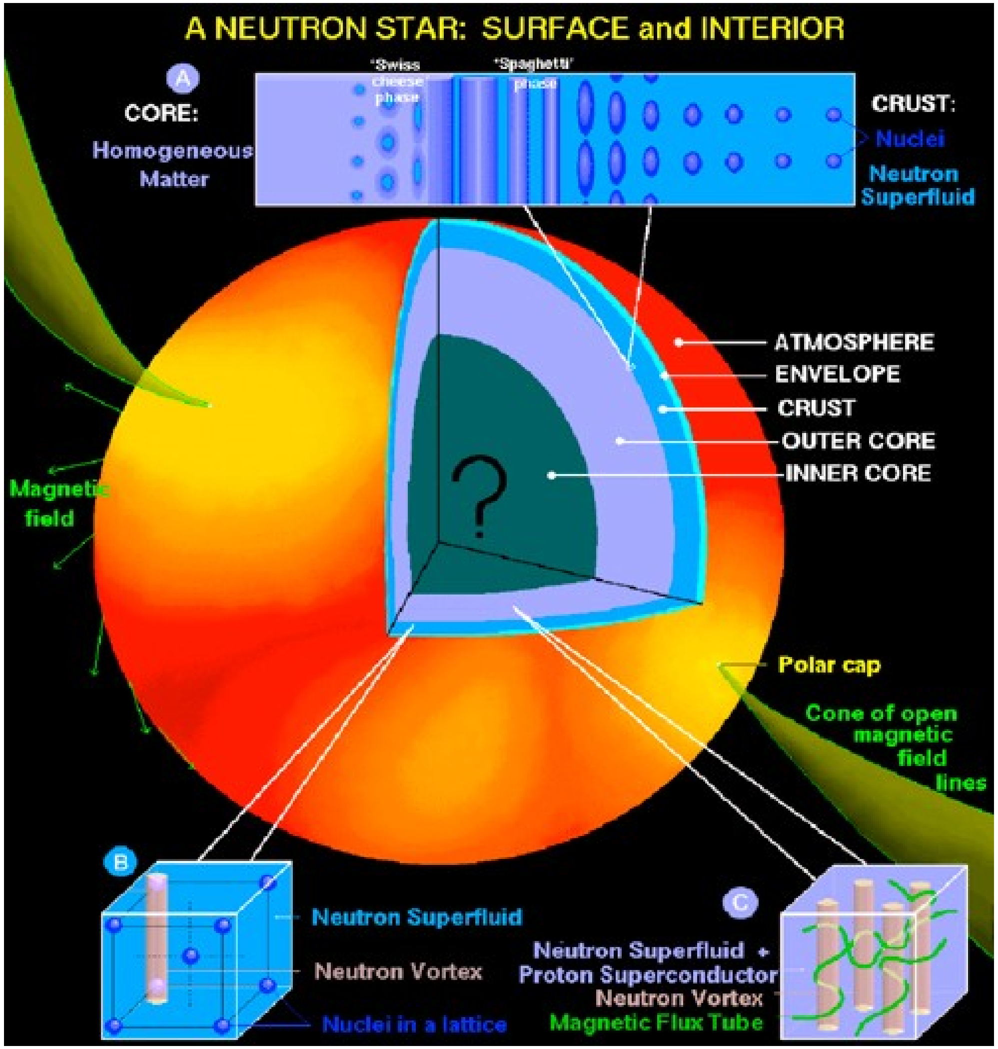
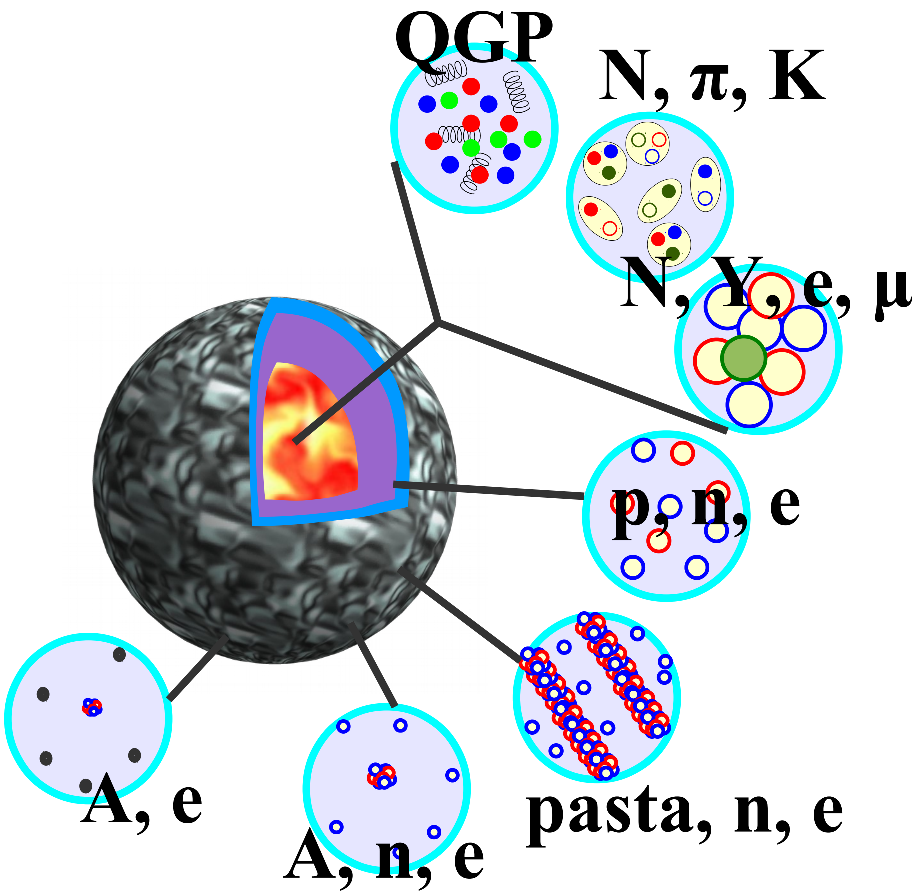
Recent developments in strangeness nuclear physics and the hyperon puzzle

Akira Ohnishi (YITP, Kyoto U.)

International Workshop on
Strangeness Nuclear Physics 2017
Mar.12-14, 2017,
Osaka Electro-communication University,
Neyagawa, Japan

Inside Neutron Stars





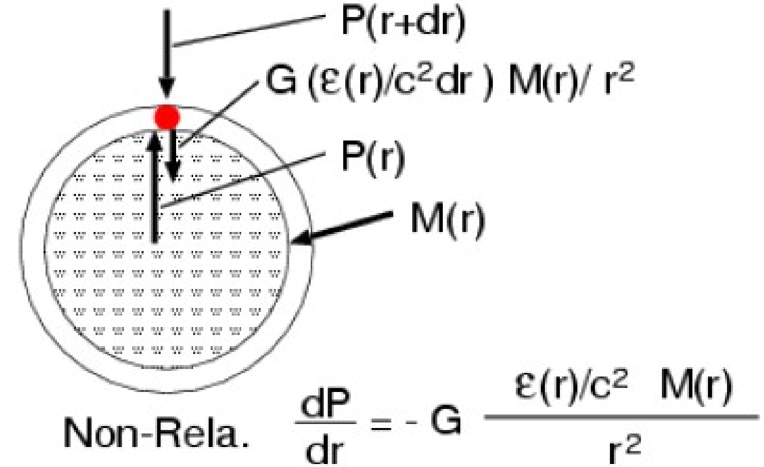
Dany Page

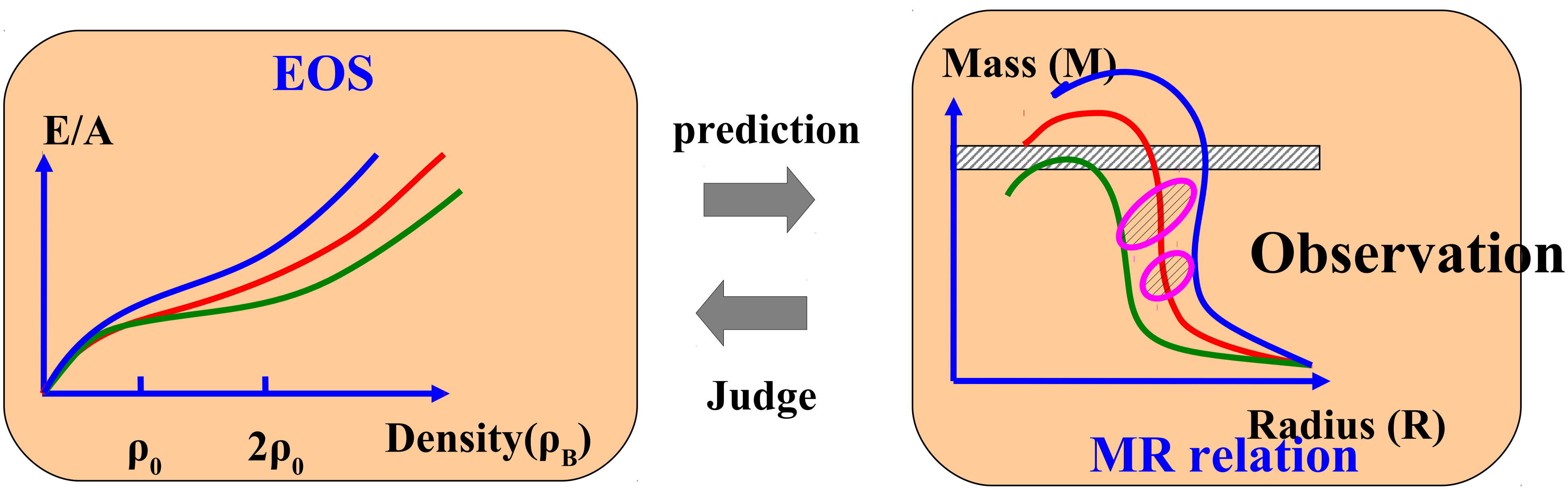
M-R curve and EOS

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

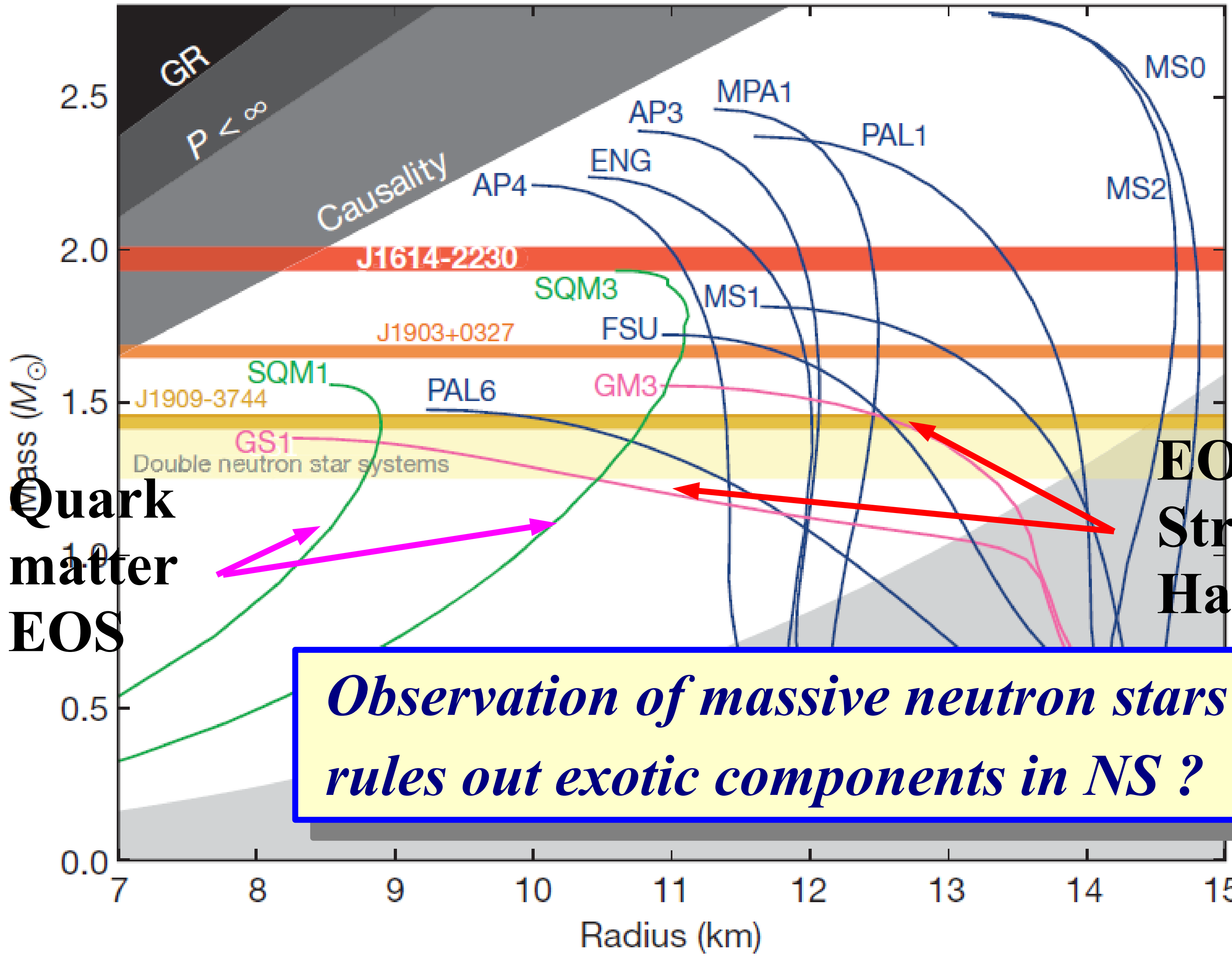
$$\frac{dP}{dr} = -G\frac{(\varepsilon/c^2 + P/c^2)(M + 4\pi r^3 P/c^2)}{r^2(1-2GM/rc^2)}$$

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





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.*

Contents

- Introduction
  – Hyperon puzzle
- Do we miss something ?
  – Recent developments in Strangeness Nuclear Physics
- Possible Solutions
  - Density dependence of UY and/or Three-body force
  - Smooth transition to quark matter
  - Modified gravity
- Summary

Do we miss something ?
– Recent developments
in Strangeness Nuclear Physics –

Strangeness Nuclear Physics

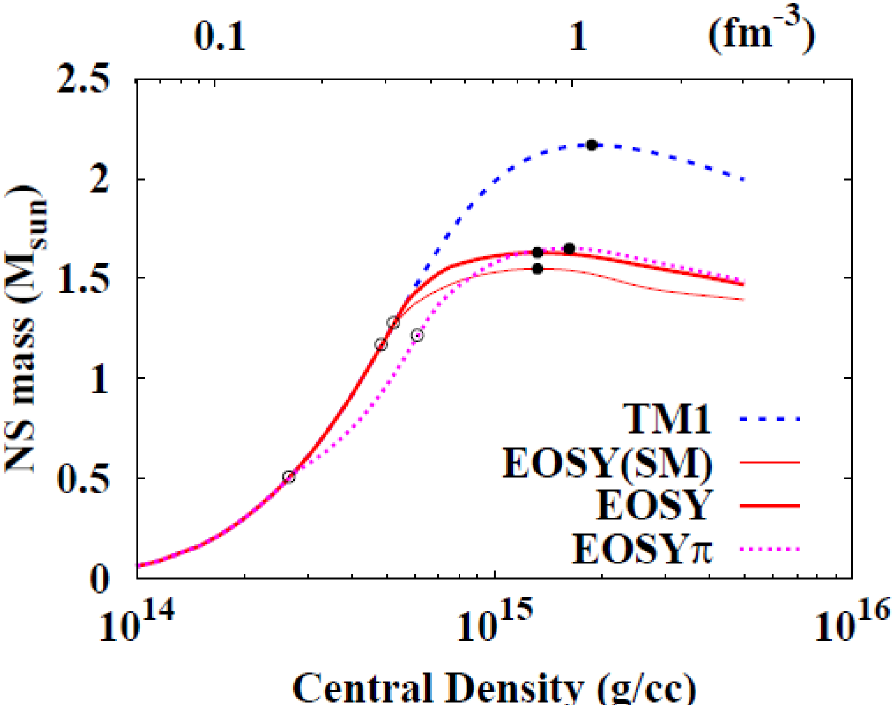
- **Before Oct.2010,**

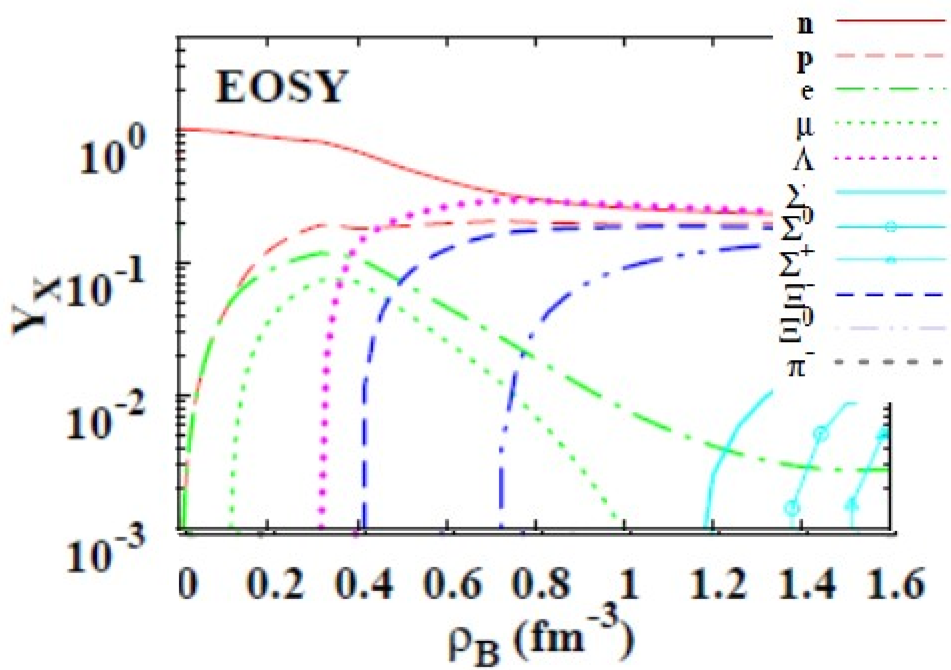
  $U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV

  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.

  + Relativistic Mean Field with SU(6) symmetry; $g_{\omega\Lambda} \sim 2/3\ g_{\omega N}$

  → Maximum mass of NS ~ 1.6 $M_\odot$





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

What did we miss ?

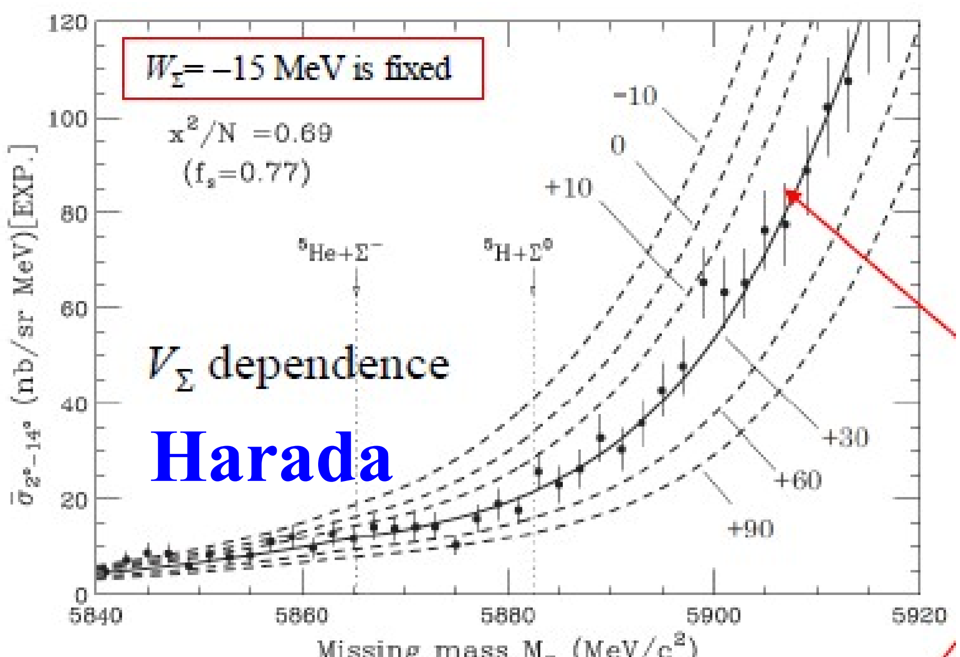
- **Hyperon potential in nuclear matter ?**
  - **$U_\Lambda(\rho_0) \sim -30$ MeV, $U_\Sigma(\rho_0) > +20$ MeV, $U_\Xi(\rho_0) \sim -14$ MeV**
  - **If $U_Y(\rho_0)$ is much more repulsive, hyperon puzzle may not exist.**
- **Hyperon-Hyperon potential ?**
  - **If vacuum ΛΛ potential is much more attractive than Nagara event implies, ΛΛN potential must be very repulsive.**
- **Kaon potential in nuclear matter ?**
- **Three-baryon (3B) interaction ?**
- **Quark matter core ?**
- **Modified gravity ?**

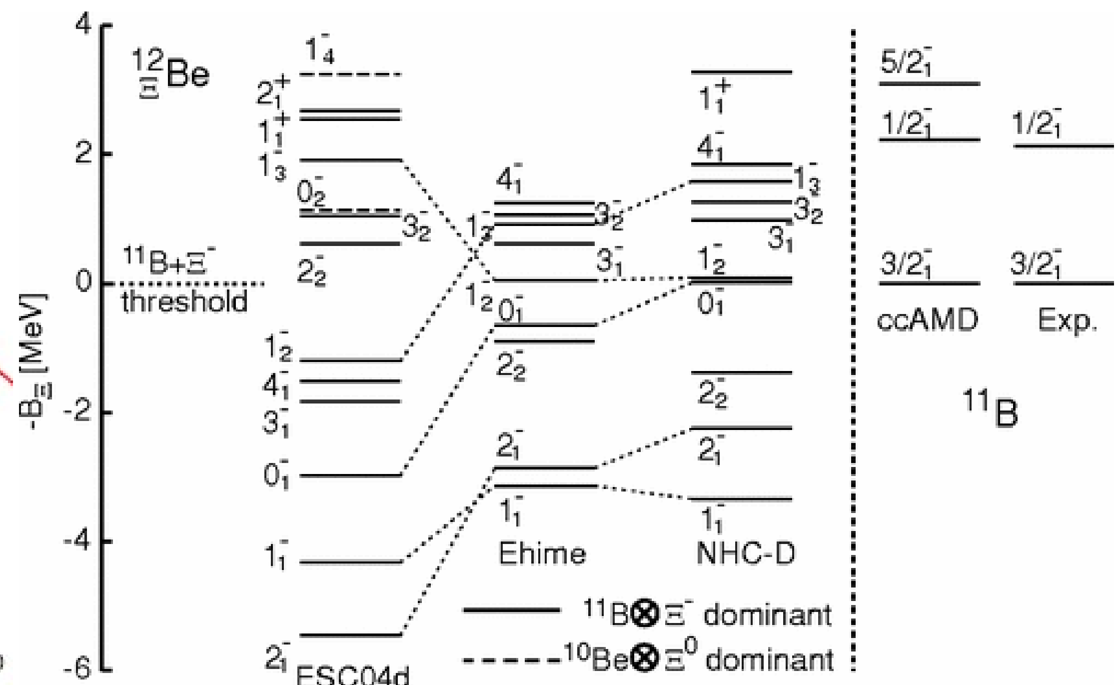
Remaining possibilities

- **Density dependence of $U_Y(\rho)$?**
  - **"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*

Σ or Ξ potential in nuclei ?

- **New analysis of Σ production reaction: ^{6}Li (π^-, K$^+$) Σ^{-} ^{5}He**
  → U_Σ ~ +30 MeV (Harada, consistent with previous estimate)
- **New Ξ hypernuclei ? → B.E. = MeV & 1 MeV**
  (Motoba, Kanatsuki, Nakazawa)
  → Deeper than previous estimate !



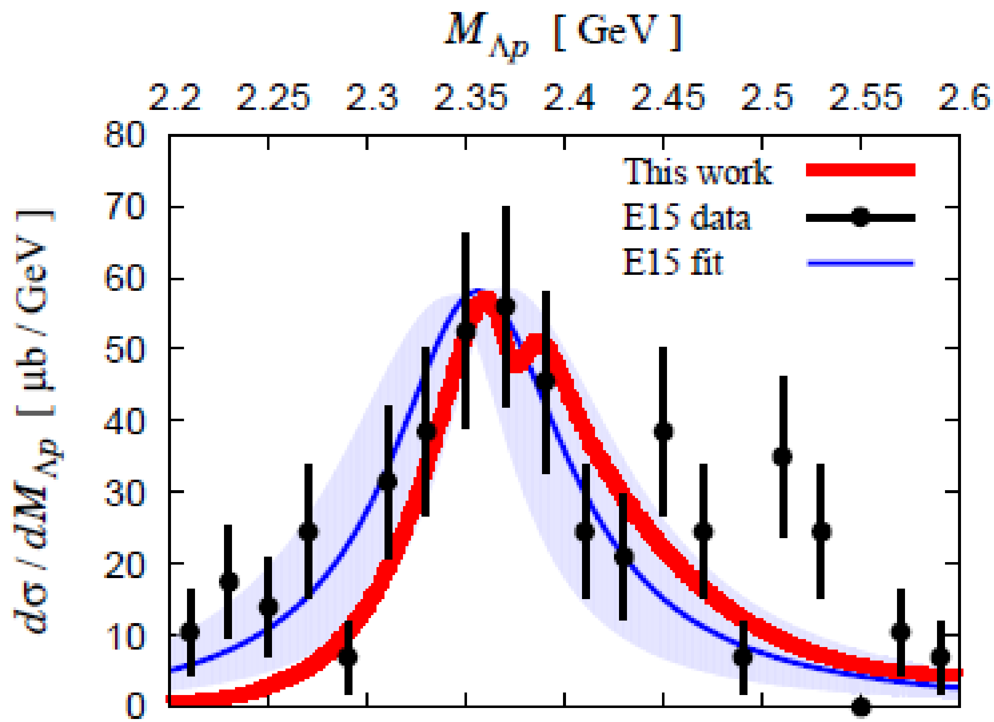


Matsumiya, Tsubakihara, Kimura, Dote, AO ('11)

Anti-Kaon potential in Nuclear Matter ?

- **K^-pp binding energy (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

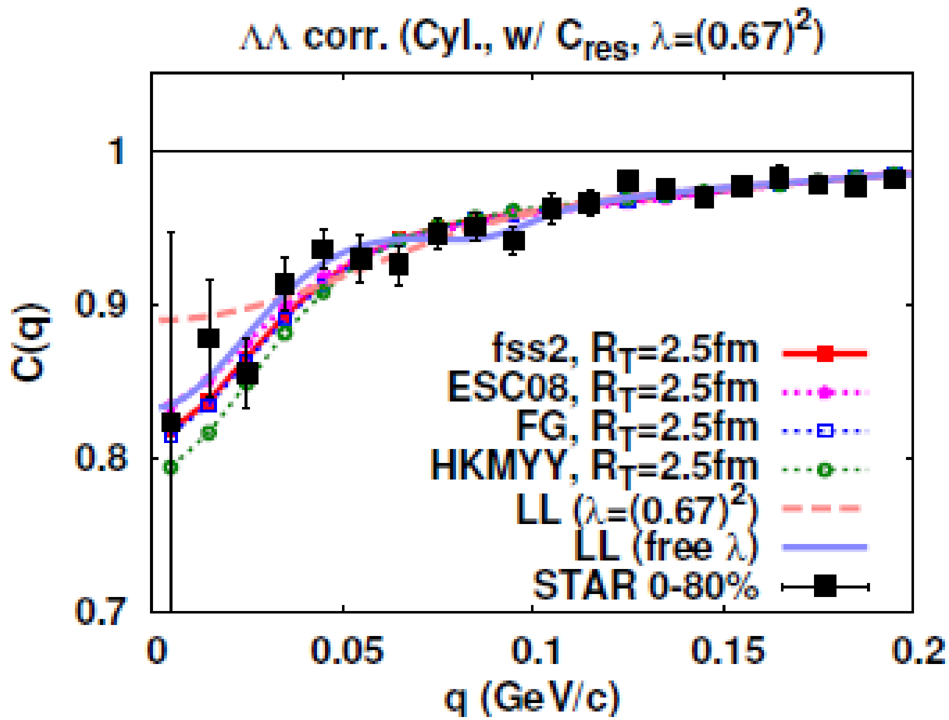
We need more work to confirm the fate of Kaon condensation

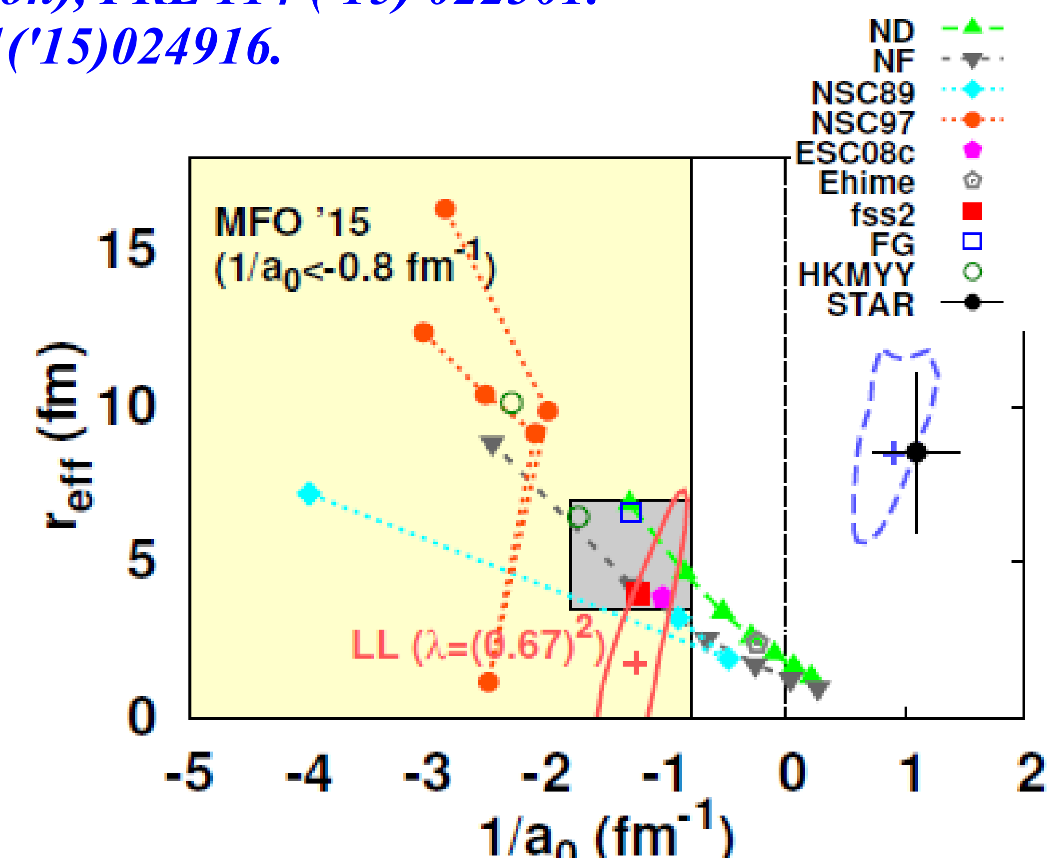


Sekihara, Oset, Ramos ('16)

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, T.Furumoto, AO, PRC91('15)024916.



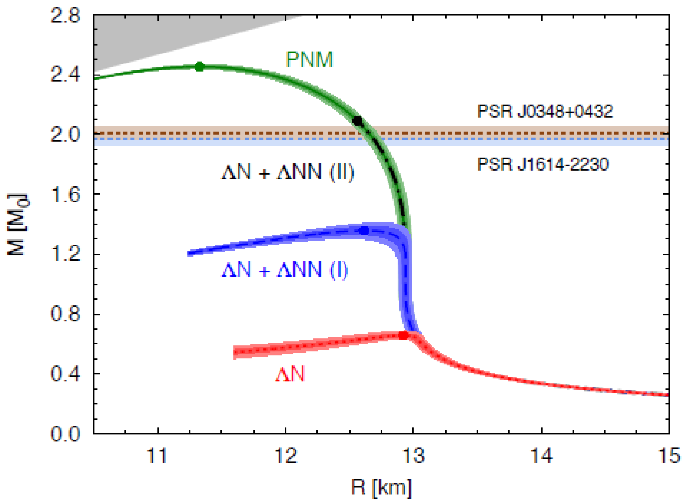


Short Summary

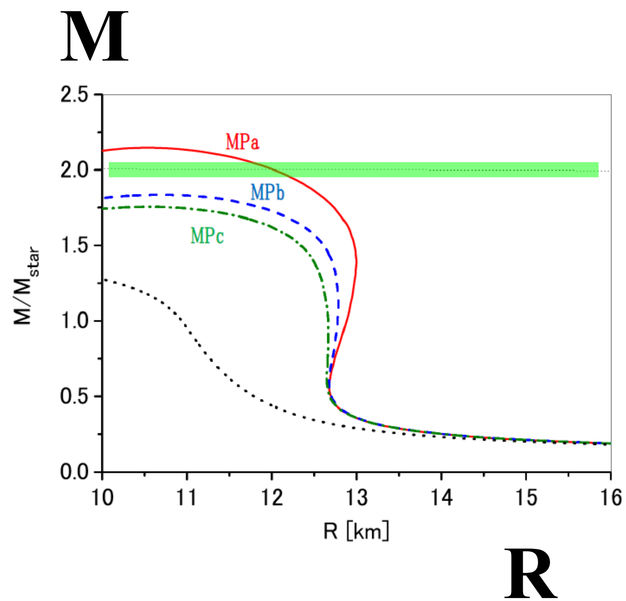
- ***We did NOT make mistakes on the strangeness potential depth which are relevant to hyperon puzzle.***
  - **$U_\Lambda \sim -30$ MeV → OK**
  - **$U_\Sigma > +20$ MeV → $U_\Sigma \sim +30$ MeV**
  - **$U_\Xi \sim -14$ MeV → $U_\Xi < -14$ MeV**
  - **Kaonic nuclei: weak or strong binding (K cond in NS)**
    → No kaon condensation at high ρ ?

Possible Solutions of Hyperon Puzzle

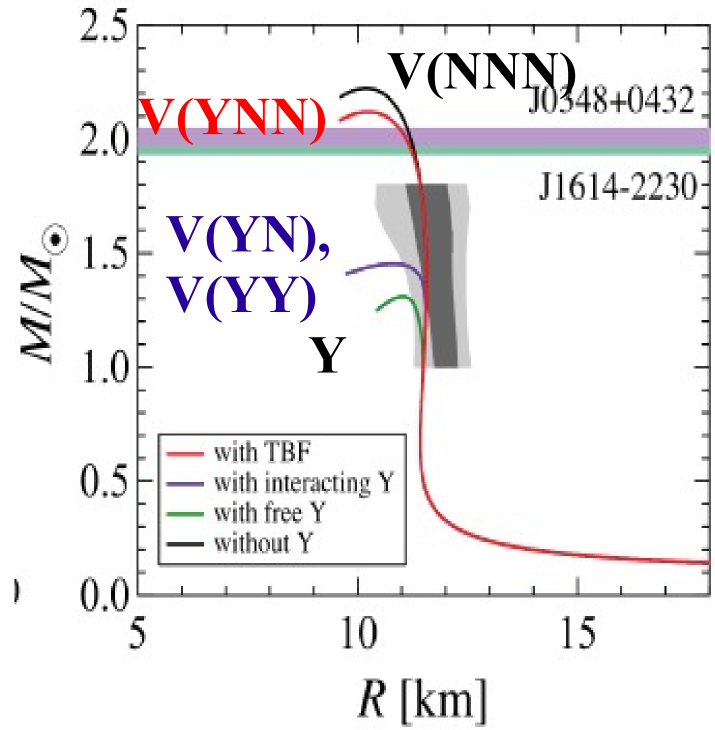
Hyperon Puzzle



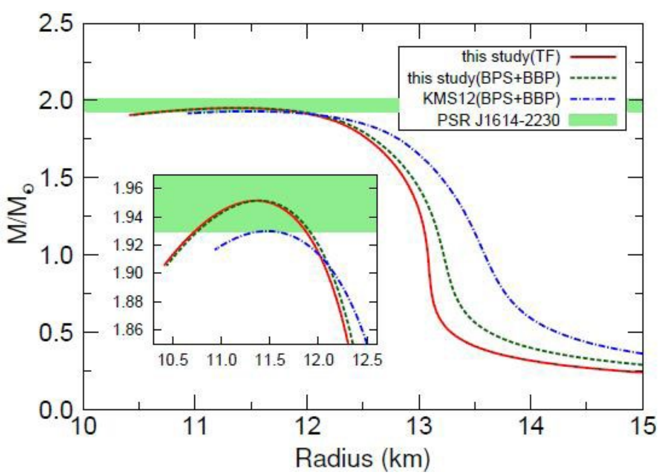
Lonardoni, Lovato, Gandolfi, Pederiva ('15),



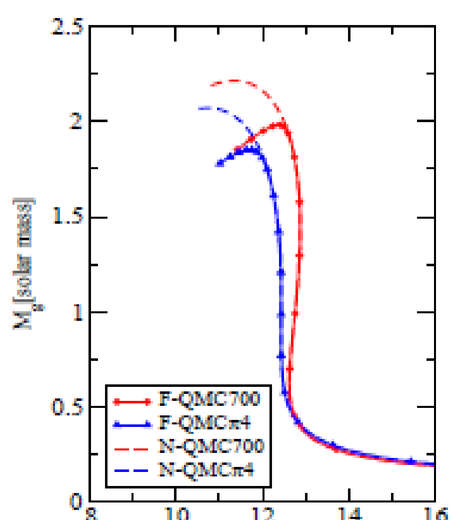
Yamamoto, Furumoto, Yasutake, Rijken ('13)



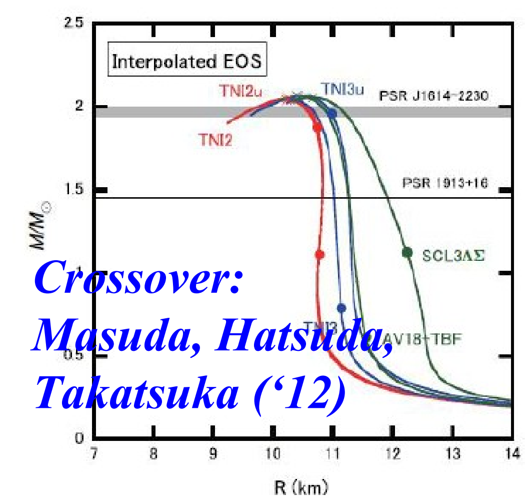
Togashi, Hiyama, Takano, Yamamoto ('16).



QMC, Miyatsu,Yamamuro, Nakazato ('13)



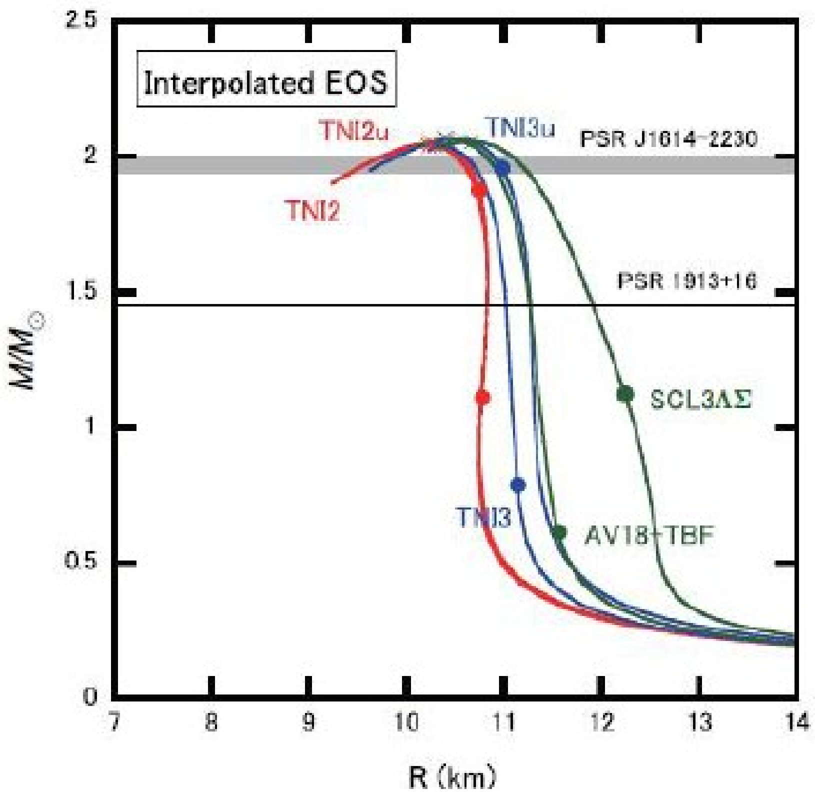
Rikovska-Stone, Guichon, Matevosyan, Thomas ('07),



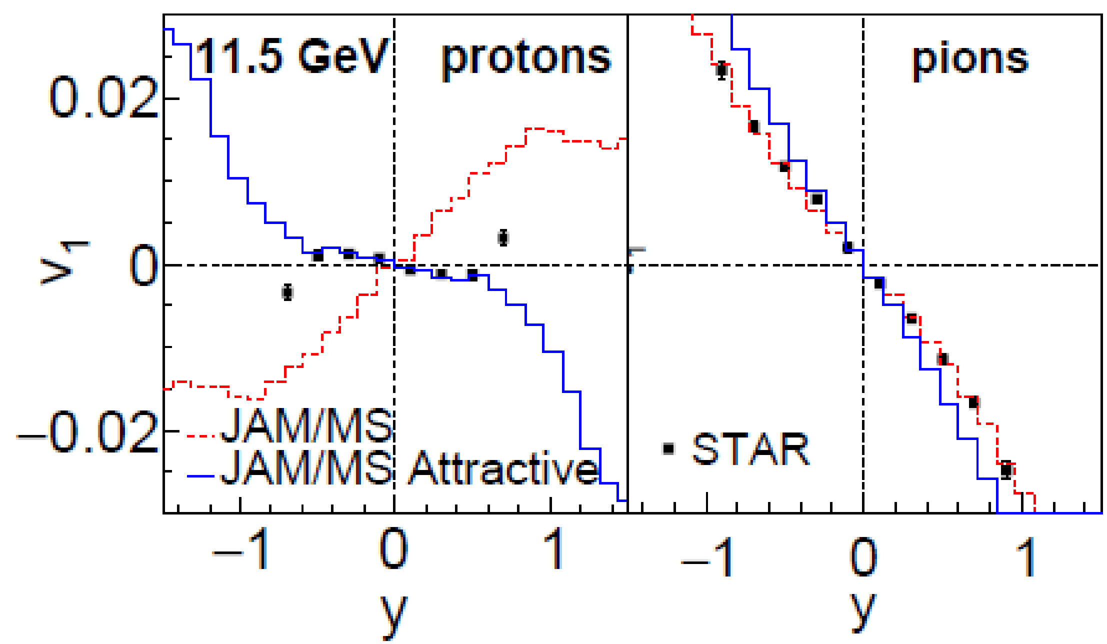
Crossover: Masuda, Hatsuda, Takatsuka ('12)

Transition to Quark Matter

- **Transition to quark matter with the first order p.t.**
  → Large radius (R ~ 14 km) (Blaschke et al.)
- **Crossover transition (Masuda et al.)**
  → Stiffened EOS by transition
  (Is it consistent with the softening found at RHIC ?)



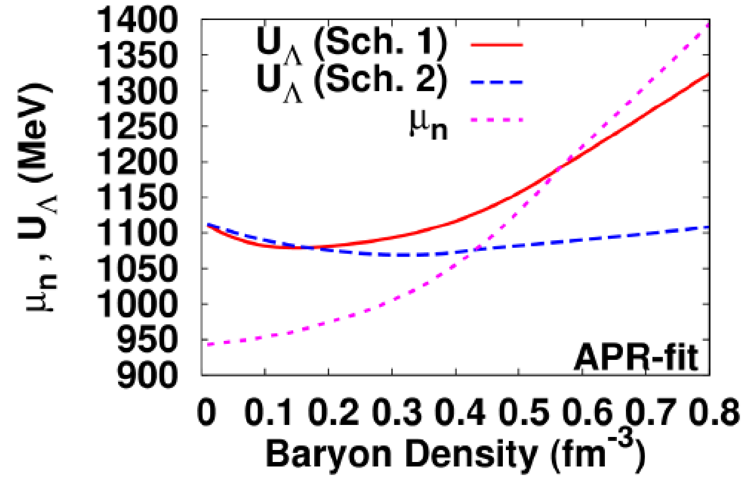
Masuda, Hatsuda, Takatsuka ('12)



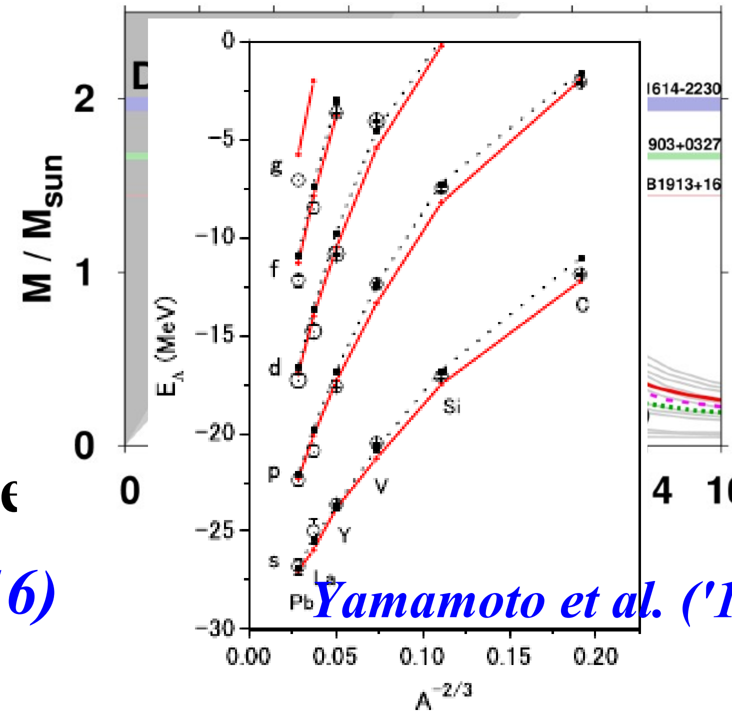
Nara, AO, Niemi, Stoecker ('16)

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.

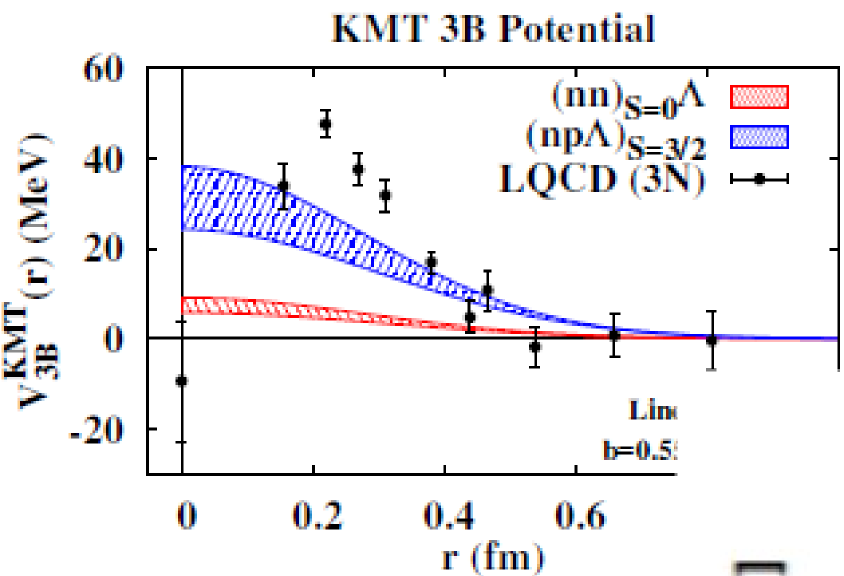


- **Collective flow of Hyperons**
- **"microscopic" 3-body force**
  - **Chiral EFT** ***Haidenbauer et al. ('13)***
    → we need more data to fix LECs
  - **Lattice 3B** ***Doi et al. (HAL QCD)('12)***
    → much CPU at Phys. point, but doable
  - **Quark model 3BF** ***Nakamoto, Suzuki ('16)***
 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

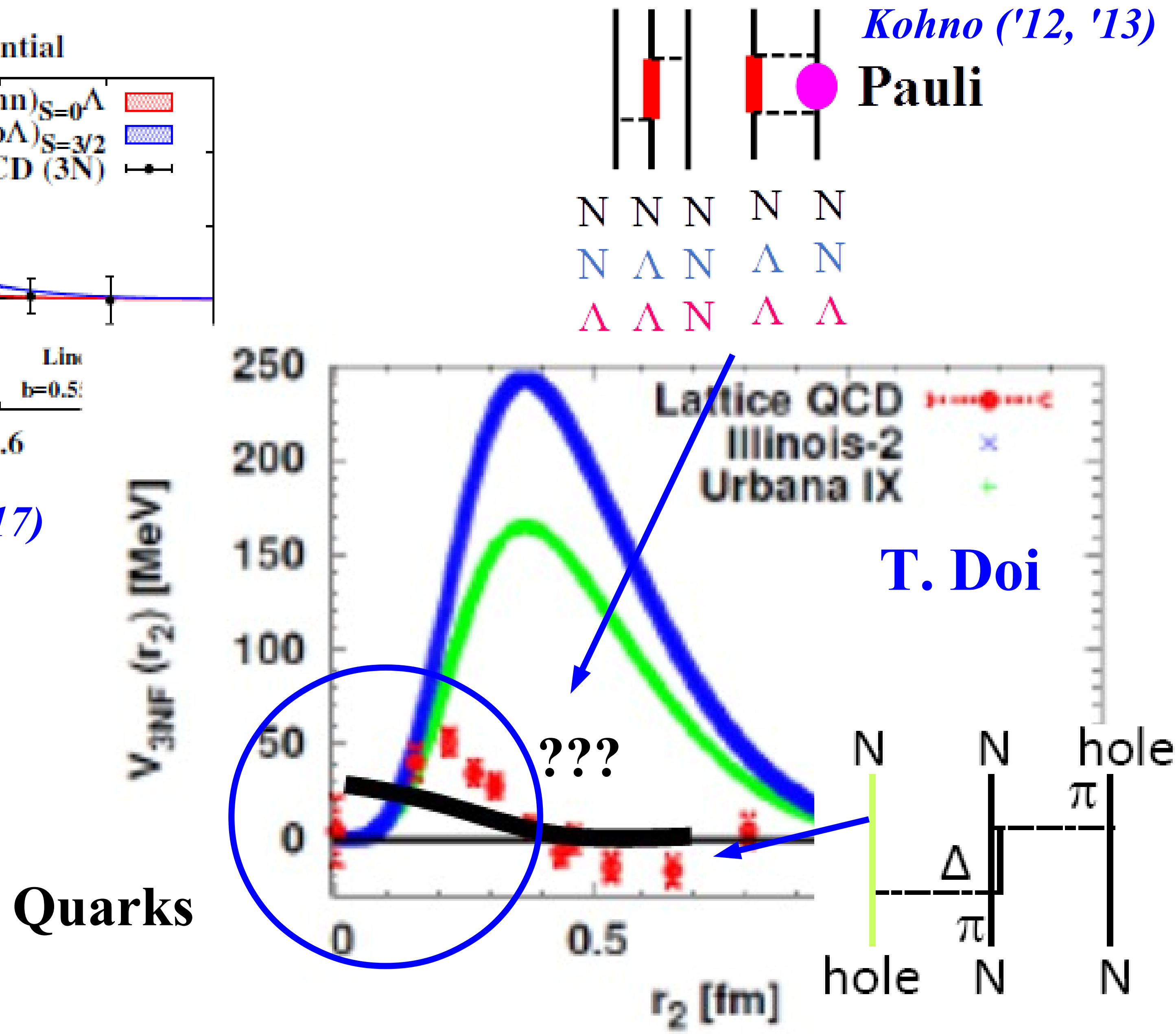


Yamamoto et al. ('14)

3B potential from KMT: Repulsive enough ?

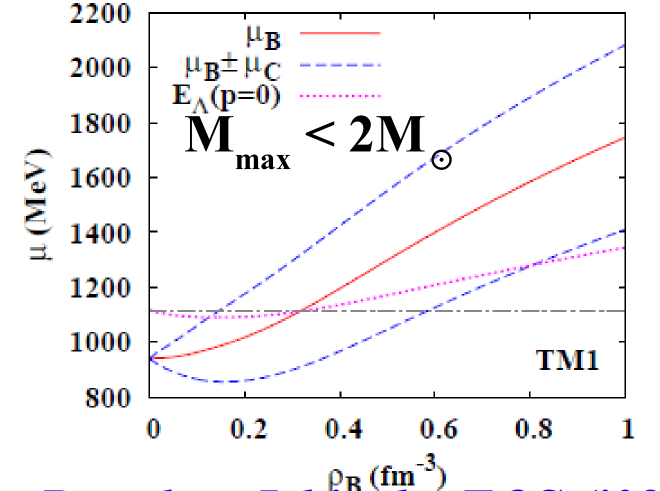


AO, Kashiwa, Morita ('17)

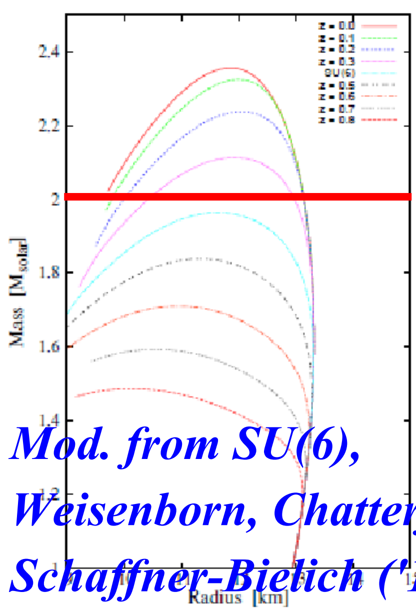


Density dependence of $U_Y(\rho)$

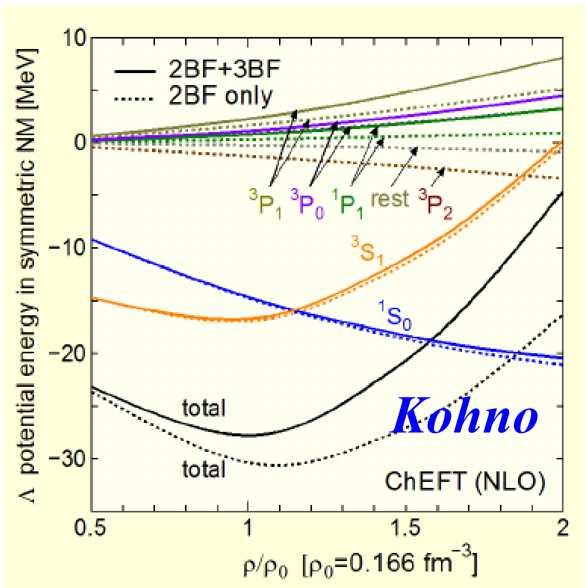
- SU(6) or quark counting rule: $g_{\omega\Lambda} \sim 2/3\, g_{\omega N}$
  → Hyperon potential is generally assumed to be weaker at high ρ.
- SU(6) breaking or 3BF (Chiral EFT) supporting 2 $M_\odot$ NS suggests earlier "turn over".



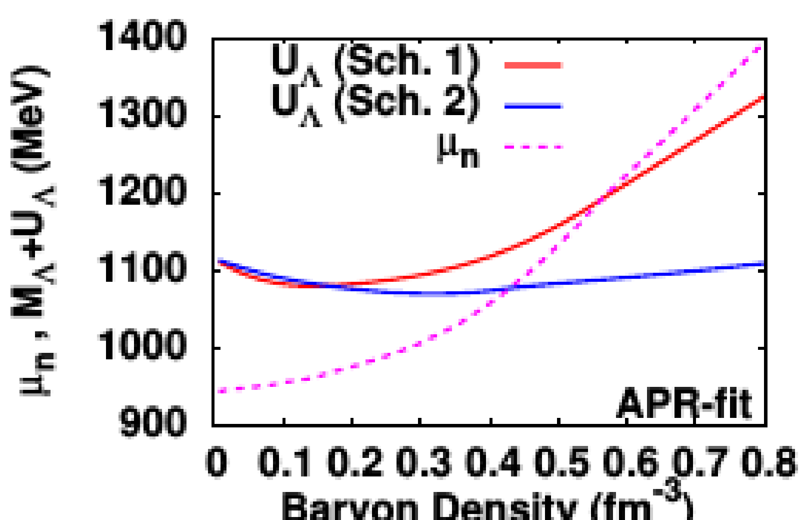
Based on Ishizuka EOS ('08)



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



Kohno

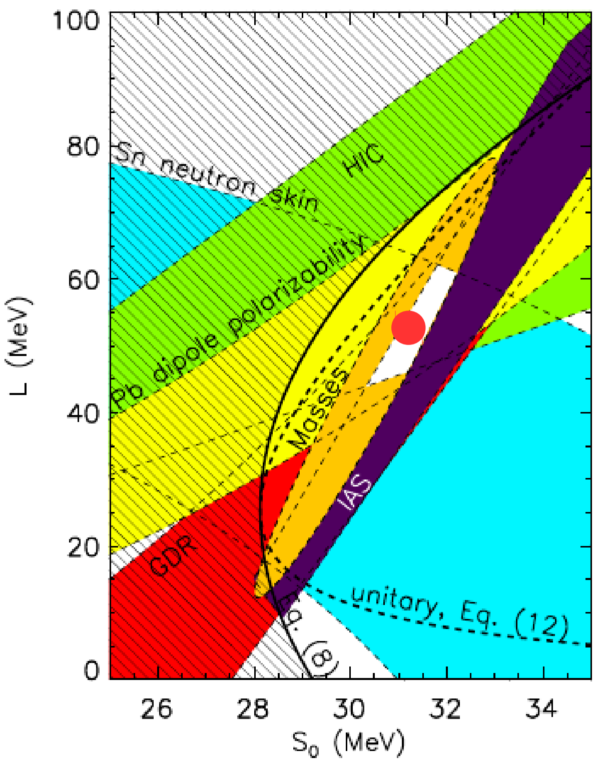


AO, Tsubakihara, Harada ('17) (NIC proc.)

Density dependence of $U_Y(\rho)$

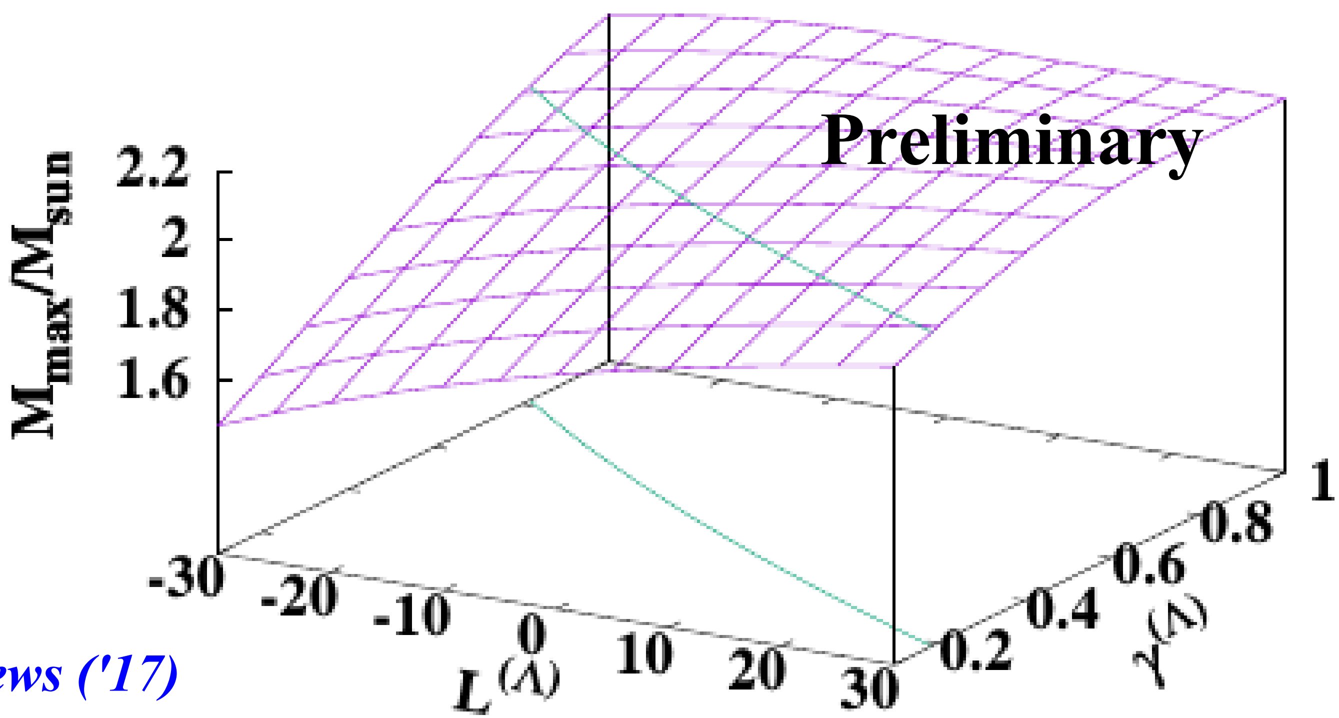
- **Let us examine the density dependence of $U_\Lambda(\rho)$**

$$U_\Lambda(u) = S_0^{(\Lambda)} + \frac{L^{(\Lambda)}}{3}(u-1) + \frac{K^{(\Lambda)}}{18}(u-1)^2 + \mathcal{O}((u-1)^3)$$
$$\simeq \alpha^{(\Lambda)} u + \beta^{(\Lambda)} u^{\gamma^{(\Lambda)}+1}$$
$$(u = (\rho - \rho_0)/\rho_0)$$

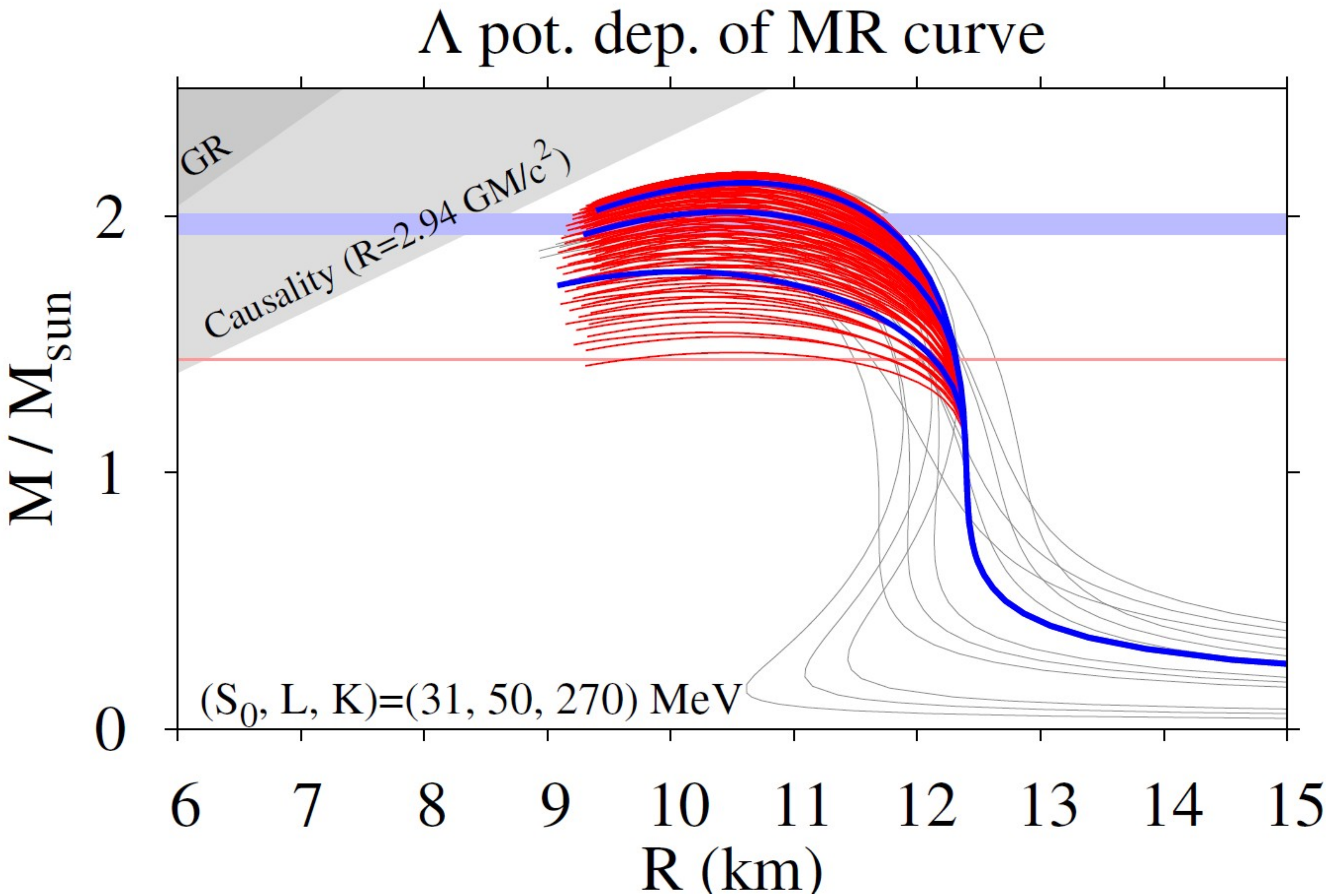


Kolomeitsev, Lattimer, AO, Tews ('17)

(S_0,L,K)=(31,50,270) MeV, $S_0^{(\Lambda)}$=30 MeV



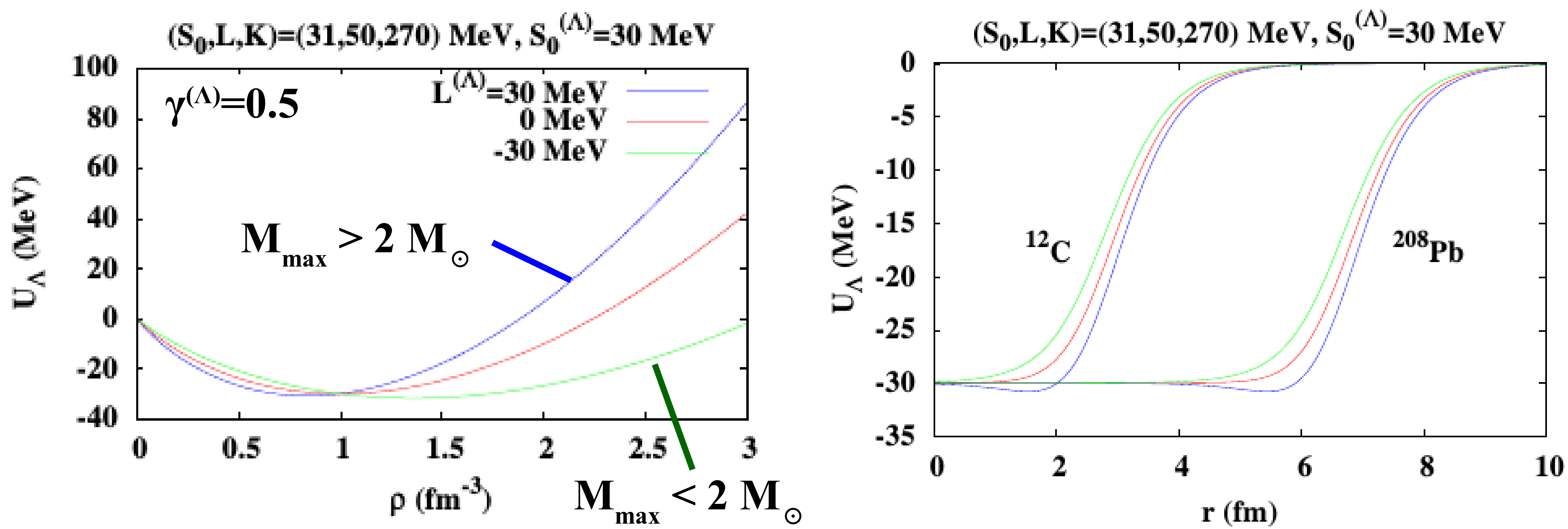
Density dependence of $U_Y(\rho)$



S0(Λ)=30 MeV, L(Λ)= –30, 0, +30 MeV, γ(Λ)=0.5

Can we discriminate in experiments ?

- $M_{max} > 2\ M_\odot$ may be achieved at $L^{(\Lambda)} > 0$,
  but dependence on $L^{(\Lambda)}$ is small in finite nuclei.
  - $L^{(\Lambda)} > 0 \rightarrow$ deeper U_Λ at $\rho < \rho_0$ $\rightarrow$ Small nuclei, Large L state, …
- (Sub)MeV hypernuclear spectroscopy is necessary !
  p-, d-wave ΛN interactions are necessary !



Summary

- **Hyperon puzzle is a serious problem in hypernuclear physics and astrophyics.**
  - **Hyperon potential depth & SU(6) symmetry for mean field by vector mesons.**
  - **Recent hypernuclear experiments confirms the depth.**
- **Hyperon puzzle MAY NOT BE a puzzle.**
  There are some missing piecies.
  - **Density dependence of $U_Y(\rho)$ is not yet known well.**
    – S0(Λ), L(Λ), K(Λ) → helps in solving hyperon puzzle
- **Hyperonic matter is as stiff as nuclear matter at high density.**
  - **Phen. EOS with $(S_0$,L,K)~(31,50,240) MeV barely supports $2M_\odot$ NS.**
  - **Approximately flavor blind EOS suggests roles of partonic DOF.**