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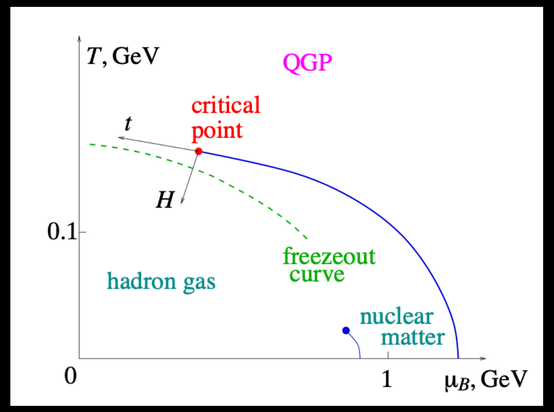
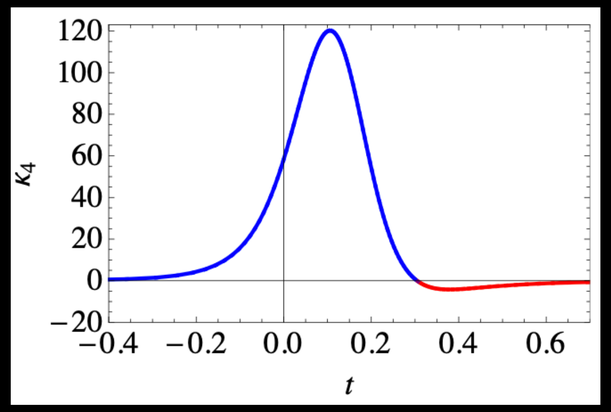
# HADRONIC TRANSPORT: LOOSE ENDS

## Strategies:

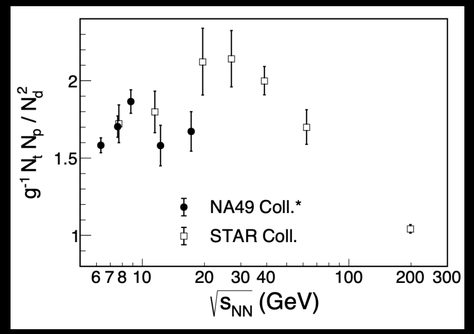
- Look for specific shape in baryon number fluctuations against $\sqrt{s_{NN}}$




*[Stephanov:2011pb]*

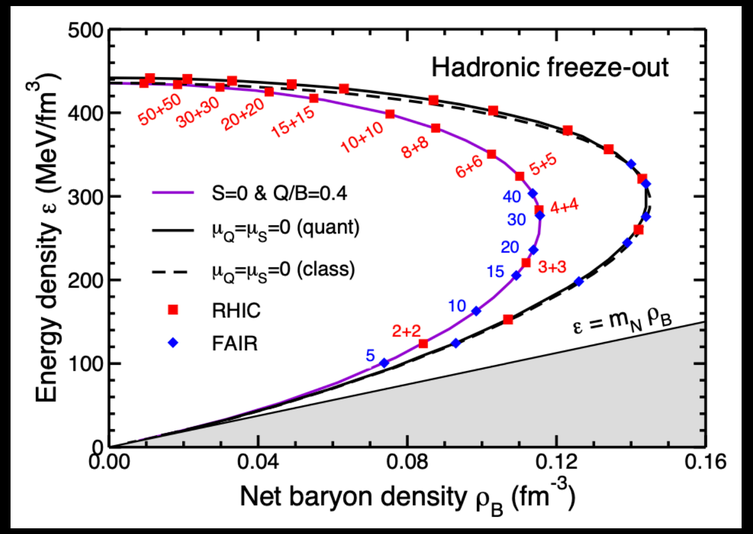
- Look for peaks in some light nuclei yield ratios vs $\sqrt{s_{NN}}$, ratios are related to baryon density fluctuations




*[Sun:2017xrx, Sun:2018jhg, works of Shuryak & Torres-Rincon]*

## Notes:

- Probing low baryon-density region: $\rho_B < 0.8\rho_0$ at chemical freeze-out at any $\sqrt{s_{NN}}$, hoping that critical fluctuations are not "forgotten" from possibly high-$\rho_B$ critical point




*[Randrup:2006nr]*

- These strategies may confirm existence of CP. How precisely can they locate the $(T_{CP}, \mu_{CP})$?

# GOAL II: CONSTRAIN EQUATION OF STATE (EOS) AT HIGH BARYON DENSITY

Ideal world strategy:

- Parametrize EoS $p(\epsilon, \rho_B)$ [hydro] , or
  some mean field [BUU transport], or
  some potential [QMD transport]
- Constrain the EoS by known physics, fit remaining free parameters to match HIC observables
- Win! Apply constrained EoS to astrophysics

State-of-the-art:

- One parameter – varying incompressibility K,
  and with PT / without PT option
- No model describes the majority of observables simultaneously
- Theoretical uncertainties and different model disagreements

Relevant energy range: $E_{kin} \sim 1 - 200$ A GeV or $\sqrt{s_{NN}} \simeq 2.3 - 20$ GeV

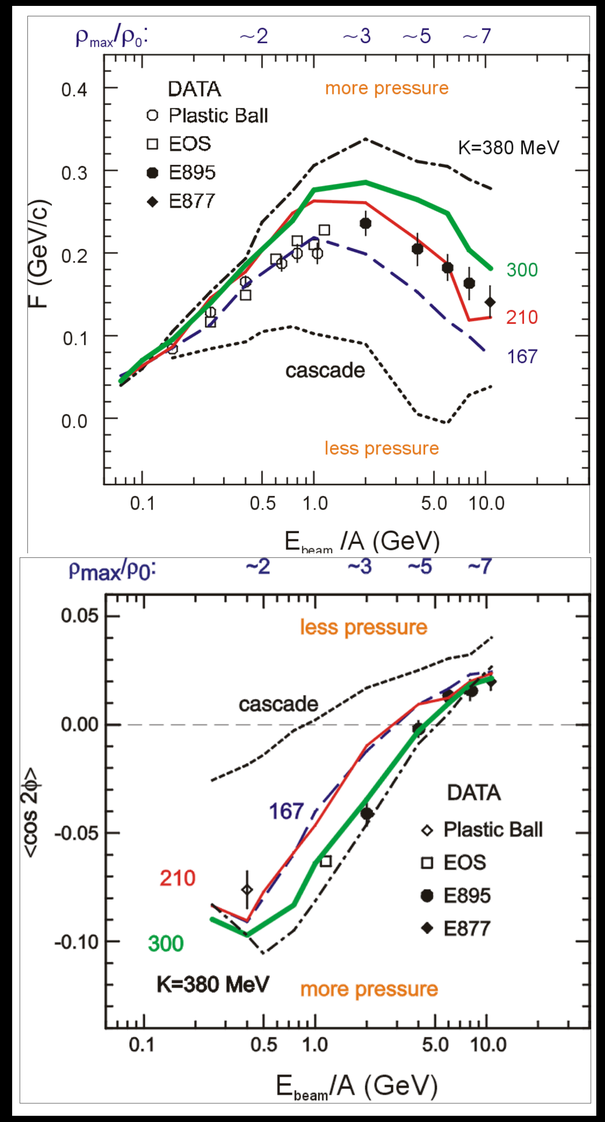
Experiments: [HADES, AGS, STAR BES, NICA, FAIR]

- At lower energies not enough compression
- At higher energies nuclei become transparent, no stopping
  Formally density $2\gamma\rho_0$ can be reached, but it does not probe EoS

What is the highest density
to which heavy ion collision observables are sensitive?

- Maybe $\simeq (6-8)\rho_0$, depends strongly on how hard/soft EoS is

Danielewicz-Lacey-Lynch constraint: most prominent so far




Science, 298 (2002) 1592

## Hydro (+ transport)

- Straightforward to parametrize EoS
- Harder to treat phase transitions, need surface tension
- Uncertainties of initial state and particlization

## Transport

- Harder to parametrize EoS, not obvious what degrees of freedom to use at high density
- Easier to treat phase transitions
- Uncertainties from unknown resonance properties, cross sections

- Overall complementary approaches at $\sqrt{s_{NN}} < 20$ GeV
- Need either hydro + transport or hadrons + partons transport to describe flow and strangeness at $\sqrt{s_{NN}} > 20$ GeV

NEED BOTH

| Observable | Status and challenges |
|---|---|
| Protons, pions: spectra & yields | • Physics: resonances, strings. Some sensitivity to EoS. Usually reasonable reproduction of data.<br>• Missing resonance properties<br>• How to treat multi-product reactions at low energies?<br>(e.g. $pp \to pp + 10\pi$ ) The Lund string model is for high energies |
| Protons, pions: flow | • Physics: mean fields, squeeze-out. Large sensitivity to EoS. Spectators matter.<br>• Physics meaning and origin generally understood, but<br>• Hard to describe v1 and v2 simultaneously, no model describes dv1/dy as a function of energy<br>• Need more works with parametrized EoS |
| Strangeness | • Physics: resonances, strings, strangeness exchange reactions, sensitive to strange mean field, QGP phase<br>• Multi-strange baryons underestimated by hadronic transport, need partonic phase<br>• Strange resonances missing in PDG?<br>• $K/\pi, \Lambda/\pi$ description seems to need chiral transition |
| Light nuclei | • Physics: production mechanism debated – blast wave / coalescence / reactions<br>• Overall not too far off in all models, but<br>• Increasingly important at lower energies, need better precision from models |
| Fluctuations | • Need good understanding of light nuclei production to compute proton fluctuations<br>• Sensitive to mean fields and need large statistics, therefore enormous computing time<br>• Challenging to extract fluctuations from BUU-type transport |
| Femtosopy | • Physics: measuring volume of the system and lifetime, but also sensitive to flow |

# CHALLENGES FOR TRANSPORT I: FLOW

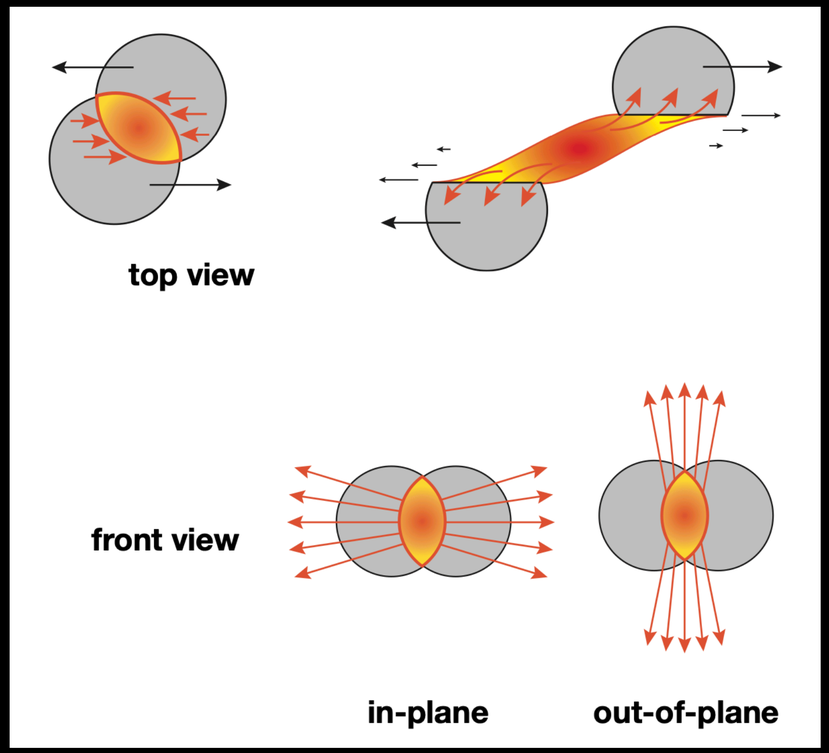
$v_1 = \langle \cos \varphi \rangle$ characterizes expansion strength and attraction/repulsion to spectators

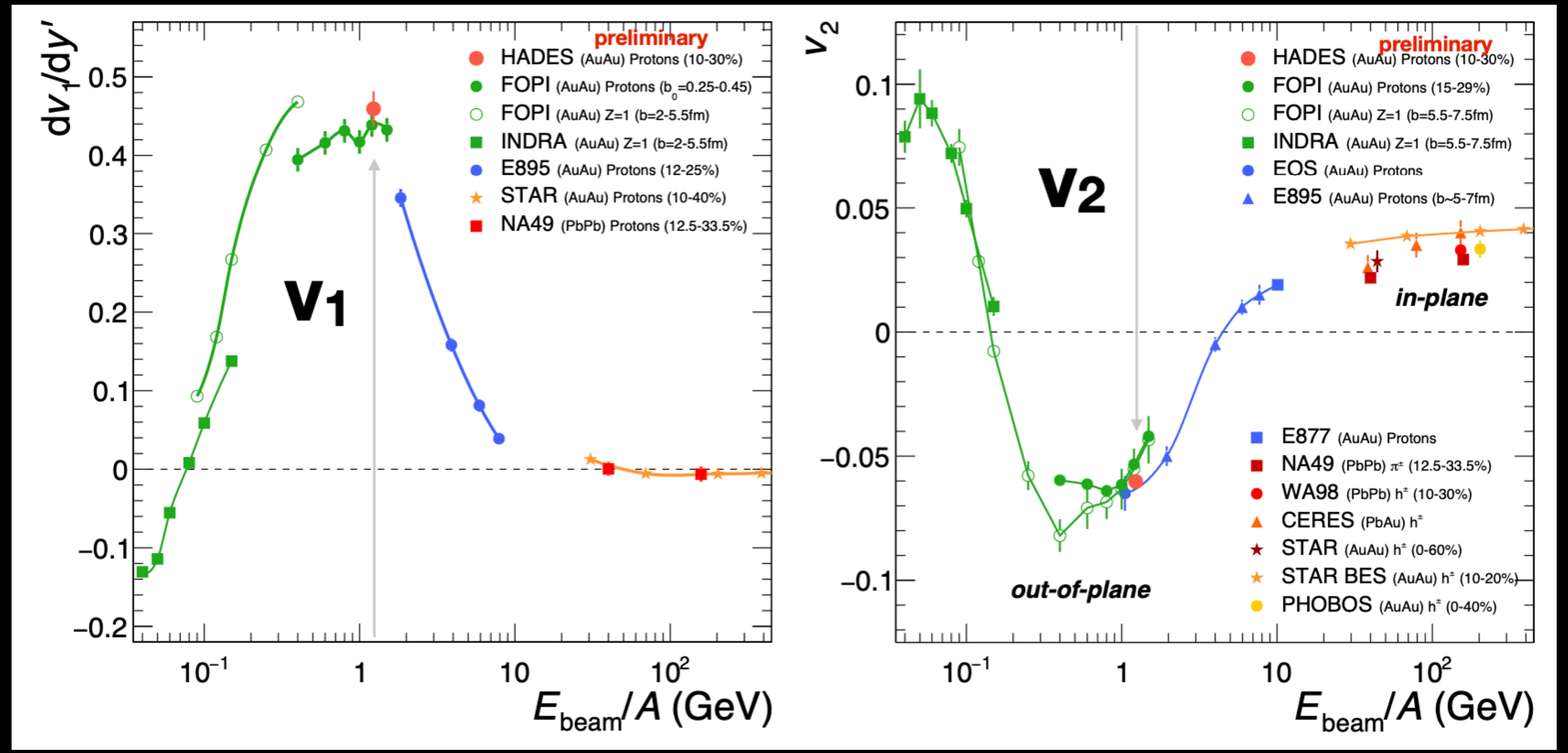
$v_2 = \langle \cos 2\varphi \rangle$ competition between squeeze-out by spectators and fireball expansion

$v_2 > 0$ when spectators pass faster than fireball expands

$v_2 < 0$ when spectators pass slower than fireball expands

Stiffer EoS – faster fireball expansion – more negative $v_2$, larger $dv_1/dy$



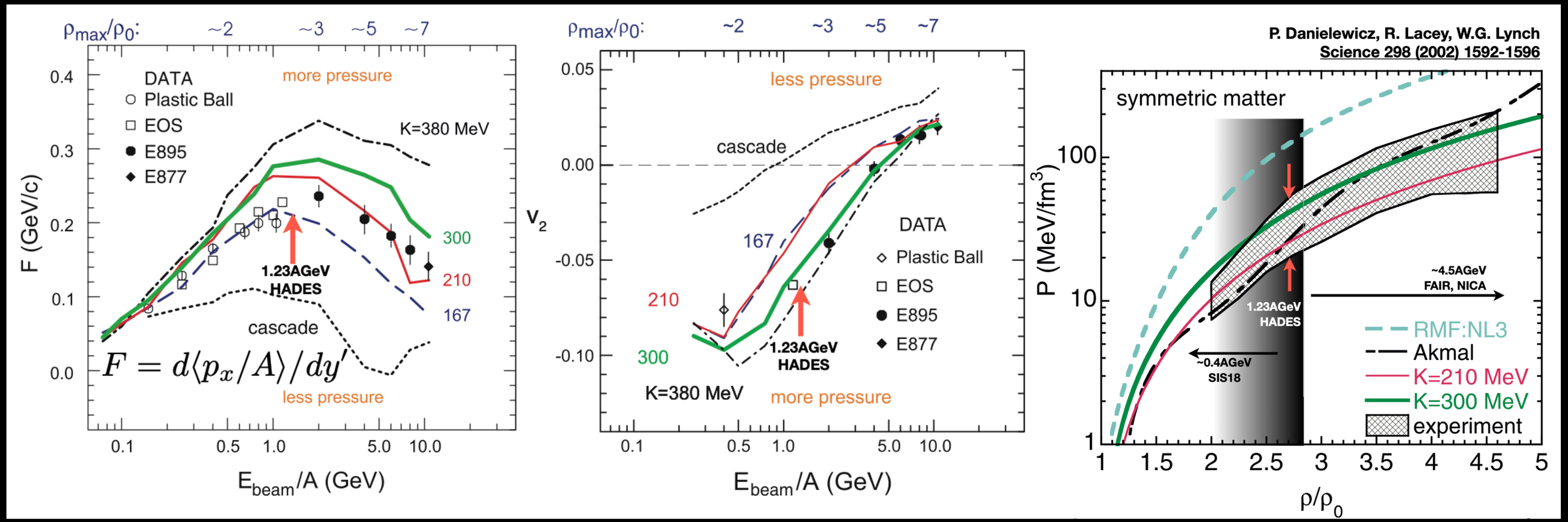




Illustrations and plots from presentation by B. Kardan (HADES)

# CHALLENGES FOR TRANSPORT I: FLOW

Stiffer EoS – faster fireball expansion – more negative $v_2$, larger $dv_1/dy$

Momentum dependence $v_1(p_T)$, $v_2(p_T)$ sensitive to momentum dependence of mean field




Good precision of data, but not very tight constraint. Why?

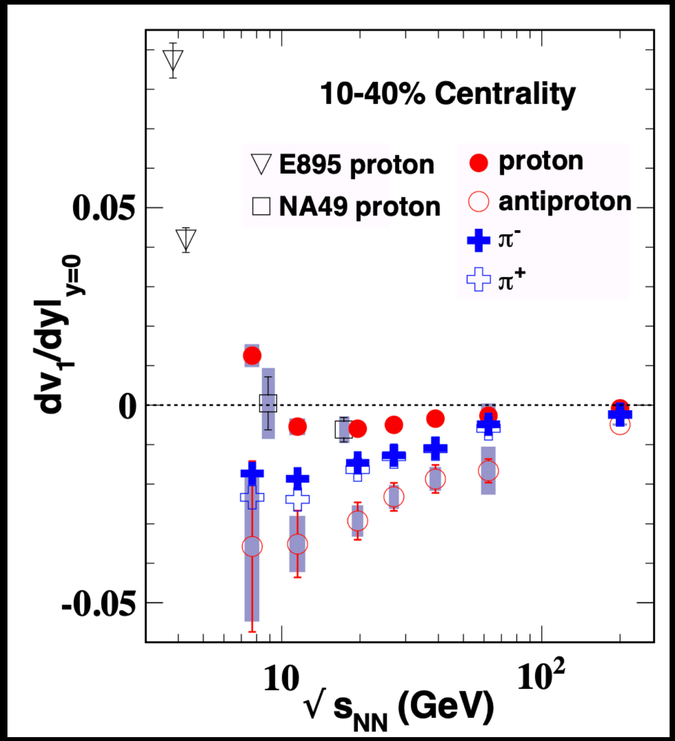
Because it's hard to describe $dv_1/dy$ and $v_2$ when the whole EoS is parametrized by only one parameter $K$

Idea: $K(\rho)$, softer EoS at lower density, stiffer EoS at high density

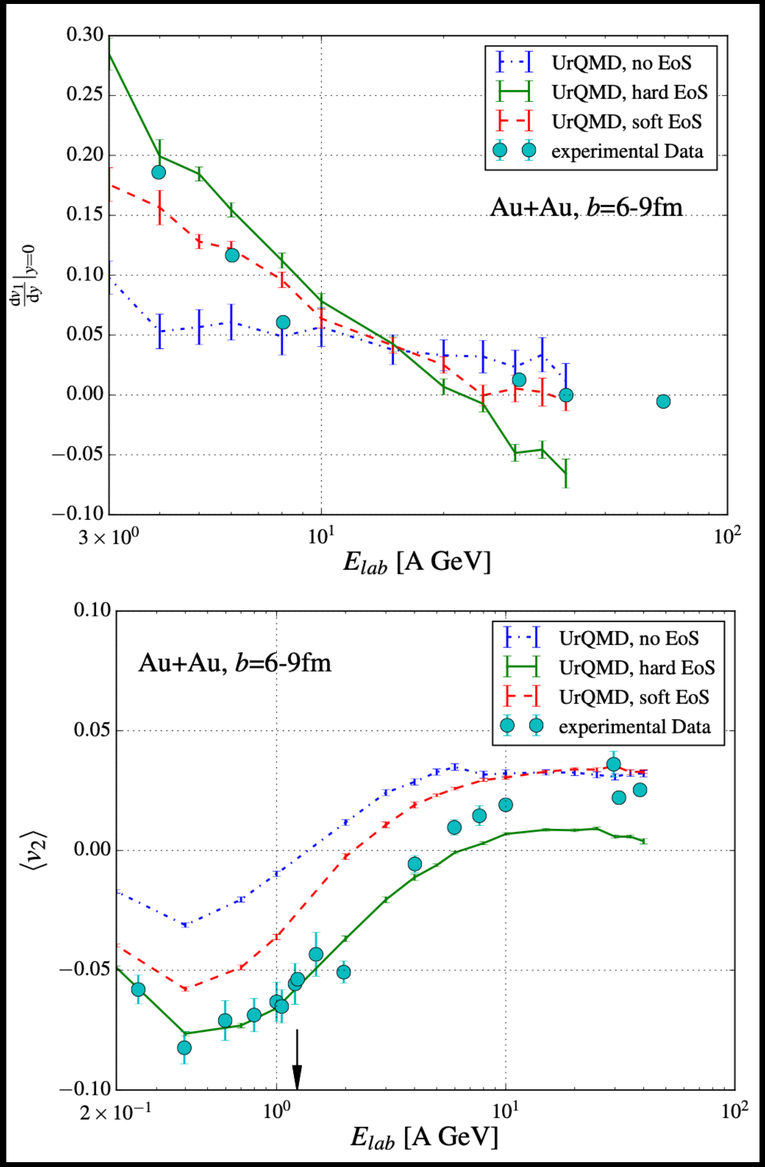
# CHALLENGES FOR TRANSPORT II: V1 AS A FUNCTION OF ENERGY

Negative $dv_1/dy$ of protons:

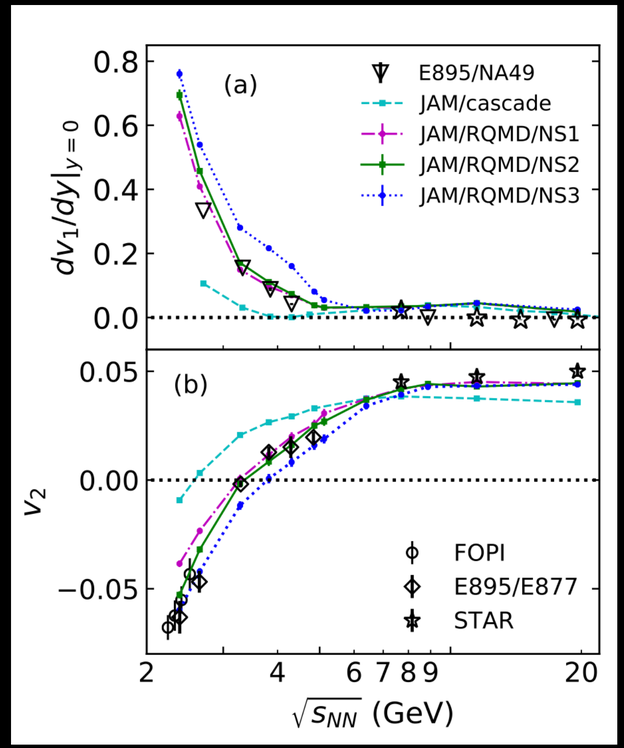
- Softest point signature
- Challenging to reproduce by transport together with $v_2$




STAR2014:clz




Hillmann2018:nmd




Nara:2020ztb

Softer EoS at low density and stiffer at high density? Momentum dependence of potential is important (absent in UrQMD)

# FLEXIBLE EOS PARAMETRIZATION I

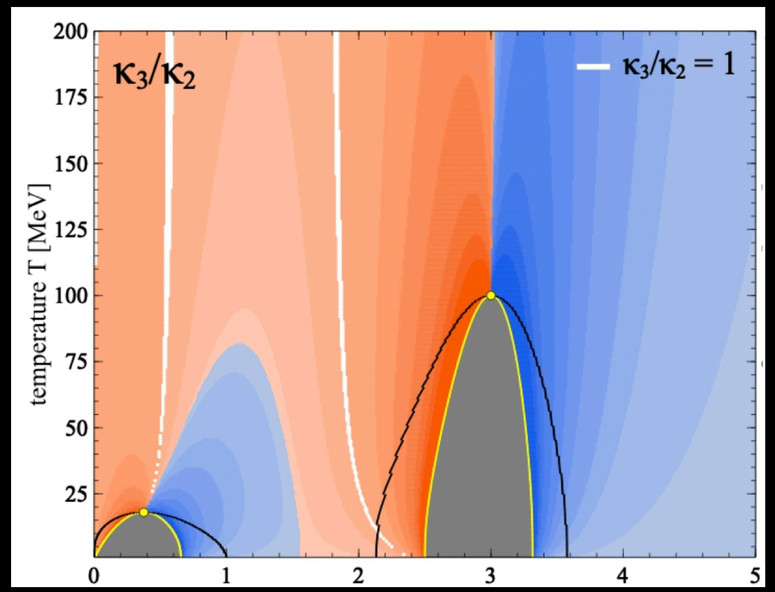
- Vector density functional (VDF) model [Sorensen2020:ygf]
- Mean field proportional to baryon current: $A^\mu = \alpha(\rho) j^\mu, \rho_B^2 = j^\mu j_\mu$
- Function $\alpha(\rho)$ can be chosen arbitrarily
- Thermodynamically consistent, derived from energy density functional, usable in transport
- Test particle equations of motion

$$\frac{dx^\mu}{dt} = \frac{\Pi^\mu}{\Pi^0}$$

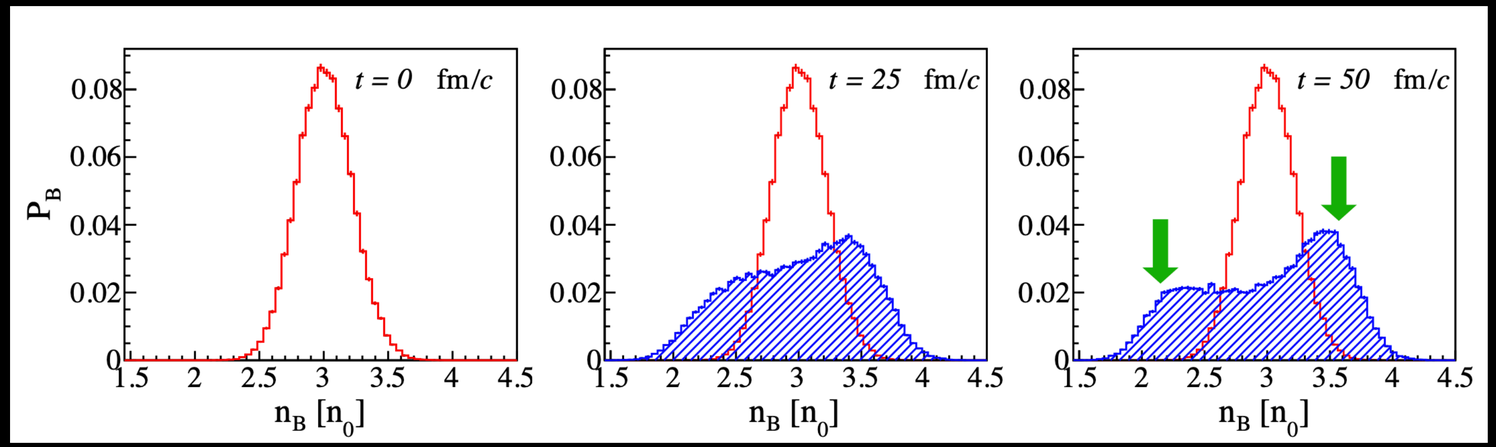
$$\frac{d\Pi^\mu}{dt} = \frac{\Pi^\mu}{\Pi^0}(\partial^\mu A^\nu - \partial^\nu A^\mu)$$

$$\Pi^\mu \Pi_\mu = m^2$$

Set $\alpha(\rho)$ to be polynomial constrained by nuclear matter and custom "QGP-like" phase transition



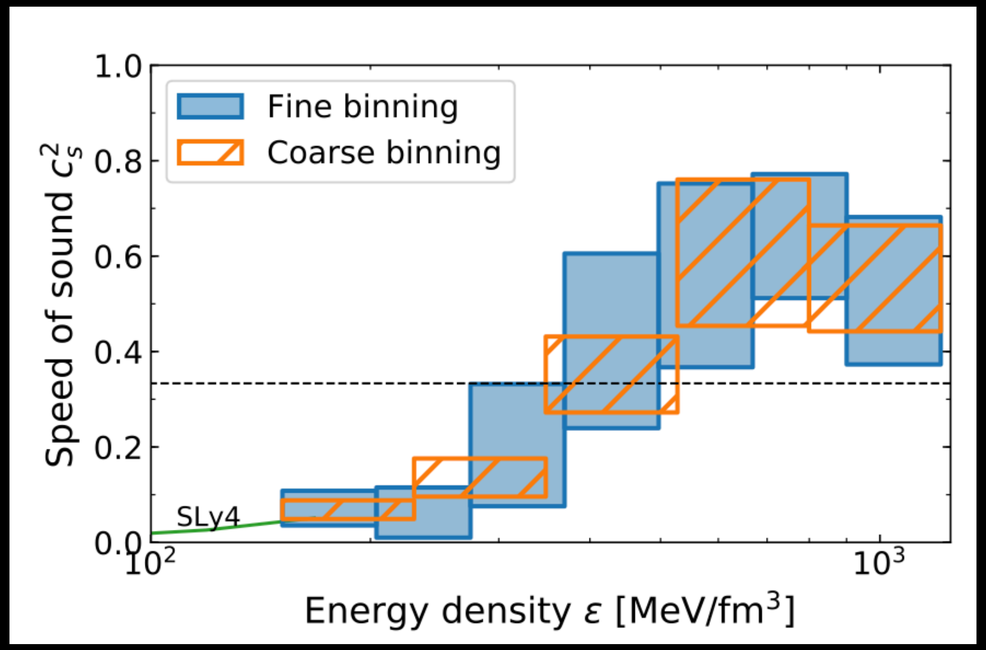

Let particles in the box evolve: observing phase separation in finite volume



# FLEXIBLE EOS PARAMETRIZATION II

- Same vector density functional (VDF) [Sorensen2020:ygf] approach
- But now $\alpha(\rho)$ set to reproduce custom speed of sound at T = 0
- Inspired by [Fujimoto:2021zas] fit to neutron stars data:
  Can we obtain a similar constraint from heavy ion collisions?

DO, Work in progress

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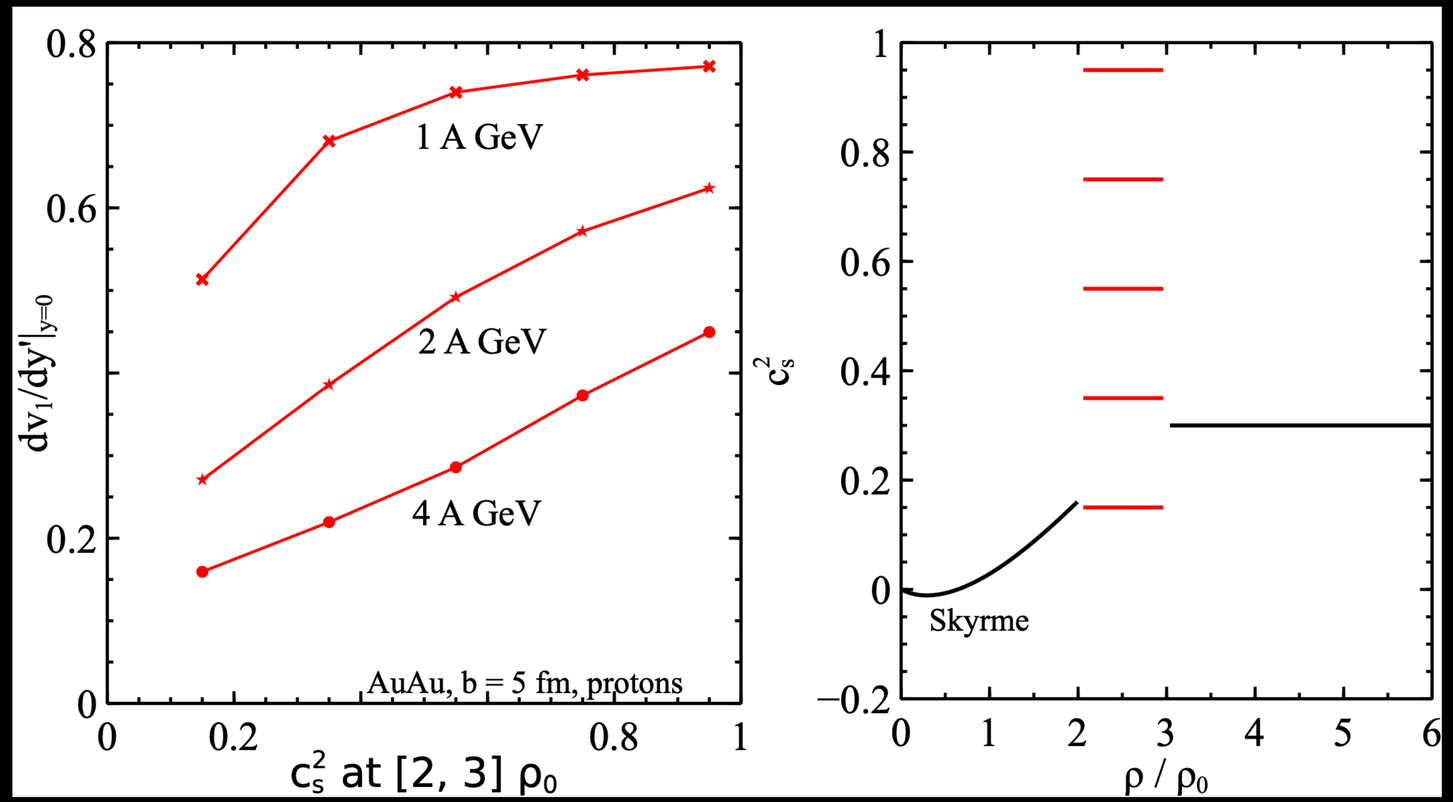

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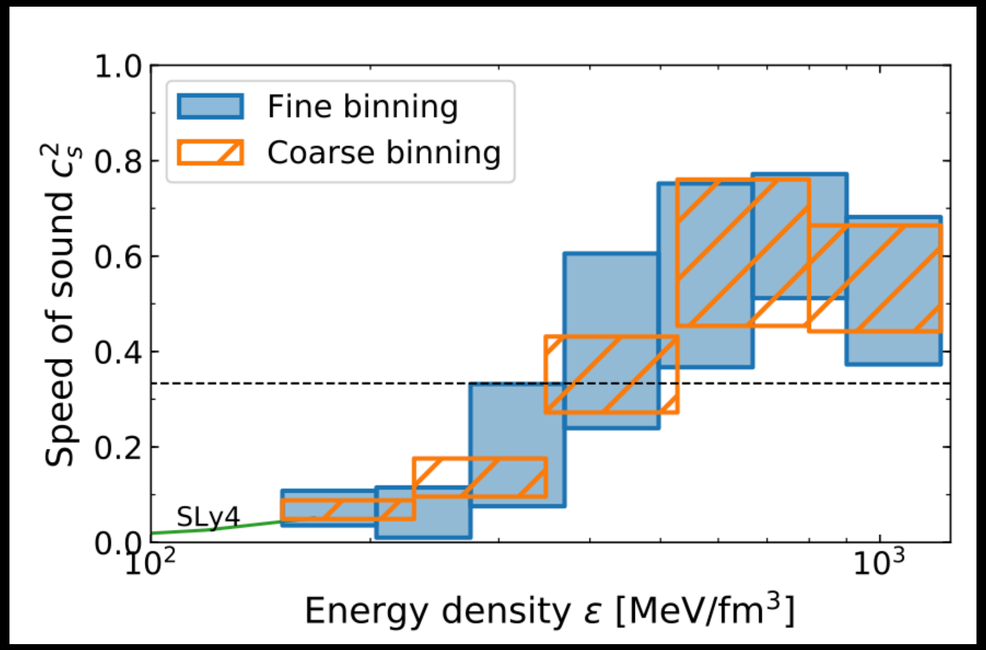


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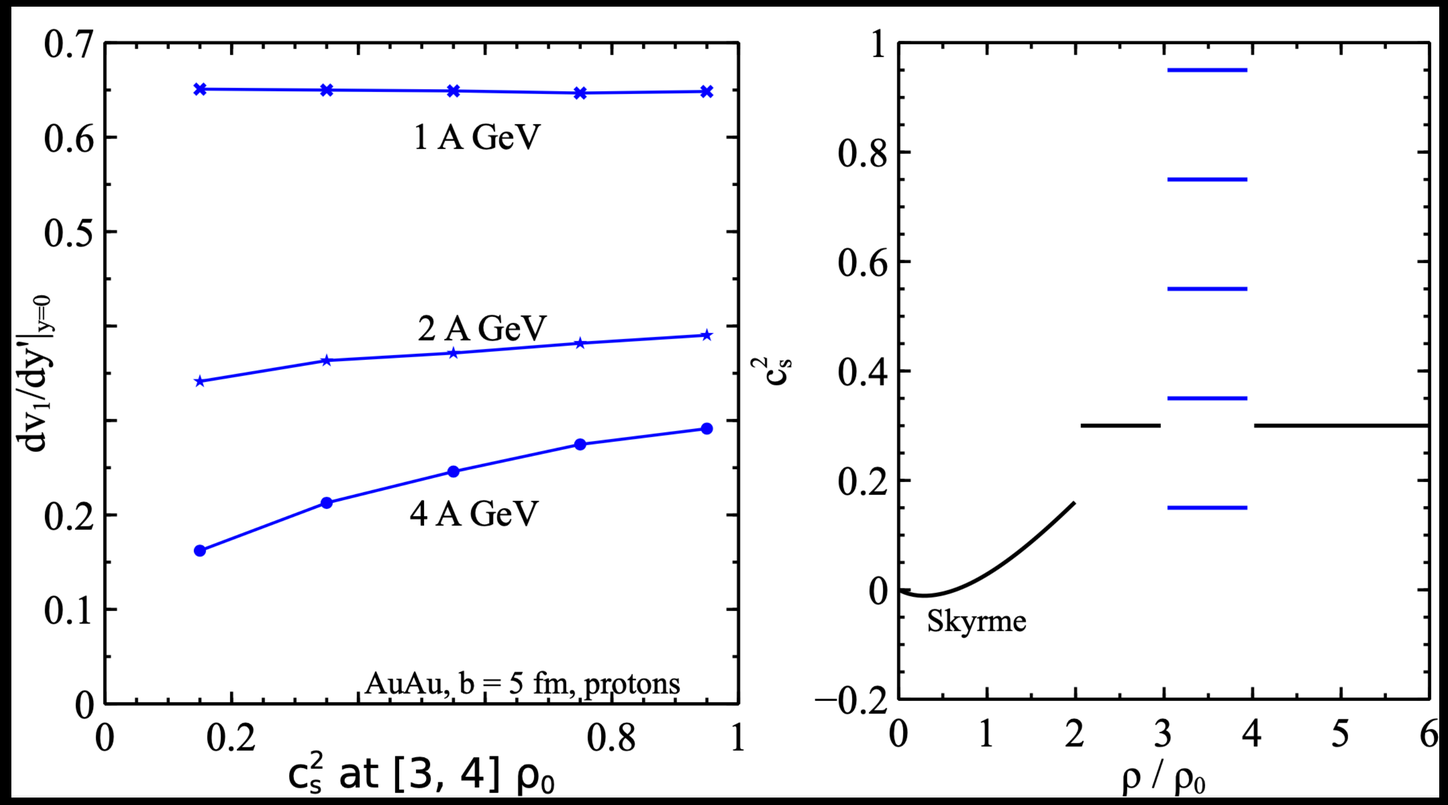

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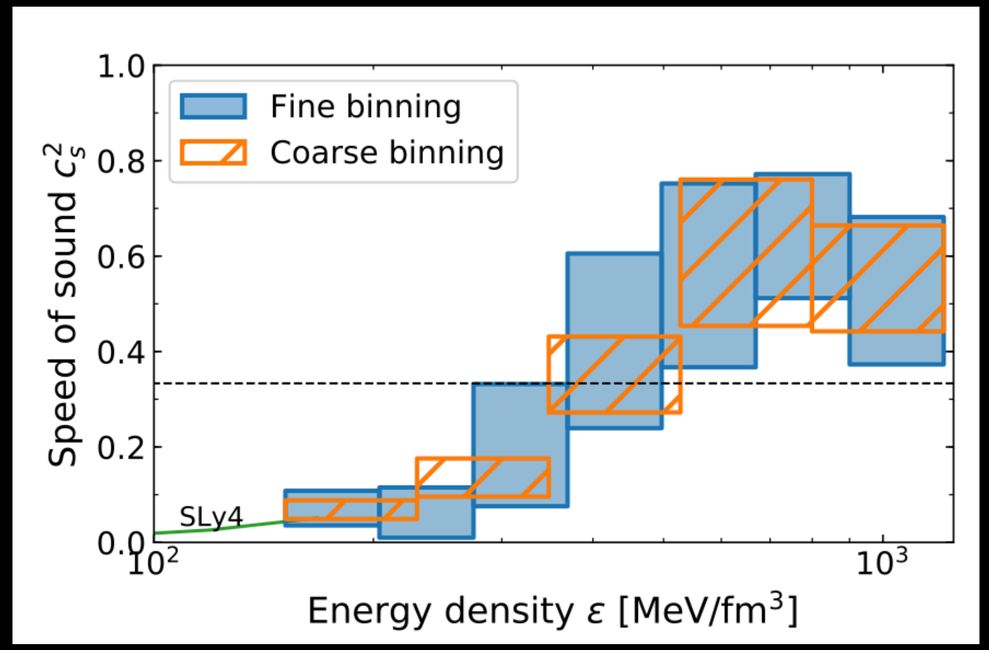


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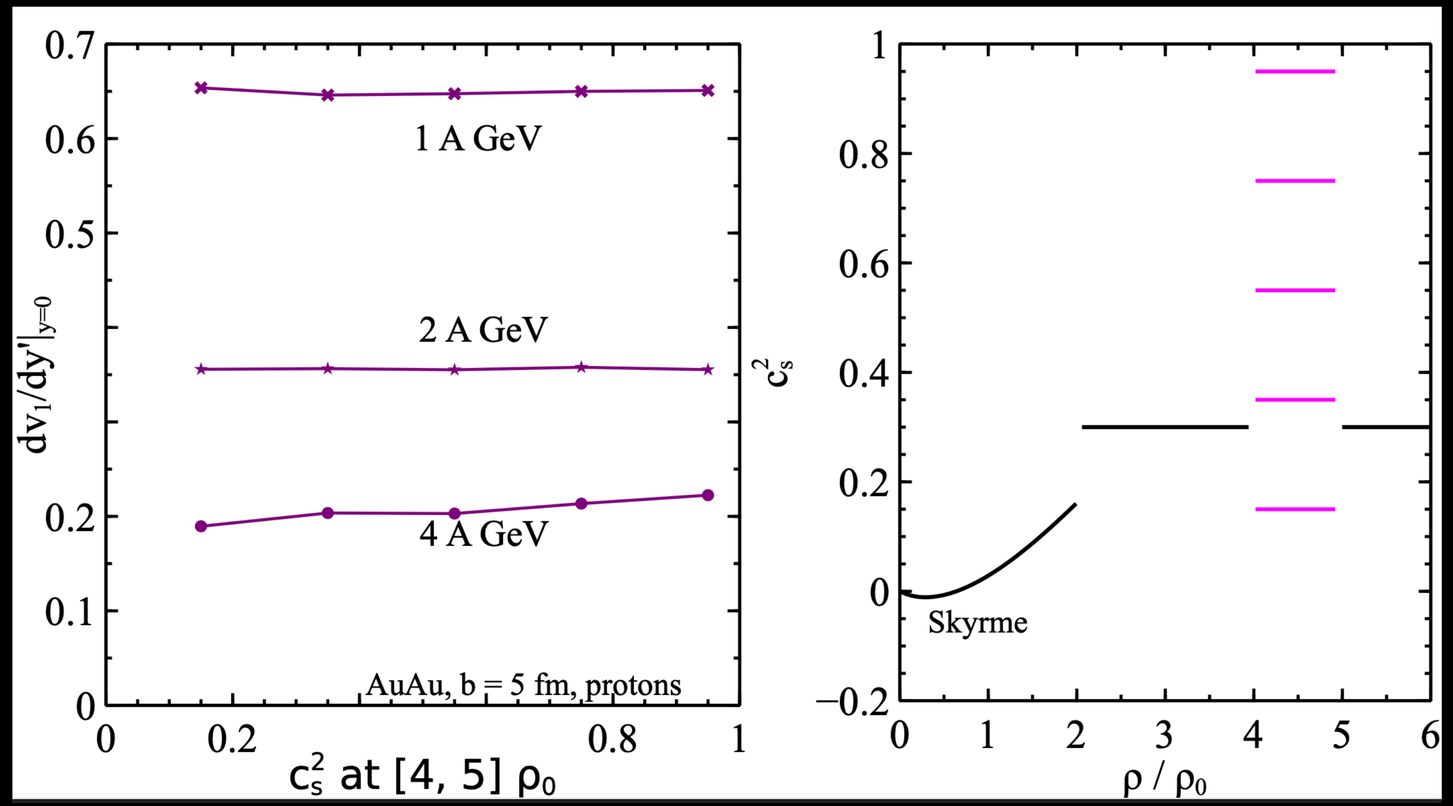
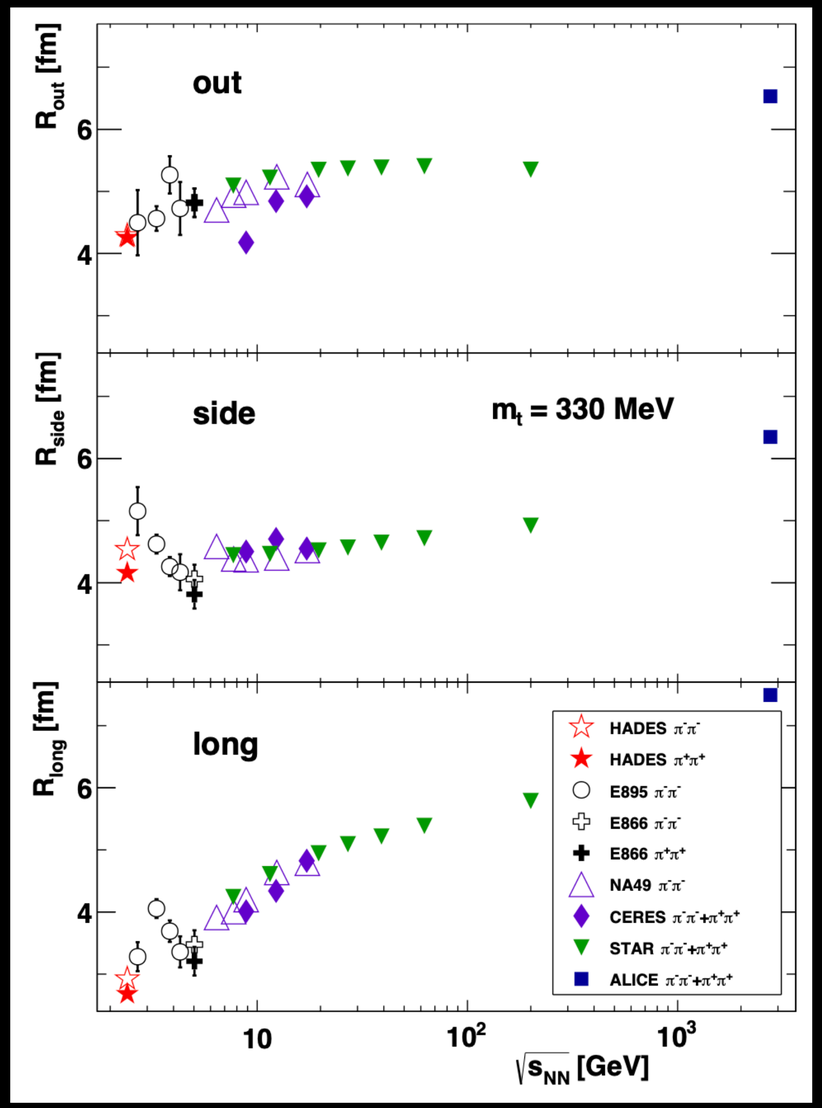
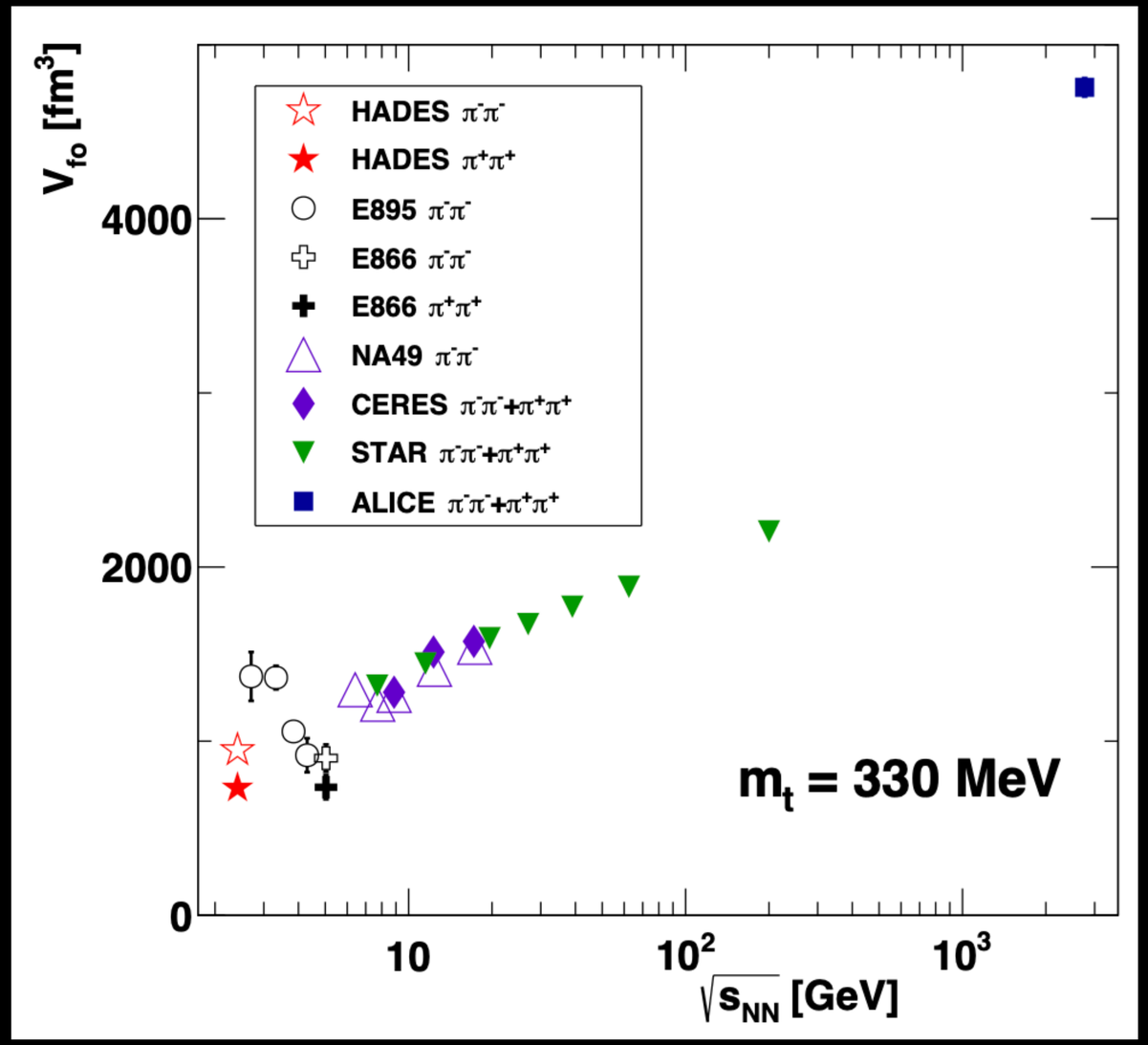
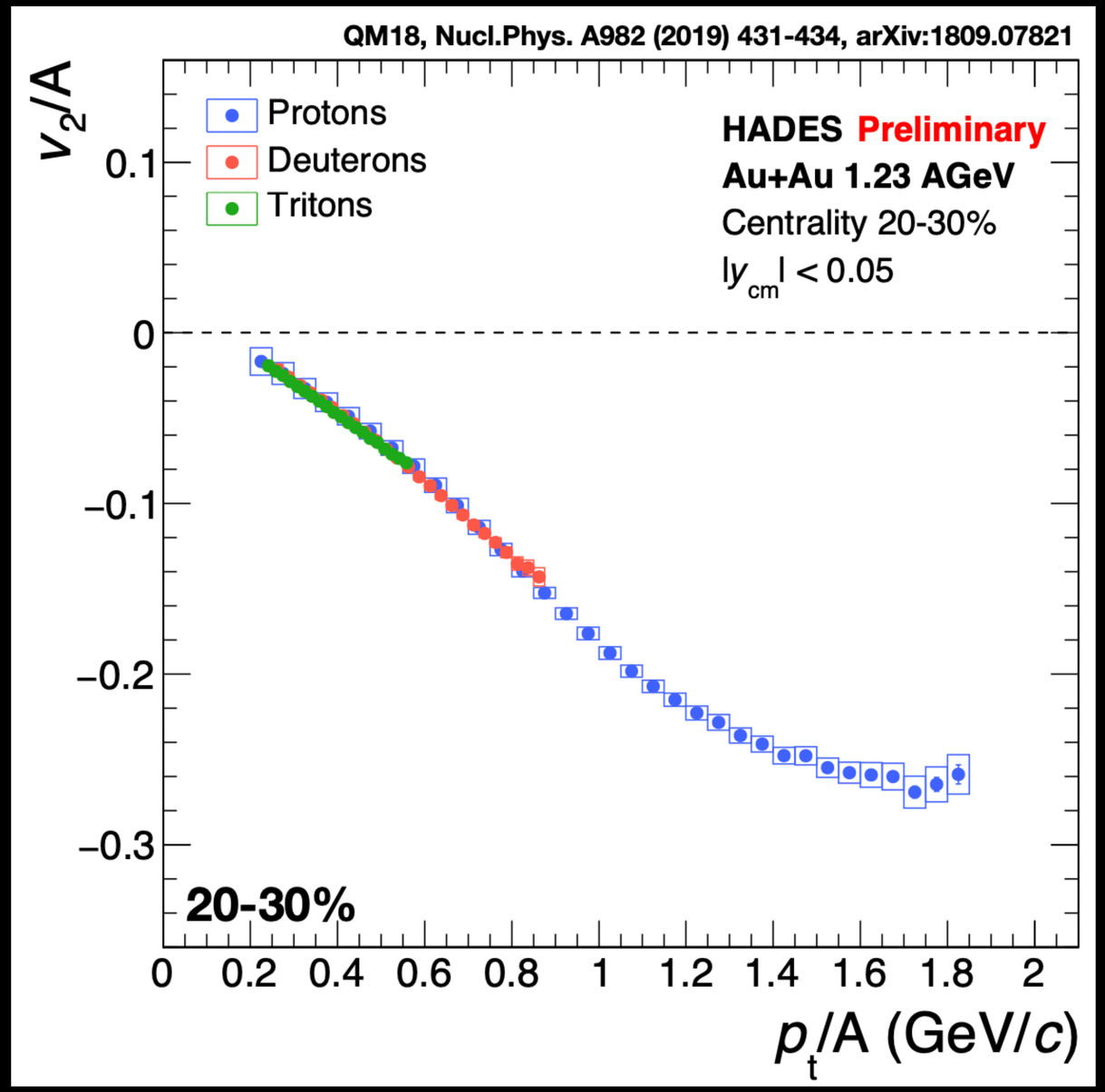


Can transport explain this wiggle? Is it related to flow?

HADES2019:lek



- Need fast transport with flexibly parametrized mean fields: work in progress
  - Satisfying nuclear physics constraints
    Momentum dependence of potentials is important
  - Transport with mean fields is very slow: maybe gpu implementation?
- Refining Danielewicz constraint of EoS is realistic,
  especially with new flow and HBT data and modern computing power
- Hydro + transport and pure transport simulations
  are complementary at BES FXT energies
  Both have a set of theoretical uncertainties

- Simplification for theory: no need to be too careful about light nuclei treatment