DJBUU:
A new transport model for RAON experiments

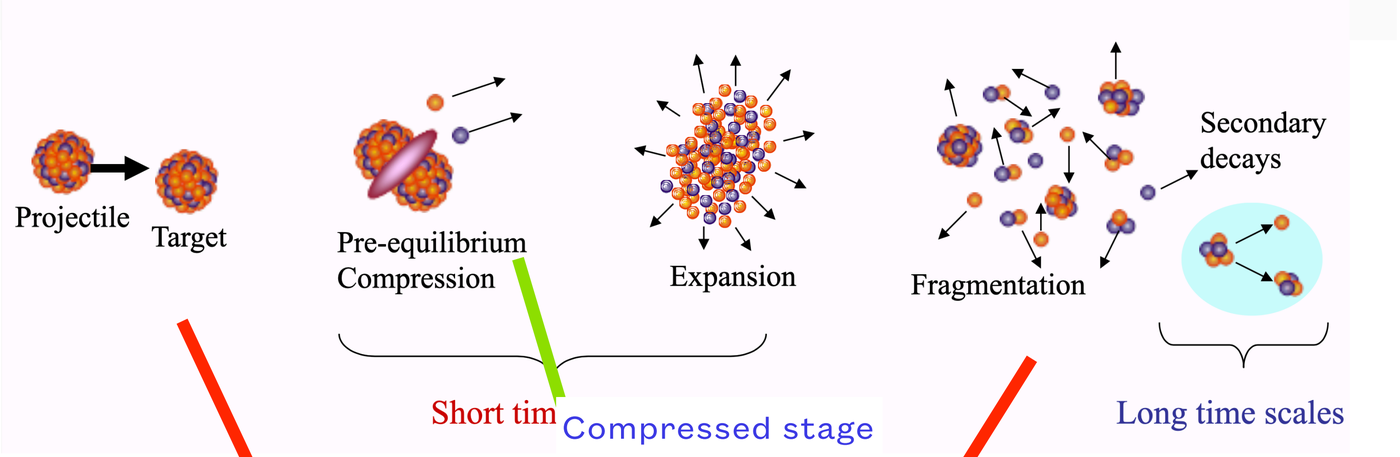
Myungkuk Kim (김명국)
Center for Exotic Nuclear Studies, IBS

in collaboration with S. Jeon, C.-H. Lee, Y. Kim and Y.-M. Kim

Content

- Introduction
- Transport theory / DJBUU model
- Results comparison with TMEP
- For RAON experiments

Heavy-ion collisions: why study?



Compressed stage

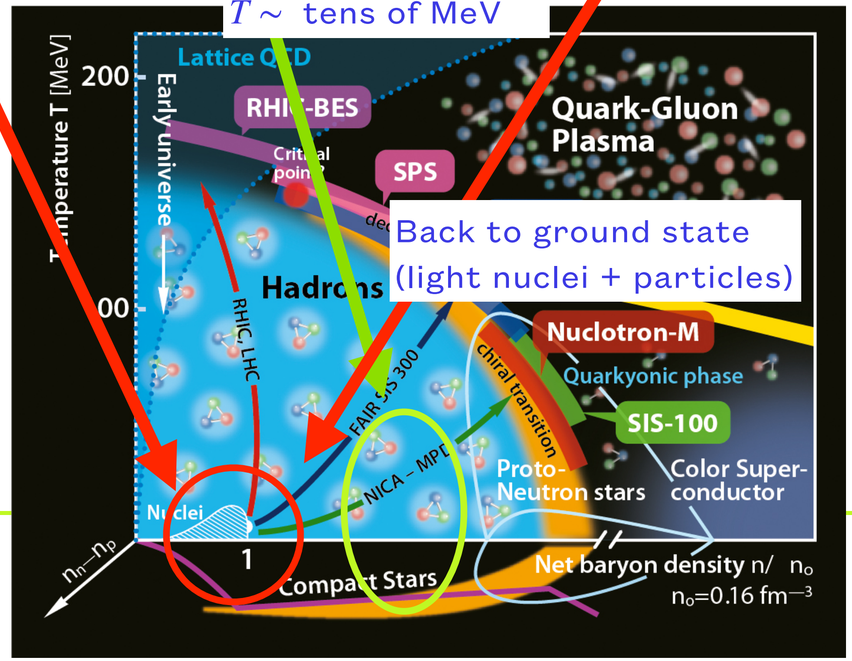
$\rho \sim$ a few ρ_0

$T \sim$ tens of MeV

Initial stage

$\rho_0 = 0.16$ fm^{-3}

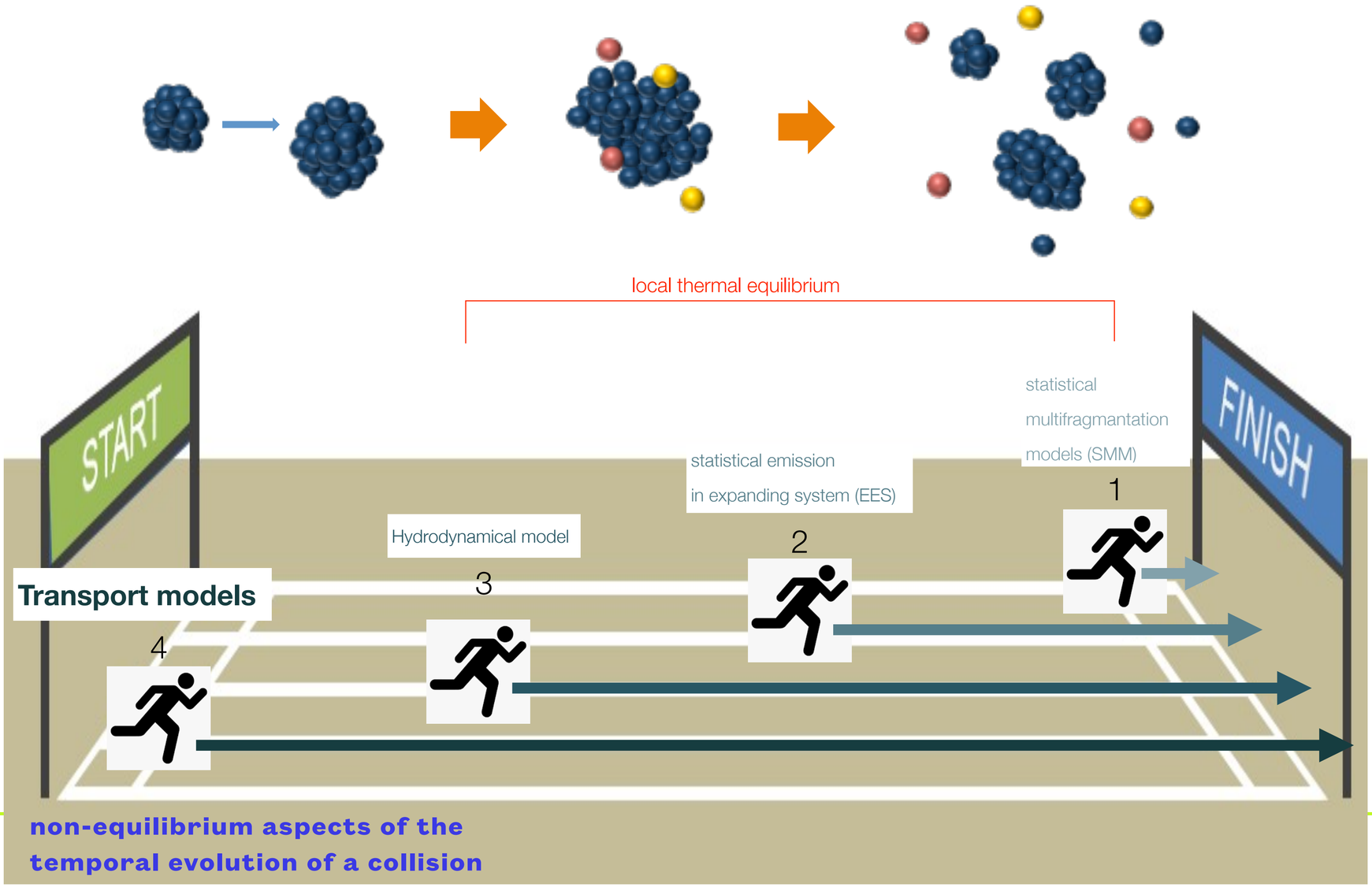
$T \sim 0$ MeV



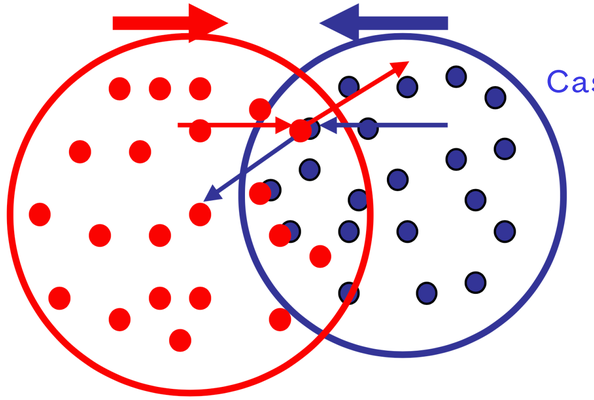
Back to ground state
(light nuclei + particles)

- explore phase diagram of strongly interacting matter in the hadronic sector
- nuclear matter above saturation: EOS & hadronic properties in dense medium
- importance for astrophysics: SN and NS

Levels of descriptions in HICs

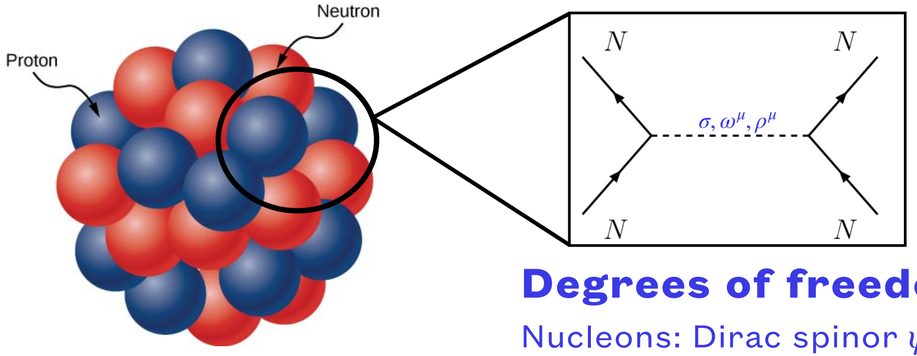


Collisions and microscopic interactions



Cascade model

- simple and first model focusing only *NN* collisions (no interactions)
- collision criterion: point of closest approach (Bertsch prescription)
- scattering can be elastic or inelastic
- giving great insight of heavy-ion physics



Degrees of freedom

Nucleons: Dirac spinor ψ

Interaction: $\sigma, \omega^\mu, \rho^\mu$ mesons

- free Lagrangian for Dirac field + interaction Lagrangian for meson field

$$\left[i\gamma_\mu \partial^\mu - \underbrace{(m_N + g_\sigma \sigma)}_{\text{Dirac mass, effective mass, } m^*} - g_\omega \gamma_0 \omega^0 - g_\rho \gamma_0 \tau_3 \rho_3^0 - \frac{e}{2}\gamma_0 (1+\tau^3) A^0 \right] \psi = 0$$

$$m_\sigma^2 \sigma + a\sigma^2 + b\sigma^3 = -g_\sigma \rho_S$$

$$m_\omega^2 \omega^0 = g_\omega \rho_B$$

$$m_\rho^2 \rho_3^0 = g_\rho \rho_{B,I3}$$

TABLE I. Parameter sets.

Parameter	Set I	Set II	NL3
f_σ (fm^2)	10.33	same	15.73
f_ω (fm^2)	5.42	same	10.53
f_ρ (fm^2)	0.95	3.15	1.34
f_δ (fm^2)	0.00	2.50	0.00
A (fm^{-1})	0.033	same	−0.01
B	−0.0048	same	−0.003

B. Liu et al. PRC 65, 045201

Relativistic transport equation (BUU eq.)

Aim: microscopic description of nucleus-nucleus collisions

$$(p^{*0})^{-1}\left[p^{*\mu}\partial_\mu - \underbrace{\left(p^{*\mu}\mathscr{F}^{\mu i} - m^*\partial^i m^*(x)\right)}_{\text{under the RMF potential}}\frac{\partial}{\partial p^{*i}}\right]\underbrace{f(\vec{x},\vec{p}^*)}_{\text{propagation of } f(x,p^*)} = \underbrace{C(\vec{x},\vec{p}^*)}_{\text{up to 2-body coll.}}$$

cross sections

$$C^{(2)}(\vec{x},\vec{p}_1) = \frac{1}{2}\int\frac{d^3p_2}{(2\pi)^3 2p_2^0}\int\frac{d^3p_{1'}}{(2\pi)^3 2p_{1'}^0}\int\frac{d^3p_{2'}}{(2\pi)^3 2p_{2'}^0}\left|\mathscr{M}_{12\to 1'2'}\right|^2(2\pi)^4\delta(p_1+p_2-p_{1'}-p_{2'})$$

energy cons.

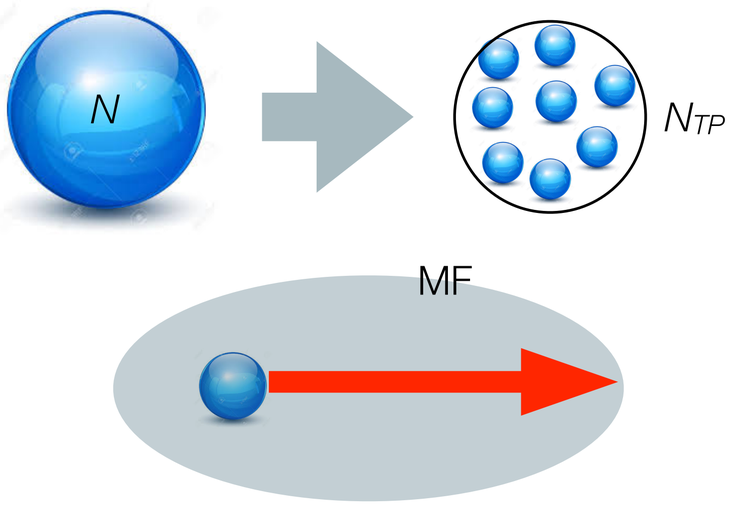
$$\left[f_{1'}(\vec{x},\vec{p}_{1'})f_{2'}(\vec{x},\vec{p}_{2'})\tilde{f}_1(\vec{x},\vec{p}_1)\tilde{f}_2(\vec{x},\vec{p}_2) - f_1(\vec{x},\vec{p}_1)f_2(\vec{x},\vec{p}_2)\tilde{f}_{1'}(\vec{x},\vec{p}_{1'})\tilde{f}_{2'}(\vec{x},\vec{p}_{2'})\right]$$

Pauli blocking

- possible collisions up to two-body collisions
- uncorrelated momenta of two incoming (p_1, p_2) as well as outgoing ($p_{1'}$, $p_{2'}$)
- local collisions in time & space ($x_i = x_{i'}$)
- Pauli exclusion principle in collision term by 1-f(x,p)

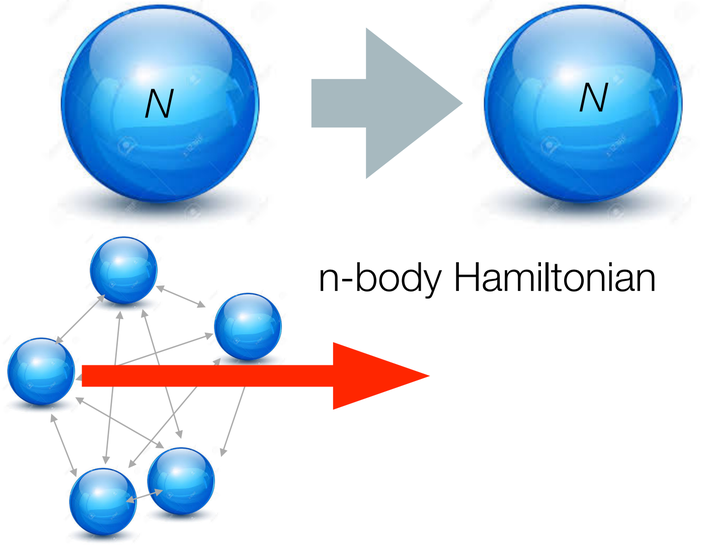
Transport model and families

Boltzmann-Uehling-Uhlenbeck (BUU)



- nucleons divided by N_{TP}
  (infinite N_{TP} = exact solution of BUU eq.)
- 1-body phase-space function under MF potential
- Point or finite size of particles

Quantum Molecular Dynamics (QMD)



- Gaussian wave packets (N_{TP} = 1)
- n-body Hamiltonian
- Correlation & fluctuations

What DJBUU is

Philosophy: EASY HANDLING & OPTIMIZING to RAON experiments

- DaeJeon Boltzmann-Uehling-Uhlenbeck project
- Oct. 2015 - DJBUU project initiated by S. Jeon in RISP (C.-H. Lee and Y. Kim)
- Jan. 2016 - Primary version of DJBUU (c/c++)
- 2016 ~ 2017 - innumerable test runs by M. Kim (short article in New Physics: Sae Mulli)
  supporting parallel calculation by openMP
- 2018 - advertising and joining Transport Model Evaluation Project (TMEP)
- 2019 ~ 2020 - application of parity doublet model in HIC (dynamical properties)
- 2021 ~ - study of pion production and symmetry energy

Transport Model Evaluation Project

- Transport2014 (2014): Mainly 100A MeV, also 400A MeV Au+Au collisions. Stability, stopping, and flow of NN scatterings

Understanding transport simulations of heavy-ion collisions at 100*A* and 400*A* MeV: Comparison of heavy-ion transport codes under controlled conditions

PHYSICAL REVIEW C **93**, 044609 (2016)

Jun Xu,[1,*] Lie-Wen Chen,[2,†] ManYee Betty Tsang,[3,‡] Hermann Wolter,[4,§] Ying-Xun Zhang,[5,‖] Joerg Aichelin,[6] Maria Colonna,[7] Dan Cozma,[8] Pawel Danielewicz,[3] Zhao-Qing Feng,[9] Arnaud Le Fèvre,[10] Theodoros Gaitanos,[11] Christoph Hartnack,[6] Kyungil Kim,[12] Youngman Kim,[12] Che-Ming Ko,[13] Bao-An Li,[14] Qing-Feng Li,[15] Zhu-Xia Li,[5] Paolo Napolitani,[16] Akira Ono,[17] Massimo Papa,[18] Taesoo Song,[19] Jun Su,[20] Jun-Long Tian,[21] Ning Wang,[22] Yong-Jia Wang,[15] Janus Weil,[19] Wen-Jie Xie,[23] Feng-Shou Zhang,[24] and Guo-Qiang Zhang[1]

RBUU from Germany

- Transport2017 (2017): Box calculation of NN scatterings, mean-field evolutions, and pion-like particle production

Comparison of heavy-ion transport simulations: Collision integral in a box

PHYSICAL REVIEW C **97**, 034625 (2018)

Ying-Xun Zhang,[1,2,*] Yong-Jia Wang,[3,†] Maria Colonna,[4,‡] Pawel Danielewicz,[5,§] Akira Ono,[6,‖] Manyee Betty Tsang,[5,¶] Hermann Wolter,[7,#] Jun Xu,[8,**] Lie-Wen Chen,[9] Dan Cozma,[10] Zhao-Qing Feng,[11] Subal Das Gupta,[12] Natsumi Ikeno,[13] Che-Ming Ko,[14] Bao-An Li,[15] Qing-Feng Li,[3,11] Zhu-Xia Li,[1] Swagata Mallik,[16] Yasushi Nara,[17] Tatsuhiko Ogawa,[18] Akira Ohnishi,[19] Dmytro Oliinychenko,[20] Massimo Papa,[4] Hannah Petersen,[20,21,22] Jun Su,[23] Taesoo Song,[20,21] Janus Weil,[20] Ning Wang,[24] Feng-Shou Zhang,[25,26] and Zhen Zhang[14]

Comparison of heavy-ion transport simulations: Collision integral with pions and Δ resonances in a box

PHYSICAL REVIEW C **100**, 044617 (2019)

Akira Ono,[1,*] Jun Xu,[2,3,†] Maria Colonna,[4] Pawel Danielewicz,[5] Che Ming Ko,[6] Manyee Betty Tsang,[5] Yong-Jia Wang,[7] Hermann Wolter,[8] Ying-Xun Zhang,[9,10] Lie-Wen Chen,[11] Dan Cozma,[12] Hannah Elfner,[13,14,15] Zhao-Qing Feng,[16] Natsumi Ikeno,[17,18] Bao-An Li,[19] Swagata Mallik,[20] Yasushi Nara,[21] Tatsuhiko Ogawa,[22] Akira Ohnishi,[23] Dmytro Oliinychenko,[24] Jun Su,[25] Taesoo Song,[13] Feng-Shou Zhang,[26,27] and Zhen Zhang[25]

DJBUU from Korea

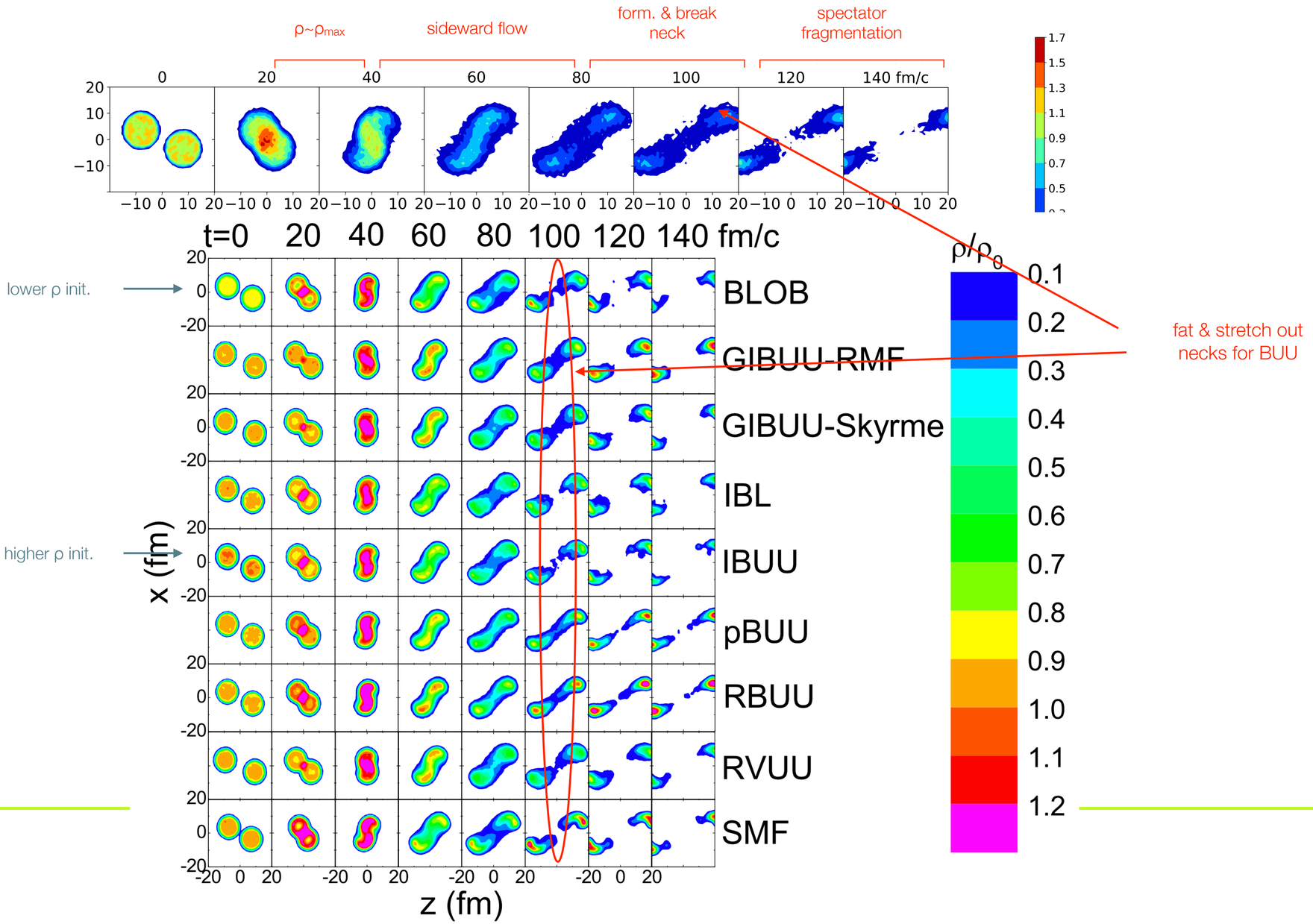
Comparison of heavy-ion transport simulations: Mean-field dynamics in a box

PHYSICAL REVIEW C **104**, 024603 (2021)

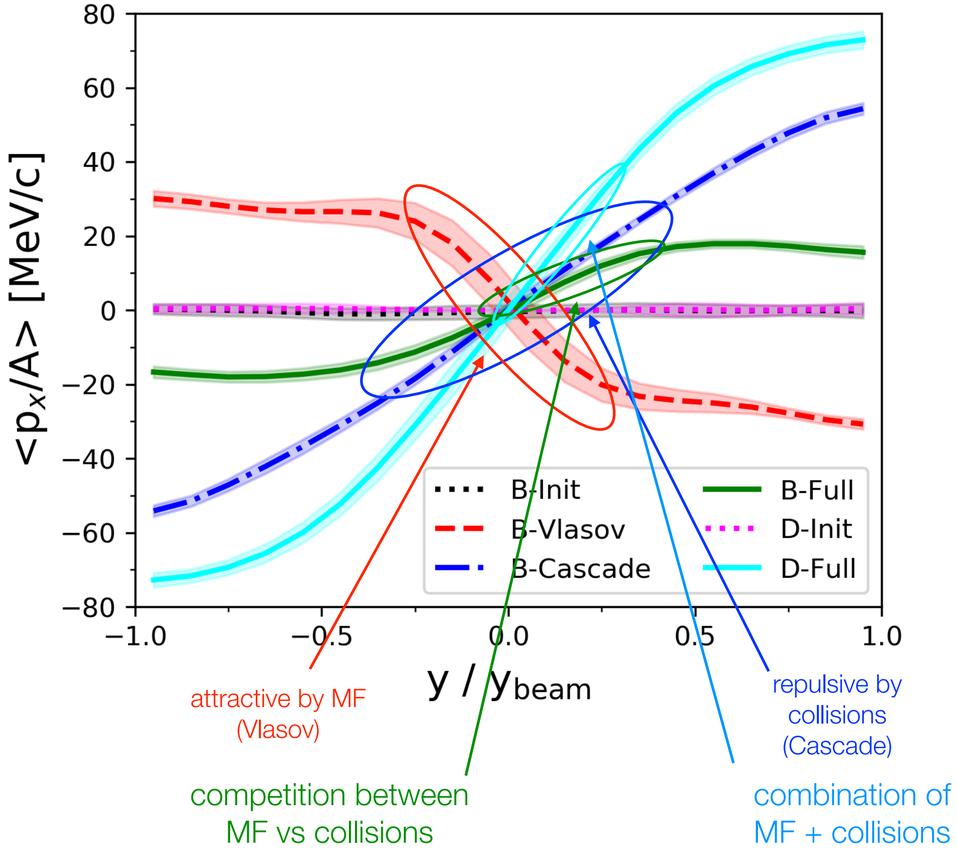
Maria Colonna,[1,*] Ying-Xun Zhang,[2,3,†] Yong-Jia Wang,[4,‡] Dan Cozma,[5] Pawel Danielewicz,[6,§] Che Ming Ko,[7] Akira Ono,[8,‖] Manyee Betty Tsang,[6,¶] Rui Wang,[9,10] Hermann Wolter,[11,#] Jun Xu,[12,9,**] Zhen Zhang,[13] Lie-Wen Chen,[14] Hui-Gan Cheng,[15] Hannah Elfner,[16,17,18] Zhao-Qing Feng,[15] Myungkuk Kim,[19] Youngman Kim,[20] Sangyong Jeon,[21] Chang-Hwan Lee,[22] Bao-An Li,[23] Qing-Feng Li,[4,24] Zhu-Xia Li,[2] Swagata Mallik,[25] Dmytro Oliinychenko,[26,27] Jun Su,[13] Taesoo Song,[16,28] Agnieszka Sorensen,[29] and Feng-Shou Zhang[30,31]

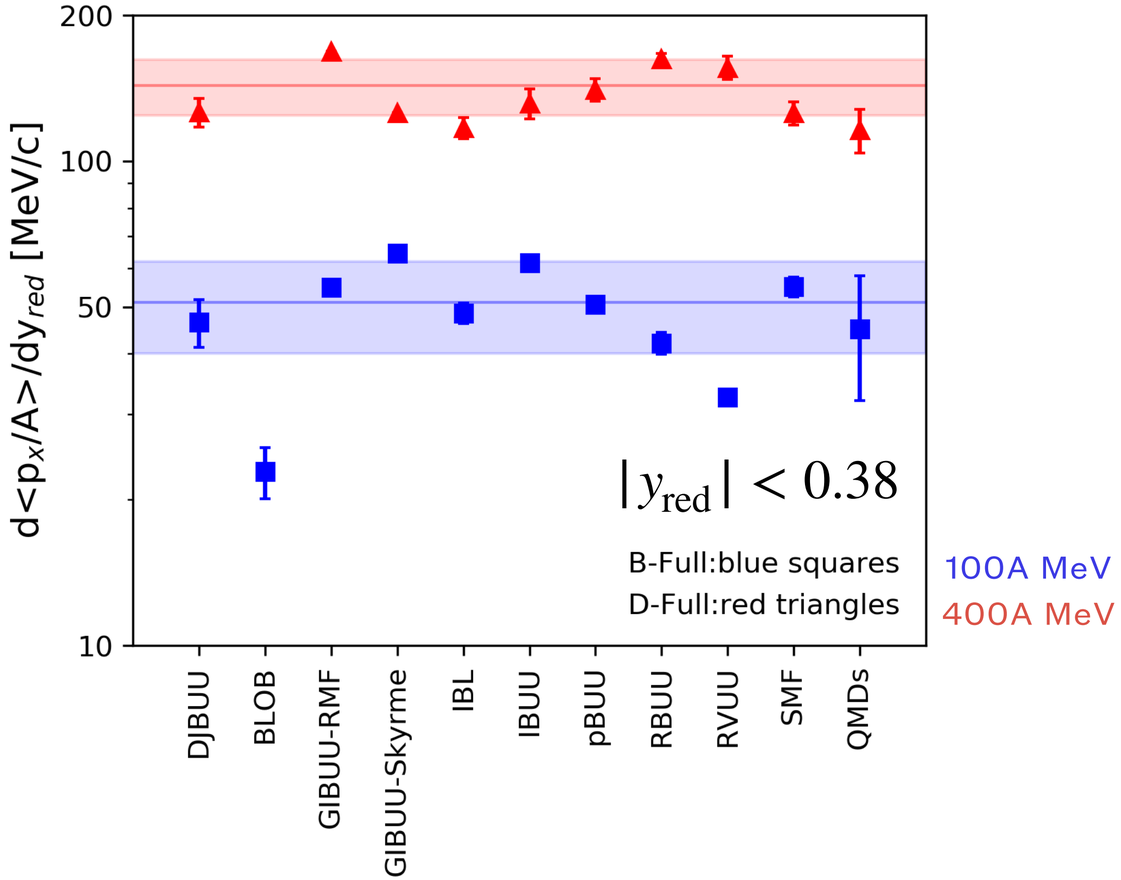
- Transport2019 (2019): production of pion-like particles at 270A MeV Sn+Sn collisions.

Average density in time steps of Au+Au @ 100A MeV



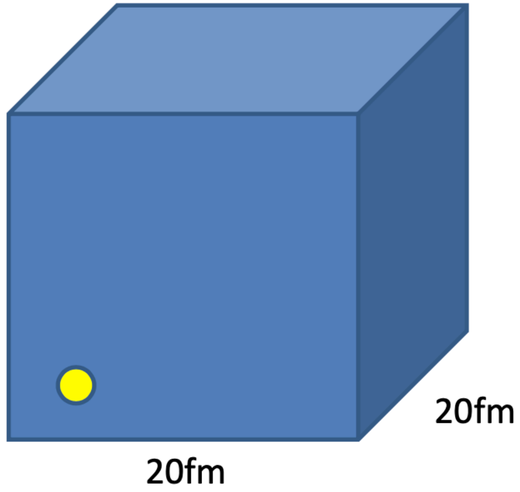
Transverse flow and slop parameter





- Theoretical uncertainties of flow parameter: about 30% at 100A MeV and 13% at 400A MeV
- What is the origin of the uncertainties? from collisions or interactions (MF)

Box calculations with periodic boundary conditions

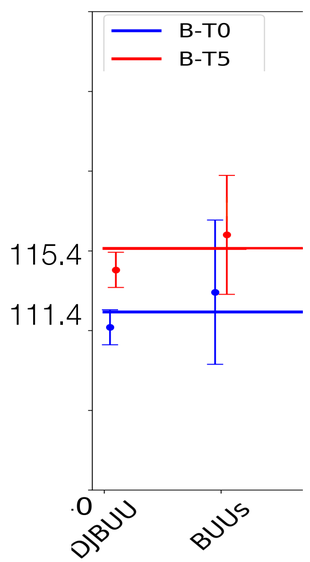


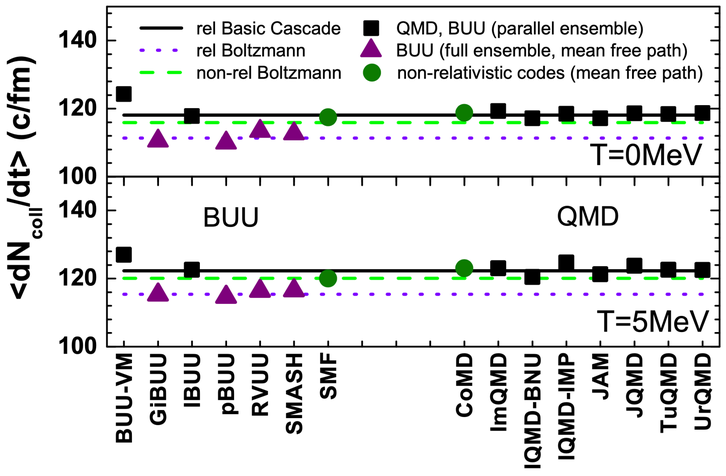
- Details of periodic boundary conditions
  - a box of volume V = L1*L2*L3, where the system is confined
  - the position of the center of box is (L1/2, L2/2, L3/2)
  - a particle leaving the box, entering the opposite side w/ same momentum (number of particle is conserved)
- Initialization
  - uniform density with $\rho_0 = 0.16$ fm^{-3}, with isospin asymmetry = 0 (1280 nucleons, 640 protons and 640 neutrons)

Box-Cascade calculation

without Pauli blocking

averaged over t=60-140 fm/c



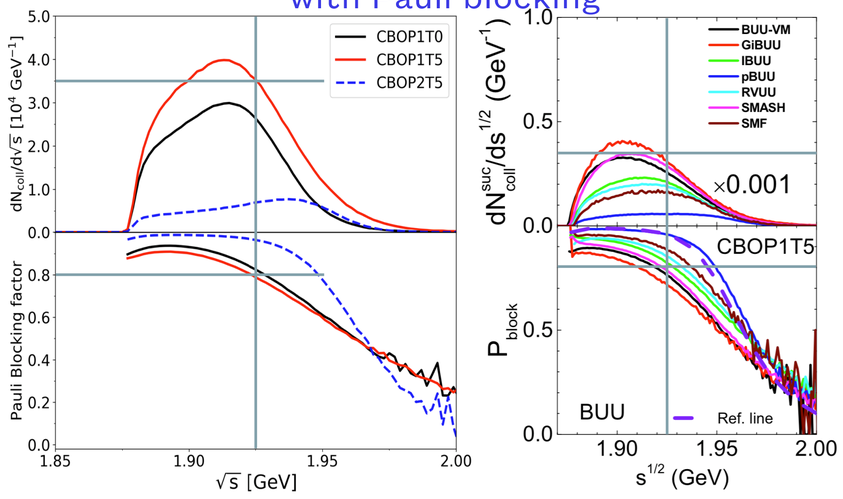


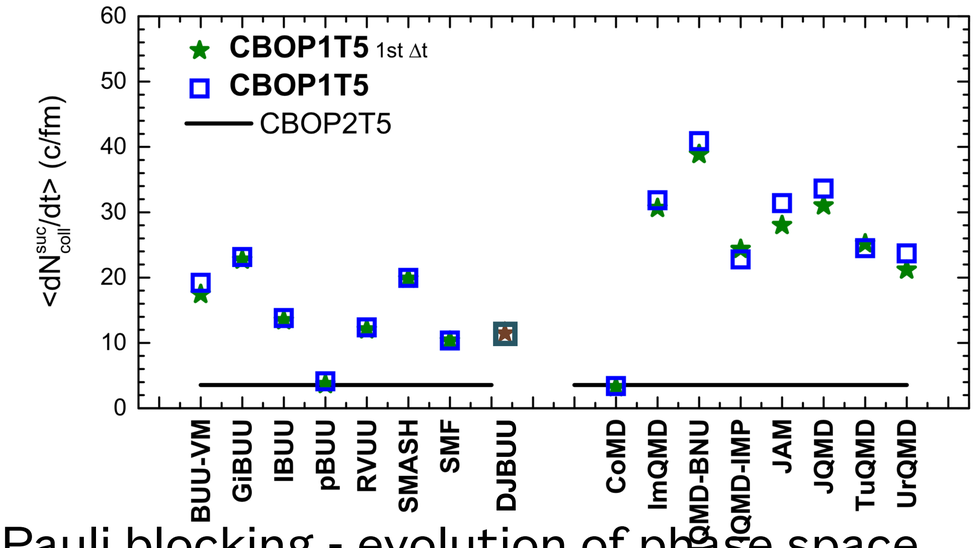
Y.X. Zhang, et al., PRC (2018)

comparable DJBUU with rel. kinetic theory

- well under control
- not essentially affect to results of HIC simulation

with Pauli blocking

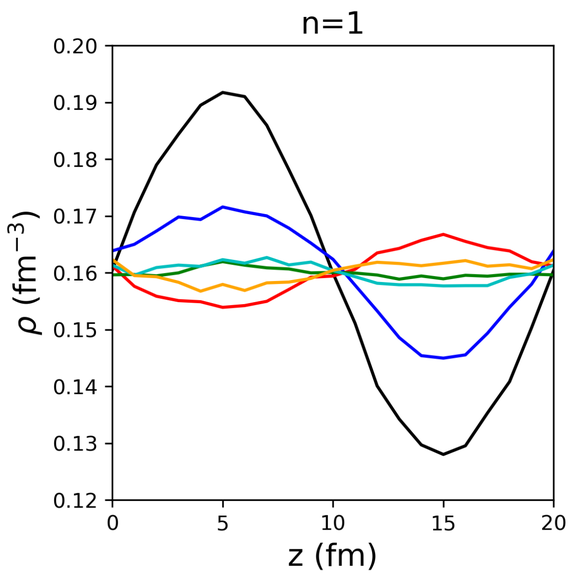


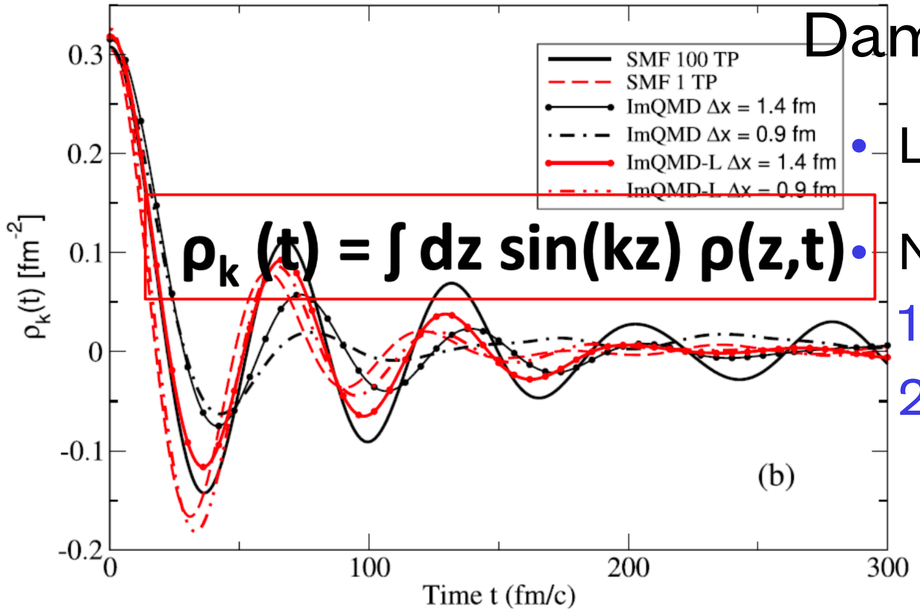


- Pauli blocking - evolution of phase space occupations
- numerical fluctuations
  - BUU - shape & TP, QMD - width

Box-Vlasov calculation

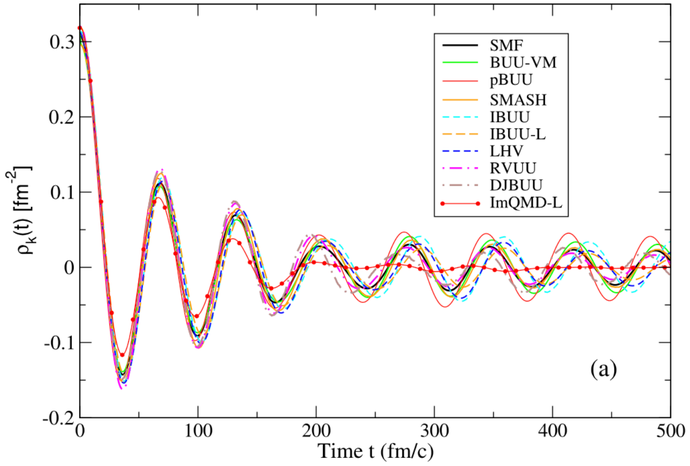
M. Colonna, et al., PRC (2021)

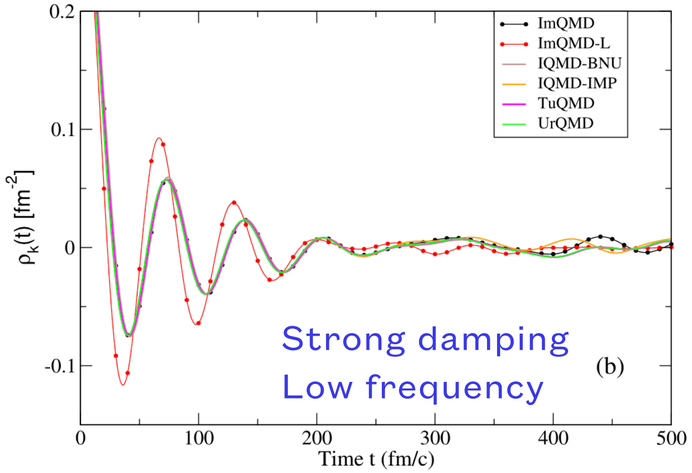


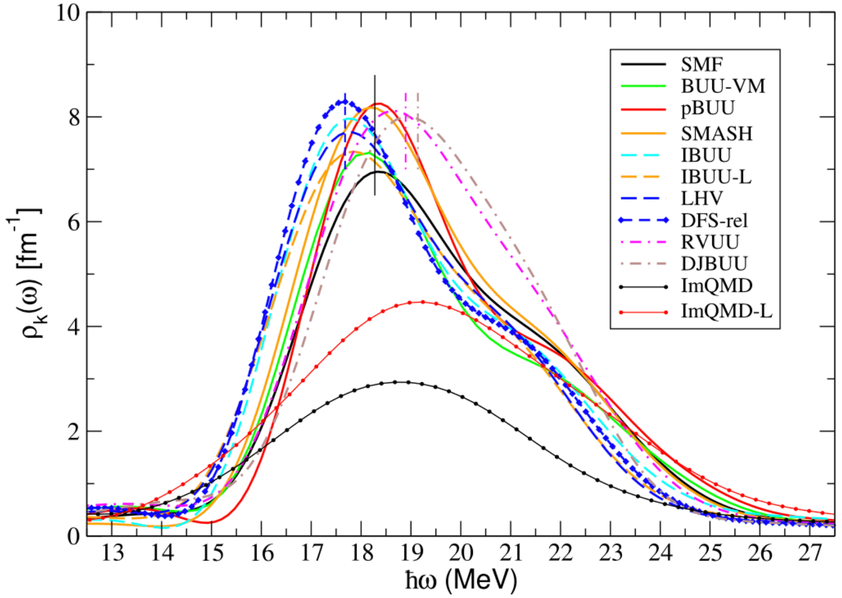


Damping sources:

- Landau damping: mixing modes
- Numerical damping: fluctuations
  1. Decreases with increasing TP numbers
  2. Decreases with increasing particle size





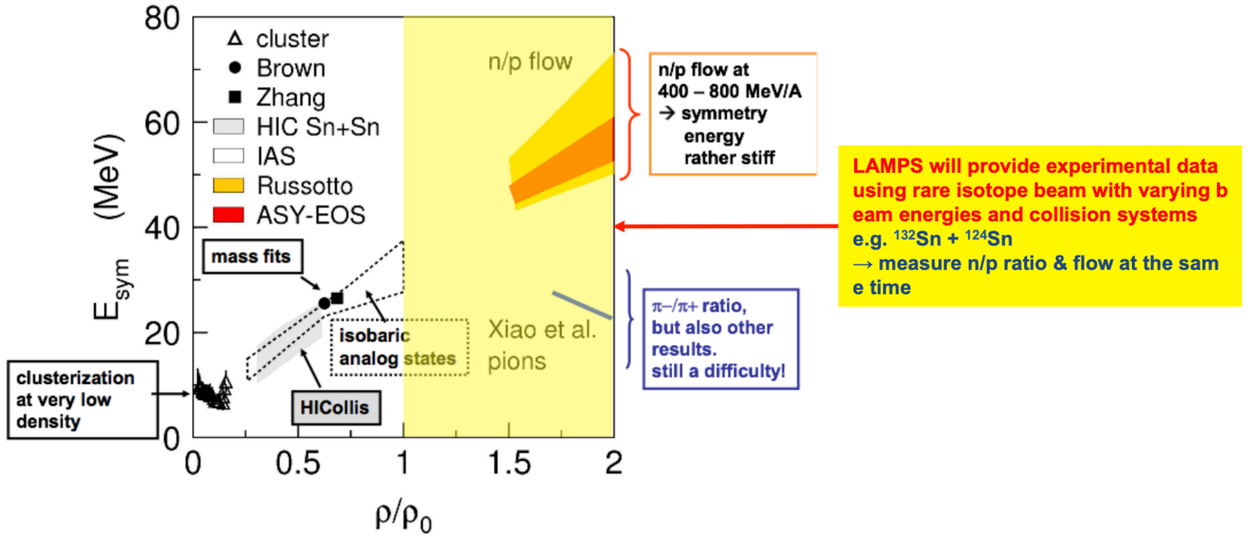


RAON / LAMPS

LAMPS
(Large Acceptance Multi-Purpose Spectrometer)

- Possible experiment
  - Using 18.5 ~ 250 MeV/u RI beam through IF separtor, perform N/Z controlled heavy-ion collision experiment for studying density dependent symmetry energy of nuclear matter possible Day-1 experiment : ^{50,54}Ca+^{40}Ca to measure proton, neutron spectrum
  - Then, series of experiment for ^{50,54}Ca+^{40}Ca, ^{68,70,72}Ni + ^{58}Ni, ^{106,112,124,130,132}Sn + ^{112,118,124}Sn to measure particle spectrum, yield, ratio, collective flow etc. at the same time

Present Constraints on the Symmetry Energy (shown as $E_{sym}(\rho/\rho_0)$)

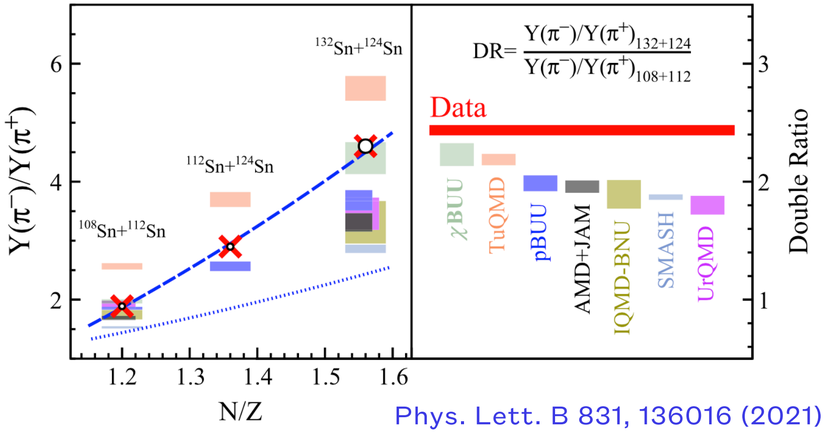


- Experimental data are measured with stable beams
- data of pion ratio and data of n/p flow are from different experiments
- Models in the market show different results even within same observable

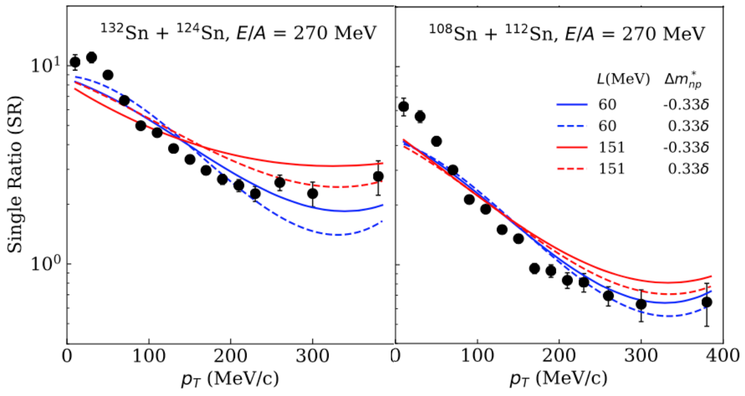
2

Symmetry energy and pion productions

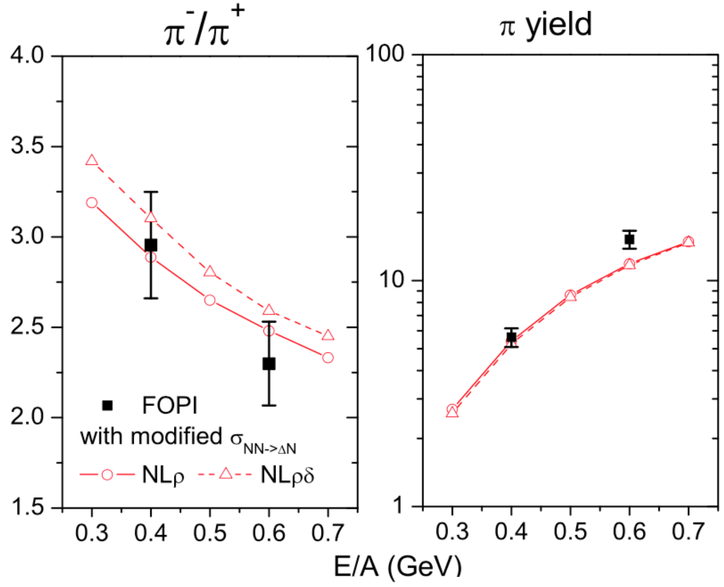
- *Pion production and comparison with SπRIT @ RIKEN and FOPI @ GSI experiments*
- Pion production w/ our NL model set in DJBUU (on going)
- Expansion to HICs with rare isotope : π^- from neutron-rich
- rare isotope HICs @ RAON can be a key for symmetry energy since more π^- from neutron rich



Phys. Lett. B 831, 136016 (2021)



PRL 126, 162701 (2021)



PRC 91, 014901 (2015)

Hulk vs Iron man, Marvel comics

Thank you.