同濟大學 TONGJI UNIVERSITY

Studies on the Symmetry Energy of Strong-Interacting Matter

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5. Quark matter E_{sym}

The 1st International Workshop on Physics at High Baryon Density (PHD2024), CCNU, Wuhan

Definition of E_{sym}

energy per nucleon in asymmetric nuclear matter (EOS)

$$E(\rho,\delta) \approx E_0(\rho) + E_{sym}(\rho)\delta^2 + E_{sym}^{(4)}(\rho)\delta^4 + \ldots$$

SNM EOS

nucleon density $\rho = \rho_n + \rho_p$ **isospin asymmetry** $\delta = \dfrac{\rho_n - \rho_p}{\rho}$

expansion around saturation density ρ_0

$$E_{sym}(\rho) = E_{sym}(\rho_0) + L\left(\frac{\rho-\rho_0}{3\rho_0}\right) + \frac{K_{sym}}{2!}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^2 + \frac{Q_{sym}}{3!}\left(\frac{\rho-\rho_0}{3\rho_0}\right)^3 + \ldots$$

slope

$$L = 3\rho_0 \left.\frac{dE_{sym}}{d\rho}\right|_{\rho_0}$$

curvature

$$K_{sym} = 9\rho_0^2 \left.\frac{d^2E_{sym}}{d\rho^2}\right|_{\rho_0}$$

skewness

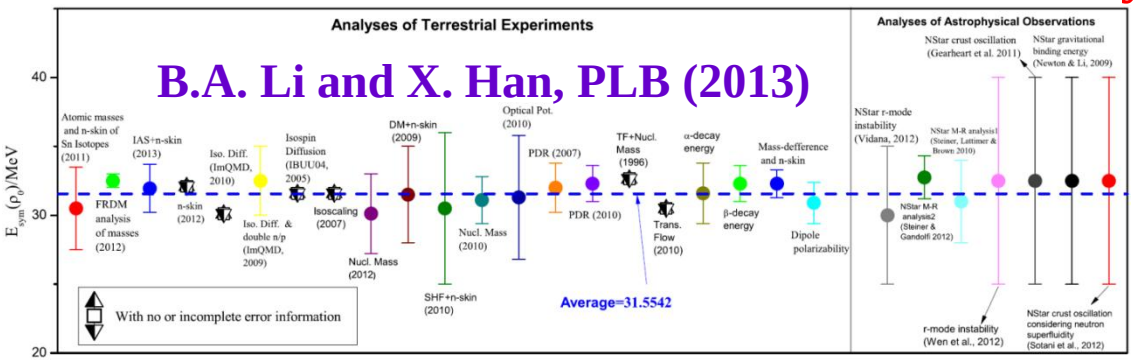
$$Q_{sym} = 27\rho_0^3 \left.\frac{d^3E_{sym}}{d\rho^3}\right|_{\rho_0}$$

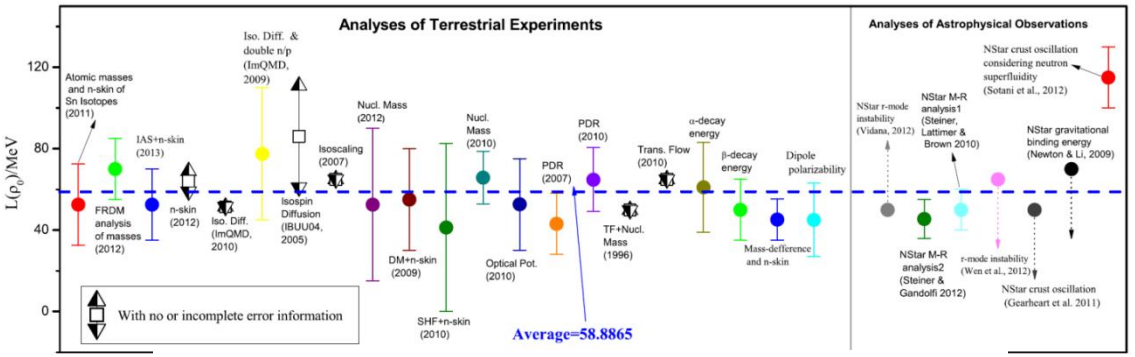
mean-field potential

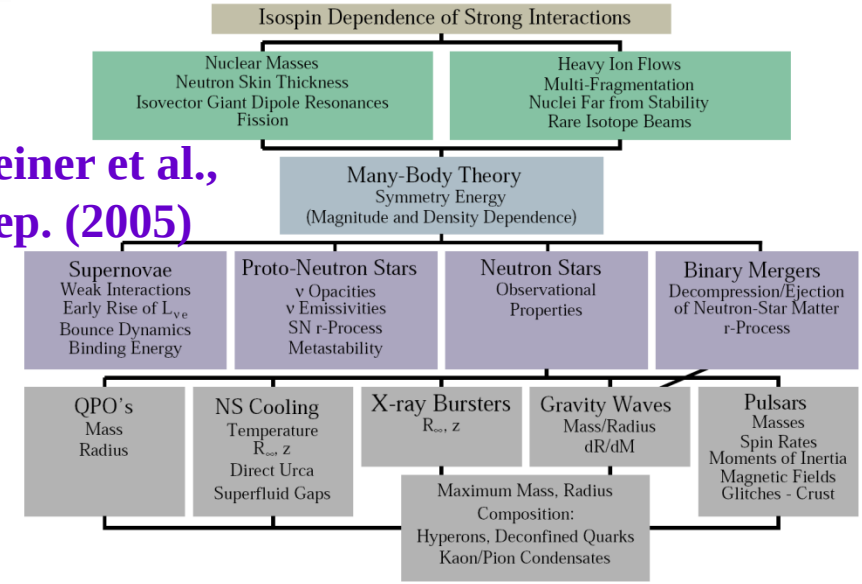
$$U_{n/p}(\rho,\delta) \approx U_0(\rho) \pm U_{sym}(\rho)\delta + U_{sym}^{(2)}(\rho)\delta^2 + \ldots$$

symmetry potential

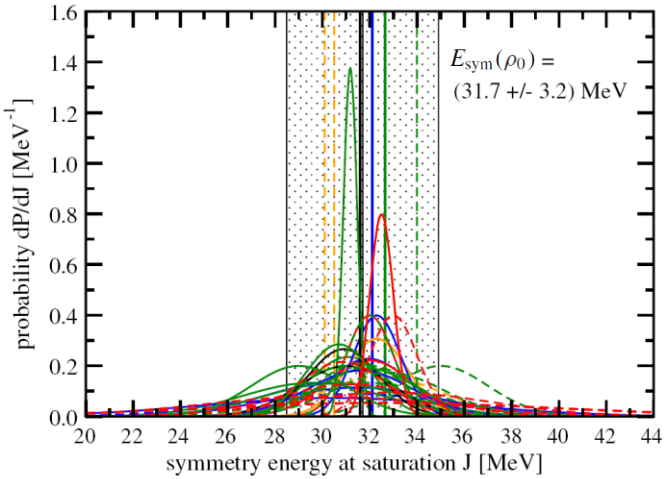
Various constraints on $E_{sym}(\rho_0)$ and $L(\rho_0)$

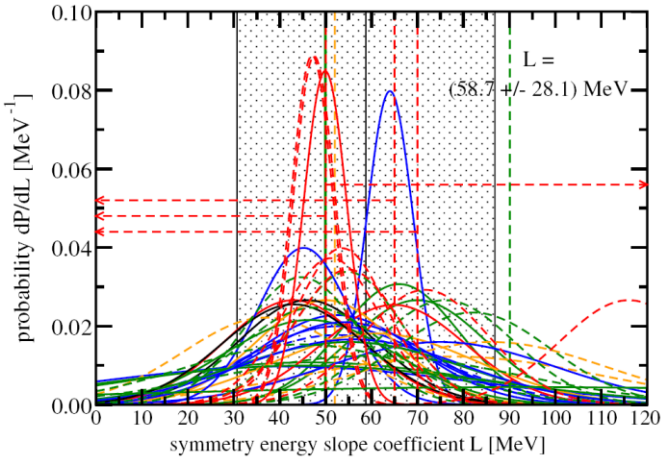






A.W. Steiner et al., Phys. Rep. (2005)

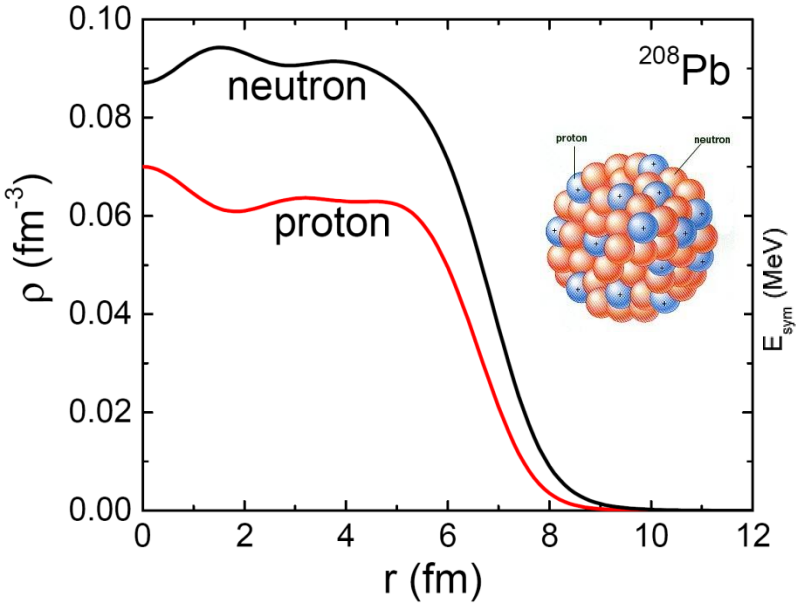


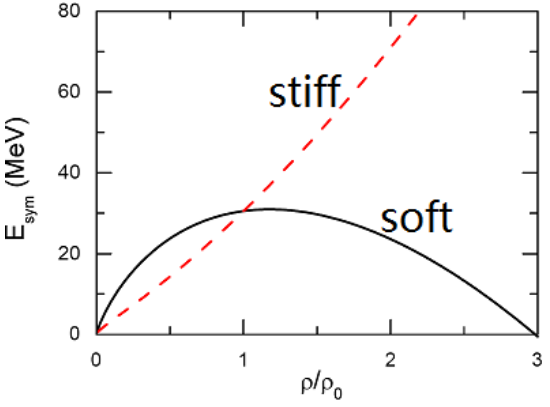


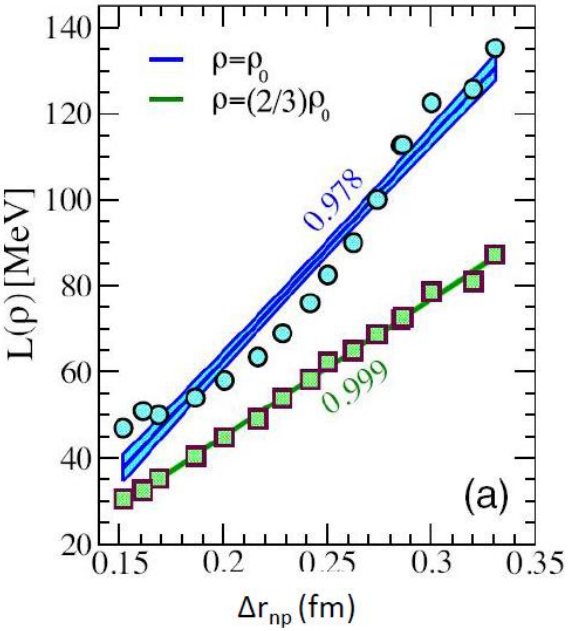
M. Oertel et al., RMP (2017)

Symmetry energy PACS: 21.65.Ef

E_{sym} and neutron skin







Neutron-Skin Thickness:

$$\Delta r_{np} = \sqrt{\langle r_n^2 \rangle} - \sqrt{\langle r_p^2 \rangle} \quad \text{(fm)}$$

from parity-violating electron scatterings

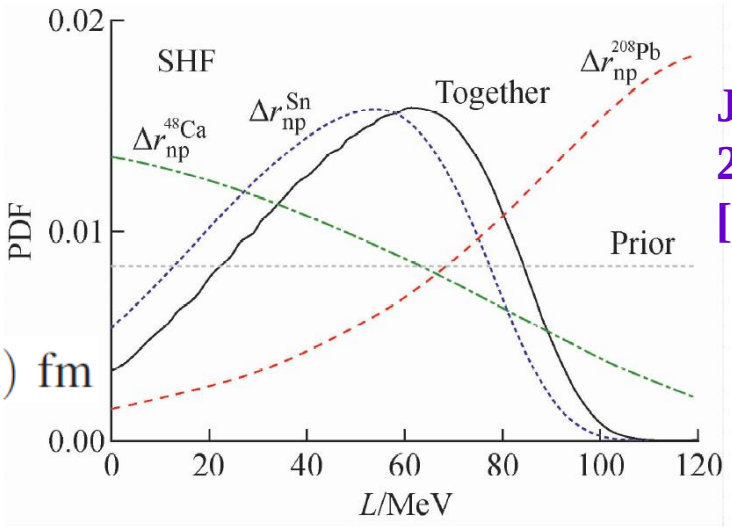
^{208}Pb (PREXII)

$$\Delta r_{np} = 0.283 \pm 0.071 \text{ fm}$$

^{48}Ca (CREX)

$$\Delta r_{np} = 0.121 \pm 0.026(\text{exp}) \pm 0.024(\text{model}) \text{ fm}$$

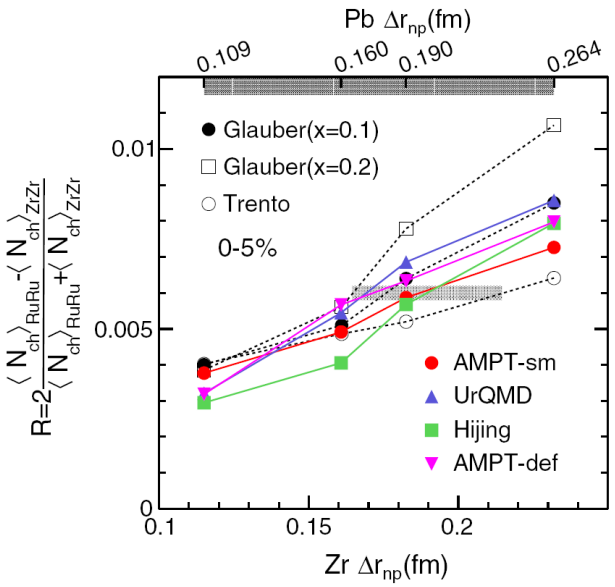
Posterior PDF of L from Bayesian inference



JX, 2301.07884 [nucl-th]

Probing Δr_{np} with relativistic HIC

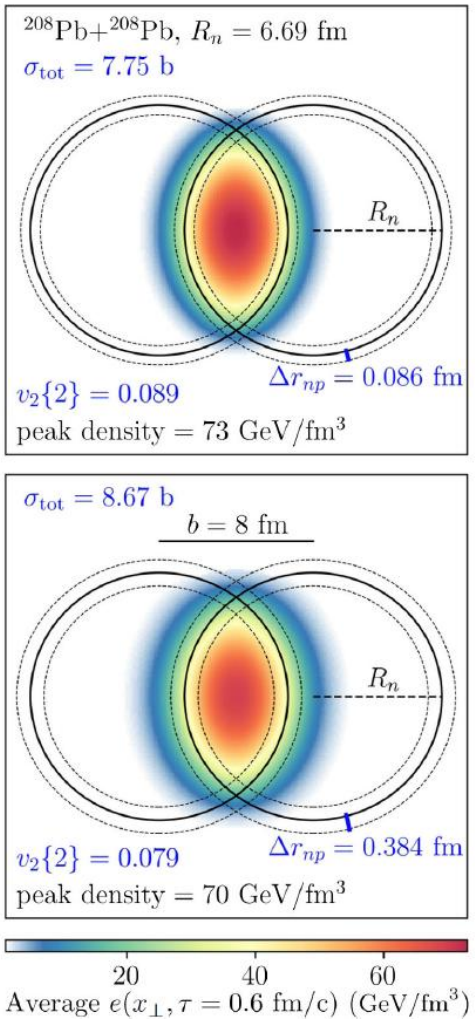
Charged-particle multiplicity



H. L. Li, H. J. Xu, Y. Zhou, X. B. Wang, J. Zhao, L. W. Chen, and F. Q. Wang, PRL (2020)

using observables at midrapidities

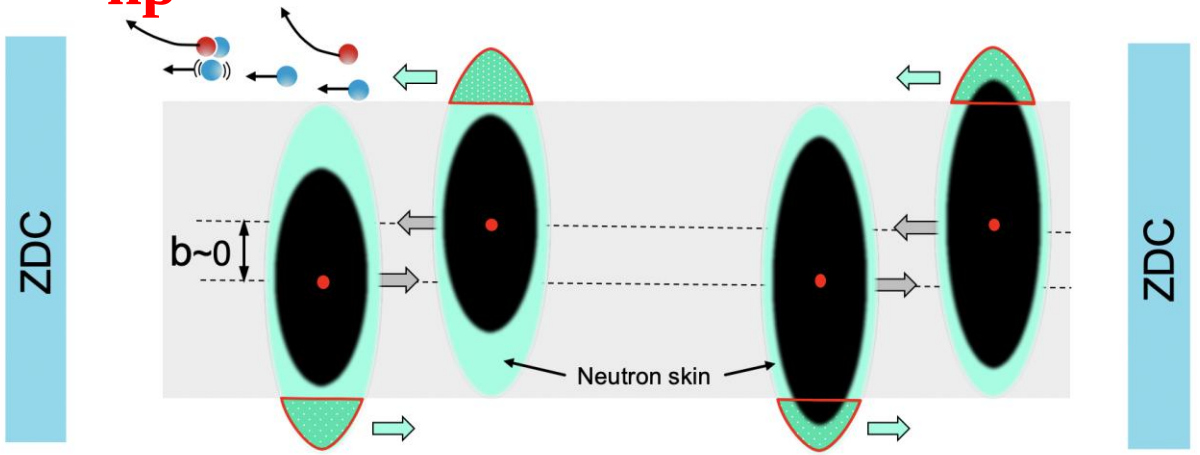
v_2 and $\langle p_T \rangle$

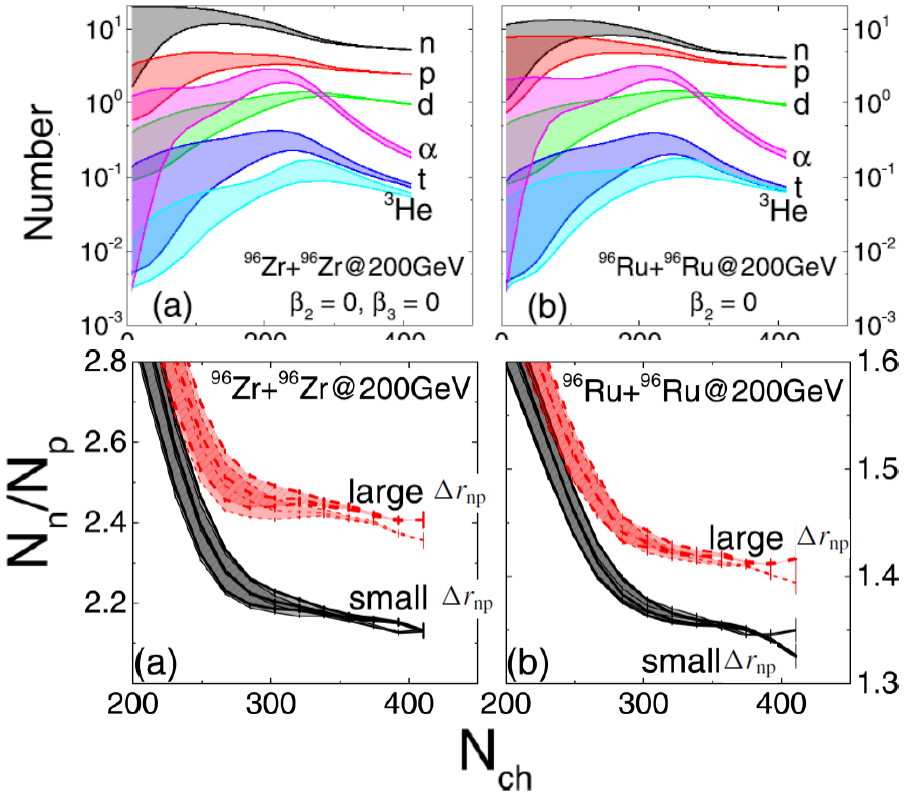


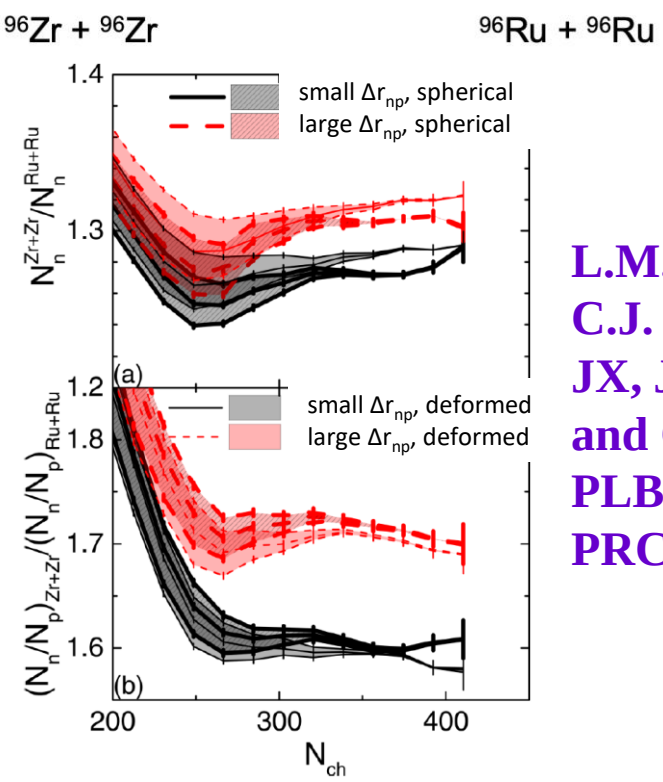
G. Giacalone, G. Nijs, and W. van der Schee, PRL (2023)

Probing Δr_{np} with relativistic HIC

using spectator particle yield at beam rapidity





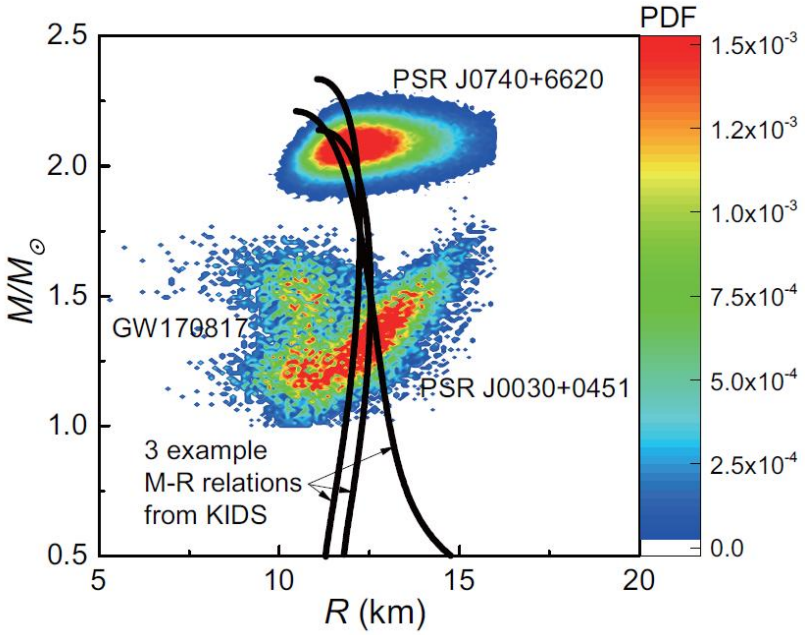


L.M. Liu, C.J. Zhang, JX, J.Y. Jia, and G.X. Peng, PLB (2022); PRC (2022)

E_{sym} and neutron stars

3 energy-density functionals:

- **Skyrme-Hartree-Fock (SHF)**
- **Korea-IBS-Daegu-SKKU (KIDS)**
- **Relativistic Mean-Field (RMF)**



nucleonic DOF EOS P(ε)

↓

TOV equation

↓

M-R relation

↓

model coefficients

↕

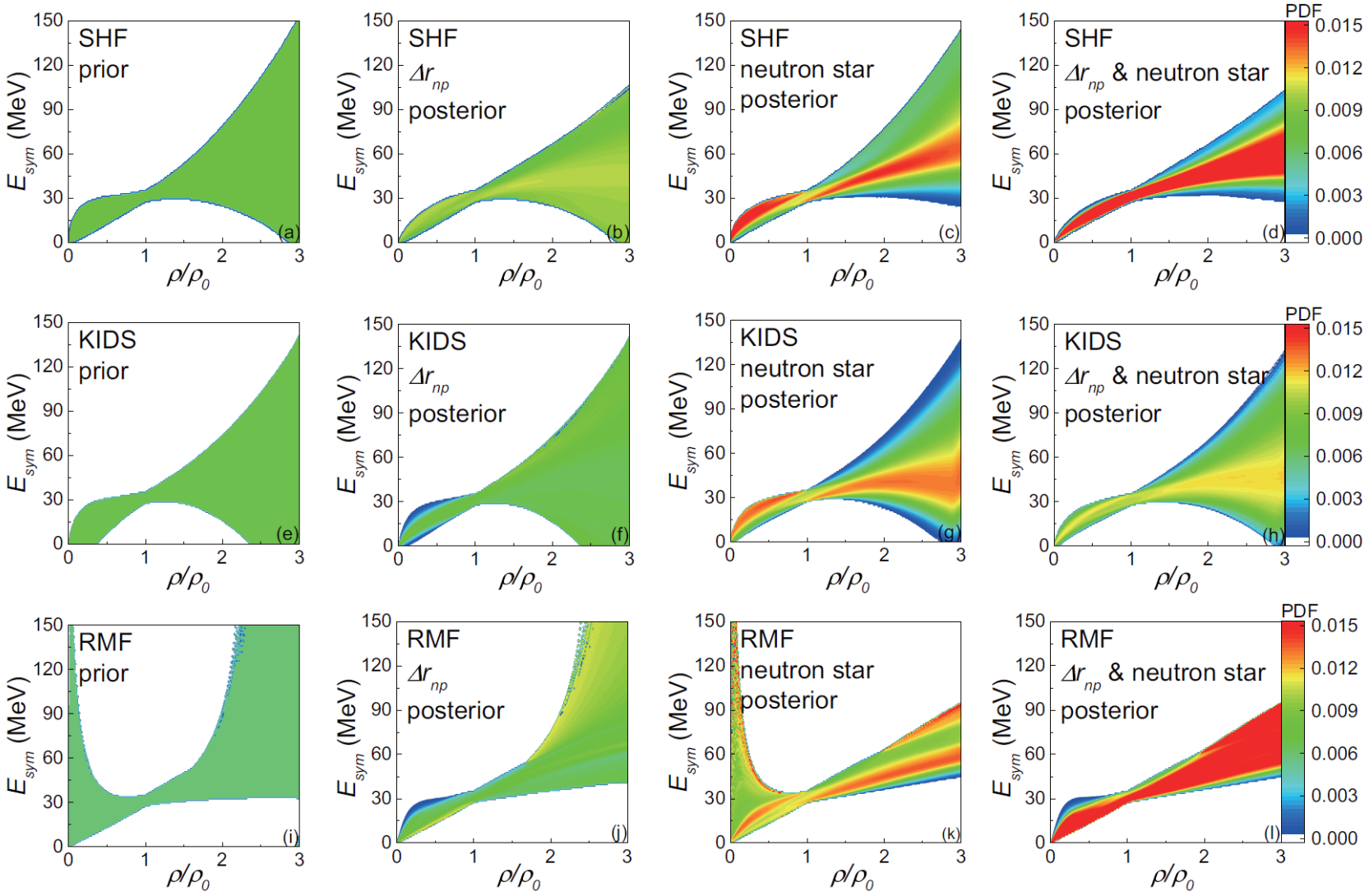
physics quantities

Bayesian analysis

Table 1 Prior ranges of model parameters in the standard SHF, KIDS, and RMF models for the Bayesian analysis in the present study

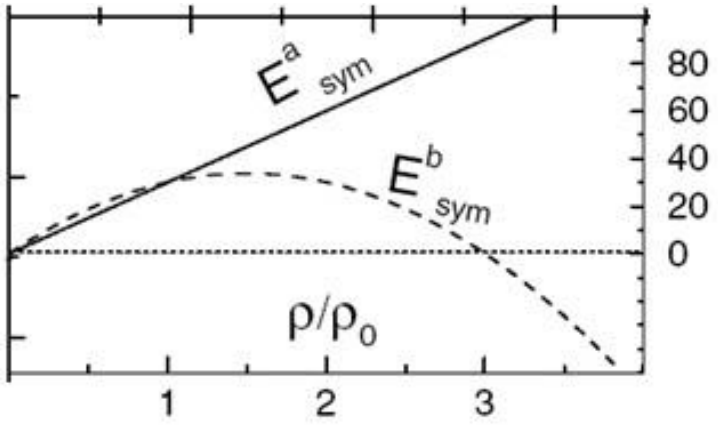
Parameters	SHF	KIDS	RMF
K_0 (MeV)	220-260	220-260	220-260
Q_0 (MeV)	–	−800-400	−800-400
E^0_{sym} (MeV)	28.5-34.9	28.5-34.9	28.5-34.9
L (MeV)	30-90	30-90	30-90
K_{sym} (MeV)	–	−400-100	–
Q_{sym} (MeV)	–	−200-800	–
$m^\star_s/m$	0.5-0.9	0.5-0.9	0.5-0.9
$m^\star_v/m$	0.5-0.9	0.5-0.9	–

E_{sym} from both neutron stars and Δr_{np}

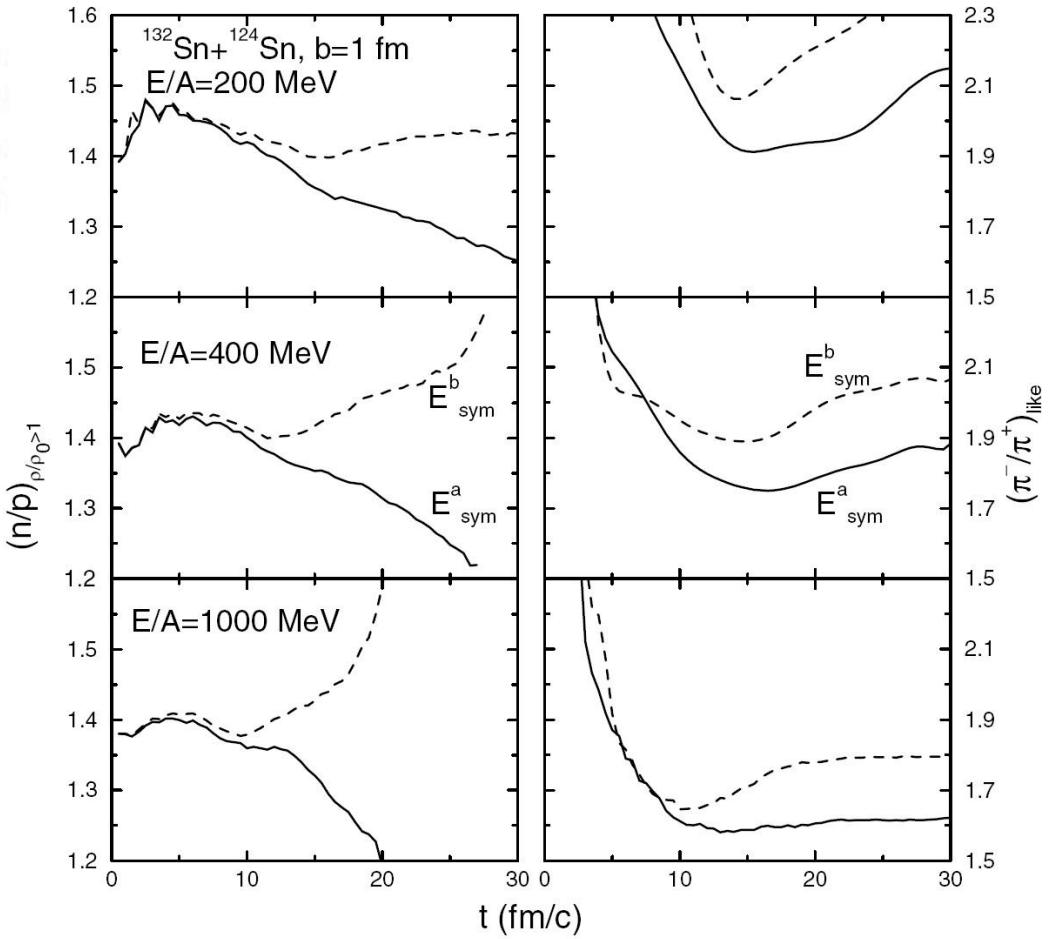


J. Zhou and JX, Sci. China-Phys. Mech. Astron. (2024)

E_{sym} and π^-/π^+ ratio in HIC



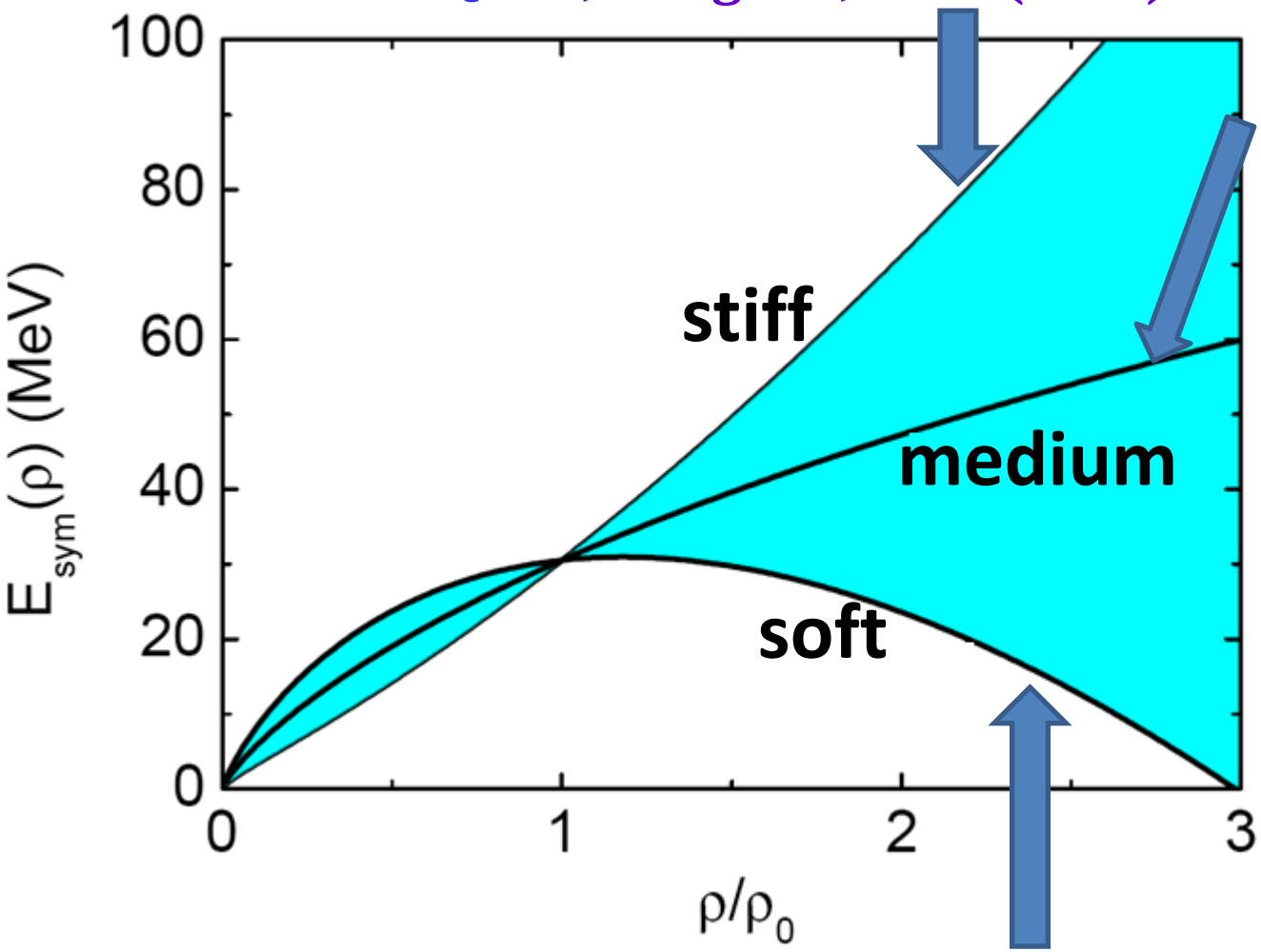
B.A. Li, PRL (2002)



$$n + n \rightarrow \Delta^- + p,\ \Delta^- \rightarrow n + \pi^- \quad p + p \rightarrow \Delta^{++} + n,\ \Delta^{++} \rightarrow p + \pi^+$$

Divergence of E_{sym} from FOPI π^-/π^+ data

LQMD, Feng/Jin, PLB (2010)



IBUU04, Xiao/Chen/Li/Zhang, PRL, (2009)

IBL, Xie/Su/Zhu/Zhang, PLB, (2013)

TuQMD

Cozma/Trauntmann/Li, PRC (2013)

Pion s&p-wave from thermal model

Xu/Ko/Oh, PRC (2010)

Xu/Chen/Li/Ko/Ma, PRC (2013)

Pion s-wave from pBUU

Hong/Pawel, PRC (2014)

Pion threshold effect from RVUU

Song/Ko, PRC (2015)

Energy conservation from TuQMD

Cozma, PLB (2016)

Clustering and PB from JAM/AMD

Ikeno/Ono/Nara/Ohnishi, PRC (2016,2019)

Pion s&p-wave from RVUU

Zhang/Ko (2017,2018)

...

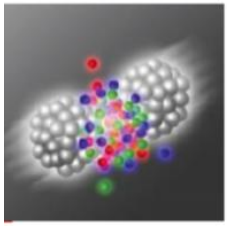
Reduce uncertainty of transport simulation (TMEP)

Transport simulation
- initialization
- collision
  - elastic
  - inelastic
  - Pauli blocking
- mean-field

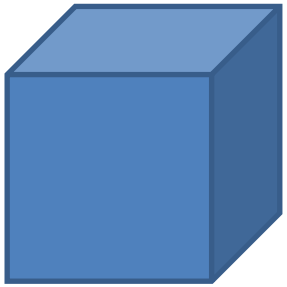
14 Boltzmann-Uehling-Uhlenbeck
12 Quantum Molecular Dynamics

Model dependence

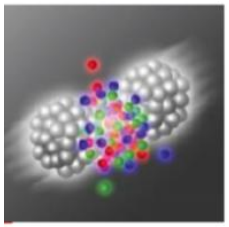
HIC simulation



box simulation
(theoretical limit)



HIC simulation



JX, et al.,
PRC (2016)

initialization;
theoretical error
of directed flow

Y.X. Zhang, et al., PRC (2018)
elastic collisions, Pauli blocking

A. Ono, JX, et al., PRC (2019)
inelastic collisions, π production

M. Colonna, et al., PRC (2021)
mean-field evolution

JX, et al.,
PRC (2024)

reduce uncertainty of
π^-/π^+ from 5.2%
to 1.6%

main uncertainties:
mean-field, Pauli blocking

Quark matter E_{sym}

strange quark matter EOS

$$E(\rho_B,\delta,\rho_s)=E_0(\rho_B,\rho_s)+E_{\rm sym}(\rho_B,\rho_s)\delta^2+\vartheta(\delta^4)$$

baryon density $\rho_B=(\rho_u+\rho_d+\rho_s)/3$ **isospin asymmetry** $\delta=3\dfrac{\rho_d-\rho_u}{\rho_d+\rho_u}$

$$E_{\rm sym}(\rho_B,\rho_s)=\frac{1}{2!}\frac{\partial^2 E(\rho_B,\delta,\rho_s)}{\partial\delta^2}\bigg|_{\delta=0}$$

Nambu-Jona-Lasinio model

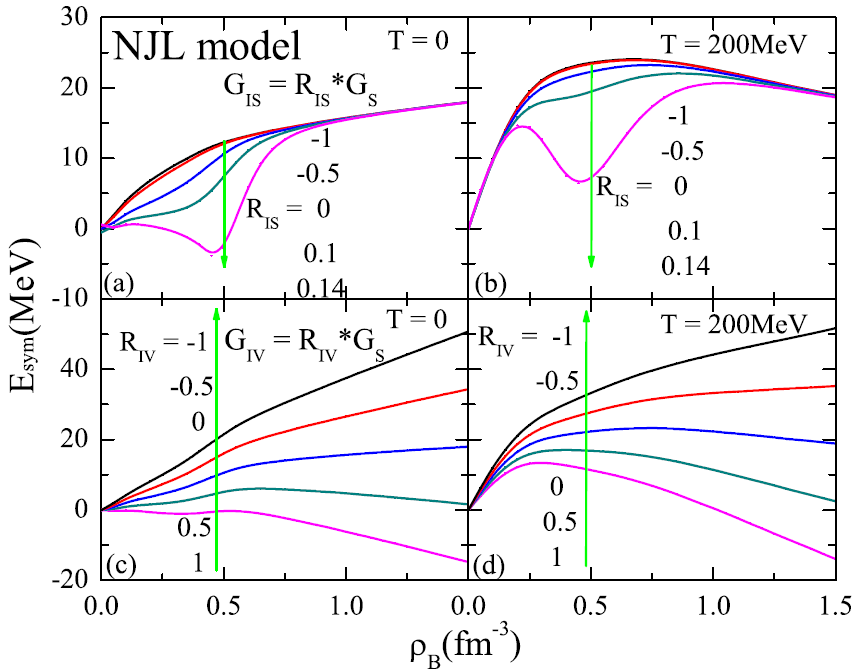
$$\mathcal{L}_{\rm NJL}=\bar{q}(i\partial\!\!\!/-\hat{m})q+\frac{G_S}{2}\sum_{a=0}^{8}[(\bar{q}\lambda_a q)^2+(\bar{q}i\gamma_5\lambda_a q)^2]$$

$$+\frac{G_V}{2}\sum_{a=0}^{8}[(\bar{q}\gamma_\mu\lambda_a q)^2+(\bar{q}\gamma_5\gamma_\mu\lambda_a q)^2]$$

$$-K\{\det[\bar{q}(1+\gamma_5)q]+\det[\bar{q}(1-\gamma_5)q]\}$$

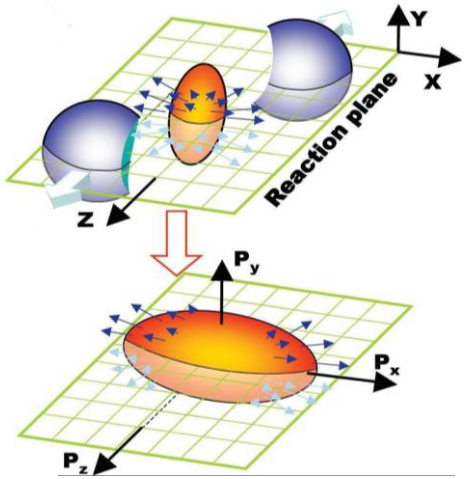
$$+G_{IS}\sum_{a=1}^{3}[(\bar{q}\lambda_a q)^2+(\bar{q}i\gamma_5\lambda_a q)^2]$$

$$+G_{IV}\sum_{a=1}^{3}[(\bar{q}\gamma_\mu\lambda_a q)^2+(\bar{q}\gamma_5\gamma_\mu\lambda_a q)^2],$$

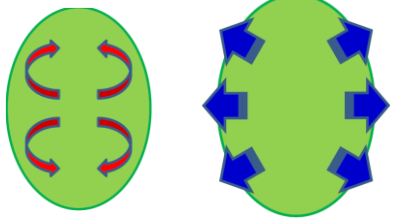


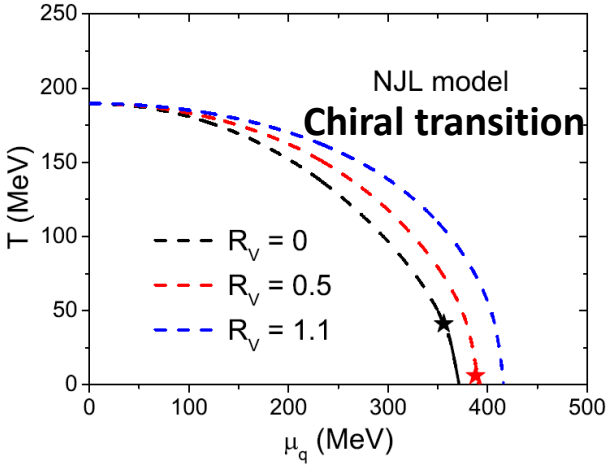
Baryon-antibaryon "E_{sym}"

$$v_2 = \langle (p_x^2 - p_y^2)/p_T^2 \rangle$$

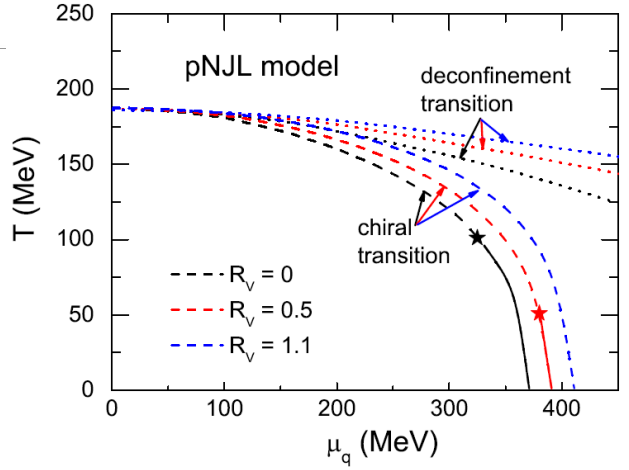


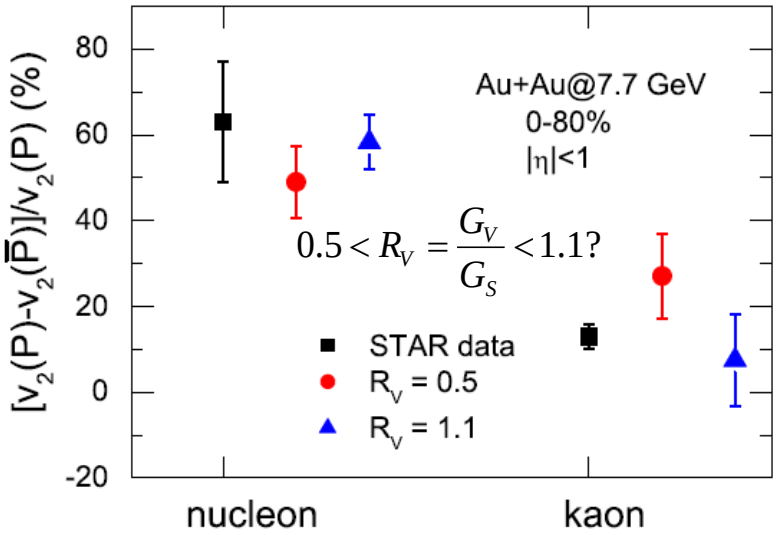
attractive **repulsive**





$$H_i = \sqrt{M_i^2 + p_i^{*2}} \pm \frac{2}{3} G_V (\rho_u^0 + \rho_d^0 + \rho_s^0)$$



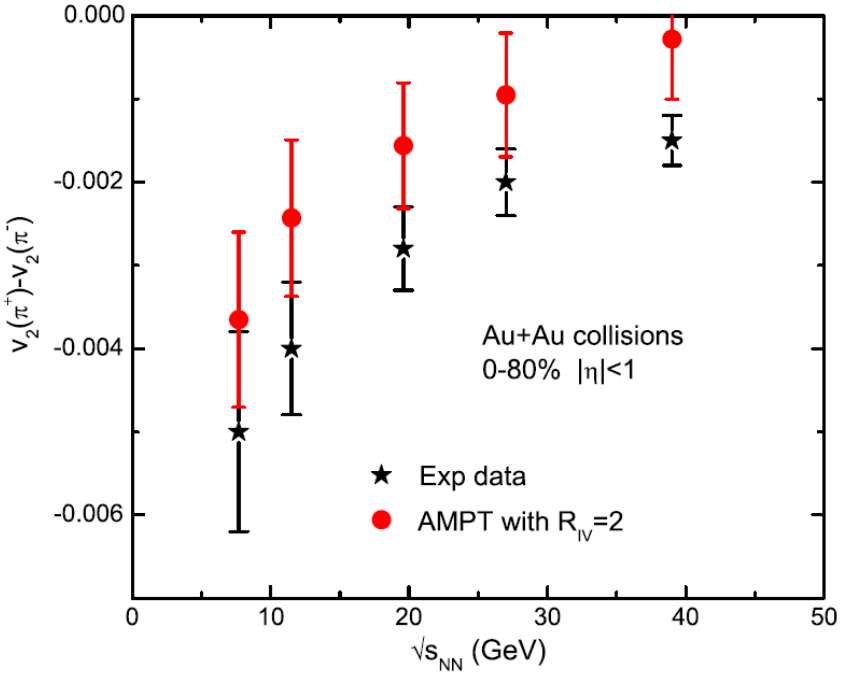


JX, T. Song, C.M. Ko, and F. Li, PRL (2014)

u-d quark E_{sym}

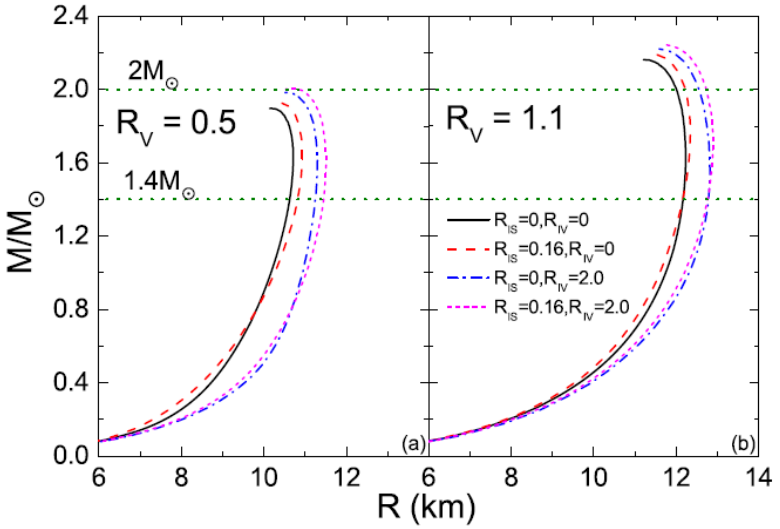
$$H_i = \sqrt{M_i^2 + p_i^{*2}} \pm \frac{2}{3} G_V (\rho_u^0 + \rho_d^0 + \rho_s^0) \pm G_{IV} \tau_{3i} (\rho_u^0 - \rho_d^0)$$

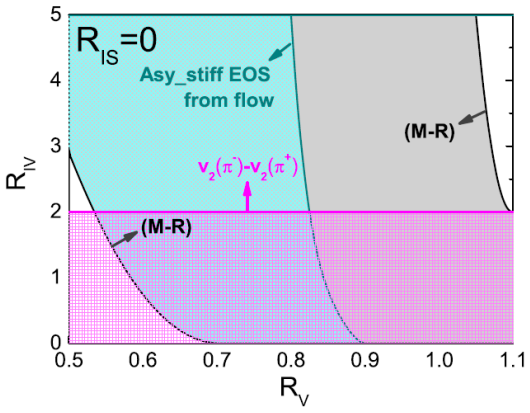
$$R_V = G_V / G_S \qquad R_{IV} = G_{IV} / G_S \qquad R_{IS} = G_{IS} / G_S$$

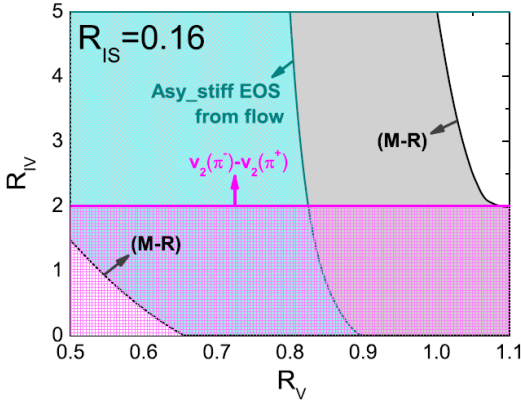


H. Liu, F.T. Wang, K.J. Sun, JX, and C.M. Ko, PLB (2019)

M-R relation for strange quark stars







H. Liu, JX, and C.M. Ko, PLB (2020)

A few remarks

- **Our knowledge on asymmetric matter is still lacking compared with that on symmetric matter**
- **Constraints on E_{sym} generally need accurate and reliable theoretical models**
- **Different probes are needed to constrain E_{sym} at various densities/temperatures (Bayesian analysis)**

Thank you!

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