Physics of Neutron Star Matter
– current status and challenges –

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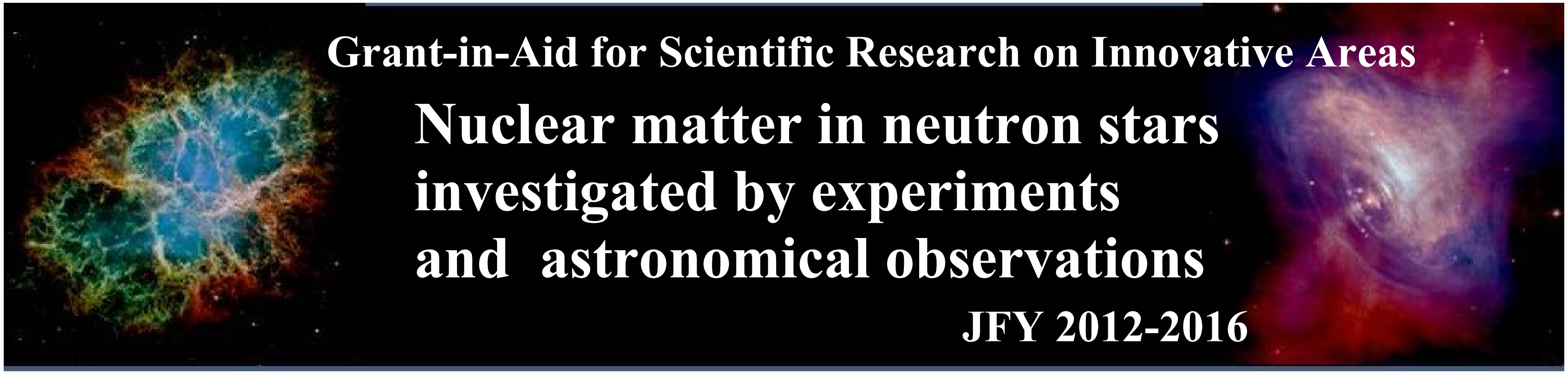


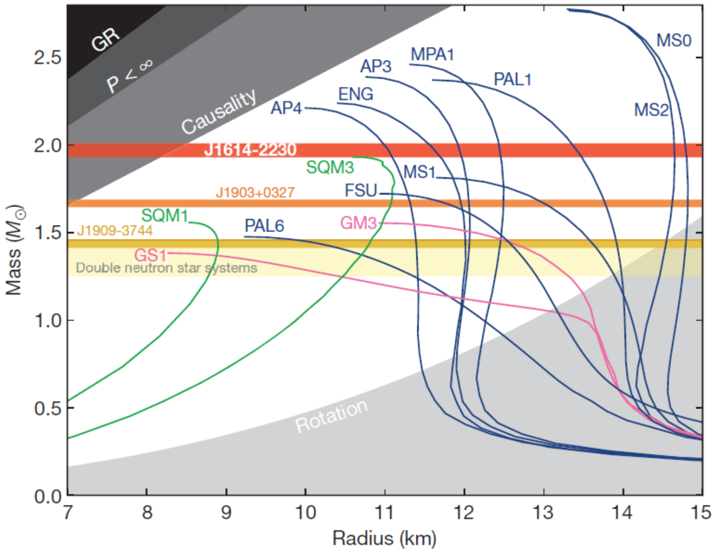
Grant-in-Aid for Scientific Research on Innovative Areas

Nuclear matter in neutron stars investigated by experiments and astronomical observations

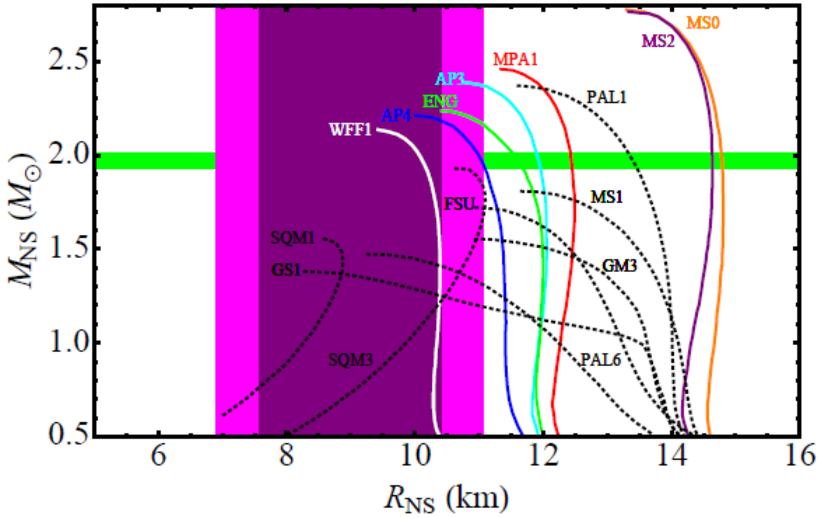
JFY 2012-2016

Contents and Summary

- **Neutron star (NS)**
  - **Giant neutron-rich hypernuclei**
    & Almost causal limit object
  - **Massive ($\sim 2\,M_\odot$) & Compact (~ 9 km)**
    NS puzzle.
  - **Grant-in-aid study on NS matter**
    J-PARC + RIBF + ASTRO-H +Theory
- **Challenges in neutron star matter physics**
  - **How can we solve massive NS puzzle ?**
    → Three-body force as a candidate
  - **What determines M-R relation of low-mass neutron stars ?**
    → New parameter $\eta=(KL^2)^{1/3}$



Demorest et al. (2010)



Guillot et al. (2013)

Physics of Neutron Stars – Basics and Puzzles –

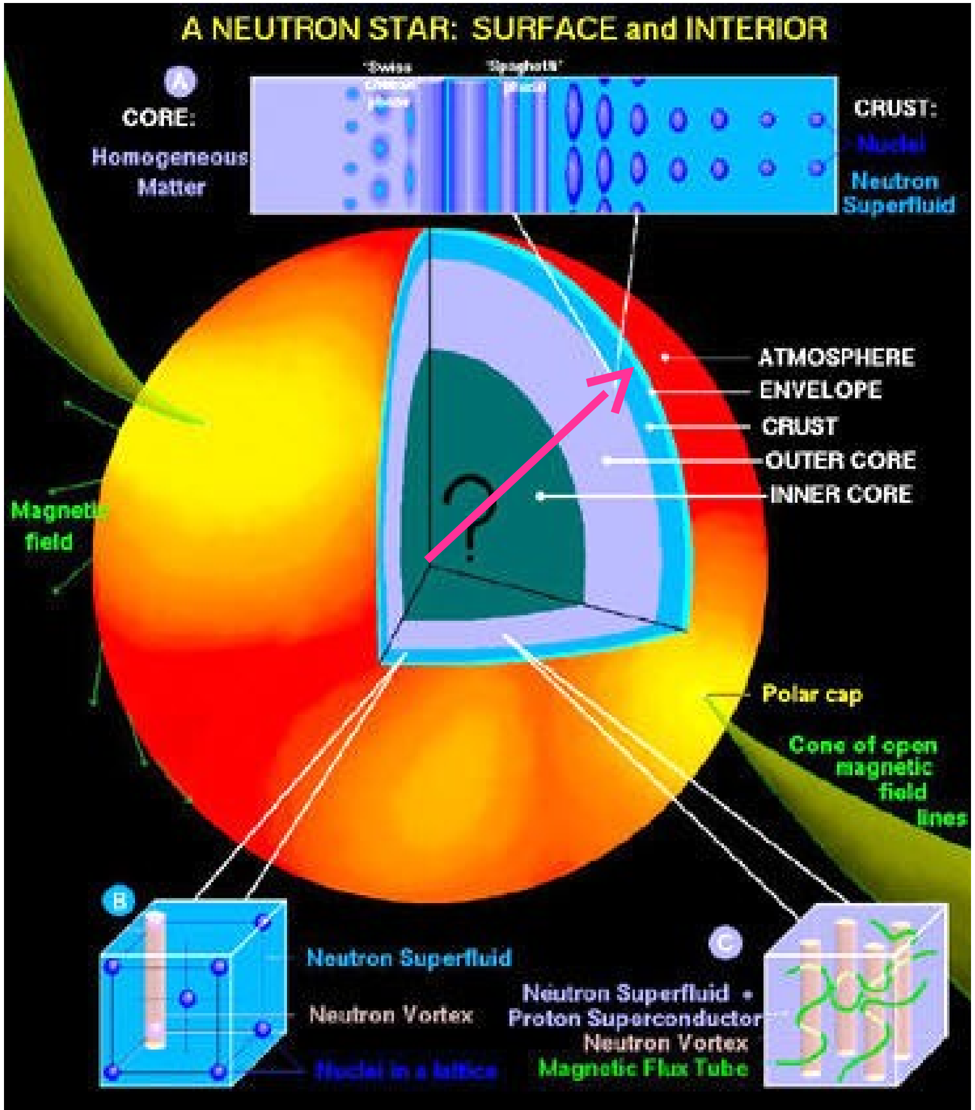
Basic properties of neutron stars

- **Mass: $M = (1\text{-}2)\, M_\odot$ ($M \sim 1.4\, M_\odot$)**
- **Radius: 5 km < R < 20 km (R ~ 10 km)**
- **Supported by Nuclear Pressure**
  c.f. Electron pressure for white dwarfs
- **Cold enough ($T \sim 10^6$ K ~ 100 eV) compared to neutron Fermi energy.**

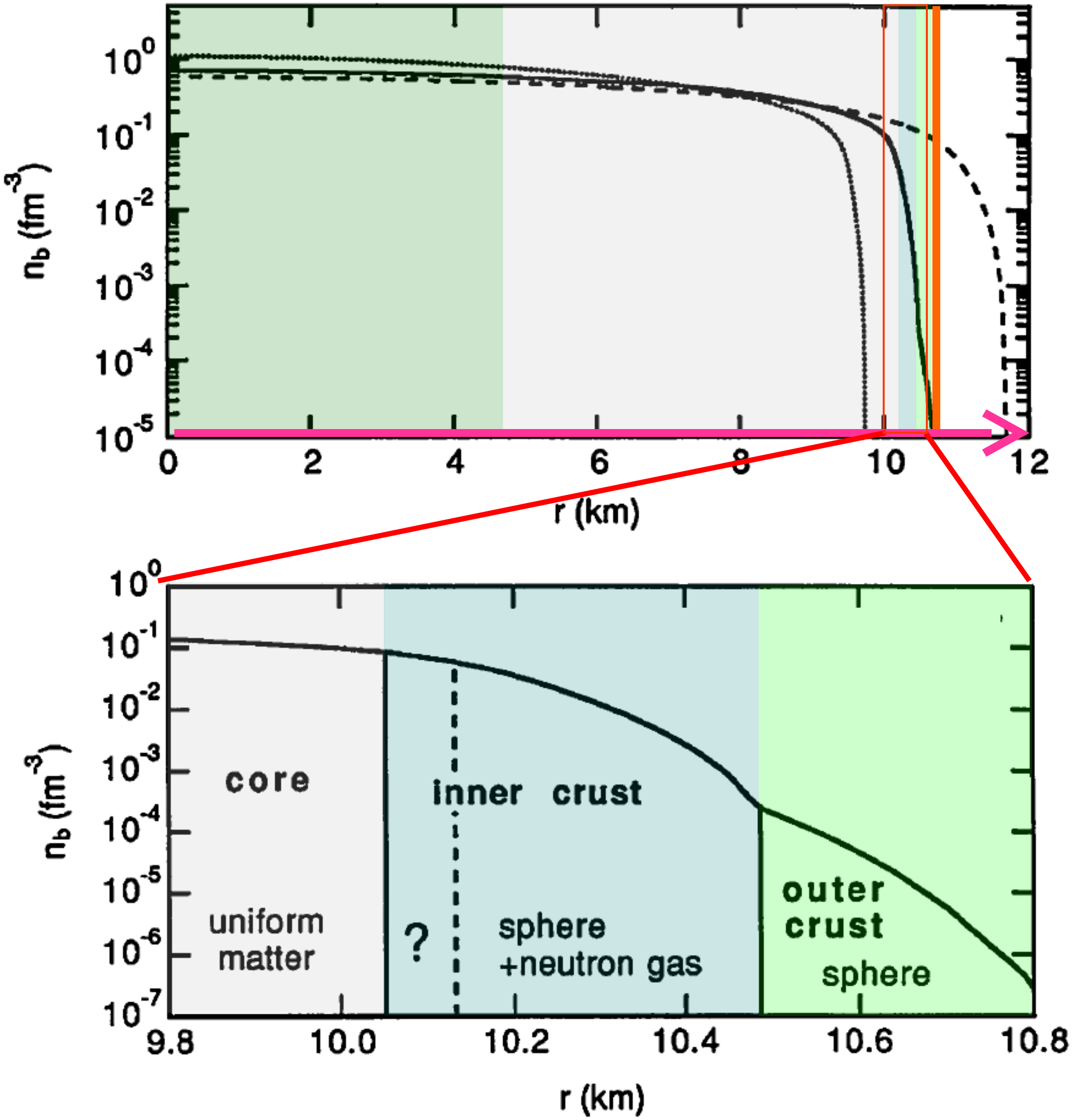
google & zenrin

Neutron Star Structure

- **Dense core + Thin Crust**



http://www.astro.umd.edu/~miller/nstar.html



by Nakazato

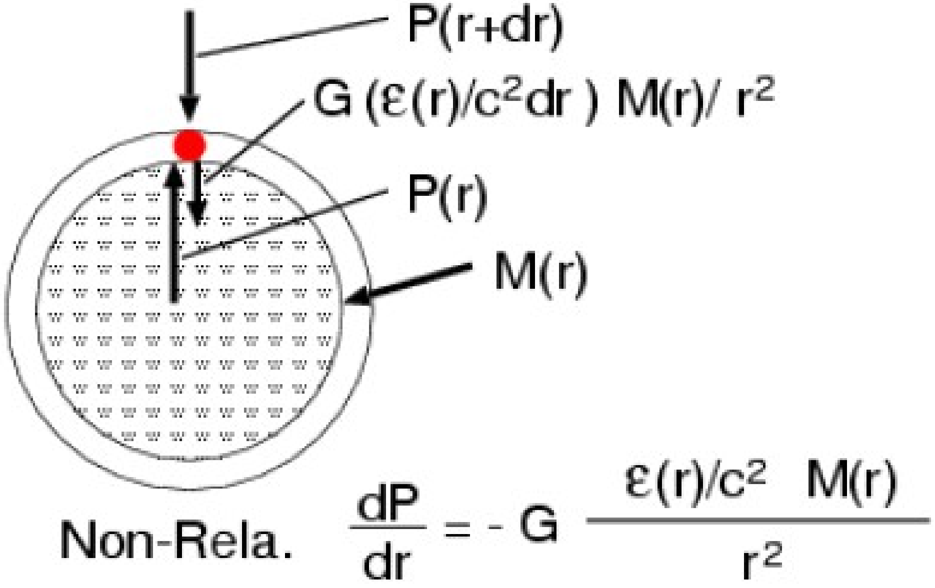
TOV equation

- **General Relativistic Hydrostatic Equation**
  = TOV(Tolman-Oppenheimer-Volkoff) equation

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

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

- **Spherical and non-rotating.**
- **3 Variables (ε(r), P(r), M(r)), 3 Equations.**



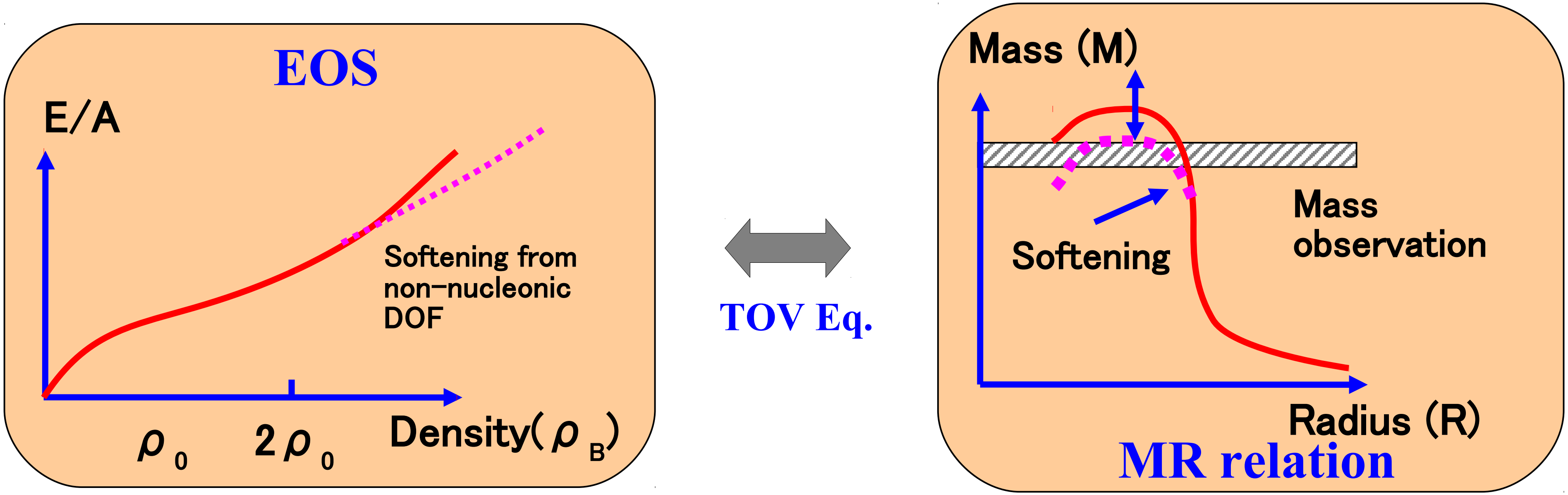
Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$

M-R Relation and EOS

- **Solving TOV eq.**
  starting from the “initial” condition, $\varepsilon(r=0) = \varepsilon_c$ = given
  until the “boundary” condition $P(r)=0$ is satisfied.
  → M and R are the functions of $\varepsilon(r=0)$ and functionals of EOS, $P=P(\varepsilon)$.

$$M = M(\varepsilon_c)[P(\varepsilon)] \quad , \quad R = R(\varepsilon_c)[P(\varepsilon)]$$

→ M-R curve and NS matter EOS : 1 to 1 correspondence



Nuclear Mass

- **Bethe-Weizsacker mass formula**
  Nuclear binding energy is roughly given by Liquid drop.
  Nuclear size measurement → $R = r_0 A^{1/3}$

$$B(A,Z) = \underline{a_v A} - \underline{a_s A^{2/3}} - \underline{a_C \frac{Z^2}{A^{1/3}}} - \underline{a_a \frac{(N-Z)^2}{A}} + \underline{a_p \frac{\delta_p}{A^\gamma}}$$

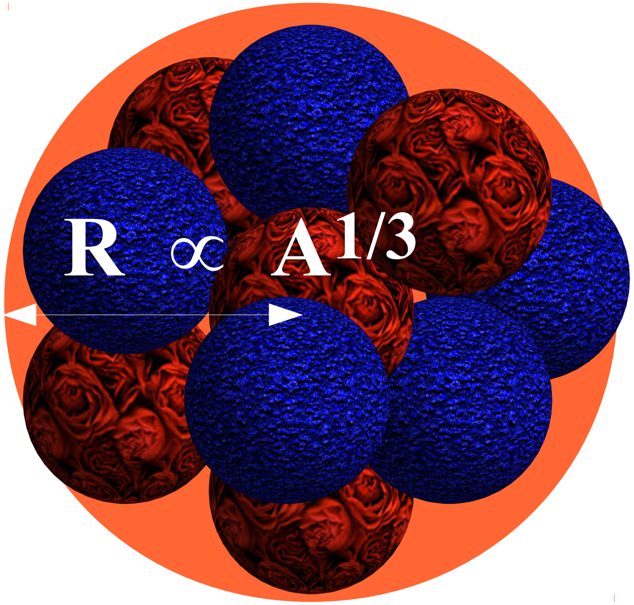
Volume Surface Coulomb Symmetry Paring

$$A \propto \frac{4\pi}{3} R^3 \qquad A^{2/3} \propto 4\pi R^2 \qquad \propto \frac{Q^2}{R}$$

- **Ignore Coulomb, consider A → ∞,**

$$B/A = a_v(\rho) - a_a(\rho)\delta^2 \quad , \quad \delta = (N-Z)/A$$

$$a_v \simeq 16\,\mathrm{MeV} \quad , \quad a_a \simeq 30\,\mathrm{MeV}$$



Coef. may depend on the number density ρ
→ Nuclear Matter EOS

Nuclear Matter EOS

- Energy per nucleon in nuclear matter

$$E(\rho,\delta)=E_{\mathrm{SNM}}(\rho)+E_{\mathrm{Sym}}(\rho)\delta^2\ ,\quad \delta=(N-Z)/A$$

- Saturation point (ρ_0, E_0)

  $\rho_0 \sim 0.15\ \mathrm{fm}^{-3}$

  $E_0 = -a_v \sim -16$ MeV

  (nuclear radius and mass)

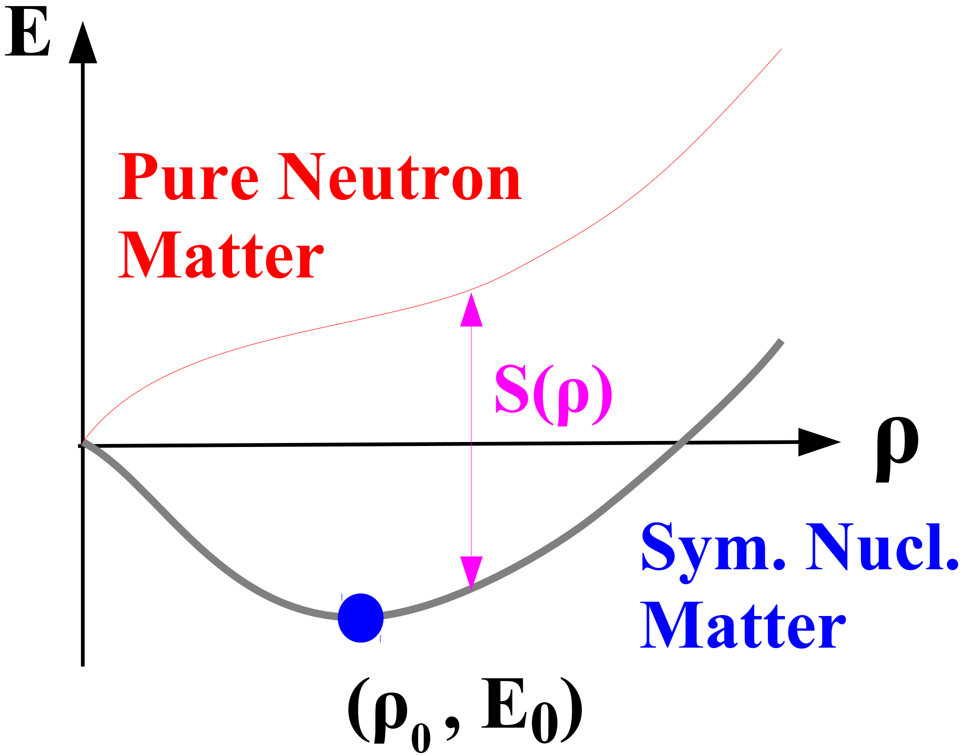
- Symmetry energy

  $S(\rho)= E_{PNM}(\rho) - E_{SNM}(\rho)$

  $= E(\rho, \delta=1) - E(\rho, \delta=0)$

  $S_0 = S(\rho_0) \sim 30$ MeV

  (mass formula)



Nuclear Matter EOS can be, in principle, determined by terrestrial (laboratory) nuclear physics experiments !

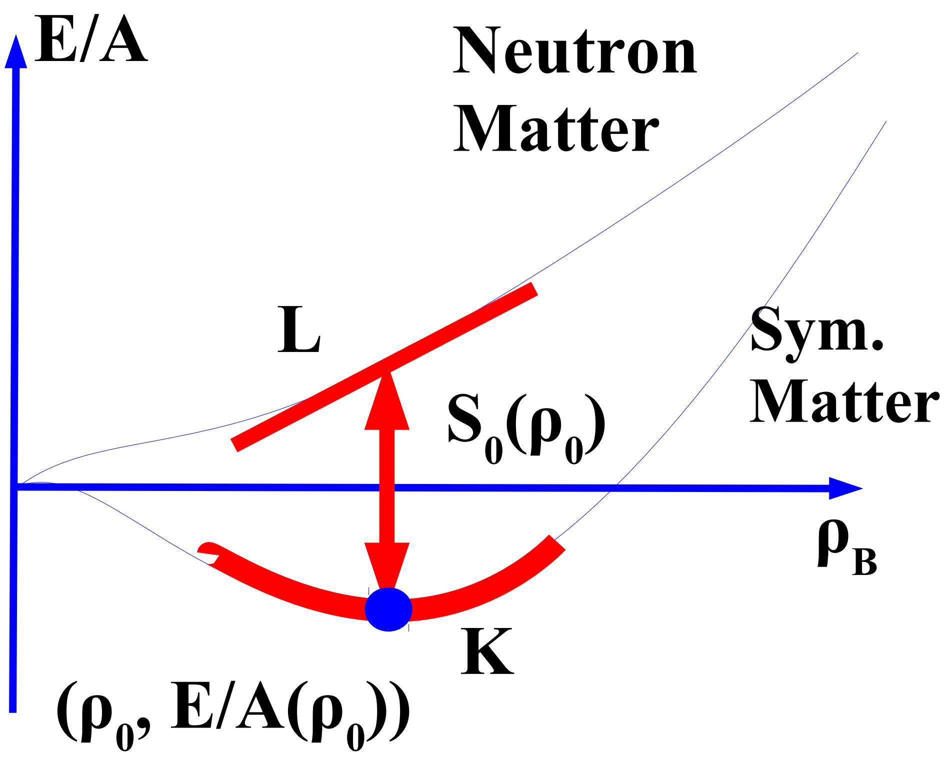
Nuclear Matter EOS

- **Additional two important parameters: K and L**
- **Pressure is given by the derivative of E via ρ**

$$P=\rho^2(\partial E/\partial\rho)$$

At ρ_0, L determines P

$$P=\rho_0 L/3 \left(\text{at} \quad \rho=\rho_0\right)$$



$$E/A(\rho,\delta)=\varepsilon(\rho)+E_{\rm sym}(\rho)\delta^2+O(\delta^4)$$

Symmetric Nuclear Matter

$$\varepsilon(\rho)=\varepsilon(\rho_0)+\frac{K(\rho-\rho_0)^2}{18\rho_0^2}+O((\rho-\rho_0)^3)$$

Symmetry Energy $(\delta=(N-Z)/A=1-2Y_p)$

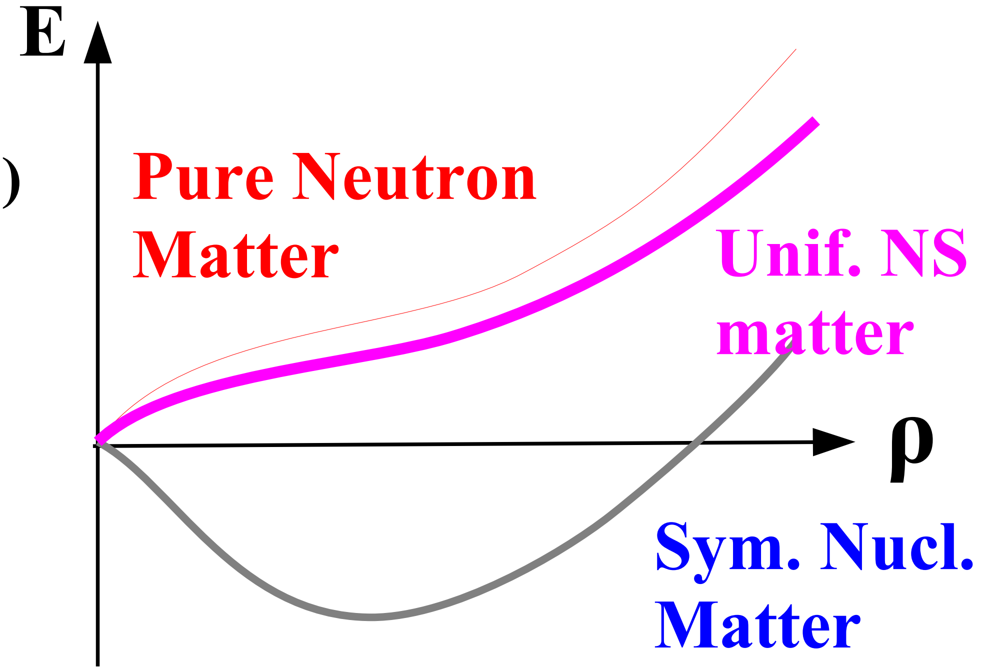
$$E_{\rm sym}(\rho)=S_0+\frac{L(\rho-\rho_0)}{3\rho_0}+\frac{K_{\rm sym}(\rho-\rho_0)^2}{18\rho_0^2}+O((\rho-\rho_0)^3)$$

Neutron Star Matter EOS

- **What happens in low-density uniform neutron star matter ?**
  - **Constituents = proton, neutron and electron**
  - **Charge neutrality → # of electons = # of protons ($\rho_e = \rho_p = \rho\ (1-\delta)/2$)**

$$E_{\mathrm{NSM}}(\rho) = E_{\mathrm{NM}}(\rho, \delta) + E_e(\rho_e = \rho_p)$$
$$= E_{\mathrm{SNM}}(\rho) + S(\rho)\delta^2 + \frac{\Delta M}{2}\delta + \frac{3}{8}\hbar k_F (1-\delta)^{4/3}$$

(electron mass neglected,
neutron-proton mass diff. incl.
k_F= Fermi wave num. in Sym. N.M.)

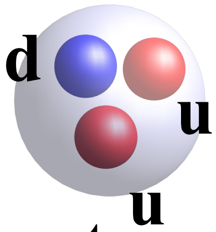


- **δ is optimized to minimize energy per nucleon**

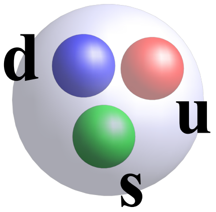
$$E_{\mathrm{NSM}}(\rho) \le E_{\mathrm{NM}}(\rho, \delta=1) = E_{\mathrm{PNM}}(\rho)$$

Neutron star – Is it made of neutrons ?

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

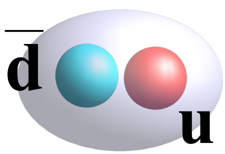


proton

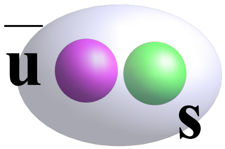


Λ hyperon

  - **Meson condensate (K, π)**

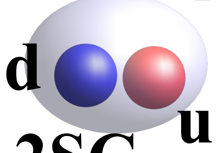


π

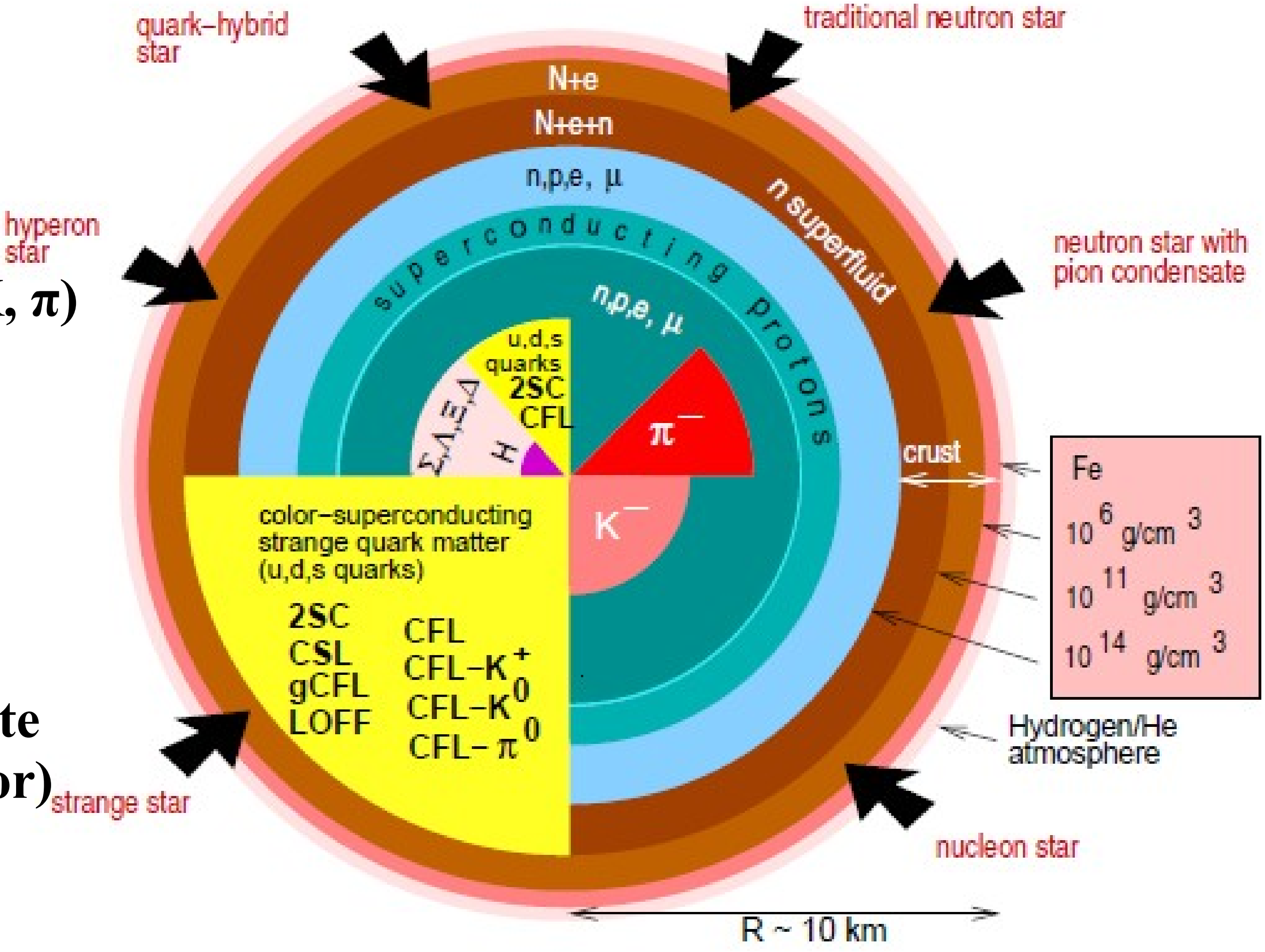


anti kaon

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



2SC



F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

High Density Neutron Star Matter

- **Hadrons other than nucleons can admix at high densities.**
  - **Proposed constituents = N, e, μ, π, Y, $\bar{K}$, q, qq**
  - **Conserved charge = Elec. Charge & Baryon number**

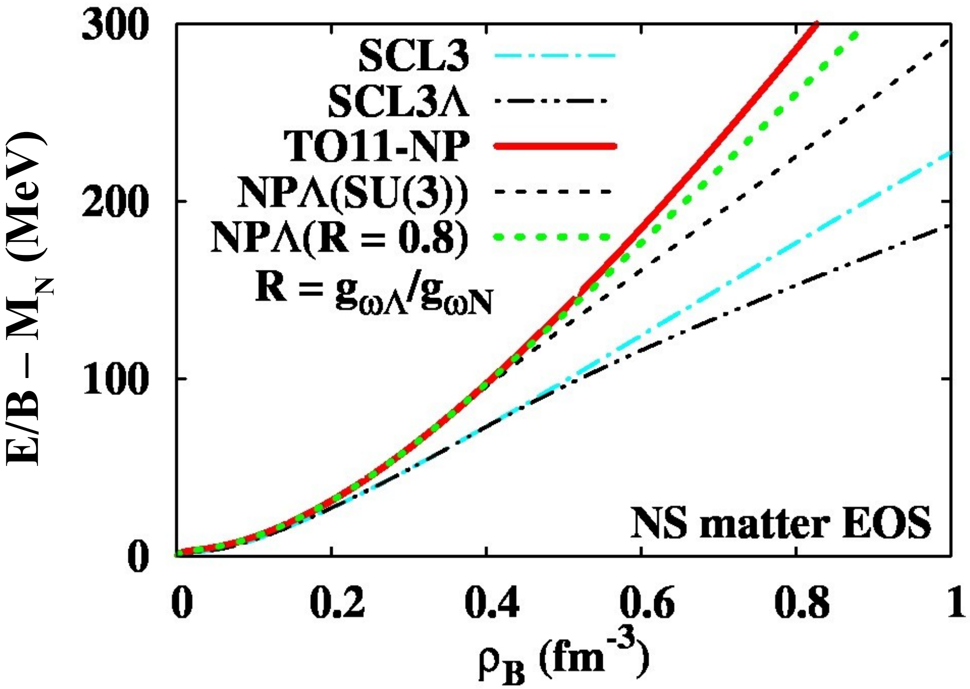
$$E_{\mathrm{NSM}}(\rho)=E_{\mathrm{HM}}(\rho_n,\rho_p,\rho_\Lambda,....)+E_e(\rho_e)+E_\mu(\rho_\mu)$$

$$\rho=\rho_B=\sum_{i\in B}\rho_i\ ,\quad \rho_Q=\sum_i Q_i\rho_i$$

$$\rightarrow \mu_i=B_i\mu_B-Q_i\mu_e$$

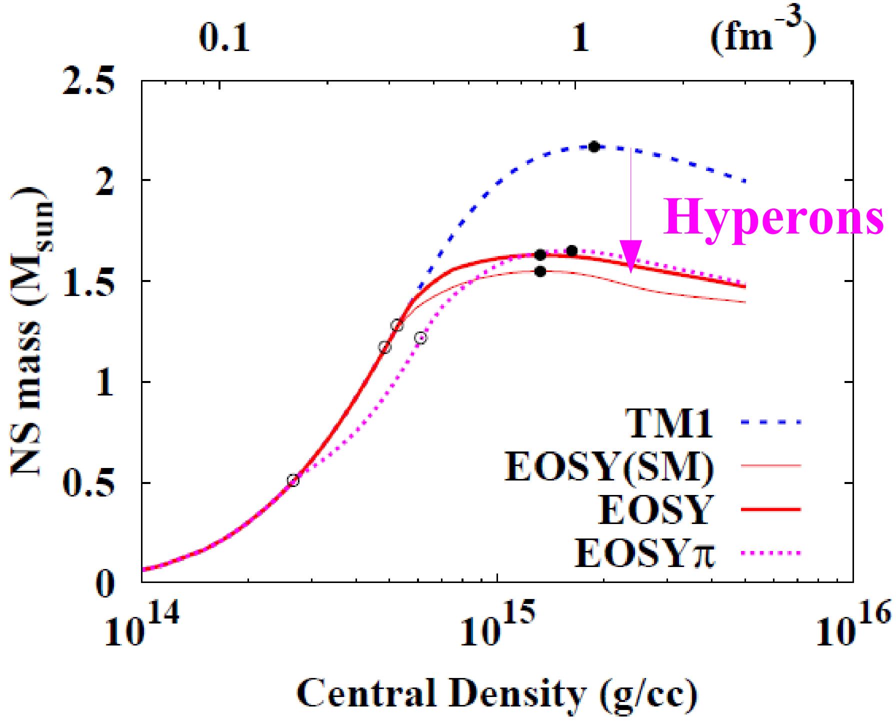
Negative charged baryons are favored.

- **Each particle fraction is determined to minimize Energy per Baryon → Softening of NS matter EOS**



Common Understanding of Neutron Star Matter (<2010)

- Neutron star crust ($\rho < \rho_0/2 \sim 10^{14}$ g/cc, 1-1.5 km)
  - Made of nuclei, free nucleons and electrons.
    We may have pasta nuclei in the inner crust.
- Outer core ($\rho_0/2 < \rho < 2\rho_0$)
  - Made of nucleons and leptons. Nucleons are in superfluid.
- Inner core ($\rho > 2\rho_0$)
  - Constituents are unknown.
  - Many calculations suggest hyperon admixture starting at $\rho = (2\text{-}4)\,\rho_0$, and EOS is softened.
  - $\bar{K}$ or quarks may appear at $\rho > 3\,\rho_0$.

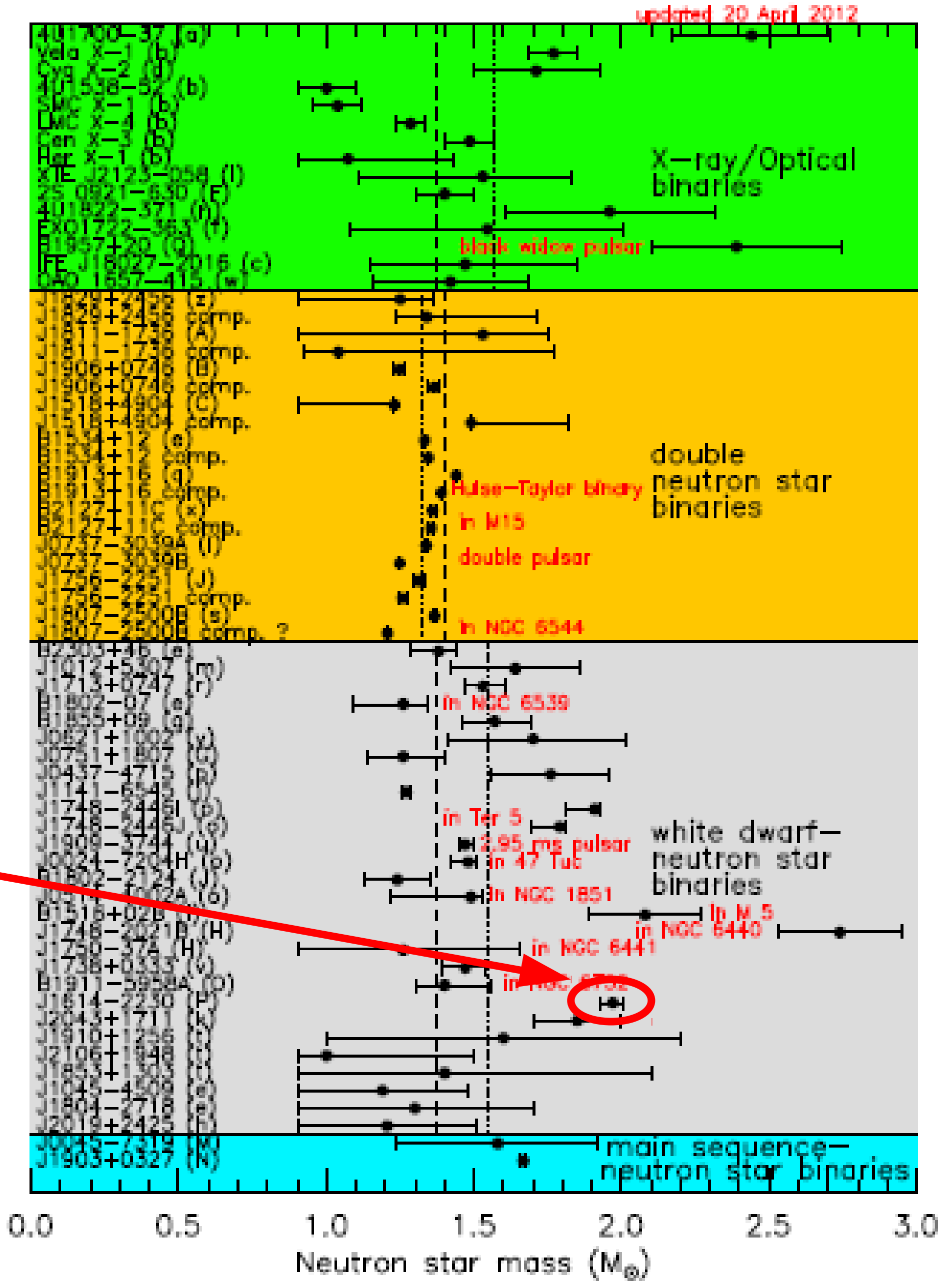


Ishizuka et al. (2008)

Neutron Star Masses

- Many NSs have masses ~ 1.4 M$_\odot$.
- Massive NS masses had large error bars, and were considered not to be conclusive (before 2010).

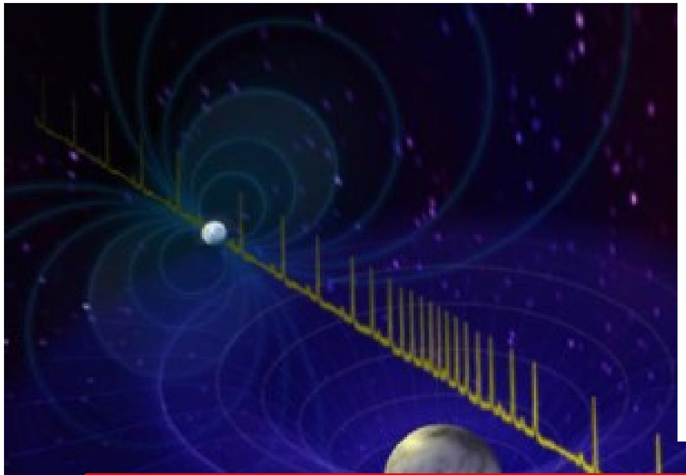
This is it !

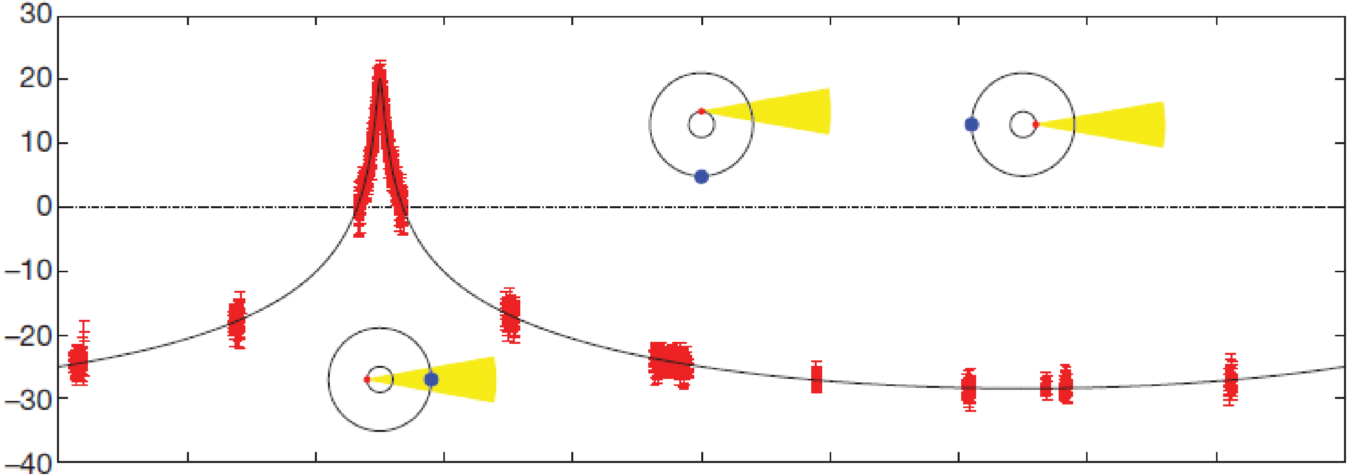


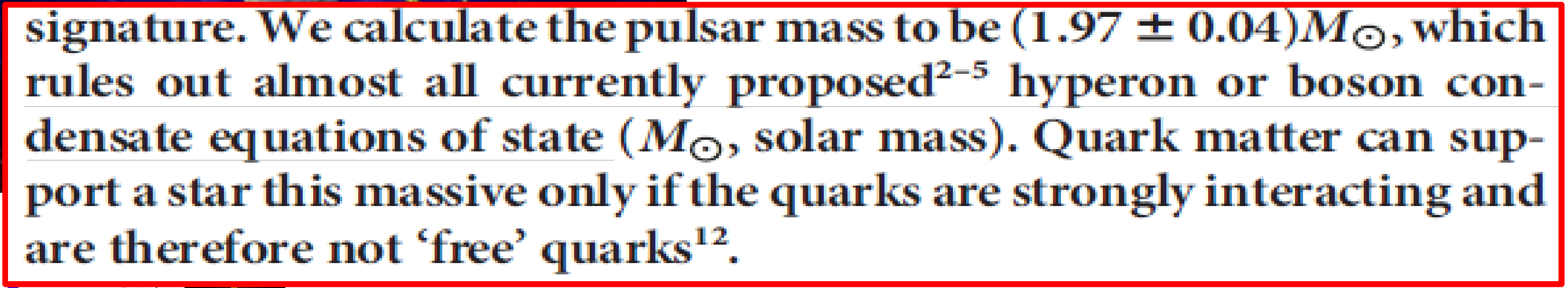
Lattimer (2013)

Massive Neutron Star "Shock" (2010)

- **Big news in 2010 autumn**
  - **A neutron star is found to have the mass of 1.97 ± 0.04 $M_{\odot}$"**
    Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).
  - **Based on "kinetic" observable**
    - **Photon from the pulsar passes near the companion white dwarf, and Shapiro delay (GR effect) was clearly observed.**



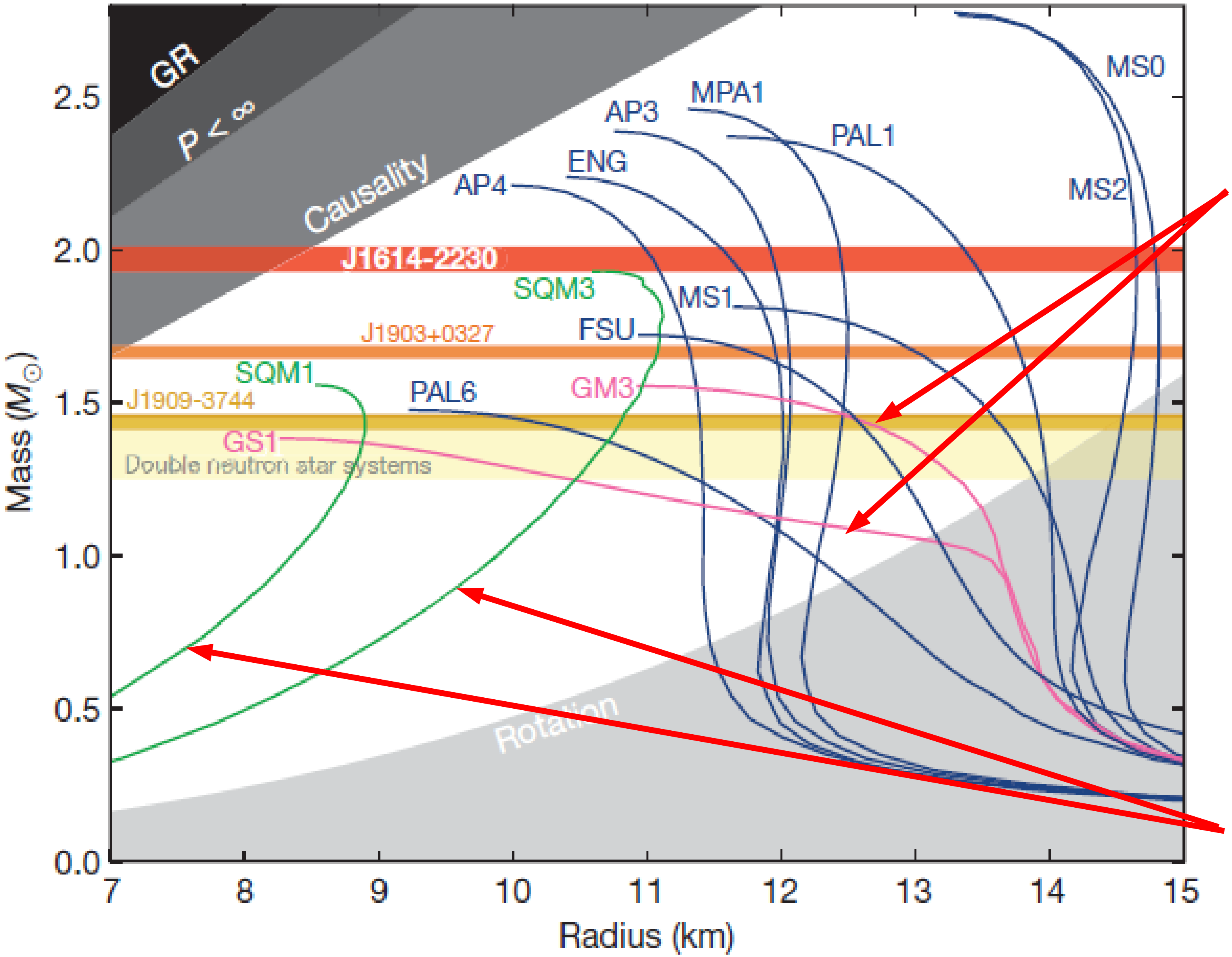




signature. We calculate the pulsar mass to be $(1.97 \pm 0.04)M_{\odot}$, which rules out almost all currently proposed[2–5] hyperon or boson condensate equations of state ($M_{\odot}$, solar mass). Quark matter can support a star this massive only if the quarks are strongly interacting and are therefore not 'free' quarks[12].

$1.97 \pm 0.04\ M_{\odot}$ Neutron Star

Demorest et al., Nature 467 (2010) 1081 (Oct.28, 2010).



EOS with hyperons or Kaons

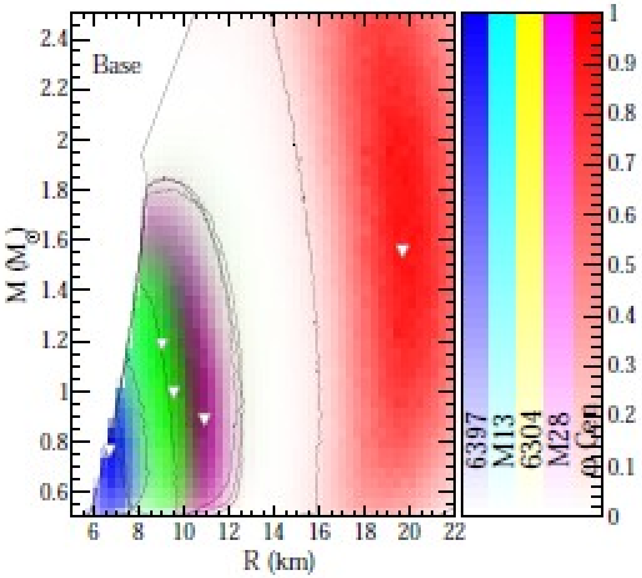
Quark matter EOS

Compact Neutron Star “Shock” (2013)

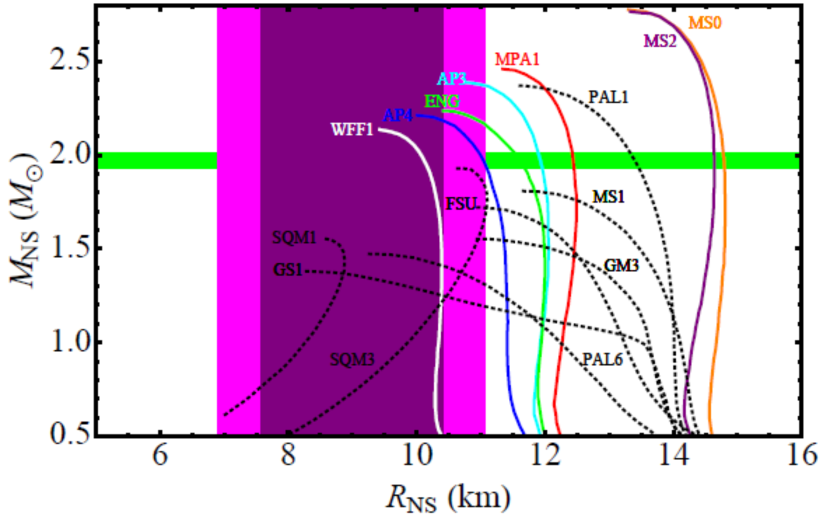
- **Compact NS “Puzzle”**
  Guillot et al. (2013); Lattimer, Steiner (2013).
  - **Markov-Chain MC fit of X-ray spectrum Baysian analysis from quiescent Low Mass X-ray Binaries (qLMXB)**
  - **Guillot+ (2013) results**

    $$R_{NS} = 9.1^{+1.3}_{-1.4} \text{ km}$$

    → Most of proposed EOSs are ruled out.
    WFF: Wiringa, Fiks, Fabrocini (1988)



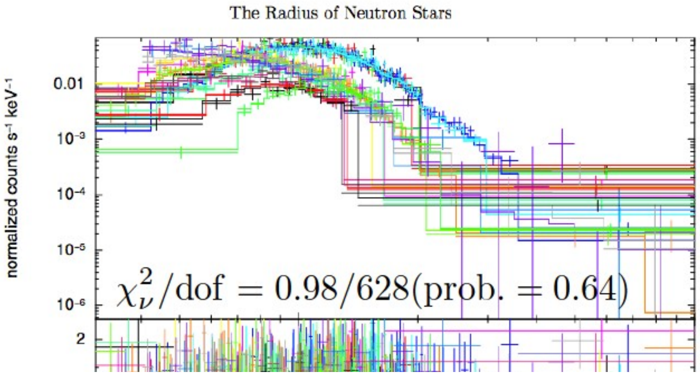
Lattimer, Steiner (2013).

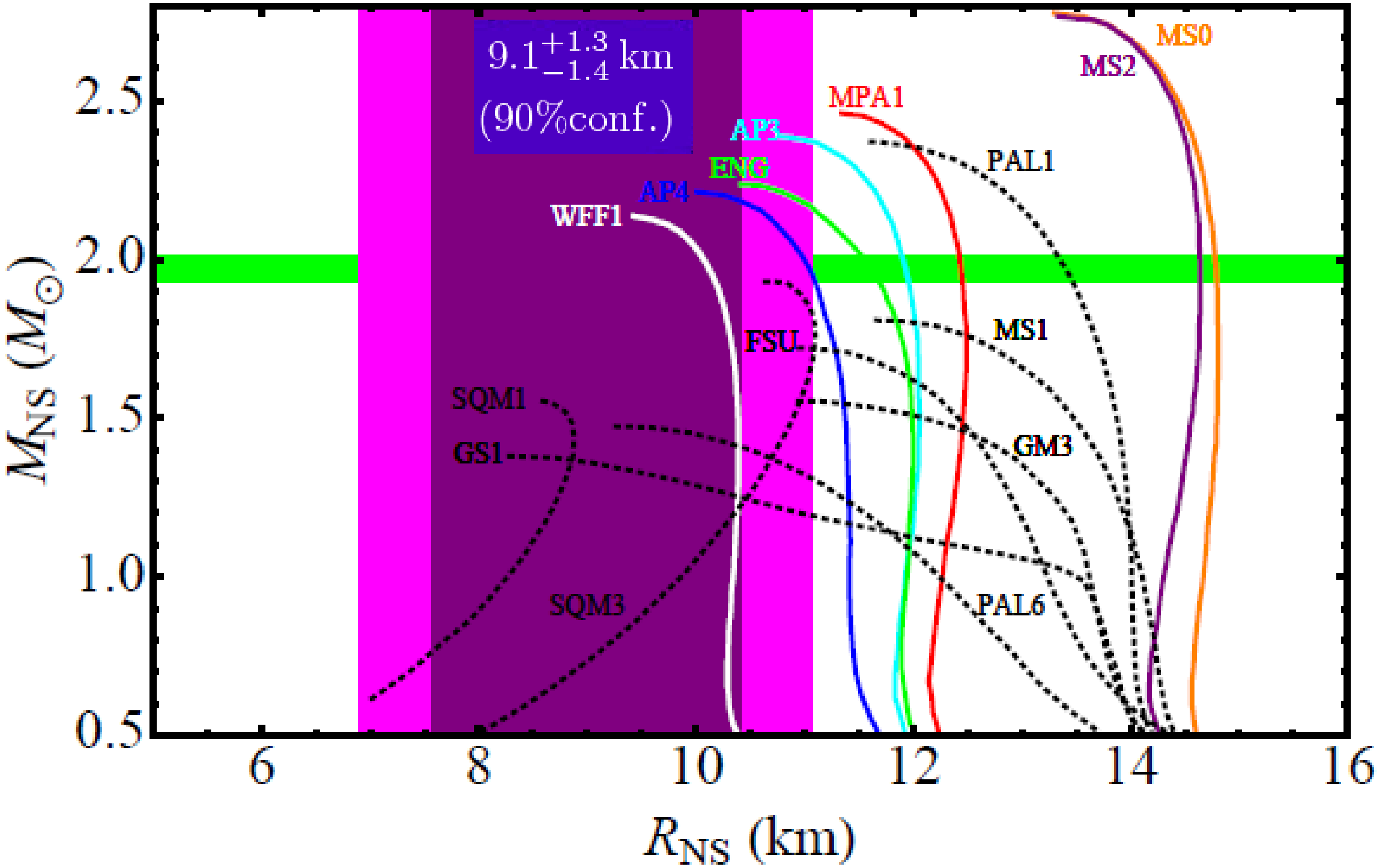


Guillot et al. (2013)

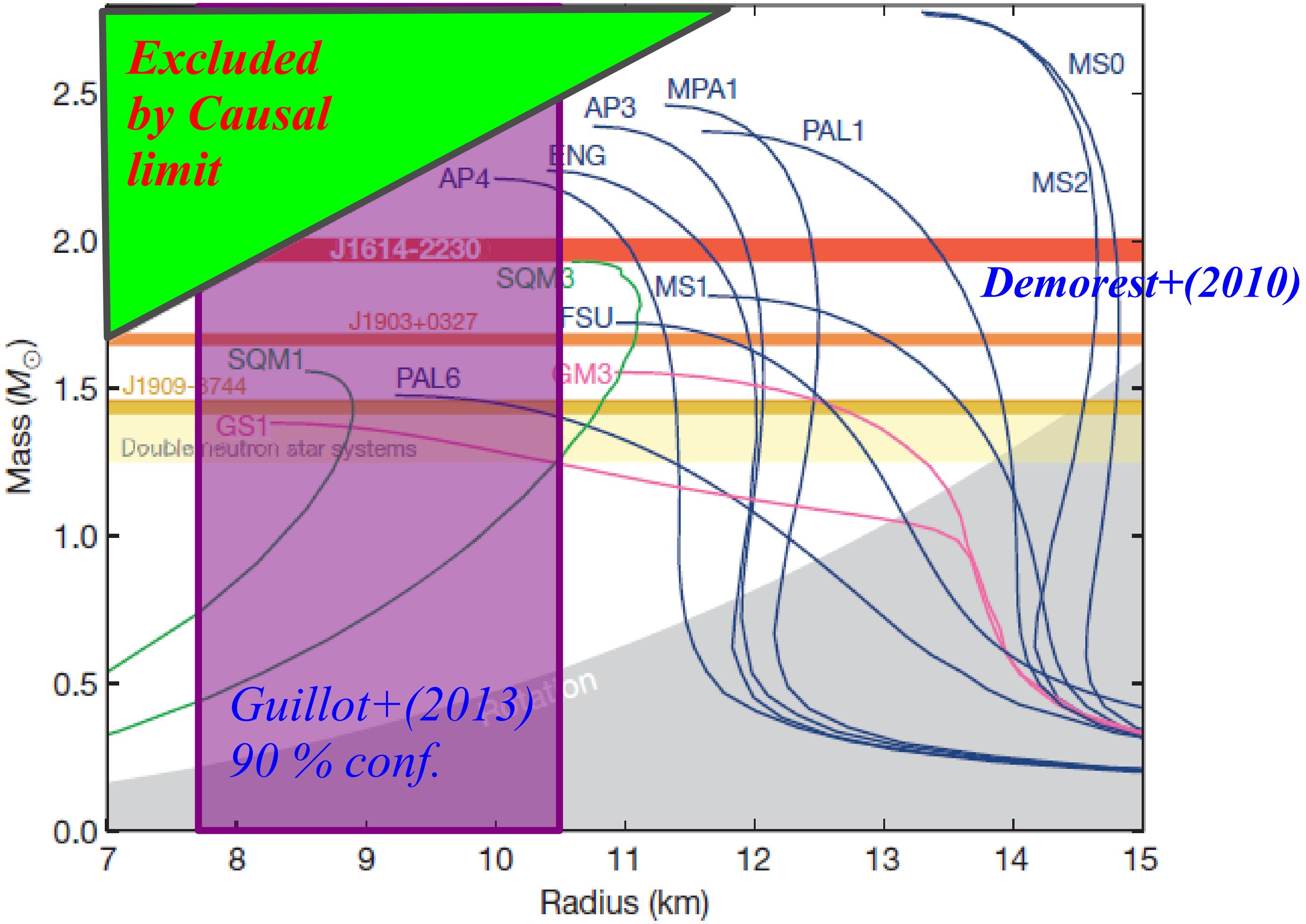
Guillot et al. (2013)

- **Assumptions**
  - **H atmosphere neutron stars.**
  - **Low B-field (<10^{10} G) neutron stars.**
  - **Emitting isotropically.**





Massive and Compact Neutron Star



NS ~ Almost causal limit object ?

Massive and Compact Neutron Star Puzzles

- **Puzzle 1:**
  Massive (~ 2 $M_\odot$) NS cannot be supported by "standard" EOS with hyperons or kaons, while theoretical model calculations based on laboratory hypernuclear physics experiments predict hyperon appearance.
  → Something is wrong !
- **Puzzle 2:**
  X-ray spectra from qLMXB seems to imply neutron star masses around 9 km, while most of theoretical model calculations based on laboratory normal and neutron-rich nuclear physics experiments predict neutron star radius above 11 km.
  → Something is wrong !

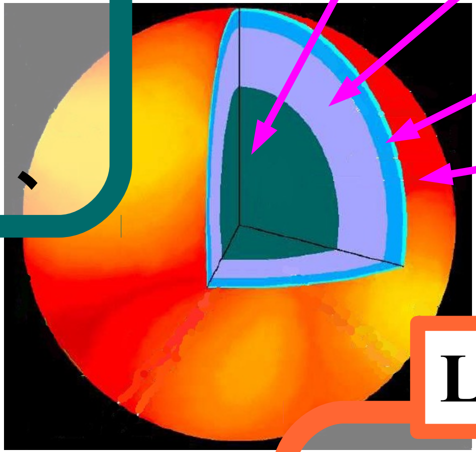
We need studies of neutron star matter EOS cooperated by Strangeness Nuclear Physics, Neutron-rich Nuclear Physics, Astronomical Observations, and Theories.

Grant-in-Aid Study on Neutron Star Matter

High ρ (Group A)

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

J-PARC



Hyperons, mesons, quarks

Asym. nuclear matter
+elec.+μ

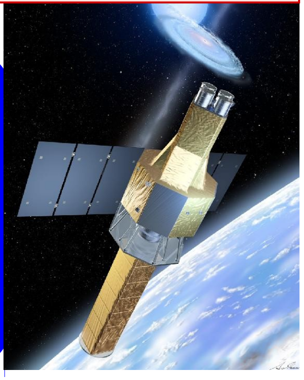
Nuclei+neutron gas+elec.

Nuclei + elec.

Low ρ (Group B)

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

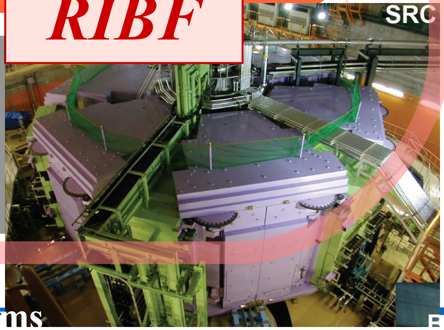
ASTRO-H



NS Obs. (Group C)

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

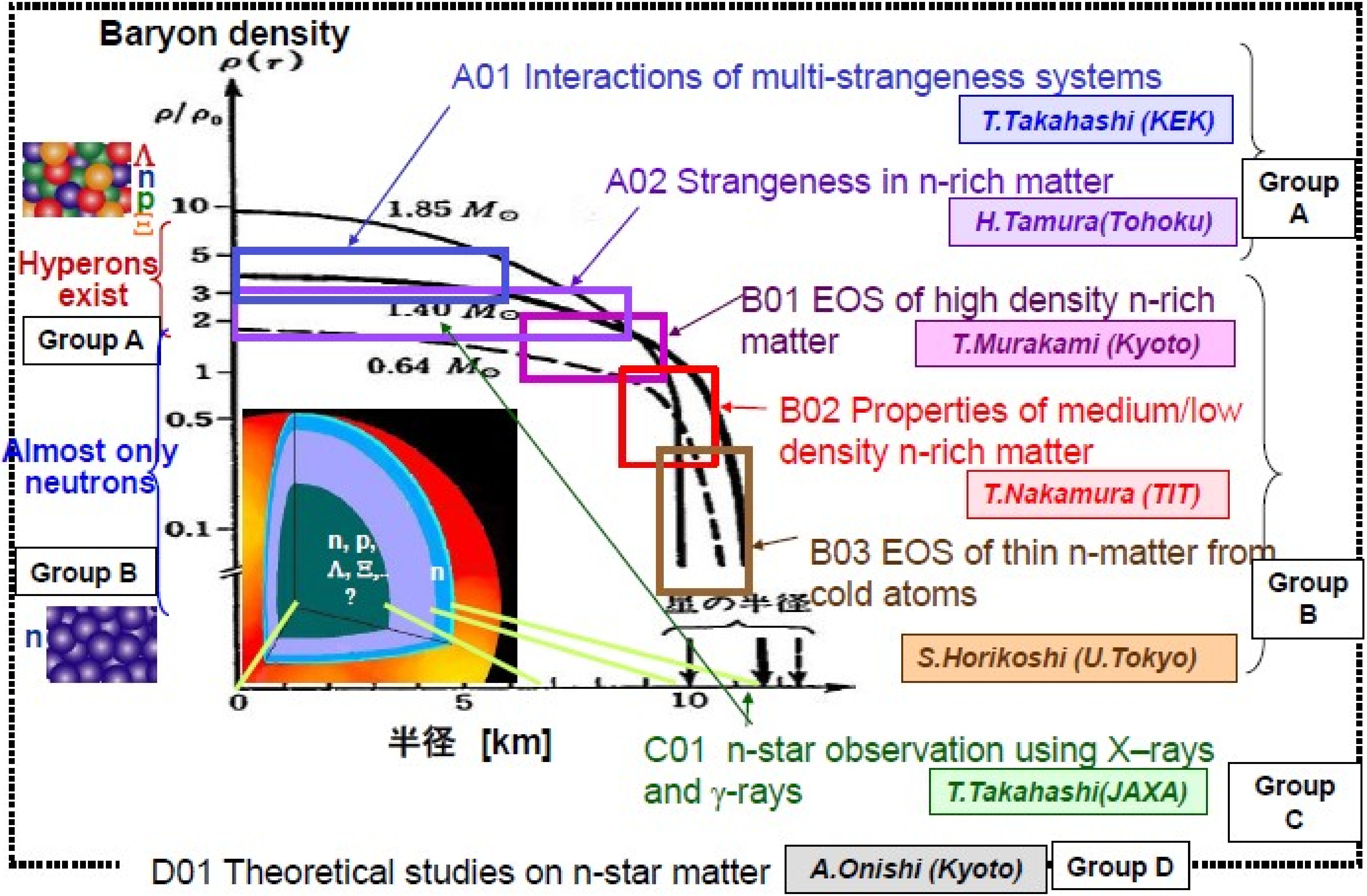
RIBF



atoms

Theory (Group D)

Groups and research subjects



Hyperons exist

Group A

Almost only neutrons

Group B

A01 Interactions of multi-strangeness systems

T.Takahashi (KEK)

A02 Strangeness in n-rich matter

H.Tamura(Tohoku)

Group A

B01 EOS of high density n-rich matter

T.Murakami (Kyoto)

B02 Properties of medium/low density n-rich matter

T.Nakamura (TIT)

B03 EOS of thin n-matter from cold atoms

S.Horikoshi (U.Tokyo)

Group B

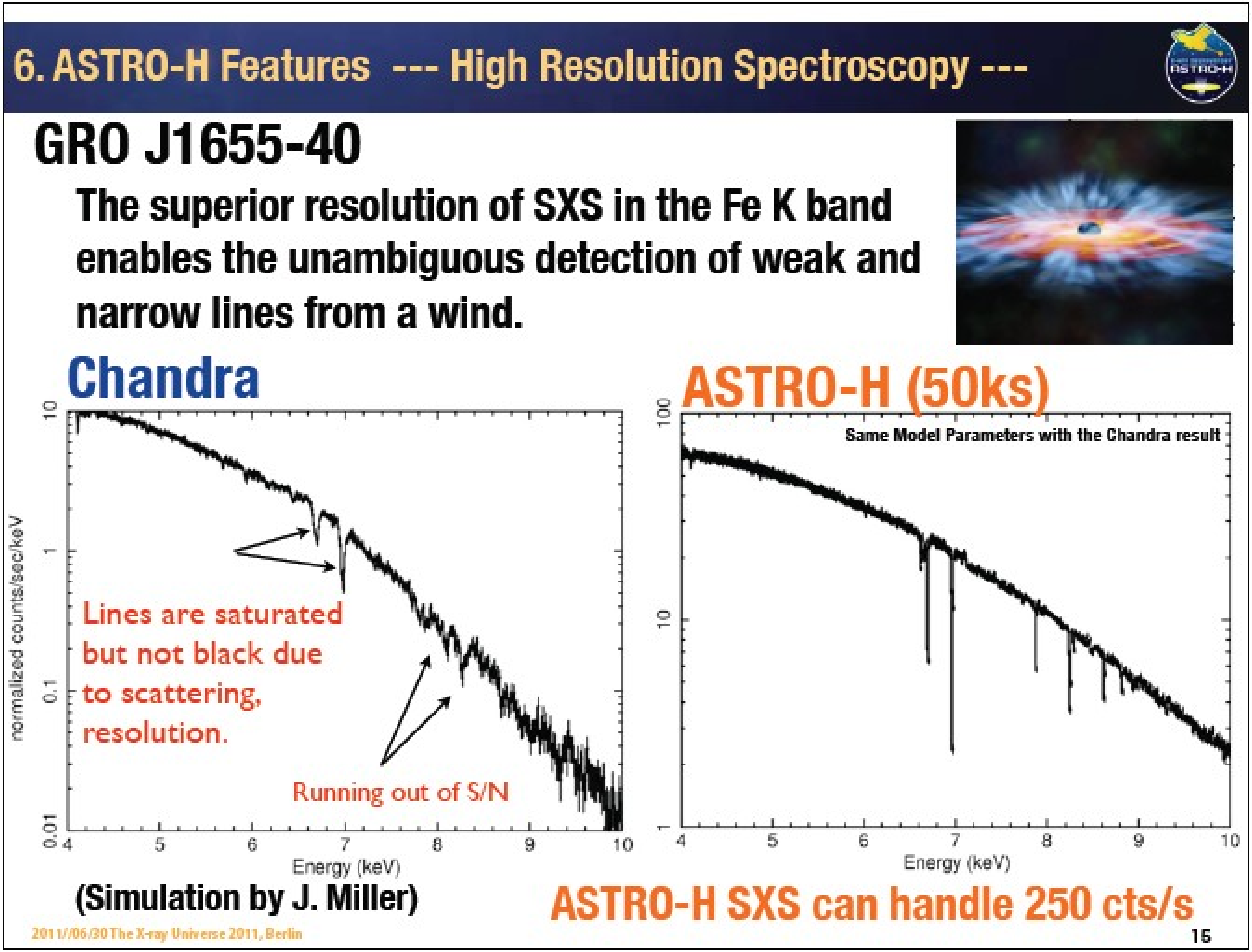
C01 n-star observation using X–rays and γ-rays

T.Takahashi(JAXA)

Group C

D01 Theoretical studies on n-star matter ***A.Onishi (Kyoto)*** **Group D**

By Tadayuki Takahashi (C1)



6. ASTRO-H Features --- High Resolution Spectroscopy ---

GRO J1655-40

The superior resolution of SXS in the Fe K band enables the unambiguous detection of weak and narrow lines from a wind.

Chandra

Lines are saturated but not black due to scattering, resolution.

Running out of S/N

ASTRO-H (50ks)

Same Model Parameters with the Chandra result

(Simulation by J. Miller)

ASTRO-H SXS can handle 250 cts/s

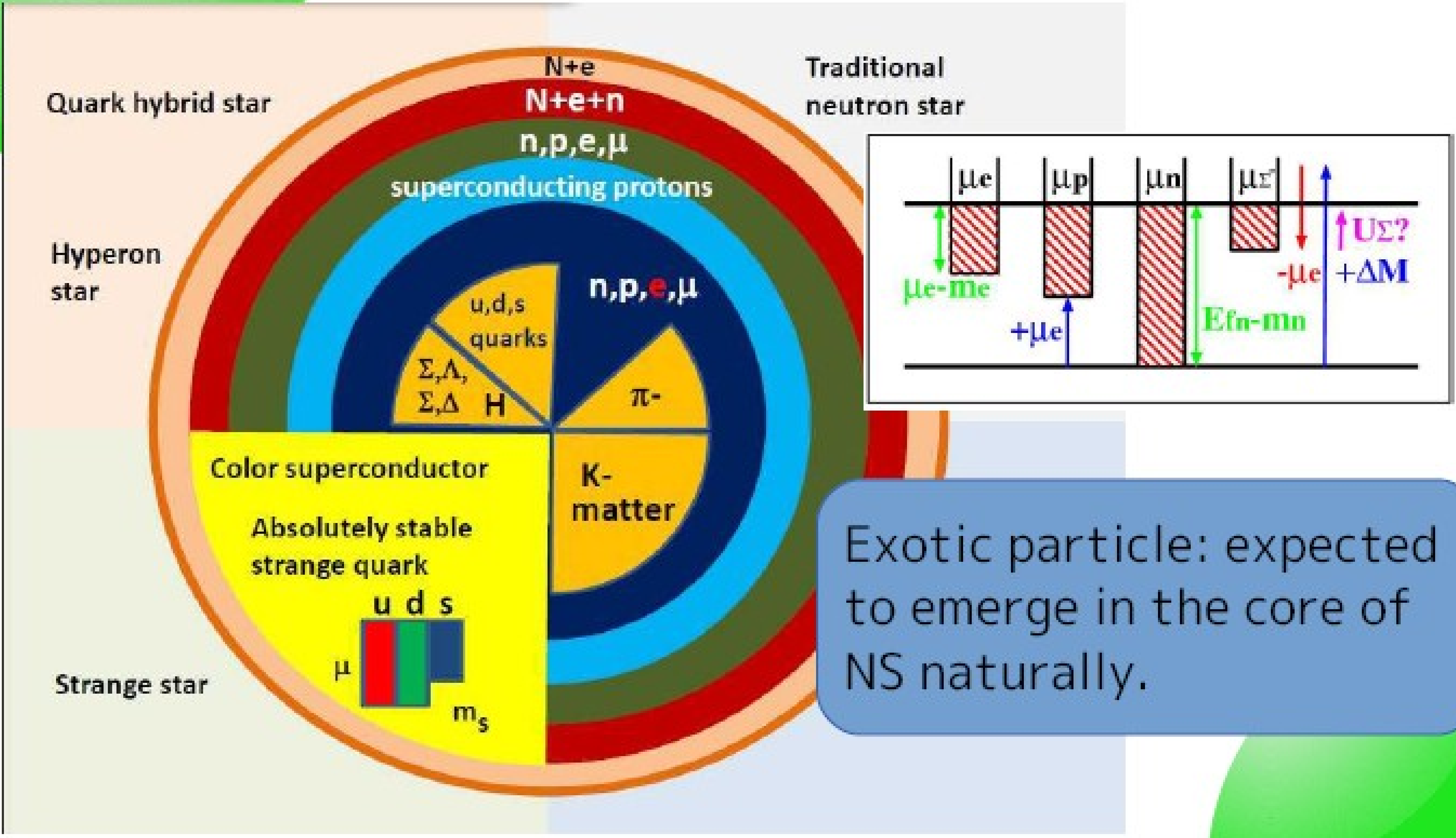
Recent Challenges

中性子星物質における対称エネルギーのもたらす影響について

椿原　康介
Osaka Electro-Communication University

in collaboration with
大西　明
YITP, Kyoto University
原田　融
Osaka Electro-Communication University

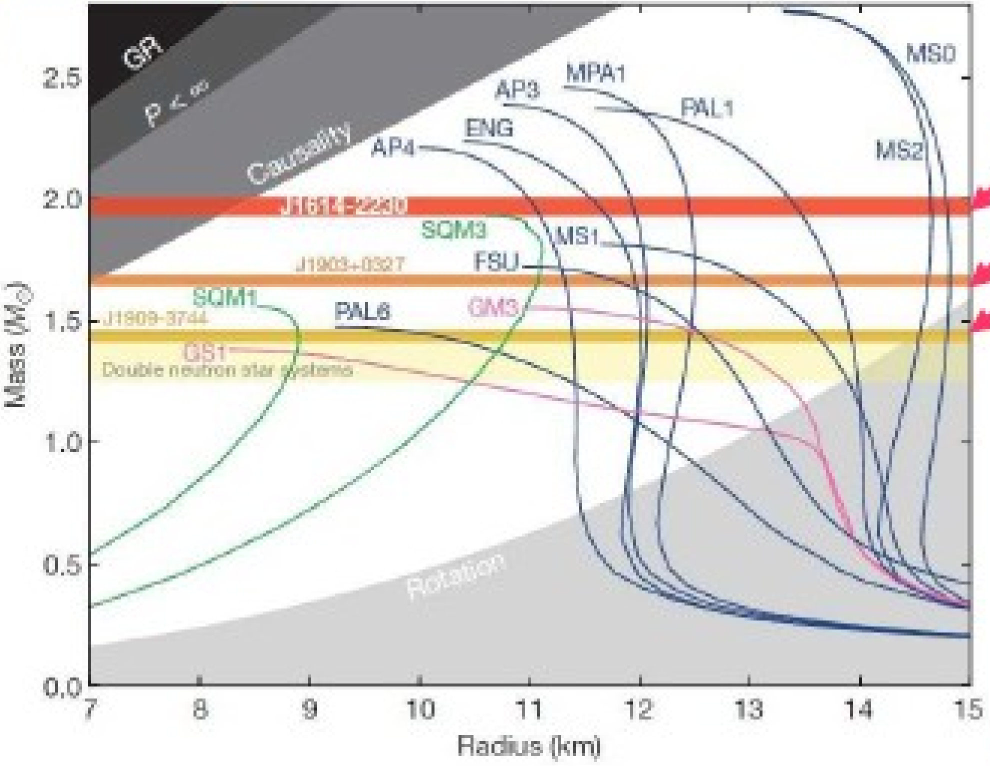
Introduction: Composition of NS



Exotic particle: expected to emerge in the core of NS naturally.

Introduction:Massive NS

- Maximum mass of NS



$1.97M_\odot$ Obsvd. 2009

$1.67M_\odot$

$1.44M_\odot$ Obsvd. 1974

"Most EOS curves involving exotic matter, such as kaon condensates or hyperons tend to predict maximum masses well below 2.0 M and are therefore ruled out"

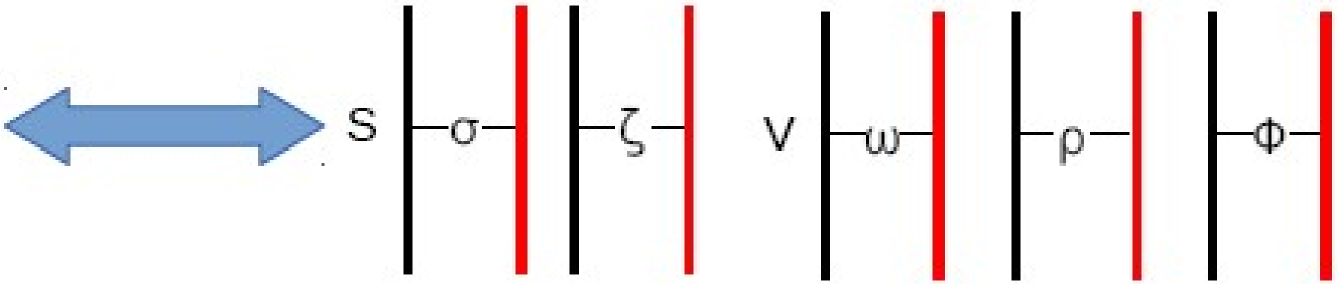
Strong restriction to high-dense matter EoS

[1] P. B. Demorest et al., Nature 467 (2010) 1081.

Introduction: RMF model

- RMF model: reasonable description to both nuclear matter and finite nuclei
- n=B/2+M+D=<u>2</u> RMF model (+ effective pot.)
  → <u>2</u>-body interaction (and rel. 3-body corr.)

$\overline{\Psi}_B g_{mB} m \Psi_B$



$$\mathcal{L} = \sum_i \bar{\psi}\left[i\partial - M_i^* - \gamma_\mu V^\mu\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$

$$+\frac{1}{2}\partial_\mu\varphi_\sigma\partial^\mu\varphi_\sigma - \frac{m_\sigma^2}{2}\varphi_\sigma^2 + \frac{1}{2}\partial_\mu\varphi_\zeta\partial^\mu\varphi_\zeta - \frac{m_\sigma^2}{2}\varphi_\zeta^2 - V_{\sigma\zeta}$$

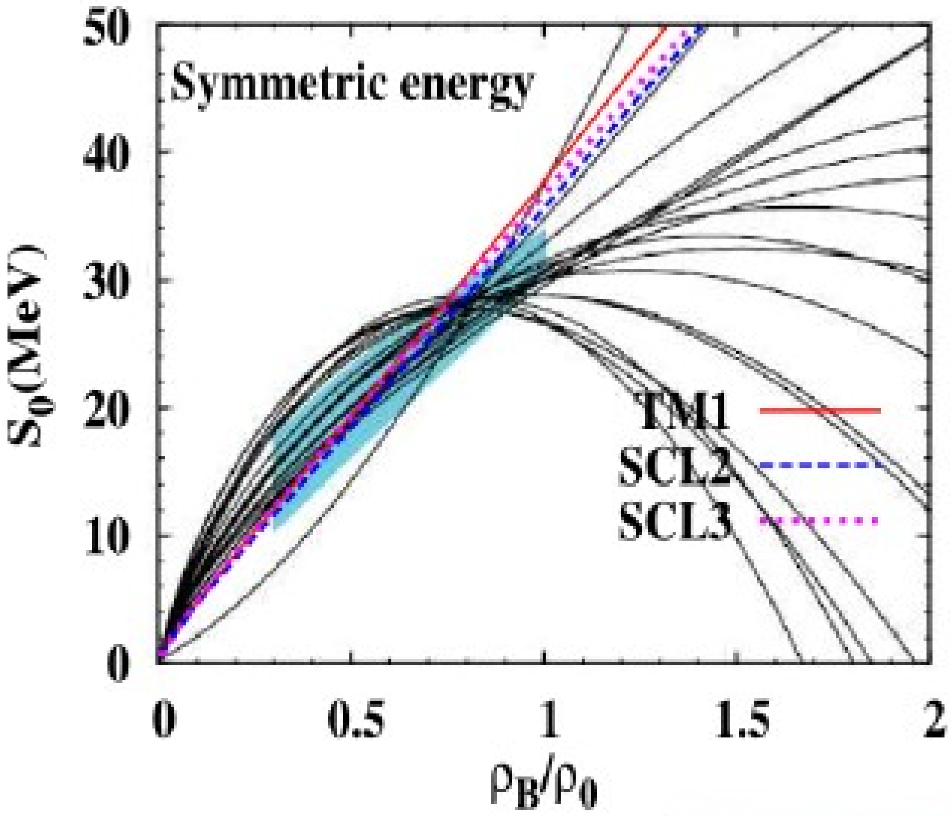
$$-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\nu - \frac{1}{4}R_{\mu\nu}R^{\mu\nu} + \frac{m_\rho^2}{2}\rho_\mu\rho^\nu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{m_\phi^2}{2}\phi_\mu\phi^\nu + \frac{C_{\omega 4}}{4}\left(\omega_\nu\omega^\nu\right)^2$$

Symmetry Energy

- Nuclear symmetry energy：The size of NS and/or thickness of neutron skin.

- Symmetry energy in RMF
  → Larger L than
  the suggestion
  from Exp.

- Density dependence: almost linear since E/A is proportional to ρ field if we adopt n=2 RMF Lagrangian.



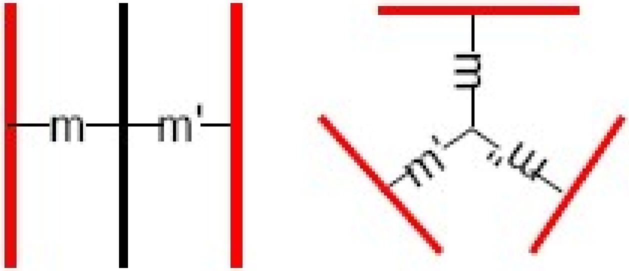
[3] M. B. Tsang et al., Phys. Rev. C 86 (2012) 015803.

Motivation

- Symmetry energy and its effect to NS-EoS:
  Can we modify them by including IV type n=3 ρ couplings to an RMF model?

n=3 coupl. → 3-body int. among baryons

$$\bar{\Psi}_B m m' \Psi_B,\ m m' m''$$



- Other systematic features:
  Can we reasonably reproduce bulk properties of finite/infinite nuclear systems?

- How to justify determined n=3 couplings:
  Can neutron skin thickness be candidate?

Model description

- n=B/2+M+D=2 RMF model + effective pot.

$$\mathcal{L} = \sum_i \bar{\psi}\left[i\partial - M_i^* - \gamma_\mu V^\mu\right] - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}$$
$$+\frac{1}{2}\partial_\mu\varphi_\sigma\partial^\mu\varphi_\sigma - \frac{m_\sigma^2}{2}\varphi_\sigma^2 + \frac{1}{2}\partial_\mu\varphi_\zeta\partial^\mu\varphi_\zeta - \frac{m_\sigma^2}{2}\varphi_\zeta^2 - V_{\sigma\zeta}$$
$$-\frac{1}{4}W_{\mu\nu}W^{\mu\nu} + \frac{m_\omega^2}{2}\omega_\mu\omega^\nu - \frac{1}{4}R_{\mu\nu}R^{\mu\nu} + \frac{m_\rho^2}{2}\rho_\mu\rho^\nu - \frac{1}{4}\phi_{\mu\nu}\phi^{\mu\nu} + \frac{m_\phi^2}{2}\phi_\mu\phi^\nu + \frac{C_{\omega 4}}{4}\left(\omega_\nu\omega^\nu\right)^2$$

N=3 Coupl.

Isoscalar → two-different-type repulsive int.(TBC5 and 6)

$$\bar{\Psi}_B\left(g_{\sigma\sigma B}\varphi_\sigma^2/f_\pi\right)\Psi_B,\ \bar{\Psi}_B\left(g_{\sigma\omega B}\varphi_\sigma\omega/f_\pi\right)\Psi_B,\ \bar{\Psi}_B\left(g_{\omega\omega B}\omega^2/f_\pi\right)\Psi_B,\ \frac{C_{\sigma\omega 2}}{2}f_\pi\varphi_\sigma\omega^2$$

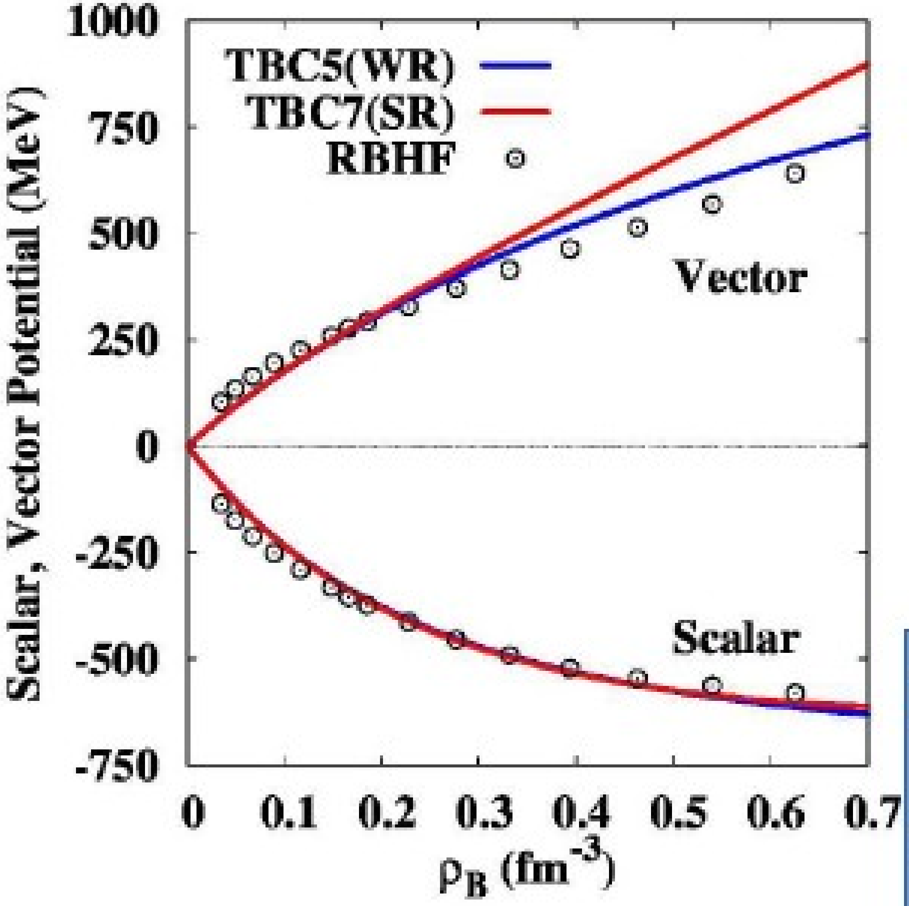
Isovector → Newly introduced so as to control IV part of EoS
(Systematics of B/A and symmetry energy at ρ$_0$)

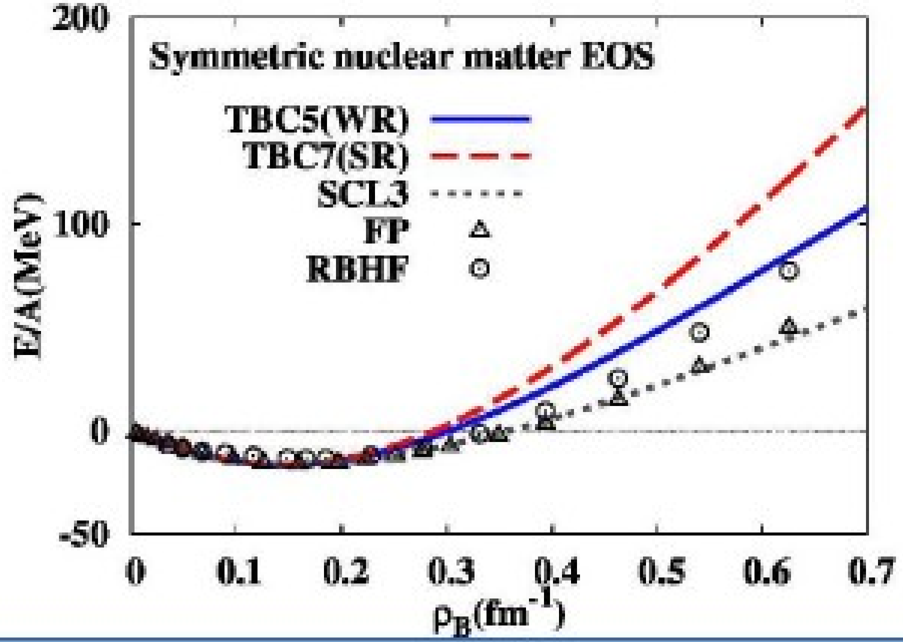
$$\bar{\Psi}_B\left(g_{\rho\sigma B}\rho\varphi_\sigma/f_\pi\right)\Psi_B,\ \bar{\Psi}_B\left(g_{\omega\rho B}\omega\rho/f_\pi\right)\Psi_B,\ \bar{\Psi}_B\left(g_{\rho\rho B}\rho^2/f_\pi\right)\Psi_B,\ \frac{C_{\sigma\rho 2}}{2}f_\pi\varphi_\sigma\rho^2$$

Red: Vector, Blue: Scalar type n=3 couplings

Results (1): Nuclear matter

- Symmetric nuclear matter EoS



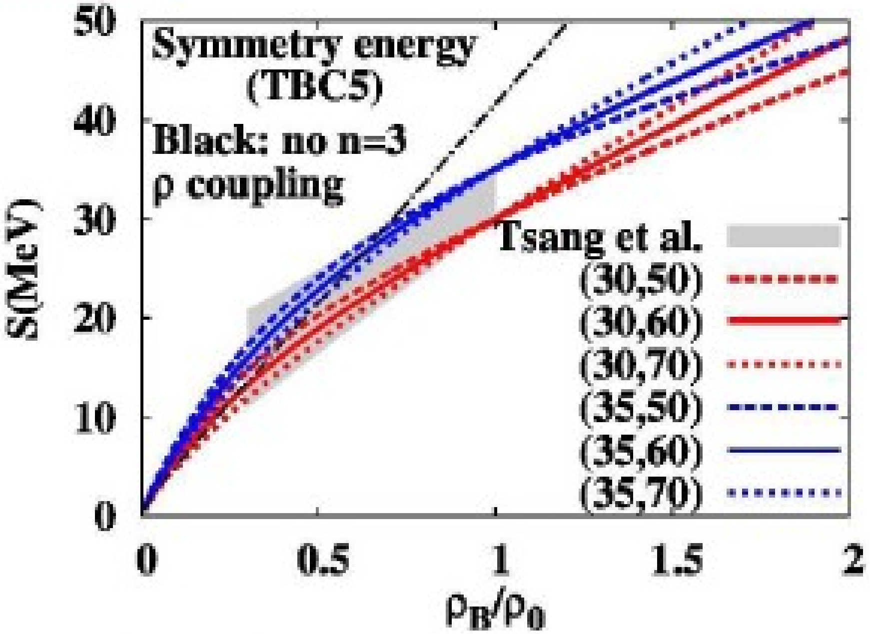


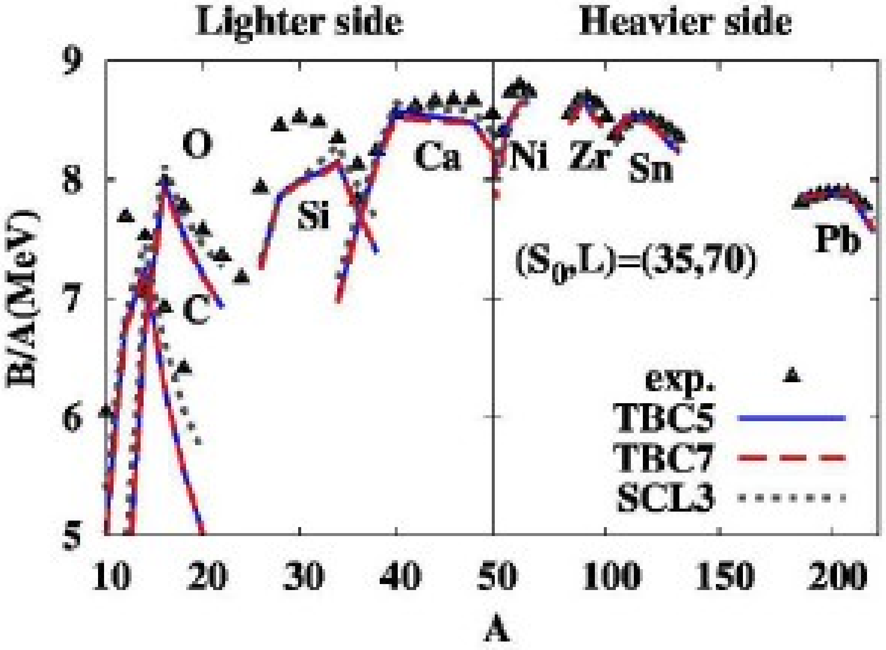
TBC5: determined so as to reporuce RBHF calc.

TBC7: More repulsive parameter set than TBC5

Results(2): Symmetry energy

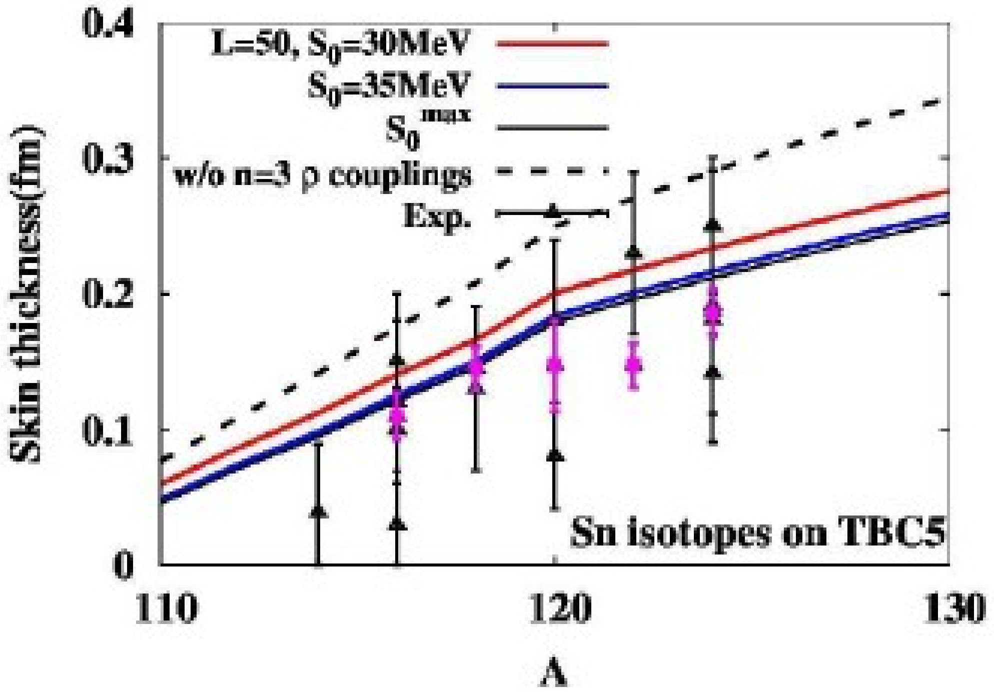
- Neutron matter w or w/o n=3 ρ coupling

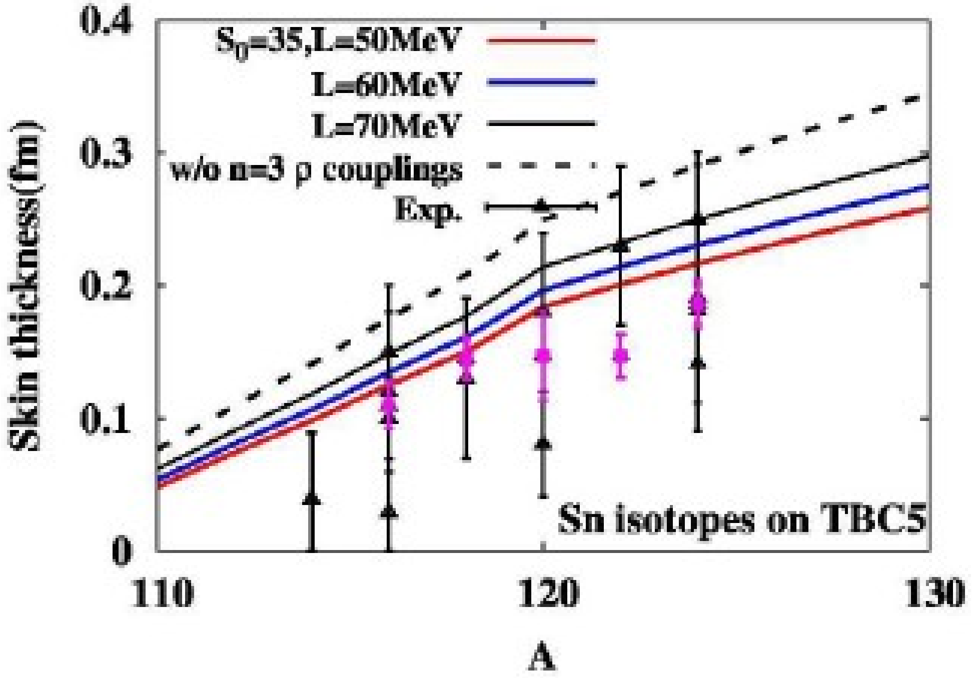




- n=3 ρ couplings: reasonably constrained by (S_0,L)
- Neutron matter: Linear behavior
  → good agreement with HIC suggestion
- B/A of finite nuclei: well-reproduced even if
  we include n=3 IV type couplings

Results (3): Neutron skin in Sn



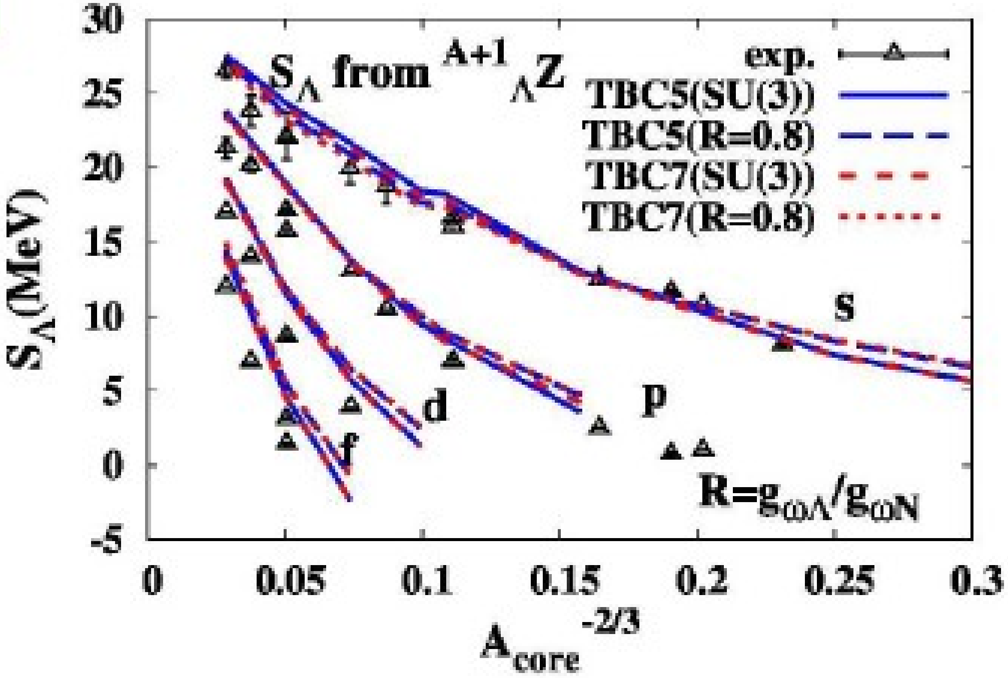


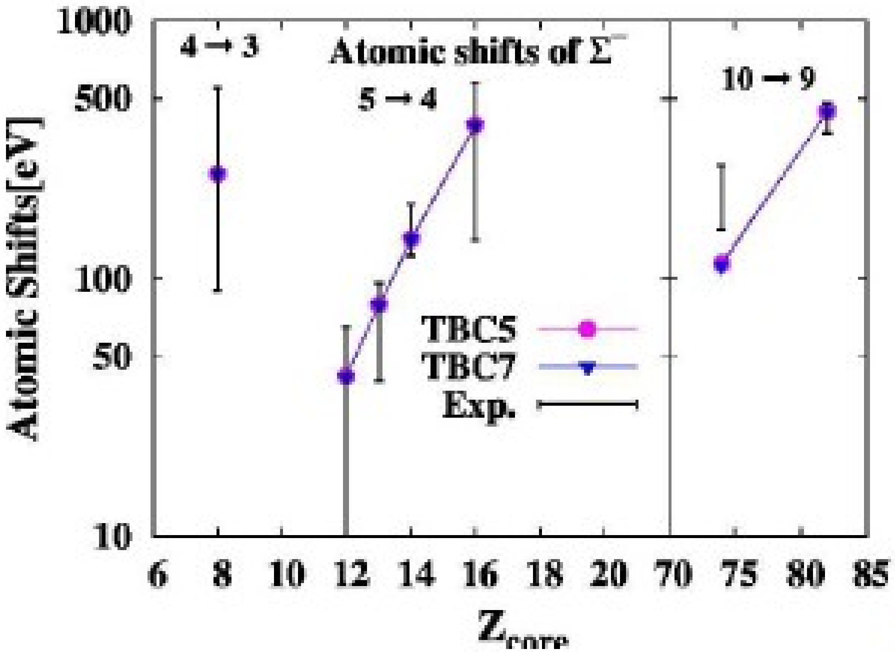
- Symmetry energy: controllable by introducing IV type n=3 couplings (TBC5: S_0~41.5MeV >> 30-40MeV, L~120MeV >>50-70MeV)
- (S_0, L)=(35,70): good agreement with the data taken at RCNP

Highlighted RCNP data: Terashima et al. PRC **77** 024317

Results (4): NS-EoS

- M-R curve on TBC parameter sets with hyperon

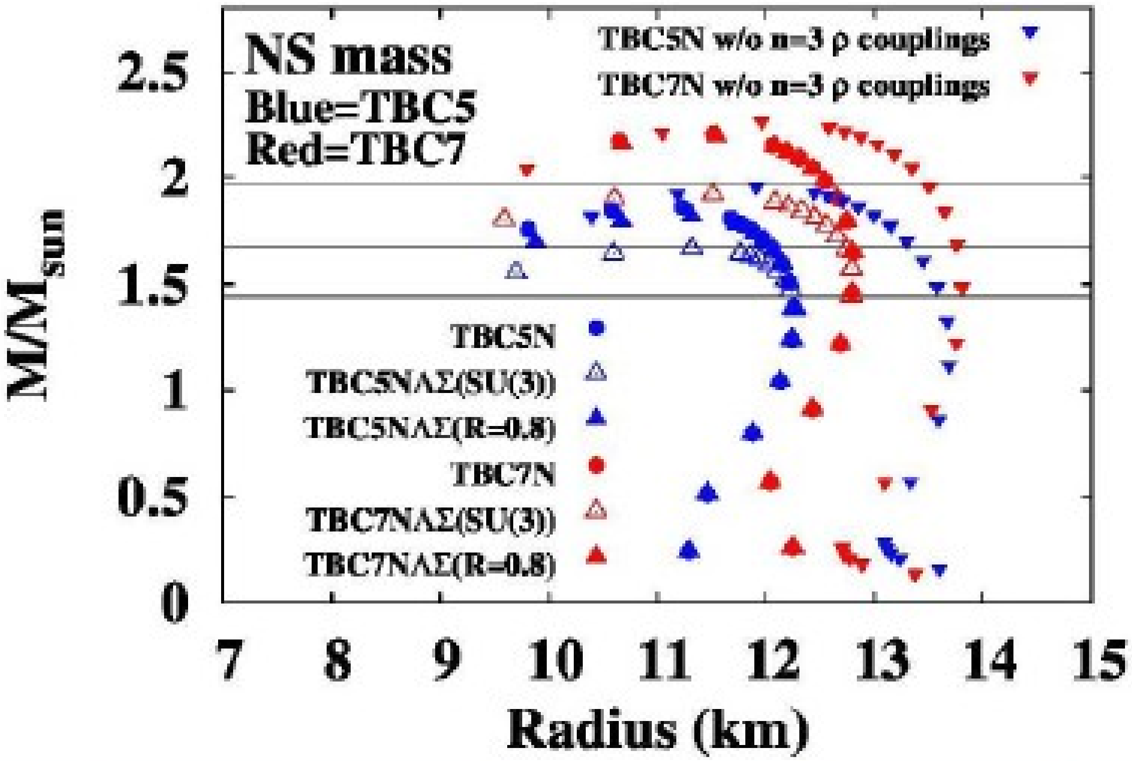




- Hypernulcear data: well reproduced even if we introduce SU(3) violation
- Introduction of n=3 ρ coupling: Large modification to the M-R relation ↔not so large modification to maximum mass of NS

Results (4): NS-EoS

- M-R curve on TBC parameter sets with hyperon



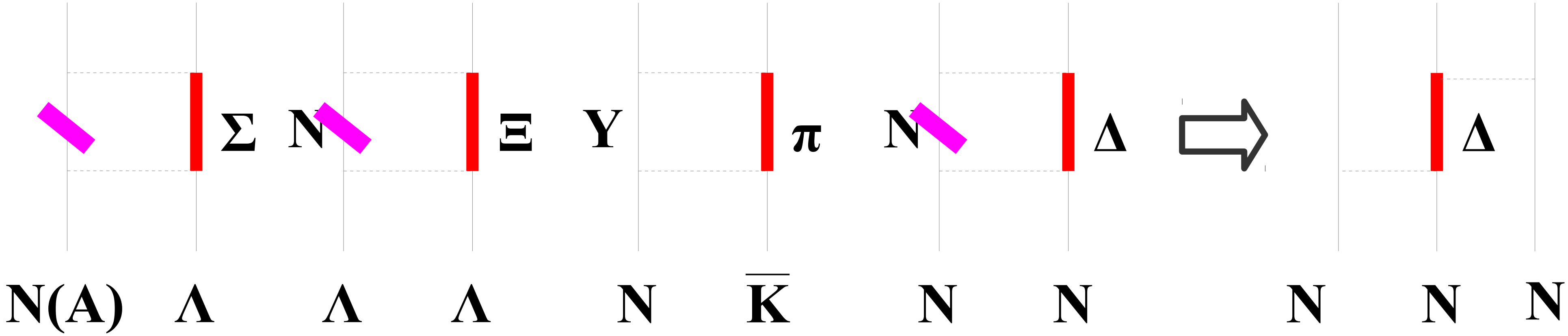
- Hypernulcear data: well reproduced even if we introduce SU(3) violation
- Introduction of n=3 ρ coupling: Large modification to the M-R relation
  ↔not so large modification to maximum mass of NS

Summary

- IV-type n=3 TBC in RMF model: Well-constrained by the data of finite and infinite nuclear systems
- Symmetry energy: Controllable by introducing the n=3 TBC and good agreement in HIC results
- Neutron skin: good constraint to (S_0,L)
  >> (35MeV, 50MeV) case seems to be in agreement with RCNP data
- If combined with hypernulcear data, TBC7(SR) parameter set with SU(3)-violation in m_v-B coupling can explain massive 2-times-solar mass.

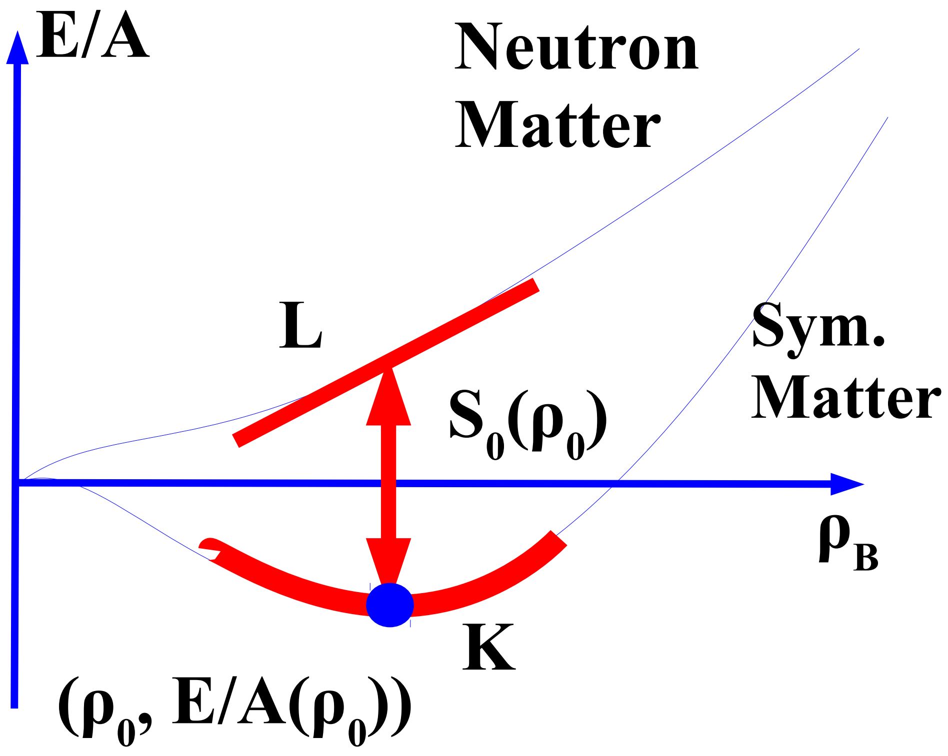
Do we have strangeness hadrons in NSs ?

- **A way to answer massive neutron star puzzle = 3-body repulsion**
  Nishizaki, Takatsuka, Yamamoto ('03); Doi et al.(HALQCD)
- **One of the possible origin of 3-body repulsion**
  → Pauli blocking in the intermediate state with resonances
  Kohno ('13), Otsuka et al.



- **Can we determine these couplings ?**
  - **Detailed study of hypernuclear properties incl. n-rich hypernuclei and S=2 hypernuclei.**

Nuclear Matter EOS



$$E/A(\rho,\delta)=\varepsilon(\rho)+E_{\mathrm{sym}}(\rho)\delta^2+O(\delta^4)$$

Symmetric Nuclear Matter

$$\varepsilon(\rho)=\varepsilon(\rho_0)+\frac{K(\rho-\rho_0)^2}{18\rho_0^2}+O((\rho-\rho_0)^3)$$

Symmetry Energy $(\delta=(N-Z)/A=1-2Y_p)$

$$E_{\mathrm{sym}}(\rho)=S_0+\frac{L(\rho-\rho_0)}{3\rho_0}+\frac{K_{\mathrm{sym}}(\rho-\rho_0)^2}{18\rho_0^2}$$
$$+O((\rho-\rho_0)^3)$$

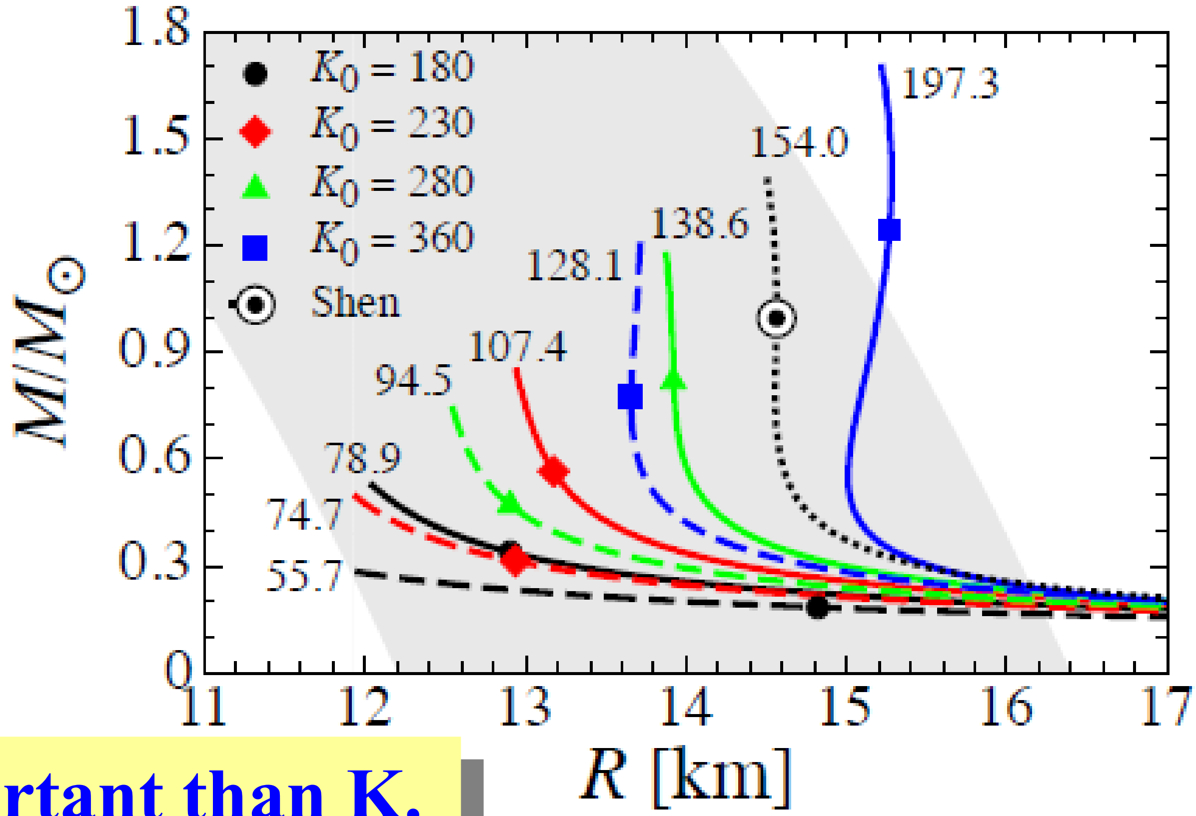
K or L

- **We have two EOS parameters, which are the derivatives of E, K and L. Which mainly determines the M-R relation ?**

  → Answer

  One parameter η = $(KL^2)^{1/3}$ characterizes M-R curve (for low mass neutron stars) !

  Sotani, Iida, Oyamatsu, AO (to be submitted)

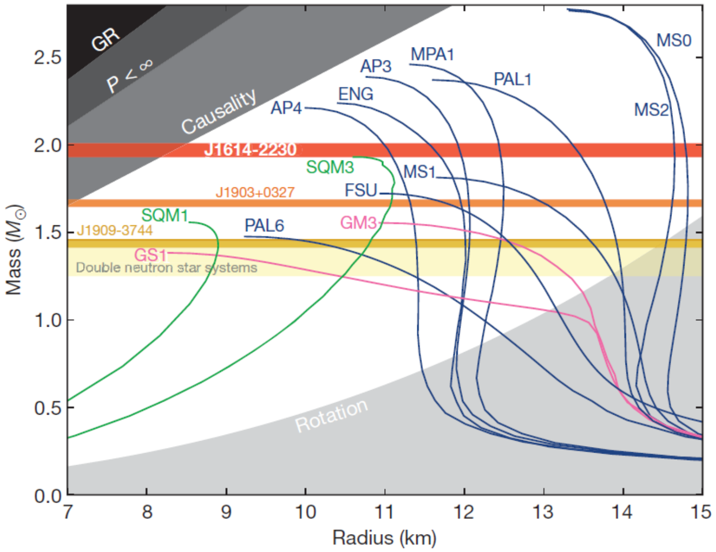


L is twice more important than K.

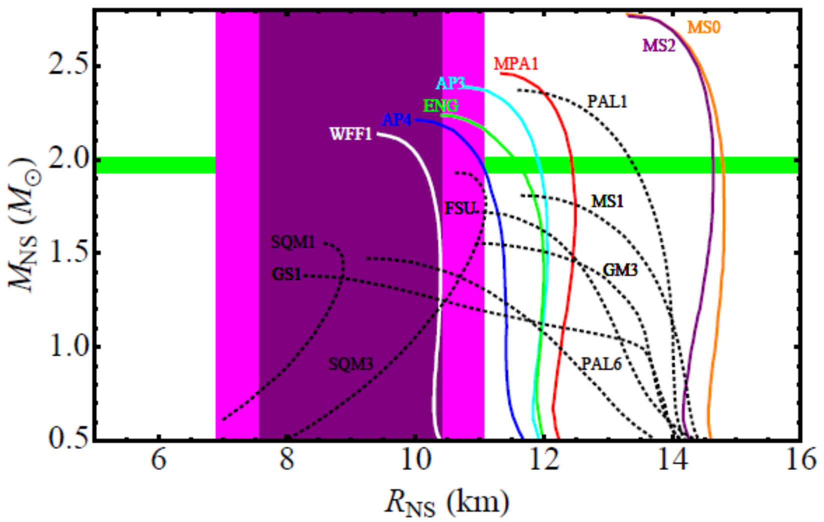
Contents and Summary

- Neutron star (NS)
  - Giant neutron-rich hypernuclei
    & Almost causal limit object
  - Massive (~ 2 $M_\odot$) & Compact (~ 9 km)
    NS puzzle.
  - Grant-in-aid study on NS matter
    J-PARC + RIBF + ASTRO-H +Theory
- Challenges in neutron star matter physics
  - How can we solve massive NS puzzle ?
    → Three-body force as a candidate
  - What determines M-R relation of
    low-mass neutron stars ?
    → New parameter $\eta=(KL^2)^{1/3}$

**We have big challenges
in neutron star physics !**



Demorest et al. (2010)



Guillot et al. (2013)

Thank you for your attention.