St.Petersburg@2017.07.24

New Heavy-Ion Transport Approach : Daejeon BUU

Chang-Hwan Lee / Pusan National University

on behalf of DJBUU Project

Contents

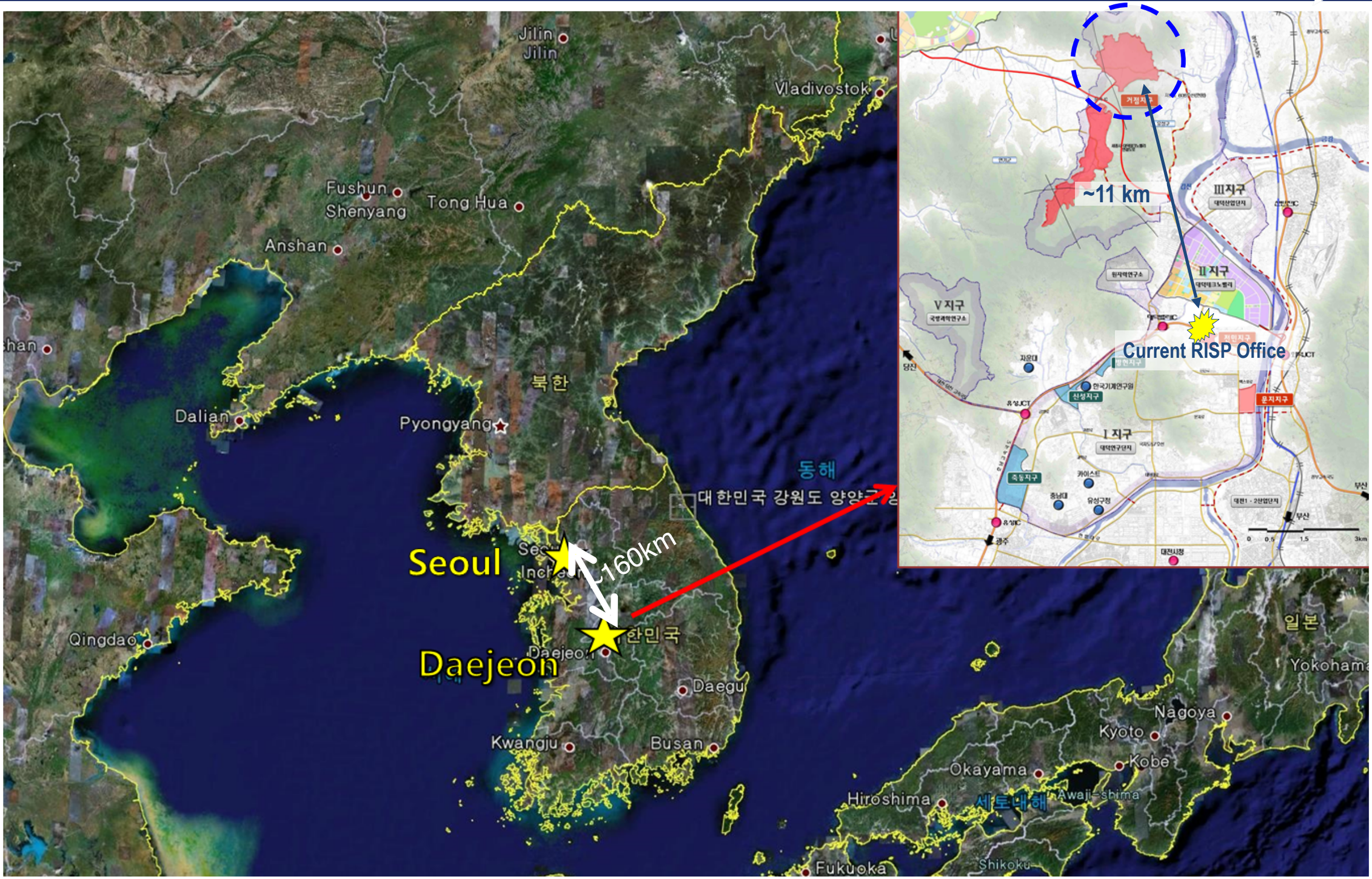
RAON

Rare isotope Accelerator complex for ON-line experiments

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

in Korean, meaning Delightful, Joyful, Happy, …

RAON Site : Sindong in Daejeon



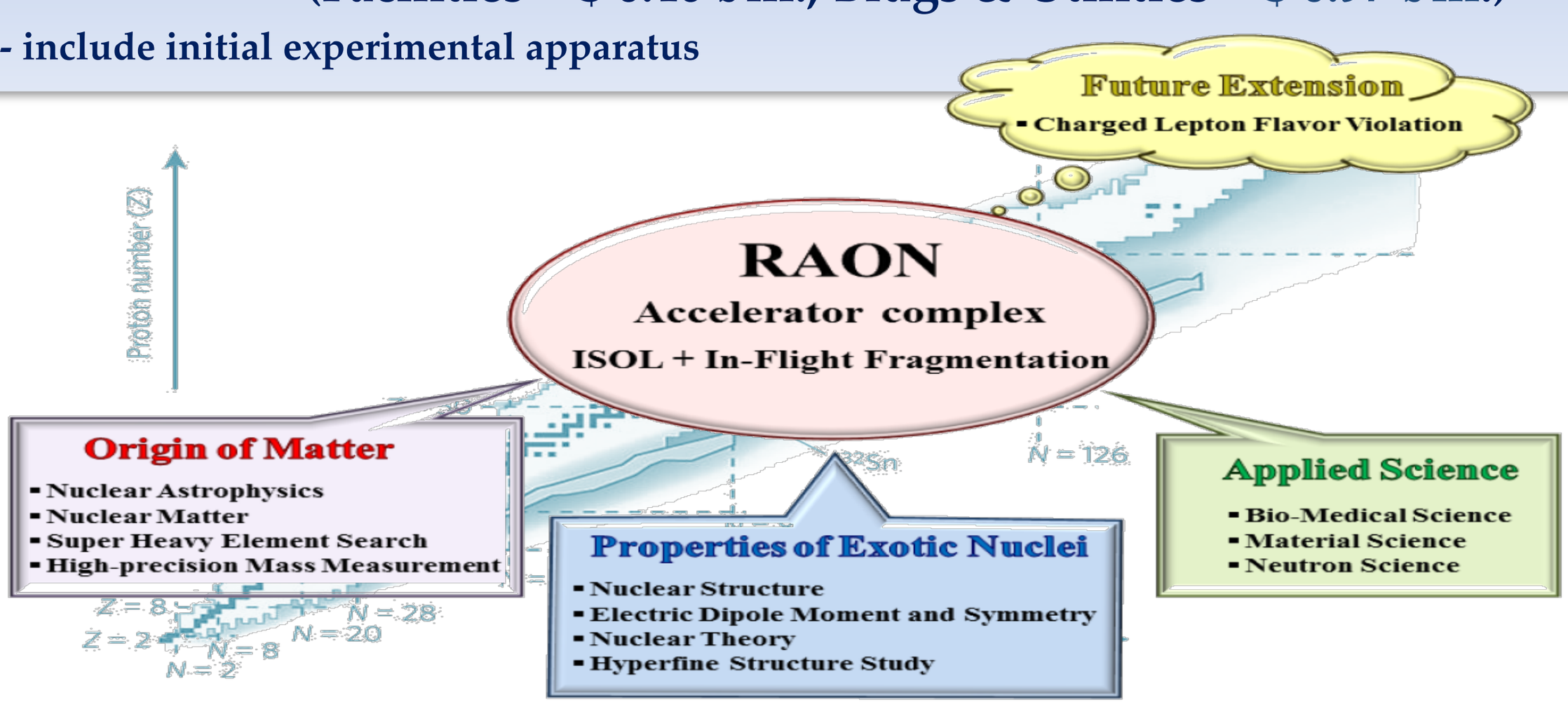
Slides from Youngman Kim (RISP)

Rare Isotope Science Project (RISP)

- ○ Goal : To build a heavy ion accelerator complex RAON for rare isotope science researches in Korea
- ○ Project period : 2011.12 - 2021.12
- ○ Total Budget : ~$ 1.43 billion

(Facilities ~ $ 0.46 bill., Bldgs & Utilities ~ $ 0.97 bill.)

- include initial experimental apparatus



RAON Concept

- High intensity RI beams by ISOL & IF

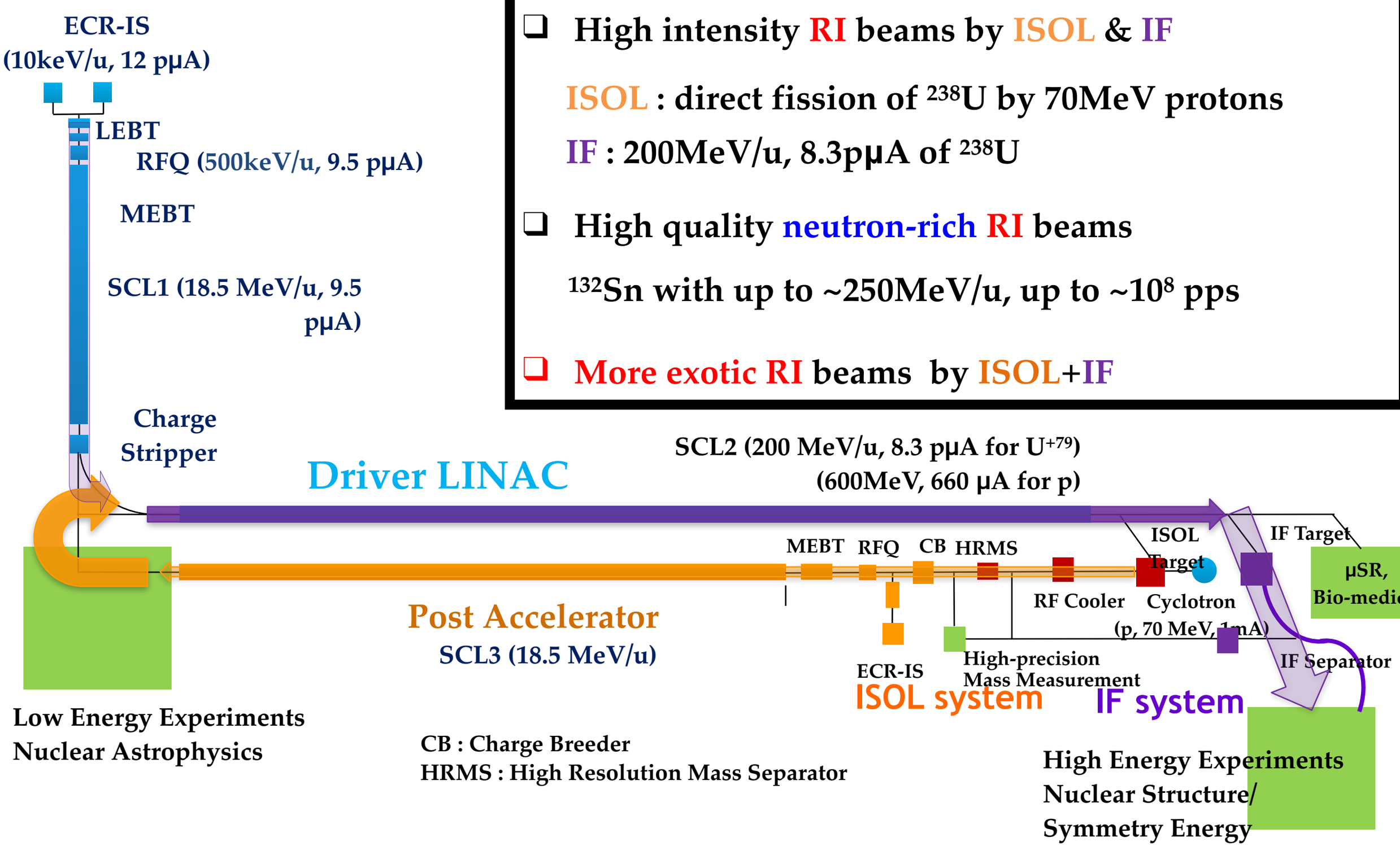
  ISOL : direct fission of ^{238}U by 70MeV protons

  IF : 200MeV/u, 8.3pμA of ^{238}U

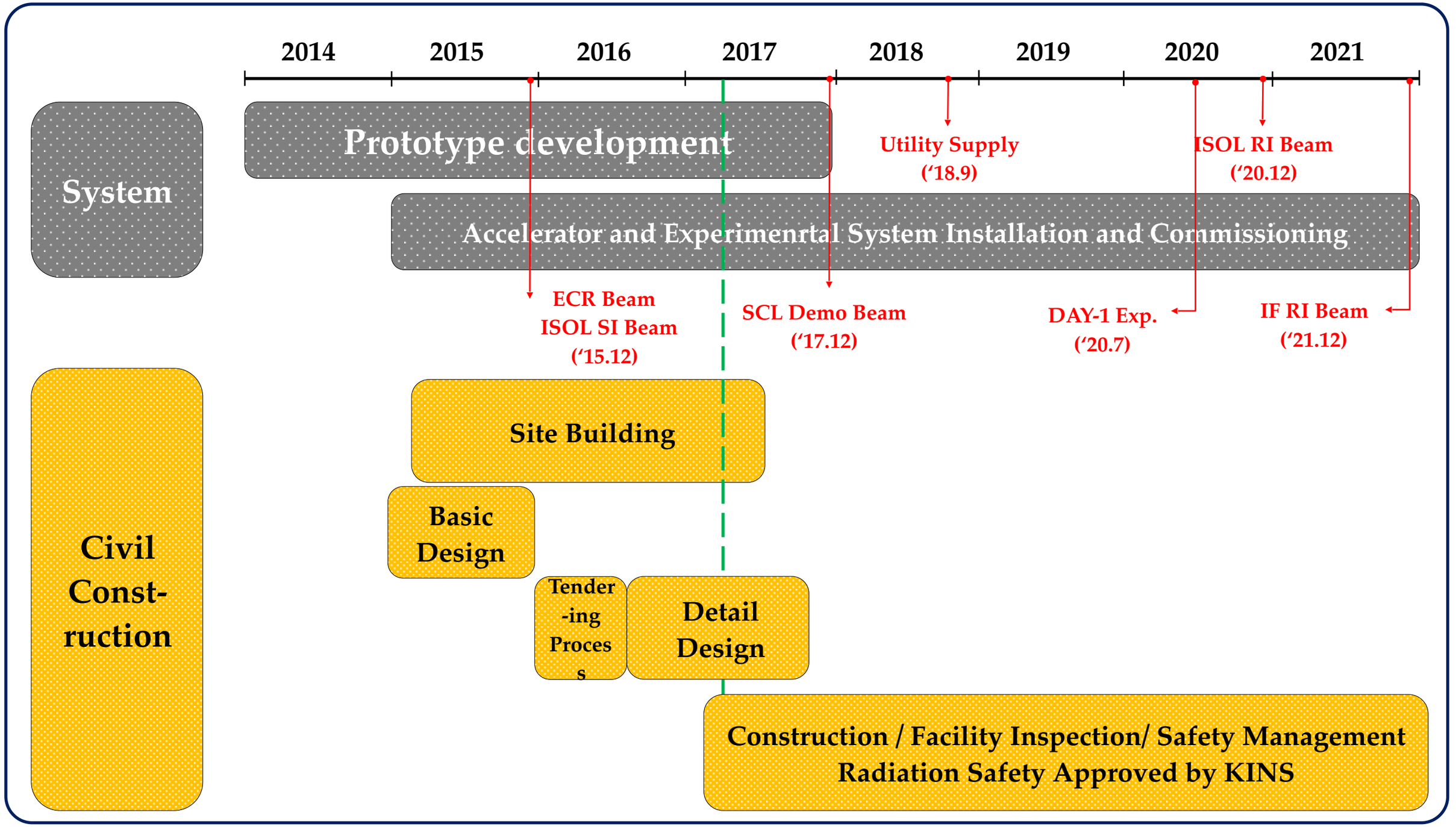
- High quality neutron-rich RI beams

  ^{132}Sn with up to ~250MeV/u, up to ~10^8 pps

- More exotic RI beams by ISOL+IF



Major Milestones



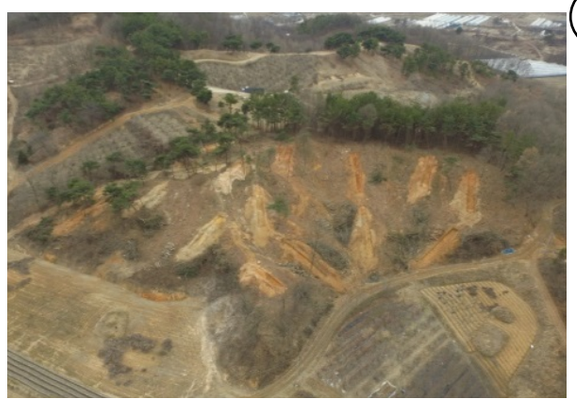
Current Status of Construction & Civil Eng.

Status of Site(Cultural assets & Site renovation/building)

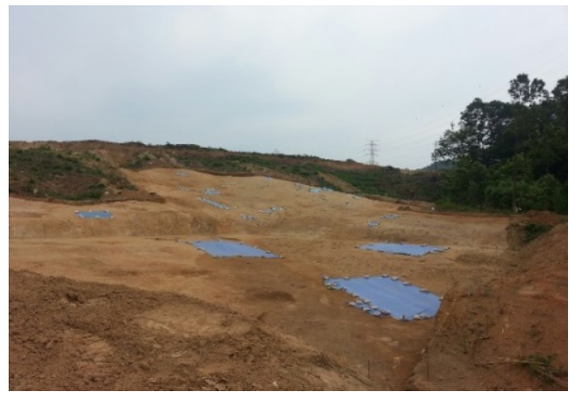
Land Purchase (`14.12.26.)	→	Land Fee Tender (`15.10.01.)	→	Land Purchase (`16.06.14.)	→	Site Building (`16.06.15.)

- Eval of Cultural assets: Acc & Exp('15.12.~'16.09.), Support Bldg('16.06.~'16.11.)

문화재 시굴작업



문화재 발굴작업



- Site Building : Acc & Exp('16.07.~'17.01.), Support bldg('16.08.~'17.06.)

지장물 철거(~'16.08.)

부지조성(절토 및 성토)

for RAON

Some experience at Stony Brook

- Kaon production in heavy-ion collisions & kaon condensation in NS
  G.Q.Li, C.-H. Lee, G.E. Brown
  PRL 79 (1997) 5214; NPA 625 (1997) 372.

- **Workshop on Kaon Production, Dresden, Germany, Dec. 1998**
  - comparison of various transport codes
  - compared cross sections channel by channel, etc.
  - RVUU code by G.Q. Li, further developed by Zhang, Song & C.M. Ko

Special Issue for RAON

New Physics: Sae Mulli, 66 (2016) 1563
http://dx.doi.org/10.3938/NPSM.66.1563

Introduction to DaeJeon BUU

- **DaeJeon BUU code description**
  - Initialization
  - Mean Field
  - Propagation
  - Collision and Pauli Blocking
  - Hadrons, cross-section and decay

- **Preliminary test results and comparison**

DJBUU project

New Physics: Sae Mulli, 66 (2016) 1563
http://dx.doi.org/10.3938/NPSM.66.1563

- What is DJBUU
  DaeJeon Boltzmann-Uehling-Uhlenbeck

- **DaeJeon** is city name in Korea where **RAON** will be built

- Current collaboration members
  S. Jeon (McGill, chair) ** developed MARTINI for RHIC/LHC
  Y. Kim, K. Kim (RISP) ** participated with RBUU last time
  Myungkuk Kim, Y.M. Kim, C.-H. Lee (PNU)

Boltzmann-Uehling-Uhlenbeck eq.

$$p_a^\mu \partial_\mu f_a(x,\mathbf{p}_a) + F_a^j(x)\frac{\partial}{\partial p_a^j} f_a(x,\mathbf{p}_a) = \mathcal{C}_a[\{f_b(x,\mathbf{p}_b)\}]$$

$$C_{ab} = \frac{1}{2}\int \frac{d^3p'}{(2\pi)^3 2E_{p'}} \int \frac{d^3k}{(2\pi)^3 2E_k} \int \frac{d^3k'}{(2\pi)^3 2E_{k'}} |\mathcal{M}_{ij}|^2 \, (2\pi)^4 \delta(p+k-p'-k')$$
$$\times \left[f_a(x,\mathbf{p}') f_b(x,\mathbf{k}') \tilde{f}_a(x,\mathbf{p}) \tilde{f}_b(x,\mathbf{k}) - f_a(x,\mathbf{p}) f_b(x,\mathbf{k}) \tilde{f}_a(x,\mathbf{p}') \tilde{f}_b(x,\mathbf{k}') \right]$$

- Boltzmann eq. - **collision term** $\mathcal{C}_a[\{f_b\}]$
- Uehling-Uhlenbeck eq. - **Pauli-blocking factor** $\tilde{f}_a(x,\mathbf{p}) = 1 - f_a(x,\mathbf{p})$
- Time evolution of the one-body phase-space density $f_a(x,\mathbf{p}_a)$ under the nuclear force (mean field potential)

Test-particle method

- 100 test particles per nucleon
- Gaussian or Power-law distribution

$$\hat{f}_a(x, \mathbf{p}) = N_{\text{test}} f_a(x, \mathbf{p})$$

$$\hat{\sigma} = \sigma / N_{\text{test}}$$

$$\hat{f}_a(x, \mathbf{p}) = \sum_{i=1}^{N_a N_{\text{test}}} (2\pi)^3 g_x(\mathbf{x} - \mathbf{x}_i(t)) g_p(\mathbf{p} - \mathbf{p}_i(t))$$

$$g(\mathbf{u}) = g(u) = \mathcal{N}_{m,n}(1 - (u/a)^m)^n \quad \text{for } 0 < u/a < 1$$

$a_x = 2.5\,\text{fm}$ $\quad a_p = s\hbar/a_x$ $\quad s \approx 0.5$ $\quad m = 2,\ n = 3$

Daejeon Boltzmann-Uehling-Uhlenbeck

- 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)

Mean Field

- We use relativistic mean field theory to calculate collective nuclear force using σ,ρ and ω fields

- make the approximation that the spatial part of the vector fields ω^{μ} and ρ^{μ} negligible

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

Mean Field

$$p^0 = E_a^* = \sqrt{(m_a^*)^2 + (\mathbf{p} - \mathbf{V})^2} + V^0$$

$$\partial^2\sigma + \frac{\partial U}{\partial \sigma} = -g_\sigma \rho_S$$
$$(\partial^2 + m_\omega^2)\omega^\nu = g_\omega j_b^\nu$$
$$(\partial^2 + m_\rho^2)\boldsymbol{\rho}^\nu = g_\rho \boldsymbol{j}_I^\nu$$

scalar potential $S = g_\sigma \sigma$

vector potential $V^\mu = g_\omega \omega^\mu + g_\rho \tau^3 \rho_3^\mu$

$$m_a^* = m_a + S$$

$$U = \frac{m_\sigma^2}{2}\sigma^2 + \frac{g_2}{3}\sigma^3 + \frac{g_3}{4}\sigma^4$$

scalar density $\rho_S = g \sum_{a=p,n,\bar{p},\bar{n}} \int \frac{d^3p}{(2\pi)^3 E_a^*} m_a^* f_a(x, \mathbf{p}_a)$

baryon current $j_b^\mu = g \sum_{a=p,n,\bar{p},\bar{n}} (-1)^a \int \frac{d^3p}{(2\pi)^3 E_a^*} p_a^\mu f_a(x, \mathbf{p}_a)$

Isospin current $j_I^{3\mu} = g \sum_{a=p,n,\bar{p},\bar{n}} \tau_a^3 \int \frac{d^3p}{(2\pi)^3 E_a^*} p_a^\mu f_a(x, \mathbf{p}_a)$

Propagation

- Equation of motion

$$\frac{d\mathbf{x}_a}{dt} = \frac{\mathbf{p}_a}{E_a}$$

$$\frac{d\mathbf{p}_a}{dt} = -\nabla V_a^0 - m_a^* \nabla S.$$

- At each time step, pair of particle is under the decision of collision within the given time interval Δt

Collision and Pauli Blocking

Criterion for collision

$$d \leq \sqrt{\frac{\hat{\sigma}}{\pi}}$$

$$d^2 = \Delta \mathbf{x}_{\mathrm{CM}} \times \mathbf{n}_{\mathrm{CM}}|^2$$

two ptl distance

unit vector along the momentum direction

$$\hat{\sigma} = \sigma / N_{\mathrm{test}}$$

inversely scaled cross-section
we adapted full ensemble method

$$t_{\mathrm{coll}} = t_{\mathrm{prev}} + \Delta t_{\mathrm{coll}}$$

$$\Delta t_{\mathrm{coll}} = -\frac{\Delta \mathbf{x} \cdot \Delta \mathbf{v}}{|\Delta \mathbf{v}|^2}.$$

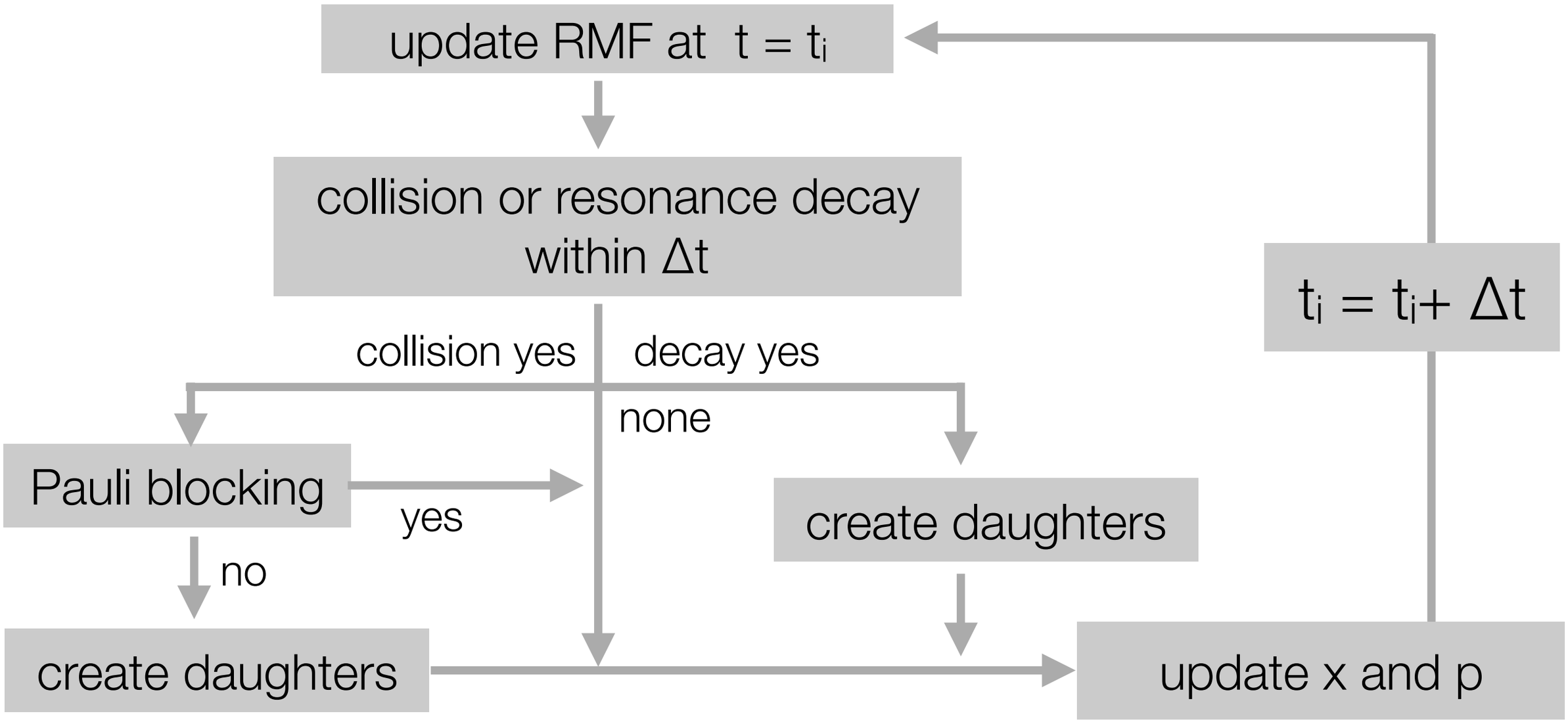
Hadrons, cross-section and decay

- E_{lab} ~ *O*(100MeV)
  p, n, π, Δ(1232), N(1440), N(1520)

- cross-sections among hadrons
  Huber and Aichelin Nucl. Phys. A 573, 587 (1994)
  Cugnon et al. Nucl. Instrum. Methods Phys. Res. Sect. B 111, 215 (1996)

- decays of resonances
  Particle data group review
  C.Patrignani et al., Chin. Phys. C 40, 100001 (2016).

Code process at each time step



Collision of decayed particles, or decay of collided particles within Δt is not considered

What has been done

- Comparison of Heavy-ion transport codes under controlled conditions
- Box calculation for collision integral and Pauli blocking

Code-comparison project

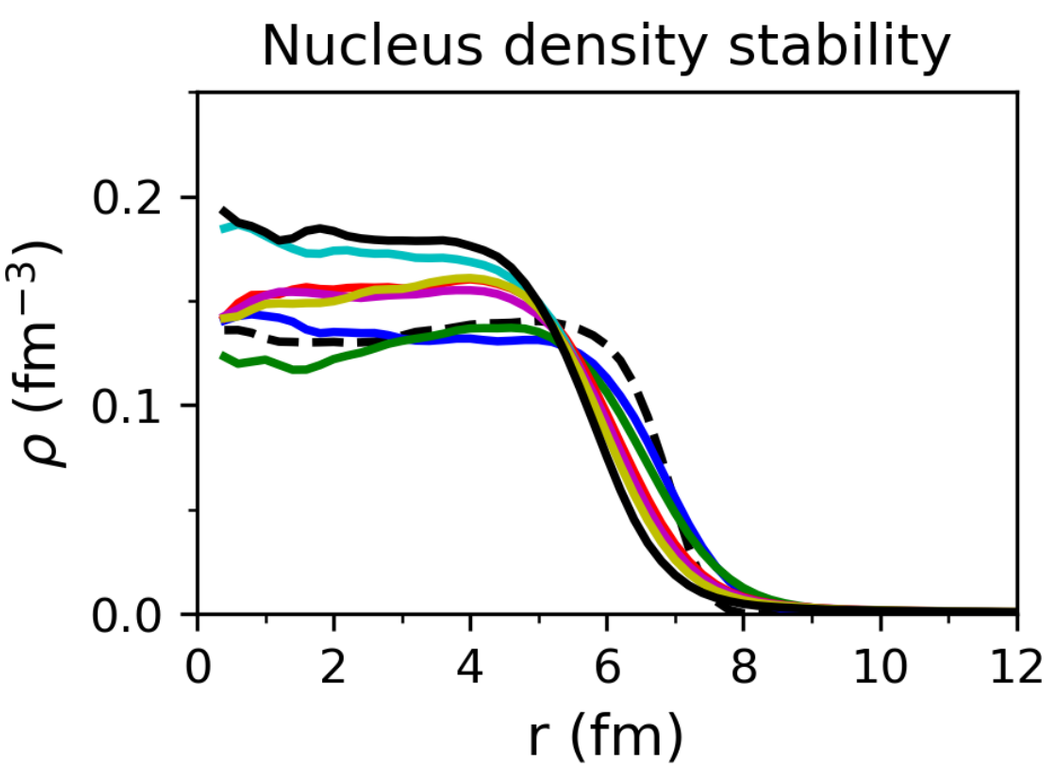
PHYSICAL REVIEW C **93**, 044609 (2016)

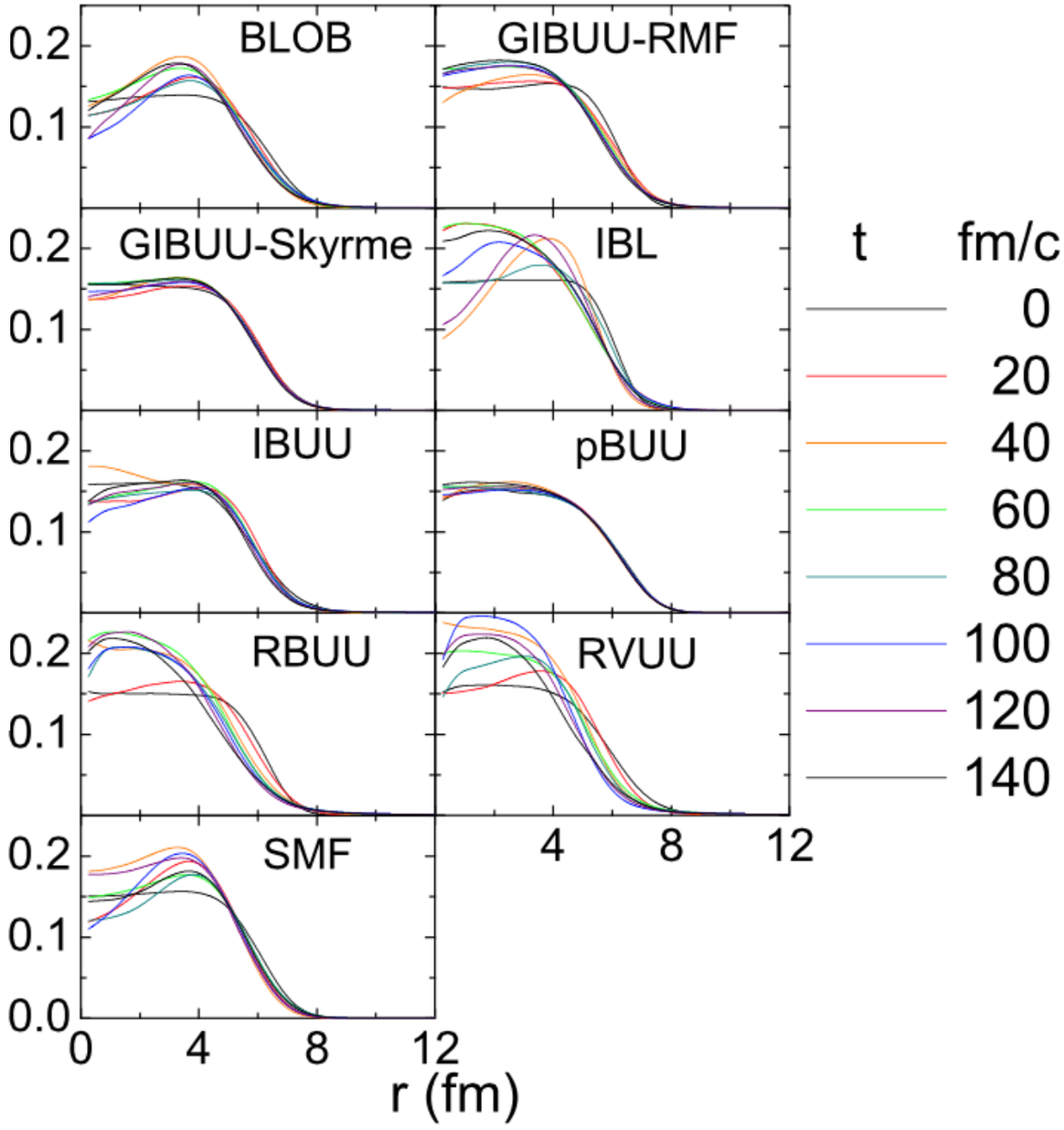
Understanding transport simulations of heavy-ion collisions at 100*A* and 400*A* MeV: Comparison of heavy-ion transport codes under controlled conditions

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]

- Single Au nucleus stability
- Au+Au time evolution
- Pauli Blocking factor
  - **B-cascade (100A MeV, without mean field)**
  - **B-full (100A MeV, with mean field)**
  - **D-full (400A MeV, with mean field)**
- dNdYrap and Transverse flow

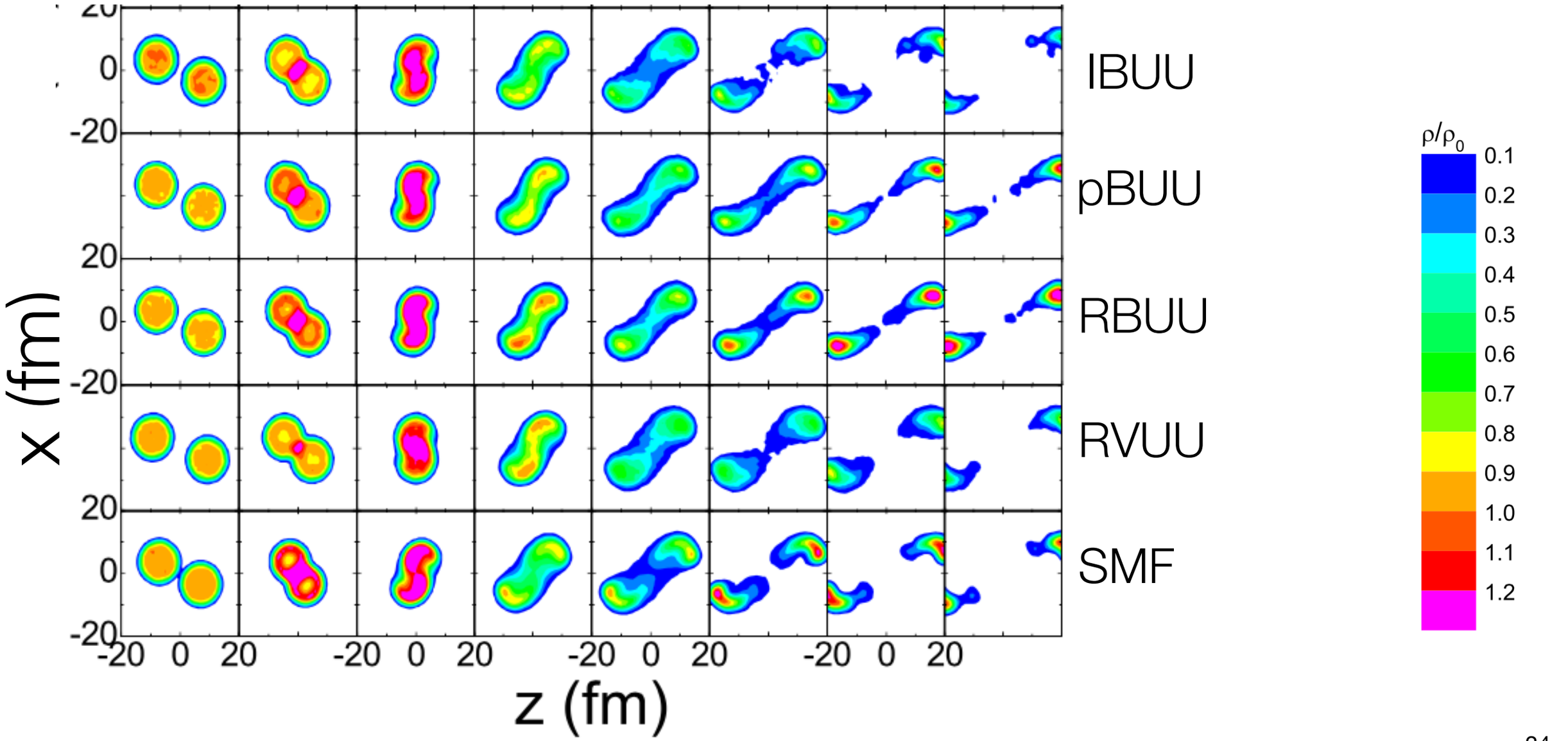
Single Au density profile





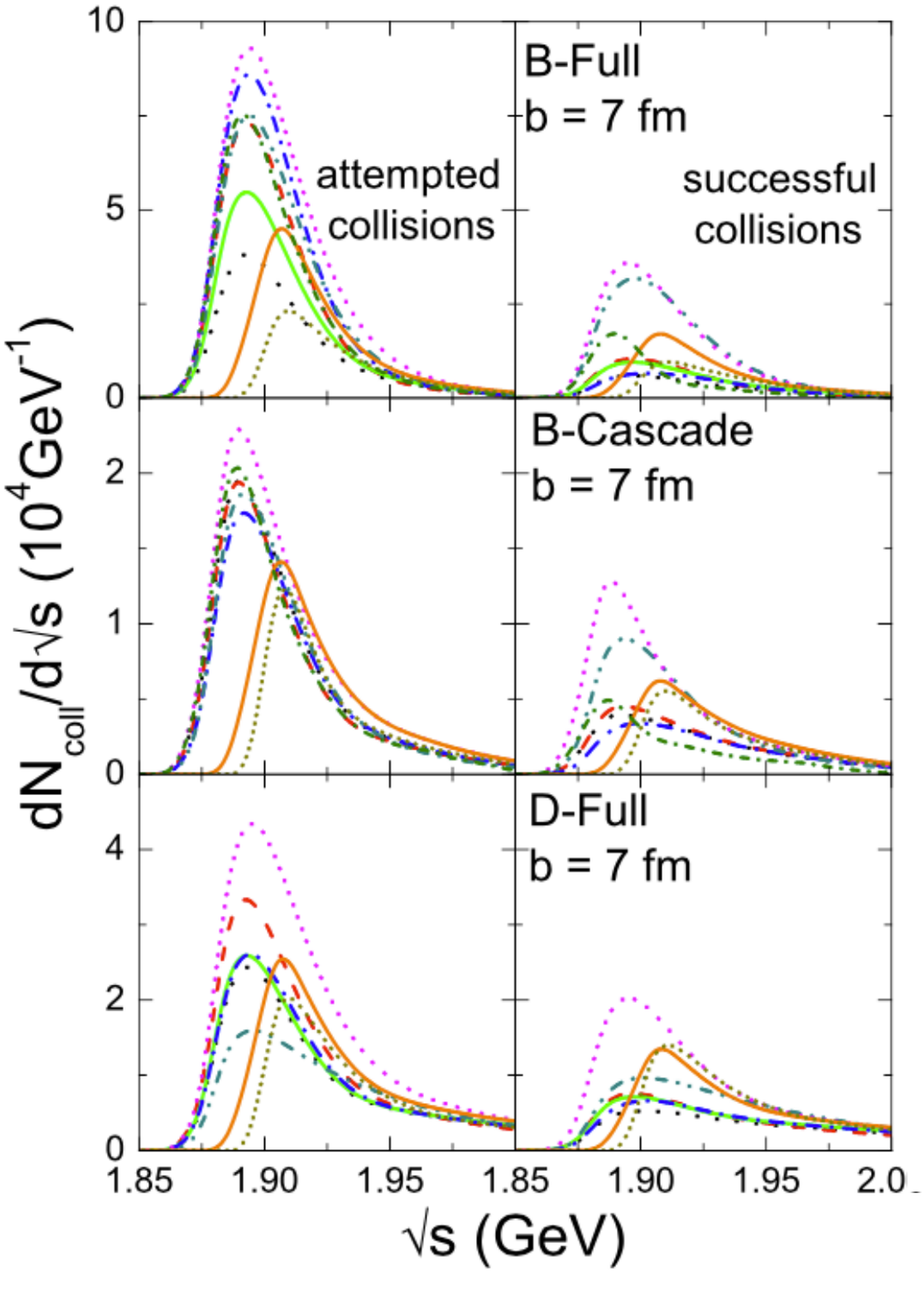
- Initial density -
  relativistic Thomas-Fermi approx.
- fluctuation 0.13~0.17 fm^{-3}

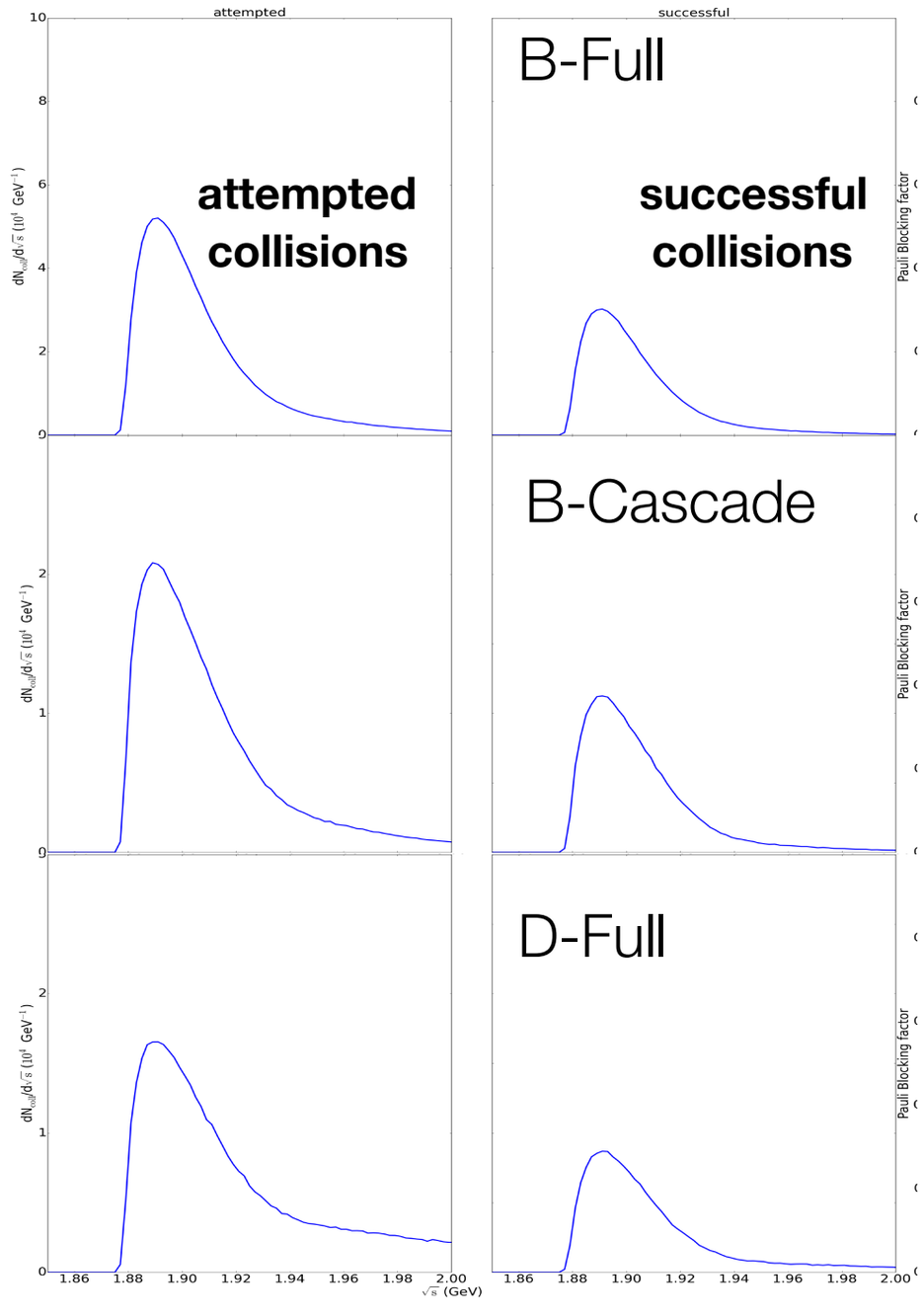
Au + Au collision @ 100 MeV/u (*b*=7 fm)



Attempted & successful collisions

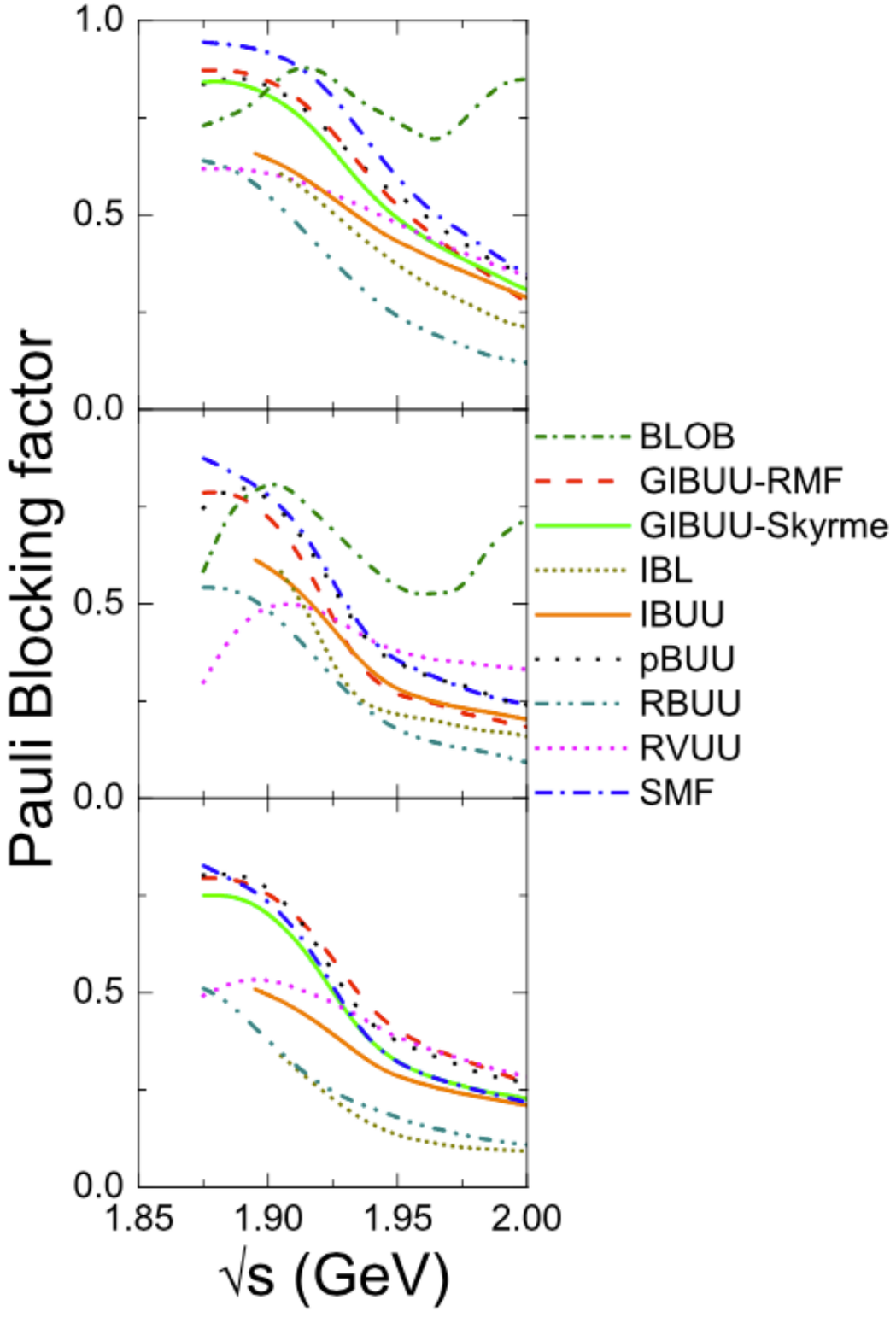
B:100A MeV
D: 400A MeV
Full: with mean fields
Cascade: no mean fields



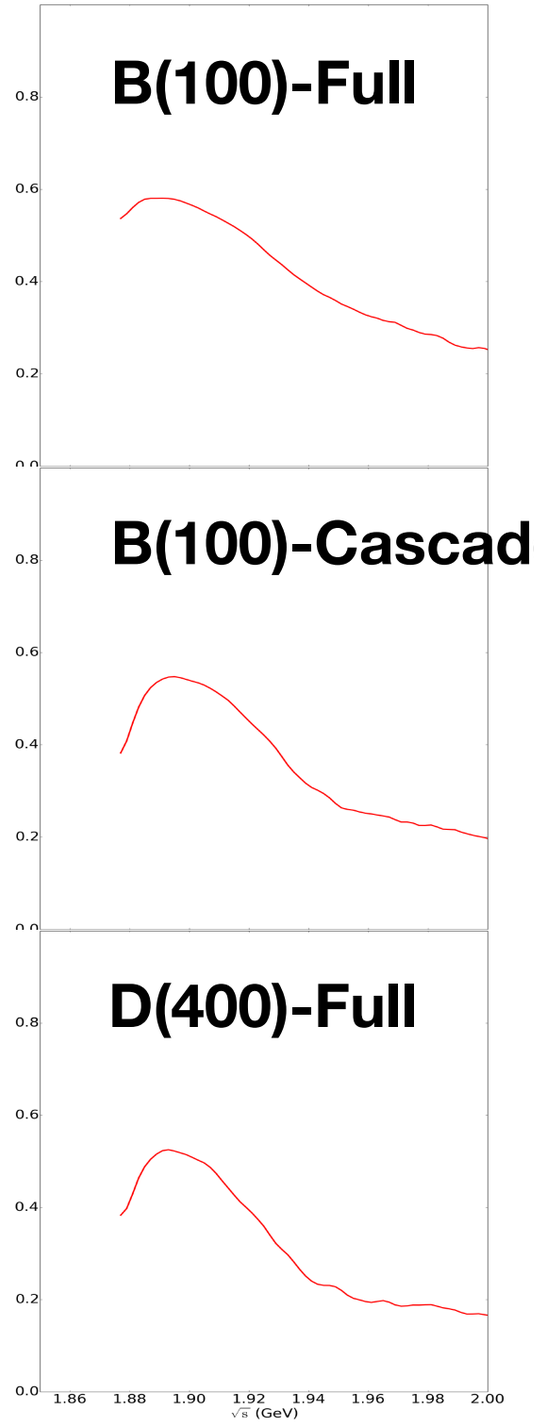


DJBUU

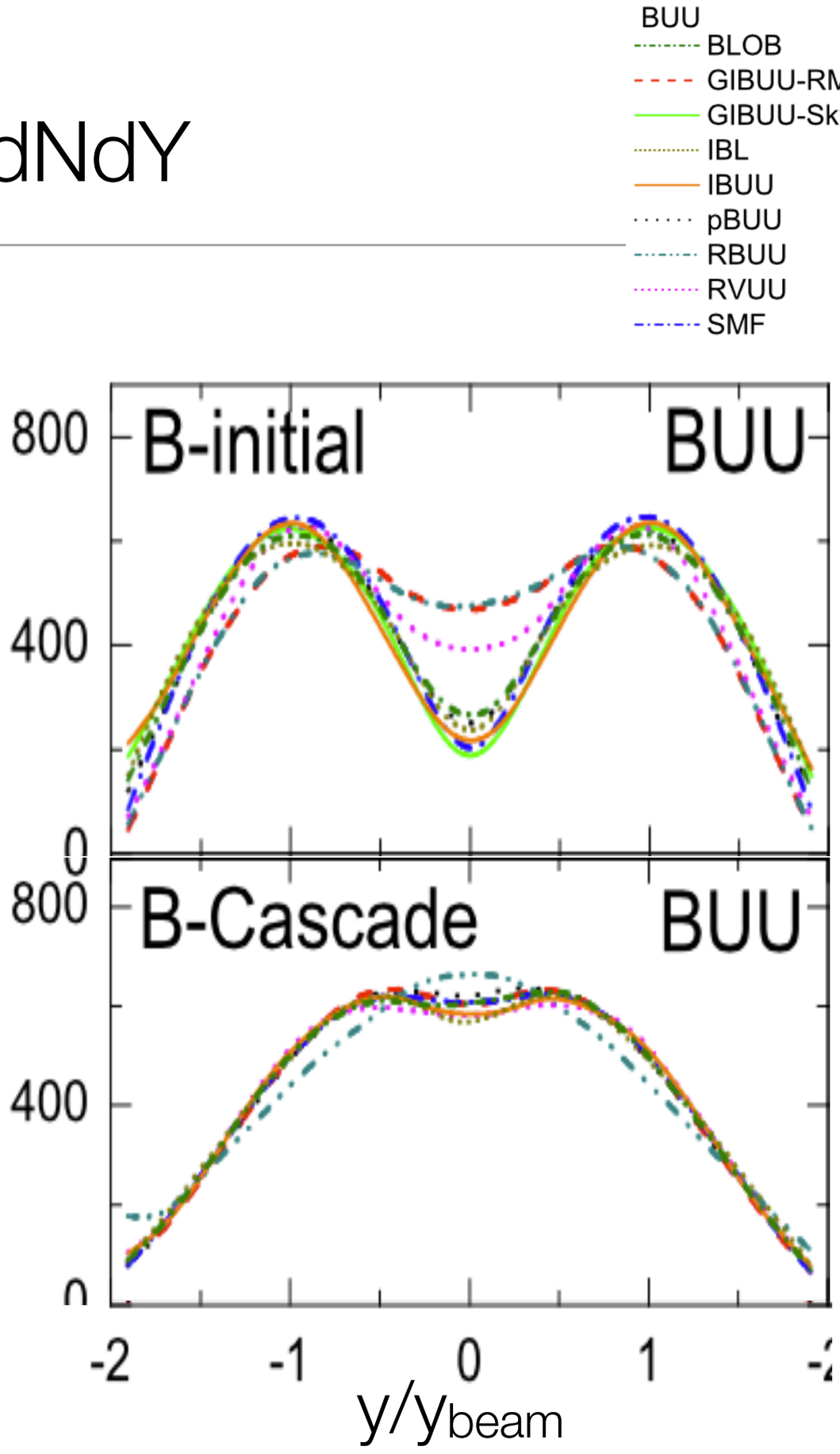
Pauli Blocking factor



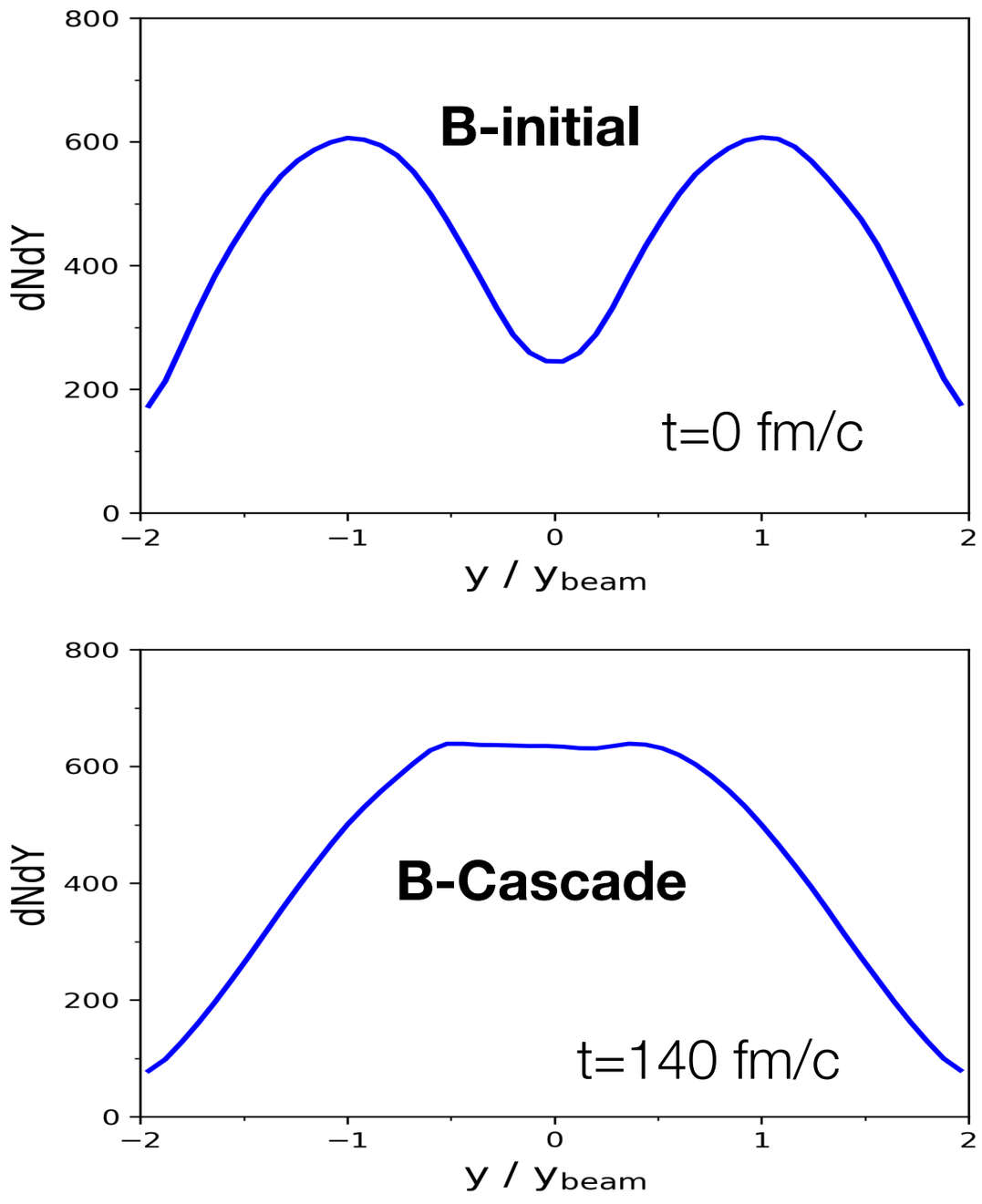
DJBUU



dNdY

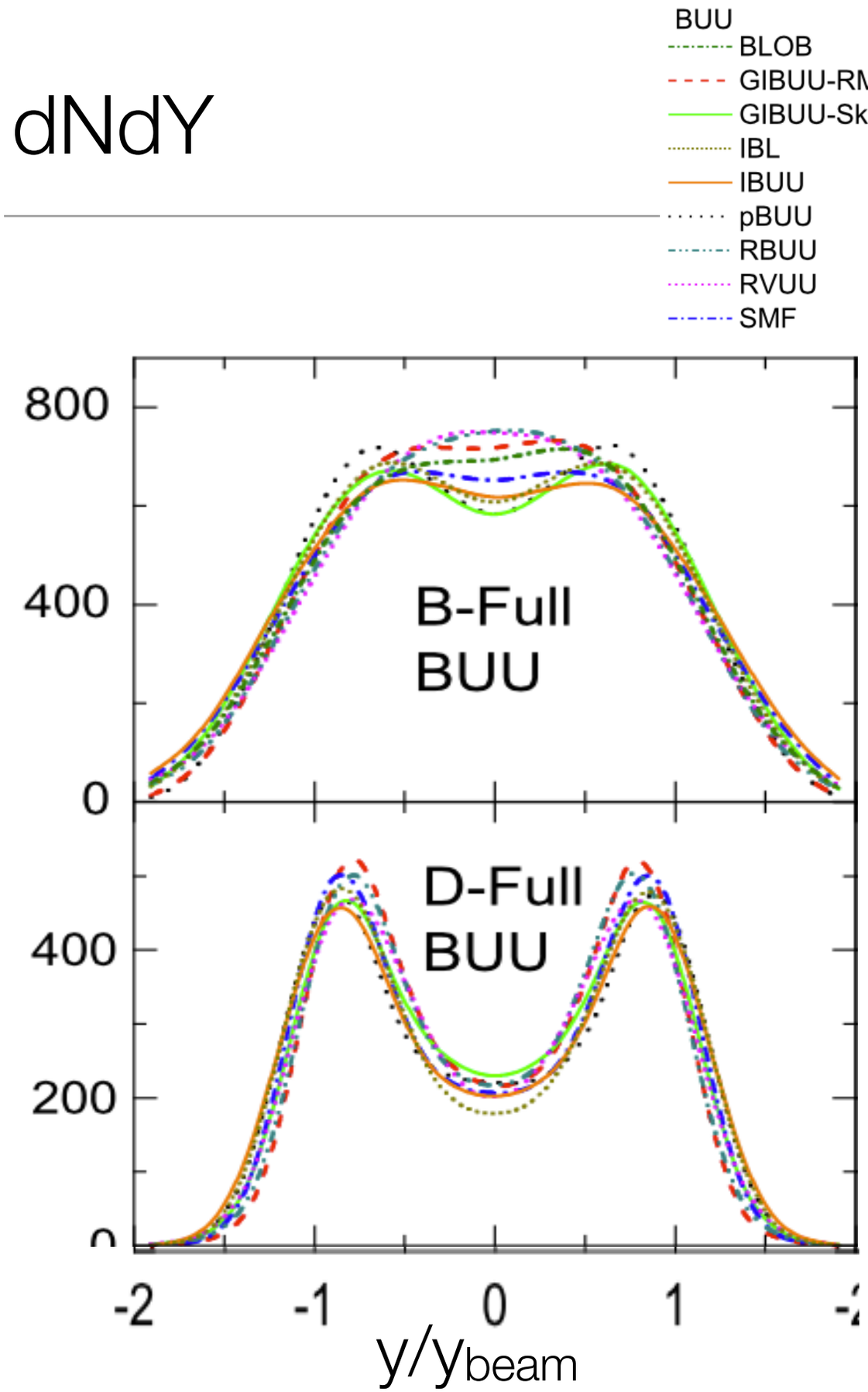

BUU
BLOB
GIBUU-RMF
GIBUU-Skyrme
IBL
IBUU
pBUU
RBUU
RVUU
SMF
B-initial
BUU
B-Cascade
BUU
800
400
0
-2
-1
0
1
y/ybeam

DJBUU

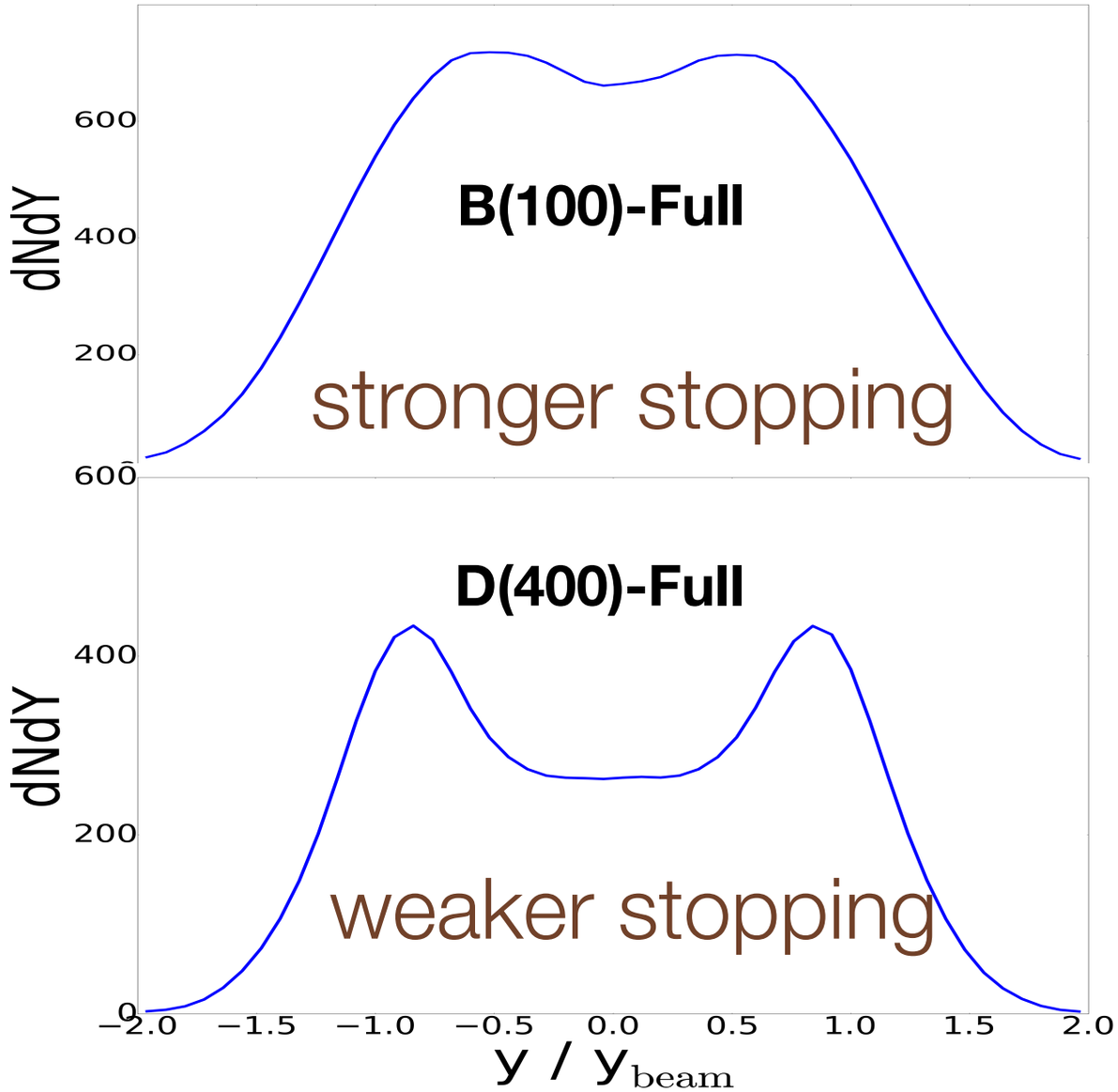

B-initial
t=0 fm/c
B-Cascade
t=140 fm/c
dNdY
y / ybeam
800
600
400
200
0
−2
−1
0
1
2

dNdY

t=140 fm/c



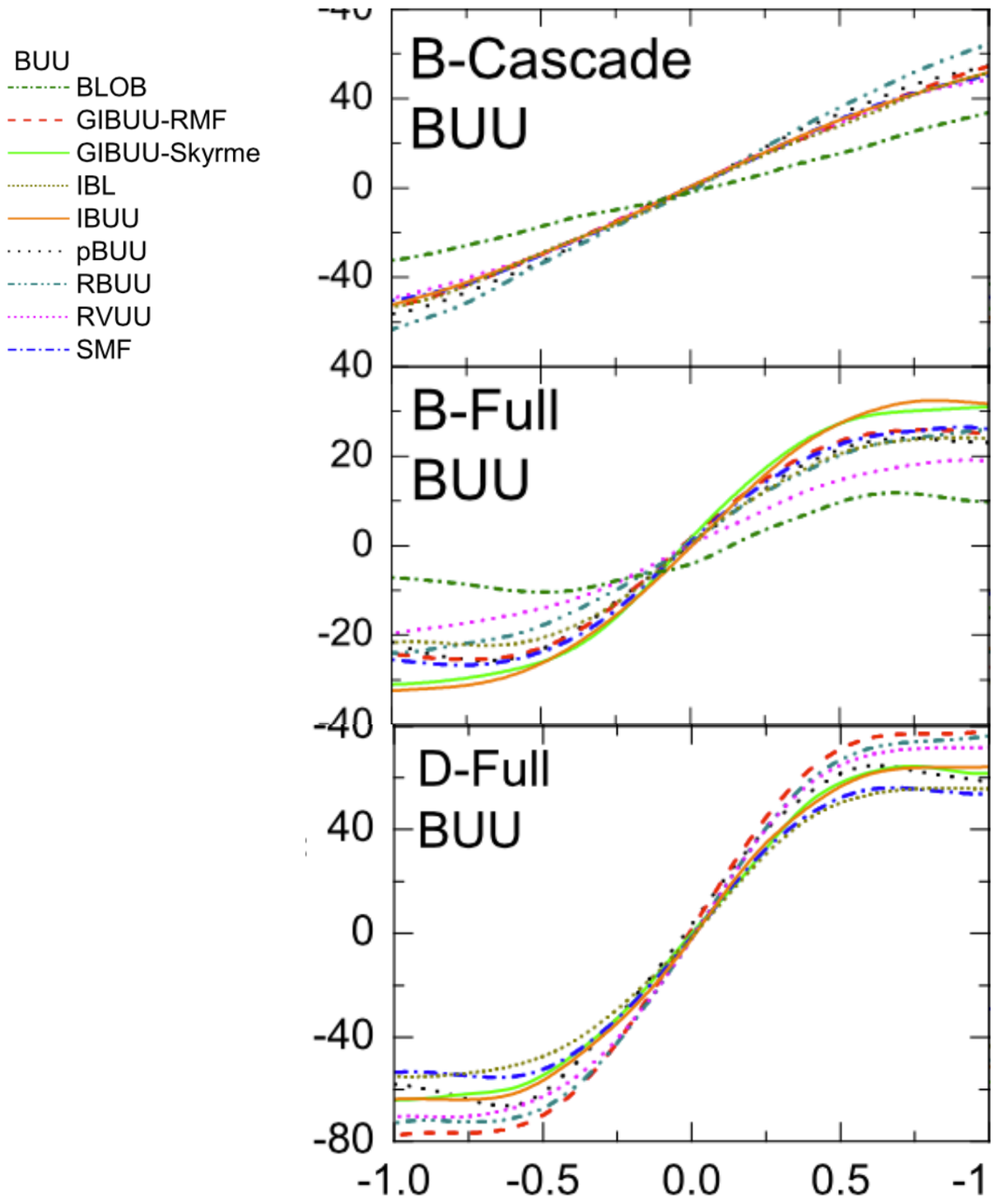
DJBUU

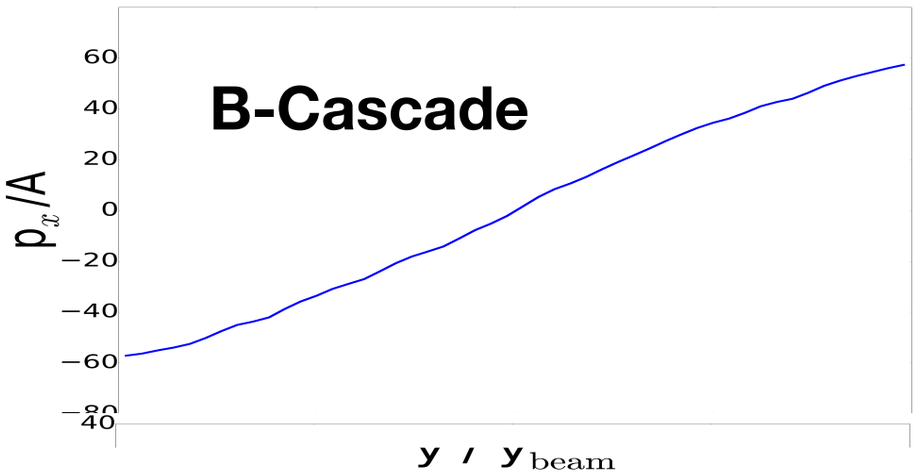


Transverse flow

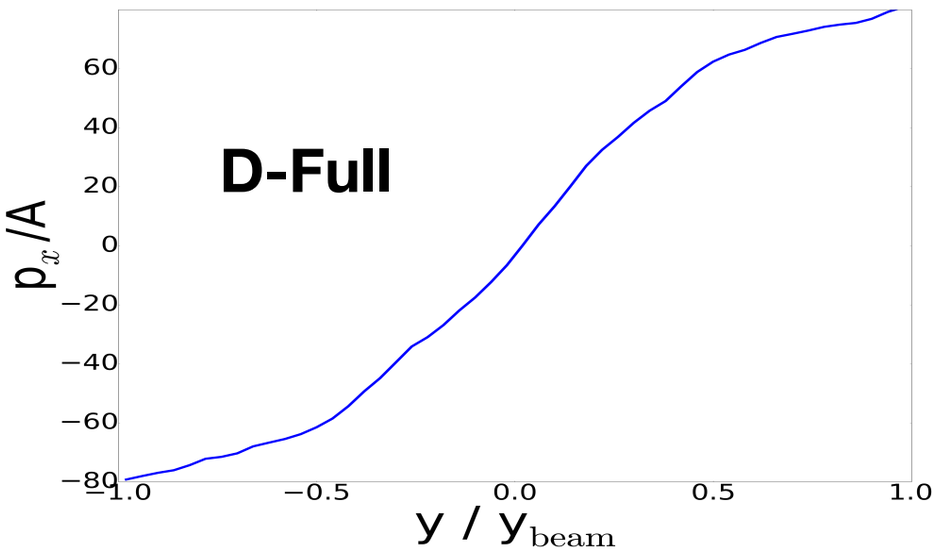
t=140 fm/c

DJBUU





B-Full



Box calculations (2016-2017)

- box size: 20 fm*20 fm*20 fm
- symmetric nuclear matter (equal p & n)
- HW1: test collisions and Pauli blocking without mean fields
- T = 0 MeV & 5 MeV (Fermi-Dirac)

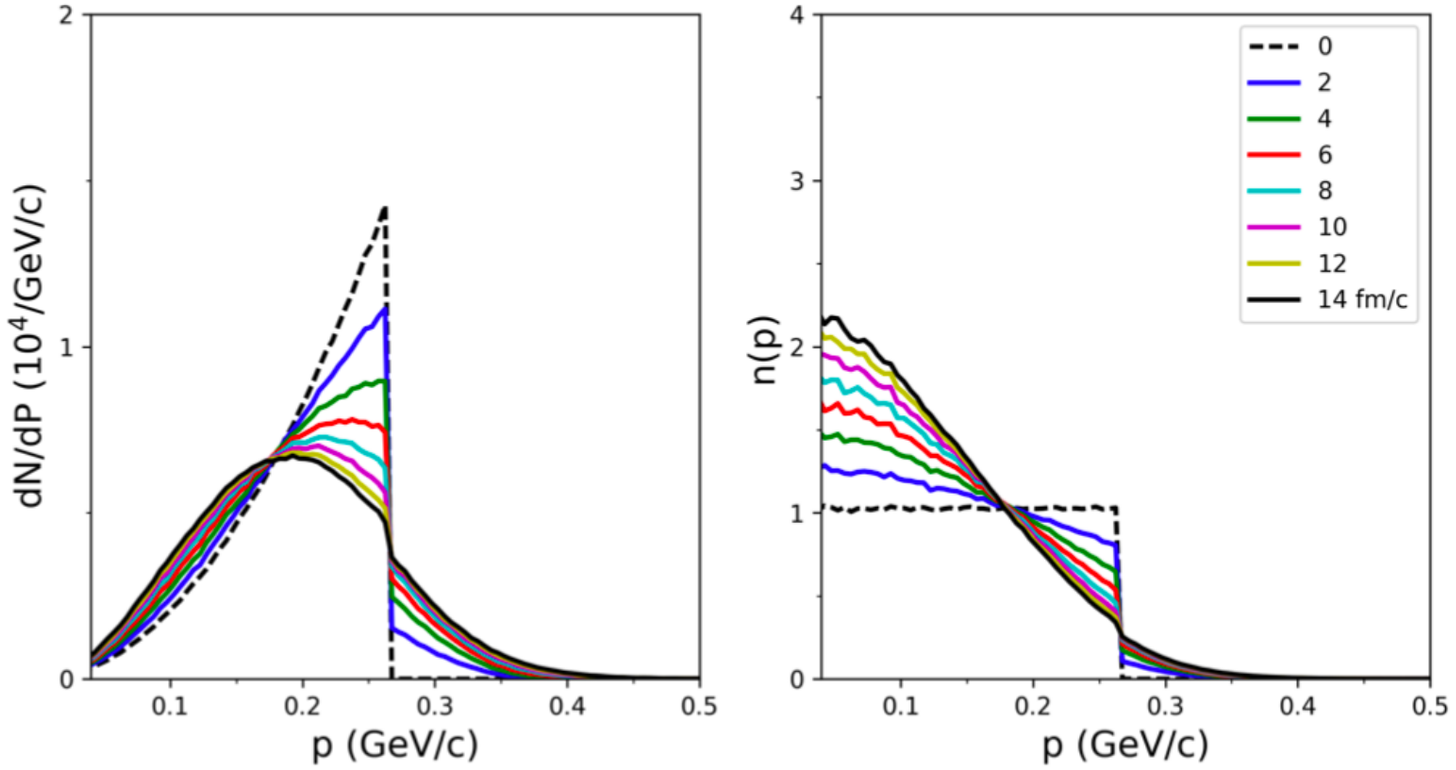
The Box Simulation Organizing Committee

Maria Colonna, Akira Ono, Yongjia Wang,
Jun Xu, Yingxun Zhang

T = 0

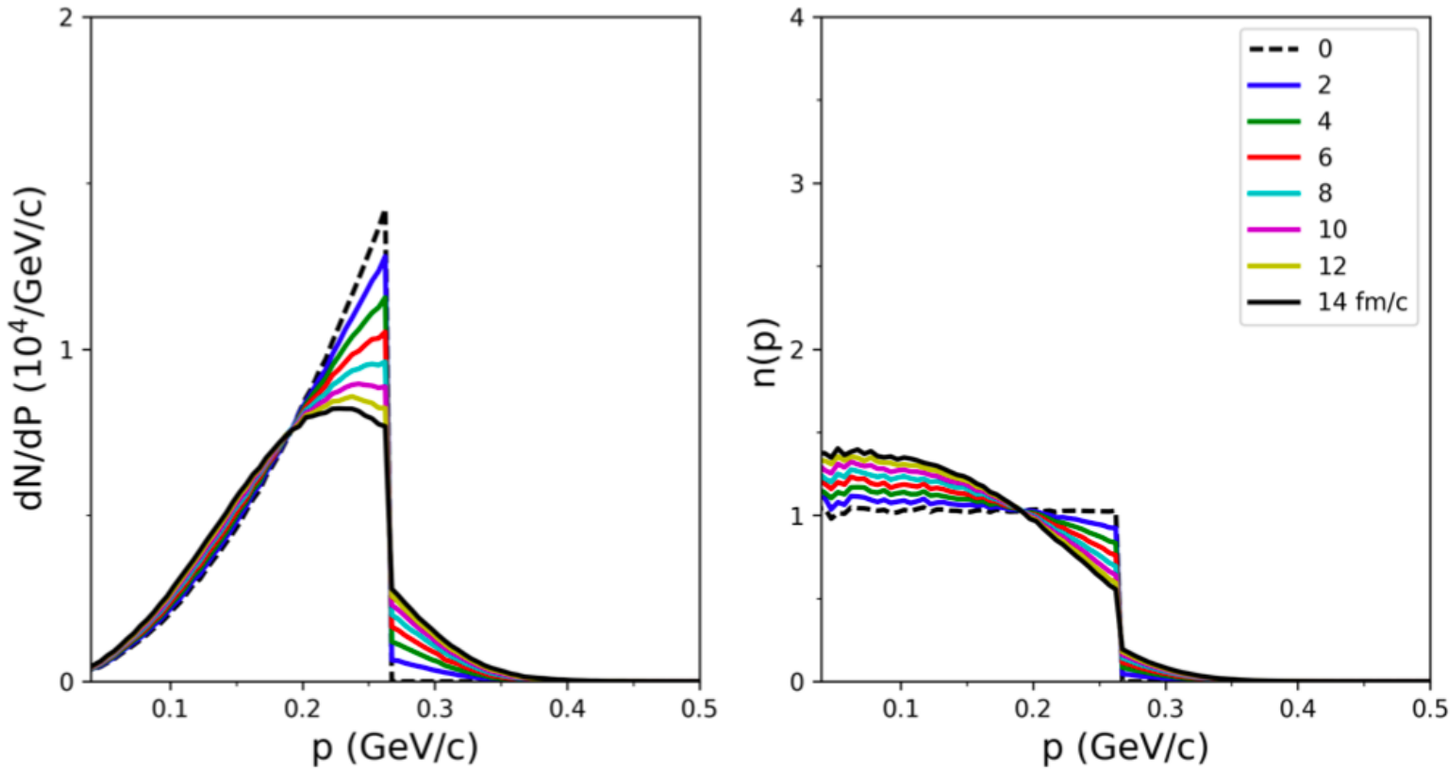
preliminary results

Without Pauli blocking



(a)Time evolution of momenum distribution within 14 fm/c at T=0 MeV in CT0

With Pauli blocking

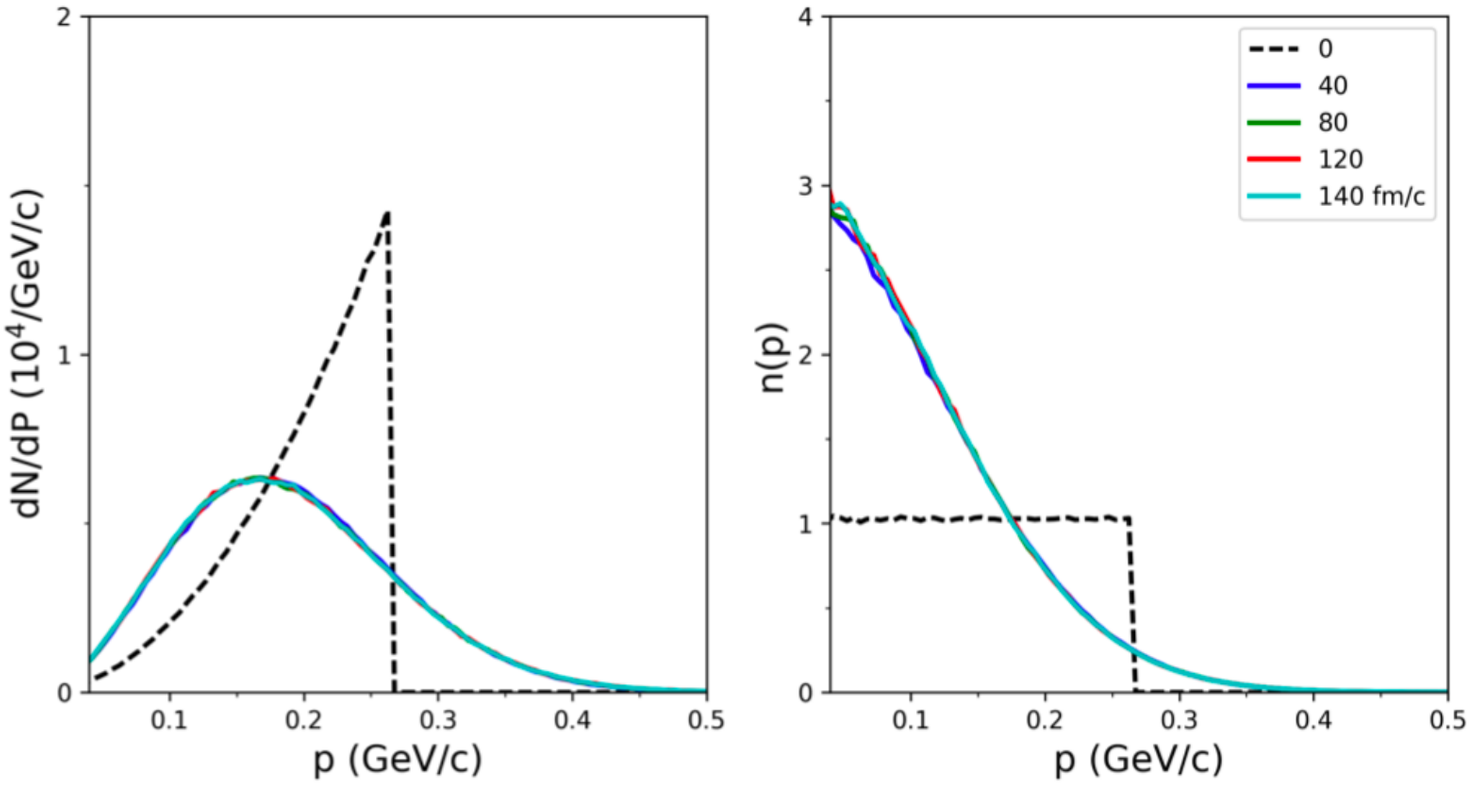


(b)Time evolution of momenum distribution within 14 fm/c at T=0 MeV in CBOP1T0

T = 0

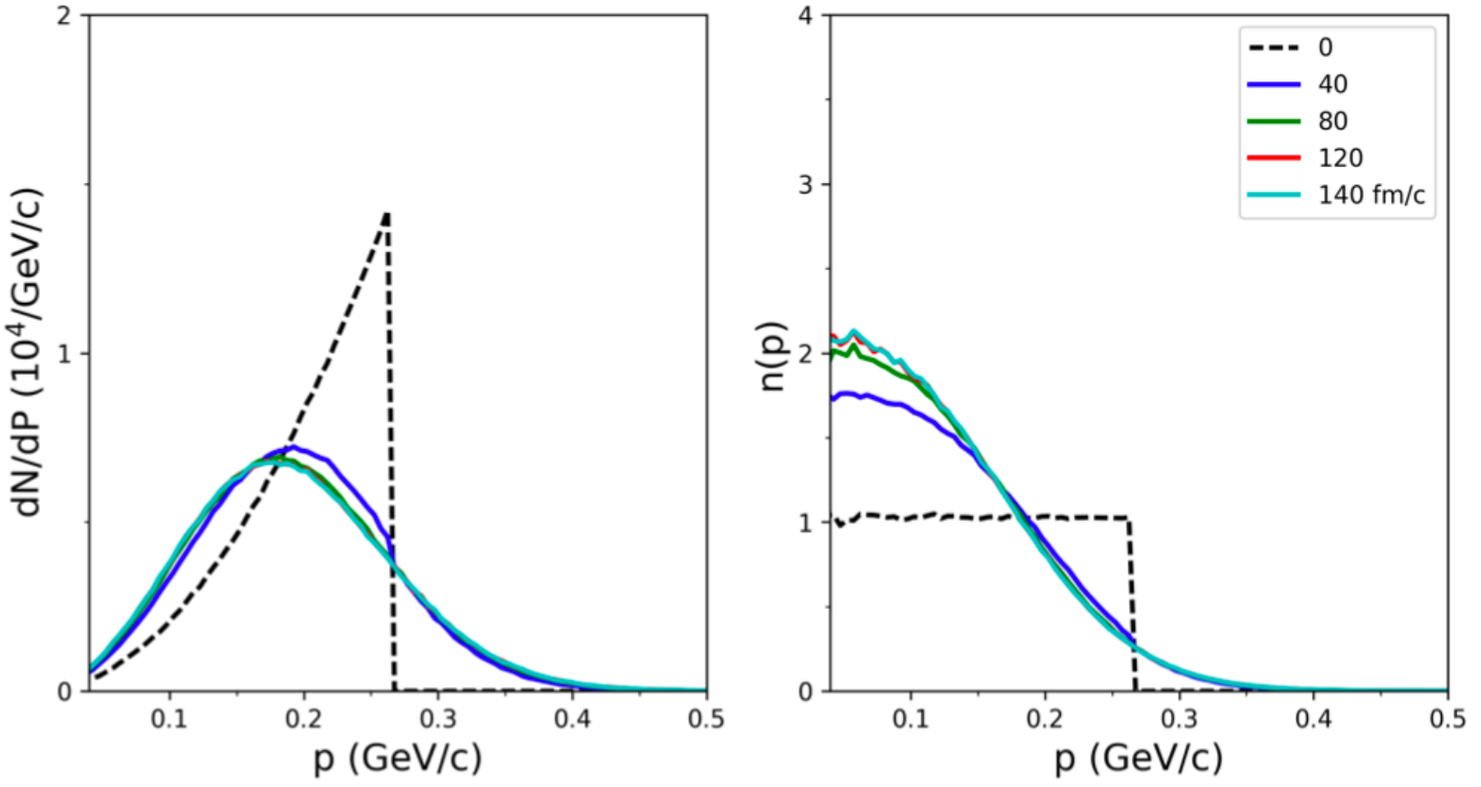
preliminary results

Without Pauli blocking



(a) Same as Fig.(4) (a) but time is until 140 fm/c

With Pauli blocking

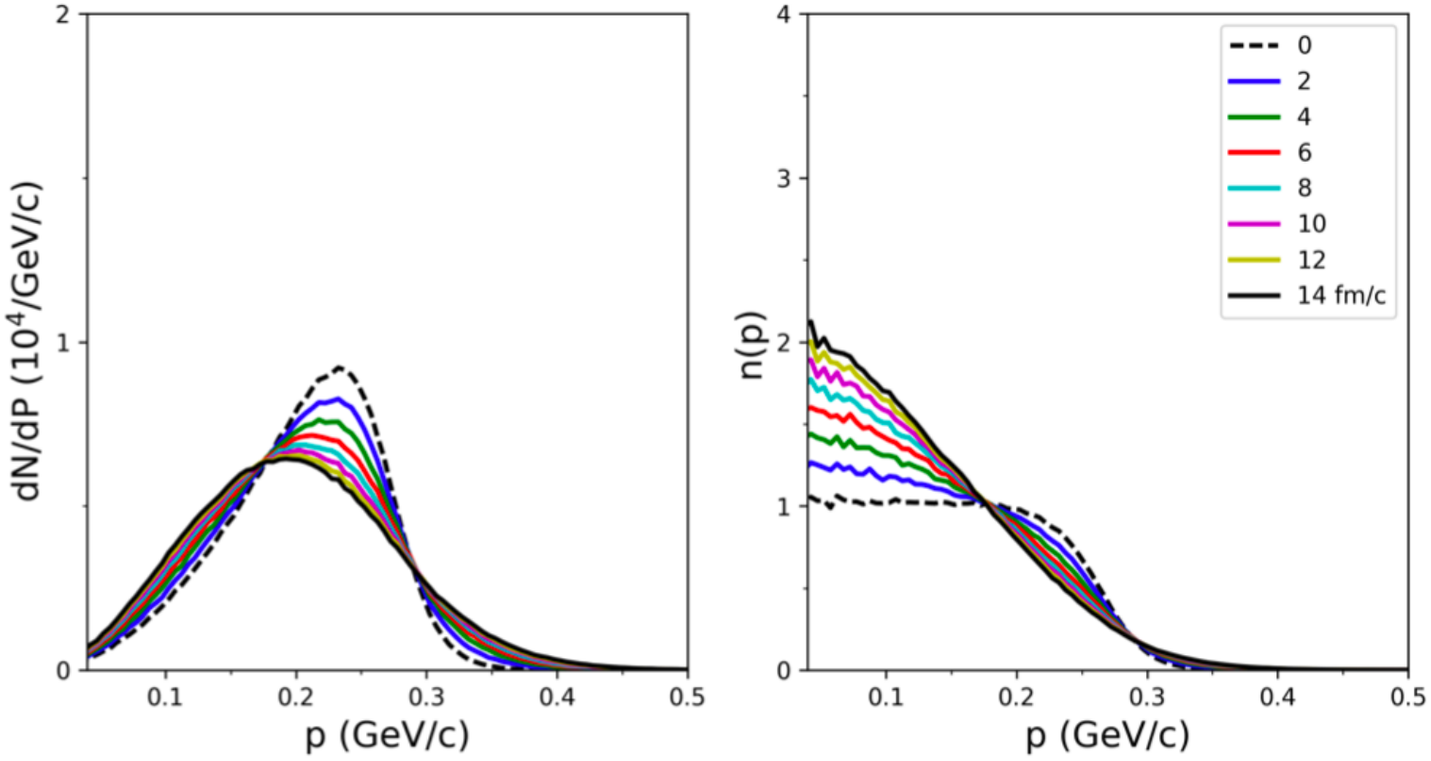


(b) Same as Fig.(4) (b) but time is until 140 fm/c

T=5 MeV

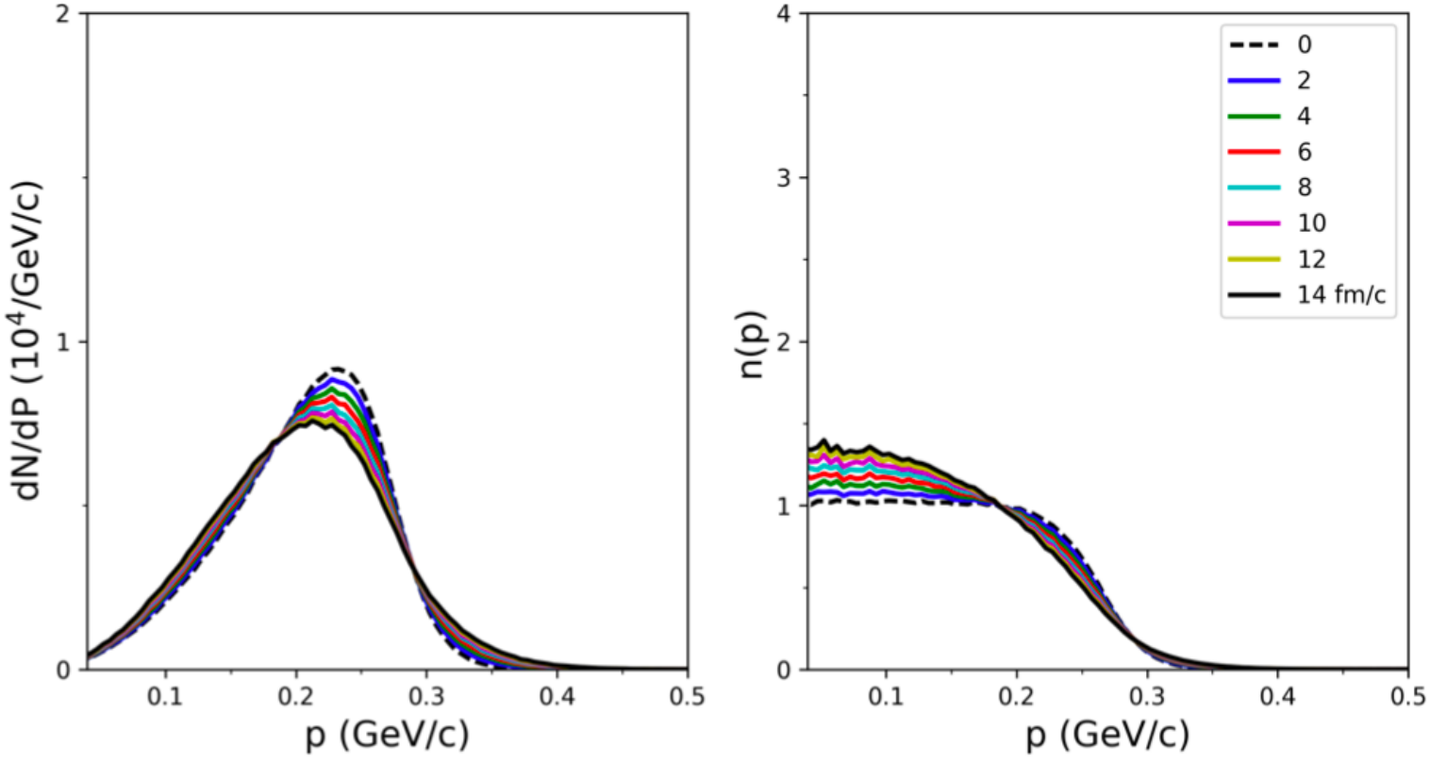
preliminary results

Without Pauli blocking



(a)Time evolution of momenum distribution within 14 fm/c at T=5 MeV in CT5

With Pauli blocking

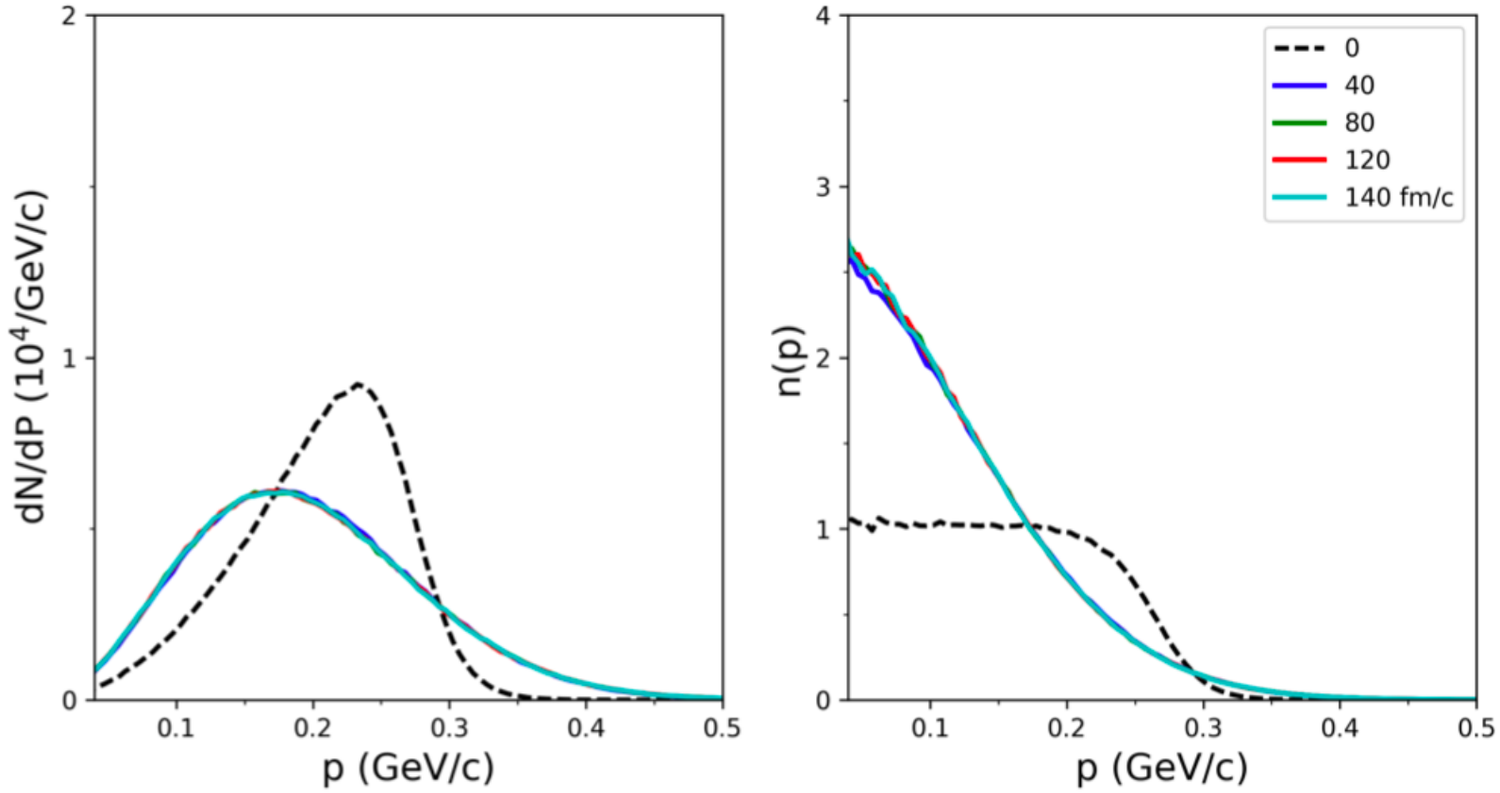


(b)Time evolution of momenum distribution within 14 fm/c at T=5 MeV in CBOP1T5

T=5 MeV

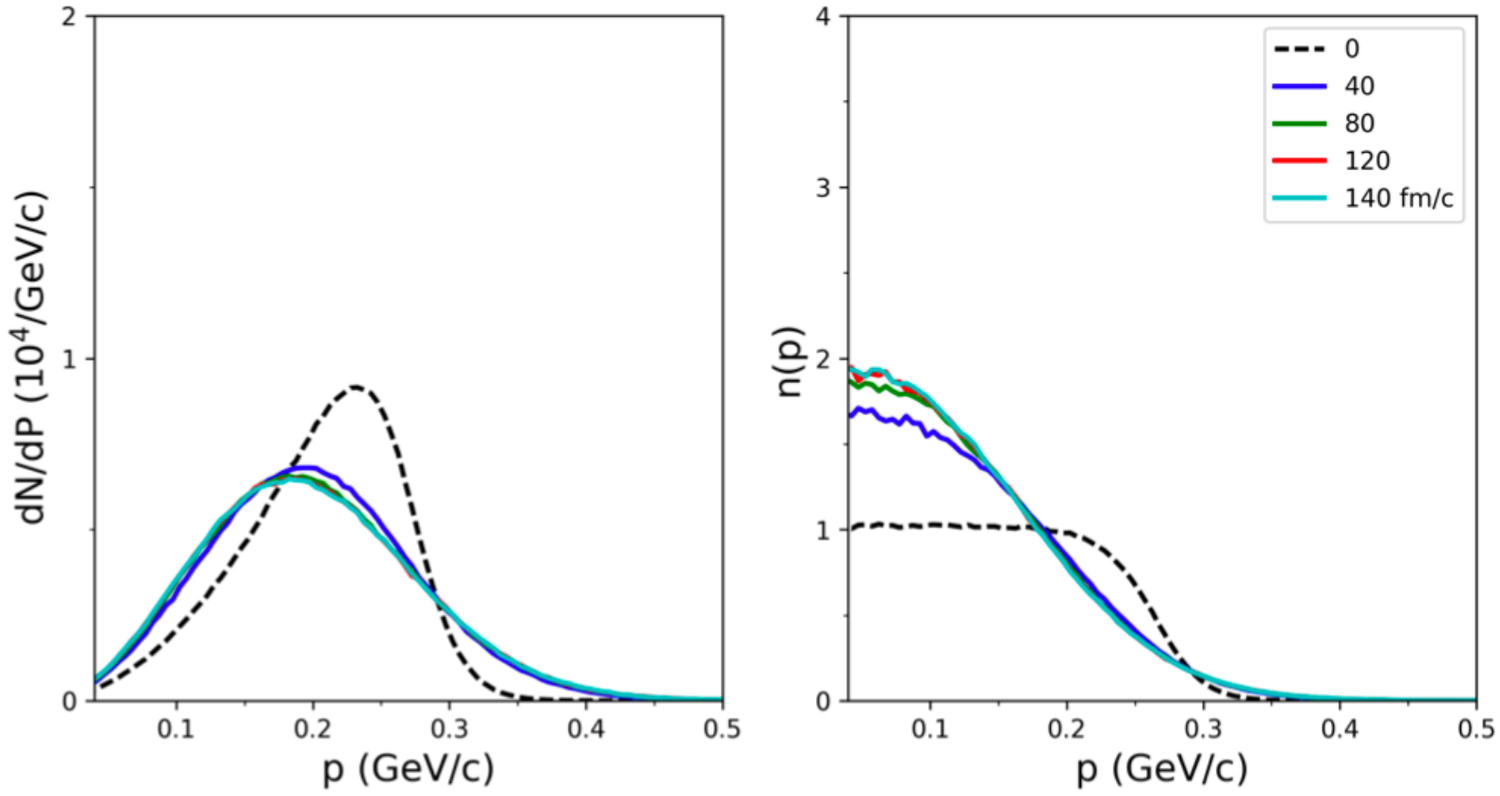
preliminary results

Without Pauli blocking



(a) Same as Fig.(4) (a) but time is until 140 fm/c

With Pauli blocking



(b) Same as Fig.(4) (b) but time is until 140 fm/c

Summary & Prospects

- **DJBUU**
  - **Daejeon BUU** (new BUU-type code) is developed
  - preliminary results are consistent with Jun Xu et al. (PRC93,044609)

    "transport code-comparison project"
  - collisions and Pauli blockings seem to be working well

- **Prospect**
  - perform code-tests (provided by Box Simulation Organizing Committee)

    HW1 (collision & Pauli blocking), HW2 (mean field), HW3 (pion)
  - investigate various nuclear equations of states
  - do simulations with various rare isotopes expected for RAON

Thanks