Probes of Esym and its density and momentum dependence (m_n^*/ m_n^*) at supra-saturation

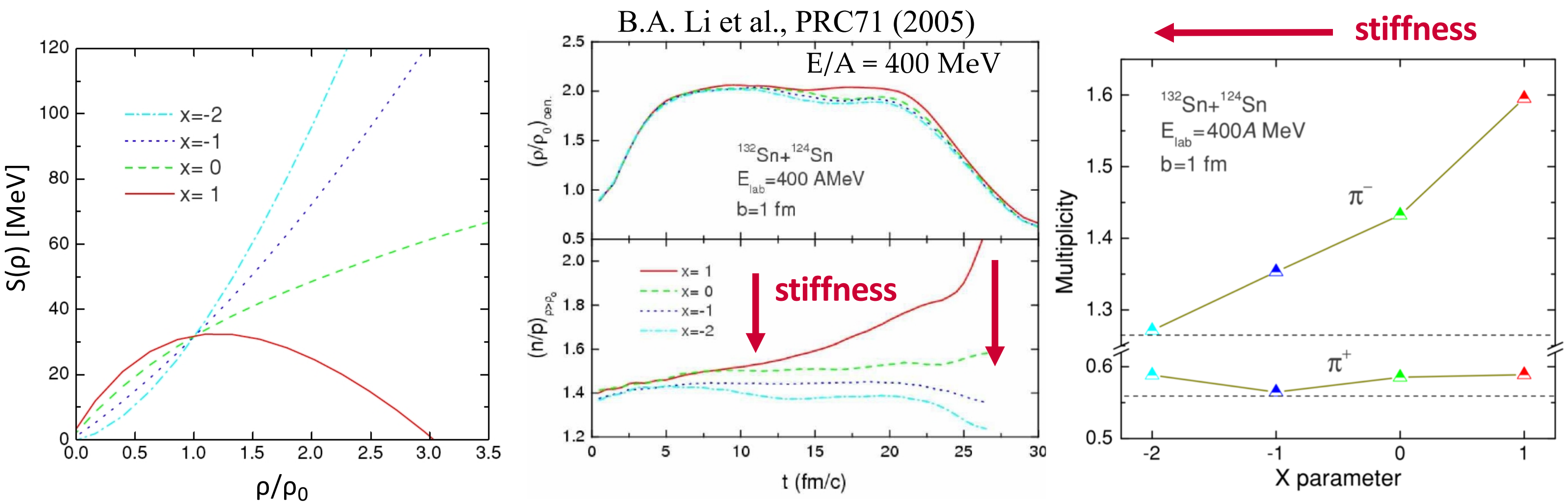
- n/p and t/^{3}He spectra
- n/p directed and elliptic flow

NSCL with SIBs
FRIB200 with RIBs

- Meson production in high density regions: π^-/π^+ and K^0/K^+

FRIB400

Effects of the S(ρ) at high density



Pressure induced by S(ρ)

expels neutrons away from

attracts protons towards

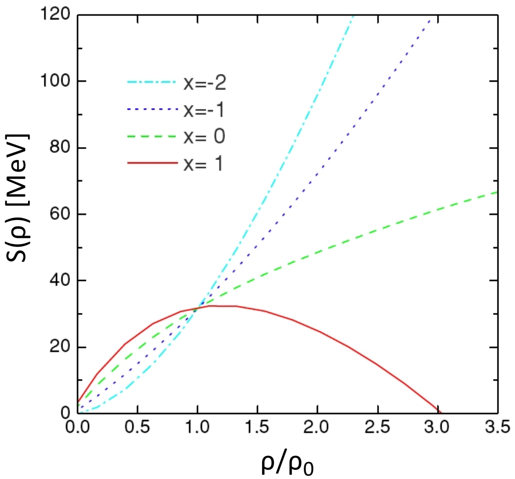
high density regions

Expts

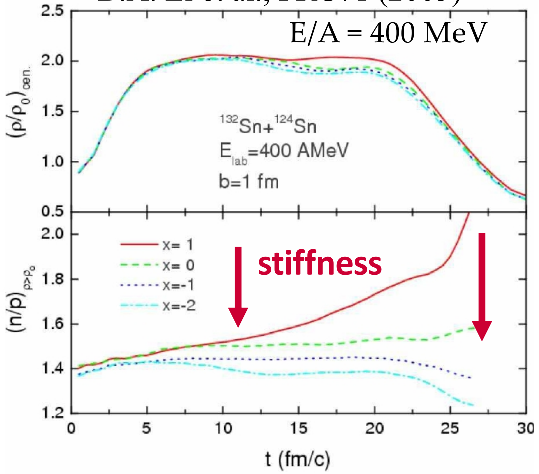
$$\frac{Y(n)}{Y(p)} \quad \frac{Y(\pi^-)}{Y(\pi^+)} \quad \frac{Y(K^0)}{Y(K^+)}$$

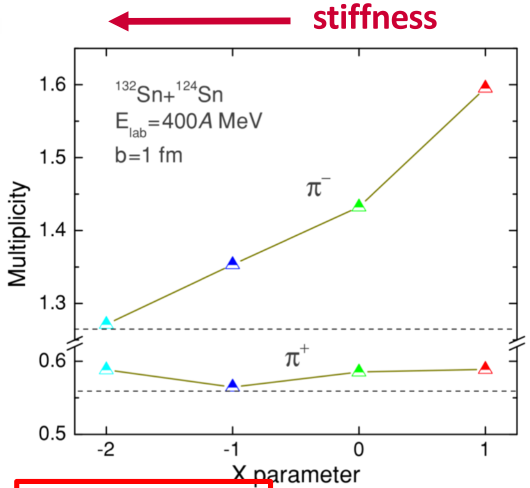
- Single particle emissions
- Collective observables: flow

Effects of the S(ρ) at high density



B.A. Li et al., PRC71 (2005)





$$\frac{Y(t)}{Y(3He)}$$

Pressure induced by S(ρ)

expels neutrons away from

attracts protons towards

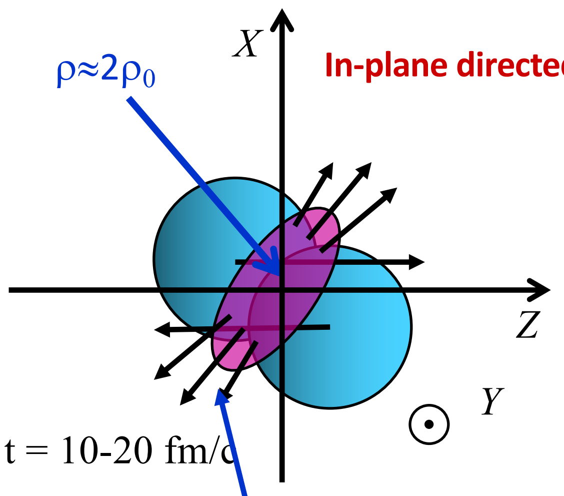
high density regions

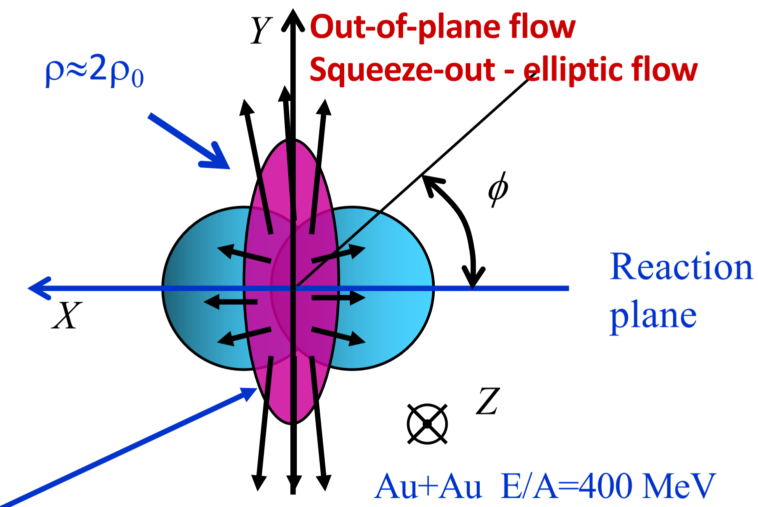
Expts

$$\frac{Y(n)}{Y(p)} \quad \frac{Y(\pi^-)}{Y(\pi^+)} \quad \frac{Y(K^0)}{Y(K^+)}$$

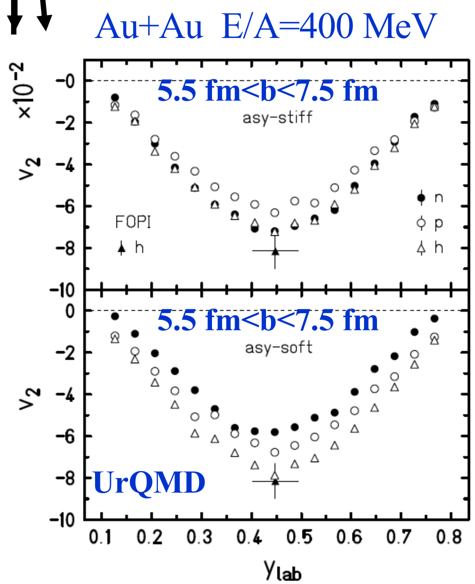
- Single particle emissions
- Collective observables: flow

Directed and Elliptic flow





$dN/d\phi = 1 + 2\cdot \mathbf{v_1}\cos(\phi) + 2\cdot \mathbf{v_2}\cos(2\phi)$



Flow on n and p of neutrons sensitive to $E_{sym}(\rho)$

Experiments at NSCL (before FRIB!) in 2018

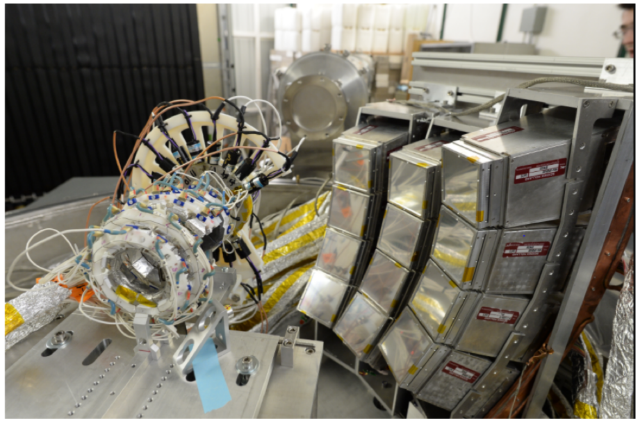
^{40,48}Ca+^{58,64}Ni, ^{40,48}Ca+^{112,124}Sn
E/A=56, and 140 MeV

Elliptic and directed flow at E/A<200 MeV → Esym
Density and momentum dependence (m_n^*/ m_p^*)

Two-particle correlations for in-medium resonances

Neutron Wall

Veto Wall



µBall HiRA

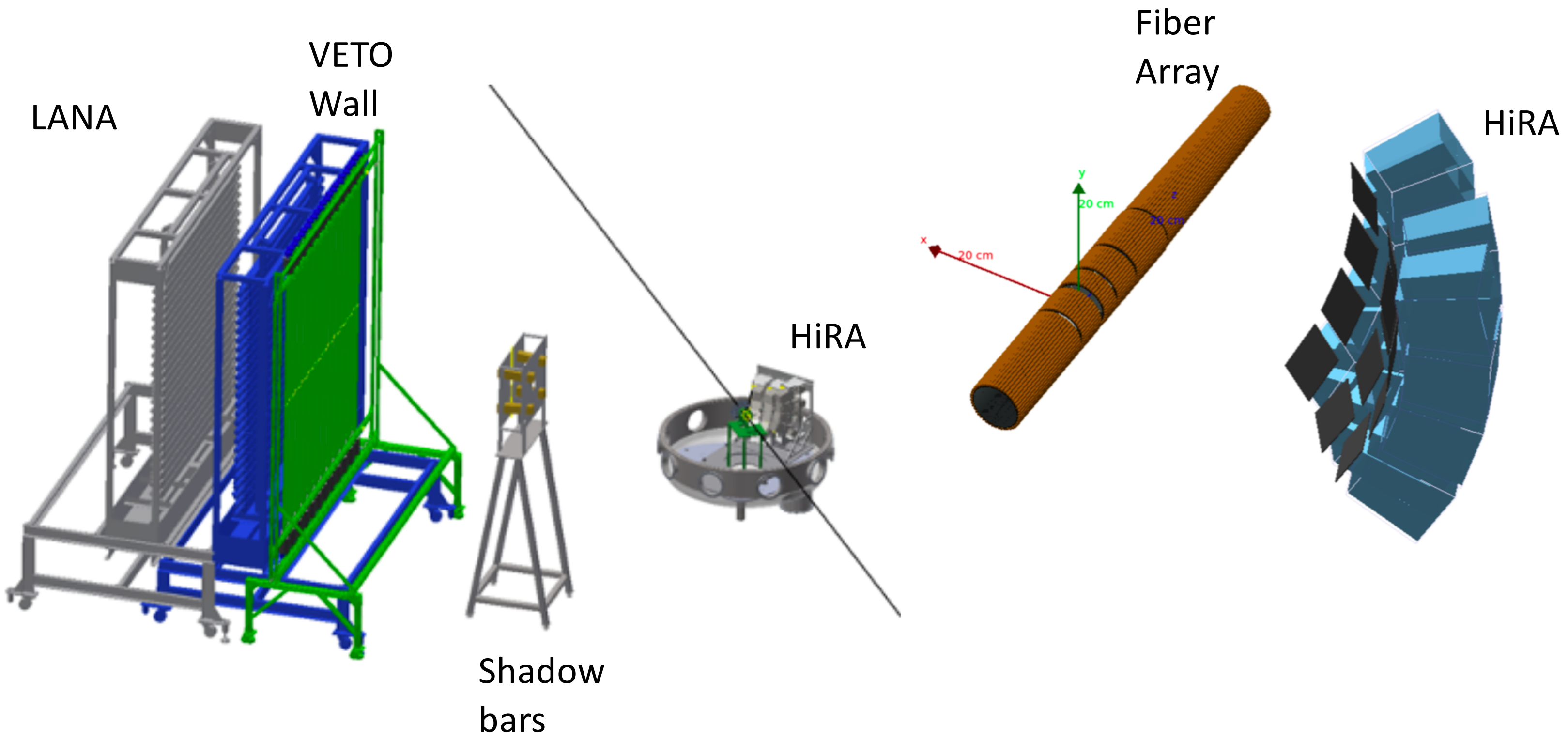
New proposal 23058 @ PAC2 FRIB

^{56,70}**Ni** + ^{58,64}Ni
E/A = 175 MeV

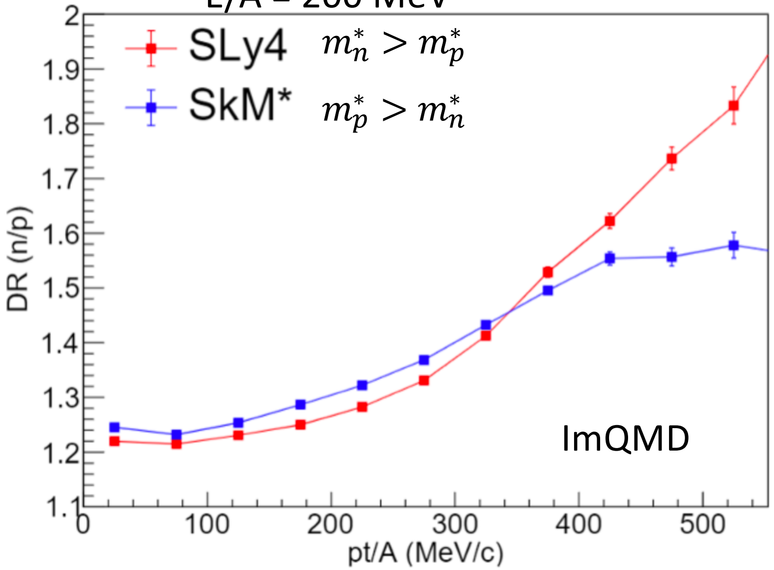
Constraining the momentum dependence of the symmetry energy and n/p effective masses

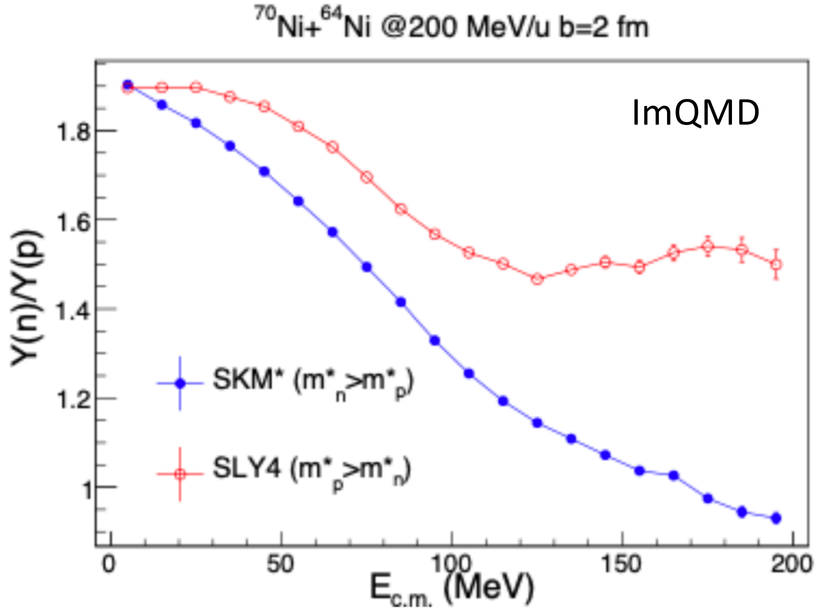
- Proposal signed FAZIAns:
  G. Verde, I. Lombardo, T. Marchi, D. Dell'Aquila @ INFN
  D. Gruyer, A. Chbihi, C. Ciampi, J.F. Ducret, Q. Fable @ IN2P3-GANIL
- Approved by PAC2 on February 2023 (^{56}Ni at 10^7 p/s and ^{70}Ni at $3x10^5$ p/s)
- To be run… 2024-2025 (?) → higher beam rates possible

Experiments at MSU: new – proposal 23058 @ PAC2



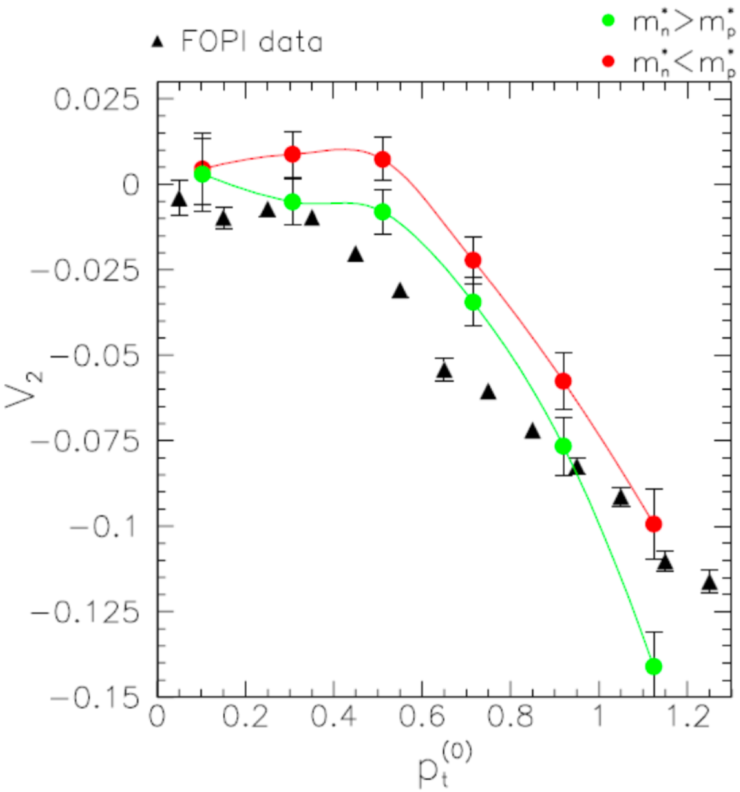
Experiments at MSU: new – proposal 23058 @ PAC2

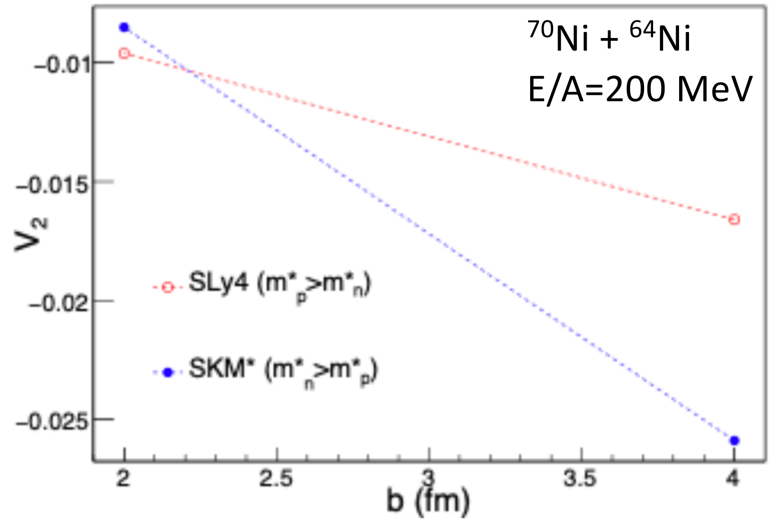




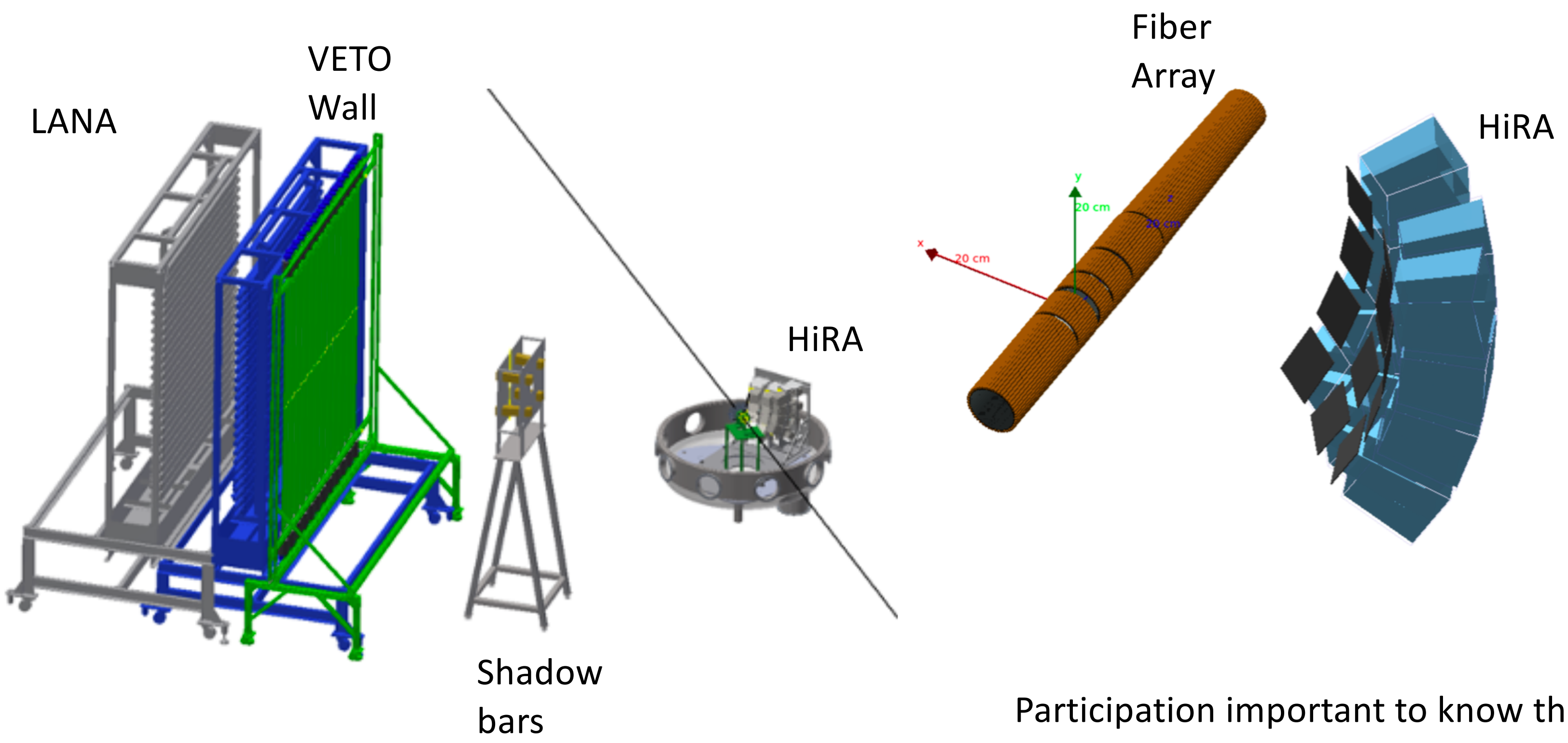
$$DR\ (n/p) = \frac{Y(^{70}Ni + {}^{64}Ni)}{Y(^{56}Ni + {}^{58}Ni)}$$

Experiments at MSU: new – proposal 23058 @ PAC2





Experiments at MSU: new – proposal 23058 @ PAC2



Participation important to know the lab and detectors

- LANA for neutrons, HiRA for correlations, …
- How to improve b, r.p., v1, v2, …?
- How to improve isotopic identification?
- How to reduce thresholds for spectator physics?

What now? a possible strategy to follow

(A) Beam Time request @ PAC3 + (B) LoI on longer term projects to be submitted possibly at next PAC (january 2024) – one document

Profit from the Presence of a EoS/Esym experts in the PAC (Yennello - TAMU)

Profit from the recent approval of 23058 proposal

- **(A) Already approved physics case + other ideas with heavier reaction systems: probing higher densities**

    Ex.: ^{132}Sn+^{124}Sn and ^{106}Sn+^{112}Sn @ E/A=200, 250… MeV

  Directed and elliptic flow; n/p ratios, t/^{3}He ratios, other isobar ratios (^{7}Li/^{7}Be, …); two-particle correlations for T and ρ; probes of σ_{NN}; other probes of Esym; clustering; SRC; …

What now? a possible strategy to follow

(A) Beam Time request @ PAC3 + (B) LoI on longer term projects to be submitted possibly at next PAC (january 2024) – one document

Profit from the Presence of a EoS/Esym experts in the PAC (Yennello - TAMU)

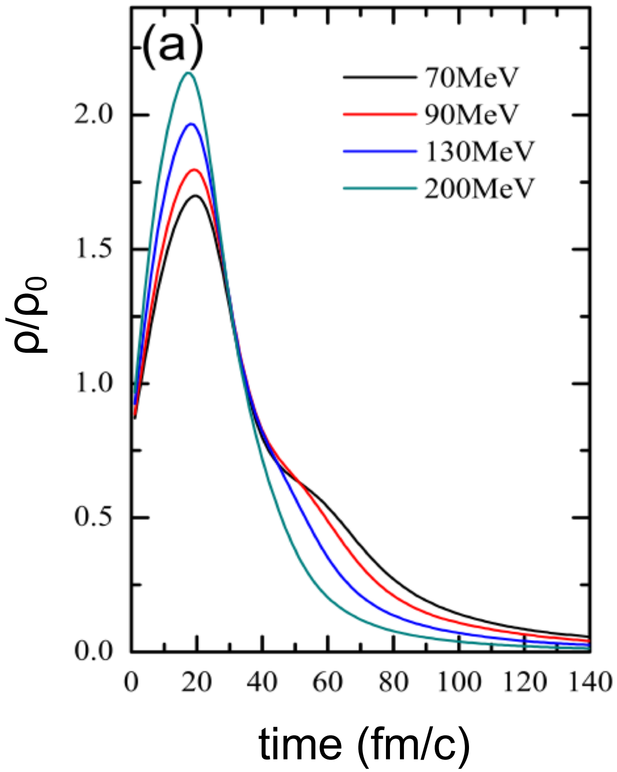
Profit from the recent approval of 23058 proposal

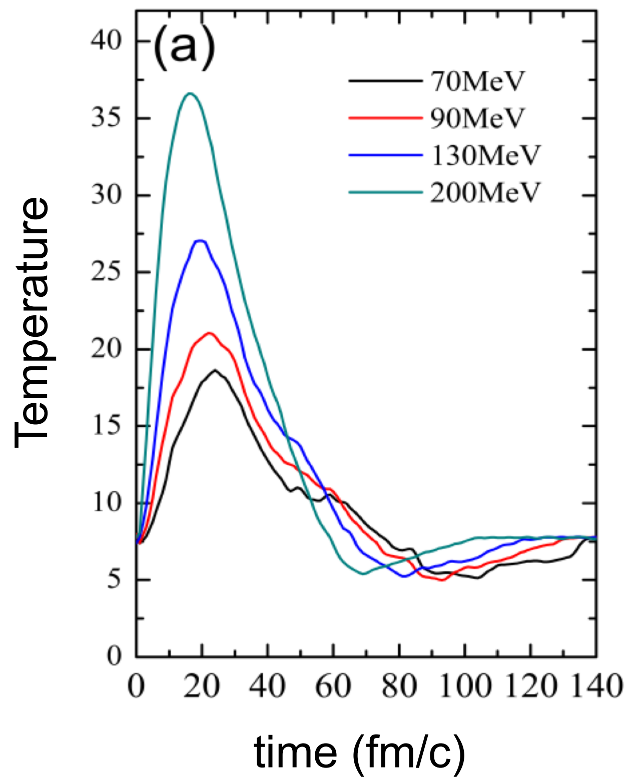
- **(B) Extend to campaigns of measurements à-la-INDRA**
  - beam energy scan, mass and isospin scan, etc.
  - Push towards maximum possible beam energy (300 MeV/nucleon ?)
  - Explore possibility to run at E/A<100 MeV (beam tracking event-by-event necessary) → IsoDiff, IsoDrift, QP breakup, etc…
  - Link to the FRIB400 phase
  - Experimental needs (chamber, detectors, etc.)

What do we need?

- ***Good simulations: transport models***
  - Expressed interest by ***AMD*** (Akira and TadaAki @ Japan), ***ImQMD*** (Yingxun Zhang@China), ***BUU*** (Rui Wang, Maria @ Italy) → some simulations are ongoing right now
- ***Deep thinking about experimental setup***
  - Do we use what we have or modify the detectors?
  - Build new detectors? Change of paradigm for 4pi detection systems?
  - Coupling to neutron detectors (LANA, Mona Lisa), to HiRA for correlations, …
  - FAZIA-like blocks for target spectators or participant (symmetric to HiRA)…
  - Etc…

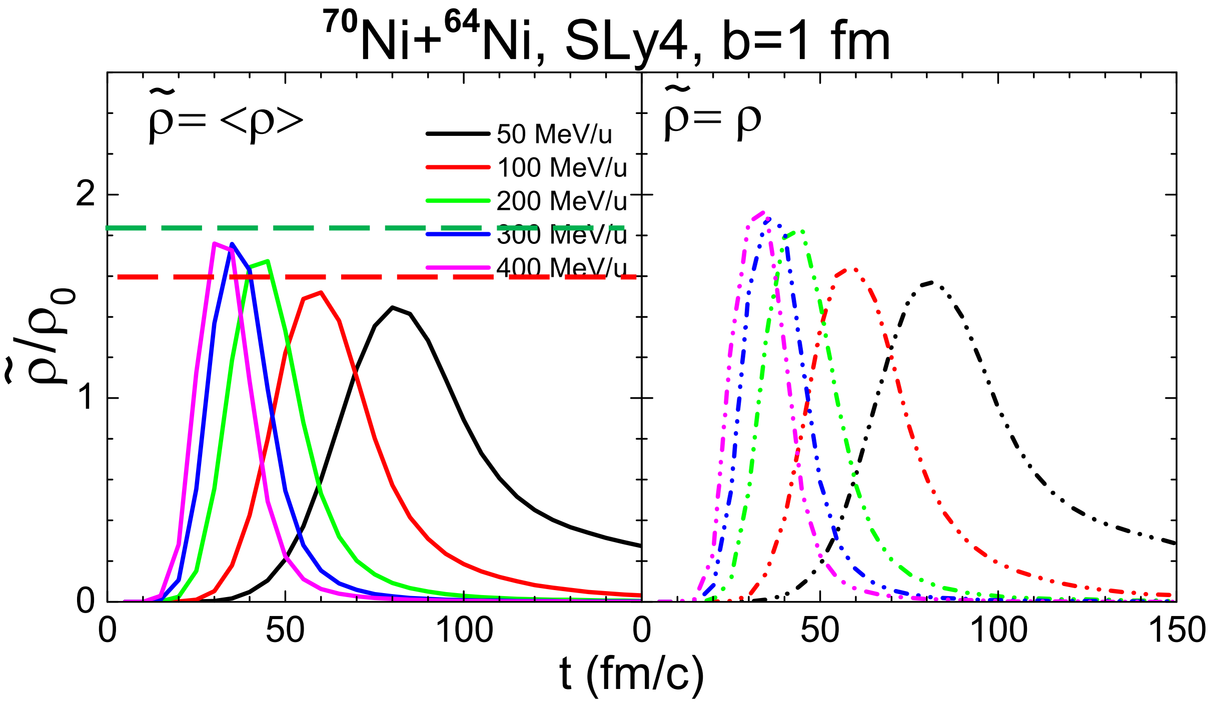
About temperatures and densities Vs. E_{beam}





Central b=1 fm
Au + Au
QMD sims

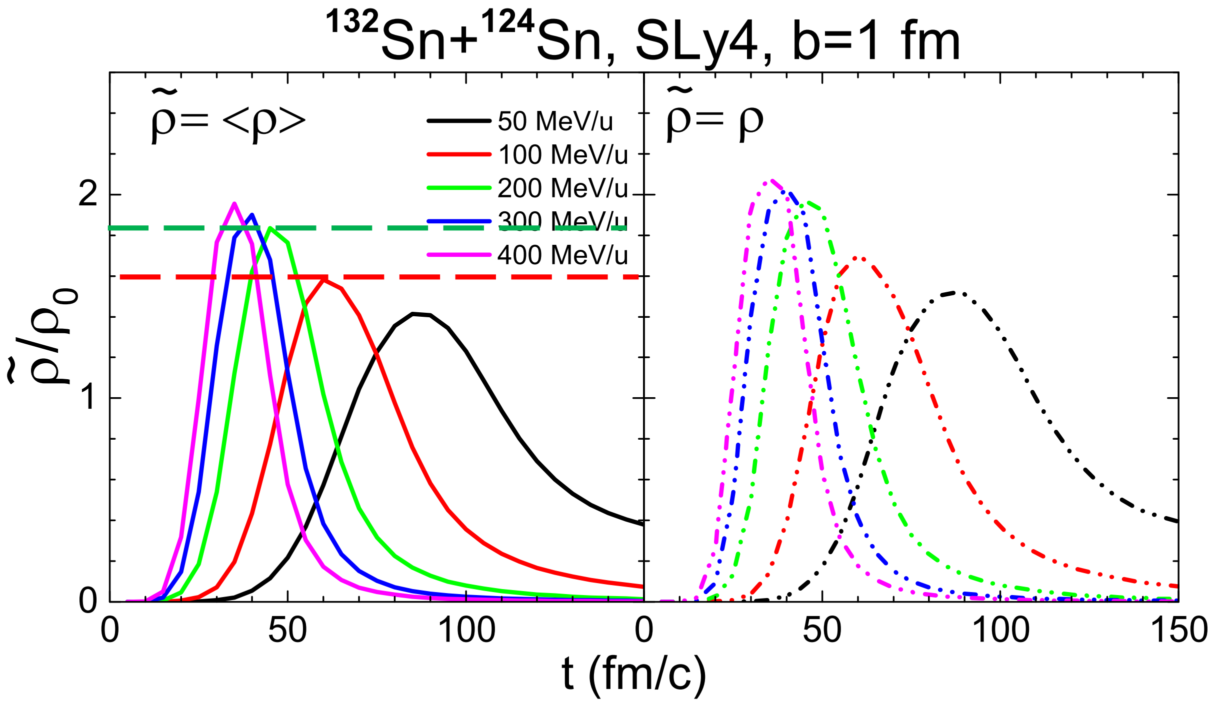
Density increases with mass - NiNi



ImQMD

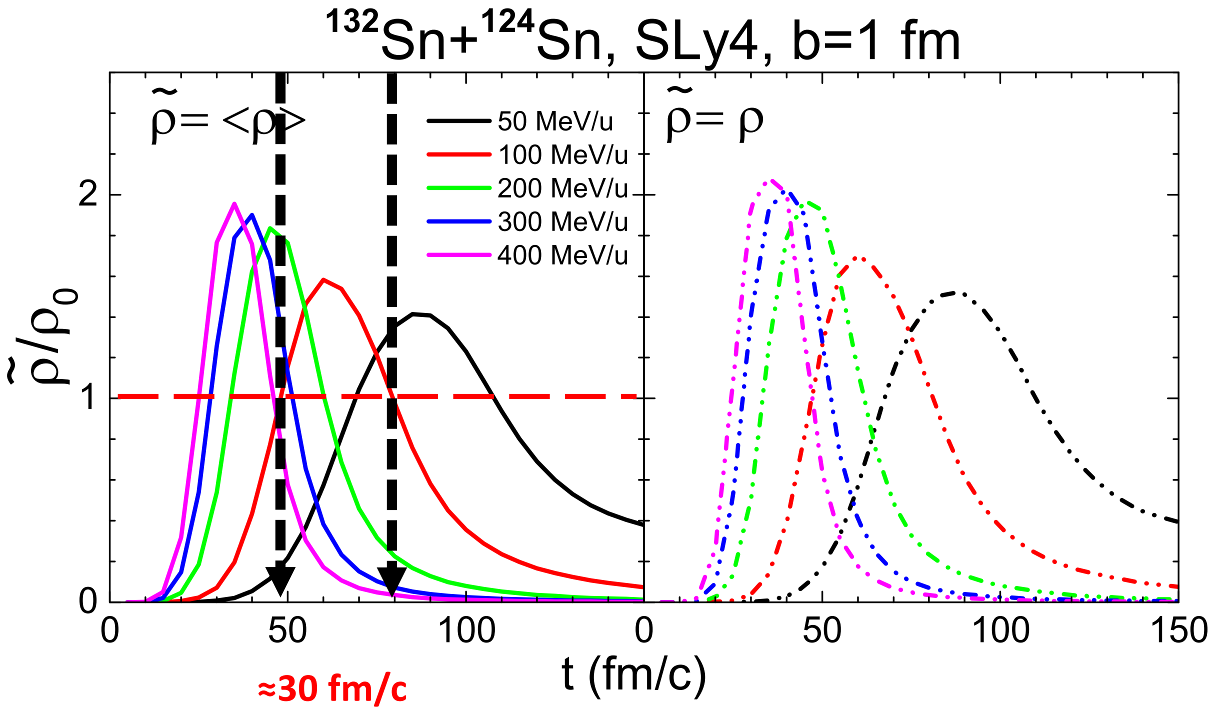
Density increases with mass - SnSn

ImQMD



Time at supra-sat densities – SnSn 100 MeV/u

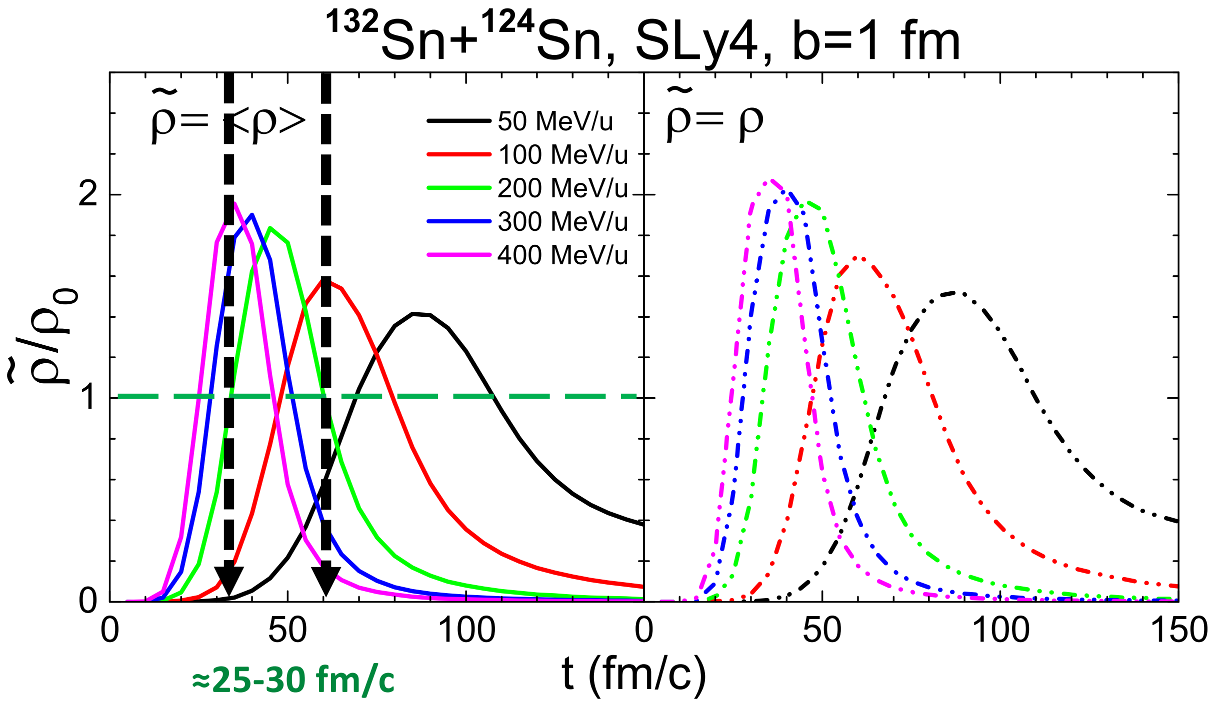
ImQMD



≈30 fm/c

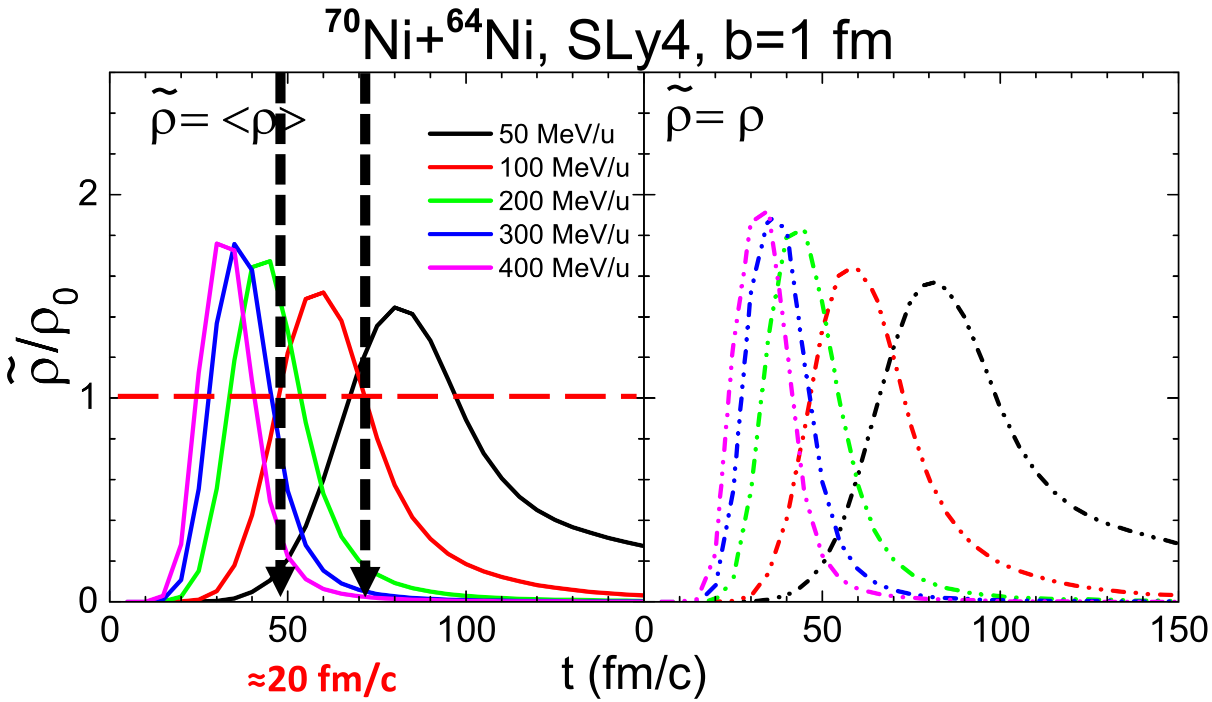
Time at supra-sat densities – SnSn 200 MeV/u

ImQMD

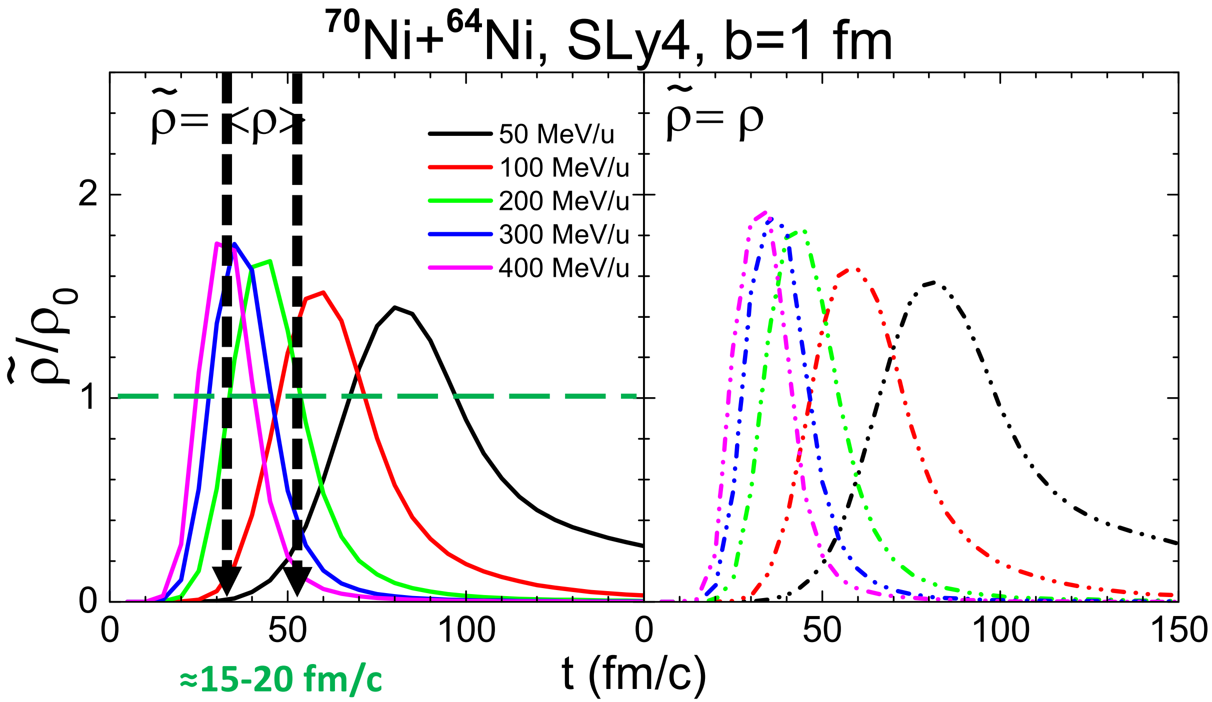


Time at supra-sat densities – NiNi 100 MeV/u

ImQMD



Time at supra-sat densities – NiNi 200 MeV/u



ImQMD

Maximum densities and times

Maximum average density

	100 MeV/u	200 MeV/u
Sn + Sn	1.6	1.8
Ni + Ni	1.55	1.65

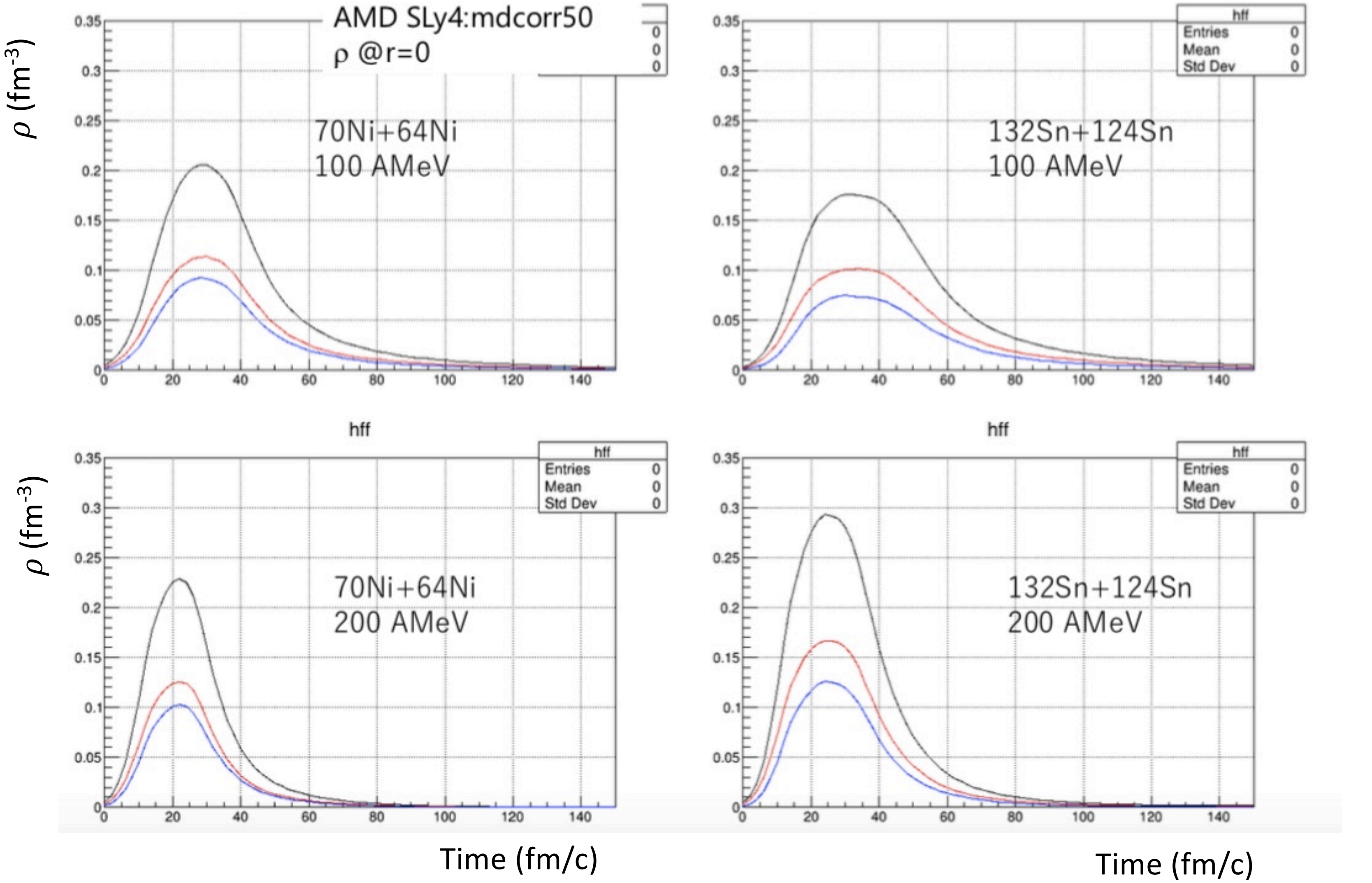
Time window at supra-saturation densities

	100 MeV/u	200 MeV/u
Sn + Sn	30 fm/c	25-30 fm/c
Ni + Ni	20 fm/c	15-20 fm/c

Seems to be mostly determined by t_{exit} (almost same t_{enter})

AMD simulations: densities

TadaAki Isobe, Akira Ono, 21-06-23



Transport model analysis

- Obtain the event files and analyse them with our own analysis programs
- Filter with exp setup
- check b determination procedures (see Quentin's recent work on AMD @INDRA-VAMOS)
- Compare to INDRA@GSI to validate some simulation aspects
- *Check observables and sensitivity to physics information (Esym, σ_{NN}, m_n^*/m_n^*, …)*

What now? a possible strategy to follow

- ***(A) Beam Time request @ PAC3 + (B) LoI on longer term projects***
  - Profit from the presence of a EoS/Esym expert in the PAC (Yennello -TAMU)
  - Probe higher densities with heavier reaction systems (and higher energies)
    - $^{132}Sn+^{124}Sn$ and $^{106}Sn+^{112}Sn$ → improved event characterization

Strategy: LoI with beam time

- **(A) Beam Time request @ PAC3**
  - Profit from the presence of a EoS/Esym expert in the PAC (Yennello -TAMU)
  - Probe higher densities with heavier reaction systems (and higher energies)
    - $^{132}Sn+^{124}Sn$ and $^{106}Sn+^{112}Sn$ → improved event characterization
- (B) LoI: ranges of beam energies and masses/isospin asymmetries
  - **Ranges of ρ and *T*** depending on E/A, b, N/Z… à la «INDRA campaigns»
    - Ranges of Sn, Xe, Ni, Kr…. With transport model support
  - Possible to run at E/A<100 MeV (beam tracking needed)→ **IsoDiff, IsoDrift, QP breakup**
  - Open problems on ***T*** and ***phase transitions*** (@ GSI and NSCL, …)
  - Open problems from ***INDRA-GSI projects***
  - Inclusion of other **non-EoS physics cases**

Organize collaboration meeting/Workshop at MSU in October/November… (Z. Chajecki and G. Verde)
We need to give some inputs to fix dates (possibly right after these FAZIA Days)

Some open problems on temperature and density measurements (ALADiN, FOPI, HodoCT@ NSCL,…)

- Nuclear temperatures, caloric curves and phase transitions
  - Comparisons between different thermoemters: problem or physics?
  - N/Z dependence of caloric curves?
  - Spectator matter and participant matter involved
- Nuclear densities
  - Multiple particle-particle correlations in spectator matter
  - Effects of Esym on two-particle correlations
  - Effects of σ_{NN} on two-particle correlations

Thermomethers and caloric curves: target spectators – the problem of low E thresholds

T and fragmentation features independent of beam energy for E/A>200 MeV

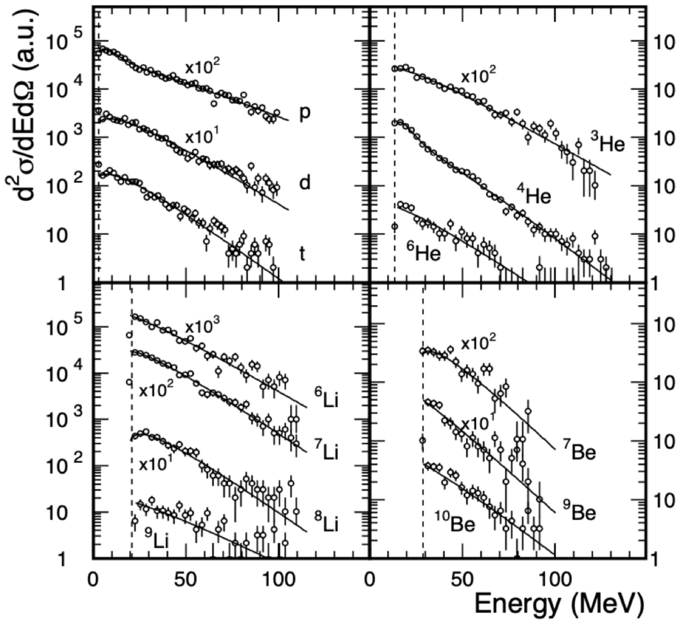


FIG. 2. Energy spectra of light charged particles and fragments with $Z \leq 4$ integrated over $20 \leq Z_{\mathrm{bound}} \leq 60$ ($\theta_{\mathrm{lab}} = 150°$). The full lines represent the fit results, and the dashed lines indicate the trigger threshold of the 300-μm detector. The same normalization is used for all spectra.

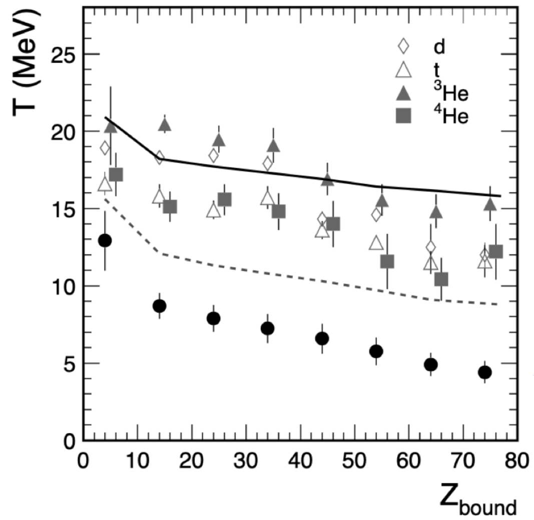


FIG. 4. Slope temperatures for light charged particles of mass $2 \leq A \leq 4$ (squares, triangles, and diamonds) and the isotope temperature T_{HeLi} (dots) as a function of Z_{bound}. The lines give the predictions for the fast breakup of a Fermi gas with finite temperature T_{HeLi} and with densities $\rho/\rho_0 = 1.0$ (full line) and 0.3 (dashed).

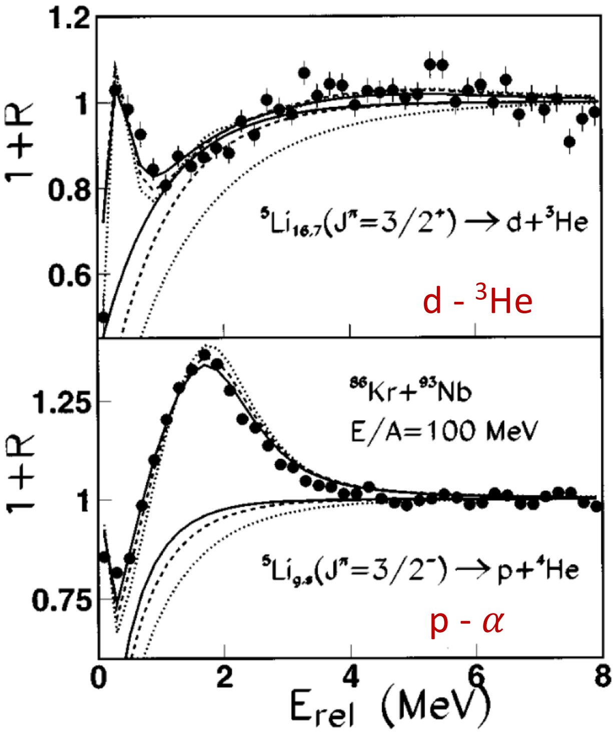
Interesting also for CNAO experiments at 400 MeV(nucleon

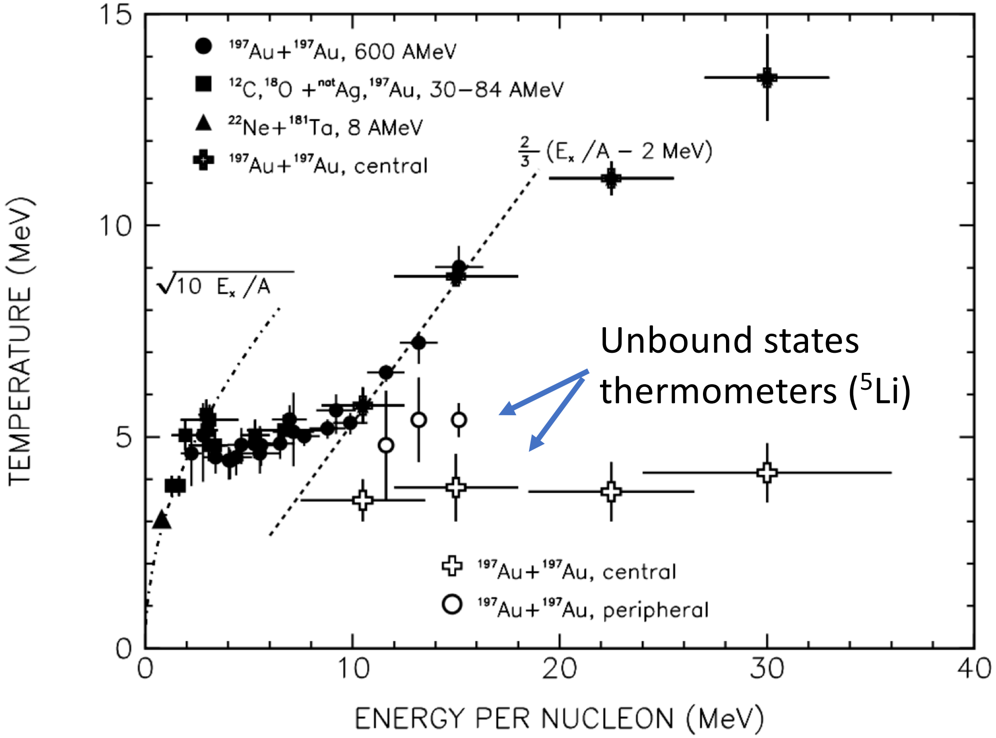
T_{HeLi}

T. Odeh et al., ALADiN, PRL84, 4557 (2000)

Unbound states thermometers in spectators

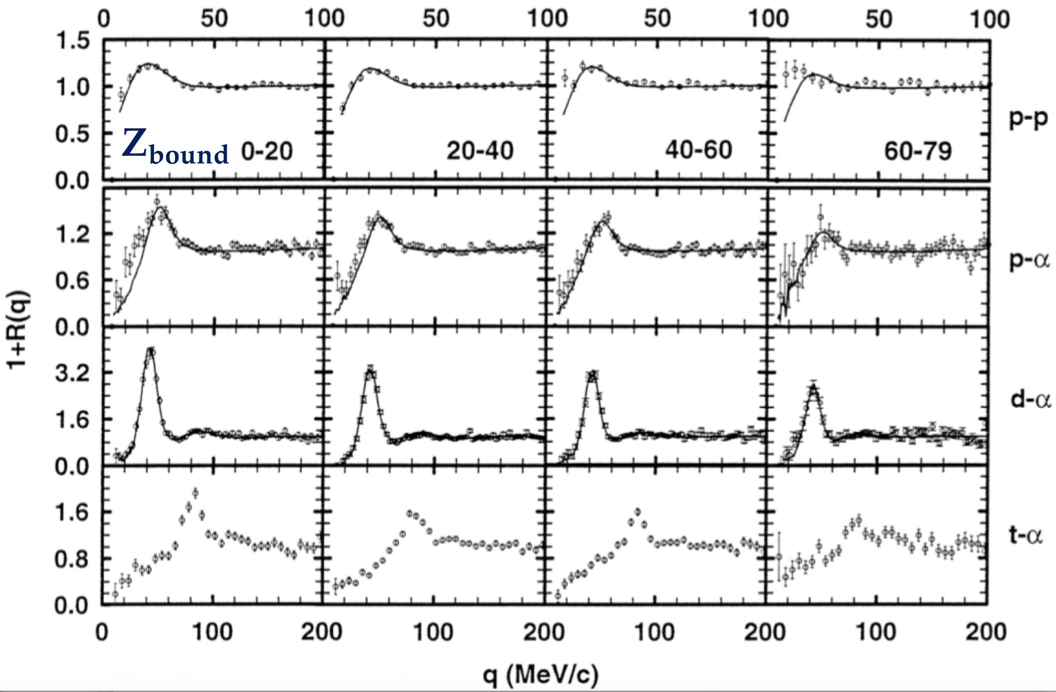
Particle-particle correlations





Densities in spectator matter

Target spectators in Au+Au E/A=1 GeV



Central
E* high

Peripheral
E* low

Correlation function

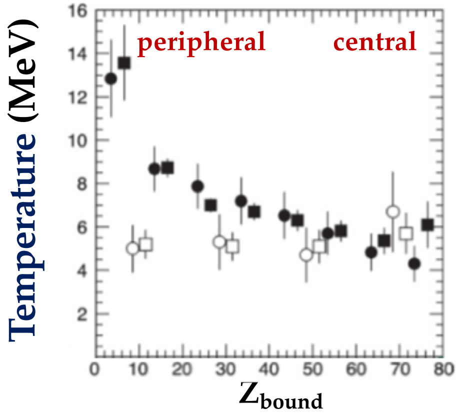
$$1 + R(q_{rel}) = \frac{Y_{coinc}(a,b)}{Y_{evt\ mixing}(a,b)}$$

→ Volume, Density, Spin

Densities in spectator matter

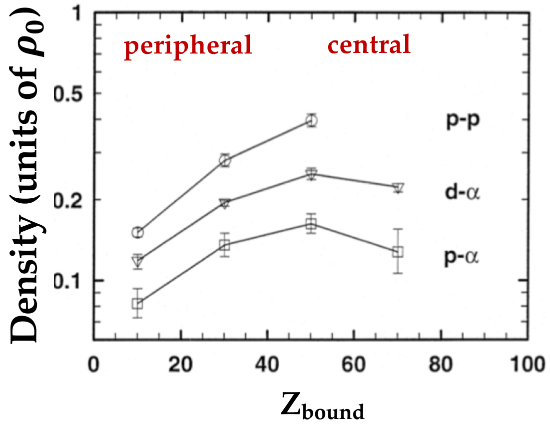
Target spectators in Au+Au   E/A=1 GeV

Temperatures



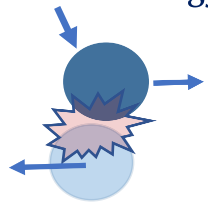
More peripheral

Densities



More peripheral

Z_{bound}≈Z of spectators
→ excitation energy

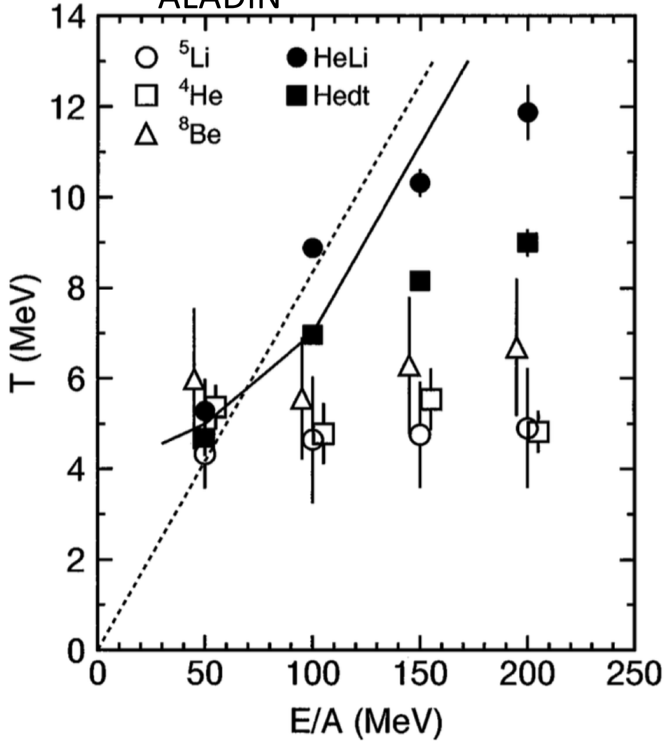


ALADiN Collaboration (G.V. PhD Thesis)

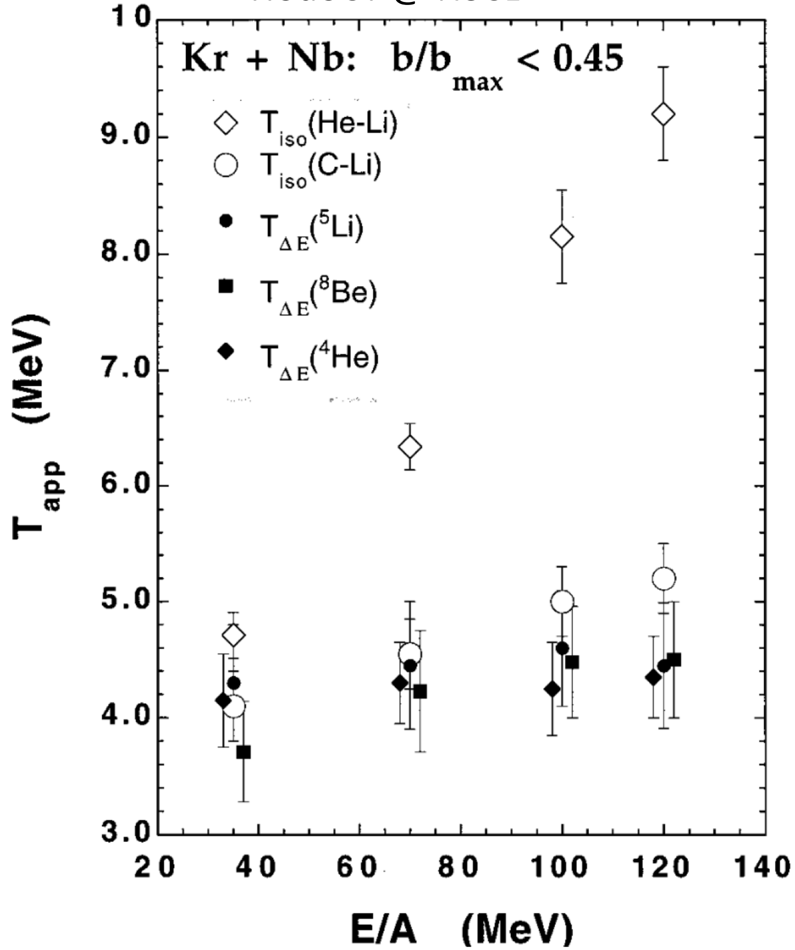
S. Fritz et al, PLB461, 315 (1999)
W. Trautmann et al., PRC76, 064606 (2007)

Temperatures in participant matter

Au + Au central @ GSI
ALADiN



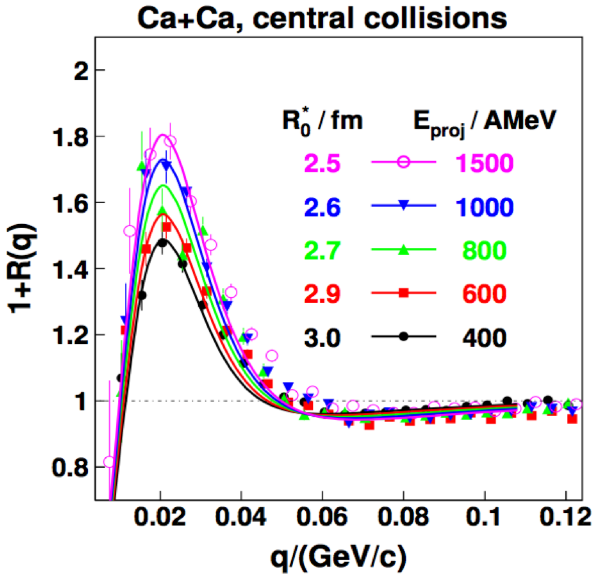
HodoCT @ NSCL



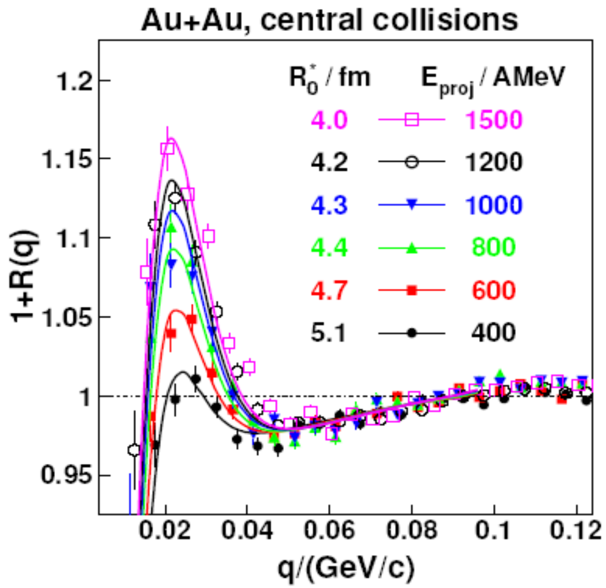
Densities in participant matter

FOPI data (Gaussian sizes: need new techniques)

Ca+Ca E/A=400-1500 MeV



Au+Au E/A=400-1500 MeV



Density

Density

- Increasing density with E_{beam}? $\rho/\rho_0 \sim 0.2 \rightarrow 0.4$

R. Kotte et al., Eur. Phys. J.A23, 271 (2005)

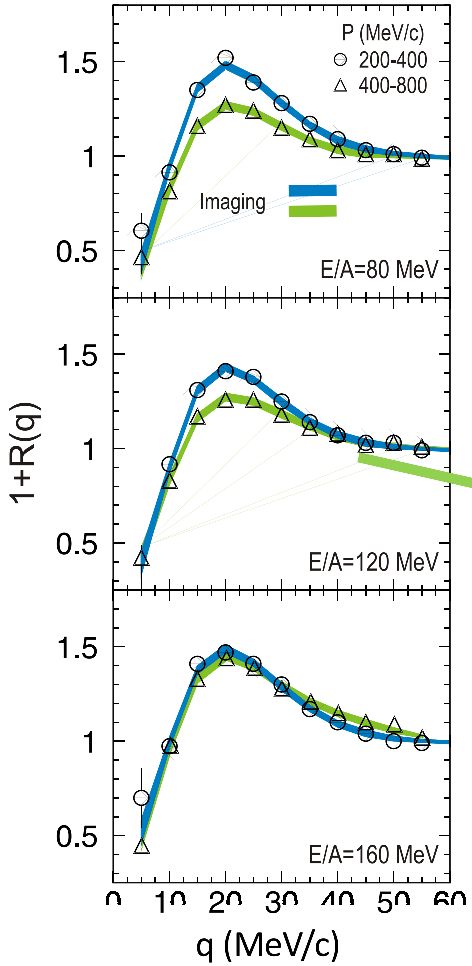
σ_{NN} and pp correlations

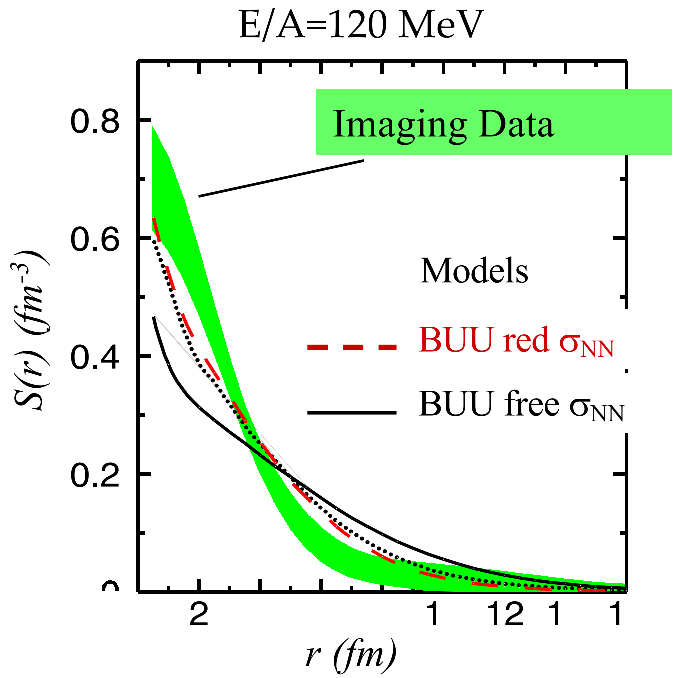
Ar + Sc central

E/A= **80 MeV**

120 MeV

160 MeV





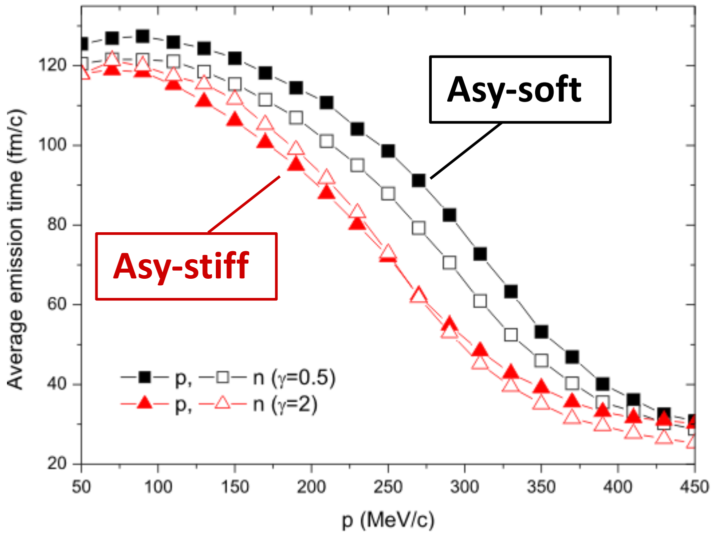
Source shape sensitive to σ_{NN}

G. Verde, P. Danielewicz et al., Phys. Rev. C67, 034606 (2003)

Symmetry energy and NN correlations

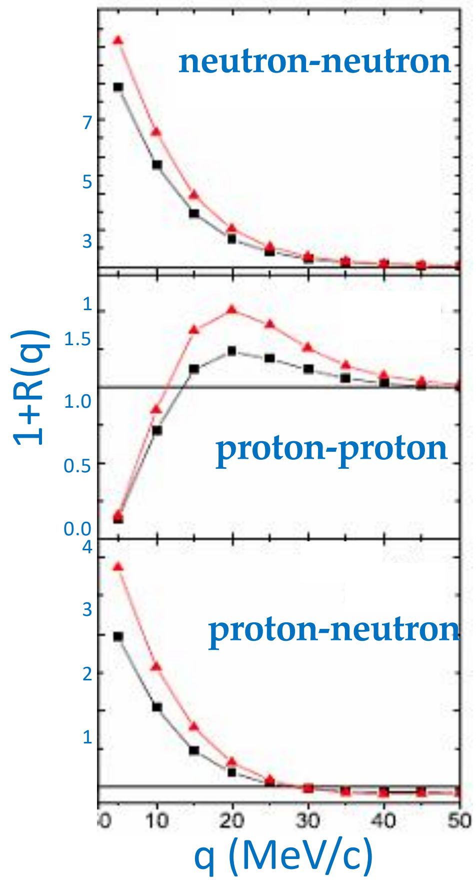
IBUU simulations

$^{52}Ca+^{48}Ca$ E/A=80 MeV Central collisions



Lie-Wen Chen et al., PRL (2003); PRC(2005)

Correlation functions



Need to check sensitivity in transport models

Not only EoS

- Other non-HIC physics might be involved in the project
  - **Clustering and nuclear struture with radioactive beams**
  - **Double-charge exchange reactions to study the nuclear matrix elements in neutrino-less double-beta decay**: part of the NUMEN project @ INFN-LNS
    - ✓ F. Cappuzzello and G. Verde (Italy), R. Zegers (MSU), H. Lenske (Germany)
    - ✓ Reaction to be studied with triton secondary beams @ FRIB:

      t + 3He → 3 protons + 3 neutrons

      Measurement of DCE cross section

      Three-proton correlations in the final state (what detectors?)

      Maybe 3 neutron detection for complete reaction kinematics…
    - ✓ **FAZIA may play an important role**

A possible strategy (recommended by MSU colleagues)

- **(A) Proposal + (B) LoI →** end of January 2024 – one unique document
- **(A) Proposal**
  - Use the same physics case (alerady accpeted and understood by the PAC) but heavier reaction system to be more sensitive to higher densities: *$^{132}Sn+^{124}Sn$, $^{106}Sn+^{112}Sn$ @ 175-200 MeV/u (10^5-10^7 pps) or similar*
  - Transport model simulations and INDRA-GSI data to validate models and understand experimental needs
- **(B) LoI with physics cases**
  - Campaigns with varying beam energy, $(N,Z)_{Proj}/(N,Z)_{Targ}$, etc.
  - Transport models, new detectors or modifications of existing ones?

Organize collaboration meeting/Workshop at MSU in October/November… (Z. Chajecki and G. Verde)
We need to give some inputs to fix dates (possibly right after these FAZIA Days)