Heavy-ion and dense matter physics in Hokkaido University

initiated

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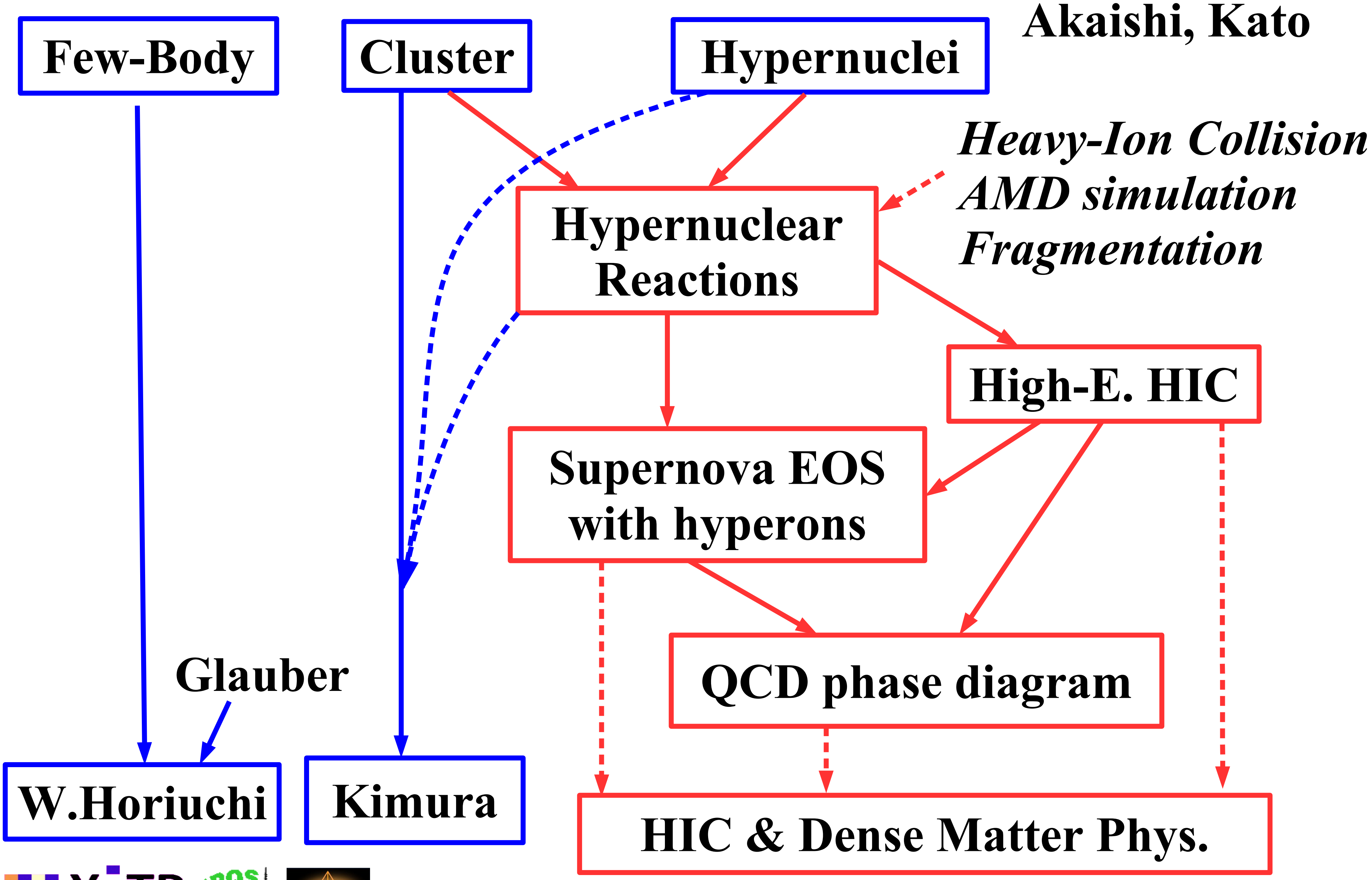
Workshop on Nuclear Cluster Physics 2017
Oct. 25-27, 2017, Sapporo, Japan.

My Research Subjects in Hokkaido University

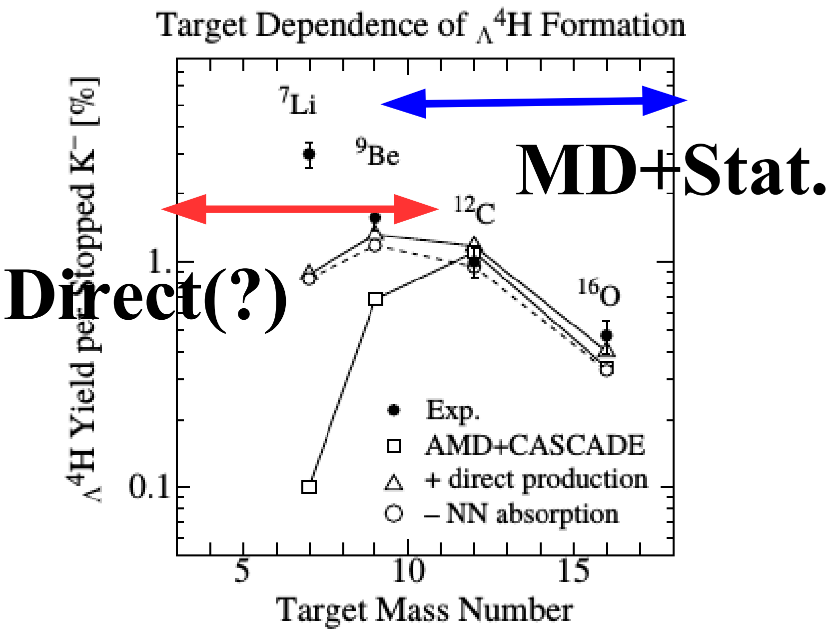
- **I belonged to Hokkaido University from 1993 to 2008.**
- **Subjects I worked on**
  - **Strangeness Nuclear Physics (Nara, Hirata, Maekawa, Tsubakihara, Matsumiya, [Isaka])**
  - **Heavy-Ion Collisions (Nara, Otuka, Isse, Yoshino, Mizukawa)**
  - **Dense Matter Physics (Okuda, Ishizuka, Ohnuma, Tsubakihara, [Miura])**
  - **Nuclear Structure (Itagaki, [Myo], Isshiki)**
  - **Nuclear Reactions (Uchida, Hirata, Maekawa, Yamaguchi)**

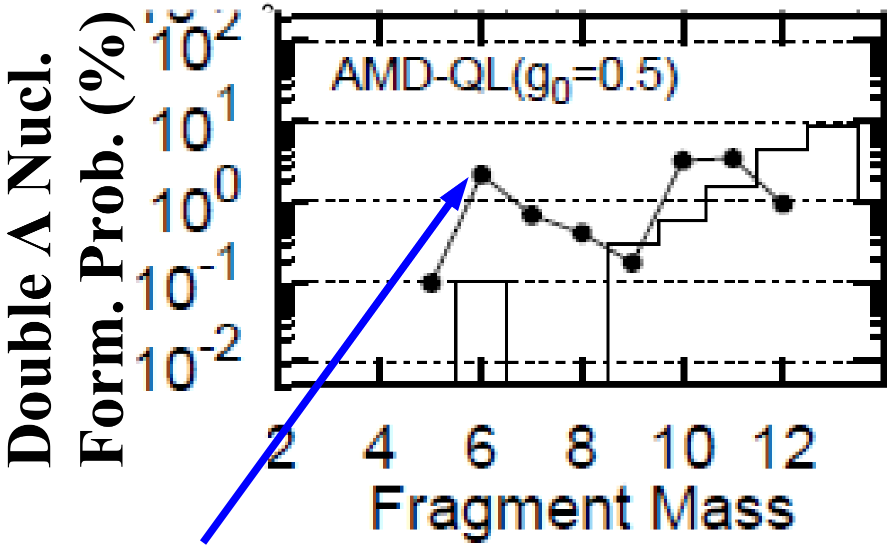
My Research Subjects in Hokkaido University



Hyperfragment Formation

- **Hypernuclear physics**
  - **Standard: Formation, Structure, Decay (c.f. Motoba's talk)**
    Binding energies, Excitation spectra, Direct reactions, Decays …
  - **Non-standard aspects: Hyperfrag. formation, YY correlation, …**
    → Simulation calculation is useful ! (c.f. Yamada's work)





$^6_{\Lambda\Lambda}$He

$^4_\Lambda$H form. prob. from stopped K$^-$

Hyperfrag. form. from stopped Ξ$^-$

Nara, AO, Harada, PLB346 ('95)217

Hirata, Nara, AO, Randrup, PTP102('99)89

(K^-, K^+) Reaction

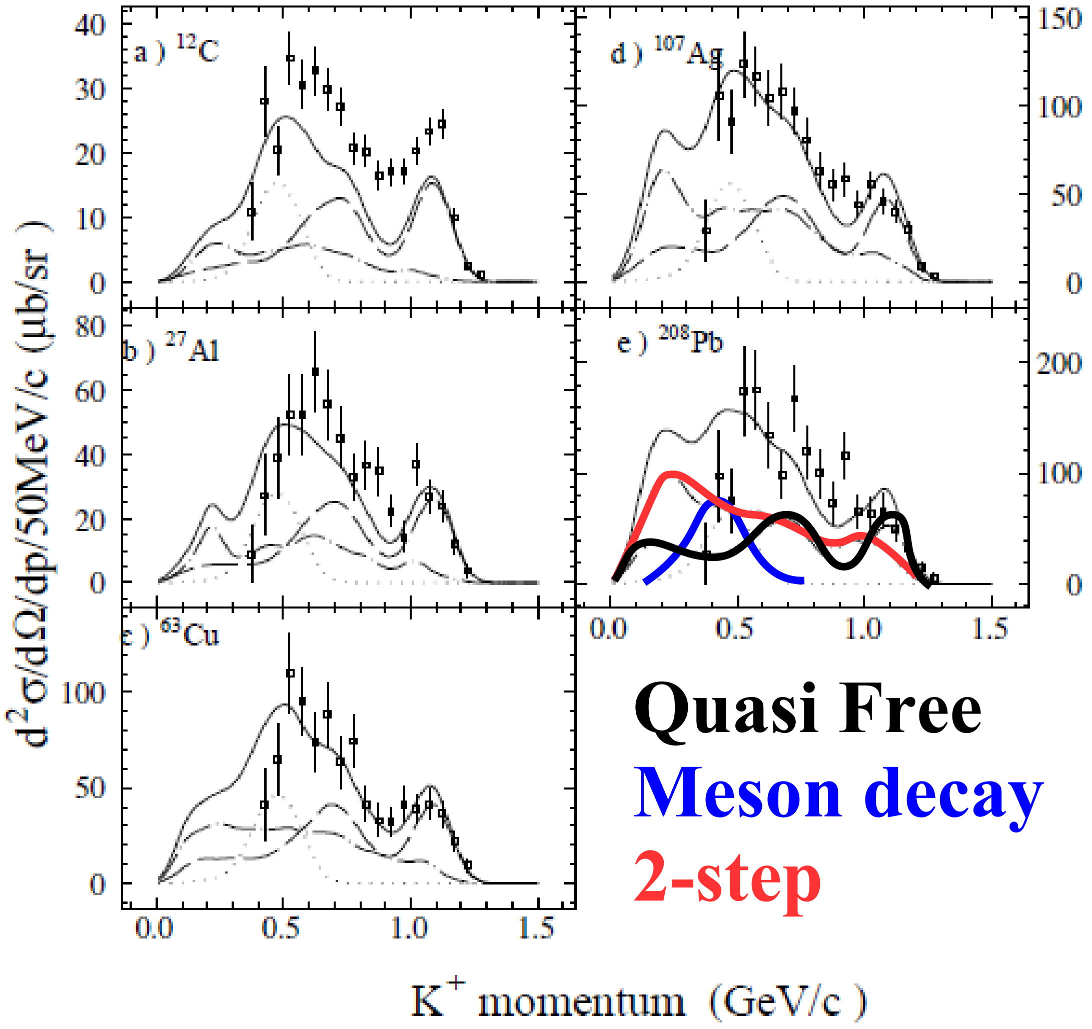
- **The primary reaction to produce Ξ^-, which is absorbed to form double Λ hypernuclei.**
- **Direct (Quasi-Free) prod. of Ξ and Ξ^* is not enough to explain the spectrum.**

$$K^- + p \to K^+ + \Xi^{-(*)}$$

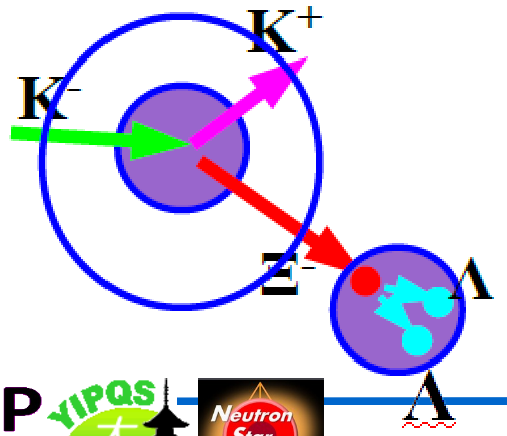
- **Various 2-step processes may contribute !**

$$K^- + N \to \pi(\eta) + \Lambda$$

$$\pi(\eta) + N \to K^+ + \Lambda$$



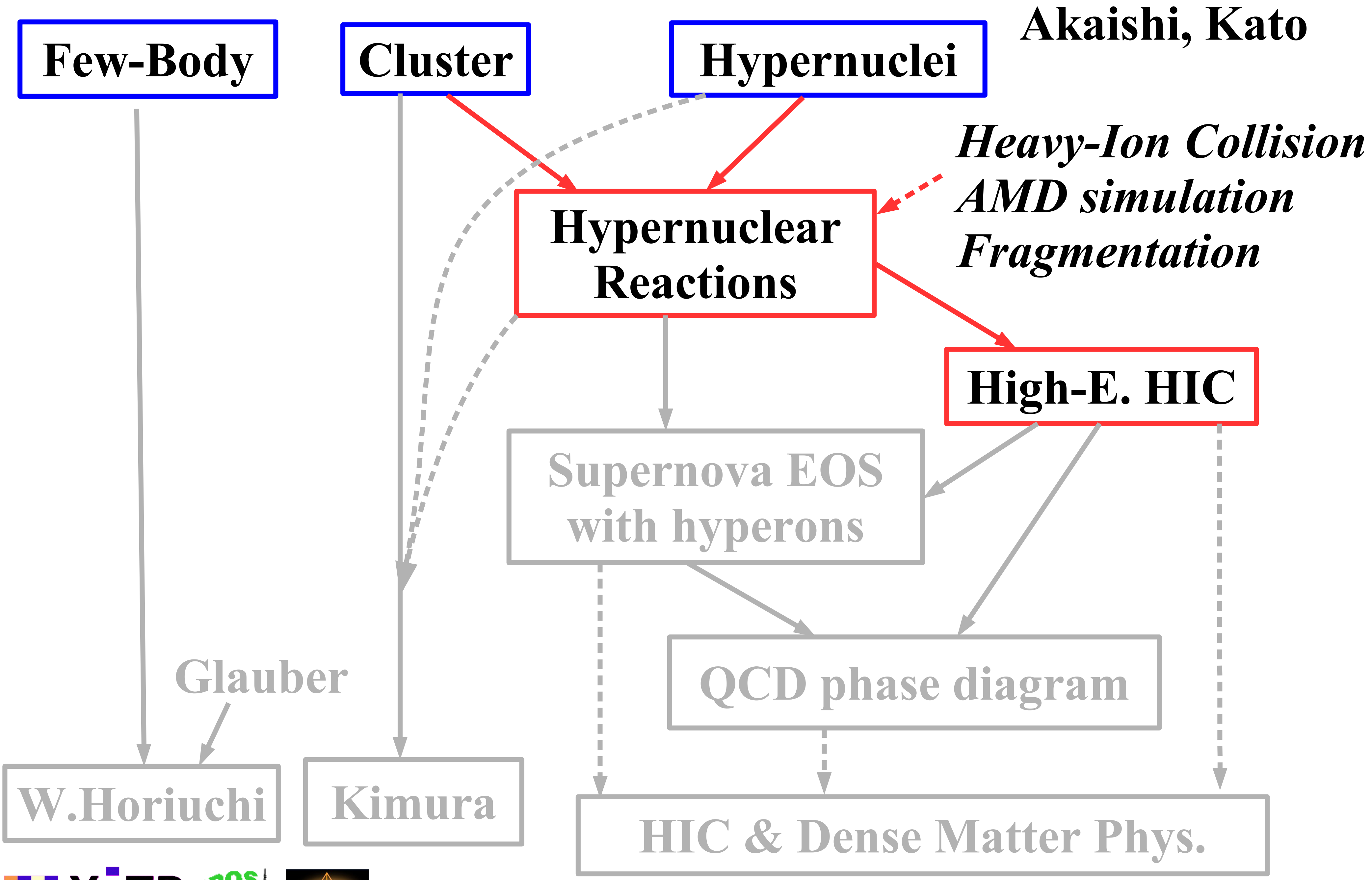
Quasi Free
Meson decay
2-step



Y. Nara, AO, T. Harada, A. Engel, NPA614 ('7), 433

High-Energy Heavy Ion Collisions

My Research Subjects in Hokkaido University



Few-Body

Cluster

Hypernuclei

Akaishi, Kato

Heavy-Ion Collision
AMD simulation
Fragmentation

Hypernuclear Reactions

High-E. HIC

Supernova EOS with hyperons

QCD phase diagram

Glauber

W.Horiuchi

Kimura

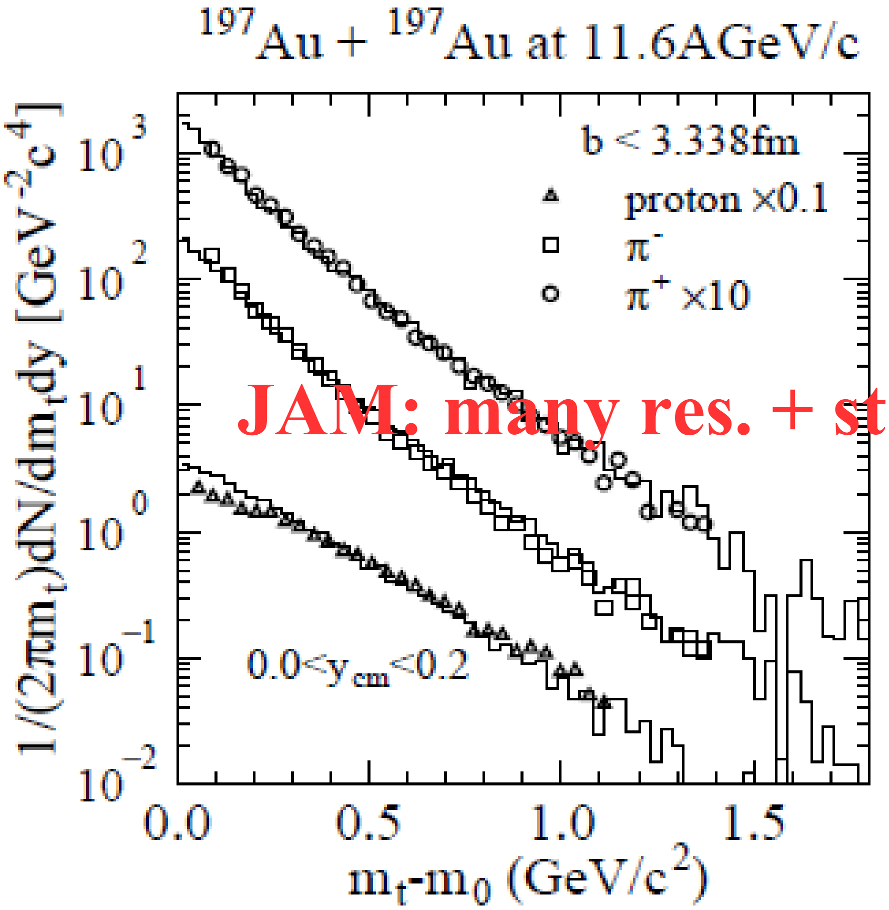
HIC & Dense Matter Phys.

High-Energy Heavy-Ion Collisions

- **Lessons from Hypernuclear Reactions**
  = Sum of small cross sections can be significant !
- **Hadron-String transport model in Heavy-Ion Collisions**
  [Jet AA Microscopic transport model (JAM)]
  - **Include as many processes as possible.**
    (Cross section book, 300 kyen !)
  - **Include as many degrees of freedom as possible.**
    → Ground state hadrons, Resonances, Strings, Jets, …
  - **Include as many ingredients as possible**
    → Two-body collisions, Mean field potential, Fluctuations, …
- **JAM is now one of the STANDARD transport models.**
  - **Describes AA and pA collisions at E/A =(1-160) GeV**
  - **Adopted in PHITS (nuclear engineering code)**
  - **High score also at low energies (E/A ~ 300 MeV)**

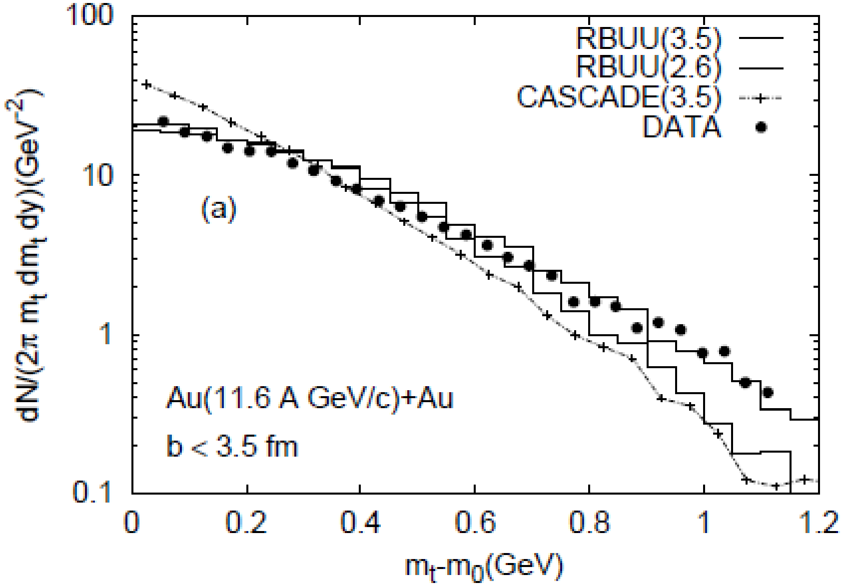
AGS energy (E/A = 10.6 GeV) HIC

- **Hadronic DOF matters.**
- **Winners in Hadron-String Cascade include Res. (M_B < 3 GeV, M_M < 2 GeV) + String (continuum) (+ MF)**



JAM: many res. + strings

RBUU(HSD):
low mass res. + string

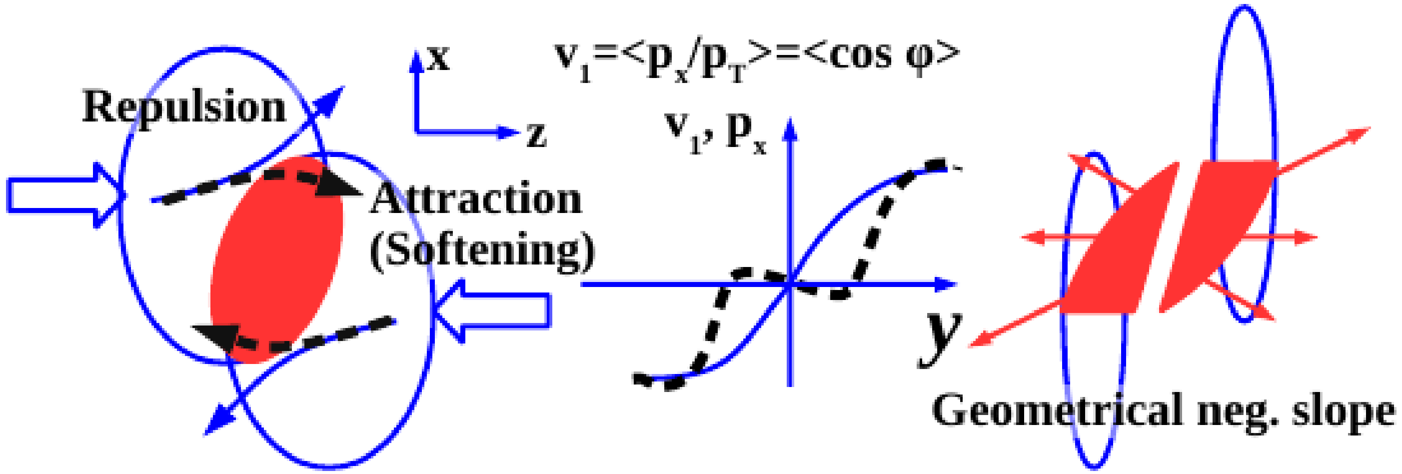


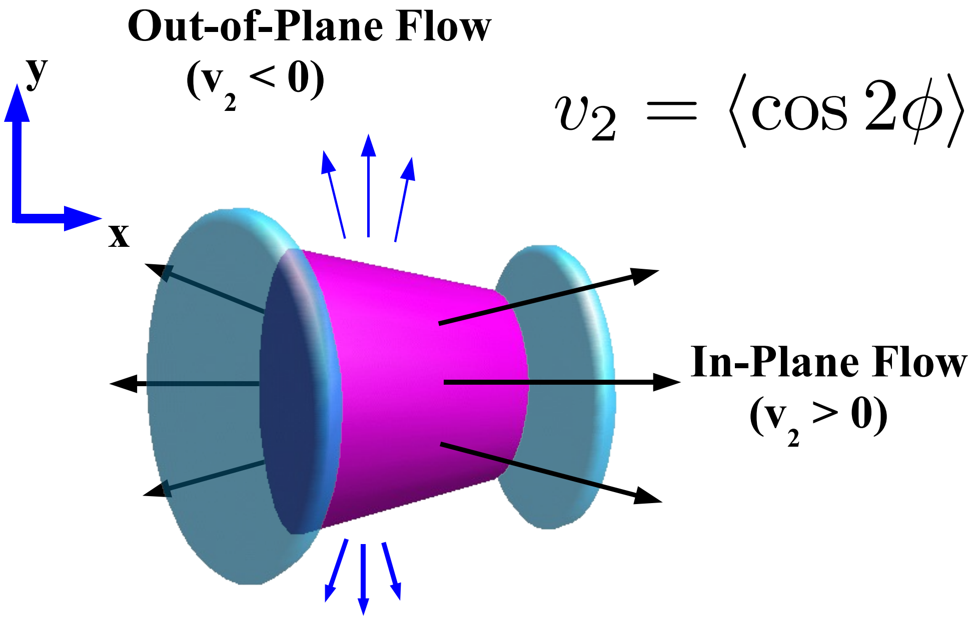
Nara, Otuka, AO, Niita, Chiba, PRC('00) , 024901

Sahu, Cassing, Mosel, AO, NPA672('00)376

Collective Flow

- **Directed flow (v_1, $<p_x>$), Elliptic flow (v_2)**
  → Generated in the Early stage, sensitive to dense matter EOS



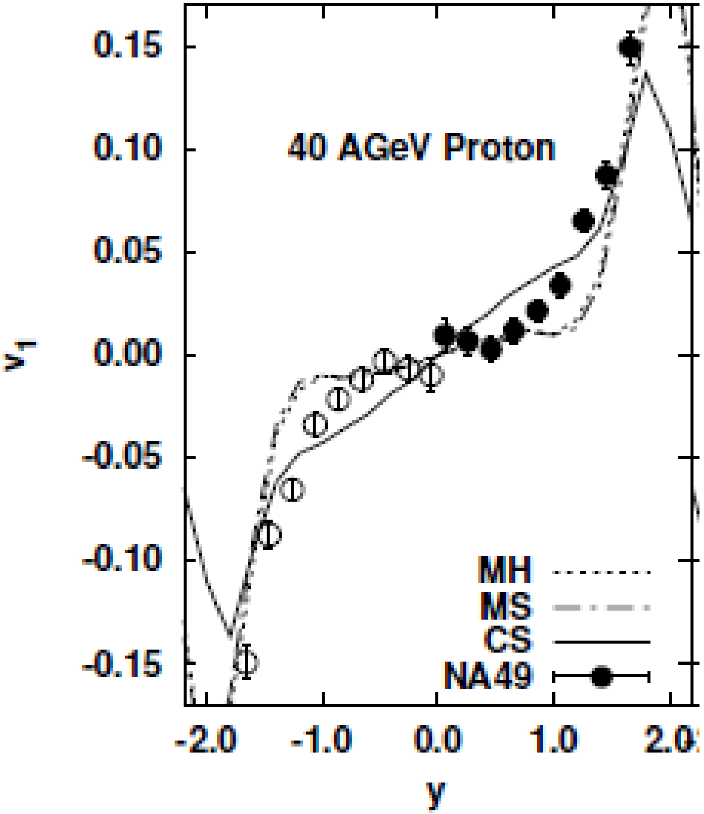


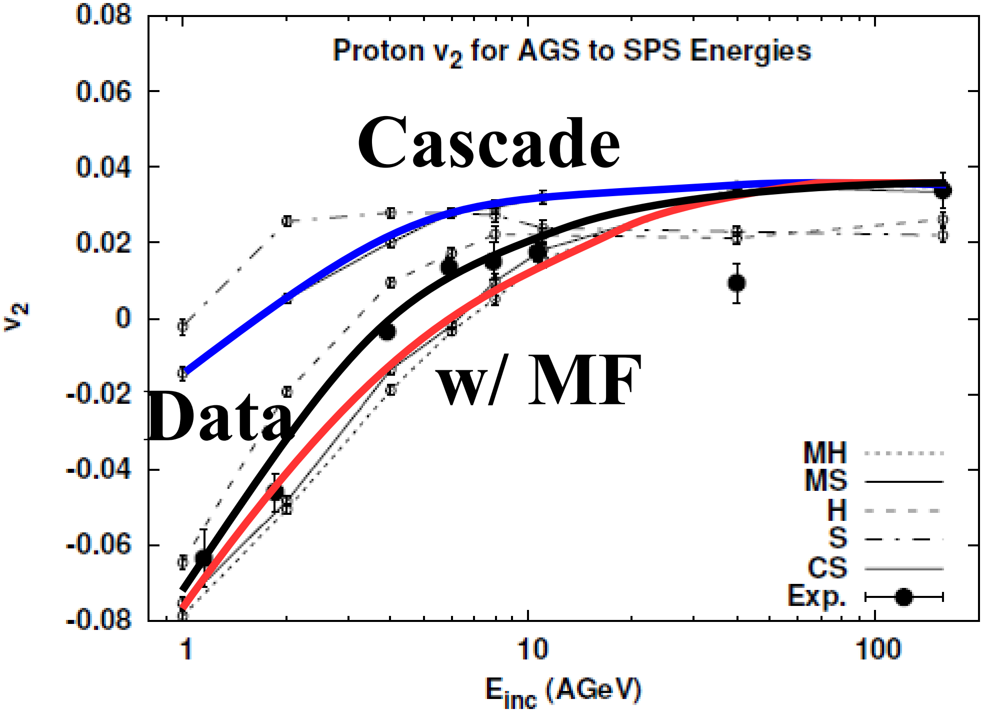
$$v_2 = \langle \cos 2\phi \rangle$$

Can we understand the flows in JAM (+MF) ?

Hadron-String Cascade with Mean Field Potential

- **Hadron-String Cascade + Mean Field (JAM-MF)**
  - **Data are in theoretical (MF) uncertainties.**
    → There is no bulk QGP formation at E/A < 160 GeV
    ($\sqrt{s_{NN}} < 20$ GeV)





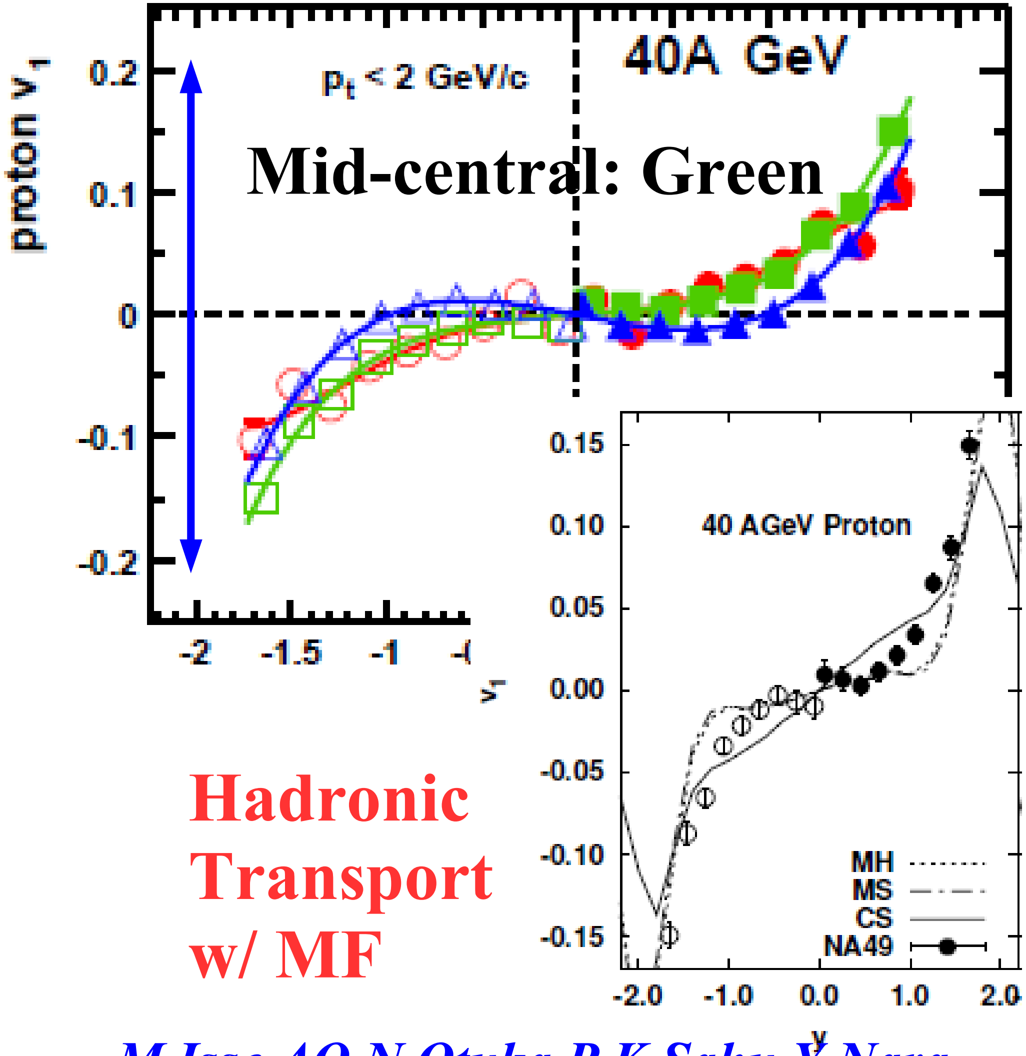
Isse, AO, Otuka, Sahu, Nara, PRC72('05)064908

No QCD phase transition below E/A=160 GeV !

SPS(NA49) vs RHIC(STAR)

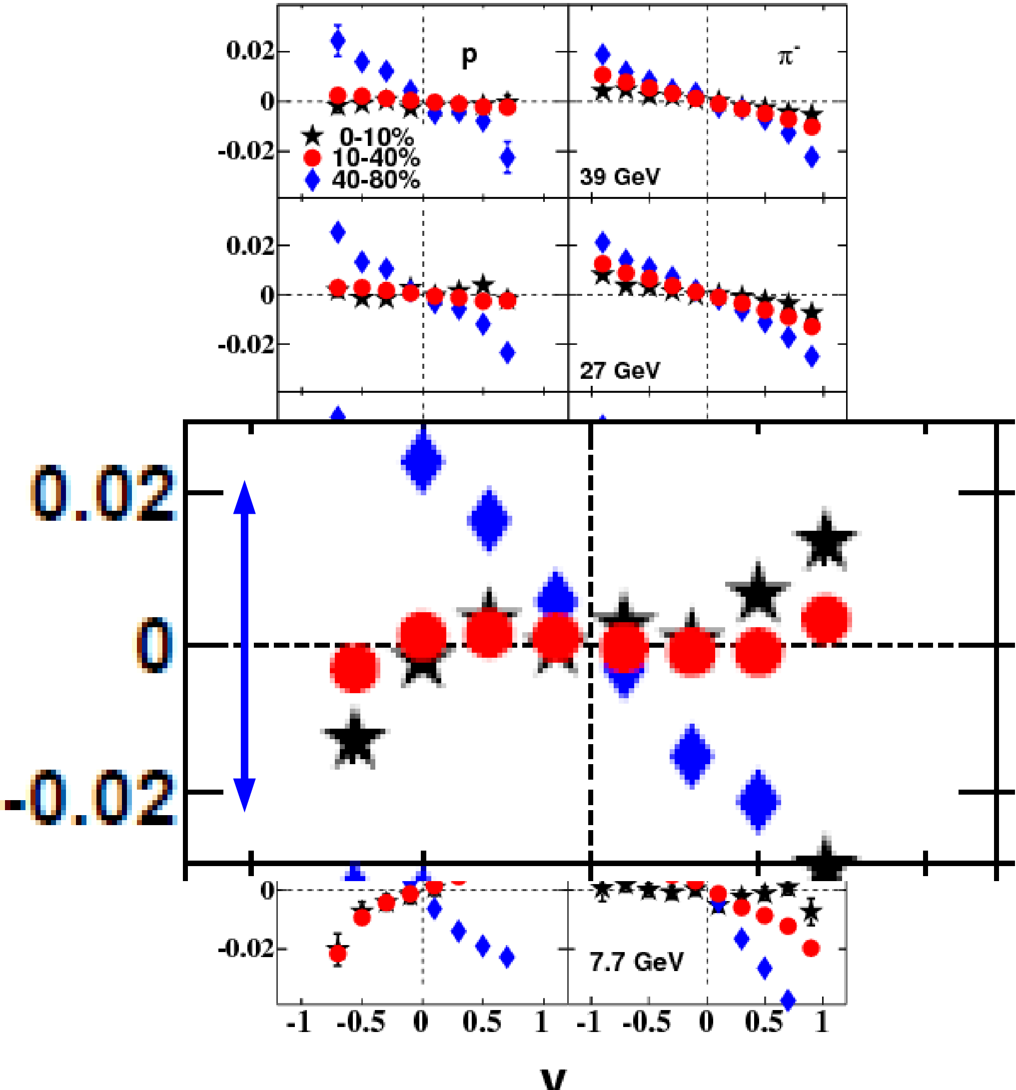
- **SPS (NA49), $\sqrt{s_{NN}} = 8.9$ GeV**
- **RHIC(STAR), 7.7-39 GeV**

C. Alt et al. (NA49), PRC68 ('03) 034903



Hadronic Transport w/ MF

M.Isse,AO,N.Otuka,P.K.Sahu,Y.Nara, PRC72 ('05)064908

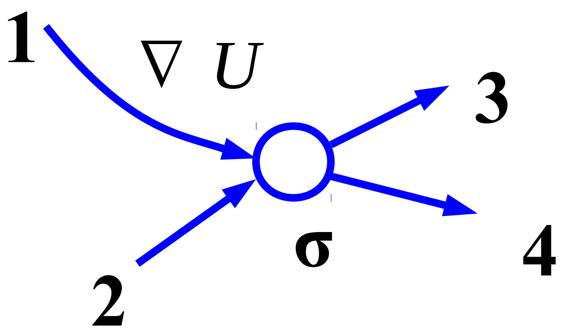


L. Adamczyk et al. (STAR), PRL 112(2014)162301

Transport model w/ EOS softening

- **Transport model (Boltzmann+MF)**

  E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190



$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla U \cdot \nabla_p f = I_{\mathrm{coll}}$$

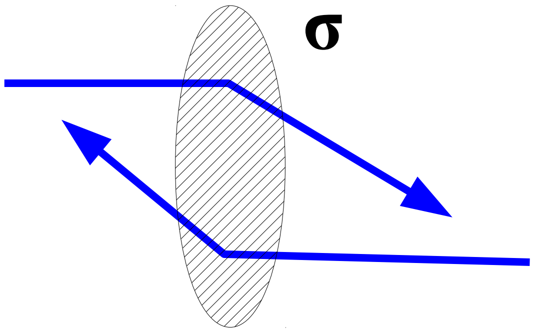
$$I_{\mathrm{coll}}(\mathbf{r},\mathbf{p}) = -\frac{1}{2}\int \frac{d\mathbf{p}_2}{(2\pi)^3} d\Omega\ v_{12}\ \frac{d\sigma}{d\Omega}\ [f f_2(1-f_3)(1-f_4)) - (12 \leftrightarrow 34)]$$

- **Simulating EOS softening in the collision term**

  Danielewicz, Pratt ('96); Sorge ('99); Nara, Niemi, AO, Stoecker ('16)

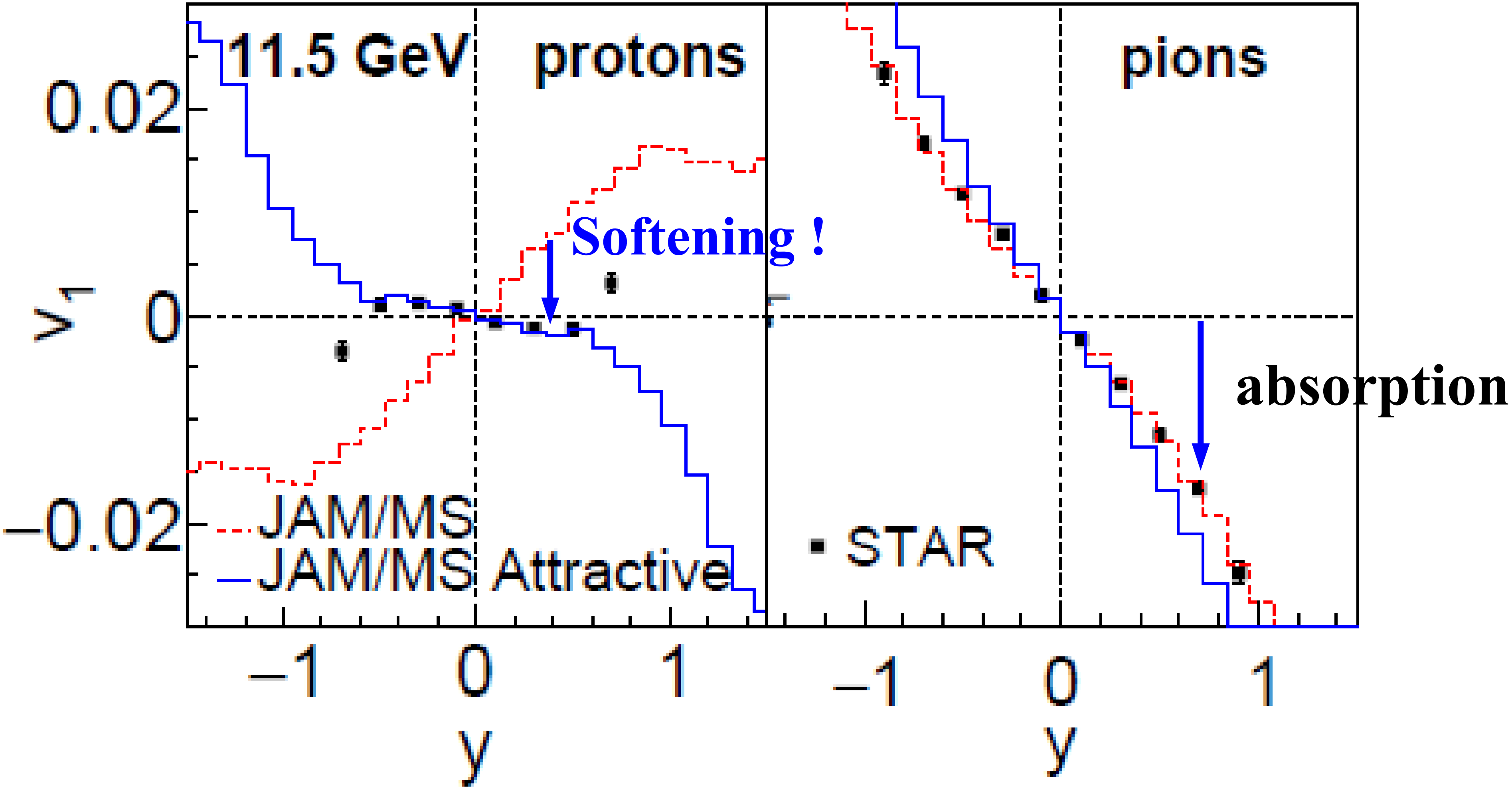
  - **Attractive orbit scattering can simulate EOS softening (Virial theorem)**

$$P = P_f + \frac{1}{3V\Delta t}\sum_{(i,j)} \boldsymbol{q}_{ij}\cdot(\boldsymbol{r}_i - \boldsymbol{r}_j)$$



Mean Field + Attractive Orbit

Nara, Niemi, AO, Stöcker ('16)

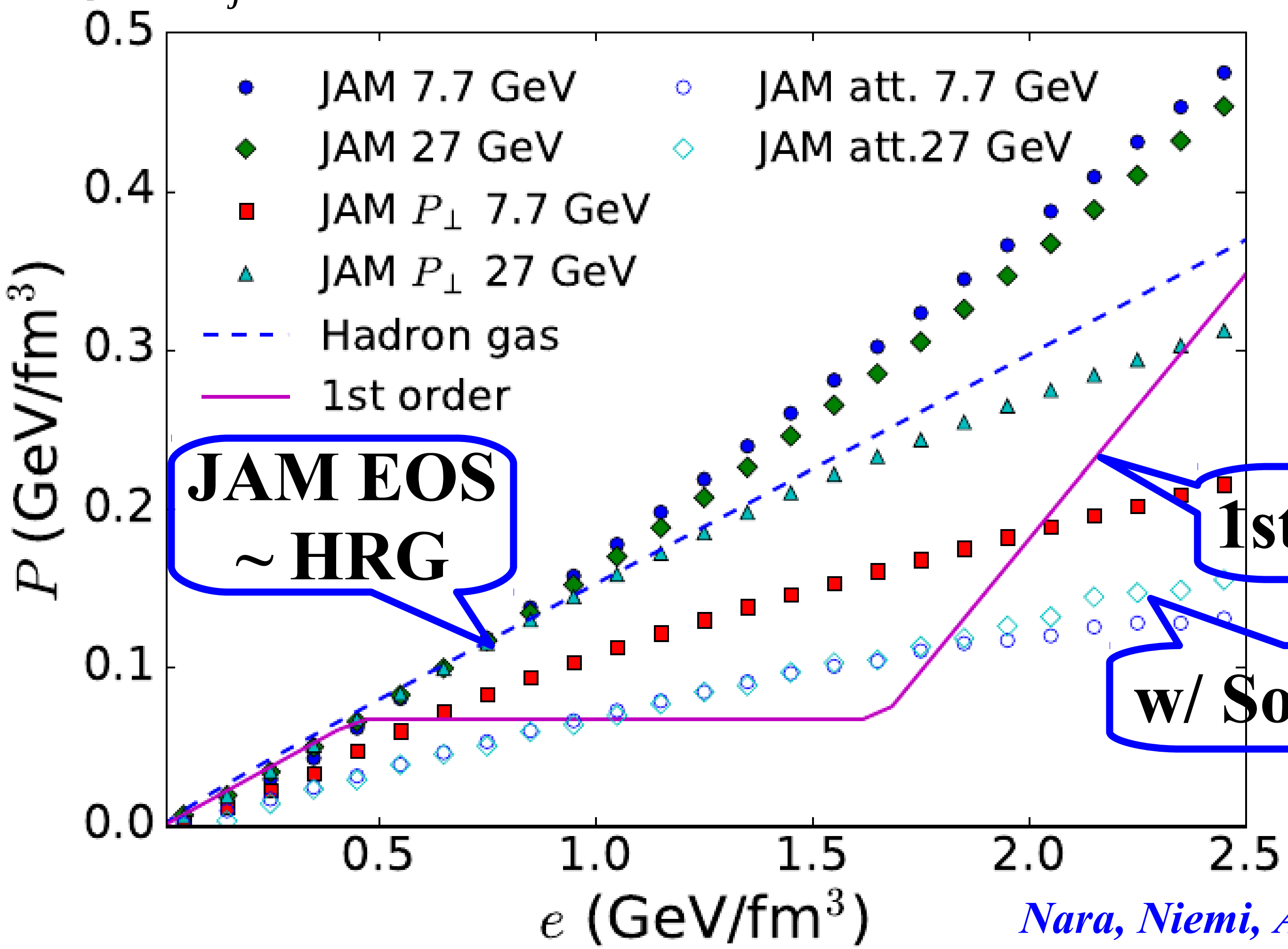


MF+Attractive Orbit make dv_1/dy negative at $\sqrt{s_{NN}}$ ~ 10 GeV

Softening of EOS by Attractive Orbits

$$\Delta P = -\frac{\rho}{3(\delta\tau_i + \delta\tau_j)}(p_i' - p_i)^{\mu}(x_i - x_j)_{\mu}$$

H. Sorge, PRL82('99)2048.



JAM EOS ~ HRG

1st order p.t.

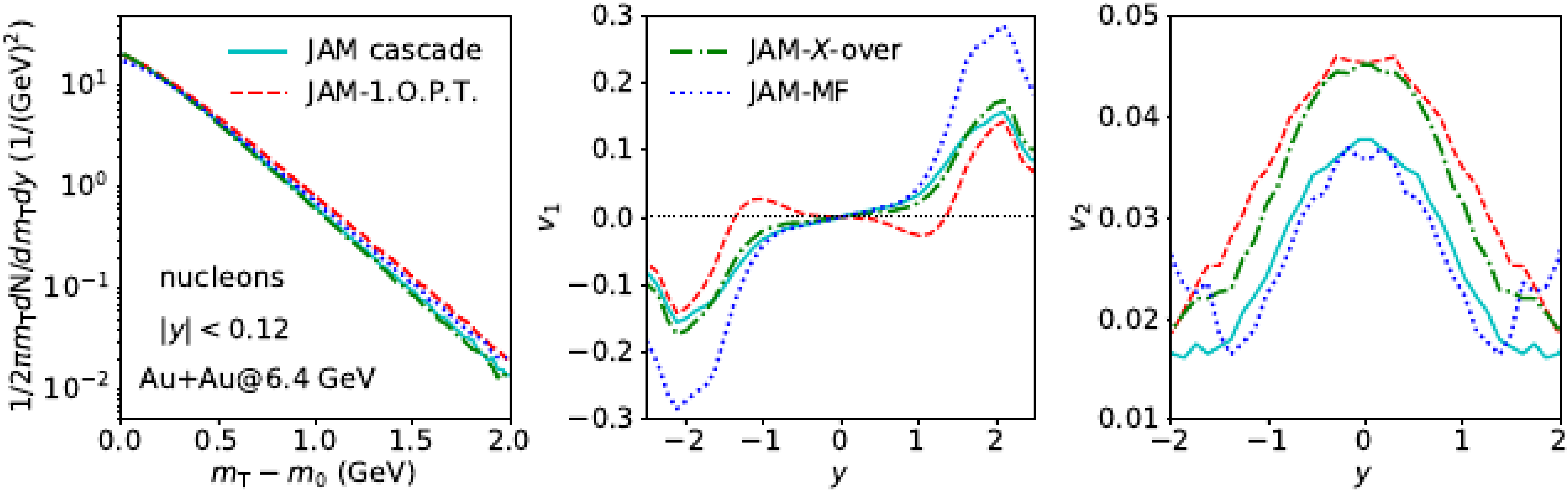
w/ Softening

Nara, Niemi, AO, Stöcker ('16)

Pressure in simulated EOS ~ EOS-Q (e.g. Song, Heinz ('08))

Can we distinguish Crossover and 1st order ?

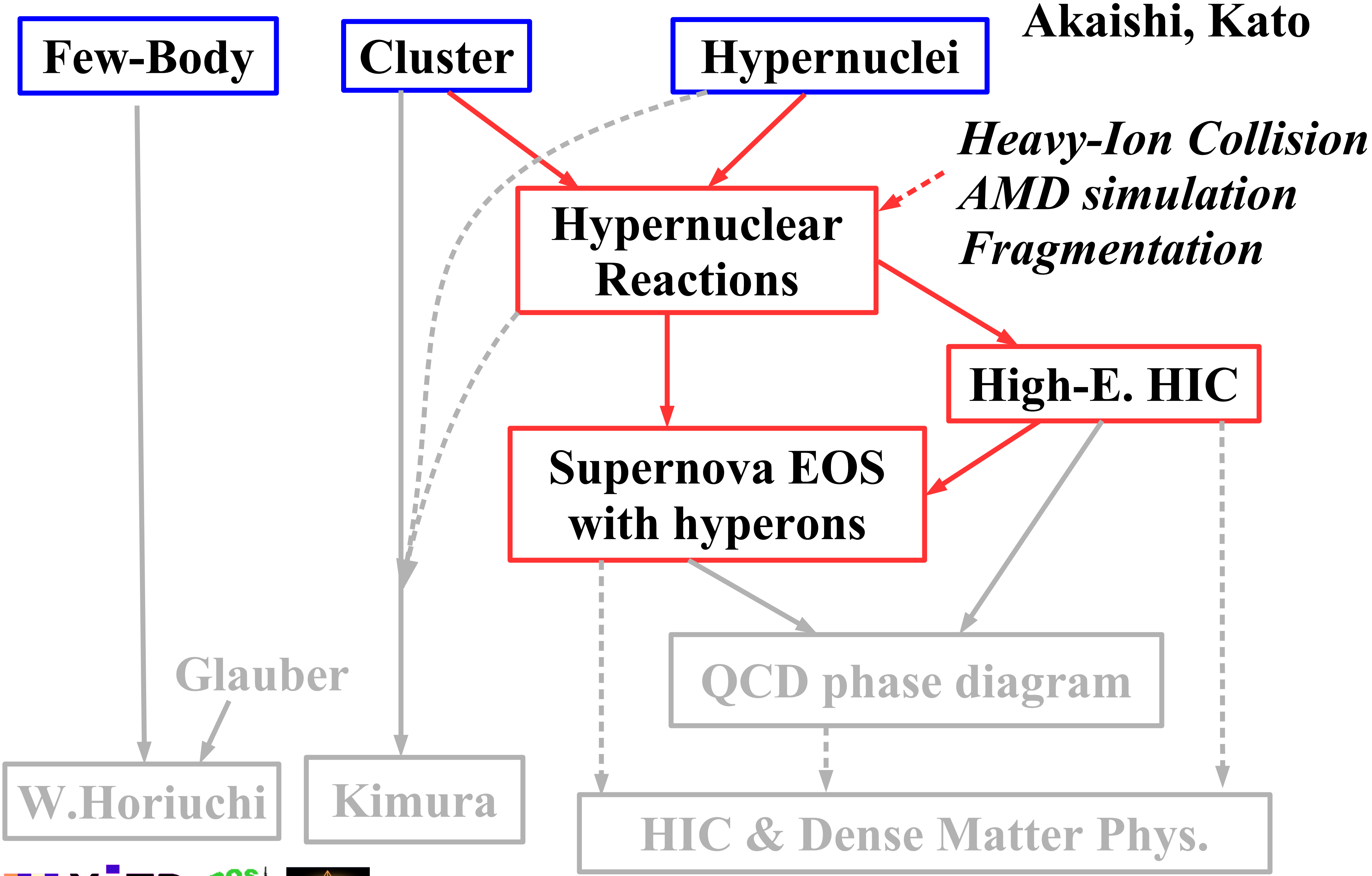
- **First ord.:** $T_{eff}\uparrow$, $dv_1/dy < 0$, $v_2\uparrow$
- **Crossover:** $T_{eff}\rightarrow$, $dv_1/dy > 0$, $v_2\uparrow$
- **Hadronic:** $T_{eff}\uparrow$, $dv_1/dy > 0$, $v_2\rightarrow$



Nara, Niemi, AO, Steinheimer, Luo, Stoecker, EPJA, in press; arXiv:1708.05617

Dense Matter Physics

My Research Subjects in Hokkaido University



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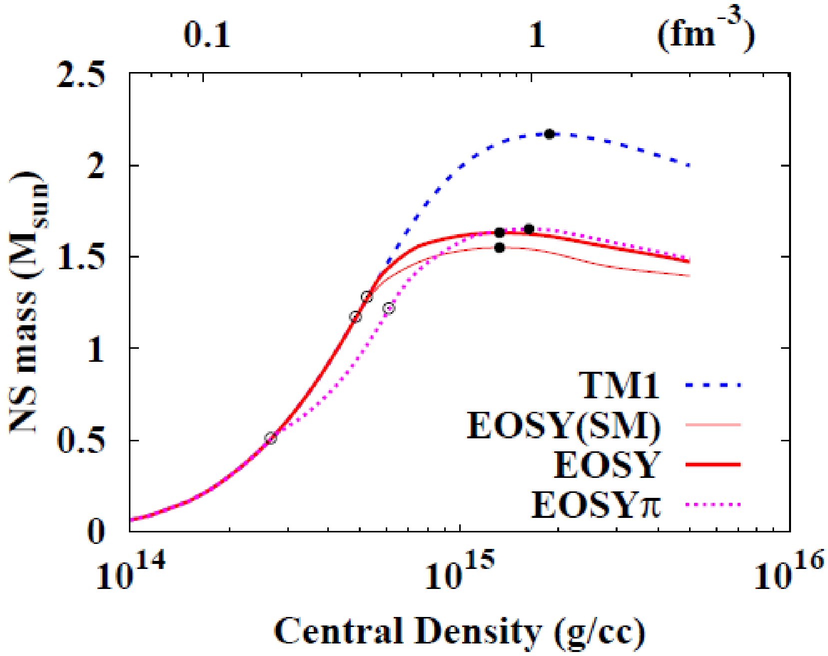
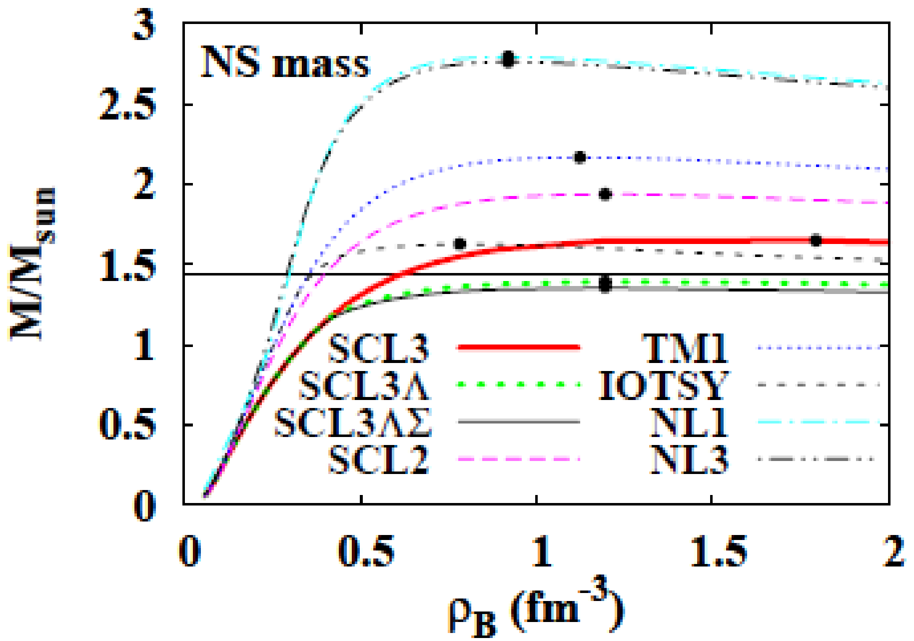
Kimura

HIC & Dense Matter Phys.

Supernova Matter EOS w/ Strangeness

- **A conclusion of hypernuclear physics**
  = Hyperon should appear in Neutron Star Matter at (2-4) ρ_0
- **Let's try to make hyperonic matter EOS for Supernovae**
  - **Need EOS in 3D (T, ρ_B, Ye) in a wide range.**
    $0 < T < 150$ MeV, $10^{11} < \rho_B < 10^{15}$ g/cc
  - **Hyperon potentials; U_Λ=-30 MeV, U_Σ=+30 MeV, U_Ξ=-15 MeV**

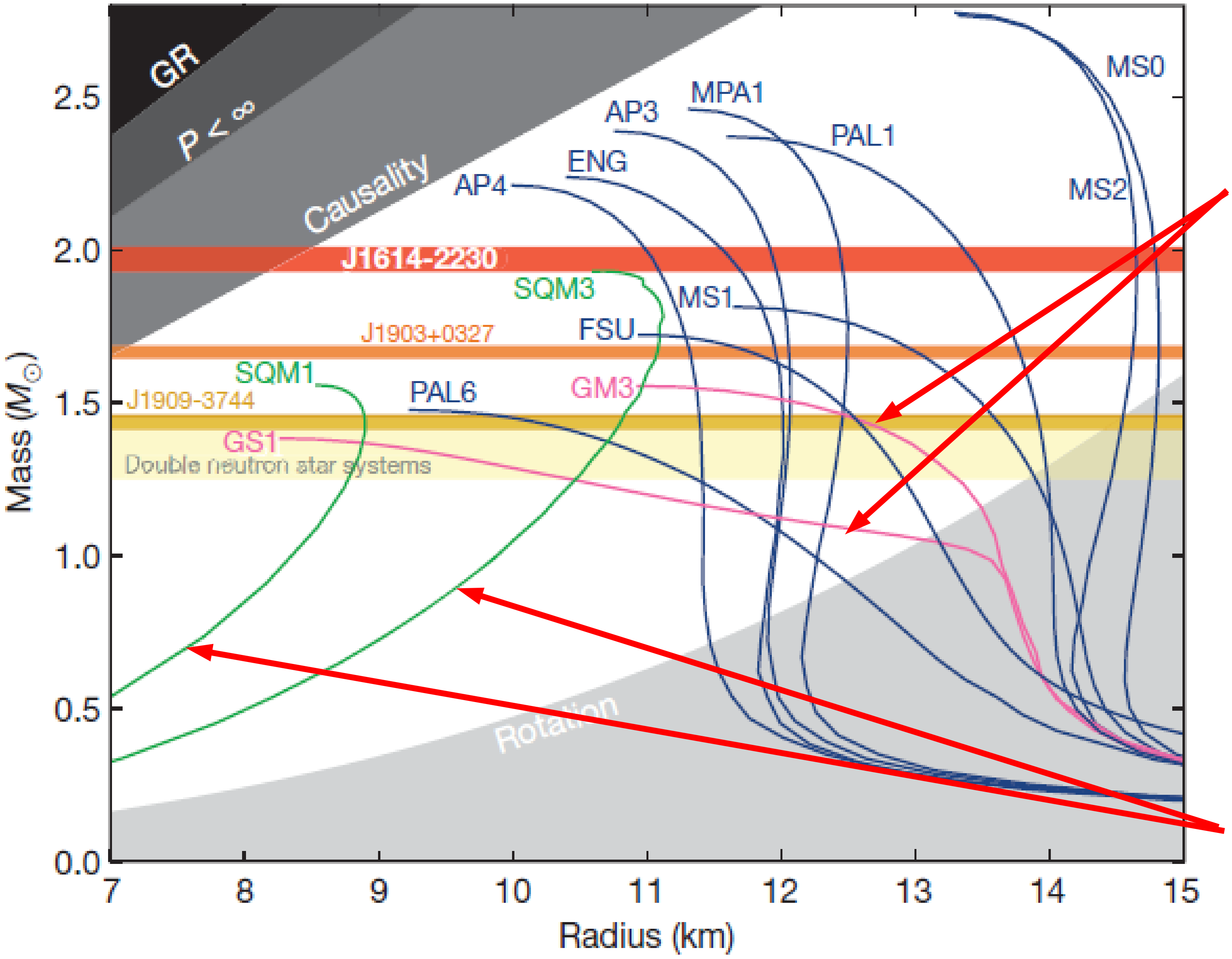




Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada ('08)

Hyperon Puzzle

Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



EOS with hyperons or Kaons

Quark matter EOS

Hyperon Puzzle

- **When we include hyperons with potentials consistent with data, EOS cannot support 2 $M_\odot$ neutron stars.**
- **Proposed solutions: 3-body force, quark matter, modified gravity**
- **Three-Body Force including hyperons**
  - **Universal Three-Body Repulsion (NNN, YNN, ….)**
    Takatsuka, Nishizaki ('17), Yamamoto, Furumoto, Yasutake, Rijken ('17)
  - **Pauli blocking in 2π attraction via Σ exch. (chiral EFT)**
    Kohno ('17), Petschauer, Haidenbauer, Meissner, Kaiser, Weise ('16)
  - **Quark cluster model 3BF**
    Nakamoto, Suzuki ('16), AO, Kashiwa, Morita ('17)
  - **RMF with multi-body coupling (no hyperons)**
    S. Typel et al. ('99), Steiner et al. ('13)

Relativistic Mean Field with Multi-body couplings

- **σωρ model +std. non-linear terms + multi-body couplings**

$$
\begin{aligned}
\mathcal{L} &= \bar{\psi}(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu)\psi + \mathcal{L}_{\sigma\omega\rho} ,\\
\mathcal{L}_{\sigma\omega\rho} &= \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho} ,\\
U_s &= -g_\sigma\sigma\left[1\boxed{-r_{\sigma\sigma}\sigma/f_\pi]}\right. + \boxed{g_\sigma\omega^\mu\omega_\mu\left[r_{\omega\omega} - r_{\sigma\omega\omega}\sigma/f_\pi)\right]} ,\\
U_\mu &= g_\omega\omega_\mu\left[1\boxed{-r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2]}\right.\\
&\quad + g_\rho\tau\cdot R_\mu\left[1\boxed{-r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2]}\right. ,\\
\mathcal{V}_{\sigma\omega\rho} &= \frac{1}{2}m_\sigma^2\sigma^2\boxed{-a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\sigma^4 + \frac{1}{3}c_{\sigma 3}f_\pi\sigma^3}\\
&\quad - \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\left[1\boxed{-c_{\sigma\omega}\sigma/f_\pi]}\right.\boxed{-\frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2}\\
&\quad - \frac{1}{2}m_\rho^2 R^\mu\cdot R_\mu\left[1\boxed{-c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2]}\right.\boxed{-\frac{1}{4}c_{\rho 4}(R^\mu\cdot R_\mu)^2} ,
\end{aligned}
$$

Scalar polarizability (A. Thomas)

ω^2 scalar (Typel)

DD coupling (Ring)

ρ^4 term

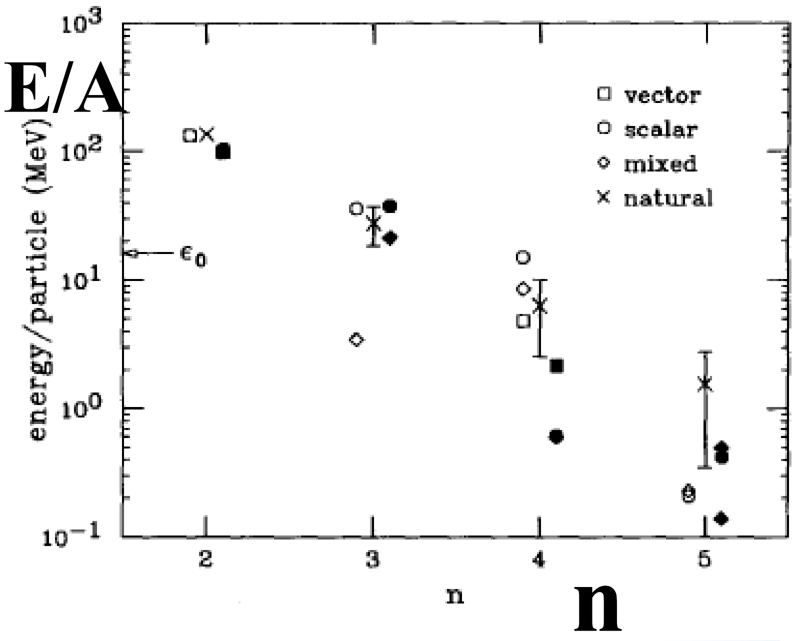
DD meson mass (e.g. Steiner, Fischer, Hempel)

Relativistic Mean Field with Multi-body couplings

- **Phen. Approach: RMF w/ Multi-body coupling**
  - **Naive dimensional analysis (NDA) and naturalness**
    Manohar, Georgi ('84)
    The vertex is called "natural" if C ~ 1 (consistent with pQCD).

$$L_{\mathrm{int}} \sim (f_\pi \Lambda)^2 \sum_{l,m,n,p} \frac{C_{lmnp}}{m!\,n!\,p!} \left(\frac{\bar{\psi} \Gamma \psi}{f_\pi^2 \Lambda}\right)^l \left(\frac{\sigma}{f_\pi}\right)^m \left(\frac{\omega}{f_\pi}\right)^n \left(\frac{R}{f_\pi}\right)^p$$

  - **FST truncation**
    R. J. Furnstahl, B. D. Serot, H. B. Tang, NPA615 ('97)441.
    Truncation the index
    n = B/2 + M + D
    (B: baryon, M: Non NG boson, D: derivatives)
    Natural → V ~ $\rho^n/n!$
    → small for large n

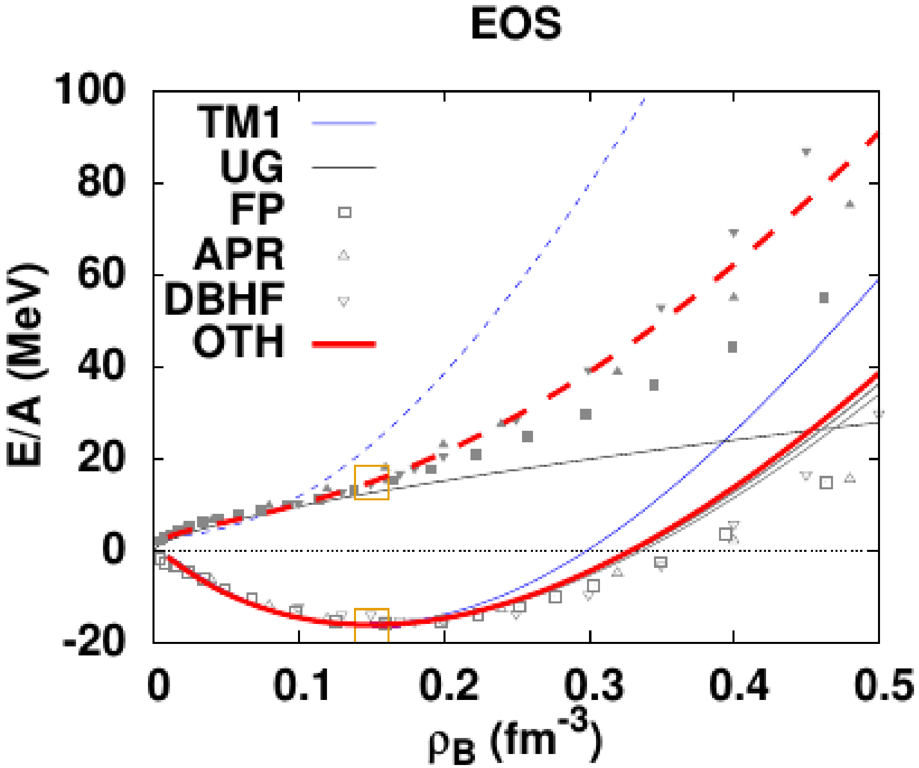


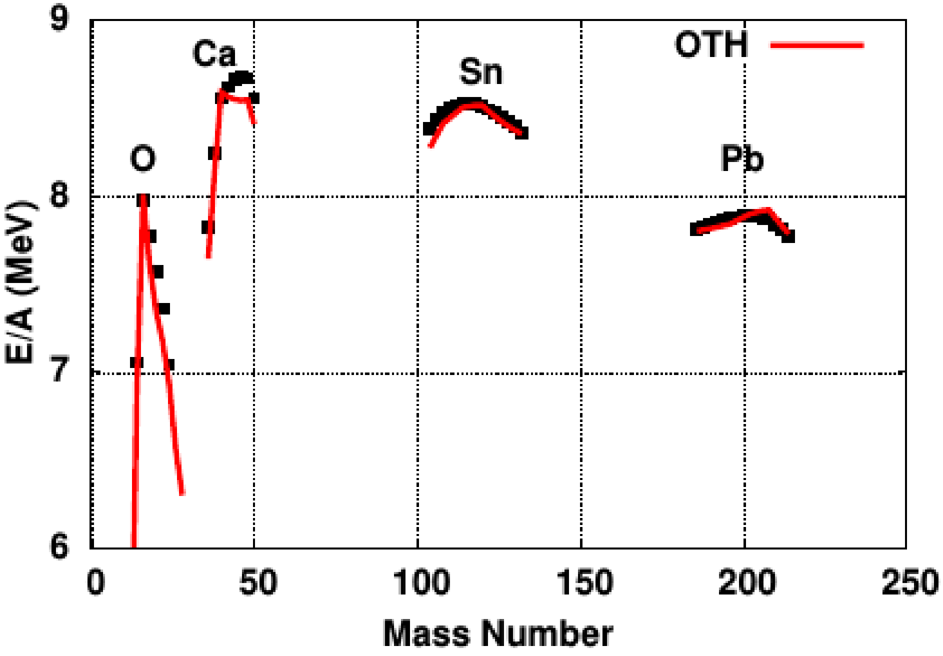
Simultaneous Fit to EOS and Finite Nuclei

- **Fitting procedure**

  = Fit finite nuclear binding energies and charge rms radius under the constraint of given (ρ_0, E_0, K, S_0, L).

EOS



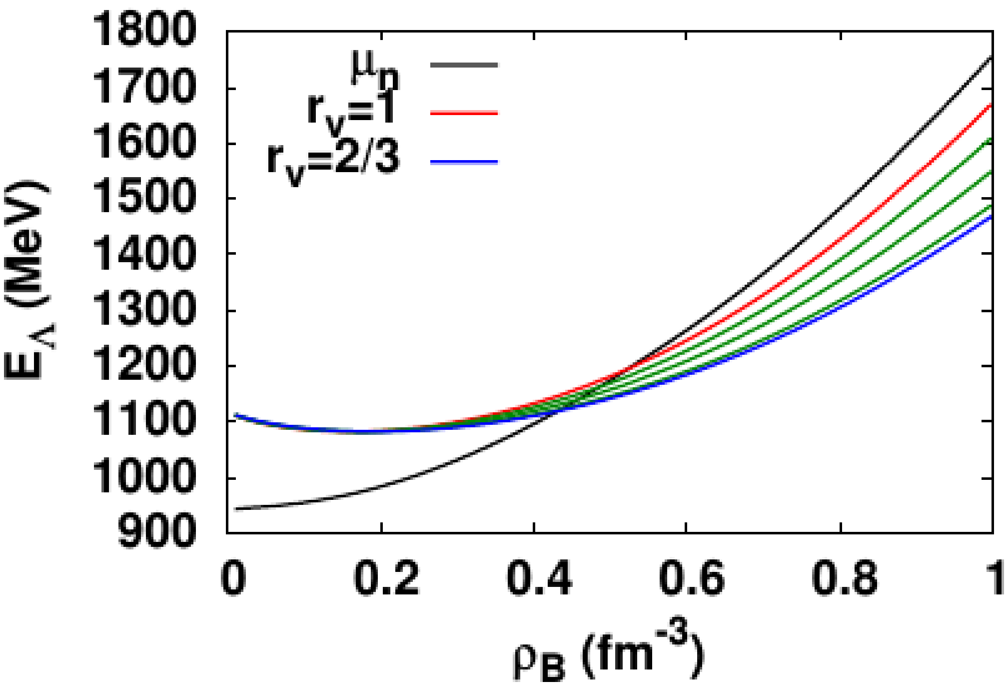


(S_0, L, K)=(31 MeV, 50 MeV, 240 MeV)

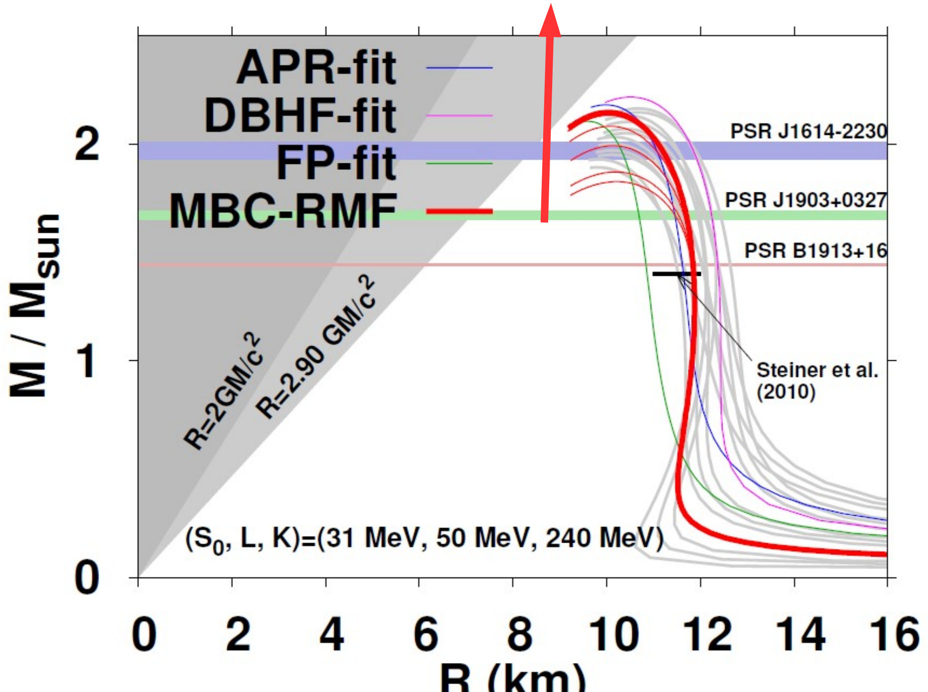
AO, Tsub=akihara, Harada (in prep.)

Hypernuclei and Neutron Star MR

- **$R_v = g_{\omega\Lambda}/g_{\omega N} = 2/3\text{-}1$ is chosen, and $g_{\sigma\Lambda}/g_{\sigma N}$ is fitted to data.**
  (Other parameters are assumed to be the same.)
  → Λ emerges at $\rho = 0.4\text{-}0.5\ \mathrm{fm}^{-3}$
  2 $M_{\square}$ neutron stars may be supported with Rv>0.8
  (Depends on nuclear matter EOS)



Rv=2/3→1

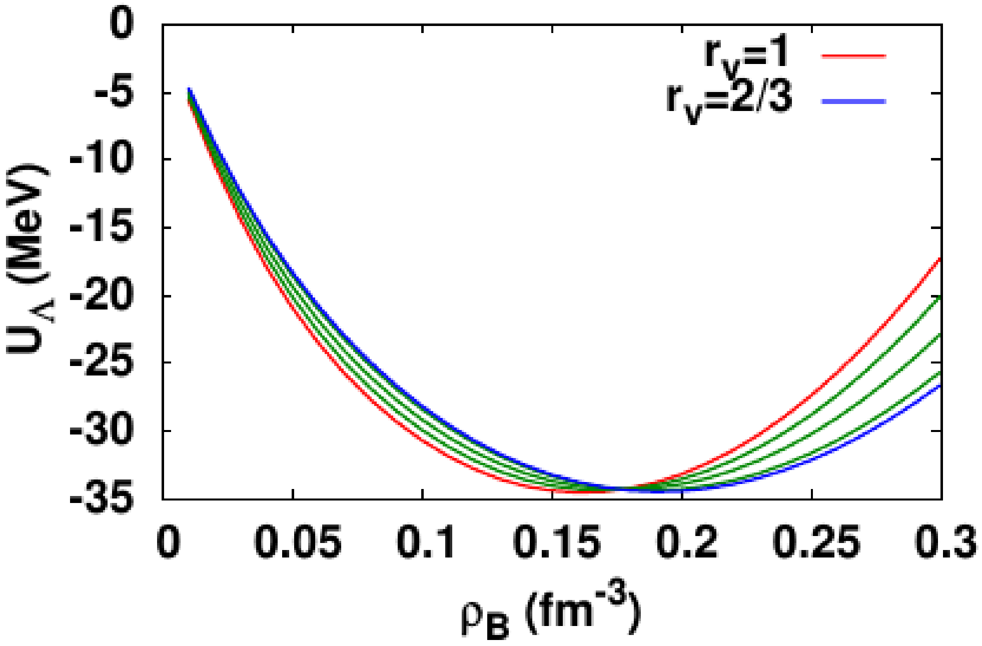


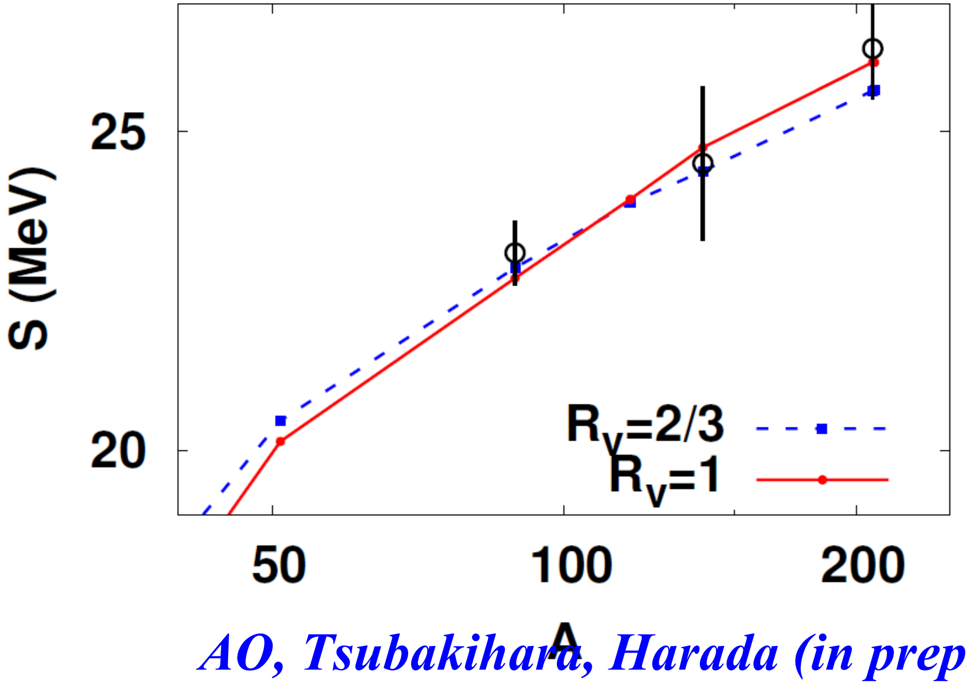
AO, Tsubakihara, Harada (in prep.)

Can we distinguish ?

- Density dependence of U_Λ
  - $dU_\Lambda/d\rho$ turns to be positive at around ρ_0
    Kohno ('17), Petschauer, Haidenbauer, Meissner, Kaiser, Weise ('16)
  - Rv=2/3 and 1 leads to the difference of S_Λ of a few 100 keV

→ sub MeV hypernuclear spectroscopy is necessary
Isaka, Yamamoto, Rijken('17); Yamamoto, Furumoto, Yasutake, Rijken('17)





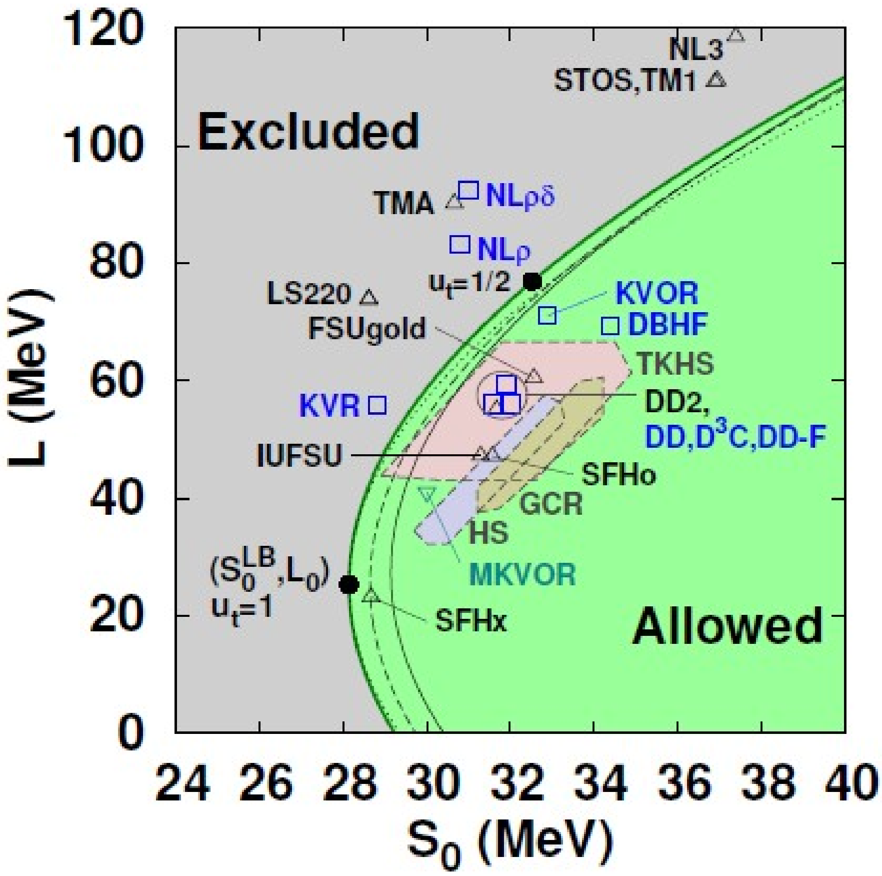
AO, Tsubakihara, Harada (in prep.)

Summary

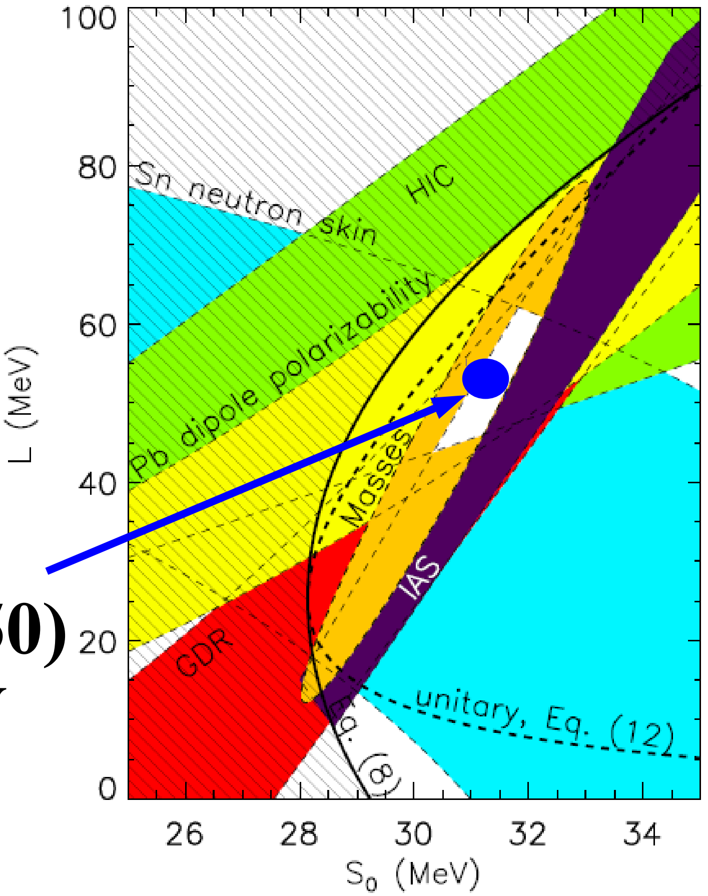
- **We may have seen QCD phase transition (1^{st} or 2^{nd}) signals at BES (or J-PARC) energies in baryon number cumulants and v_1 slope. The transport model (JAM) is utilized to elucidate the EOS softening.**
- **In order to solve the hyperon puzzle based on data, we need models which describes normal nuclei, hypernuclei, and nuclear matter in a consistent manner. RMF with multi-body coupling may be a handy framework. Turn over density ($dU_\Lambda/d\rho = 0$) is found to be around ρ_0 , then massive NS may be supported even with hyperons.**
- **I enjoyed the time in Hokkaido University.**
  Prof. Kato allowed me to work independently,
  and the high activity in Hokkaido U. required us to make works with originality and ambition.

Kato-san, Congratulations for your age Seventy, and thank you very much for your encouragements !

Symmetry Energy Constraints



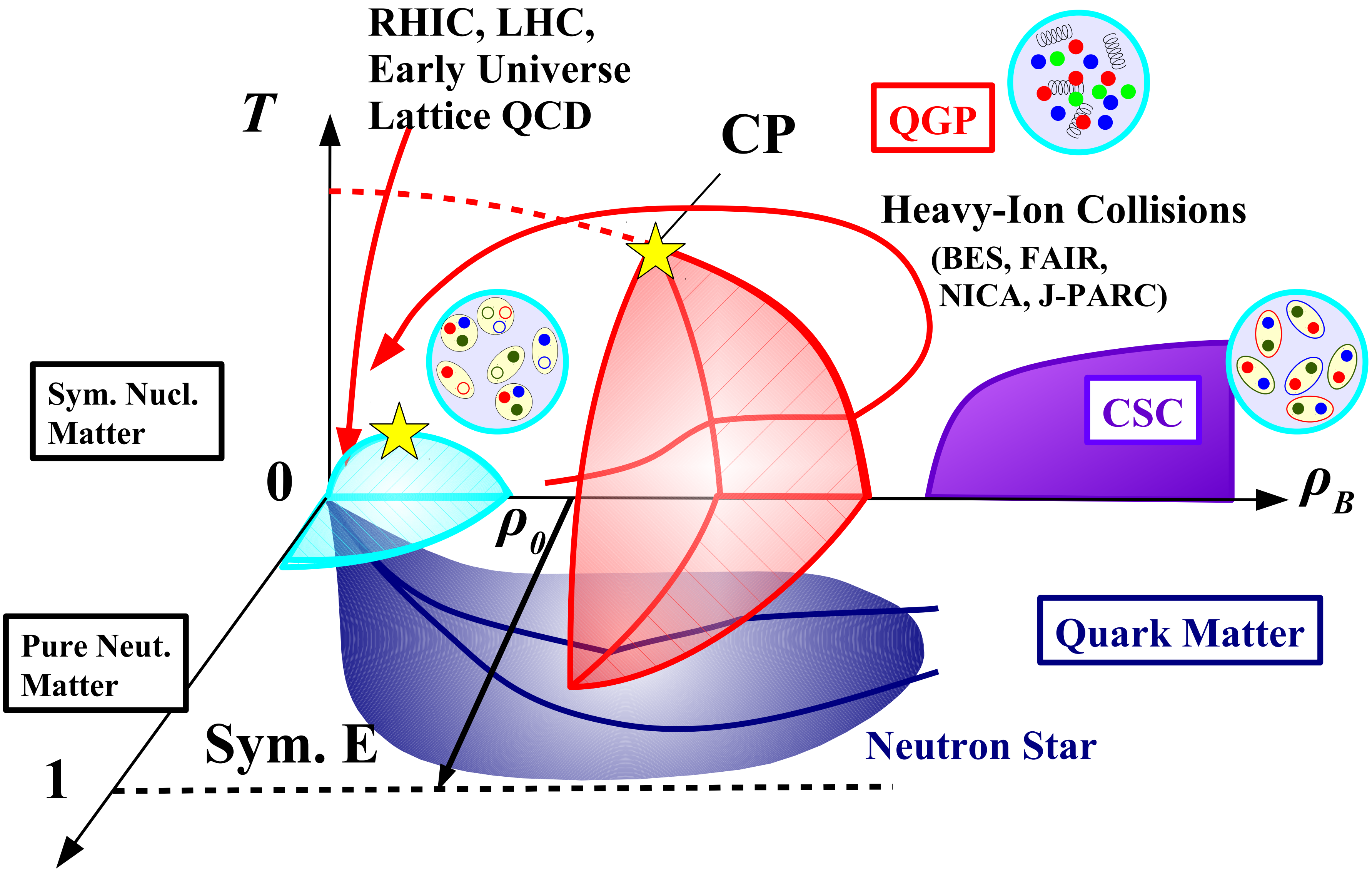
(31,50) MeV



Many of EOSs in active astrophysical use do not satisfy recent symmetry energy constraint or 2 $M_\odot$ constraint.
→ SFHo, SHFx, DD2

Tews, Lattimer, AO, Kolomeitsev ('17)

QCD Phase Diagram



RHIC, LHC,
Early Universe
Lattice QCD

T

CP

QGP

Heavy-Ion Collisions
(BES, FAIR,
NICA, J-PARC)

Sym. Nucl.
Matter

0

ρ_0

CSC

ρ_B

Pure Neut.
Matter

Quark Matter

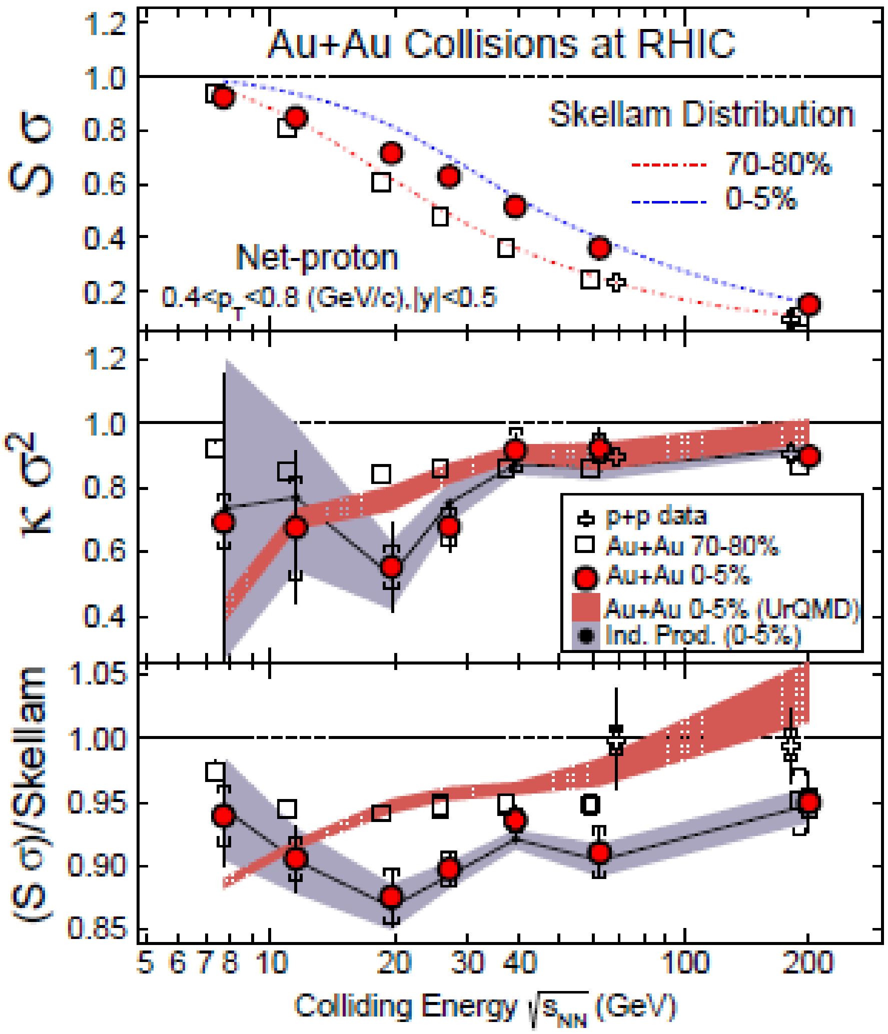
Sym. E

1

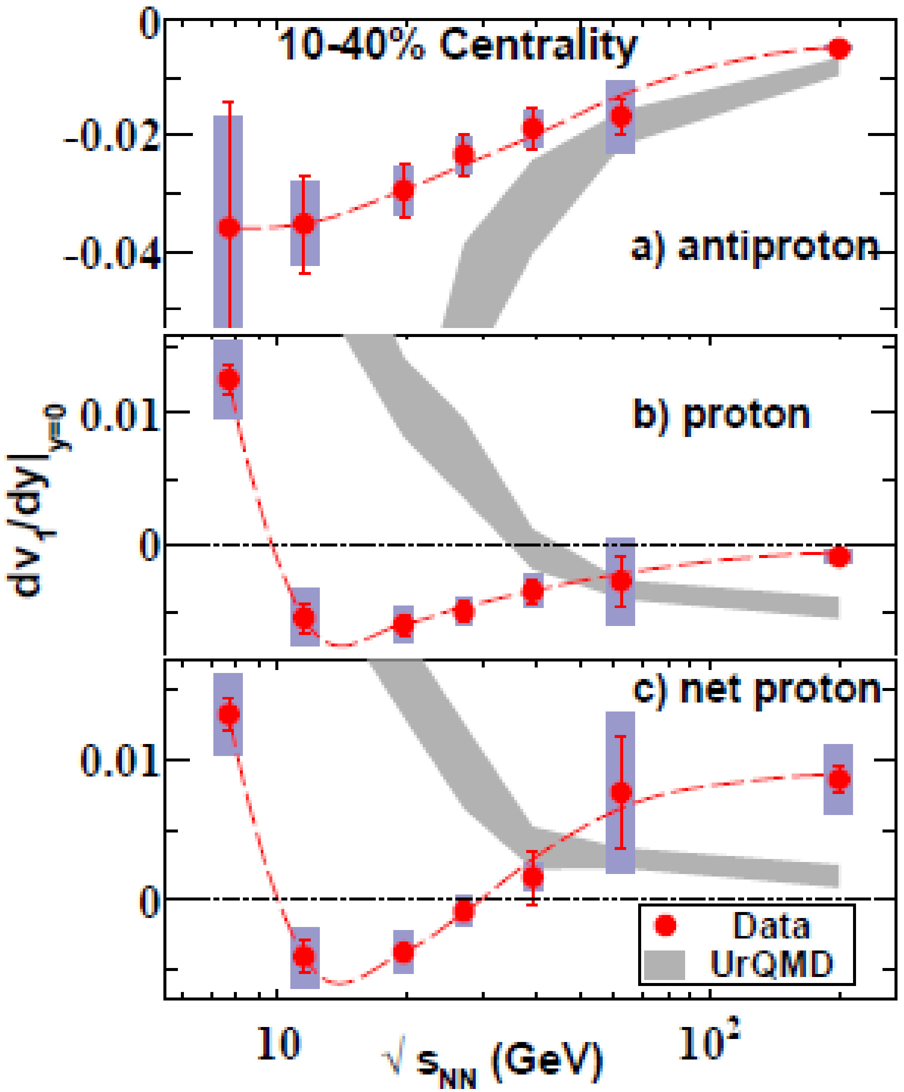
Neutron Star

δ=(N-Z)/A (or Y_Q(hadron)=Q_h/B~(1-δ)/2)

Net-Proton Number Cumulants & Directed Flow

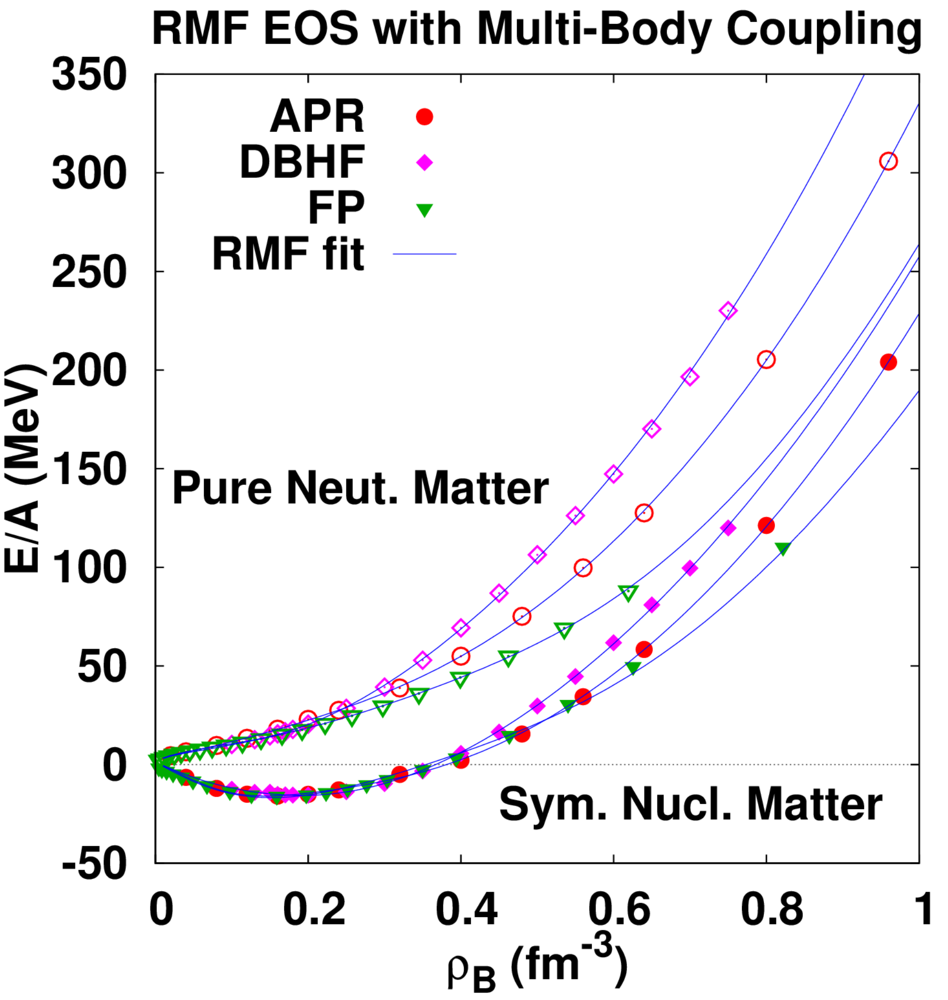


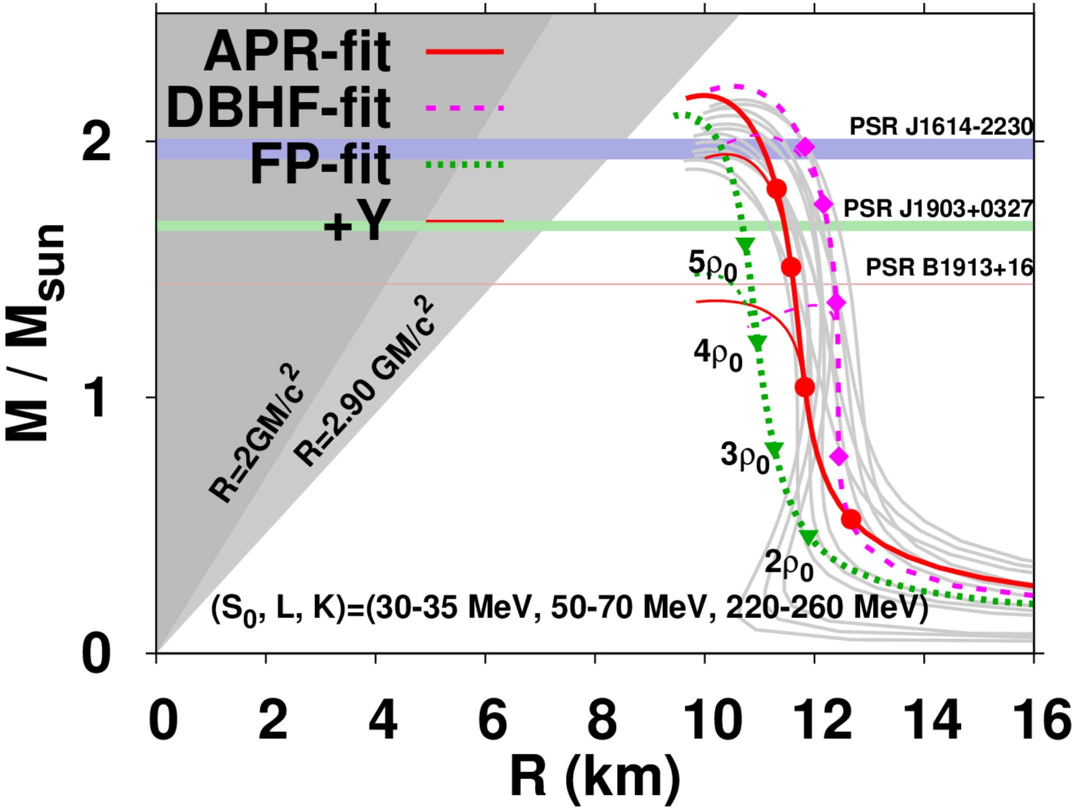
STAR Collab. PRL 112('14)032302



STAR Collab., PRL 112('14)162301.

Fitting "Ab initio" EOS via RMF

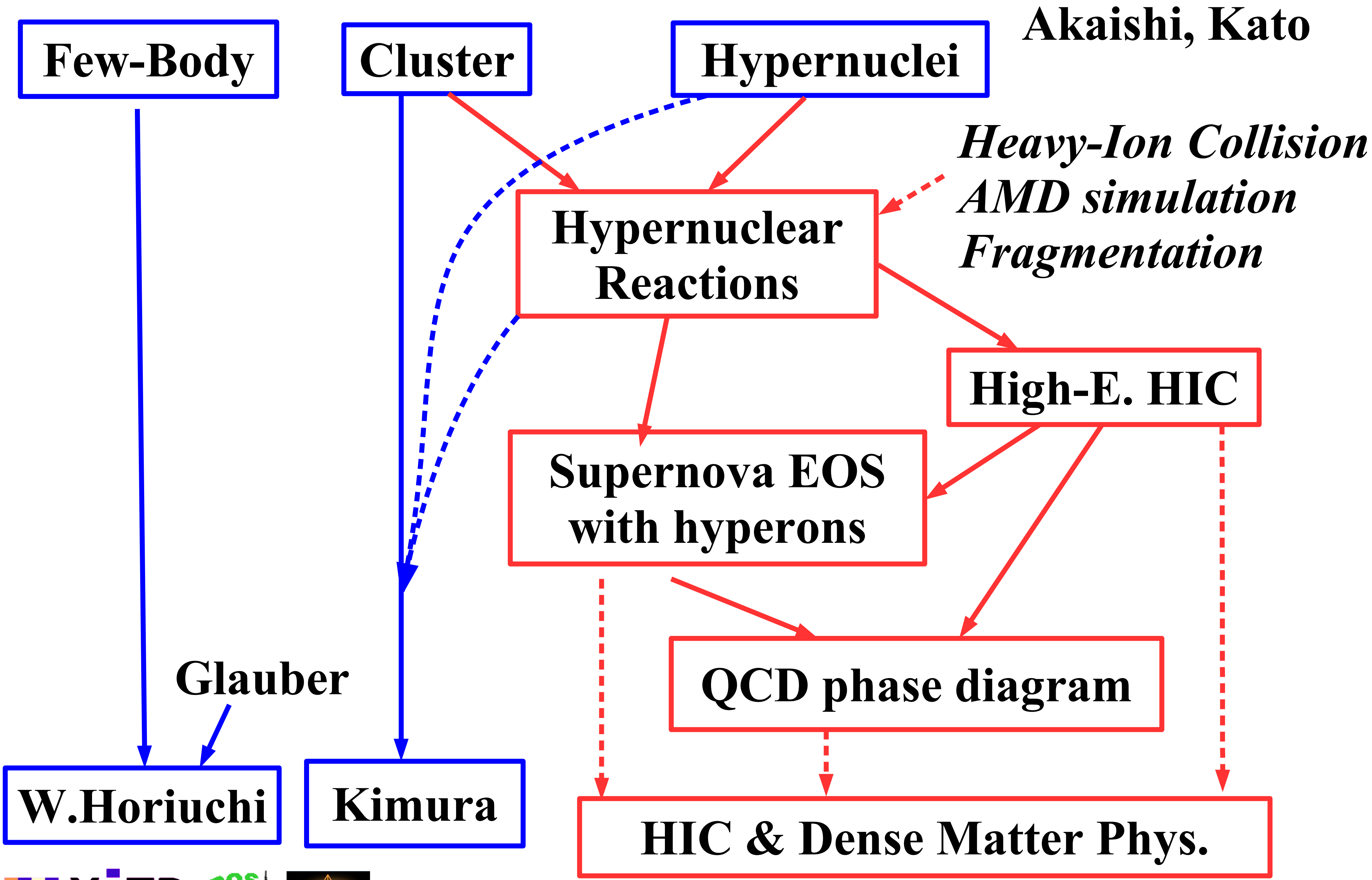

RMF EOS with Multi-Body Coupling



RMF fitting EOS does not necessarily describe finite nuclei….

AO, Tsubakihara, Harada ('16, NIC proc.)

My Research Subjects in Hokkaido University



Few-Body

Cluster

Hypernuclei

Akaishi, Kato

Heavy-Ion Collision
AMD simulation
Fragmentation

Hypernuclear Reactions

High-E. HIC

Supernova EOS with hyperons

QCD phase diagram

Glauber

W.Horiuchi

Kimura

HIC & Dense Matter Phys.

Virial Theorem

- **Virial**

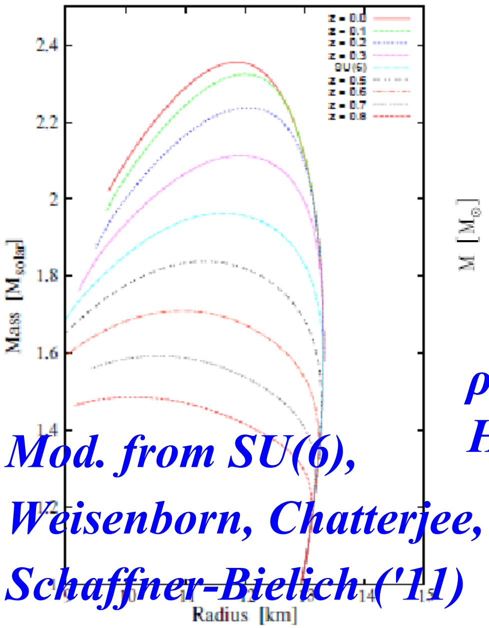
$$G = \sum_i \mathbf{p}_i \cdot \mathbf{r}_i$$

$$\to \frac{dG}{dt} = \sum_i \mathbf{p}_i \cdot \mathbf{v}_i - \sum_i \nabla_i U \cdot \mathbf{r}_i + \boxed{\frac{1}{\Delta t} \sum_{\text{collision}} \mathbf{q}_i \cdot (\mathbf{r}_i - \mathbf{r}_j)} = 3VP$$

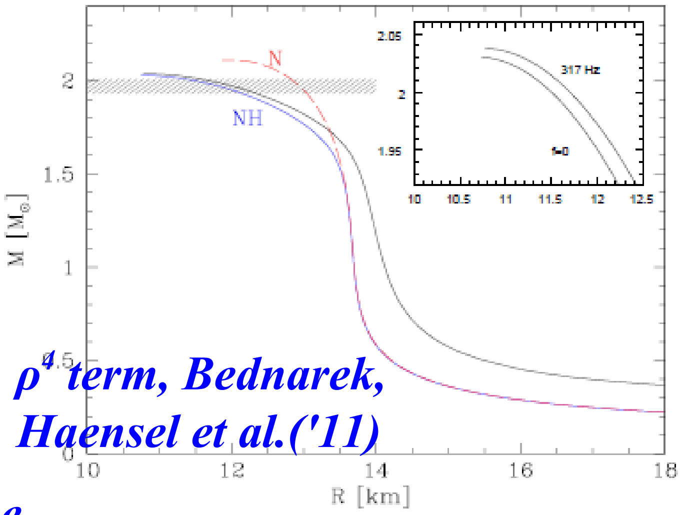
Kinetic **Potential** **Pressure from Collisions**

- **Attractive / Repulsive Orbit Scatterings**
  - **Random choice of scatt. angle → No effect on pressure**
  - **Attractive orbits → ΔP < 0 (softening)**
  - **Repulsive orbits → ΔP > 0 (hardening)**
- **Boltzmann Eq. simulating a given EOS**
  P > P(ε) → Attractive orbit, P > P(ε) → Repulsive orbit
  If collisions are frequent enough, we can simulate MF effects in Boltzmann equation.

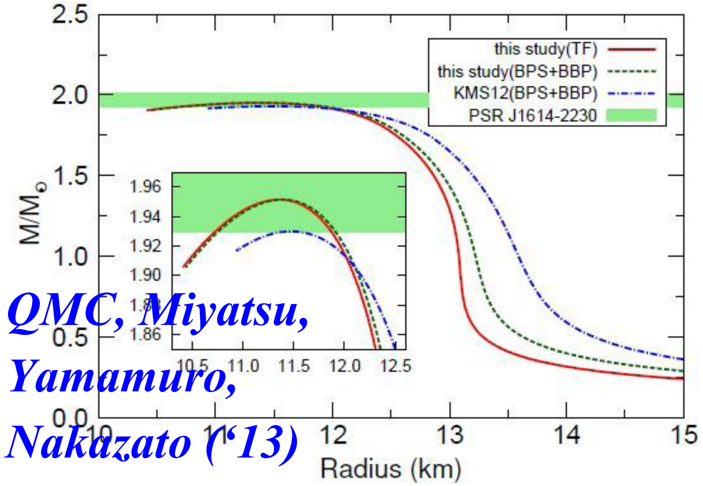
Massive Neutron Stars with Hyperons



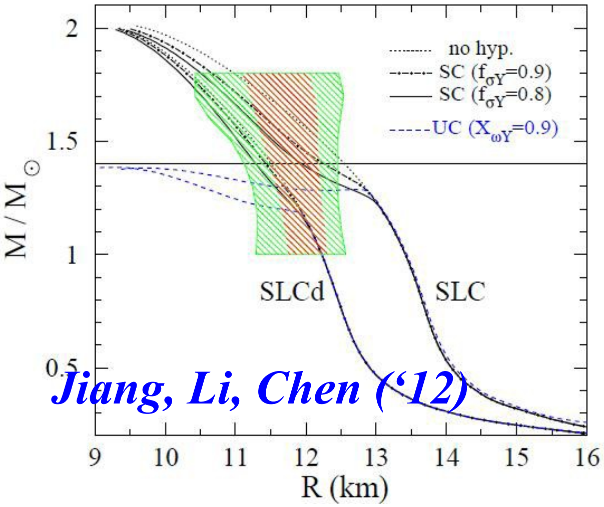
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



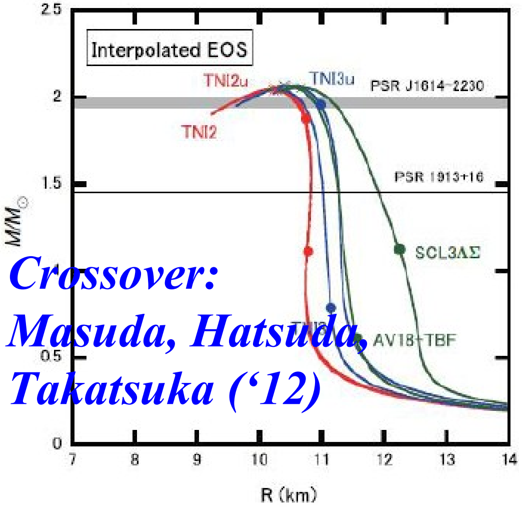
ρ^4 term, Bednarek, Haensel et al.('11)



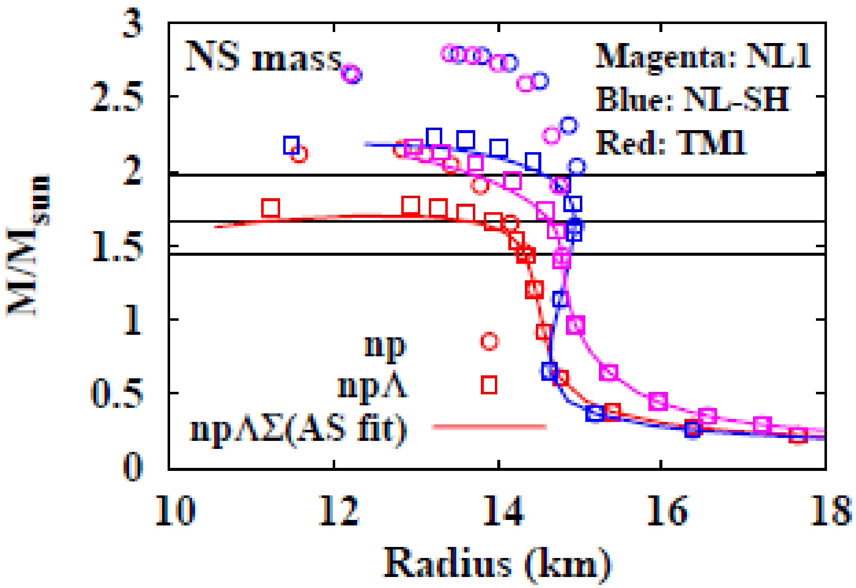
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



Crossover: Masuda, Hatsuda, Takatsuka ('12)



Tsubakihara, Harada, AO, arXiv:1402.0979

Relativistic Mean Field with Multi-body couplings

- **σωρ model** **+std. non-linear terms** **+ multi-body couplings**

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu)\psi + \mathcal{L}_{\sigma\omega\rho}\ , \\
\mathcal{L}_{\sigma\omega\rho} =& \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho}\ , \\
U_s =& -g_\sigma\sigma\,[1 \boxed{- r_{\sigma\sigma}\sigma/f_\pi]} + \boxed{g_\sigma\omega^\mu\omega_\mu\,[r_{\omega\omega} - r_{\sigma\omega\omega}\sigma/f_\pi)]}\ , \\
U_\mu =& g_\omega\omega_\mu\,[1 \boxed{- r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2]} \\
& + g_\rho\tau\cdot R_\mu\,[1 \boxed{- r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2]}\ , \\
\mathcal{V}_{\sigma\omega\rho} =& \frac{1}{2}m_\sigma^2\sigma^2 \boxed{- a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\sigma^4 + \frac{1}{3}c_{\sigma 3}f_\pi\sigma^3} \\
& - \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\,[1 \boxed{- c_{\sigma\omega}\sigma/f_\pi]} \boxed{- \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2} \\
& - \frac{1}{2}m_\rho^2 R^\mu\cdot R_\mu\,[1 \boxed{- c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2]} \boxed{- \frac{1}{4}c_{\rho 4}(R^\mu\cdot R_\mu)^2}\ ,
\end{aligned}
$$

Relativistic Mean Field with Multi-body couplings

- **σωρ model +std. non-linear terms + multi-body couplings**

Scalar polarizability (A. Thomas)

ω² scalar (Typel)

DD coupling (Ring)

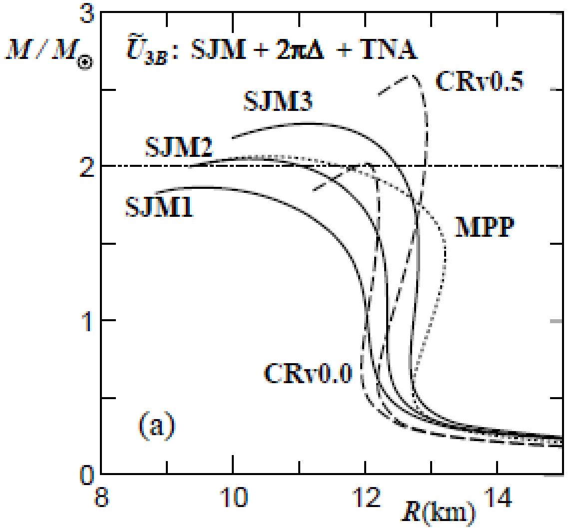
ρ⁴ term

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu)\psi + \mathcal{L}_{\sigma\omega\rho}\ , \\
\mathcal{L}_{\sigma\omega\rho} =& \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho}\ , \\
U_s =& -g_\sigma\sigma\left[1 \boxed{- r_{\sigma\sigma}\sigma/f_\pi]} + \boxed{g_\sigma\omega^\mu\omega_\mu\left[r_{\omega\omega} - r_{\sigma\omega\omega}\sigma/f_\pi)\right]}\right.\ , \\
U_\mu =& g_\omega\omega_\mu\left[1 \boxed{- r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2]}\right. \\
& + g_\rho\tau\cdot R_\mu\left[1 \boxed{- r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2]}\right.\ , \\
\mathcal{V}_{\sigma\omega\rho} =& \frac{1}{2}m_\sigma^2\sigma^2 \boxed{- a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\sigma^4 + \frac{1}{3}c_{\sigma 3}f_\pi\sigma^3} \\
& - \frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\left[1 \boxed{- c_{\sigma\omega}\sigma/f_\pi]}\right. \boxed{- \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2} \\
& - \frac{1}{2}m_\rho^2 R^\mu\cdot R_\mu\left[1 \boxed{- c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2]}\right. \boxed{- \frac{1}{4}c_{\rho 4}(R^\mu\cdot R_\mu)^2}\ ,
\end{aligned}
$$

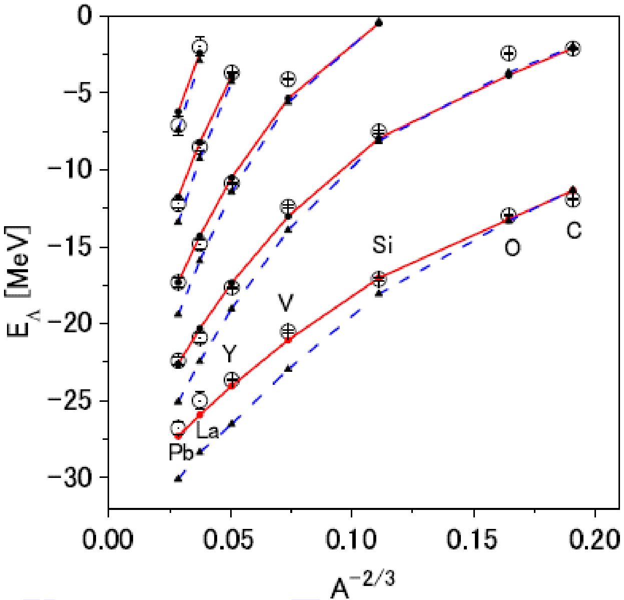
DD meson mass (e.g. Steiner, Fischer, Hempel)

Hyperon Puzzle

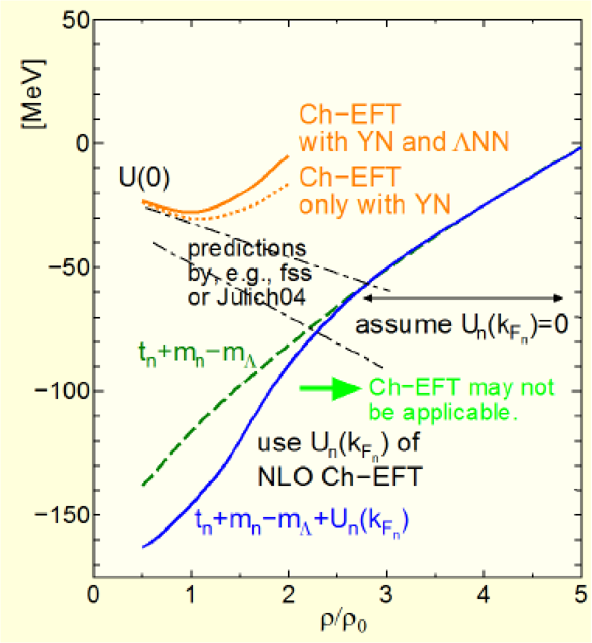
- **When we include hyperons with potentials consistent with data, EOS cannot support 2 $M_\odot$ neutron stars.**
- **Proposed solutions: 3-body force, quark matter, modified gravity**



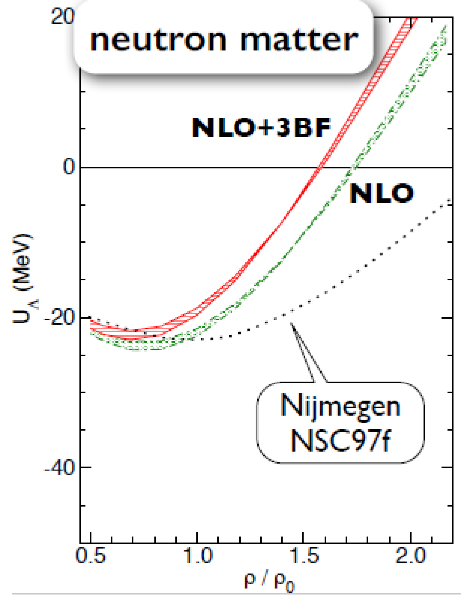
Takatsuka, Nishizaki ('17)



Yamamoto, Furumoto, Yasutake, Rijken ('17)



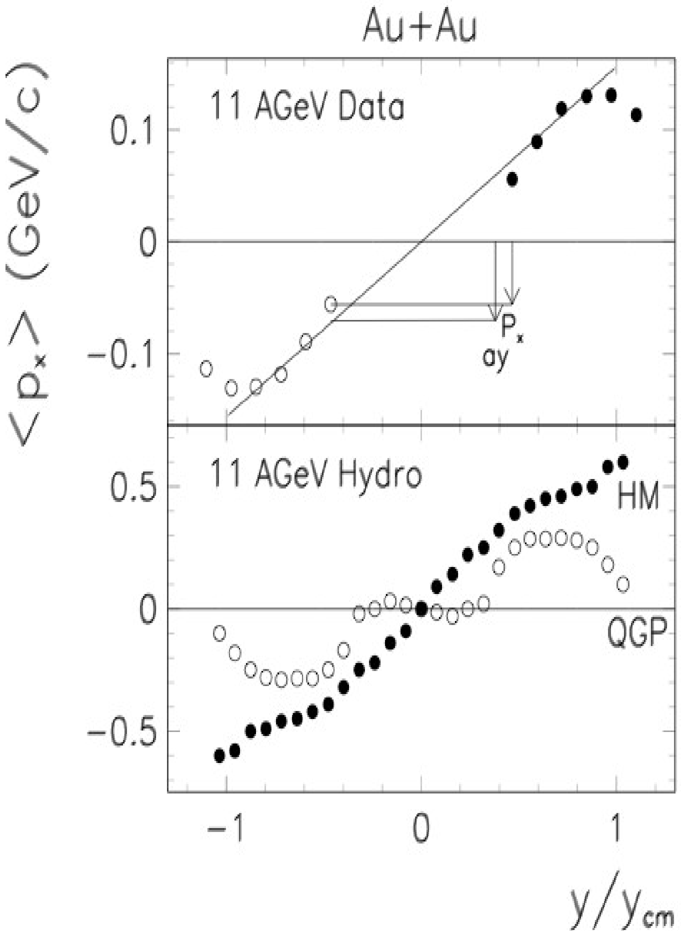
Kohno (SCHDM2017)



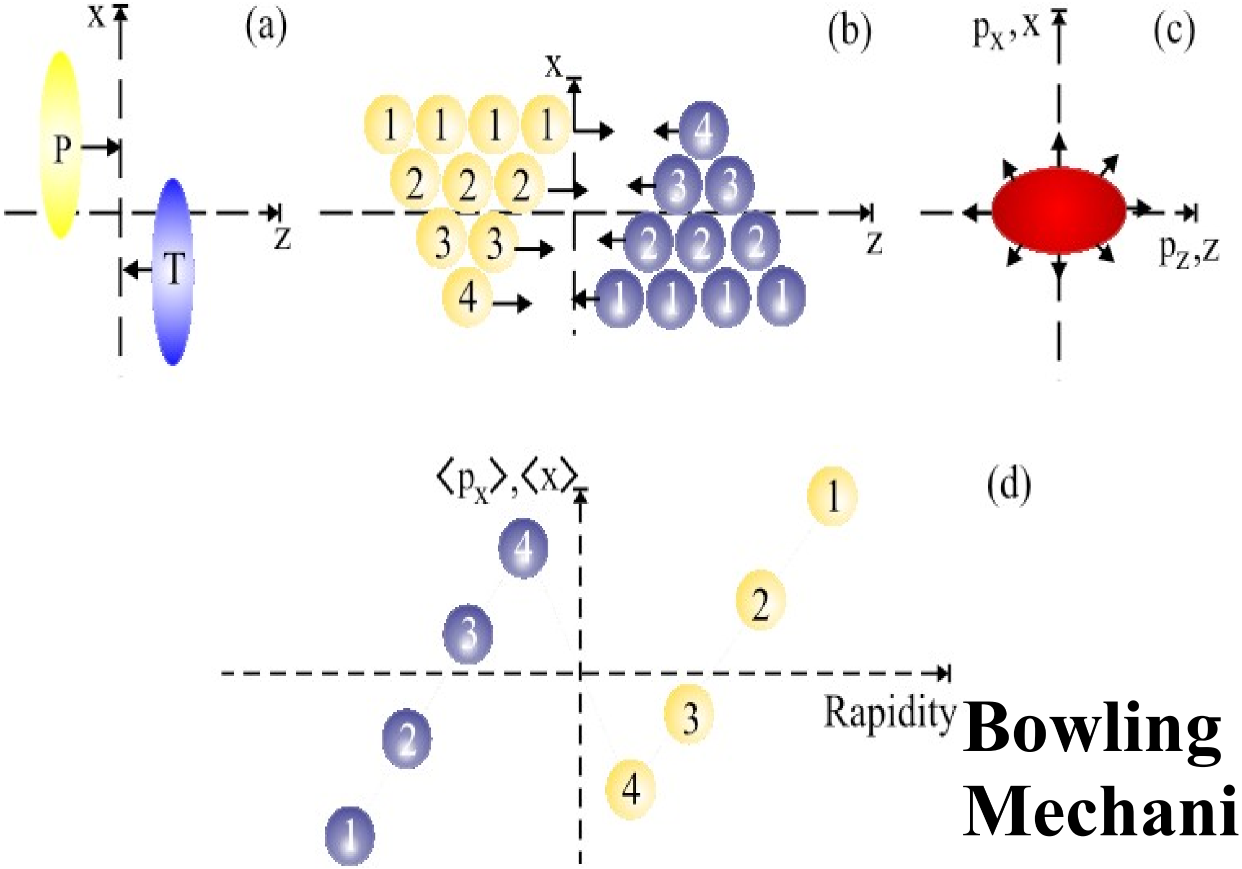
Haidenbauer, Meissner, Kaiser, Weise ('17)

Does the "Wiggle" signal the QGP ?

- **Hydro predicts wiggle with QGP EOS.**
- **Baryon stopping + Positive space-momentum correlation leads wiggle (w/o QGP)**



L. P. Csernai, D. Röhrich, PLB 45 (1999), 454.



Bowling Pin Mechanism

R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

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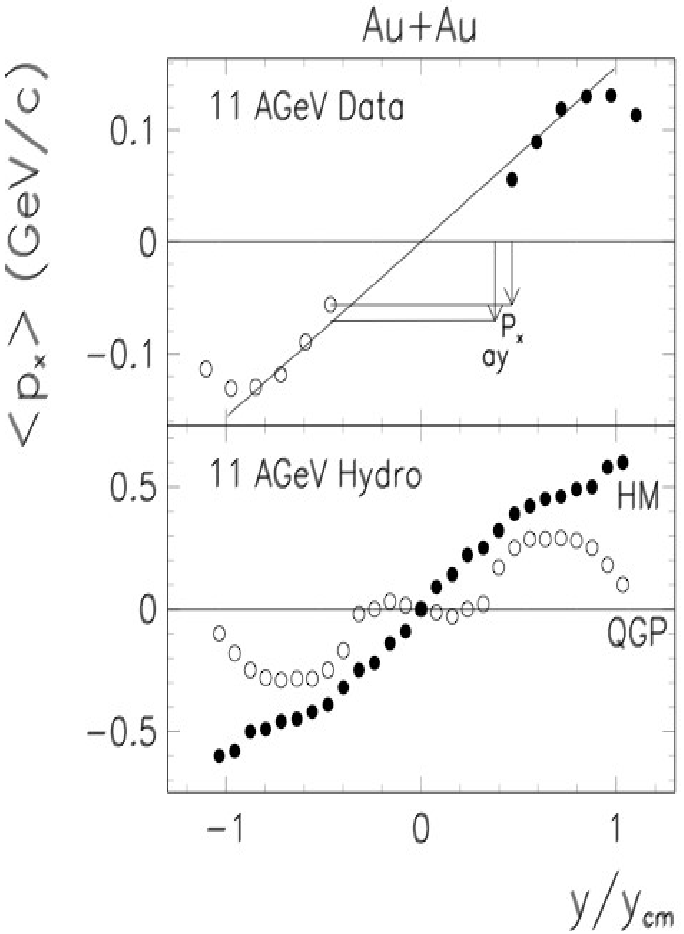

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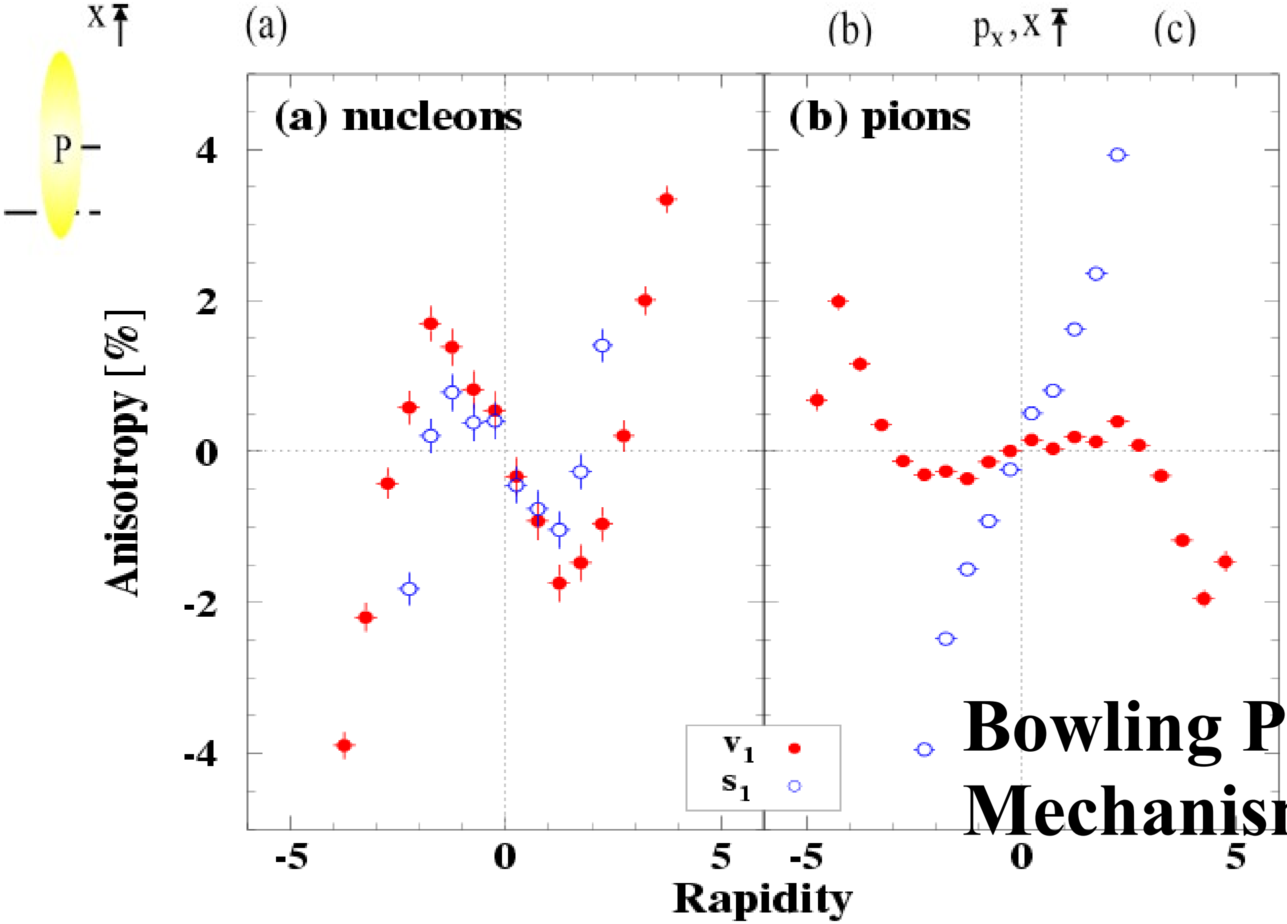


Bowling Pin Mechanism

R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL (84) 2803(2000)

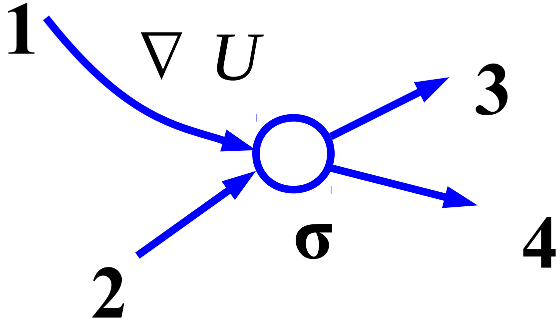
Does Directed Flow Collapse Signal Phase Tr. ?

- **Negative dv_1/dy at high-energy ($\sqrt{s_{NN}} > 20$ GeV)**
  - **Geometric origin (bowling pin mechanism), not related to FOPT**
    R.Snellings, H.Sorge, S.Voloshin, F.Wang, N. Xu, PRL84,2803('00)
- **Negative dv_1/dy at $\sqrt{s_{NN}} \sim 10$ GeV**
  - **Yes, in three-fluid simulations. → Thermalization ?**
    Y. B. Ivanov and A. A. Soldatov, PRC91('15)024915
  - **No, in transport models incl. hybrid.**
    E.g. J. Steinheimer, J. Auvinen, H. Petersen, M. Bleicher, H. Stoecker, PRC89('14)054913.
    Exception: *B.A.Li, C.M.Ko ('98) with FOPT EOS*

We investigate the directed flow at BES energies
in hadronic transport model
with / without mean field effects
with / without softening effects via attractive orbit.

Transport Model

- **Boltzmann equation with (optional) potential effects**
  E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190



$$\frac{\partial f}{\partial t} + \mathbf{v}\cdot\nabla f - \nabla U \cdot \nabla_p f = I_{\mathrm{coll}}$$

$$I_{\mathrm{coll}}(\mathbf{r},\mathbf{p}) = -\frac{1}{2}\int \frac{d\mathbf{p}_2}{(2\pi)^3} d\Omega\; v_{12}\,\frac{d\sigma}{d\Omega}\;[f f_2(1-f_3)(1-f_4)) - (12 \leftrightarrow 34)]$$

(NN elastic scattering case)

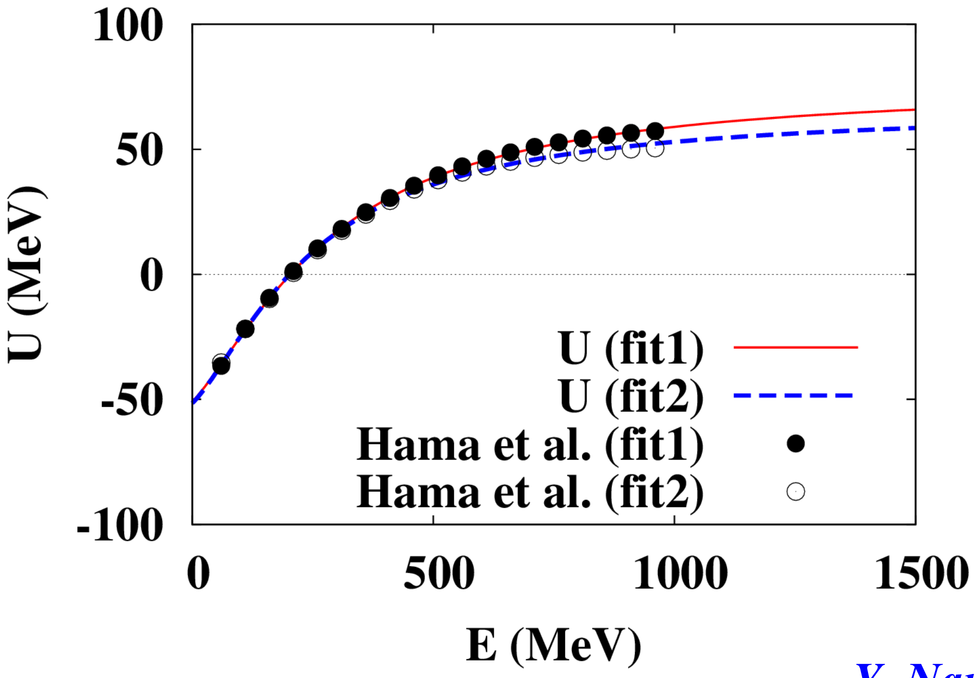
- **Hadron-string transport model JAM**
  - **Collision term → Hadronic cascade with resonance and string excitation**
    Nara, Otuka, AO, Niita, Chiba, Phys. Rev. C61 (2000), 024901.
  - **Potential term → Mean field effects in the framework of RQMD/S**
    Sorge, Stocker, Greiner, Ann. of Phys. 192 (1989), 266.
    Tomoyuki Maruyama et al., Prog. Theor. Phys. 96(1996), 263.
    Isse, AO, Otuka, Sahu, Nara, Phys.Rev. C 72 (2005), 064908.

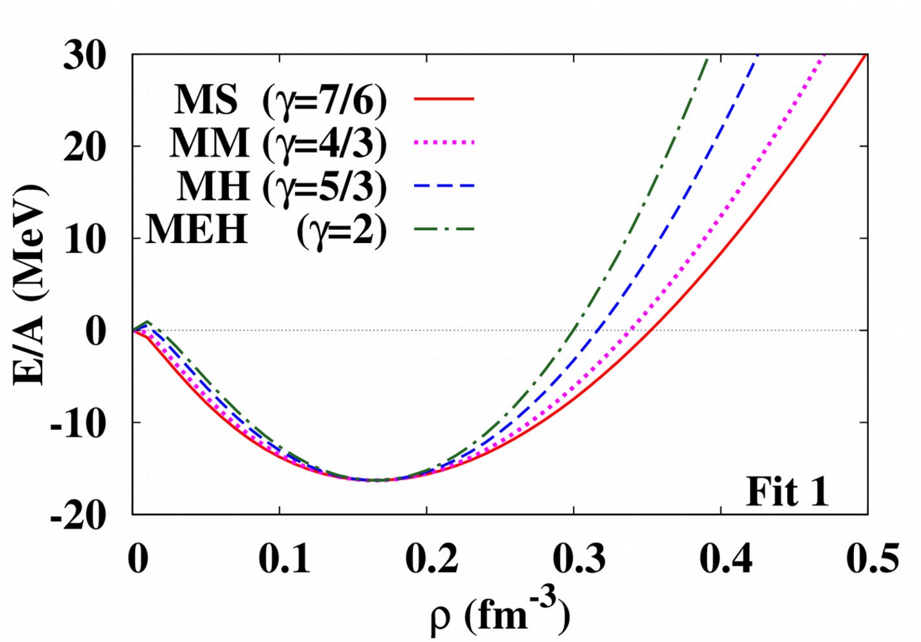
Mean Field Potential

- **Skyrme type density dependent + momentum dependent potential**

$$V = \sum_i V_i = \int d^3r \left[\frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right)^2 + \frac{\beta}{\gamma+1}\left(\frac{\rho}{\rho_0}\right)^{\gamma+1}\right] + \sum_k \int d^3\boldsymbol{r}\, d^3\boldsymbol{p}\, d^3\boldsymbol{p}' \frac{C_{ex}^{(k)}}{2\rho_0}\, \frac{f(\boldsymbol{r},\boldsymbol{p})f(\boldsymbol{r},\boldsymbol{p}')}{1+(\boldsymbol{p}-\boldsymbol{p}')^2/\mu_k^2}$$

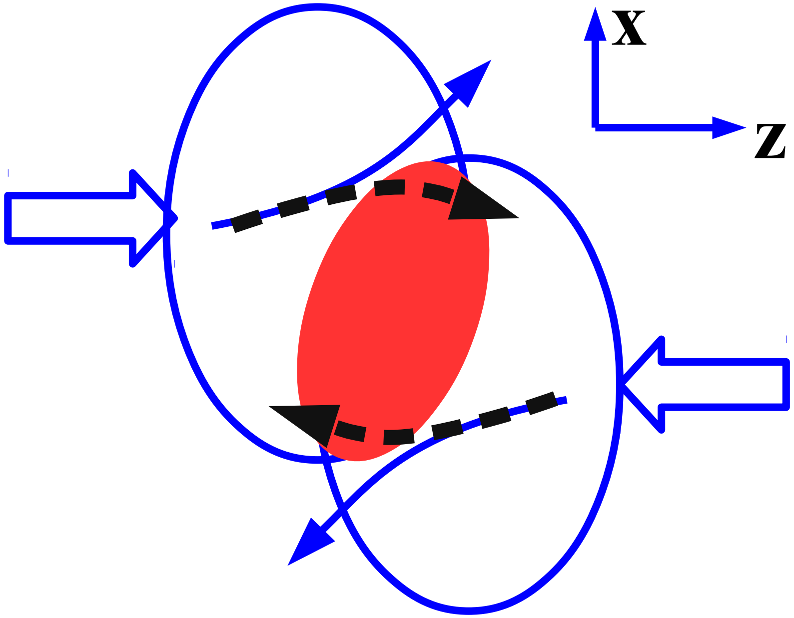
Type	α (MeV)	β (MeV)	γ	$C_{\rm ex}^{(1)}$ (MeV)	$C_{\rm ex}^{(2)}$ (MeV)	μ_1 (fm^{-1})	μ_2 (fm^{-1})	K (MeV)
MH1	-12.25	87.40	5/3	-383.14	337.41	2.02	1.0	371.92
MS1	-208.89	284.04	7/6	-383.14	337.41	2.02	1.0	272.6

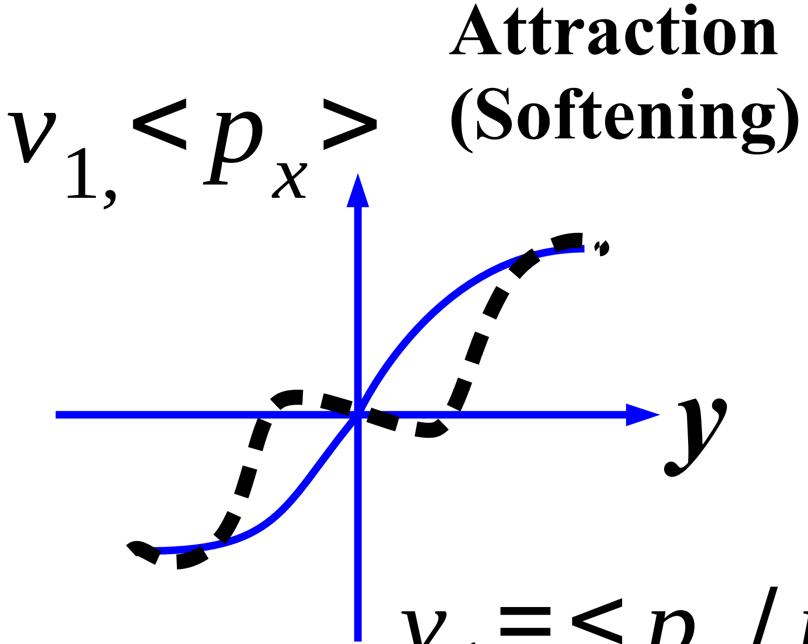




Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)
Isse, AO, Otuka, Sahu, Nara, PRC 72 (2005), 064908.

What is directed flow ?





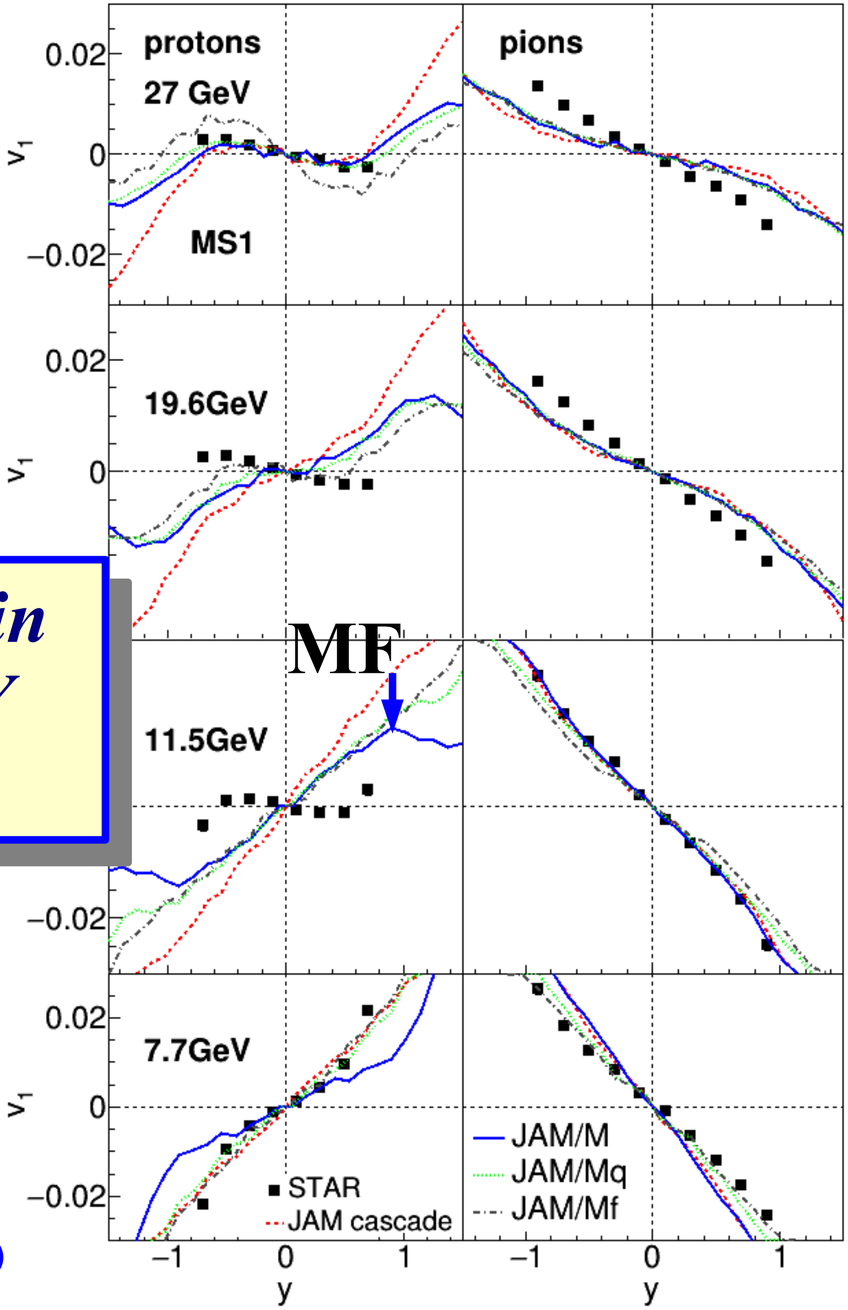
- **v_1 or $<p_x>$ as a function of y is called directed flow.**
- **Created in the overlapping stage of two nuclei**
  → Sensitive to the EOS in the early stage.
- **Becomes smaller at higher energies.**

> ***How can we explain non-monotonic dependence of dv_1/dy ?***
> ***→ Softening or Geometry***

$$v_1 = < p_x / p > = < \cos \phi >$$

Comparison with RHIC data on v_1

- **Pot. Eff. on the v_1 is significant, but dv1/dy becomes negative only at $\sqrt{s_{NN}}$ > 20 GeV.**



Hadronic approach does not explain directed flow collapse at 10-20 GeV even with potential effects.

JAM/M: only formed baryons feel potential forces
JAM/Mq: pre-formed hadron feel potential with factor 2/3 for diquark, and 1/3 for quark
JAM/Mf: both formed and pre-formed hadrons feel potential forces.

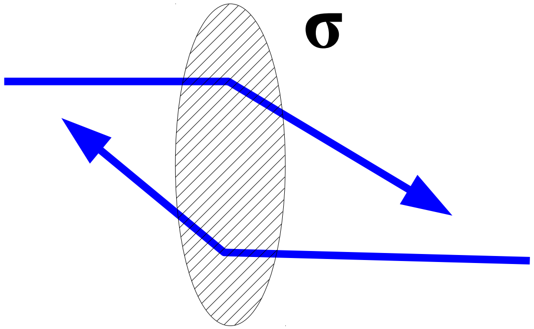
Y. Nara, AO, arXiv:1512.06299 [nucl-th] (QM2015 proc.)

Softening Effects via Attractive Orbit Scattering

- **Attractive orbit scattering simulates softening of EOS**
  P. Danielewicz, S. Pratt, PRC 53, 249 (1996)
  H. Sorge, PRL 82, 2048 (1999).

$$P = P_f + \frac{1}{3TV} \sum_{(i,j)} (q_i \cdot r_i + q_j \cdot r_j)$$

(Virial theorem)



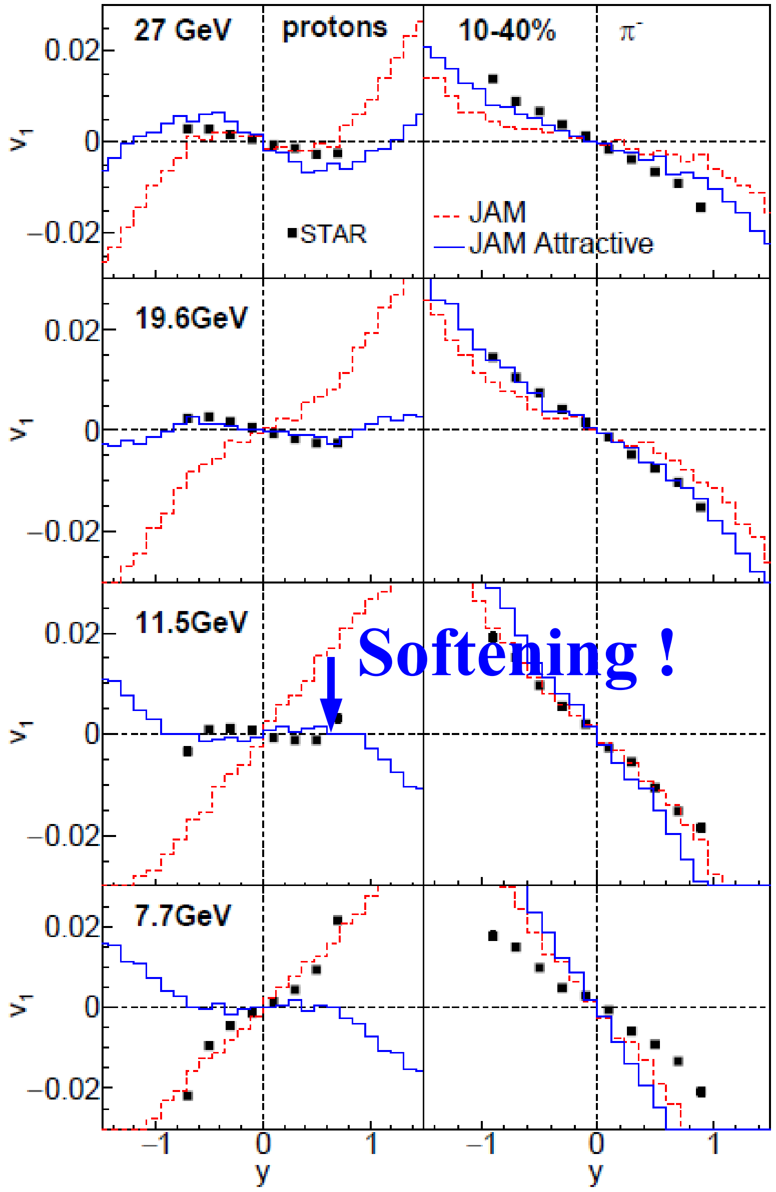
  - **Attractive orbit → particle trajectory are bended in denser region**

Let us examine the EOS softening effects,
which cannot be explained in hadronic mean field potential,
by using attractive orbit scatterings !

Y. Nara, Niemi, AO, H. Stöcker ('16)

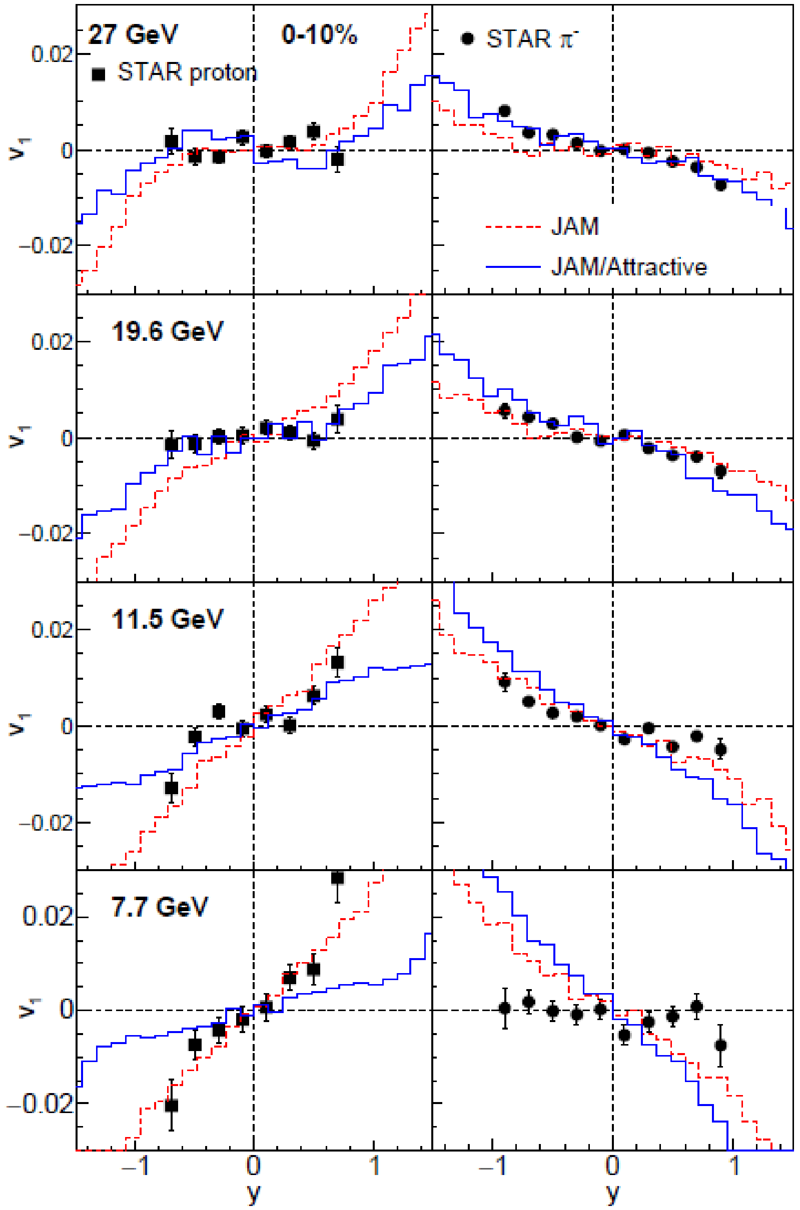
Directed Flow with Attractive Orbits

Nara, Niemi, AO, Stöcker ('16)



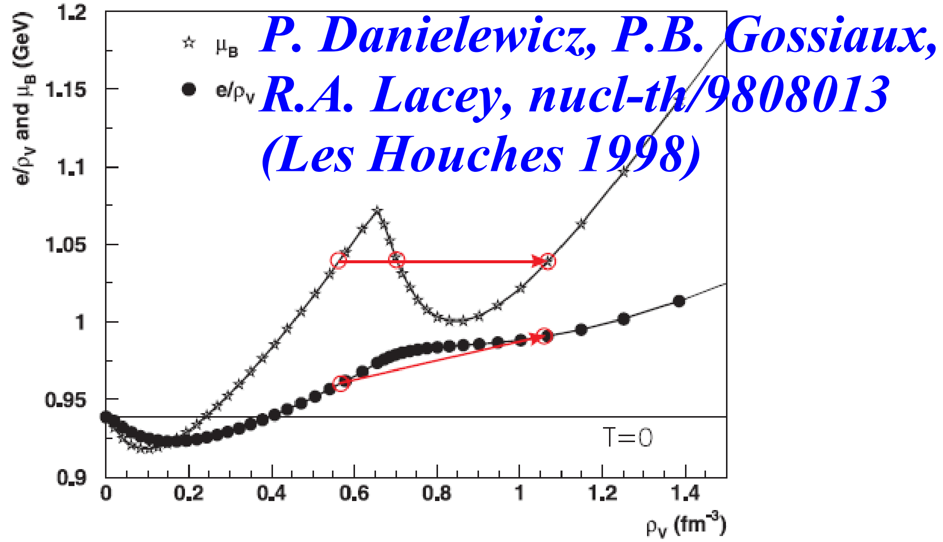
Softening !

mid-central (10-40 %)

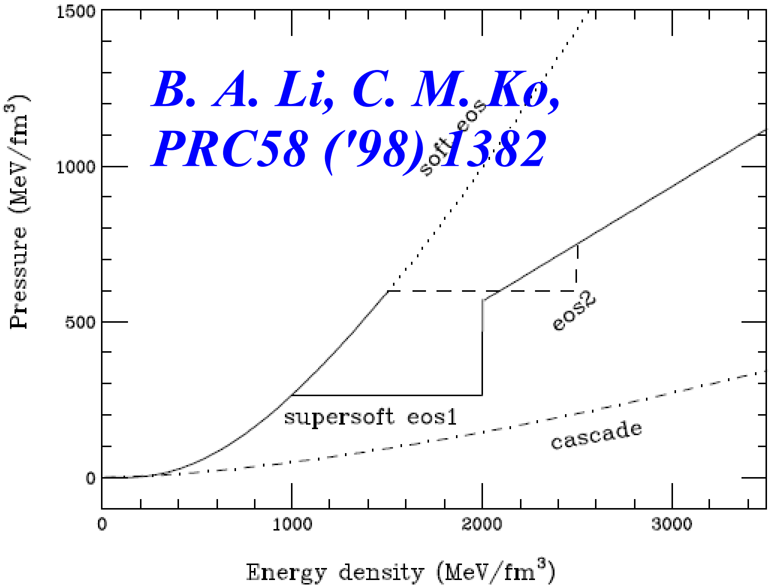


central (0-10 %)

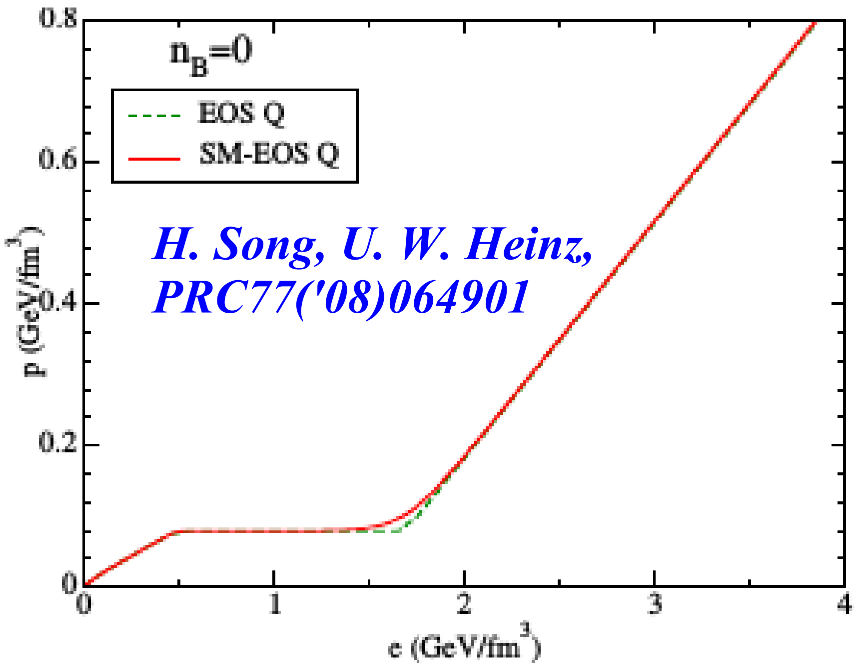
Softening: Where and How much ?



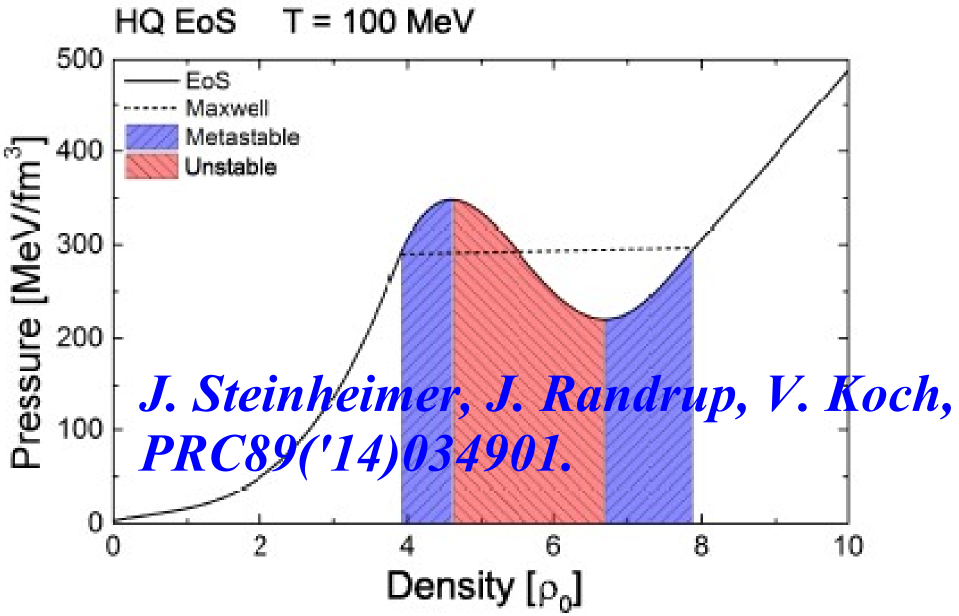
P. Danielewicz, P.B. Gossiaux, R.A. Lacey, nucl-th/9808013 (Les Houches 1998)



B. A. Li, C. M. Ko, PRC58 ('98) 1382



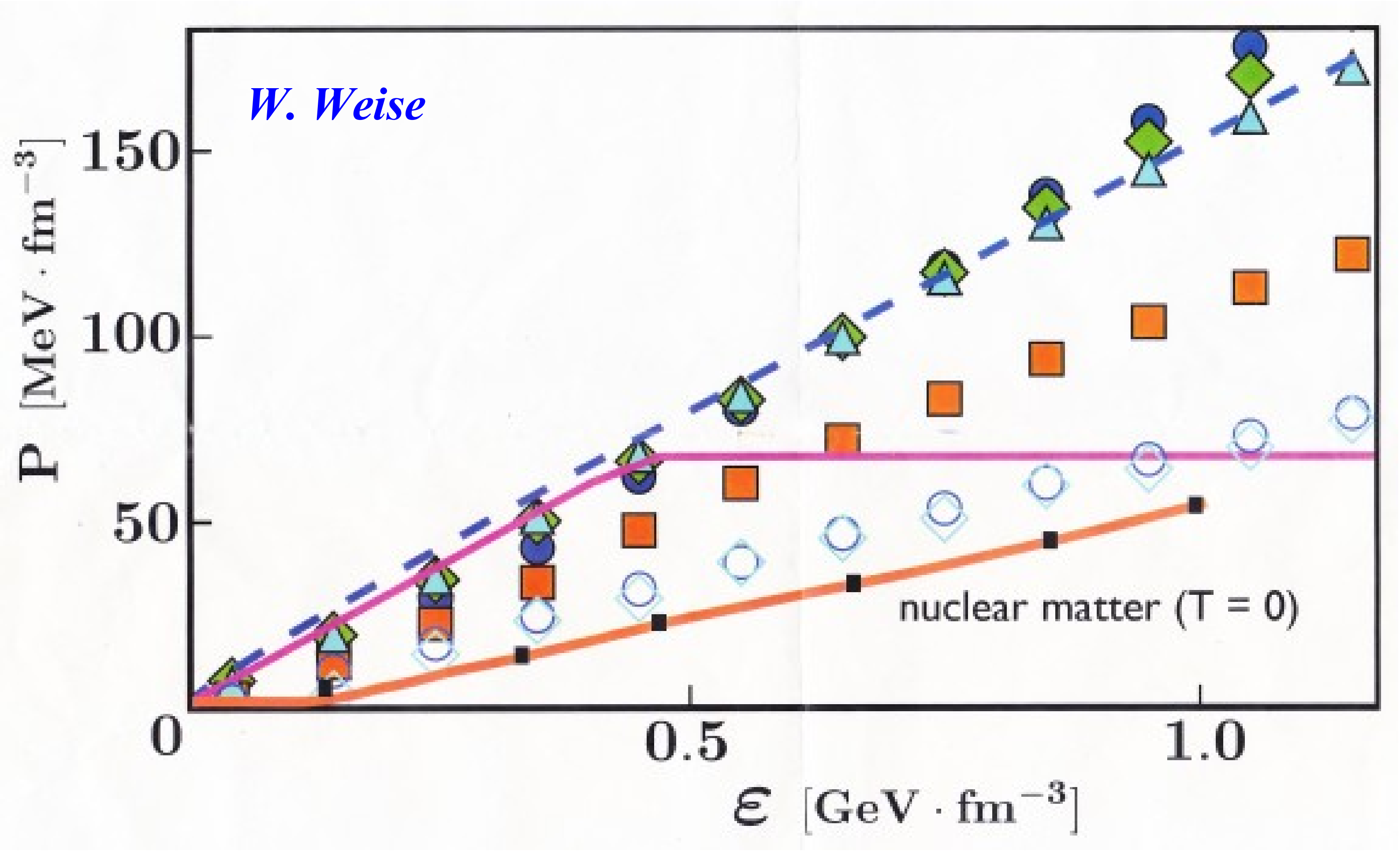
H. Song, U. W. Heinz, PRC77('08)064901



J. Steinheimer, J. Randrup, V. Koch, PRC89('14)034901.

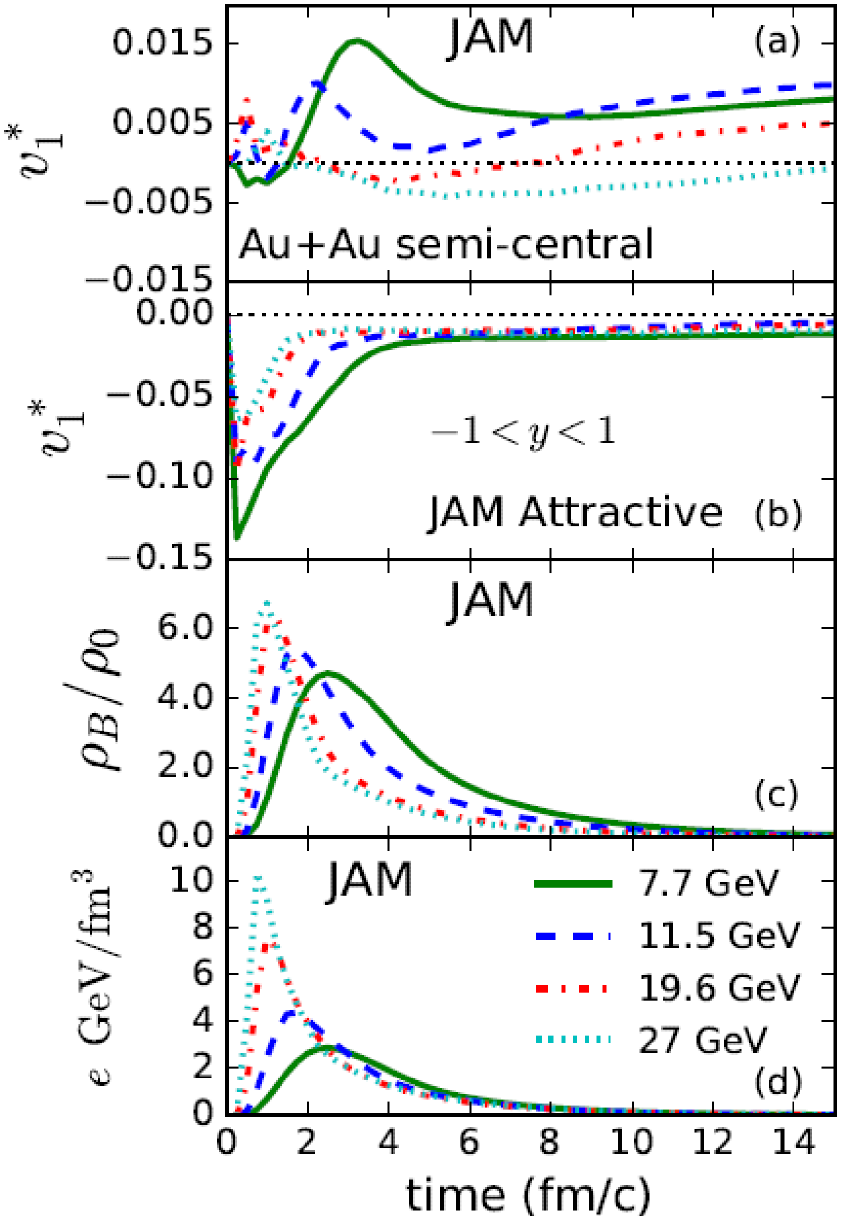
Previous analyses: ρ_B=(3-10) ρ_0, P=(80-700) MeV/fm^3

Comparison with Cold Matter EOS



FRG EOS does not reach P~70 MeV/fm^3 at ε < 1 GeV/fm^3
→ Consistent with no FOPT at ε < 1 GeV/fm^3

At which density is the softening required ?



Softening is required at $\rho > 5\rho_0$

Short Summary of the 1st part

- **We may have seen QCD phase transition (1st or 2nd) signals at BES (or J-PARC) energies in baryon number cumulants and v_1 slope.**
- **Hadronic transport models cannot explain negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**
  - **Geometric mechanism becomes manifest at higher energies.**
- **Hadronic transport with EOS softening can describe negative v_1 slope below $\sqrt{s_{NN}} = 20$ GeV.**

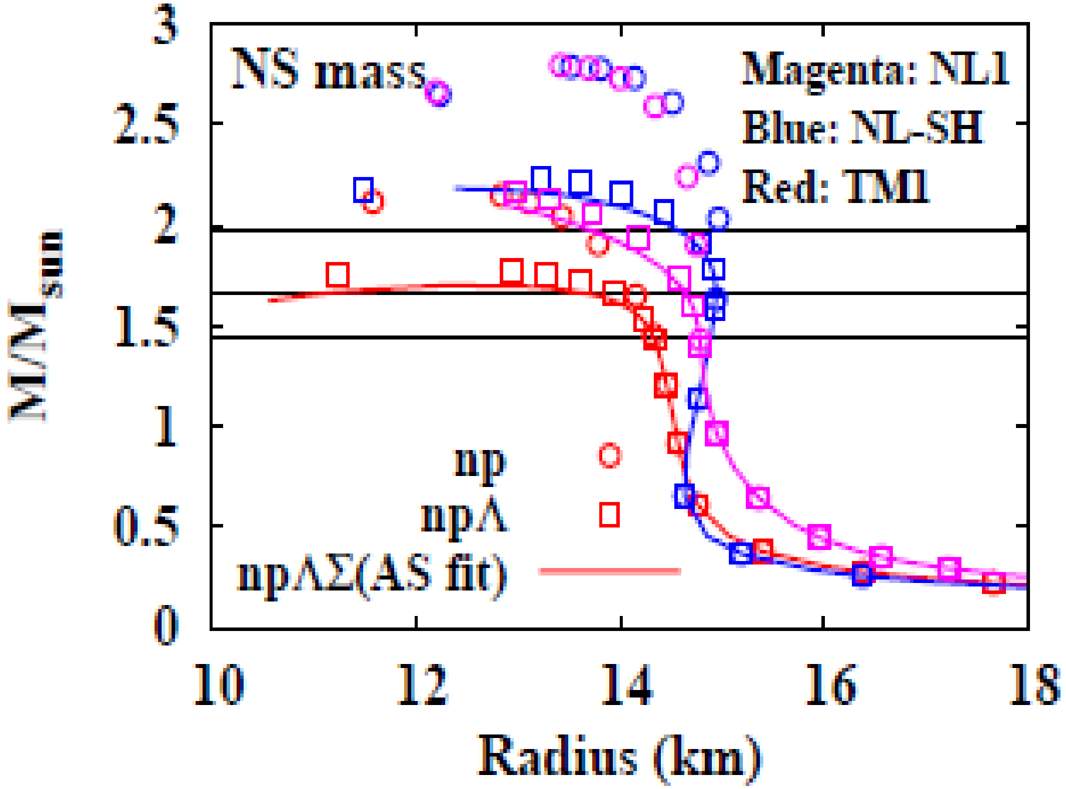
  Y. Nara, H. Niemi, A. Ohnishi, H. Stoecker, PRC94 ('16), 034906.
  - **Attractive orbit scattering simulates EOS softening (virial theorem).**
  - **We need more studies to confirm its nature.**
    First-order phase transition ? Crossover ? Forward-backward rapidities ? MF leading to softer EOS ?
- ***We need "re-hardening" at higher energies, e.g. $\sqrt{s_{NN}} = 27$ GeV.***

Dense matter EOS in neutron stars

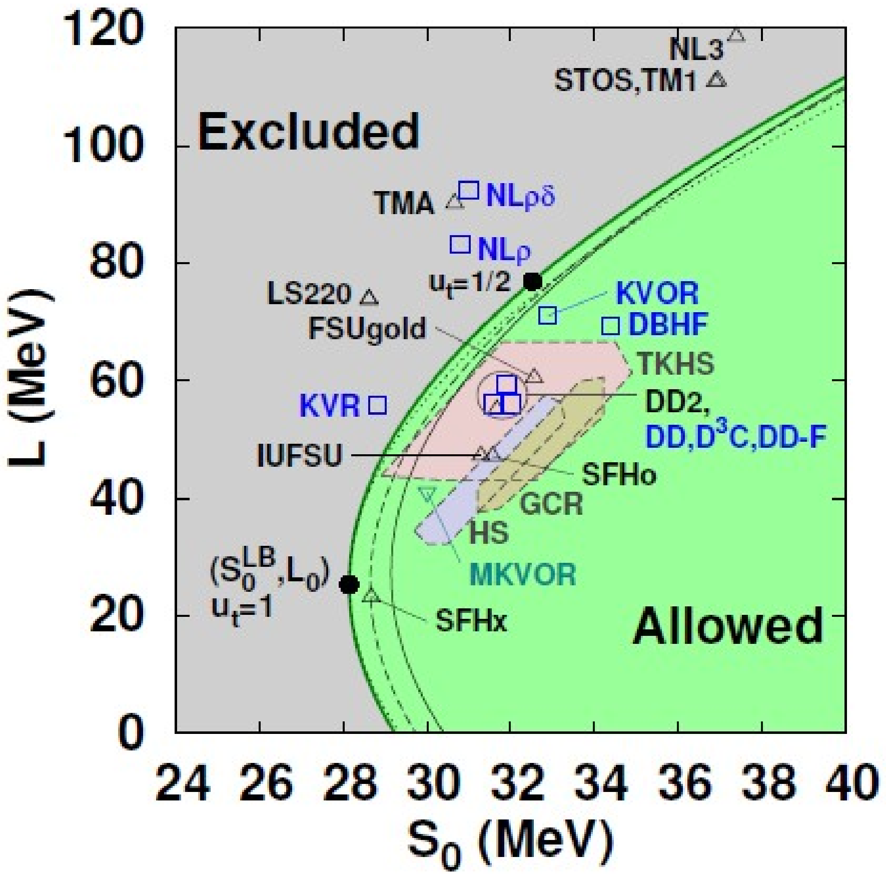
Massive Neutron Stars with Hyperons

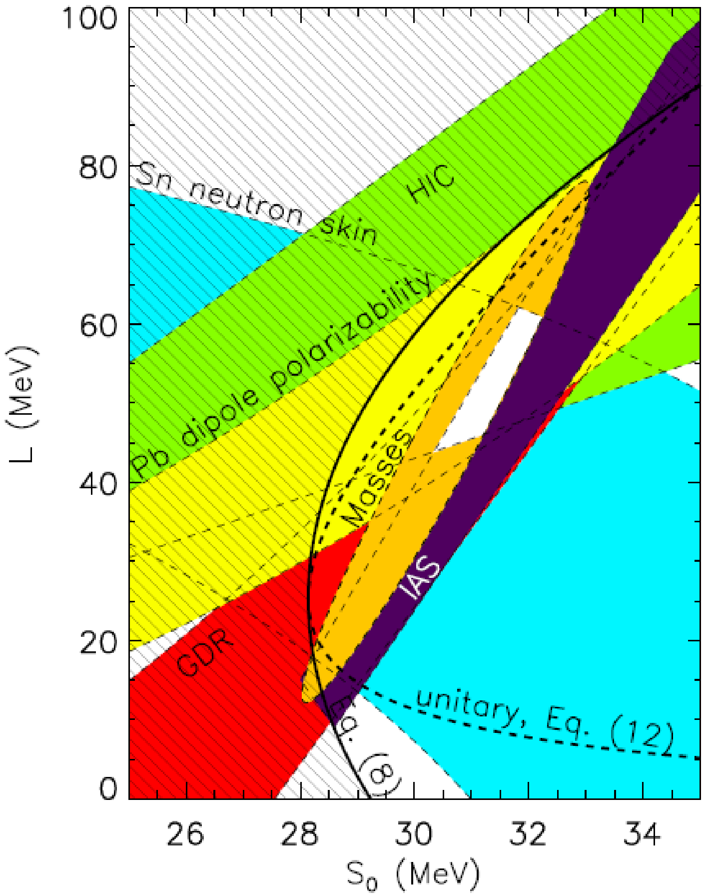
Tsubakihara, Harada, AO, arXiv:1402.0979

- **Ruled-out EOS with hyperons = GM3**
  Glendenning & Moszkowski (1991)
- **We did NOTHING special and find 2 M$_\odot$ NS can be supported.**
  - **"Typical" RMF for nucl. matter**
    NL1, NL-SH, TM1
    Reinhardt et al. ('86); Sharma, Nagarajan, Ring ('93); Sugahara, Toki ('94).
  - **$s\bar{s}$ mesons are introduced**
  - **Hypernuclear data**
    Λ, ΛΛ hypernuclei
    Σ atomic shifts
    SU(3) relation to isoscalar-vector couplings



Symmetry Energy Constraints





Many of EOSs in active astrophysical use do not satisfy recent symmetry energy constraint or 2 $M_\odot$ constraint.
→ SFHo, SHFx, DD2

Kolomeitsev, Lattimer, AO, Tews ('16)

What is necessary ?

- **Saturation properties (ρ_0, E_0, K)**
- **Symmetry energy parameters (S_0, L)**
- **Finite nuclear properties (mass, radius)**
- **Hypernuclear separation energies (S_Λ)**
- **Support 2 $M_\odot$ neutron stars**
- **(Neutron star radius at 1.4 $M_\odot$ of 12 ± 1 km)**
- **Hopefully based on microscopic calculations and/or QCD**

Relativistic mean field model with multi-body couplings

Thank you !

Heavy-ion and dense matter physics in Hokkaido University

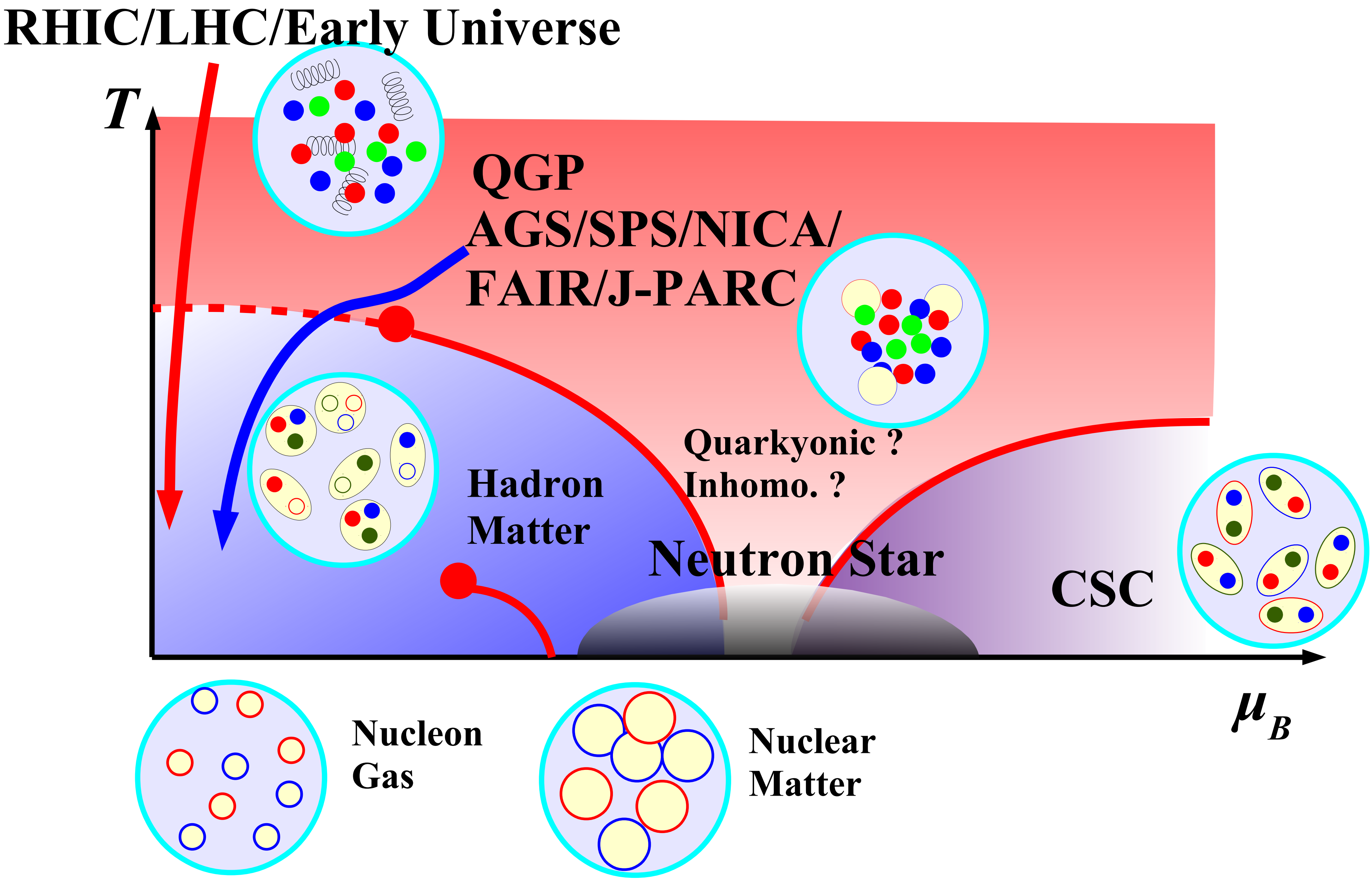
I review heavy-ion and dense matter physics developed in Hokkaido University.

Heavy-ion collision dynamics at 1-158 A GeV were investigated based on hadronic transport models in Hokkaido University. Now its achievements are utilized to understand the QCD phase transition at high densities in heavy-ion collision experiments performed in FAIR, NICA, J-PARC-HI and the Beam Energy Scan program at RHIC.

Dense matter physics investigated in Hokkaido University is now utilized to solve the hyperon puzzle. Hyperon potentials in nuclear matter were used to predict high density baryonic matter EOS, and it is found that we can support neutron star with mass M < 1.7 M_sun. In order to explain massive neutron stars with M ~ 2 M_sun, we need three-baryon interactions, which may be clarified via precise hypernuclear data.

- **1993 Nara (PhD 1996.3)**
- **1994 Itagaki (PhD 1999.3), Otsuka (PhD 2001.3)**
- **1995 Uchida (MS 1997.3)**
- **1996 Hirata (PhD 2001.3), [Myo (PhD 2002.3)]**
- **1997 Isshiki (PhD 2005.3?)**
- **1998 Okuda (~1999.3)**
- **1999 [Fukuzaki (B 2000.3)]**
- **2000 Ishizuka (PhD 2005.3)**
- **2001 Isse (PhD 2006.3)**
- **2002 Yamaguchi (MS 2004.3)**
- **2003 Maekawa (PhD 2008.3)**
- **2004 Tsubakihara (PhD 2009.3), Ohnuma (MS 2006.3)**
- **2005 Yoshino (MS 2007.3)**

QCD Phase Diagram



RHIC/LHC/Early Universe

T

QGP

AGS/SPS/NICA/
FAIR/J-PARC

Hadron
Matter

Quarkyonic ?
Inhomo. ?

Neutron Star

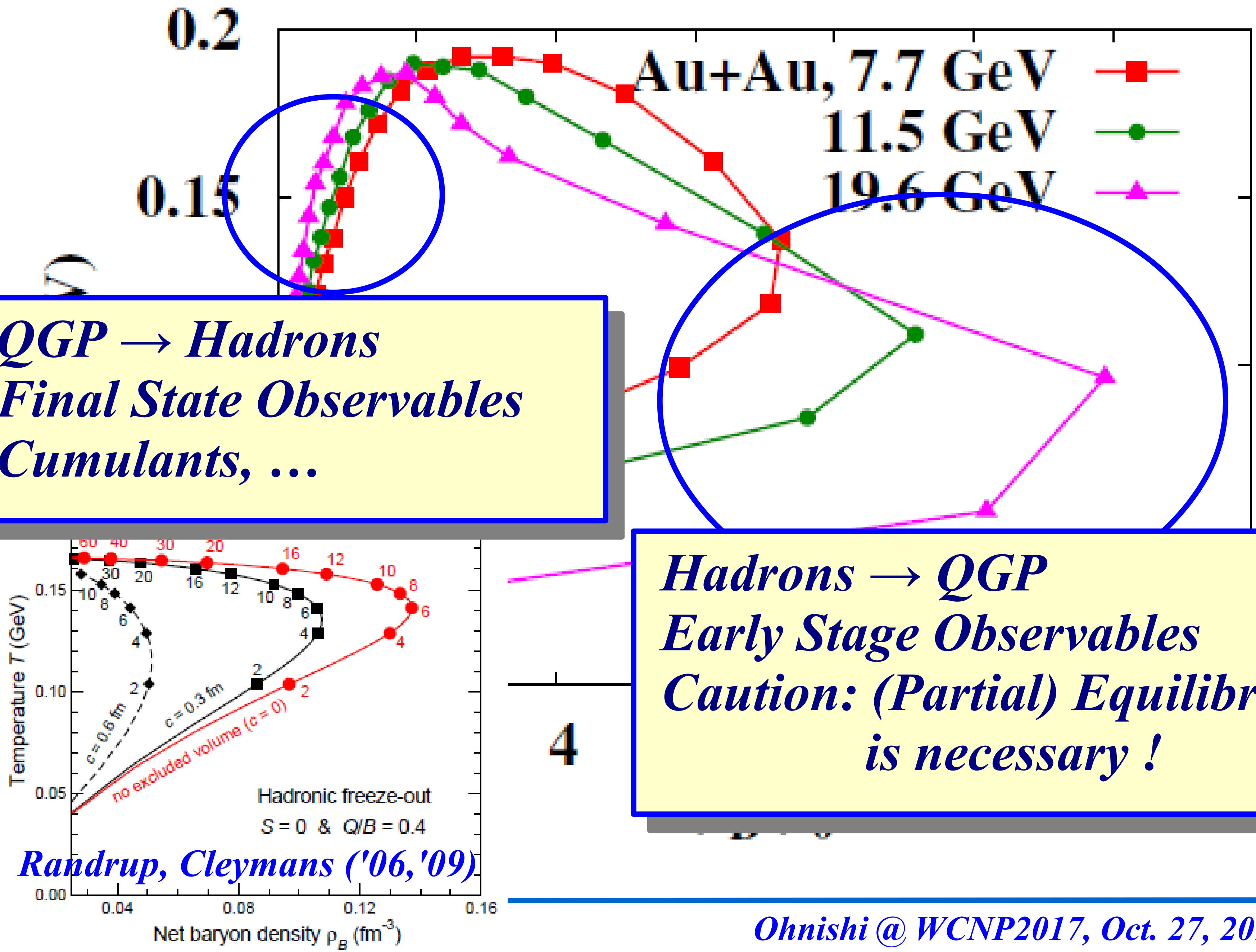
CSC

μ_B

Nucleon
Gas

Nuclear
Matter

Two ways to probe QCD phase transition



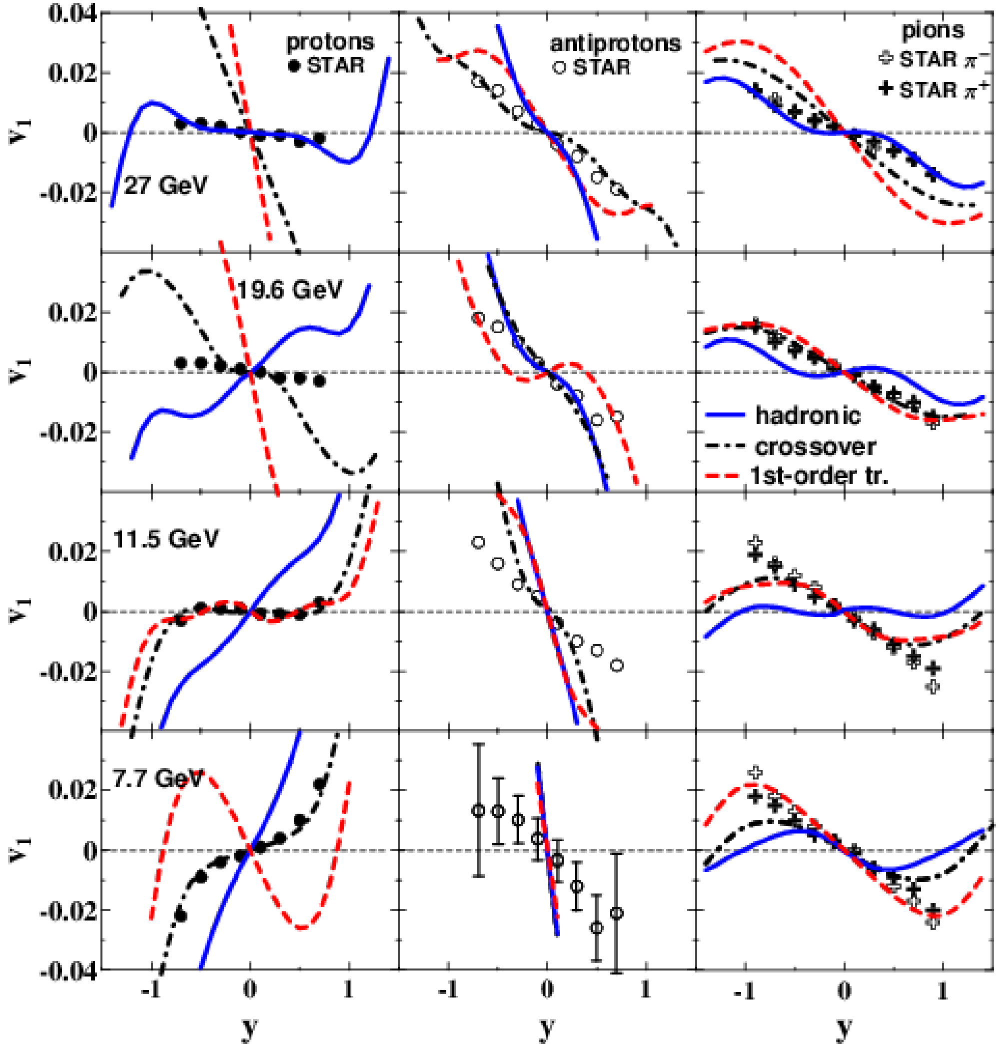
QGP → Hadrons
Final State Observables
Cumulants, …

Hadrons → QGP
Early Stage Observables
Caution: (Partial) Equilibration
is necessary !

Randrup, Cleymans ('06,'09)

Negative dv_1/dy around $\sqrt{s_{NN}} \sim 10$ GeV

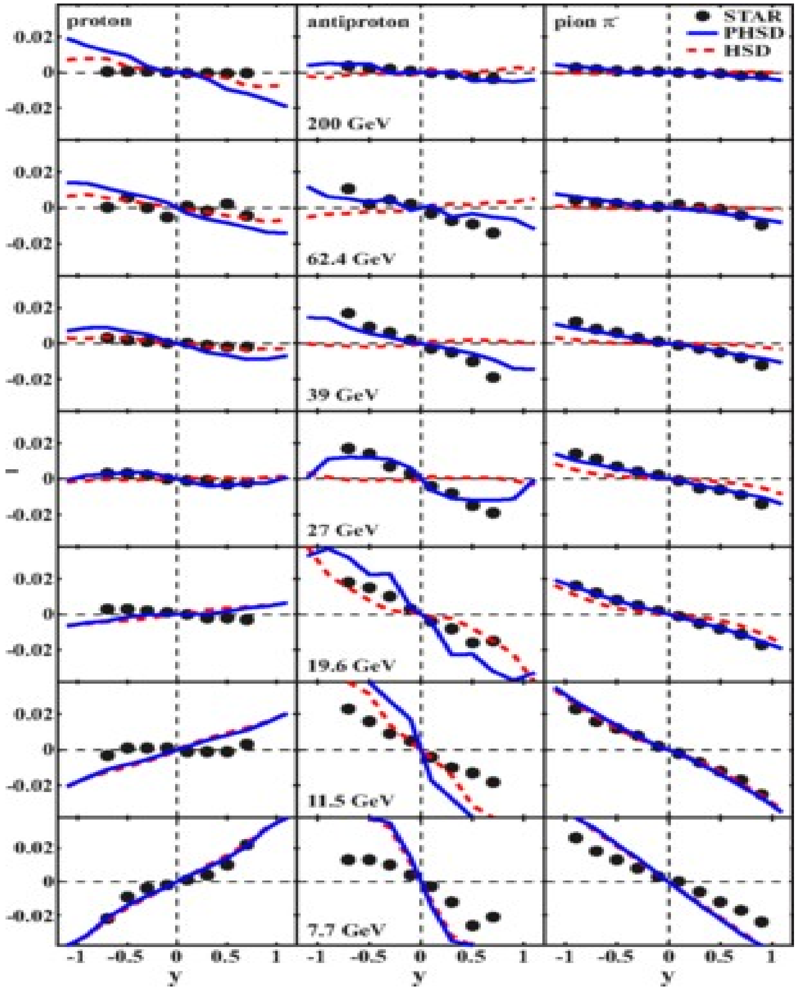
- **Yes in Hydrodynamics**



Black: Crossover, Red: 1st

Y. B. Ivanov and A. A. Soldatov, PRC91 (2015)024915

- **No at around $\sqrt{s_{NN}}$~10 GeV in transport models.**

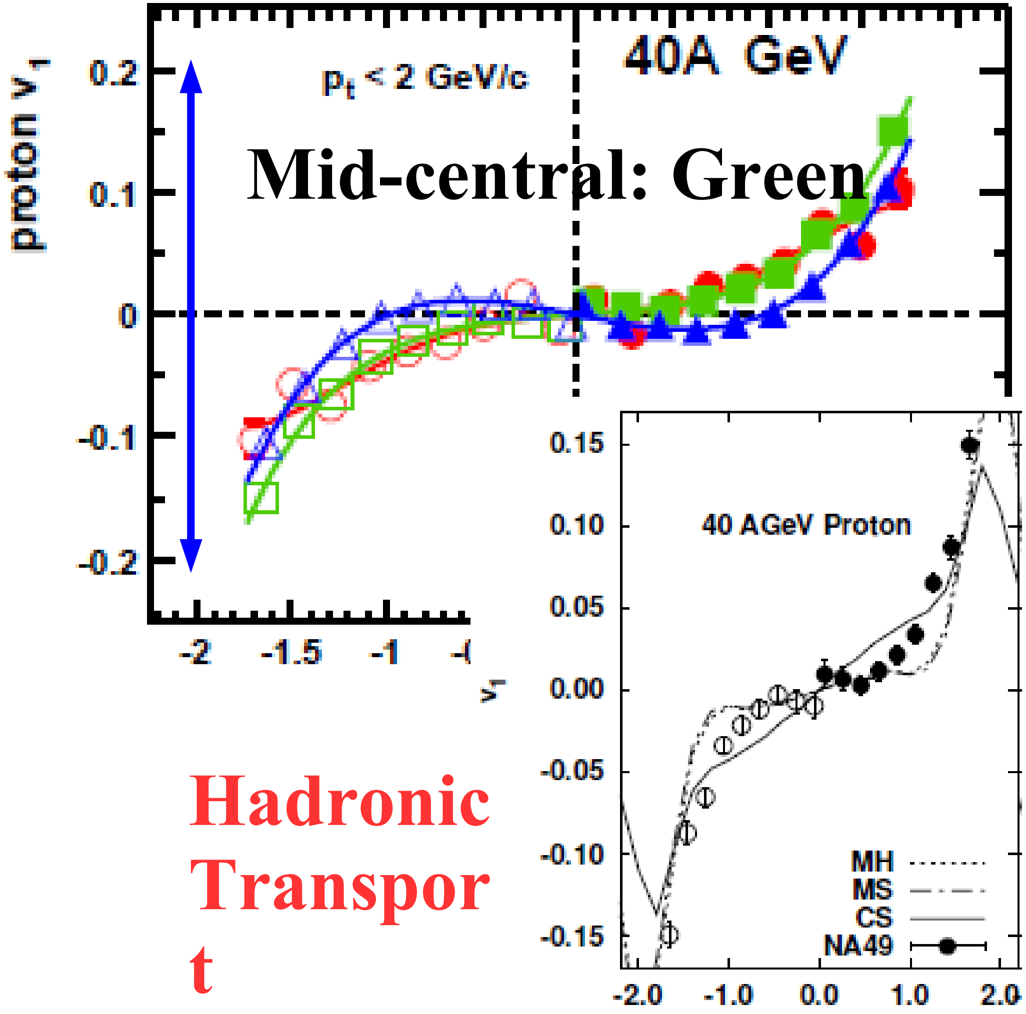


V. P. Konchakovski, W. Cassing, Y. B. Ivanov, V. D. Toneev, PRC90('14)014903

SPS(NA49) vs RHIC(STAR)

- **SPS (NA49), $\sqrt{s_{NN}}$ = 8.9 GeV**
- **RHIC(STAR), 7.7-39 GeV**

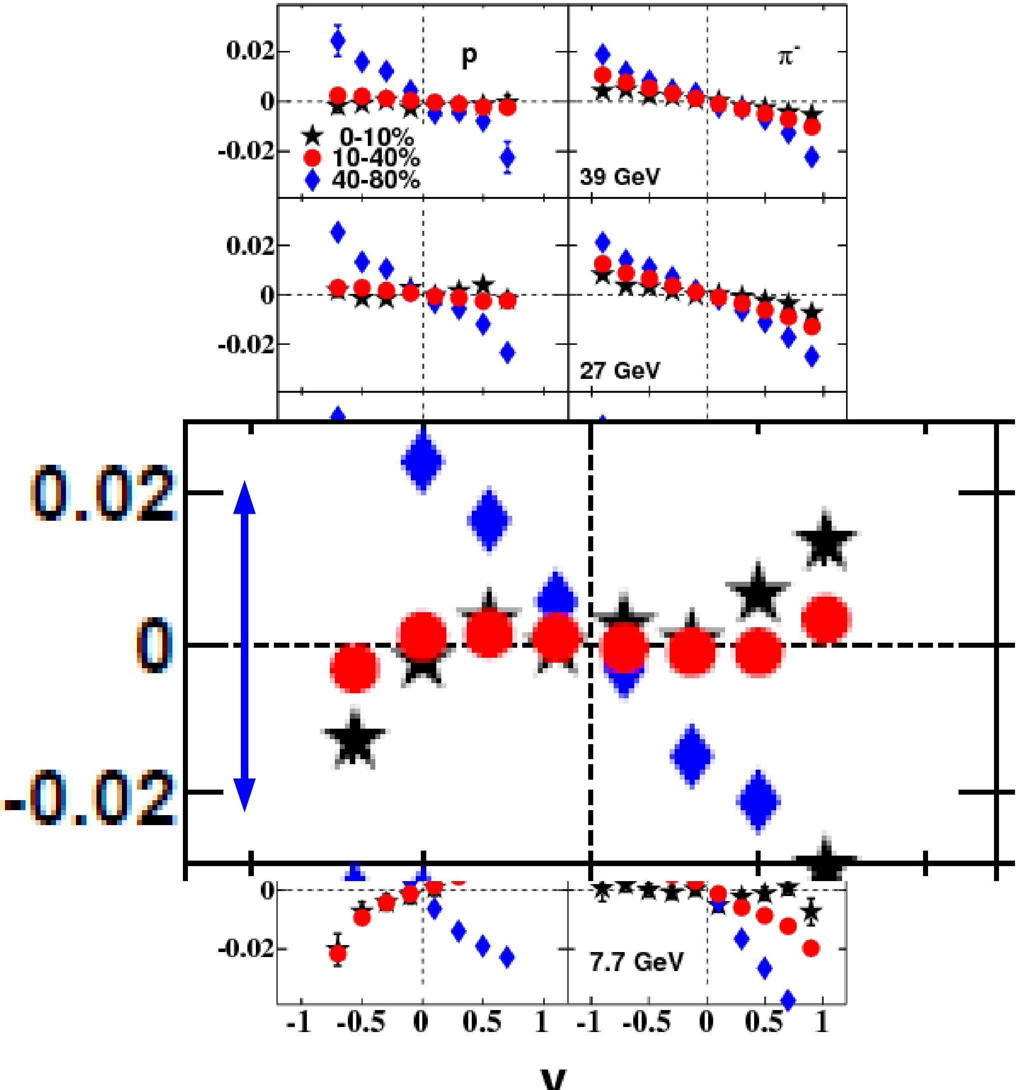
C. Alt et al. (NA49), PRC68 ('03) 034903



Mid-central: Green

Hadronic Transport w/ MF

M.Isse,AO,N.Otuka,P.K.Sahu,Y.Nara,
PRC72 ('05)064908



L. Adamczyk et al. (STAR),
PRL 112(2014)162301

Contents

- Introduction
  - Two ways to probe QCD phase transition
  - Collapse of Directed Flow at $\sqrt{s_{NN}} \sim 10$ GeV
- Hadronic Transport Model Approaches
  - Boltzmann equation with potential effects
  - Jet AA Microscopic transport model (JAM)
- Additional Softening Effects
  - Attractive Orbit Scattering
  - Transition Density and Pressure (conjecture)
- Summary

Hadronic Transport Models

- **Transport models: Boltzmann + (optional) Potential Effects**

$$\frac{\partial f}{\partial t} + \vec{v}\cdot\vec{\nabla} f - \vec{\nabla} U \cdot \vec{\nabla}_p f = C[f]$$

$$C[f] = \int \frac{d\vec{p}_2 d\vec{p}_3 d\vec{p}_4}{(2\pi)^3} v_{12}\sigma_{12\to 34}\delta^4(p_1+p_2-p_3-p_4)$$
$$\times \left[f_1 f_2(1\pm f_3)(1\pm f_4) - f_3 f_4 (1\pm f_1)(1\pm f_2)\right]$$

- **Commonly used transport models**
  - **UrQMD 3.4 Frankfurt public**
  - **PHSD Giessen (Cassing) upon request**
  - **GiBUU 1.6 Giessen (Mosel) public**
  - **AMPT public**
  - **JAM (Y. Nara) public**

Relativistic QMD/Simplified (RQMD/S)

- **RQMD is developed based on constraint Hamiltonian dynamics**
  H. Sorge, H. Stoecker, W. Greiner, Ann. Phys. 192 (1989), 266.
  - **8N dof → 2N constraints → 6N (phase space)**
  - **Constraints = on-mass-shell constraints + time fixation**
- **RQMD/S uses simplified time-fixation**
  Tomoyuki Maruyama, et al. Prog. Theor. Phys. 96(1996),263.
  - **Single particle energy (on-mass-shell constraint)**

$$p_i^0 = \sqrt{\boldsymbol{p}_i^2 + m_i^2 + 2 m_i V_i}$$

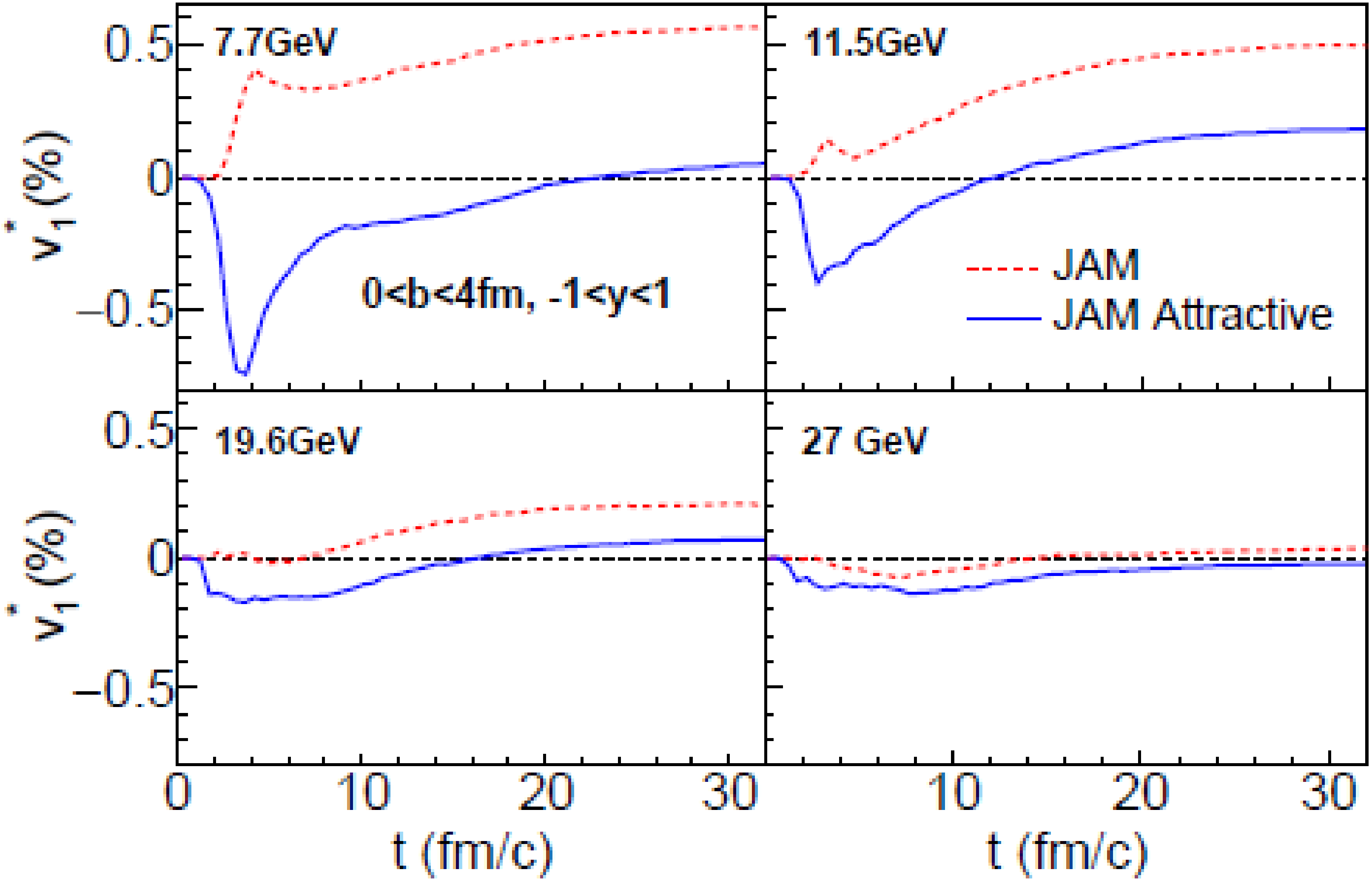
  - **EOM after solving constraints**

$$\dot{\boldsymbol{r}}_i = \frac{\boldsymbol{p}_i}{p_i^0} + \sum_j \frac{m_j}{p_j^0} \frac{\partial V_j}{\partial \boldsymbol{p}_i} \qquad \dot{\boldsymbol{p}}_i = -\sum_j \frac{m_j}{p_j^0} \frac{\partial V_j}{\partial \boldsymbol{r}_i}$$

  - **Relative distances $(r_i - r_j)^2$ are replaced with those in the two-body c.m.**
    → Potential becomes Lorentz scalar

When is negative v_1 slope generated ?

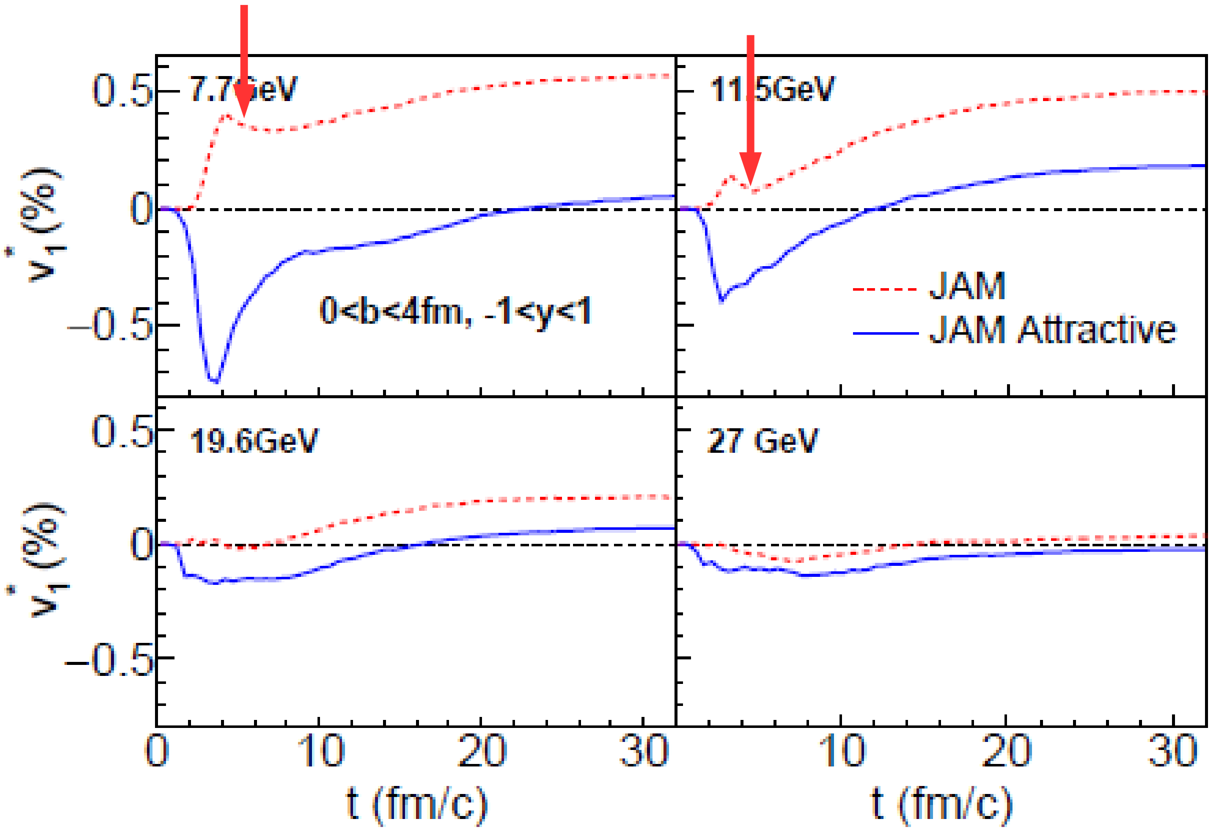
Nara, AO, Stöcker ('16)

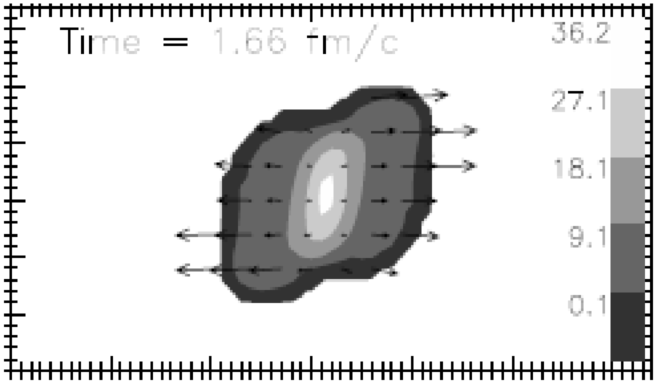


We need to make v_1 slope negative in the compressing stage.

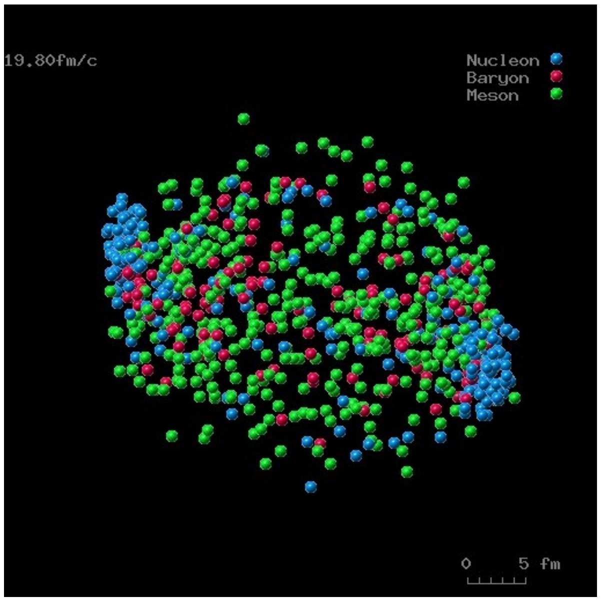
Tilted Ellipsoid ?

Nara, AO, Stöcker ('16)





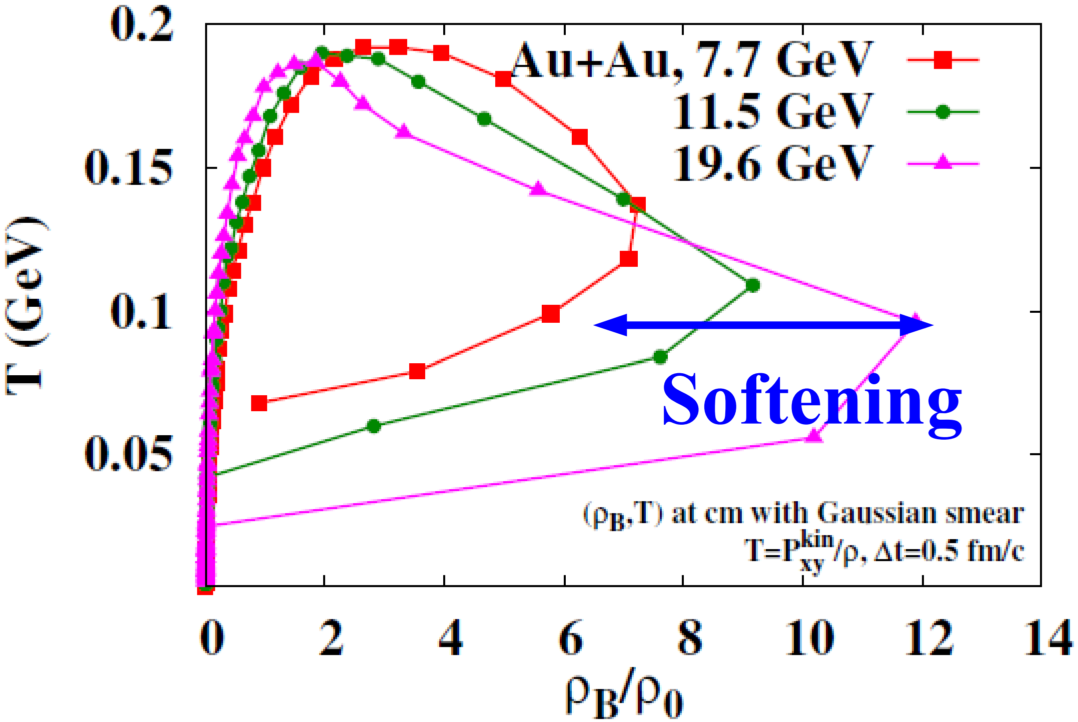
18 GeV, 3-fluid
Toneev et al. ('03)

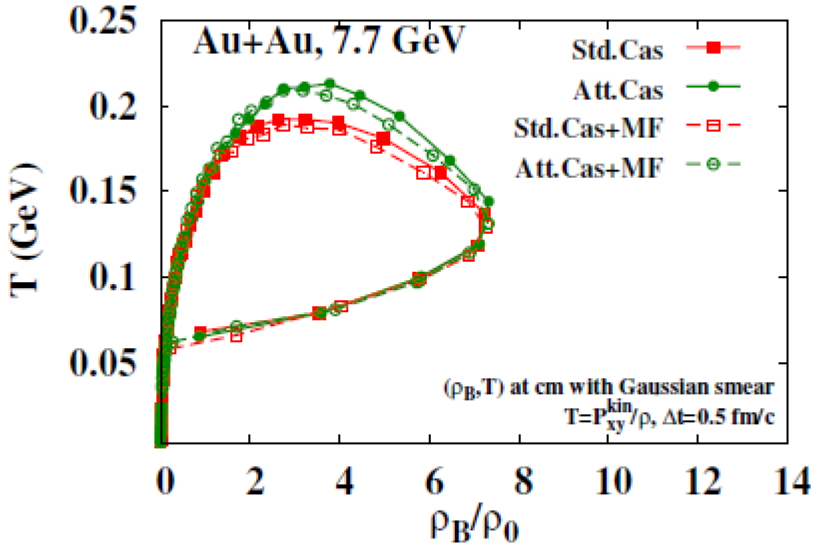


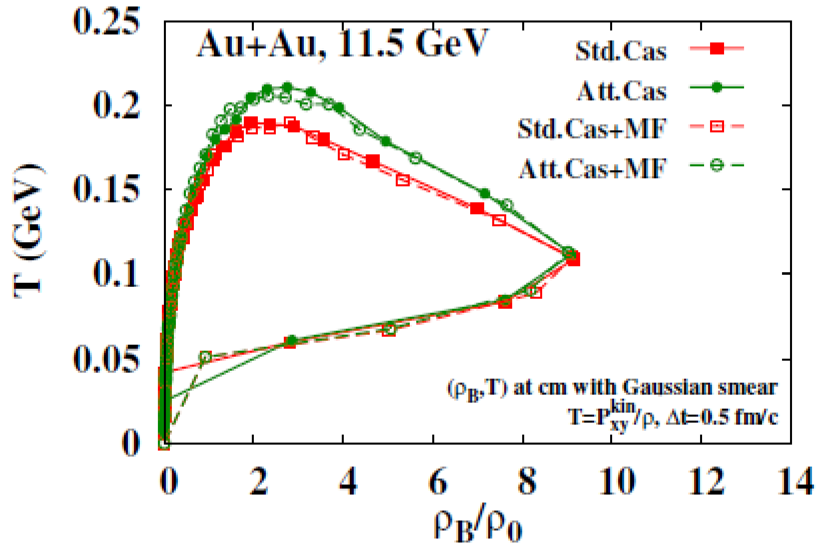
Transport model results also show tilted-ellipsoid-like behavior, but it is not enough.

Softening of EOS: Where and How much ?

- **“Softening” should take place at $\sqrt{s}_{NN}$=11.5 GeV → $\rho/\rho_B \sim$ (6-10)**
- **Attractive orbit**
  → Larger interactions
  & Higher T at later times







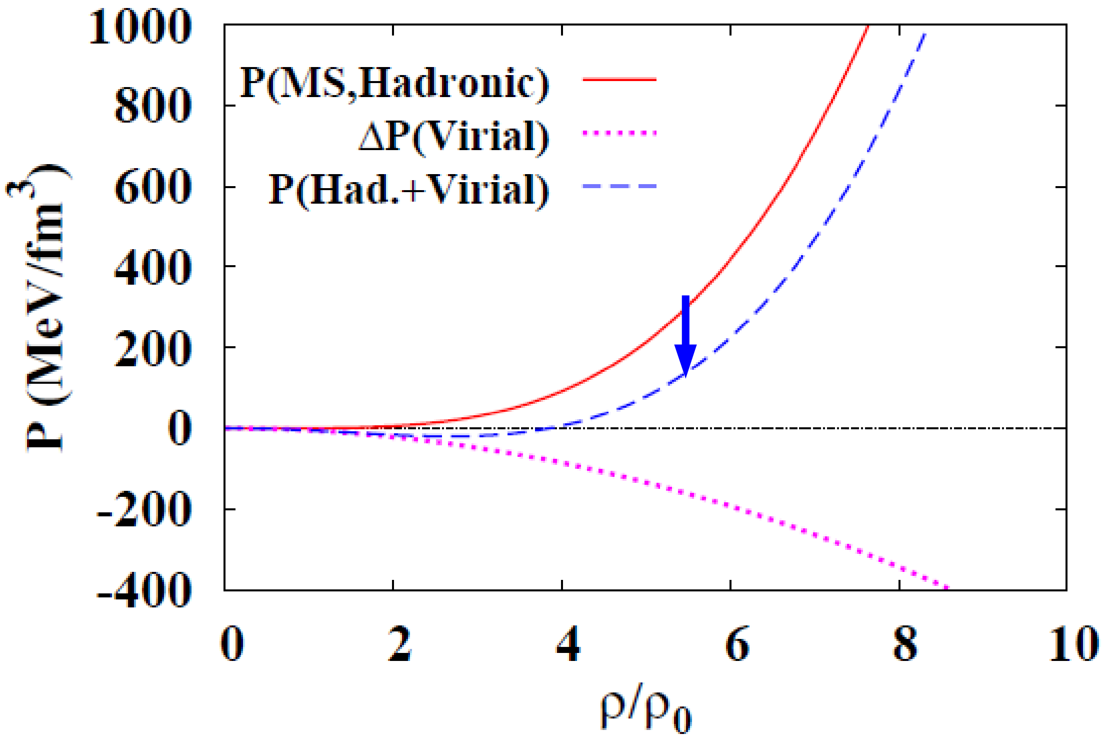
How much softening do we need ?

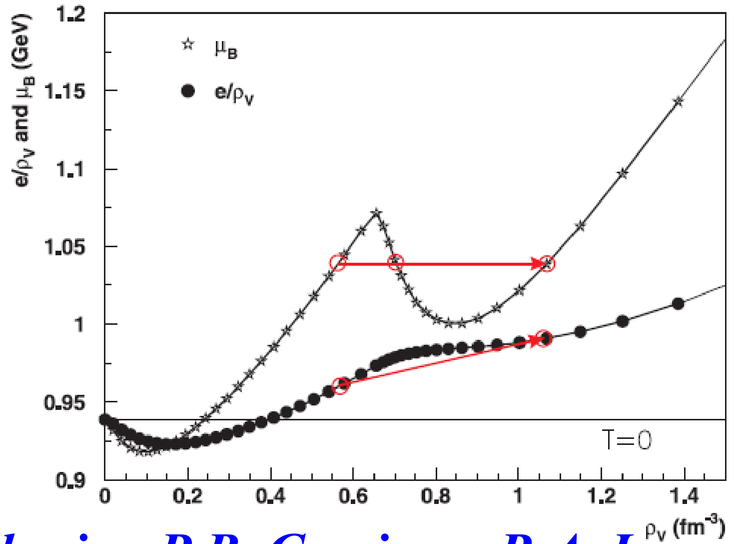
- **Virial theorem**

$$\Delta P = \frac{1}{3}\langle v\rho^2\sigma\mathbf{q}\cdot\mathbf{\Delta r}\rangle$$

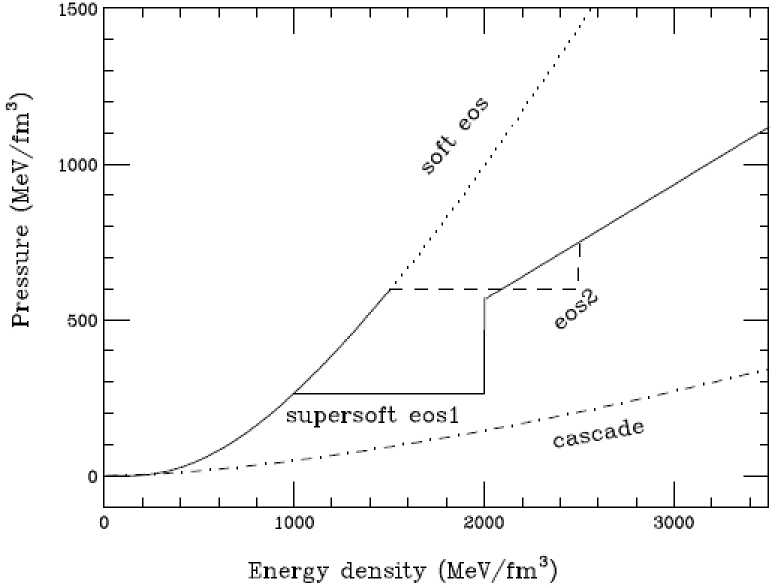
Simple esitmate:

σ= 30 mb, <q ΔR> ~ -1





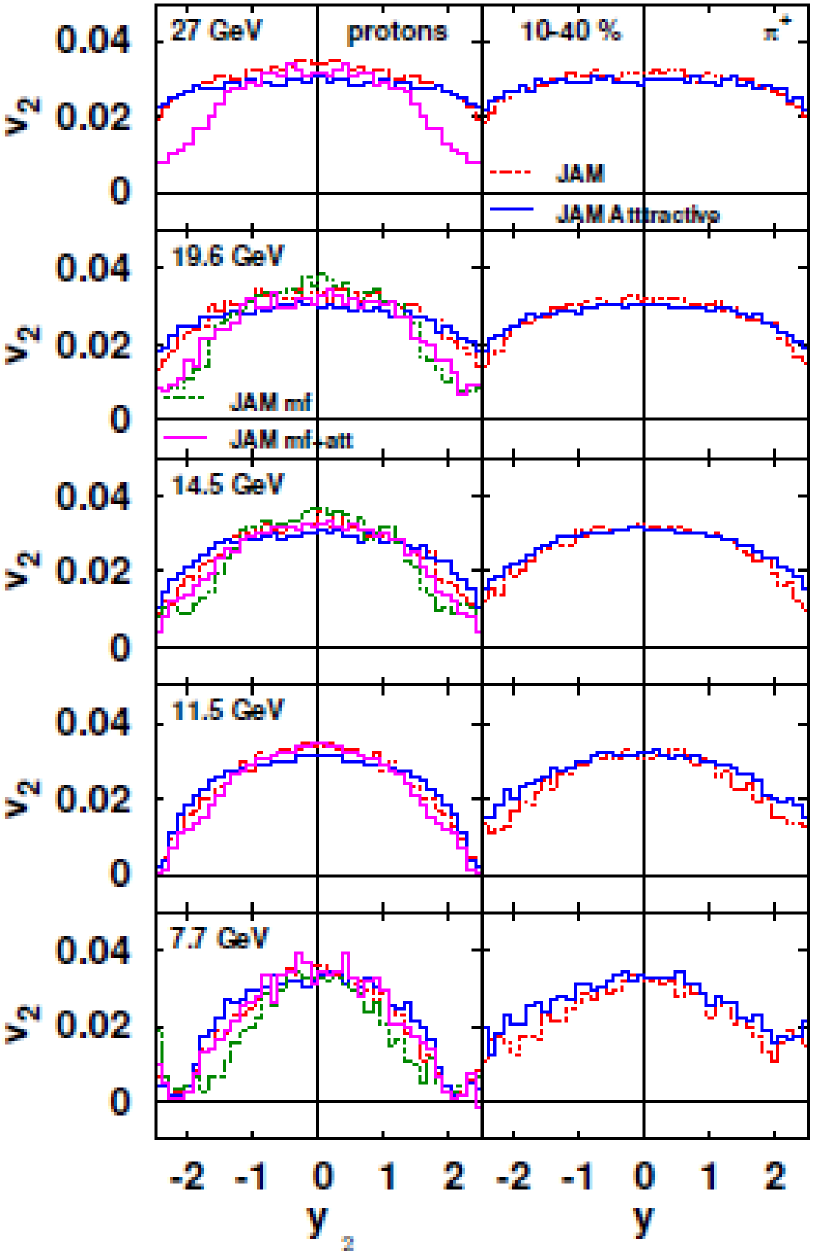
Danielewicz, P.B. Gossiaux, R.A. Lacey, ucl-th/9808013 (Les Houches 1998)



B. A. Li, C. M. Ko, PRC58 ('98) 1382

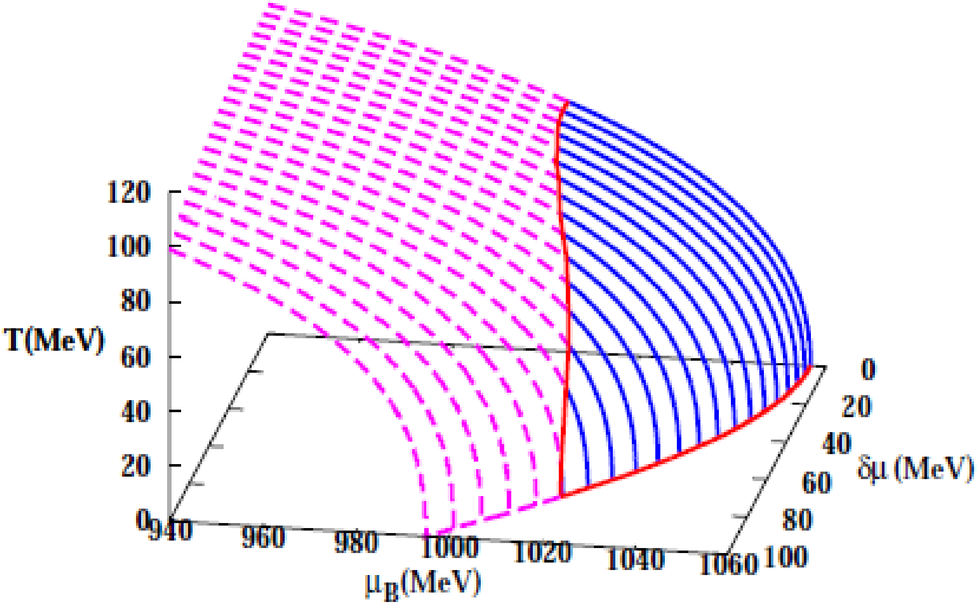
How about v_2 ?

- **Do we see softening effects in other observables, e.g. v_2 ?**
- **Yes, attractive orbits reduces proton v_2 by ~ 0.2 %.**
  (but there is no qualitative change.)



Relation to Neutron Star Matter

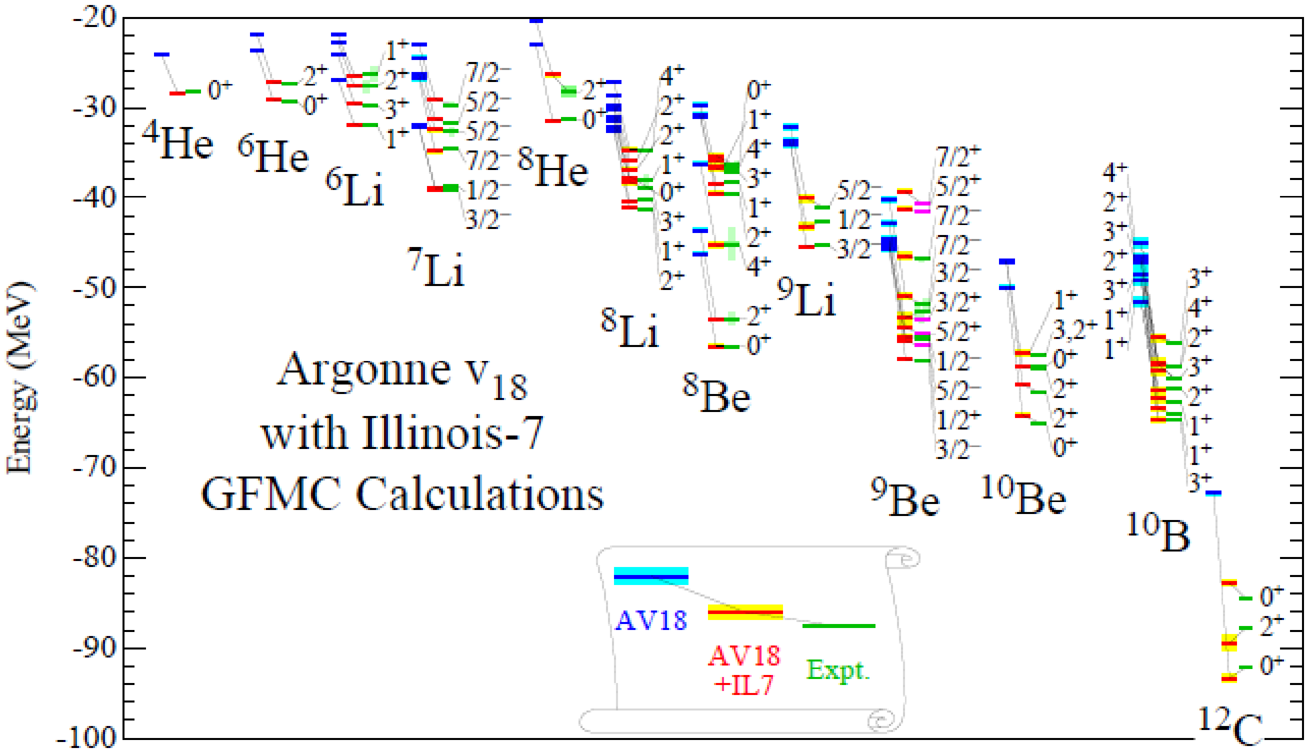
- **We may need early transition (2-5 ρ_0) to quark matter to solve the hyperon puzzle. Contradicting ?**
  → Temperature effects (T ~ 0 MeV & 100 MeV)
  Isospin chem. pot. (Weaker transition with finite δμ)
  Hyperon repulsion may push up the transition density.



AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284
H. Ueda, T. Z. Nakano, AO, M. Ruggieri, K. Sumiyoshi, PRD88('13),074006

What is necessary to solve the massive NS puzzle ?

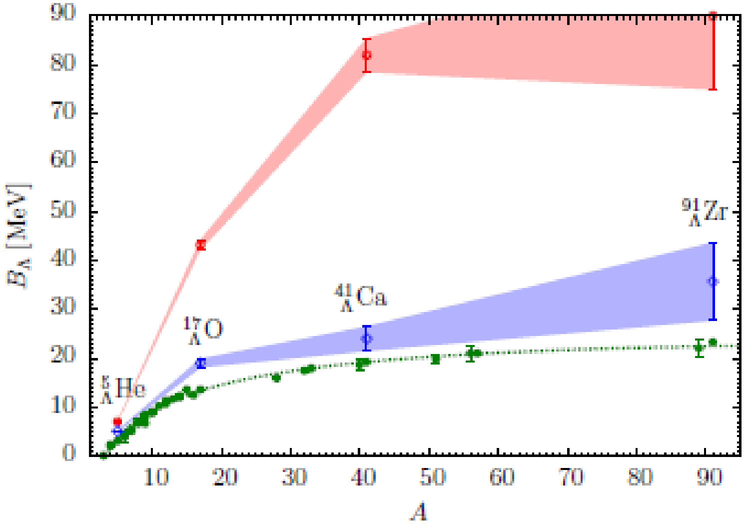
- **There are many "model" solutions.**
- **Ab initio calculation including three-baryon force (3BF)**
  - **Bare 2NF+Phen. 3NF(UIX, IL2-7) + many-body theory (verified in light nuclei).**
  - **Chiral EFT (2NF+3NF) + many-body theory**
  - **Dirac-Bruckner-HF (no 3NF)**



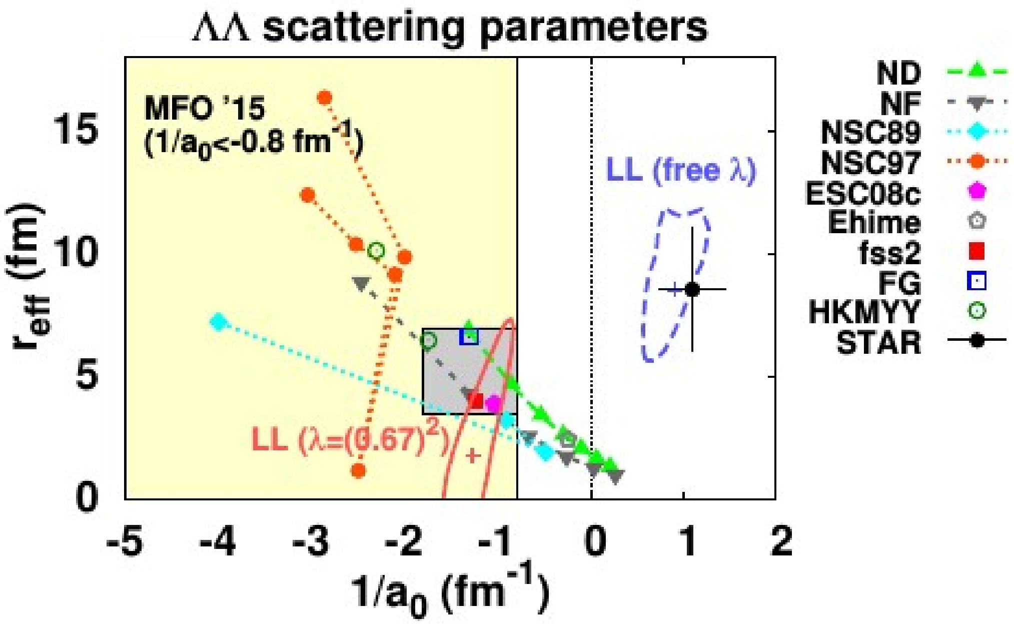
J. Carlson et al. ('14)

3BF including Hyperons

- **3BF incl. YNN, YYN and YYY should exist and contribute to EOS.**
  Nishizaki, Takatsuka, Yamamoto ('02)
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto, Suzuki; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Quant. MC study** *Lonardoni et al.('14)*
  - **Quark Meson Coupling**
    Miyatsu et al.; Thomas (HHIQCD)
  - **ΛΛN** *K. Morita, T. Furumoto, AO, PRC91('15)024916*



Caveat: Missing data



Relativistic Mean Field with Multi-body couplings

σωρ model +std. non-linear terms + multi-body couplings

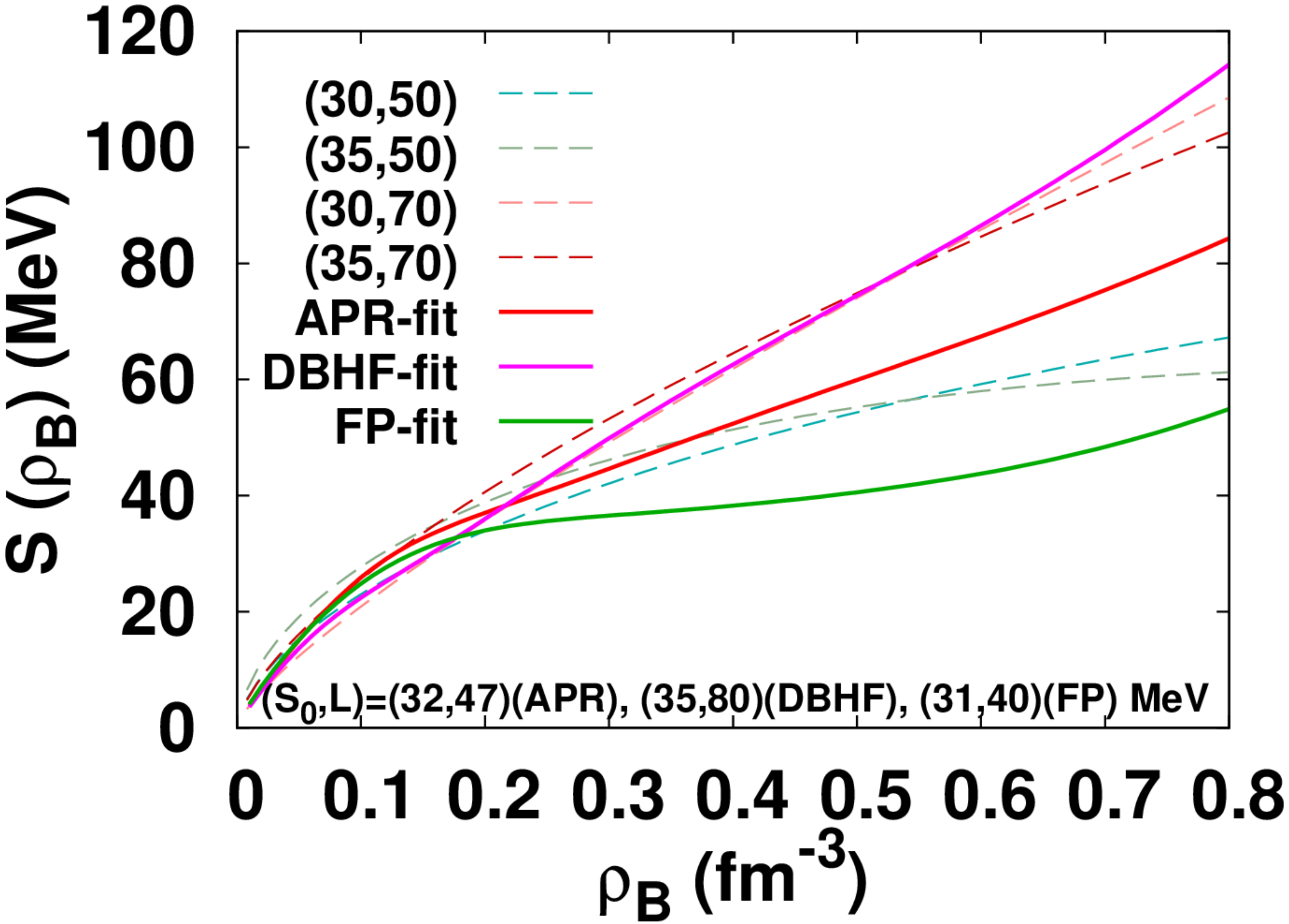
$$
\begin{aligned}
\mathcal{L}_N =& \bar{\psi}\left(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu\right)\psi + \mathcal{L}_{\sigma\omega\rho} \\
\mathcal{L}_{\sigma\omega\rho} =& \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}R_{\mu\nu}\cdot R^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho} \\
U_s =& -g_\sigma\,\sigma\ \boxed{\left[1 + r_{\sigma\sigma}(1-\sigma/f_\pi)\right] \quad + g_\sigma\omega^\mu\omega_\mu/f_\pi\ \left[r_{\omega\omega} + r_{\sigma\omega\omega}(1-\sigma/f_\pi)\right]} \\
U_\mu =& g_\omega\,\omega_\mu\ \boxed{\left[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2\right]} \\
& + g_\rho\,\boldsymbol{\tau}\cdot\boldsymbol{R}_\mu\ \boxed{\left[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2\right]} \\
\mathcal{V}_{\sigma\omega\rho} =& \frac{1}{2}m_\sigma^2\,\sigma^2 \boxed{- a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\left(\sigma^4 - 4f_\pi\sigma^3\right)} \\
& - \frac{1}{2}m_\omega^2\,\omega^\mu\omega_\mu \boxed{\left[1 - c_{\sigma\omega}\,\sigma/f_\pi\right]}\boxed{- \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2} \\
& - \frac{1}{2}m_\rho^2\,\boldsymbol{R}^\mu\cdot\boldsymbol{R}_\mu\ \boxed{\left[1 - c_{\sigma\rho}\,\sigma/f_\pi + c_{\omega\rho}\,\omega^\mu\omega_\mu/f_\pi^2\right]\ - \frac{1}{4}c_{\rho 4}\left(\boldsymbol{R}^\mu\cdot\boldsymbol{R}_\mu\right)^2}
\end{aligned}
$$

$$
f_{\log}(x) = \log(1-x) + x + \frac{1}{2}x^2 \qquad a_\sigma = f_\pi^2(m_\sigma^2 - m_\pi^2)/2 - f_\pi^4 c_{\sigma 4}
$$

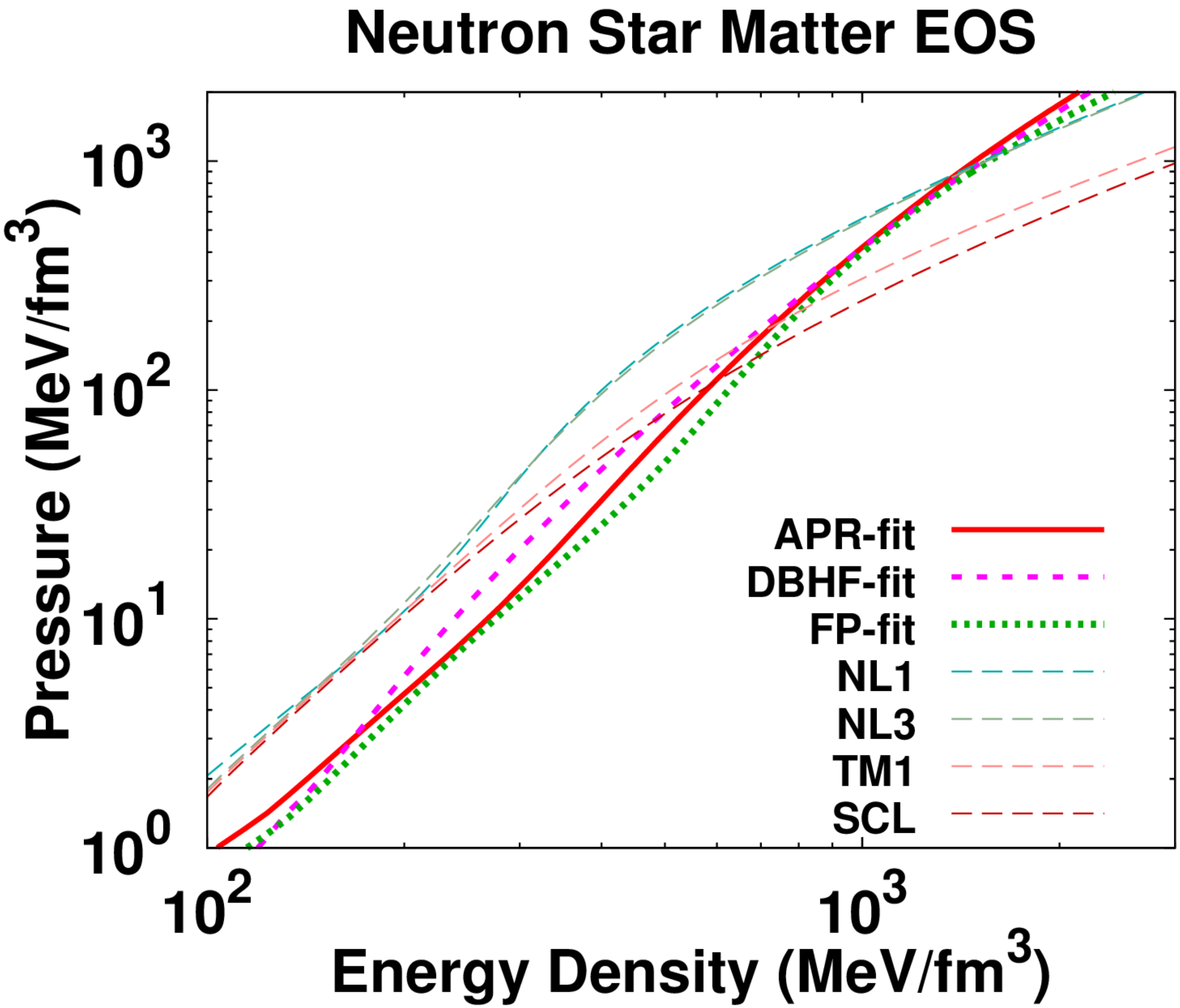
Fitting “Ab initio” EOS via RMF

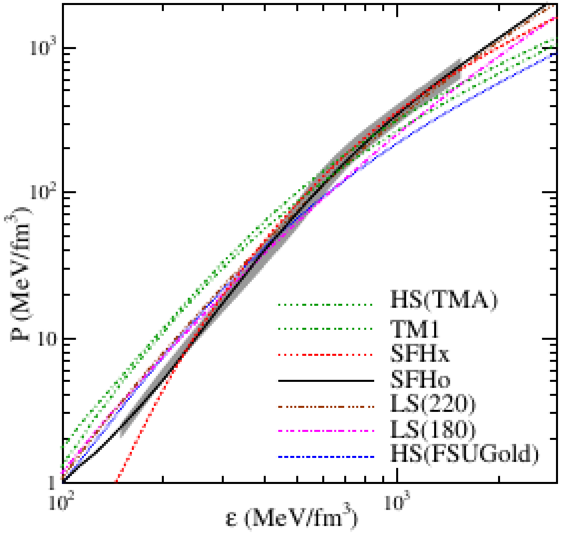
- “Ab initio” EOS under consideration
  - FP: Variational calc. (Av14+3NF(att.+repl.))
    B. Friedman, V.R. Pandharipande, NPA361('81)502.
  - APR: Variational chain summation (Av18+ rel. corr.+3NF)
    A. Akmal, V.R.Pandharipande, D.G. Ravenhall, PRC58('98)1804.
  - DBHF: Dirac Bruckner approach (Bonn A)
    G. Q. Li, R. Machleidt, R. Brockmann, PRC45('92)2782
- RMF with multi-body couplings: 16 parameters
  - n=3 *Tsubakihara, AO, NPA914 ('13), 438.*
  - Working hypothesis: σ self-energy: SCL2 model *Tsubakihara, AO ('07)*
    $M_N \to 0$ @ $\sigma \to f_\pi$
- Markov Chain Monte-Carlo (MCMC)-like parameter search
  - Langevin type shift+Metropolis judge
  - Simultaneous fit of SNM and PNM → std. dev=0.5-1.0 MeV

Symmetry Energy



Neutron Star Matter EOS

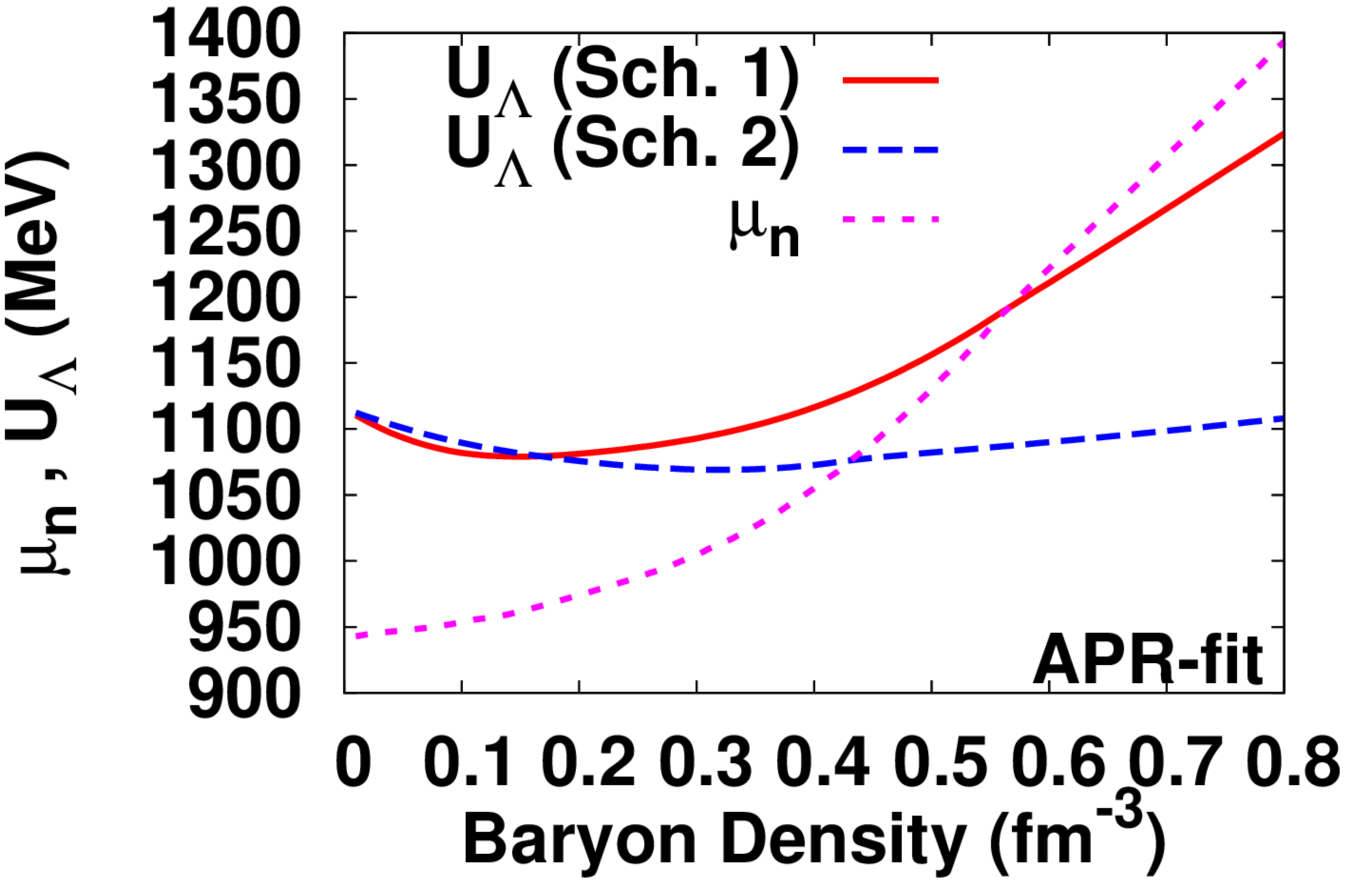




A. W. Steiner, M. Hempel, T. Fischer, ApJ 774 (2013) 17 (TMA+NSE w/ excl. vol.)

NS matter in "ab initio"-fit + Λ

- **Λ potential in nuclear matter at ρ_0 ~ -30 MeV**
  - **Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$**
  - **Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$**



M-R curve of Neutron Stars