Dense nuclear matter from HICs to NS

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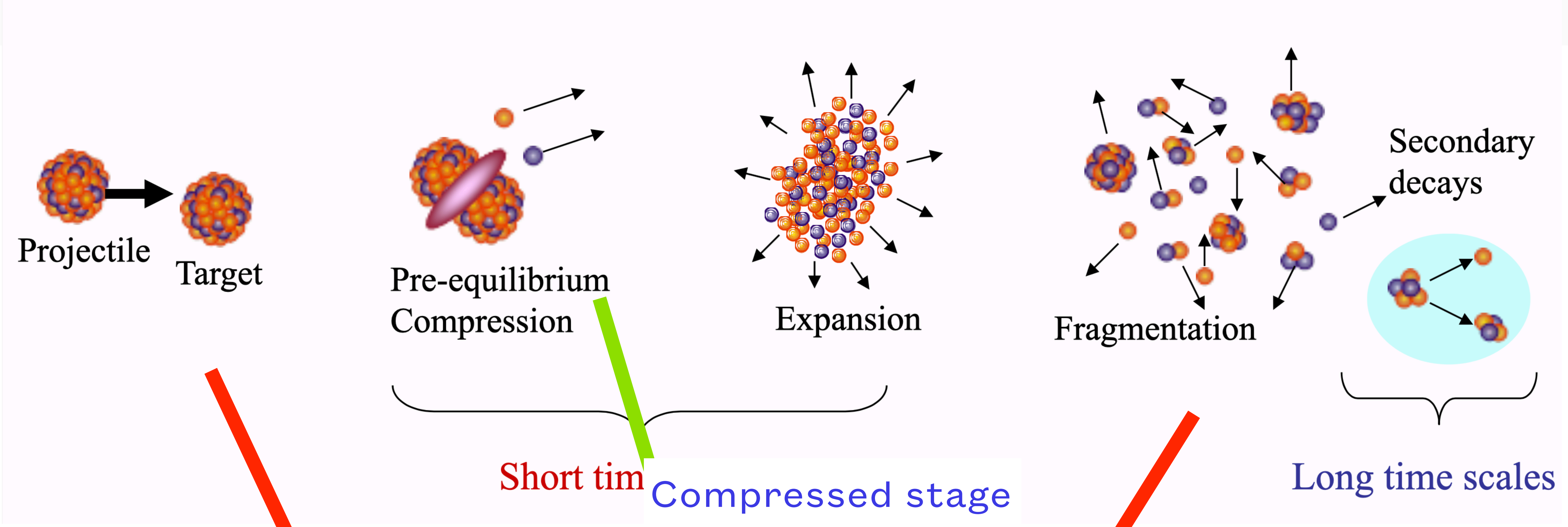
CENTER FOR EXOTIC NUCLEAR STUDIES

McGill

Content

- Introduction
- Transport theory / DJBUU model
- Results comparison with TMEP
- Pion production and symmetry energy @ LAMPS/RAON
- X-ray bursts and EOS

Heavy-ion collisions: why study?



Compressed stage

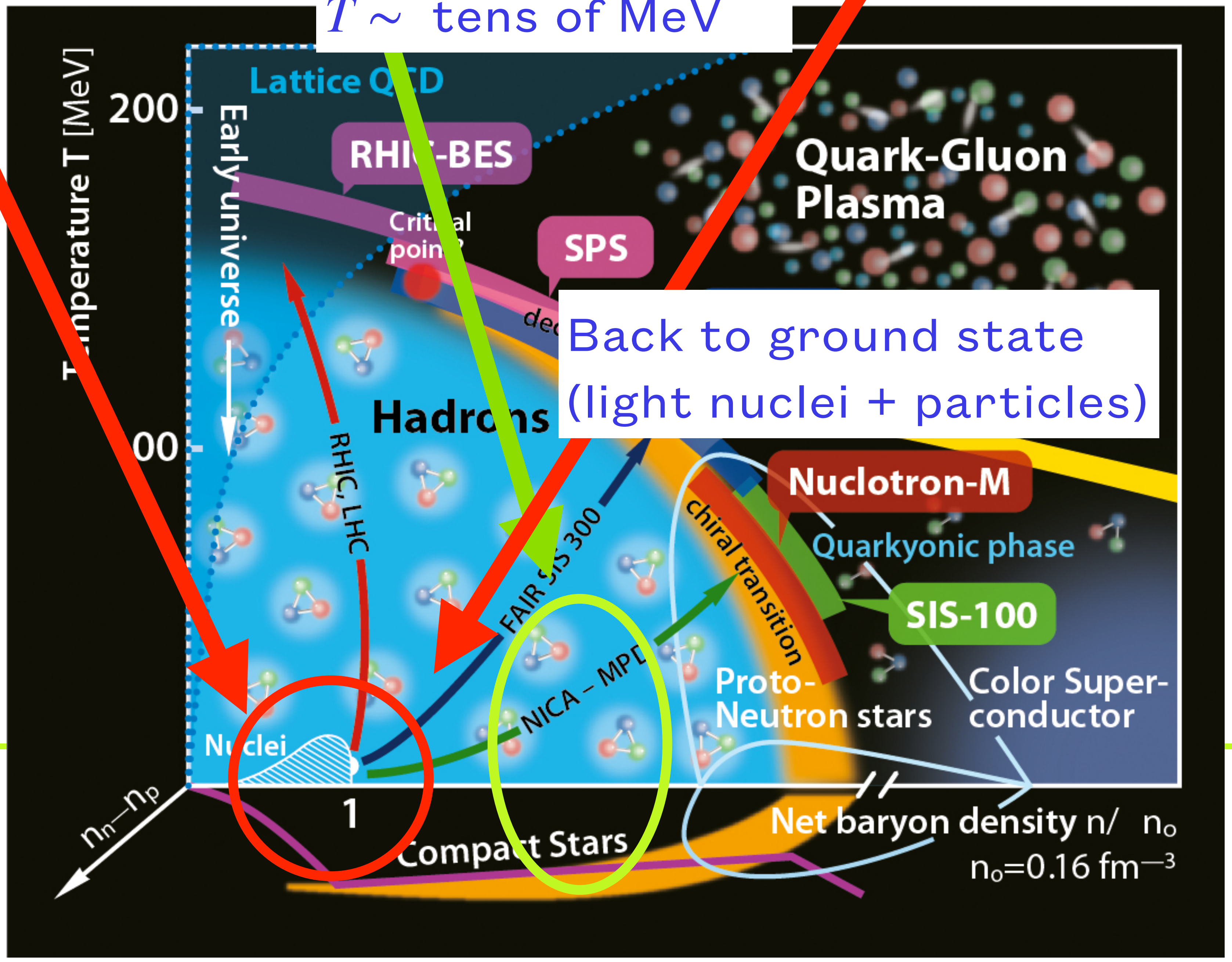
$\rho \sim$ a few ρ_0

$T \sim$ tens of MeV

Initial stage

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

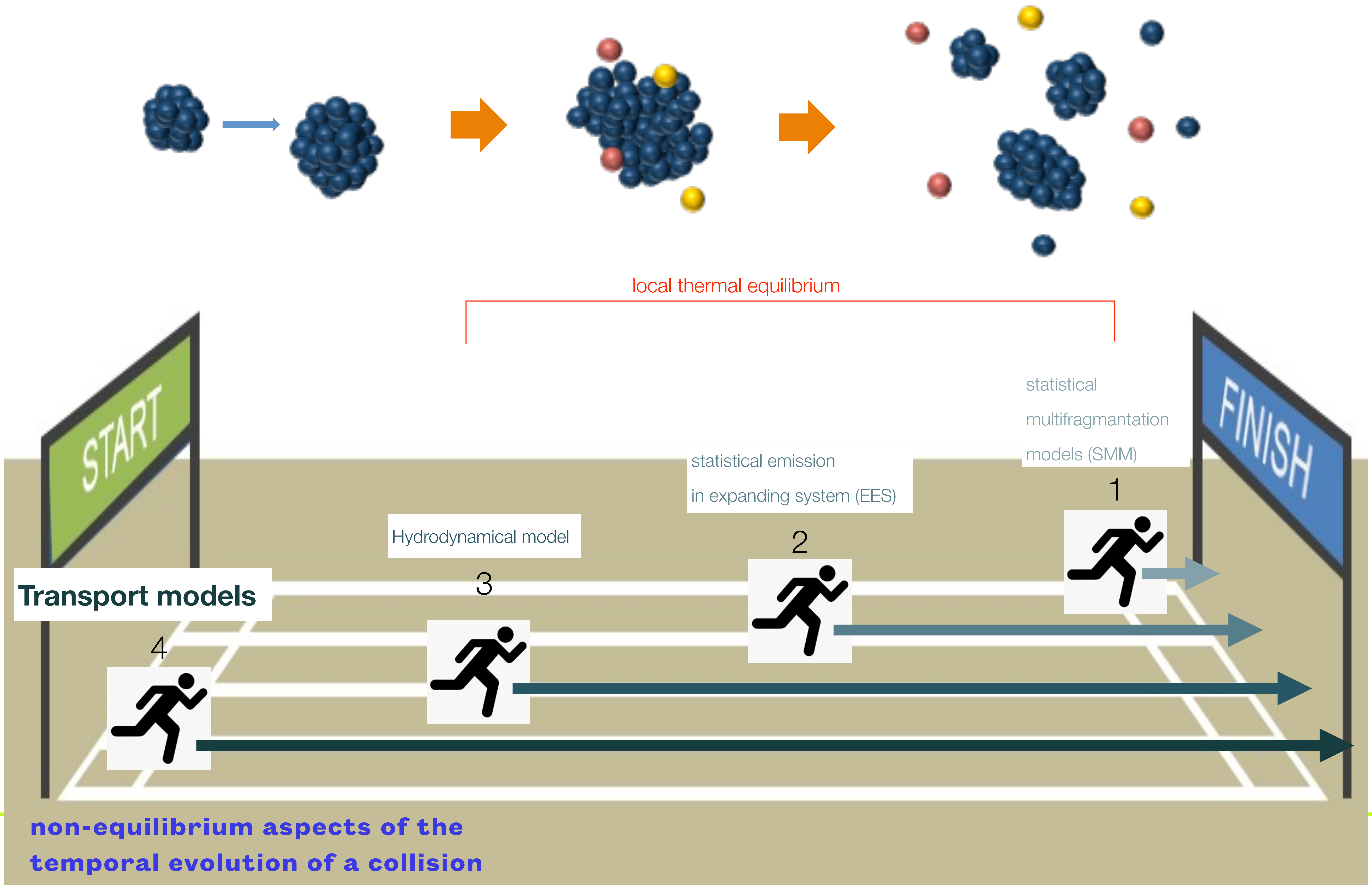
$T \sim 0$ MeV



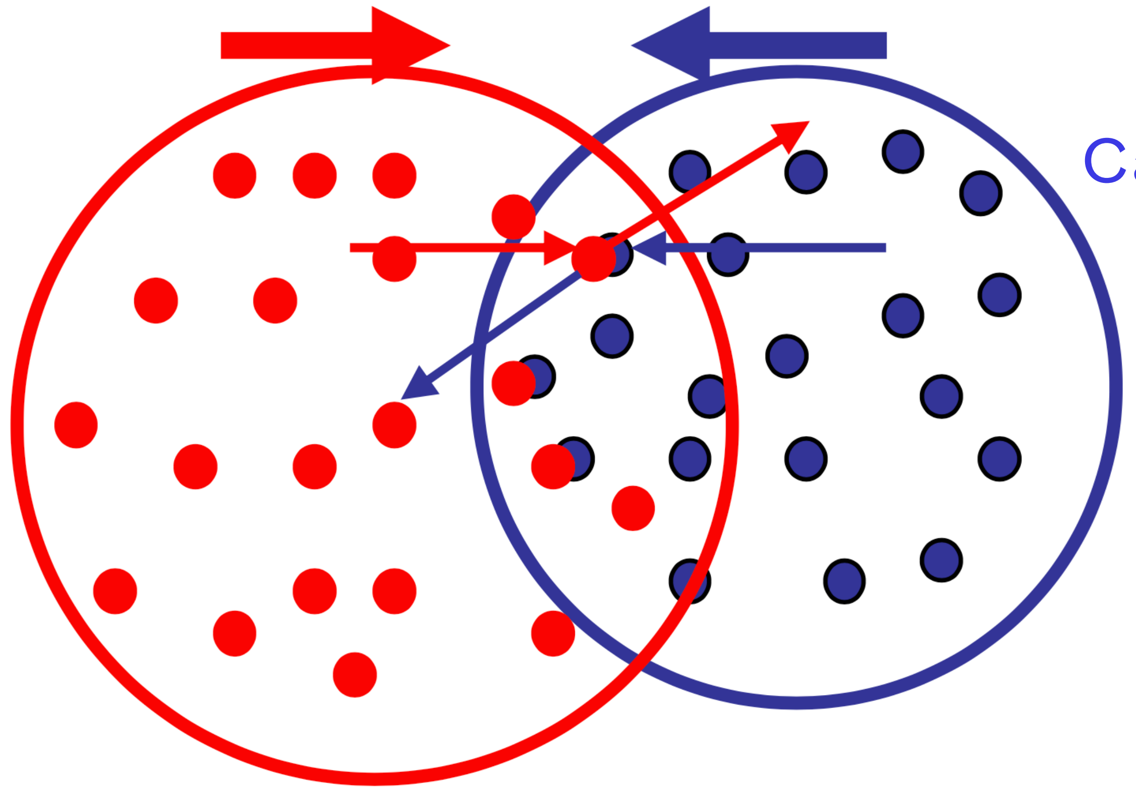
Back to ground state
(light nuclei + particles)

- 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

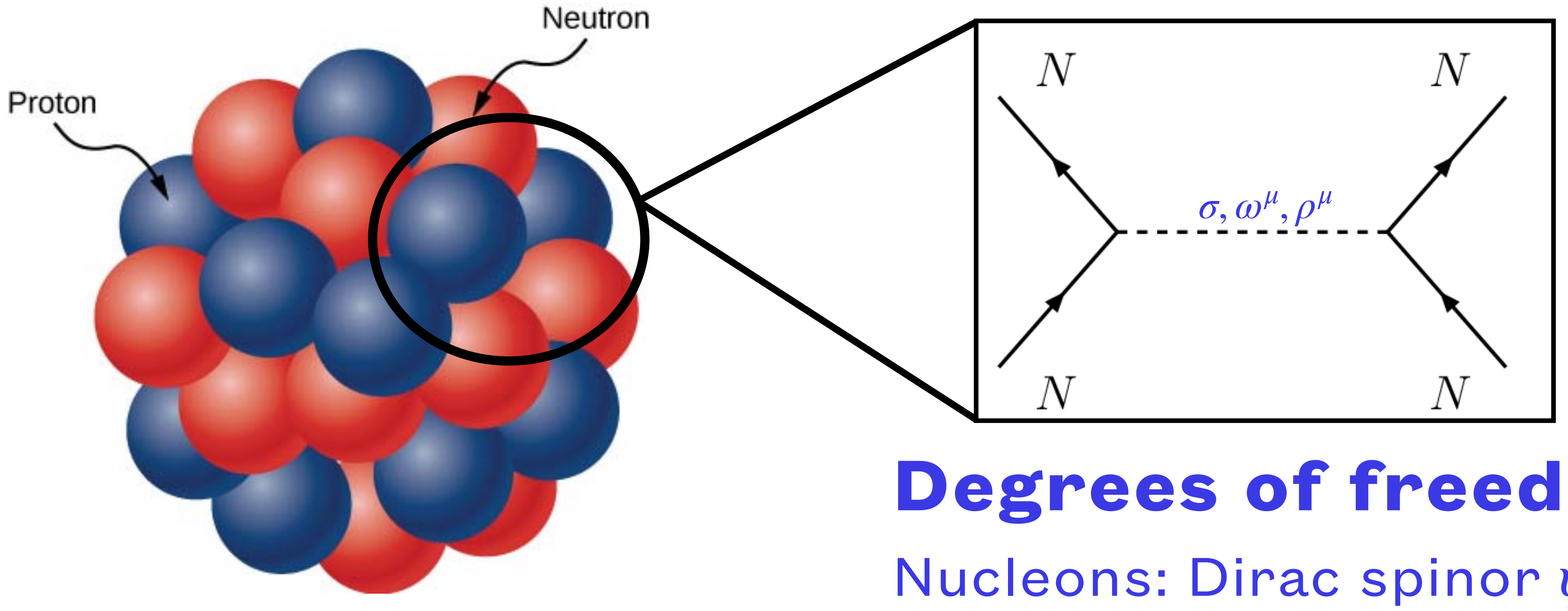
Levels of descriptions in HICs



Collisions and microscopic interactions



- 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

$$\left[i\gamma_\mu\partial^\mu - (m_N + g_\sigma\sigma) - g_\omega\gamma_0\omega^0 - g_\rho\gamma_0\tau_3\rho_3^0 - \frac{e}{2}\gamma_0(1+\tau^3)A^0\right]\psi = 0$$

Dirac mass, effective mass, m*

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

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

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

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

$$(p^{*0})^{-1}\left[p^{*\mu}\partial_\mu - \left(p^{*\mu}\mathcal{F}^{\mu i} - m^*\partial^i m^*(x)\right)\frac{\partial}{\partial p^{*i}}\right] f(\vec{x},\vec{p}^*) = C(\vec{x},\vec{p}^*)$$

under the RMF potential — propagation of $f(x,p^*)$ — up to 2-body coll.

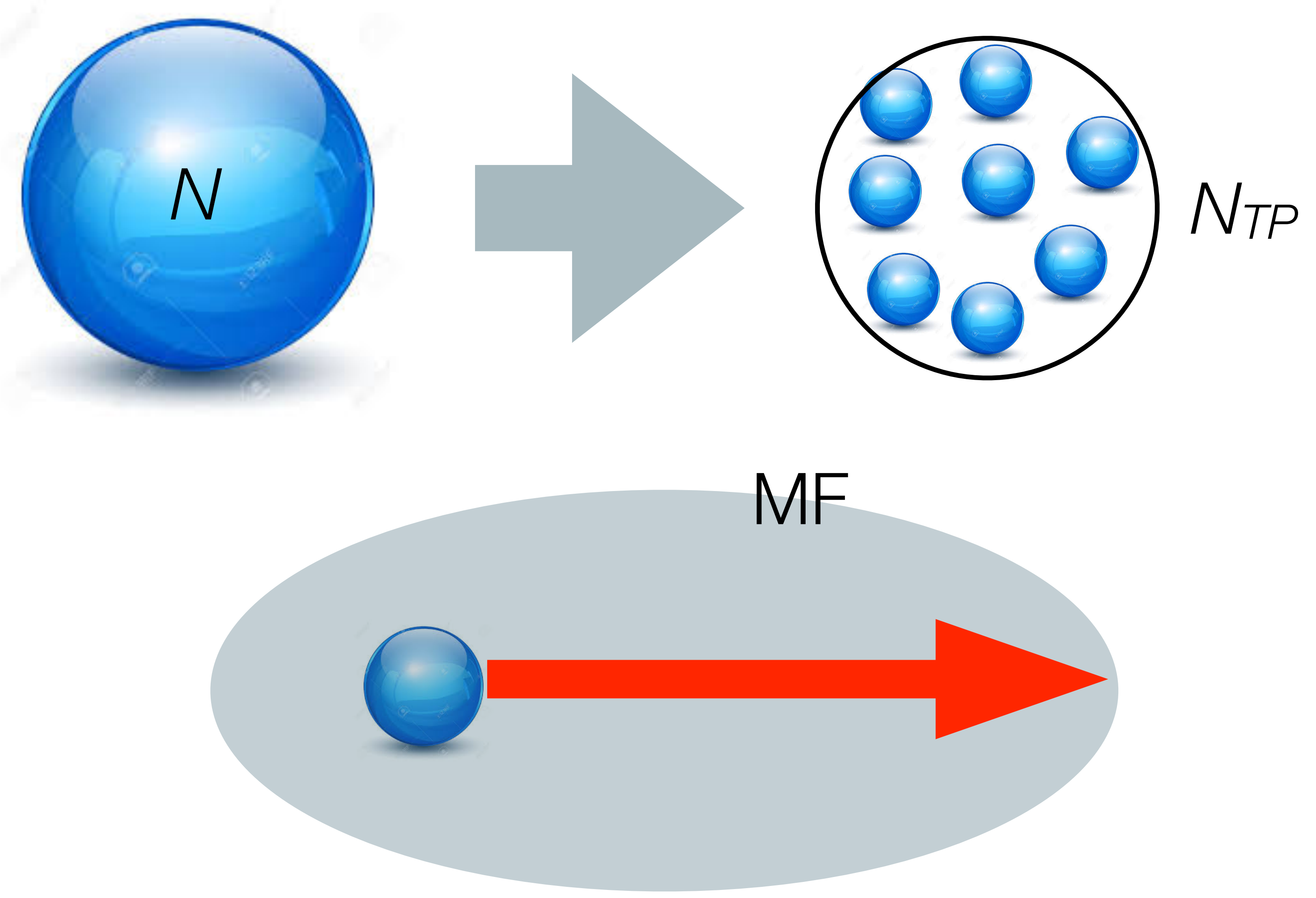
$$C^{(2)}(\vec{x},\vec{p}_1) = \frac{1}{2}\int\frac{d^3p_2}{(2\pi)^3 2p_2^0}\int\frac{d^3p_{1'}}{(2\pi)^3 2p_{1'}^0}\int\frac{d^3p_{2'}}{(2\pi)^3 2p_{2'}^0}\left|\mathcal{M}_{12\to1'2'}\right|^2(2\pi)^4\delta(p_1+p_2-p_{1'}-p_{2'})$$
$$\left[f_{1'}(\vec{x},\vec{p}_{1'})f_{2'}(\vec{x},\vec{p}_{2'})\tilde{f}_1(\vec{x},\vec{p}_1)\tilde{f}_2(\vec{x},\vec{p}_2) - f_1(\vec{x},\vec{p}_1)f_2(\vec{x},\vec{p}_2)\tilde{f}_{1'}(\vec{x},\vec{p}_{1'})\tilde{f}_{2'}(\vec{x},\vec{p}_{2'})\right]$$

cross sections — energy cons. — 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)

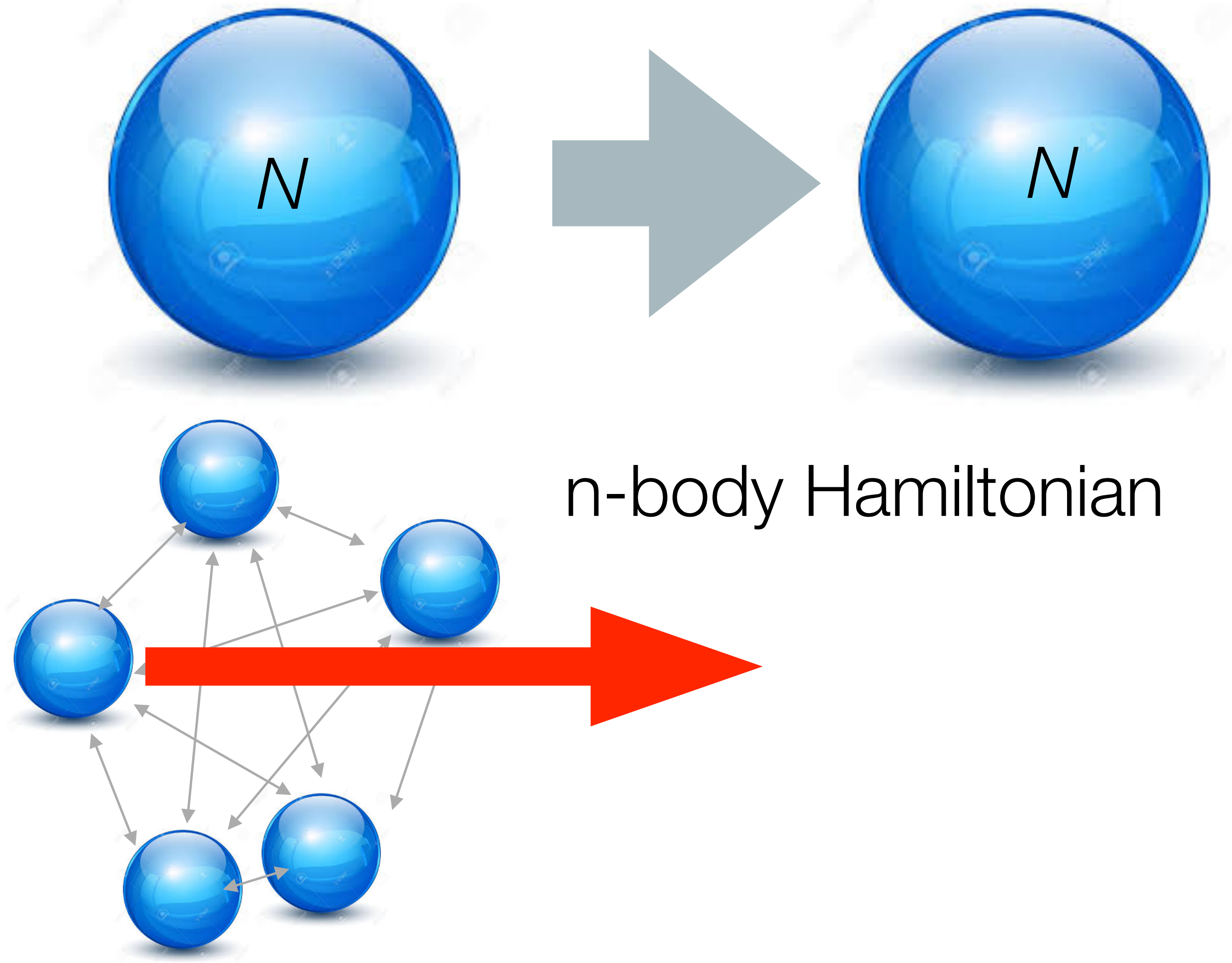
Transport model and families

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] …a 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

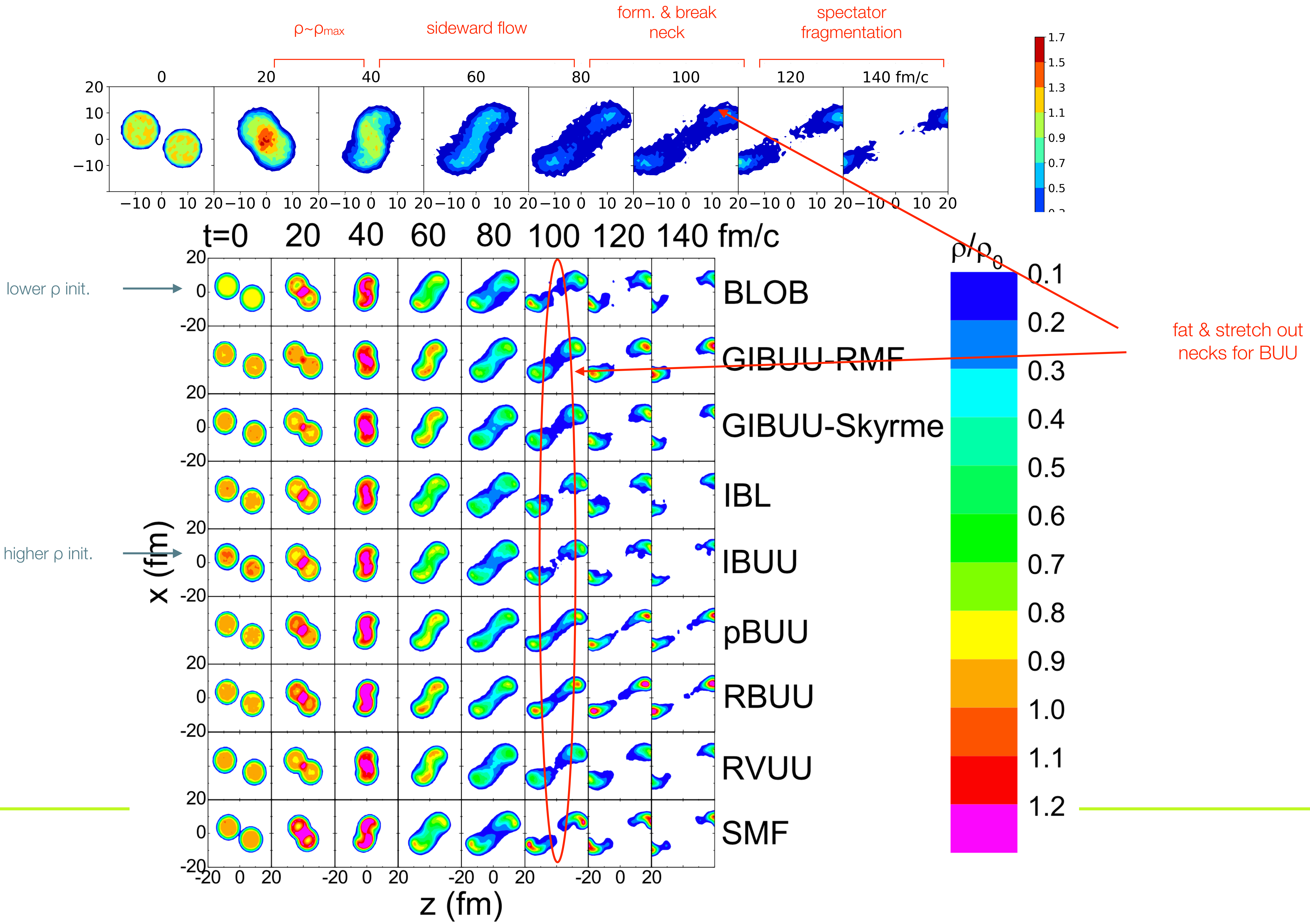
Comparison of heavy-ion transport simulations: Mean-field dynamics in a box

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

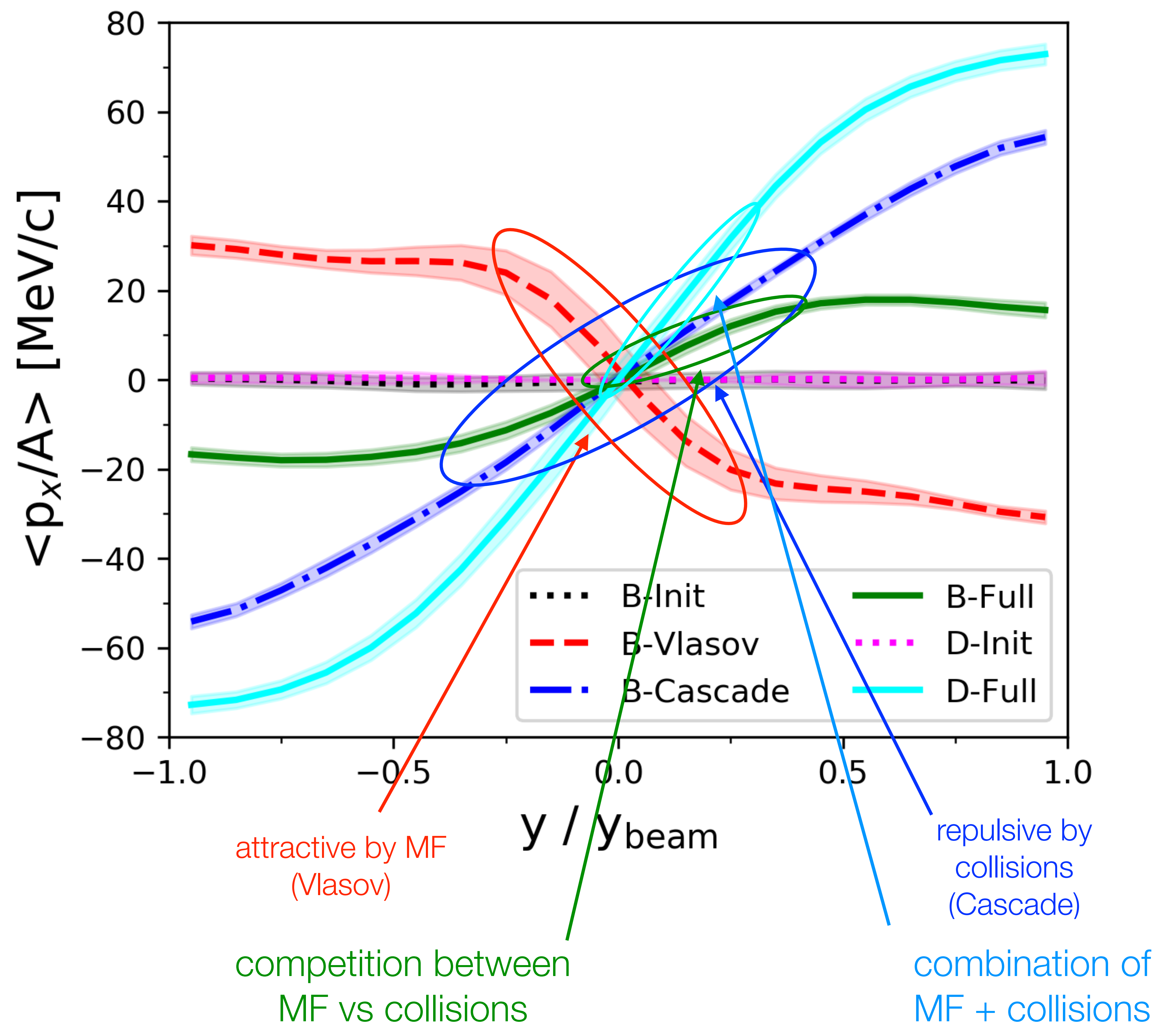
Maria Colonna,[1,*] Ying-Xun Zhang,[2,3,†] Yong-Jia Wang,[4,‡] Dan Cozma,[5] Pawel Danielewicz,[6,§] Che Ming Ko,[7] Akira Ono,[8,∥] Manyee Betty Tsang,[6,¶] Rui Wang,[9,10] Hermann Wolter,[11,#] Jun Xu,[12,9,**] Zhen Zhang,[13] Lie-Wen Chen,[14] Hui-Gan Cheng,[15] Hannah Elfner,[16,17,18] Zhao-Qing Feng, 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]

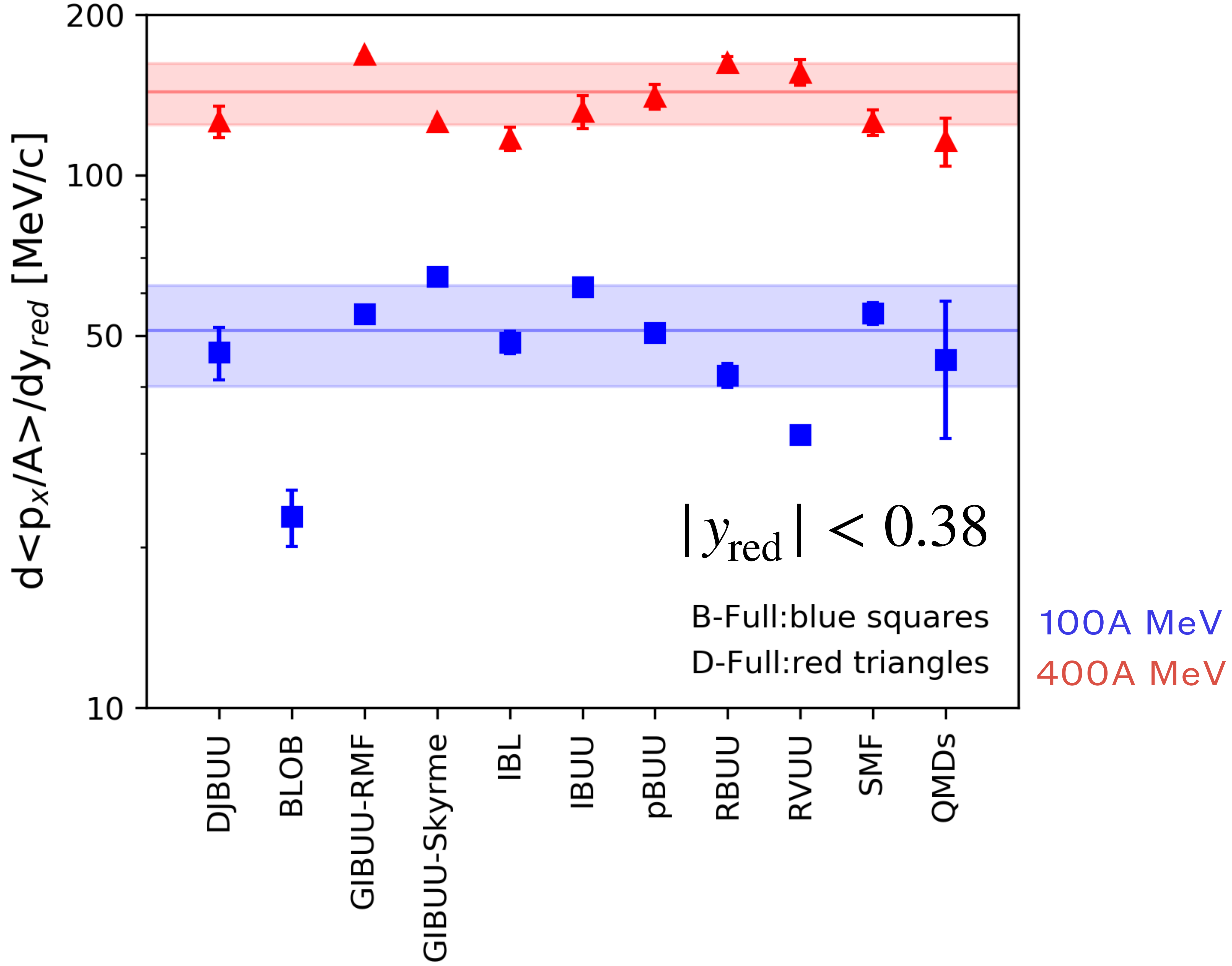
- Transport2019 (2019): production of pion-like particles at 270A MeV Sn+Sn collisions.

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



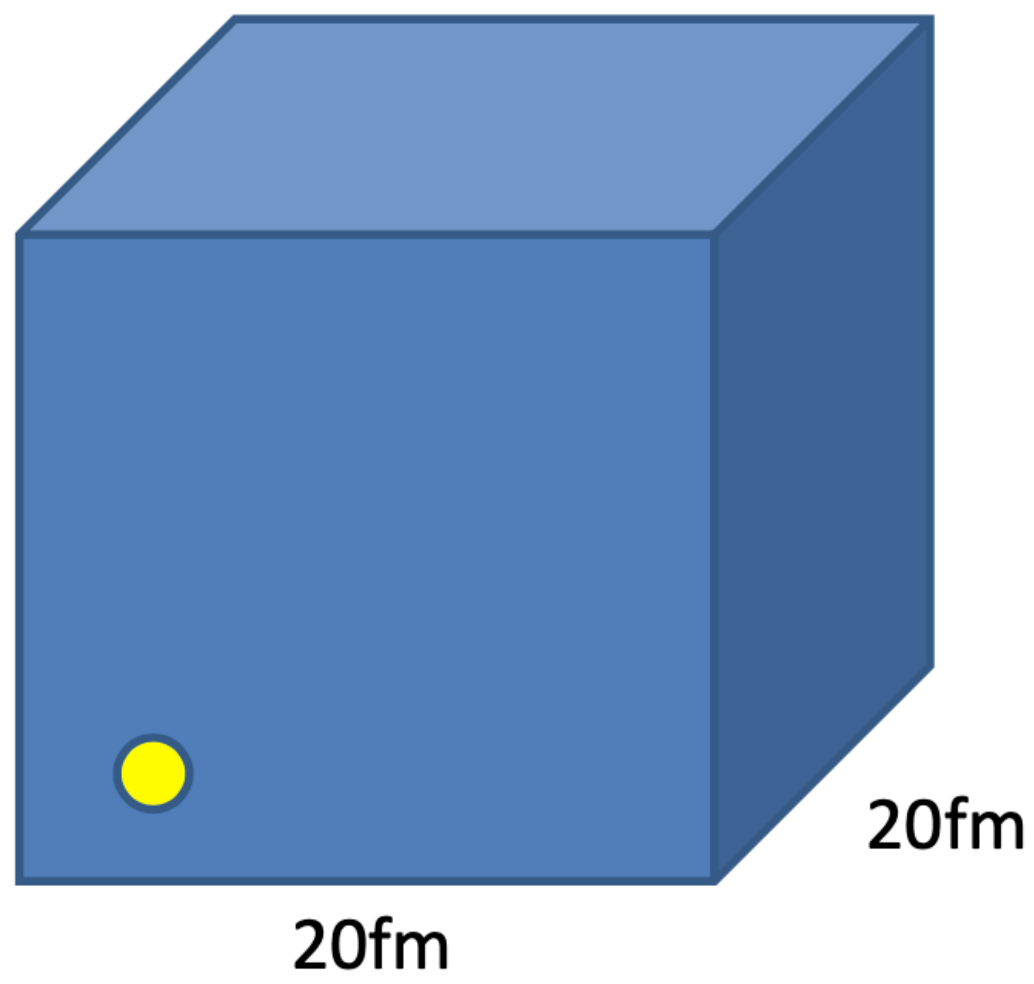
Transverse flow and slop parameter





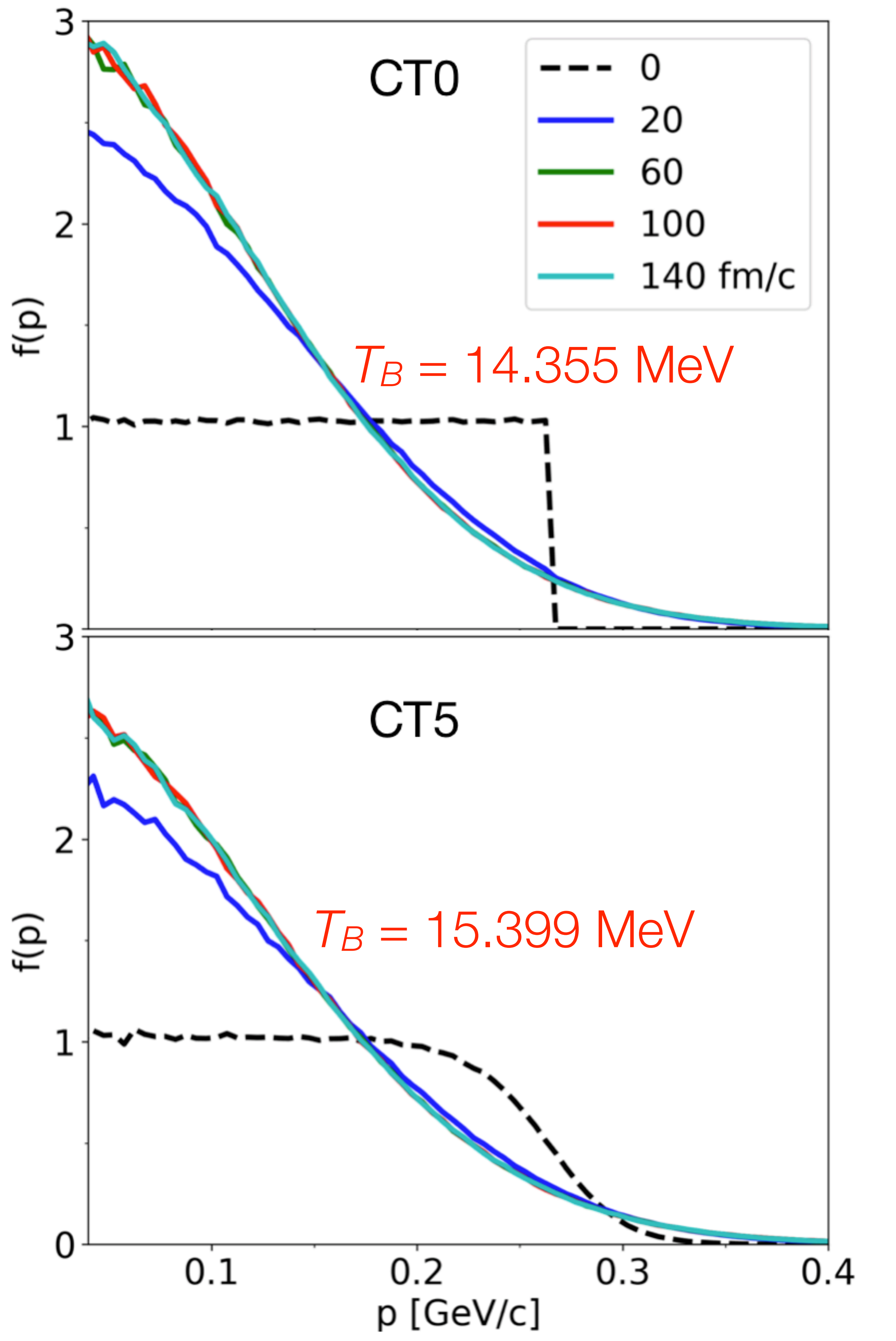
- Theoretical uncertainties of flow parameter: about 30% at 100A MeV and 13% at 400A MeV
- What is the origin of the uncertainties? from collisions or interactions (MF)

Box calculations with periodic boundary conditions

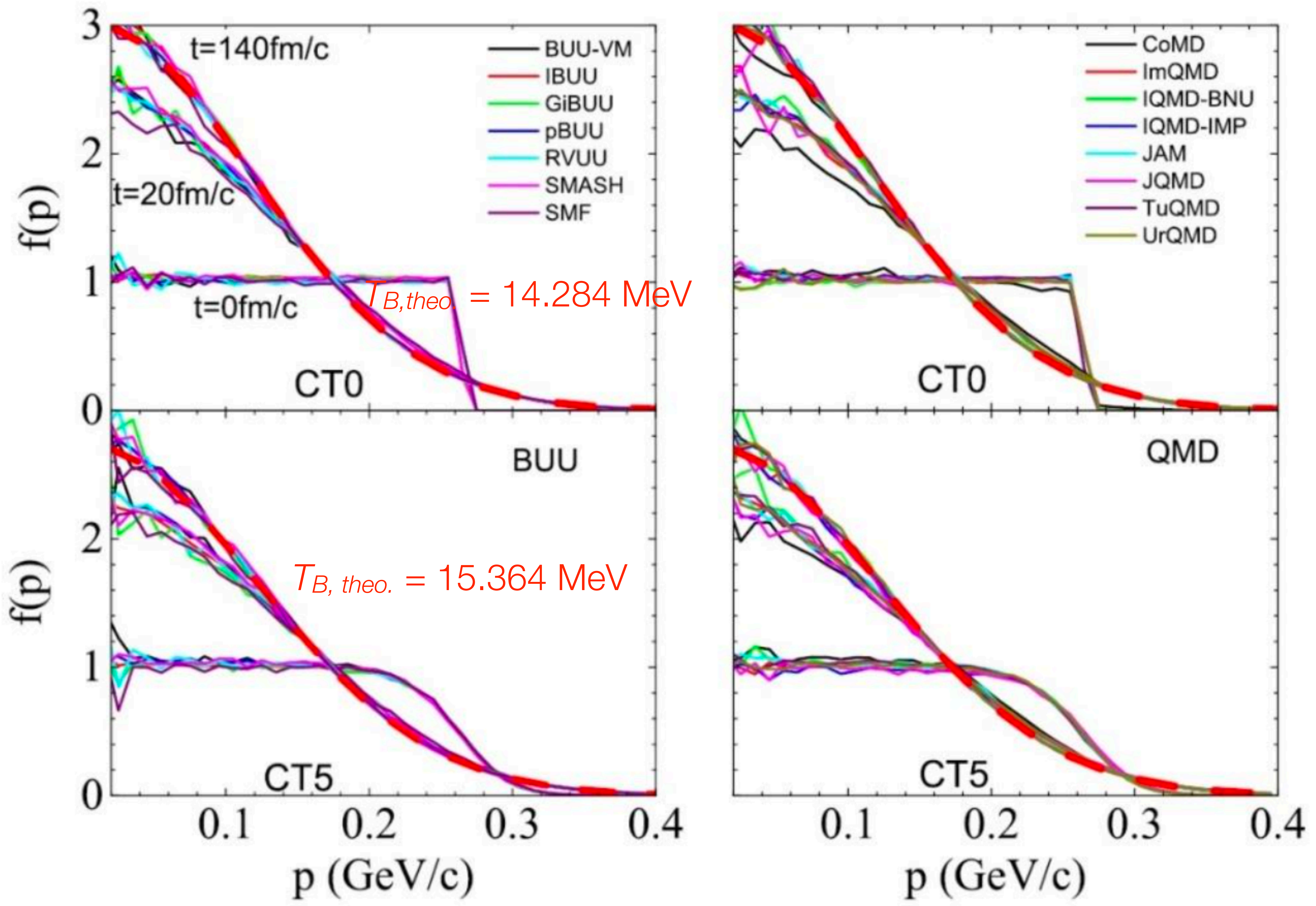


- Details of periodic boundary conditions
  - a box of volume V = L1*L2*L3, where the system is confined
  - the position of the center of box is (L1/2, L2/2, L3/2)
  - a particle leaving the box, entering the opposite side w/ same momentum (number of particle is conserved)
- Initialization
  - uniform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

Box-Cascade calculation (NN scatterings w/o PB)



Time evolution of momentum distribution

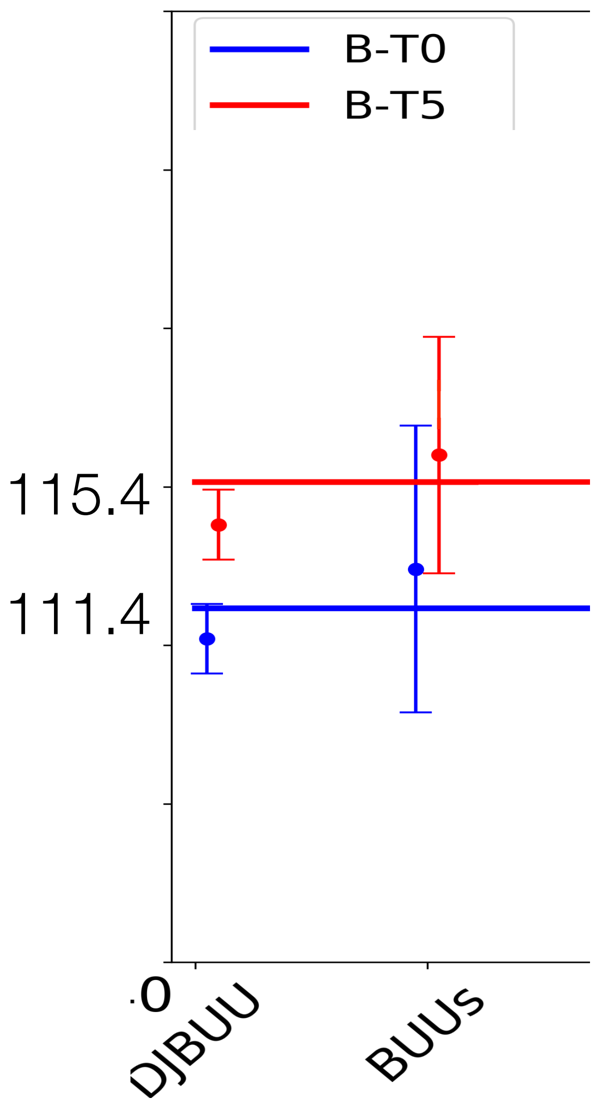


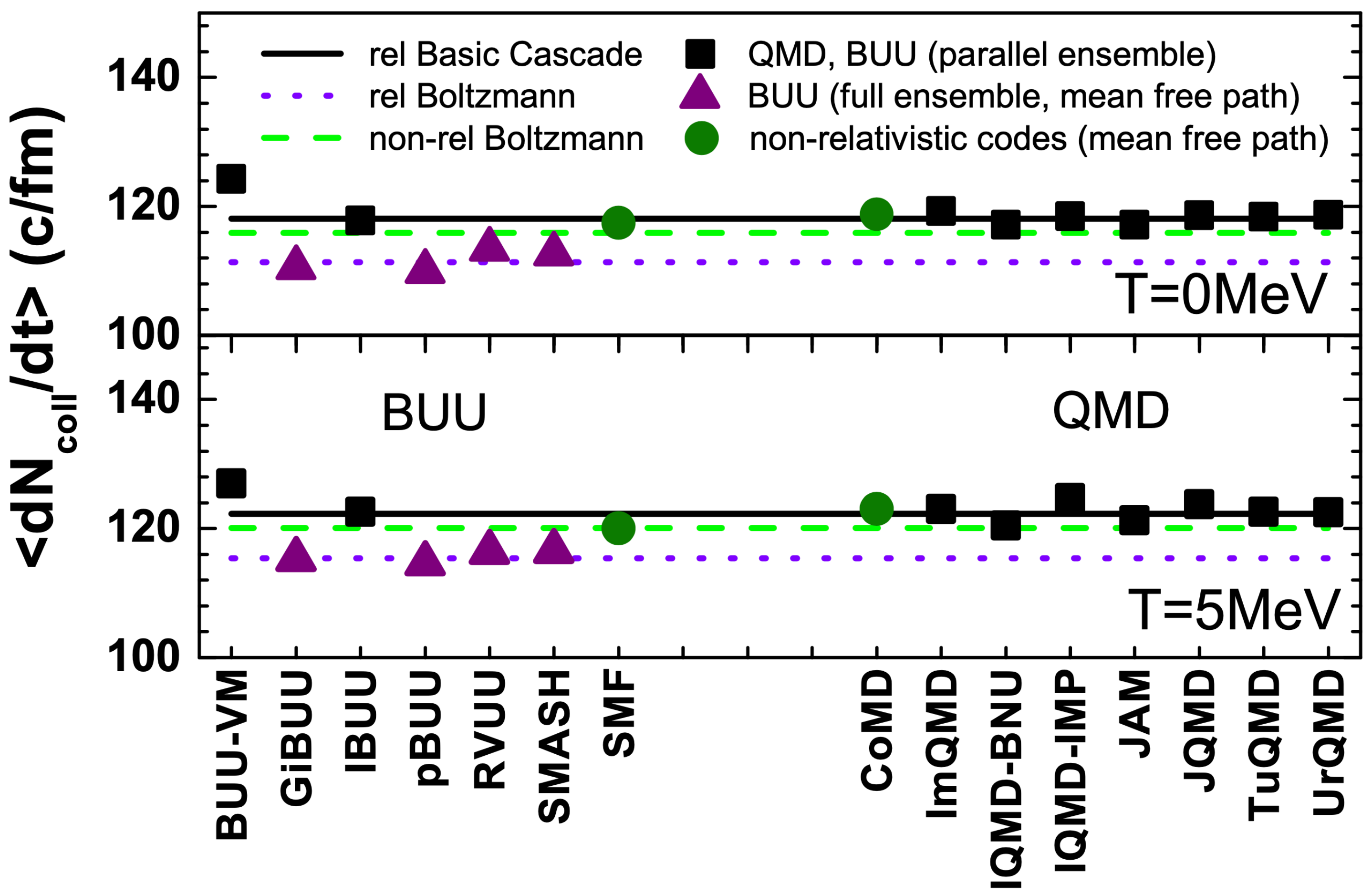
Y.X. Zhang, et al., PRC (2018)

Box-Cascade calculation

without Pauli blocking

averaged over t=60-140 fm/c



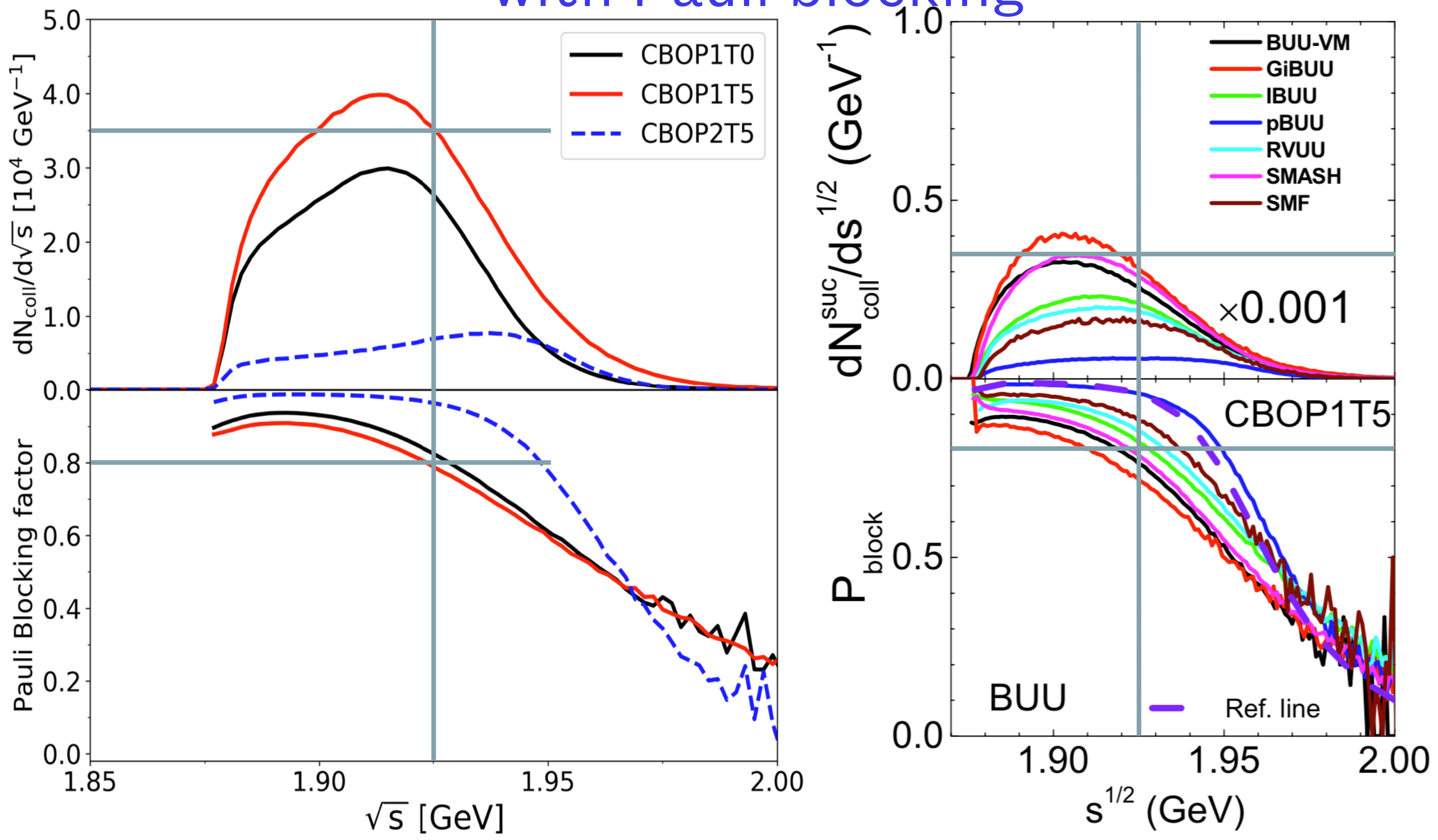


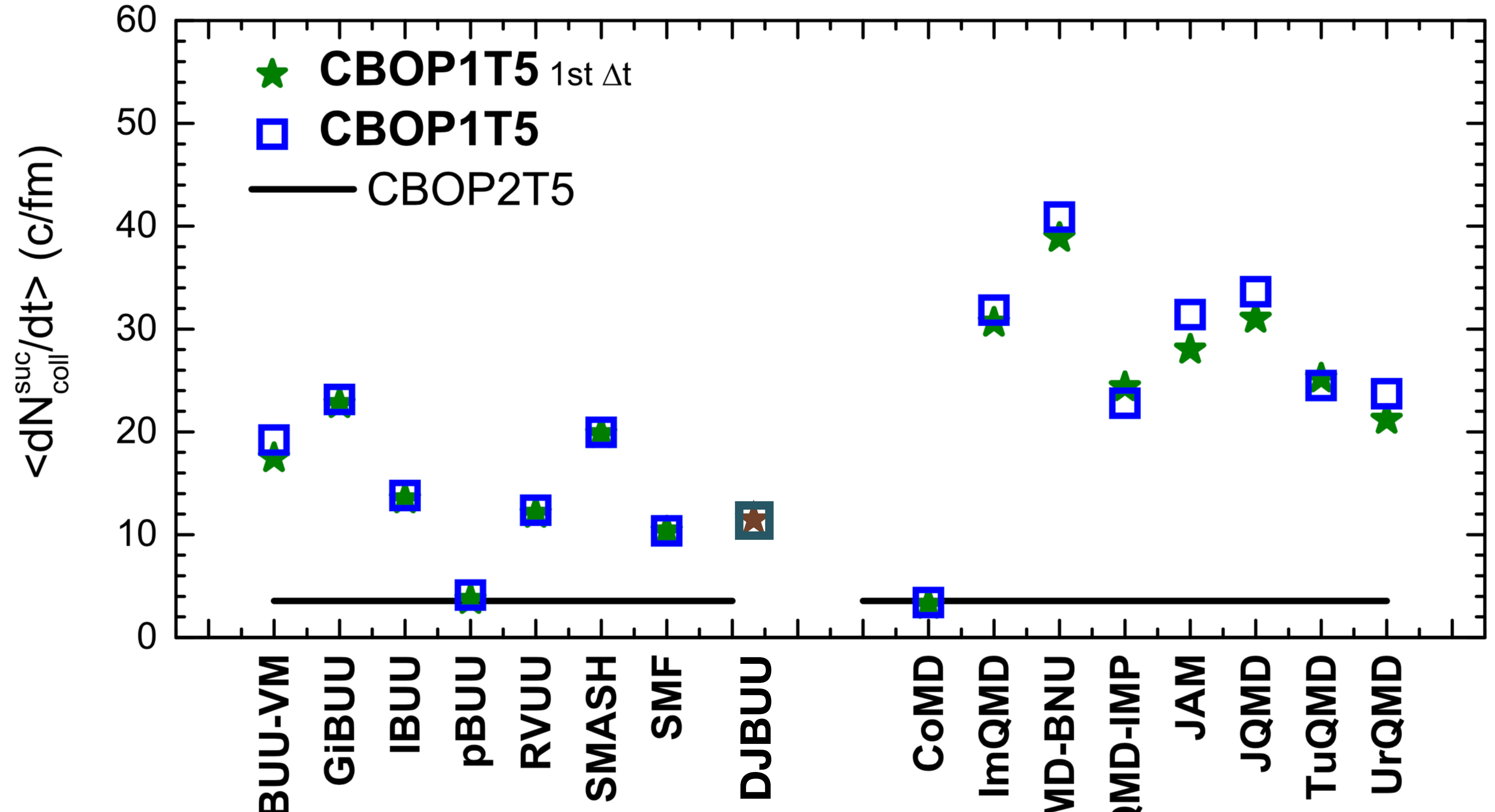
Y.X. Zhang, et al., PRC (2018)

comparable DJBUU with rel. kinetic theory

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

with Pauli blocking

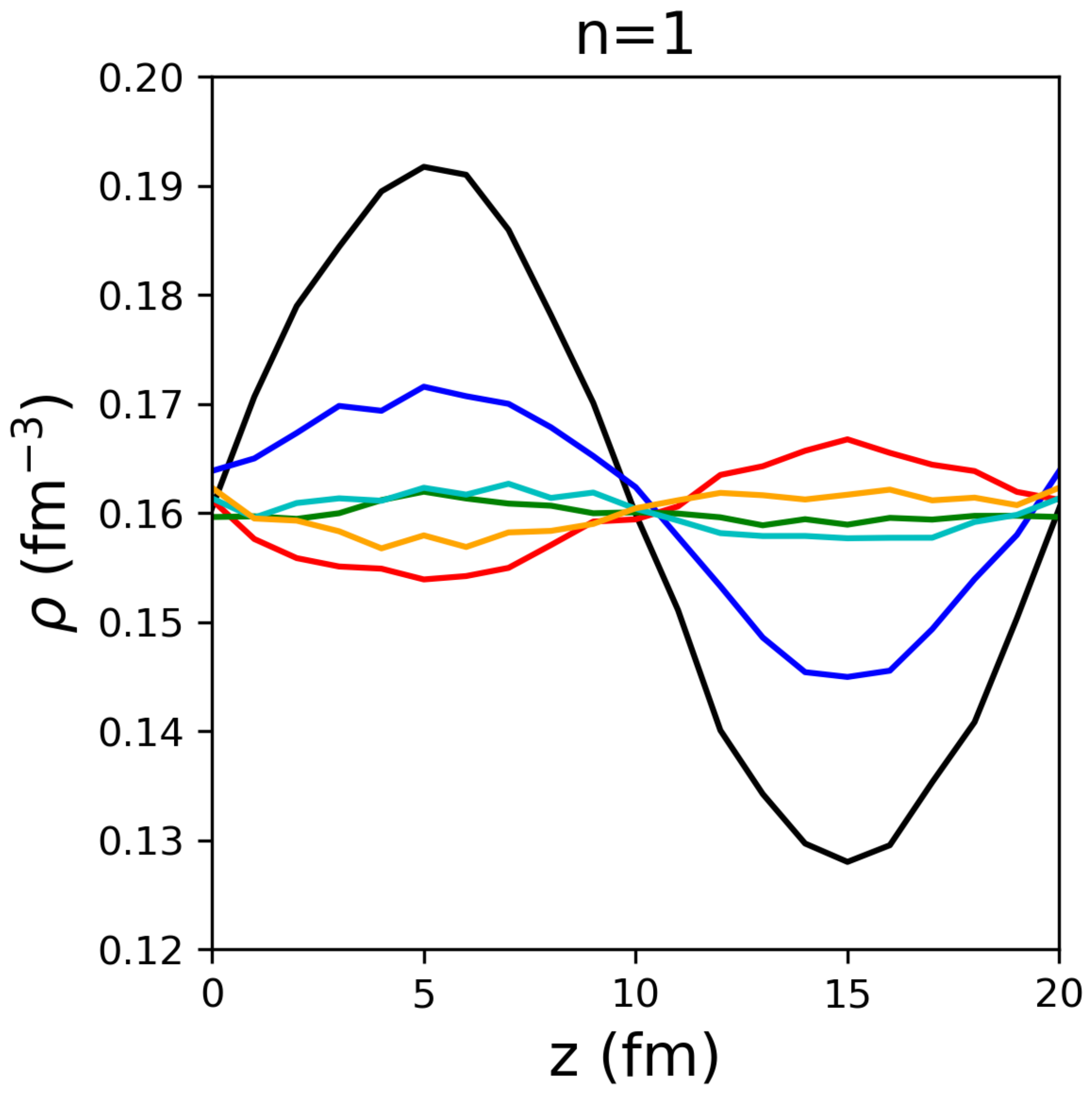


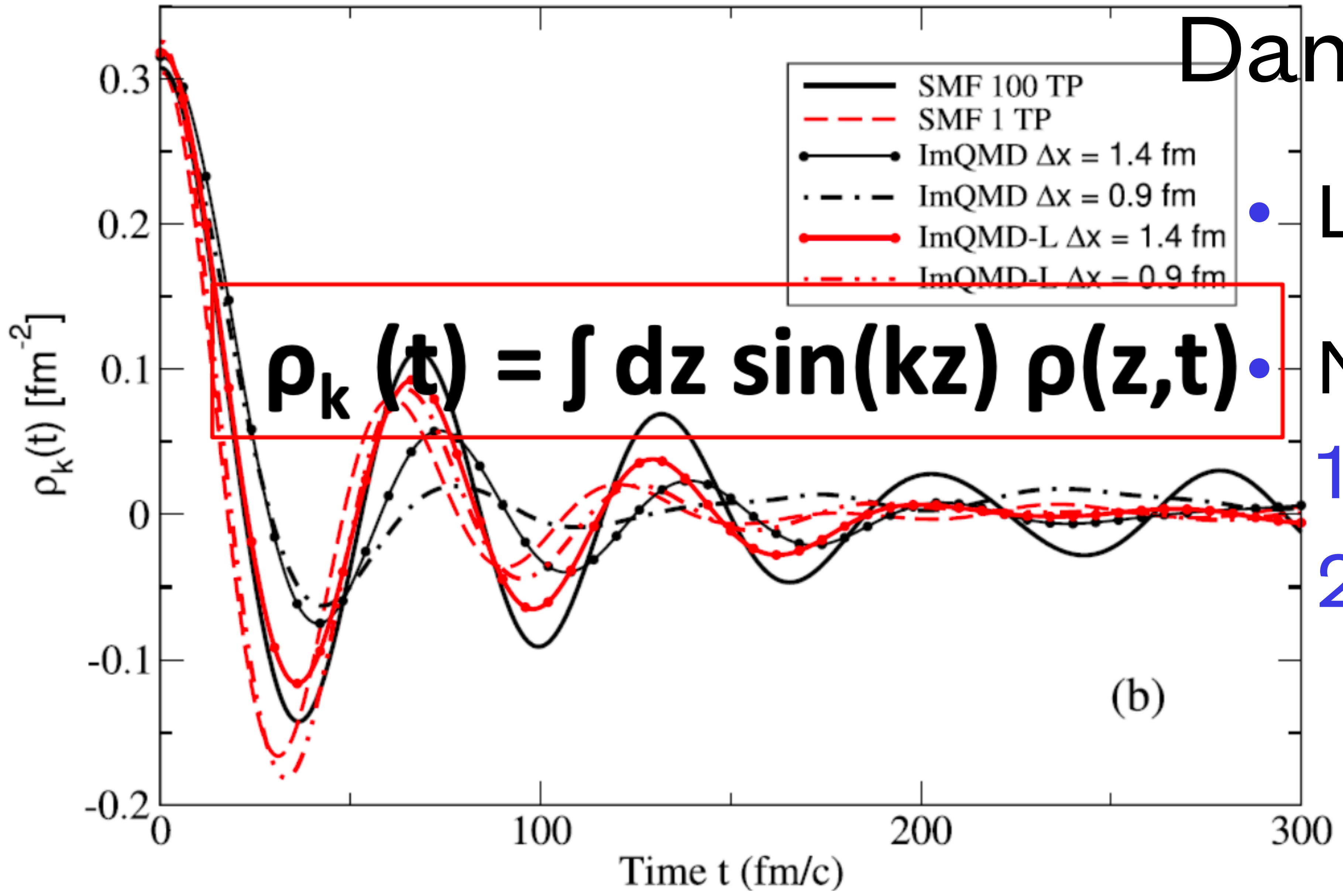


- Pauli blocking - evolution of phase space occupations
- numerical fluctuations
  - BUU - shape & TP, QMD - width

Box-Vlasov calculation

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



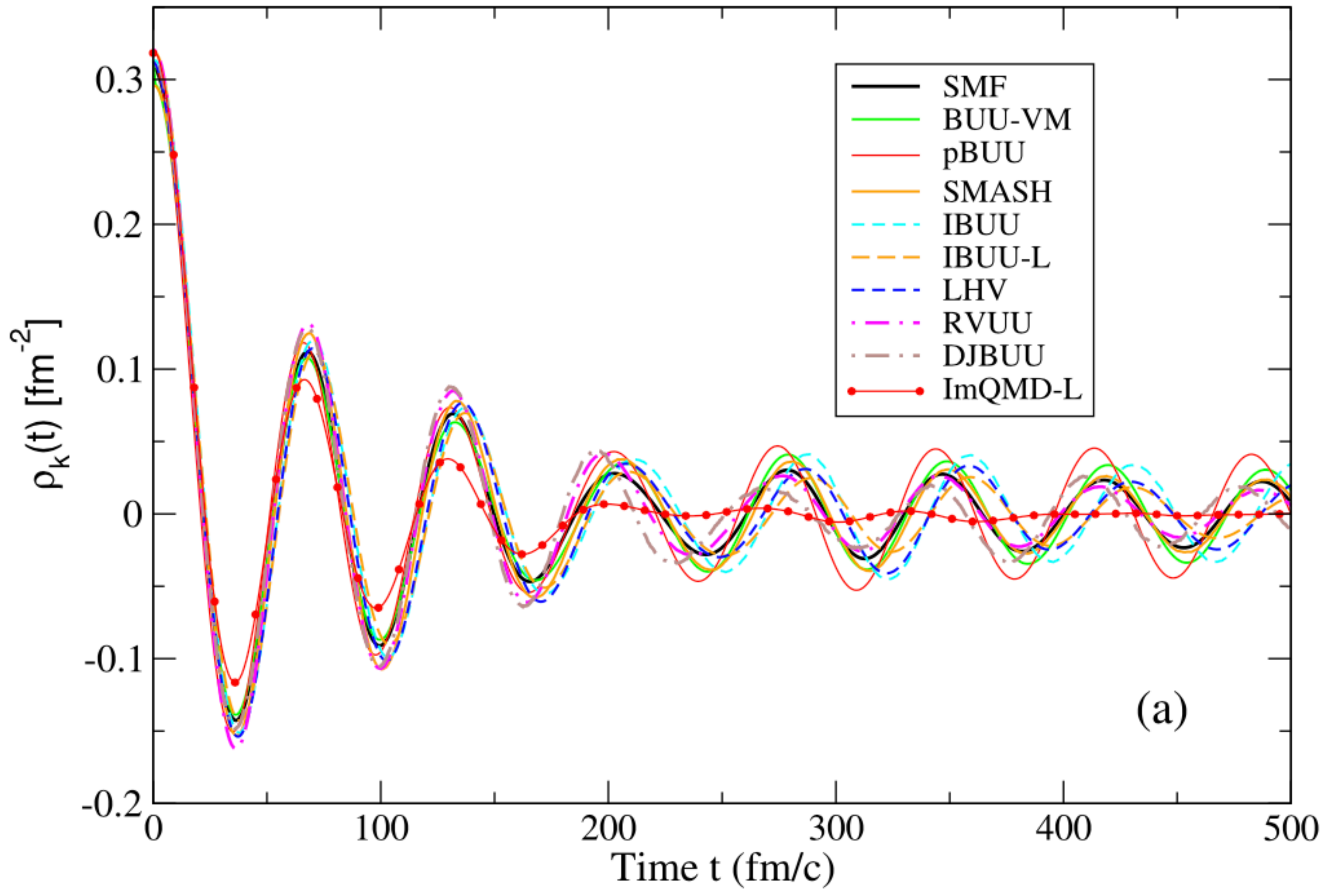


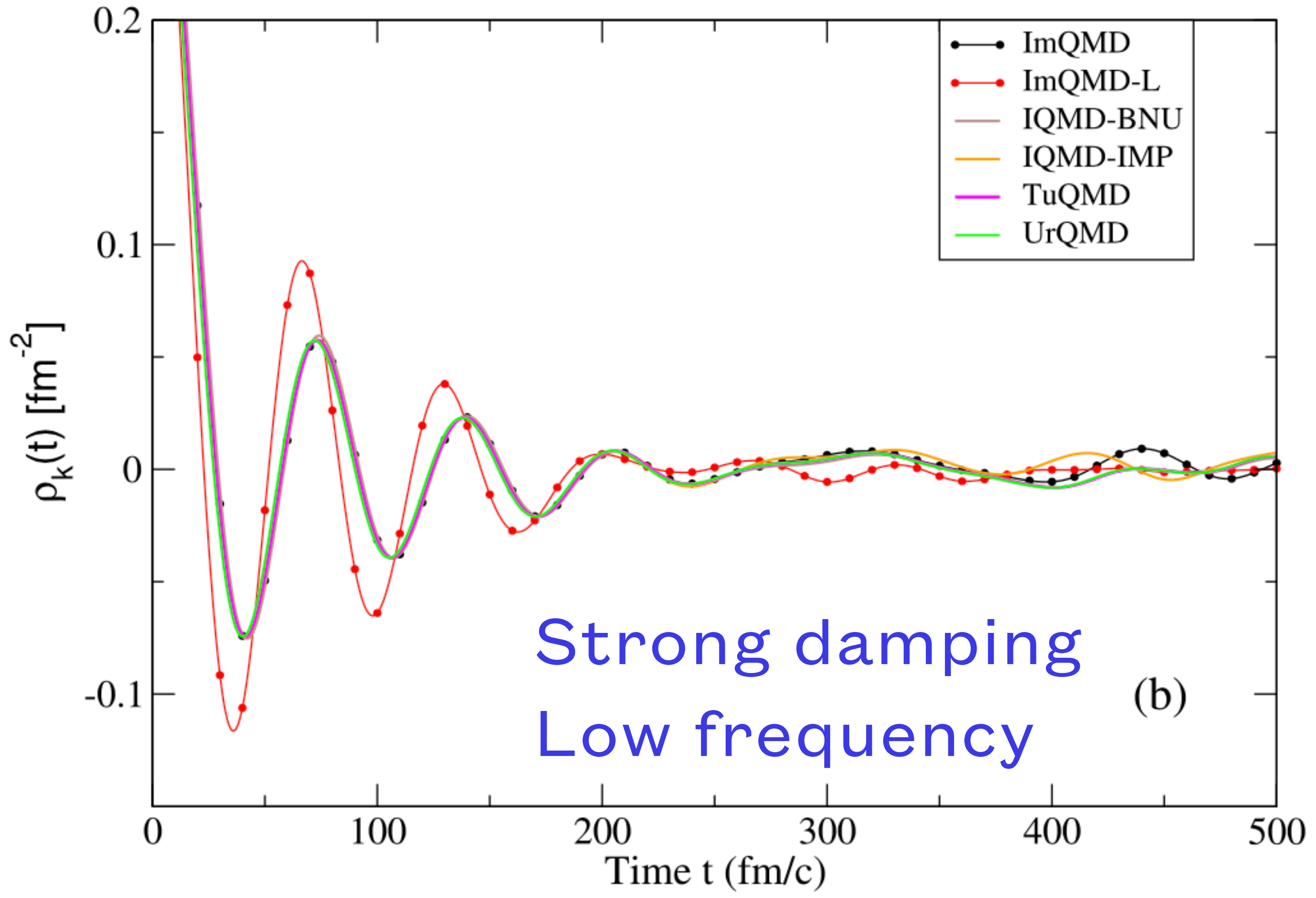
$$\rho_k(t) = \int dz \sin(kz)\, \rho(z,t)$$

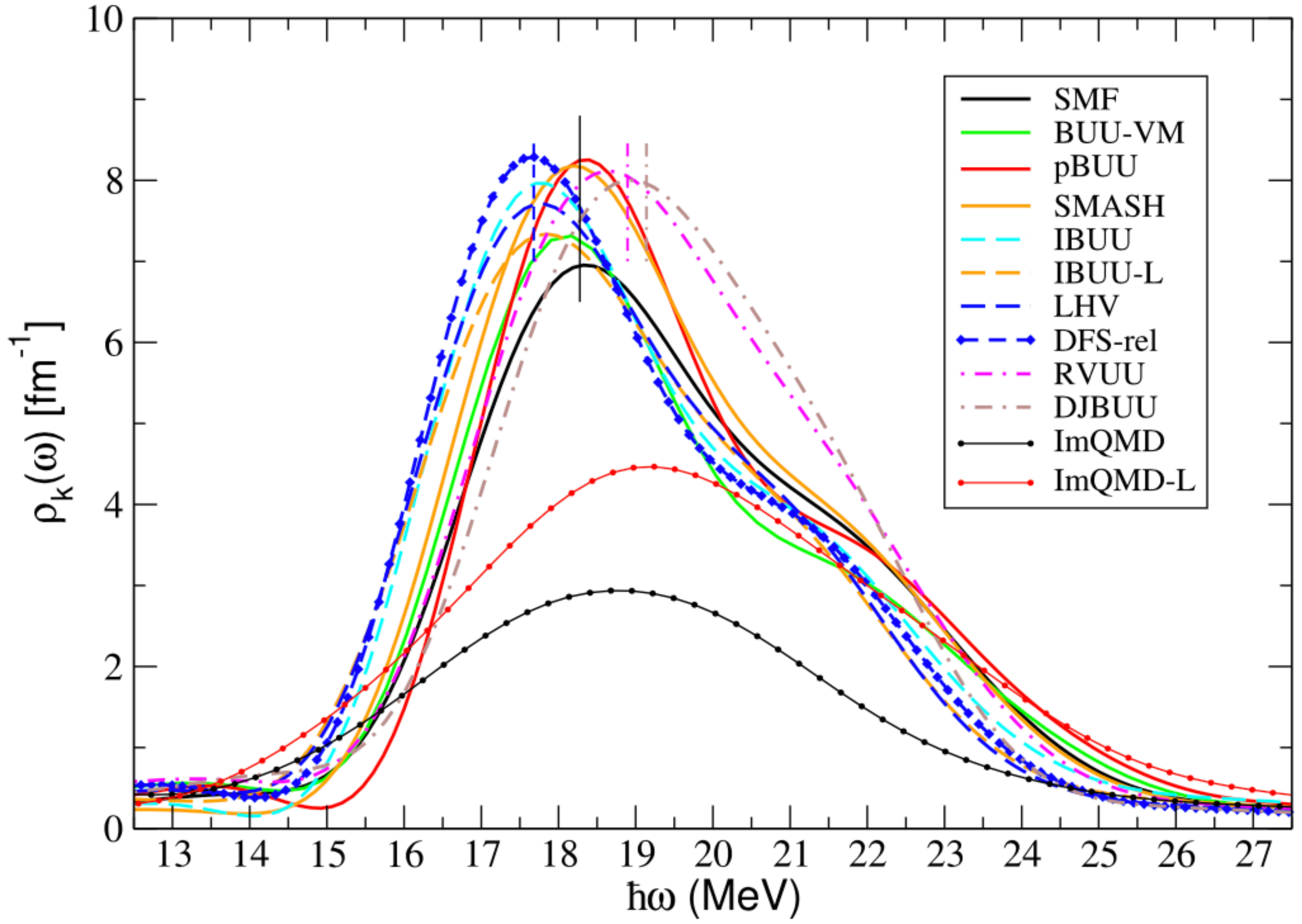
Damping sources:

- Landau damping: mixing modes
- Numerical damping: fluctuations

1. Decreases with increasing TP numbers
2. Decreases with increasing particle size

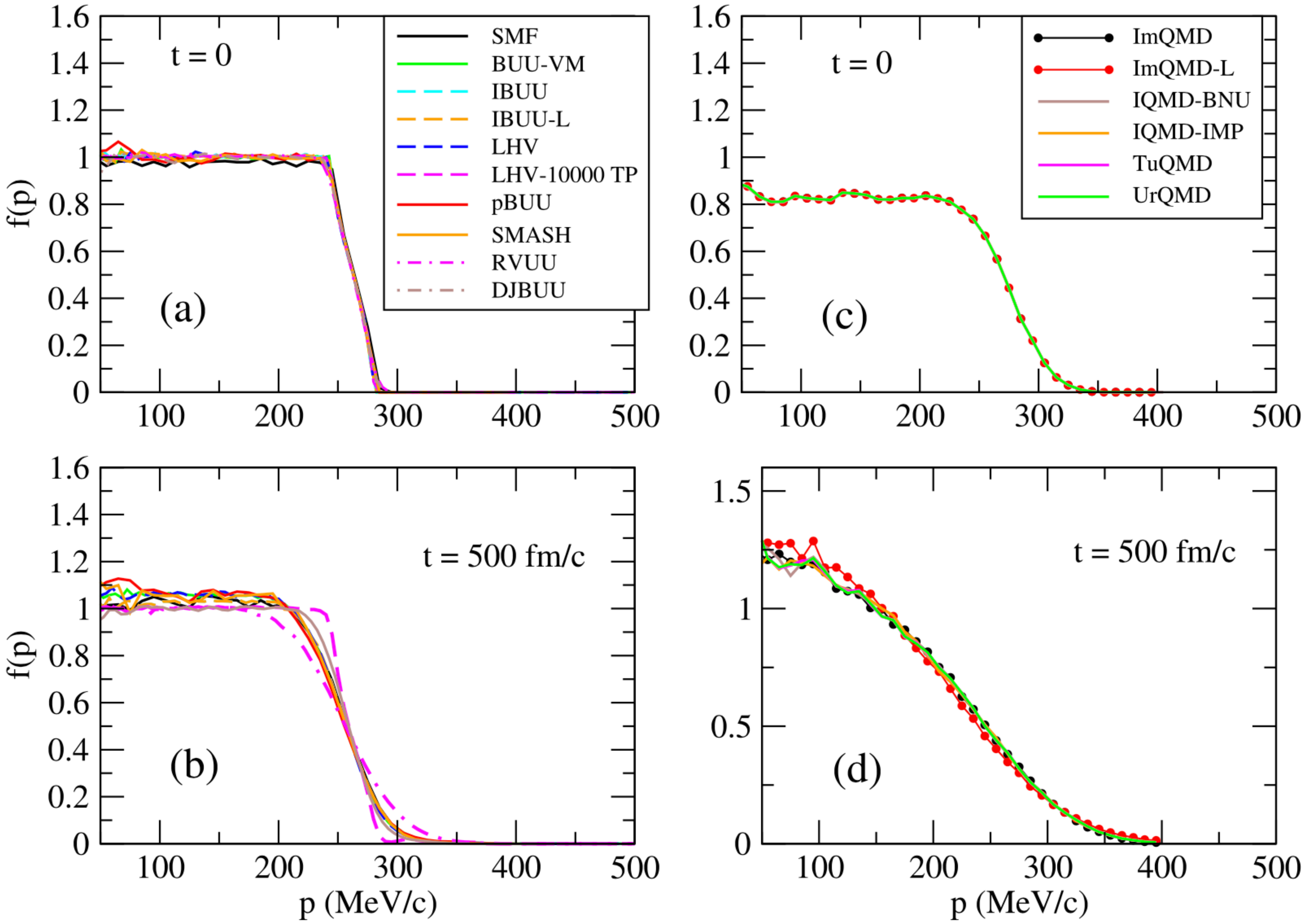






Box-Vlasov calculation

Momentum distribution



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

- top: initial configurations
- bottom: final configurations
- larger smearing in QMD due to larger intrinsic initial density fluctuations
- more Boltzmann-like statistics in QMD by inherent larger fluctuations

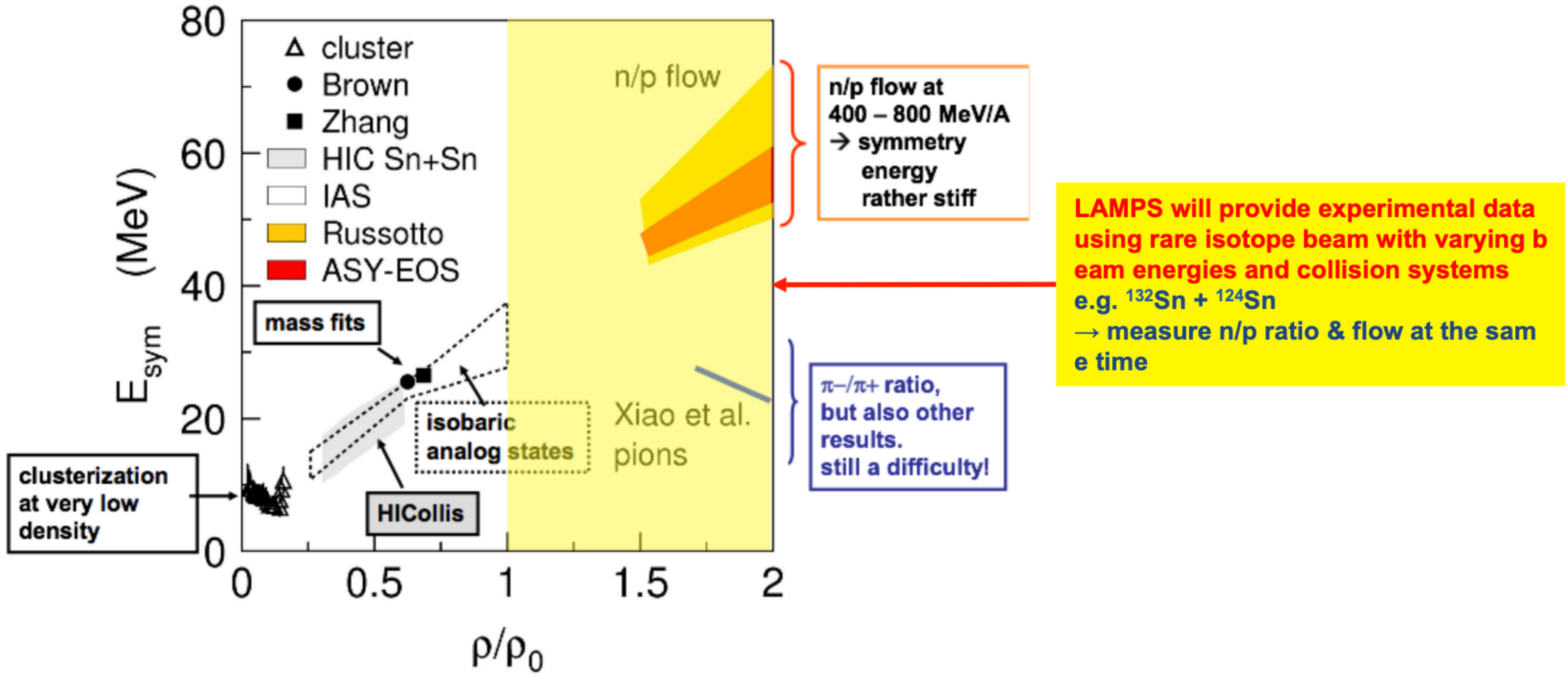
RAON / LAMPS

LAMPS
(Large Acceptance Multi-Purpose Spectrometer)

RISP

- 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 $E_{sym}(\rho/\rho_0)$)

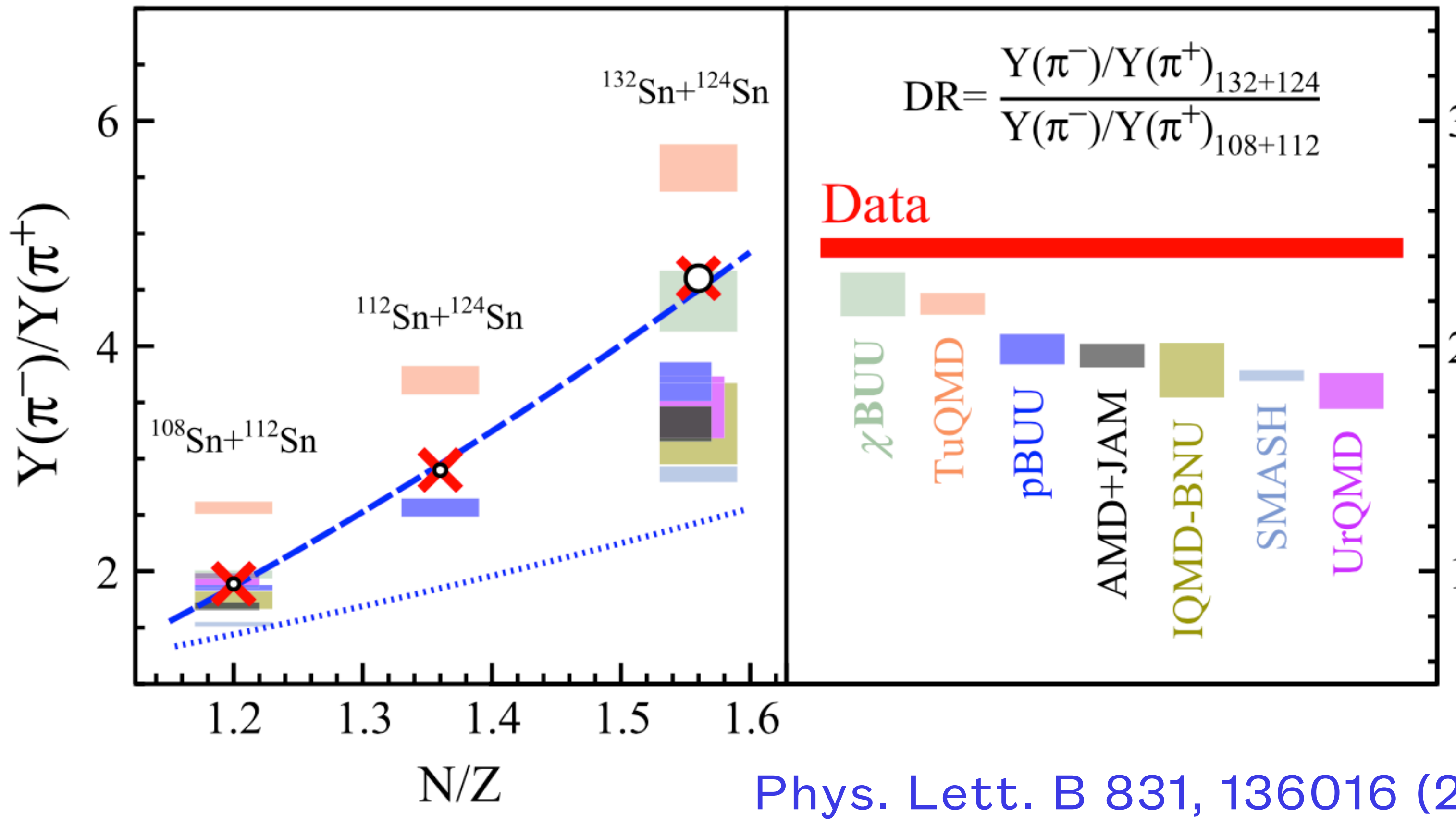


- Experimental data are measured with stable beams
- data of pion ratio and data of n/p flow are from different experiments
- Models in the market show different results even within same observable

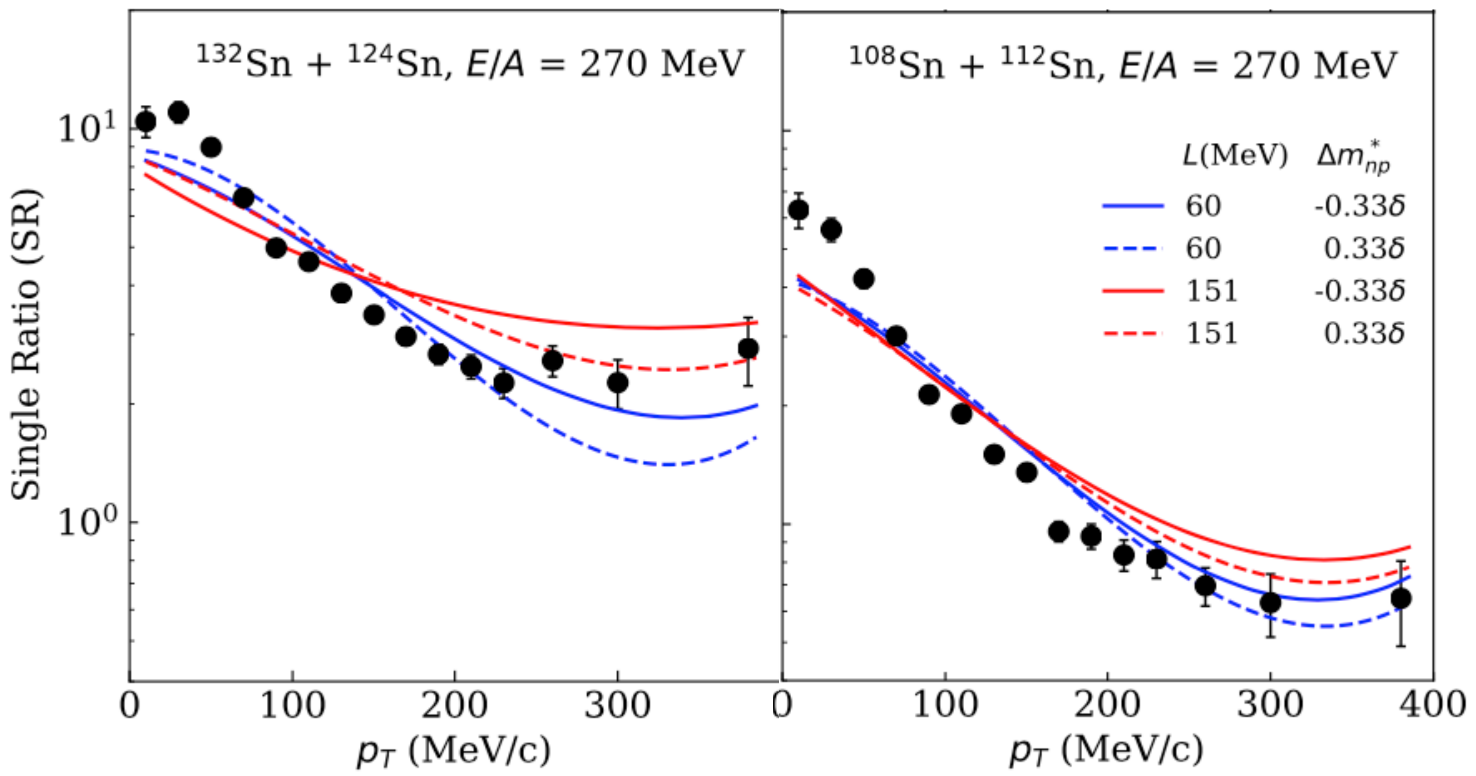
2

Symmetry energy and pion productions

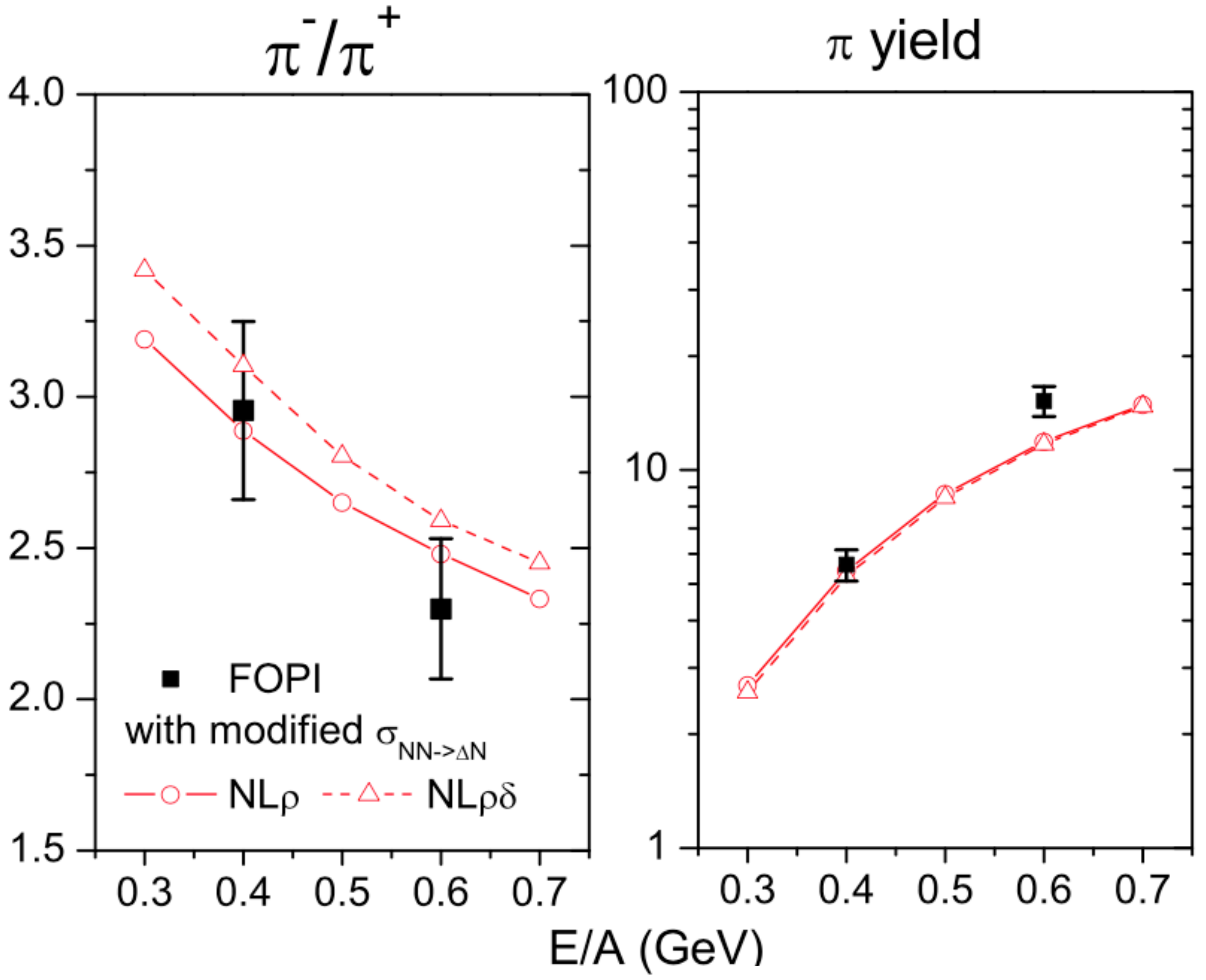
- *Pion production and comparison with SπRIT @ RIKEN and FOPI @ GSI experiments*
- Pion production w/ our NL model set in DJBUU (on going)
- Expansion to HICs with rare isotope : π^- from neutron-rich
- rare isotope HICs @ RAON can be a key for symmetry energy since more π^- from neutron rich



Phys. Lett. B 831, 136016 (2021)



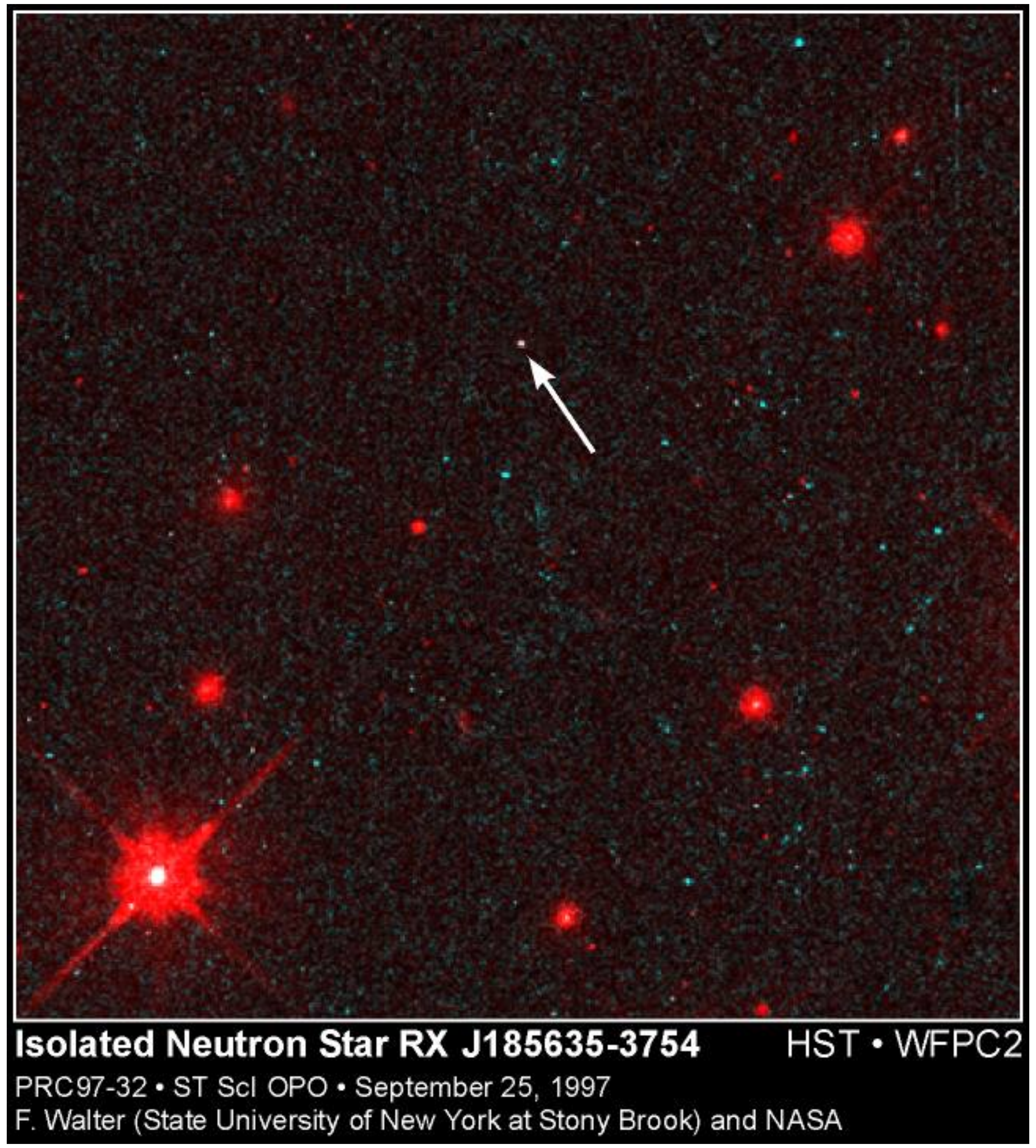
PRL 126, 162701 (2021)

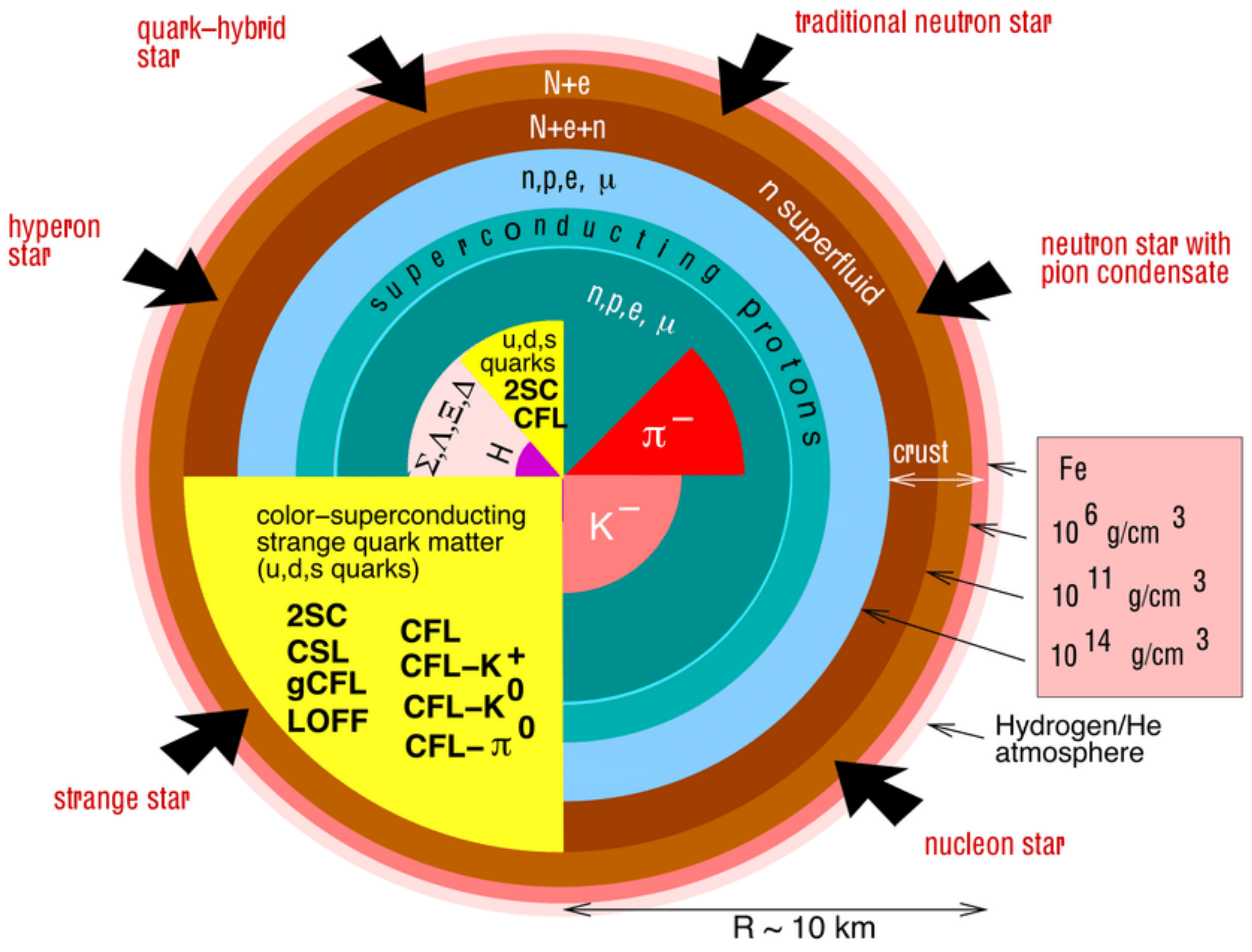


PRC 91, 014901 (2015)

Neutron Stars - dense matter in universe

- densest visible matter(?), $\rho_{center} \sim 2\text{-}8\ \rho_0$
- M: 1.5-2 solar mass, R: ~15km

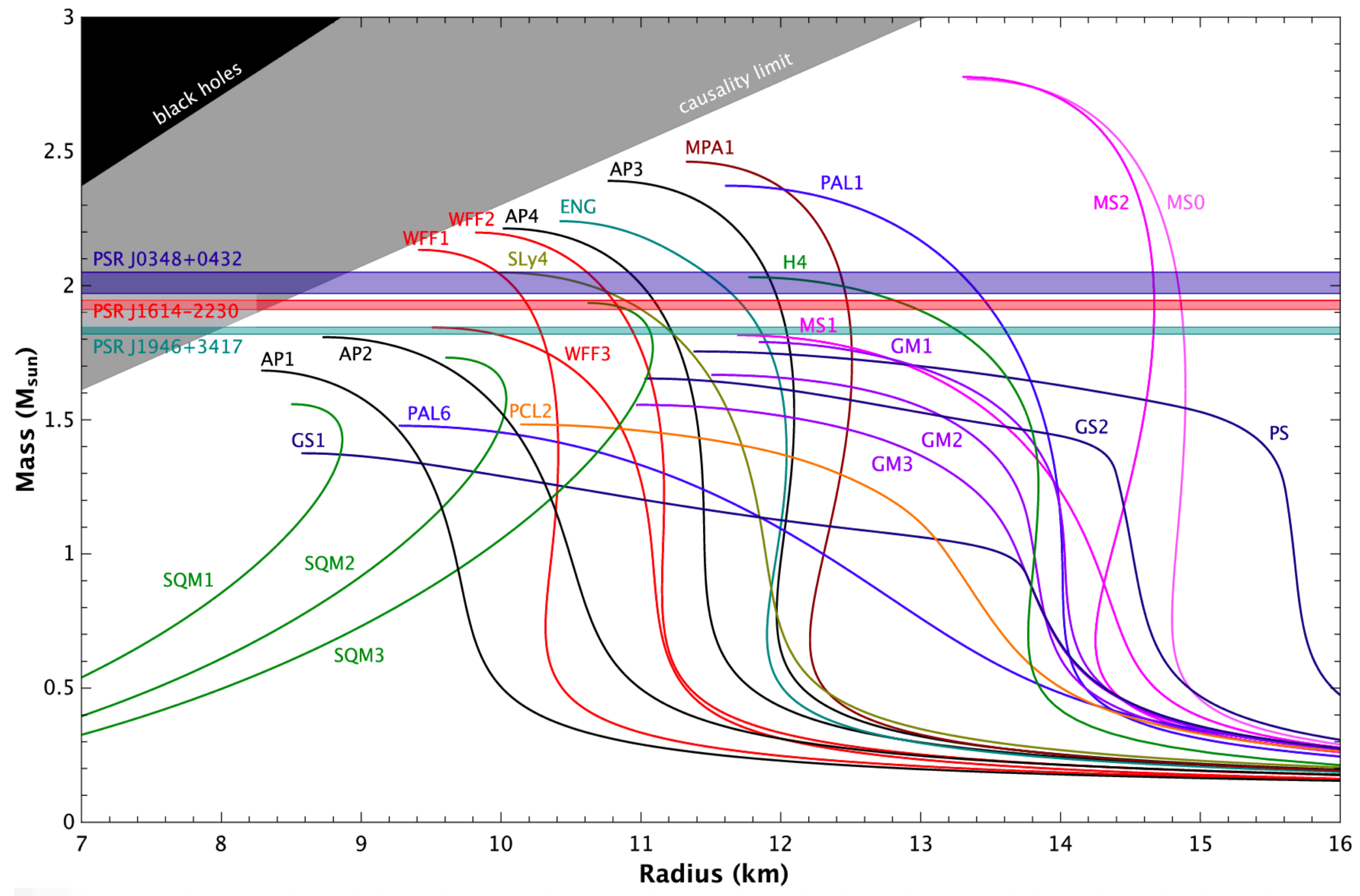




solving TOV eq.

$$\frac{dP(r)}{dr} = -G\frac{[\epsilon(r)+P(r)][M(r)+4\pi r^3 P(r)]}{r^2[1-2GM(r)/r]},$$

$$\frac{dM(r)}{dr} = 4\pi\epsilon(r)r^2,$$



Mass and Radius estimation from X-ray bursts

A&A 650, A139 (2021)
https://doi.org/10.1051/0004-6361/202038126

Astronomy & Astrophysics

Measuring the masses and radii of neutron stars in low-mass X-ray binaries: Effects of the atmospheric composition and touchdown radius

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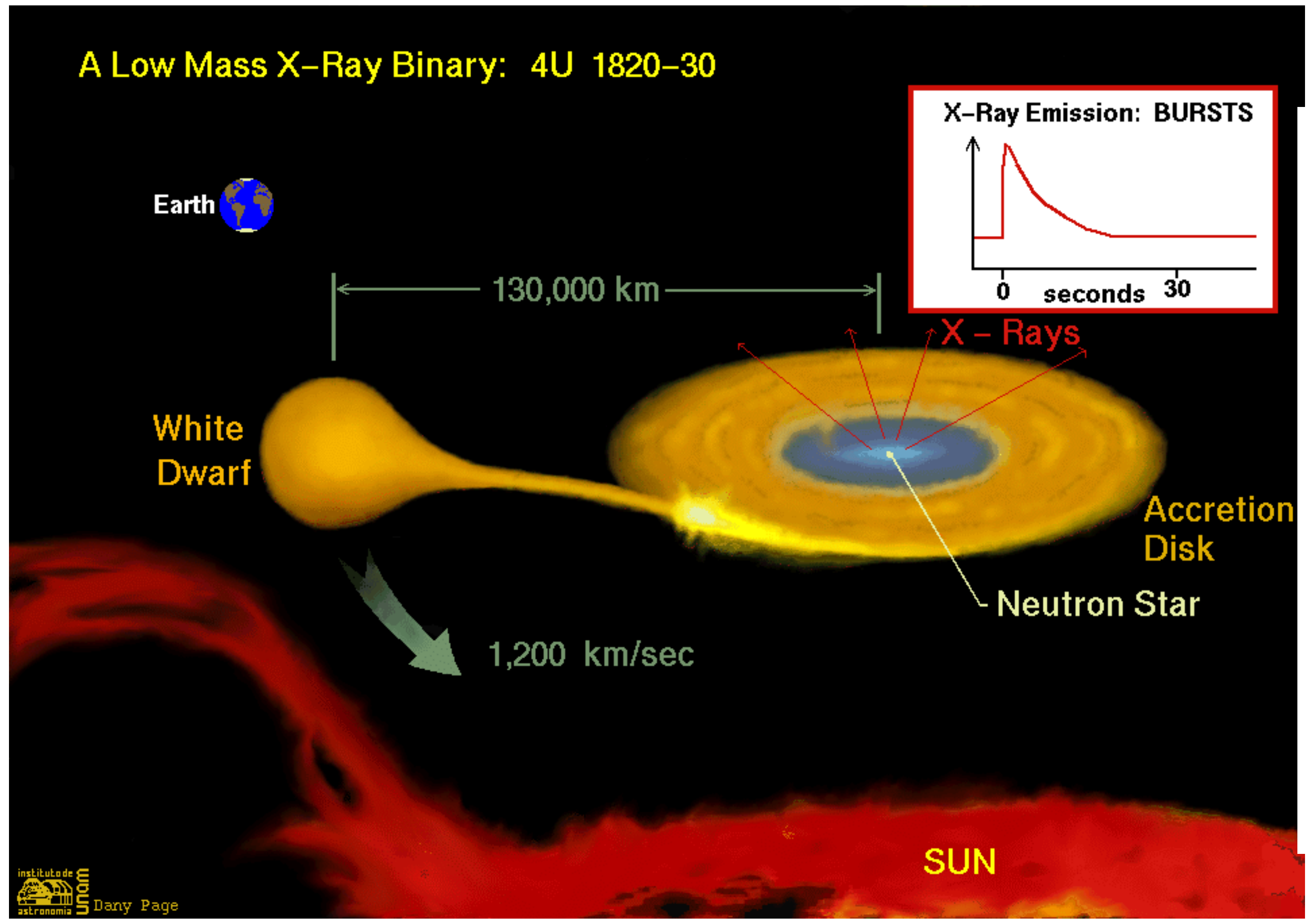
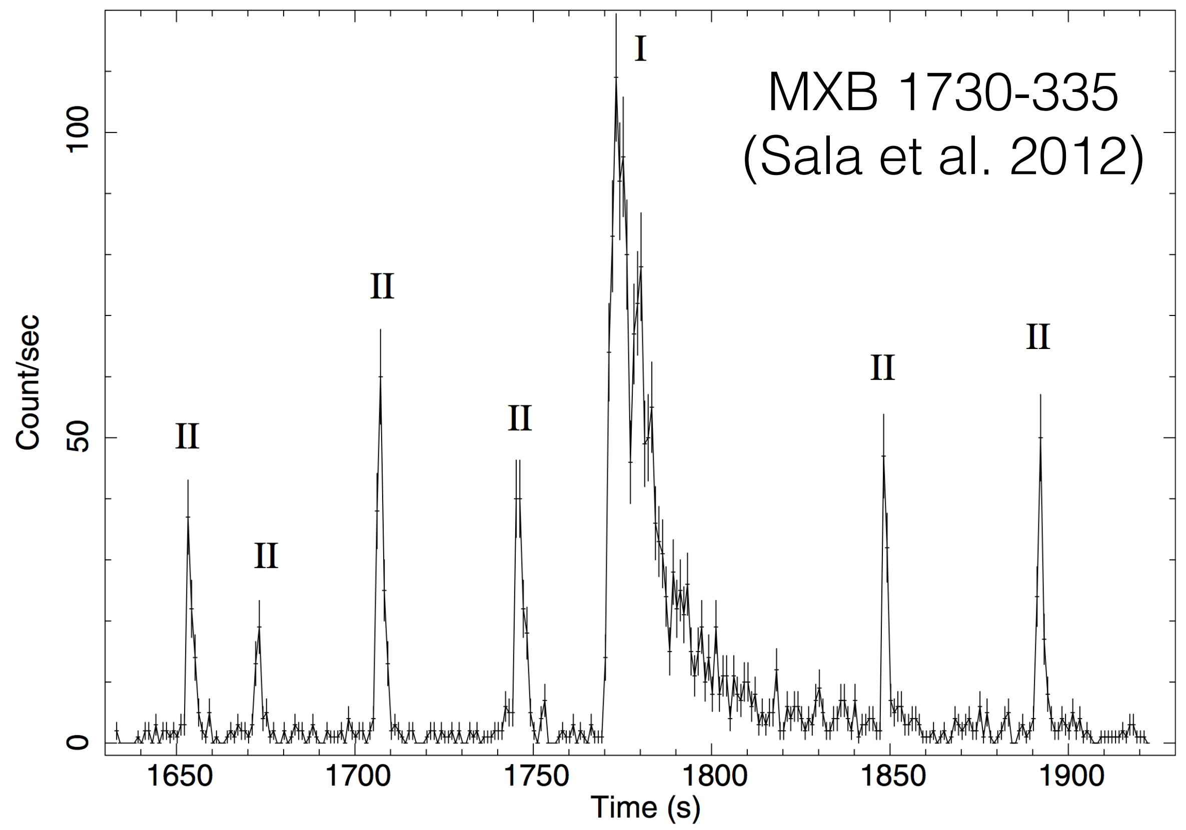
ABSTRACT

Low-Mass X-ray Binaries and X-ray Bursts

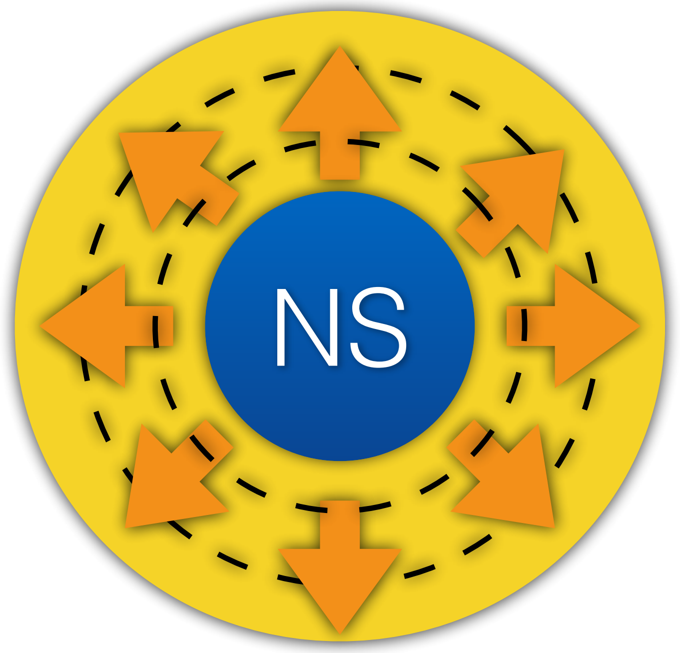
- Binary star system
  (NS or BH - MS or WD or RG)
- Mass transfer by Roche lobe overflow
- quiescent X-ray from NS surface and accretion disk



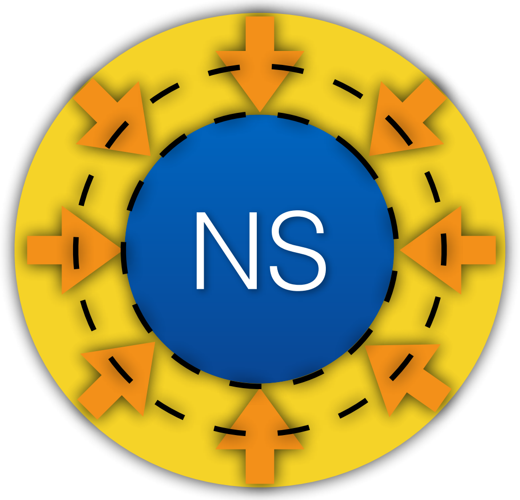


- Thermonuclear explosion (H and/or He ignition)
- Energy range ~ 10 keV (soft X-ray)
- L_{max} ~ 10^{38} erg/s (Eddington limit)
- X-ray softening during decay
- 84 bursts in 160 LMXBs (2007)

Photospheric Radius Expansion & MR estimation



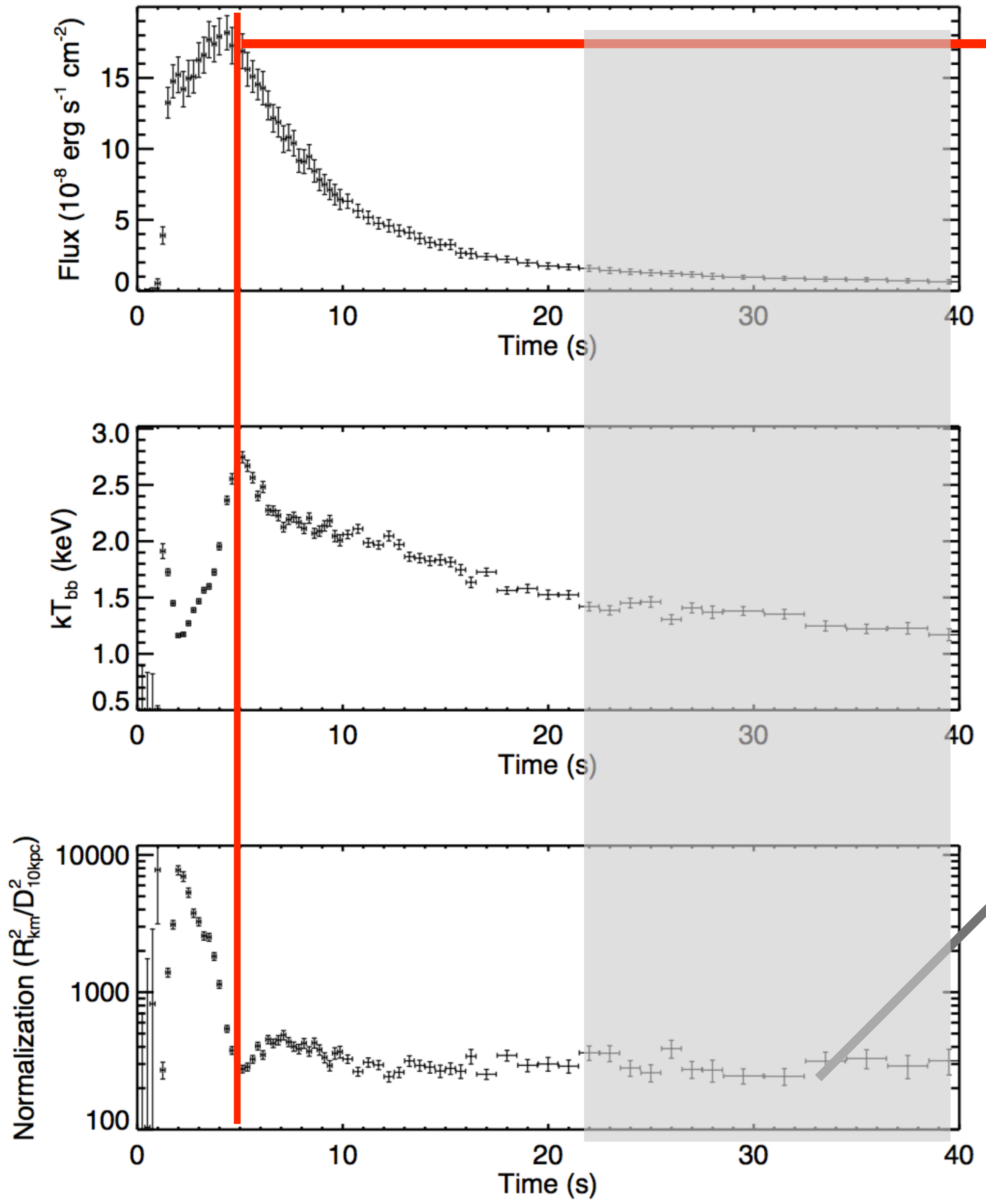
Expansion



Touchdown

Source	App. angular area $(\mathrm{km}/10\ \mathrm{kpc})^2$	Touchdown Flux $(10^{-8}\ \mathrm{erg\ cm^{-2}\ s^{-1}})$	Spin Freq.[a] (Hz)	Distance[a] (kpc)
4U 1820–30	89.9±15.9	5.98±0.66	...	7.6±0.4 (4)
				8.4±0.6 (5-6)
SAX J1748.9–2021	89.7±9.6	4.03±0.54	410 (1)	8.2±0.6 (4, 5, 7)
EXO 1745–248	117.8±19.9	6.69±0.74	...	6.3±0.63[b] (8-9)
KS 1731–260	96.0±7.9	4.71±0.52	524 (2)	7-9[c] (10)
4U 1724–207	113.8±15.4	5.29±0.58	...	7.4±0.5
4U 1608–52	314±44.3	18.5±2.0	620 (3)	4.0±2.0, $D_{\mathrm{cutoff}} > 3.9$[d]

Photospheric Radius Expansion & MR estimation



Touchdown Flux : F_{td}

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1-\frac{2GM}{Rc^2}\right)^{1/2}\left[1+\left(\frac{kT_c}{38.8\,\mathrm{keV}}\right)^{a_g}\left(1-\frac{2GM}{Rc^2}\right)^{-a_g/2}\right]$$

apparent radius : A_∞

$$A = f_c^{-4}\frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}\left\{1+\left[\left(0.108-0.096\frac{M}{M_\odot}\right)+\left(-0.061+0.114\frac{M}{M_\odot}\right)\frac{R}{10\mathrm{km}}-0.128\left(\frac{R}{10\mathrm{km}}\right)^2\right]\left(\frac{f_{\mathrm{NS}}}{1000\mathrm{Hz}}\right)^2\right\}^2 .$$

- need two more theoretical parameters, $f_c = 1.4$ & $\kappa = 0.2(1+X)\ \mathrm{cm}^2\,\mathrm{g}^{-1}$

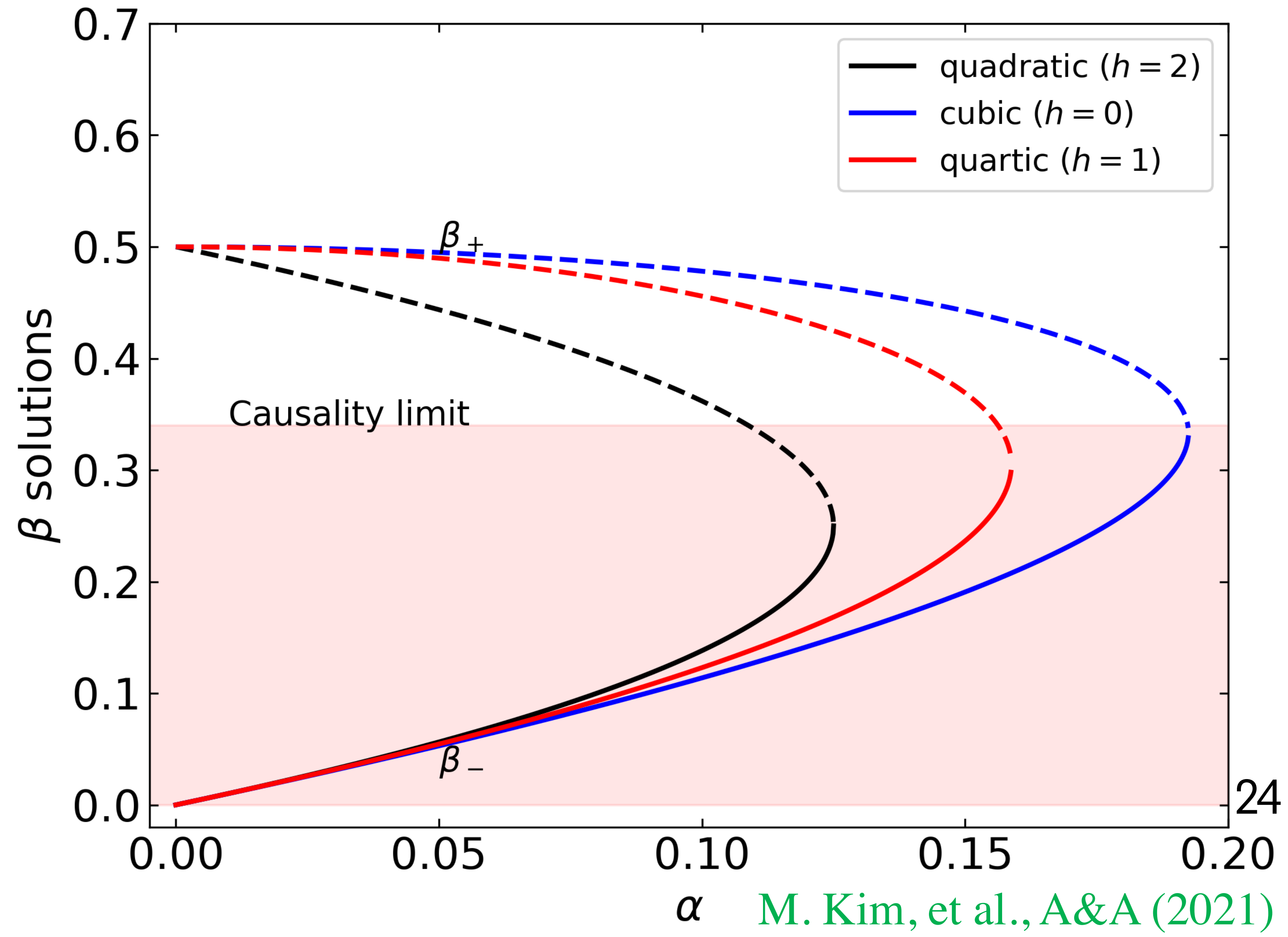
Mass and radius estimation

obs. $$\alpha \equiv \frac{F_{\rm td}}{\sqrt{A_\infty}} \frac{\kappa D}{c^3 f_c^2} \qquad \gamma \equiv \frac{A_\infty c^3 f_c^4}{F_{\rm td}\kappa} \qquad \beta = \frac{GM}{Rc^2}$$

eq. $$\alpha = \beta\sqrt{1-2\beta}\sqrt{1-h\beta} \qquad \gamma = \frac{R}{\beta(1-2\beta)\sqrt{1-h\beta}}$$

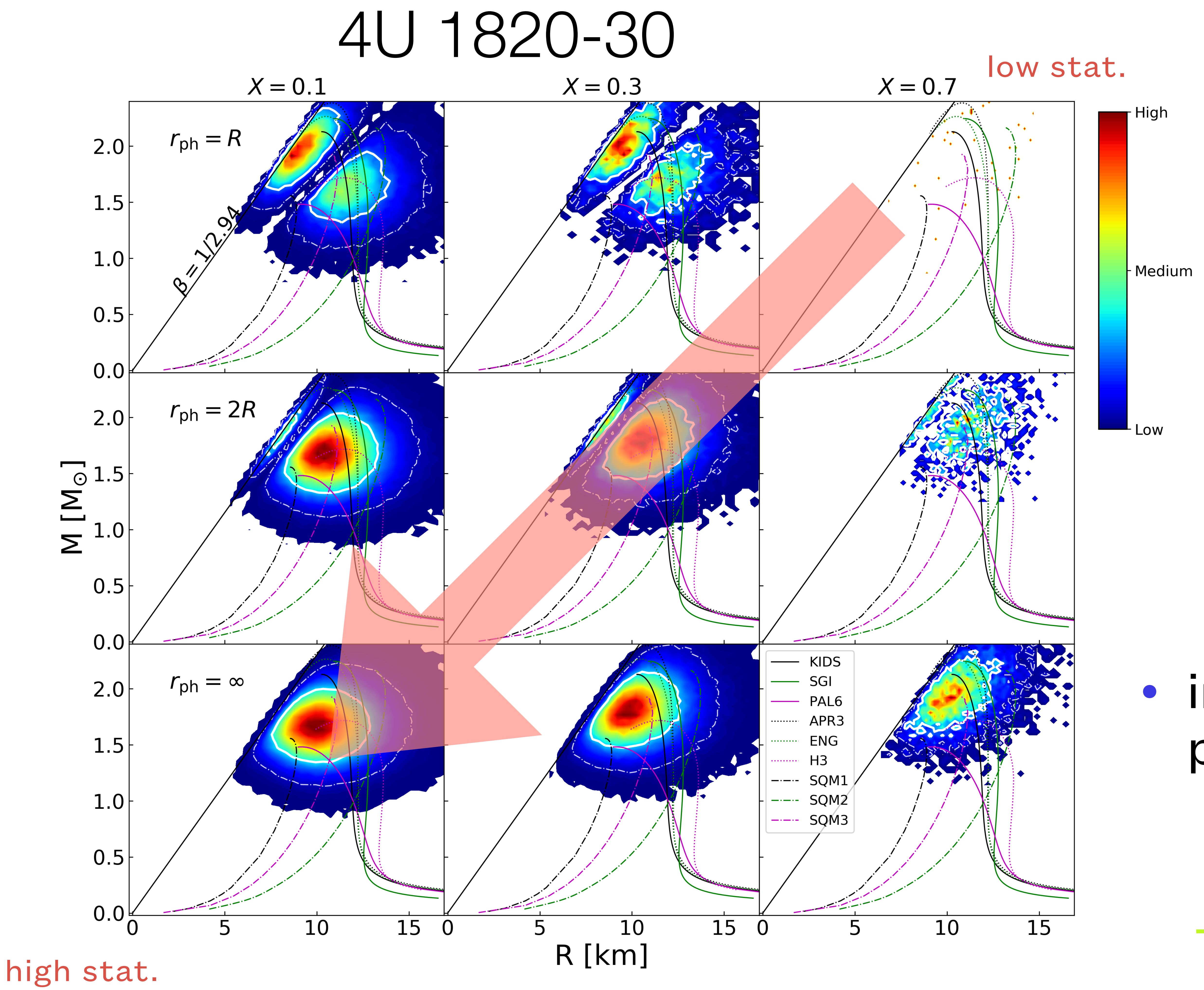
$$R = \alpha\gamma\sqrt{1-2\beta}$$
$$M = \beta R c^2/G$$

- introducing two parameters α, γ then quadratic to quartic eq. of beta
- $h = 2R_{ns} / r_{ph}$ (h = 0 ~ 2)
- Monte Carlo sampling (~ 5,000,000)



M. Kim, et al., A&A (2021)

MR credible regions and acceptance rate

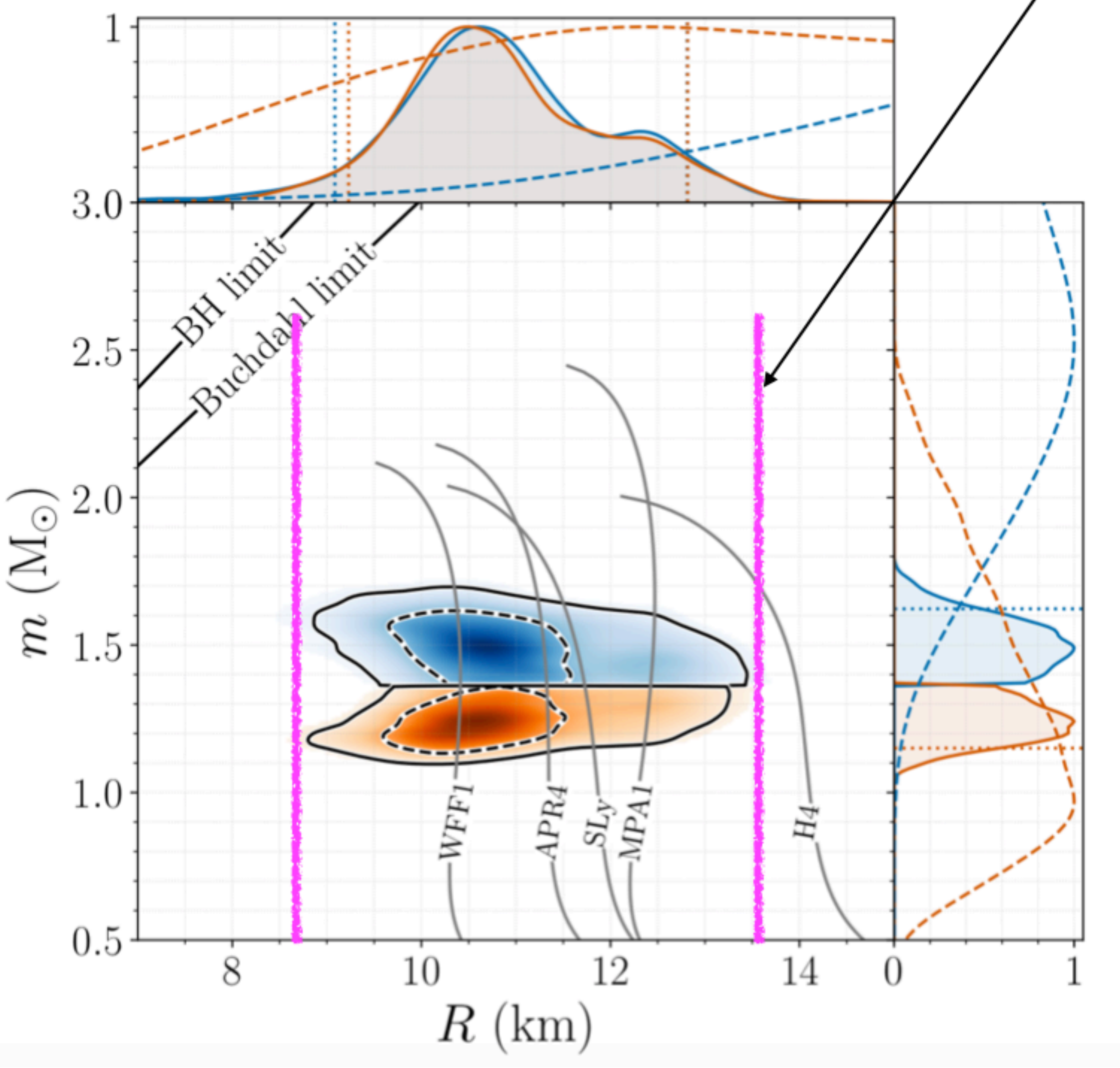


$r_{ph} = R$	4U 1820–30	$r_{ph} = 2R$	4U 1820–30	$r_{ph} = \infty$	4U 1820–30
		hydrogen poor (X=0.1)			
Sol.	1.2 (1.0)	Sol.	12.2 (1.1)	Sol.	31.4 (0)
Causality	0 (0.3)	Causality	0 (11.1)	Causality	0 (31.2)
Unphys.	≥98.7	Unphys.	87.8 (87.8)	Unphys.	68.6 (68.8)
		intermediate (X=0.3)			
Sol.	≤0.08	Sol.	1.8 (0.2)	Sol.	7.5 (0)
Causality	0 (0.01)	Causality	0 (1.6)	Causality	0 (7.4)
Unphys.	≥99.9	Unphys.	98.2 (98.2)	Unphys.	92.5 (92.6)
		hydrogen rich (X=0.7)			
Sol.	0.0	Sol.	≤0.05	Sol.	≤0.2
Causality	0.0	Causality	≤0.05	Causality	≤0.2
Unphys.	100.0	Unphys.	≥99.9	Unphys.	≥99.6

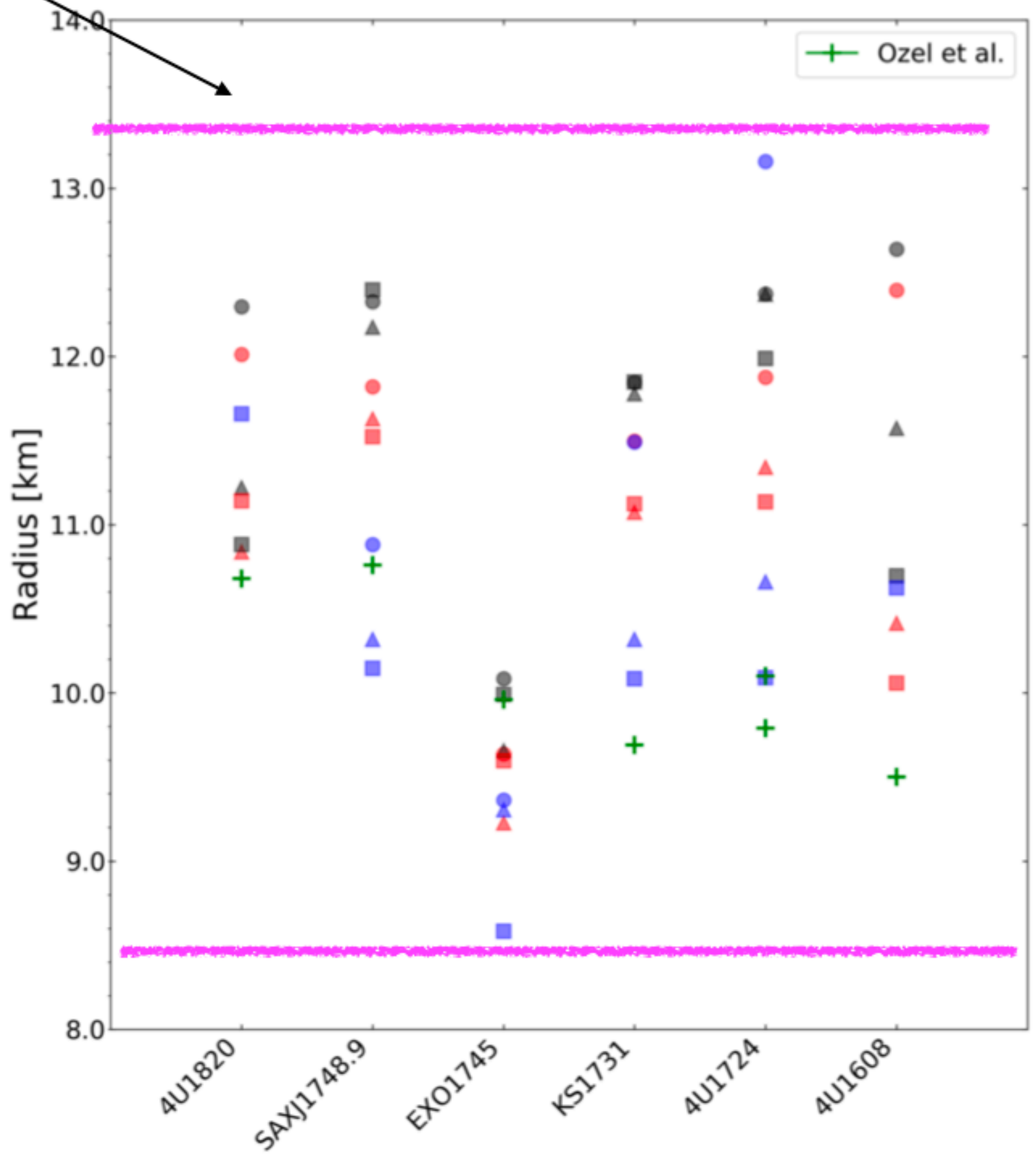
- in Monte Carlo samplings, h=0 and hydrogen poor are favored

Most probable vales and GW constraint

consistent



Abbott et al. (LSC and Virgo), PRL 121.161101



M. Kim, Y.-M. Kim et al. (A&A 2021)

Summary

- We developed a new BUU type transport model aiming for LAMPS/RAON experiments
- We tested DJBUU for elastic reactions and compared with TMEP results for Au+Au collisions, Box-collisions and Box-MF dynamics
- We expect DJBUU will give hints for symmetry energy by pion-like particle productions
- We estimated the mass and radius of neutron stars showing PRE in X-ray bursts
- We can give constraints of EoS by using the MR estimations

Hulk vs Iron man, Marvel comics

Thank you.