D01 班報告

京大基研　大西　明

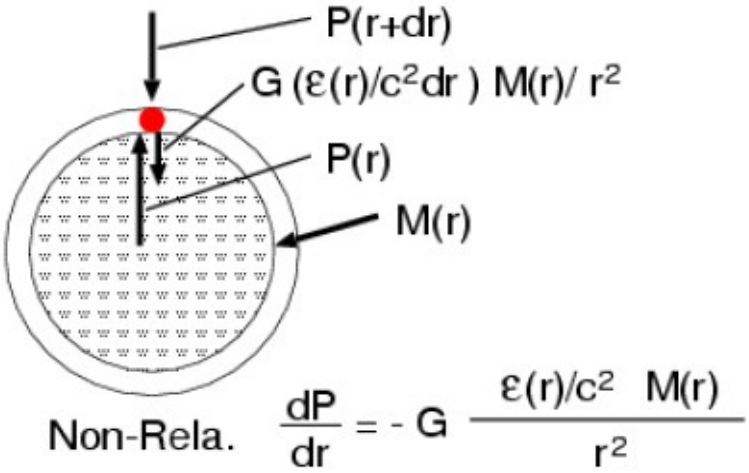
新学術領域「中性子星核物質」
第 5 回ウインタースクール・研究会
「中性子星の核物質」
2017 年 2 月 16-18 日
福島飯坂温泉　福すむ宿 福住旅館

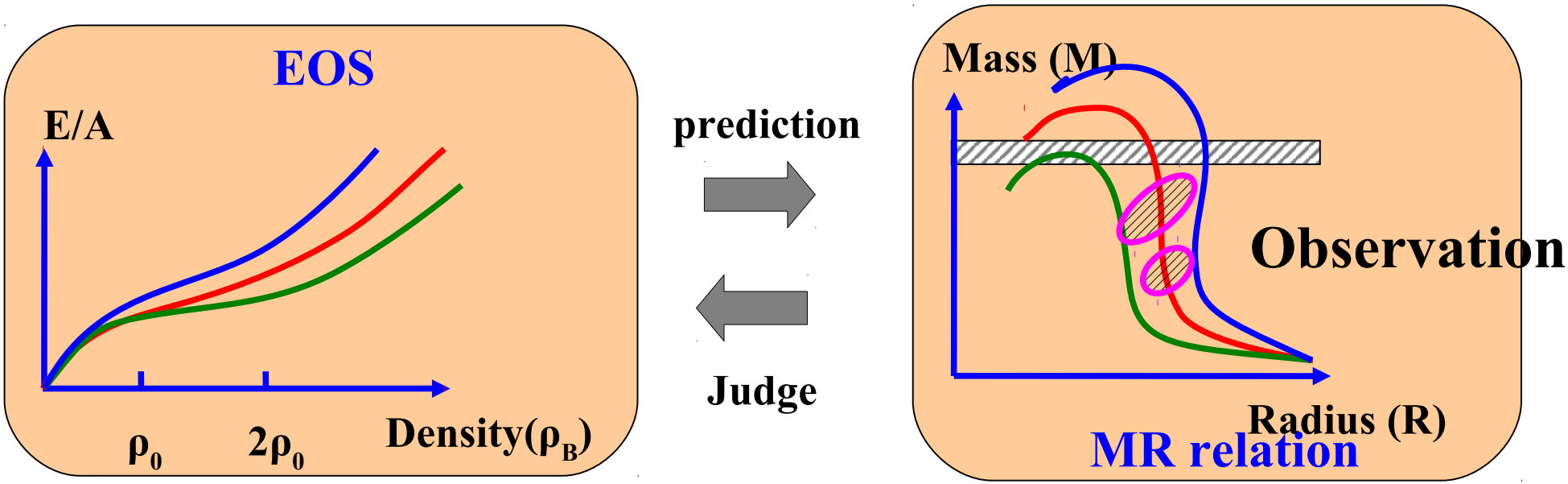
M-R curve and EOS

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

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

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





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)

Hyperons, mesons, quarks

Asym. nuclear matter +elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.

J-PARC

Area PI: H. Tamura

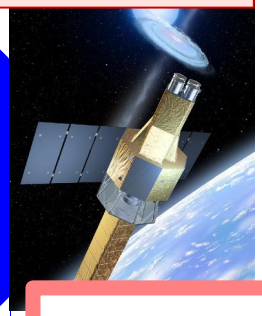
Low ρ (Group B)
PI: Murakami, Nakamura, Horikoshi

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

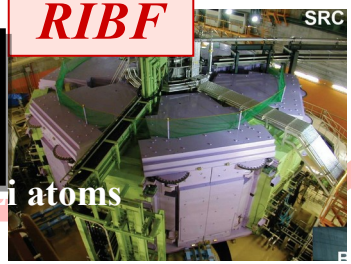
NS Obs. (Group C)
PI: Takahashi

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

ASTRO-H



RIBF



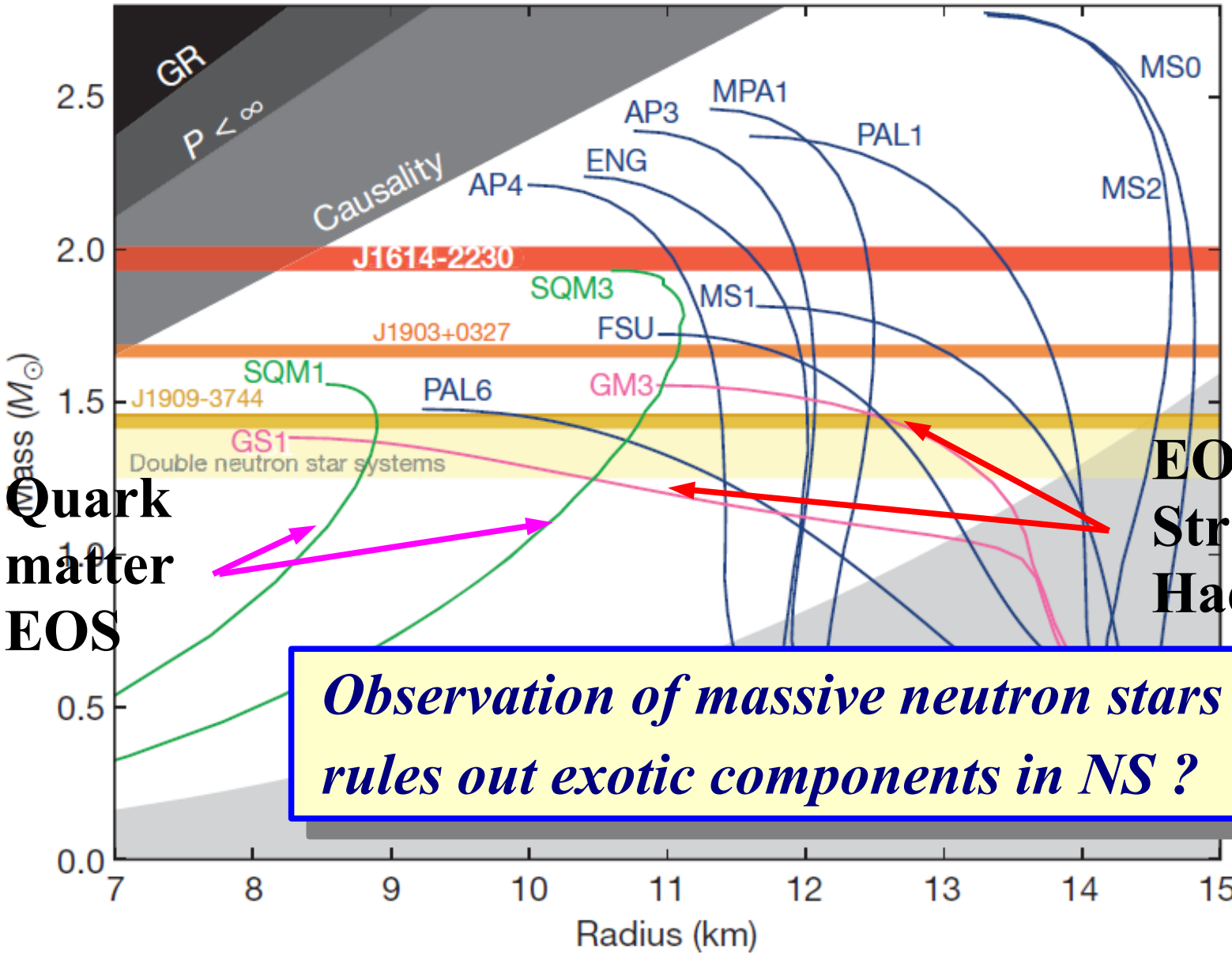
oled ^{6}Li atoms

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

高密度中性子星物質: 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.*

高密度中性子星物質: *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 ?**

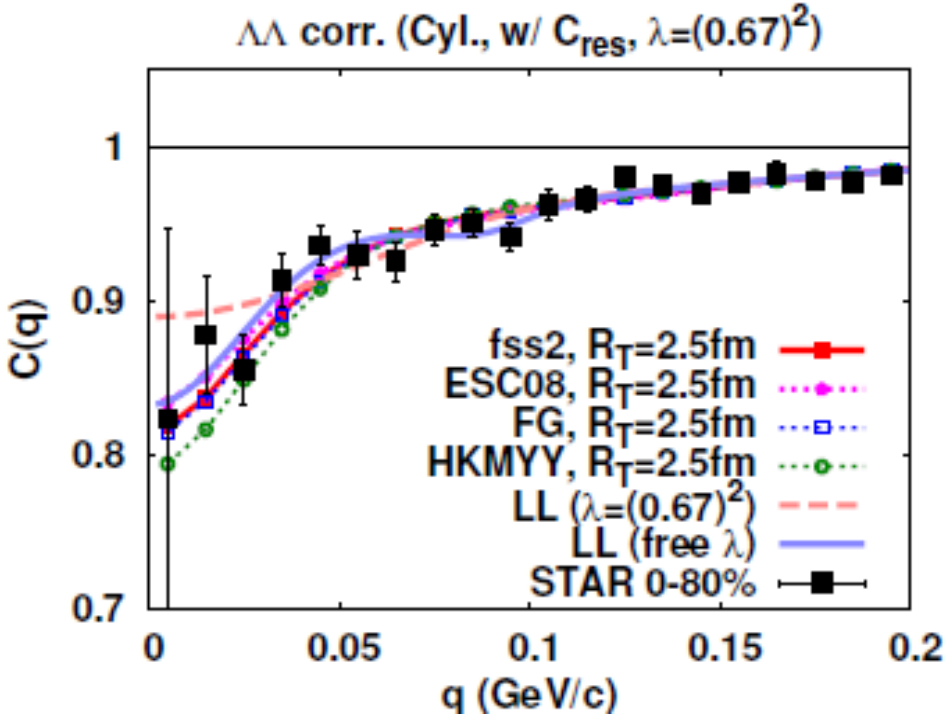
高密度中性子星物質: ΛΛ potential

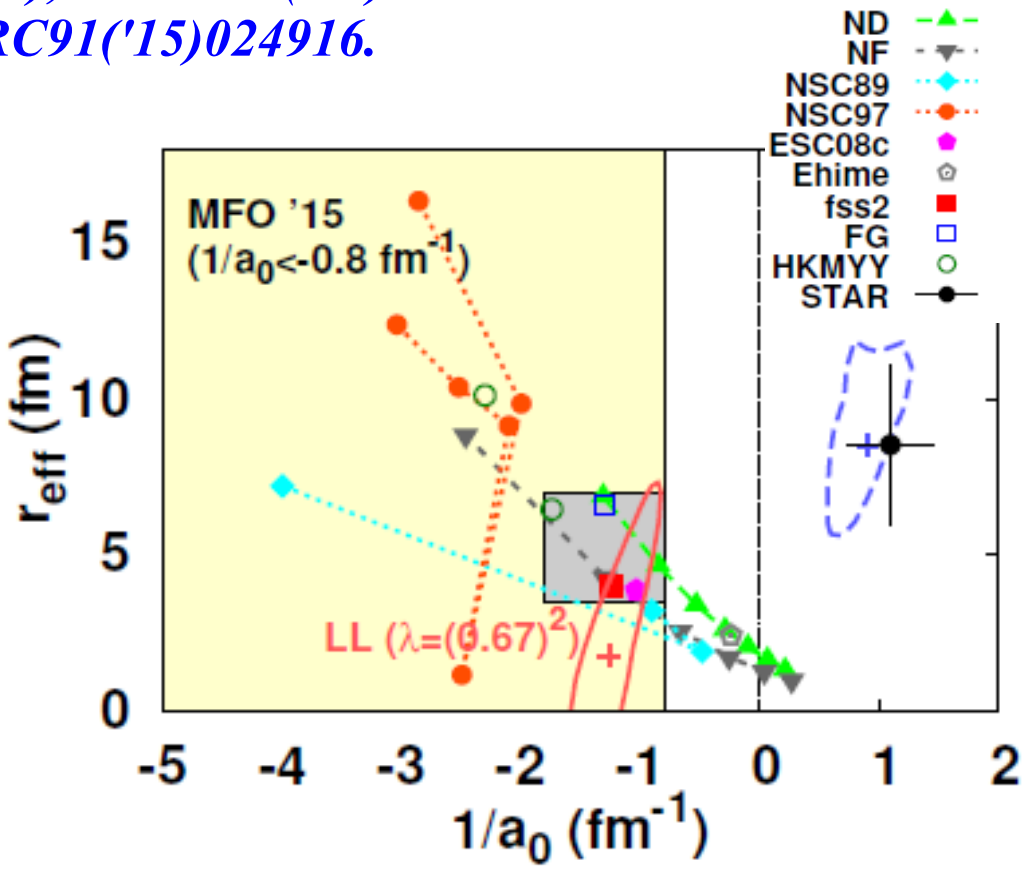
- **Nagara fit → $a_0(\Lambda\Lambda)$= - 0.575 fm or - 0.77 fm**

  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)

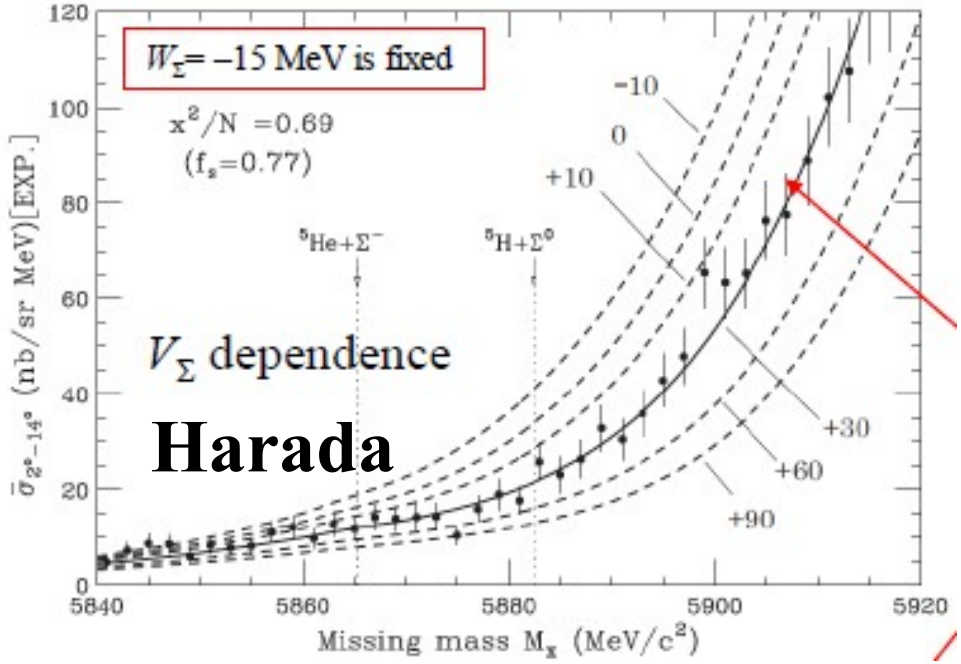
  Exp: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.
  Theor.:Morita et al., T.Furumoto, AO, PRC91('15)024916.

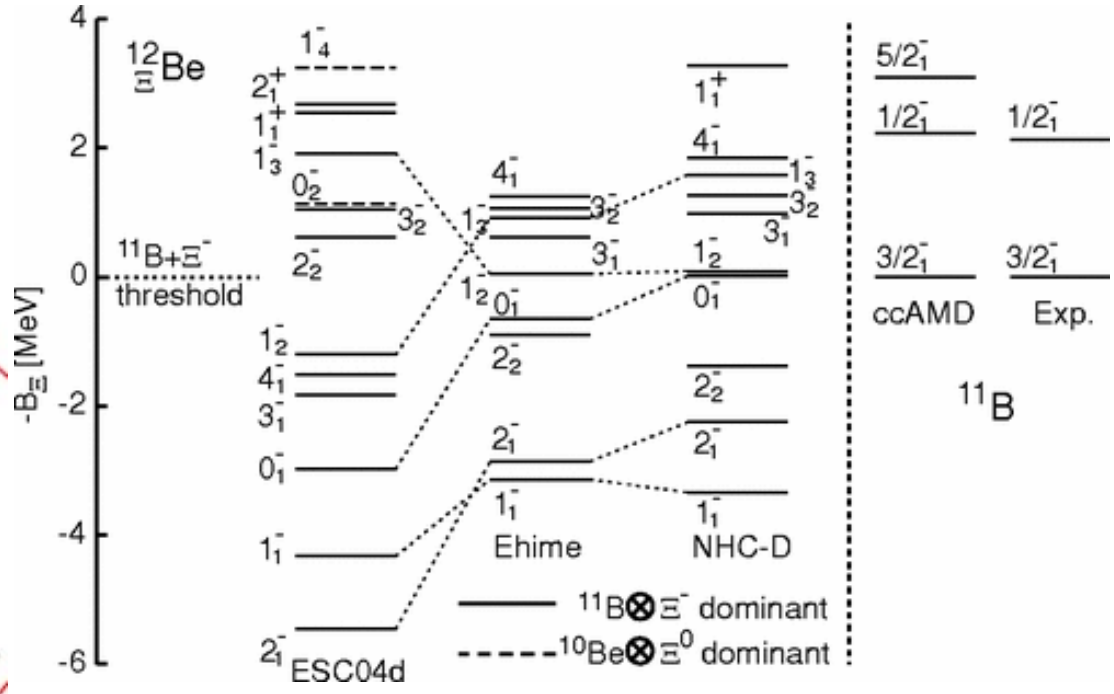




高密度中性子星物質 : Σ or Ξ potential in nuclei ?

- New analysis of Σ production reaction: ^{6}Li (π^-, K^+) Σ^- ^{5}He
  → $U_\Sigma \sim +30$ MeV Harada+
- New Ξ hypernuclei → B.E. = [redacted] MeV & (4 or 1) MeV
  (Takahashi (A01), Nakazawa, Kanatsuki, Yamamoto)
  → Deeper than previous estimate

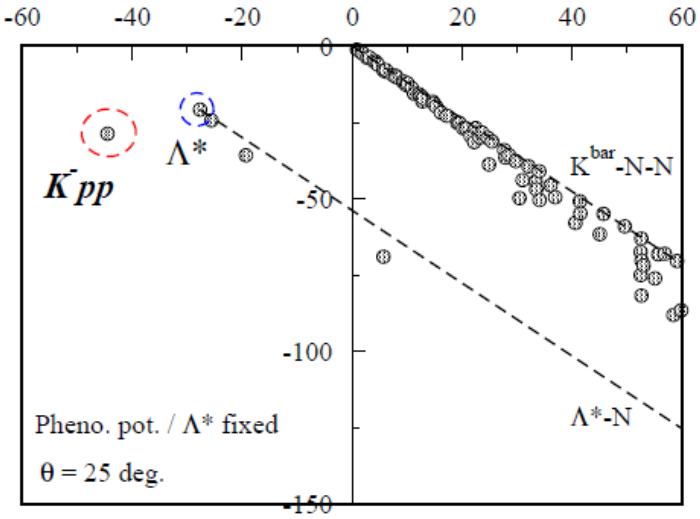


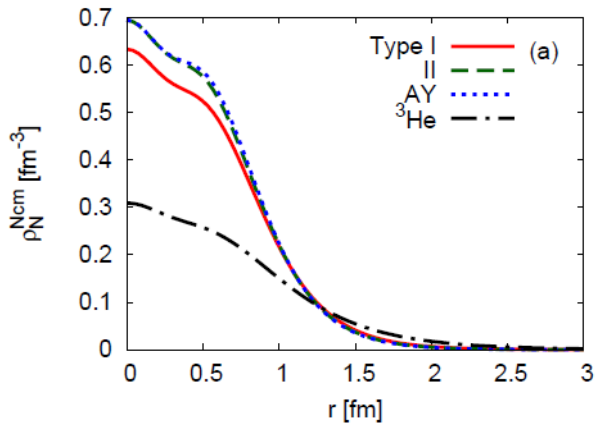


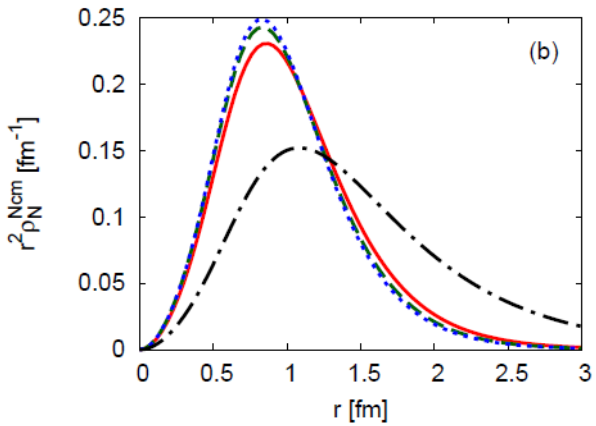
Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

高密度中性子星物質： Kaonic Nuclei

- 反 K 中間子核 : K^-pp & K^- 核
  (Yamagata-Sekihara, Dote, S.Ohnishi, ….)
- K^-pp 核 :Chiral SU(3) 相互作用に基づく
  pole search *Dote, Inoue, Myo ('15)*
  Threshold 近辺に束縛状態
- K^- 核の系統的研究
  S.Ohnishi, Horiuchi, Hoshino, Miyahara, Hyodo, ('17) arXiv:1701.07589
  K^- が加わることにより数 10% 密度が上昇

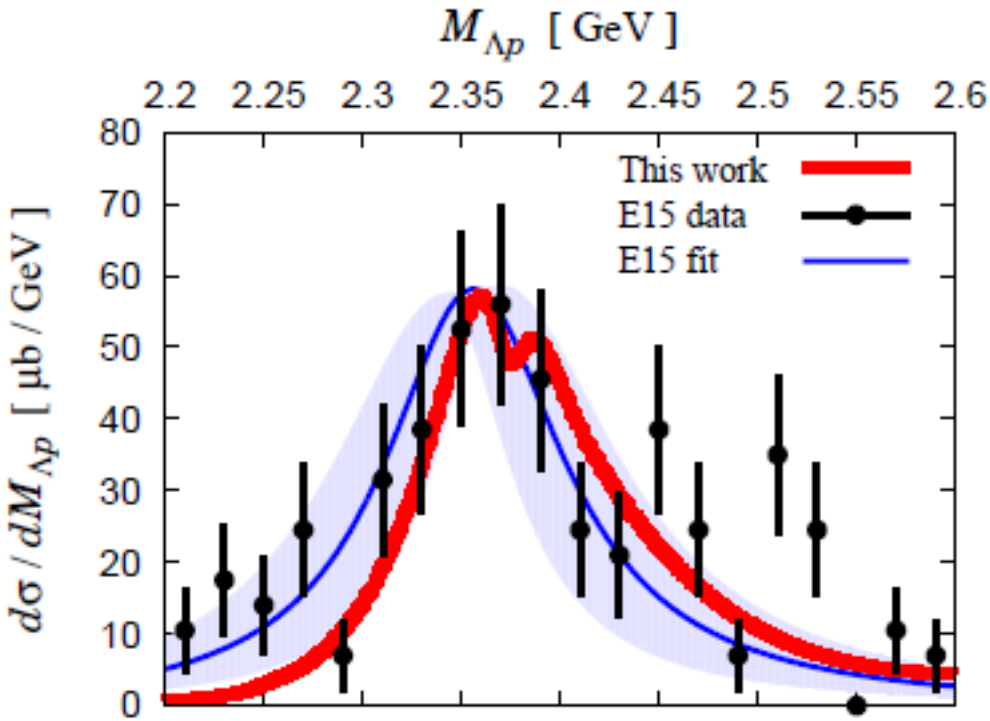






高密度中性子星物質: $\bar{K}$ potential in Nuclear Matter ?

- 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



Sekihara, Oset, Ramos ('16)

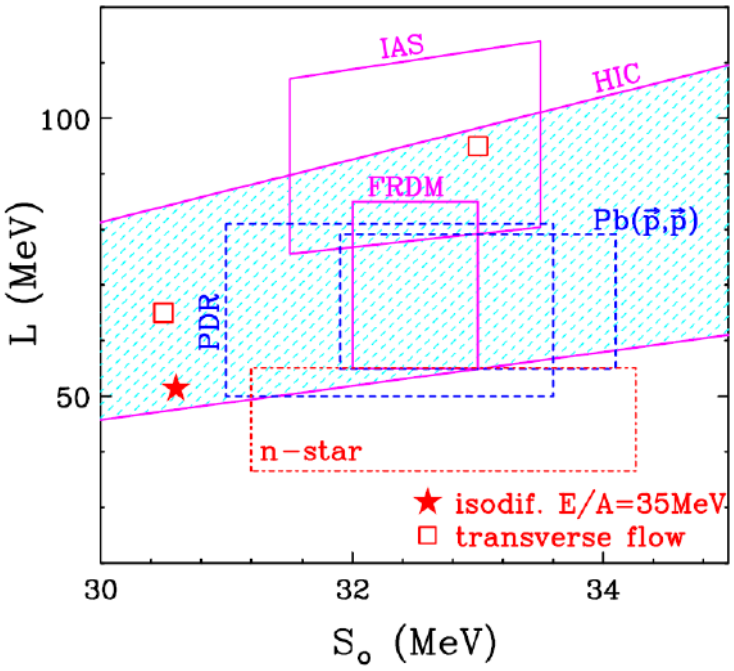
We need more work to confirm the fate of Kaon condensation

低密度中性子星物質: Symmetry Energy

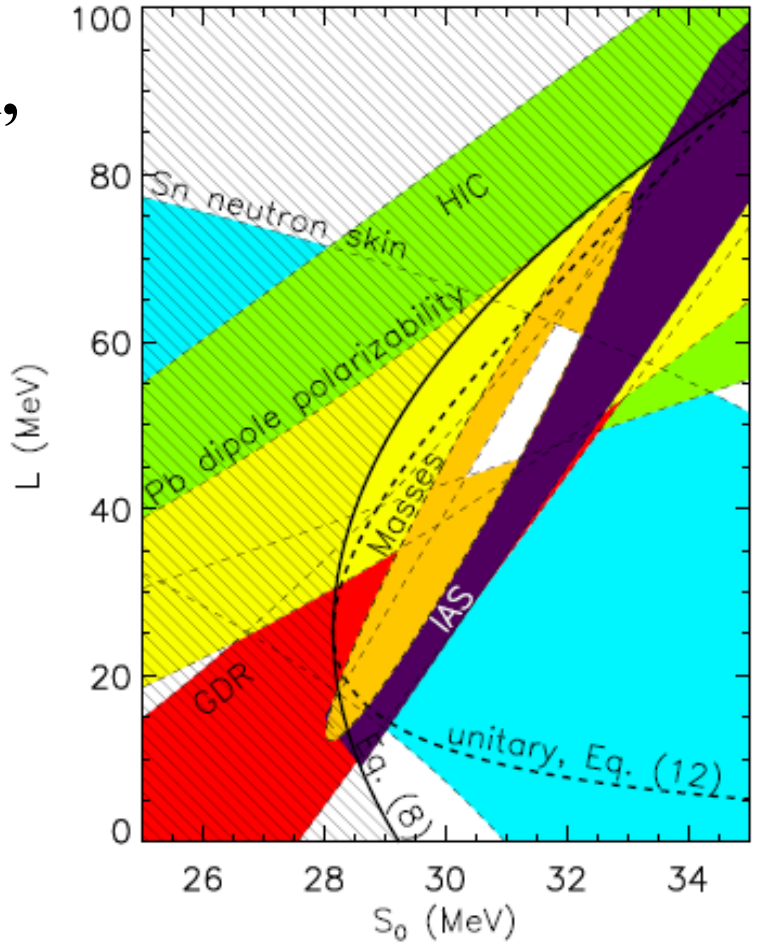
- **Symmetry Energy Parameters**

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

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



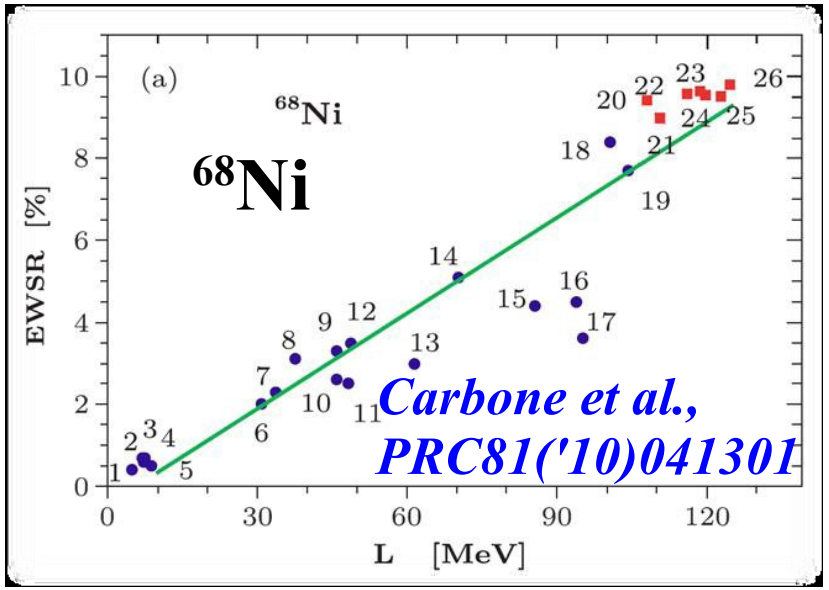
Tsang et al. ('12): NuSYM 2011



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

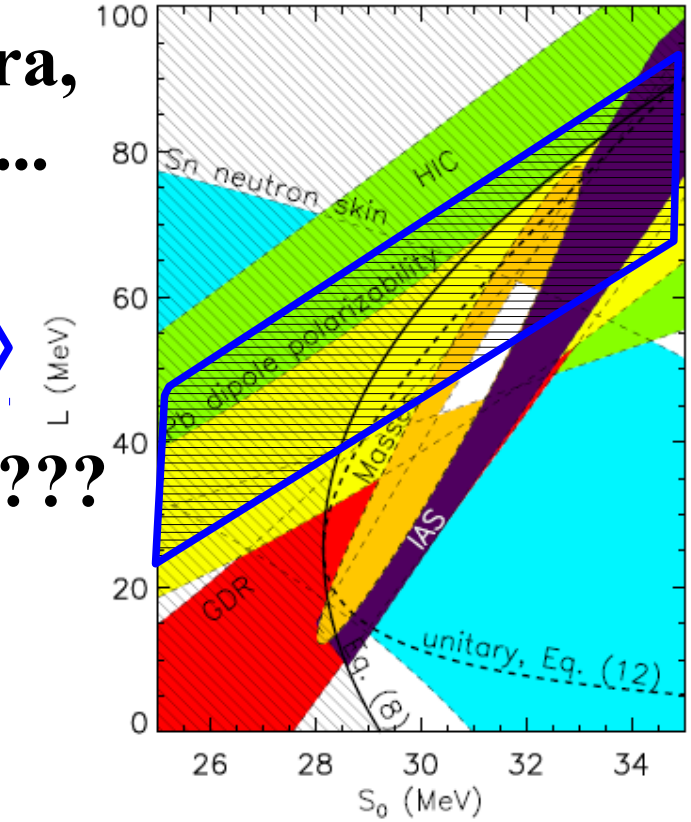
低密度中性子星物質: Low Energy Dipole Strength

- **Low Energy Dipole Strength and L (Inakura, Nakada, Matsuo)**



Carbone et al., PRC81('10)041301

Nakamura, Togano, ... (B02)



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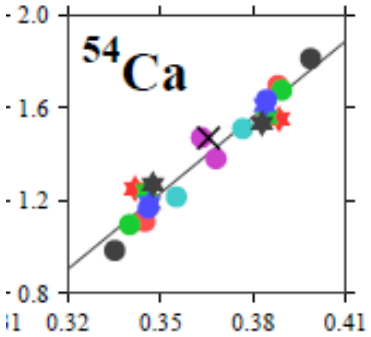
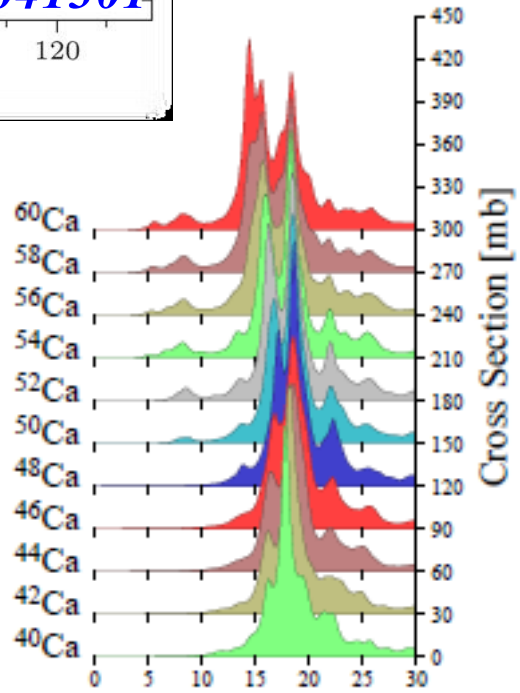




Inakura, Nakatsukasa, Yabana, PRC84('11)021302; PRC88('13)051305

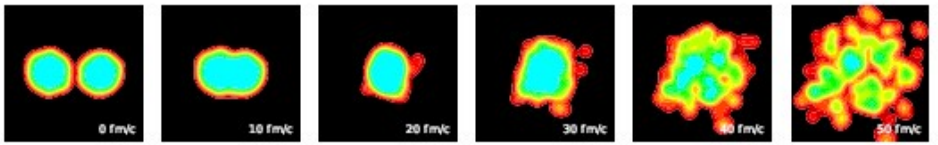
Let's wait for B02 experiments !

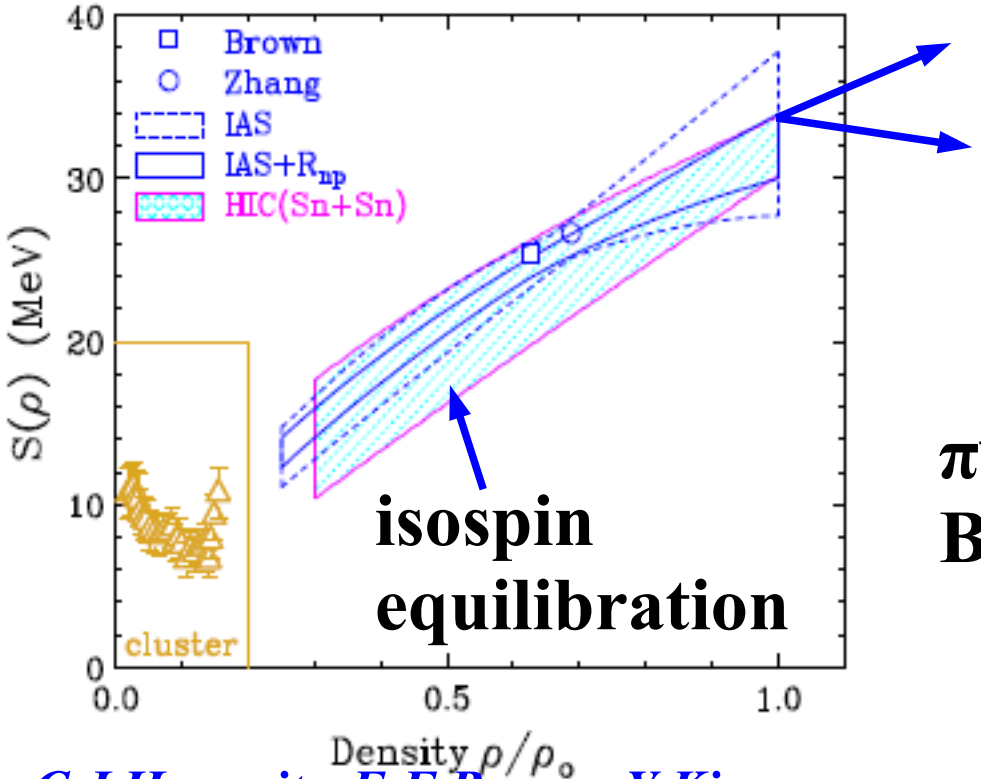
低密度中性子星物質: High Density Symmetry Energy

- 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)



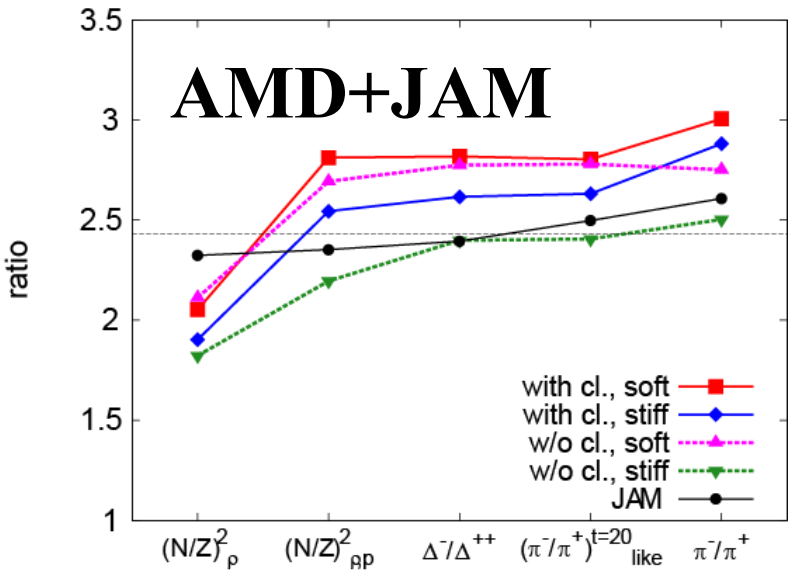


C.J.Horowitz, E.F.Brown, Y.Kim, W.G.Lynch, R.Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, H.H.Wolter (NuSYM13), JPG41('14) 093001

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

π^-/π^+

B.A.Li



Ikeno, Ono, Nara, AO ('16)

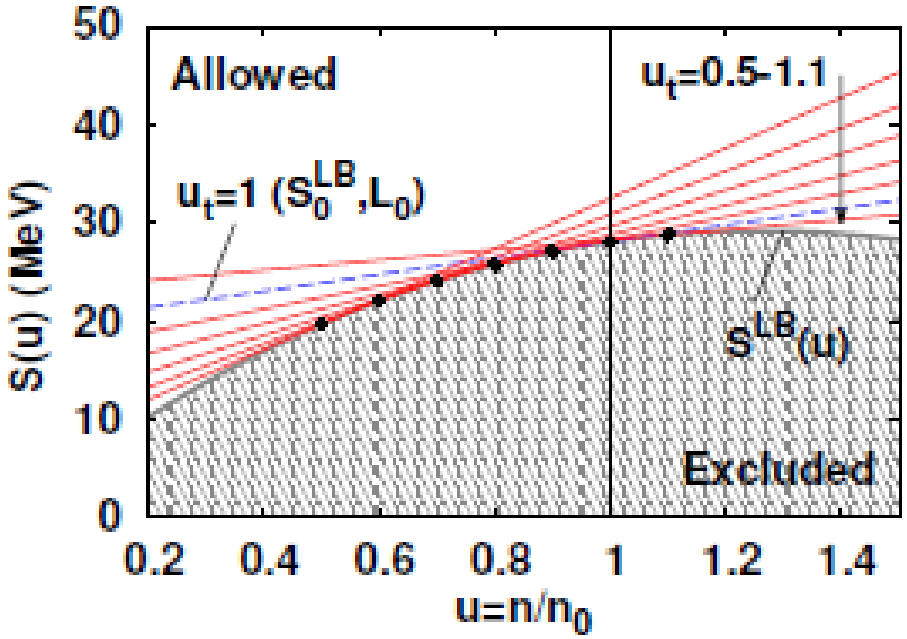
低密度中性子星物質: Unitary gas & Sym. E.

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

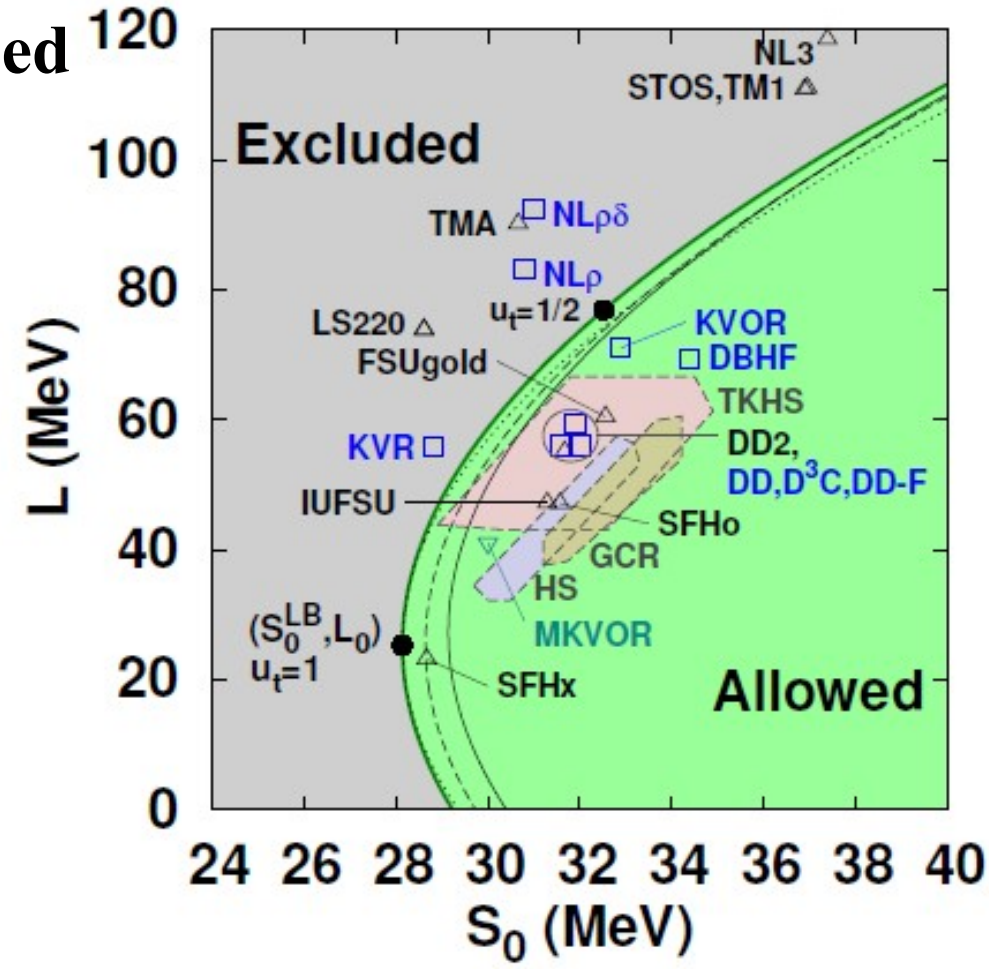
$$S(u) \geq E_{\rm UG}^0 u^{2/3} - \left[E_0 + \frac{K}{18}(u-1)^2 \right] \equiv S^{\rm LB}(u)$$

→ Sym. E. parameters are constrained !

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

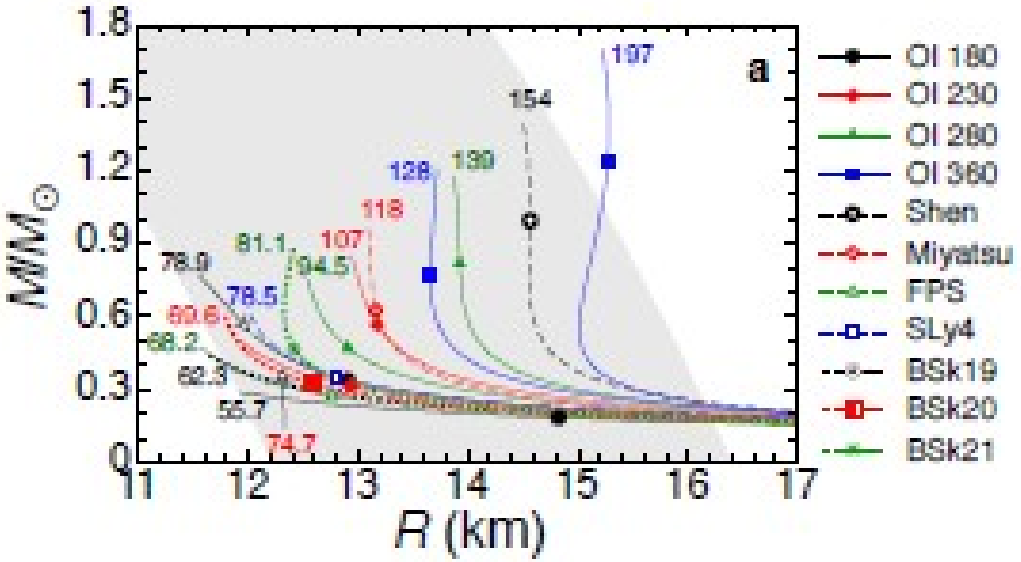


Kolomeitsev, Lattimer, AO, Tews ('16)

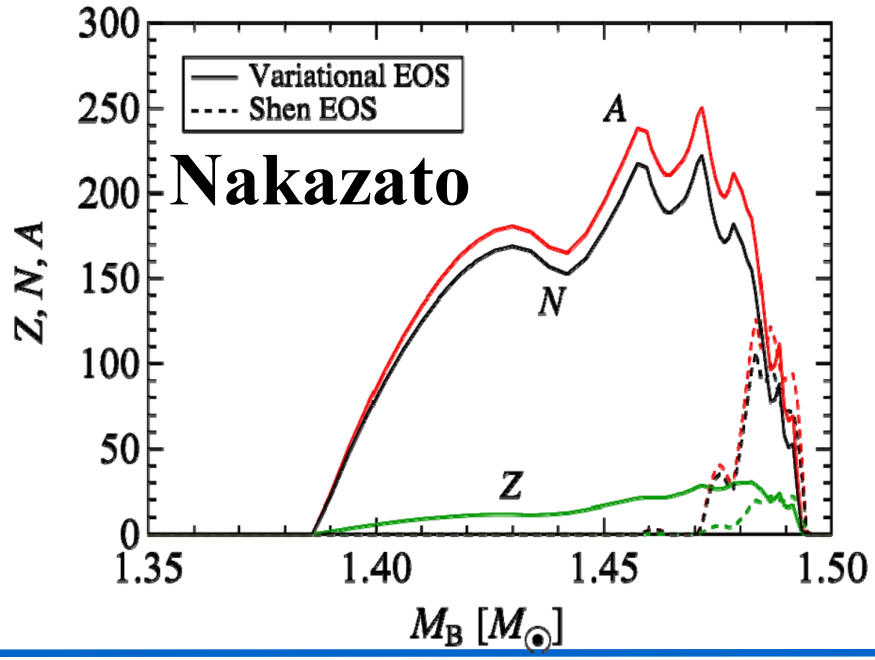


天体物理 : Symmetry Energy → Neutron Star

- 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.

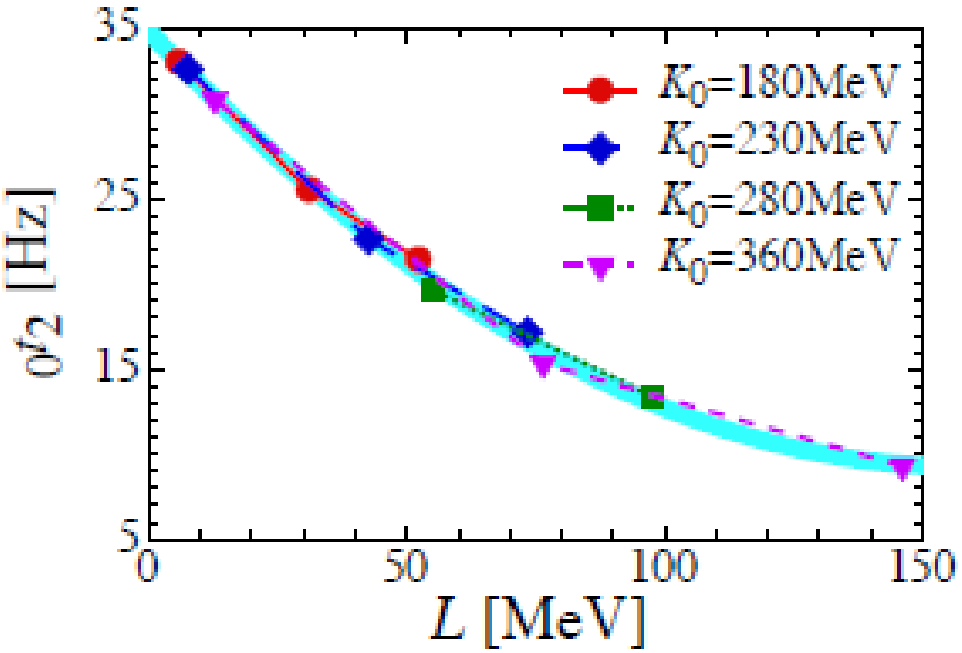


Sotani, Iida, Oyamatsu, AO ('14)

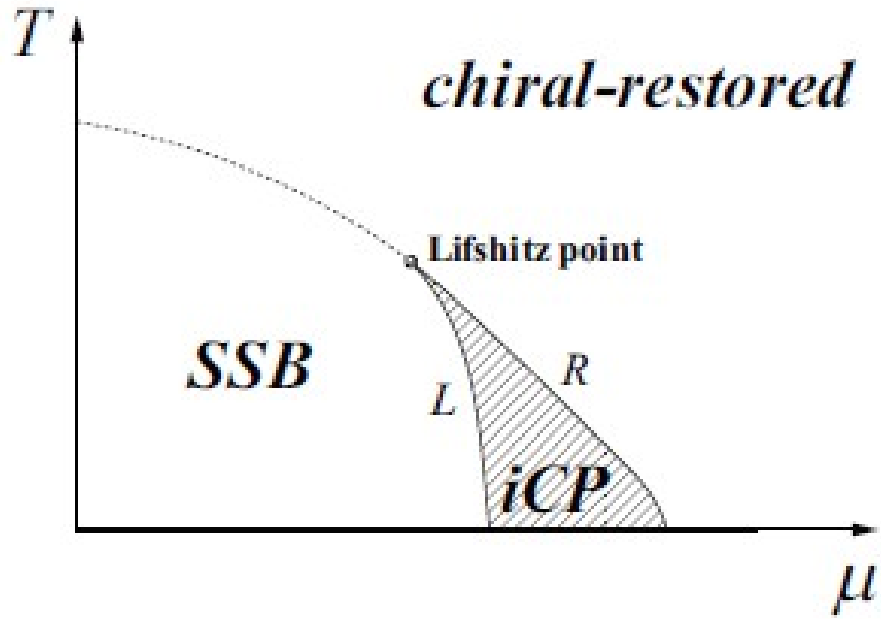


天体物理 : Sym. E (cont.) and Inhomo. χ cond.

- 中性子星の振動から対称エネルギーの制限
  Sotani, Nakazato, Iida, Oyamatsu ('12, '13, '13, ...)
- 高密度における QCD 相転移が非一様 Chiral 凝縮相を通じておこるかもしれない。
  → Inhomogeneous Chiral Condensate
  (Tatsumi; Yoshiike, Lee, Tatsumi ('15))

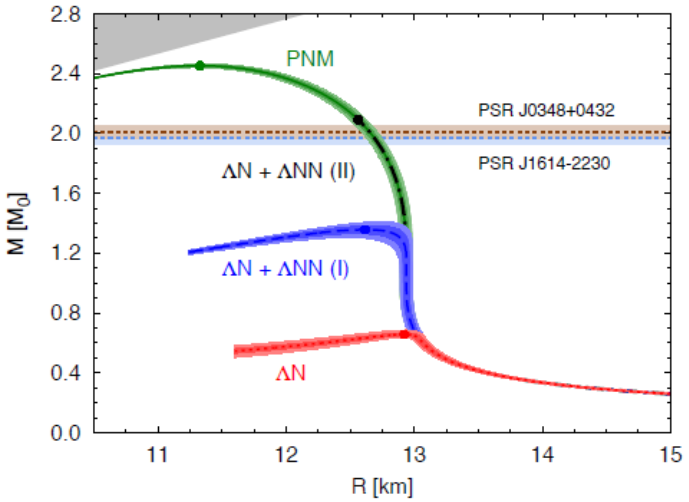


Sotani, Nakazato, Iida, Oyamatsu ('13)

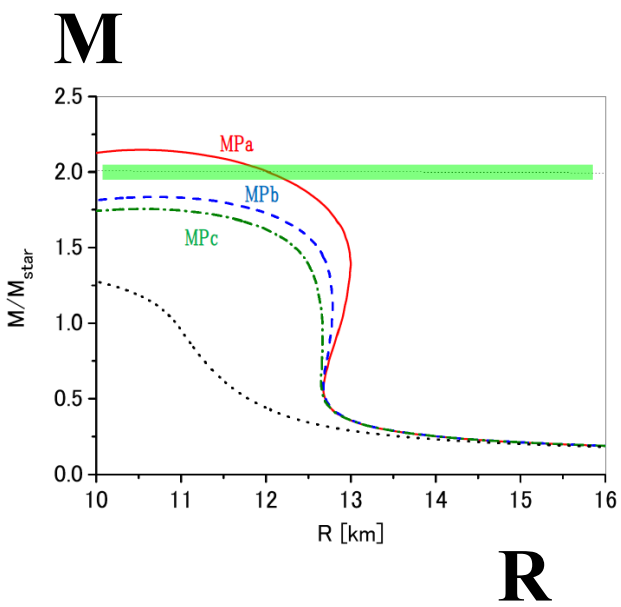


Yoshiike, Lee, Tatsumi ('15)

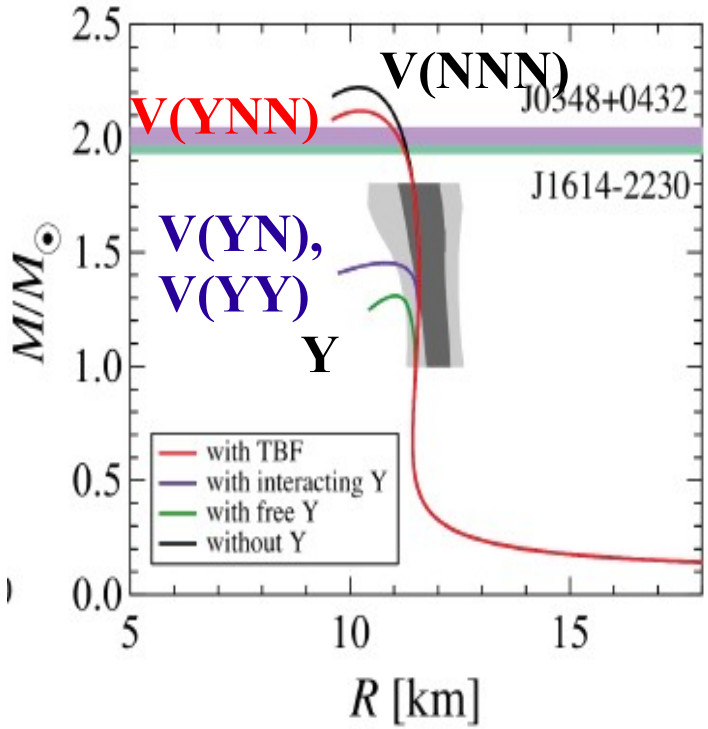
天体物理 : Neutron Star Matter EOS



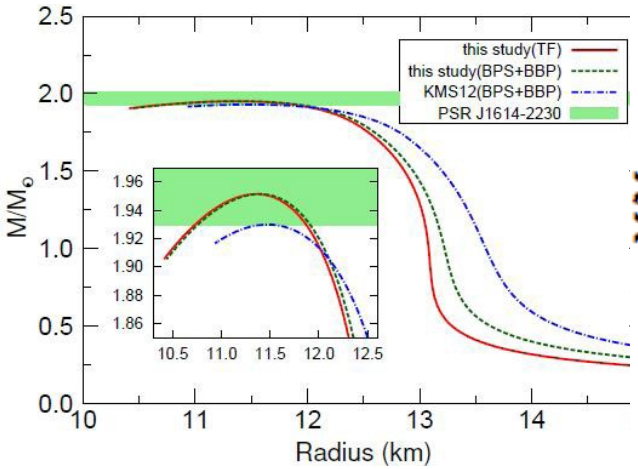
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



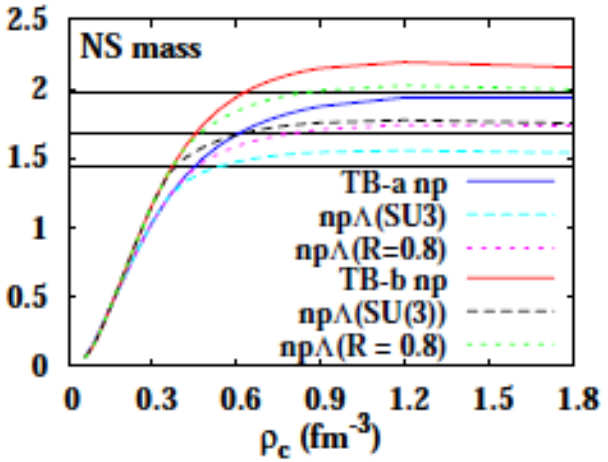
Yamamoto, Furumoto, Yasutake, Rijken ('13)



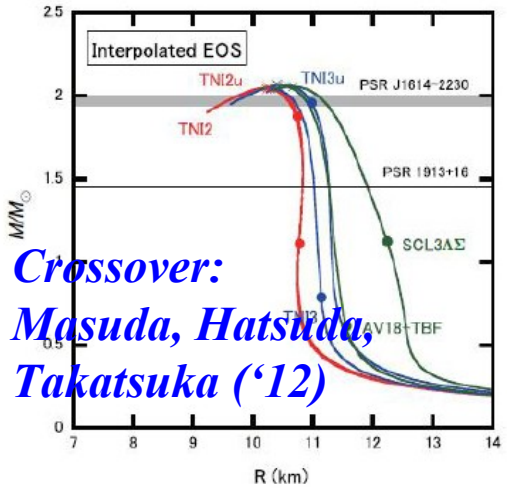
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu,Yamamuro, Nakazato ('13)



Three-baryon coupling, Tsubakihara, AO ('13)



Crossover: Masuda, Hatsuda, Takatsuka ('12)

Summary

- 理論班としての実験・観測班への貢献
  → A01, A02, B01, B02, B03, C01
  - ハイパー核物理、中性子過剰核と対称エネルギー、天体物理
- 独自な理論研究としての発展 (論文数 ＞200 編 / 5 年)
  (H24:54, H25:79, H26:54, H27:50)
  → 中里、稲倉
- 積み残した課題
  「A 班、B 班の成果を基にして原子核・ハドロン・クォーク物質にまたがる状態方程式を作成し、C 班の観測結果と比較する。」
  → to be continued
- 連携研究者を含む分野の研究者にも感謝！