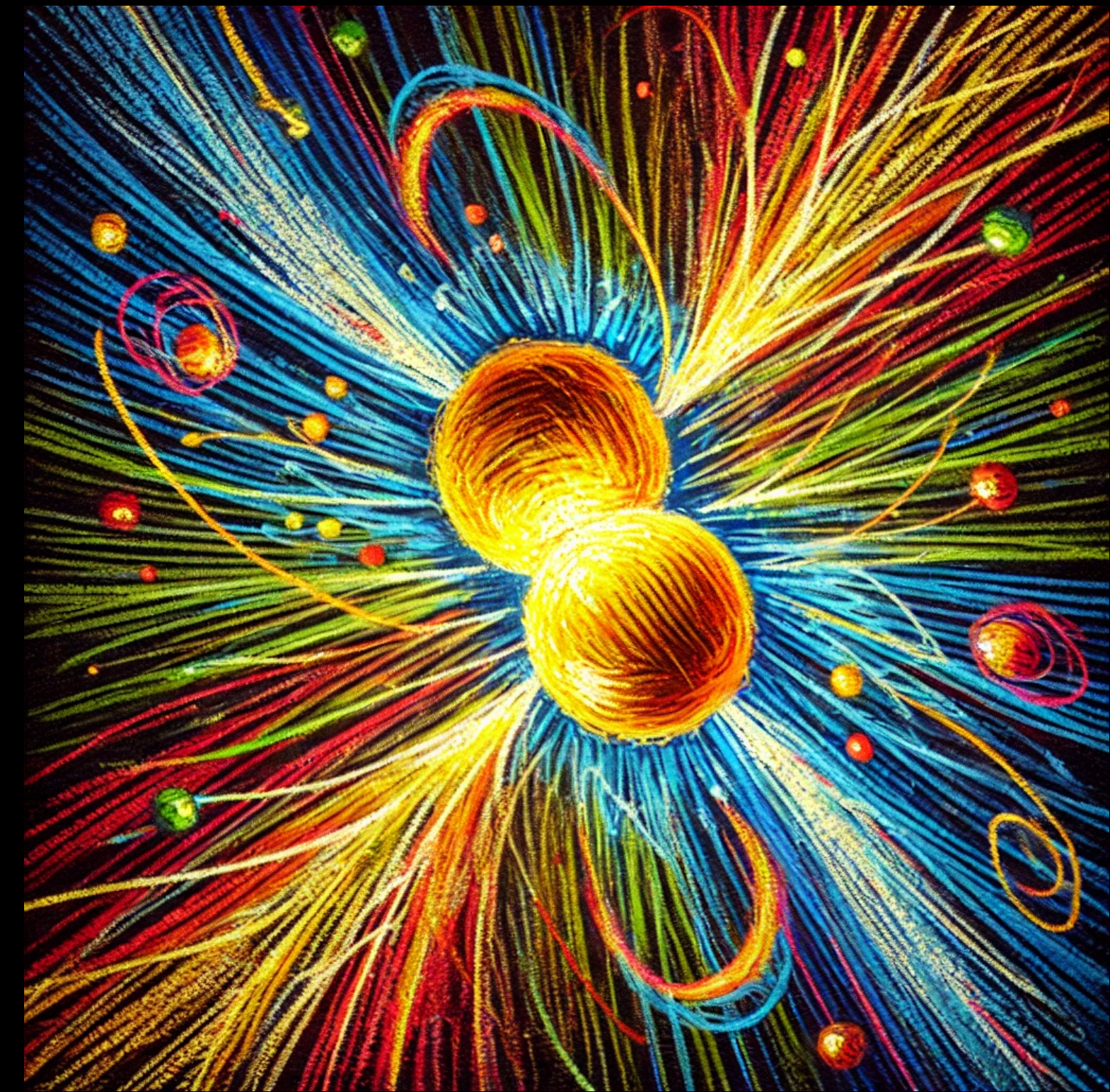


QCD Phase Structure at High Density Region

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

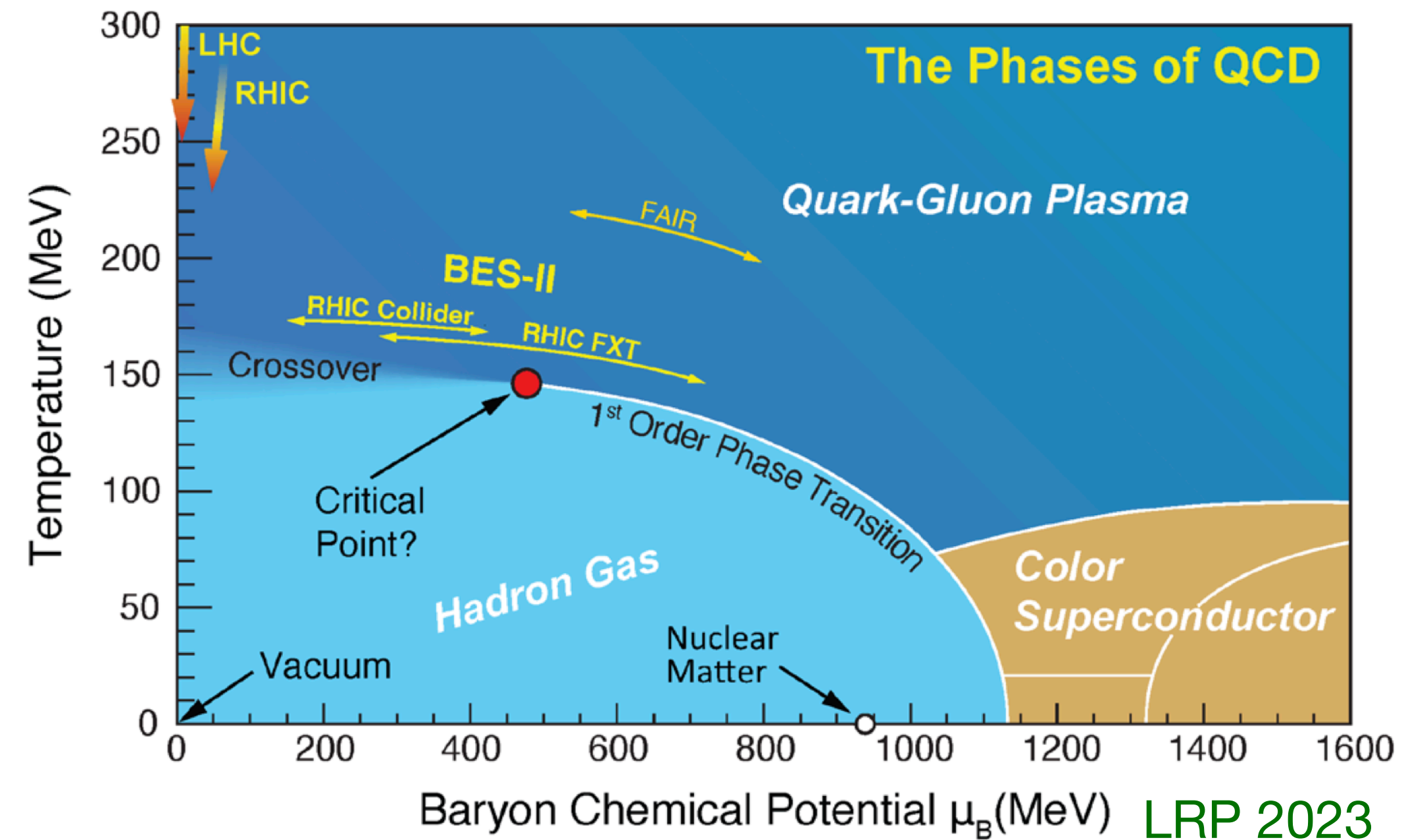
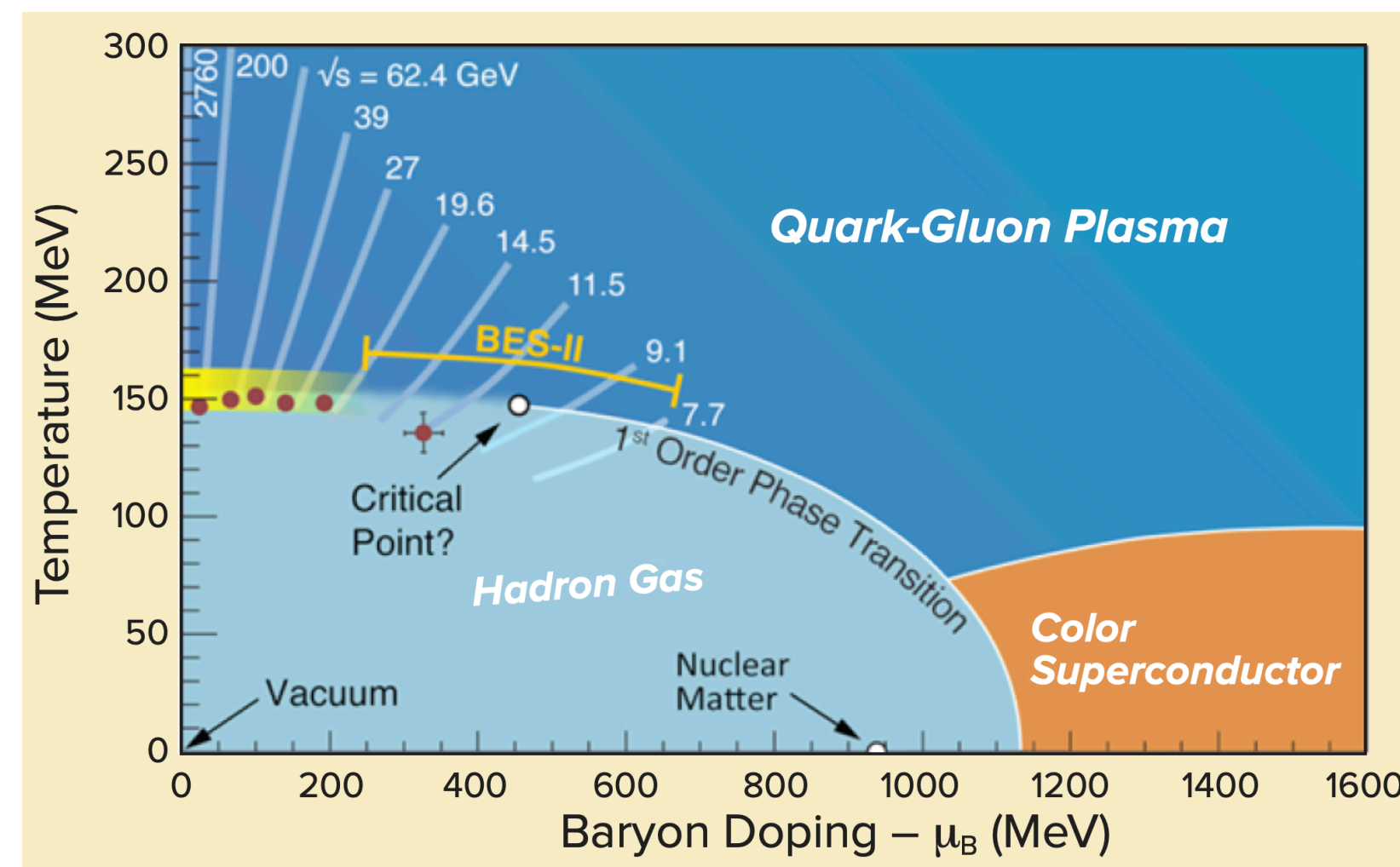
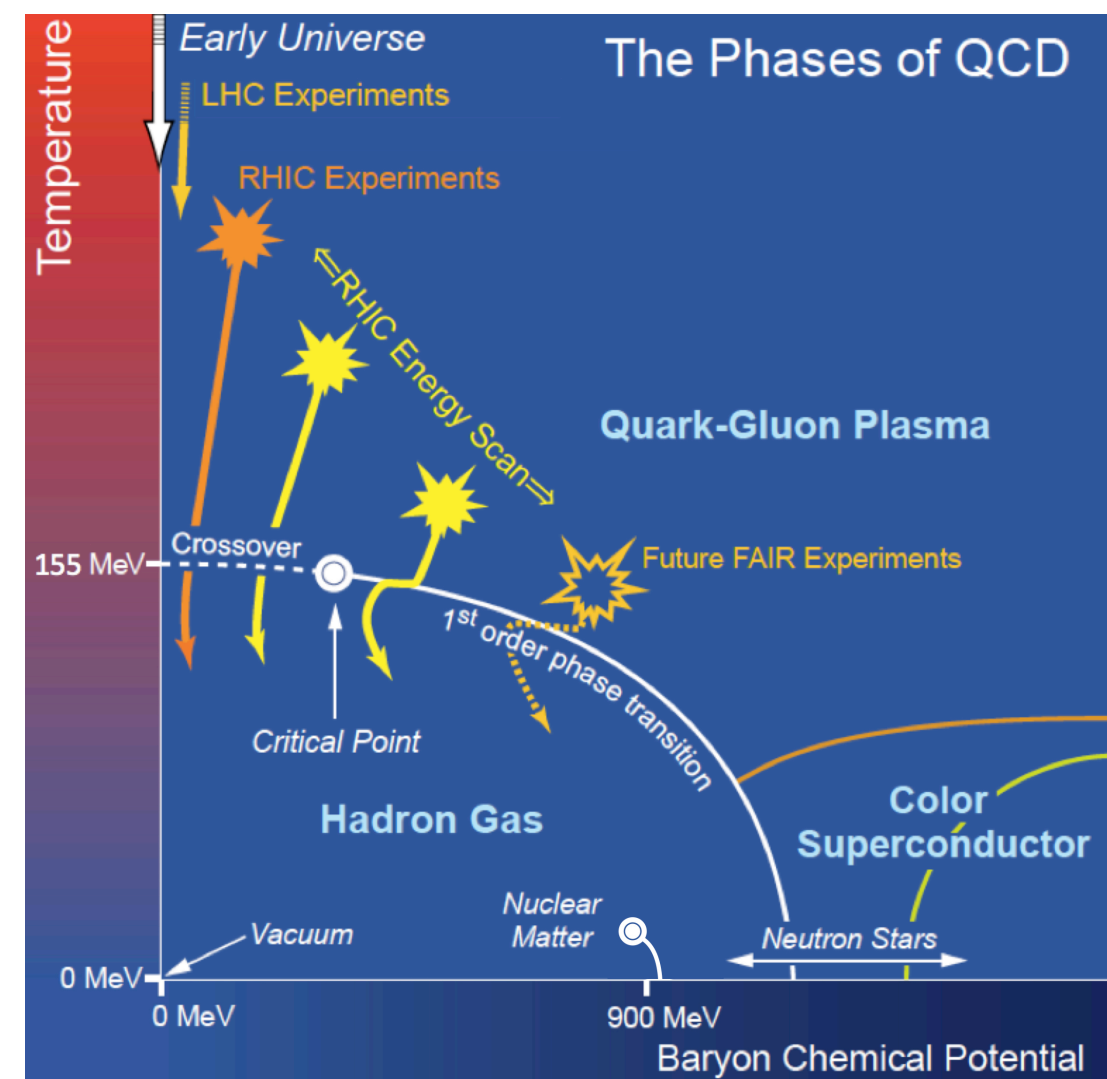
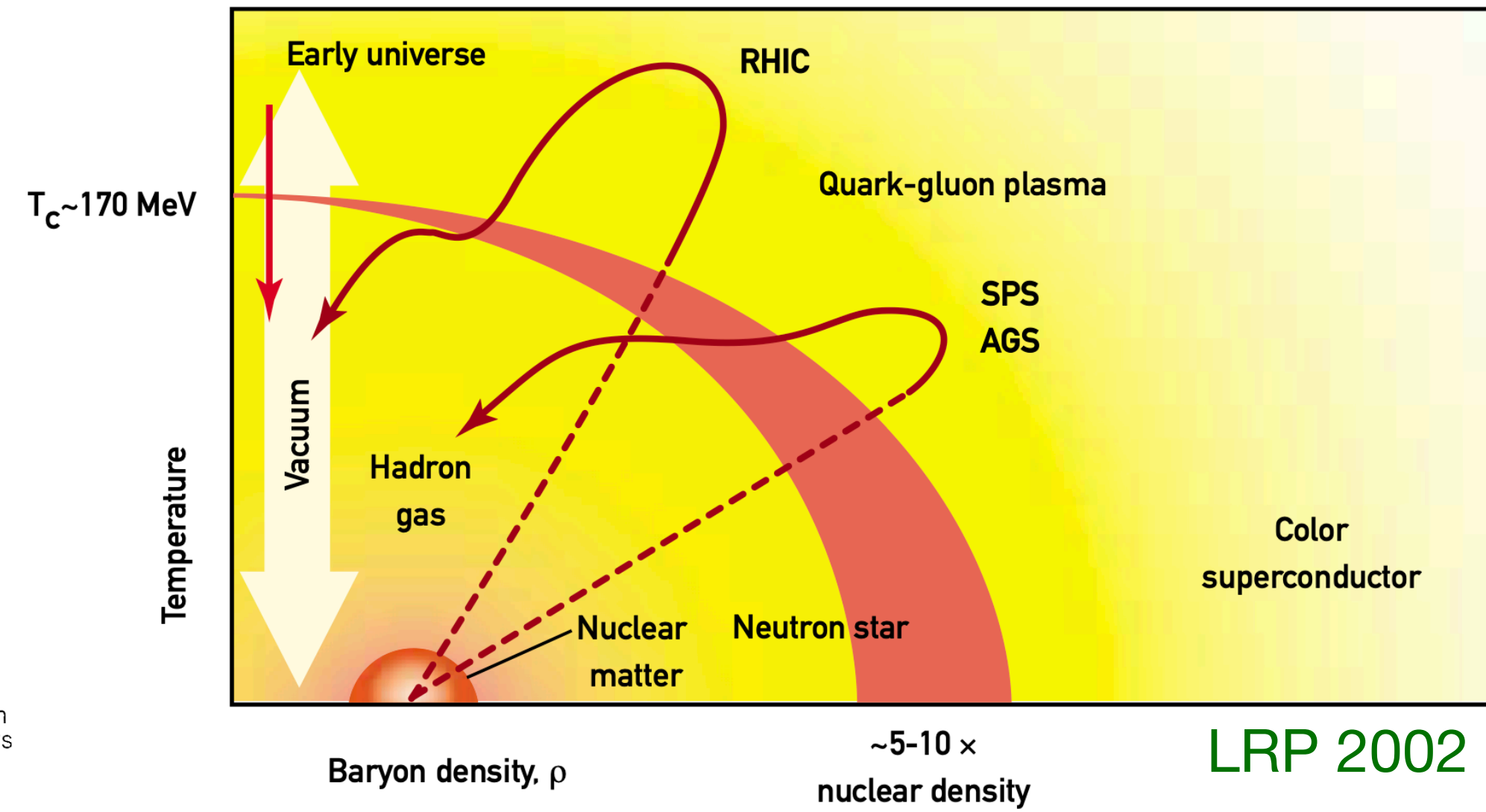
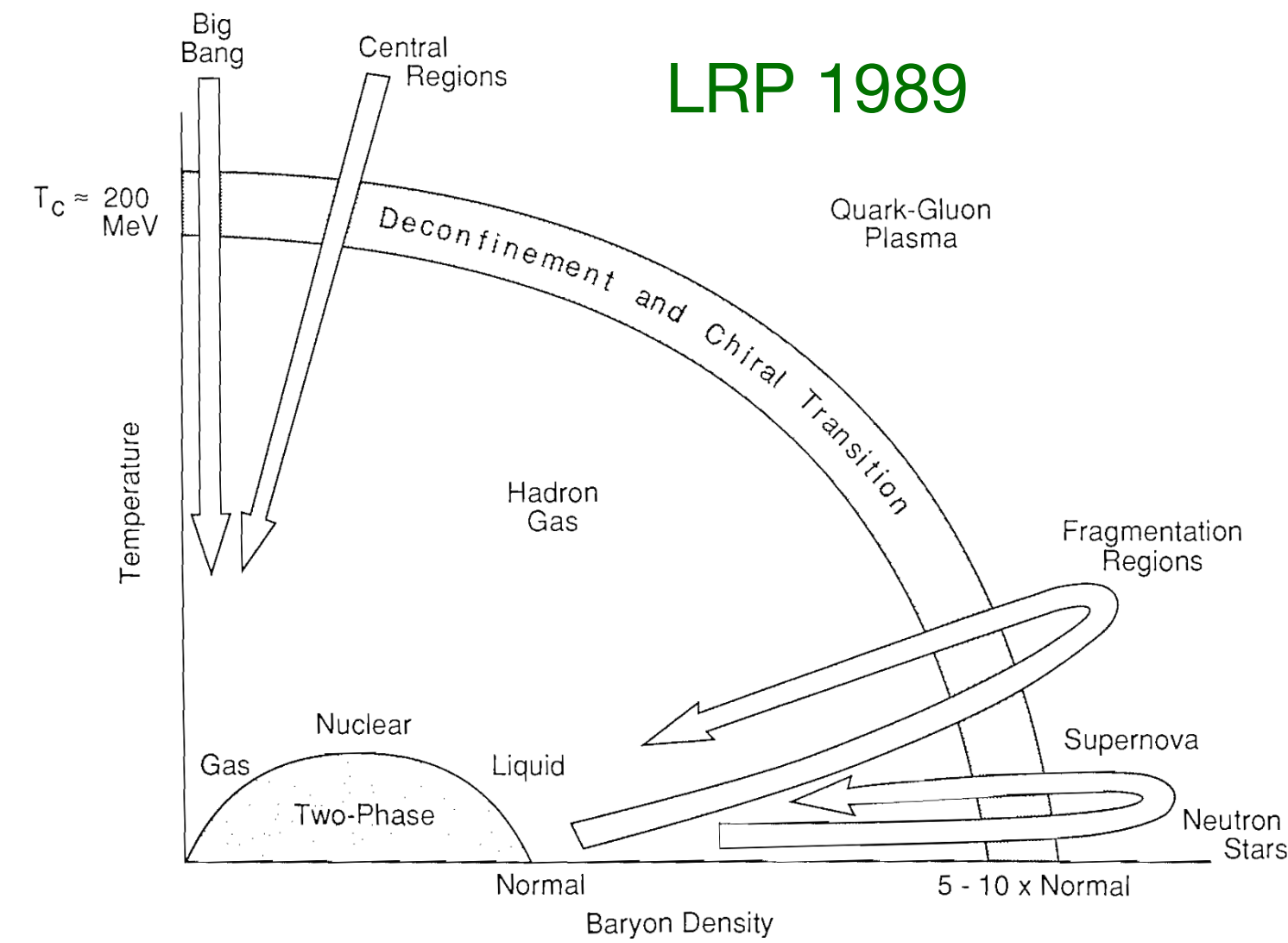
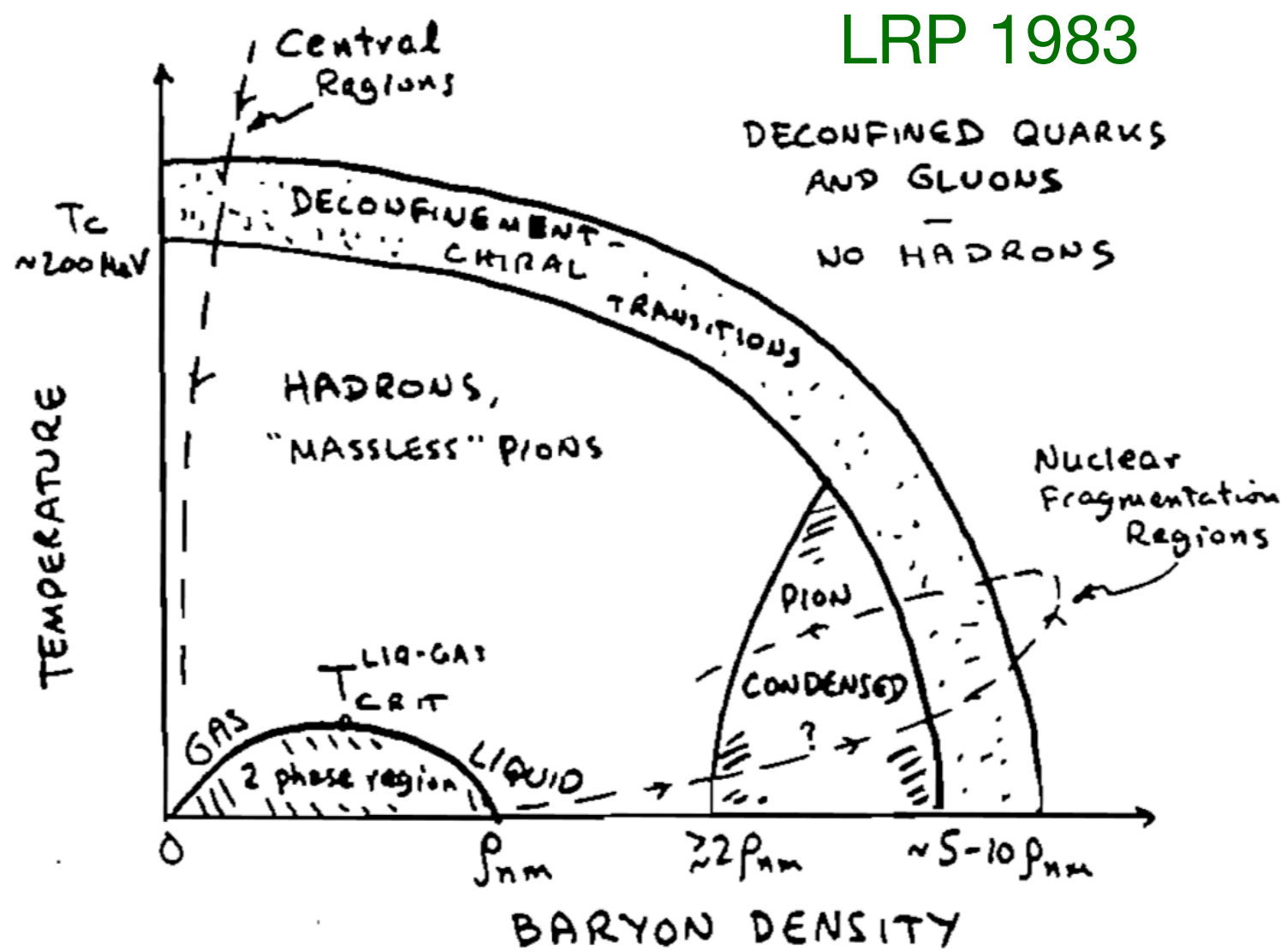
Agnieszka Sorensen

Facility for Rare Isotope Beams
Michigan State University

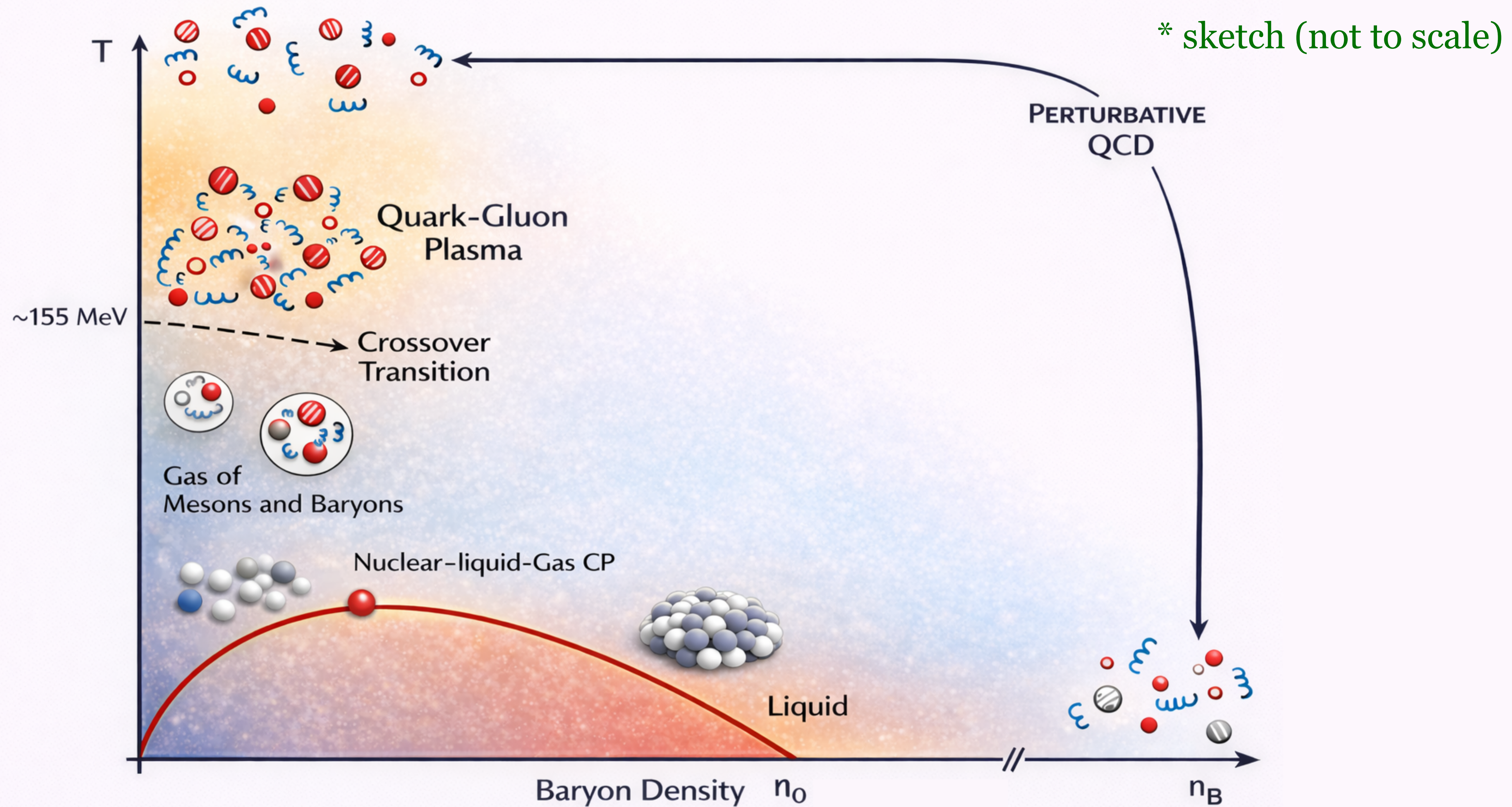


The QCD phase diagram as seen in U.S. Long Range Plans

PHASE DIAGRAM OF NUCLEAR MATTER

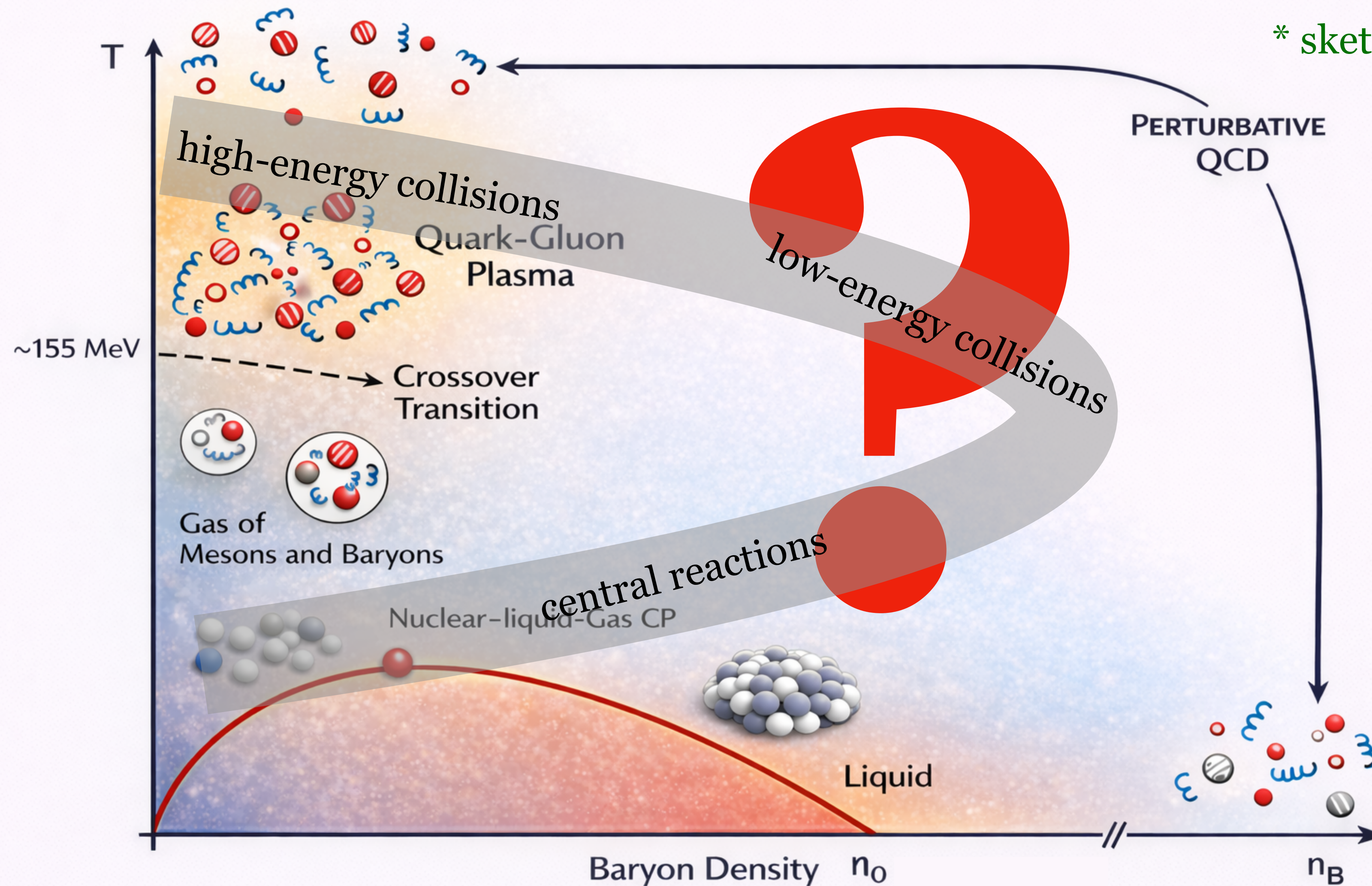


What do we *really* know about the high density region?*

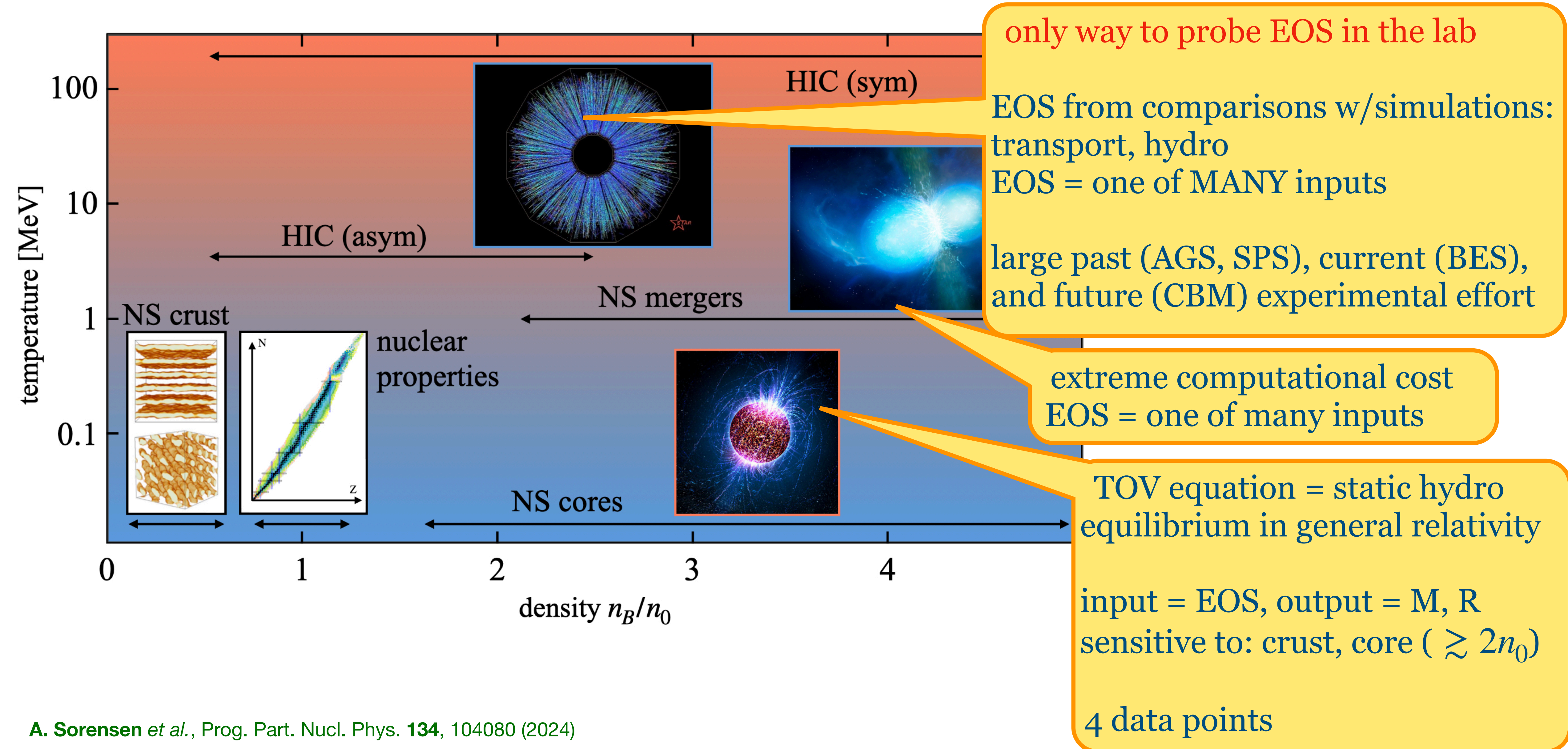


What do we *really* know about the high density region?*

* sketch (not to scale)



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

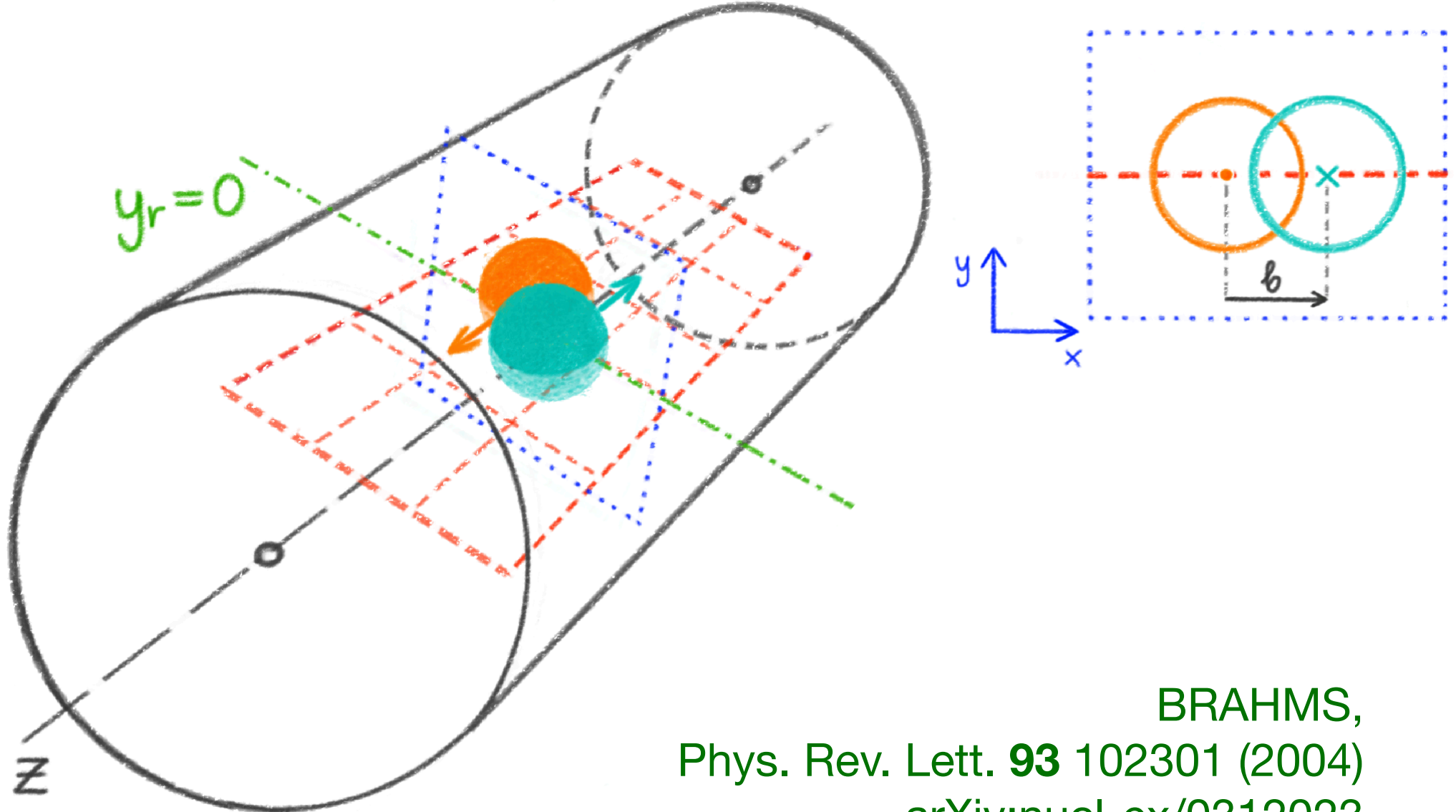
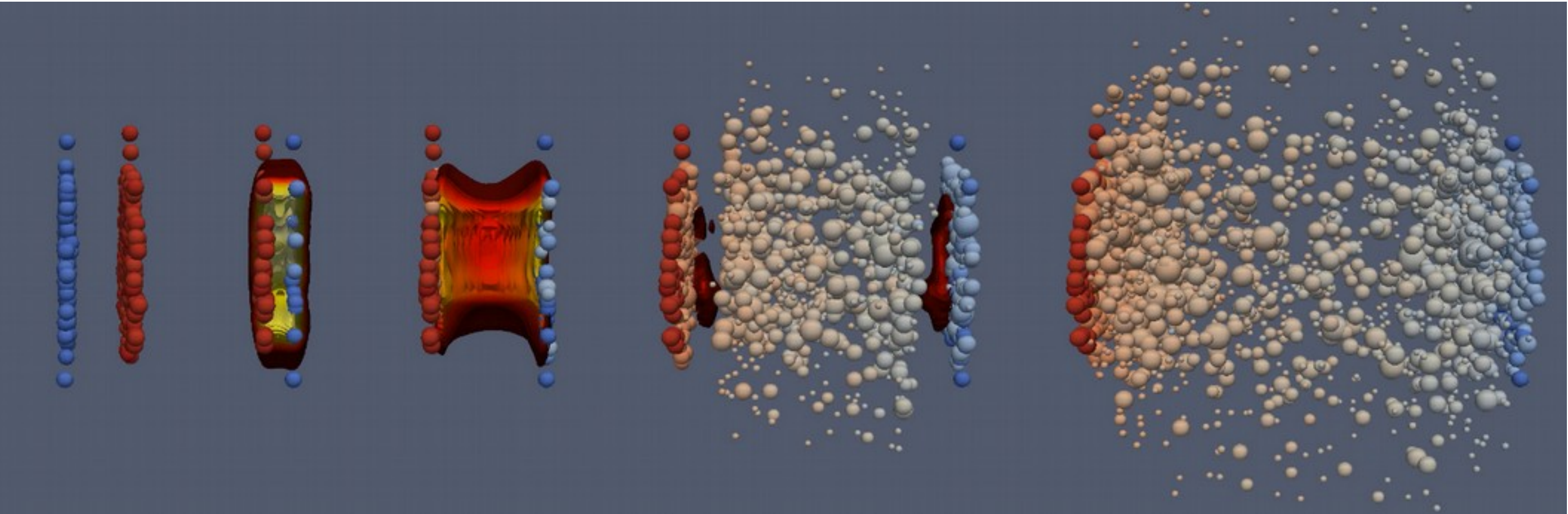


A. Sorensen et al., Prog. Part. Nucl. Phys. **134**, 104080 (2024)

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

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

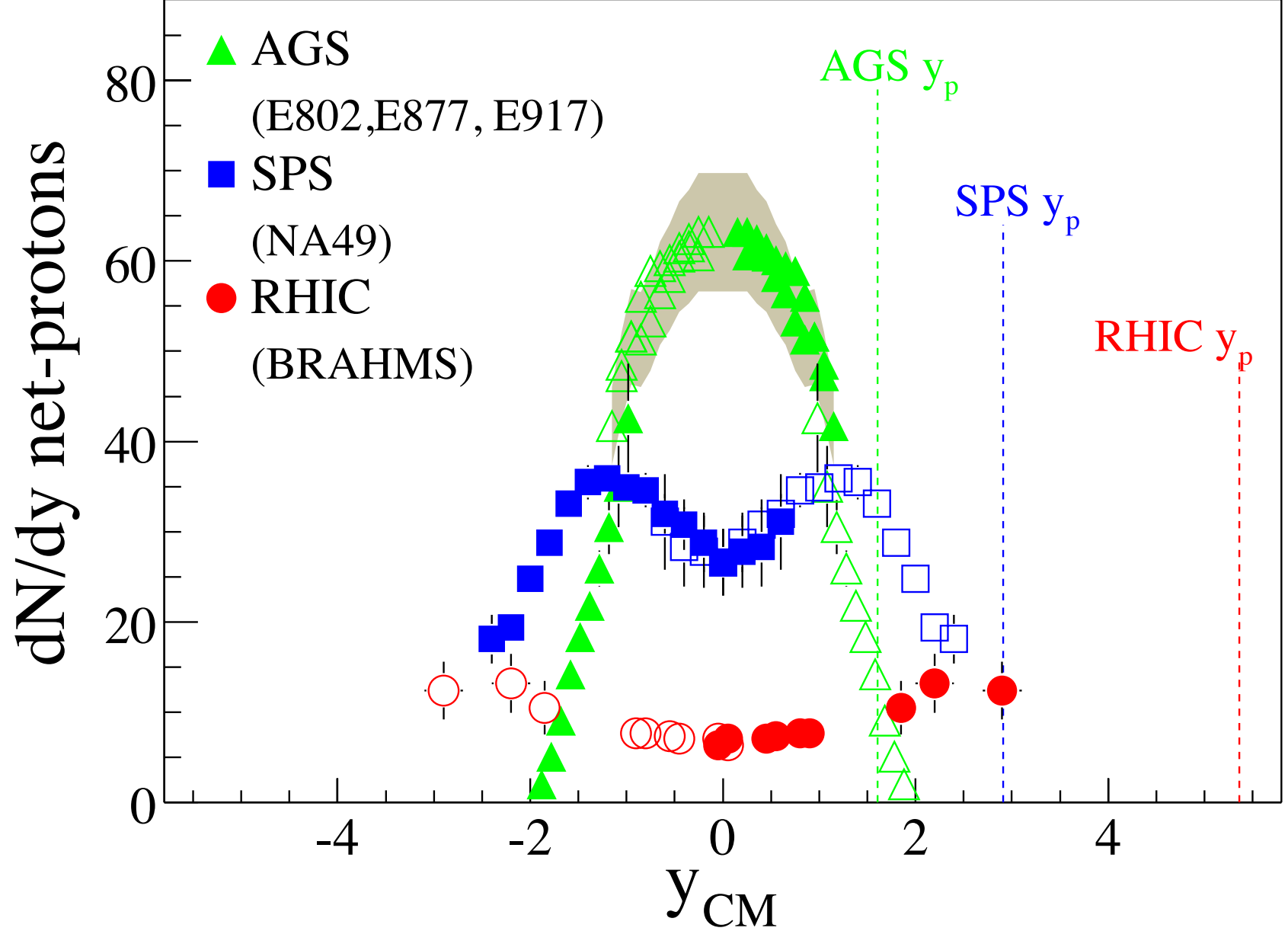
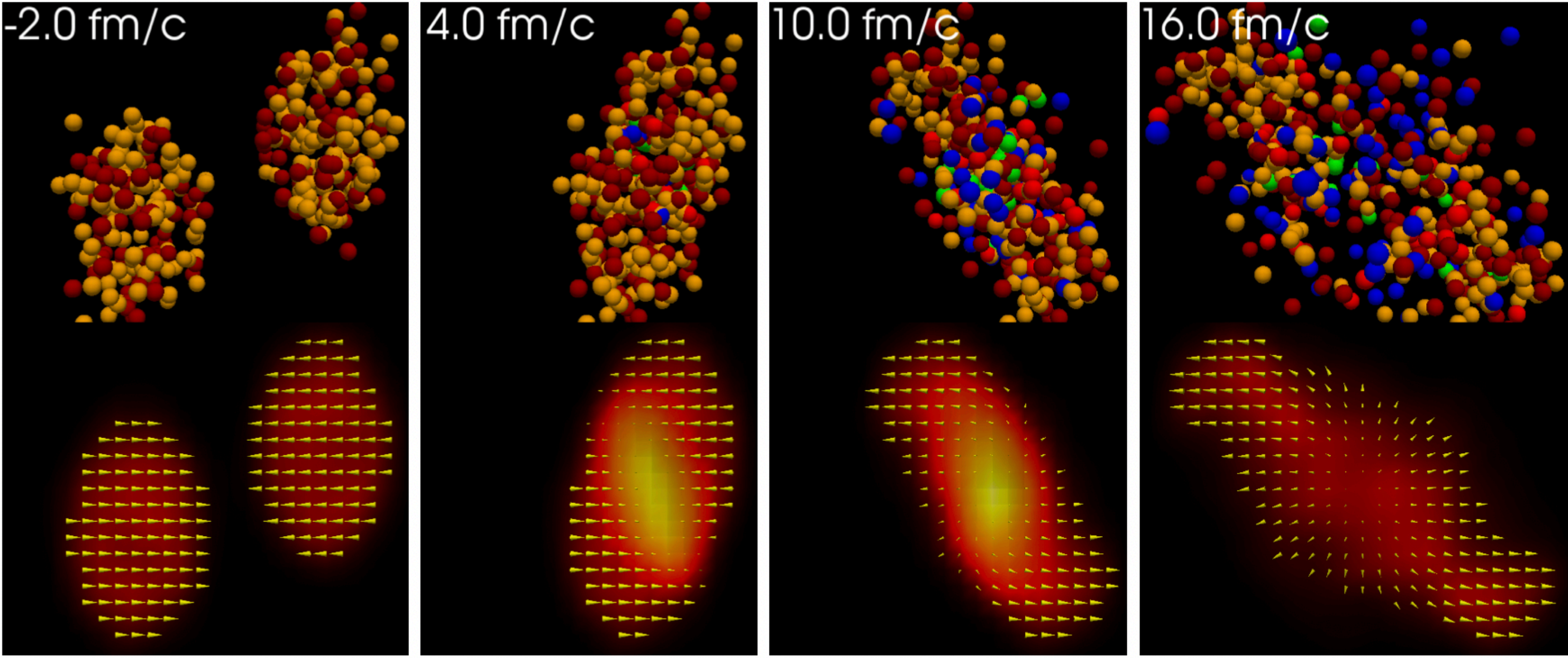
H. Elfner (Petersen), J. Bernhard, MADAI collaboration

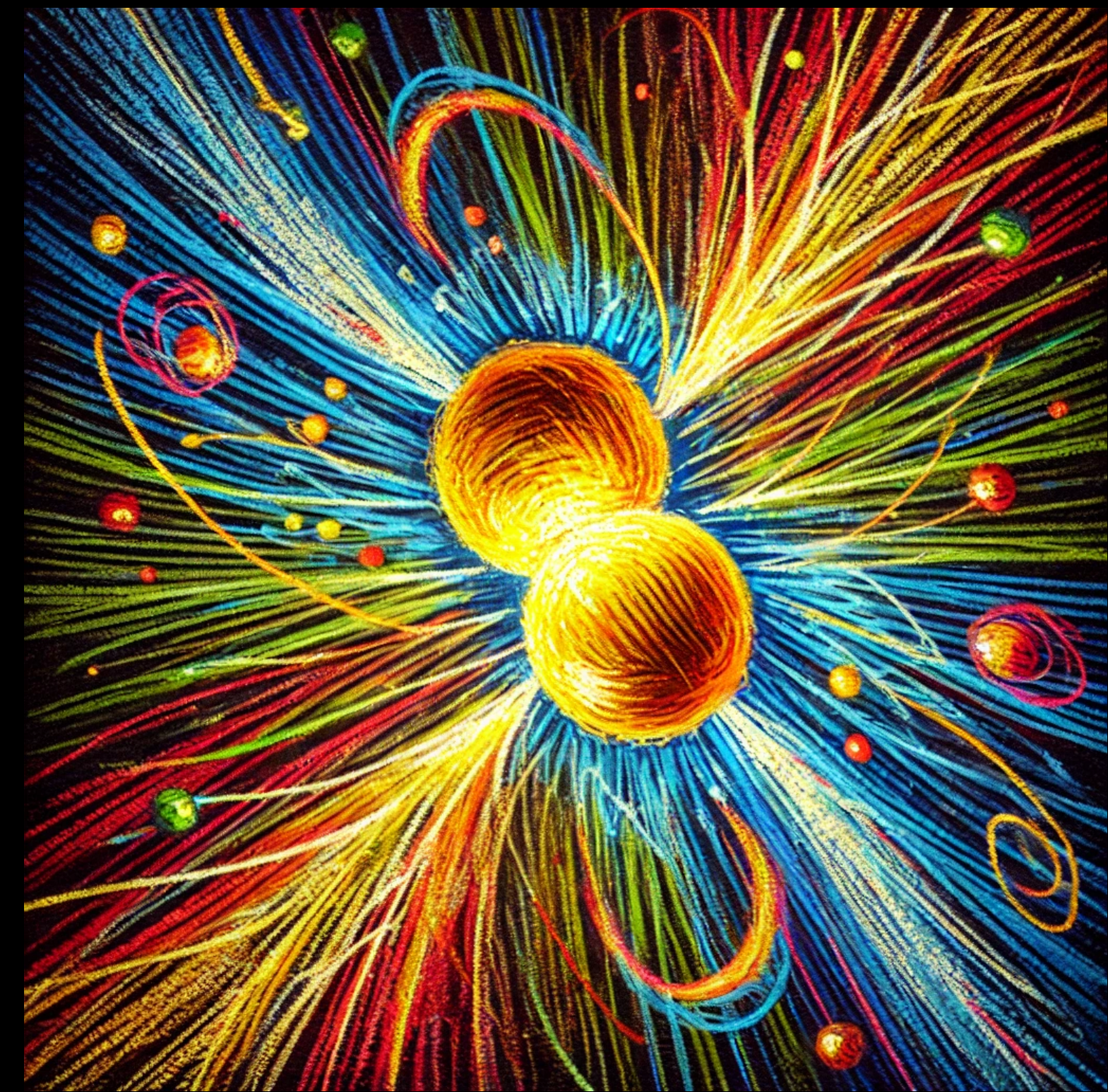


BRAHMS,
Phys. Rev. Lett. **93** 102301 (2004)
arXiv:nucl-ex/0312023

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

from D. Oliinychenko's slides





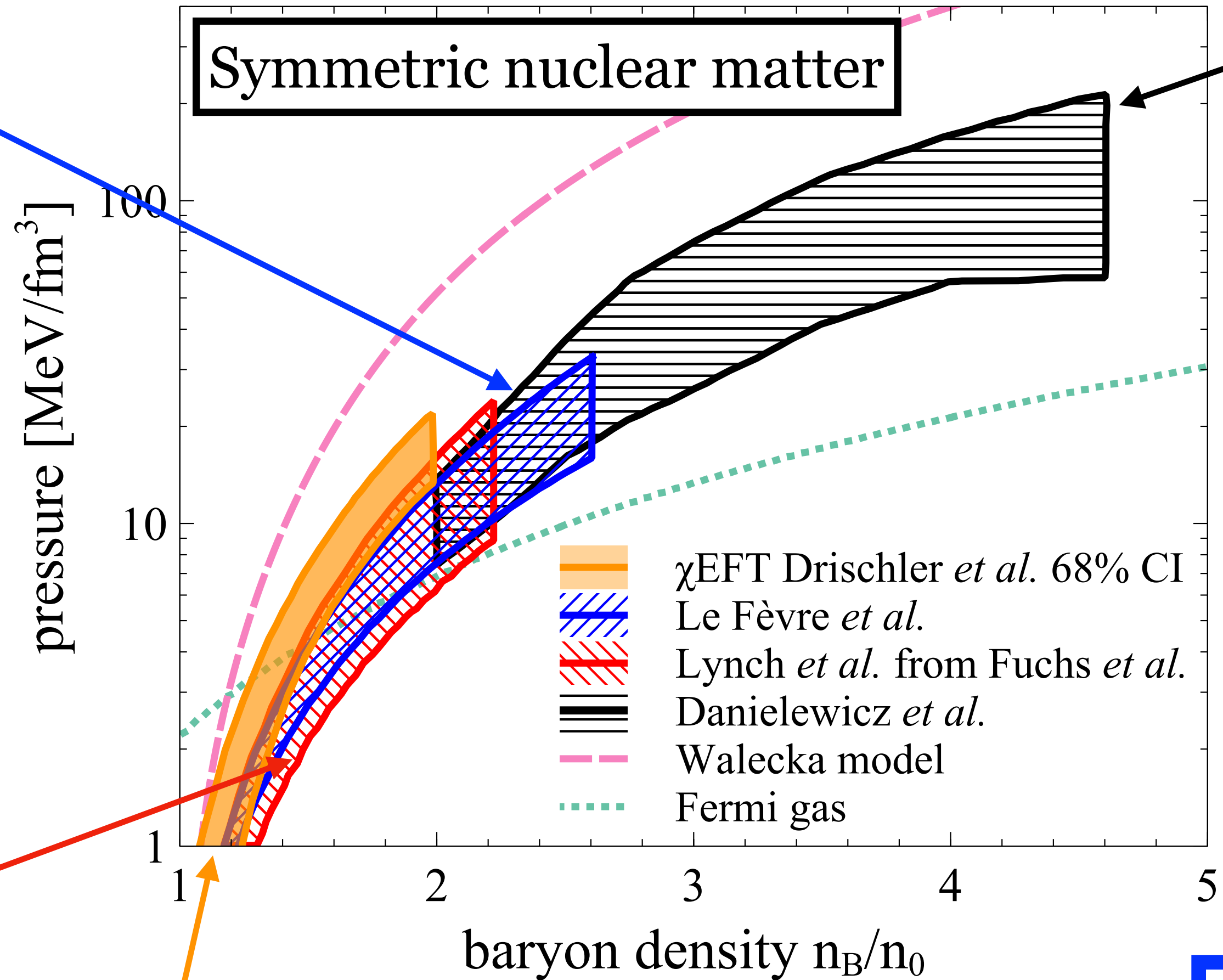
DALL-E

Selected results for the EOS
@ high baryon density

EOS of symmetric nuclear matter: *selected* results

197Au+197Au @ 0.4–1.5 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



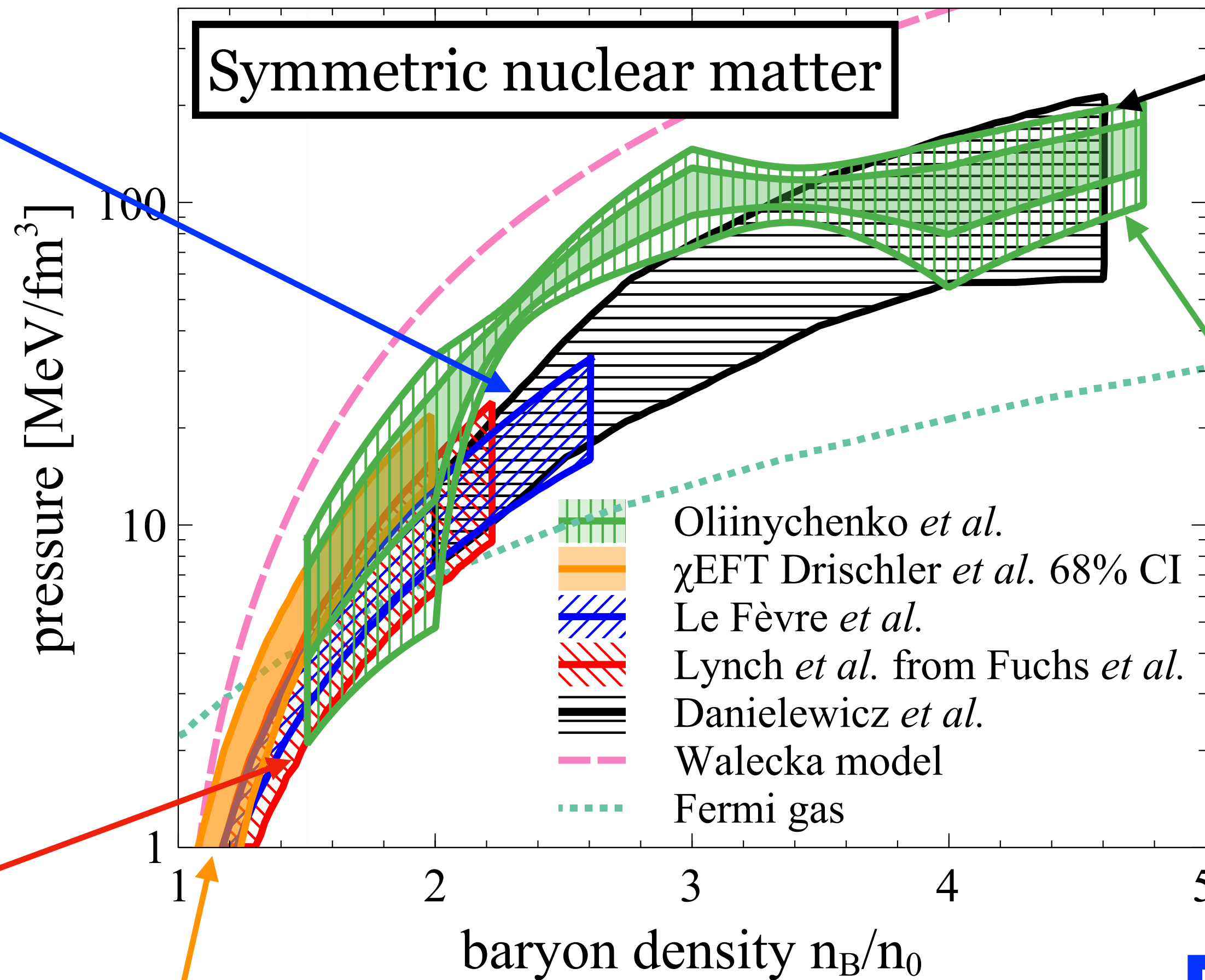
197Au+197Au @ 0.15–10 GeV/u
 ($\sqrt{s_{NN}} = 1.95 - 4.72$ GeV)
 observables: proton flow
 (Plastic Ball, EOS, E877, E895)
 model used: **pBUU** w/ nucleons, Δ ,
 $N^*(1440)$, pions;
 EOS parametrized by K_0 ;
 momentum dependence
 P. Danielewicz, R. Lacey, W. G. Lynch,
 Science **298**,1592–1596 (2002)

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

“old” models:
 limited particle lists
 momentum dependence
 limited variation in the EOS

EOS of symmetric nuclear matter: *selected* results

Symmetric nuclear matter



197Au+197Au @ 0.4–1.5 GeV/u
 $(\sqrt{s_{NN}} = 2.07 - 2.52 \text{ GeV})$
 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 @ 0.15–10 GeV/u
 $(\sqrt{s_{NN}} = 1.95 - 4.72 \text{ GeV})$
 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
 $(\sqrt{s_{NN}} = 3 - 4.5 \text{ GeV})$
 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)

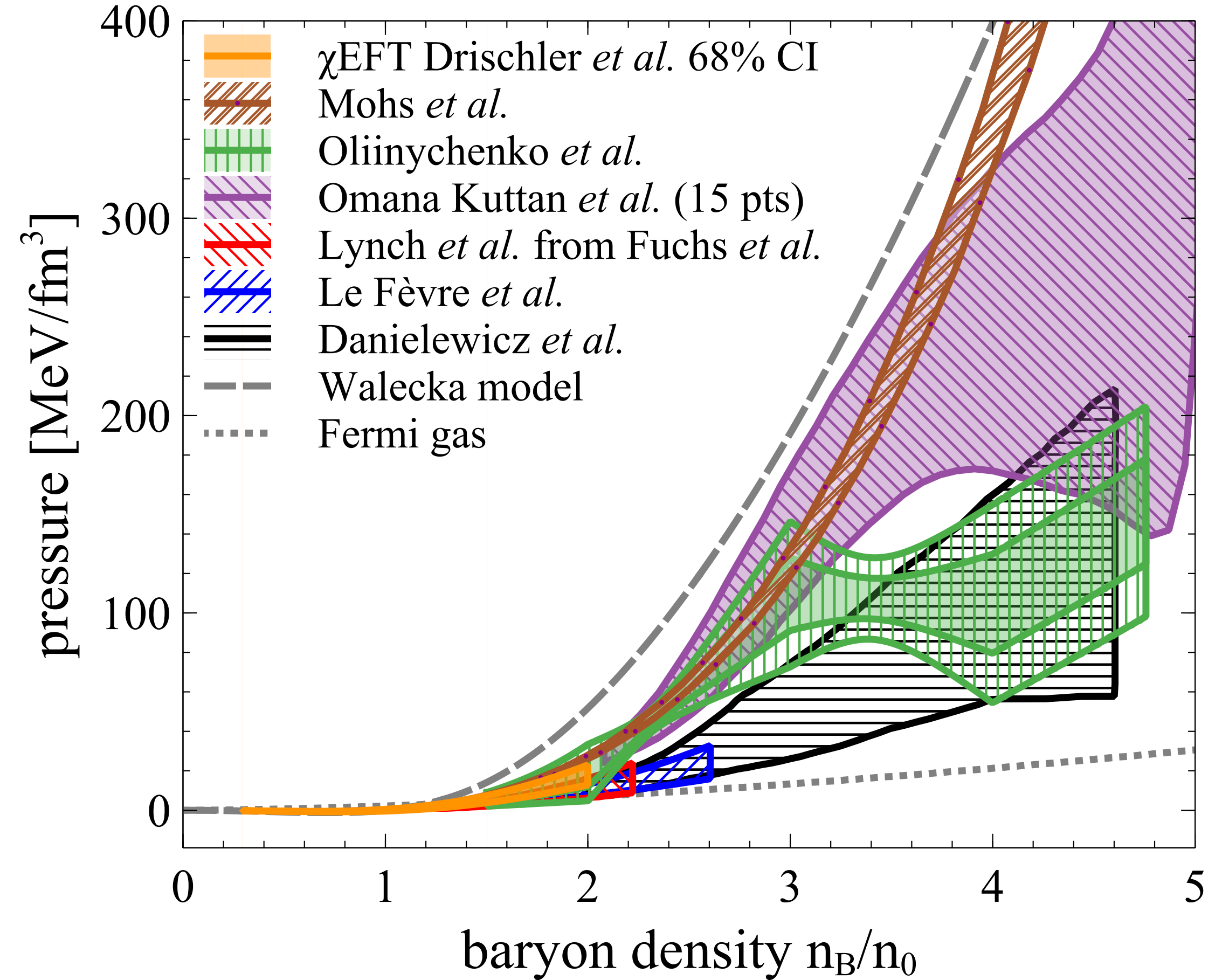
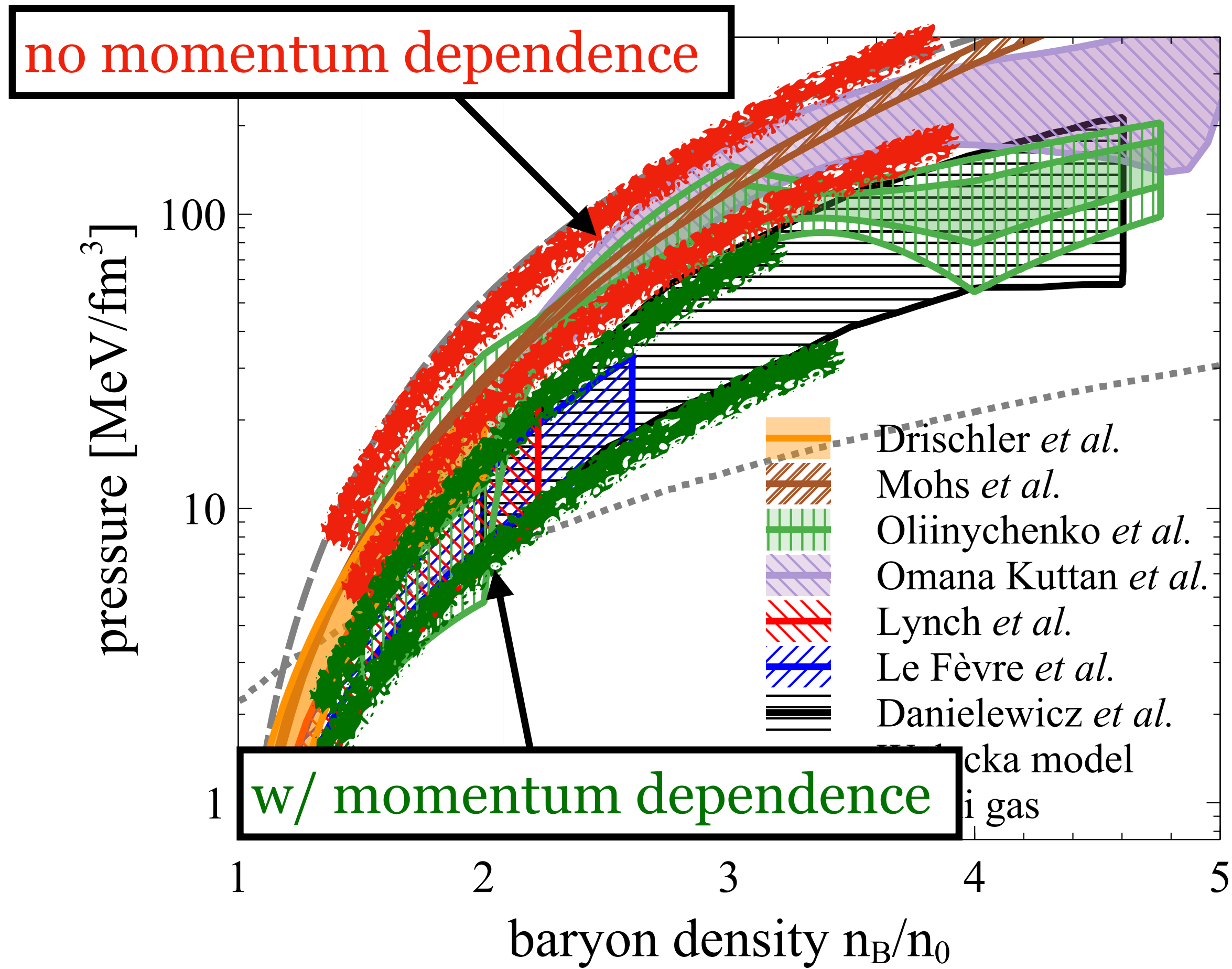
197Au+197Au & 12C+12C @ < 1.5 GeV/u
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 $N^*(1440)$, pions, kaons;
 EOS parametrized by K_0 ;
 kaon potentials, momentum dependence
 C. Fuchs *et al.*, Prog. Part. Nucl. Phys. **53**,
 113–124 (2004) arXiv:nucl-th/0312052

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

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

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

EOS of symmetric nuclear matter: *selected* new results



“new” model(s):
do not agree

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)

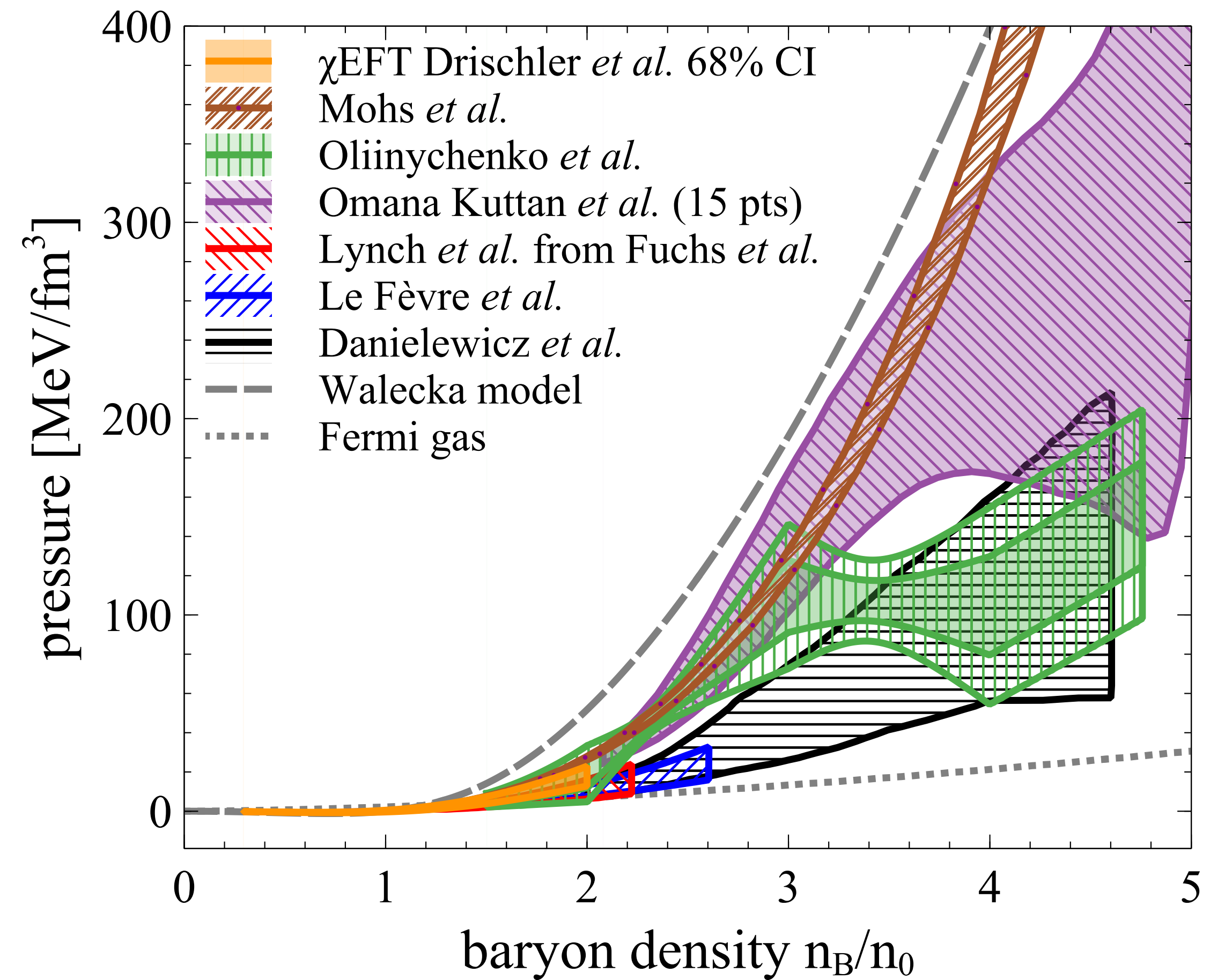
EOS of symmetric nuclear matter: *selected* new results

Results are meaningless without evaluation of model uncertainties

On the other hand, transport:

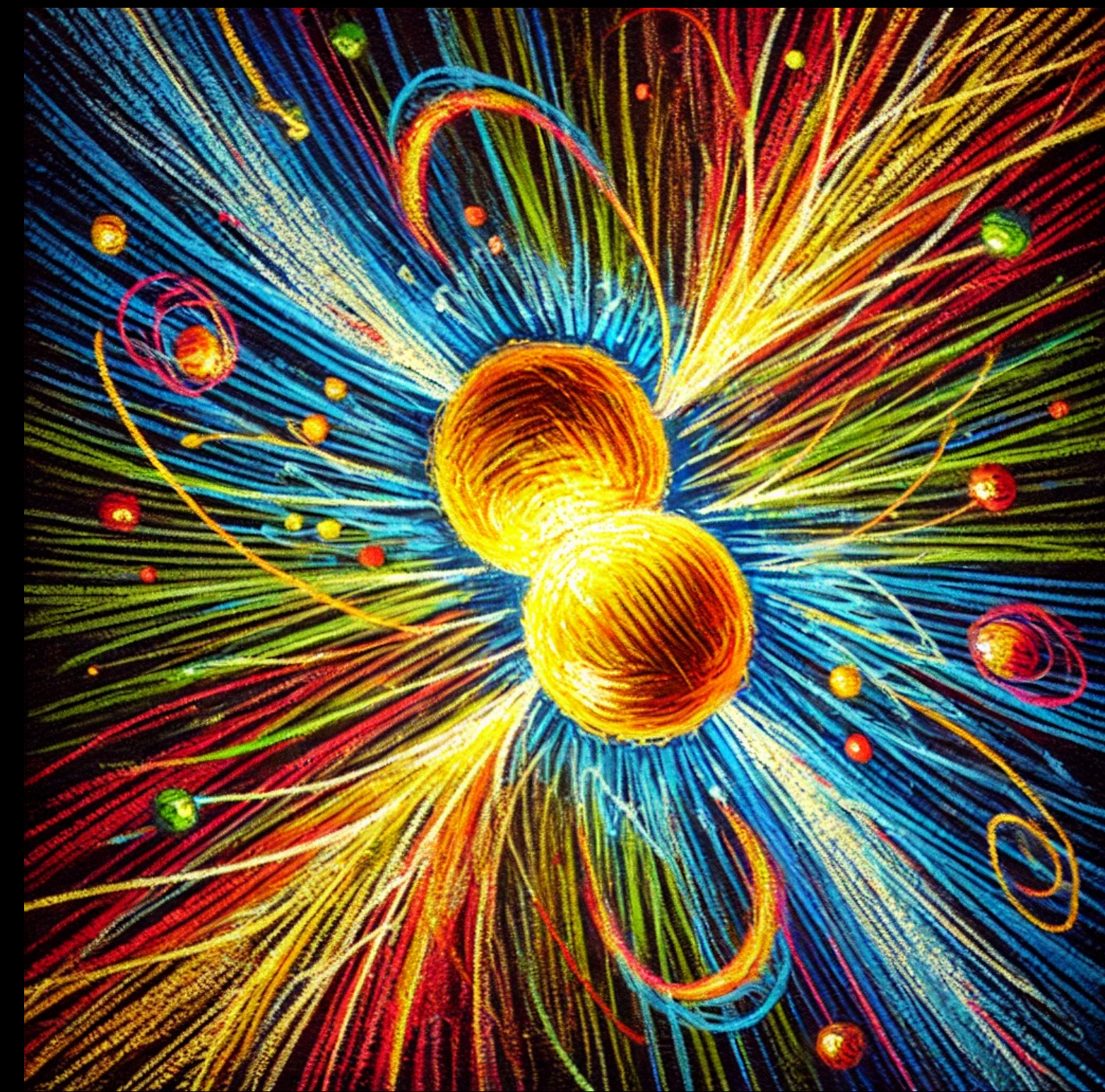
- Has good control of the initial state
- Handles non-equilibrium evolution
- No model interfaces (another source of uncertainty)

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)



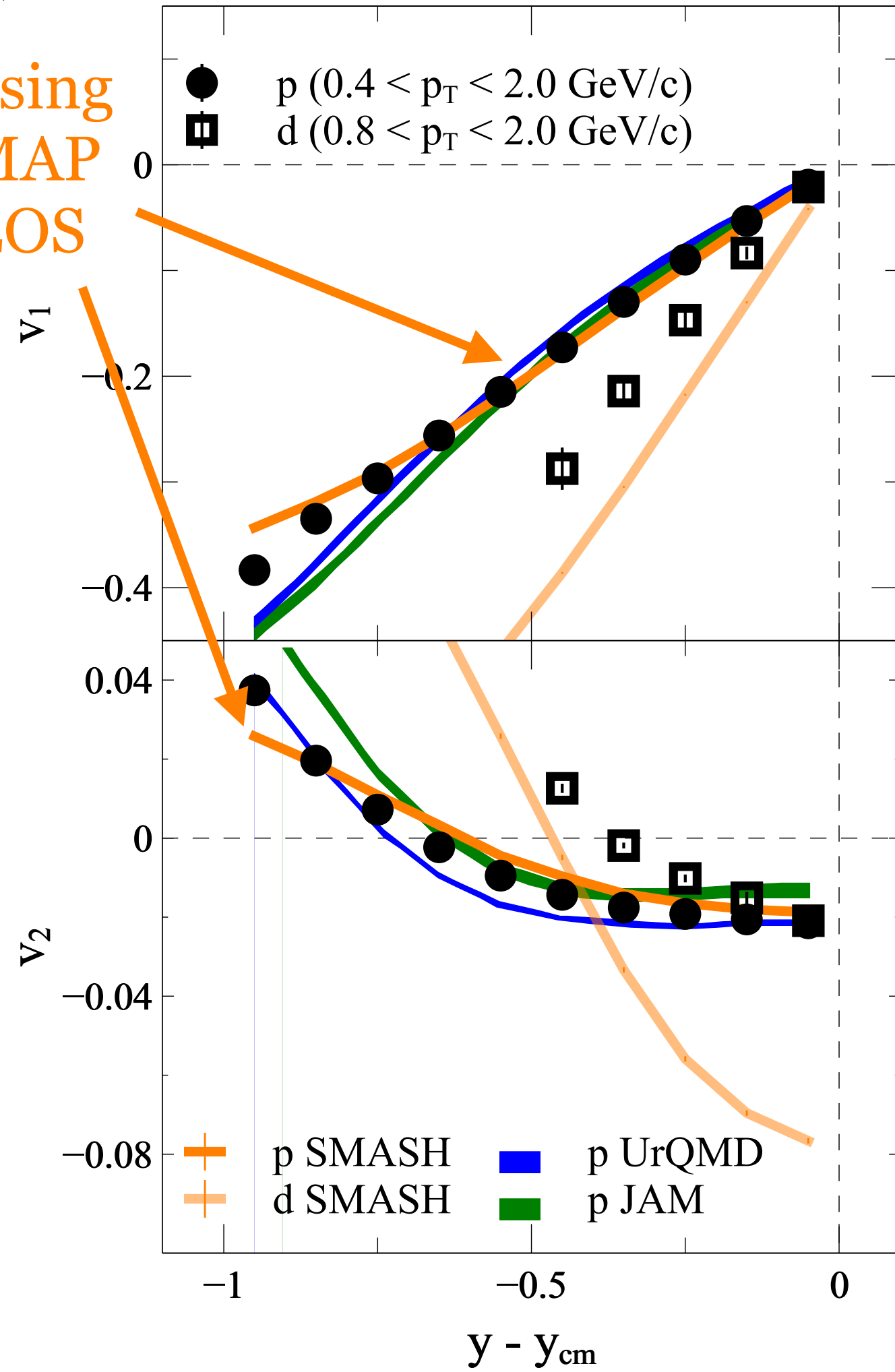
DALL-E

Glimpse of the rich physics
in HICs @ high baryon density

Describing proton flow is not enough: cluster production

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

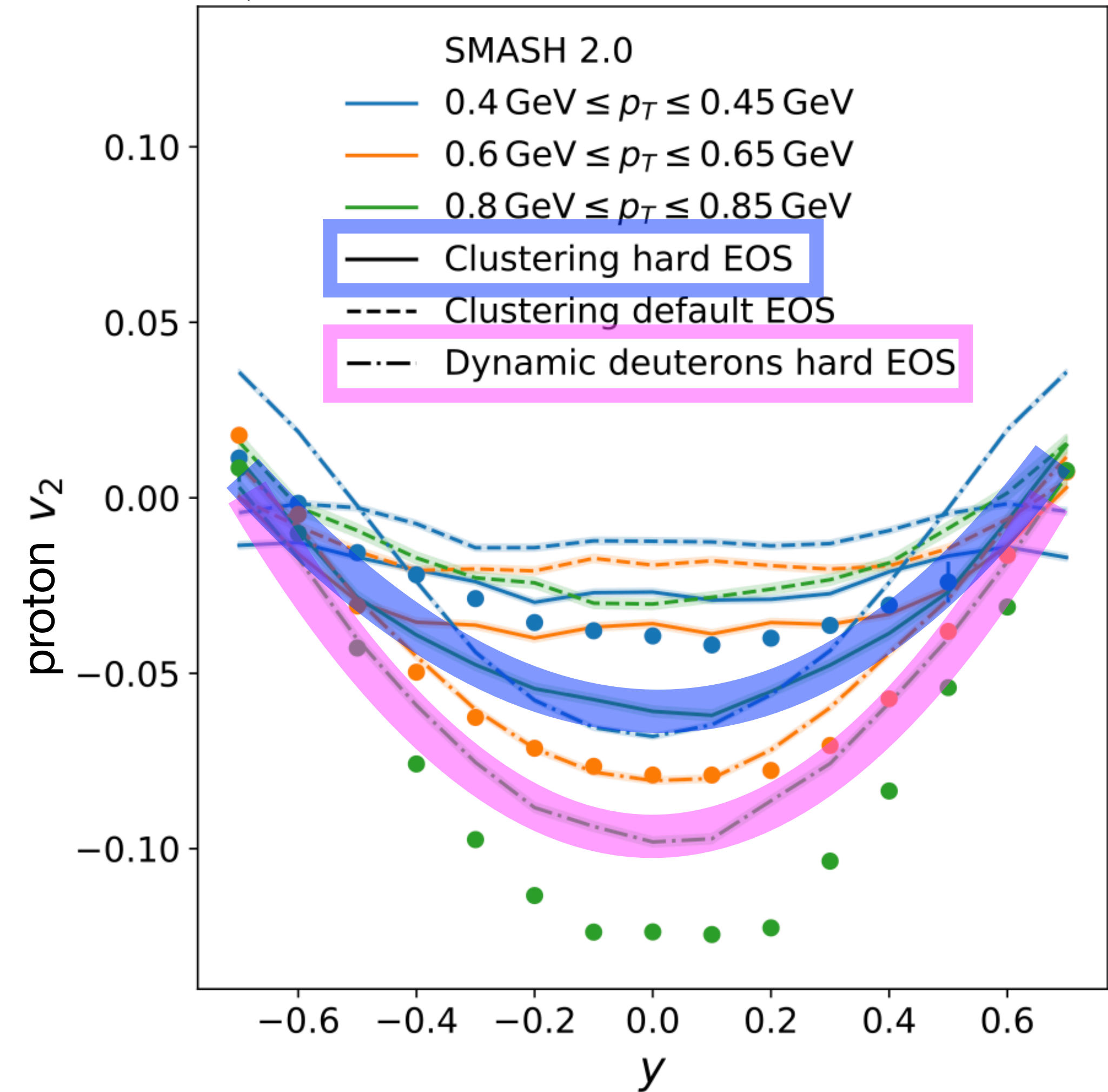
using
MAP
EOS



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

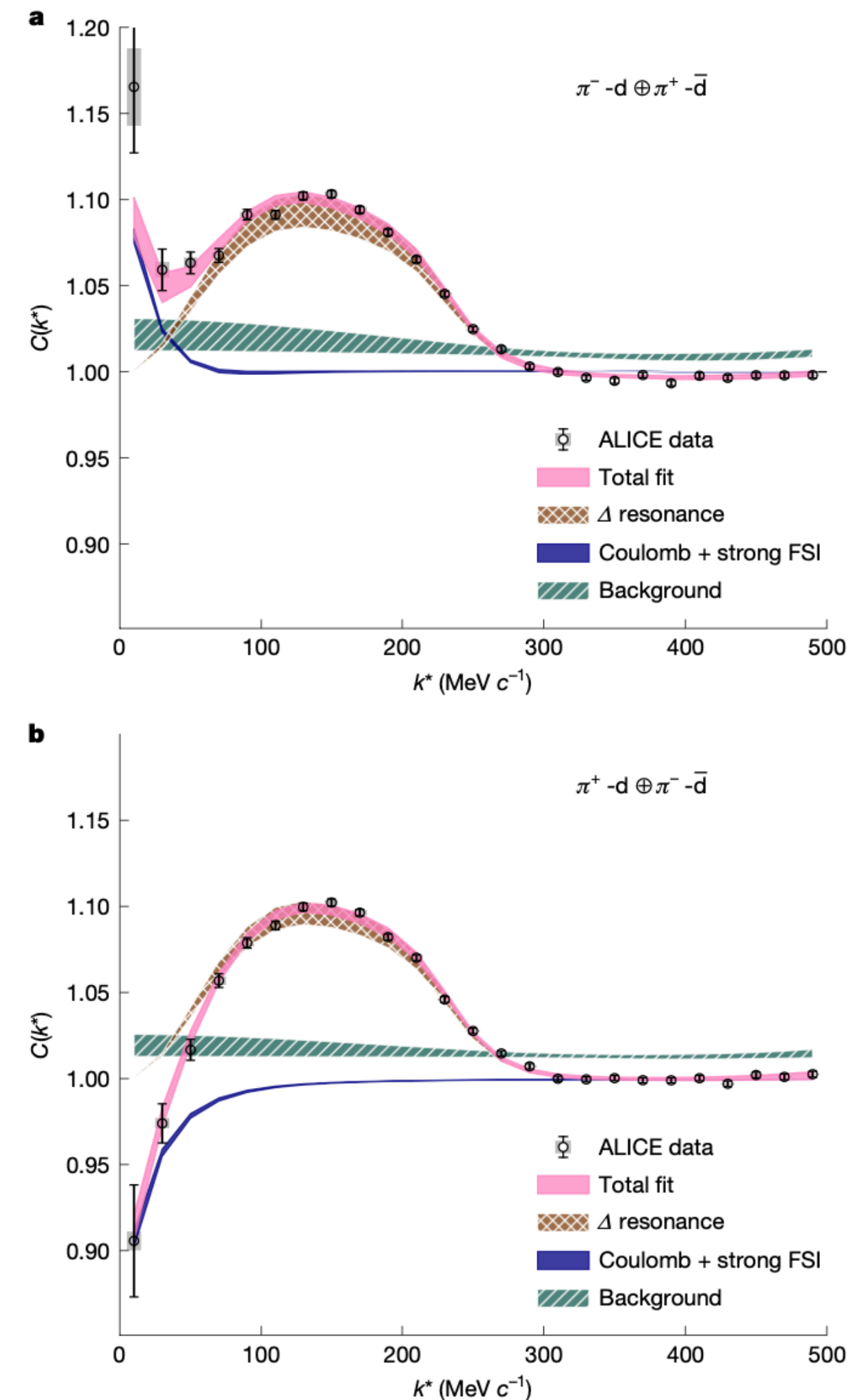
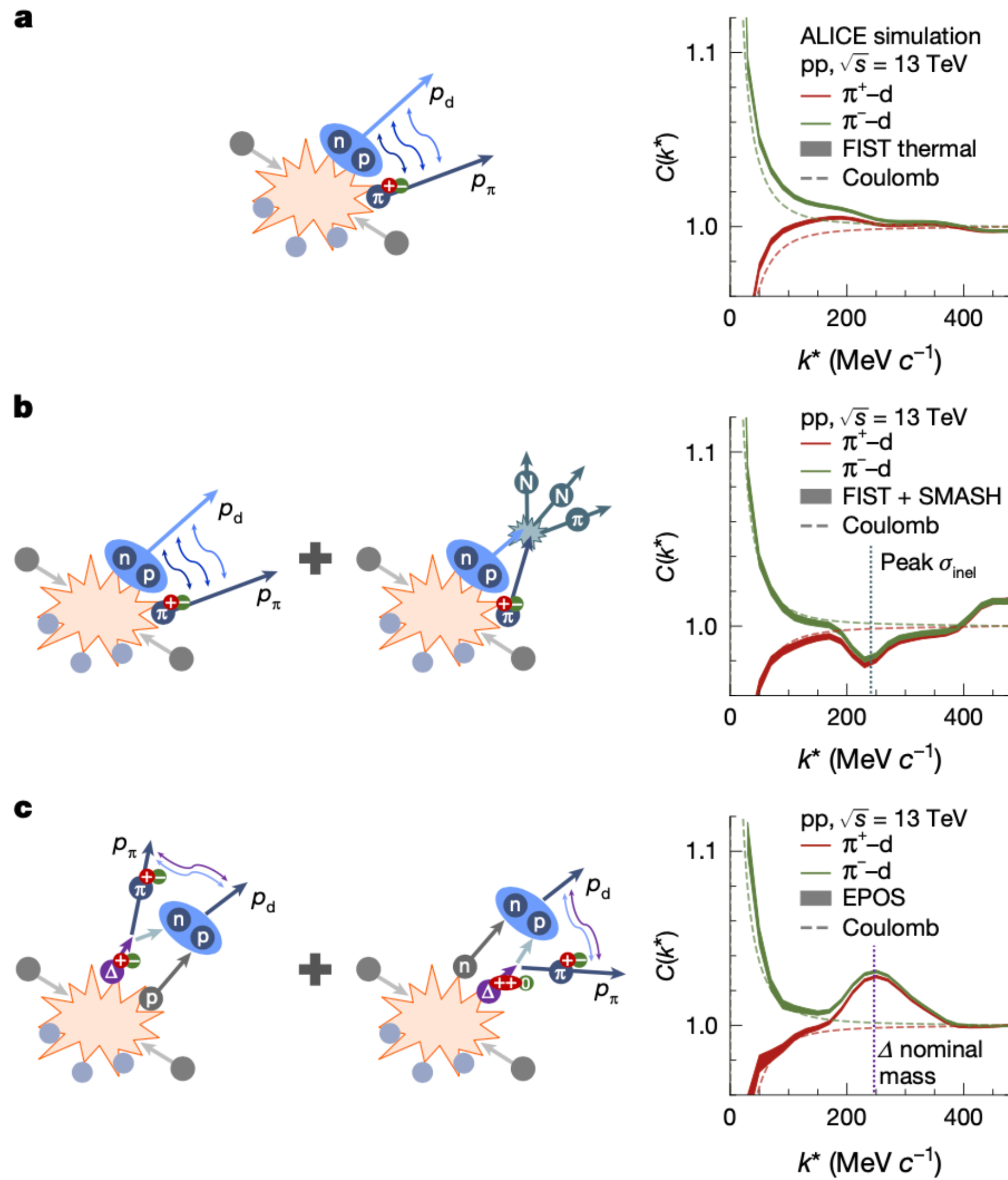
D. Oliinychenko, **A. Sorensen**, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023), arXiv:2208.11996

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

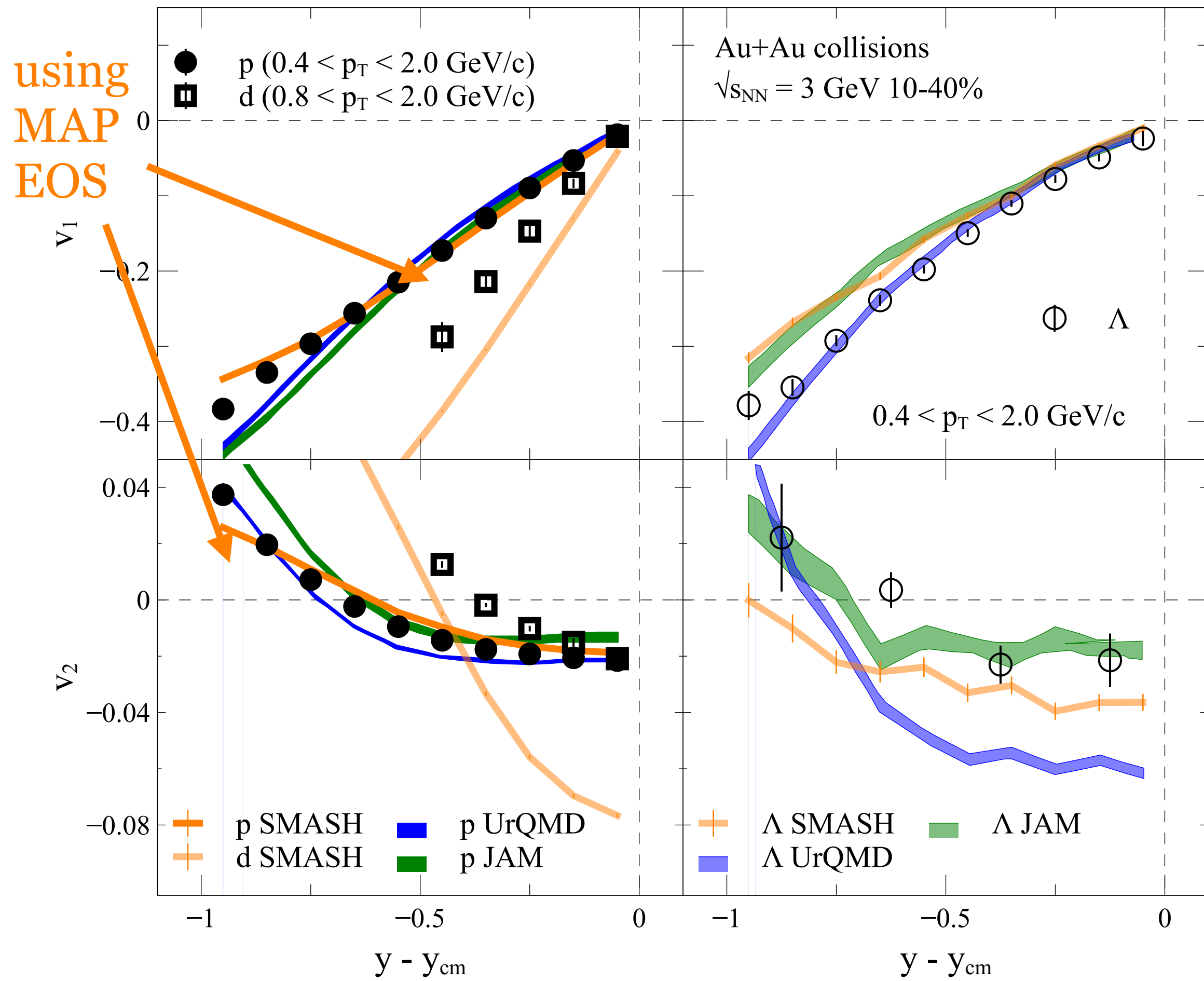
Femtoscopy: ALICE, Nature **648**, 8093, 306-311 (2025)
 ~90% of deuterons form in resonance-induced coalescence



Word of warning:
 coalescence algorithms
 (as understood in
 transport modeling) often
 do not conserve energy;
 one should be cautious to
 endorse an idea which
 does not seem to
 correspond to the
 measurement

Study at BES energies?

Describing proton flow is not enough: strange sector



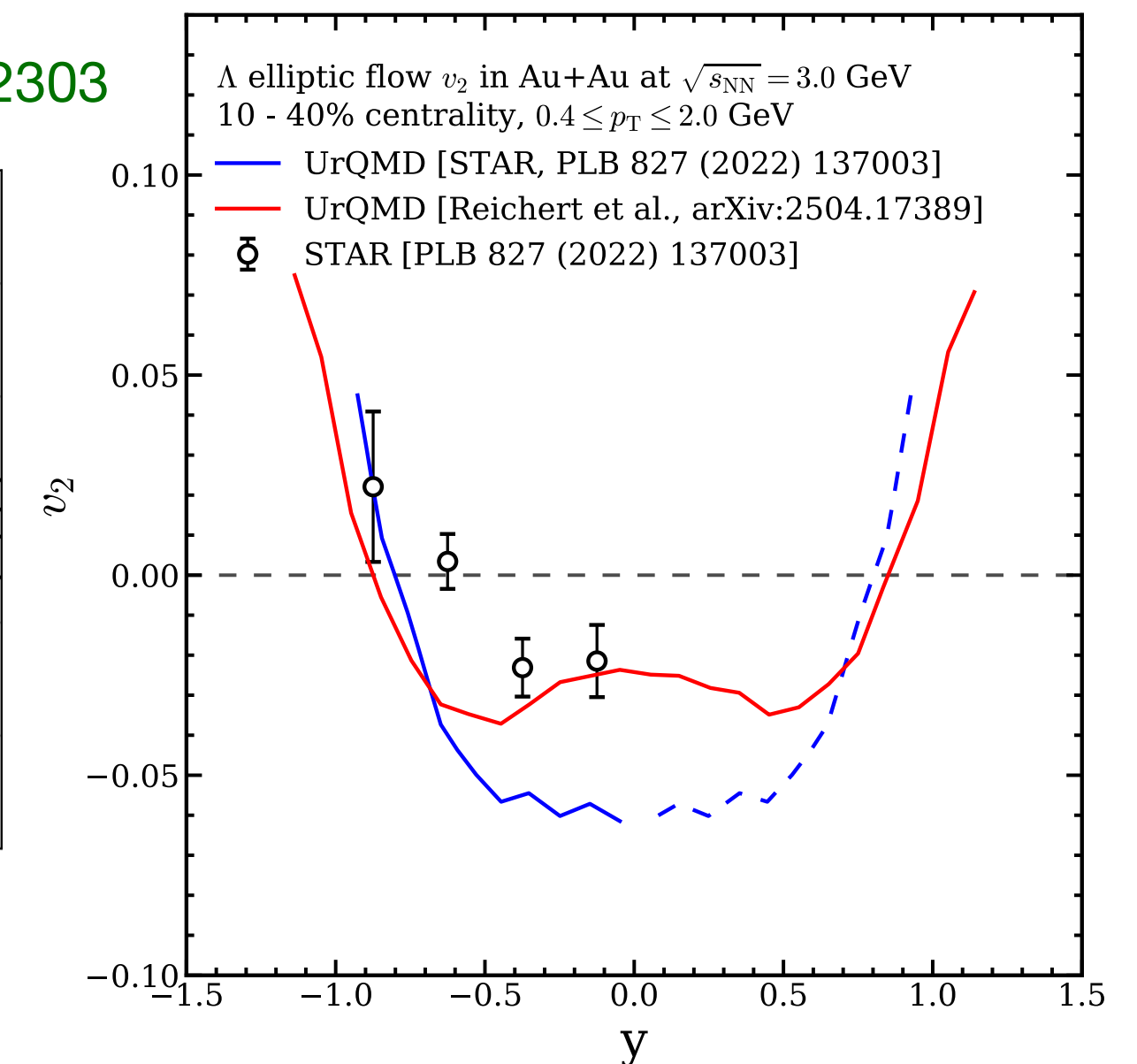
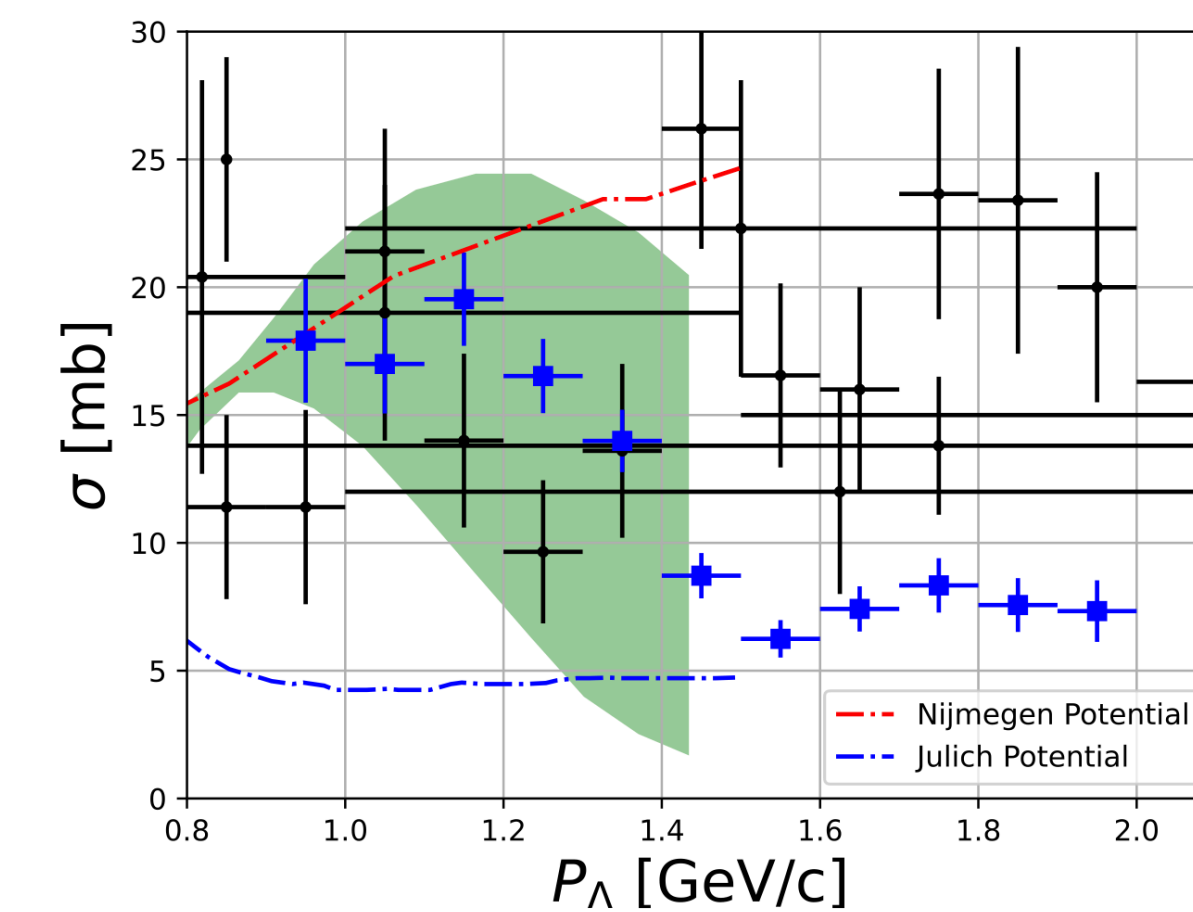
Strange baryons are not well described — why?

- 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



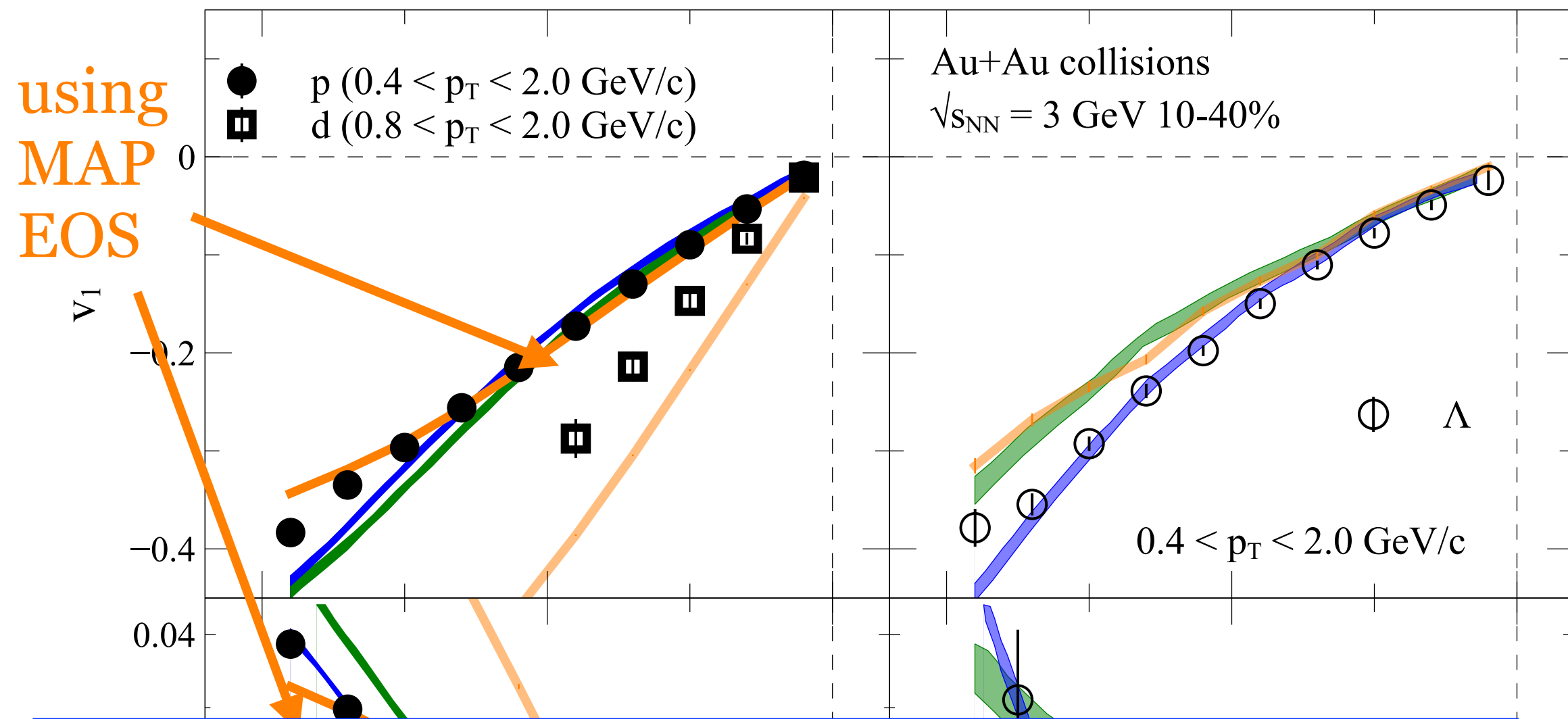
T. Reichert *et al.*, Phys. Rev. C **112**, 6, 064909 (2025)

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



Strange baryons are not well described — why?

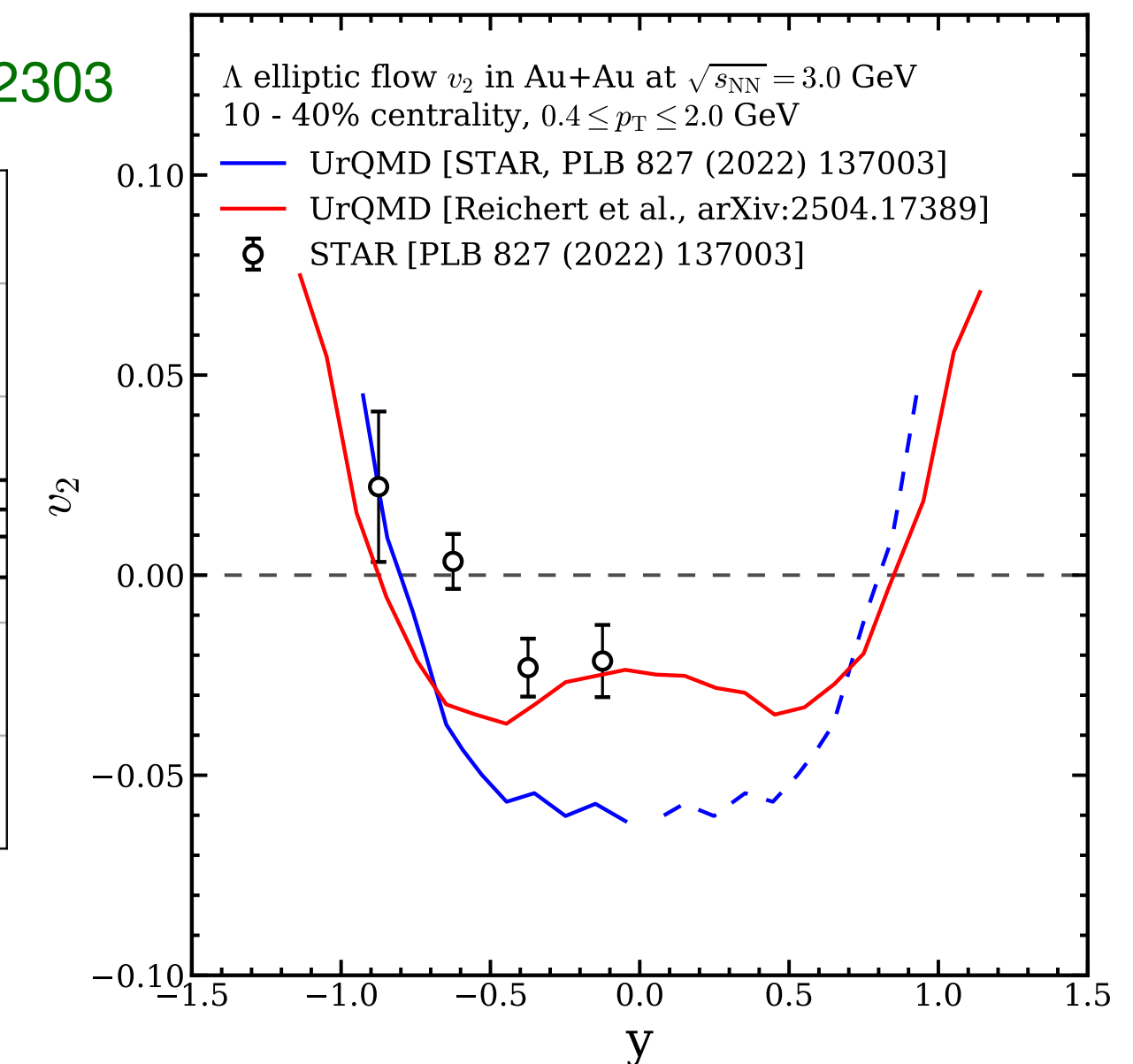
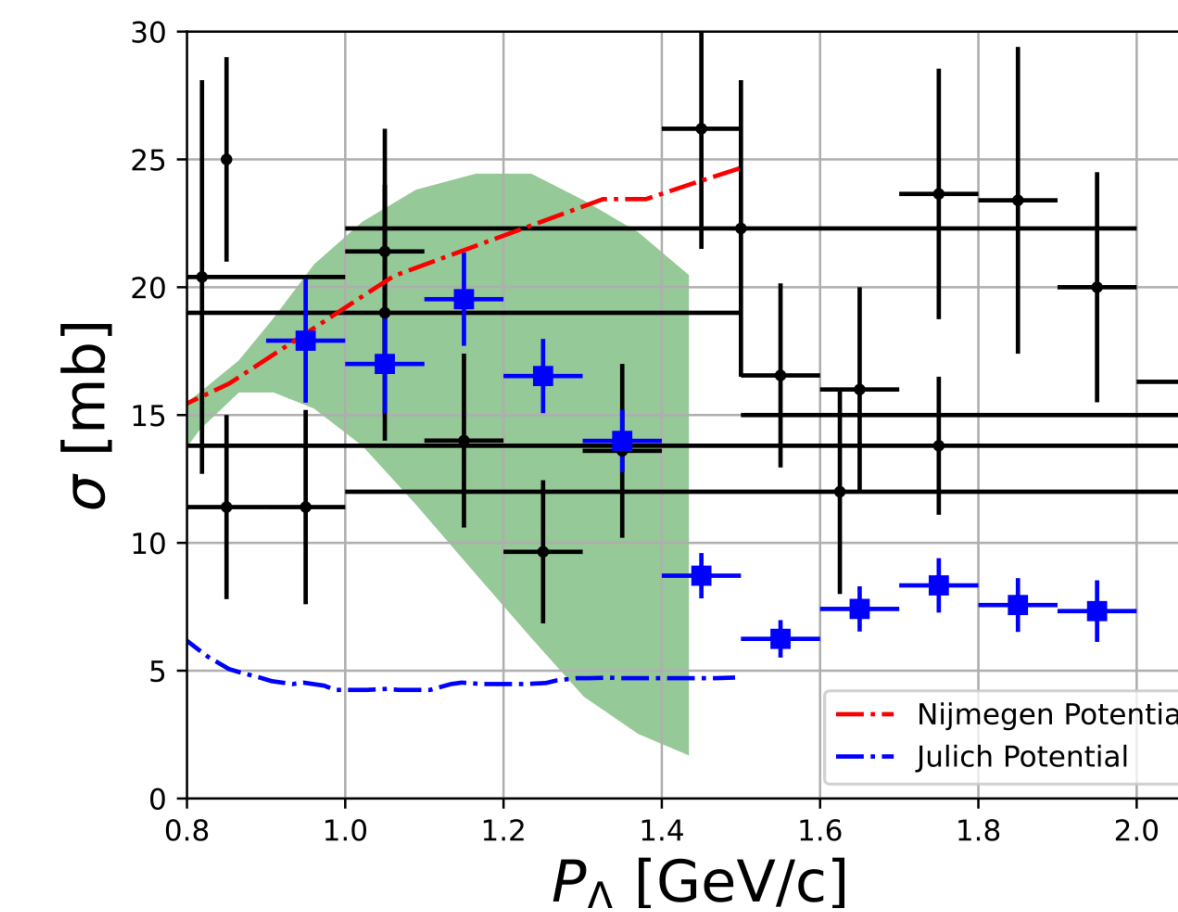
- N-hyperon and hyperon-hyperon interactions?
- in-medium modifications of interactions?

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)

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

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



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

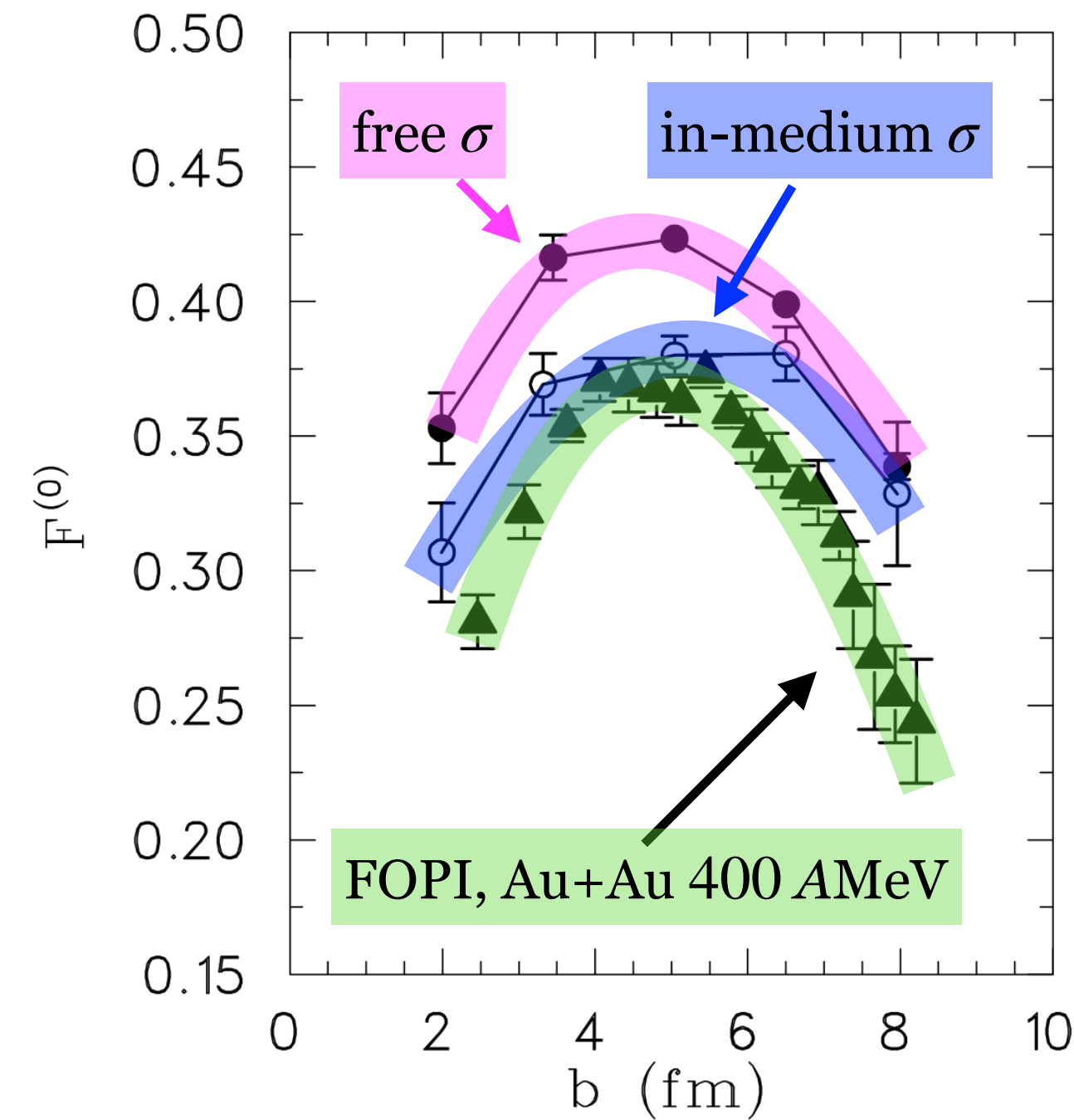
STAR, Phys. Lett. B **827**, 137003 (2022)

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

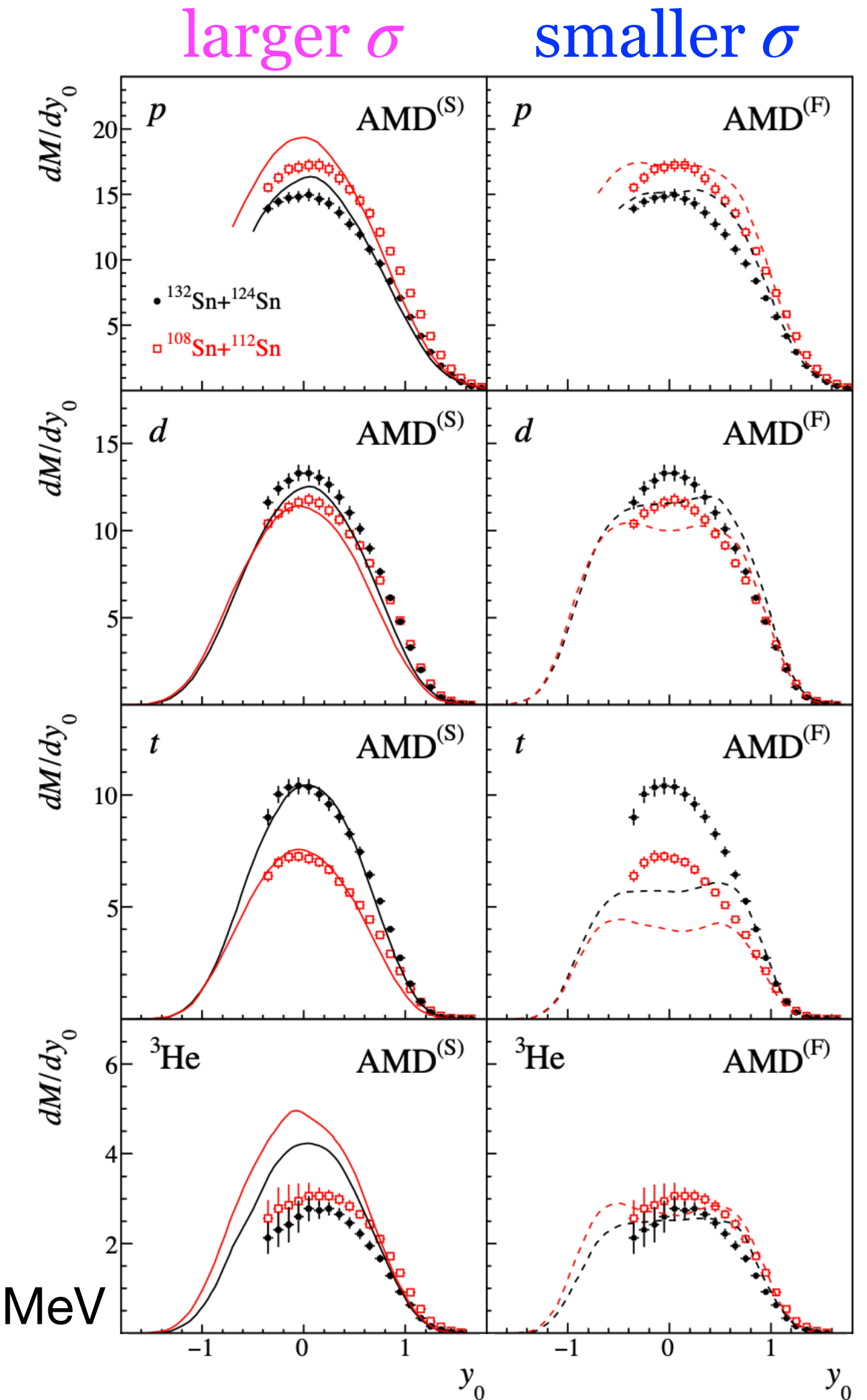
- free nucleon cross sections (σ 's) lead to **excessive stopping**
- microscopic calculations: N-N σ is **reduced** in the medium
- isospin dependence of in-medium σ 's **generally unknown**
- $S\pi$ RIT experiment data indicate in-medium σ 's **need further studies**
- particle-particle scatterings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



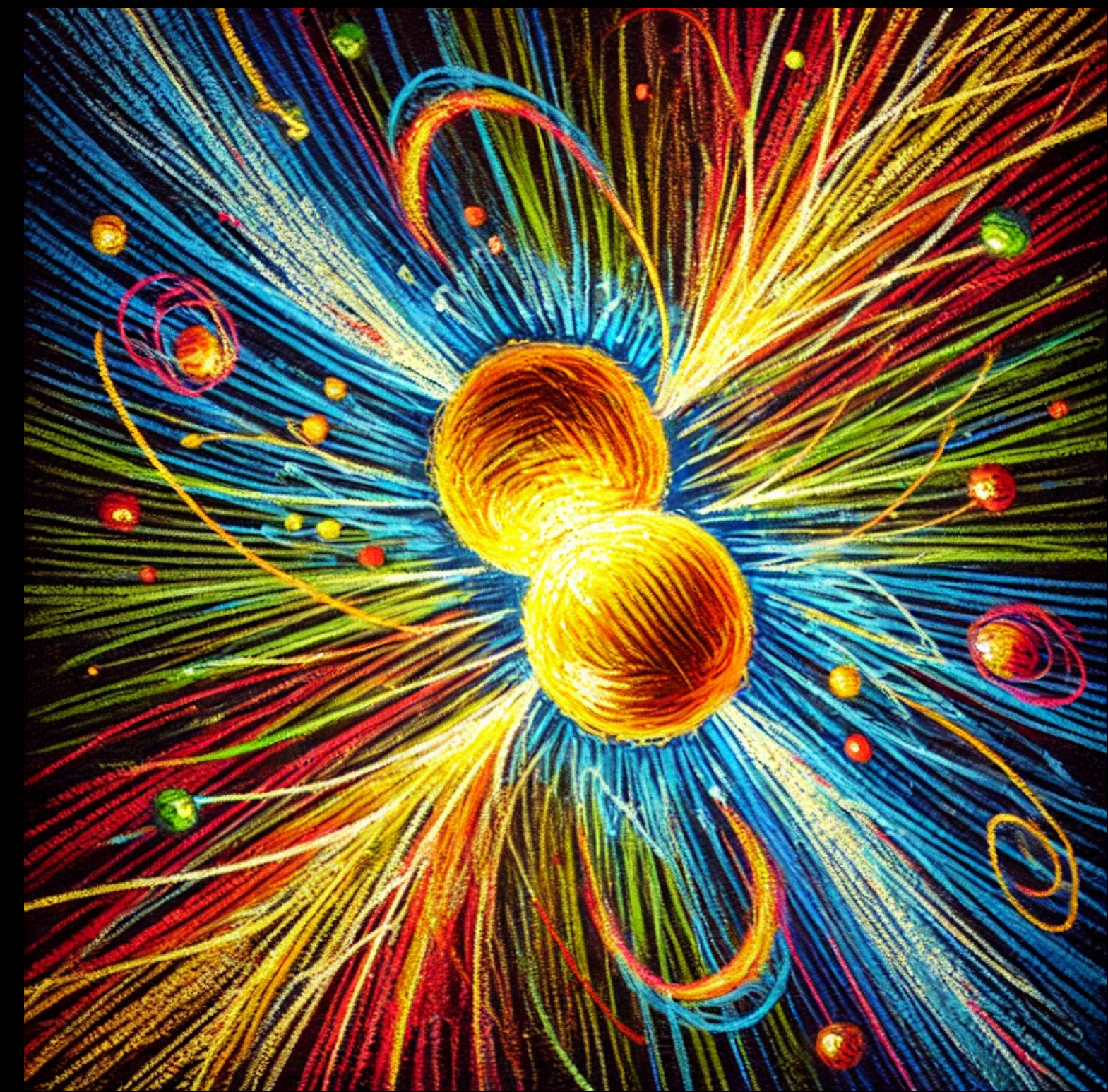
D. Persram, C. Gale, Phys. Rev. C **65**, 064611 (2002), arXiv:nucl-th/0111035

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

270 AMeV



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

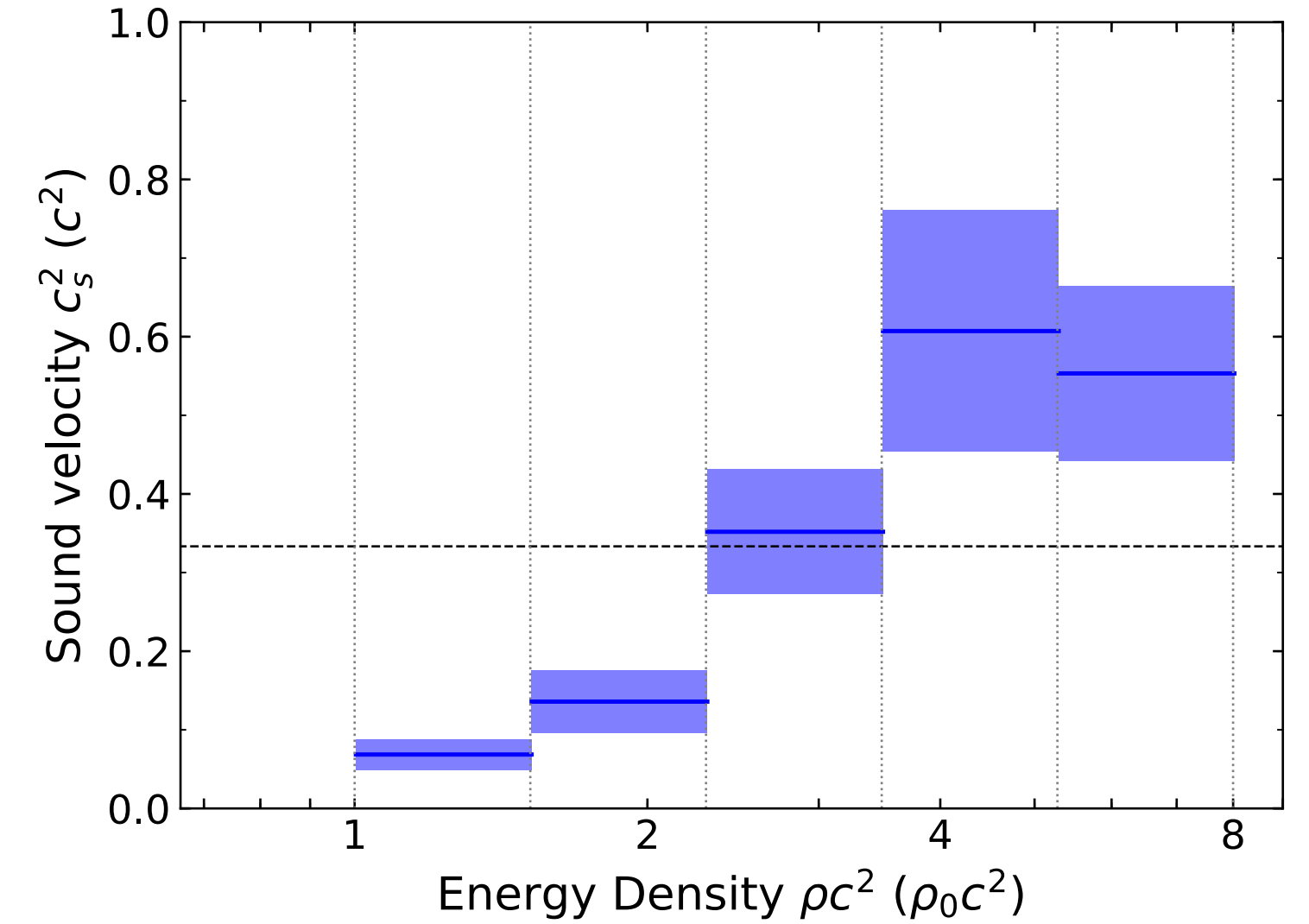
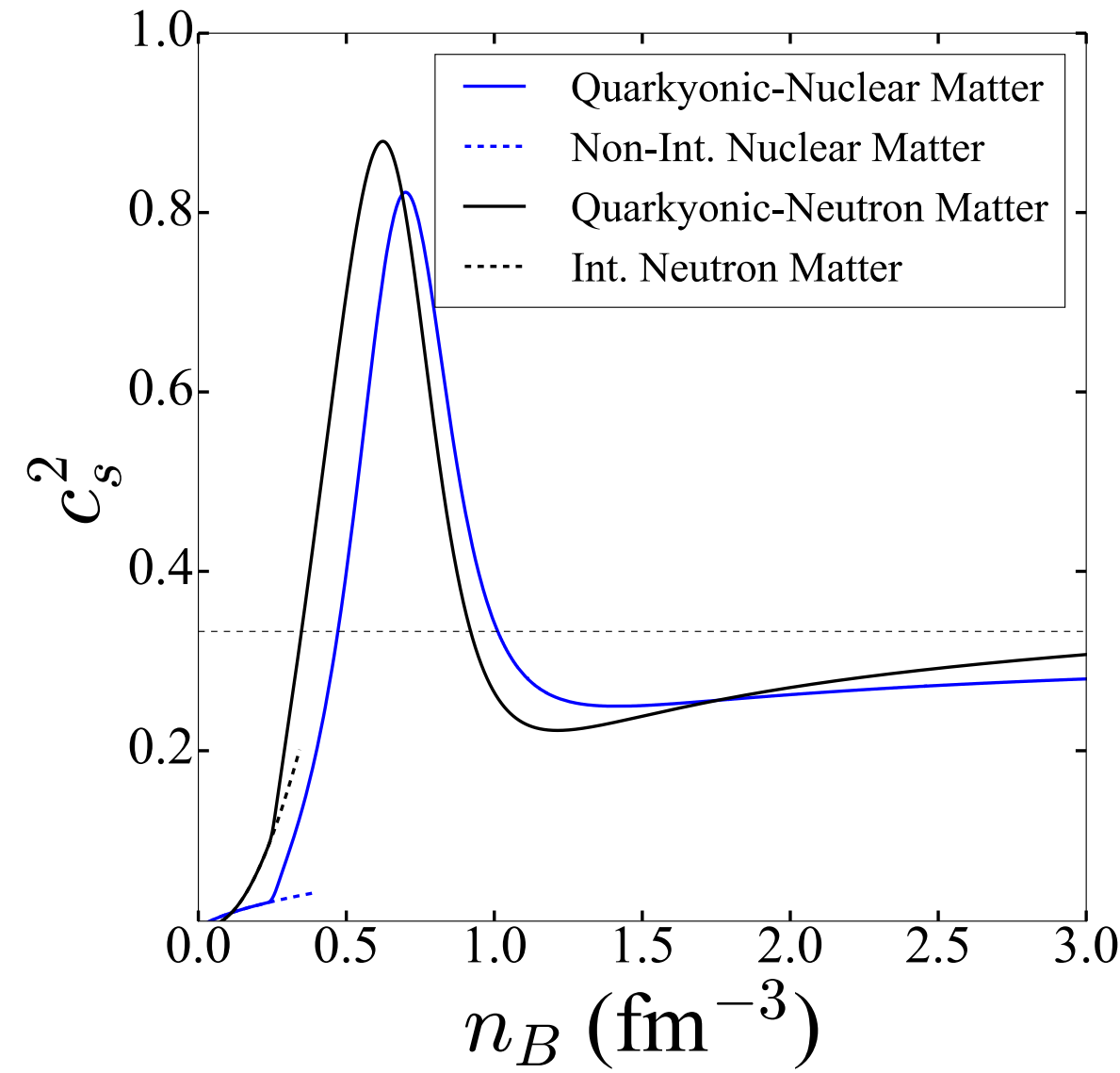
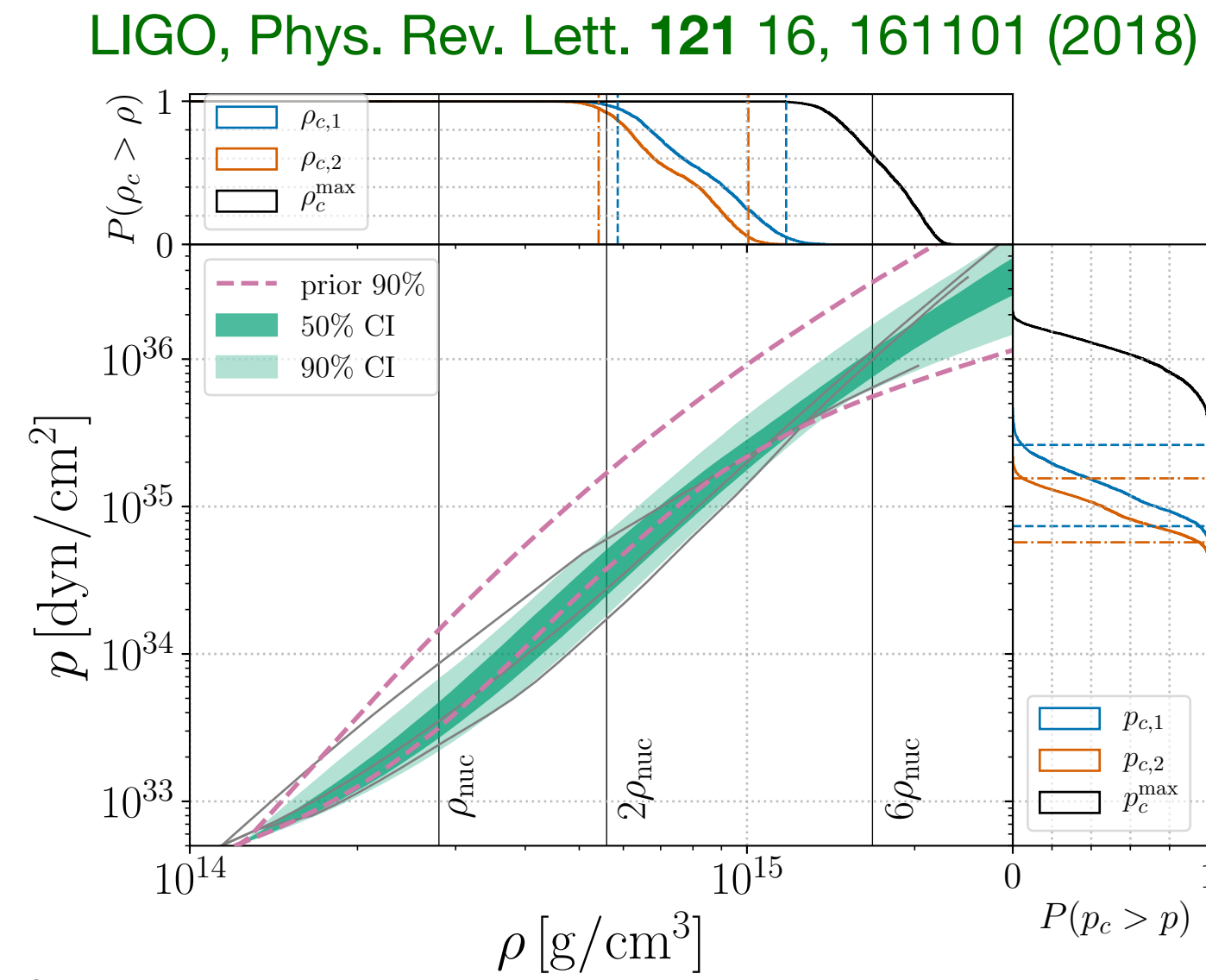
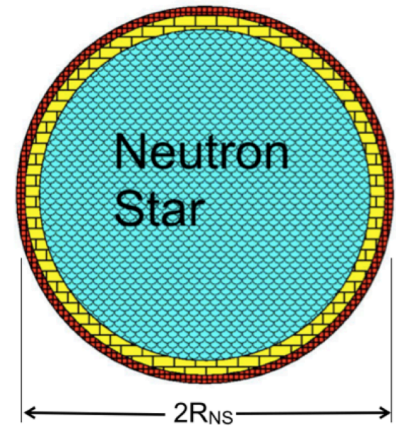


DALL-E

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

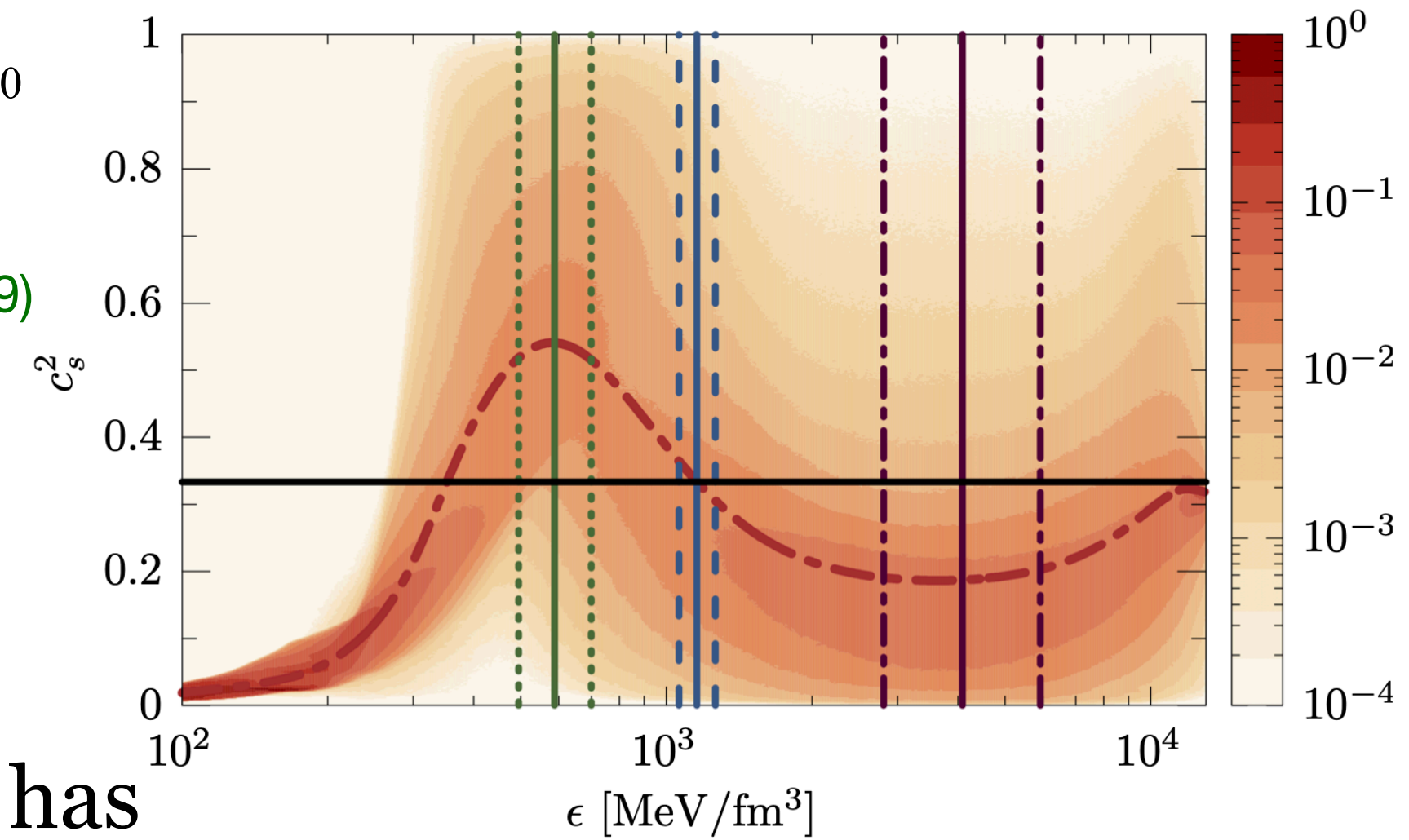
Results from analyses of astrophysical observations

Are these results compatible with HIC data?

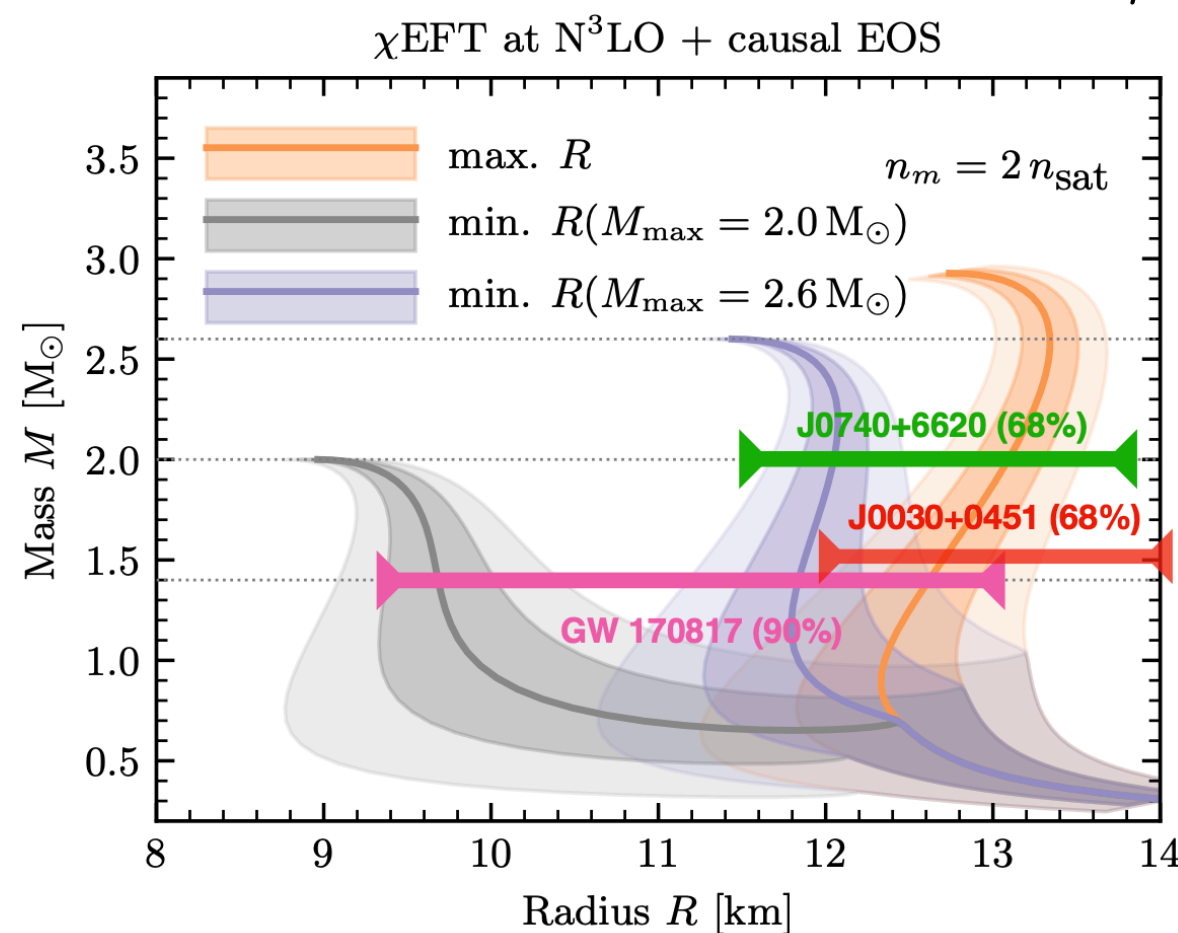


Y. Fujimoto, K. Fukushima, K. Murase, Phys. Rev. D **101**, 5, 054016 (2020)

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



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

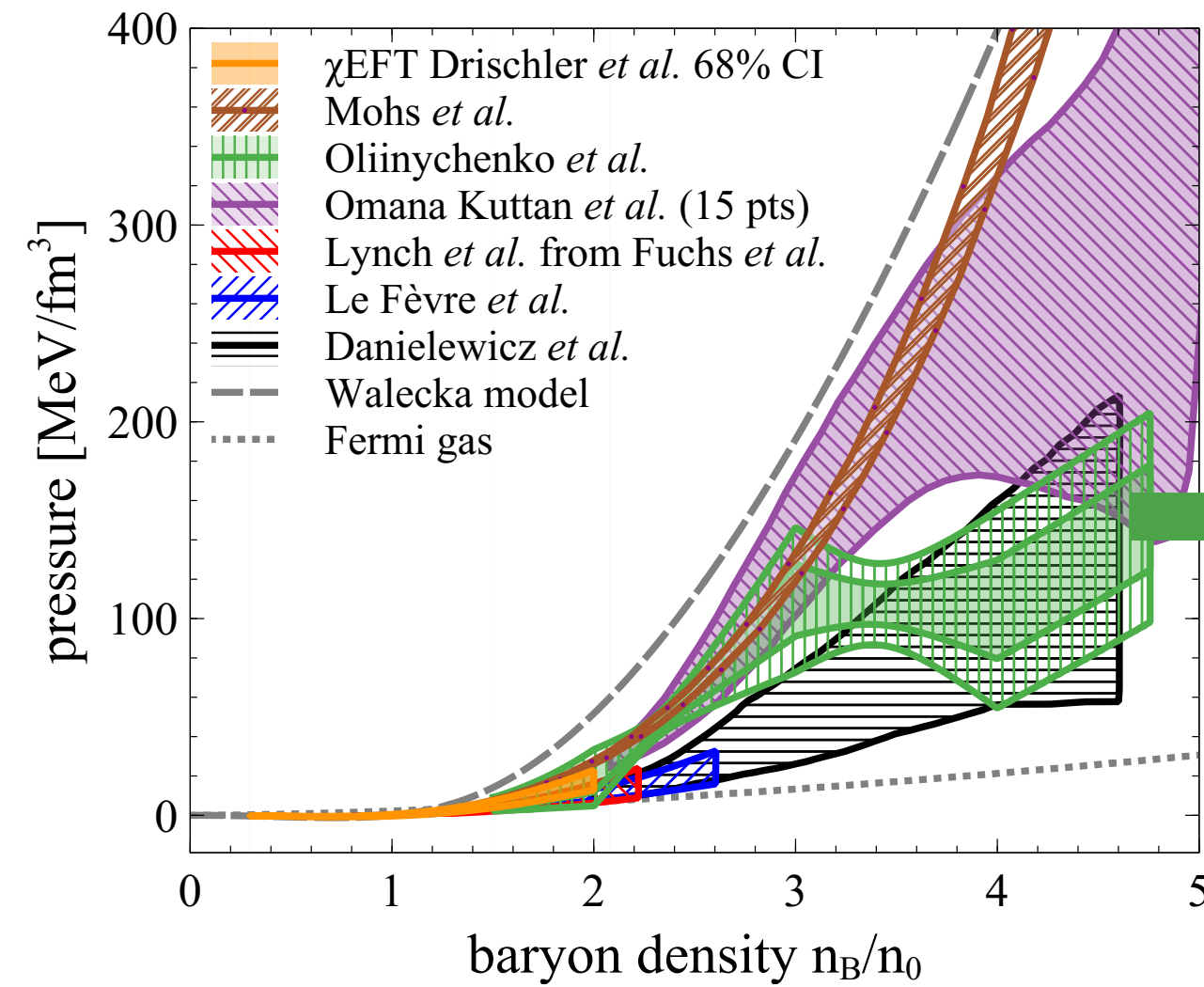


* from S. Reddy's slides; M-R results: C. Drischler *et al.*, Phys. Rev. C **103** 4, 045808 (2021)

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

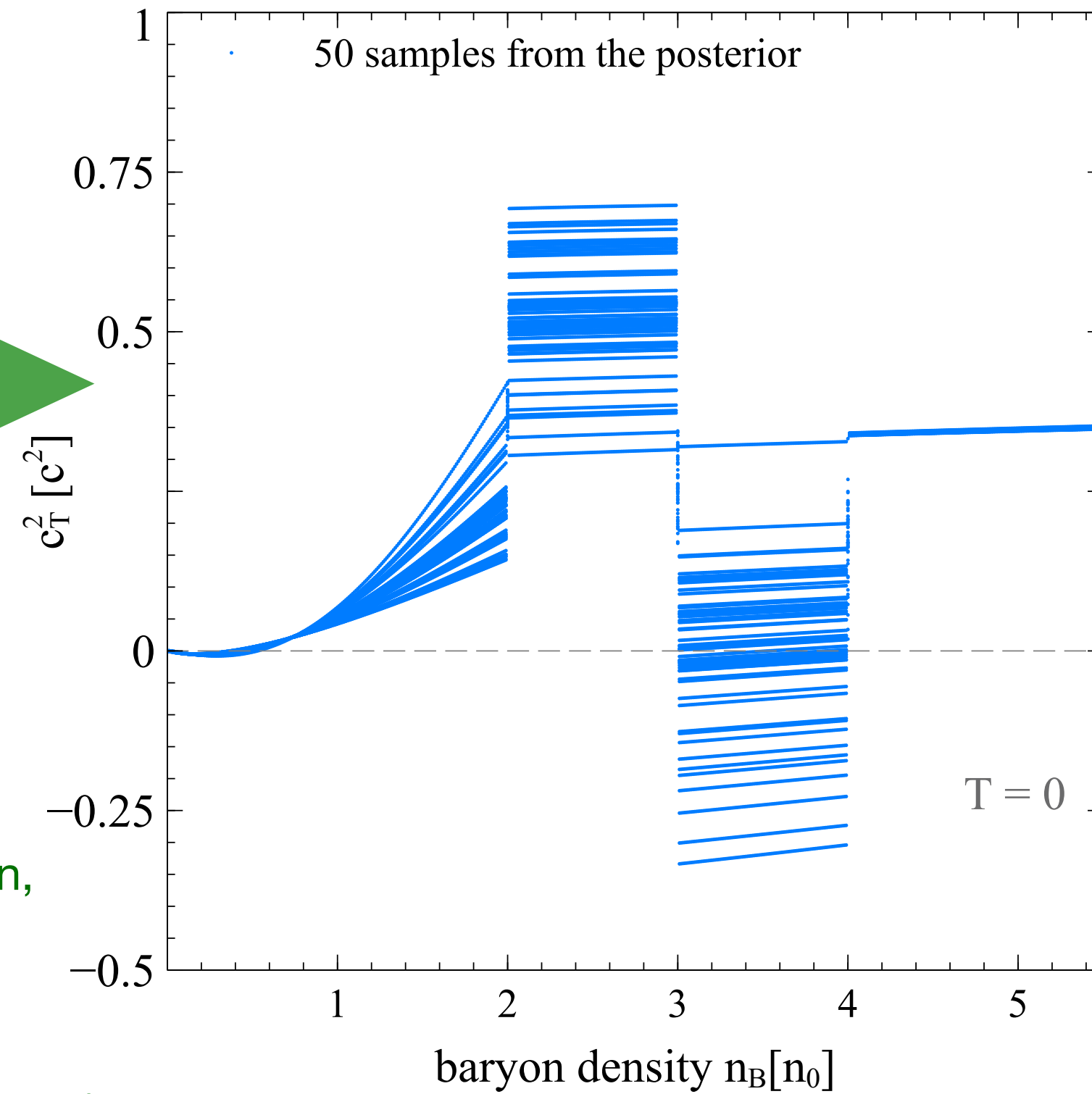
Results from analyses of astrophysical observations

Are these results compatible with HIC data?

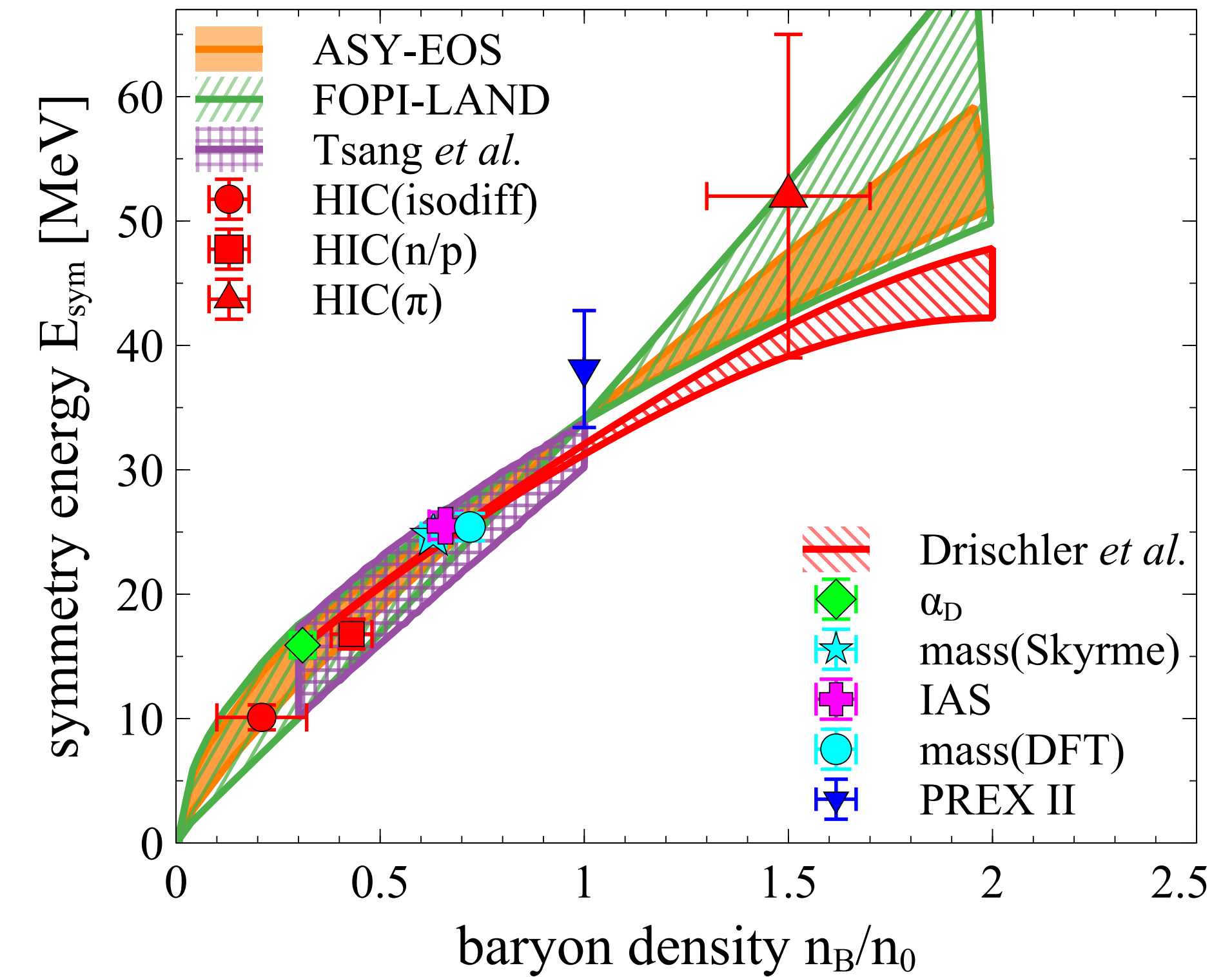


D. Oliinychenko, A. Sorensen, V. Koch, L. McLerran, Phys. Rev. C **108**, 3, 034908 (2023)

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

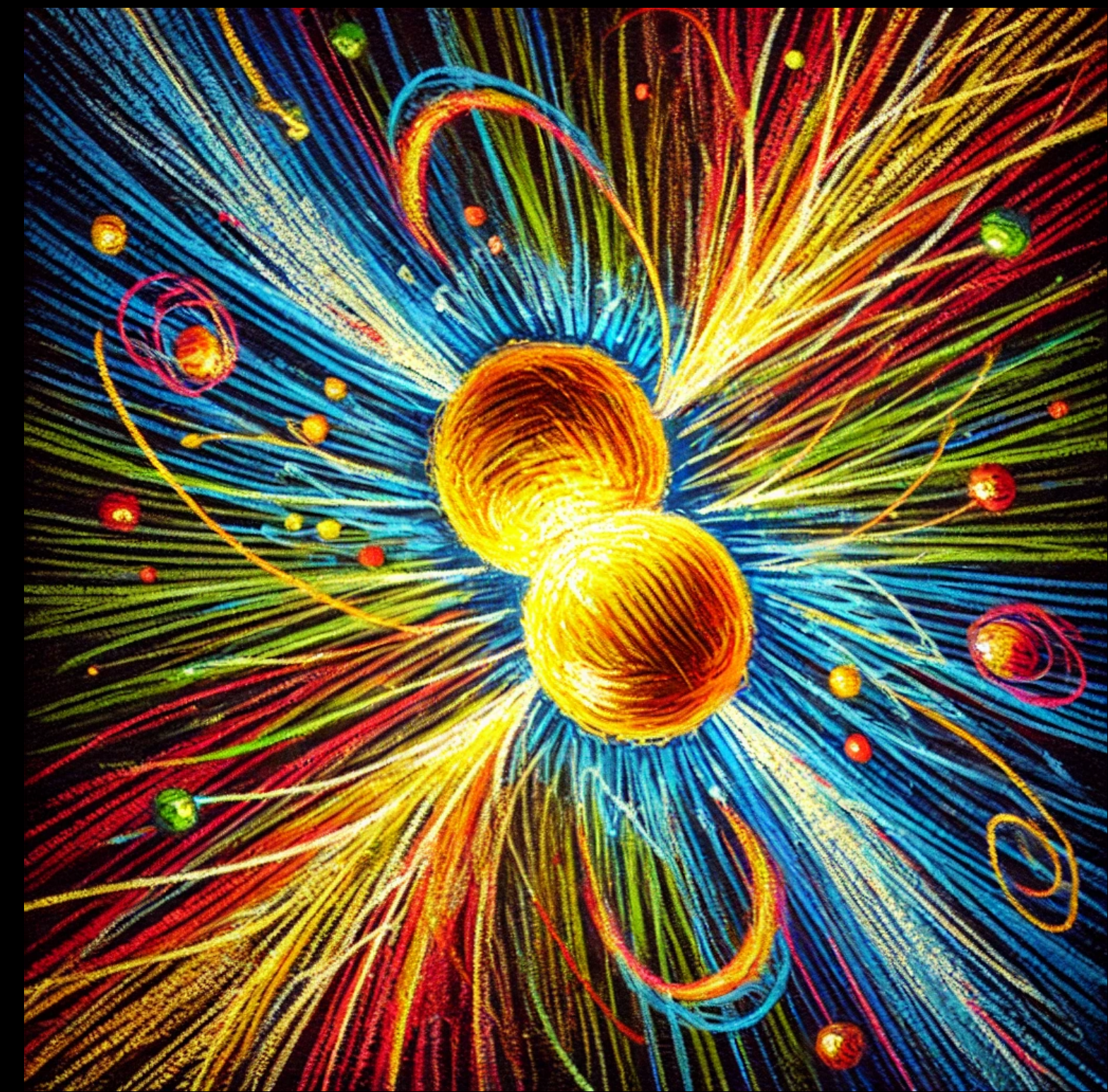


Modeling of experiments at RIB facilities is key



Connecting HICs to NSs needs isospin dependence

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

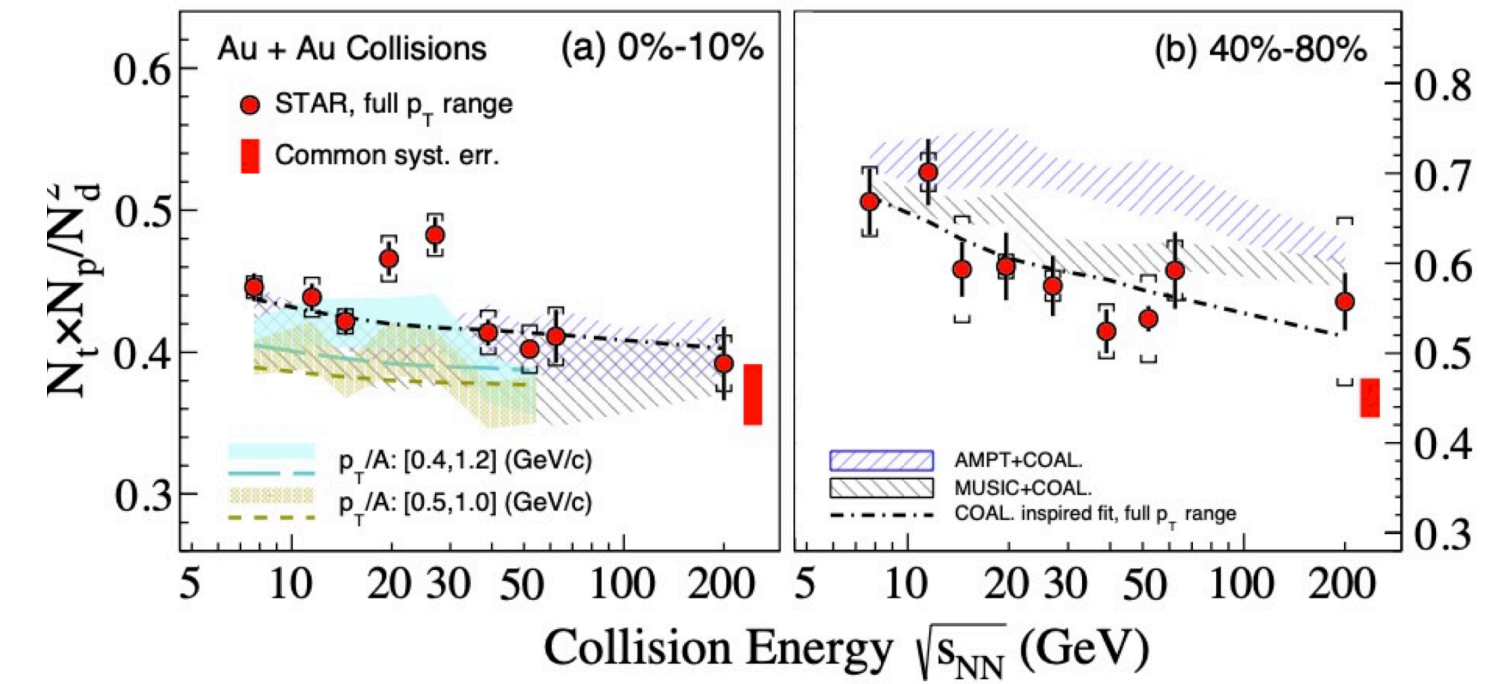
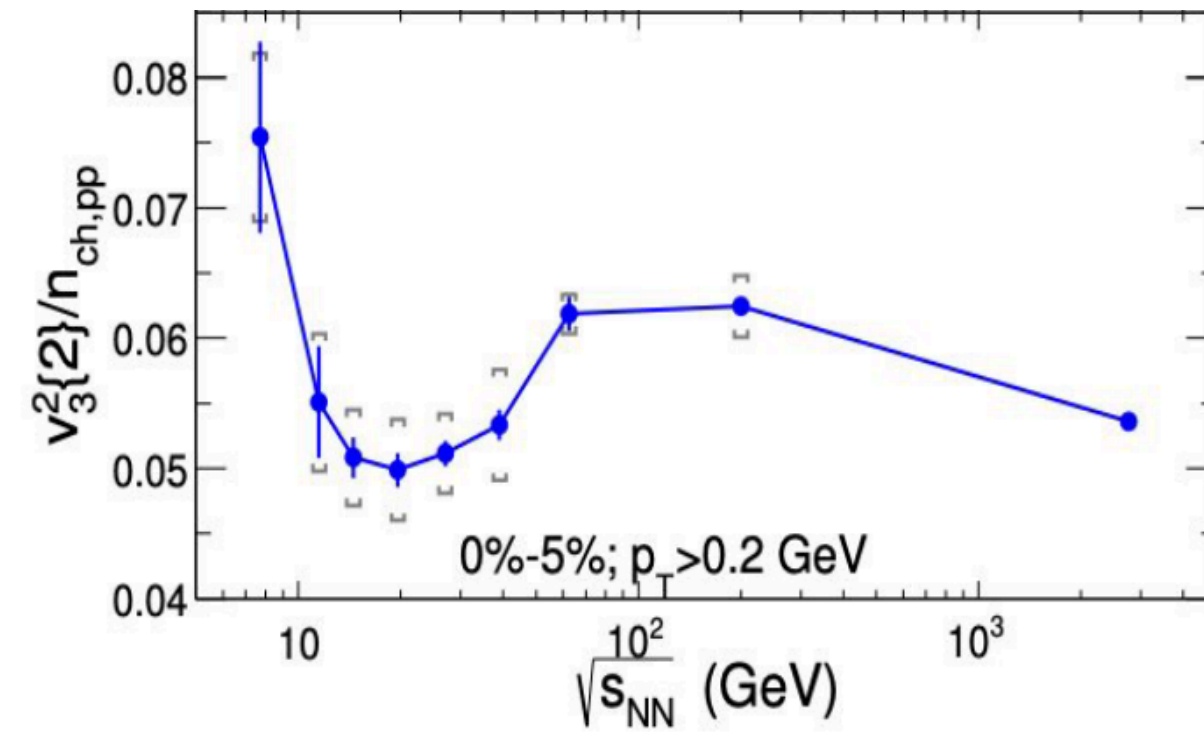
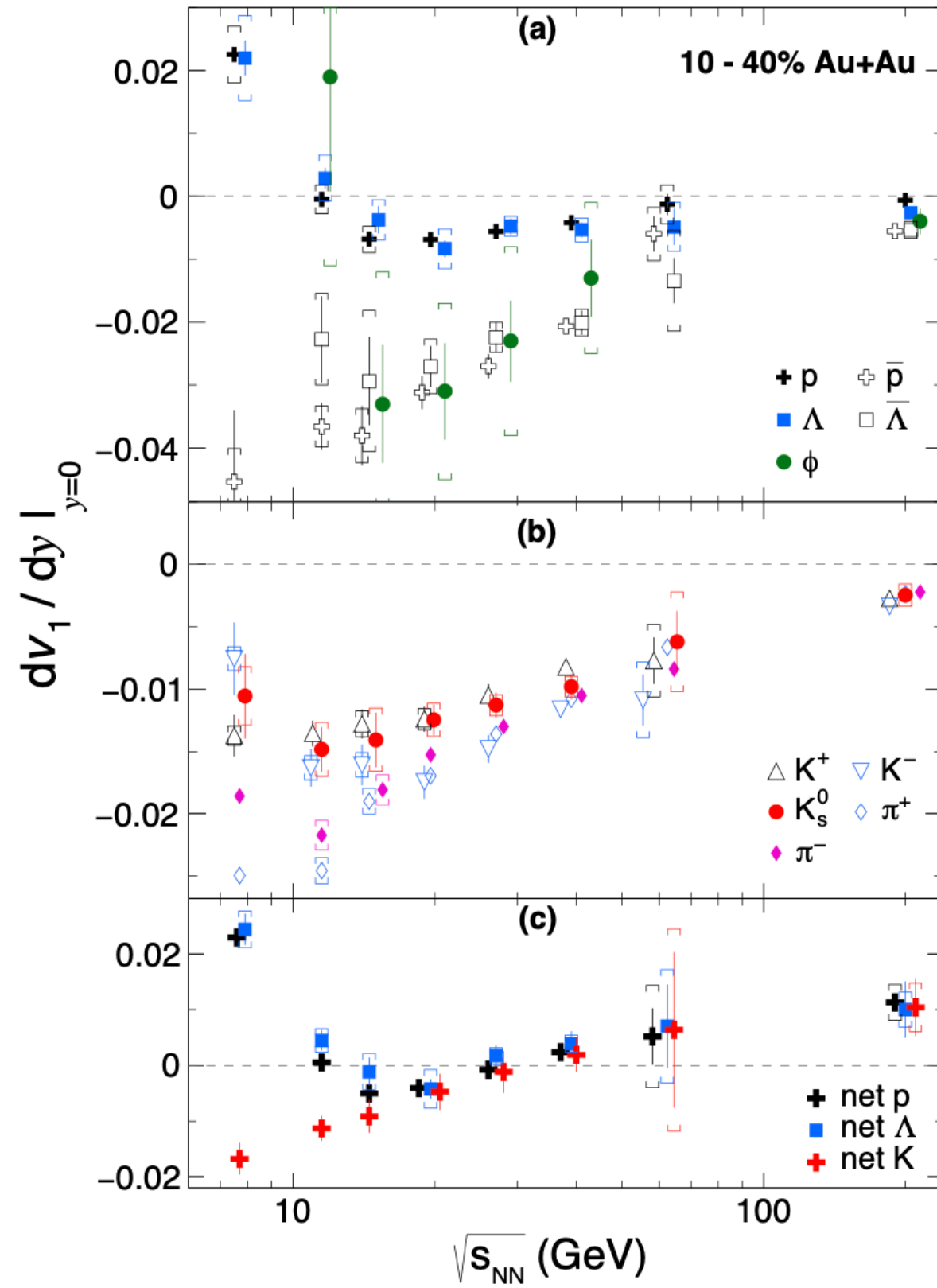


DALL-E

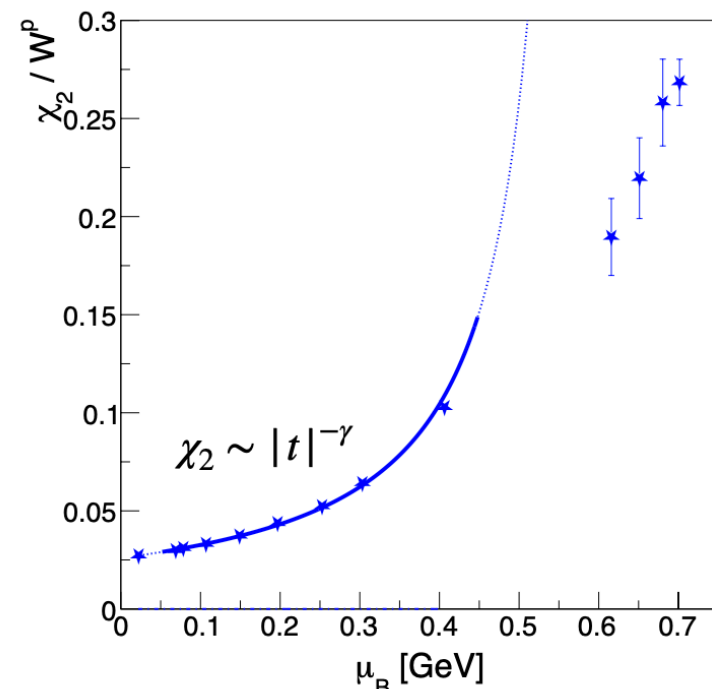
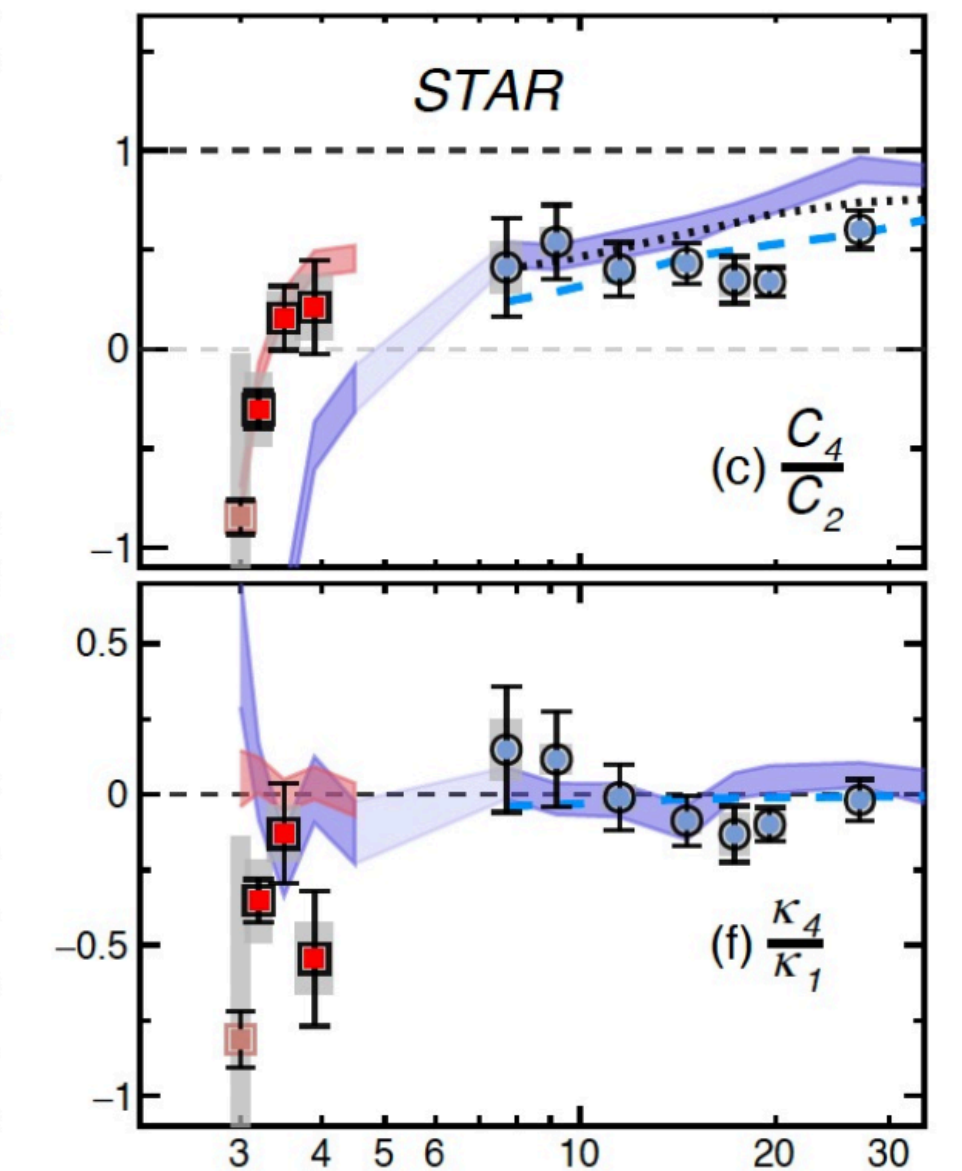
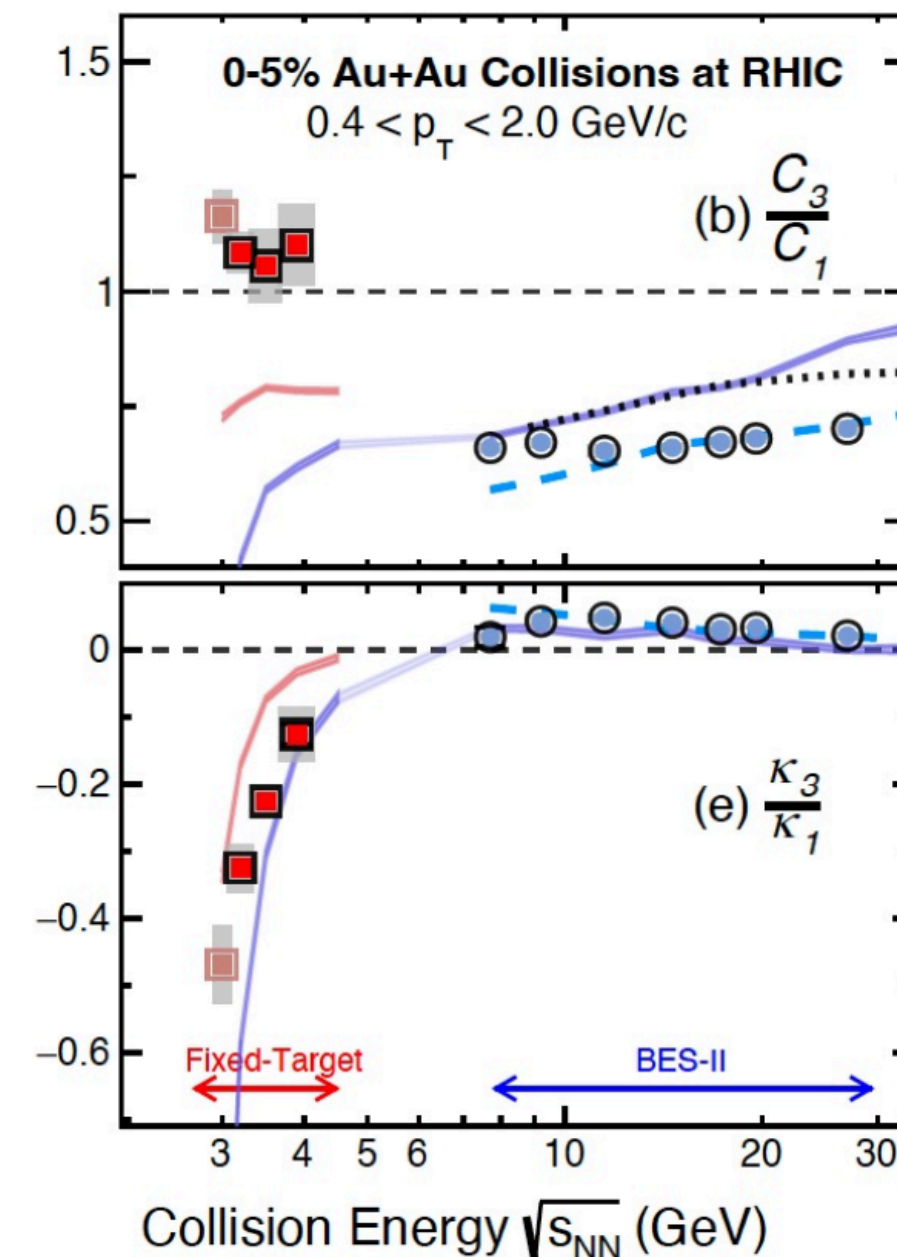
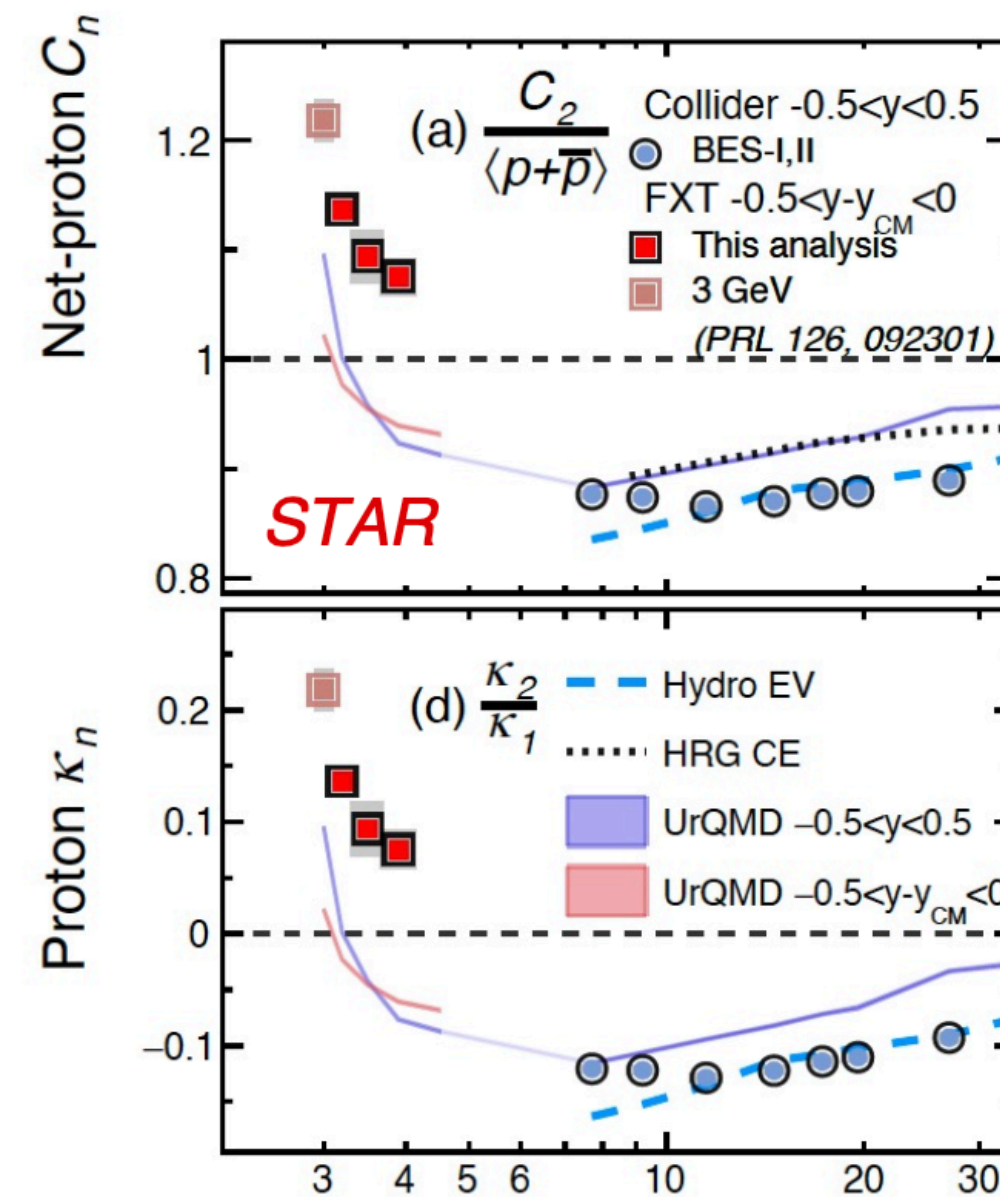
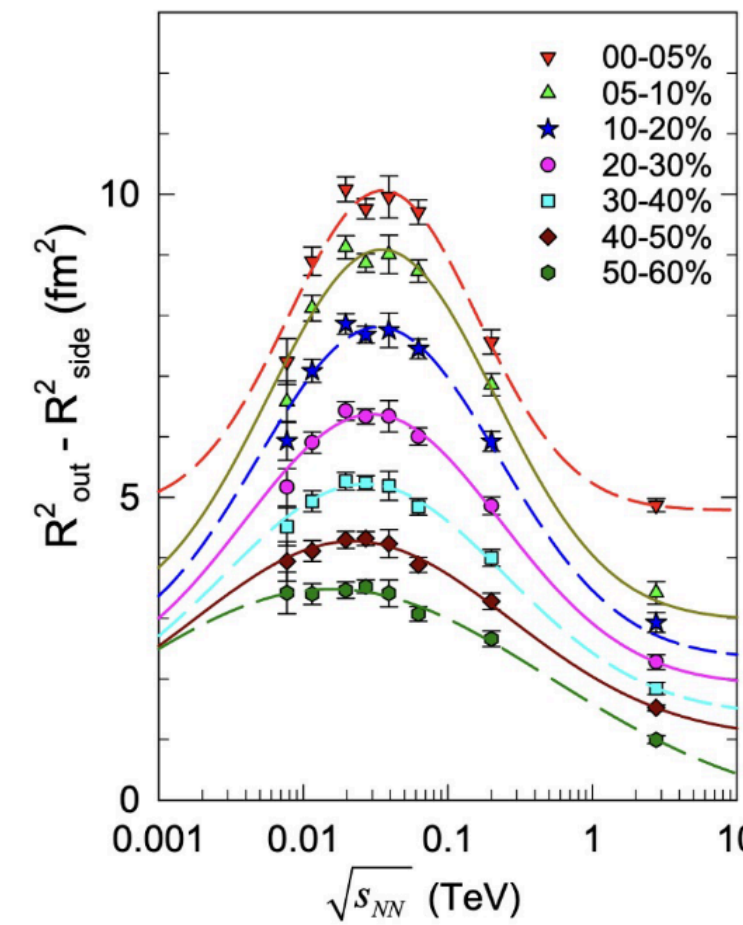
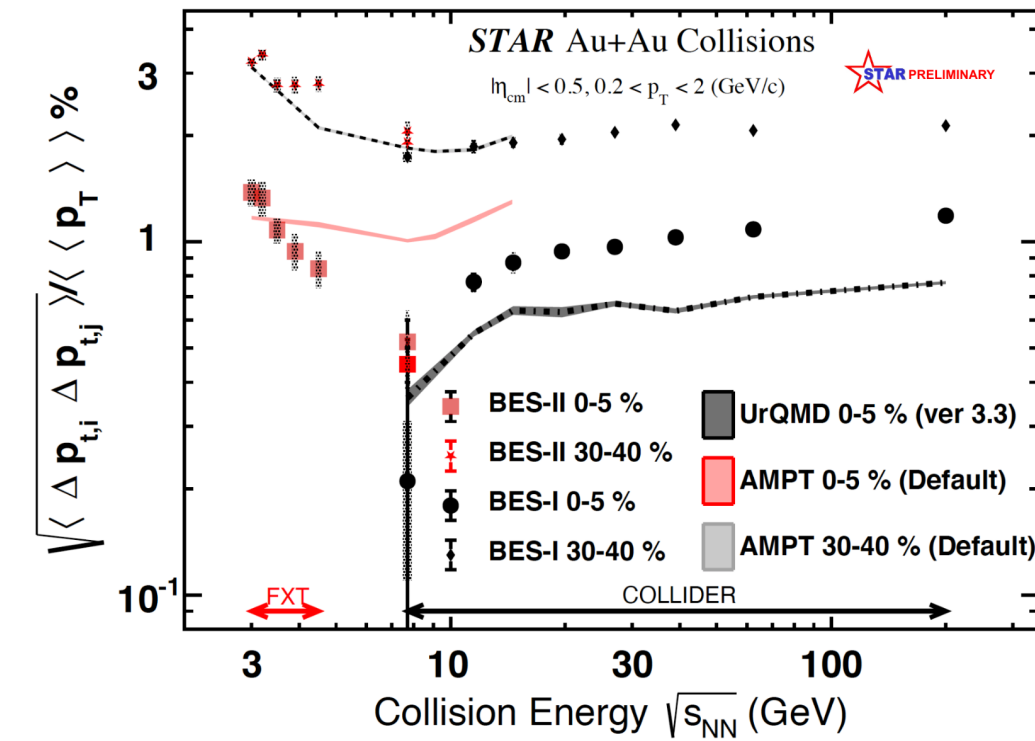
QCD phase diagram @ high density:
what is next?

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

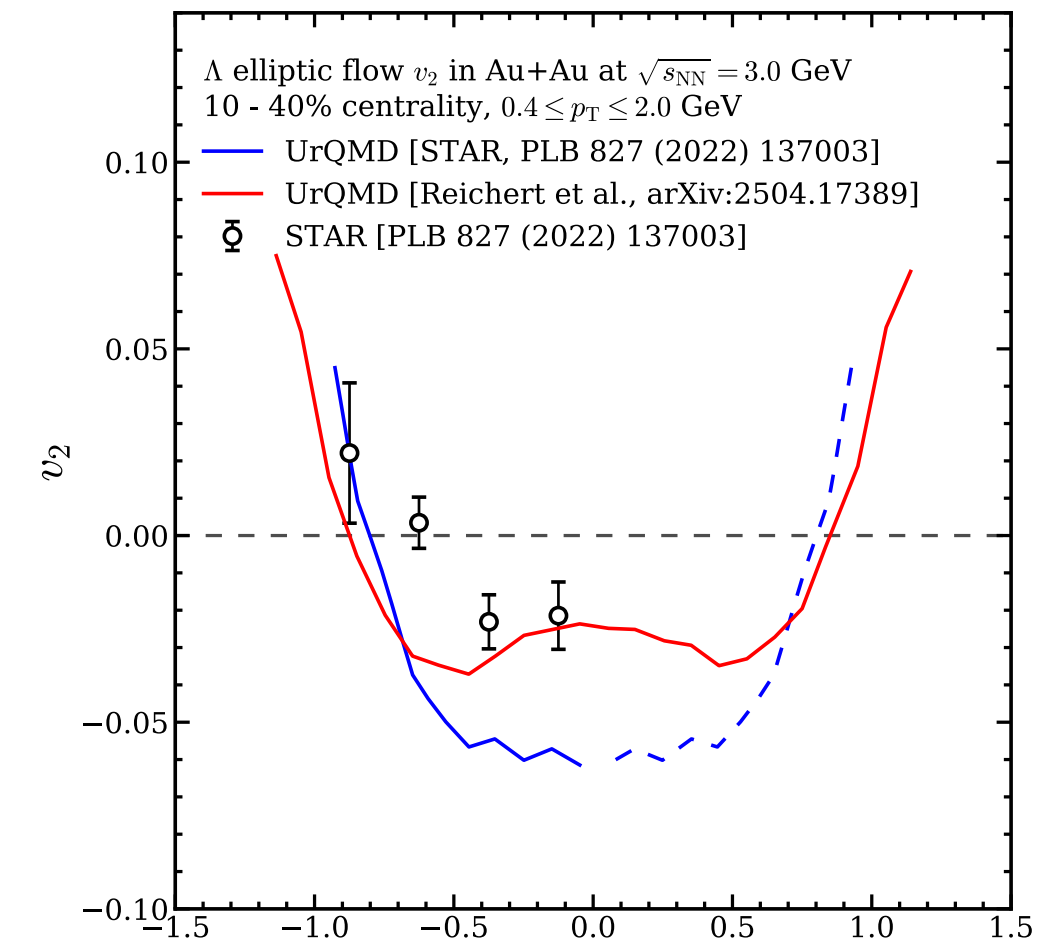
Main conclusions:

1) fundamental input in models is of key importance

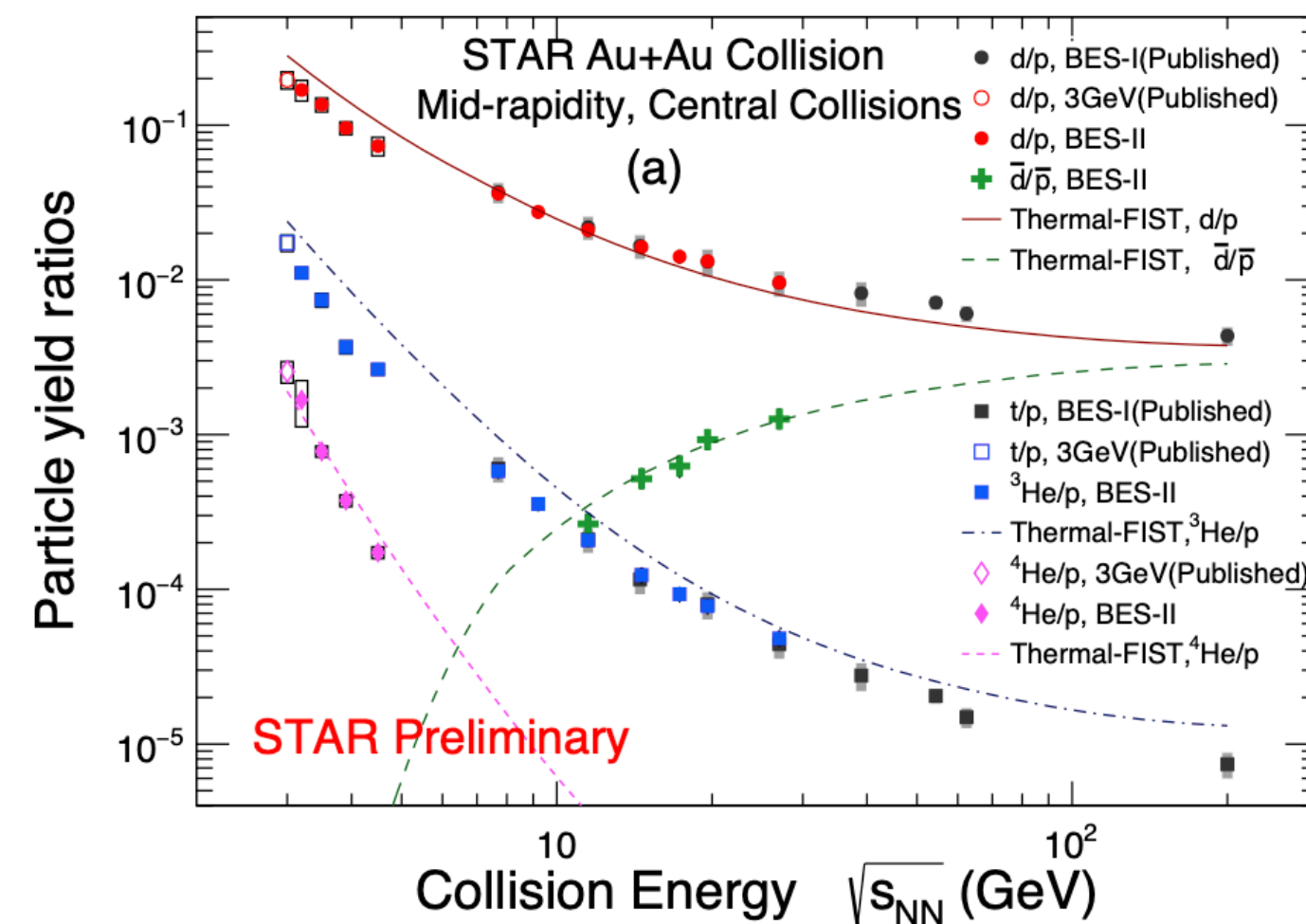
2) where measurements are not available, “ordinary” yield and spectra data are *key* to calibrate models

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

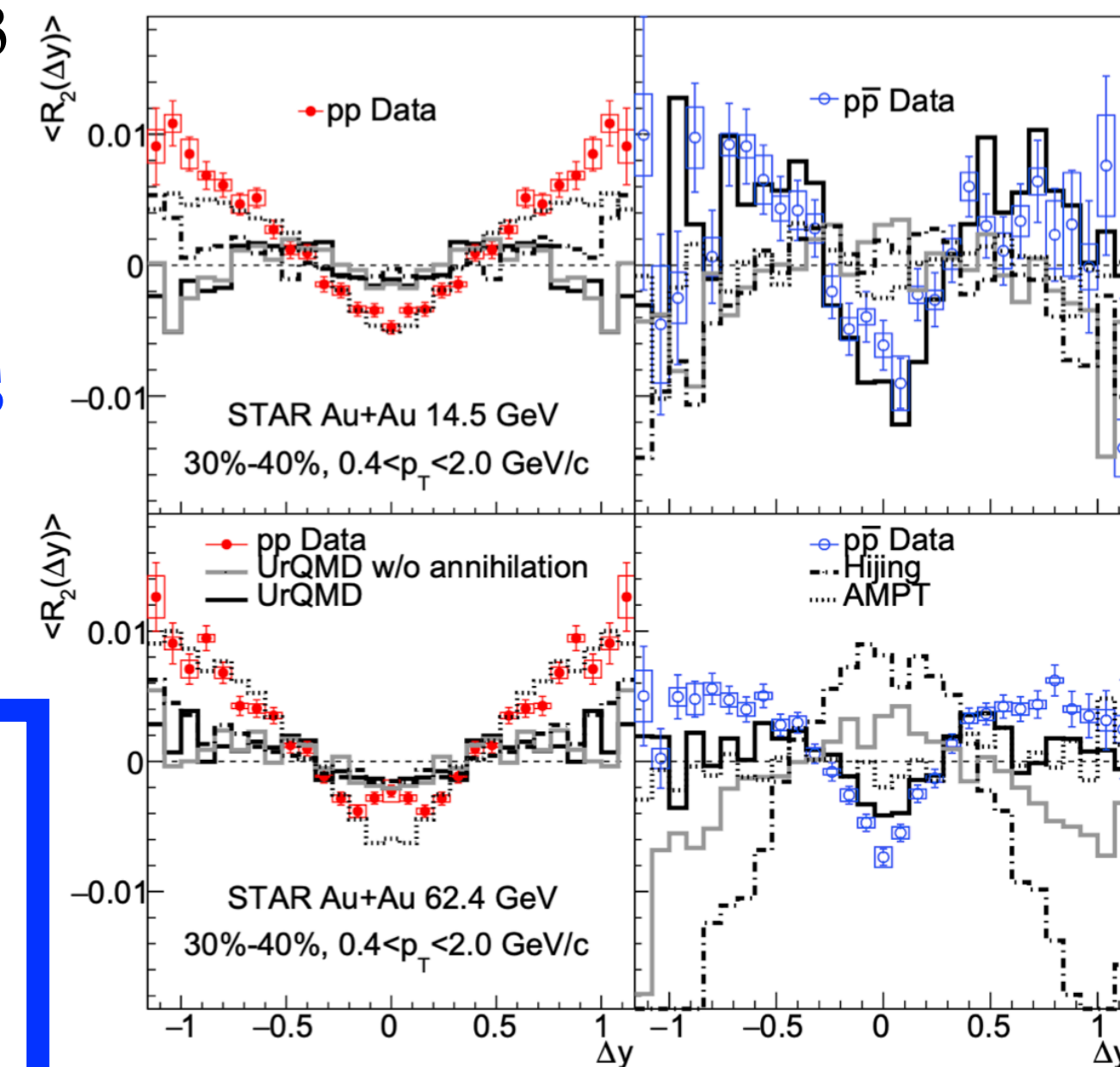
3) differential analyses (as opposed to single numbers) are key in model to data comparisons
models can reproduce single numbers without agreeing on the details



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



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



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

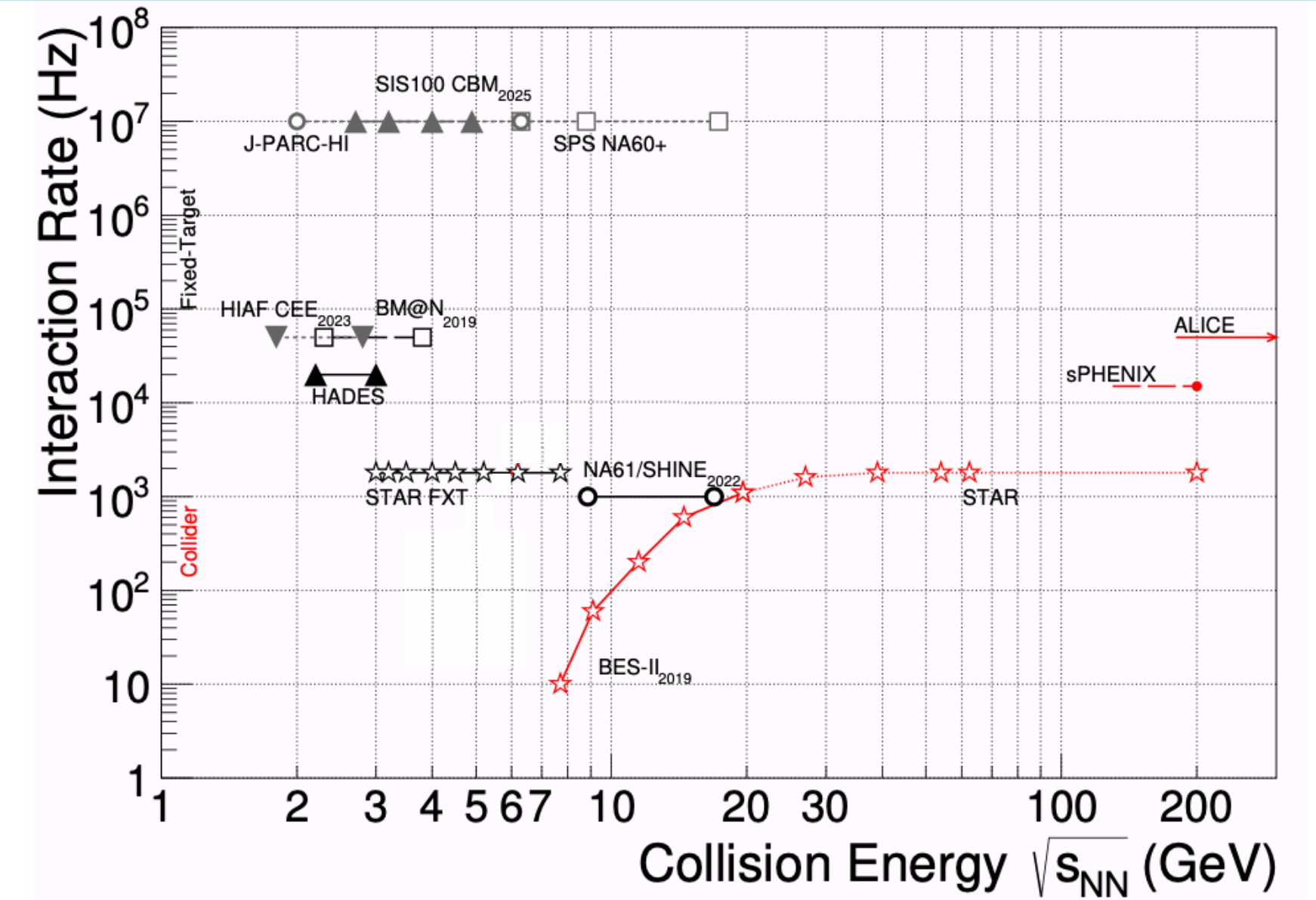
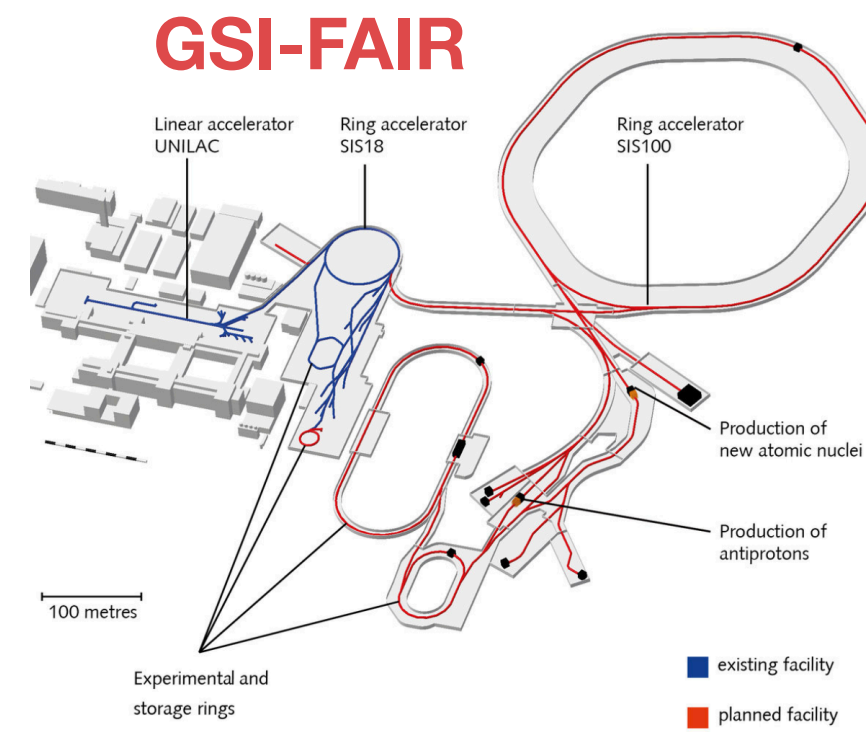
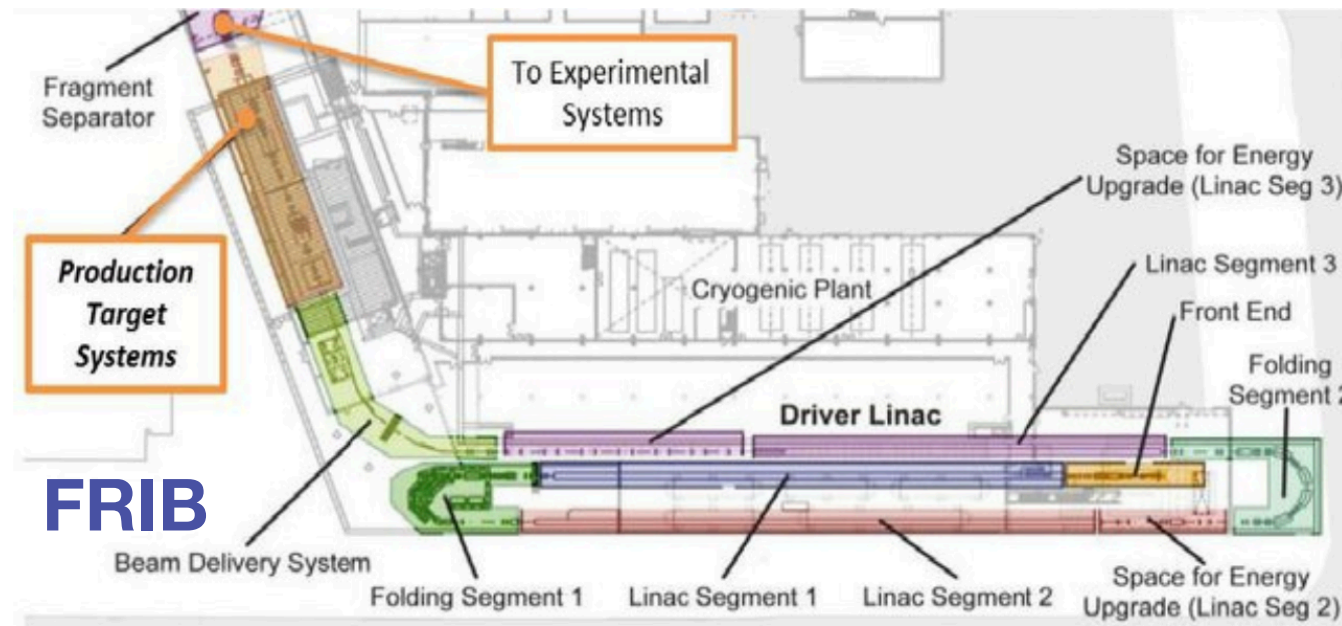
Currently running & future facilities

Facility for Antiproton and Ion Research (FAIR):

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

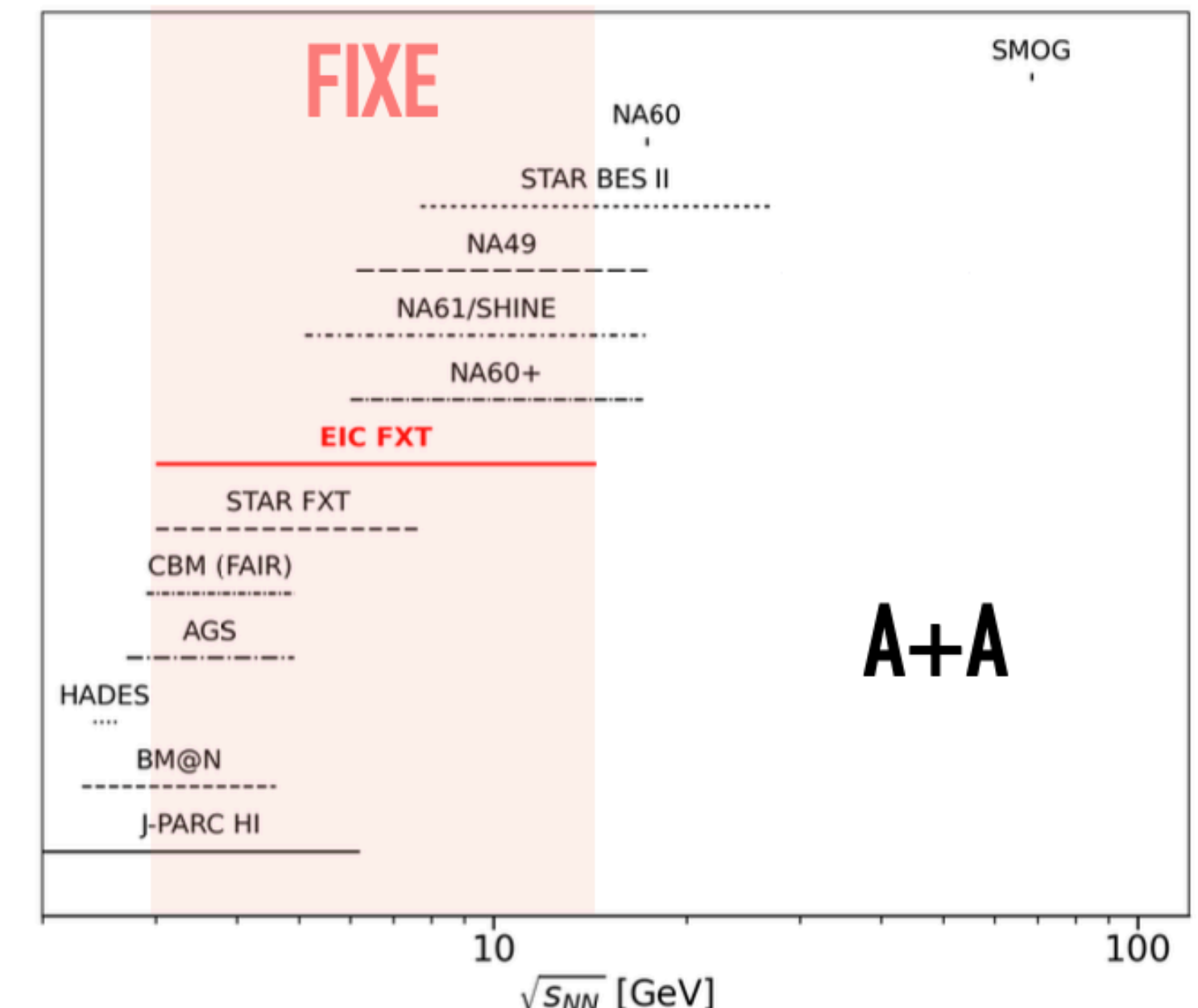
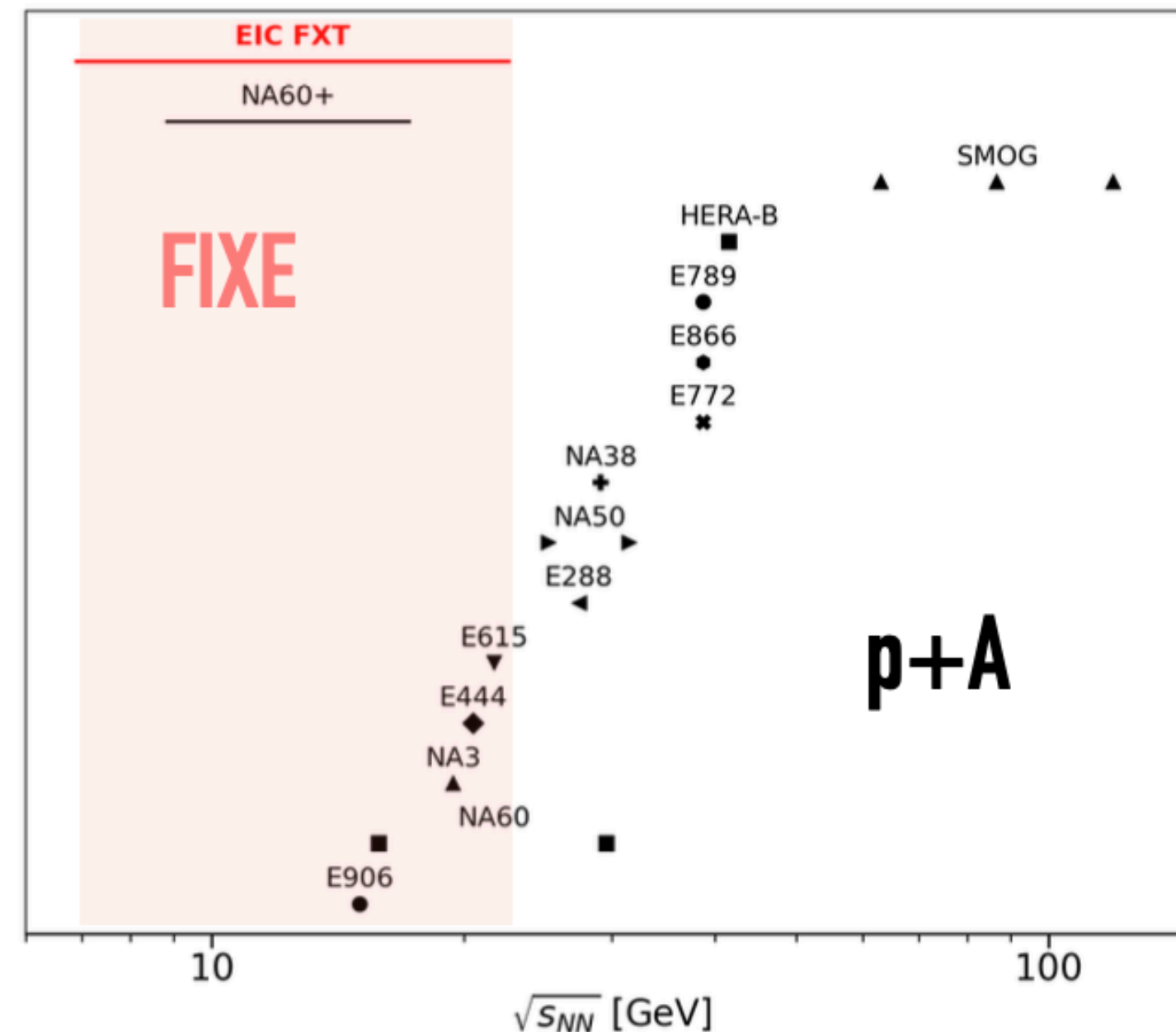
Facility for Rare Isotope Beams (FRIB):

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

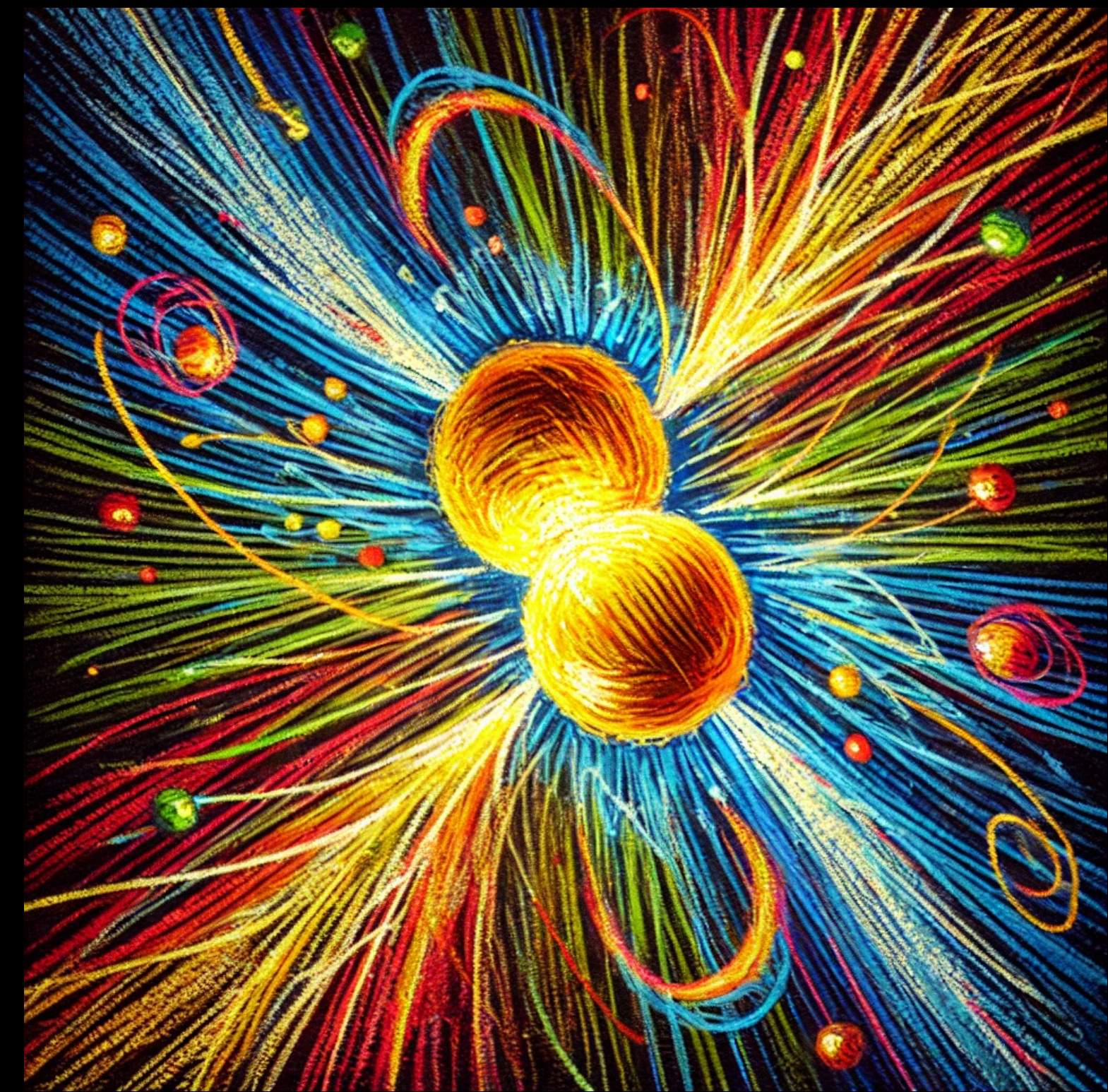


Possible fixed-target HIC program at the EIC (FIXE)?

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



from C.-J. Naim



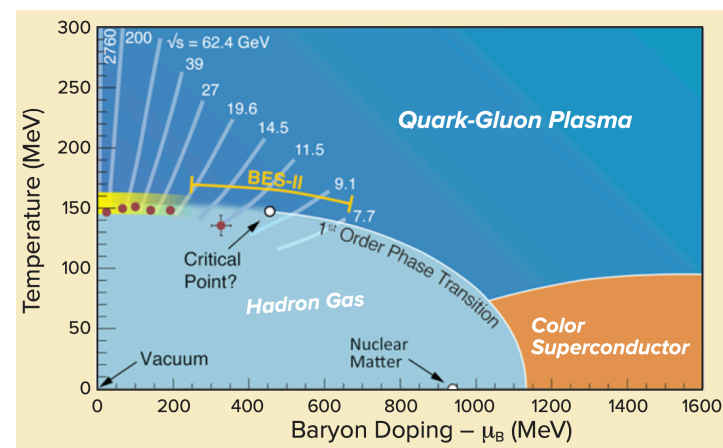
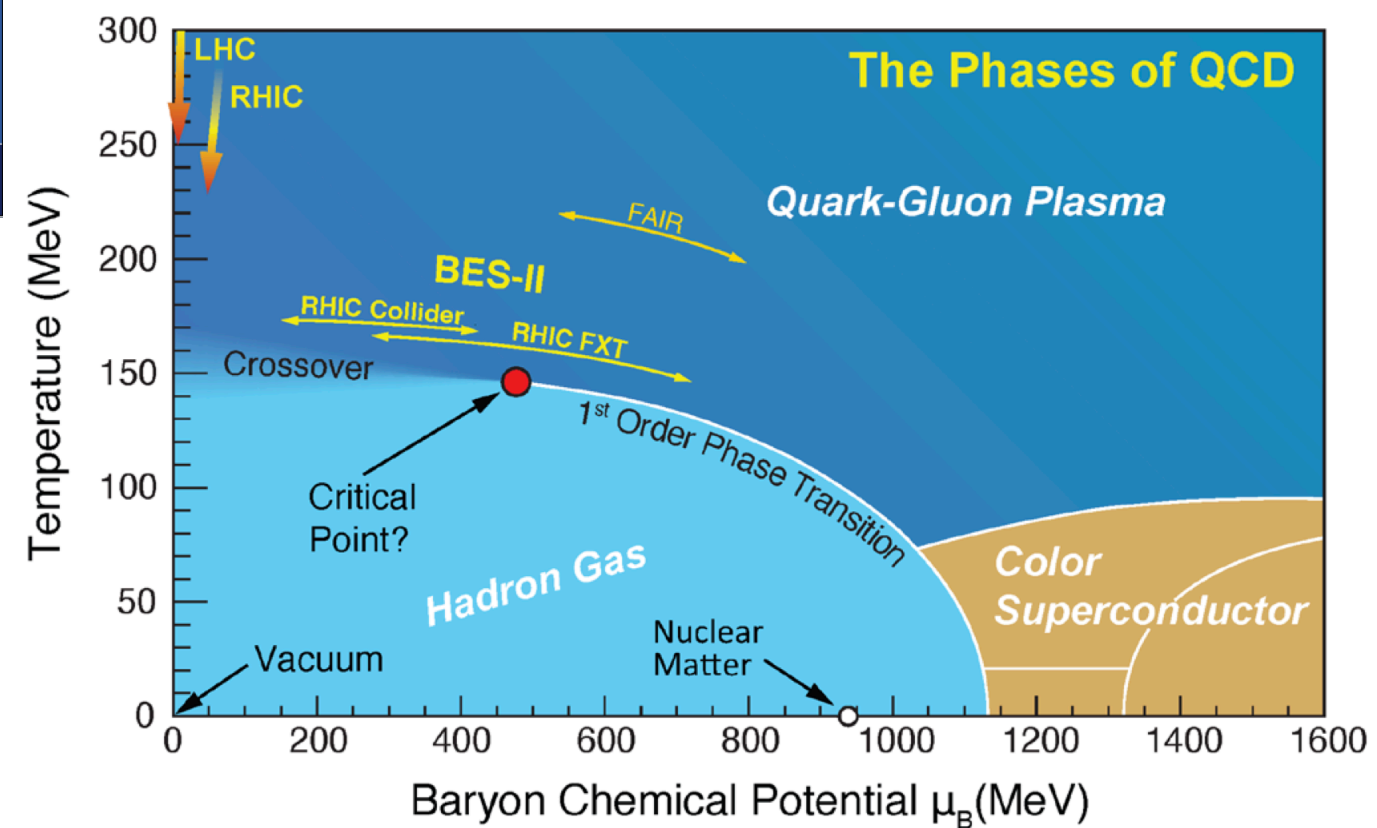
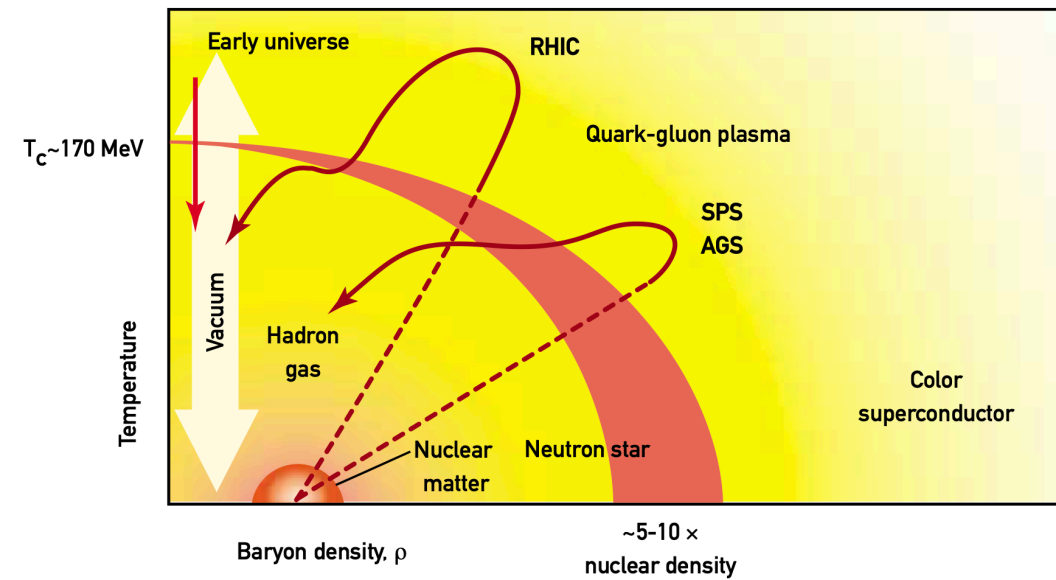
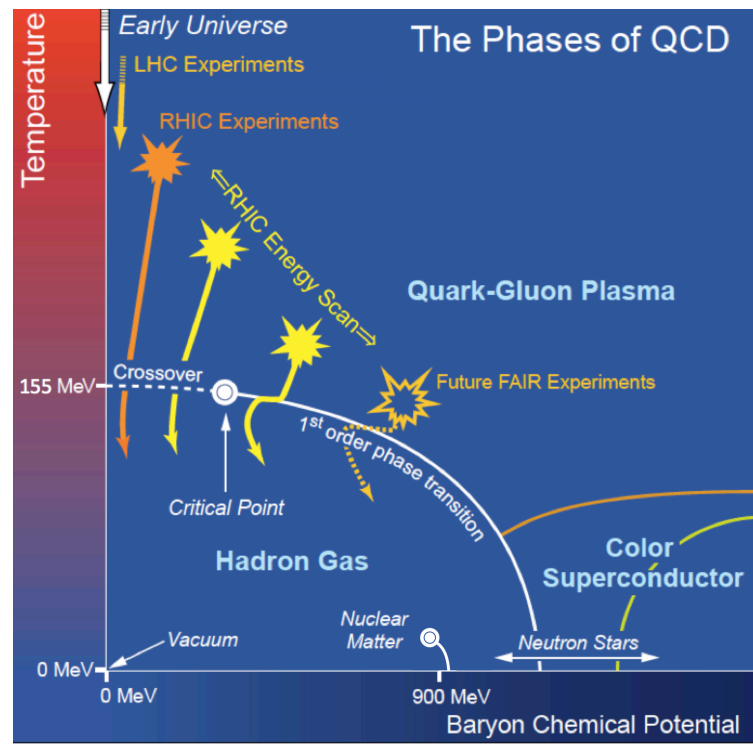
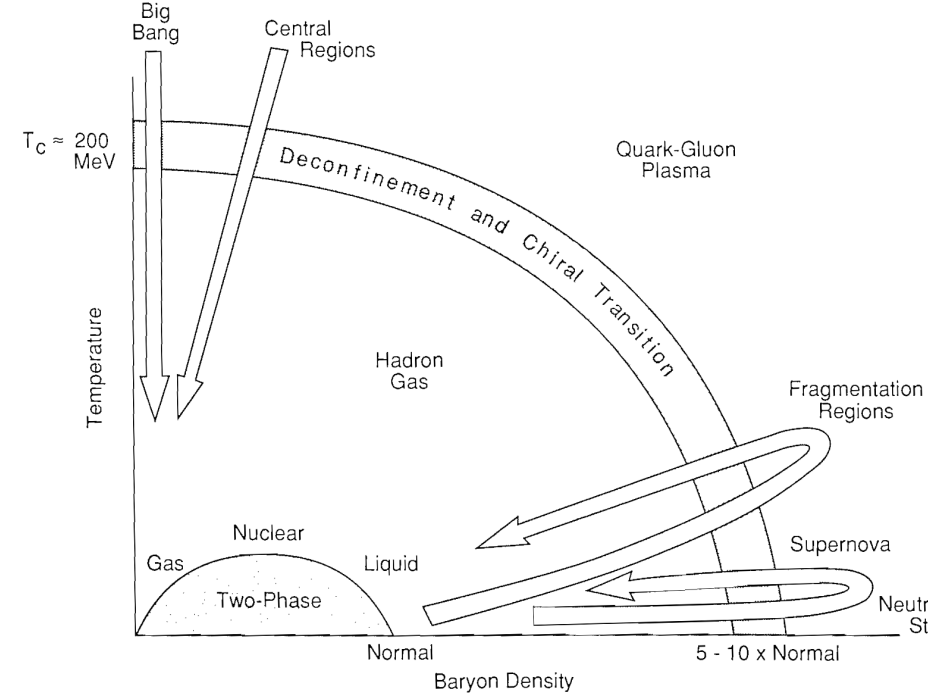
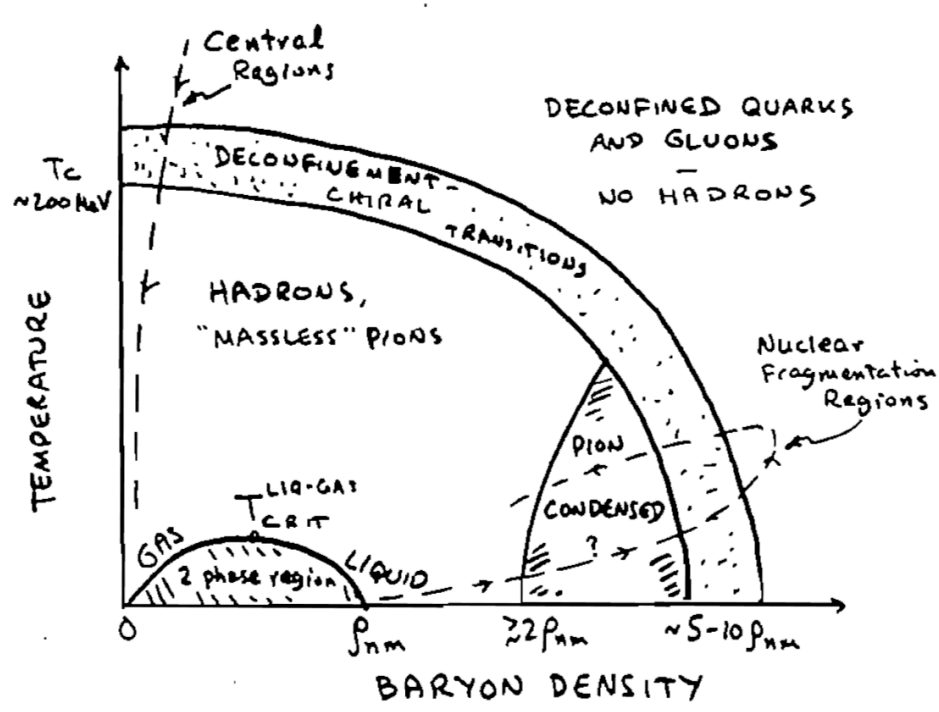
DALL-E

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

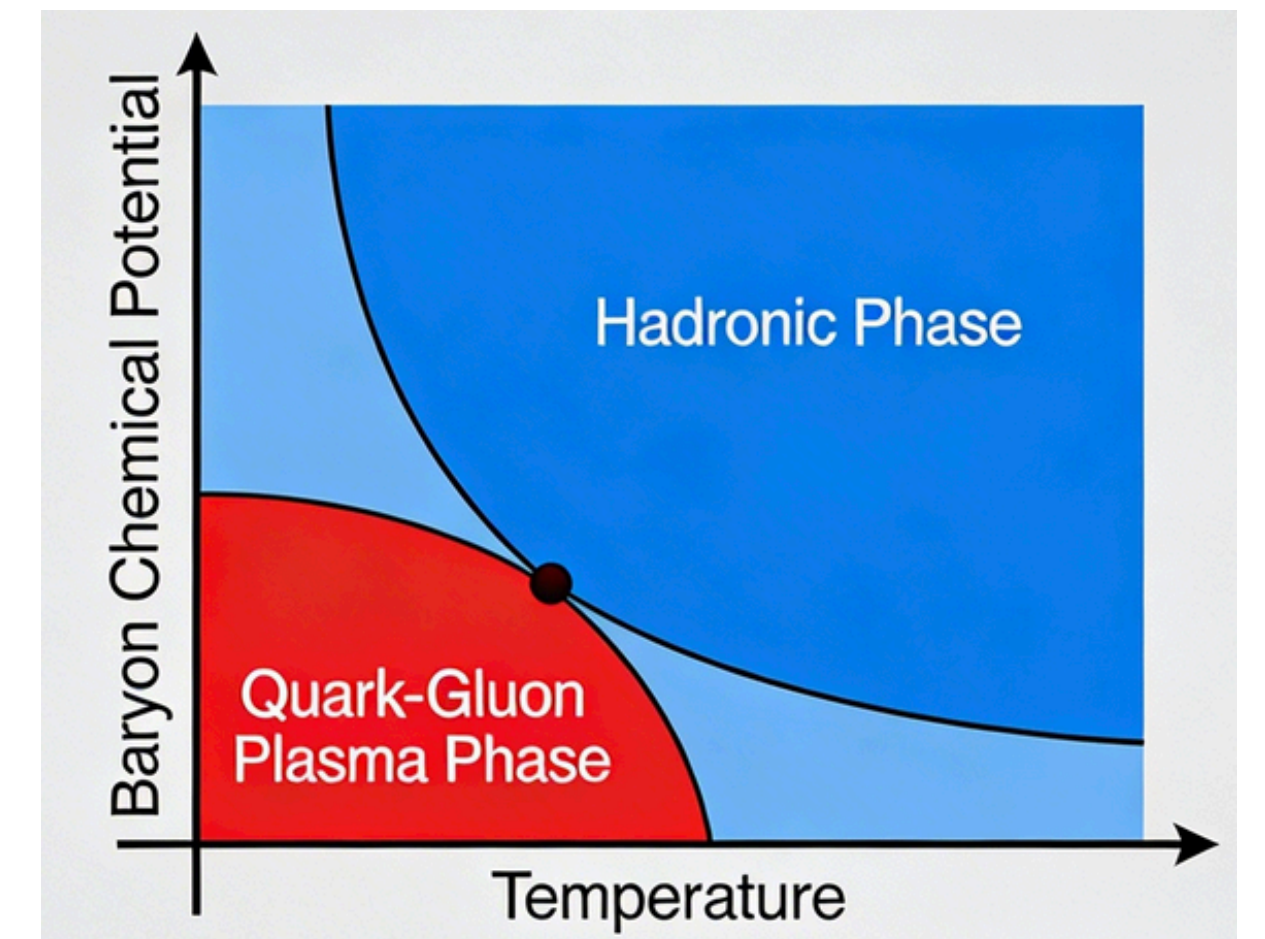
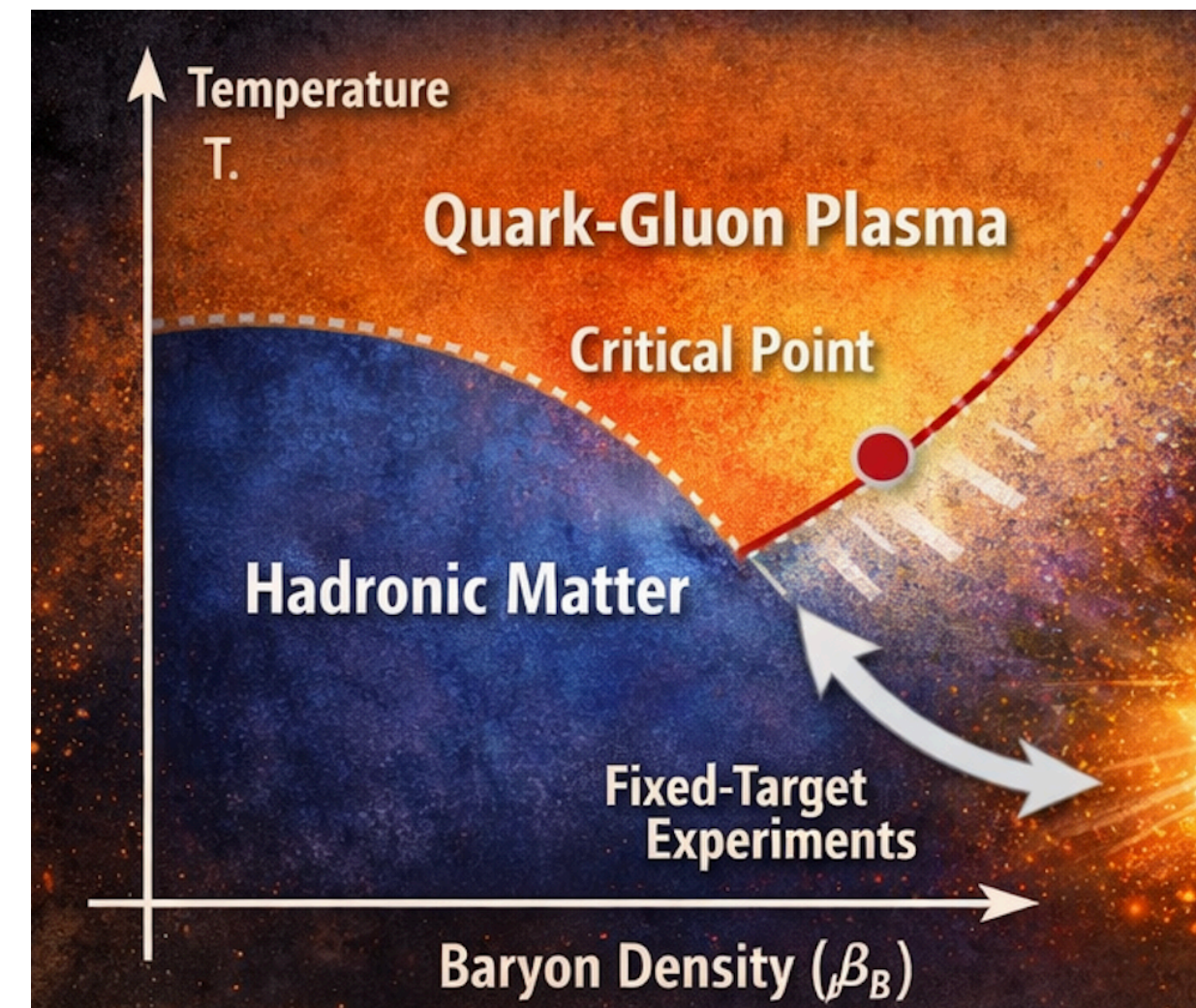
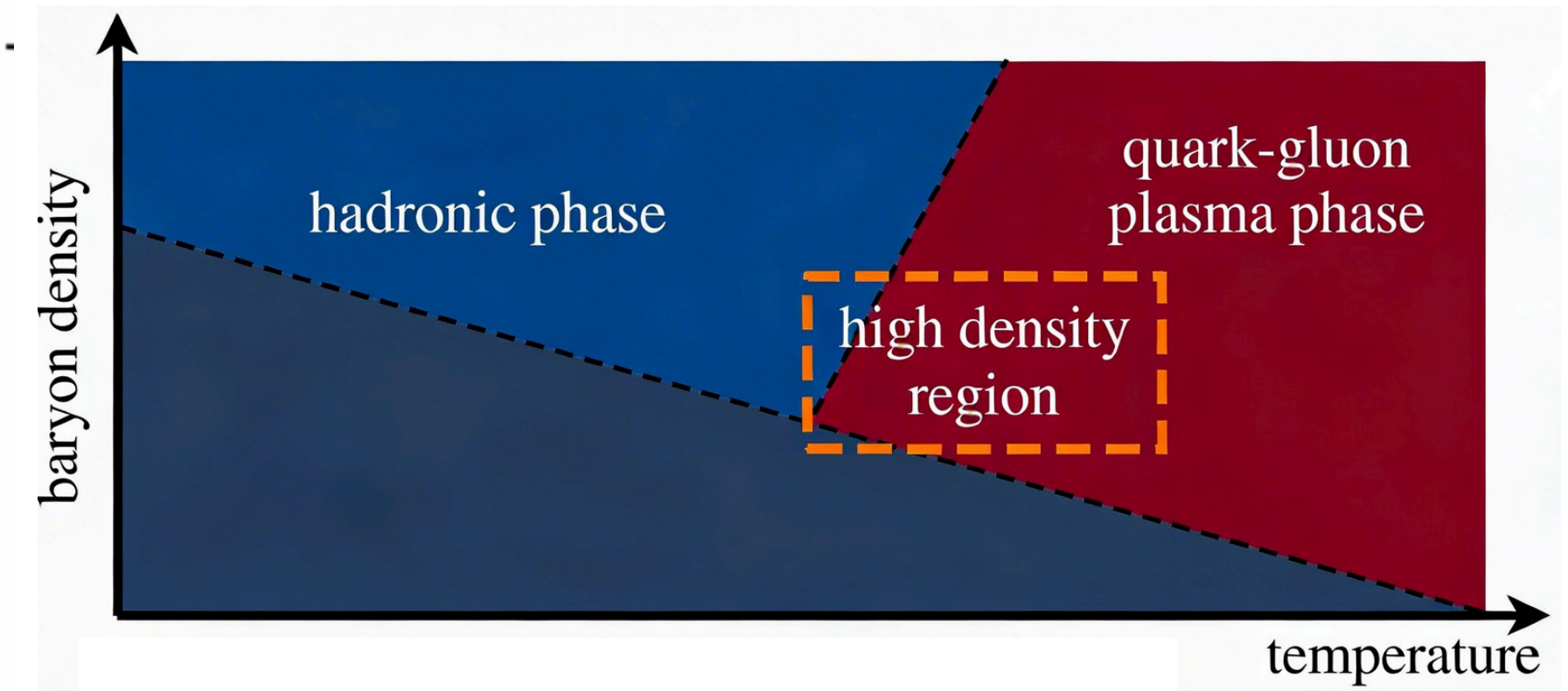
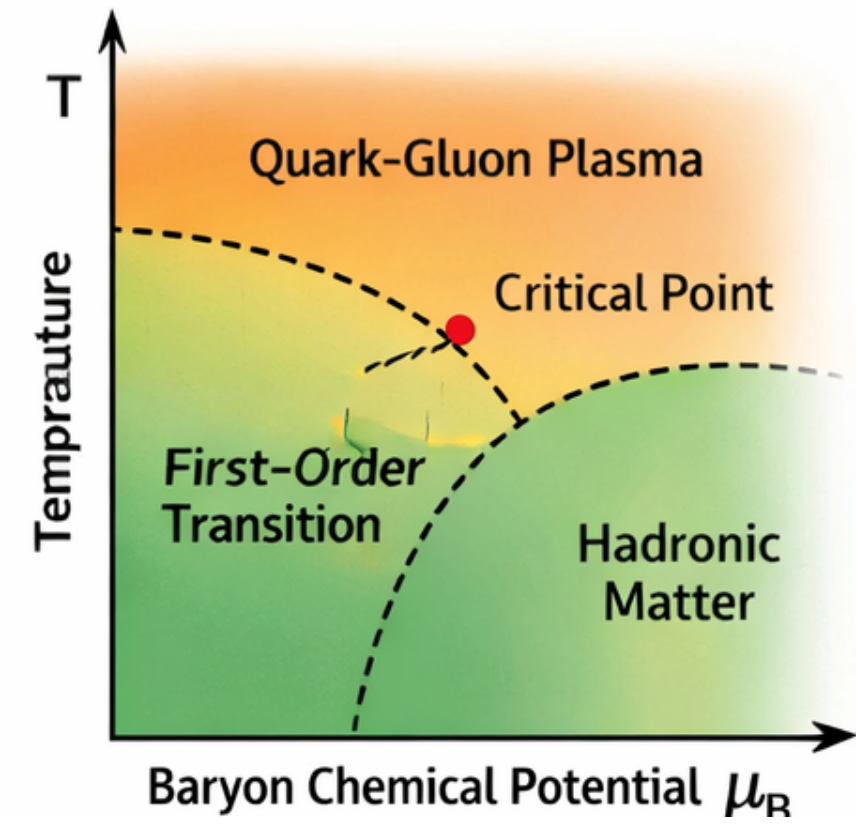
QCD phase diagram — are we flexible enough?

Nuclear physicists:

PHASE DIAGRAM OF NUCLEAR MATTER

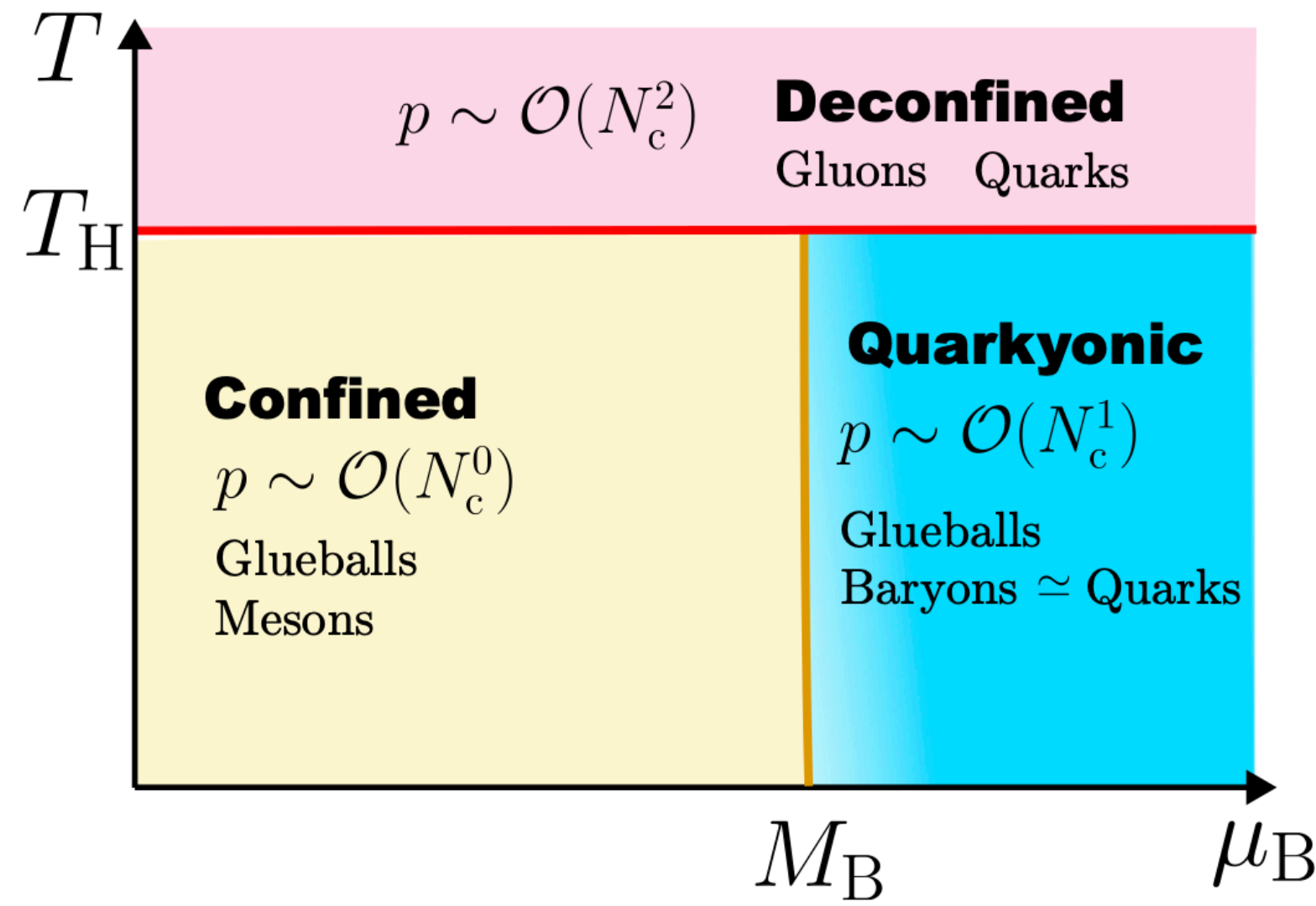


AI:



QCD phase diagram – are we flexible enough?

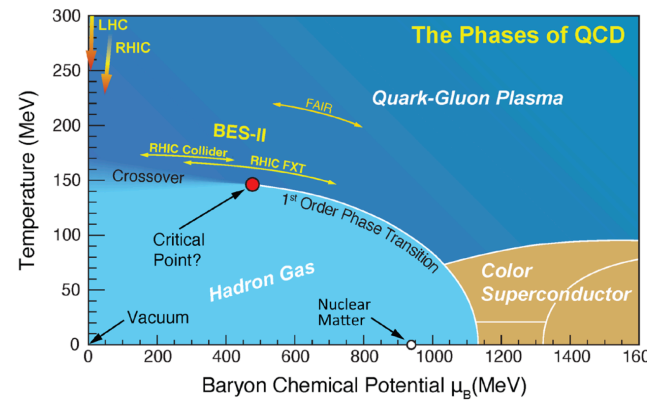
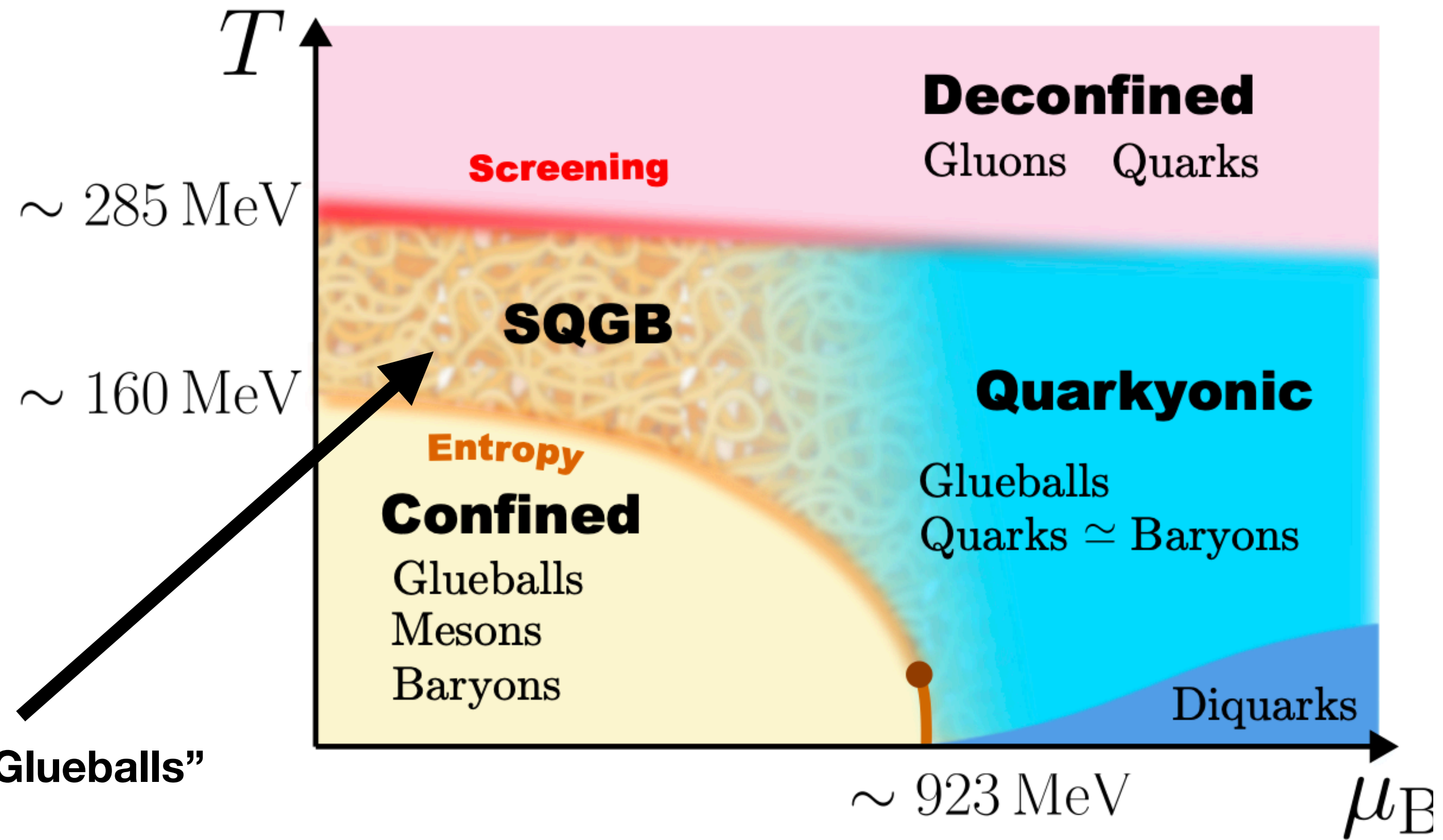
strict large N_c limit



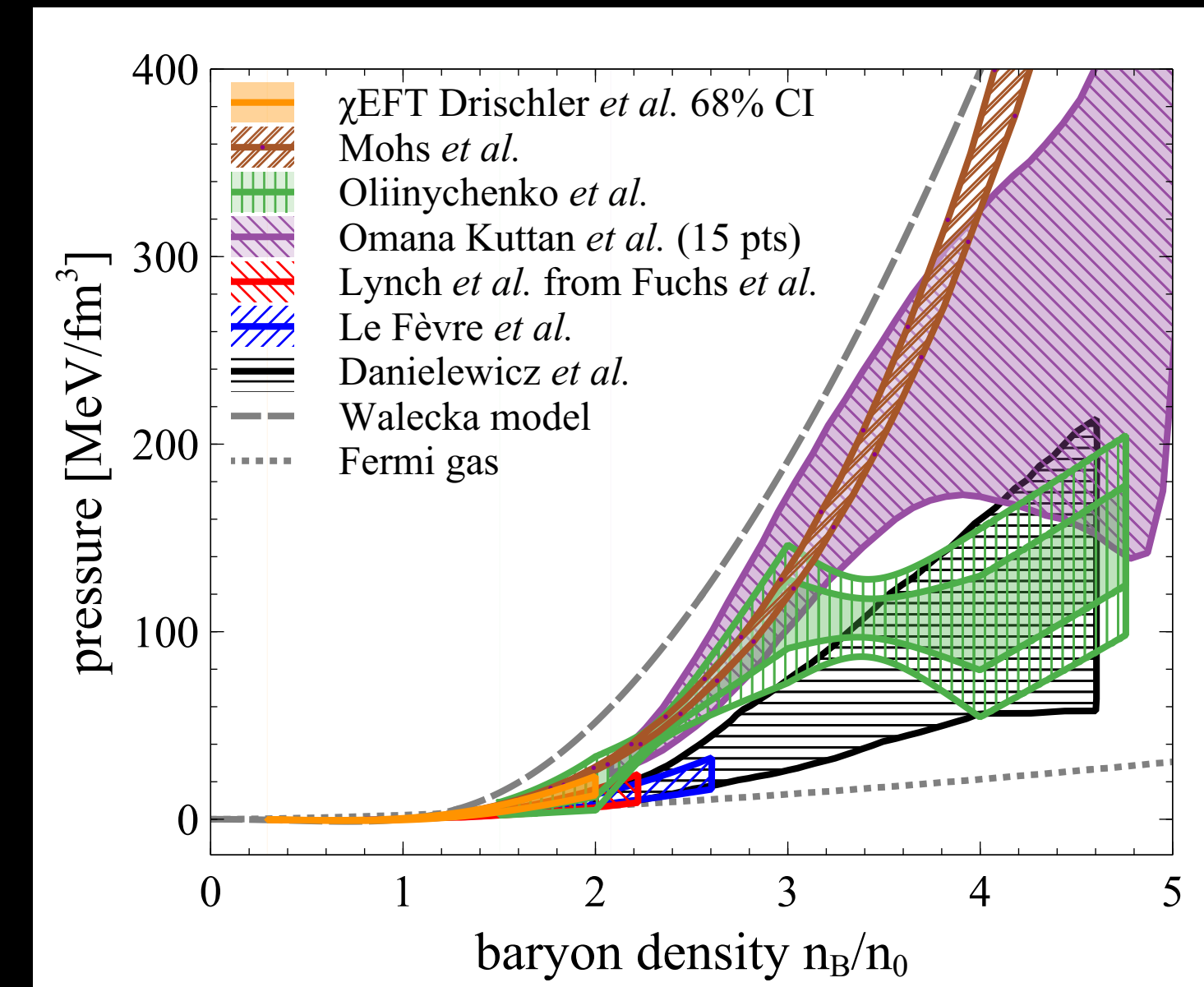
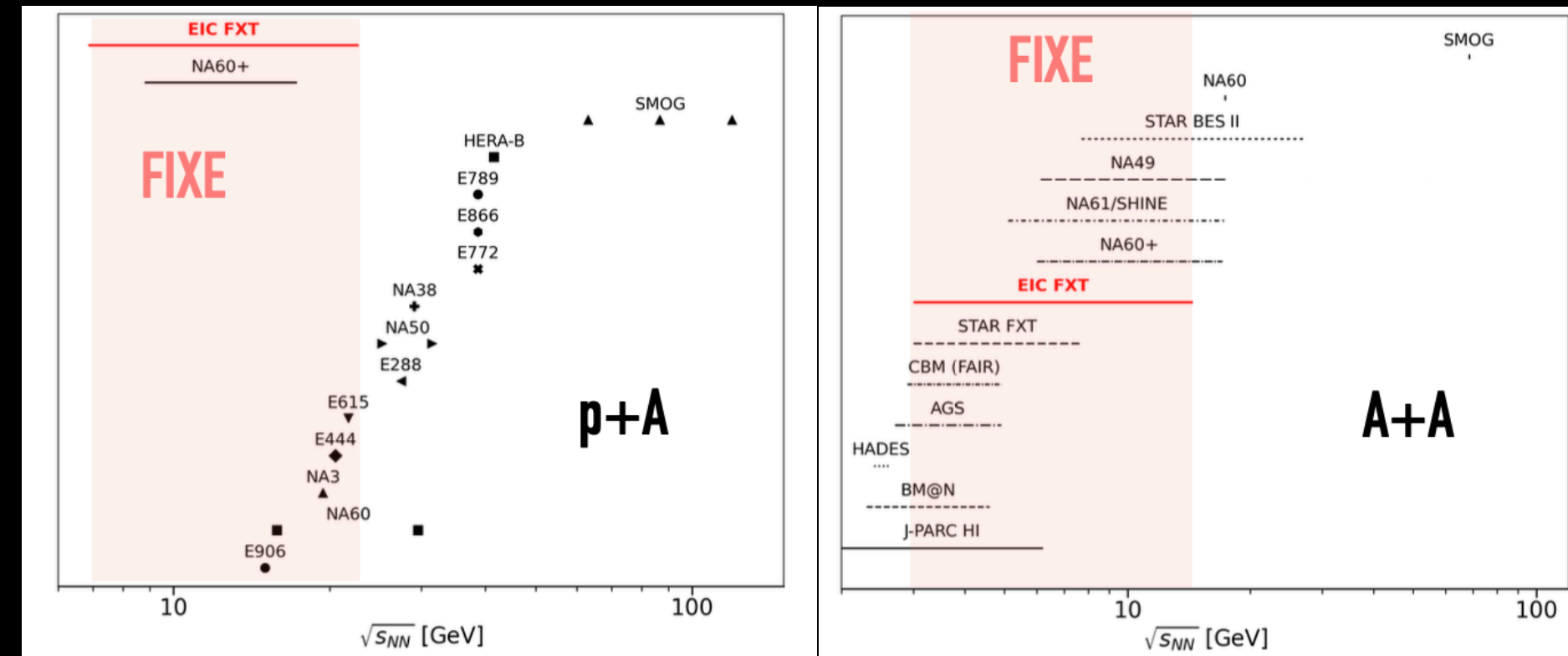
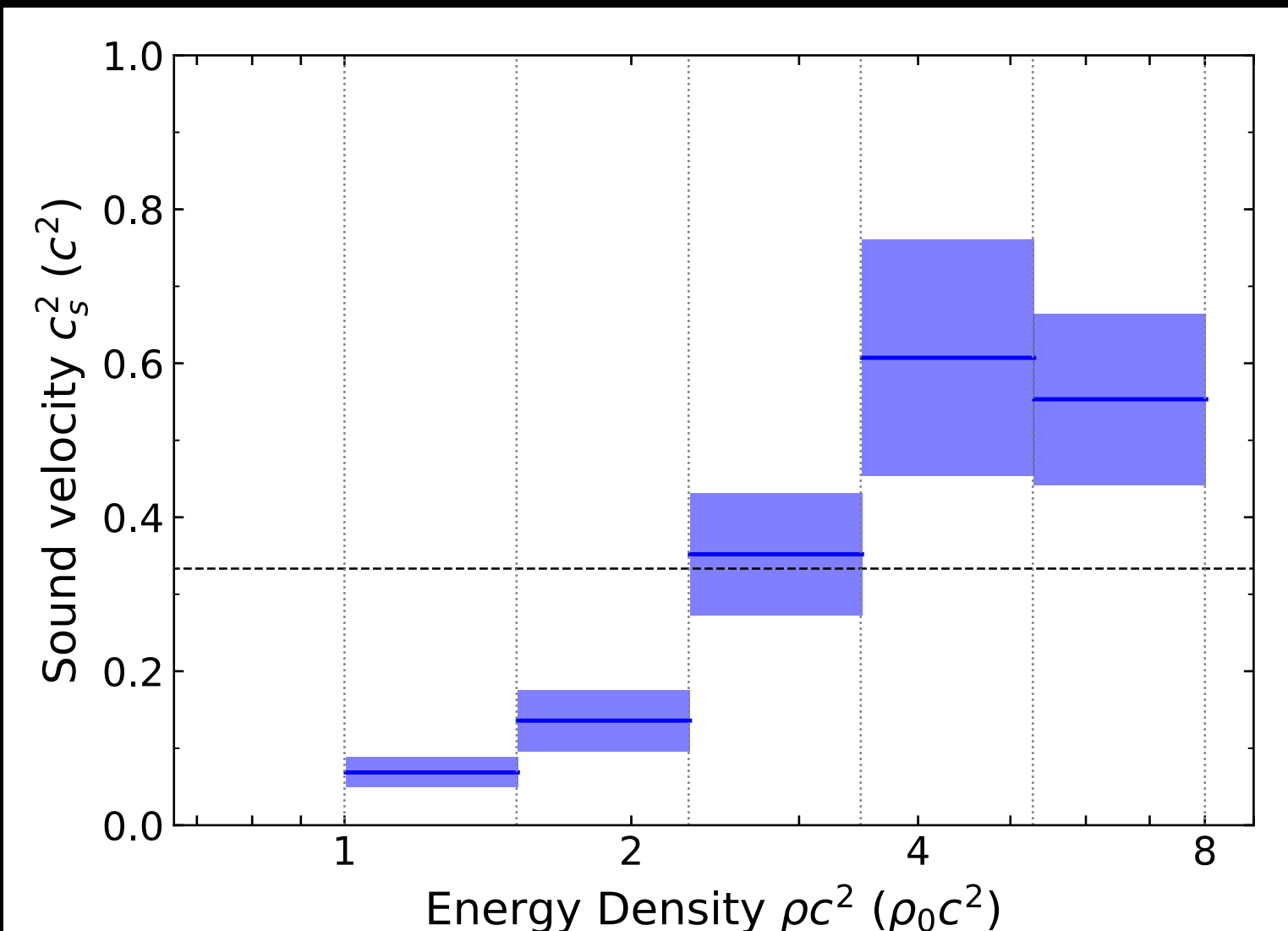
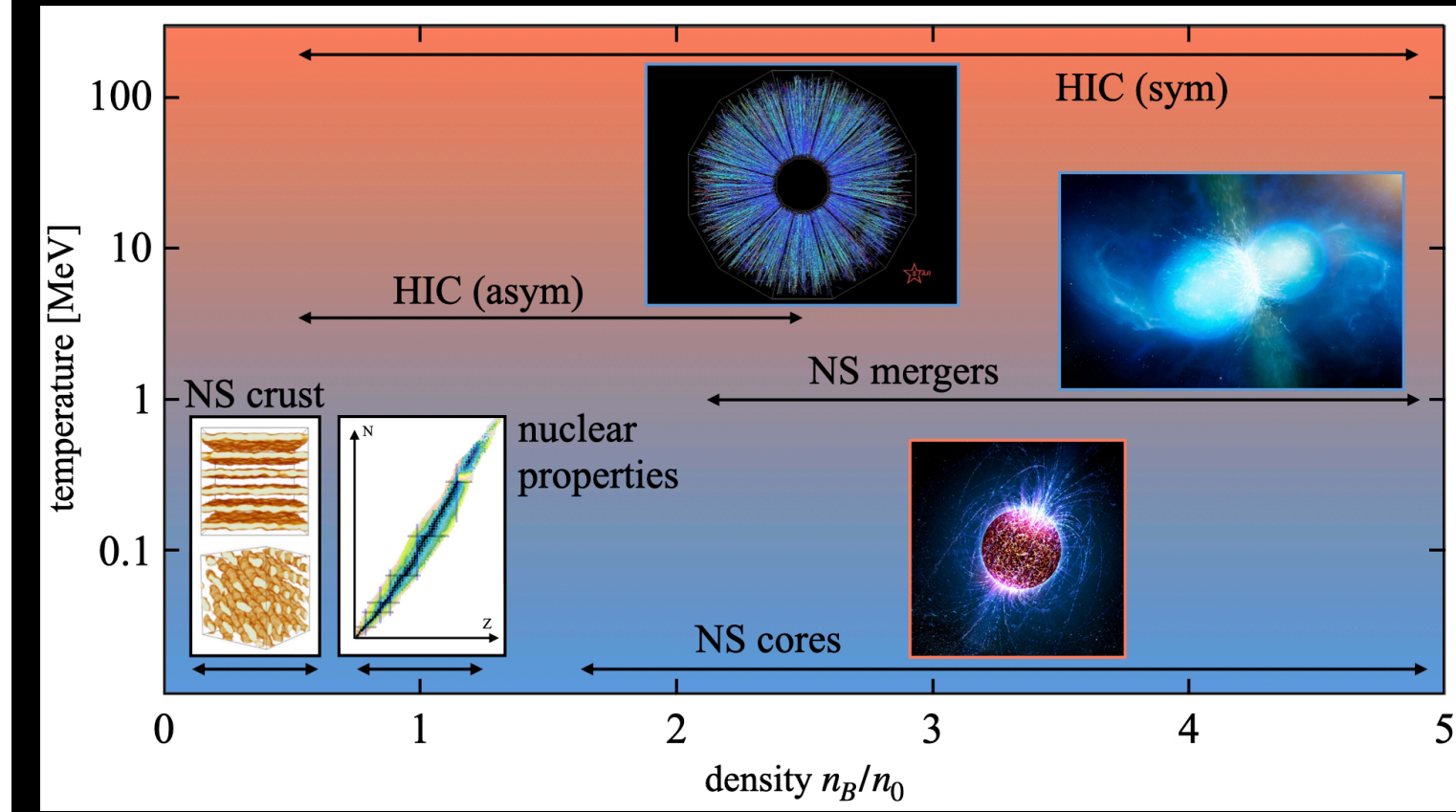
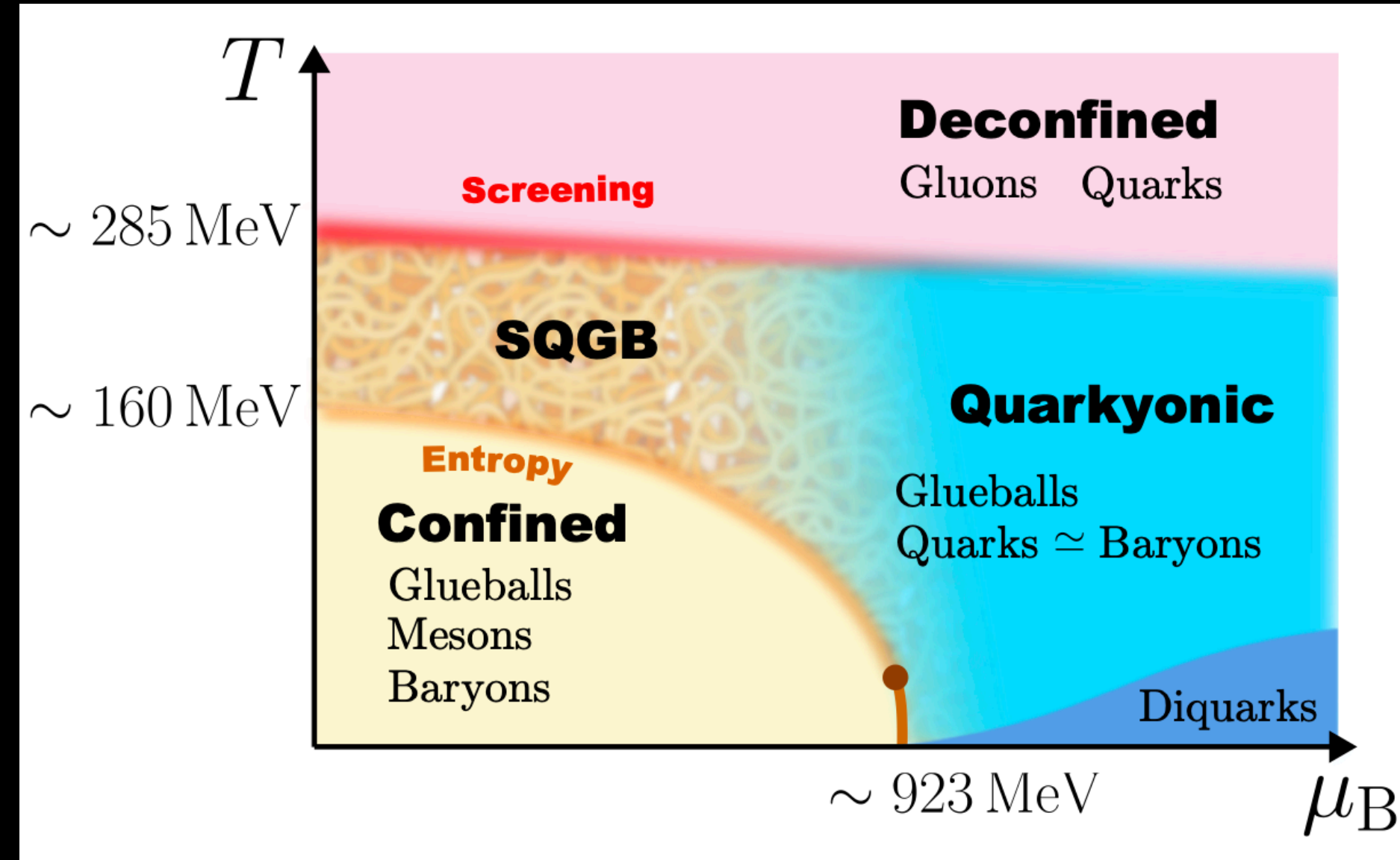
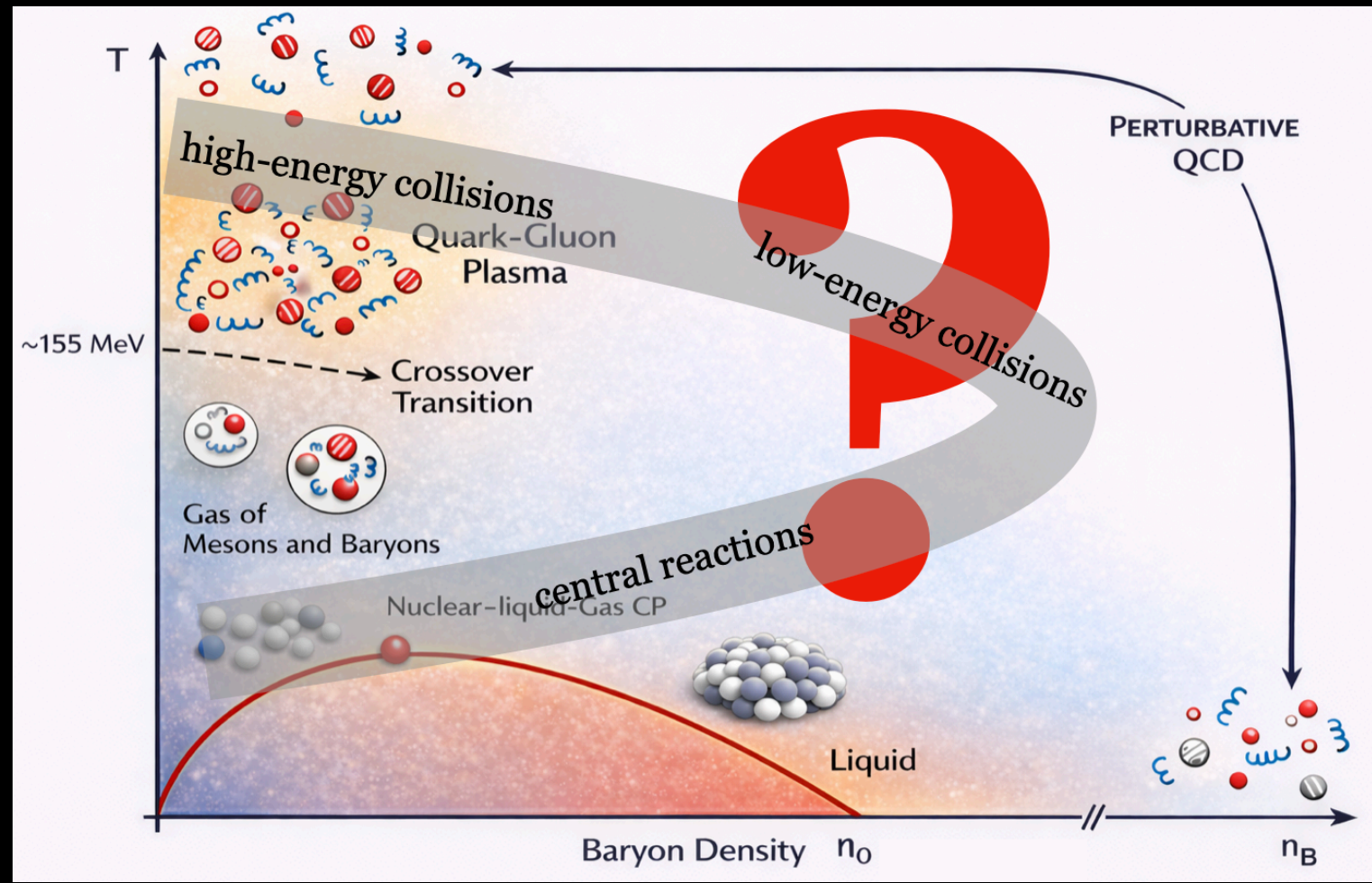
Y. Fujimoto *et al.*, Phys. Rev. D **112**, 7, 074006 (2025)

“Spaghetti of Quarks with Glueballs”

“realistic vision” for $N_c = 3$



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



Thank you for your attention