Constraints on the dense nuclear matter EOS from Au+Au collisions in the BES FXT range

Agnieszka Sorensen

University of Washington

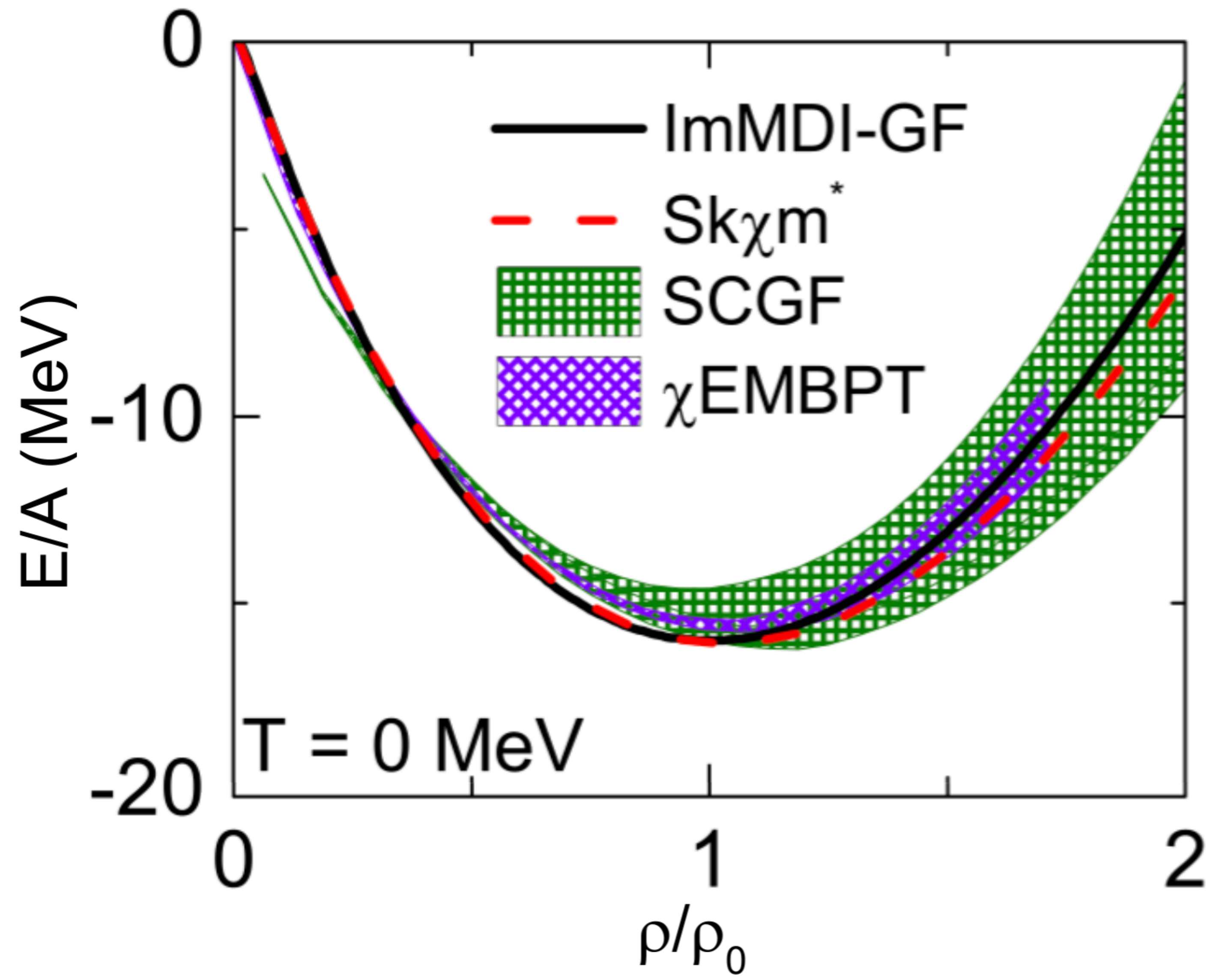
INSTITUTE for NUCLEAR THEORY

INT WORKSHOP INT-20R-1C

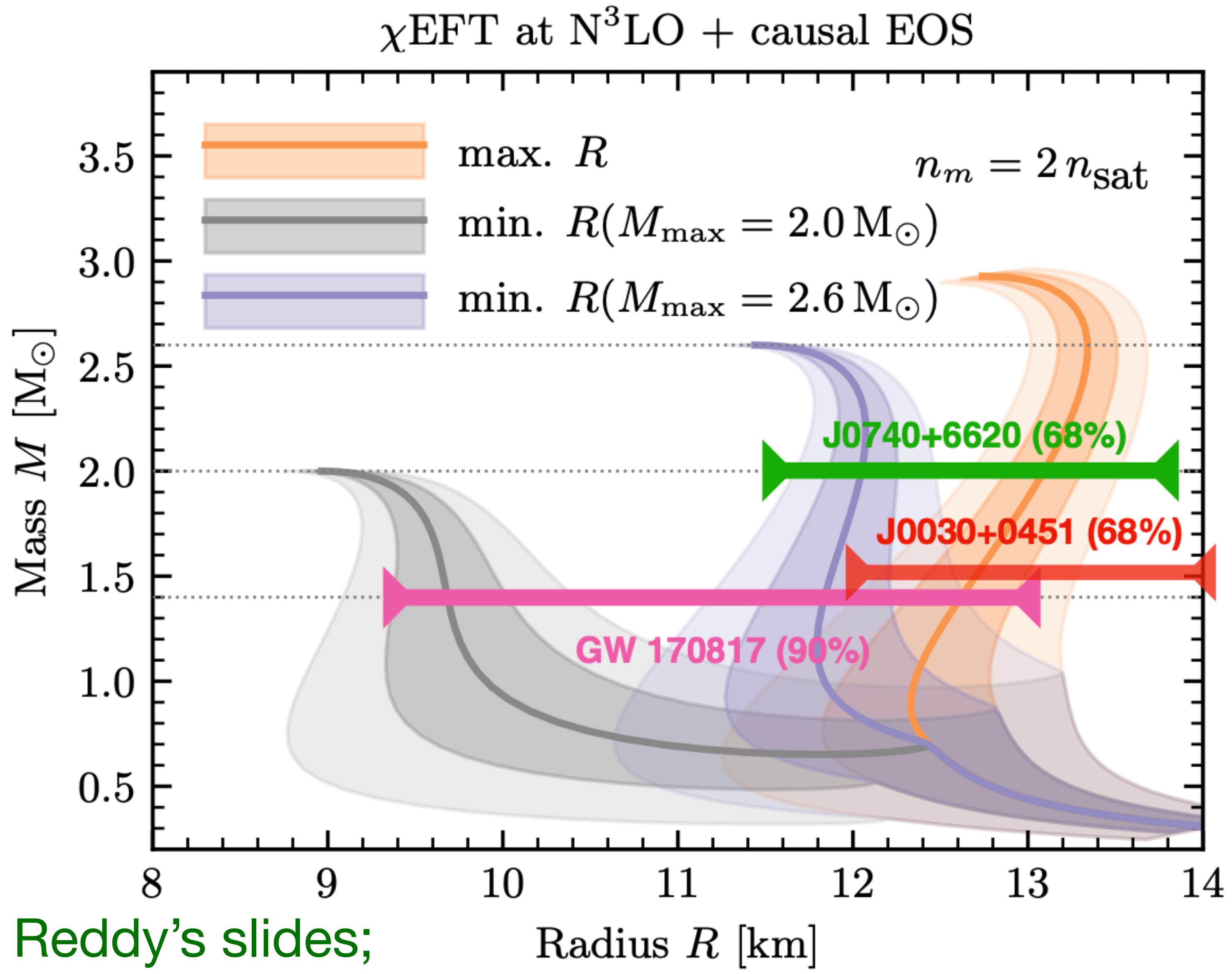
Chirality and Criticality: Novel Phenomena in Heavy-Ion Collisions

August 21, 2023 - August 25, 2023

The EOS = key to understanding fundamental properties of QCD matter

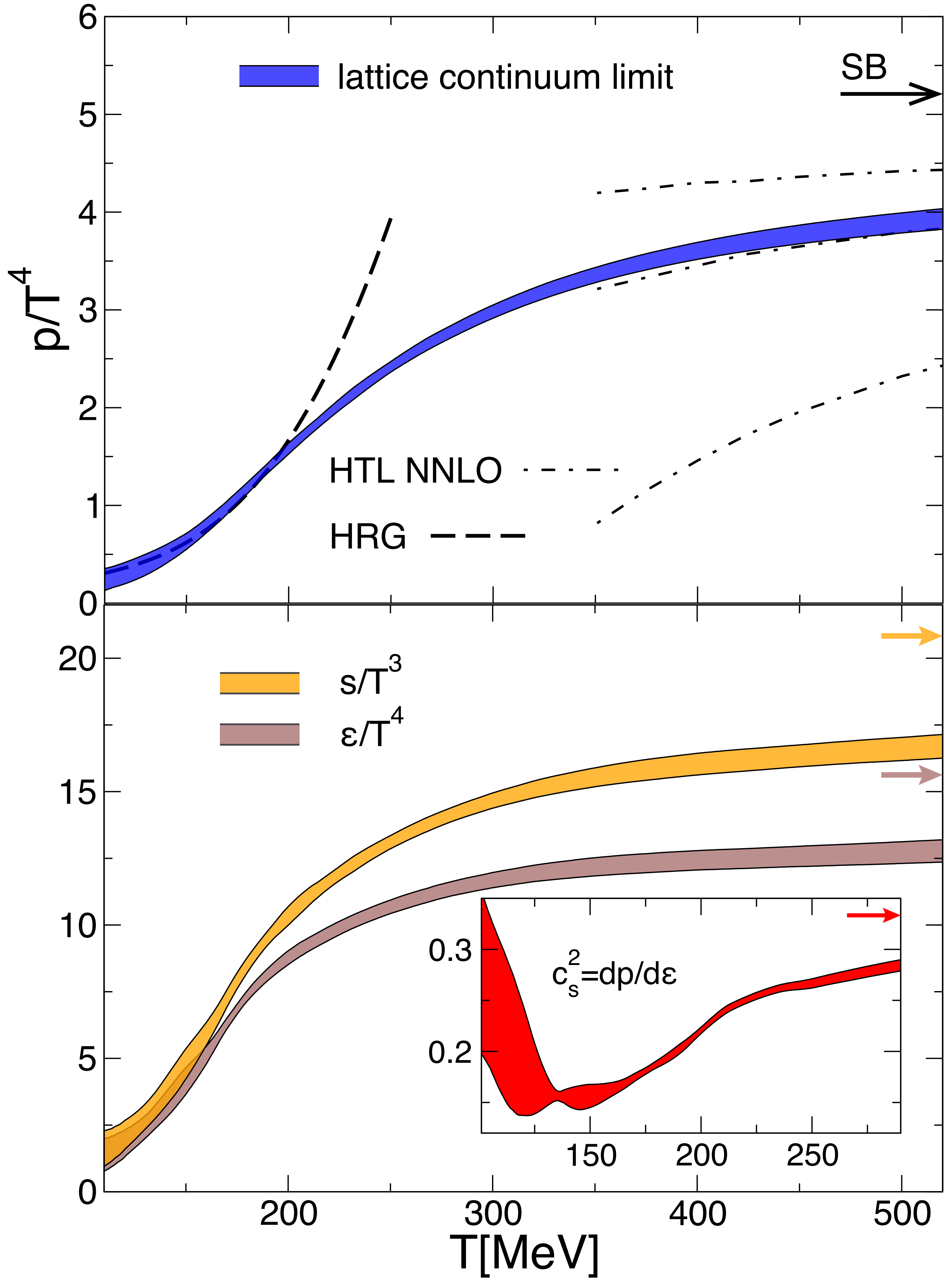


J. Xu, A. Carbone, Z. Zhang, C.-M. Ko, Phys. Rev. C **100**, 2, 024618 (2019) arXiv:1904.09669

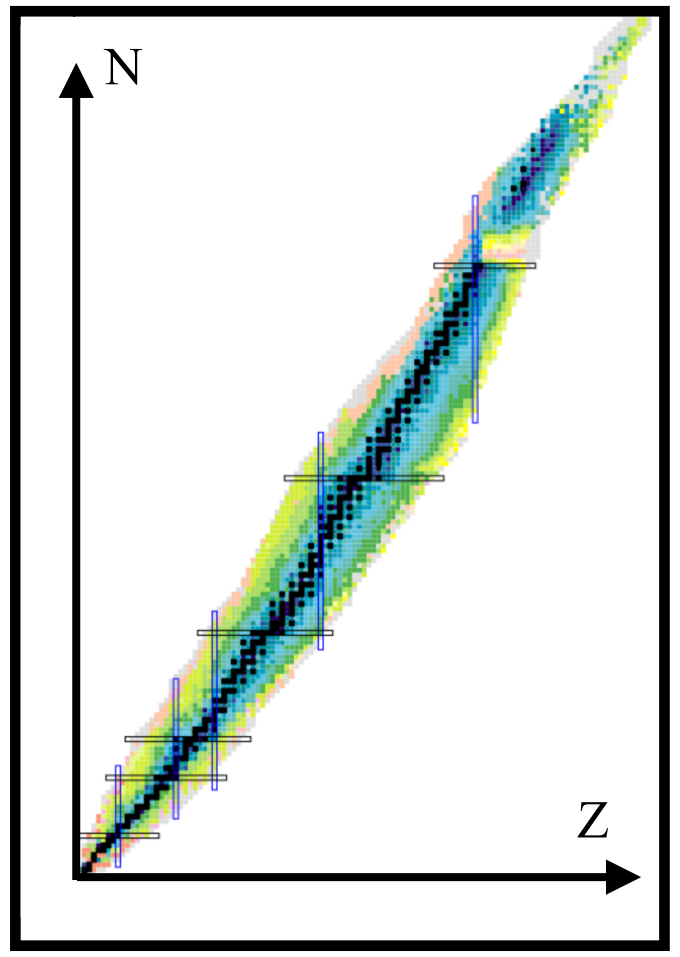


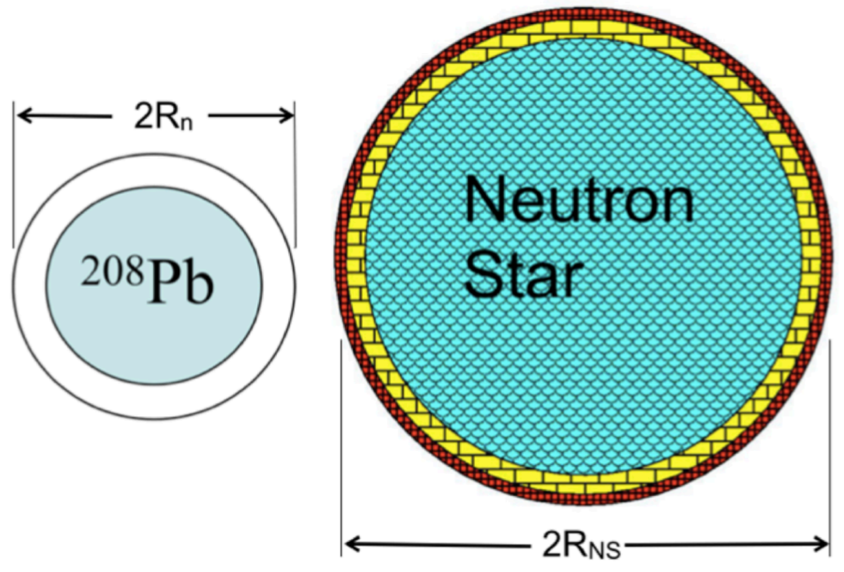
* from S. Reddy's slides;

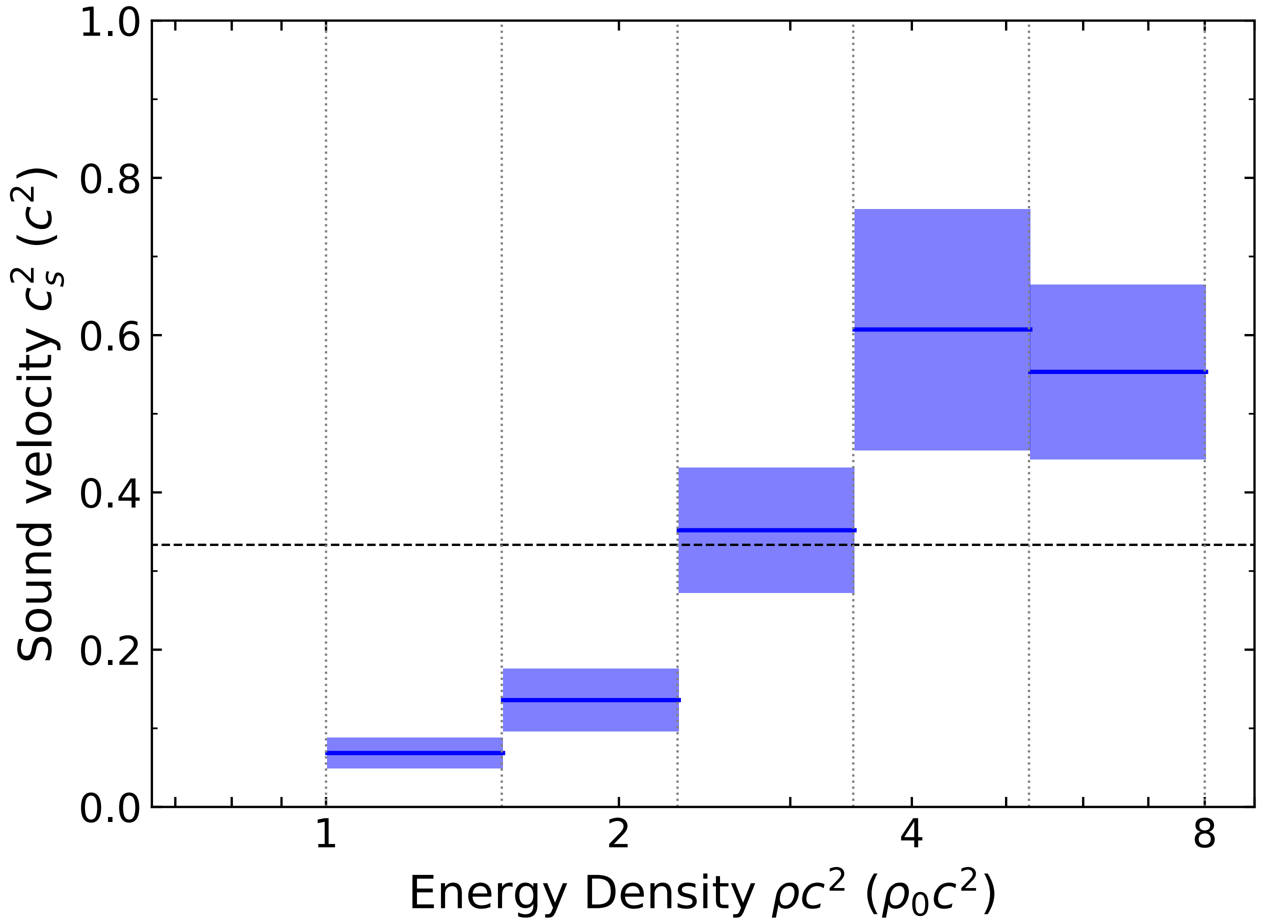
M-R results: C. Drischler, S. Han, J. M. Lattimer, M. Prakash, S. Reddy, T. Zhao, Phys. Rev. C **103** 4, 045808 (2021), arXiv:2009.06441



S. Borsanyi, Z. Fodor, C. Hoelbling, S. Katz, S. Krieg, K. K. Szabo, Phys. Lett. B **730** 99–104 (2014) arXiv:1309.5258







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

The EOS is a common effort within the nuclear physics community

A. Sorensen *et al.*, 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]

Endorsing authors:

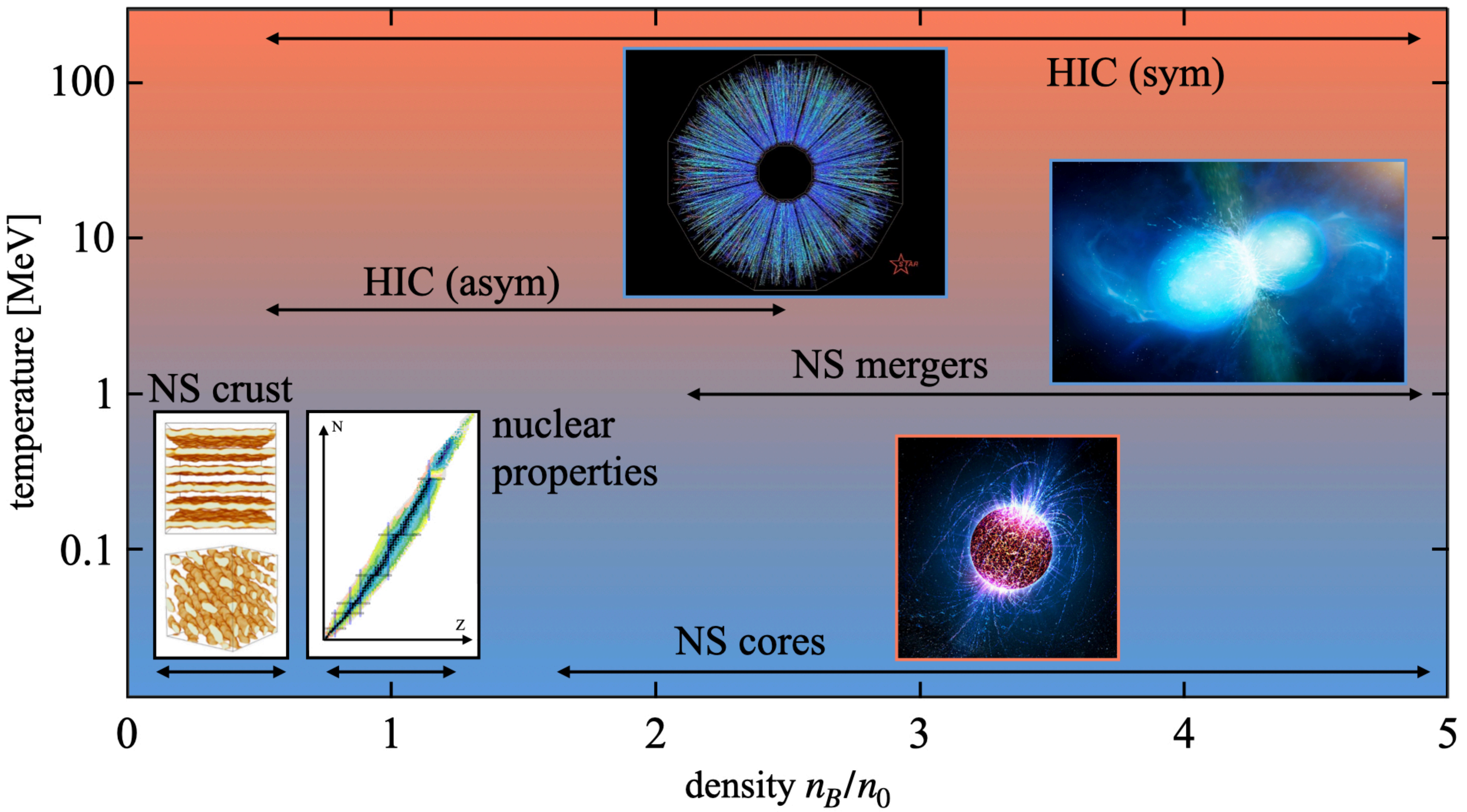
Navid Abbasi[19], Jörg Aichelin[20,21], Anton Andronic[22], Steffen A. Bass[23], Francesco Becattini[24,25], David Blaschke[26,27,28], Marcus Bleicher[29,30], Christoph Blume[31], Elena Bratkovskaya[14,29,30], B. Alex Brown[3,6], David A. Brown[32], Alberto Camaiani[33], Giovanni Casini[25], Katerina Chatziioannou[34,35], Abdelouahad Chbihi[36], Maria Colonna[37], Mircea Dan Cozma[38], Veronica Dexheimer[39], Xin Dong[40], Travis Dore[41], Lipei Du[42], José A. Dueñas[43], Hannah Elfner[14,21,29,30], Wojciech Florkowski[44], Yuki Fujimoto[1], Richard J. Furnstahl[45], Alexandra Gade[3,6], Tetyana Galatyuk[14,46], Charles Gale[42], Frank Geurts[47], Sašo Grozdanov[48,49], Kris Hagel[10], Steven P. Harris[1], Wick Haxton[40,50], Ulrich Heinz[45], Michal P. Heller[51], Or Hen[52], Heiko Hergert[3,6], Norbert Herrmann[53], Huan Zhong Huang[54], Xu-Guang Huang[55,56,57], Natsumi Ikeno[10,58], Gabriele Inghirami[14], Jakub Jankowski[26], Jiangyong Jia[59,60], José C. Jiménez[61], Joseph Kapusta[62], Behruz Kardan[31], Iurii Karpenko[63], Declan Keane[39], Dmitri Kharzeev[60,64], Andrej Kugler[65], Arnaud Le Fèvre[14], Dean Lee[3,6], Hong Liu[66], Michael A. Lisa[45], William J. Llope[67], Ivano Lombardo[68], Manuel Lorenz[31], Tommaso Marchi[69], Larry McLerran[1], Ulrich Mosel[70], Anton Motornenko[21], Berndt Müller[23], Paolo Napolitani[71], Joseph B. Natowitz[10], Witold Nazarewicz[3,6], Jorge Noronha[72], Jacquelyn Noronha-Hostler[72], Grażyna Odyniec[40], Panagiota Papakonstantinou[73], Zuzana Paulínyová[74], Jorge Piekarewicz[75], Robert D. Pisarski[60], Christopher Plumberg[76], Madappa Prakash[7], Jørgen Randrup[40], Claudia Ratti[77], Peter Rau[1], Sanjay Reddy[1], Hans-Rudolf Schmidt[2,14], Paolo Russotto[37], Radoslaw Ryblewski[78], Andreas Schäfer[79], Björn Schenke[60], Srimoyee Sen[80], Peter Senger[81], Richard Seto[82], Chun Shen[67,83], Bradley Sherrill[3,6], Mayank Singh[62], Vladimir Skokov[83,84], Michał Spaliński[85,86], Jan Steinheimer[21], Mikhail Stephanov[87], Joachim Stroth[14,31], Christian Sturm[14], Kai-Jia Sun[88], Aihong Tang[60], Giorgio Torrieri[89,90], Wolfgang Trautmann[14], Giuseppe Verde[91], Volodymyr Vovchenko[77], Ryoichi Wada[10], Fuqiang Wang[92], Gang Wang[54], Klaus Werner[20], Nu Xu[40], Zhangbu Xu[60], Ho-Ung Yee[87], Sherry Yennello[9,10,93], Yi Yin[94]

Hot QCD

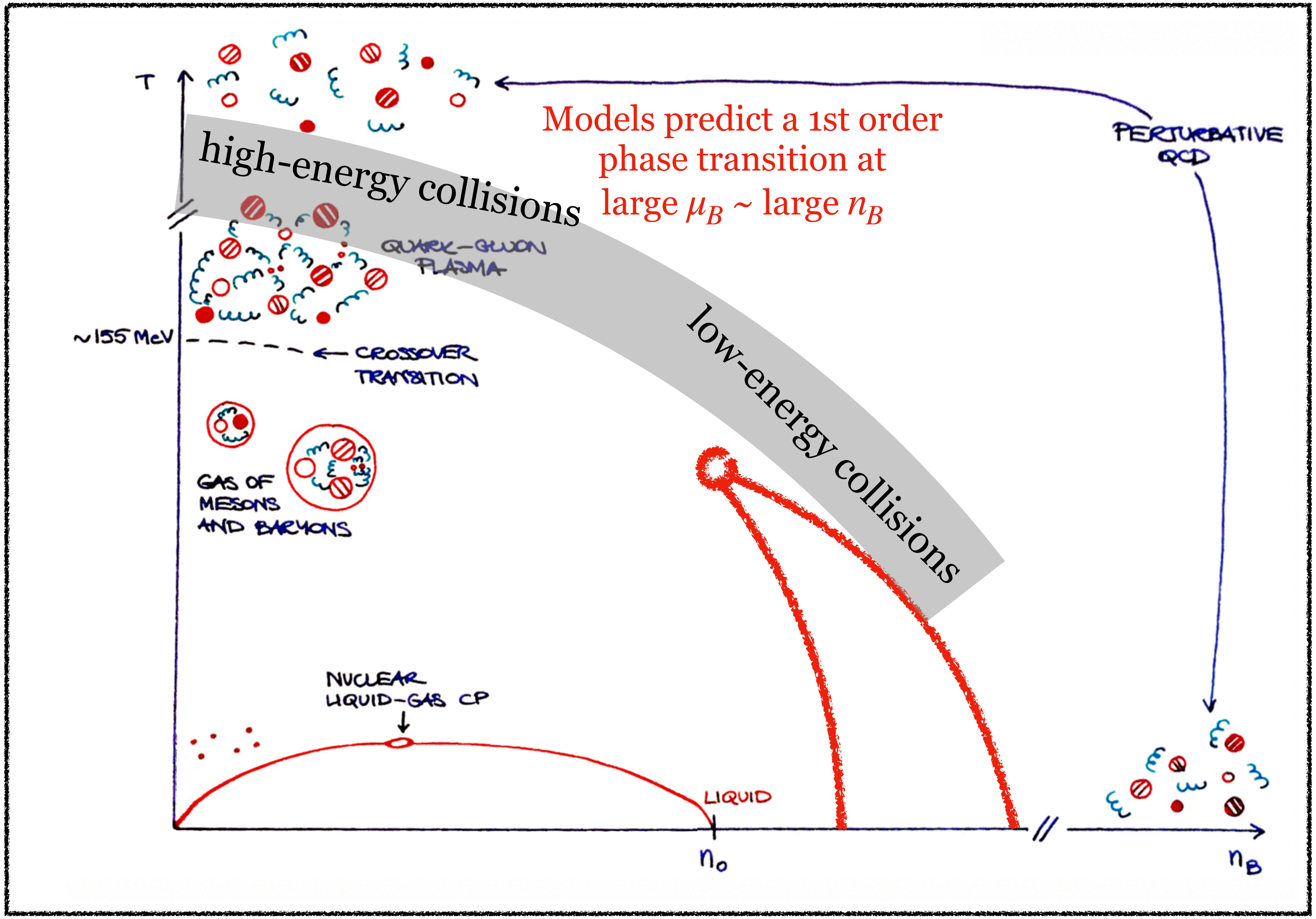
Cold QCD

Nucl. reactions + astro

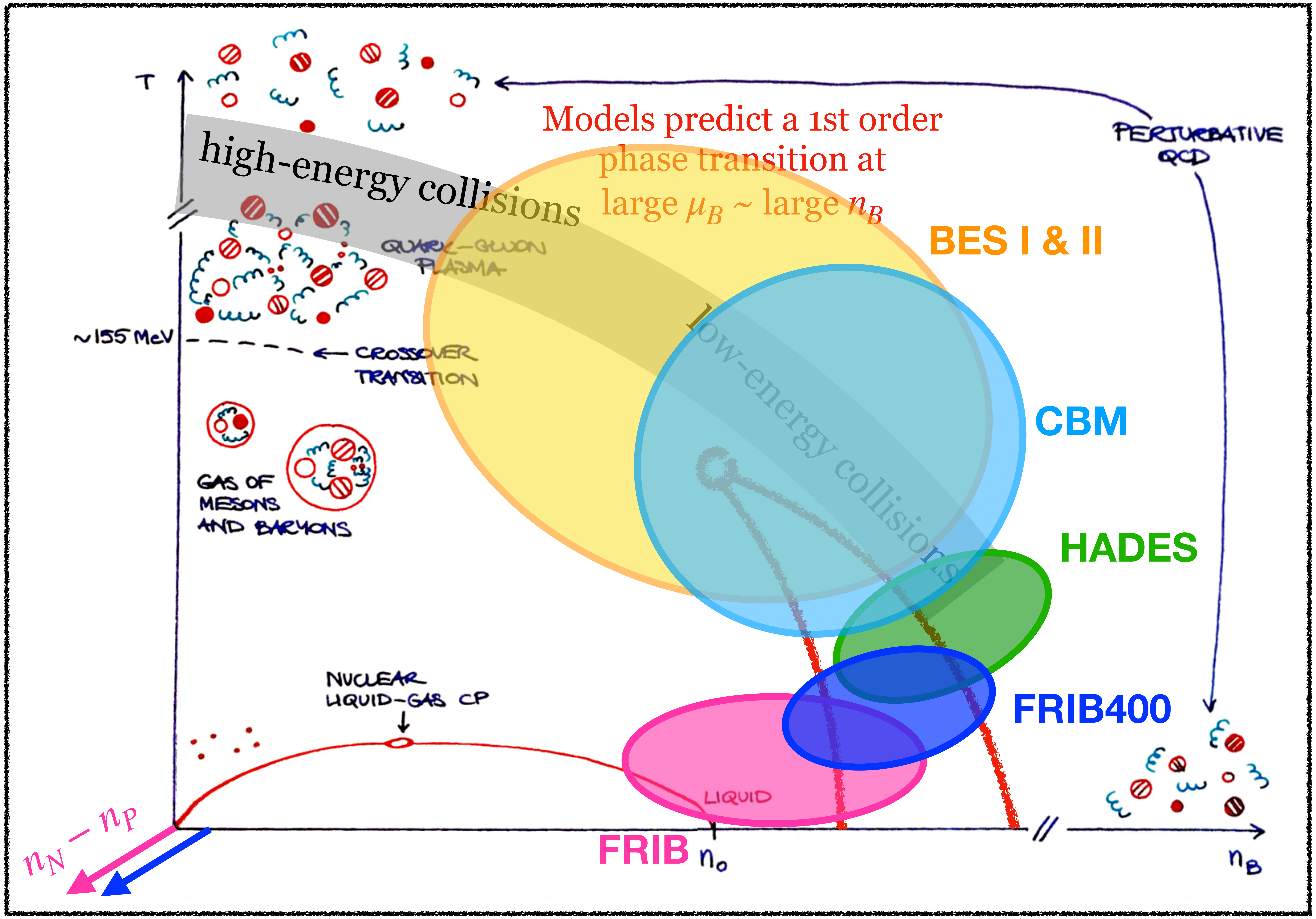
Fundamental sym.



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

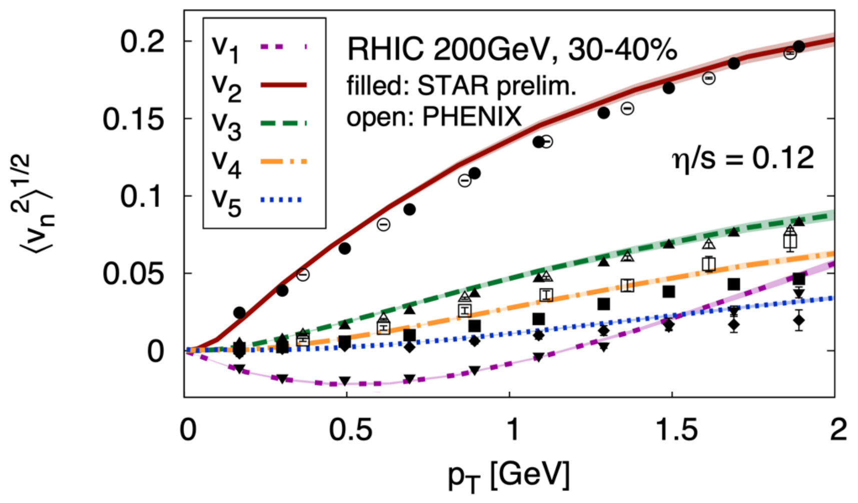


The QCD phase diagram: great interest in behavior at high n_B



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

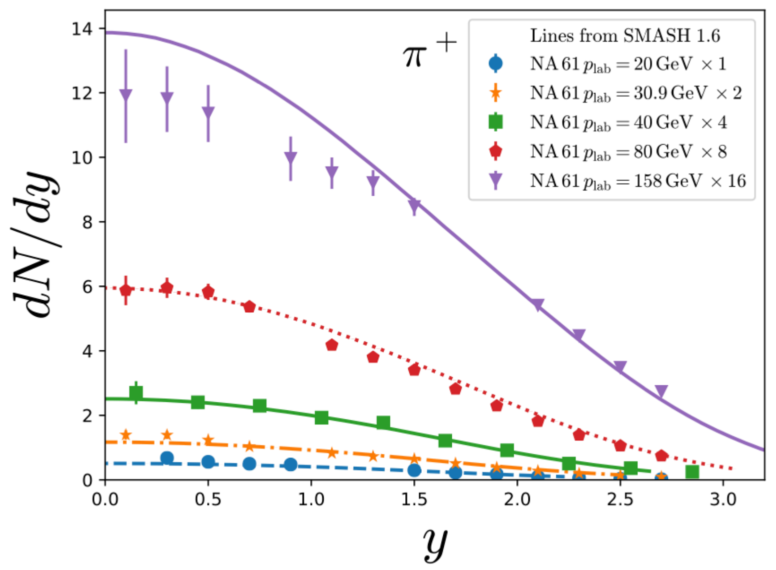
Relativistic viscous hydrodynamic simulations with LQCD EOS: amazing agreement with data from high-energy collisions



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

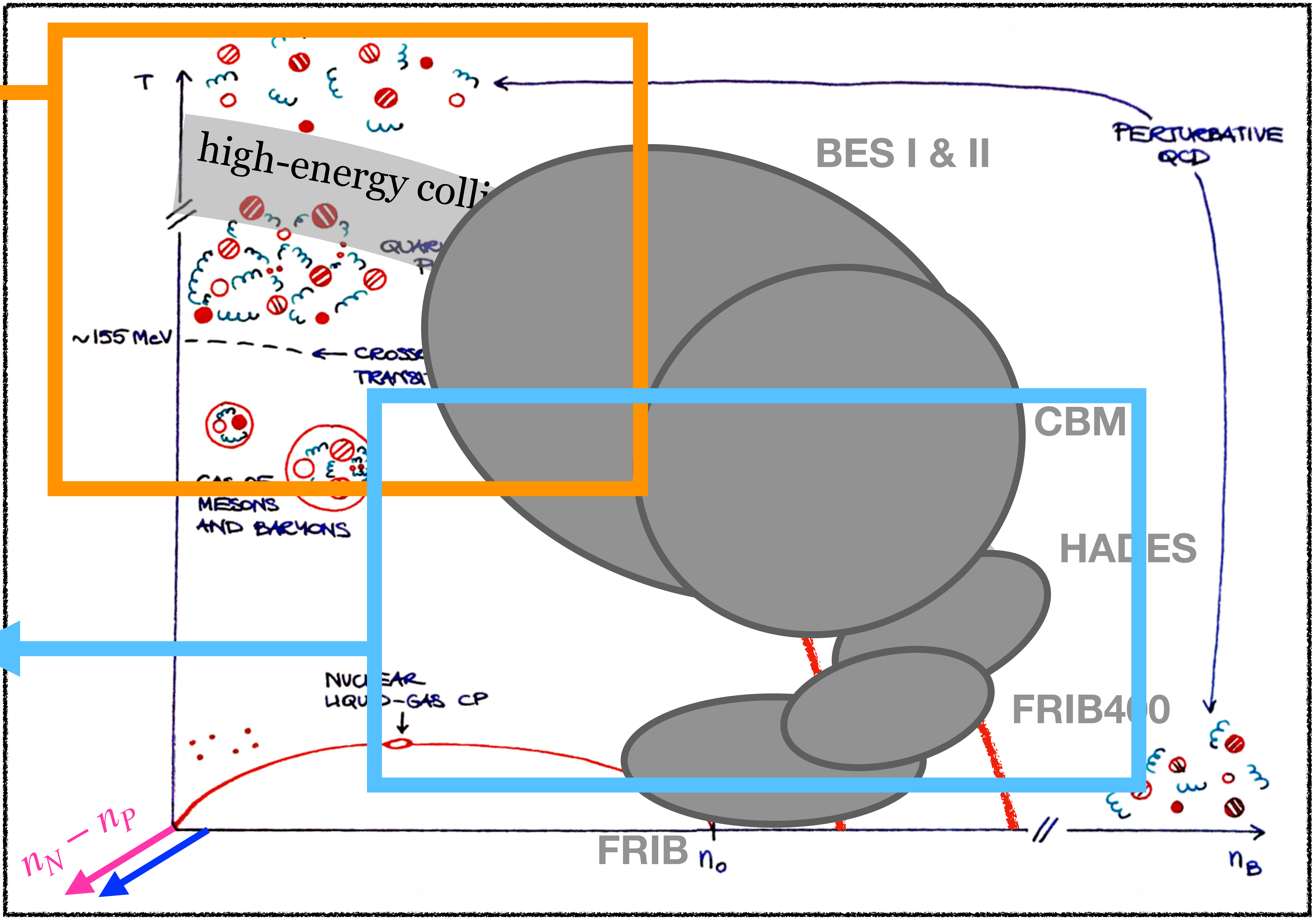
fast equilibration = hydro applies

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



Transport model simulations of heavy-ion collisions

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

  - solve coupled Boltzmann equations $\forall i:$

$$\frac{\partial f_i}{\partial t} + \frac{d\mathbf{x}_i}{dt}\frac{\partial f_i}{\partial \mathbf{x}_i} + \frac{d\mathbf{p}_i}{dt}\frac{\partial f_i}{\partial \mathbf{p}_i} = I_{\text{coll}}^{(i)}$$

  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 gradients of 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

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

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

  with the meth ber of discrete test-particles, (test particles

  - forces from gr y calculation!)

  - collision term

Transport ***automatically*** includes:

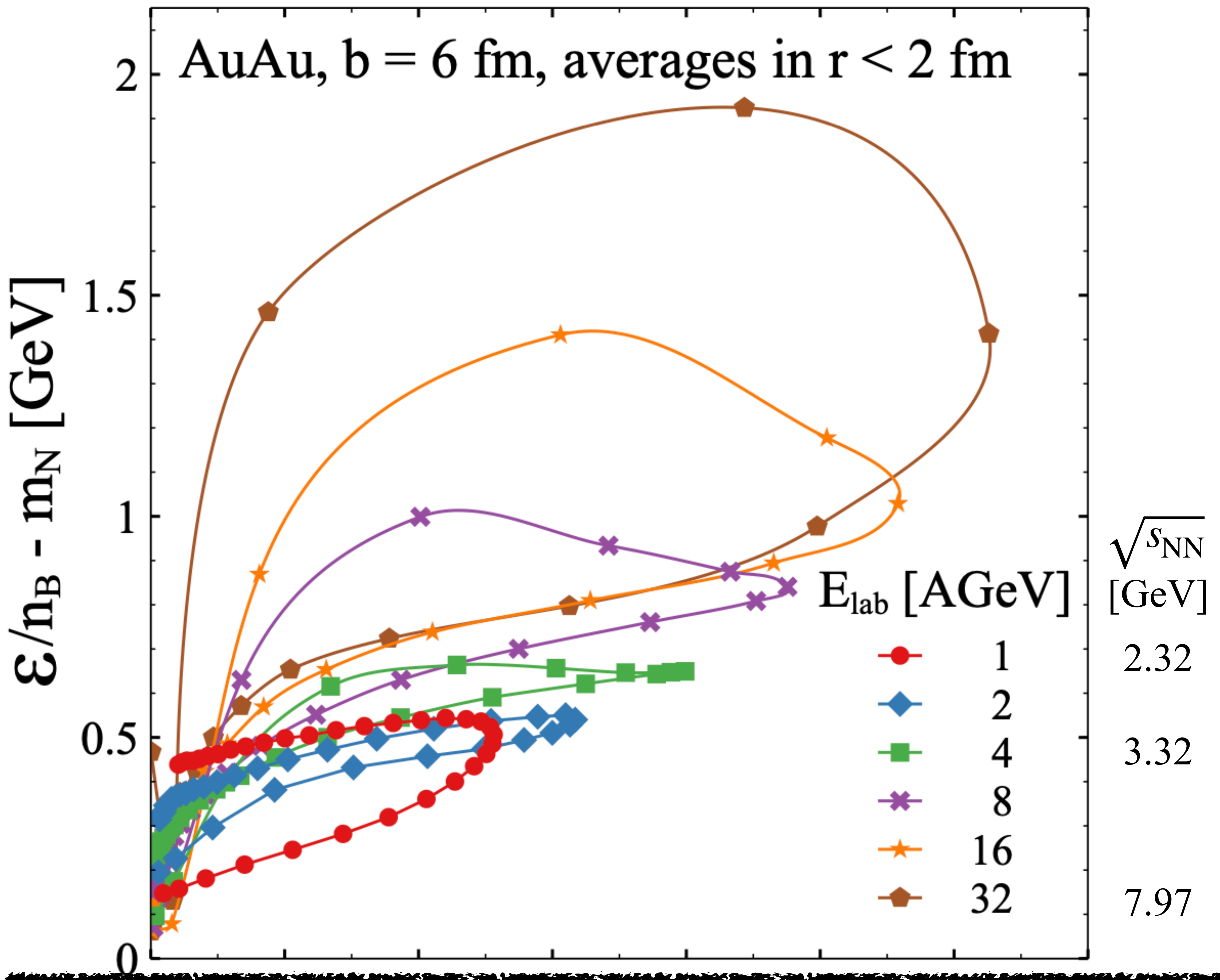
- non-equilibrium evolution, including triggered by probing unstable regions of the phase diagram
- effects due to the interplay between participants and spectators
- baryon, strangeness, charge transport/diffusion

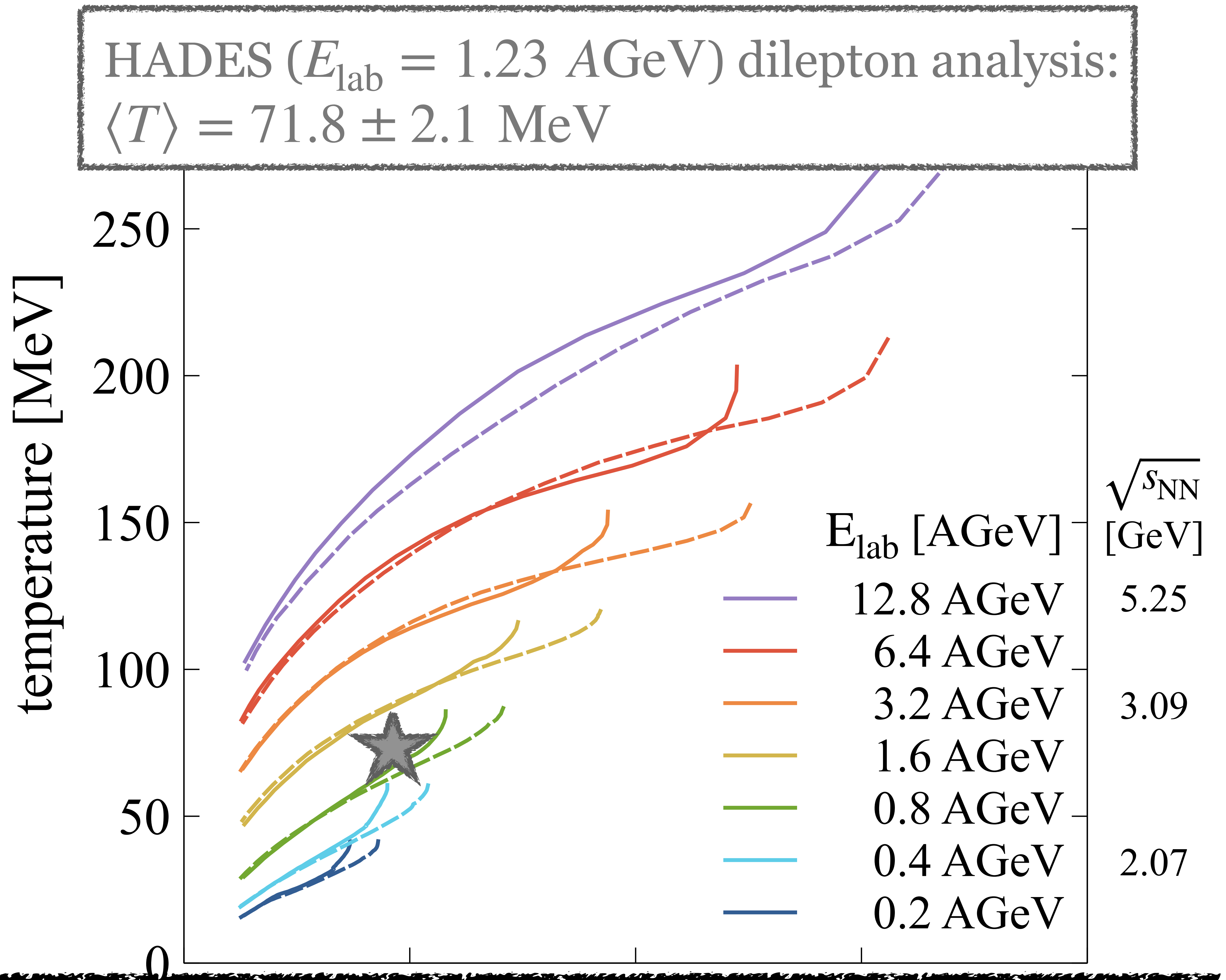
- Quantum Mole
  - solve molecul

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

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

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

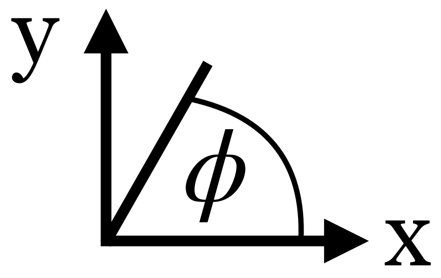




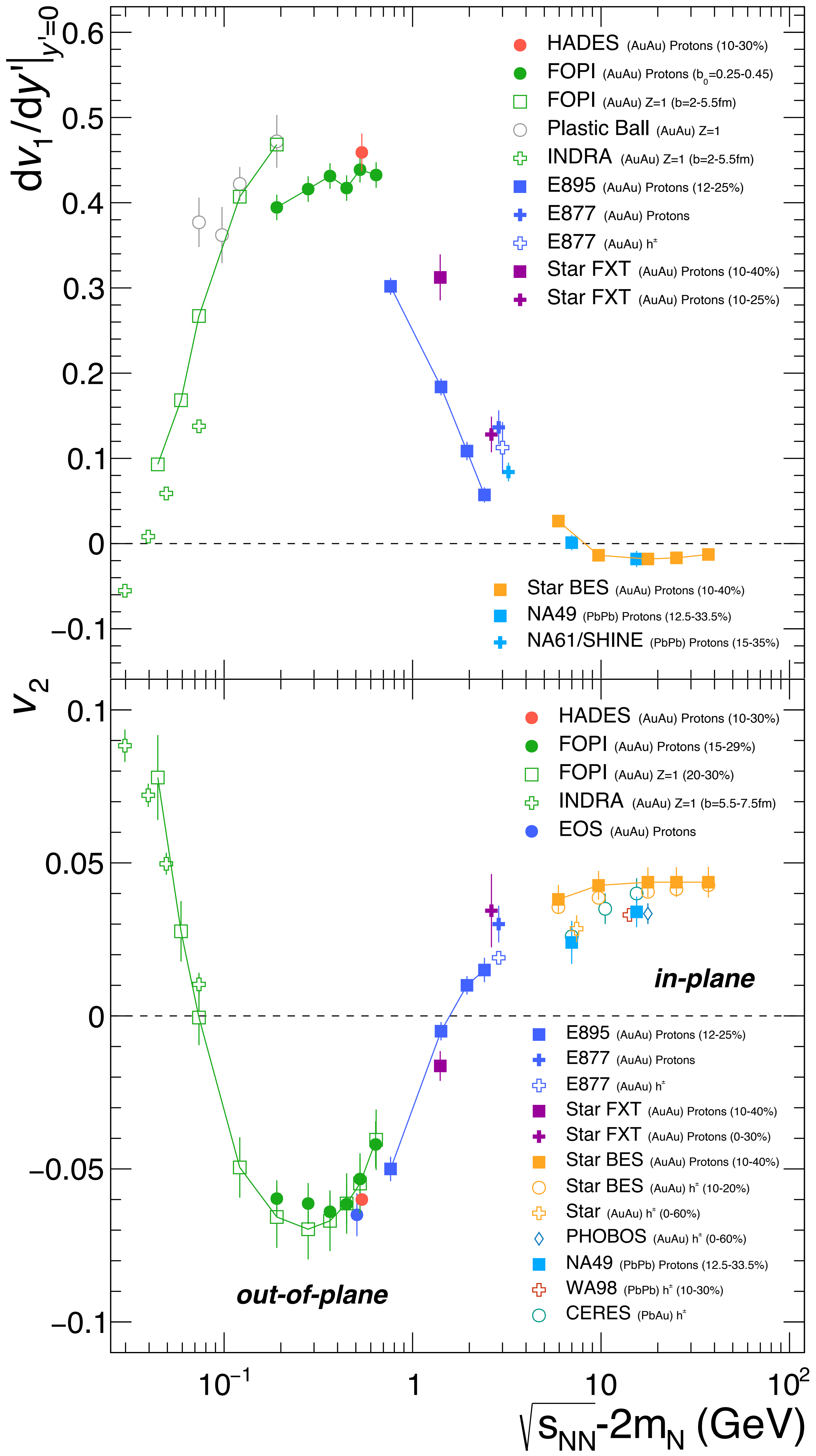
- HICs = the only means to probe densities away from n_0 in controlled terrestrial experiments
- Hadronic transport is necessary to interpret the results: BES FXT, HADES, CBM, FRIB, FRIB400

EOS from flow observables in heavy-ion collisions

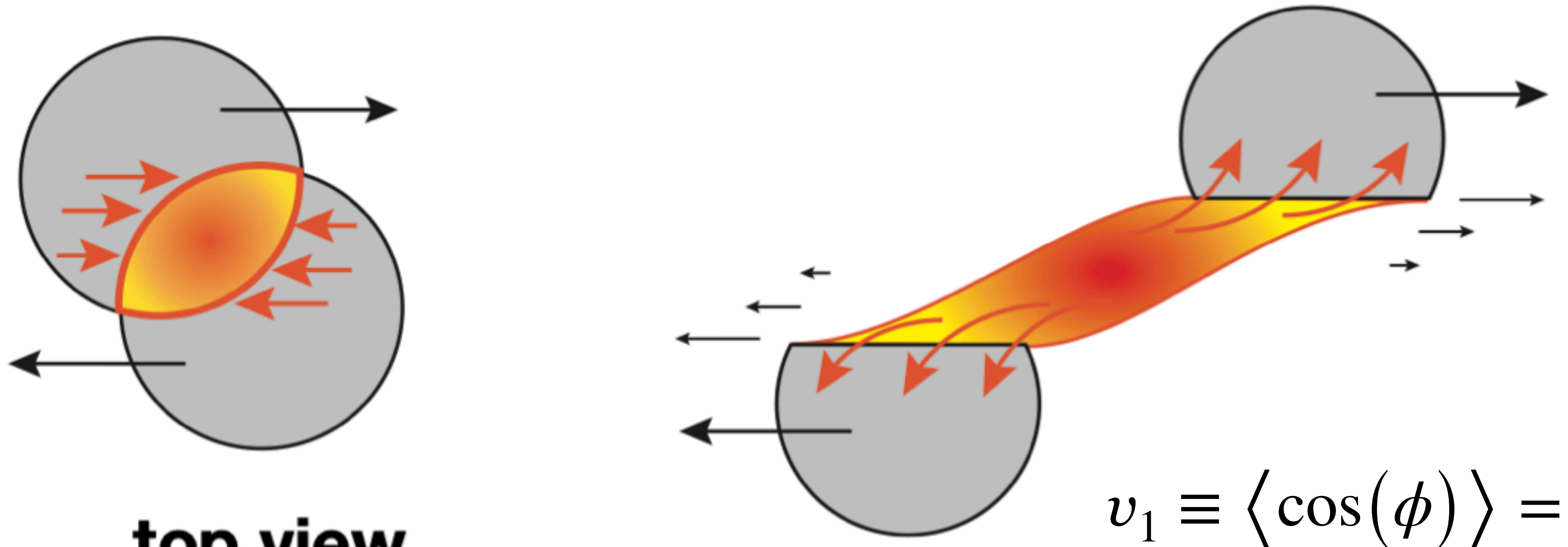
Flow $\quad v_n \equiv \langle \cos(n\phi) \rangle$



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



directed flow v_1 (dv_1/dy ~ longitudinal expansion)

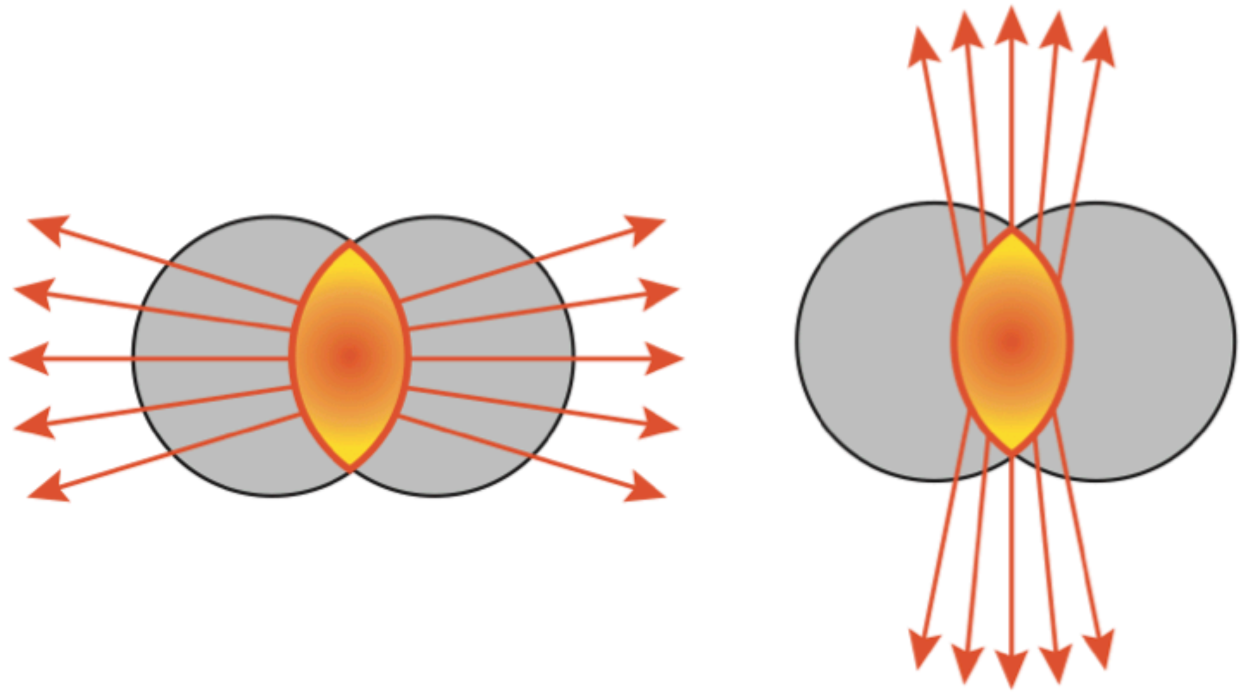


$v_1 \equiv \langle \cos(\phi) \rangle = \langle \frac{p_x}{p_T} \rangle$

These observables are extremely sensitive to the EOS

elliptic flow v_2 ($v_2(y \approx 0)$ ~ midrapidity)

front view

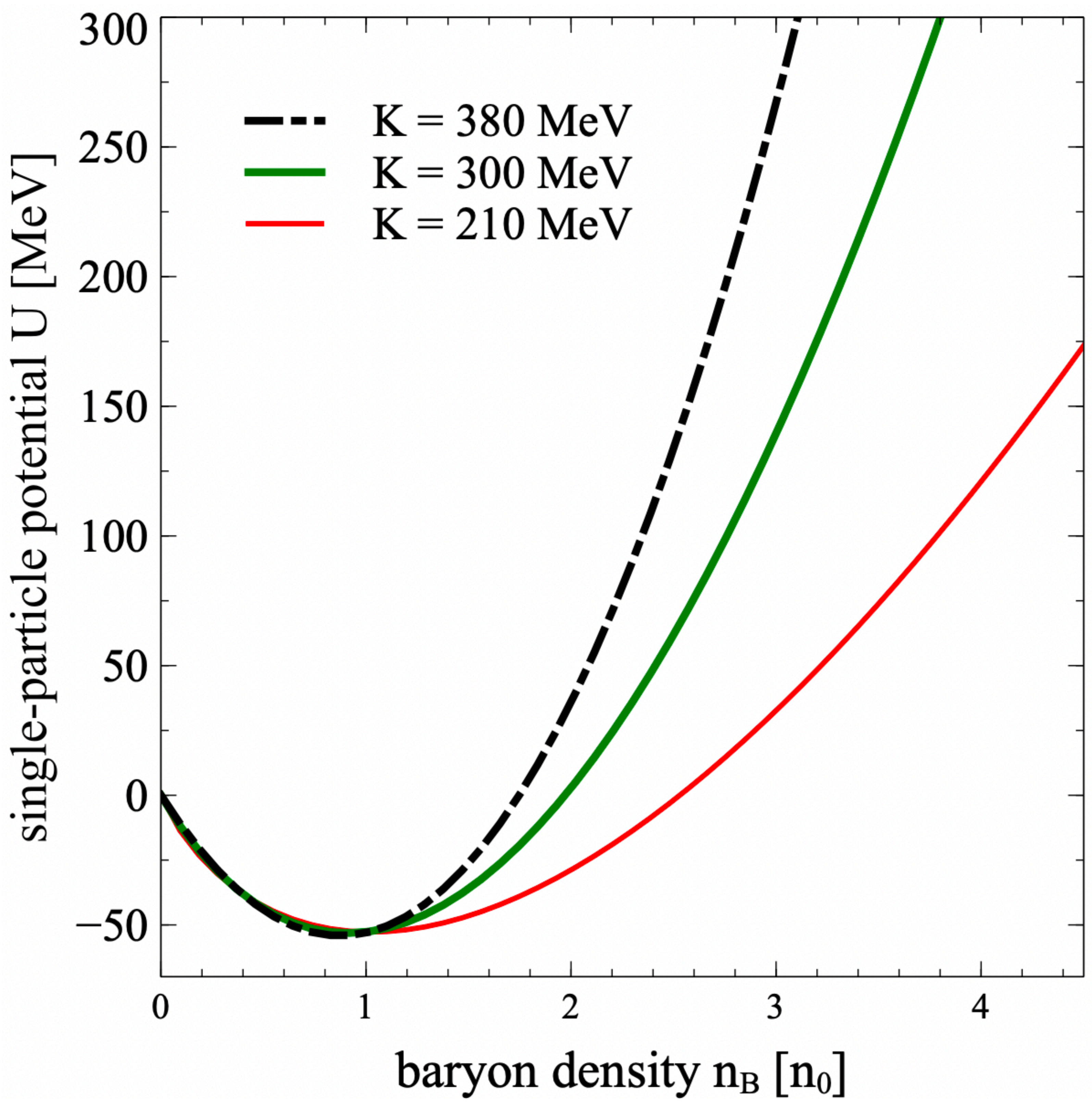


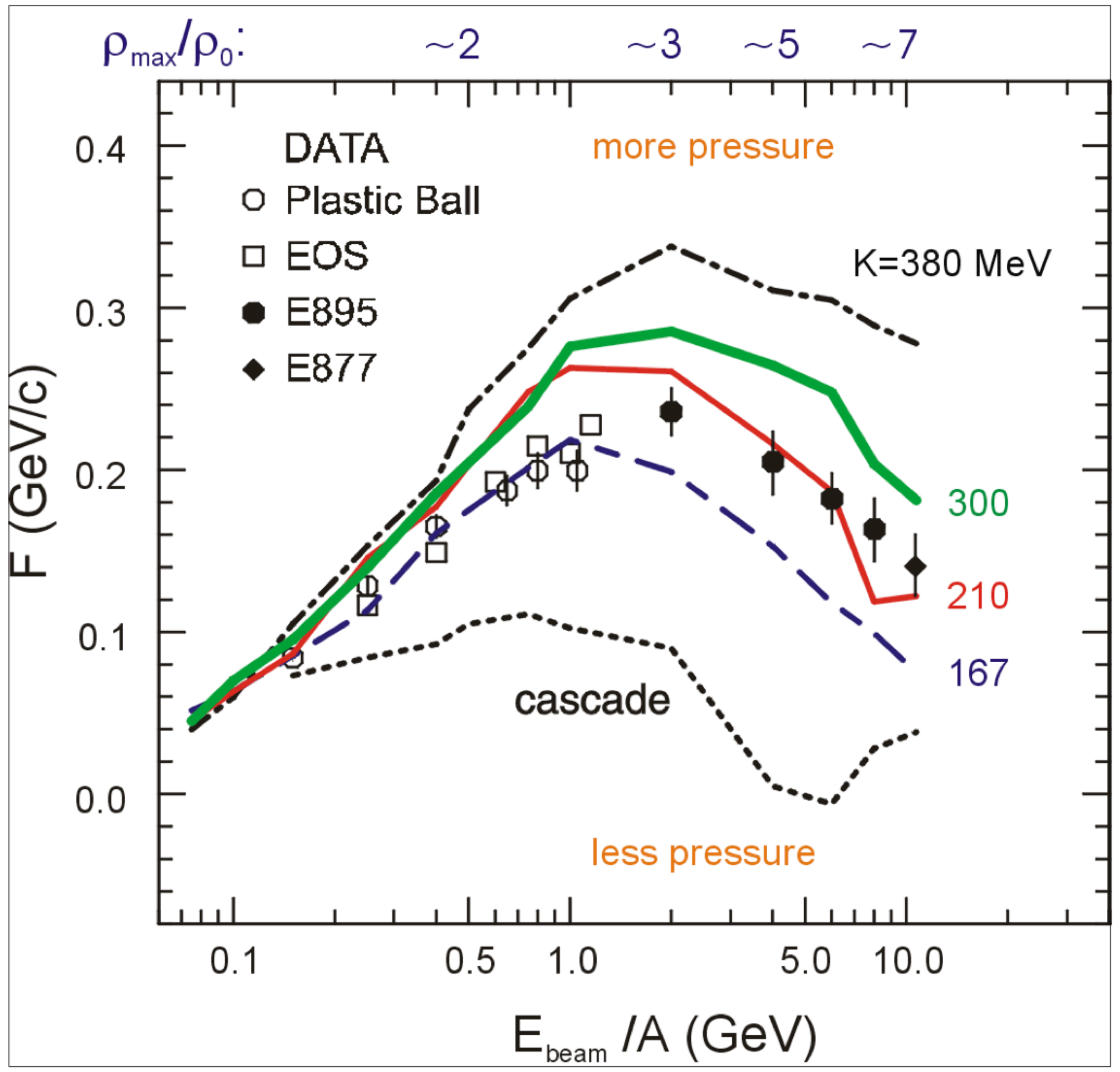
$v_2 \equiv \langle \cos(2\phi) \rangle$ **in-plane** **out-of-plane**

illustrations from a presentation
by B. Kardan (HADES)

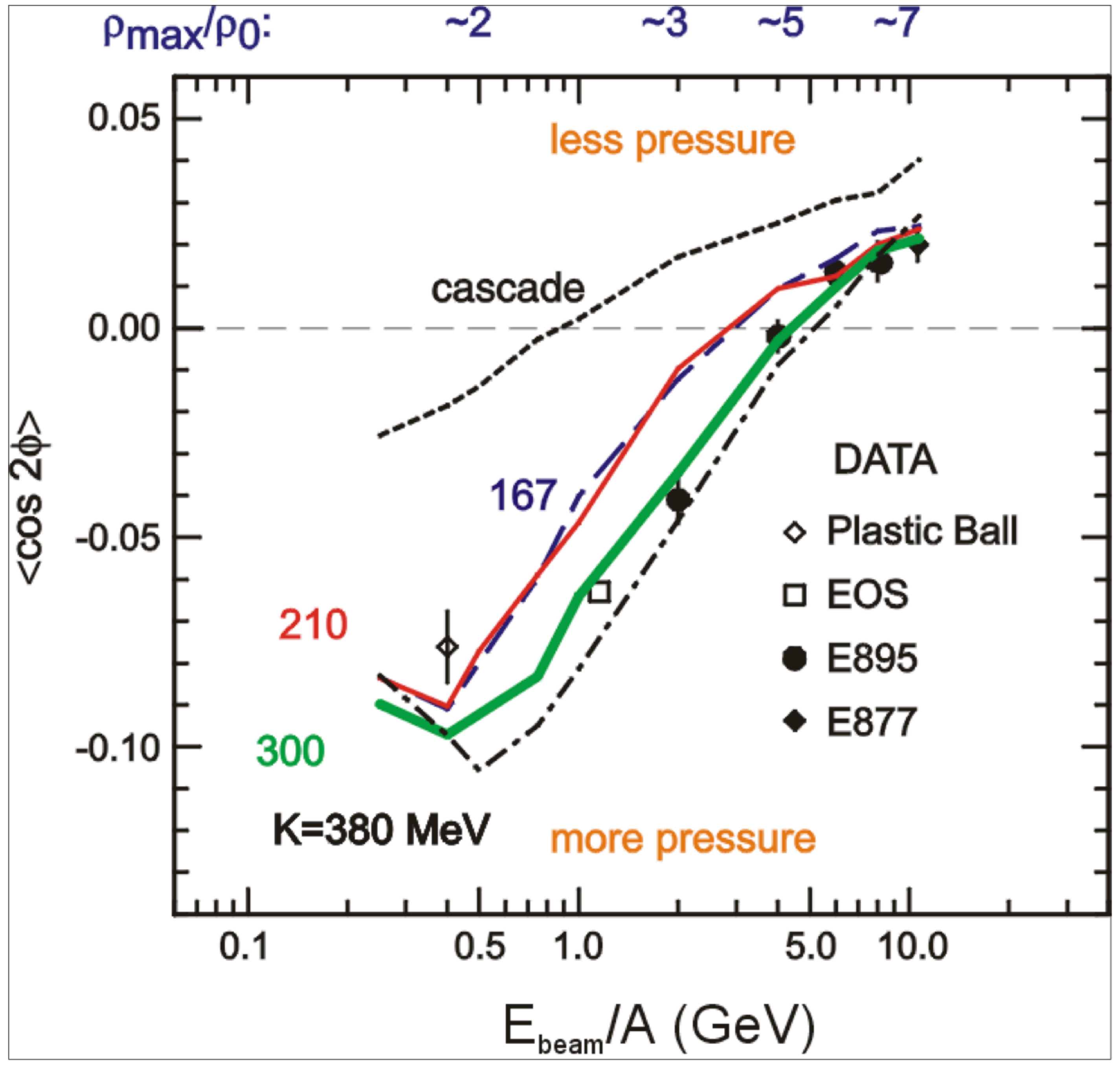
Standard way of modeling the EOS: Skyrme potential

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





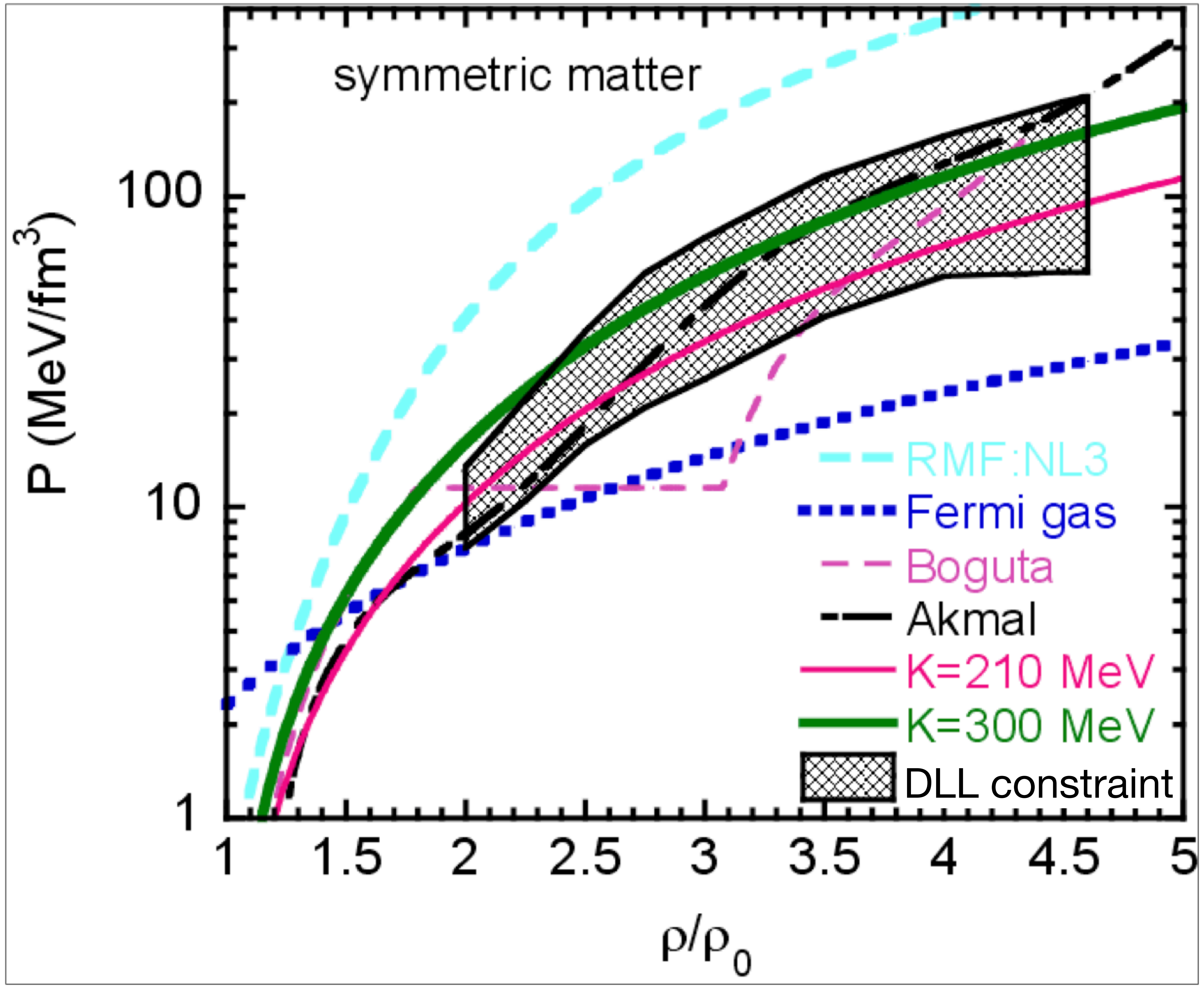
$$F = \left.\frac{d\langle p_x/A\rangle}{d(y/y_{cm})}\right|_{y/y_{cm}=1}$$



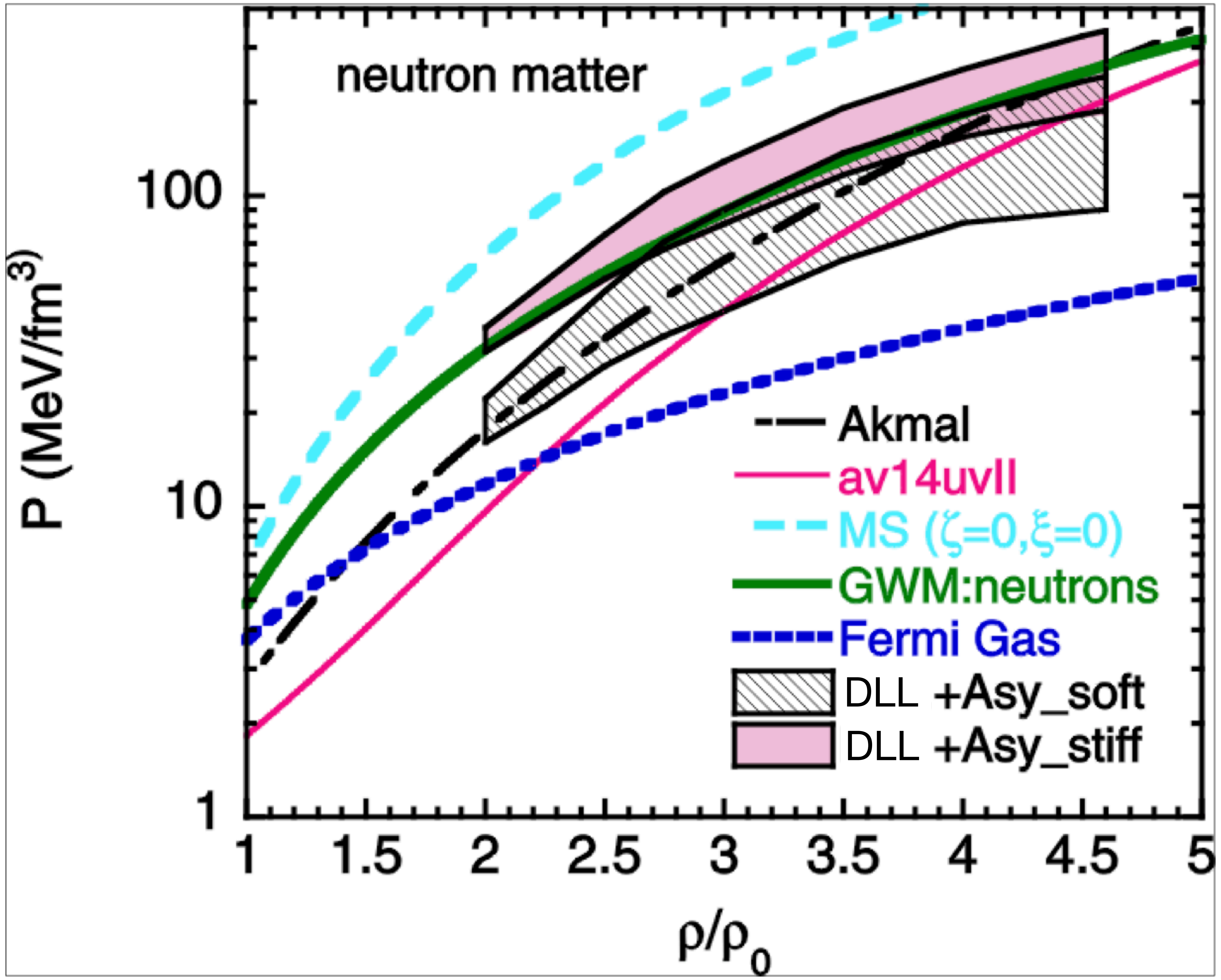
P. Danielewicz, R. Lacey, W. G. Lynch,
Science **298**, 1592–1596 (2002), arXiv:nucl-th/0208016

Standard way of modeling the EOS: Skyrme potential

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

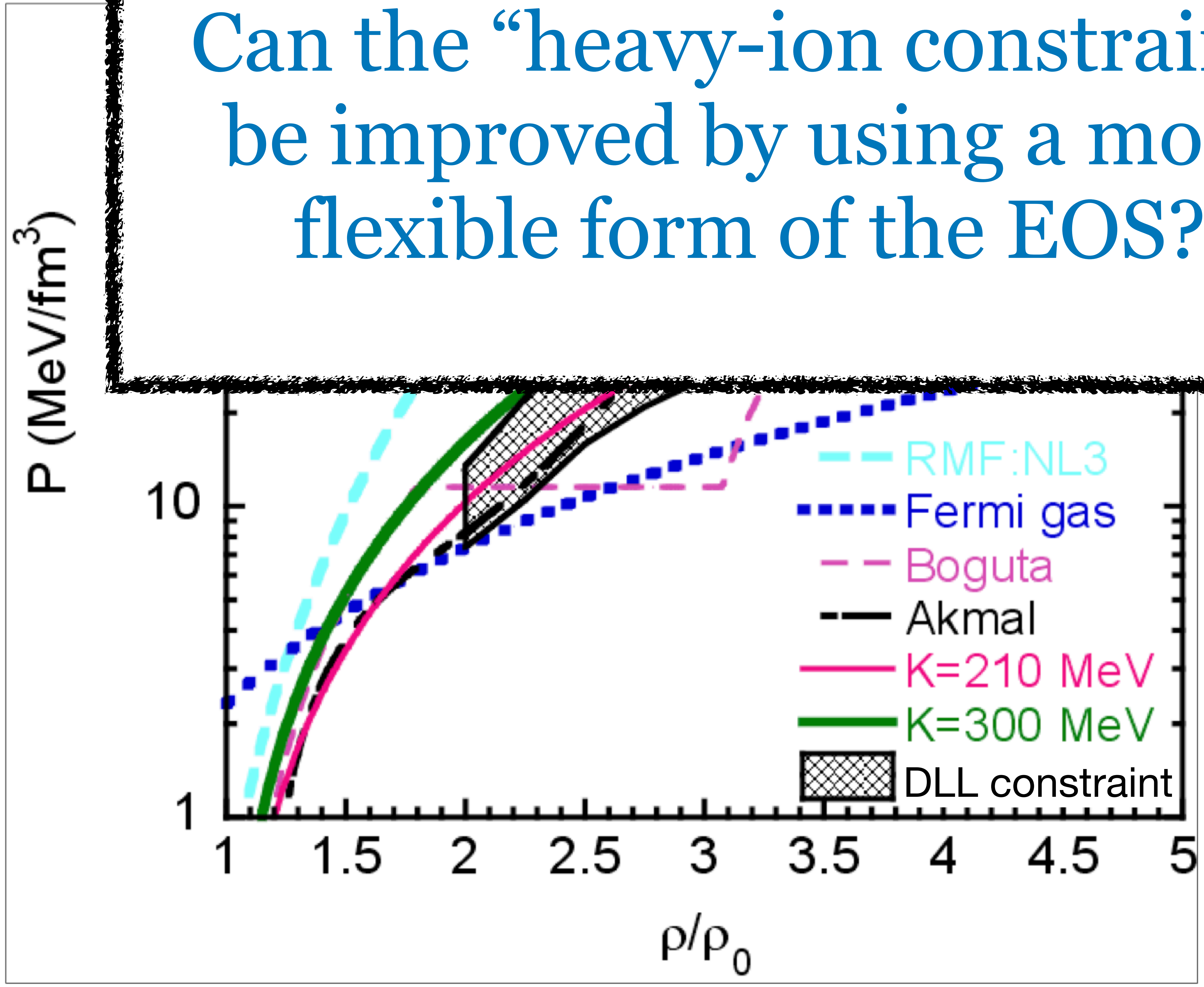


“the heavy-ion constraint”

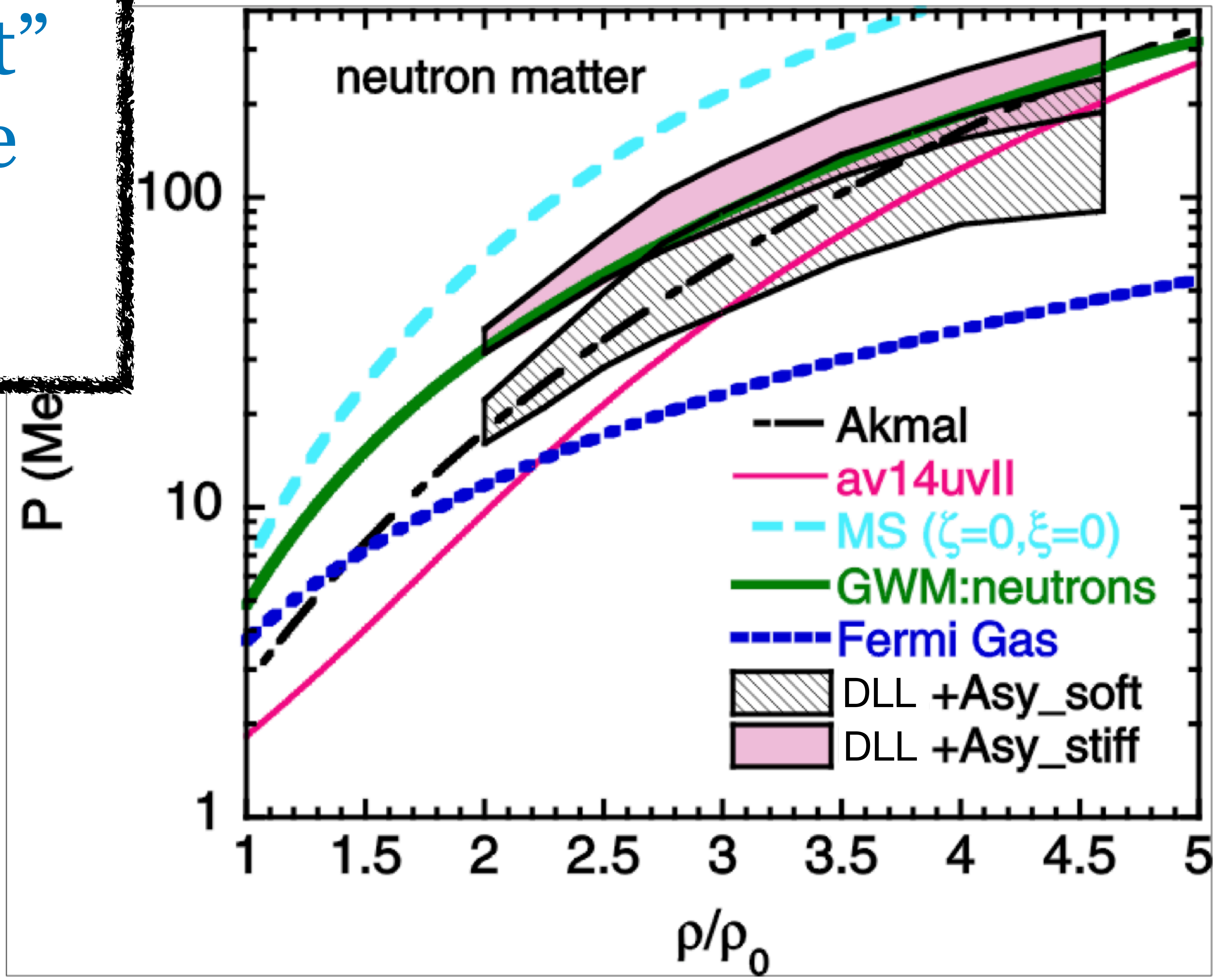


Standard way of modeling the EOS: Skyrme potential

Can the "heavy-ion constraint" be improved by using a more flexible form of the EOS?



"the heavy-ion constraint"



Relativistic vector density functional (VDF) model

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

inspired by relativistic Landau Fermi-liquid theory: G. Baym, S. A. Chin, Nucl. Phys. A **262**, 527 (1976)

$$j_\mu j^\mu = n_B^2$$

$$\epsilon_{\text{kin}} = \sqrt{\left(\vec{p} - \sum_{i=1}^{N} C_i (j_\mu j^\mu)^{\frac{b_i}{2}-1} \vec{j}\right)^2 + m^2}$$

1) Postulate the energy density of the system:

$$\mathcal{E}_N = \mathcal{E}_N[f_{\mathbf{p}}] = g \int \frac{d^3p}{(2\pi)^3}\, \epsilon_{\text{kin}}\, f_{\mathbf{p}} + \sum_{i=1}^{N} C_i \left(j_\mu j^\mu\right)^{\frac{b_i}{2}-1} \left[j^0 j^0 - g^{00} \left(\frac{b_i - 1}{b_i}\right) j_\lambda j^\lambda \right]$$ ⟵ Lorentz covariant

$$\mathcal{E}_N \Big|_{\substack{\text{rest}\\ \text{frame}}} = g \int \frac{d^3p}{(2\pi)^3} \sqrt{\vec{p}^{\,2} + m^2}\, f_{\mathbf{p}} + \sum_{i=1}^{N} \frac{C_i}{b_i} n_B^{b_i}$$ ⟵ mean-field interactions parameterized by C_i and b_i

thermodynamic consistency!

2) Quasiparticle energy: $$\varepsilon_{\mathbf{p}} \equiv \frac{\delta \mathcal{E}[f_{\mathbf{p}}]}{\delta f_{\mathbf{p}}} = \epsilon_{\text{kin}} + \sum_{i=1}^{N} C_i \left(j_\mu j^\mu\right)^{\frac{b_i}{2}-1} j^0$$

3) Get EOMs: $$\frac{dx^i}{dt} \equiv -\frac{\partial \varepsilon_{\mathbf{p}}}{\partial p_i}\,, \qquad \frac{dp^i}{dt} \equiv \frac{\partial \varepsilon_{\mathbf{p}}}{\partial x_i}$$ ⟵ input to transport code; use in Boltzmann eq. to obtain $T^{\mu\nu}$

4) Use $T^{\mu\nu}$ to get the pressure: $$P_N = \frac{1}{3} \sum_k T^{kk} \Big|_{\substack{\text{rest}\\ \text{frame}}} = g \int \frac{d^3p}{(2\pi)^3}\, T \ln\left[1 + e^{-\beta(\varepsilon_{\mathbf{p}} - \mu_B)}\right] + \sum_{i=1}^{N} C_i \frac{b_i - 1}{b_i} n_B^{b_i}$$

VDF model: two 1st order phase transitions

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

Systems with two 1st order phase transitions: nuclear and "quark/hadron", or "QGP-like"

- degrees of freedom: nucleons
- "QGP-like" PT: "more dense" matter coexists with "less dense" matter
- minimal model: 4 interactions terms = 8 parameters to fix:

$$P = g \int \frac{d^3p}{(2\pi)^3}\, T \ \ln\left[1 + e^{-\beta(\epsilon_{\mathbf{p}} - \mu_B)}\right] \ + \ \sum_{i=1}^{N=4} C_i \frac{b_i - 1}{b_i} n_B^{b_i}$$

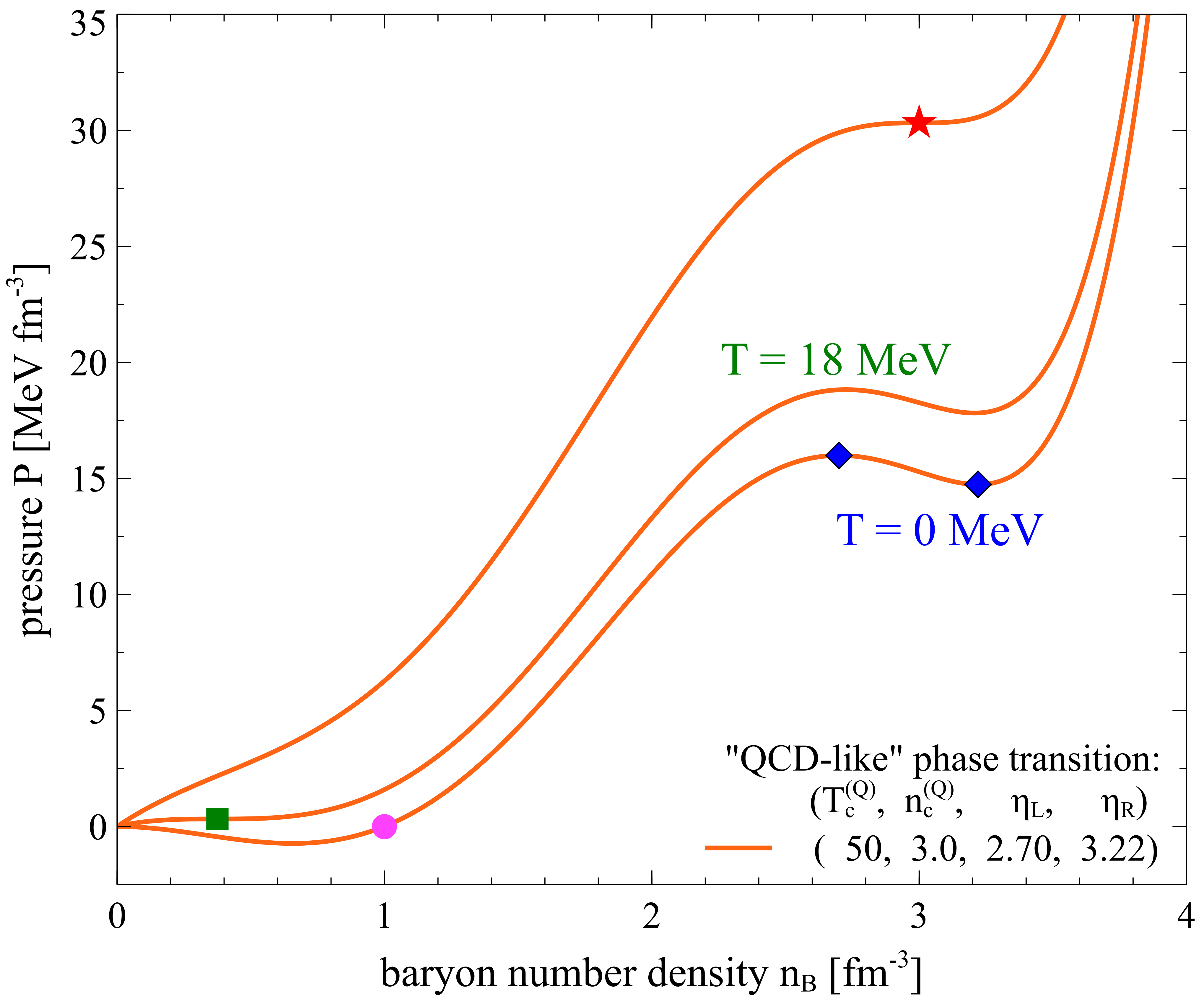
C_i and b_i are fitted to reproduce:

$n_0 = 0.160\ \mathrm{fm}^{-3}$, $E_B = -16.3$ MeV

$T_c^{(N)} = 18$ MeV, $n_c^{(N)} = 0.375 n_0$

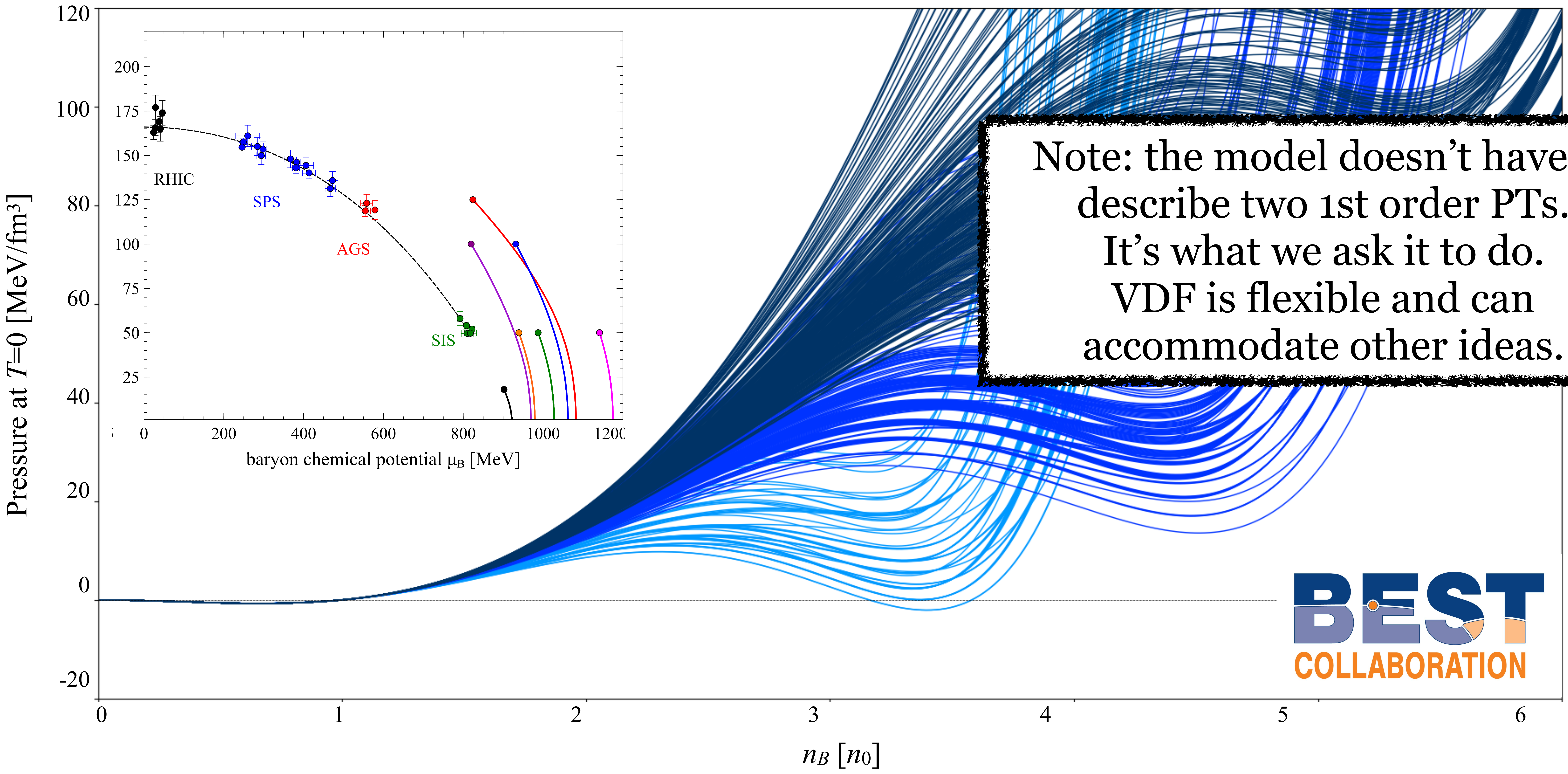
$T_c^{(Q)} = ?$, $n_c^{(Q)} = ?$

$\eta_L = ?$, $\eta_R = ?$



VDF model: two 1st order phase transitions

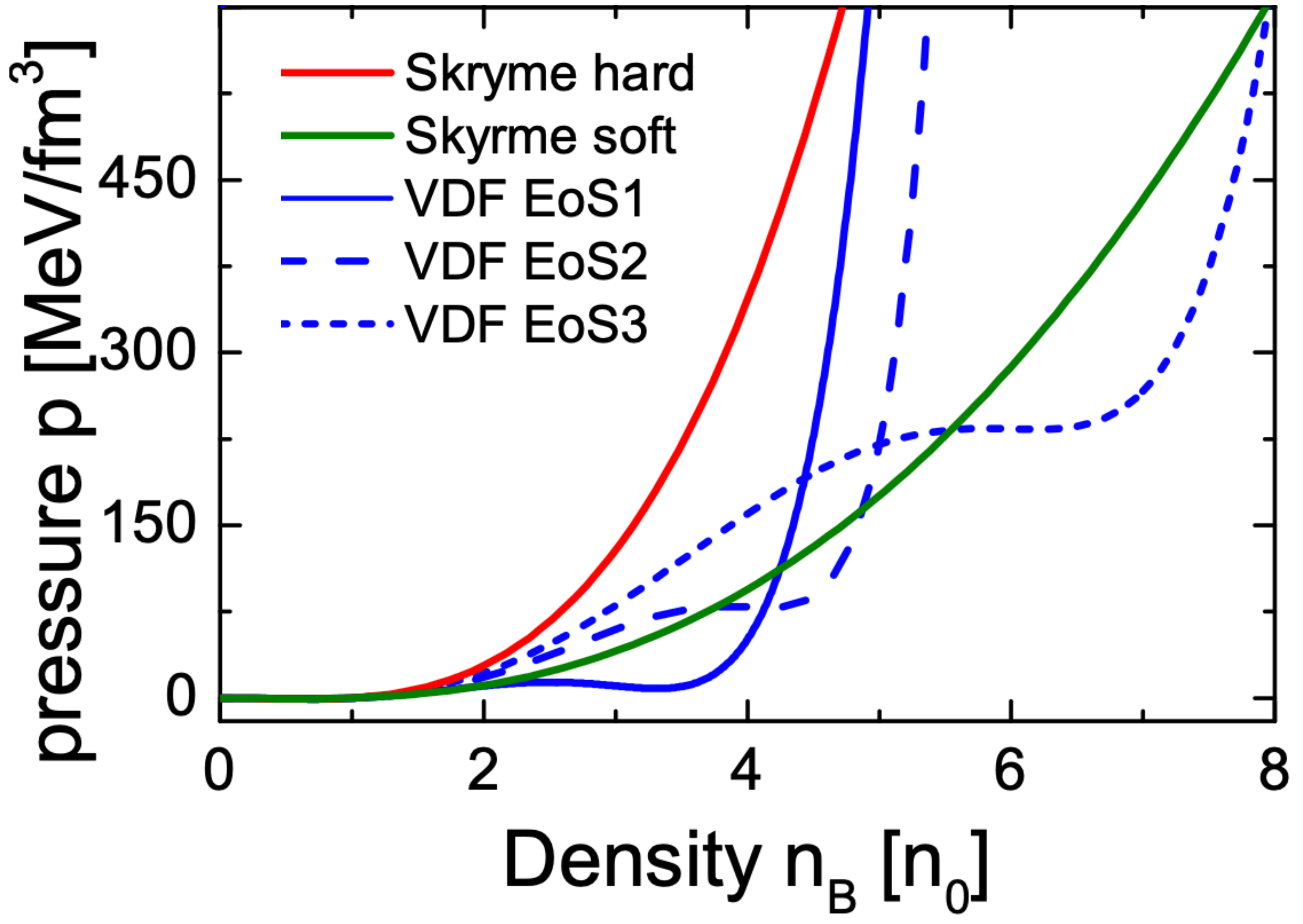
A. Sorensen, V. Koch, Phys. Rev. C **104** (2021) 3, 034904, arXiv:2011.06635



Note: the model doesn't have to describe two 1st order PTs. It's what we ask it to do. VDF is flexible and can accommodate other ideas.

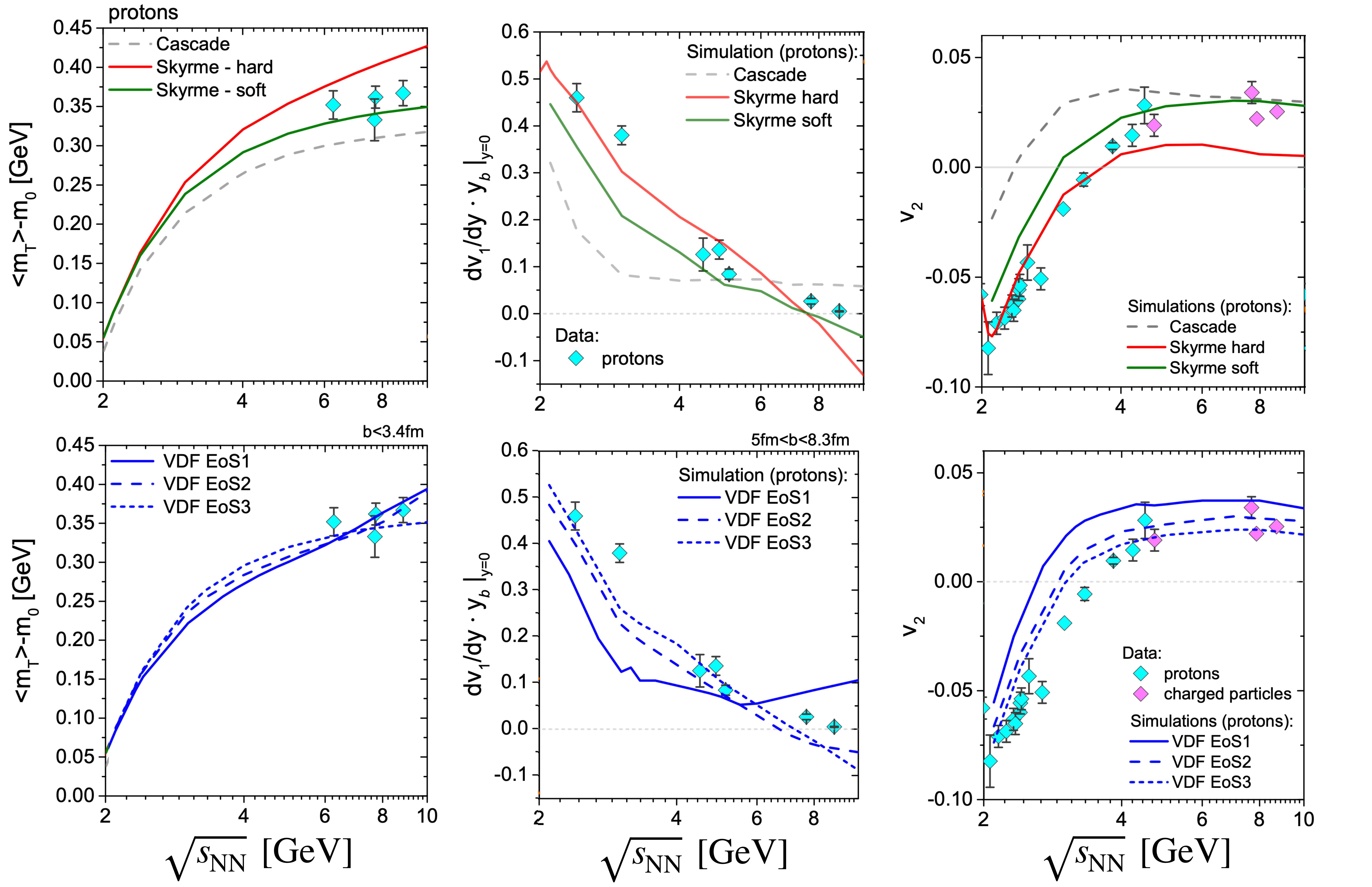
Results from UrQMD with (non-relativistic) VDF

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

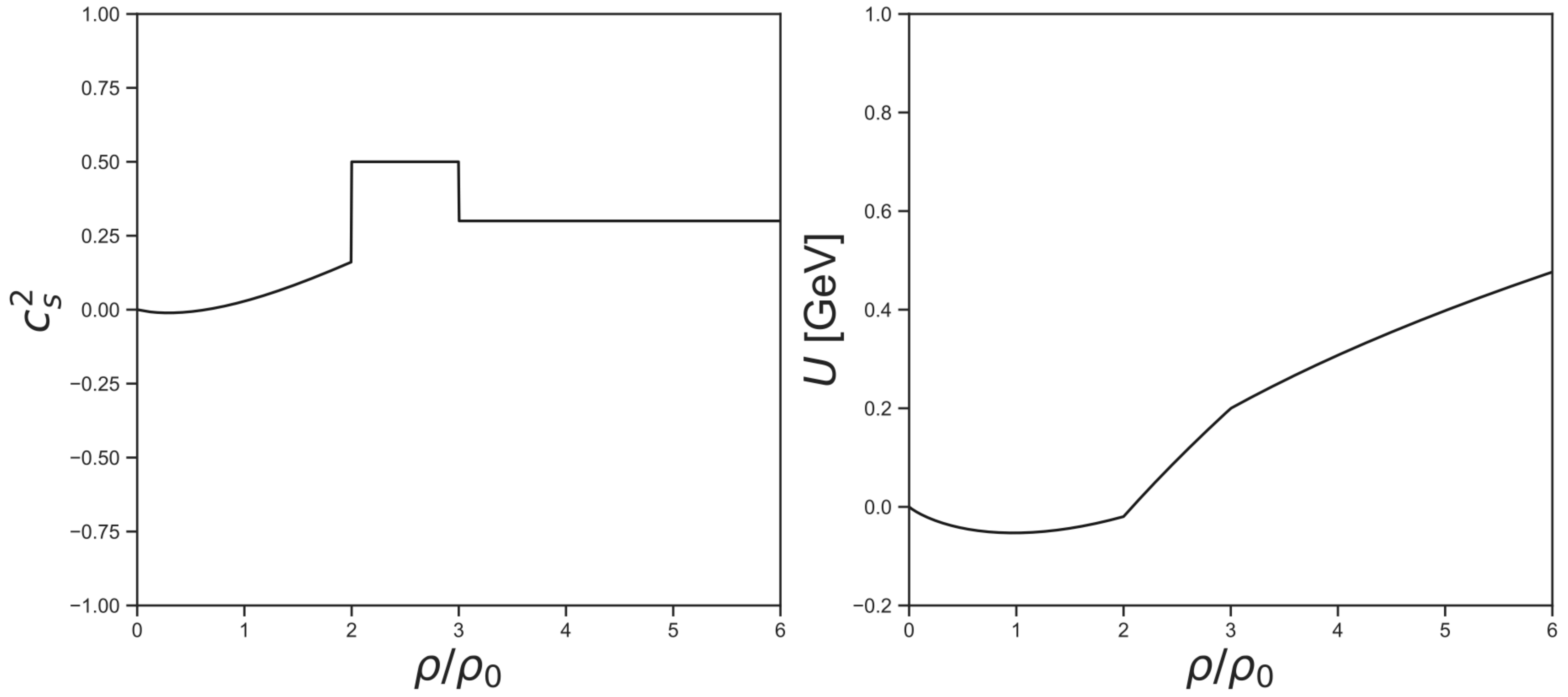
Very soft EOS at $n_B \in (2,3)n_0$ not supported in VDF+UrQMD



Better suited for detailed studies: piecewise parametrization of c_s^2

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

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



Single-particle potential $U(n_B) = \alpha(n_B)n_B$:

$$U(n_B) = \begin{cases} U_{\rm Sk}(n_B)\ , & n_B < n_1 = 2n_0 \\ \Big[U_{\rm Sk}(n_1) + \mu^*(\rho_1)\Big]\left(\frac{\rho}{n_1}\right)^{c_1^2} - \mu^*(n_B)\ , & n_1 < n_B < n_2 \\ \Big[U_{\rm Sk}(n_1) + \mu^*(n_1)\Big]\left(\frac{n_B}{n_k}\right)^{c_k^2} \prod_{i=2}^{k}\left(\frac{n_i}{n_{i-1}}\right)^{c_{i-1}^2} - \mu^*(n_B)\ , & n_k < n_B < n_{k+1} \end{cases}$$

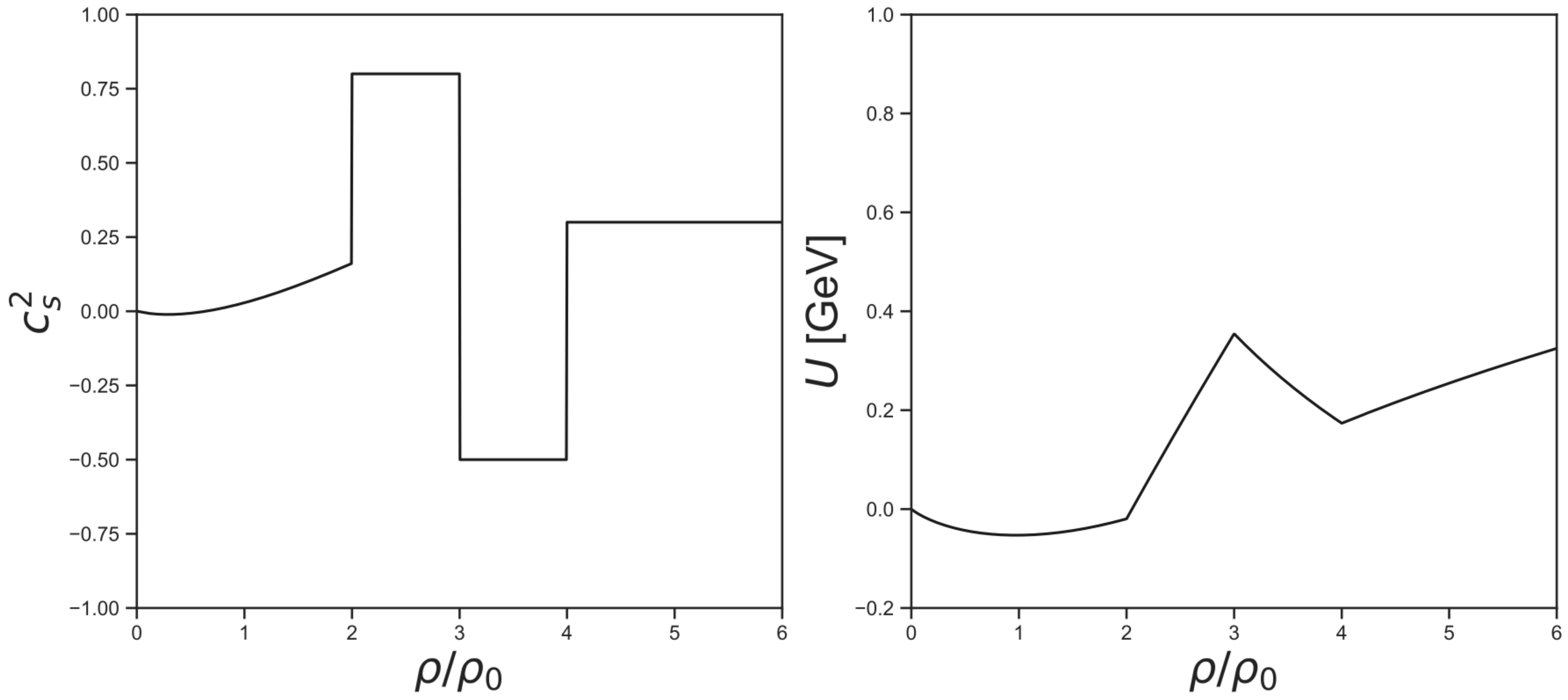
Gradients of $U(n_B)$ enter the EOMs!

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

Better suited for detailed studies: piecewise parametrization of c_s^2

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

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



Single-particle potential $U(n_B) = \alpha(n_B) n_B$:

$$U(n_B) = \begin{cases} U_{\text{Sk}}(n_B)\ , & n_B < n_1 = 2n_0 \\ \left[U_{\text{Sk}}(n_1) + \mu^*(\rho_1)\right] \left(\frac{\rho}{n_1}\right)^{c_1^2} - \mu^*(n_B)\ , & n_1 < n_B < n_2 \\ \left[U_{\text{Sk}}(n_1) + \mu^*(n_1)\right] \left(\frac{n_B}{n_k}\right)^{c_k^2} \prod_{i=2}^{k} \left(\frac{n_i}{n_{i-1}}\right)^{c_{i-1}^2} - \mu^*(n_B)\ , & n_k < n_B < n_{k+1} \end{cases}$$

Gradients of $U(n_B)$ enter the EOMs!

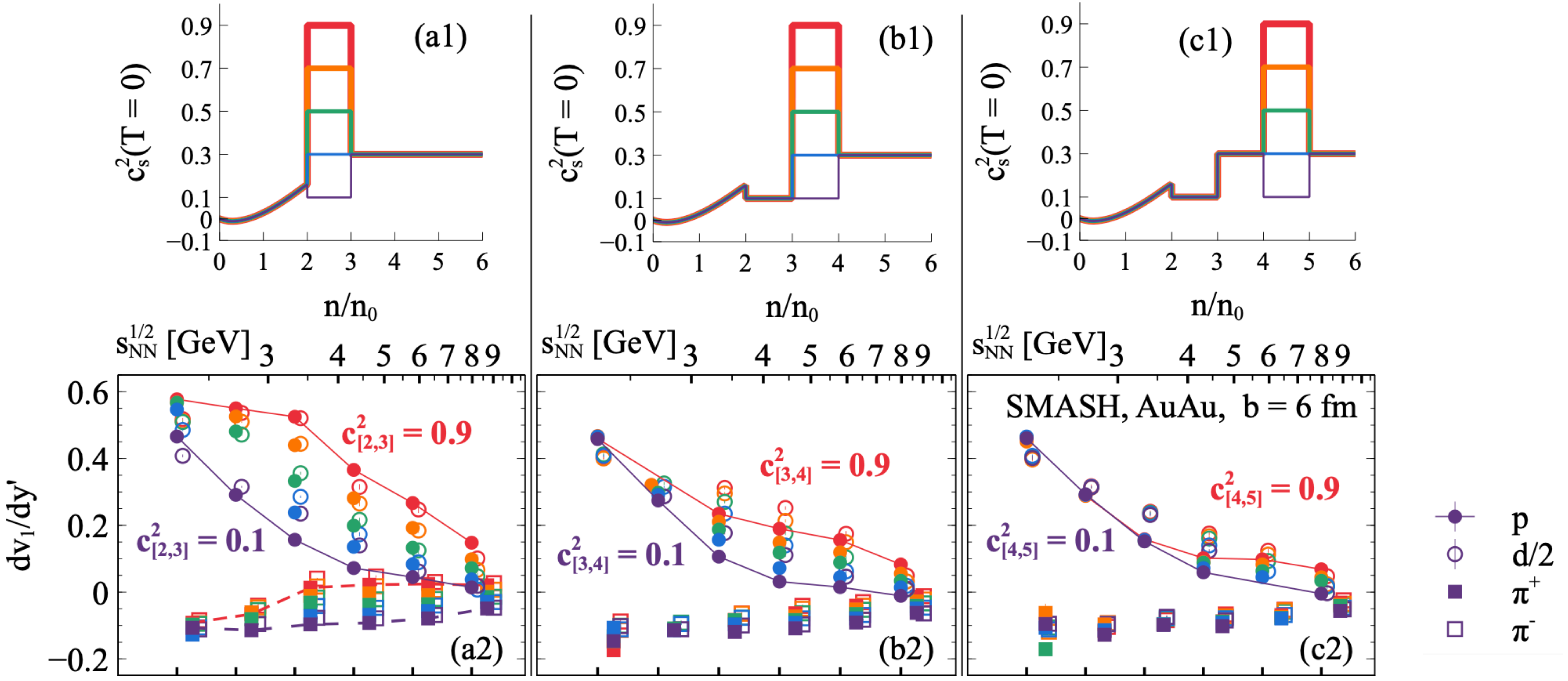
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996

Hadronic transport with c_s^2-parametrized mean-fields

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

Generalized VDF (n_B-dependent interaction coefficients):

mean-field potential piecewise parametrized by (constant) values of c_s^2 for $n_i < n_B < n_j$

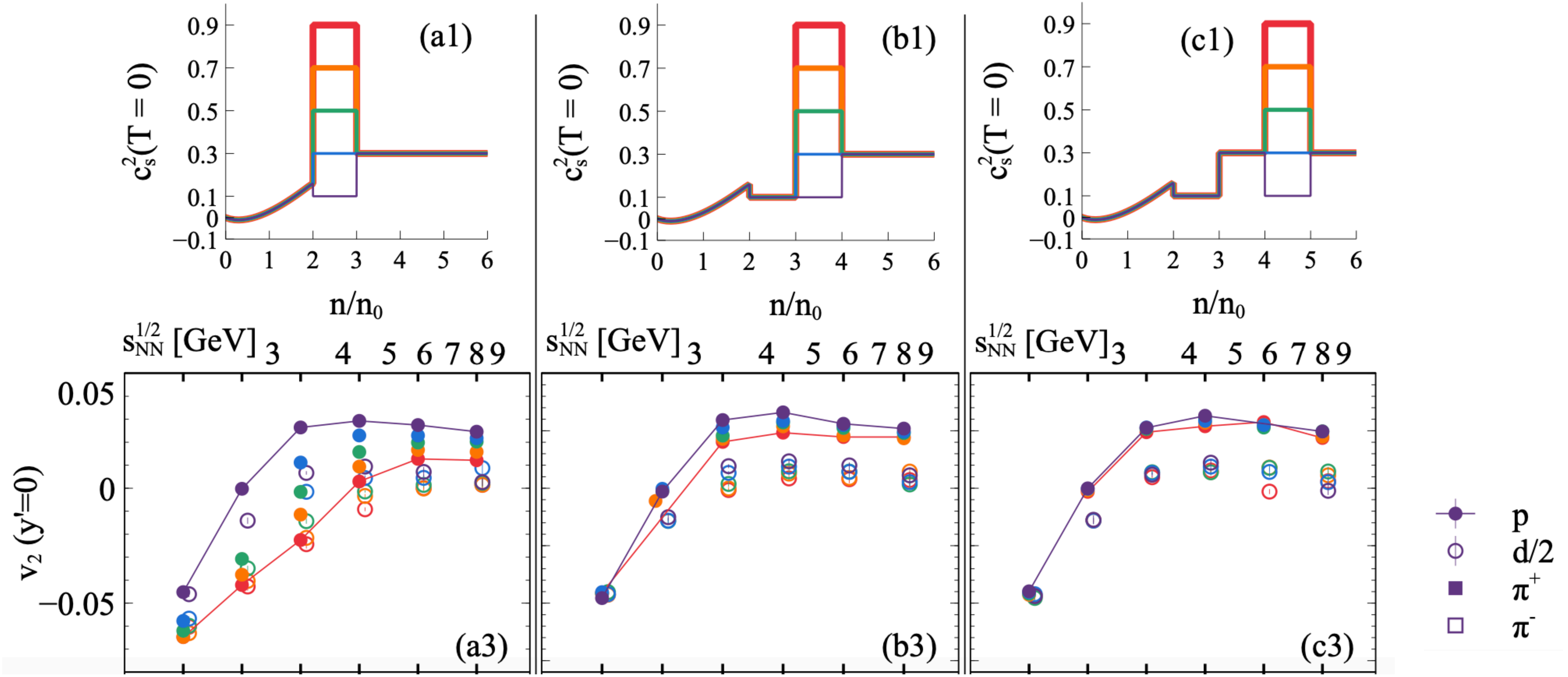


Hadronic transport with c_s^2-parametrized mean-fields

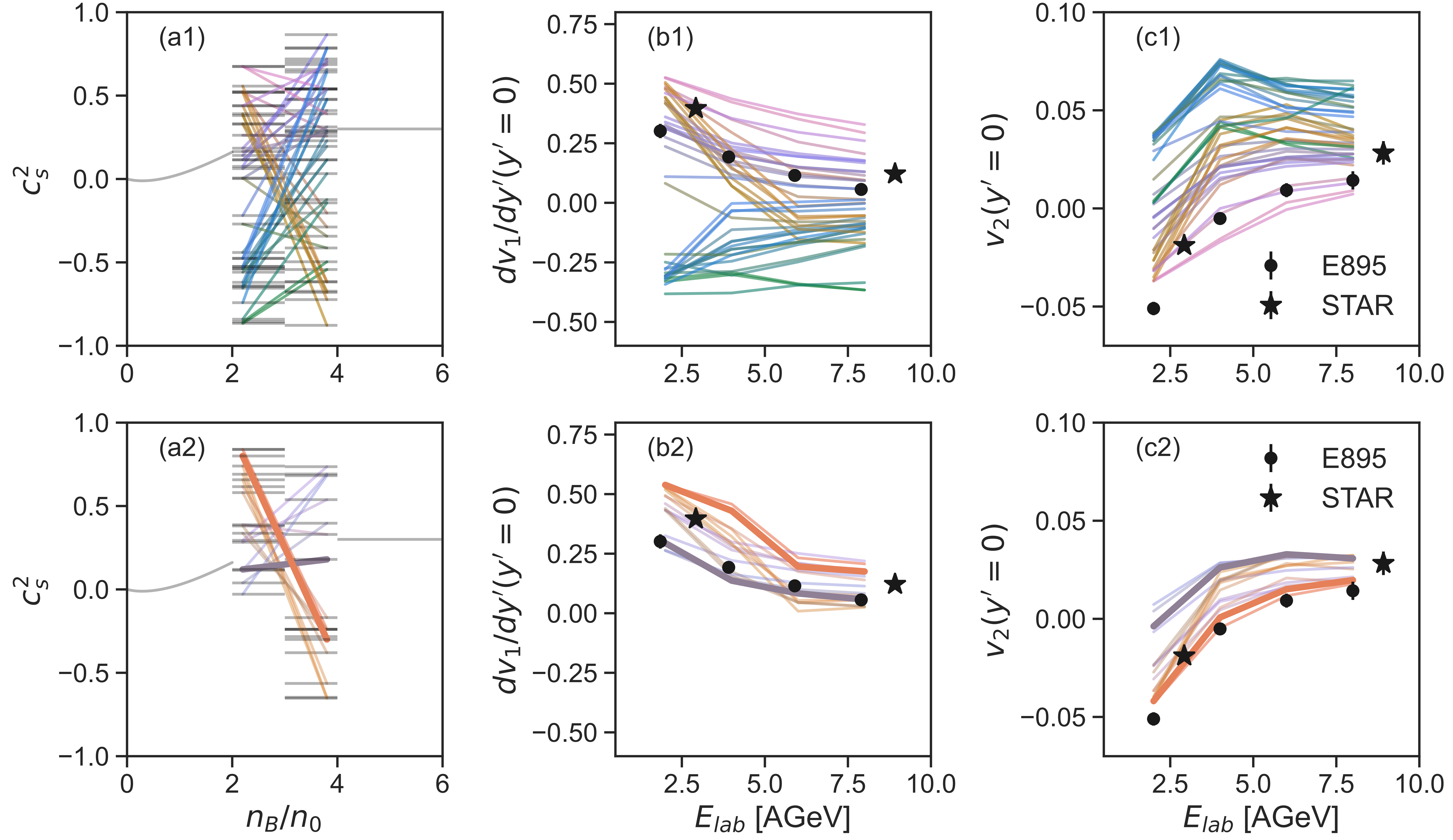
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran,
arXiv:2208.11996

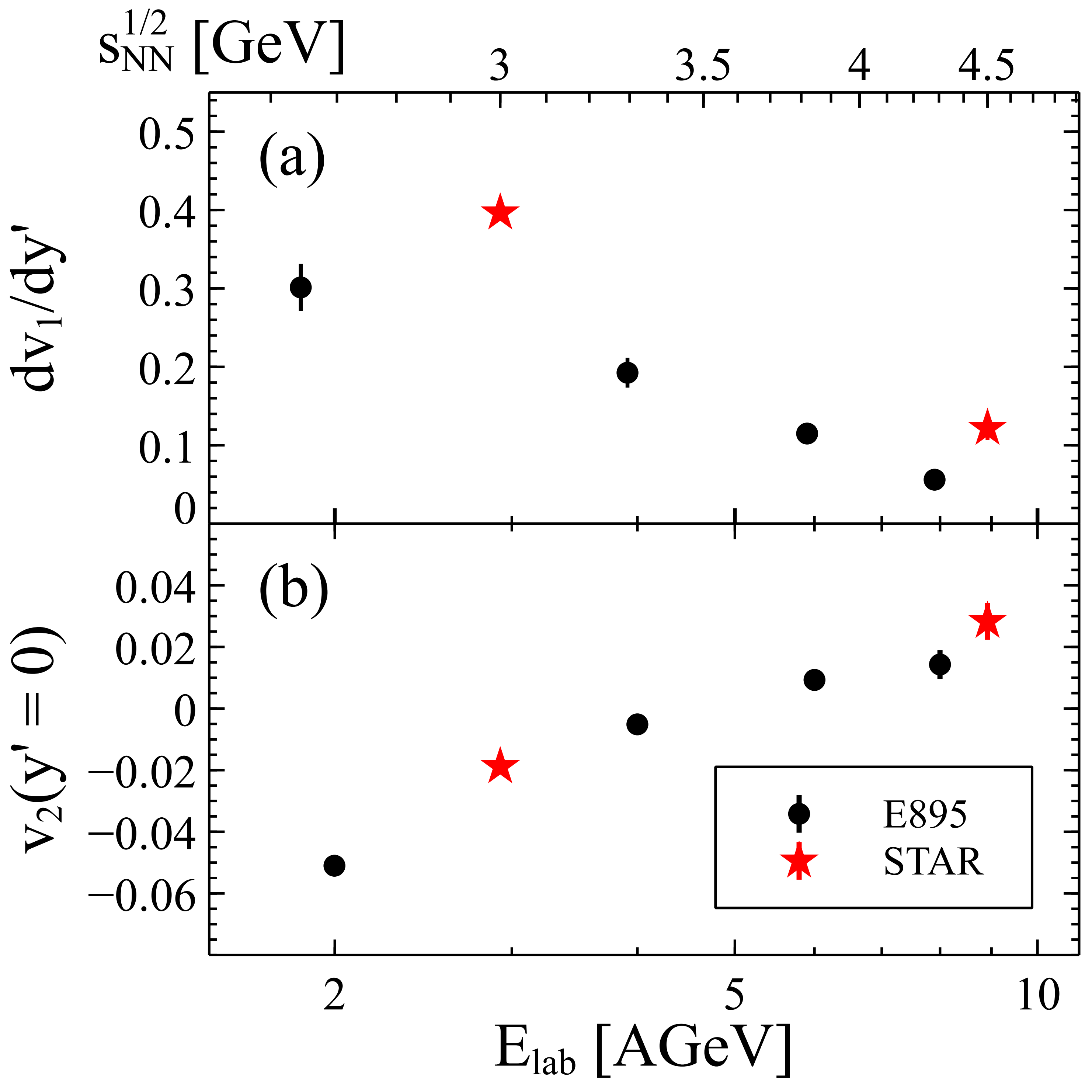
Generalized VDF (n_B-dependent interaction coefficients):

mean-field potential piecewise parametrized by (constant) values of c_s^2 for $n_i < n_B < n_j$



STAR and E895 data cannot be simultaneously described

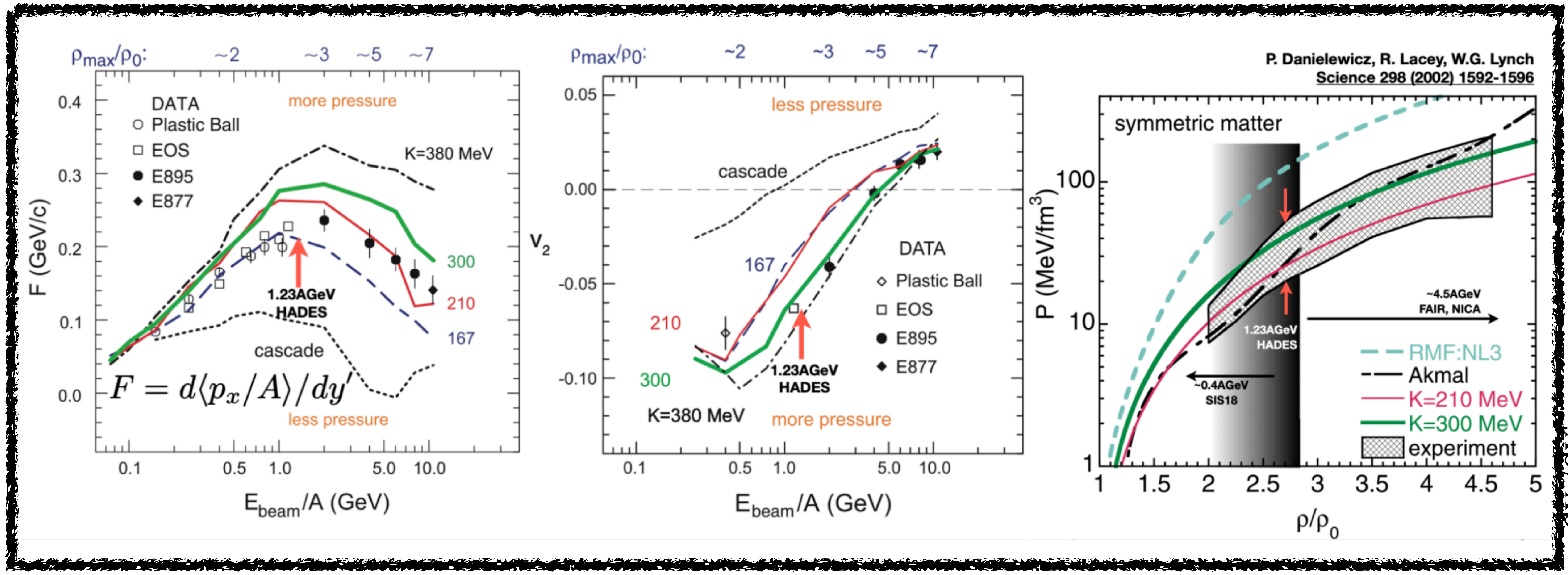




tension between the data sets

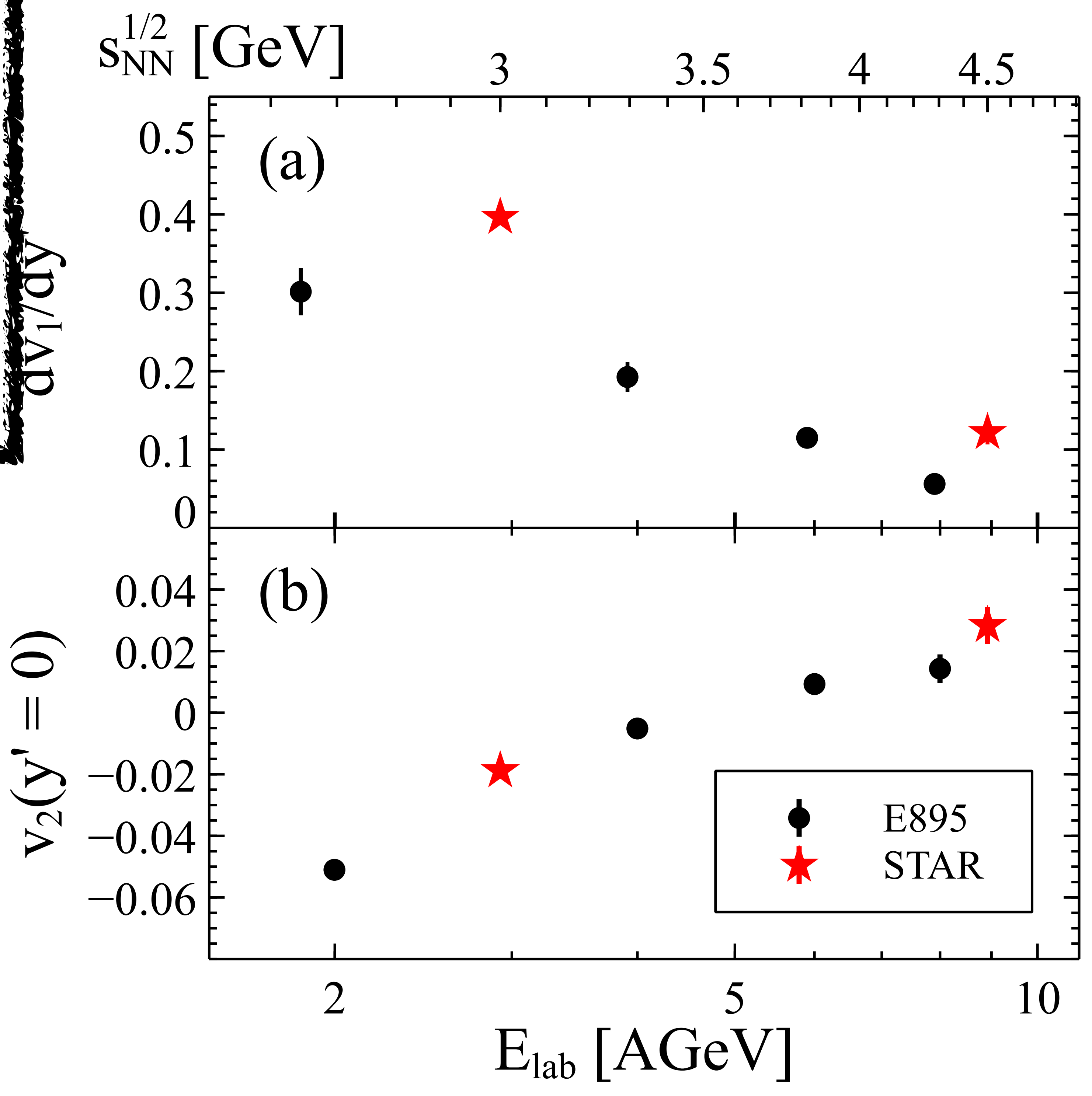
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996

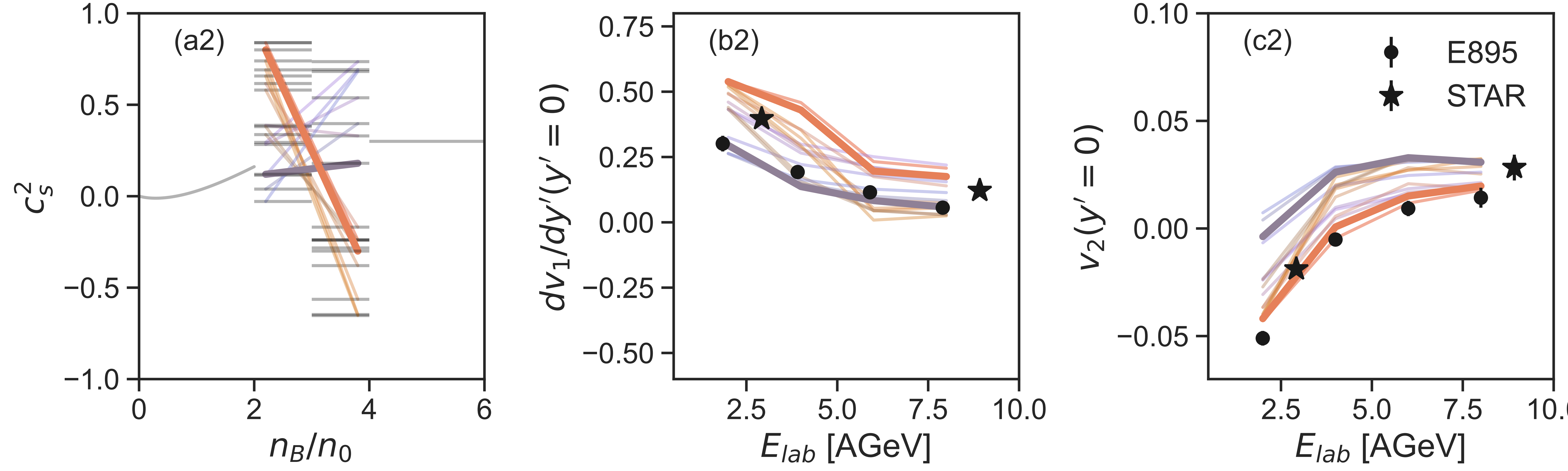
STAR and E895 data cannot be simultaneously described



Same problem as in the DLL constraint!

Danielewicz, Lacey, Lynch, Science **298**,1592–1596 (2002)

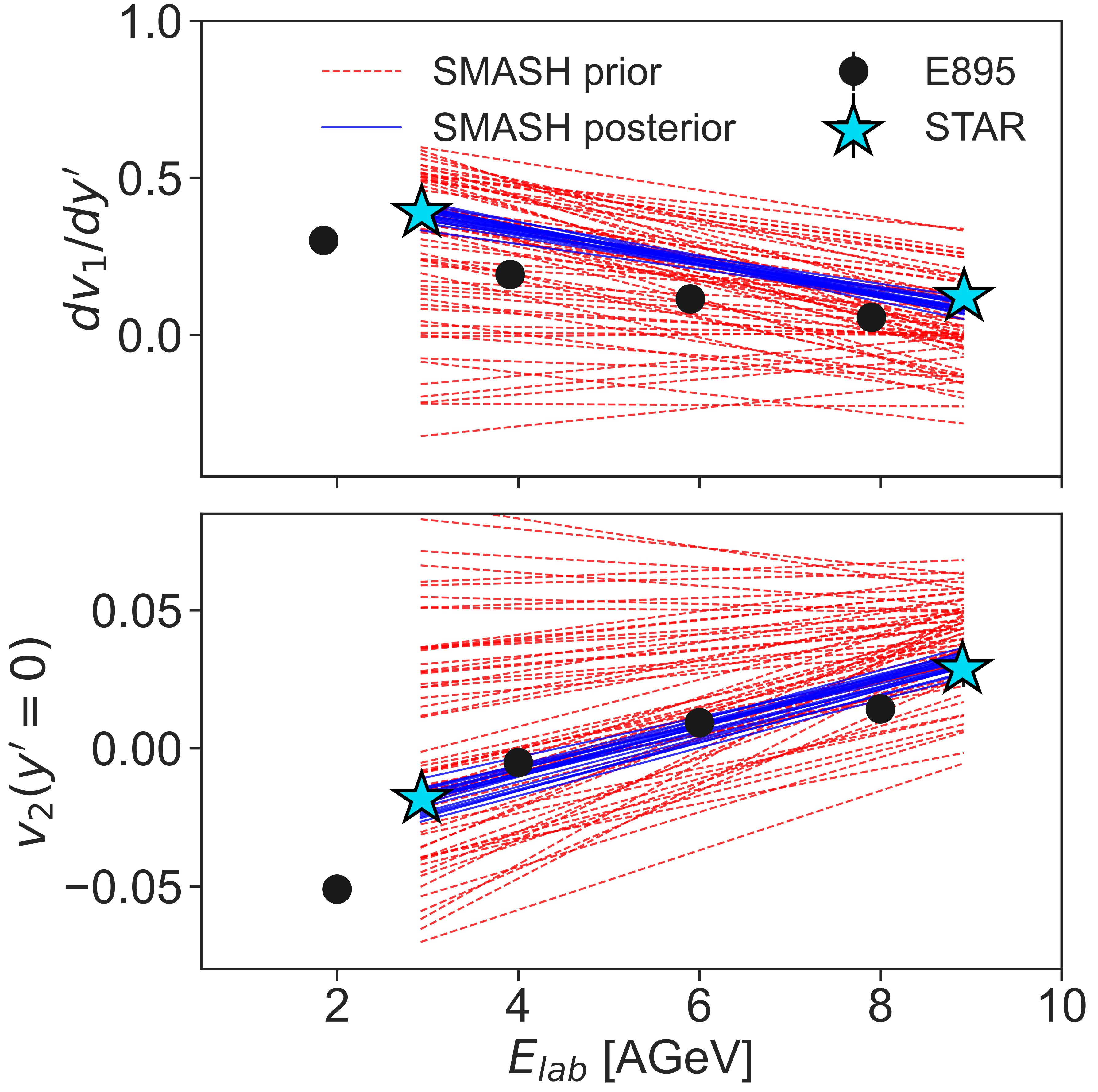


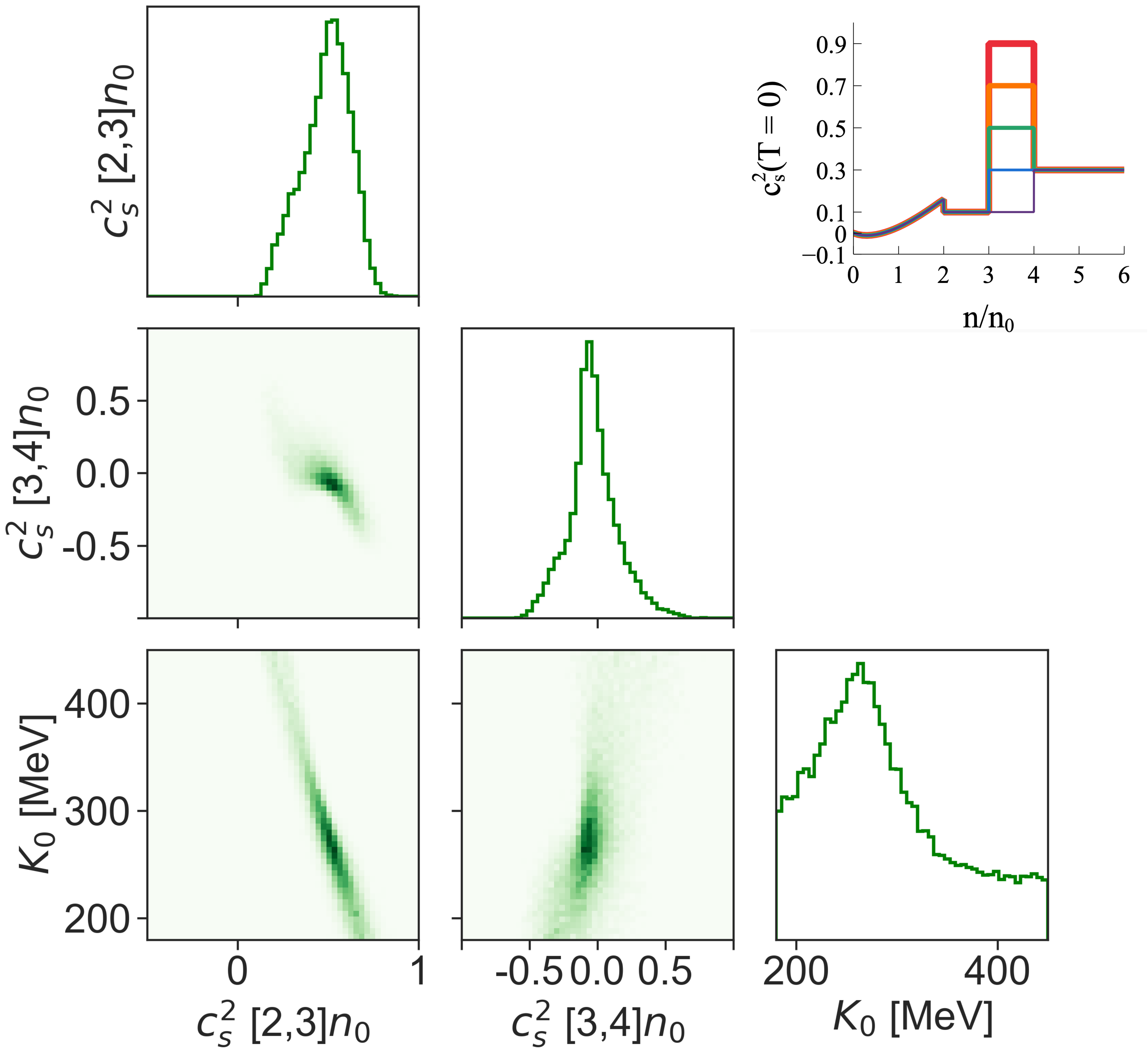


tension between the data sets

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

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



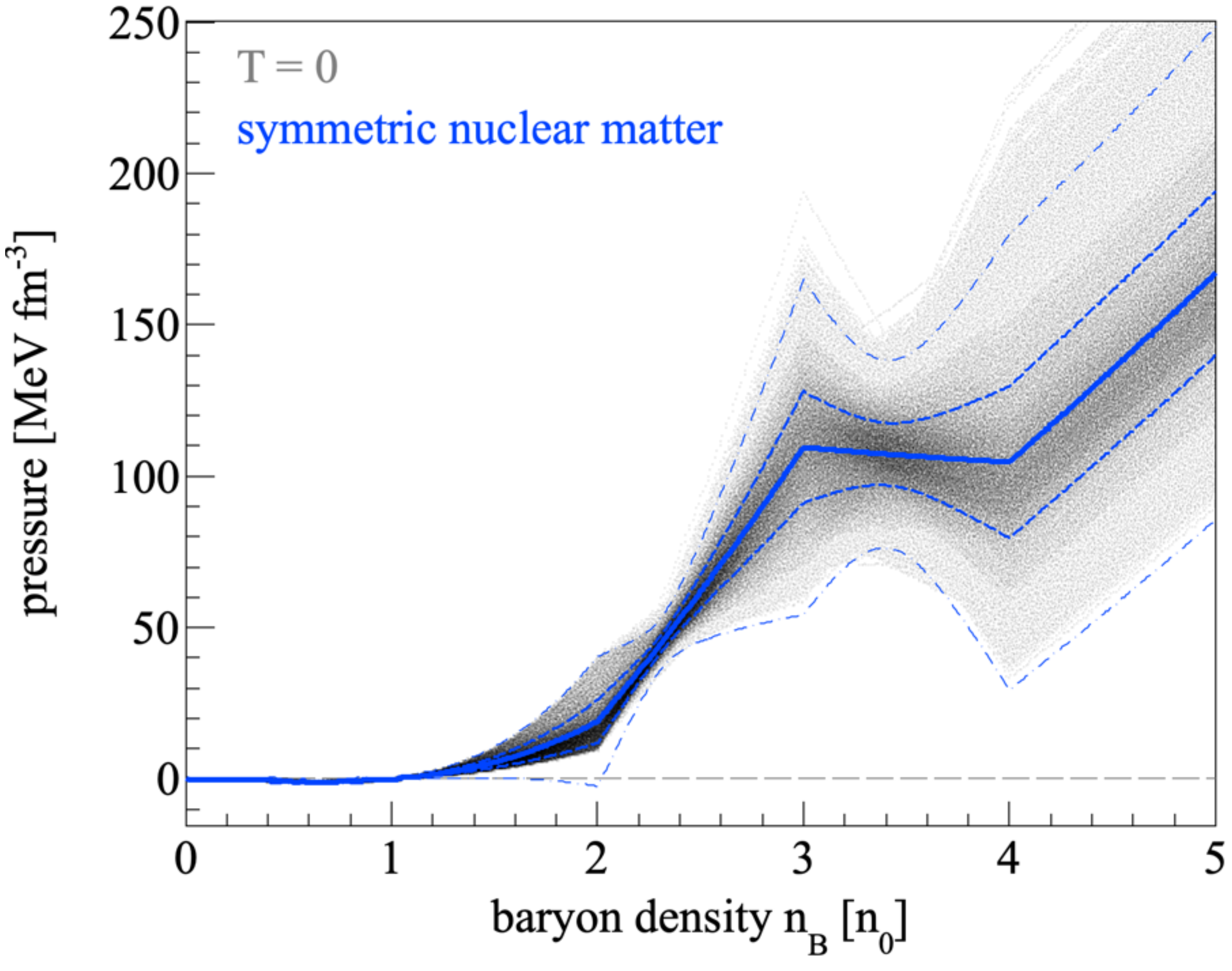


The maximum a posteriori probability (MAP) parameters are

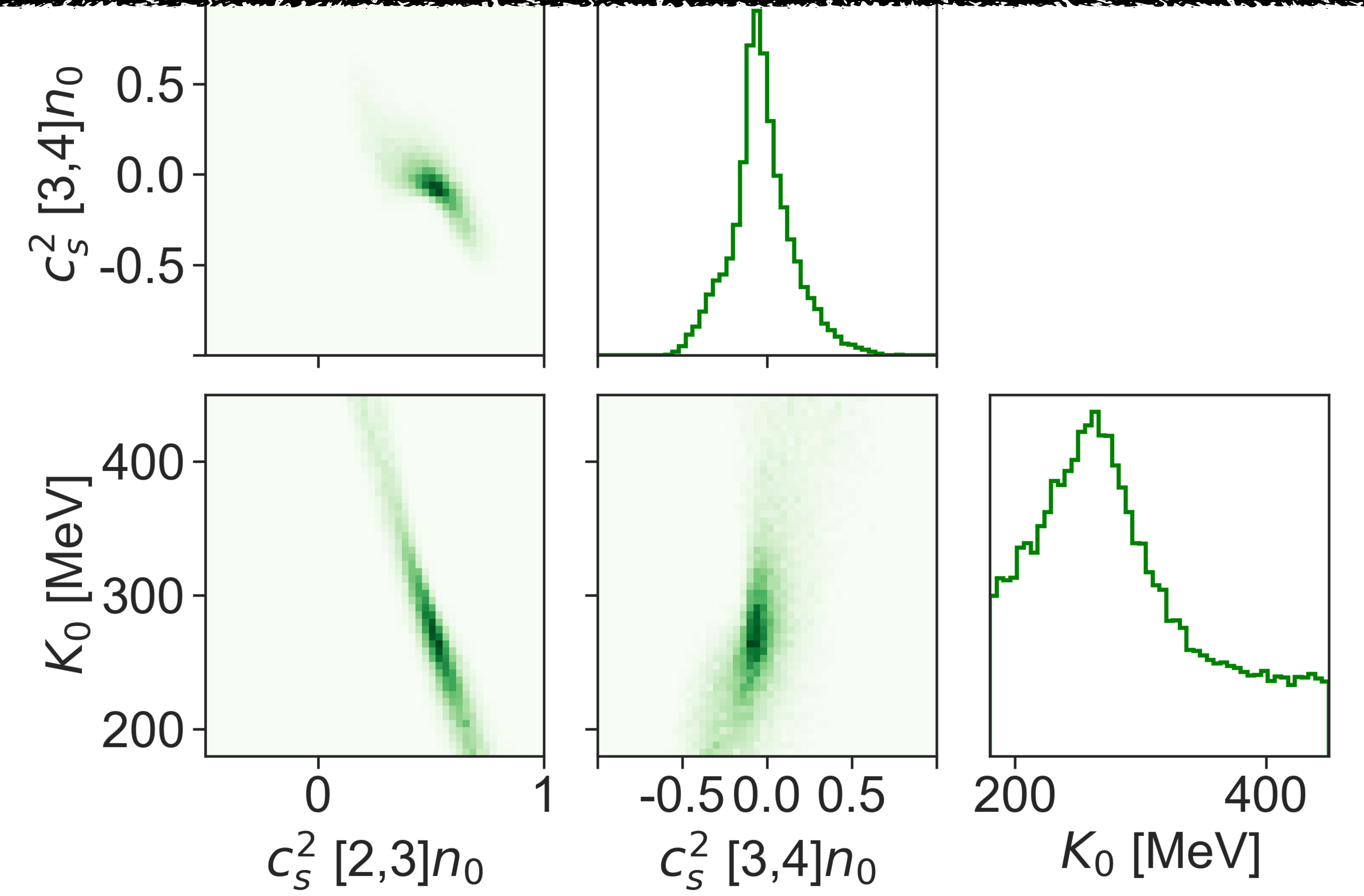
$K_0 = 285 \pm 67$ MeV, $\quad c^2_{[2,3]n_0} = 0.49 \pm 0.13, \quad c^2_{[3,4]n_0} = -0.03 \pm 0.15$

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

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



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



The maximum a posteriori probability (MAP) parameters are

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

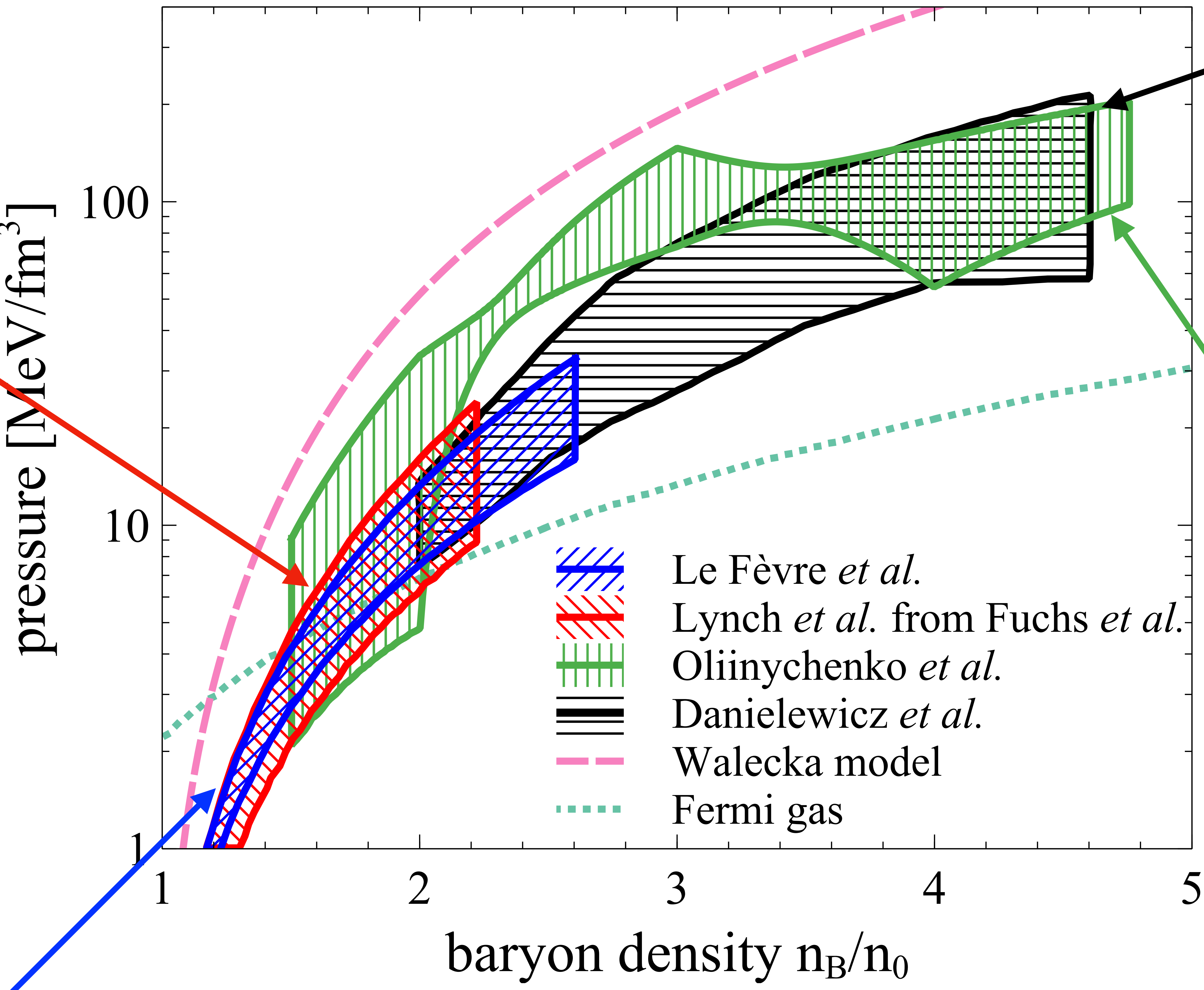
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996

EOS of symmetric nuclear matter: selected results

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



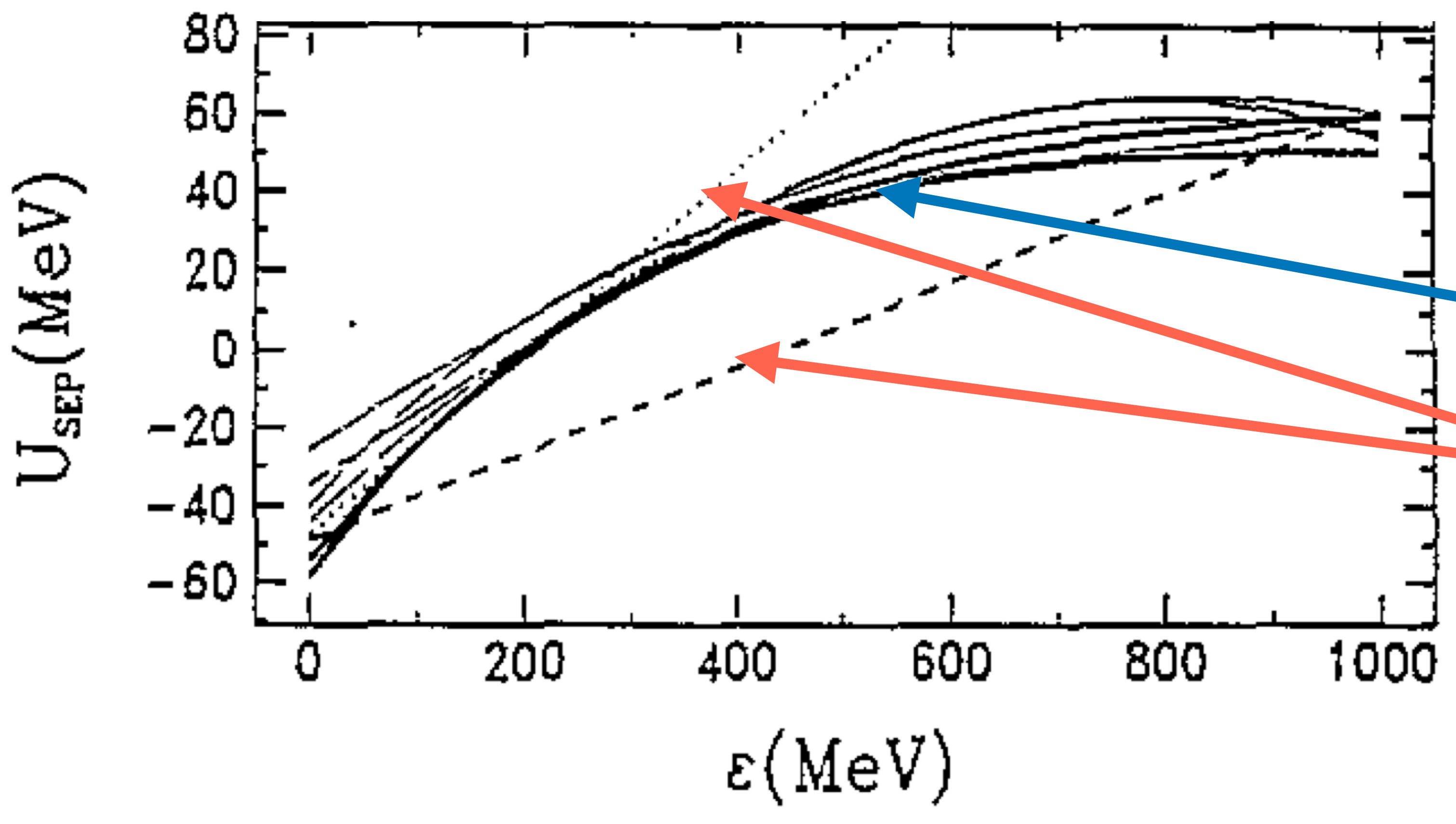
A. Sorensen *et al.*, arXiv:2301.13253

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

Momentum-dependent mean-fields are a necessary component

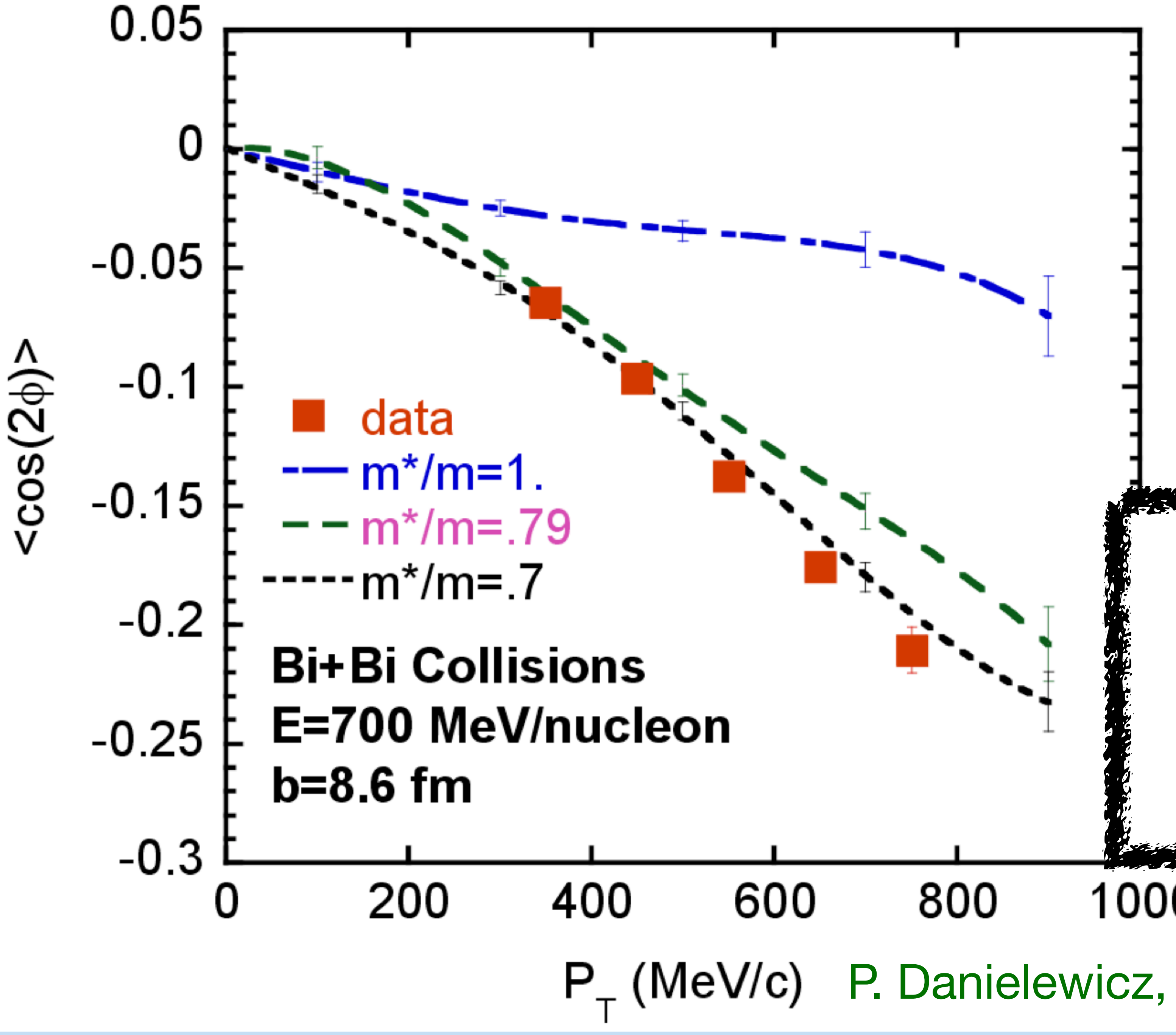
Measured in scattering experiments:



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

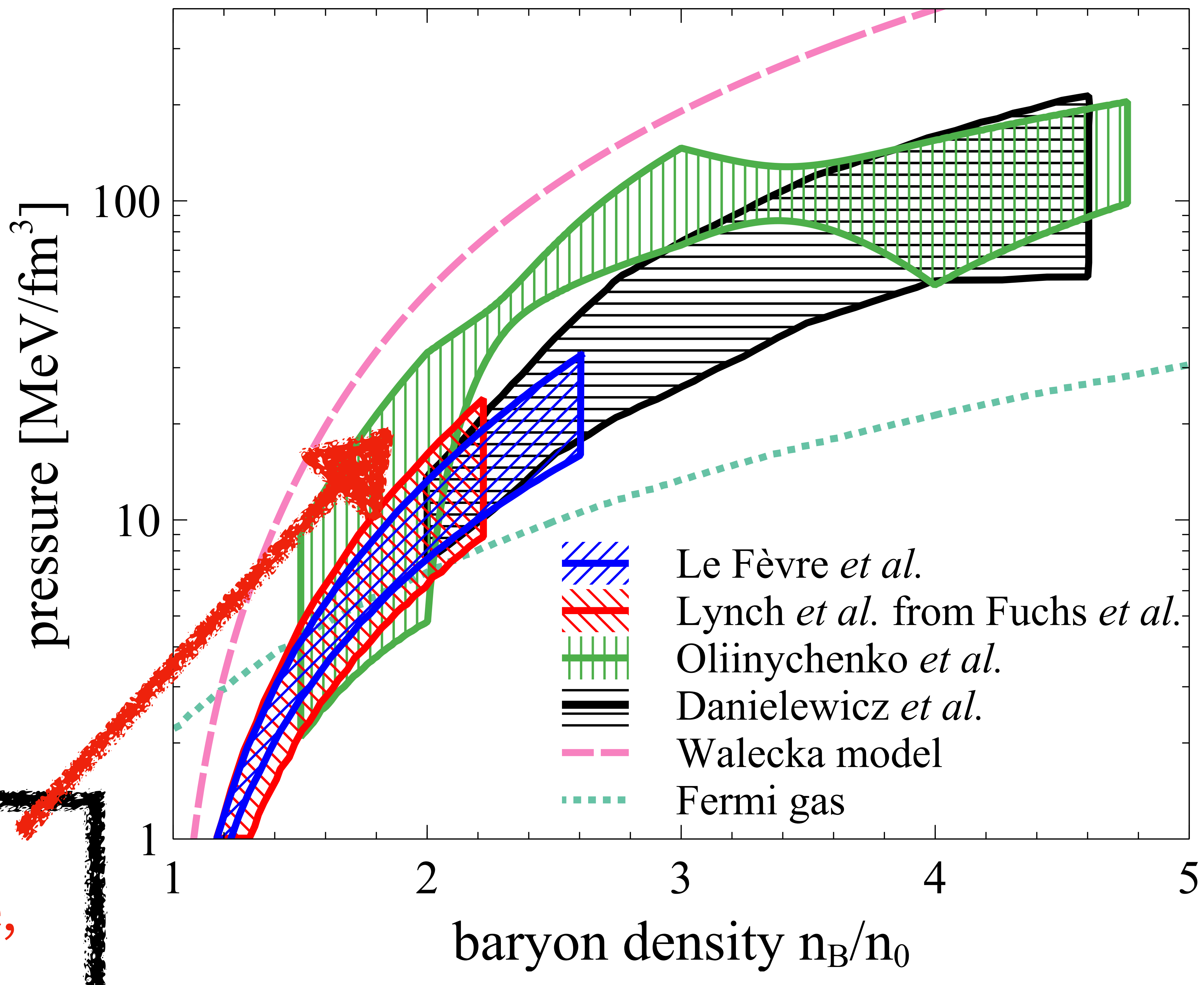
fits to data

parametrizations of the Walecka model



Affects the p_T-dependence of the elliptic flow

Without momentum dependence, the extracted EOS is too stiff!

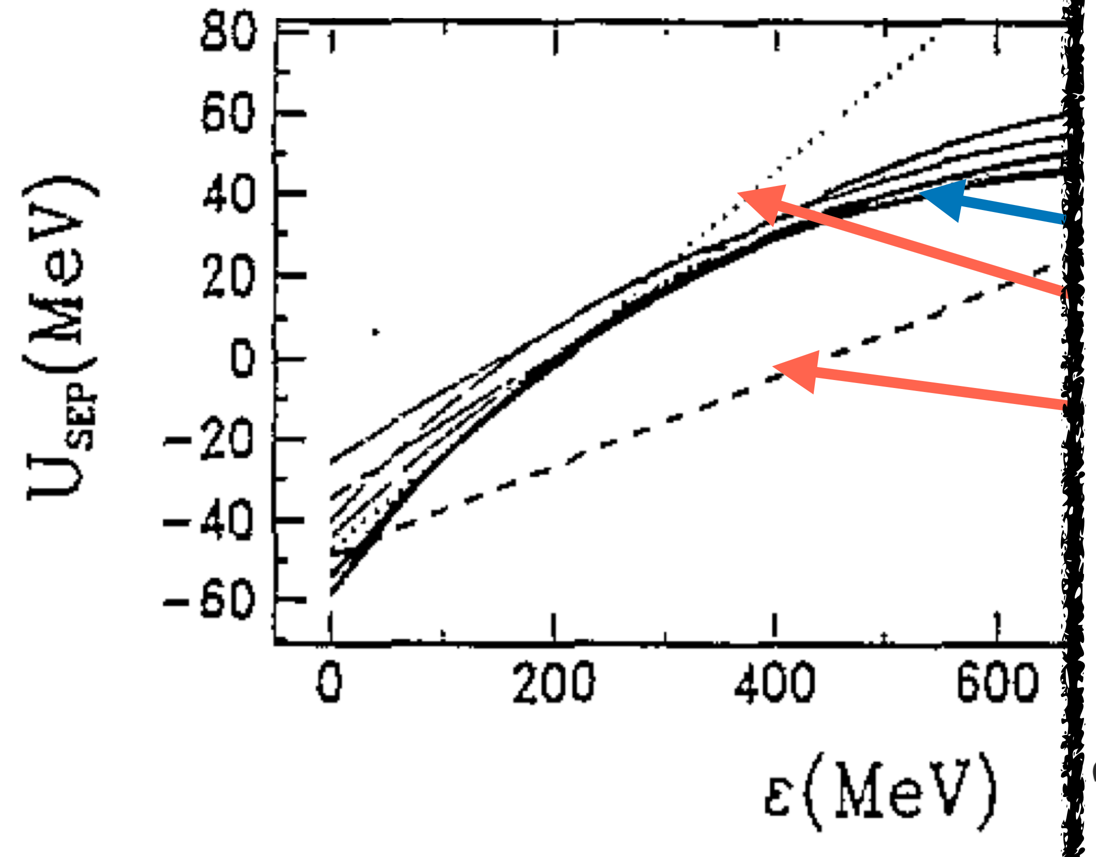


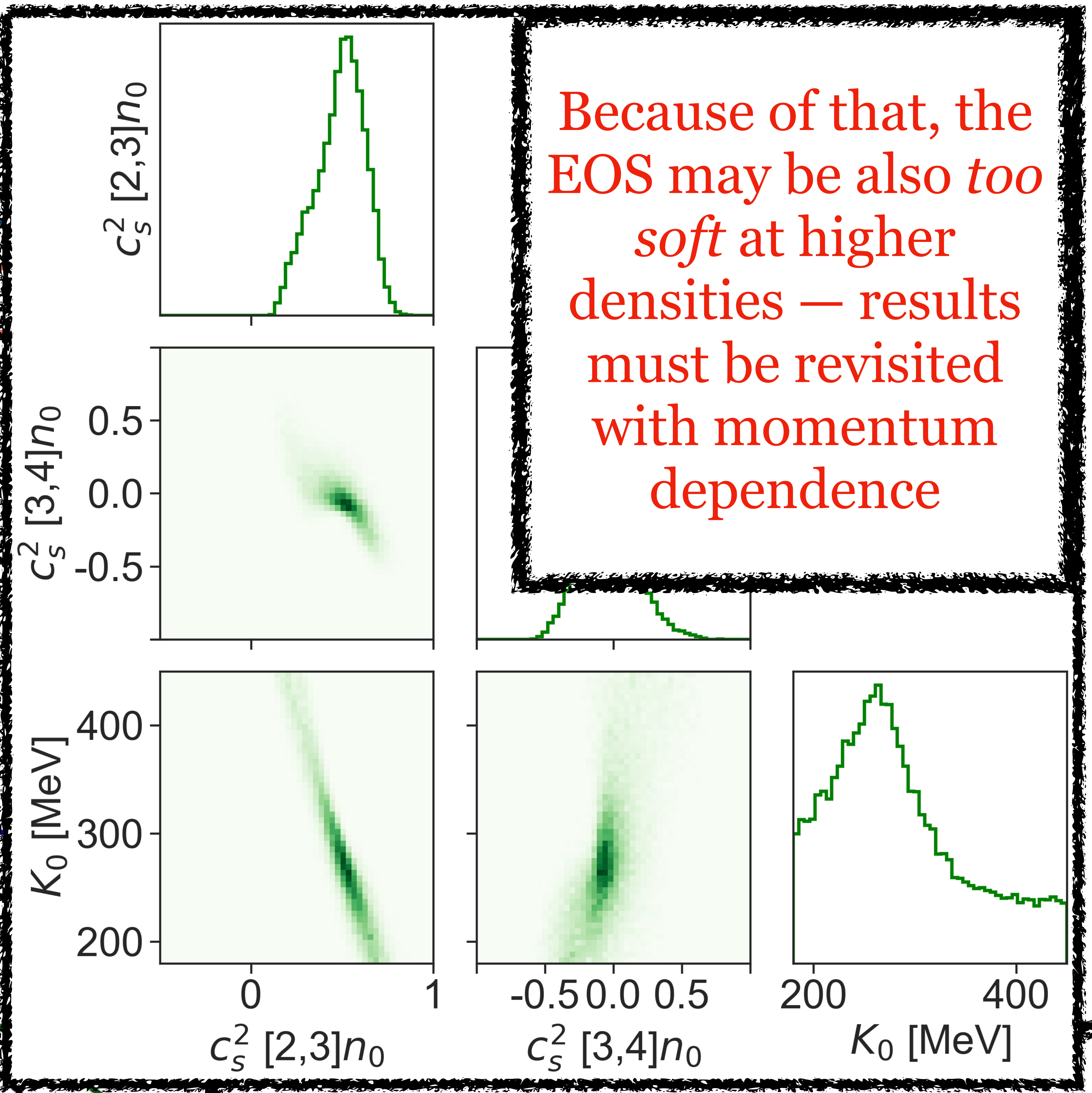
A. Sorensen *et al.*, arXiv:2301.13253

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

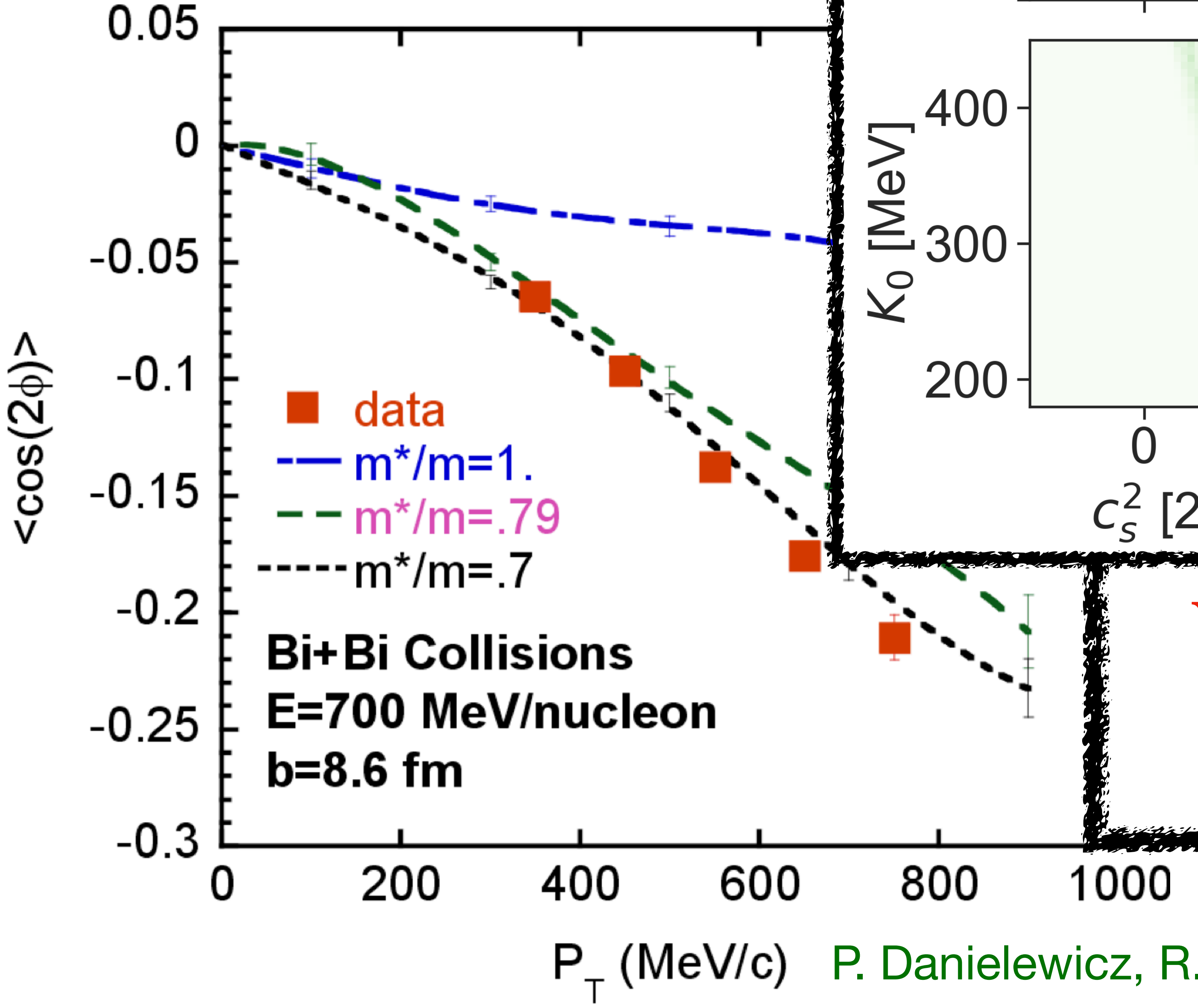
Momentum-dependent mean-fields are a necessary component

Measured in scattering ex

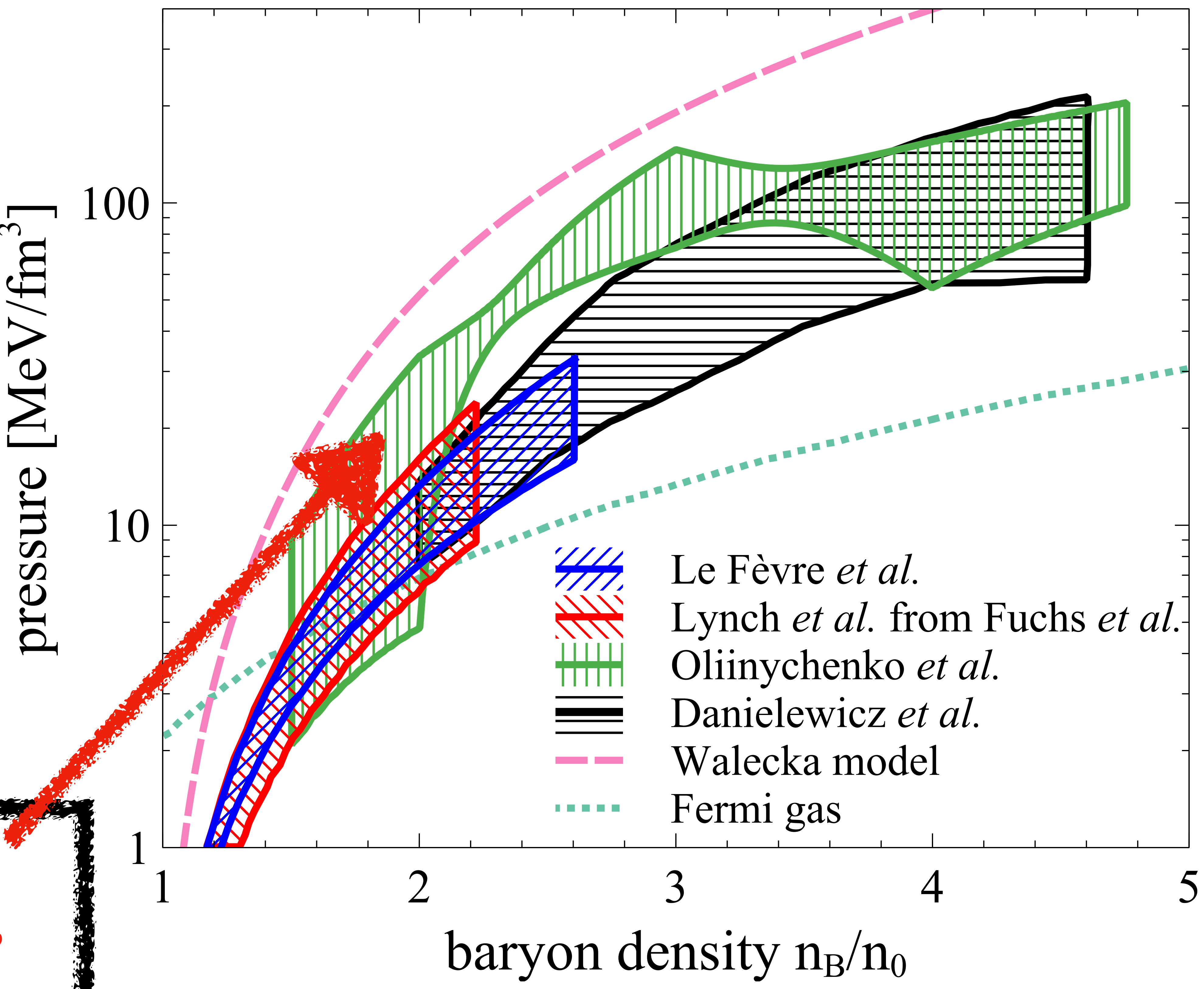




Because of that, the EOS may be also *too soft* at higher densities — results must be revisited with momentum dependence



Without momentum dependence, the extracted EOS is too stiff!

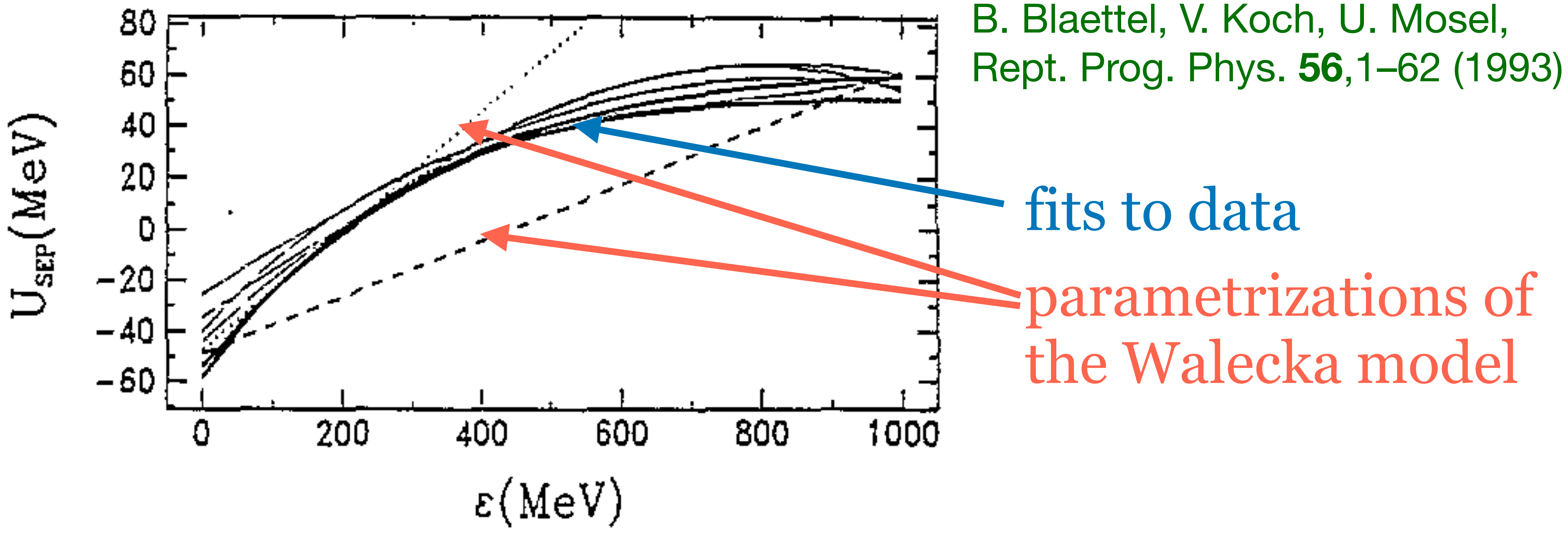


A. Sorensen *et al.*, arXiv:2301.13253

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

Work in progress: Flexible momentum-dependent mean-fields

Measured in scattering experiments:



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

Solution:
vector+scalar density functional model (VSDF)

Challenge: scalar fields are costly to compute

VDF model:

$$\mathscr{E}_N = g\int \frac{d^3p}{(2\pi)^3}\,\epsilon_{\mathrm{kin}}\,f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00}\sum_{i=1}^{N}\left(\frac{b_i-1}{b_i}\right)A_k^\lambda j_\lambda$$

$$A_k^\mu = C_k\left(j_\lambda j^\lambda\right)^{\frac{b_k}{2}-1} j^\mu\,, \qquad j_\mu j^\mu = n_B^2\,, \qquad j^\mu = g\int \frac{d^3p}{(2\pi)^3}\,\frac{p^\mu - A^\mu}{\epsilon^*_{kin}}\,f_{\mathbf{p}}$$

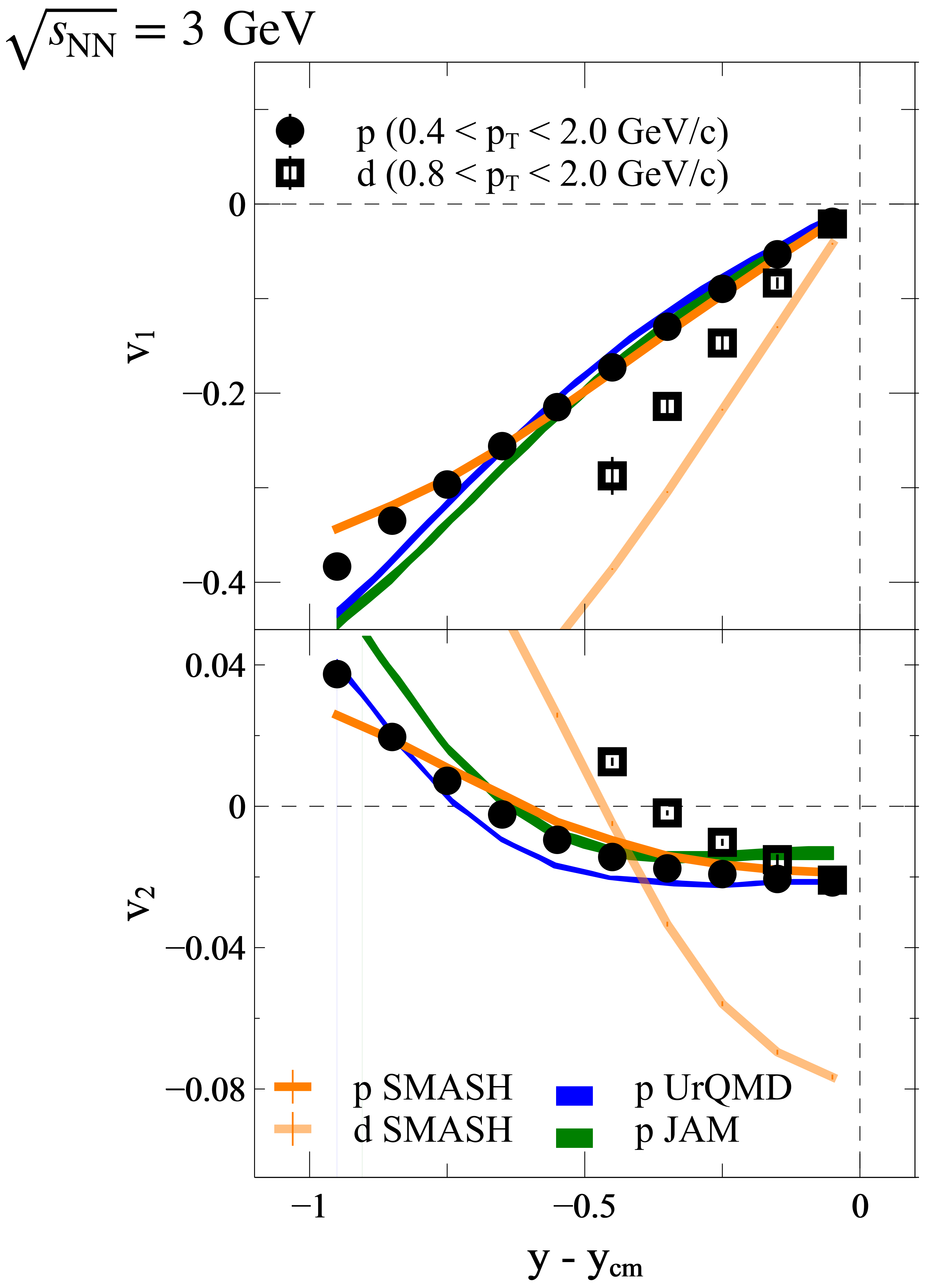
VSDF model:

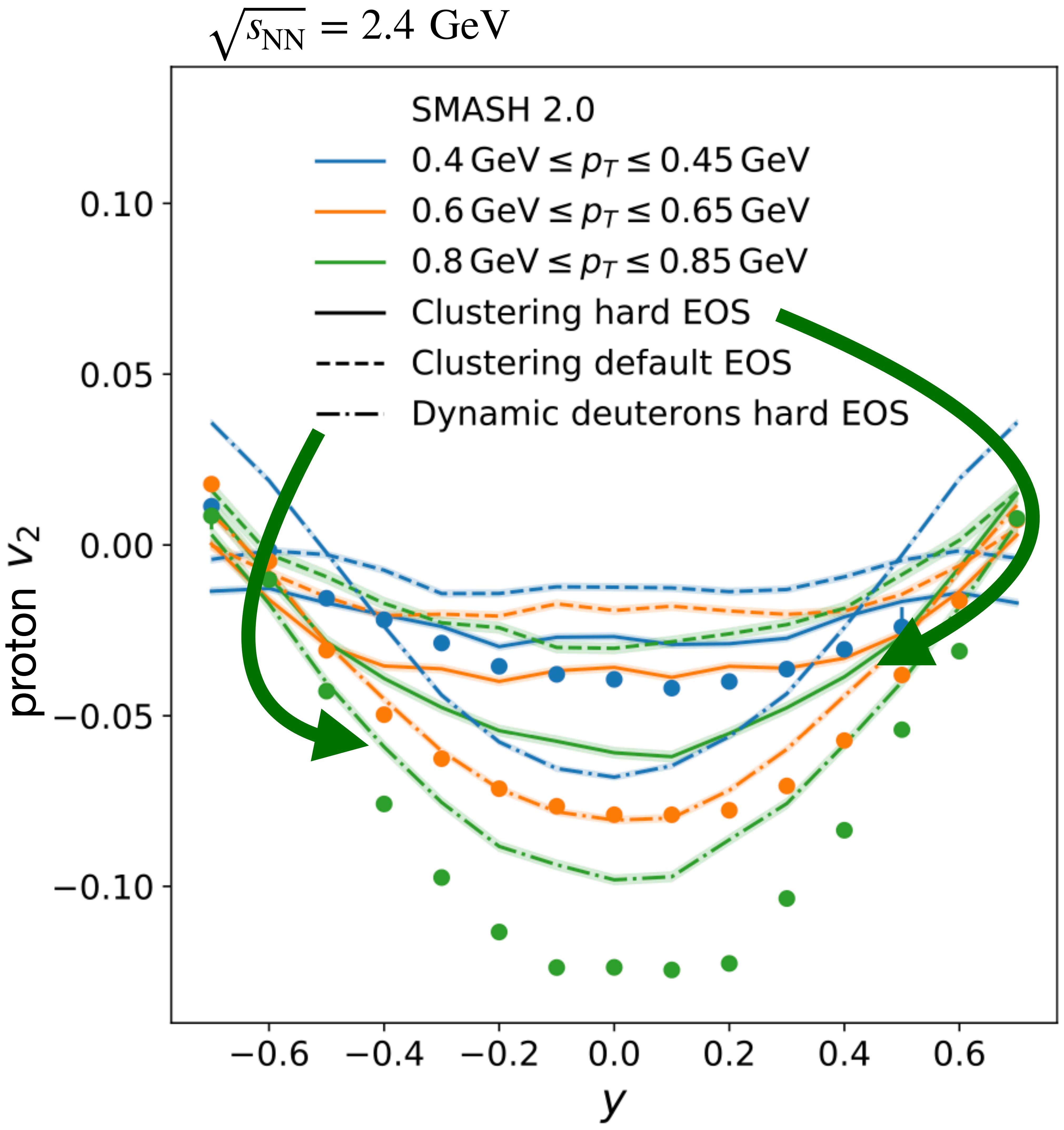
$$\mathscr{E}_{N,\,M} = g\int \frac{d^3p}{(2\pi)^3}\,\epsilon^*_{\mathrm{kin}}\,f_{\mathbf{p}} + \sum_{i=1}^{N} A_k^0 j_0 - g^{00}\sum_{i=1}^{N}\left(\frac{b_i-1}{b_i}\right)A_k^\lambda j_\lambda + g^{00}\sum_{m=1}^{M} G_m\left(\frac{d_m-1}{d_m}\right)n_s^{d_m}$$

$$m^* = m_0 - \sum_{m=1}^{M} G_m n_s^{d_m-1} \qquad n_s = g\int \frac{d^3p}{(2\pi)^3}\,\frac{m^*}{\epsilon^*_{\mathrm{kin}}}\,f_{\mathbf{p}}$$

A. Sorensen, "Density Functional Equation of State and Its Application to the Phenomenology of Heavy-Ion Collisions," arXiv:2109.08105, Sorensen:2021zxd

Describing proton flow is not enough





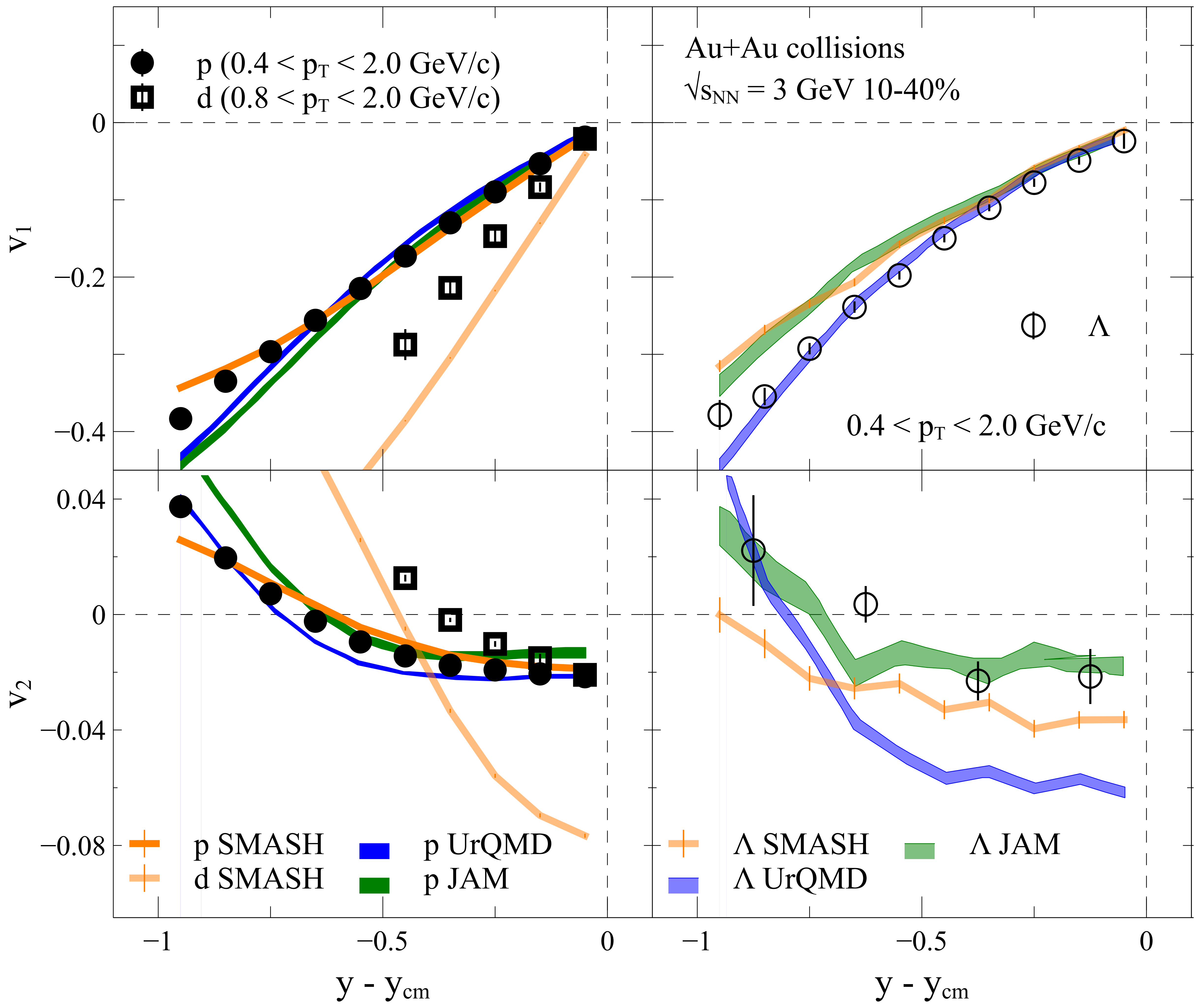
Realistic description of light cluster production needed:

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

STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253

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

Describing proton flow is not enough



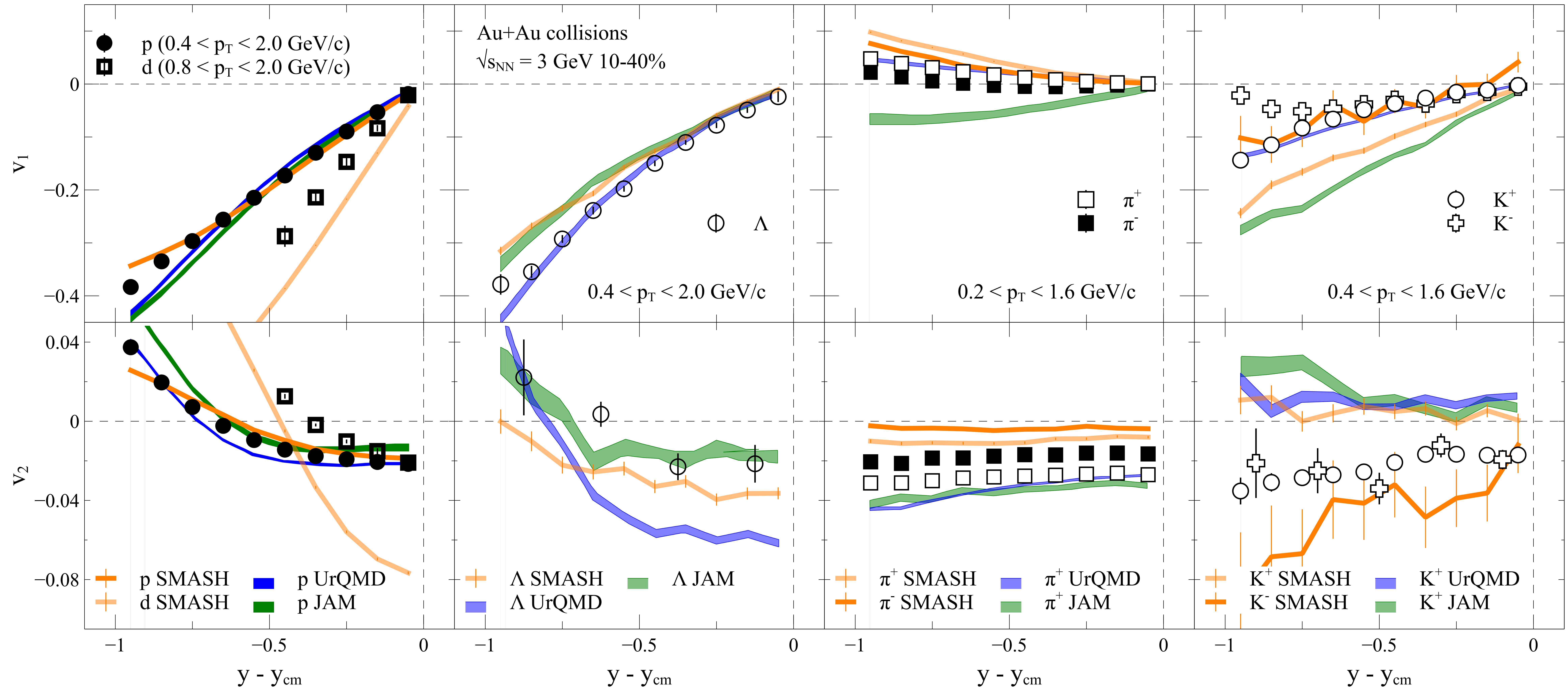
Strange baryons are not well described
- the results may depend on:

- nucleon-hyperon and hyperon-hyperon interactions
- in-medium modifications of interactions

Models of interactions exists and could be tested; interactions could be based on those obtained within first-principle calculations (e.g., HALQCD collaboration
HAL QCD, Nucl. Phys. A **998** 121737 (2020), arXiv:1912.08630)

STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253

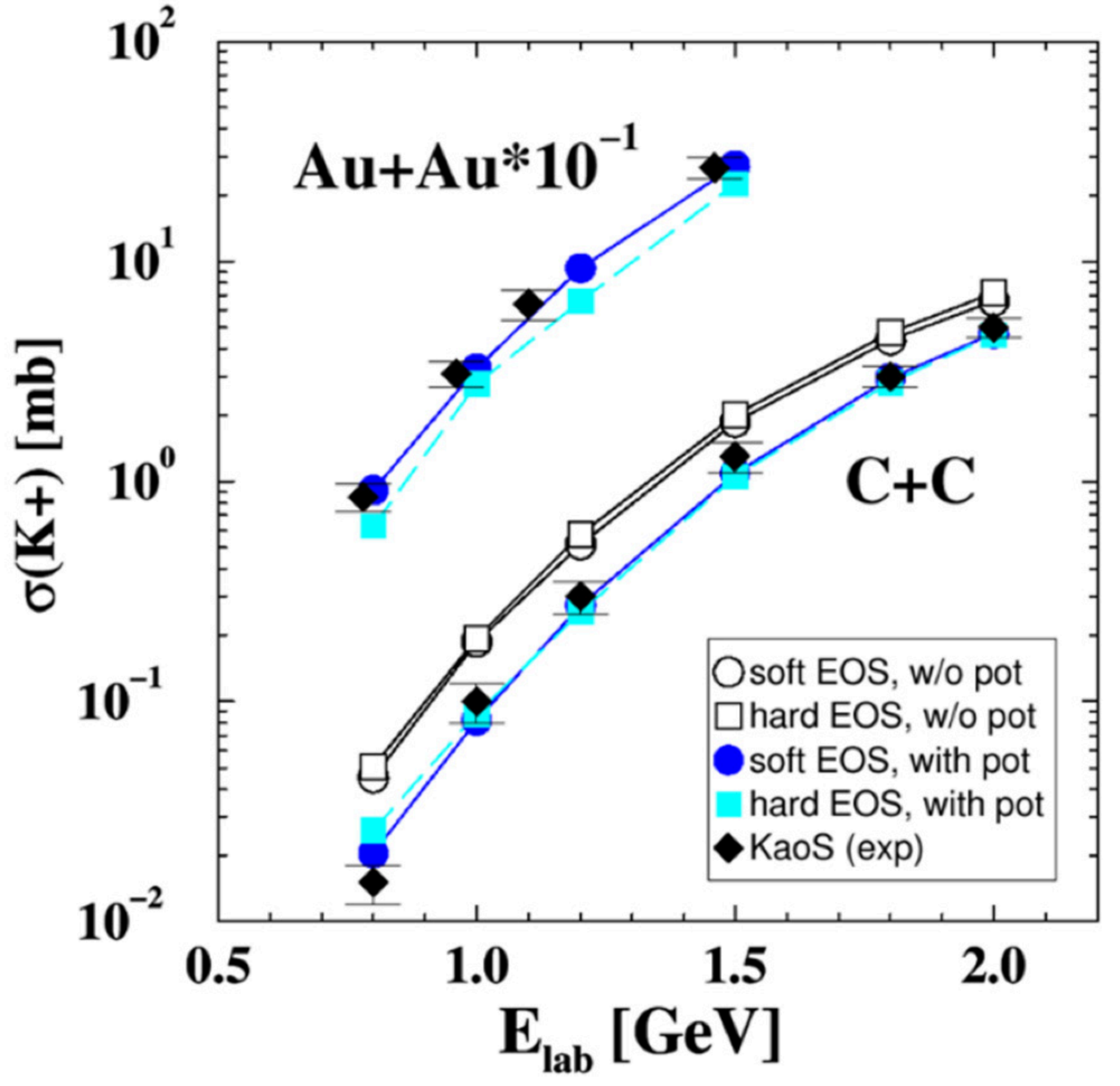
Describing proton flow is not enough



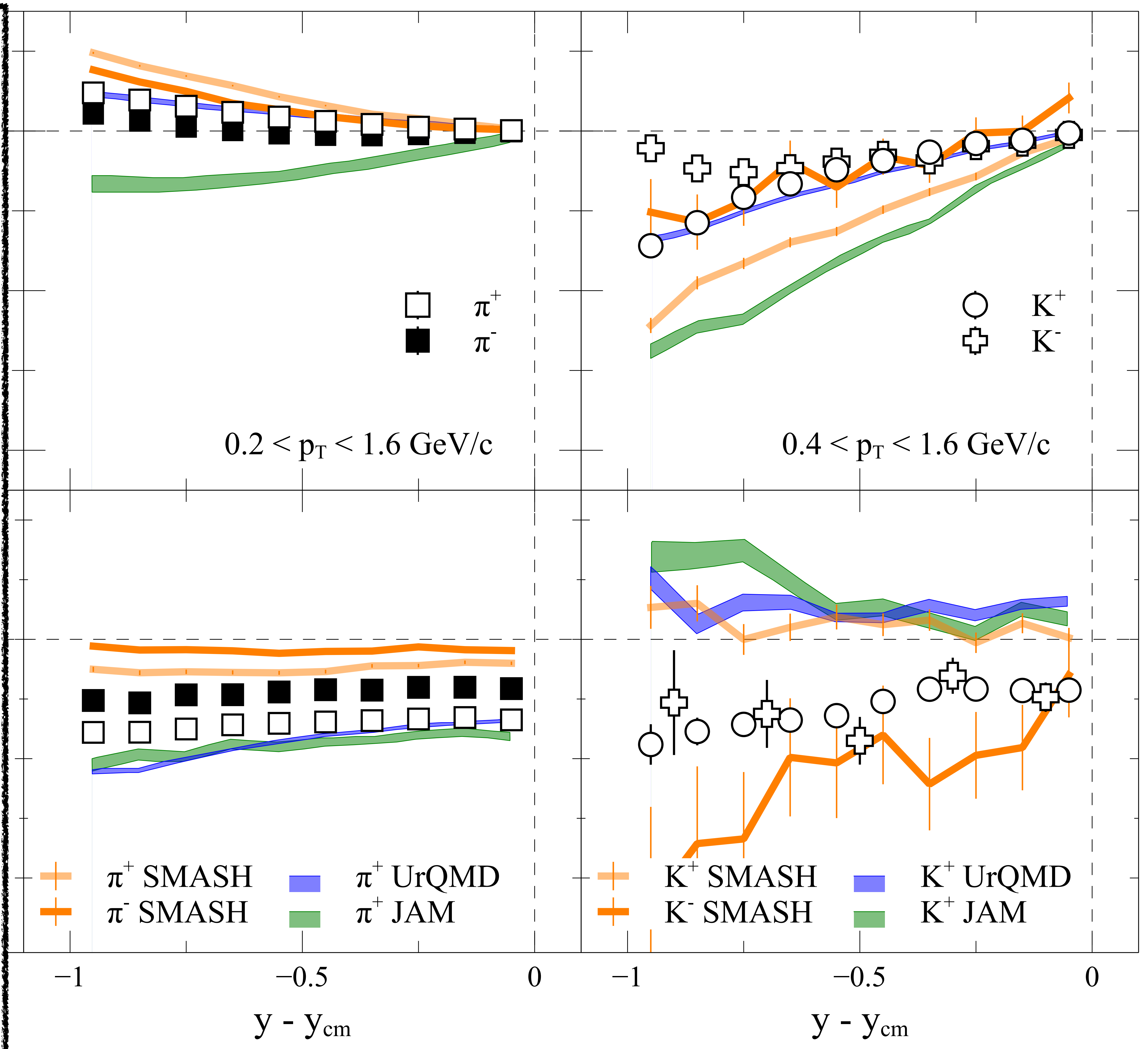
STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253

Describing proton flow is not enough

Pions and kaons NOT described!
Not very surprising: UrQMD, JAM, and SMASH don't have mean-fields for mesons

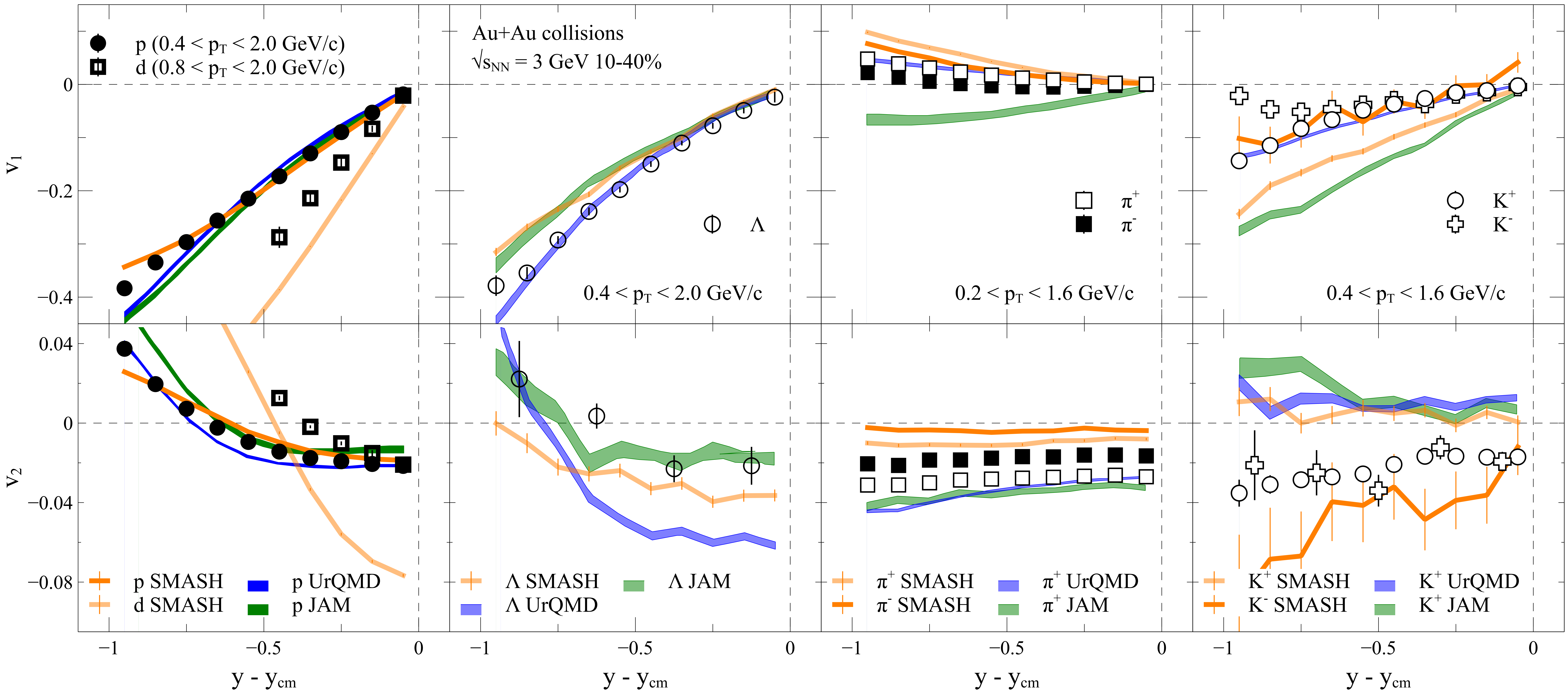


C. Fuchs, PoS CPOD07 060 (2007) arXiv:0711.3367



STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, arXiv:2208.11996
A. Sorensen *et al.*, arXiv:2301.13253

Describing proton flow is not enough



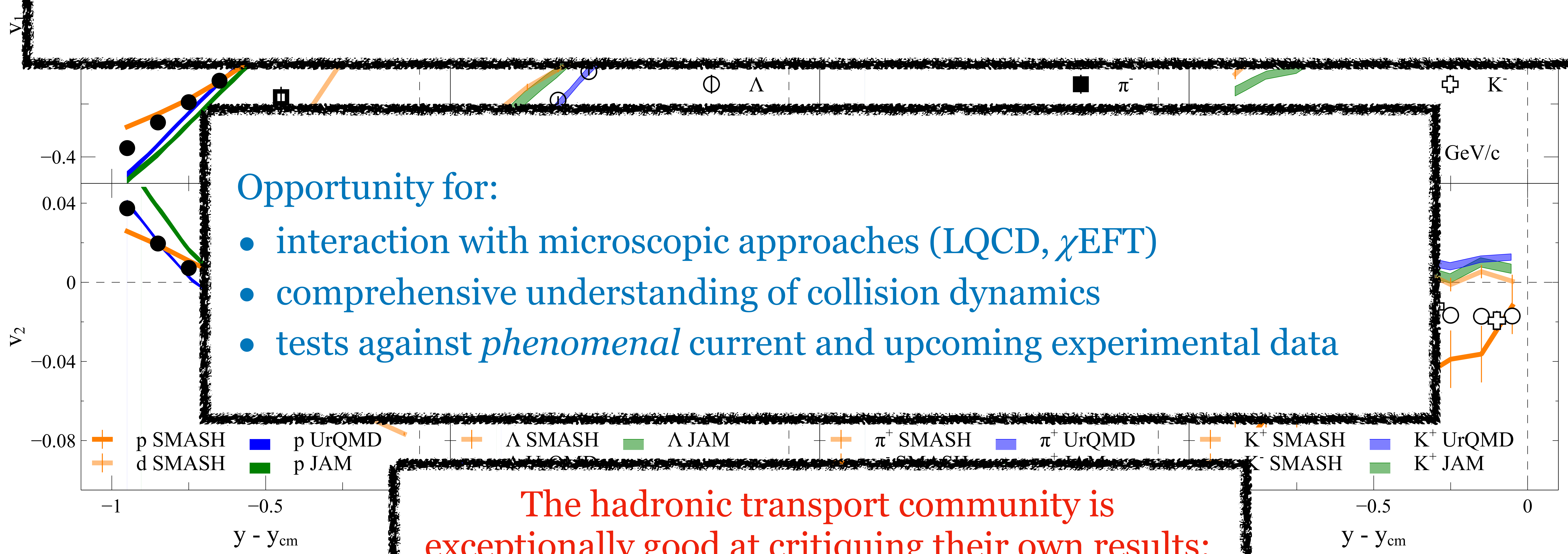
STAR, Phys. Lett. B **827**, 137003 (2022) arXiv:2108.00908

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

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

Describing proton flow is not enough

In a comprehensive Bayesian analysis, all relevant observables should be understood



Opportunity for:

- interaction with microscopic approaches (LQCD, χEFT)
- comprehensive understanding of collision dynamics
- tests against *phenomenal* current and upcoming experimental data

The hadronic transport community is exceptionally good at critiquing their own results: this leads to progress!

STAR, Phys. Lett. B **827**, 137003 (2022) arXiv
D. Oliinychenko, **A. Sorensen**, V. Koch, L. Mc
A. Sorensen *et al.*, arXiv:2301.13253

Better modeling is necessary

Ideas to explore:

- threshold effects,
- light cluster production,
- neutron-proton effective mass splitting, ...

Strong efforts by the Transport Model Evaluation Project (TMEP) collaboration to identify code-dependencies and best model practices!

Transport model comparison studies of intermediate-energy heavy-ion collisions #1
TMEP Collaboration • Hermann Wolter (Munich U.) et al. (Feb 14, 2022)
Published in: *Prog.Part.Nucl.Phys.* 125 (2022) 103962 • e-Print: 2202.06672 [nucl-th]
pdf DOI cite claim reference search 31 citations

Comparison of heavy-ion transport simulations: Mean-field dynamics in a box #2
TMEP Collaboration • Maria Colonna (INFN, LNS) et al. (Jun 23, 2021)
Published in: *Phys.Rev.C* 104 (2021) 2, 024603 • e-Print: 2106.12287 [nucl-th]
pdf DOI cite claim reference search 29 citations

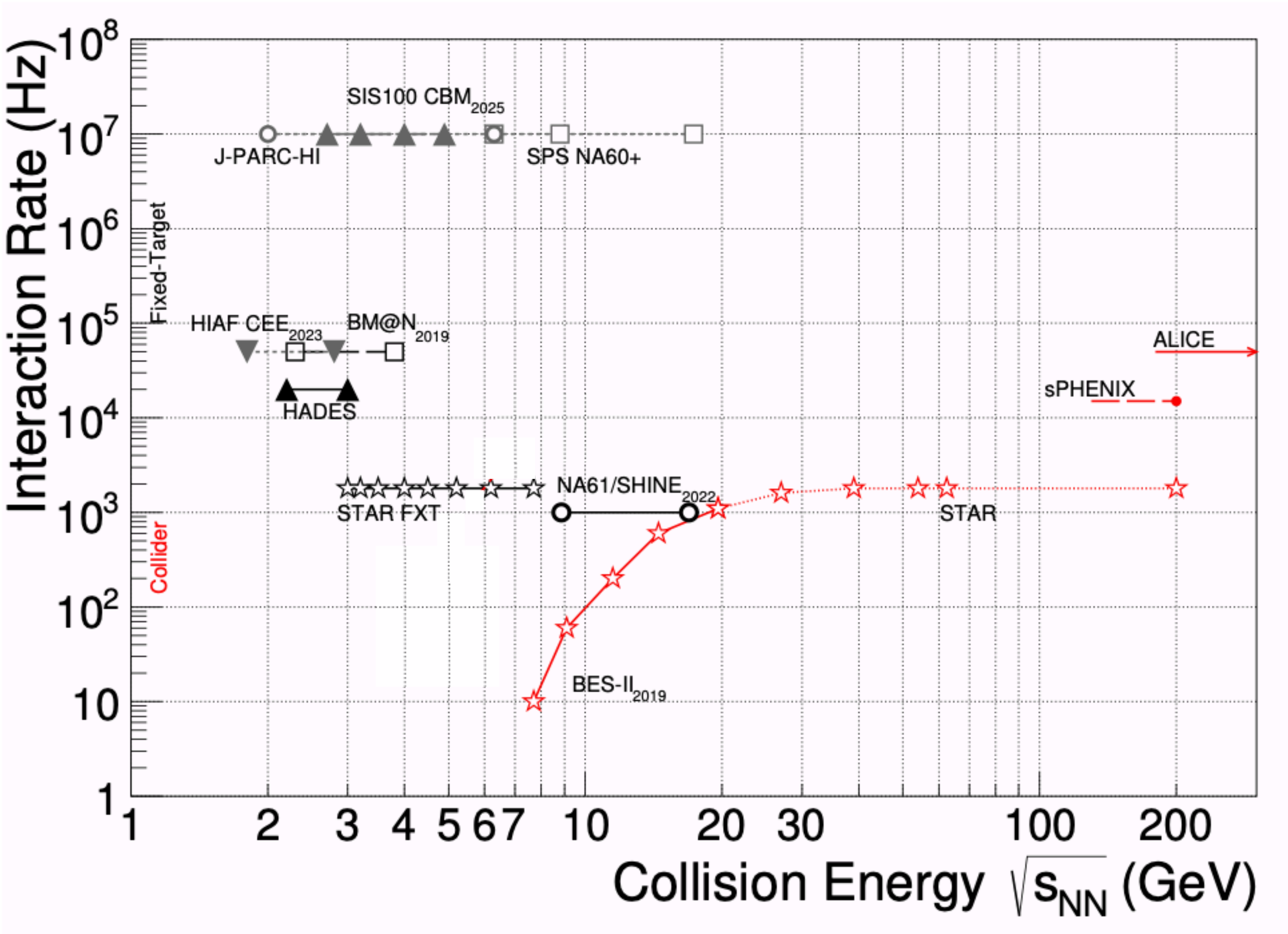
Symmetry energy investigation with pion production from Sn+Sn systems #3
SpiRIT and TMEP Collaborations • G. Jhang et al. (Dec 13, 2020)
Published in: *Phys.Lett.B* 813 (2021) 136016 • e-Print: 2012.06976 [nucl-ex]
pdf DOI cite claim reference search 34 citations

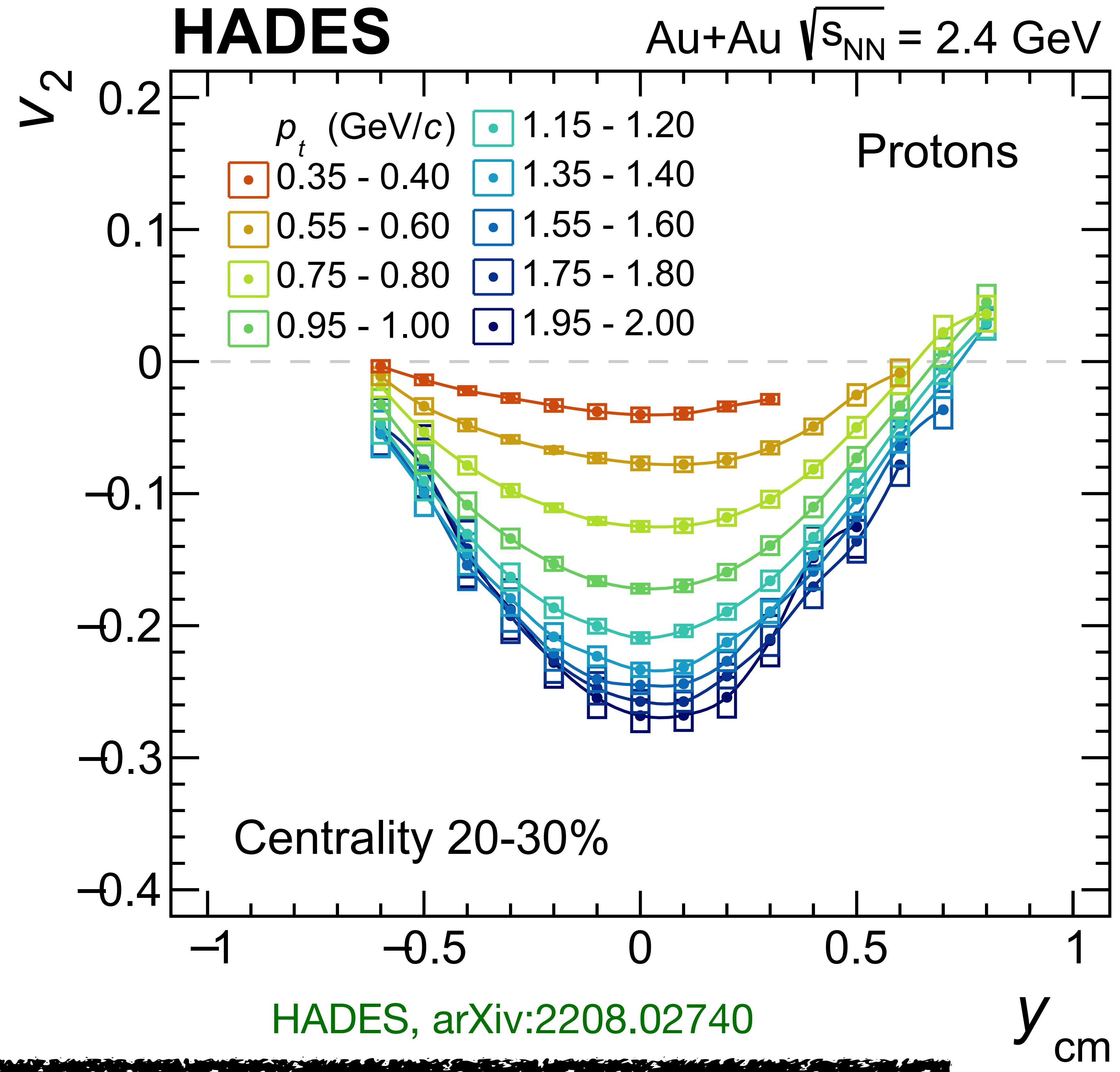
Comparison of heavy-ion transport simulations: Collision integral with pions and Δ resonances in a box #4
TMEP Collaboration • Akira Ono (Tohoku U.) et al. (Apr 5, 2019)
Published in: *Phys.Rev.C* 100 (2019) 4, 044617 • e-Print: 1904.02888 [nucl-th]
pdf DOI cite claim reference search 59 citations

Comparison of heavy-ion transport simulations: Collision integral in a box #5
TMEP Collaboration • Ying-Xun Zhang (Beijing, Inst. Atomic Energy and Guangxi Normal U.) et al. (Nov 16, 2017)
Published in: *Phys.Rev.C* 97 (2018) 3, 034625 • e-Print: 1711.05950 [nucl-th]
pdf DOI cite claim reference search 103 citations

Understanding transport simulations of heavy-ion collisions at 100A and 400A MeV: Comparison of heavy-ion transport codes under controlled conditions #6
TMEP Collaboration • Jun Xu (SINAP, Shanghai) et al. (Mar 26, 2016)
Published in: *Phys.Rev.C* 93 (2016) 4, 044609 • e-Print: 1603.08149 [nucl-th]

Precision era of heavy-ion collisions





HADES, arXiv:2208.02740

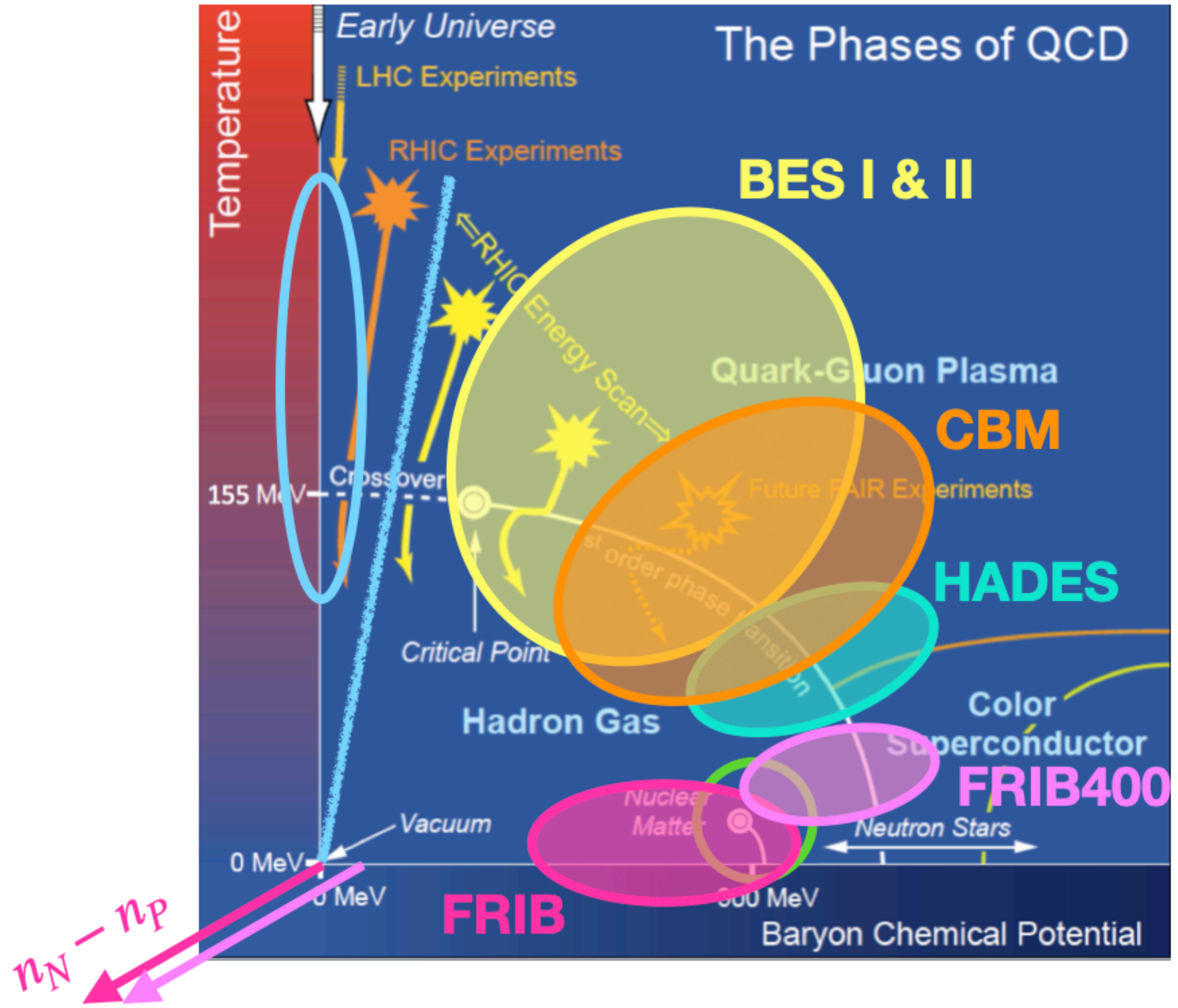
Precision experiments NEED precision simulations

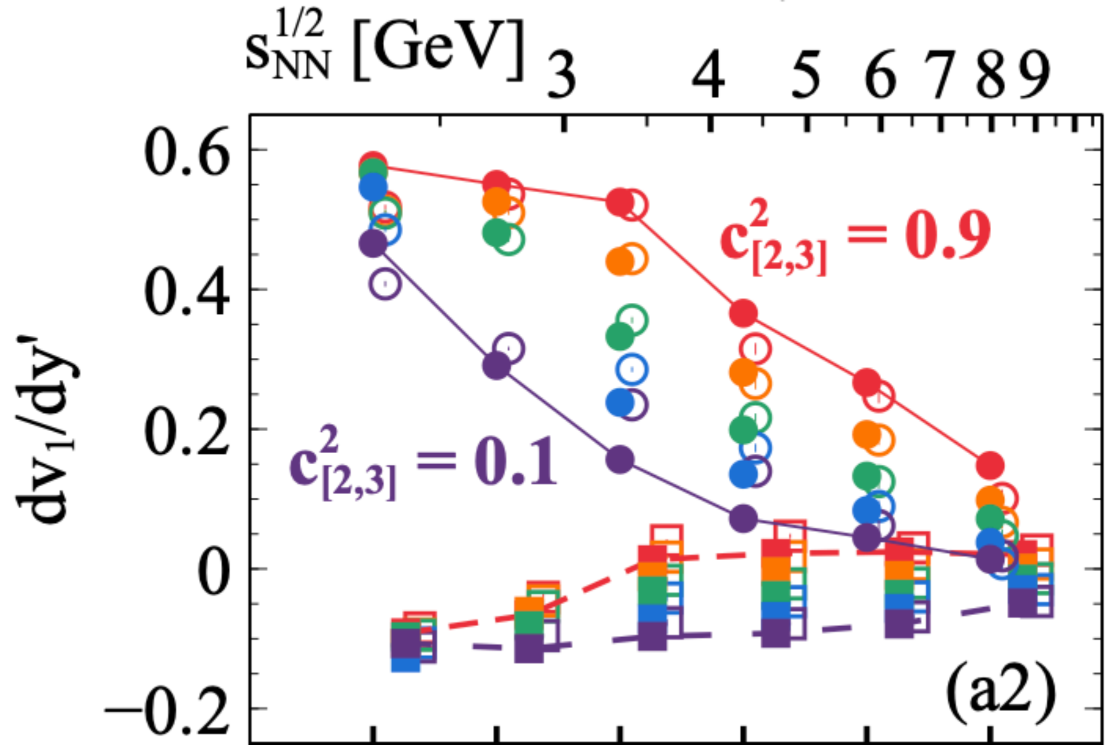
Very high-quality, high-statistics data are imminent from BES FXT, HADES, CBM, FRIB, FRIB400: perhaps observables are now available which were previously inaccessible?

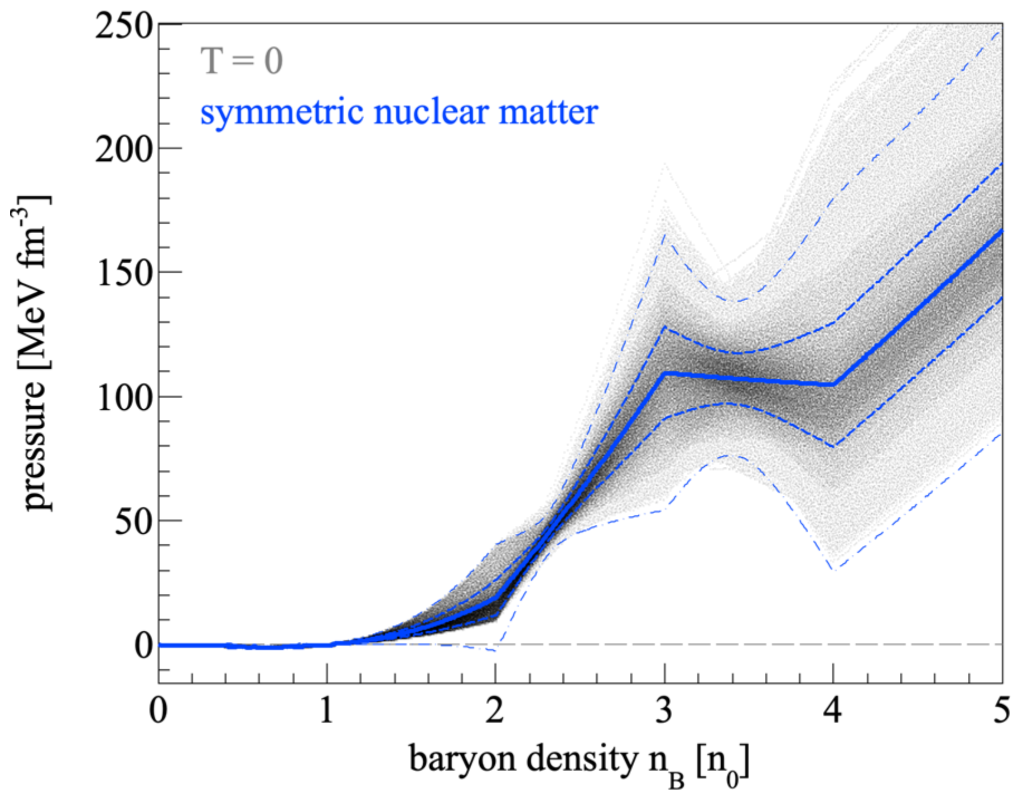
Summary

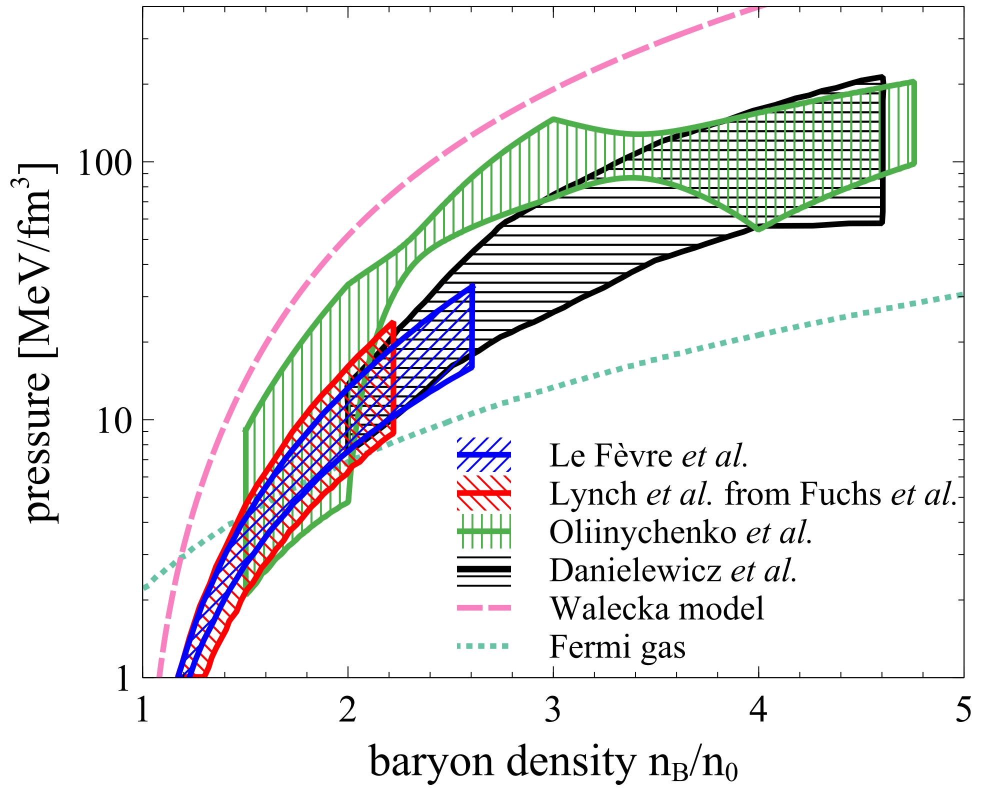
What's different, new, exciting about *now*?

- New analyses, new understanding: e.g., triangular flow, quark number scaling, cumulants
- New detectors, new data: unprecedented measurements, from ultra-precise triple-differential flow observables to hyperon-hyperon interactions
- New computing capabilities: large-scale simulations possible with state-of-the-art, benchmarked hadronic transport codes
- New approach to constraining the EOS: Bayesian analyses using flexible parametrizations of the EOS









Thank you for your attention