Equation of State and Neutron Stars

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Tri area workshop,
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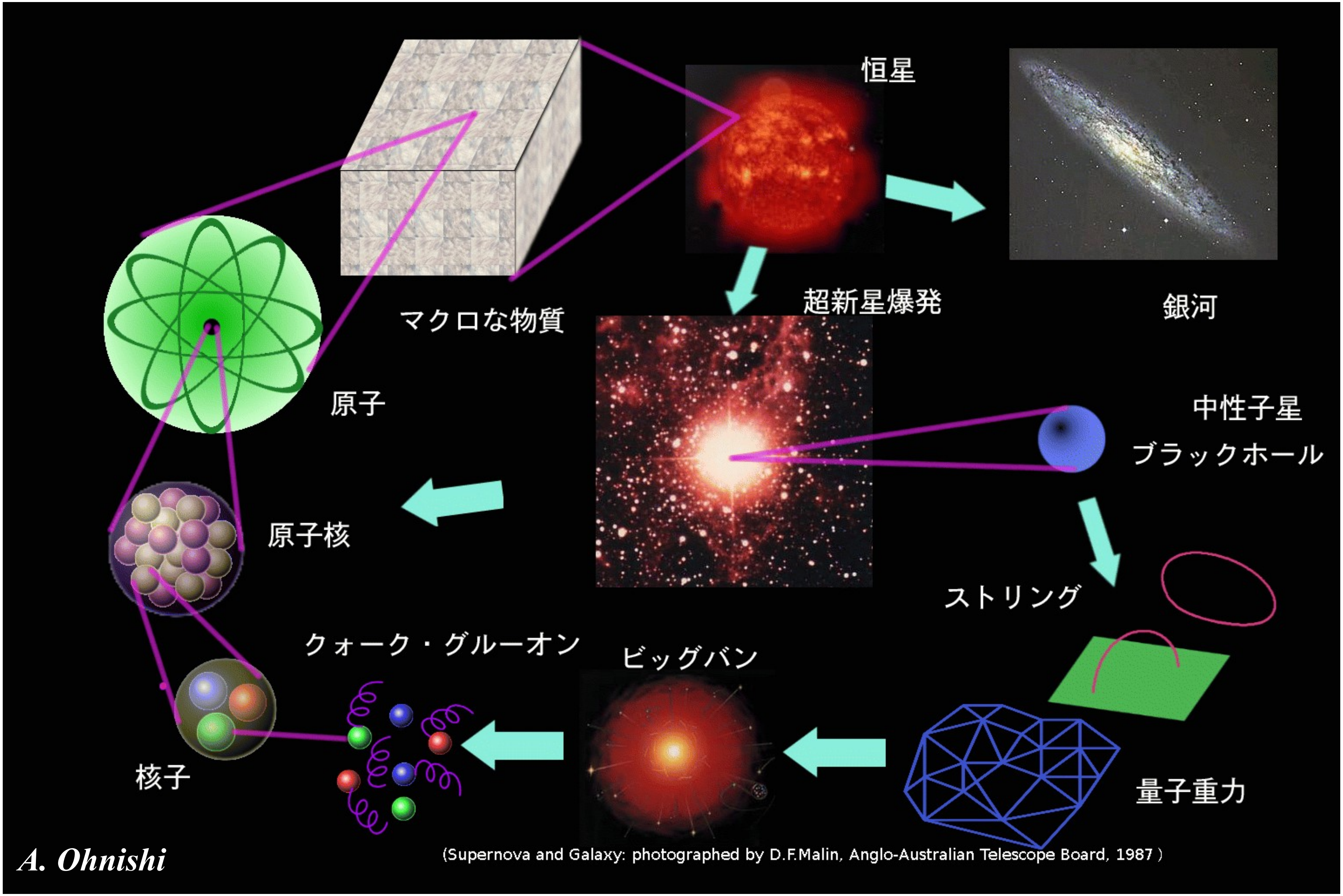
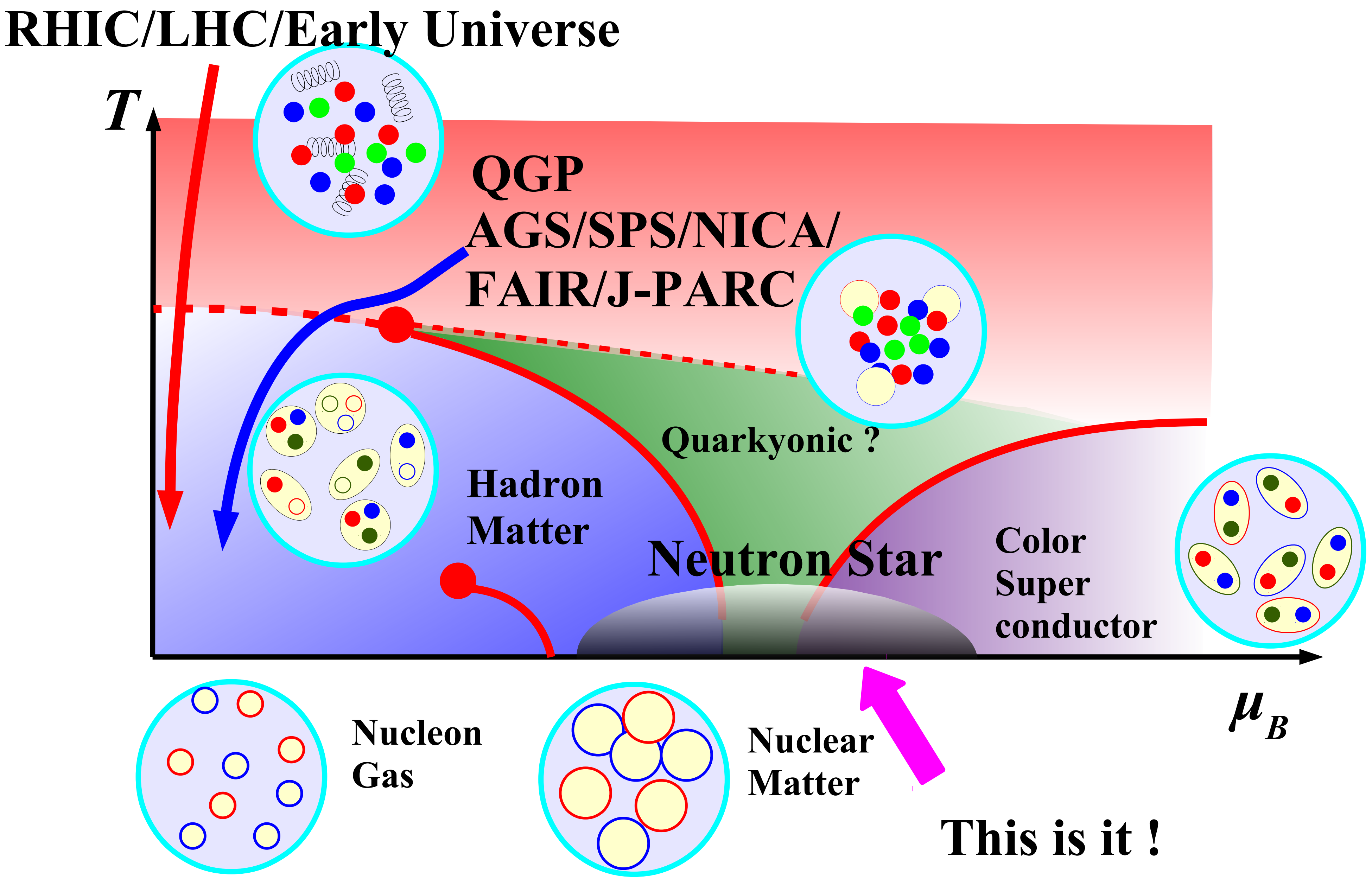
- **Introduction**
- **Neutron Star Matter EOS**
- **Toward the solution of the Massive Neutron Star Puzzle**
- **Summary**

Birth, Life and Death of Matter in Our Universe

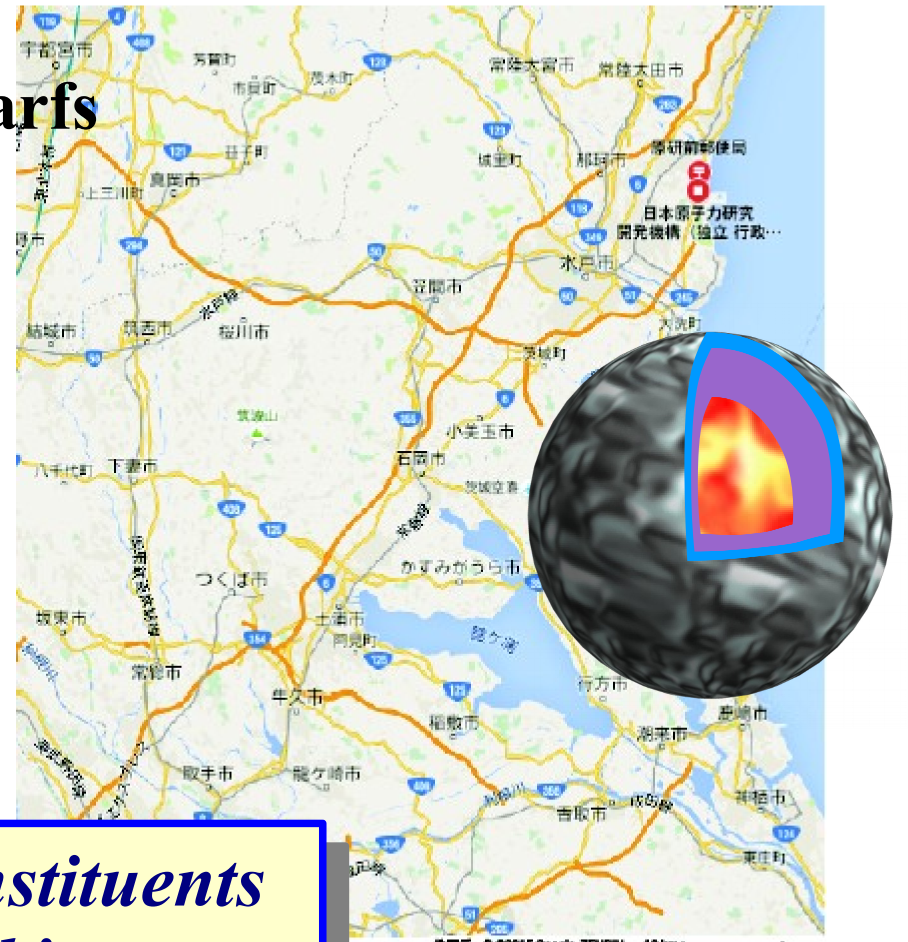


QCD Phase Diagram



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 with
  neutron Fermi energy.
- **Various constituents**
  (conjectured)
  n, p, e, μ, Y, $\bar{K}$, π, q, g, qq, ….



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

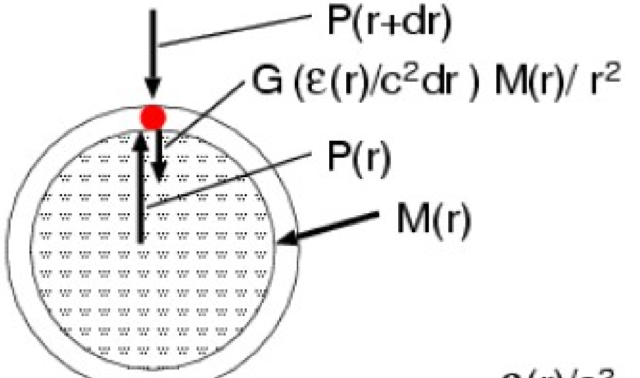
google & zenrin

M-R curve and EOS

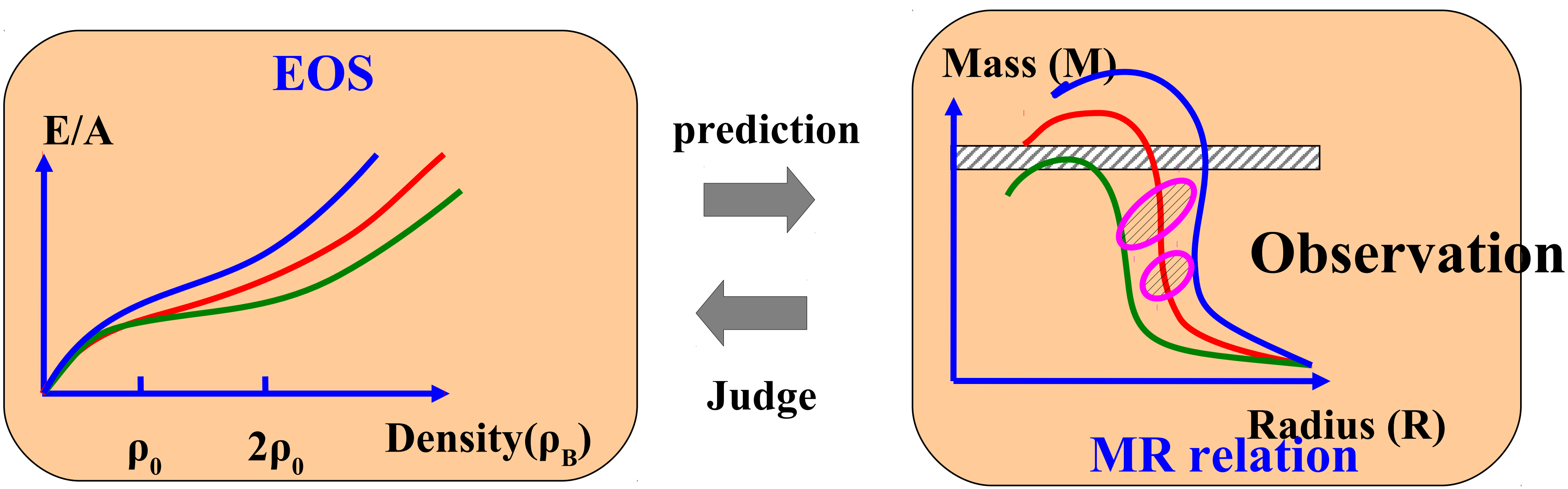
- **M-R curve and NS matter EOS has 1 to 1 correspondence**
  - **TOV(Tolman-Oppenheimer-Volkoff) equation =GR Hydrostatic Eq.**

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

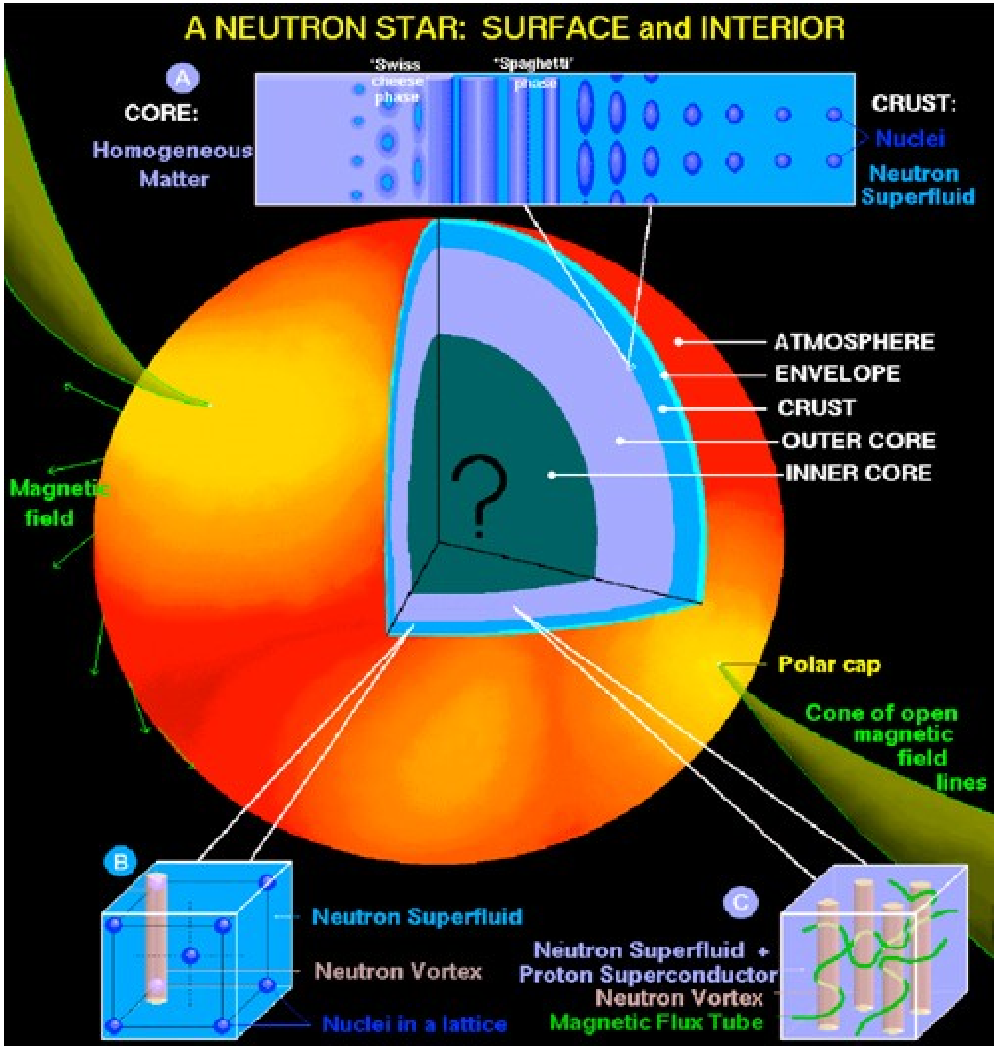
$$\frac{dM}{dr} = 4\pi r^2 \varepsilon/c^2, \quad P = P(\varepsilon) \quad \text{(EOS)}$$

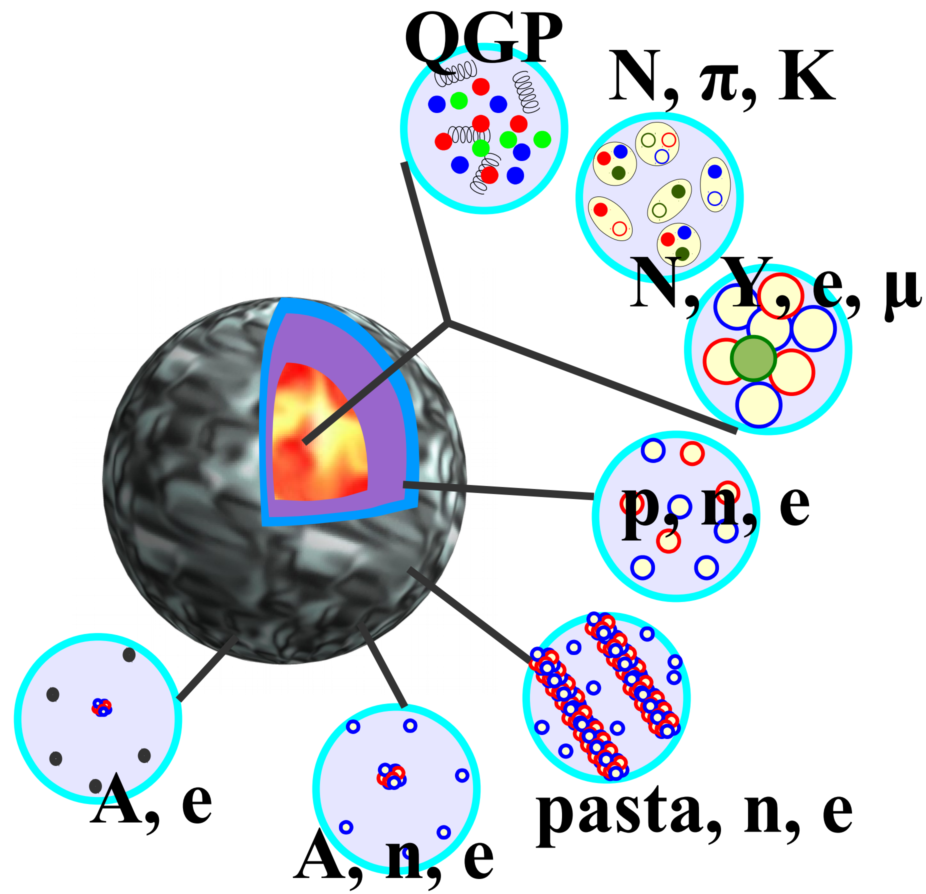


Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$



Inside Neutron Stars





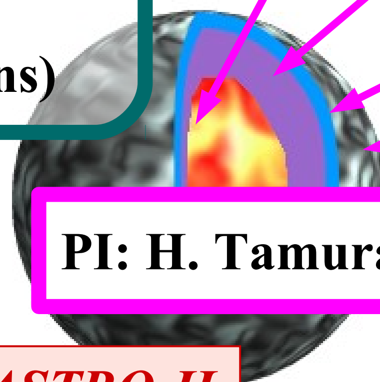
Dany Page

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

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.

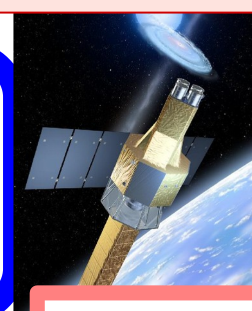
PI: H. Tamura

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

ASTRO-H



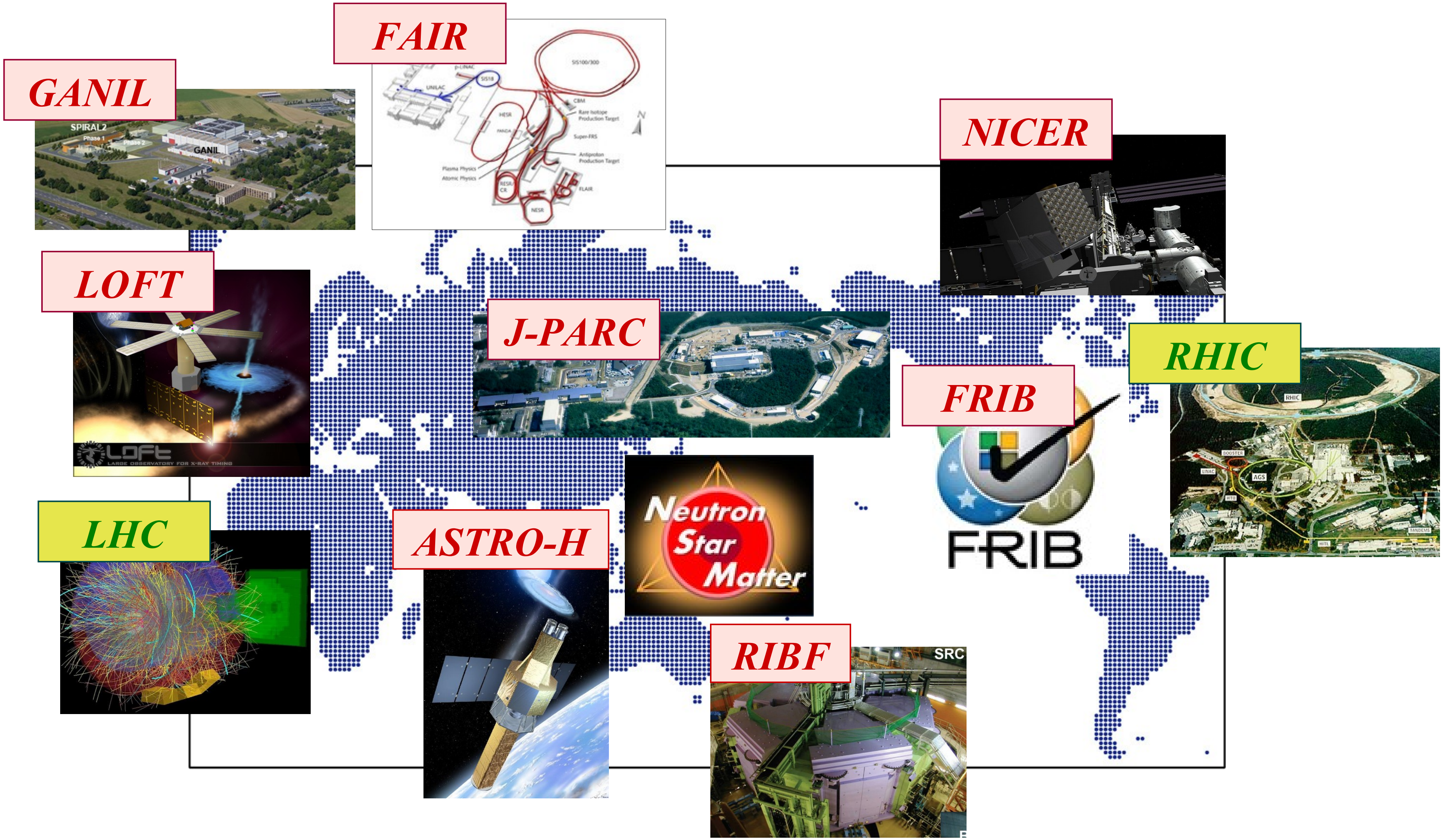
Radius, Mass,
Temp. (Cooling),
Star quake, Pasta

RIBF

Theory (Group D)
head: Ohnishi

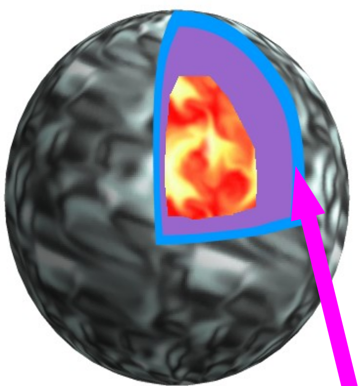
US: UNEDF, ICNT, FRIB, RHIC, NICER...
Europe: CompStar, EMMI, FAIR, GANIL, LOFT, ...

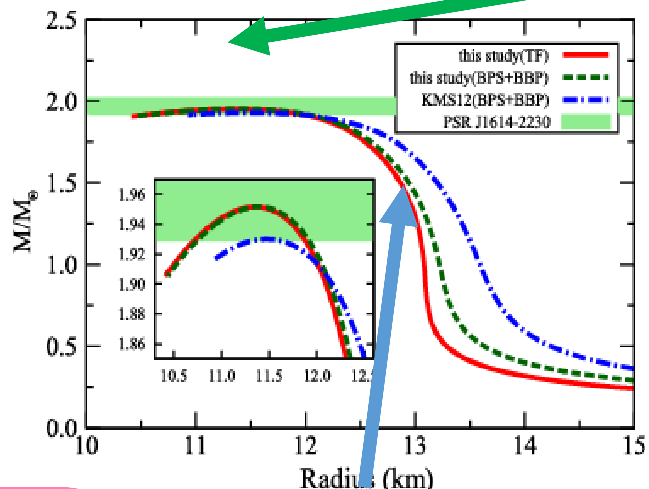
Accelerators and Satellites for Neutron Star Physics



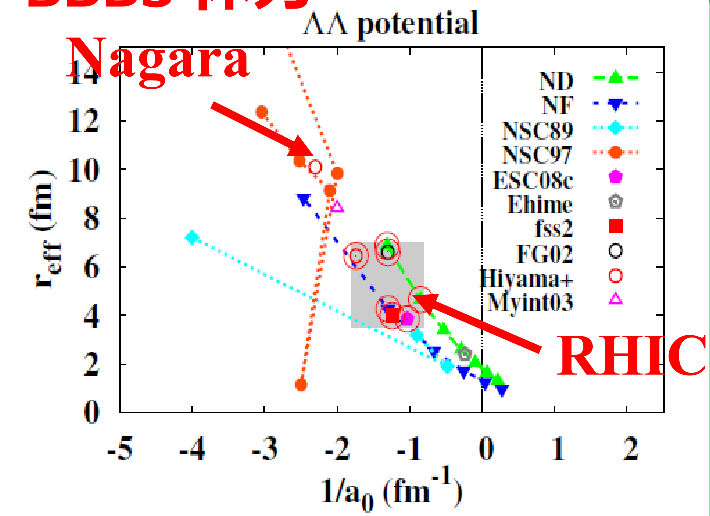
計画研究 D01 中性子星と核物質の理論研究

- 目標：中性子星物質 EOS 構築と
  中性子星にかかわる天体現象の理解

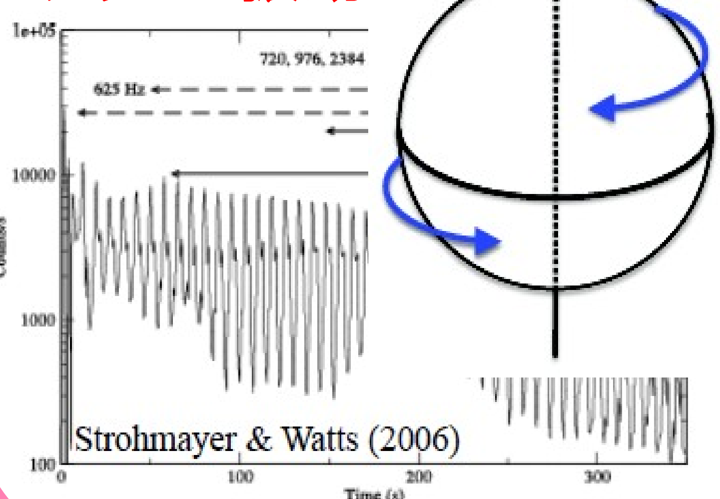




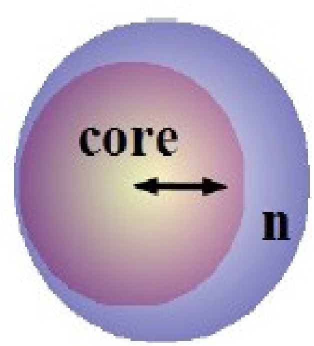
BBB3 体力

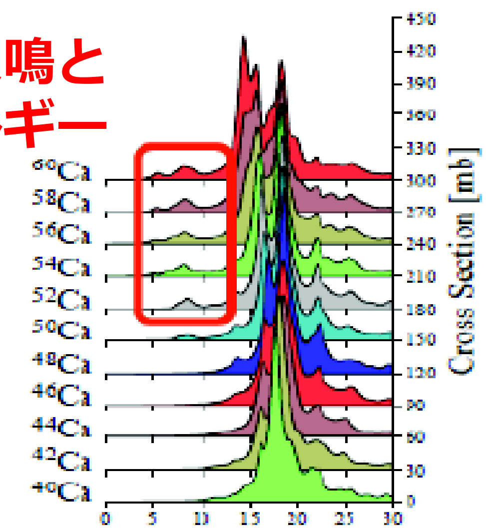


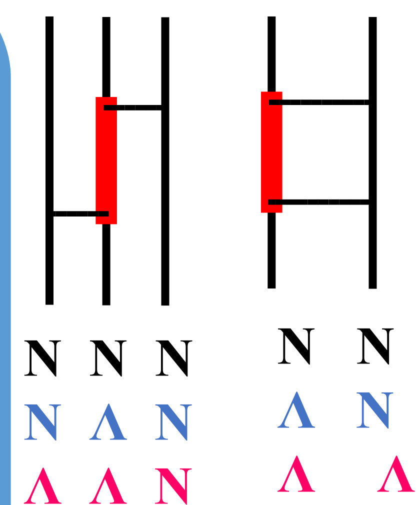
クラスト振動と EOS



ピグミー共鳴と対称エネルギー







Contents

- Introduction
  - Neutron Stars as laboratory of matter under extreme conditions
- Neutron Star Matter Equation of State
  - Nuclear matter parameters: ρ_0, $E/A(\rho_0)$, K, S_0, L, …
  - Effects on Neutron Star (M, R)
- Massive Neutron Star Puzzle
  - Does massive neutron stars ($M \sim 2M_\odot$) rule out exotic component in neutron stars ?
  - Proposed solutions of the massive neutron star puzzle
- Summary

Neutron Star Matter EOS

Neutron Star Matter EOS

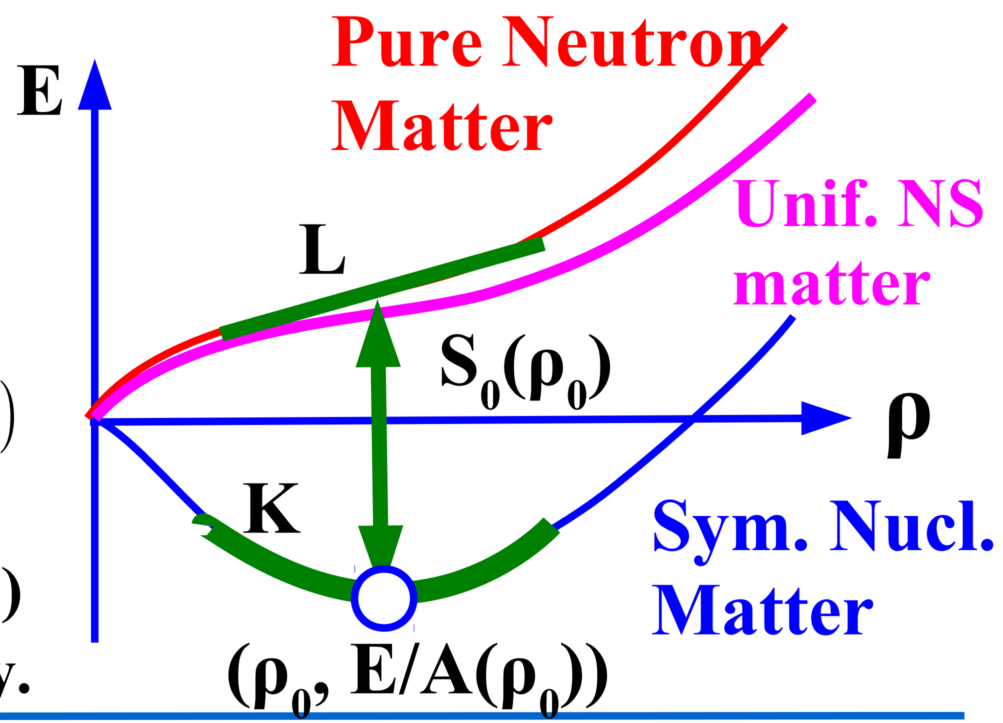
- **Energy per nucleon in nuclear matter**

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

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

  - **Saturation point (ρ_0, E_0) ~ (0.16 fm^{-3} , –16 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.



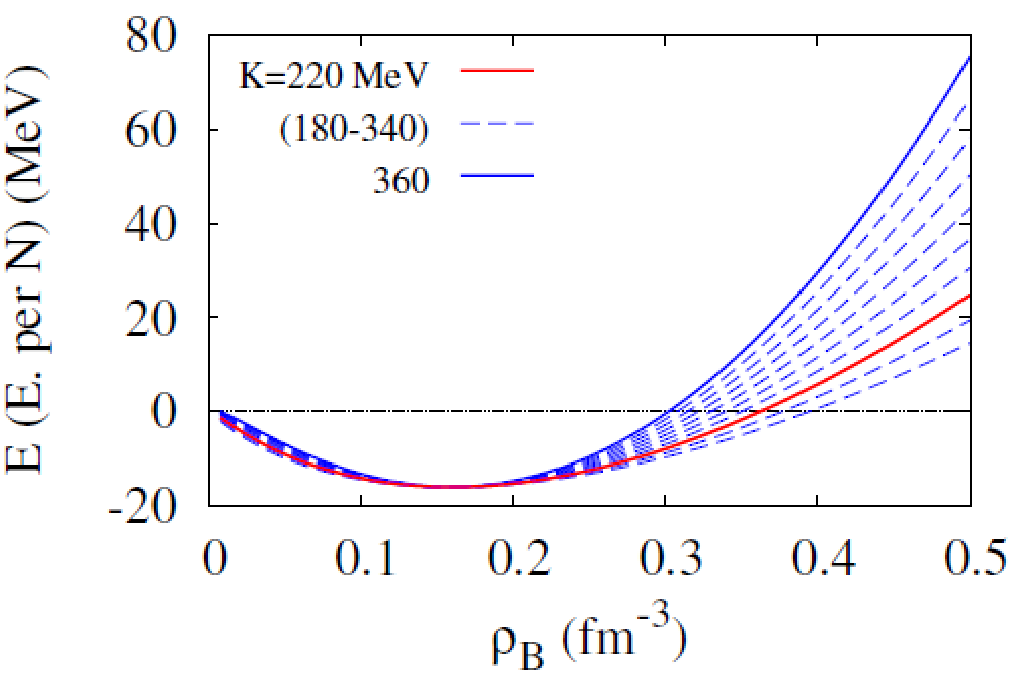
Simple parametrized EOS

- **Skyrme int. motivated parameterization**

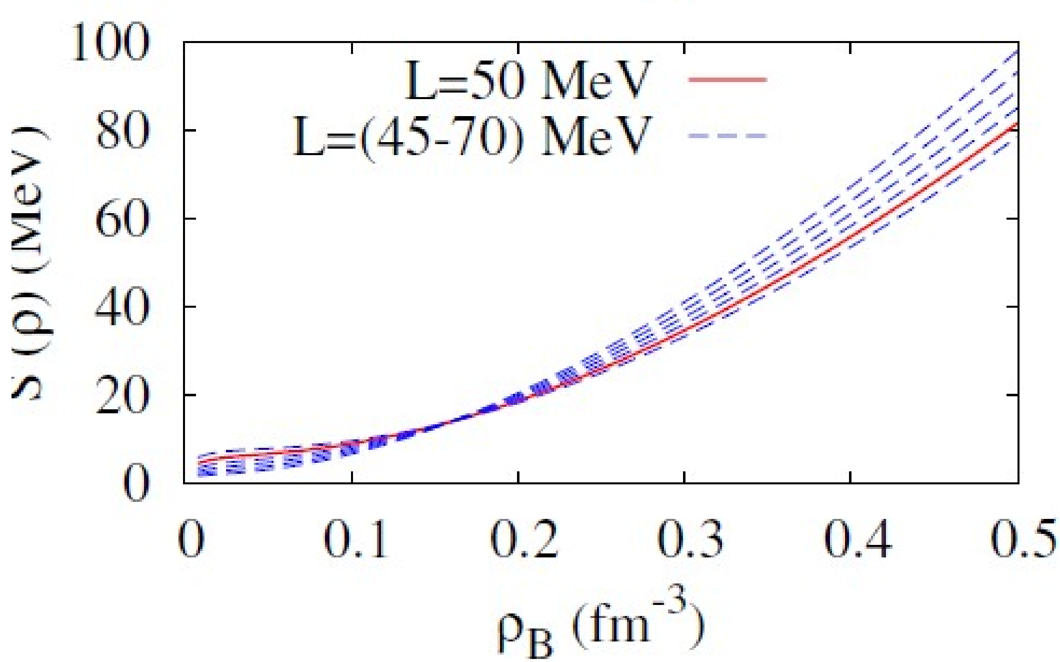
$$E_{\mathrm{SNM}} = \frac{3}{5}E_F(\rho) + \frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right) + \frac{\beta}{2+\gamma}\left(\frac{\rho}{\rho_0}\right)^{1+\gamma}$$

$$S(\rho) = \frac{1}{3}E_F(\rho) + \left[S_0 - \frac{1}{3}E_F(\rho_0)\right]\left(\frac{\rho}{\rho_0}\right)^{\gamma_{\mathrm{sym}}}$$

- **ρ_0, E/A(ρ_0), K → α, β, γ , L → γ_{sym}**

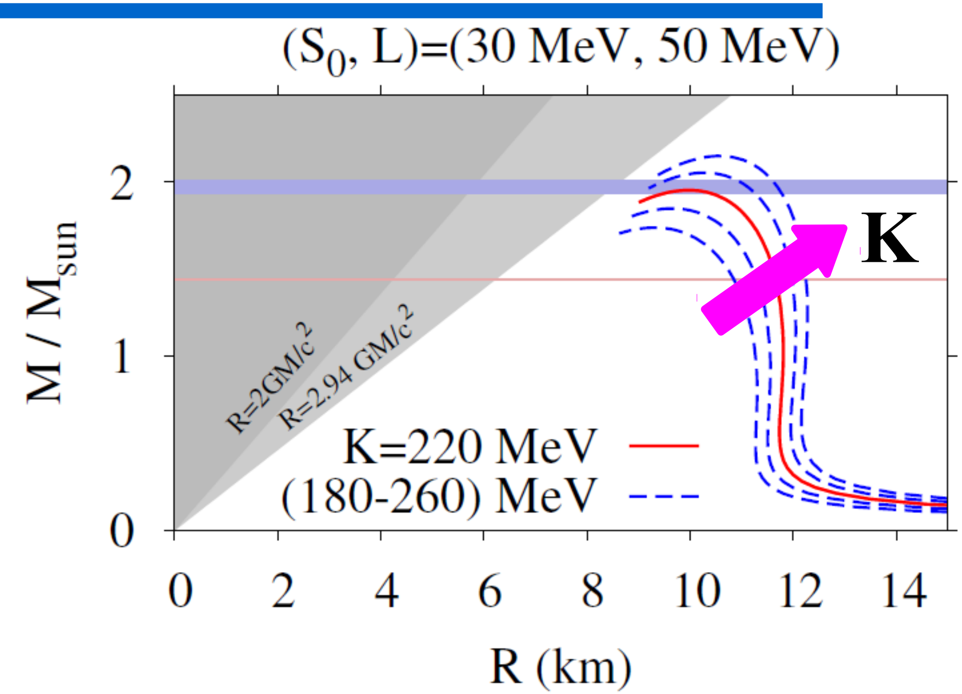


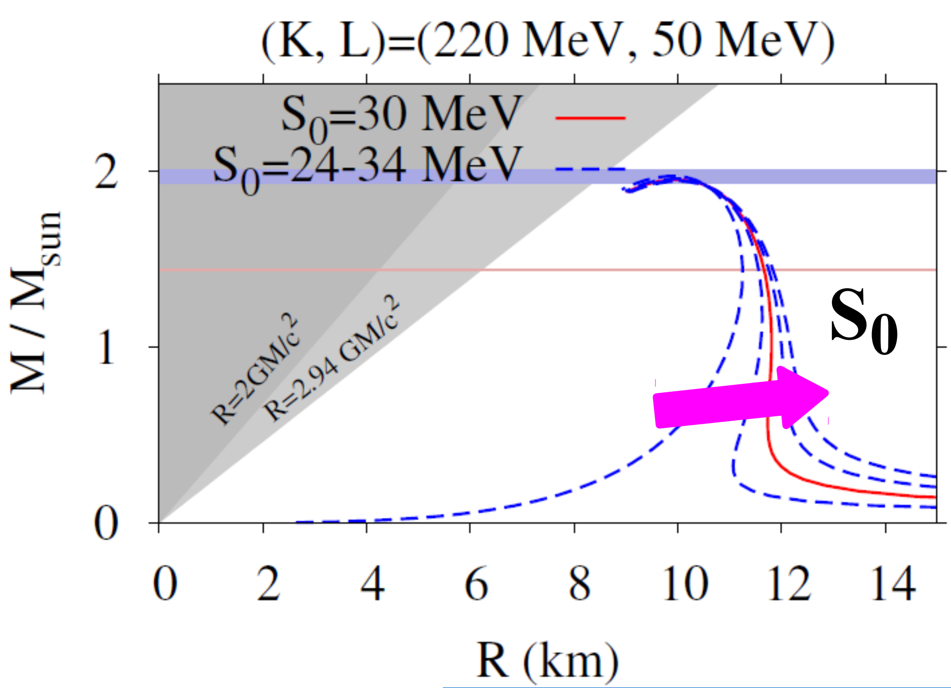
K=220 MeV, S_0=30 MeV

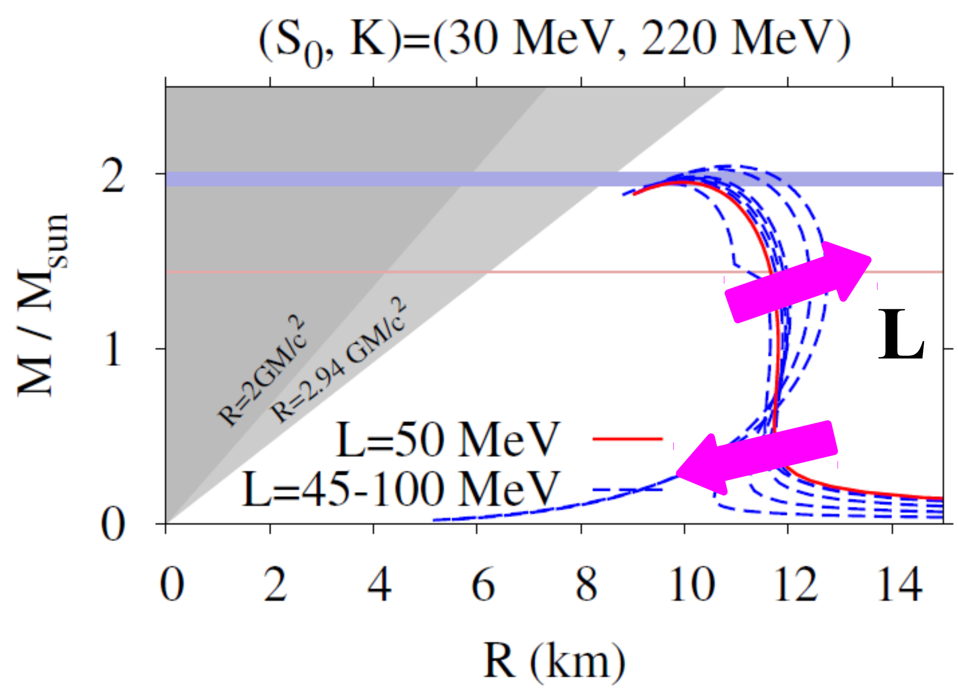


Simple parametrized EOS

- **Larger K → M ↑, R ↑**
- **Larger S_0 → R ↓ at small M**
- **Larger L**
  → R ↑(↓) at large (small) M



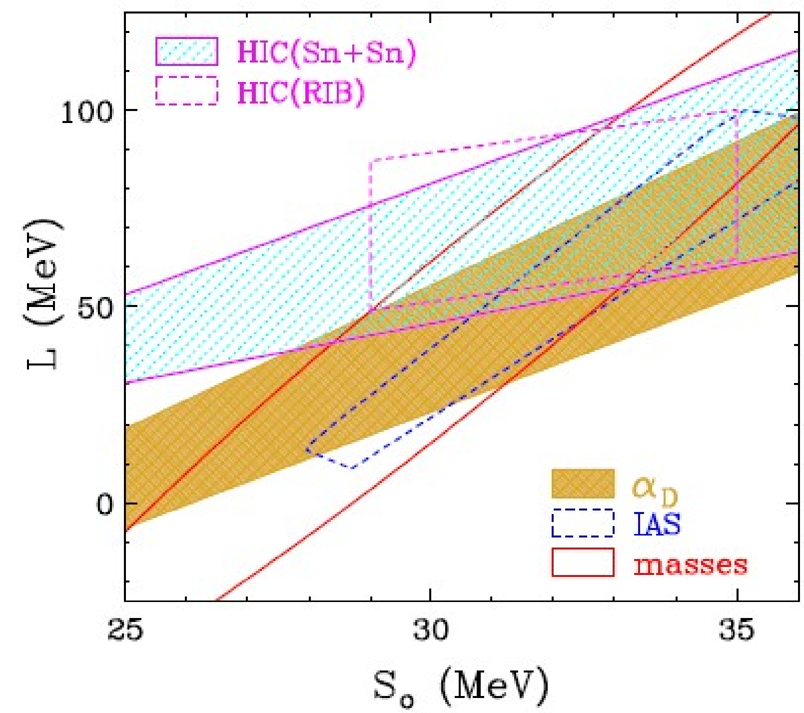


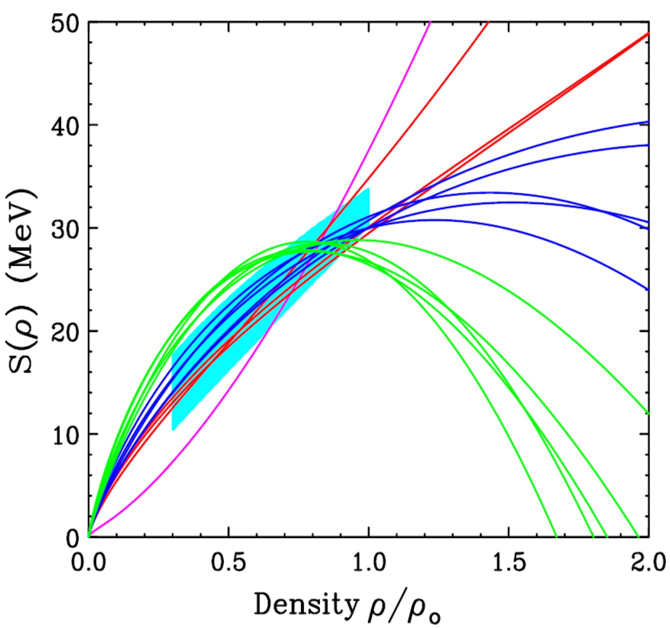


Symmetry Energy

- **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 = 30-35 MeV, L = 50-90 MeV
Is it enough for NS radii ?



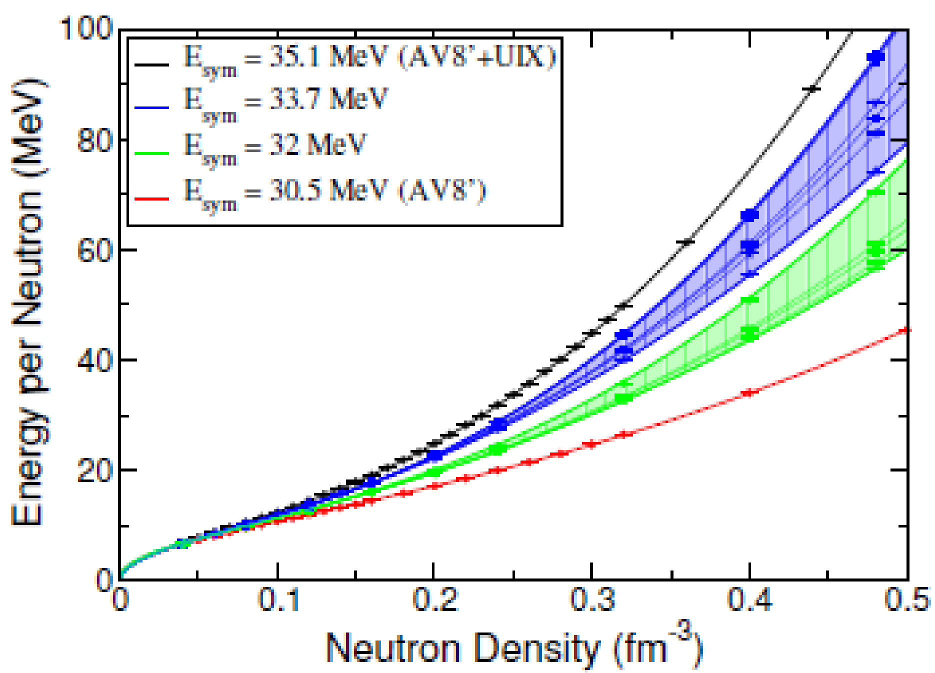


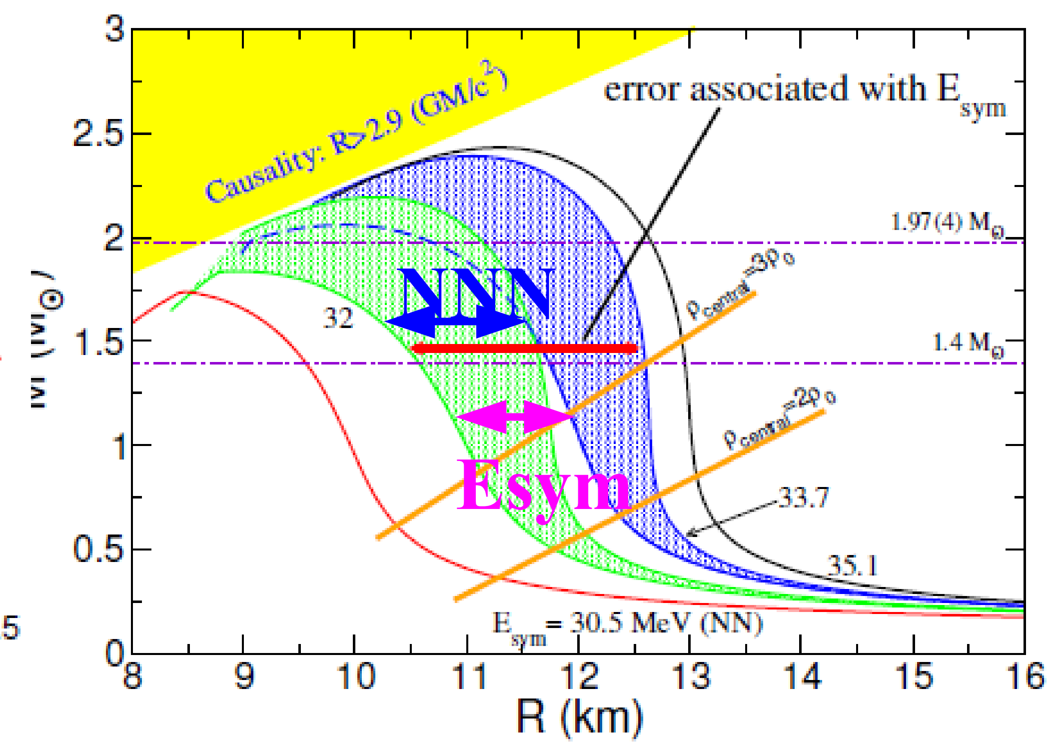
M.B.Tsang et al. (NuSYM2011), PRC 86 ('12)015803.

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

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}.**



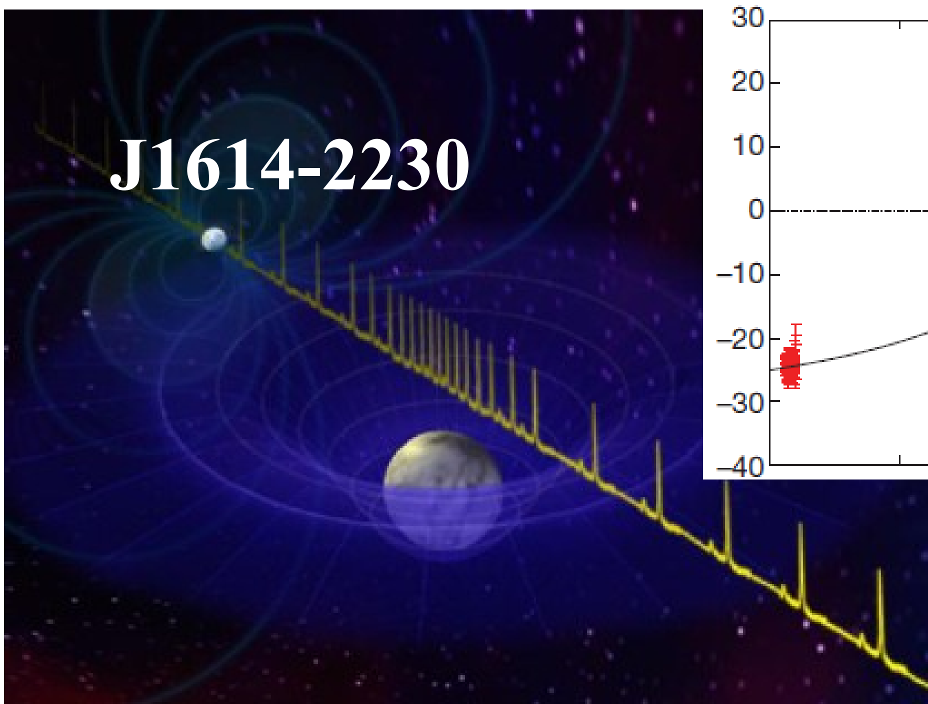


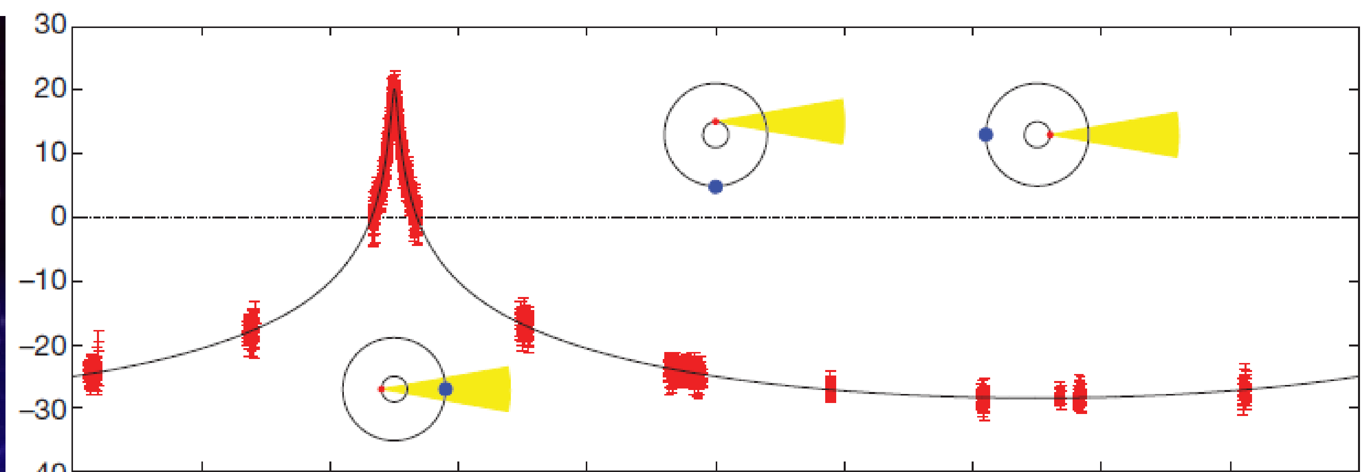
Gandolfi, Carlson, Reddy, PRC 032801, 85 (2012).

Massive Neutron Star puzzle

Massive Neutron Star

- **General Relativity Effects on Time Delay**
  - **Einstein delay : varying grav. red shift**
  - **Shapiro delay : companion's grav. field**
- **A massive neutron star (J1614-2230)**
  - **$M = 1.97 \pm 0.04\ M_{\odot}$ is obtained using the Shapiro delay**
    Demorest et al. (2010)

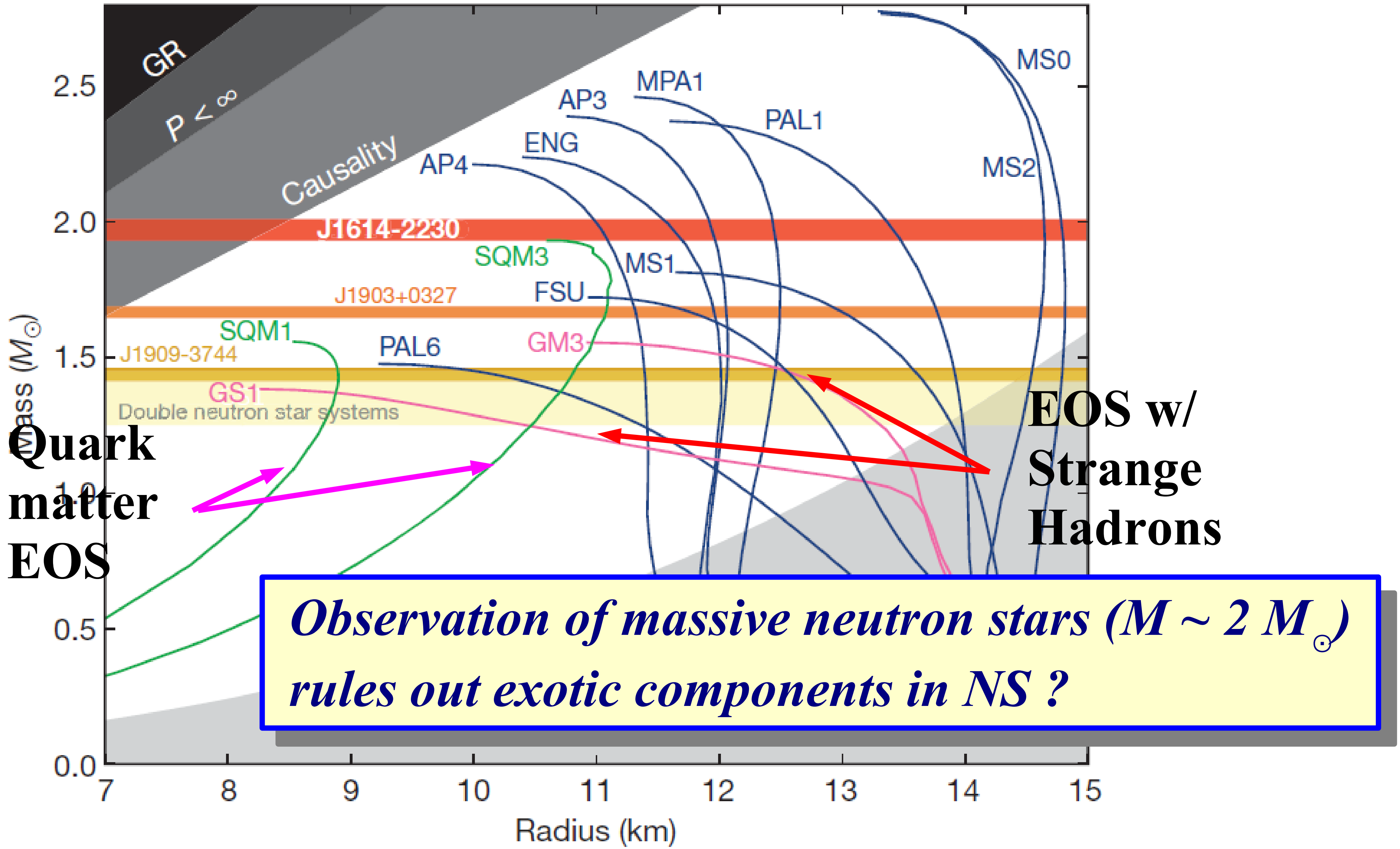




$$\Delta_S = -2m \left[\ln \frac{r}{a} + \ln \left(1 - \sin i \sin \phi \right) \right]$$

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

Massive Neutron Star Puzzle



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

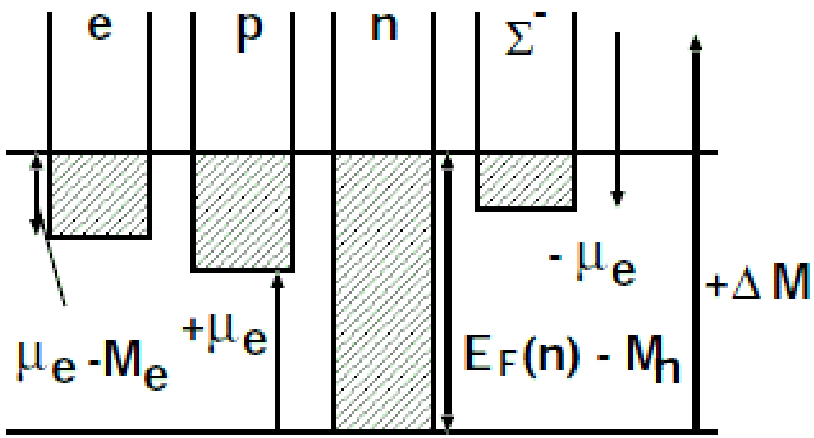
PSR J1614-2230: 1.97 ± 0.04 $M_\odot$ *Demorest et al., Nature 467('10)1081 (Oct.28, 2010).*

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

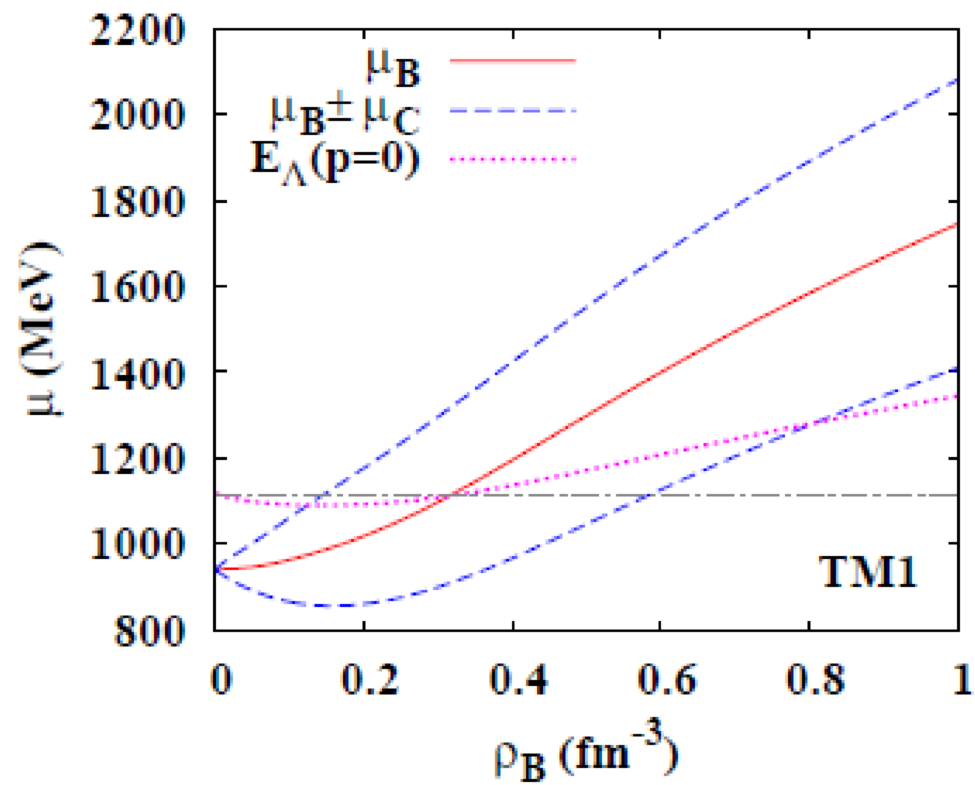
Hyperons in Dense Matter

- What appears at high density ?
  - Nucleon superfluid ($^3S_1$, $^3P_2$), Pion condensation, Kaon condensation, Baryon Rich QGP, Color SuperConductor (CSC), Quarkyonic Matter, ...
  - Hyperons

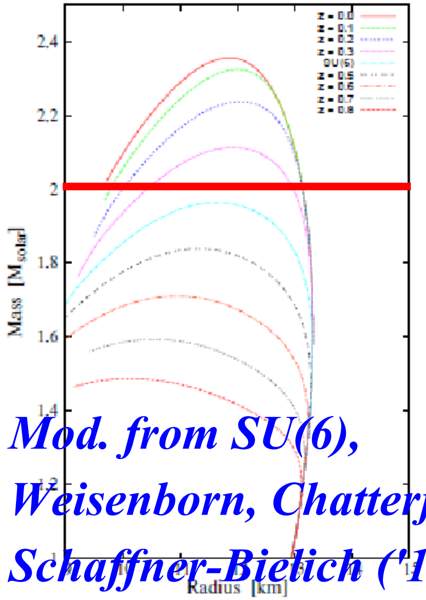
    Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, Weigel; Sugahara, Toki; Schaffner, Mishustin; Balberg, Gal; Baldo et al.; Vidana et al.; Nishizaki,Yamamoto, Takatsuka; Kohno,Fujiwara et al.; Sahu,Ohnishi; Ishizuka, Ohnishi, Sumiyoshi, Yamada; ...



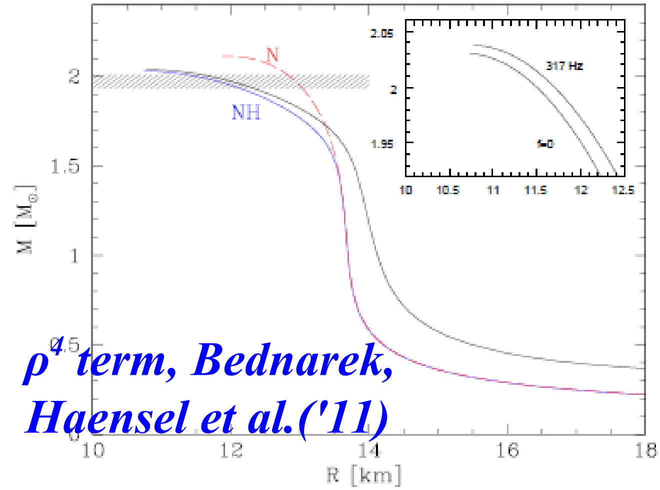
Chemical potential overtakes Λ mass → appearance of Λ



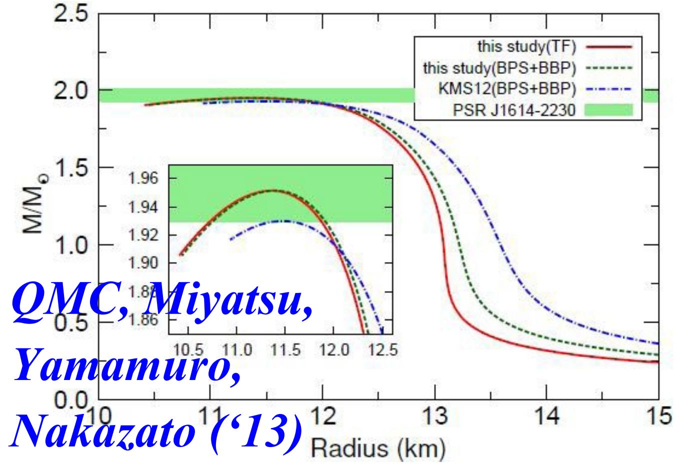
NS matter EOS with hyperons



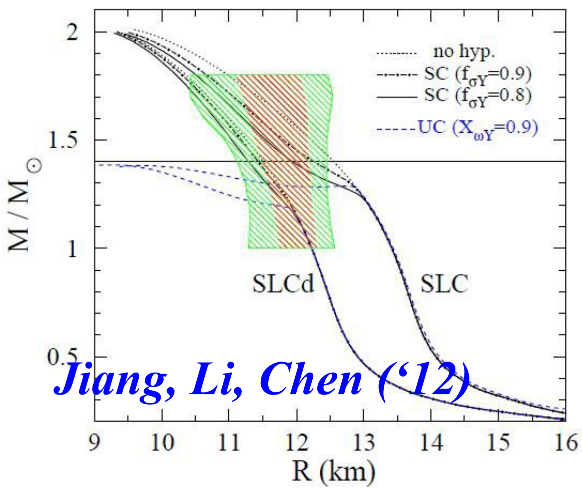
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



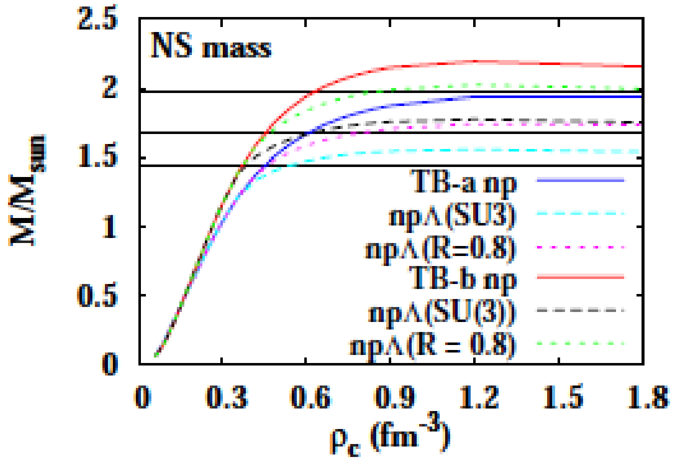
ρ^4 term, Bednarek, Haensel et al.('11)



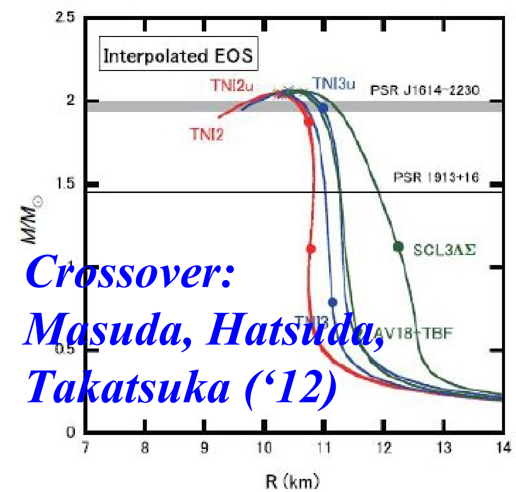
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



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



Crossover: Masuda, Hatsuda, Takatsuka ('12)

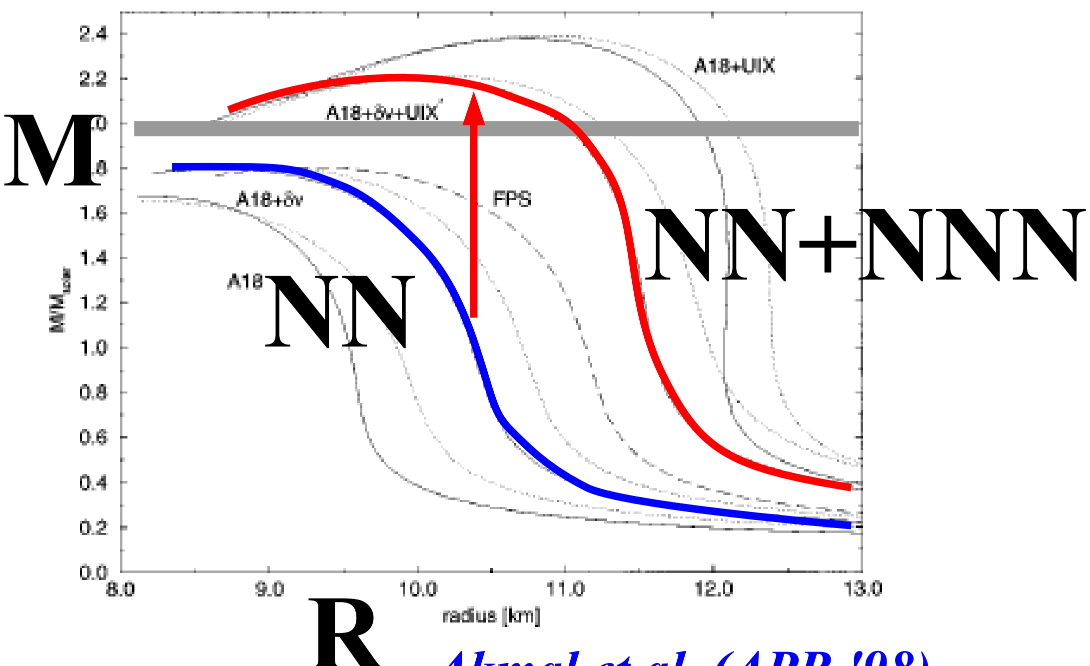
> ***These are phenomenological "solutions". How can we examine them ?***

Possible Solutions to Massive NS puzzle

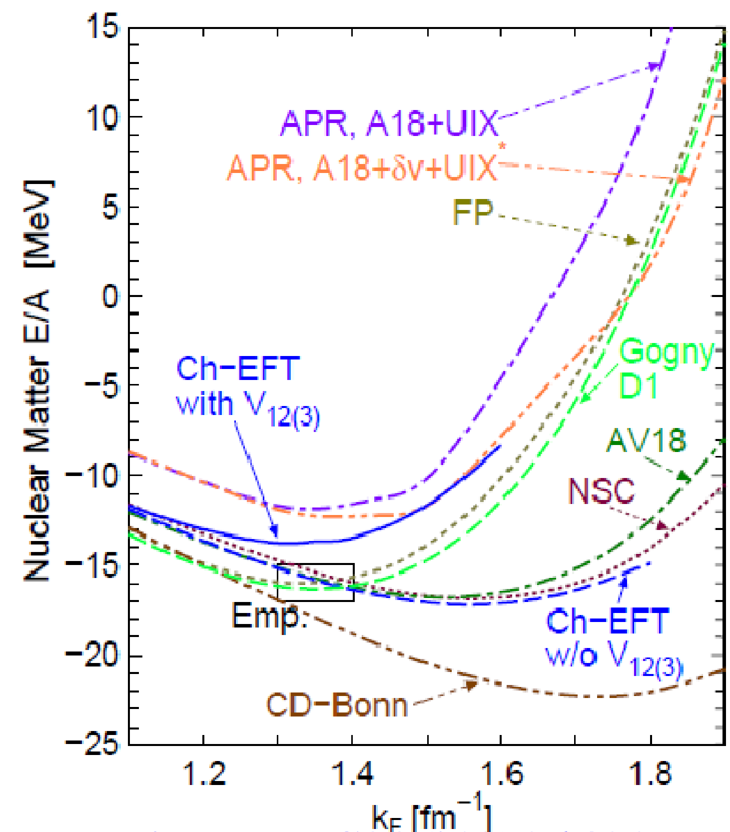
- **Proposed "Solutions" of Massive NS puzzle**
  - **Choose Stiff EOS for nuclear matter** *Tsubakihara, Harada, AO ('14)*
  - **Modification of YN interaction** *Weisenborn, Chatterjee, Schaffner-Bielich ('11); Jiang, Li, Chen ('12); Tsubakihara, AO ('13)*
  - **Introducing BBB repulsion** *S. Nishizaki, T. Takatsuka,Y. Yamamoto ('02); Bednarek, Haensel et al.('11); Miyatsu, Yamamuro, Nakazato ('13); Tamagaki ('08). Togashi, Hiyama, Takano, Yamamoto; Nakamoto, Suzuki; ….*
  - **Early transition to quark matter** *Masuda, Hatsuda, Takatsuka ('12)*
- **What is necessary to solve the massive NS puzzle ?**
  - **EOS of symmetric nuclear matter at high density**
  - **Symmetry Energy at supra nuclear density.**
  - **Yet un-explored YN & YY interactions**
  - **Three-body interaction including hyperons (YNN, YYN, YYY) and its effects on EOS**
  - **Finding onset density of quark matter**

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



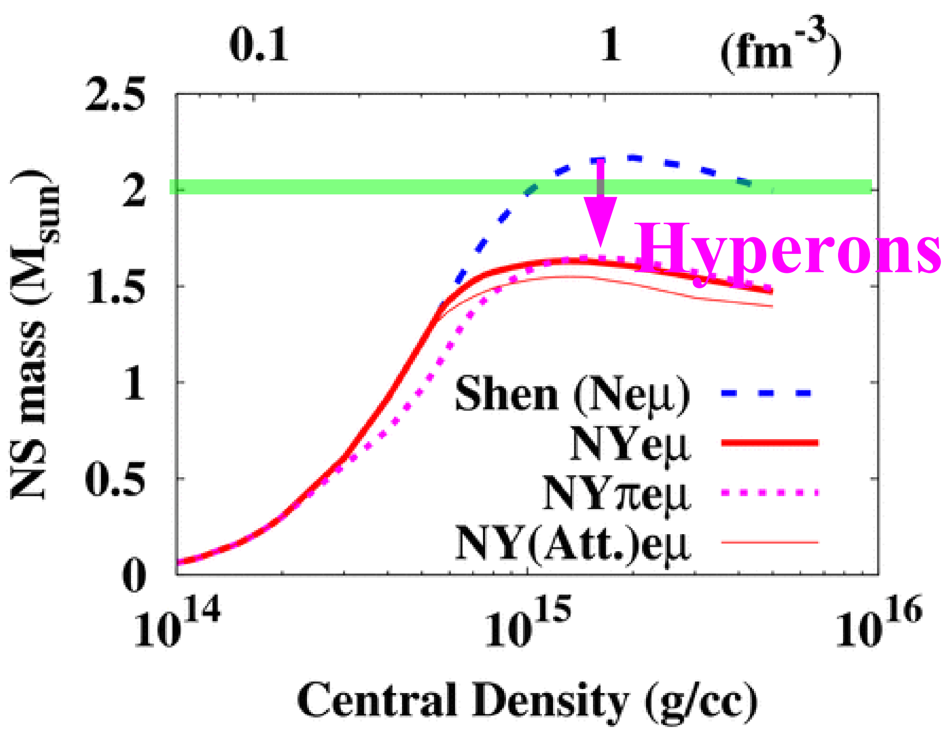
Akmal et al. (APR,'98)



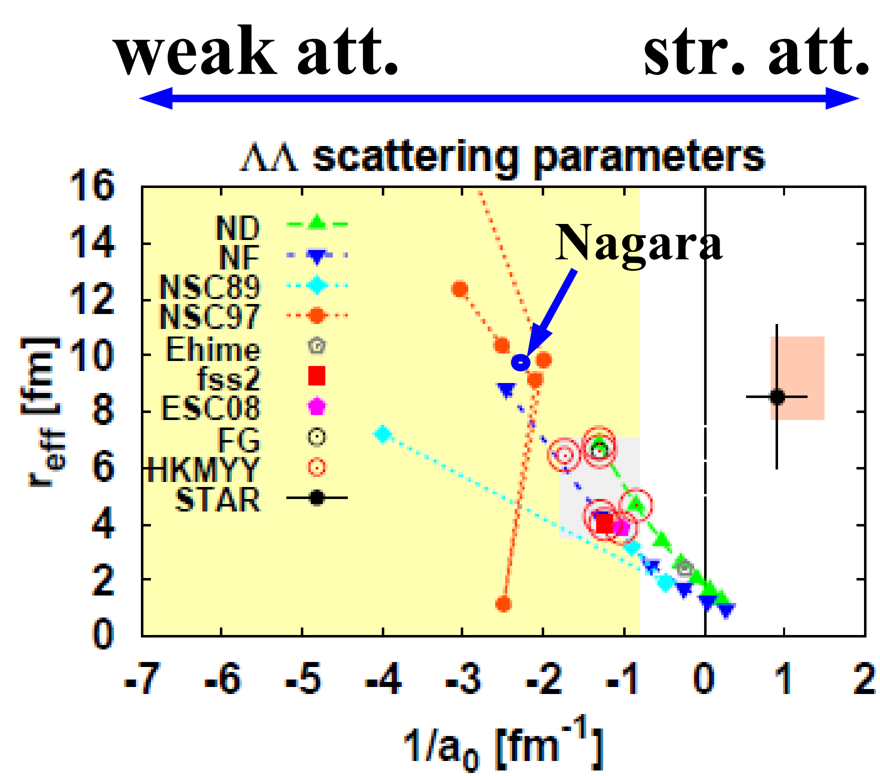
M. Kohno, PRC88('13)064005

Hyperons & YY interaction

- Hyperons are expected to appear in NS and soften EOS.
  - Hypernuclear data → max. NS mass reduction of (0.5-1.0) M□
  - Nagara event (ΛΛ nuclei) and heavy-ion collisions (ΛΛ correlation) implies ΛΛ int. is weakly attractive.



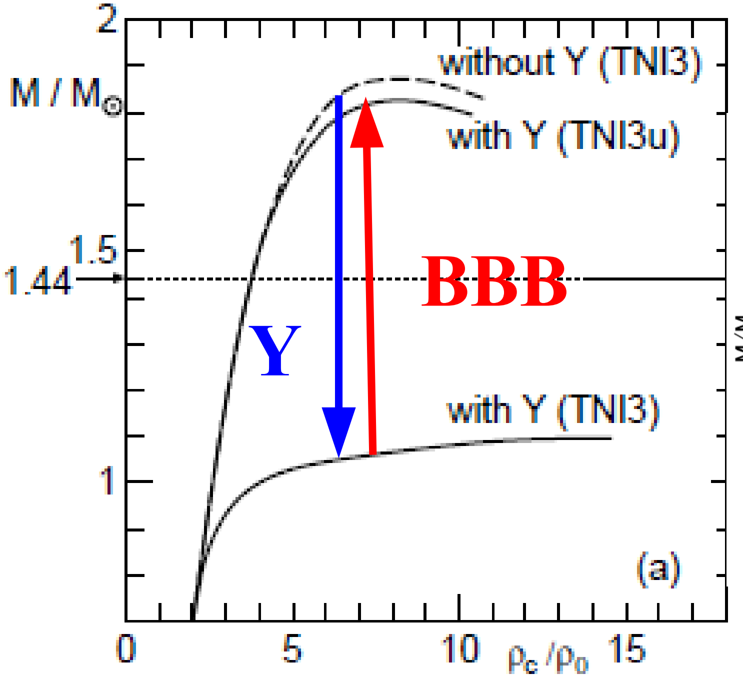
Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08),085201



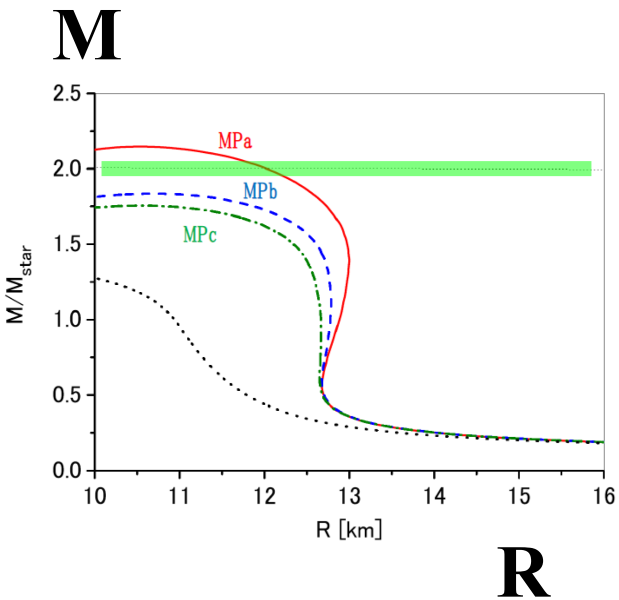
Morita, Furumot, AO ('15)

BBB force including Hyperons

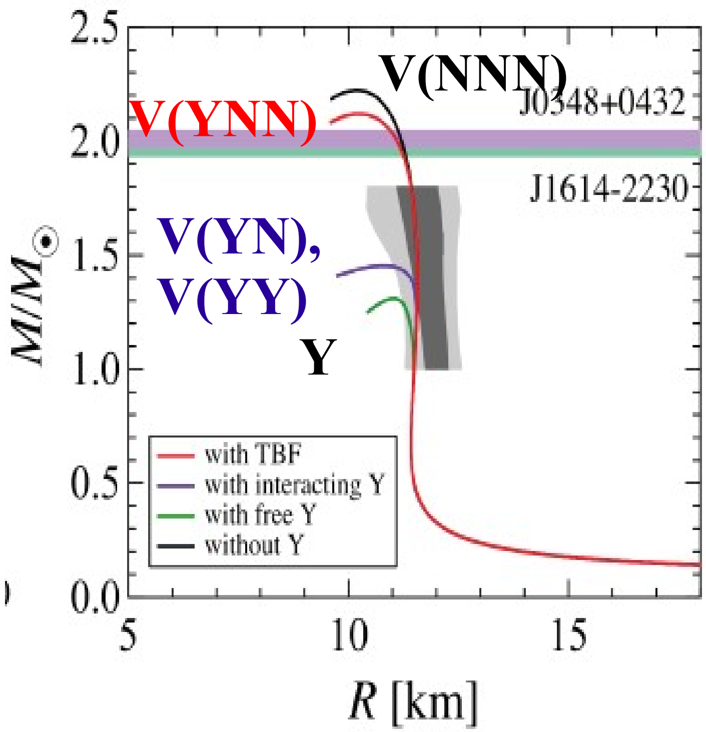
- Repulsive BBB int. incl. Y is necessary to support 2 $M_\odot$ NS.
  - "Universal" BBB force
    Nishizaki,Takatsuka,Yamamoto ('02), Yamamoto,Furumoto,Yasutake,Rijken('13)
  - Variational calc. including hyperons *Togashi et al. (in prep.)*



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



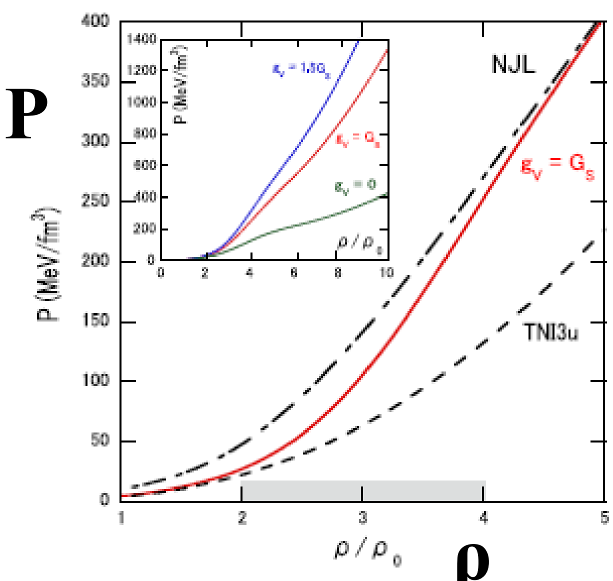
Yamamoto, Furumoto, Yasutake, Rijken ('13)

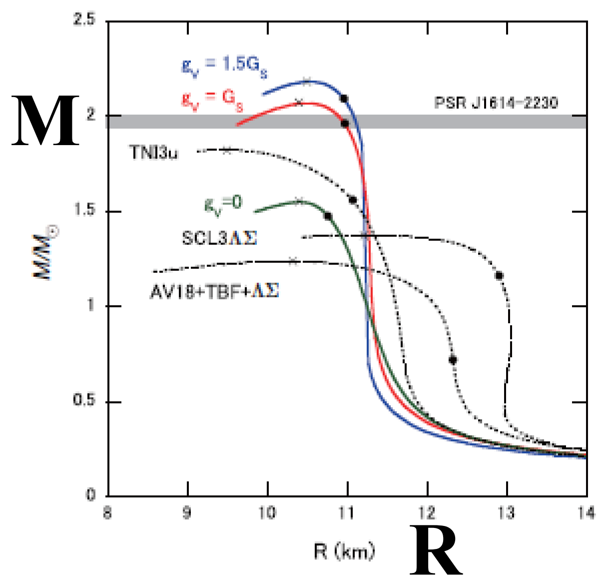


Togashi, Hiyama, Takano, Yamamoto, in prep.

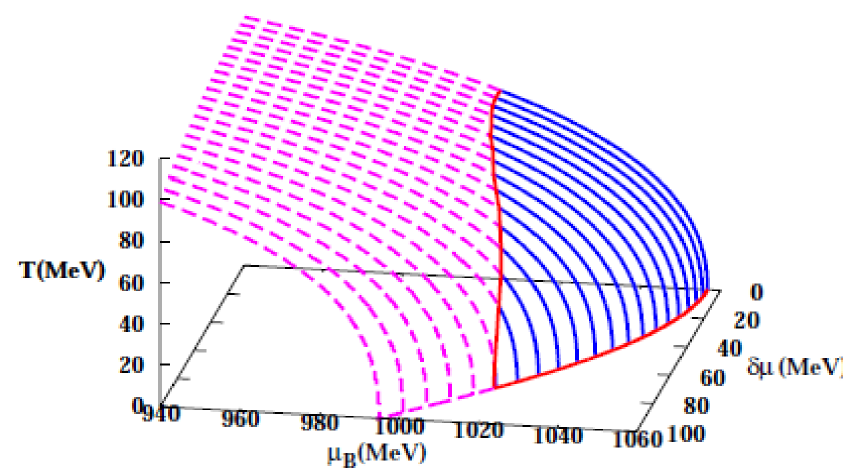
Early crossover transition to quark matter

- **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)

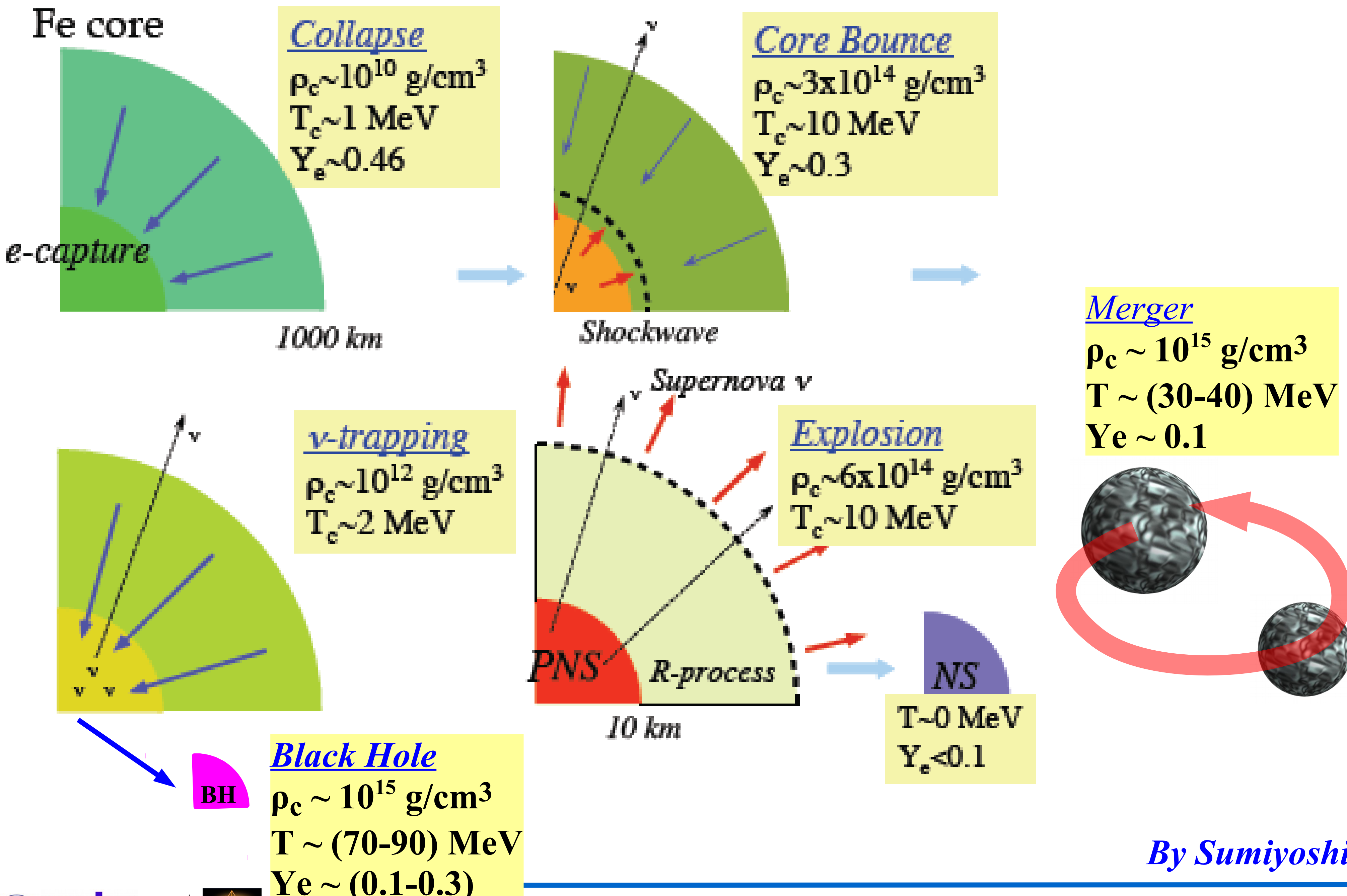


AO, Ueda, Nakano, Ruggieri, Sumiyoshi, PLB704('11),284
H. Ueda, et al. PRD88('13),074006

Summary

- **Neutron Stars (and compact stars) are laboratories of matter under extreme conditions.**
  - **Dense, Highly isospin asymmetric, Exotic components.**
- **Neutron Star Matter EOS is extensively and actively studied.**
  - **RI accelerators, Hadron beam accelerators, Heavy-ion accelerators**
  - **Many Satellites would be launched.**
  - **Theoretical works are in progress.**
- **Possible solutions of massive neutron star puzzle**
  - **Hadronic scenario: Repulsive BBB force including hyperons.**
    Strength of BBB force from chi EFT (Kohno),
    spin-orbit force (Nakada), Λ and ΛΛ nuclei.
  - **Quark matter scenario:**
    Crossover transition does not soften EOS much, and quark matter can be stiff with vector int. (*Masuda+*) or Magnetic field (*Sotani+*)
    How can we examine ?

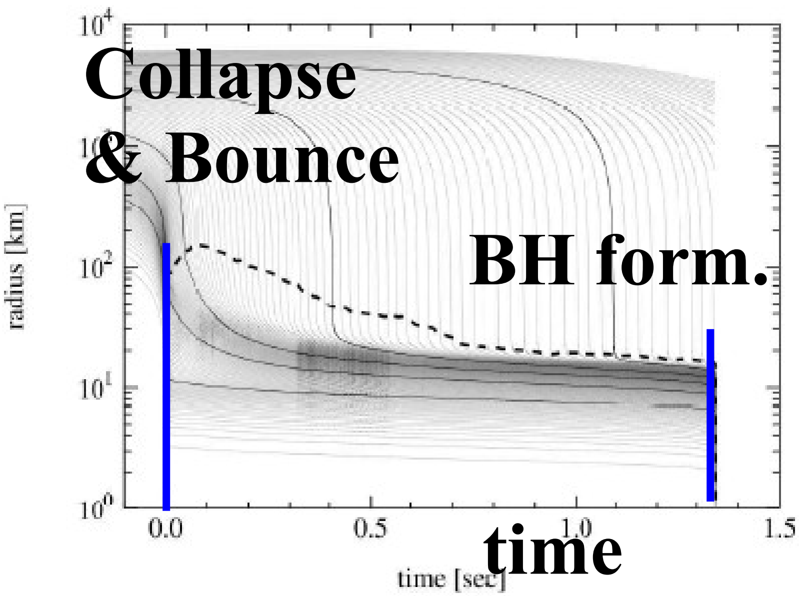
Gravitational Collapse of Massive Star



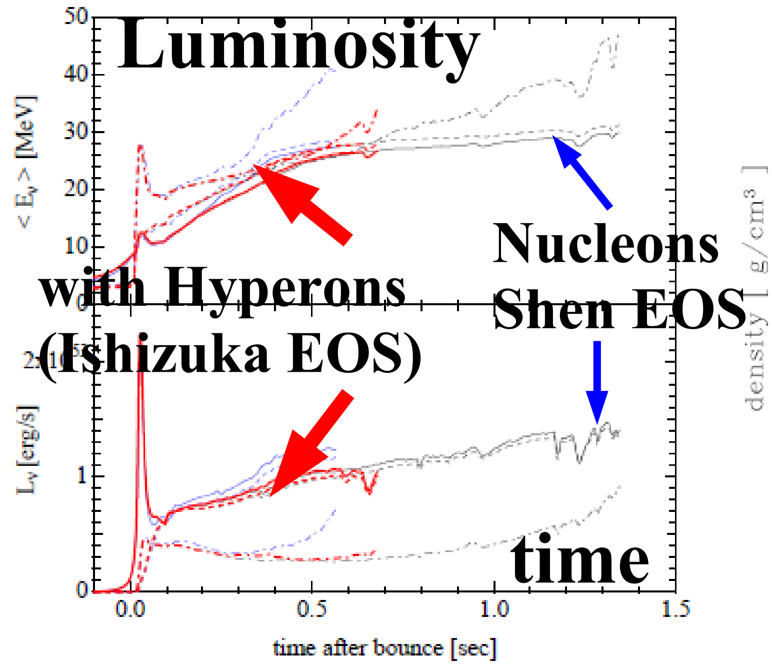
By Sumiyoshi

Dynamical Black Hole Formation

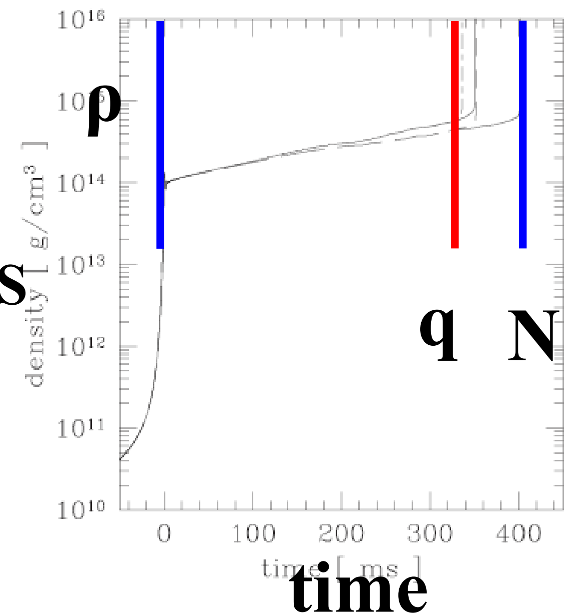
- **Gravitational collapse of heavy (e.g. 40 $M_\odot$) progenitor would lead to BH formation.**
  - **Shock stalls, and heating by ν is not enough to take over strong accretion. → failed supernova**
  - **ν emission time ~ (1-2) sec w/o exotic matter.**
  - **emission time is shortened by exotic dof (quarks, hyperons, pions).**



Sumiyoshi, Yamada, Suzuki, Chiba, PRL 97('06)091101.



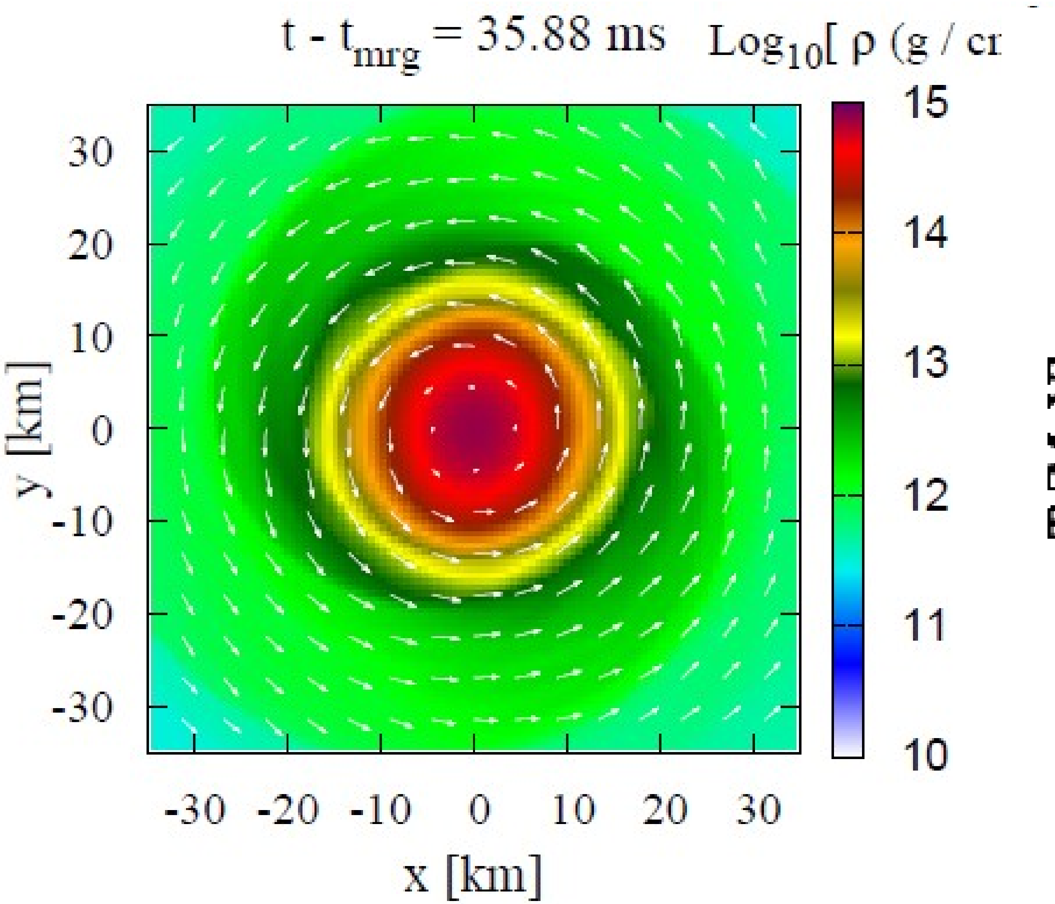
Sumiyoshi,Ishizuka, AO, Yamada, Suzuki, ApJL 690('09)43.

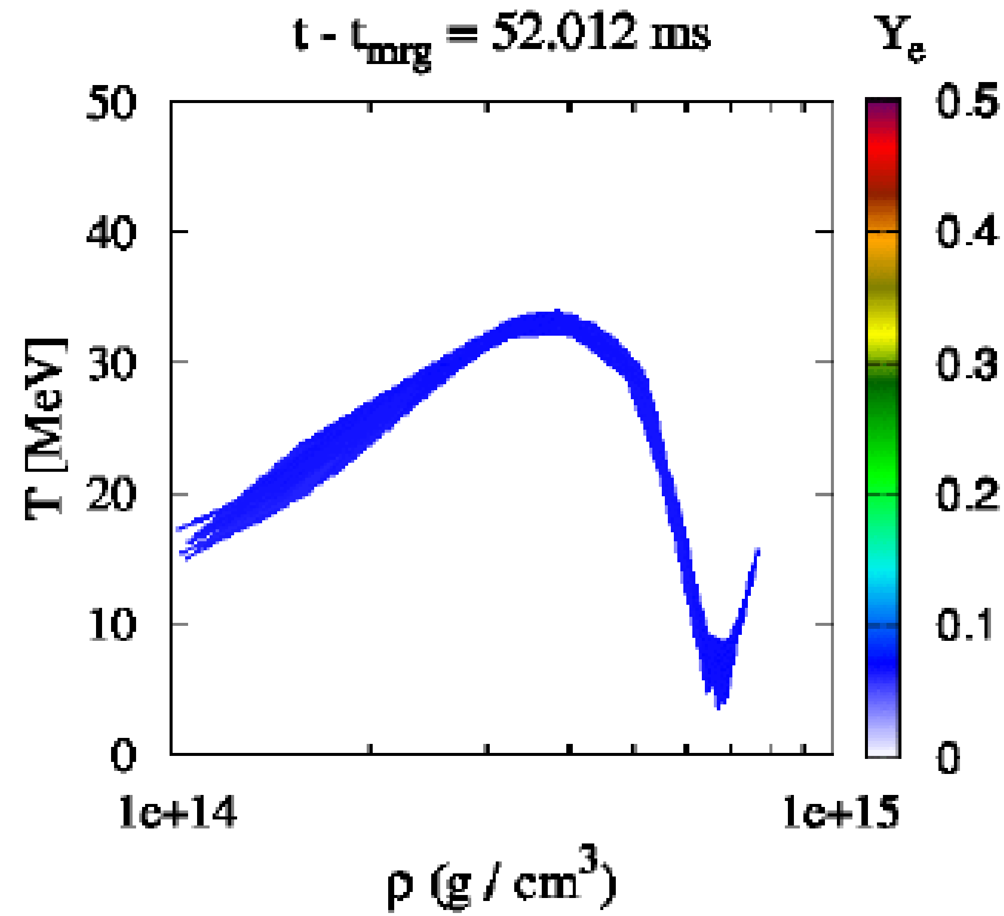


Nakazato, Sumiyoshi, Yamada, PRD77('08)103006

Binary Neutron Star Merger

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



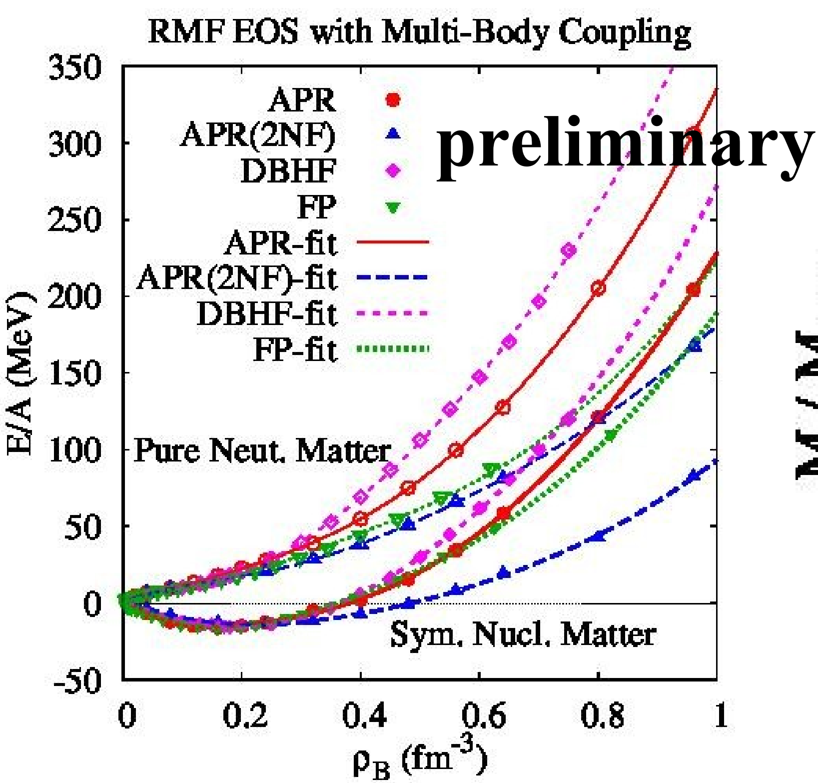


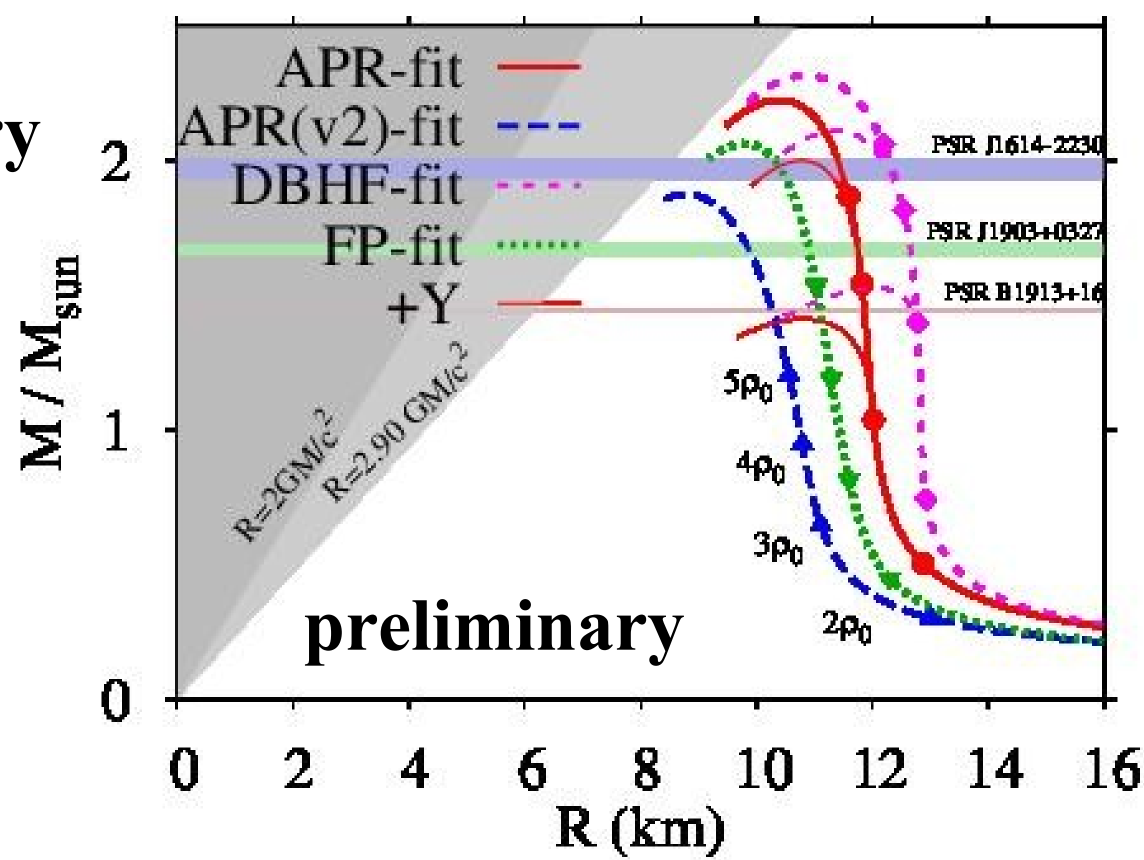
Courtesy of K. Kiuchi
Data are from Y. Sekiguchi, K. Kiuchi, K. Kyotoku, M. Shibata, PRD91('15)064059.

Thank you for your attention !

NS matter in "ab initio"-fit + Λ

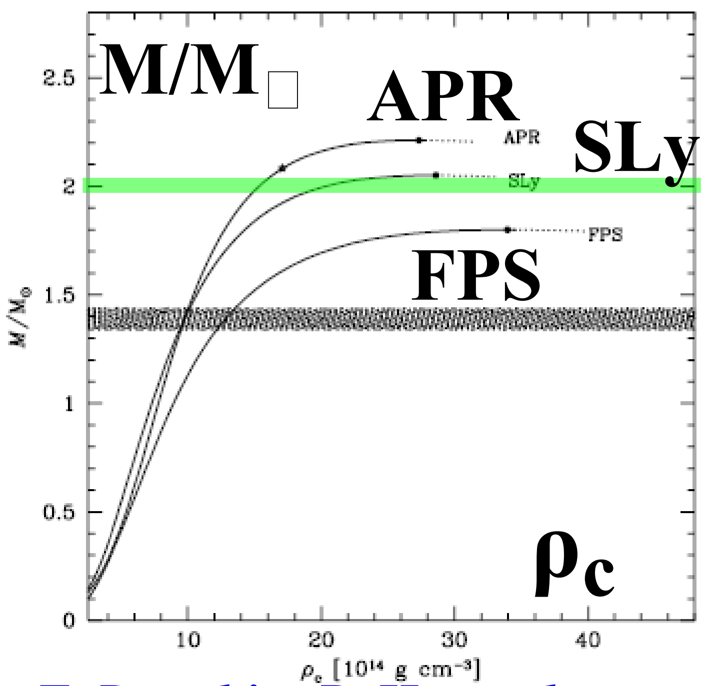
- **Fit to ab initio EOS (FP, APR, DBHF)**
  + phen. Λ potential (U(ρ_0) ~ -30 MeV)



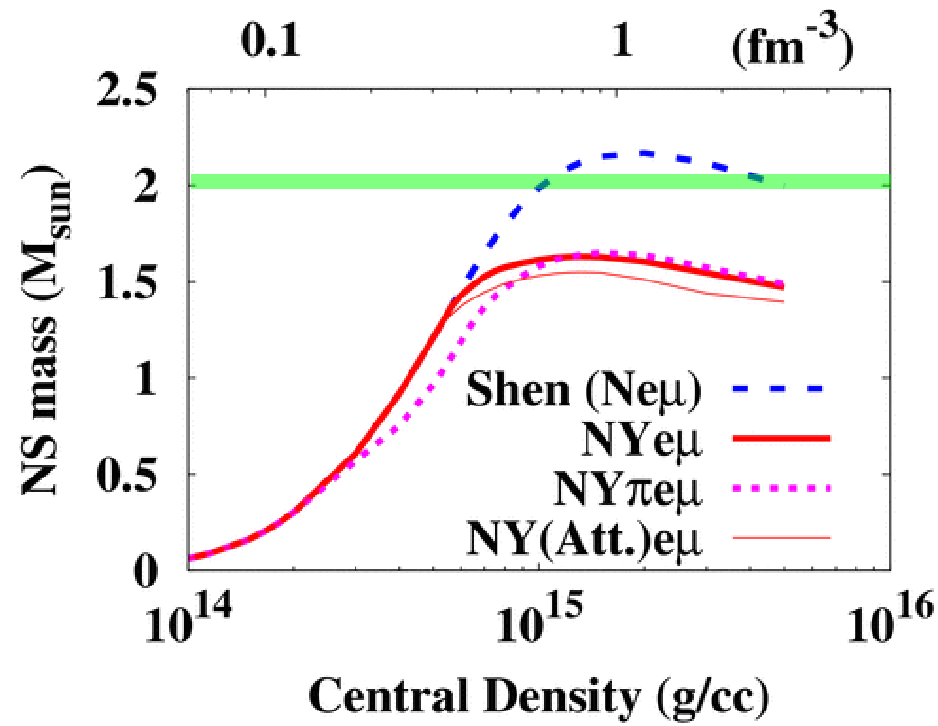


Mean Field models

- **Fit parameters to nuclear properties (B.E., radius, …) → predict neutron star (M,R).**
  - **Non-Rel. treatment with SLy (std. parametrization), FPS (impr.) → Mmax ~ (1.8-2.0) M**
  - **Rel. MF (TM1) → Mmax ~ 2.2 M**



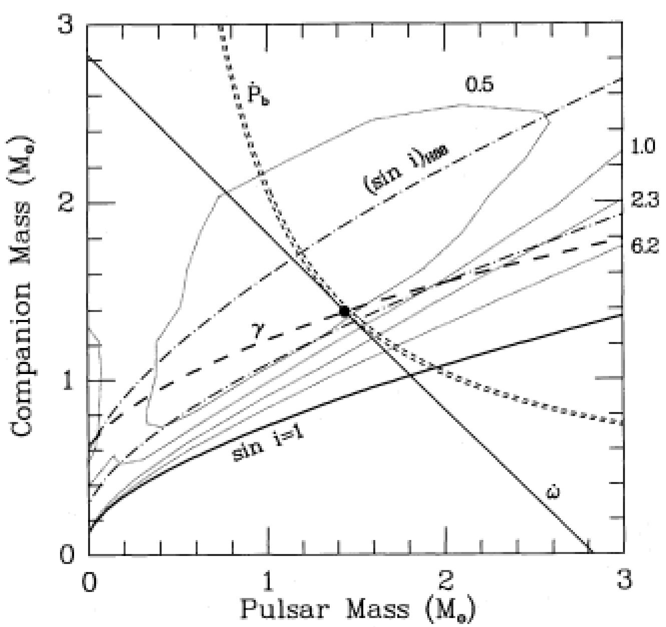
F. Douchin, P. Haensel. Astron.Astrophys.380('01)151.

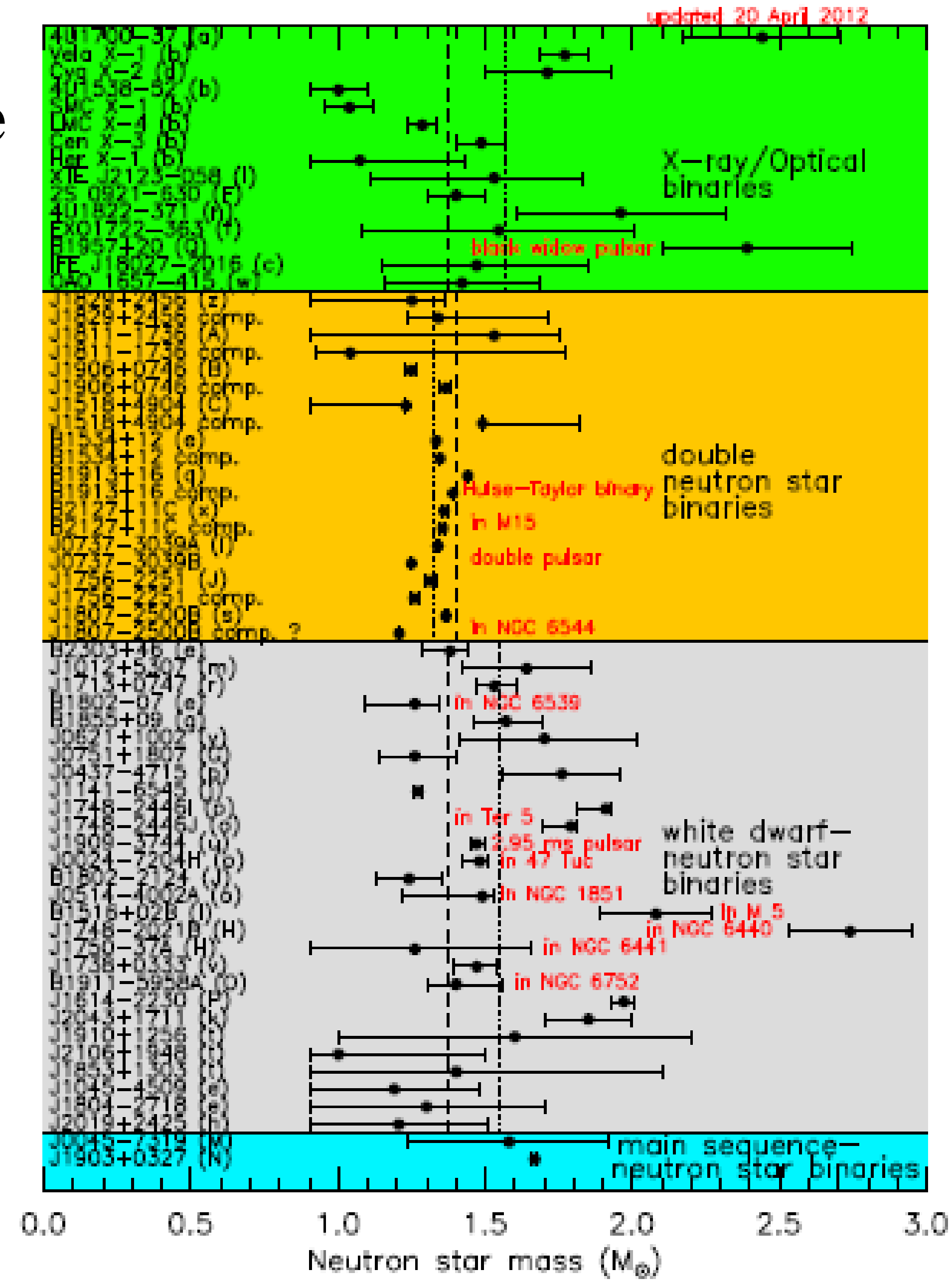


Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08),085201
c.f. H.Shen+('09) → n, p, Λ EOS

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





Lattimer (2013)