Probing the Equation of State Through Heavy-Ion Collisions and Simulations

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Workshop on Dense Nuclear Matter Equation of State from Heavy-Ion Collisions

Institute for Nuclear Theory

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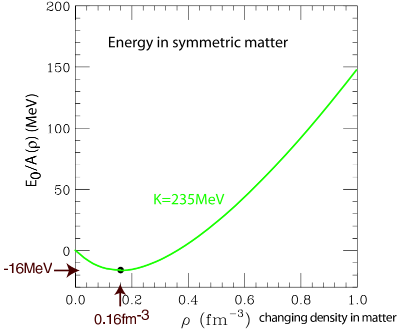
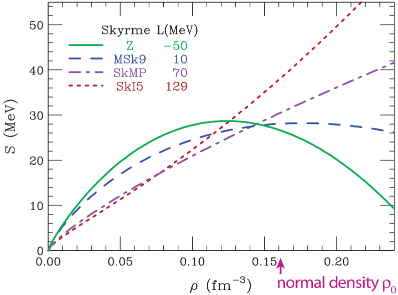
Cold EOS Breakdown

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

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





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

$$S(\rho) = S_0 + \frac{L}{3}\frac{\rho-\rho_0}{\rho_0} + \ldots$$

Known: $B \approx 16\,\text{MeV}$ $K \sim 235\,\text{MeV}$

Unknown: S_0 ? L ?

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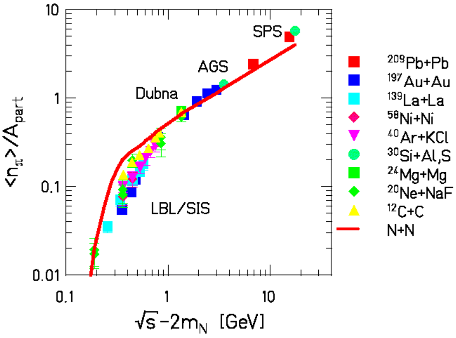
Heavy-Ion Collisions

- Equilibrium reached only late in collisions, so transport theory is needed to simulate the collisions and extrapolate to equilibrium
- Collision energy changes densities reached, but also excitation above zero temperature and degrees of freedom



Senger, ProgPartNuclPhy 53(04)1

Transport Theory

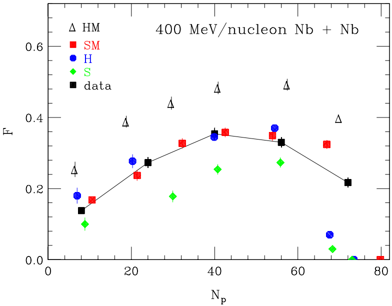
Phase-space characteristics of hadronic degrees of freedom followed in semiclassical transport theory

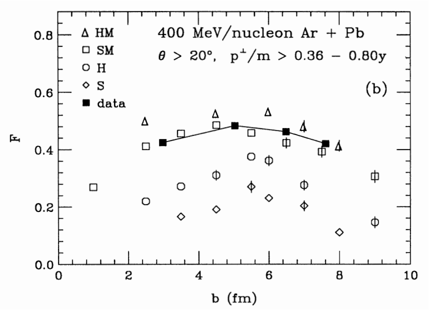
Besides EOS uncertainties include:

- Dependence of mean fields on density, momentum and nonequilibrium features of phase-space distributions
- In-medium interaction rates
- Space-time nonlocalities in collisions $\rightarrow$ impact on entropy
- Off-shell effects
- Optimal observables for testing individual uncertainties

Example: Mean-Field ρ vs p Dependence

Impact of centrality and momentum bracket on flow may be used to resolve these dependencies:





Qiubao Pan & PD PRL70(93)2063

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EOS and Flow Anisotropies

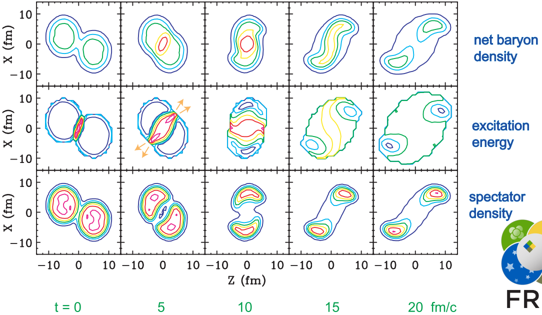
EOS assessed through reaction plane anisotropies characterizing particle collective motion.

Hydro? Euler eq. in $\vec{v} = 0$ frame: $m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p$

where p - pressure. From features of v, knowing Δt, we may learn about p in relation to ρ. Δt fixed by spectator motion.

For high p, expansion rapid and much affected by spectators.

For low p, expansion sluggish and completes after spectators gone.



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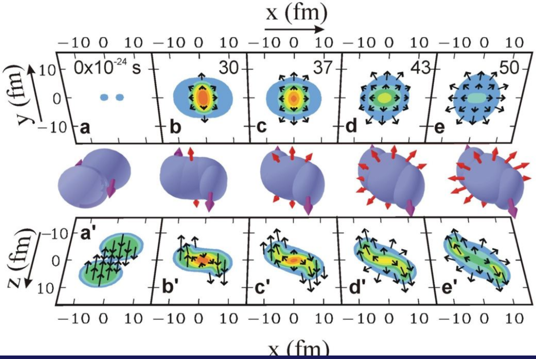


Sideward Flow Systematics

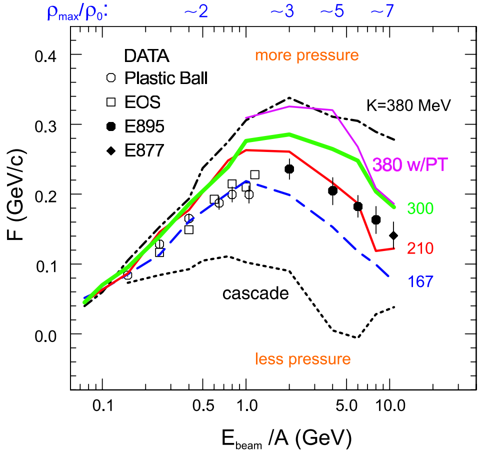
Deflection of forwards and backwards moving particles away from the beam axis, within the reaction plane

Au + Au Flow Excitation Function

Note: *K* used as a label

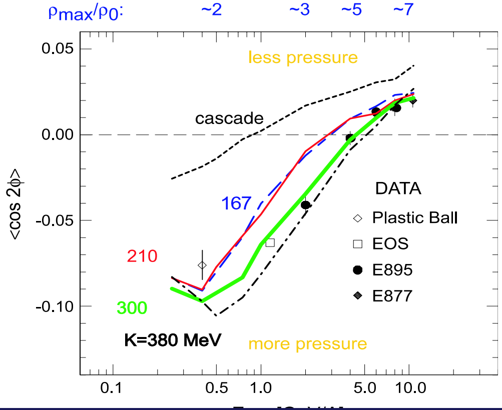
PD, Lacey & Lynch Science298(02)1592

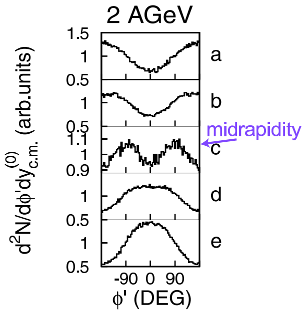
The sideward-flow observable results from dynamics that spans a density range varying with the incident energy



2^{nd}-Order or Elliptic Flow

Another anisotropy, studied at midrapidity: $v_2 = \langle \cos 2\phi \rangle$, where ϕ is azimuthal angle relative to reaction plane.

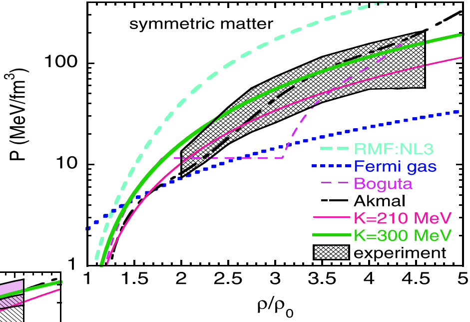


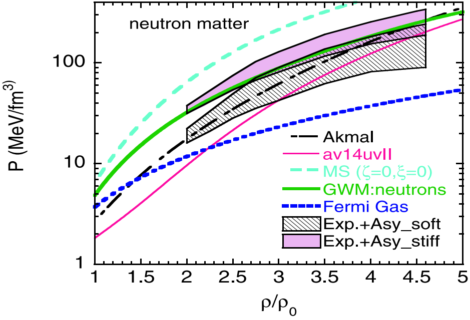


Au+Au v_2 Excitation Function

Constraints on EOS

Au+Au flow anisotropies:
$\rho \simeq (2 - 4.6)\rho_0$.
No one EOS yields both flows right. Discrepancies: inaccuracy of theory.
Most extreme models for EOS can be eliminated.





PD, Lacey & Lynch
Science298(02)1592

Neutron Matter:

Uncertainty in symmetry energy

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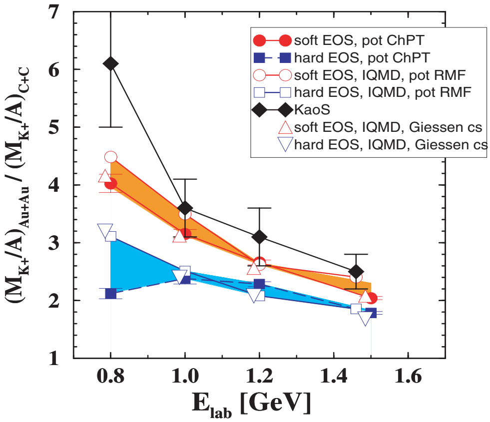
Subthreshold Kaon Production



Ratio of kaons per participant nucleon in Au+Au collisions to kaons in C+C collisions vs beam energy

filled diamonds: KaoS data

open symbols: theory

Fuchs *et al.*
ProgPartNuclPhy 53(04)113

Kaon yield sensitive to EOS because multiple interactions needed for production, testing density

The data suggest a relatively soft EOS

In-medium threshold effects?? (Dan Cozma)

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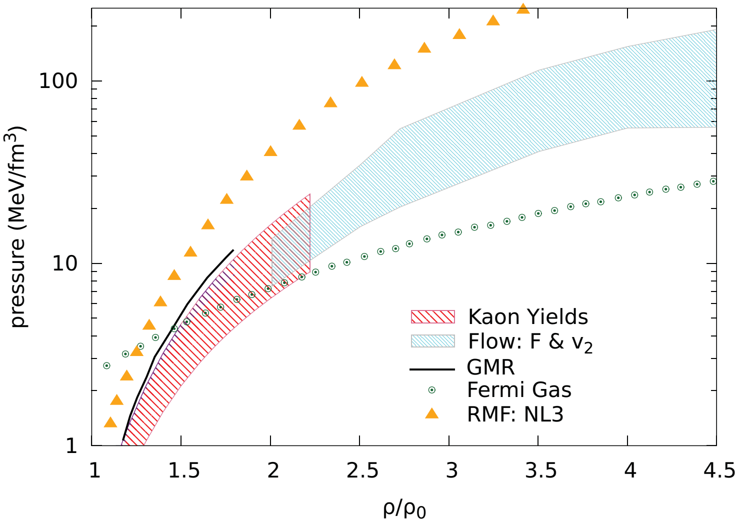
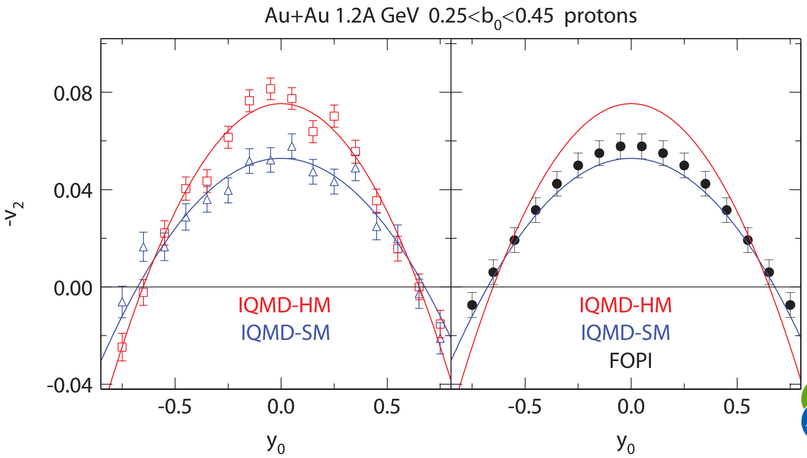
Combination/Consistency of the Constraints?



Flow Probing Vicinity of ρ_0

Le Fevre *et al.*NPA945(16)112

Elliptic flow in Au + Au between 0.4 and 1.5 GeV/u



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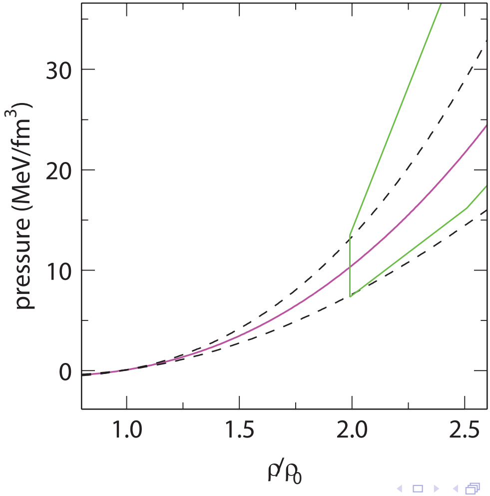
Flow Testing Vicinity of ρ_0

Le Fevre *et al.*NPA945(16)112

Comparison to higher-ρ inference



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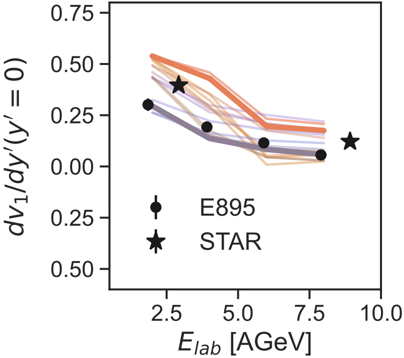
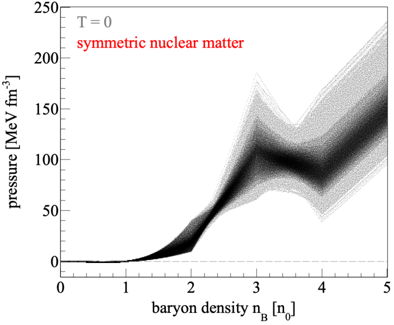
Flow in SMASH

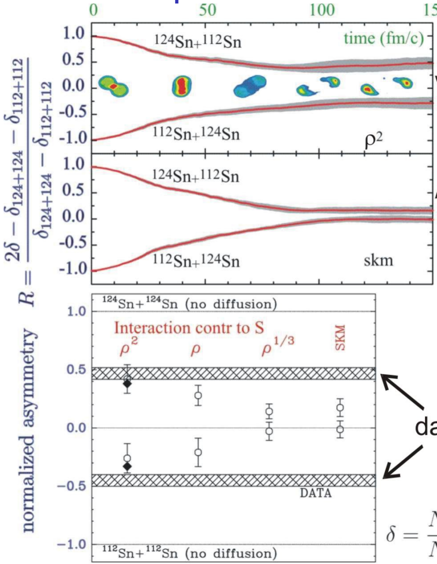
Oliinychenko, Sorensen *et al.* arXiv:2208.11996

Changing speed of sound in density intervals and comparing to flow data





Isospin Diffusion: Low-ρ Symmetry Energy



weak S
at low ρ

complete
equilibration

strong S
at low ρ

data

$$\delta = \frac{N-Z}{N+Z}$$

Linear theory:

$$\vec{j}_{np} \simeq -4\nu \vec{\nabla} \, [S \, \delta]$$

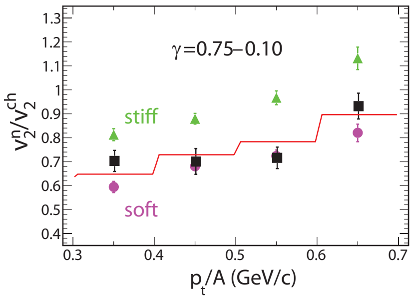
Tsang *et al.*
PRL92(04)062701

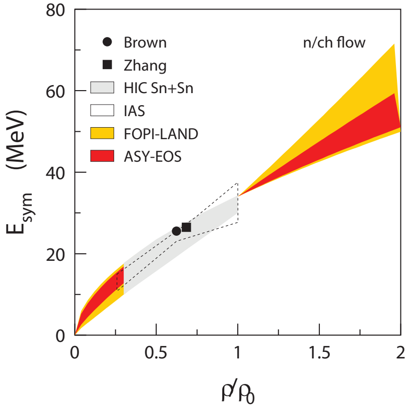
Shi&PD
PRC68(03)064604

Supranormal Densities: Baryon Differential Flow

Russotto *et al.* PRC94(16)034608

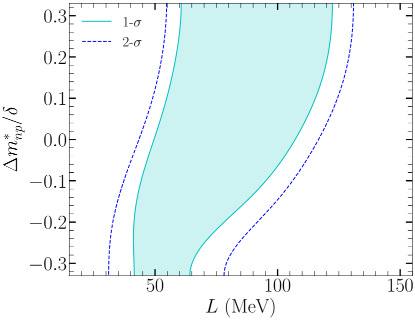
Au + Au @ 400MeV/u, neutron measurements with LAND

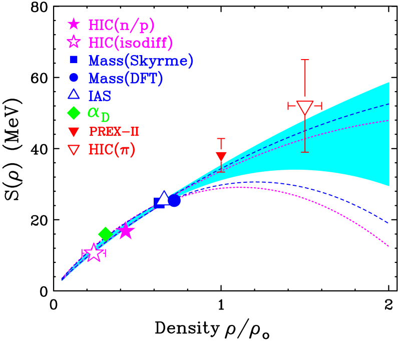




Constraints from Charged Pion Yields

Bao-An Li PRL88(02)192701





Reisdorf *et al.* NPA781(07)459; Estee *et al.* PRL126(21)162701
Liu *et al.* PRC103(21)014616; Lynch&Tsang PLB830(22)137098

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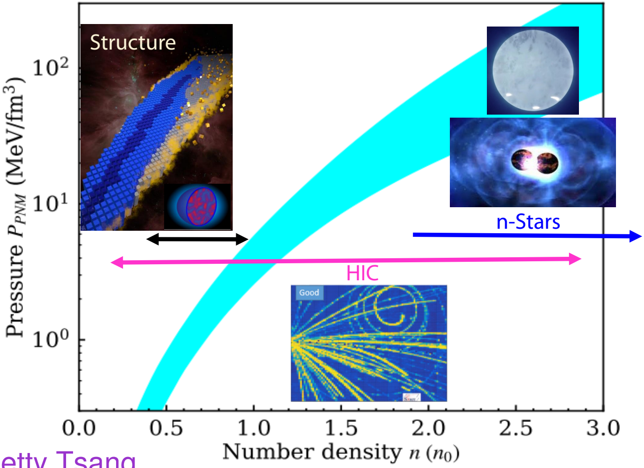
Combined Inferences: HIC + Structure + Astrophysics

Different probed densities



From Betty Tsang

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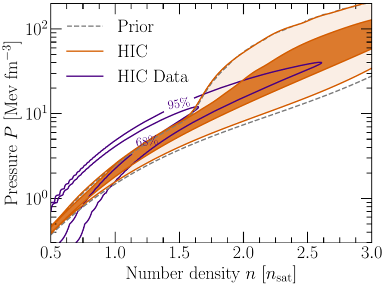
Analysis by Huth et al.

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

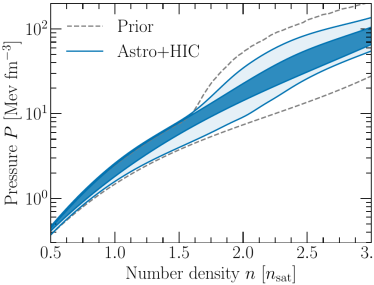
Constraining neutron-star matter with microscopic and macroscopic collisions

Bayesian combinations

HIC experiments:



HIC and Astro combined:



Astrophysical observations narrow constraints above $2\rho_0$

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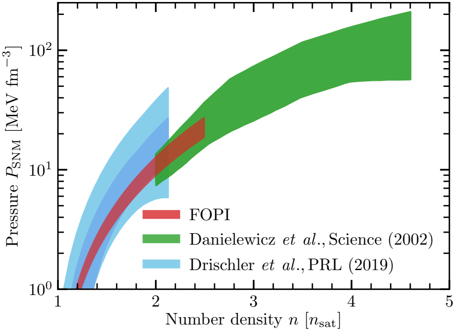
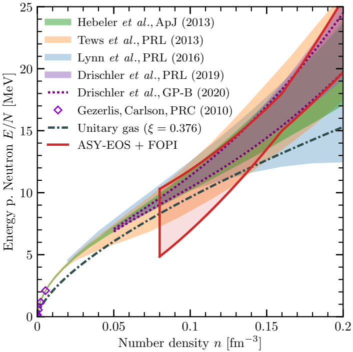
Huth et al: Theory vs Heavy Ions

Symmetric Matter



Neutron Matter



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Conclusions

- Heavy-ion collisions allow to dial densities for studying EOS, by changing beam energy
- Window in the energy that addresses the densities around $2\rho_0$, where the collisions are particularly called for, is actually easier from the standpoint of transport than either significantly lower or significantly higher energies
- FRIB400 should deliver a wider range of exotic projectiles, at intensities needed for heavy-ion experiments focussed on EOS, than any other accelerator in the world in the foreseeable future
- More refined observables are needed for more stringent EOS constraints

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