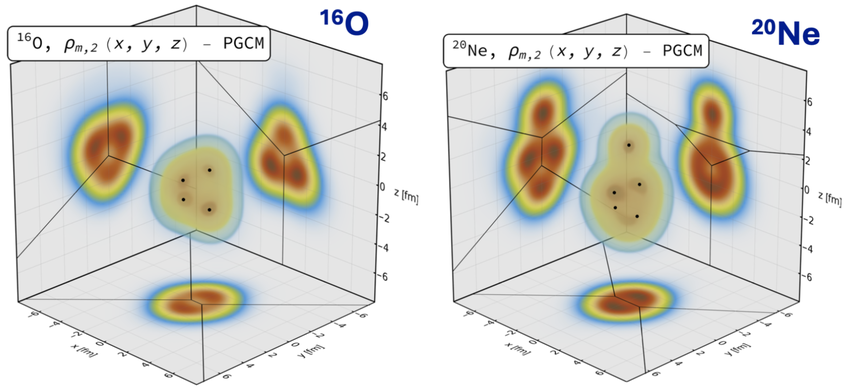
QCD phase diagram with heavy and light ion collisions and connection to neutron stars

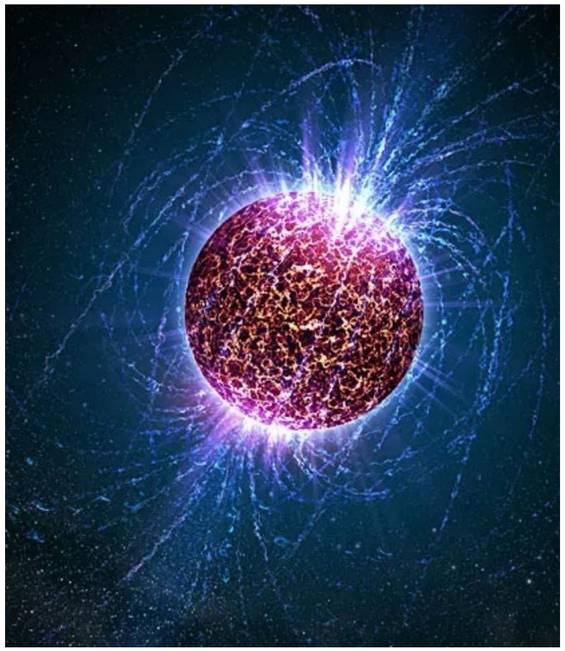
Jacquelyn Noronha-Hostler

Emmi Workshop Heidelberg, Sept ‘26

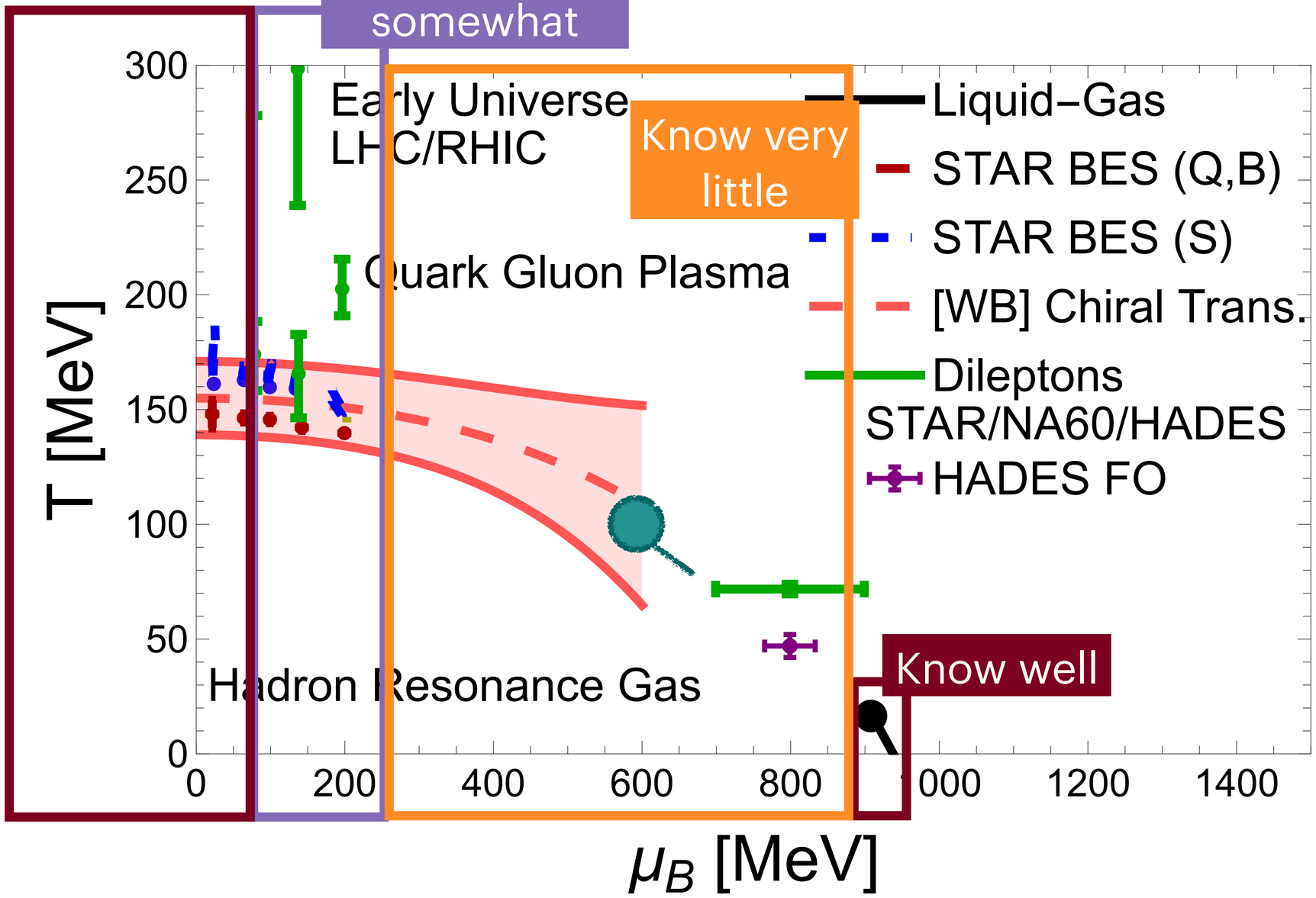


Nucleon densities of ^{16}O and ^{20}Ne showing deformed geometries with well-separated structures. In ^{16}O they form an irregular tetrahedron with two short and two long edges. For ^{20}Ne, one sees a characteristic bowling-pin-like ^{16}O+α.

Ref: Giacalone et al., PRL, 135, 012302 (2025)



QCD: what we know, what we don't



Hydro simulations from $\sqrt{s} = [3,7.7,27]\ GeV$
Shen&Schenke, Phys. Rev. C 105, 064905 (2022)

(T, μ_B) extracted from STAR net-(p,π,K), net-p, net-K fluctuations
Alba, et al, Phys. Rev. C 101, 054905 (2020)

Chiral transition from lattice QCD
[WB] Phys. Rev. Lett. 125, 052001 (2020)

Dilepton measurements from
[STAR] 2402.01998 [nucl-ex]
[HADES] Nature Phys. 15, 1040 (2019)
[NA60] Eur.Phys.J.C59:607-623,2009

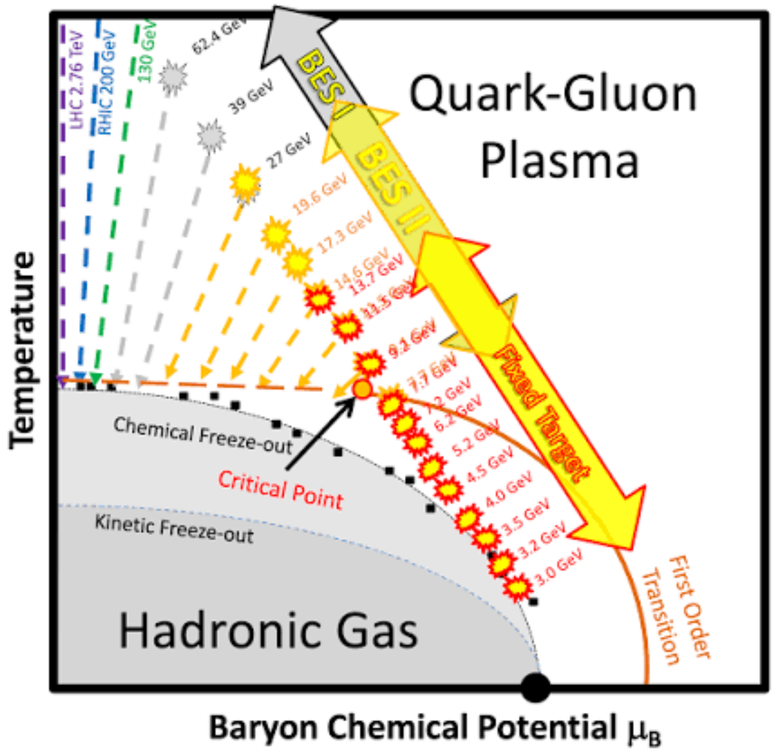
Statistical Hadronization Model
[HADES] Phys. Rev. C 102, 054903 (2020)

Liquid-gas phase transition location
Elliott, et al, Phys. Rev. C 87, 054622 (2013)
μ_B estimate Vovchenko, et al, Phys. Rev. Lett. 118, 182301 (2017)

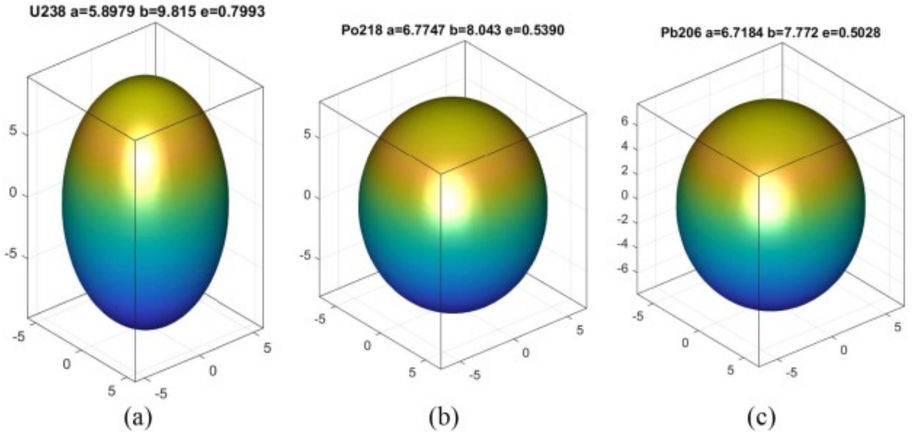
Hints of a QCD critical point beginning to appear...

What we get from heavy-ion collision

$\Downarrow \sqrt{s_{NN}}$, then $\Uparrow n_B$



Imaging nuclei from v_n +other observables



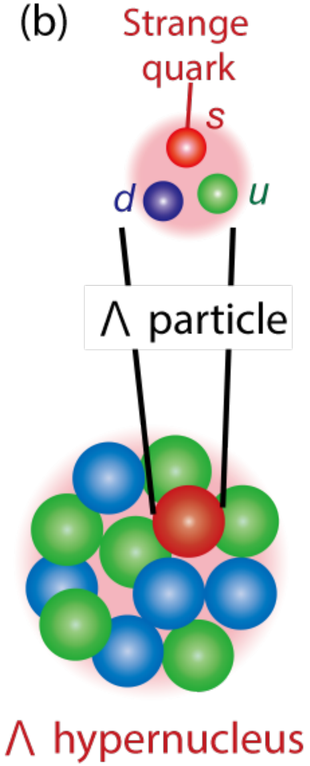
Change $Y_Q = Z/A$ of colliding nuclei

$Z/A = 0$



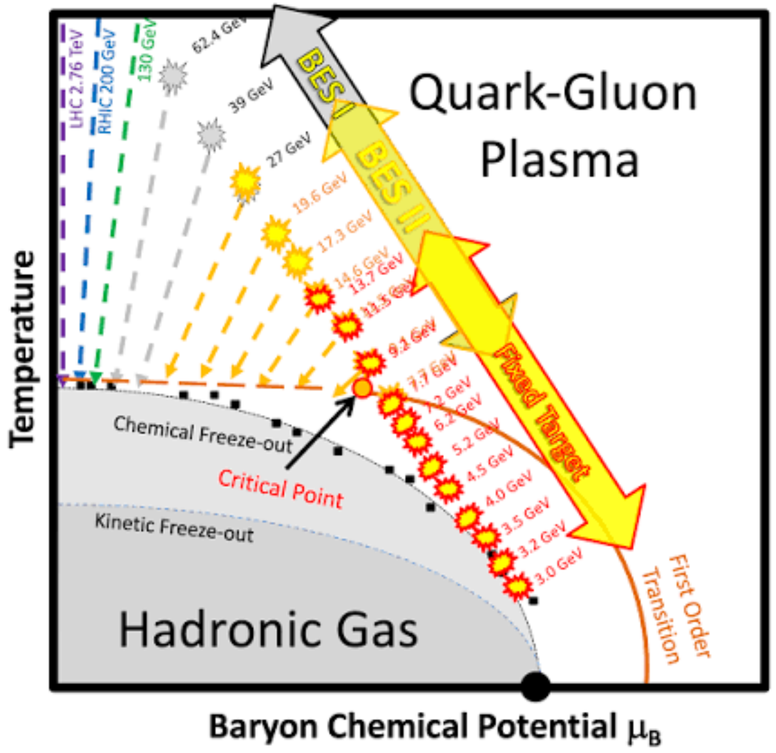
$Z/A = 0.5$

Measuring light & hyper-nuclei that appear in the final state

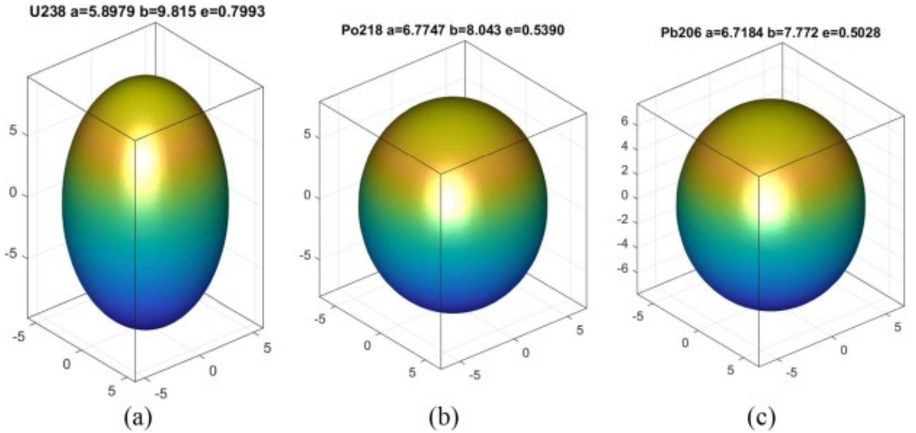


What we get from heavy-ion collision

$\Downarrow \sqrt{s_{NN}}$, then $\Uparrow n_B$



Imaging nuclei from v_n +other observables



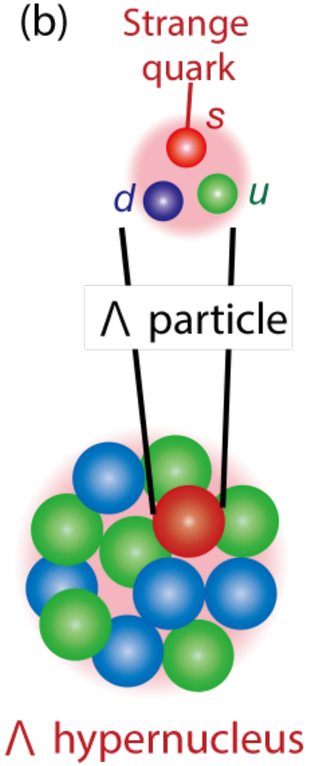
Change $Y_Q = Z/A$ of colliding nuclei

$Z/A = 0$



$Z/A = 0.5$

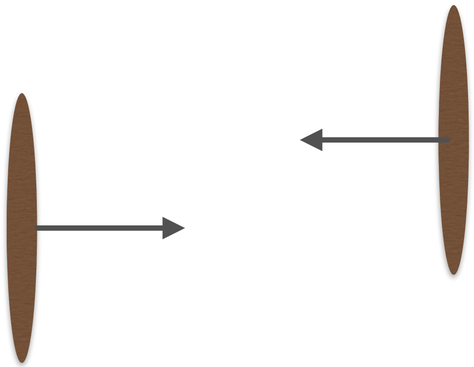
Measuring light & hyper-nuclei that appear in the final state



Doping the Quark gluon plasma with baryons

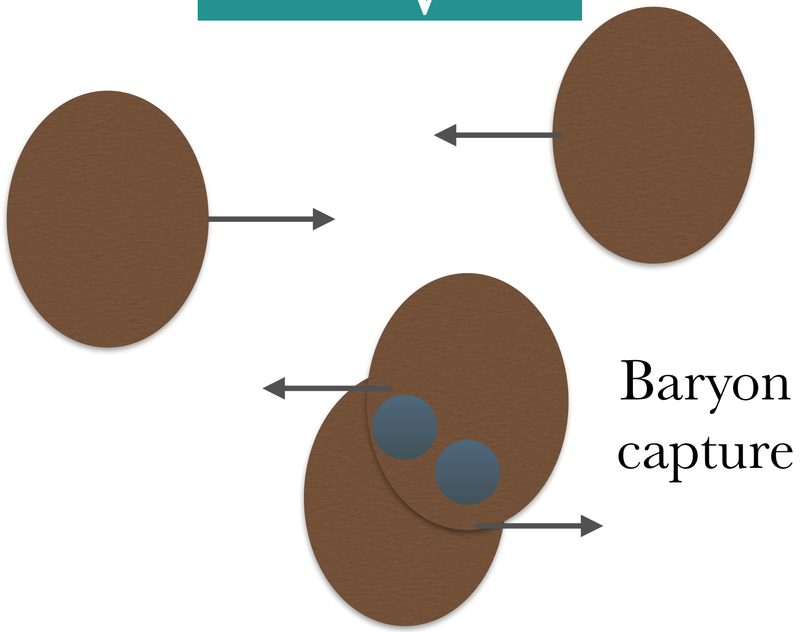
RHIC's Beam Energy Scan

Large $\sqrt{s_{NN}}$



- Lorentz contracted (2D)
- Nuclei pass through instantaneously
- Too quick to capture baryons

Small $\sqrt{s_{NN}}$



- 3D nuclei pass slowly
- Time to capture baryons

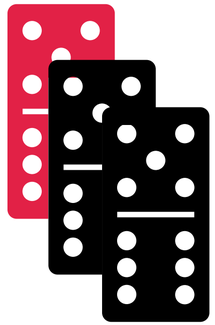
Sounds like a dynamics problem, but it changes the entire picture!

Only for AuAu collisions, Z/A=0.4

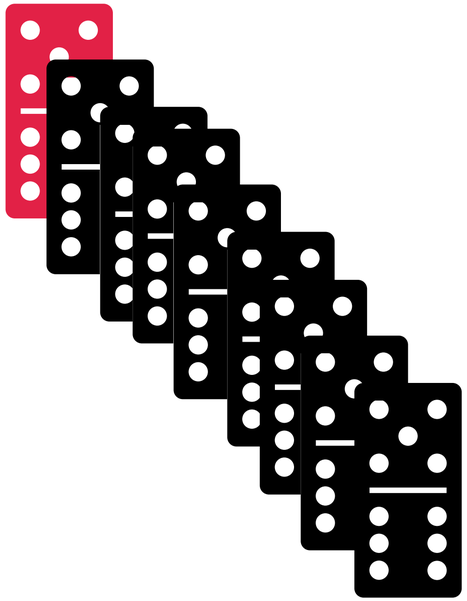
Signatures of the QCD critical point

At the critical point, the correlation length diverges $\xi \to \infty$

Small ξ



Large ξ



Leads to large fluctuations in the net-baryon number!

Susceptibilities of the pressure scale with ξ

$$\chi_n \equiv \frac{\partial^n p}{(\partial \mu_B)^n}$$

Net-baryon number = first susceptibility

$$\chi_1 = n_B$$

Kurtosis $\kappa \propto \xi^7$ scales strongly with ξ at the critical point, to cancel volume...

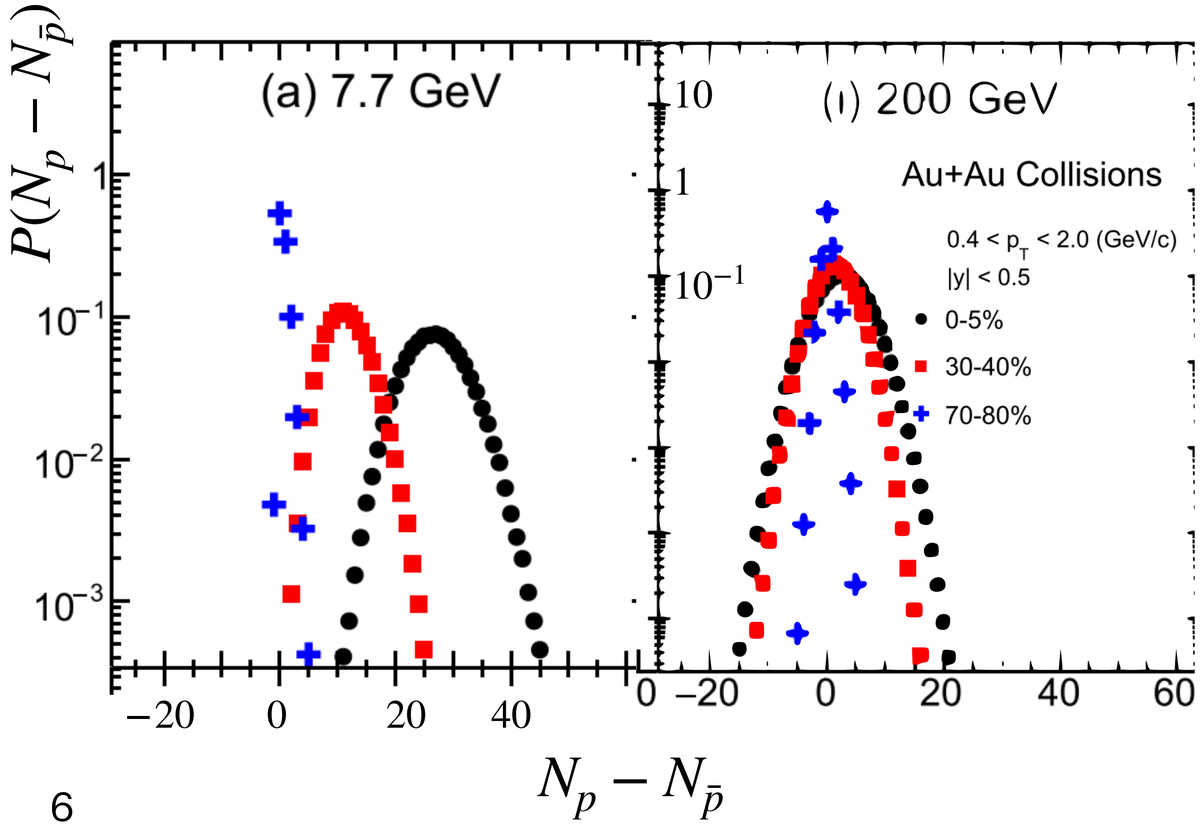
$$\kappa\sigma^2 = \frac{\chi_4}{\chi_2} \propto \xi^5$$

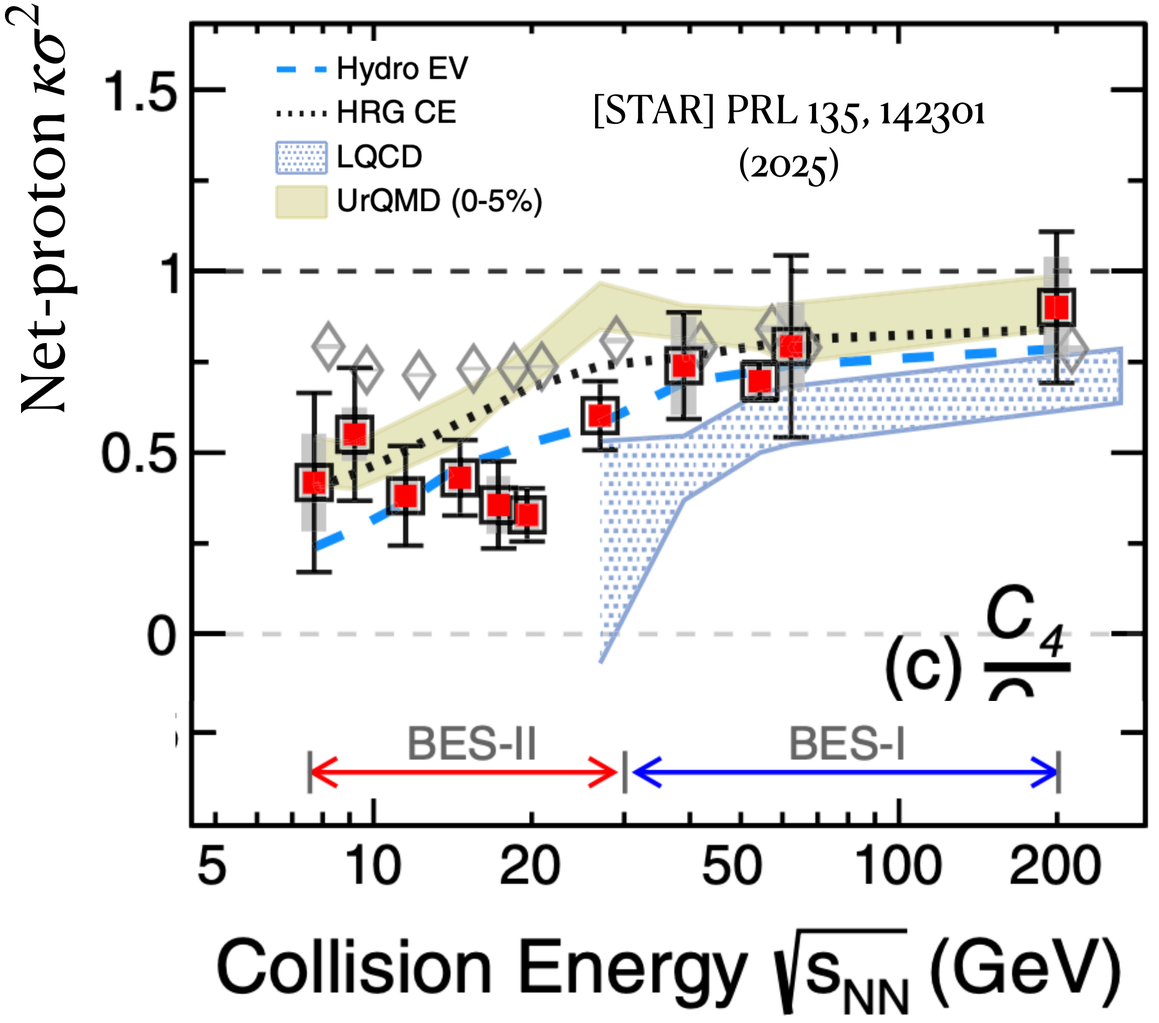
Stephanov *Phys.Rev.Lett.* 102 (2009) 032301 Karsch, Central Eur.J.Phys. 10 (2012) 1234-1237

Experimental measurements of the kurtosis

RHIC: measure net-proton distribution

[STAR] Phys. Rev. C **111**, 029902

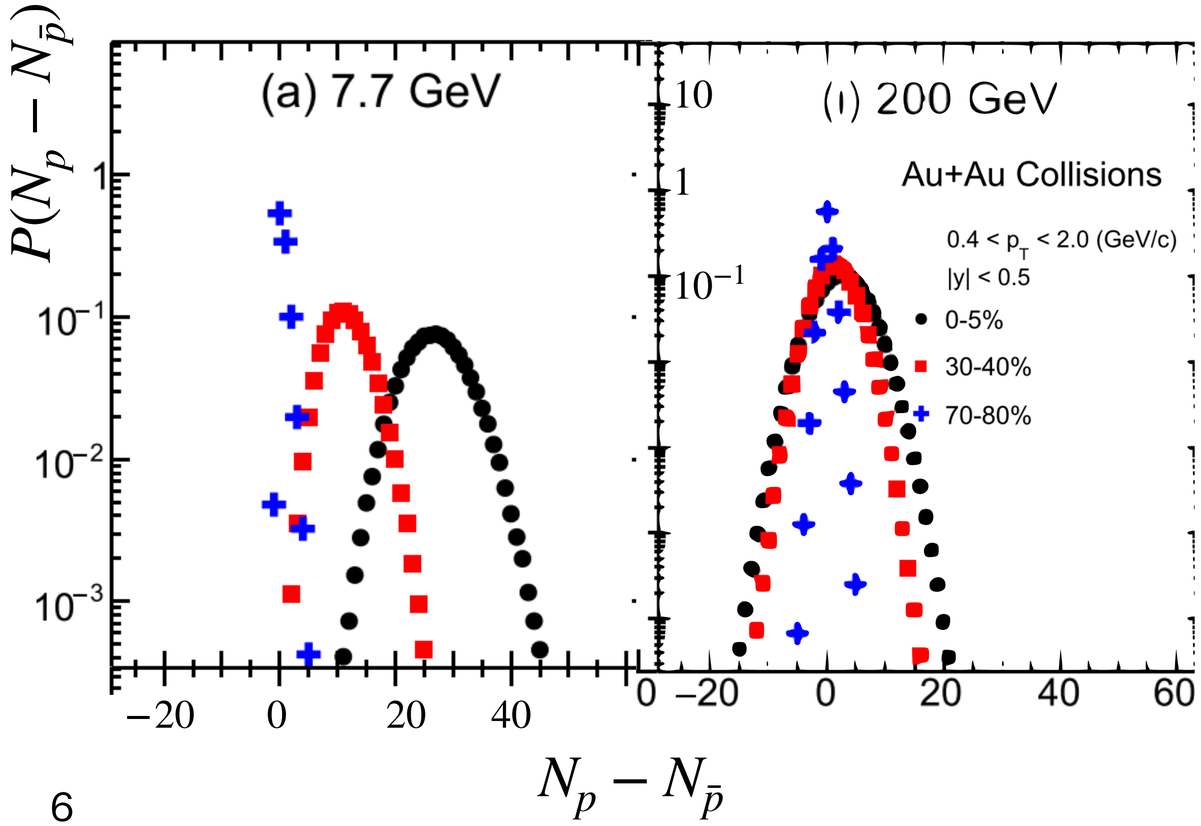


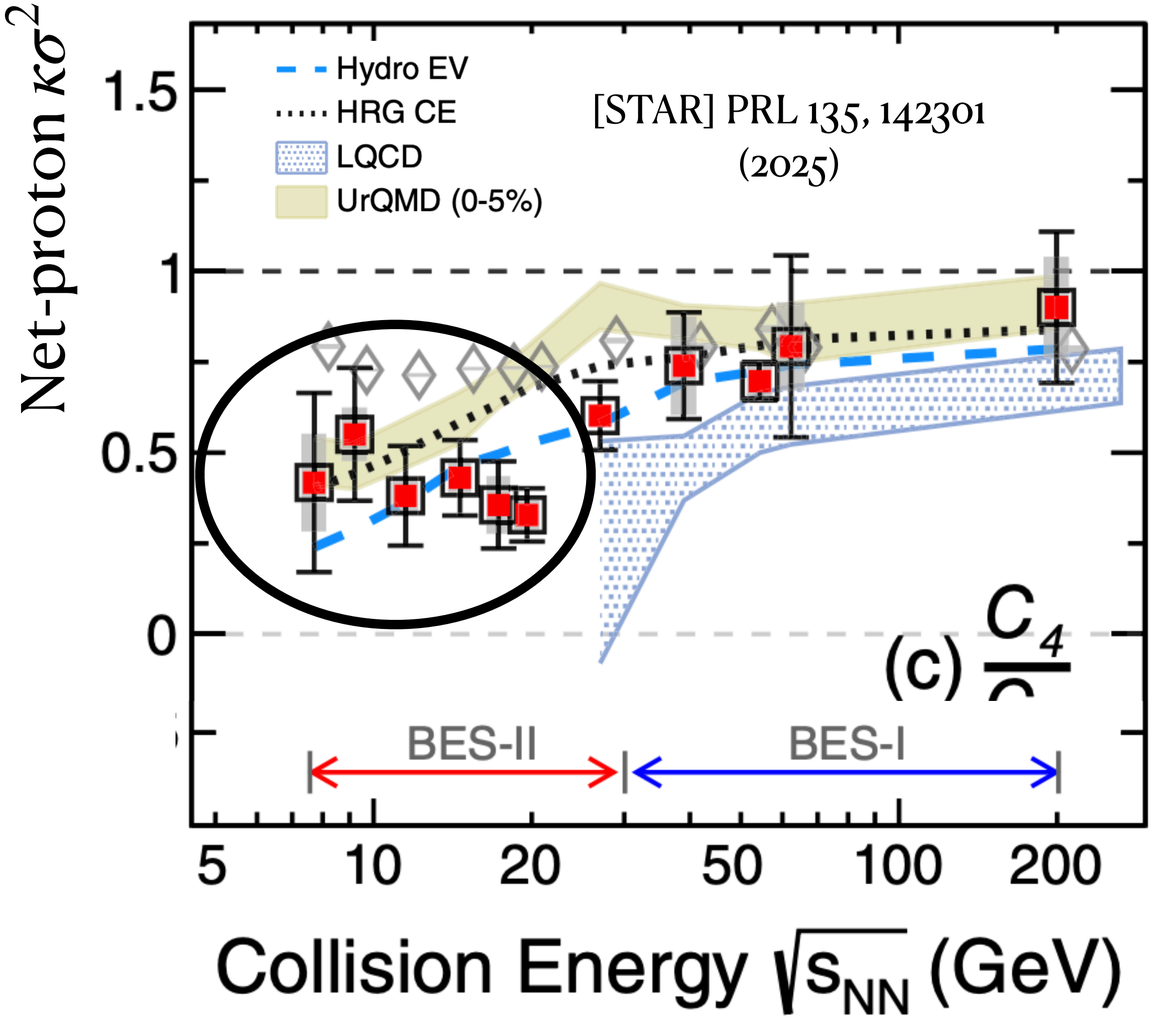


Experimental measurements of the kurtosis

RHIC: measure net-proton distribution

[STAR] Phys. Rev. C **111**, 029902

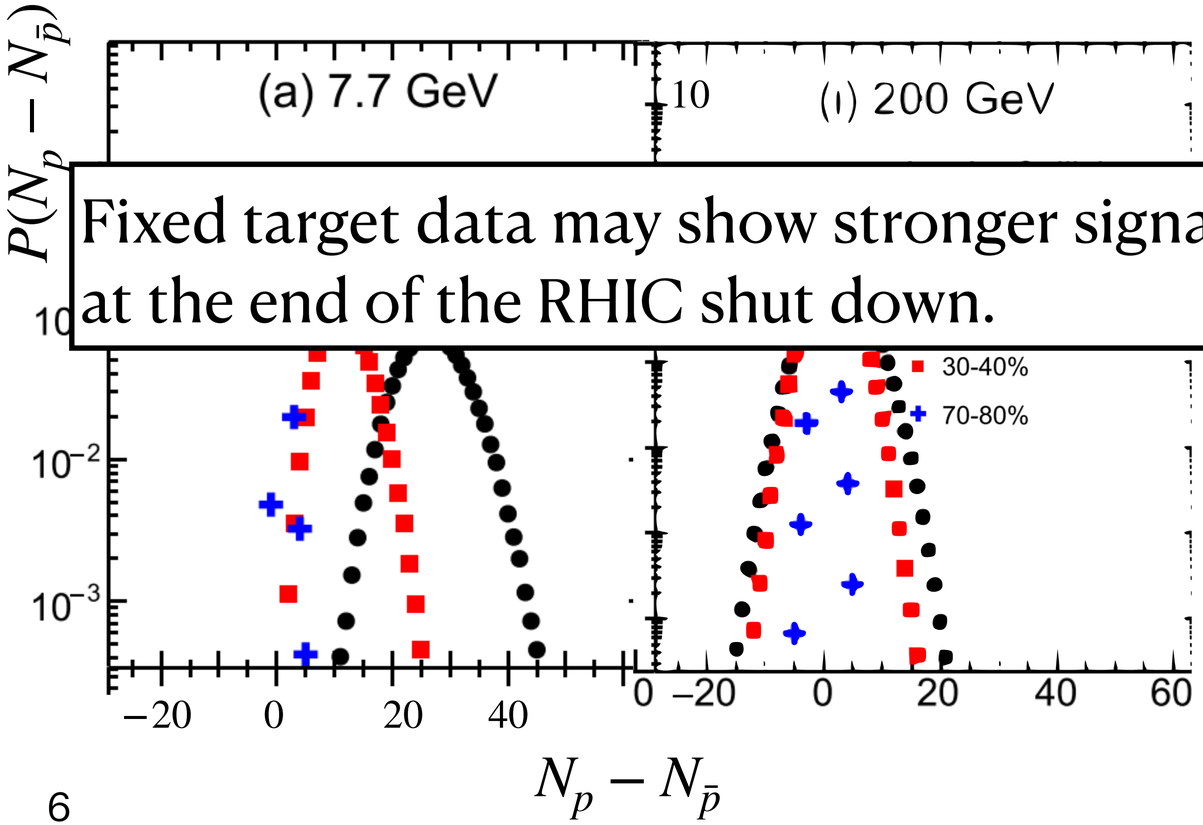




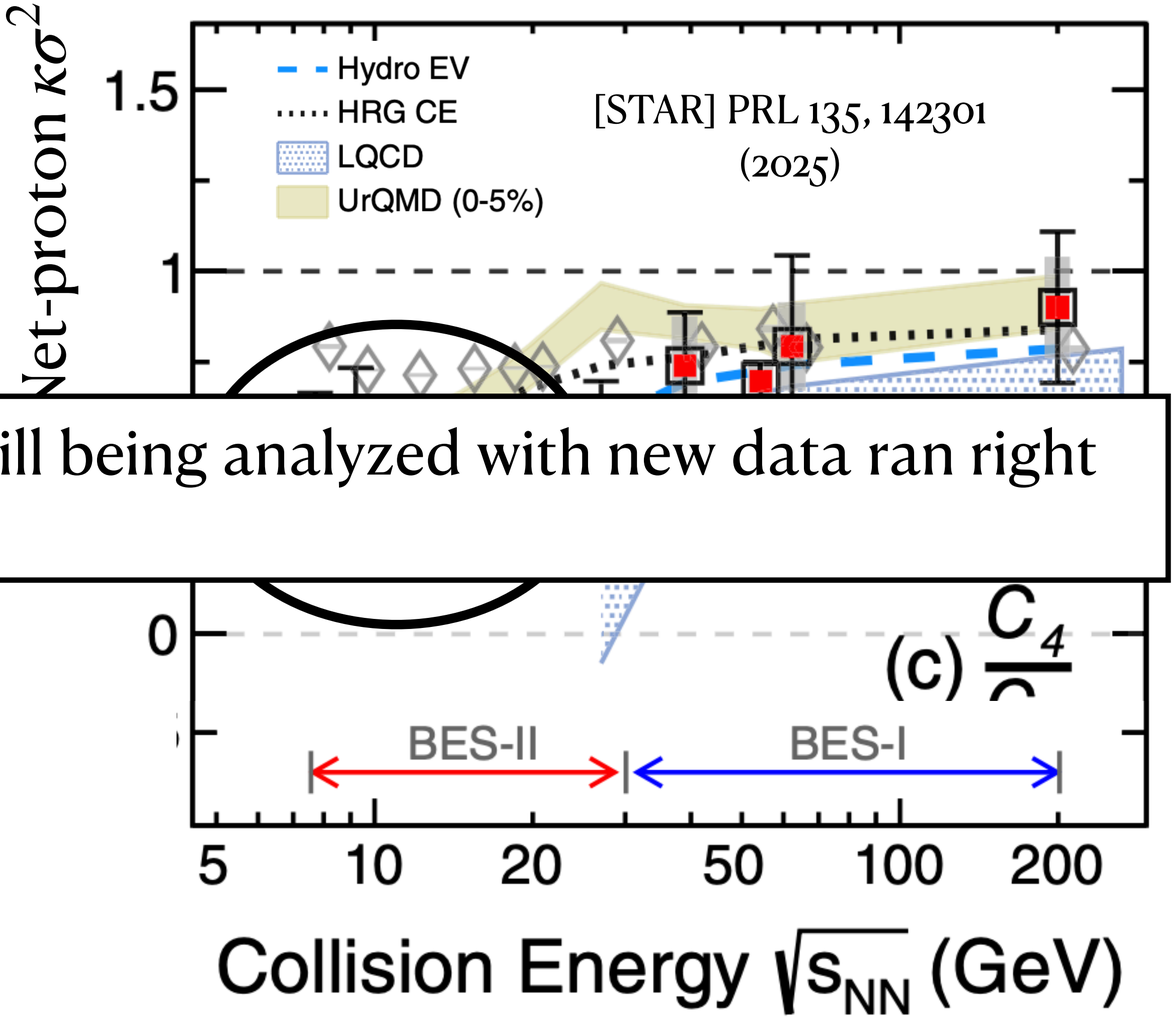
Experimental measurements of the kurtosis

RHIC: measure net-proton distribution

[STAR] Phys. Rev. C **111**, 029902



Fixed target data may show stronger signal, still being analyzed with new data ran right at the end of the RHIC shut down.

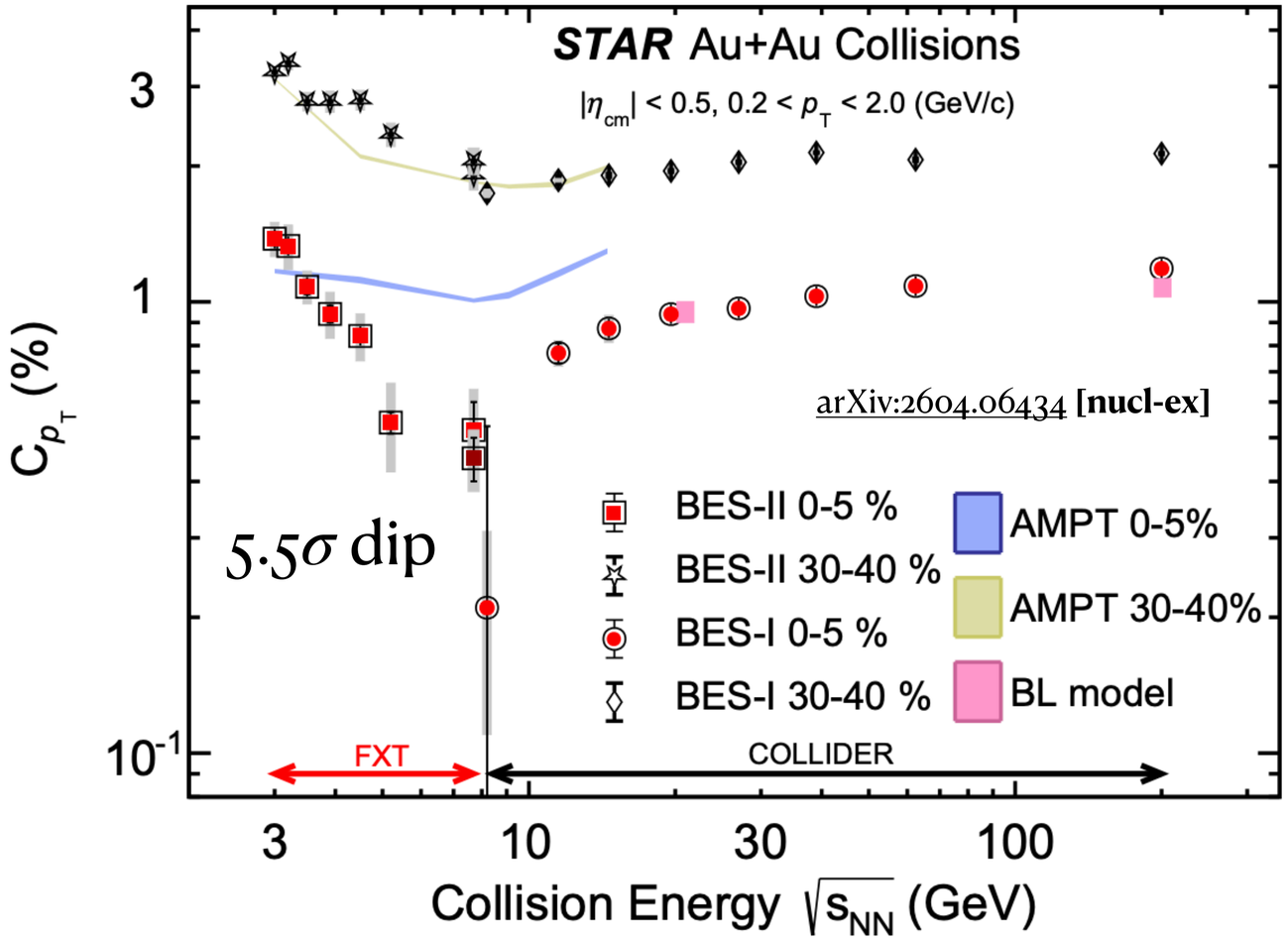


Fluctuations in the average momentum of protons

Possible hints in the fixed-target region?

Larger fluctuations in the the transverse momentum where we anticipate the critical point.

Could appear due to changes in the equation of state and/or critical scaling of transport coefficients

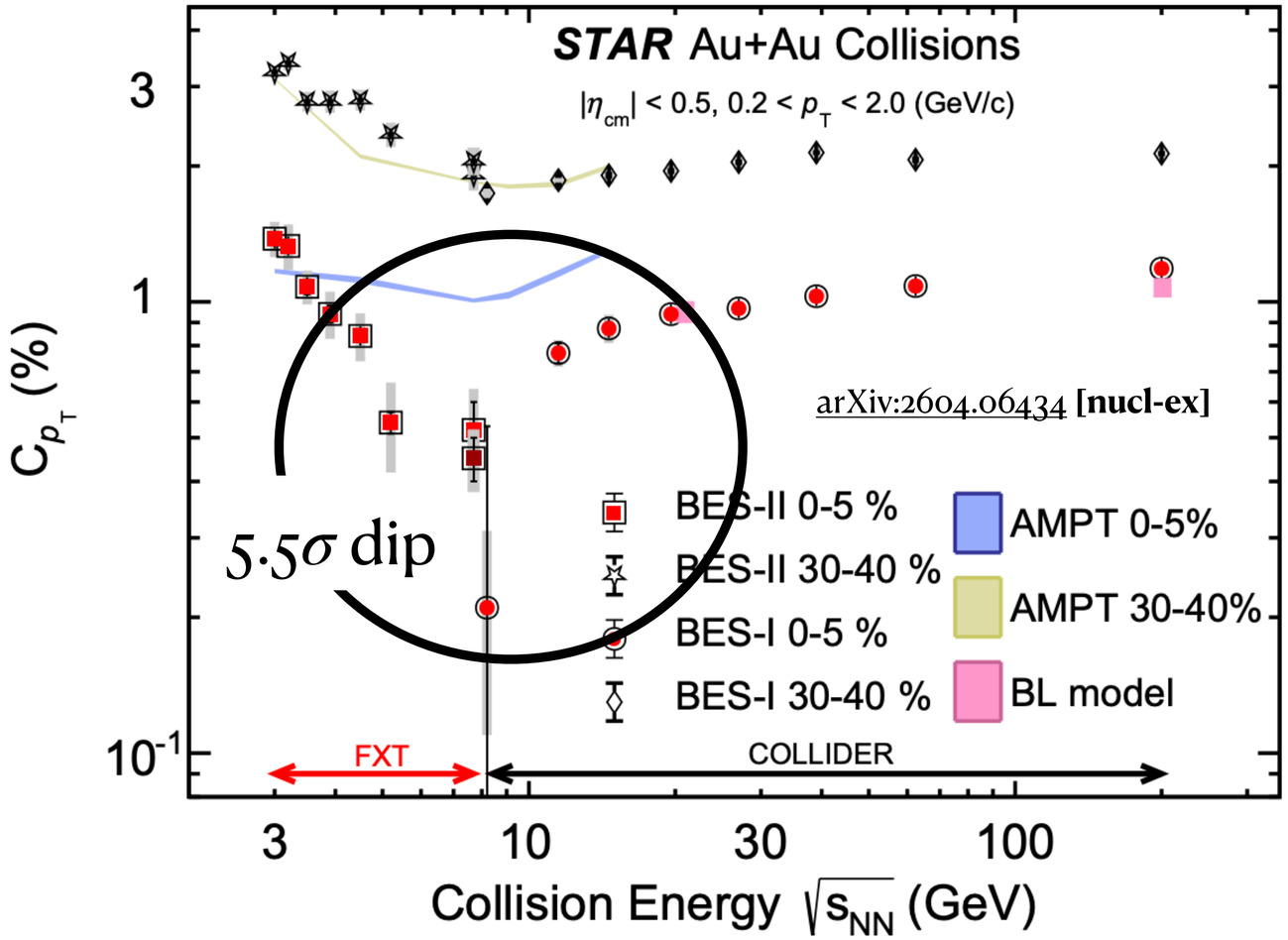


Fluctuations in the average momentum of protons

Possible hints in the fixed-target region?

Larger fluctuations in the the transverse momentum where we anticipate the critical point.

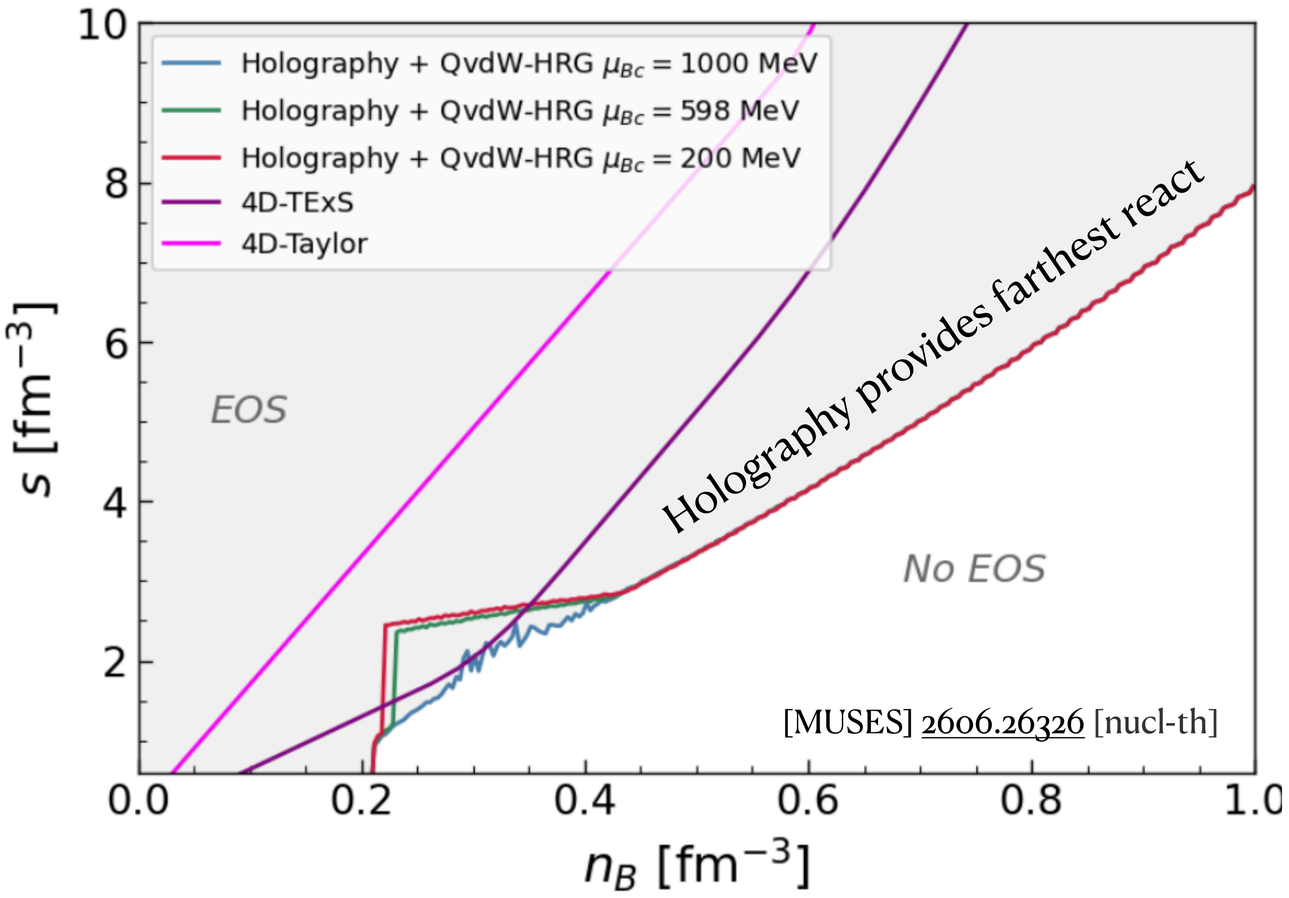
Could appear due to changes in the equation of state and/or critical scaling of transport coefficients



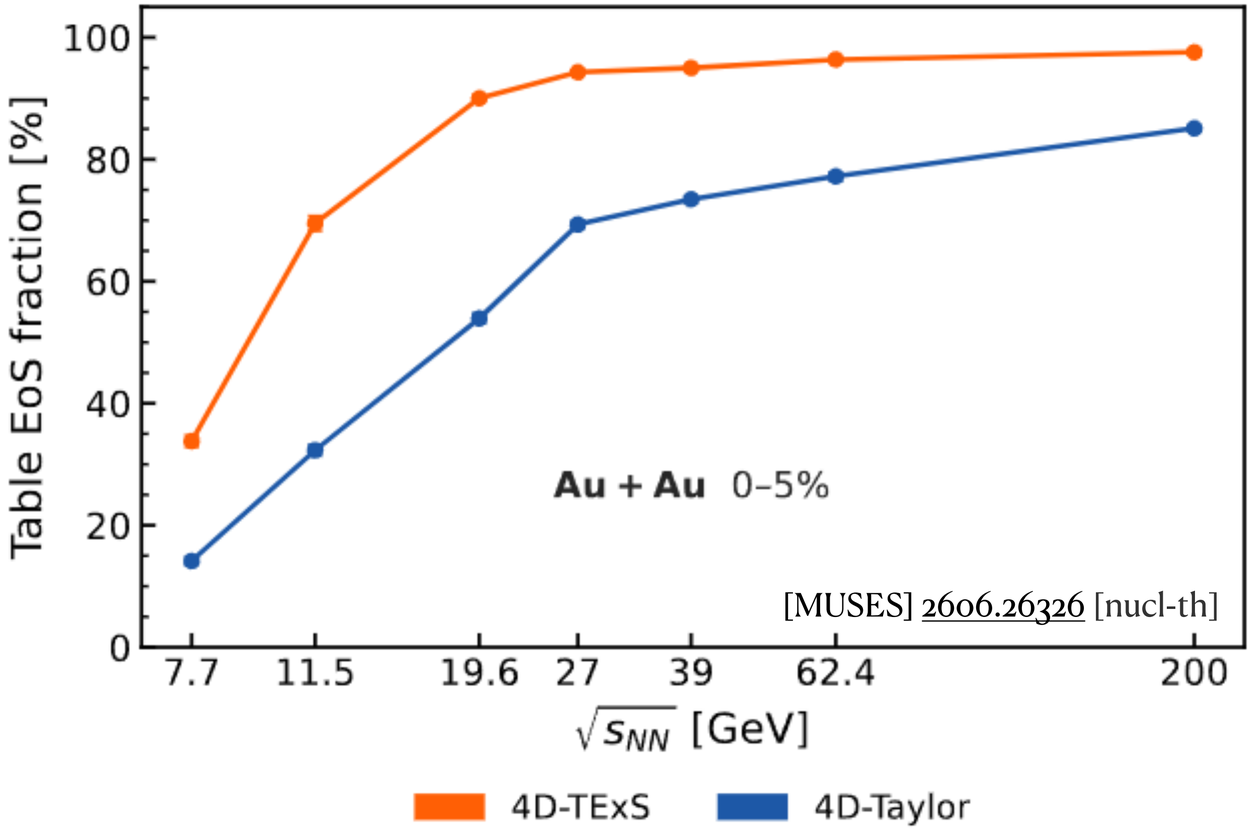
Where are the theory comparisons

It's really hard...

muses



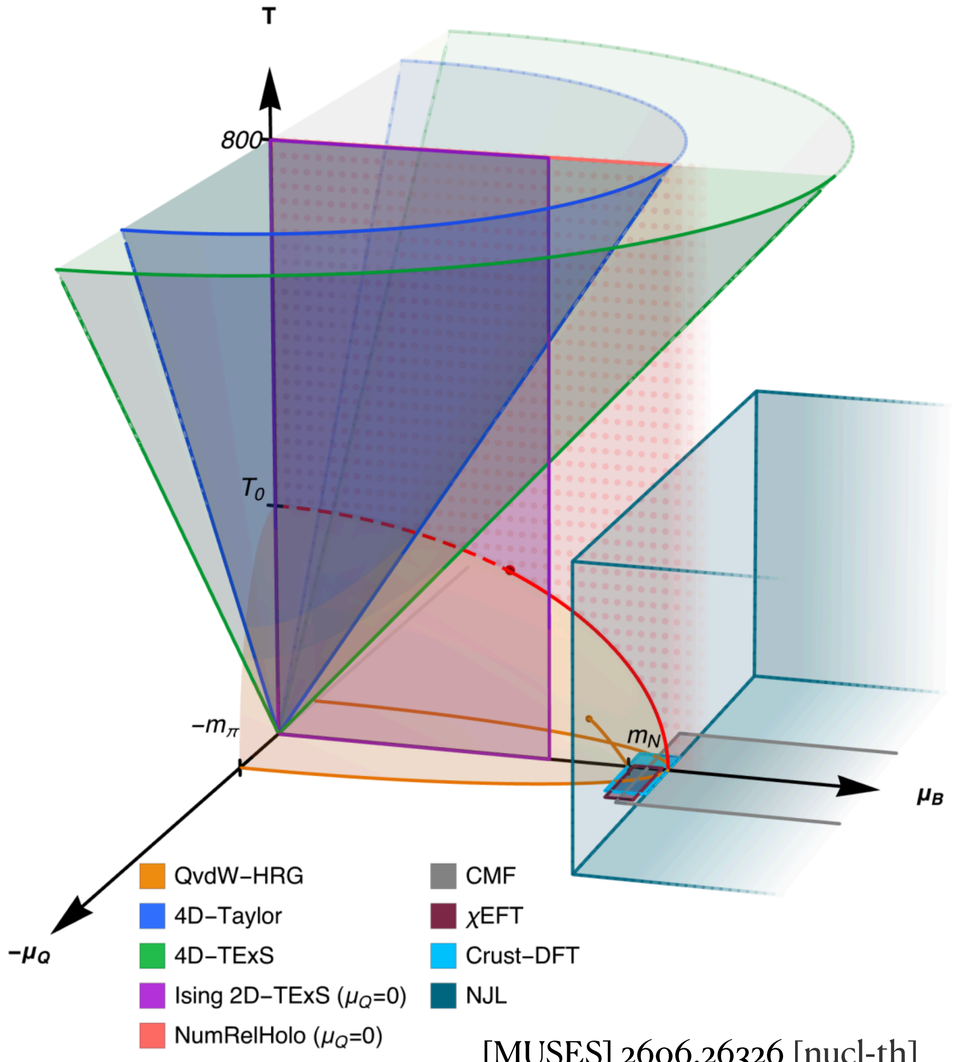
Must resort to "back-up" equation of state, due to out-of-bound fluid cells



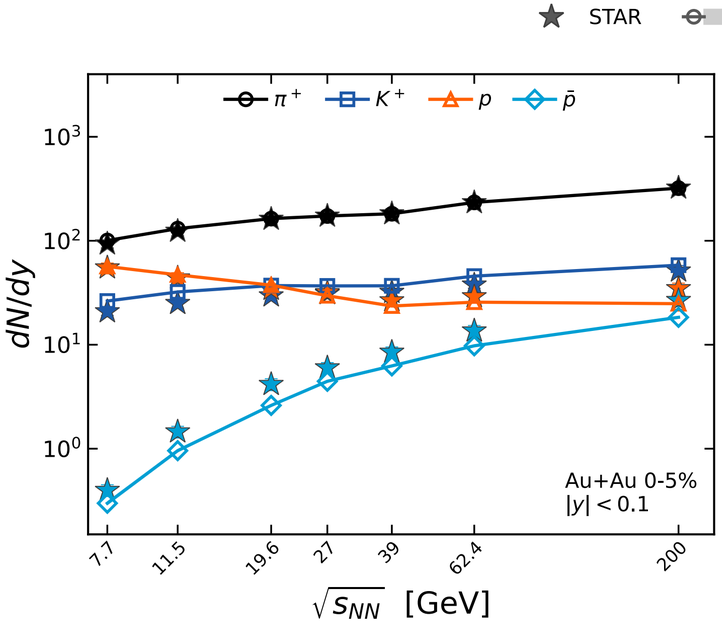
Lattice QCD-based equations of state

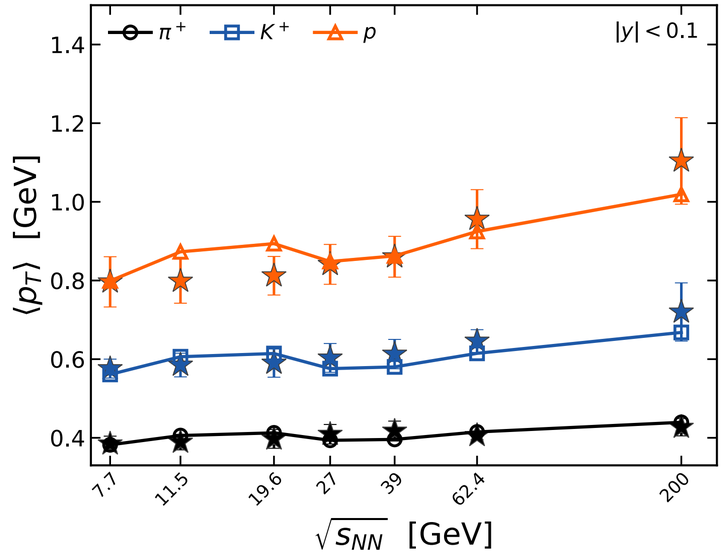
Theory comparisons soon from the MUSES collaboration

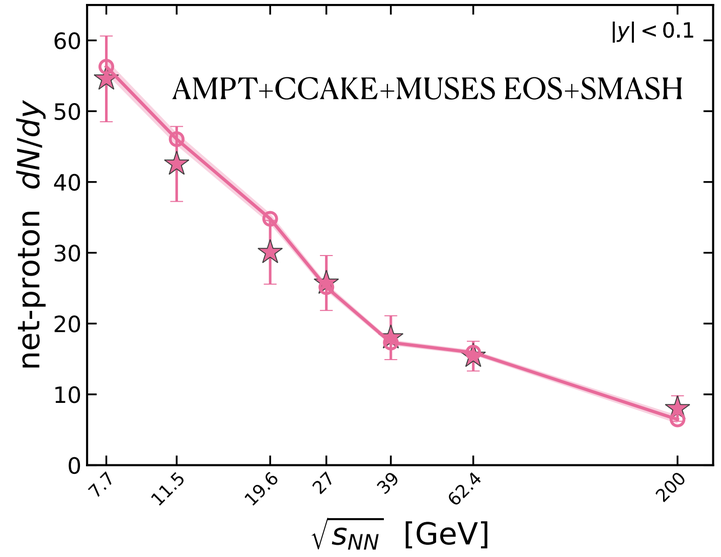
Kevin Pala, Weds

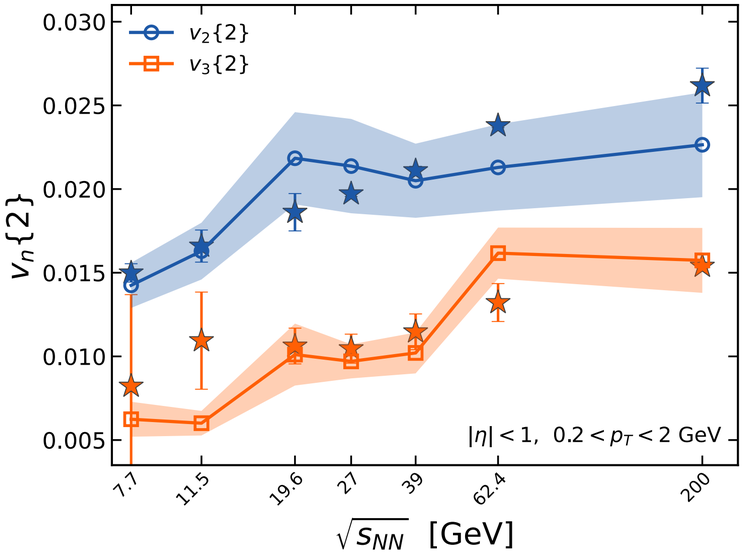


[MUSES] 2606.26326 [nucl-th]



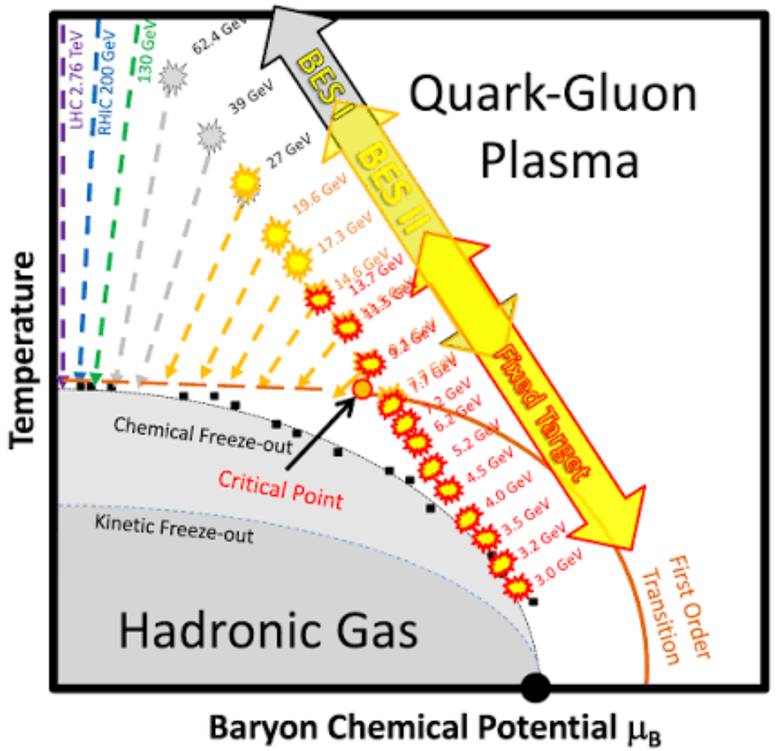




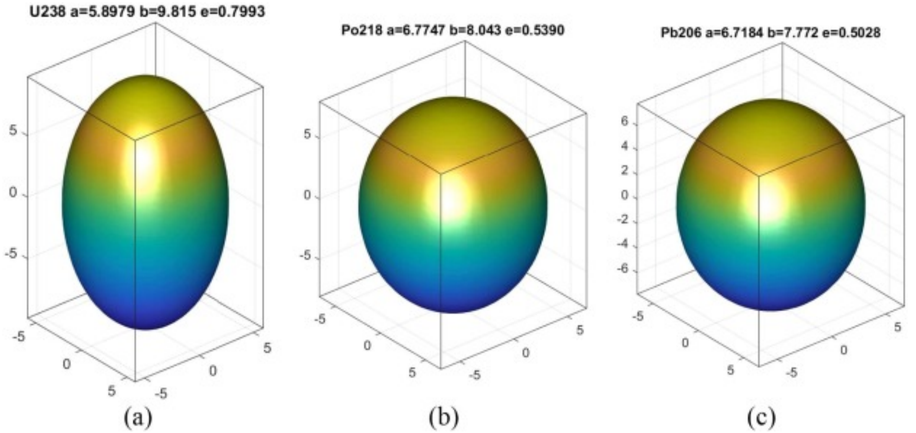


What we get from heavy-ion collision

$\Downarrow \sqrt{s_{NN}}$, then $\Uparrow n_B$



Imaging nuclei from v_n +other observables



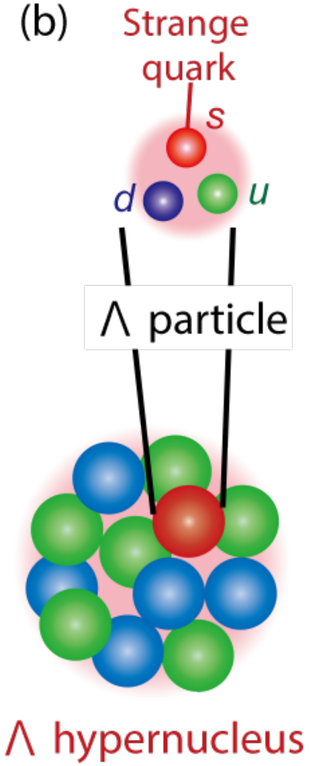
Change $Y_Q = Z/A$ of colliding nuclei

$Z/A = 0$



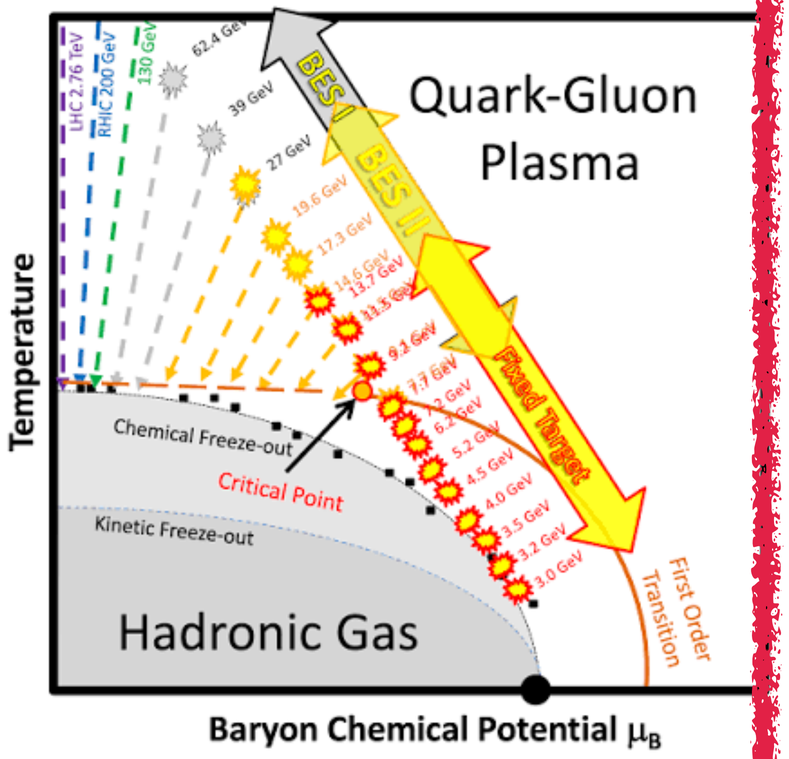
$Z/A = 0.5$

Measuring light & hyper-nuclei that appear in the final state

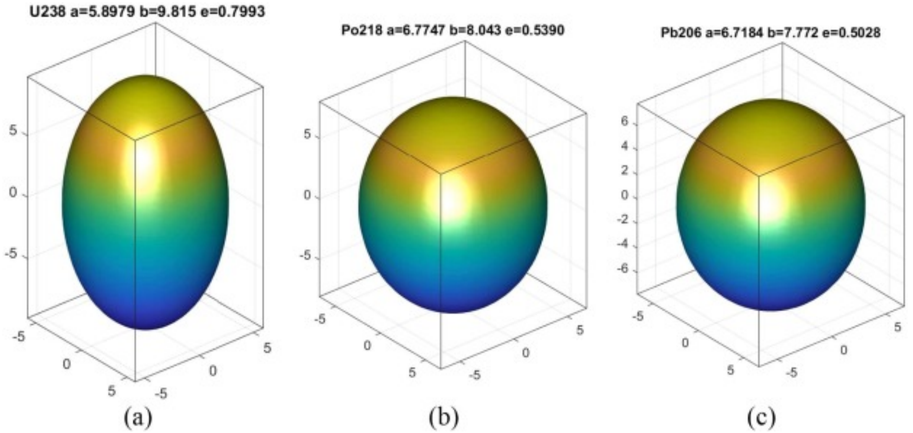


What we get from heavy-ion collision

$\Downarrow \sqrt{s_{NN}}$, then $\Uparrow n_B$



Imaging nuclei from v_n +other observables



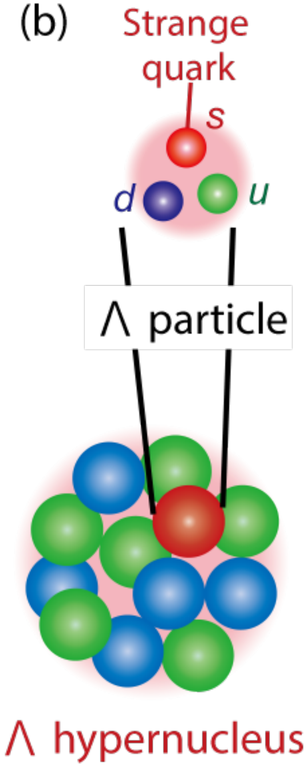
Change $Y_Q = Z/A$ of colliding nuclei

$Z/A = 0$

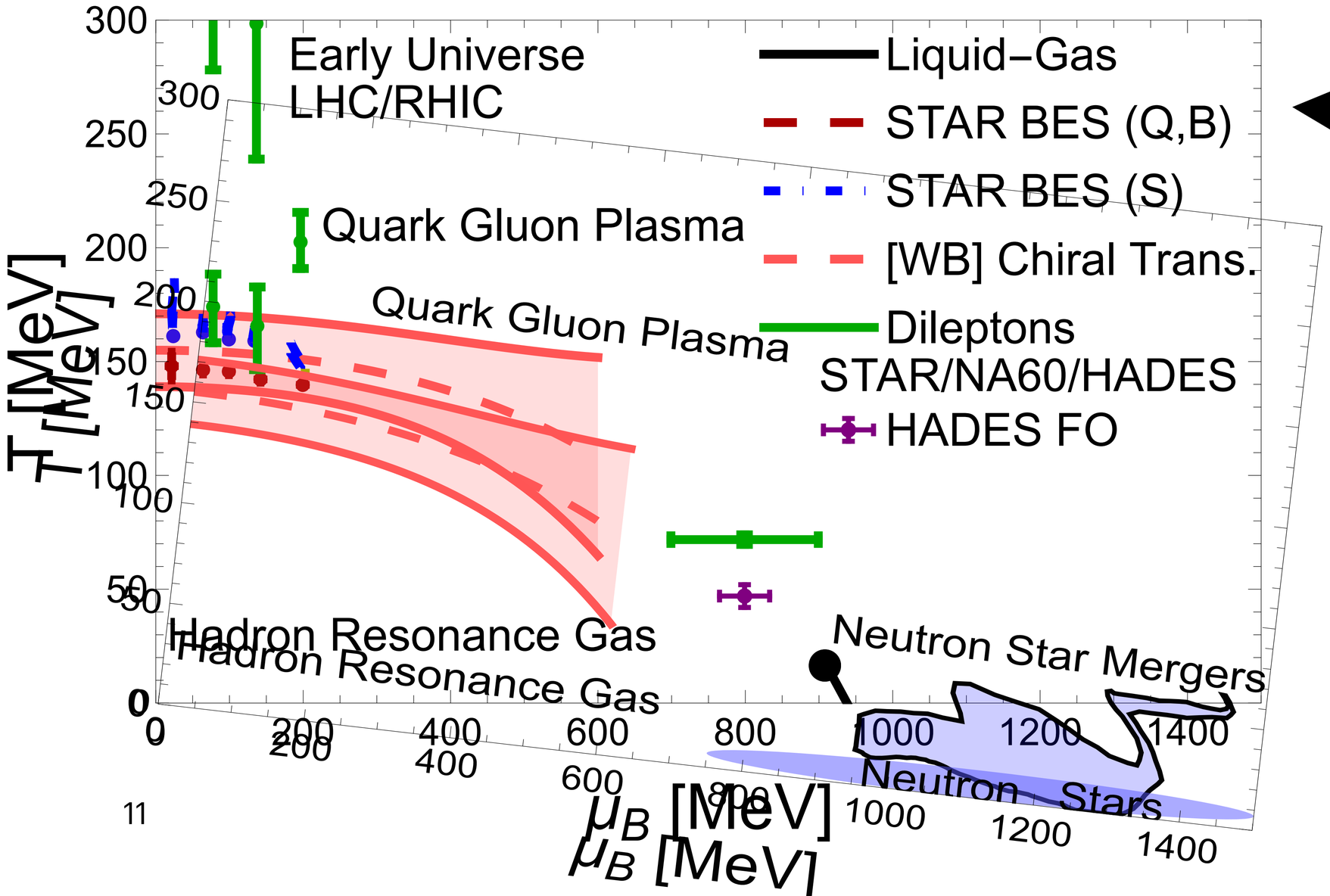


$Z/A = 0.5$

Measuring light & hyper-nuclei that appear in the final state



Multi-dimensional phase diagram, μ_Q matters a lot!



Heavy-ion collisions

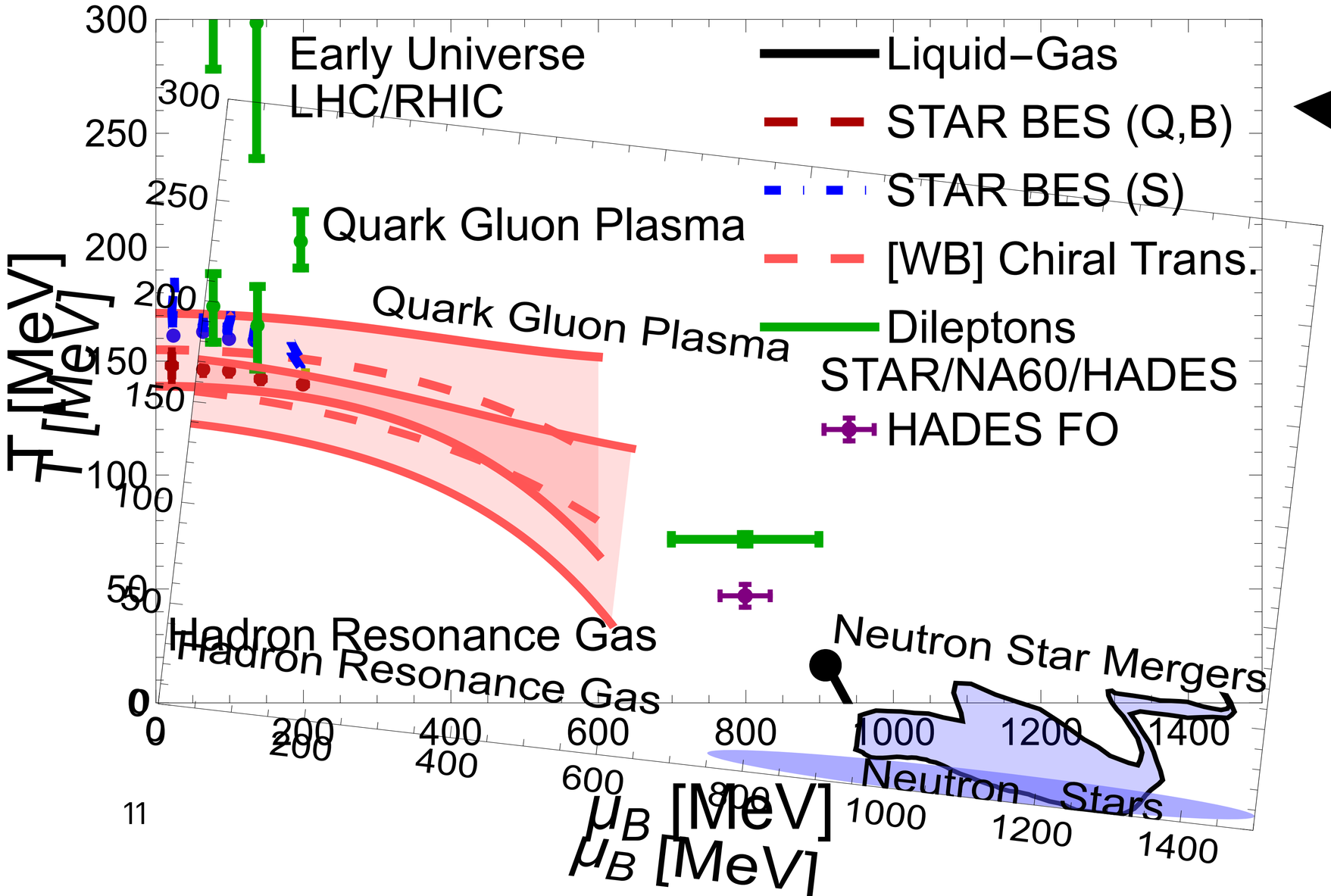
$$\frac{n_Q}{n_B} \sim [0.4,0.5]$$

Neutron Stars

$$\frac{n_Q}{n_B} \sim [0.01,0.2]$$

Caution: if/where a phase transition appears can change with n_Q/n_B

Multi-dimensional phase diagram, μ_Q & μ_S matters a lot!



Heavy-ion collisions

$$\frac{n_Q}{n_B} \sim [0.4,0.5]$$

Neutron Stars

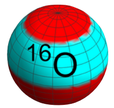
$$\frac{n_Q}{n_B} \sim [0.01,0.2]$$

Caution: if/where a phase transition appears can change with n_Q/n_B

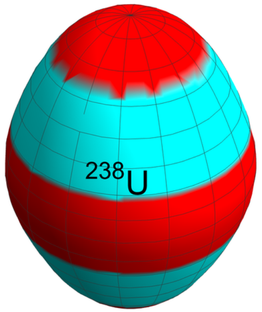
Charge fraction of ions

Isospin asymmetry

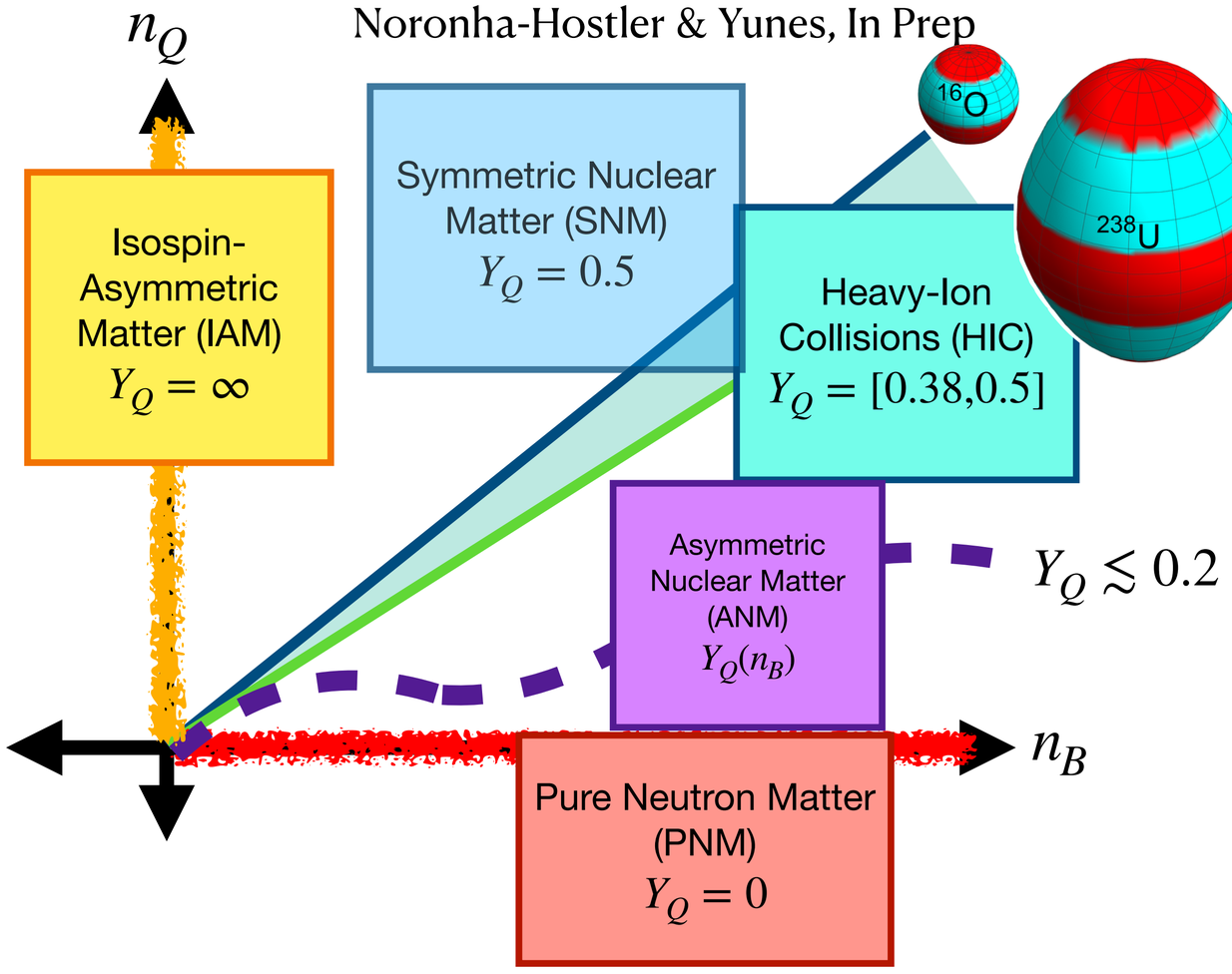
$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$



System	Z	A	Y_Q	Data?
O+O	8	16	0.5	some
Ne+Ne	10	20	0.5	no
Mg+Mg	12	24	0.5	no
Ca+Ca	20	40	0.5	no
Cu+Cu	29	63	0.46	yes
Ru+Ru	44	96	0.458	some
Ar+Ar	18	40	0.45	no
Xe+Xe	54	128	0.419	yes
Zr+Zr	40	96	0.417	some
Au+Au	79	198	0.399	yes
U+U	92	238	0.387	yes



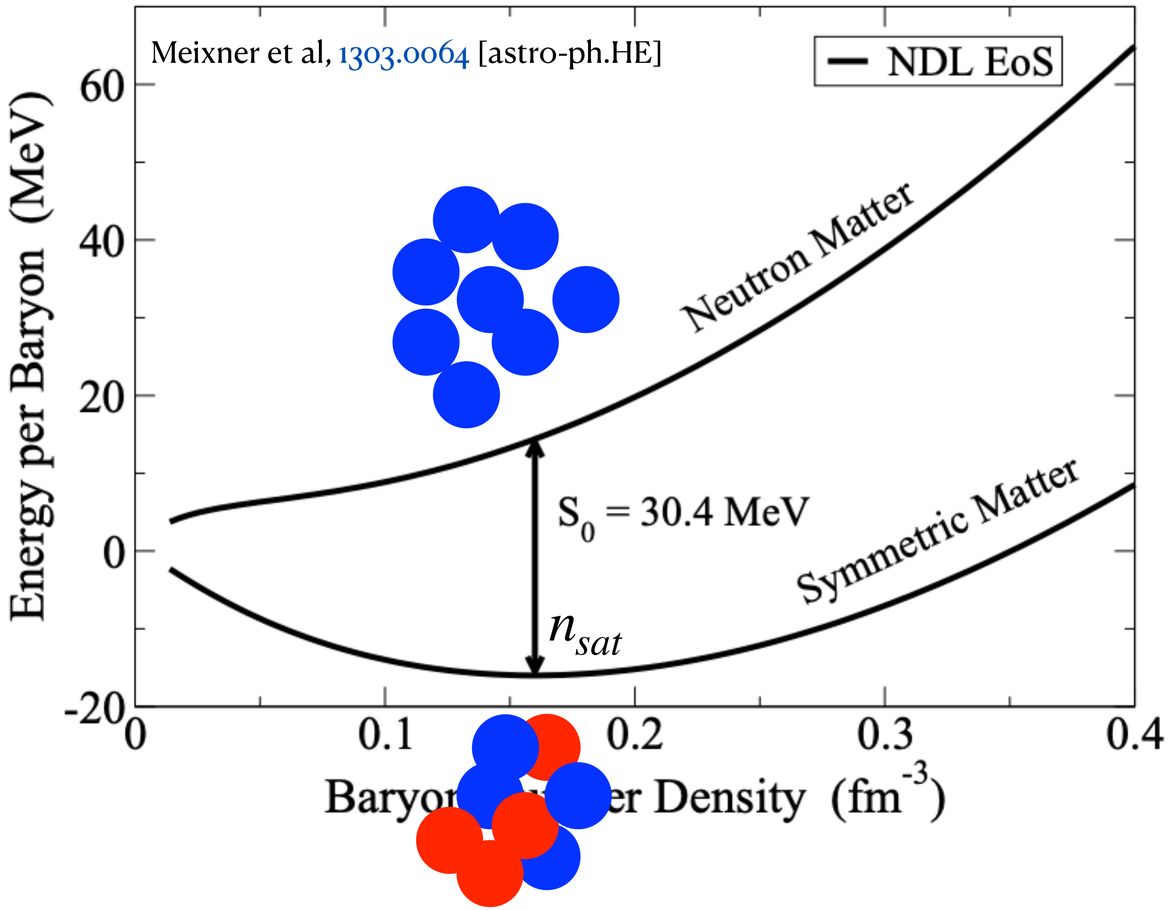
Noronha-Hostler & Yunes, In Prep



Heavy-Ions and Neutron Stars are all on the same phase diagram, but very different Y_Q

Connecting heavy-ion collisions to neutron stars

"Symmetry Energy" Expansion



Symmetric nuclear matter

$$\mu_Q = 0$$

Isospin asymmetry $\delta = 1 - 2Y_Q = 0$

$$Y_Q = 0.5$$

ONLY true for neutrons and protons!

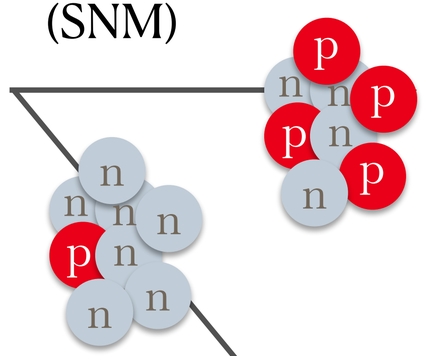
Symmetry energy

$$S(n_B) = \frac{\varepsilon_{PNM}}{n_B} - \frac{\varepsilon_{SNM}}{n_B}$$

IGNORE Strange: Symmetry Energy Expansion

Connecting NS to HIC across Y_Q

Symmetric matter (SNM)



$Y_Q = 0.5$

$Y_Q \lesssim 0.1$

Asymmetric matter (ANM)

Original symmetry energy expansion from binding energies
Bombaci & Lombardo *Phys.Rev.C* 44 (1991) 1892-1900

Isospin asymmetry $\delta = 1 - 2Y_Q$

where $\delta = 0$ for SNM and $\delta = 1$ for PNM

$$\frac{E_{ANM}}{N_B} = \frac{E_{SNM}}{N_B} + E_{sym,2}\delta^2 + \mathcal{O}(\delta^4)$$

Expand in δ where odd terms drop due to isospin symmetry

Convert EOS from NS to HIC, expand around n_{sat}

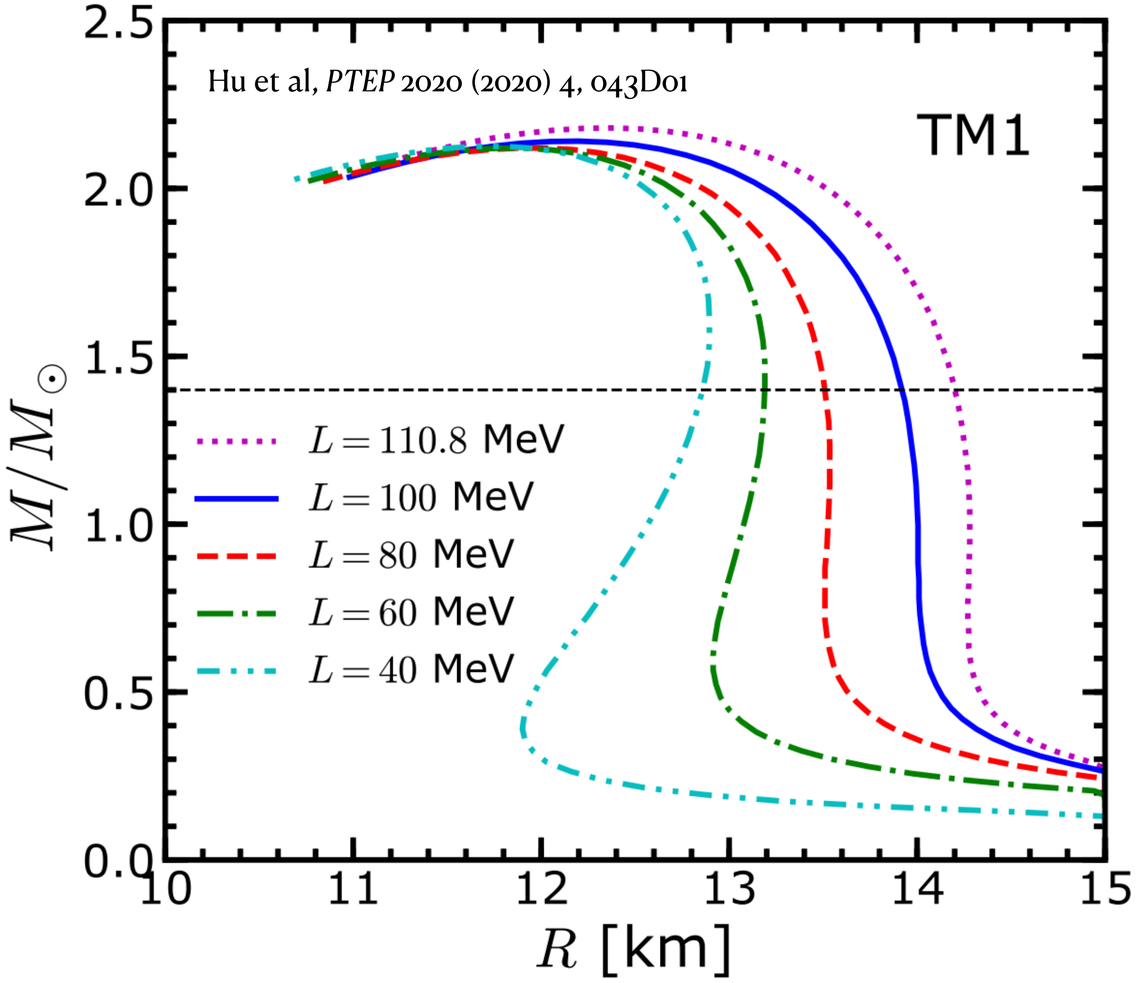
$$\varepsilon_{HIC} = \varepsilon_{NS} - 4n_B \left[E_{sym,sat} + \frac{L}{3}\left(\frac{n_B}{n_{sat}} - 1\right) + \frac{K}{18}\left(\frac{n_B}{n_{sat}} - 1\right)^2 + \frac{J}{162}\left(\frac{n_B}{n_{sat}} - 1\right)^3 \right] \left[\left(Y_Q^{HIC} - Y_{Q,NS}\right) + \left(Y_{Q,NS}^2 - \left(Y_Q^{HIC}\right)^2\right) \right]$$

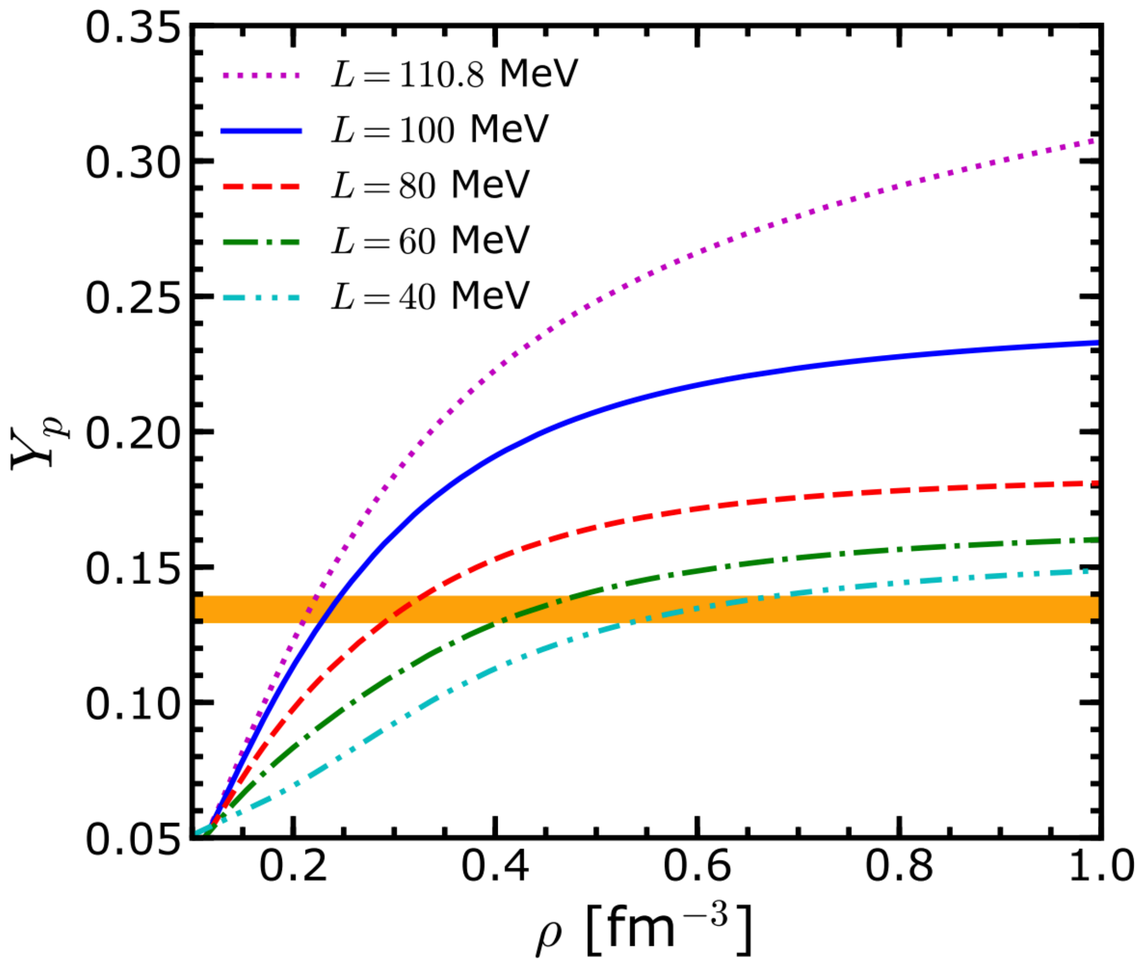
$E_{sym,2}(n_B)$ unknowns

To varing Y_Q^{HIC}
Yao et al, *Phys.Rev.C* 109 (2024) 6, 065803

What do we learn from the slope L?

Generally, large $L \rightarrow$ "fluffier" neutron star and more proton rich

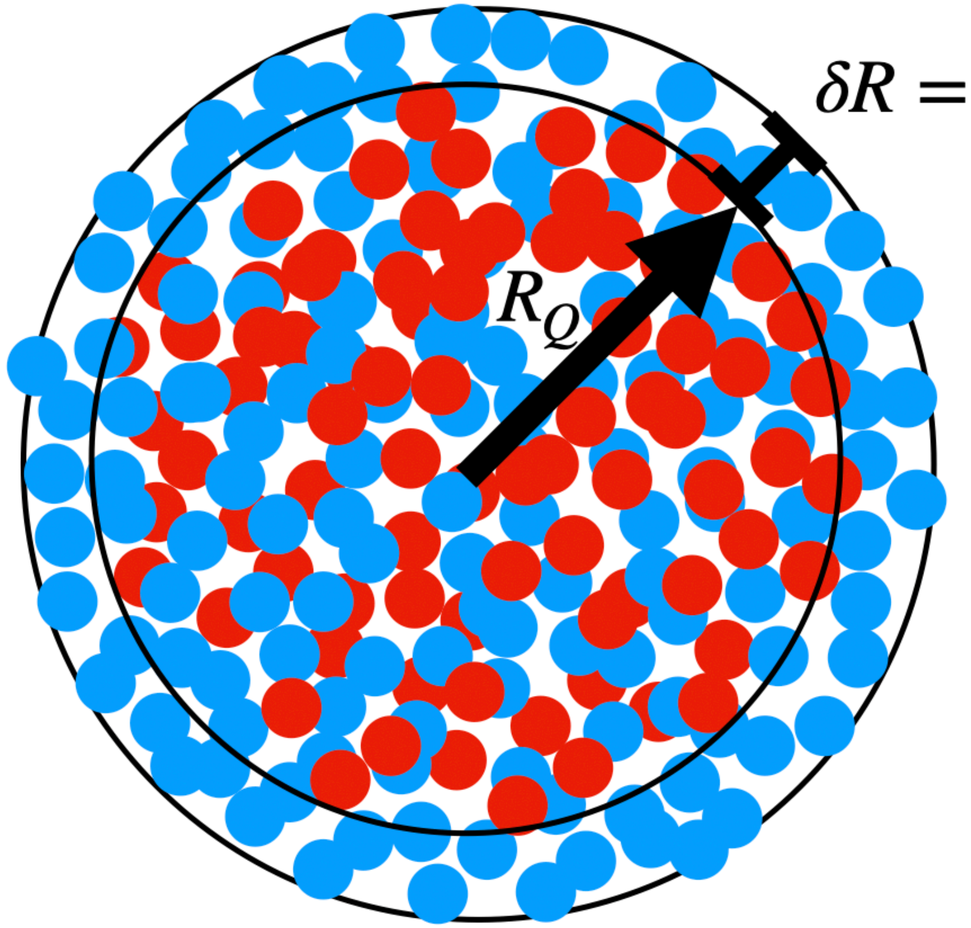




Caution: exact effects are model dependent, but general trends hold

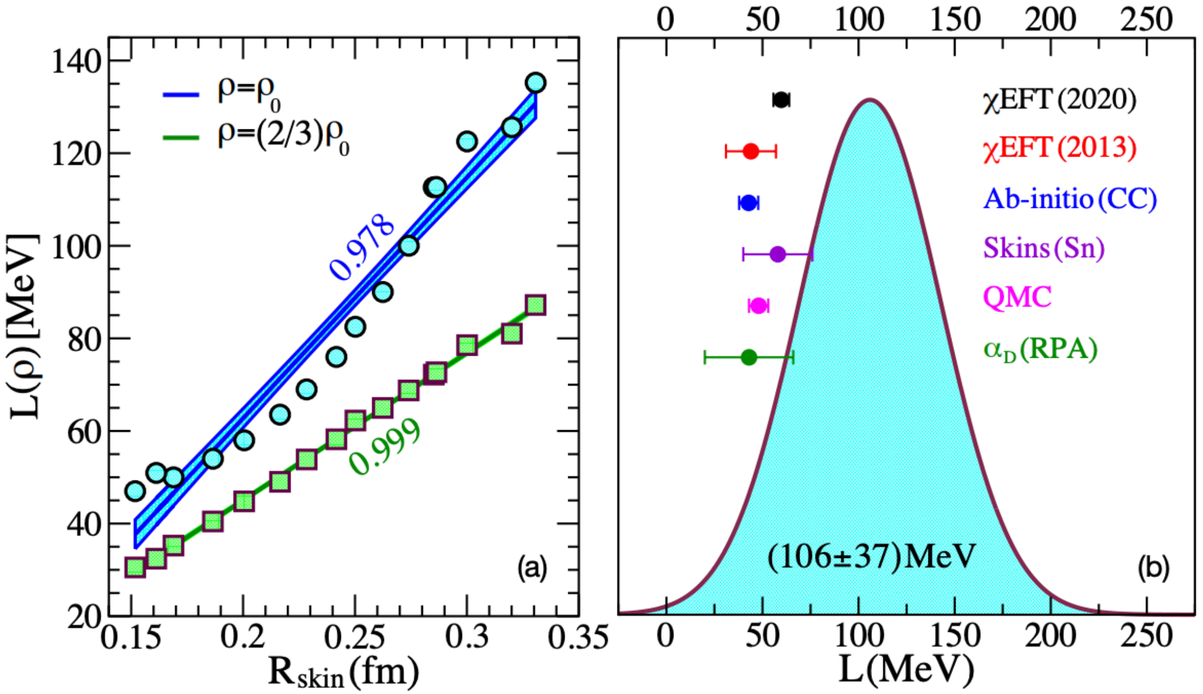
L - Slope of Symmetry energy

Neutron skins



Models of nucleonic matter - used for the equation of state OR nuclear structure

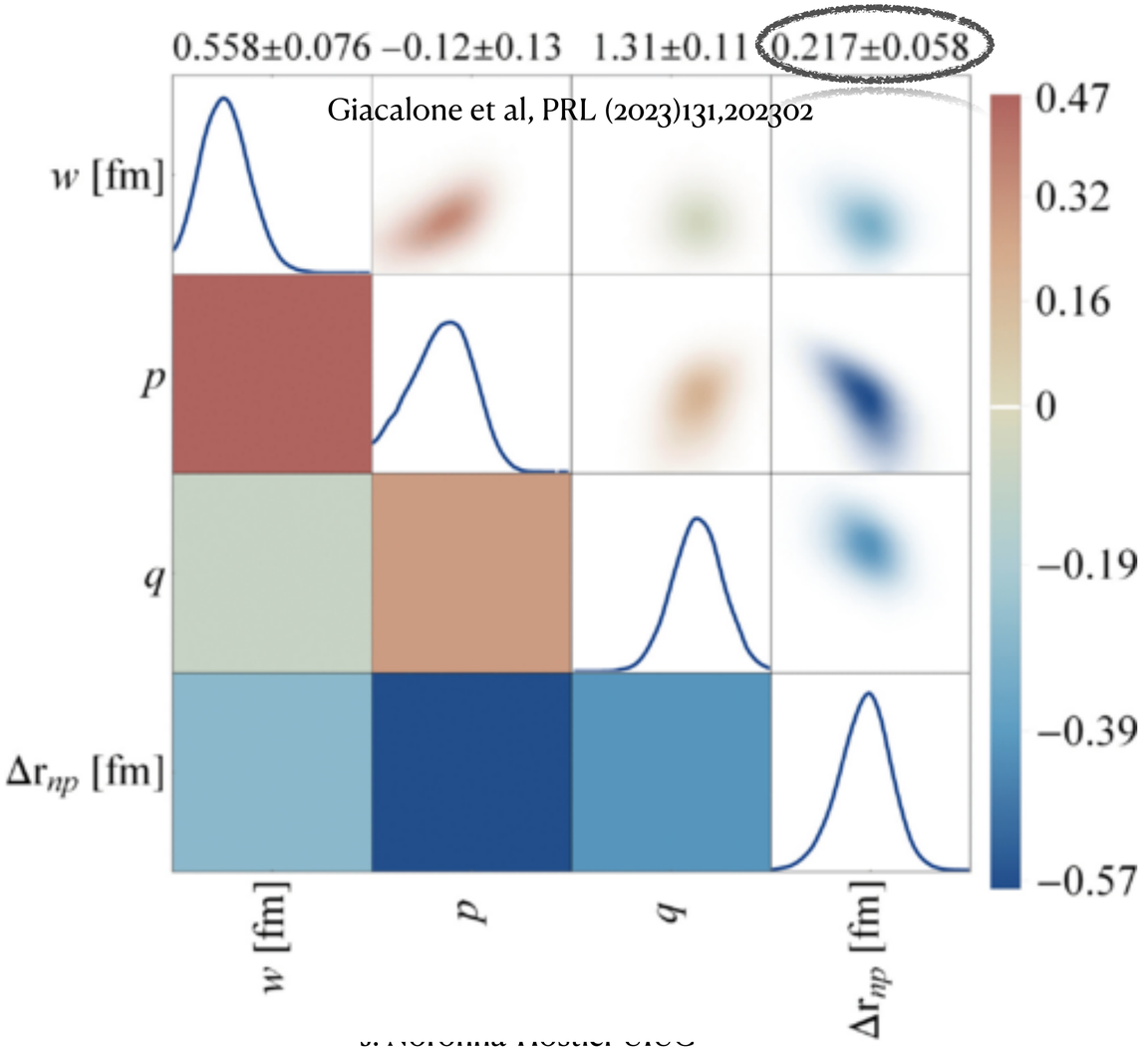
Neutron skin important constraint on L



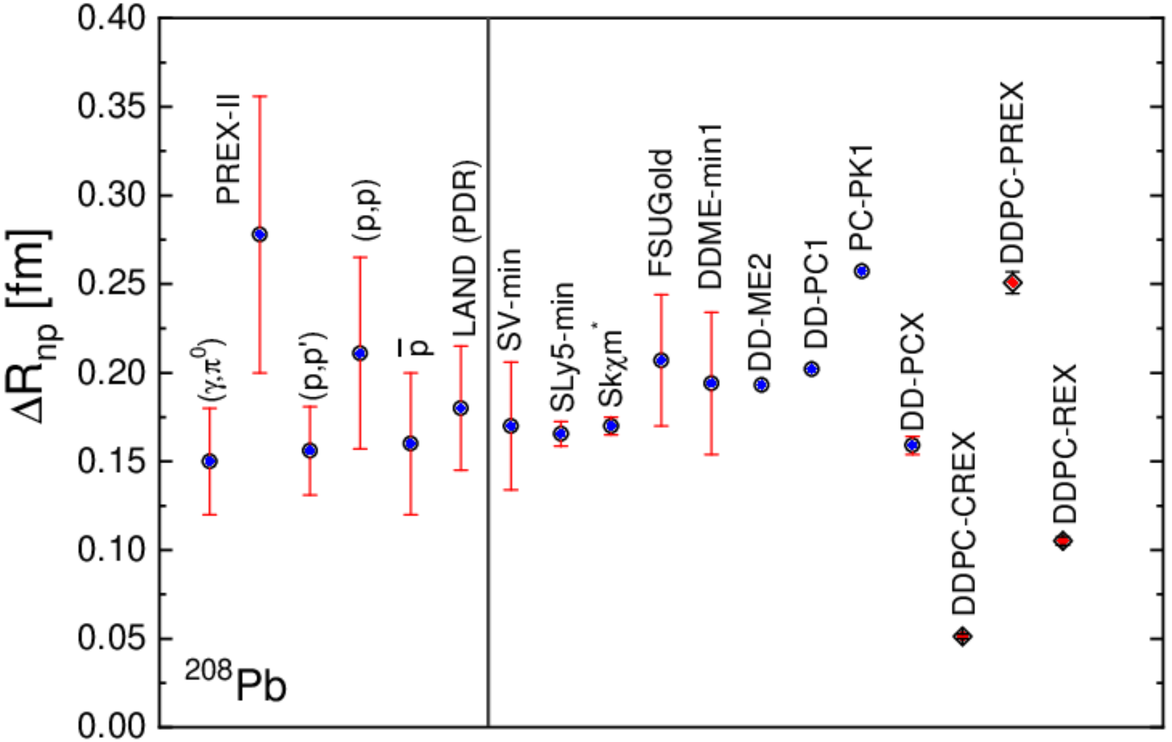
Reed et al, *Phys.Rev.Lett.* 126 (2021) 17, 172503

Neutron skin of ^{208}Pb from heavy-ion collision

Extraction from Bayesian analysis



Giacalone et al, PRL (2023)131,202302



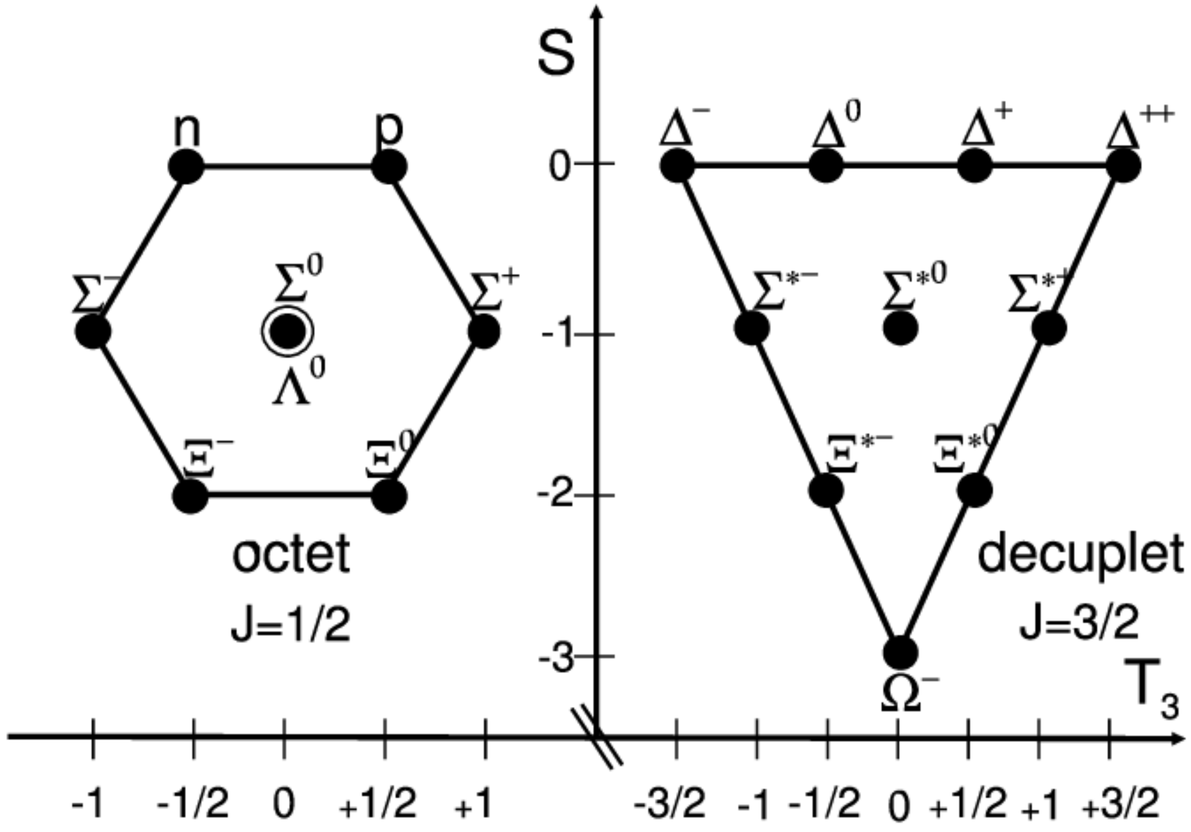
Extraction from Ultraperipheral heavy-ion collision data

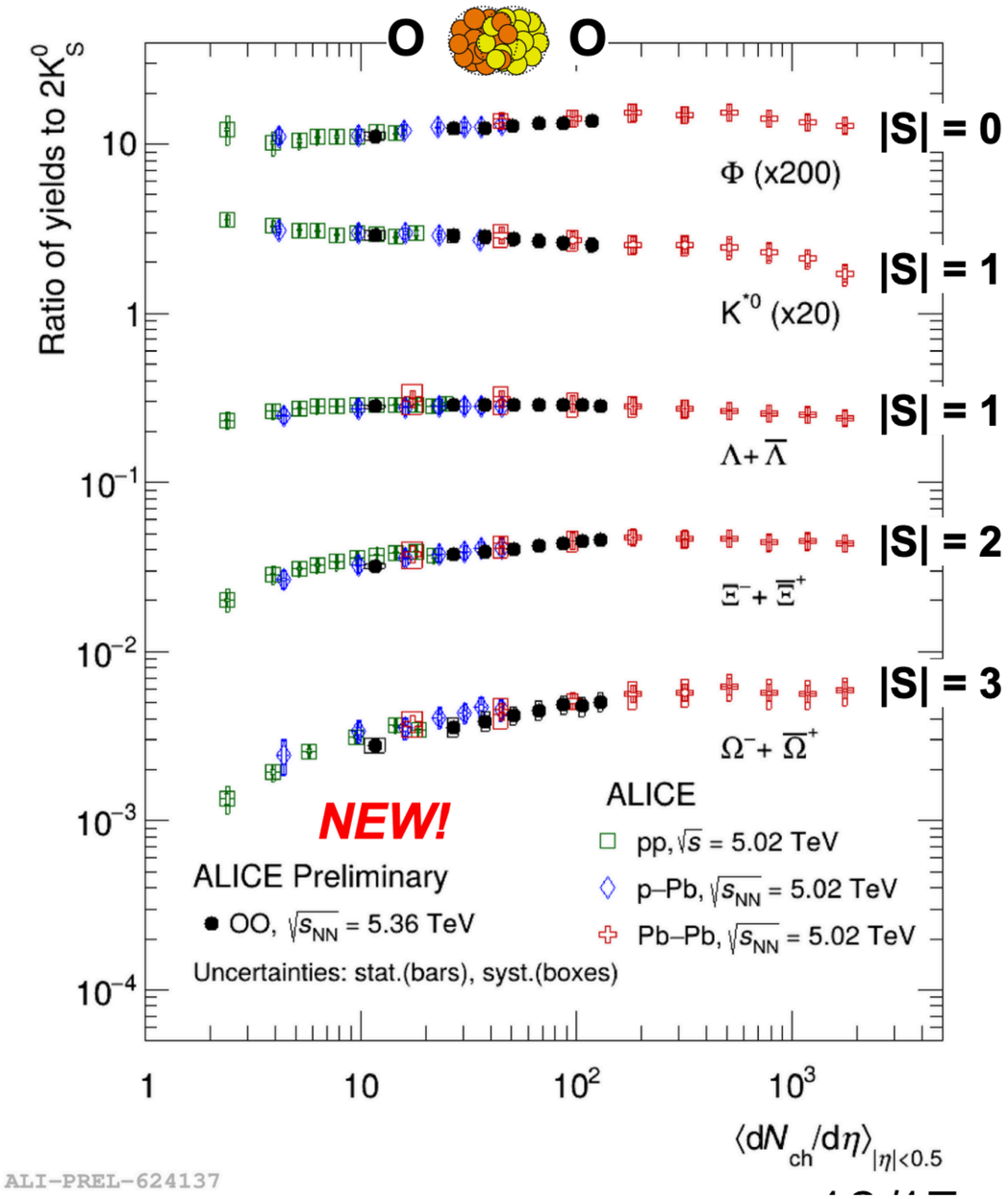
[STAR] Sci.Adv. 9 (2023) 1, eabq3903

$$R_n - R_p = 0.17 \pm 0.03(stat) \pm 0.08(syst) \text{ for } ^{197}Au$$

$$R_n - R_p = 0.44 \pm 0.05(stat) \pm 0.08(syst) \text{ for } ^{238}U$$

But, heavy-ion collisions are StRanGe








What about hyperons?

Symmetry energy expansion with strangeness

Yang et al, *Phys.Rev.C* 113 (2026) 4, 045805

Original symmetry energy expansion considered only protons, neutrons

isospin asymmetry: $\delta_Q \equiv 1 - 2\,Y_Q$

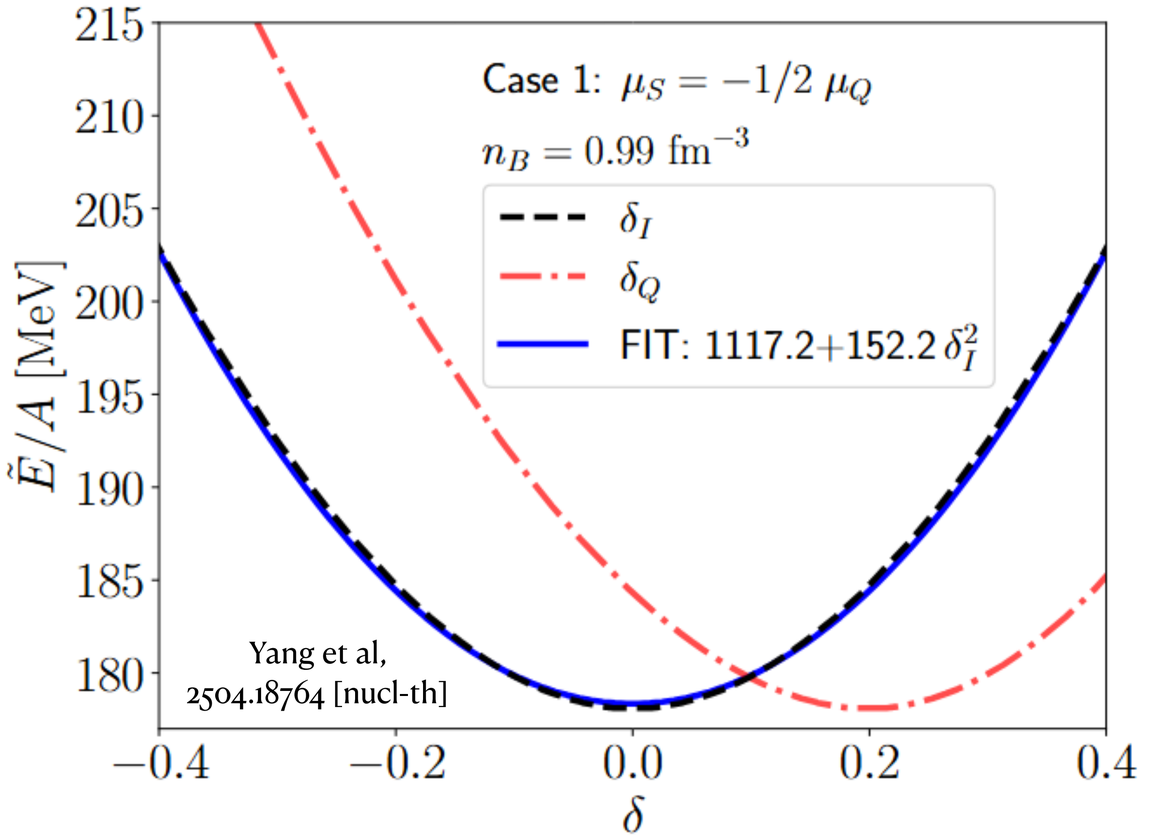
Gell-Mann-Nishijima formula

$$Q = I_z + \frac{1}{2}\,(B + \mathcal{S})$$

Corrected isospin asymmetry

$$\delta_I \equiv 1 + Y_S - 2\,Y_Q$$

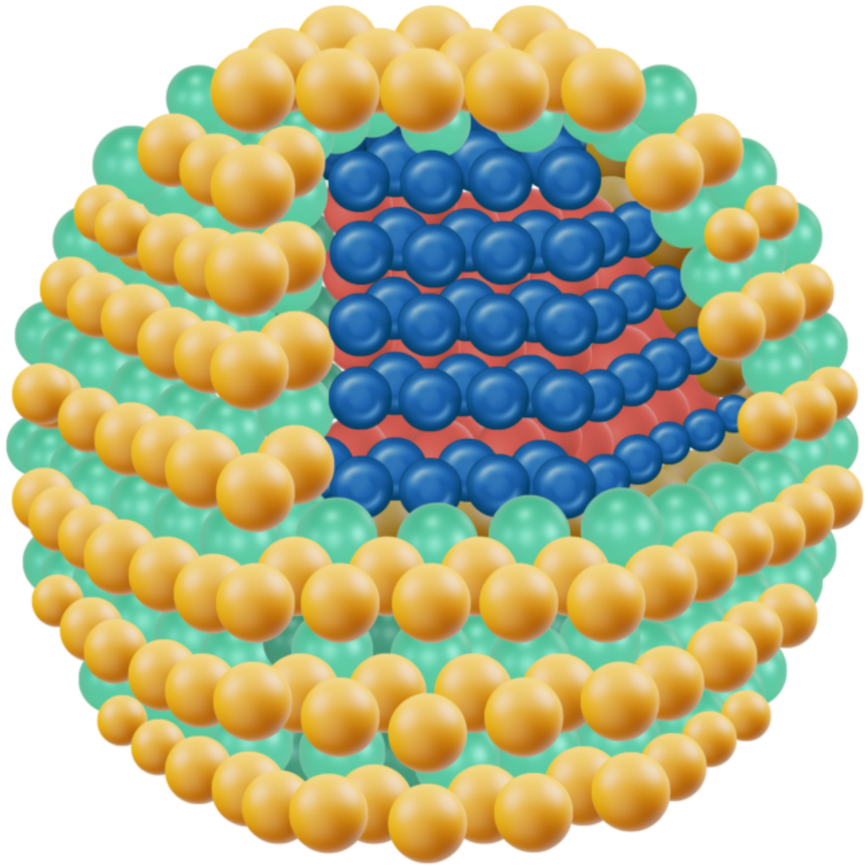
Original symmetry energy expansion misses the ground state of nuclear matter when hyperons are present




AND NOW FOR
SOMETHING
COMPLETELY
DIFFERENT

A lesson from Quantum Dots

I promise this is related!



Quantum dots are self-bound systems, where on their own they are NOT thermodynamical.

But their response to stimuli can capture the background mesoscopic thermodynamics

Chemical potential: change in energy from adding/subtracting an electron:

$$\mu_e = E(N_e) - E(N_e - 1)$$

Nuclei as quantum dots

$$E = mc^2 = \left(Zm_p + (A - z)m_n + BA \right) c^2$$

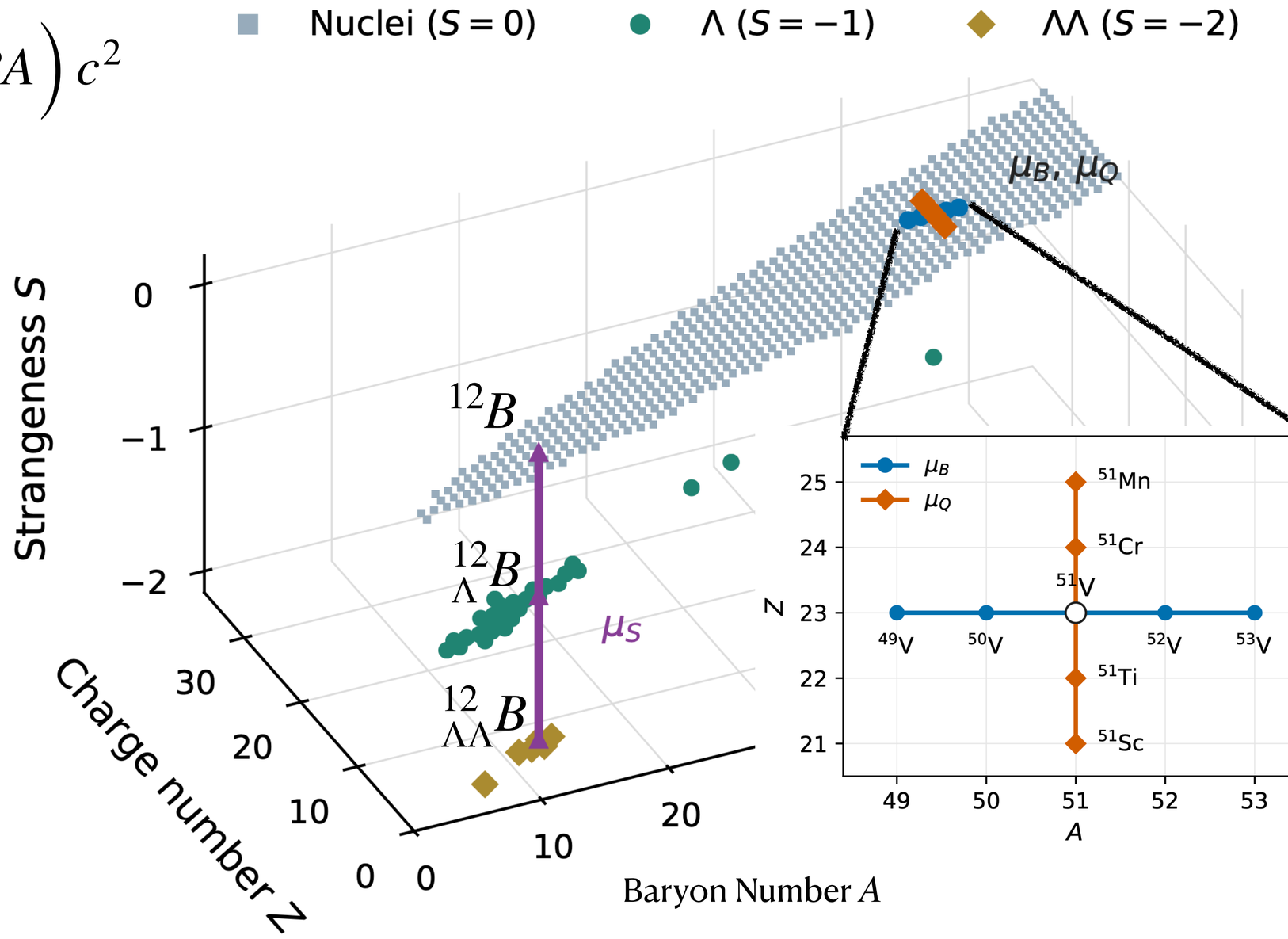
Vanishing temperatures, self-bound system at saturation

$$T = 0, p = 0, n_B = n_{sat}$$

$$A, N_\Lambda, Z -> B, S, Q$$

$$\frac{\varepsilon}{n_{sat}} = \mu_B + \frac{Z}{A}\mu_Q + \frac{N_\Lambda}{A}\mu_S$$

$$= \mu_B + Y_Q\mu_Q + Y_S\mu_S$$



Chemical potentials of (hyper nuclei)

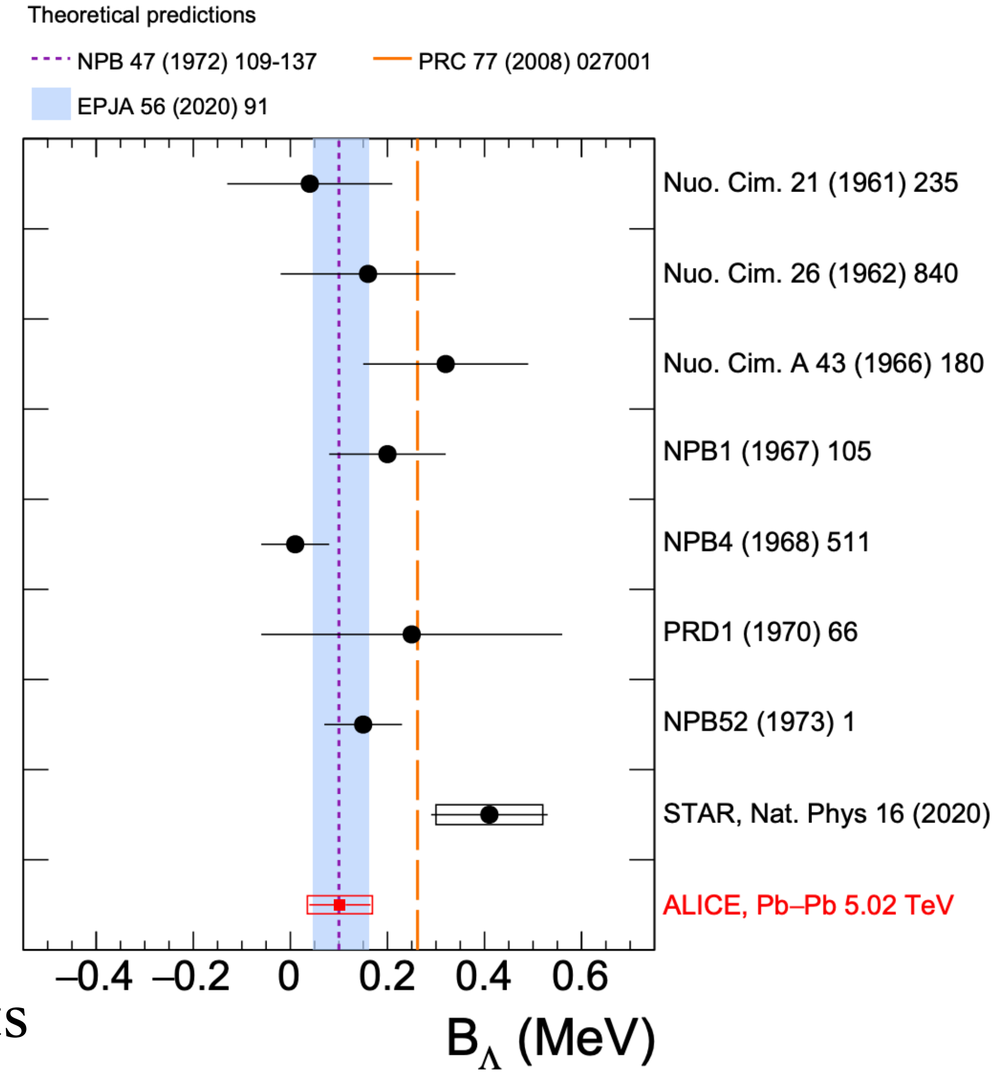
Binding energies of hypernuclei from ALICE help a lot!

Analogously, mass of nuclei can be used to calculate chemical potentials across the (hyper)nuclear landscape!

$$\mu_S = \left.\frac{\partial \tilde{E}}{\partial S}\right|_{B,Q} = \mu_S^E\left(A, Z, \frac{N_{\Lambda,1} + N_{\Lambda,2}}{2}\right)$$

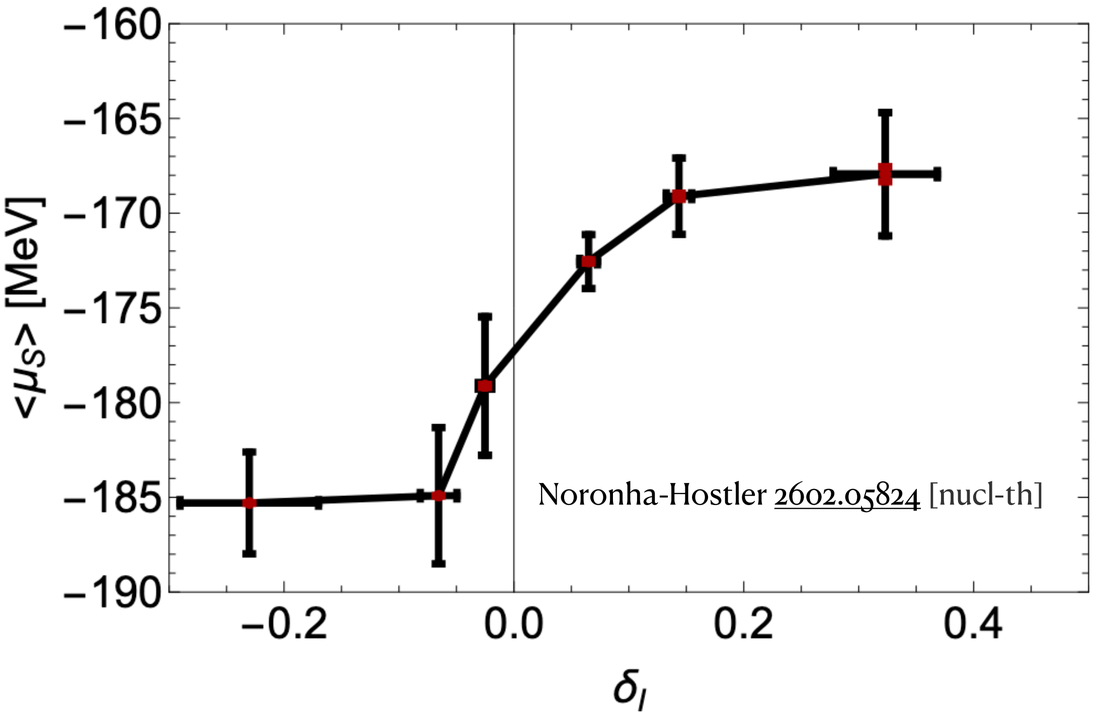
$$= -\frac{\tilde{E}_2\left(A, Z, N_{\Lambda,2}\right) - \tilde{E}_1\left(A, Z, N_{\Lambda,1}\right)}{N_{\Lambda,1} - N_{\Lambda,2}}$$

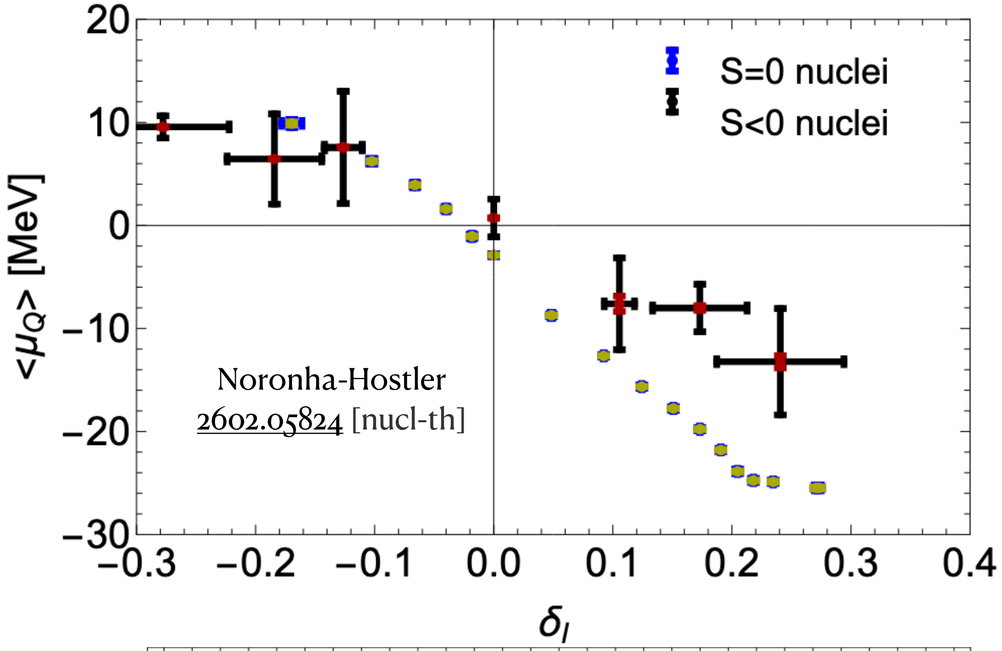
Noronha-Hostler 2602.05824 [nucl-th]



Need binding energy and ideally charge radii measurements

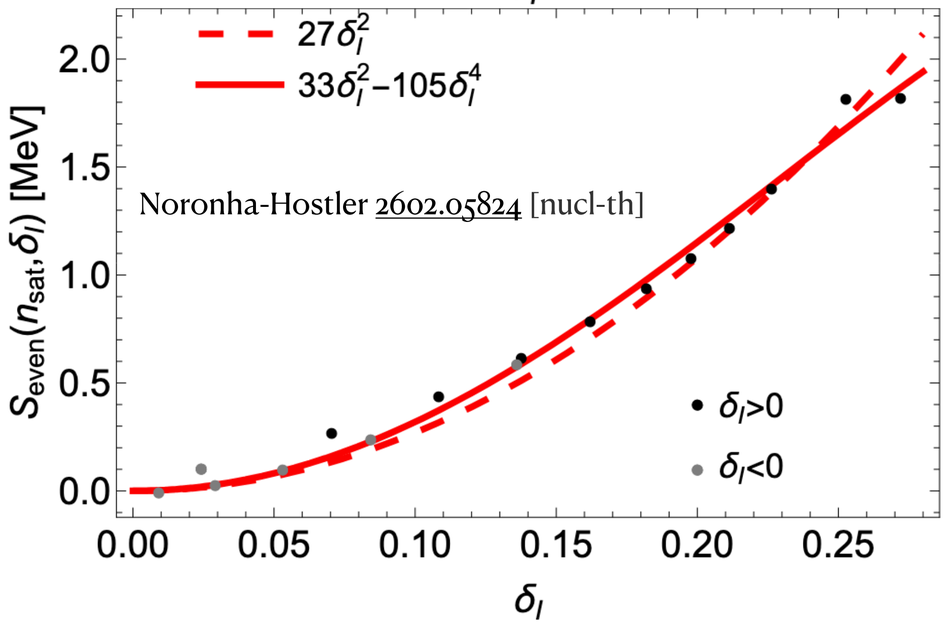
Chemical potentials and Symmetry Energy





Directly connects to the symmetry energy's dependence on isospin asymmetry

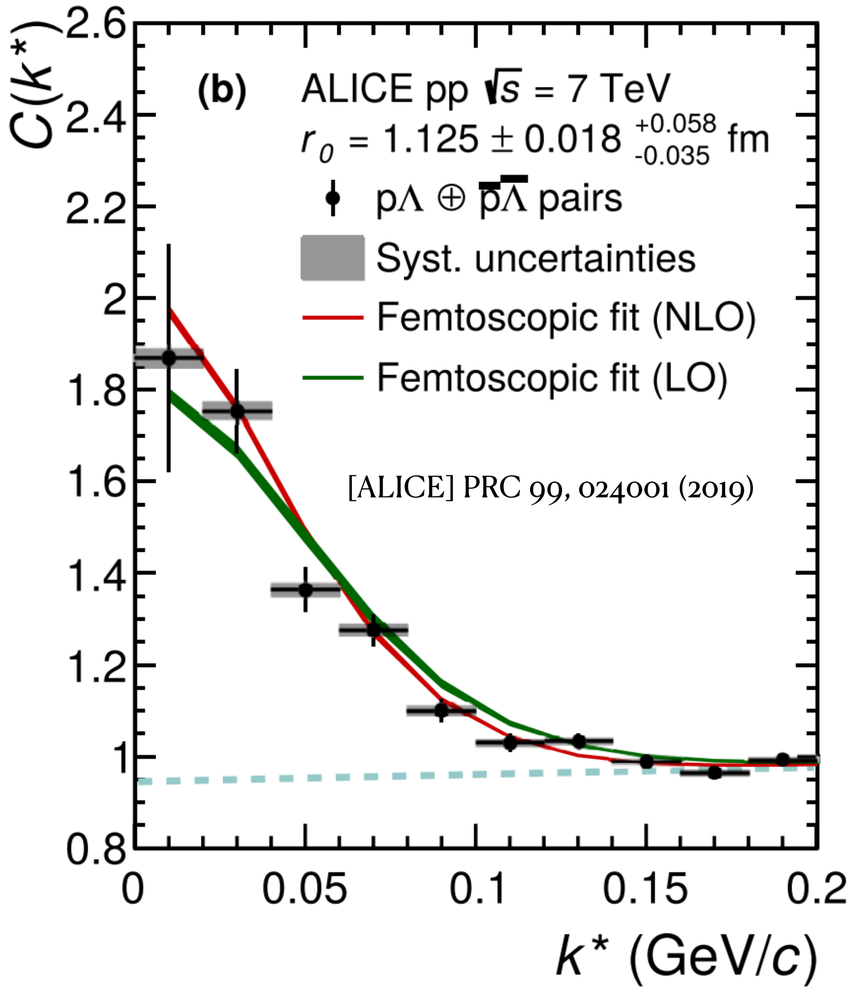
$$\mu_Q(n_B, \delta_I) = -2\left(\frac{\partial S(n_B, \delta_I)}{\partial \delta_I}\right)_{n_B}$$



Correlation functions

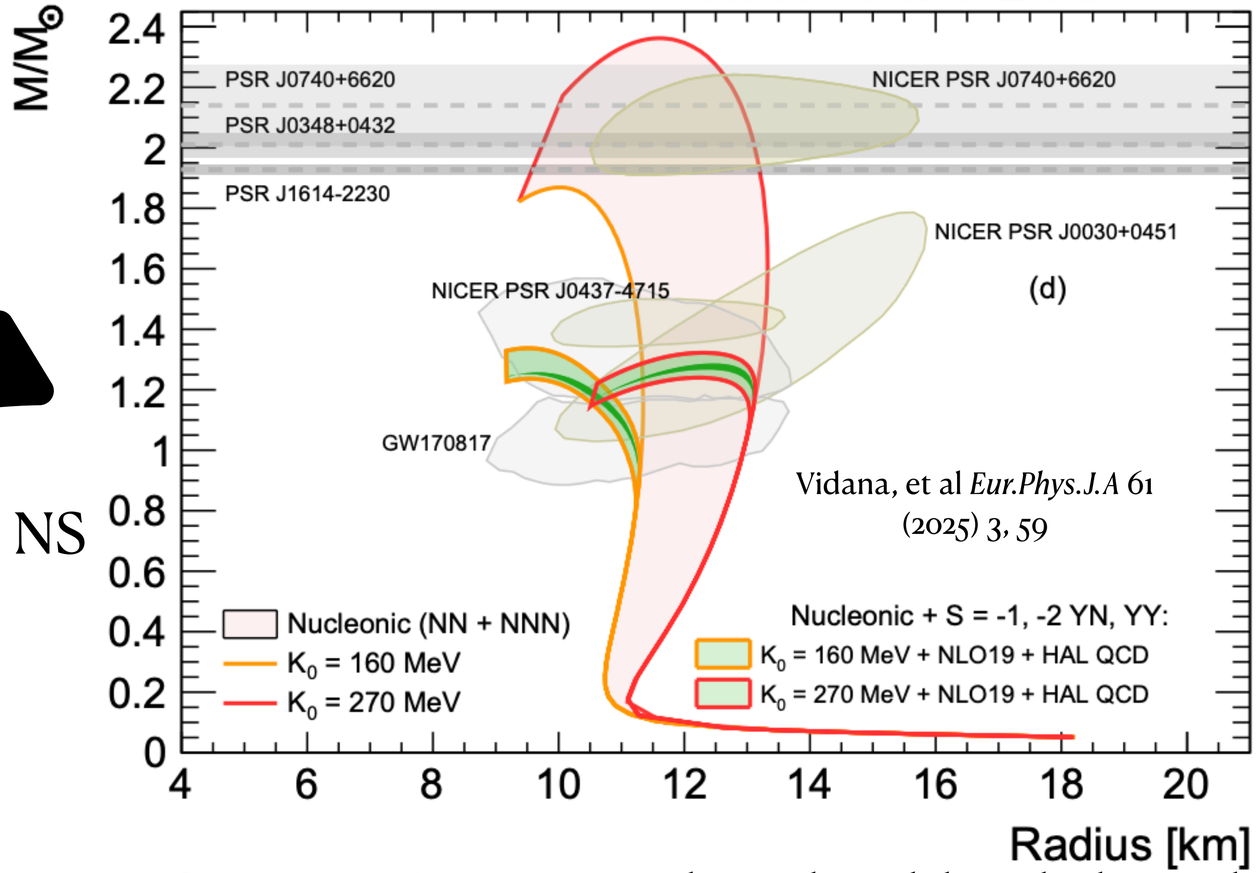
nucleon-hyperon correlations

Correlation functions of 2-3 bodies measured



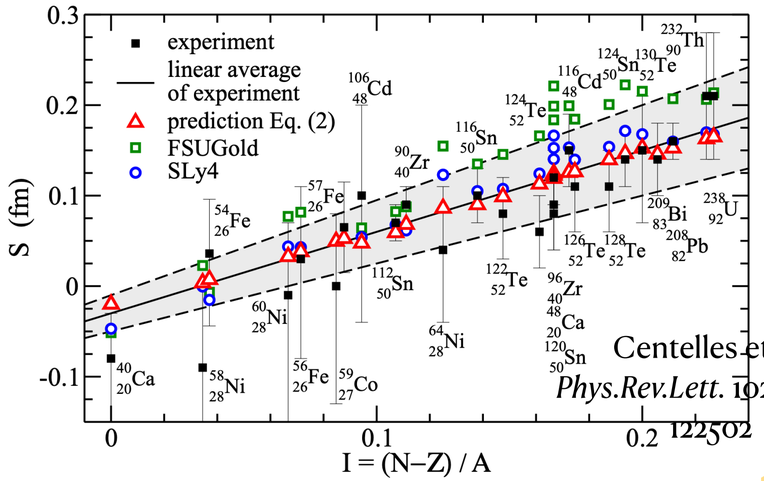
Applied to NS

More work needed on how to relate to the EOS



Caveat using χEFT that should only be valid up to $n_B \lesssim 1.5 n_{sat}$ up to $6 n_{sat}$

What else would be useful?



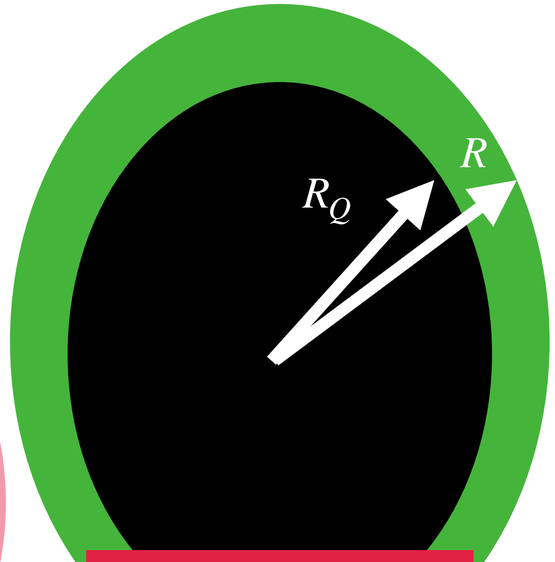
Centelles et al, *Phys.Rev.Lett.* 102 (2009) 122502

Interesting neutron skin

Let's runs this!

Possible to run with the collider

Interesting deformations or structure



Weds, many talks

Year	Spring	Summer		Autumn
		[User]		
2026	Run 3	Run 3		Mg or C [NA61++]
2027	LS	LS		C or Mg [NA61++]
2028	LS	Cocktail / Ge / Kr / Xe		Pb [HEARTS]
2029	?	O SPS slip-stacking & O^{8+} in LEIR		Pb [HEARTS]
2030	O [NA61++]	?		Pb [HEARTS & NA]
2031	Mg [NA61++]	OR / AND	Mg → C [LHC]	
2032	C [NA61++]	OR	O → He [LHC]	
2033	?	OR	Ge → Kr or (Ba → Xe) or (^{48}Ca) [LHC]	

Schedule beyond 2027 is speculative

X – test, no physics users LS – Long

Y – physics run

Monday Slupecki

Nuclei vs Z/A, BUT would be best in fixed-target

For an equal number of protons and neutrons, Z/A=0.5 and $\mu_Q = 0$

Neutrons stars have $\mu_Q \sim [-50, -150]$ MeV

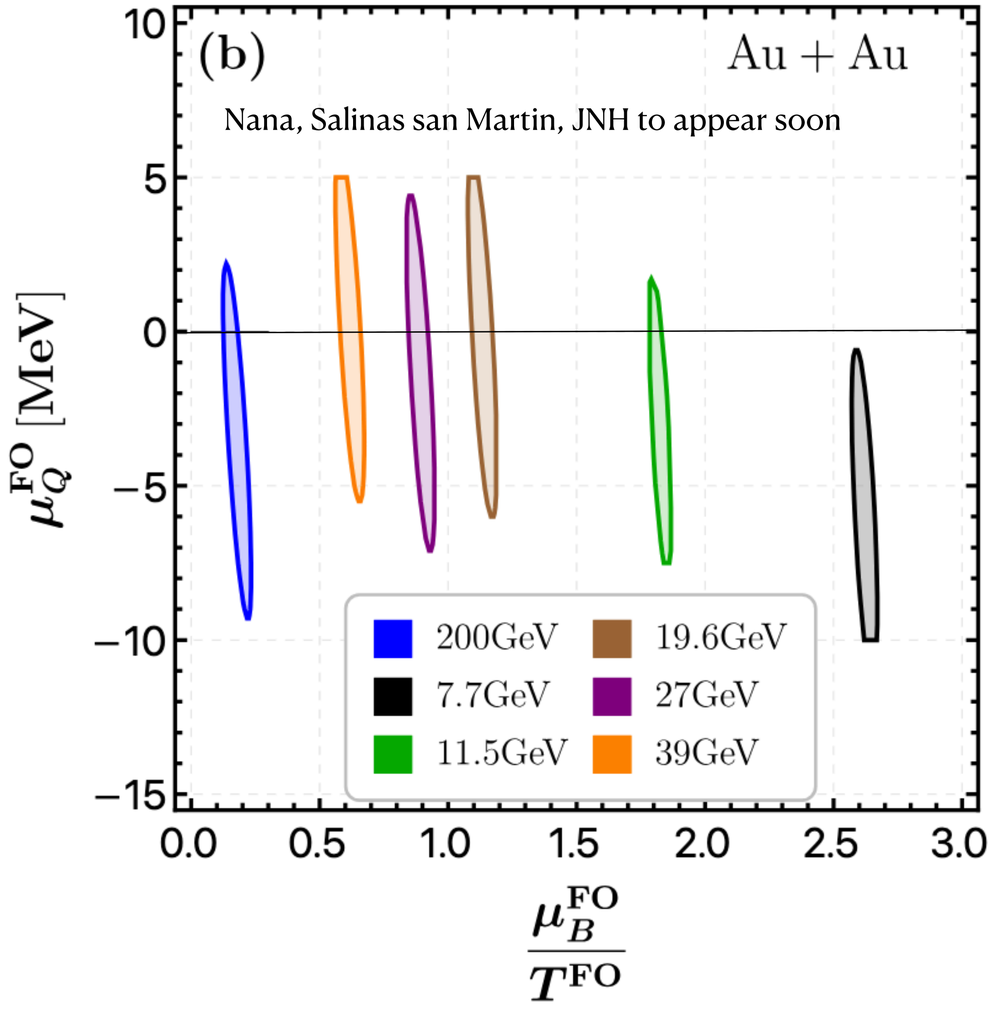
Ideally, varying Z/A of nuclei can extract EOS information vs μ_Q

But kinematics and baryon stopping is complicated [STAR] *Science* 393 (2026) 6812, ads5962

Ran Z/A range from 0.5-0.38, but nearly all at $\sqrt{s_{NN}} \geq 200$ GeV

Not enough baryon stopping to be sensitive to $\mu_Q \neq 0$

Need enough baryon stopping, for Z/A to matter



Conclusions and Outlook

- The Beam Energy Scan is already providing information about dense QCD matter, model-to-data comparisons are underway.
  - All MUSES tools are open-source if you want to play with them, see [MUSES] arXiv:2606.26326
- Symmetry energy information needed to connect neutron stars to heavy-ion collisions
  - Extracting the neutron skin of heavy nuclei provides important information!
  - Strangeness needs to be handled carefully between the limits
  - Binding energies and R_Q allows one to calculate chemical potentials, useful for NS equation of state models
- Future needs: more heavy nuclei to extract skins, light nuclei to determine size and shape, nuclei with different Z/A at low beam energies...