中性子星物理入門
Introduction to Physics of Neutron Stars

京大基研　大西　明
Akira Ohnishi (YITP, Kyoto U.)

原子核三者若手夏の学校 2015
8/17-22, 2015, ホテルたつき，蒲郡

- **Introducton**
- **Basics of Neutron Star Physics**
- **Neutron Star Matter EOS**
- **Massive NS Puzzle**
- **Summary**

中性子星物理入門

京大基研　大西　明
Akira Ohnishi (YITP, Kyoto U.)

原子核三者若手夏の学校 2015
8/17-22, 2015, ホテルたつき，蒲郡

概要

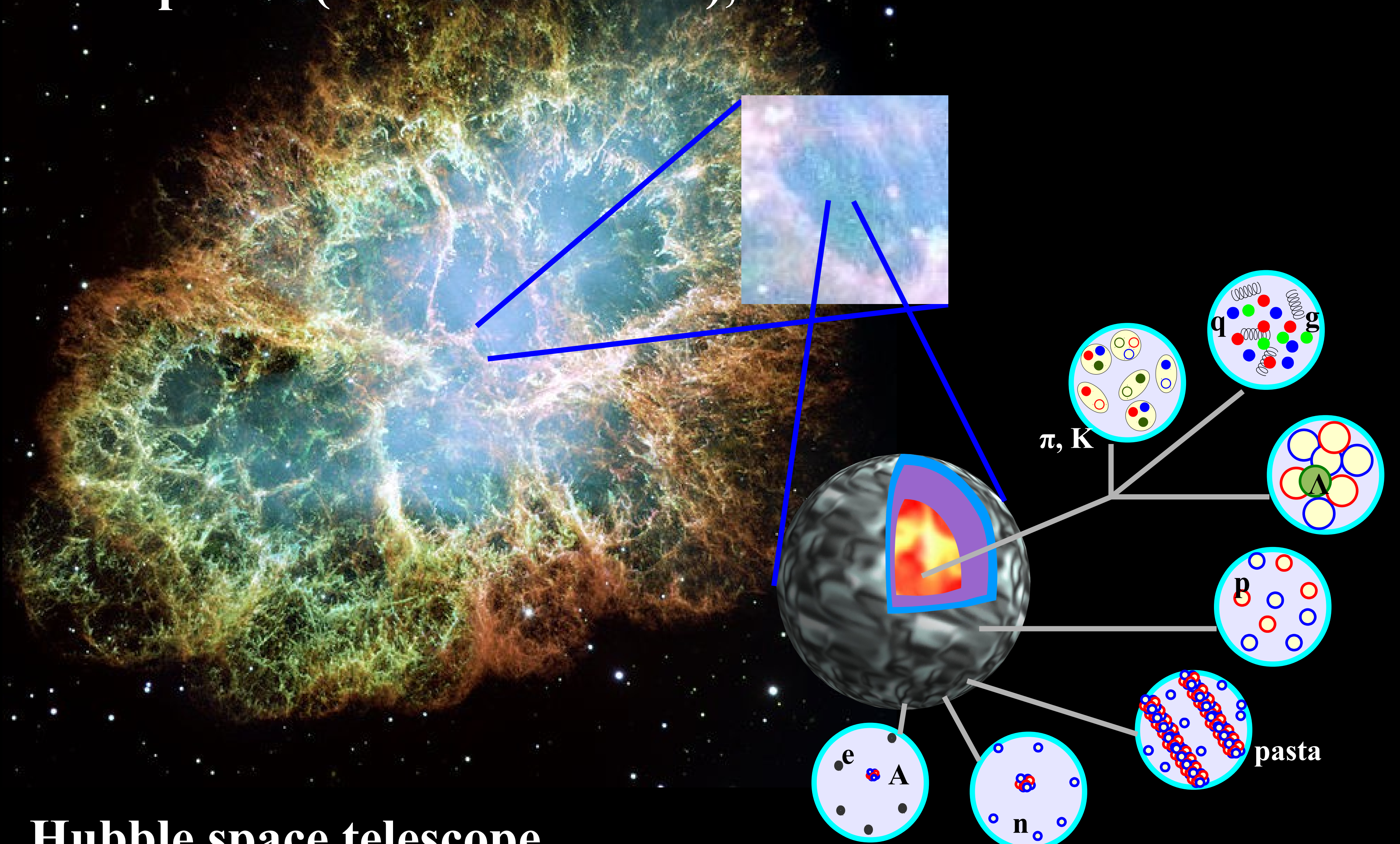
中性子星は密度、構成要素ともにバラエティに富む多体問題の宝庫であり、近年の実験・観測の進展により、実験データから示唆される相互作用の性質と観測データをつき合わせて中性子星物質状態方程式を定量的に議論できる時代を迎えつつある。

この三者共通講義では、まず中性子星の大まかな性質を概観した後、近年大きな問題となっている重い中性子星パズル・コンパクトな中性子星パズル・中性子星の冷却・中性子星の強い磁場などについて解説する。次に状態方程式を理解する上で基本となる理論の枠組みを解説し、理論・実験・観測による最近の取り組みを紹介する。

Contents

- Introduction
- Neutron star basics
  - NS mass: Kepler motion, Mass function, and GR effects
  - NS radius: Stephan-Boltzmann, Eddington limit, Red shift
  - A little on NS cooling and magnetic field
- Nuclear matter and neutron star matter EOS
  - Tolman-Oppenheimer-Volkoff (TOV) equation
  - Saturation Point, Incompressibility, and Symmetry Energy
- Massive neutron star puzzle
  - How can we sustain two-solar-mass NSs ?
  - Proposed mechanisms to sustain massive NSs
  - What is necessary to solve massive NS puzzle ?
- Summary

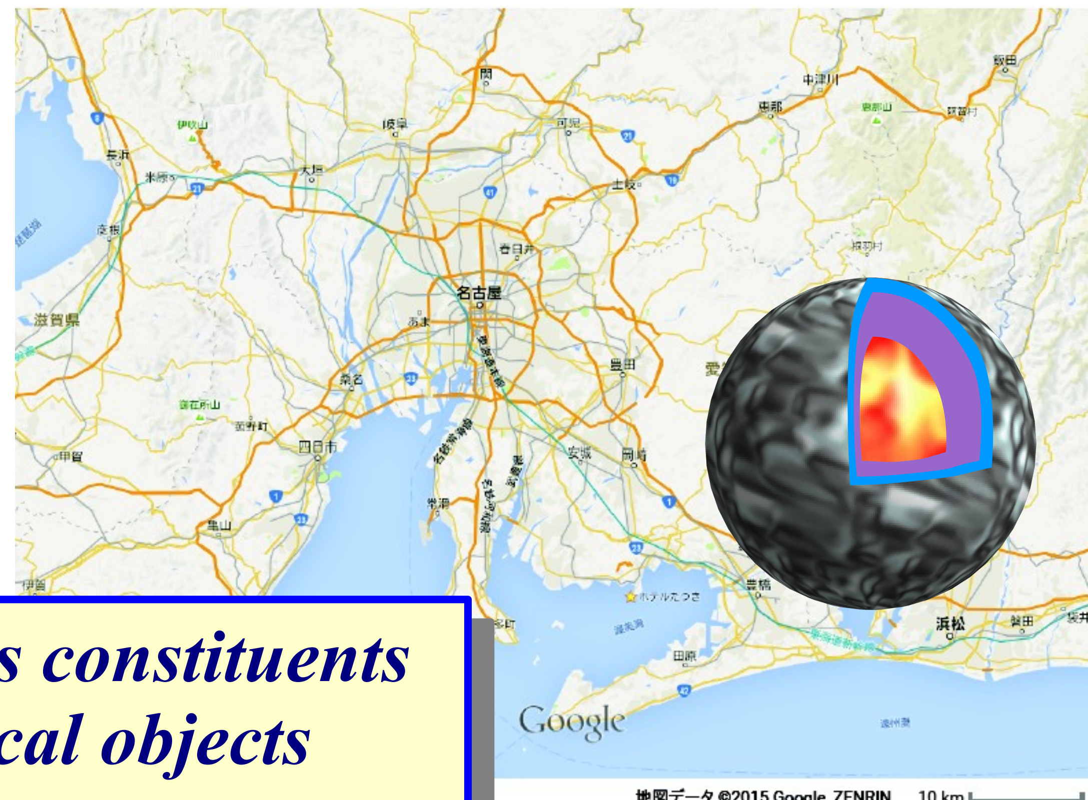
Crab Nebula
SN1054 (e.g. Meigetsu-ki, Teika Fujiwara)
Crab pulsar (PSR J0534+2200), discovered in 1968.



Hubble space telescope

Basic properties of neutron stars

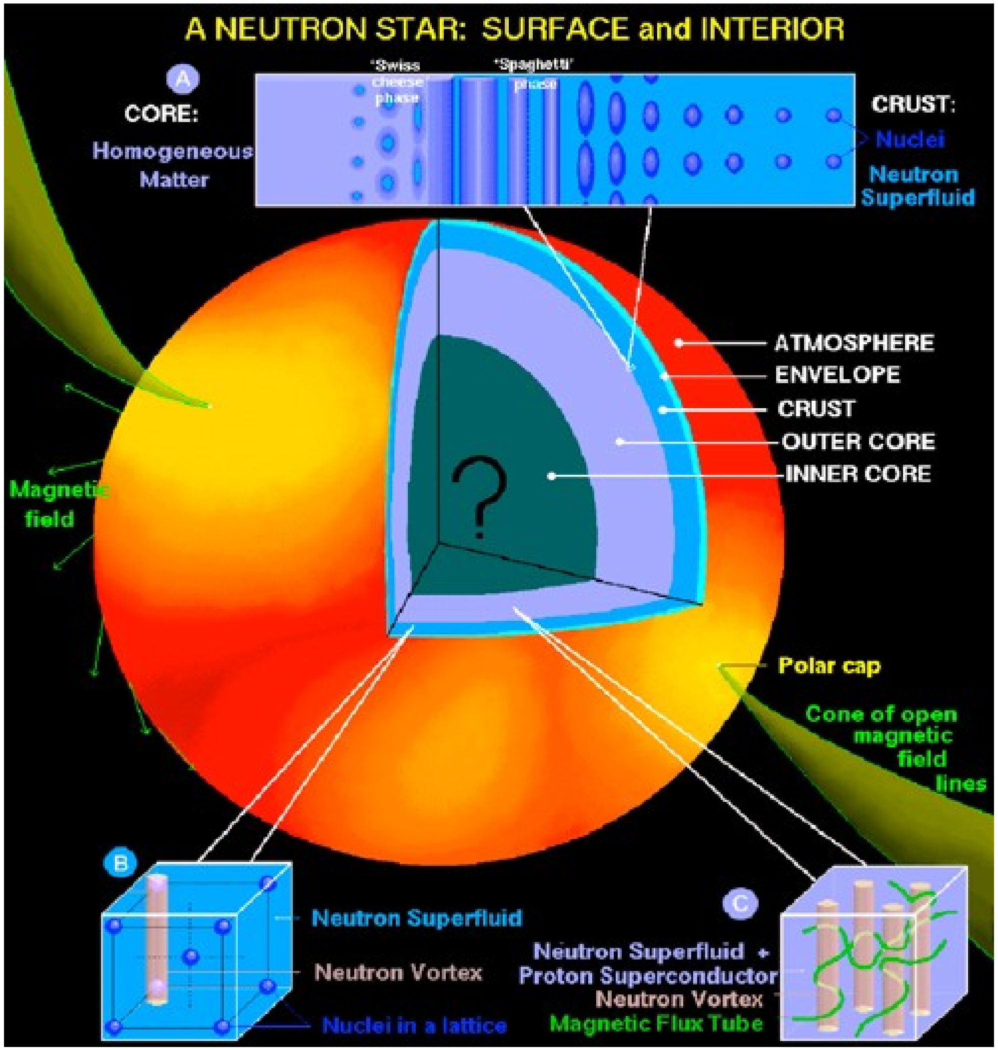
- **Mass: M = (1-2) $M_\odot$ (M ~ 1.4 $M_\odot$)**
- **Radius: 5 km < R < 20 km (R ~ 10 km)**
- **Supported by Nuclear Pressure**
  c.f. Electron pressure for white dwarfs
- **Cold enough**
  (T ~ 10^6 K ~ 100 eV)
  compared with
  neutron Fermi energy.
- **Various constituents**
  (conjectured)
  n, p, e, μ, Y, $\bar{K}$, π, q, g, qq, ….

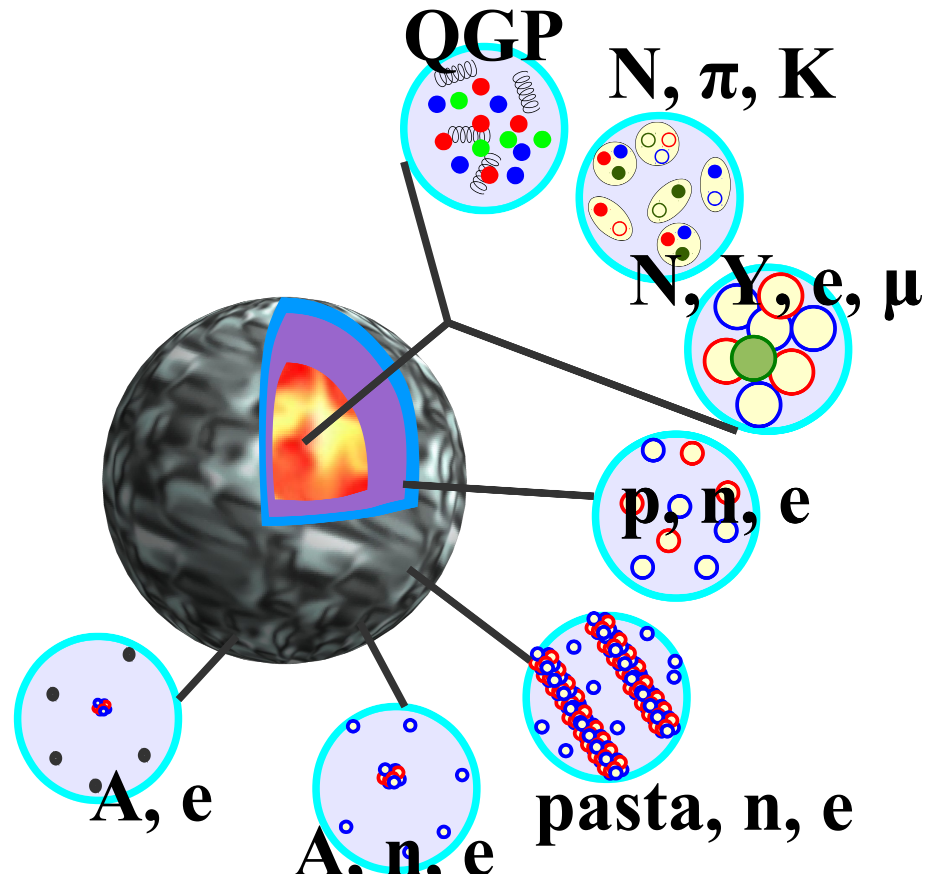


google & zenrin

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

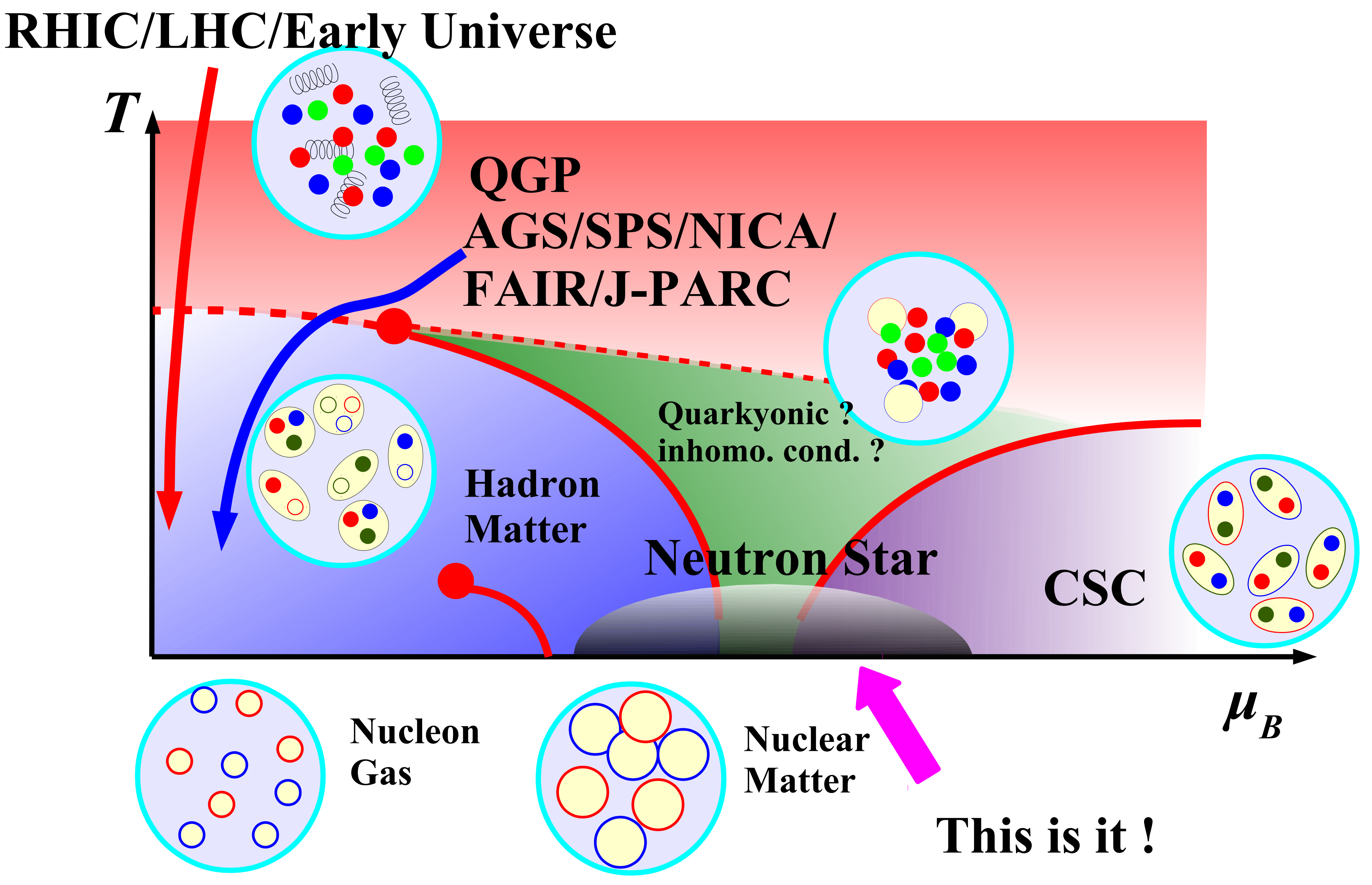
Inside Neutron Stars





Dany Page

QCD Phase Diagram

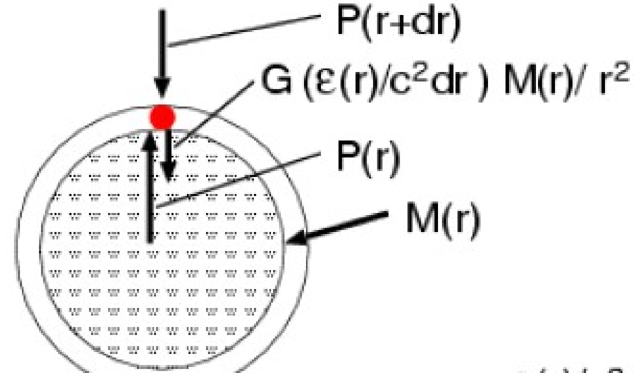


M-R curve and EOS

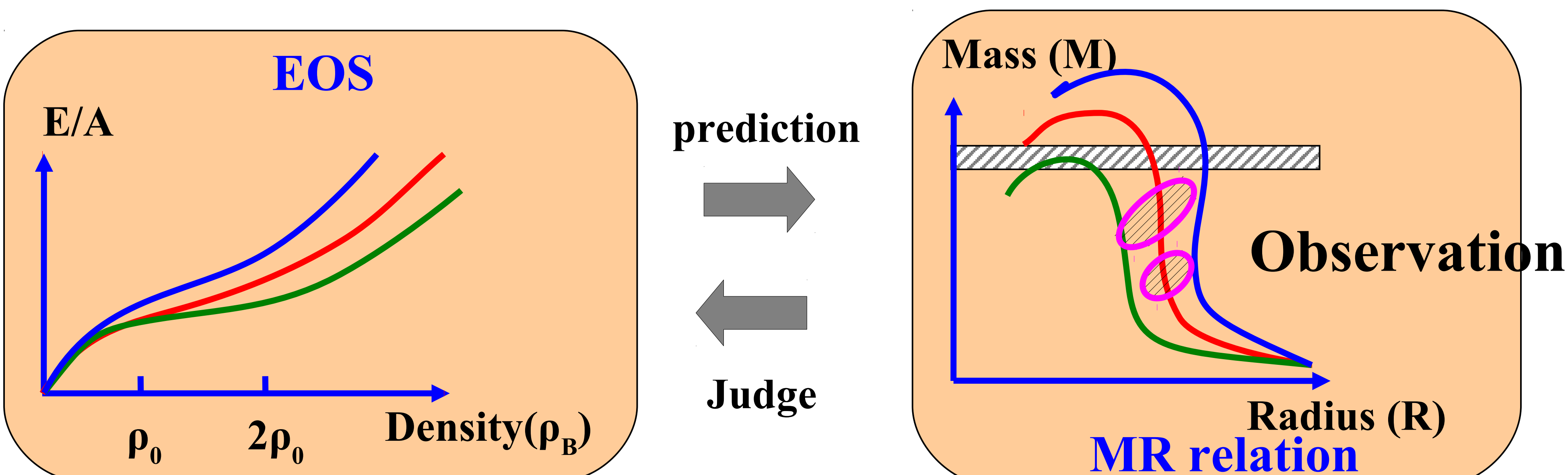
- **M-R curve and NS matter EOS has 1 to 1 correspondence**
  - **TOV(Tolman-Oppenheimer-Volkoff) equation =GR Hydrostatic Eq.**

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

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



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



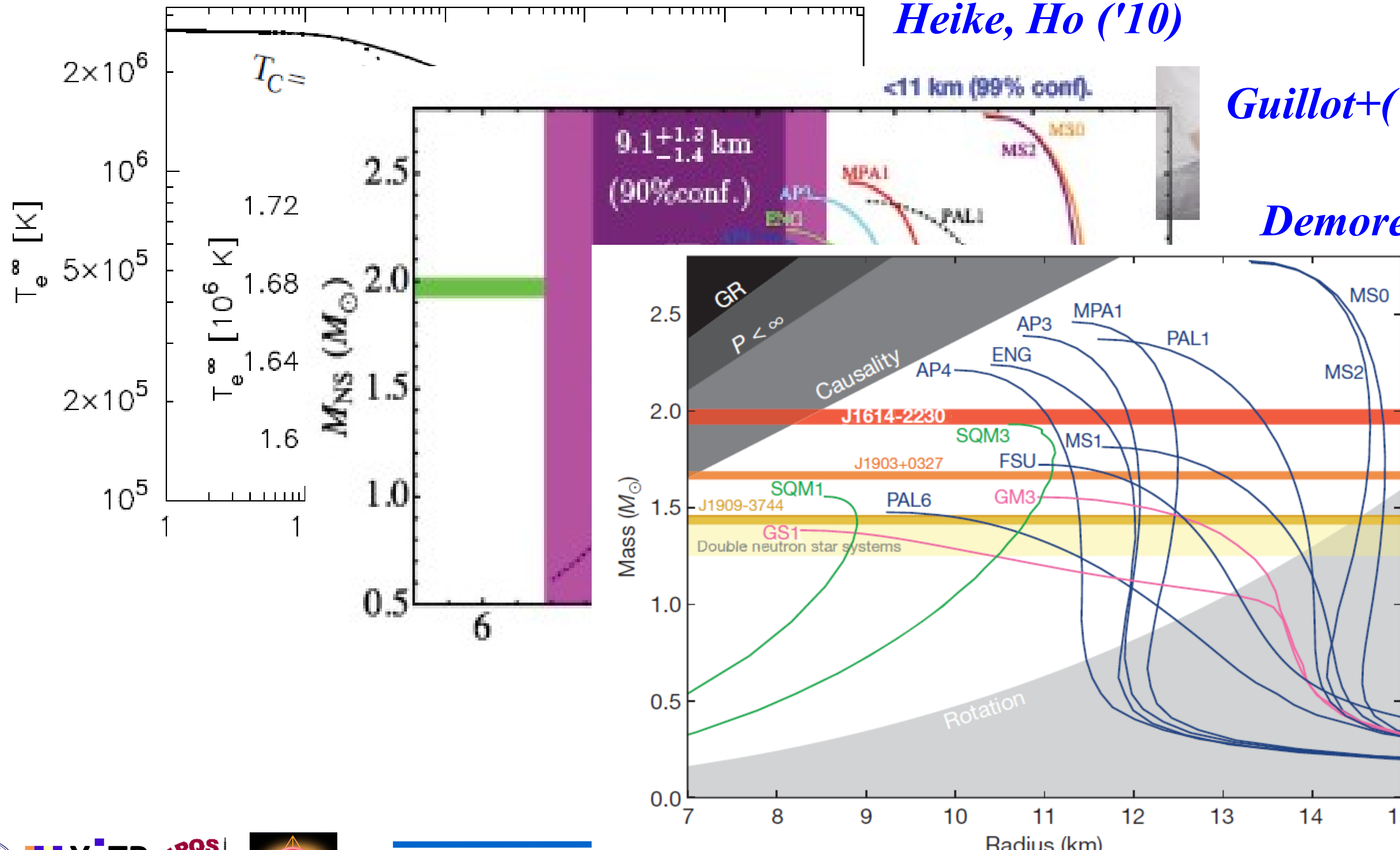
Puzzles of NS

- **Magnetar, NS oscillation, ….**
- **Rapid NS cooling puzzle (CasA cools too fast ?)**
- **Compact NS problem (9 km NS ?)**
- **Massive NS puzzle (2 $M_\odot$ NS ?)**

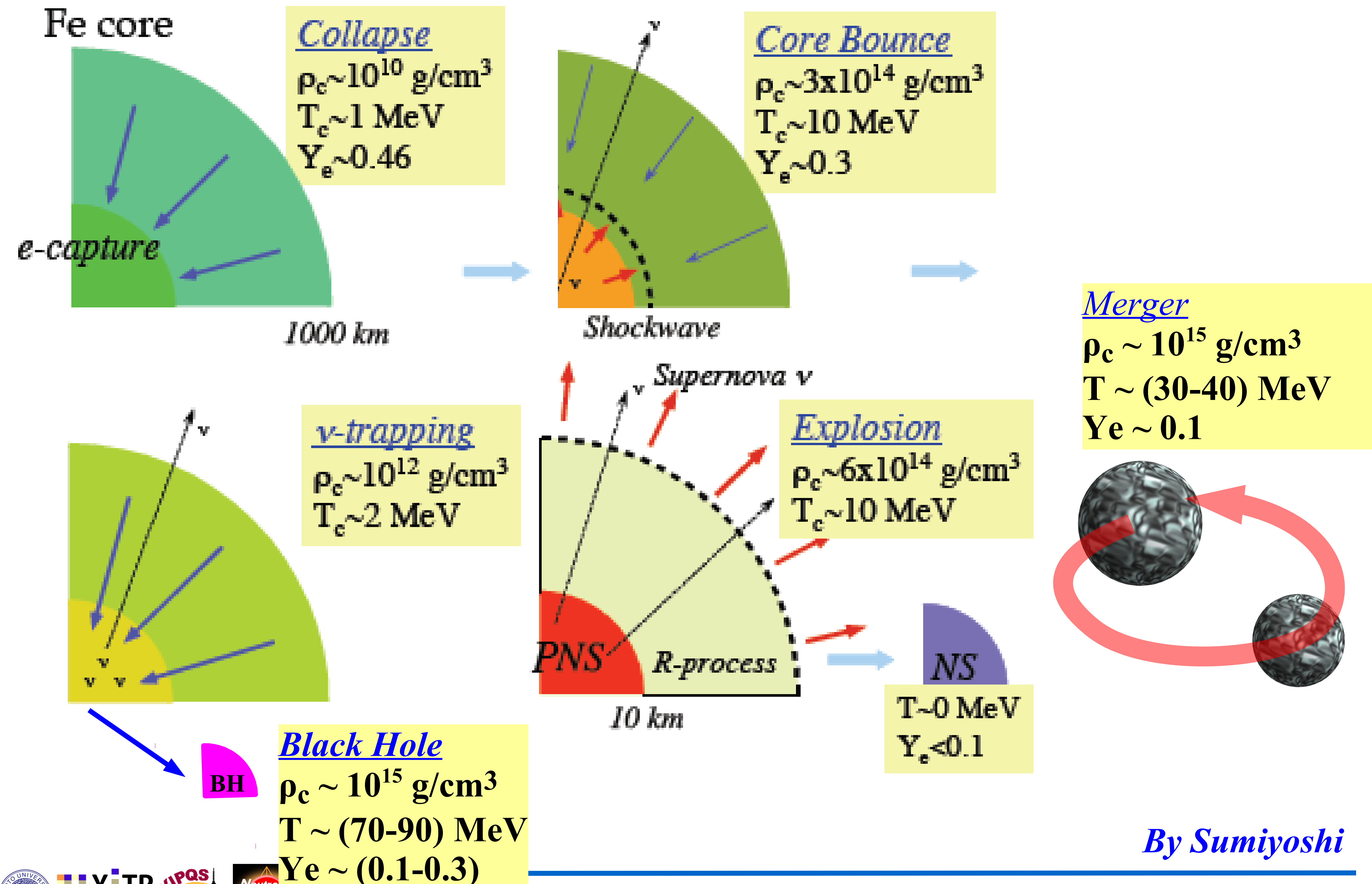
Heike, Ho ('10)

Guillot+('13)

Demorest+('10)



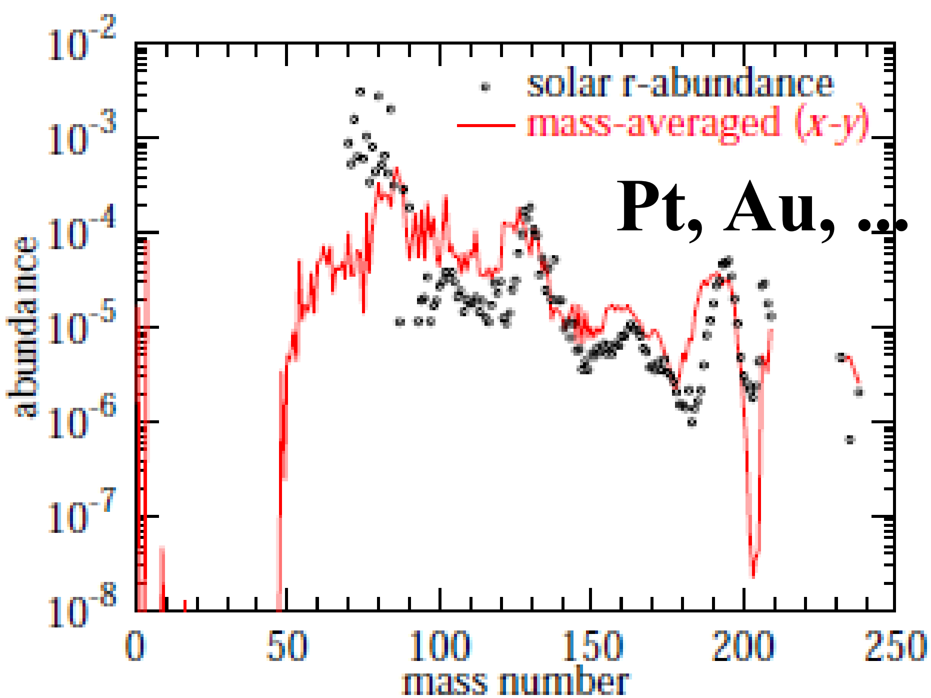
Gravitational Collapse of Massive Star

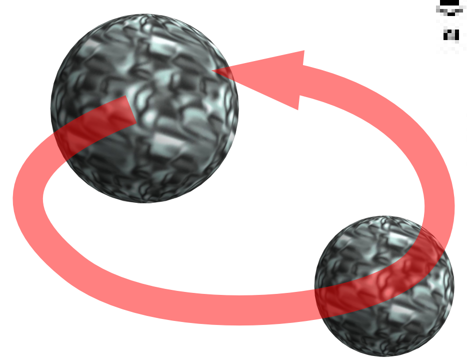


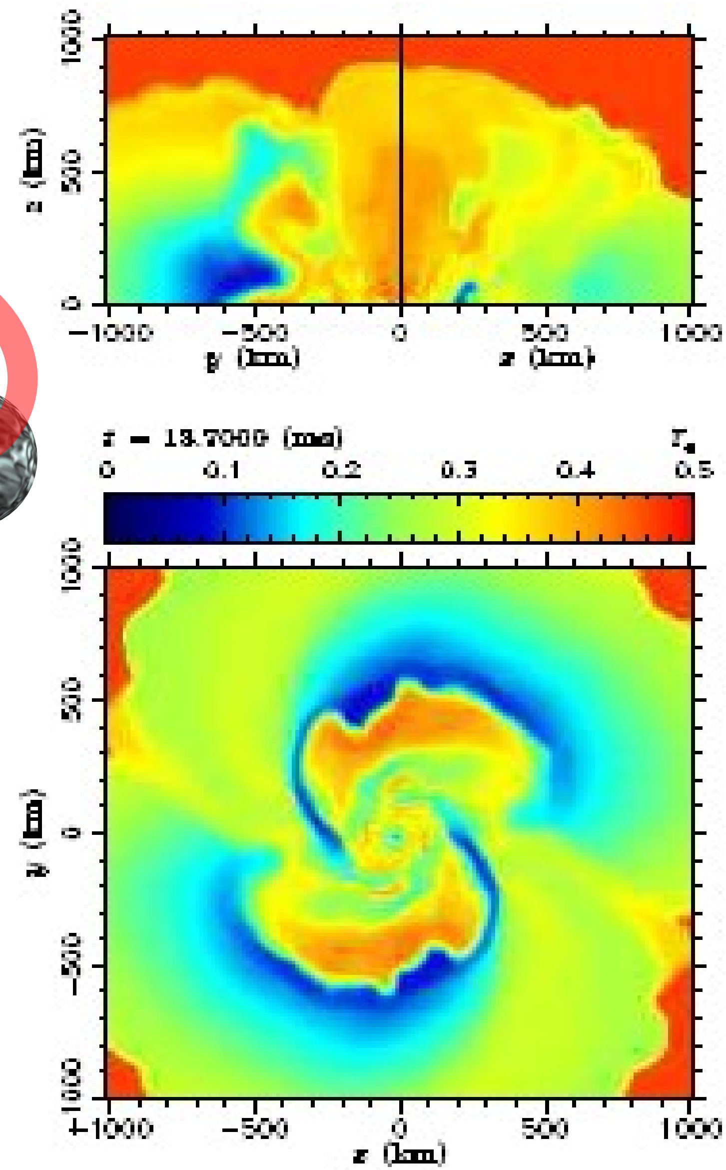
By Sumiyoshi

Binary Neutron Star Mergers and Nucleosynthesis

- **New possibility of r-process nucleosynthesis**
  - **Element ratio from binary NS merger is found to reproduce Solar abundance.**



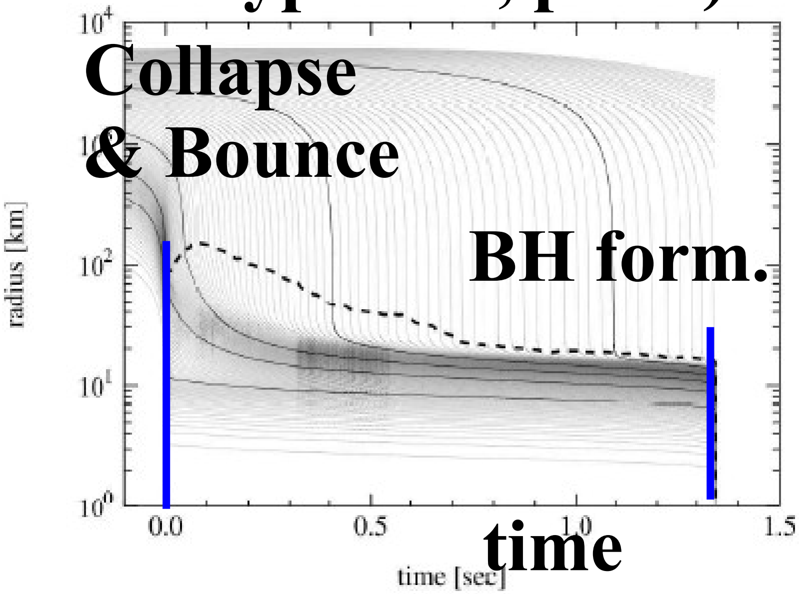


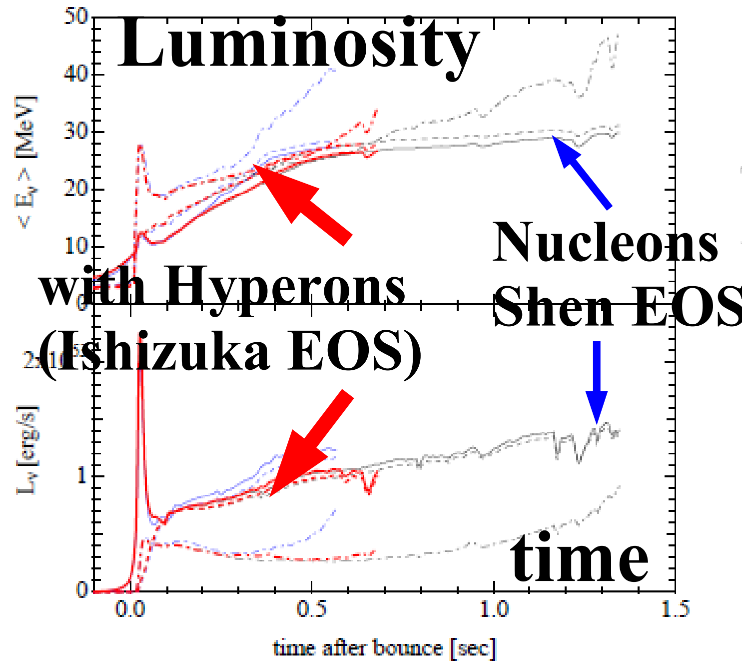


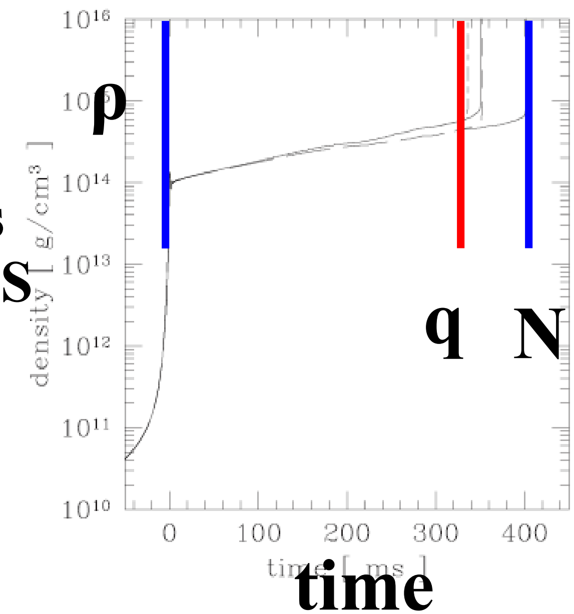
Wanajo, Sekiguchi ('14)

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).**







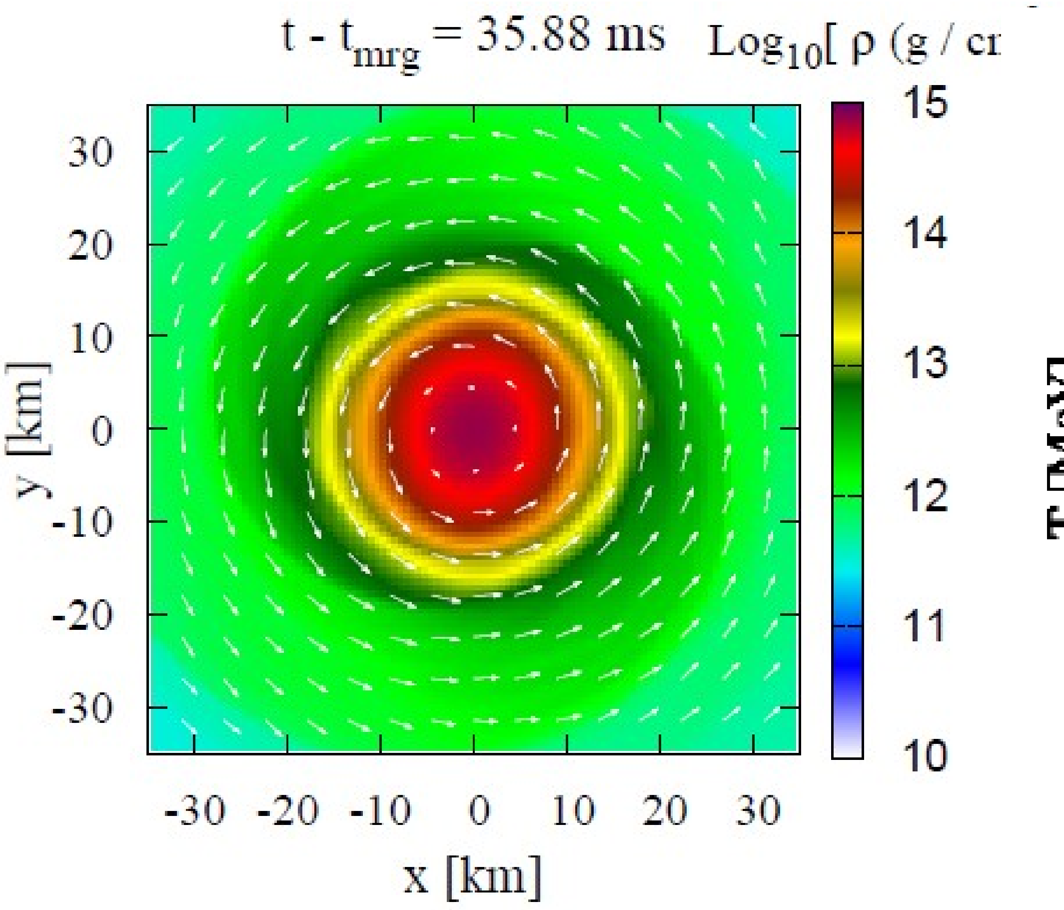
Sumiyoshi, Yamada, Suzuki, Chiba, PRL 97('06)091101.

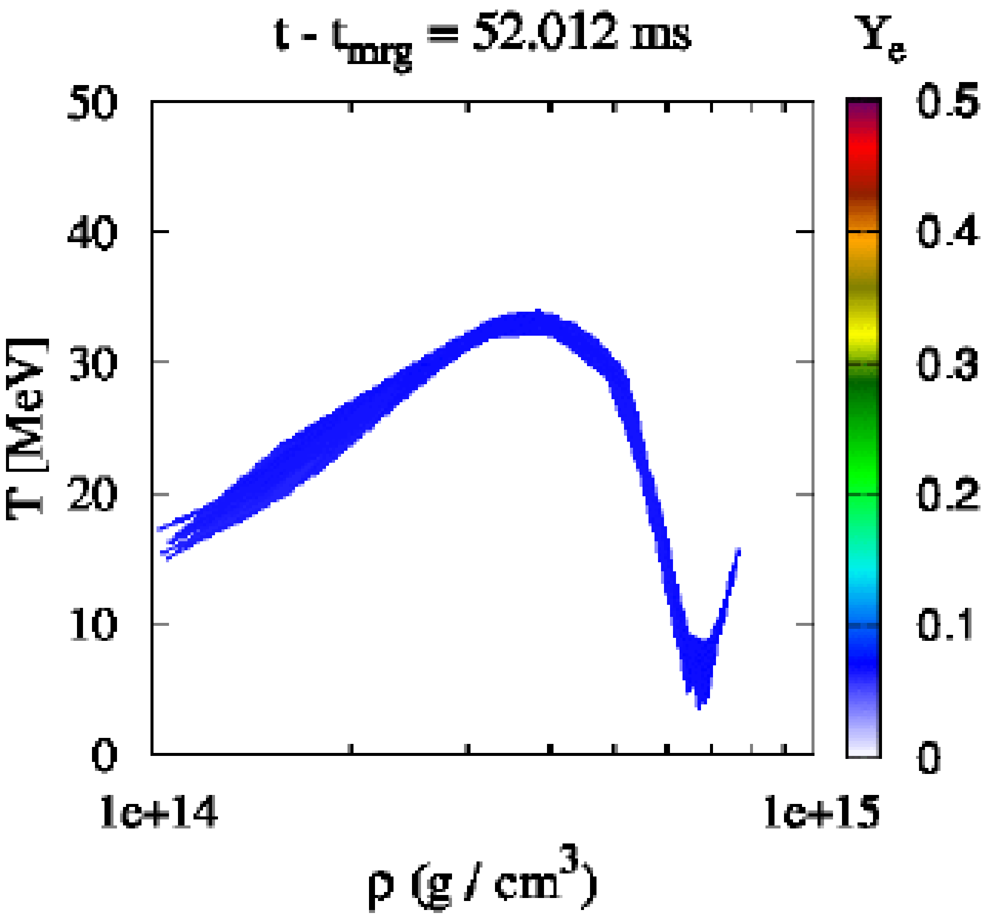
Sumiyoshi,Ishizuka, AO, Yamada, Suzuki, ApJL 690('09)43.

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

Binary Neutron Star Merger

- **T ~ 40 MeV, $\rho_B \sim 10^{15}$ g/cm^3 ~ 4 ρ_0 ($\rho_0 \sim 2.5 \times 10^{14}$ g/cm^3), Ye ~ 0.1**





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

Physics Opportunities in Neutron Stars

- Equation of state of dense matter
  - Laboratory of exotic constituents
  - Laboratory of QCD phase transition at high density
- Equation of state of isospin asymmetric matter
  - Symmetry energy connect laboratory exp. and astronomical obs.
  - Baryon superfluidity above nuclear density
  - Realization of unitary gas, which can be simulated by cold atoms
- Compact astrophysical objects, whose structure is yet unknown
  - Challenge to measure mass, radius, temperature, magnetic field, …
- Promising site of gravitational wave source
- Promising site of r-process nucleosynthesis
- Examination of general relativity
- Neutrino emission determines the cooling of NSs.

科研費新学術領域の複数がコンパクト天体に関連

- 重力波天体
  領域代表:中村卓(京大)
- 地下素核研究
  領域代表:井上邦雄(東北大
- 中性子星核物質
  領域代表:田村裕和(東北大

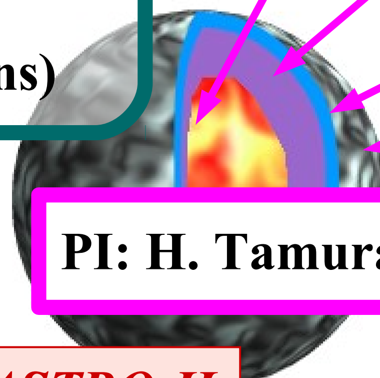
- ニュートリノフロンティア
  領域代表:中家剛(京大)

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



PI: H. Tamura

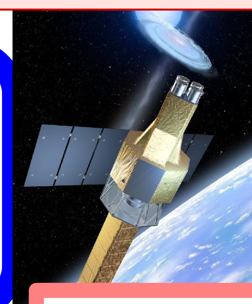
Low ρ (Group B)
head: Murakami,
Nakamura, Horikoshi

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



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

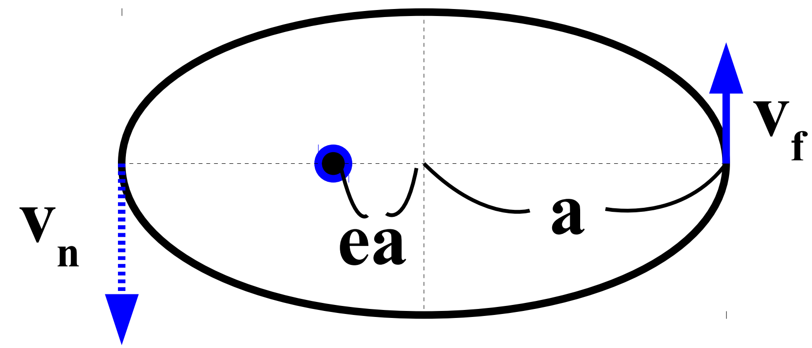
Contents

- **Introduction**
- **Neutron star basics**
  - **NS mass: Kepler motion, Mass function, and GR effects**
  - **NS radius: Stephan-Boltzmann, Eddington limit, Red shift**
  - **A little on NS cooling and magnetic field**
- **Nuclear matter and neutron star matter EOS**
  - **Tolman-Oppenheimer-Volkoff (TOV) equation**
  - **Saturation Point, Incompressibility, and Symmetry Energy**
- **Massive neutron star puzzle**
  - **How can we sustain two-solar-mass NSs ?**
  - **Proposed mechanisms to sustain massive NSs**
  - **What is necessary to solve massive NS puzzle ?**
- **Summary**

Mass & Radius Measurements of Neutron Stars

Neutron Star Observables: Mass (1)

- **Please remember Kepler motion basics**
  - **major axis=a, eccentricity=e, reduced mass=m, total mass=M**



$$E/m=\frac{1}{2}v_f^2-\frac{GM}{a(1+e)}=\frac{1}{2}v_n^2-\frac{GM}{a(1-e)}$$

$$L=mv_f a(1+e)=mv_n a(1-e)$$

$$\rightarrow v_f^2=\frac{GM}{a}\frac{1-e}{1+e},\ L=2m\frac{dS}{dt}=m\sqrt{GMa(1-e^2)}$$

$$\rightarrow P=S/(dS/dt)=2\pi a^2\sqrt{1-e^2}/\sqrt{GMa(1-e^2)}=2\pi a^{3/2}/\sqrt{GM}$$

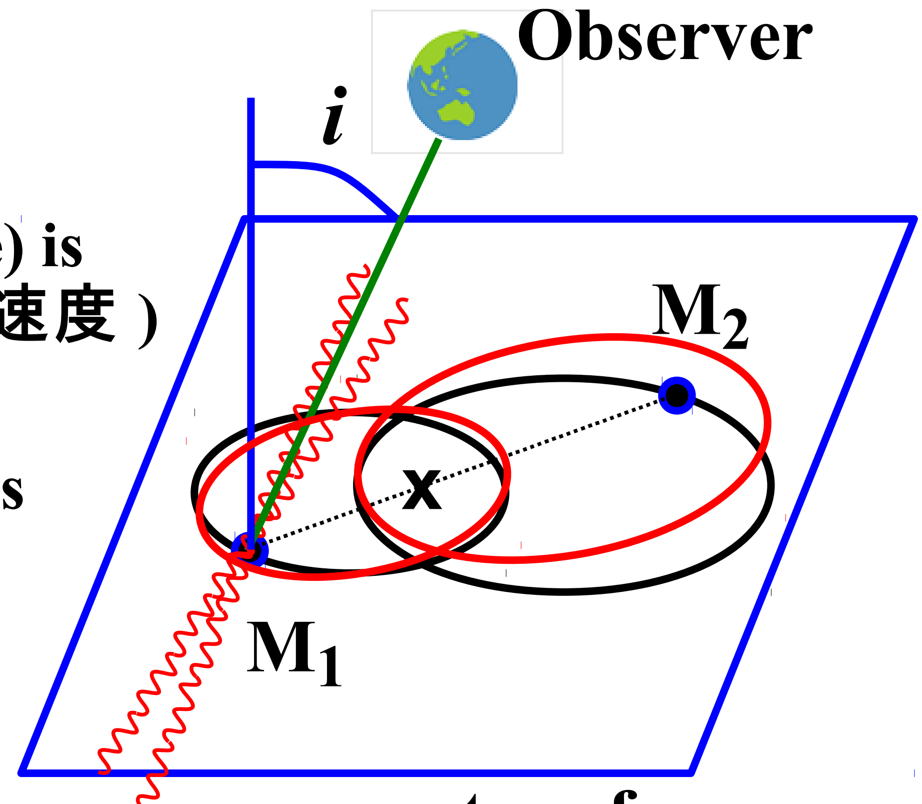
- **Binary stars**
  - **inclination angle = *i***
  - **Doppler shift (Pulse timing change) is given by the radial velocity (視線速度)**
    $K = v \sin i$
  - **Radial velocity → orbit parameters**
  - **Mass function (observable)**

$$f \equiv \frac{(M_2 \sin i)^3}{M^2} = \frac{4\pi^2 (a_1 \sin i)^3}{G} P^2$$

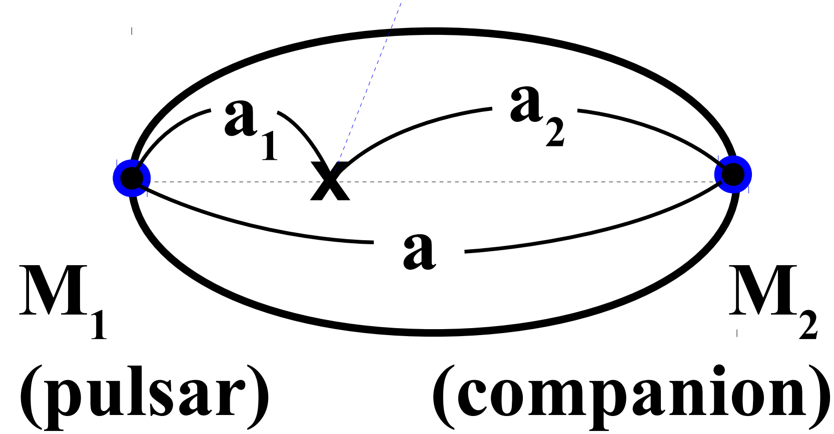
$$= \frac{K^3 P (1-e^2)^{3/2}}{2\pi G}$$

$$(K = v \sin i\,,\ M = M_1 + M_2)$$

  - **and GR effects ...**



center of mass



Hulse-Taylor Pulsar (PSR 1913+16)

- **Precisely (and firstly) measured neutron star binary (1993 Nobel prize to Hulse & Taylor)**
- **Radial velocity → P, e, K →Mass function**

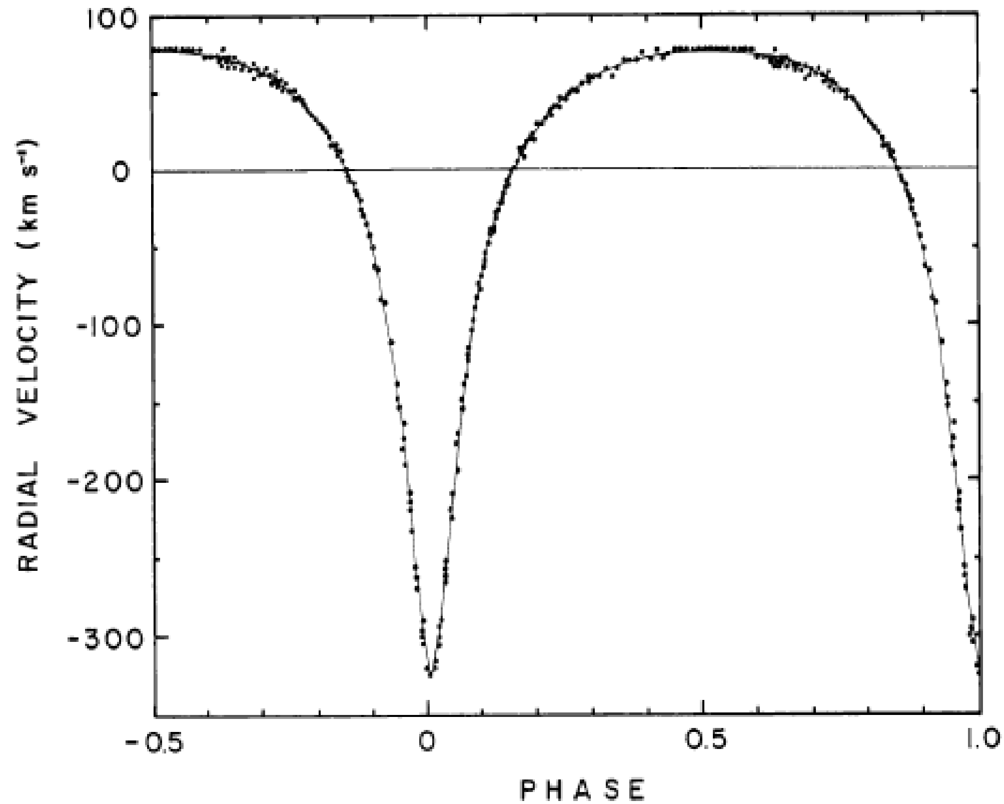
TABLE 2

ELEMENTS OF THE ORBIT

$$K_1 = 199 \pm 5 \text{ km s}^{-1}$$
$$P_b = 27908 \pm 7 \text{ s}$$
$$e = 0.615 \pm 0.010$$
$$\omega = 179° \pm 1°$$
$$T = \text{JD } 2{,}442{,}321.433 \pm 0.002$$
$$a_1 \sin i = 1.00 \pm 0.02 \ R_\odot$$
$$f(m) = 0.13 \pm 0.01 \ M_\odot$$


1993 Nobel Prize

HULSE AND TAYLOR



Hulse-Taylor ('75)

More on Hulse-Taylor Pulsar (PSR 1913+16)

- **General Relativistic Effects**
  - **Perihelion shift (近日点移動)**

$$\dot{\omega} = 3\left(\frac{2\pi}{P}\right)^{5/3} \frac{(GM)^{2/3}}{(1-e^2)c^2}$$

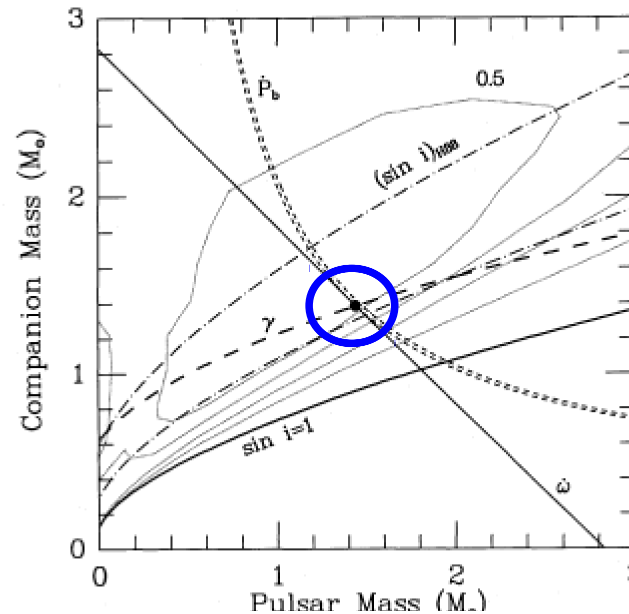
  - **Einstein delay**

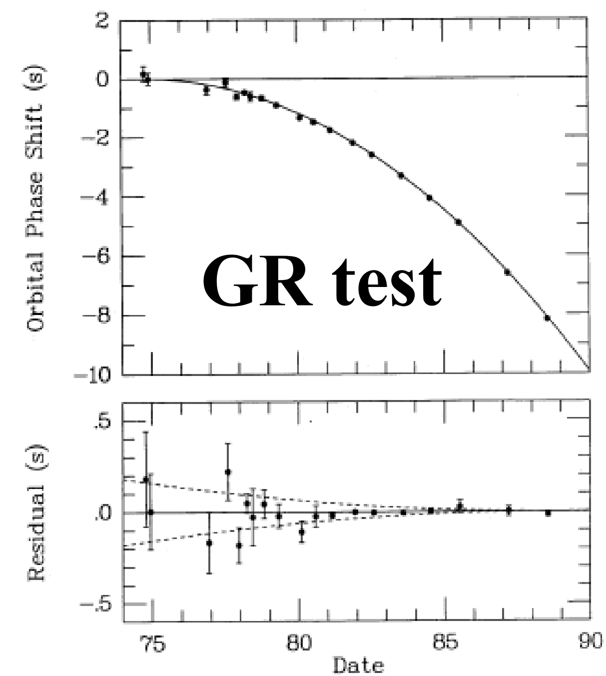
$$\Delta_E = \gamma \sin u$$
$$(u = \text{eccentric anomaly})$$

$$\gamma = \frac{eP_b G m_2 (m_1 + 2m_2)}{2\pi c^2 a_R M} \qquad \frac{a_R^3}{P_b^2} = \frac{GM}{4\pi^2}\left[1 + \left(\frac{m_1 m_2}{M^2} - 9\right)\frac{GM}{2a_R c^2}\right]^2$$

  - **Two observable**
    → Precise measurement of m_1 and m_2.

$$m_1 = 1.442 \pm 0.003\, M_{\rm sun}$$
$$m_2 = 1.386 \pm 0.003\, M_{\rm sun}$$

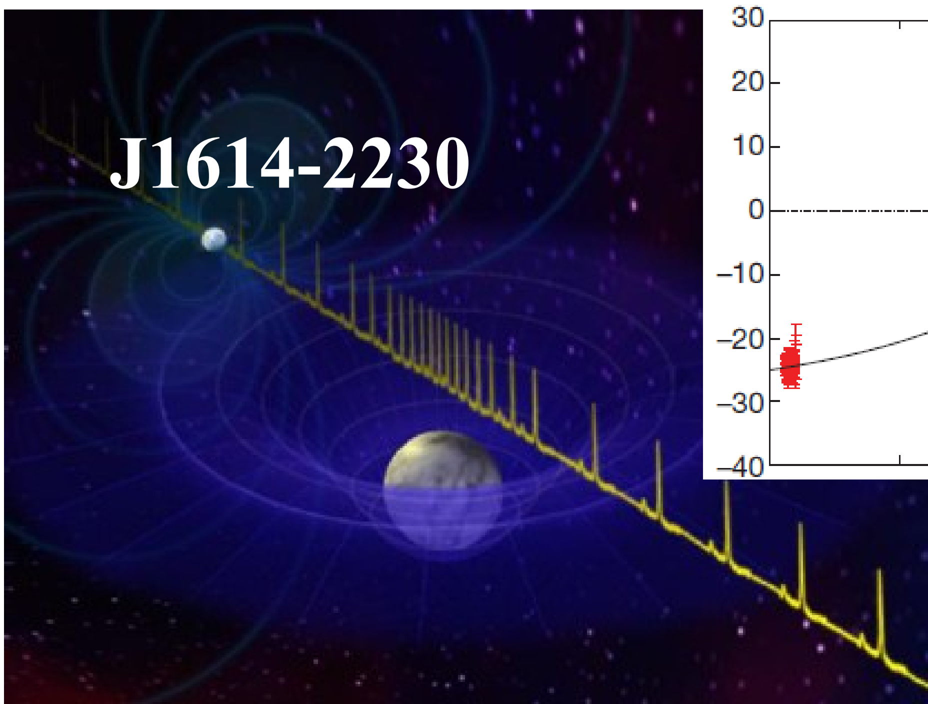


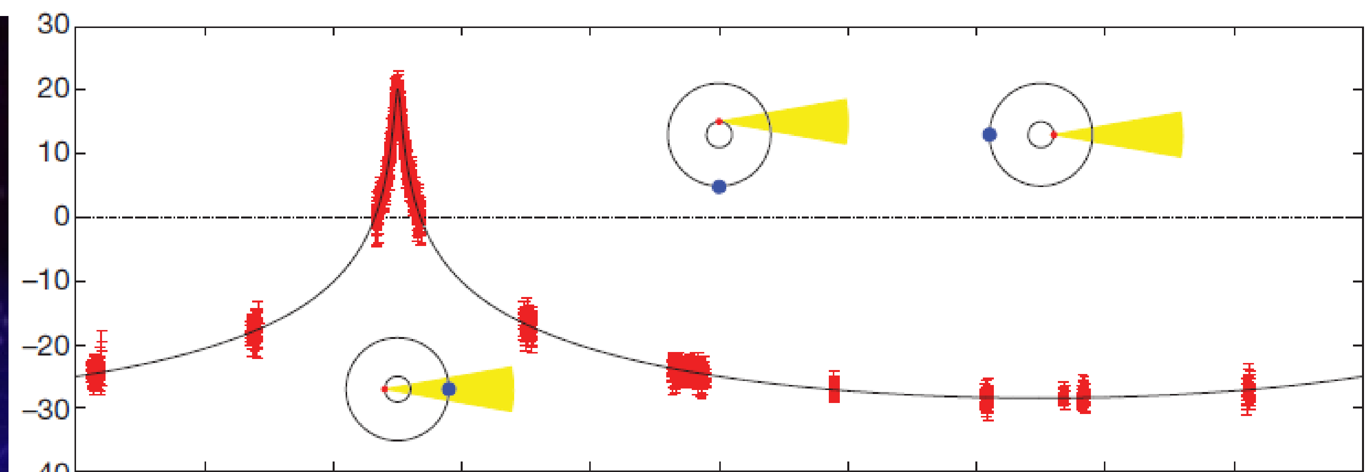


Taylor, Weisenberg ('89)

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)





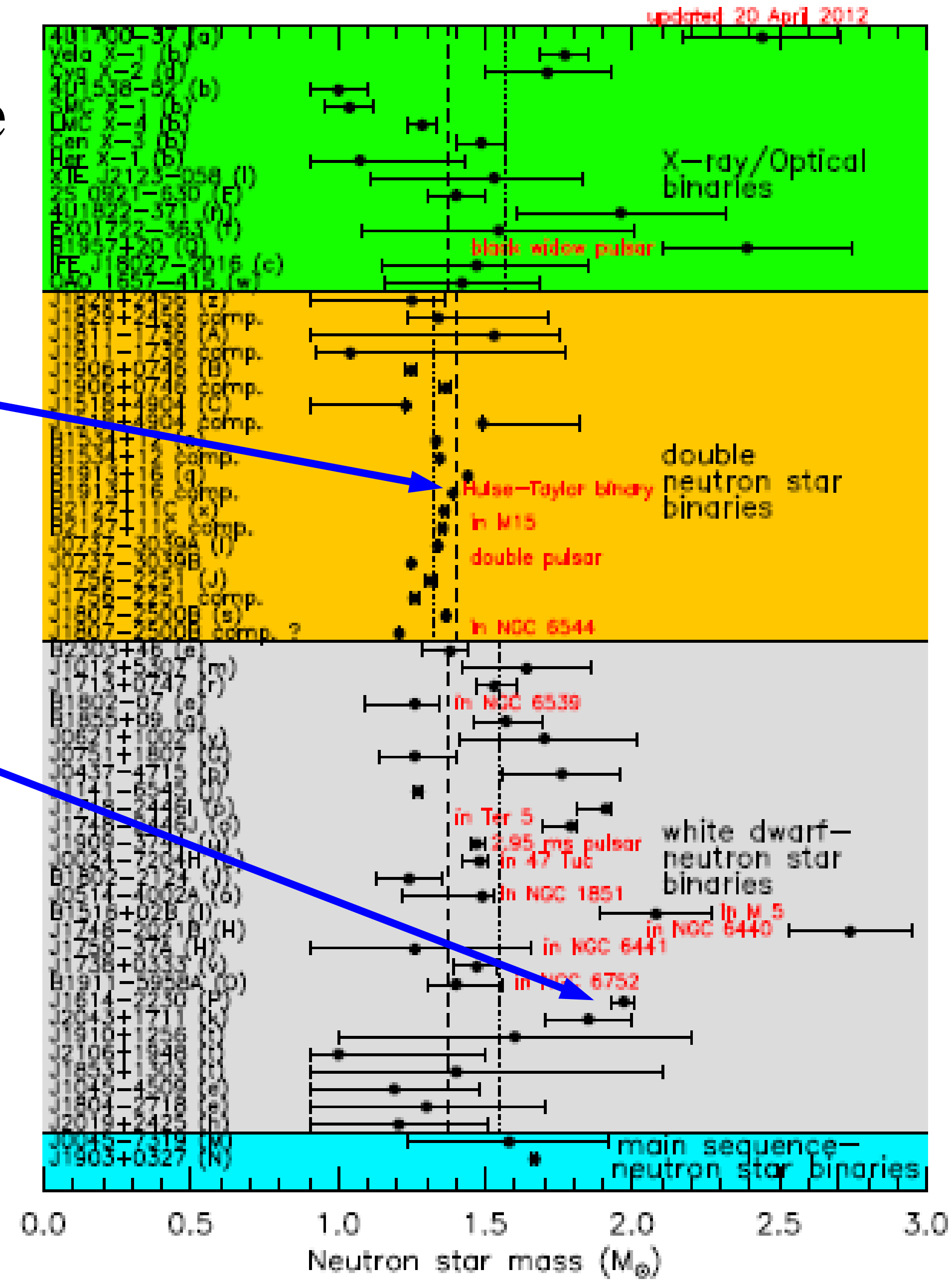
$$\Delta_S = -2m\left[\ln\frac{r}{a} + \ln\left(1 - \sin i \sin\phi\right)\right]$$

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

Neutron Star Masses

- **NS masses in NS binaries can be measured precisely by using some of GR effects.**
  - **Perihelion shift+Einstein delay**
    → $M = 1.442 \pm 0.003\ M_\odot$
    (Hulse-Taylor pulsar)
    Taylor, Weisenberg ('89)
  - **Shapiro delay**
    → $M = 1.97 \pm 0.04\ M_\odot$
    Demorest et al. ('10)
  - **Another obs.: $M = 2.01 \pm 0.04\ M_\odot$**
    Antoniadis et al. ('13)

Neutron Star Mass
$M = (1\text{-}2)\ M_\odot$
Canonical value = $1.4\ M_\odot$



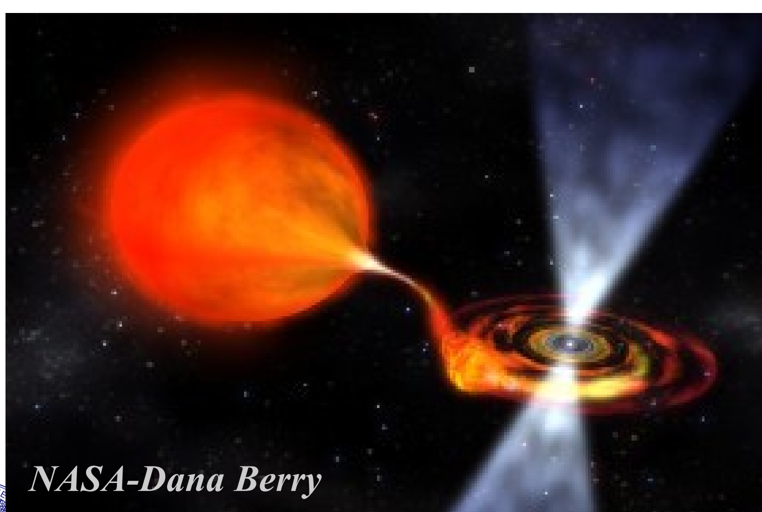
Lattimer (2013)

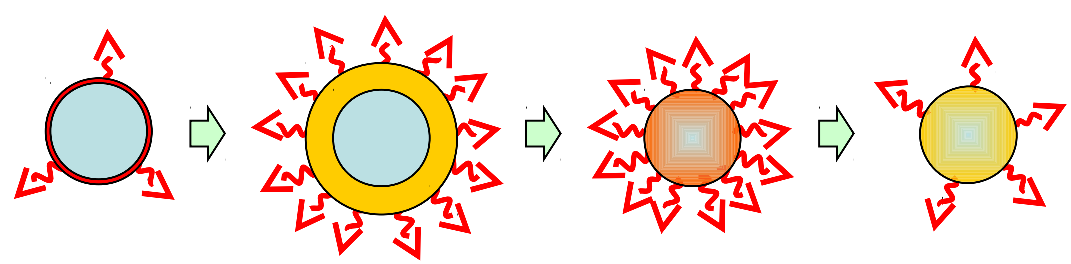
Neutron Star Radius

- **How can we measure 10 km radius of a star with 10-100 thousands light year distance from us ?**
  - **Size of galaxy ~ 3 x 10^{14} km (~ 10 kpc ~ 3 x 10^4 light year)**

→ Model analysis is necessary !

- **X-ray burster**
  - **Mass accretion from companion occasionally induces explosive hydrogen / helium burning.**
  - **High temperature → NS becomes bright !**
  - **Three methods to measure NS radius**



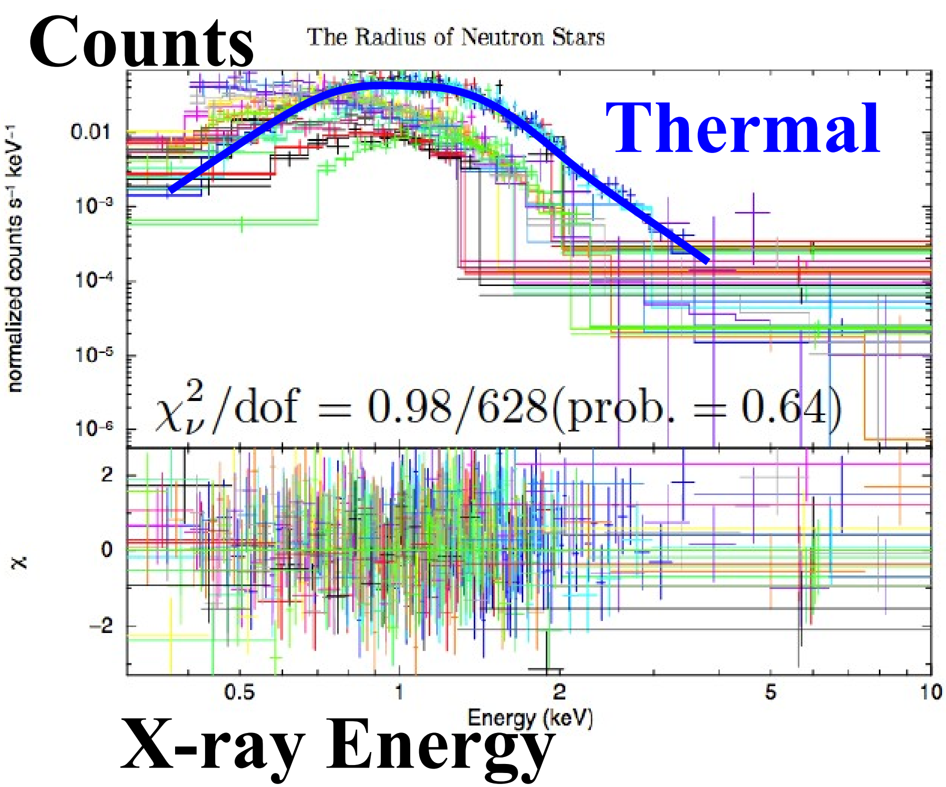


NS Radius Measurement (1)

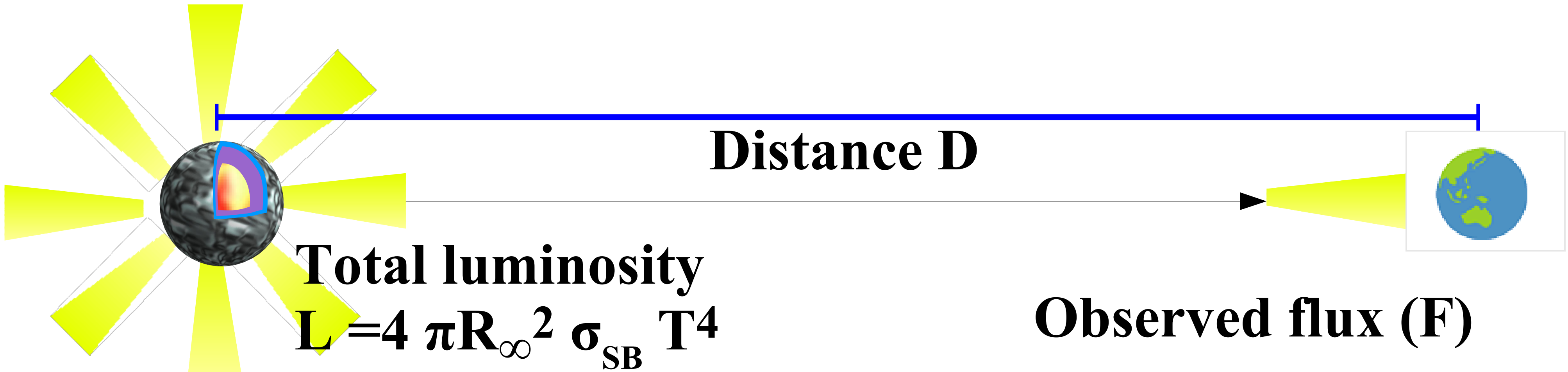
- **Surface emission**
  - **Stefan-Boltzmann law is assumed → NS radius is obtained from Flux, Temperature, and Distance measurement.**

$$L = 4\pi R_\infty^2 \sigma_{SB} T^4 \quad , \quad F = \frac{L}{4\pi D^2}$$

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



Guillot et al. (2013)

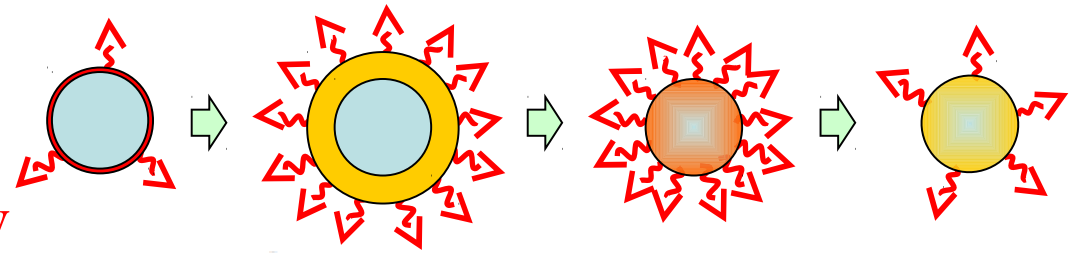


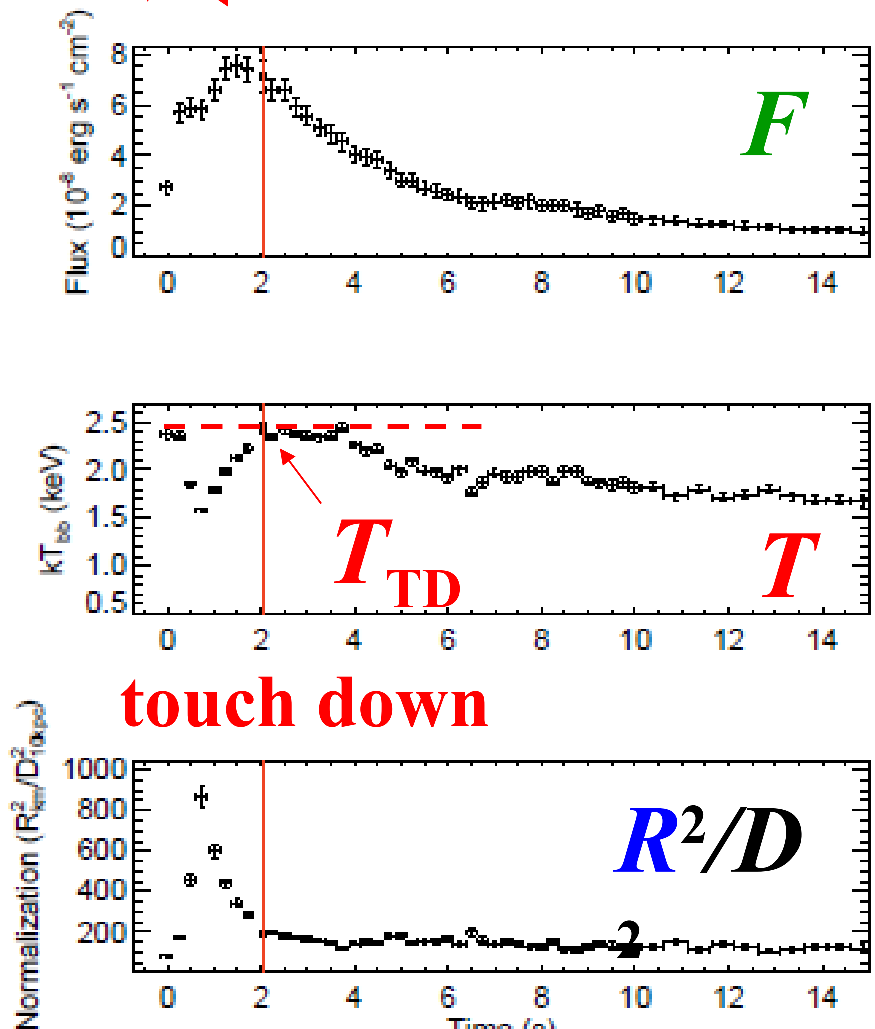
NS Radius Measurement (2)

- **Eddington Limit**
  - **Eddington Limit**
    radiation pressure = gravity

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

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





Guver et al., ApJ 747 (2012) 47

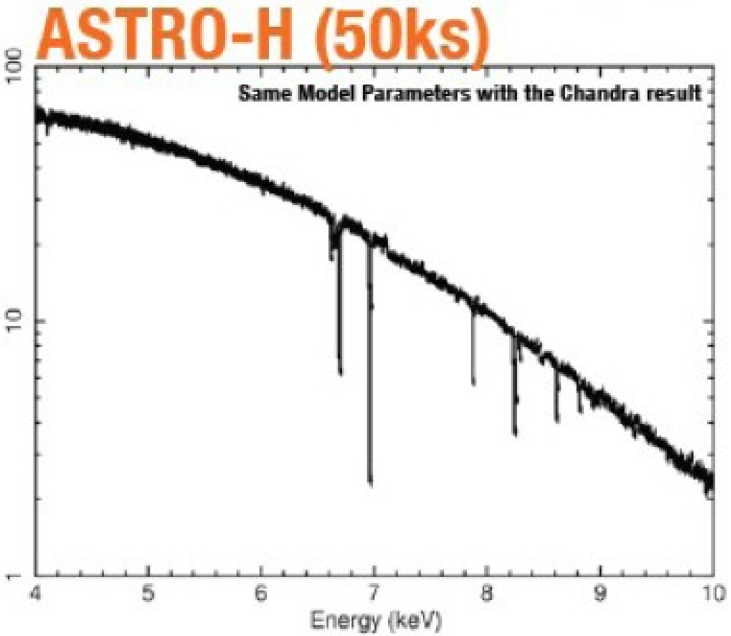
  - **Eddington limit is assumed to be achieved at "touch down".**
  - **Electron-nucleon ratio**
    $N_e/N_N=(1+X)/2$
    (X=1 for hydrogen atmosphere
    X=0 for light elements)

NS Radius Measurement (3)

- **Red Shift**
  - **Neutron Star surface is expected to contain Irons.**
  - **Absorption lines should be red shifted.**
    → Almost direct observation of M/R.

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

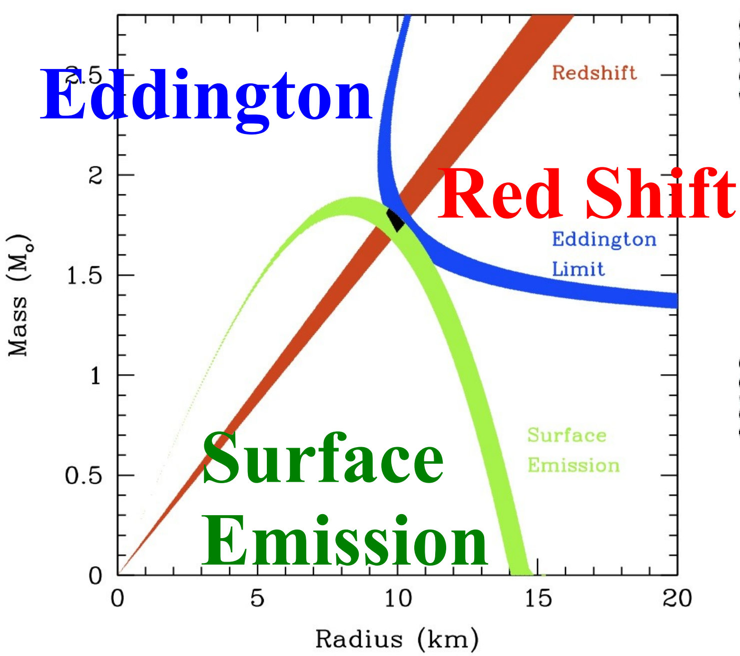
  - **ASTRO-H will measure Iron absorption line from NS, and determine M/R with 1 % accuracy !**

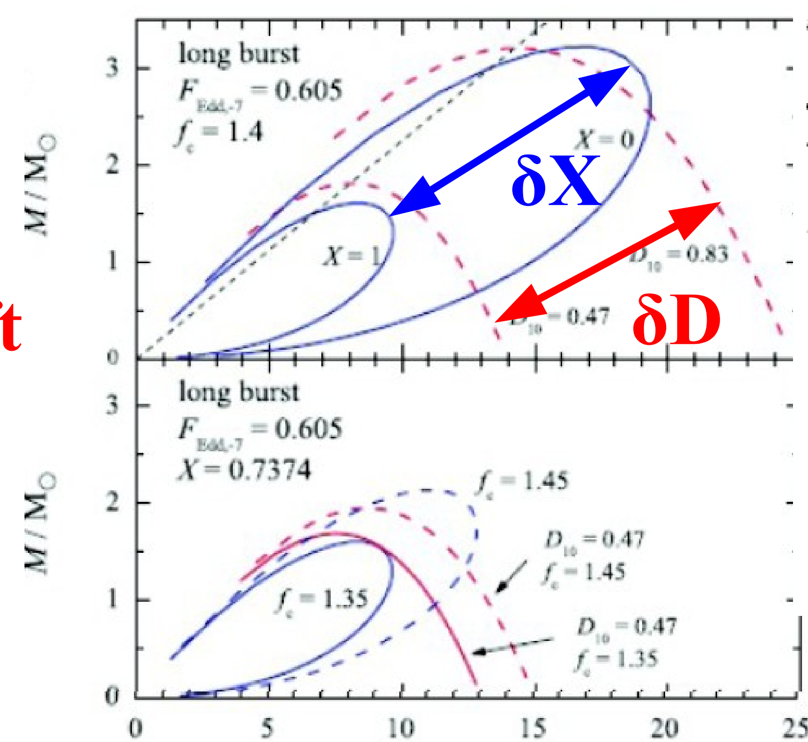


ASTRO-H simulation

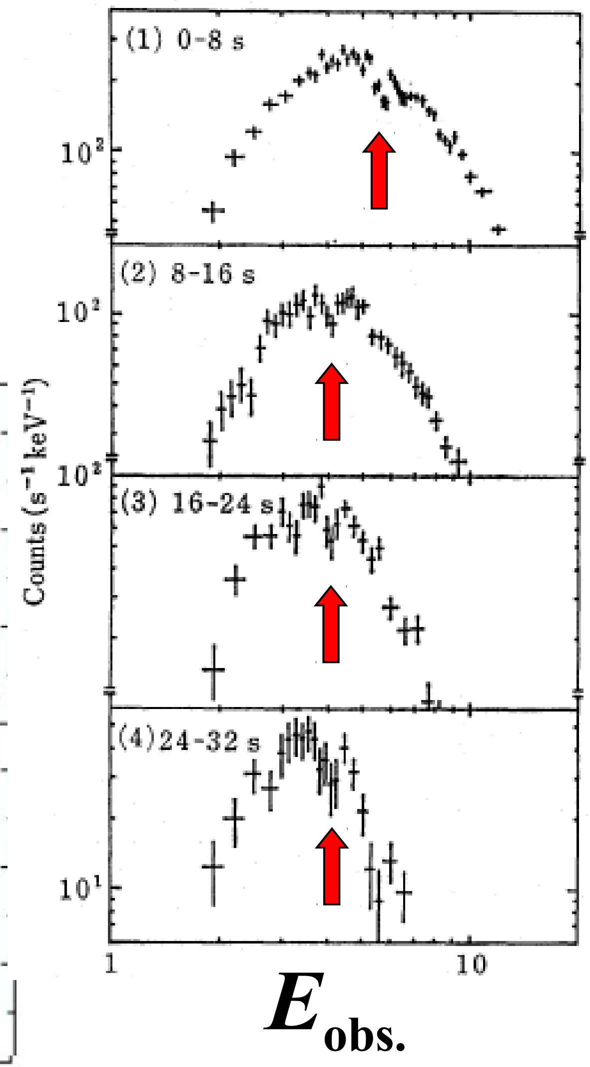
Neutron Star Radius

- Do three methods give consistent (M, R) ?
  - Surface emission & Eddington limit have large error bars from Distance & Composition uncertainty.
  - Red shift of discrete lines have not been observed unambiguously.





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

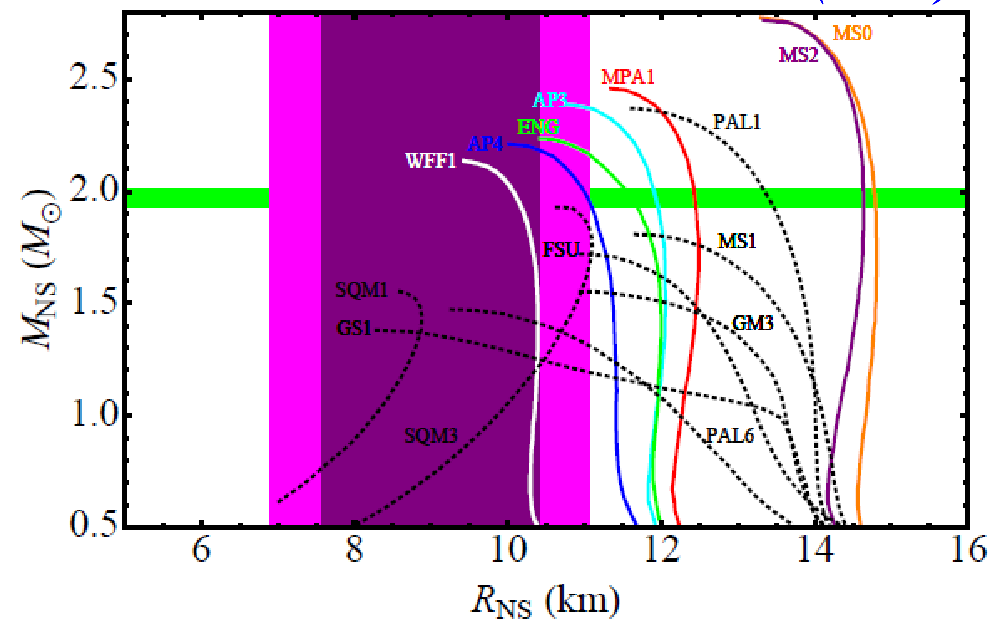


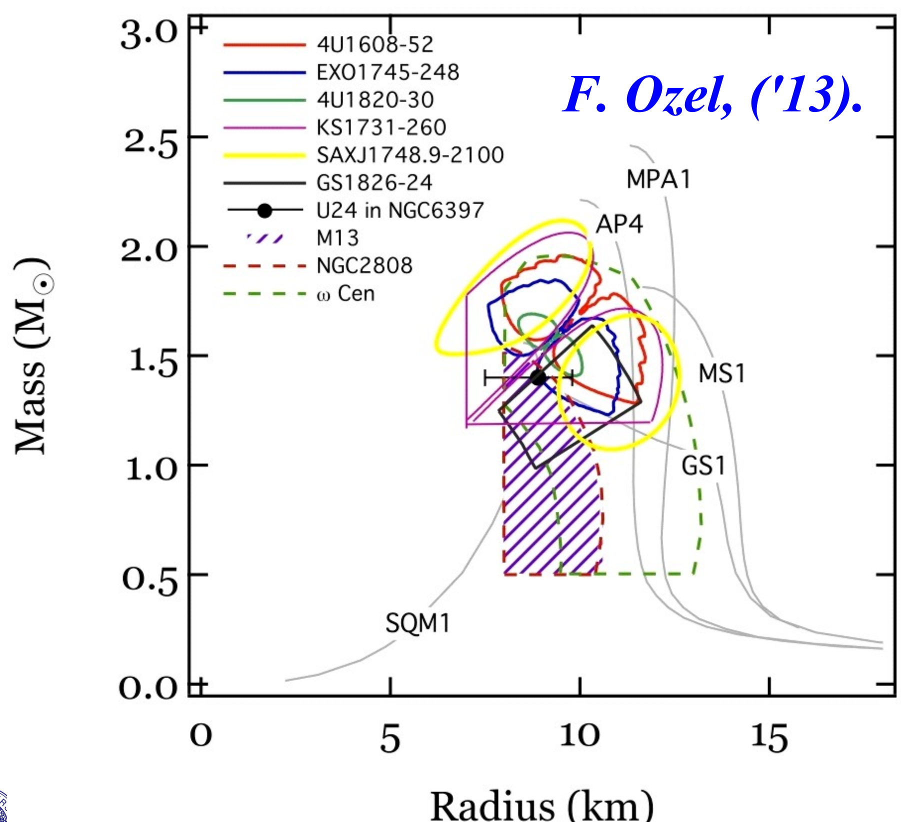
Waki et al., PASJ36('84)819

Compact NS puzzle

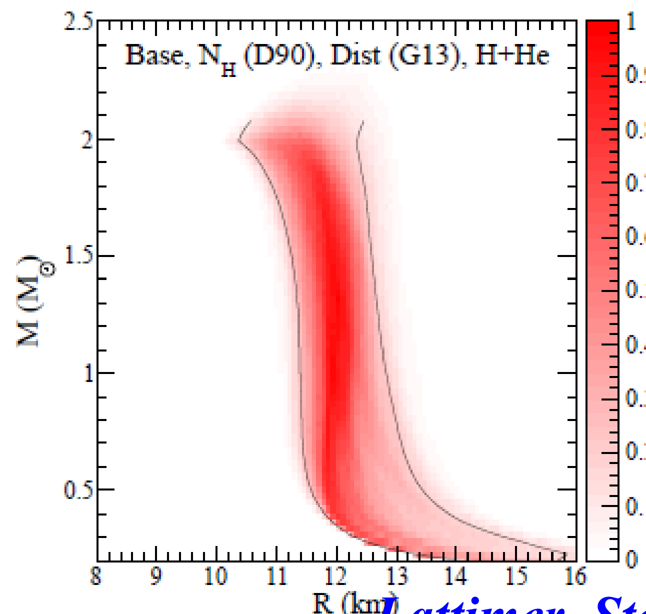
- **Some analyses suggest smaller R_{NS} than nucl. phys. predictions.**
- **Some make objections.**
  Suleimanov+, $R_{1.4} > 13.9$ km
  Lattimer+, $R_{1.4} = 12 \pm 1.4$ km

Guillot et al. (2013)



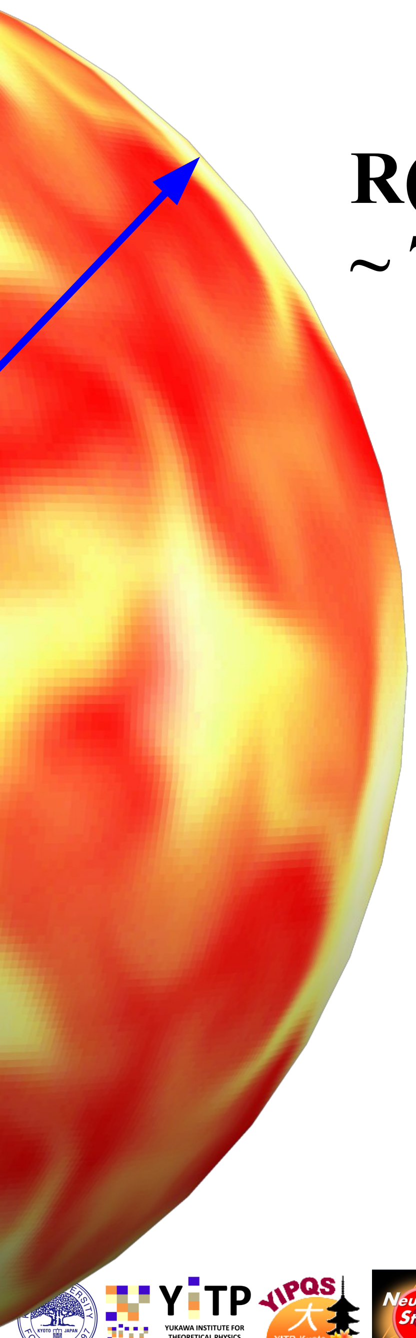


F. Ozel, ('13).

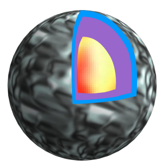


Lattimer, Steiner (2014).

Neutron Star Density

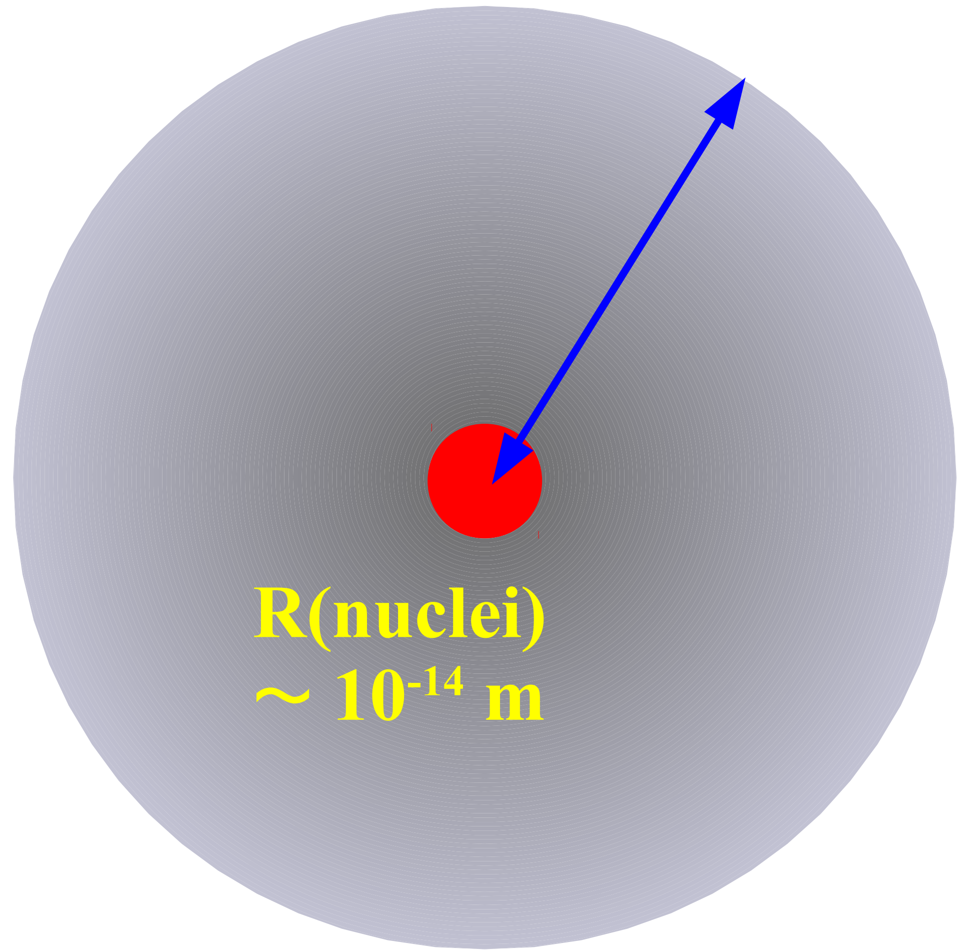


R(Sun)
~ 700,000 km



R(NS)~ 10 km
M(NS)~1.4 $M_\odot$

R(atom)
~ 10^{-10} m

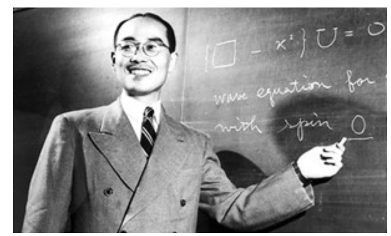


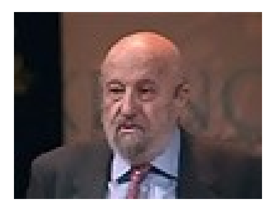
Very High Density !
$m_N\,\rho(NS) \sim (2\text{-}7) \times 10^{14}\ g / cm^3 \sim (1\text{-}3)\ m_N\,\rho_0$

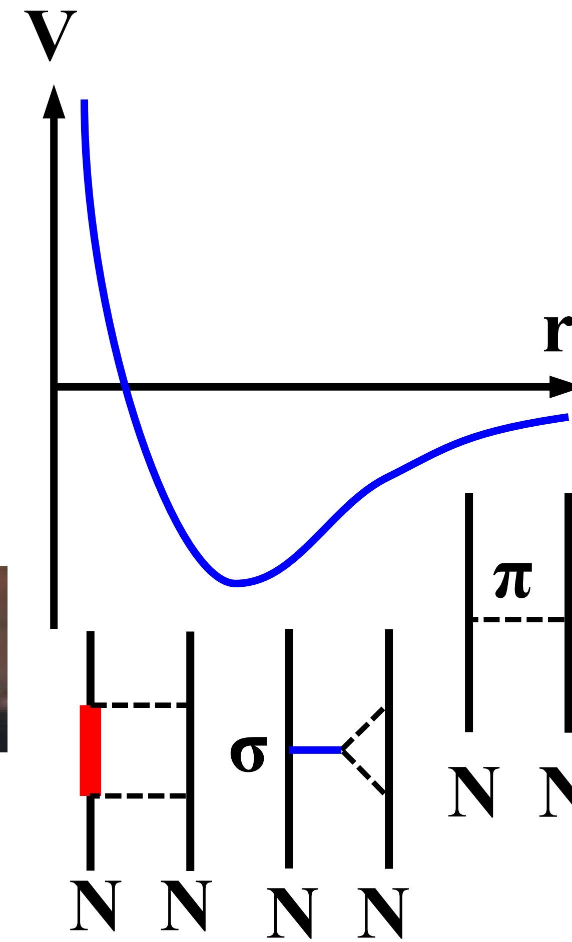
Neutron Stars are supported by Nuclear Force !

- **Average density of NS ~ (1-3) ρ_0, Max. density ~ (5-10) ρ_0**
  → Supported by Nuclear Force
  c.f. White Dwarfs are supported by electron pressure.

- **Nuclear Force**
  - **Long-range part: π exchange**
    Yukawa (1935)
  - **Medium-range attraction:**
    2 π exchange, σ exchange, ….
    Nambu, Jona-Lasinio (1961)
  - **Short-range repulsion:**
    Vector meson exchange,
    Pauli blocking btw. quarks
    Gluon exchange
    Neudatchin, Smirnov, Tamagaki;
    Oka, Yazaki; Aoki, Hatsuda, Ishii





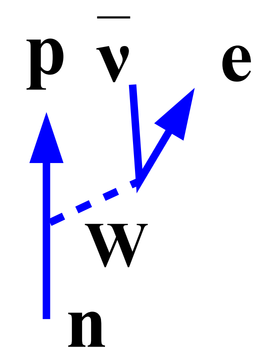


A little on NS cooling & Magnetic Field

Neutron Star Cooling

- **Direct URCA process**

Casino de Urca @ Rio



$$n \to p + e^- + \bar{\nu}_e \ , \quad e^- + p \to n + \nu_e$$

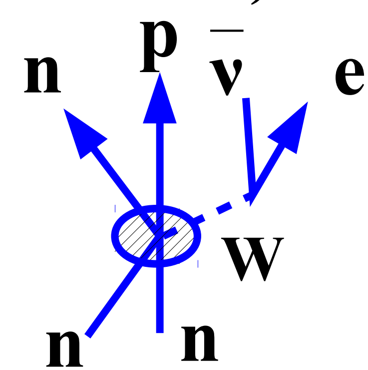
  - **Dominant at high T (T>10^9 K)**
  - **Suppressed at low T (T < 10^9 K)**

- **Modified URCA process**

$$n + n \to n + p + e^- + \bar{\nu}_e \ , \quad n + p + e^- \to n + n + \nu_e$$

  - **"Standard" cooling process of young NS (t < 10^4 yrs, T > 10^8 K)**

- **Non-standard cooling processes**



  - **Y-URCA**

$$Y \to N + e^- + \bar{\nu}_e \ , \quad e^- + Y \to N + \nu_e$$

  - **π cooling**

$$\pi^- + n \to n + e^- + \bar{\nu}_e \ , \quad n + e^- \to n + \pi^- + \nu_e$$

  - **quark beta decay**

$$d \to u + e^- + \bar{\nu}_e \ , \quad u + e^- \to d + \nu_e$$

Direct URCA suppression

- **D-URCA is suppressed at $Y_p < 0.11$**
  - **Equilibrium condition: $\mu_n = \mu_p + \mu_e$**

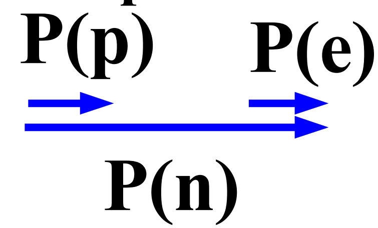
$$\frac{P_F^2(n)}{2M_n} + M_n + U_n = \frac{P_F^2(p)}{2M_p} + M_p + U_p + P_F(e)$$

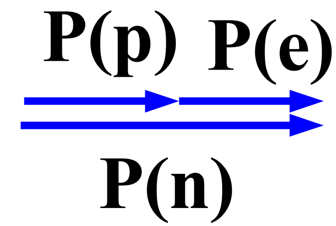
  - **Charge neutrality: $P_F(p)=P_F(e)$**
  - **Momentum conservation for zero momentum ν emission**

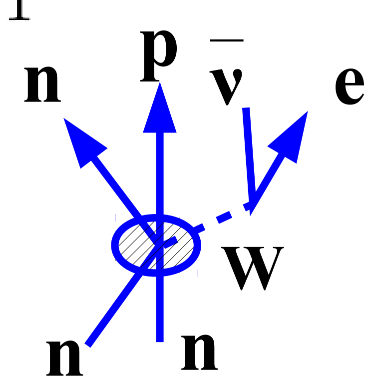
$$P_F(n) = 2P_F(p) \ \to \ Y_p = Z/(N+Z) = 1/9 = 0.11$$

  - **Y-DURCA and q-DURCA is free from suppression**
- **M-URCA is slow**

$Y_p < 1/9$







$$\Gamma = \frac{(2\pi)^4}{\hbar V}\int \delta(E_f - E_i)\delta^3(\mathbf{p}_f - \mathbf{p}_i)|H_{fi}|^2 f_1 f_2 (1-f_1')(1-f_p)(1-f_e)\prod_i V\frac{d^3p_i}{(2\pi)^3}$$

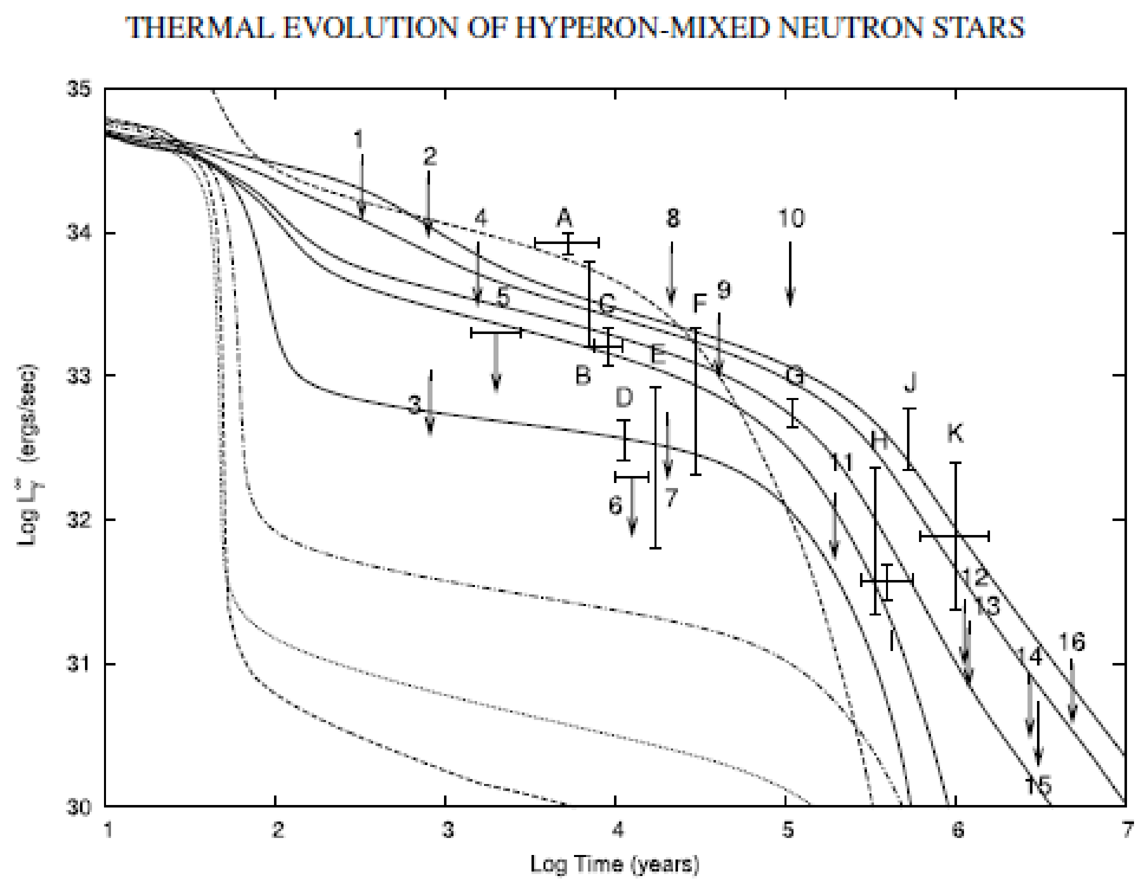
$$L_\nu^{\rm mURCA} = C\frac{M}{M_\odot}\left(\frac{\rho_0}{\rho}\right)^{1/3}\left(\frac{T}{10^9\ {\rm K}}\right)^8 \quad (C \simeq (0.8-5)\times 10^{39}{\rm erg/s})$$

Shapiro texbookt

Neutron Star Cooling (cont.)

- **Many of neutron star temperature observations are consistent with "standard" modified URCA cooling (with some heating).**
- **Some require faster cooling.
Need some exotics.**
- **Exotic cooling is too fast if there is no suppression mechanism. Superfluidity is a promising candidate.**

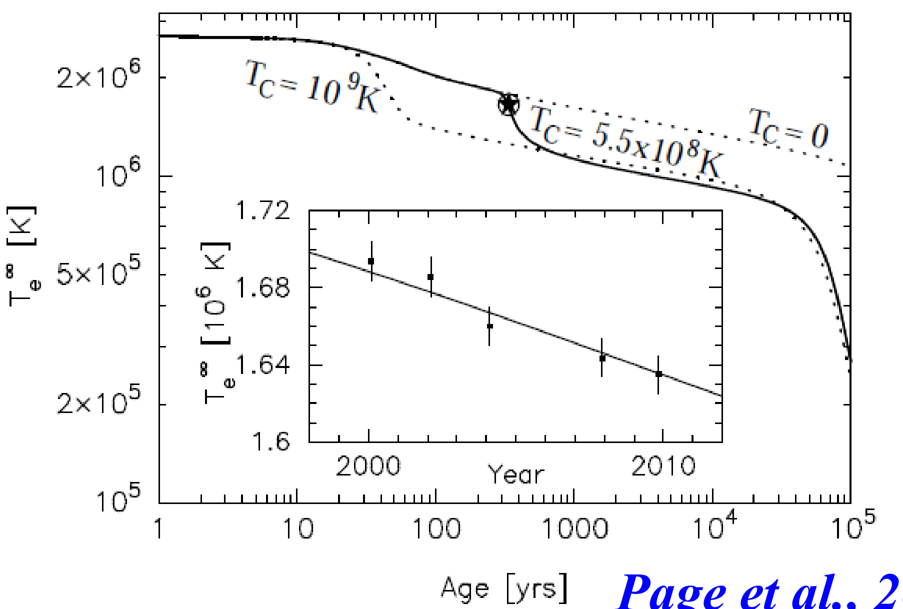
S. Tsuruta, Grossmann Medalist, 2015



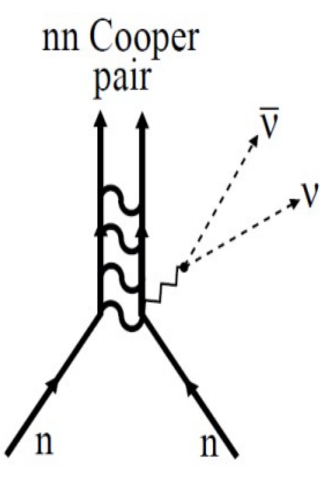
Tsuruta et al., ('09)

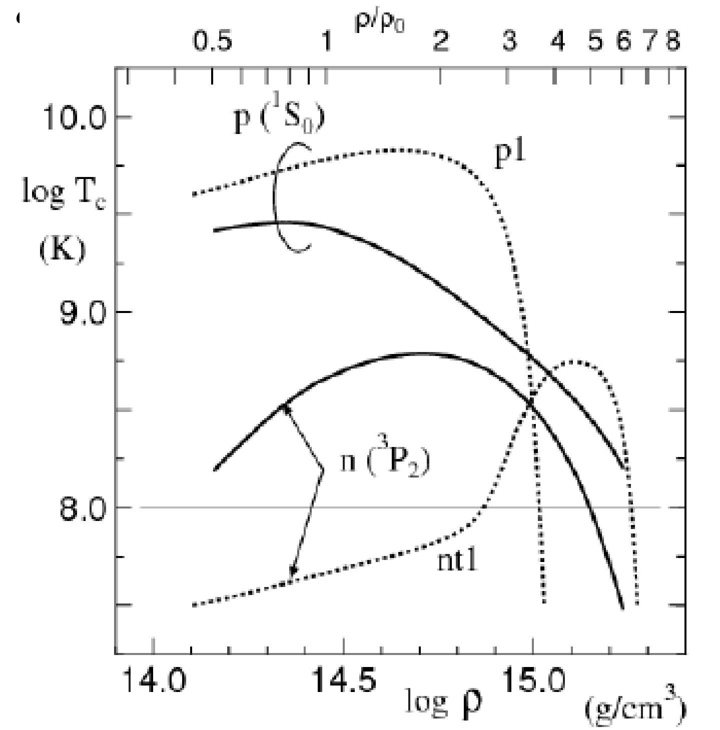
Nuclear Superfluidity and Cooling Curve

- **Surface T measurement and Cooling curve**
  - **Stable superfluid → Gap → Suppression of ν emission**
  - **Onset of superfluidity → Rapid cooling**
  - **Precise T and Cooling rate measurement in Cas A**
    Heinke, Ho, ApJ 719('10) L167 [arXiv:1007.4719]
    Page et al., PRL 106 ('11) 081101 [arXiv:1011.6142]
- **Can we predict the pairing cap around $5\rho_0$?**



Page et al., 2011





Takatsuka

Magnetic Field

- **Magnetic Dipole Model**
  (cf. Shapiro, Teukolsky)
  - **Magnetic Dipole Moment**

$$|\mathbf{m}| = \frac{1}{2} B_p R^3 \ ,$$

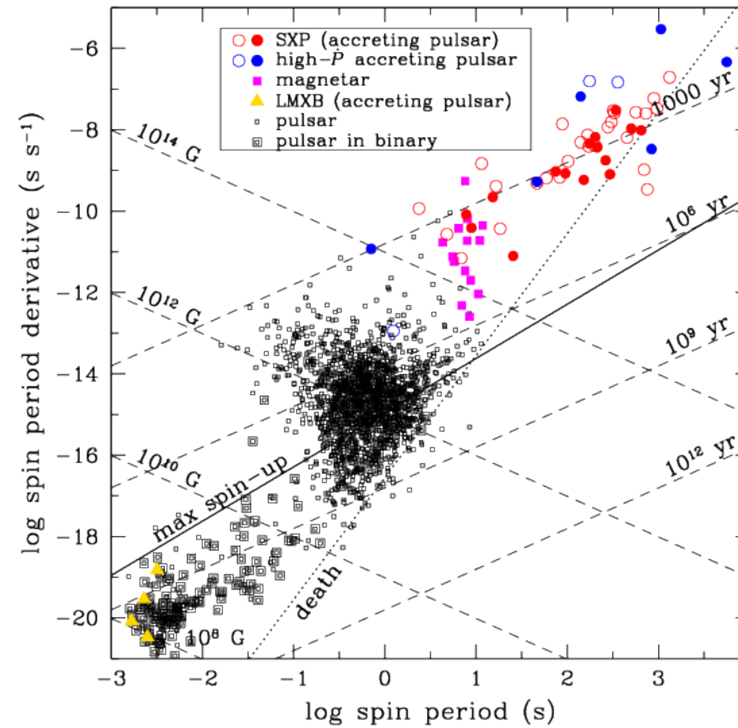
$$\dot{E} = -\frac{2}{3c^3}|\ddot{\mathbf{m}}|^2 = -\frac{B_p^2 R^6 \Omega^4 \sin^2\alpha}{6c^3}$$

  - **Rotation Energy of NS**

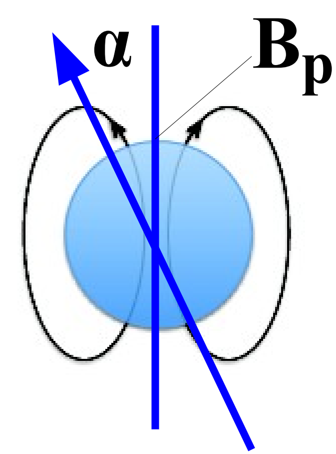
$$E = \frac{1}{2} I\Omega^2 \ , \quad \dot{E} = I\Omega\dot{\Omega} \ ,$$

$$T \equiv -\left(\frac{\Omega}{\dot{\Omega}}\right)_0 = \frac{6Ic^3}{B_p^2 R^6 \sin^2\alpha\, \Omega_0^2} \ ,$$

$$\text{age} : t \simeq T/2$$



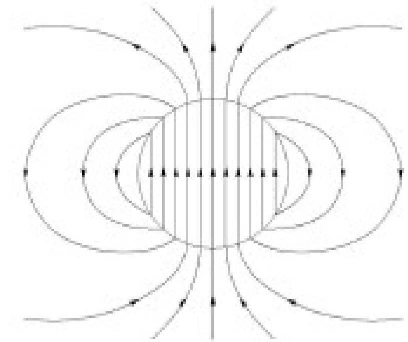
Ho, Klus, Coe, Andersson ('13)

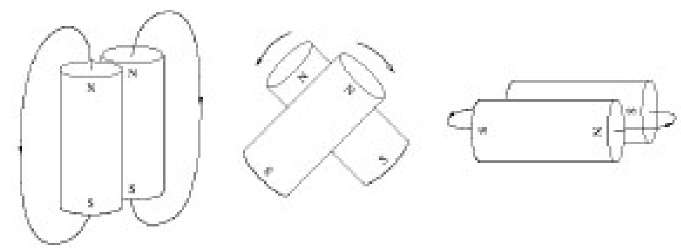


- **Magnetic field in NS B = 10^{12} – 10^{15} G**
  - **From P and dP/dt, we can guess B and t (age) of NS**

Origin of Strong Magnetic Field

- **How can we make strong B ?**
  cf. H. C. Spruit, AIP Conf.Proc.983('08)391.
  - **Fossil field hypothesis (化石磁場) (flux conservation)**
  - **Dynamo process in progenitor star evolution**
  - **Ferromagnetism**
    e.g. Yoshiike, Nishiyama, Tatsumi ('15)

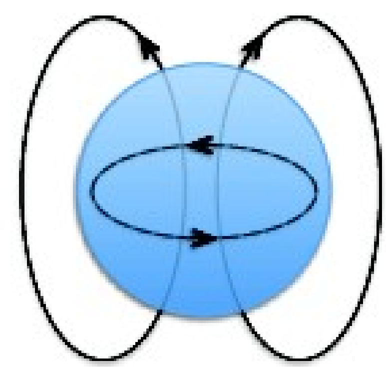




Flowers, Ruderman ('77)

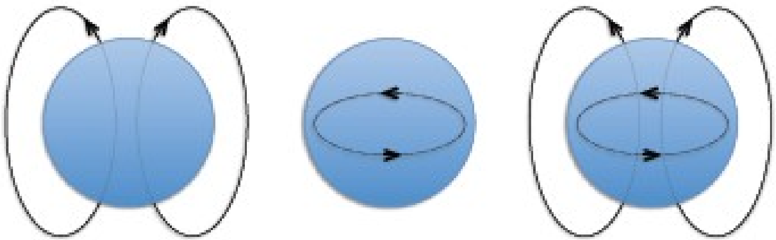
- **How can we keep strong B ?**
  - **Dipole magnetic field is not stable Flowers, Ruderman ('77)**
  - **Finite magnetic helicity** $\mathcal{H} = \int d\boldsymbol{x}\, \boldsymbol{A} \cdot \boldsymbol{B}$

    makes magnetic field stable.
    Prendergast ('56); AO, N. Yamamoto, arXiv:1402.4760; D. Grabowska, D. B. Kaplan, S. Reddy, PRD('15)085035.



Chiral Plasma Instability ?

- **Chiral Plasma Instability**
  AO, N. Yamamoto, arXiv:1402.4760



  - **Left-handed electrons are eaten in electron capture → chiral chem. pot.**

$$p + e_L^- \to n + \nu_L^e;$$

  - **Chiral plasma instability: N_5 is converted to magnetic helicity**
    Akamatsu, Yamamoto ('13, '14)

$$j_z = \frac{2\alpha}{\pi}\mu_5 B_z, \qquad \frac{d}{dt}\left(N_5 + \frac{\alpha}{\pi}\mathcal{H}\right) = 0, \quad N_5 = \int dx\, n_5$$

  - **Finite magnetic helicity makes magnetic field stable.**

$$\mathcal{H} = \int dx\, A \cdot B$$

  - **Electron Mass may kill the instability.**
    D. Grabowska, D. B. Kaplan, S. Reddy, PRD('15)085035

Contents

- Introduction
- Neutron star basics
  - NS mass: Kepler motion, Mass function, and GR effects
  - NS radius: Stephan-Boltzmann, Eddington limit, Red shift
  - A little on NS cooling and magnetic field
- Nuclear matter and neutron star matter EOS
  - Tolman-Oppenheimer-Volkoff (TOV) equation
  - Saturation Point, Incompressibility, and Symmetry Energy
- Massive neutron star puzzle
  - How can we sustain two-solar-mass NSs ?
  - Proposed mechanisms to sustain massive NSs
  - What is necessary to solve massive NS puzzle ?
- Summary

Neutron Star Matter EOS

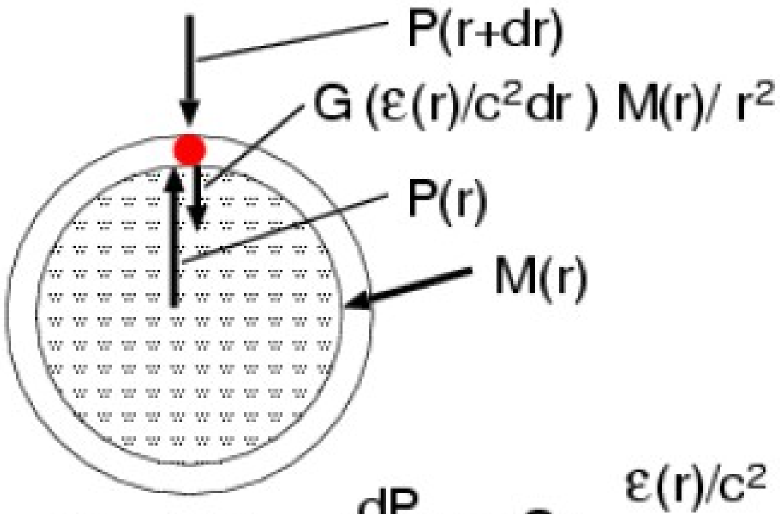
TOV equation

- **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.**
- **Initial cond. ε(r=0) Solve TOV until P=0**



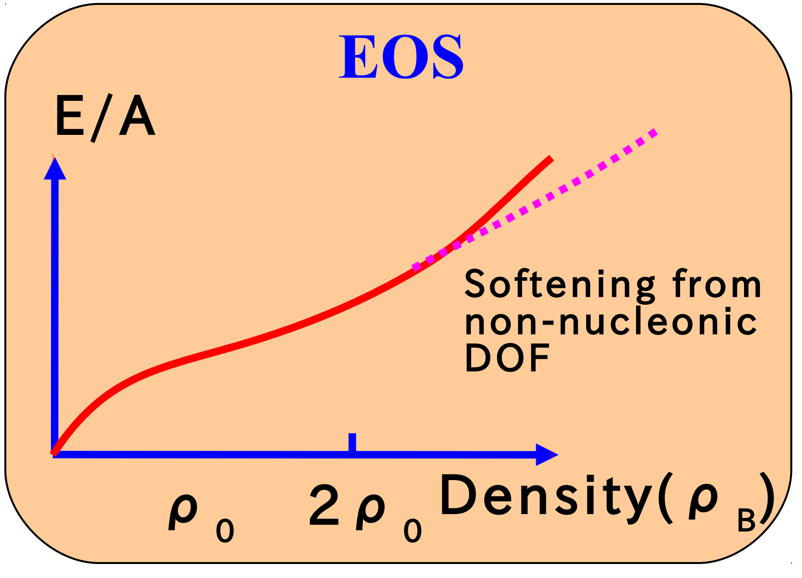
$$\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$$

M-R Relation and EOS

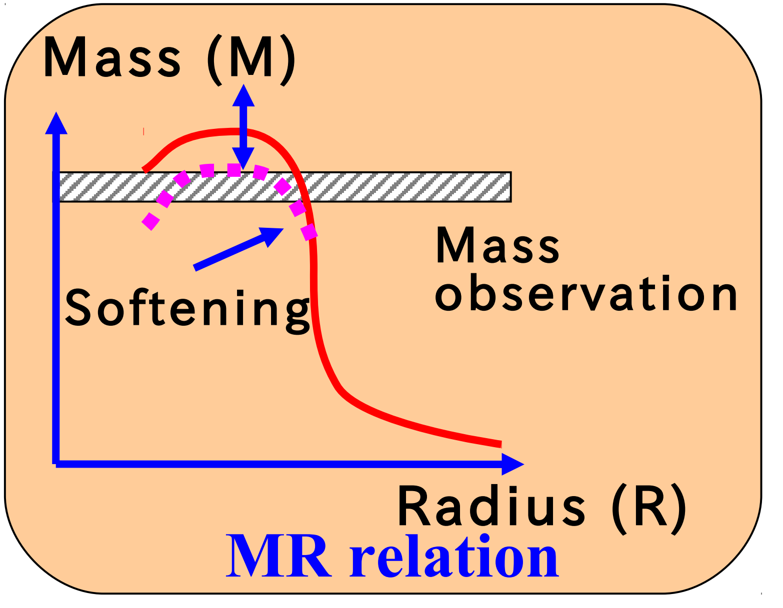
- **Solving TOV eq.**
  starting from the "initial" condition, $\varepsilon(r=0) = \varepsilon_c$ = given
  until the "boundary" condition P(r)=0 is satisfied.
  → M and R are the functions of ε(r=0)
  and functionals of EOS, P=P(ε).

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

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



TOV Eq.



Nuclear Mass

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

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

Volume **Surface** **Coulomb** **Symmetry** **Pairing**

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

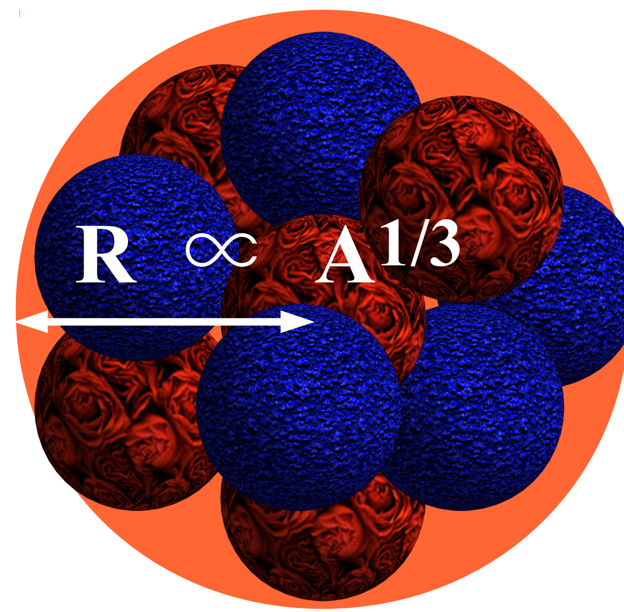
- **Ignore Coulomb, consider A → ∞,**

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

$$a_v \simeq 16\,\mathrm{MeV}$$

$$a_a \simeq 23\,\mathrm{MeV}\,(a_a(\mathrm{vol}) \simeq 30\,\mathrm{MeV})$$

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



Neutron Star Matter EOS

- **Energy per nucleon in nuclear matter**

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

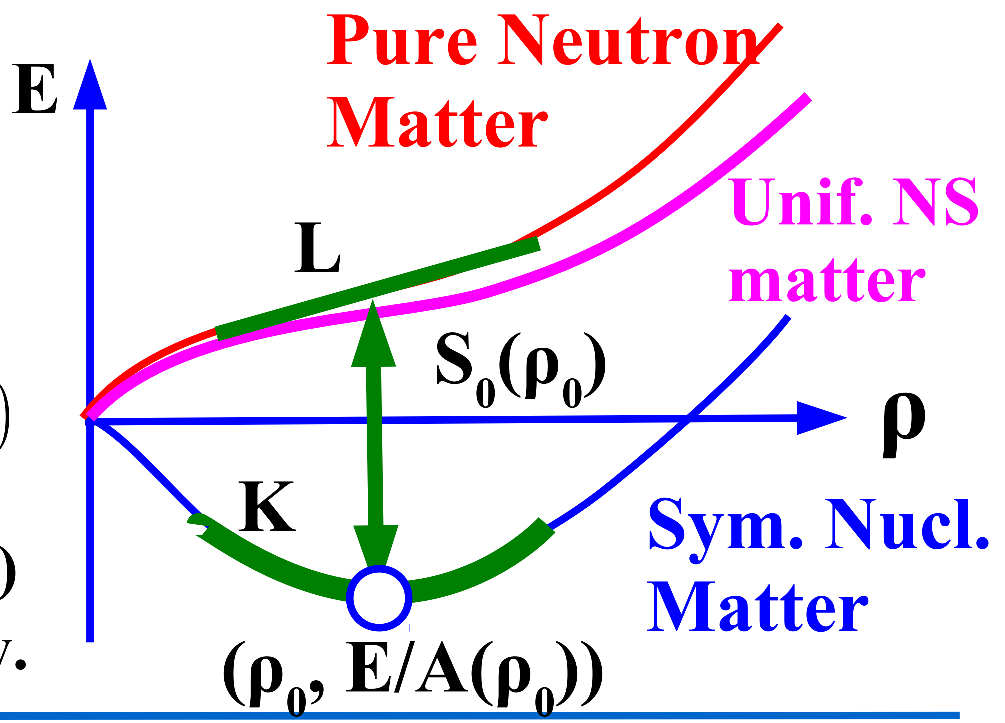
$$E_{\rm SNM}(\rho) \simeq E_0 + \frac{K(\rho-\rho_0)^2}{18\rho_0^2} \ , \quad S(\rho) = S_0 + \frac{L(\rho-\rho_0)}{3\rho_0}$$

  - **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**

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

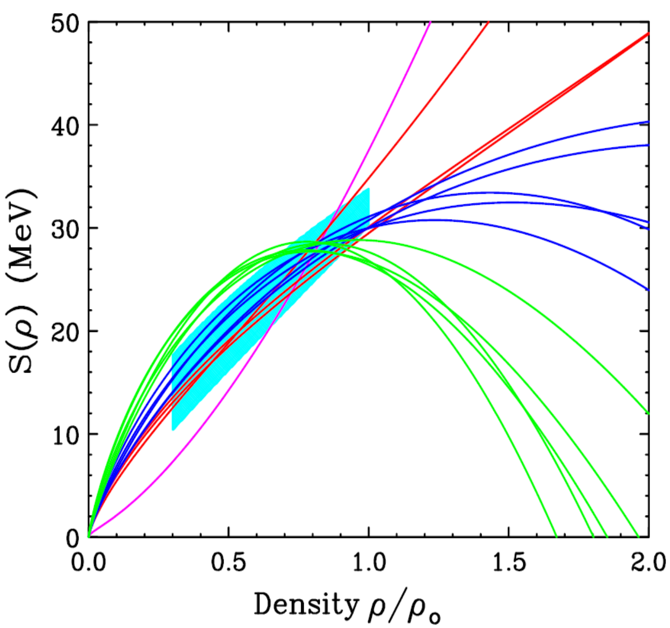
  - **Charge neutrality**
    → ρ(elec.)= ρ(p) ($\rho_e = \rho_p = \rho(1-\delta)/2$)
    δ is optimized to minimize energy.



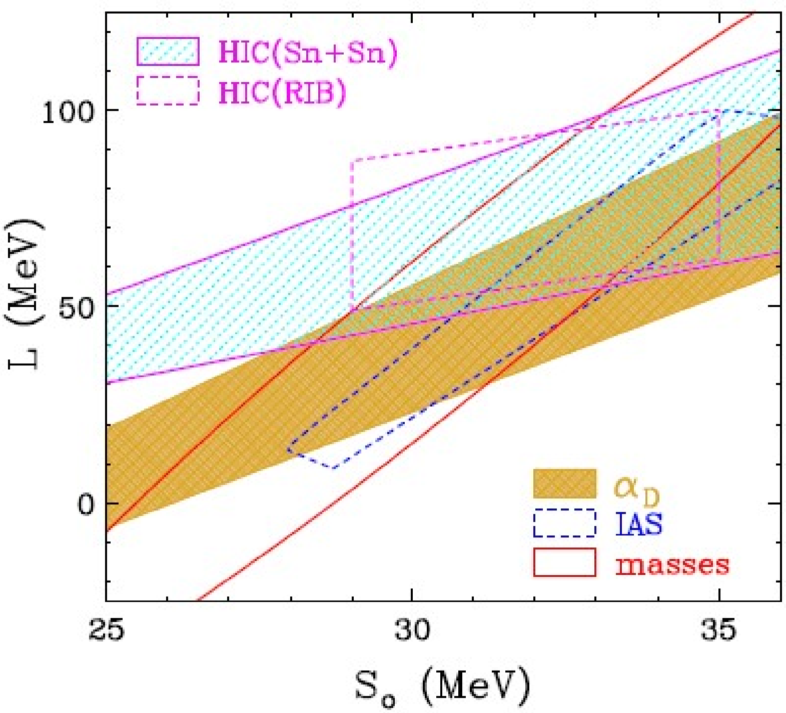
Symmetry Energy

- **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 = 40-90 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

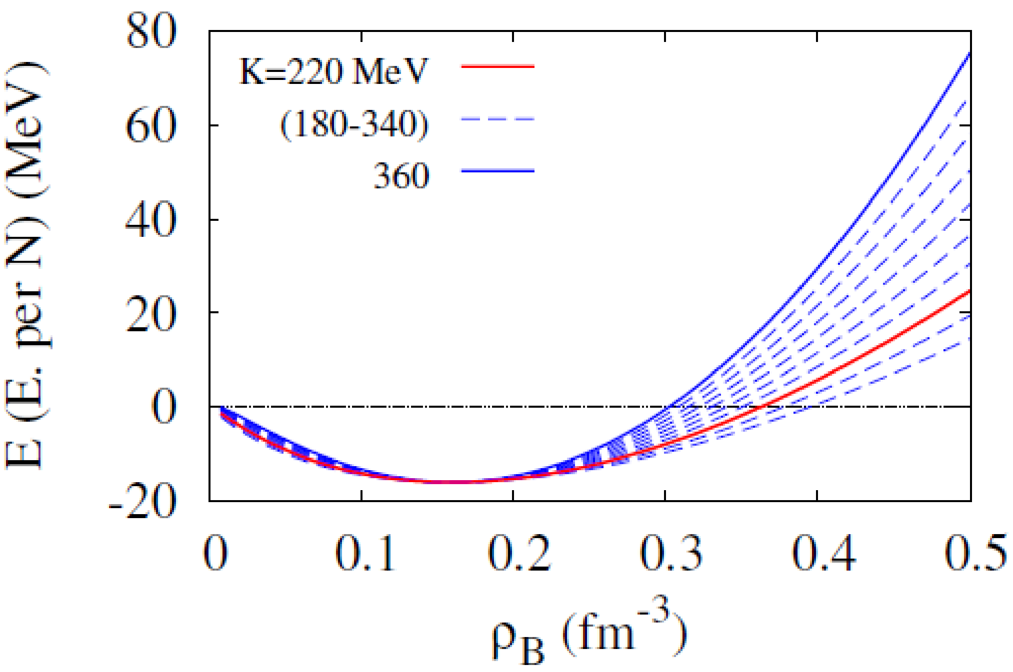
Simple parametrized EOS

- **Skyrme int. motivated parameterization**

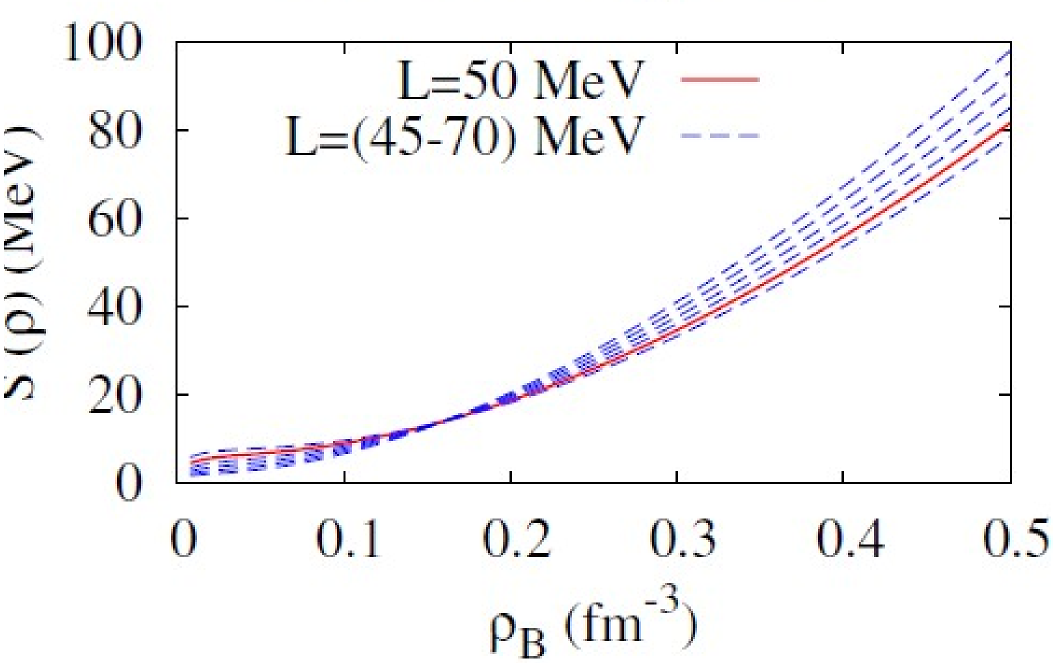
$$E_{\rm SNM} = \frac{3}{5}E_F(\rho) + \frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right) + \frac{\beta}{2+\gamma}\left(\frac{\rho}{\rho_0}\right)^{1+\gamma}$$

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

- **$(\rho_0, E/A(\rho_0), K) \to (\alpha, \beta, \gamma), L \to \gamma_{sym}$**

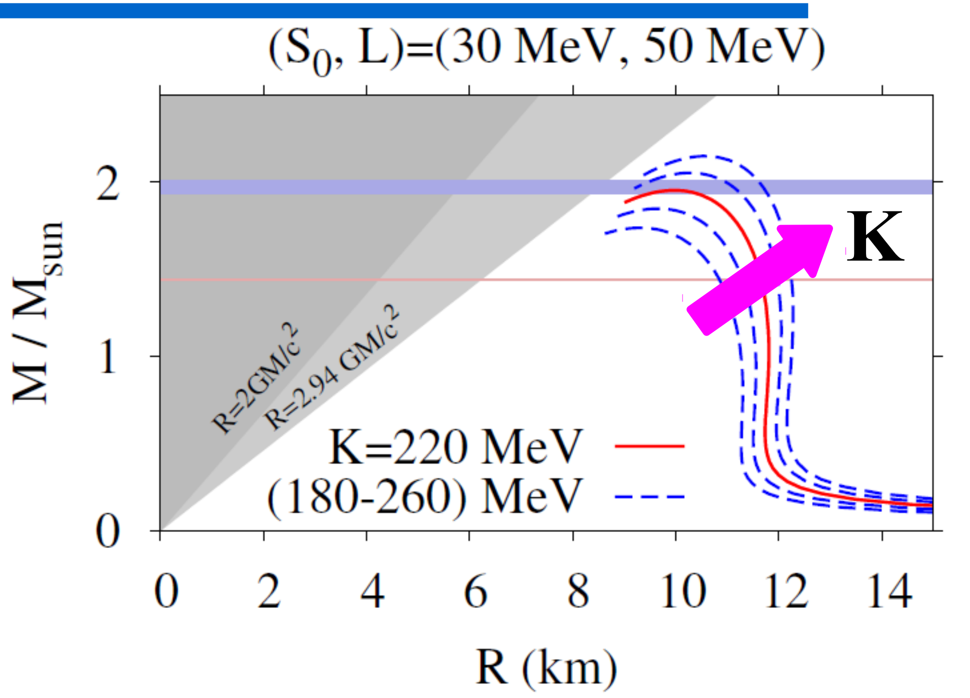


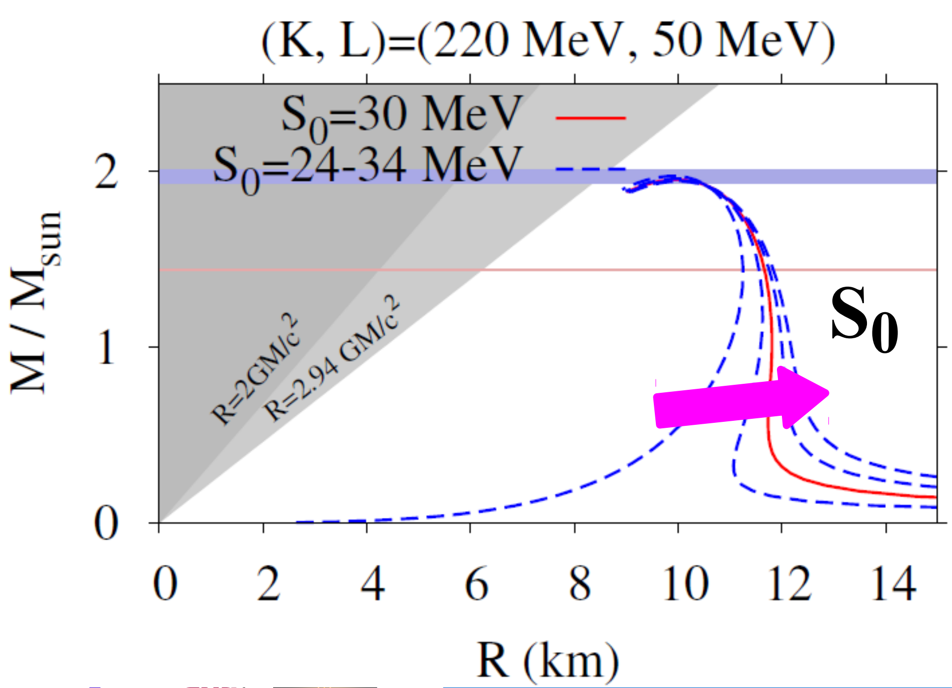
K=220 MeV, S_0=30 MeV

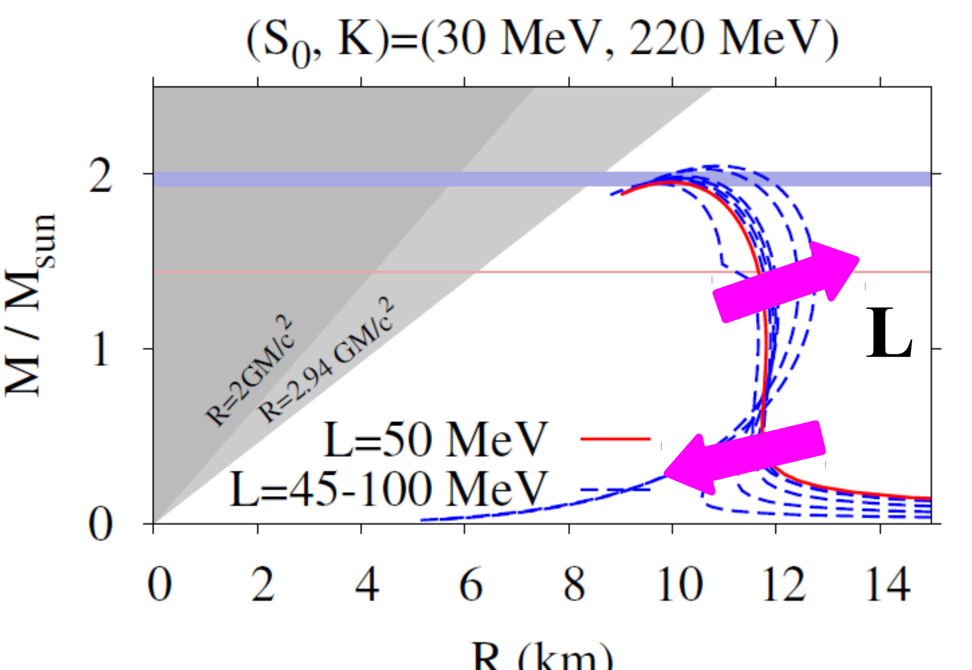


Simple parametrized EOS

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







Theories/Models for Nuclear Matter EOS

- **Mean Field from Effective Int. ~ Nuclear Density Functionals**
  - **Skyrme Hartree-Fock**
    - **Non.-Rel.,Zero Range, Two-body + Three-body (or ρ-dep. two-body)**

$$\frac{E}{A} = \left\langle \frac{\mathbf{p}^2}{2m^*} \right\rangle + V(\rho,\delta)\ , \quad V \simeq \frac{\alpha}{2}\frac{\rho}{\rho_0} + \frac{\alpha'\delta}{2}\frac{\rho}{\rho_0} + \frac{\beta}{1+\gamma}\left(\frac{\rho}{\rho_0}\right)^\gamma + \ldots$$

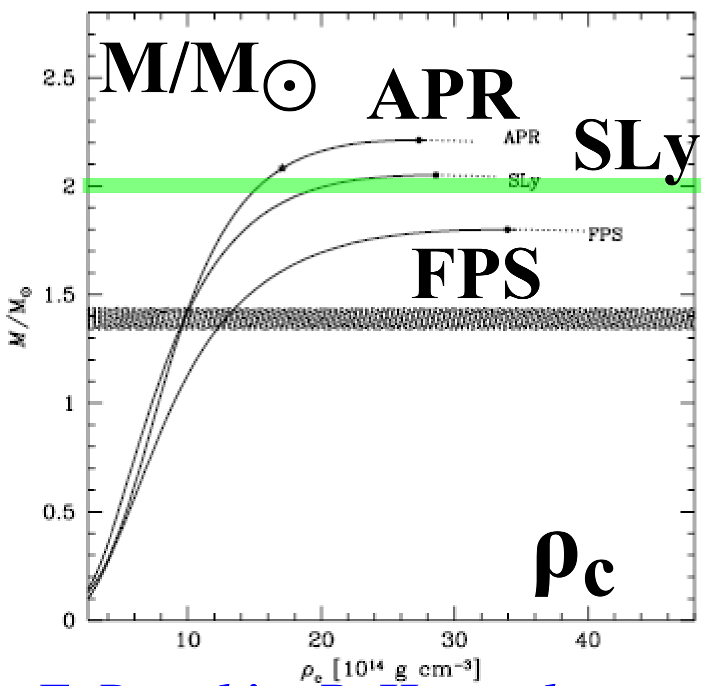
  - **Relativistic Mean Field**
    - **Relativistic, Meson-Baryon coupling, Meson self-energies**

$$\frac{E}{A} = \left\langle \sqrt{\mathbf{p}^2 + (M - g_\sigma\sigma)^2} \right\rangle + g_\omega\omega + \frac{1}{\rho_B}\left[\frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{2}m_\omega^2\omega^2 + \ldots\right]$$

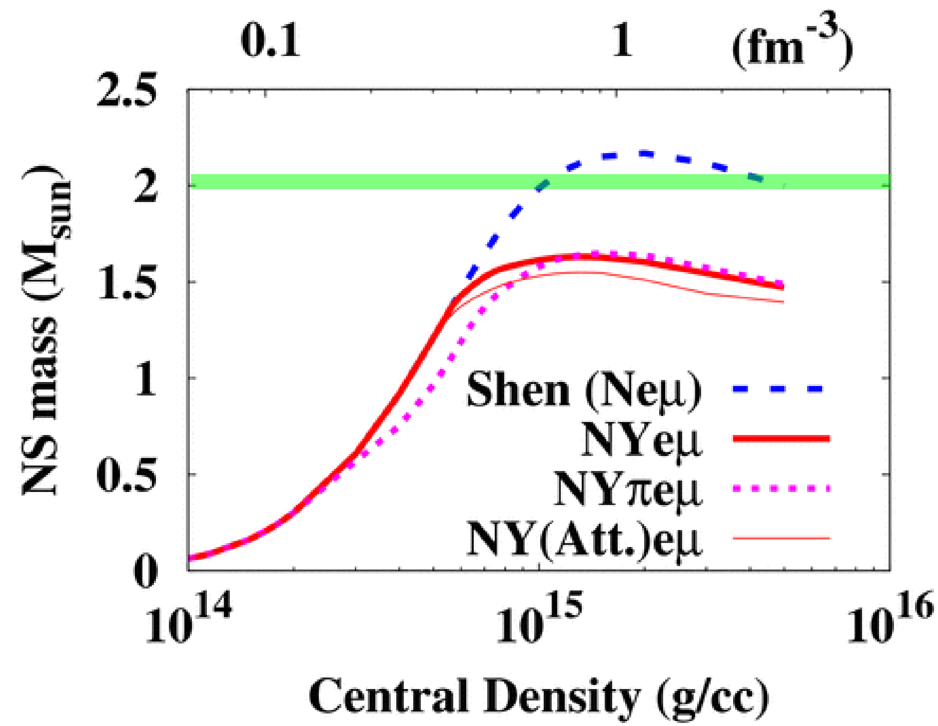
- **Microscopic (ab initio) Approaches (starting from bare NN int.)**
  - **Variational calculation**
  - **Quantum Monte-Carlo**
  - **Bruckner Theory (G-matrix)**

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⊙**



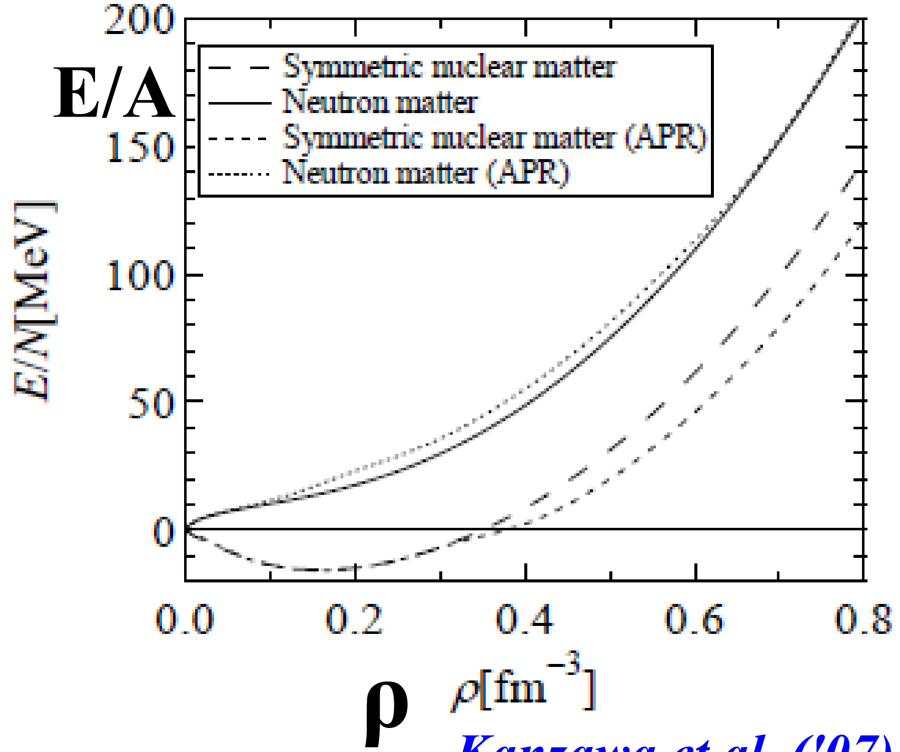
F. Douchin, P. Haensel. Astron.Astrophys.380('01)151.



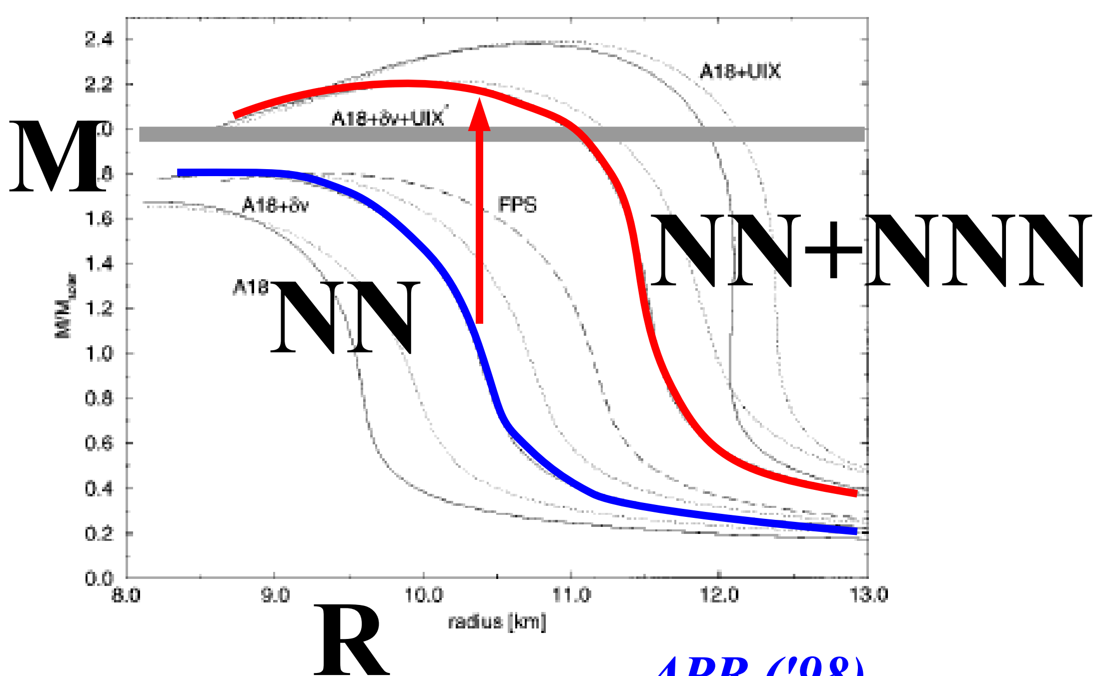
Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08),085201
c.f. H.Shen+('09) → n, p, Λ EOS

Variational Calculation

- **Variational Calculation starting from bare nuclear force**
  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.
  - **Argonne v18(v14) + Rel. corr. + Three Nucleon Int.**



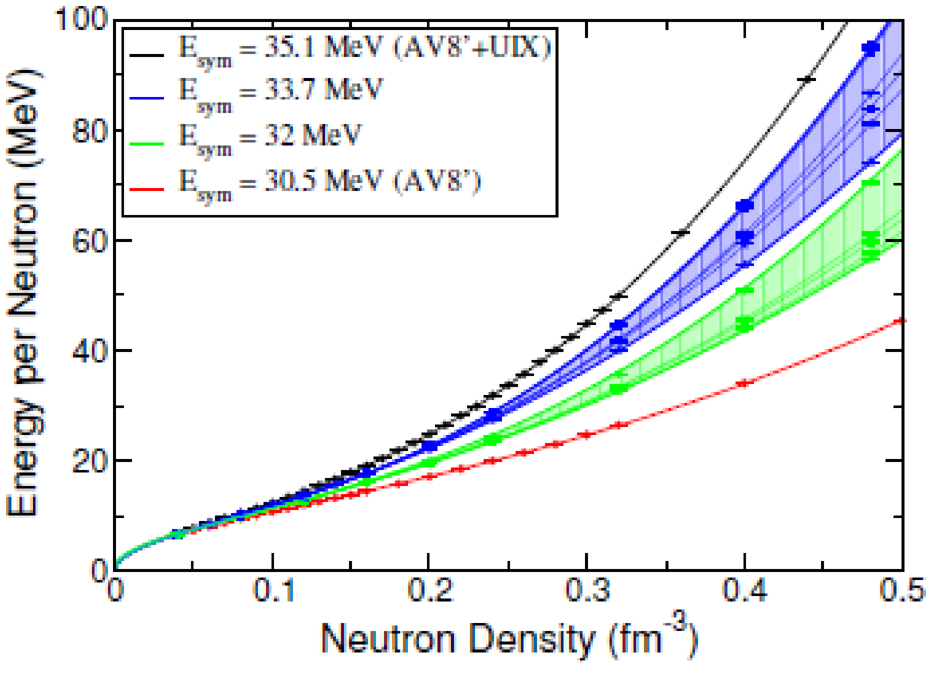
Kanzawa et al. ('07)

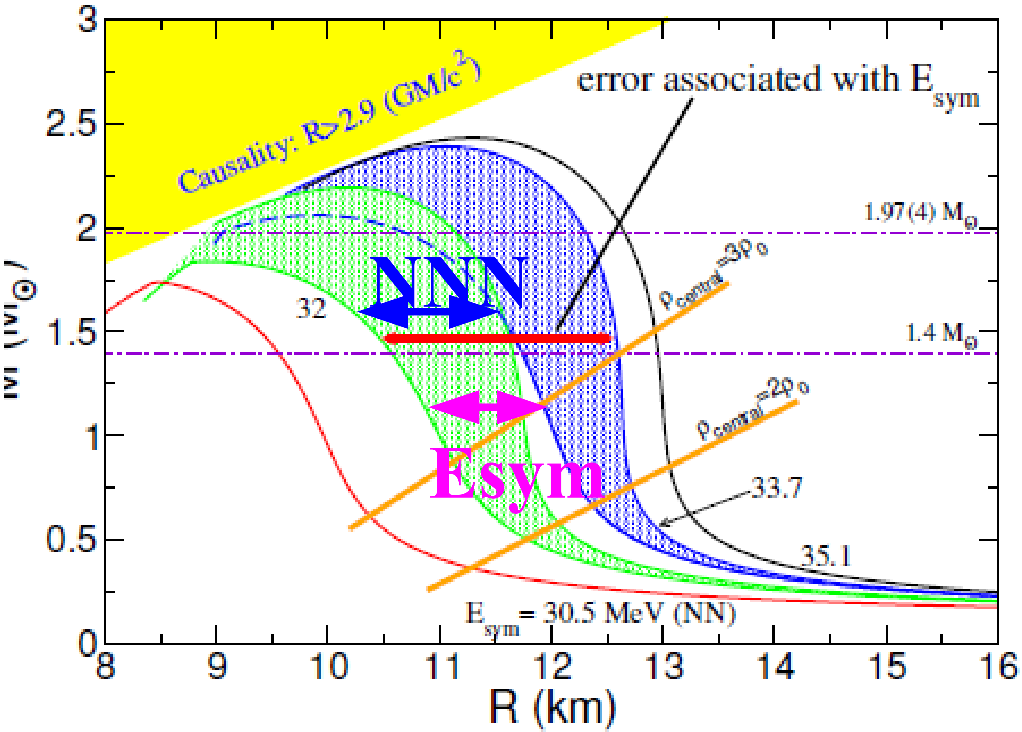


APR ('98)

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}.**





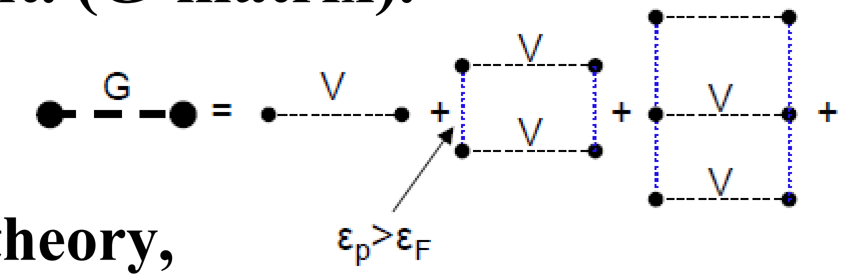
Gandolfi, Carlson, Reddy, PRC 032801, 85 (2012).

Bruckner-Hartree-Fock

- **Effective interaction from bare NN int. (G-matrix).**

$$g(E) = V + V \frac{Q}{E - H_0} g(E)$$

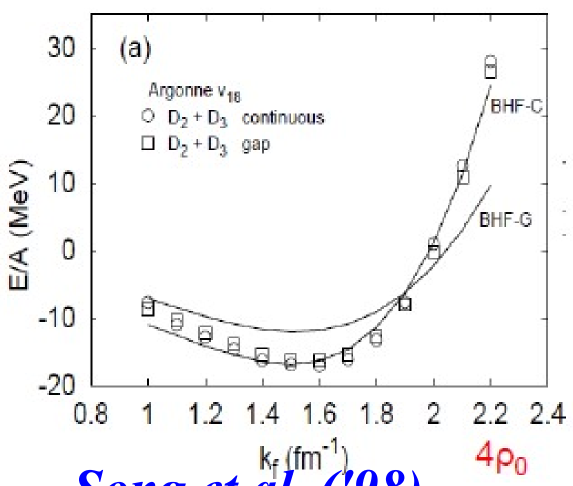
Pauli



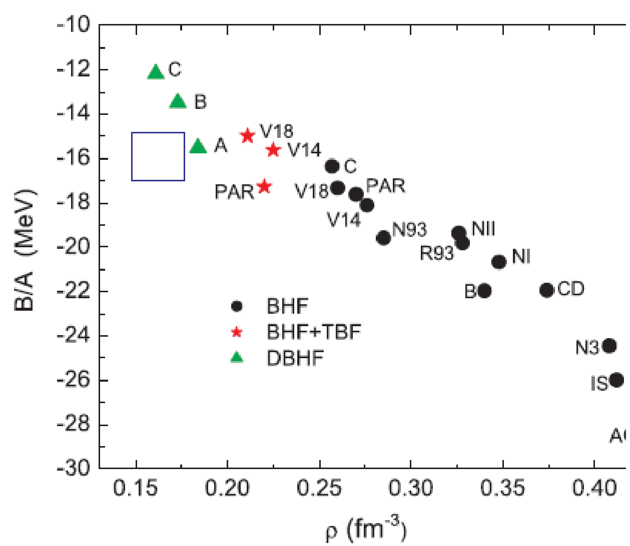
  - **G-matrix = Lowest order Bruckner theory, but next-to-leading terms give small effects at $\rho < 4\rho_0$.**

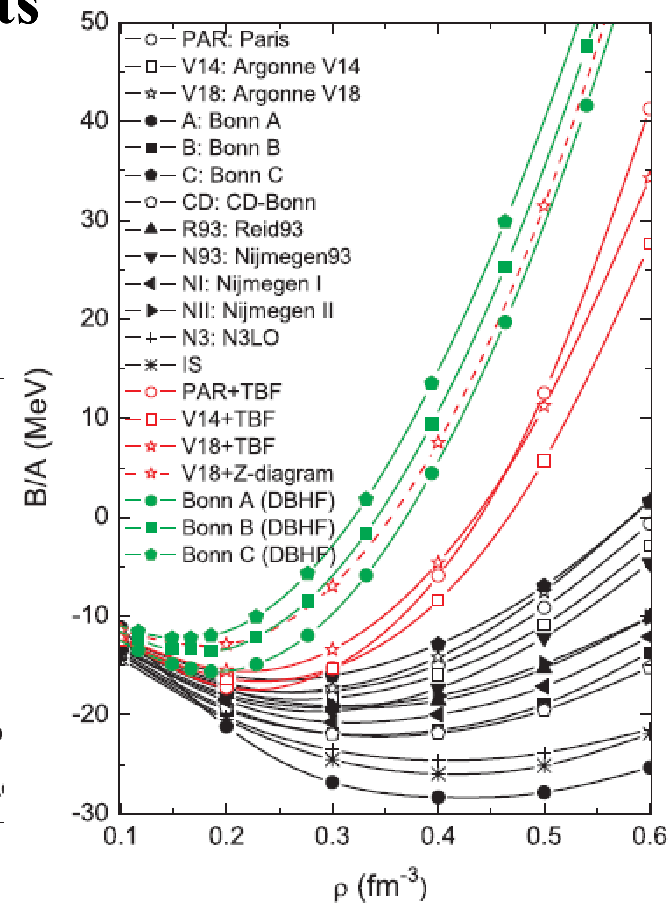
    Song, Baldo, Giansiracusa, Lombardo ('98)

  - **Need 3-body force to reproduce saturation point.**



Song et al. ('98)

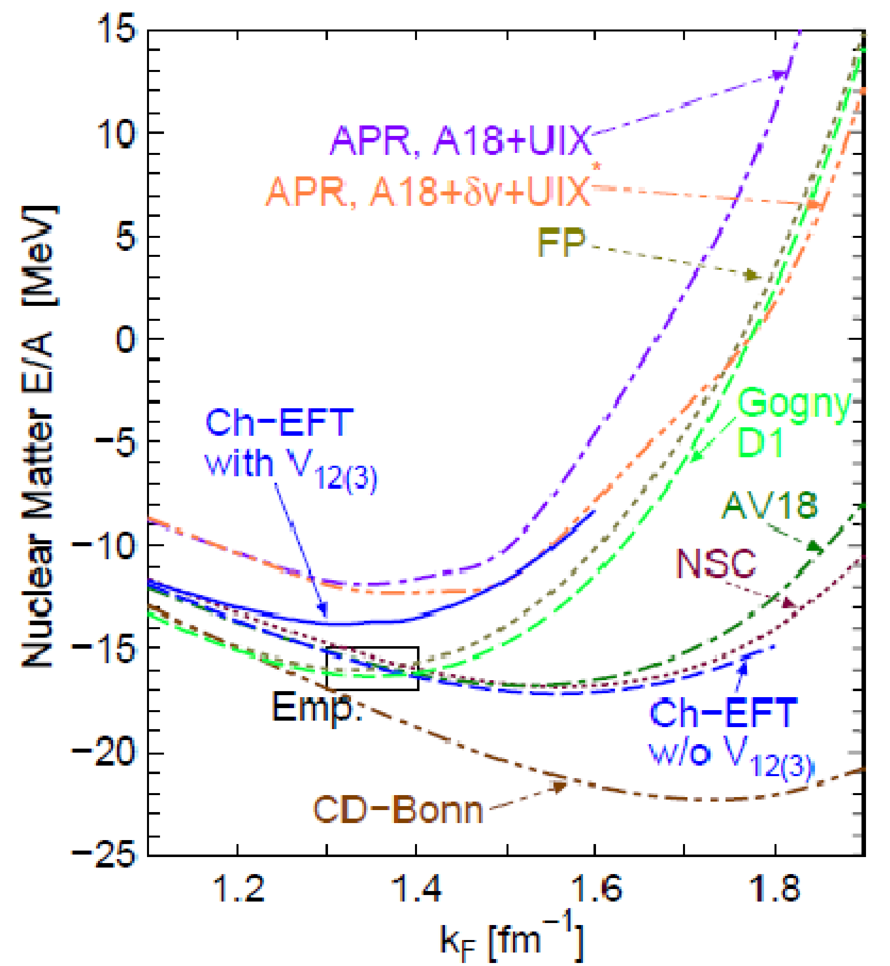




Z.H.Li, U. Lombardo, H.-J. Schulze, W. Zuo, L. W. Chen, H. R. Ma, PRC74('06)047304.

BHF with Ch-EFT & Lattice NN force

- **Bruckner-HF calc. with NN (N3LO)+3NF(N2LO) interactions from Chiral Effective Field Theory** *M.Kohno ('13)*
  - **Ch-EFT = Eff. Field Theory with the same symmetry as QCD**
    Weinberg; Gasser, Leutwyler ('84)
    → Systematically gives NN & NNN interaction terms.
    Epelbaum, Gockle, Meissner ('05)
- **Bruckner HF calc. with NN int. from Lattice QCD.**
  Inoue et al. (HAL QCD Coll.), PRL111 ('13)112503
  - **Not yet reliable but promising !**



M. Kohno, PRC88('13)064005

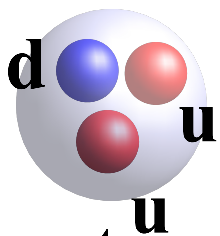
Contents

- Introduction
- Neutron star basics
  - NS mass: Kepler motion, Mass function, and GR effects
  - NS radius: Stephan-Boltzmann, Eddington limit, Red shift
  - A little on NS cooling and magnetic field
- Nuclear matter and neutron star matter EOS
  - Tolman-Oppenheimer-Volkoff (TOV) equation
  - Saturation Point, Incompressibility, and Symmetry Energy
- Massive neutron star puzzle
  - How can we sustain two-solar-mass NSs ?
  - Proposed mechanisms to sustain massive NSs
  - What is necessary to solve massive NS puzzle ?
- Summary

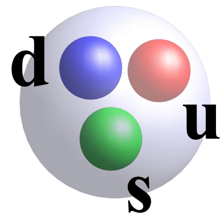
Massive Neutron Star puzzle

Neutron star – Is it made of neutrons ?

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

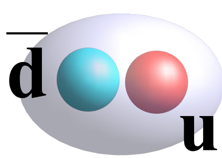


proton

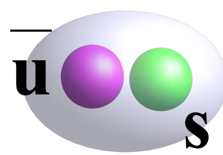


Λ hyperon

  - **Meson condensate (K, π)**

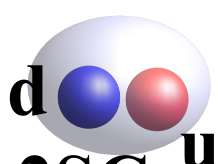


π

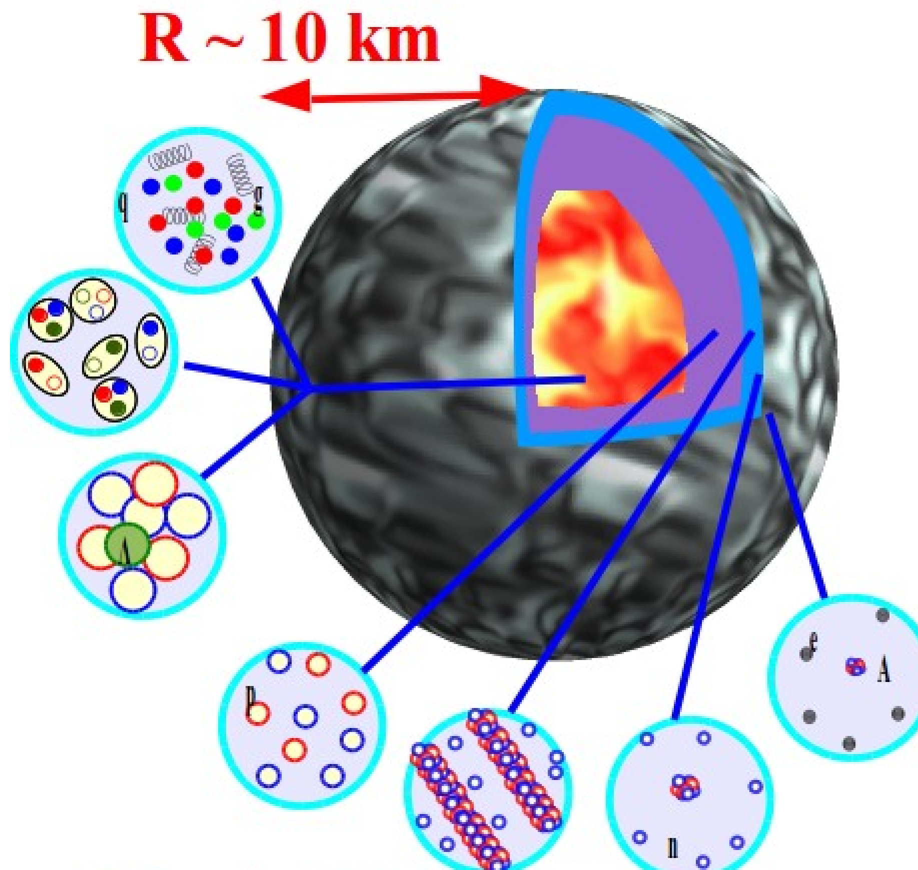


anti kaon

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



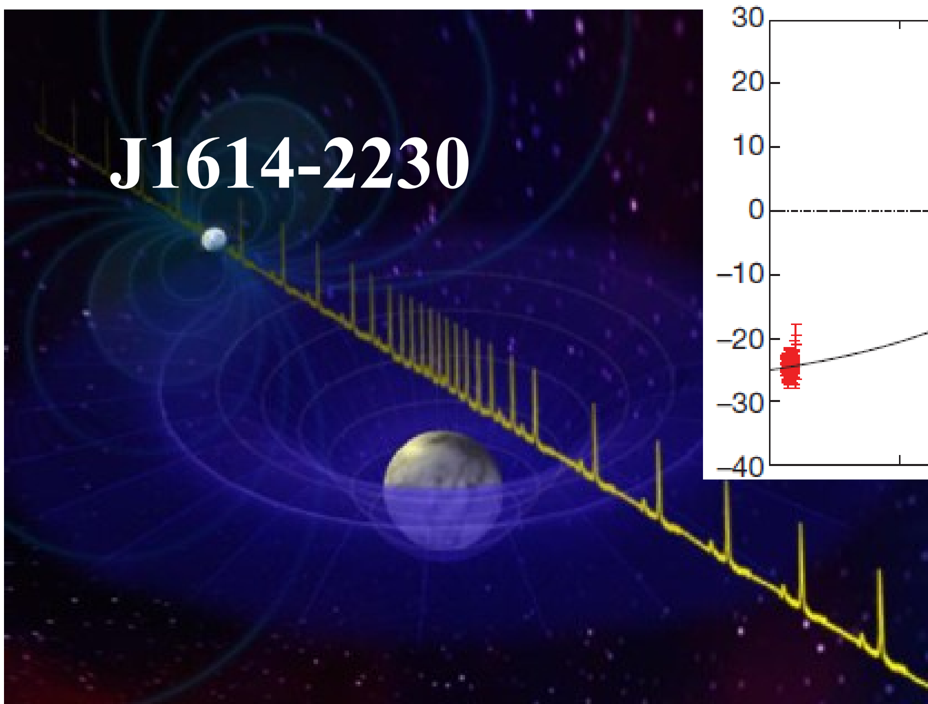
2SC

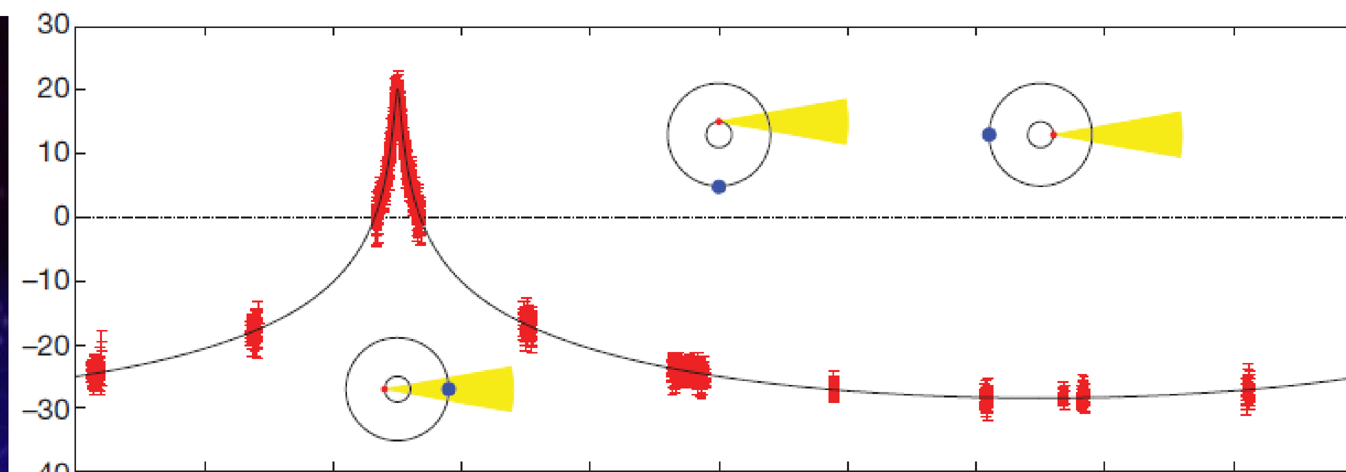


$M \sim 1.4\, M_\odot$, $\rho_c \sim (3\text{-}10)\, \rho_0$

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)

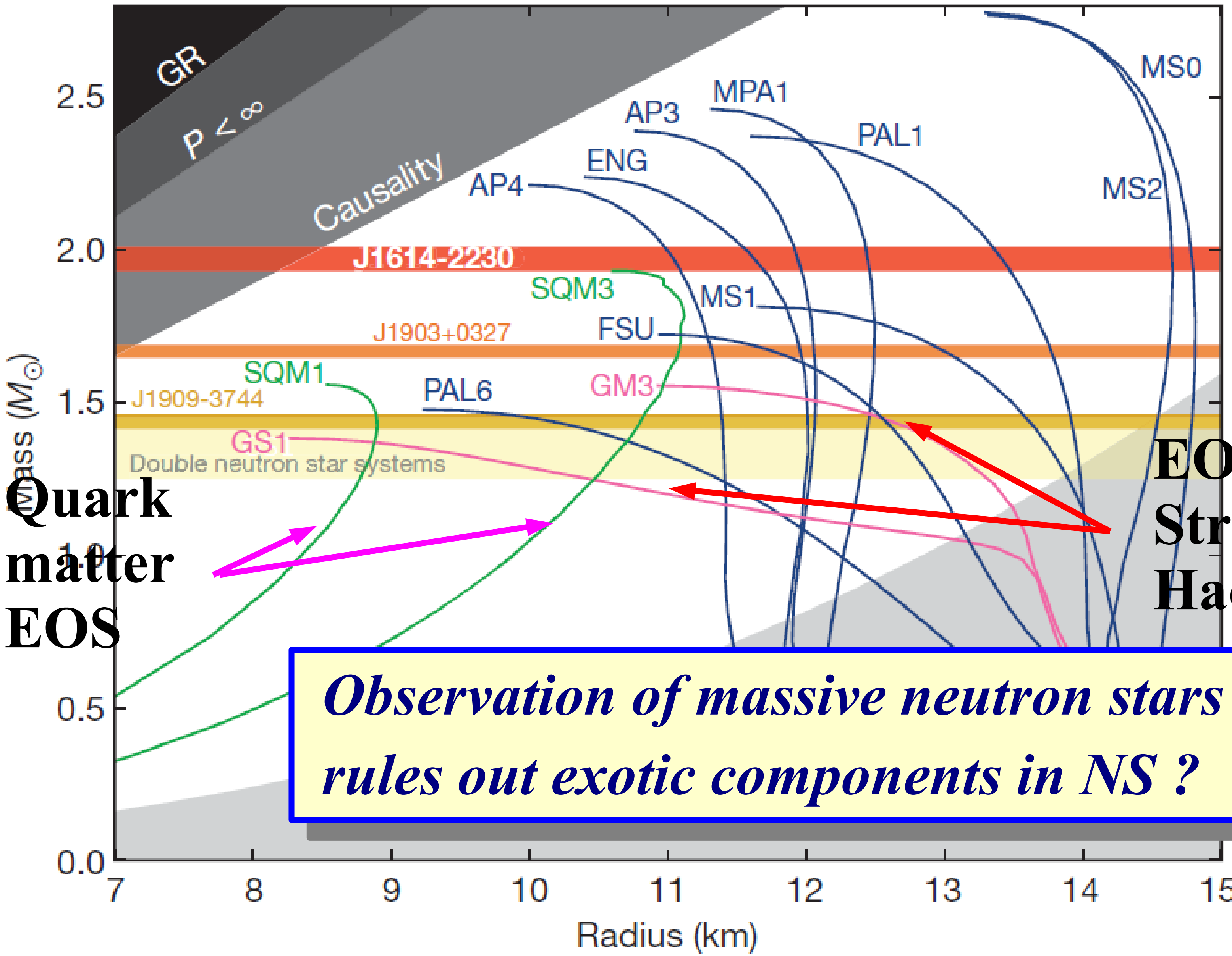




$$\Delta_S = -2m\left[\ln\frac{r}{a} + \ln\left(1 - \sin i \sin\phi\right)\right]$$

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

Massive Neutron Star Puzzle



Quark matter EOS

EOS w/ Strange Hadrons

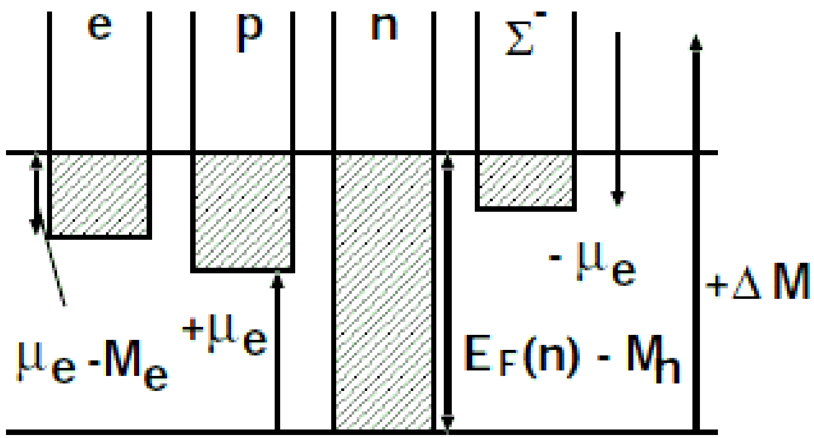
Observation of massive neutron stars ($M \sim 2\ M_\odot$) rules out exotic components in NS ?

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

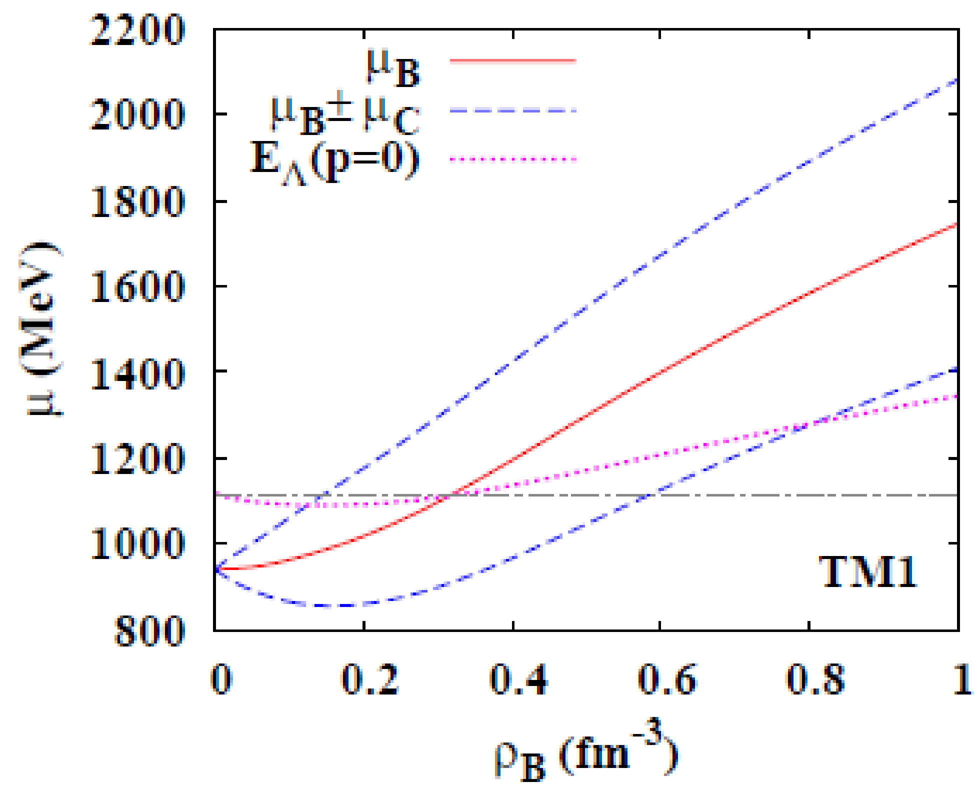
PSR J0348+0432: 2.01 ± 0.04 $M_\odot$ *Antoniadis et al., Science 340('13)1233232.*

Hyperons in Dense Matter

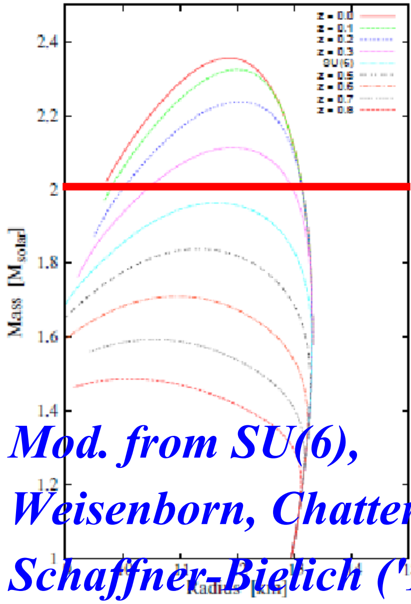
- **What appears at high density ?**
  - **Nucleon superfluid ($^3S_1$, $^3P_2$), Pion condensation, Kaon condensation, Baryon Rich QGP, Color SuperConductor (CSC), Quarkyonic Matter, ...**
  - **Hyperons**
    Tsuruta, Cameron (66); Langer, Rosen (70); Pandharipande (71); Itoh(75); Glendenning; Weber, 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; ...



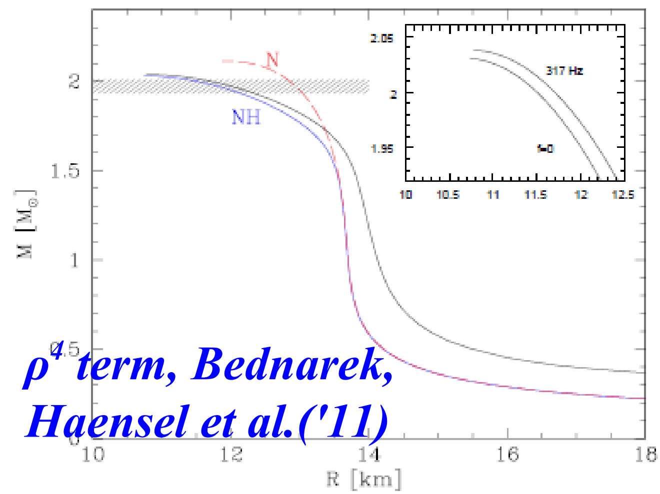
Chemical potential overtakes Λ mass → appearance of Λ



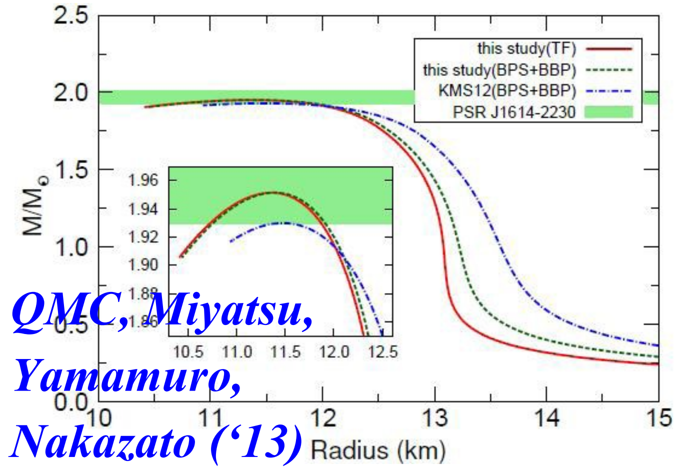
NS matter EOS with hyperons



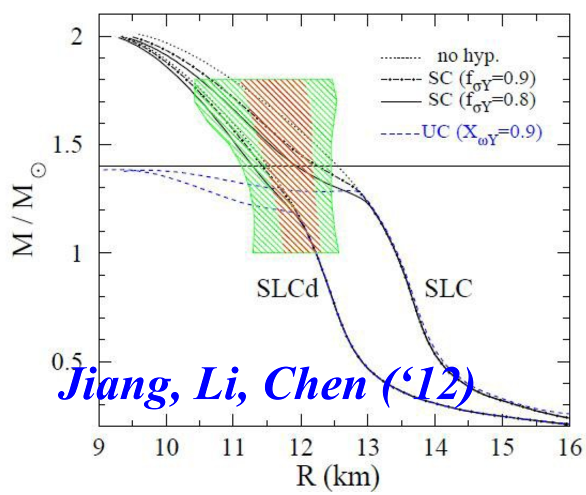
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



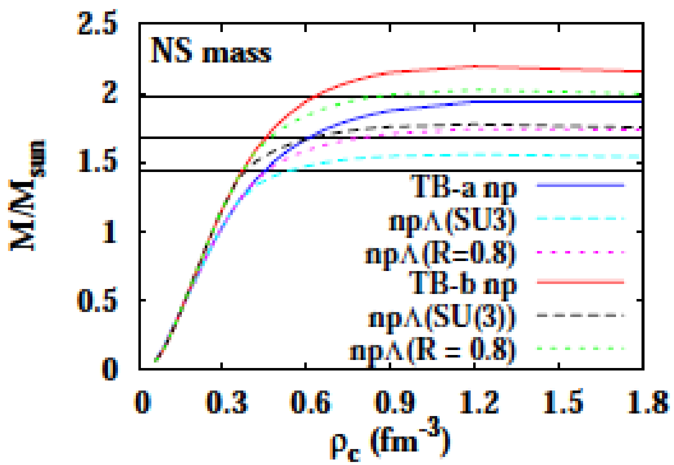
ρ^4 term, Bednarek, Haensel et al.('11)



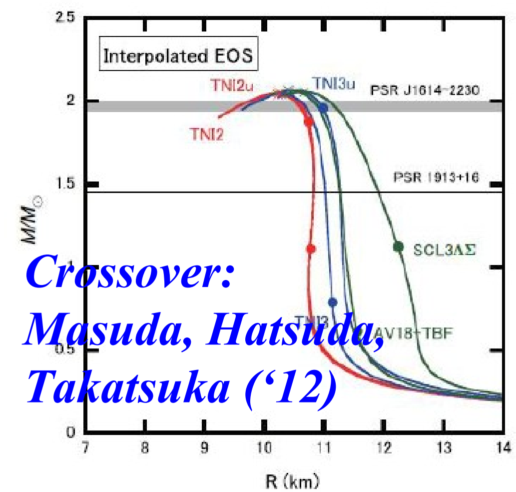
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



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



Crossover: Masuda, Hatsuda, Takatsuka ('12)

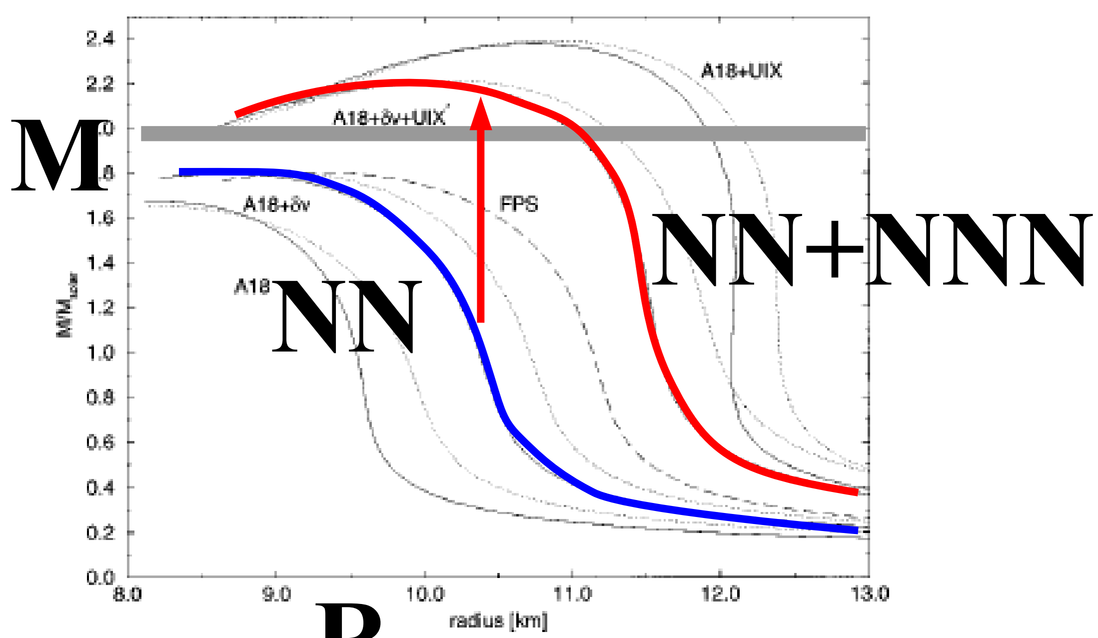
> ***These are phenomenological "solutions". How can we examine them ?***

Possible Solutions to Massive NS puzzle

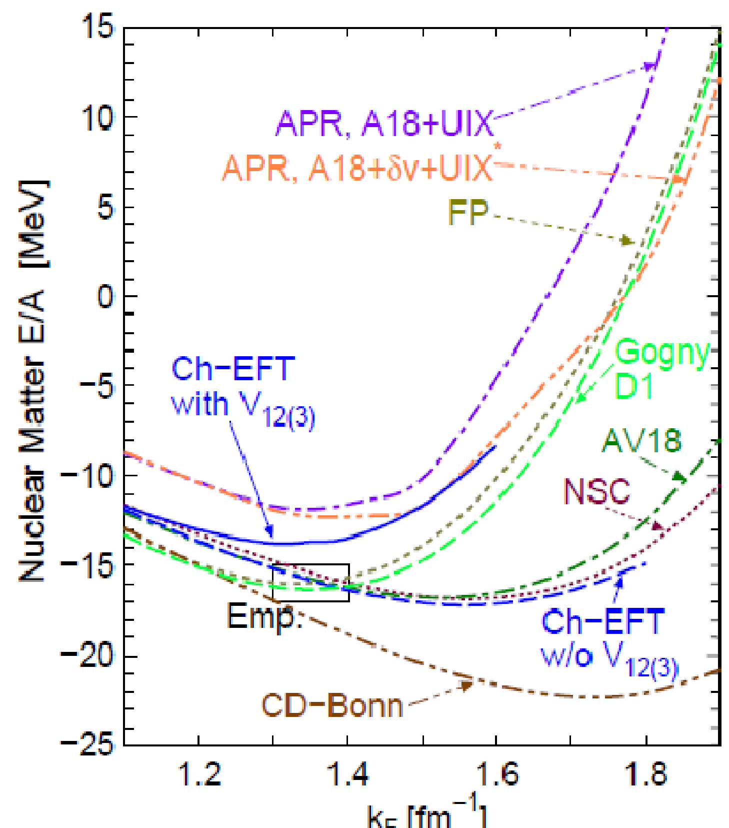
- **Proposed "Solutions" of Massive NS puzzle**
  - **Choose Stiff EOS for nuclear matter** *Tsubakihara, Harada, AO ('14)*
  - **Modification of YN interaction** *Weisenborn, Chatterjee, Schaffner-Bielich ('11); Jiang, Li, Chen ('12); Tsubakihara, AO ('13)*
  - **Introducing BBB repulsion** *S. Nishizaki, 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



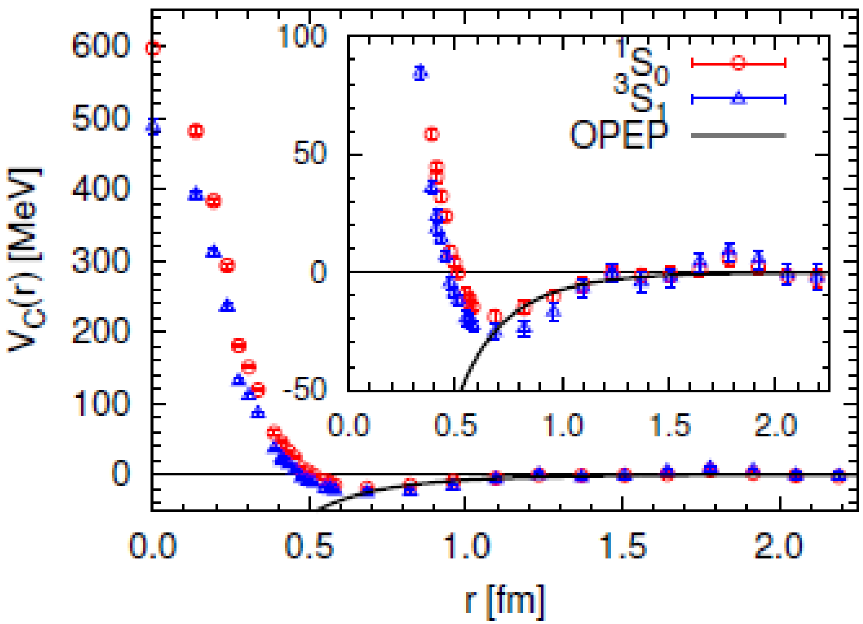
Akmal et al. (APR,'98)



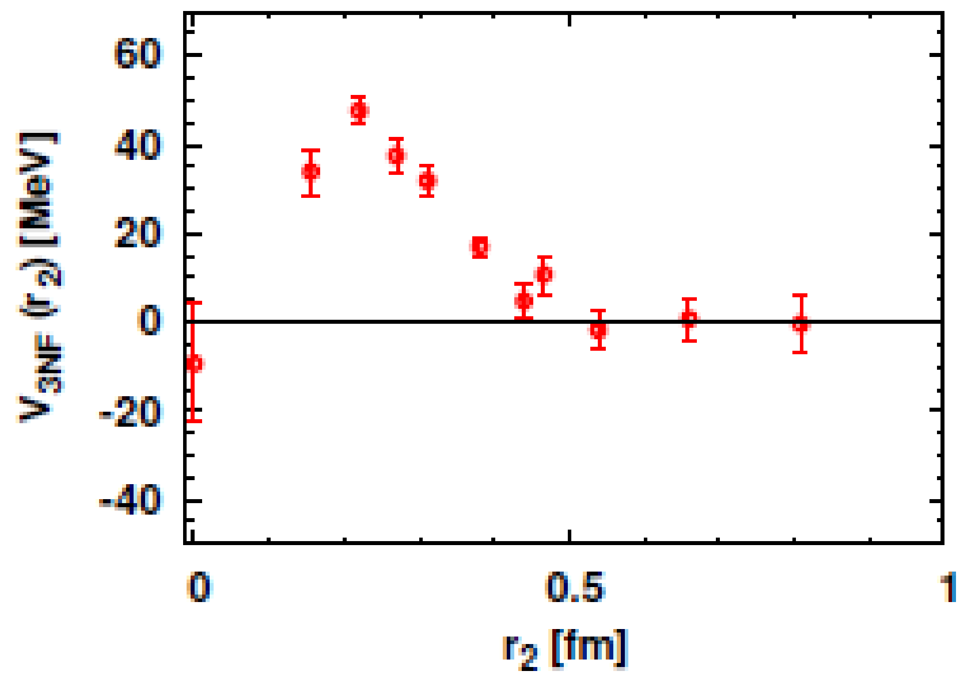
M. Kohno, PRC88('13)064005

NNN force from Lattice QCD

- **HAL QCD method for BB int.** *Aoki, Hatsuda, Ishii ('07)*
  Nambu-Bethe-Salpeter amplitude ~ w.f.
  → NN force from Sch. Eq.
  - **Consistent with Luscher's method in asymptotic region**
    Luscher ('91), NPLQCD Collab. ('06, ππ)
- **NNN force T. Doi (HAL QCD Collab.)('12)**



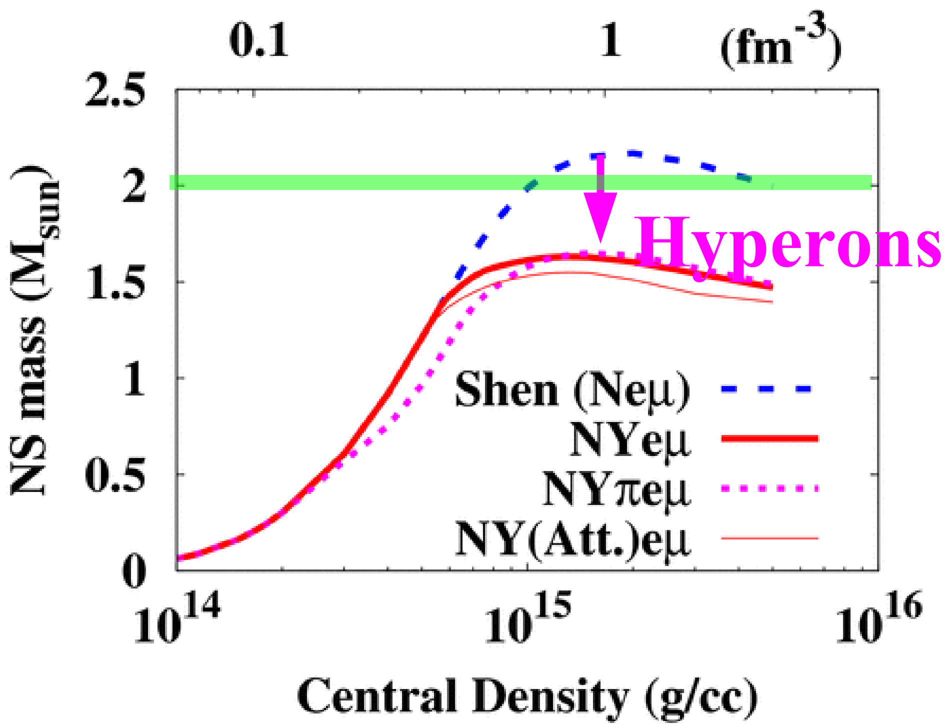
Aoki, Hatsuda, Ishii ('07)



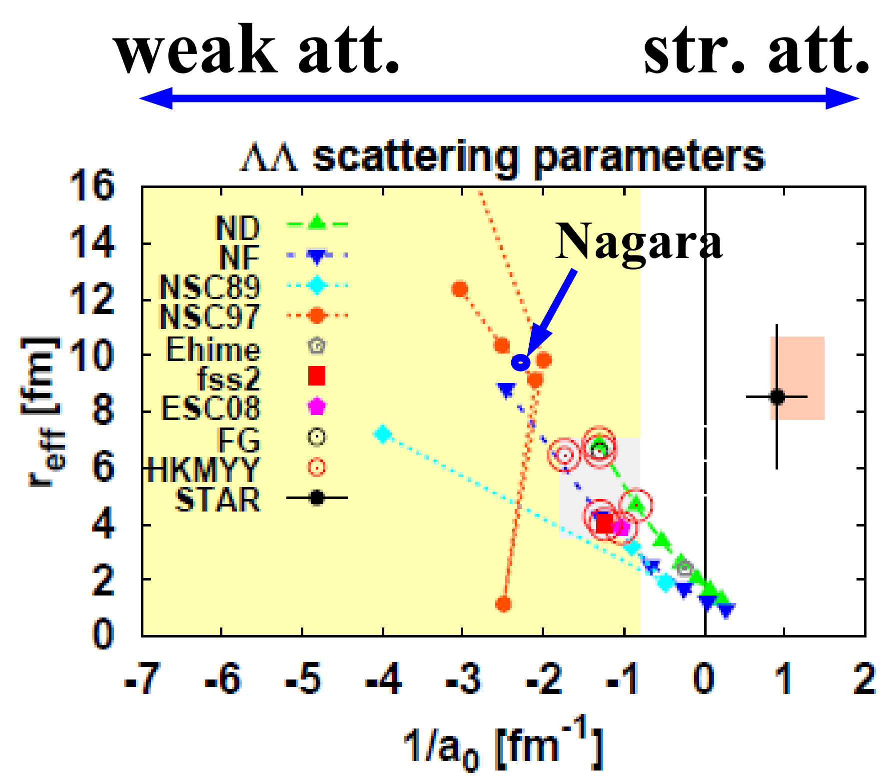
T. Doi et al. (HAL QCD Collab.) ('12)

Hyperons & YY interaction

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



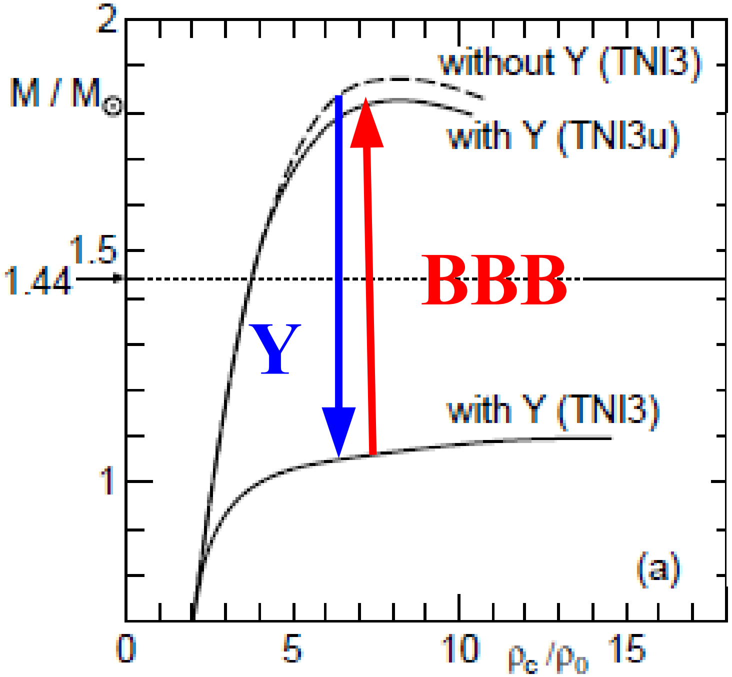
Ishizuka, AO, Tsubakihara, Sumiyoshi, Yamada, J. Phys. G35(08),085201



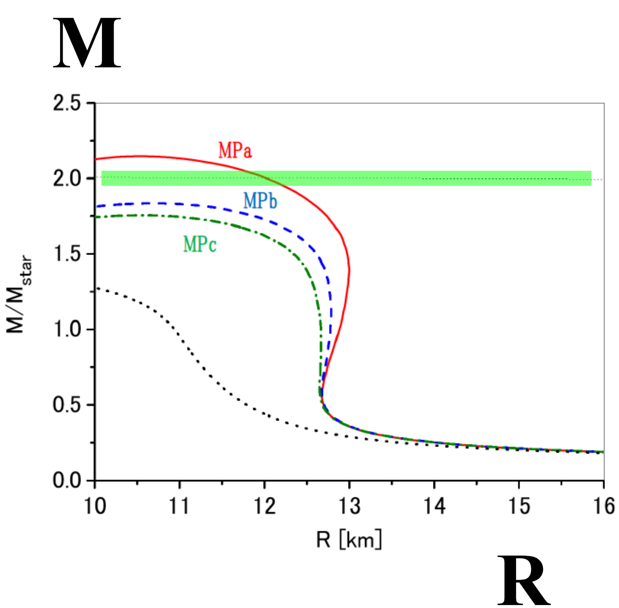
Morita, Furumot, AO ('15)

BBB force including Hyperons

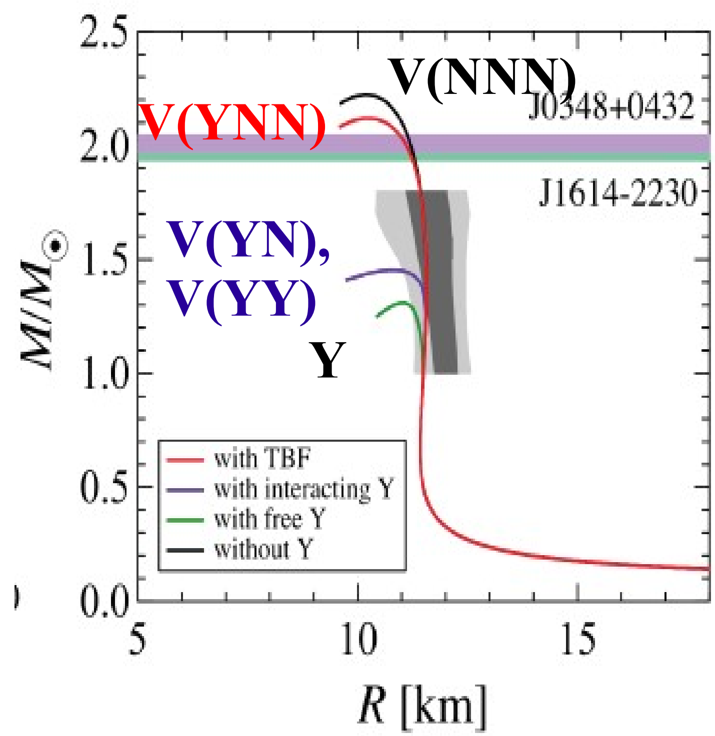
- **Repulsive BBB int. incl. Y is necessary to support 2 $M_\odot$ NS.**
  - **"Universal" BBB force**
    Nishizaki,Takatsuka,Yamamoto ('02), Yamamoto,Furumoto,Yasutake,Rijken('13)
  - **Variational calc. including hyperons** *Togashi et al. (in prep.)*



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



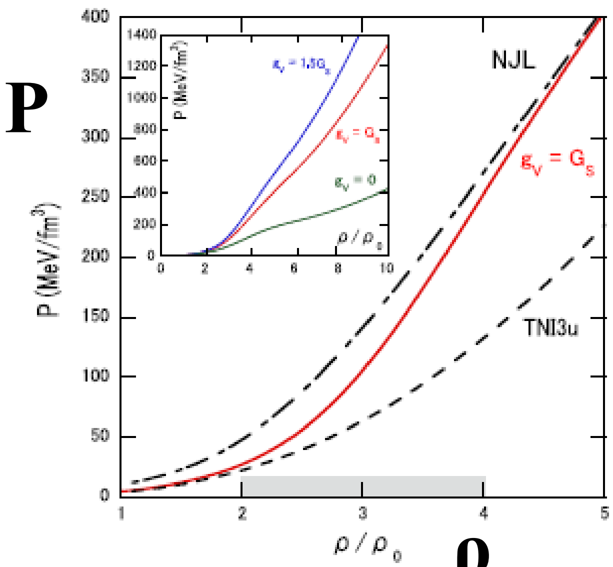
Yamamoto, Furumoto, Yasutake, Rijken ('13)

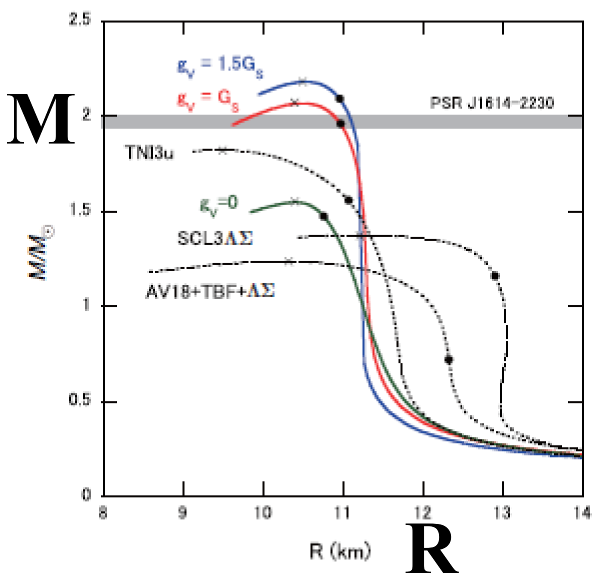


Togashi, Hiyama, Takano, Yamamoto, in prep.

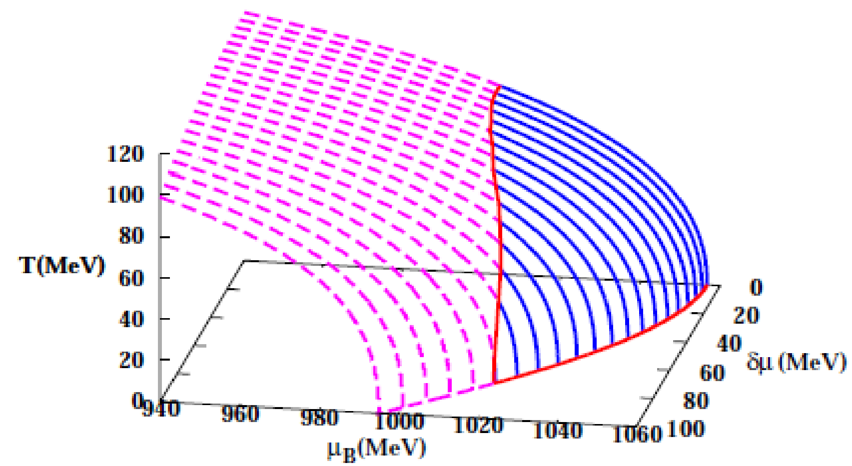
Early crossover transition to quark matter

- **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

- 中性子星は「極限状況の物質」物理の宝庫である。
  - 高密度、アイソスピン非対称、超流動、エキゾチックな構成要素
- 中性子星物質状態方程式の研究が活発に行われている。
  - RI 加速器施設 (RIBF, FRIB, SPIRAL, RAON, ...) 、ハドロン加速器 (J-PARC, JLAB, …), 重イオン衝突型加速器 (RHIC, LHC, NICA, FAIR, J-PARC, …)
  - 人工衛星による観測 (ASTRO-H, LOFT, NICER, …)
  - 理論研究 (量子モンテカルロ、カイラル EFT 、格子 QCD 、有効相互作用、...)
- 現在、中性子星にまつわる複数のパズルが存在
  - 重い中性子星パズル、中性子星半径の謎、急速な冷却、強い磁場の起源、....
  - 重い中性子星パズル：ハイペロンを含む3体力？クォーク物質？

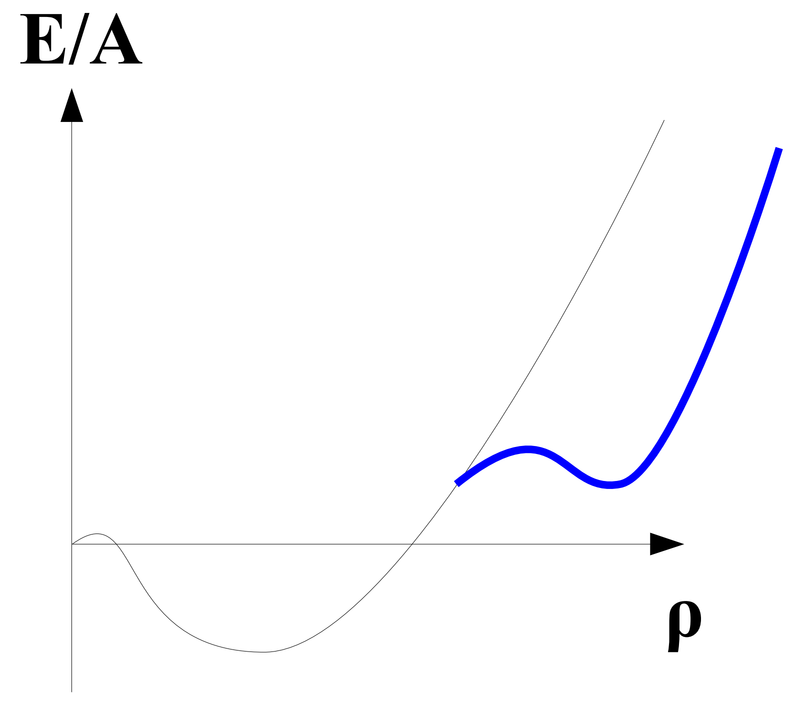
Thank you for your attention !

Q: なぜクォーク物質では M→0 で R→0？

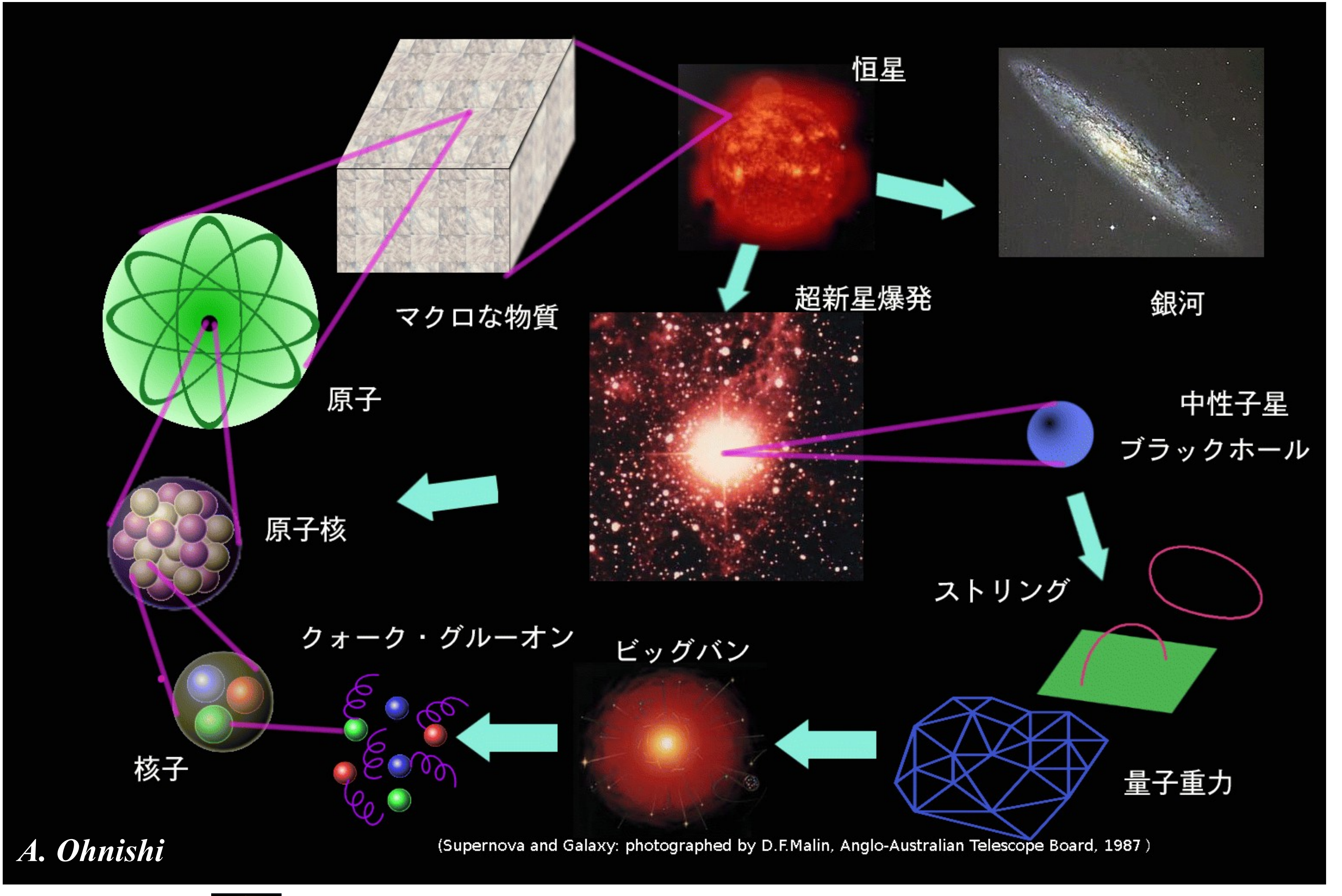
- **Ans: Self-bound するから。**
  - クォーク物質では u:d:s=1:1:1 で電気的に中性。
  - 準安定な密度が存在すると、圧力は 0

$$P = \rho_B^2 \frac{\partial(E/A)}{\partial \rho_B}$$

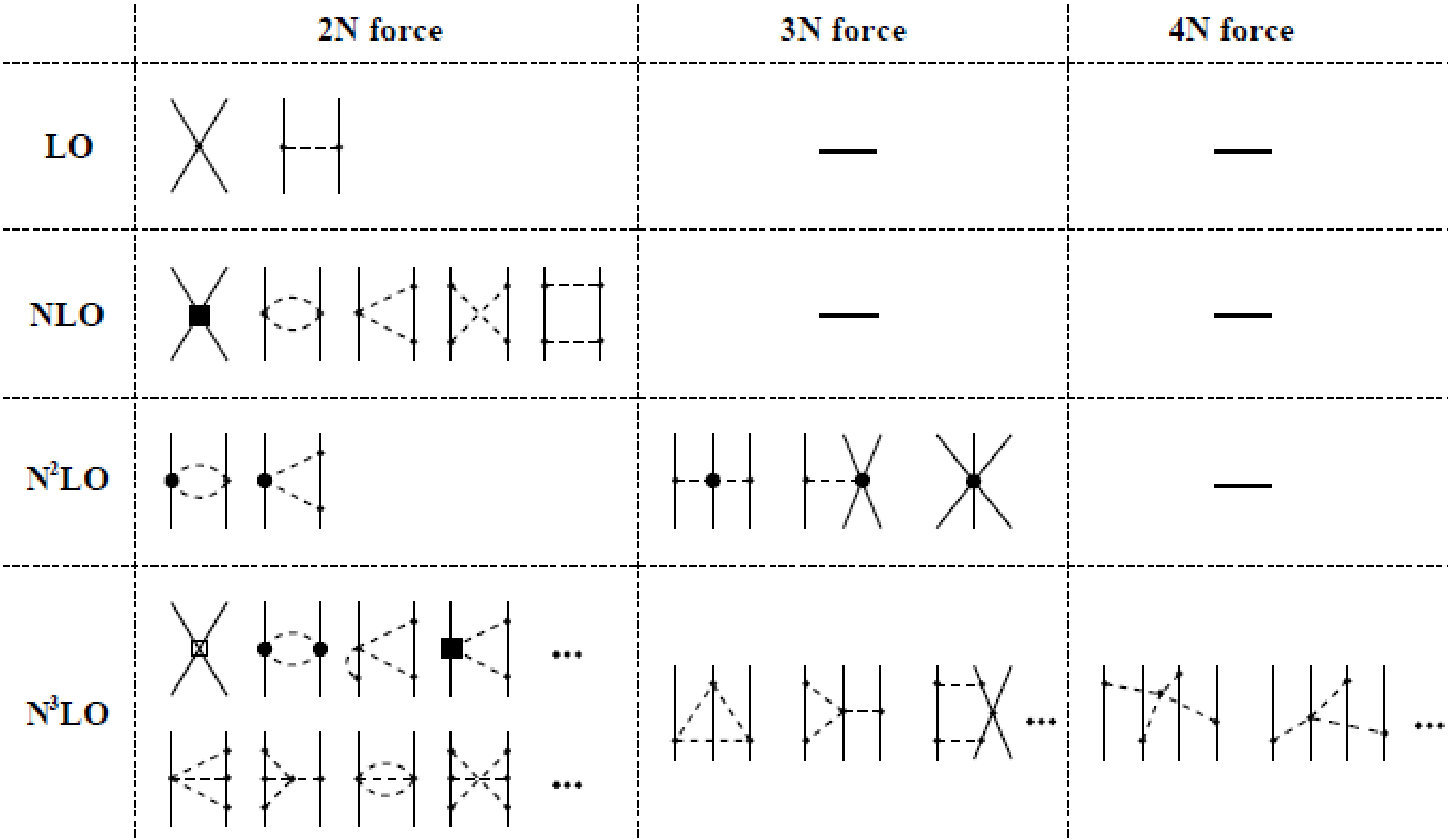
  - 表面で準安定な密度と真空が接触。



Birth, Life and Death of Matter in Our Universe



Chiral EFT NN & NNN force



E. Epelbaum ('09)

中性子物質と冷却原子

- **BEC-BCS crossover and unitary gas**
  - **散乱長 >> 粒子間距離 → EOS は普遍的 (unitary gas)**

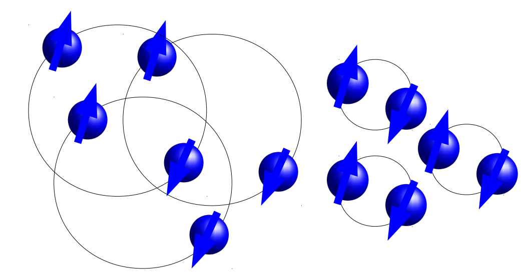
$$E^{\mathrm{Unitary}} = \xi E^{\mathrm{Free}} \quad \xi \simeq 0.4 \left(\mathrm{Bertsch\ parameter}\right)$$

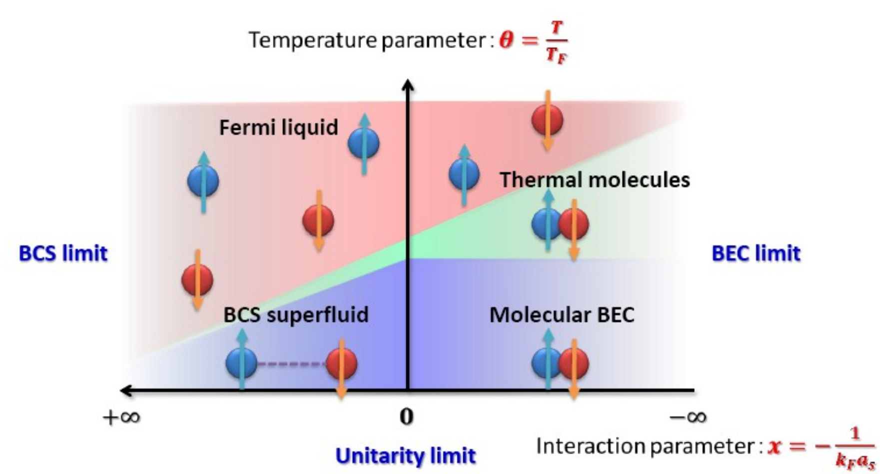
  - **nn 間の $^1S_0$ 散乱長は長い！($a_0 = -18.5$ fm)**
    → Drip した中性子ガスは、ほぼ unitary gas (-1/ $k_F a_0 \sim 0.1$)

- **My question**
  - **核子あたりの相互作用エネルギー**
    $\propto k_F^2 \propto \rho^{2/3}$

$$\frac{V^{\mathrm{Unitary}}}{N} = (\xi - 1)\frac{3}{5}\frac{\hbar^2 k_F^2}{2m} \propto \rho^{2/3}$$

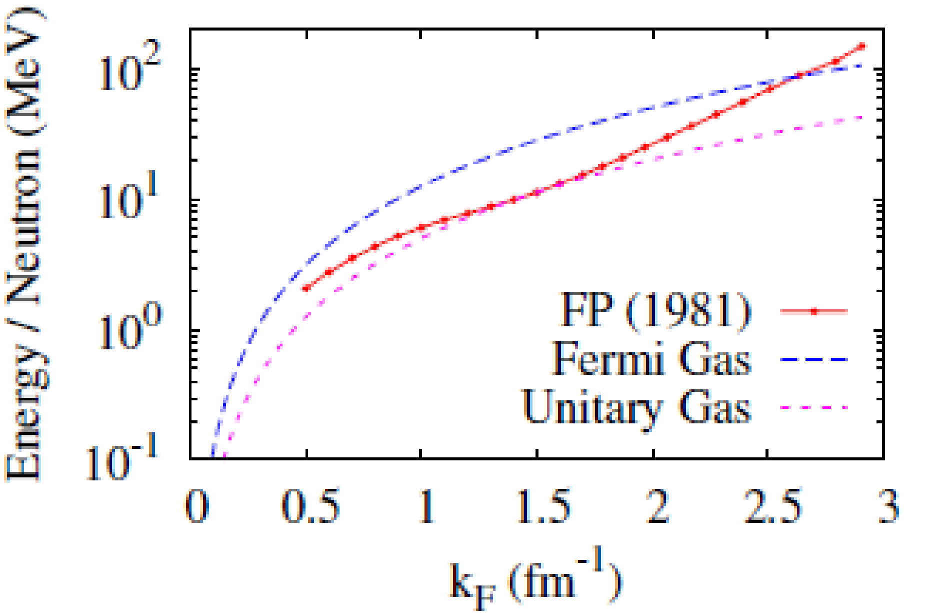
  - **どのようにして EOS(密度汎関数) 取り込むか？(Hartree なら $\propto \rho$)**
  - **unitary gas / BEC-BCS crossover は クラスト・原子核の性質に どのような影響を及ぼすか？**

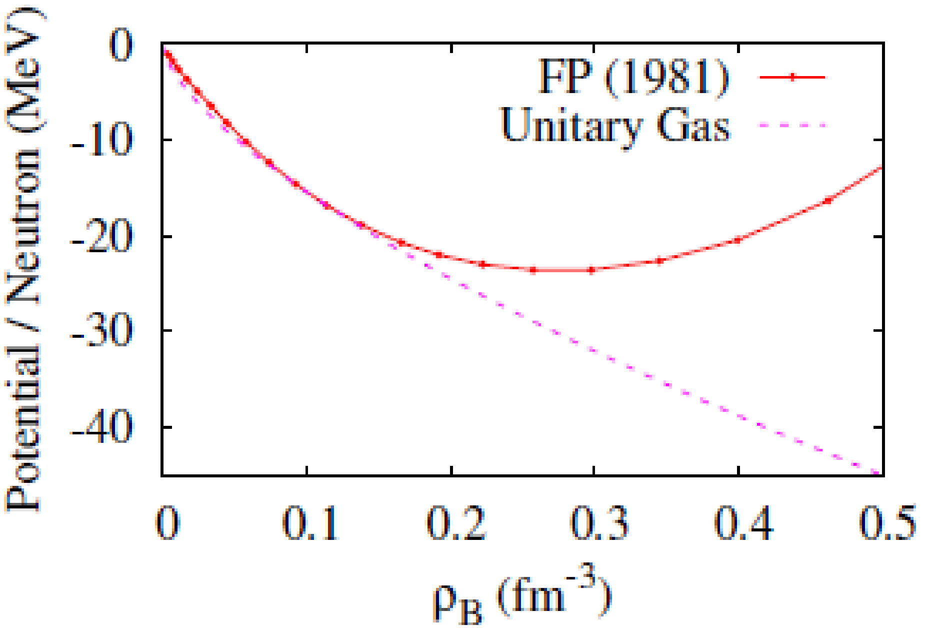




中性子星物質の状態方程式

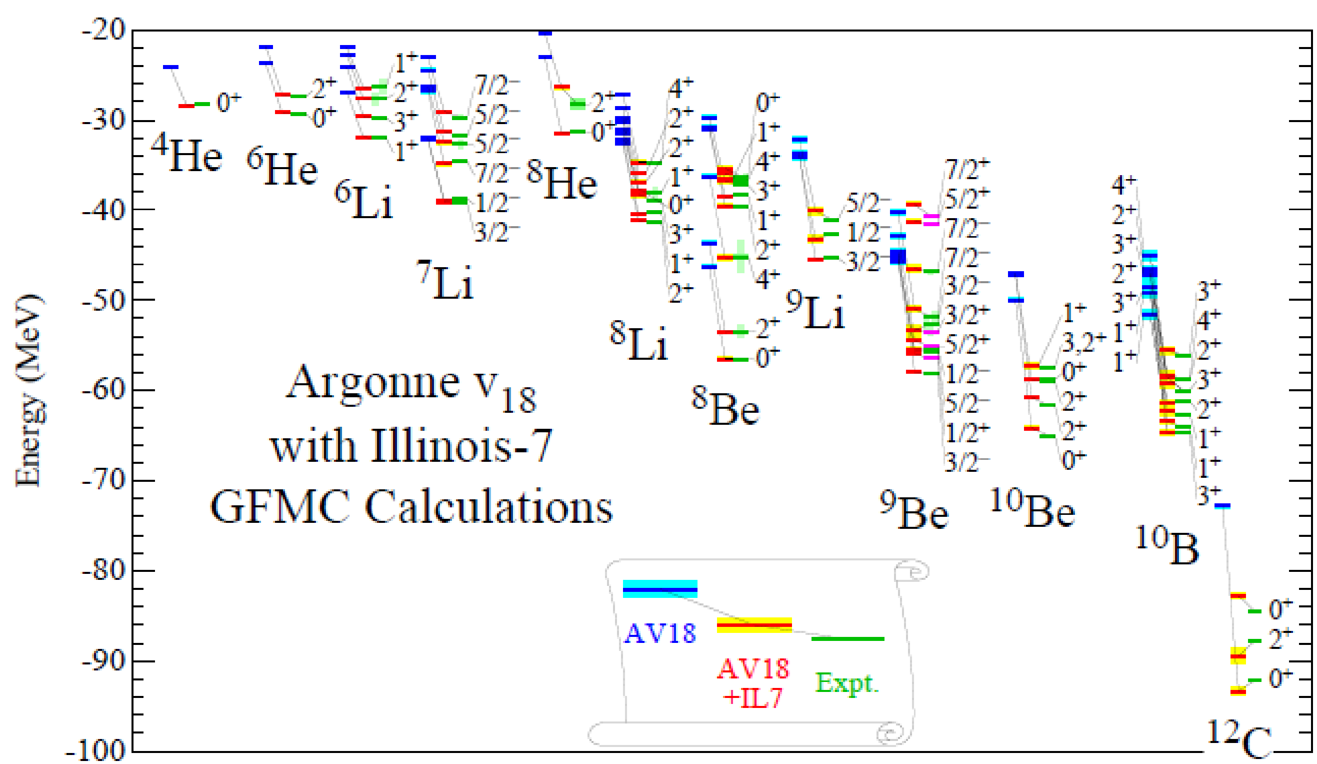
- 変分法による計算結果
  Friedman-Pandharipande (1981)
  - 広い密度領域において
    $E_{unit} < E_{FP} < E_{Fermi}$
  - 低密度領域でポテンシャルエネルギーは $\rho^{2/3}$ と振る舞っているか？





What is necessary to solve the massive NS puzzle ?

- **There are many "model" solutions.**
- **Ab initio calculation including three-baryon force (3BF)**
  - **Bare 2NF+Phen. 3NF(UIX, IL2-7) + many-body theory (verified in light nuclei).**
  - **Chiral EFT (2NF+3NF) + many-body theory**
  - **Dirac-Bruckner-HF (no 3NF)**

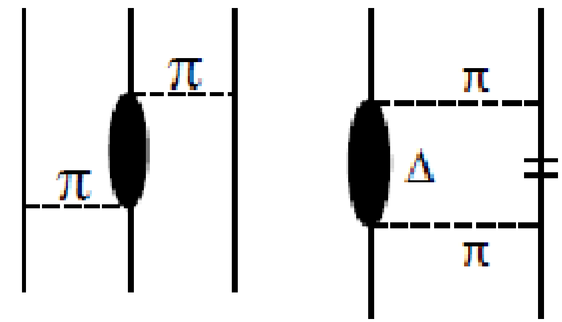


J. Carlson et al. ('14)

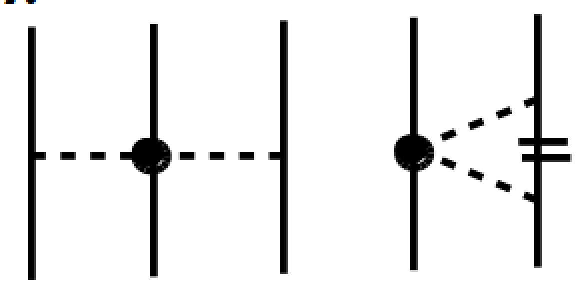
"Universal" mechanism of "Three-body" repulsion

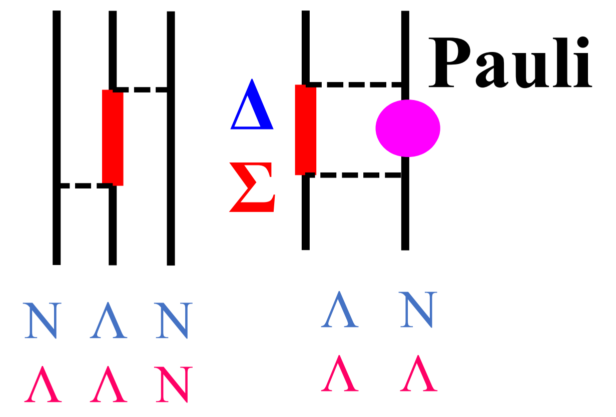
- **Mechanism of "Universal" Three-Baryon Repulsion.**
  - **"σ"-exchange ~ two pion exch. w/ res.**
  - **Large attraction from two pion exchange is suppressed by the Pauli blocking in the intermediate stage.**

Physical Picture



χ EFT



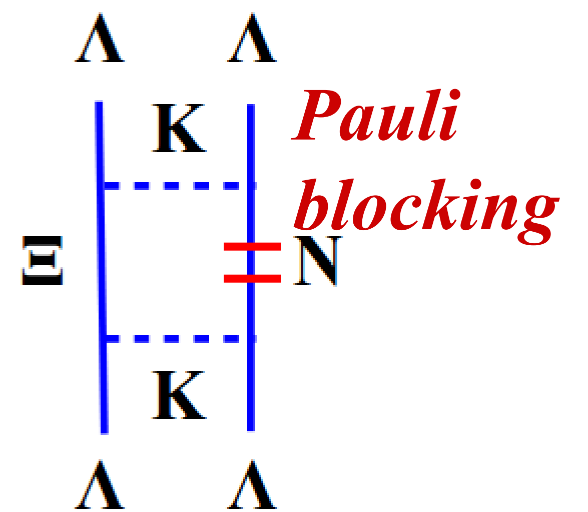


"Universal" TBR
- ***Coupling to Res. (hidden DOF)***
- ***Reduced "σ" exch. pot. ?***

How about YNN or YYN ?

ΛΛ interaction in vacuum and in nuclear medium

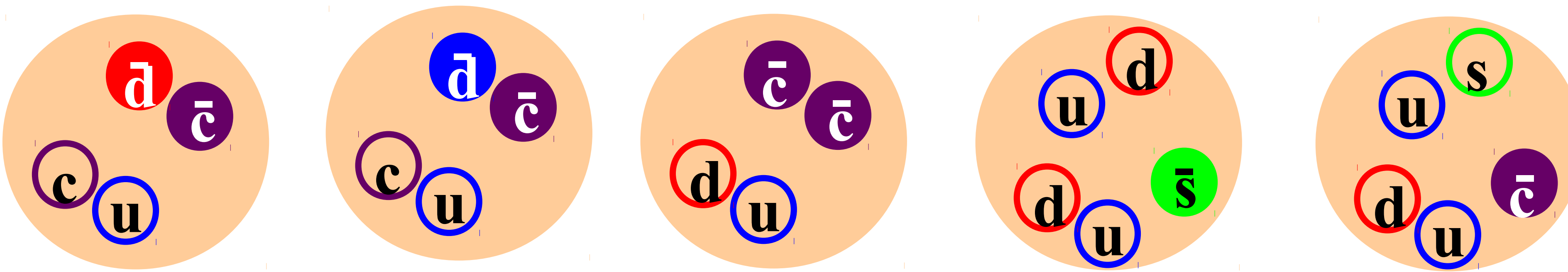
- **Vacuum ΛΛ interaction may be theoretically accessible**
  Lattice QCD calc. HAL QCD ('11) & NPLQCD ('11)
- **In-medium ΛΛ interaction may be experimentally accessible**
  - **a_0(Nagara fit) = - 0.575 fm, -0.77 fm ($\Delta B_{\Lambda\Lambda}$=1.0 MeV)**
    Hiyama et al. ('02), Filikhin, Gal ('02)
  - **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 ?***

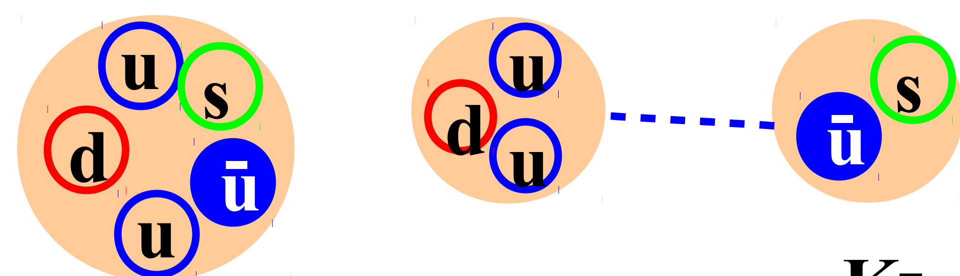
Exotic Hadrons

- Exotic hadrons
  → X, Y, Z, Θ⁺, ... Discovered/Proposed at LEPS, Belle, BaBar,...



Z(4430) X(3872) T_{cc} Θ^+ Θ^+_{cs}

- Various pictures
  - Di-quark component
  - Hadronic molecule
  - $Q\bar{Q}$ couples with $Q\bar{Q}\, q\bar{q}$



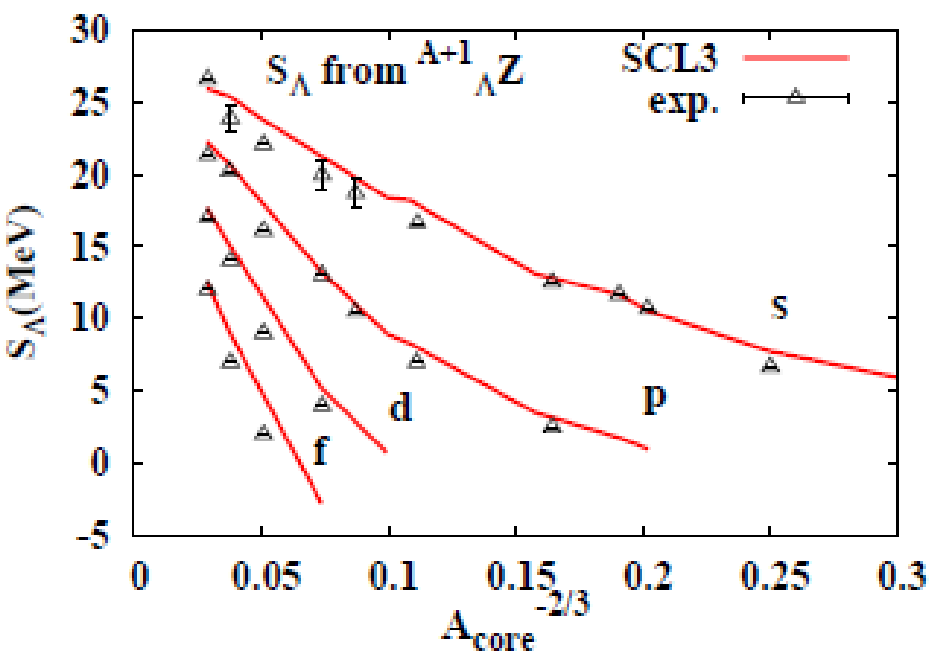
$uuds\bar{u}$ p K^-

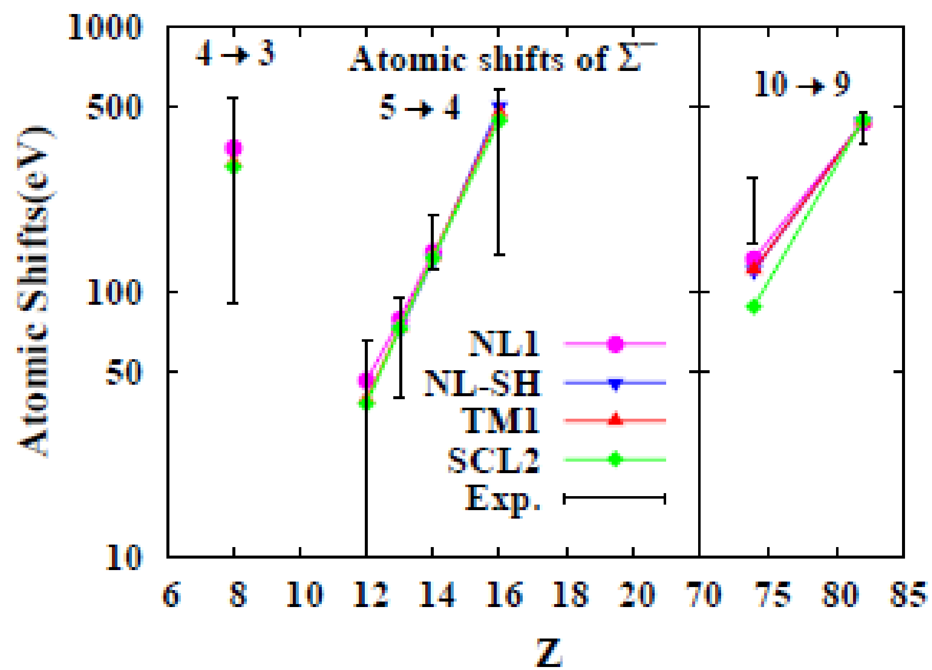
Λ (1405)

Ab initio EOS fit + Hyperons in RMF with multi-body couplings

Alternative approach

- **Alternative method**
  ~ "Ab initio" Nucl. Matter EOS + Y phen.
  - **Fit "Ab initio" EOSs in a phen. model,**
  - **Include hyperons, and explain hypernuclear data.**



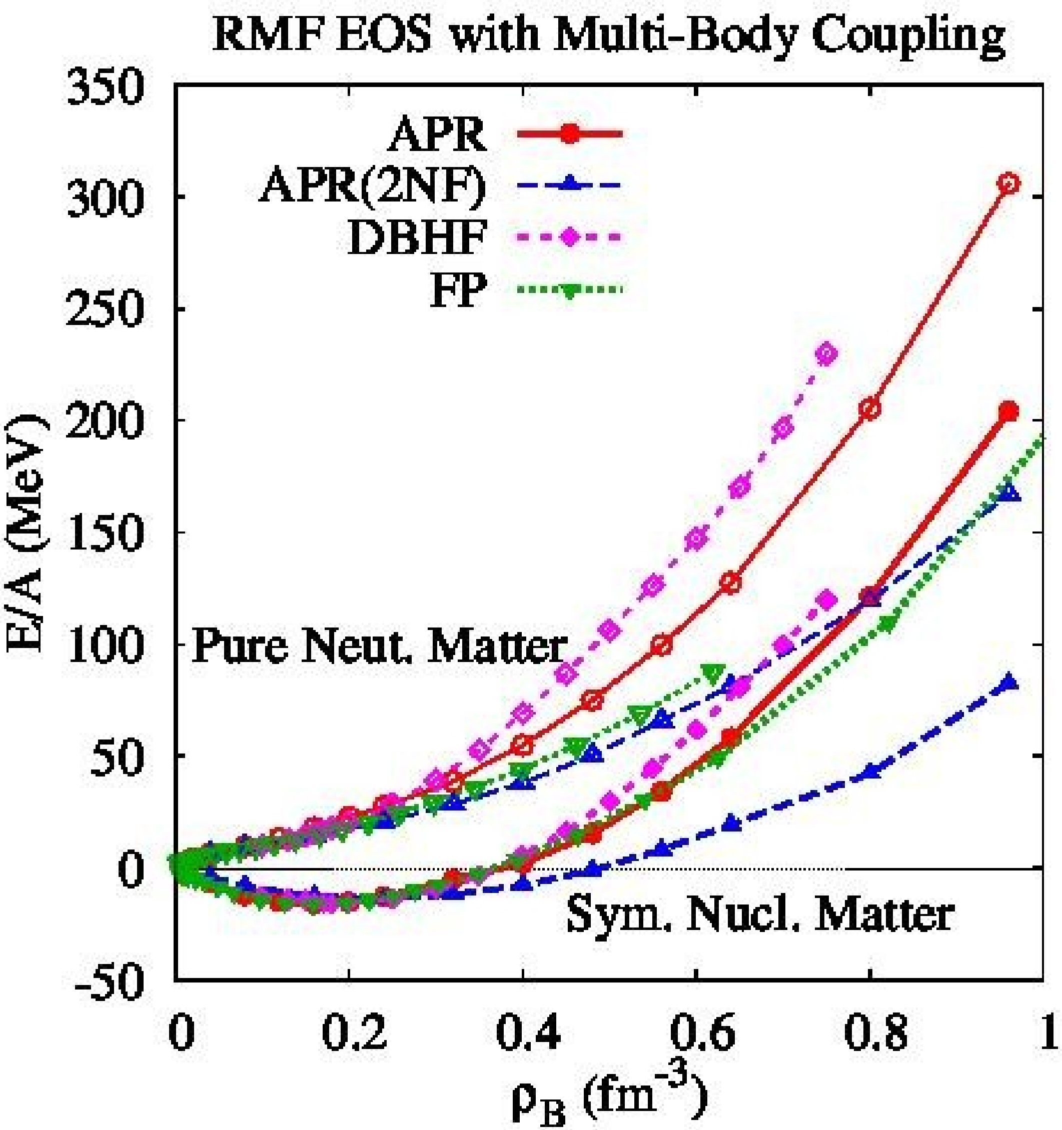


Tsubakihara et al., PRC81('10)065206 *Tsubakihara, Harada, AO, arXiv:1402.0979*

We fit ab initio EOS in RMF with multi-body couplings, and introduce hyperons.

“Ab initio” EOS

- “Ab initio” EOS under consideration
  - FP: Variational calc. (Av14+3NF(att.+repl.))
    B. Friedman, V.R. Pandharipande, NPA361('81)502.
  - APR: Variational chain summation (Av18+rel. corr. ; Av18+ rel. corr.+3NF)
    A. Akmal, V.R.Pandharipande, D.G. Ravenhall, PRC58('98)1804.
  - DBHF: Dirac Bruckner approach (Bonn A)
    G. Q. Li, R. Machleidt, R. Brockmann, PRC45('92)2782

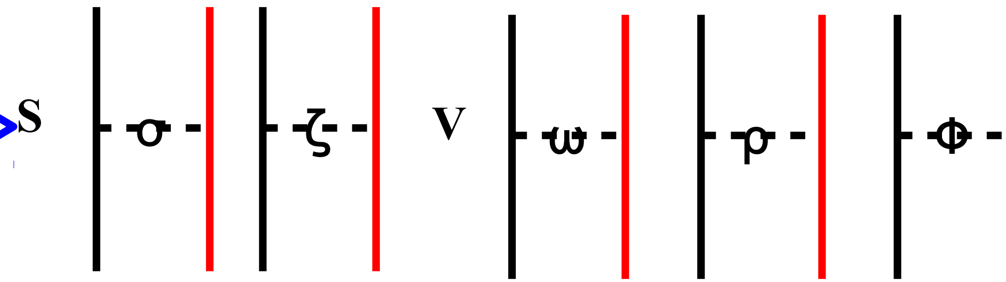


n=2 and n=3 terms in RMF

Tsubakihara

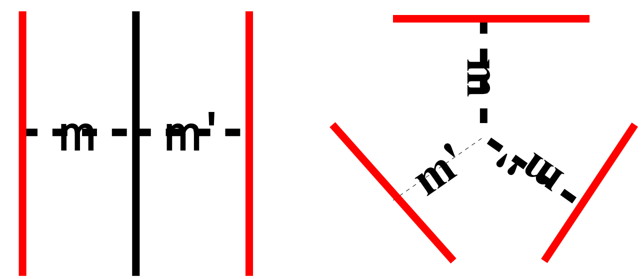
- **n=B/2+M+D=2 RMF model (+ effective pot.)**
  →2-body interaction (and rel. 3-body corr.)

$$\bar{\Psi}_B g_{mB} m \Psi_B \Longleftrightarrow$$



- **n=3 model → 3-body coupling**

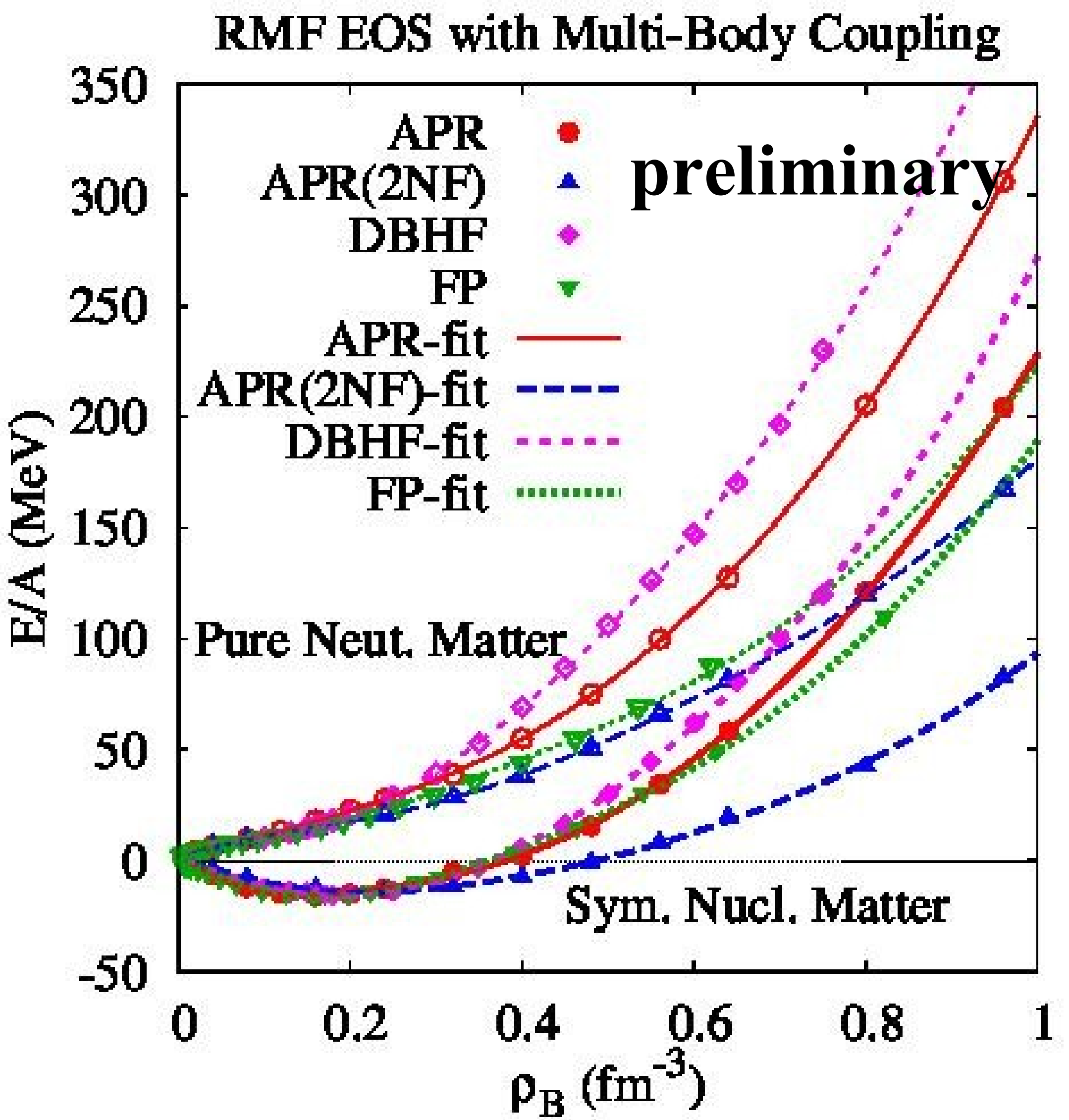
$$g_{mm'B} \bar{\Psi} m m' \Psi$$
$$c_{mm'm''} m m' m'' \Longleftrightarrow$$



Bmm terms are ignored in FST paper (field redefinitions).

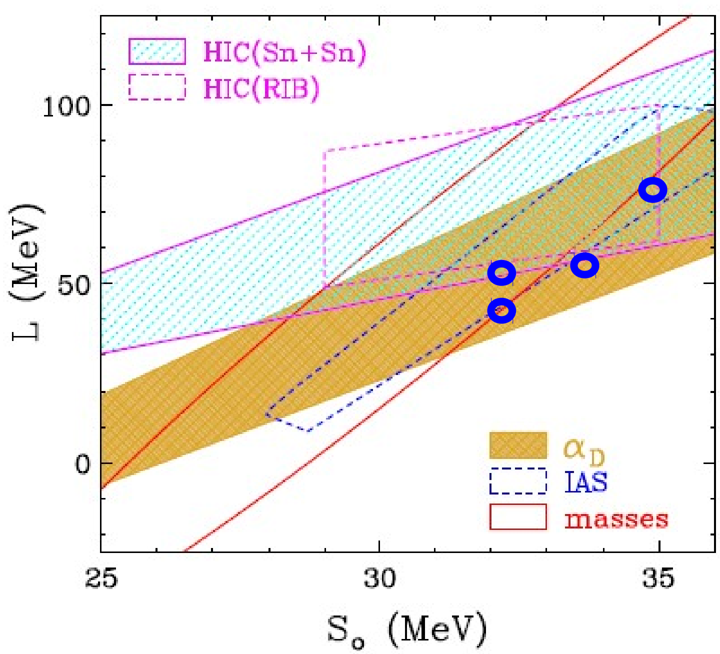
Fitting "Ab initio" EOS via RMF

- **RMF with multi-body couplings: 15 parameters**
  - **Working hypothesis**
    σ self-energy: SCL2 model
    Tsubakihara, AO ('07)
    $M_N \to 0$ @ $\sigma \to f_\pi$
- **Markov Chain Monte-Carlo (MCMC)-like parameter search**
  - **Langevin type shift +Metropolis judge**
  - **Simultaneous fit of SNM and PNM is essential.**
  - **std. dev=0.5-0.7 MeV**



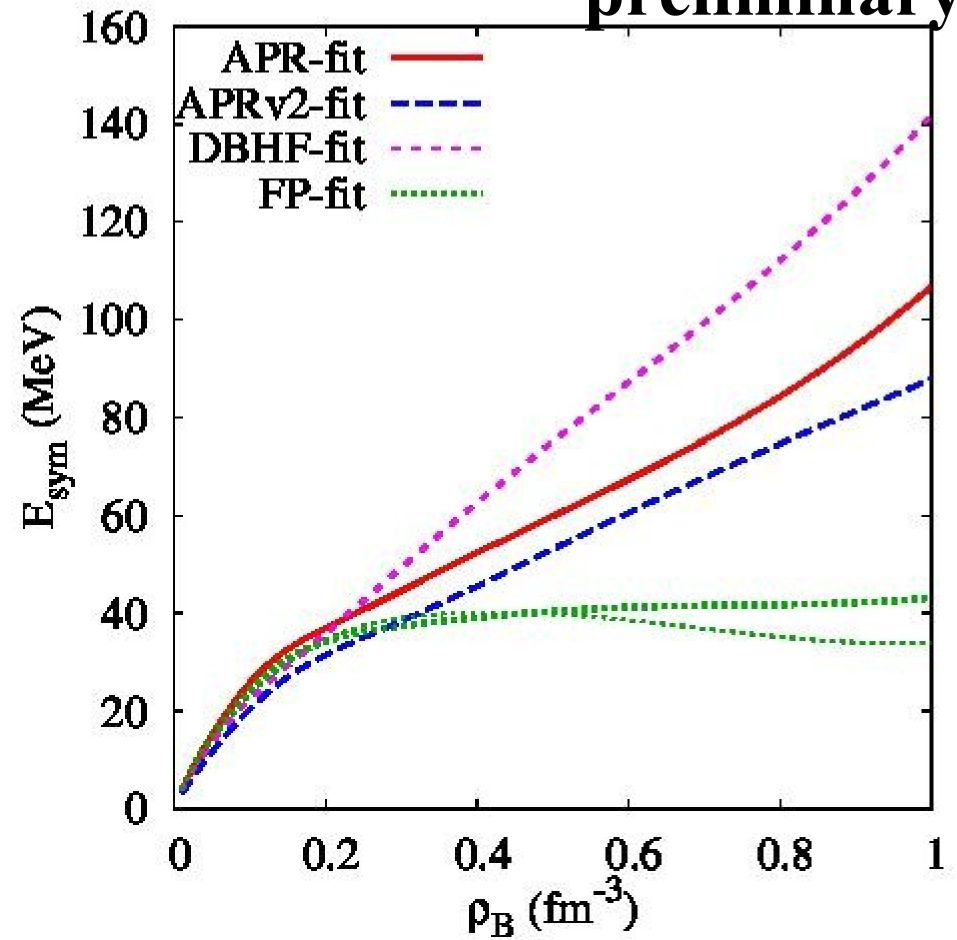
Symmetry Energy

- Symmetry E. = E(PNM)-E(SNM)
  - APR-fit: $(S_0, L)=(32, 47)$ MeV
  - APRv2-fit: $(S_0, L)=(33, 47)$ MeV
  - DBHF-fit: $(S_0, L)=(35, 75)$ MeV
  - FP-fit: $(S_0, L)=(32, 40)$ MeV



Horowicz et al. ('14)

preliminary

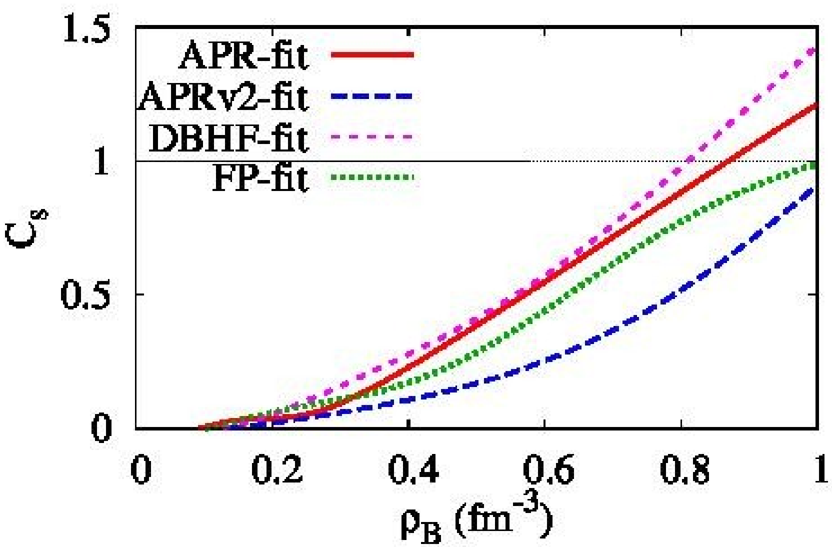


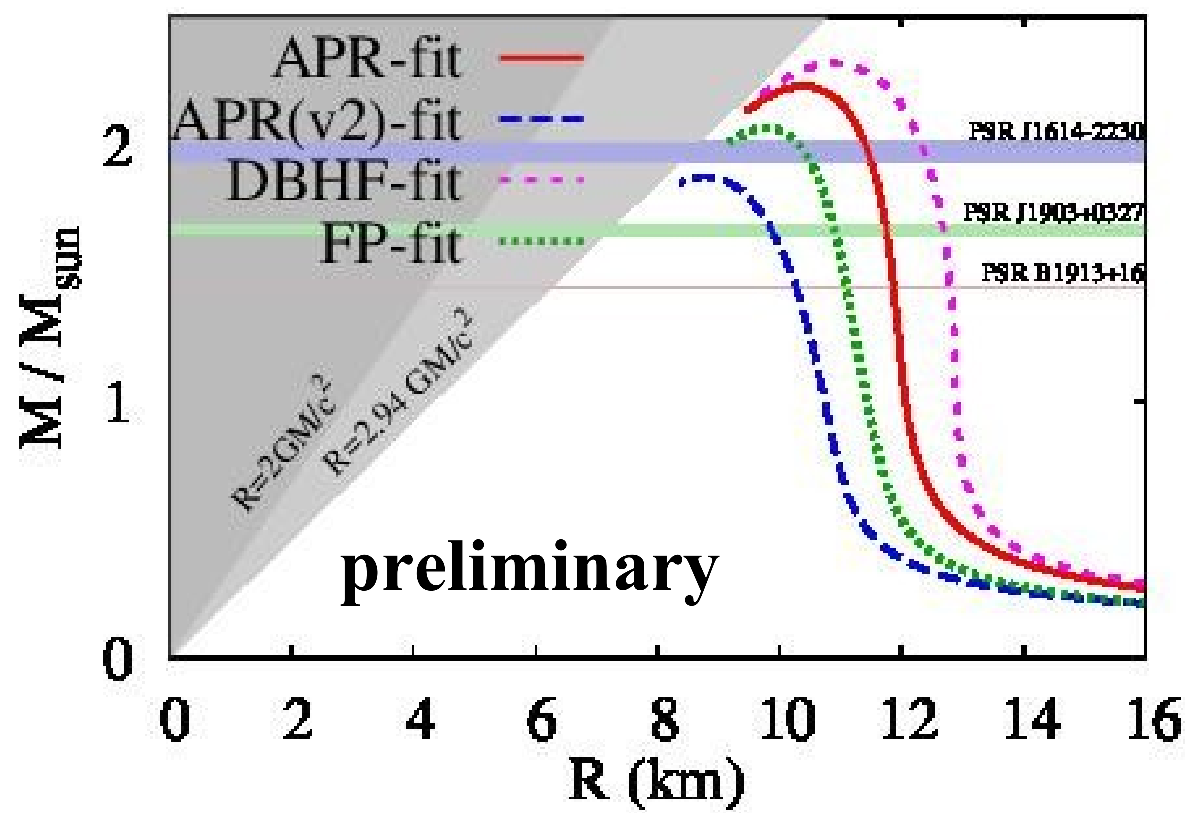
Neutron Star Matter EOS

- **Asymmetric Nuclear Matter EOS**
  $E_{ANM}(\rho)=E_{SNM}(\rho)+\delta^2 S(\rho)$
  β-equilibrium condition → NS matter EOS
- **Max. mass in the fit EOS deviates from the original one by ~ 0.1 $M_\odot$.**

$\eta=(KL^2)^{1/3}$?
Sotani et al.(2014)

- **Caveat:**
  $c_s > c$ at high density





NS matter in "ab initio"-fit + Λ

- Λ potential in nuclear matter at $\rho_0 \sim -30$ MeV
  - Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$
  - Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$