Probing Equation of State of Dense Baryonic-Matter w/Heavy-Ion Collisions & Transport Simulations

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XVI Workshop on Particle Correlations and Femtoscopy
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Physics Shopping List for Intermediate-Energy HI Collisions

- Bulk isovector properties of nuclear matter up to $2\rho_0$
  - symmetry energy
  - isovector component of proton and neutron mean fields w/*p*-dependence or isovector m^*
  - isospin conductance/diffusion
  - uncertainty quantification in conclusions

- Improved constraints on isoscalar properties of nuclear matter and connection to neutron stars
  - pressure as a function of density up to five times the normal density
  - role of momentum dependence of isoscalar mean fields and in-medium cross sections
  - new observables such as triple-differential momentum distributions

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Physics Shopping List for HI Collisions Cont.

- Refined understanding of bulk properties
  - pressure and energy at finite temperature and connection to neutron-star mergers
  - connection to effective field theory
  - role of off-shellness in in-medium subthreshold production of mesons
  - role of fluctuations and correlations in central-reaction dynamics

- Advances in transport theory
  - implementation of aspects of chiral effective theory
  - structure effects in initial conditions
  - mechanisms of cluster production
  - off-shell transport
  - fully quantal transport applicable down to Coulomb barrier

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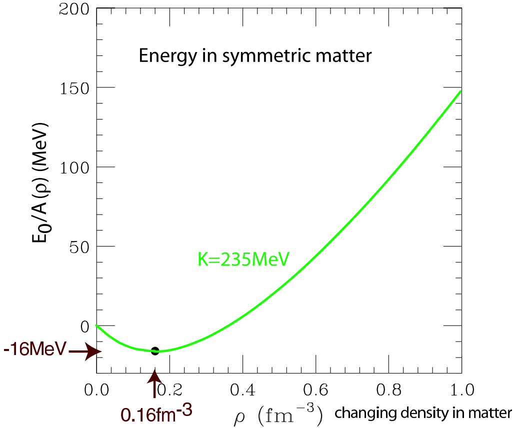
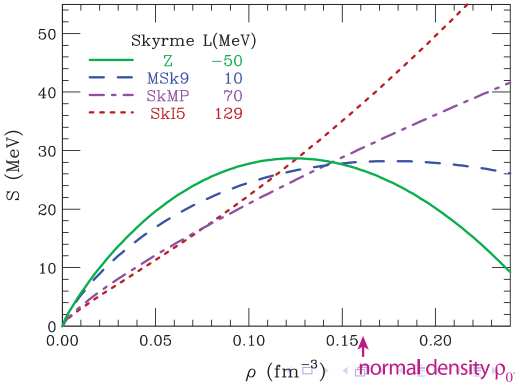
Cold EOS Breakdown

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

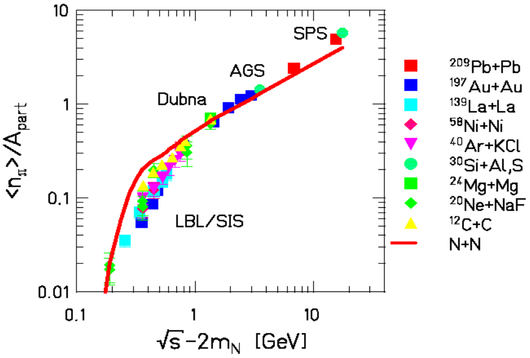
symmetric matter (a)symmetry energy $\rho = \rho_n + \rho_p$





Intermediate-Energy Heavy-Ion Collisions

- Measurements very inclusive
- Equilibrium reached only late in collisions, so transport theory needed to simulate collisions and extrapolate to equilibrium
- Collision energy changes densities reached, but also excitation above zero temperature & degrees of freedom
- Parallel data analyses carried over time



Senger ProgPartNuclPhy 53(04)1

Transport Theory

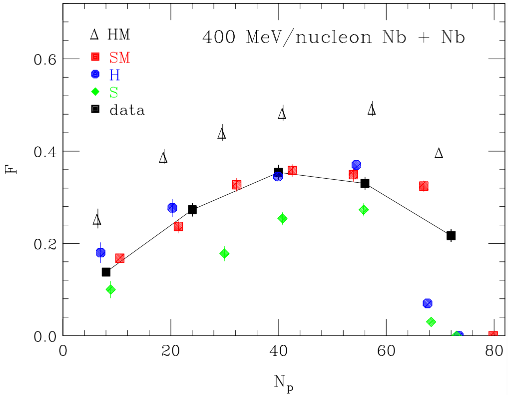
Phase-space characteristics of hadronic degrees of freedom followed in semiclassical transport theory

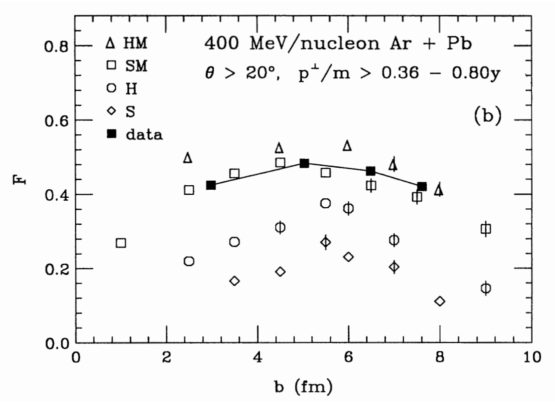
Besides EOS uncertainties include:

- 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

EOS and Flow Anisotropies

EOS assessed through reaction plane anisotropies characterizing particle collective motion

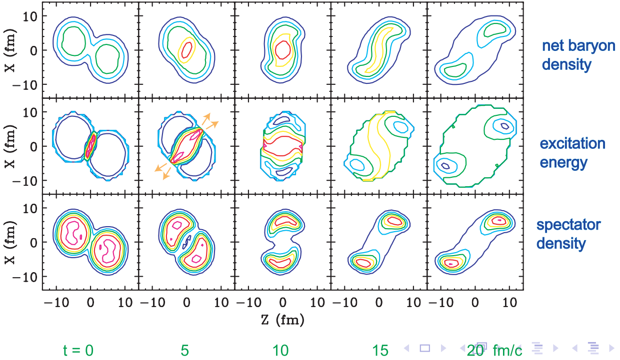
Hydro? Euler eq. in $\vec{v} = 0$ frame: $m_N \, \rho \, \frac{\partial}{\partial t} \, \vec{v} = -\vec{\nabla} p$

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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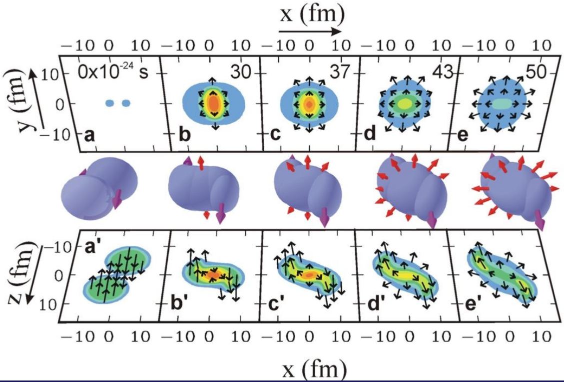


Sideward Flow Systematics

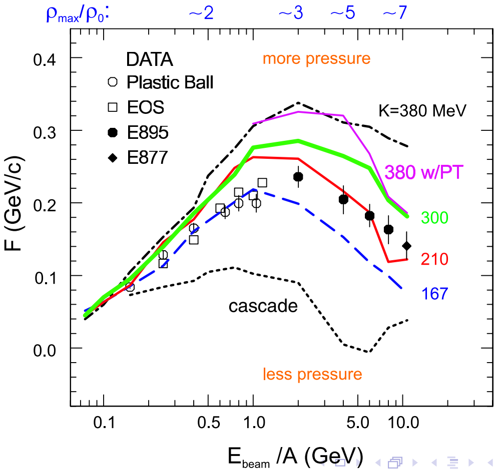
Deflection of forwards and backwards moving particles away from the beam axis, within the reaction plane

Au + Au Flow Excitation Function

Note: *K* used as a label

PD, Lacey & Lynch
Science298(02)1592

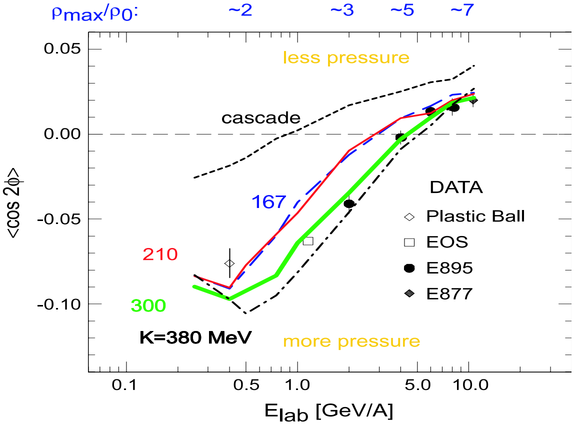
The sideward-flow observable results from dynamics that spans a density range varying with the incident energy

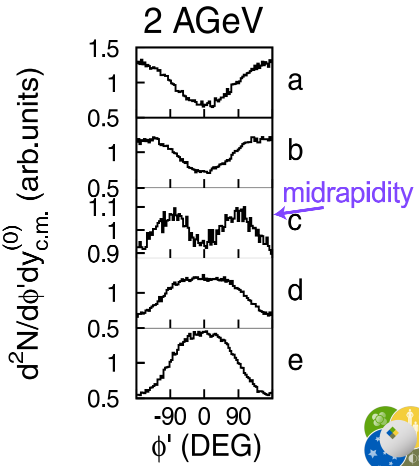


2^{nd}-Order or Elliptic Flow

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

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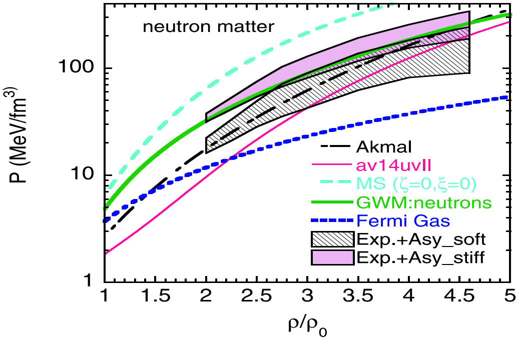
Constraints on EOS

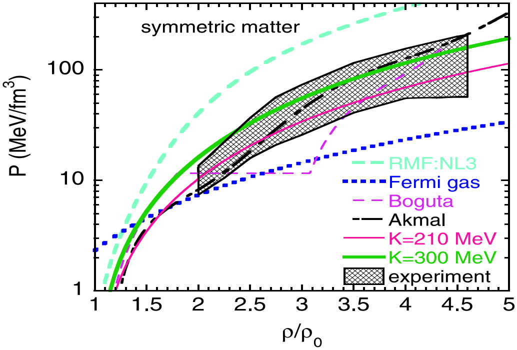
Au+Au flow anisotropies: $\rho \simeq (2-4.6)\rho_0$

No single 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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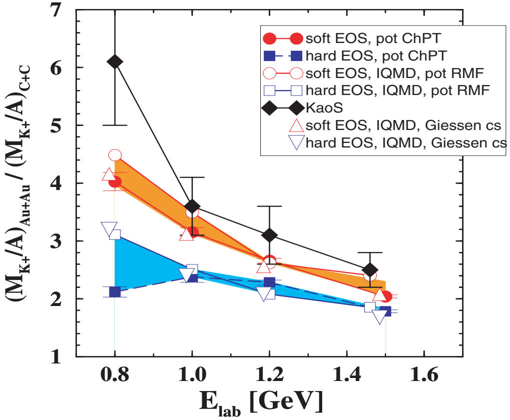
Subthreshold Kaon Production



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

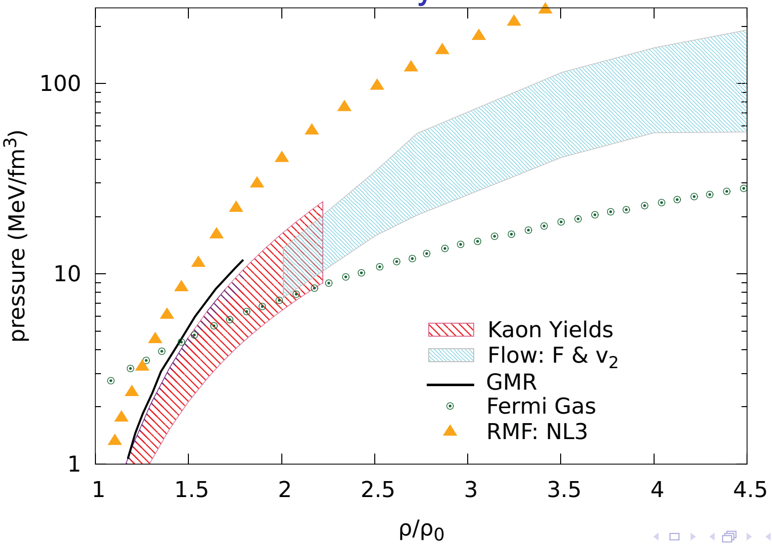
Fuchs *et al.* ProgPartNuclPhy 53(04)113

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

The data suggest a relatively soft EOS

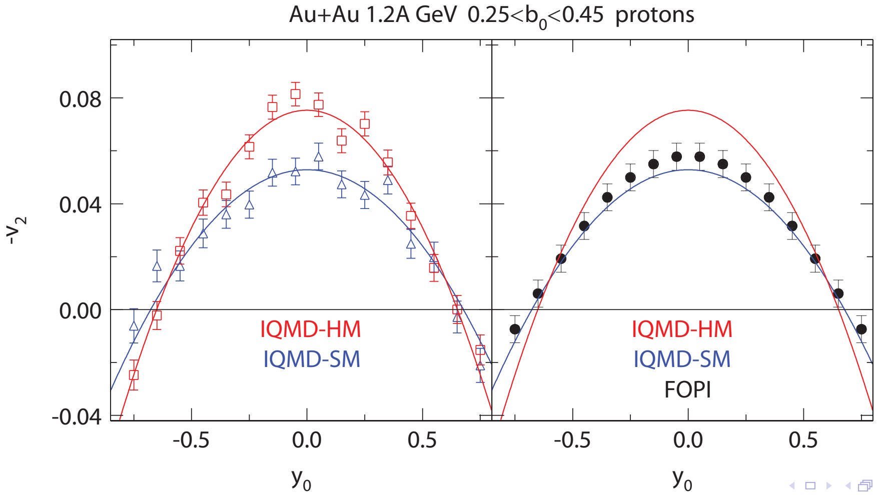
In-medium threshold effects?? (Dan Cozma)

Combination/Consistency of the Constraints?



Flow Probing Vicinity of ρ_0

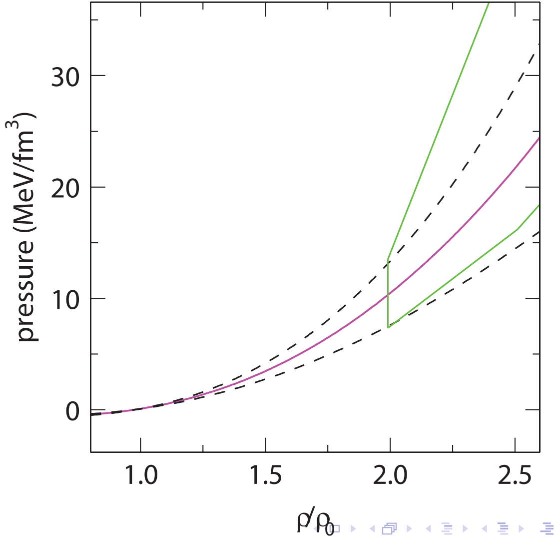
Le Fevre *et al.* NPA945(16)112 Elliptic flow in Au + Au between 0.4 and 1.5 GeV/u



Flow Testing Vicinity of ρ_0

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

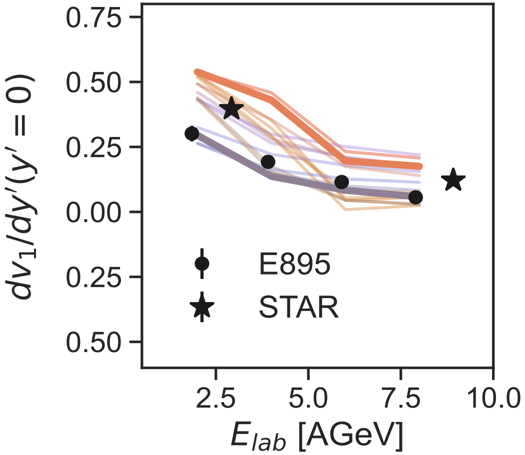
Comparison to higher-ρ inference

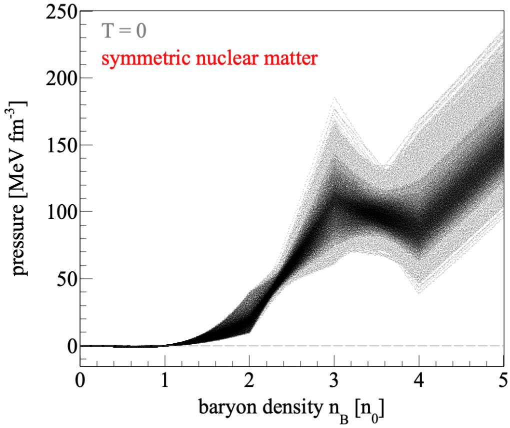


Flow in SMASH

Oliinychenko, Sorensen *et al.* arXiv:2208.11996, PRC in press

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





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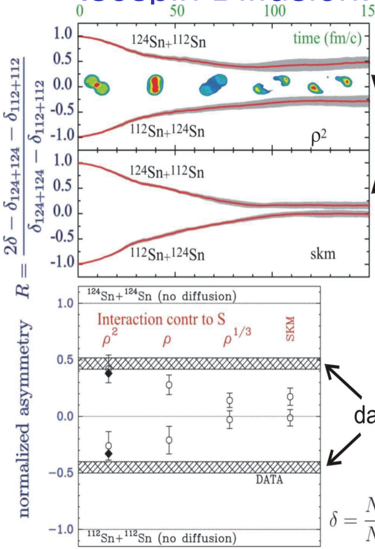
Isospin Diffusion: Low-ρ Symmetry Energy



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

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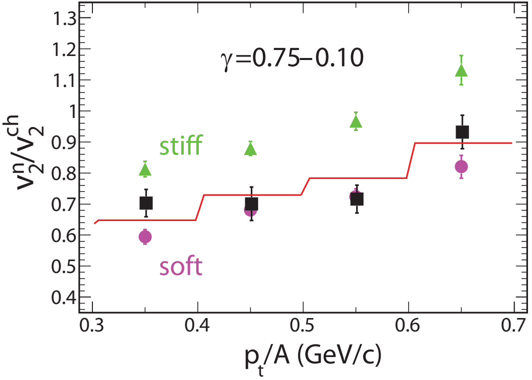
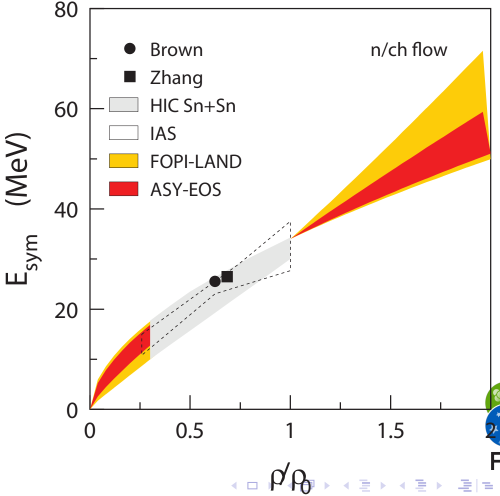
Supranormal Densities: Baryon Differential Flow

Russotto *et al.* PRC94(16)034608 Au+Au @ 400MeV/u, neutron measurements w/LAND





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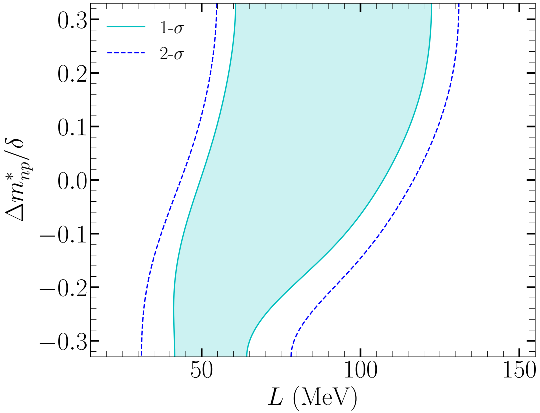
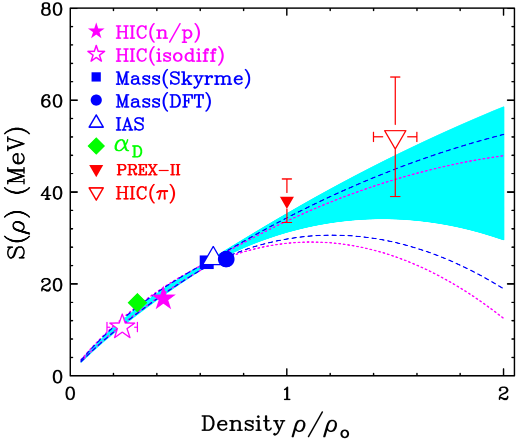
Constraints from Charged Pion Yields

proposition: Bao-An Li PRL88(02)192701





results: 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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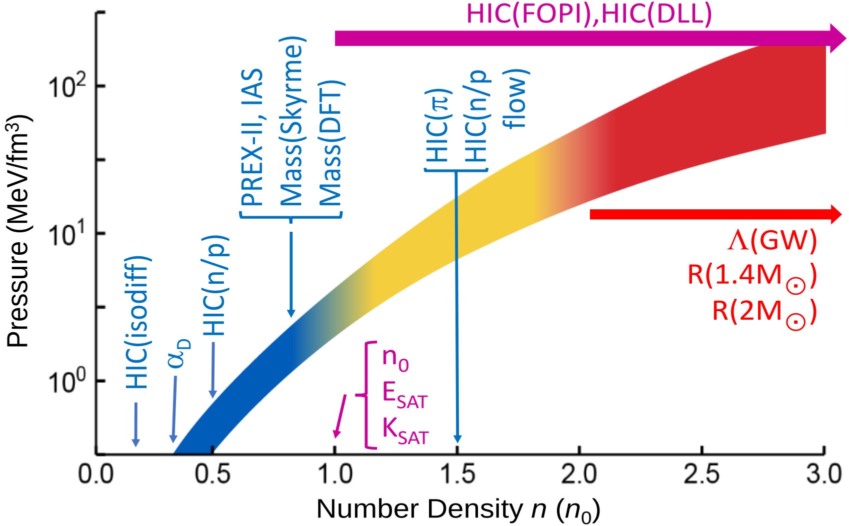
Combined Inferences: HIC + Structure + Astrophysics

Different probed densities



From Betty Tsang Nature Astronomy, in print

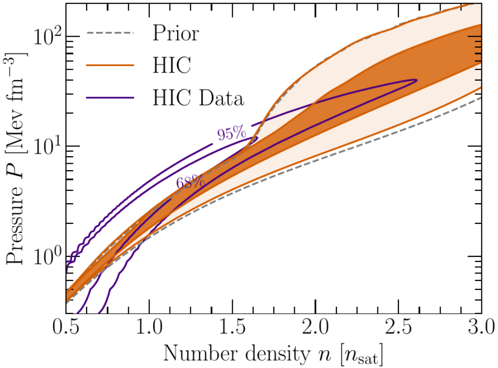
Analysis by Huth et al.

Constraining neutron-star matter with microscopic and macroscopic collisions

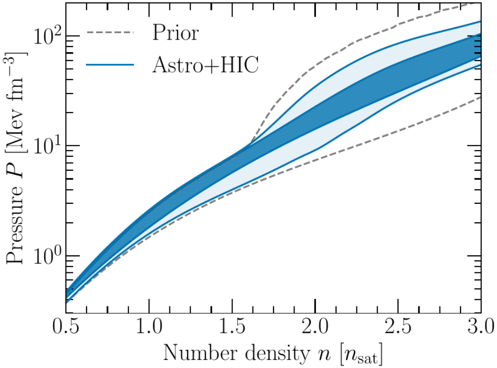
Bayesian combinations

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

HIC experiments:



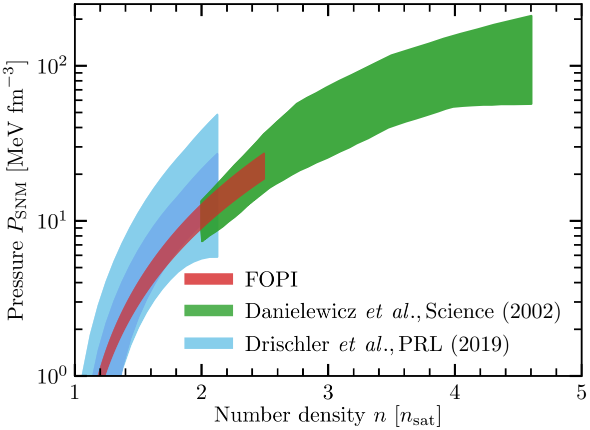
HIC and Astro combined:



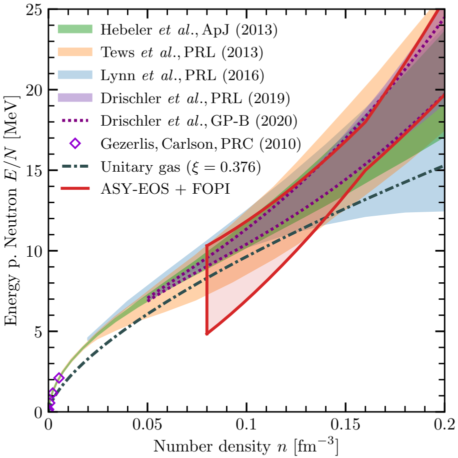
Astrophysical observations narrow constraints above $2\rho_0$

Huth et al: Theory vs Heavy Ions

Symmetric Matter



Neutron Matter



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
- FRIB 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
  (PD 3D: need beam separation from products)

Supported by US Department of Energy under Grant US DE-SC0019209

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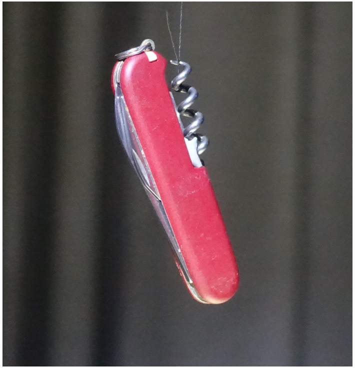
Paradigm: Triple-Differential Yields from Data

Distributions for *Fixed Direction of Reaction Plane* from Theory and Experiment

no control over plane

some control, v_n



full control, $\frac{d^3N}{dp^3}$

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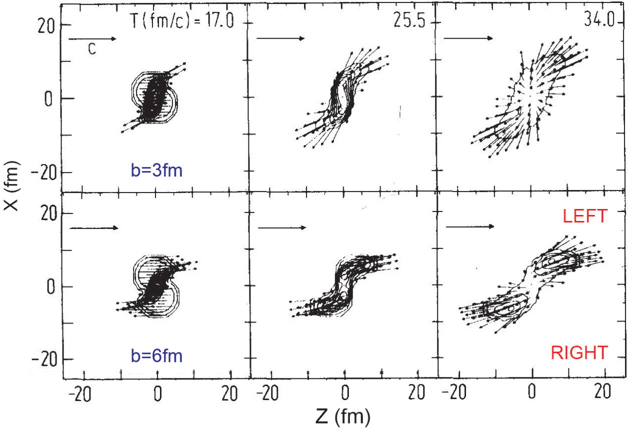
Claim: You can go from center to right panel through deblurring

Side Splash in Hydrodynamic Calculations

Matter dispersed in the final stage, but most likely direction of motion away from the beam, e.g., in the calculations by Buchwald for Nb + Nb at 400 MeV/nucl

Stöcker&Greiner Phys.Rep. 137(86)277



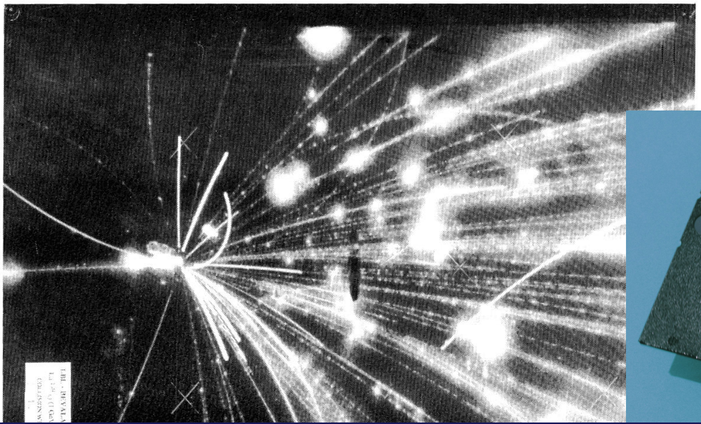
Can this be seen experimentally??

Ar + KCl @ 1.8 GeV/nucl

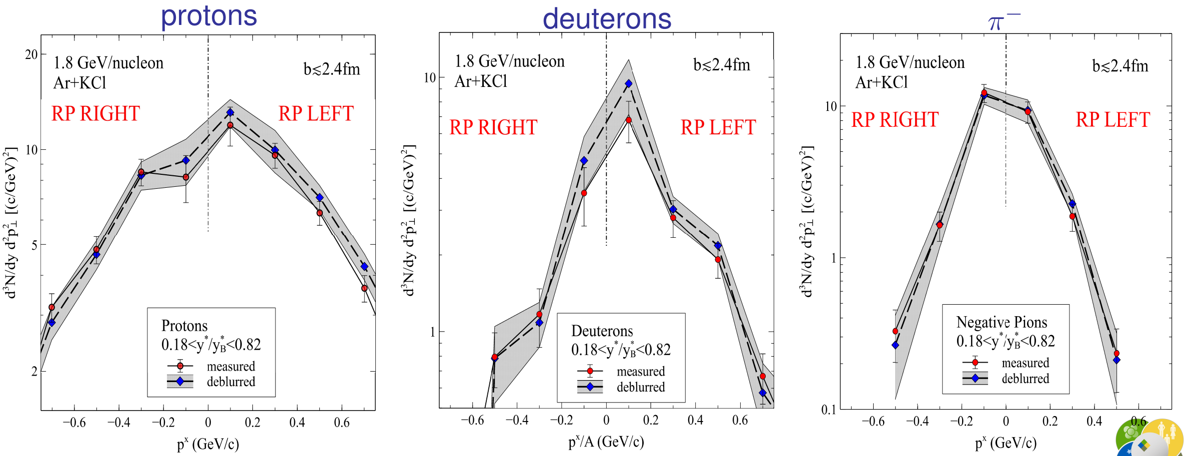
Ströbele PRC 27(83)1349

495 events from Streamer Chamber, $b \lesssim 2.4\,\mathrm{fm}$

PD&Odyniec PLB 157(85)146

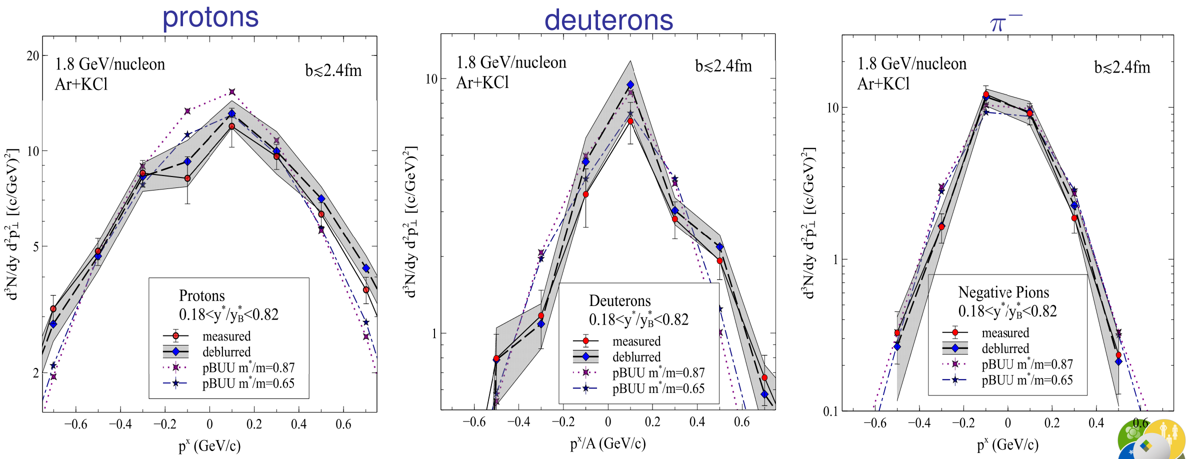


Side-Splash in Ar + KCl 1.8 GeV/nucl



Particles in the forward hemisphere, $y^* \sim 0.5 y_B^*$

Side-Splash: Experiment vs Theory



Calculations in pBUU: sensitivity to mean-field *p*-dependence in Ar+KCl