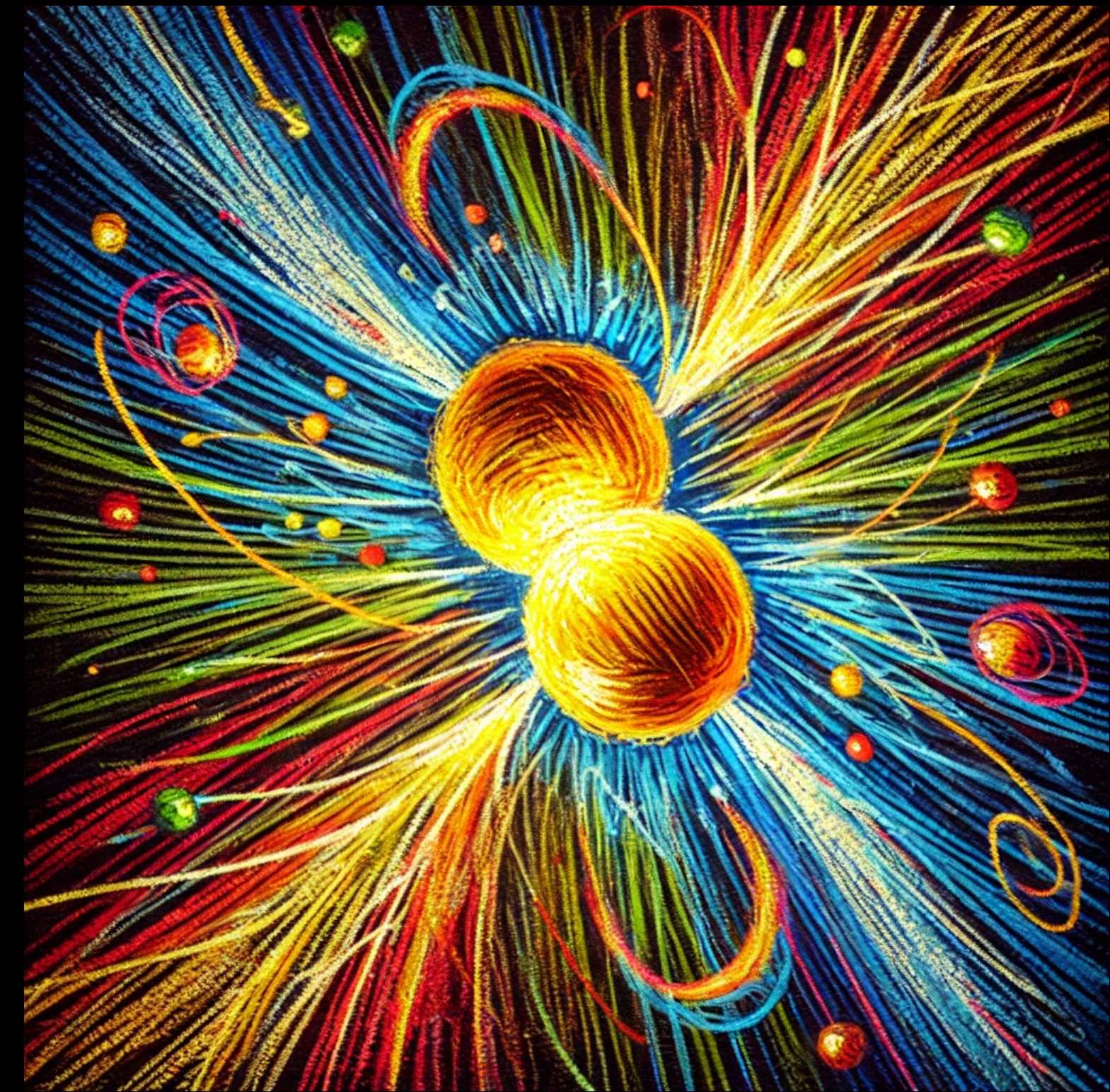


QCD Phase Structure at High Density Region



DALL-E

Agnieszka Sorensen

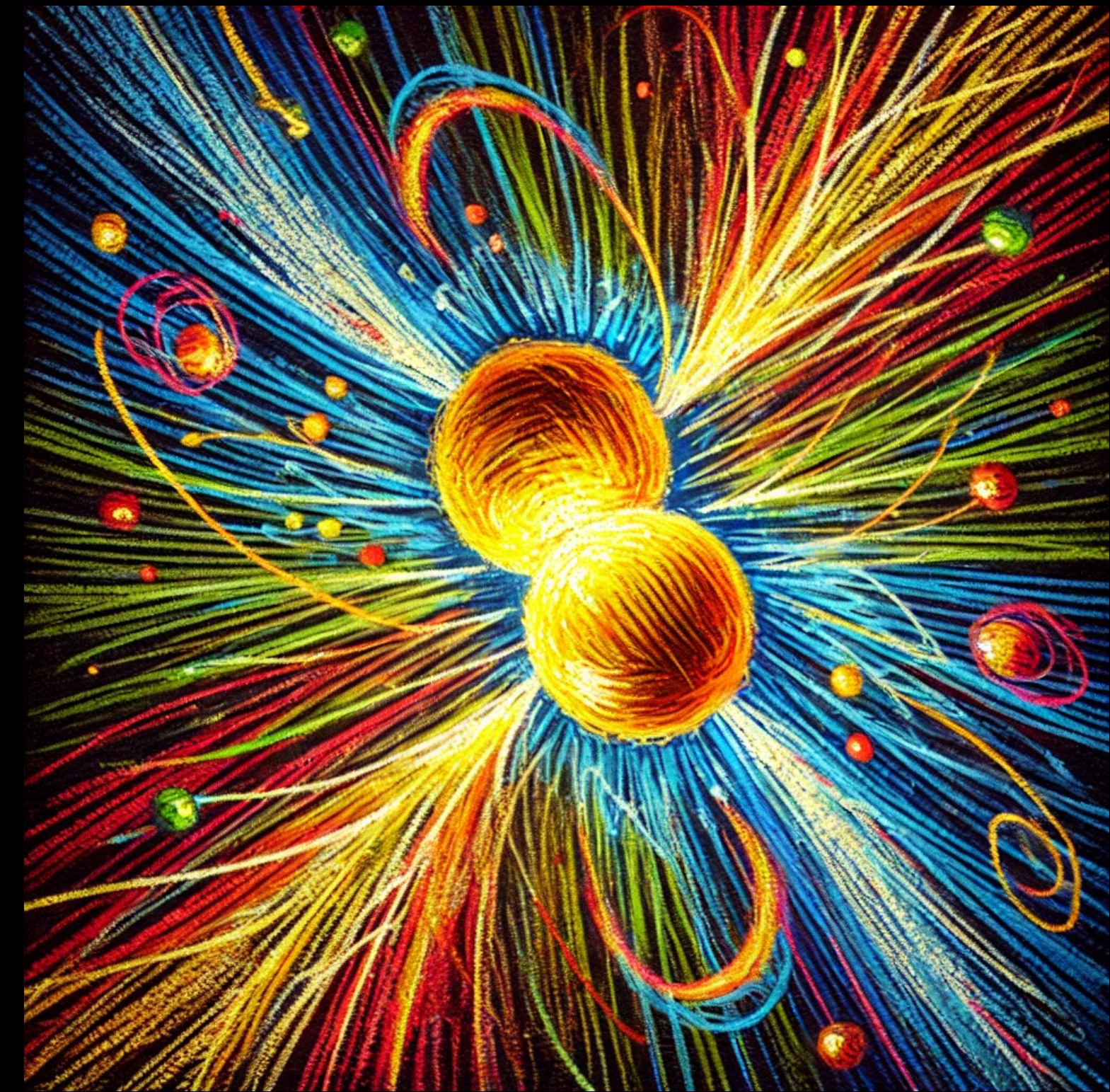
Facility for Rare Isotope Beams
Michigan State University



QCD Phase Structure at High Density Region

Also about the phase diagram @SQM:

- L. Du (this session):
dynamic simulations
- M. Pradeep (Thu II morning session):
QCD critical point predictions
- M. Pelicer (Fri I morning session):
EOS & astrophysics



DALL-E

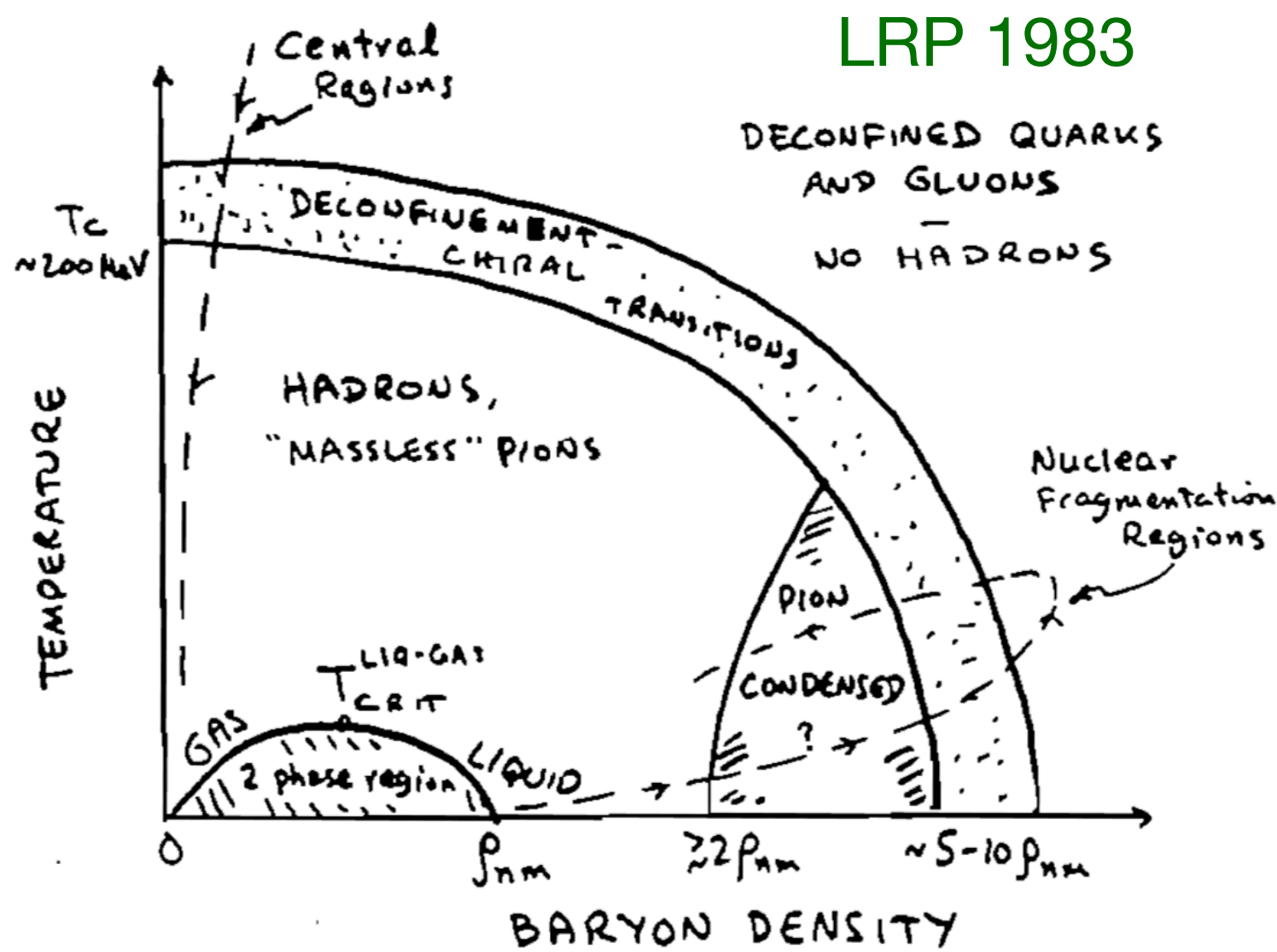
Agnieszka Sorensen

Facility for Rare Isotope Beams
Michigan State University

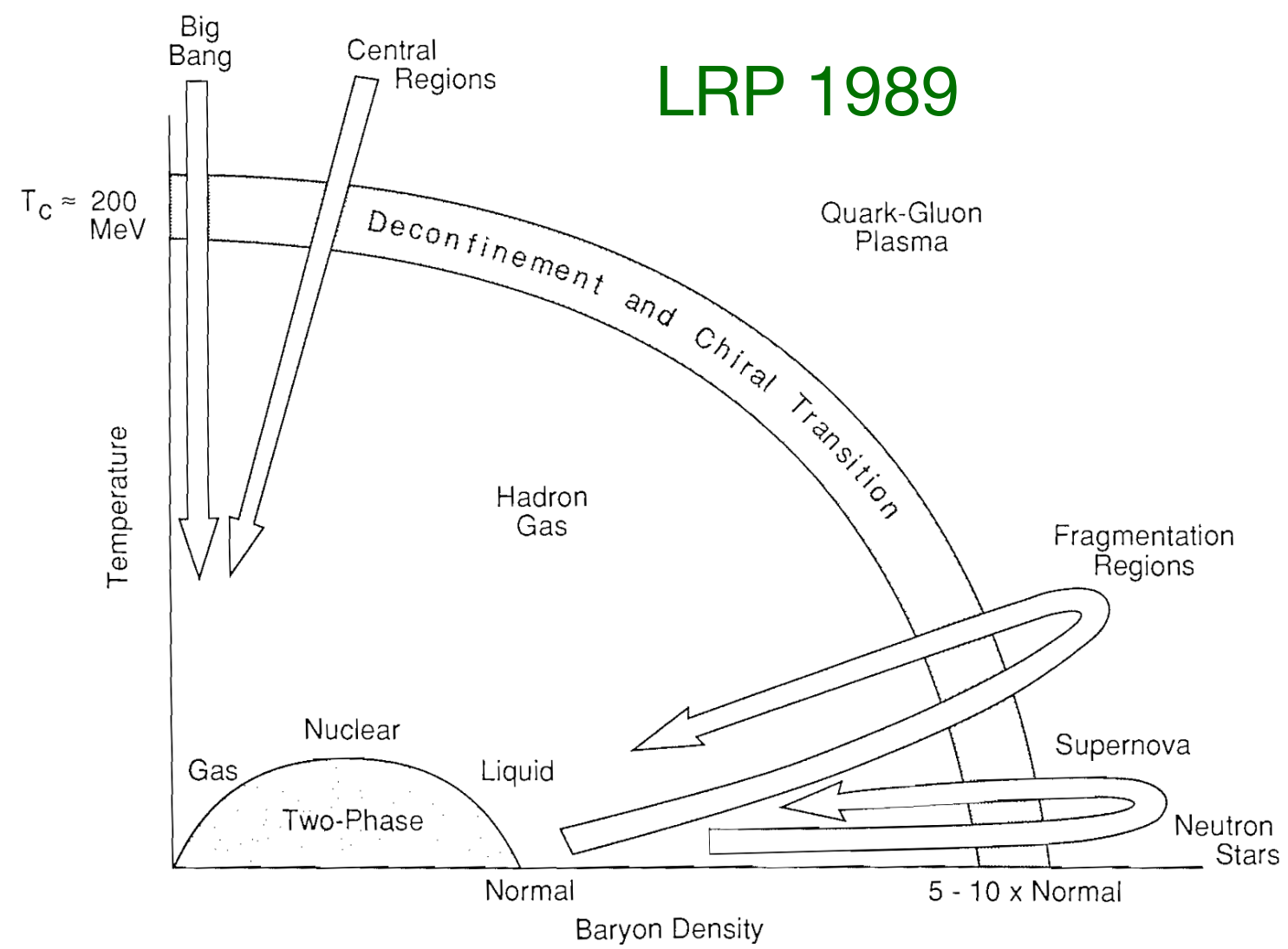


The QCD phase diagram as seen in U.S. Long Range Plans

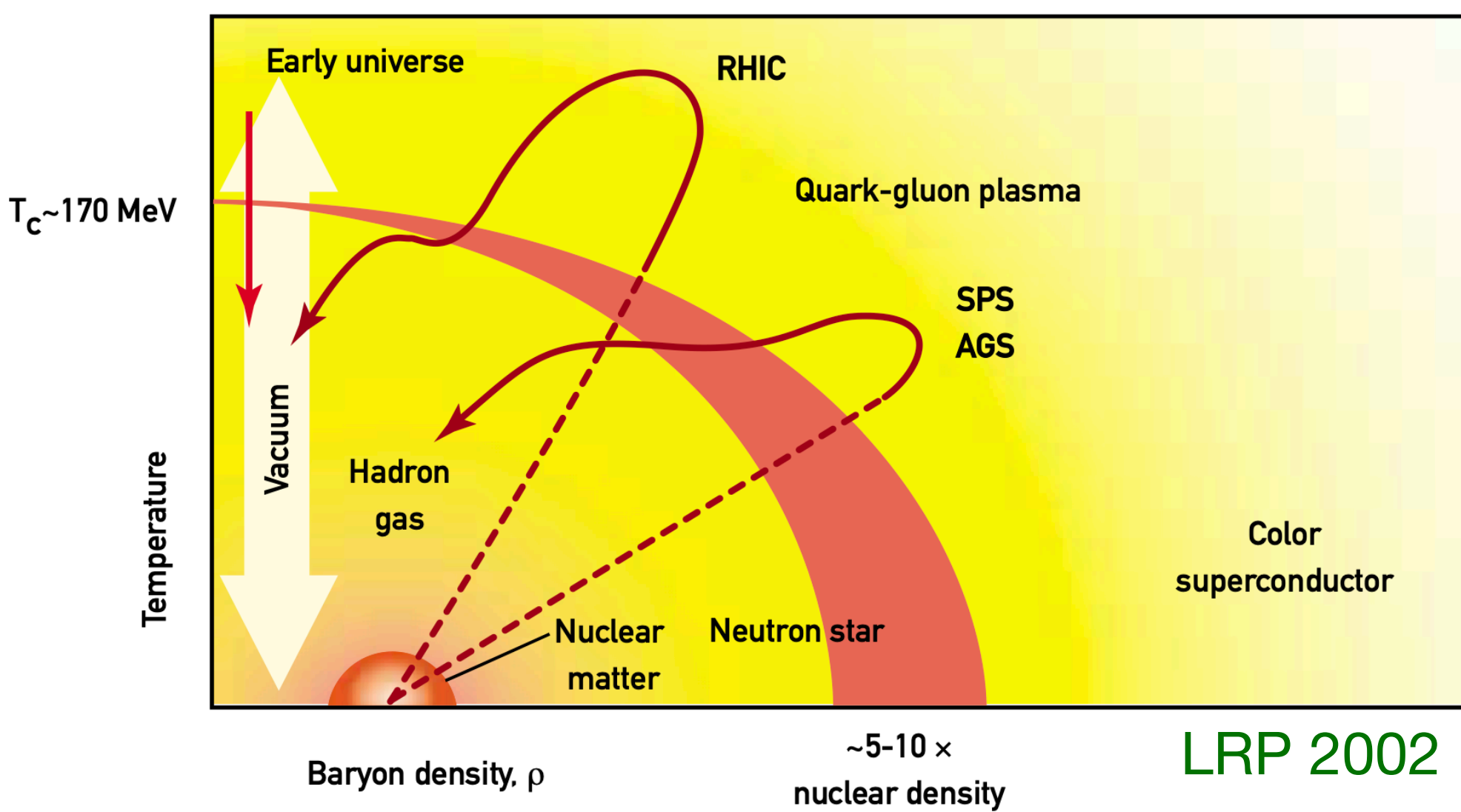
PHASE DIAGRAM OF NUCLEAR MATTER



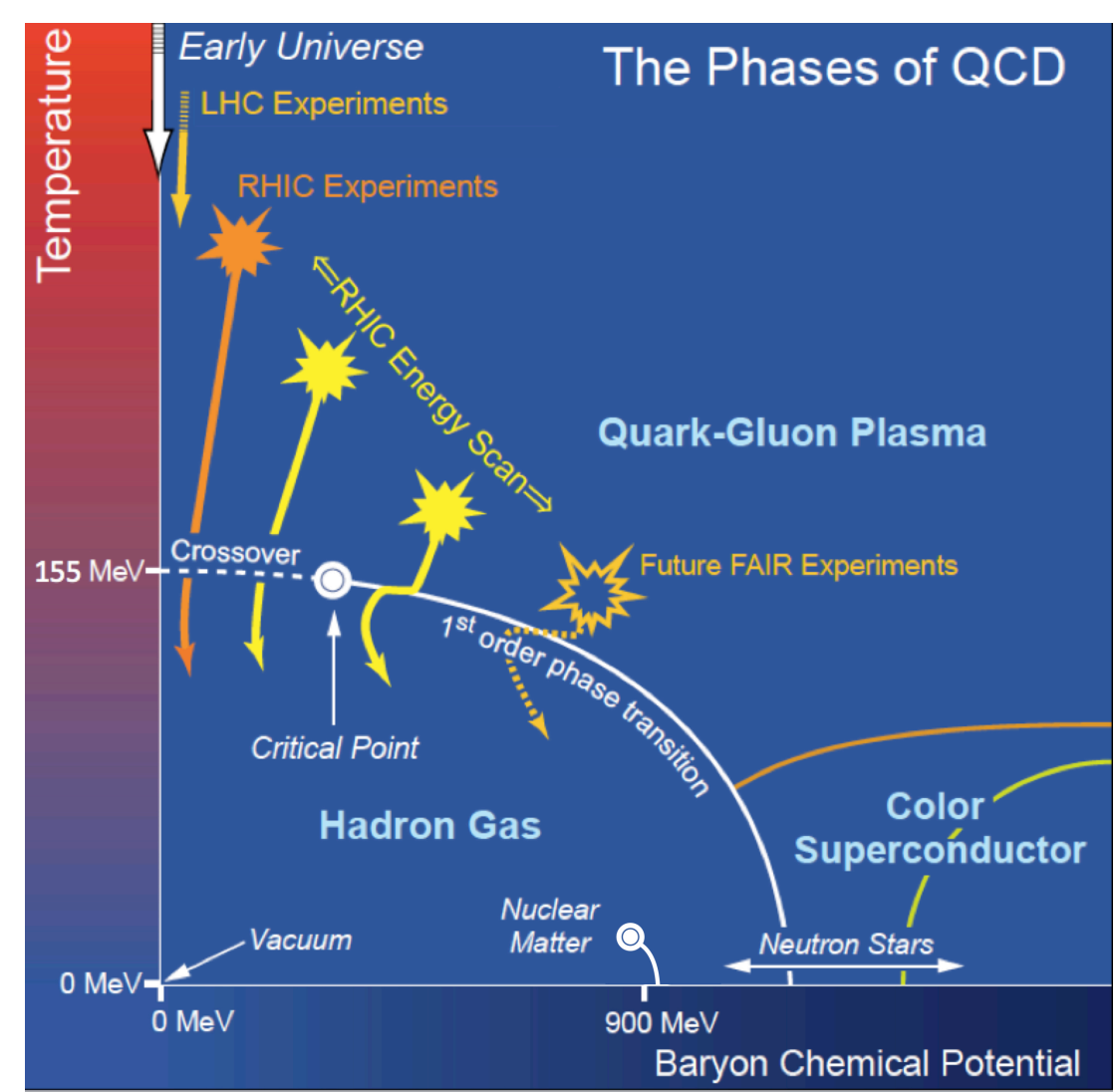
LRP 1983



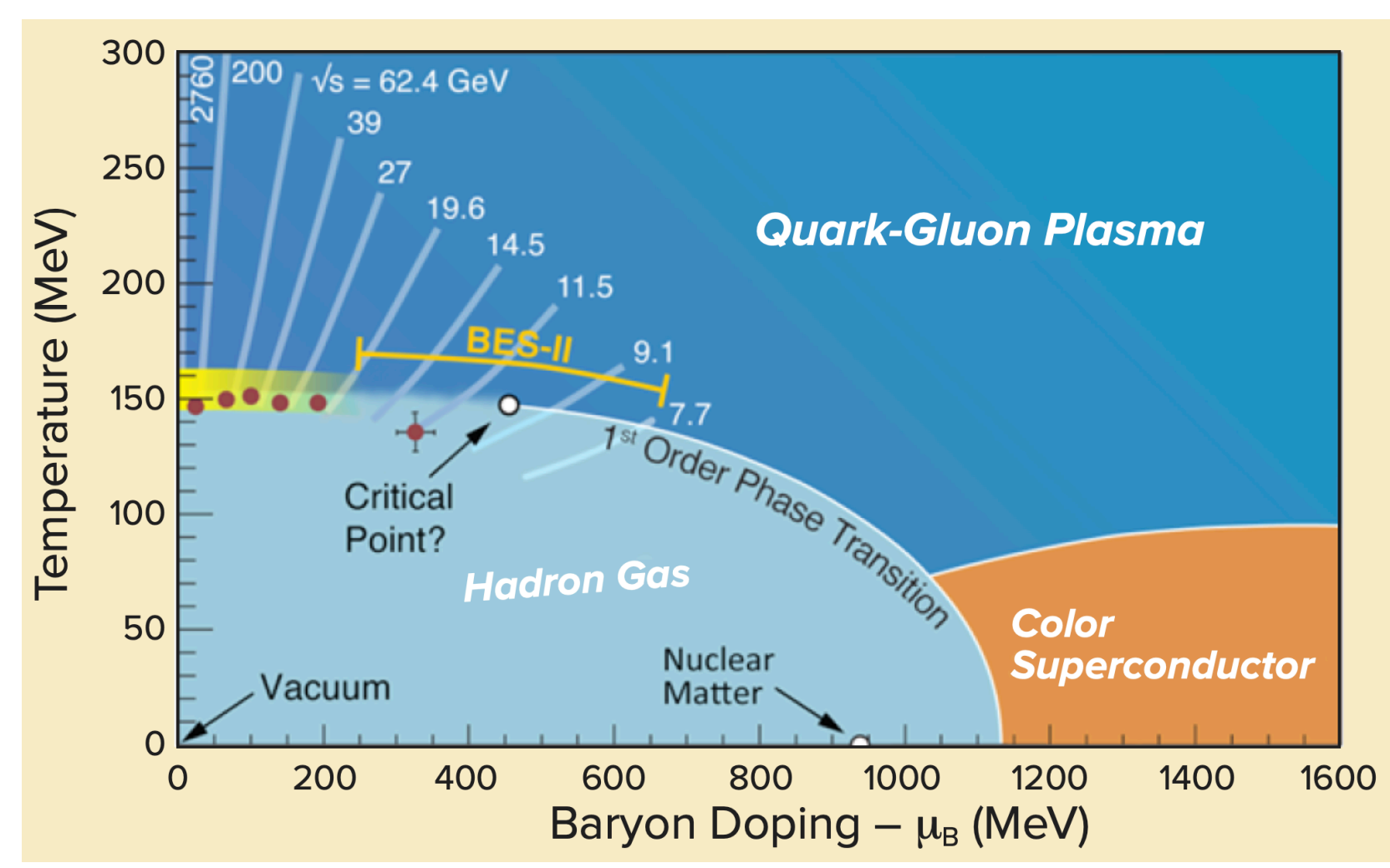
LRP 1989



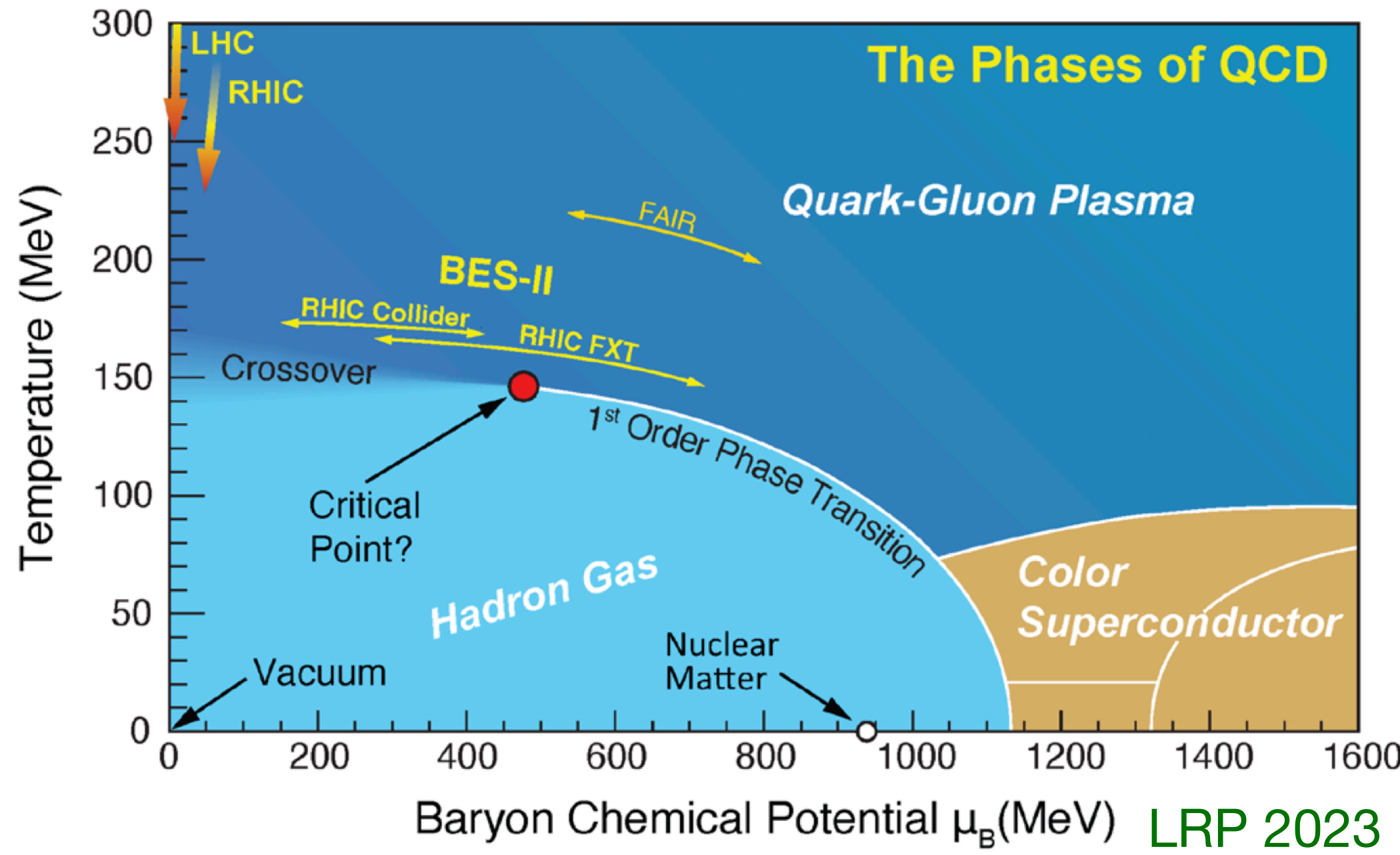
LRP 2002



LRP 2007



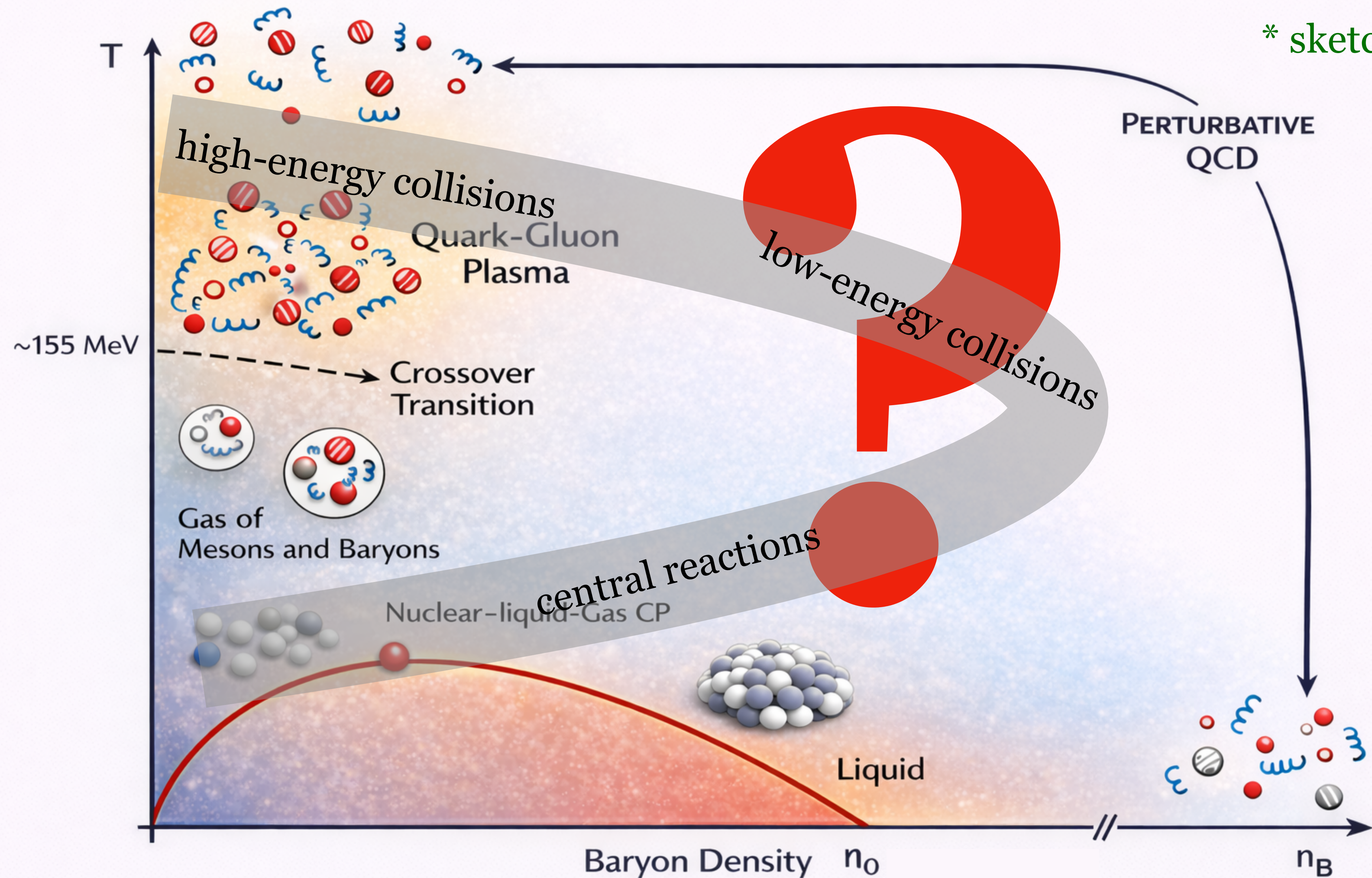
LRP 2015



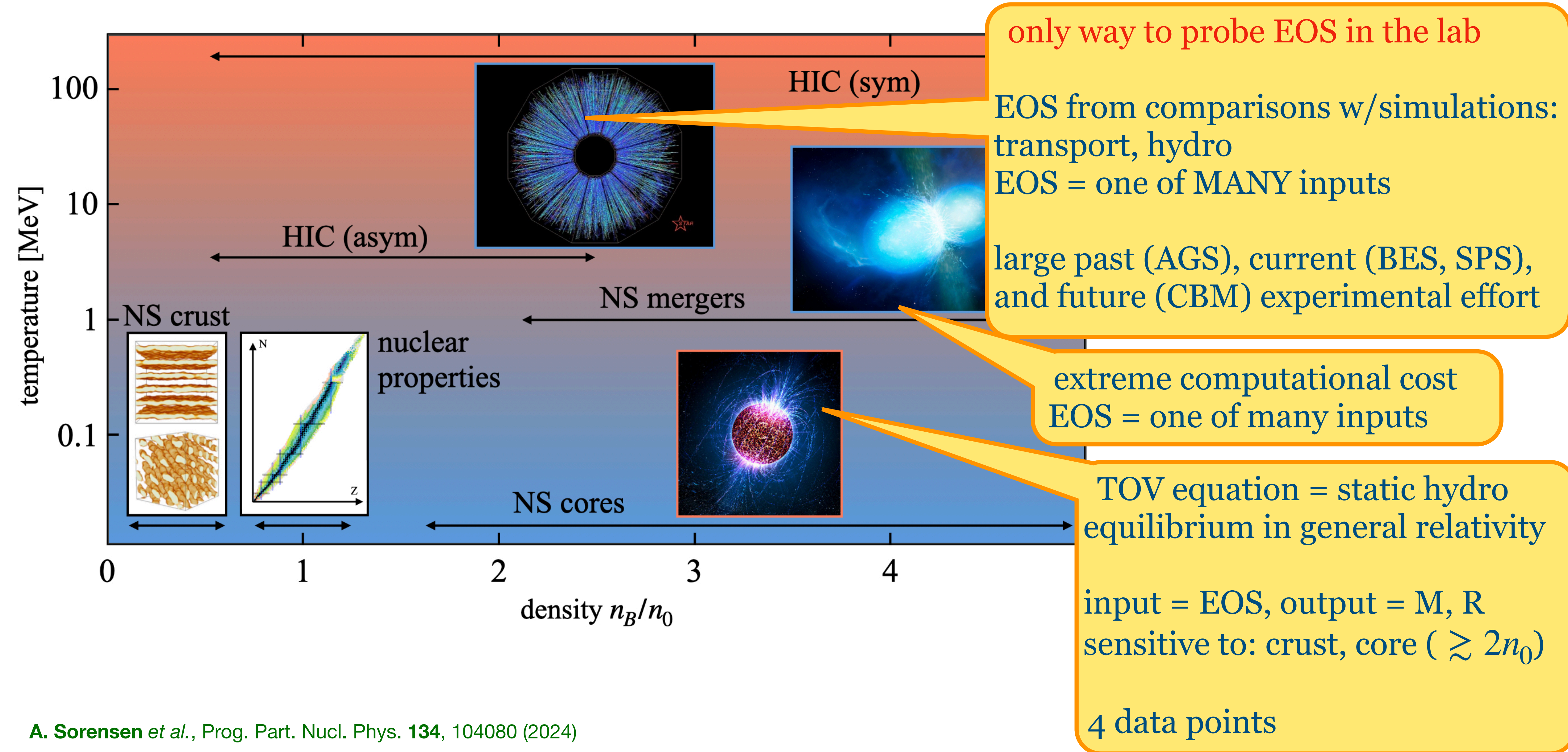
LRP 2023

What do we *really* know about the high density region?*

* sketch (not to scale)



How can we find out about the QCD phase diagram at high density?

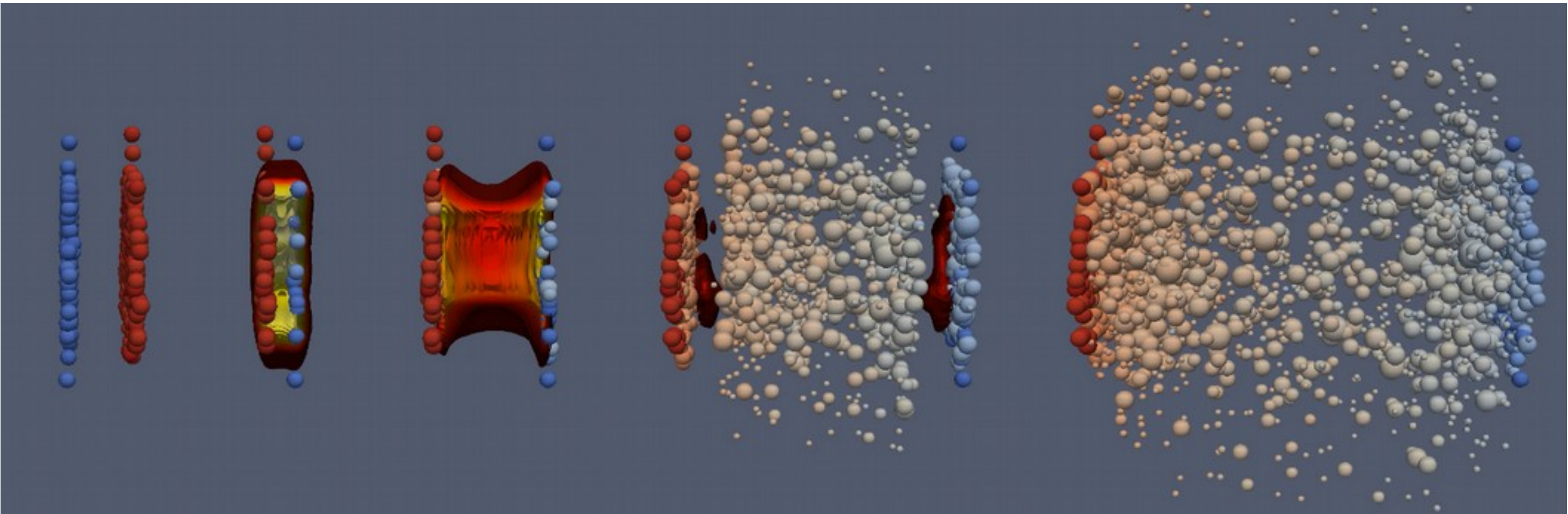


A. Sorensen *et al.*, Prog. Part. Nucl. Phys. **134**, 104080 (2024)

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

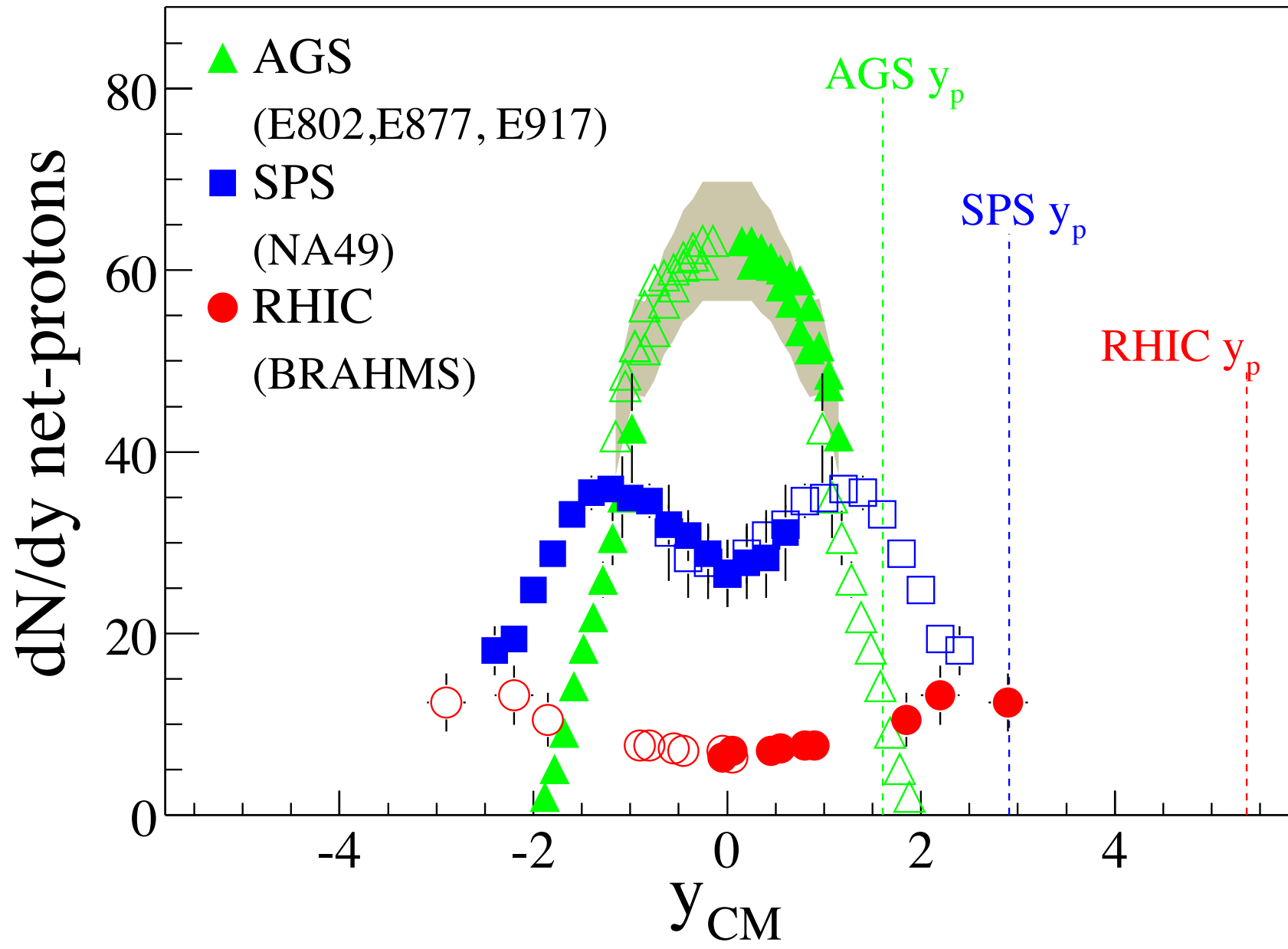
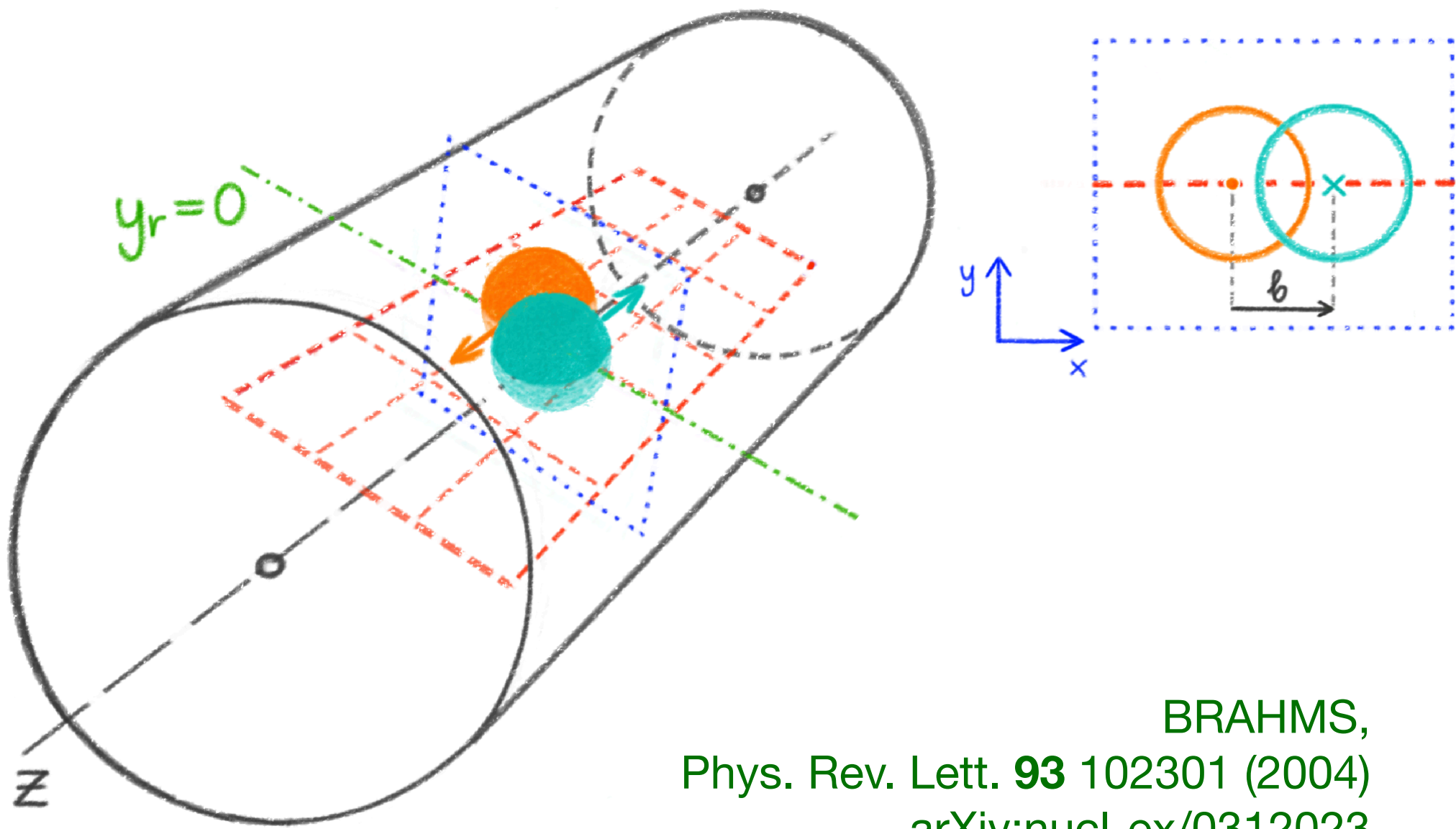
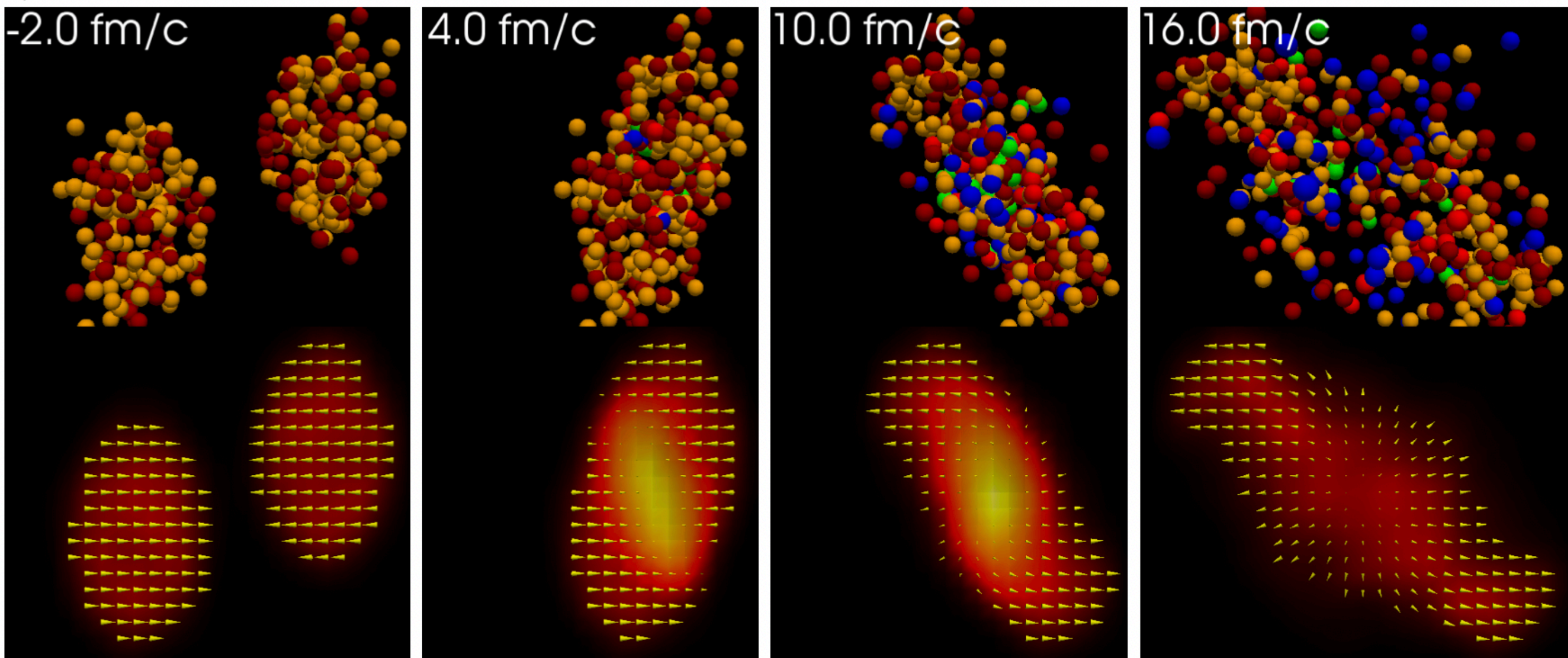
$\sqrt{s_{NN}} = 200 \text{ GeV}$:

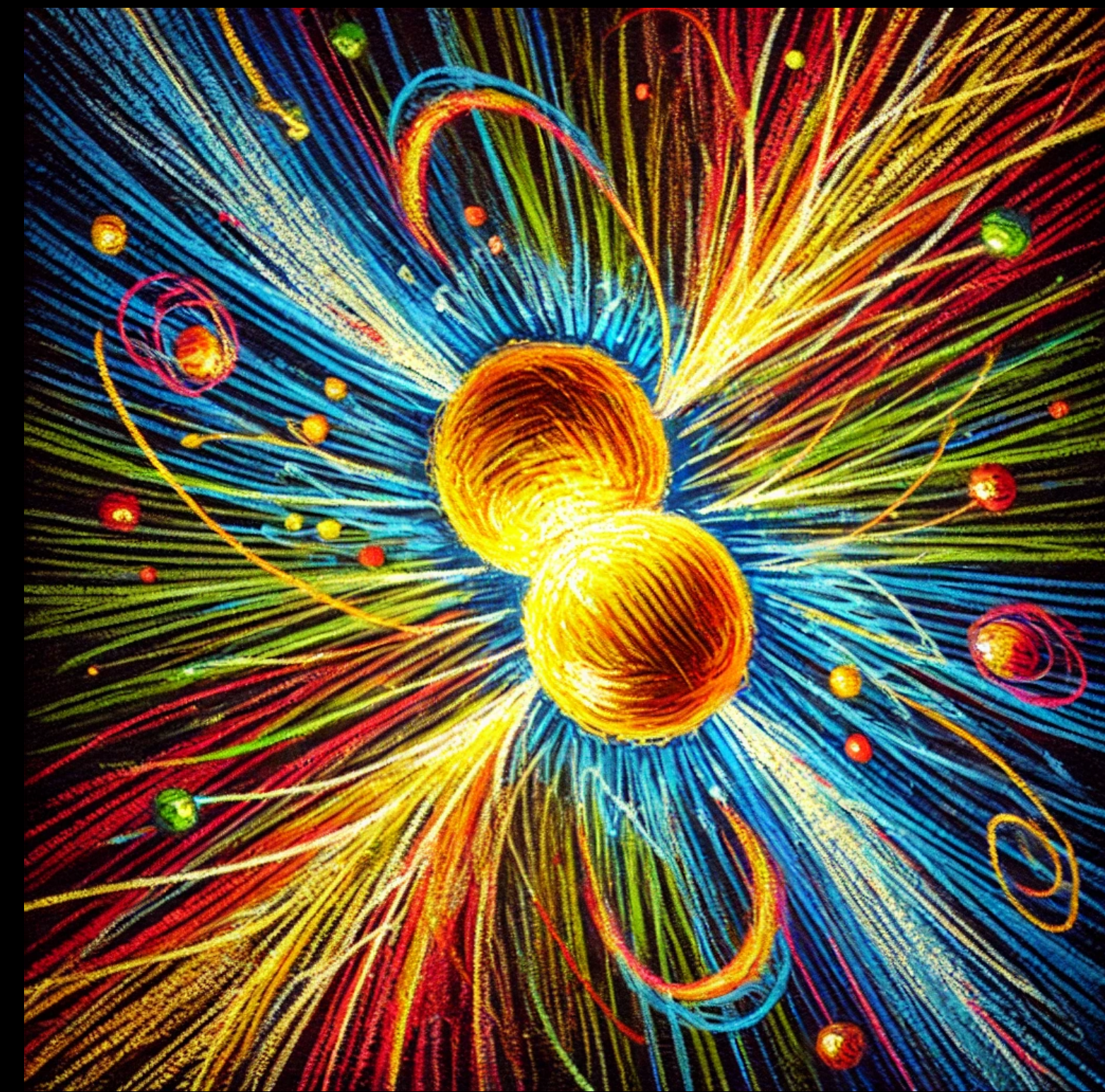
H. Elfner (Petersen), J. Bernhard, MADAI collaboration



$\sqrt{s_{NN}} = 3 \text{ GeV}$:

from D. Oliinychenko's slides

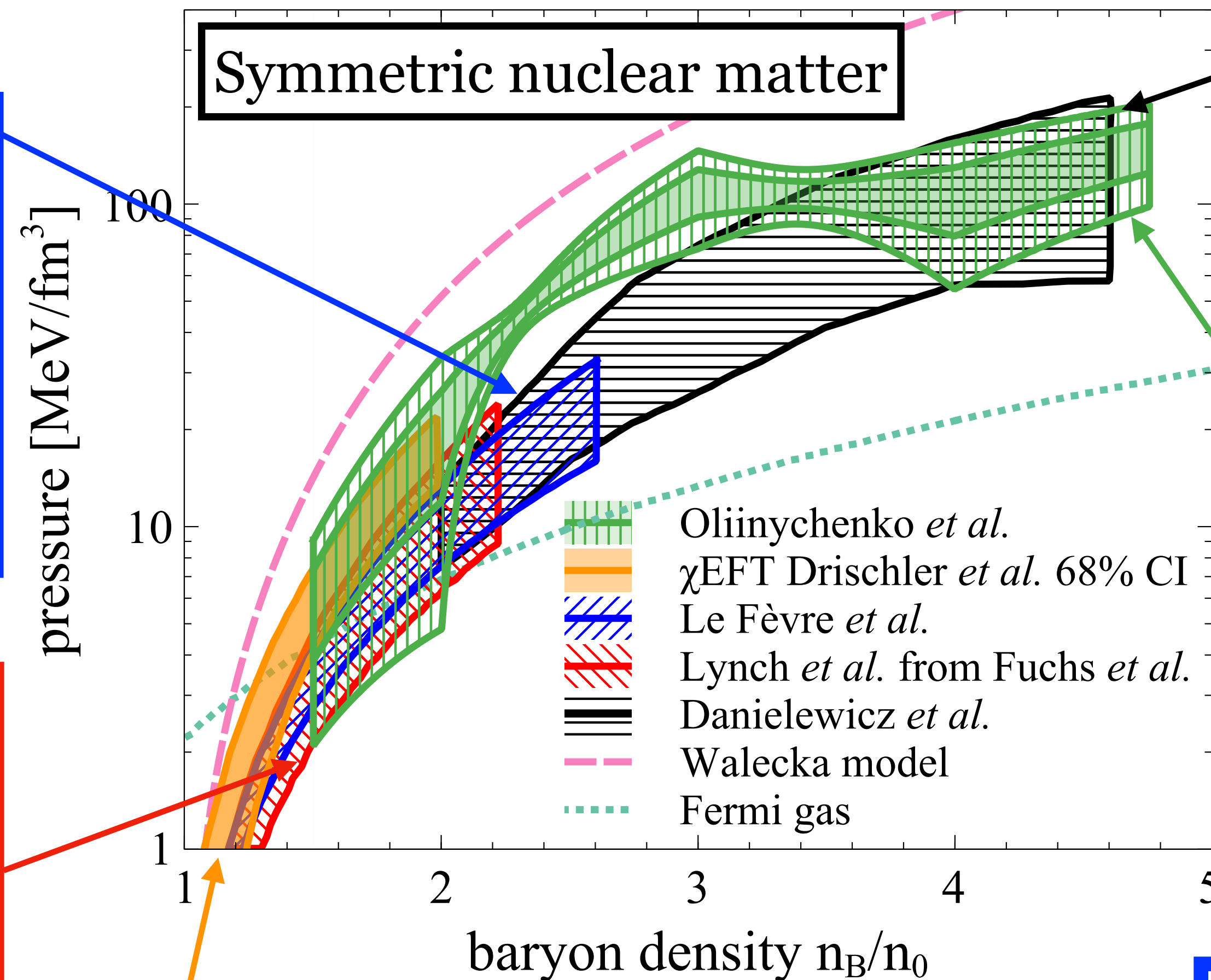




DALL-E

Selected results for the EOS
@ high baryon density

EOS of symmetric nuclear matter: *selected* results



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)

“new” model(s):
comprehensive particle lists
no momentum dependence
variable EOS

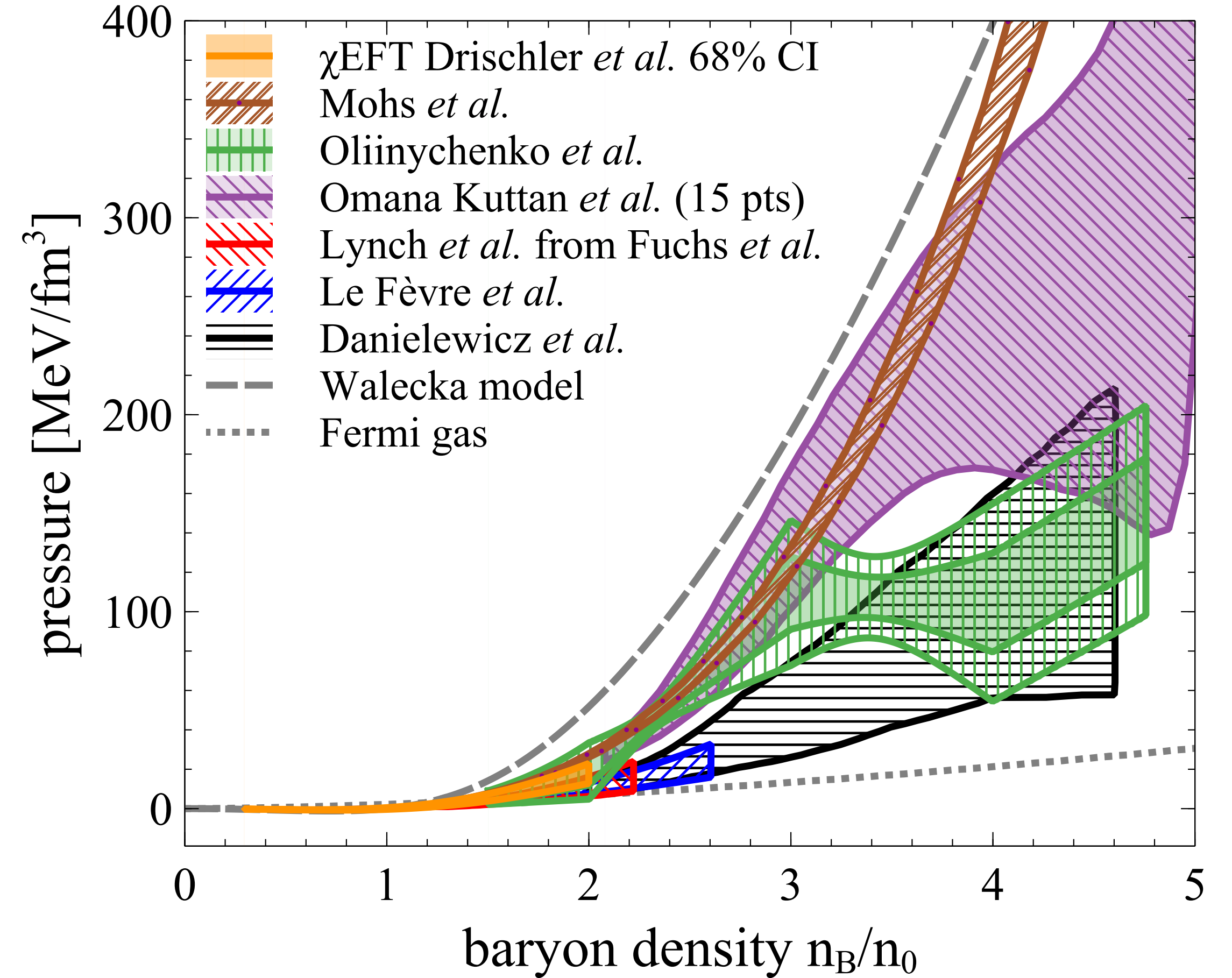
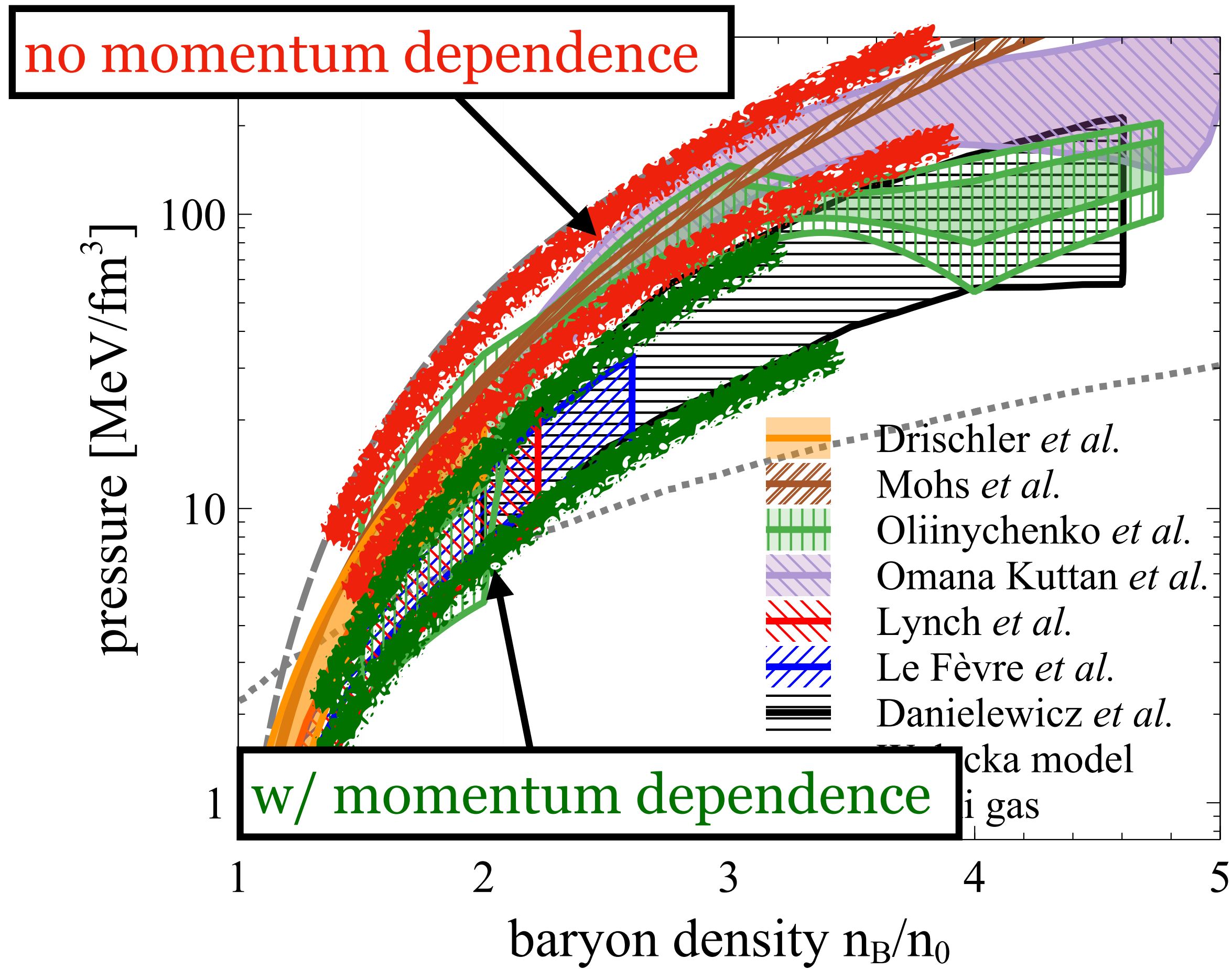
197Au+197Au @ 0.4–1.5 GeV/u
($\sqrt{s_{NN}} = 2.07 - 2.52$ GeV)
observables: proton flow (FOPI)
model used: **isospin QMD (IQMD)** w/
nucleons, Δ , $N^*(1440)$, deuterons, tritons;
EOS parametrized by K_0 ;
momentum dependence
A. Le Fèvre, Y. Leifels, W. Reisdorf, J.
Aichelin, C. Hartnack, Nucl. Phys.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

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

EOS of symmetric nuclear matter: *selected* new results



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

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

J. Mohs, S. Spies, H. Elfner, Phys. Rev. C **112**, 4, 044905 (2025)

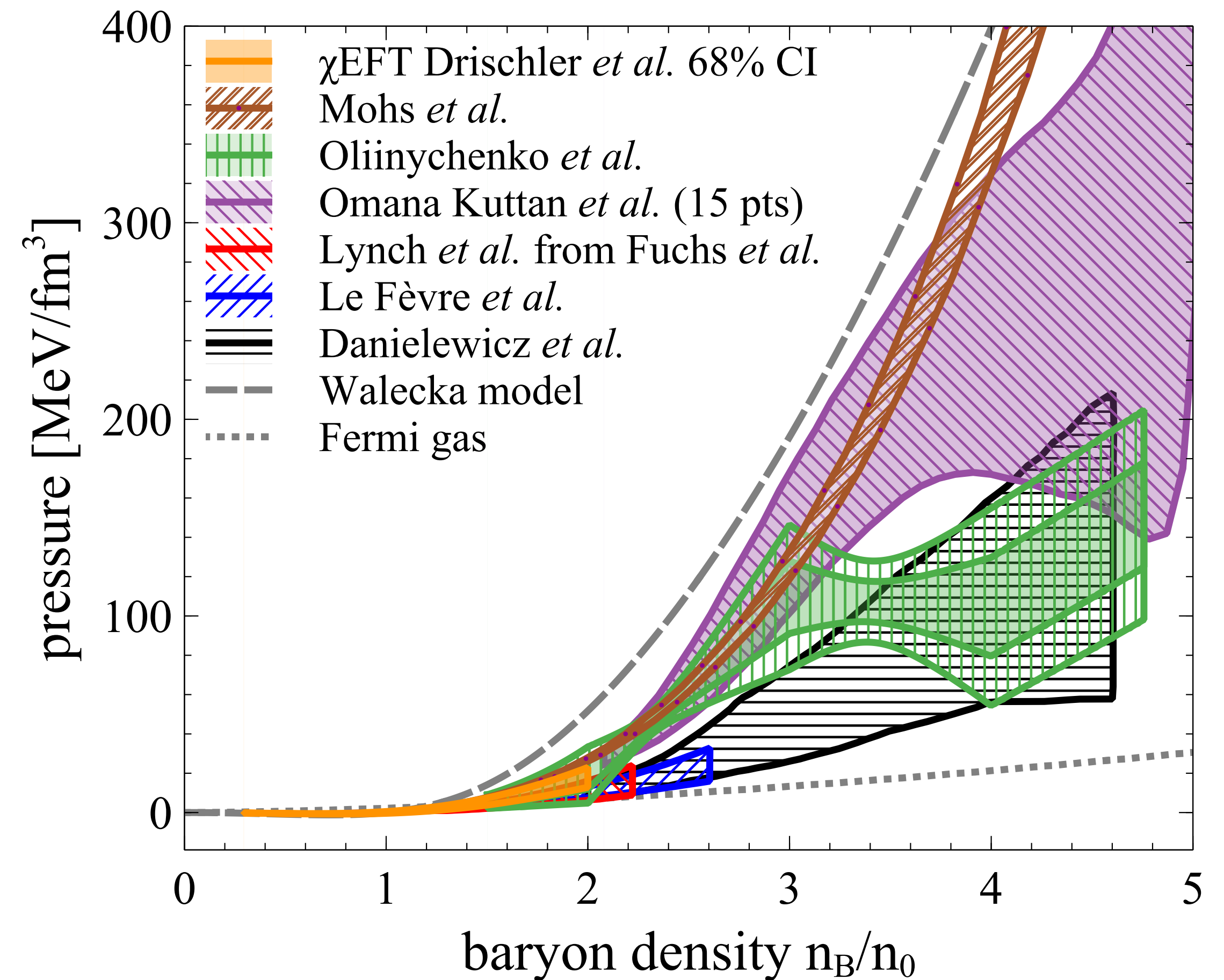
EOS of symmetric nuclear matter: *selected* new results

Results are meaningless without evaluation of model uncertainties

On the other hand, transport:

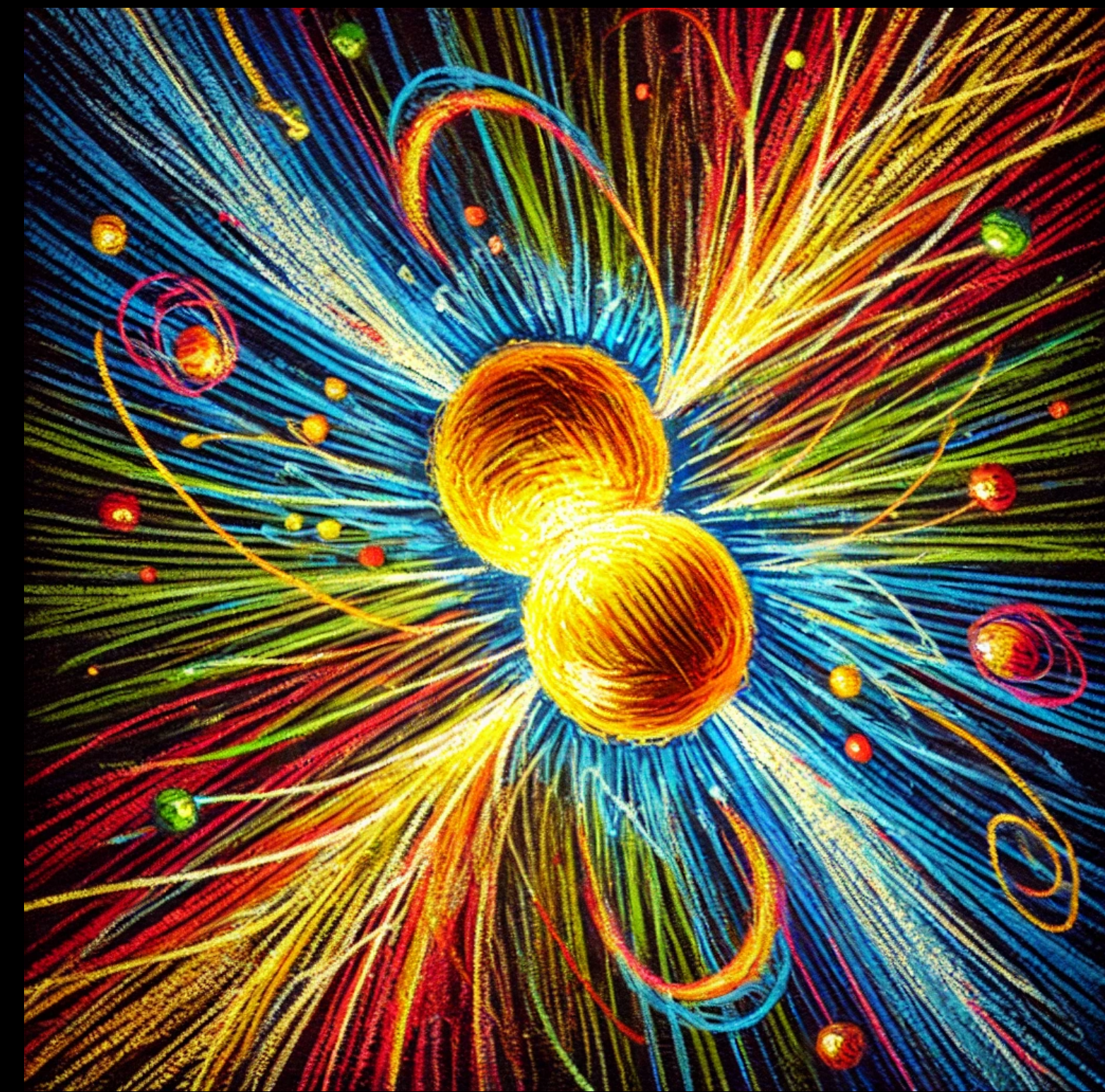
- Has good control of the initial state
- Handles non-equilibrium evolution
- No model interfaces (another source of uncertainty)

To uncover the QCD phase diagram, we need to address the complex physics at high baryon density



“new” model(s):
do not agree

3)
3 (2023)



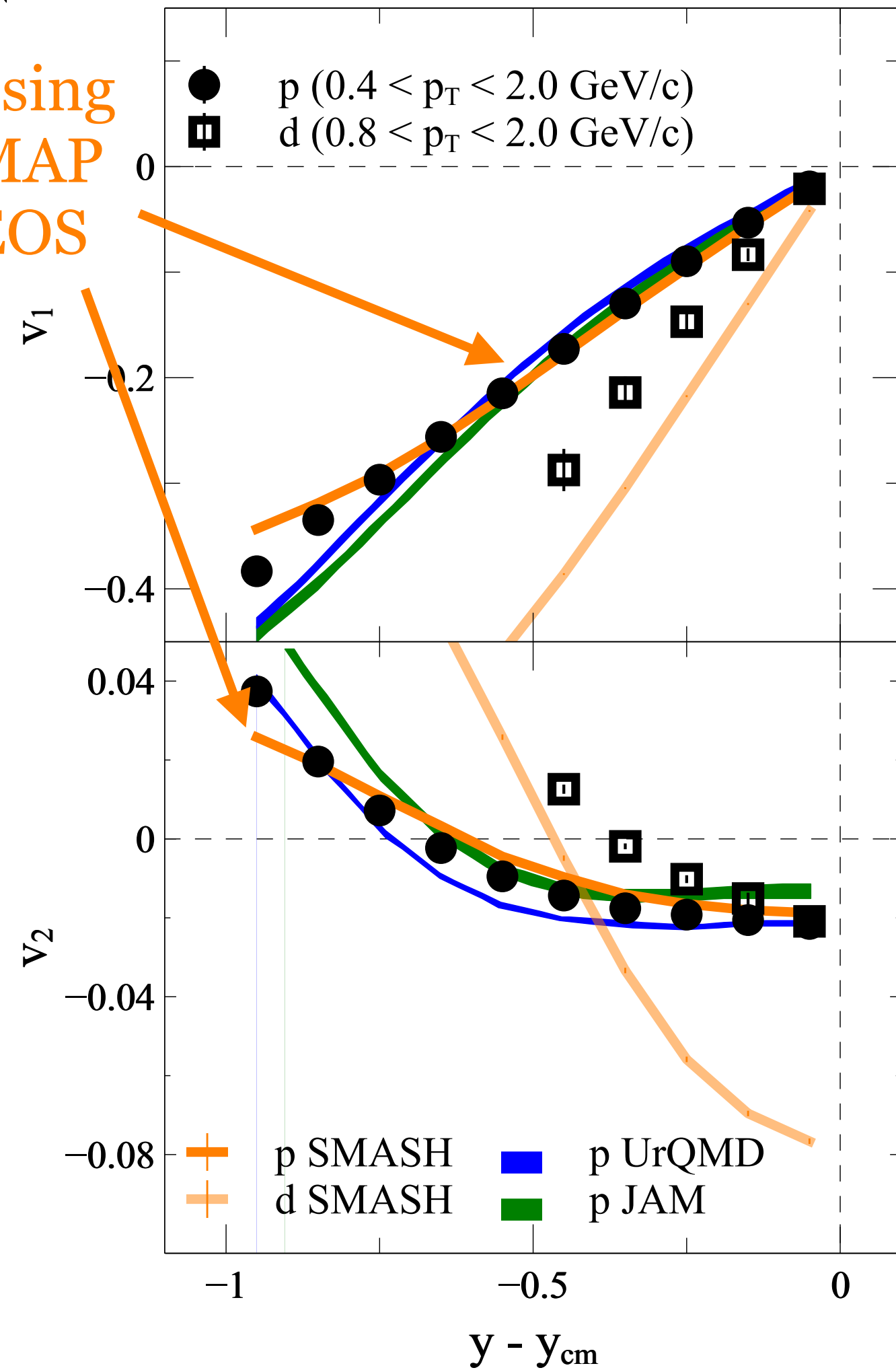
DALL-E

Glimpse of the rich physics
in HICs @ high baryon density

Describing proton flow is not enough: cluster production

$\sqrt{s_{NN}} = 3 \text{ GeV}$

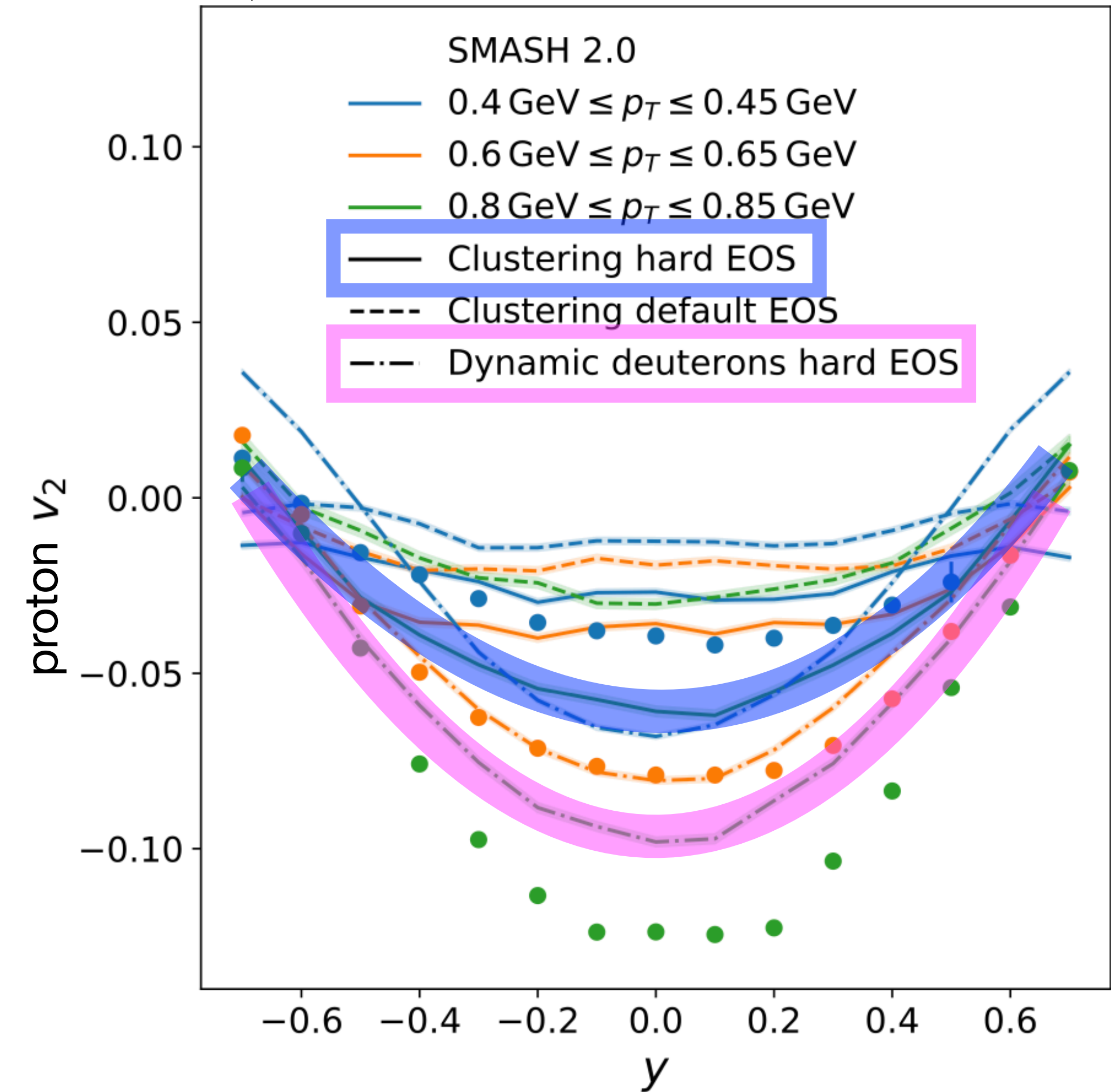
using
MAP
EOS



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

$\sqrt{s_{NN}} = 2.4 \text{ GeV}$



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

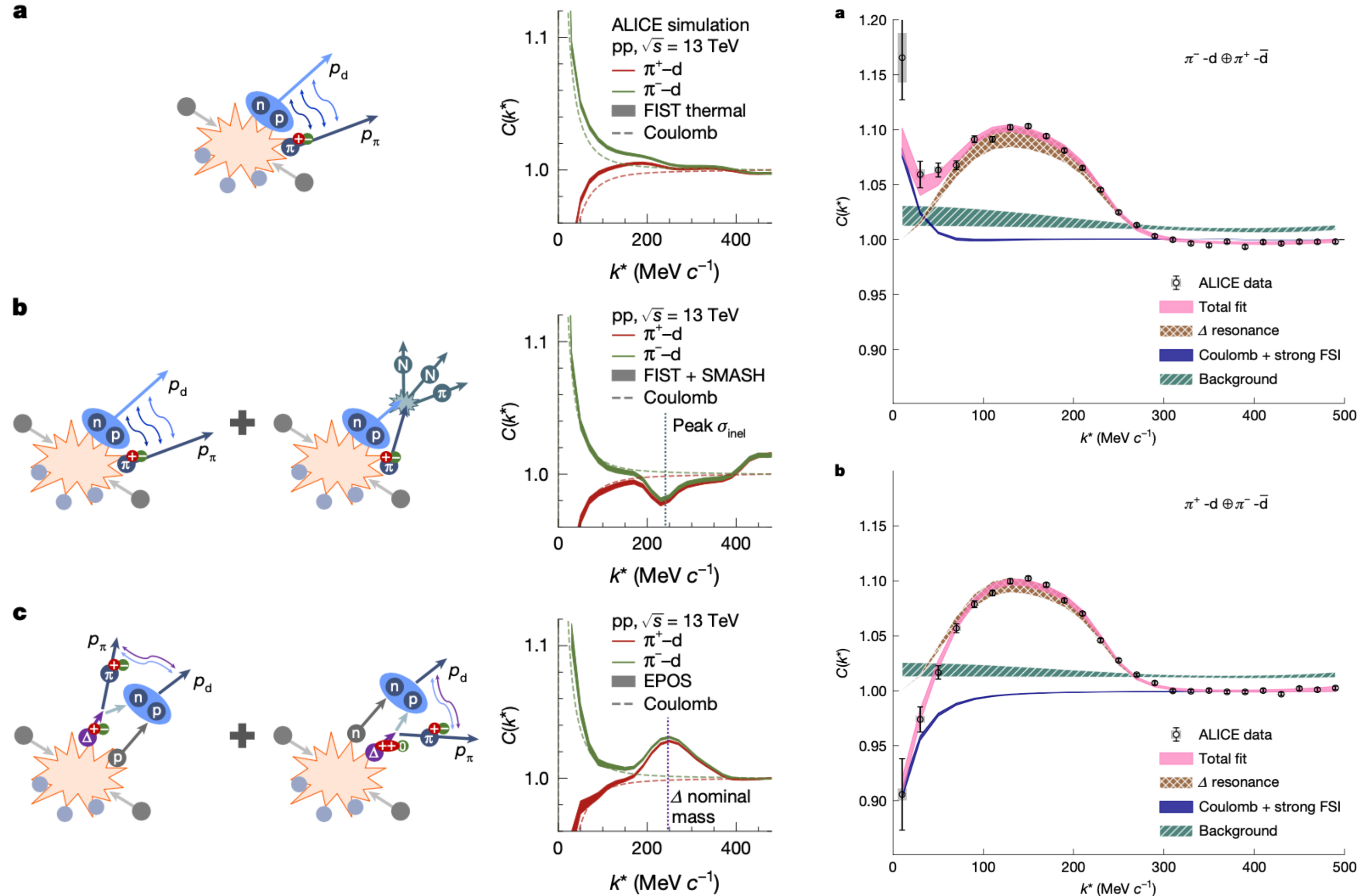
A. Sorensen et al., Prog. Part. Nucl. Phys. **134**, 104080 (2024), arXiv:2301.13253

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

Cluster production is a long-standing mystery

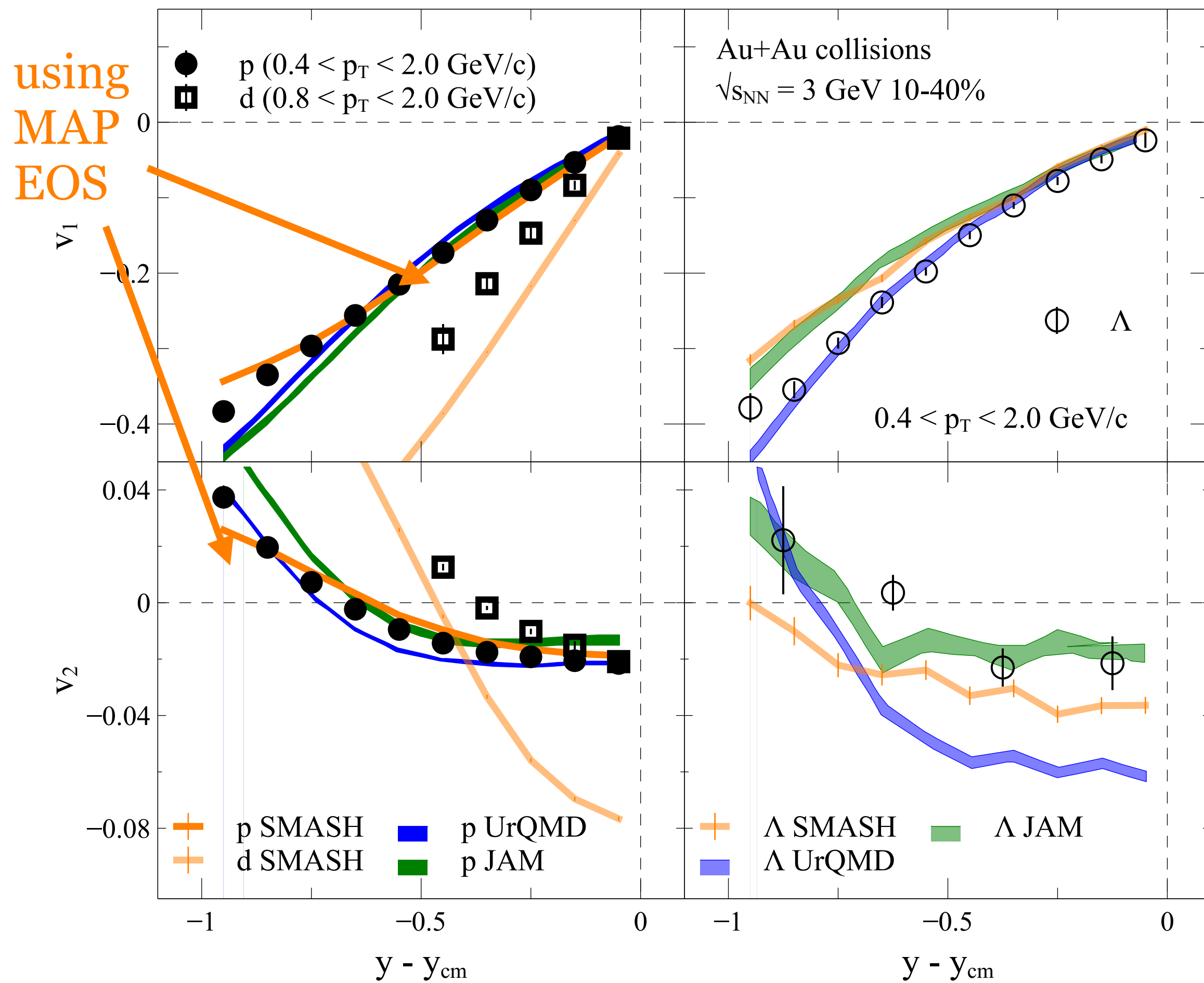
Femtoscopy: **ALICE, Nature **648**, 8093, 306-311 (2025)**

~90% of deuterons form in resonance-induced coalescence



Study at BES energies?

Describing proton flow is not enough: strange sector



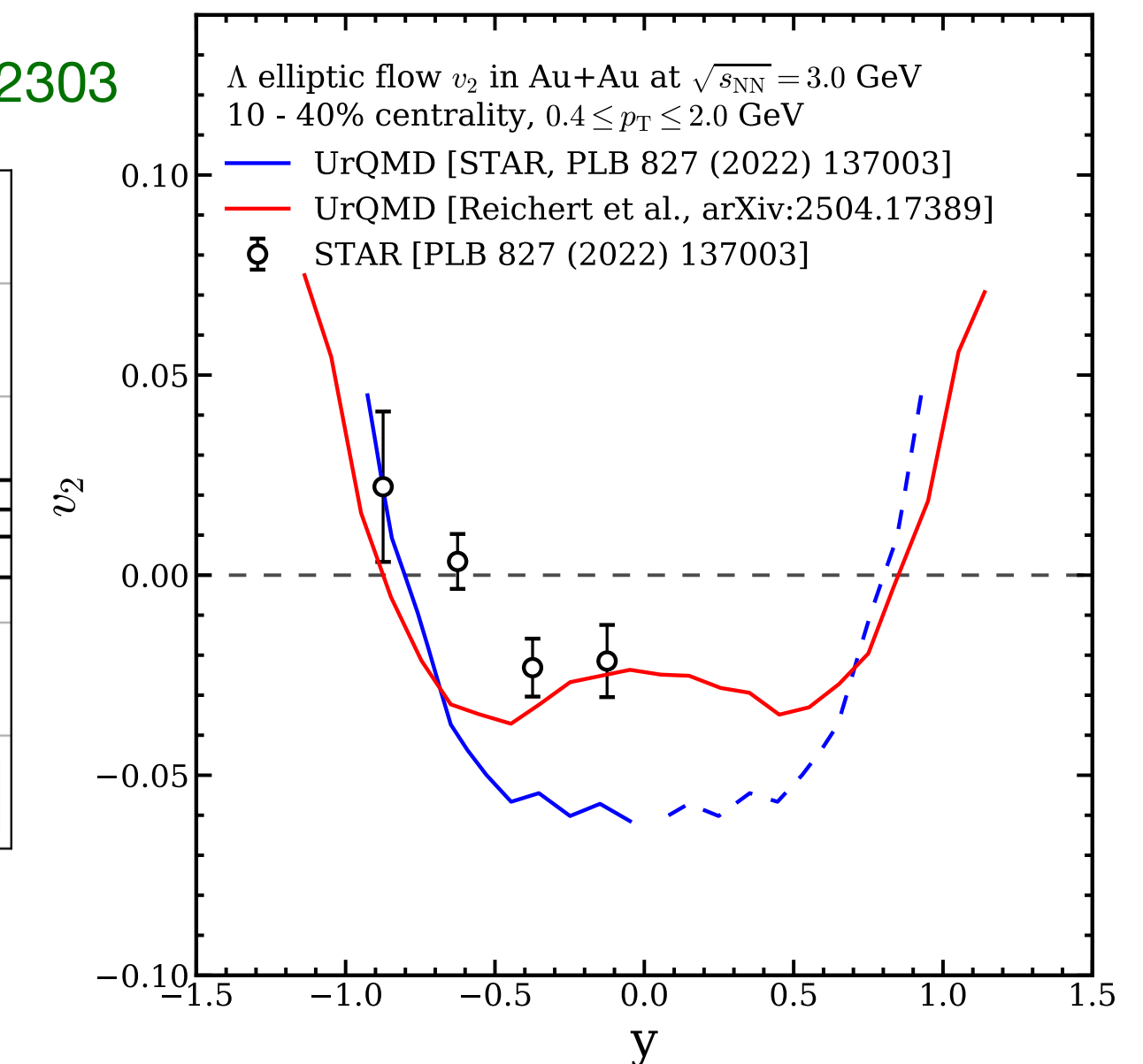
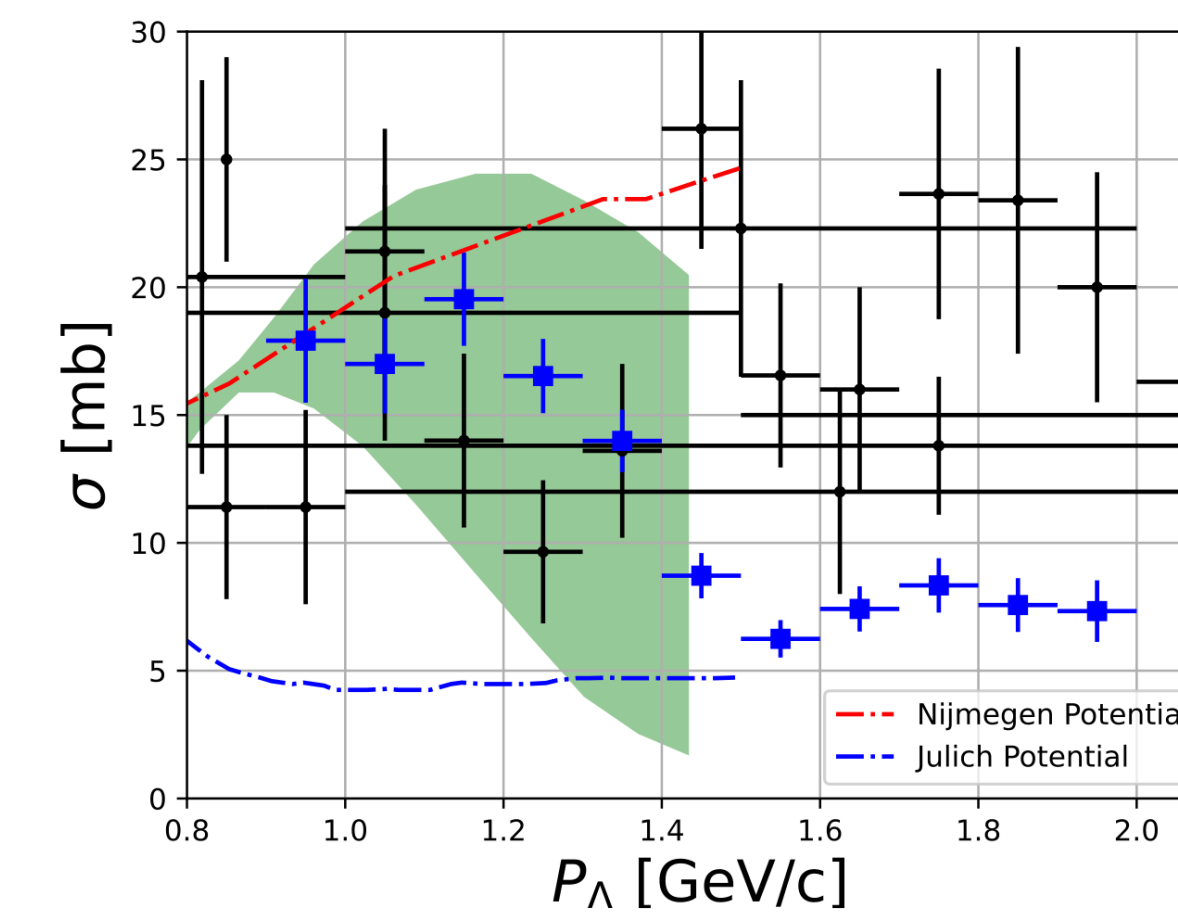
Strange baryons are not well described — why?

- N-hyperon and hyperon-hyperon interactions?
- in-medium modifications of interactions?

Models of interactions exist and could be tested;
interactions from first-principle calculations?
(e.g., HALQCD collaboration)

HAL QCD, Nucl. Phys. A **998** 121737 (2020)

CLAS, Phys. Rev. Lett. **127** (2021) 27, 272303



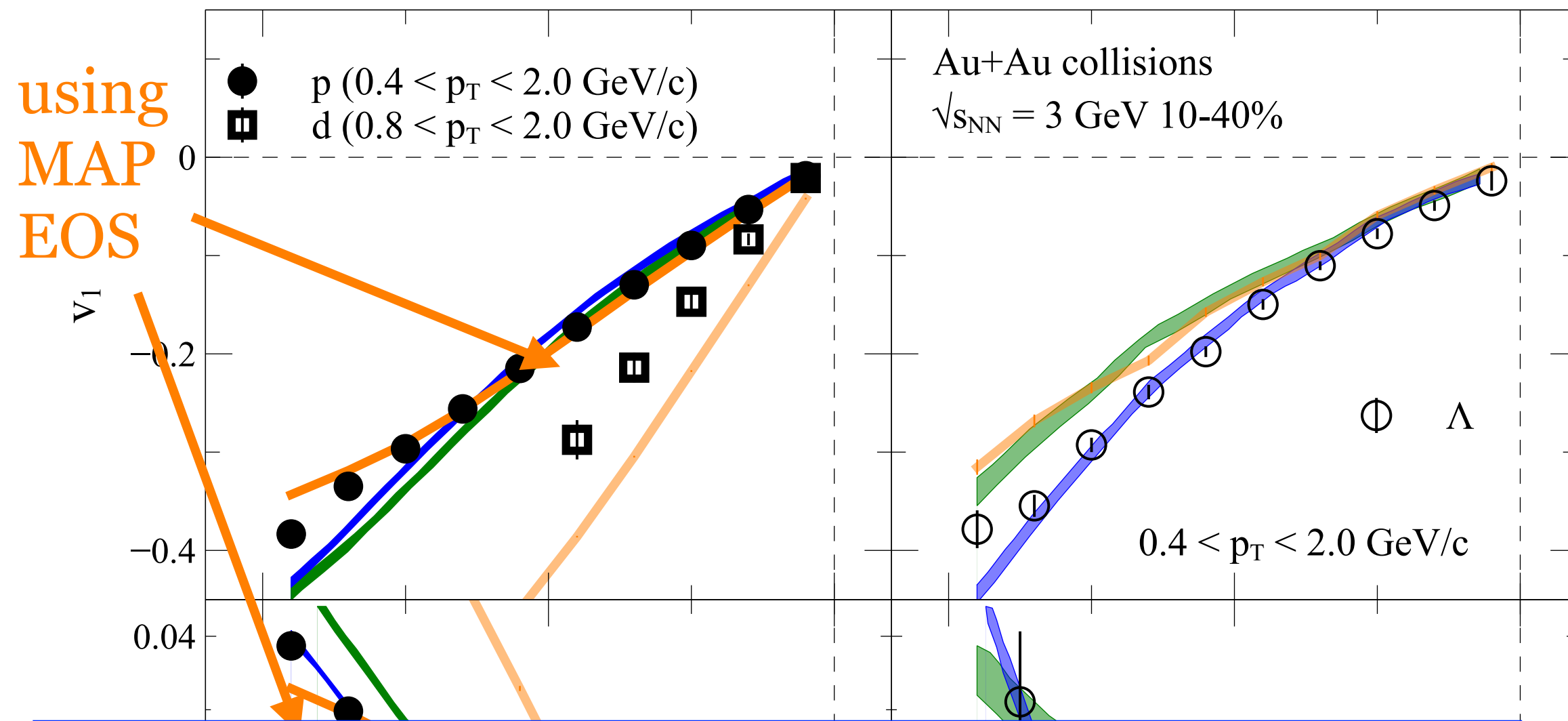
T. Reichert *et al.*, Phys. Rev. C **112**, 6, 064909 (2025)

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

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

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

Describing proton flow is not enough: strange sector



Where cross sections for elementary processes are not available (*most* hadronic species!),
dN/dy measurements help constrain models

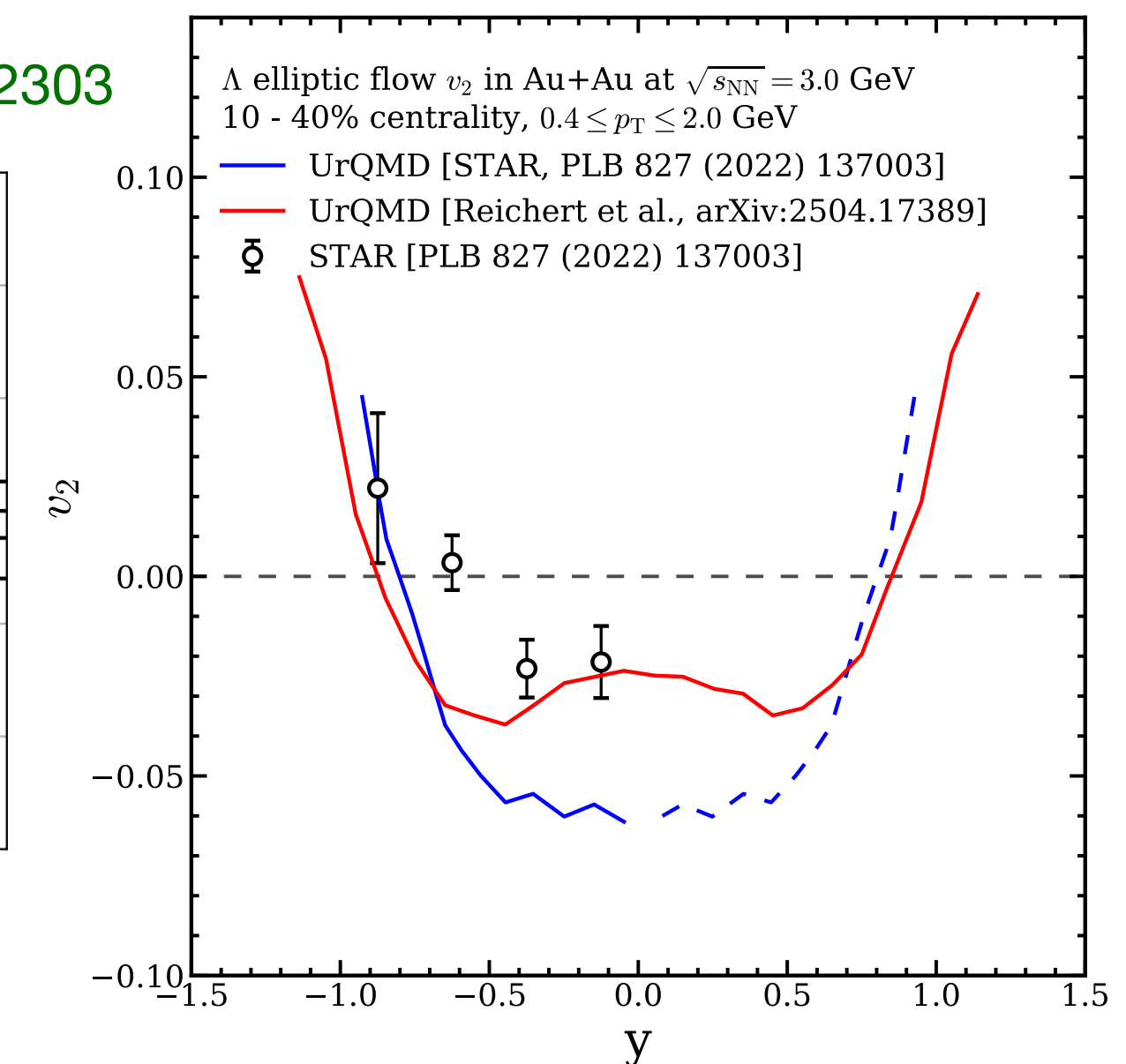
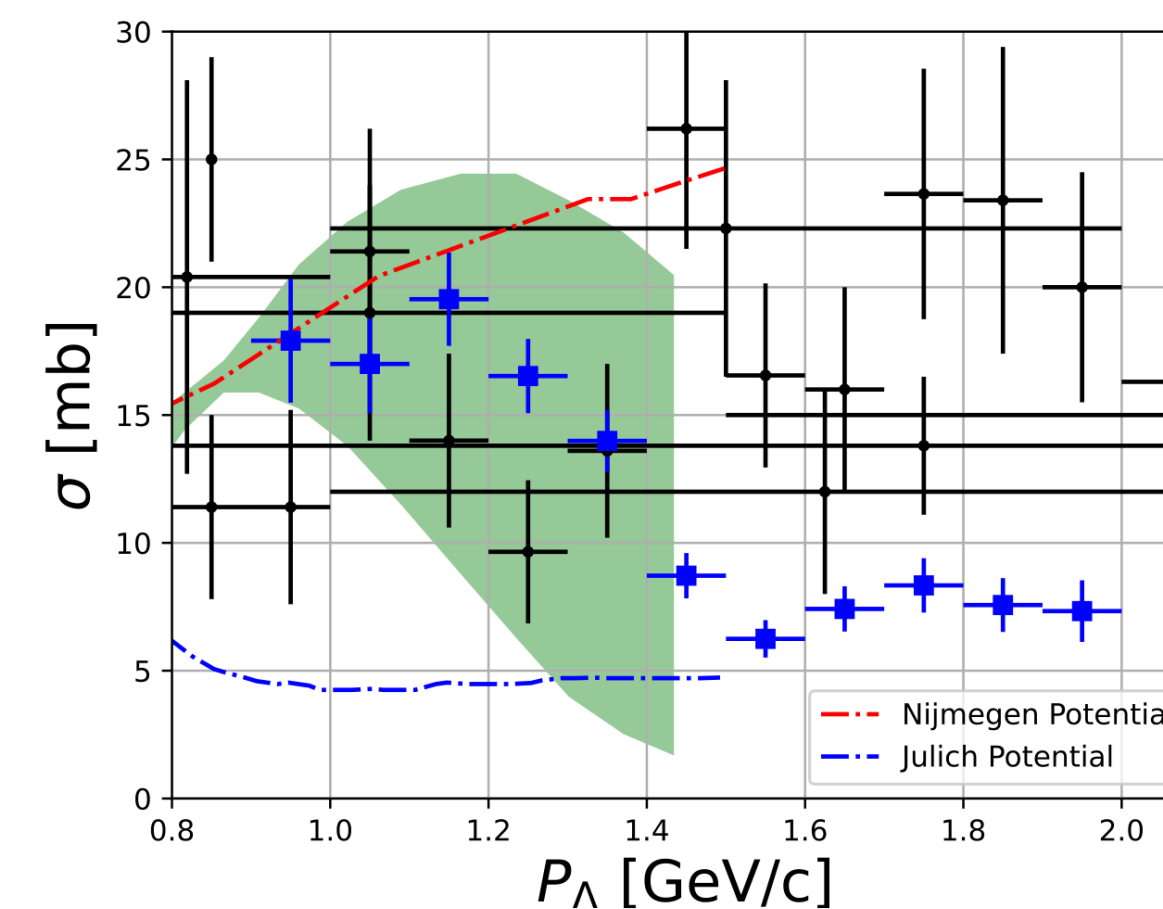
Strange baryons are not well described — why?

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HAL QCD, Nucl. Phys. A **998** 121737 (2020)

CLAS, Phys. Rev. Lett. **127** (2021) 27, 272303



T. Reichert *et. al.*, Phys. Rev. C **112**, 6, 064909 (2025)

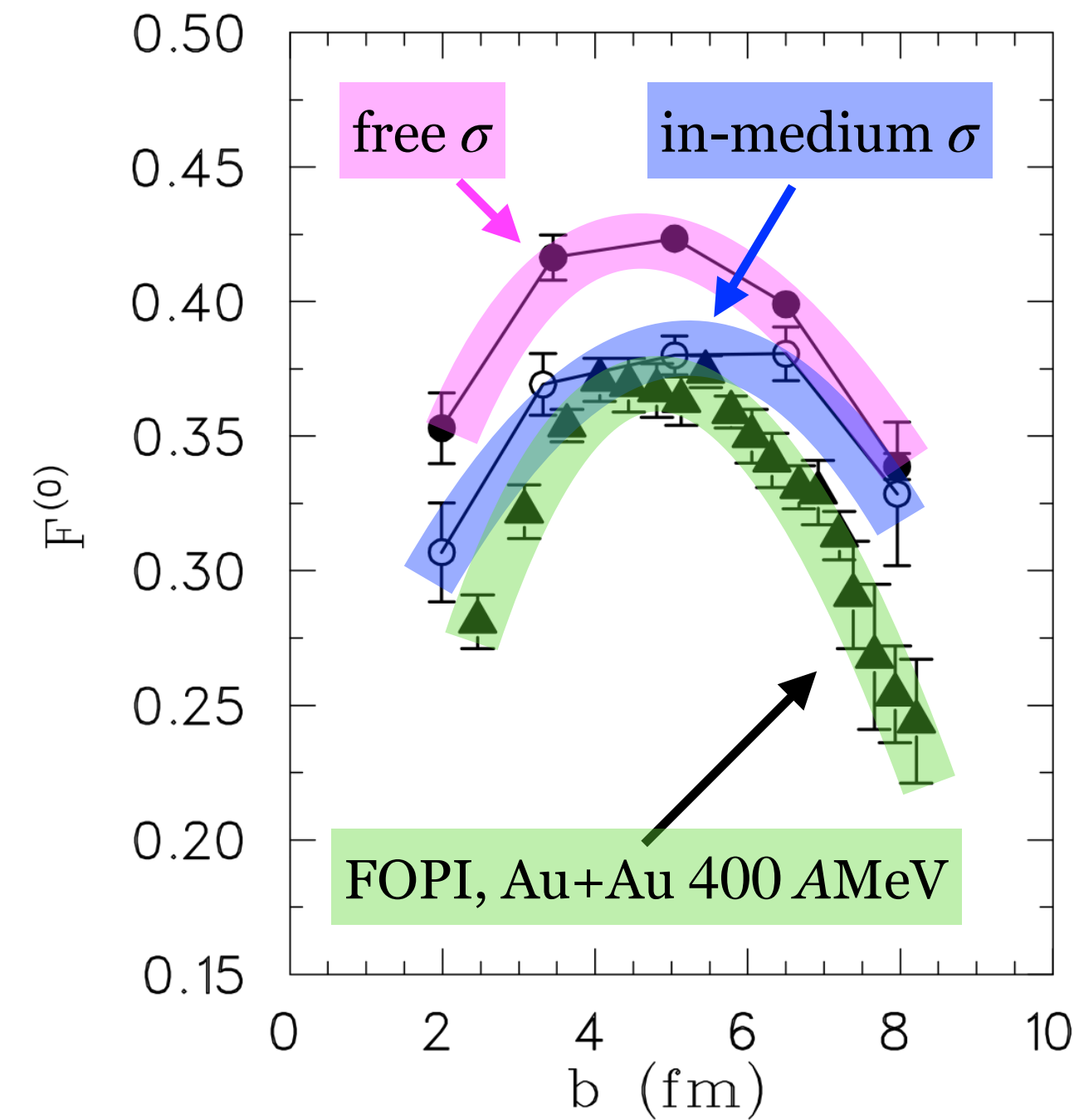
STAR, Phys. Lett. B **827**, 137003 (2022)

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

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

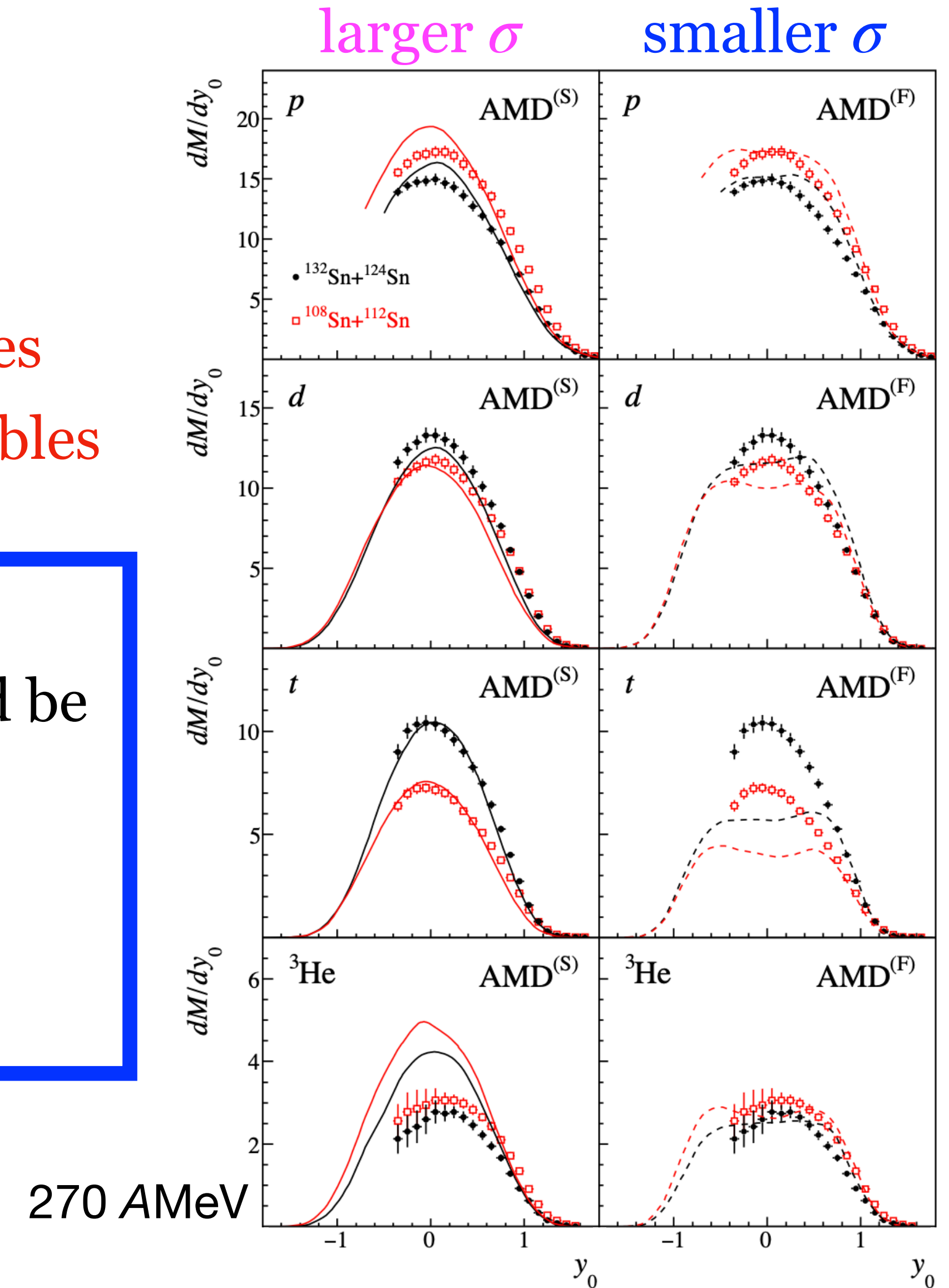
In-medium scattering cross-sections

- 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**
- $S\pi$ RIT experiment data indicate in-medium σ 's **need further studies**
- particle-particle scatterings contribute **$\approx 30\text{-}50\%$ to flow observables**

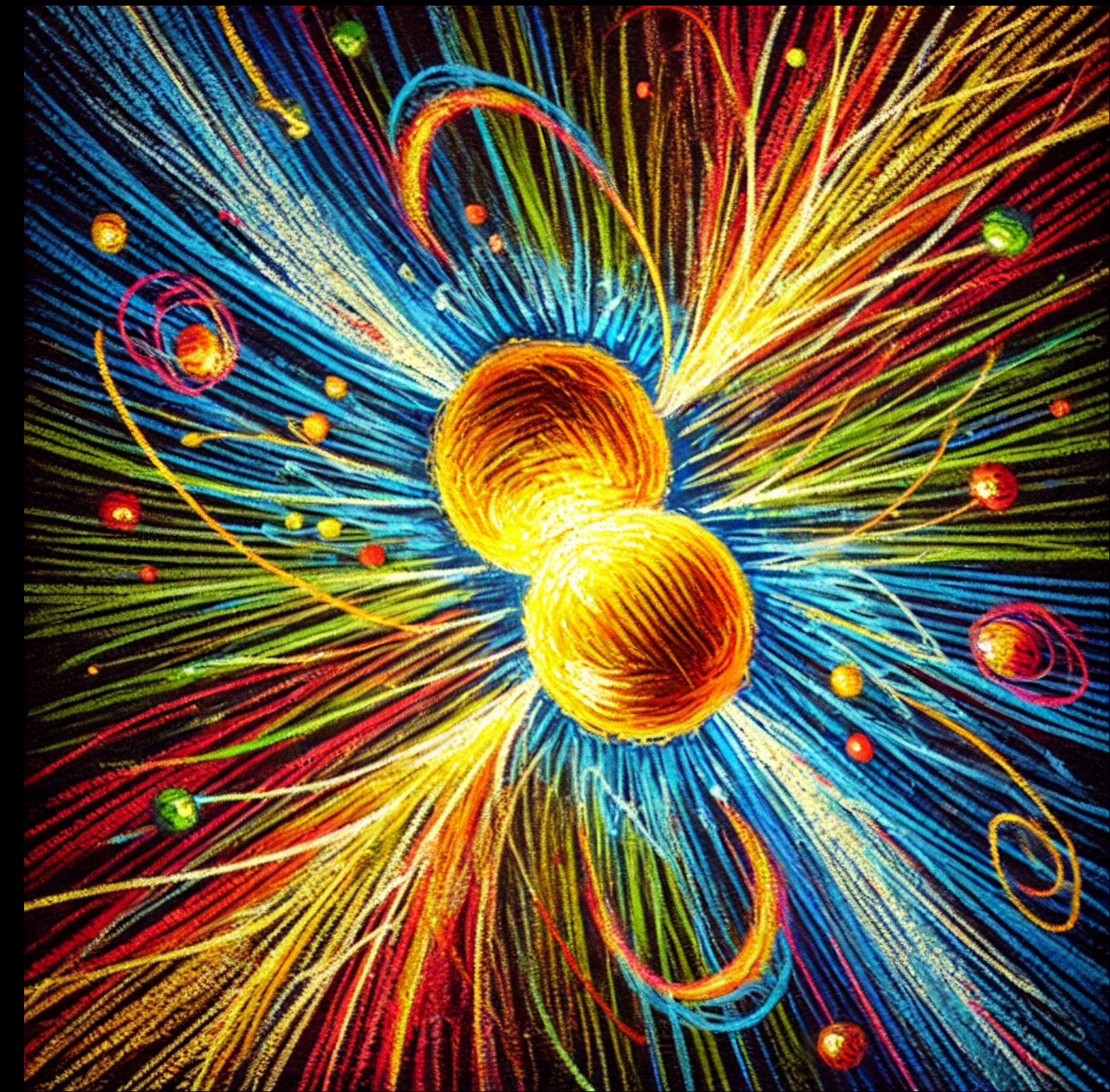


D. Persram, C. Gale, Phys. Rev. C **65**, 064611 (2002), arXiv:nucl-th/0111035

- 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

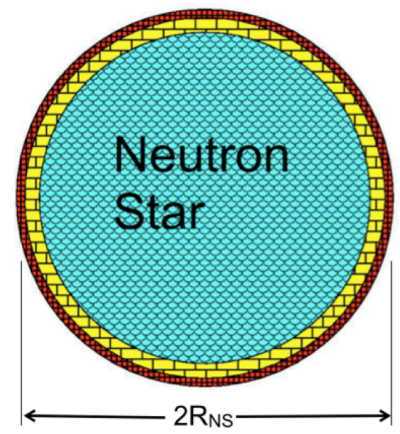


DALL-E

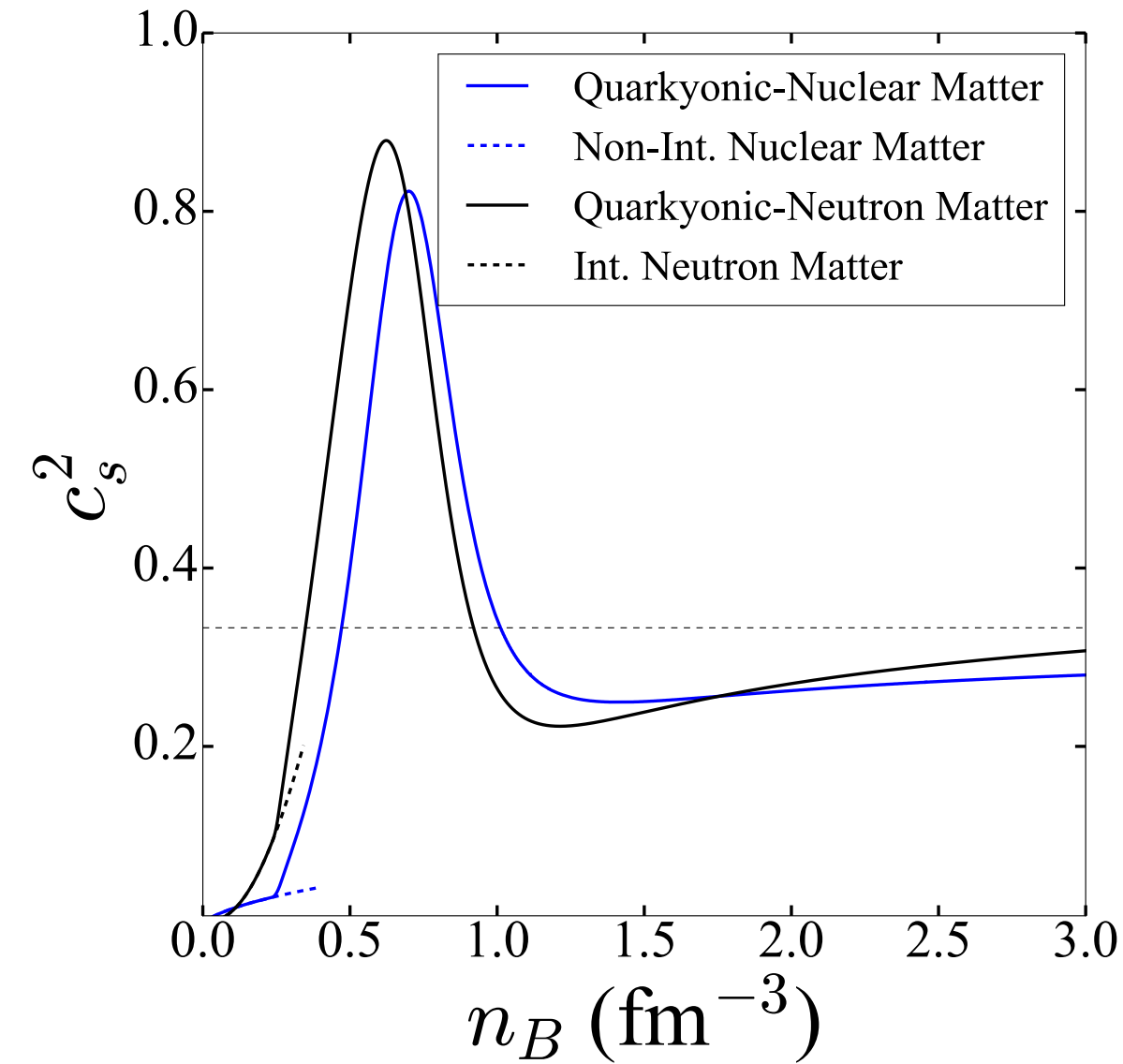
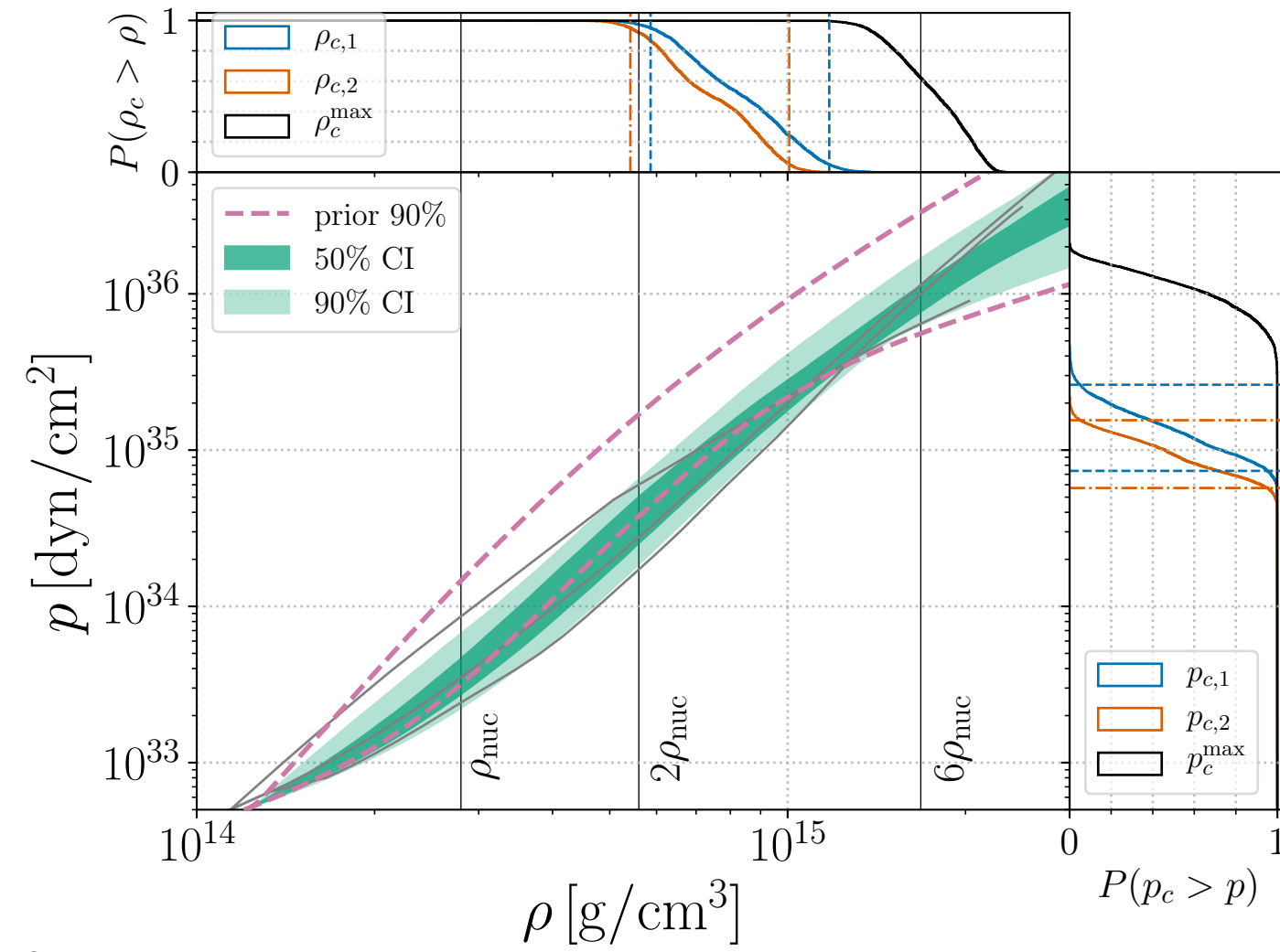
QCD phase diagram @ high density:
what do we know from neutron stars?

Results from analyses of astrophysical observations

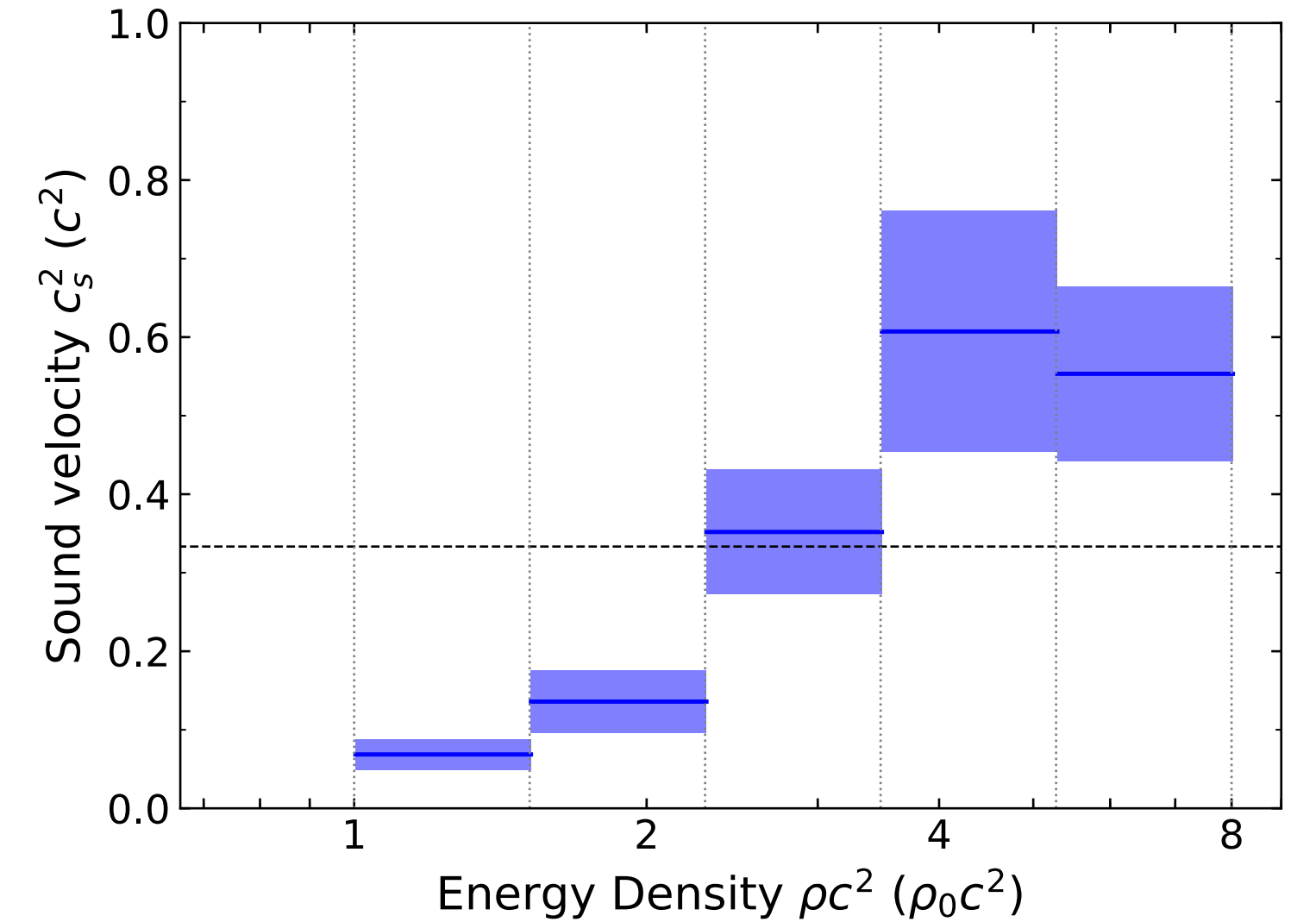
Are these results compatible with HIC data?



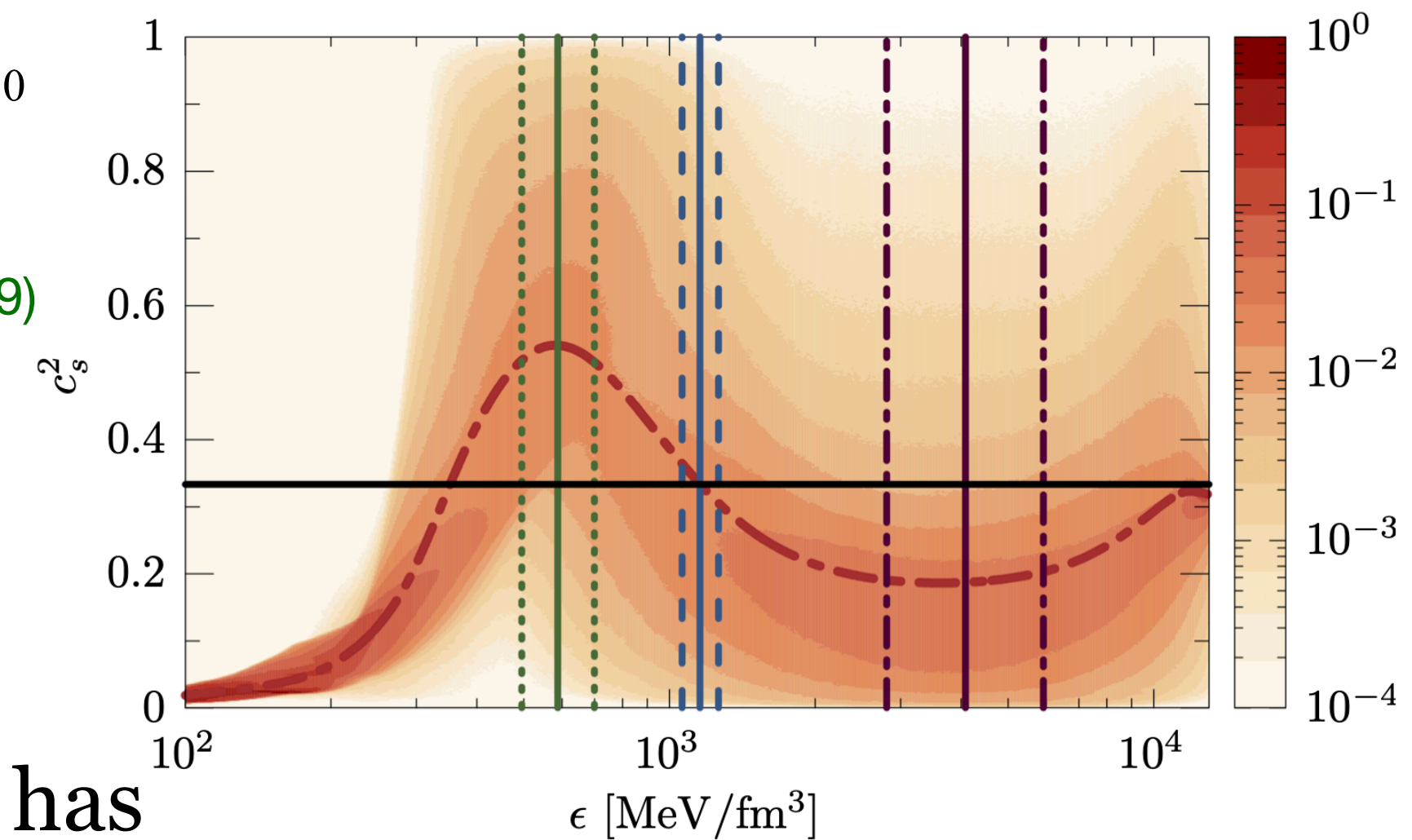
LIGO, Phys. Rev. Lett. **121** 16, 161101 (2018)



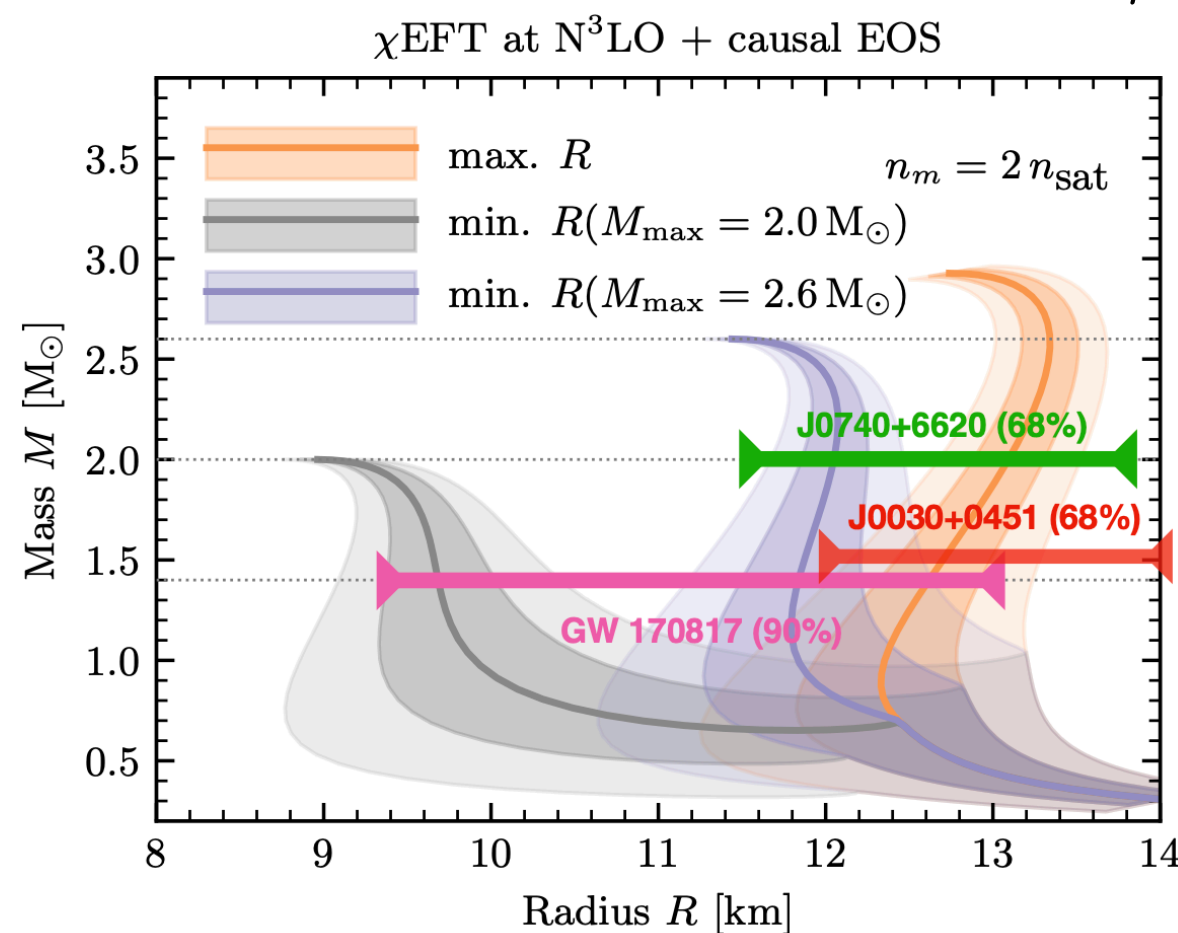
L. McLerran and S. Reddy,
Phys. Rev. Lett. **122**, no.12, 122701 (2019)



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



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

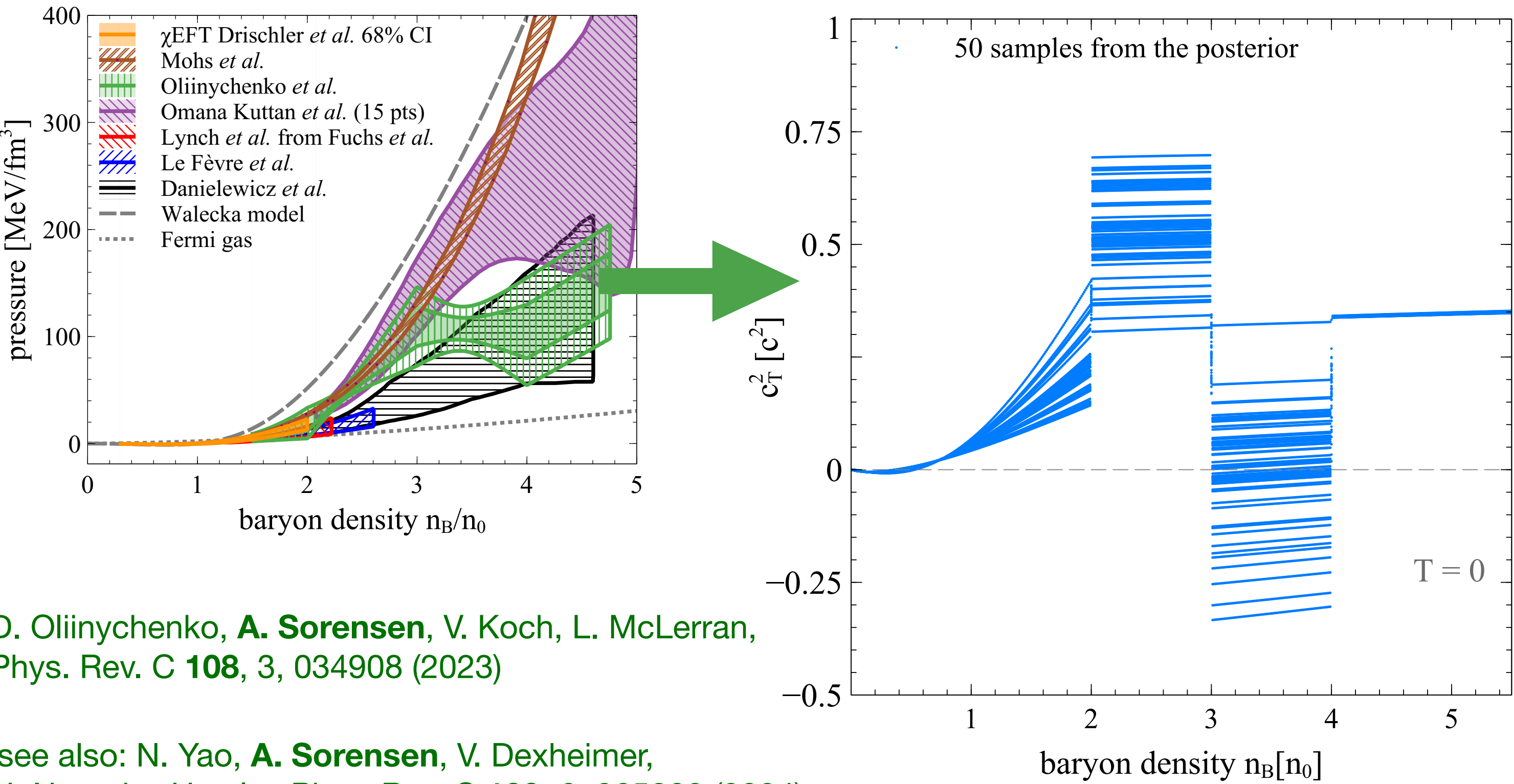


* from S. Reddy's
slides; M-R results:
C. Drischler *et al.*,
Phys. Rev. C **103** 4,
045808 (2021)

Recent astrophysical
measurements suggest NS EOS has
a nontrivial density-dependence

Results from analyses of astrophysical observations

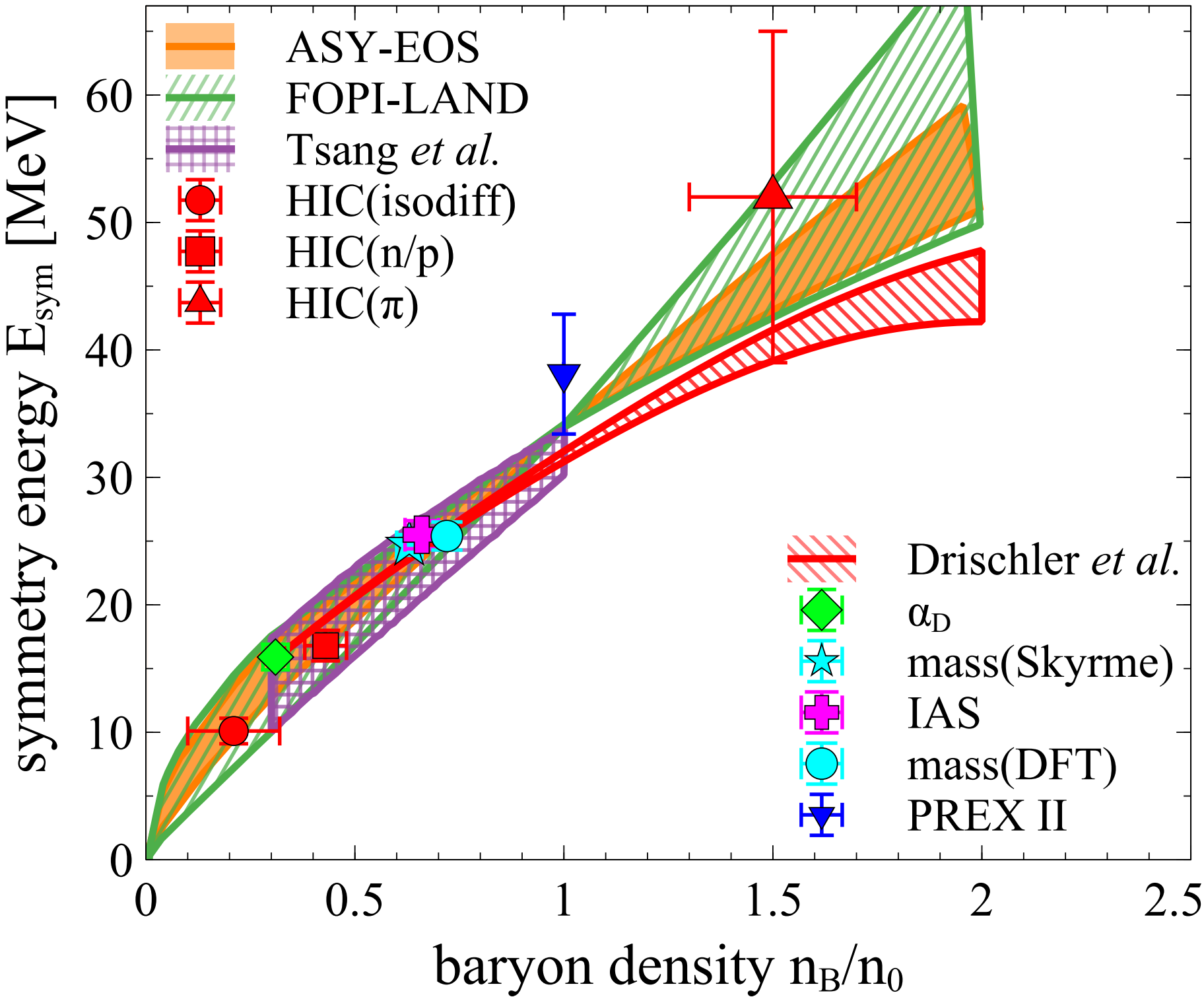
Are these results compatible with HIC data?



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

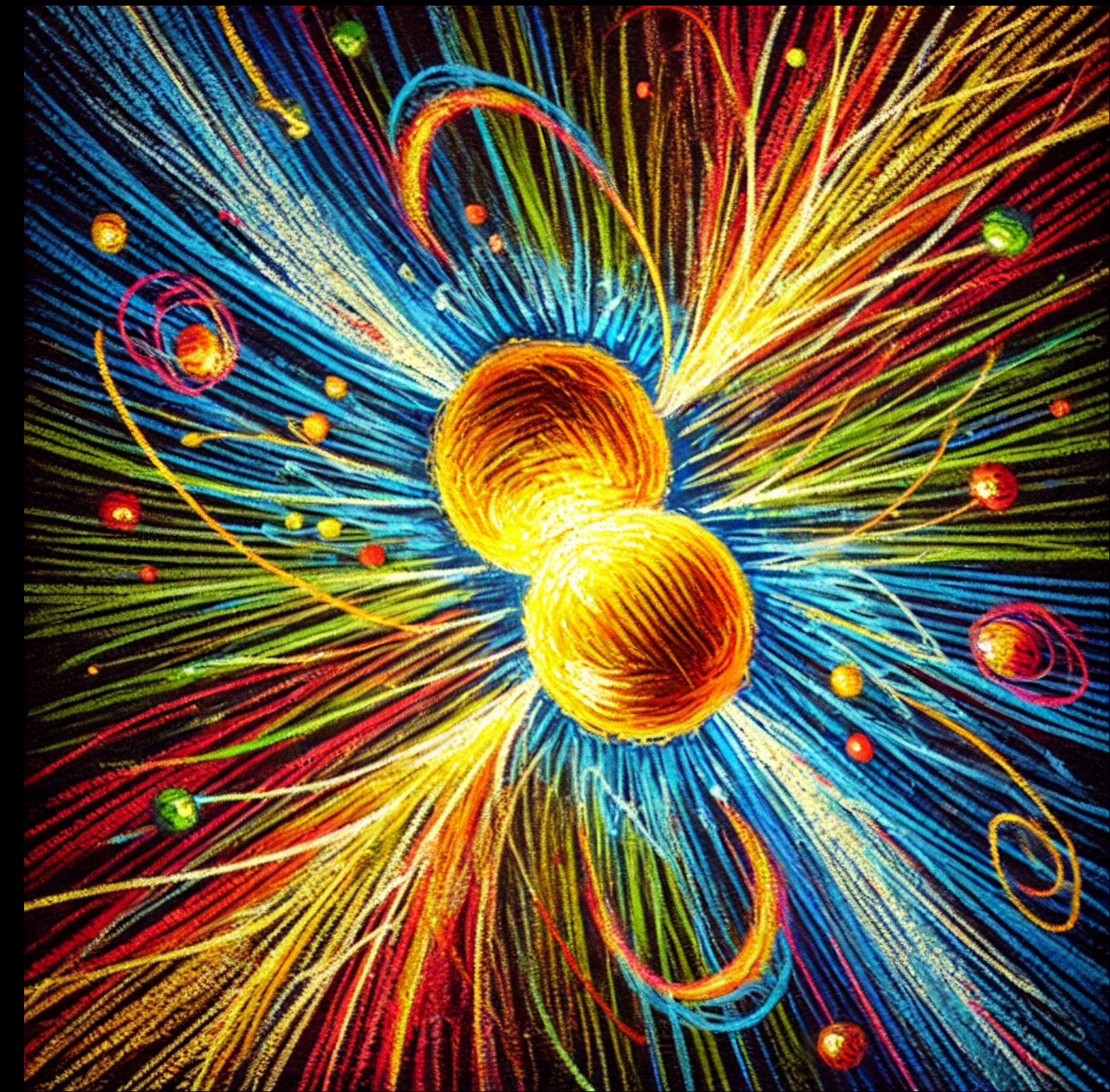
see also: N. Yao, **A. Sorensen**, V. Dexheimer, J. Noronha-Hostler, Phys. Rev. C **109**, 6, 065803 (2024)

Modeling of experiments at RIB facilities is key



Connecting HICs to NSs needs isospin dependence

Are there HIC observables constraining isospin-dependence at higher densities?

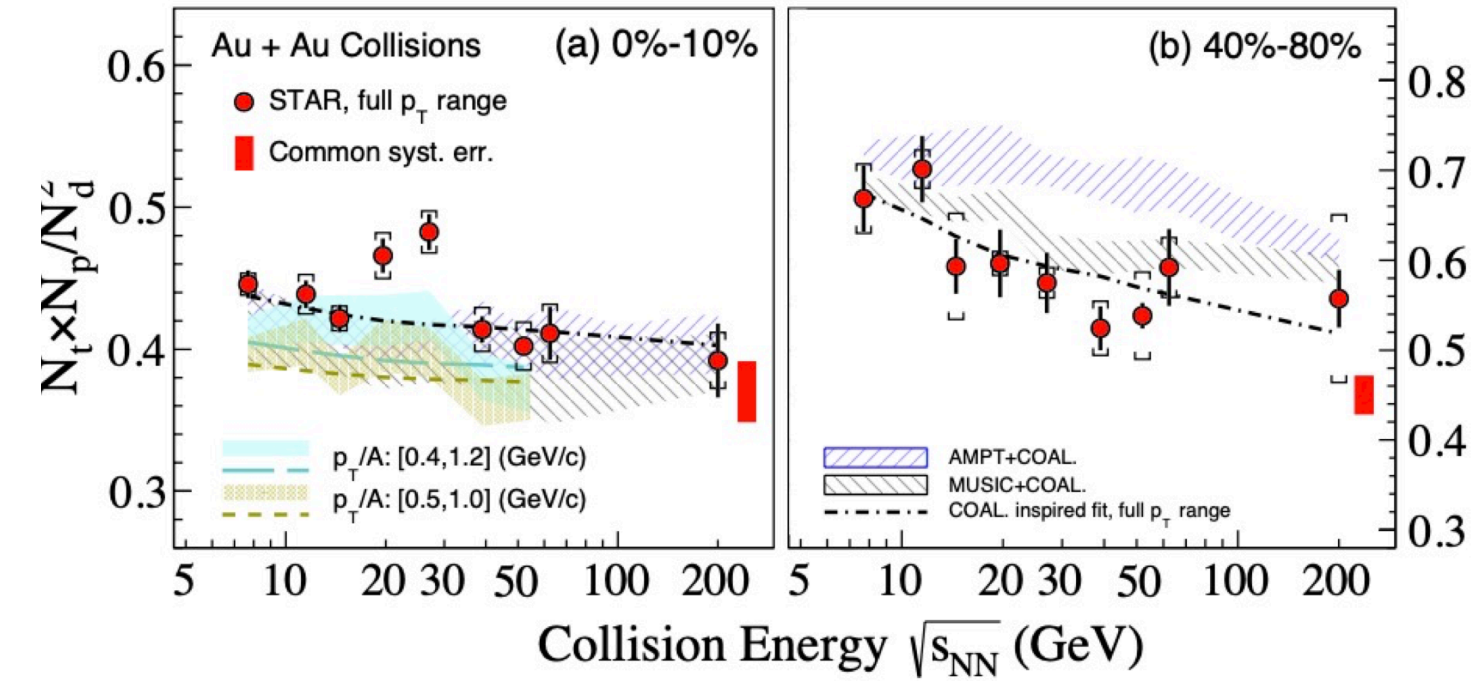
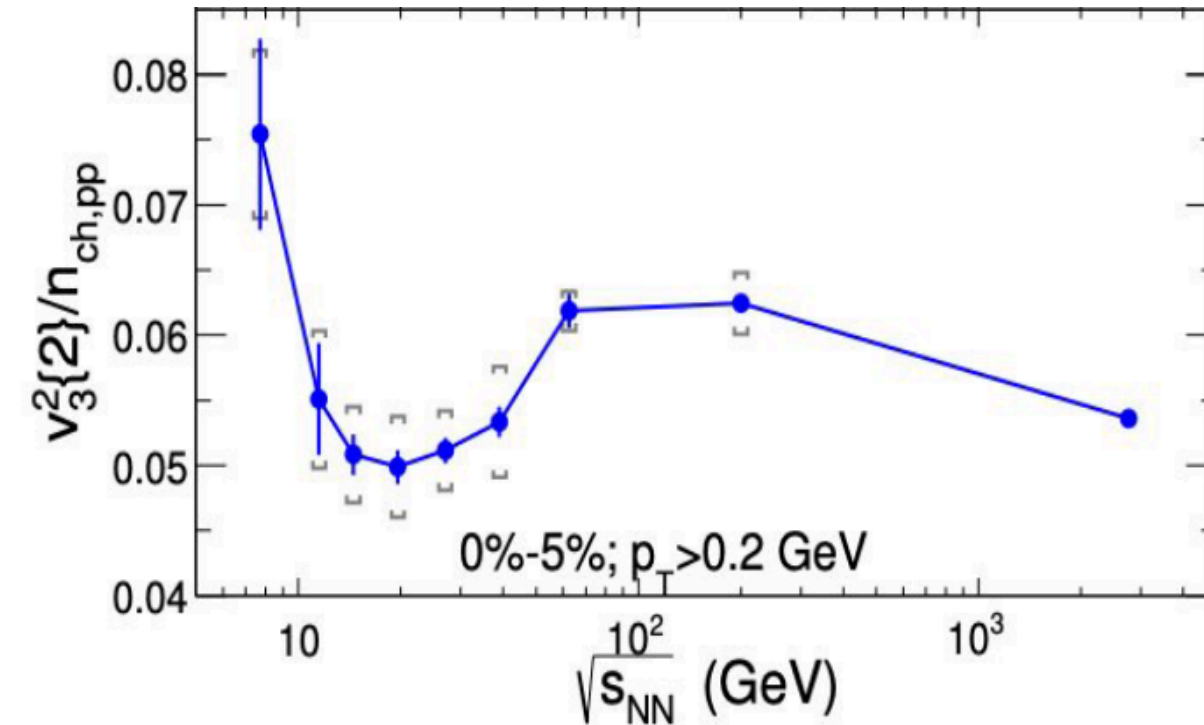
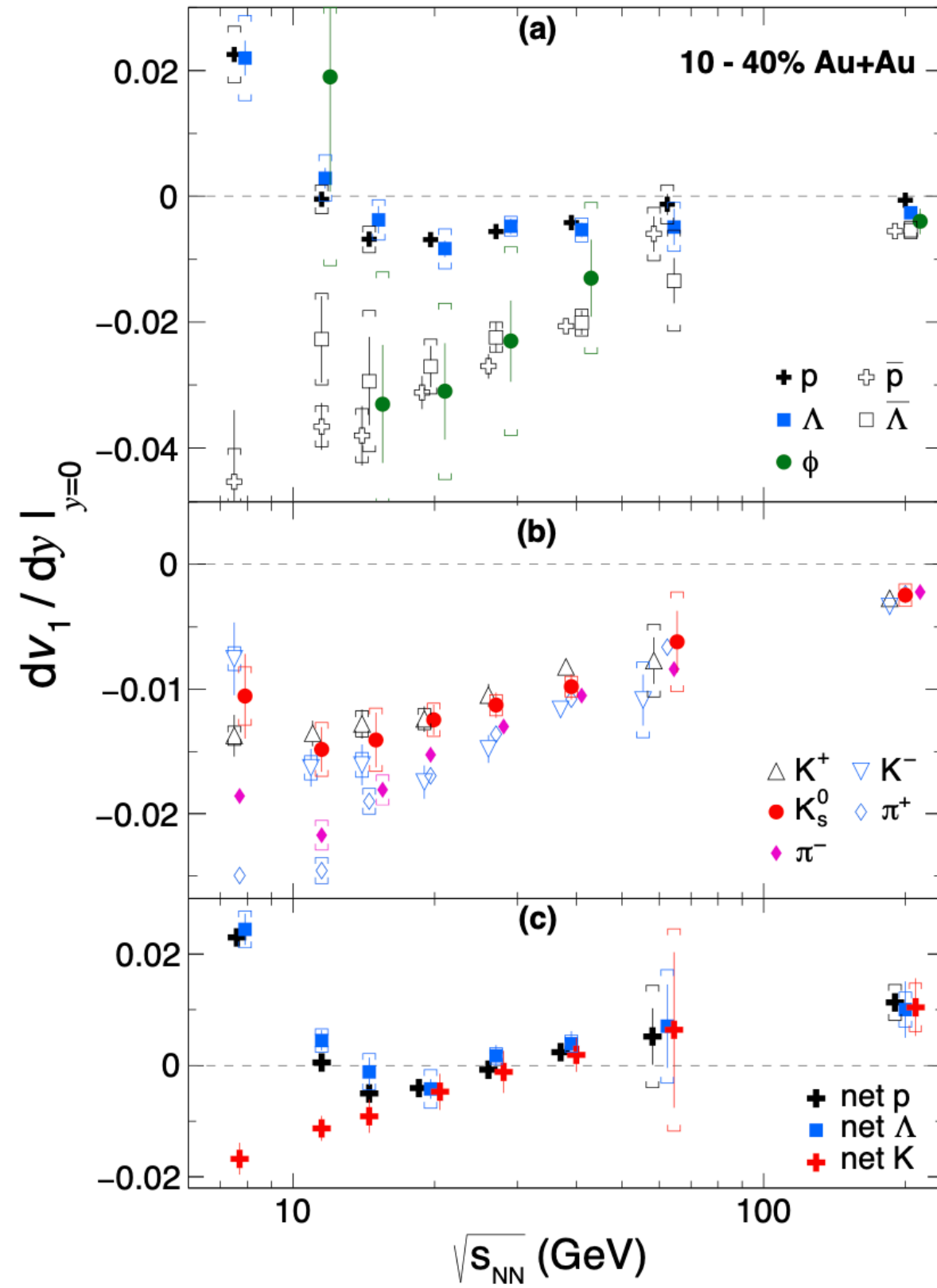


DALL-E

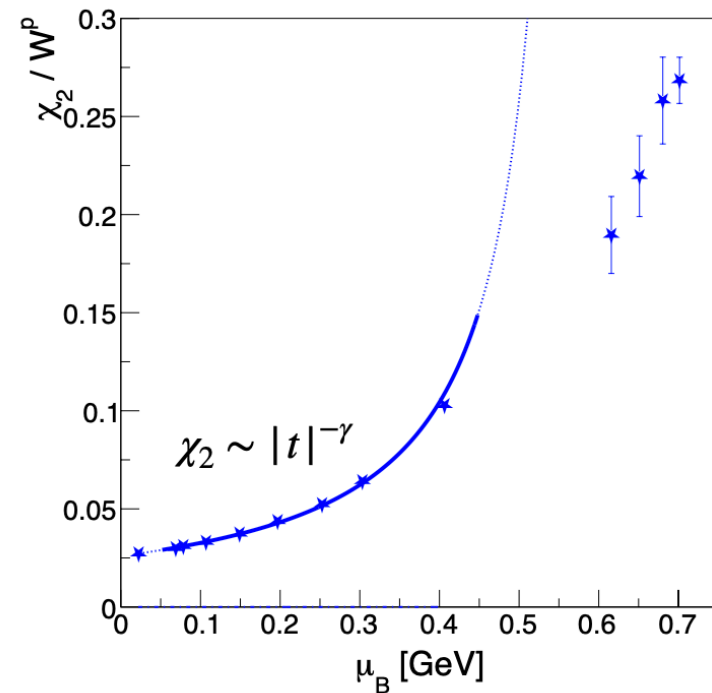
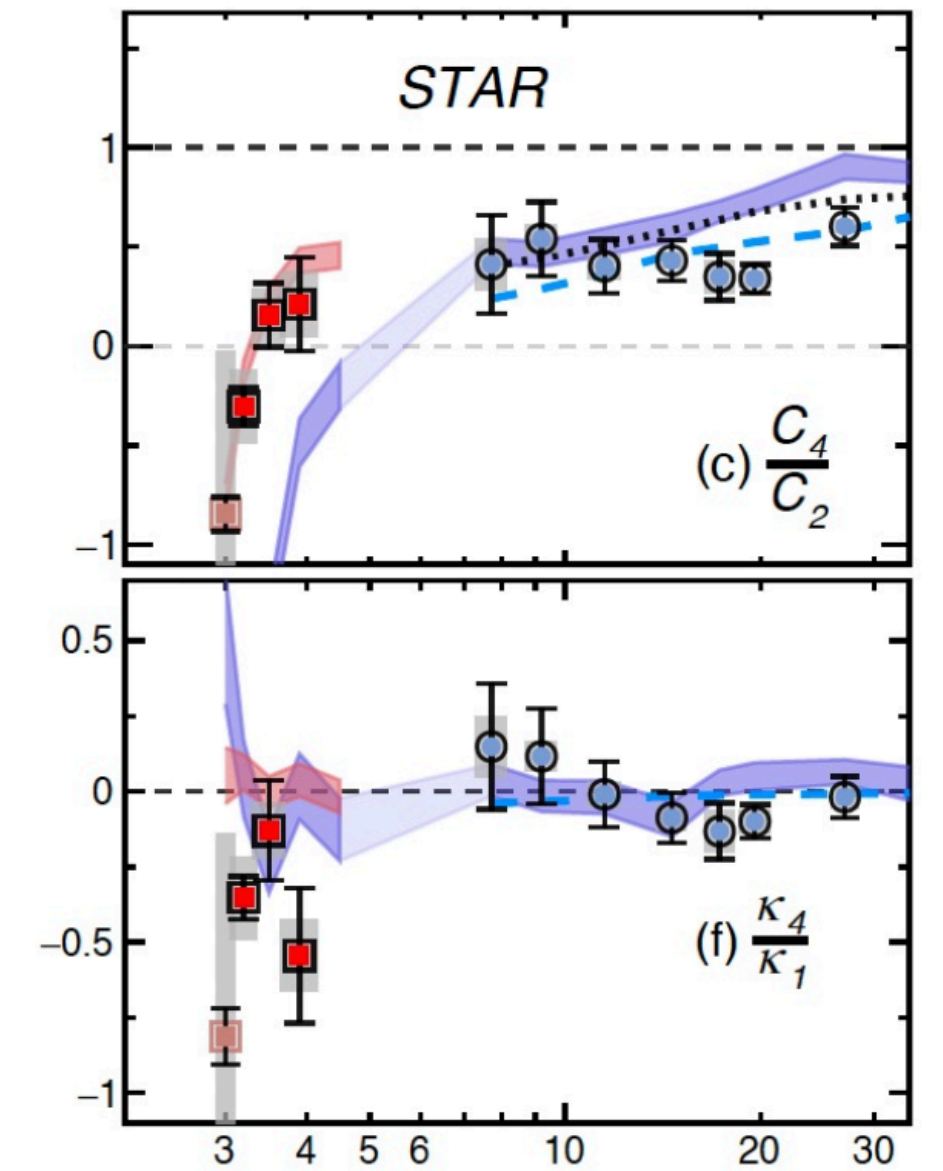
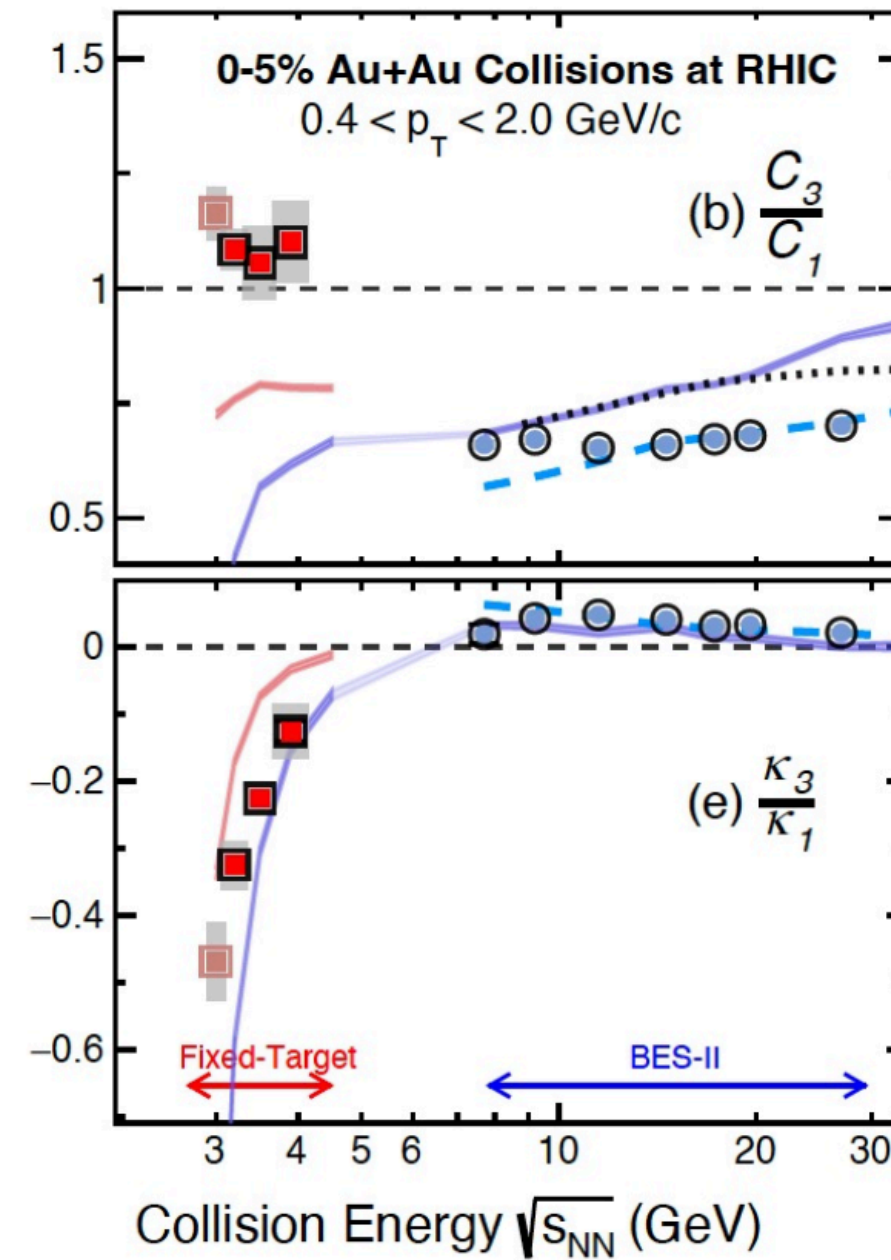
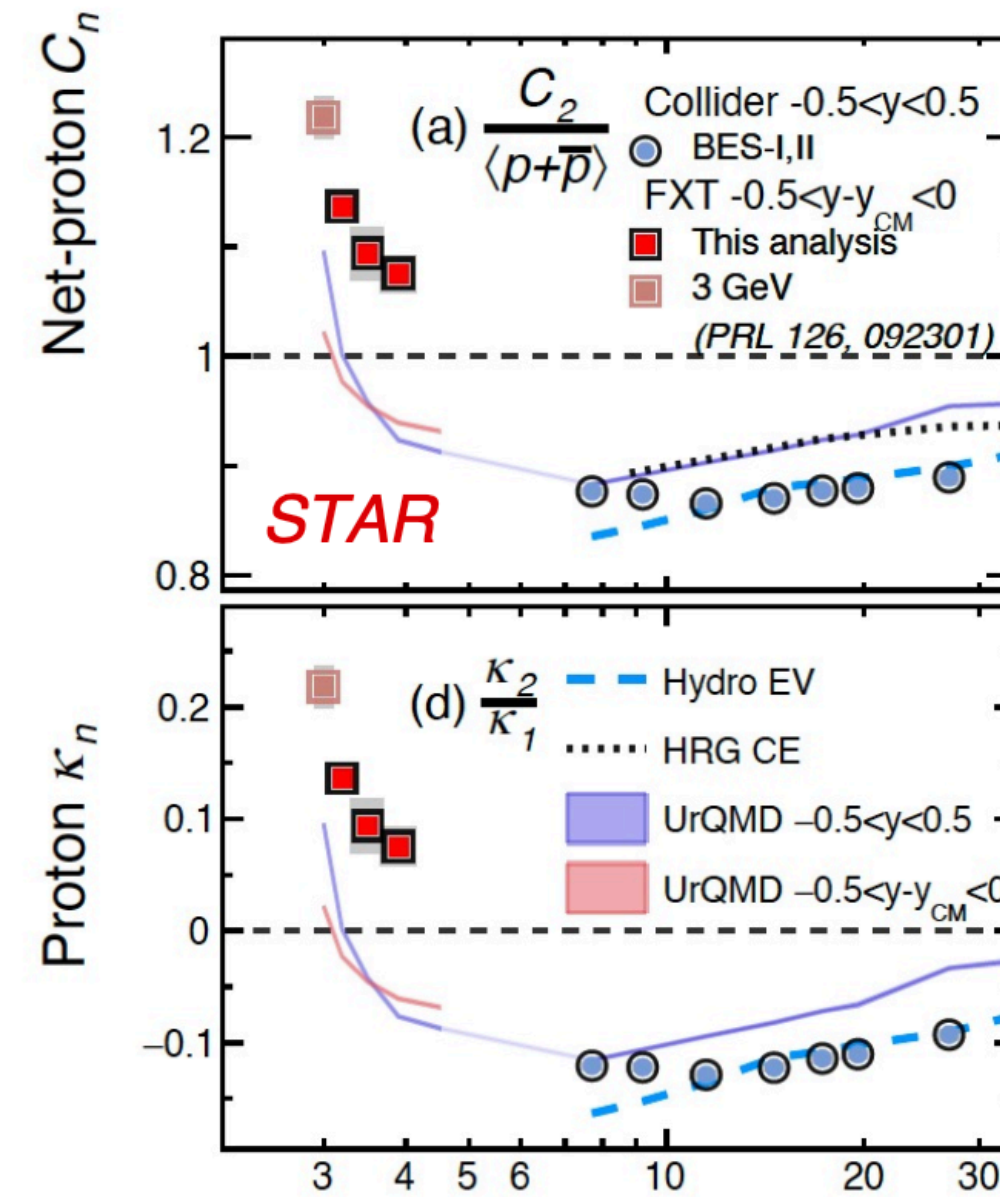
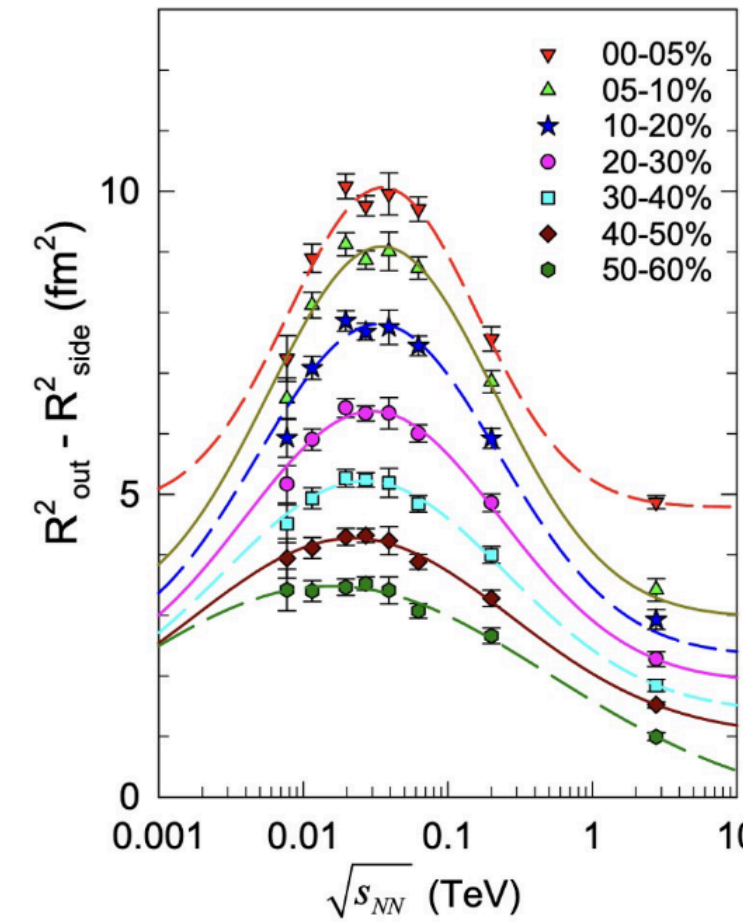
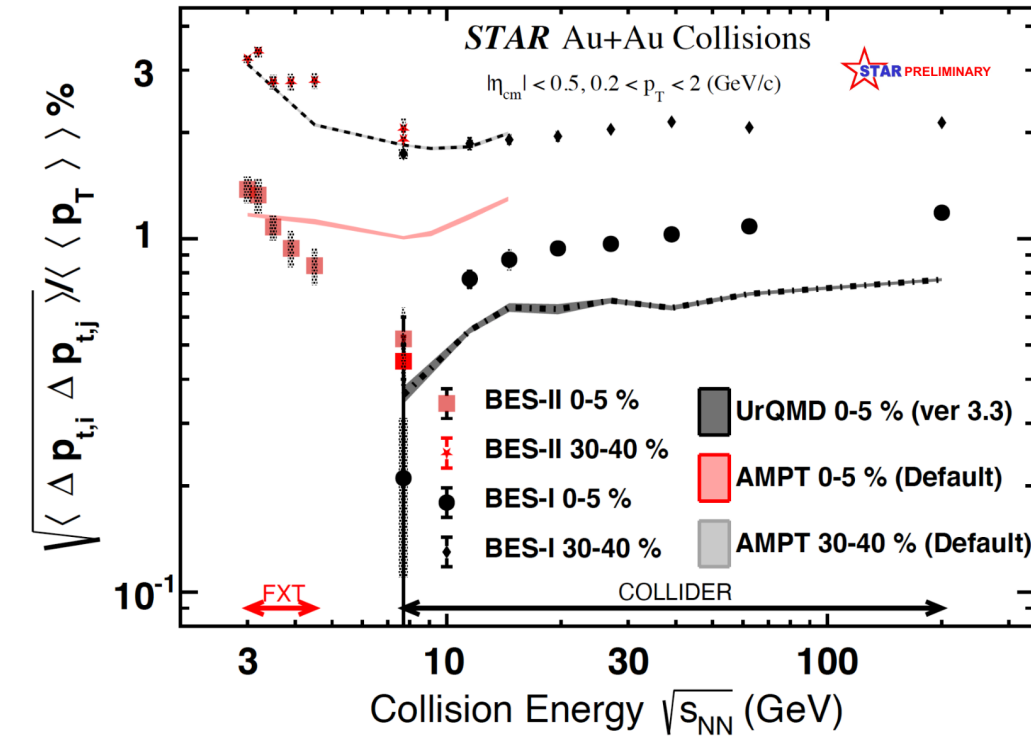
QCD phase diagram @ high density:
what is next?

Recent INT program: “The QCD Critical Point: Are We There Yet?”

PRL 120 (2018) 6, 062301



STAR, *Phys.Rev.Lett.* 130 (2023) 202301



Lots of dips and peaks

Recent INT program: “The QCD Critical Point: Are We There Yet?”

- Goals:
- review available measurements and theoretical results
 - establish a list of “homework” tasks to confirm/refute interpretations

Main conclusions:

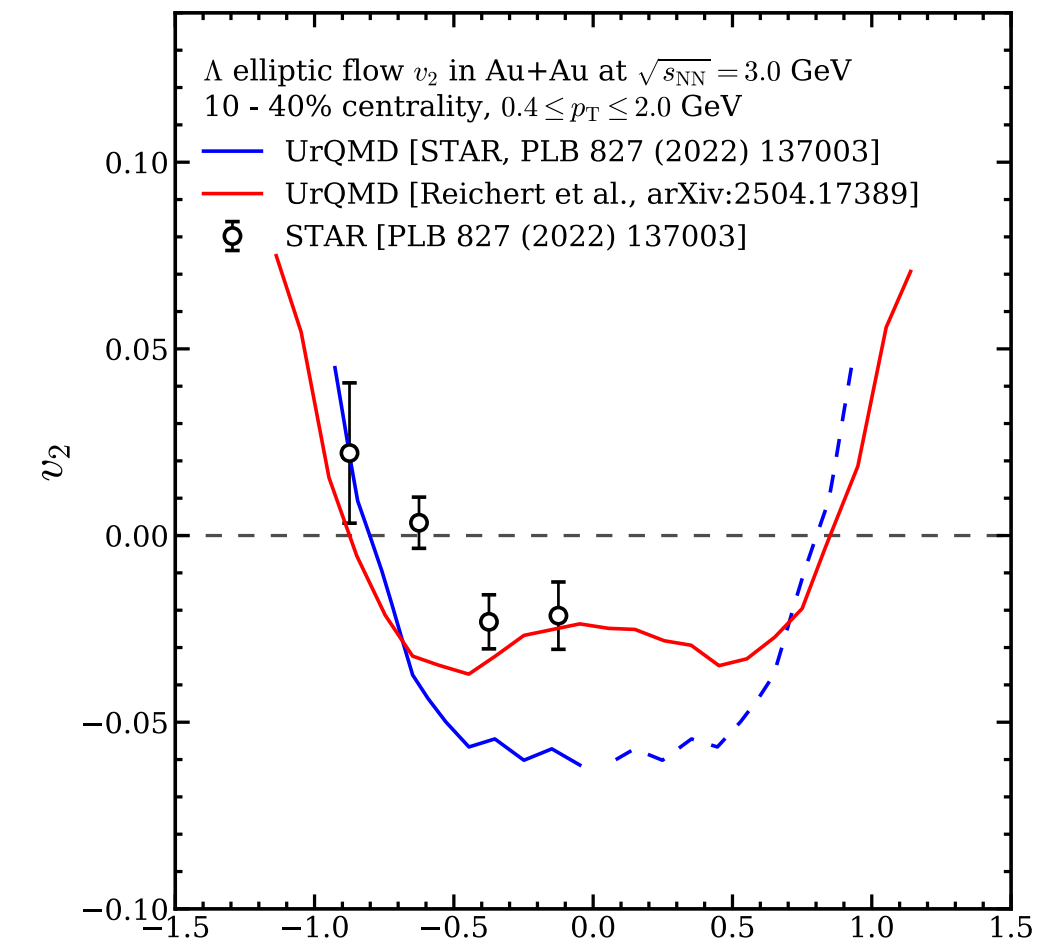
1) fundamental input in models is of key importance

2) where measurements are not available, “ordinary” yield and spectra data are *key* to calibrate models

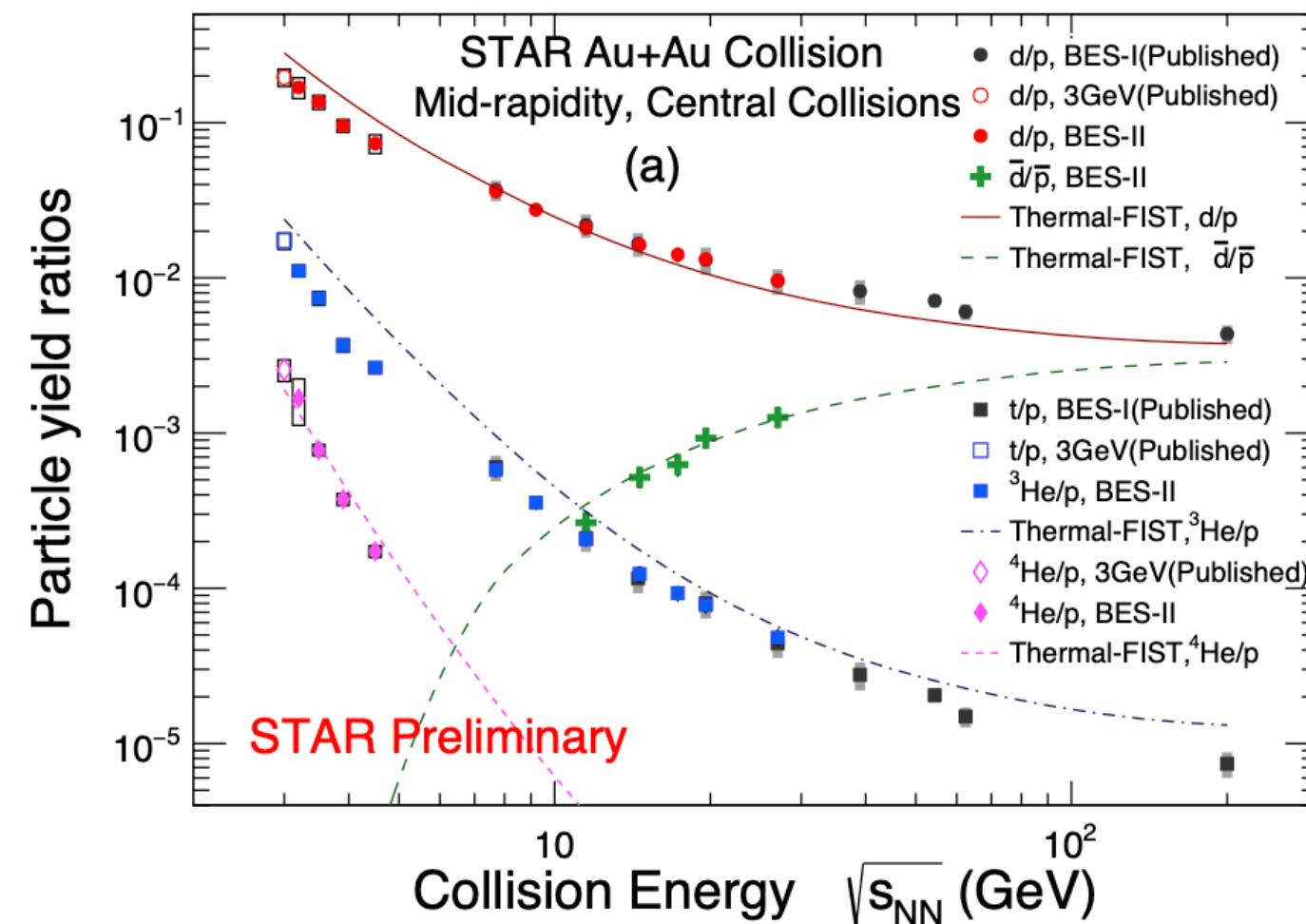
STAR & HADES provide unprecedented statistics, CBM will beat that by $\sim 10^3$

3) differential analyses (as opposed to single numbers) are key in model to data comparisons
models can reproduce single numbers without agreeing on the details

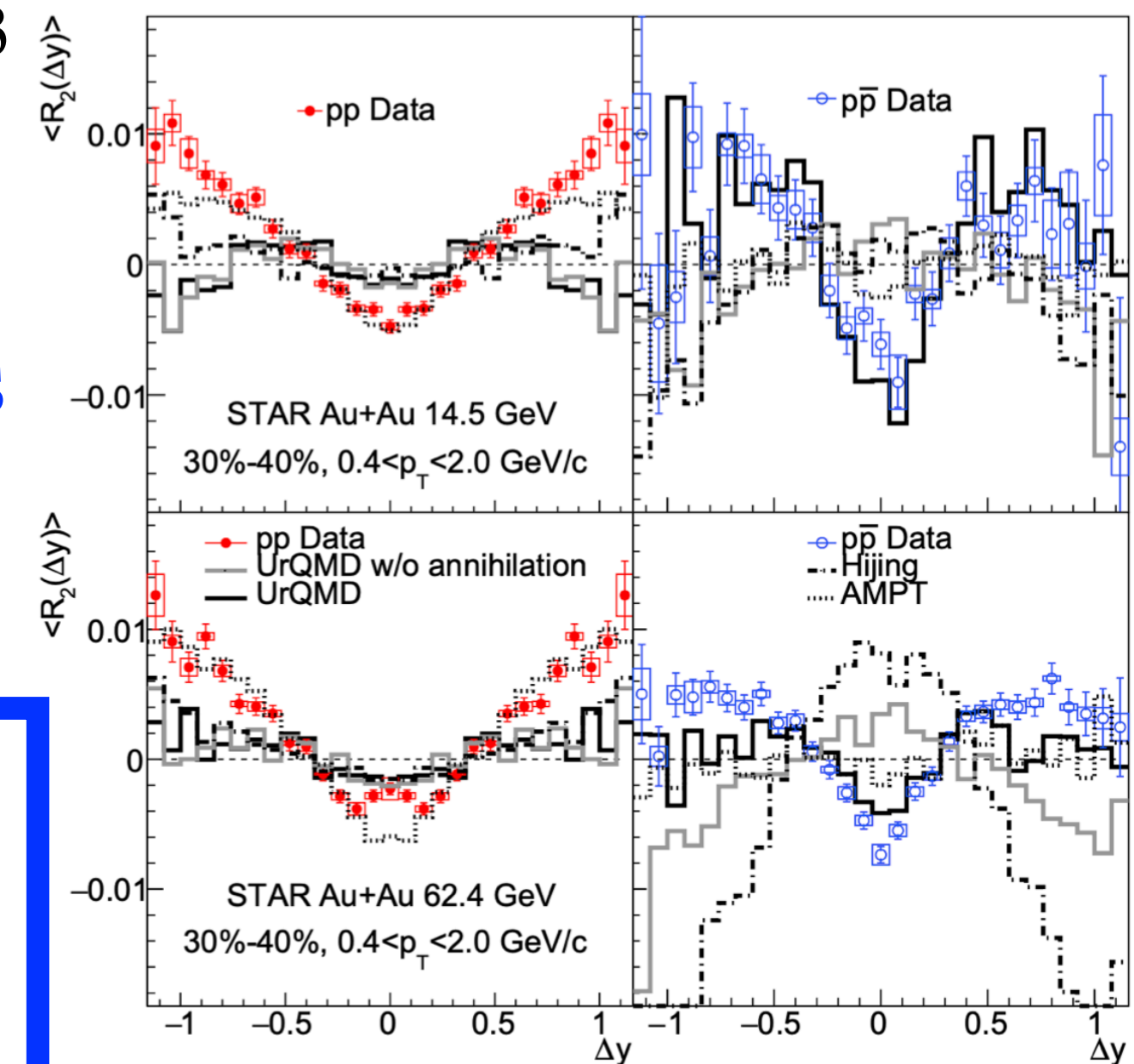
Homework list has been established,
results are starting to come out



T. Reichert *et al.*, Phys. Rev. C **112**, 6, 064909 (2025)



Y. Jin for the STAR Collaboration,
QM25 proceedings, arXiv:2512.05295



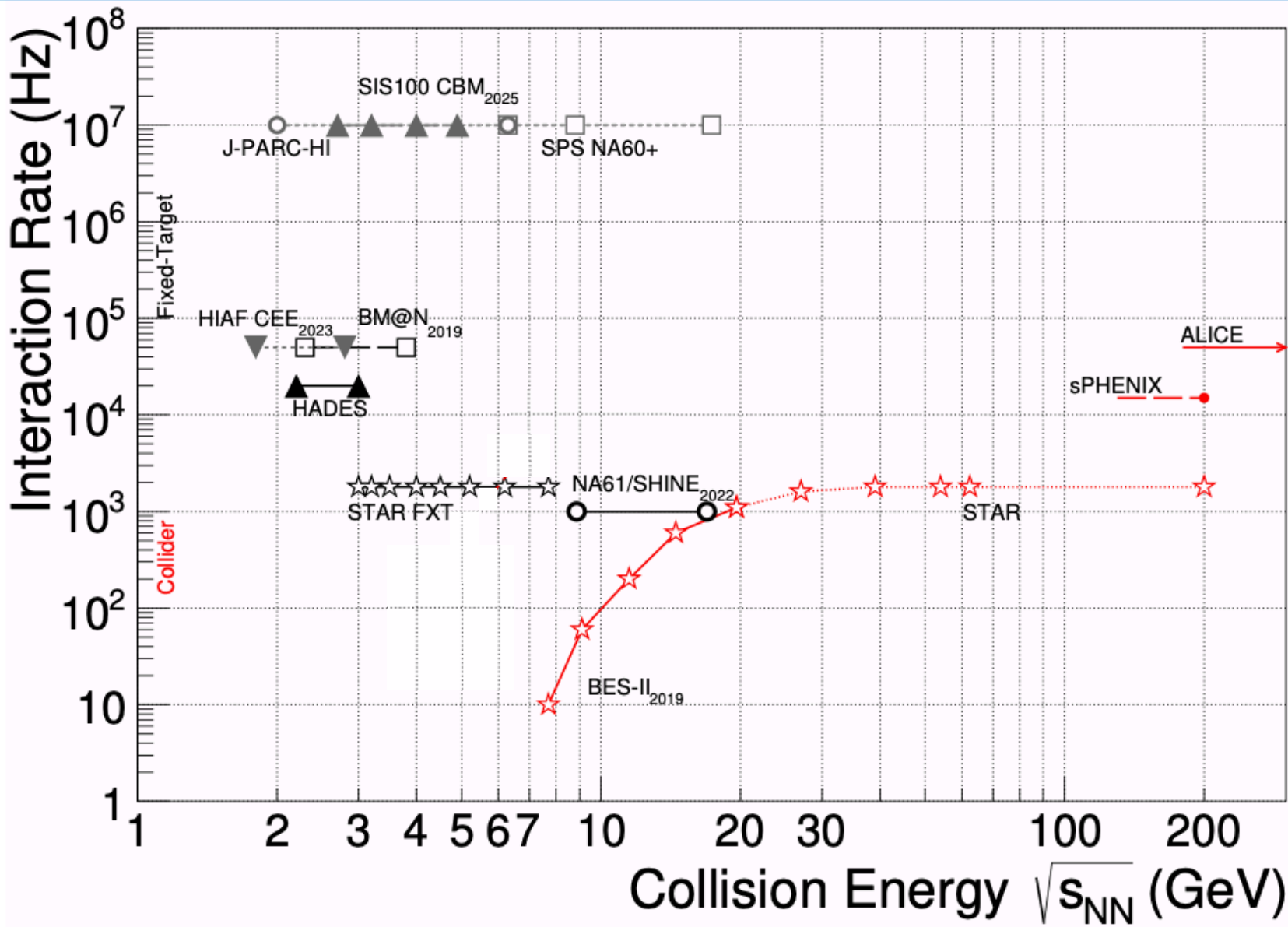
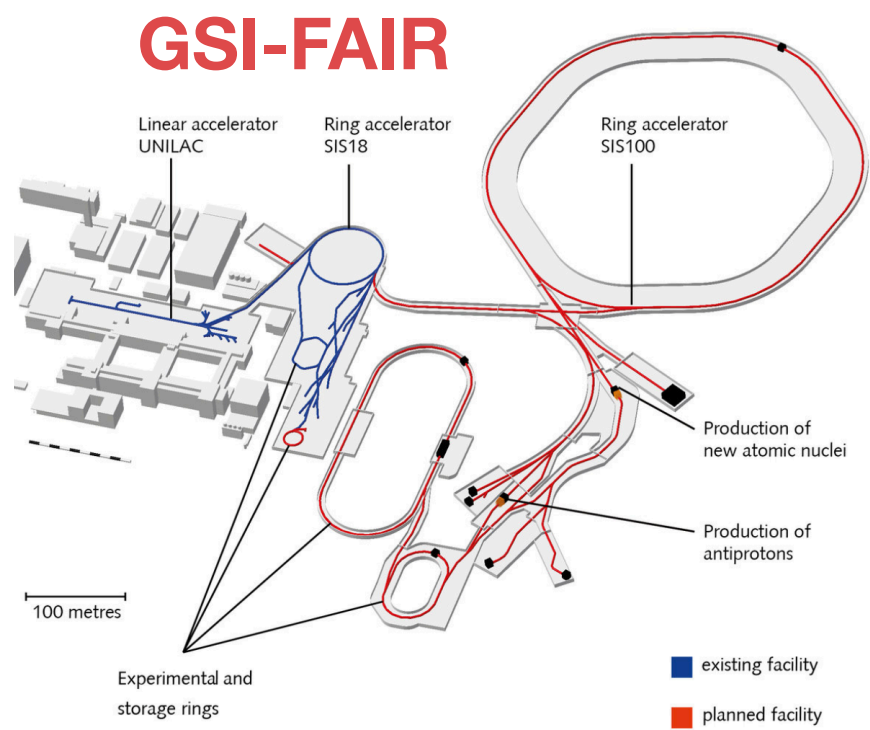
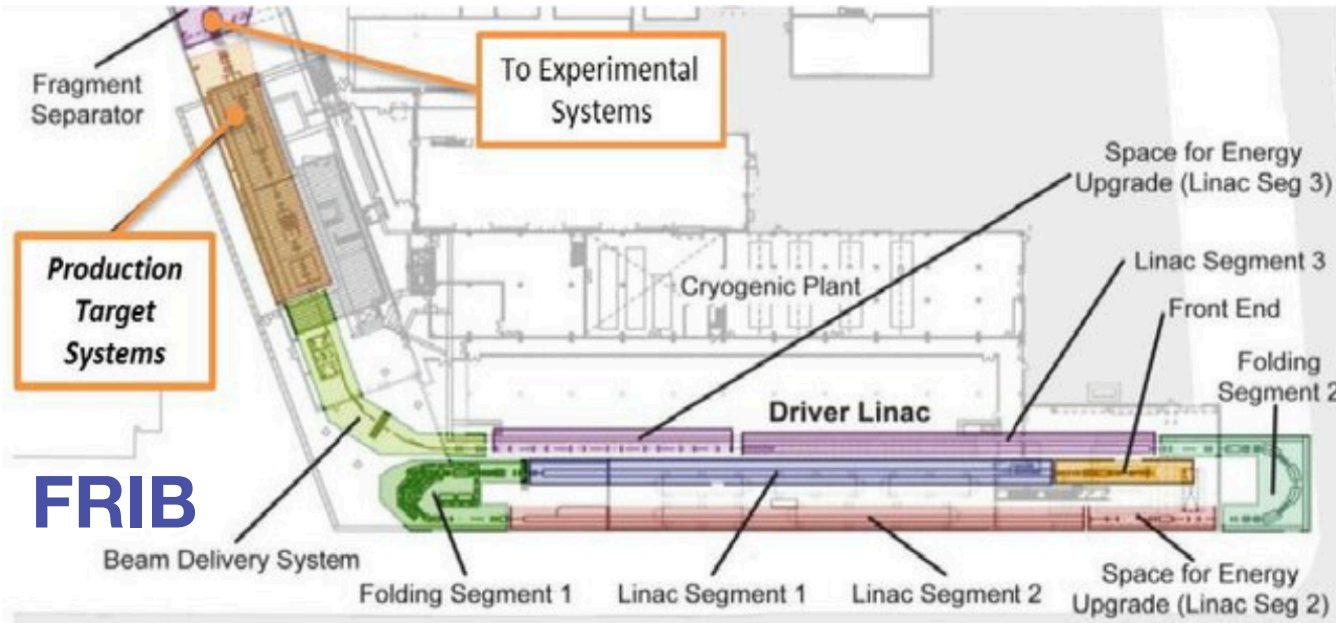
Currently running & future facilities

Facility for Antiproton and Ion Research (FAIR):

small energies in fixed-target collisions ($\sqrt{s_{NN}} \sim 5$ GeV),
high interaction rates (great statistics!)

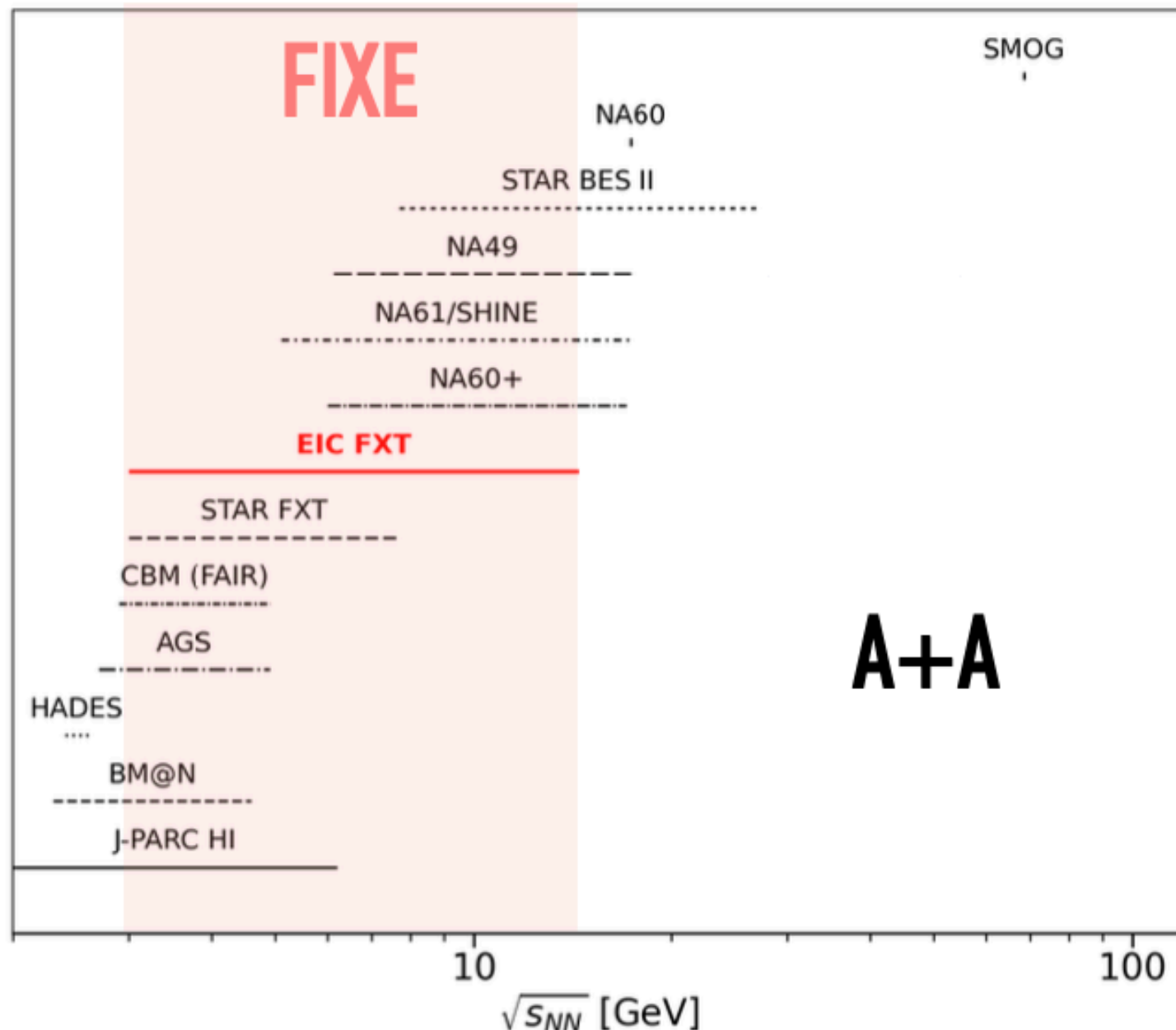
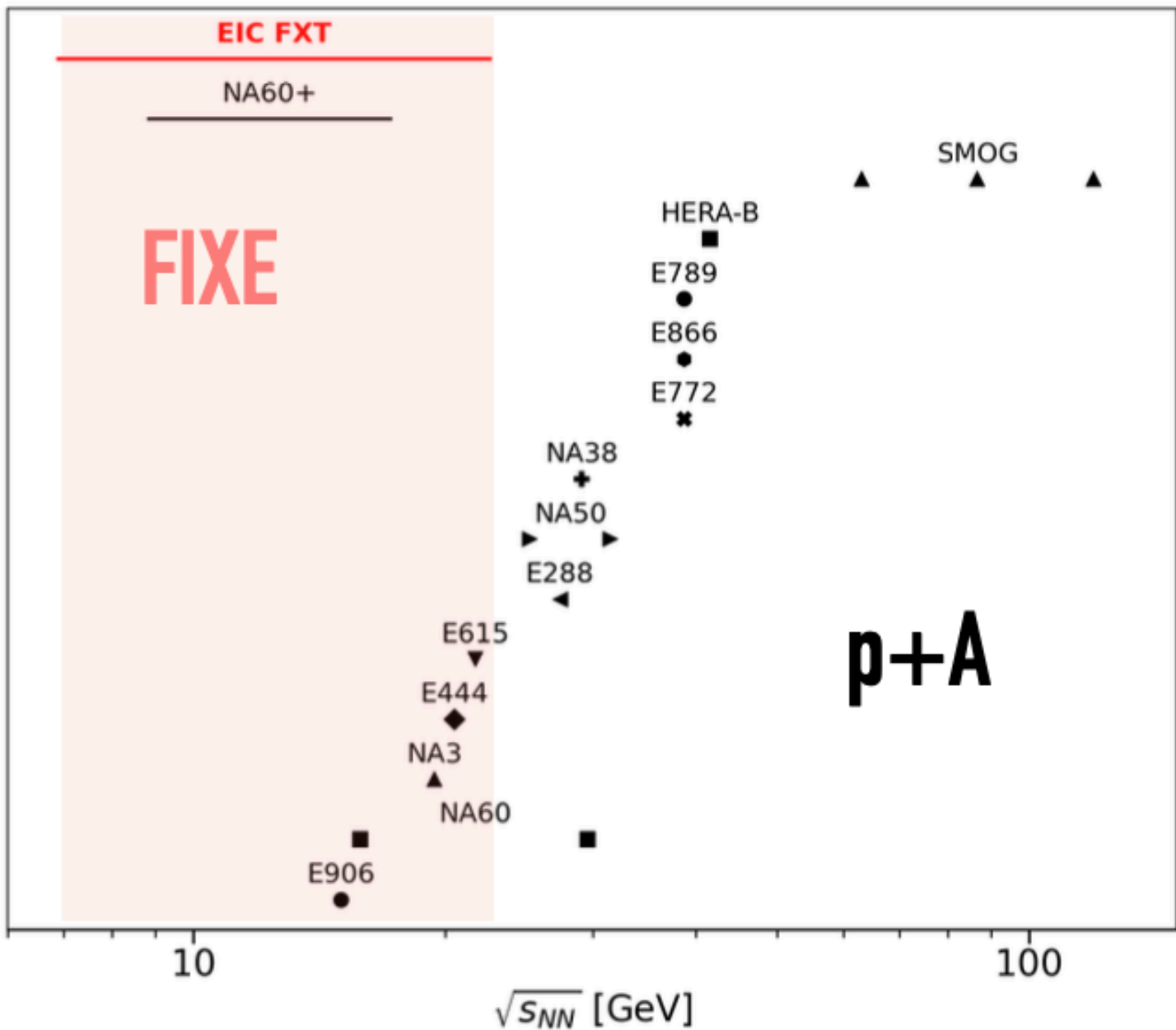
Facility for Rare Isotope Beams (FRIB):

very small energies in fixed-target collisions,
rare neutron-rich isotopes available

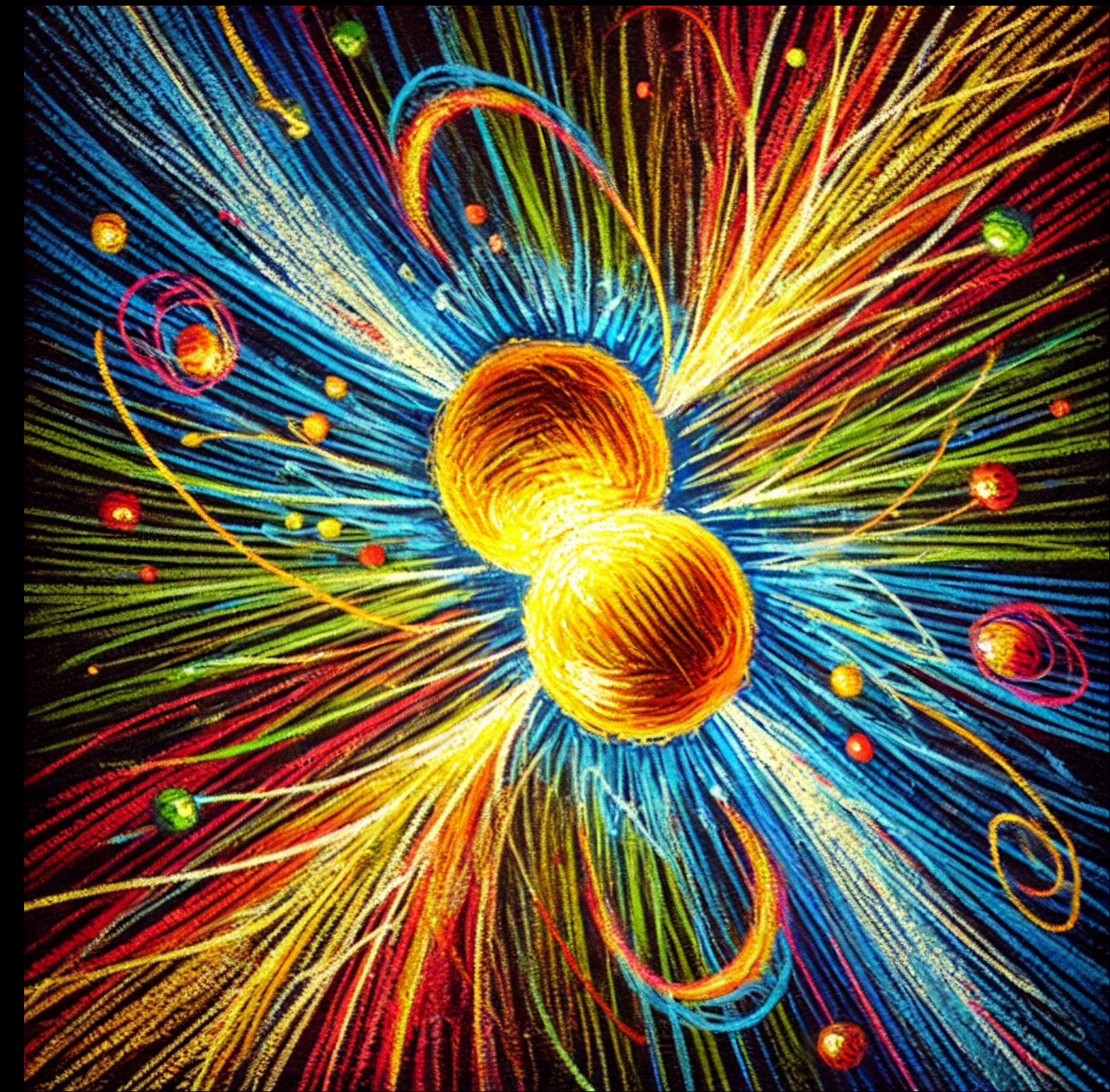


Possible fixed-target HIC program at the EIC (FIXE)?

C.-J. Naïm, A. Sorensen *et al.*, arXiv:2603.00265



from C.-J. Naïm



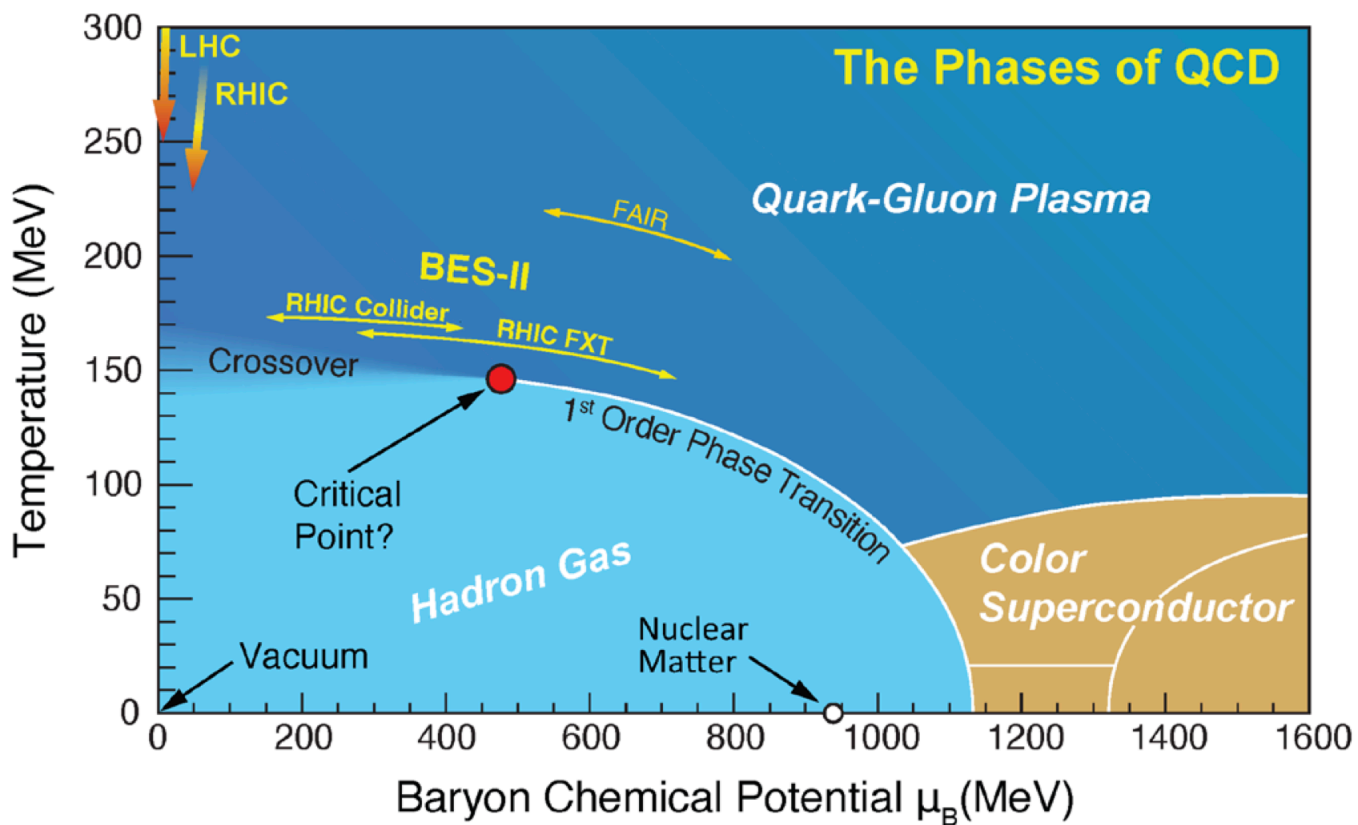
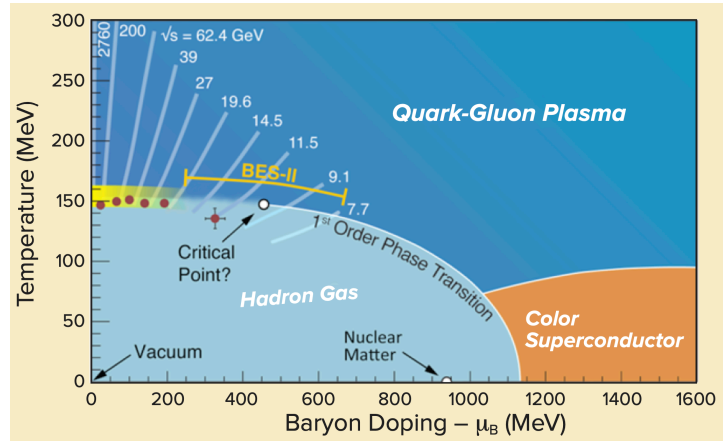
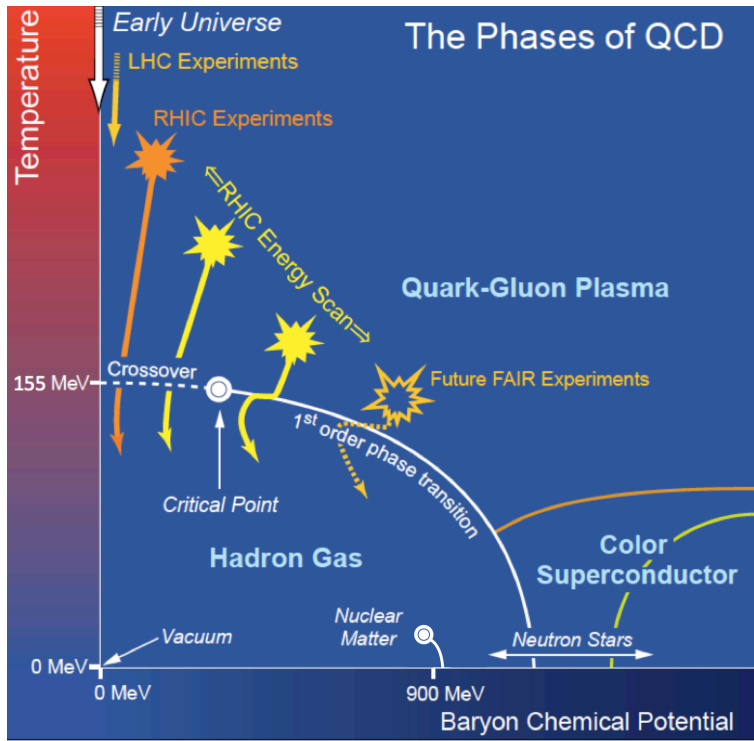
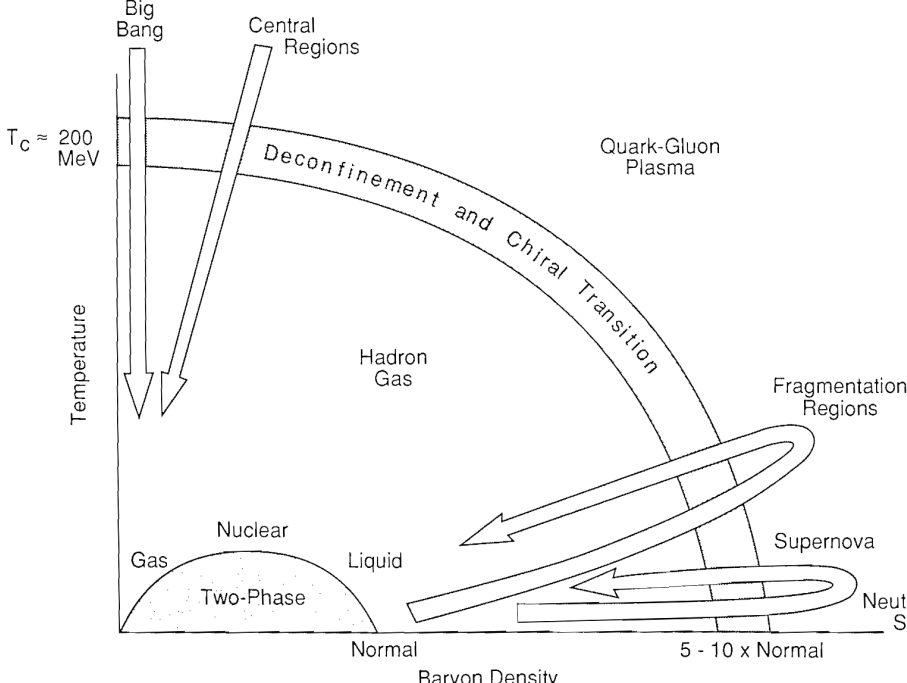
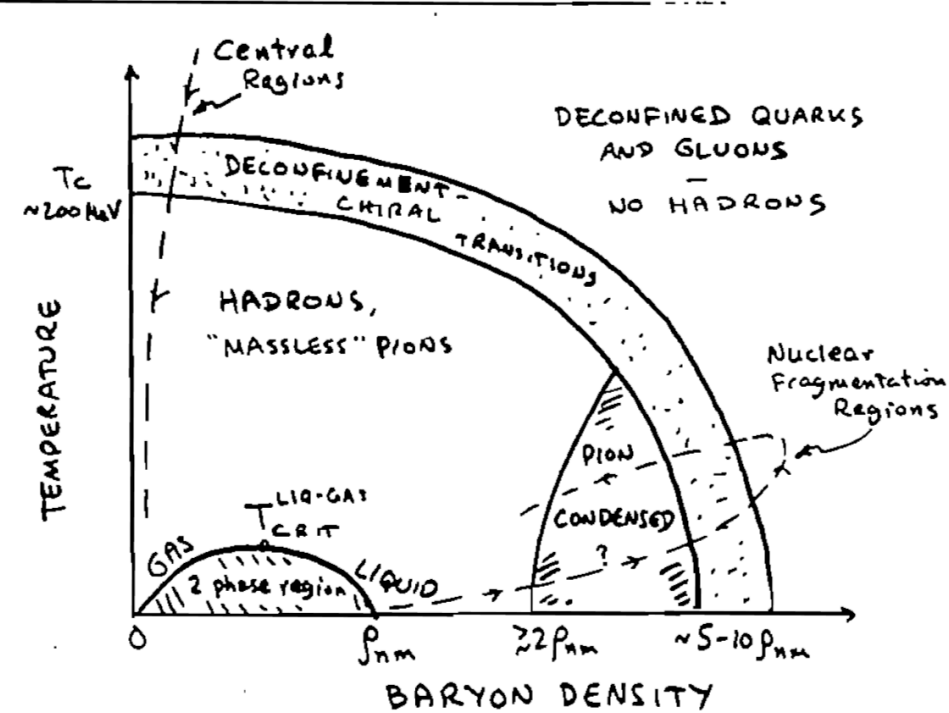
DALL-E

QCD phase diagram @ high density:
thinking outside of the box

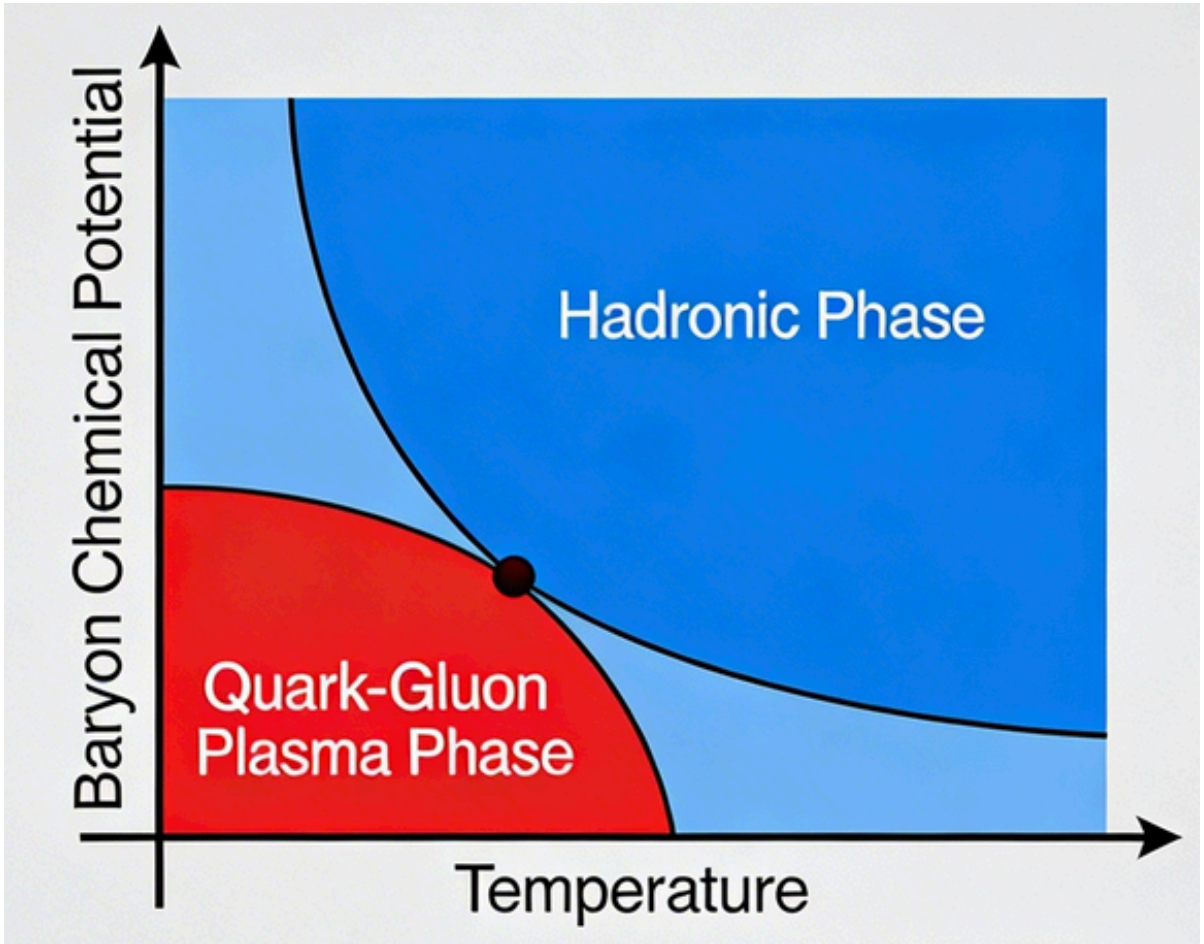
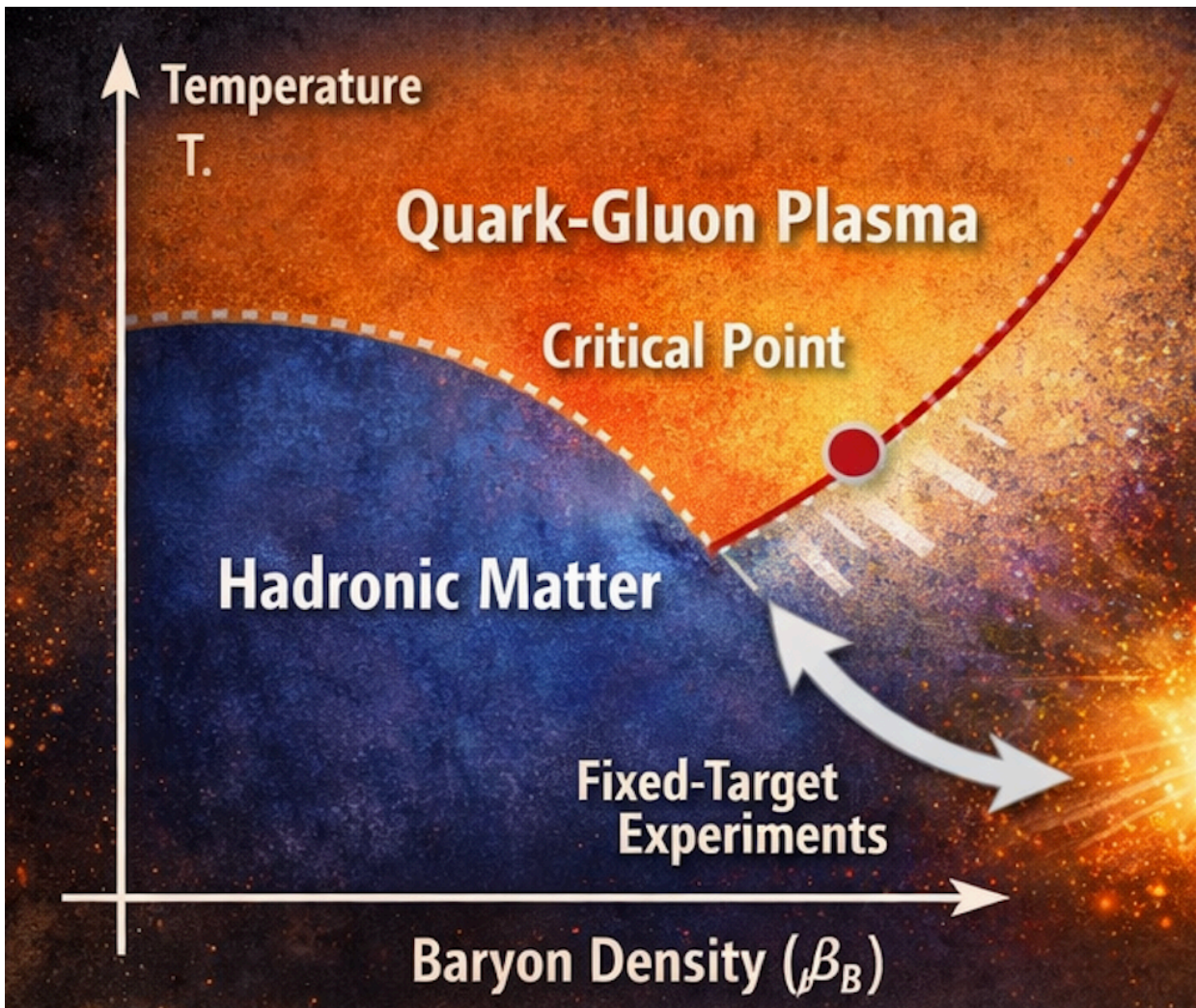
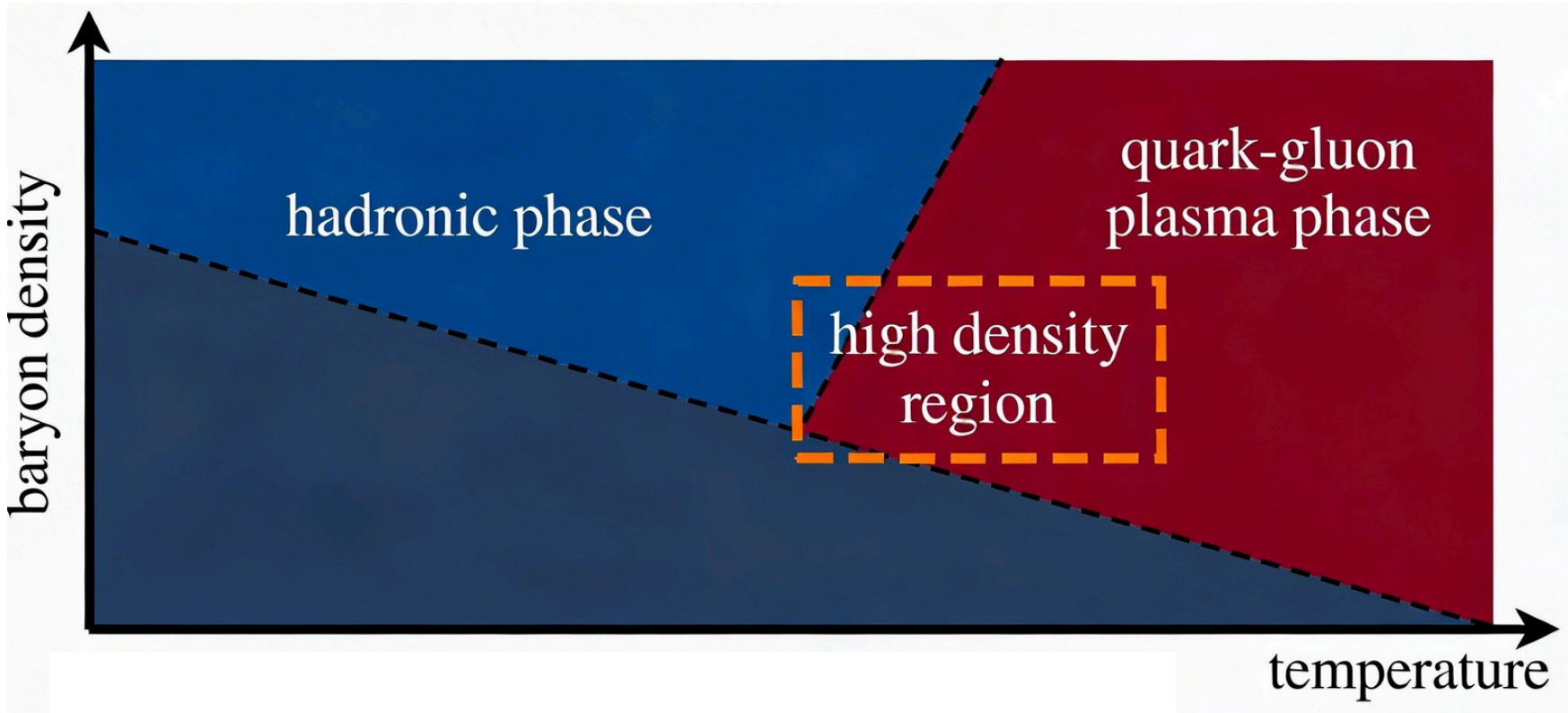
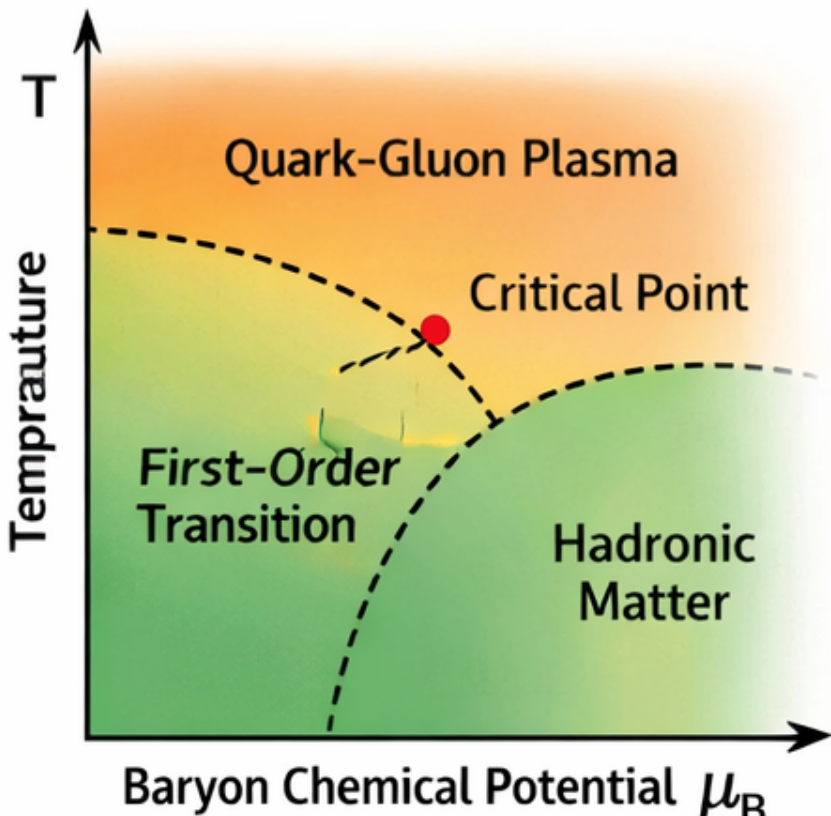
QCD phase diagram — are we flexible enough?

Nuclear physicists:

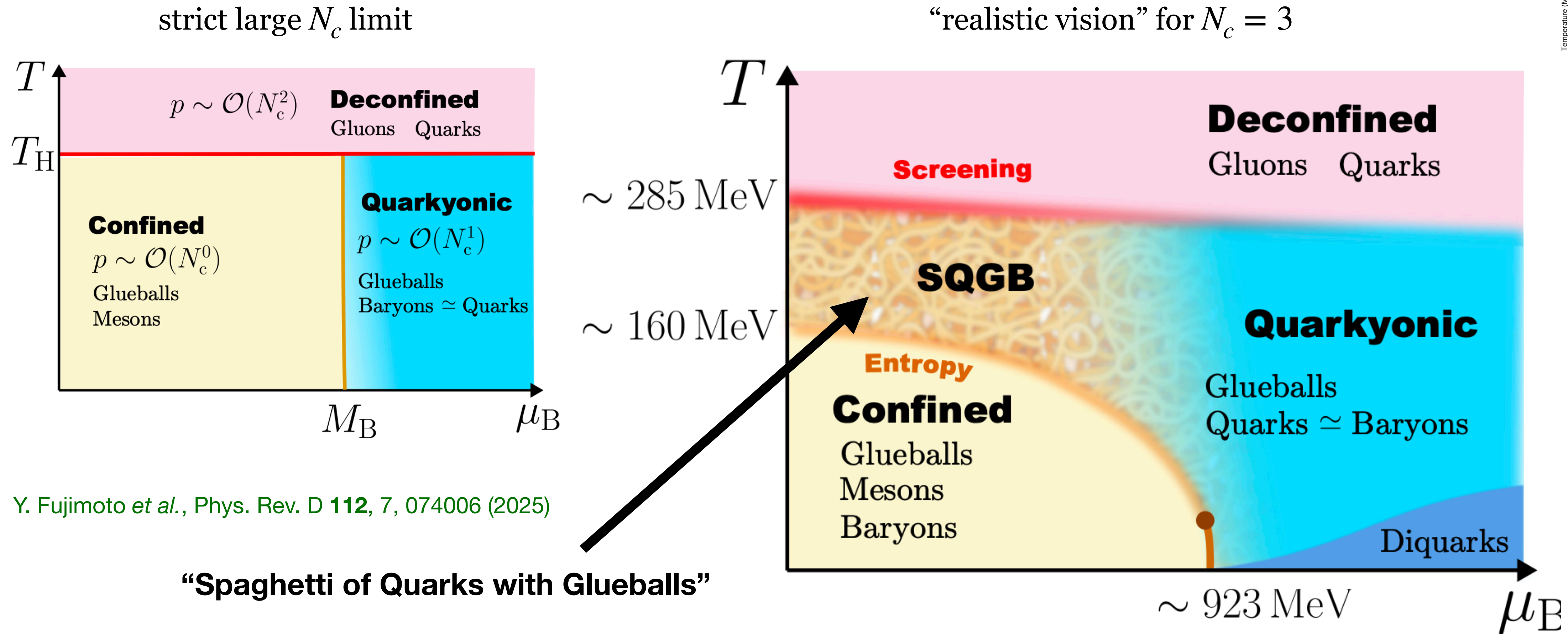
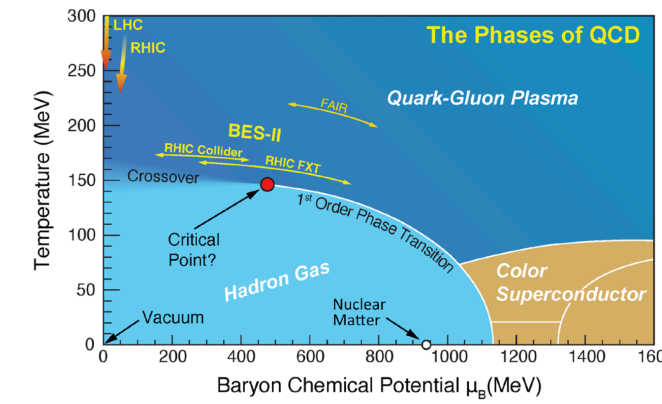
PHASE DIAGRAM OF NUCLEAR MATTER



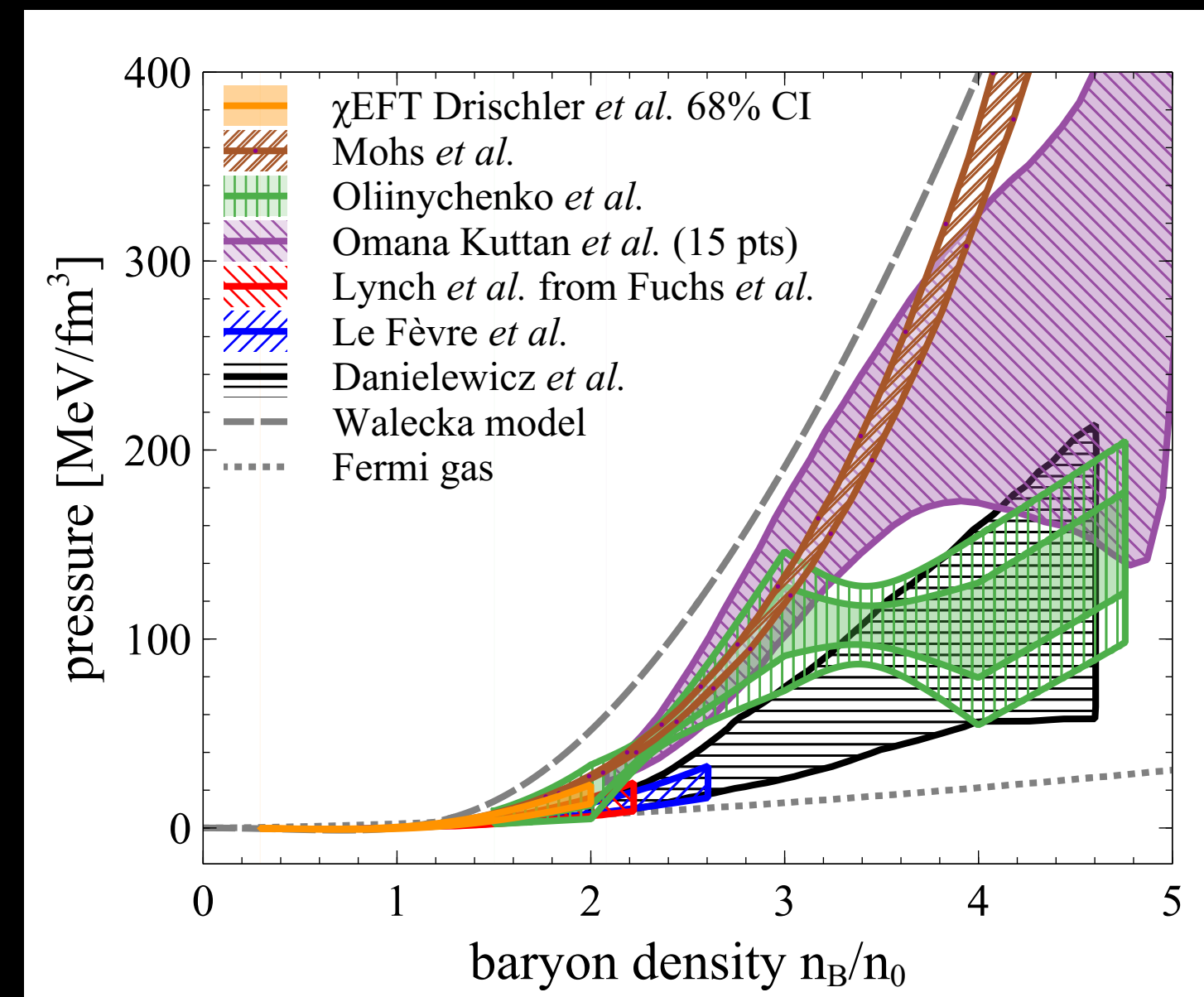
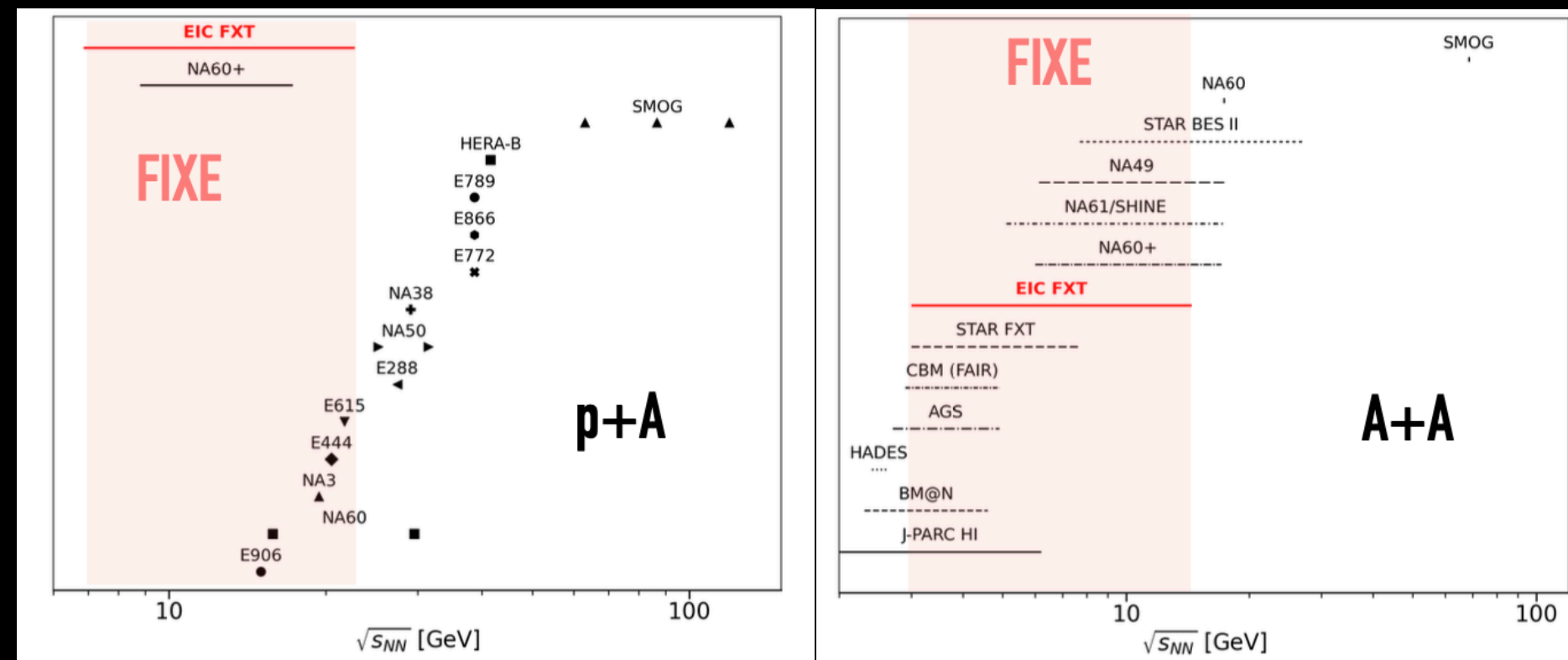
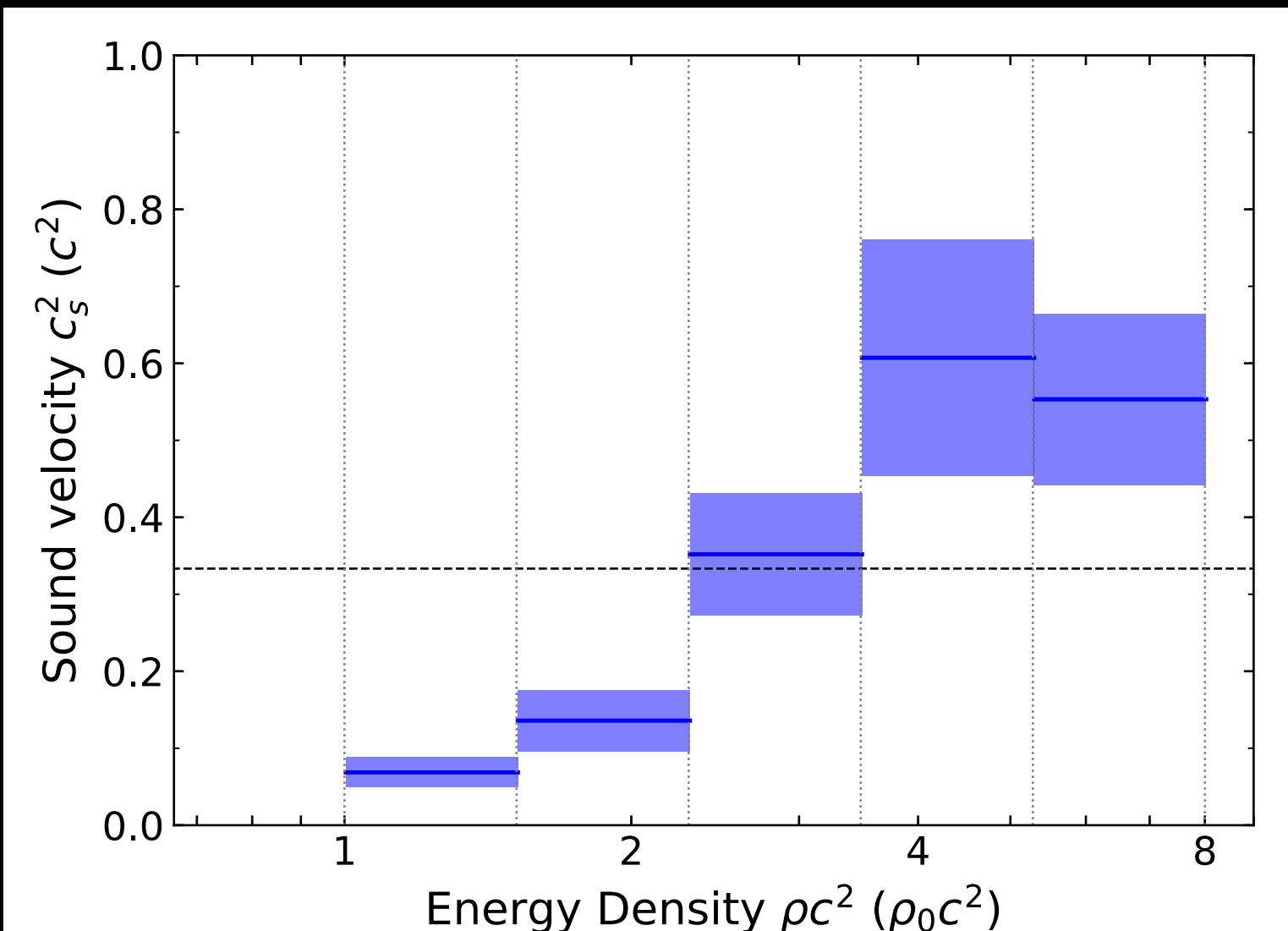
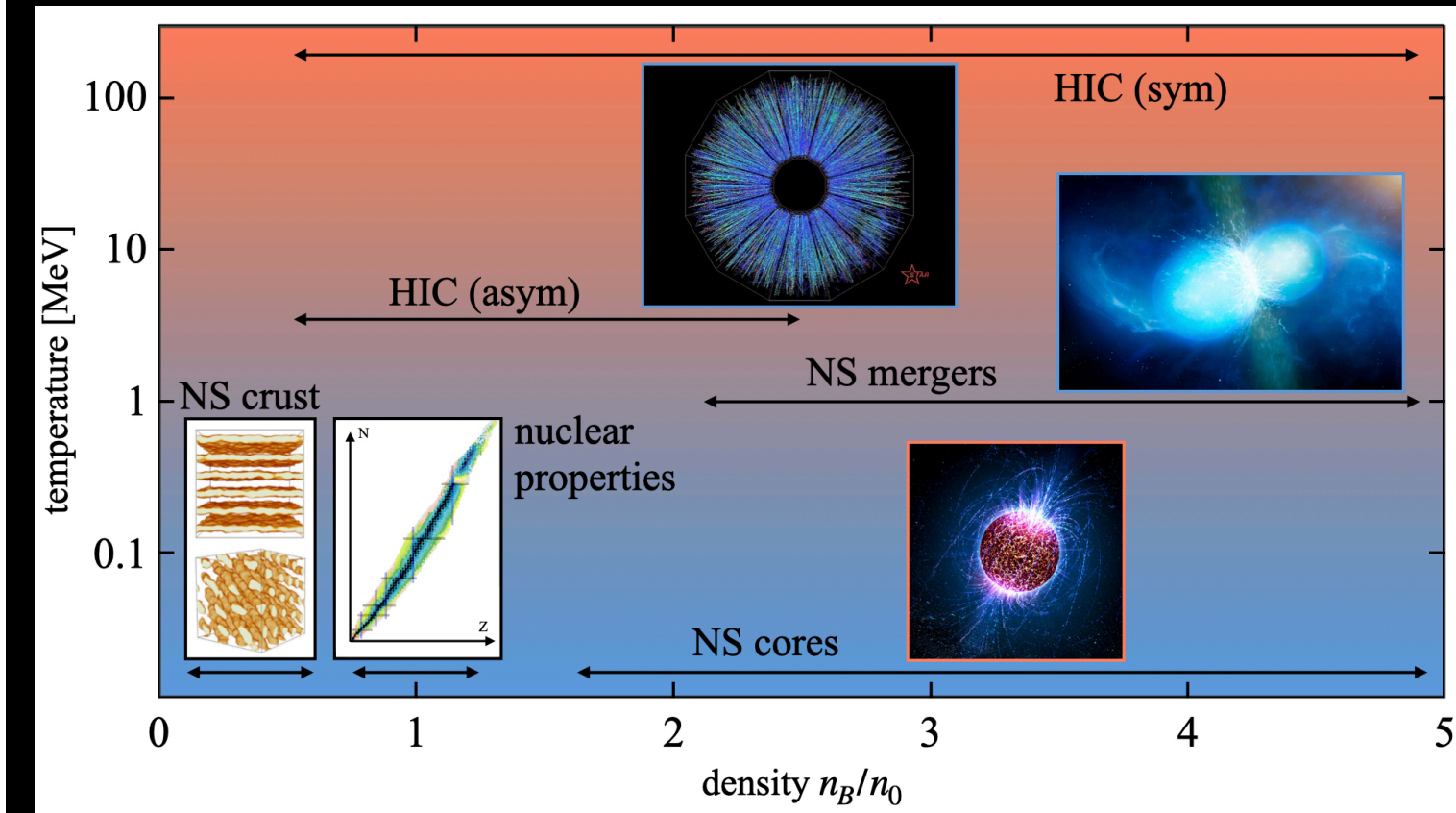
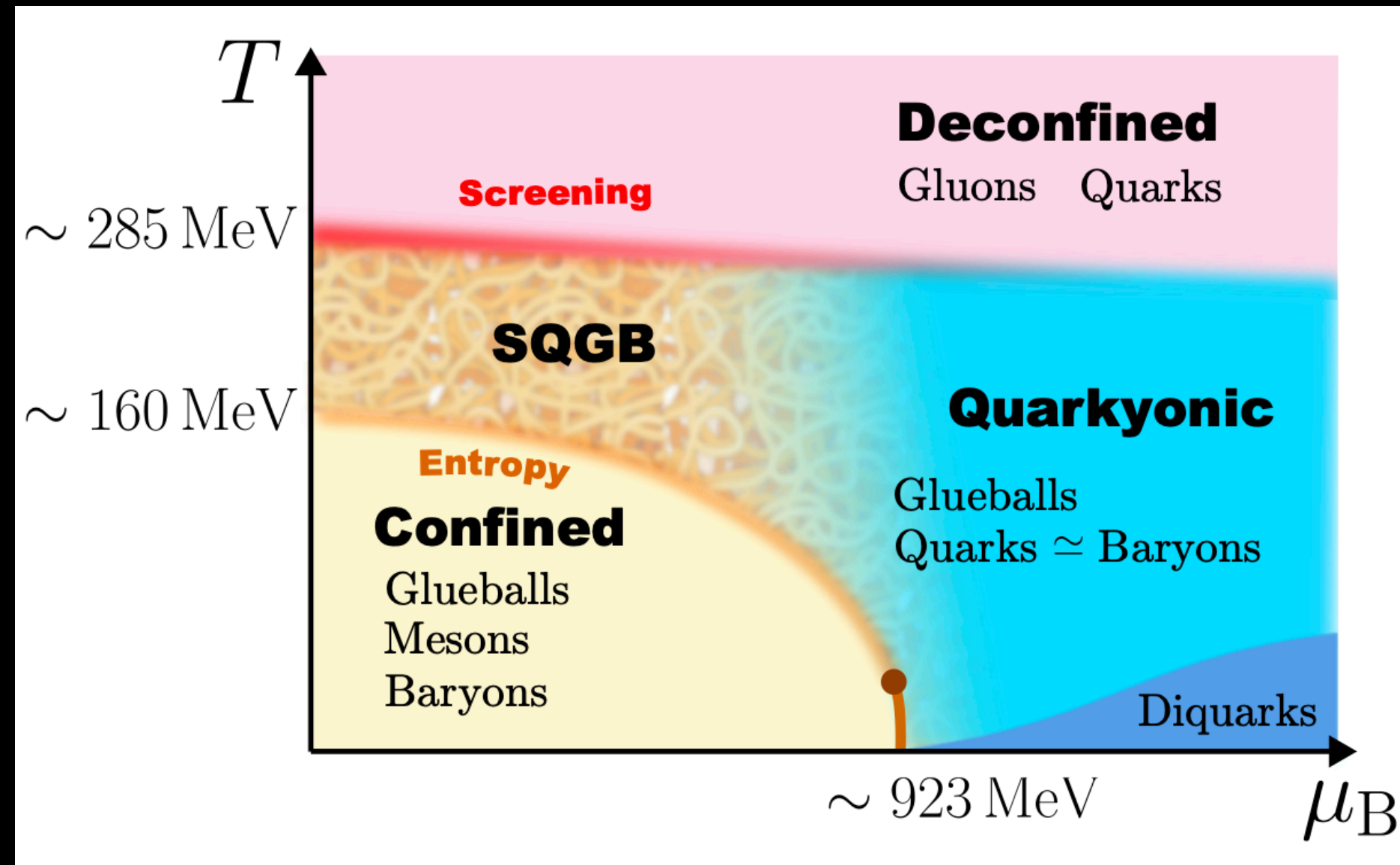
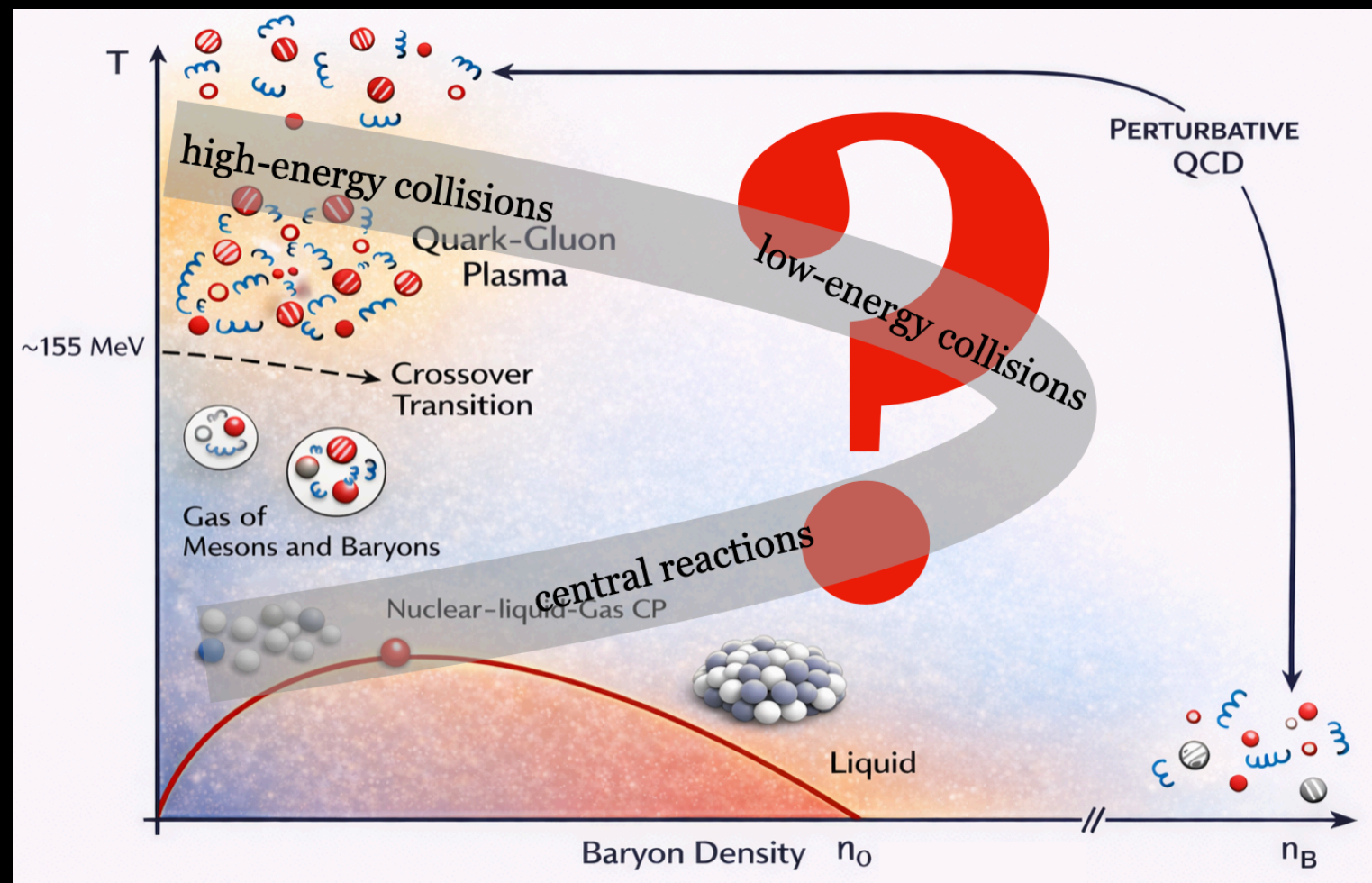
AI: (all obviously wrong, but...)



QCD phase diagram — are we flexible enough?



We should be open to see things we don't expect



Thank you for your attention