Status, Problems, and Perspectives on Symmetry Energy

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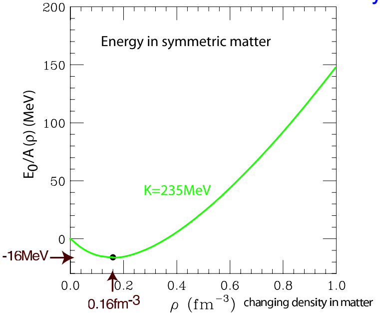
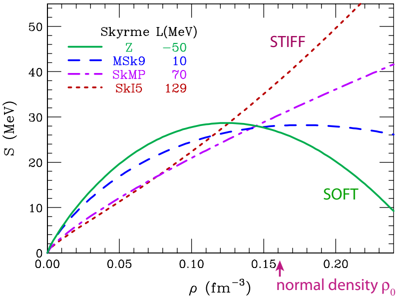
Energy in Uniform Matter

$$\frac{E}{A}(\rho_n, \rho_p) = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 + \mathcal{O}(\ldots^4)$$

symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$





$$\frac{E_0}{A}(\rho) = -a_V + \frac{K}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots$$

$$S(\rho) = a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0} + \frac{K_{sym}}{18}\left(\frac{\rho - \rho_0}{\rho_0}\right)^2 + \ldots$$

Known: $a_a \approx 16$ MeV $K \sim 235$ MeV

Unknown: a_a^V ? L ? K_{sym} ?

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Symmetry-Energy in *n*-Star & Other Basics

$$\frac{E}{A} = \frac{E_0}{A}(\rho) + S(\rho)\left(\frac{\rho_n - \rho_p}{\rho}\right)^2 \qquad S \simeq a_a^V + \frac{L}{3}\frac{\rho - \rho_0}{\rho_0}$$

Neutron matter: $\rho_p \approx 0, \quad \rho_n \approx \rho$ & $\frac{E}{A}(\rho) \approx \frac{E_0}{A}(\rho) + S(\rho)$ & $S(\rho) \approx \frac{E_n}{A}(\rho) - \frac{E_0}{A}(\rho)$

$\Rightarrow$Pressure: $P = \rho^2 \frac{\mathrm{d}}{\mathrm{d}\rho}\frac{E}{A} \simeq \rho^2 \frac{\mathrm{d}S}{\mathrm{d}\rho} \simeq \frac{L}{3\rho_0}\rho^2$

Stiffer symmetry energy $\Rightarrow$ larger max mass of neutron star & larger radii

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Speed of sound: $c_s^2 = \frac{\mathrm{d}P}{\mathrm{d}e}$, where $e = \rho\left(\frac{E}{A} + m_N\right)$

Quark-matter free-asymptotics: $P \approx e/3$, $c_s^2 \approx 1/3$, & in degenerate gas

$\frac{E_n}{A} \approx 5.66\,\hbar c\,\rho^{1/3}$, $\frac{E_0}{A} \approx 5.52\,\hbar c\,\rho^{1/3}$, $S \approx 0.14\,\hbar c\,\rho^{1/3}$ MINUTE

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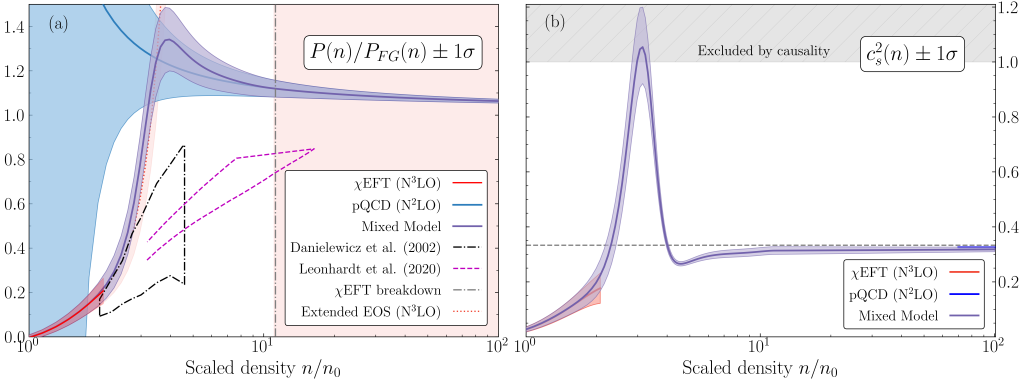
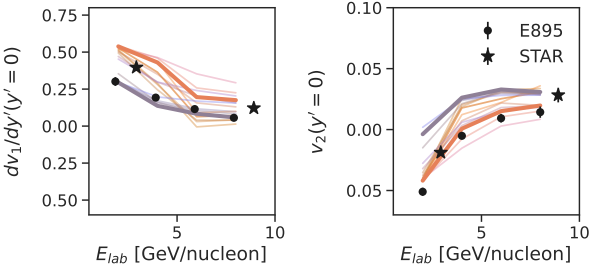
Pressure of Symmetric Matter

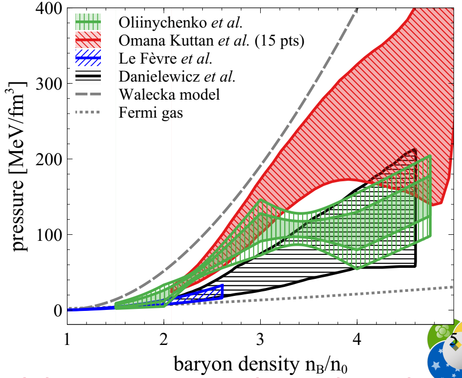
On microscopic side, chiral effective field theory (EFT) aims to extrapolate nuclear properties up to $\rho \sim 2\rho_0$. Interpolation btw such ρ & perturbative-QCD region suggests large intermediate increase in c_s^2 Semposki *et al* arXiv.2404.06323



Heavy-Ion Data Interpretation

STAR Collaboration Au+Au beam-energy scan probes different regions of symmetric-matter equation of state (EOS). Tension btw STAR & older E895 results and different flow coefficients in theory analyses w/o momentum dependence in interactions





Oliinychenko *et al* PRC108(23)034908
Kuttan *et al* PRL131(23)202303

⇒Importance of constraining momentum dependence!

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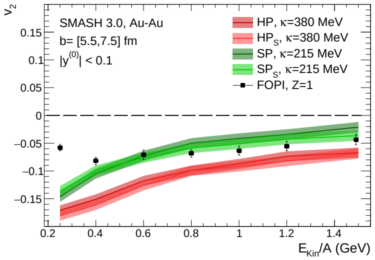
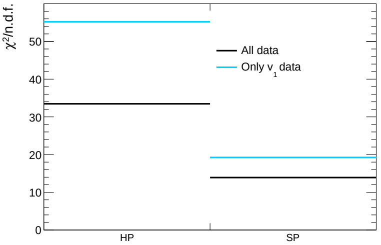
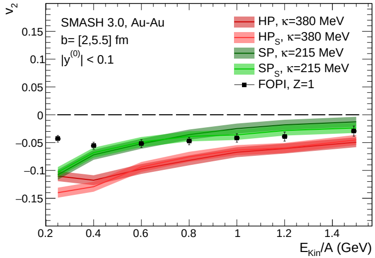
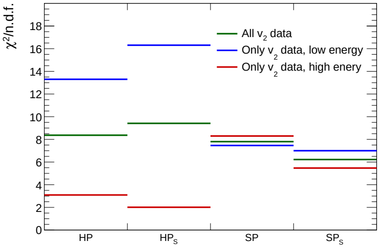
FOPI Flow Analyzed in SMASH









Flow: anisotropy associated w/reaction plane in emission, $v_n = \langle \cos n\phi \rangle$

Tarasovicova *et al* arXiv:2405.09889

Lower-energy data favor soft momentum-dependent (SP) interaction and higher-energy favor stiff (HP)

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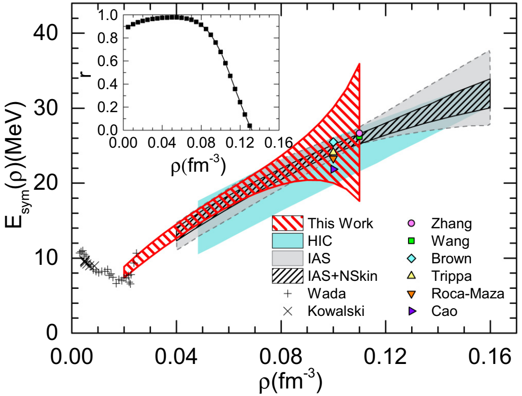
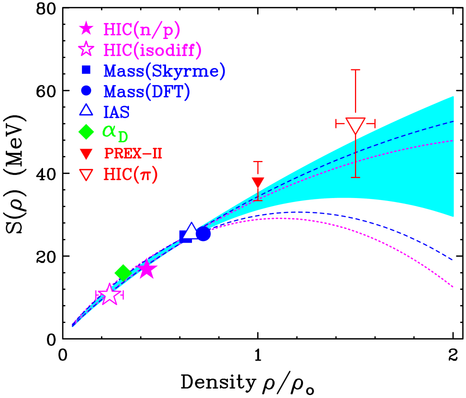
Different Data Test Symmetry Energy at Different ρ



Zhang&Chen PRC92(15)031301

Electric dipole polarizability tests symmetry energy at $\rho_0/3$: Pearson coef



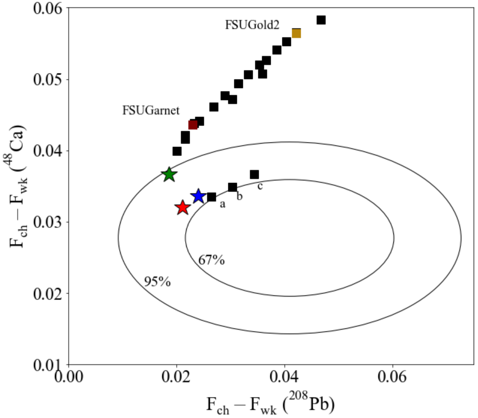
Lynch&Tsang PLB830(22)137098

Tension btw inferences released when they are attributed to proper ρ

Including Tension Between PREX & CREX Results??

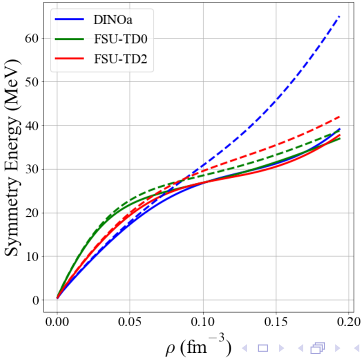
Salinas&Piekarewicz PRC109(24)045807

Reed *et al* PRC109(24)035803



Average ρ lower in ^{48}Ca than ^{208}Pb

Tension btw ^{208}Pb and ^{48}Ca neutron-skin measurements could be resolved w/symmetry energy that quickly changes character near ρ_0 and lacks parabolic form. Other problems result!



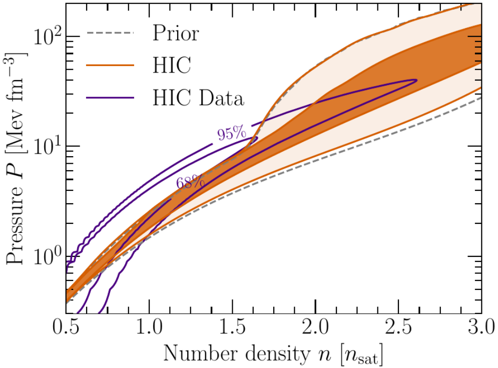
Combining Laboratory w/Astronomical Data

Constraining neutron-star matter with microscopic and macroscopic collisions

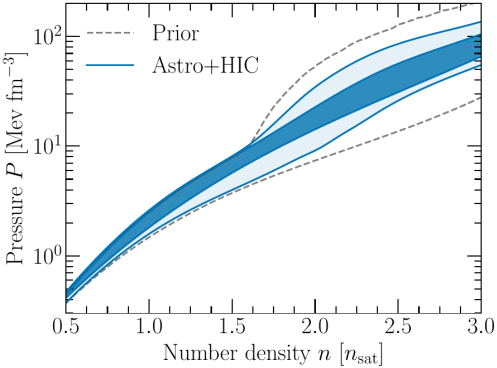
Bayesian combinations

Huth, Pang *et al* Nature 606(22)276

HIC experiments:



HIC and Astro combined:



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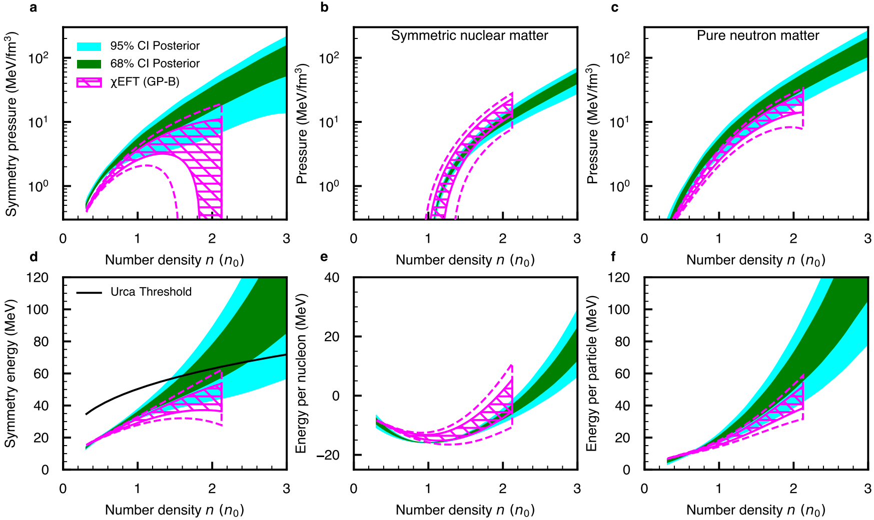
Astrophysical observations narrow constraints above $2\rho_0$

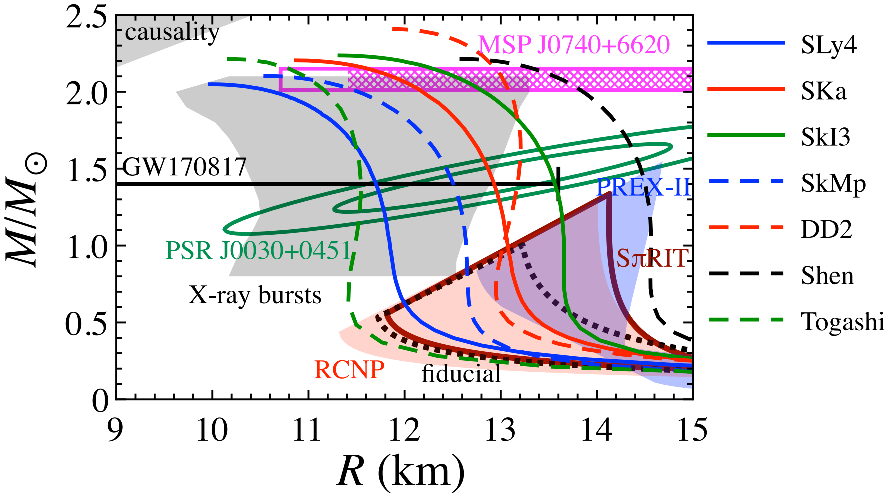
Updated Analysis



(Tommy) Tsang *et al* Nature Astronomy 8(24)328

Additional symmetry-energy constraints included

Impact of Terrestrial Experiments on Neutron-Star Expectations?



Sotani *et al* PTEP2022 (22)041D01

Reducing Fragility of Transport Conclusions

Transport-Model Evaluation-Project: Models evaluated under controlled conditions
Review: Wolter *et al* PPNP122(22)103962

History

- 2009/2014, Au + Au at 100 & 400 MeV/nucl Xu *et al* PRC93(16)044609
  $\rho(\mathbf{r})$-evolution & nucleonic observables (stopping, flow)
  differences hard to understand $\rightarrow$ switch to simplified conditions
- 2018-21, Box w/periodic boundaries, close to equilibrium, analytic limits
  Mean field, collision term, π production in cascade mode
- 2023, Again HIC: Sn + Sn at 270 MeV/nucl Xu *et al* PRC109(24)044609
  Subthreshold π production for different symmetry energies in the context of SπRIT measurements

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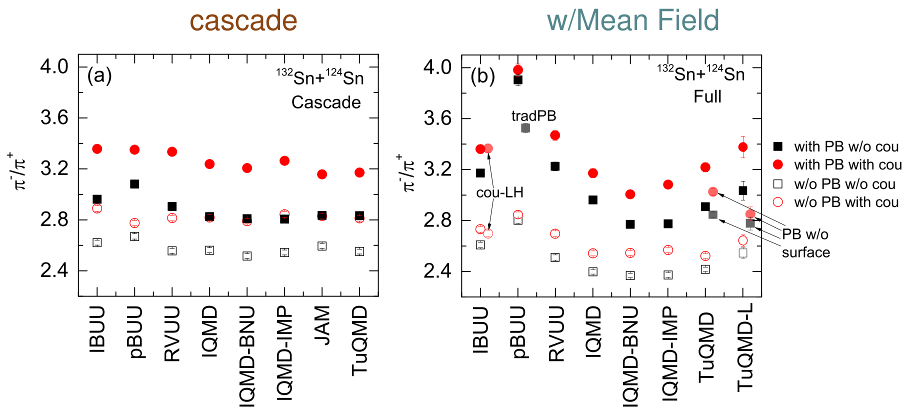
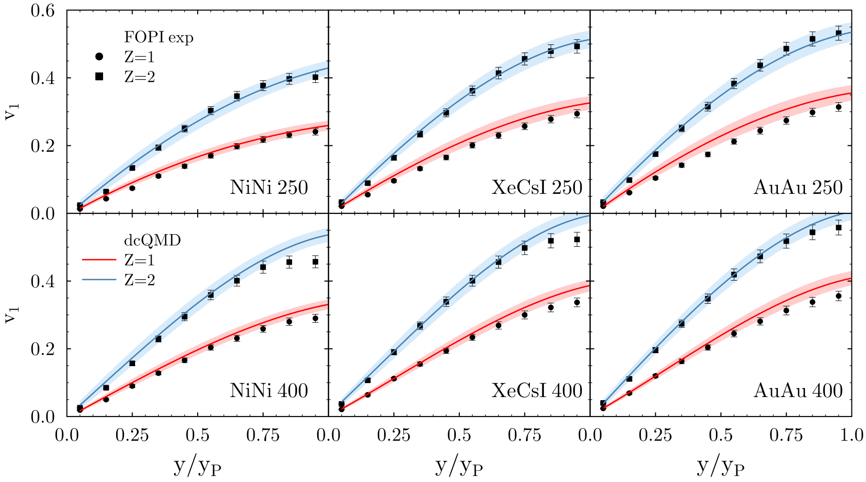
Charged Pion Ratio in Sn + Sn at 270 MeV/nucl



Good agreement w/o mean field, but not so good with, due to differences in nucleon evolution

Comprehensive Data Analysis Needed



Analysis of stopping and flow in FOPI measurements

$v_n = \langle \cos n\phi \rangle$

Cozma arXiv:2407.16411

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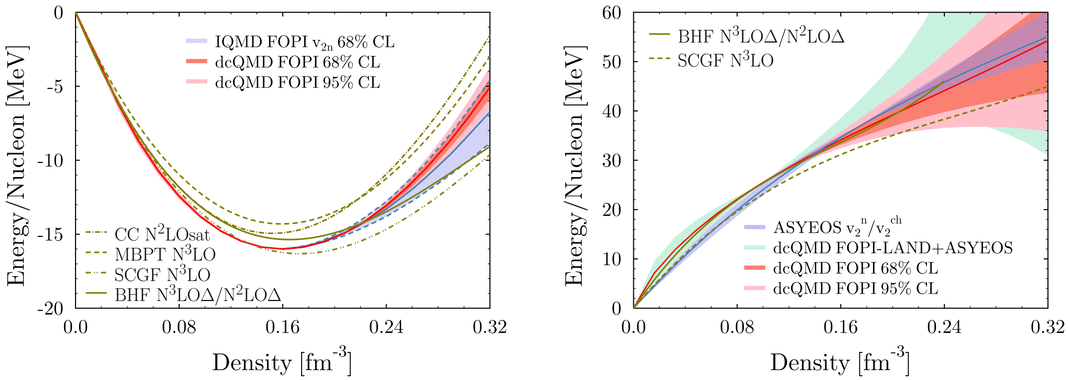
Comprehensive Data Analysis Needed



Many parameters & assumptions & very narrow constraints!

Cozma arXiv:2407.16411

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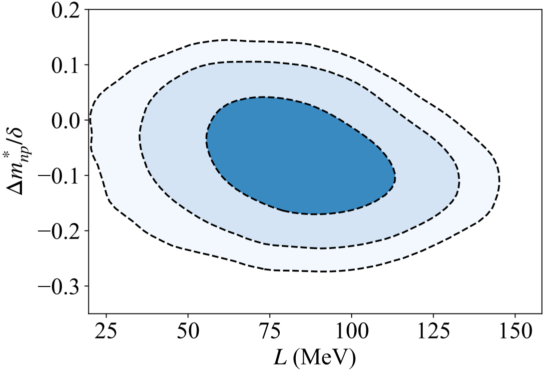
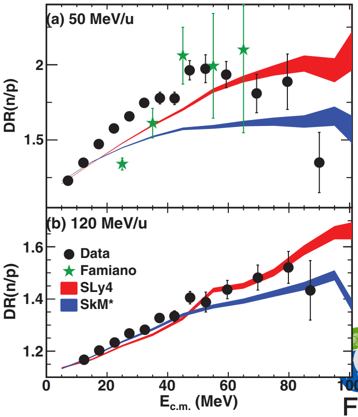
Other Important Asymmetry-Dependent Unknowns

E.g. effective mass splitting $\Delta m^*_{np}/(m\,\delta)$, where $\Delta m^*_{np} = m^*_n - m^*_p$ & $\delta = (\rho_n - \rho_p)/\rho$

Transport analyses of Sn+Sn collision-data yield negative splitting





(Tommy) Tsang *et al* PLB853(24)138661

Coupland *et al* PRC94(16)011601

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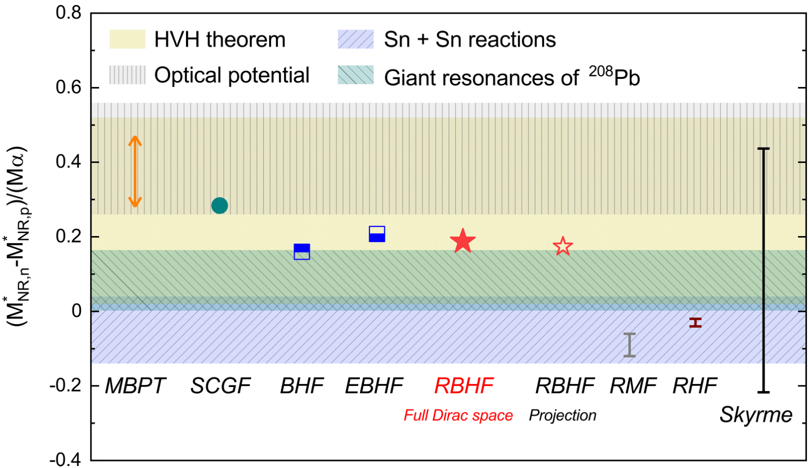
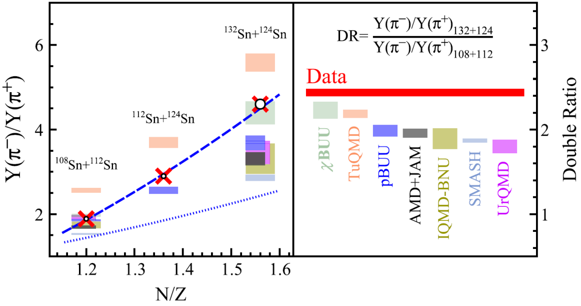
Other Inferences Point to Positive Splitting



Wang *et al* PRC108(23)L031303

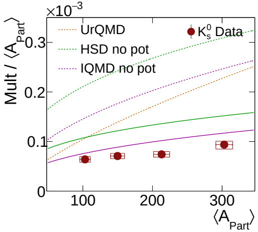
Transport Struggles w/Subthreshold Processes

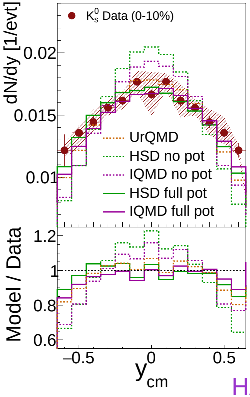
Jhang *et al* PLB813(21)136016



Pions in 270MeV/nucl Sn+Sn

Without novel assumptions, models miss the data





HADES

PLB793(19)457

K_s^0 mesons in 1.2GeV/nucl Au+Au

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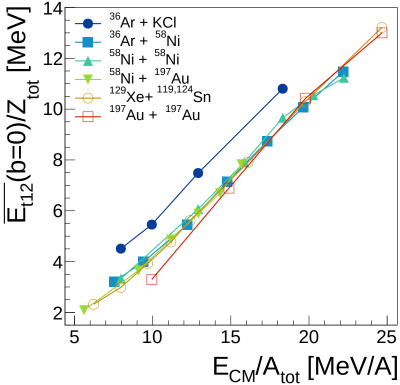
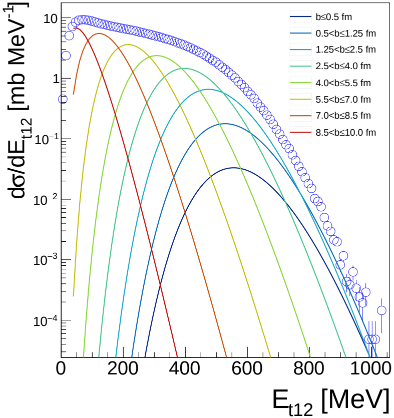
High-Statistics Opportunities in Data: Impact Parameter

Towards more discerning information by suppressing impact-parameter averaging

Frankland *et al* PLB793(19)457

$$\mathcal{O}(b_{est}) = \int \mathcal{O}(b_{tru})\, P(b_{est}|b_{tru})\, db_{tru}$$





Also, better *b*-estimation from machine learning
Li *et al* PRC104(21)034608

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Reaction-Plane Orientation

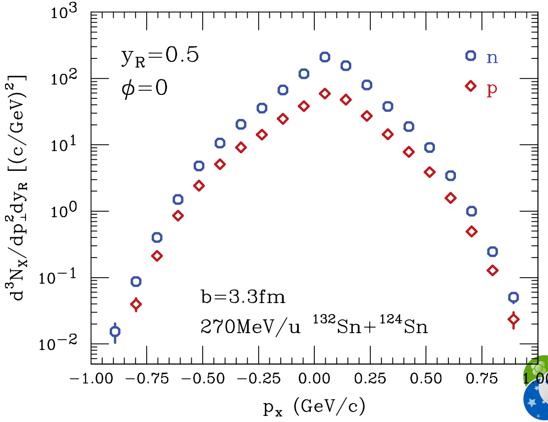
Single-particle distributions relative to fixed direction of reaction plane

PD&Kurata-Nishimura PRC105(22)034608

$$dN(\phi_{est}) = \int dN(\phi_{tru})\, P(\phi_{est}|\phi_{tru})\, d\phi_{tru}$$

Bayesian deconvolution to yield distributions relative to true reaction plane

Figure from transport theory; data processed



Conclusions

- Symmetry energy relatively small in high-ρ limit of asymptotic freedom
- For complicated energy functionals, symmetry energy may depend on definition
- At $\rho > \rho_0$, only data for EOS of symmetric matter from heavy-ion collisions
- Speed of sound maximizes between low and high ρ
- Different data constrain $S(\rho)$ @ different ρ
- Reducing transport-model uncertainties critical f/narrowing EOS constraints
- High-statistics of data can facilitate extraction of new observables

DOE DE-SC0019209

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