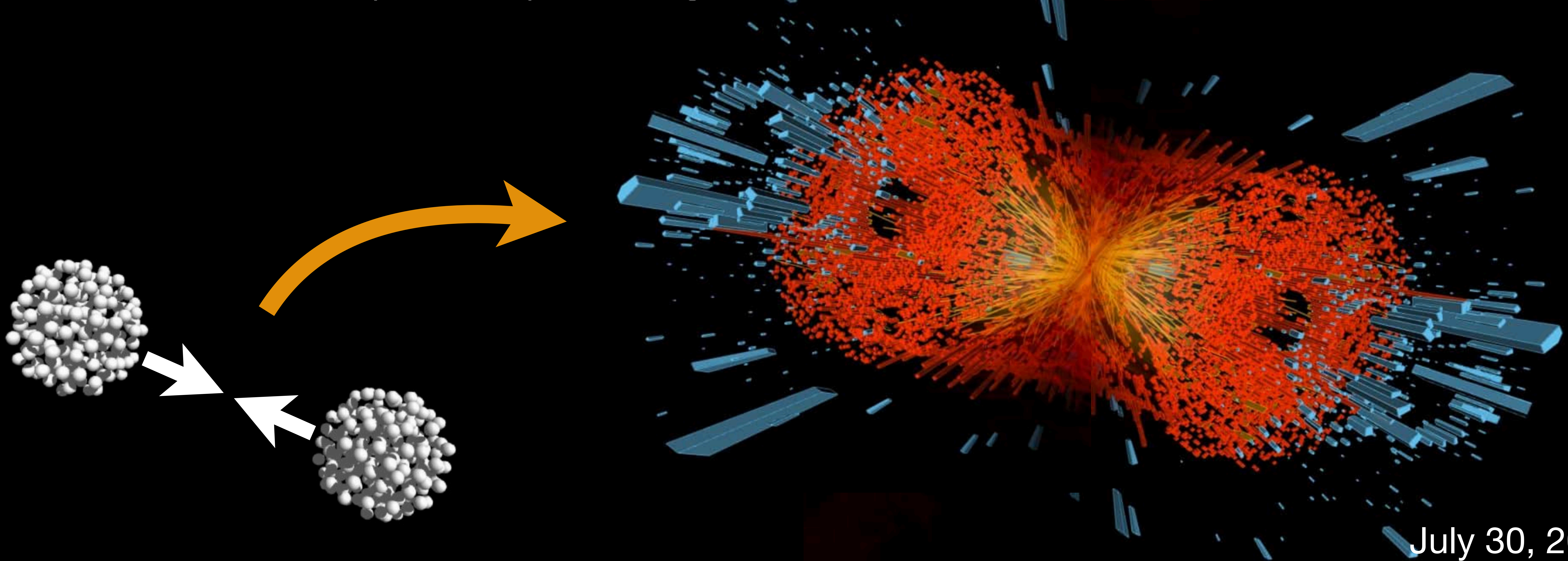


July 30, 2024

INT PROGRAM INT-24-2B

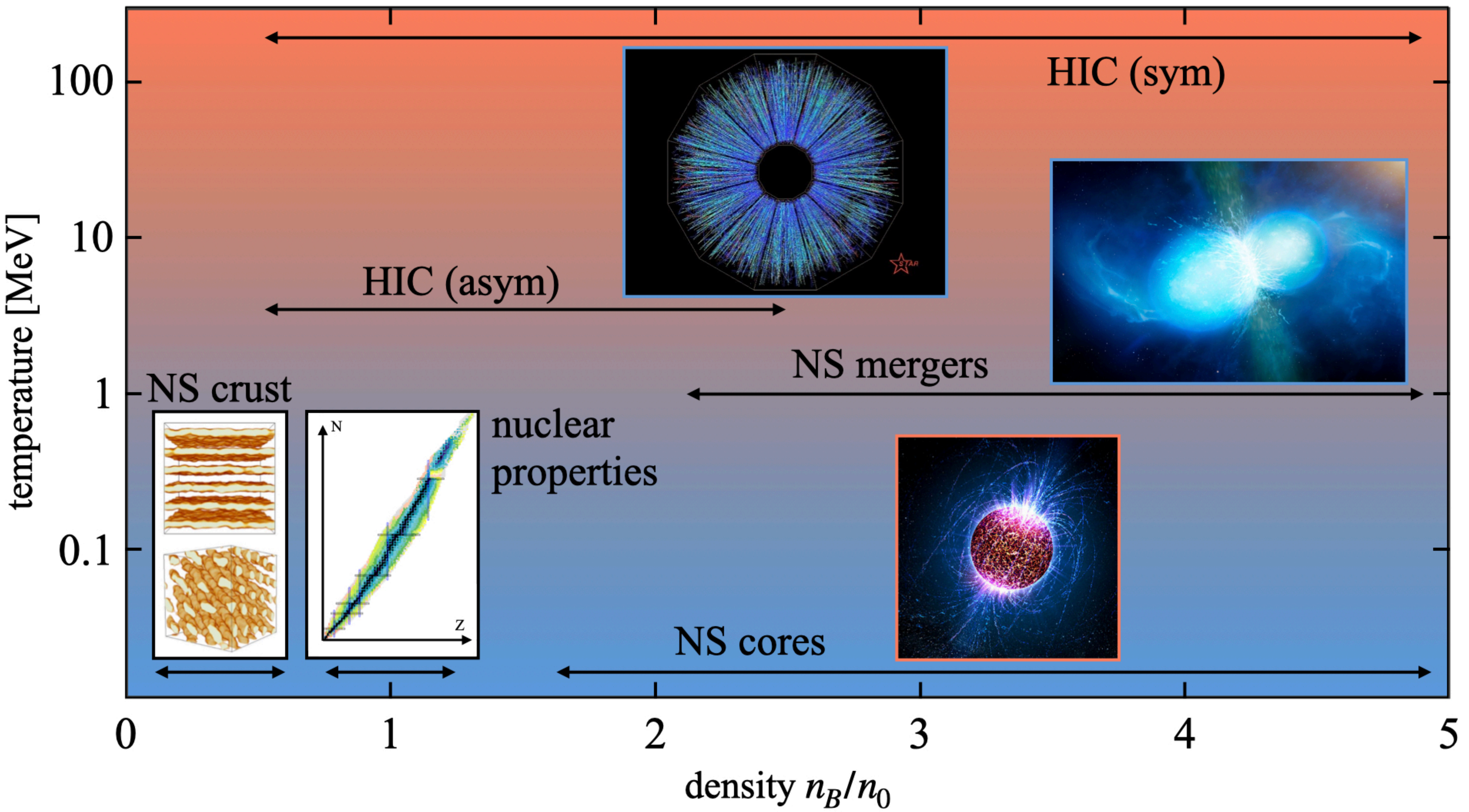
“Heavy Ion Physics in the EIC Era”

Transport simulations for extracting the properties of dense nuclear matter

Outline:

1. Introduction
2. Results: historic & recent
3. Future opportunities

Dense nuclear matter properties = common interest in nuclear physics

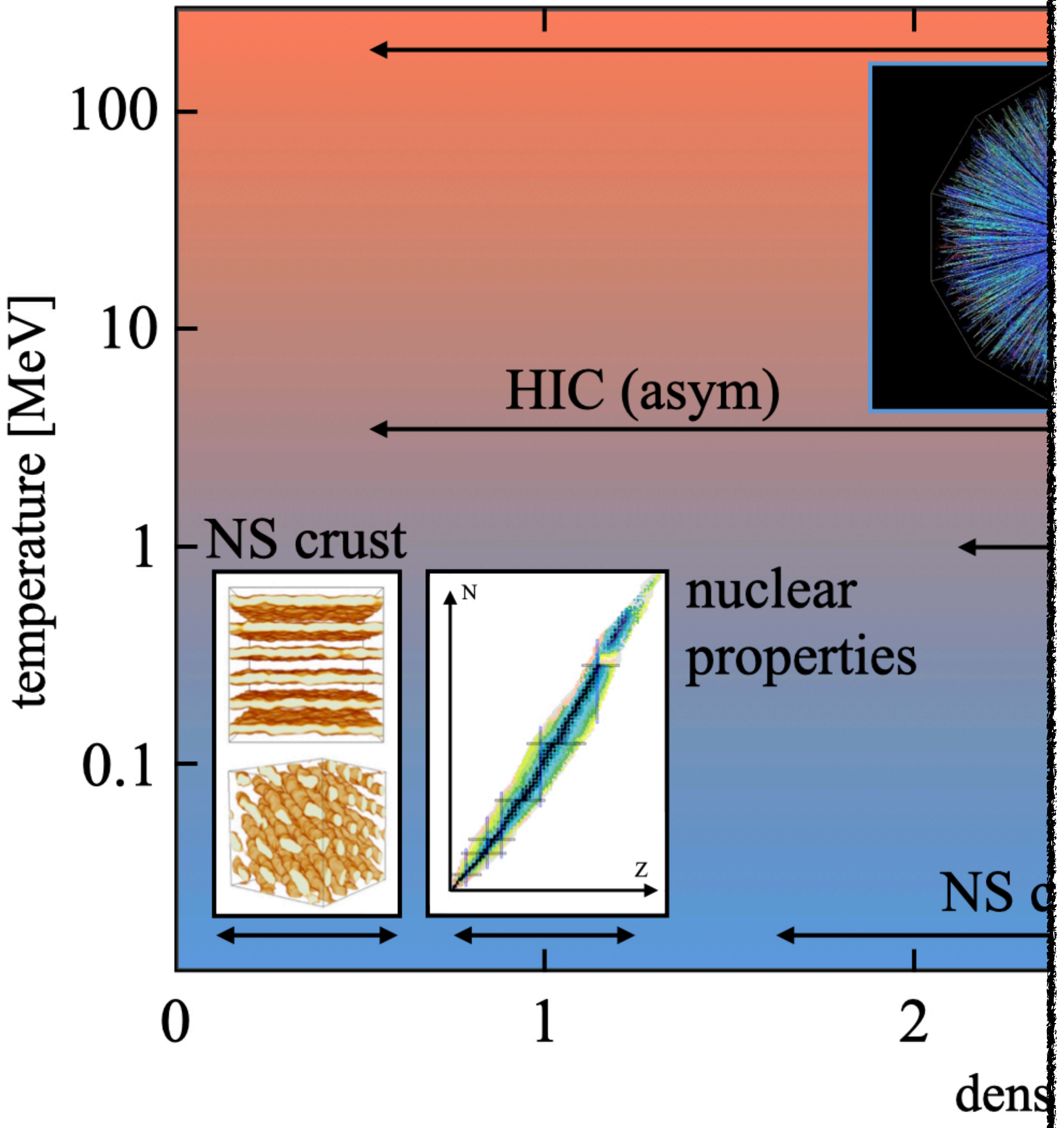


A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024)
arXiv:2301.13253

Properties of dense nuclear matter:

- necessary input to studies of neutron stars & their mergers, supernovae
- reflected in the structure of heavy nuclei
- necessary input to simulations of heavy-ion collisions
- test beds for theories & models
- conveniently "summarized" in the equation of state (EOS)

Dense nuclear matter properties = common interest in nuclear physics



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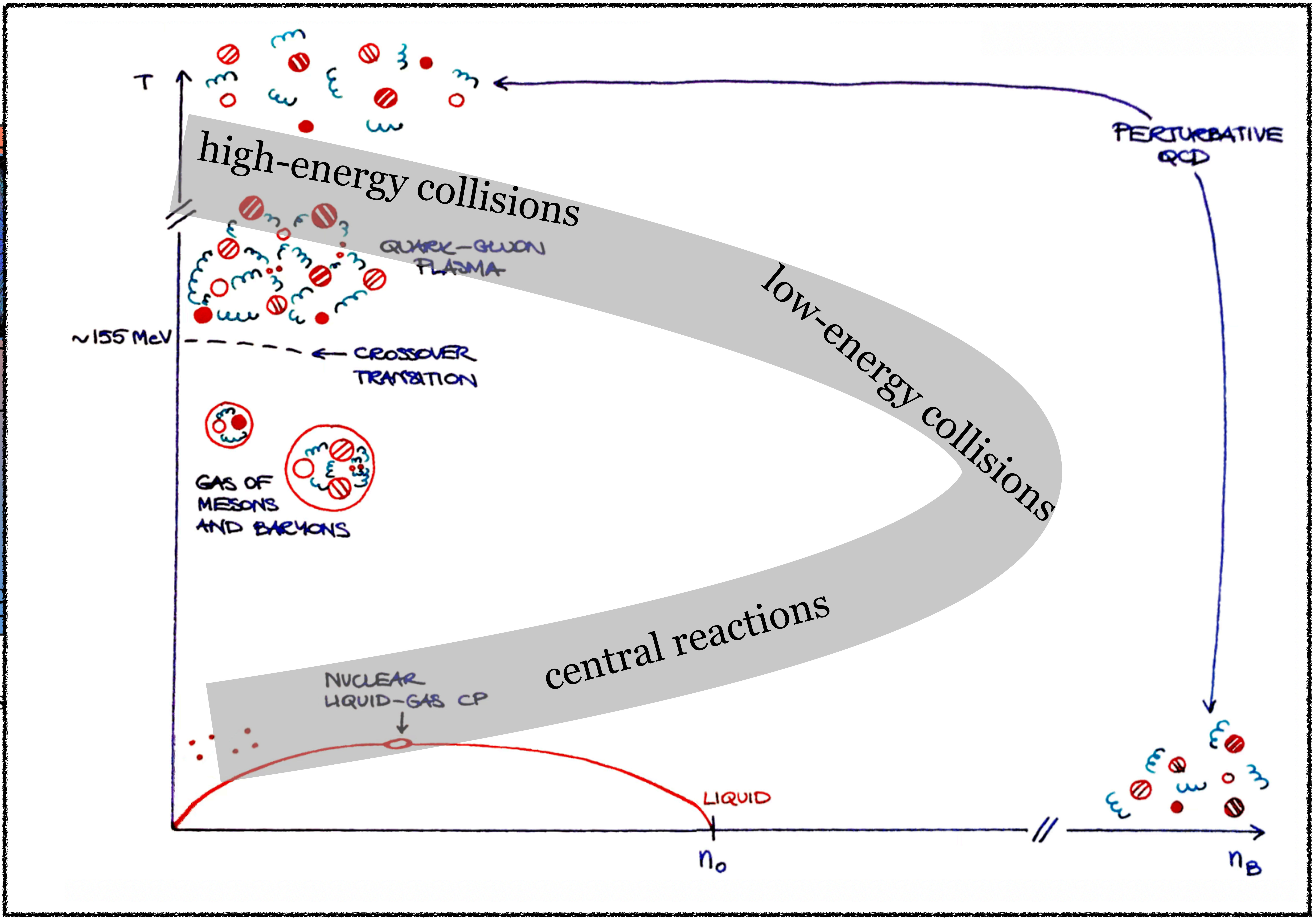
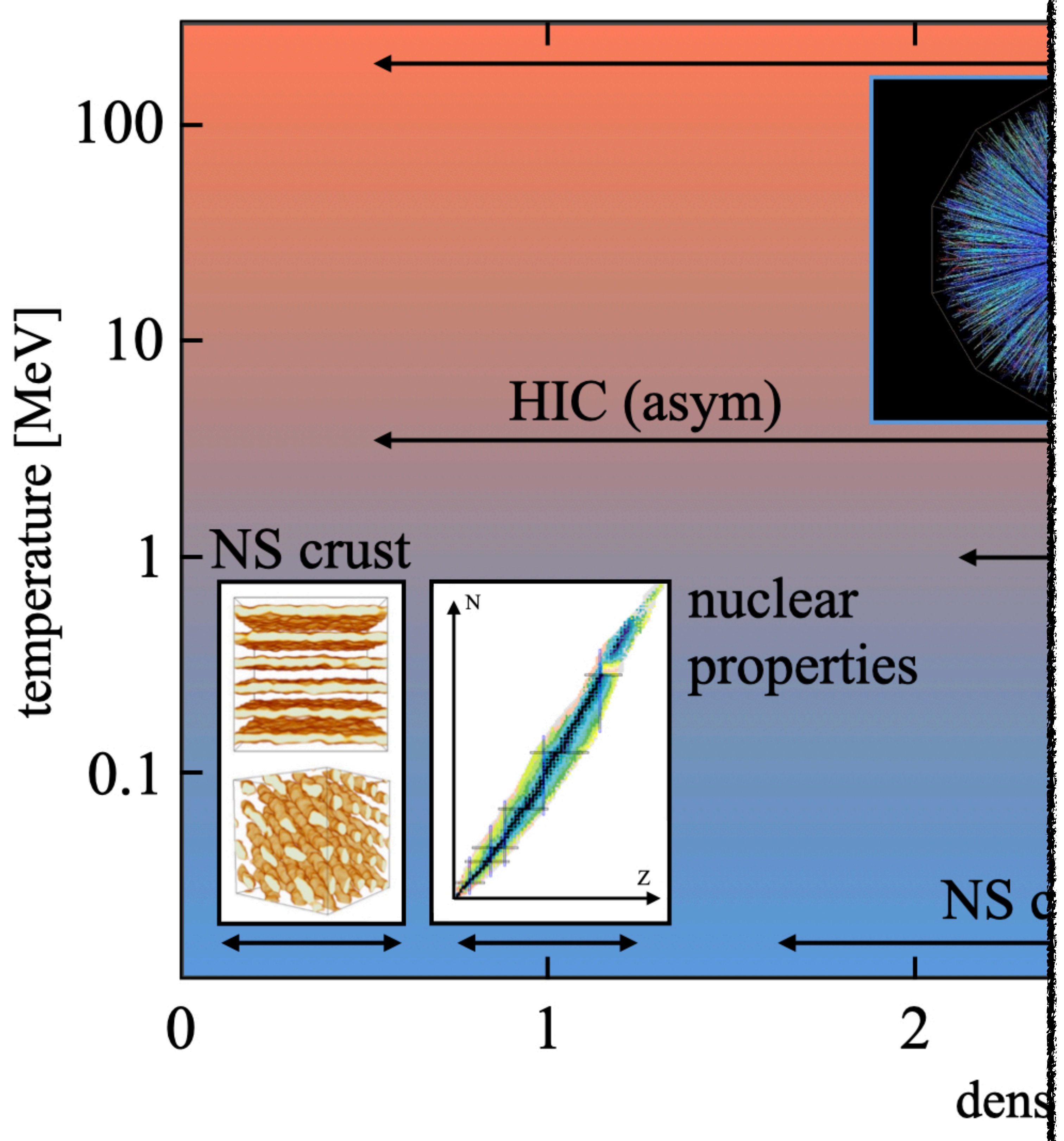


Dense nuclear matter properties = common interest in nuclear physics



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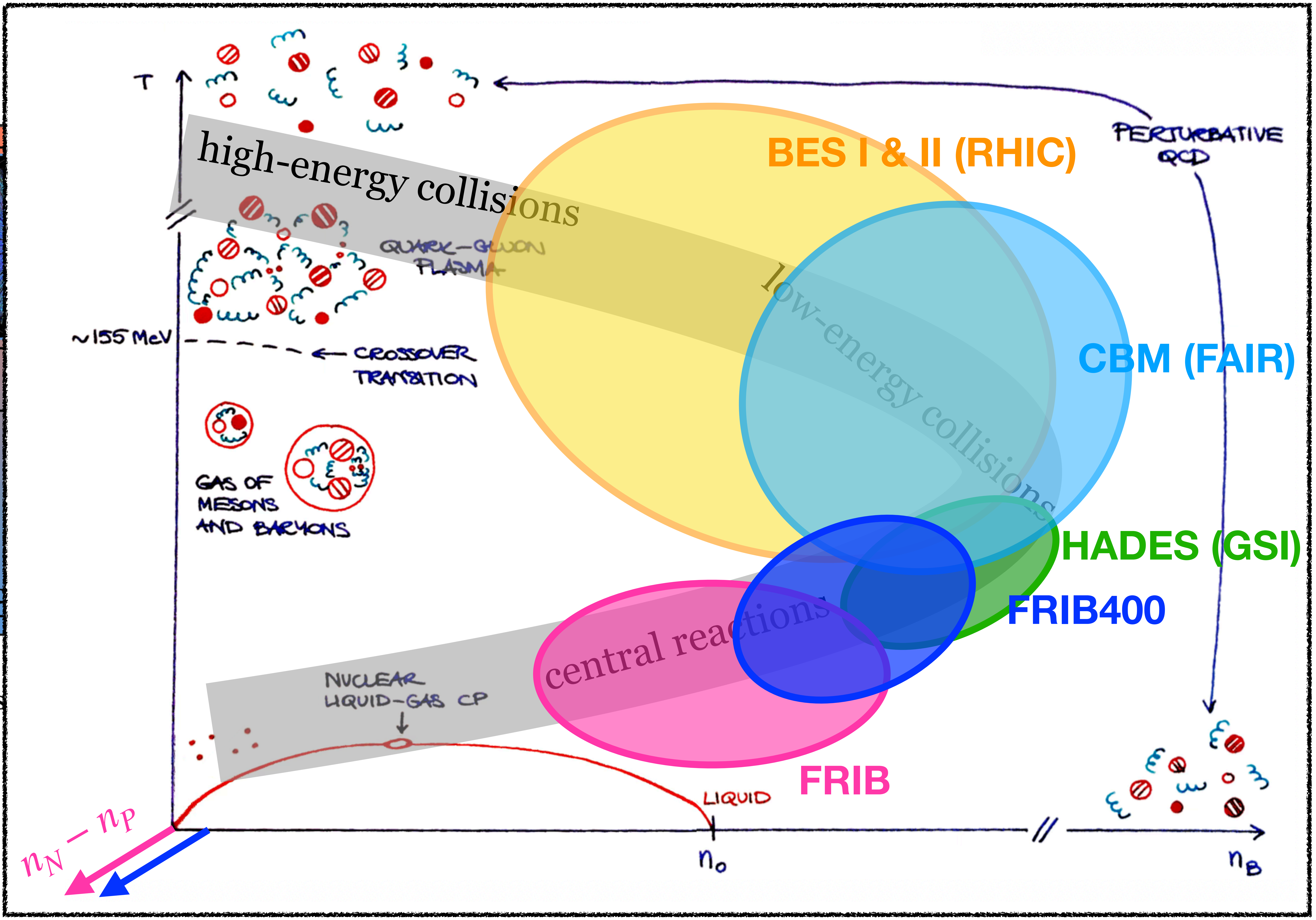

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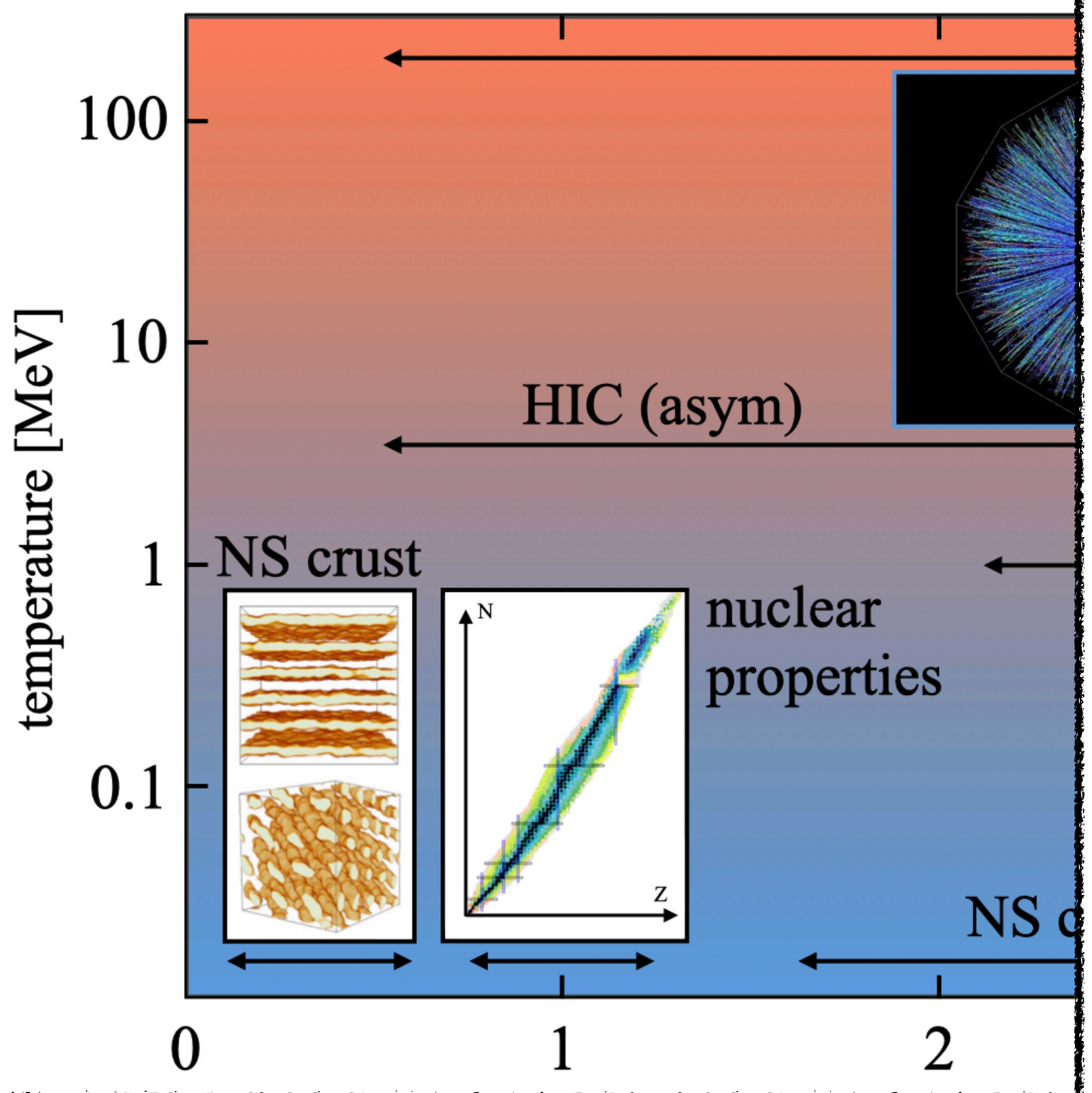
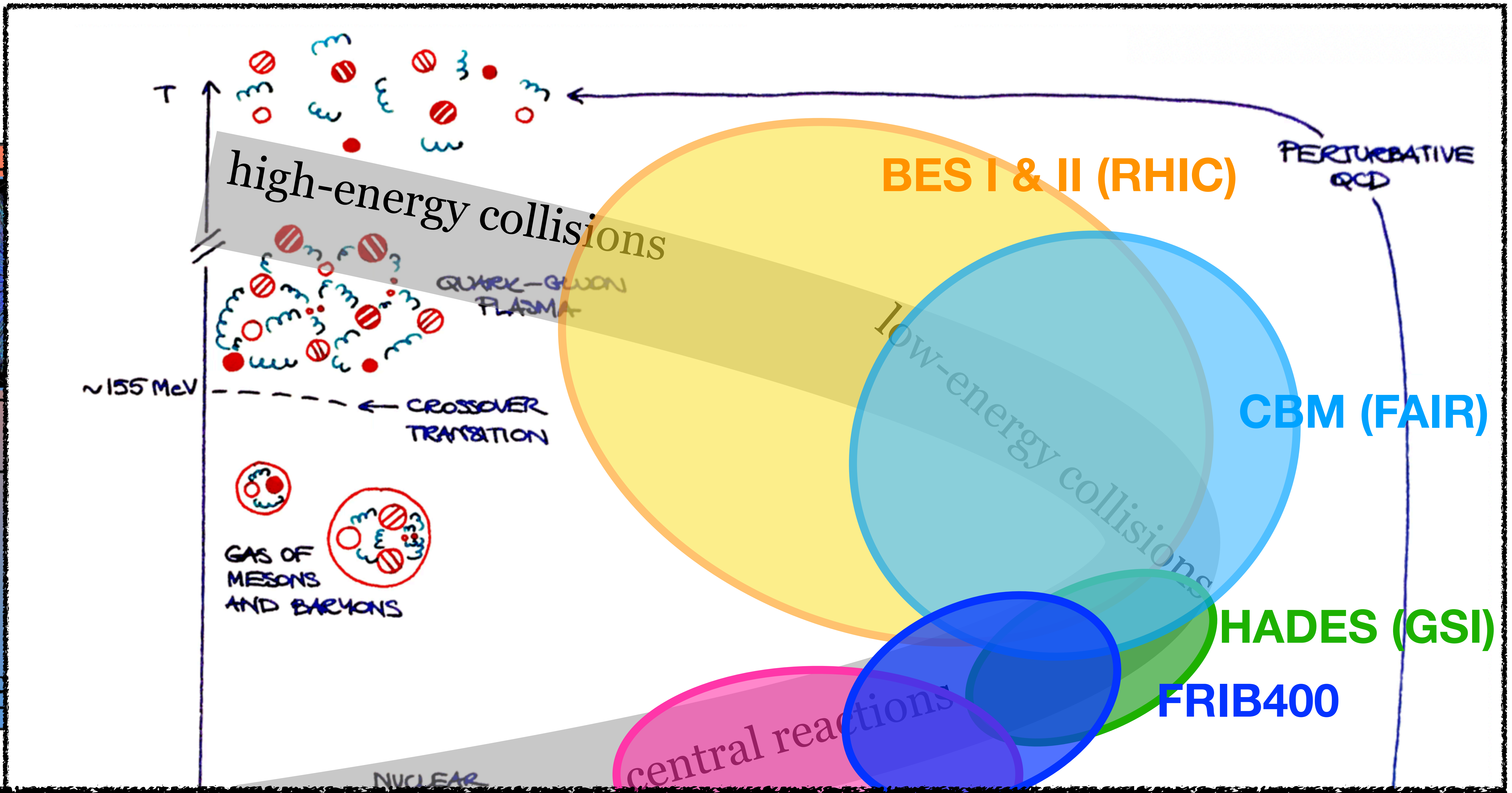
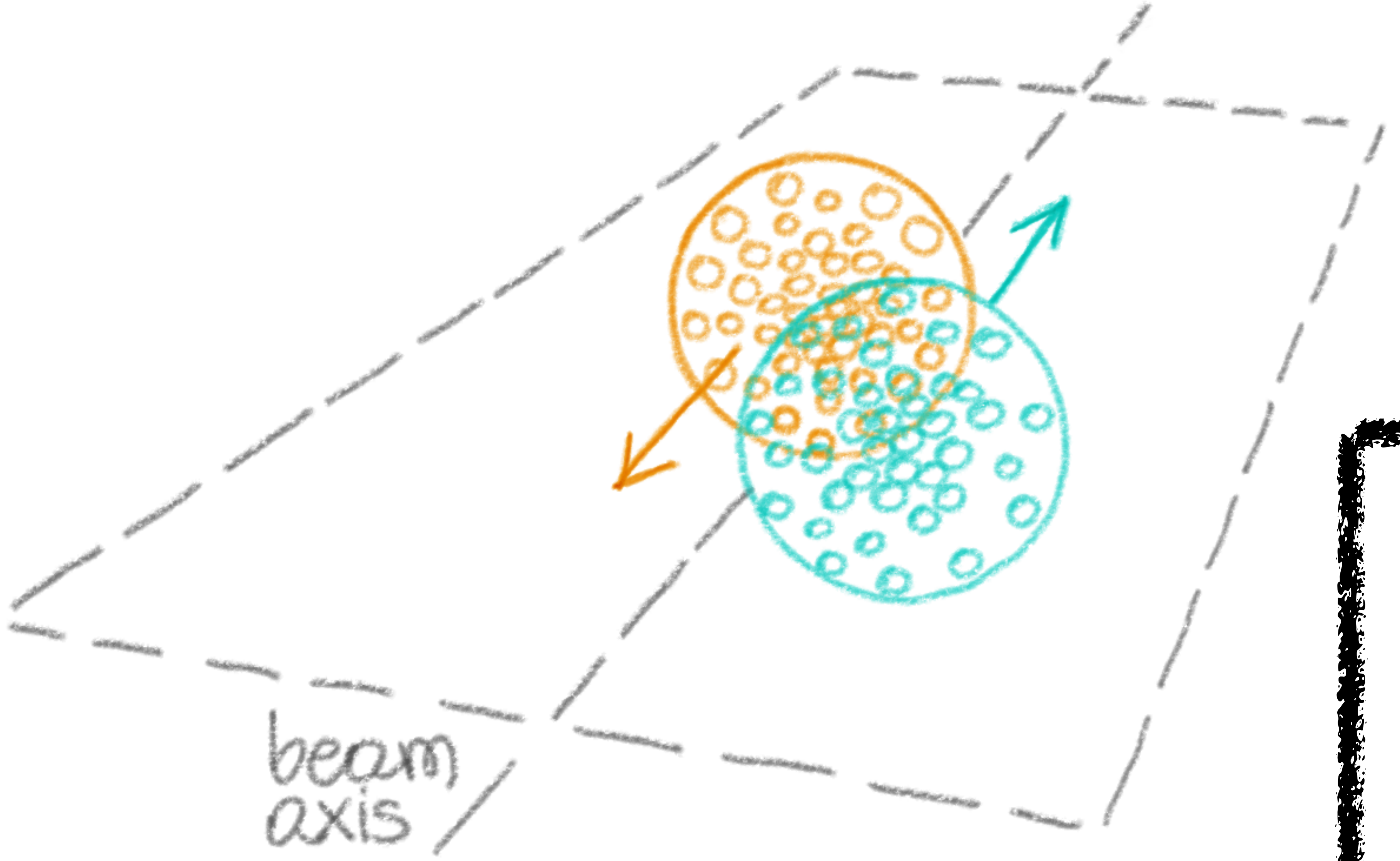




- HICs = the **only** means to probe densities above n_0 in controlled terrestrial experiments
- EOS extracted from comparison to dynamical simulations
- At low energies, prolonged initial state and out-of-equilibrium evolution: **microscopic transport**

Microscopic transport model simulations of heavy-ion collisions

- 2 types of models:
  - Boltzmann-Uehling-Uhlenbeck (BUU): evolve the distribution function of the system
  - Quantum Molecular Dynamics (QMD): evolve wave packets associated with particles



- forces:
  - 2-body interactions ("pure" QMD)
  - gradients of single-particle energies = mean-field (BUU, QMD)
- collisions:
  - based on measured cross sections for scatterings and decays
  - cross sections may be modified in the medium

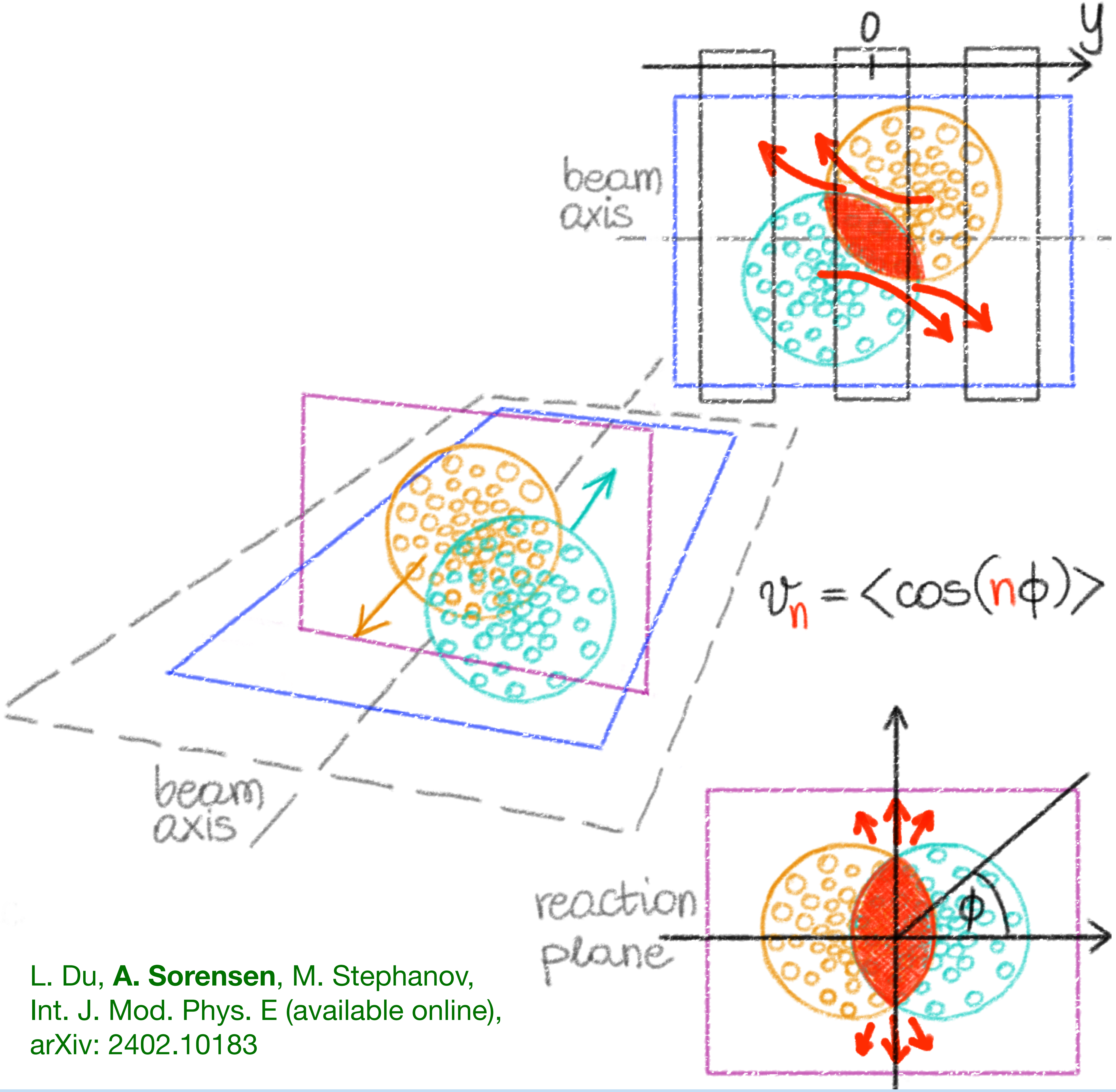
General idea:

- take nucleons from the initial state (nuclei about to collide)
- evolve them in time
- compute observables and compare with experiment

Chapter on "Microscopic transport description of dense nuclear matter dynamics" in a recent review:
L. Du, **A. Sorensen**, M. Stephanov, "The QCD phase diagram and Beam Energy Scan physics: a theory overview", Quark-Gluon Plasma 6, Int. J. Mod. Phys. E (available online), arXiv: 2402.10183

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

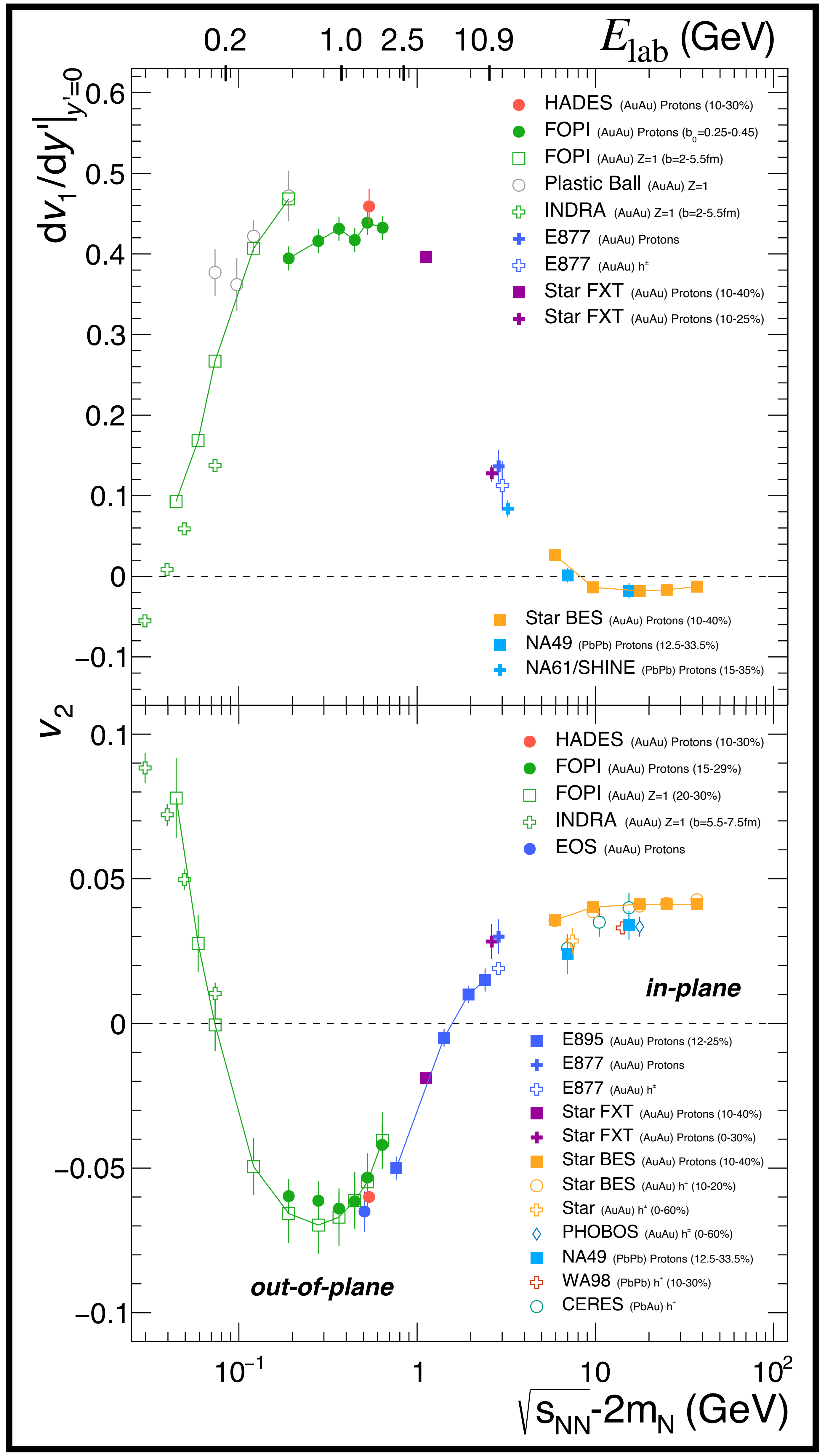
J. Adamczewski-Musch *et al.* (HADES),
Eur.Phys.J.A 59 (2023) 4, 80,
arXiv:2208.02740



v_1 = directed flow

stiffer EOS
=
more pushing

v_2 = elliptic flow



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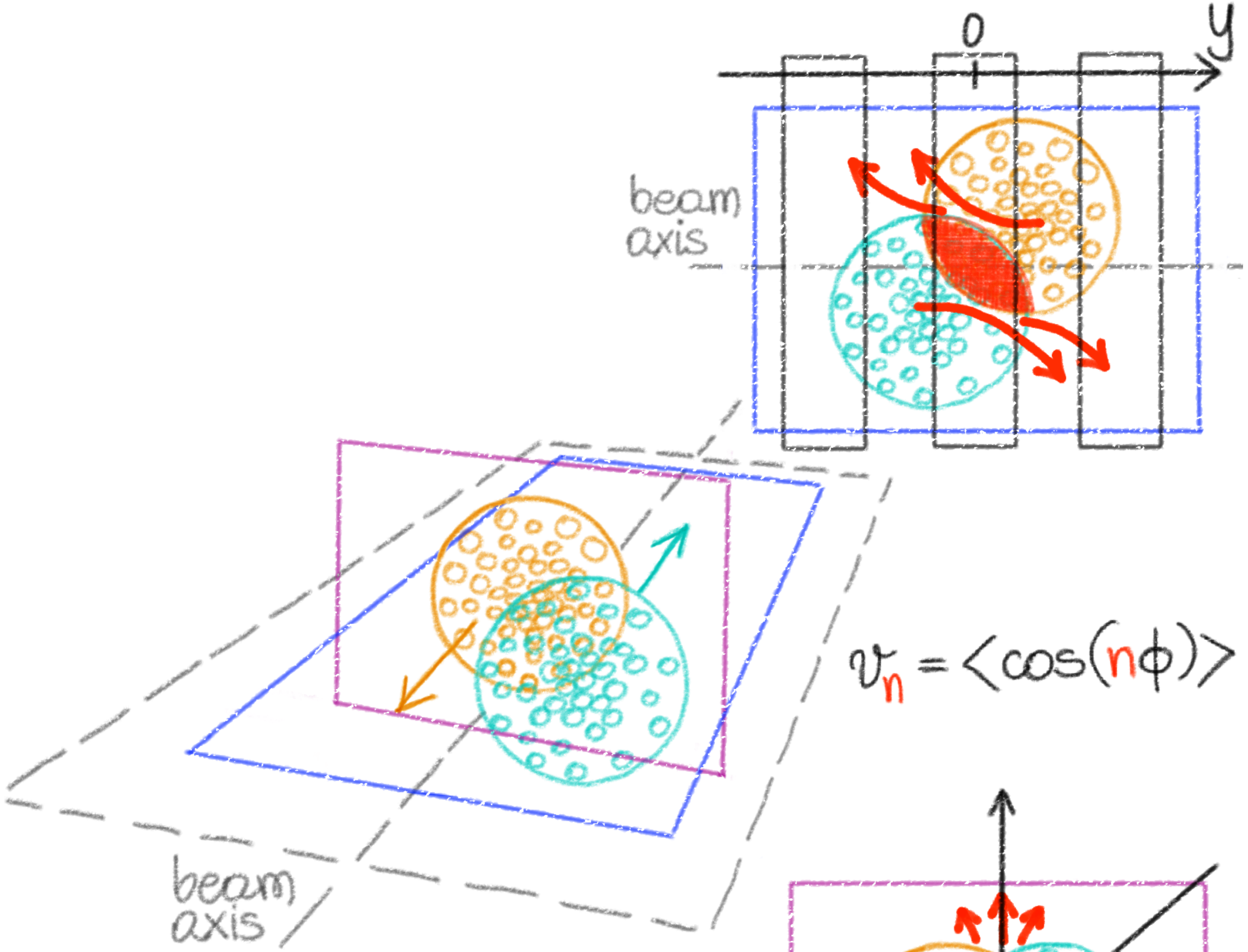

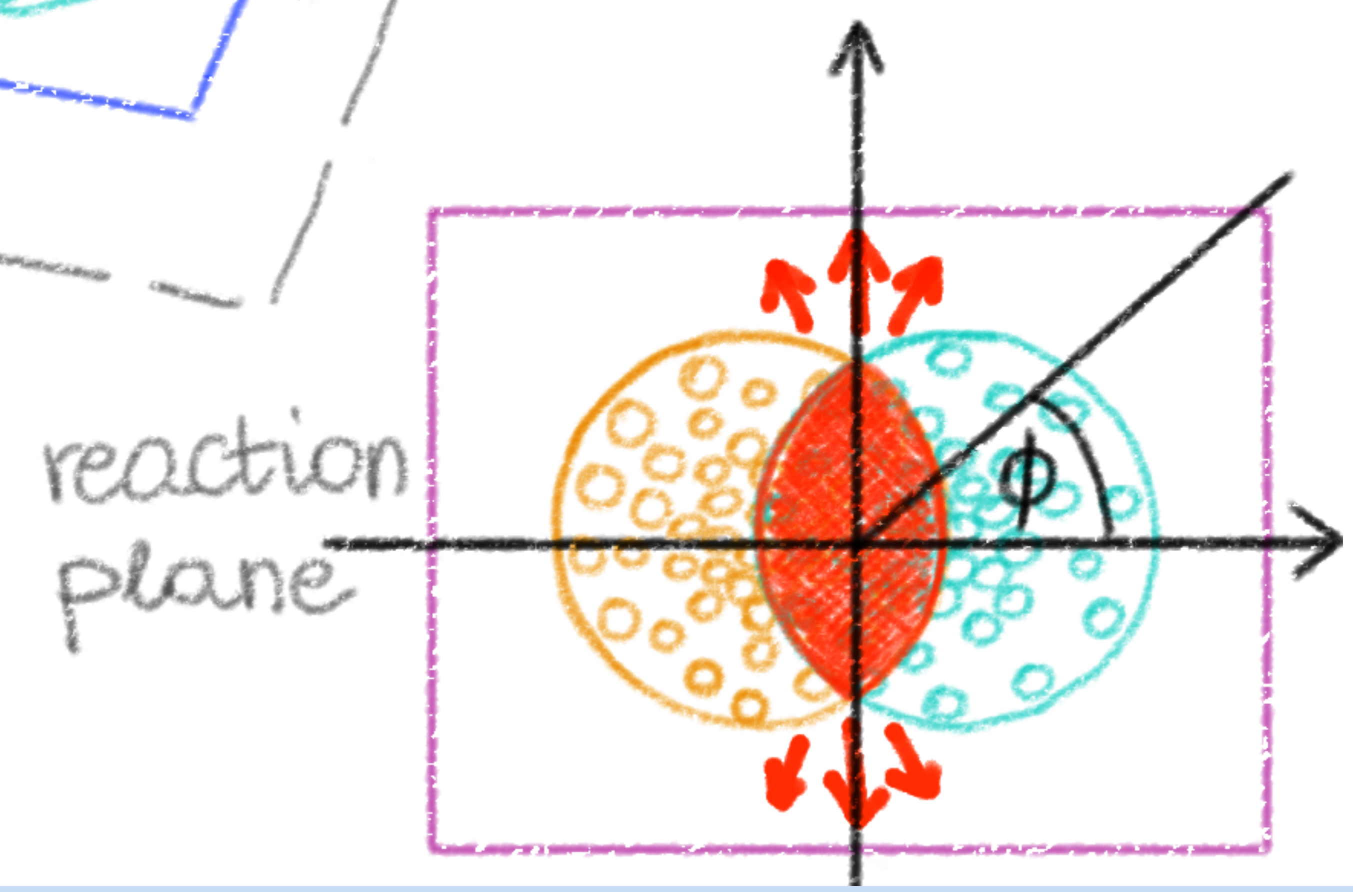

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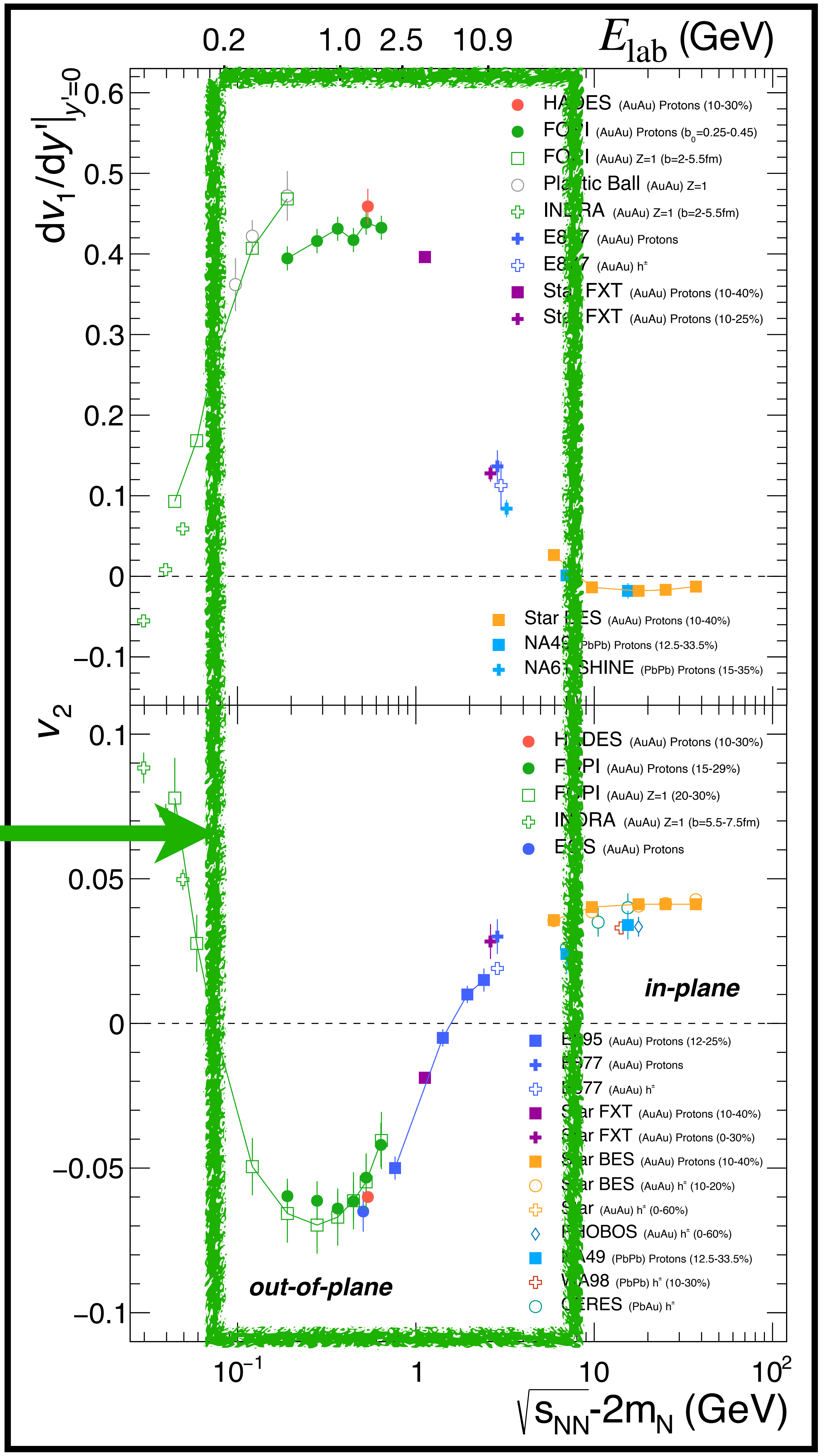
Eur.Phys.J.A 59 (2023) 4, 80,
arXiv:2208.02740

v_1 = directed flow

v_2 = elliptic flow

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



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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
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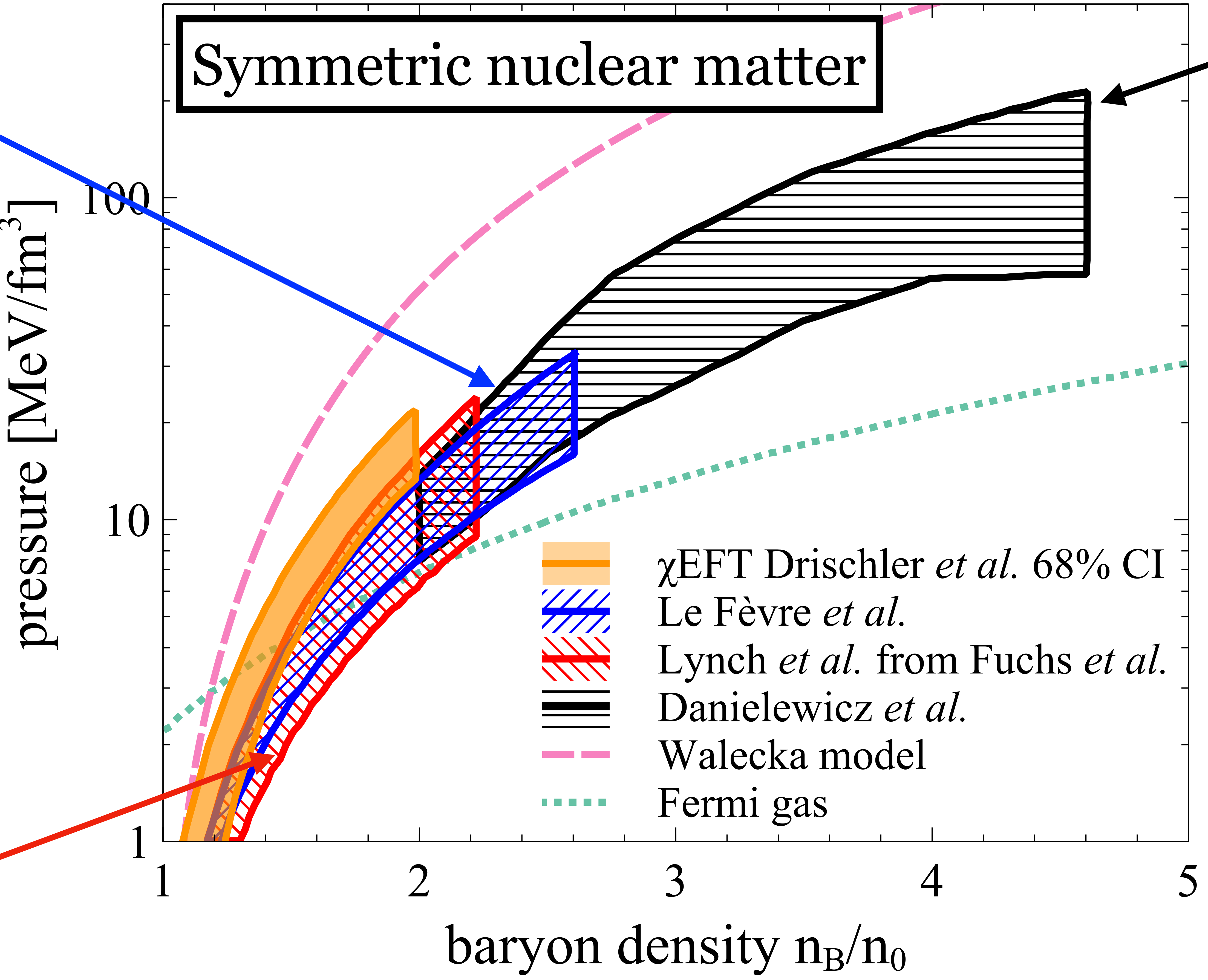
observables: subthreshold kaon production (KaoS)
model used: **QMD** w/ nucleons, Δ, N*(1440), pions, kaons;
EOS parametrized by K_0;
kaon potentials, momentum dependence
C. Fuchs *et al.*, Prog. Part. Nucl. Phys. **53**, 113–124 (2004) arXiv:nucl-th/0312052



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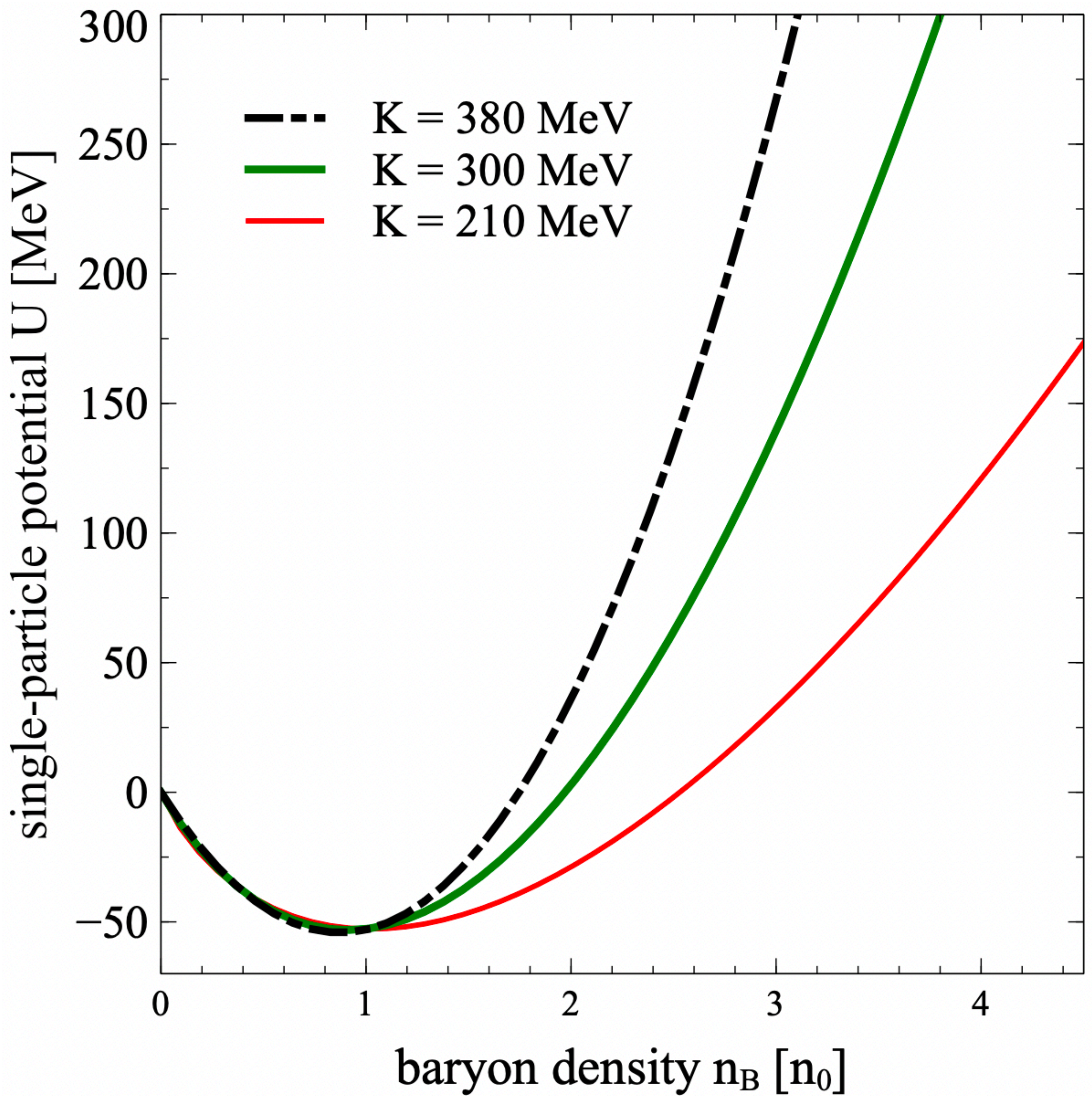
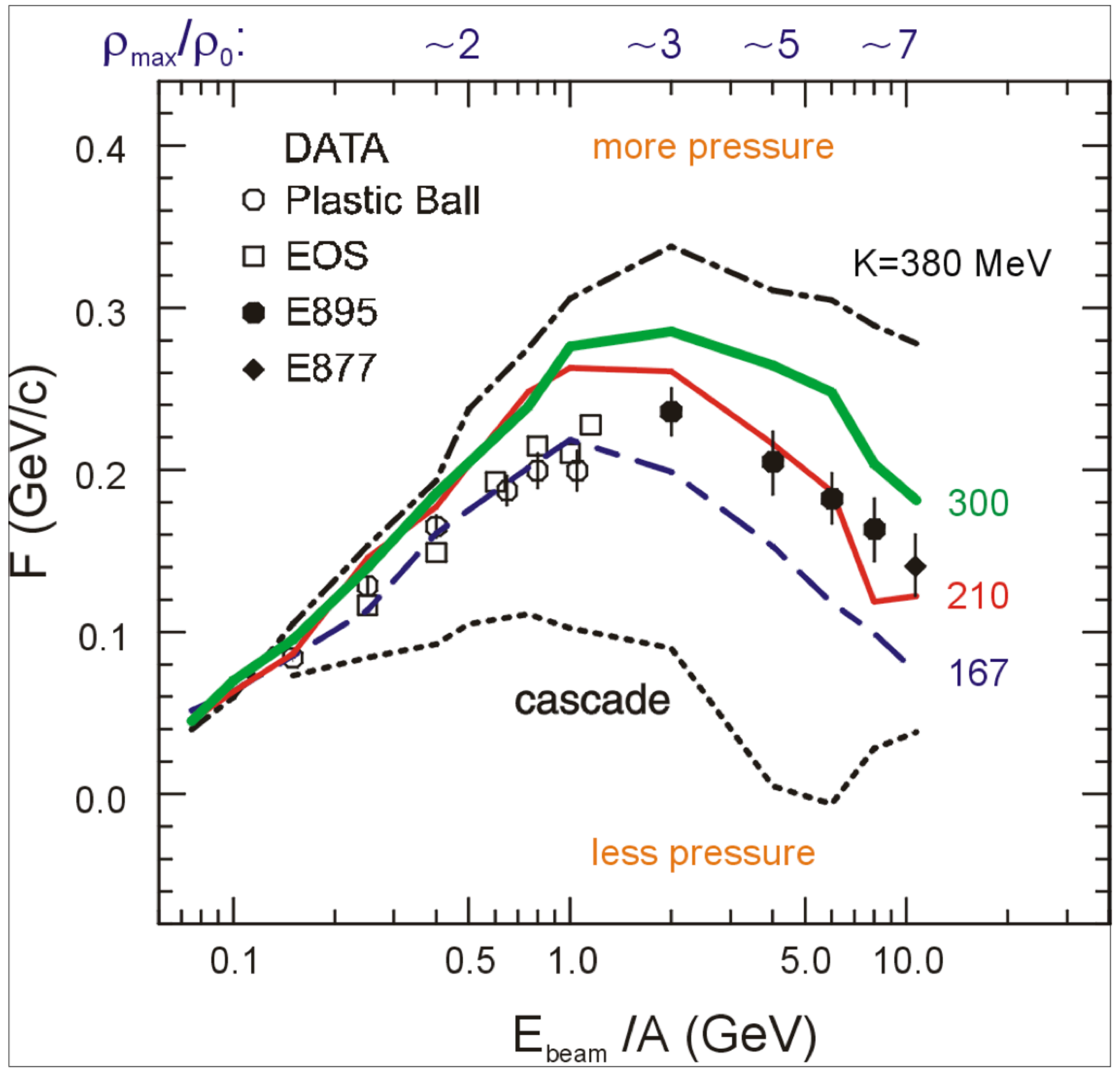
observables: proton flow
(Plastic Ball, EOS, E877, E895)
model used: **pBUU** w/ nucleons, Δ, N*(1440), pions;
EOS parametrized by K_0;
momentum dependence
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

Standard way of modeling the EOS: Skyrme potential

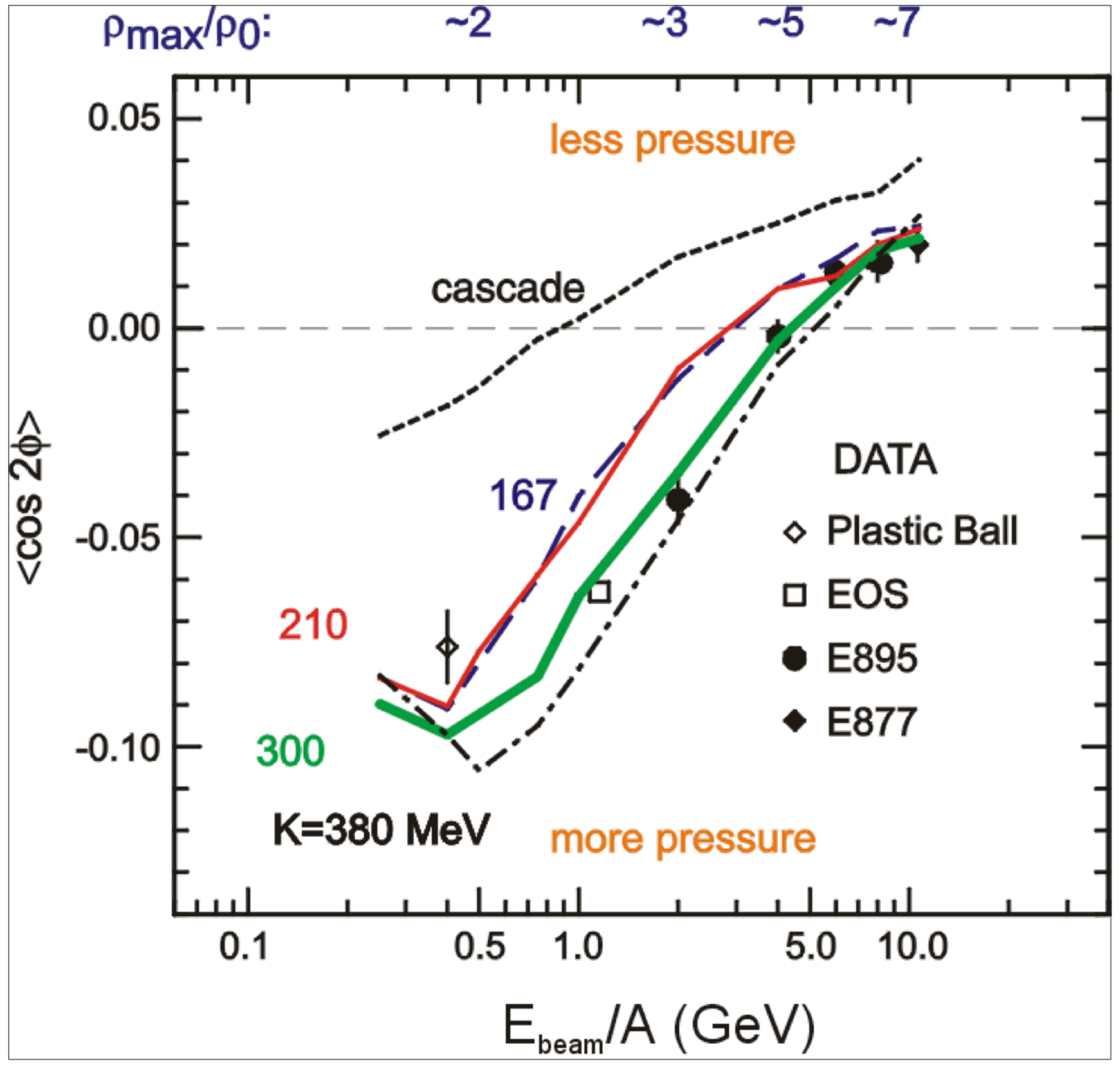
The most common form of the EOS is the "Skyrme potential": $U(n_B) = A\left(\frac{n_B}{n_0}\right) + B\left(\frac{n_B}{n_0}\right)^{\tau}$



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



v_2

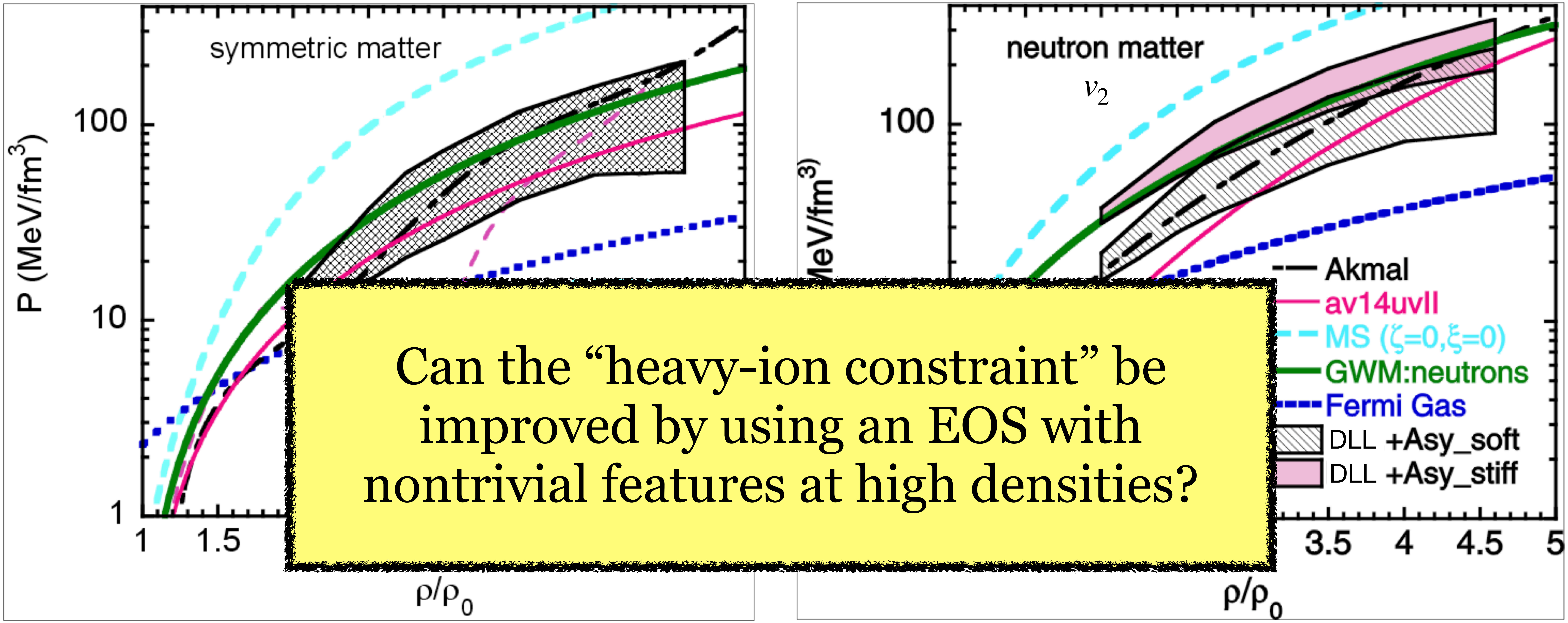


P. Danielewicz, R. Lacey, W. G. Lynch,
Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

Standard way of modeling the EOS: Skyrme potential

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

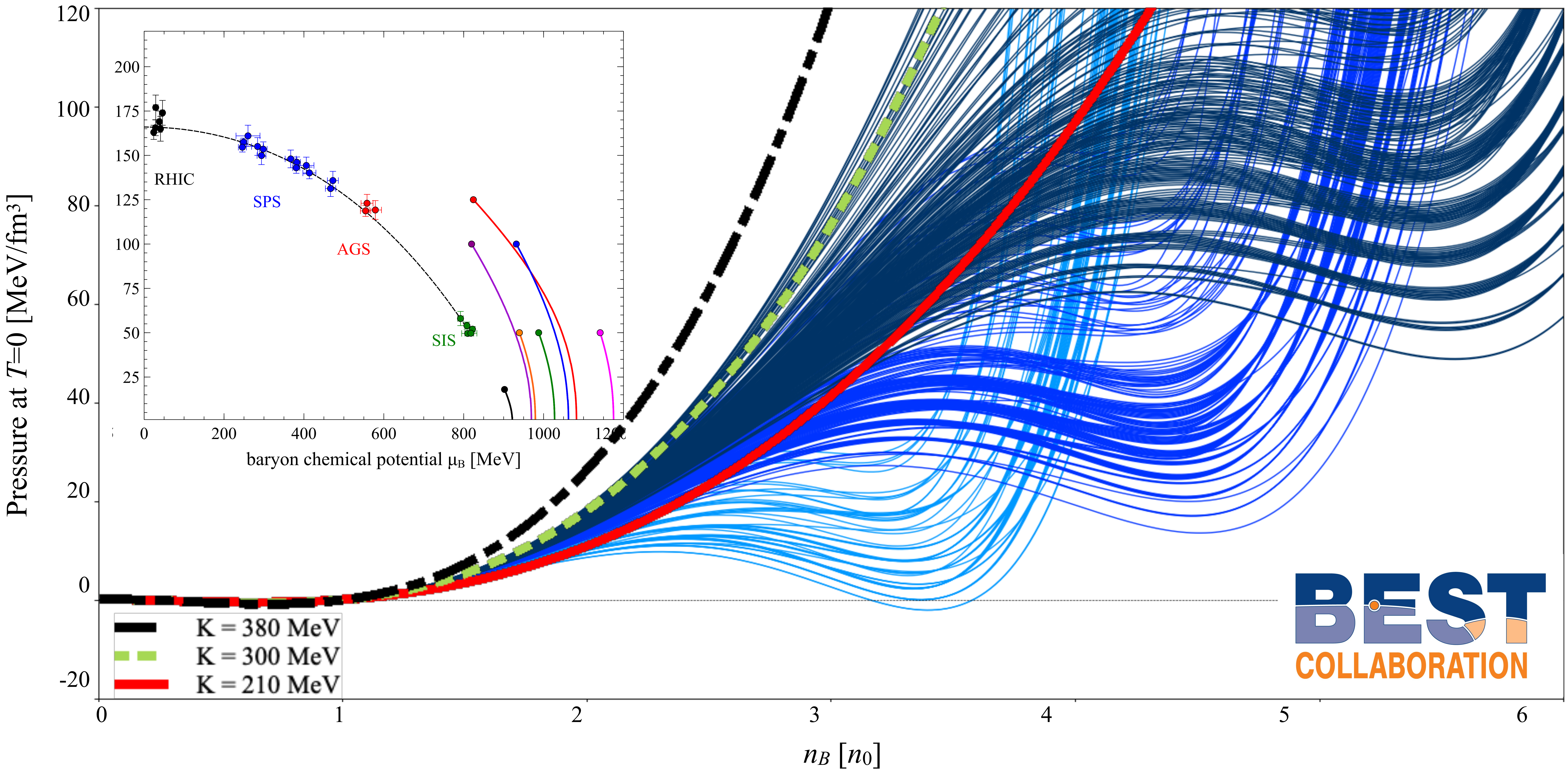
"the heavy-ion constraint"



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

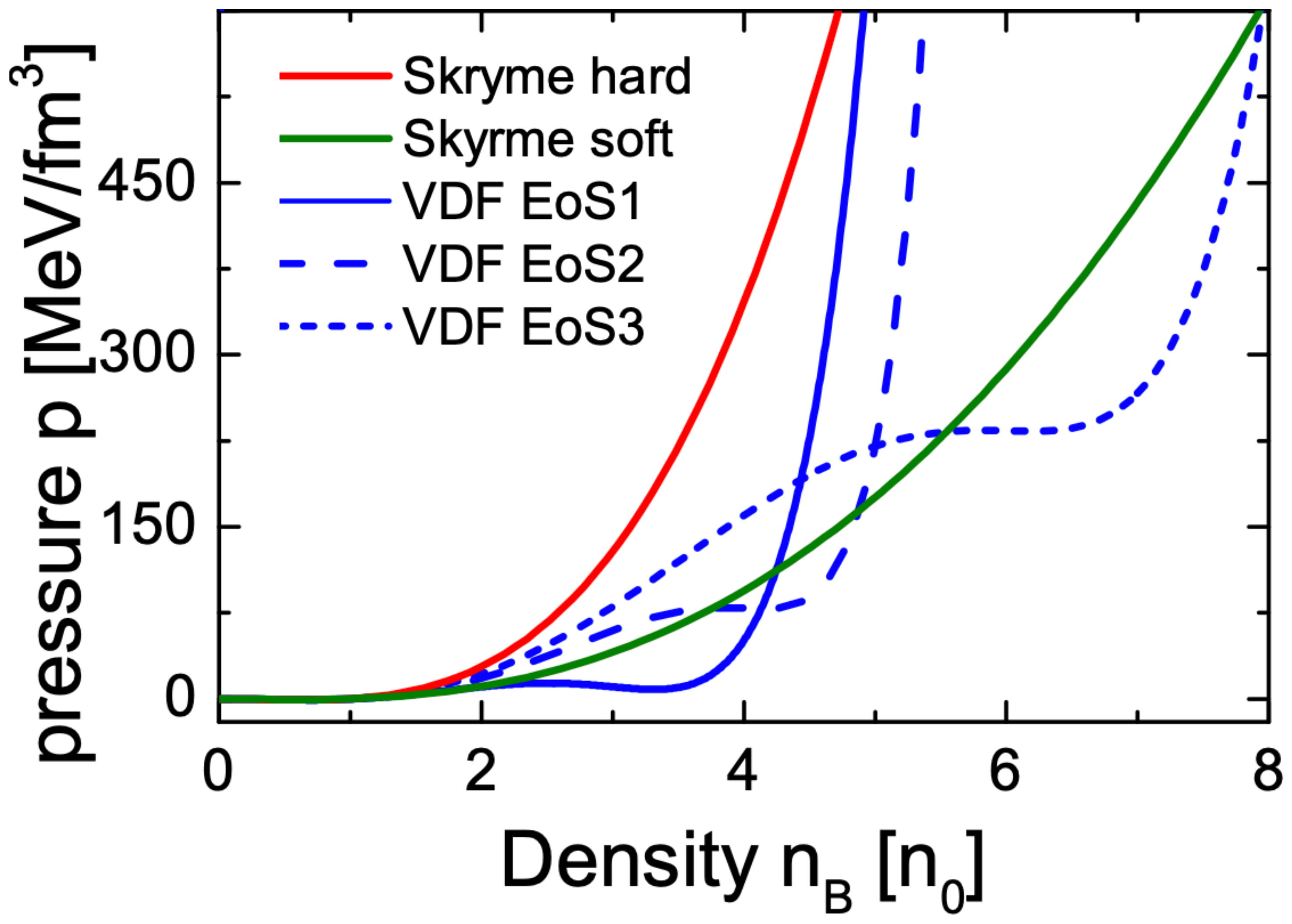
VDF model: relativistic potentials with two 1st order phase transitions

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



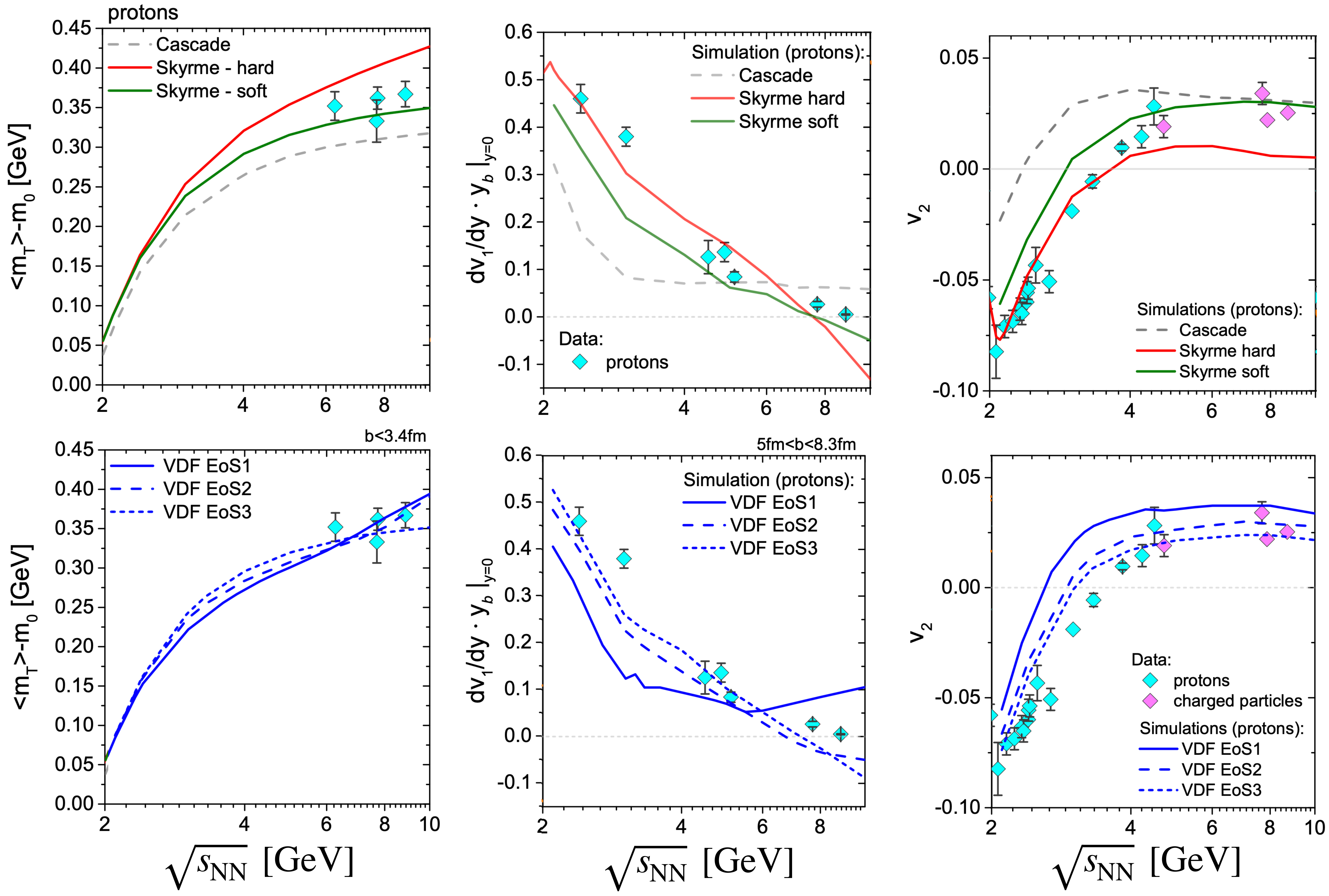
Results from UrQMD with (non-relativistic) VDF

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

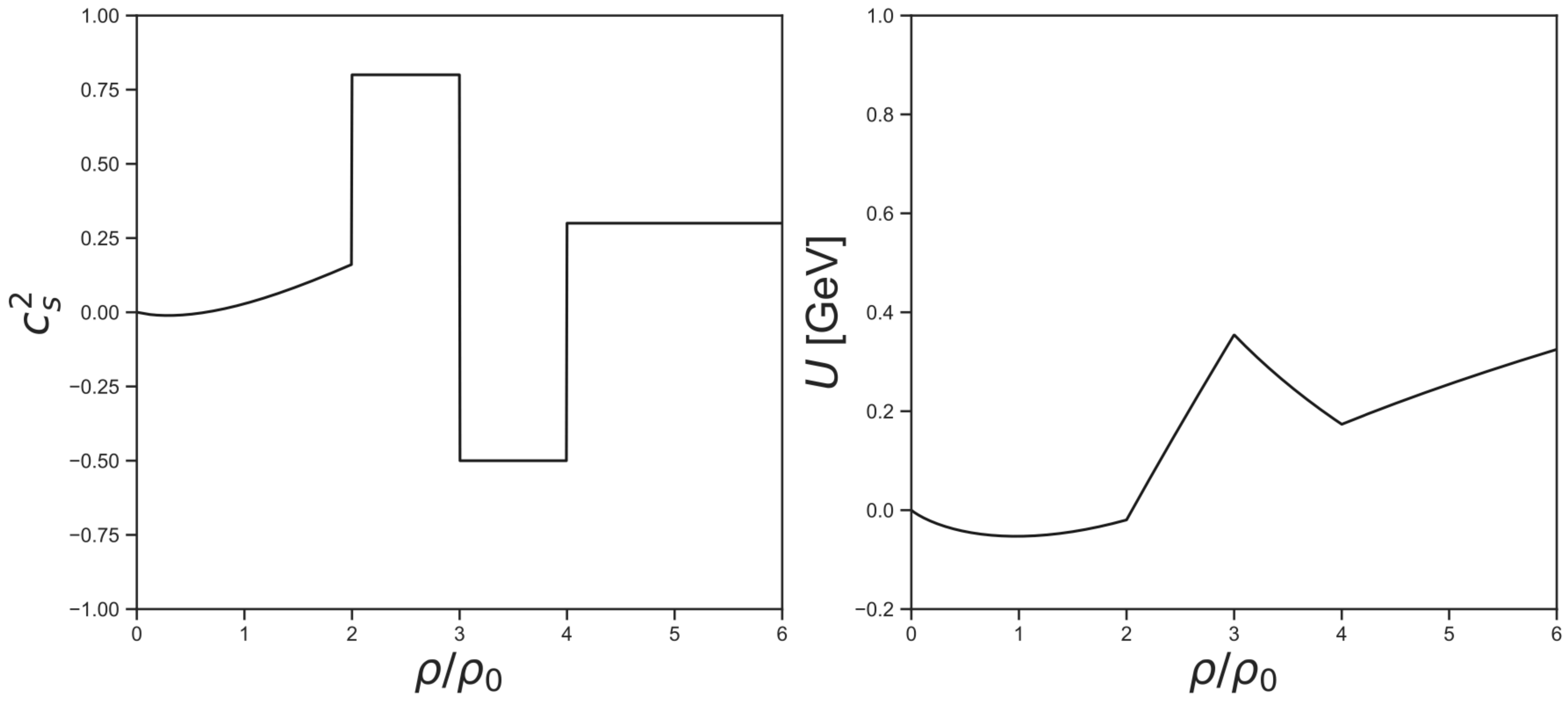
Very soft EOS at $n_B \in (2,3)n_0$
not supported in VDF+UrQMD



Better suited for Bayesian analyses: 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 $U(n_B)$:

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

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

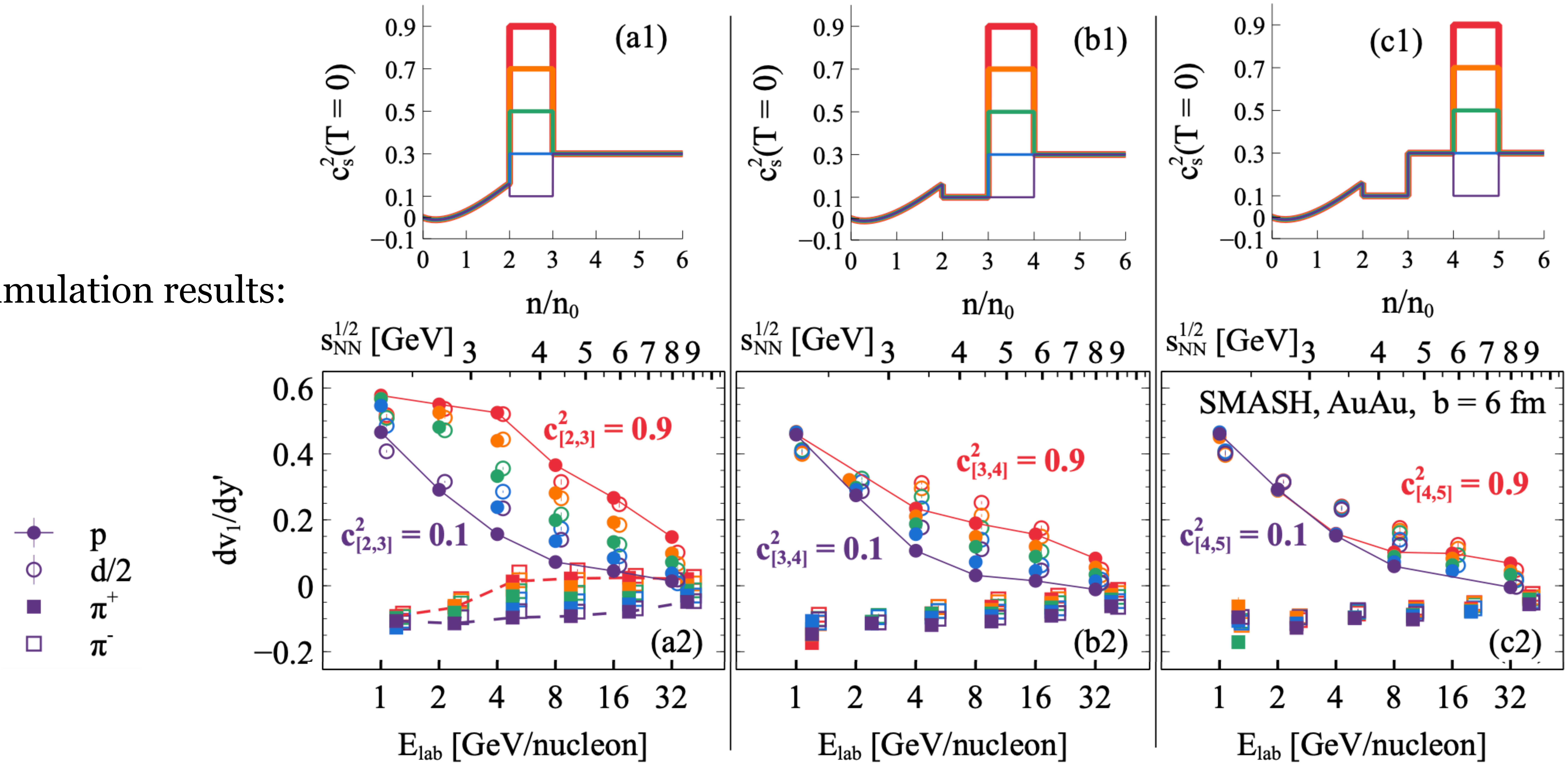
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

Sensitivity of HIC observables to the EOS at different beam energies

Mean-field piecewise-parametrized by values of c_s^2 for $n_i < n_B < n_j$:

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

Simulation results:



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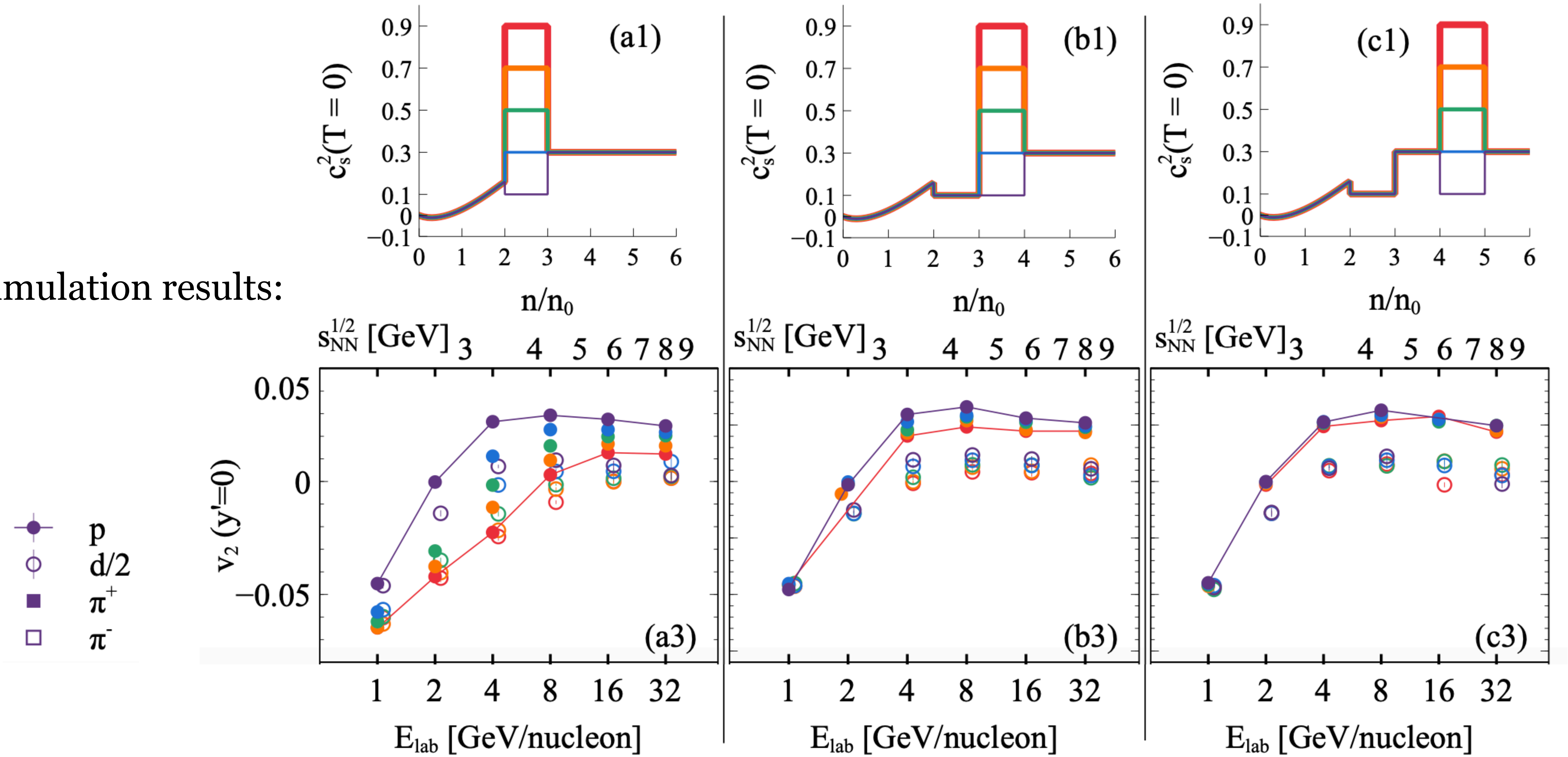
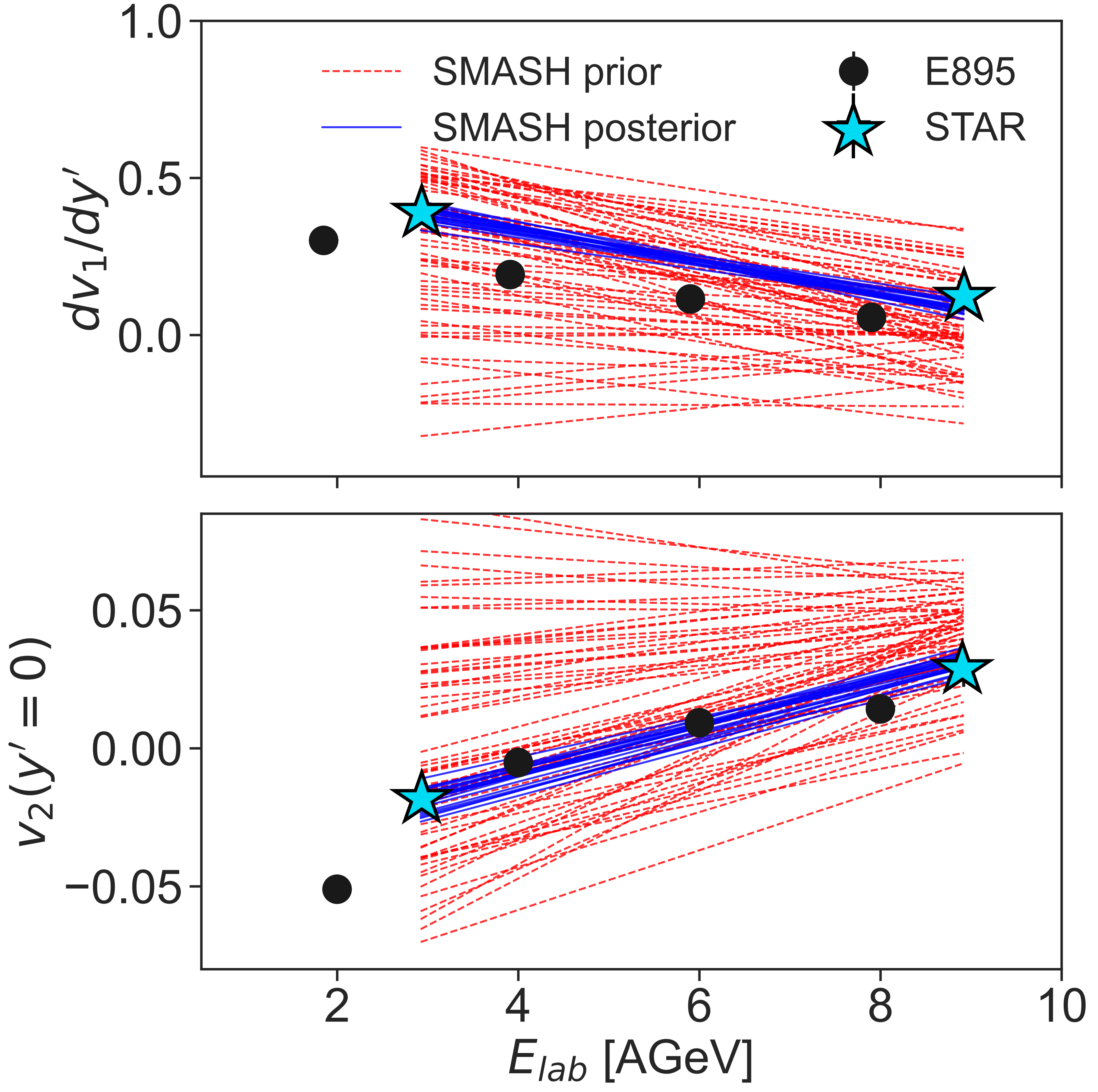
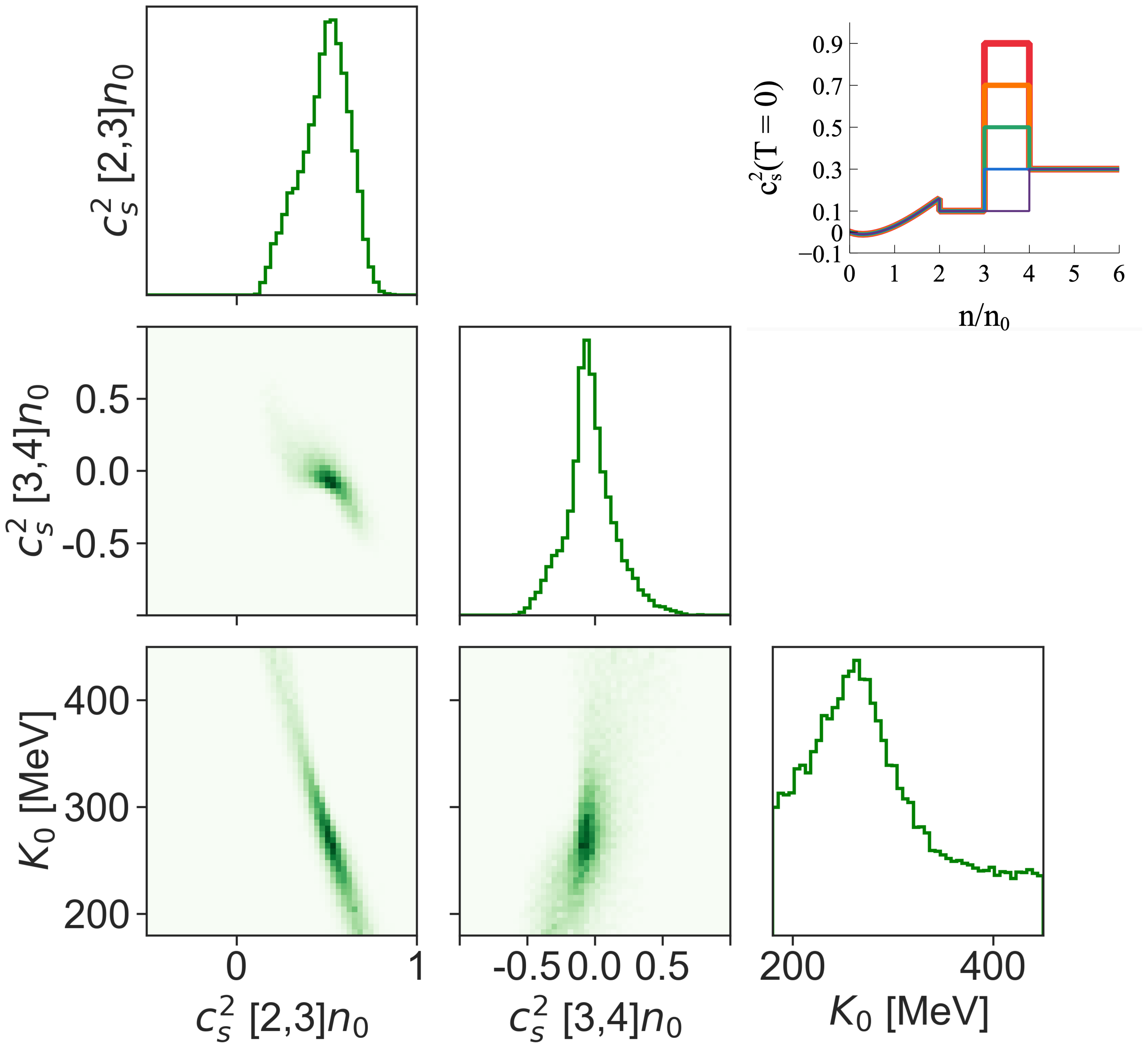


Bayesian analysis of BES FXT flow in BUU with varying K_0, $c^2_{[2,3]n_0}$, $c^2_{[3,4]n_0}$





The maximum a posteriori probability (MAP) parameters are

$K_0 = 285 \pm 67$ MeV, $\quad c^2_{[2,3]n_0} = 0.49 \pm 0.13, \quad c^2_{[3,4]n_0} = -0.03 \pm 0.15$

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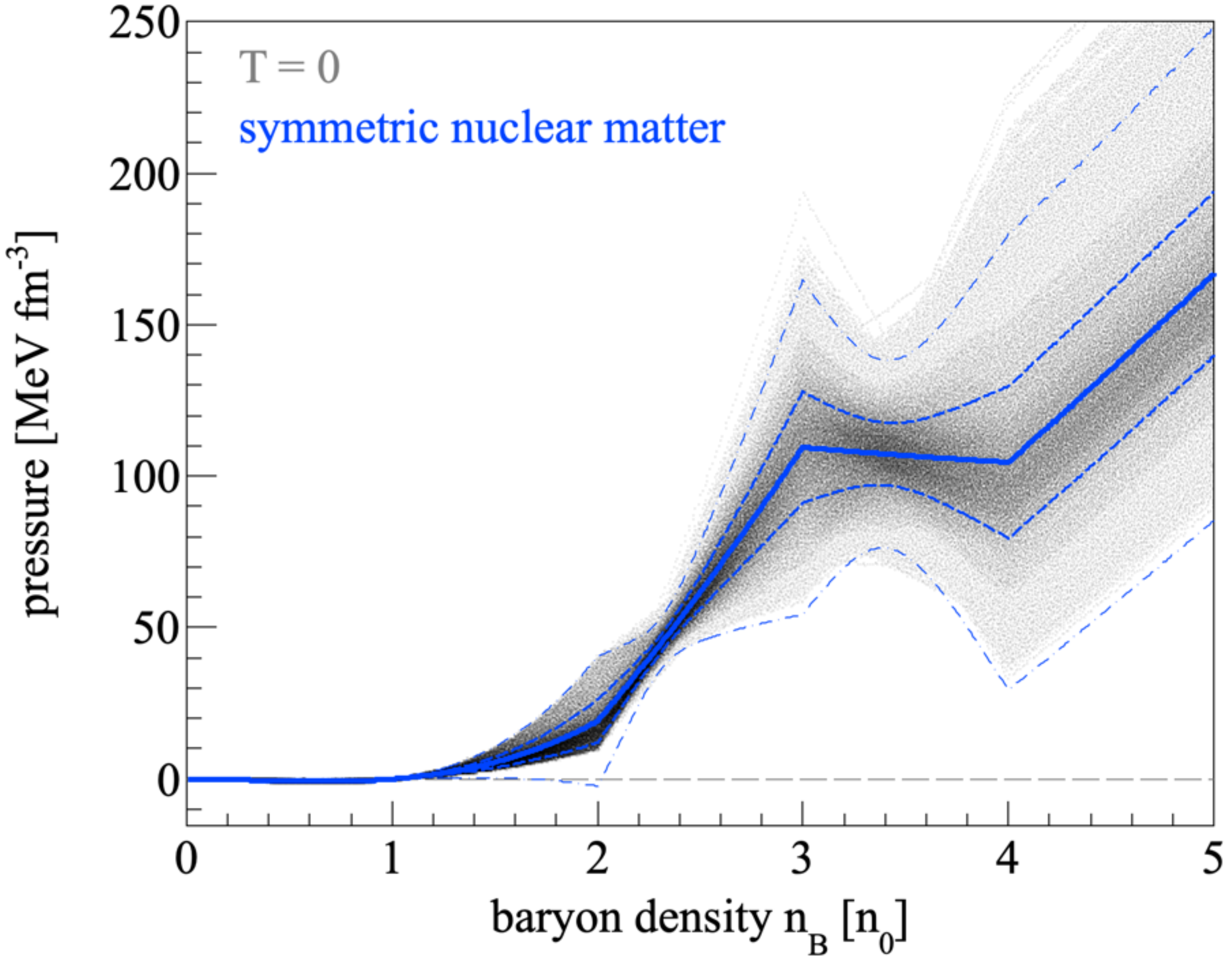
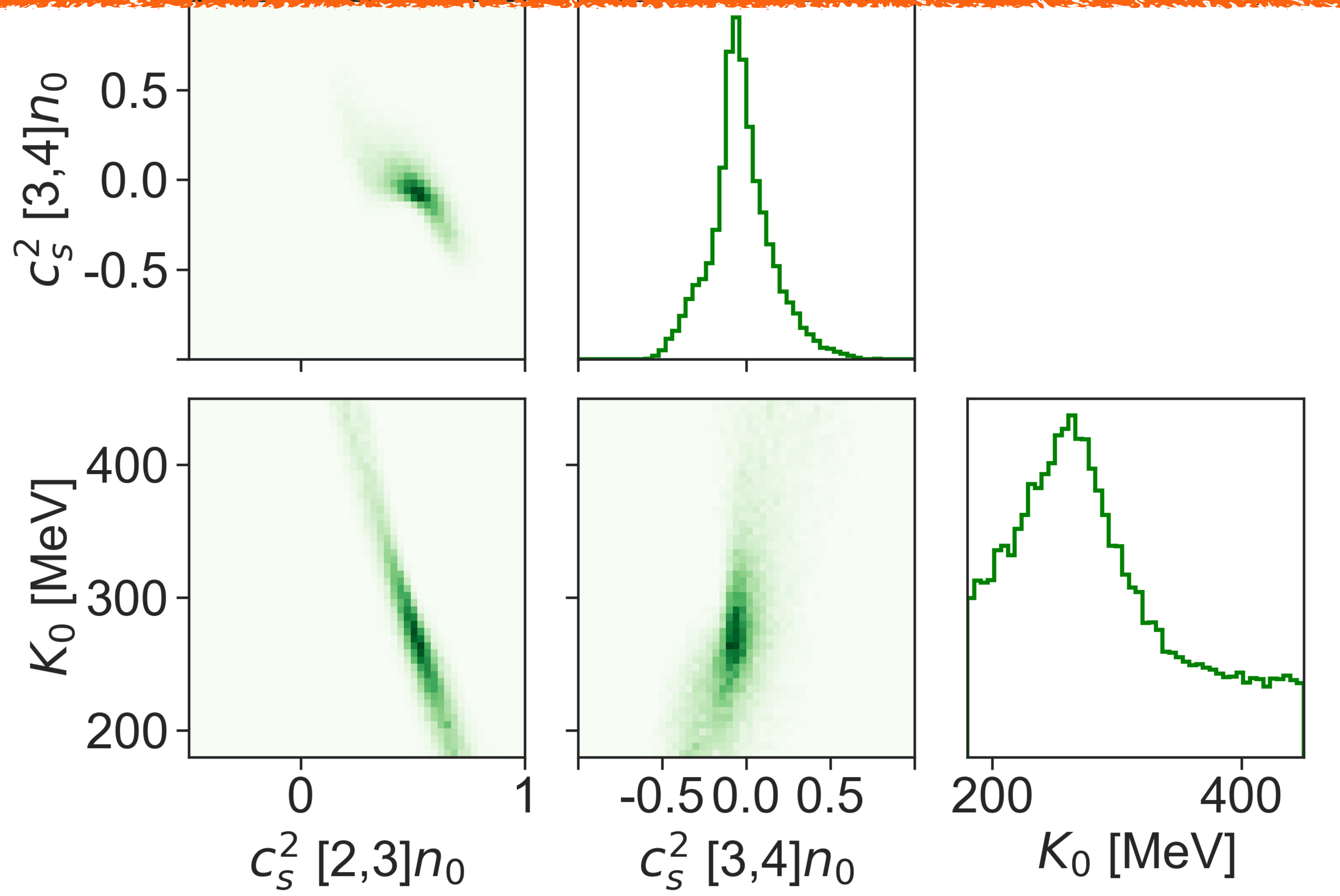


The constrained EOS is very stiff at $n_B \in (2,3)n_0$ and very soft at $n_B \in (3,4)n_0$



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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

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

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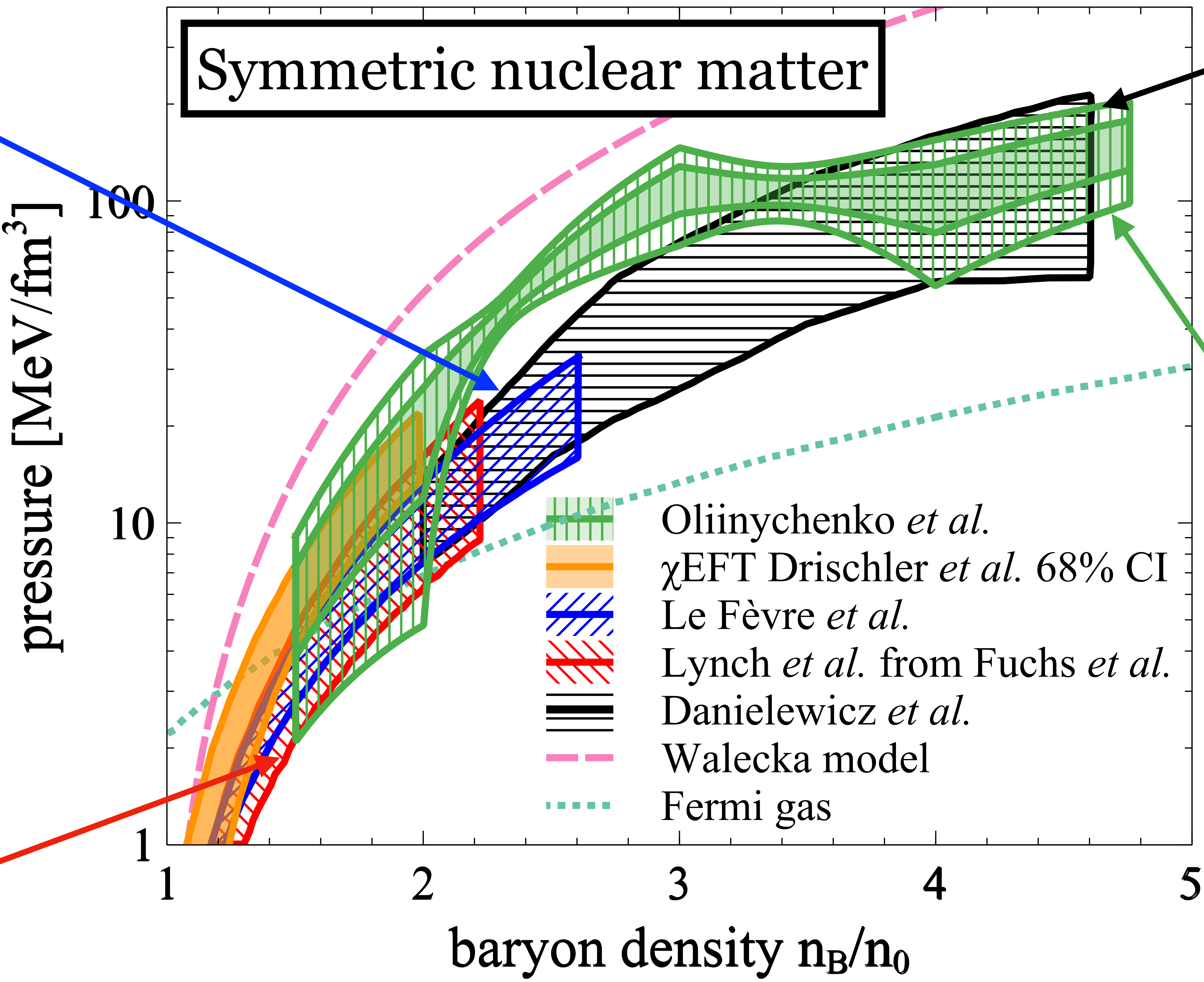

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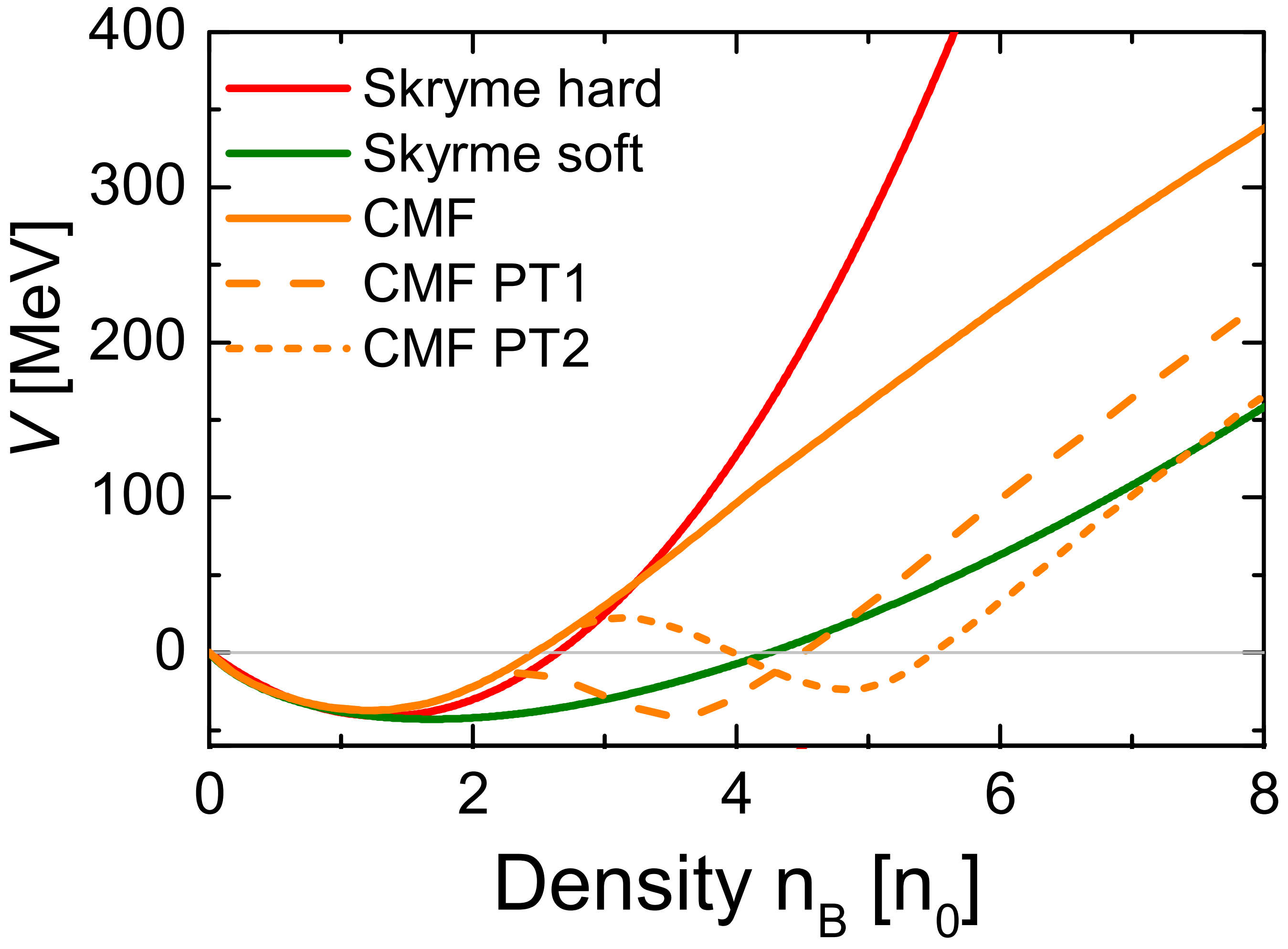
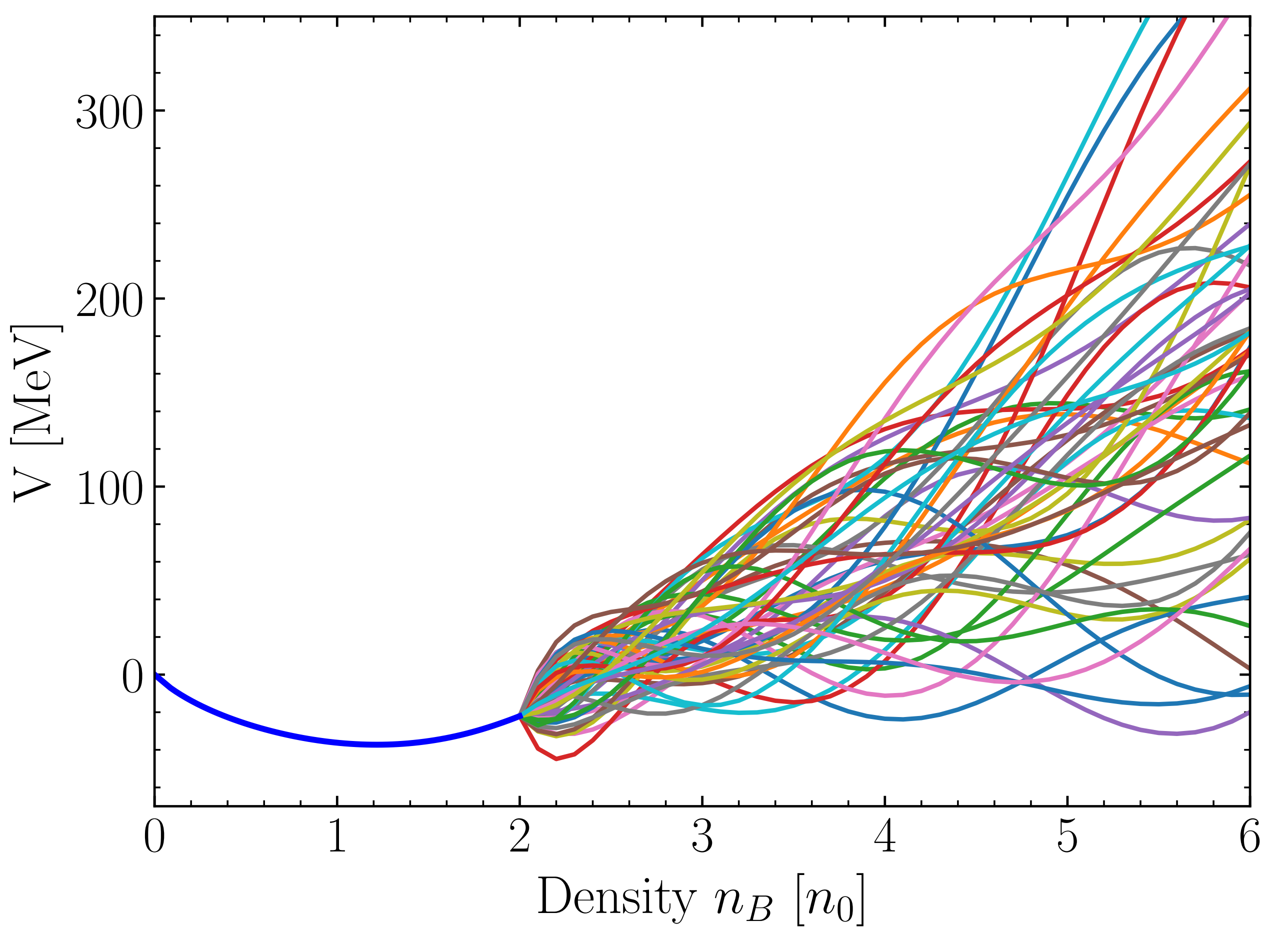
momentum dependence
P. Danielewicz, R. Lacey, W. G. Lynch, Science **298**,1592–1596 (2002)

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

Bayesian analysis of flow data in UrQMD





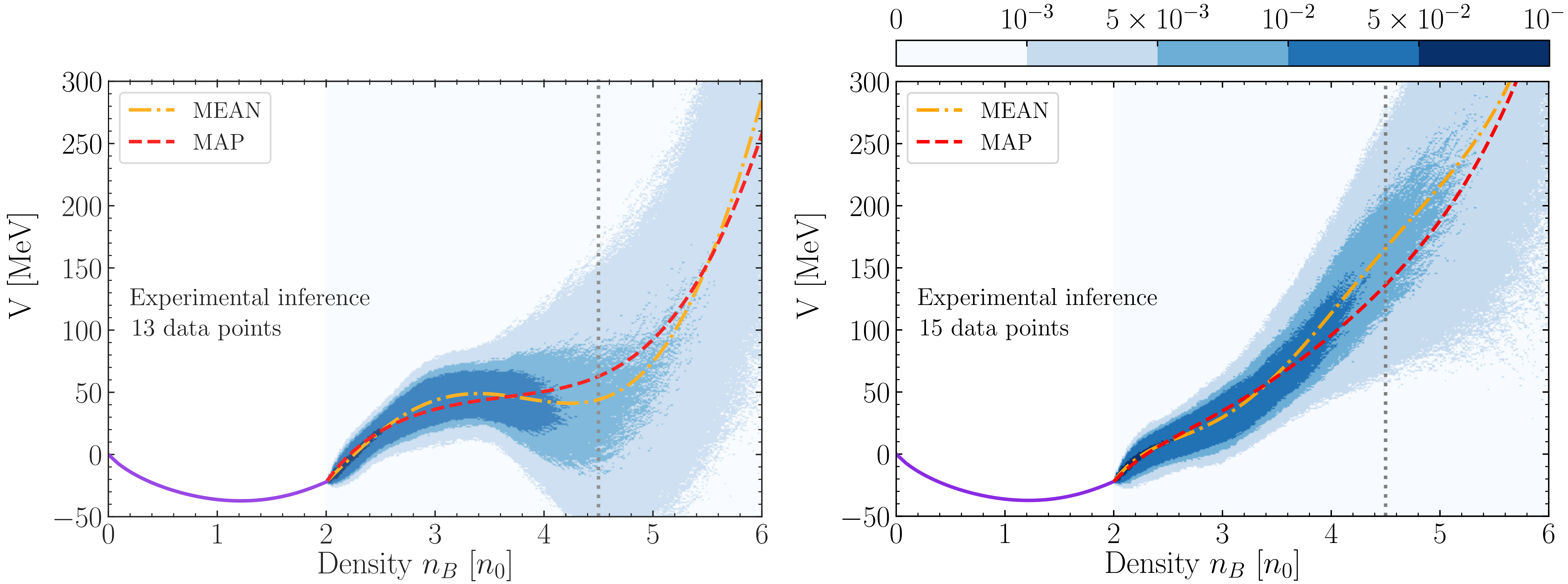
M. Omana Kuttan, J. Steinheimer, K. Zhou, H. Stoecker,
Phys. Rev. Lett. **131** 20, 202303 (2023)
arXiv:2211.11670

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

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

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

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



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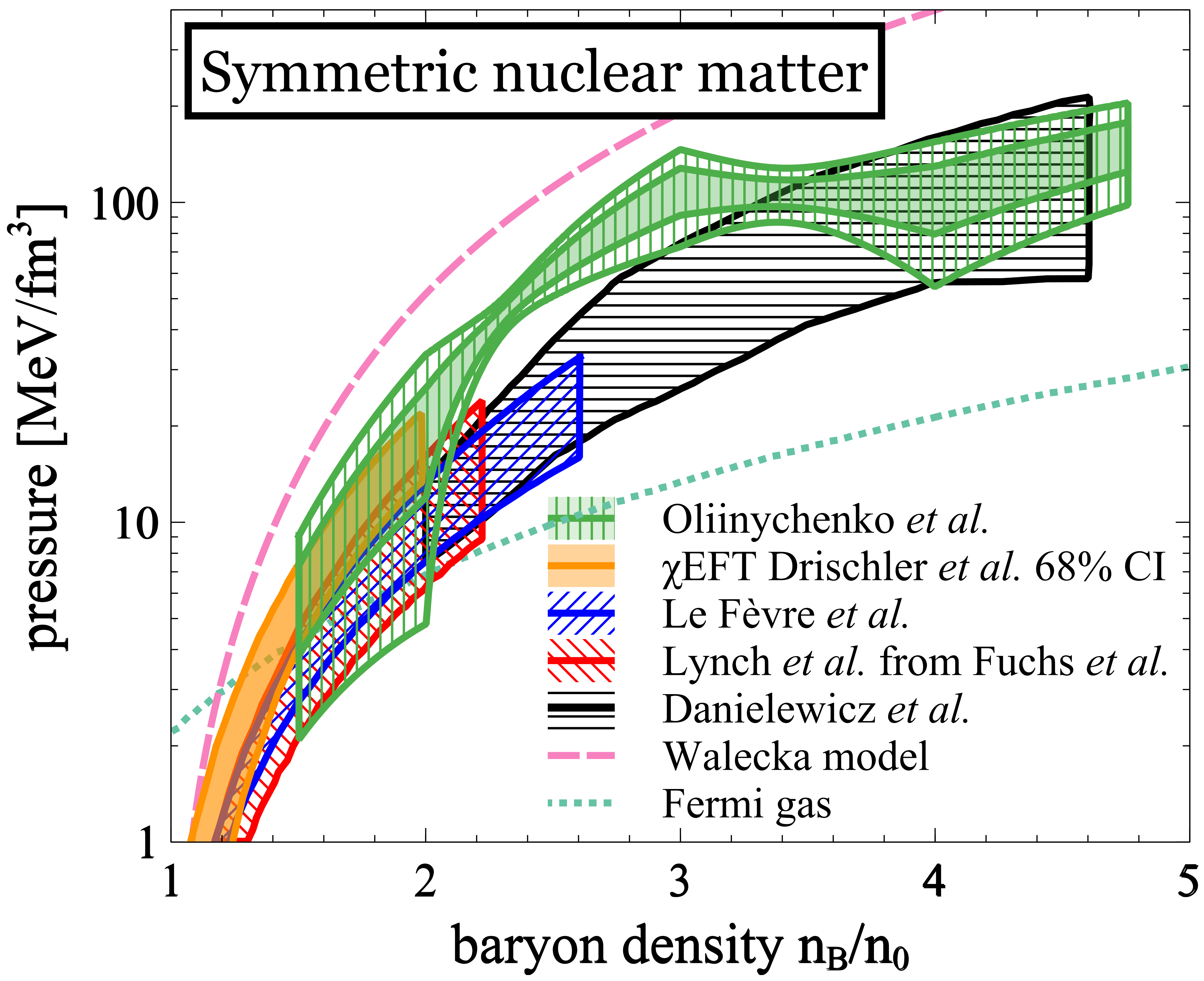

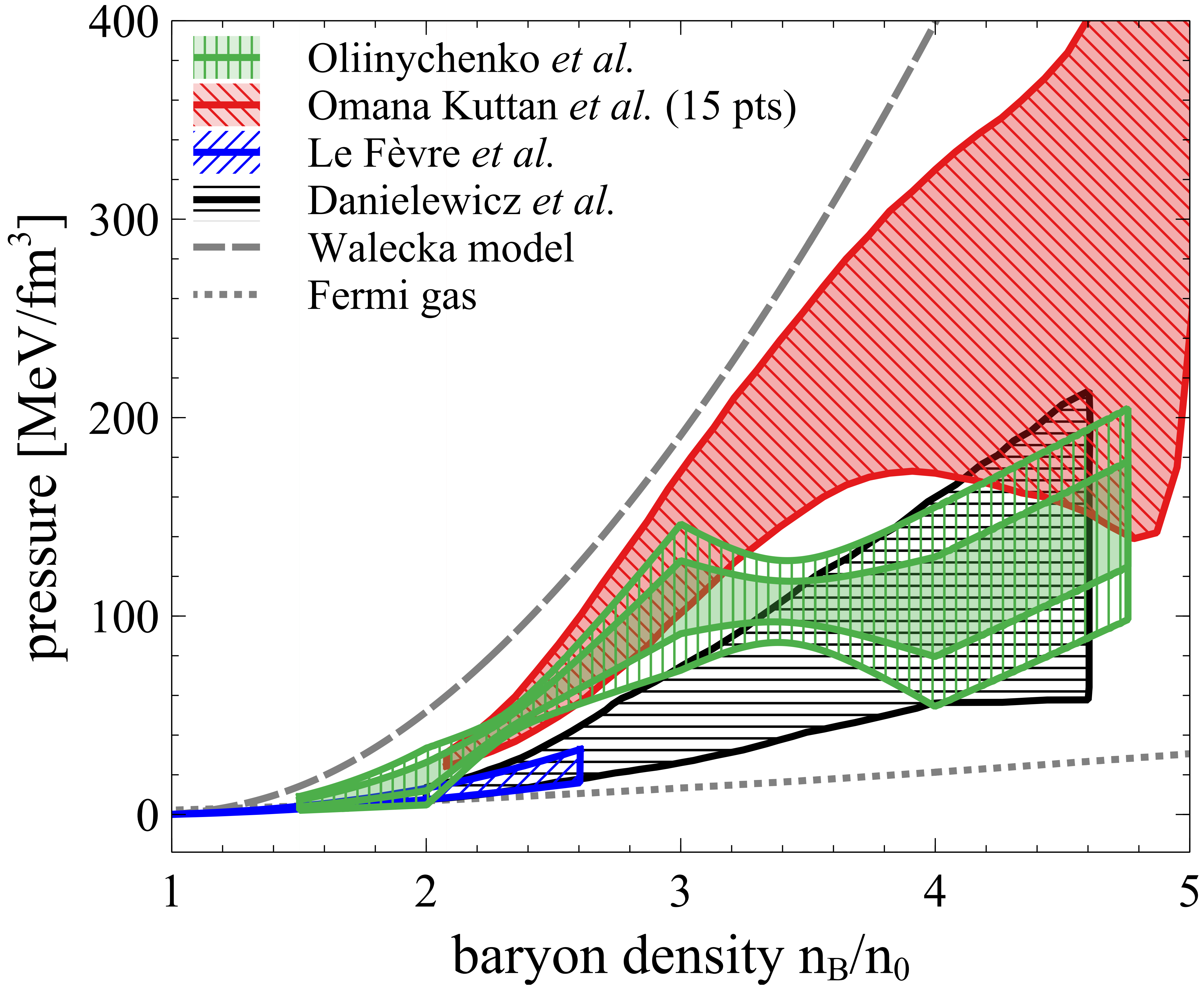

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L. Du, **A. Sorensen**, M. Stephanov, Int. J. Mod. Phys. E (available online), arXiv: 2402.10183

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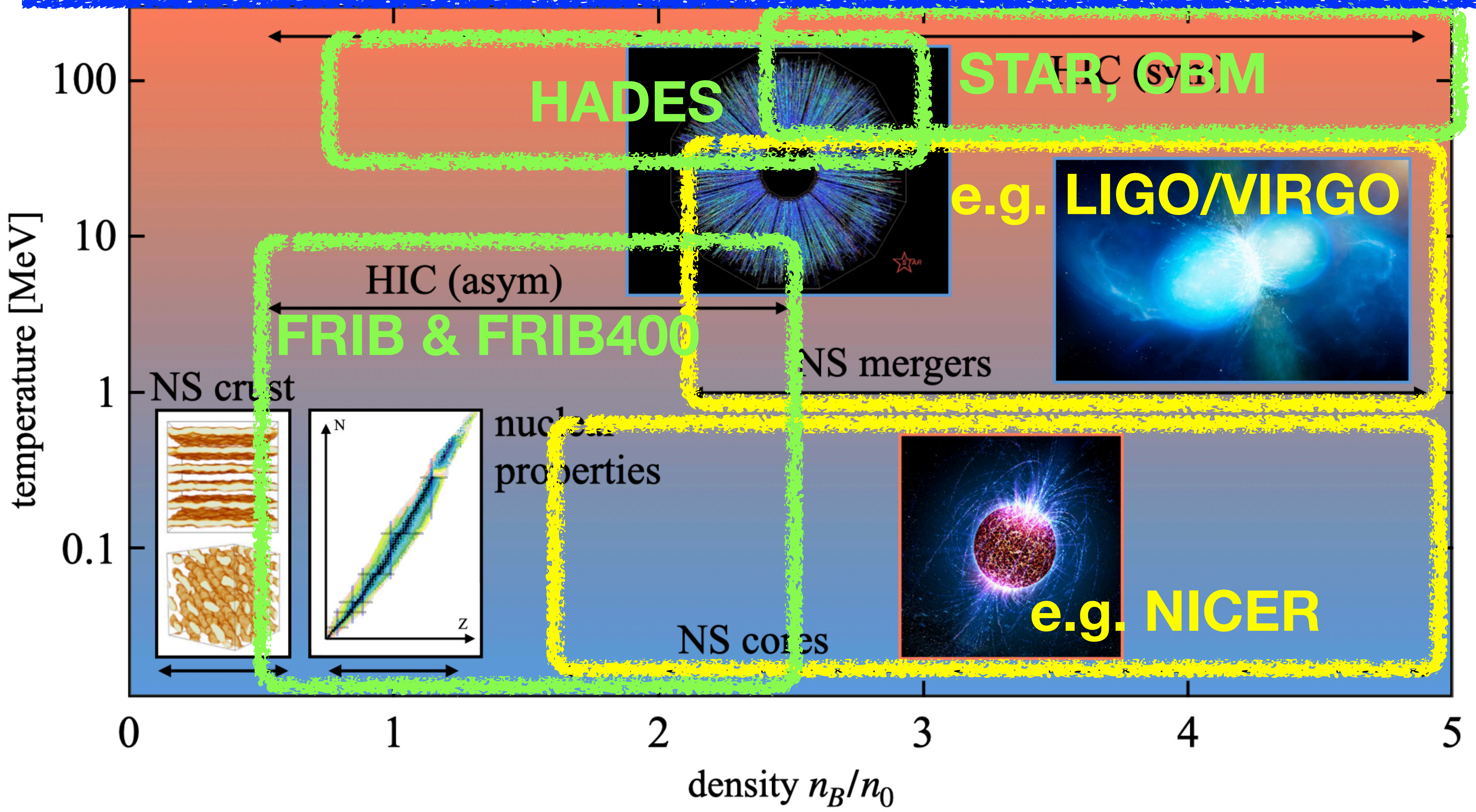
3. Future opportunities:
   - momentum-dependence of nuclear matter interactions
   - in-medium scattering cross-sections
   - cluster production

Golden age for studies of the EOS

- EOS is of interest to multiple diverse communities
- opportunity to study in-medium properties of nuclear matter & address outstanding problems



Hot QCD

Cold QCD

Nucl. reactions + astro

Fundamental sym.

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]

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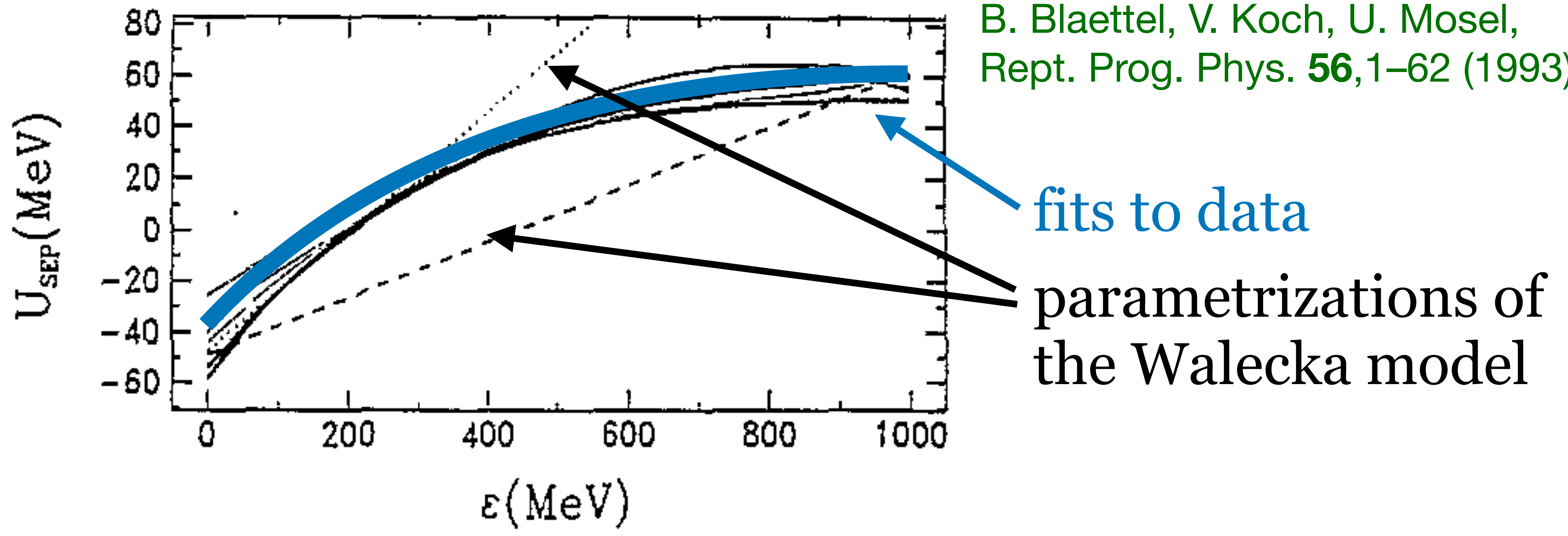
highest cited of all* WPs for the 2023 LRP!

*published (arXiv, journal, etc.)

Momentum-dependence of nuclear matter interactions

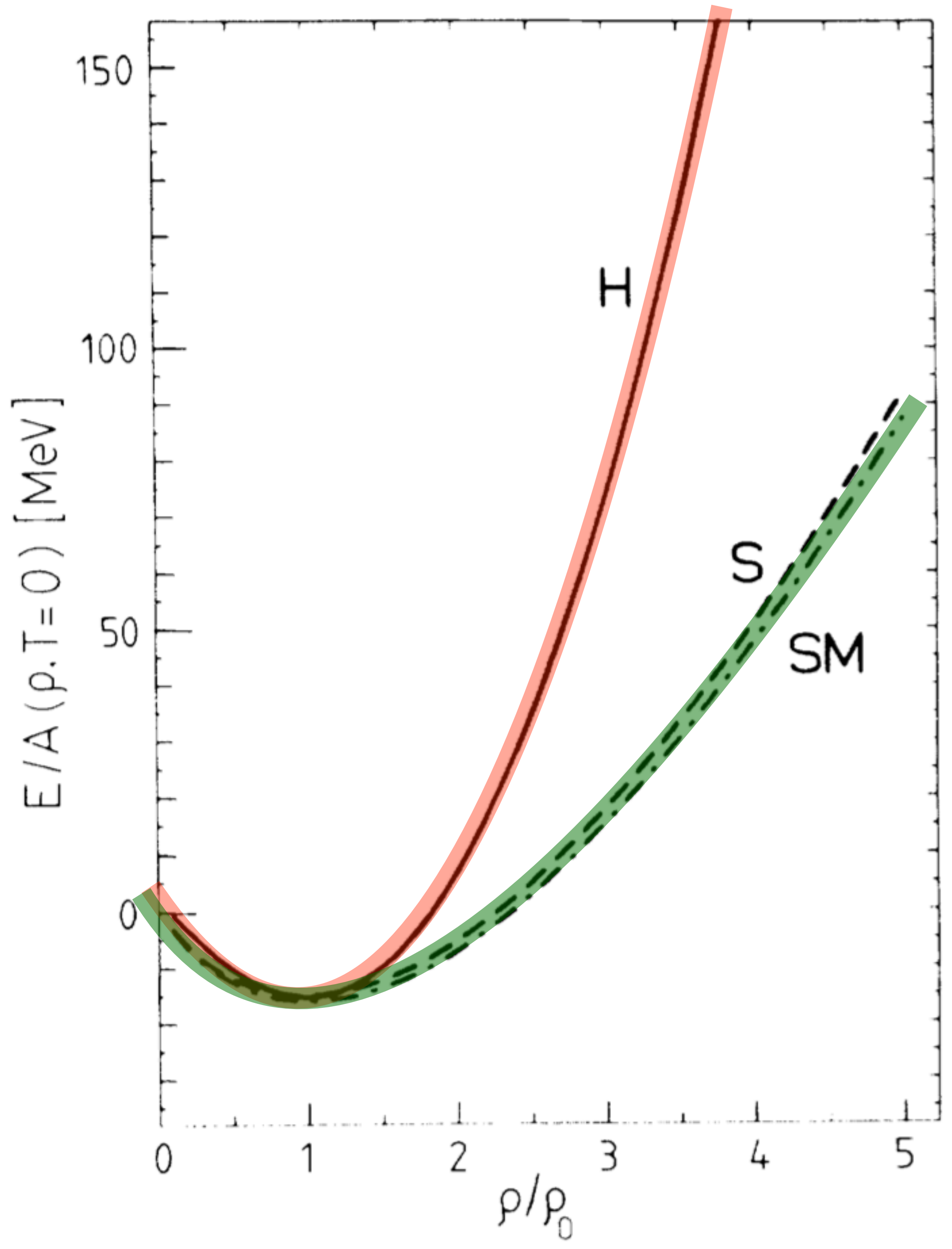
Momentum-dependence of interactions is a necessary component

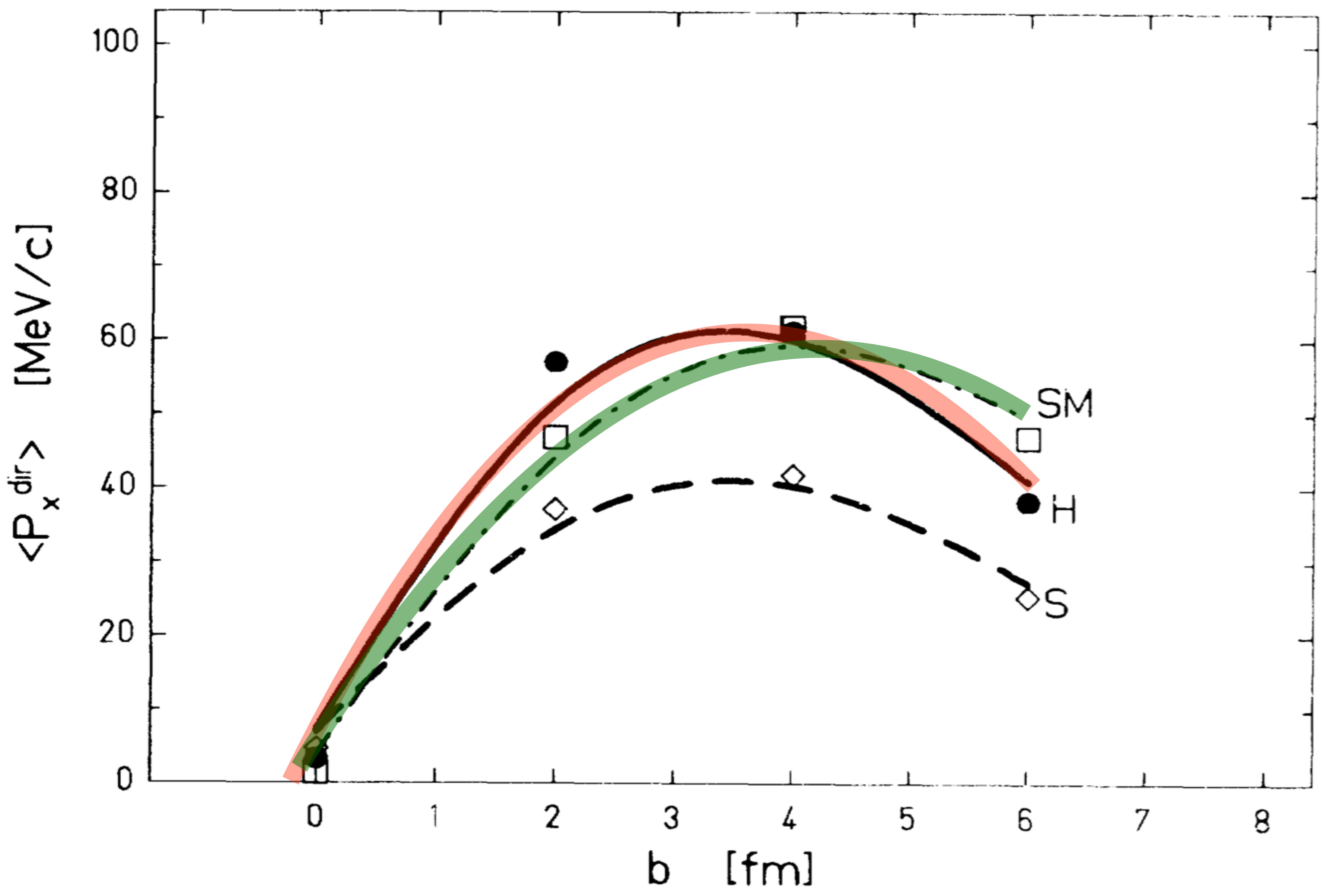
Measured in scattering experiments (at n_0):



B. Blaettel, V. Koch, U. Mosel, Rept. Prog. Phys. **56**,1–62 (1993)

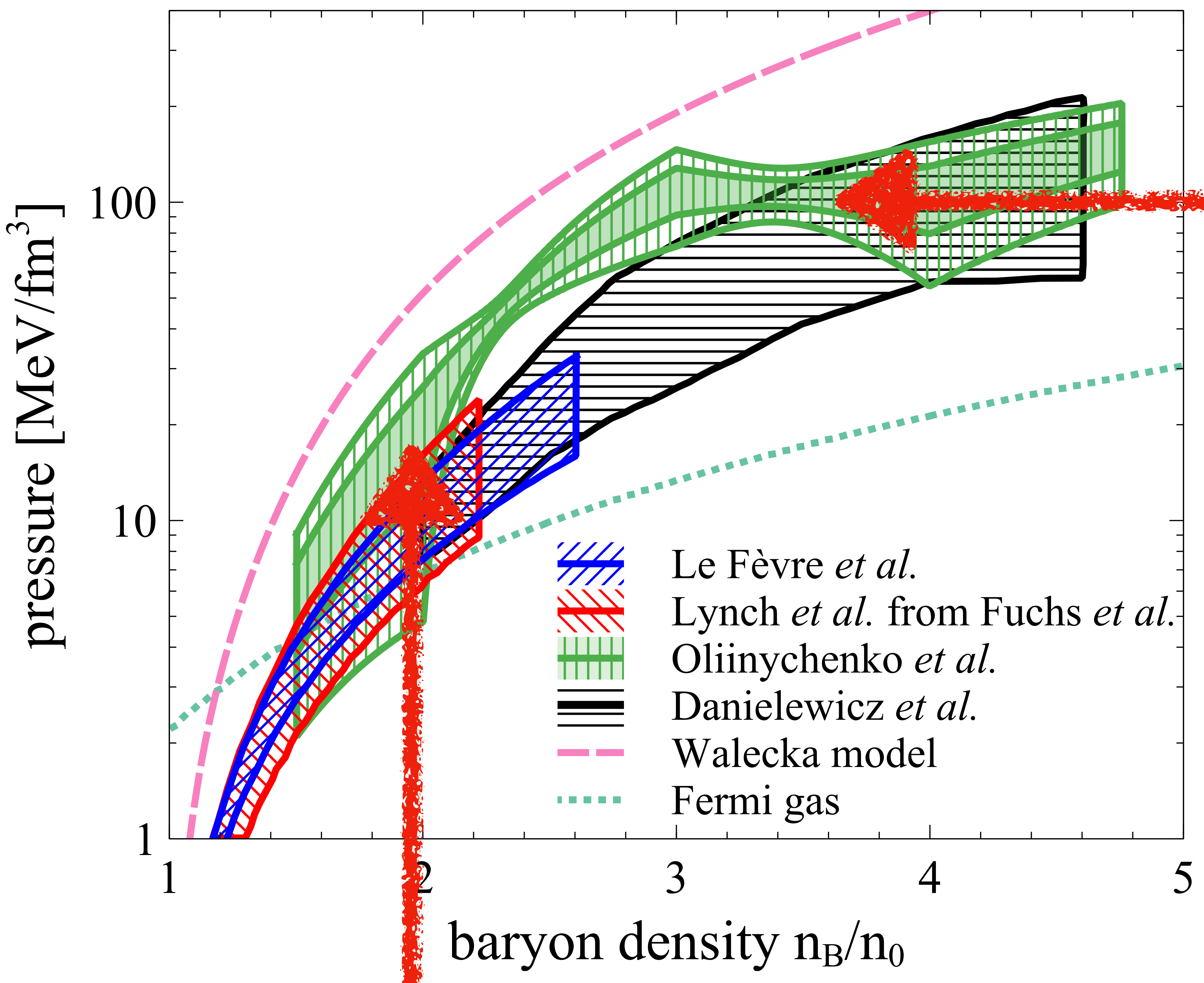
Influence: flow from a hard EOS looks like flow from a soft EOS with *p*-dependence!





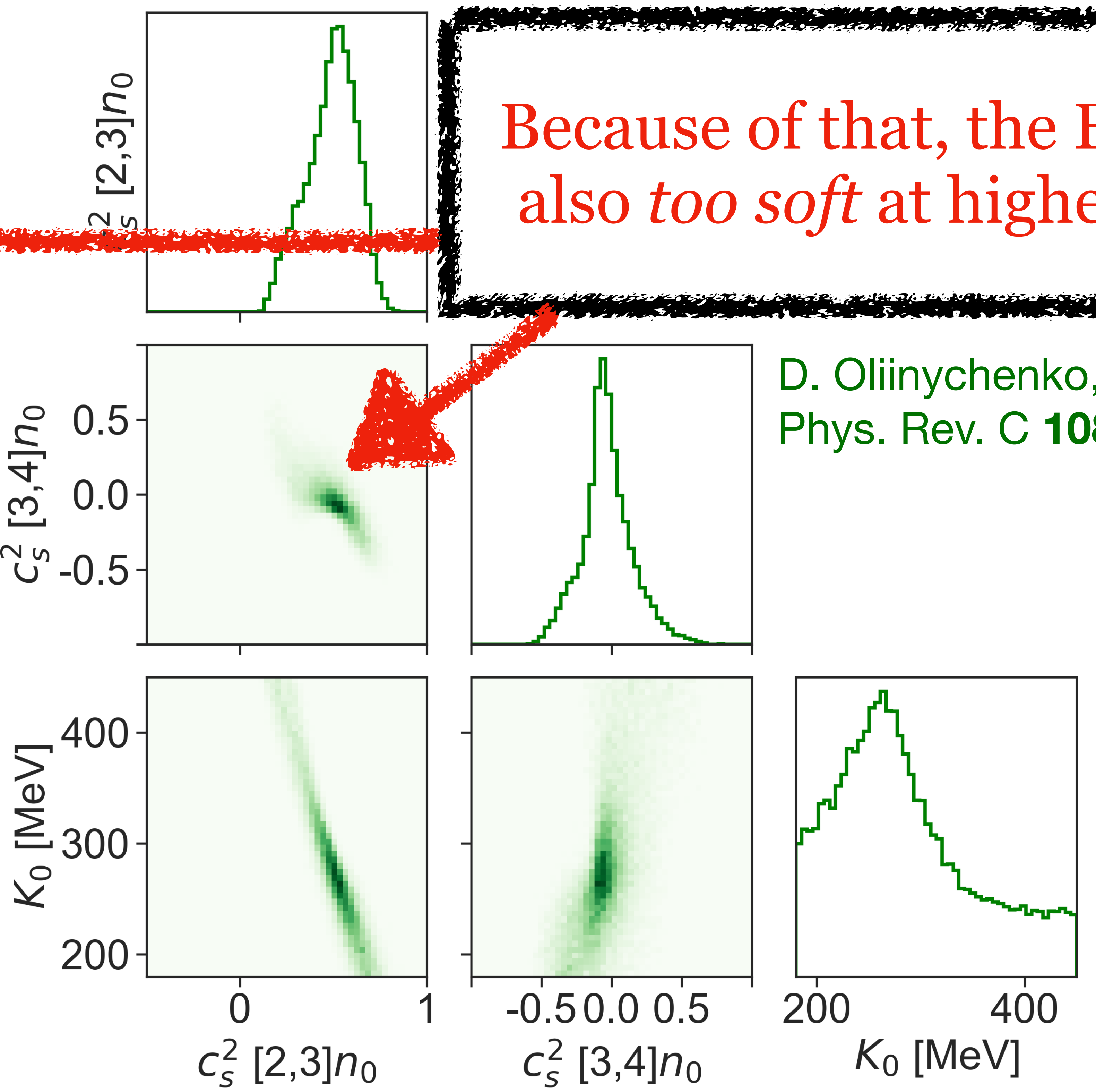
J. Aichelin, A. Rosenhauer, G. Peilert, H. Stoecker, W. Greiner, Phys. Rev. Lett. **58** 1926–1929 (1987)

Momentum-dependence of nuclear matter interactions



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

Without momentum dependence, “artificial” additional source of repulsion is needed = the extracted EOS is too stiff?

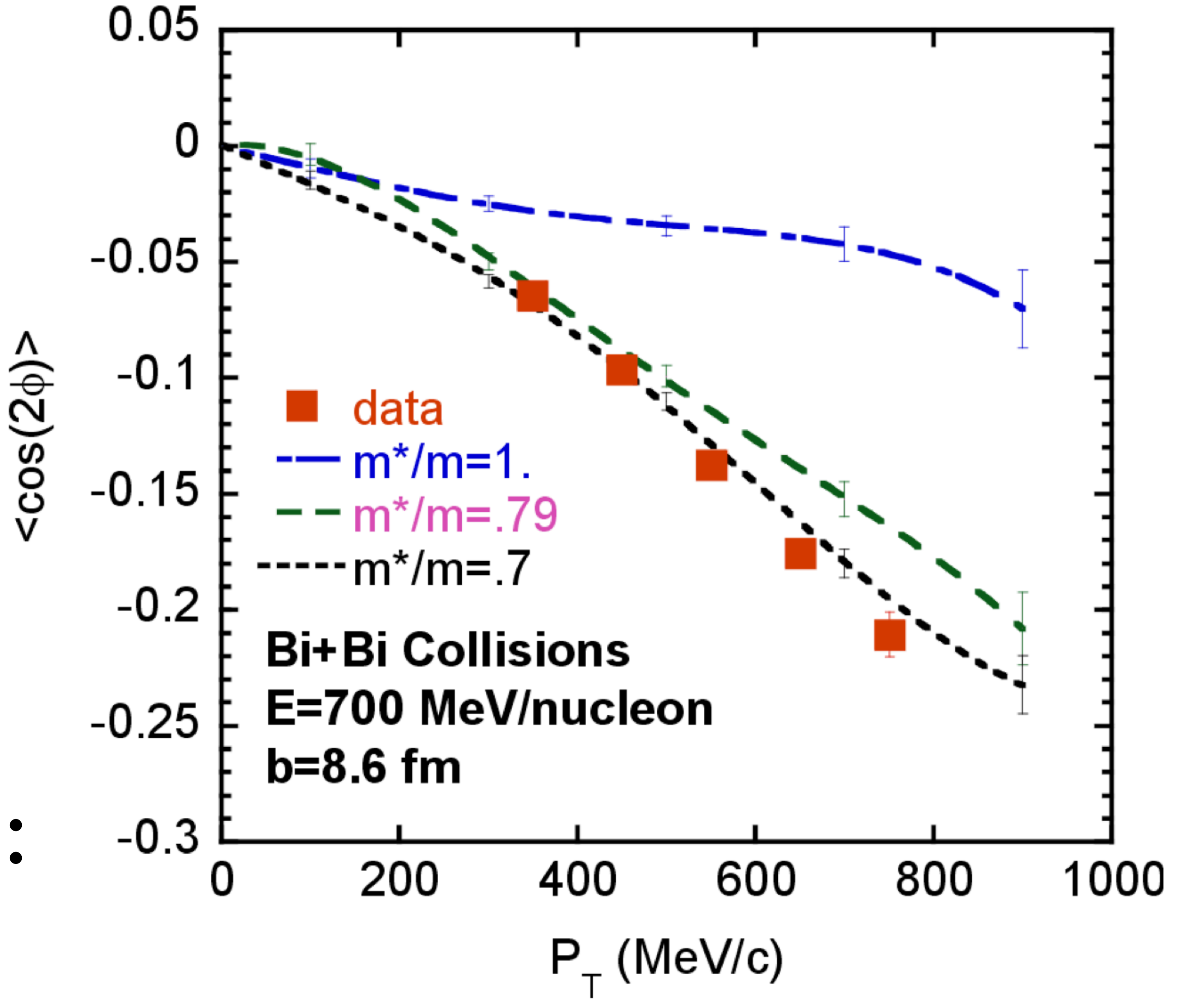


Because of that, the EOS may be also *too soft* at higher densities

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

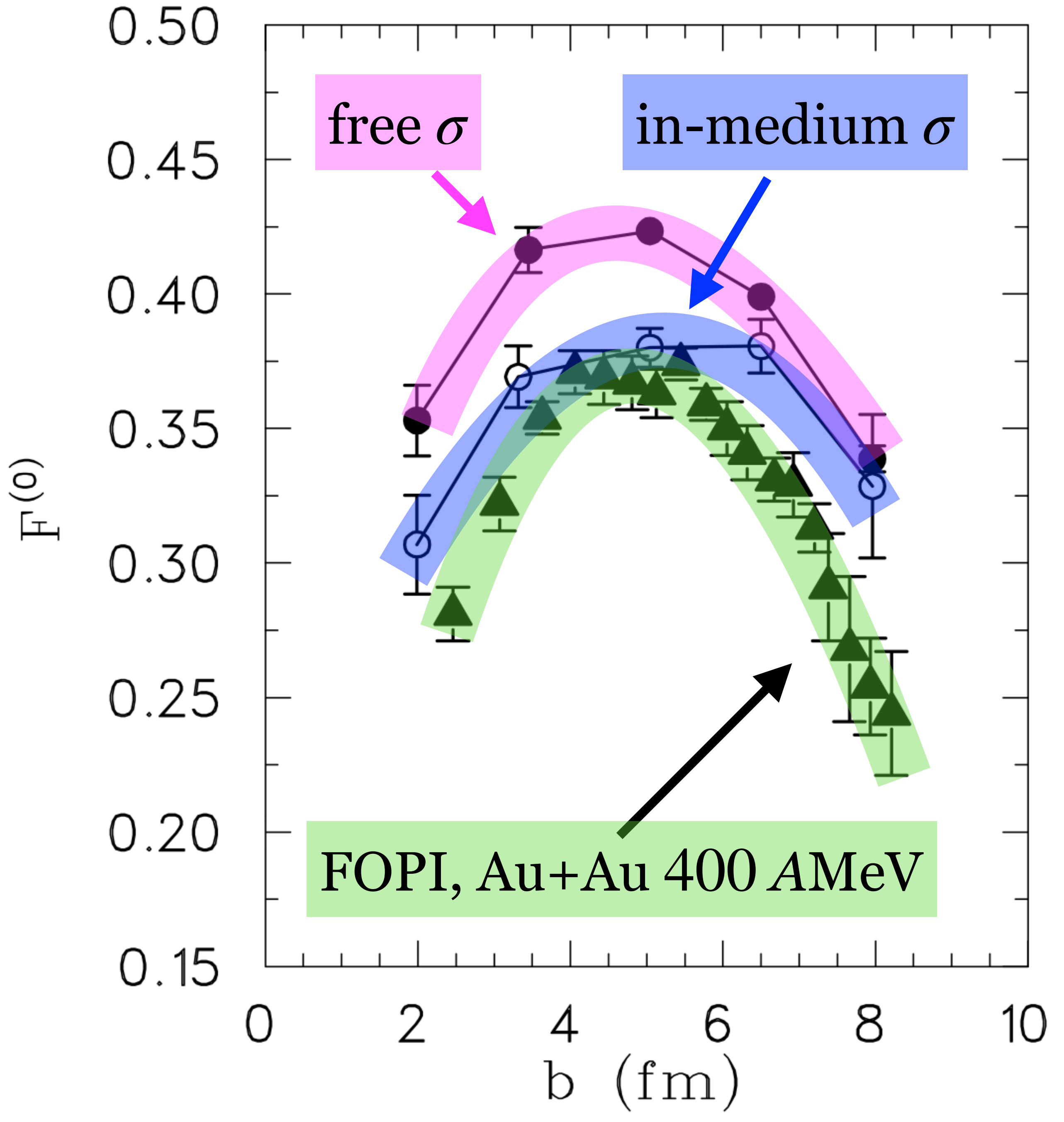
P. Danielewicz, R. Lacey, and W. G. Lynch, Science **298**, 1592 (2002), arXiv:0208016

Use peripheral collisions to constrain the *p*-dependence:



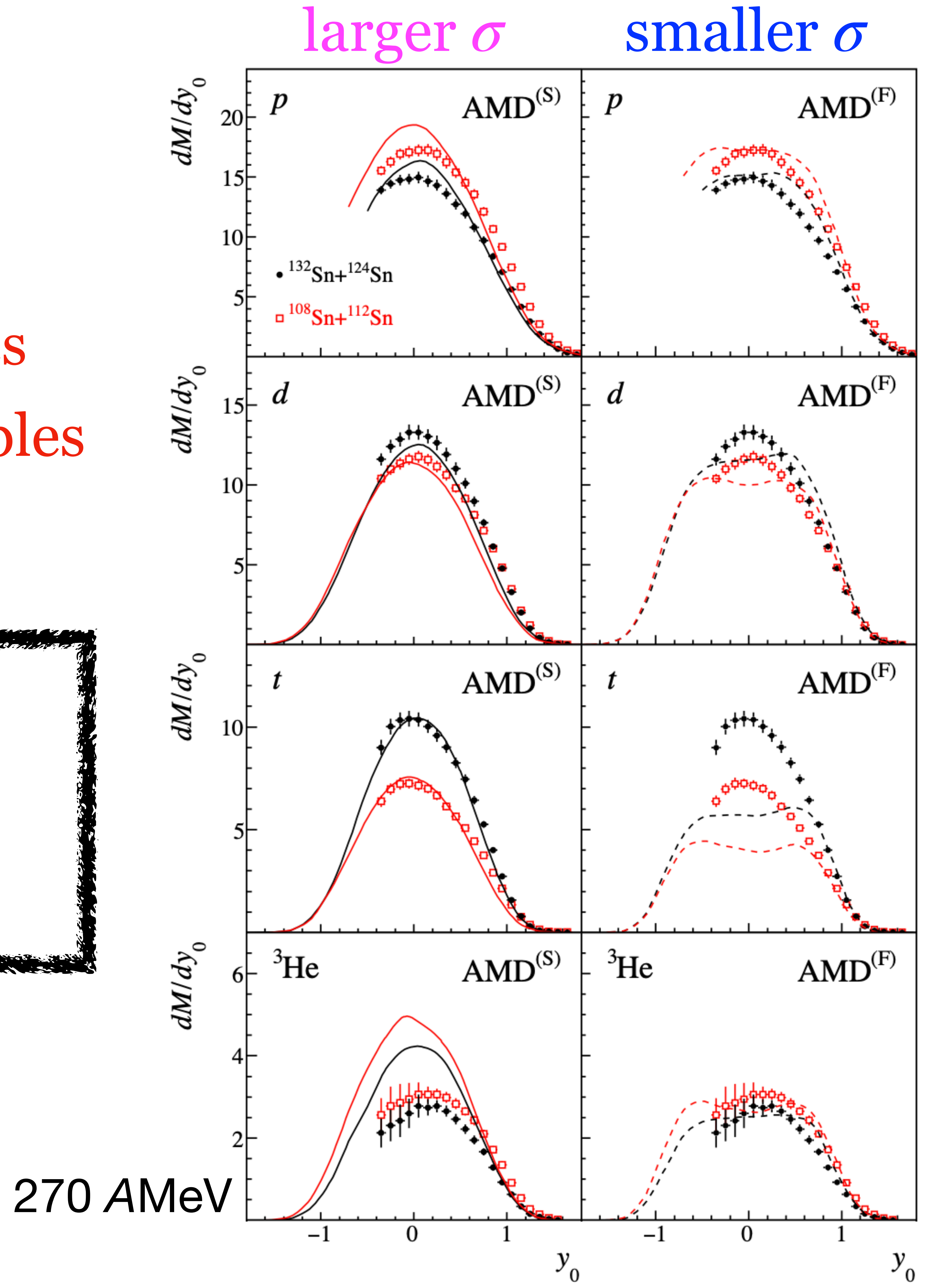
In-medium scattering cross-sections

- free nucleon cross sections (σ's) lead to excessive stopping
- microscopic calculations: N-N σ is reduced in the medium
- isospin dependence of in-medium σ's generally unknown
- SπRIT experiment data indicate in-medium σ's need further studies
- particle-particle scatterings contribute $\approx$ 30-50 % to flow observables



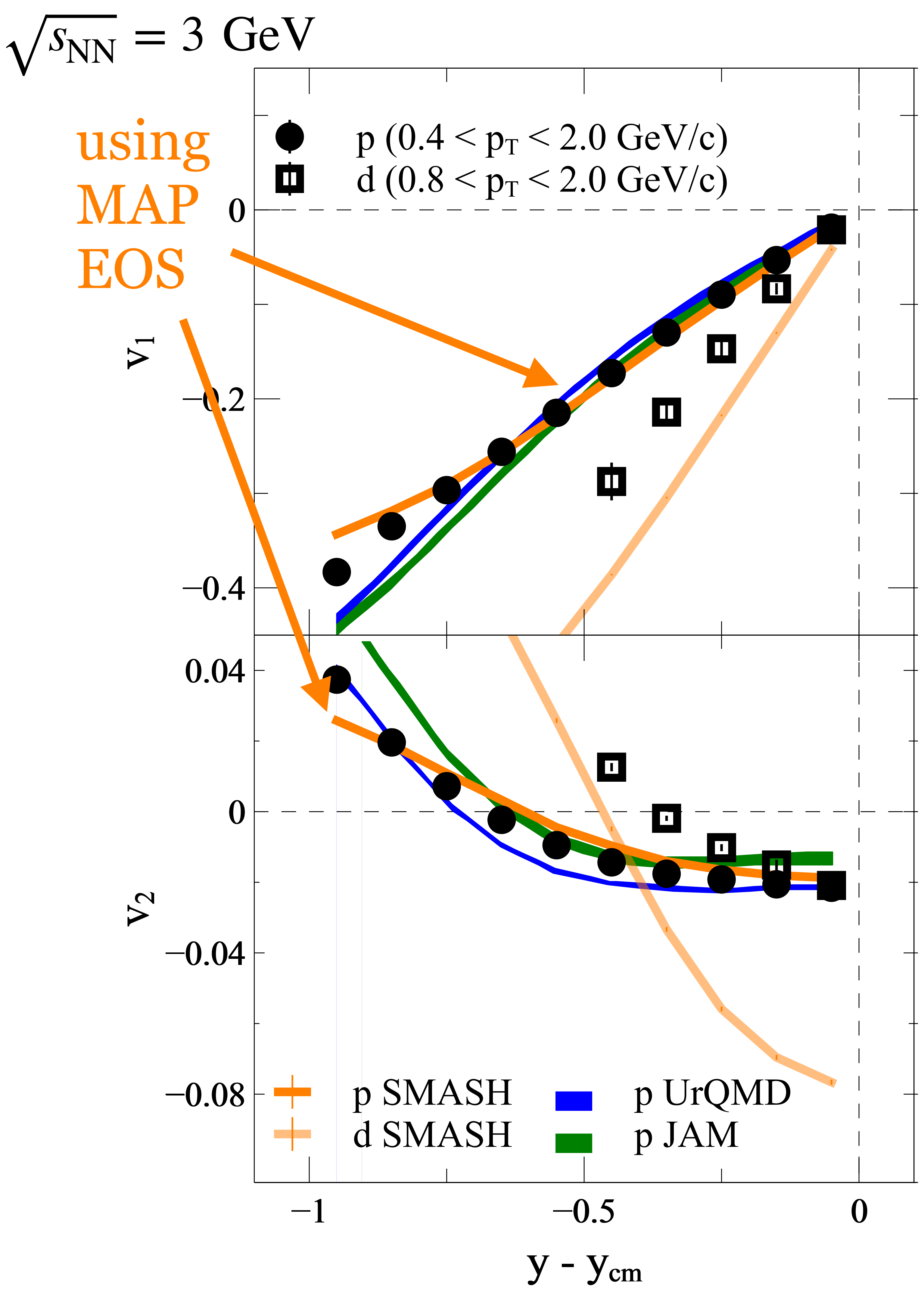
D. Persram, C. Gale, Phys. Rev. C **65**, 064611 (2002), arXiv:nucl-th/0111035

- cross sections and mean-fields should be consistent
- opportunity to collaborate w/ theory, *ab initio* calculations, ...



J. W. Lee *et al.* (SpiRIT), Eur. Phys. J. A **58**, 201 (2022), arXiv:2211.02837

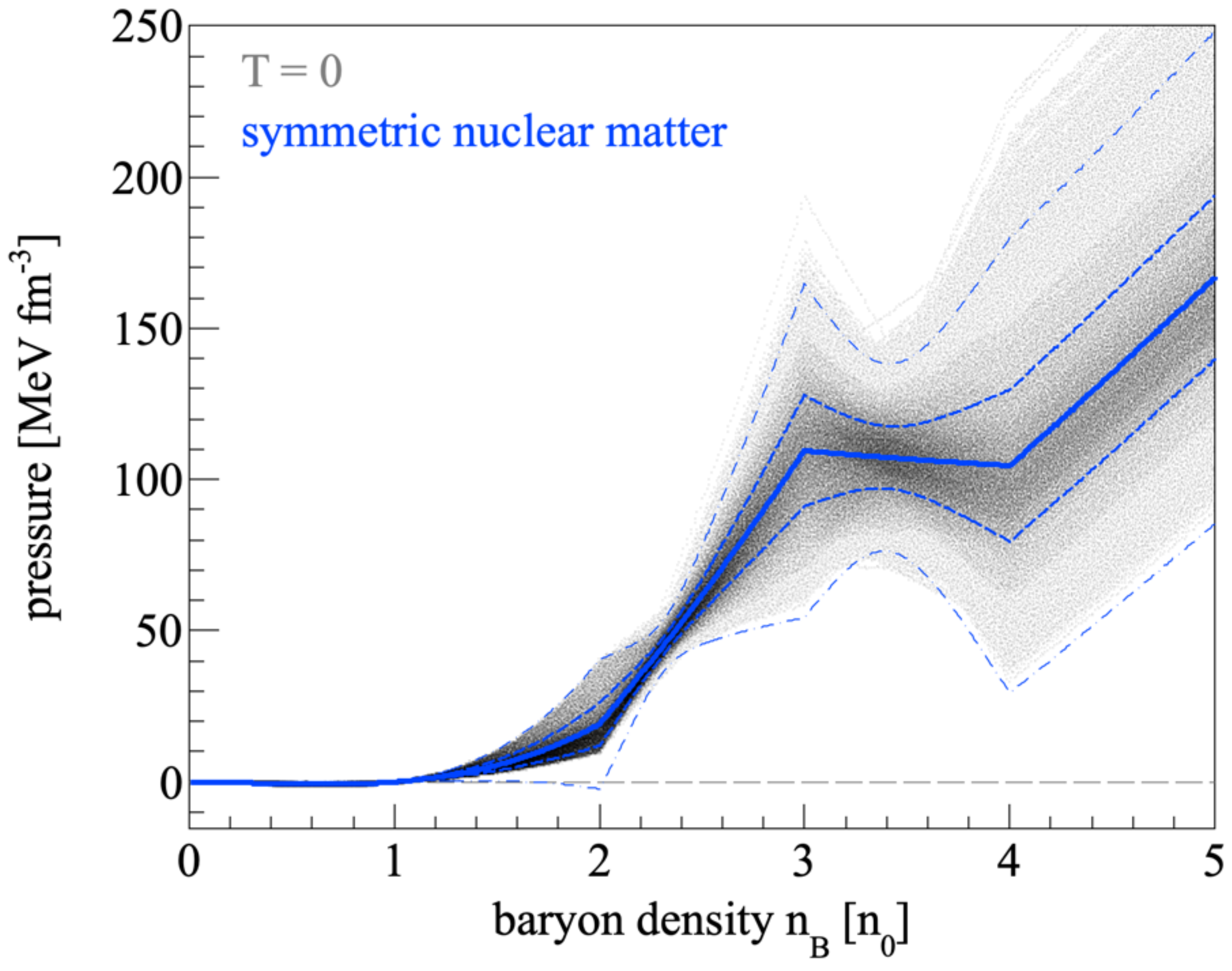
Cluster production



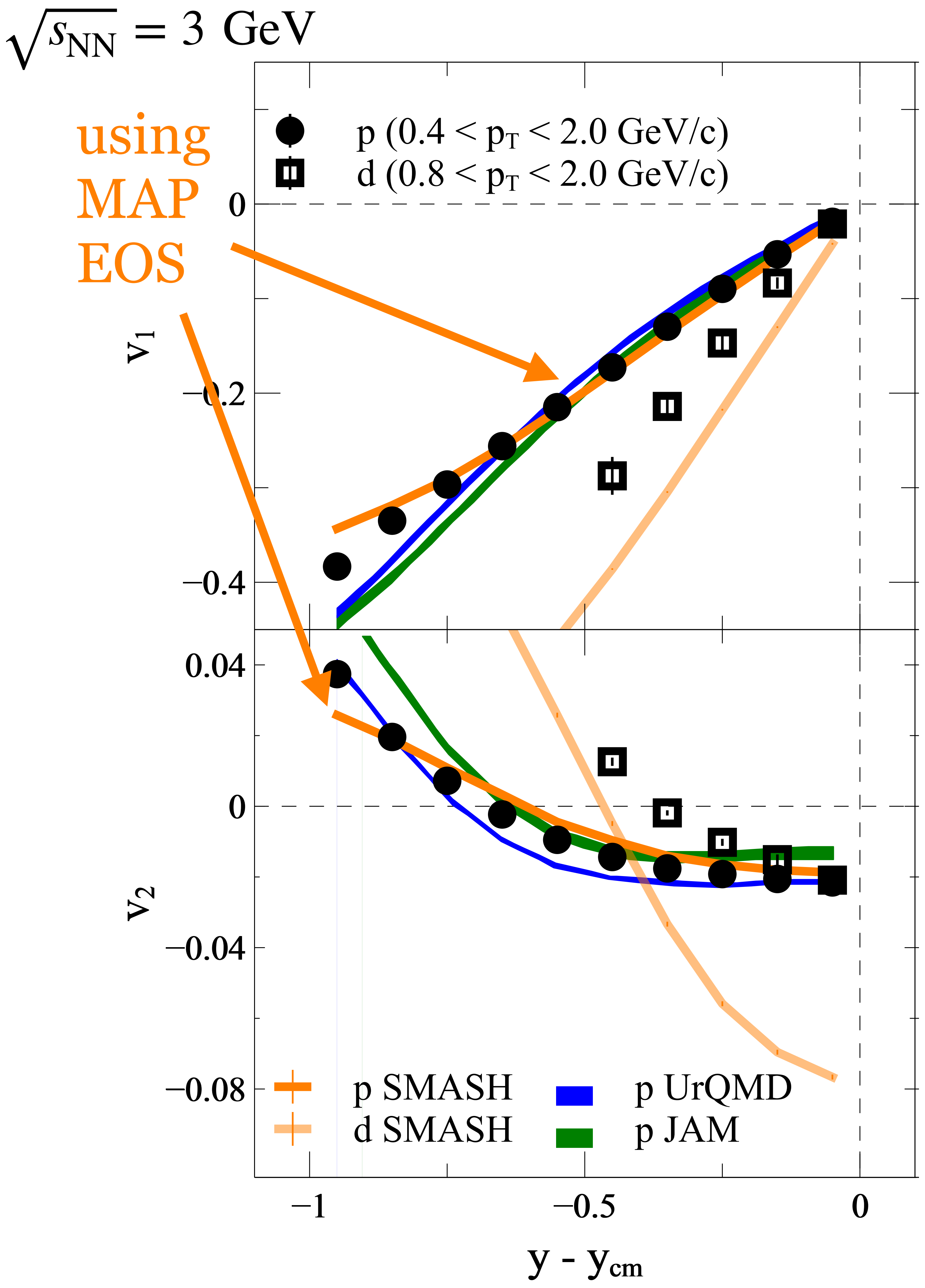
Description of light cluster production needed:

- coalescence/clustering: doesn't take into account the dynamic role of light clusters throughout the evolution
- dynamic nucleon/pion catalysis: consider as separate degrees of freedom, produced through N or π collisions
- dynamical production through potentials???

MAP EOS:



STAR, Phys. Lett. B **827**, 137003 (2022), arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996
A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024), arXiv:2301.13253



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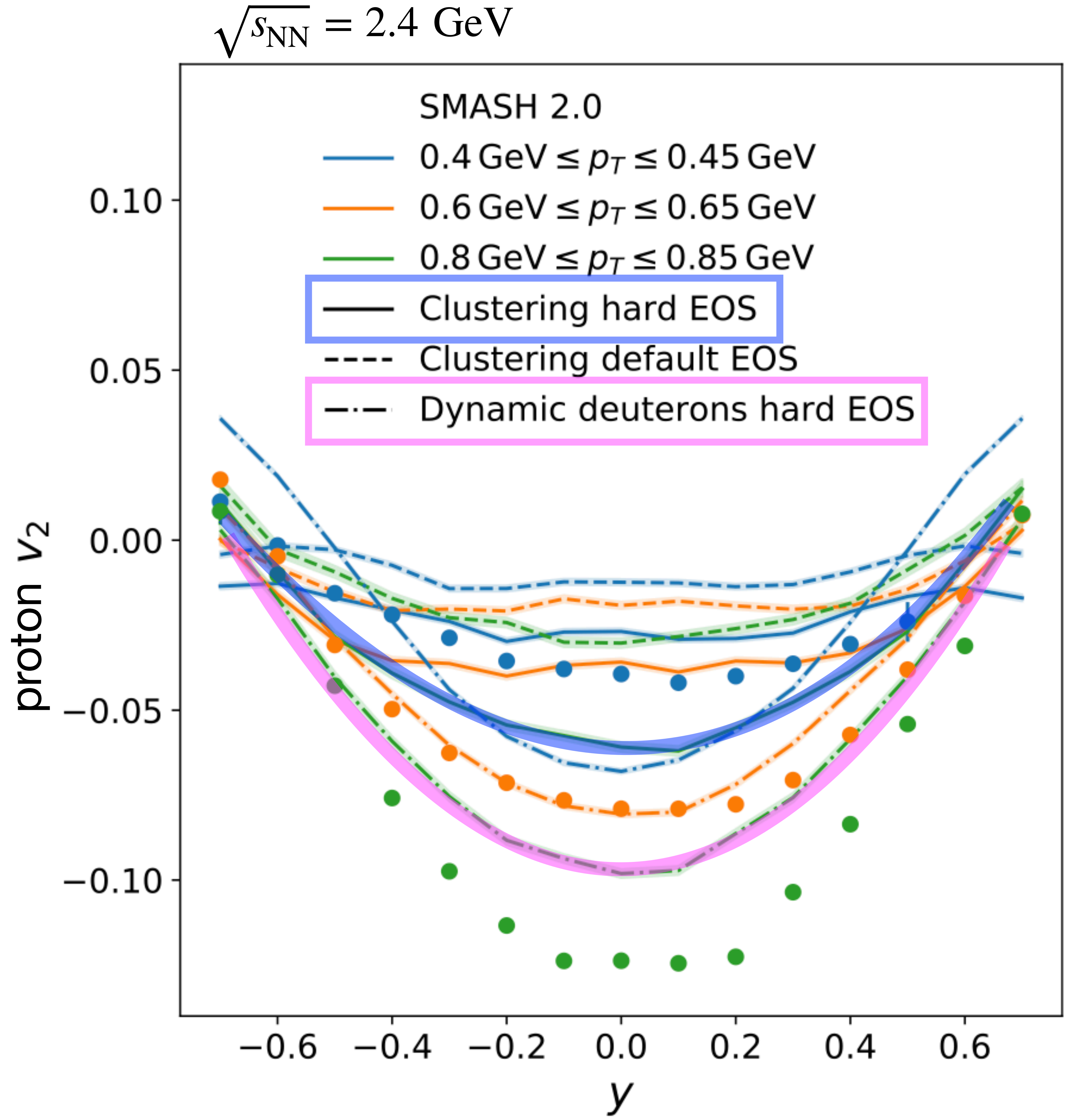

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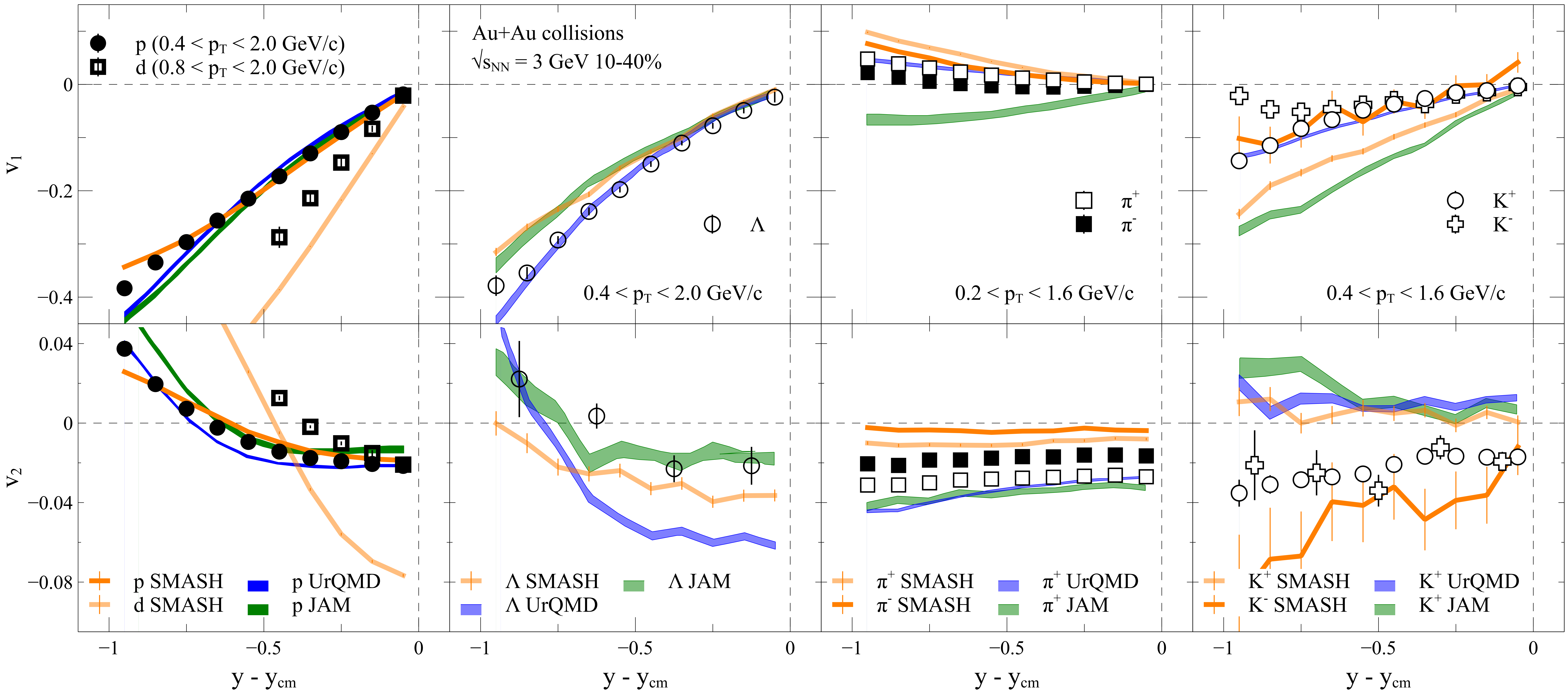
J. Mohs, M. Ege, H. Elfner, M. Mayer, Phys. Rev. C **105** 3, 034906 (2022), arXiv:2012.11454

Describing proton flow is not enough

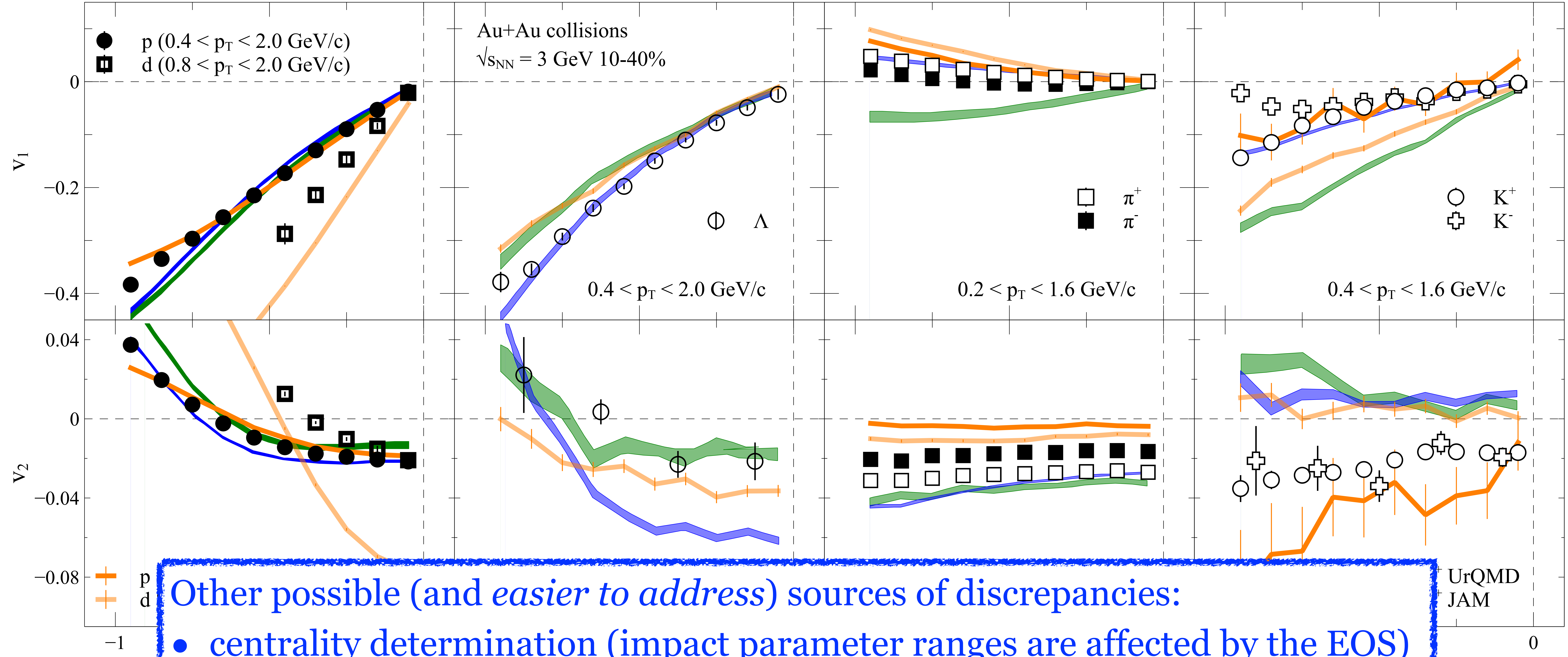


STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908

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

A. Sorensen *et al.*, arXiv:2301.13253, to appear in JPPNP

Describing proton flow is not enough



Other possible (and *easier to address*) sources of discrepancies:

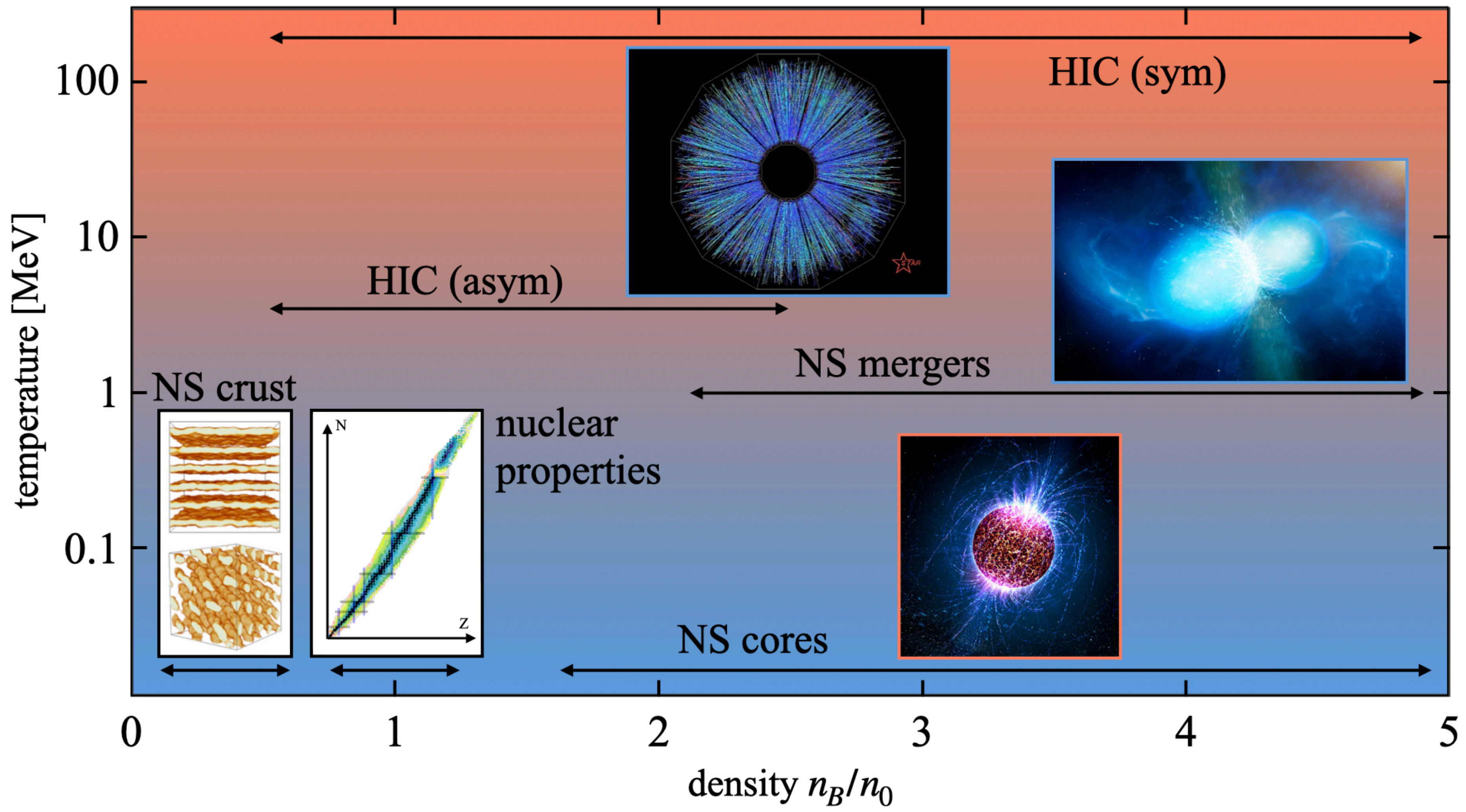
- centrality determination (impact parameter ranges are affected by the EOS)
  Note: simulations are numerically costly & this will increase that cost
- method of calculating flow (event plane vs. two-particle correlations)
  (are experiment-experiment and experiment-theory comparisons reliable?)

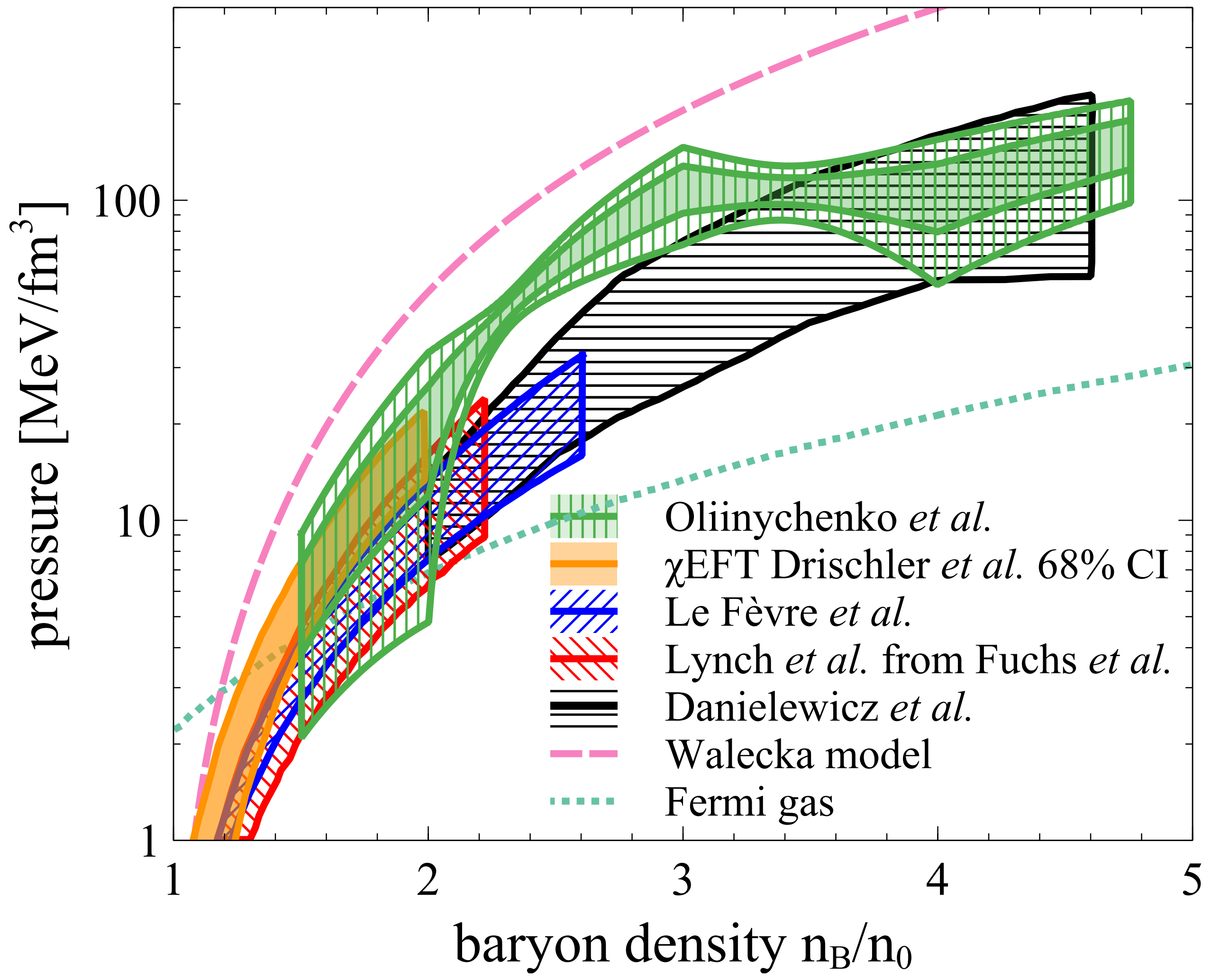
STAR, Phys. Lett. B 8
D. Oliinychenko, **A. S**
A. Sorensen *et al.*, a

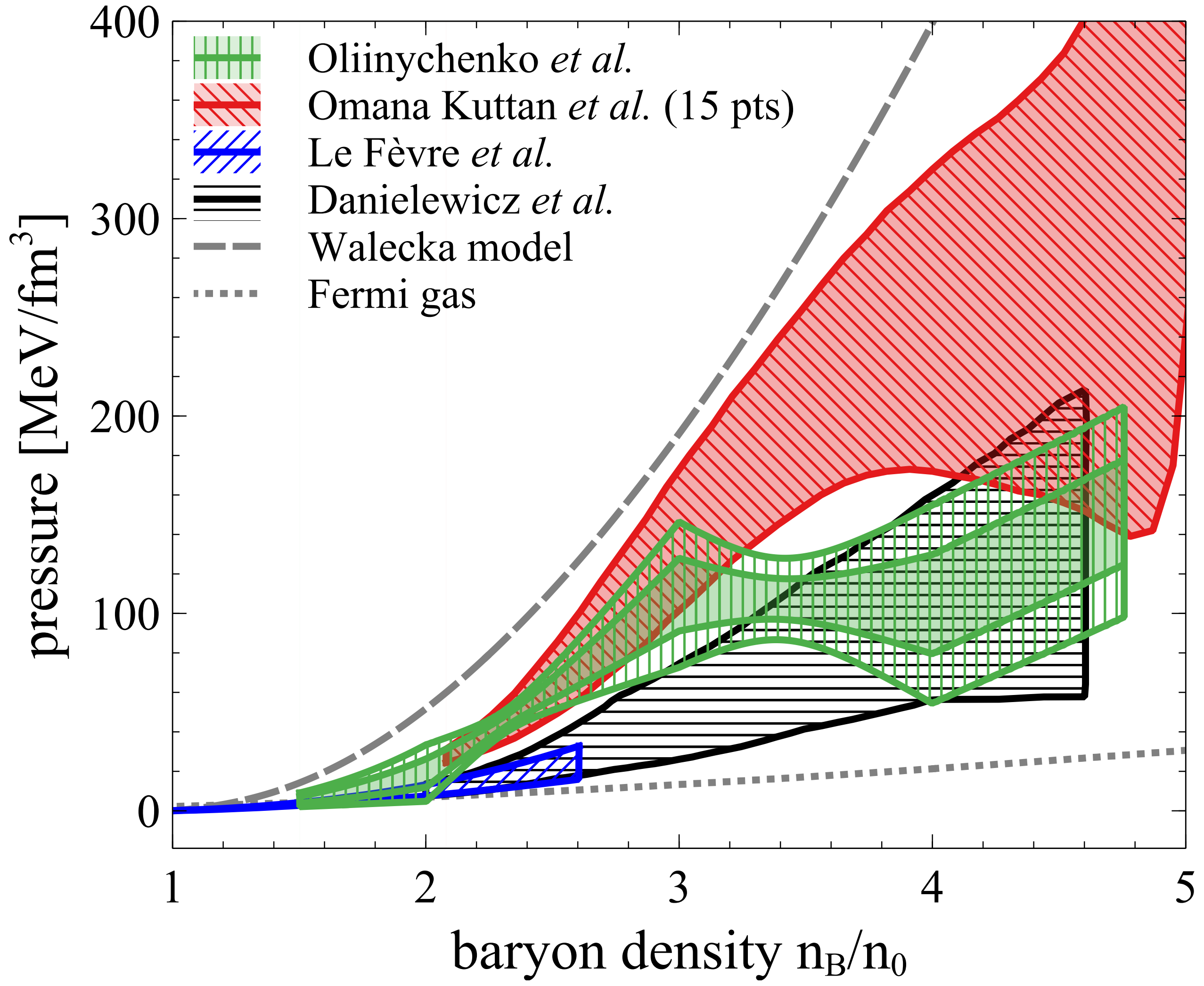
Summary

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

- Needed for interpreting low-$\sqrt{s_{NN}}$ experiments (STAR FXT, HADES, FRIB, CBM, FRIB400)







Open questions

- 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 clear guidance from theory?
  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]

- What are the limits of microscopic transport?
  (dense systems, change of degrees of freedom, short-range correlations, etc.)

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

- Could any of that be of use for physics at the EIC?