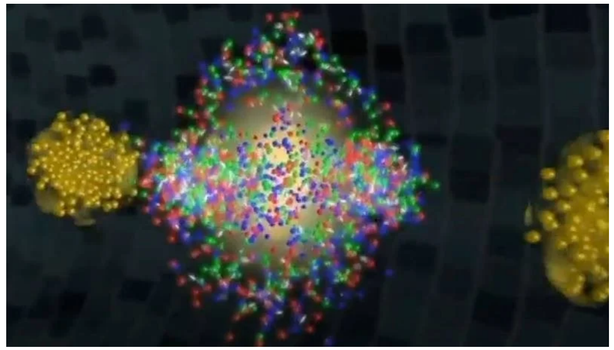
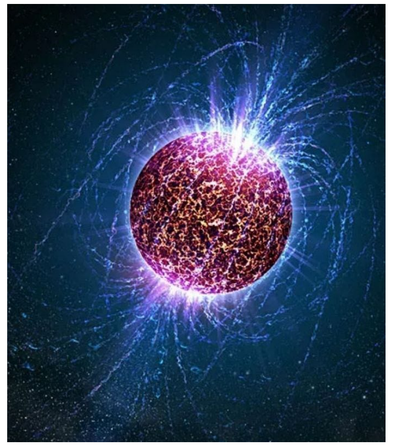
What can we learn from a Z/A scan?

Jacquelyn Noronha-Hostler



Exploring a Fixed-Target Program at the EIC: Feasibility and Physics Opportunities

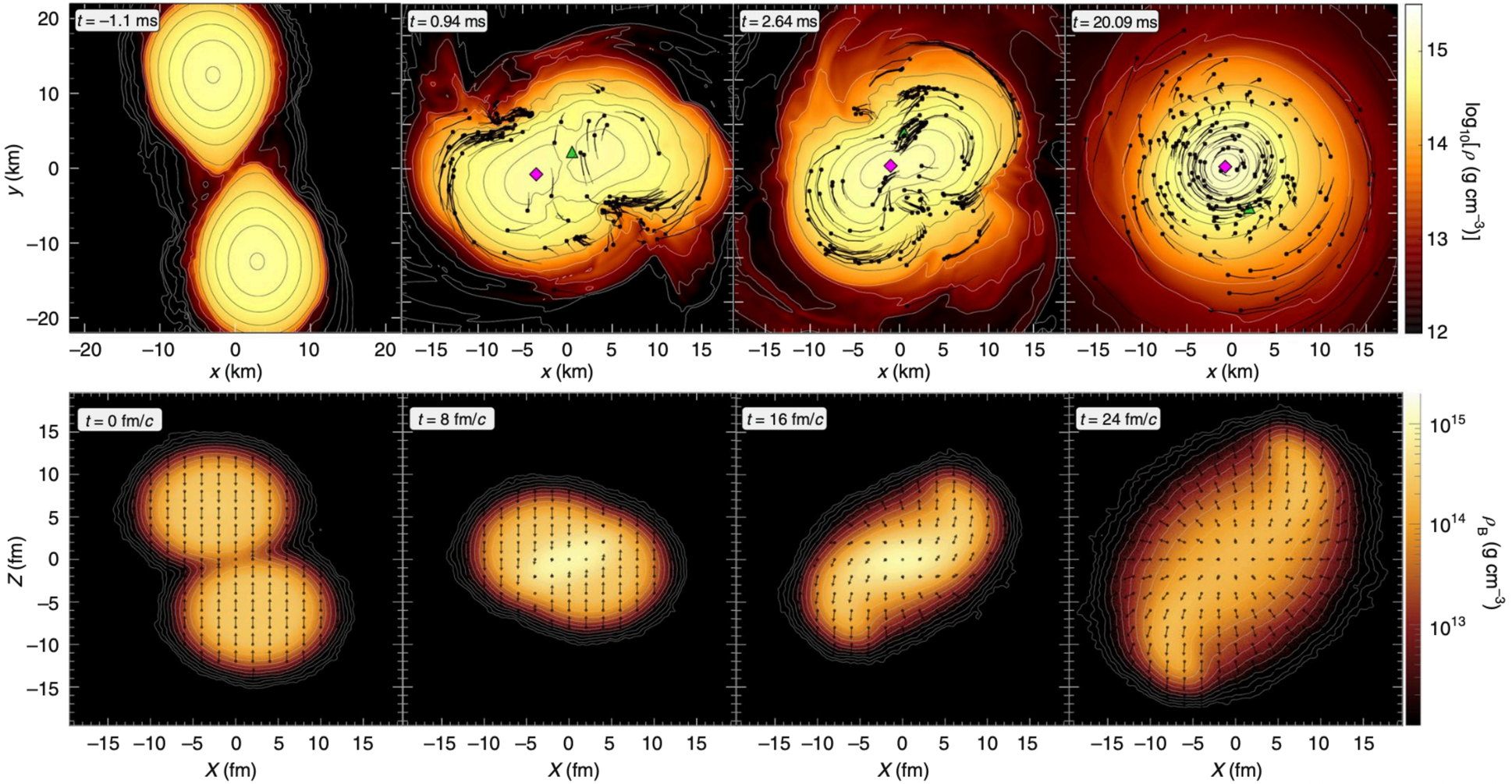
Sept, 2025



Heavy-ion collisions (HIC) vs Binary neutron star (NS) mergers

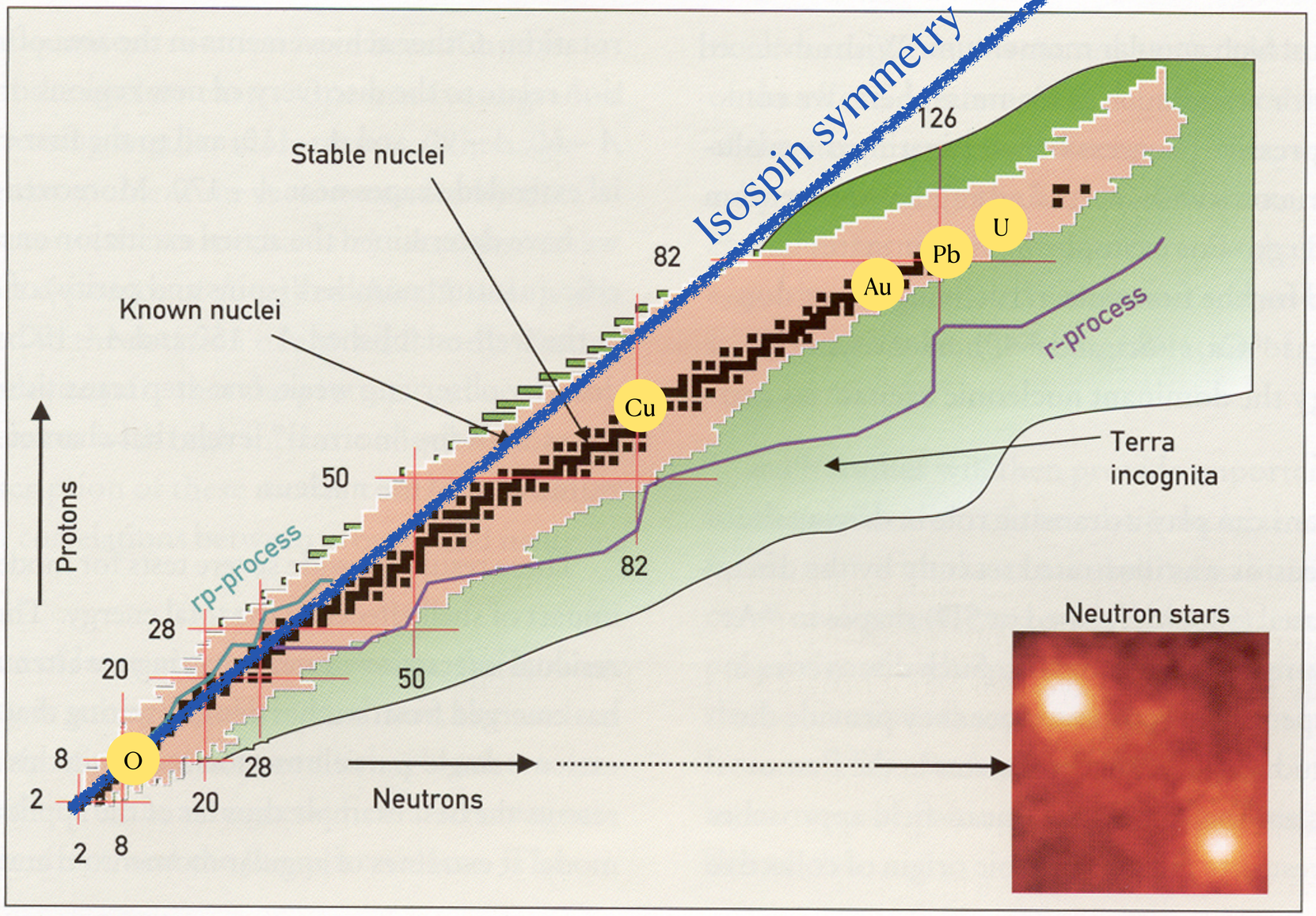
Neutron Star Mergers (Numerical Relativity)

[HADES] Nature Phys. 15 (2019) 10, 1040-1045

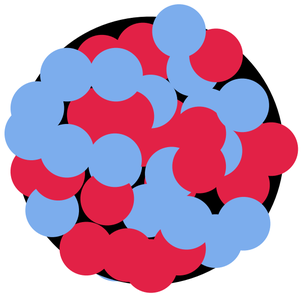


Low-energy Heavy-Ion Collisions (hadron transport)

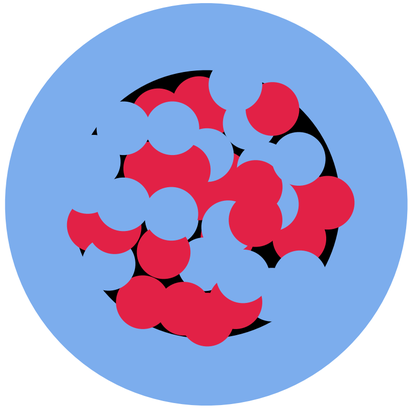
(Some) Nuclei ran in heavy-ions



Isospin symmetric nuclei



Neutron-rich nuclei



What have already ran? Charge fraction of ions

Isospin asymmetry

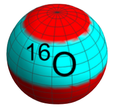
$$Y_Q = \frac{Z}{A} = \frac{n_Q}{n_B}$$

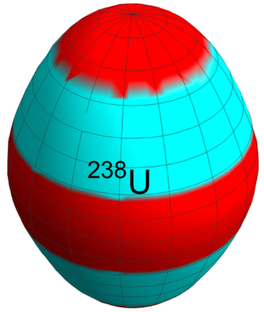
Heavy-ions:

$$Y_Q^{HIC} \sim [0.38, 5]$$

Neutron stars:

$$Y_Q^{NS} \lesssim 0.2$$





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

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

Charge vs isospin

I'll use these fairly interchangeably...

Yang et al, 2504.18764 [nucl-th]

Gell-Mann-Nishijima Formula: Relation between isospin I_z, charge Q, baryon number B, and strangeness S

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

Works at number densities...

$$n_Q = n_{I_z} + \frac{1}{2}\left(n_B + n_S\right)$$

And charge fractions: (Divide by n_B)

$$Y_Q = Y_{I_z} + \frac{1}{2}\left(1 + Y_S\right)$$

+ Strangeness neutrality

$$Y_Q = Y_{I_z} + \frac{1}{2}$$

Isospin asymmetry is then:

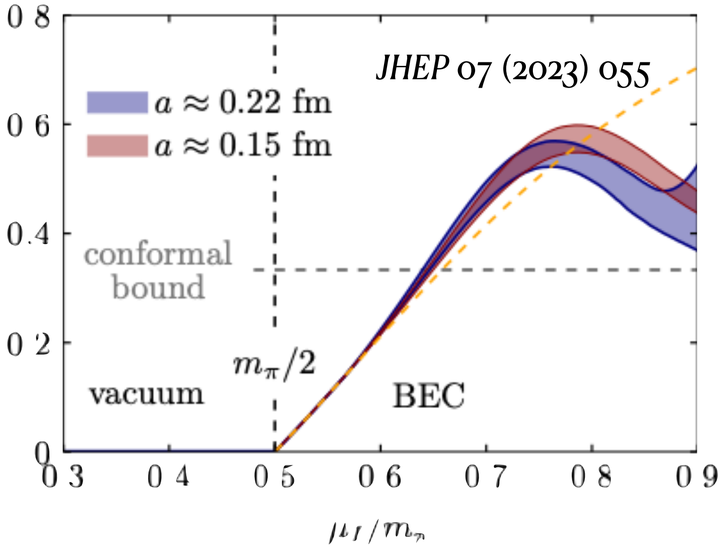
$$\delta = 1 - 2Y_Q$$

Symmetric matter: $\delta = 0$ Pure neutral matter: $\delta = 1$

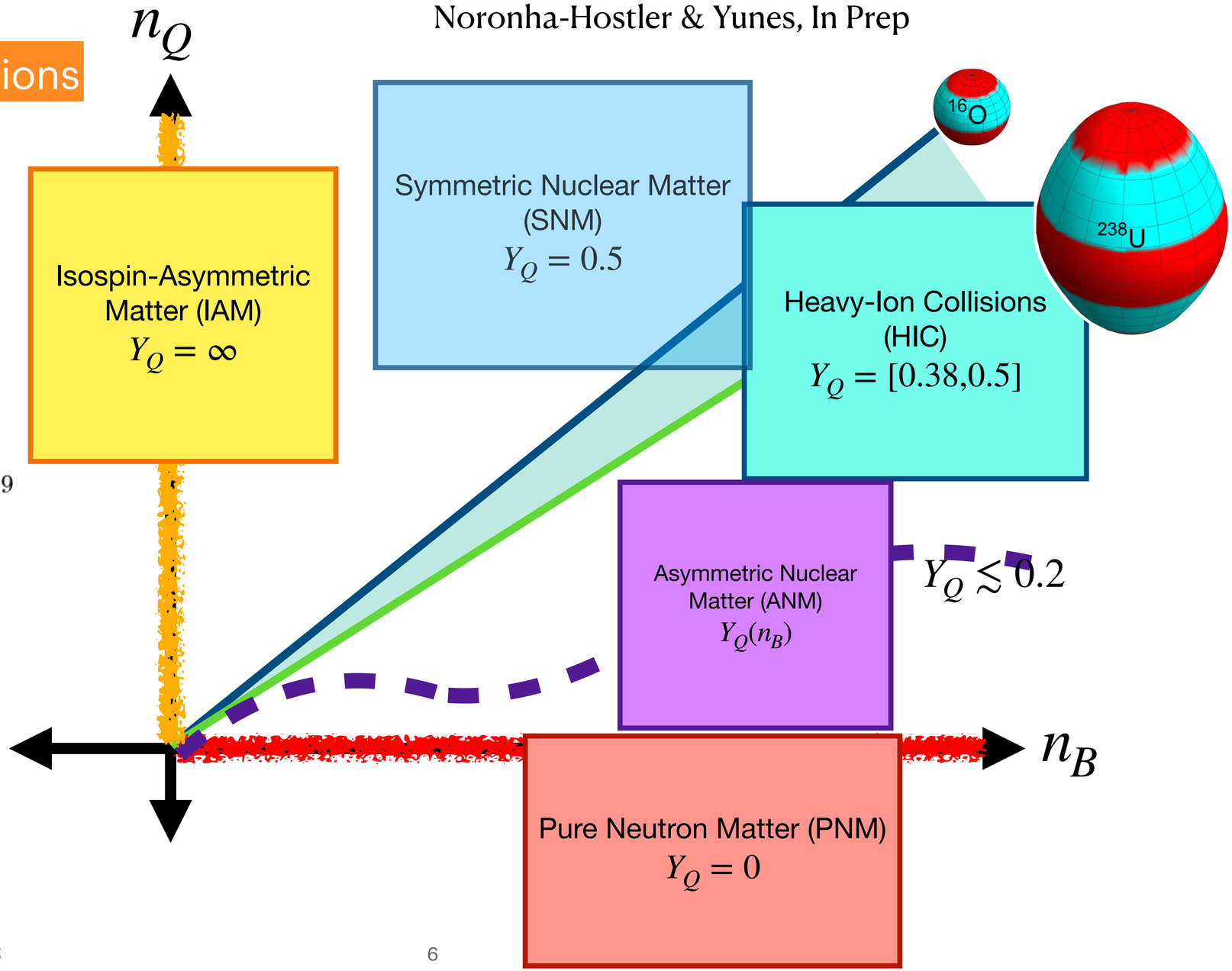
$\delta_{HIC} \sim [0,0.24]$ $\delta_{NS} \sim [0.6,1]$

QCD phase diagram at $T = 0$

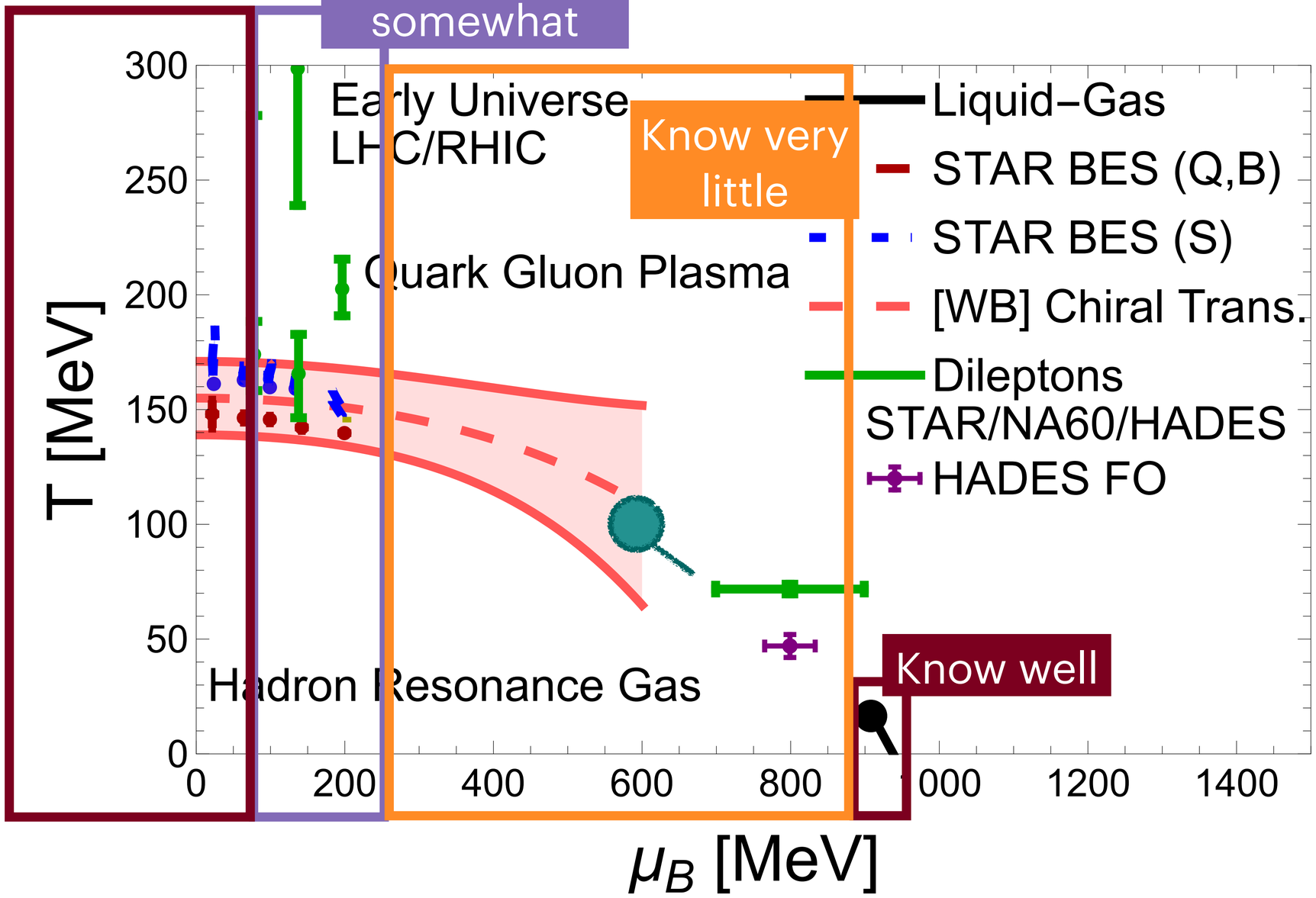
Existing lattice QCD calculations



Noronha-Hostler & Yunes, In Prep



UIUC ...at 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)

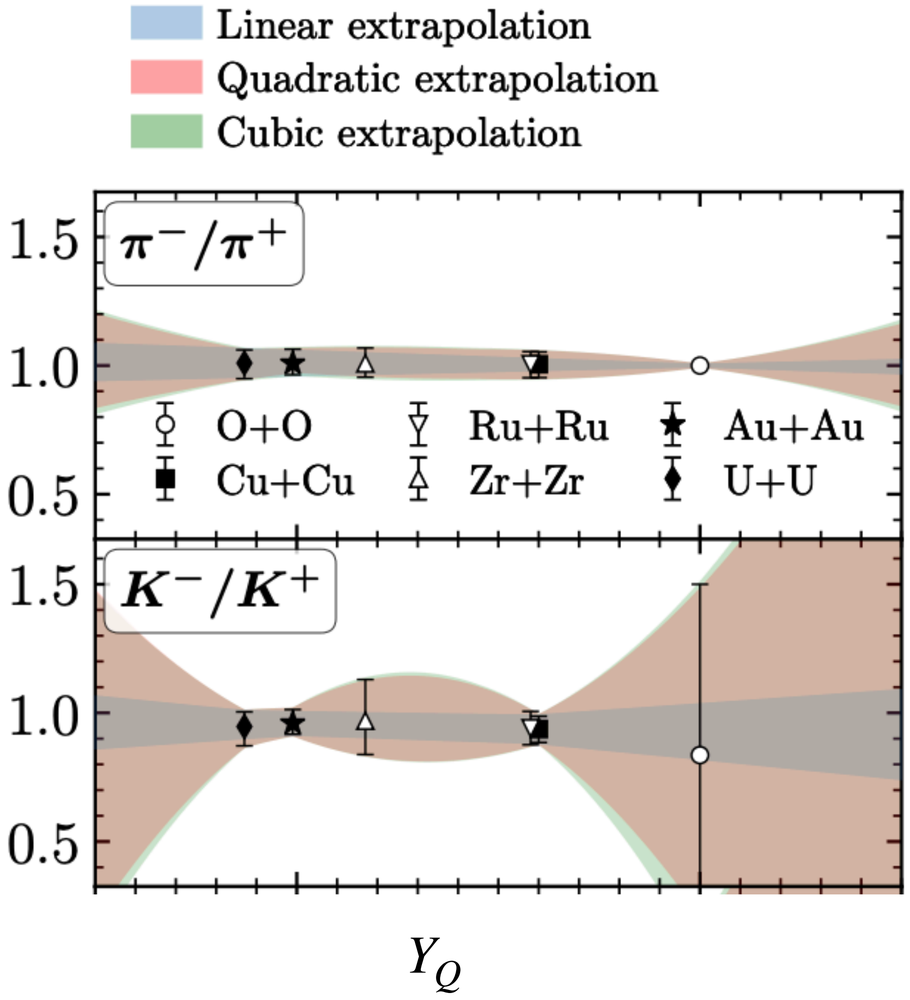
Liquid-gas phase transition location
Elliott, et al, Phys. Rev. C 87, 054622 (2013)
μ_B estimate Vovchenko, et al, Phys. Rev. Lett. 118, 182301 (2017)

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

RHIC's isospin scan at $\sqrt{s_{NN}} = 200\,\mathrm{GeV}$

Nana, Salinas san Martin, JNH 2411.03705 [nucl-th]

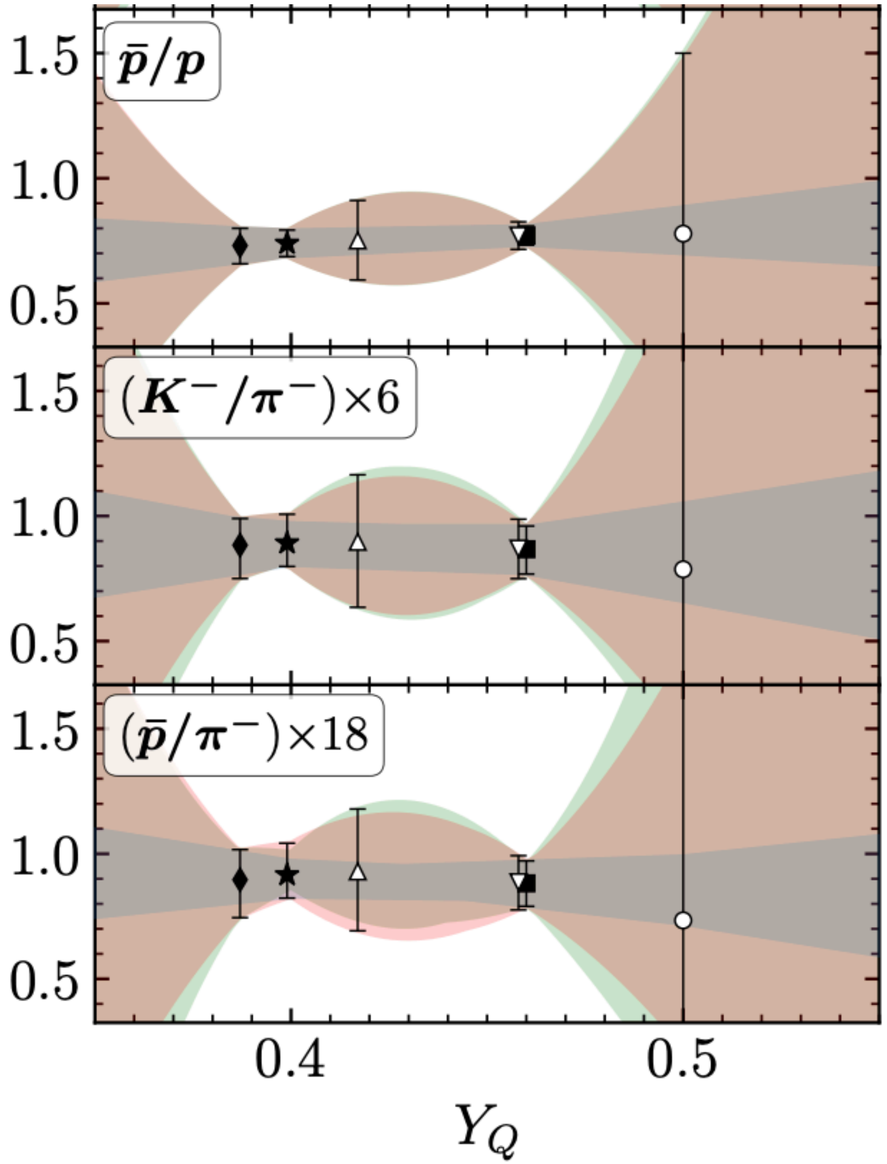
Yields vs Y_Q: is HIC data sensitive to isospin?



Little baryon stopping here..

$\mu_B \sim 20$ MeV

Jury is still out



We have an isospin scan at $\sqrt{s_{NN}} = 200$ GeV, but this is WAY more useful for neutron stars at low $\sqrt{s_{NN}} < 10$ GeV

Open questions with isospin and $Y_Q = Z/A$

- Can we extract the equation of state vs Y_Q?
  - New phases of matter may appear (or disappear!) across Y_Q
  - What would the critical point look like across isospin? Stronger or weaker?
  - Constraints on symmetry energy
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  - Baryon junctions
  - "Noise" from gluon splittings into $g \to q\bar{q}$ pairs
  - BSQ diffusion
- Can we better understand isospin symmetry breaking in neutral kaons?
- Nuclear structure?
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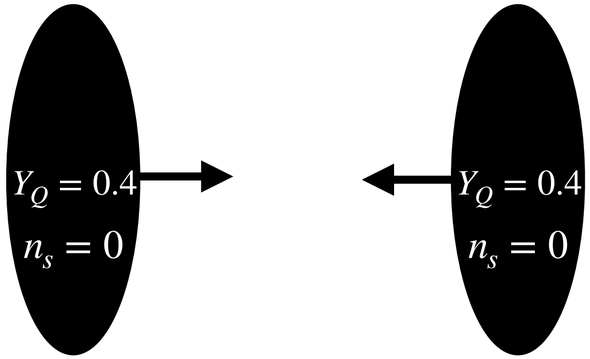
BSQ: Global vs local constraints?

QCD conserves BSQ at each vertex, but what does that mean for HIC?

Global AND local BSQ constraints



Assume, local fluctuations are too small scale to affect observables

$$\langle n_Q \rangle = 0.4 \langle n_B \rangle$$
$$\langle n_S \rangle = 0$$

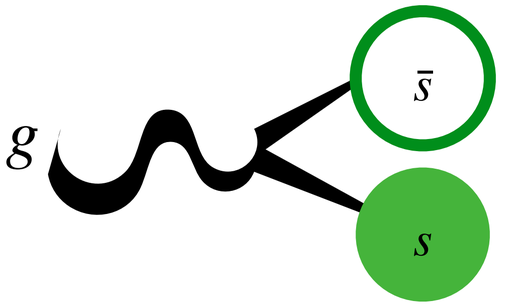
$\mu_S(T, \mu_B)$
$\mu_Q(T, \mu_B)$

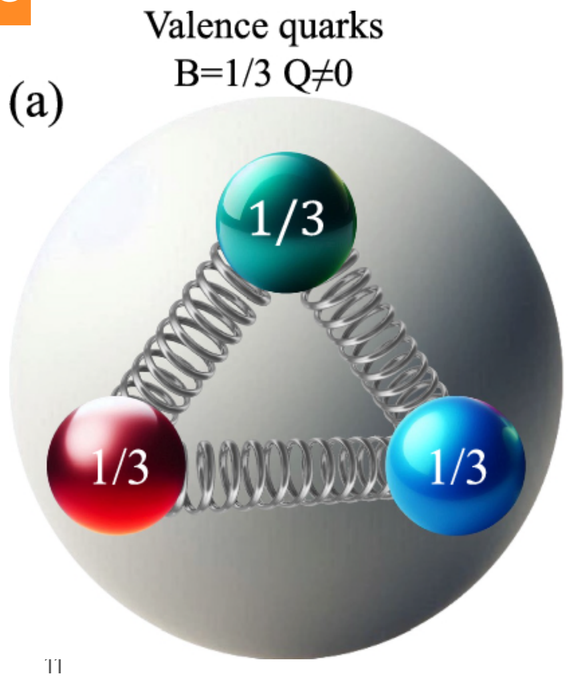
Let's start here

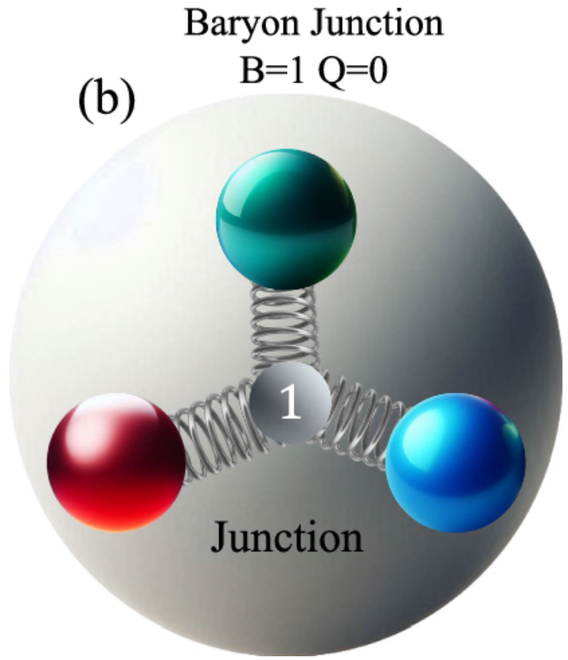
VS

Global BSQ constraints ONLY

Gluon splitting



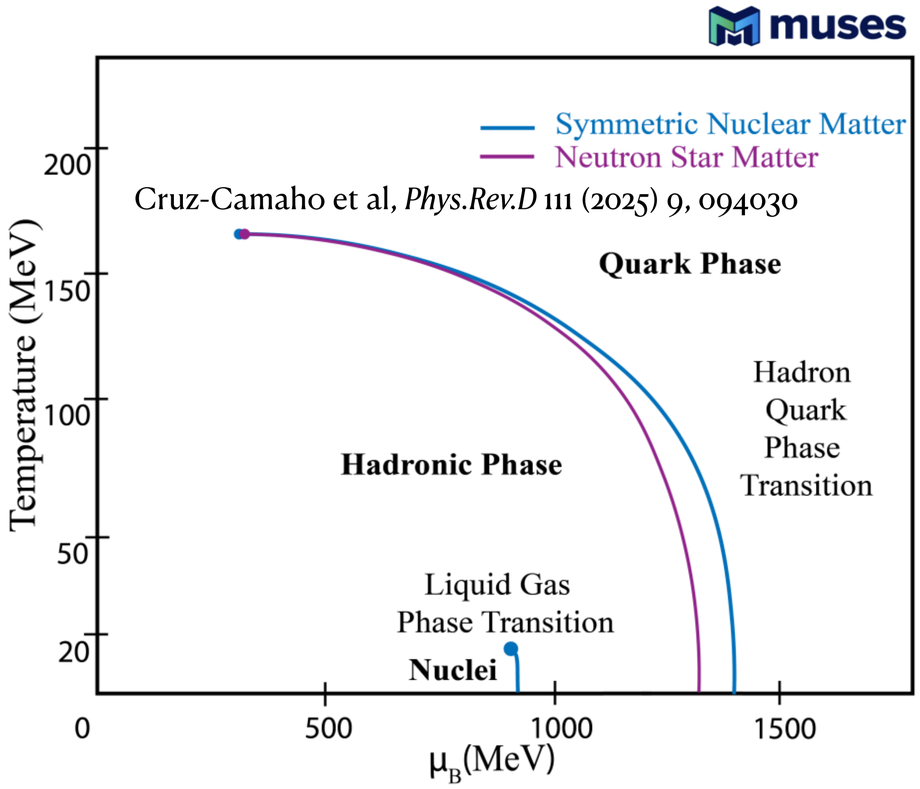




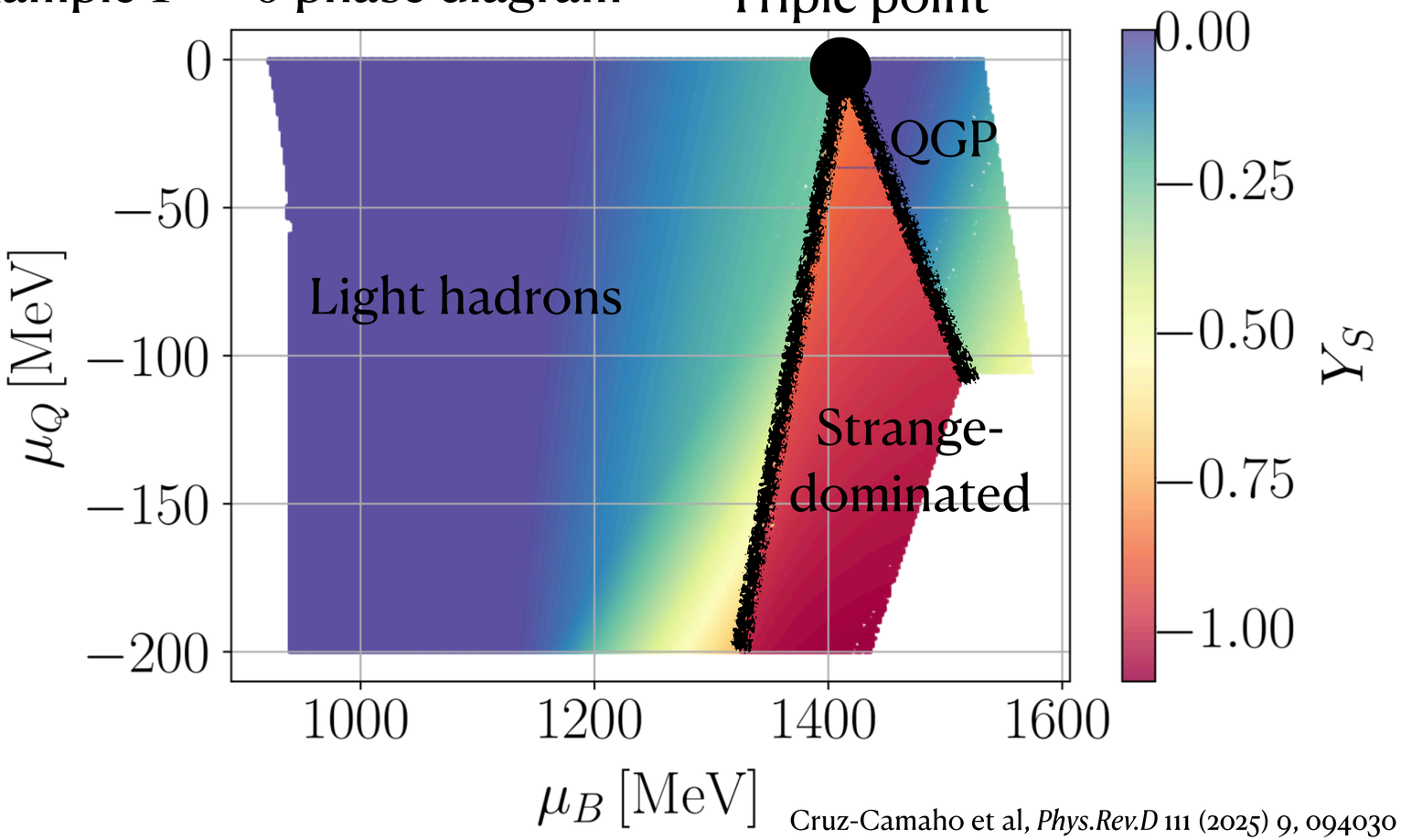
QCD phase diagram vs isopin/Y_Q

Y_Q changes phases of matter, location of phase transitions

One small example...



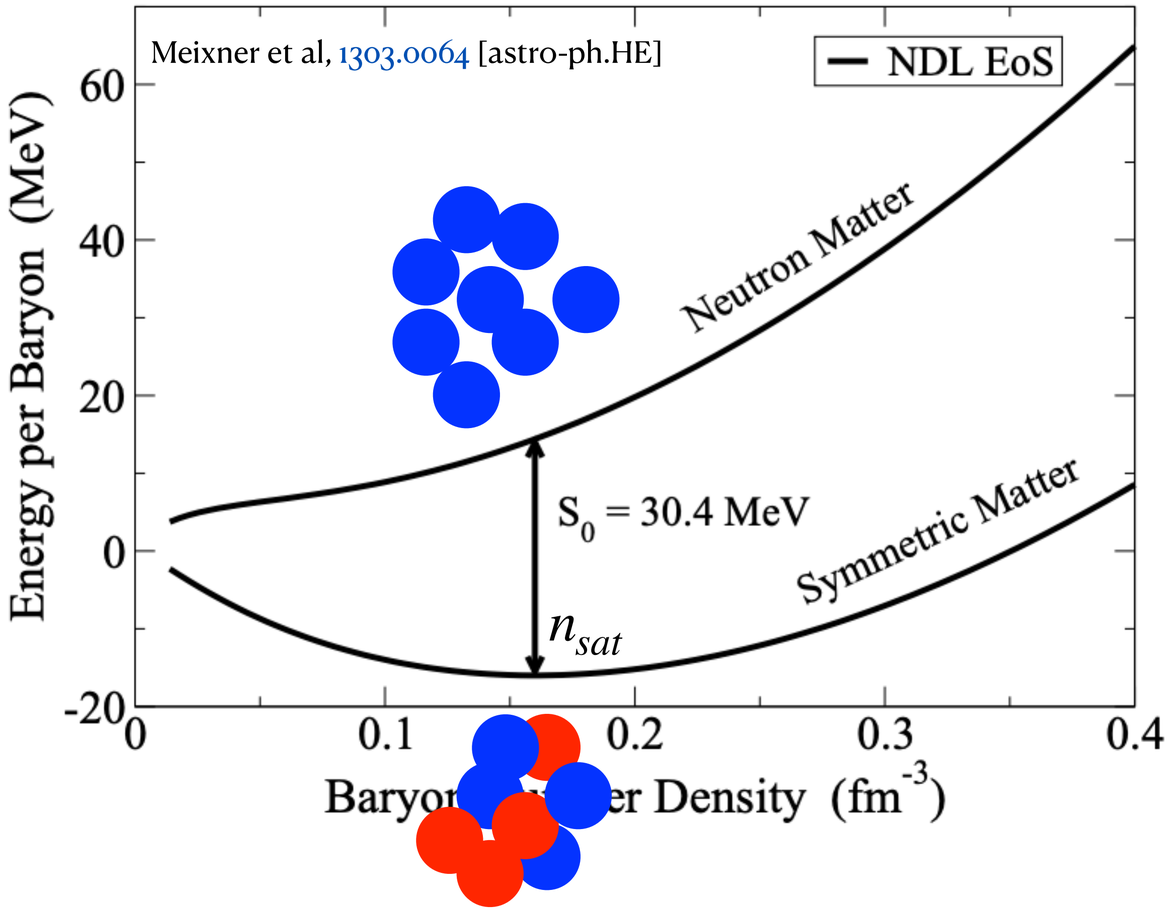
Example $T = 0$ phase diagram



Cruz-Camaho et al, *Phys.Rev.D* 111 (2025) 9, 094030

Symmetric matter vs Pure Matter

"Symmetry Energy"



Symmetric nuclear matter

$$\mu_Q = 0$$

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

$$Y_Q = 0.5$$

ONLY true for neutrons and protons!

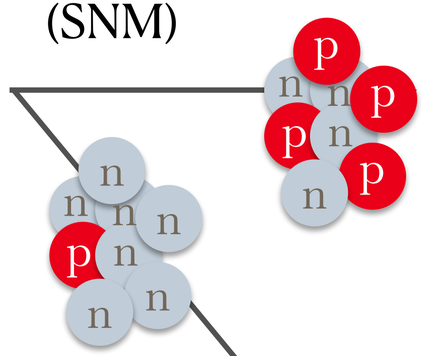
Symmetry energy

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

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}

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

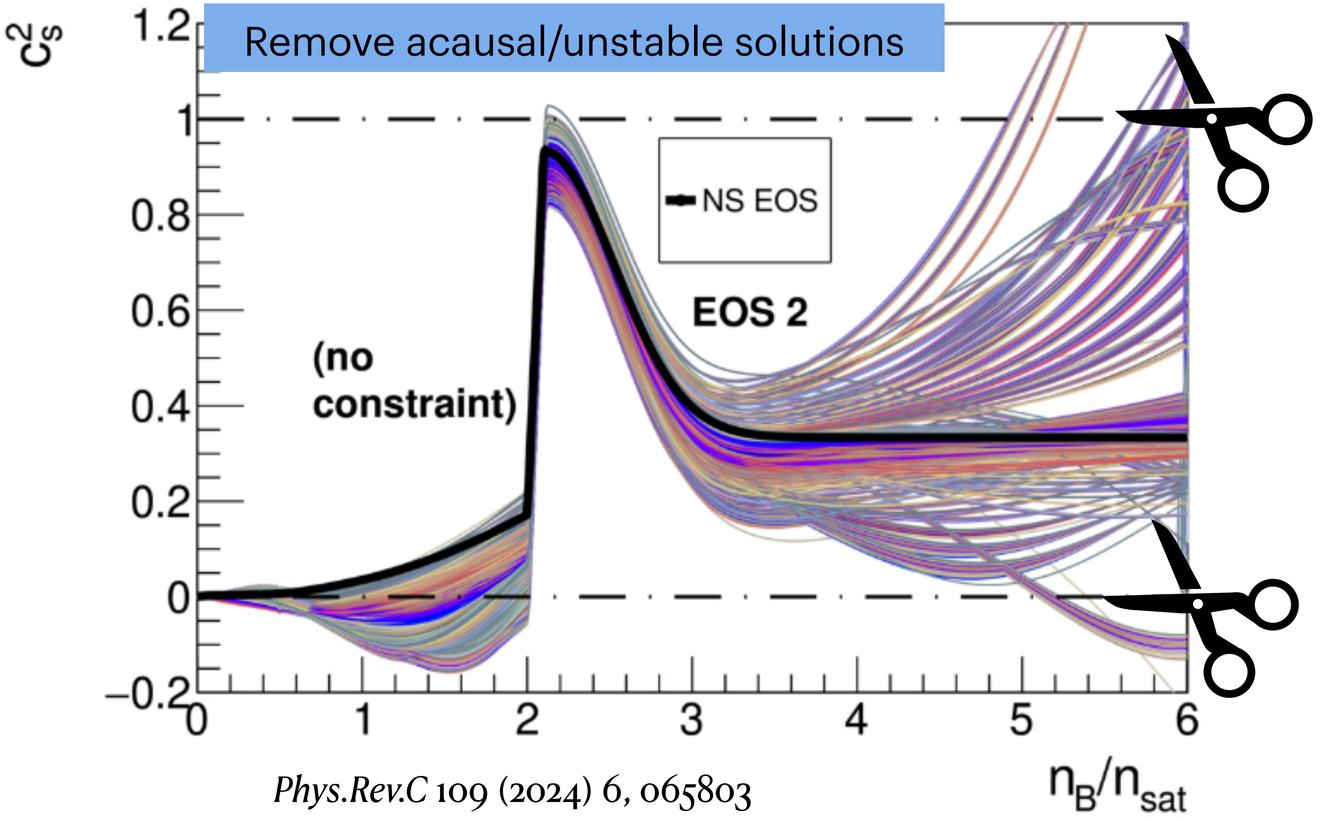
$E_{sym,2}(n_B)$ 4 unknowns

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

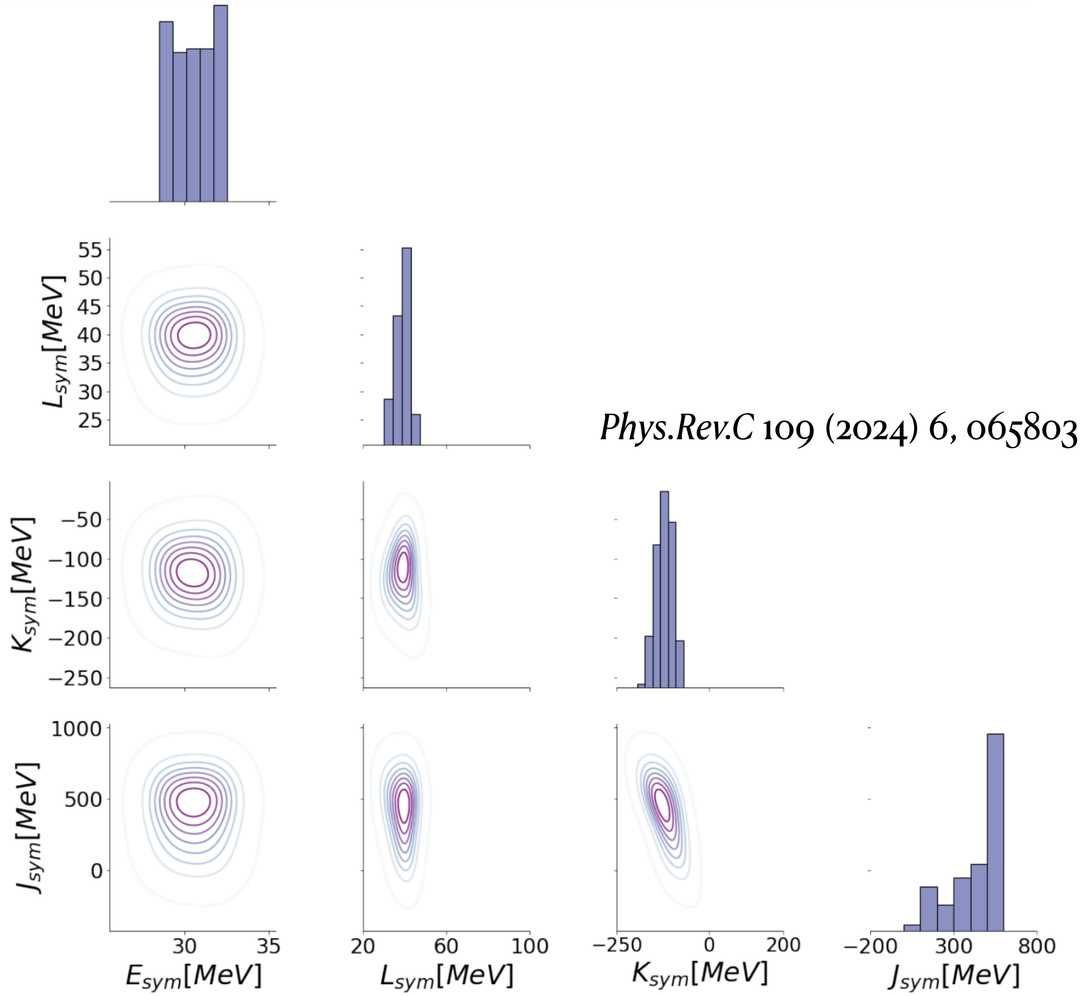
How do low-energy heavy-ion collisions at $T = 0$ connect to neutron stars?

Symmetry energy expansion

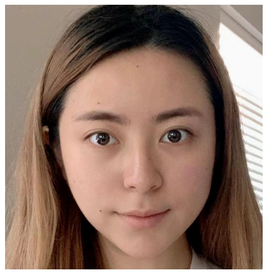
Given neutron star equation of state → convert to HIC and can constrain by $0 \leq c_s^2 \leq 1$ and saturation properties.



Phys.Rev.C 109 (2024) 6, 065803

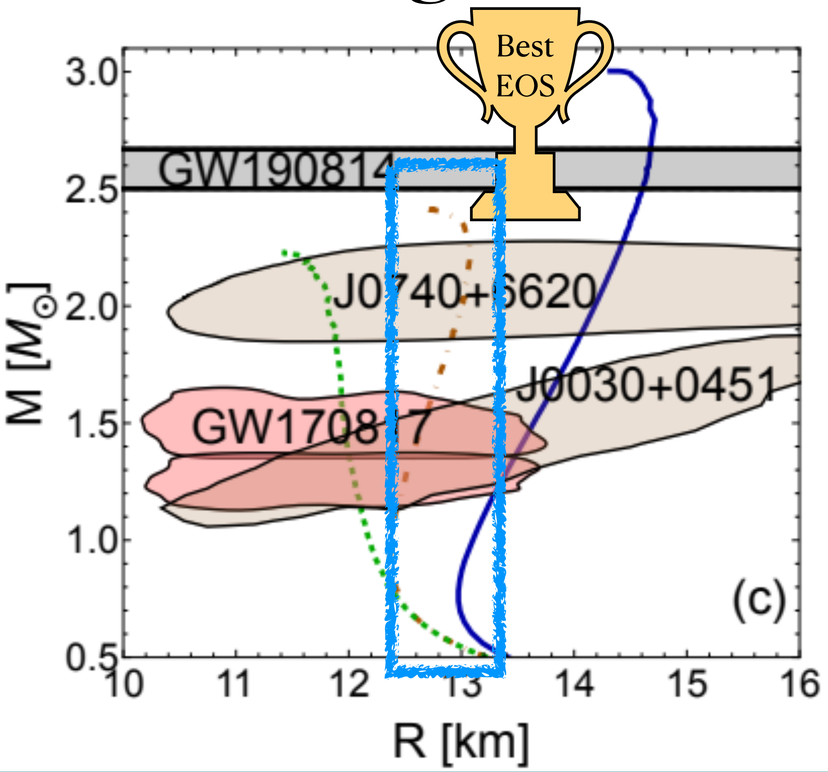


Phys.Rev.C 109 (2024) 6, 065803

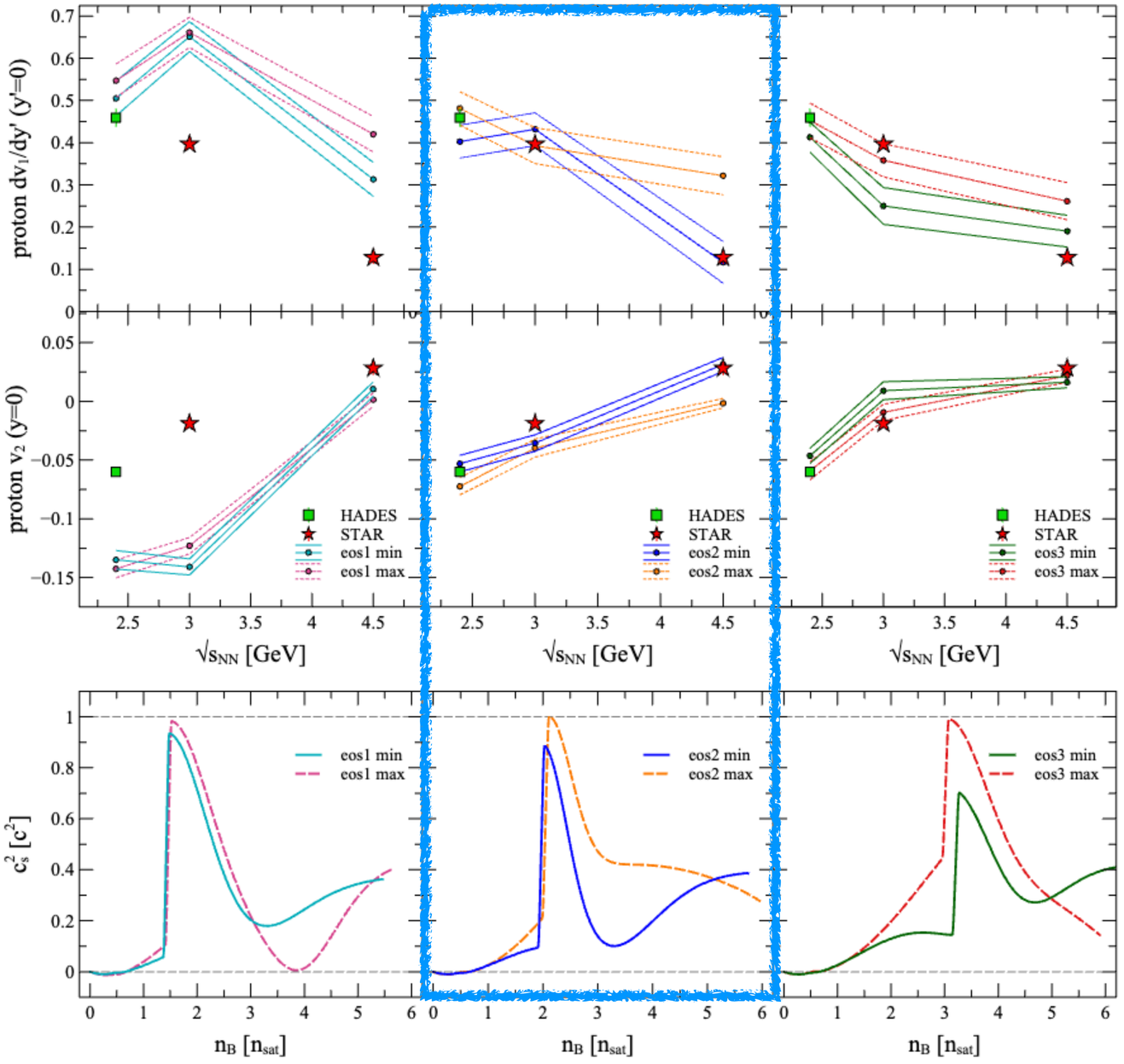


Testing $T = 0$ EOS in HIC with hadron transport

Phys.Rev.C 109 (2024) 6, 065803



This was just a proof-of-principle study, but we flow and multiplicity data across Y_Q could significantly constrain symmetry energy and EOS!



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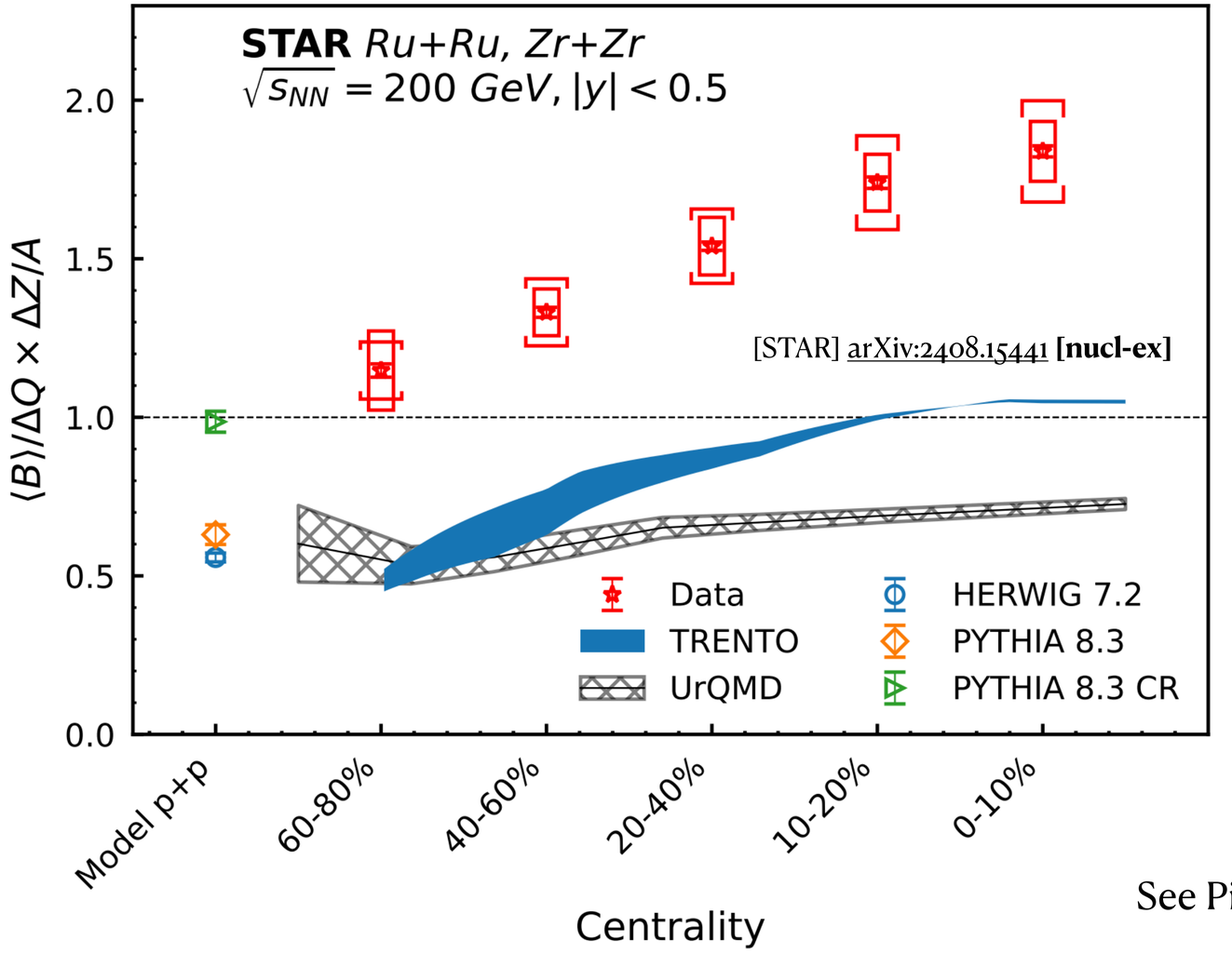
Interesting results from STAR, but what do they mean?

Baryon junctions or just dynamics?



More data across a wider range of Y_Q would help enormously here.

What does ^{238}U vs ^{16}O look like?

Would expect a much larger effect at lower $\sqrt{s_{NN}}$..

What about PID collective flow observables?

See Pihan et al *Phys.Rev.Lett.* 133 (2024) 18, 182301 for other sensitive observables

Heavy-Ion Collisions: Equilibrium vs Out-of-Equilibrium

Energy-Momentum Tensor

$$T^{\mu\nu} = T_0^{\mu\nu} + \Pi + \pi^{\mu\nu}$$

Equation of State (EOS)

Local rest frame

$$T_0^{\mu\nu} = \begin{bmatrix} \varepsilon & 0 & 0 & 0 \\ 0 & p & 0 & 0 \\ 0 & 0 & p & 0 \\ 0 & 0 & 0 & p \end{bmatrix}$$

Bulk Pressure $\Pi = Tr\left[T^{\mu\nu} - T_0^{\mu\nu}\right]$

Shear stress tensor $\pi^{\mu\nu} = T^{\mu\nu} - T_0^{\mu\nu} - \Pi$

Conserved Currents

Baryon Current $N_B^\mu = n_B u^\mu + q_B^\mu$

Strangeness Current $N_S^\mu = n_S u^\mu + q_S^\mu$

Electric Charge Current $N_Q^\mu = n_Q u^\mu + q_Q^\mu$

Diffusion

Contains diffusion matrix and gradients of μ/T

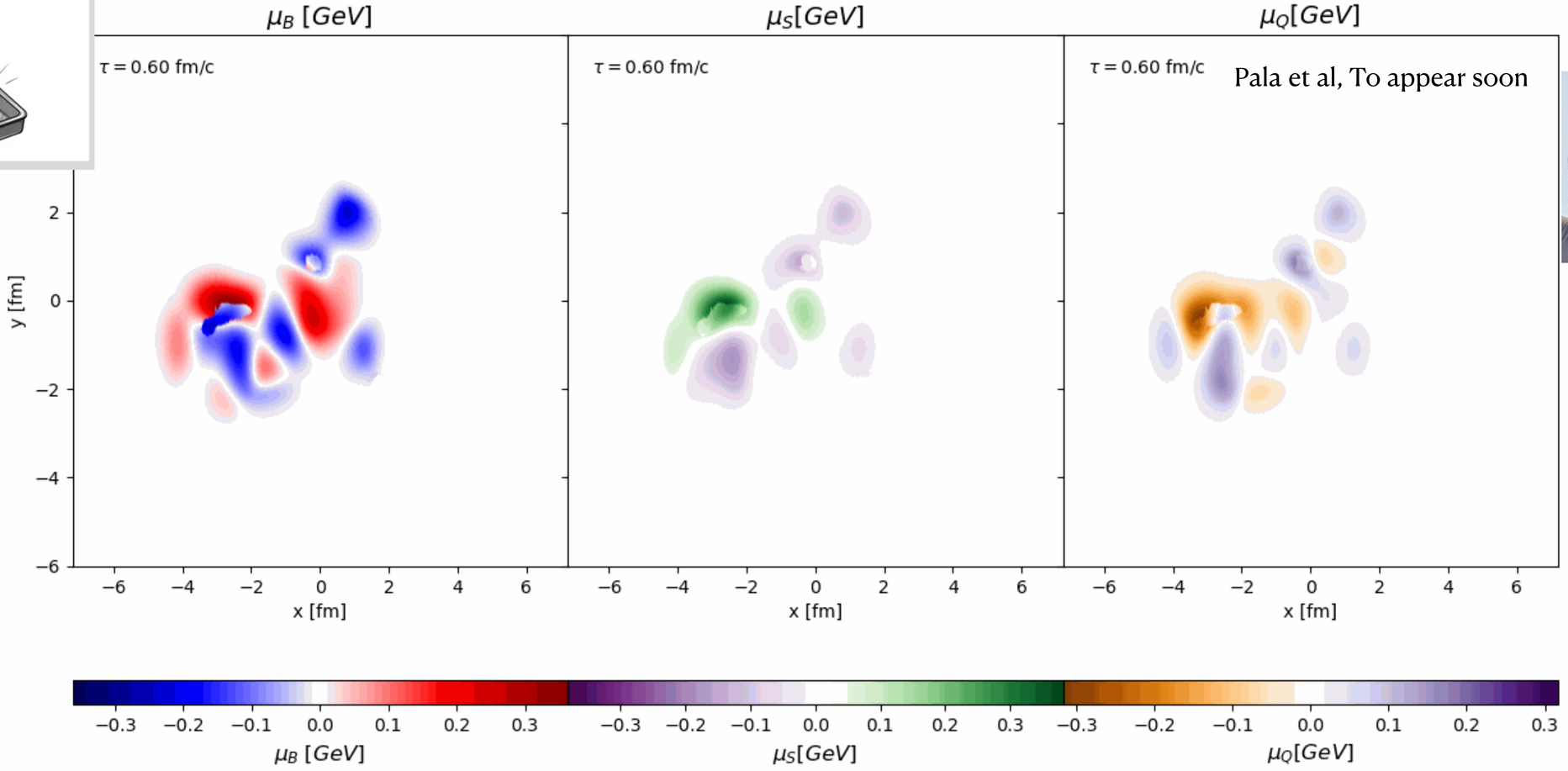
$$\kappa = \begin{bmatrix} \kappa_{BB} & \kappa_{BS} & \kappa_{BQ} \\ \kappa_{SB} & \kappa_{SS} & \kappa_{SQ} \\ \kappa_{QB} & \kappa_{QS} & \kappa_{QQ} \end{bmatrix}$$

Greif et al, *Phys.Rev.Lett.* 120 (2018) 24, 242301; Fotakis et al, *Phys.Rev.D* 106 (2022) 3, 036009

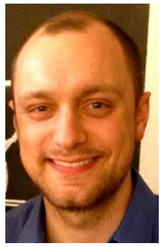
BSQ diffusion matrix may play a big role here!

BSQ diffusion matrix: non-trivial movement of charges

CCAKE 2.0 coming soon



Pala et al, To appear soon

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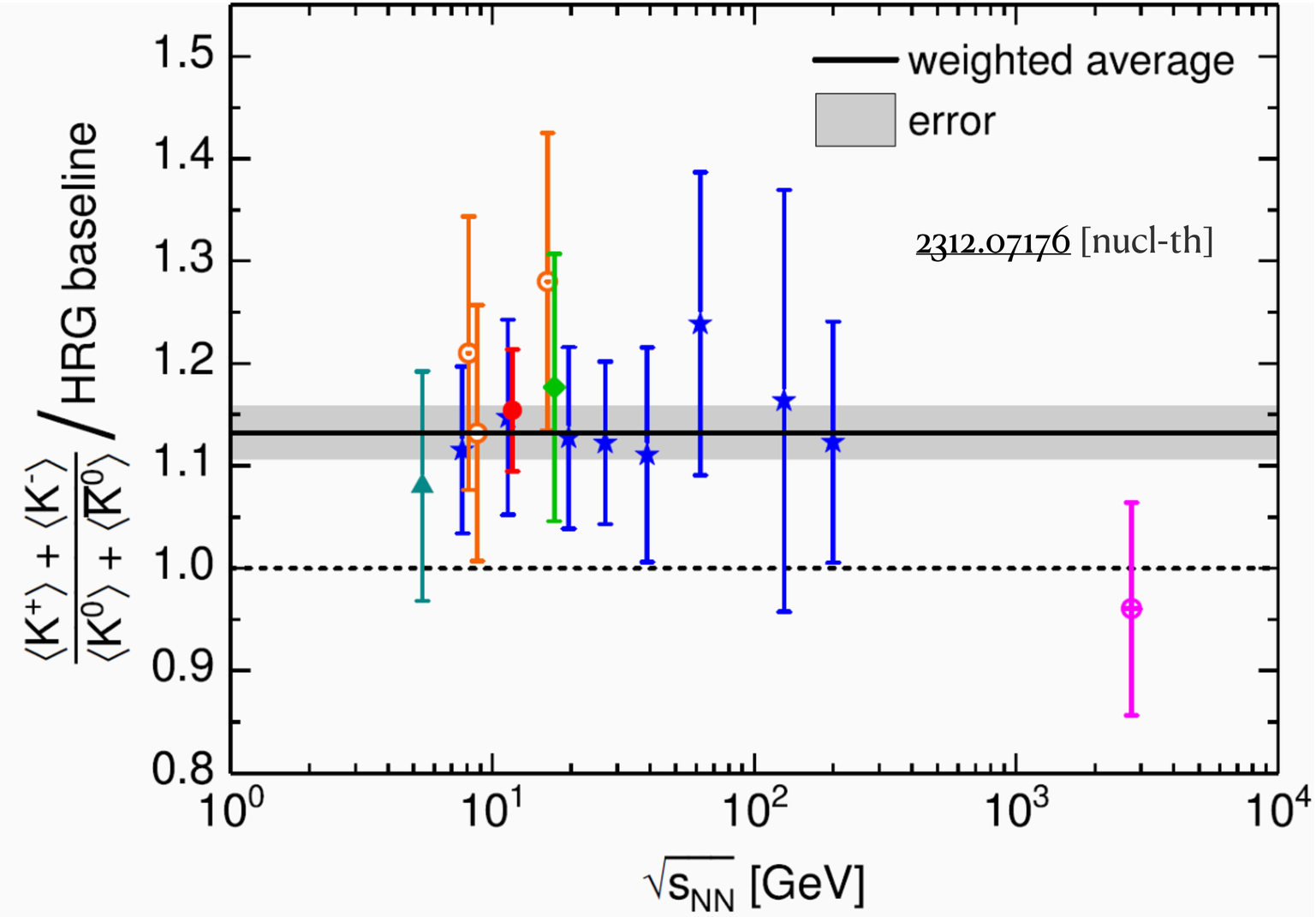
Kaon isospin symmetry breaking?

Lots of theories, but a Y_Q scan could help



Does this scale with Y_Q of the colliding ions?

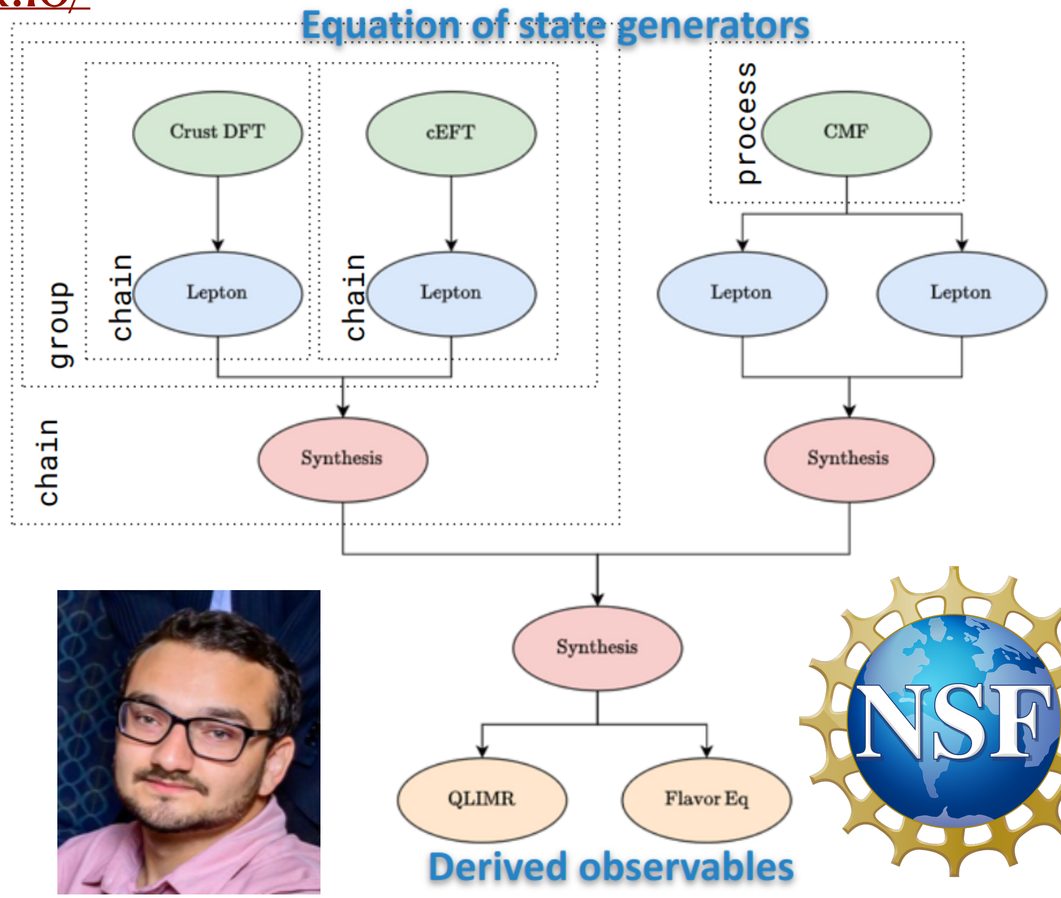
Are we missing important physics in the strangeness sector?

Open-source tools for more cross-disciplinary connections!

muses https://ce.musesframework.io/

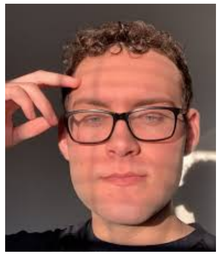
- 7 available equation of state (EOS) modules
- 6 new EOS modules in next year+2D synthesis
- 3 available observable modules (2+ coming soon)
- Both heavy-ion and neutron star EOS available
- β-release out and available! Possible to run crust to core of a neutron star+calculate mass, radius, tidal deformability etc
- Looking for new collaborators!

Software across the QCD phase diagram



Later releases will connect heavy-ion and neutron star EOS across the entire phase diagram!

Thank you to my group + collaborators!

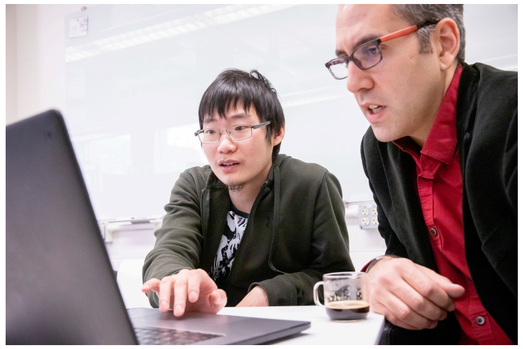















Conclusions and Outlook

- The isobar was a good starting point, but there's a lot more we could get out of an isospin scan or rather a $Y_Q = Z/A$ scan at lower $\sqrt{s_{NN}}$
- Enormous uncertainties when going from $Y_Q \sim 0.5$ (HIC) to $Y_Q < 0.2$ (NS)
  - Coefficients in the symmetry energy expansion
  - Extract isospin dependent EOS
  - New phases of matter (or at different locations!)
- Dynamics of conserved charges significantly under explored
  - PID observables across $\sqrt{s_{NN}}$, Z/A. Think about collective flow or other correlations
  - Diffusion or baryon junctions?
  - Something funky is going on with kaons...