HIM@RISP.2016.11.25

Introduction of DJBUU : New Transport code

Chang-Hwan Lee / Pusan National University

partially on behalf of DJBUU Project

RAON

a pure Korean word meaning Delightful, Joyful, Happy, …

in 2011, Korean government approved a **Rare Isotope Accelerator Project**

My recent works have been related to neutron stars

- NS EoS / Dense Matter
- NS Binary Evolution / Gravitational Waves

for RAON

better to start from where you have an advantage

Some experience on Heavy Ion Collisions at Stony Brook

- Lee, Wirstam, Zahed, Hansson, PLB 448, 168 (1999)
- Lee, Yamagishi, Zahed, PRC 58, 2899 (1998)
- Lee, Yamagishi, Zahed, NPA 653, 185 (1999)

Contents

Part I : EM Radiation for RHIC & LHC

Part II : DJBUU for Rare Isotope Collisions

Part I: EM Radiation in Hot QCD Matter

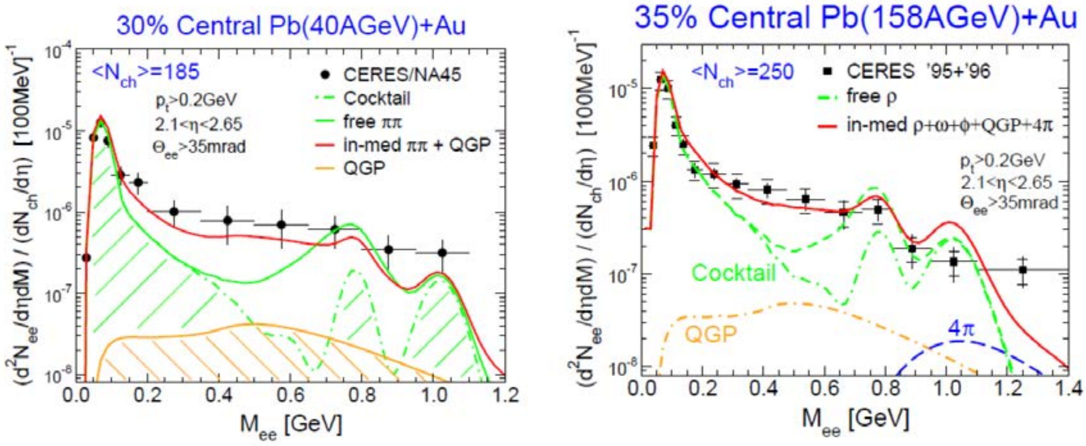
in collaboration with
Y.M. Kim (PNU), D. Teaney, I. Zahed (Stony Brook)
PRC 90, 025204 (2014) & arXiv:1610.06213

Why Photons & Dileptons ?

- No strong interaction
- Can provide direct information on dense medium
- Right time to revisit

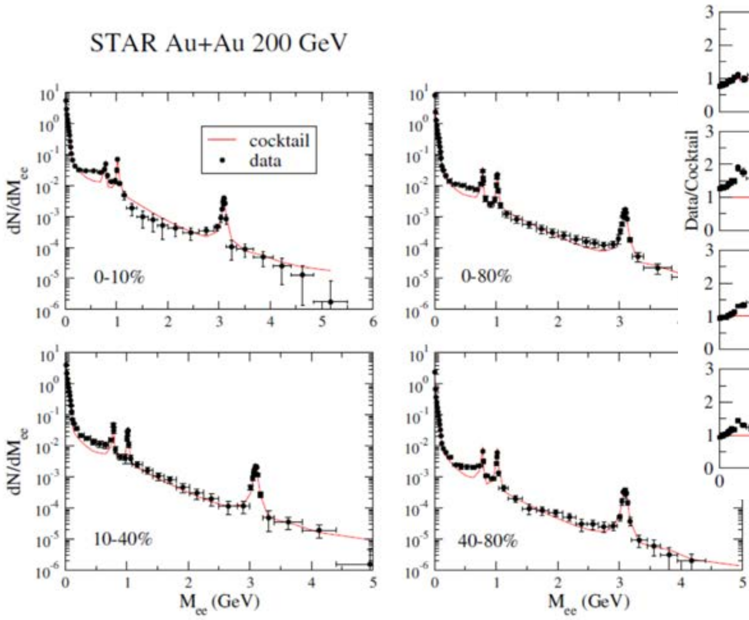
CERES/NA45 Pb+Au 8.8 & 17.3 GeV

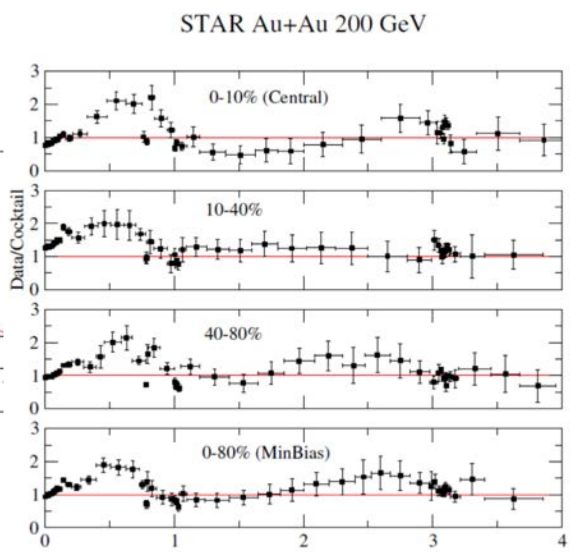
R.Rapp, arXiv:1306.6394



Key question : low-mass dilepton enhancement

STAR Dilepton Enhancement Au+Au 200 GeV

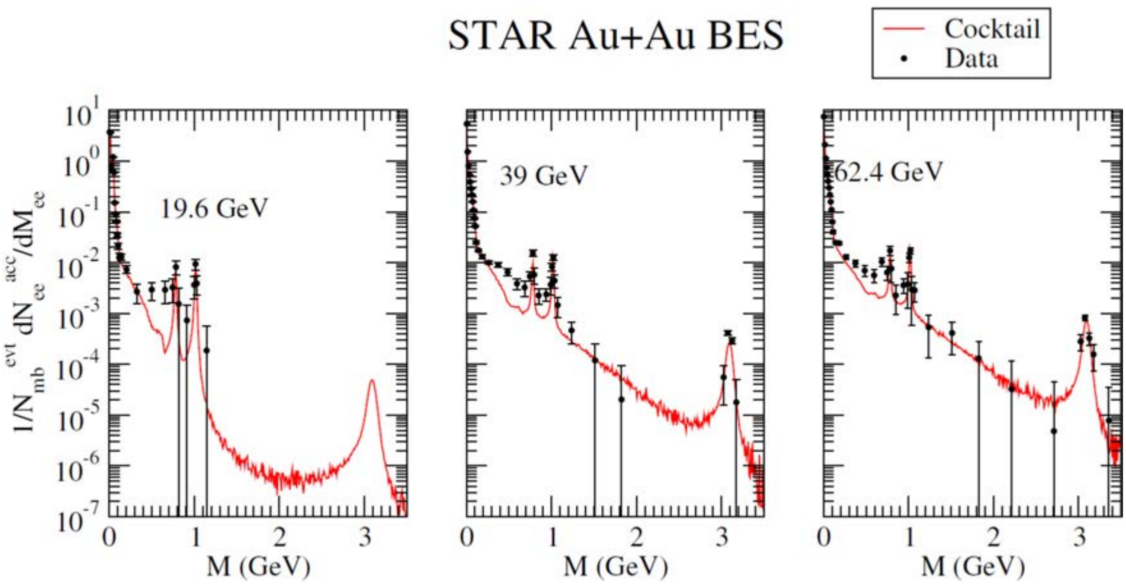




arXiv:1305.5447

STAR Beam Energy Scan

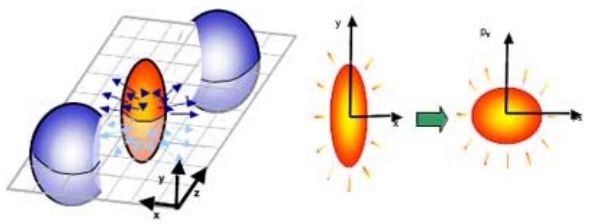
arXiv:1305.5447

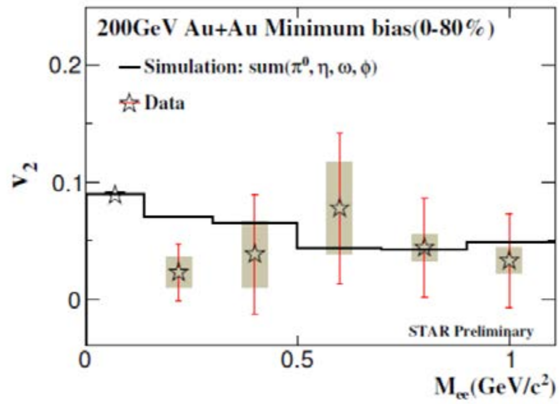


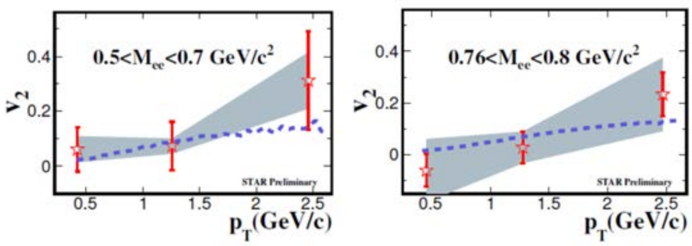
STAR Au+Au 200 GeV

arXiv:1305.5447

Elliptic Flow



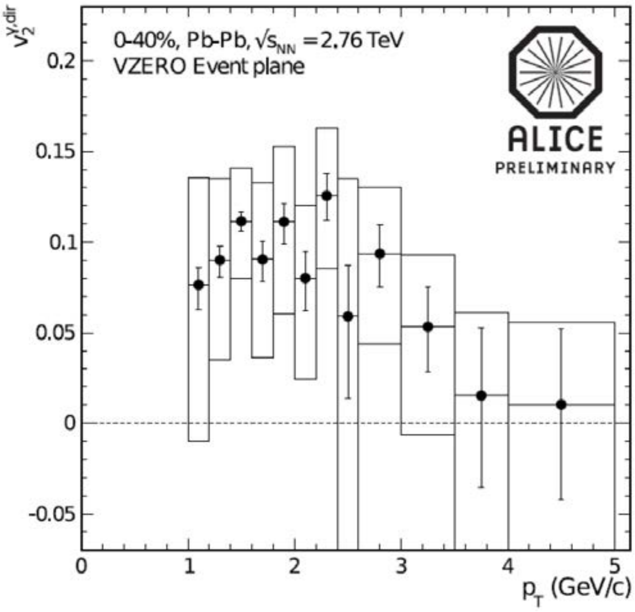




ALICE Pb+Pb 2.76 TeV

arXiv:1212.3995

Elliptic Flow



Theory vs Experiment

Hadronic Gas & sQGP
Perturbative Approach

Quark Number Susceptibility
Electric Conductivity
Flavor Diffusion Constant
… …

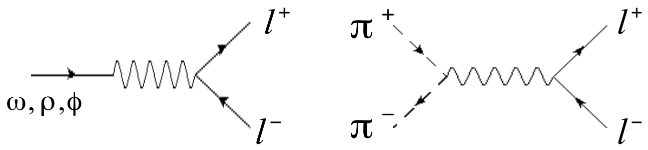
… …
Photon & Dilepton Rates
Azimuthal Anisotropy

Lattice Simulation

Experiments

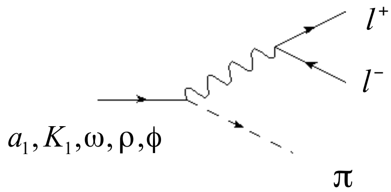
Dilepton rates from hadronic gas

$$i\int d^4x\, e^{iq\cdot x}\left\langle 0\middle|T^* J^\mu(x) J_\mu(0)\middle|0\right\rangle$$



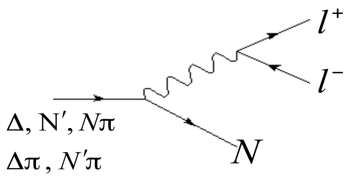
+ ...

$$+\sum_a i\int d\pi\int d^4x\, e^{iq\cdot x}\left\langle \pi^a_{in}(k)\middle|T^* J^\mu(x) J_\mu(0)\middle|\pi^a_{in}(k)\right\rangle$$



+ ...

$$+\sum_{s,I} i\int dN\int d^4x\, e^{iq\cdot x}\left\langle N^{s,I}_{in}(k)\middle|T^* J^\mu(x) J_\mu(0)\middle|N^{s,I}_{in}(k)\right\rangle$$



+ ...

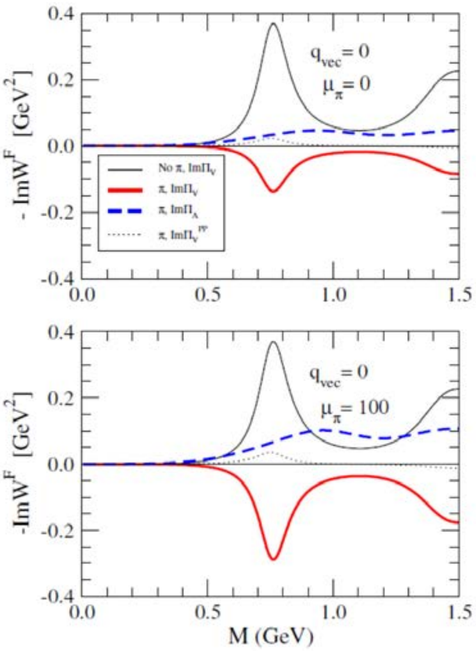
Pionic Gas

$$\mathbf{W}^F(q) = \mathbf{W}_0^F(q) + \frac{1}{f_\pi^2}\int d\pi \mathbf{W}_\pi^F(q,k) + \frac{1}{2!}\frac{1}{f_\pi^4}\int d\pi_1 d\pi_2 \mathbf{W}_{\pi\pi}^F(q,k_1,k_2) + \cdots$$

$$\int d\pi = \int \frac{d^3k}{(2\pi)^3}\frac{n(E-\mu_\pi)}{2E}$$

$$\begin{aligned}
\mathbf{W}_0^F(q) &= i\int d^4x e^{iq\cdot x}\langle 0|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|0\rangle \\
\mathbf{W}_\pi^F(q,k) &= if_\pi^2\int d^4x e^{iq\cdot x}\langle \pi^a(k)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k)\rangle \\
\mathbf{W}_{\pi\pi}^F(q,k_1,k_2) &= if_\pi^4\int d^4x e^{iq\cdot x}\langle \pi^a(k_1)\pi^b(k_2)|T^*\mathbf{J}^\mu(x)\mathbf{J}_\mu(0)|\pi^a(k_1)\pi^b(k_2)\rangle
\end{aligned}$$

Mixing between vector-axial : Chiral symmetry restoration



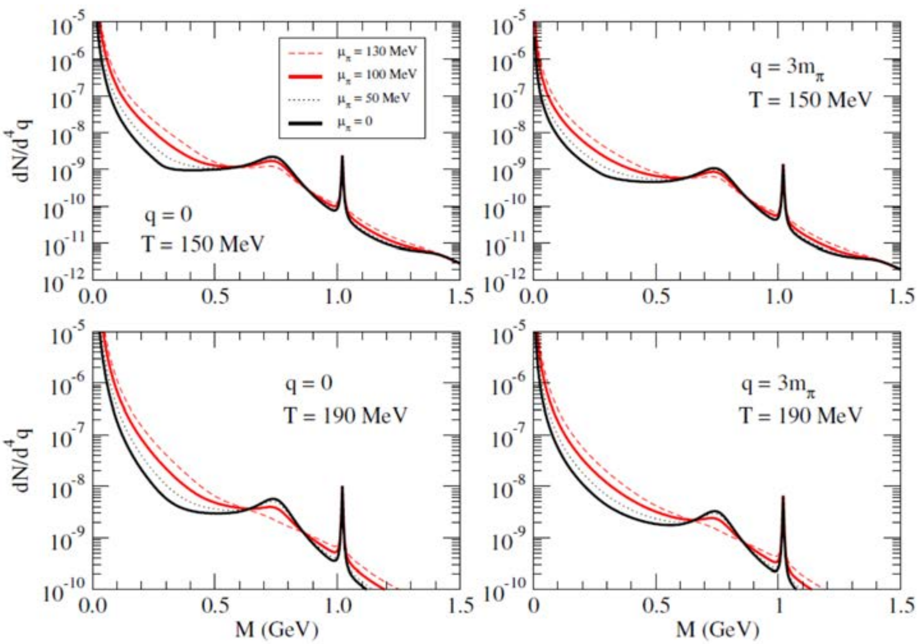
As pion chemical potential increase

- **Reduction of Vector Contribution** due to the cancellation (no pion + pion contribution)
- **Enhancement of Axial Contribution**

Lee & Zahed PRC 90, 025204 (2014)

Dilepton Rates up to two pion

Low-mass enhancement due to mixing between vector & axial



Lee & Zahed PRC 90, 025204 (2014)

Conclusion of Part I

- **Low-mass dilepton enhancement (PRC 90, 025204, 2014)**
  - partial restoration of chiral symmetry
  - mixing between vector & axial correlators
- **Charged particle elliptic flow (arXiv:1610.06213)**
  - pion is better than (anti-)proton
  - hadronic rates dominate the photon emissivity rates
  - still misses ALICE high qT data
- **Future Plan**
  - inclusion of nucleons for STAR BES

Part II

DJBUU

DJBUU project

- What is DJBUU
  Dae Jeon Boltzmann-Uehling-Uhlenbeck

- Current collaboration members
  S. Jeon (McGill, chair) at RISP during 2015.10~2016.01
  Y. Kim, J. Hong, K. Kim (RISP)
  M.K.Kim, Y.M. Kim, C.-H. Lee (PNU)

- Supported by RISP

Contents of Part II

1. Boltzmann-Uehling-Uhlenbeck (BUU)
2. Daejeon Boltzmann-Uehling-Uhlenbeck (DJBUU)
3. What has been done before with RBUU
   - Sn + Pb @ 200 MeV/u
   - Xe + Pb @ 200 MeV/u
   - Au + Au @ 200 MeV/u
4. What we are doing now
   - Single Au density profile
   - Au + Au @ 100 MeV/u
   - Pauli Blocking factor
5. Summary and Plan

Nuclear transport theory

- Treats non-equilibrium process
- One-body phase-space distribution in heavy-ion collision
  - *mean field + two-body collision + Pauli blocking*
- Boltzmann-Vlasov type :
  - *evolution of the one-body phase-space density under the influence of a mean field*
- molecular-dynamics type :
  - *nucleon coordinates and momenta under the action of a many-body Hamiltonian*
- test particle
  - *solve nonlinear integro-differential eq. (= BUU eq.)*

Relativistic mean field theory

$$\begin{aligned}\mathcal{L} &= \bar{\psi}\left[i\partial\!\!\!/ - (m_N - g_\sigma \sigma) - g_\omega \omega\!\!\!/ - g_\rho \vec{\tau}\cdot \vec{\rho\!\!\!/}\right]\psi \\ &+ \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2\right) - \frac{1}{3} a \sigma^3 + \frac{1}{4} b \sigma^4 \\ &+ \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\left(\partial_\mu \omega_\nu - \partial_\nu \omega_\mu\right)\left(\partial^\mu \omega^\nu - \partial^\nu \omega^\mu\right) \\ &+ \frac{1}{2} m_\rho^2 \vec{\rho}_\mu \cdot \vec{\rho}^\mu - \frac{1}{4}\left(\partial_\mu \vec{\rho}_\nu - \partial_\nu \vec{\rho}_\mu\right)\cdot\left(\partial^\mu \vec{\rho}^\nu - \partial^\nu \vec{\rho}^\mu\right).\end{aligned}$$

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

Phys. Rev. C, 65, 045201 (2002)

- Describe nuclear structure (phenomenological)
- Applied from finite nuclei to neutron star
- Mean field theory including σ, ω, ρ meson fields (exclude δ-meson field in DJBUU simulation)

Boltzmann-Uehling-Uhlenbeck eq.

$$\left[\tilde{k}\cdot\partial^{(x)} + \left(\tilde{k}_\nu F^{\mu\nu} + m^\star \partial^\mu m^\star\right)\partial_\mu^{(\tilde{k})}\right] f(x,\tilde{k})|_{\tilde{k}=k_1+\Sigma}$$
$$= \frac{1}{2}\int \mathcal{D}_{k_2,k_3,k_4} W(k_1 k_2|k_3 k_4)\delta^4(k_1+k_2-k_3-k_4)$$
$$\times\left[f_3 f_4(1-f_1)(1-f_2) - f_1 f_2(1-f_3)(1-f_4)\right].$$

- Boltzmann eq. - **collision term**
- Uehling-Uhlenbeck eq. - **Pauli-blocking factor**
- Time evolution of the one-body phase-space density under the mean field potential

Numerical realization

RBUU code : simulate Heavy-ion collisions

- 1995, first developed in Munich (C. Fuchs)
- 1996-2000, density-dep. RMF models, DBHF approaches (T. Gaitanos, C. Fuchs)
- 2002-2005, isospin effects in the production thresholds (G. Ferini, T. Gaitanos)
- 2005-2010, in-medium isospin effects in cross sections&kaon pot. (V. Prassa, T. Gaitanos)
- 2014, improvement in stability (RISP)

Test particle method > Parallel ensemble method

single particle phase-space distribution function
represented by N covariant Gaussian test particles

$$g(x,x_i) = \frac{1}{(\pi\sigma^2)^{3/2}} e^{[(x_\mu - x_{i\mu})^2 - ((x_\mu - x_{i\mu})u_i^\mu)^2]/\sigma^2}$$

$$g(k^*,k_i^*) = \frac{1}{(\pi\sigma_k^2)^{3/2}} e^{[k_\mu^{*2} - (k_\mu^* u_i^\mu)^2]/\sigma_k^2}$$

▶ $$f(x,k^*) = \frac{1}{N}\sum_{i=1}^{AN} g(x,x_i)g(k^*,k_i^*)$$

σ = 1.4fm
σ_k = 0.346fm^{-1}
N=100

slide from Y.J. Lee

Baryon density $\rho_B(x) = \frac{1}{N}\sum_{i=1}^{AN} g(x, x_i) u_{i0}$

Isospin asymmetry $\rho_I(x) = \frac{[\rho_n(x) - \rho_p(x)]}{\rho_B(x)}$

Local temperature by a fit of the **RBUU momentum distribution** to the **Fermi-Dirac distribution**, assuming **local thermodynamic equilibrium**

$$n(x, \boldsymbol{k}) = \frac{(2\pi)^3}{4}\frac{1}{N(\pi\sigma\sigma_k)^3}\sum_{i=1}^{AN} e^{[(x_\mu - x_{i\mu})^2 - ((x_\mu - x_{i\mu})u_i^\mu)^2]/\sigma^2} e^{[k^{*2} - (k^*_\mu u_i^\mu)^2]/\sigma_k^2}$$

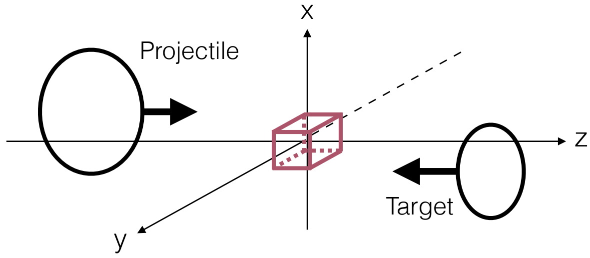
Nucl. Phys. A, 589, 732, (1995)

$$n(x, \boldsymbol{k}, T) = \frac{1}{1 + \exp[-(\mu^* - k^*_\mu u^\mu)/T]} \quad \left(k_0^* = \sqrt{\boldsymbol{k}^{*2} + m^{*2}}\right)$$

… T is the only free parameter, μ* is T-dependent parameter,

Determine μ* from the **baryon number conservation**

$$j_0(x) = 4\int \frac{d^3k}{(2\pi)^3} n(x, \boldsymbol{k}, T)$$



Consider the point x=0

… practically, **a (5×5×5)fm³ cubical box** around the center

slide from Y.J. Lee

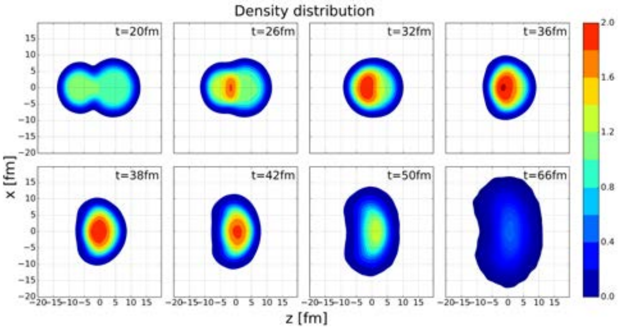
RBUU results (what has been done before)

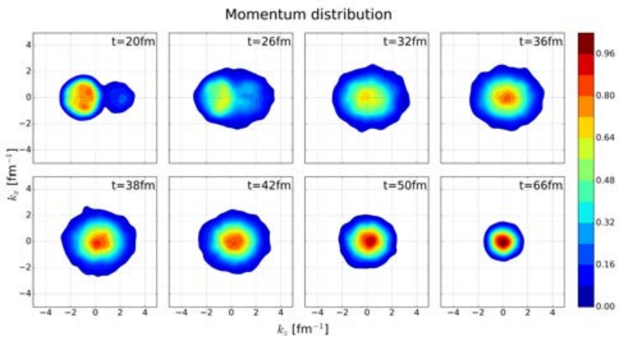
JKPS,69, 1430 (2016), Y. Lee, C.-H. Lee, T. Gaitanos, Y. Kim

NPSM (2017), Myungkuk Kim, Y. Lee, Y. M. Kim, C.-H. Lee

Result 1 : $^{132}Sn + ^{208}Pb$ @ 200 MeV/u

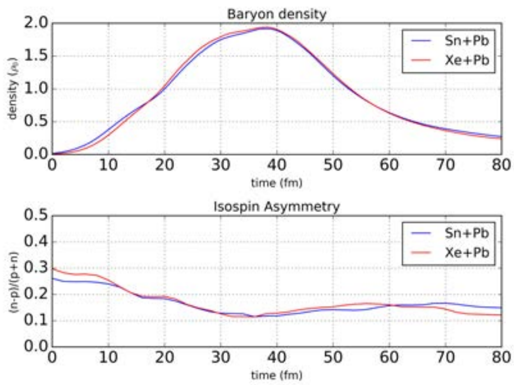
$^{132}Sn + ^{208}Pb$ $^{132}Sn + ^{208}Pb$

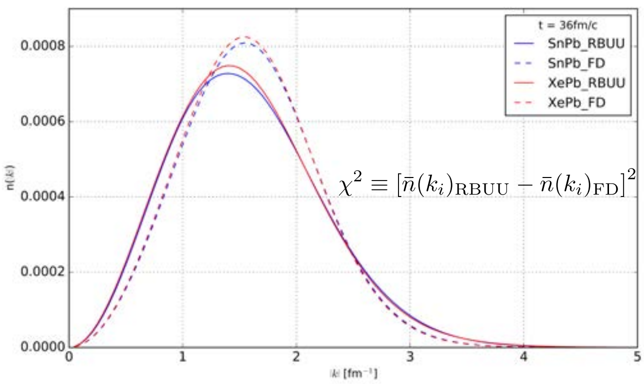




- Nuclear structure : near the magic number 126
- Neutron star internal structure
- Dense matter : symmetry energy and collective flow
- $^{140}Xe + ^{208}Pb$: similar evolution history for density and momentum

Central density and effective temperature

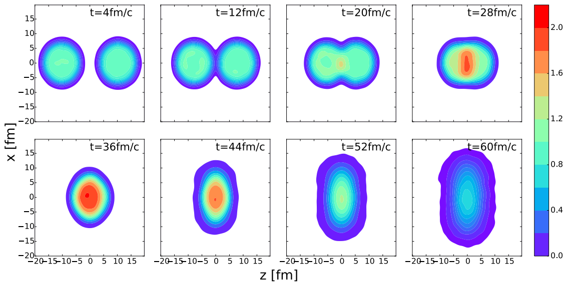




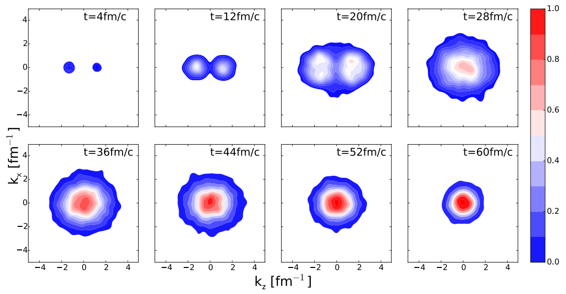
- Central density reaches up to $2\rho_0$ (~0.16 fm^{-3}) at t = 36 ~ 38 fm/c
- Symmetry energy ∝ density (excluding δ-meson field)
- T (MeV) - 27.1 and 27.8 @ 36 fm/c
- μ_B (MeV) - 721.7 and 706.3 @ 36 fm/c

Result 2 : ^{197}Au + ^{197}Au @ 200 MeV/u

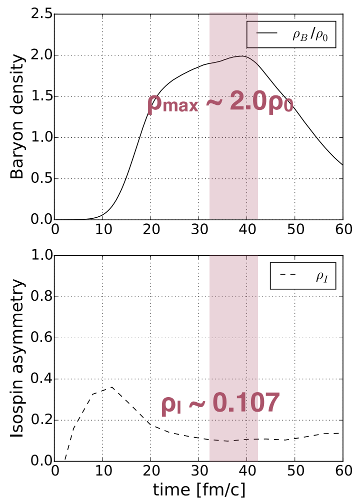
▼ Time evolution of density distribution



▼ Time evolution of momentum distribution at **x=0**

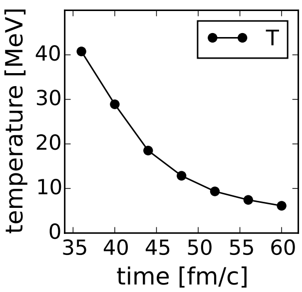


▼ Time evolution of baryon density and isospin asymmetry at the center

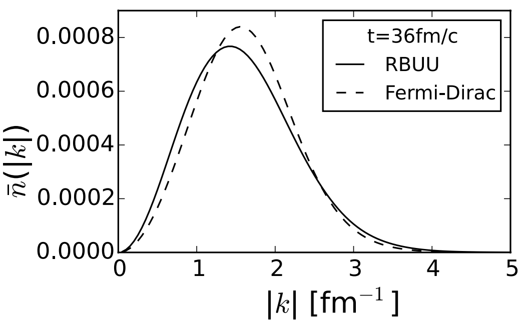


(ρ_0 : saturation density, ~0.16fm^{-3})

slide from Y.J. Lee



time [fm/c]	36	40	44	48	52	56	60
T [MeV]	**40.8**	**28.9**	**18.5**	**12.6**	**9.3**	**7.4**	**6.1**
μ* [MeV]	**771.7**	**802.9**	**813.4**	**842.3**	**867.2**	**885.9**	**899.1**



◀ 1-dimensional RBUU & fitted Fermi momentum distribution at the center at time t=36fm/c

$\chi^2 = 2.41\times10^{-7}$

($\chi^2 \equiv [\bar{n}(k_i)_{\rm RBUU} - \bar{n}(k_i)_{\rm FD}]^2$, i : all grid points)

▶ The first application of a transport model to HIC **at low energy**.

slide from Y.J. Lee

What we have done with RBUU

- Simulation of HIC by using the RBUU transport code for estimation of properties of nuclear matter that is expected to be created in RAON

- Baryon density, isospin asymmetry, local temperature for $^{132}Sn + ^{208}Pb$ and $^{140}Xe + ^{208}Pb$ @ 200AMeV
  : $\rho_{max} \sim 2\rho_0$, $\rho_I \sim 0.1$, $T_{loc} \sim 27$ MeV.

- Quantitative discussion on the possibility of QCD phase transition, liquid-gas phase transition, pion condensation, …etc. at RAON

- Simulations with more neutron-rich isotopes/deformed nuclei.

- Ongoing development of advanced transport calculation code for better results.

slide from Y.J. Lee

DJBUU

Daejeon Boltzmann-Uehling-Uhlenbeck eq.

- c / c++ language
- openMP (Open Multi-Processing) implemented
- easy to follow & modify
- simulated mainly in Mac OSX

```
E_beam_NN_for_Heavy_Ion_Collision_in_GeV 0.2
Record_p_n_densities_at_the_center_1_for_on_0_for_off 1
Radius_for_density_calc_in_fm 3.0
Record_interval 10
Record_particle_states_1_for_on_0_for_off 1
Record_Interval 10
Turn_on_Coulomb_1_for_on_0_for_off 0
Number_of_grid_points_in_x 100
SigmaNN_CutOff_in_mb 50
Uncertainty_param_dxdp 0.6
```

RBUU code

- 1995, first developed in Munich (C. Fuchs)
- 1996-2000, density-dep. RMF models, DBHF approaches (T. Gaitanos, C. Fuchs)
- 2002-2005, isospin effects in the production thresholds (G. Ferini, T. Gaitanos)
- 2005-2010, in-medium isospin effects in cross sections&kaon pot. (V. Prassa, T. Gaitanos)
- 2014, improvement in stability (RISP)

DJBUU preliminary results

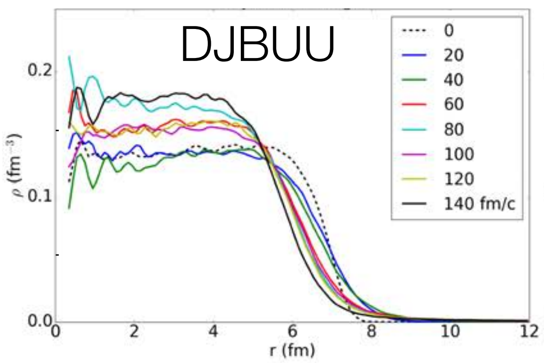
- time evolution of single Au density profile
- average density contours in Au + Au collision @ 100 MeV/u (*b*=7 fm)
- Pauli blocking

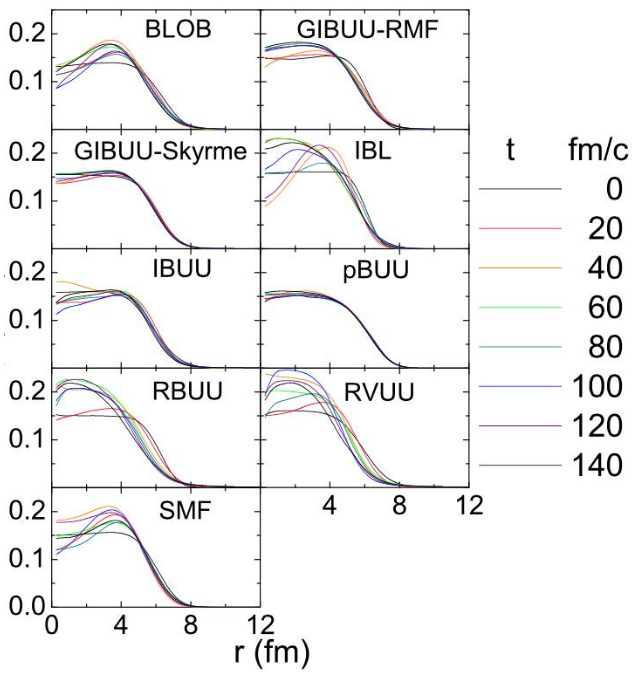
NPSM, RI Science Special Issue, M. Kim, CHL, Y.Kim, S. Jeon

DJBUU vs RBUU result

- 현재 직접적인 비교 불가 할 것으로 판단됩니다.
  (comments by **Myungkuk Kim**)

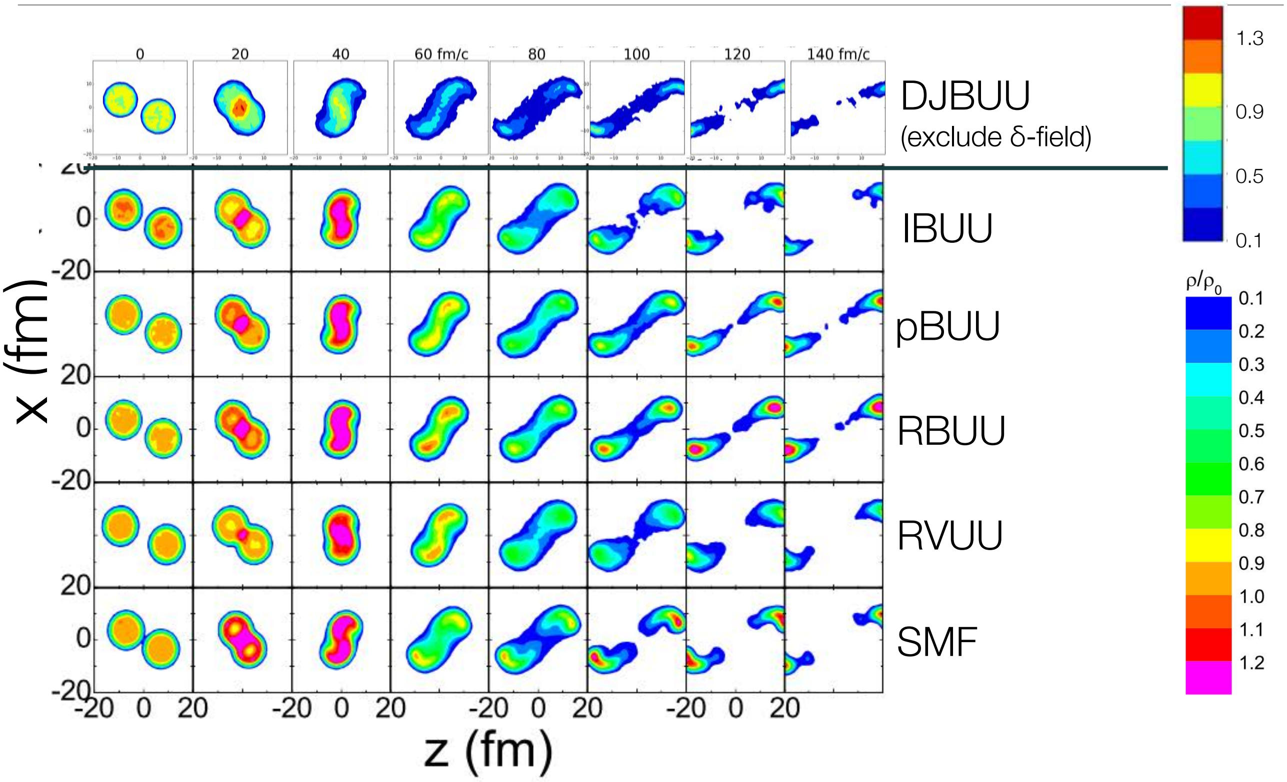
Single Au density profile (preliminary)



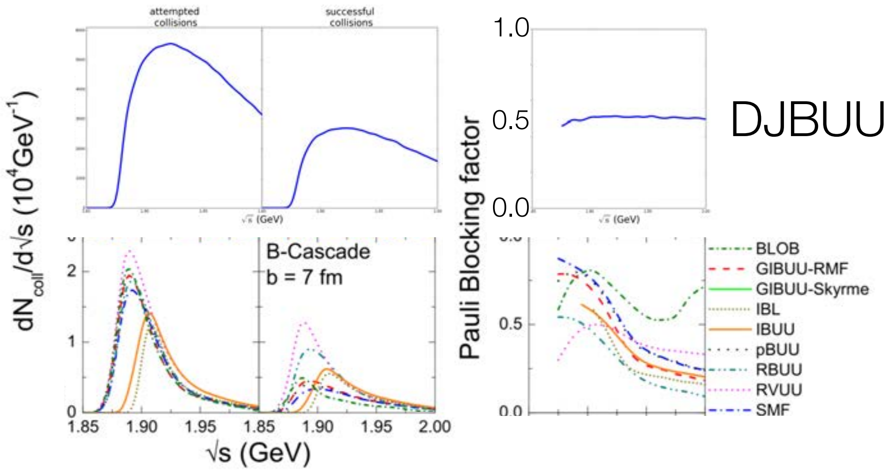


- Check the stability and initial condition
  (3 run, 100 test particle)
- Initial density ~ 0.15 fm^{-3}
  (from relativistic Thomas-Fermi approx.)
- fluctuation 0.13~0.17 fm^{-3}

Au + Au collision @ 100 MeV/u (*b*=7 fm) (preliminary)



Pauli Blocking factor (for one case) (preliminary)



- B : 100 MeV/u
- Cascade - turn off the mean field (collision term)
- Pauli Blocking factor = 1 - (successful / attempted)

Part II: Summary & Plan

- **DJBUU**
  - new BUU-type code is developed.
  - DJBUU code is stable, but still preliminary.
  - requires fine tuning.

- **Plan**
  - test new equation of states