Neutron star matter equation of state – current status and challenges –

Akira Ohnishi (YITP, Kyoto U.)

Mini-Symposium on Nuclear Matter in Neutron Stars I (EoS and Structure)

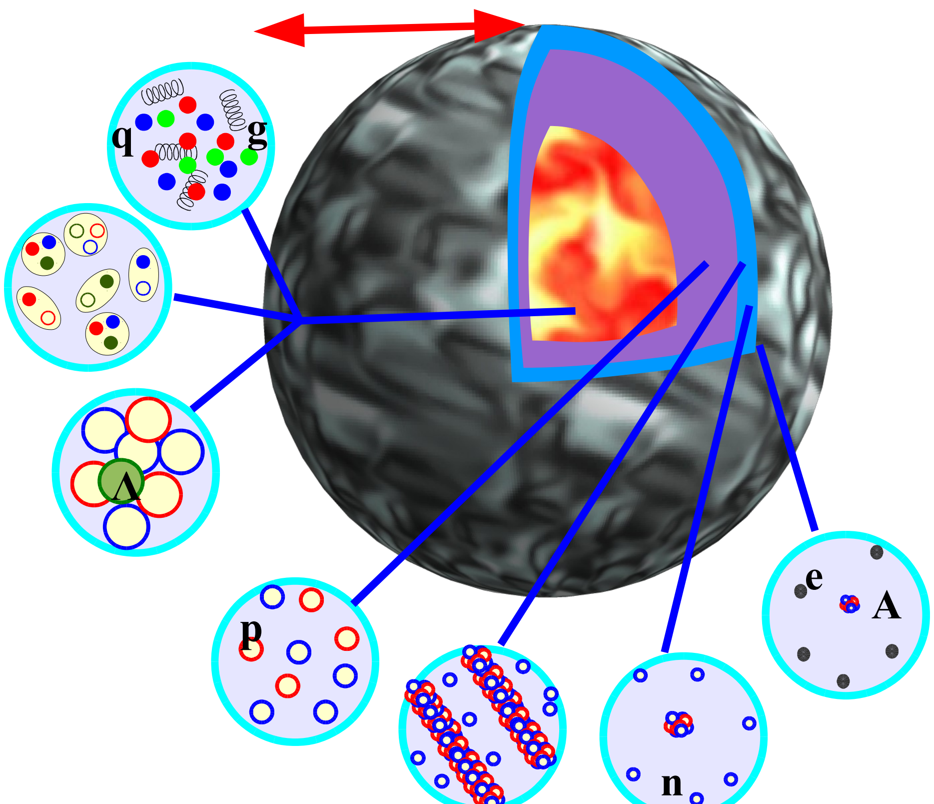
4th Joint Meeting of the APS Division of Nuclear Physics and the Physical Society of Japan,

October 7–11, 2014, Waikoloa, Hawaii, USA

Neutron Star

Star supported by nuclear force

R ~ 10 km



M ~ 1.4 $M_\odot$, ρ_c ~ (3-10) ρ_0

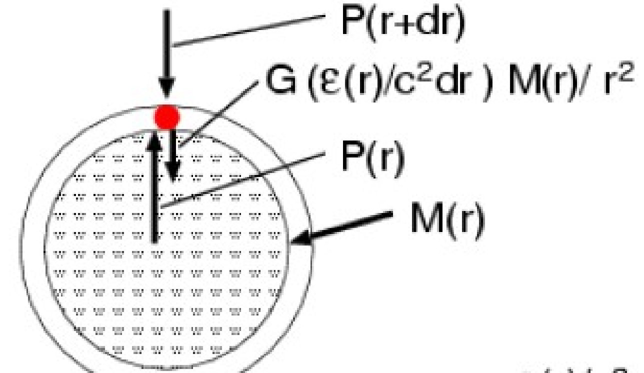
Wide density range → various constituents
NS = high-energy astrophysical objects
and laboratories of dense matter.

M-R curve and EOS

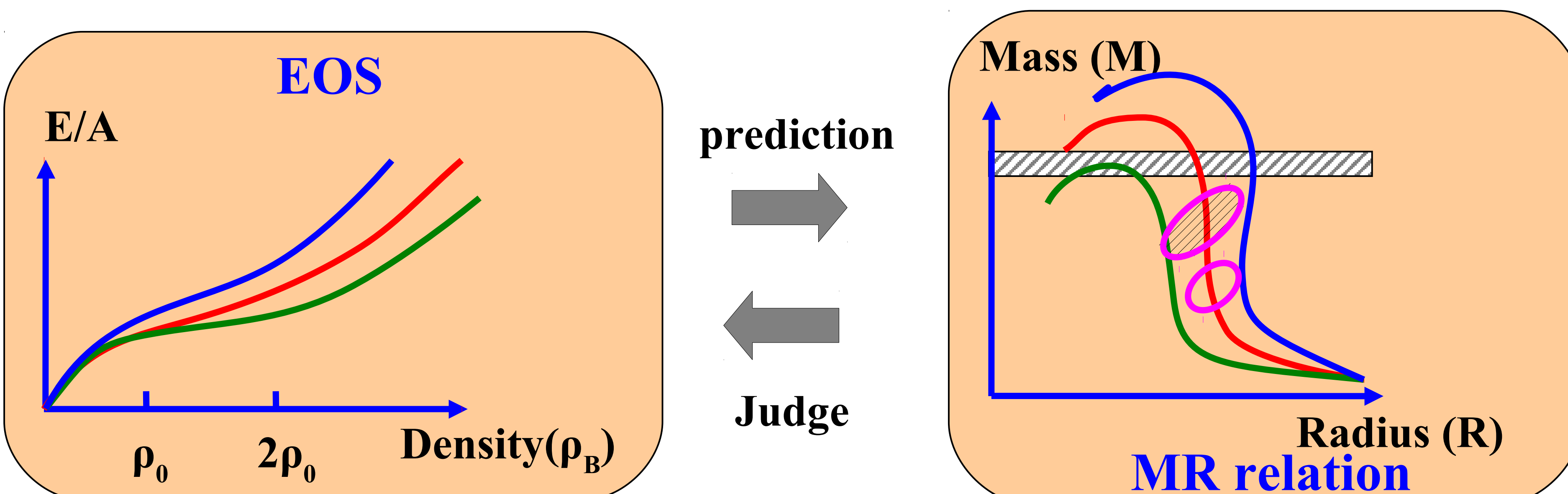
- **M-R curve and NS matter EOS has 1 to 1 correspondence**
  - **TOV(Tolman-Oppenheimer-Volkoff) equation =GR Hydrostatic Eq.**

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

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

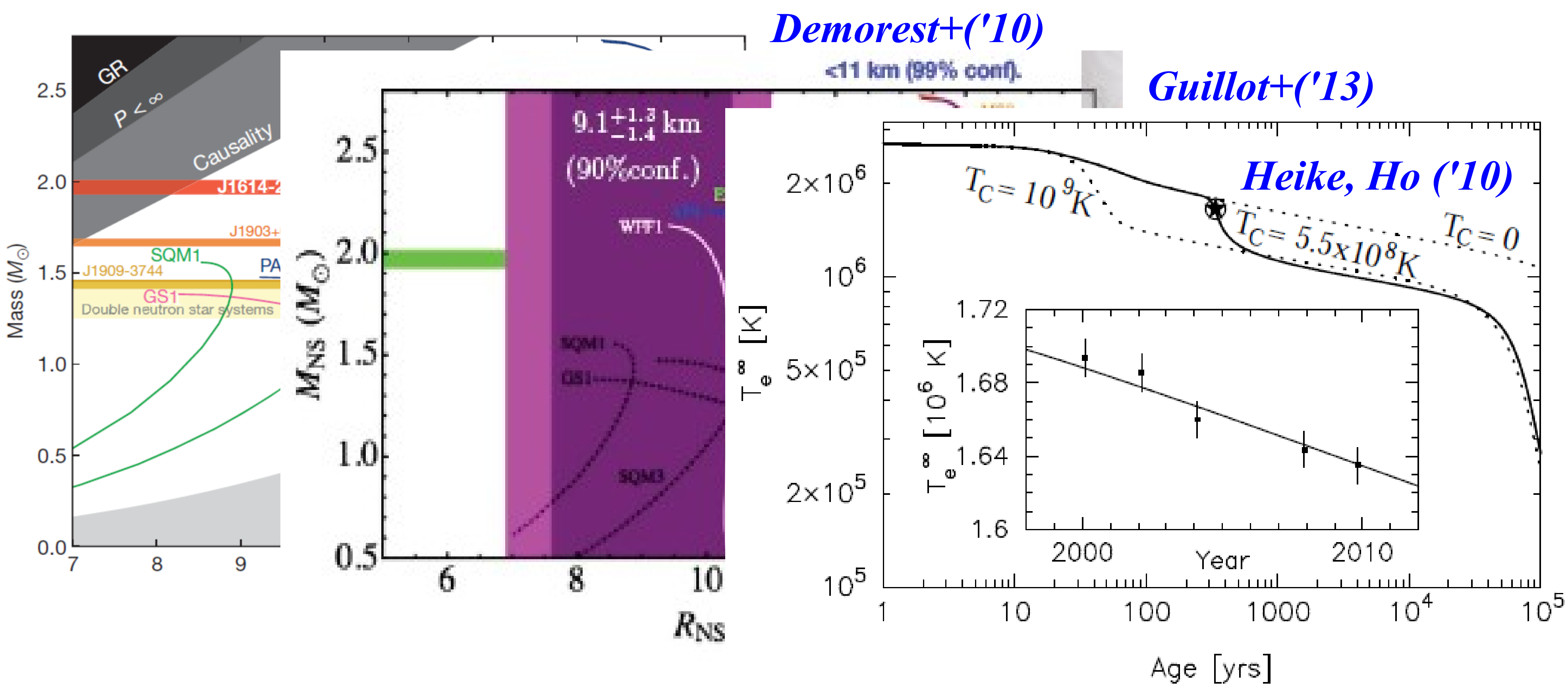


Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$



Current Big Puzzles in NS Physics

- **Massive NS puzzle (2 $M_\odot$ NS ?)**
- **Compact NS puzzle (9-10 km NS ?)**
- **Rapid NS cooling mystery (CasA cools too fast ?), Origin of Strong Mag. Field, …..**



Mini-Symp. on Nuclear Matter in Neutron Stars

- **DL: Mini-Symposium on Nuclear Matter in Neutron Stars I (EoS and Structure)**
  - **Ab initio EOS (Togashi, Thin, Gandolfi, Takano)**
  - **EOS from effective interactions (Sotani, Tsubakihara)**
  - **Pasta nuclei (Horowitz)**
  - **NS Cooling (Brown)**
  - **Roles of light nuclei in SNe (Sumiyoshi, Nakamura)**
- **EL: Mini-Symposium on Nuclear Matter in Neutron Stars II (Symmetry Energy and Hypernuclei)**
  - **Lead speaker: W. Lynch**
- **FL: Mini-Symposium on Nuclear Matter in Neutron Stars III (Experimental Prospects on Strangeness)**

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

High ρ (Group A)
head: Tamura, Takahashi

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

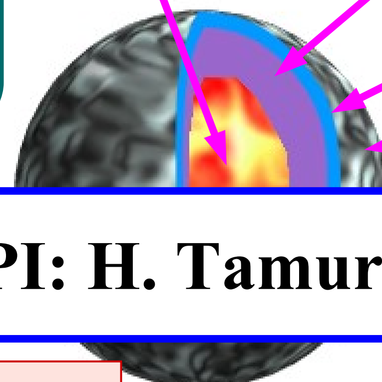
J-PARC

Hyperons, mesons, quarks

Asym. nuclear matter +elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.



PI: H. Tamura

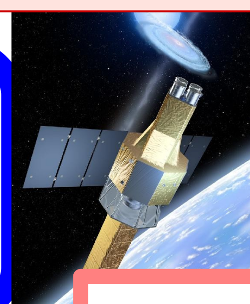
Low ρ (Group B)
head: Murakami, Nakamura, Horikoshi

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

NS Obs. (Group C)
head: Takahashi

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

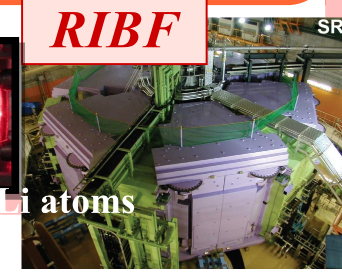
ASTRO-H



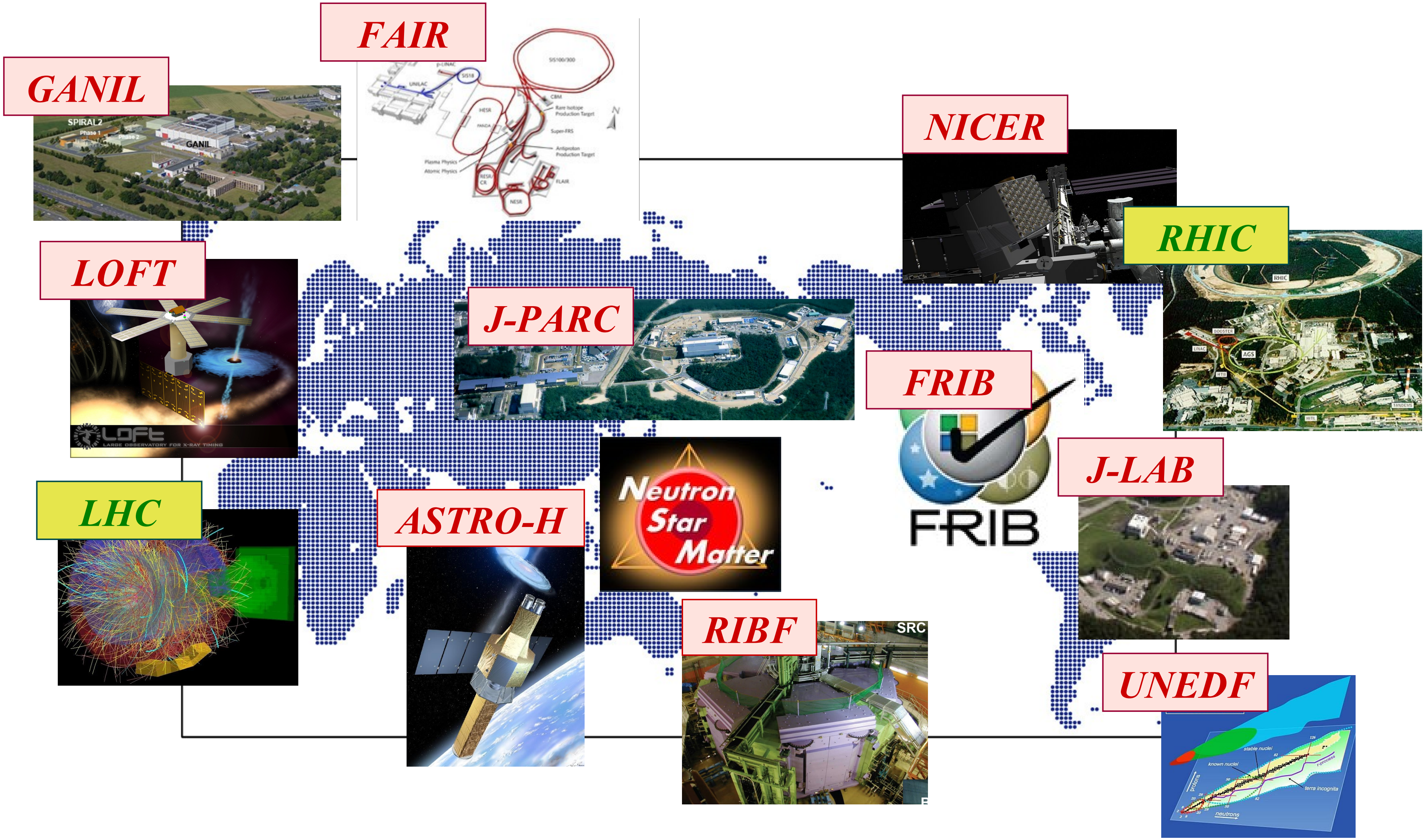
Theory (Group D)
head: Ohnishi

Laser cooled ^{6}Li atoms

RIBF



Accelerators and Satellites for Neutron Star Physics



Contents

- Mini-Symposium on Nuclear Matter in Neutron Stars
  - Current/Future Projects in Japan and US
- Compact NS puzzle
  - NS radius measurements
  - Nuclear Symmetry Energy
  - R_{NS}(measured) < R_{NS} (theory) ?
- NS mass and Massive NS puzzle
  - Role of three-baryon (BBB) force
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Compact Neutron Star puzzle

Symmetry Energy

- **Energy per nucleon in nuclear matter**

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

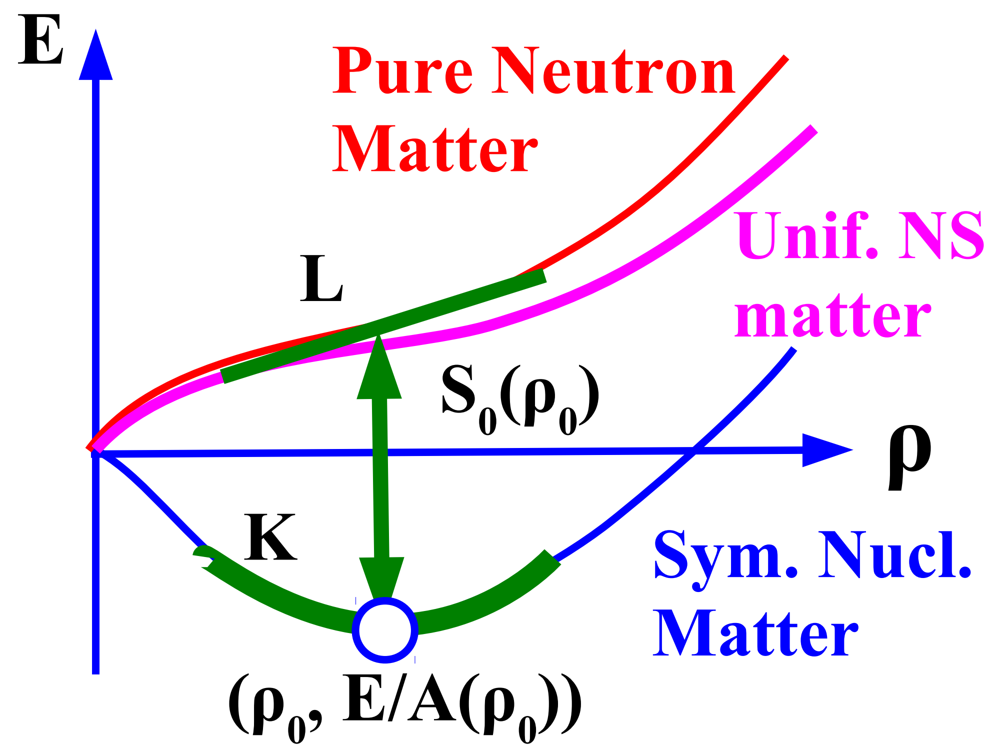
$$E_{\rm SNM}(\rho) \simeq E_0 + \frac{K(\rho-\rho_0)^2}{18\rho_0^2} \ , \quad S(\rho) = S_0 + \frac{L(\rho-\rho_0)}{3\rho_0}$$

  - **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**

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

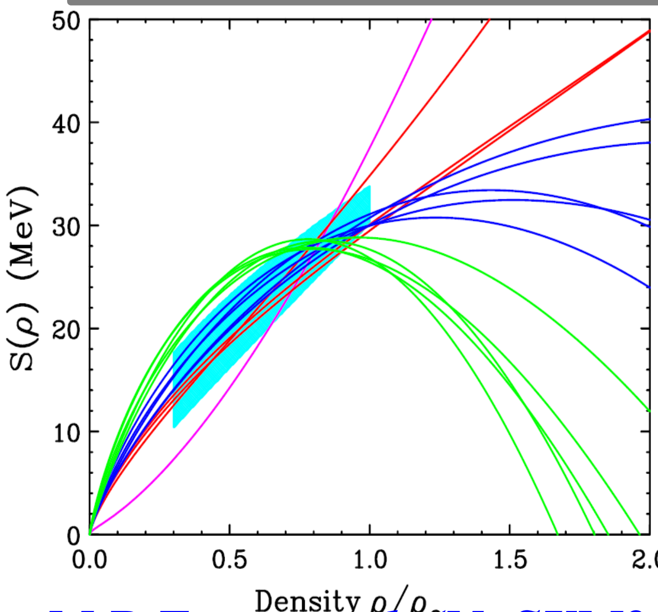
  - **Charge neutrality**
    → ρ(elec.)= ρ(p) ($\rho_e=\rho_p=\rho(1-\delta)/2$)
    δ is optimized to minimize energy.



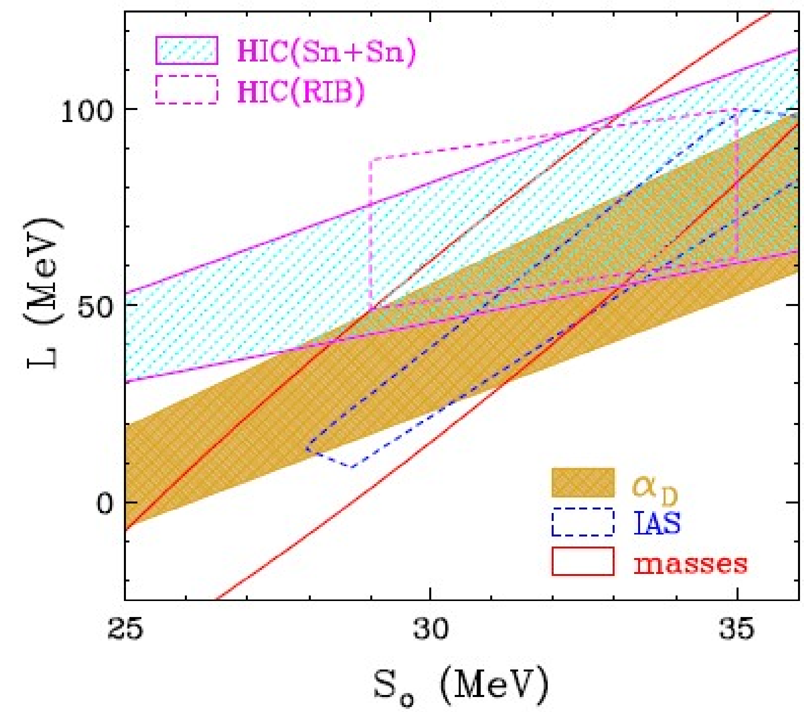
Symmetry Energy

- **Symmetry Energy has been extracted from various observations.**
  - **Mass formula, Isobaric Analog State, Pygmy Dipole Resonance, Isospin Diffusion, Neutron Skin thickness, Dipole Polarizability, Asteroseismology**

Recent recommended value
S_0 = 31-35 MeV, L = 50-90 MeV
Is it enough for NS radii ?



M.B.Tsang et al. (NuSYM2011), PRC 86 ('12)015803.

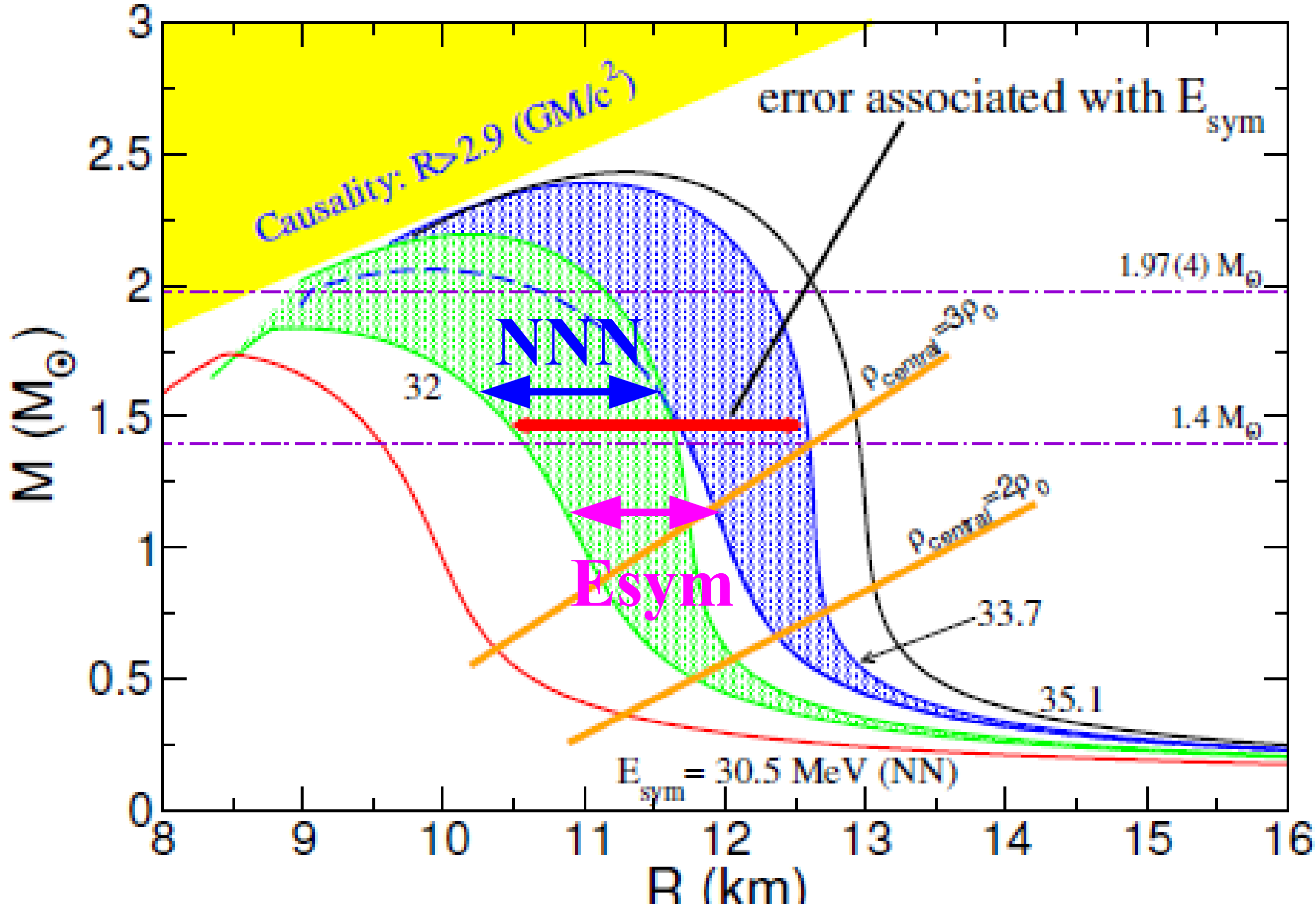


C.J.Horowitz, E.F.Brown, Y.Kim, W.G.Lynch, R.Michaels, A. Ono, J. Piekarewicz, M. B. Tsang, H.H.Wolter (NuSYM13), JPG41('14) 093001

[See also Lynch (Thu Evening)]

Symmetry Energy affects MR Relation of NS

- **Nuclear pressure at ρ_0 comes ONLY from Esym, then Esym dominates pressure around ρ_0 !**
- **2 MeV Difference in Esym results in 1.5 km (15 %) difference in R_{NS}.**



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

Neutron Star Radius

- **Black-body radiation (Stefan-Boltzmann law)**

$$L = 4\pi R_\infty^2 \sigma_{SB} T^4 \ , \quad F = \frac{L}{4\pi D^2} \ \rightarrow \ R = \sqrt{\frac{F D^2}{\sigma_{SB} T^4}} \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}$$

(F=flux, D=dist. from the earth)

- **Eddington Limit at touch down**
(balance of radiation pressure & gravity)

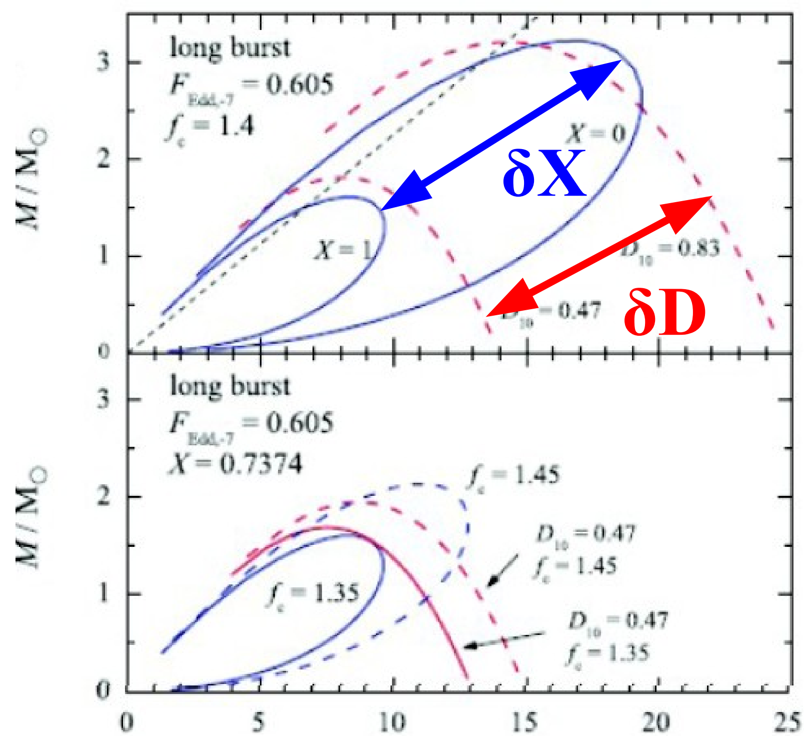
$$\frac{4\pi r^2 \sigma_{SB} T^4}{4\pi r^2 c} \cdot N_e \cdot \sigma_T = \frac{GM}{r^2} \cdot N_N \cdot m_N$$

$$\rightarrow \quad R_\infty^2 = \frac{2GMcm_N}{\sigma_T \sigma_{SB} T^4} \frac{N_N}{N_e}$$

(electron-nucleon ratio N_e/N_N=(1+X)/2)

- **Surface Redshift measurement**

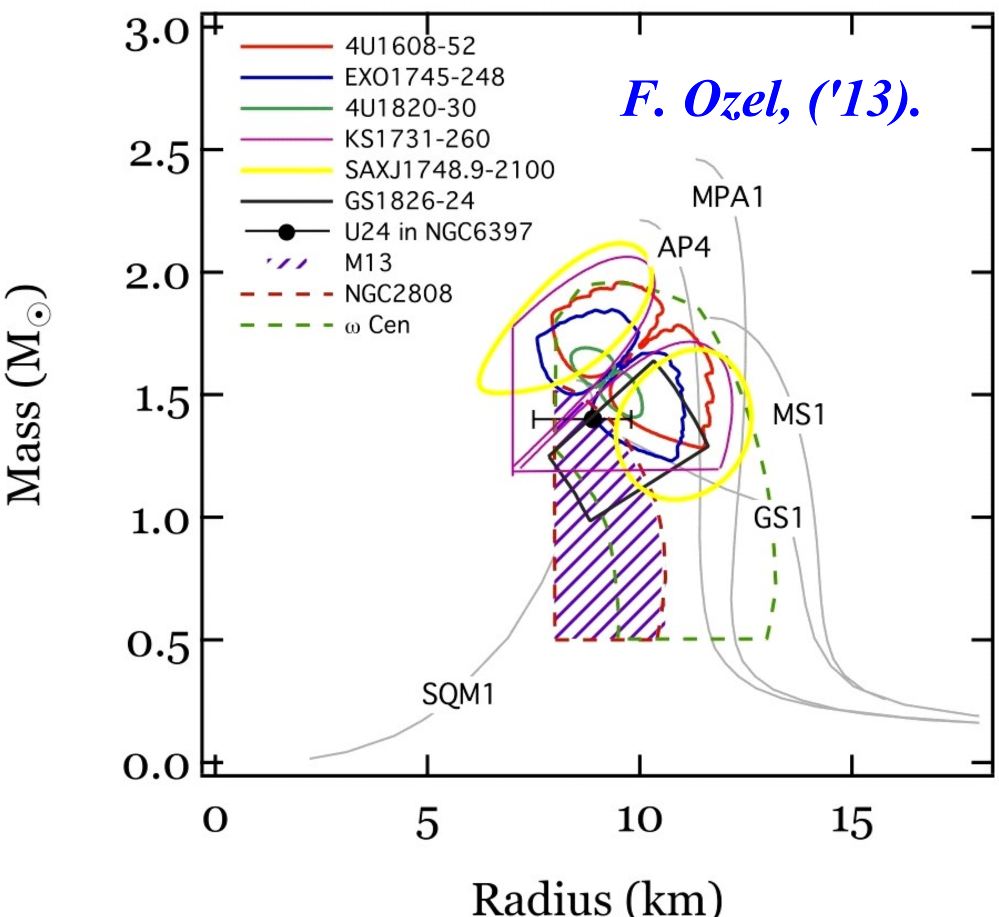
$$E_{obs} = E_{surf} \sqrt{1 - \frac{2GM}{Rc^2}}$$



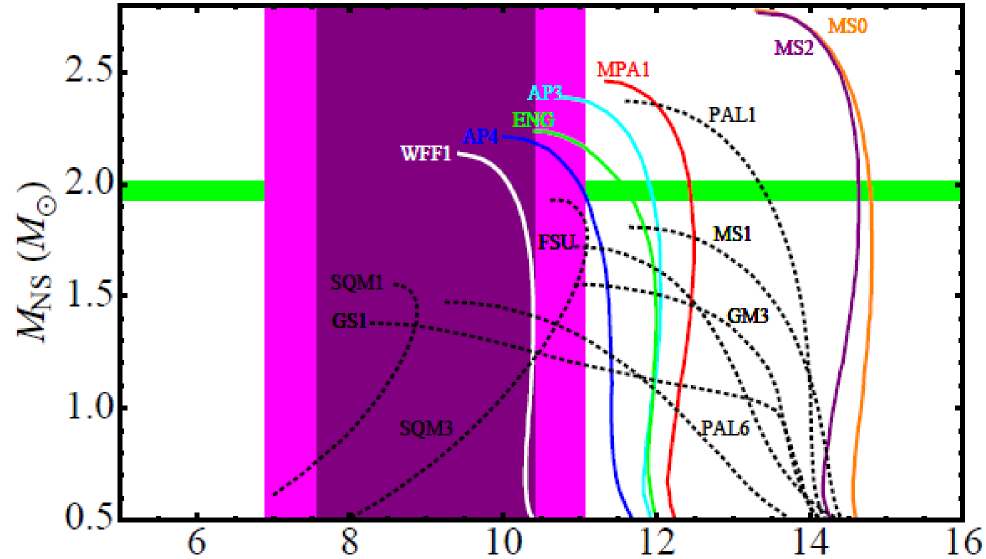
4U 1724-307, Suleimanov et al., ApJ742('11),122

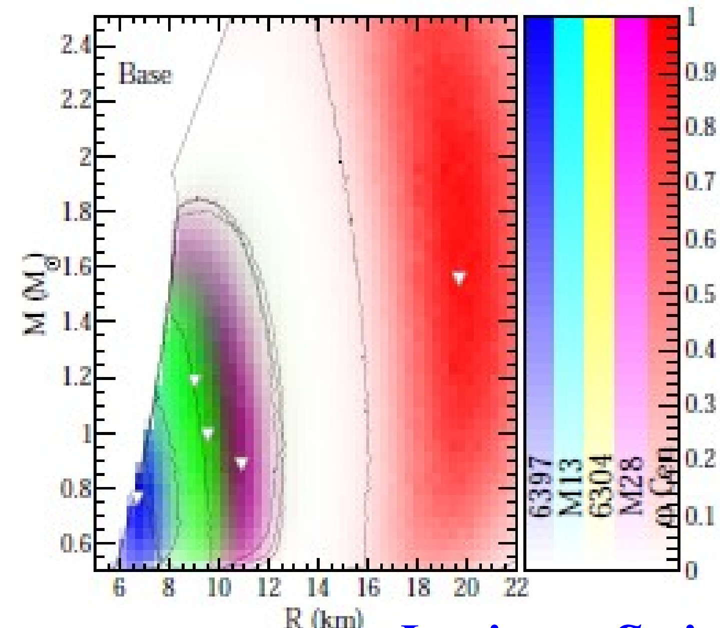
Compact NS puzzle

- **NS radii from X-ray analyses are smaller than nucl. phys. predictions.**
  - **Except for Suleimanov+, long PRE bursts, $R_{1.4} > 13.9$ km**
    Lattimer+, $R_{1.4} = 12 \pm 1.4$ km



Guillot et al. (2013)



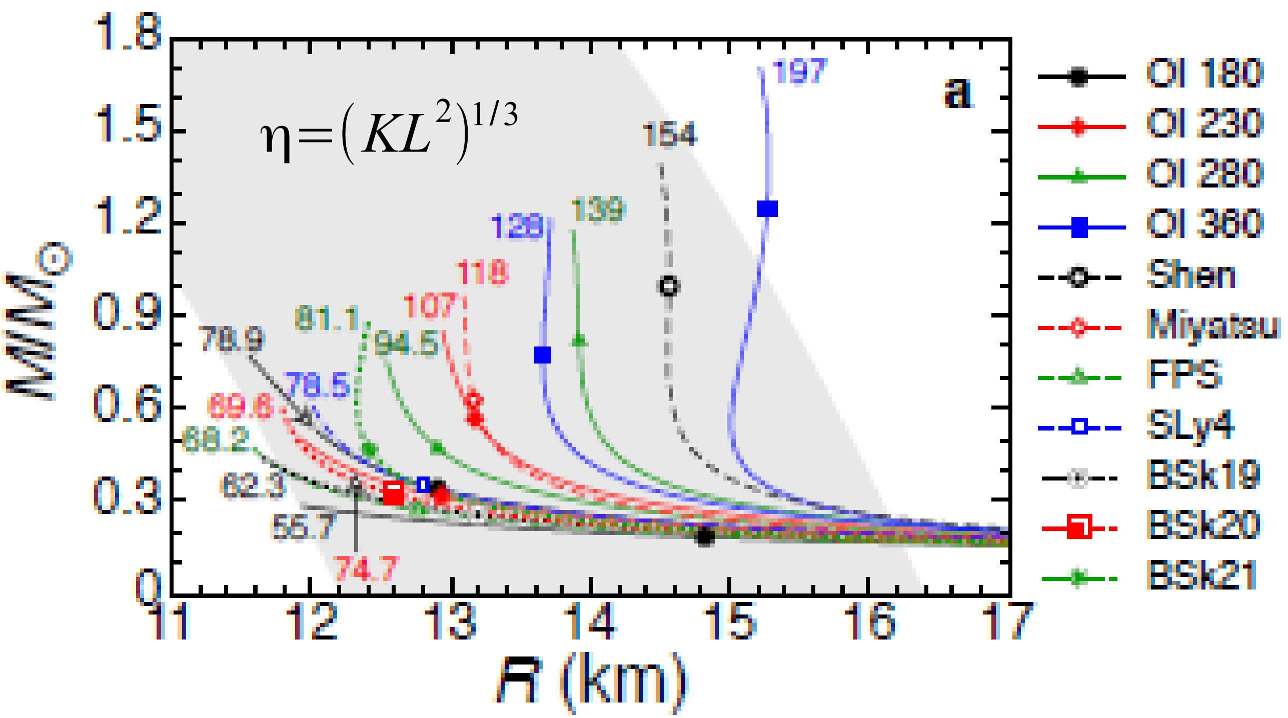


Lattimer, Steiner (2013).

Compact NS puzzle

- NS radii from X-ray analyses are smaller than nucl. phys. predictions.

[Sotani (Thu Morning)]

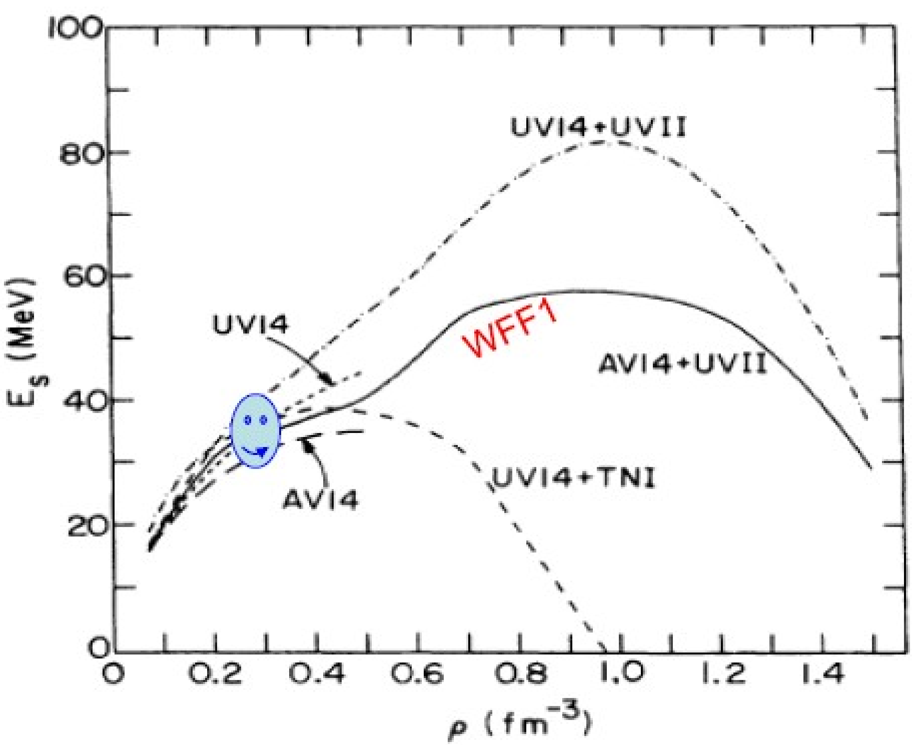


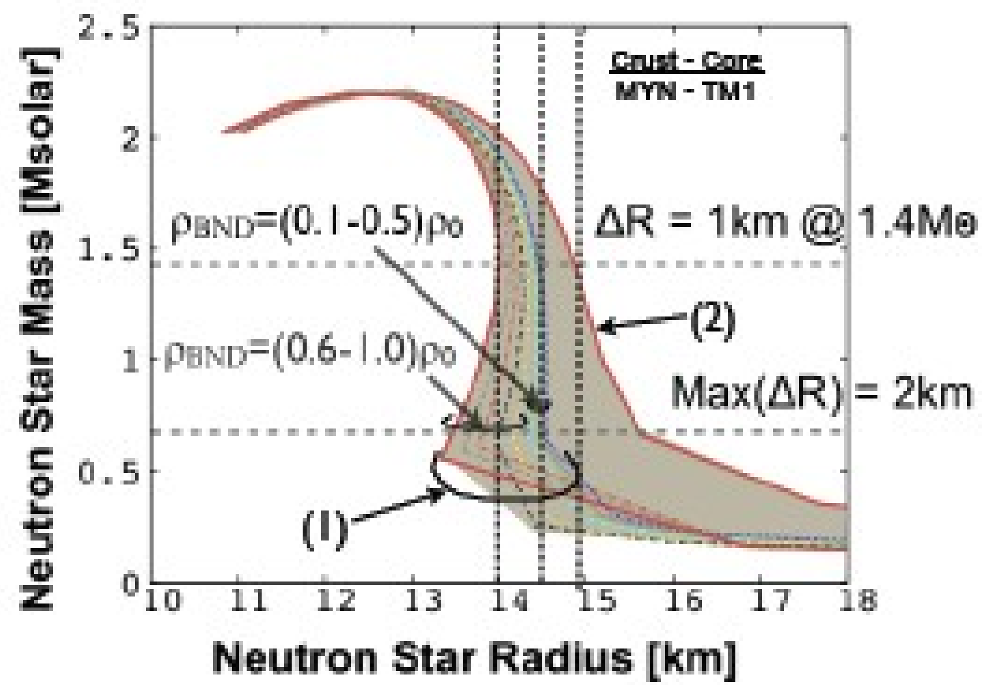
EOS	K_0 (MeV)	L (MeV)	S_0 (MeV)	η (MeV)
OI-EOSs	180	31.0	30.5	55.7
	180	52.2	32.4	78.9
	230	42.6	31.0	74.7
	230	73.4	33.6	107
	280	54.9	31.7	94.5
	280	97.5	34.5	139
	360	76.4	32.7	128
	360	146	39.0	197
Shen	281	114	37.9	154
Miyatsu	274	77.1	33.6	118
FPS	261	34.9	29.9	68.2
SLy4	230	45.9	32.0	78.5
BSk19	237	31.9	30.0	62.3
BSk20	241	37.4	30.0	69.6
BSk21	246	46.6	30.0	81.1

Sotani, Iida, Oyamatsu, AO ('14)

Compact NS puzzle: Can we solve it ?

- **Small sym. E. at ρ=(2-3) ρ_0 ? Wiringa, Fiks, Fabrocini (1988)**
  → To be confirmed in HIC experiments **[Lynch, Thu. evening]**
- **Crust-Core boundary density → (1-1.5) km diff.**
  Ishizuka, Nakazato, AO, in prep.
- **Other mech. to soften EOS at ρ=(2-3) ρ_0 (e.g. π cond.)**
- **NS rotation → ~ 4 % correction to RNS** *Ozel+ ('14)*

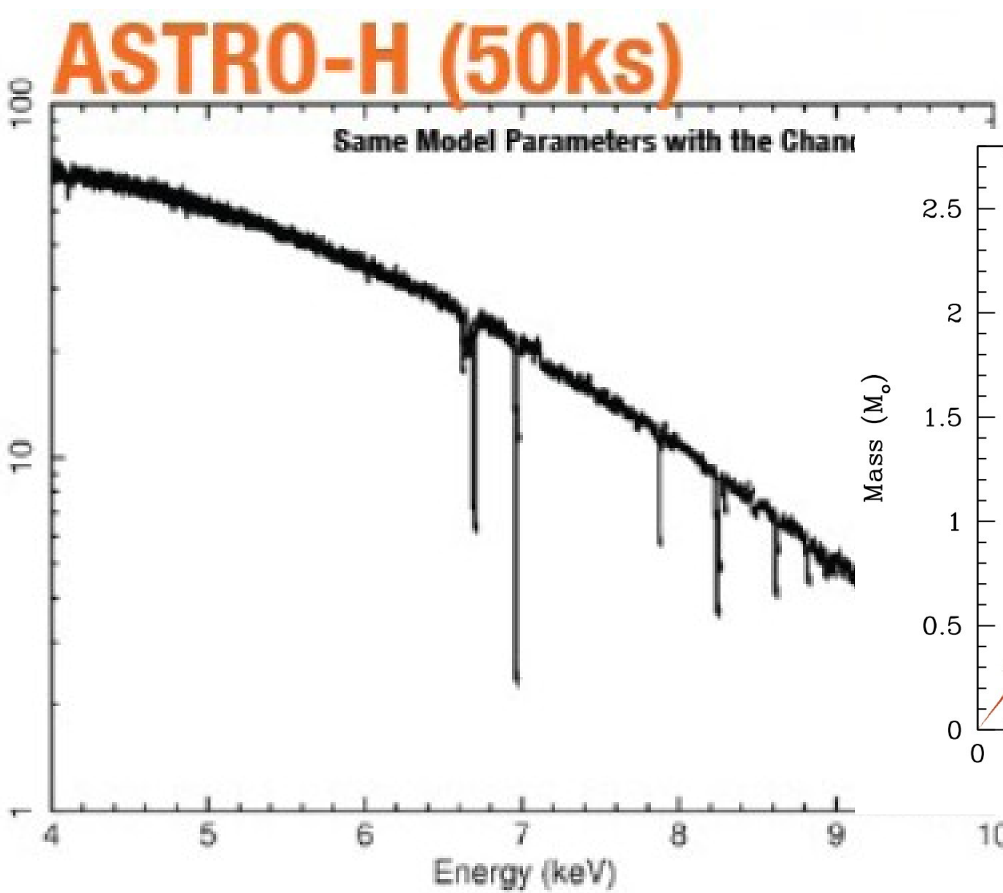


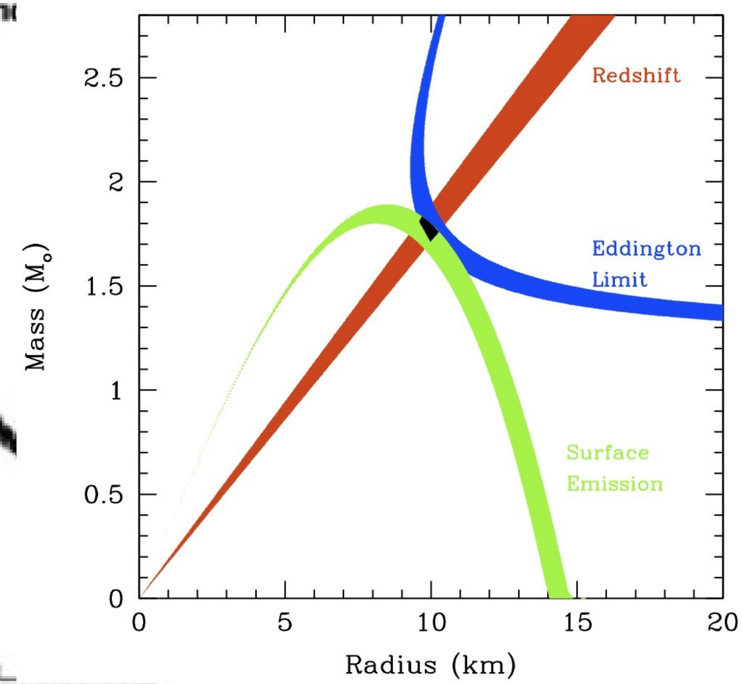


Ishizuka, Nakazato, AO (in prep.)

Further Astronomical Observation

- **Redshift measurement of absorption lines**
  = Model independent measurement of R_{NS}
- **R_{NS} / ($2GM/c^2$) is expected to be measured with 1 % accuracy in ASTRO-H !**





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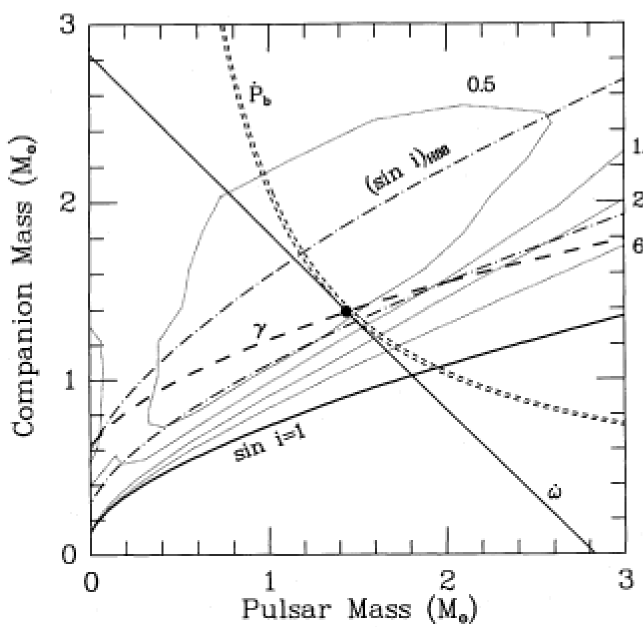
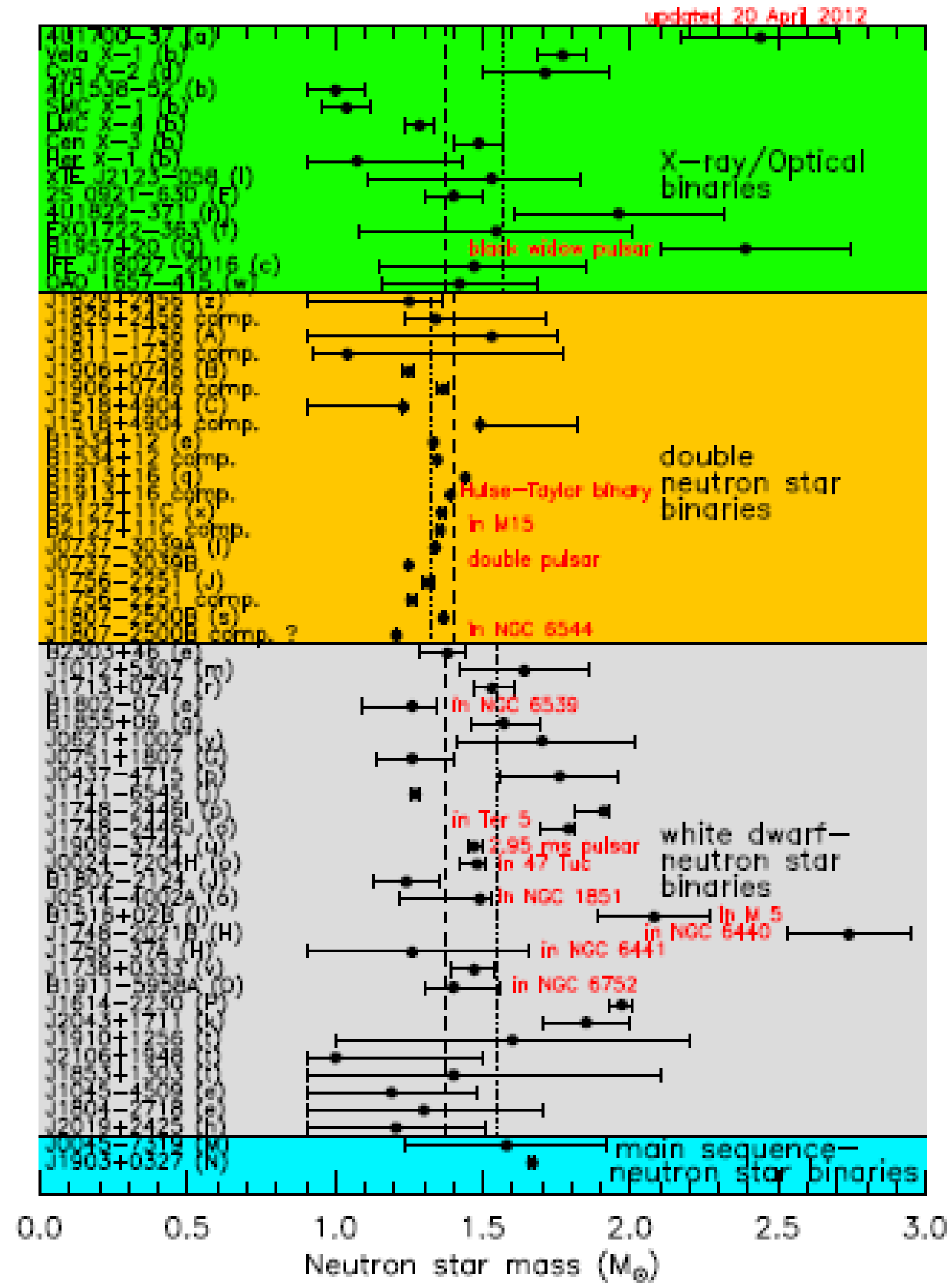
Massive Neutron Star puzzle

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 $\rightarrow M = 1.442 \pm 0.003\, M_\odot$ (Hulse-Taylor pulsar)**
    Taylor, Weisenberg ('89)
- **Many NSs have $M \sim 1.4\, M_\odot$.**



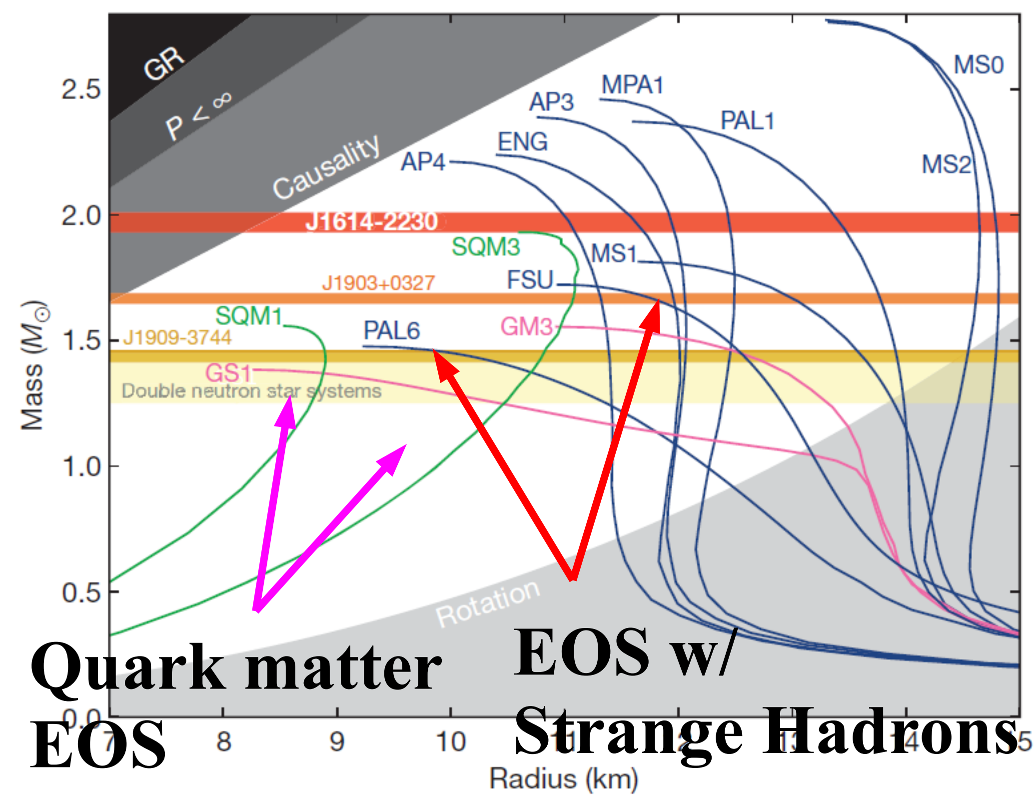


Lattimer (2013)

Massive Neutron Star Puzzle

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

No Exotics in NS ?

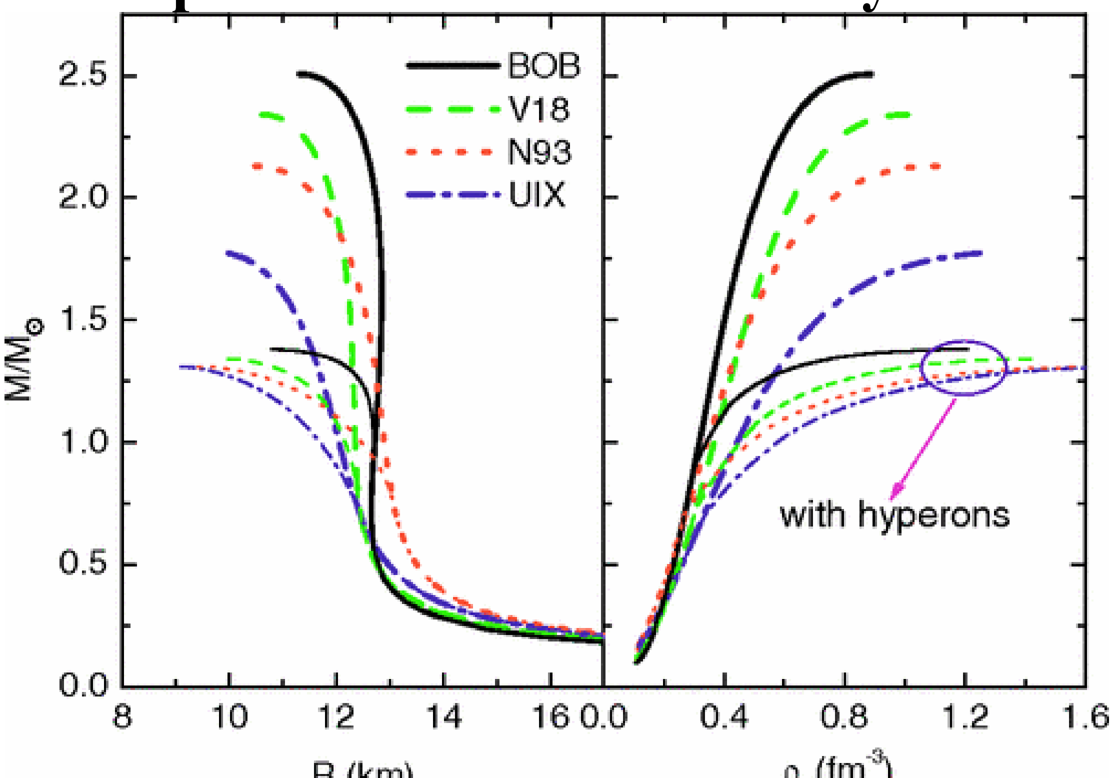


Quark matter EOS

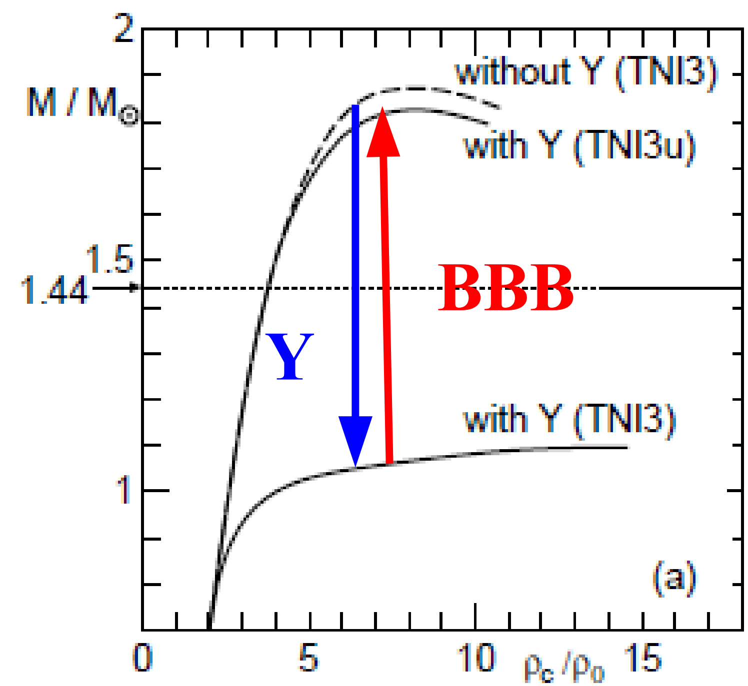
EOS w/ Strange Hadrons

Bruckner-Hartree-Fock theory with Hyperons

- **Microscopic G-matrix calculation (Bruckner-Hartree-Fock theory) with realistic NN, YN potential and NNN (or BBB) force.**
  → Hyperons (Y) should appear.
- **Quantum MC calc. also gives qualitatively the same conclusion. [J. Carlson, Mon.]**
- **BBB repulsion should exist in any combination of BBB ("Universal").**



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

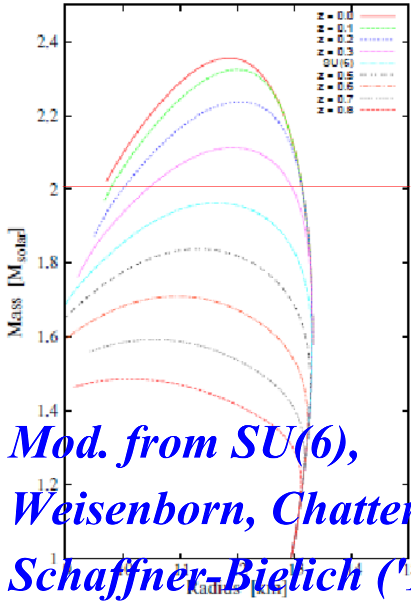


S. Nishizaki, T. Takatsuka, Y. Yamamoto, PTP108('02)703.

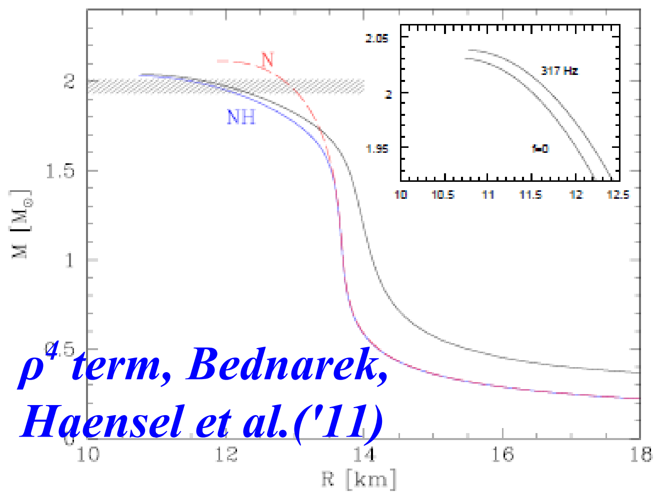
Possible Solutions to Massive NS puzzle (Hyperon Crisis)

- **EOS is stiff enough even with hyperons** **[Talk by Tsubakihara]**
  - **Modification of YN interaction**
    Weisenborn, Chatterjee, Schaffner-Bielich ('11); Jiang, Li, Chen ('12); Tsubakihara, AO ('13)
  - **Introducing BBB repulsion**
    Bednarek, Haensel et al.('11); Miyatsu, Yamamuro, Nakazato ('13); Tsubakihara, this session.
- **Hyperons do not appear**
  - **Early crossover transition to quark matter**
    Masuda, Hatsuda, Takatsuka ('12)

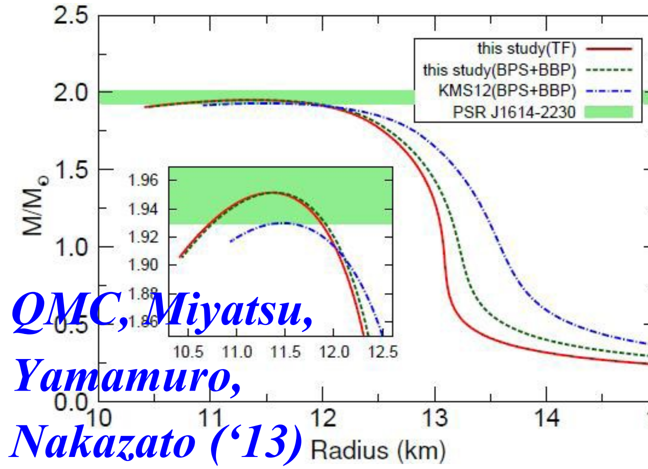
NS matter EOS with hyperons



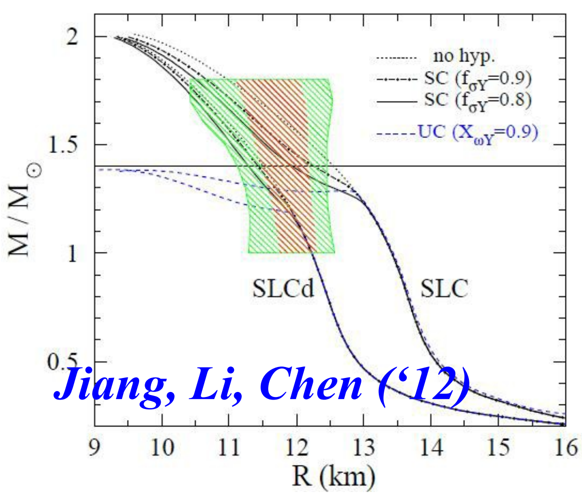
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



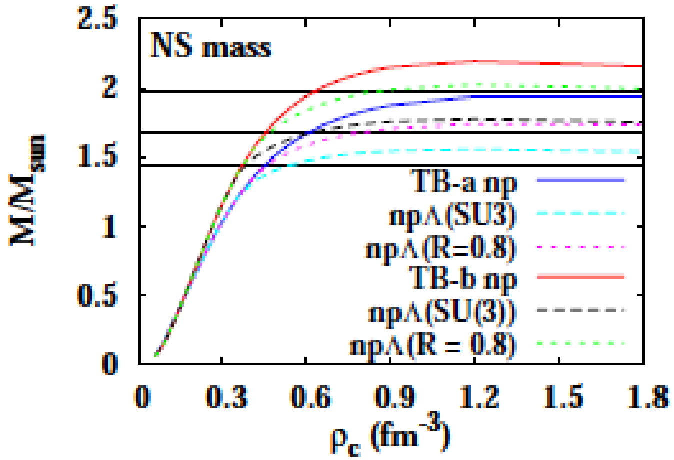
ρ^4 term, Bednarek, Haensel et al.('11)



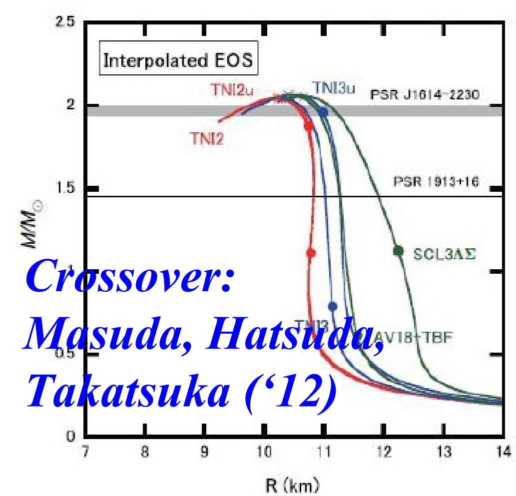
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



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

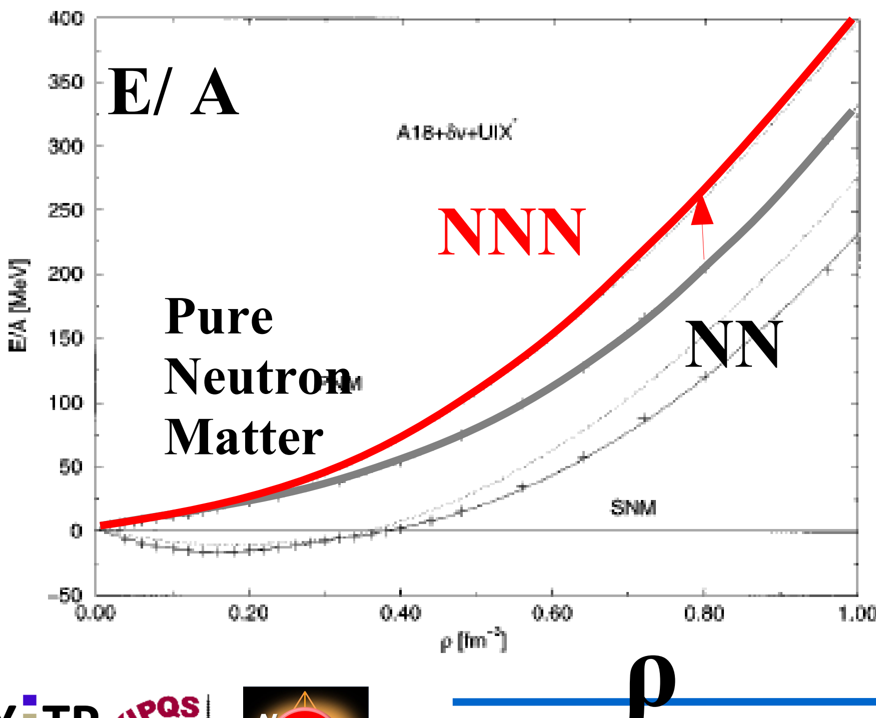


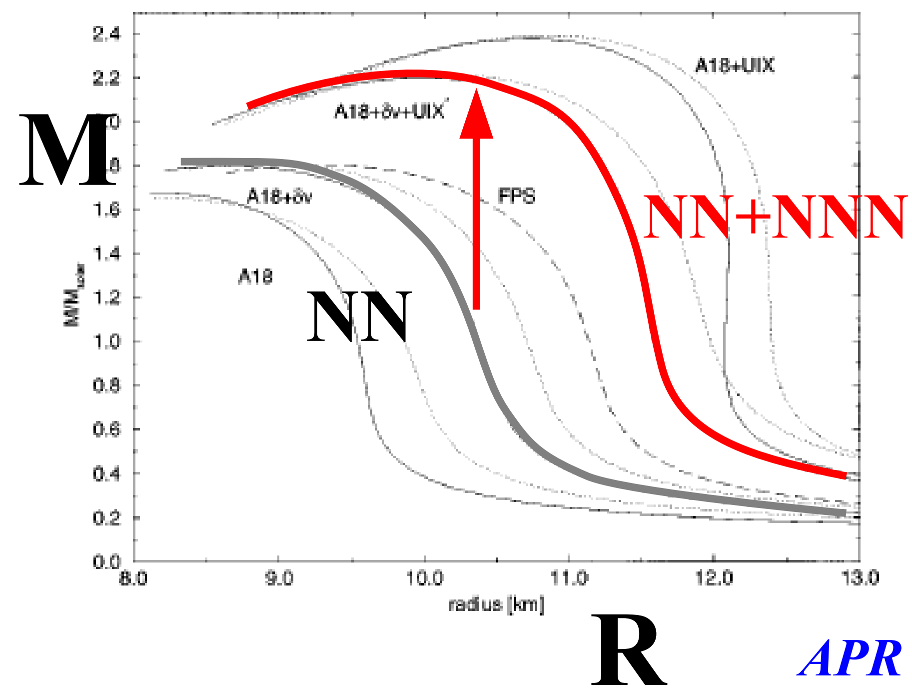
Crossover: Masuda, Hatsuda, Takatsuka ('12)

These are phenomenological "solutions". How can we examine them ?

Ab initio EOSs

- **Variational Approaches** [Talk by Togashi, Takano]
  B. Friedman, V.R. Pandharipande, NPA361('81)502; A. Akmal, V.R.Pandharipande, D.G. Ravenhall, PRC58('98)1804; H. Kanzawa, K. Oyamatsu, K. Sumiyoshi, M. Takano, NPA791 ('07) 232; Togashi, Thin, Gandolfi, Takano
- **Quantum Monte-Carlo** [Talk by Carlson (Mon.), Gandolfi]
  S. Gandolfi, J. Carlson, S. Reddy, A. W. Steiner, and R. B. Wiringa (2012)
- **Bruckner-Hartree-Fock method**
  Nishizaki, Takatsuka, Yamamoto ('02); Z.H.Li et al., PRC74('06)047304; Inoue et al. (HAL QCD Coll.), PRL111 ('13)112503.

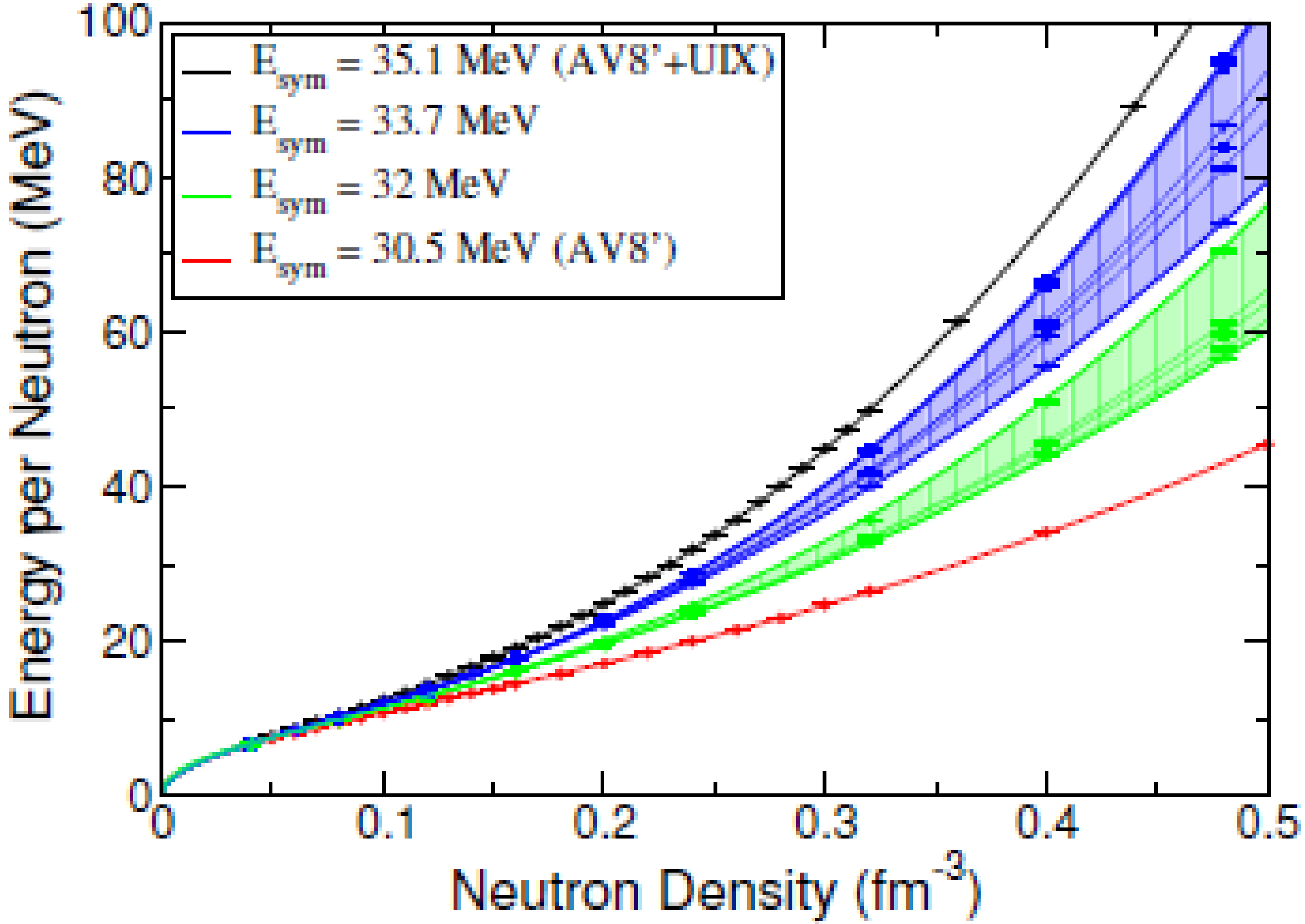




APR ('98)

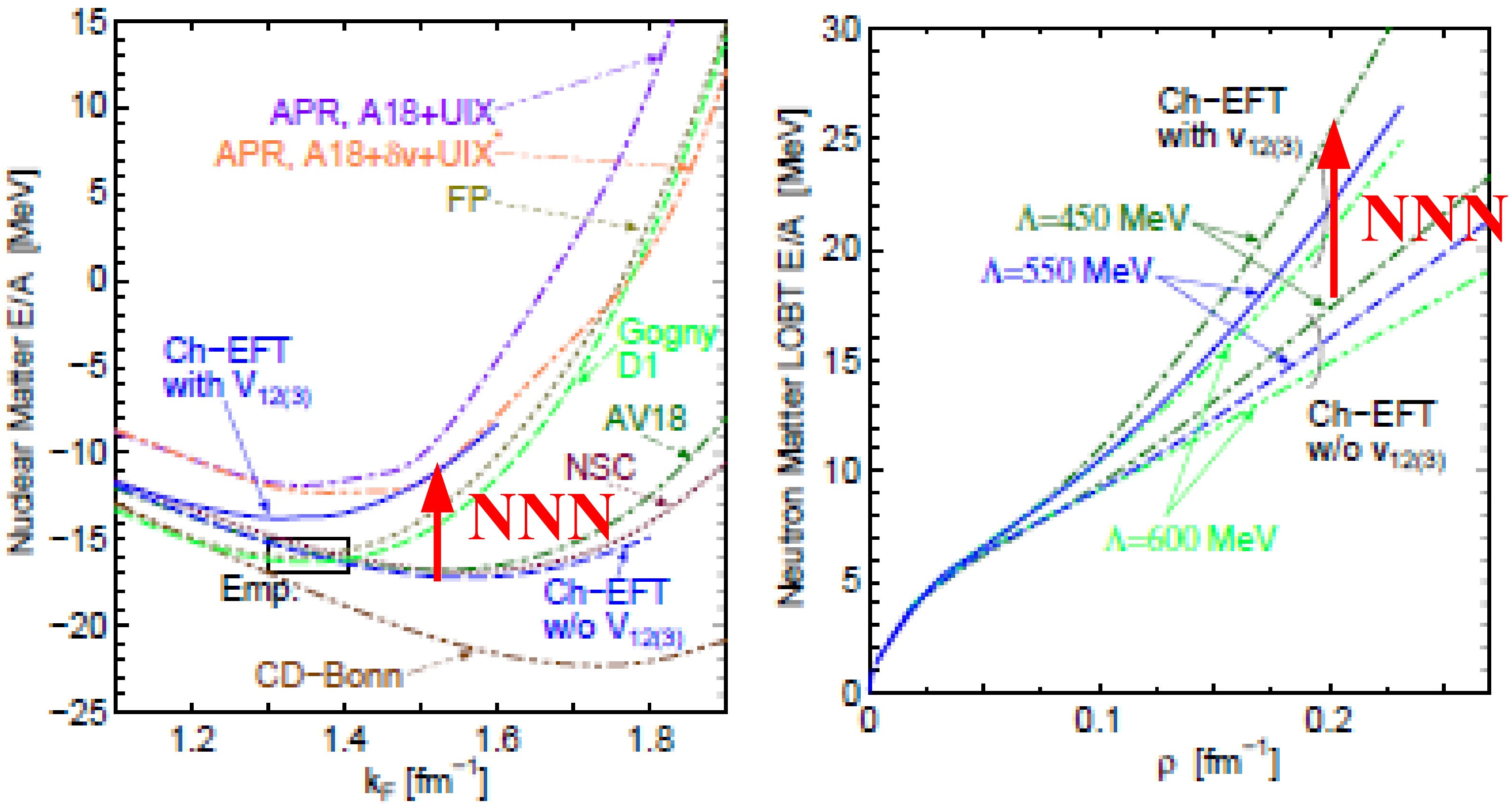
Quantum Monte-Carlo result

- **S. Gandolfi, J. Carlson, S. Reddy, A. W. Steiner, and R. B. Wiringa (2012)**



Ab initio NNN force

- **Ch-EFT gives NNN force systematically based on symmetry in QCD**
  E. Epelbaum,W. Göckle, U.-G.Meißner, NPA747('05)362.
- **G-matrix calc. based on Chiral EFT is promising.**
  M. Kohno, PRC88 ('13)065005.
  - **NN (N3LO)+NNN(N2LO) → reproduce ρ_0 and repulsion at high ρ**

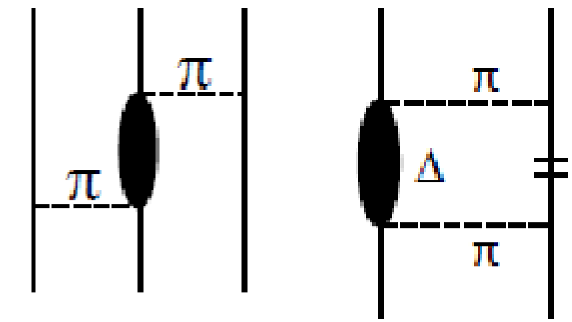


M. Kohno ('13)

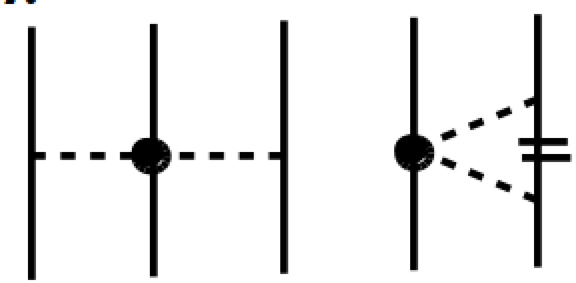
“Universal” mechanism of “Three-body” repulsion

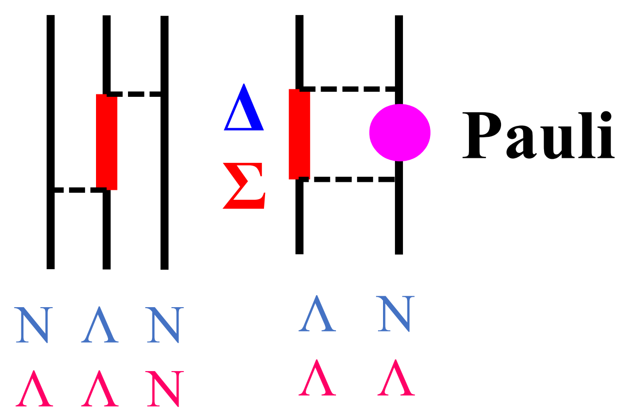
- **Mechanism of “Universal” Three-Baryon Repulsion.**
  - **“σ”-exchange ~ two pion exch. w/ res.**
  - **Large attraction from two pion exchange is suppressed by the Pauli blocking in the intermediate stage.**

Physical Picture



χ EFT



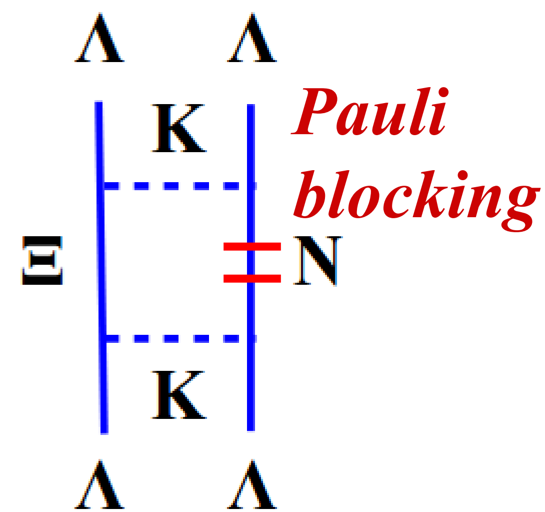


> ***“Universal” TBR***
> - ***Coupling to Res. (hidden DOF)***
> - ***Reduced “σ” exch. pot. ?***
>
> ***How about YNN or YYN ?***

ΛNN [J. Carlson (Mon)]

ΛΛ interaction in vacuum and in nuclear medium

- **Vacuum ΛΛ interaction may be theoretically accessible**
  Lattice QCD calc. HAL QCD ('11) & NPLQCD ('11)
- **In-medium ΛΛ interaction may be experimentally accessible**
  - **a_0(Nagara fit) = - 0.575 fm, -0.77 fm ($\Delta B_{\Lambda\Lambda}$=1.0 MeV)**
    Hiyama et al. ('02), Filikhin, Gal ('02)
  - **Bond energy of $^{6}_{\Lambda\Lambda}$He: $\Delta B_{\Lambda\Lambda}$=1.0 MeV → 0.6 MeV**
    Nakazawa, Takahashi ('10)
- **Difference of vacuum & in-medium ΛΛ int. would inform us ΛΛN int. effects.**
  - **ΛΛ-ΞN couples in vacuum**
  - **Coupling is suppressed in $^{6}_{\Lambda\Lambda}$He**

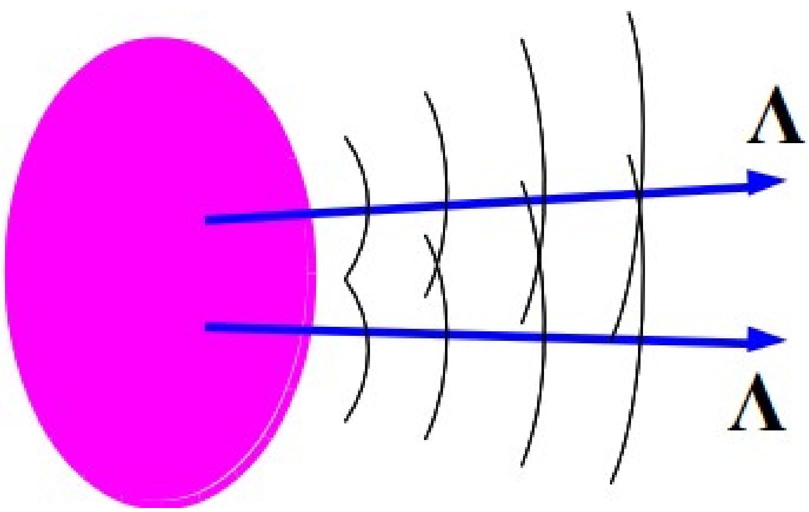


Is there Any way to access "vacuum" ΛΛ int. experimentally ?

Hadron-Hadron correlation in HIC

- **Correlation function formula** *Bauer, Gelbke, Pratt ('92); Lednicky ('09)*.

$$C(q) = \int d\boldsymbol{x}_{12} \underbrace{S(\boldsymbol{x}_{12})}_{\text{Source}} \underbrace{|\Psi(\boldsymbol{x}_{12})|^2}_{\text{wave fn.}}$$



  - **Free boson + Gaussian source = Hanbury-Brown & Twiss effect**

$$C(\boldsymbol{q}) = 1 + \exp(-4q^2R^2)$$

  - **Free fermion + Gaussian source**

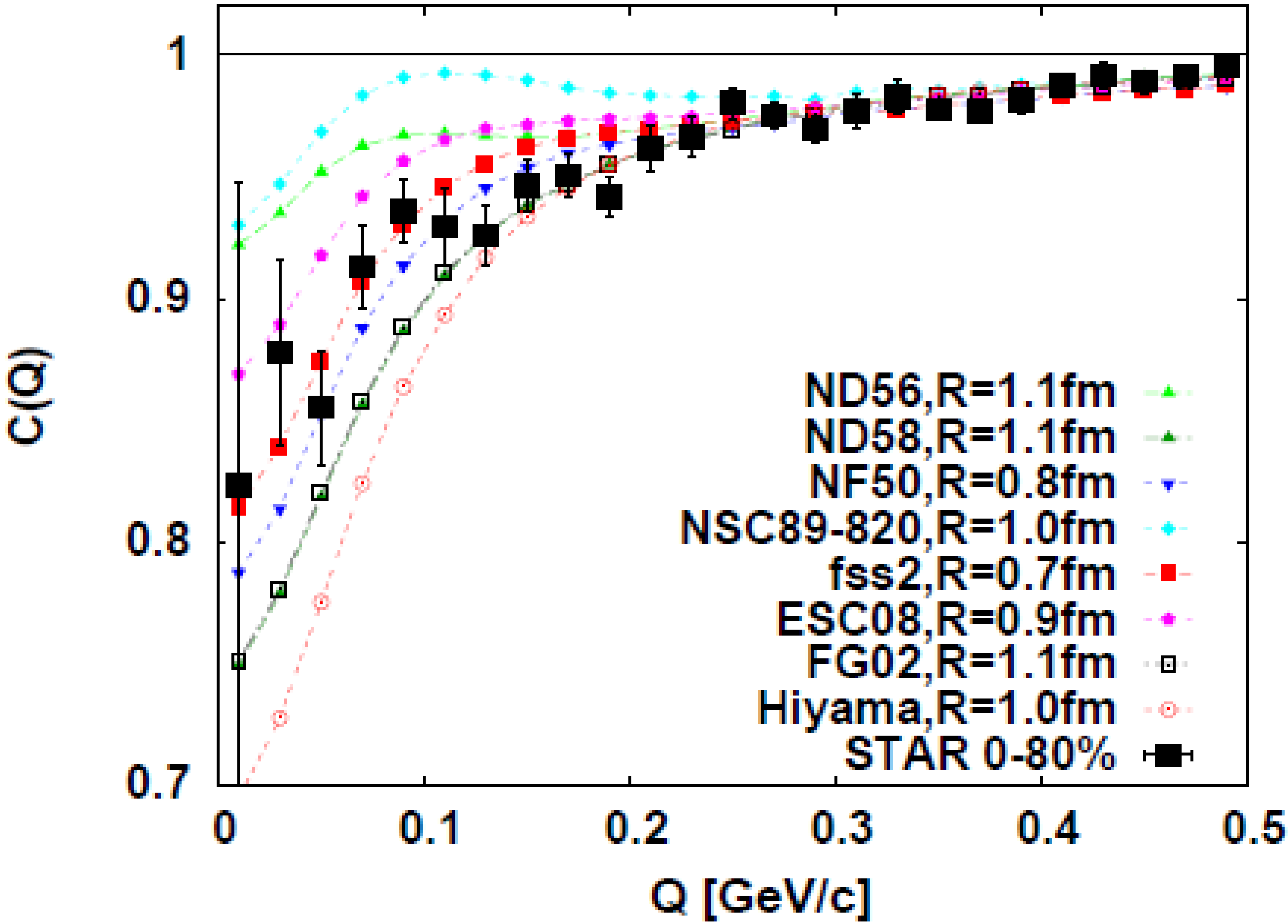
$$C(\boldsymbol{q}) = 1 - \frac{1}{2}\exp(-4q^2R^2)$$

  - **Correlation fn. has info. both on source and w.f. (~ int.)**

- **ΛΛ correlation measurement**
  - **(K-,K+) reaction** *C.J.Yoon et al. (KEK-E522)('07); J.K.Ahn et al. (KEK-E224); AO, Hirata, Nara, Shinmura, Akaishi ('01).*
  - **Heavy-ion collisions** *STAR collab. arXiv:1408.4360; C. Greiner, B. Muller ('89); AO, Hirata, Nara, Shinmura, Akaishi ('01).*

ΛΛ correlation and favored ΛΛ interaction

ΛΛ correlation with long. and transverse flow effects

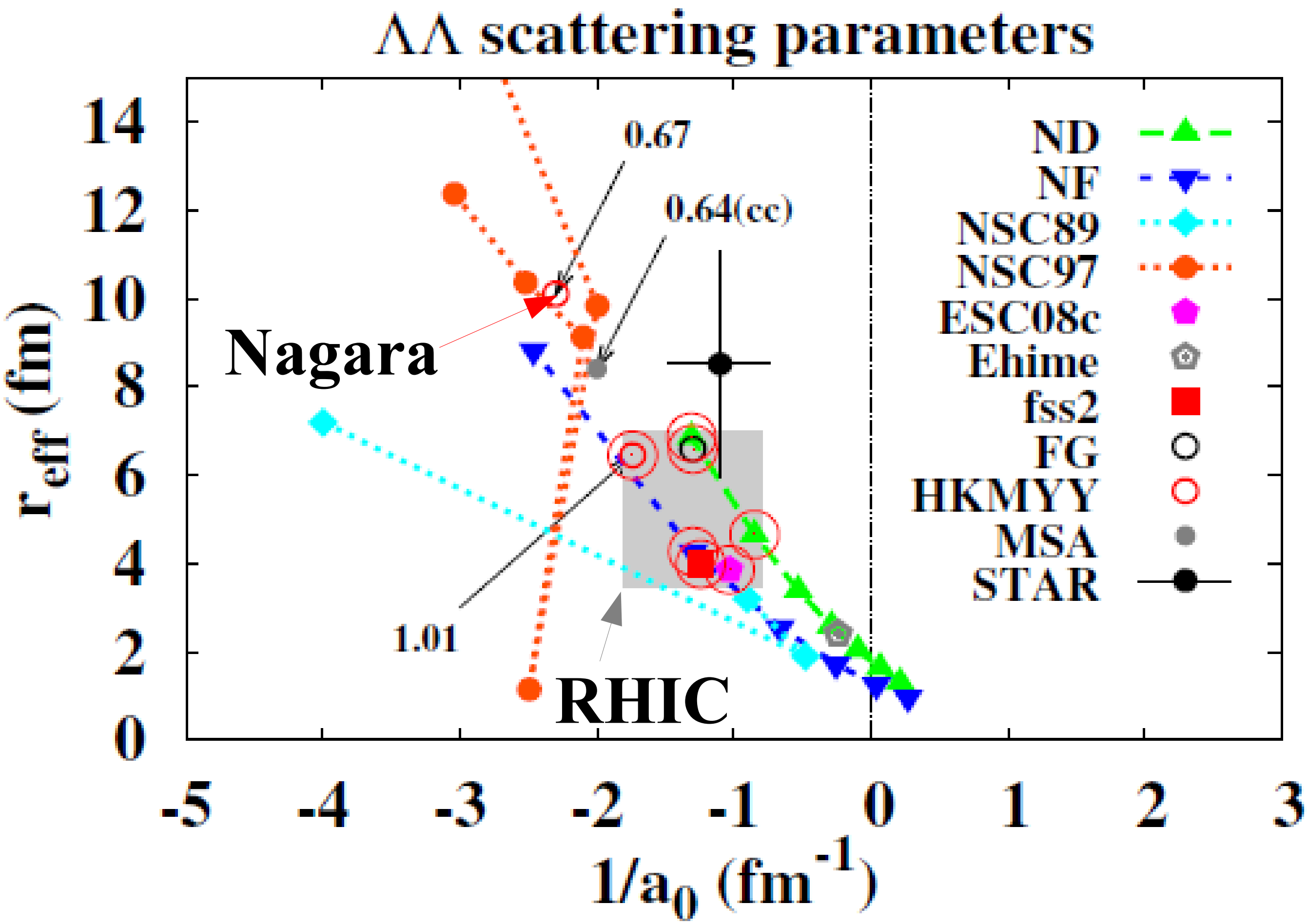


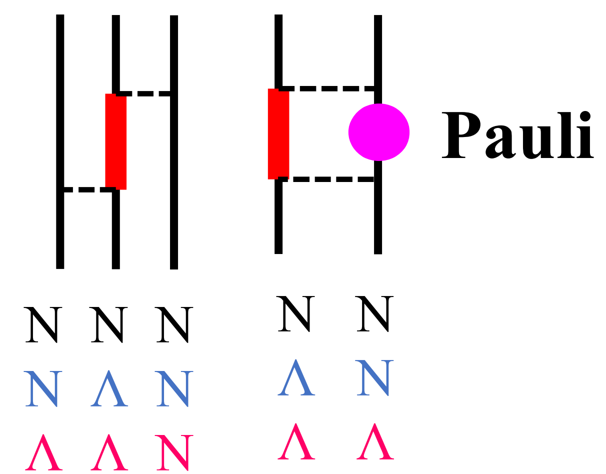
Data: STAR collab. arXiv:1408.4360

K.Morita, T.Furumoto, A.Ohnishi, arXiv:1408.6682

Do we see ΛΛN interaction ?

- **$V_{\Lambda\Lambda}$ from RHIC seems to be more attractive than $V_{\Lambda\Lambda}$ from Nagara**
  - **Mechanism: Pauli blocking in the intermediate ΞN channel**
    ***Kohno ('13) / Myint, Shinmura, Akaishi ('03) / Nishizaki, Takatsuka, Yamamoto('02)* / *Machleidt*.**





Summary

- Neutron Star physics is attracting much attention, and many current/future facilities/projects are aiming at solving NS puzzles.
  - Radioactive beam facilities → Sym. E. at $\rho < \rho_0$ and $\rho \sim (2\text{-}3)\ \rho_0$
    Hadron machines → YN and YY interactions, Hadrons in nuclear matter
    Heavy-ion machines → EOS at high density, Hadron-Hadron Interactions
- Compact NS puzzle: R_{NS}(measured) < R_{NS}(nucl. phys. EOS) ?
  - We need more precise measurement of (M,R) of NSs
    and Sym. E. below and above ρ_0 .
    → ASTRO-H, NICER, LOFT / RIBF, FRIB, …. [Lynch, Thu Evening]
- Massive NS puzzle: Y should appear, but EOS must be kept stiff.
  - How can we justify phen. proposed "answers" ? Experiment / Ab initio
  - BBB interactions including NNN, YNN, YYN are now experimentally accessible, at least partially. [RHIC/LHC joined the NS game !]
- Cooling, Magnetic field, Pasta, finite T, ... were not discussed.
  → Enoto [Mon], Brown, Horowitz, Sumiyoshi, Nakamura ....

Thank you for your attention.