High Density EOS – Heavy-Ion Collisions, Compact Stars and Strangeness –

Akira Ohnishi (YITP, Kyoto U.)

Quarks and Compact Stars 2017
Feb.19-22, 2017, Kyoto, Japan

2017 KYOTO JAPAN

- **Introduction**
- **EOS softening probed in heavy-ion collisions**
- **Compact star matter EOS and Strangeness**
- **Summary**

Contents

- **Request from organizers (Muto)**
  Review of dense matter & strangeness nuclear physics with emphasis on heavy-ion physics and QGP formation
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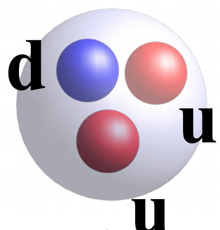
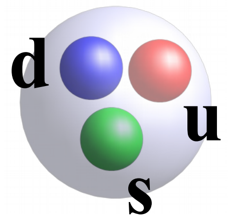
Neutron star – Is it made of neutrons ?

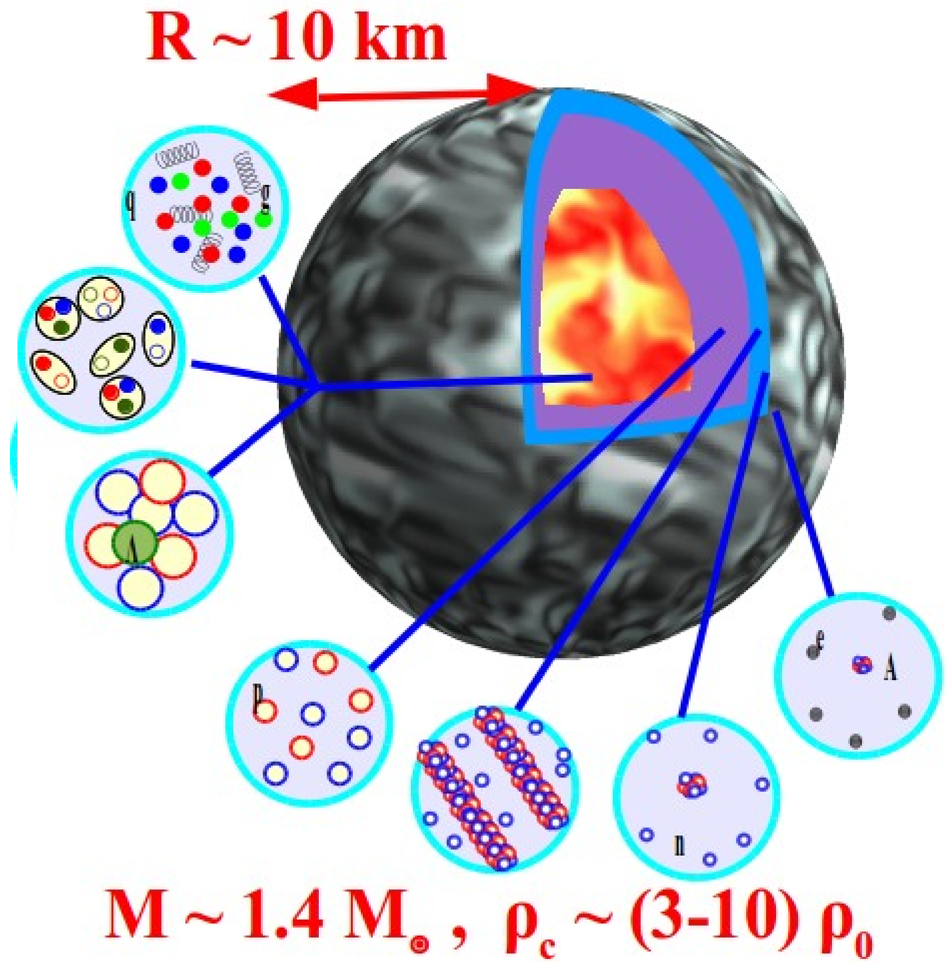
- **Possibilities of various constituents in neutron star core**
  - **Strange Hadrons**



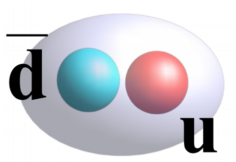
proton



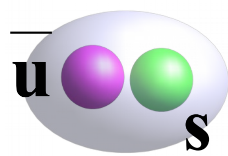
Λ hyperon



  - **Meson condensate (K, π)**

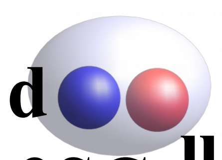


π



anti kaon

  - **Quark matter**
  - **Quark pair condensate (Color superconductor)**



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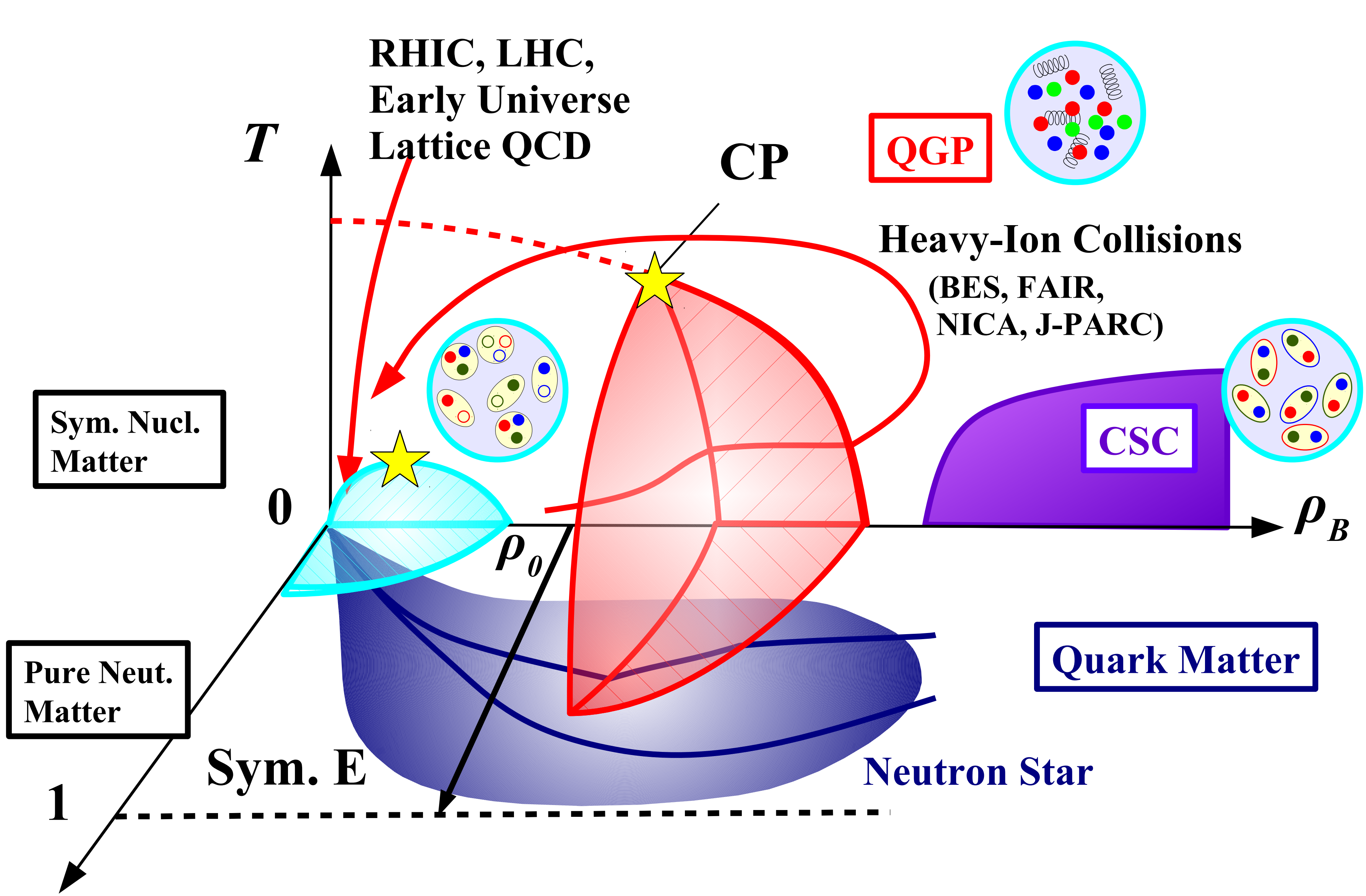
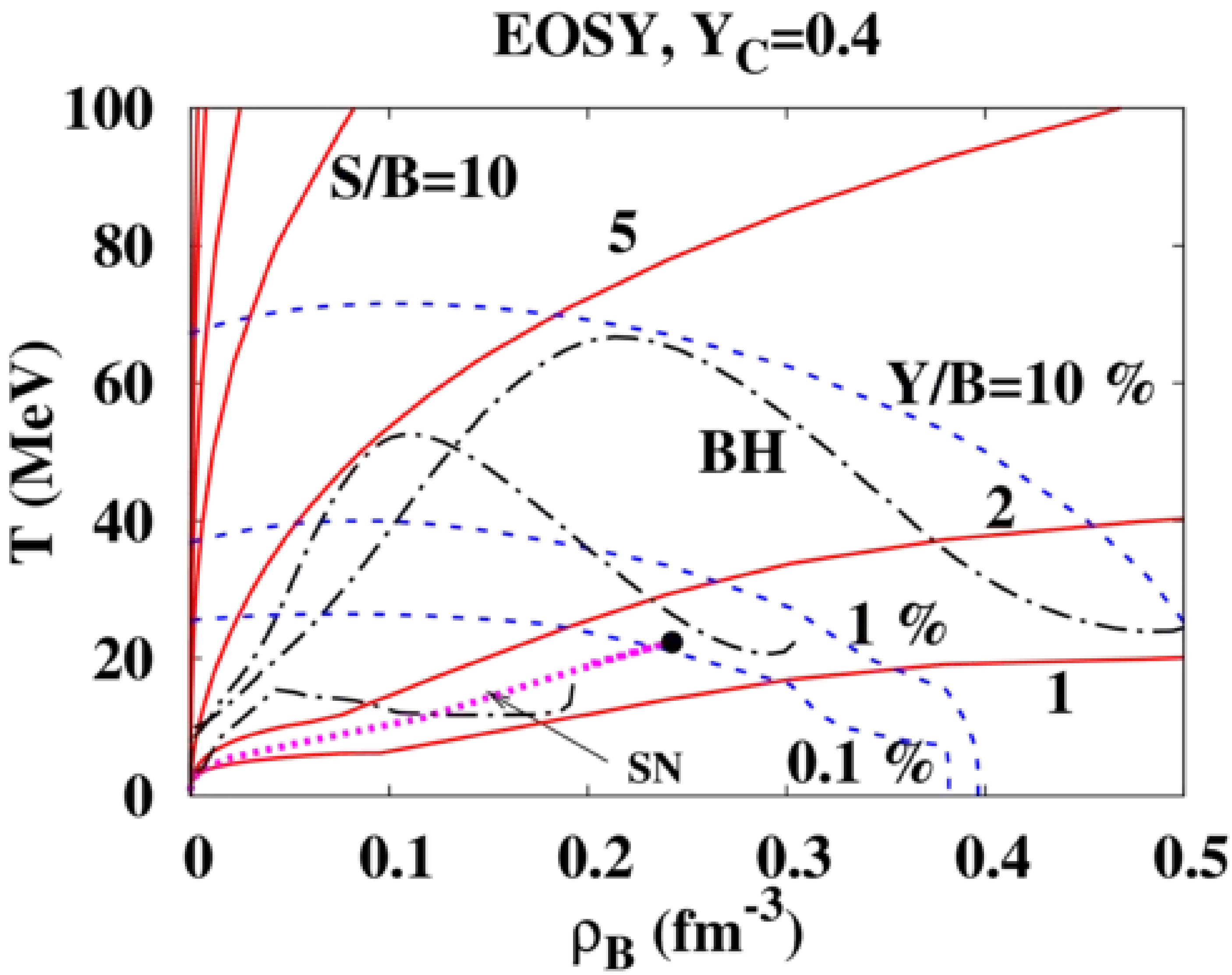
> ***NS core = Densest stable matter existing in our universe.***

QCD Phase Diagram



$\delta=(N-Z)/A$ (or $Y_Q(hadron)=Q_h/B \sim (1-\delta)/2$)

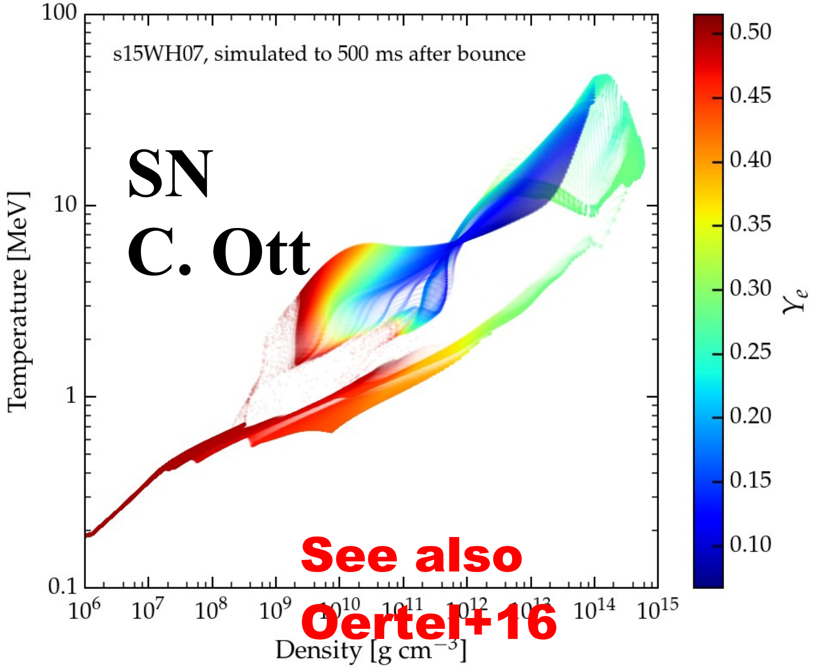
(ρ, T) during SN & BH formation

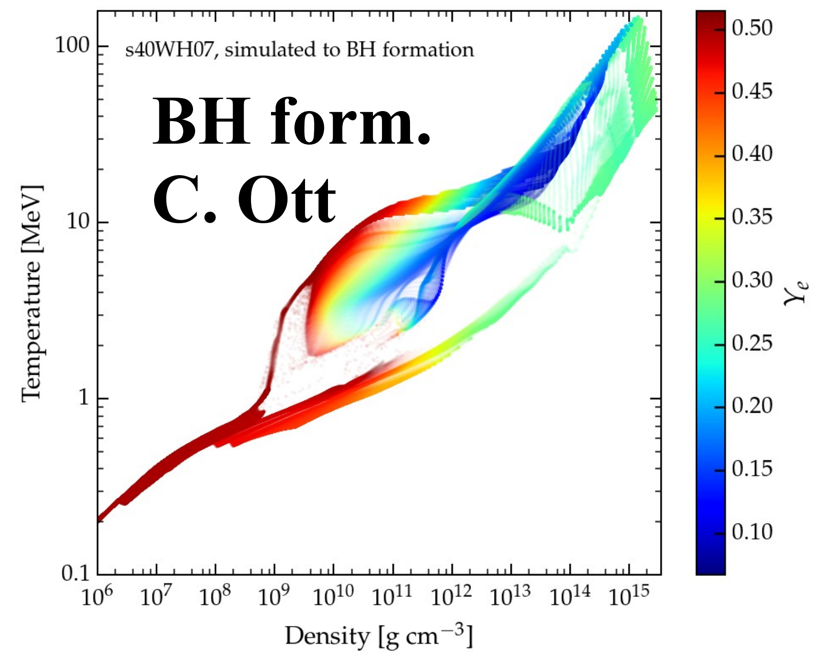


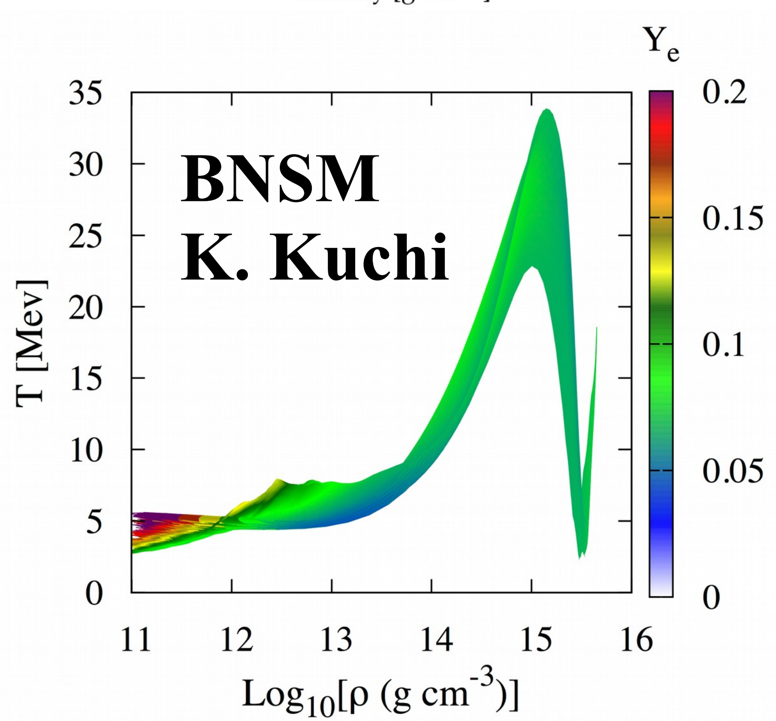
Shen EOS + hyperons

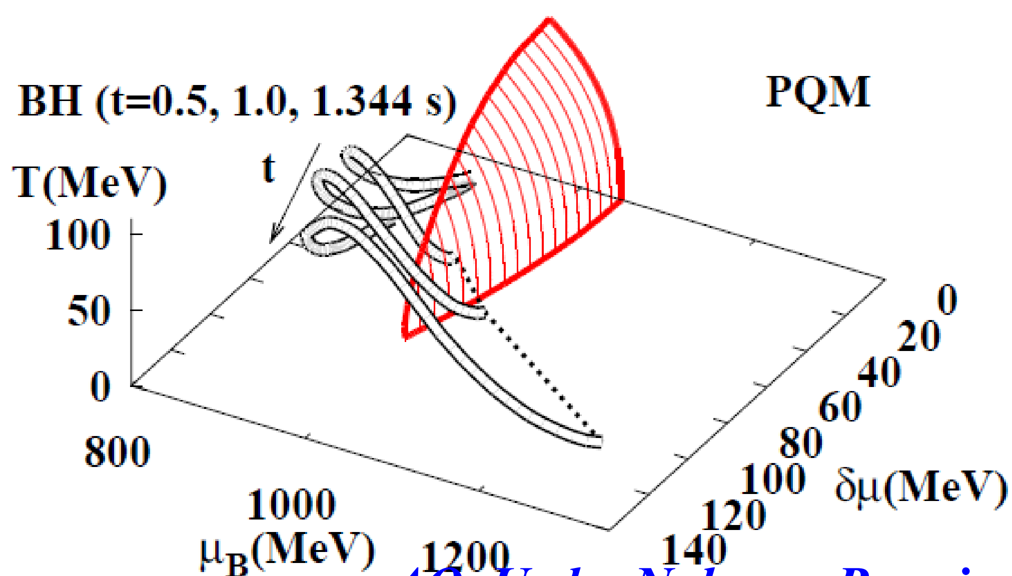
Ishizuka,AO, Tsubakihara, Sumiyoshi, Yamada, JPG 35('08) 085201; AO et al., NPA 835('10) 374.

(ρ, T, Y_e) during SN, BH formation, BNSM



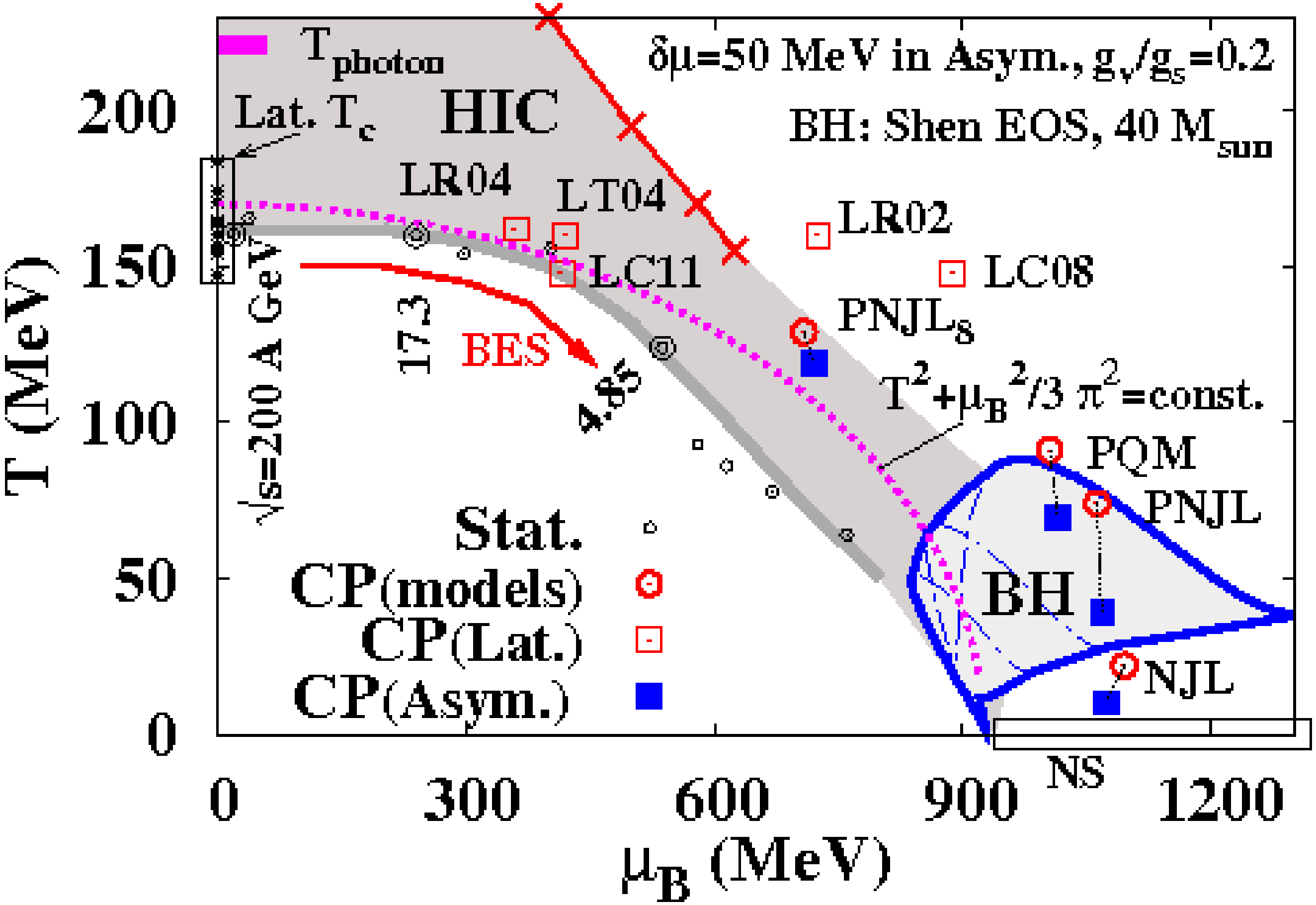






AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284

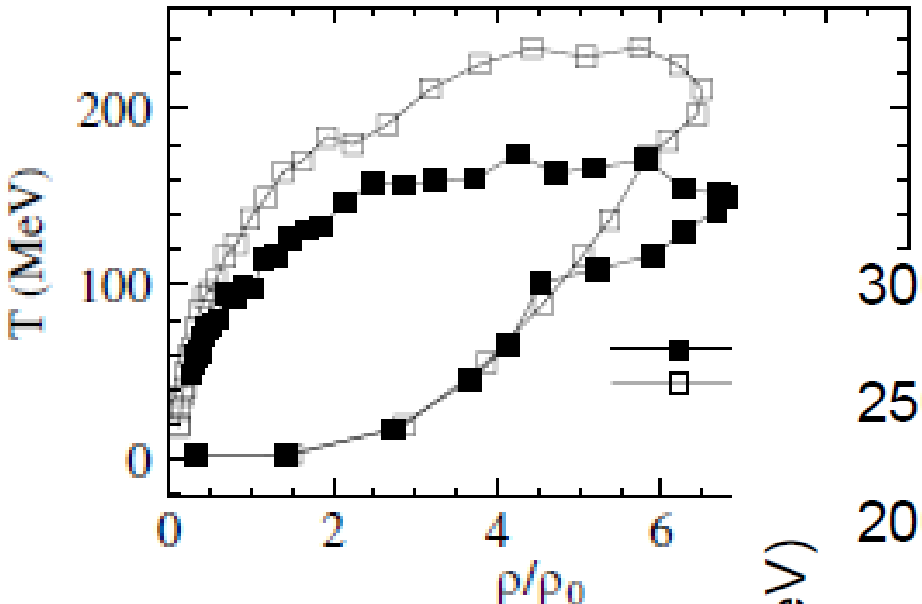
QCD phase diagram (Exp. & Theor. Studies)



QCD phase transition is not only an academic problem, but also a subject which would be measured in HIC or Compact Stars

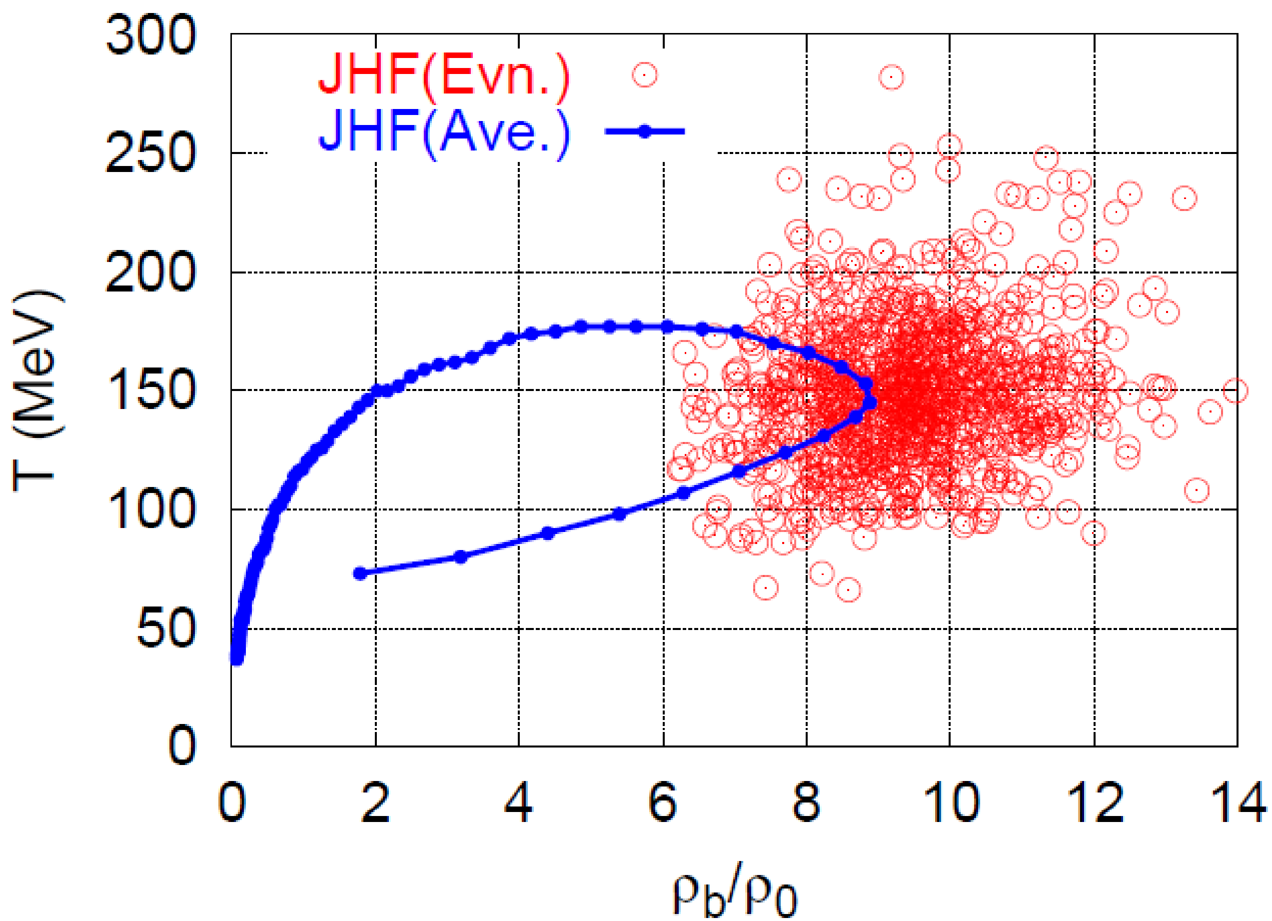
AO, PTPS 193('12)1

Highest Density Matter at J-PARC ?



Nara, Otuka, AO,
Maruyama ('97)

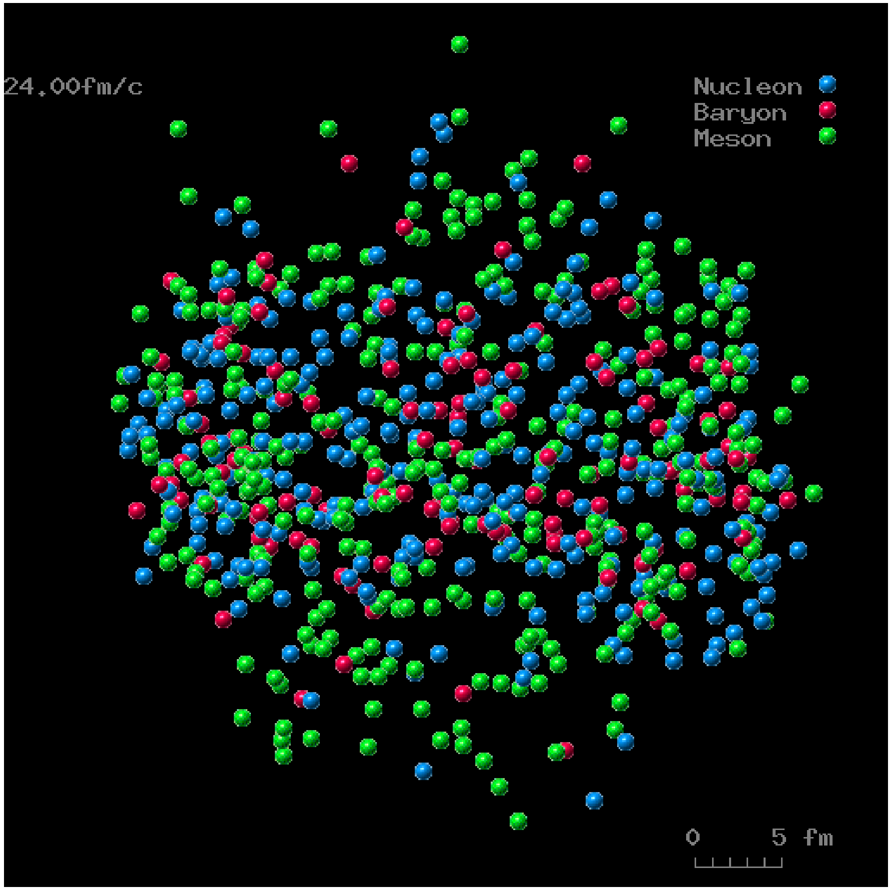
AO, JHF workshop ('02);
J. Phys. Conf. Ser. 668 ('16)012004



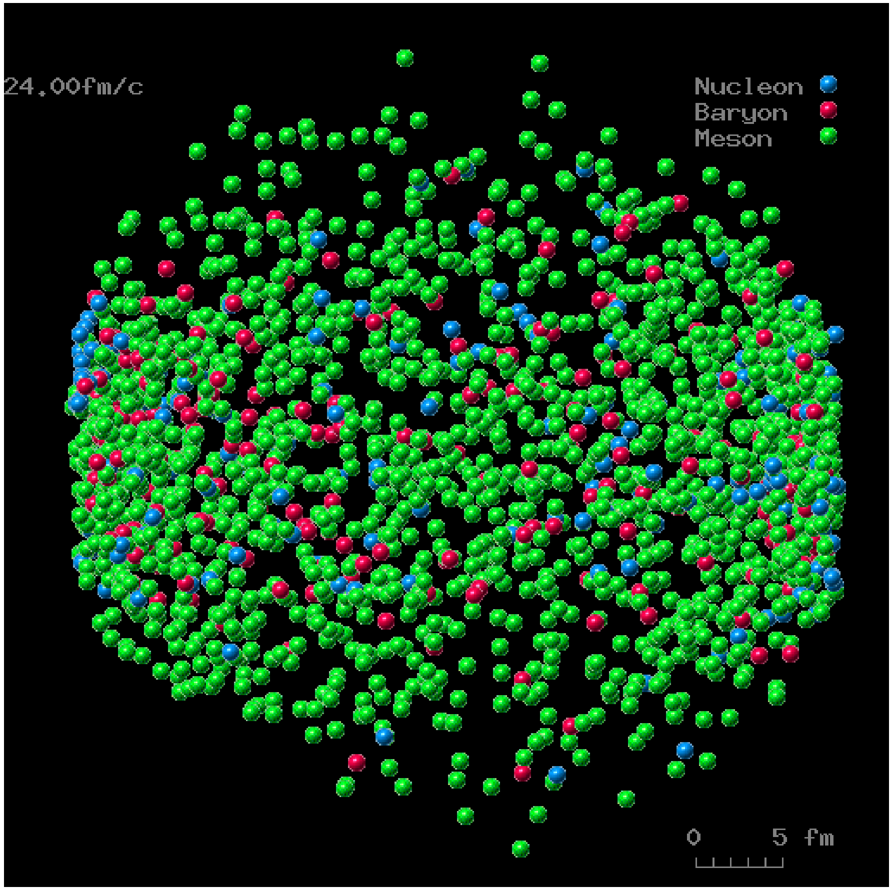
Central 1 fm^3 cube.

How do heavy-ion collisions look like ?

Au+Au, 10.6 A GeV



Pb+Pb, 158 A GeV



JAMming on the Web http://www.jcprg.org/jow/

Contents & Conclusions

- **Request from organizers (Muto)**
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- **Conclusions**
  - **We may find a (first-order) QCD phase transition at $\sqrt{s_{NN}}$=(5-20)GeV (J-PARC energy) via collective flow analysis.**
  - **Massive NSs imply stiff EOS at isospin asymmetric dense matter, and suggest (at least) one of 3B repulsive force, transition to stiff quark matter, or modified gravity is necessary.**

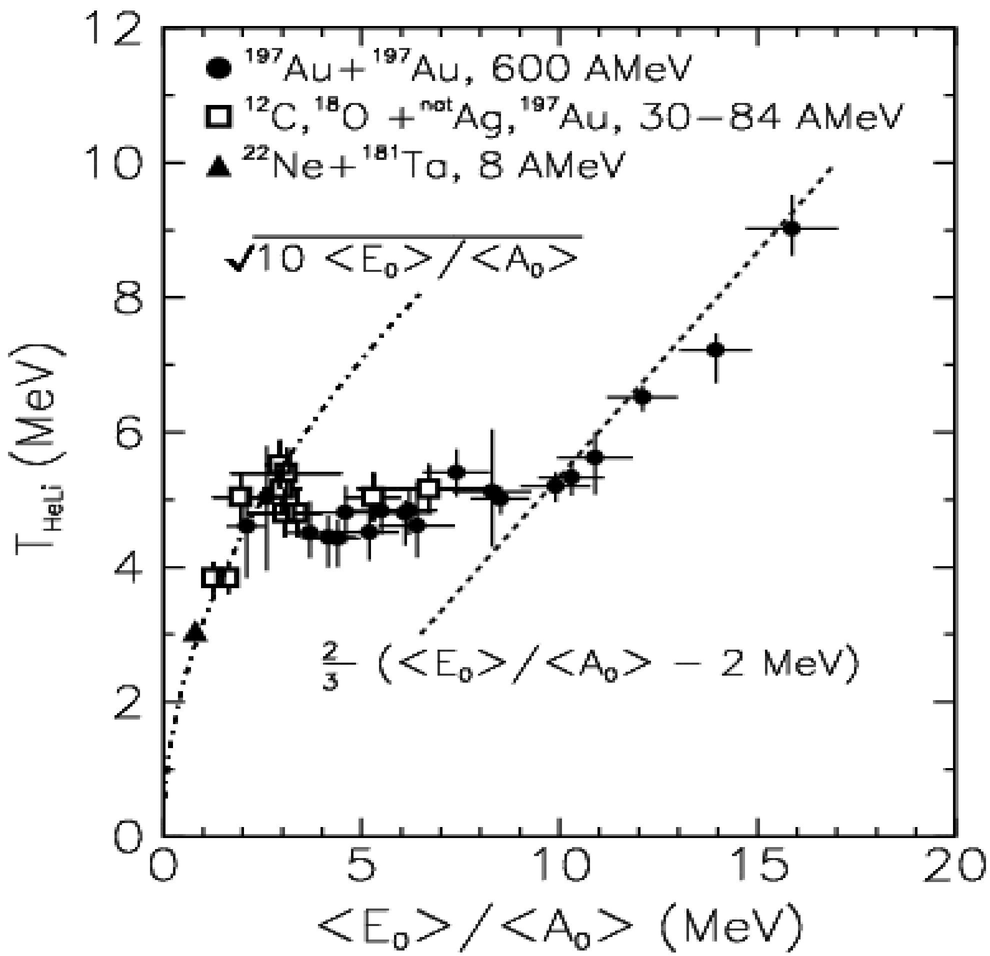
EOS softening probed in heavy-ion collisions

QCD phase transition

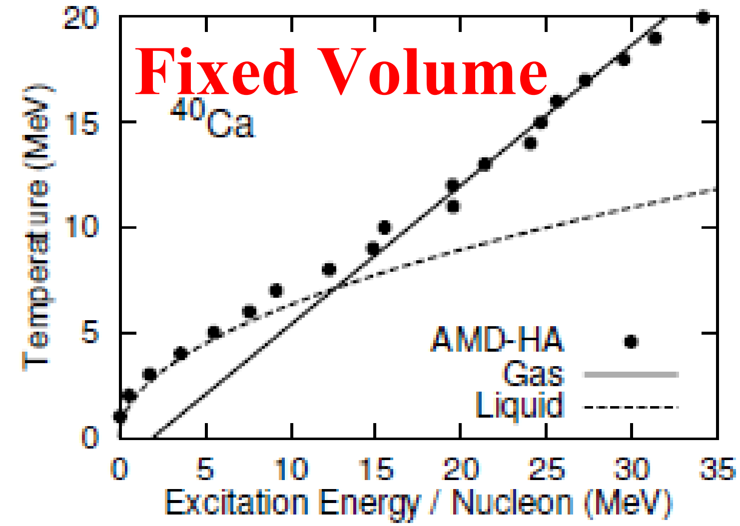
- **QCD phase transition at top RHIC & LHC energies**
  - **Jet quenching, Nuclear Modification Factor (Energy loss), Statistical Hadron Production, Parton Collectivity (v_2), …**
    → QGP formation
  - **Crossover (lattice QCD)**
- **One of Next Grand Challenges**
  =Detecting 1st or 2nd order phase transition in QCD

Nuclear Liquid-Gas Phase Transition

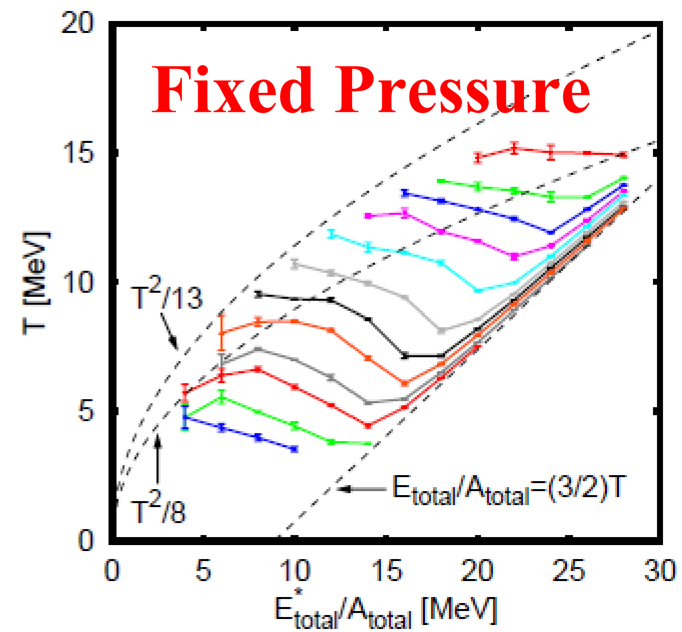
- **Caloric curve → LG phase transition (Smoking gun)**



J. Pochadzalla et al. (GSI-ALLADIN collab.), PRL 75 (1995) 1040.

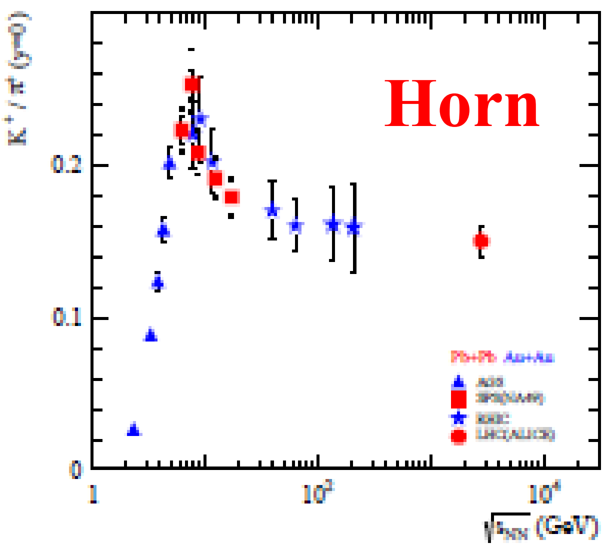


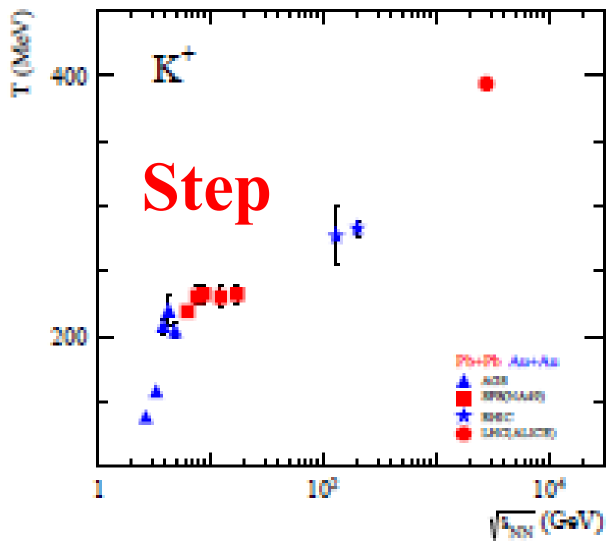
AO, Randrup ('98)

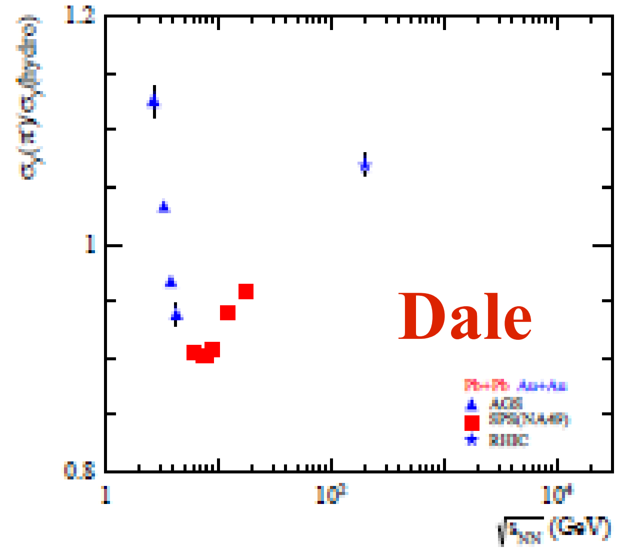


T. Furuta, A.Ono ('09)

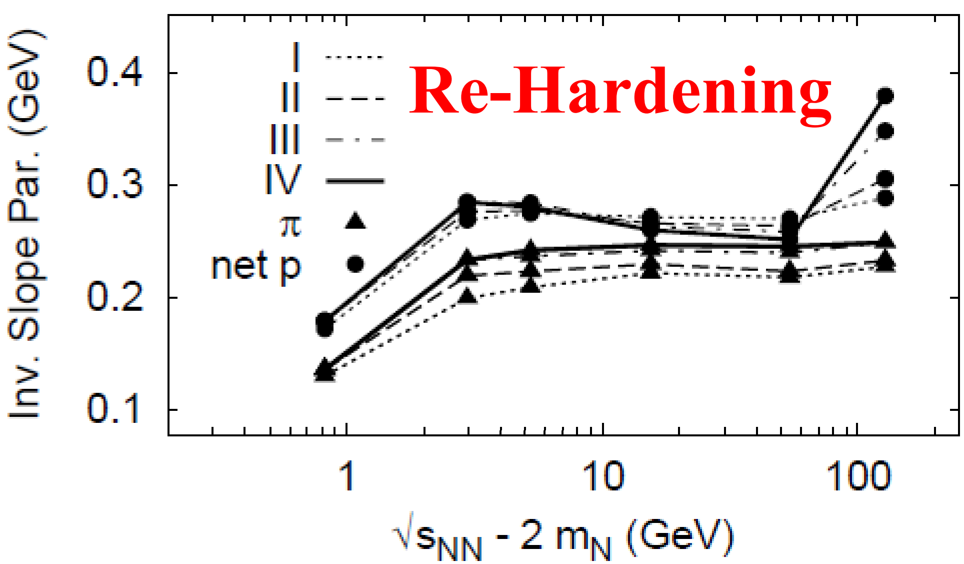
- **Non-monotonic behavior in K^+/π^+ ratio (Horn), m_T slope par. (Step or re-hardening), rapidity dist. width of π**







E.g. A. Rustamov (2012)



N. Otuka, P.K.Sahu, M. Isse, Y. Nara, AO, nucl-th/010205

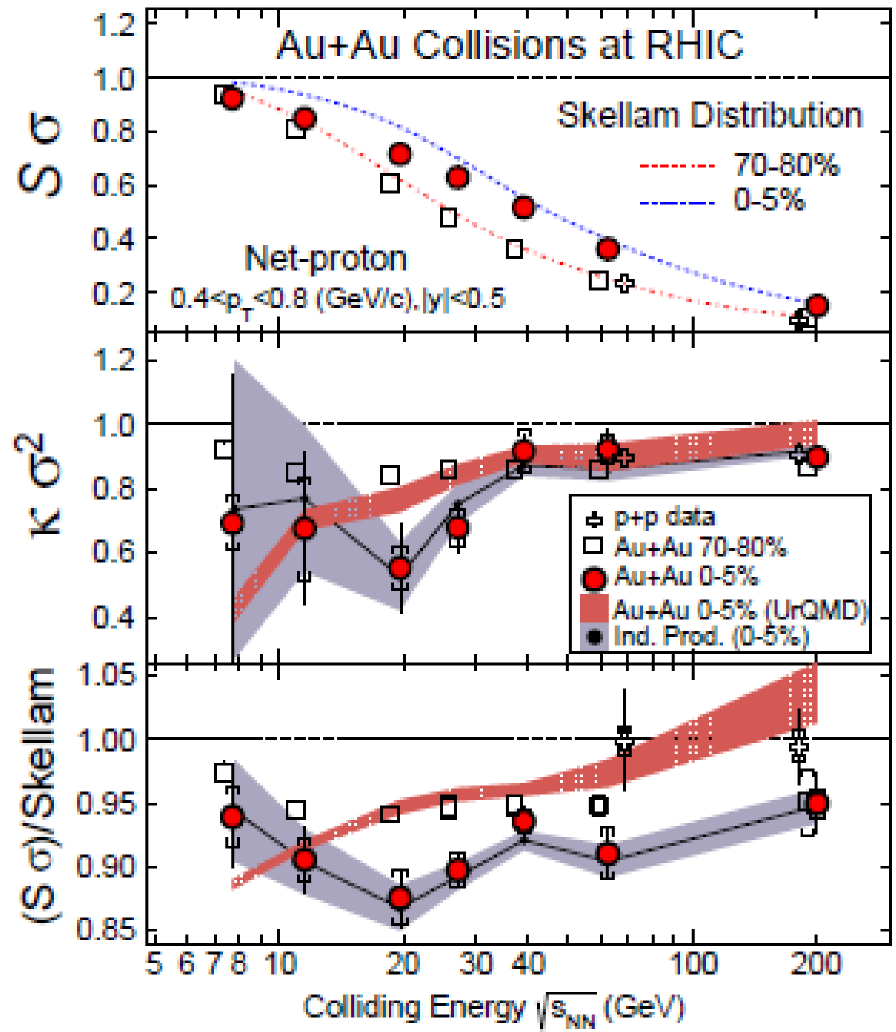
QCD phase transition

- **QCD phase transition at top RHIC & LHC energies**
  - **Jet quenching, Nuclear Modification Factor (Energy loss), Statistical Hadron Production, Parton Collectivity (v_2), …**
    → QGP formation
  - **Crossover (lattice QCD)**
- **One of Next Grand Challenges**
  =Detecting 1st or 2nd order phase transition in QCD
  - **(Partial) Chiral restoration → Modification of hadron properties**
  - **Critical Point → Large fluctuation of conserved charges**
  - **First-order phase transition → Softening of EOS**

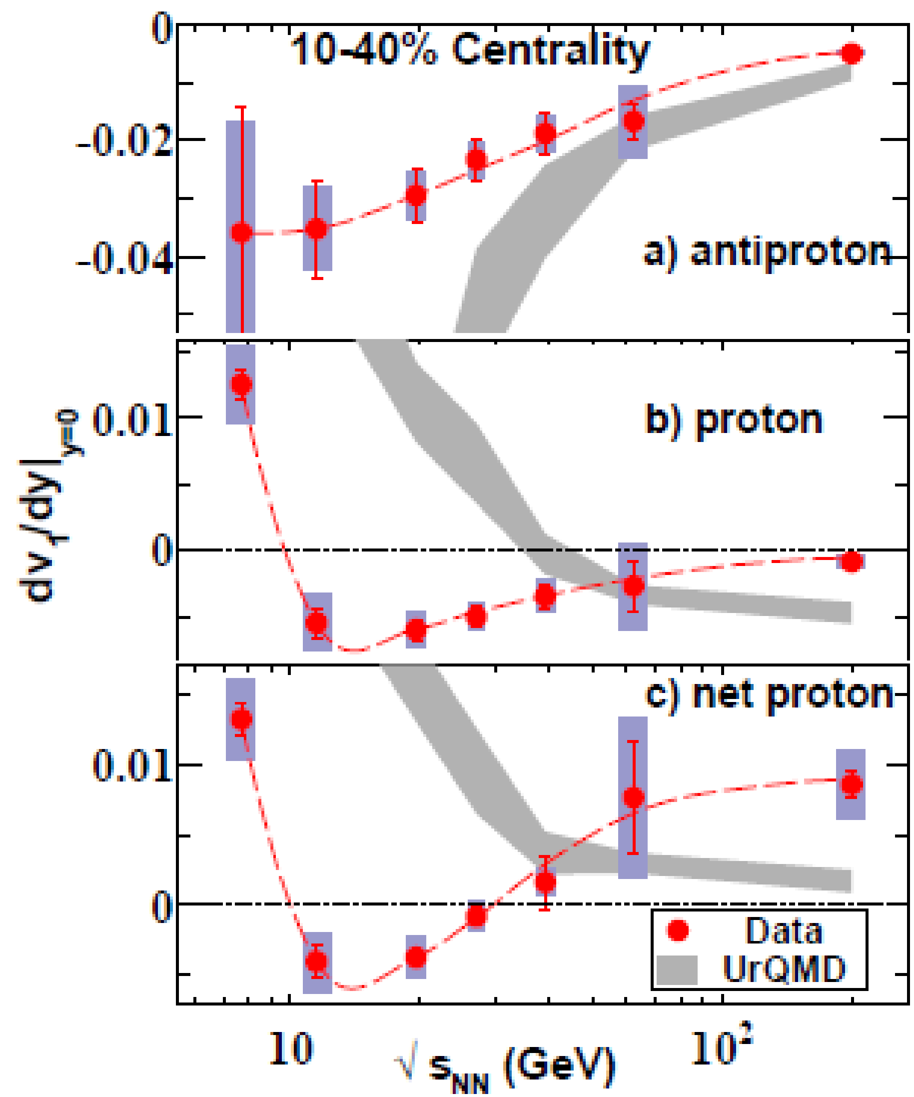
→ Non-monotonic behavior of proton number moment ($\kappa\sigma^2$) and collective flow (dv_1/dy)

Net-Proton Number Moments & Directed Flow

- Non-monotonic behavior of $\kappa\sigma^2$ and dv_1/dy. CP & FOPT signal ?

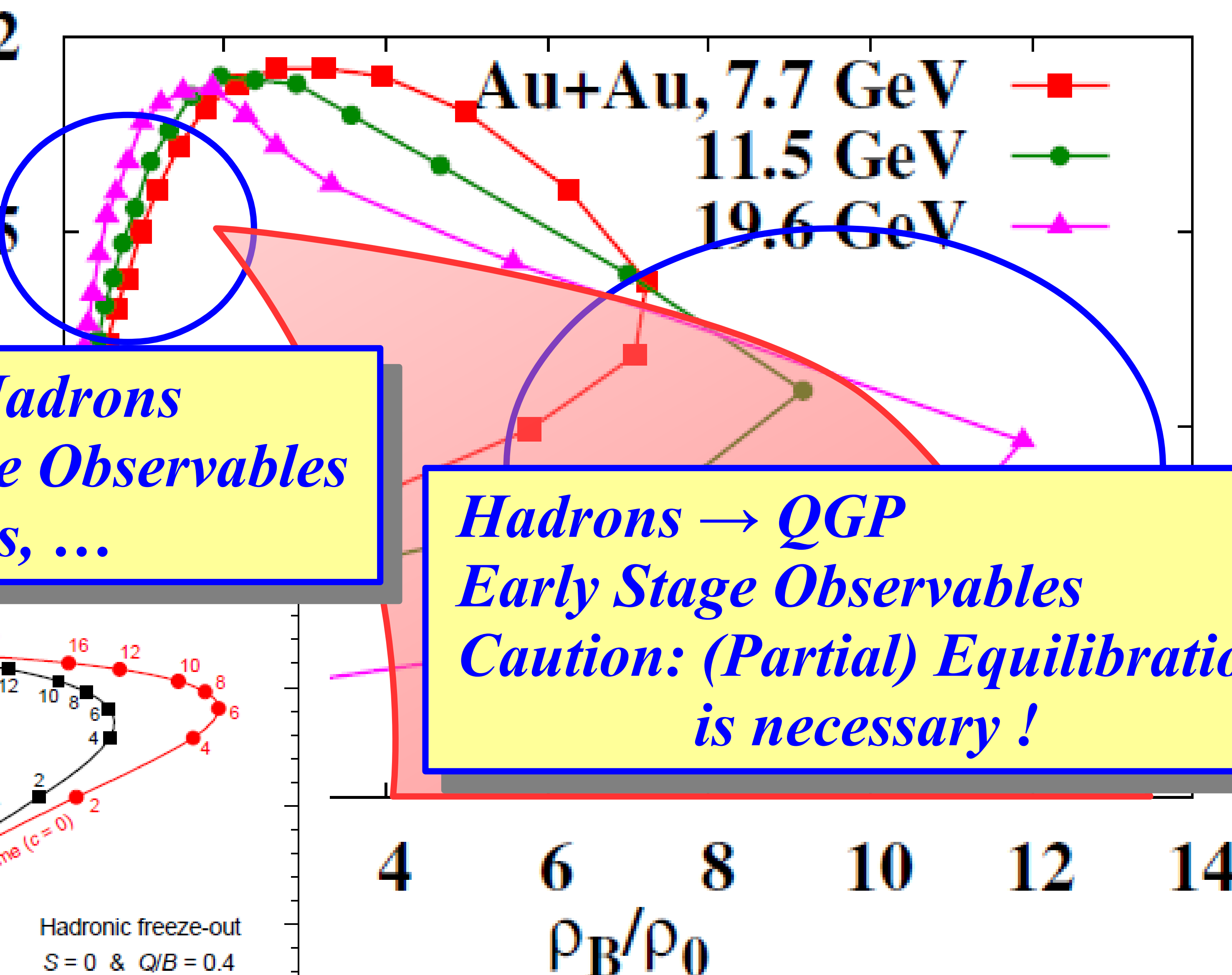


STAR Collab. (PRL 112('14)032302



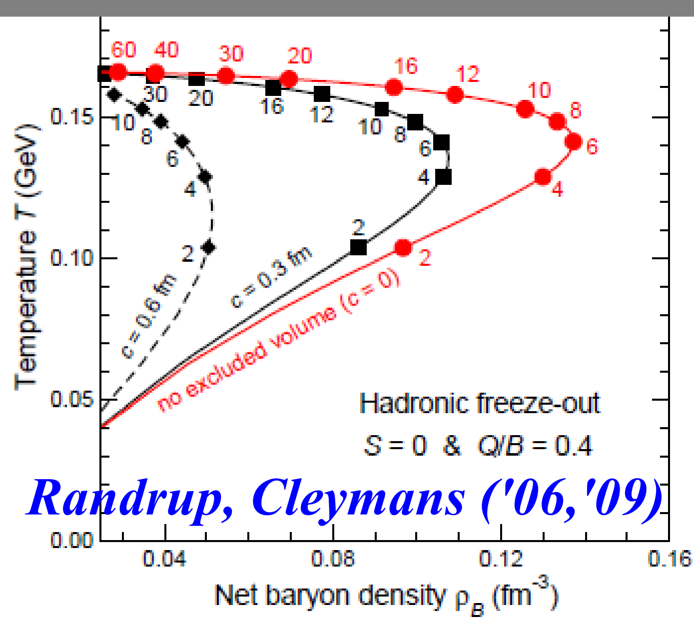
STAR Collab., PRL 112('14)162301.

Two ways to probe QCD phase transition



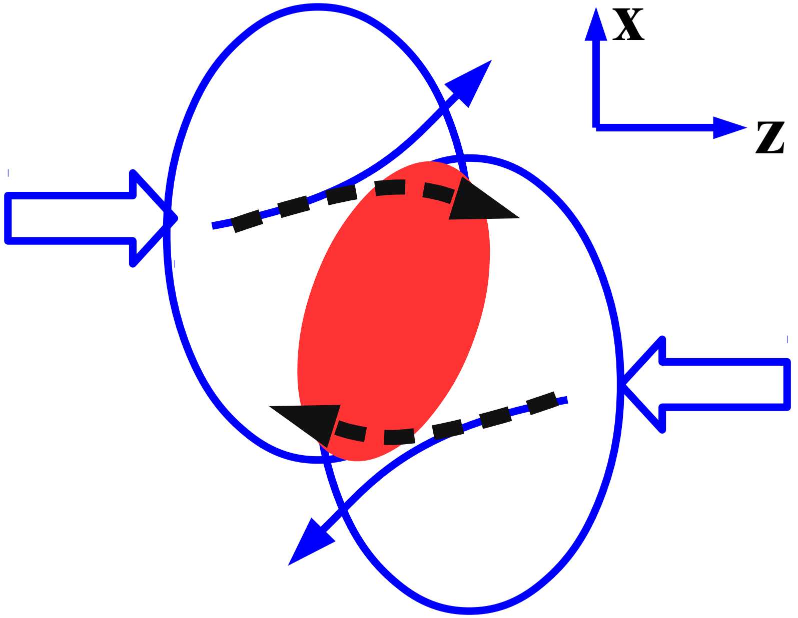
QGP → Hadrons
Final State Observables
Cumulants, …

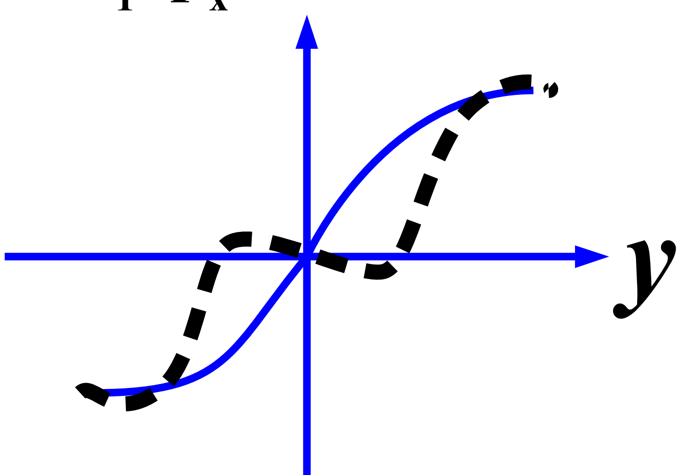
Hadrons → QGP
Early Stage Observables
Caution: (Partial) Equilibration is necessary !



Randrup, Cleymans ('06,'09)

What is directed flow ?





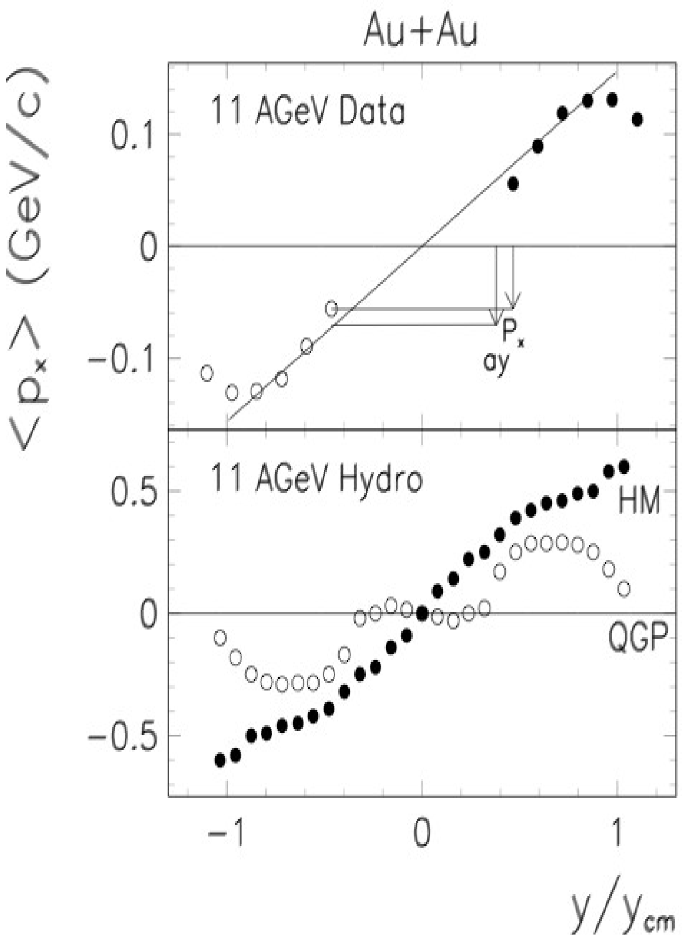
- v_1 or $\langle p_x \rangle$ as a function of y is called directed flow.
- Created in the overlapping stage of two nuclei
  → Sensitive to the EOS in the early stage.
- Becomes smaller at higher energies.

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

$v_1 = \langle p_x/p_T \rangle = \langle \cos\varphi \rangle$

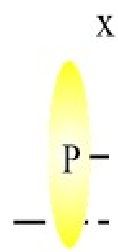
Does the "Wiggle" signal the QGP ?

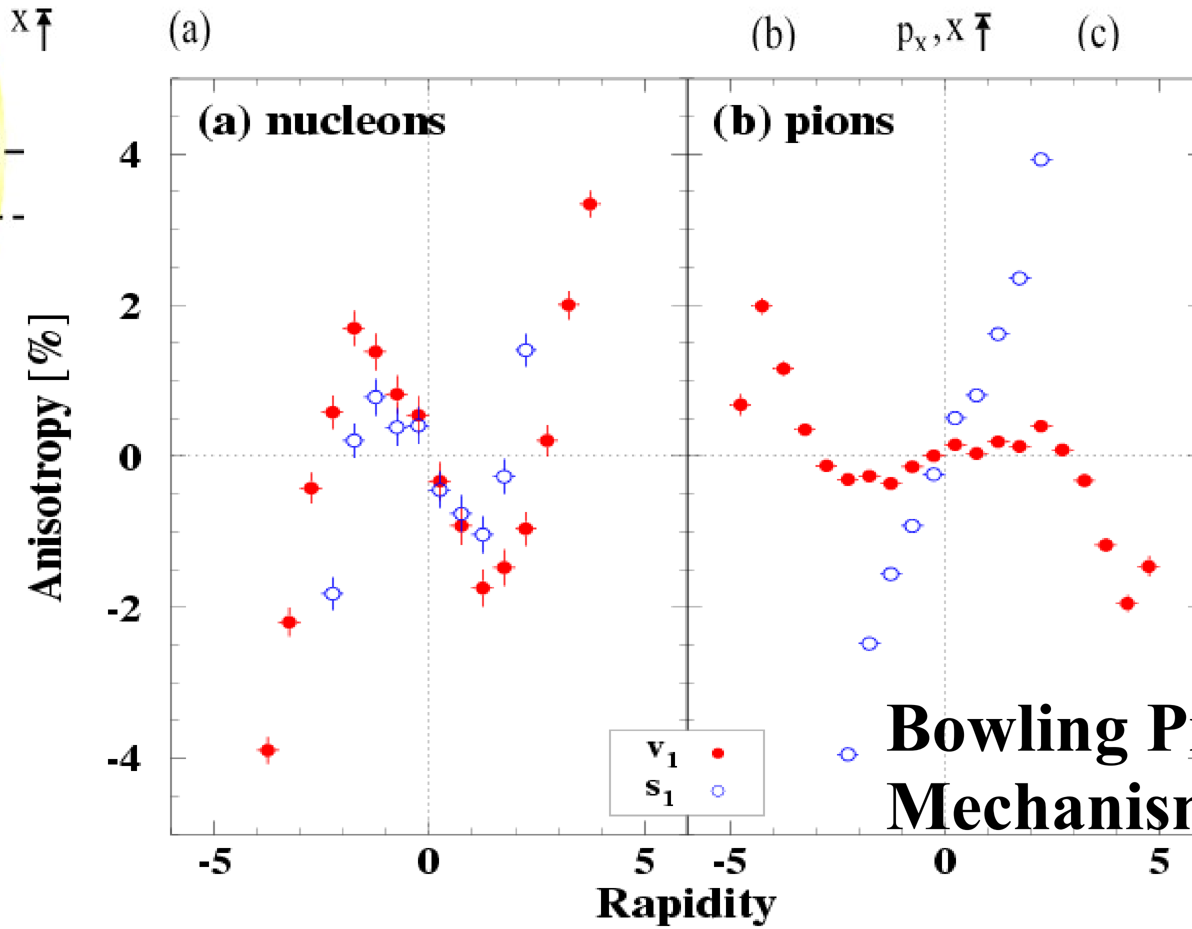
- **Hydro predicts wiggle with QGP EOS.**



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

- **Baryon stopping + Positive space-momentum correlation leads wiggle (w/o QGP)**



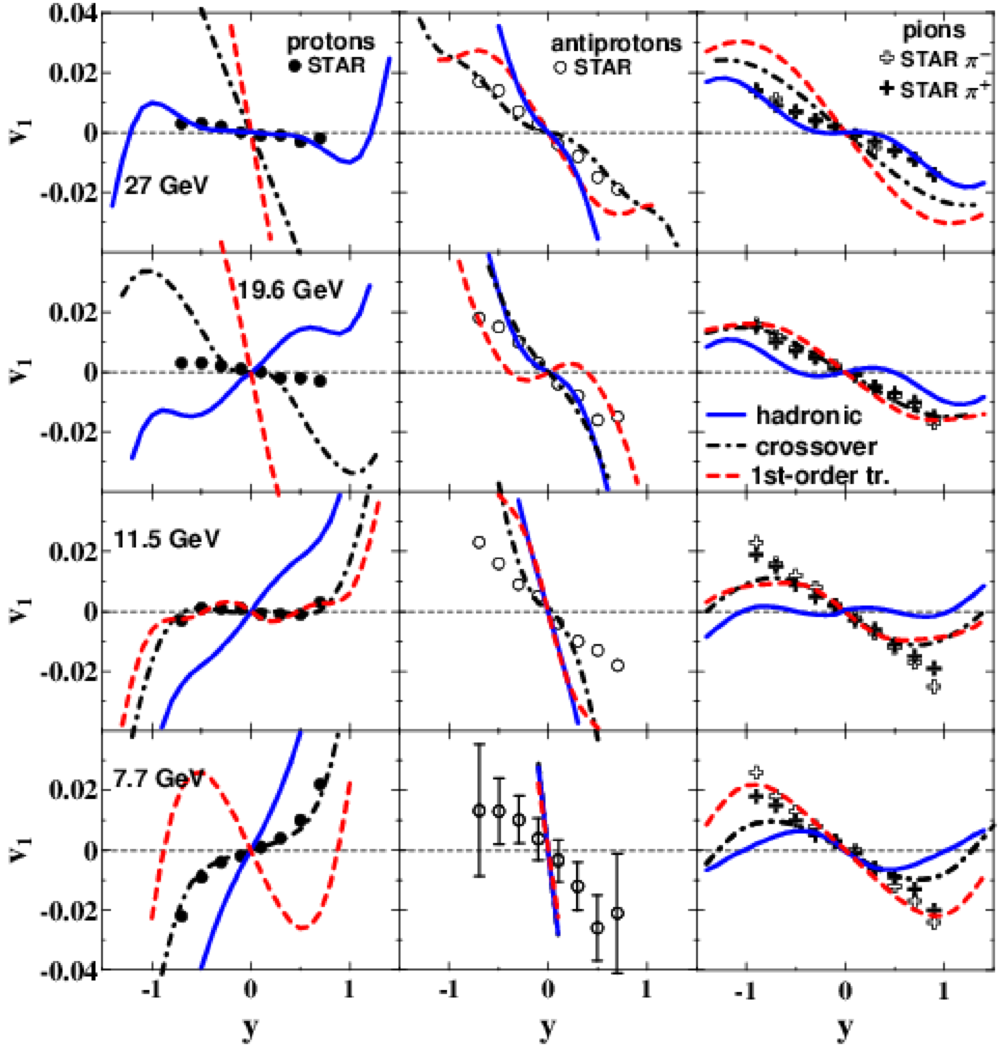


Bowling Pin Mechanism

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

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

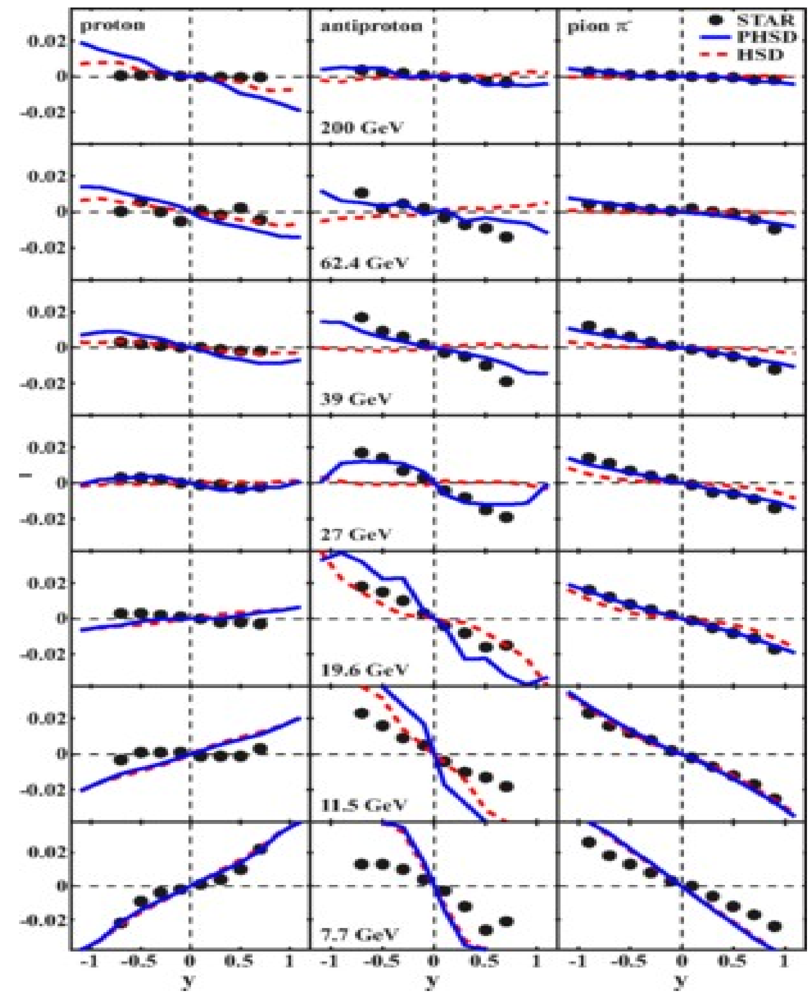
- **Yes in Hydrodynamics**



Black: Crossover, Red: 1st

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

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



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

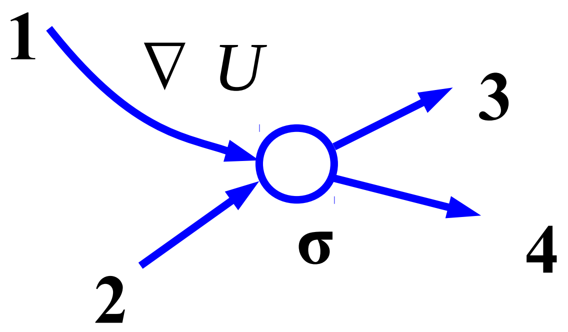
Does Directed Flow Collapse Signal Phase Tr. ?

- 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.

Hadron Transport Model

- **Microscopic Transport Models**
  = Boltzmann Eq. with potential effects
  E.g. Bertsch, Das Gupta, Phys. Rept. 160(88), 190



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

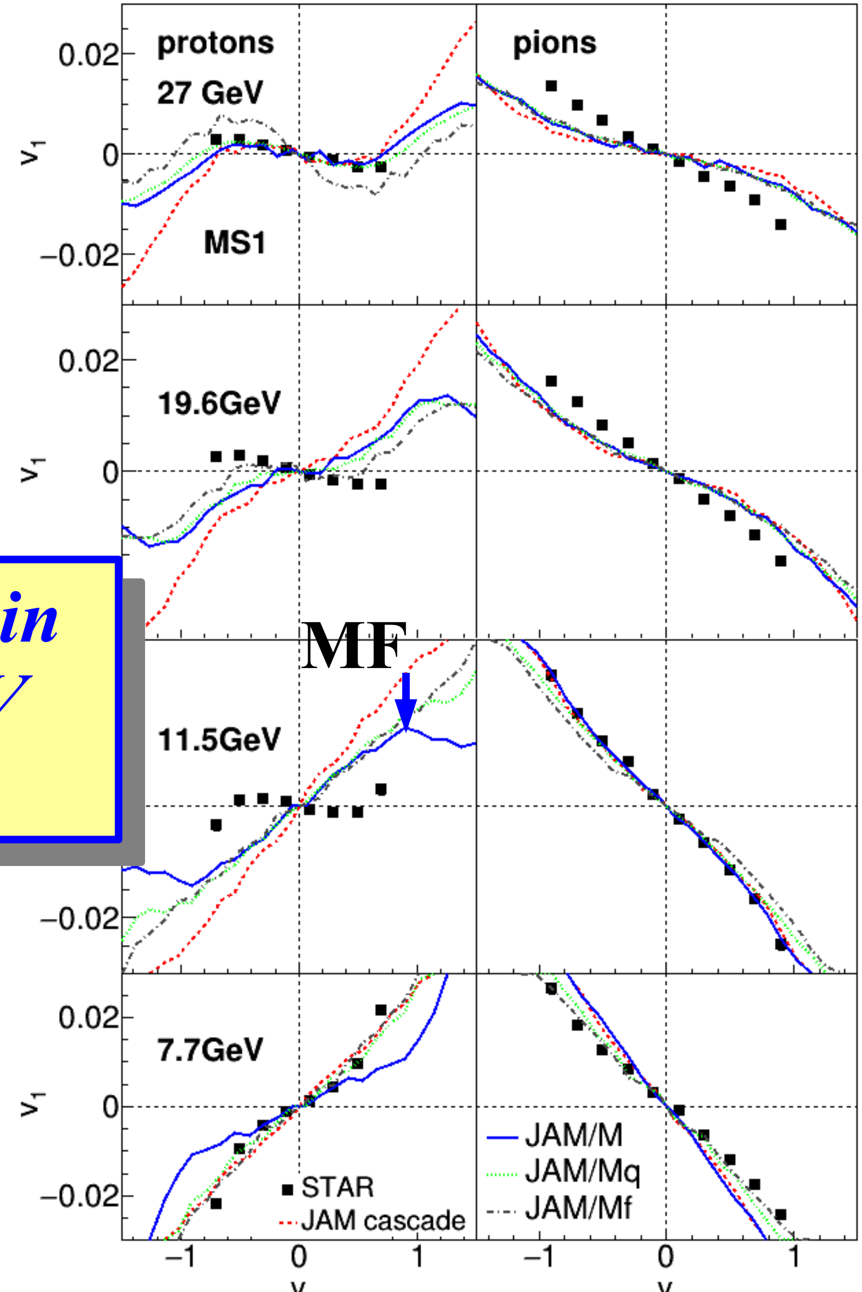
$$I_{\rm coll}(\mathbf{r},\mathbf{p}) = -\frac{1}{2}\int \frac{d\mathbf{p}_2}{(2\pi)^3} d\Omega\ v_{12}\ \frac{d\sigma}{d\Omega}\ [f f_2(1-f_3)(1-f_4)) - (12 \leftrightarrow 34)]$$

  - **UrQMD 3.4 (Frankfurt), PHSD Giessen (Cassing), GiBUU 1.6 Giessen (Mosel), AMPT (Texas A&M), JAM (Y. Nara)**

- **Hadron-string transport model JAM**
  - **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.

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.**



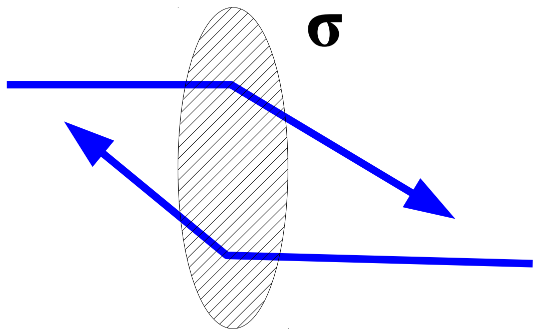
Hadronic approach does not explain directed flow collapse at 10-20 GeV even with potential effects.

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, NPA 956 ('16), 284 (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).



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

(Virial theorem)

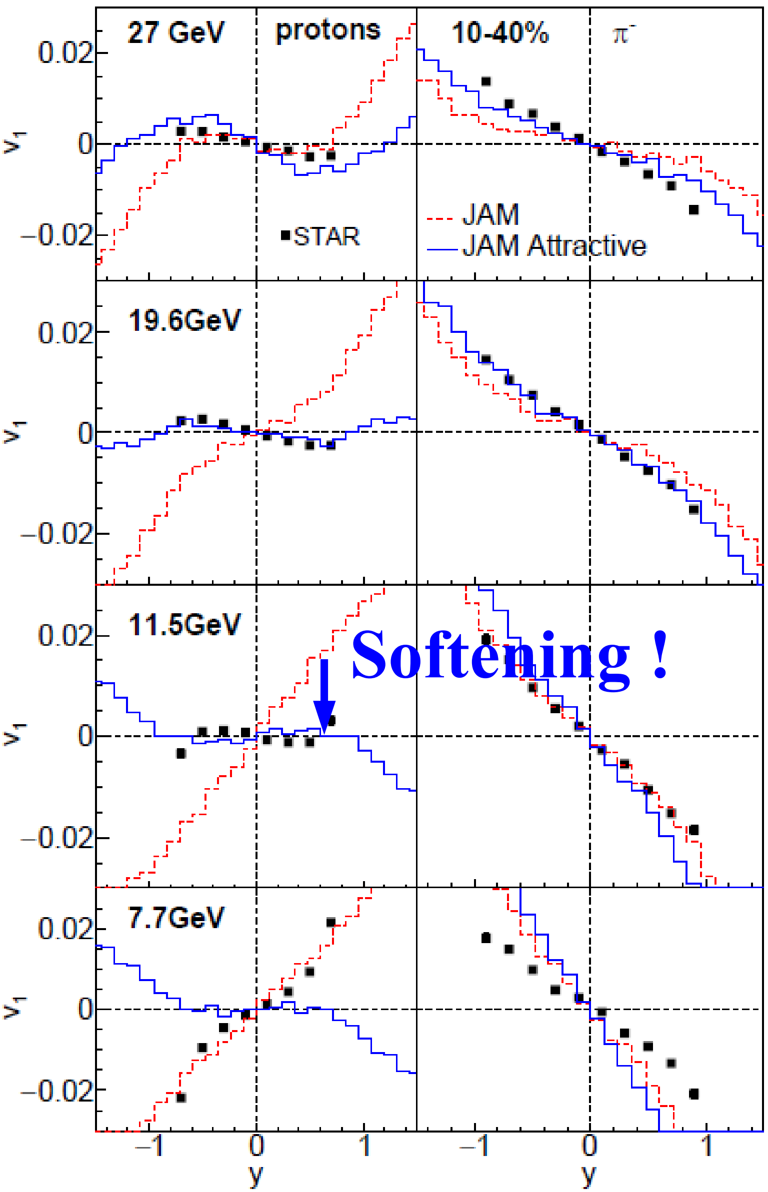
- **With attractive orbit, particle trajectories are bended toward denser region.**
  → ***Attractive orbit scattering simulates time evolution with softer EOS !***

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

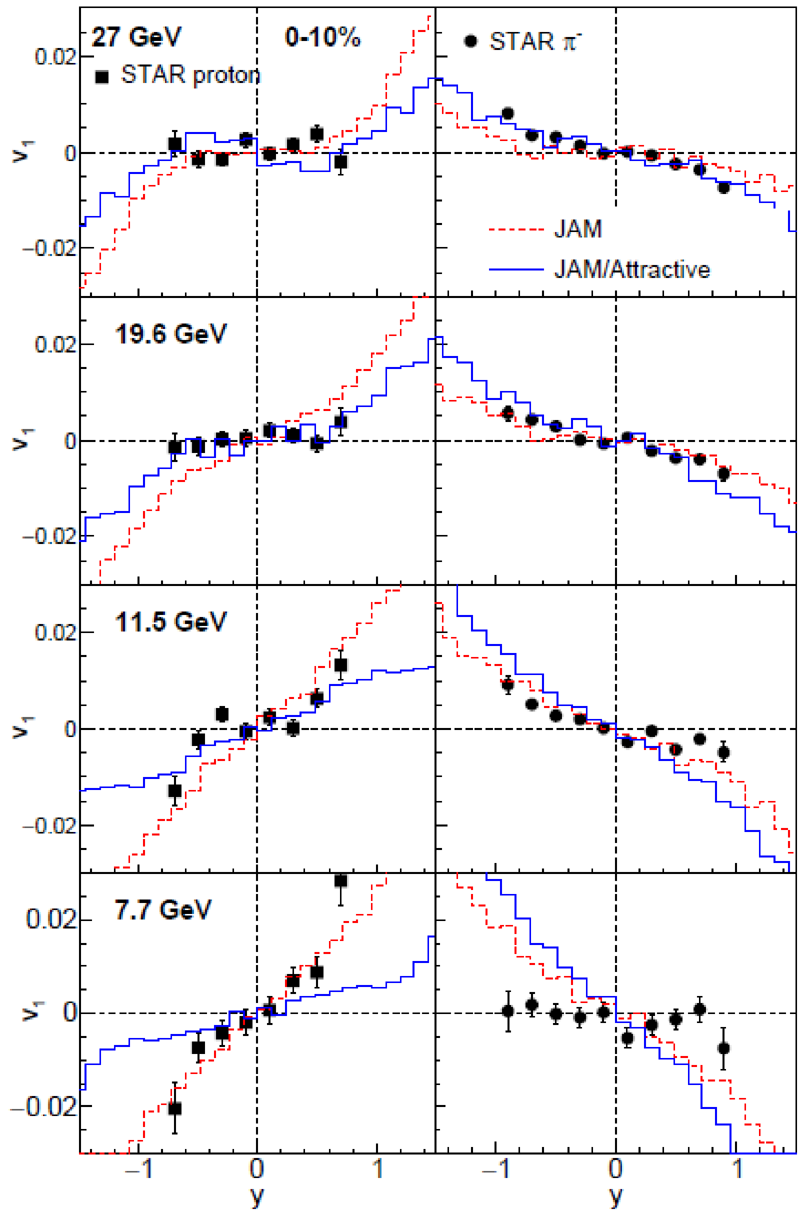
Y. Nara, H. Niemi, AO, H. Stöcker, PRC 94 ('16), 034906

Directed Flow with Attractive Orbits

Nara, Niemi, AO, Stöcker ('16)



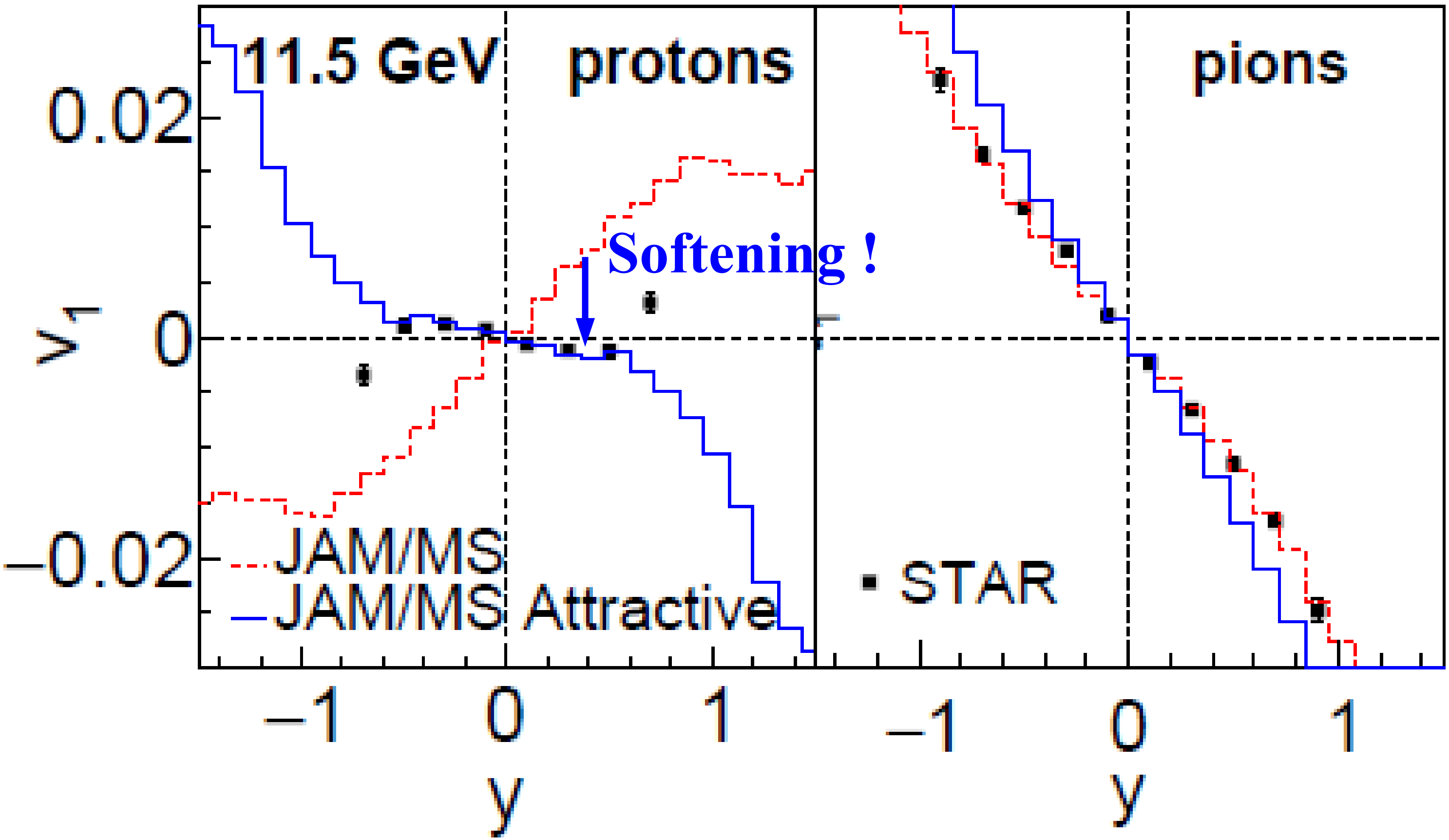
mid-central (10-40 %)



central (0-10 %)

Mean Field + Attractive Orbit

Nara, Niemi, AO, Stöcker ('16)

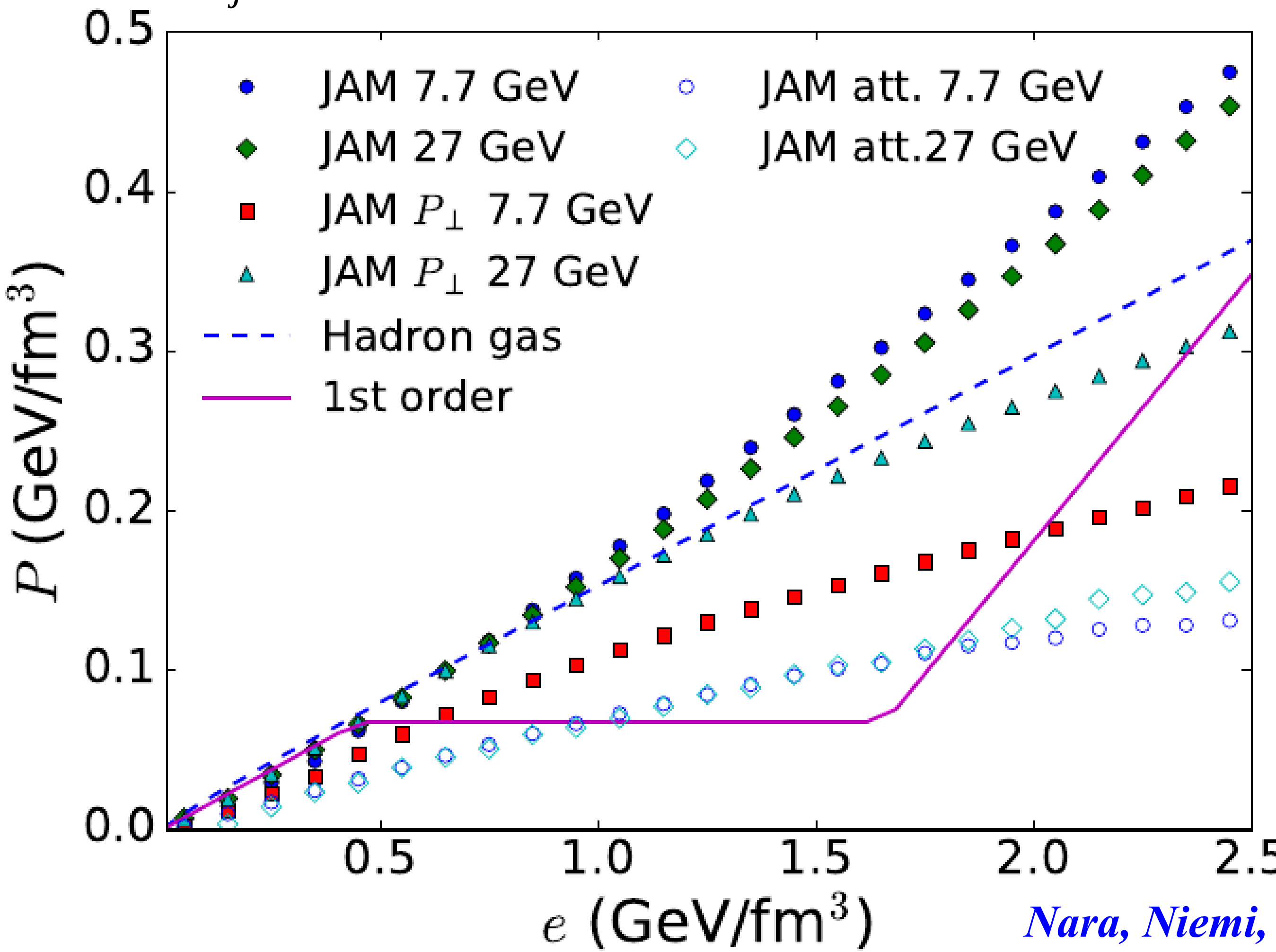


MF+Attractive Orbit make dv_1/dy negative at $\sqrt{s_{NN}}$ ~ 10 GeV

Softening of EOS by Attractive Orbits

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

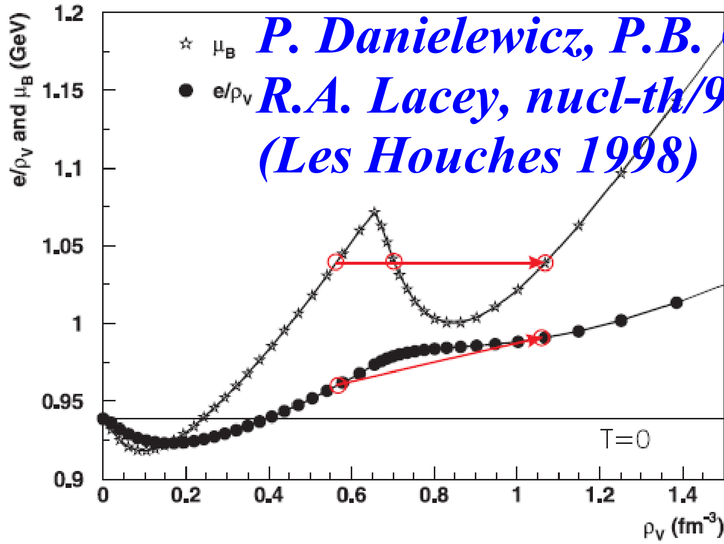
H. Sorge, PRL82('99)2048.

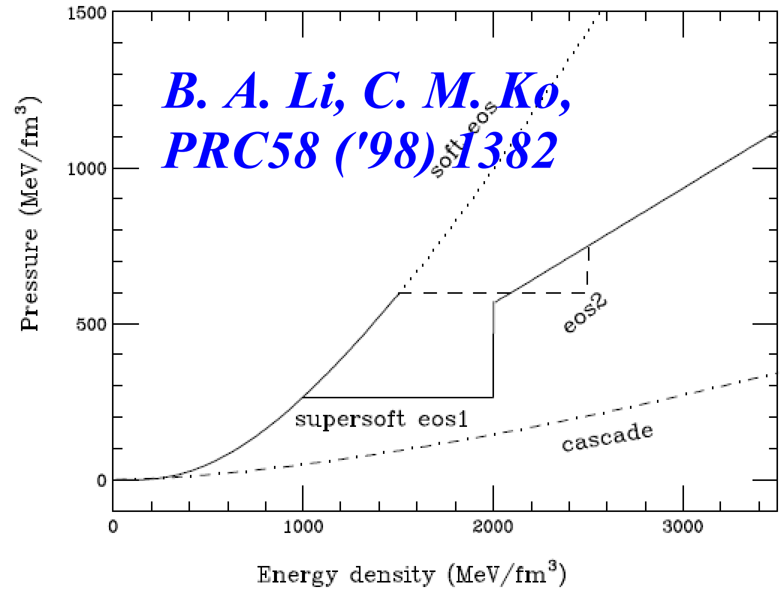


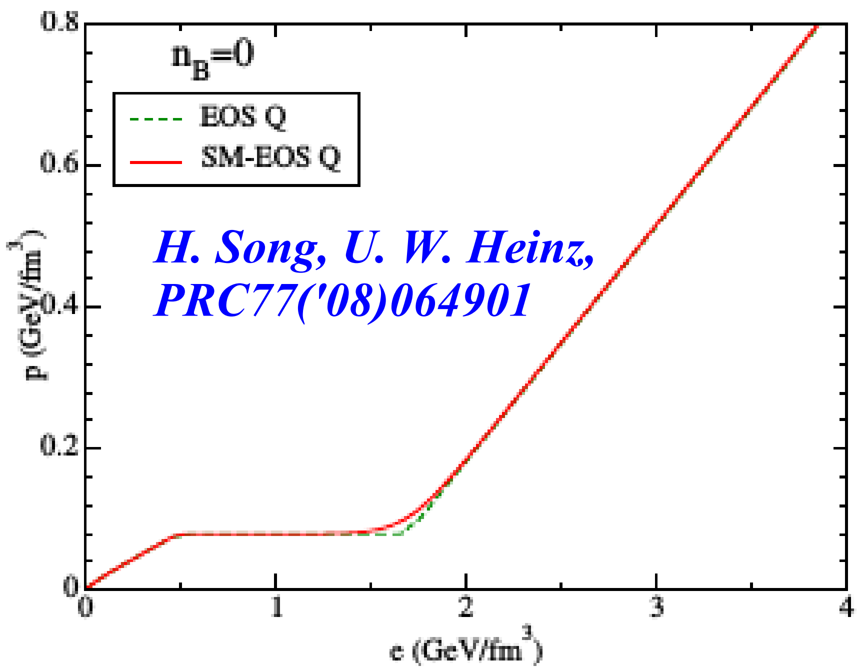
Nara, Niemi, AO, Stöcker ('16)

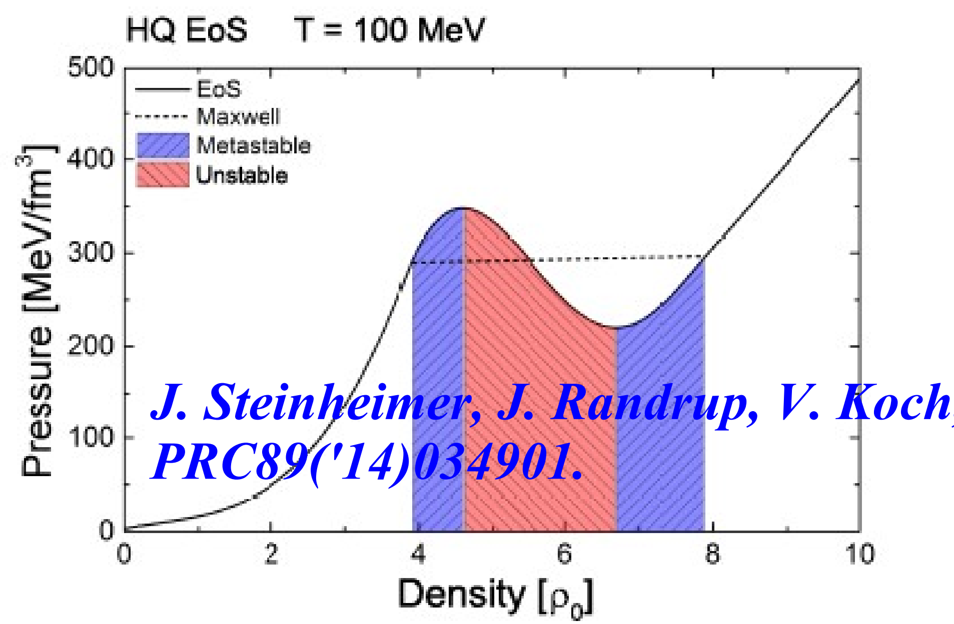
Pressure in simulated EOS ~ EOS-Q (e.g. Song, Heinz ('08))

Softening: Where and How much ?







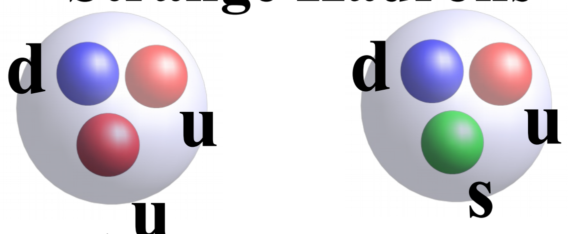


Previous analyses: $\rho_B = (3\text{-}10)\, \rho_0$, $P = (80\text{-}700)\ \mathrm{MeV/fm^3}$

Compact star matter EOS and Strangeness

Neutron star – Is it made of neutrons ?

- **Possibilities of various constituents in neutron star core**
  - **Strange Hadrons**

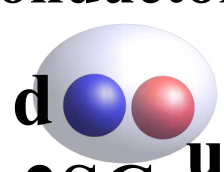


proton **Λ hyperon**

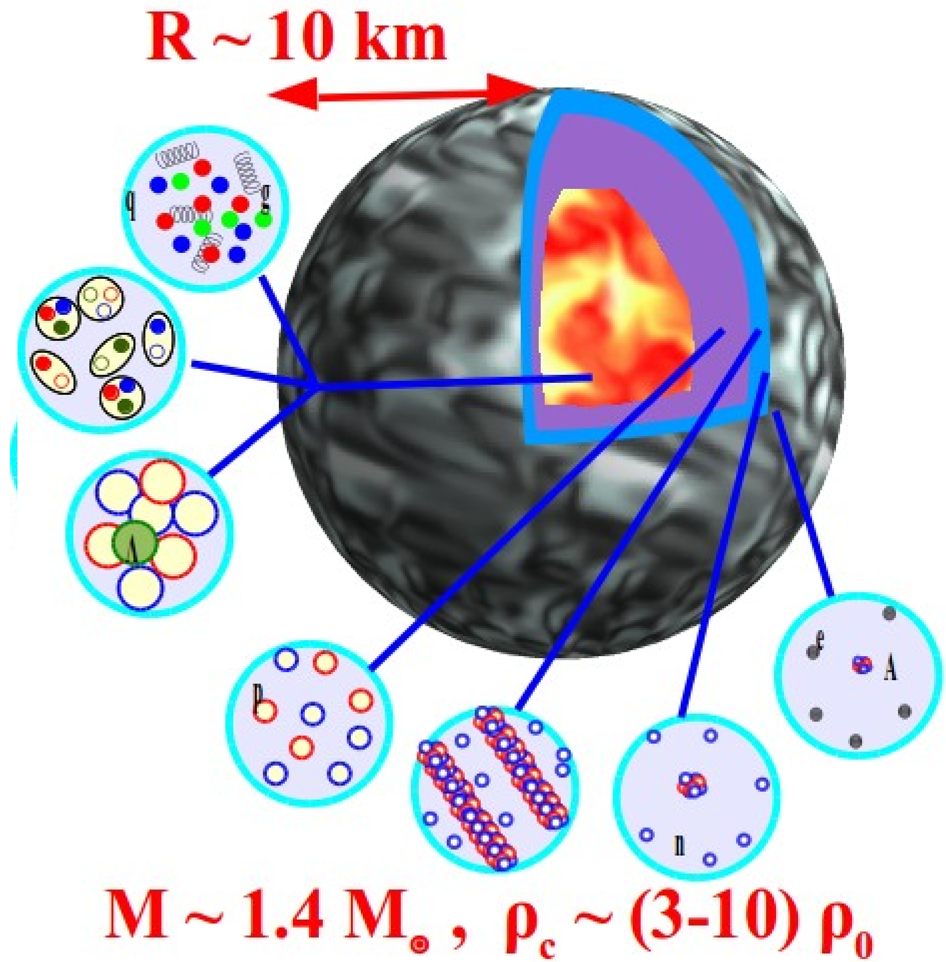
  - **Meson condensate (K, π)**

π **anti kaon**

  - **Quark matter**
  - **Quark pair condensate (Color superconductor)**



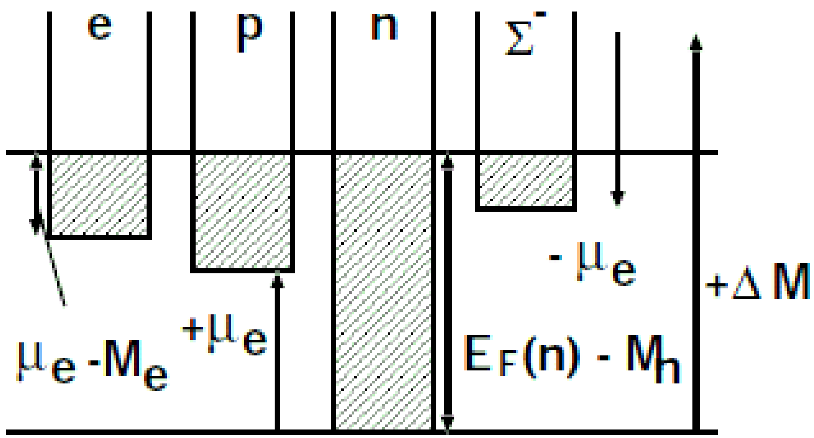
2SC



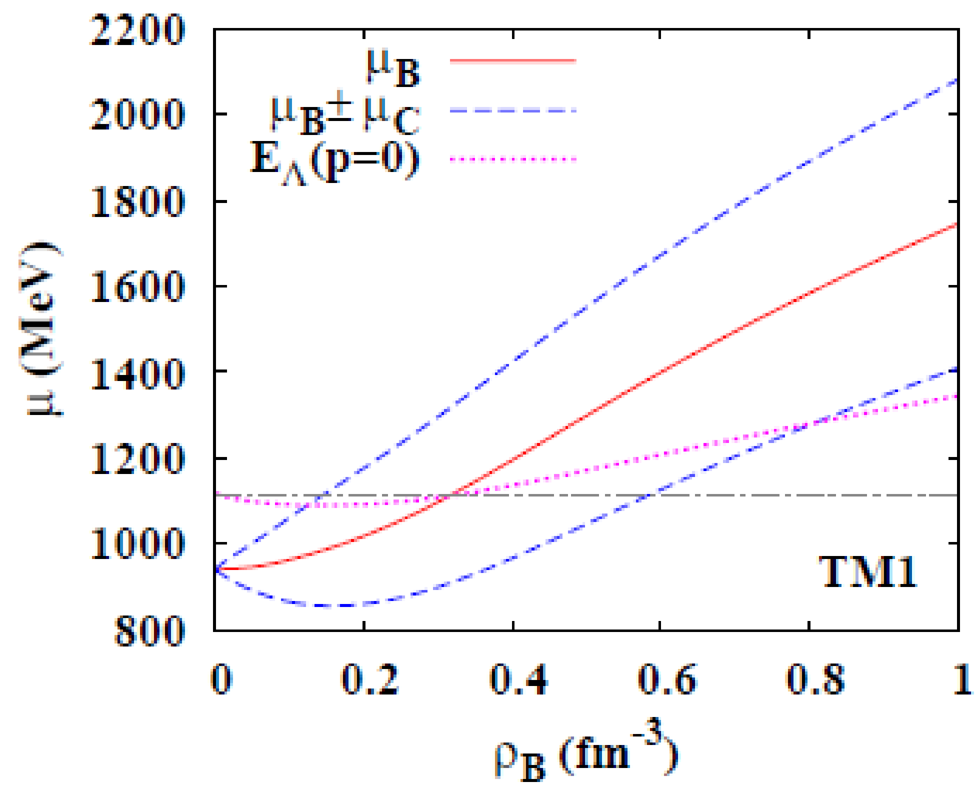
NS core = Densest stable matter existing in our universe.

Hyperons in Dense Matter

- **What appears at high density ?**
  - **Nucleon superfluid ($^3S_1$, $^3P_2$), Pion condensation, Kaon condensation, Baryon Rich QGP, Color SuperConductor (CSC), Quarkyonic Matter, ...**
  - **Hyperons**
    Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, Weigel; Sugahara, Toki; Schaffner, Mishustin; Balberg, Gal; Baldo et al.; Vidana et al.; Nishizaki,Yamamoto, Takatsuka; Kohno,Fujiwara et al.; Sahu,Ohnishi; Ishizuka, Ohnishi, Sumiyoshi, Yamada; ...

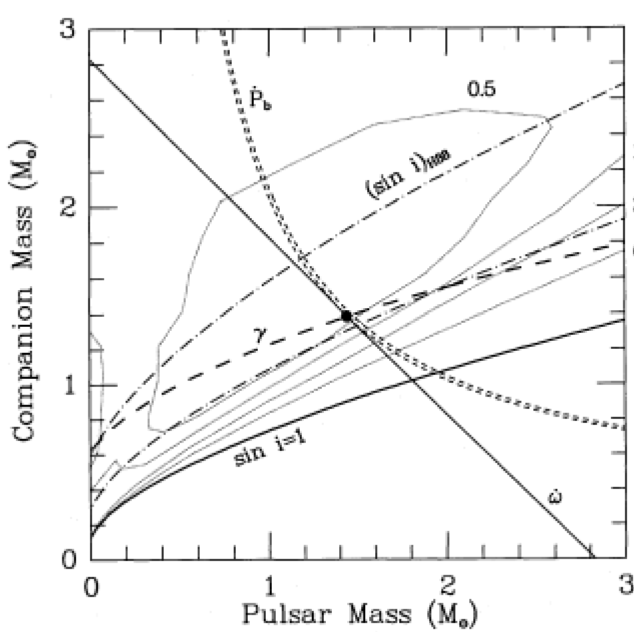


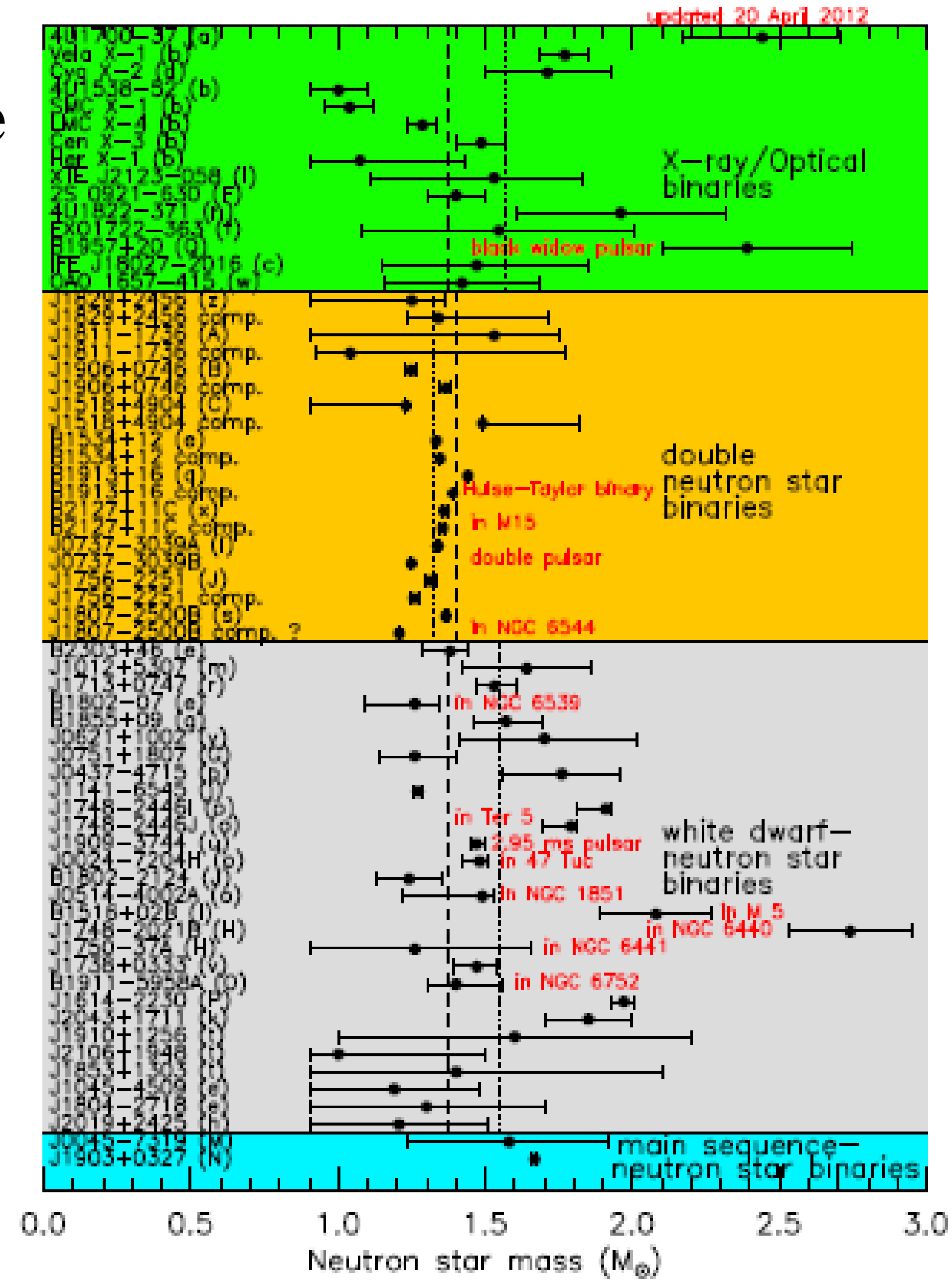
Chemical potential overtakes Λ mass → appearance of Λ



Neutron Star Masses

- **NS masses in NS binaries can be measured precisely by using some of GR effects via doppler shifts.**
  - **Perihelion shift+Einstein delay**
    → $M = 1.442 \pm 0.003\, M_\odot$
    (Hulse-Taylor pulsar)
    Taylor, Weisenberg ('89)
- **Many NSs have $M \sim 1.4\, M_\odot$.**

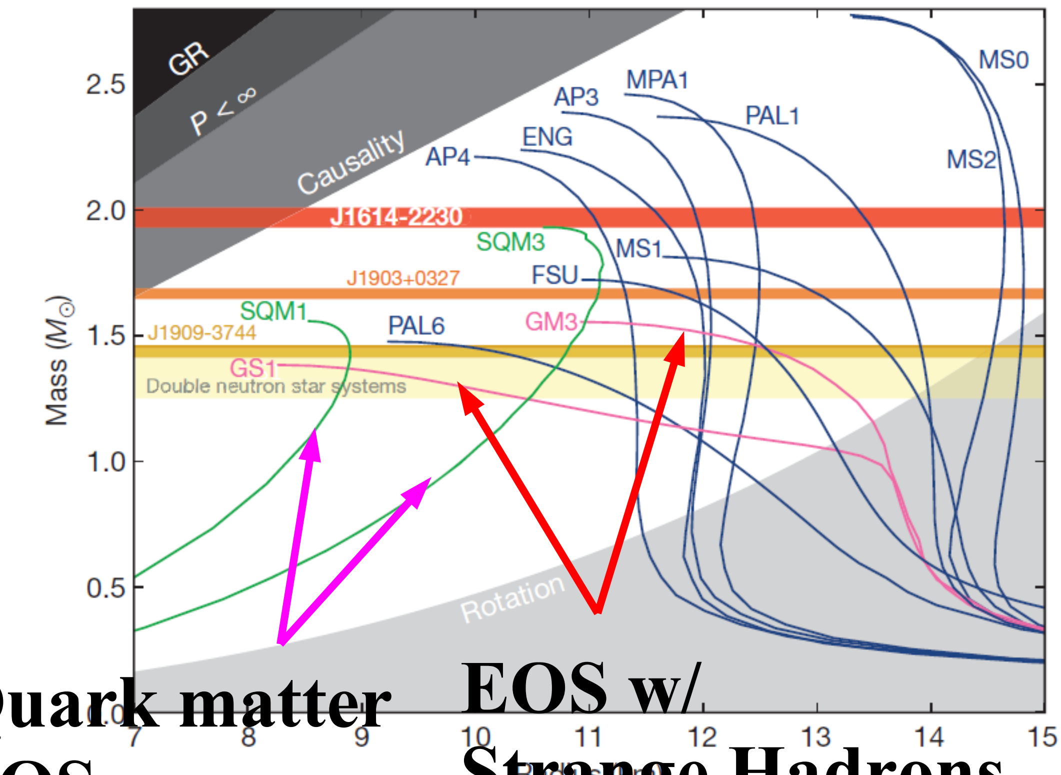




Lattimer (2013)

Massive Neutron Star Puzzle

- **Observation of massive neutron stars (M ~ 2 $M_\odot$)**
  - **PSR J1614-2230 (NS-WD binary), 1.97 ± 0.04 $M_\odot$**
    Demorest et al., Nature 467('10)1081 (Oct.28, 2010).
    ”Kinematical” measurement (Shapiro delay, GR) + large inclination angle
  - **PSR J0348+0432 (NS-WS binary), 2.01 ± 0.04 $M_\odot$**
    Antoniadis et al., Science 340('13)1233232.



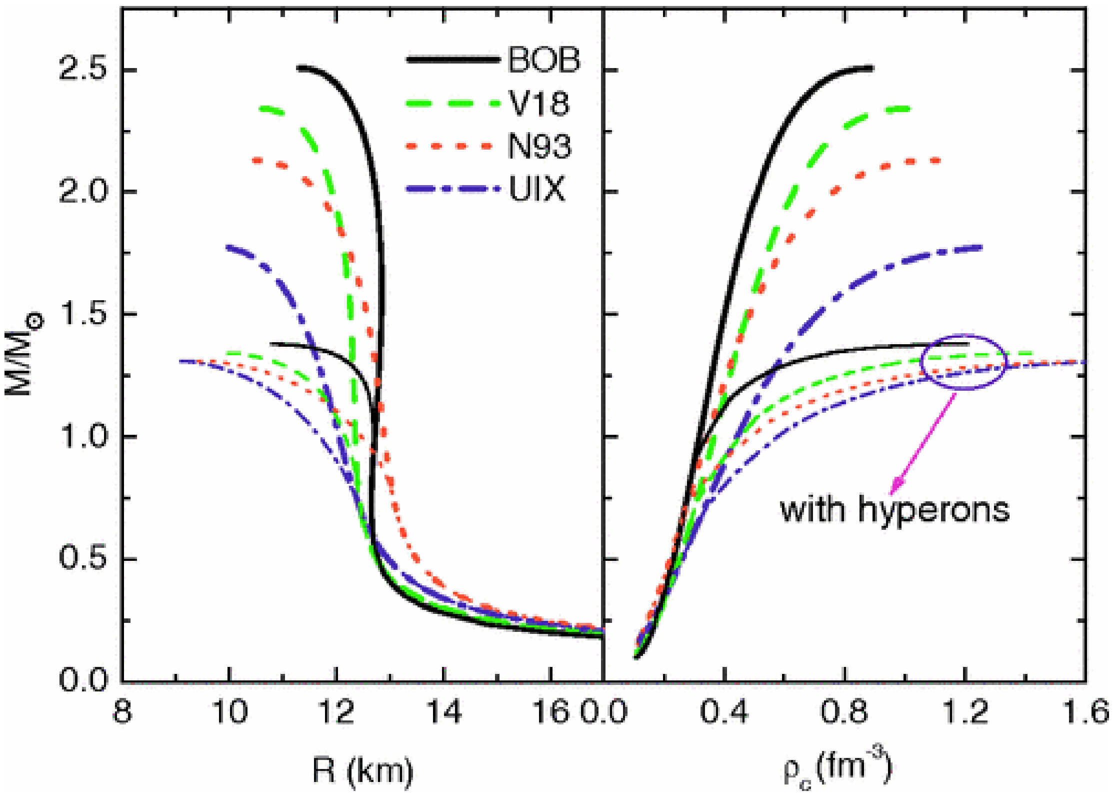
Quark matter EOS

EOS w/ Strange Hadrons

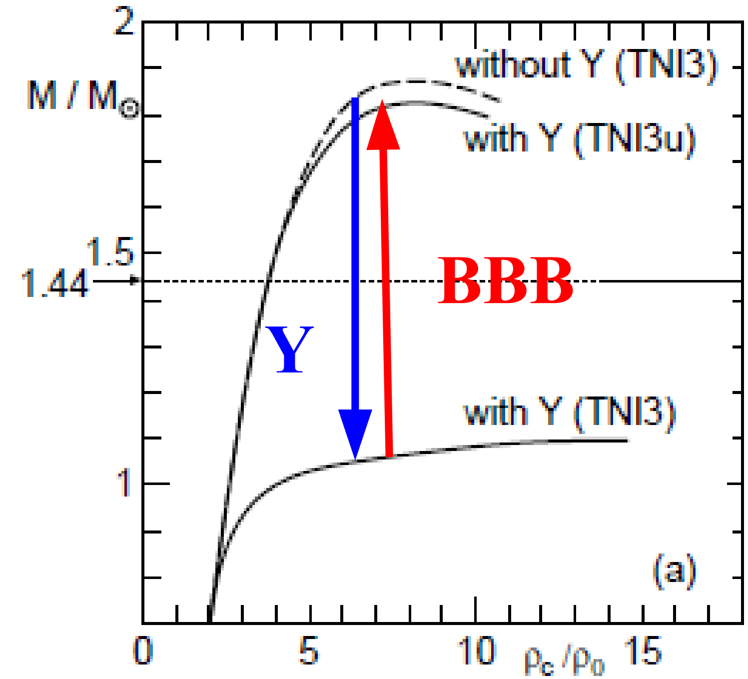
No Exotics in NS ?

Bruckner-Hartree-Fock theory with Hyperons

- **Microscopic G-matrix calculation with realistic NN, YN potential and microscopic (or phen.) 3N force (or 3B force).**
  - **Interaction dep. (V18, N93, ...) is large → Need finite nuclear info.**
    E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.
  - **NS collapses with hyperons w/o 3BF.**



Z.H.Li, H.-J.Schulze,PRC78('08),028801.



S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

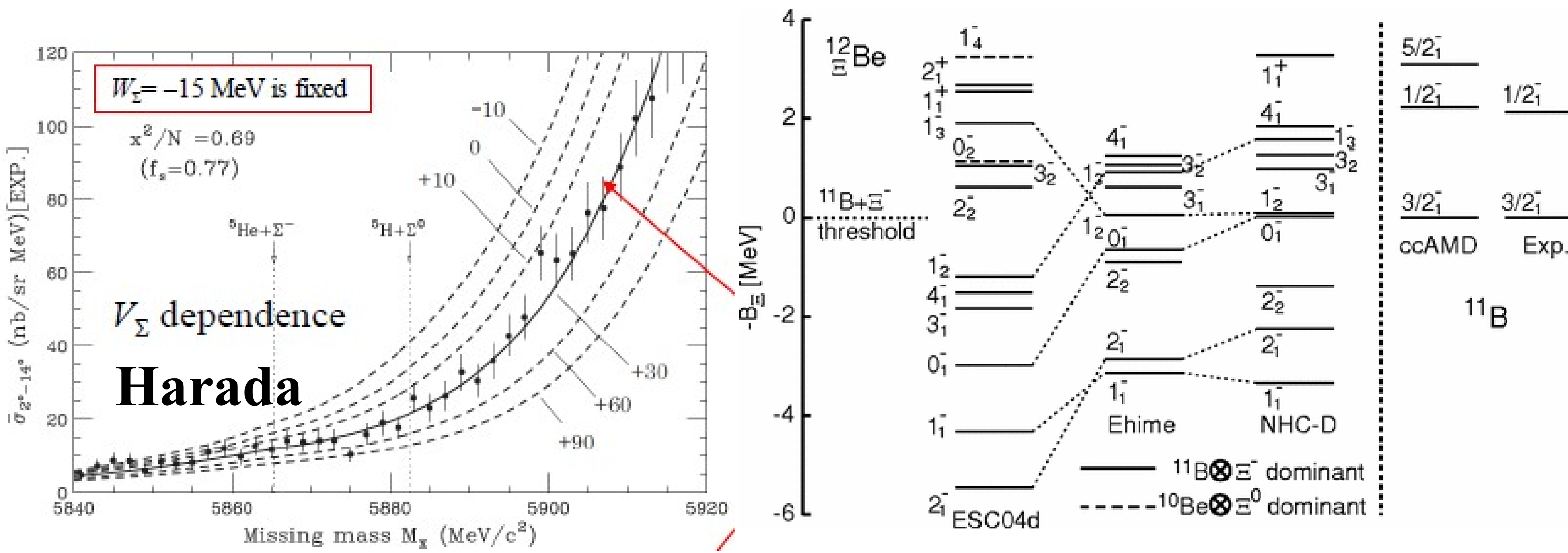
What did we miss ?

- **Hyperon potential in nuclear matter ?**
  - **$U_\Lambda(\rho_0) \sim$ -30 MeV, $U_\Sigma(\rho_0) >$ +20 MeV, $U_\Xi(\rho_0) \sim$ -14 MeV**
- **Hyperon-Hyperon potential ?**
  - **If vacuum ΛΛ potential is much more attractive than Nagara event implies, ΛΛN potential must be very repulsive.**
- **Kaon potential in nuclear matter ?**
- **Three-baryon (3B) interaction ?**
- **Quark matter core ?**
- **Modified gravity ?**

Σ or Ξ potential in nuclei ?

- **New analysis of Σ production reaction: ^{6}Li (π^-, K^+) Σ^- ^{5}He (Honda, Harada)**
  → U_Σ ~ +30 MeV (consistent)

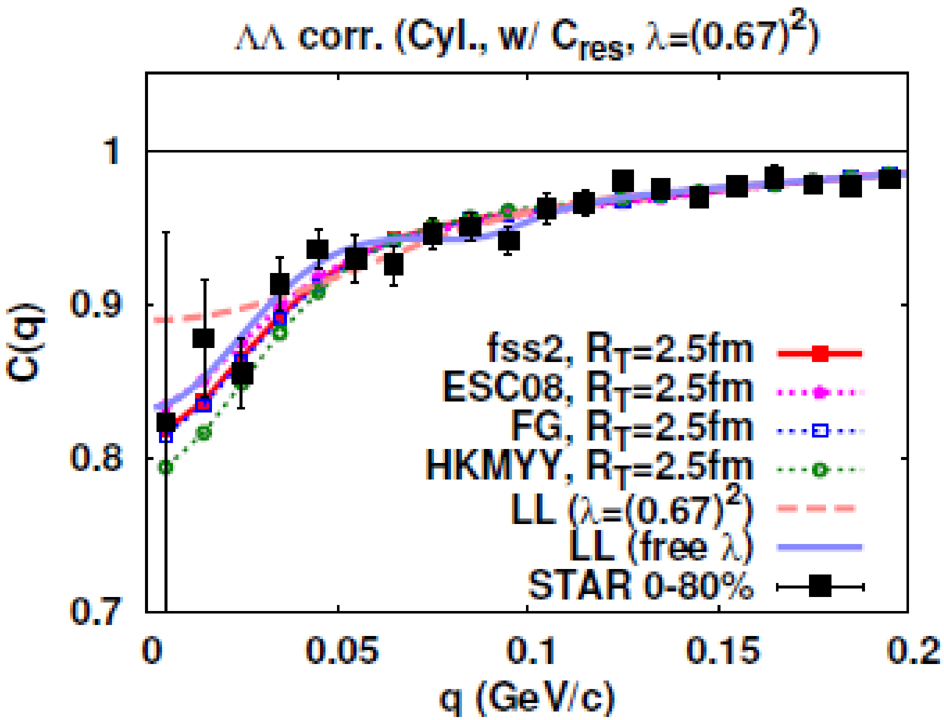
- **New Ξ hypernuclei → B.E. = 9 MeV & 1 MeV (Takahashi (A01), Nakazawa, Kanatsuki, Yamamoto)**
  → Deeper than previous estimate !

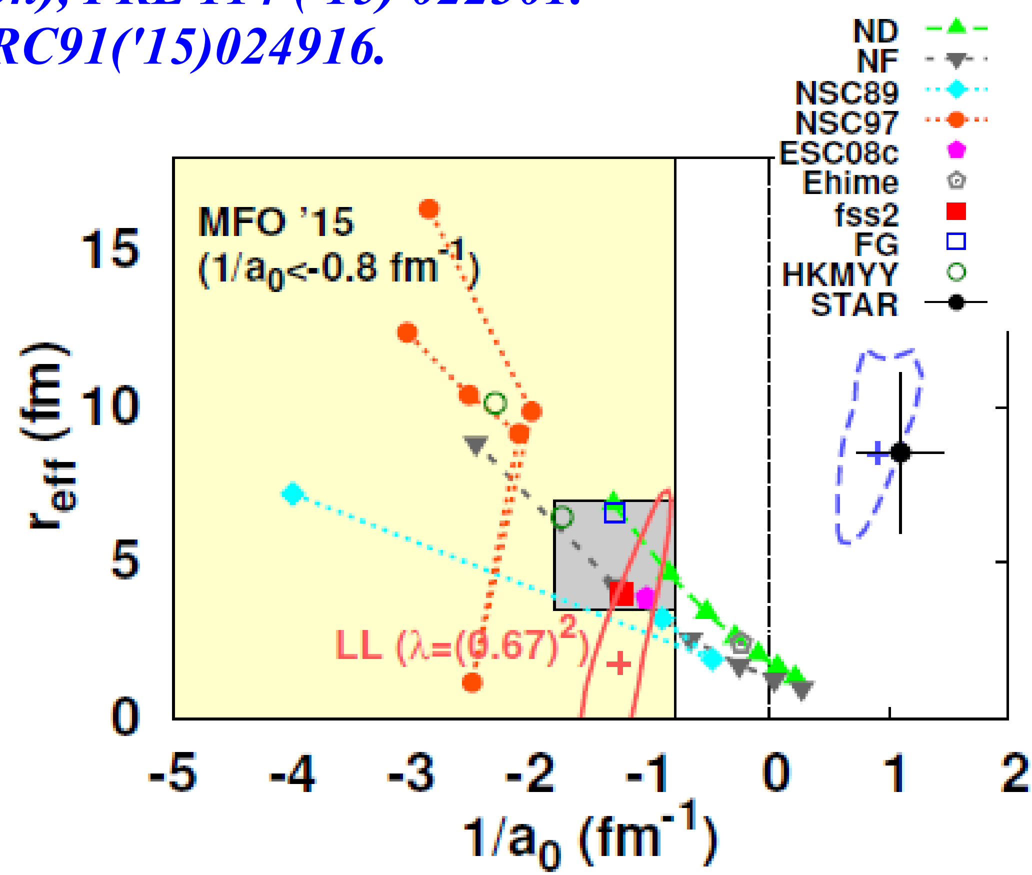


Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

ΛΛ potential ?

- **Nagara fit → $a_0(\Lambda\Lambda)$= - 0.575 fm or - 0.77 fm**
  Hiyama, Kamimura, Motoba, Yamada, Yamamoto ('02), Filikhin, Gal ('02)
- **New approach: ΛΛ correlation from HIC (Morita)**
  → -1.25 fm < $a_0(\Lambda\Lambda)$ < 0 (Consistent with Nagara)
  Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  Theor.:Morita et al., T.Furumoto, AO, PRC91('15)024916.

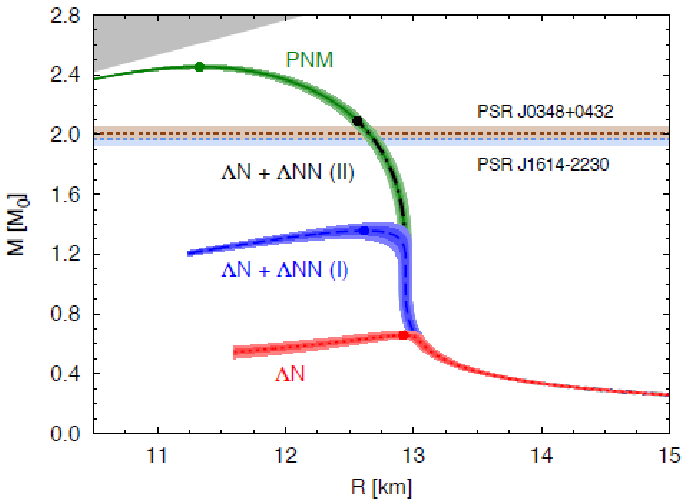




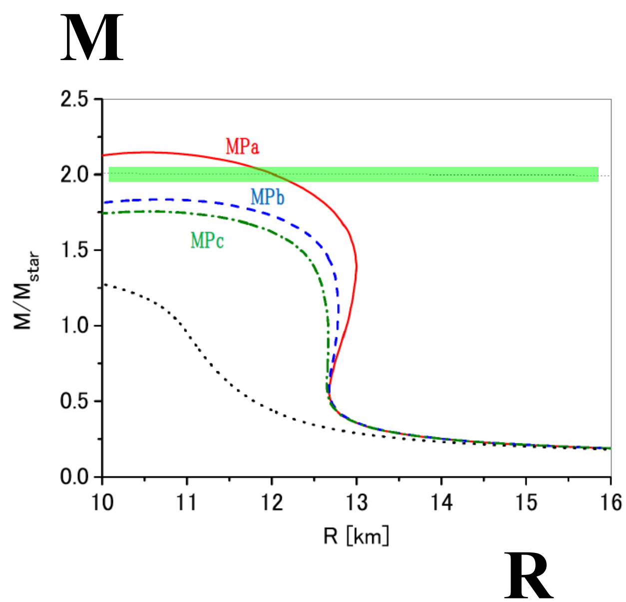
Remaining possibilities

- **Three-baryon (3B) interaction ?**
  - **"Universal" 3B repulsion**
    Nishizaki, Takatsuka, Yamamoto ('02), Tamagaki ('08), Yamamoto, Furumoto, Yasutake, Rijken ('13)
  - **Repulsive ΛNN potential (or density dep. ΛN pot.)**
    Lonardoni, Lovato, Gandolfi, Pederiva ('15), Togashi, Hiyama, Yamamoto, Takano ('16), Tsubakihara, Harada, AO ('16)
  - **Medium modification of baryons (Quark Meson Coupling model)**
    J.Rikovska-Stone, P.A.M.Guichon, H.H.Matevosyan, A.W.Thomas ('07), Miyatsu, Yamamuro, Nakazato ('13)
- **Quark matter NS core ?**
  - **First order phase transition**
    L. Bonanno, A. Sedrakian, Astron. Astrophys. 539 (2012) A16; M. Bejger, D. Blaschke, P. Haensel, J. L. Zdunik, M. Fortin, arXiv:1608.07049.
  - **Crossover transition to quark matter** *Masuda, Hatsuda, Takatsuka ('12)*
- **Modified Gravity** *Astashenok et al. ('14), M.-K. Cheoun's talk*

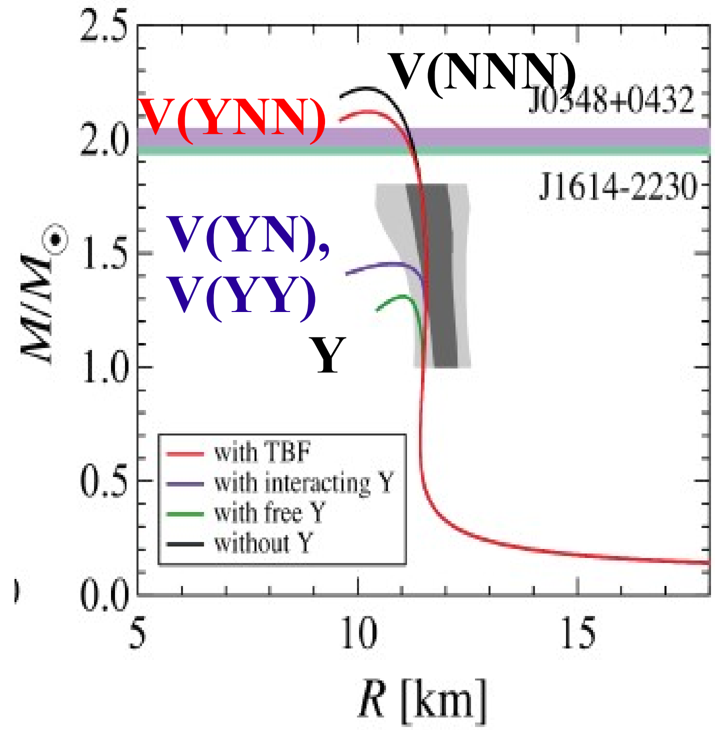
Hyperon Puzzle



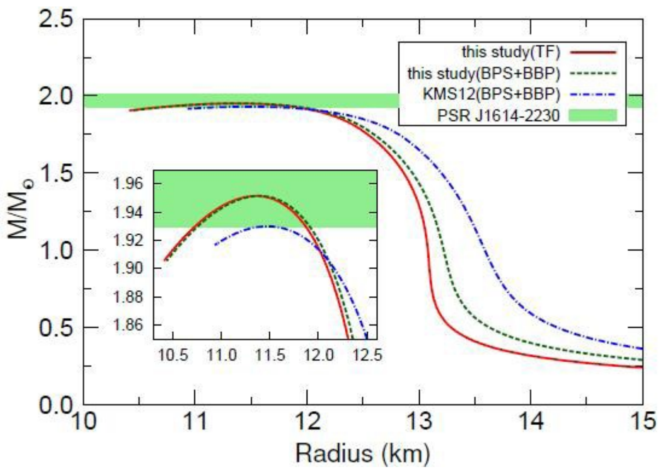
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



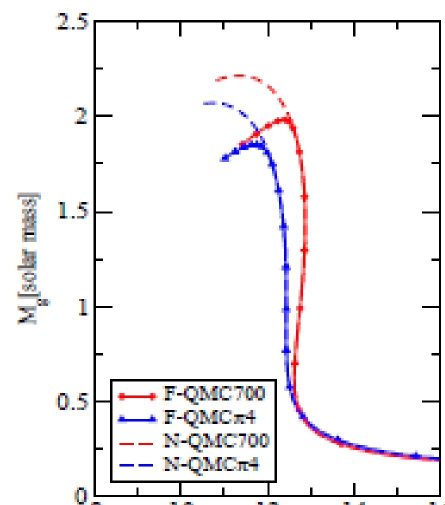
Yamamoto, Furumoto, Yasutake, Rijken ('13)



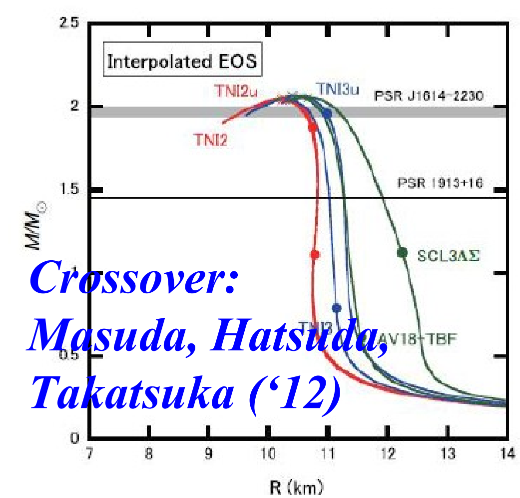
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu,Yamamuro, Nakazato ('13)



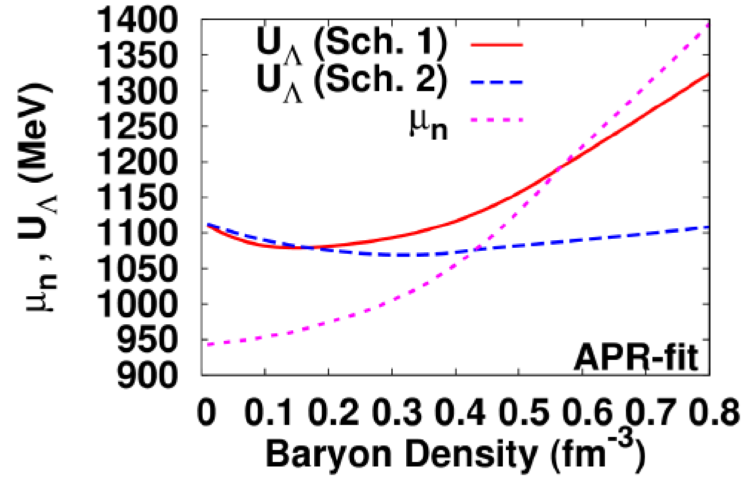
Rikovska-Stone, Guichon, Matevosyan, Thomas ('07),



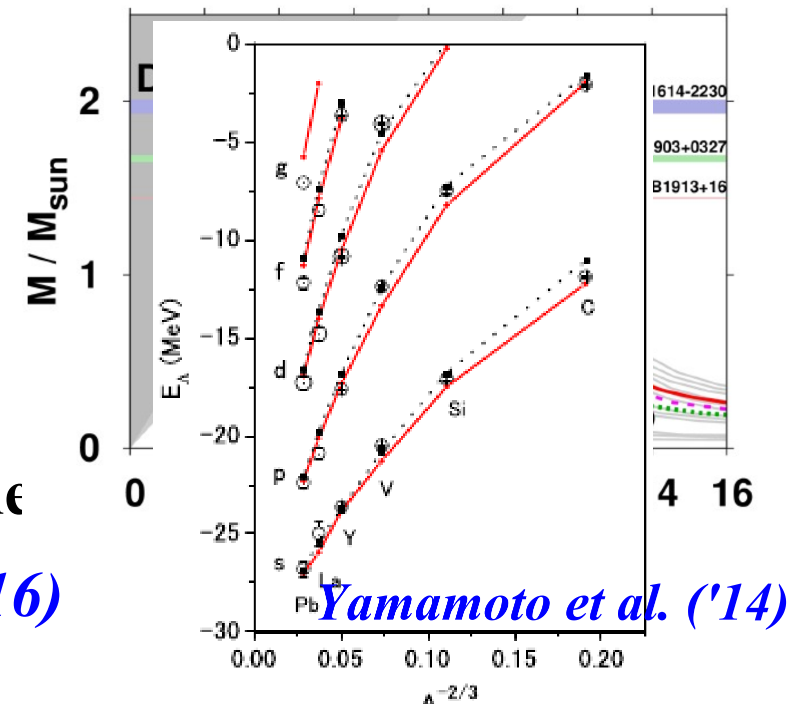
Crossover: Masuda, Hatsuda, Takatsuka ('12)

How can we discriminate 3B force ?

- **Precise measurement and calc. of Λ separation energy (J-PARC, JLab) and Few-body hypernuclei**
  E.g. E. Hiyama, Y. Kino, M. Kamimura, PPNP51('03)223.
  → **Λ potential depth, shape and A-dep.**



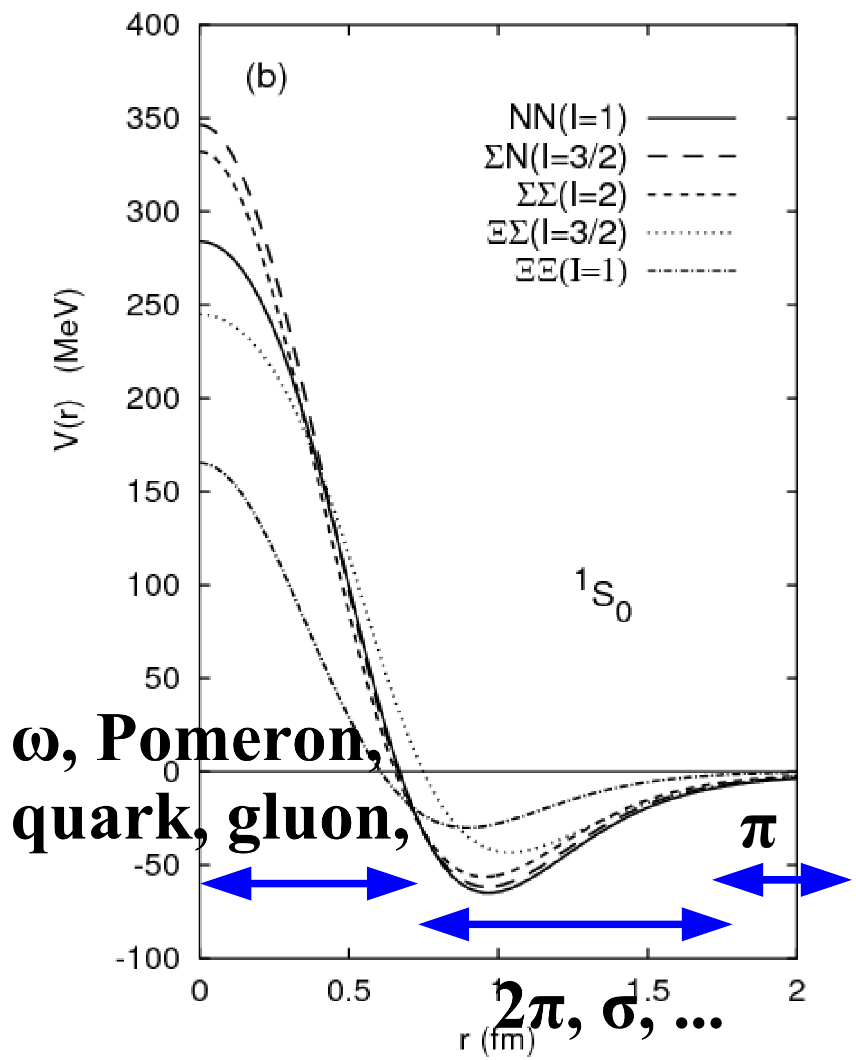
- **Collective flow of Hyperons**
- **"microscopic" 3-body force**
  - **Chiral EFT** *Haidenbauer et al. ('13)*
    → **we need more data to fix LECs**
  - **Lattice 3B** *Doi et al. (HAL QCD)('12)*
    → **much CPU at Phys. point, but doable**
  - **Quark model 3BF** *Nakamoto, Suzuki ('16)*
    → **3B Pauli blocking effects are small**
  - **Quark model 3B force with KMT** *AO, Kashiwa, Morita*



What is the origin of repulsive 3B force

- **Short range (r < 0.6 fm) core of 2B force**
  vector boson exch., Pomeron exch., quark exclusion + one gluon exch., …

We may need quark-gluon DOF to understand 3B repulsion.
→ Quark Meson Coupling,
Lattice QCD 3B force (HAL QCD),
Quark Cluster model (Nakamoto)



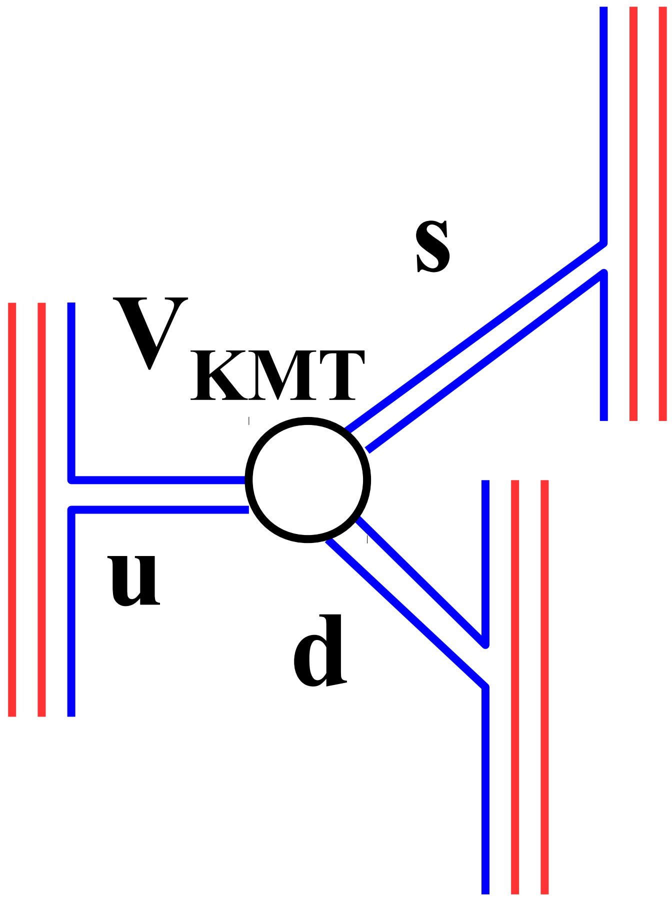
Fujiwara, Suzuki, Nakamoto ('07)

From 3-quark int. to 3B force

- **KMT interaction** *Kobayashi, Maskawa ('70), 't Hooft ('76)*

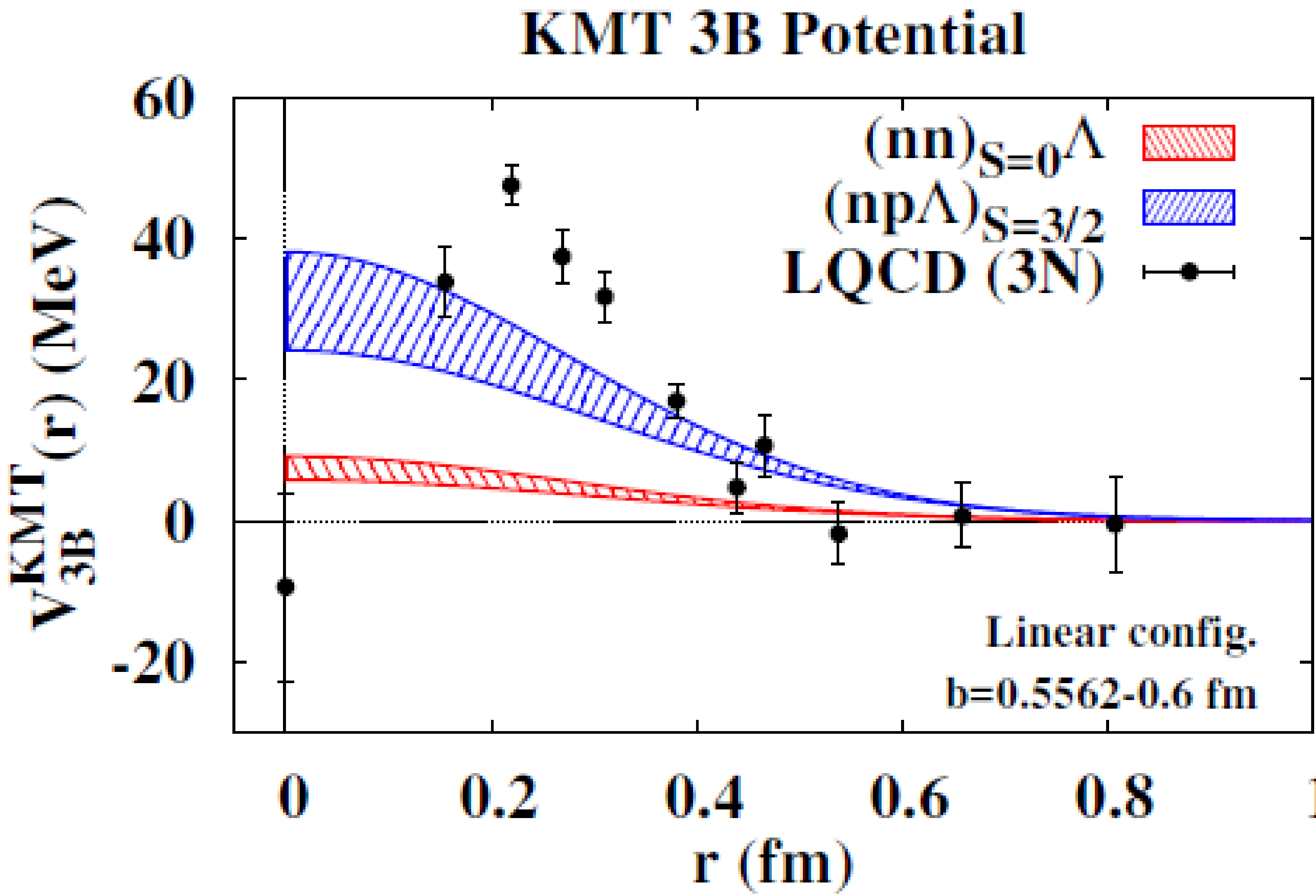
$$\mathcal{L}= g_D \ (\det \Phi + \mathrm{h.c.}) \ , \quad \Phi_{ij} = \bar{q}_j (1-\gamma_5) q_i$$

- **Resnponsible for $U(1)_A$ anomaly**
- **3-body int. among u,d,s quarks**
- **g_D is fixed by η-η' mass diff.**
  → g_D= – 9.29 *Hatsuda, Kunihiro ('94)*
  – 12.36 *Rehberg, Klevanski, Hufner ('96)*
- **Repulsive in ΛΛ system**
  → Pushes up H particle energy.
  Takeuchi, Oka ('91)



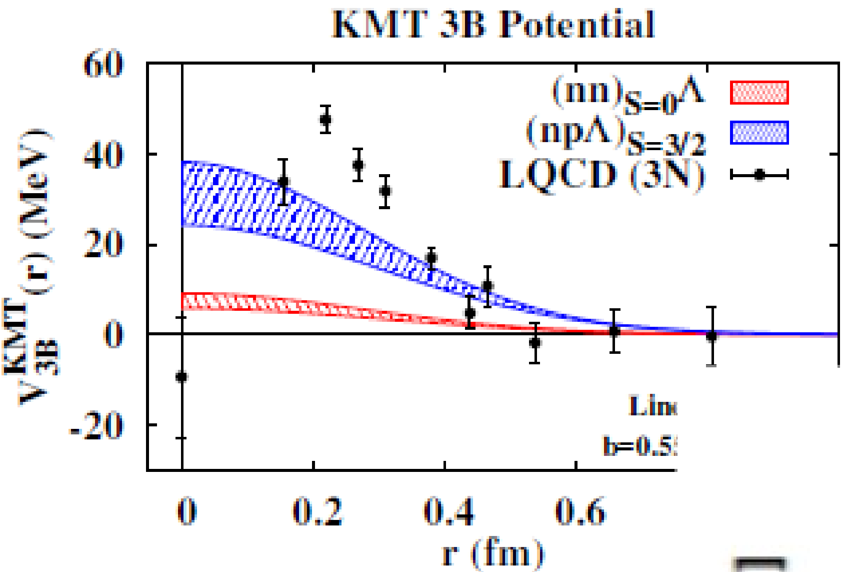
Does the anomaly support NS ?

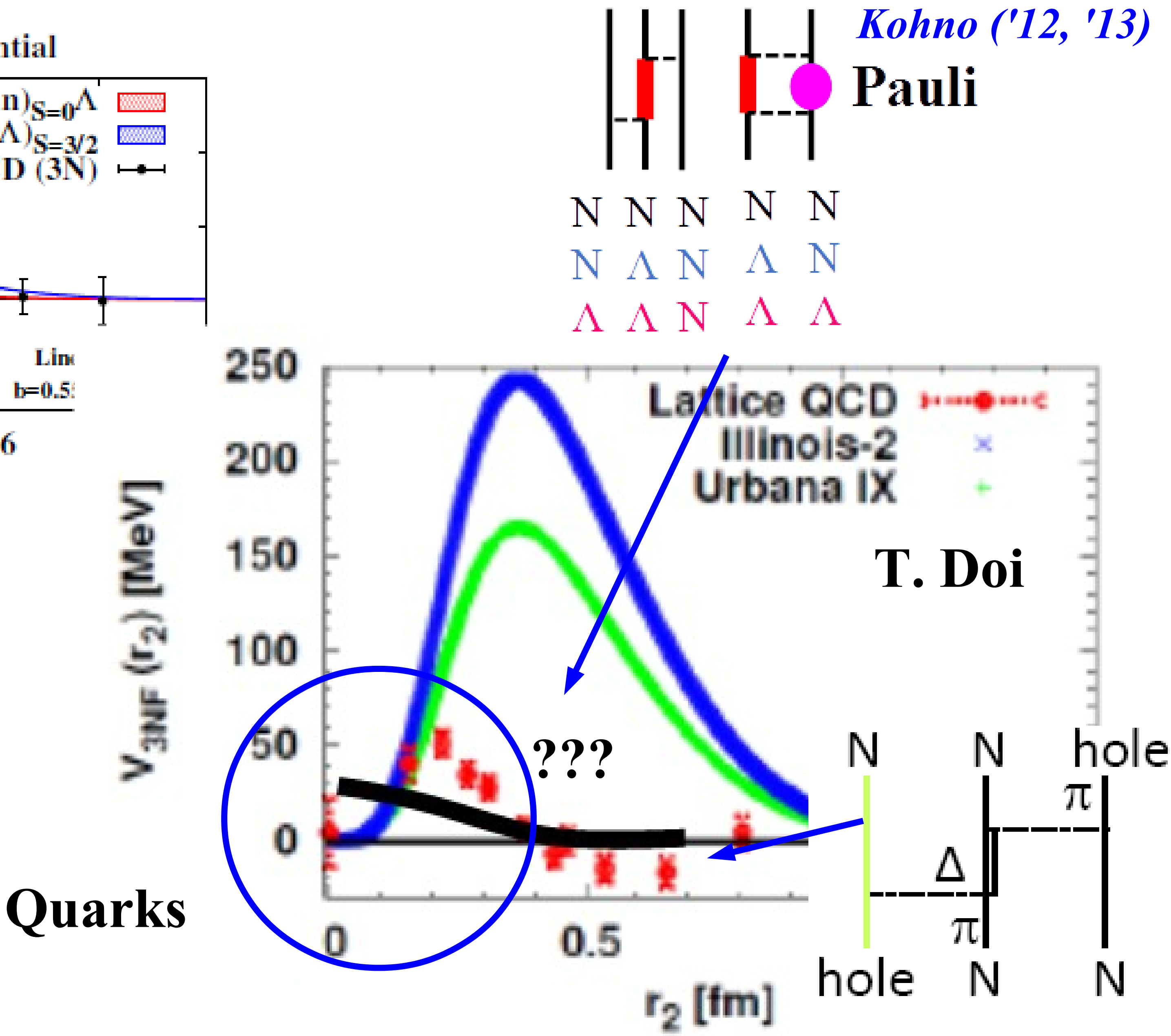
3B potential from KMT interaction



AO, Kashiwa, Morita, arXiv:1610.06306
Lattice data: Doi et al. (HAL QCD) ('07)

3B potential from KMT: Repulsive enough ?





Summary

- **Dense matter EOS is important in nuclear physics and astrophysics.**
  - **In compact star phenomena (neutron stars, supernovae, black hole formation, binary neutron star mergers), very dense matter would be created, and non-nucleonic hadrons and quarks may admix.**
  - **In heavy-ion collisions at $\sqrt{s_{NN}}$=(5-20) GeV, very dense (and partially equilibrated) matter would be formed.**
- **Recent observation of the directed flow collapse ($dv_1/dy < 0$) seems to indicate softening of the EOS at high densities. This softening may signal a first-order QCD phase transition.**
- **Massive NSs imply stiff EOS at isospin asymmetric dense matter, and suggest (at least) one of 3B repulsive force, transition to stiff quark matter, or modified gravity is necessary.**
- **Can we understand the above two in a consistent manner ?**