Neutron Stars and Hypernuclei

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JAEA-ASRC-TPI Theory Lecture Series
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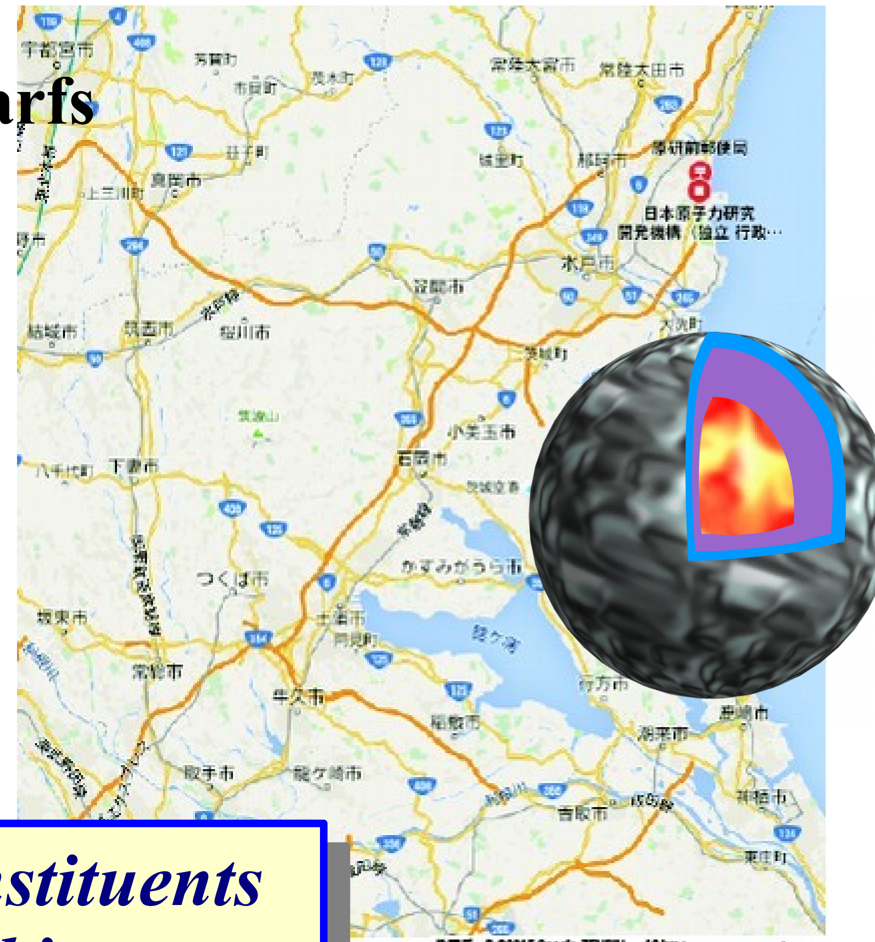
- Introduction
- Part I : Basics of Neutron Star Physics
- Part II : Hypernuclear Physics & Neutron Stars
- Summary

Basic properties of neutron stars

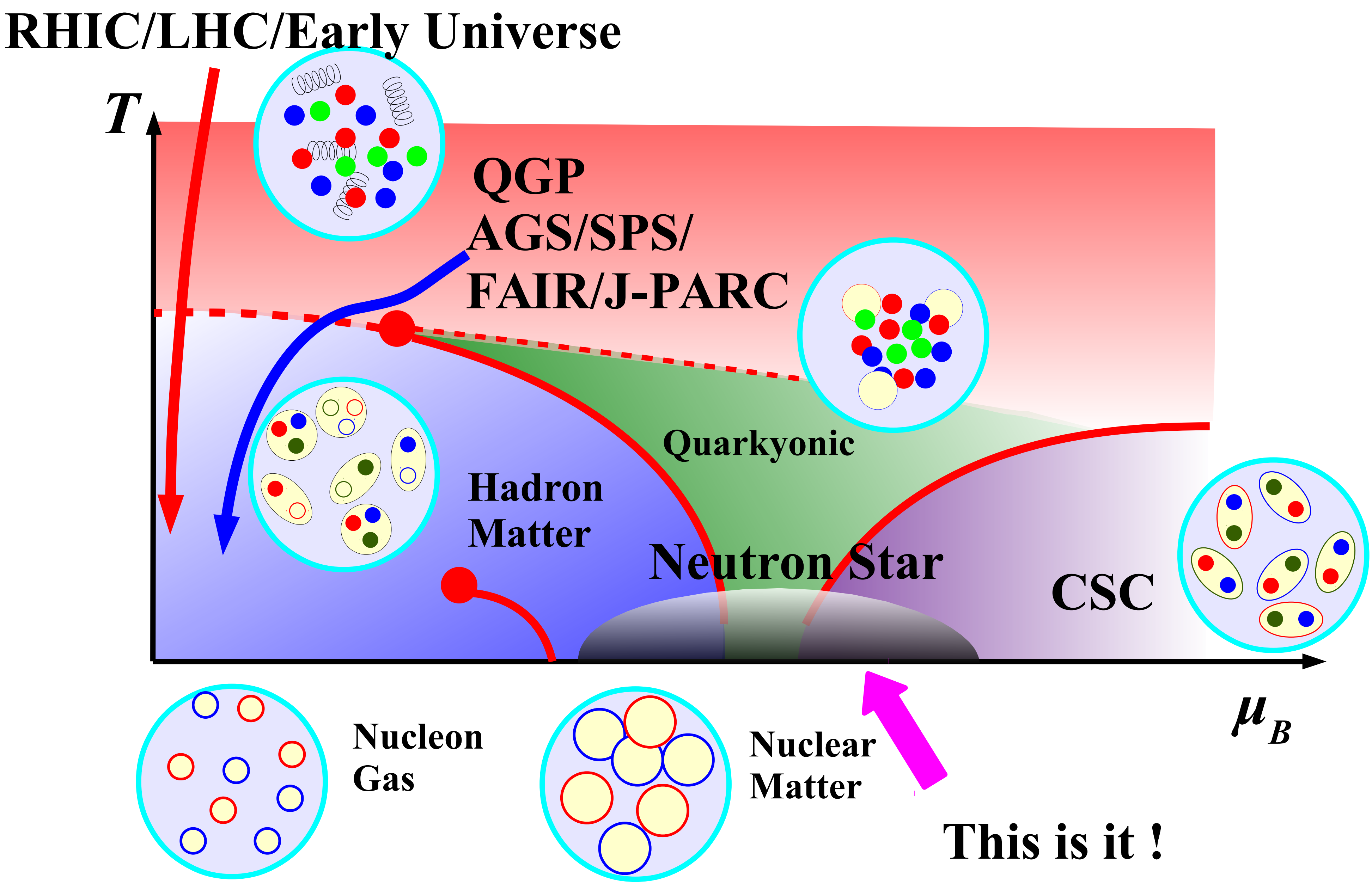
- **Mass: $M = (1\text{-}2)\ M_\odot$ ($M \sim 1.4\ M_\odot$)**
- **Radius: 5 km < R < 20 km (R ~ 10 km)**
- **Supported by Nuclear Pressure**
  c.f. Electron pressure for white dwarfs
- **Cold enough**
  ($T \sim 10^6$ K ~ 100 eV)
  compared with
  neutron Fermi energy.
- **Various constituents**
 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



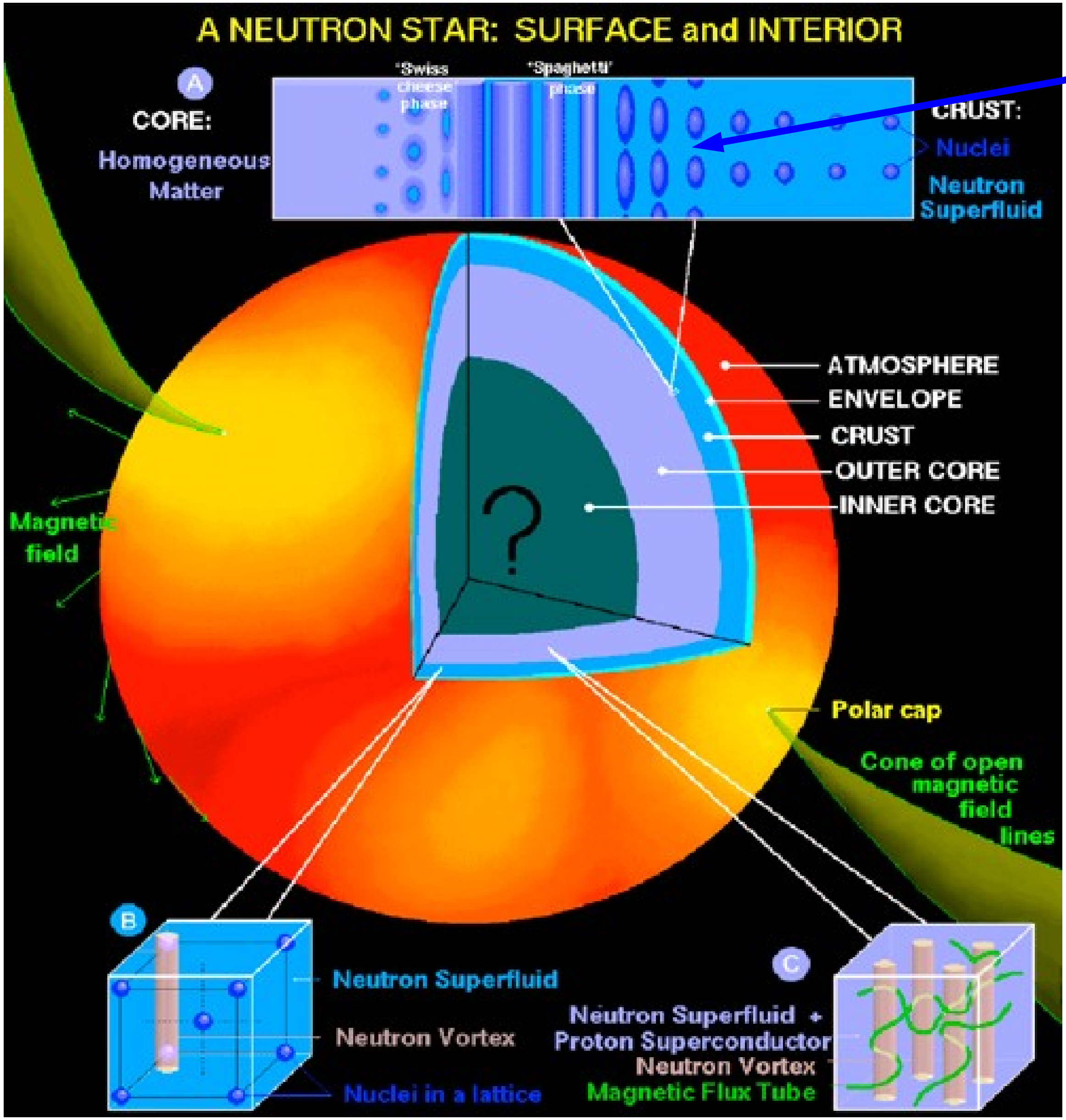
google & zenrin

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

QCD Phase Diagram



Inside Neutron Stars



For pasta nuclei, ask Maruyama-san

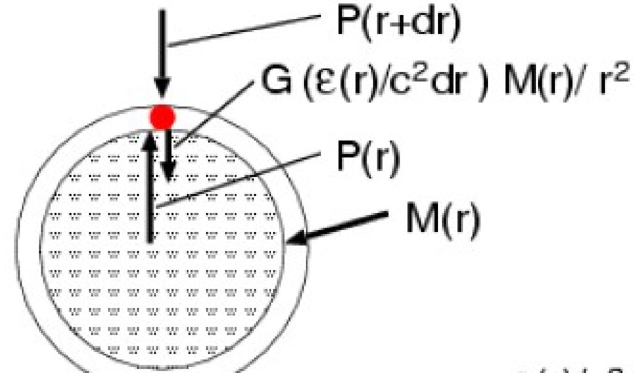
Dany Page

M-R curve and EOS

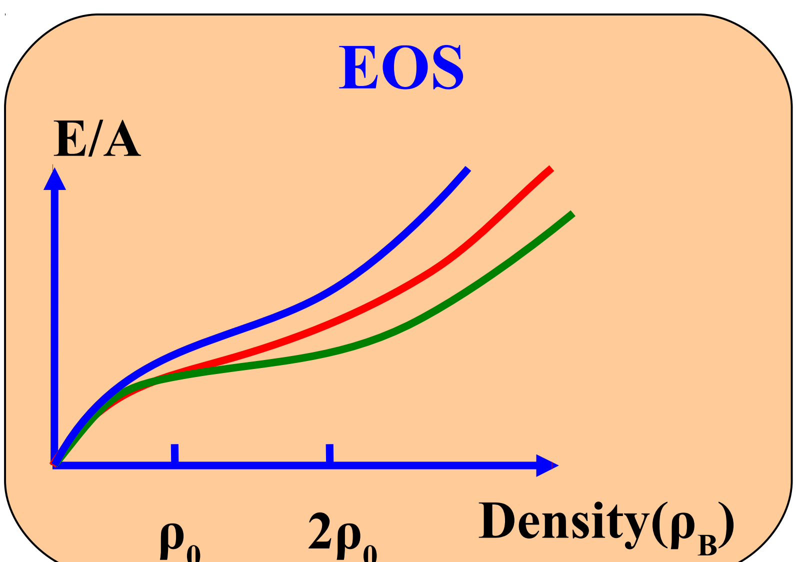
- **M-R curve and NS matter EOS has 1 to 1 correspondence**
  - **TOV(Tolman-Oppenheimer-Volkoff) equation =GR Hydrostatic Eq.**

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

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

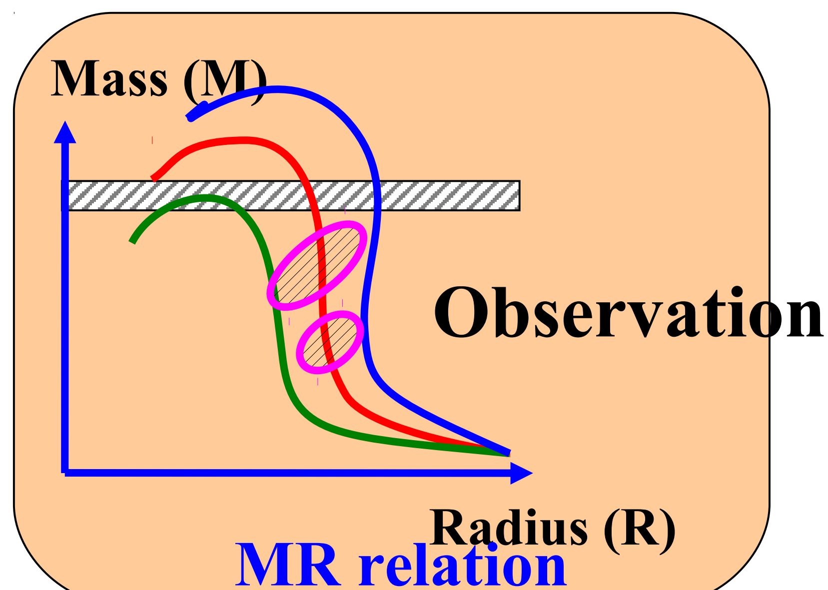


Non-Rela. $\frac{dP}{dr} = -G\frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$



prediction

Judge



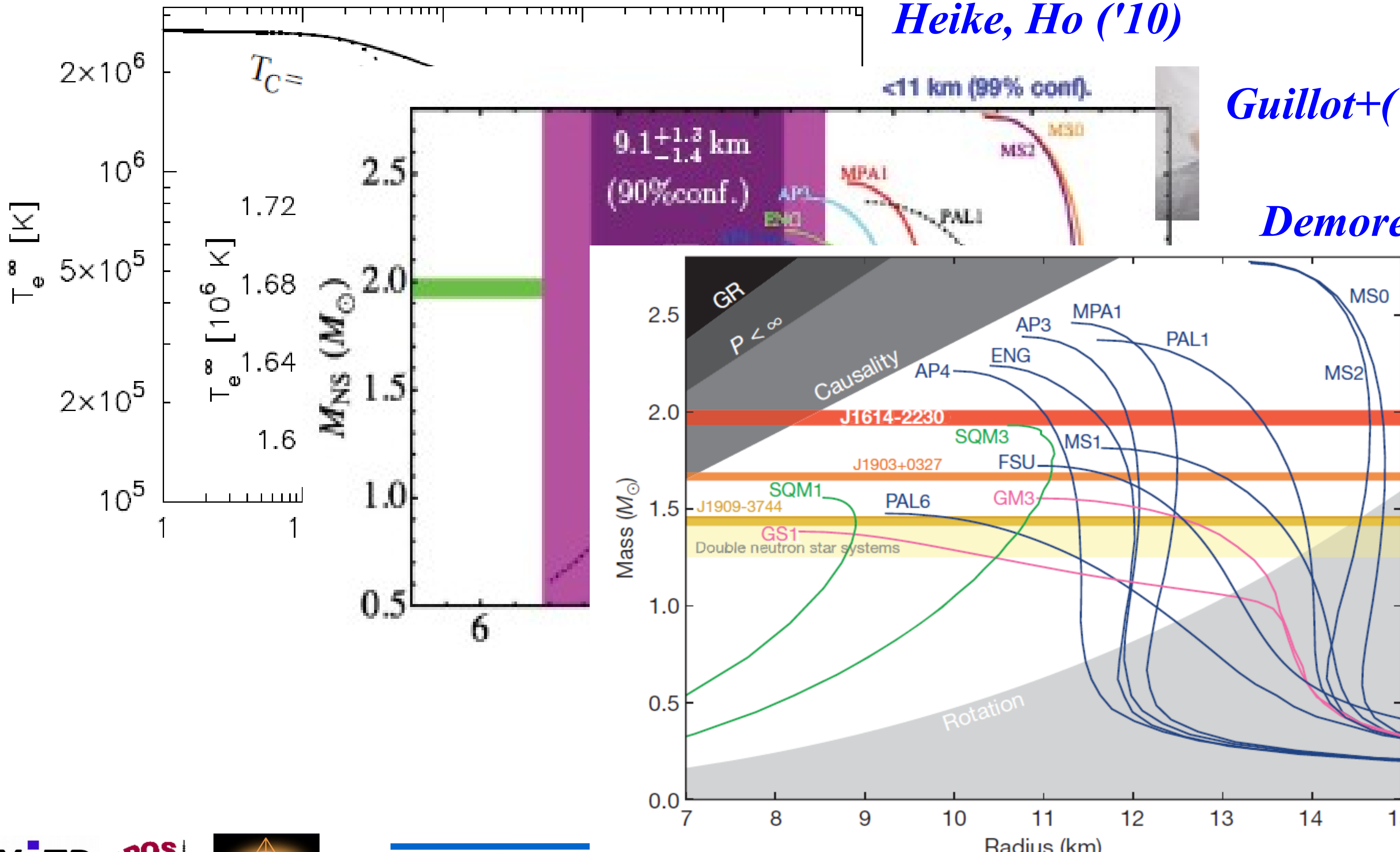
Puzzles of NS

- 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)

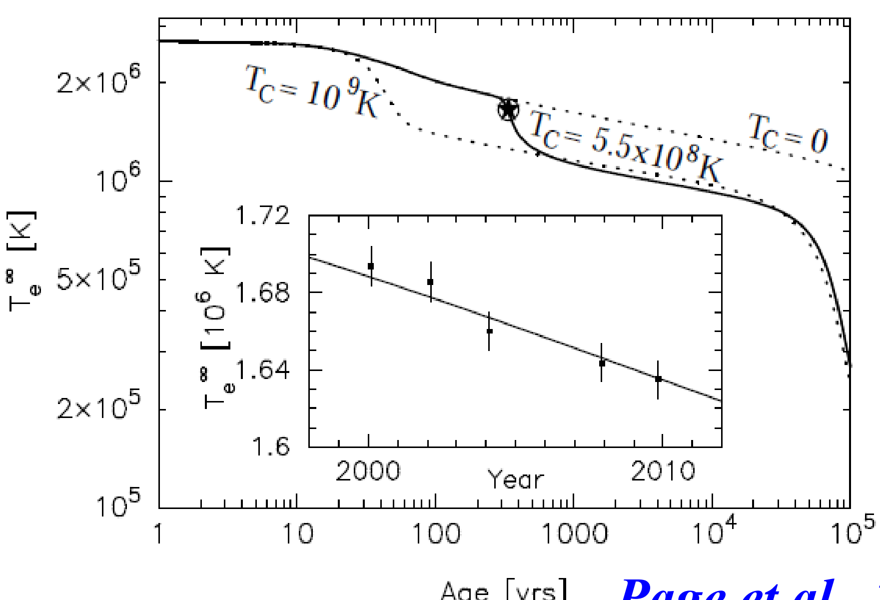
Guillot+('13)

Demorest+('10)

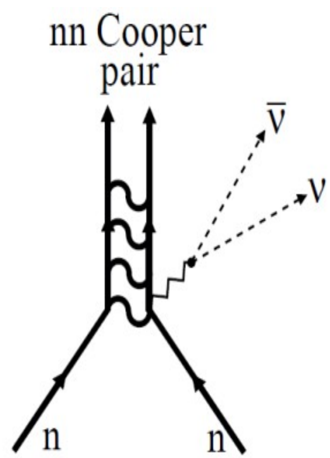


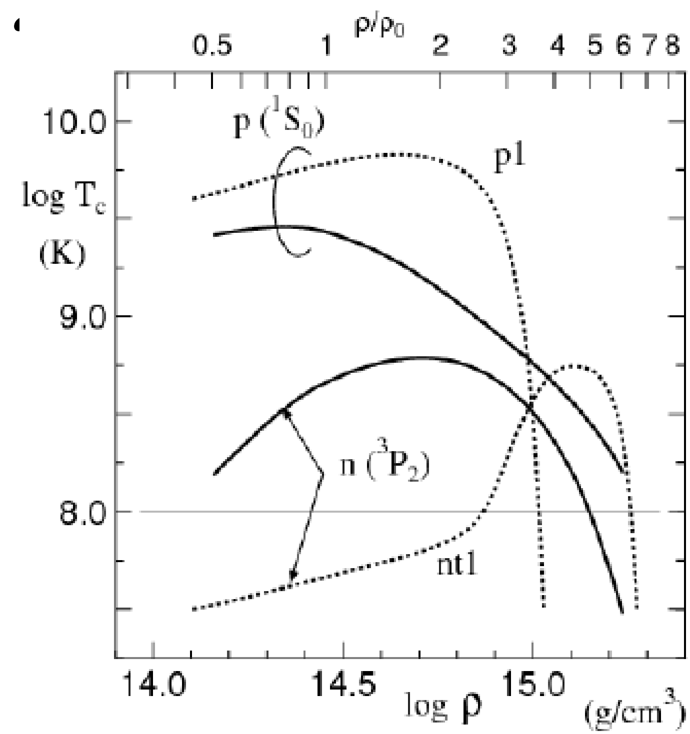
Nuclear Superfluidity and Cooling Curve

- **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 $5\rho_0$ ‘**



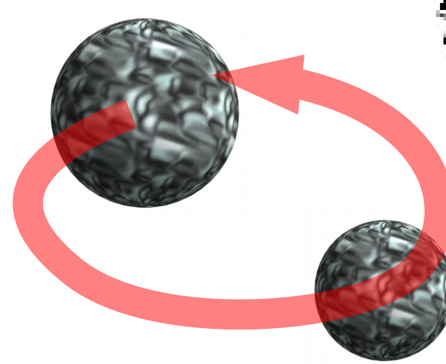
Page et al., 2011

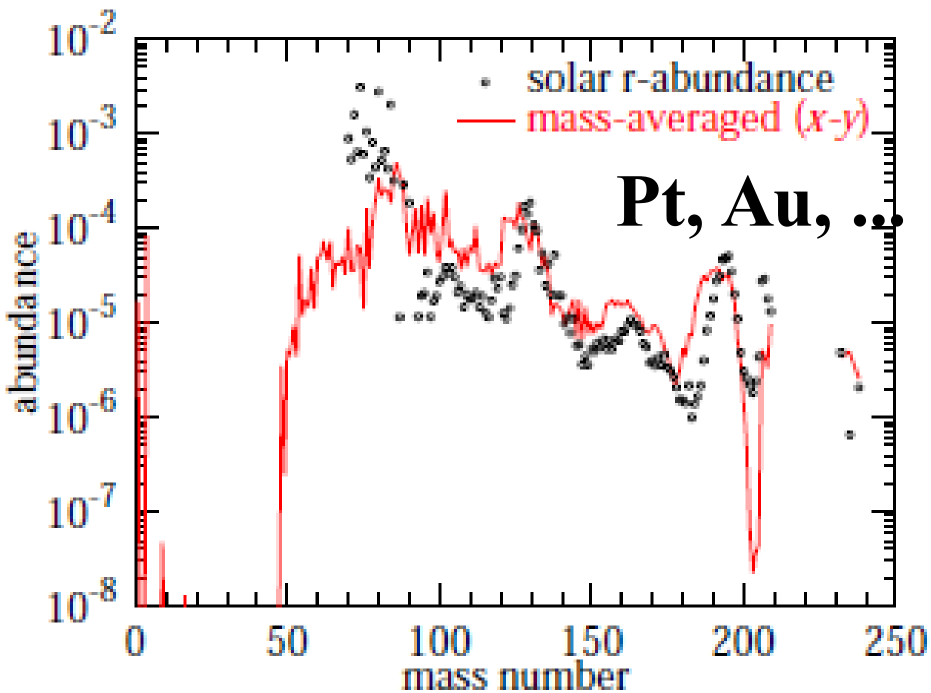


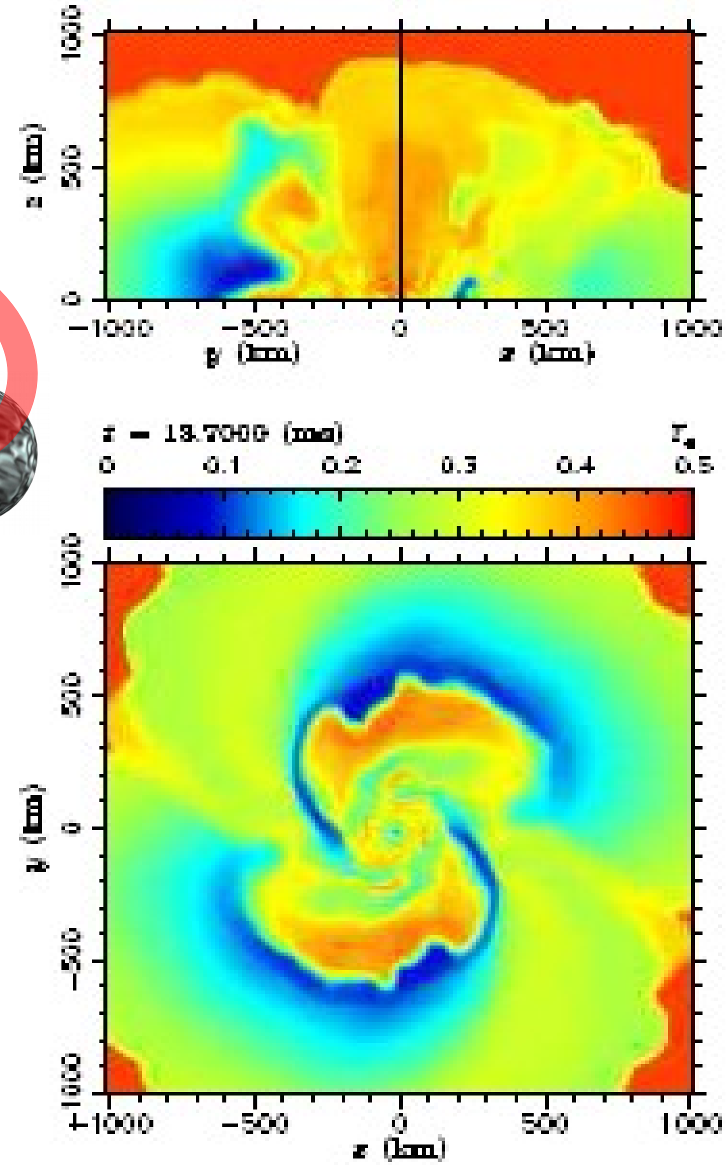


Takatsuka

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



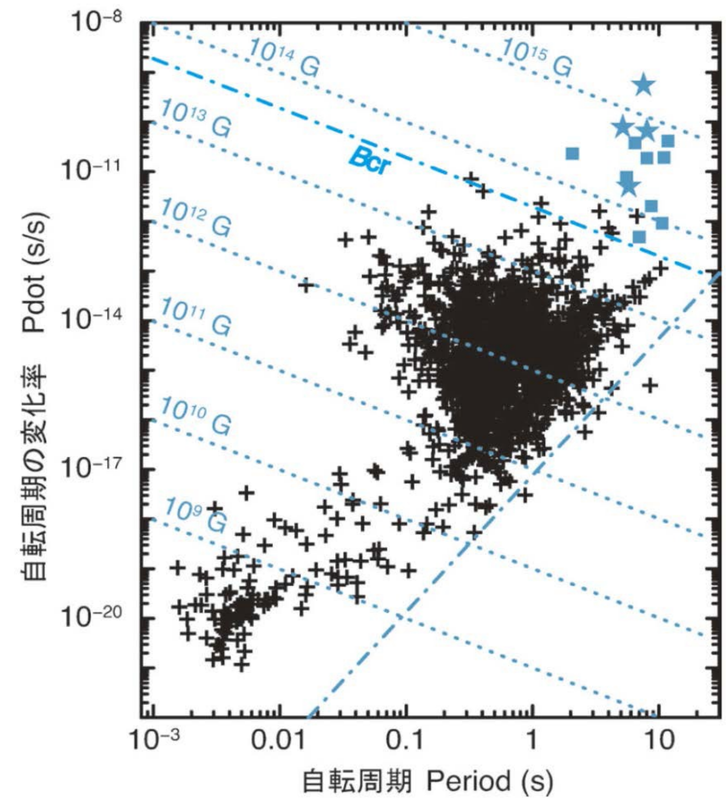


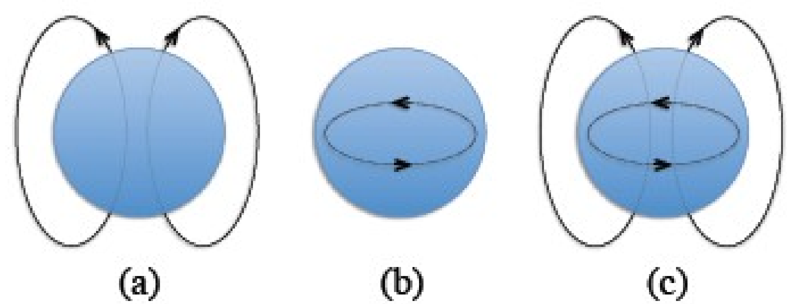


Wanajo, Sekiguchi ('14)

Origin of Strong Magnetic Field

- **Magnetic field in NS   B = $10^{12} – 10^{15}$ G**
  - **How can we make strong B ?**
  - **How can we keep strong B ?**
  - **Fossil, Dynamo, Ferromagnetism, ...**
- **A new idea: 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**
    $$j_z = \frac{2\alpha}{\pi}\mu_5 B_z \qquad \frac{d}{dt}\left(N_5 + \frac{\alpha}{\pi}\mathcal{H}\right) = 0, \quad N_5 = \int dx\, n_5$$
  - **Finite magnetic helicity makes magnetic field stable.** $\mathcal{H} = \int dx\, A \cdot B$





See also, D. Grabowska, D. B. Kaplan, S. Reddy, PRD('15)085035

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)

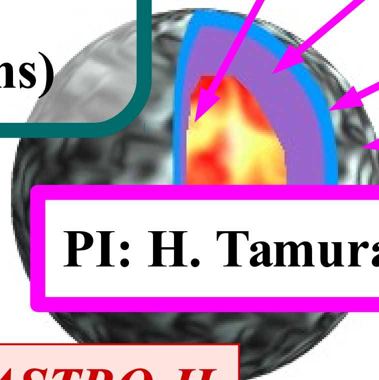
J-PARC

Hyperons, mesons, quarks

Asym. nuclear matter +elec.+μ

Nuclei+neutron gas+elec.

Nuclei + elec.



PI: H. Tamura

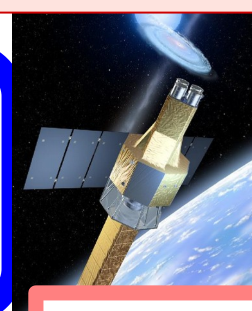
Low ρ (Group B)
head: Murakami,
Nakamura, Horikoshi

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

NS Obs. (Group C)
head: Takahashi

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

ASTRO-H

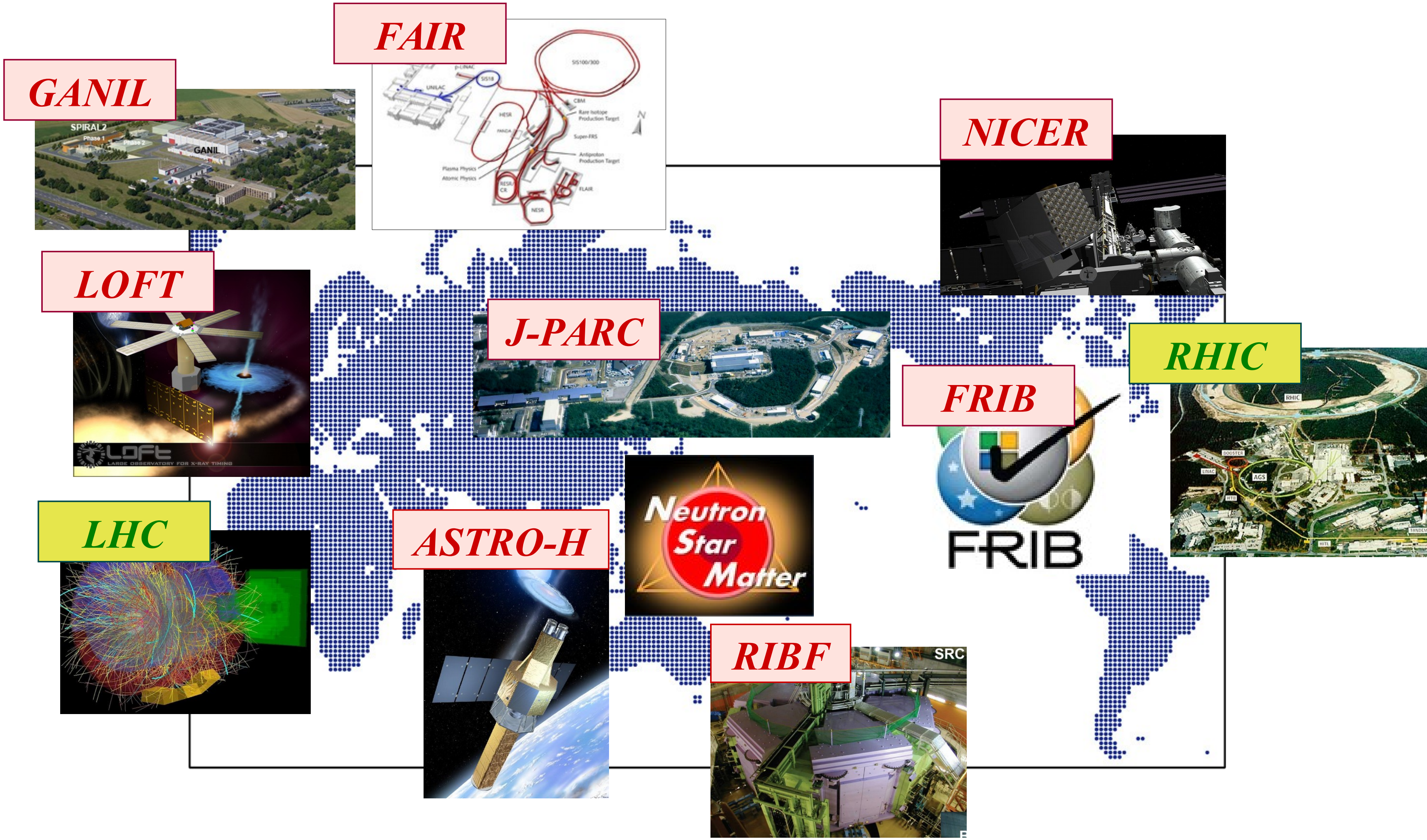


RIBF

Theory (Group D)
head: Ohnishi

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

Accelerators and Satellites for Neutron Star Physics



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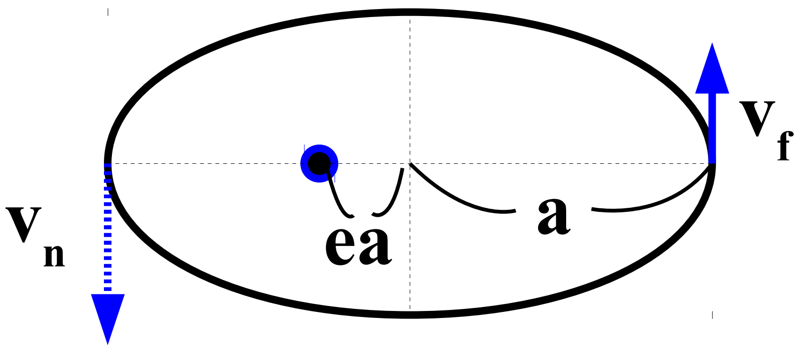
- Part I : Basics of Neutron Star Physics
  - Neutron star mass & radius observations
  - Nuclear matter EOS and neutron stars
  - Massive Neutron Star Puzzle
- Part II : Hypernuclear Physics & Neutron Stars
  - Hypernuclear Physics : Implications from Experiments
  - What is necessary to solve massive NS puzzle ?
  - Recent Attempts toward the 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**



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

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

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

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

Neutron Star Observables: Mass (2)

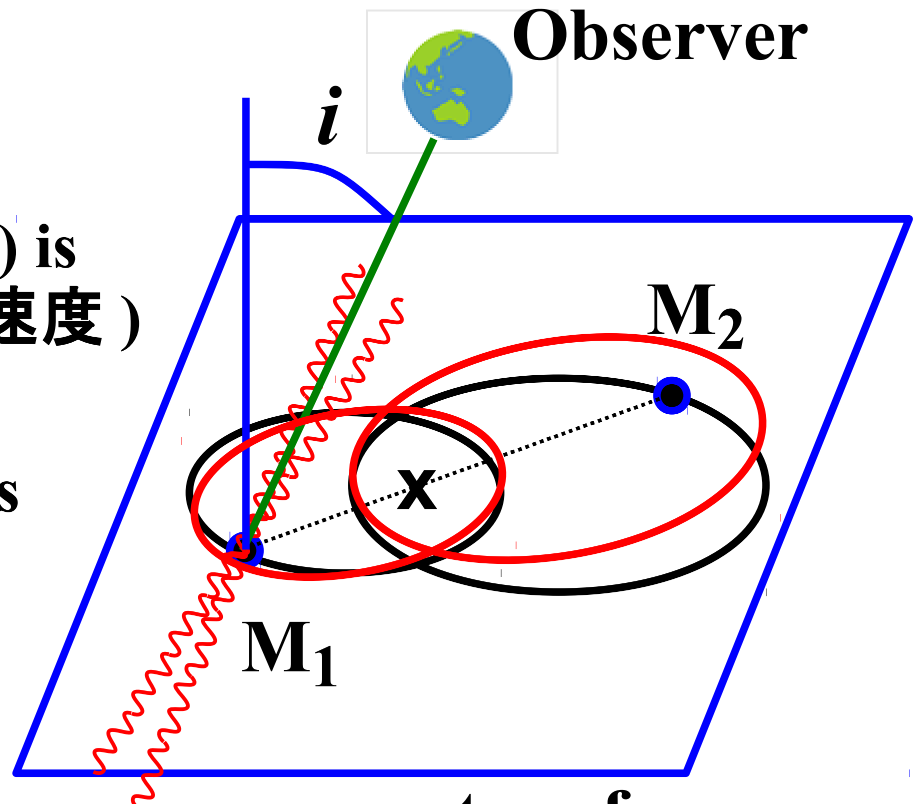
- **Binary stars**
  - **inclination angle = *i***
  - **Doppler shift (Pulse timing change) is given by the radial velocity (視線速度)**
    $K = v \sin i$
  - **Radial velocity → orbit parameters**
  - **Mass function (observable)**

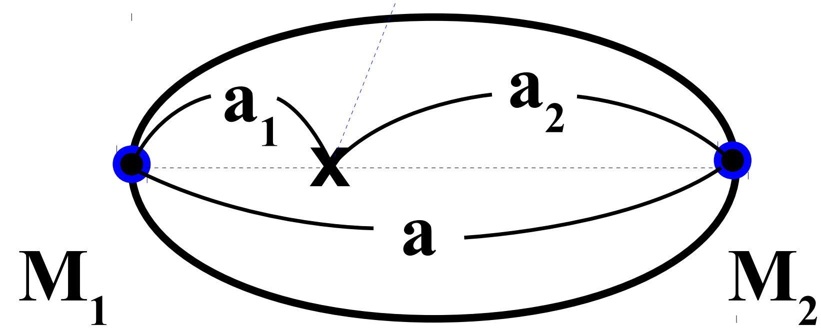
$$f \equiv \frac{(M_2 \sin i)^3}{M^2} = \frac{4\pi^2 (a_1 \sin i)^3}{G} P^2$$

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

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

  - **and GR effects ...**





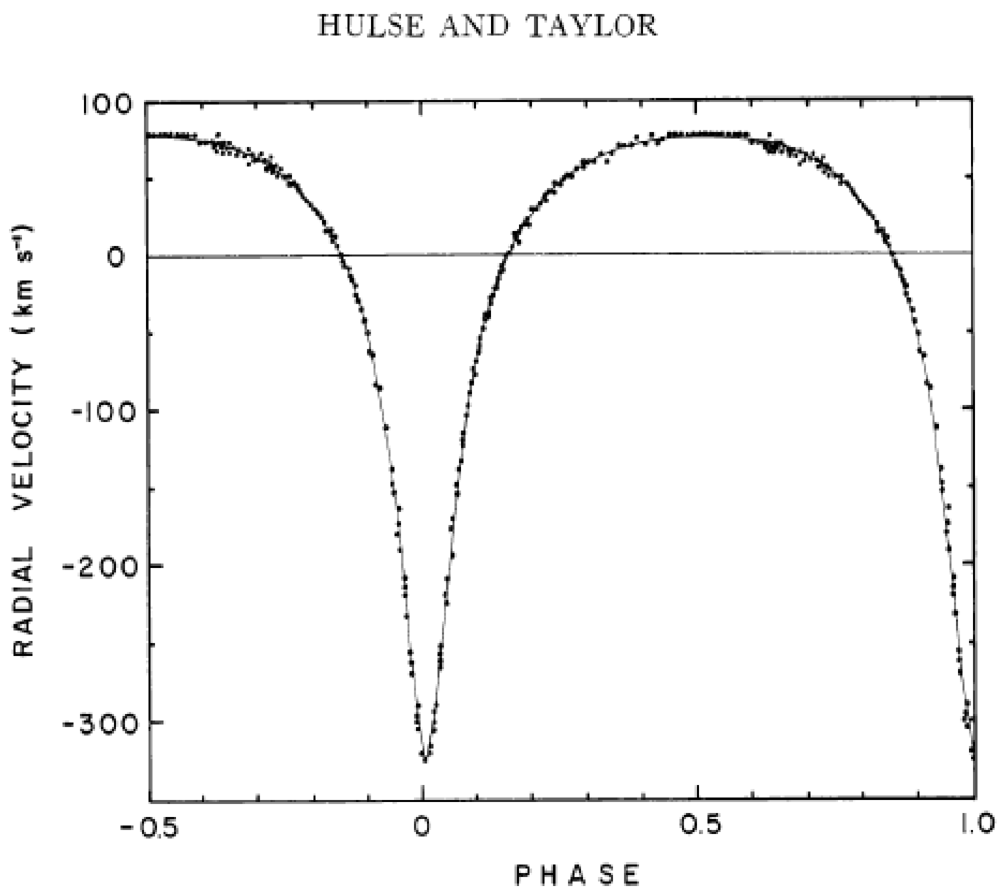
Hulse-Taylor Pulsar (PSR 1913+16)

- **Precisely (and firstly) measured neutron star binary (1993 Nobel prize to Hulse & Taylor)**
- **Radial velocity → P, e, a_1 sin *i* → Mass function**

TABLE 2

ELEMENTS OF THE ORBIT

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



Hulse-Taylor ('75)

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

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

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

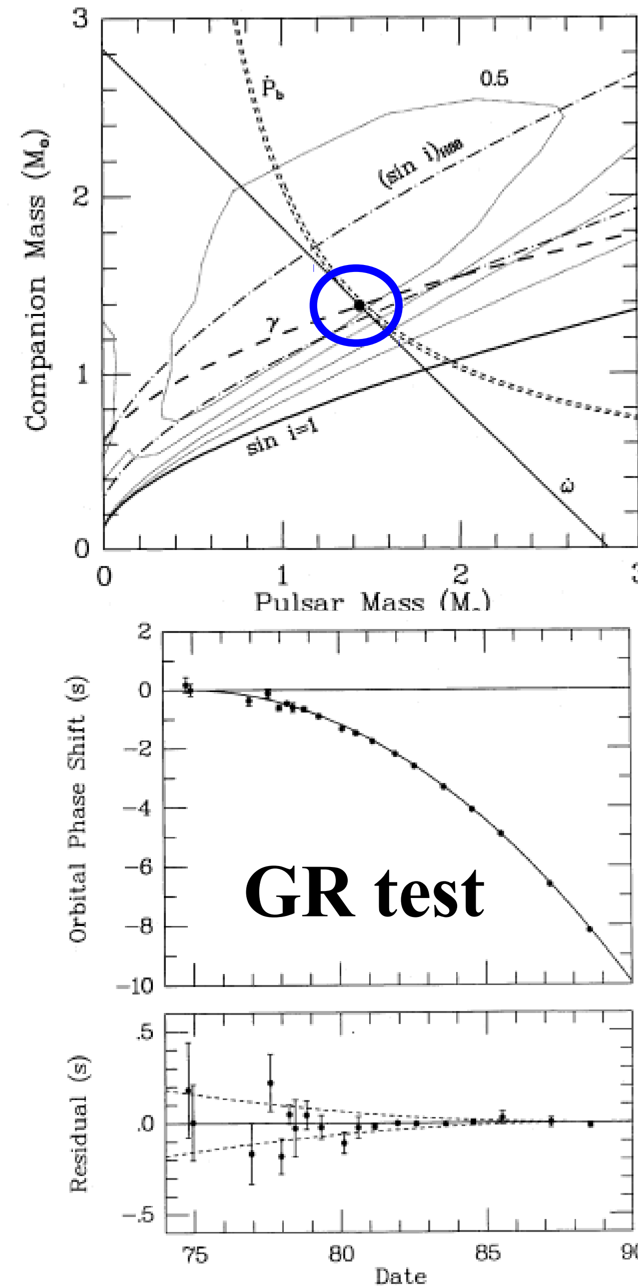
  - **Einstein delay**

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

$$\gamma=\frac{eP_bGm_2(m_1+2m_2)}{2\pi c^2 a_R M} \qquad \frac{a_R^3}{P_b^2}=\frac{GM}{4\pi^2}\left[1+\left(\frac{m_1m_2}{M^2}-9\right)\frac{GM}{2a_R c^2}\right]^2$$

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

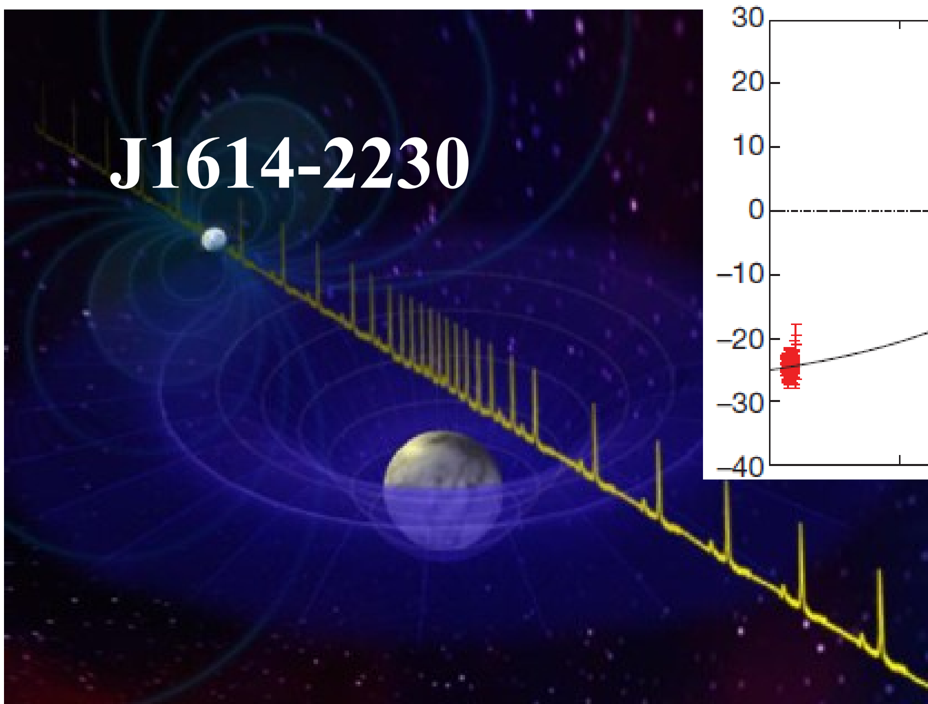
$$m_1=1.442\pm0.003\,M_{\rm sun}$$
$$m_2=1.386\pm0.003\,M_{\rm sun}$$

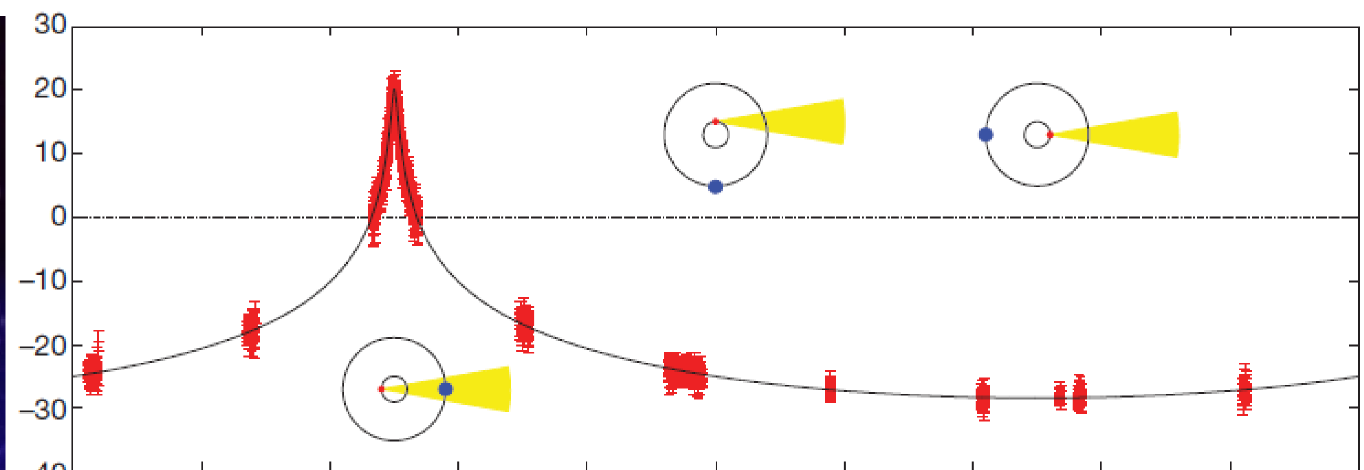


Taylor, Weisenberg ('89)

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)**





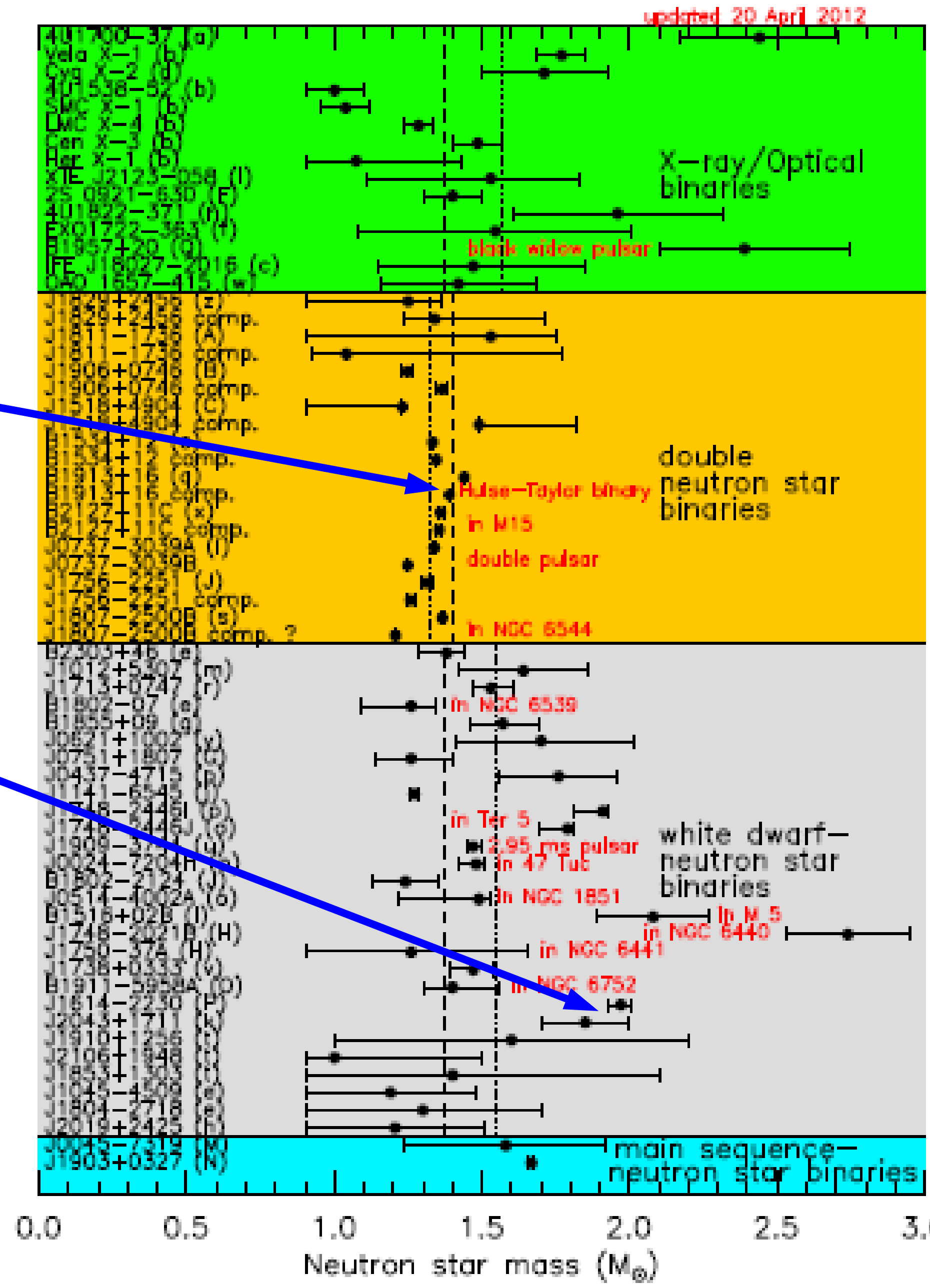
$$\Delta_S = -2m\left[\ln\frac{r}{a} + \ln\left(1 - \sin i \sin\phi\right)\right]$$

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 $M_\odot$***



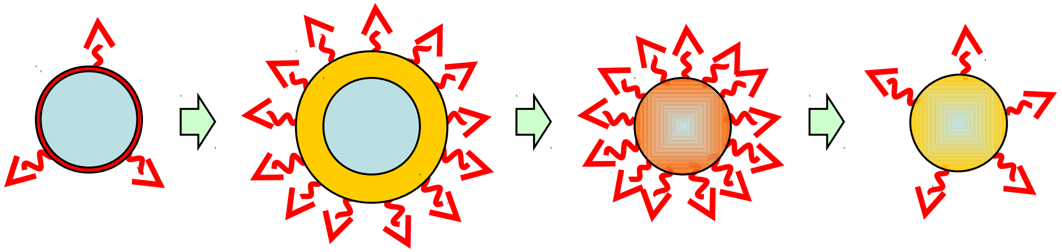
Lattimer (2013)

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



Ignition

Touch down

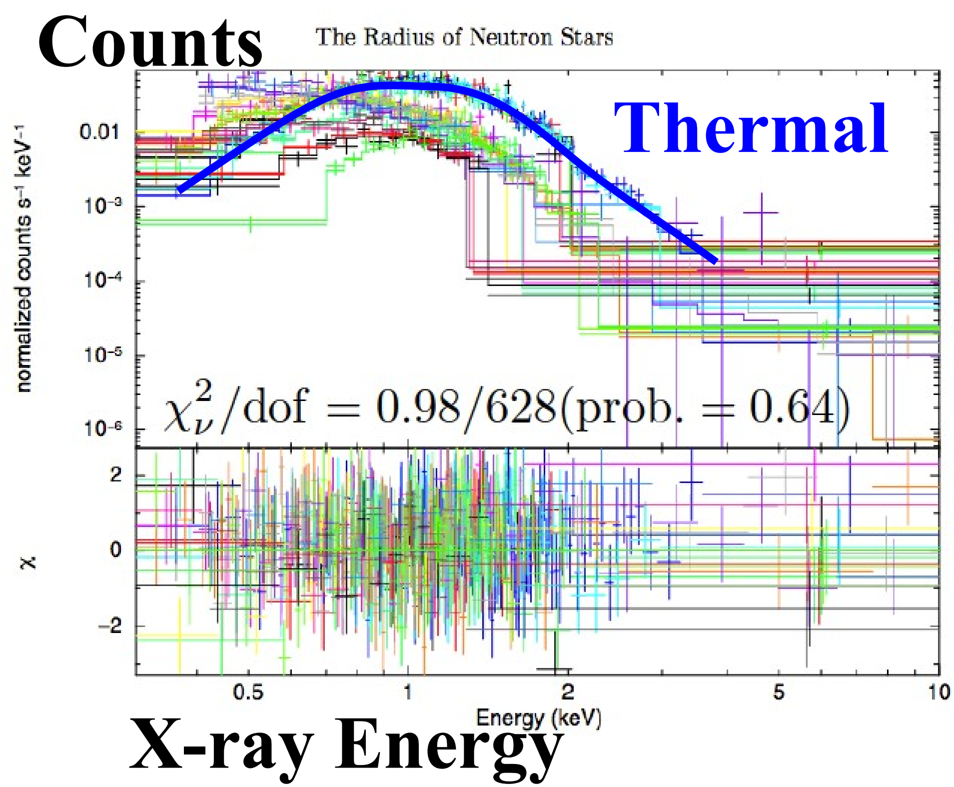
Nakazato

NS Radius Measurement (1)

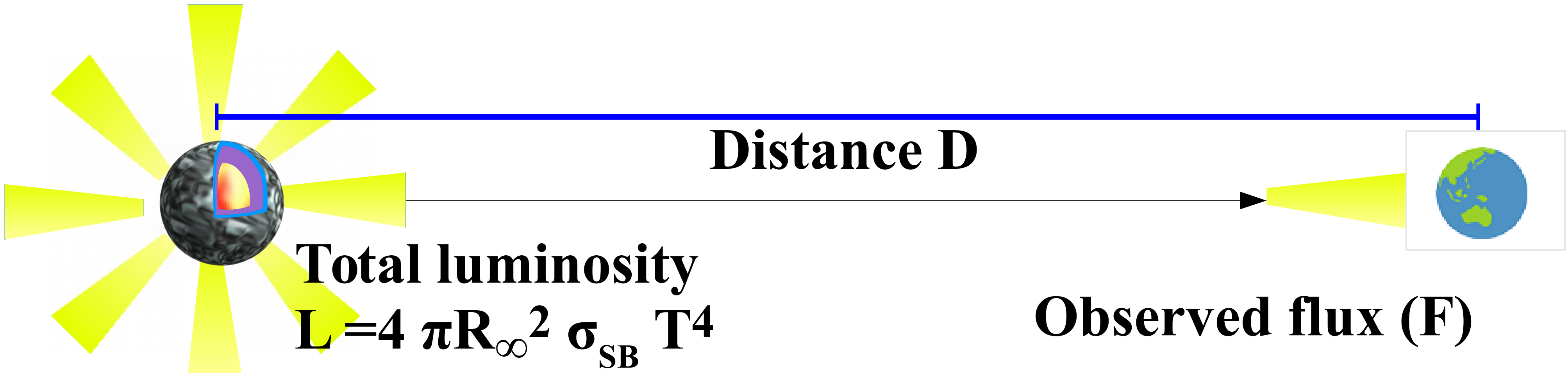
- **Surface emission**
  - **Stefan-Boltzmann law is assumed**
    → NS radius is obtained from Flux, Temperature, and Distance measurement.

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

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



Guillot et al. (2013)



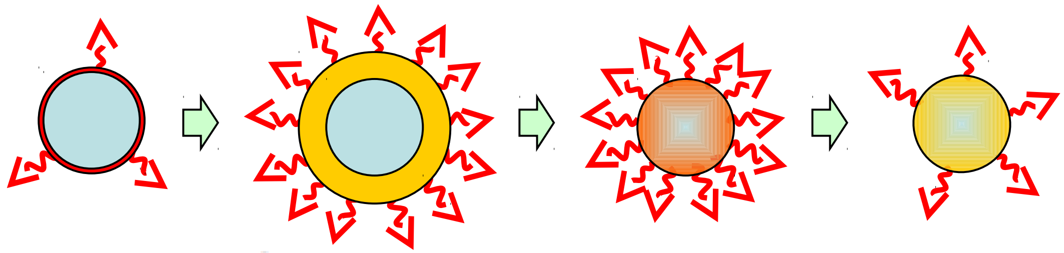
NS Radius Measurement (2)

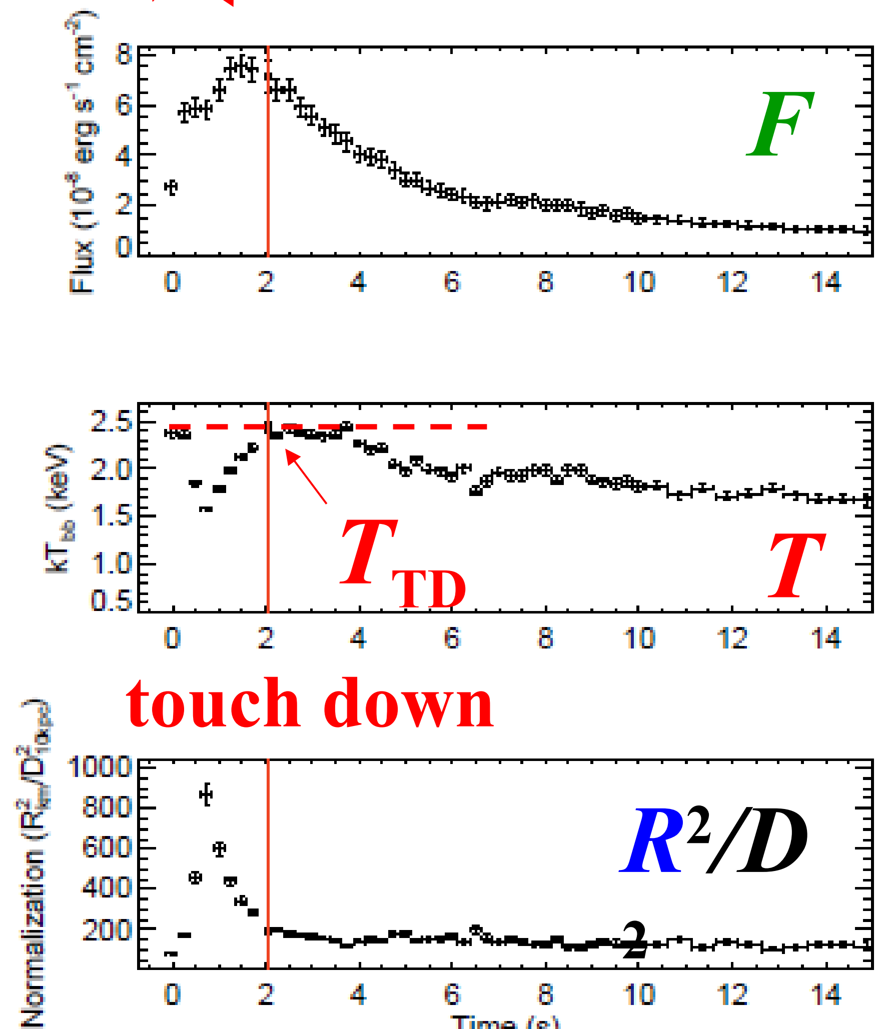
- **Eddington Limit**
  - **Eddington Limit**
    radiation pressure = gravity

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

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

  - **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)





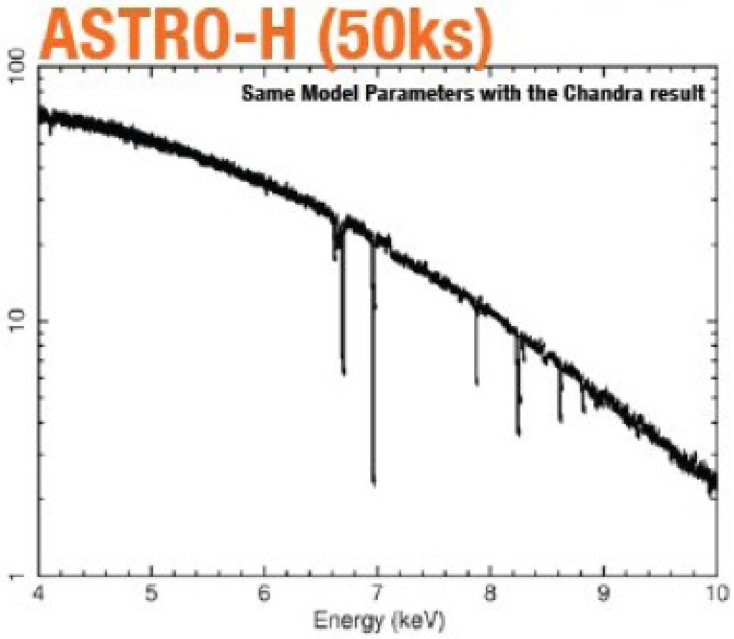
Guver et al., ApJ 747 (2012) 47

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.

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

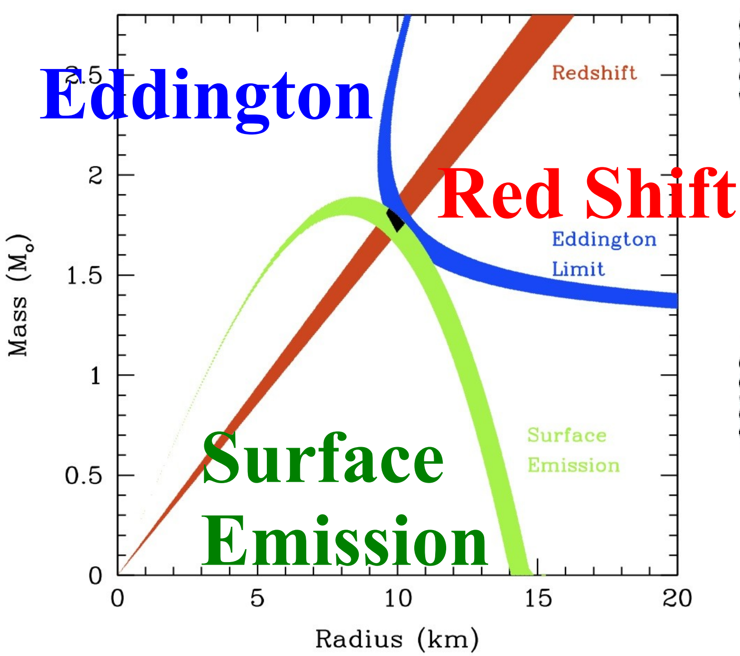
  - **ASTRO-H will measure Iron absorption line from NS, and determine M/R with 1 % accuracy !**

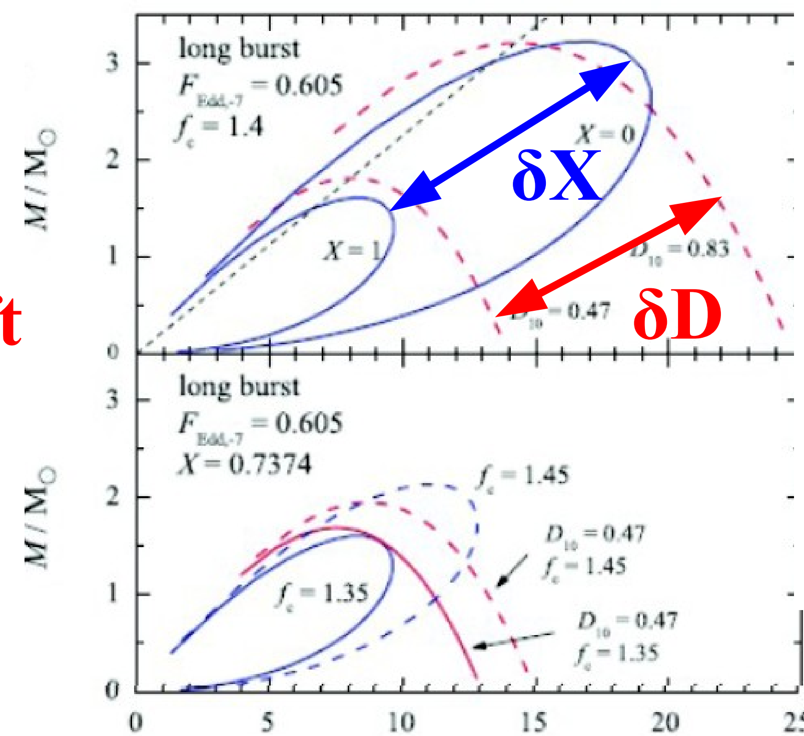


ASTRO-H simulation

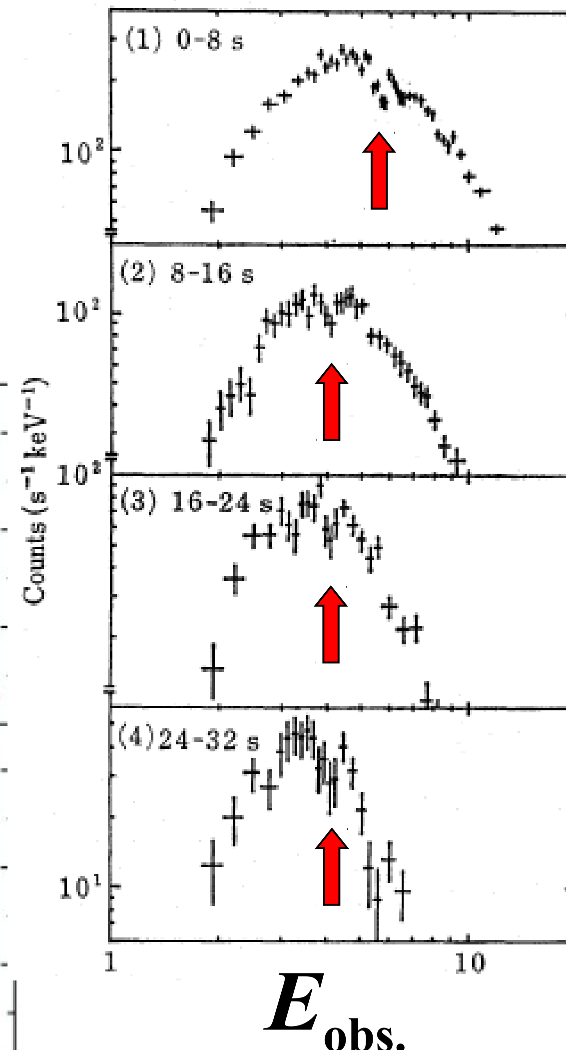
Neutron Star Radius

- 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

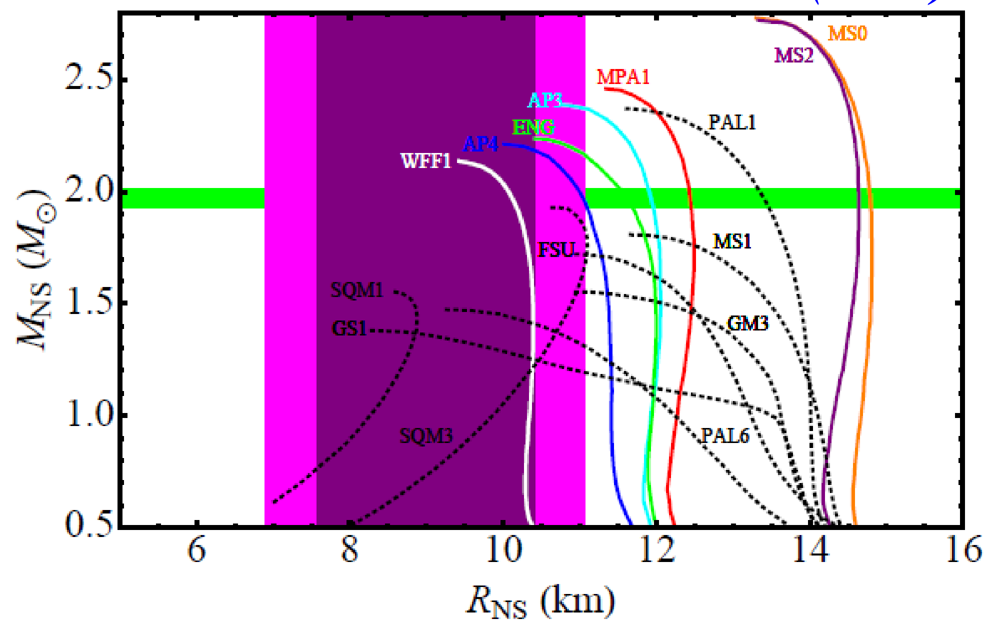


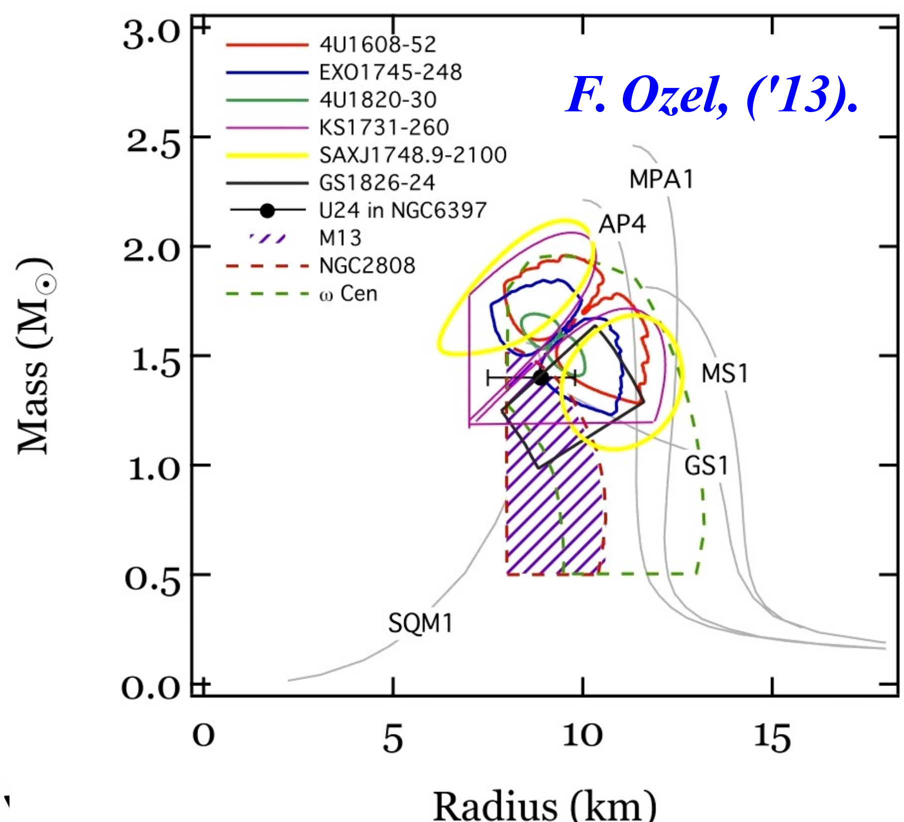
Waki et al., PASJ36('84)819

Compact NS puzzle

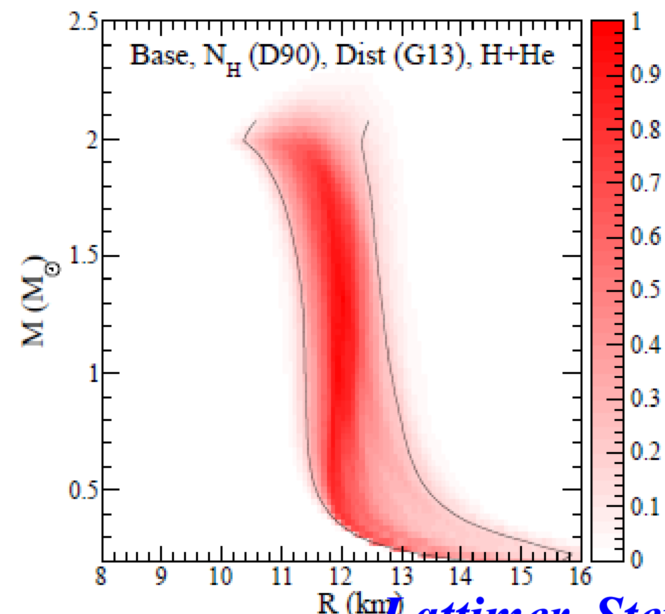
- **Some analyses suggest smaller R_{NS} than nucl. phys. predictions.**
- **Some make objections.**
  Suleimanov+, $R_{1.4} > 13.9$ km
  Lattimer+, $R_{1.4} = 12 \pm 1.4$ km

Guillot et al. (2013)



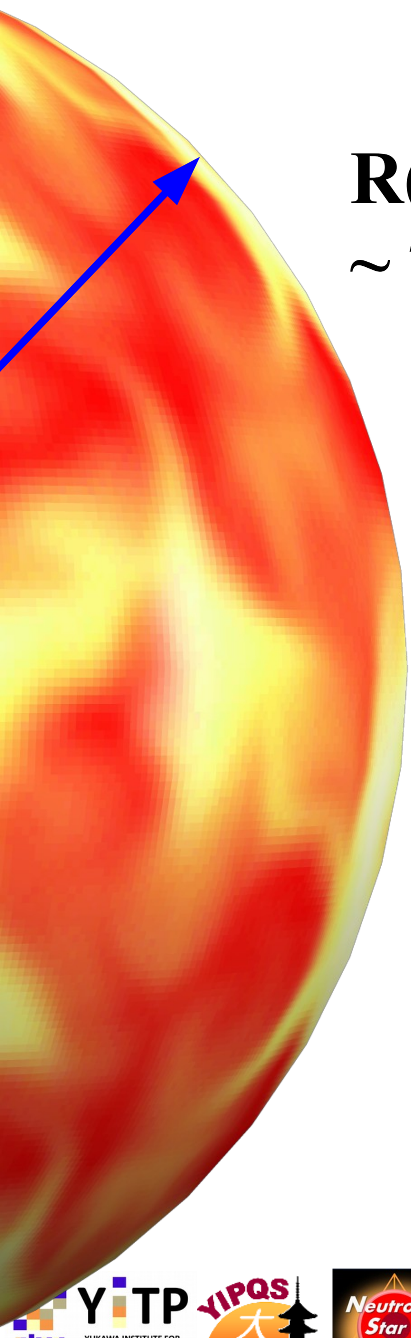


F. Ozel, ('13).

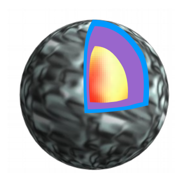


Lattimer, Steiner (2014).

Neutron Star Density

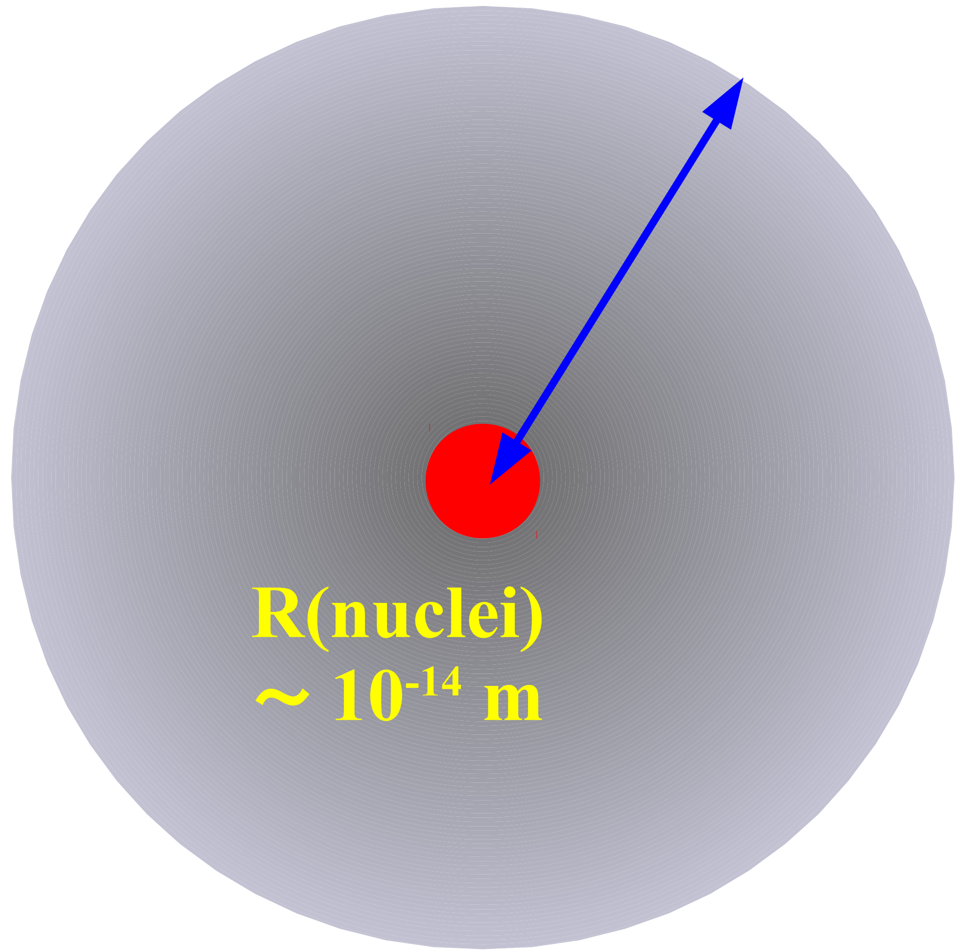


R(Sun)
~ 700,000 km



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

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



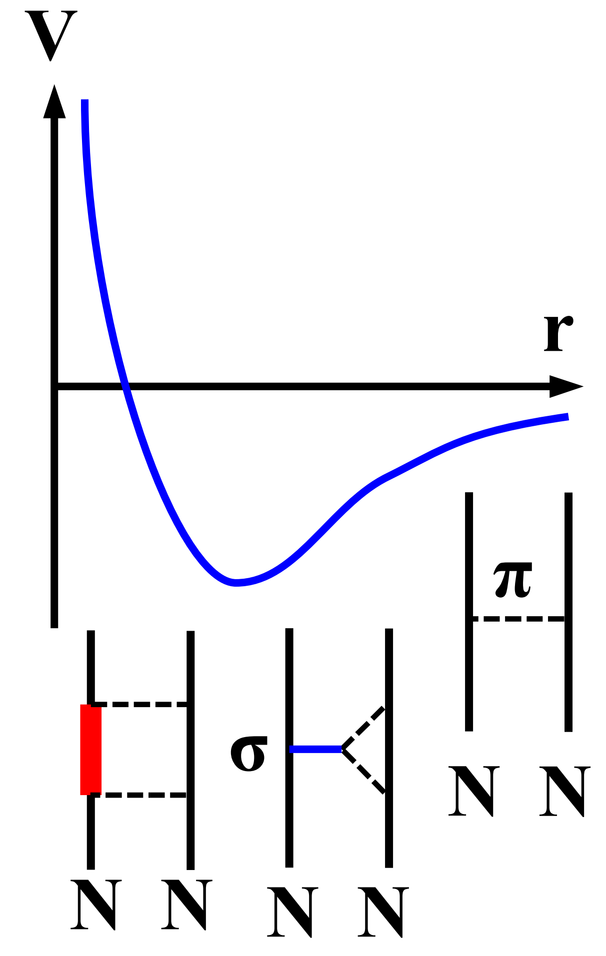
Very High Density !

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

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, ….
  - **Short-range repulsion:**
    Vector meson exchange,
    Pauli blocking btw. quarks
    Gluon exchange
    Tamagaki; Oka, Yazaki;
    Aoki, Hatsuda, Ishii



Neutron Star Matter EOS

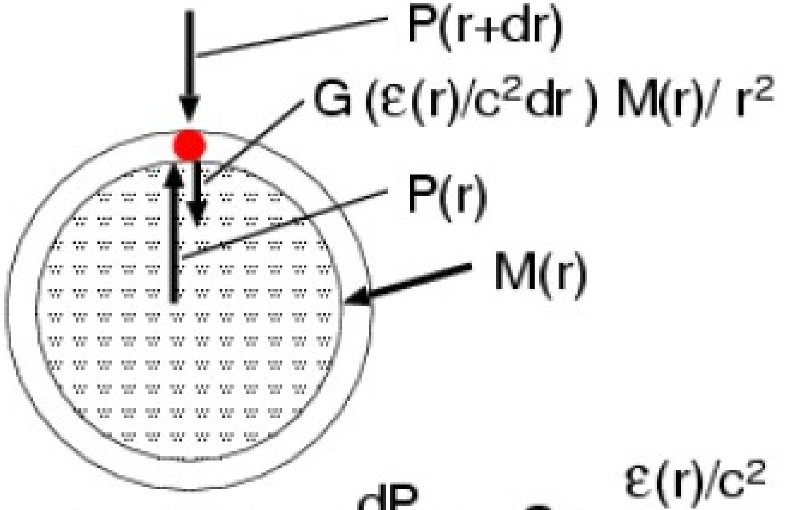
TOV equation

- **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**



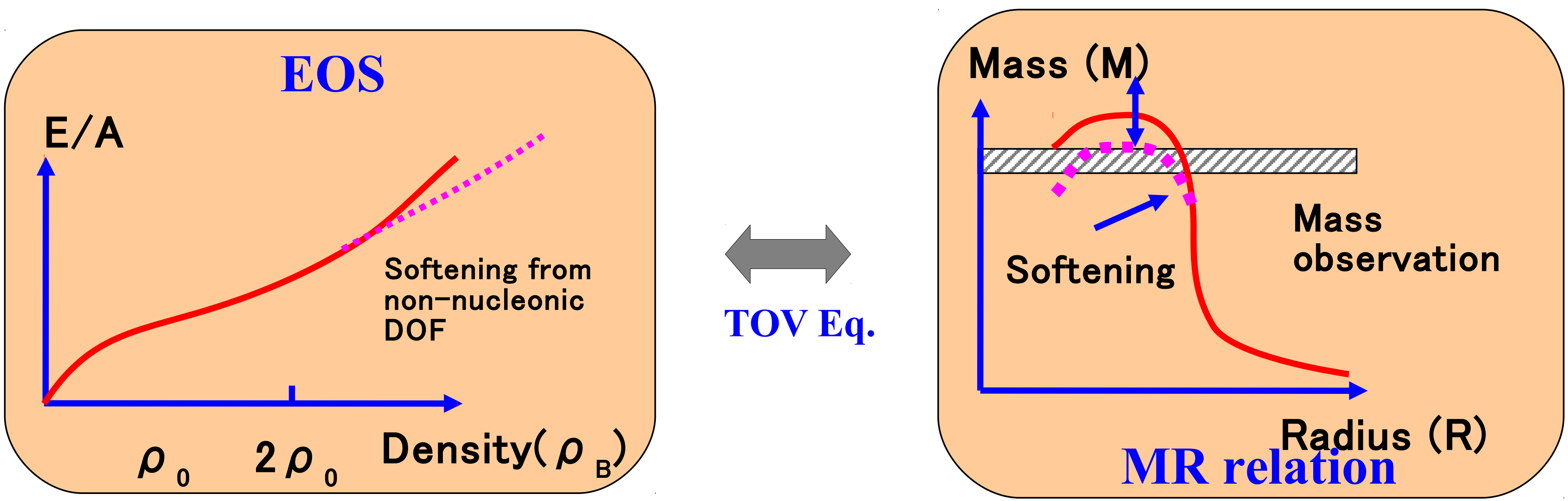
$$\frac{dP}{dr} = -G \frac{\varepsilon(r)/c^2 \; M(r)}{r^2}$$

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 $\varepsilon(r=0)$
  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

Ask Koura for details

- **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**

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

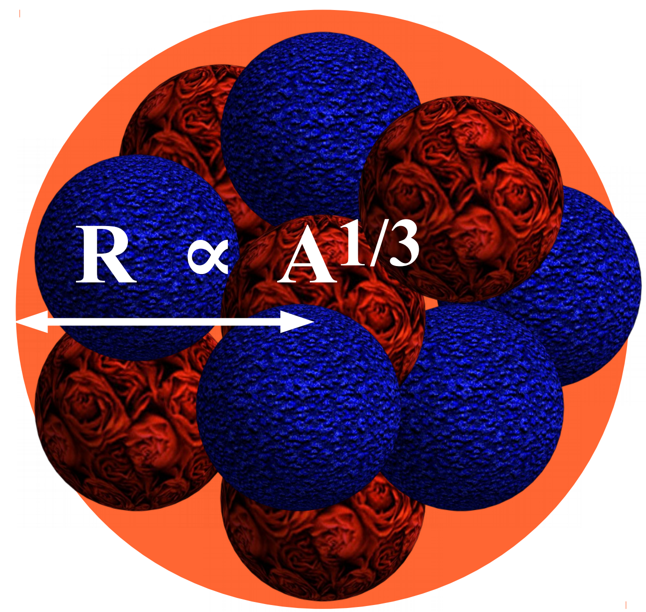
- **Ignore Coulomb, consider A → ∞,**

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

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

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

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



Neutron Star Matter EOS

- **Energy per nucleon in nuclear matter**

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

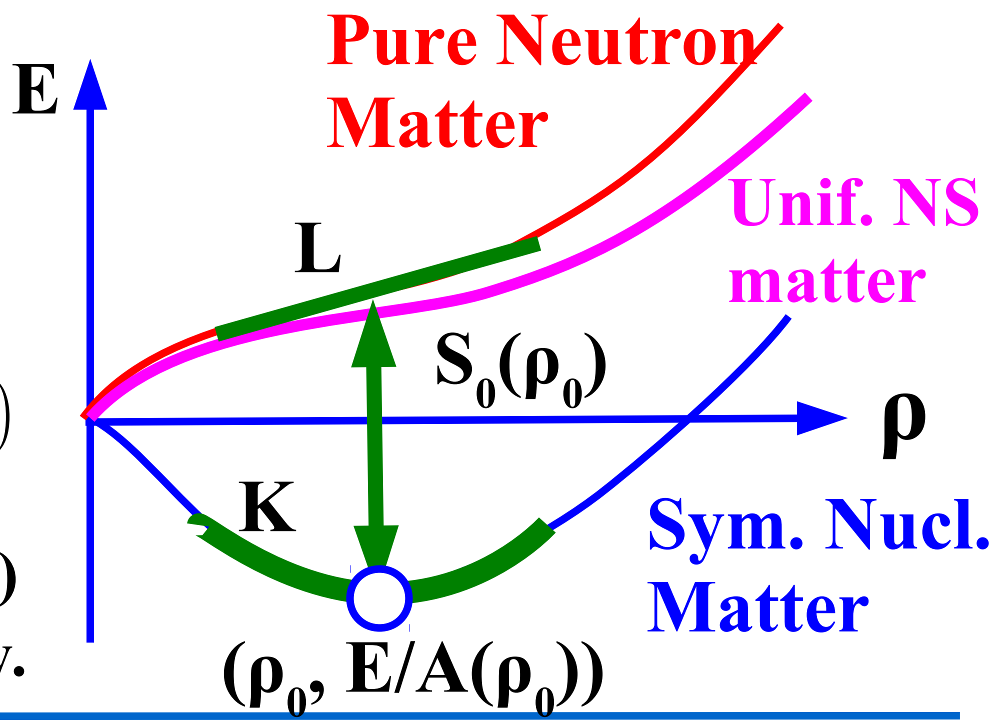
$$E_{\rm SNM}(\rho) \simeq E_0 + \frac{K(\rho-\rho_0)^2}{18\rho_0^2} \ , \quad S(\rho) = S_0 + \frac{L(\rho-\rho_0)}{3\rho_0}$$

  - **Saturation point $(\rho_0, E_0) \sim (0.16\ \mathrm{fm}^{-3}, -16\ \mathrm{MeV})$**
  - **Symmetry energy parameters (S_0 (=J), L) ~ (30 MeV, 70 MeV)**
  - **Incompressibility K ~ 230 MeV**

- **Uniform neutron star matter**
  - **Constituents at low density = proton, neutron and electron**

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

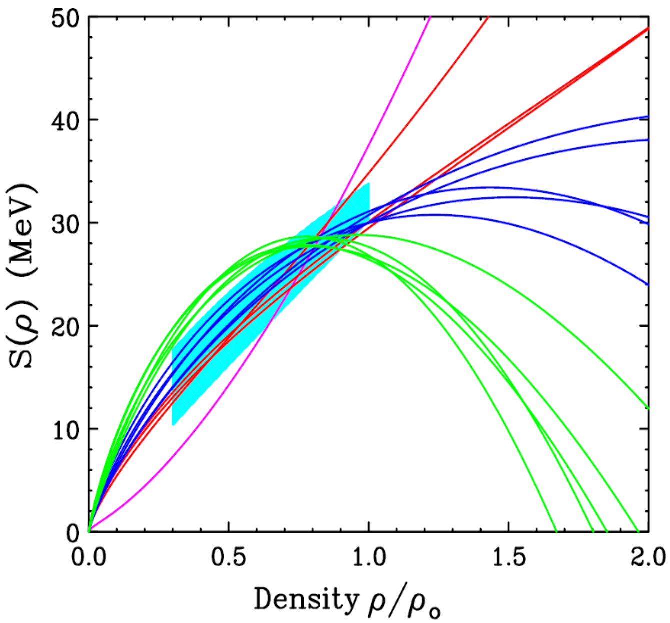
  - **Charge neutrality → ρ(elec.)= ρ(p) ($\rho_e = \rho_p = \rho(1-\delta)/2$) δ is optimized to minimize energy.**

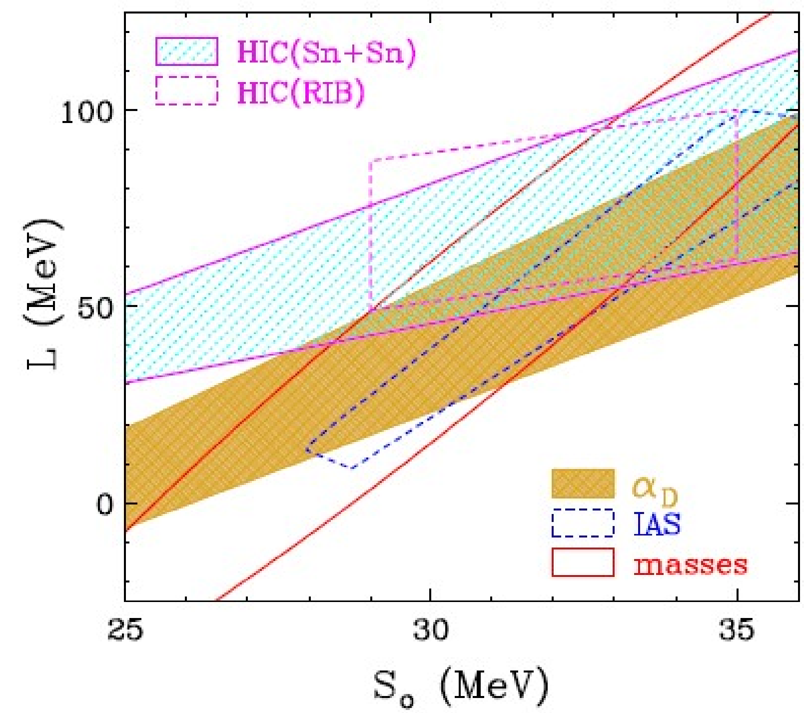


Symmetry Energy

- **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 = 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

Simple parametrized EOS

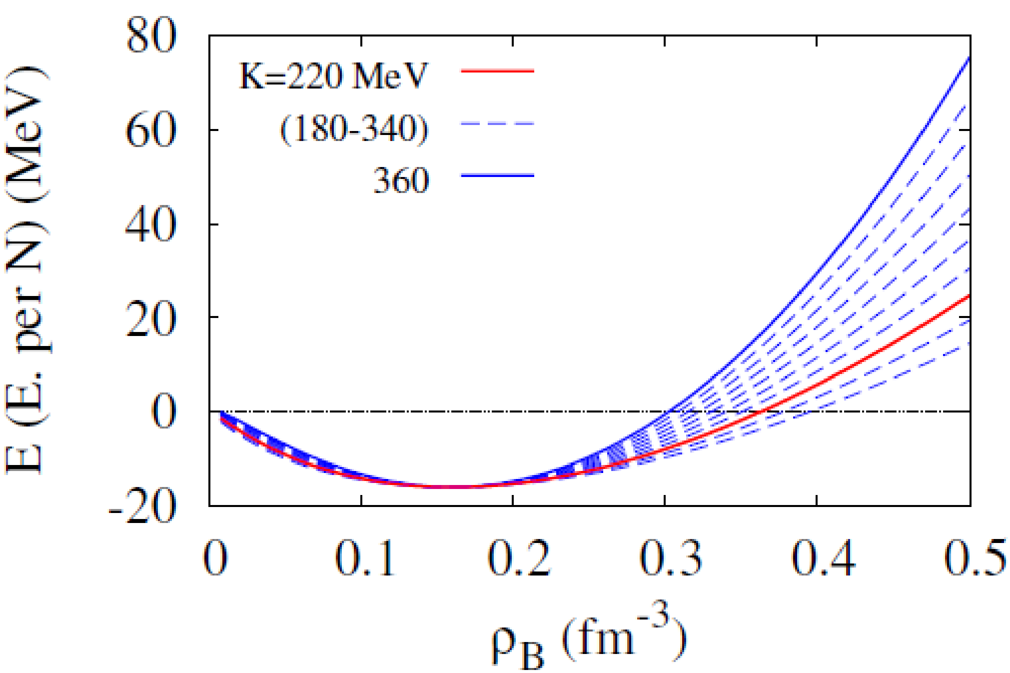
- **Skyrme int. motivated parameterization**

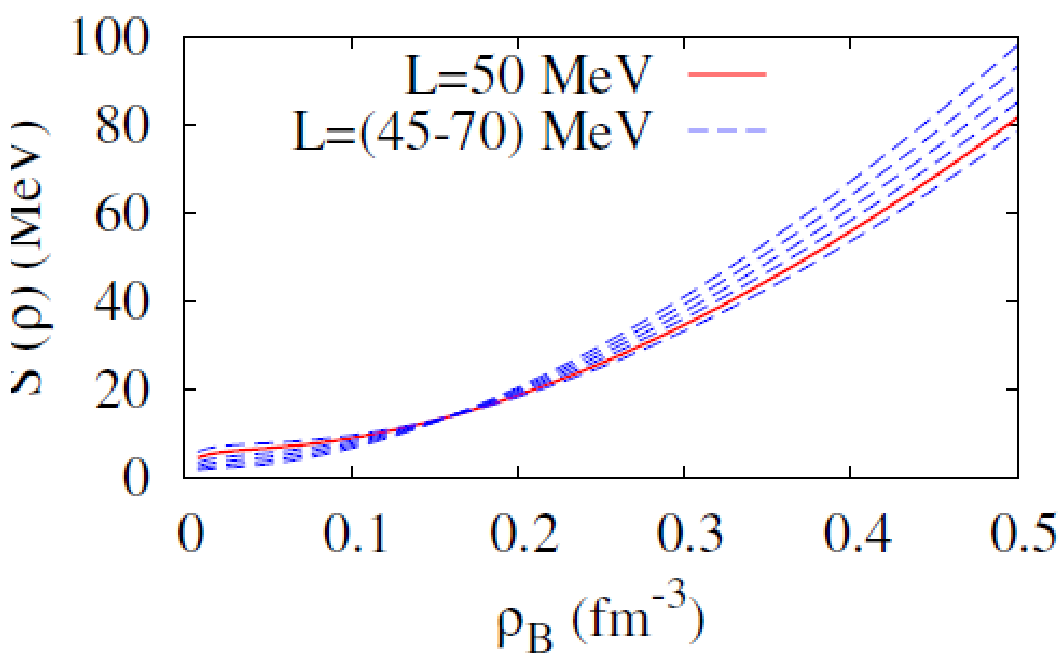
$$E_{\mathrm{SNM}} = \frac{3}{5}E_F(\rho) + \frac{\alpha}{2}\left(\frac{\rho}{\rho_0}\right) + \frac{\beta}{2+\gamma}\left(\frac{\rho}{\rho_0}\right)^{1+\gamma}$$

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

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

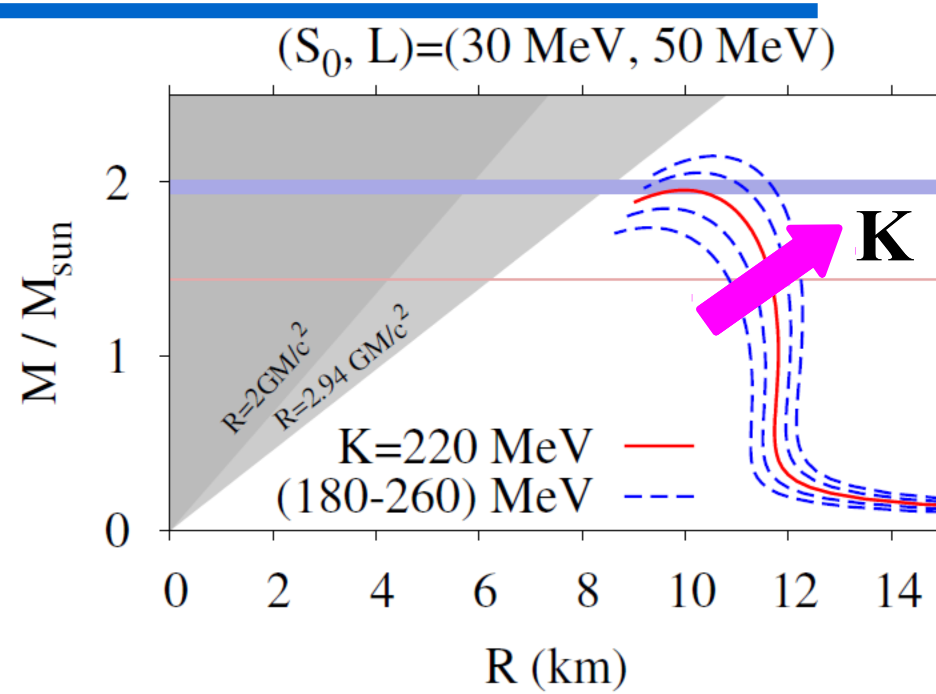
K=220 MeV, S_0=30 MeV

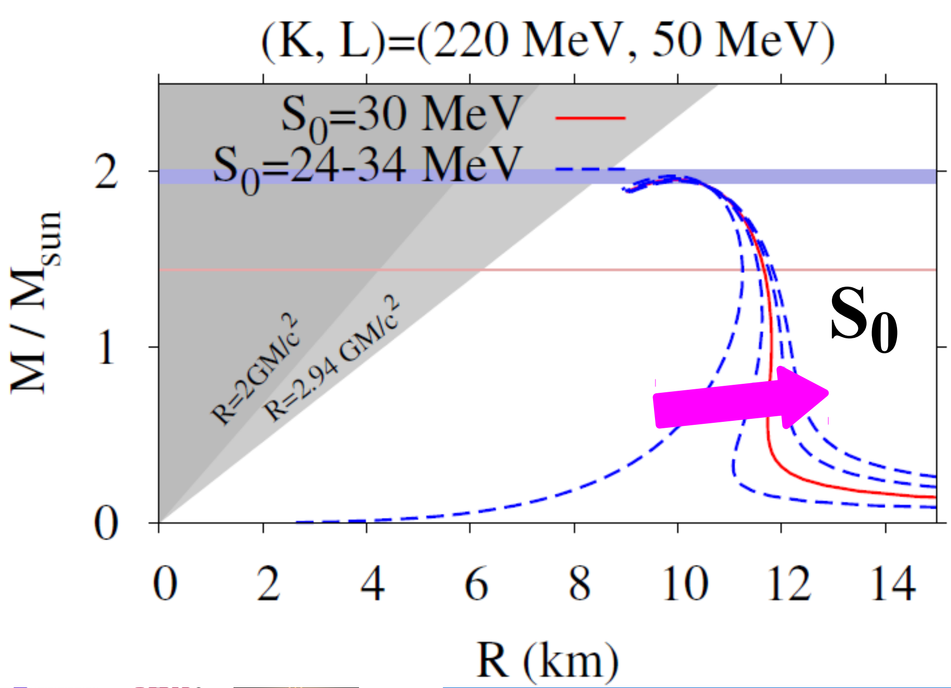


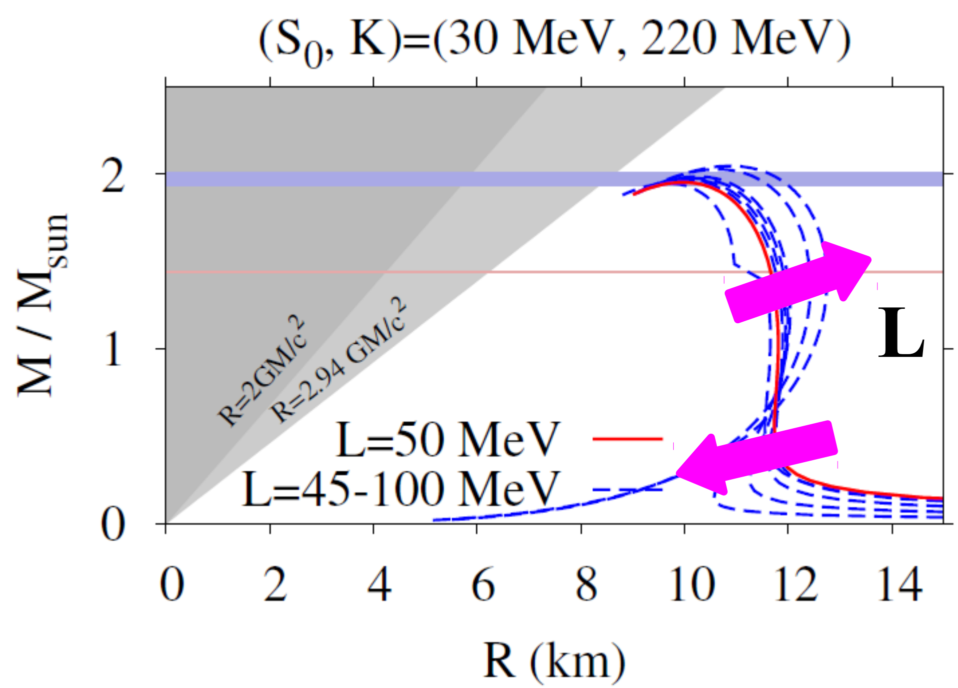


Simple parametrized EOS

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







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)**

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

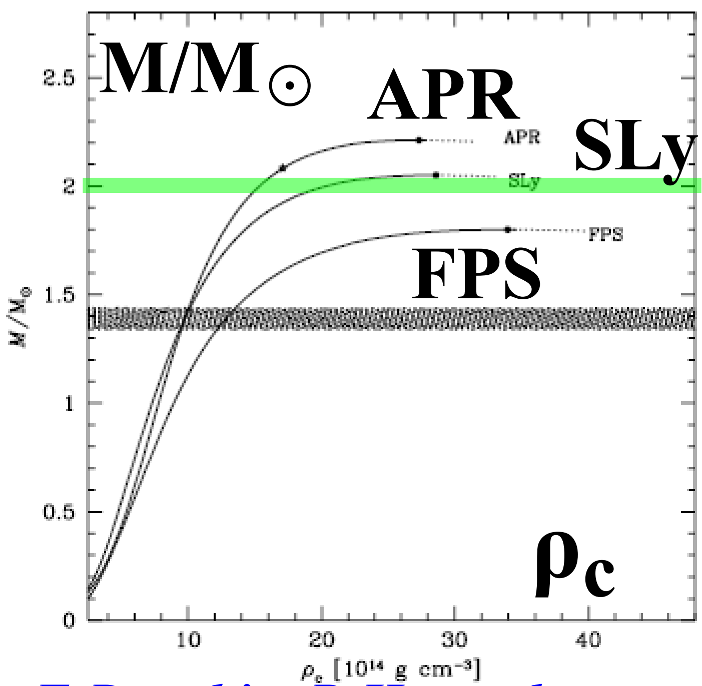
  - **Relativistic Mean Field**
    - **Relativistic, Meson-Baryon coupling, Meson self-energies**

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

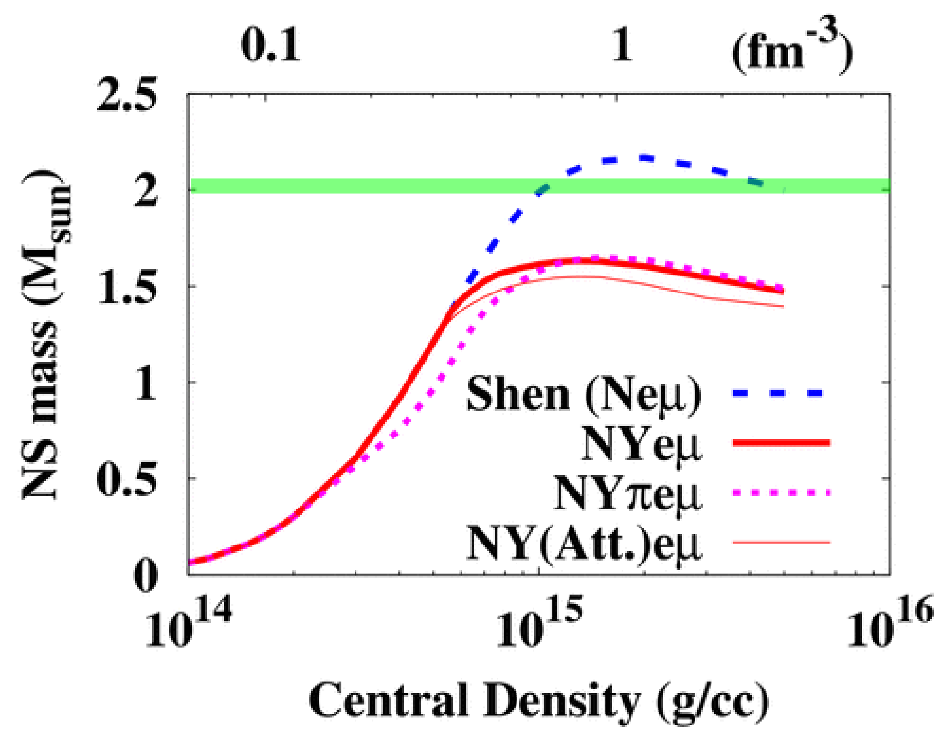
- **Microscopic (ab initio) Approaches (starting from bare NN int.)**
  - **Variational calculation**
  - **Quantum Monte-Carlo**
  - **Bruckner Theory (G-matrix)**

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) $M_\odot$
  - **Rel. MF (TM1) → Mmax ~ 2.2 $M_\odot$**



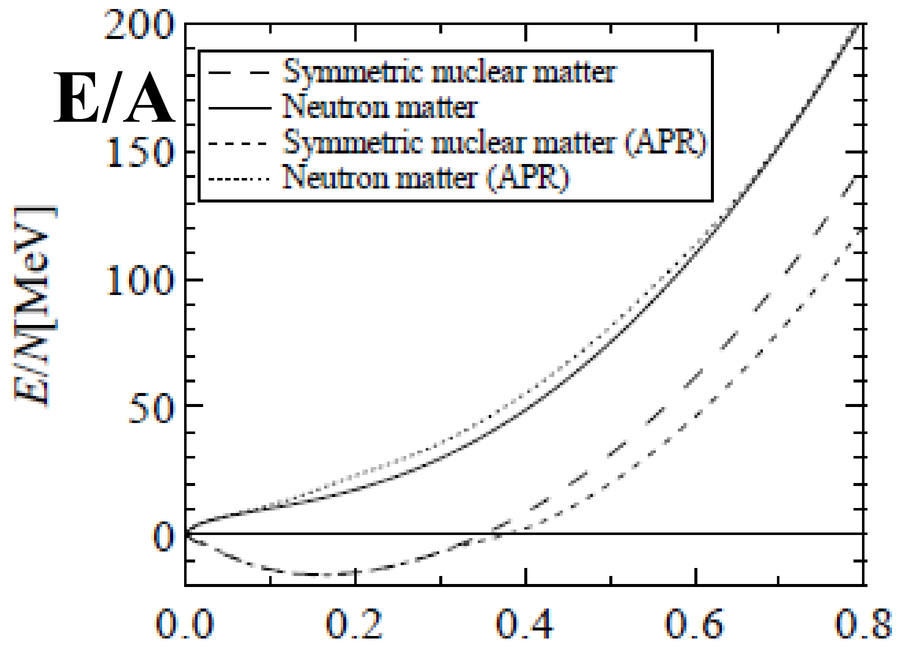
F. Douchin, P. Haensel.
Astron.Astrophys.380('01)151.



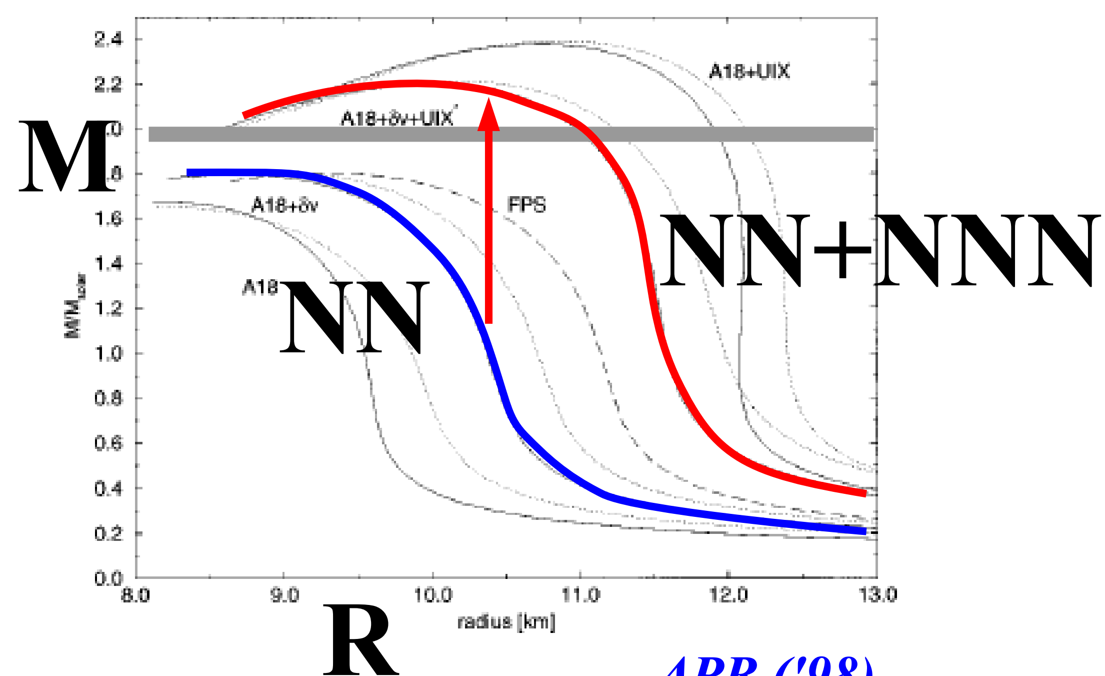
Ishizuka, AO, Tsubakihara, Sumiyoshi,
Yamada, J. Phys. G35(08),085201
c.f. H.Shen+('09) → n, p, Λ EOS

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.**



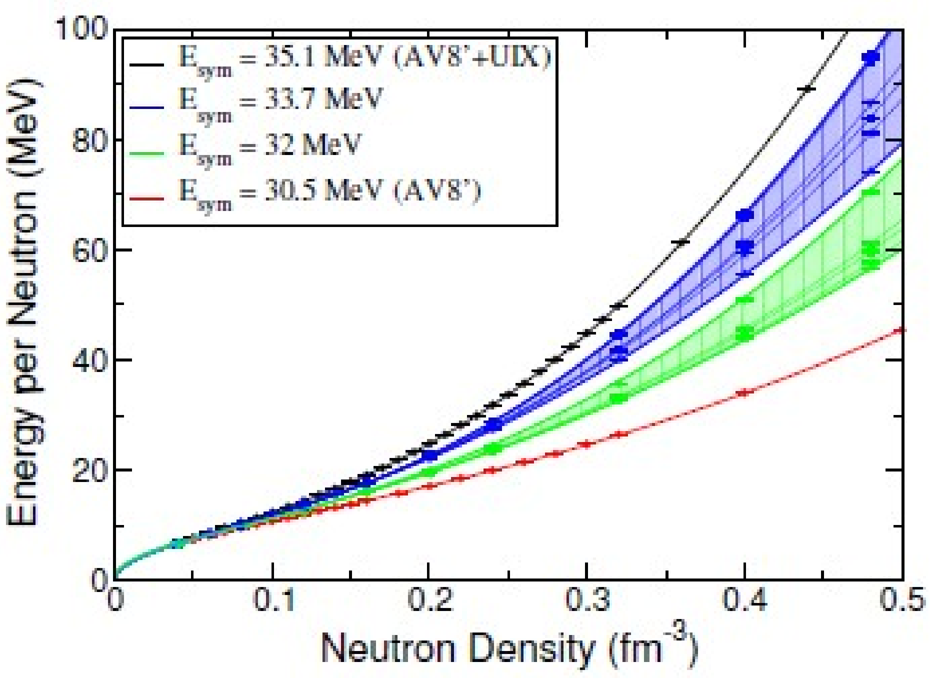
Kanzawa et al. ('07)

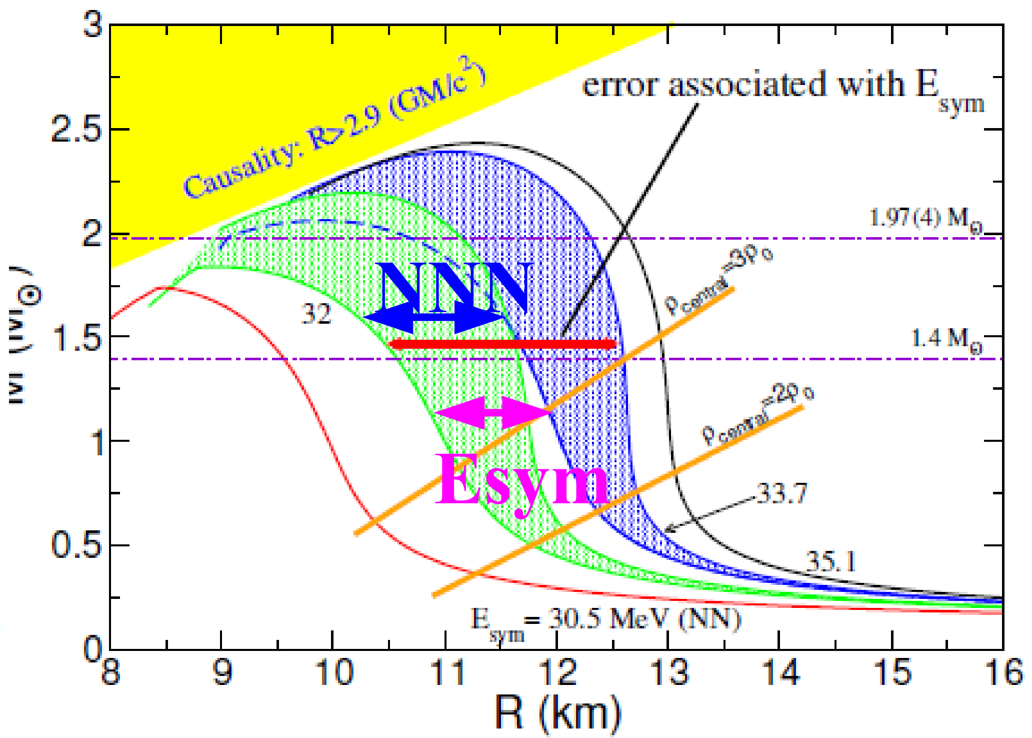


APR ('98)

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}.**





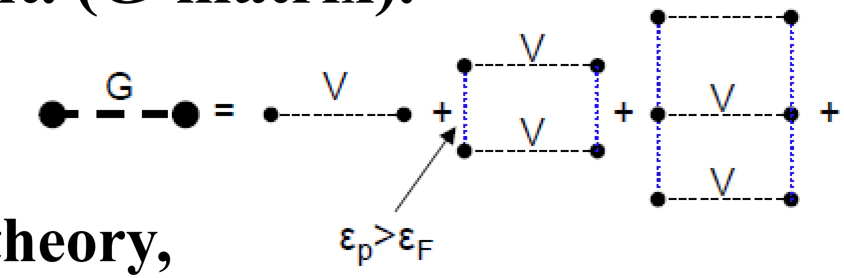
Gandolfi, Carlson, Reddy, PRC 032801, 85 (2012).

Bruckner-Hartree-Fock

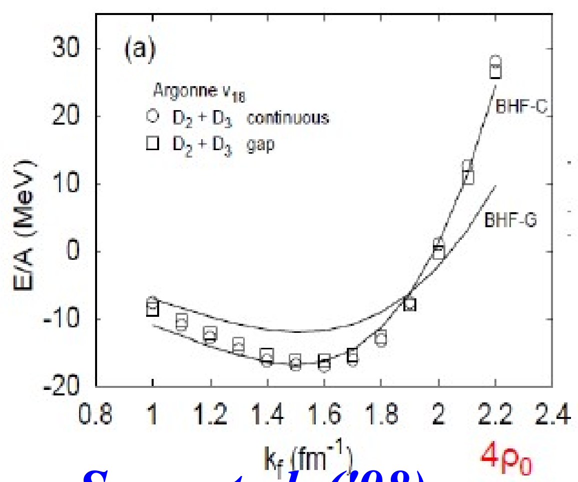
- **Effective interaction from bare NN int. (G-matrix).**

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

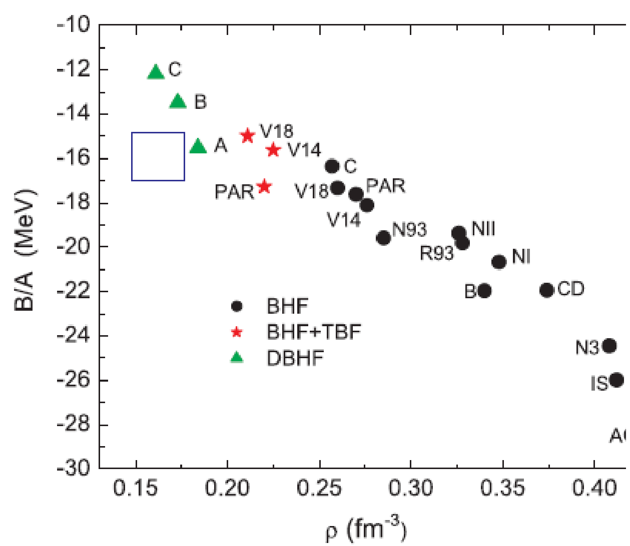
Pauli

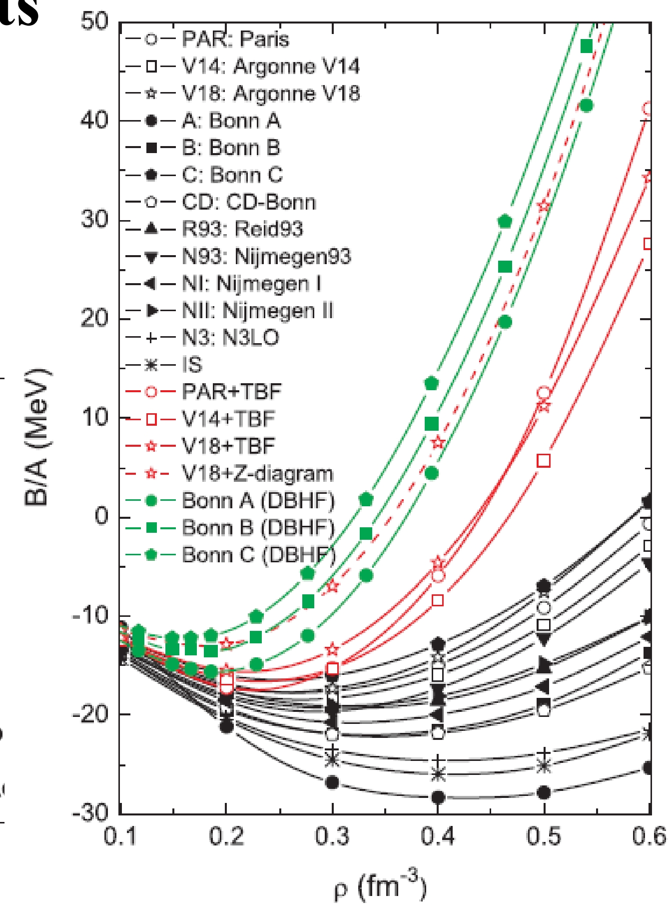


  - **G-matrix = Lowest order Bruckner theory, but next-to-leading terms give small effects at ρ < 4 ρ_0.**
    Song, Baldo, Giansiracusa, Lombardo ('98)
  - **Need 3-body force to reproduce saturation point.**



Song et al. ('98)

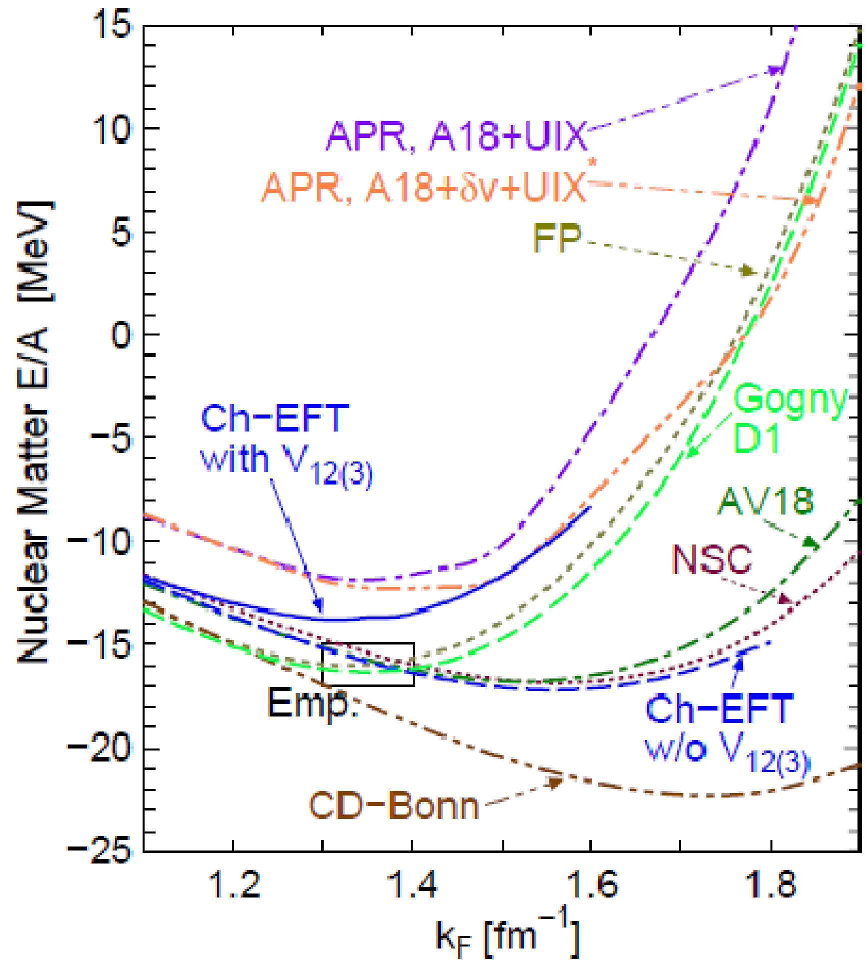




Z.H.Li, U. Lombardo, H.-J. Schulze, W. Zuo, L. W. Chen, H. R. Ma, PRC74('06)047304.

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 !**

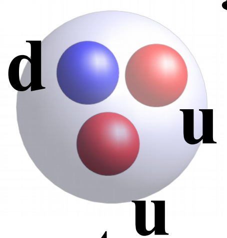


M. Kohno, PRC88('13)064005

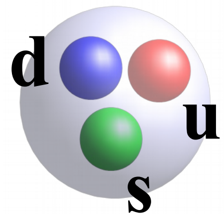
Massive Neutron Star puzzle

Neutron star – Is it made of neutrons ?

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

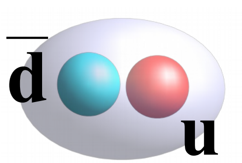


proton

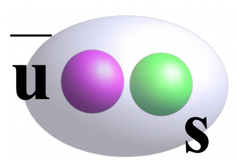


Λ hyperon

  - **Meson condensate (K, π)**

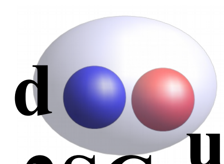


π

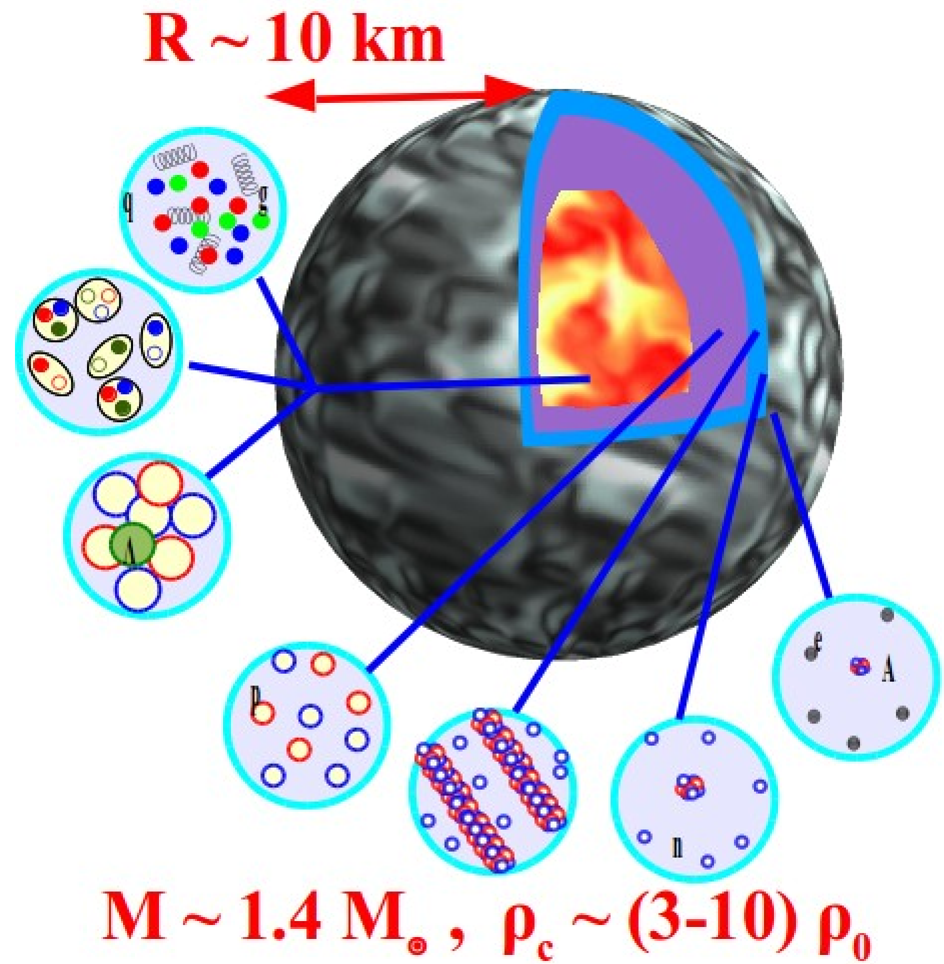


anti kaon

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

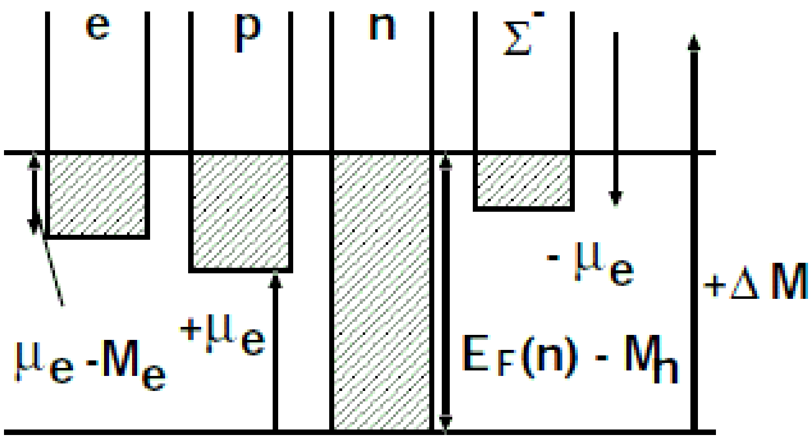


2SC

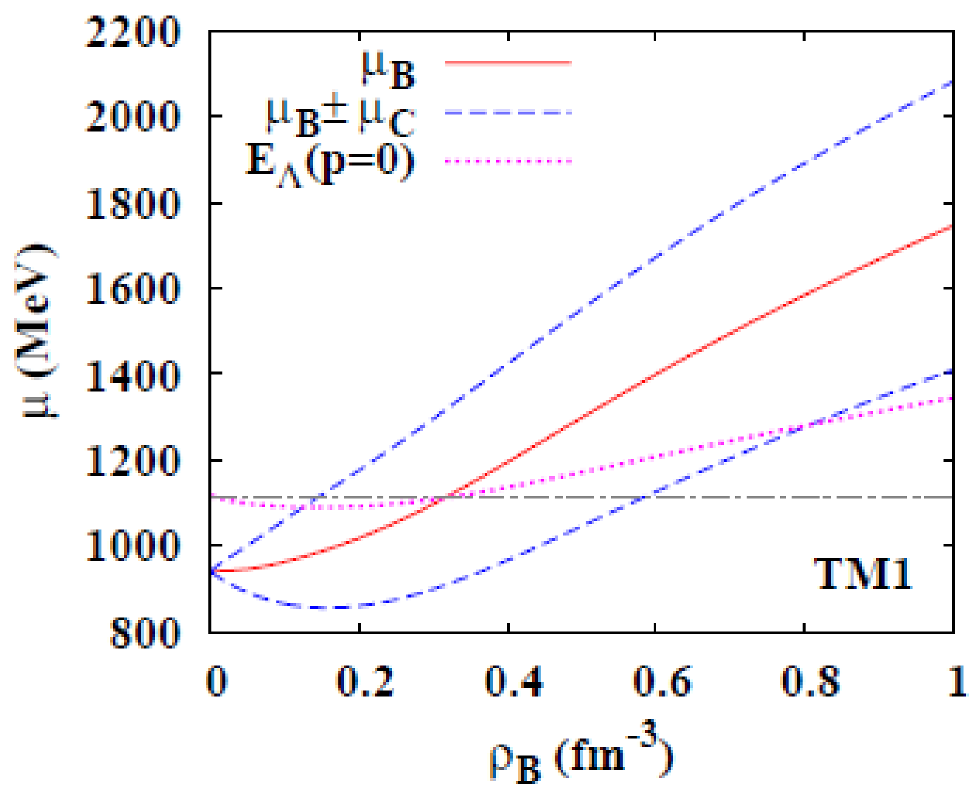


Hyperons in Dense Matter

- **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; ...

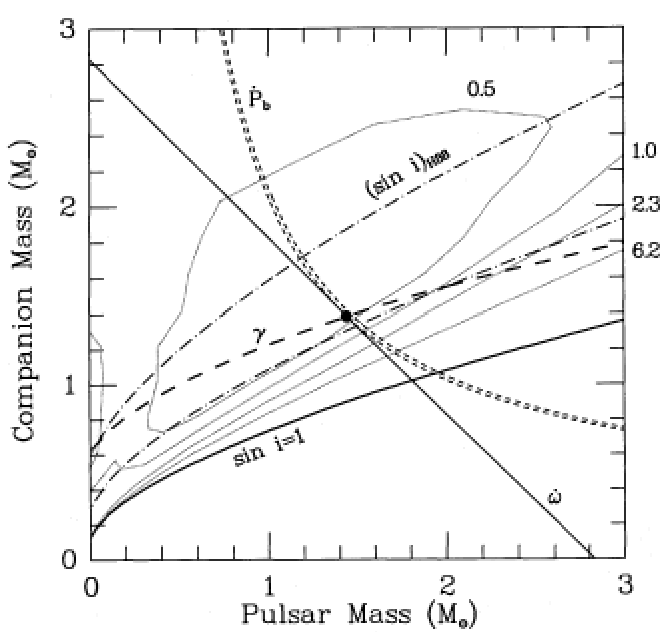


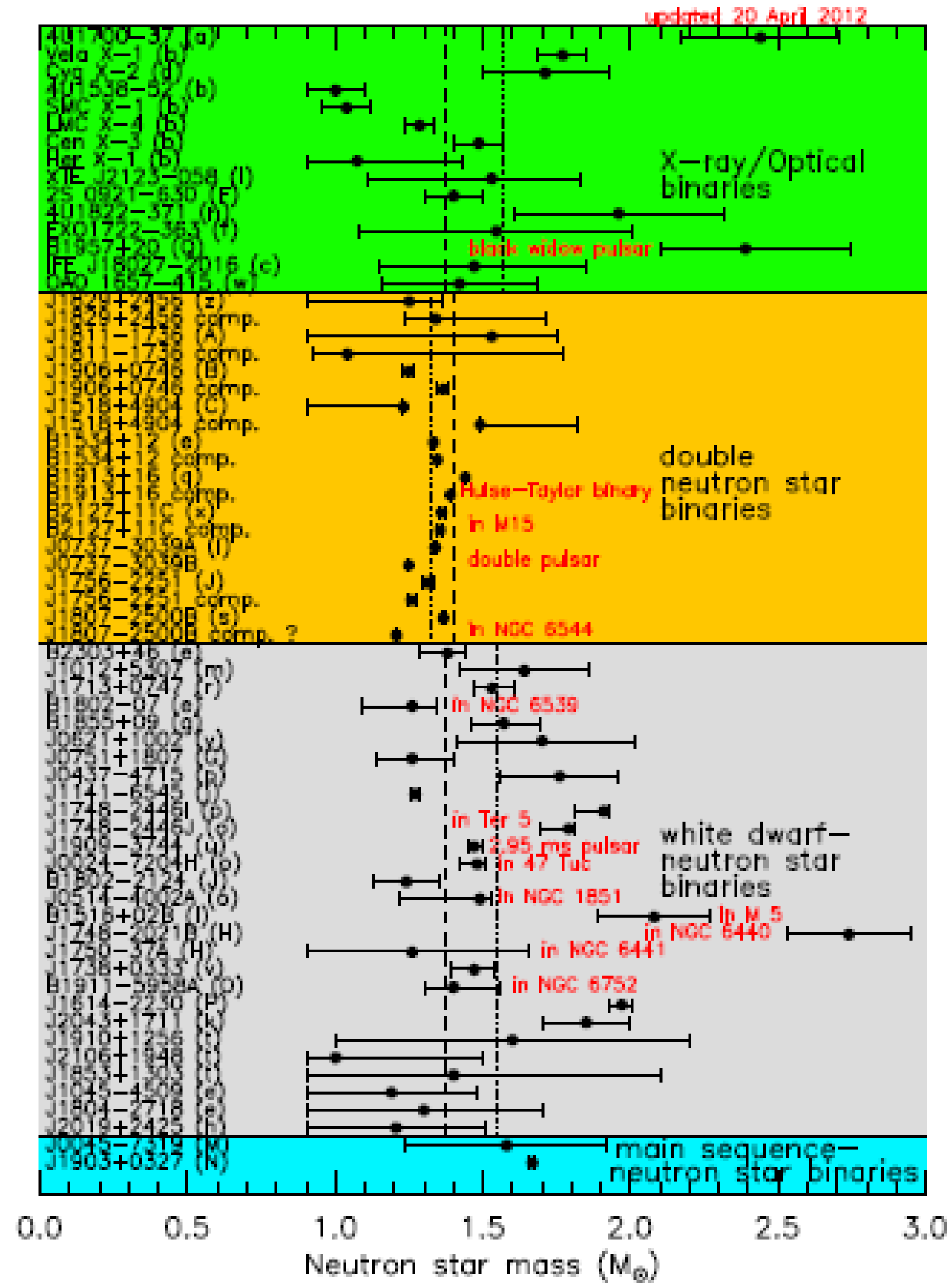
Chemical potential overtakes Λ mass → appearance of Λ



Neutron Star Masses

- **NS masses in NS binaries can be measured precisely by using some of GR effects via doppler shifts.**
  - **Perihelion shift+Einstein delay**
    $\rightarrow$ $M = 1.442 \pm 0.003\, M_\odot$
    (Hulse-Taylor pulsar)
    Taylor, Weisenberg ('89)
- **Many NSs have $M \sim 1.4\, M_\odot$.**

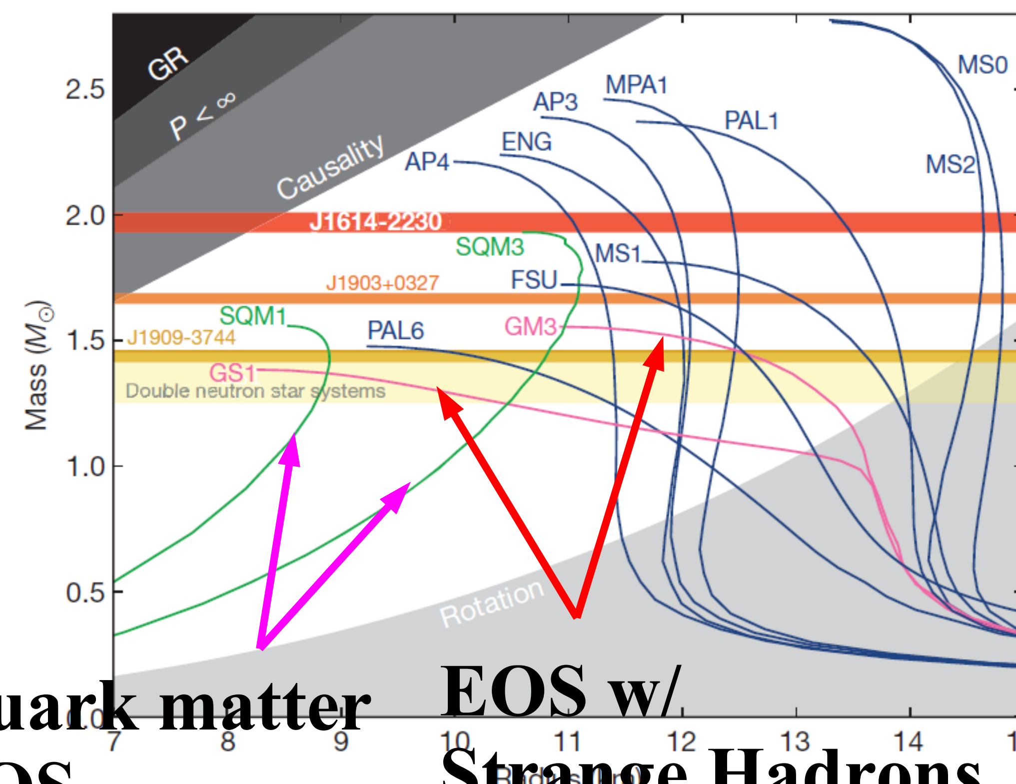




Lattimer (2013)

Massive Neutron Star Puzzle

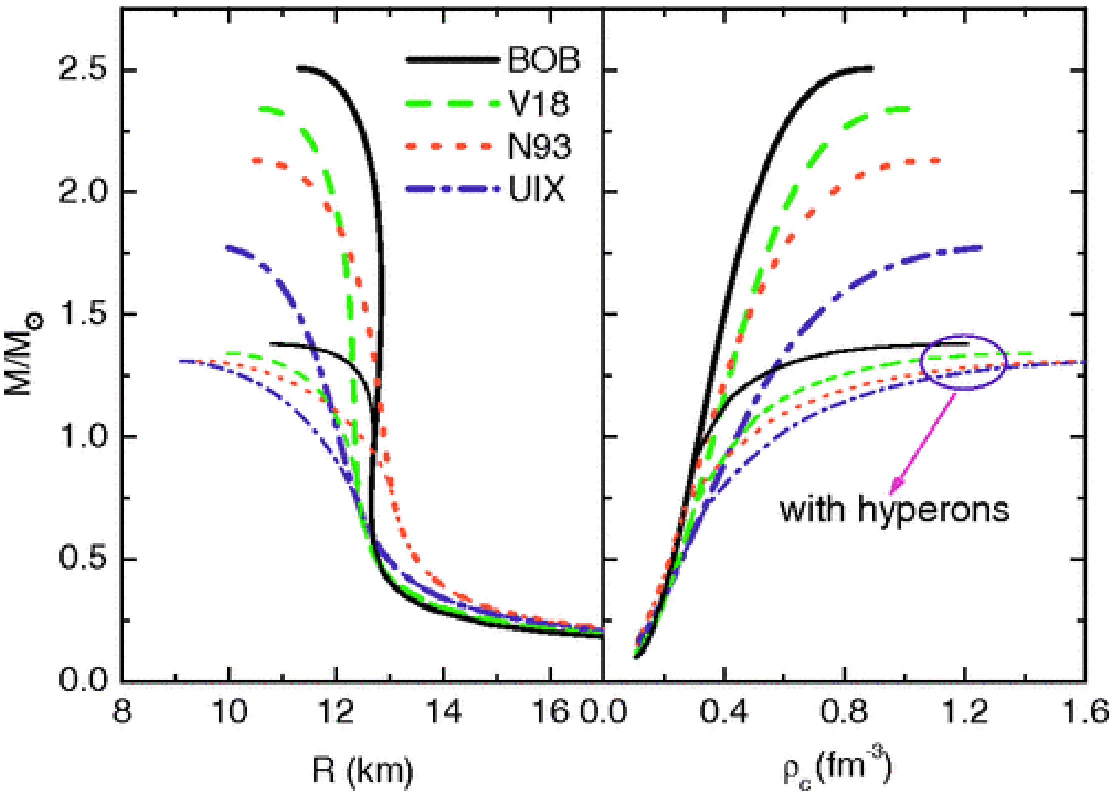
- **Observation of massive neutron stars ($M \sim 2\ M_\odot$)**
  - **PSR J1614-2230 (NS-WD binary), $1.97 \pm 0.04\ M_\odot$**
    Demorest et al., Nature 467('10)1081 (Oct.28, 2010).
    "Kinematical" measurement (Shapiro delay, GR)
    + large inclination angle
  - **PSR J0348+0432 (NS-WS binary), $2.01 \pm 0.04\ M_\odot$**
    Antoniadis et al., Science 340('13)1



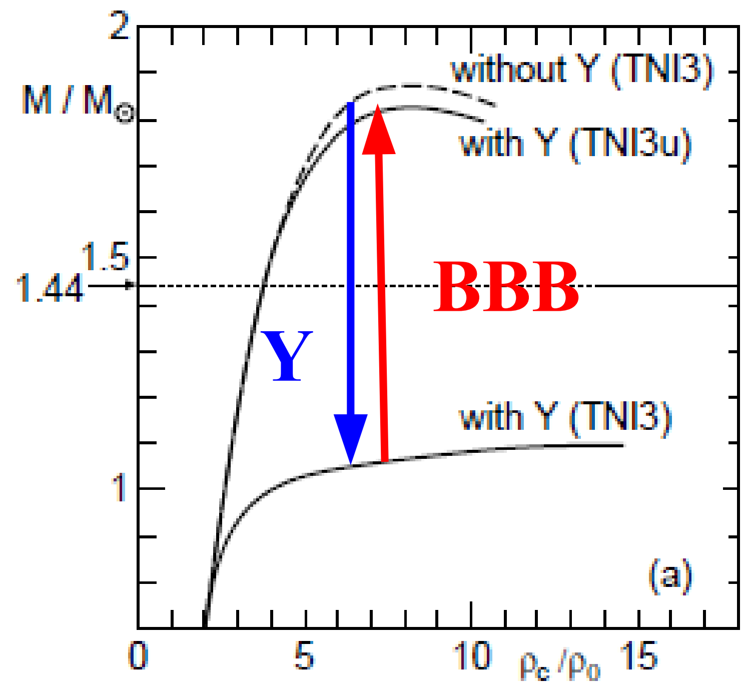
No Exotics in NS ?

Bruckner-Hartree-Fock theory with Hyperons

- **Microscopic G-matrix calculation with realistic NN, YN potential and microscopic (or phen.) 3N force (or 3B force).**
  - **Interaction dep. (V18, N93, ...) is large → Need finite nuclear info.**
    E.Hiyama, T.Motoba, Y.Yamamoto, M.Kamimura / M.Tamura et al.
  - **NS collapses with hyperons w/o 3BF.**



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



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

RMF with Hyperons (Single Λ hypernuclei)

- **RMF for Λ hypernuclei**

x ~ 1/3: R. Brockmann, W. Weise, PLB69('77)167; J. Boguta and S. Bohrmann, PLB102('81)93.
x ~ 2/3: N. K. Glendenning, PRC23('81)2757, PLB114('82)392;
Tensor: Y. Sugahara, H. Toki, PTP92('94)803; H. Shen, F. Yang, H. Toki, PTP115('06)325; J. Mares, B. K. Jennings, PRC49('94)2472.
ρ-dep. coupling: H. Lenske, Lect. Notes Phys. 641('04)147; C. M. Keil, F. Hofmann, H. Lenske, PRC 61('00)064309.
SU(3) or SU(6) (ς, φ): J. Schaffner, C. B. Dover, A. Gal, C. Greiner, H. Stoecker,PRL71('93)1328; Schaffner et al., Ann.Phys.235('94)35; J. Schaffner, I. N. Mishustin, PRC 53('96)1416.
Chiral SU(3) RMF: K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

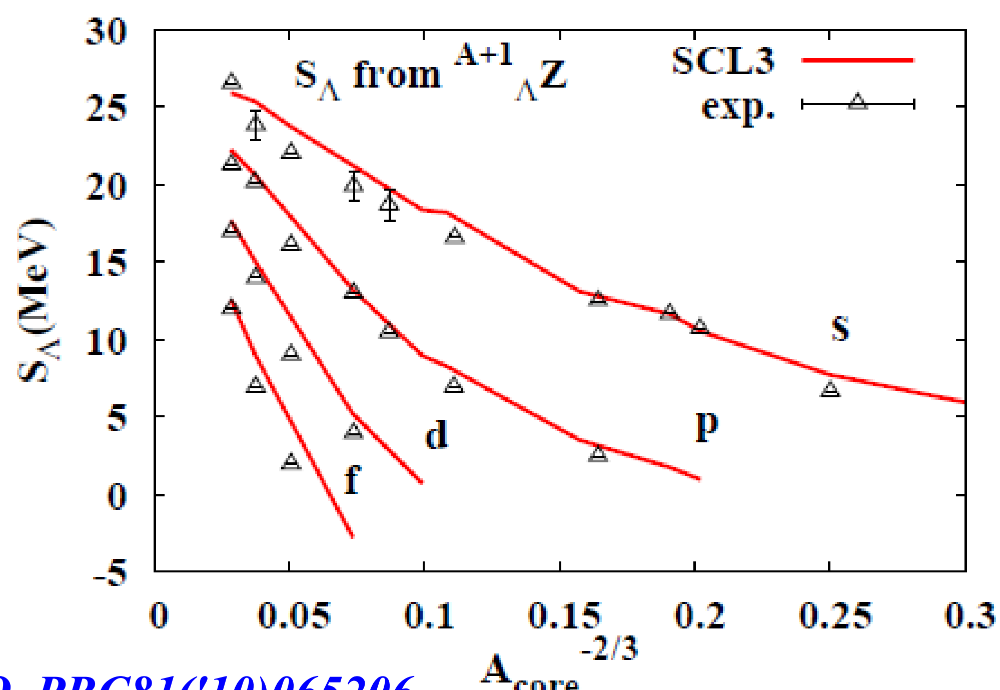
- Sep. E. of Λ is well fitted by $U_\Lambda \sim -30$ MeV $\sim 2/3\ U_N$
- Coupling with mesons

  $x_M = g_{M\Lambda}/g_{MN}$

  quark counting: $x_\sigma \sim 2/3$

  π exchanges: $x_\sigma \sim 1/3$

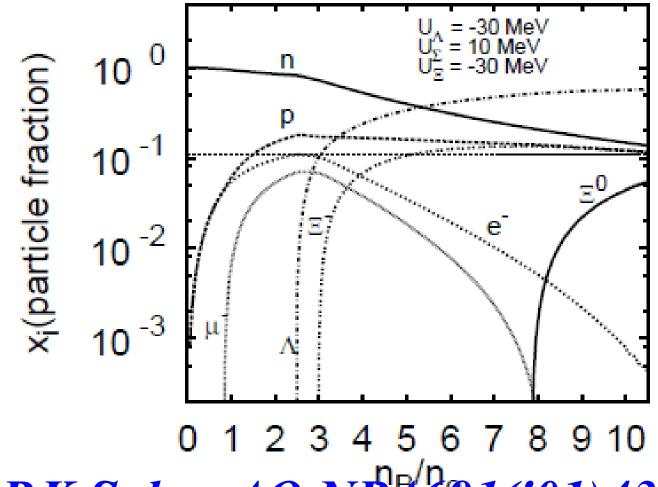
  → Which is true ?



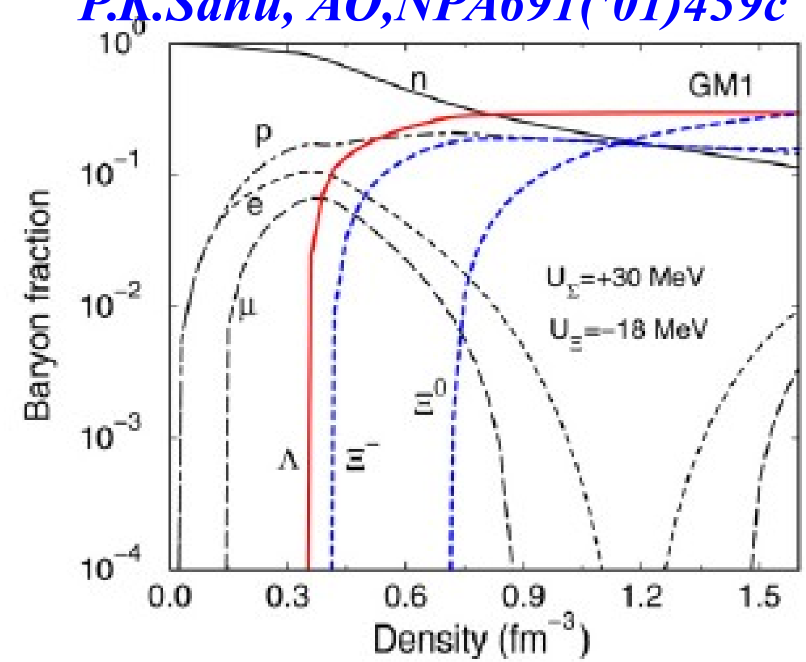
K. Tsubakihara, H. Maekawa, H. Matsumiya, AO, PRC81('10)065206.

Hyperon Composition in Dense Matter

- **Hyperon start to emerge at (2-3)ρ_0 in Neutron Star Matter !**
- **Hyperon composition in NS is sensitive to Hyperon potential.**
  - **U_Λ ~ -30 MeV: Well-known**
  - **U_Ξ ~ -(12-15) MeV**
    (K^-,K^+) reaction, twin hypernuclei
    P. Khaustov et al. (E885),PRC61('00)054603;
    S. Aoki et al., PLB355('95)45.
  - **U_Σ~ -30 MeV (Old conjecture)**
    → Σ- appears prior to Λ
  - **U_Σ > 0 (repulsive) → No Σ in NS**
    Σ atom (phen. fit), QF prod.
    S. Balberg, A. Gal, NPA625('97)435;
    H. Noumi et al., PRL89('02)072301;
    T. Harada, Y. Hirabayashi, NPA759('05)143;
    M. Kohno et al. PRC74('06)064613.



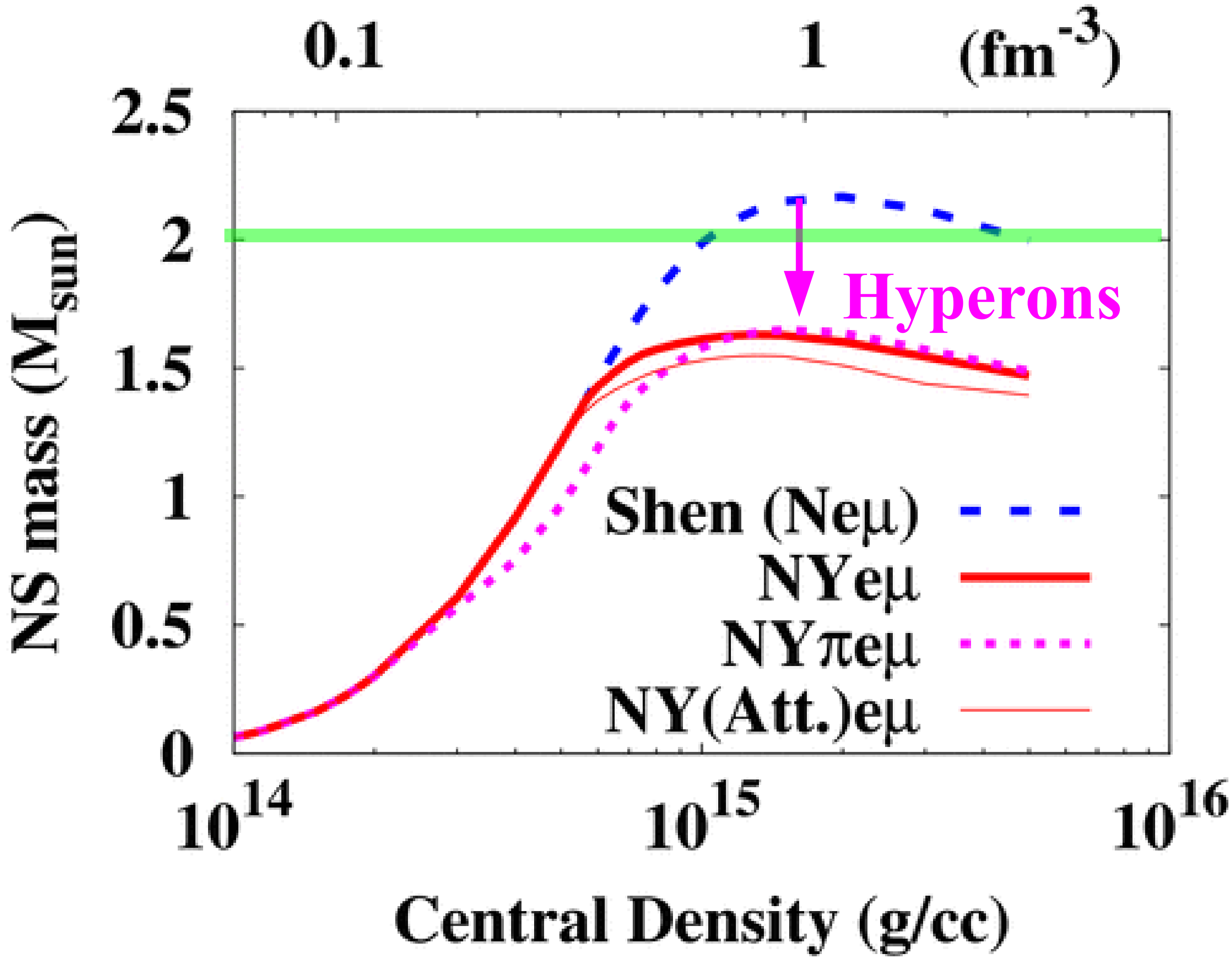
P.K.Sahu, AO,NPA691('01)439c



J. Schaffner-Bielich, NPA804('08)309.

NS M-R Relation in RMF with Hyperons

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



c.f. H.Shen+('09) → n, p, Λ EOS

Summary of Part I

- **Neutron star can be regarded as a gigantic nucleus**
  - **$M \sim 1.4\ M_\odot$, $R \sim 10$ km → Density $\sim (1\text{-}3)\ \rho_0$**
- **Some of NS masses have been obtained precisely.**
  - **Kepler orbit + General Relativity corrections → m_1, m_2**
  - **Two NSs are found to have $M \sim 2\ M_\odot$ recently.**
    PSR J1614-2230, PSR J0348+0432
- **NS radii are more difficult to measure, and model dependent.**
  - **Three methods: Surface emission, Eddington limit, Redshift.**
  - **Conservative estimate: $R_{NS} = (8\text{-}15)$ km.**
- **Nuclear matter EOSs have been studied in various ways.**
  - **Microscopic calc. (starting from bare NN force),**
    Phen. model calc. (using effective NN force).
  - **Many of them with hyperons predict NS max. mass < 2 $M_\odot$.**

Thank you for your attention !
See you 15(?) minutes later.

Contents

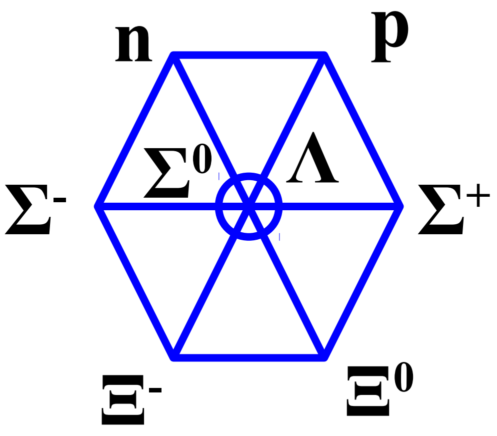
- Introduction
- Part I : Basics of Neutron Star Physics
  - Neutron star mass & radius observations
  - Nuclear matter EOS and neutron stars
  - Massive Neutron Star Puzzle
- Part II : Hypernuclear Physics & Neutron Stars
  - Hypernuclear Physics : Implications from Experiments
  - What is necessary to solve massive NS puzzle ?
  - Recent Attempts toward the massive NS puzzle
- Summary

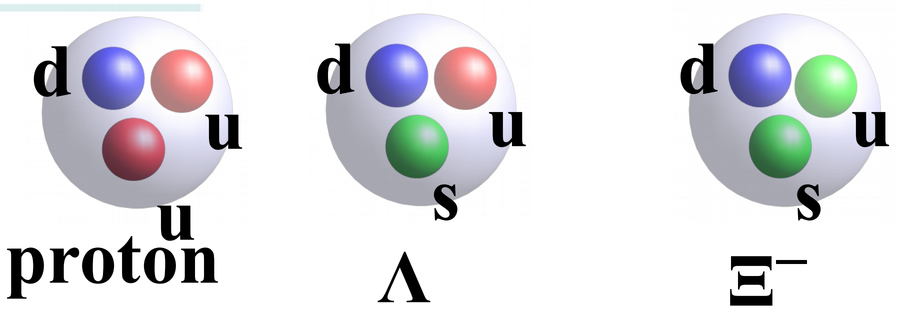
Hypernuclear Physics Implications from Experiments

Hyperons (Baryons with Strangeness)

- **Ground state baryon $SU(3)_f$ octet (J^π=1/2+)**

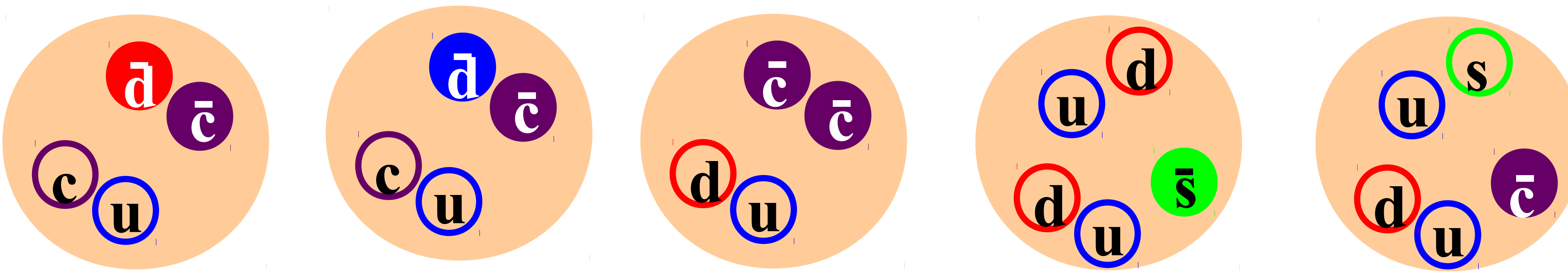
Baryon	M(Mev)	S	Comp.
n	940	0	udd
p	938	0	uud
Λ	1116	-1	$(uds-dus)/\sqrt{2}$
Σ^+	1189	-1	uus
Σ^0	1193	-1	$(uds+dus)/\sqrt{2}$
Σ^-	1197	-1	dds
Ξ^0	1315	-2	uss
Ξ^-	1321	-2	dss





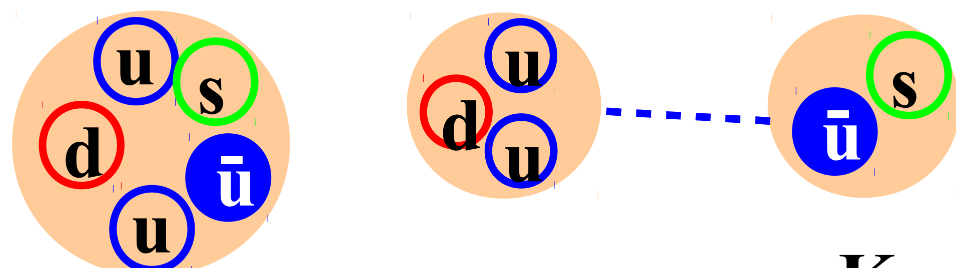
Exotic Hadrons

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

Λ (1405)

$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q'=U\,q\ (U \in SU(3))$**
- **Diquark $D_i = \varepsilon_{ijk}\, q_j\, q_k \to D' = D\,U^+$**
- **Baryon octet $B_{ij} = D_j\, q_i \to B'=UBU^+$**

$$\begin{pmatrix} [ds]u & [su]u & [ud]u \\ [ds]d & [su]d & [ud]d \\ [ds]s & [su]s & [ud]s \end{pmatrix} = \begin{pmatrix} \frac{\Lambda}{\sqrt{6}} + \frac{\Sigma^0}{\sqrt{2}} & \Sigma^+ & p \\ \Sigma^- & \frac{\Lambda}{\sqrt{6}} - \frac{\Sigma^0}{\sqrt{2}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$SU(3)_f$ transformation

- **Fundamental triplet $(u,d,s)^T = q \to q' = U q$ ($U \in SU(3)$)**
- **Anti-quark $\bar{q} \to \bar{q}' = \bar{q}\, U^+$**
- **Meson octet $M_{ij} = \bar{q}_j q_i \to M' = UMU^+$**

$$\begin{pmatrix} \bar{u}u & \bar{d}u & \bar{s}u \\ \bar{u}d & \bar{d}d & \bar{s}d \\ \bar{u}s & \bar{d}s & \bar{s}s \end{pmatrix} = \begin{pmatrix} \frac{\eta}{\sqrt{6}} + \frac{\pi^0}{\sqrt{2}} & \pi^+ & K^+ \\ \pi^- & \frac{\eta}{\sqrt{6}} - \frac{\pi^0}{\sqrt{2}} & K^0 \\ K^- & \bar{K}^0 & -\frac{2\eta}{\sqrt{6}} \end{pmatrix} = P$$

$$S = \begin{pmatrix} \frac{\sigma}{\sqrt{2}} + \frac{a_0}{\sqrt{2}} & a_0^+ & \kappa^+ \\ a_0^- & \frac{\sigma}{\sqrt{2}} - \frac{a_0}{\sqrt{2}} & \kappa^0 \\ \kappa^- & \bar{\kappa}^0 & \zeta \end{pmatrix} \qquad V = \begin{pmatrix} \frac{\omega}{\sqrt{2}} + \frac{\rho^0}{\sqrt{2}} & \rho^+ & K^{*+} \\ \rho^- & \frac{\omega}{\sqrt{2}} - \frac{\rho^0}{\sqrt{2}} & K^{*0} \\ K^{*-} & \bar{K}^{*0} & \varphi \end{pmatrix}$$

$SU(3)_f$ invariant coupling

- **Baryon-Meson coupling**

$$\mathcal{L}_{\rm BV} = \sqrt{2}\{g_s \,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_D\,{\rm tr}\,(\bar{B}\{M_v, B\}) + g_F\,{\rm tr}\,(\bar{B}[M_v, B])\}$$

$$= \sqrt{2}\{g_s\,{\rm tr}\,(M_v)\,{\rm tr}\,(\bar{B}B) + g_1\,{\rm tr}\,(\bar{B}M_vB) + g_2\,{\rm tr}\,(\bar{B}BM_v)\}$$

- **Assumption**
  - **BM coupling is SU(3) invariant**
  - **N does not couple with $s\bar{s}$ vector meson**

$$g_{\omega\Lambda} = \frac{5}{6}g_{\omega N} - \frac{1}{2}g_{\rho N}, \quad g_{\phi\Lambda} = \frac{\sqrt{2}}{6}(g_{\omega N} + 3g_{\rho N})$$

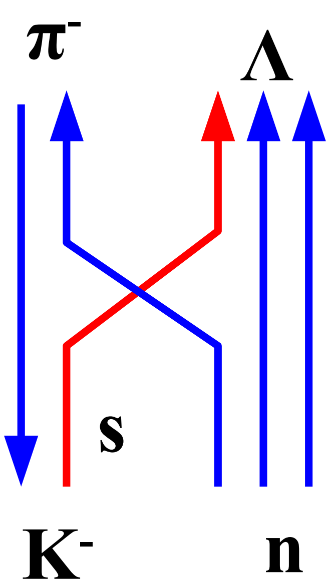
- **Further simplification: $g_{\rho N} = g_{\omega N}/3$ (quark counting)**

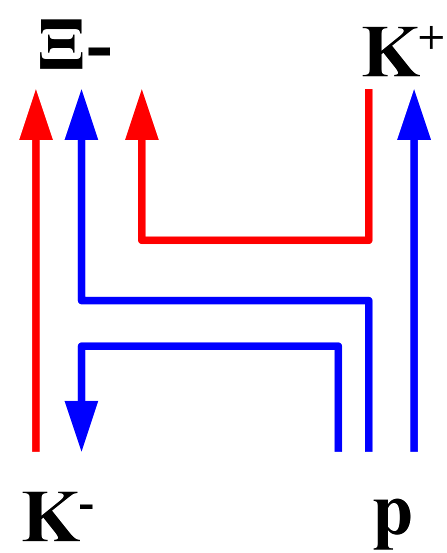
$$g_{\omega N} = g_v, \quad g_{\rho N} = g_v/3, \quad g_{\omega\Lambda} = 2g_v/3, \quad g_{\varphi\Lambda} = \sqrt{2}\,g_v/3$$

Hypernuclear formation

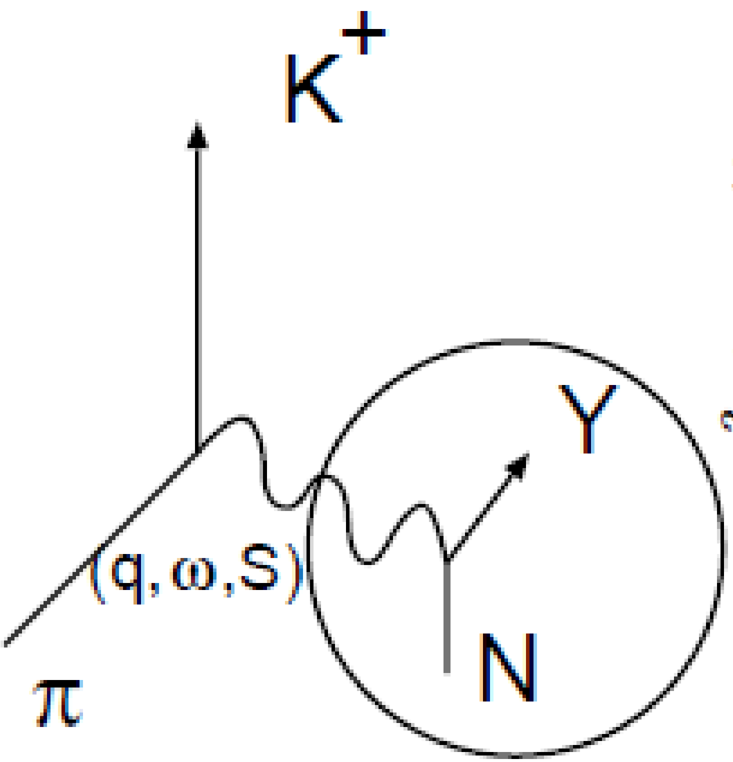
- **(K^-, π), (π, K^+), and (K^-,K^+) reactions on nuclei → Hypernuclei**

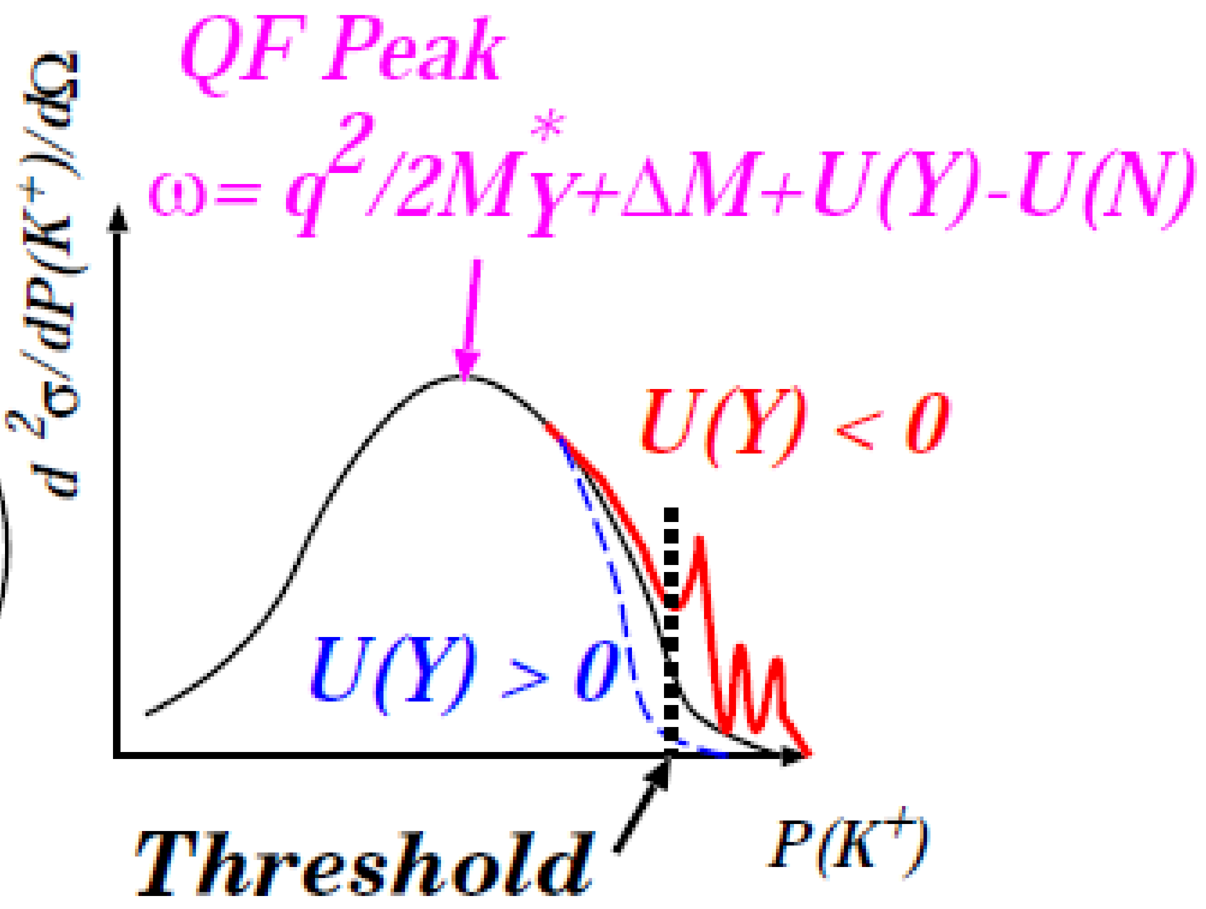
Reaction	Elementary Processes Main Process	 Other Processes
(K^-, π^-)	$K^- n \to \pi^- \Lambda$,	$K^- n \to \pi^- \Sigma^0$, $K^- p \to \pi^- \Sigma^+$
(K^-, π^+)	$K^- p \to \pi^+ \Sigma^-$,	$K^- pp \to \pi^+ \Lambda n$ (n-rich hypernuclear formation)
(π^+, K^+)	$\pi^+ n \to K^+ \Lambda$,	$\pi^+ n \to K^+ \Sigma^0$, $\pi^+ p \to K^+ \Sigma^+$
(π^-, K^+)	$\pi^- p \to K^+ \Sigma^-$,	$\pi^- pp \to K^+ \Lambda n$ (n-rich hypernuclear formation)
(K^-, K^+)	$K^- p \to K^+ \Xi^-$,	$K^- pp \to K^+ \Lambda\Lambda$





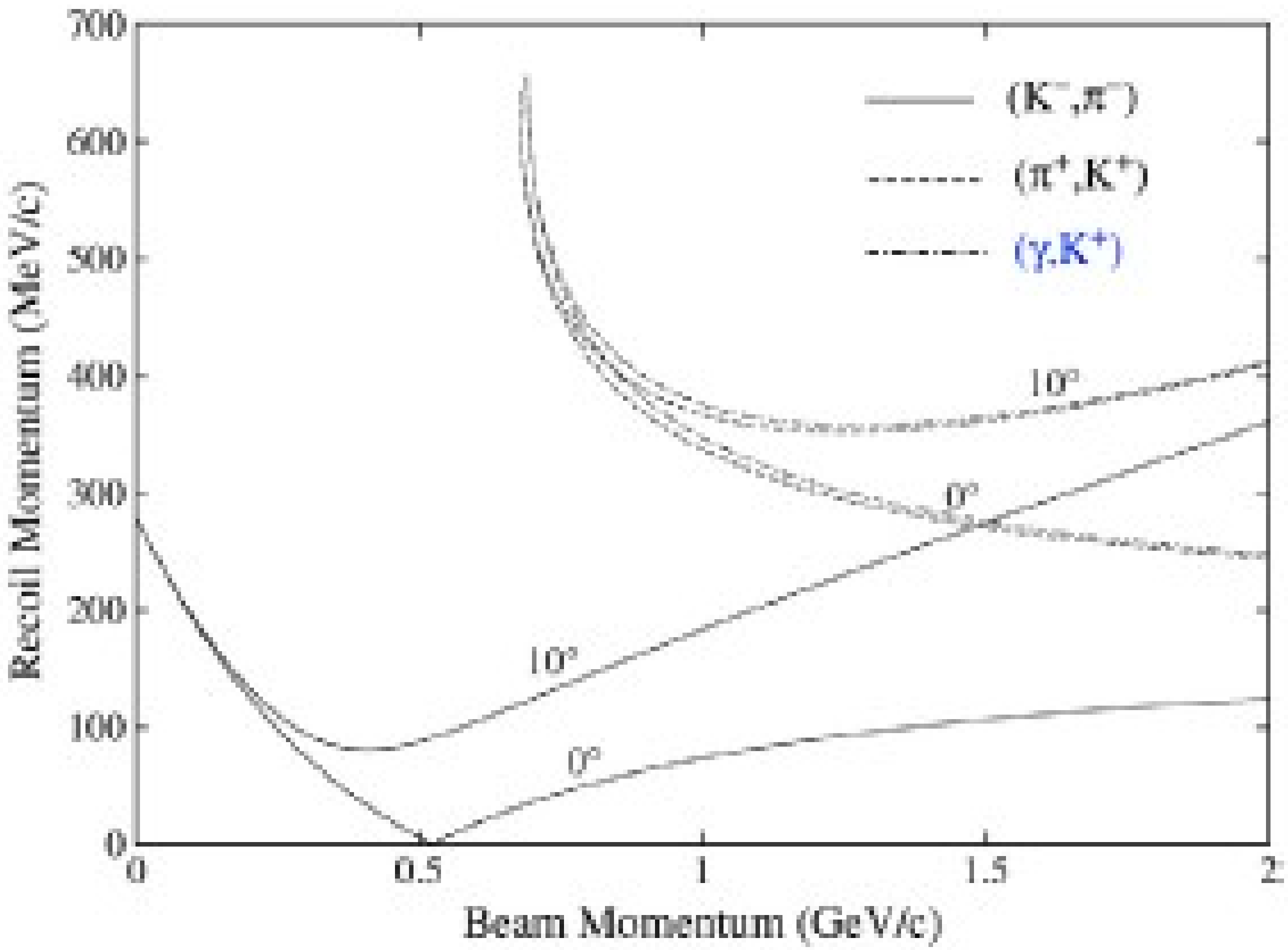
Hypernuclear formation





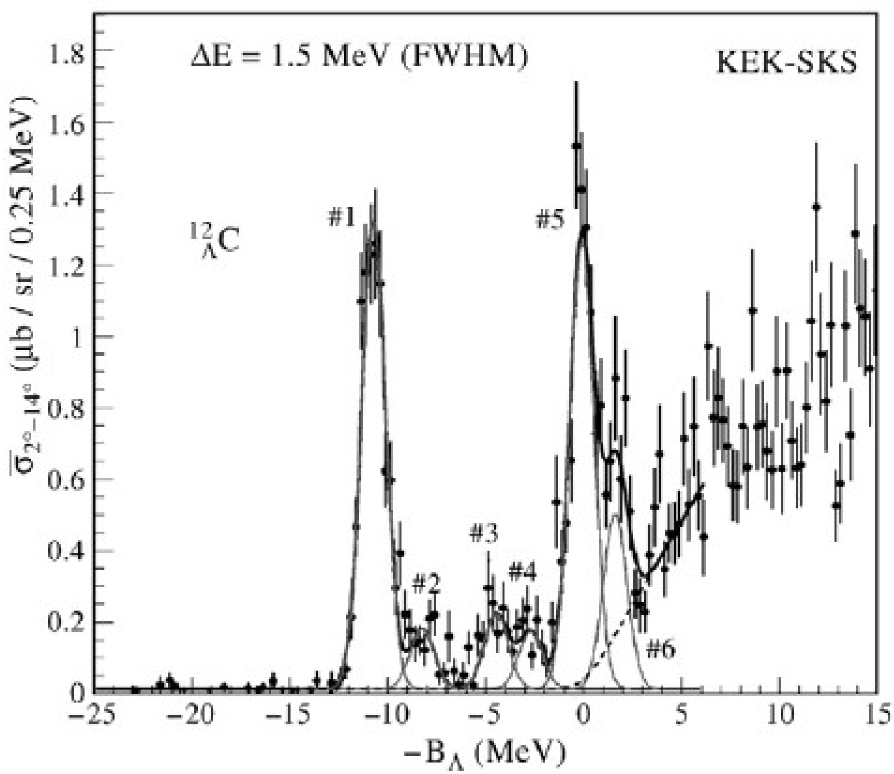
Hypernuclear formation

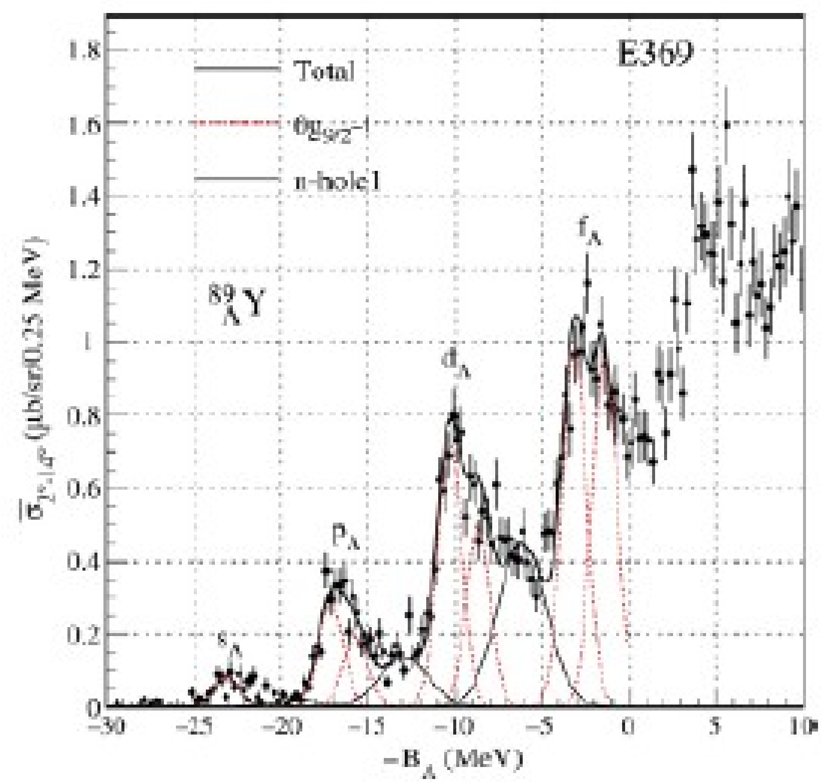
- **(K^-, π^-): Q>0, Small momentum transfer → substitutional reaction**
- **(π, K^+): Q<0, Momentum transfer ~ 300 MeV/c ~ k_F**



Λ hypernuclear formation

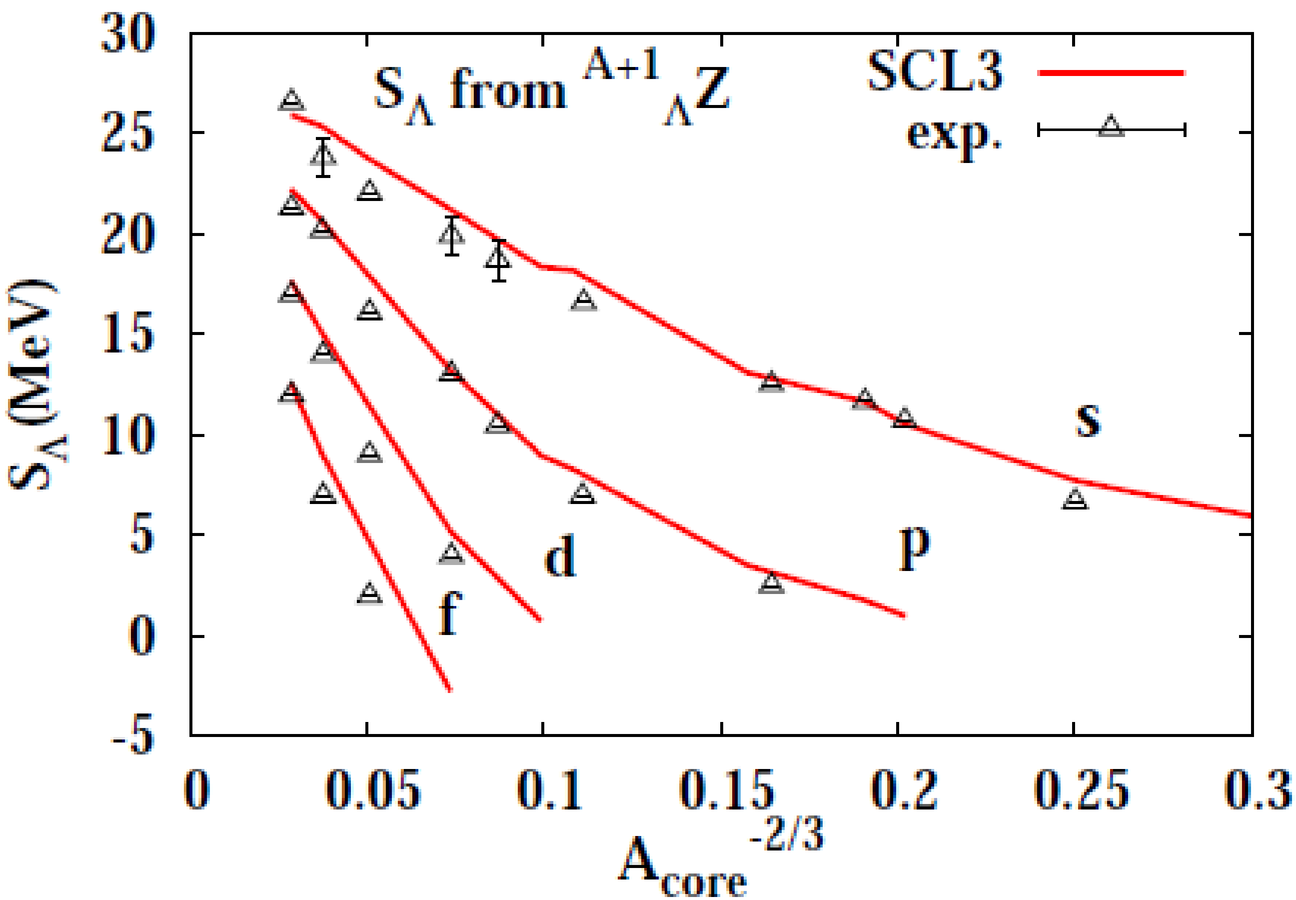
- (π^+, K^+) reactions on nuclei
  - $q \sim k_F \rightarrow$ various s.p. states of Λ are populated

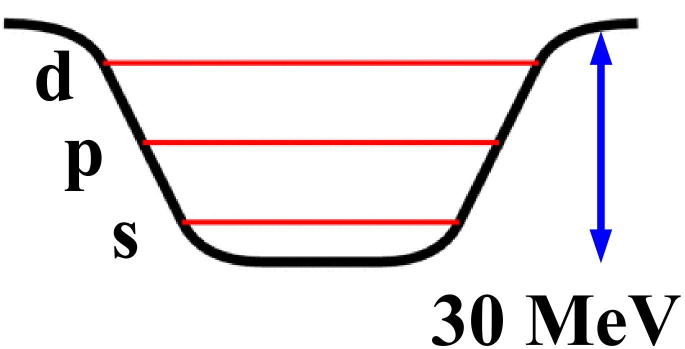




Single particles states of Λ in nuclei

- **Single particle potential depth of Λ is around -30 MeV**
  - **s, p, d, f, … states are clearly seen**
  - **$A_{core}^{-2/3} \propto R^{-2} \propto$ K.E. of Λ**





Σ production in nuclei

- Only one bound state ${}^{4}_{\Sigma}$He (Too light !)
  → Continuum (Quasi-Free) Spectroscopy is necessary
- Cont. Spec. Theory = Distorted Wave Impulse Approx. (DWIA)

$$\frac{d^2\sigma}{dE_K\, d\Omega_K} = \beta \left(\frac{d\sigma}{d\Omega}\right)^{Elem.}_{N\pi\to KY} S(E, \boldsymbol{q})$$

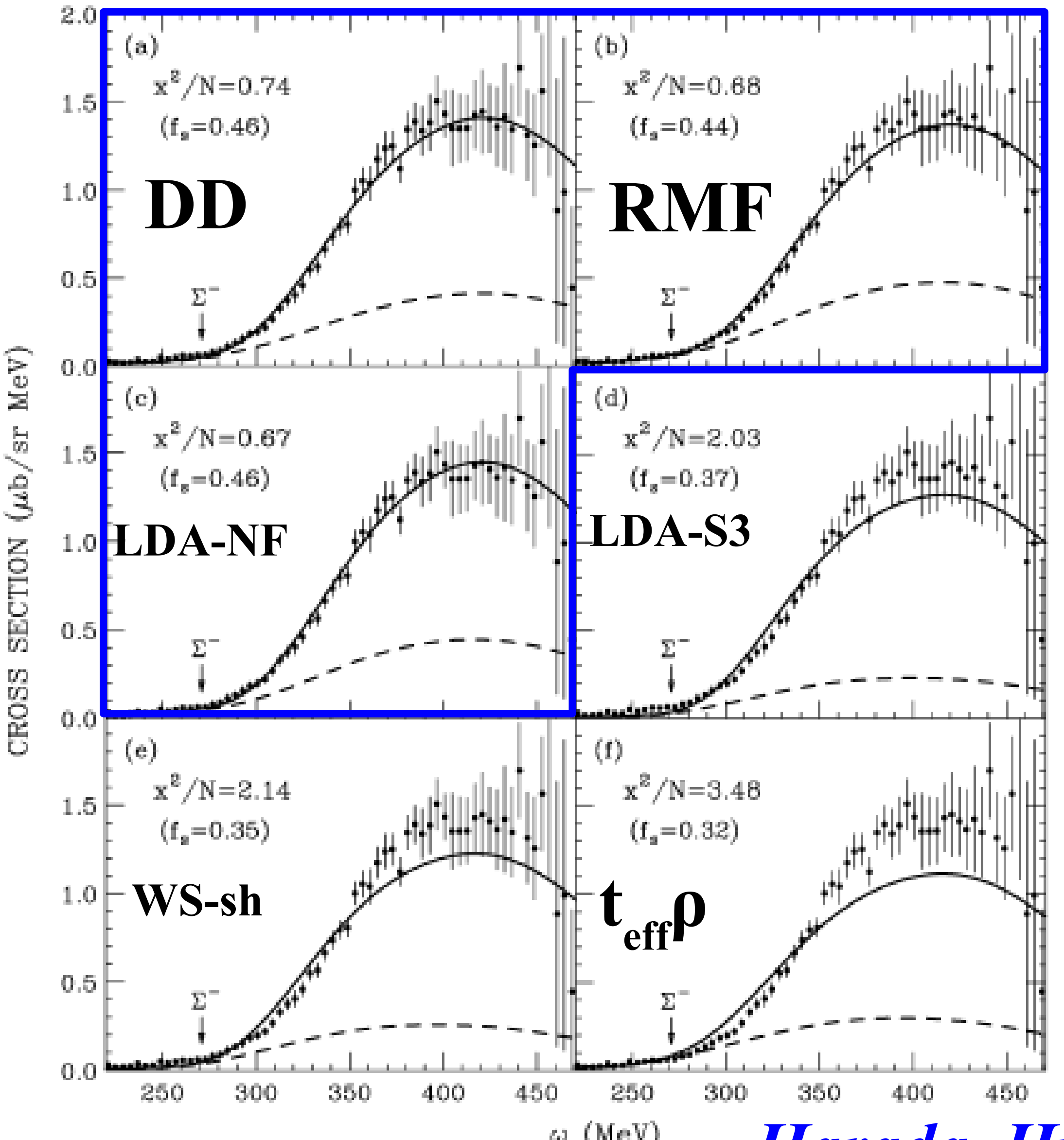
Kinematical Factor — Elem. Cross Sec. — Strength Func.

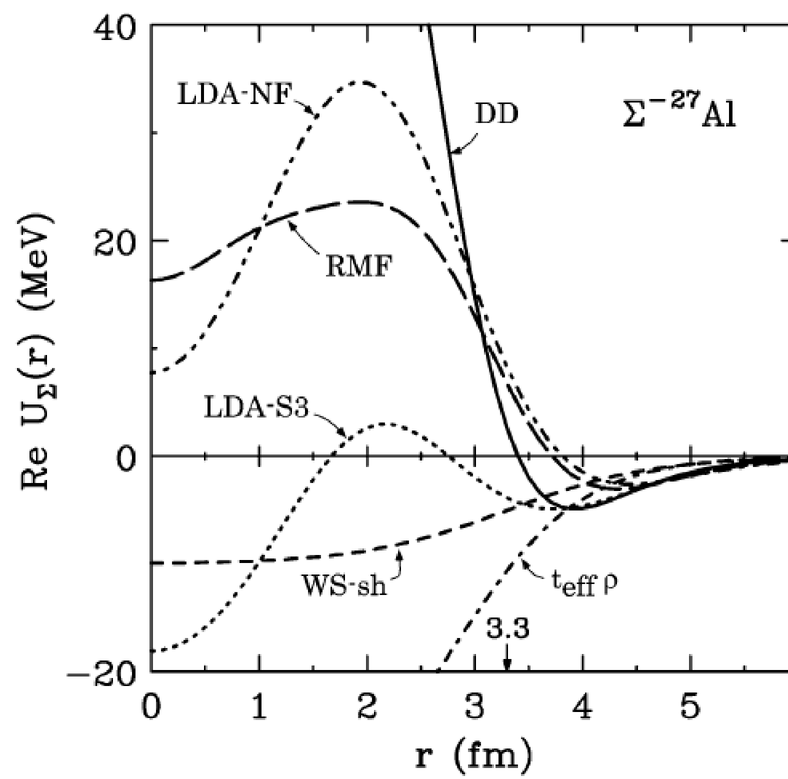
  - Large (ω, q) range → Important to respect On-Shell Kinematics
- Another way: Σ^- atomic shift
  - Atomic shift of Σ^- with O, Mg, Al, S, Si, W, Pb core are measured
- Σ potential in nuclei
  - Isoscalar part: 15-35 MeV repulsion
  - Isovector part: 20-30 % of SU(3) value

Σ production in nuclei

$\chi^2/DOF < 1$

$^{28}Si(\pi^-, K^+)$

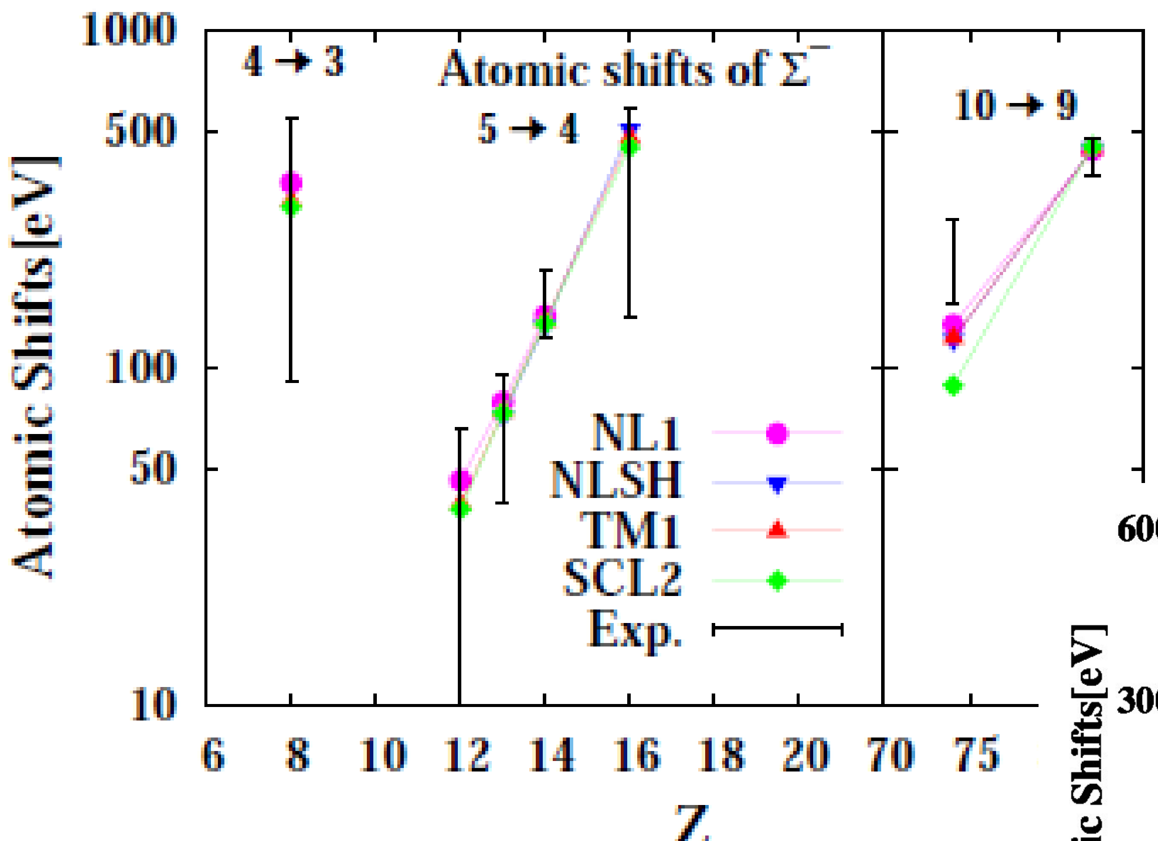


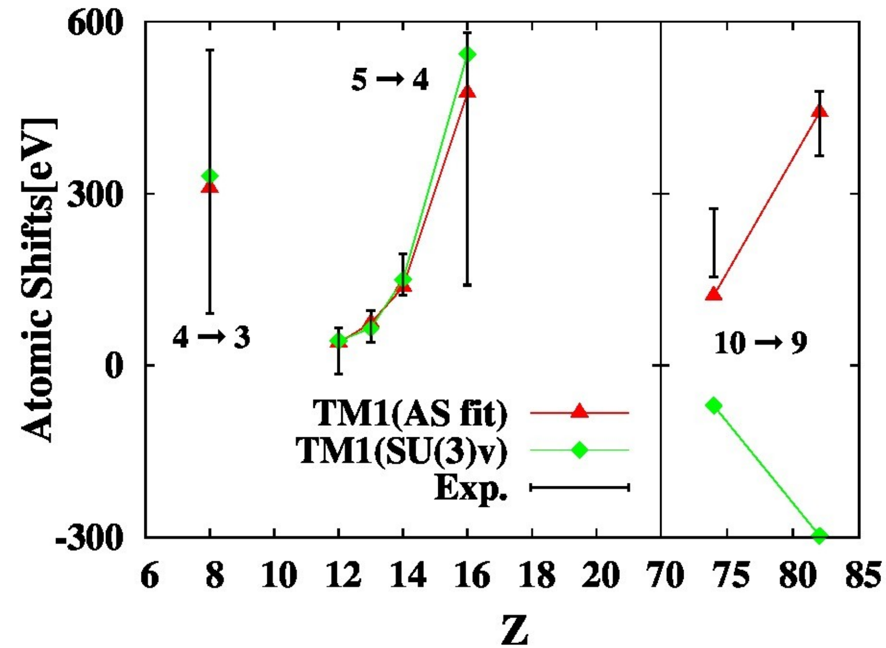


Harada, Hirabayashi ('05)

Data: Noumi et al. ('02); Saha et al. ('04)

Σ- atomic shift



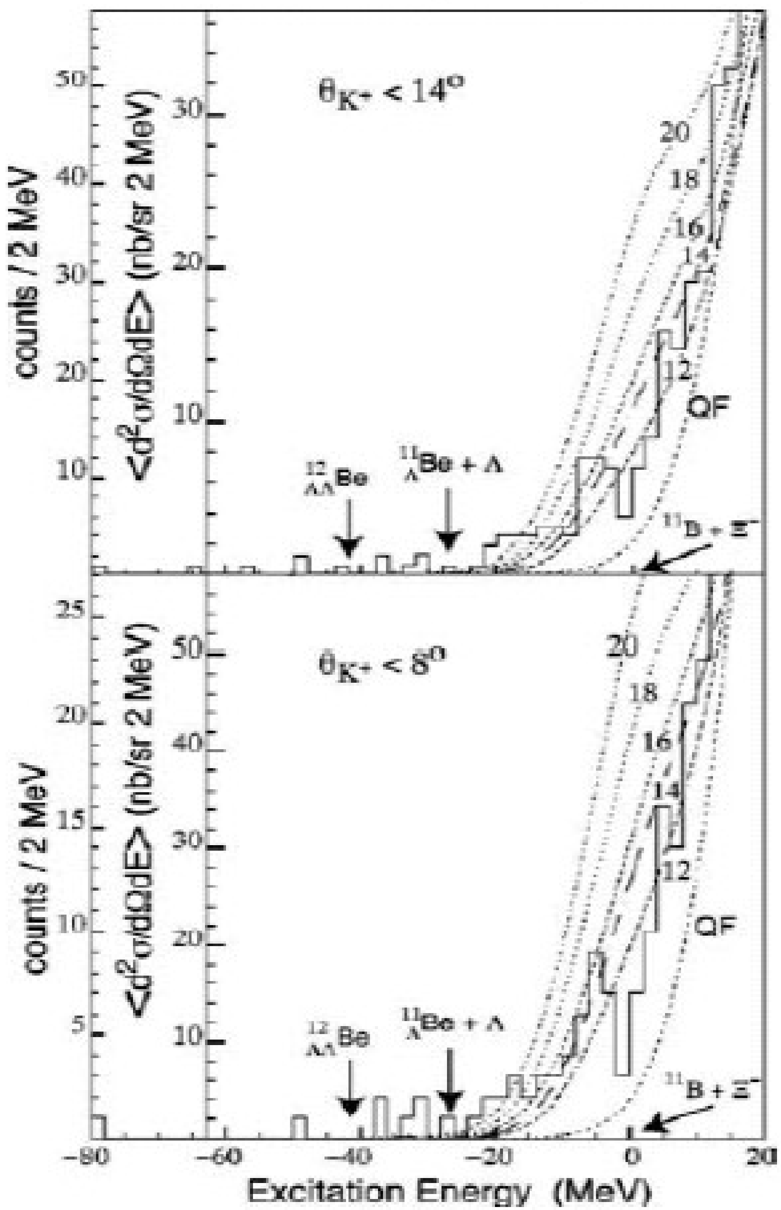


Compiled data: Mares, Friedman, Gal, Jennings ('95)
Calc.: Tsubakihara, Harada, AO: arXiv:1402.0979

Ξ hypernuclear formation

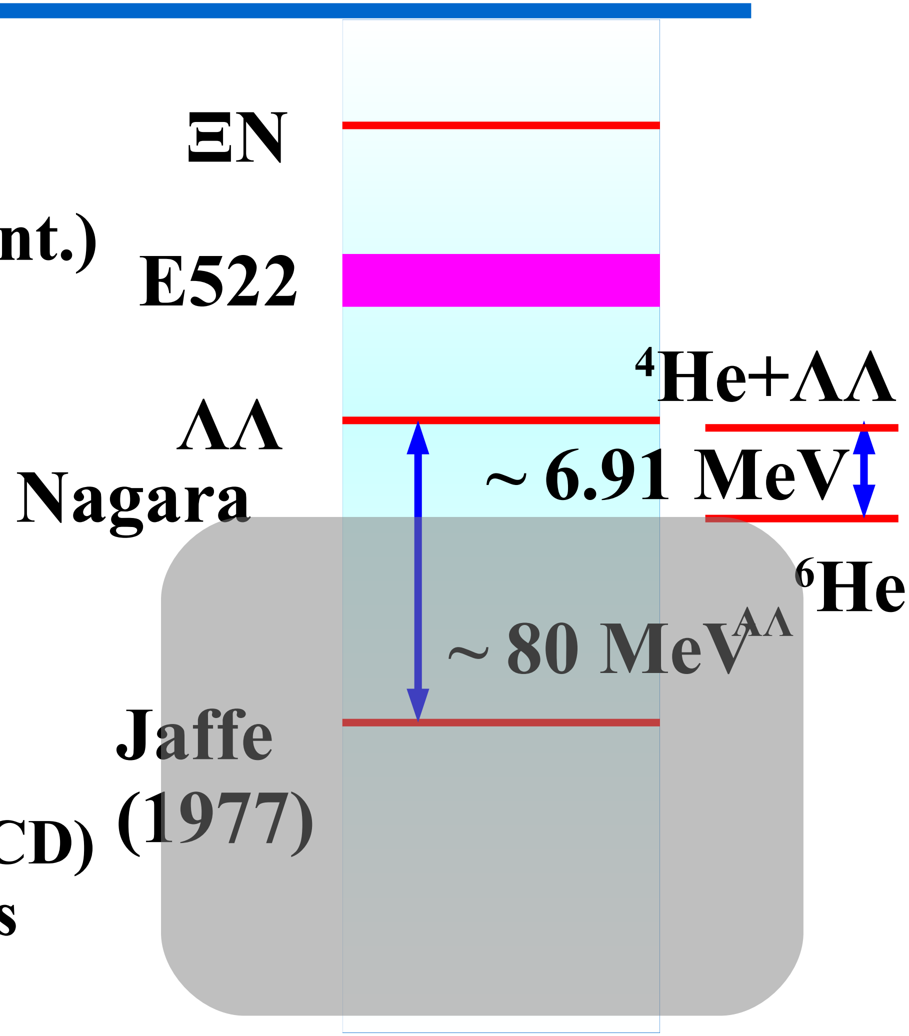
- **Missing mass spectroscopy BNL E885 $^{12}C(K^-,K^+)$**
  Fukuda et al. PRC58('98),1306;
  Khaustov et al. PRC61('00), 054603.
  - **No clear bound states found**
- **Twin hypernuclear formation**
  Aoki et al. PLB355('95),45.
- **Potential depth**
  $U_{\Xi} \sim -14$ MeV

E885 (BNL)



Where is the S=-2 dibaryon (uuddss) "H" ?

- **Jaffe's prediction (1977)**
  → 80 MeV below ΛΛ
  (strong attraction from color mag. int.)
- **Double hypernuclei $_{\Lambda\Lambda}{}^{6}$He (Nagara)**
  → No deeply bound "H"
- **Resonance or Bound "H" ?**
  - **KEK-E522 (Yoon et al., ('07))**
    → "bump" at $E_{\Lambda\Lambda}$ ~ 15 MeV
  - **Lattice QCD (HAL QCD & NPLQCD)**
    → bound H at large ud quark mass
- **How about HIC ?**
  - **RHIC & LHC = Hadron Factory including Exotics**
  - **"H" would be formed as frequently as stat. model predicts.**
    Cho,Furumoto,Hyodo,Jido, Ko, Lee,Nielsen,AO,Sekihara,Yasui,Yazaki (ExHIC Collab.), PRL('11)212001; arXiv:t:1107.1302



Nagara event

- ${}_{\Lambda\Lambda}{}^{6}$He hypernuclei

  Takahashi et al., PRL87('01)212502

  (KEK-E373 experiment)

Lambpha

$m({}^{6}_{\Lambda\Lambda}\mathrm{He}) = 5951.82 \pm 0.54\,\mathrm{MeV}$

$B_{\Lambda\Lambda} = 7.25 \pm 0.19^{+0.18}_{-0.11}\,\mathrm{MeV}$

$\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}\,\mathrm{MeV}$

(assumed $B_{\Xi^-} = 0.13$ MeV)

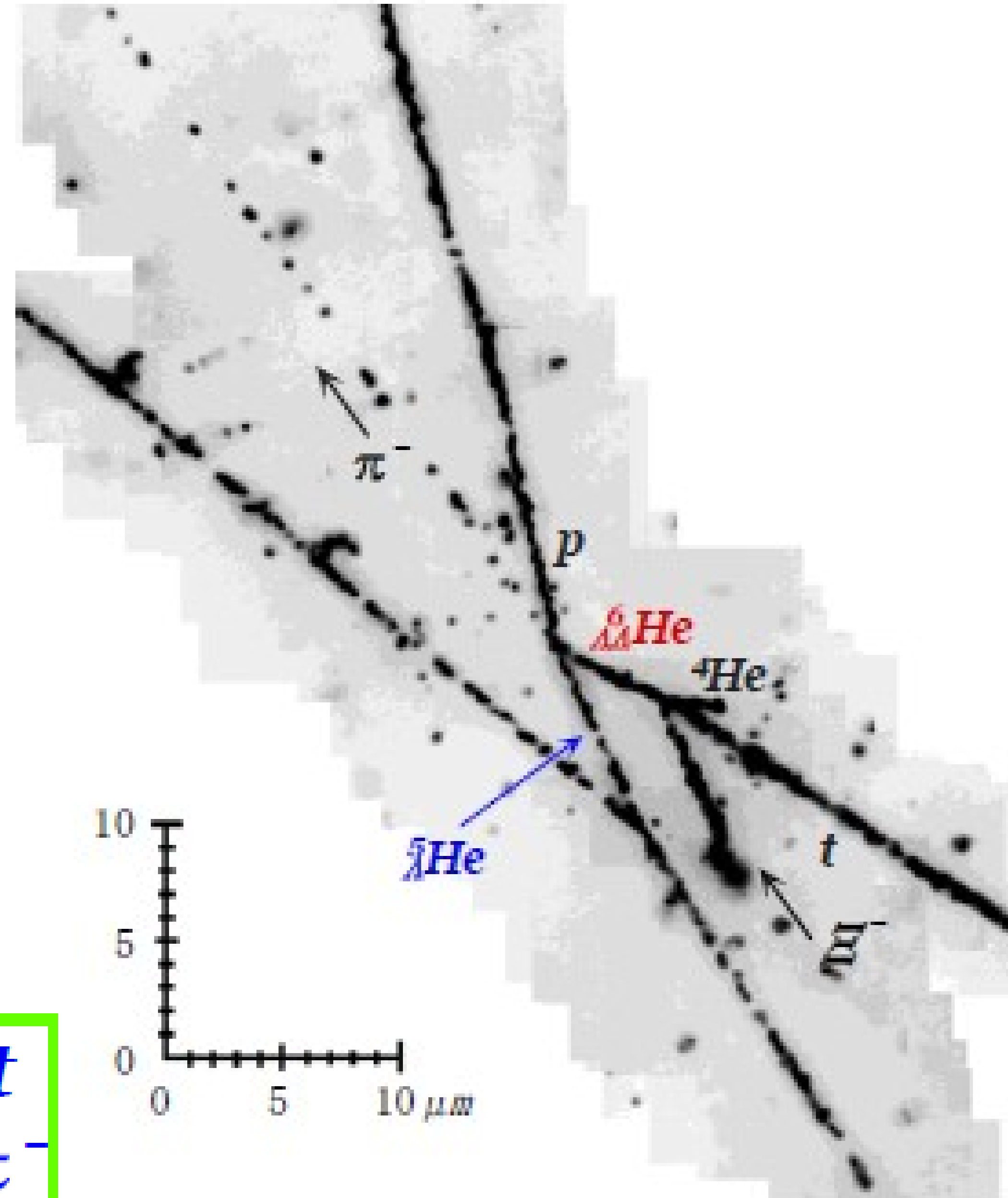
→ $B_{\Lambda\Lambda}$= 6.91 MeV

(PDG modified(updated)

Ξ^- mass)

$$\Xi^- + {}^{12}\mathrm{C} \longrightarrow {}^{6}_{\Lambda\Lambda}\mathrm{He} + {}^{4}\mathrm{He} + t$$

$$ {}^{6}_{\Lambda\Lambda}\mathrm{He} \longrightarrow {}^{5}_{\Lambda}\mathrm{He} + p + \pi^- $$

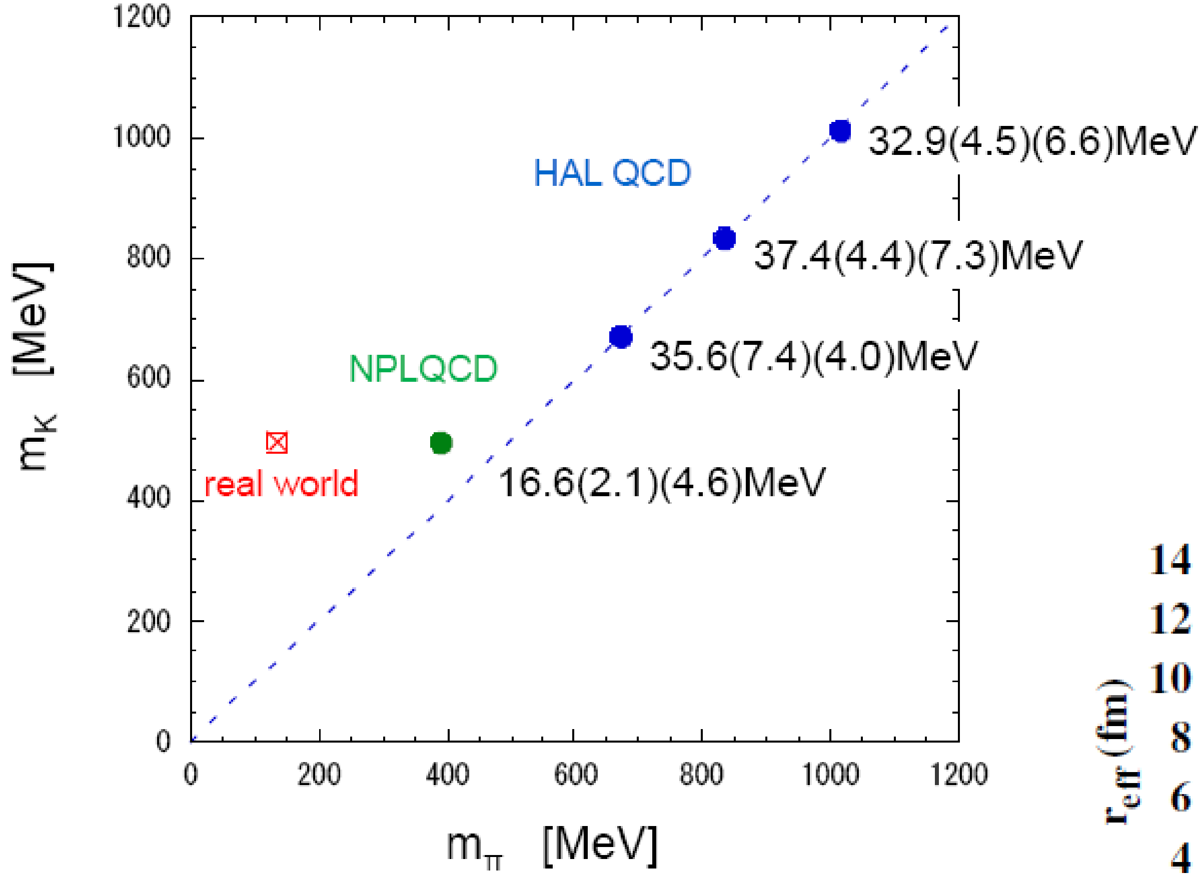


ΛΛ interaction models

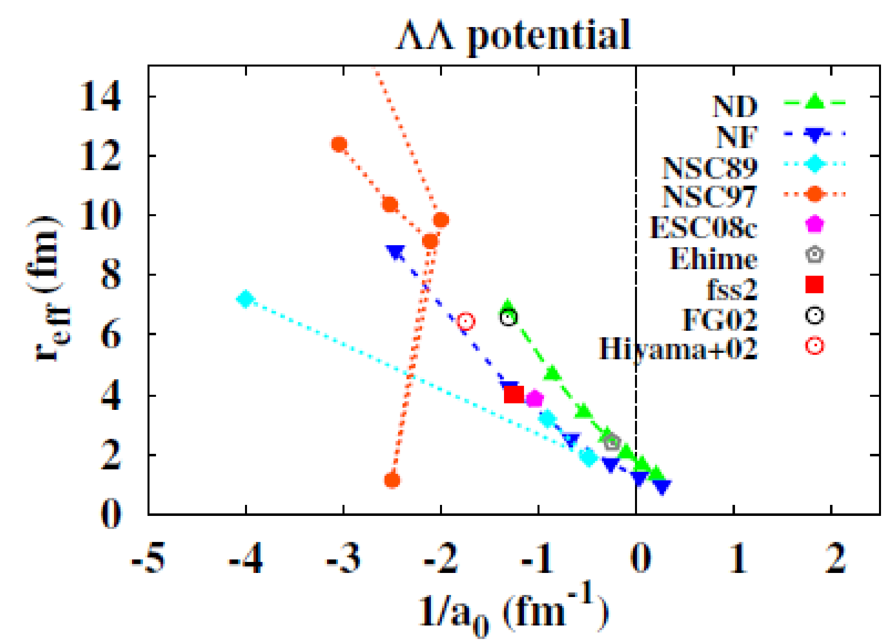
- Boson exchange potentials
  - Nijmegen potentials: various versions *Rijken et al., ('77-'10)*
    Hard core: Nijmegen model D & F (ND, NF)
    Soft core: Nijmegen soft core '89 & '97 (NSC89, NSC97)
    Extended soft core: ESC08
  - Ehime potential: would be too attractive. *Ueda et al., ('98)*
    Ehime fits old double Λ hypernucl. data, $\Delta B_{\Lambda\Lambda}$ =4 MeV
- Quark cluster model
  - fss2 *Fujiwara, Kohno, Nakamoto, Suzuki ('01)*
    Short range repulsion from quark Pauli blocking & OGE
    Core is softer due to non-locality
- Modified Nijmegen potentials fitting Nagara data.
  Filikhin, Gal ('02), Hiyama et al.('02)
  - Potential Fitting Nagara data $\Delta B_{\Lambda\Lambda}$ =1.0 MeV

Lattice QCD predicts bound "H"

- **"H" bounds with heavy π (M_π > 400 MeV)**



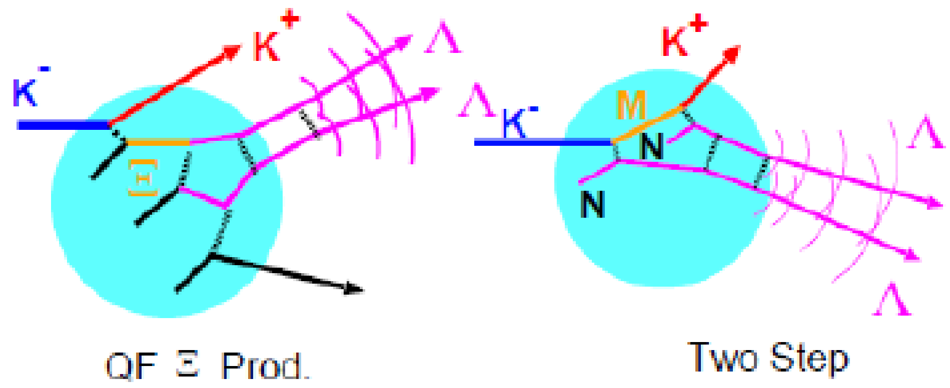
NPLQCD Collab., PRL 106 (2011) 162001;
HAL QCD Collab.,PRL 106 (2011) 162002

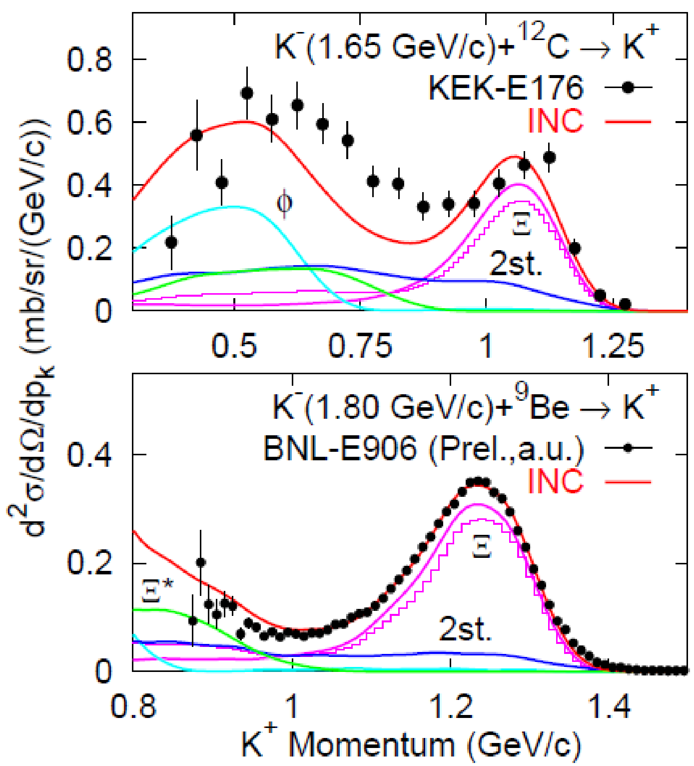


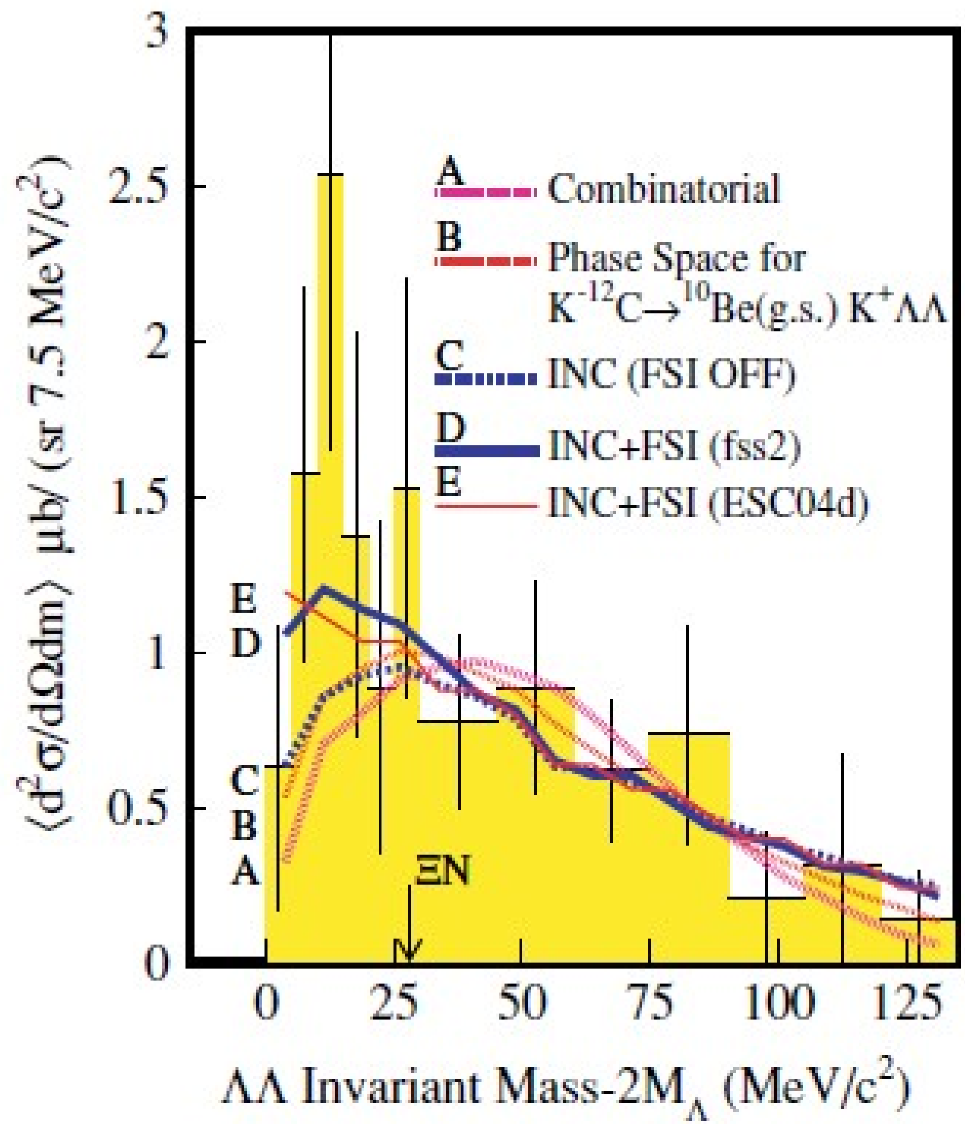
Models

ΛΛ correlation from (K⁻,K⁺ΛΛ) reaction

- **Enhancement at ~ 2 M(Λ)+ 10 MeV,**







C.J.Yoon, …, (KEK-E522),AO, PRC75 (2007) 022201(R)
J. K. Ahn et al. (KEK-E224).

"Stars" of Hyperon Potentials (A la Michelin)

- $U_\Lambda(\rho_0) \sim -30$ MeV
  - *Bound State Spectroscopy + Continuum Spectroscopy*
- $U_\Sigma(\rho_0) > +15$ MeV
  - Continuum (Quasi-Free) spectroscopy
  - Atomic shift data (attractive at surface) should be respected.
- $U_\Xi(\rho_0) \sim -14$ MeV
  - No confirmed bound state, No atomic data,
High mom. transf., ... → Small Potential Deps.
  - Continuum low-res. spectrum shape → – 14 MeV
- $V_{\Lambda\Lambda}$: Weakly attractive.

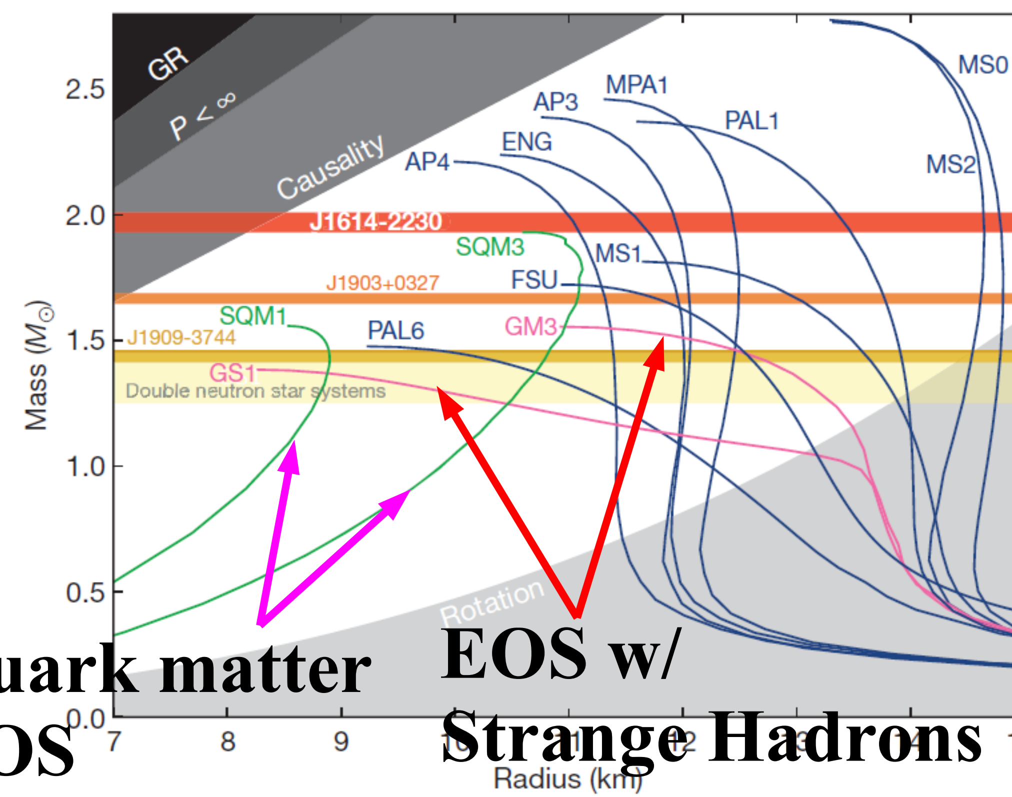
But these potentials lead to collapse of massive NS

Toward the Solution of Massive Neutron Star puzzle

Massive Neutron Star Puzzle

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

No Exotics in NS ?



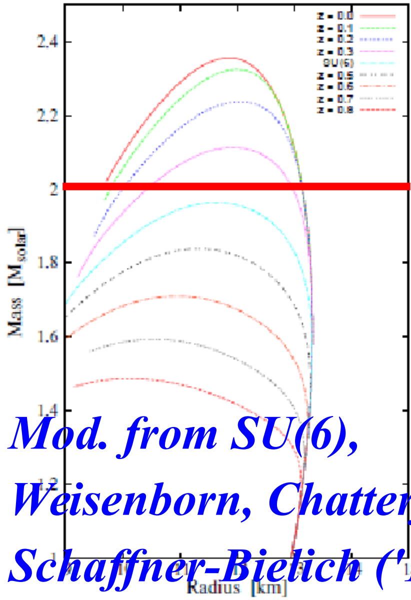
Quark matter EOS

EOS w/ Strange Hadrons

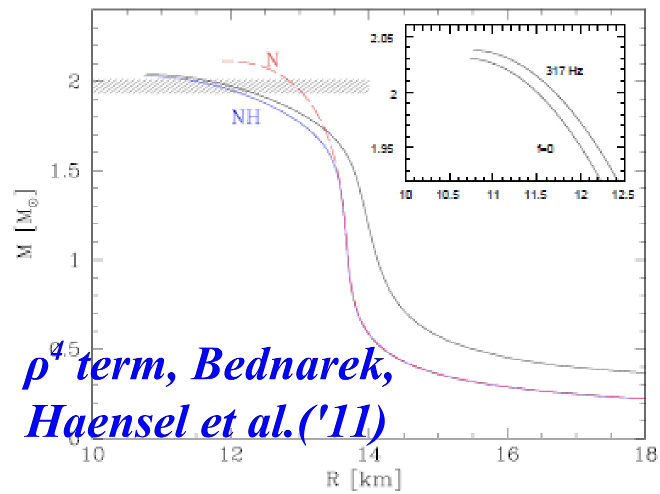
Possible Solutions to Massive NS puzzle

- **Proposed "Solutions" of Massive NS puzzle**
  - **Modification of YN interaction**
    Weisenborn, Chatterjee, Schaffner-Bielich ('11); Jiang, Li, Chen ('12); Tsubakihara, AO ('13)
  - **Introducing BBB repulsion**
    Bednarek, Haensel et al.('11); Miyatsu, Yamamuro, Nakazato ('13); Tsubakihara, this session.
  - **Early crossover transition to quark matter**
    Masuda, Hatsuda, Takatsuka ('12)
  - **Choose Stiff EOS for nuclear matter** *Tsubakihara, AO ('14)*

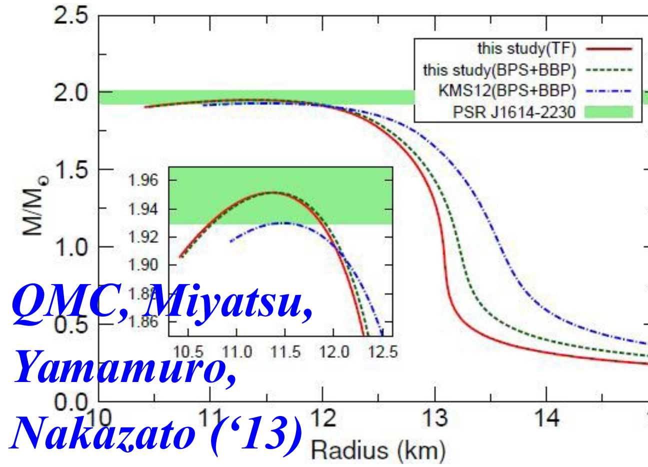
NS matter EOS with hyperons



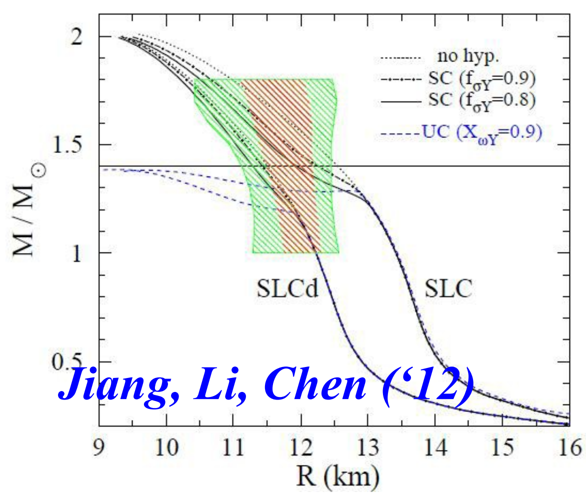
Mod. from SU(6), Weisenborn, Chatterjee, Schaffner-Bielich ('11)



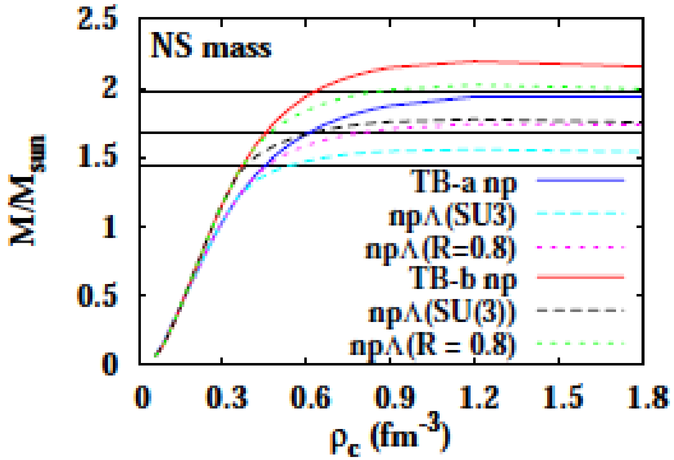
ρ^4 term, Bednarek, Haensel et al.('11)



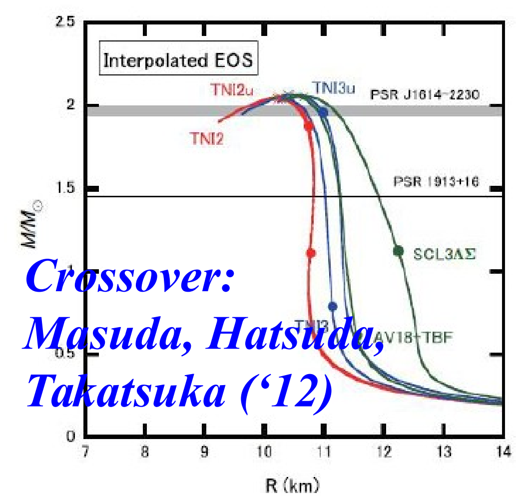
QMC, Miyatsu, Yamamuro, Nakazato ('13)



Jiang, Li, Chen ('12)



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

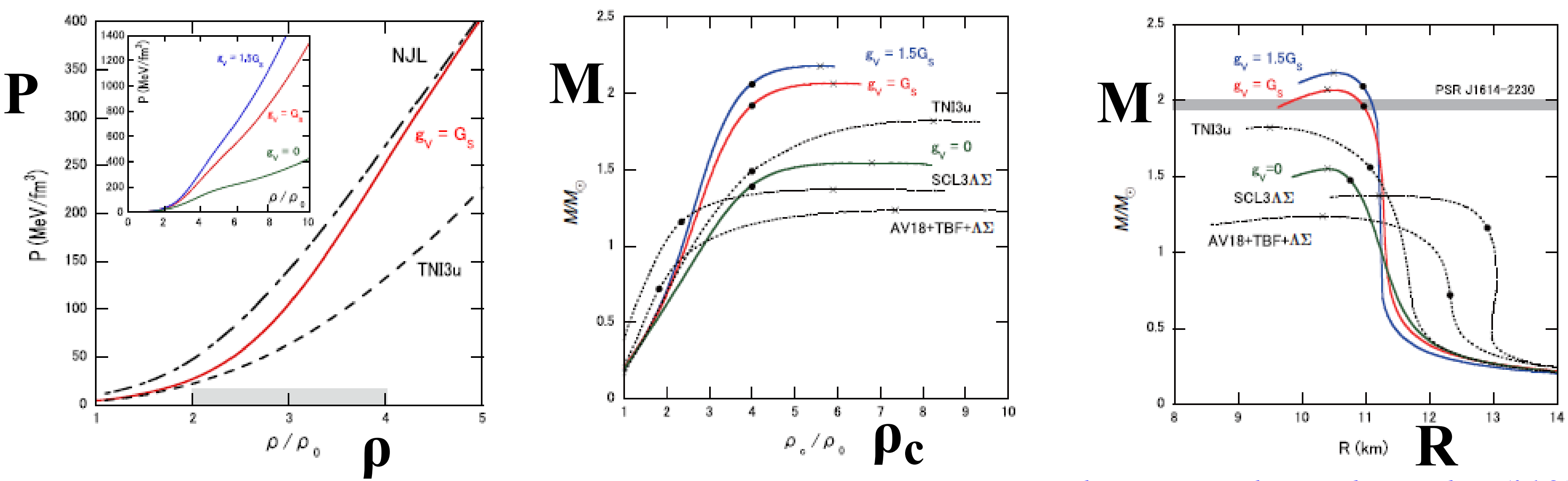


Crossover: Masuda, Hatsuda, Takatsuka ('12)

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

Early crossover transition to quark matter

- **A possible solution of the massive NS puzzle = quark matter**
  K. Masuda, T. Hatsuda, T. Takatsuka, ApJ764('13)12
  - **With large vector qq coupling, finite density QCD phase transition can be crossover.**
  - **Crossover transition → EOS can be stiffer and can support 2 $M_\odot$**
  - **Transition density = (2-4) ρ_0 .**
    Is it consistent with heavy-ion collisions ?



Masuda, Hatsuda, Takatsuka ('13)

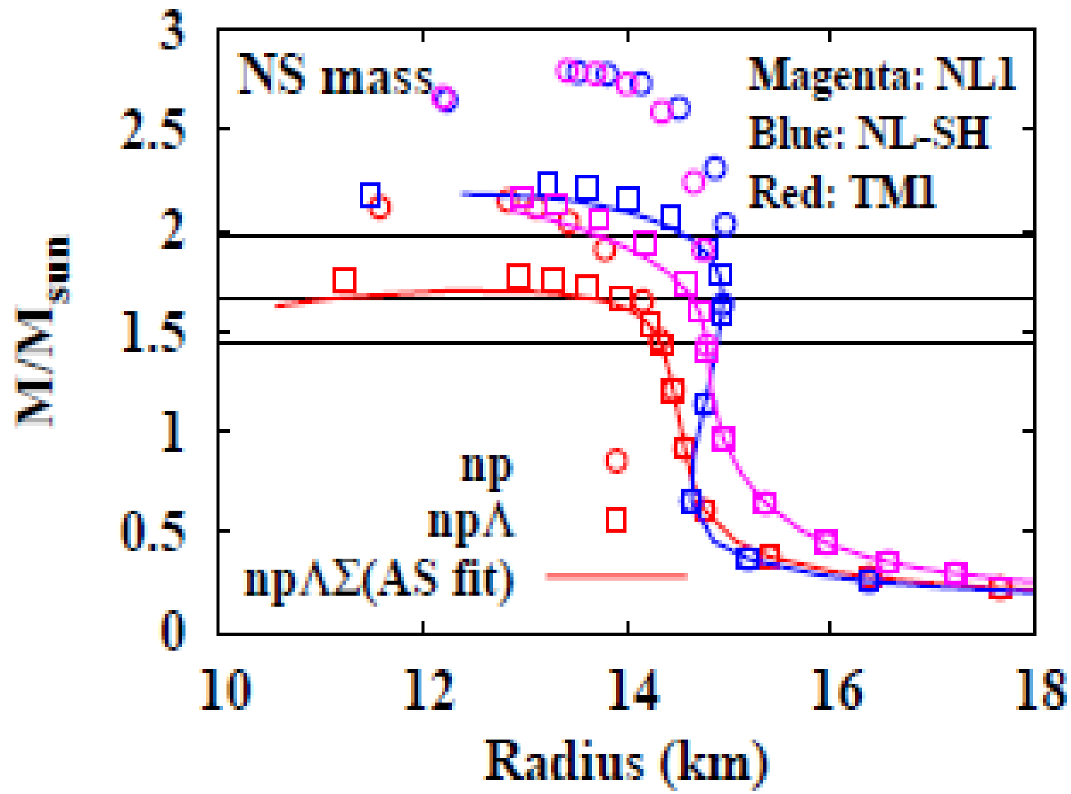
Possible Solutions to Massive NS puzzle

- **Proposed "Solutions" of Massive NS puzzle**
  - **Modification of YN interaction**
    Weisenborn, Chatterjee, Schaffner-Bielich ('11); Jiang, Li, Chen ('12); Tsubakihara, AO ('13)
  - **Introducing BBB repulsion**
    Bednarek, Haensel et al.('11); Miyatsu, Yamamuro, Nakazato ('13).
  - **Early crossover transition to quark matter**
    Masuda, Hatsuda, Takatsuka ('12)
  - **Choose Stiff EOS for nuclear matter** *Tsubakihara, AO ('14)*
- **What is necessary to solve the massive NS puzzle ?**
  - **EOS of nucleon matter need to be precisely settled.**
  - **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**

Massive Neutron Stars with Hyperons

Tsubakihara, Harada, AO, arXiv:1402.0979

- **Ruled-out EOS with hyperons = GM3**
  Glendenning & Moszkowski (1991)
- **We did NOTHING special and find 2 $M_\odot$ NS can be supported.**
  - **"Typical" RMF for nucl. matter**
    NL1, NL-SH, TM1
    Reinhardt et al. ('86);
    Sharma, Nagarajan, Ring ('93);
    Sugahara, Toki ('94).
  - **$s\bar{s}$ mesons are introduced**
  - **Hypernuclear data**
    Λ, ΛΛ hypernuclei
    Σ atomic shifts
    SU(3) relation to isoscalar -vector couplings

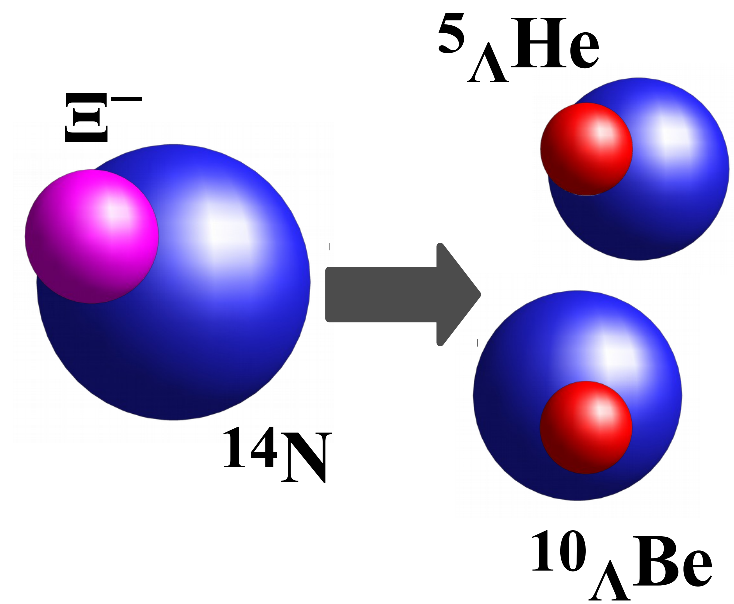


Yet Un-explored YN & YY Interactions

- **ΞN interaction**
  - **Indirect evidence of $U_\Xi(\rho_0) \sim -14$ MeV**
  - **First evidence of deeply bound Ξ hypernucleus $\Xi^- + {}^{14}N$**

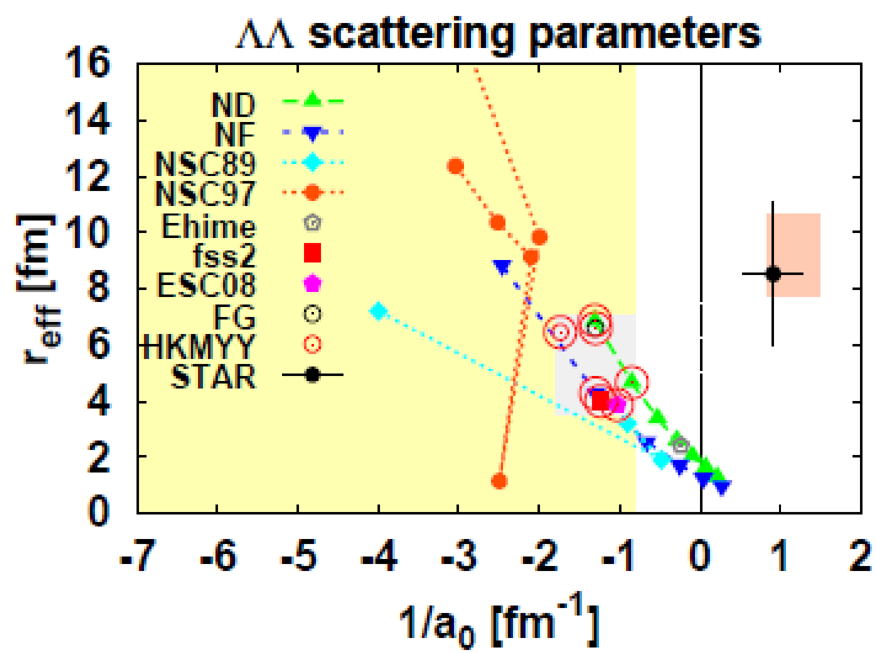
    K. Nakazawa et al., PTEP 2015, 033D02.

    B(Ξ^-)= 4.38 ± 0.25 MeV (g.s.) or 1.11 ± 0.25 MeV (exc.)



- **ΛΛ interaction**
  - **Double hypernuclear bond energy $\Delta B_{\Lambda\Lambda}({}^6{}_{\Lambda\Lambda}He)=0.67 \pm 0.16$ MeV**
  - **ΛΛ int. from two-particle corr. from heavy-ion collisions**

    $-1.25\ \text{fm} < a_0(\Lambda\Lambda) < 0$



- **Isospin dependent part of ΣN**

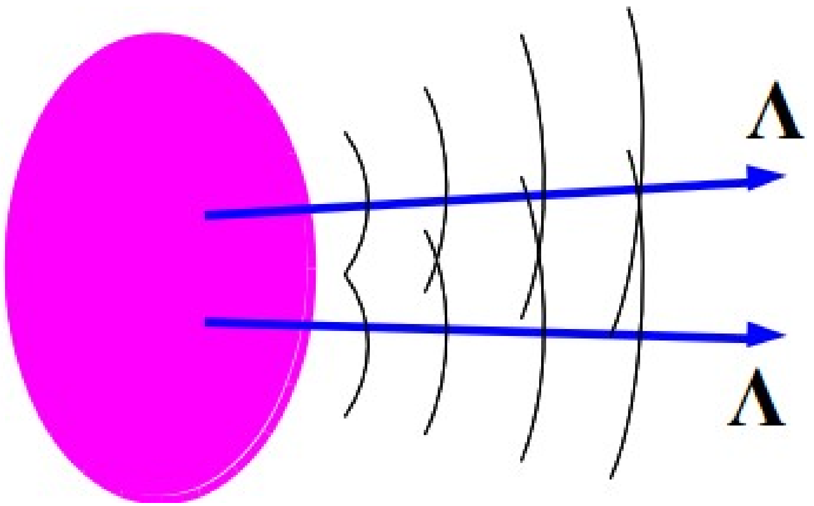
K. Morita, T. Furumoto, AO, PRC91('15),024916

Hadron-Hadron correlation in HIC

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

$$C(q) = \int d\,\boldsymbol{x}_{12}\ \underline{S(\boldsymbol{x}_{12})}\ \underline{|\Psi(\boldsymbol{x}_{12})|^2}$$

Source **wave fn.**



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

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

  - **Free fermion + Gaussian source**

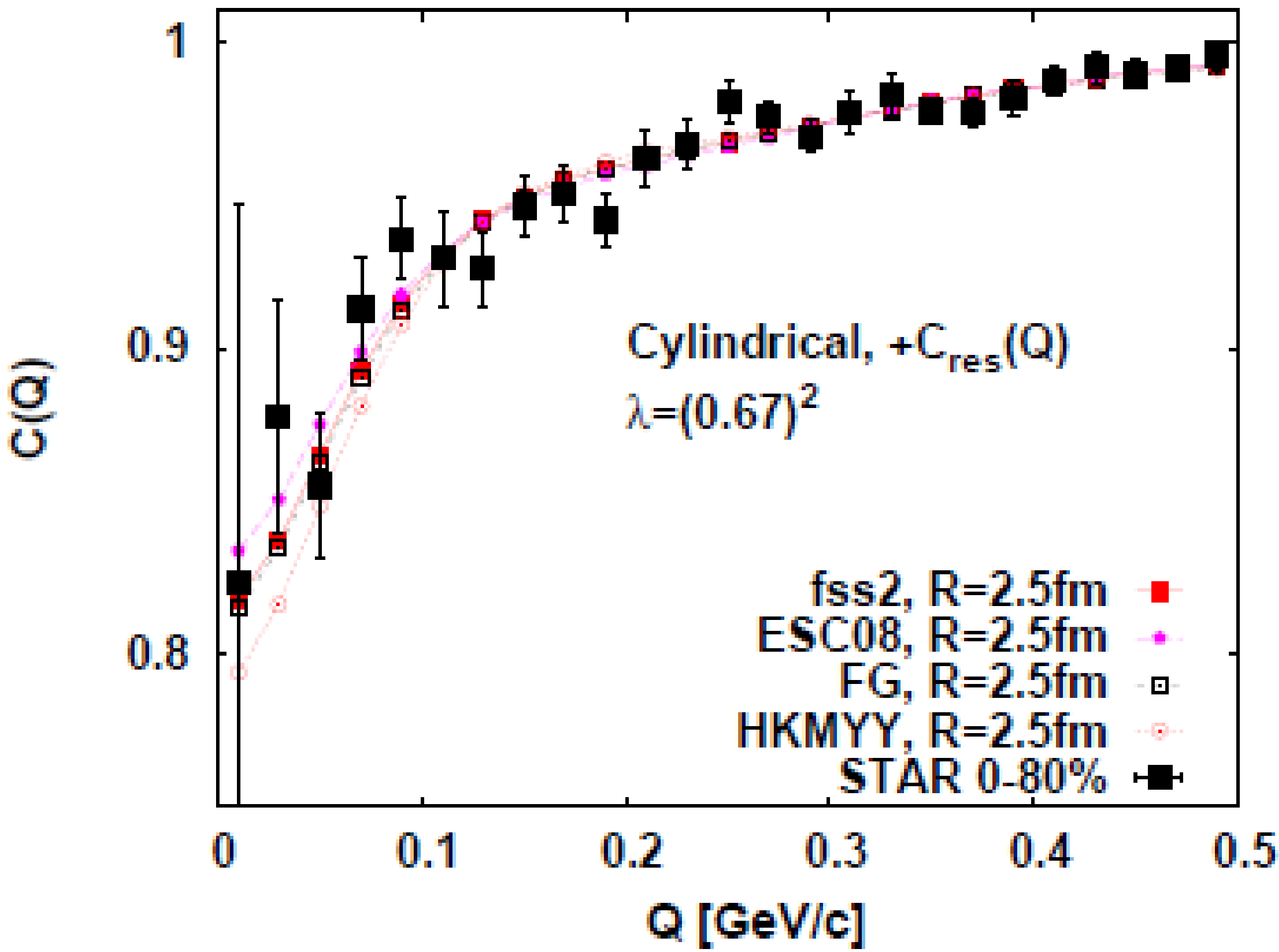
$$C(\boldsymbol{q}) = 1 - \frac{1}{2}\exp(-4q^2R^2)$$

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

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

ΛΛ correlation and favored ΛΛ interaction

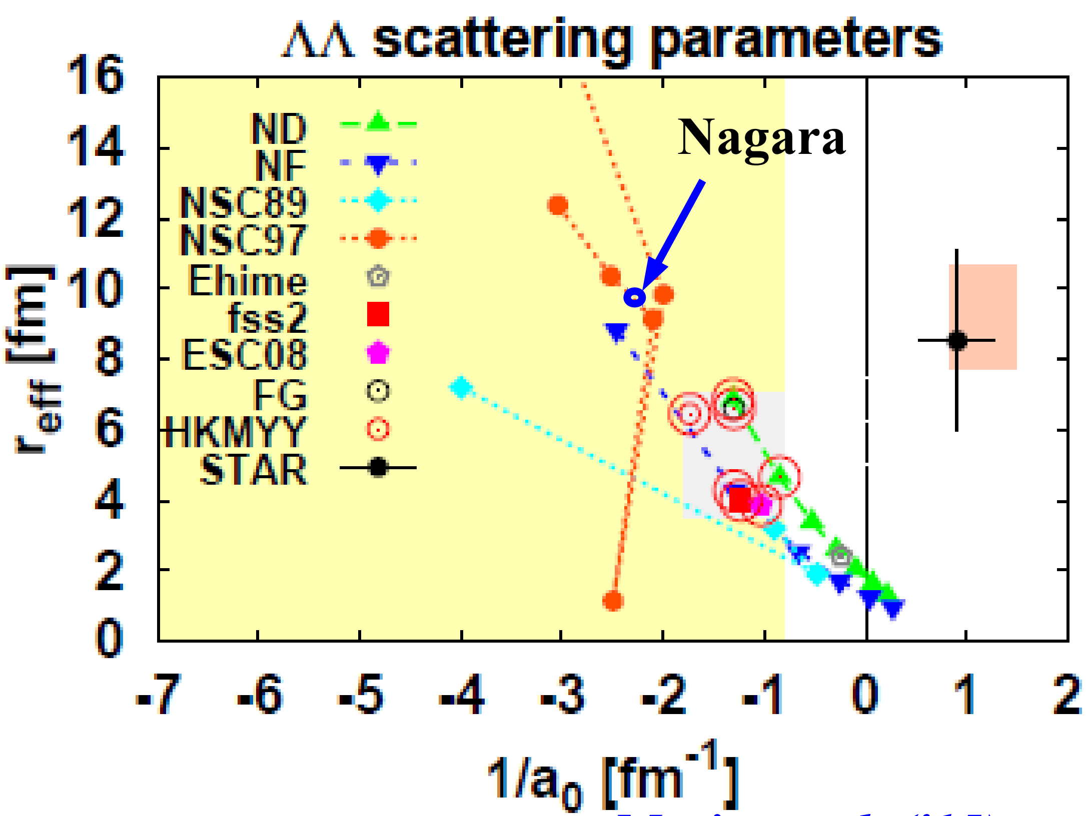
ΛΛ correlation with long. and transverse flow effects, Σ0 feed down, and unknown long tail effects



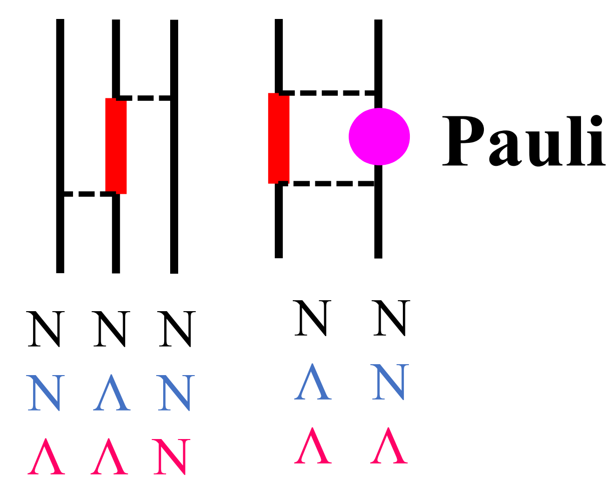
K.Morita, T.Furumoto, AO, PRC91('15)024916 [arXiv:1408.6682]
Data: Adamczyk et al. (STAR Collaboration), PRL 114 ('15) 022301.

Do we see ΛΛN interaction ?

- Do we see diff. btw
  $V_{\Lambda\Lambda}$ from RHIC (~ vacuum ΛΛ int.) and $V_{\Lambda\Lambda}$ from Nagara ?
  Hiyama et al. ('02); Filikhin, Gal ('02)
  - Mechanism: Pauli blocking in the intermediate ΞN channel
    Kohno ('13) / Myint, Shinmura, Akaishi ('03) / Nishizaki, Takatsuka, Yamamoto('02) / ***Machleidt***.

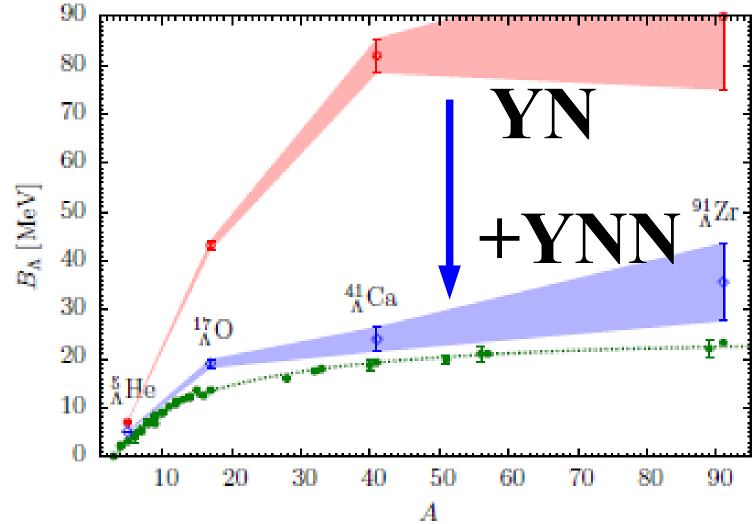


Morita et al. ('15)

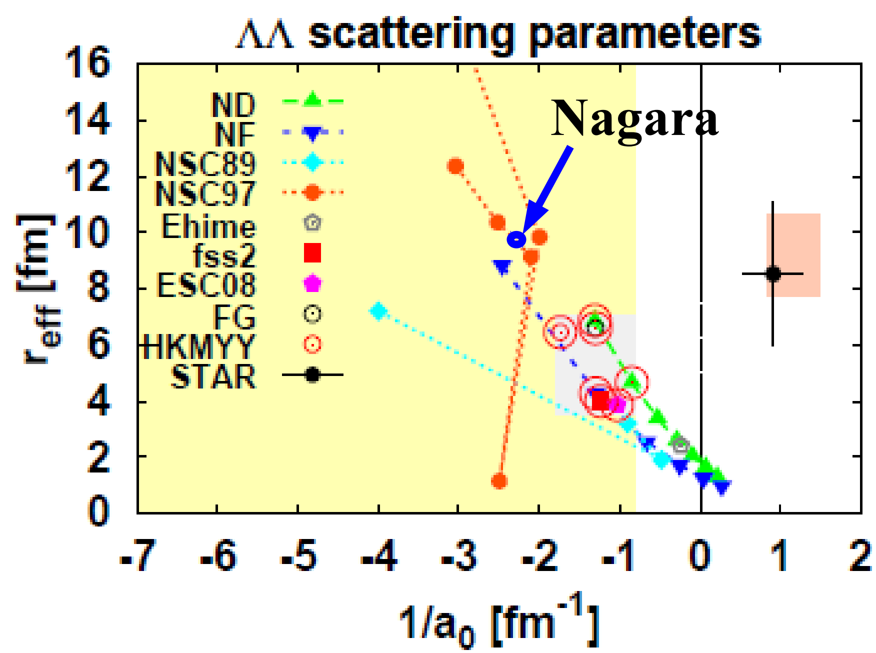


BBB interaction including Hyperons

- **BBB int. incl. YNN, YYN and YYY should exist and contribute to EOS.**
  Nishizaki, Takatsuka, Yamamoto ('02)
  - **Chiral EFT, Multi-Pomeron exch., Quark Pauli, Lattice 3BF, SJ, ..**
    Kohno('10); Heidenbauer+('13); Yamamoto+('14); Nakamoto, Suzuki; Doi+(HALQCD,'12); Tamagaki('08); …
  - **Quant. MC study**
    D.Lonardoni, S.Gandolfi, F.Pederiva.('13)
  - **Quark Meson Coupling**
    Miyatsu et al.; Thomas (HHIQCD)
  - **ΛΛN** *K. Morita, T. Furumoto, AO, PRC91('15)024916*
- **Caveat: Missing data (or data precision is low ...)**



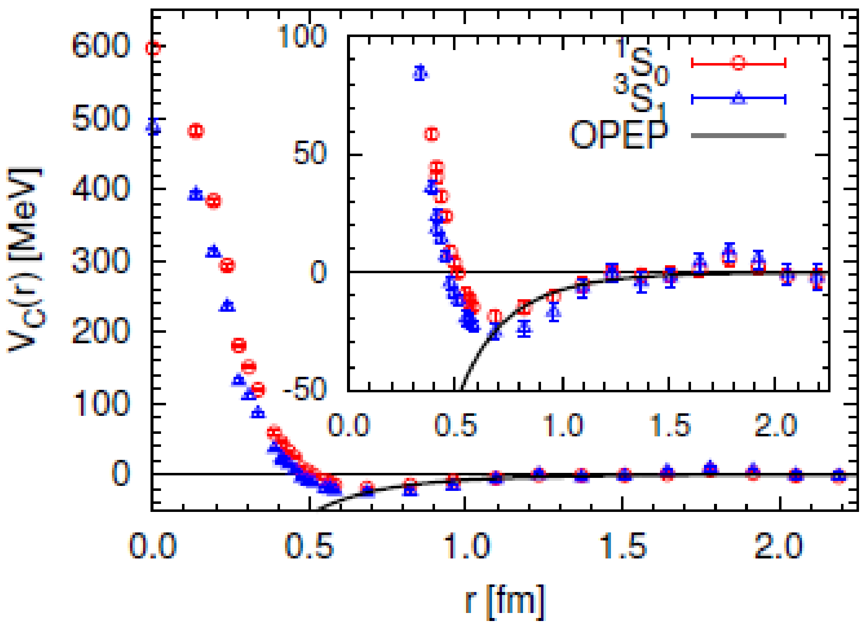
Lonardoni et al.('14)



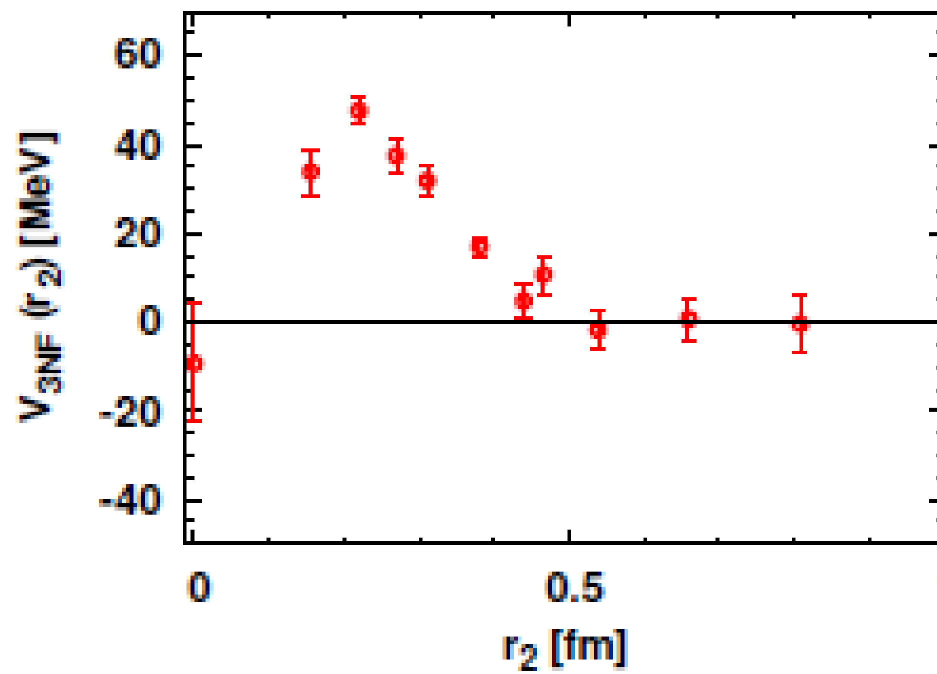
Morita et al. ('15)

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)



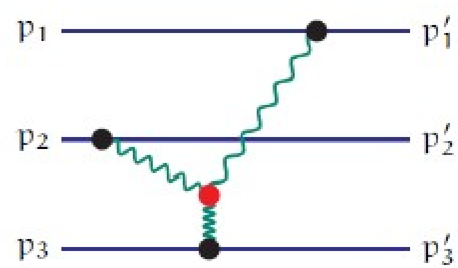
T. Doi et al. (HAL QCD Collab.) ('12)

BBB force incl. hyperons

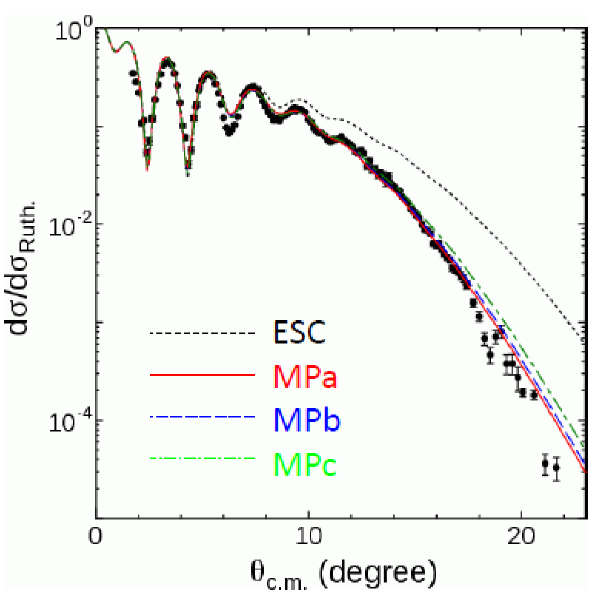
- **Triple pomeron vertex model of BBB repulsion**

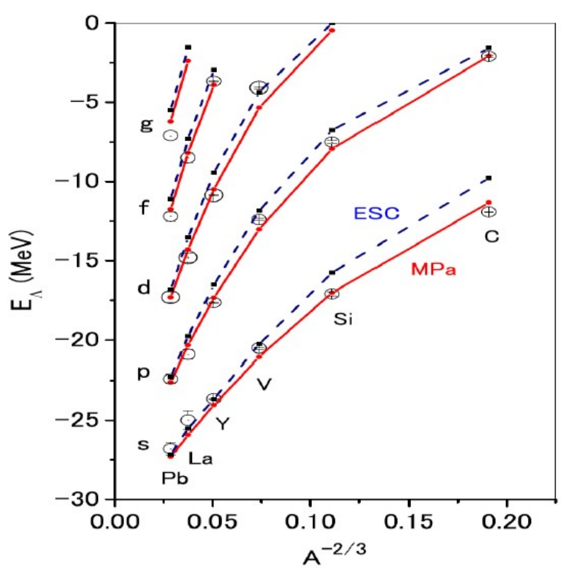
$$\mathcal{L}_{PPP} = g_{3P} \mathcal{M}\, \sigma_P^3(x)/3!$$

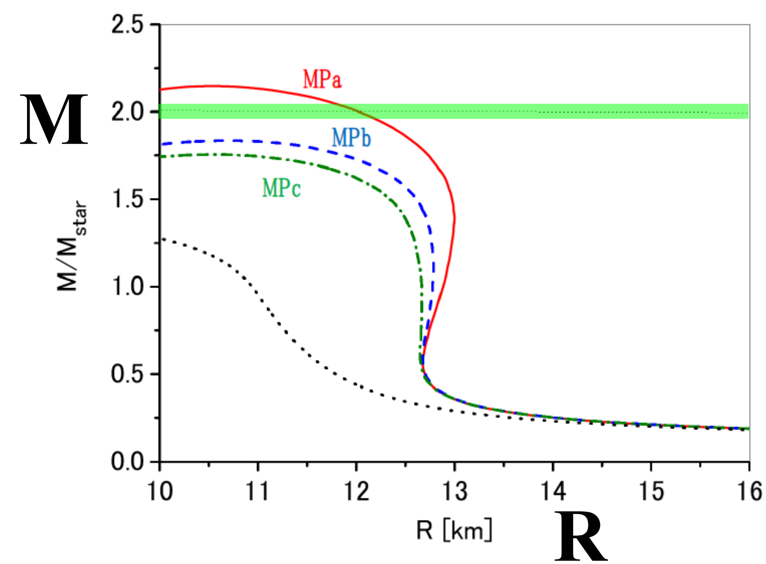
  - **Pomeron = gluon ladder, flavor blind, induces BB repulsion**



- **How can we fix BBB force strength ?**
  - **Multi-pomeron coupling strength is determined in AA scattering.**
  - **Multi-baryon force gives better S_Λ, and may support 2 $M_\odot$ NS.**

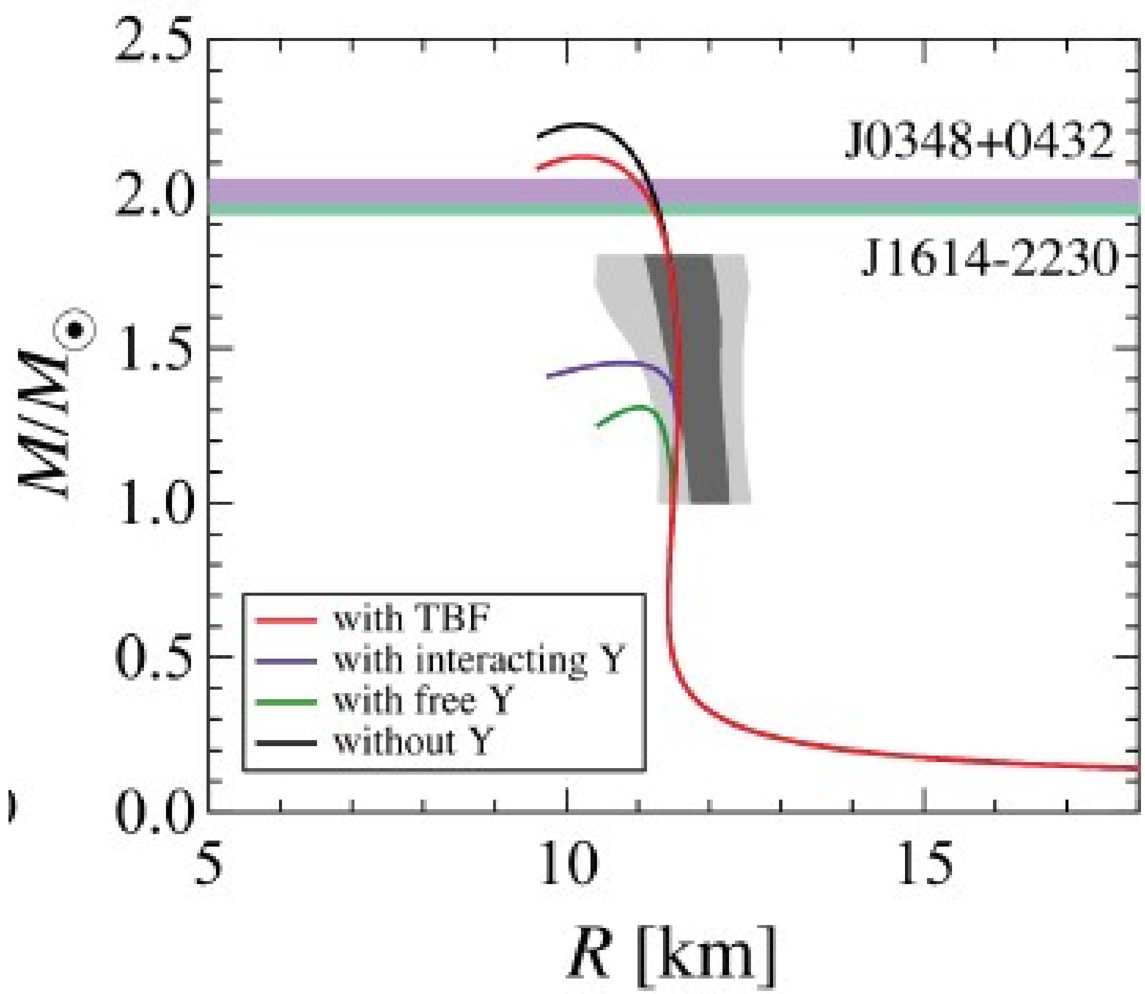






Yamamoto, Furumoto, Yasutake, Rijken ('13)

Variational Calculation including Hyperons



Togashi, Hiyama, Takano, Yamamoto

Summary of Part II

- **Strangeness nuclear physics has extracted the depths of hyperons in nuclei, and EOSs based on these potentials fail to support $2M_\odot$ NS. (Massive NS puzzle)**
- **Solving the massive NS puzzle is a big challenge in physics.**
  - **All relevant BB (and MB) interactions, Many-body theories, Multi-body interactions, and Transition to quark matter have to be understood properly.**
- **There are several attempts to answer the massive NS puzzle, but not convincing yet.**
  - **How can we justify "model assumptions" ?**
  - **How can we access various YY (and MB) interactions ?**
    → J-PARC experiments, heavy-ion collisions, ...
  - **How can we determine BBB (and BBBB) force ?**
    → Chiral EFT, Lattice QCD, Quark model (Nakamoto), ...
    "Model" BBB force + phenomenology (precise S_Λ is necessary)

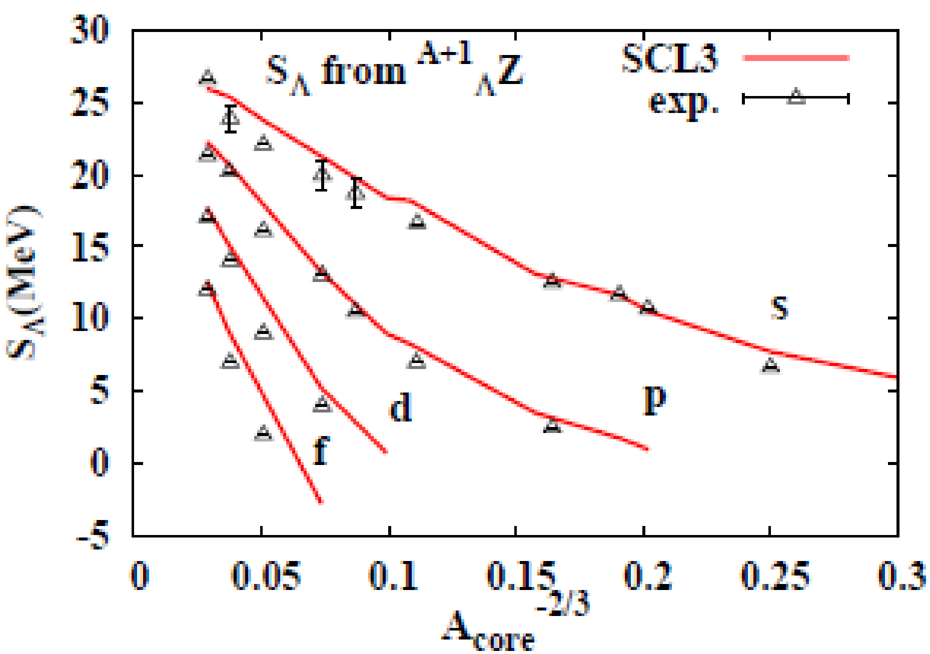
Summary

- **Neutron Star physics is attracting much attention, and many current/future facilities/projects are aiming at solving NS puzzles.**
  - **Radioactive beam facilities → Sym. E. at $\rho < \rho_0$ and $\rho \sim (2\text{-}3)\ \rho_0$**
    Hadron machines → YN and YY int., Hadrons in nuclear matter
    Heavy-ion machines → EOS at high density, hh int.
- **More NS observations are necessary !**
  - **Precise (and assumption free) measurement of R_{NS}**
    → many satellites will be launched soon: ASTRO-H, NICER, LOFT
  - **Larger NS mass will further constrain (or kill ?) nuclear physics.**
- **There are more subjects in neutron star physics.**
  - **Cooling, Magnetic field, Crust, Pasta, finite T, ... were not discussed.**
    (Ask Maruyama-san on Pasta and Crust.)

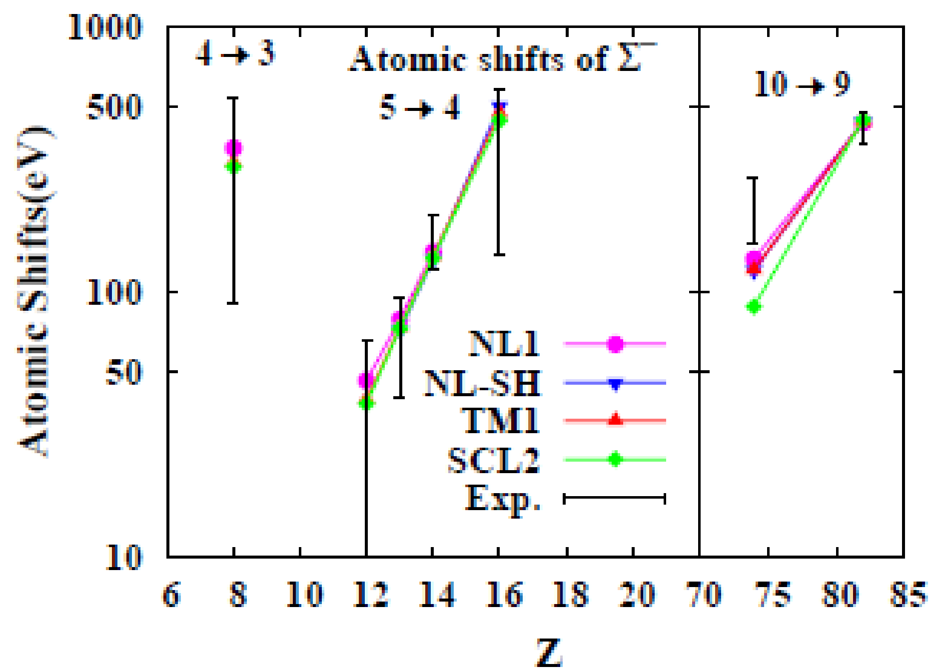
Do I have time ?

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

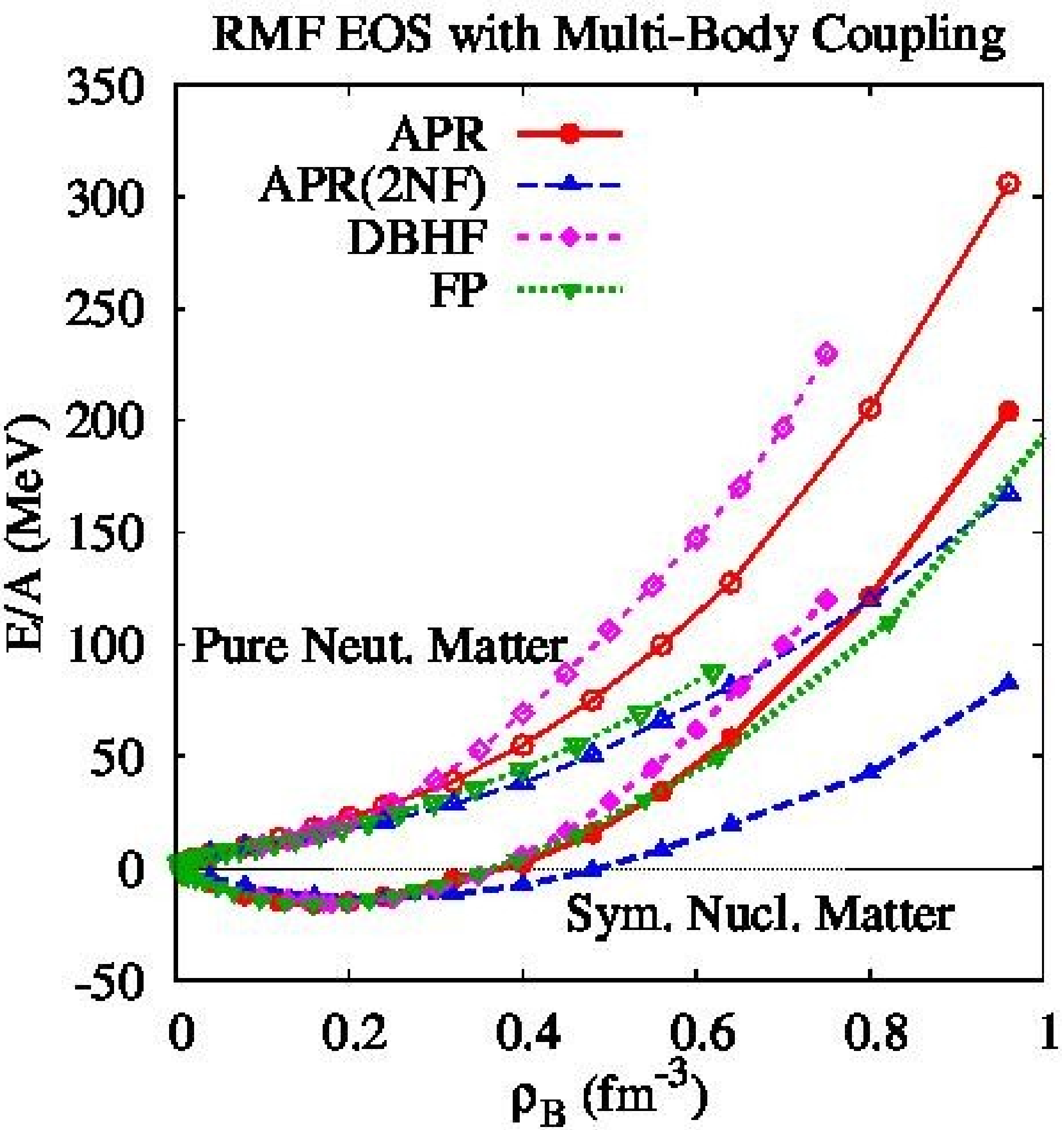


Tsubakihara, Harada, AO, arXiv:1402.0979

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

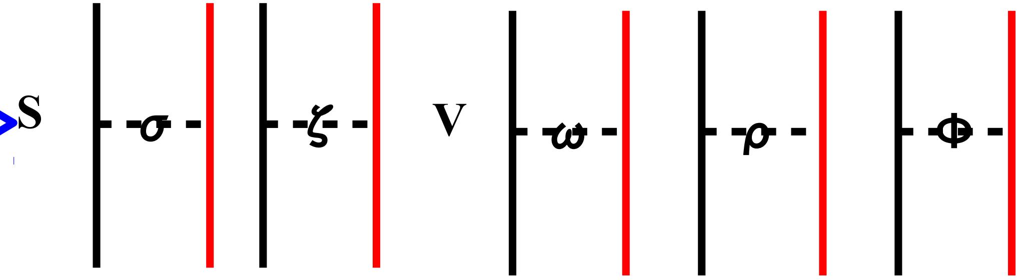


n=2 and n=3 terms in RMF

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

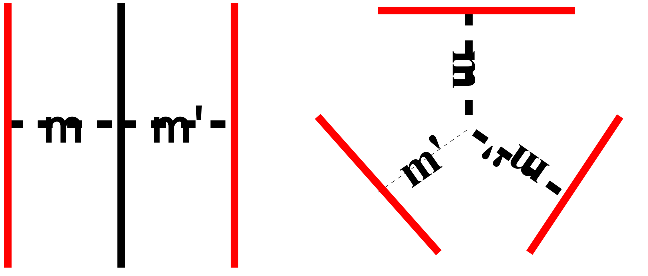
Tsubakihara

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



- **n=3 model → 3-body coupling**

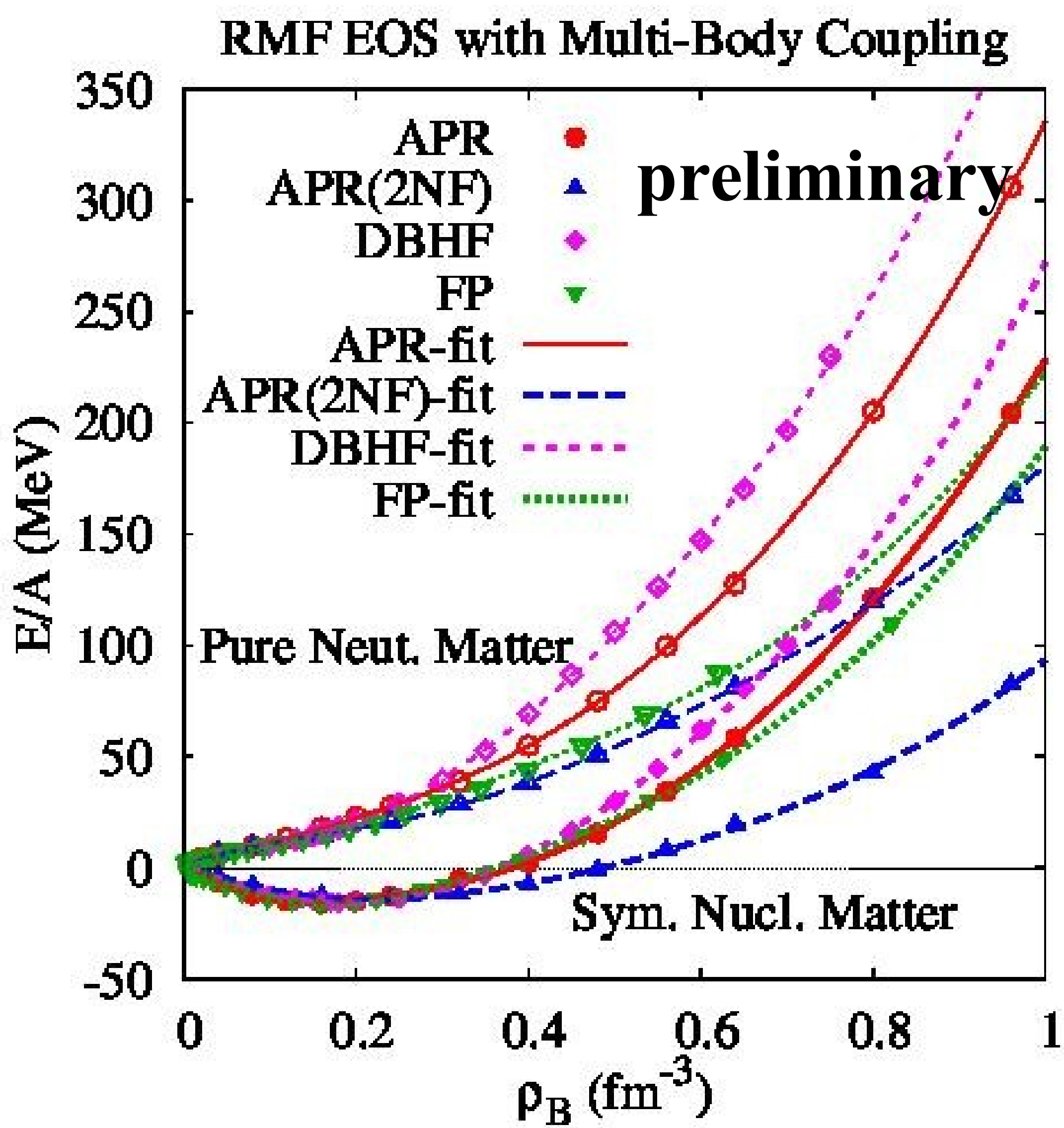
$$g_{mm'B} \bar{\Psi} m m' \Psi$$
$$c_{mm'm''} m m' m'' \Longleftrightarrow$$



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

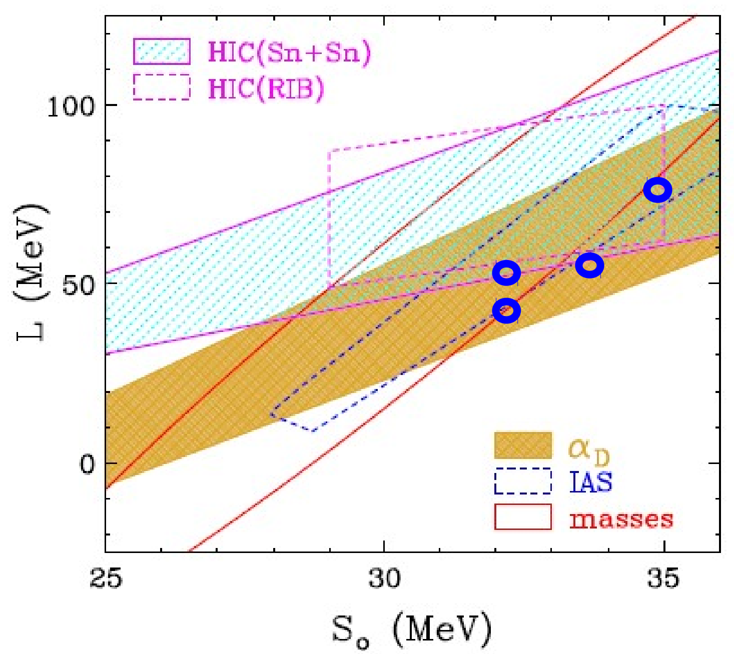
Fitting "Ab initio" EOS via RMF

- **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**

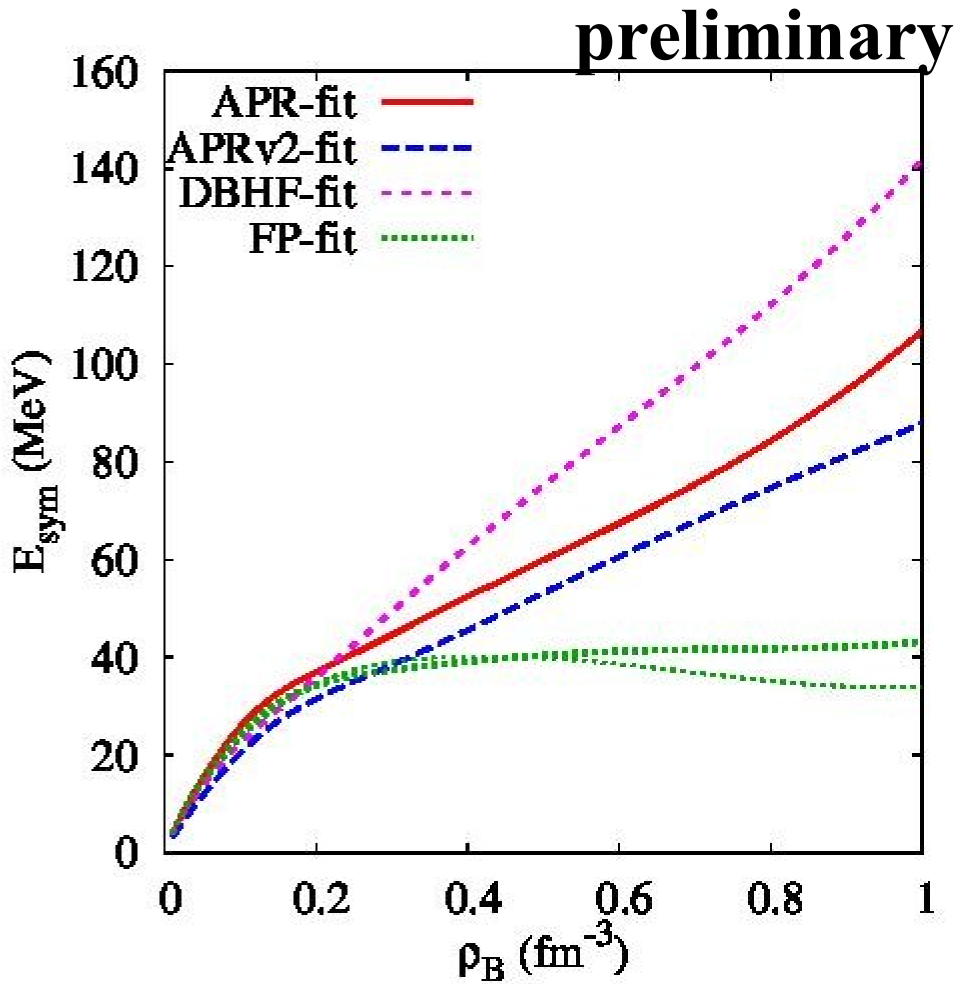


Symmetry Energy

- 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



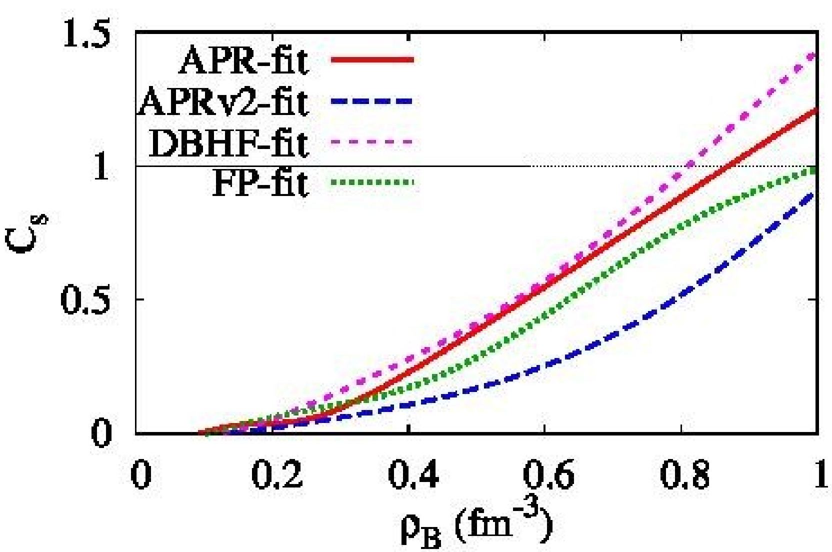
Horowicz et al. ('14)

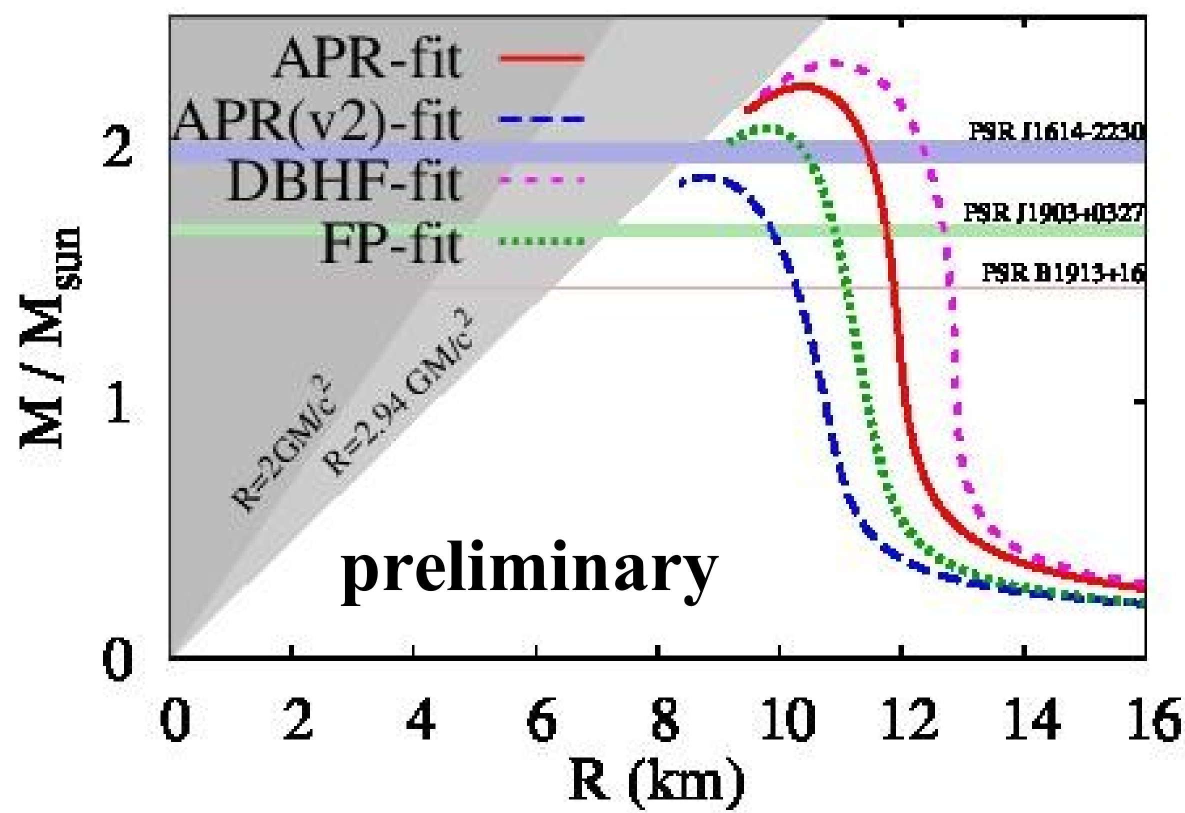


Neutron Star Matter EOS

- 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 $M_\odot$.
- Caveat:
  $c_s > c$ at high density

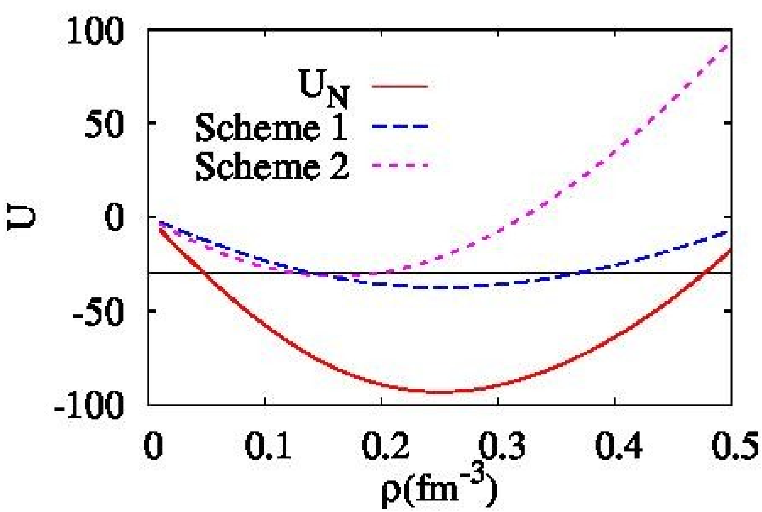
$\eta=(KL^2)^{1/3}$?
Sotani et al.(2014)

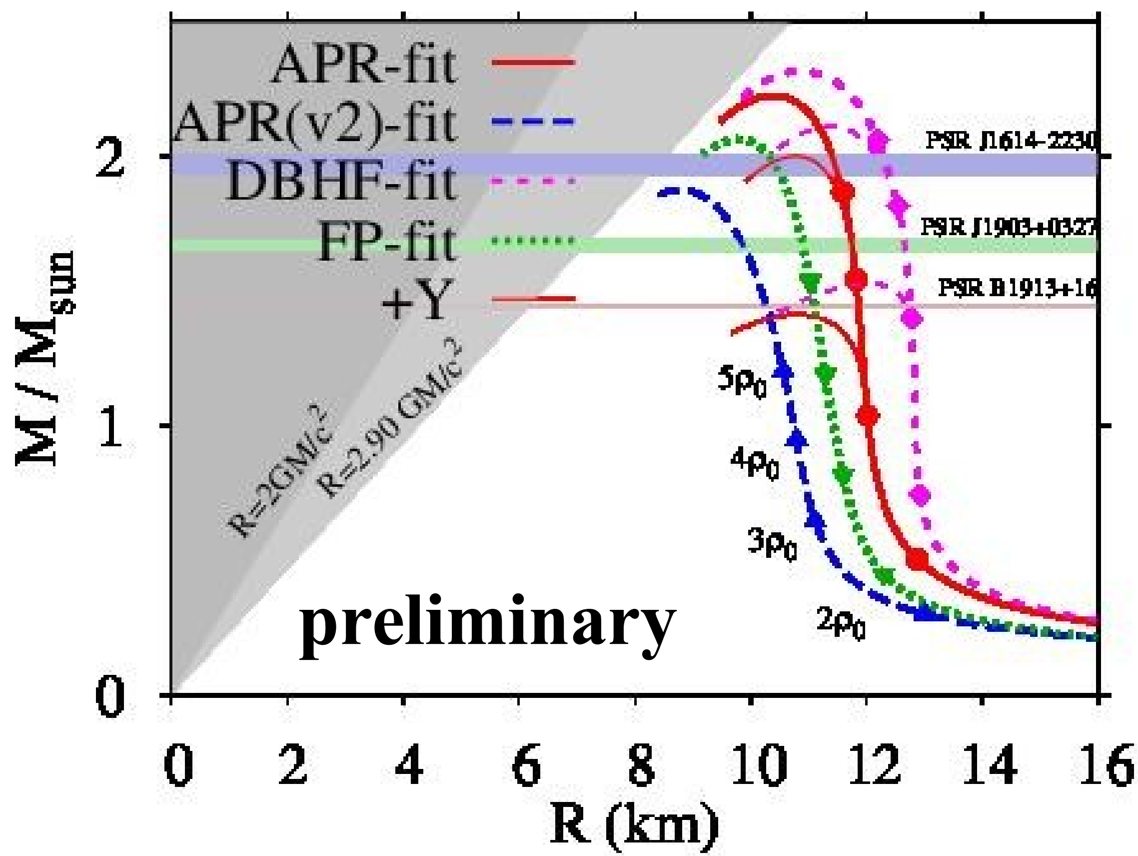




NS matter in "ab initio"-fit + Λ

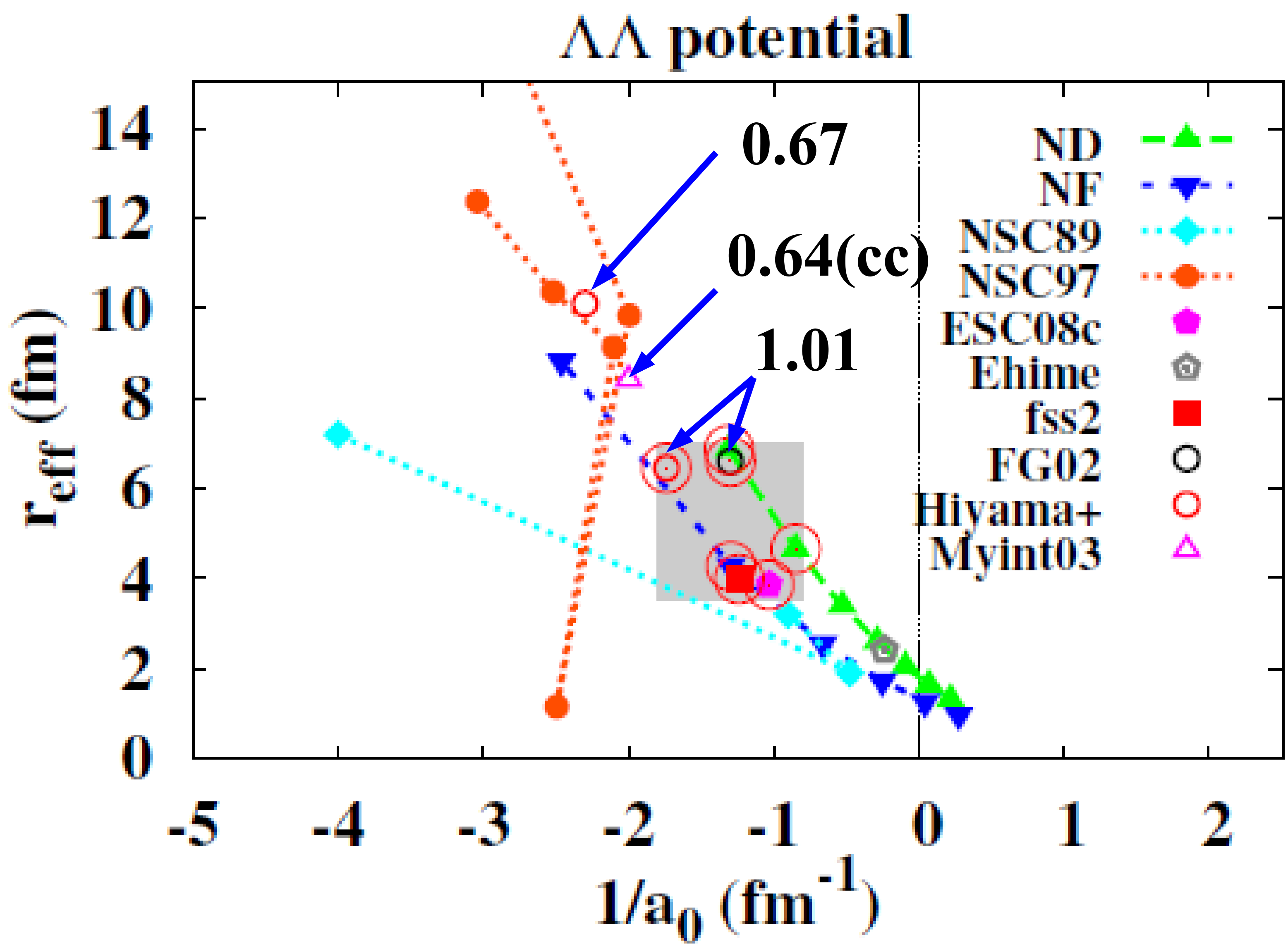
- Λ potential in nuclear matter at $\rho_0 \sim -30$ MeV
  - Scheme 1: $U_\Lambda(\rho) = \alpha\, U_N(\rho)$
  - Scheme 2: $U_\Lambda(\rho) = 2/3\, U^{n=2}_N(\rho) + \beta\, U^{n>2}_N(\rho)$



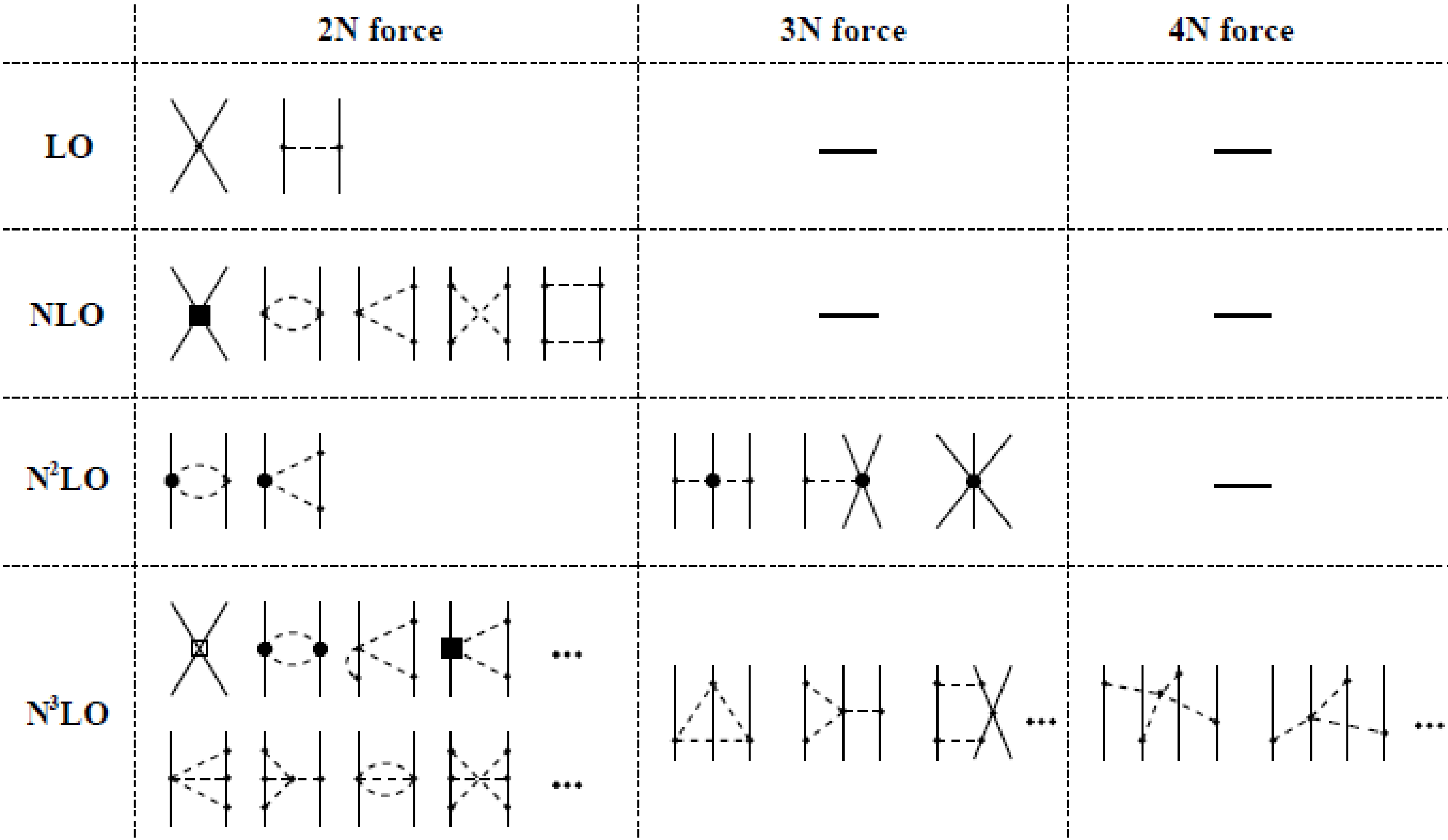


Thank you !

Results with smaller ΛΛ bond energy



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)

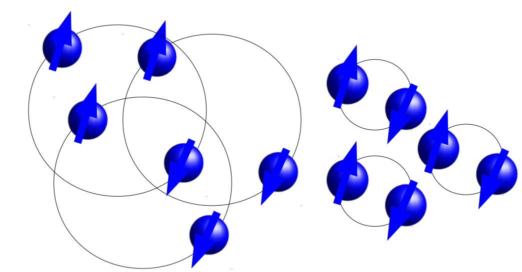
$$E^{\mathrm{Unitary}} = \xi E^{\mathrm{Free}} \quad \xi \simeq 0.4 \left(\text{Bertsch parameter}\right)$$

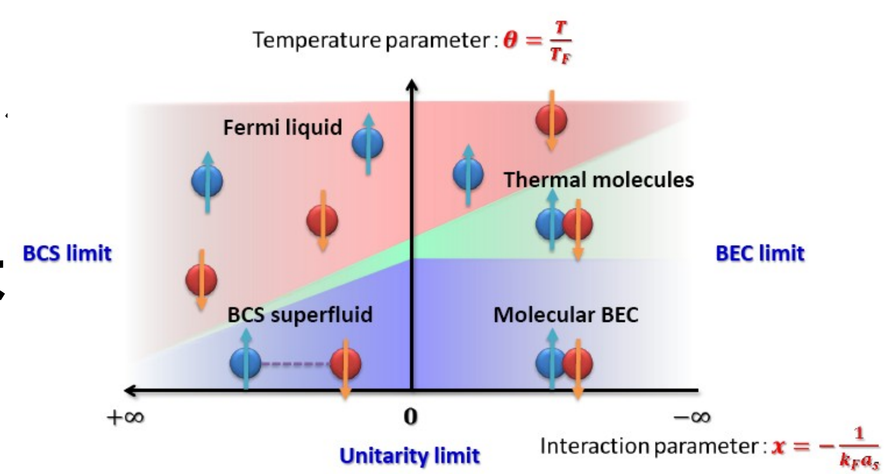
  - nn 間の $^1S_0$ 散乱長は長い！($a_0 = -18.5$ fm)
    → Drip した中性子ガスは、ほぼ unitary gas (-1/ $k_F a_0 \sim 0.1$)

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

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

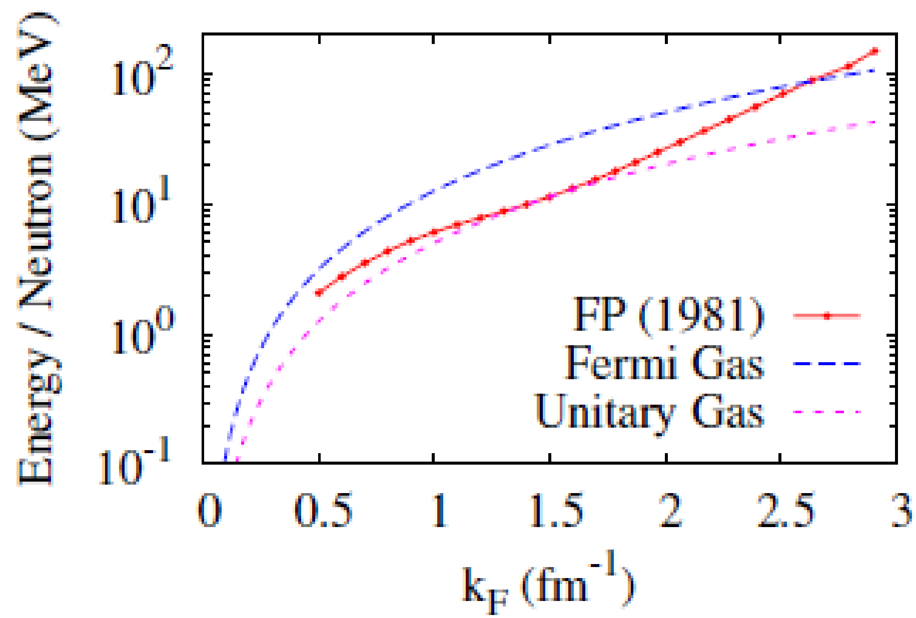
  - どのようにして EOS(密度汎関数)
    取り込むか？ (Hartree なら ∝ ρ)
  - unitary gas / BEC-BCS crossover は
    クラスト・原子核の性質に
    どのような影響を及ぼすか？

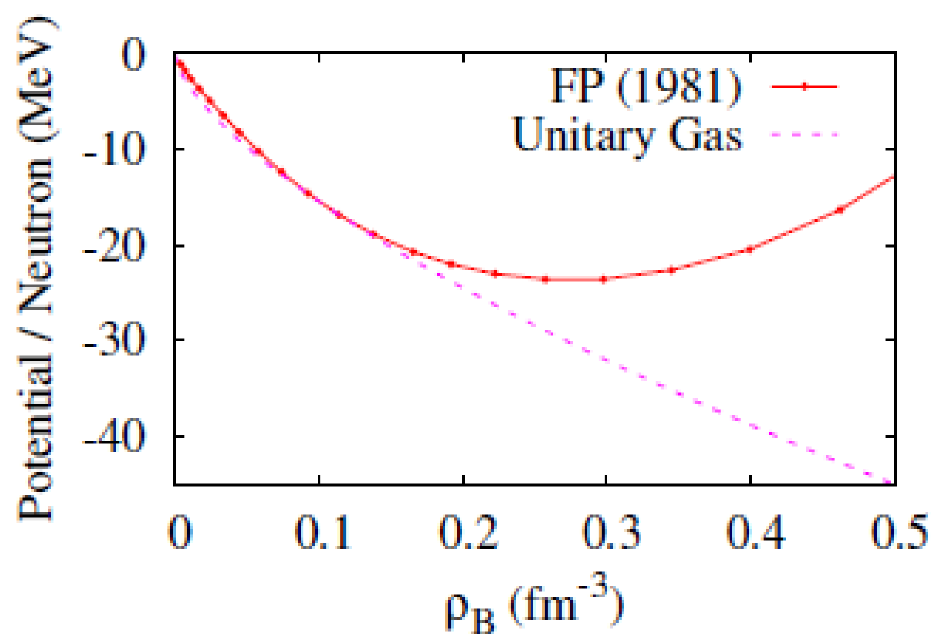




中性子星物質の状態方程式

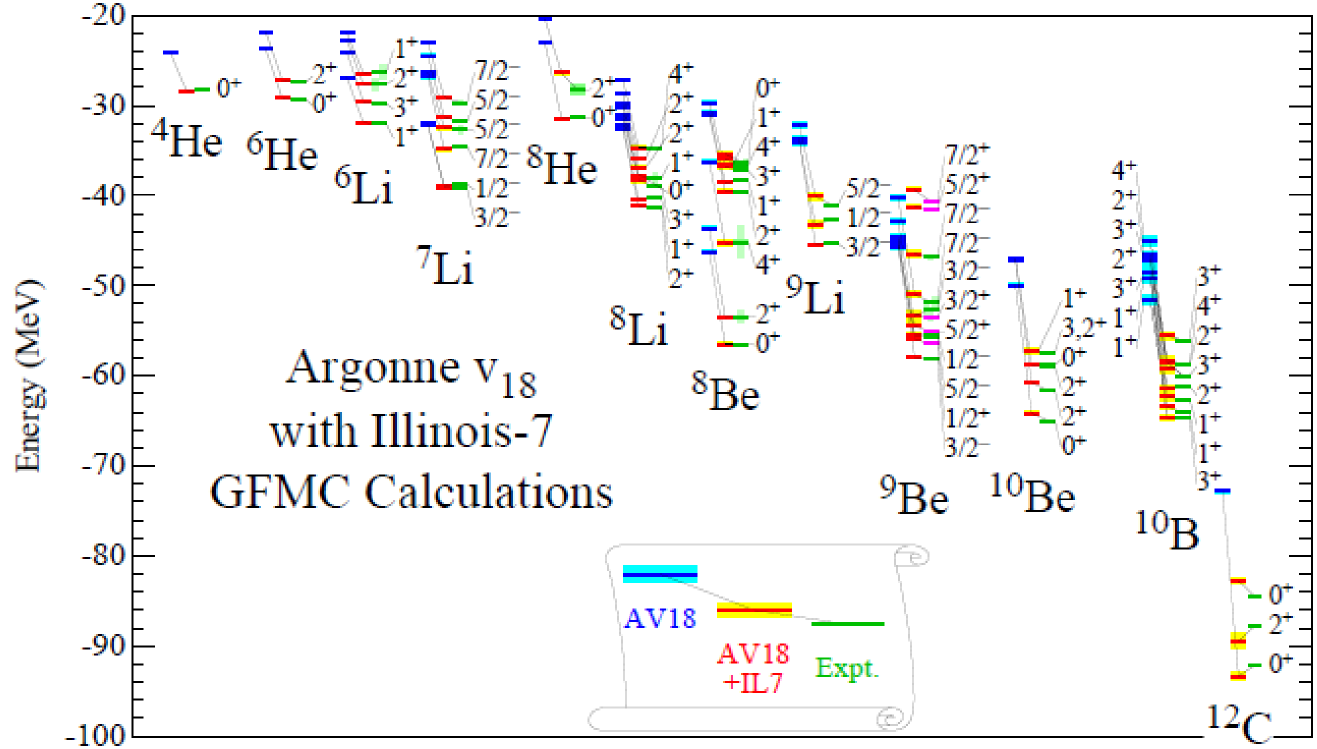
- 変分法による計算結果
  Friedman-Pandharipande (1981)
  - 広い密度領域において
    $E_{unit} < E_{FP} < E_{Fermi}$
  - 低密度領域でポテンシャルエネルギーは $\rho^{2/3}$ と振る舞っているか？





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)

Relativistic Mean Field with Multi-body couplings

σωρ model +std. non-linear terms + multi-body couplings

$$\mathcal{L}_N = \bar{\psi}\left(i\gamma^\mu\partial_\mu - M_N - U_s - \gamma^\mu U_\mu\right)\psi + \mathcal{L}_{\sigma\omega\rho}$$

$$\mathcal{L}_{\sigma\omega\rho} = \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} - \frac{1}{4}\boldsymbol{R}_{\mu\nu}\cdot\boldsymbol{R}^{\mu\nu} - \mathcal{V}_{\sigma\omega\rho}$$

$$U_s = -g_\sigma\sigma\left[1 + r_{\sigma\sigma}(1-\sigma/f_\pi)\right] + g_\sigma\omega^\mu\omega_\mu/f_\pi\left[r_{\omega\omega} + r_{\sigma\omega\omega}(1-\sigma/f_\pi)\right]$$

$$U_\mu = g_\omega\omega_\mu\left[1 - r_{\sigma\omega}\sigma/f_\pi + r_{\omega 3}\omega^\nu\omega_\nu/f_\pi^2\right]$$

$$+ g_\rho\boldsymbol{\tau}\cdot\boldsymbol{R}_\mu\left[1 - r_{\sigma\rho}\sigma/f_\pi + r_{\omega\rho}\omega^\nu\omega_\nu/f_\pi^2\right]$$

$$\mathcal{V}_{\sigma\omega\rho} = \frac{1}{2}m_\sigma^2\sigma^2 - a_\sigma f_{\log}(\sigma/f_\pi) + \frac{1}{4}c_{\sigma 4}\left(\sigma^4 - 4f_\pi\sigma^3\right)$$

$$-\frac{1}{2}m_\omega^2\omega^\mu\omega_\mu\left[1 - c_{\sigma\omega}\sigma/f_\pi\right] - \frac{1}{4}c_{\omega 4}(\omega^\mu\omega_\mu)^2$$

$$-\frac{1}{2}m_\rho^2\boldsymbol{R}^\mu\cdot\boldsymbol{R}_\mu\left[1 - c_{\sigma\rho}\sigma/f_\pi + c_{\omega\rho}\omega^\mu\omega_\mu/f_\pi^2\right] - \frac{1}{4}c_{\rho 4}(\boldsymbol{R}^\mu\cdot\boldsymbol{R}_\mu)^2$$

$$f_{\log}(x) = \log(1-x) + x + \frac{1}{2}x^2 \qquad a_\sigma = f_\pi^2(m_\sigma^2 - m_\pi^2)/2 - f_\pi^4 c_{\sigma 4}$$

RMF with many-body coupling

- **Naive dimensional analysis (NDA) and naturalness**

  Manohar, Georgi ('84)

  The vertex is called "natural" if C ~ 1.

$$L_{\rm int} \sim (f_\pi \Lambda)^2 \sum_{l,m,n,p} \frac{C_{lmnp}}{m!\,n!\,p!} \left(\frac{\bar\psi \Gamma \psi}{f_\pi^2 \Lambda}\right)^l \left(\frac{\sigma}{f_\pi}\right)^m \left(\frac{\omega}{f_\pi}\right)^n \left(\frac{R}{f_\pi}\right)^p$$

  → Consistent with the idea that the vertex is generated by loop diagrams under the assumption that the QCD coupling is small.

- **FST truncation**

  R. J. Furnstahl, B. D. Serot, H. B. Tang, NPA615 ('97)441.

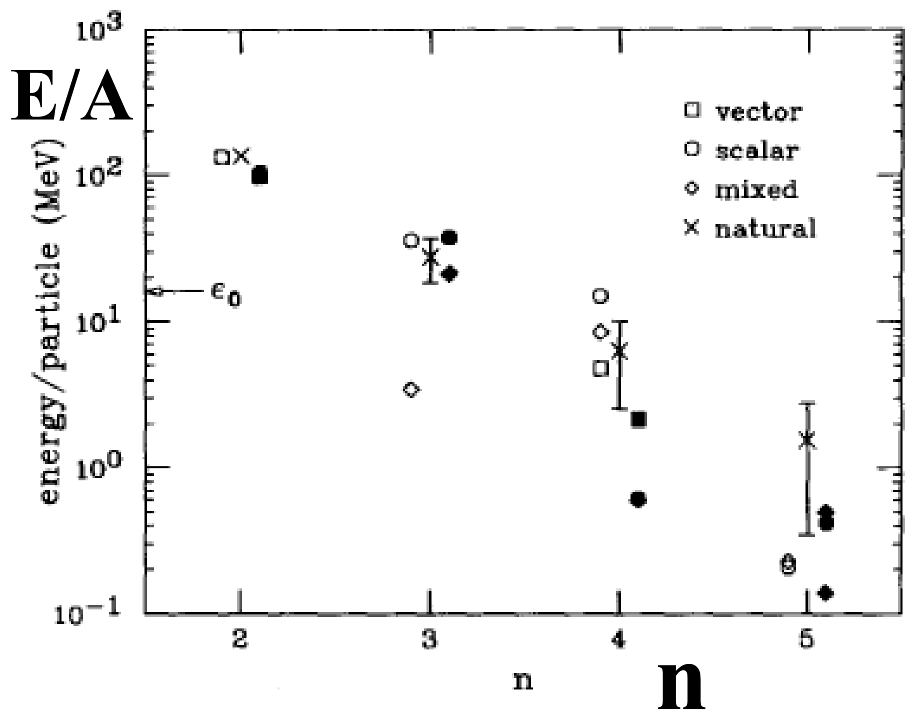
  At a given density, we can truncate the Lagrangian by the index

  n = B/2 + M + D

  (B: baryon field, M: Non NG boson, D: derivatives)

  Naturalness → V ~ $\rho^n/n!$

  → small for large n

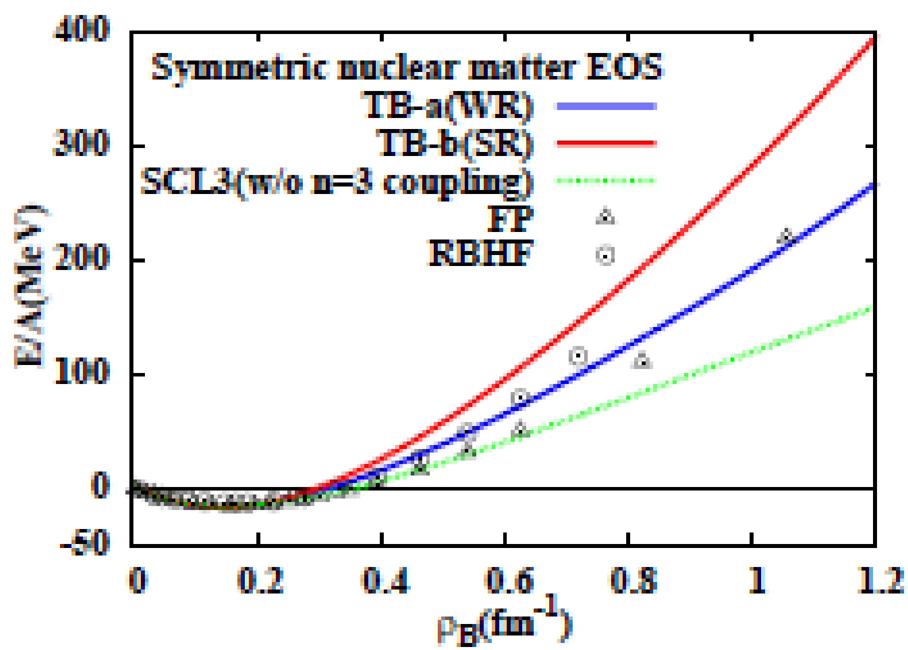


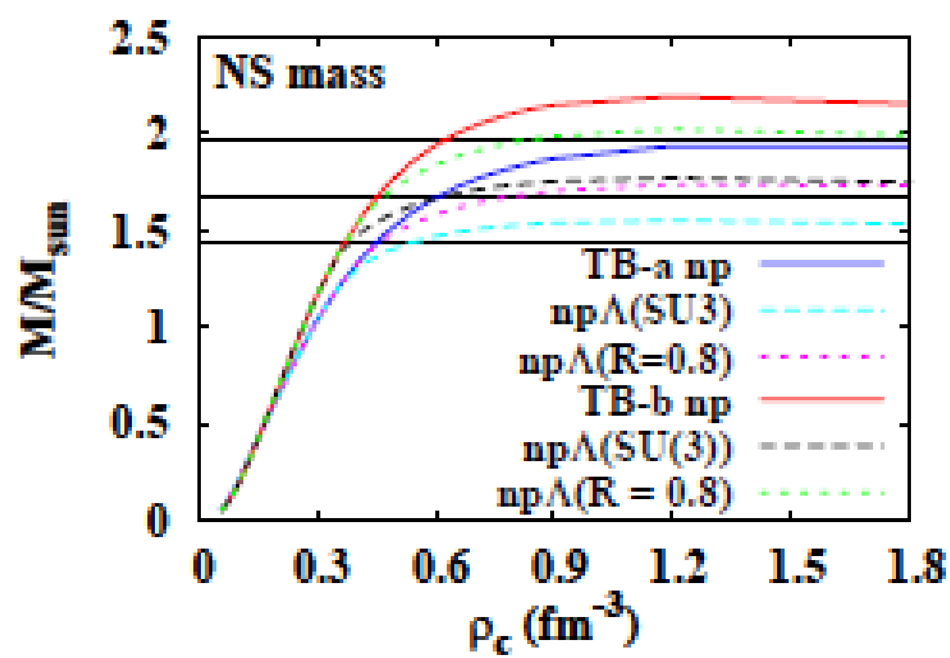
n=3 coupling terms

- **RMF with n=3 terms**
  - **n=B/2+M+D; baryon, meson, derivative**

$$\mathcal{L}_{n=3}^{\sigma\omega} = -\frac{1}{f_\pi}\sum_B \bar{\psi}_B\left[g_{\sigma\sigma B}\sigma^2 + g_{\omega\omega B}\omega_\mu\omega^\mu - g_{\sigma\omega B}\sigma\omega_\mu\gamma^\mu\right]\psi_B - c_{\sigma\omega\omega} f_\pi\sigma\omega_\mu\omega^\mu$$

  - **$g_{\sigma\Lambda}/ g_{\sigma N} \sim 0.8 > 2/3 \to 2\ M_\odot$ NS**
  - **Parameter fitting: (ρ_0, E/A), Vector pot. in DBHF, S_0, L, ...**



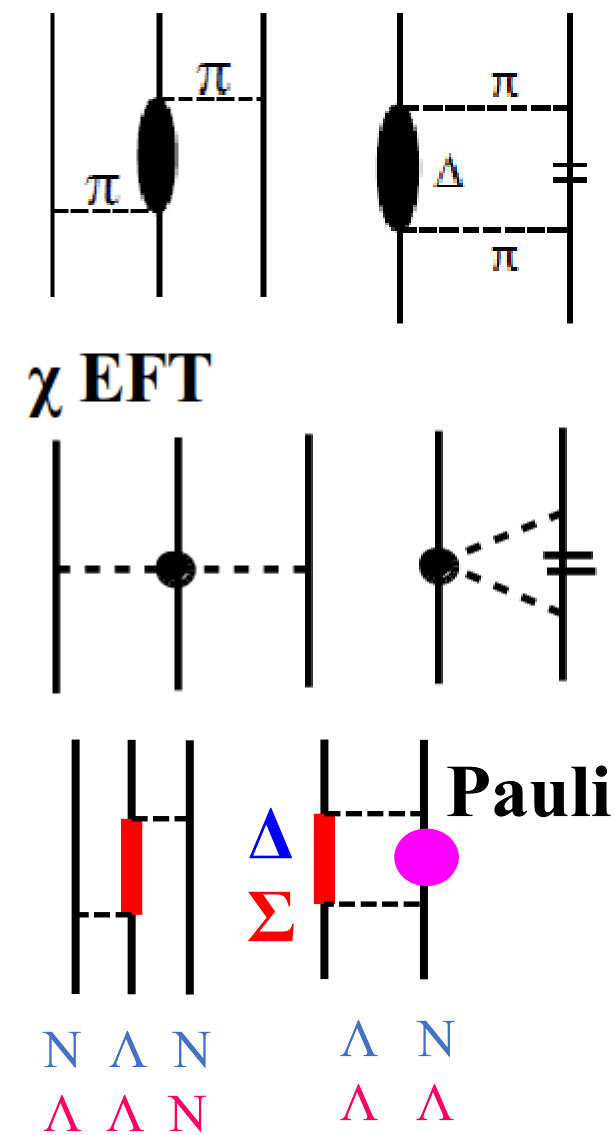


Tsubakihara, AO, NPA914 ('13), 438.

“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

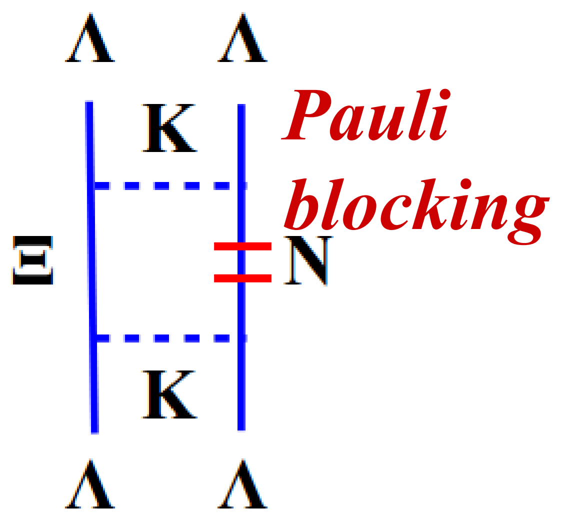


“Universal” TBR
- *Coupling to Res. (hidden DOF)*
- *Reduced “σ” exch. pot. ?*

How about YNN or YYN ?

ΛΛ interaction in vacuum and in nuclear medium

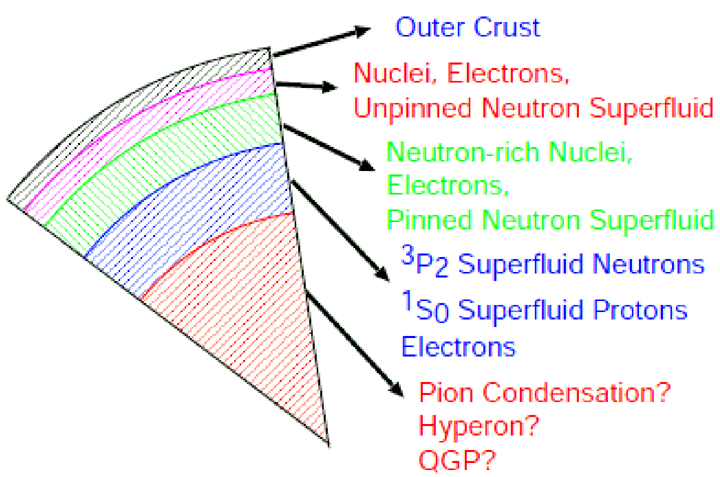
- **Vacuum ΛΛ interaction may be theoretically accessible**
  Lattice QCD calc. HAL QCD (‘11) & NPLQCD ('11)
- **In-medium ΛΛ interaction may be experimentally accessible**
  - **a_0(Nagara fit) = - 0.575 fm, -0.77 fm ($\Delta B_{\Lambda\Lambda}$=1.0 MeV)**
    Hiyama et al. ('02), Filikhin, Gal ('02)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

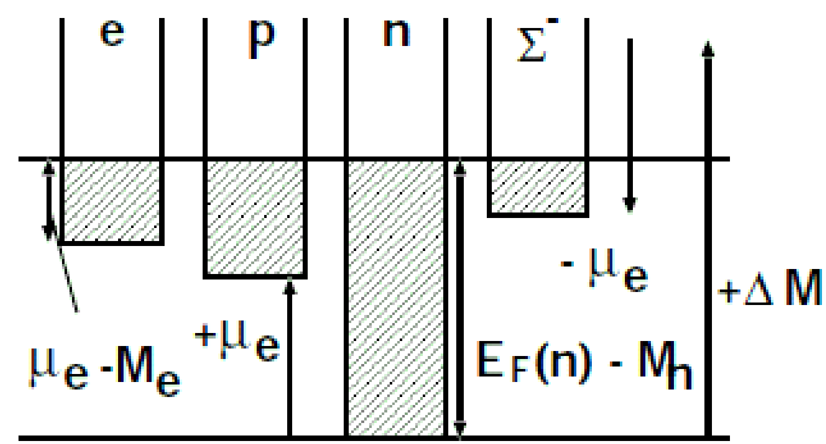


Is there Any way to access “vacuum” ΛΛ int. experimentally ?

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; ...





Nobody says "Hyperons cannot appear in neutron star core" !

Y appears when $\mu_B = E_F(n) + U(n) \geq M(Y) + U(Y) + Q_Y \mu_e$