The Role of Femtoscopy in Constraining the Eq. of State of High-Baryon-Density Matter

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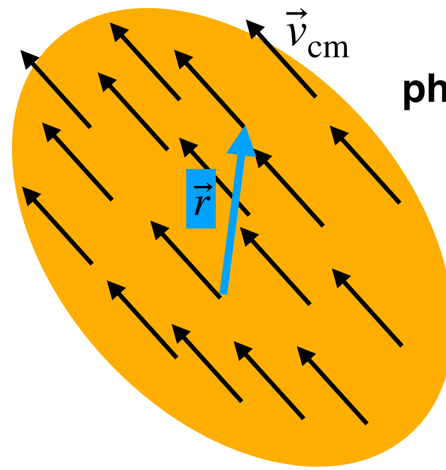
MICHIGAN STATE UNIVERSITY Founded 1855

U.S. DEPARTMENT OF ENERGY | Office of Science

FRIB

Femtoscopy Theory (one slide)



phase space cloud

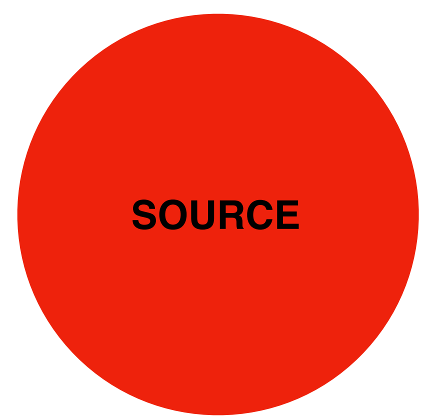
$$C(\vec{p}_1, \vec{p}_2) = \frac{P(\vec{p}_1, \vec{p}_2)}{P(\vec{p}_1)P(\vec{p}_2)}$$
$$= C(\vec{v}_{\rm cm}, \vec{q})$$
$$= \int d^3r \, S(\vec{v}_{\rm cm}, \vec{r}) \, |\phi_{\vec{q}}(\vec{r})|^2 ,$$

source function

wave function

$$S(\vec{v}_{\rm cm}, \vec{r}) = \frac{\int d^3r_1 d^3r_2 \; f_{\rm cm}(\vec{v}_{\rm cm}, \vec{r}_1, t) f_{\rm cm}(\vec{v}_{\rm cm}, \vec{r}_2, t) \delta(\vec{r}_1 - \vec{r}_2 - \vec{r})}{\int d^3r_1 d^3r_2 \; f_{\rm cm}(\vec{v}_{\rm cm}, \vec{r}_1, t) f_{\rm cm}(\vec{v}_{\rm cm}, \vec{r}_2, t)}$$

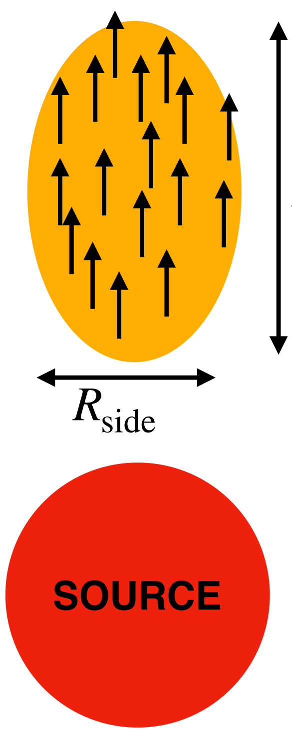
“SOURCE FUNCTION” measures phase space cloud, not source!!!



GOAL: Measure $C(\vec{p}_1, \vec{p}_2)$ **to infer** $S(\vec{v}_{\rm cm}, \vec{r})$
For identical bosons: $|\phi|^2 = 1 + \cos(2\vec{q} \cdot \vec{r})$
Strong/Coulomb makes inversion more complicated

Basic Idea

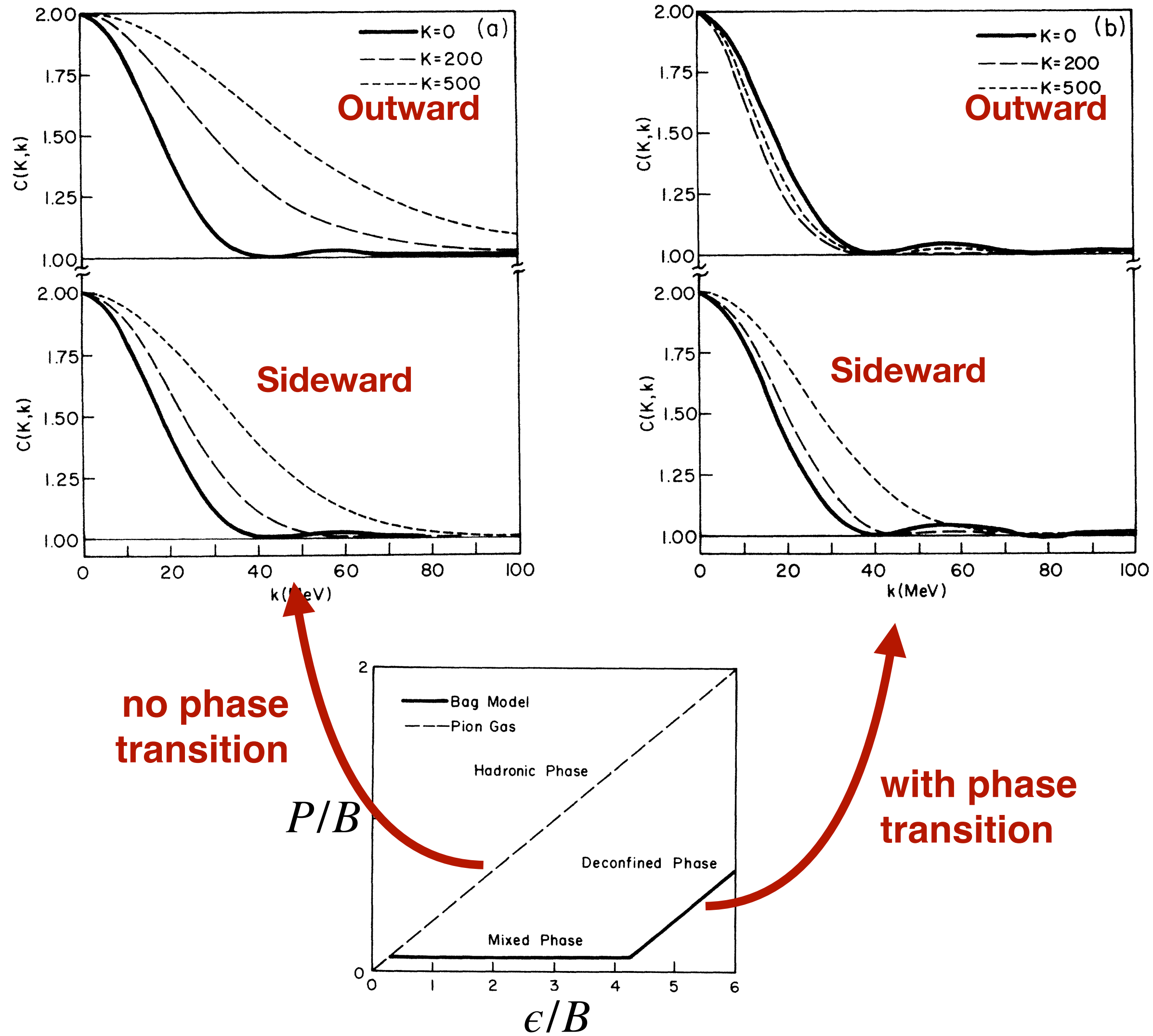
Softer EoS →Longer Lifetime
Longer Lifetime → $R_{\text{out}} > R_{\text{side}}$
& R_{beam} **increases**
Longer R_{out} **→ Narrow C.F.**



$$R_{\text{out}} \sim \sqrt{R_{\text{side}}^2 + v^2\tau^2}$$

S.P. Phys. Rev. D (1986)

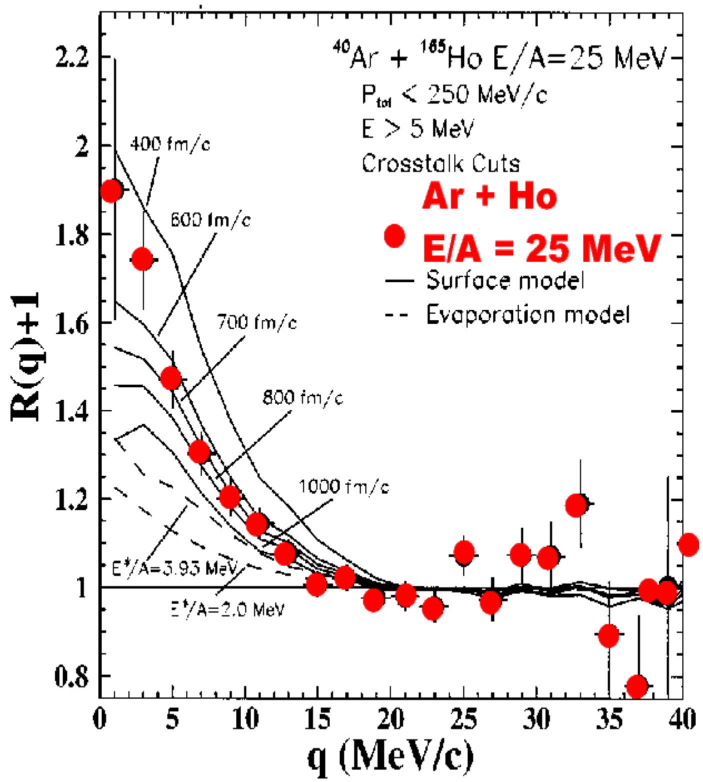
Two-Pion Correlation Function



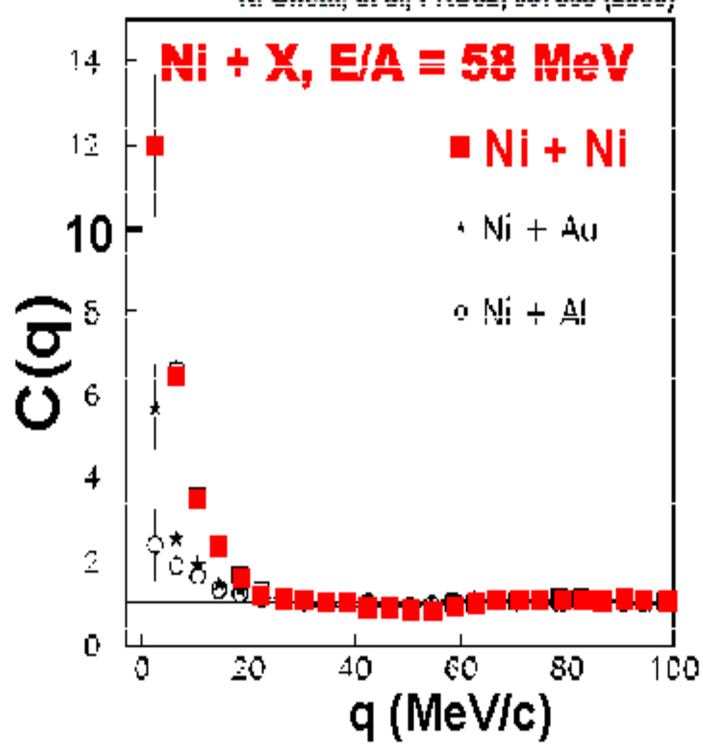
Phase Transition at Low Energy

neutron-neutron correlations at 25A MeV and 58A MeV

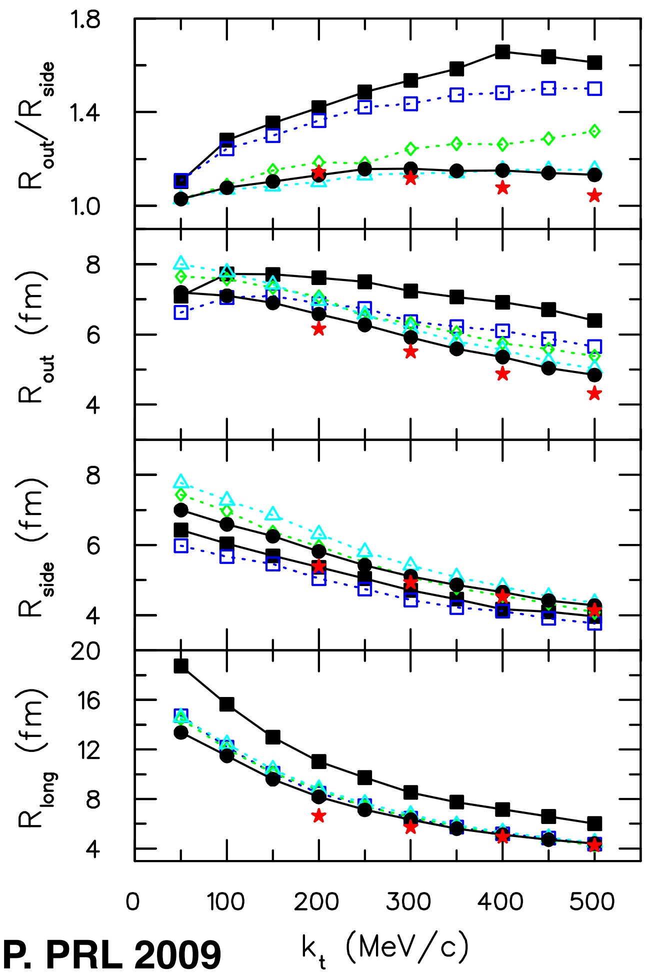
S.Gaff et al, PRC58, 2161 (98)



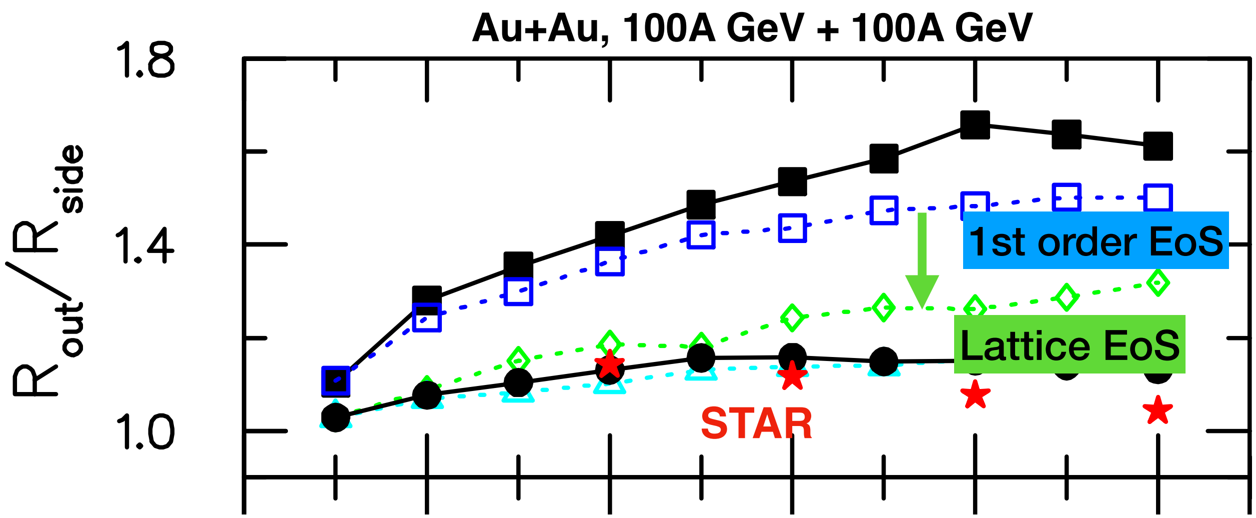
R. Ghetti, et al, PRC62, 037603 (2000)



Sensitivity to EoS (realistic calc.s)



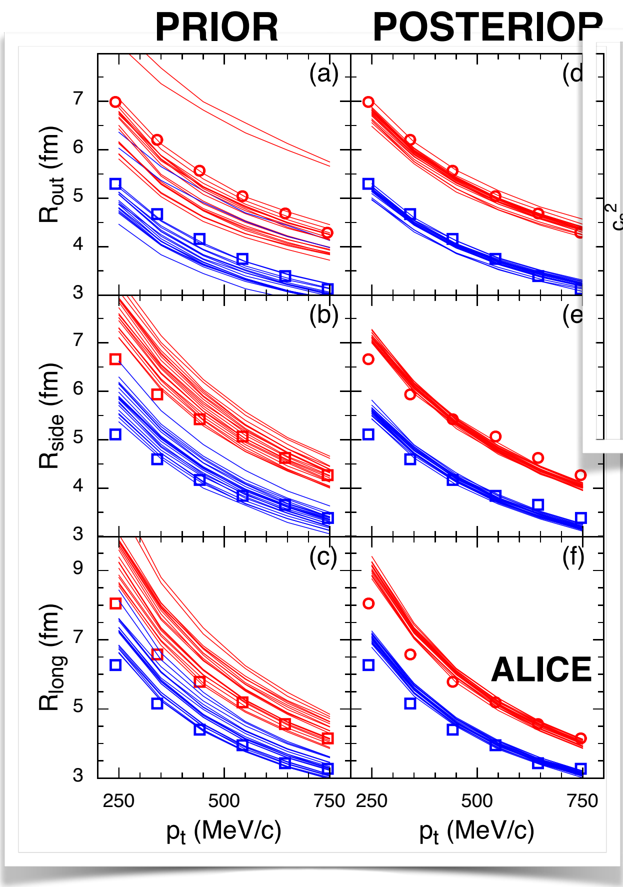
S.P. PRL 2009

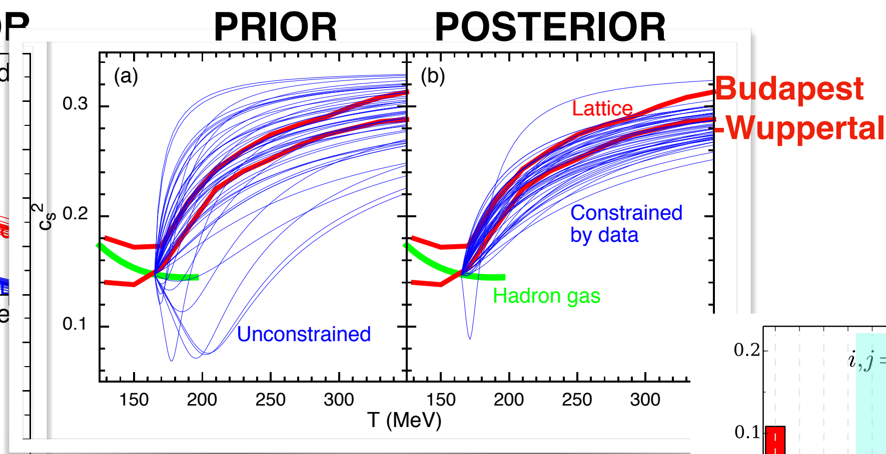


Model=hydro + cascade
Significant sensitivity to EoS

other corrections: initial flow, shear viscosity, better wave function

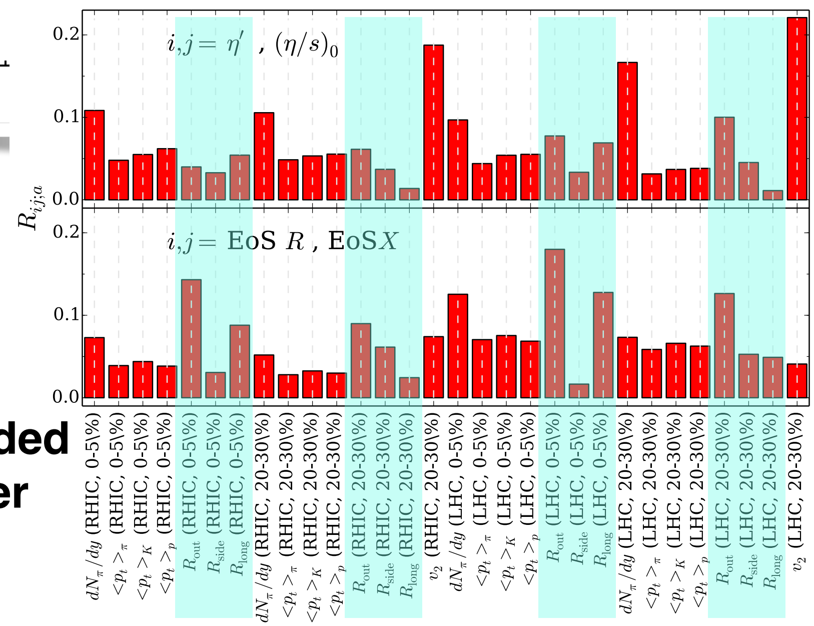
Role of Femtoscopy in Global Analysis





S.P, E.Sangaline,P.Sorensen
& H.Wang, PRL 2016

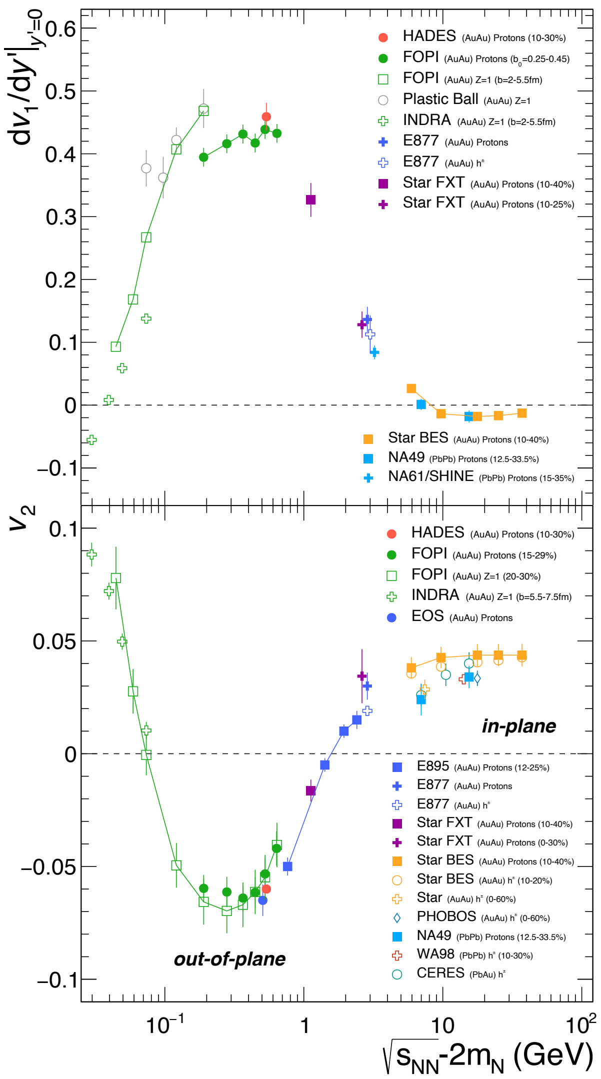
Resolving Power



Pionic femtoscopy provided most of resolving power of EoS

E.Sangaline & S.P, PRC 2016

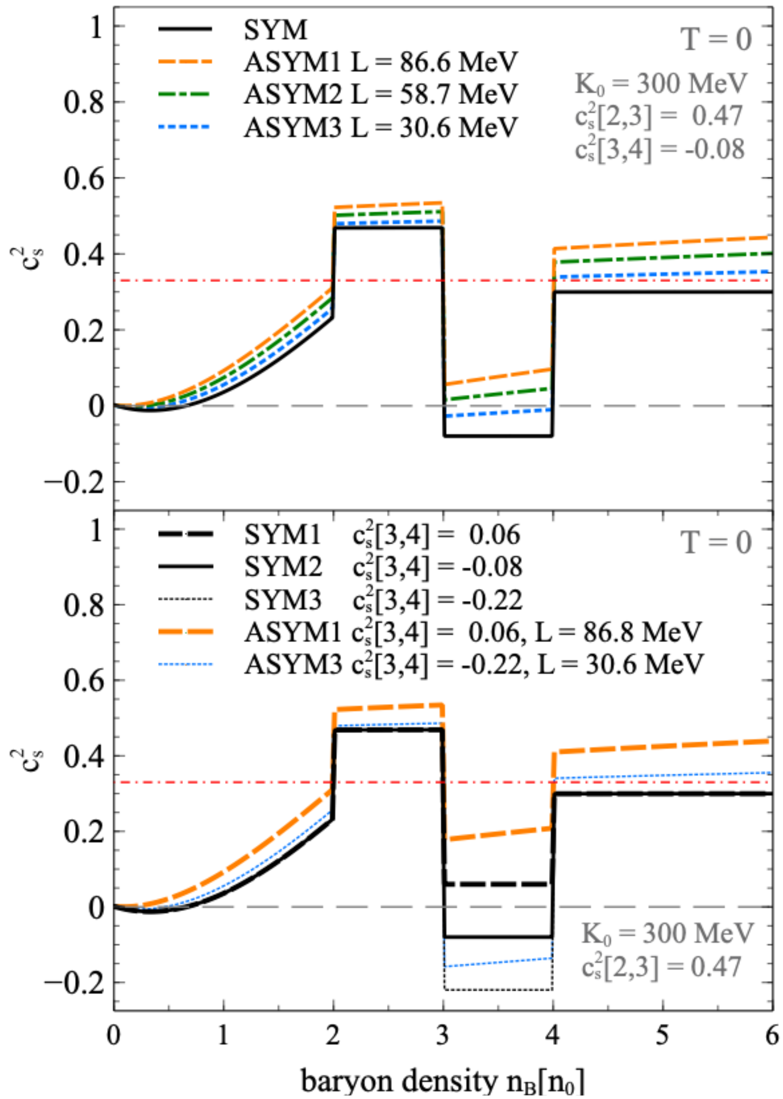
Evidence of EoS Stiffening & Softening from v_1, v_2



v_1 **rises and falls with beam energy**

A.Sorensen et al., nucl-th2301.13253

D.Oliinychenko,A.Sorensen,V.Koch,L.McLerran
nucl-th 2208.11996

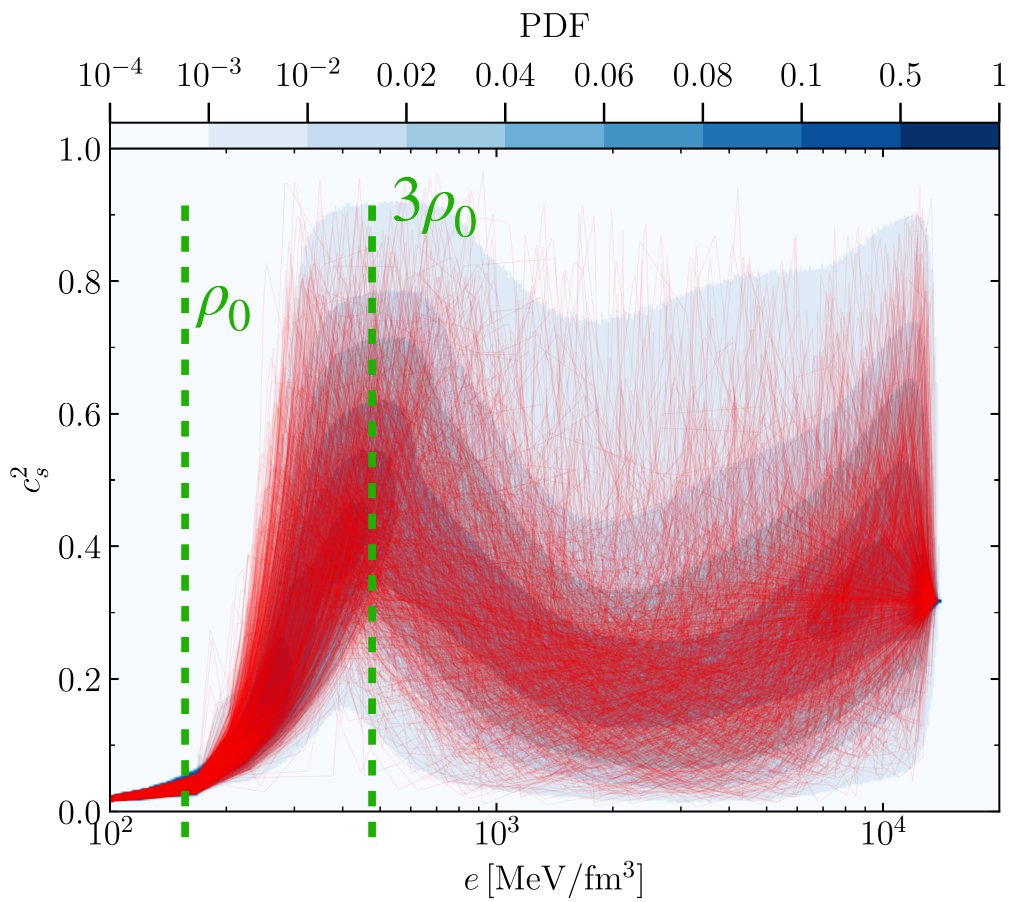


Bayesian Analysis of v_1, v_2

Calculations has some questions:

- **momentum dependence of potential**
- **role of string/flux-tubes on v_1**

S.Altiparmak,C.Ecker,L.Rezzola, Ast.J.Lett. (2022)



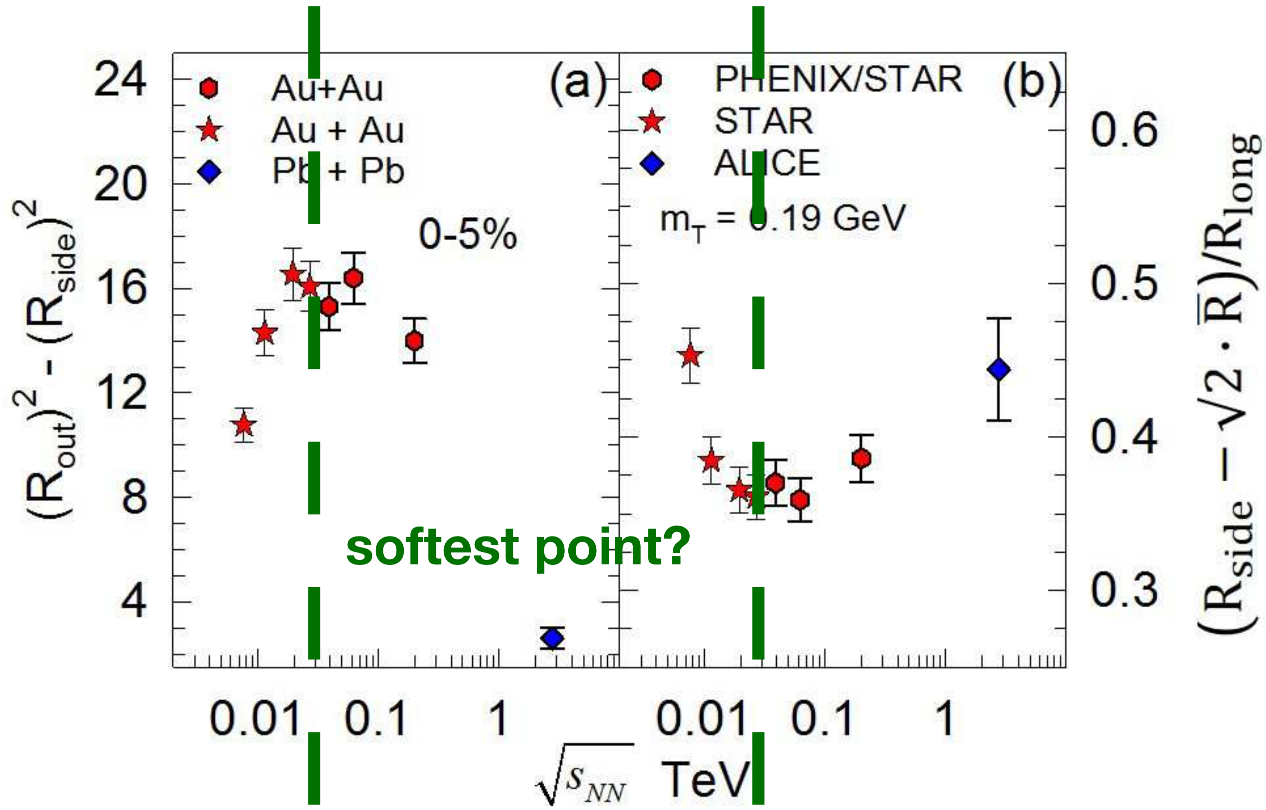
Neutron Stars

Evidence of stiffness for $\rho \sim 3\rho_0$ from neutron star observations
— c_s^2 higher for neutron-rich matter

Source Radii vs Beam Energy

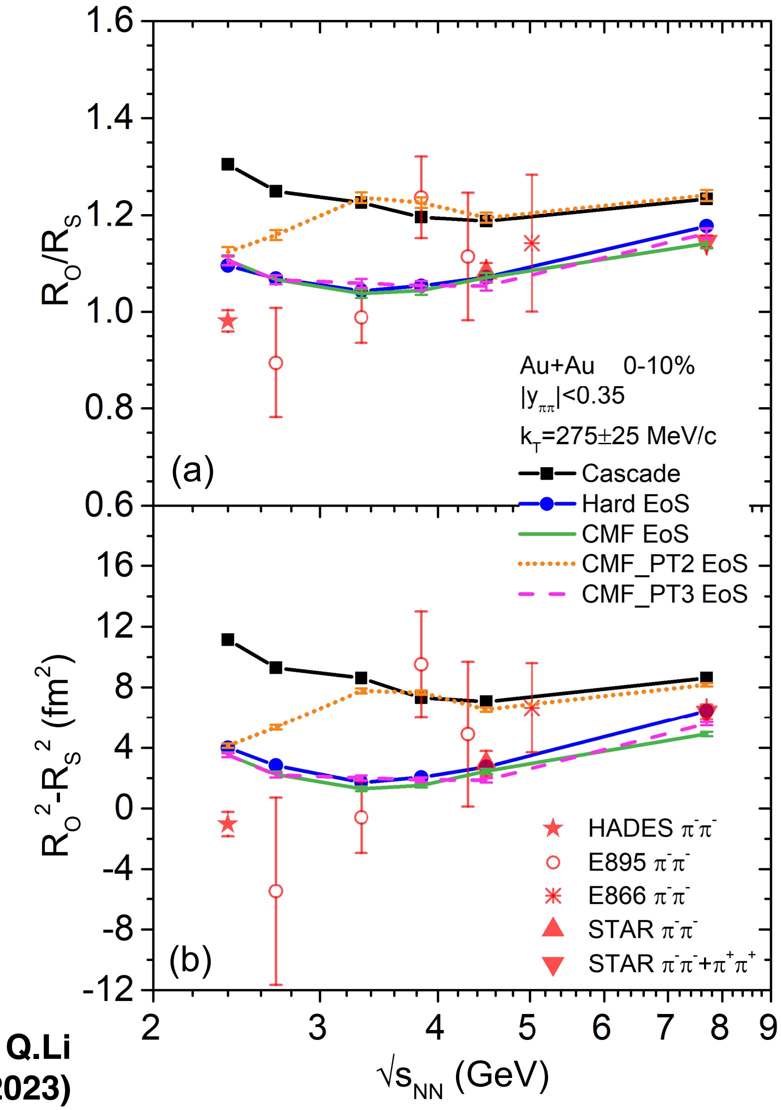
R.Lacey,NPA 2018

REMARKABLE!
Lowering beam energy below 19.6 GeV yields higher speed of sound despite higher p/π ratio!



UrQMD vs STAR/HADES

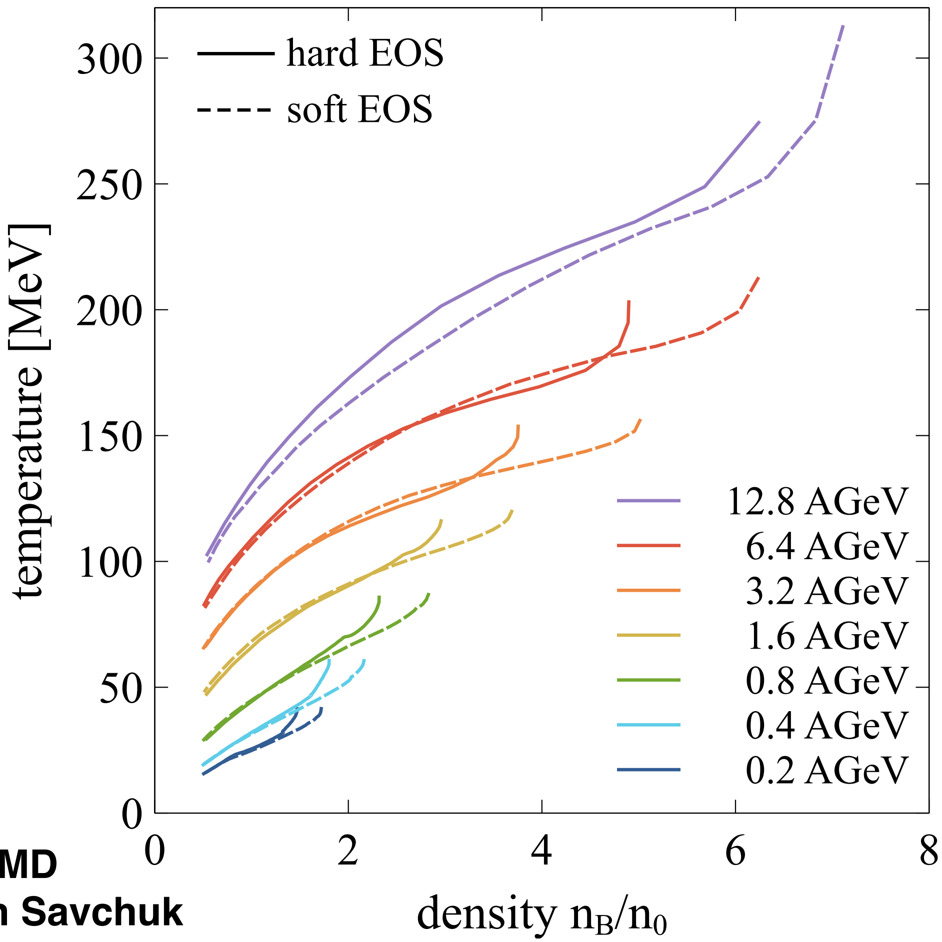
Stiffer EoS looks better!



P.Li,J.Steinheimer,A.Kittiratpattana,M.Bleicher & Q.Li
Sci.China, Phys.Mech.Astron. (2023)

Where to go from here…

Which Beam Energies?



UrQMD
Oleh Savchuk

Lower BES (FXT) energies and HADES energies

- **explore up to $\lesssim 3\rho_0$ without becoming QGP**
- **can then avoid hydro**

Isospin degree of freedom

- **crucial for astrophysical correction**
- **FRIB - 400 program?**

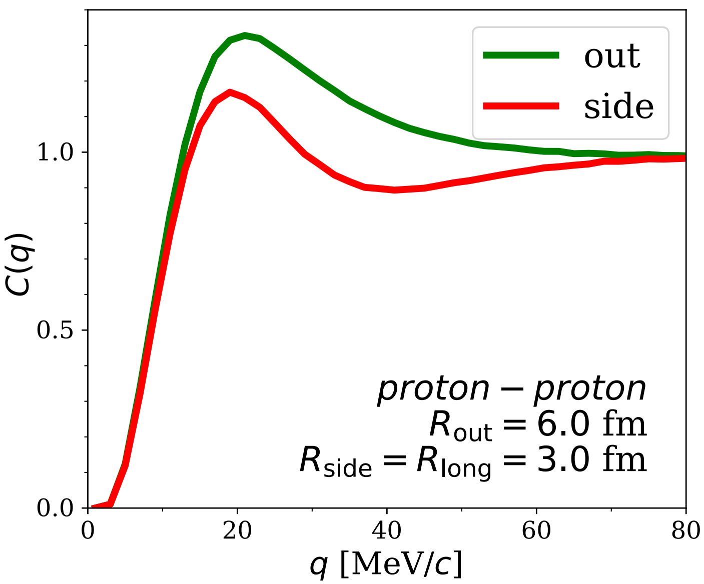
What to Measure

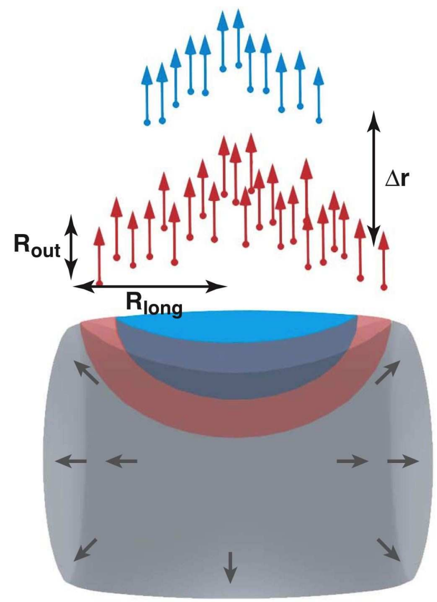
emphasis on sensitivity to EoS

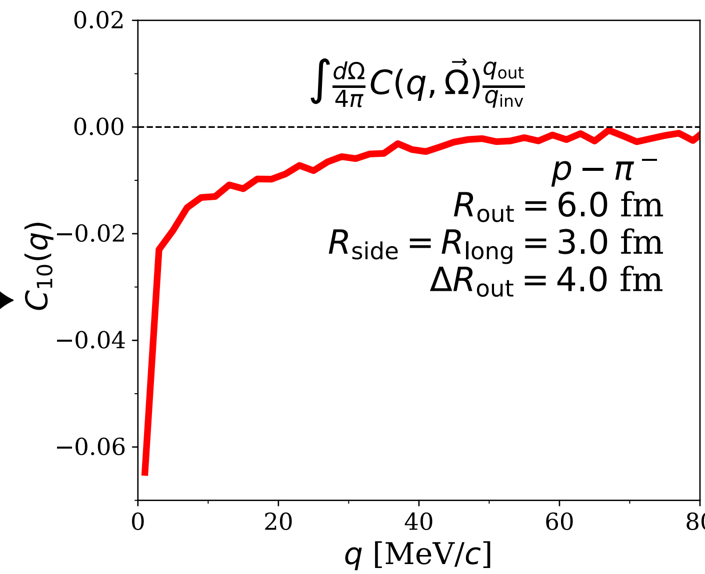
1. **Pions**
   — **tilt and azimuthal sensitivity**
   — **away from mid-rapidity (important at lower energy)**

2. **Protons & Kaons**
   — **also good shape sensitivity**

3. **Non-identical particles**
   — $S(\vec{r})$ **not reflection symmetric**







What to Calculate

emphasis on sensitivity to EoS

READY TO GO:

1. ***CoRAL*** **(Correlations Analysis Library)**
   - **Calculates 3D Correlations**
   - **Wide variety of species pairs**
   - **Need only provide OSCAR output**
   - **Not turnkey, but easily adaptable**

2. **Emulation software for Bayesian Analysis**
   - ***Smooth Emulator*** **(developed at MSU for BAND Collab.)**
   - **Initial state parameters, EoS, viscosity need to be simultaneously analyzed**

TO DO:

1. **Improve Transport Theory**
   - **Momentum dependence**
   - **Initial stopping**
   - **Parameterize possibilities for Bayesian analysis**

2. **Improve data/model comparisons**
   - **Extracting Gaussian radii for** ***pp…***
   - **Compare angular decompositions?**

What to take away from this talk

I. The physics of high-baryon density in hadron phase is fundamentally interesting
   — Eq. of state
   — Astrophysical connection

II. Femtoscopy will play large role in that effort!