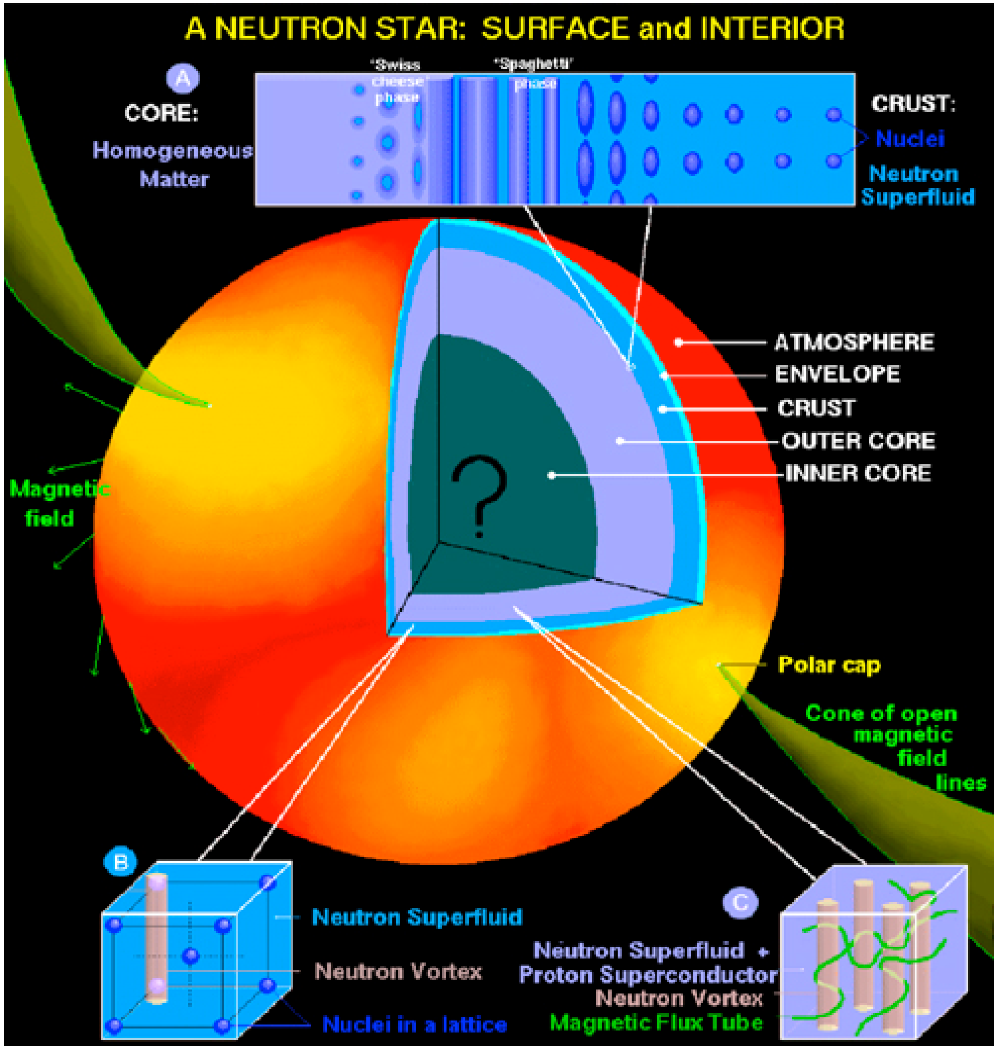
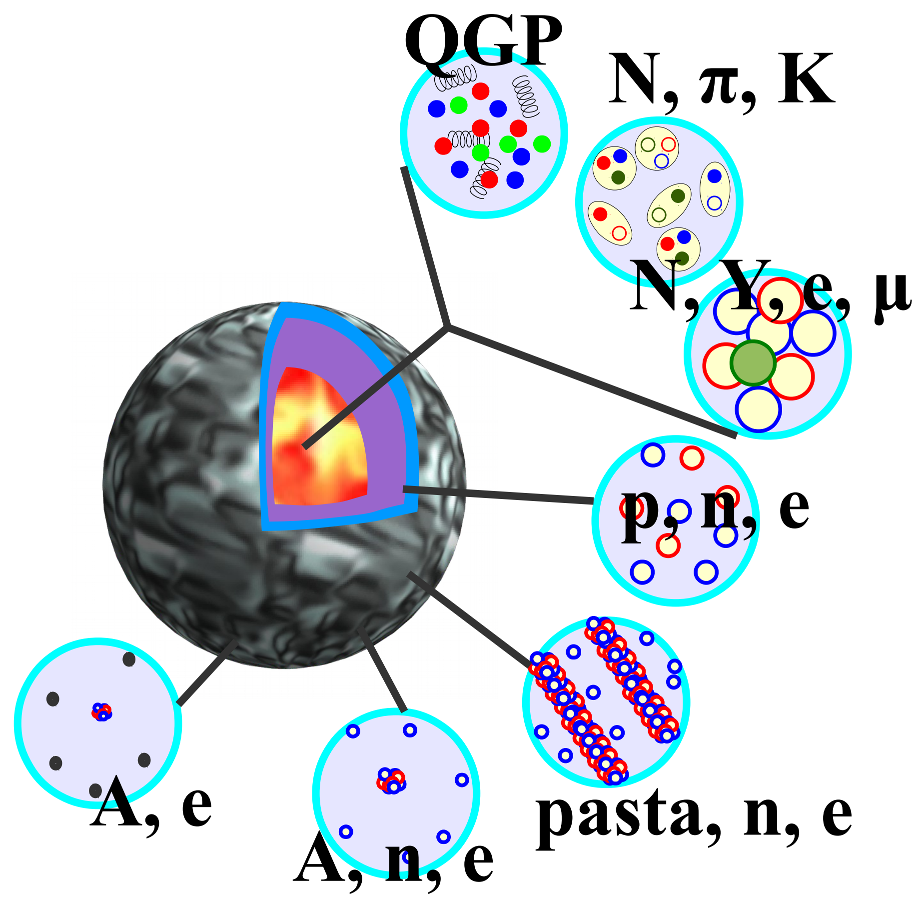
Theoretical developments in physics of neutron star matter (Report from Group D01)

Akira Ohnishi (YITP, Kyoto U.)

International Symposium on Neutron Star Matter 2016 (NSMAT2016) Nov.21-23, 2016, Sendai, Japan

Inside Neutron Stars





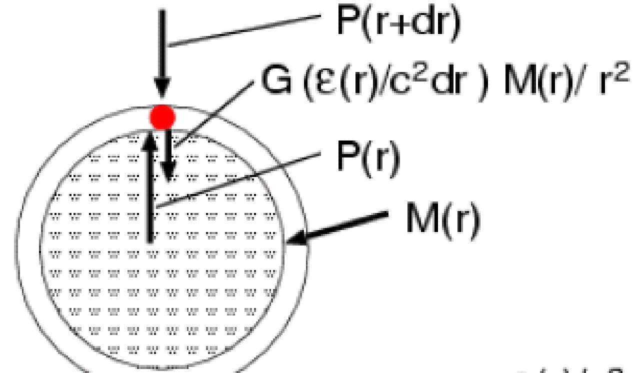
Dany Page

M-R curve and EOS

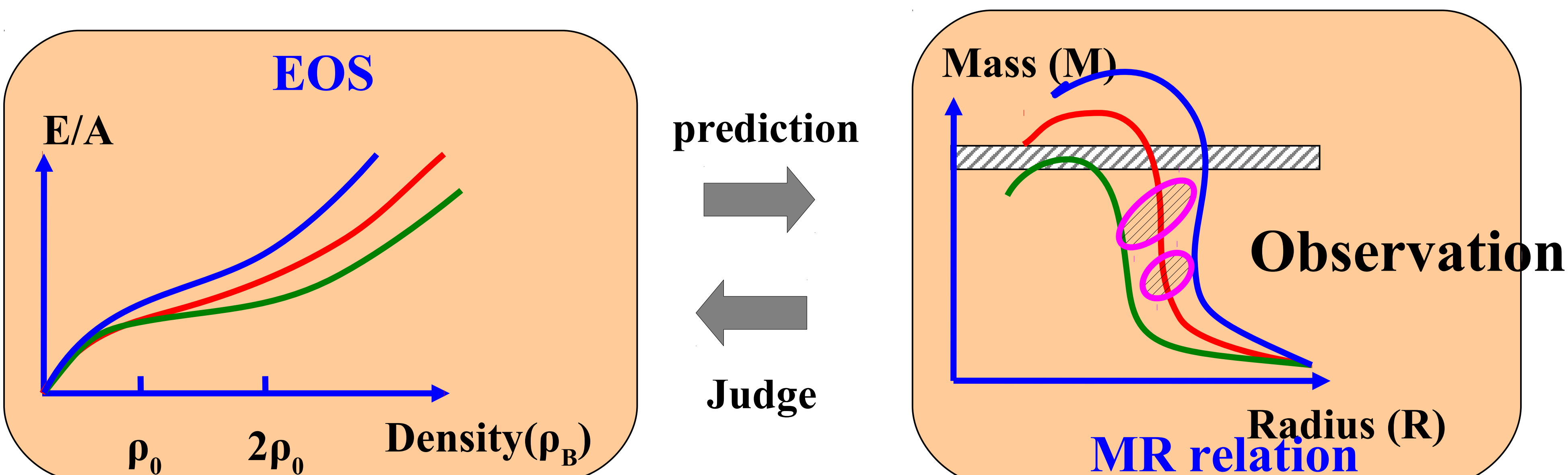
- **M-R curve and NS matter EOS has 1 to 1 correspondence**
  - **TOV(Tolman-Oppenheimer-Volkoff) equation =GR Hydrostatic Eq.**

$$\frac{dP}{dr}=-G\frac{(\varepsilon/c^2+P/c^2)(M+4\pi r^3 P/c^2)}{r^2(1-2GM/rc^2)}$$

$$\frac{dM}{dr}=4\pi r^2 \varepsilon/c^2, \quad P=P(\varepsilon) \quad (\mathrm{EOS})$$



Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$



NS matter Grant-in-Aid Study (2012-2017)

High ρ (Group A)
PI: Tamura, Takahashi

Hypernuclei, Kaonic nuclei
YN & YY int.,
Eff. Interaction
(Heavy-ion collisions)

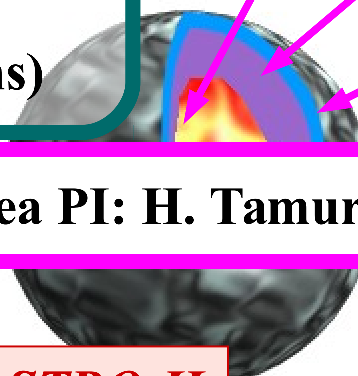
J-PARC

Hyperons, mesons, quarks

Asym. nuclear matter
+elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.



Area PI: H. Tamura

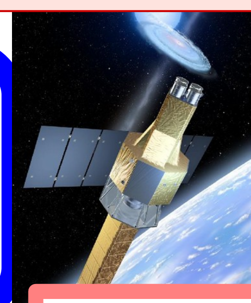
Low ρ (Group B)
PI: Murakami,
Nakamura, Horikoshi

Sym. E, Pairing gap,
BEC-BEC cross over,
Cold atom, Unitary gas

NS Obs. (Group C)
PI: Takahashi

Radius, Mass,
Temp. (Cooling),
Star quake, Pasta

ASTRO-H



RIBF

Theory (Group D)
PI: Ohnishi

D01 members

- **Project members:**
  A. Ohnishi, T. Harada, H. Nakada, K. Iida, M. Matsuo, M. Kimura, T. Tatsumi, A. Ono, A. Dote, K. Nakazato
- **Project PDs:**
  H. Sotani, K. Morita, J. Yamagata-Sekihara, K. Tsubakihara, S. Ohnishi, T. Inakura, N. Ikeno, C. Ishizuka, T.-G. Lee
- **Research Collaborators:**
  T. Kunihiro, S. Nishizaki, K. Oyamatsu, T. Maruyama, H. Abuki, Y. Ohashi, N. Shibazaki, Y. Yamamoto, T. Takatsuka, M. Kohno, T. Miyagawa, T. Muto, K. Sumiyoshi, H. Sagawa
- **Proposed Project PIs:**
  K. Hagino, H. Nemura, K. Kiuchi, N. Yasutake, Y. Ohashi, M. Nitta, H. Sotani, T. Furumoto

Challenges in Neutron Star Physics

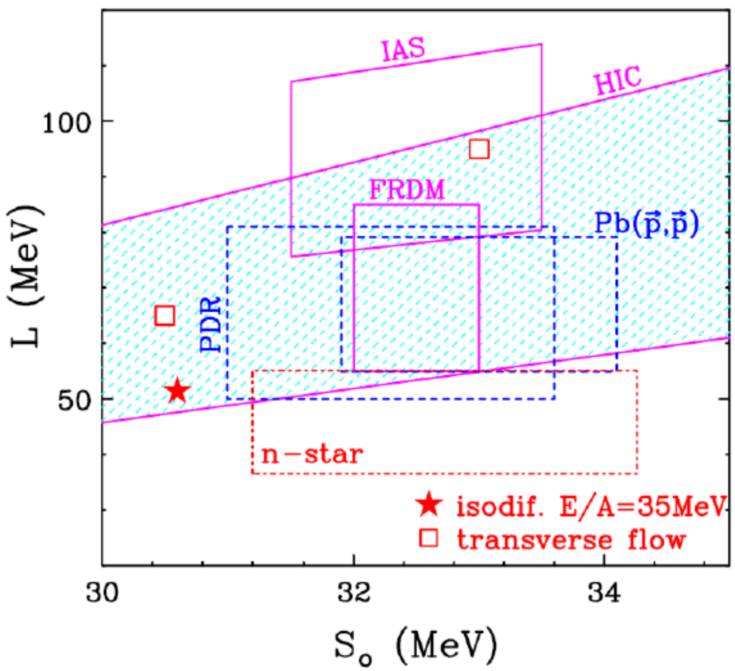
- Symmetry Energy
  - Symmetry Energy Parameters (S0, L)
  - Symmetry Energy at Supernuclear densities
  - Effects of Symmetry Energy on NS matter EOS
- Relation of Neutron Star Matter and Cold Atom
  - Low density Neutron Matter EOS and Cold Atom EOS
- Strangeness in Nuclear Matter
  - Hyperons and anti-Kaons in Nuclear Matter
- NS Matter EOS
  - Mass and Radius of Neutron Stars
  - Hyperon Puzzle
  - Do we have quark matter in NS ?
- NS astrophysics: QPO, Cooling, Glitches, Magnetic field, ...

Symmetry Energy

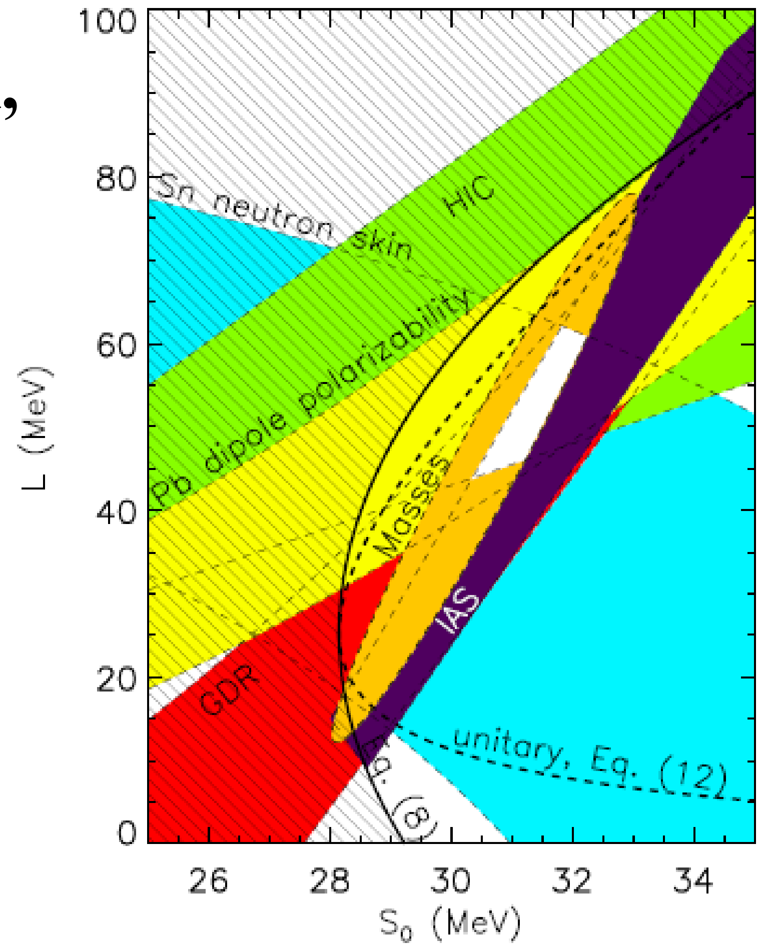
- **Symmetry Energy Parameters**

$$S(u) = S_0 + \frac{L}{3}(u-1) + \frac{K_{\rm sym}}{18}(u-1)^2 + \mathcal{O}[(u-1)^3] \qquad (u=n/n_0)$$

(Nakamura, Li, Trautmann, Murakami, Ono, Zenihiro, Colo, Aumann, Tamii, Inakura)



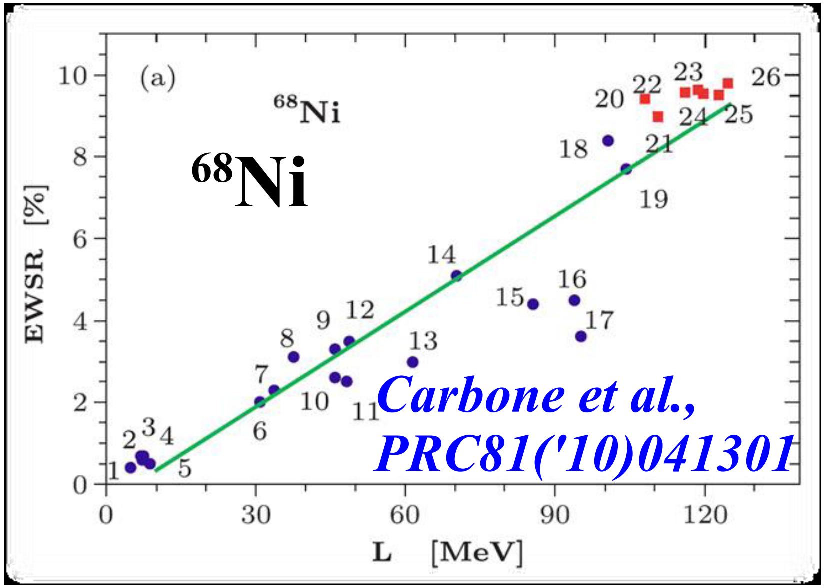
Tsang et al. ('12): NuSYM 2011



Lattimer, Lim ('13), Lattimer, Steiner ('14)
Kolomeitsev, Lattimer, AO, Tews ('16)

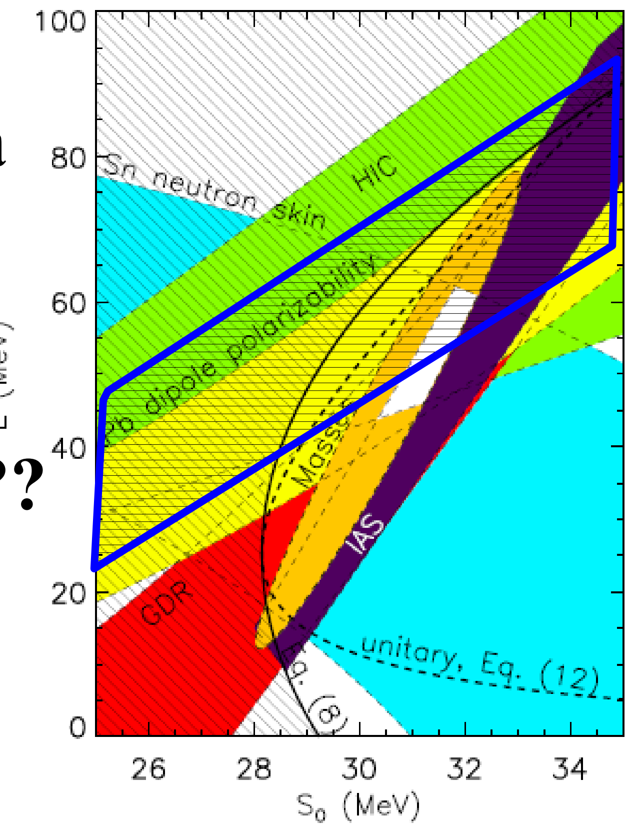
Low Energy Dipole Strength

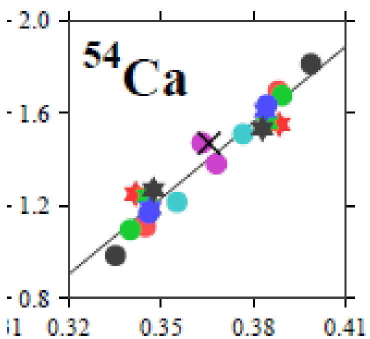
- **Low Energy Dipole Strength and L (Nakamura, Inakura, Colo, Aumann)**

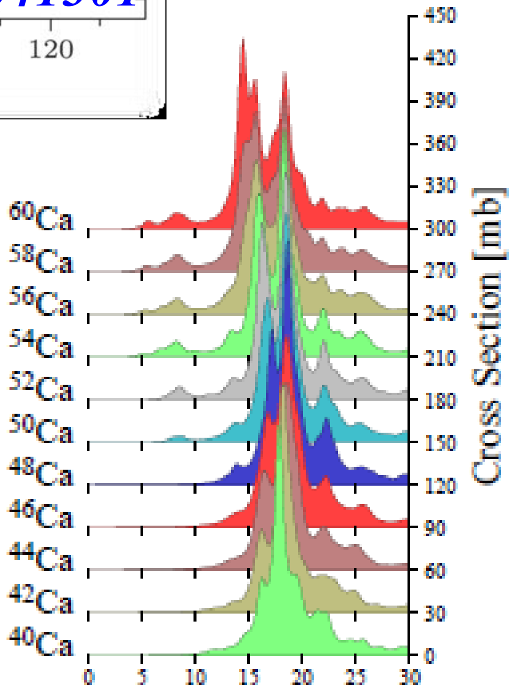


Nakamura (B02)

???





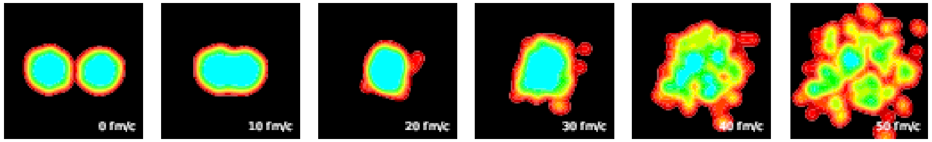


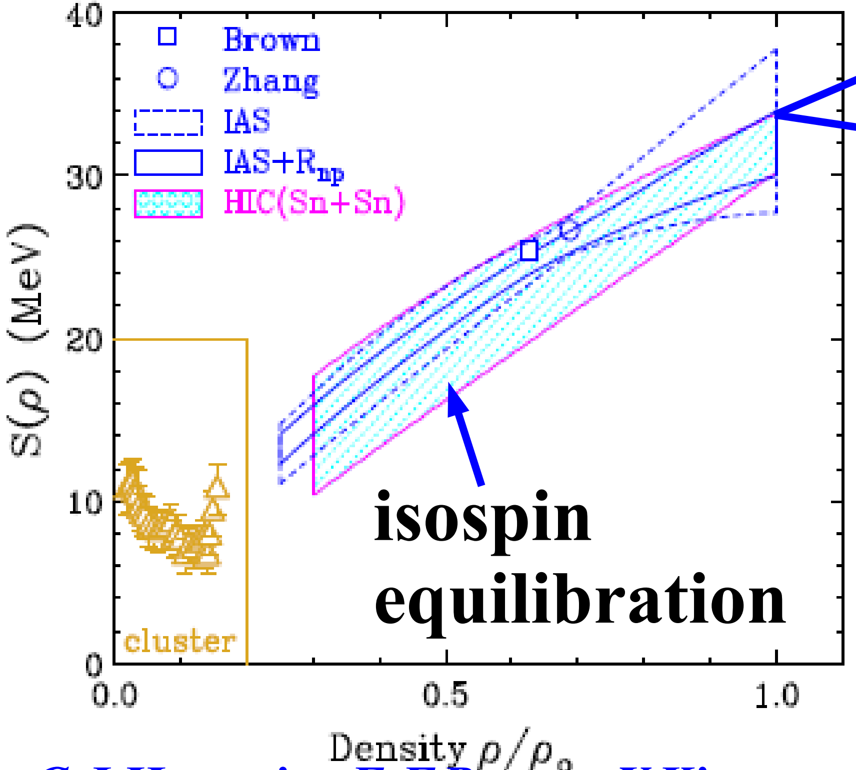
Inakura, Nakatsukasa, Yabana, PRC84('11)021302; PRC88('13)051305

Let's wait for B02 experiments !

High Density Symmetry Energy

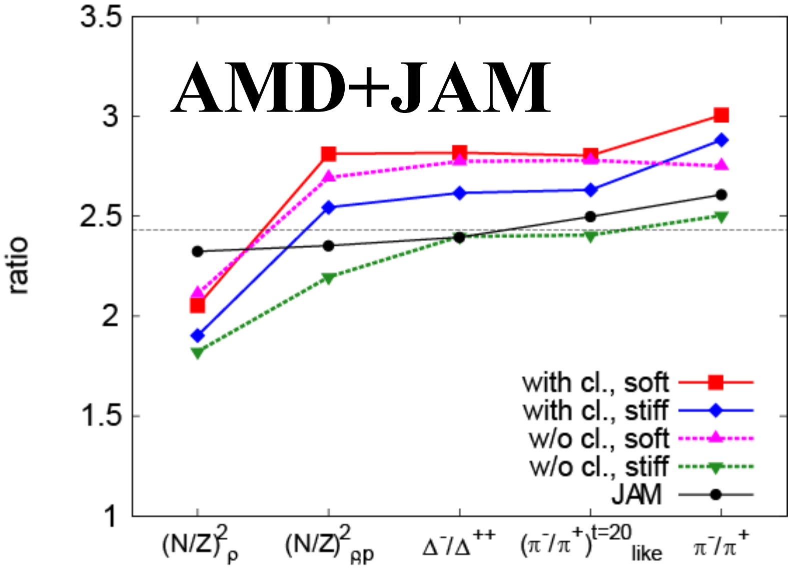
- Symmetry energy at ρ=(2-4) ρ_0 dominantly determines NS radius.
  → Central Heavy-Ion collisions at a few 100 MeV !
  (Li, Trautmann, Murakami, Ono)





Let's wait for SπRIT B01 results (Murakami) ! More theor. work needed.

π^-/π^+
B.A.Li

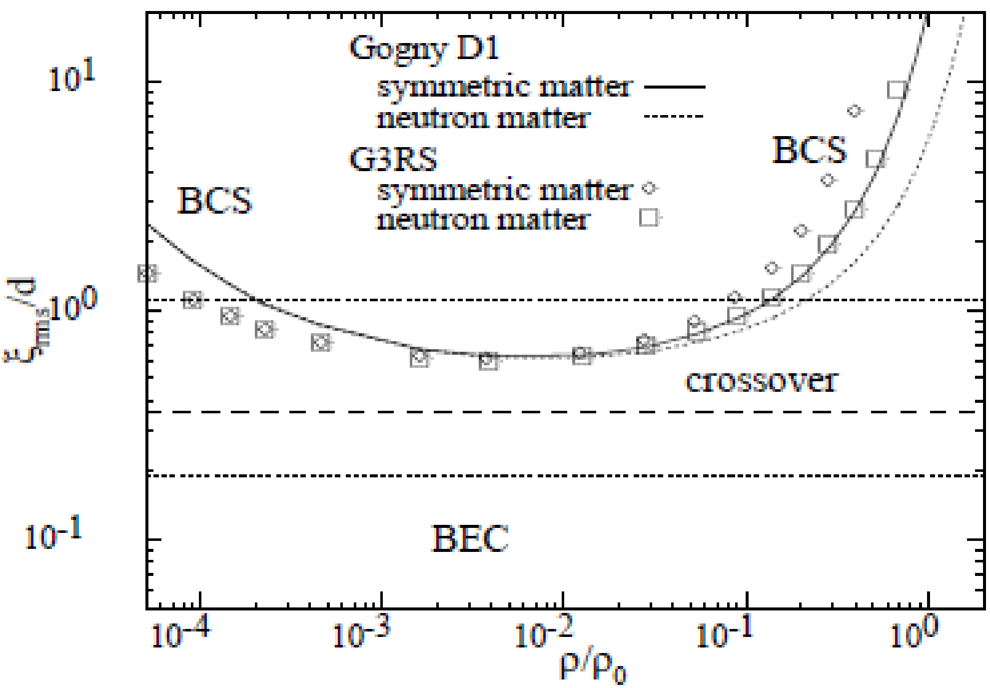


C.J.Horowitz, E.F.Brown, Y.Kim, W.G.Lynch, R.Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, H.H.Wolter (NuSYM13), JPG41('14) 093001

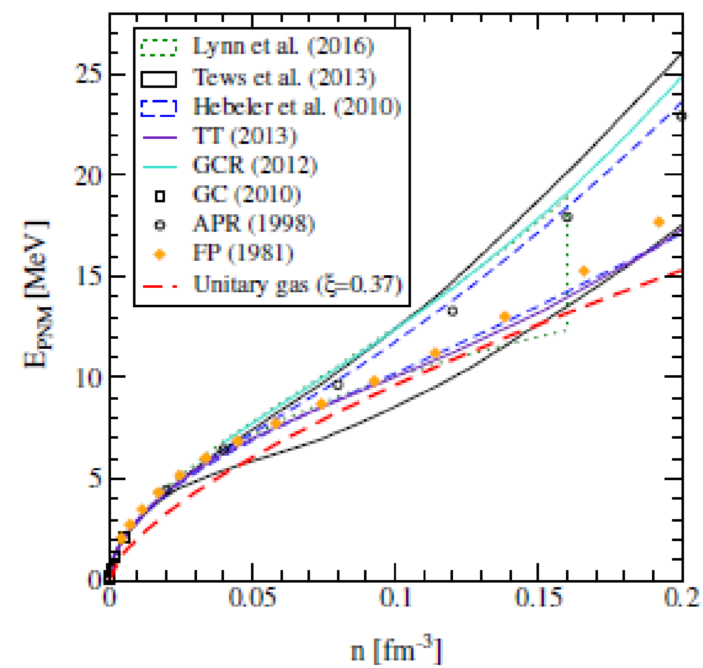
Ikeno, Ono, Nara, AO ('16)

Cold Atom around crossover and Neutron Matter

- **Neutron matter at low ρ ~ Unitary gas ($1/a_0\, k_F \to 0$, $r_{eff}\, k_F \to 0$) (Tan, Horikoshi, Ohashi)**
  - **Large nn scattering length (a_0=18.9 fm → $1/a_0\, k_F$ = 0.03 at ρ_0)**
  - **Cooper pair rms radius ~ nn average distance**
- **Unitary gas E. ~ Lower bound of neutron matter E. (Conjecture)**



M.Matsuo, PRC73('06)044309



Kolomeitsev, Lattimer, AO, Tews ('16)
arXiv:1611.07133 (today !)

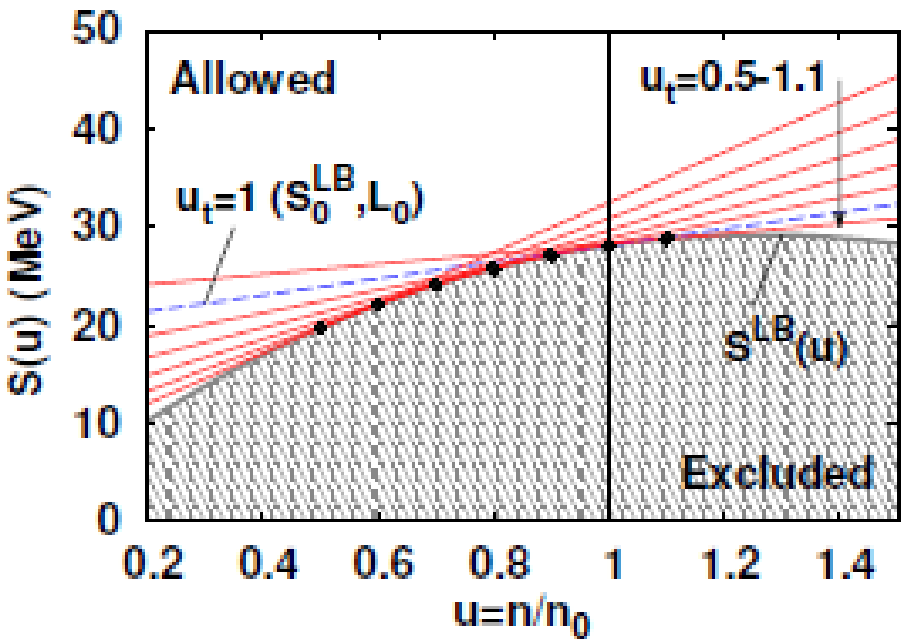
Unitary gas constraint on symmetry energy parameters

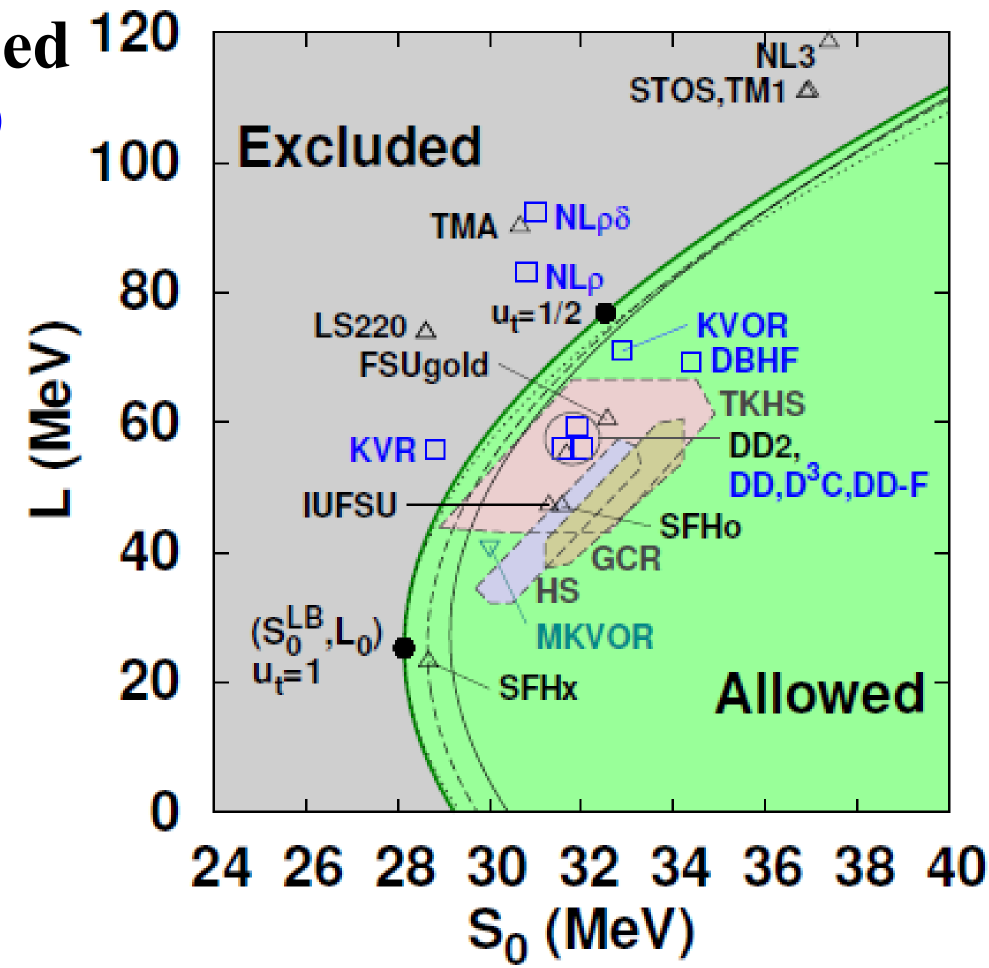
- **Conjecture: E(neutron matter) > E(unitary gas)**

$$S(u) \geq E_{\rm UG}^0 u^{2/3} - \left[E_0 + \frac{K}{18}(u-1)^2\right] \equiv S^{\rm LB}(u)$$

→ Sym. E. parameters are constrained !

- **Many tabulated EOSs are excluded**
  Fisher et al.('14), Klahn et al.('06)

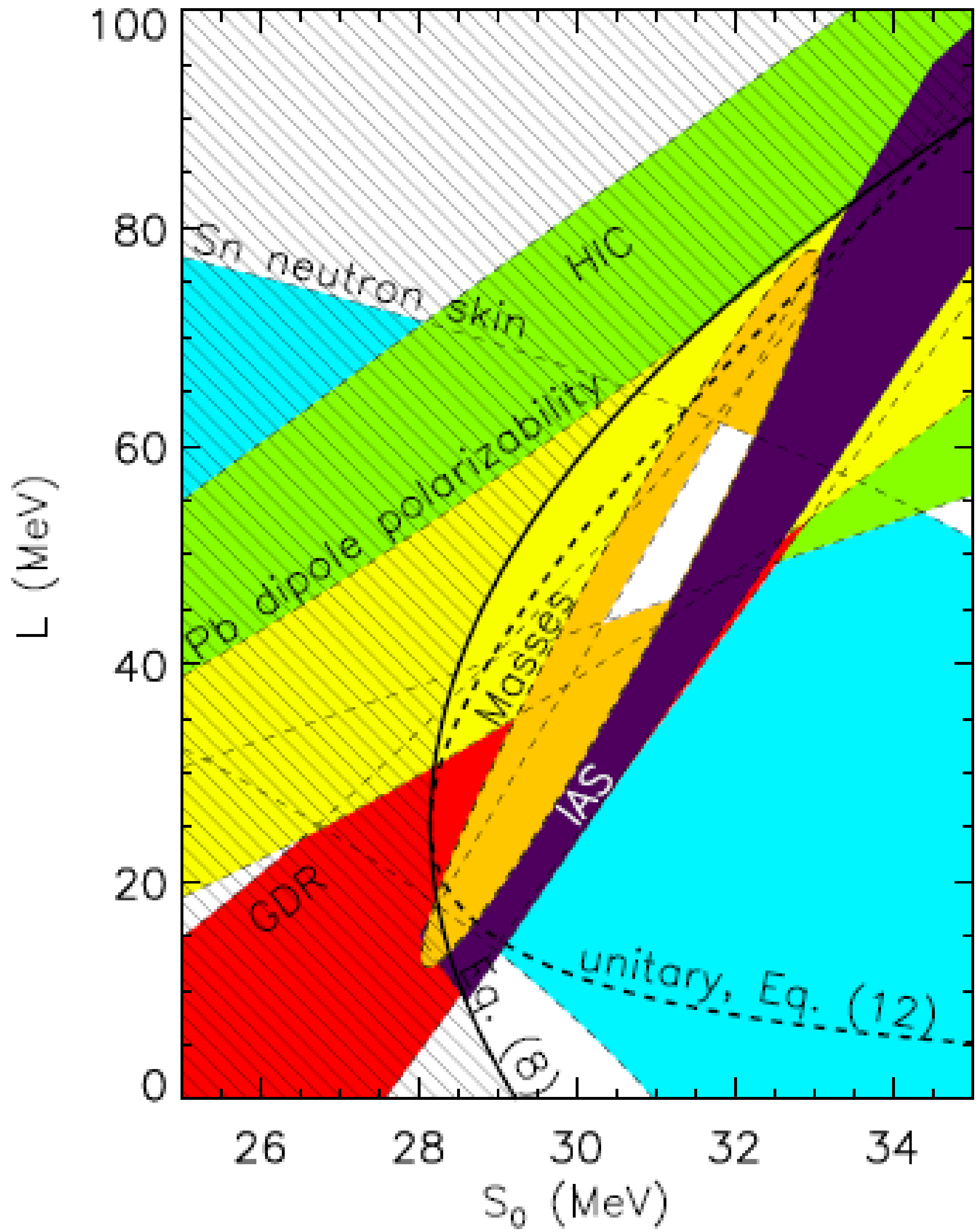




Kolomeitsev, Lattimer, AO, Tews ('16)

Unitary gas constraint on symmetry energy parameters

- **Unitary gas constraint is consistent with experimental constraints.**

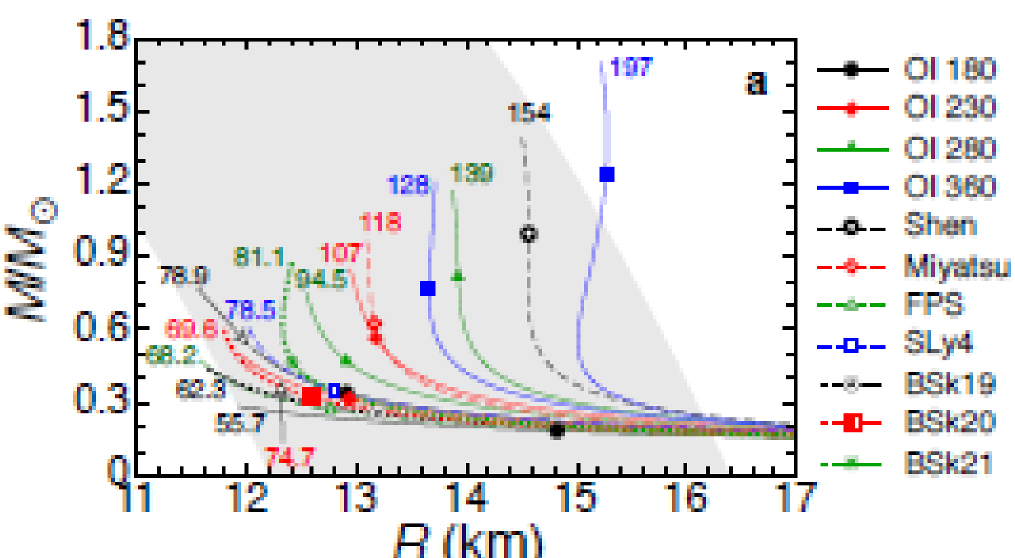


Does Cold atom EOS with finite $1/a_0\, k_F$ constrain (S_0, L) more severely ?
Horikoshi, Ohashi
We need more works !

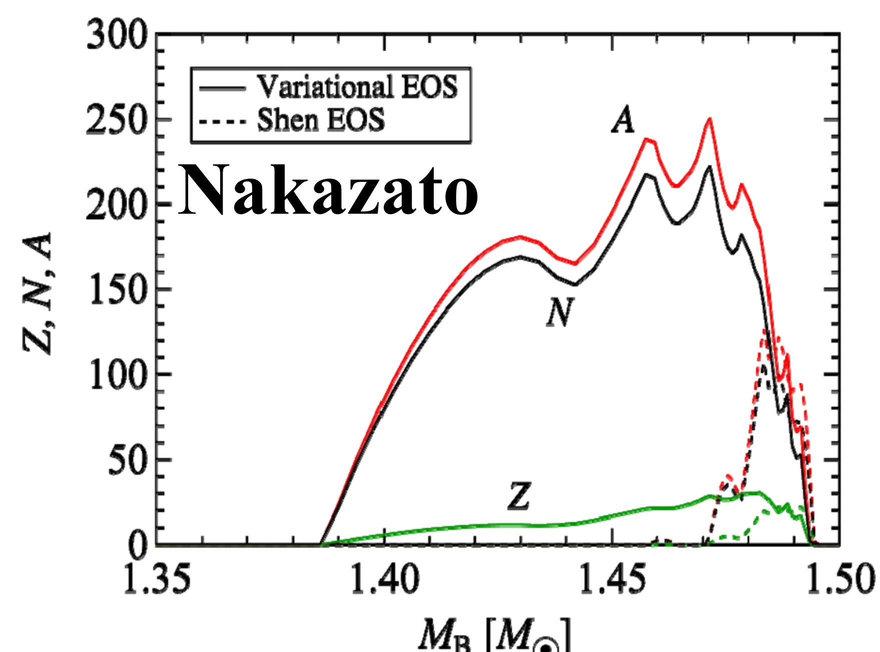
Kolomeitsev, Lattimer, AO, Tews ('16)

Symmetry Energy → Neutron Star

- **Sym. E dominantly determines NS radius.** *Lattimer, Prakash('01)*
- **What is the role of K (incompressibility) ?**
  → With EOS fitted to finite nuclear masses and radii,
  $\eta = (KL^2)^{1/3}$ determines low mass NS radii !
- **Small L enlarges the density range of pasta phase**
  Shen EOS (L=111 MeV) → Variational EOS (L=35 MeV)
- **NS torsional oscillation remains as a problem.**



Sotani, Iida, Oyamatsu, AO ('14)

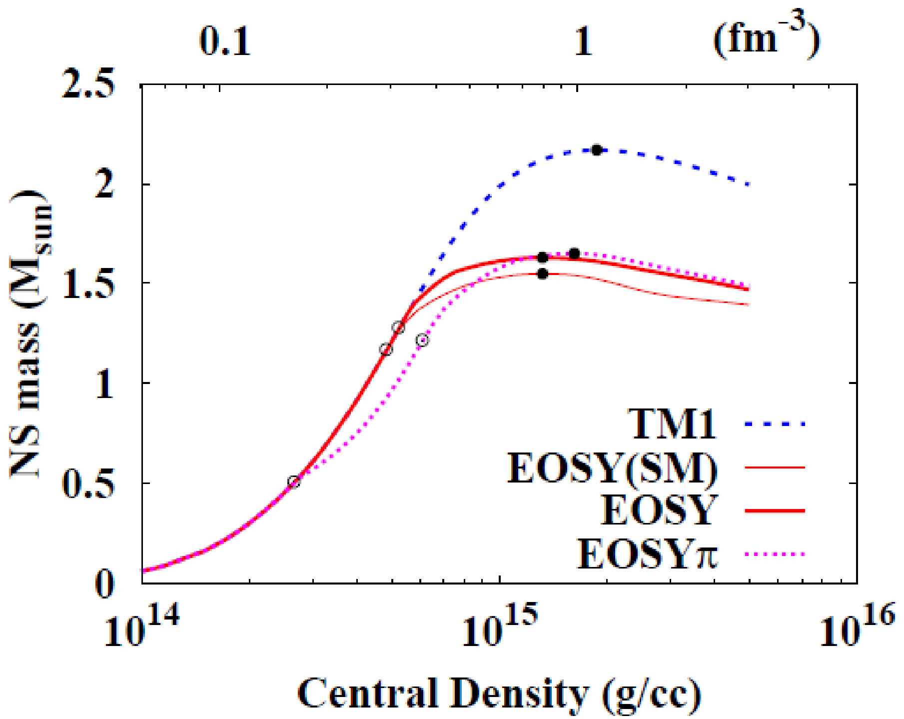


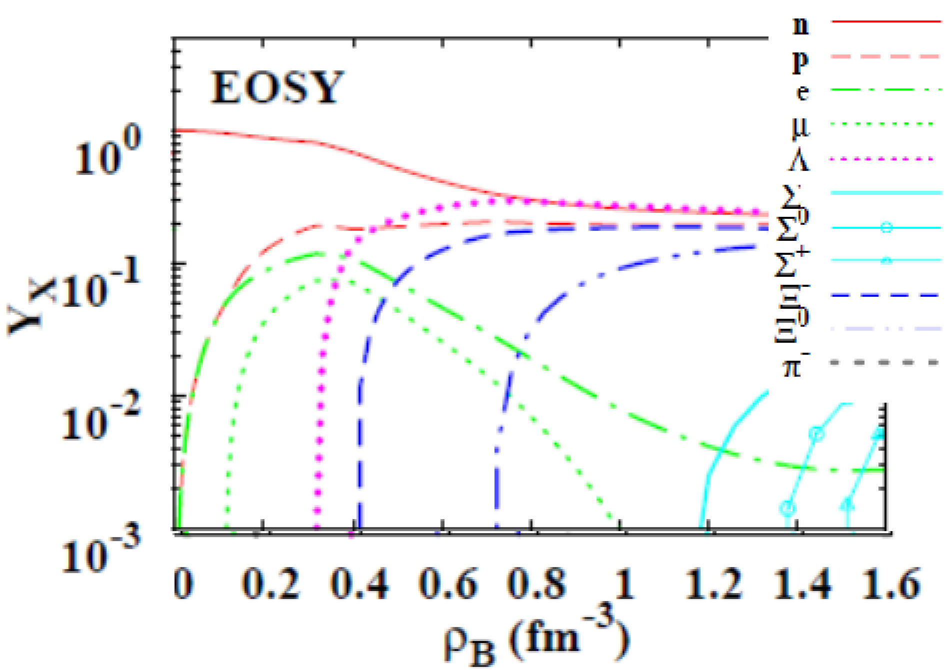
Strangeness Nuclear Physics

- **Before Oct.2010,**
  $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV

Harada, Hirabayashi ('05), Noumi et al. ('02),
Fukuda et al. PRC58('98),1306; Khaustov et al. PRC61('00), 054603;
Aoki et al. PLB355('95),45.

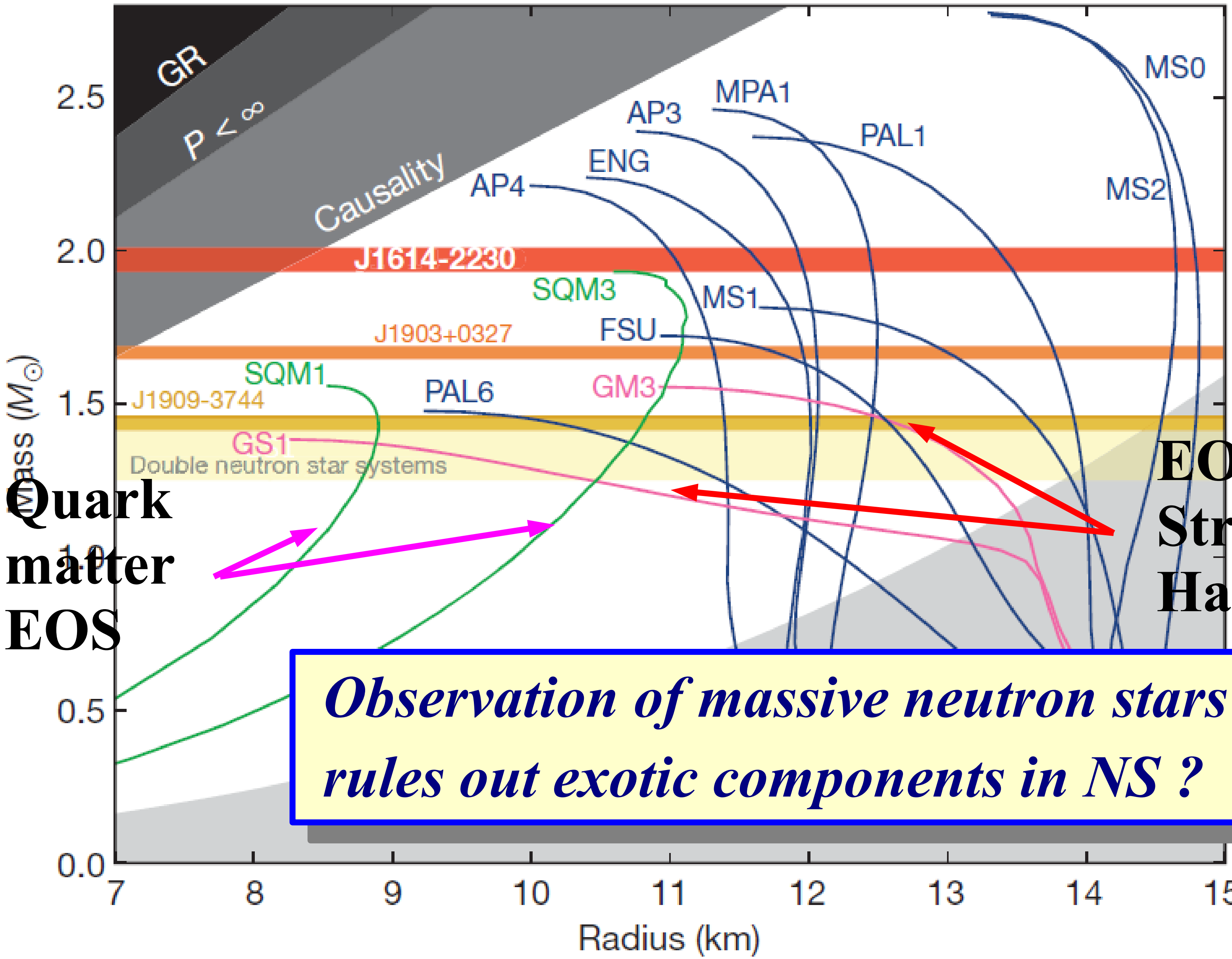
→ Maximum mass of NS ~ 1.6 $M_\odot$





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

Hyperon Puzzle



Quark matter EOS

EOS w/ Strange Hadrons

Observation of massive neutron stars ($M \sim 2\ M_\odot$) rules out exotic components in NS ?

PSR J1614-2230: 1.97 ± 0.04 $M_\odot$ *Demorest et al., Nature 467('10)1081 (Oct.28, 2010).*

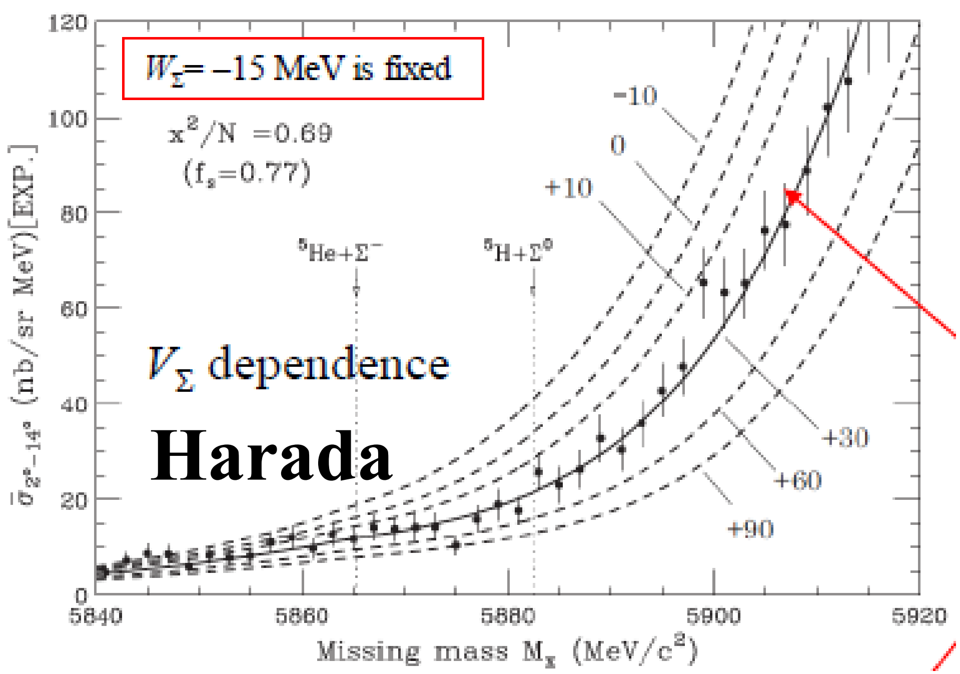
PSR J0348+0432: 2.01 ± 0.04 $M_\odot$ *Antoniadis et al., Science 340('13)1233232.*

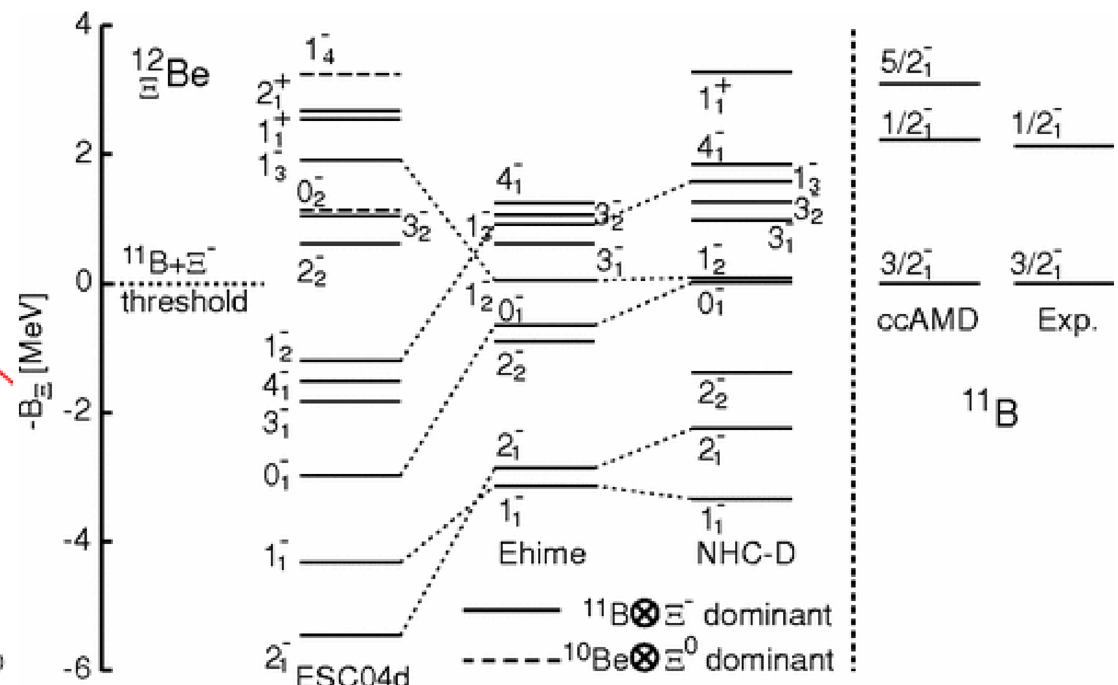
What did we miss ?

- **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 !



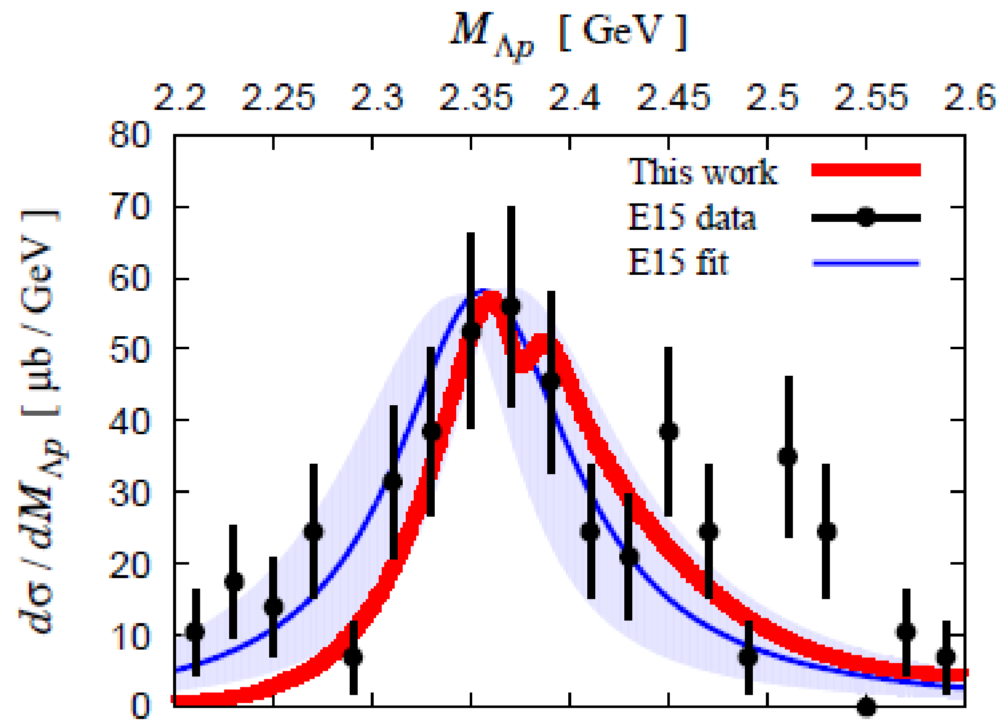


Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

Anti-Kaon potential in Nuclear Matter ?

- **$K^{-}pp$ binding energy (Takahashi (A02), Outa, Dote)**
  - **E15: One state at B.E.~ (15-30) MeV, Strength at B.E. ~ 100 MeV**
    E27: B.E.~100 MeV ?
  - **Dote: Higher pole B.E.~ 27 MeV, Lower pole B.E.~ 79 MeV (?)**
    Akaishi: B.E. ~ 100 MeV (DISTO, FINUDA)
    S.Ohnishi: Saturating B.E. in heavier kaonic nuclei

We need more work to confirm the fate of Kaon condensation

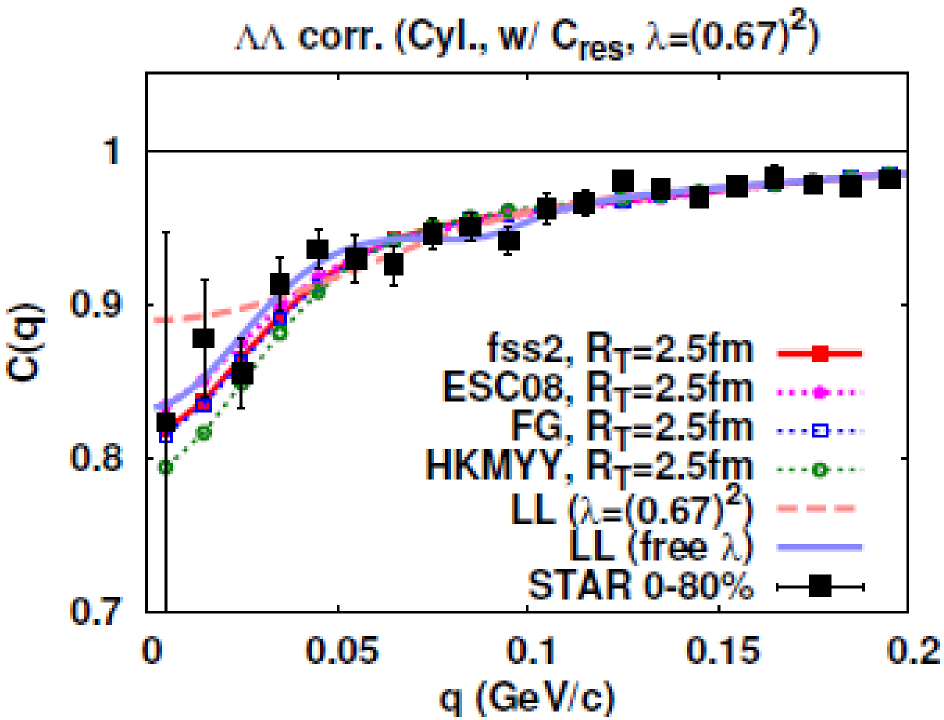


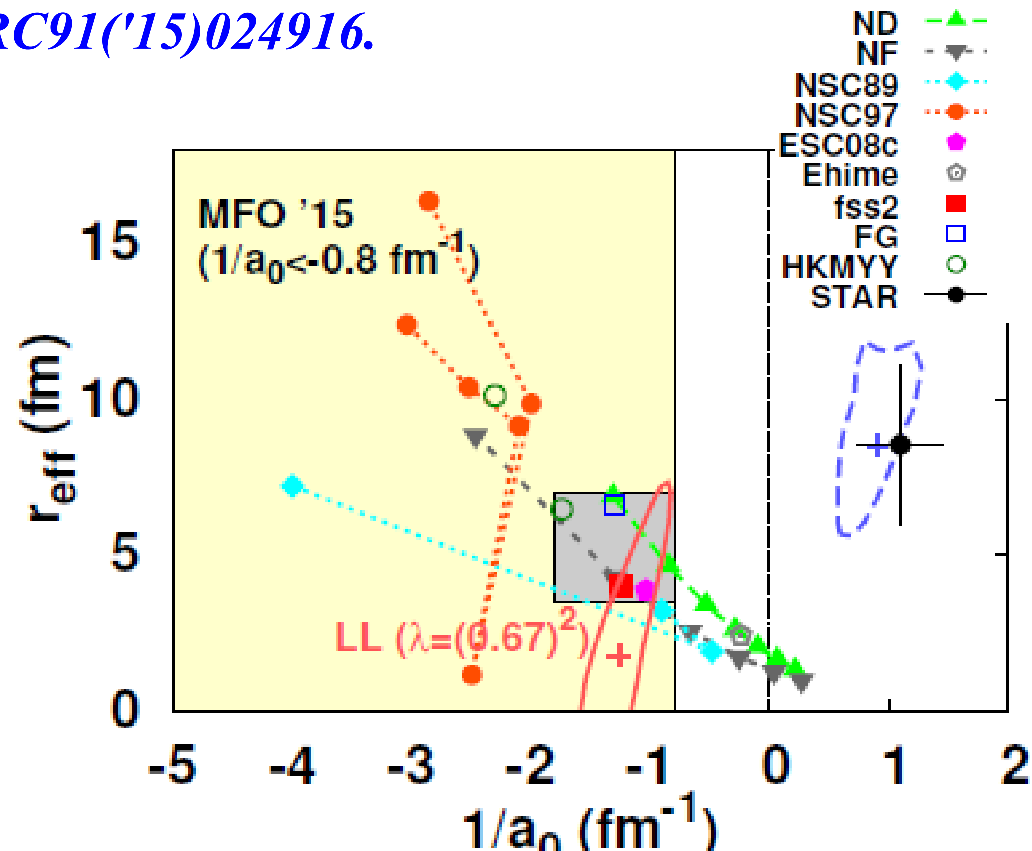
Muto

Sekihara, Oset, Ramos ('16)

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.

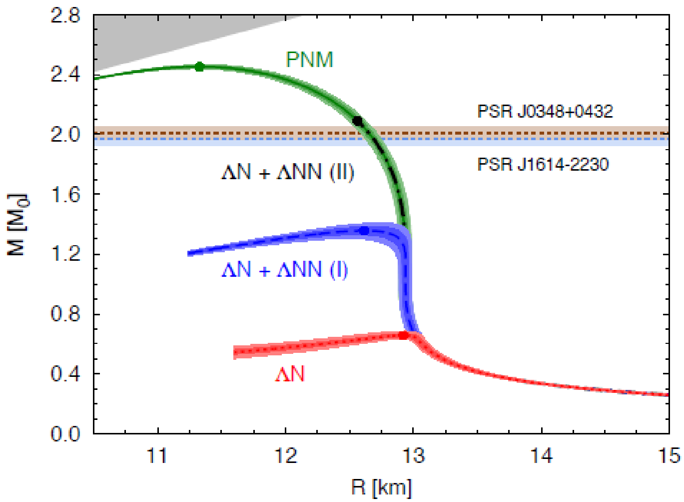




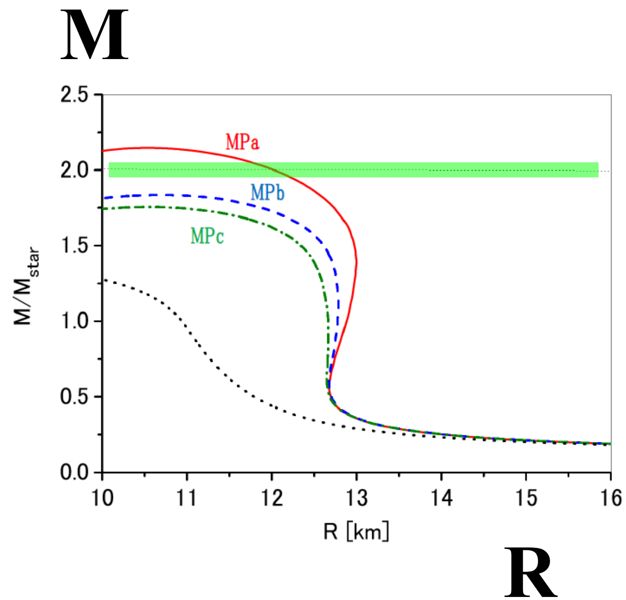
Remaining possibilities

- **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*

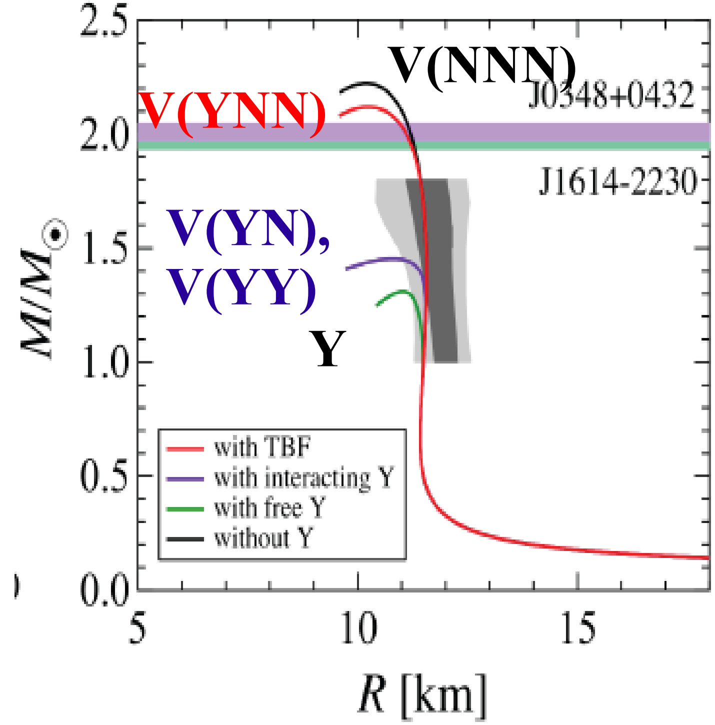
Hyperon Puzzle



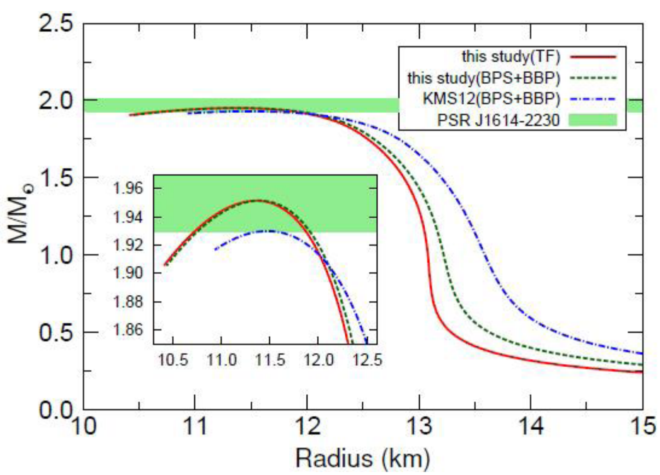
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



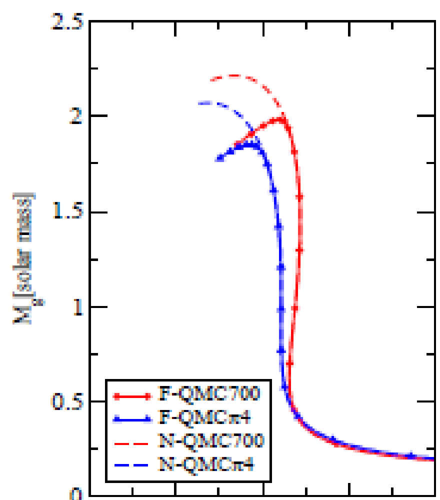
Yamamoto, Furumoto, Yasutake, Rijken ('13)



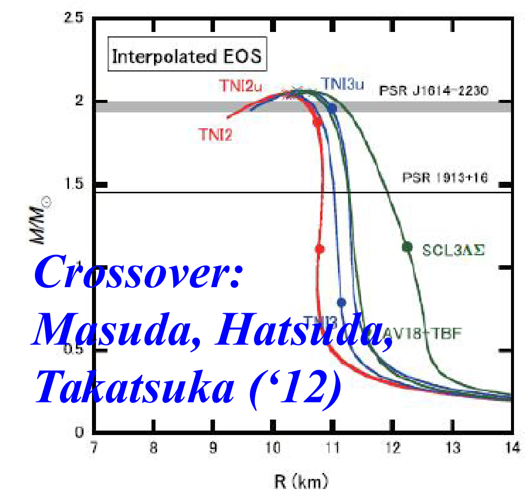
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu, Yamamuro, Nakazato ('13)



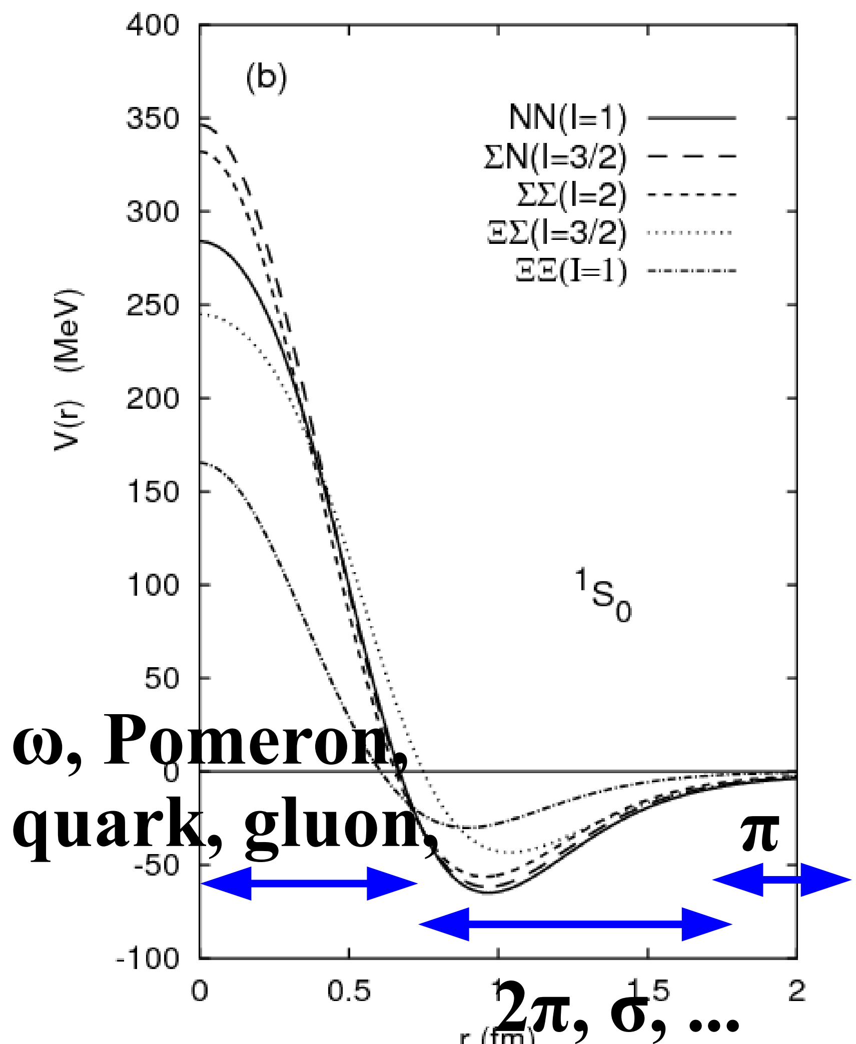
Rikovska-Stone, Guichon, Matevosyan, Thomas ('07),



Crossover: Masuda, Hatsuda, Takatsuka ('12)

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., …



Fujiwara, Suzuki, Nakamoto ('07)

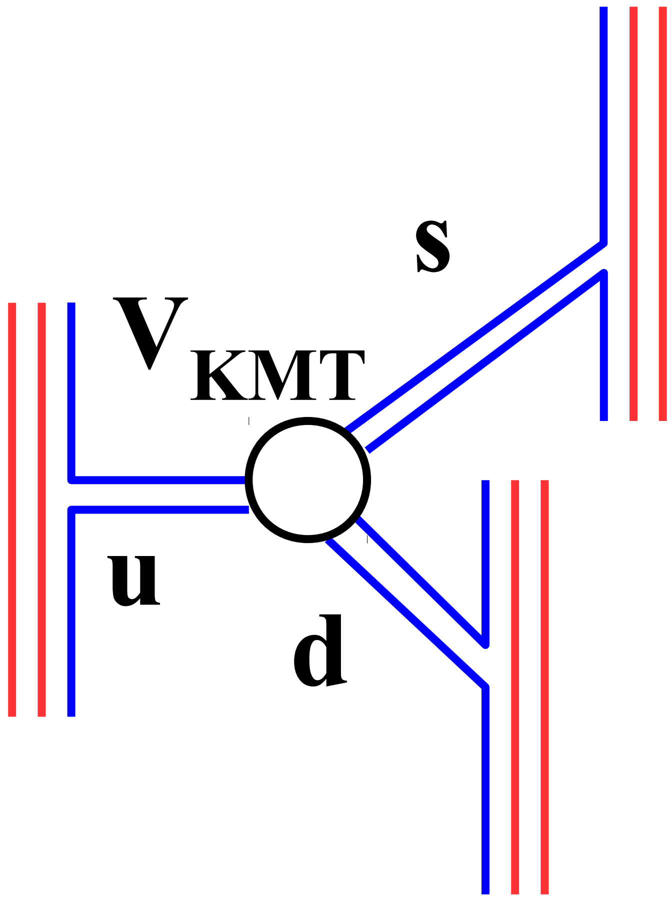
We may need quark-gluon DOF to understand 3B repulsion.
→ Quark Meson Coupling (Thomas),
Lattice QCD 3B force (HAL QCD),
Quark Cluster model (Nakamoto)

From 3-quark int. to 3B force

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

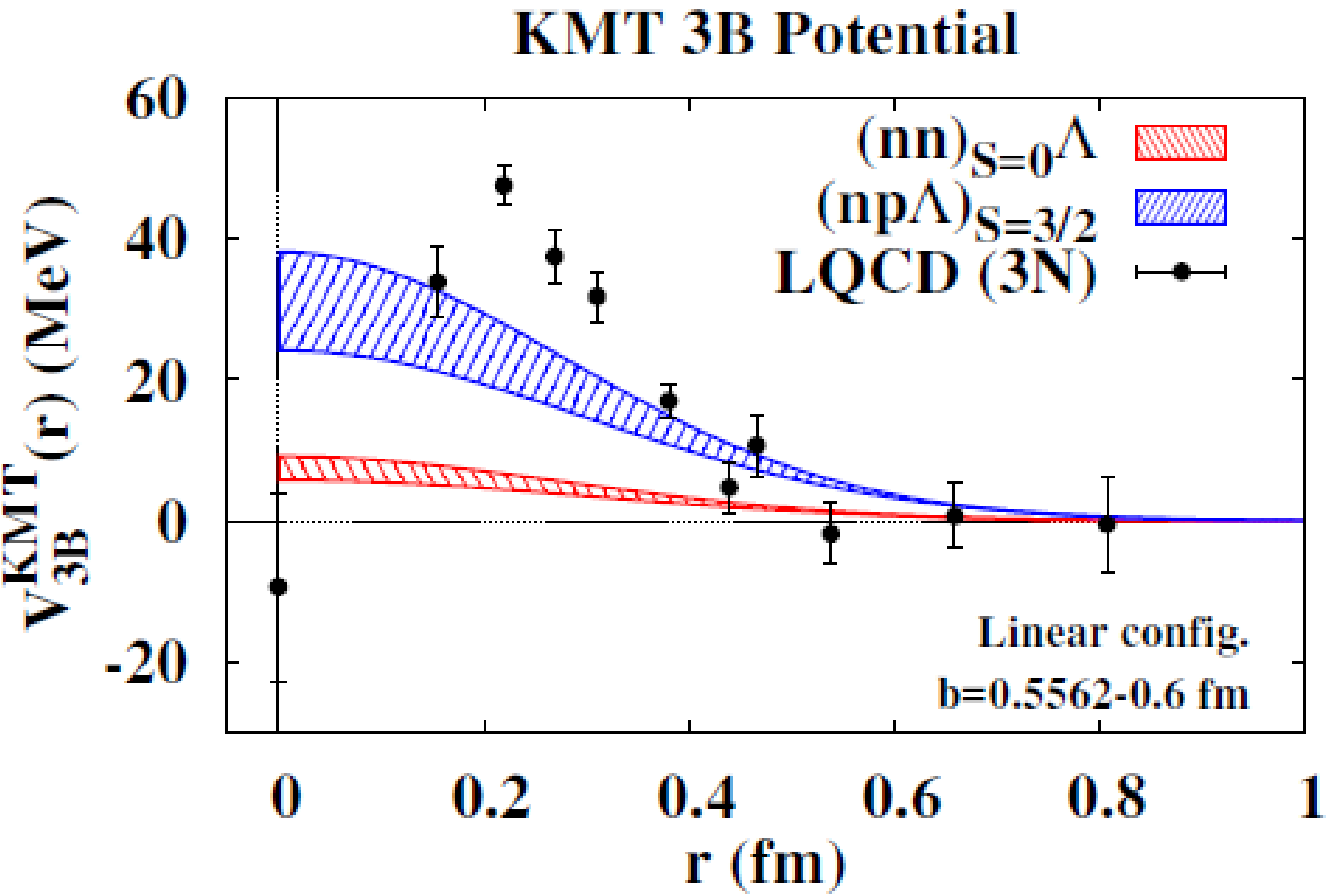
$$\mathcal{L}_{=} g_D \ (\det \Phi + \mathrm{h.c.}) \ , \quad \Phi_{ij} = \bar{q}_j (1 - \gamma_5) q_i$$

- **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)



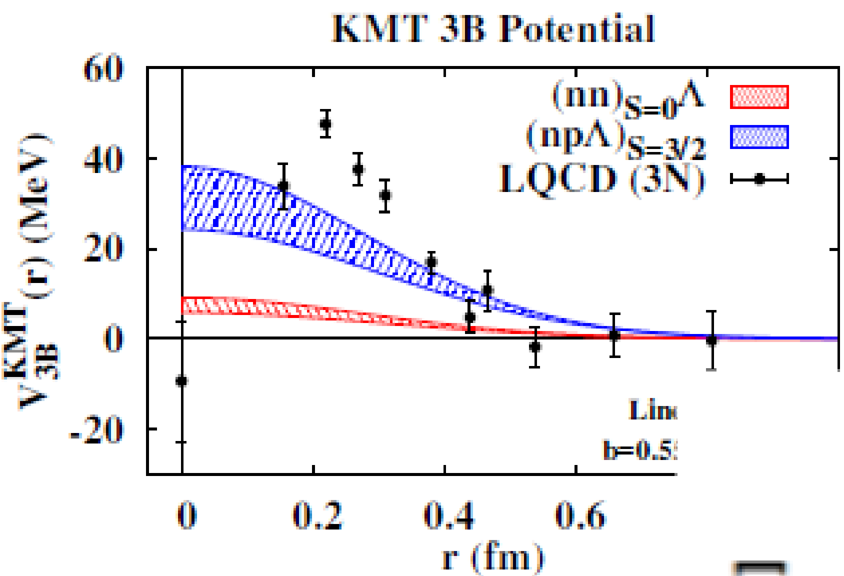
Does the anomaly support NS ?

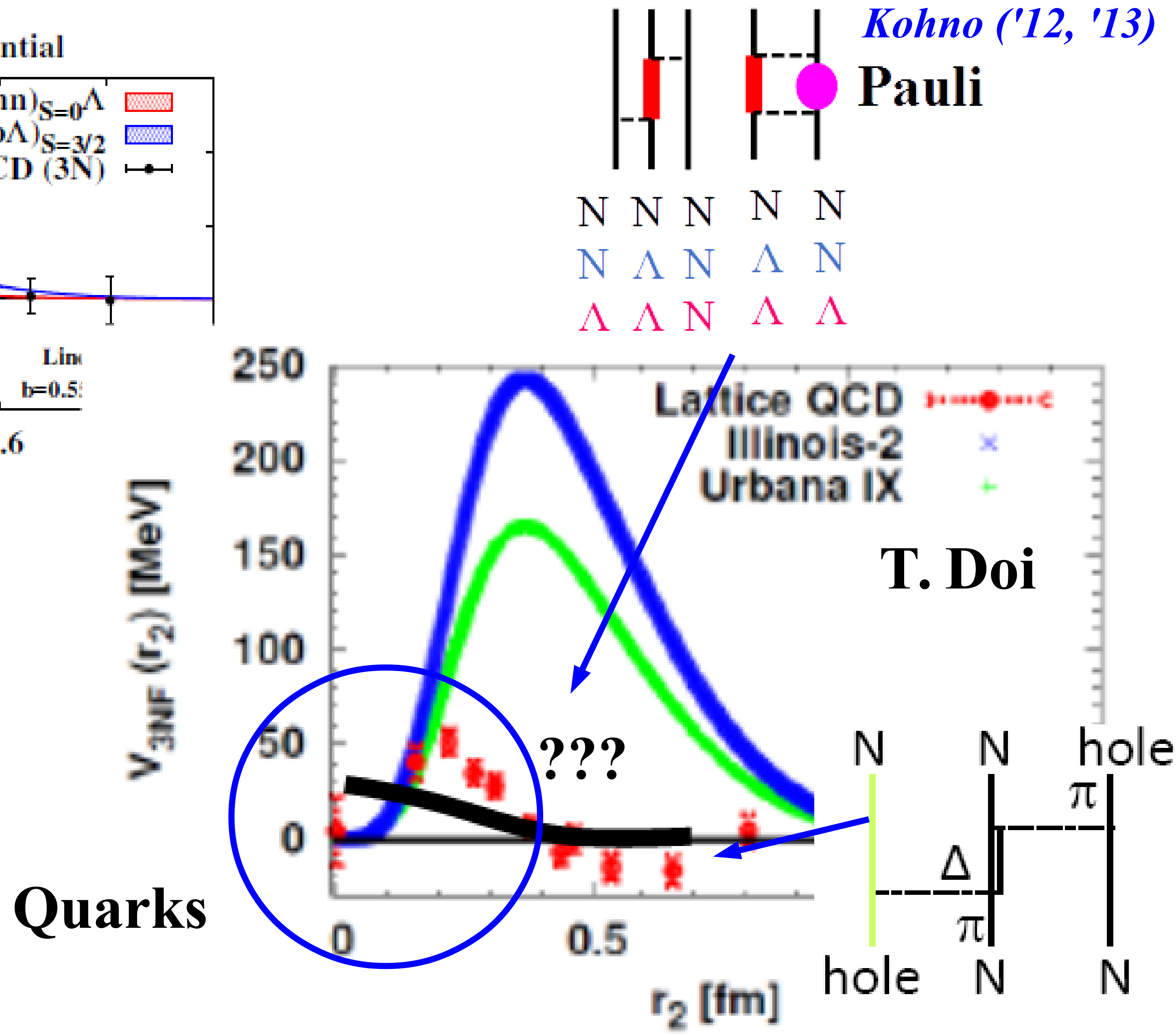
3B potential from KMT interaction



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

3B potential from KMT: Repulsive enough ?





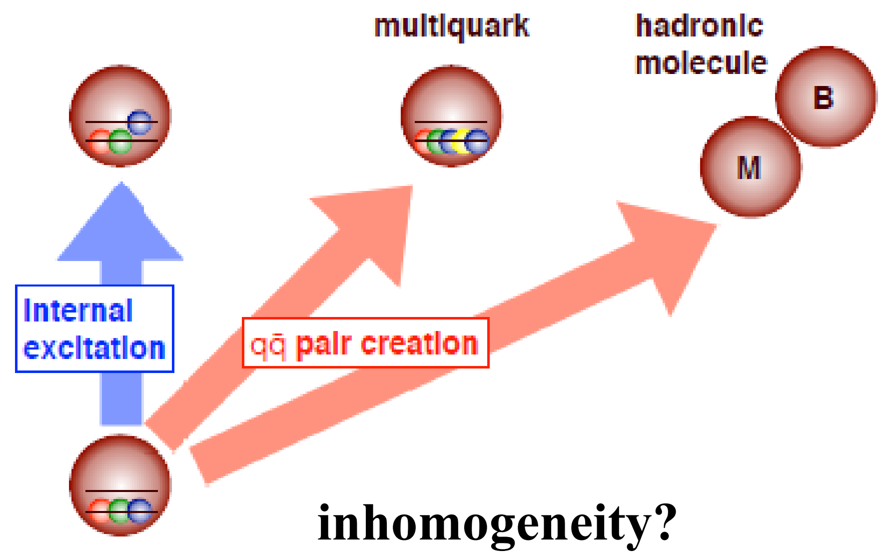
Summary

- **Neutron Stars are treasury of various field of physics.**
- **NS matter grant studies have advanced understanding of NS !**
  - **A01, A02: Strangeness Nuclear Physics (Λ, Ξ, K, Σ, ΛΛ, H, ΣN, …)**
  - **B01, B02: Symmetry energy (skin, pol., pygmy, and $S(\rho \sim 2\rho_0)$...)**
    and role of pairing
  - **B03: Cold atom EOS, mixed condensate,**
    quantum simulation of neutron matter (r_{eff}), ...
  - **C01: ASTRO-H, NICER → (M,R)**
  - **D01 (Theory): Support of other groups**
    quark matter, pasta, NS oscillation,
    EOS using the achievements by A,B,C groups …

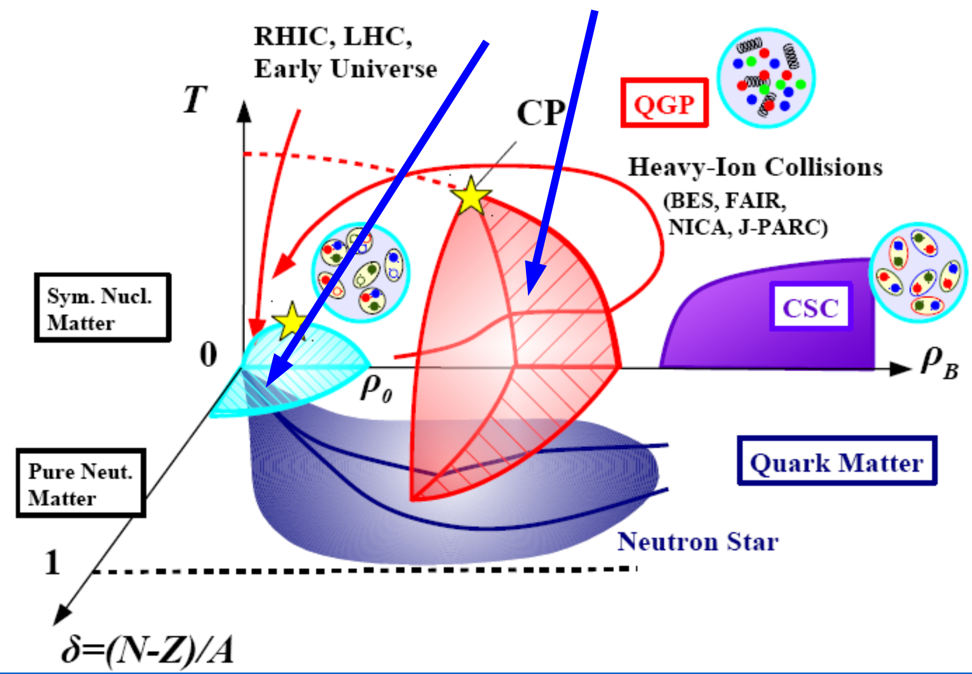
  (Sorry, members. I did not touch subjects other than EOS)
- **We still need much more works to understand Neutron Stars.**

Future Direction (Personal Prospect)

- Neutron Star Physics requires various interactions; fermion-fermion, fermion-boson, boson-boson (BB, BM, MM), which appears most strongly around the threshold
  → "Cluster" physics
- Neutron Star matter is condensed matter with possible phase transition.
  → QCD phase transition
- EOS dependence of Gravitational Wave is also important.



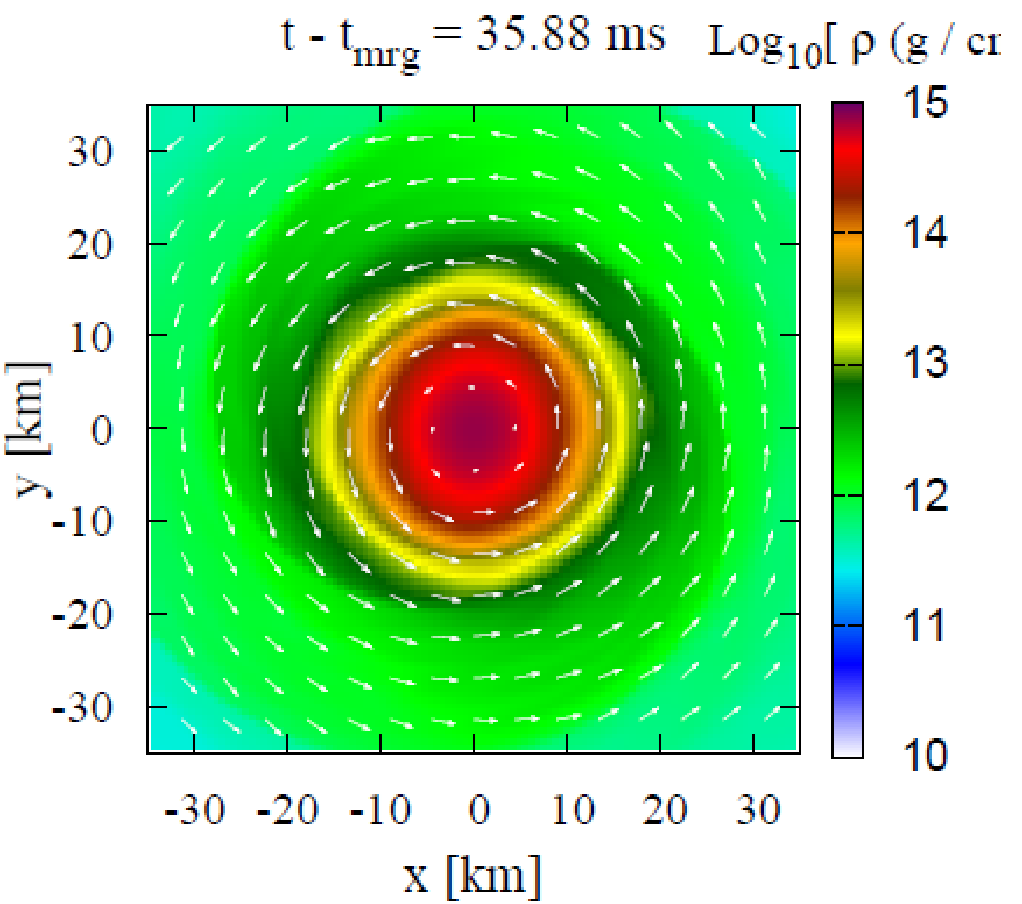
inhomogeneity?
(Nakazto, Tatsumi, Lee)

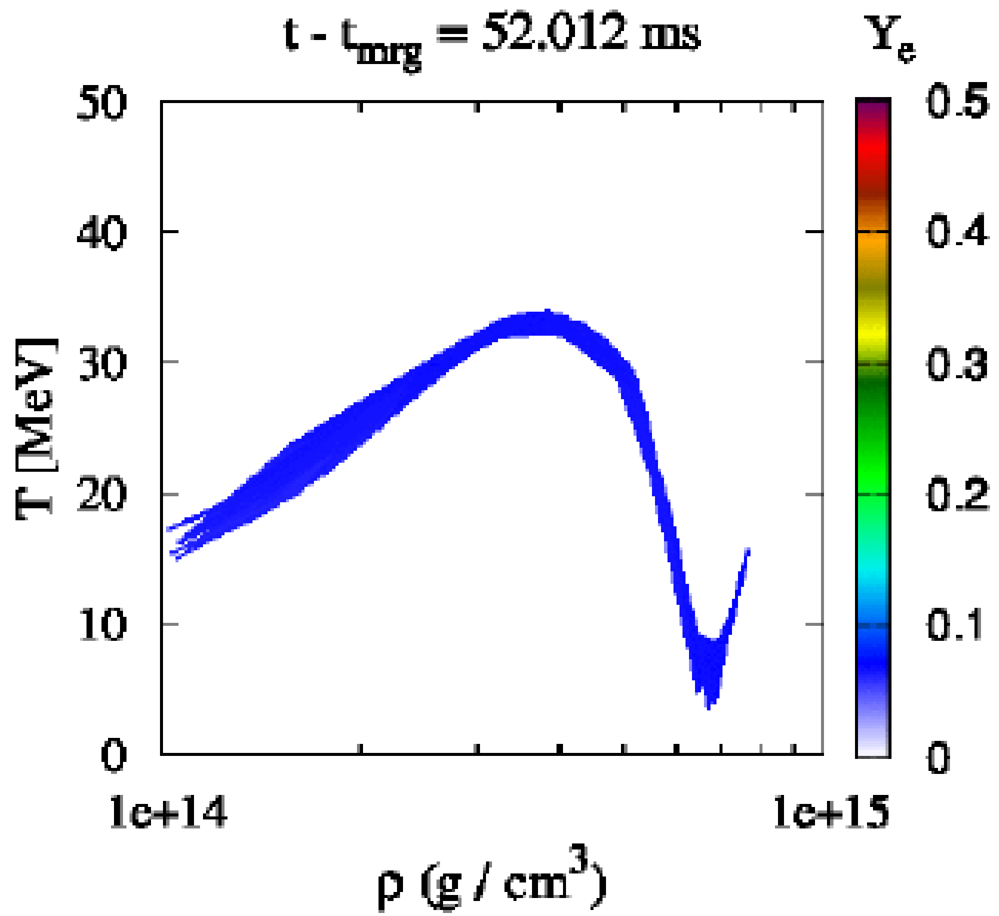


Thank you for your attention !

Binary Neutron Star Merger

- **T ~ 40 MeV, $\rho_B \sim 10^{15}$ g/cm^3 ~ 4 ρ_0 ($\rho_0 \sim 2.5 \times 10^{14}$ g/cm^3), Ye ~ 0.1**





Courtesy of K. Kiuchi
Data are from Y. Sekiguchi, K. Kiuchi, K. Kyotoku, M. Shibata, PRD91('15)064059.

Neutron Star Matter EOS

- **Energy per nucleon in nuclear matter**

$$E_{\rm NM}(\rho,\delta) = E_{\rm SNM}(\rho) + S(\rho)\delta^2\ ,\quad \delta = (N-Z)/A$$

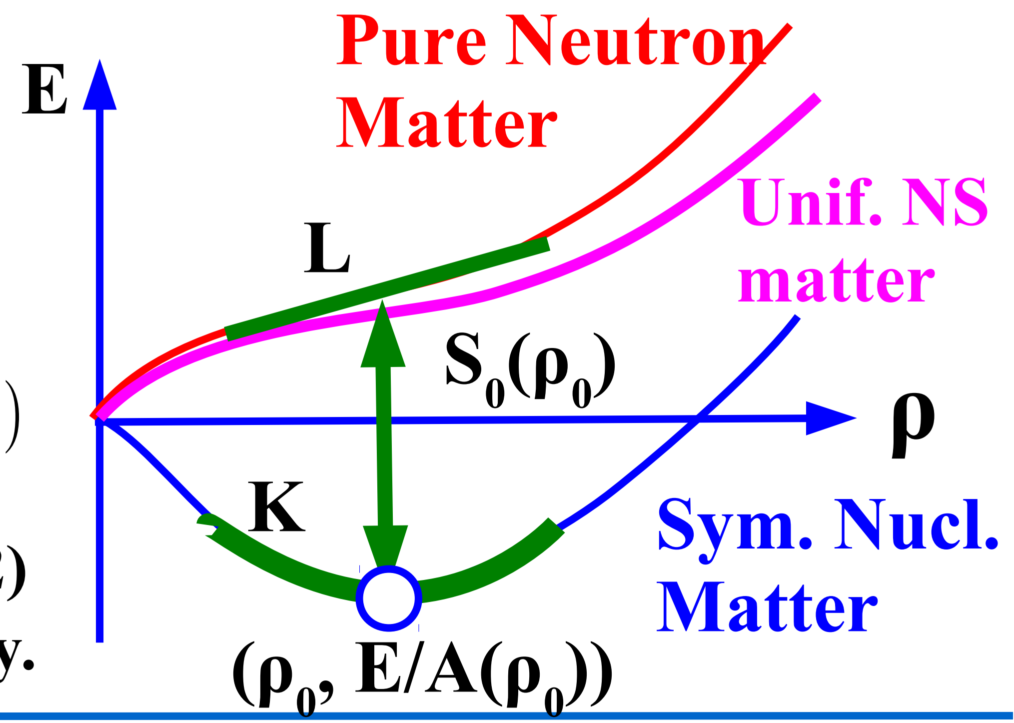
$$E_{\rm SNM}(\rho) \simeq E_0 + \frac{K(\rho-\rho_0)^2}{18\rho_0^2}\ ,\quad S(\rho) = S_0 + \frac{L(\rho-\rho_0)}{3\rho_0}$$

  - **Saturation point $(\rho_0, E_0) \sim (0.16\ \mathrm{fm}^{-3}, -16\ \mathrm{MeV})$**
  - **Symmetry energy parameters (S_0 (=J), L) ~ (30 MeV, 70 MeV)**
  - **Incompressibility K ~ 230 MeV**

- **Uniform neutron star matter**
  - **Constituents at low density = proton, neutron and electron**

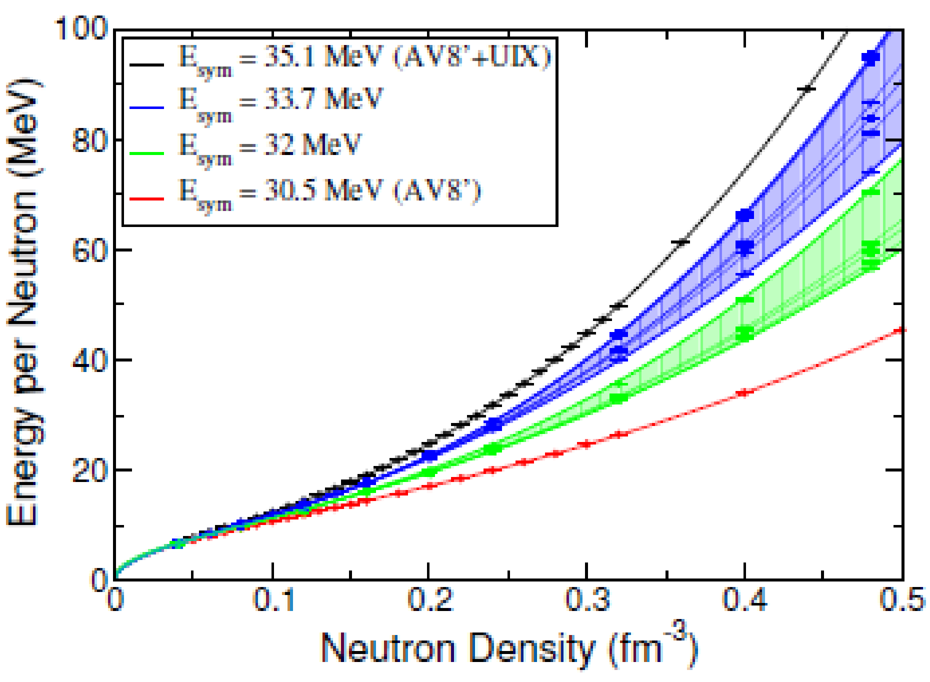
$$E_{\rm NSM}(\rho) = E_{\rm NM}(\rho,\delta) + E_e(\rho_e=\rho_p)$$

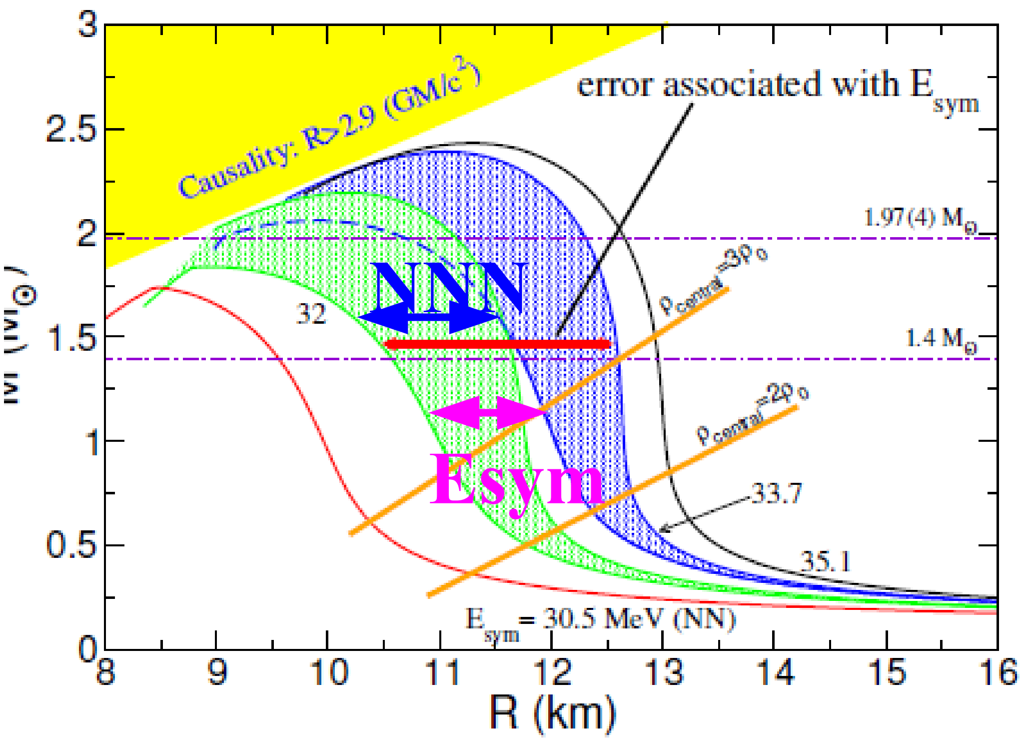
  - **Charge neutrality → ρ(elec.)= ρ(p) ($\rho_e=\rho_p=\rho(1-\delta)/2$)**
    δ is optimized to minimize energy.



Quantum Monte-Carlo calc.

- Auxiliary Field Diffusion Monte-Carlo (AFDMC) calc.
  - Hubbard-Stratonovich transf. + MC integral over aux. fields.
  - 3n force parameters are tuned to fit finite nuclei.
  - 2 MeV Difference in Esym results in 1.5 km (15 %) diff. in R_{NS}.

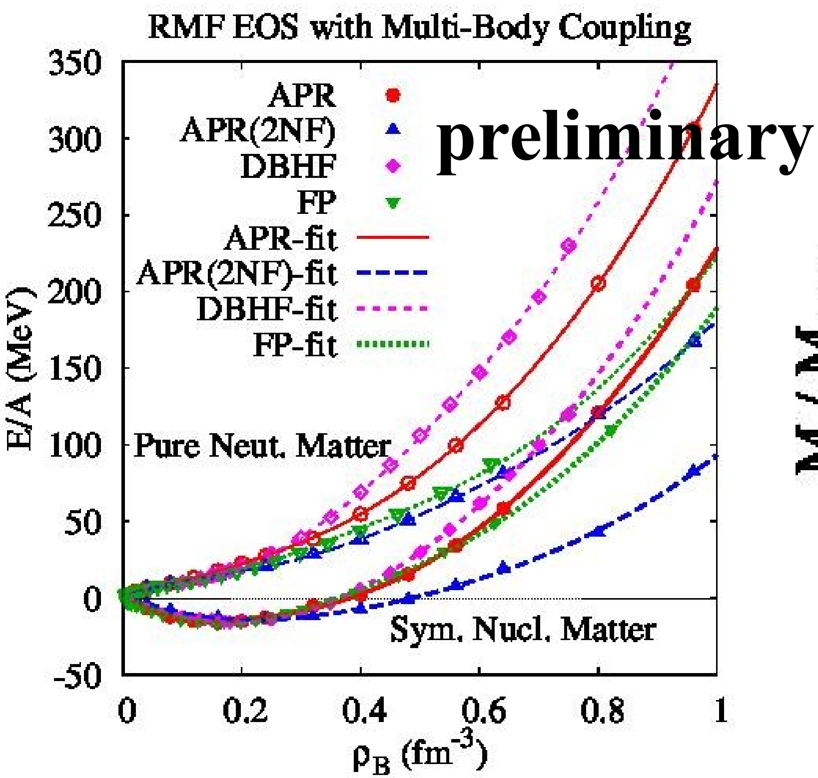


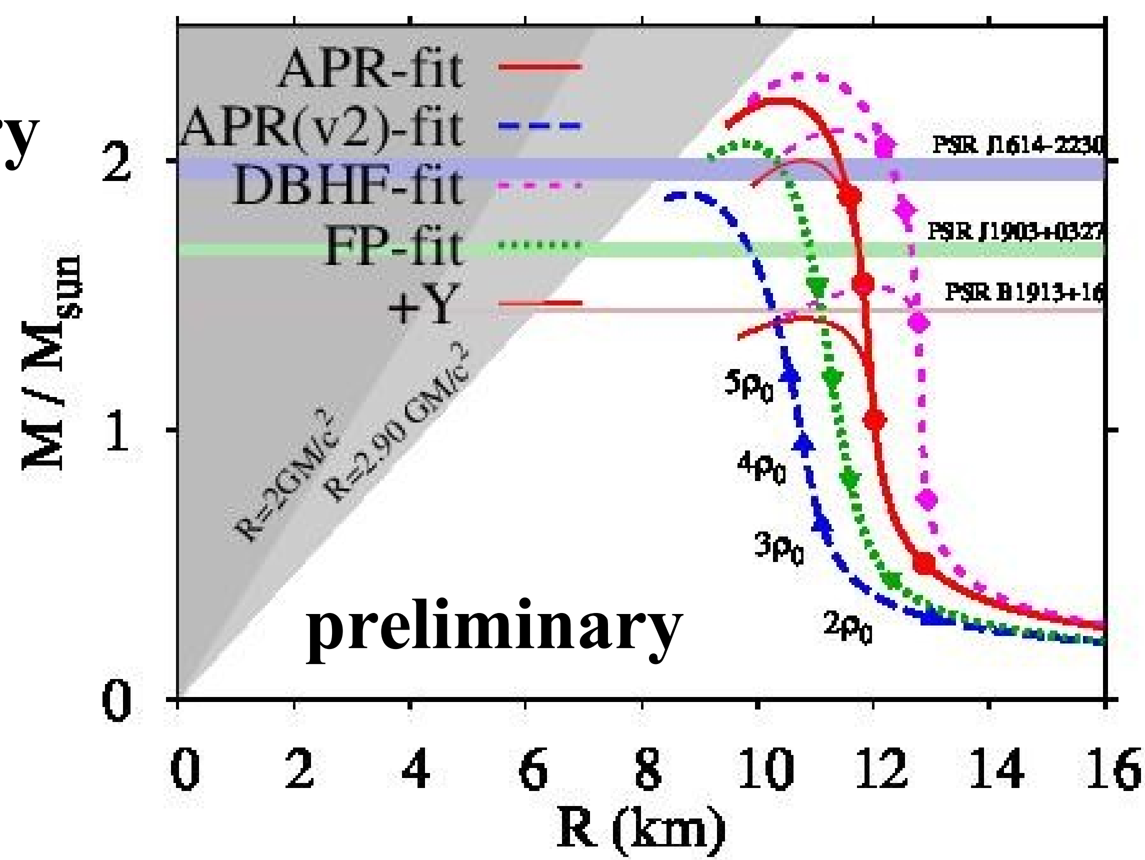


Gandolfi, Carlson, Reddy, PRC 032801, 85 (2012).

NS matter in "ab initio"-fit + Λ

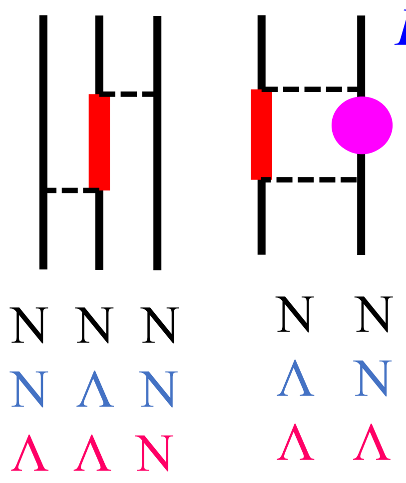
- **Fit to ab initio EOS (FP, APR, DBHF)**
  + phen. Λ potential (U(ρ_0) ~ -30 MeV)

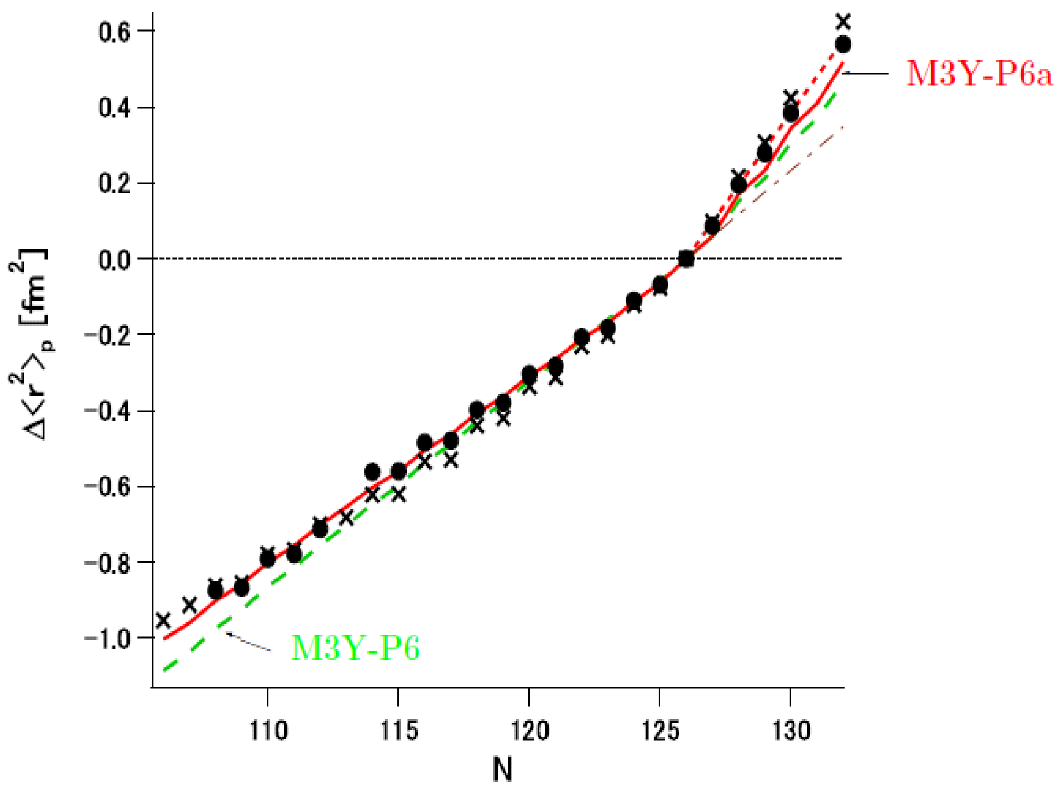




Strength of BBB force

- **Three-body force leads to stiff EOS and stronger LS int.**
  Kohno ('12, '13)
- **Density dep. LS int. explains long-standing Pb isotope puzzle.**
  Nakada, Inakura ('15)

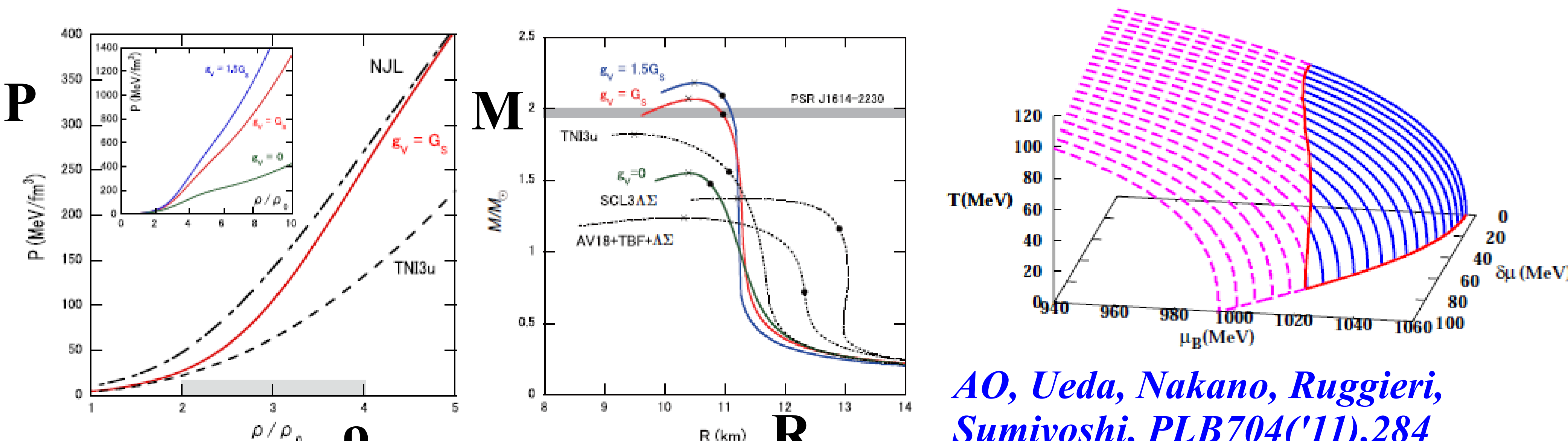




Nakada, Inakura ('15)

Early crossover transition to quark matter

- **Early *crossover* to quark matter → massive NS**
  K. Masuda, T. Hatsuda, T. Takatsuka, ApJ764('13)12
- **QCD phase diagram in asymmetric matter**
  AO et al. ('11), Ueda et al. ('13)
  - **Disappearance of 1st order phase transition at large isospin chem. pot.**

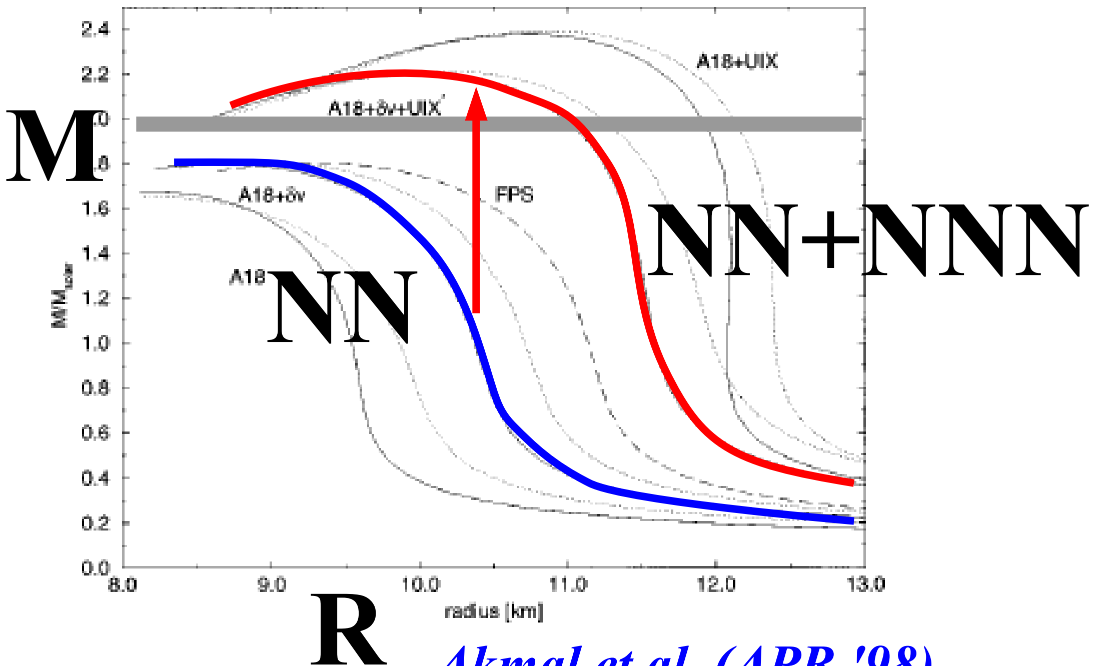


Masuda, Hatsuda, Takatsuka ('13)

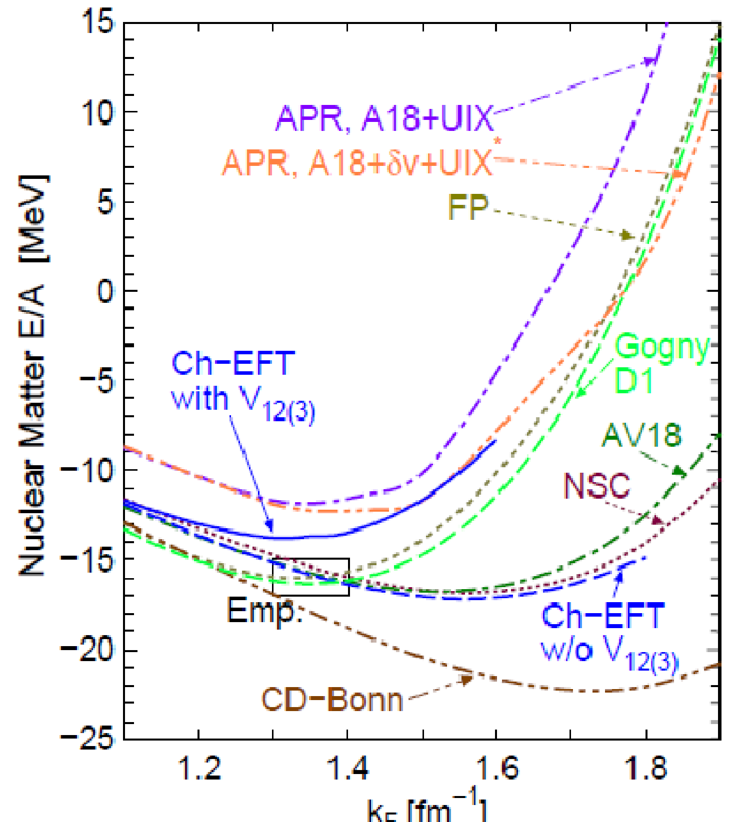
AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284
H. Ueda, et al. PRD88('13),074006

NNN force

- **NNN force is necessary to reproduce saturation point and to support massive neutron stars**
  - **Variational cal. + phen. NNN force**
    A. Akmal, V.R.Pandharipande, D.G. Ravenhall, PRC58('98)1804;
    H. Kanzawa, K. Oyamatsu, K. Sumiyoshi, M. Takano, NPA791 ('07) 232.
  - **Chiral EFT NN+NNN force**
    M. Kohno, PRC88('13)064005



Akmal et al. (APR,'98)



M. Kohno, PRC88('13)064005