Nuclear Astrophysics

-Neutron Stars, Nuclear Matter, Symmetry Energy-

Kei Iida (Kochi University)

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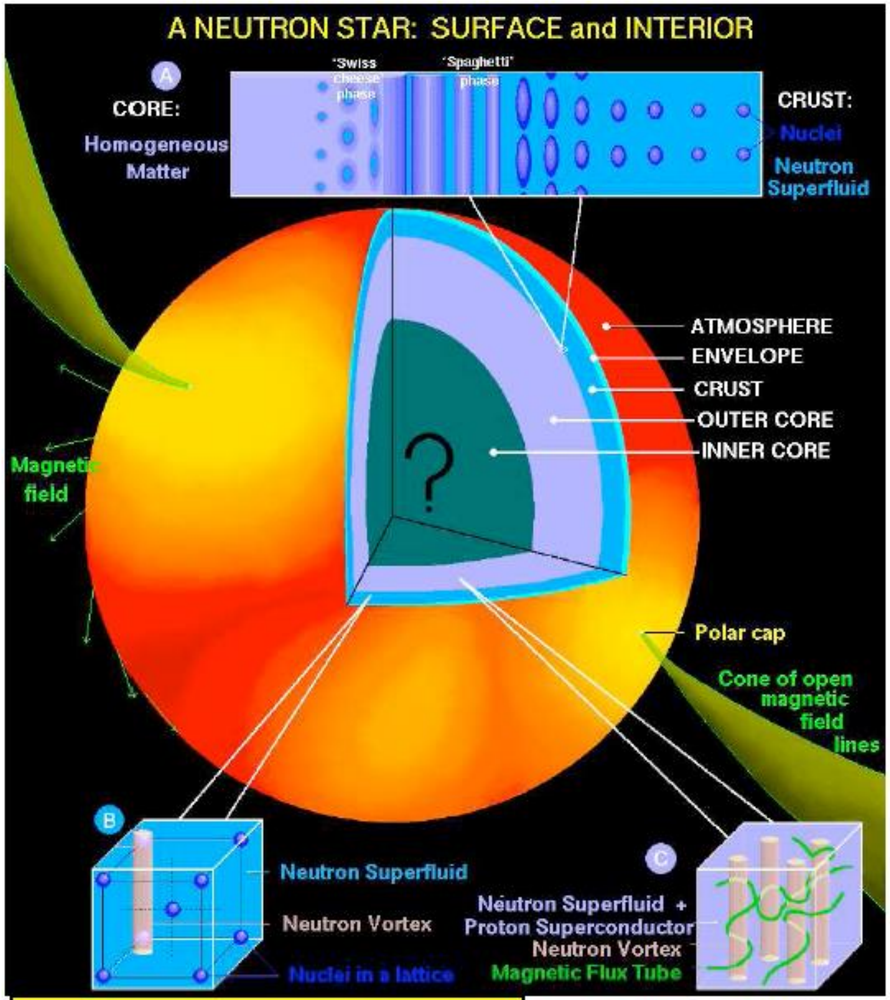
Neutron stars

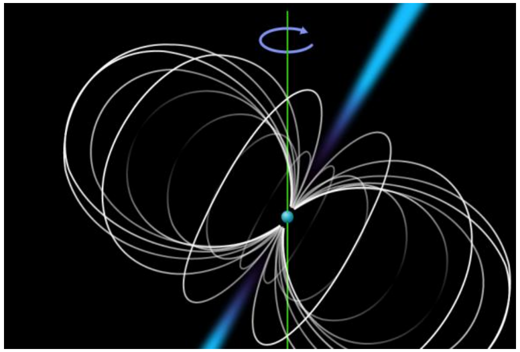


Lattimer and Prakash, astro-ph0405262

Figure by D. Page

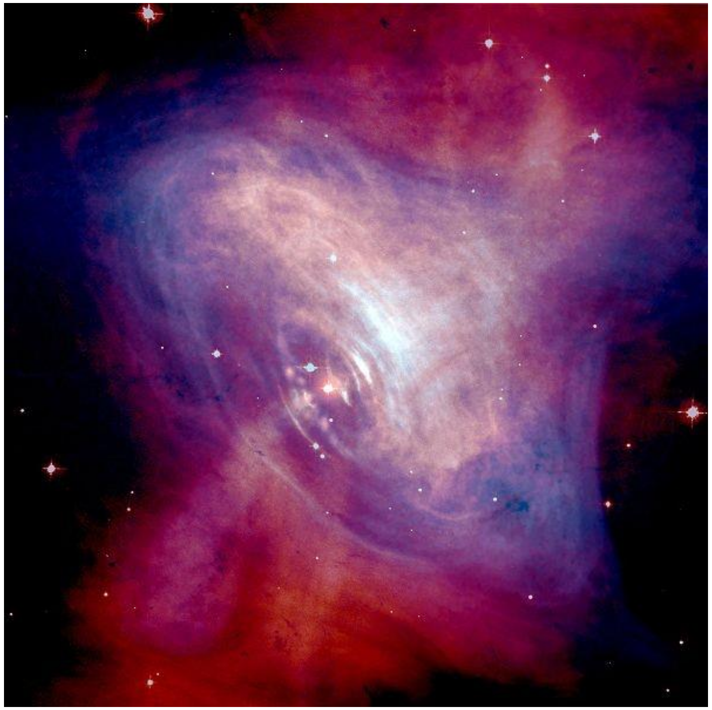
Discovery of pulsars and neutron star observations

In 1967, Hewish & Bell discovered a "pulsar" emitting periodic radio pulses, PSR B1919+21 (at that time, referred to as LGM "Little Green Men"-1.)

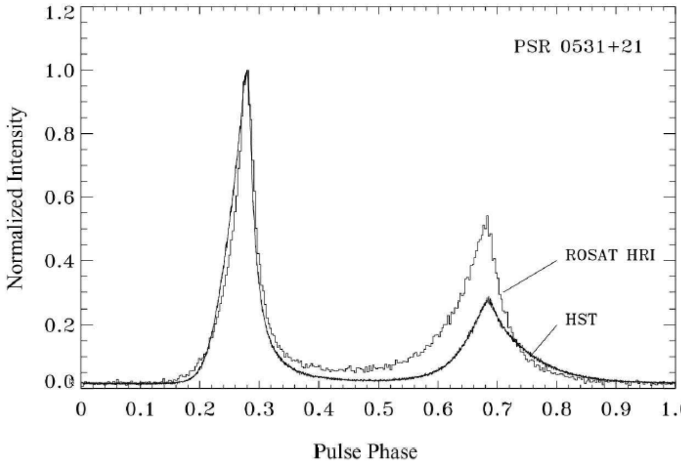


Imaginary drawing of a pulsar (gigantic "dynamo")

1968: A pulsar discovered in the Crab Nebula.



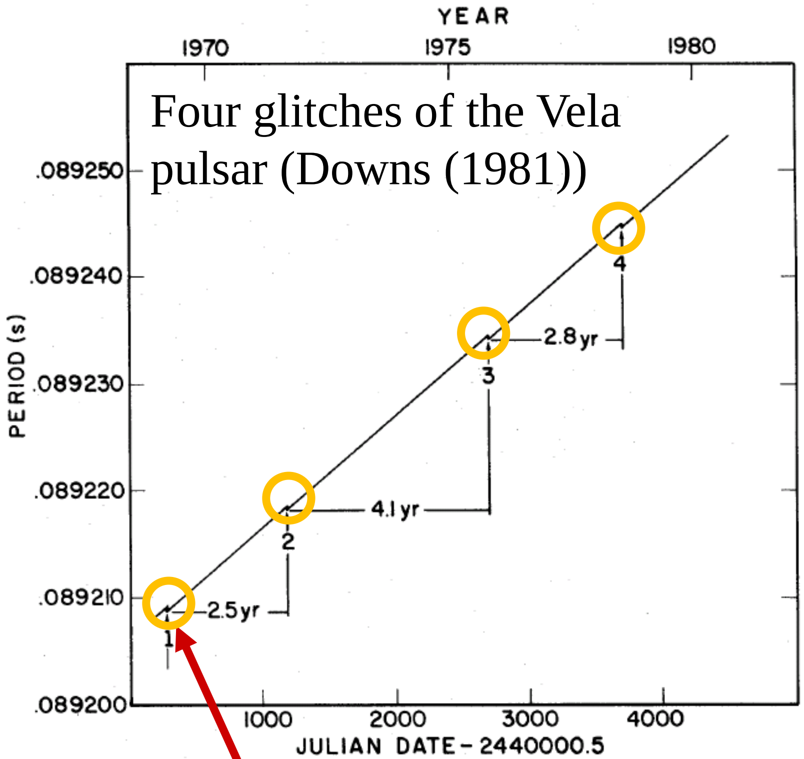
Crab Nebula (NASA/ESA)



The very short (33 msec) period of the Crab pulsar helped to identify pulsars as neutron stars!

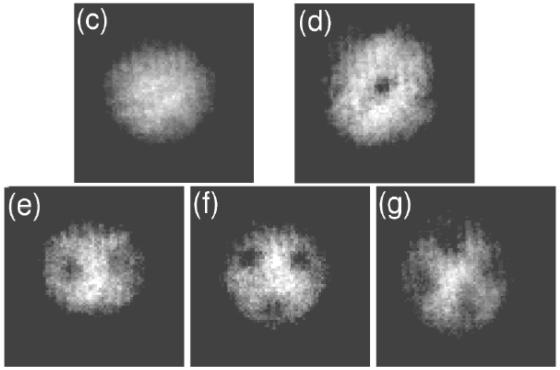
Pulsar glitch

From young pulsars, glitches, sudden decrease in the pulse period, are frequently observed.

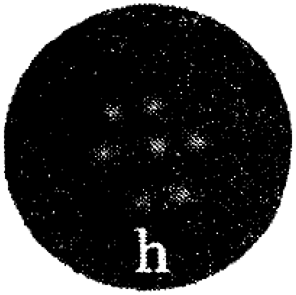


Four glitches of the Vela pulsar (Downs (1981))

Consistent with backreaction to disappearance of outwardly moving vortices, suggesting that superfluidity should occur in a neutron star!



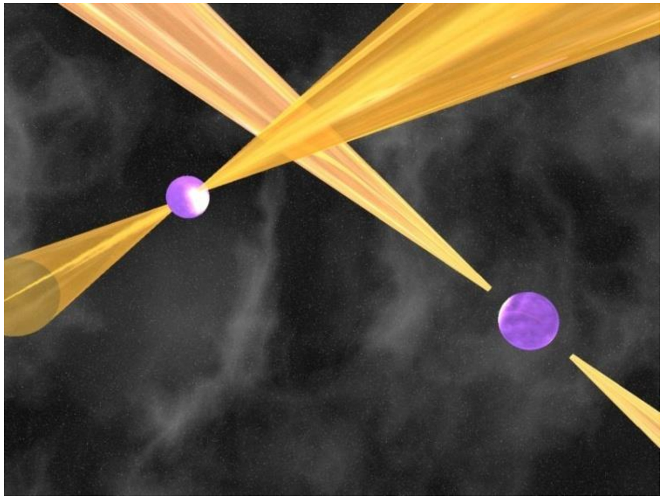
Vortices in rotating Bose condensate of Rb atoms (Madison et al.(2000))



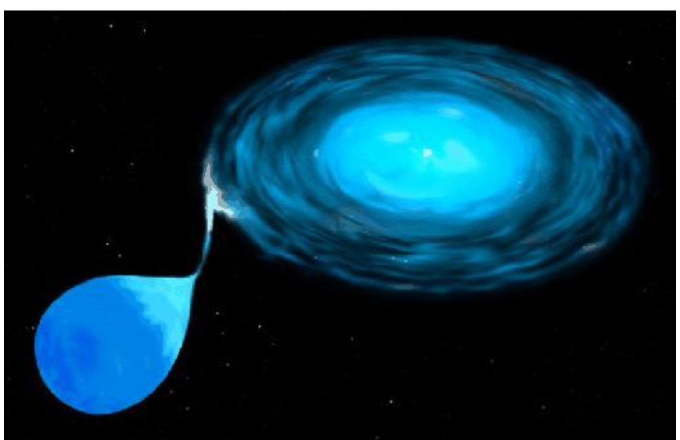
Vortices in rotating superfluid helium (Yarmchuk et al.(1979))

Various types of pulsars

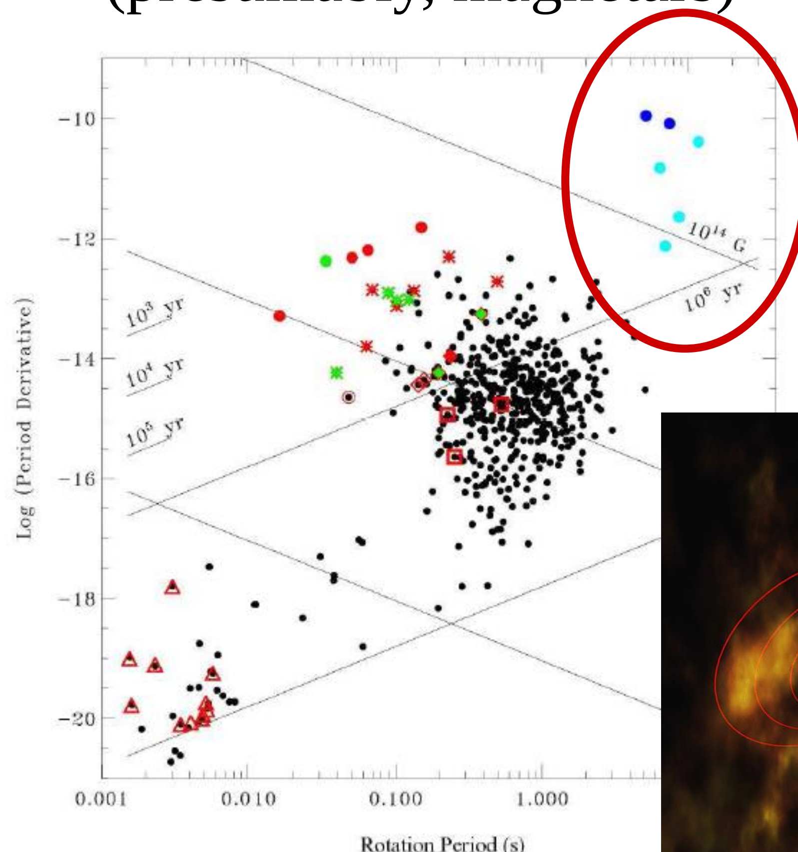
- Double pulsar (PSR J0737-3039 alone)

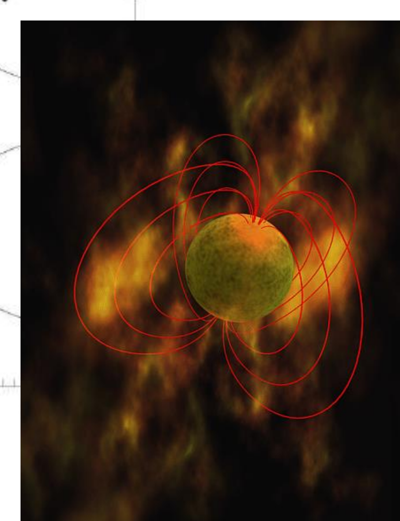


- X-ray pulsars
(accretion-powered pulsars)



- Anomalous X-ray pulsars
(presumably, magnetars)

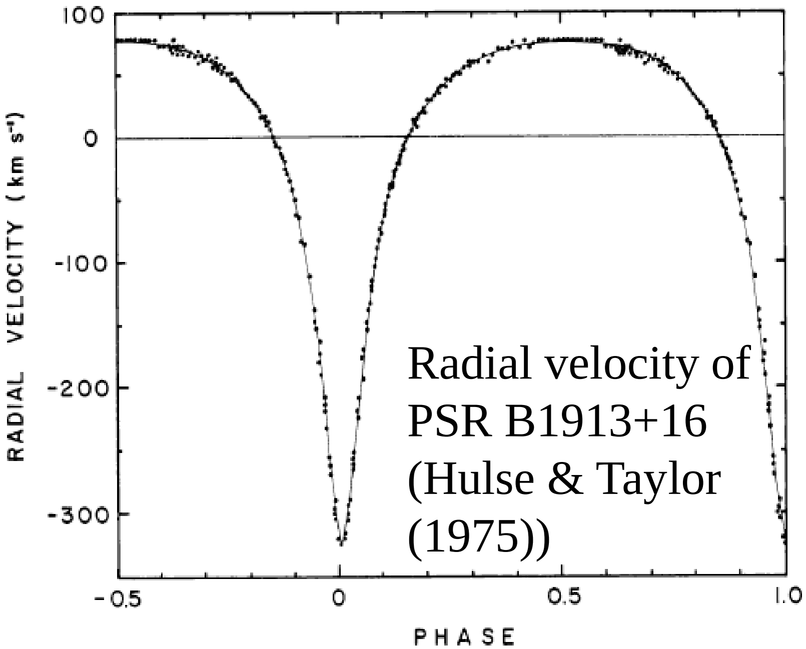




Imaginary drawing by NASA

Neutron star mass determination by Hulse & Taylor

A pulsar with a binary companion:
Observed orbital motion → mass measurement!



Radial velocity of PSR B1913+16 (Hulse & Taylor (1975))

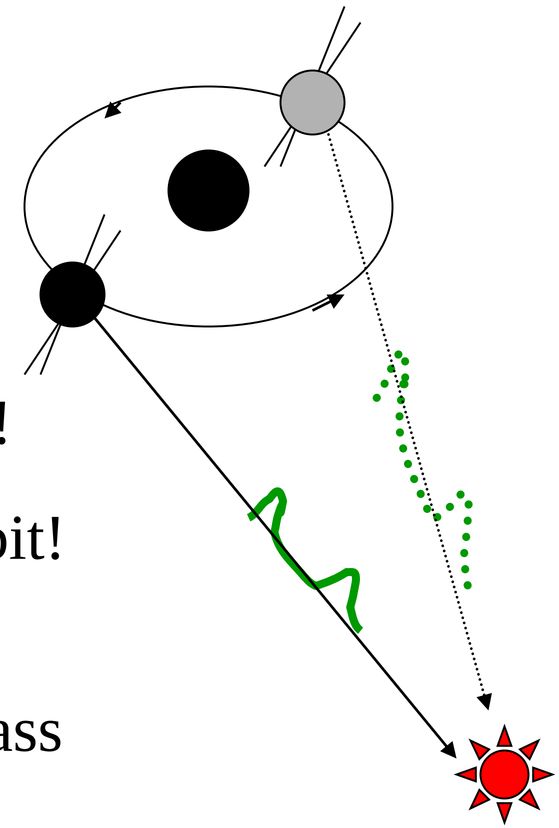
The companion of PSR B1913+16 is also a neutron star!

⇩

Post-Keplerian orbit!

⇩

General relativity allows accurate mass determination!



Neutron star–neutron star binaries

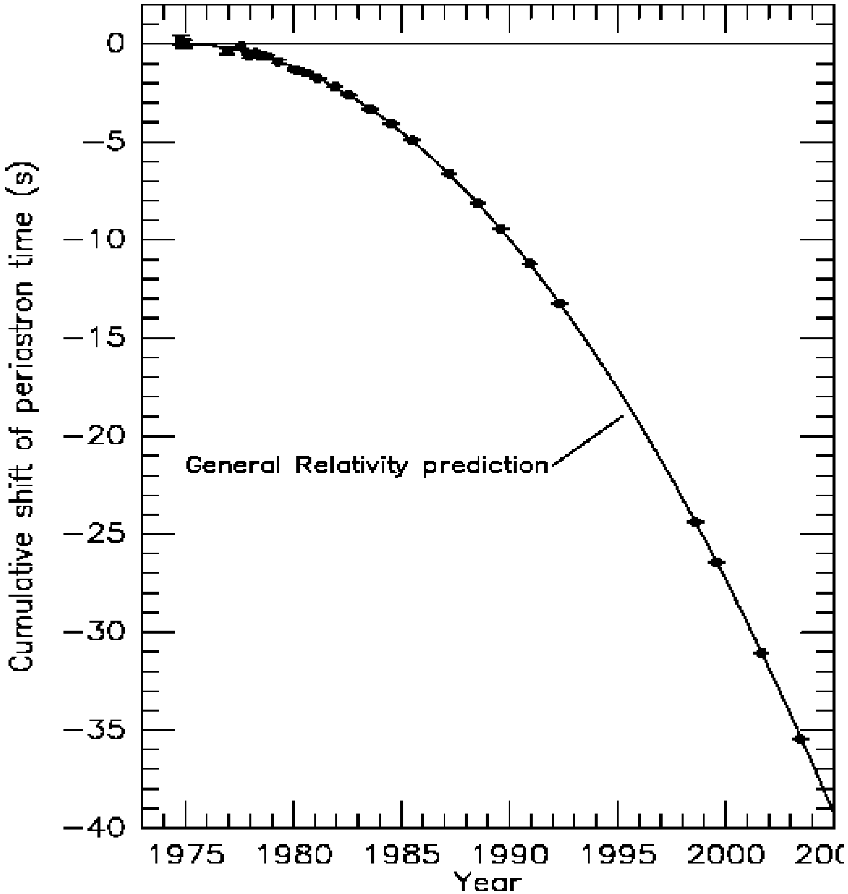
1518+49	$1.56^{+0.13}_{-0.44}$	(88)	1518+49 companion	$1.05^{+0.45}_{-0.11}$	(88)
1534+12	$1.3332^{+0.0010}_{-0.0010}$	(88)	1534+12 companion	$1.3452^{+0.0010}_{-0.0010}$	(88)
1913+16	$1.4408^{+0.0003}_{-0.0003}$	(88)	1913+16 companion	$1.3873^{+0.0003}_{-0.0003}$	(88)
2127+11C	$1.349^{+0.040}_{-0.040}$	(88)	2127+11C companion	$1.363^{+0.040}_{-0.040}$	(88)
J0737-3039A	$1.337^{+0.005}_{-0.005}$	(46)	J0737-3039B	$1.250^{+0.005}_{-0.005}$	(46)

Mean = 1.34 $M_\odot$, weighted mean = 1.41 $M_\odot$

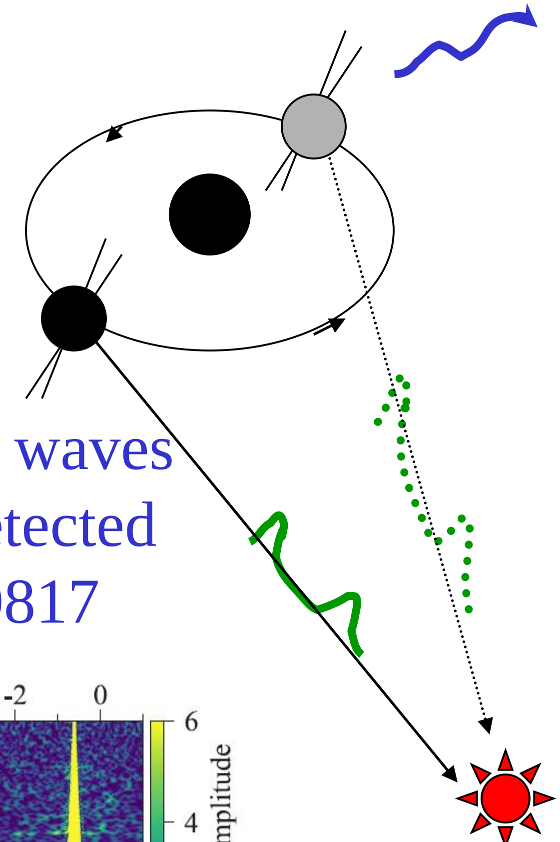
Lattimer & Prakash (2004)

Neutron star mass determination by Hulse & Taylor (contd.)

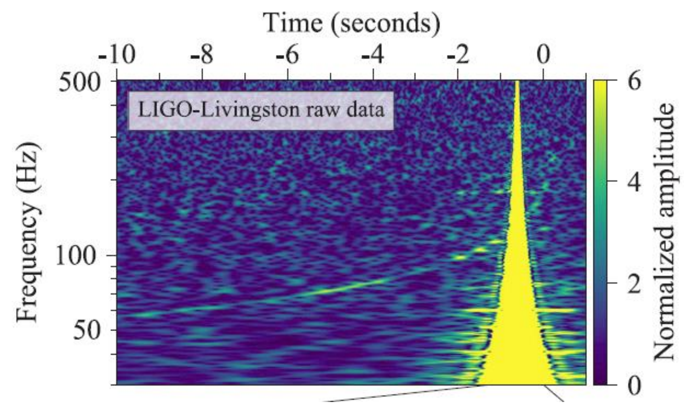
Observed decrease in the orbital period was successfully explained by emission of gravitational waves predicted by general relativity.



Decreasing orbital period of PSR B1913+
(Weisberg & Taylor (2004))

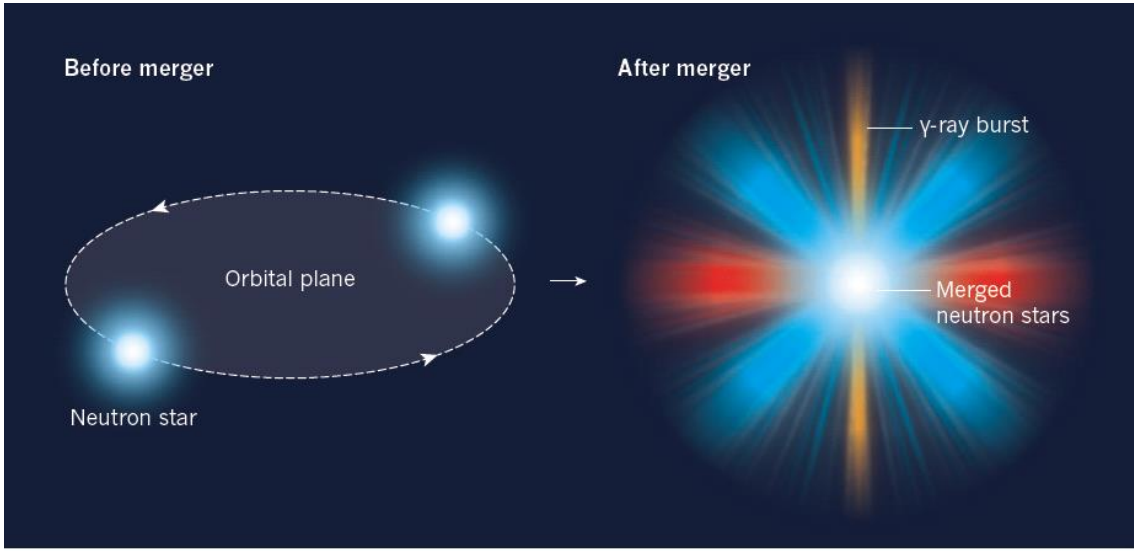


Gravitational waves eventually detected from GW170817

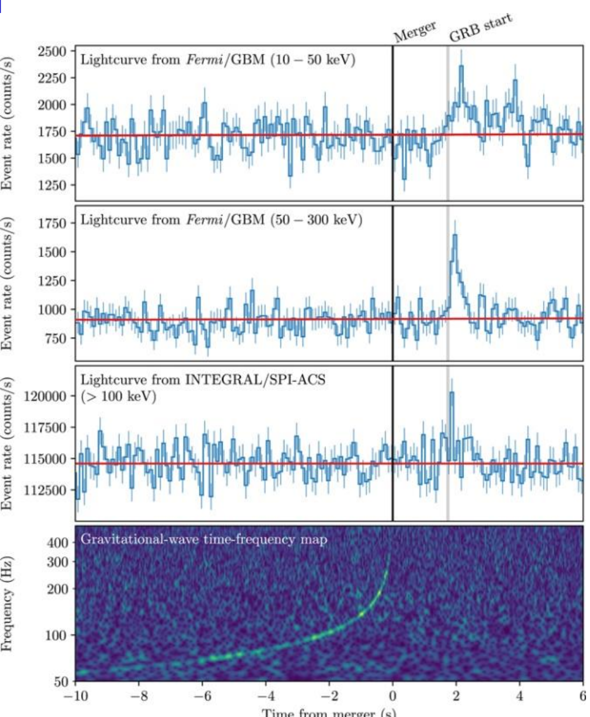


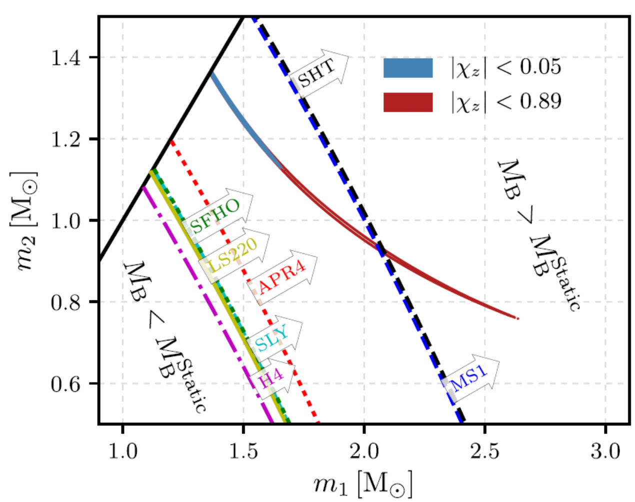
LIGO-Livingston (2017)

Multimessenger observations of GW170817



By Coleman Miller
(Nature **551,** 36 (2017))





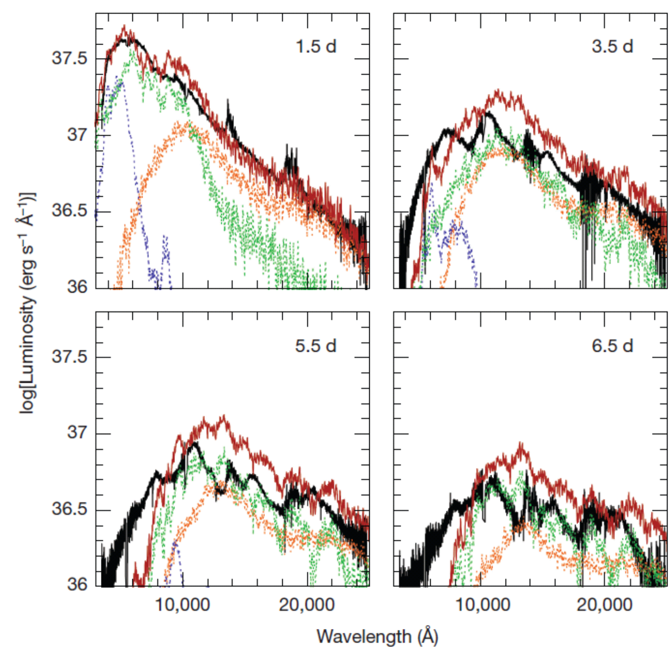


Figure 3 | Kilonova models compared with the AT 2017gfo spectra.

Abbott et al. ApJ **848,** L13 (2017).

Pian et al. Nature **551,** 67 (2017).

観測されている高密度縮退星

白色矮星

<孤立>

視差

↓

輻射スペクトル・偏光 → R, M, B, P

<近接連星系>

矮新星

新星爆発

磁気激変星

輻射スペクトル・偏光→B

X線輝線→M, R

超軟X線源？

I型超新星爆発？

中性子星

<孤立>

回転駆動型パルサー→ P, (B, age)

軟X線源（超新星残骸中、**再起性γ線バースター(SGR)**、異常なX線パルサー(AXP)、孤立した若い中性子星(XDINS)、...）

<近接連星系>

X線バースター

輻射スペクトル→ P, (R)

降着駆動型パルサー → P

サイクロトロン吸収線→B

公転→M

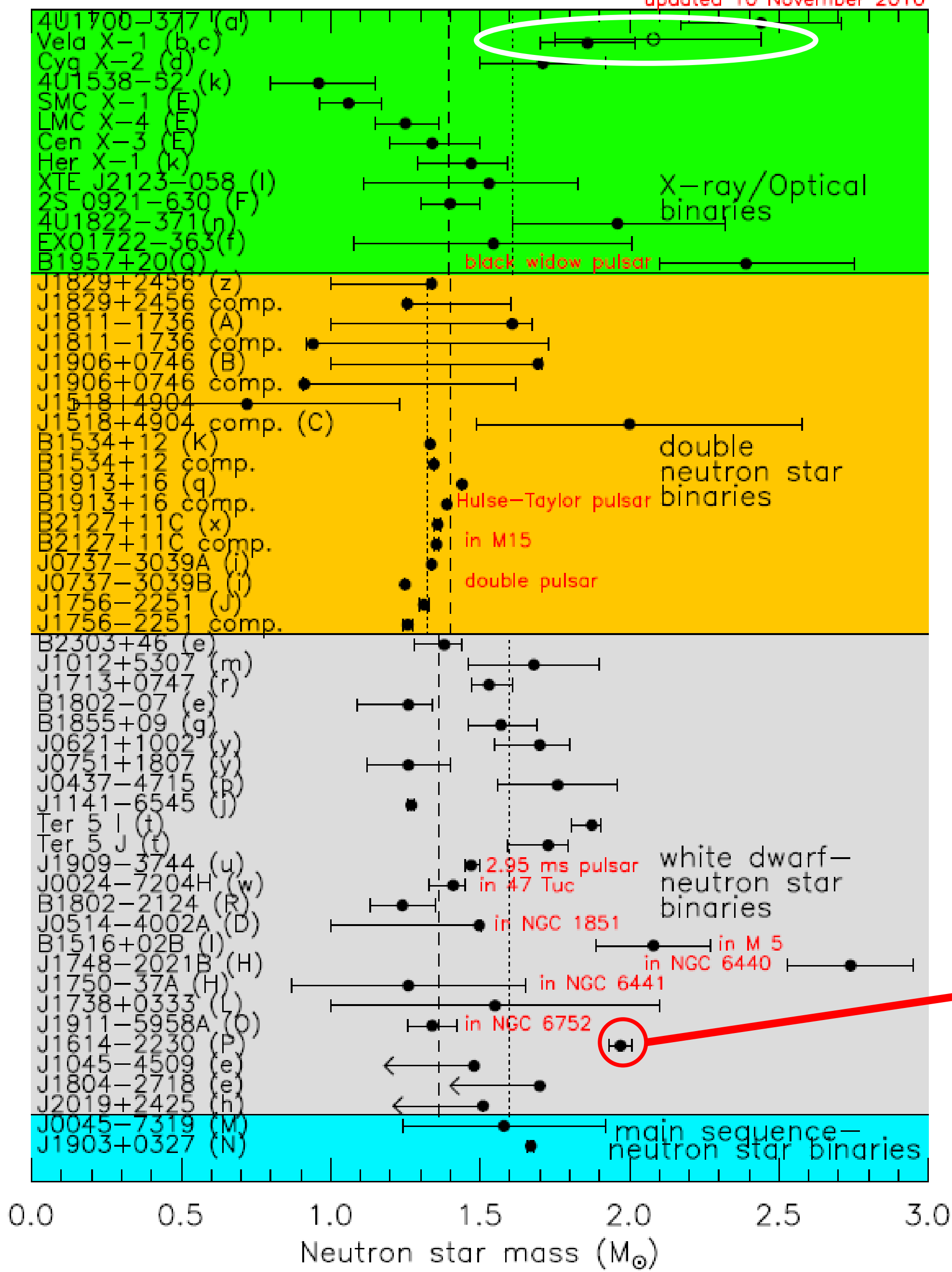
回転駆動型パルサー → P

公転→M

γ線バースター？

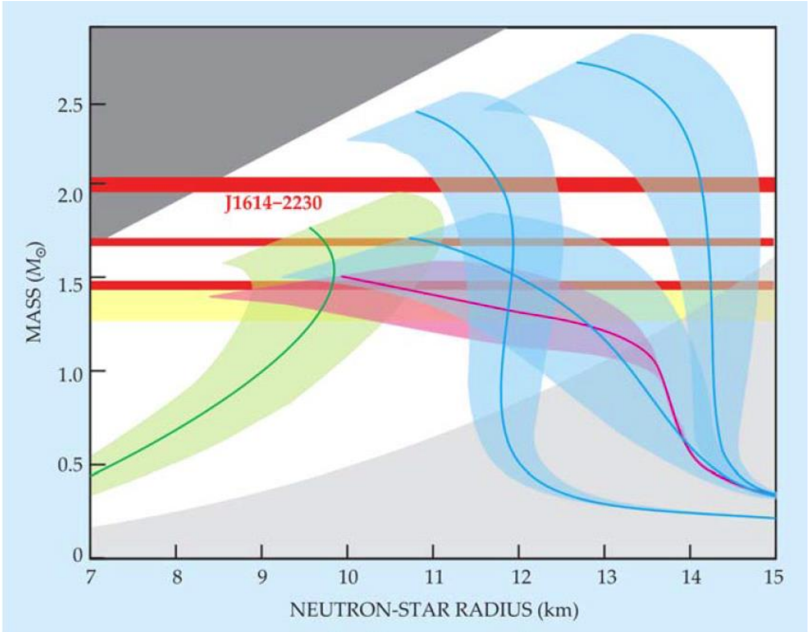
Welcome to the neutron star world!

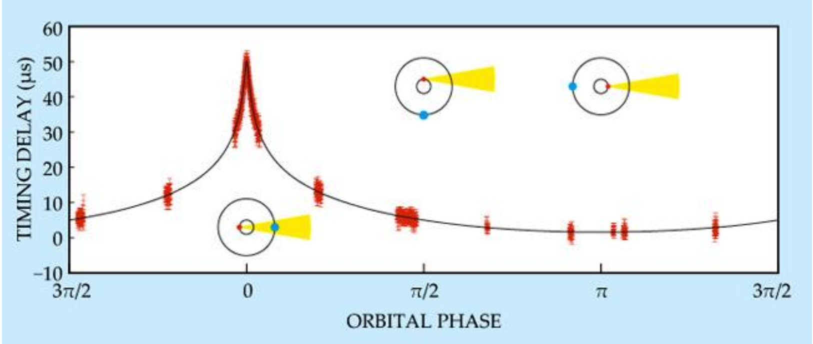
Observed masses



Lattimer & Prakash, arXiv:1012.3208.

Pulsar twice as heavy as the Sun





Demorest et al. (2010)

The Best Measured Neutron Star Radii

$R_\infty < 5\%$

Name	R_∞ (km/D)	D (kpc)	$kT_{eff,\infty}$ (eV)	N_H (10^{20} cm^{-2})	Ref.
omega Cen (Chandra)	13.5 ± 2.1	5.36 ±6%	66^{+4}_{-5}	(9)	Rutledge et al (2002)
omega Cen** (XMM)	13.6 ± 0.3	5.36 ±6%	67 ±2	9 ± 2.5	Gendre et al (2002)
M13** (XMM)	12.6 ± 0.4	7.80 ±2%	76 ±3	(1.1)	Gendre et al (2002)
47 Tuc X7 (Chandra)	34_{-13}^{+22}	5.13 ±4%	84^{+13}_{-12}	$0.13^{+0.06}_{-0.04}$	Heinke et al (2006)
M28** (Chandra)	$14.5_{-3.8}^{+6.9}$	5.5 ±10%	90_{-10}^{+30}	26 ± 4	Becker et al (2003)
M30 (Chandra)	$16.9_{-4.3}^{+5.4}$	--	94_{-12}^{+17}	$2.9^{+1.7}_{-1.2}$	Lugger et al (2006)
NGC 2808 (XMM)	??	9.6 (?)	103_{-33}^{+18}	18^{+11}_{-7}	Webb et al (2007)

Caveats:

- All IDd by X-ray spectrum (47 Tuc, Omega Cen now have optical counterparts)
- calibration uncertainties

Distances:
Carretta et al (2000), Thompson et al (2001)

Quiescent low-mass X-ray binaries in globular clusters

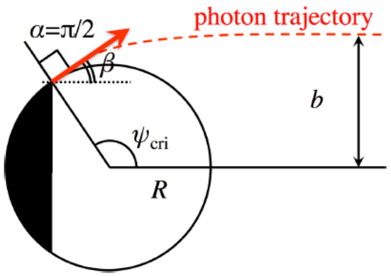
Apparent radius:

$$R_\infty = \frac{R}{\sqrt{1 - 2GM/Rc^2}}$$

Distance to the globular cluster

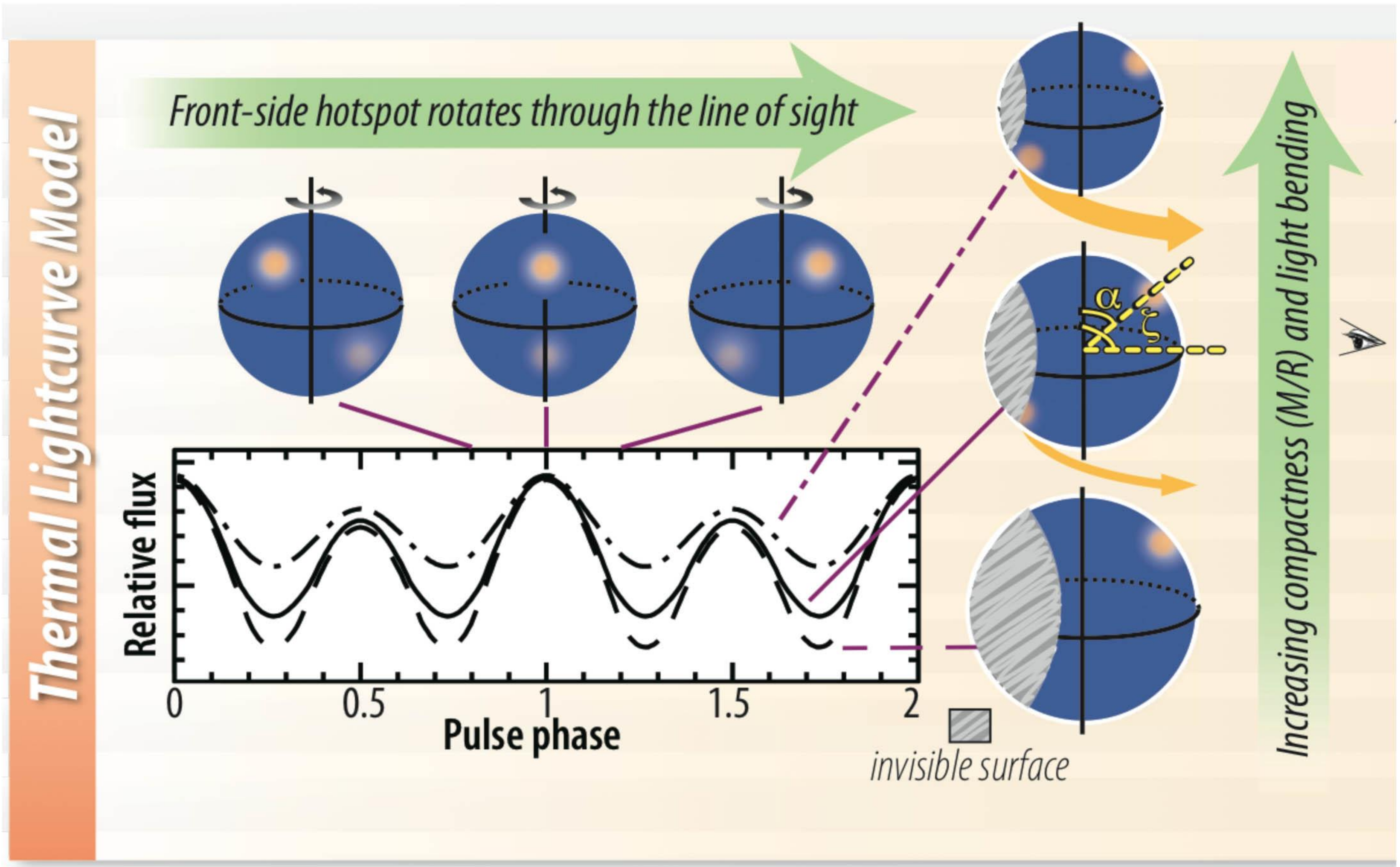
Rutledge (2010)

NICER (Neutron star Interior Composition ExploreR)



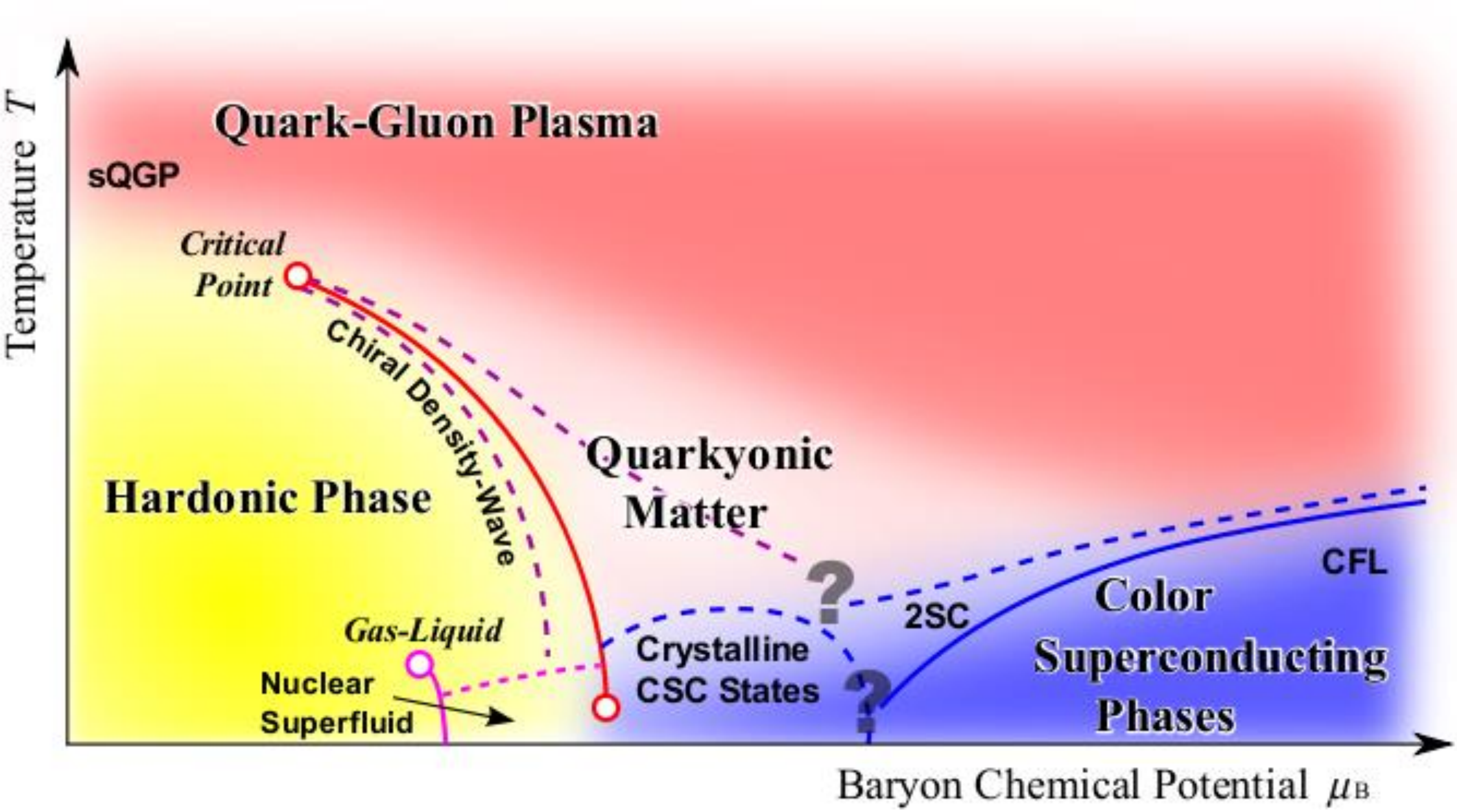
Deducing *M/R* from light curves of msec pulsars

Sotani & Miyamoto (2017)



https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about.html

Nuclear matter

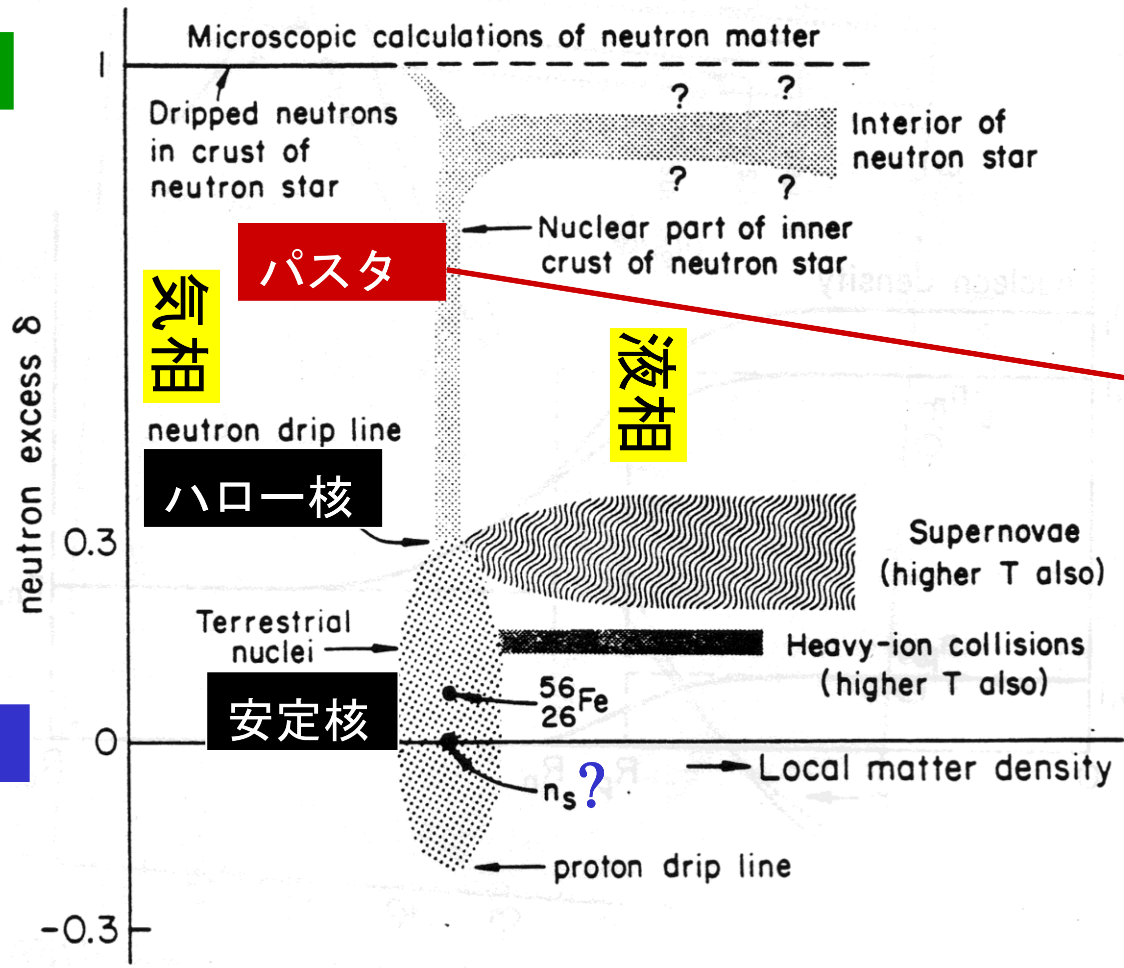


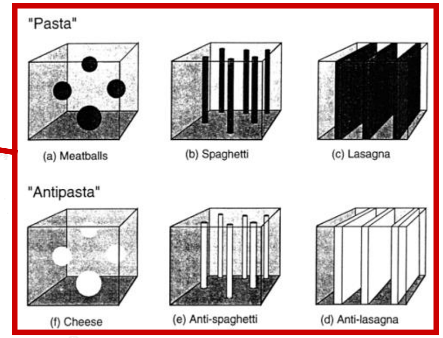
By Fukushima

Systems composed of nuclear matter

中性子物質

対称核物質





From Lamb (1991).

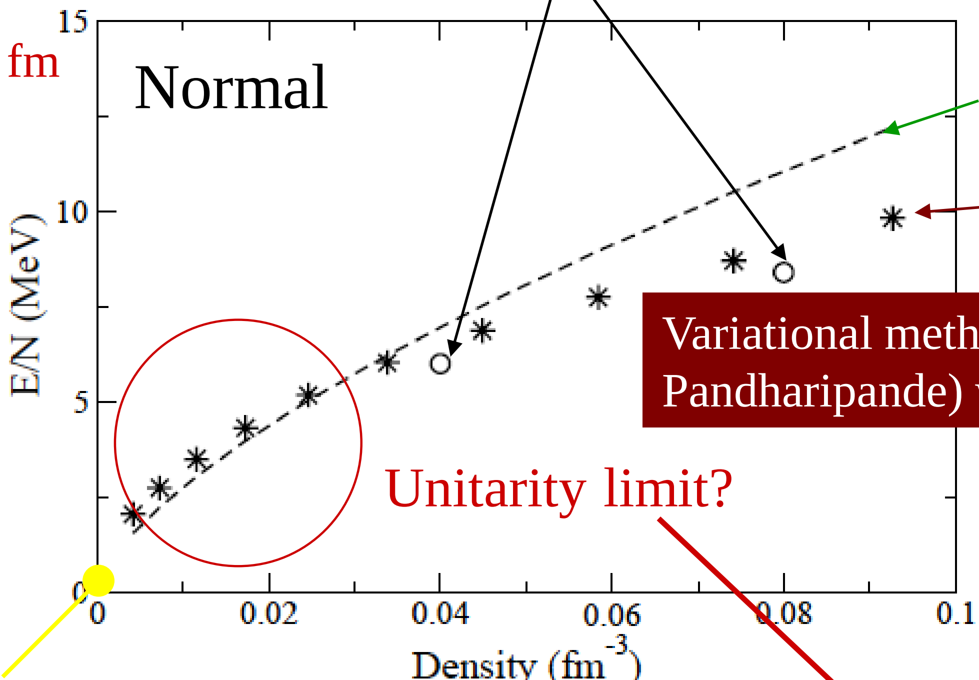
Pethick & Ravenhall, ARNPS **45** (1995) 429.

Microscopic EOS calculations

Pure neutron matter

Scattering length $a \approx -18$ fm
Effective range ≈2 fm

Green's function Monte-Carlo (GFMC) with Argonne v_8'



$0.5E_{FG}/N$

Variational method (Friedman-Pandharipande) with Urbana v_{14}+TNI

Unitarity limit?

$|a| >> k_F^{-1} >> R$

Low - density expansion :

$$E = E_{FG}\left[1 + \frac{10}{9\pi}k_F a + \frac{4}{21\pi^2}(11 - 2\ln 2)(k_F a)^2 + \ldots\right]$$

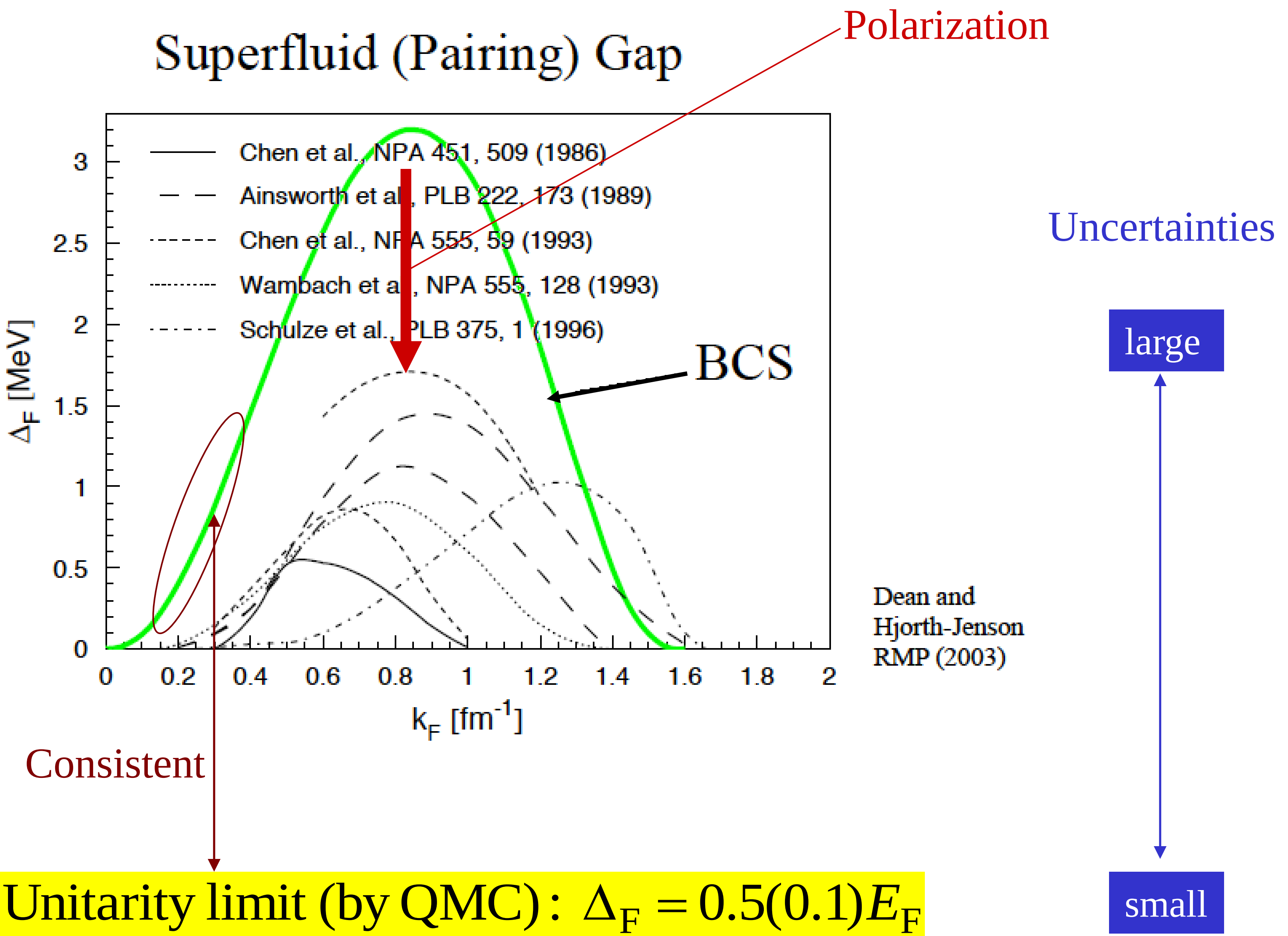
Ref. Carlson et al., PRC **68** (2003) 025802.

Symmetric nuclear matter

Variational method: Overbinding without phenomenological three-nucleon forces

Microscopic EOS calculations (contd.)

Pure neutron matter



$$\text{Unitarity limit (by QMC)}: \ \Delta_F = 0.5(0.1) E_F$$

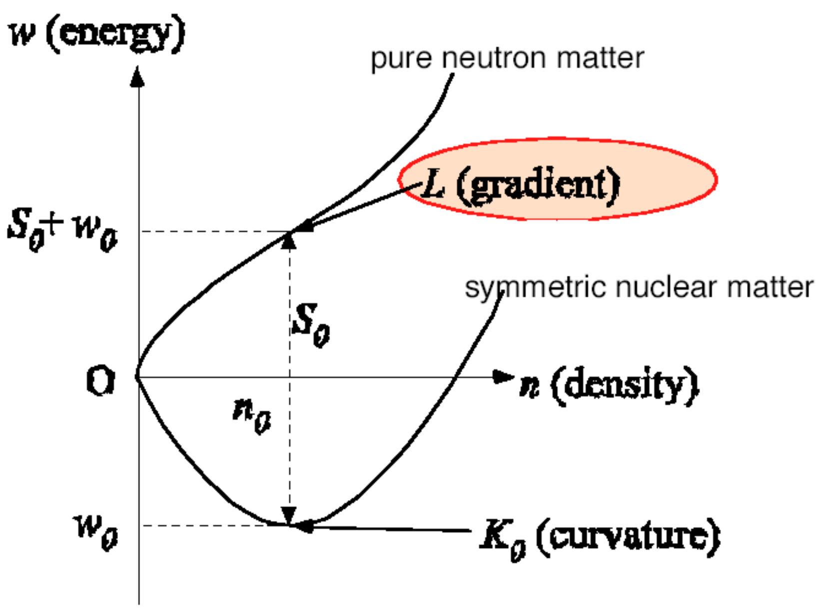
Ref. Carlson and Reddy, PRL **95** (2005) 060401.

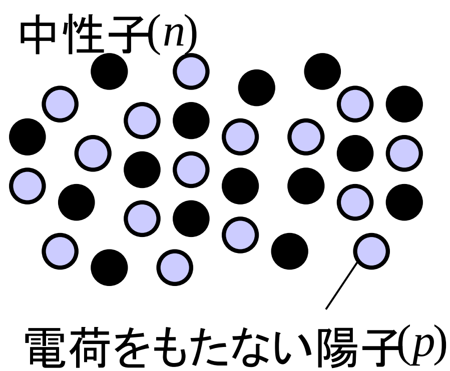
Phenomenological EOS parameters

Energy per nucleon of bulk nuclear matter near the saturation point (nucleon density n, neutron excess $\alpha=(n_n-n_p)/n$):

$$w = w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\alpha^2$$

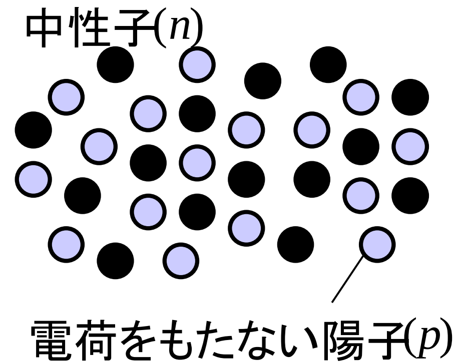
n_0, w_0	saturation density & energy of symmetric nuclear matter
S_0	symmetry energy coefficient
K_0	incompressibility
L	density symmetry coefficient





核物質（仮想的）

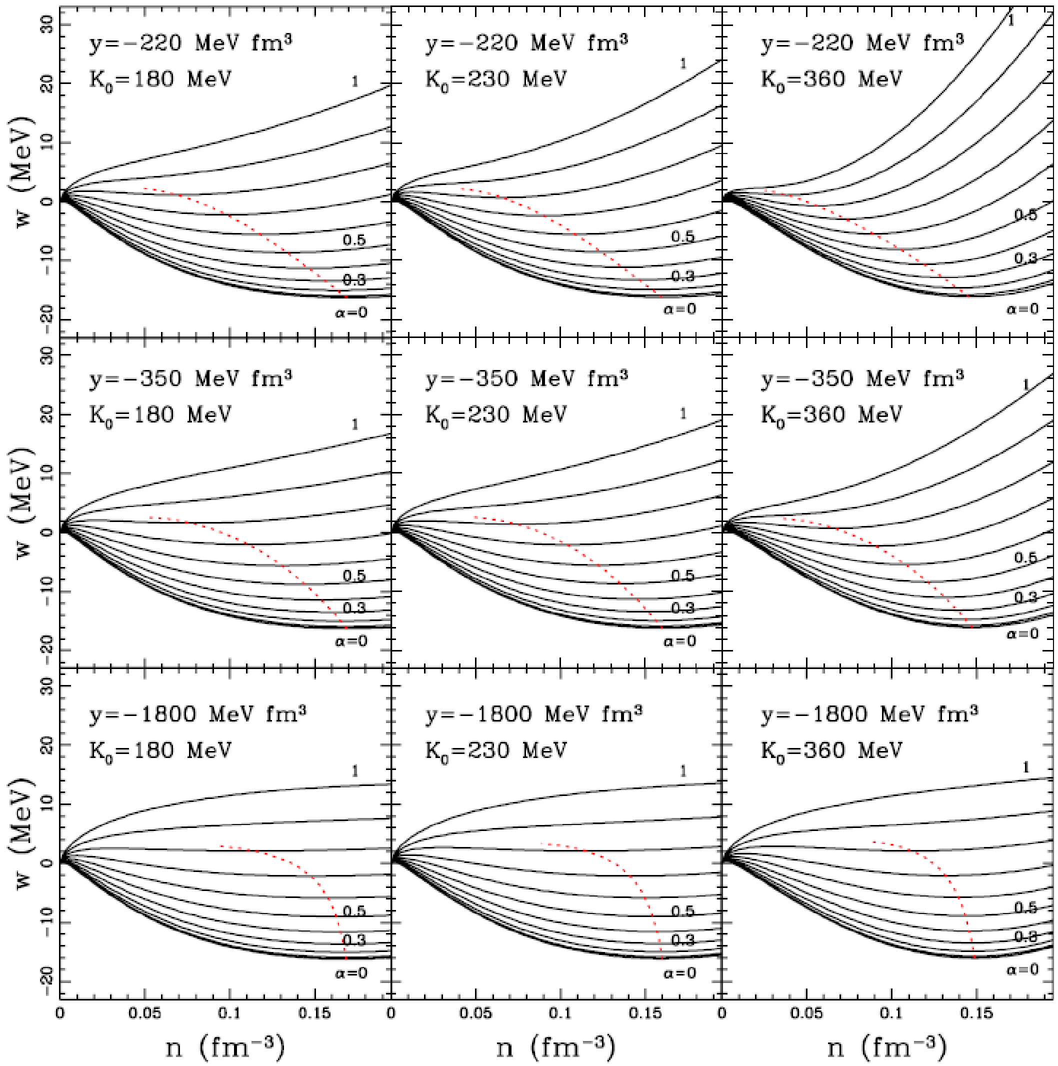
ゼロ温度での核物質の状態方程式



核物質（仮想的）

非圧縮率 →

対称エネルギーの密度勾配 ↑



9つの極端な例

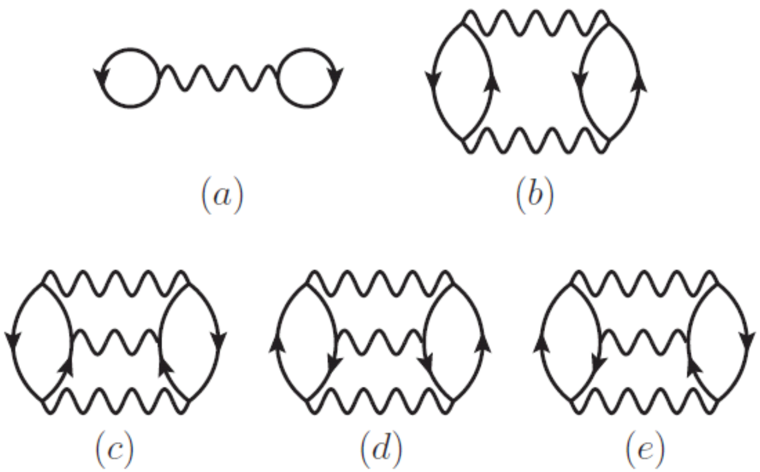
・安定核の半径・質量データは同様に再現

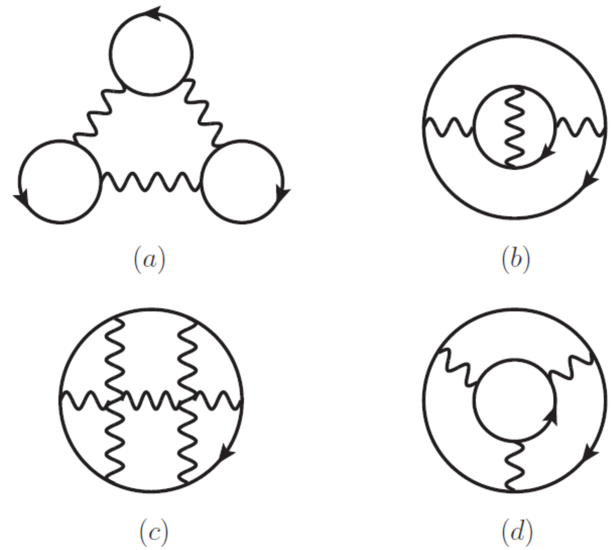
・将来の不安定核データで峻別可能？

Ref. Oyamatsu & Iida, PTP **109** (2003) 631 ; Kohama, Iida, & Oyamatsu PRC **72** (2005) 024602.

Many-body perturbation calculations with chiral 2N, 3N, 4N interactions

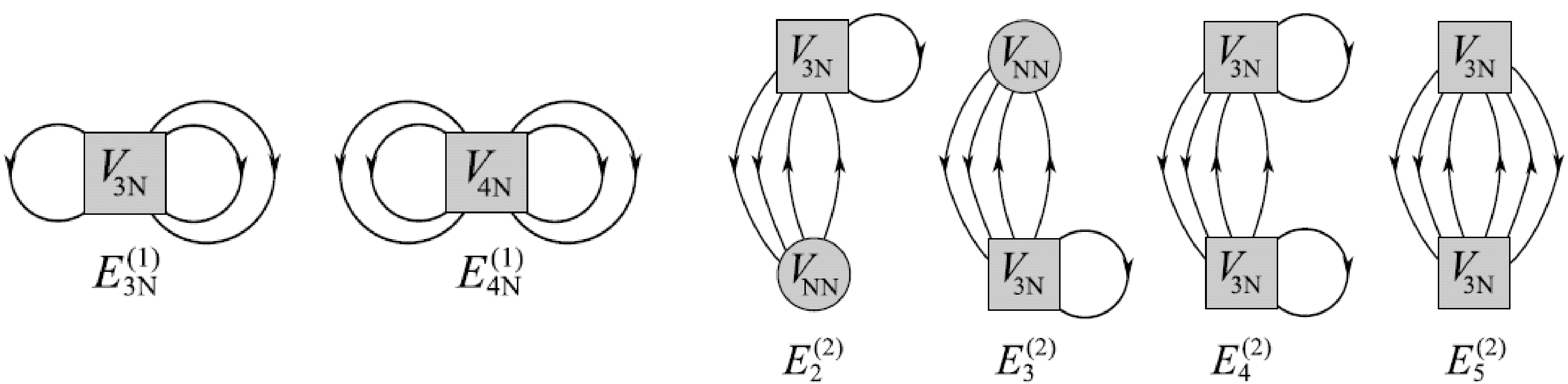
1^{st}, 2^{nd}, 3^{rd} order pp and 3^{rd} ph contributions due to 2N interactions:





Ref. Holt & Kaiser, PRC **95** (2017) 034326.

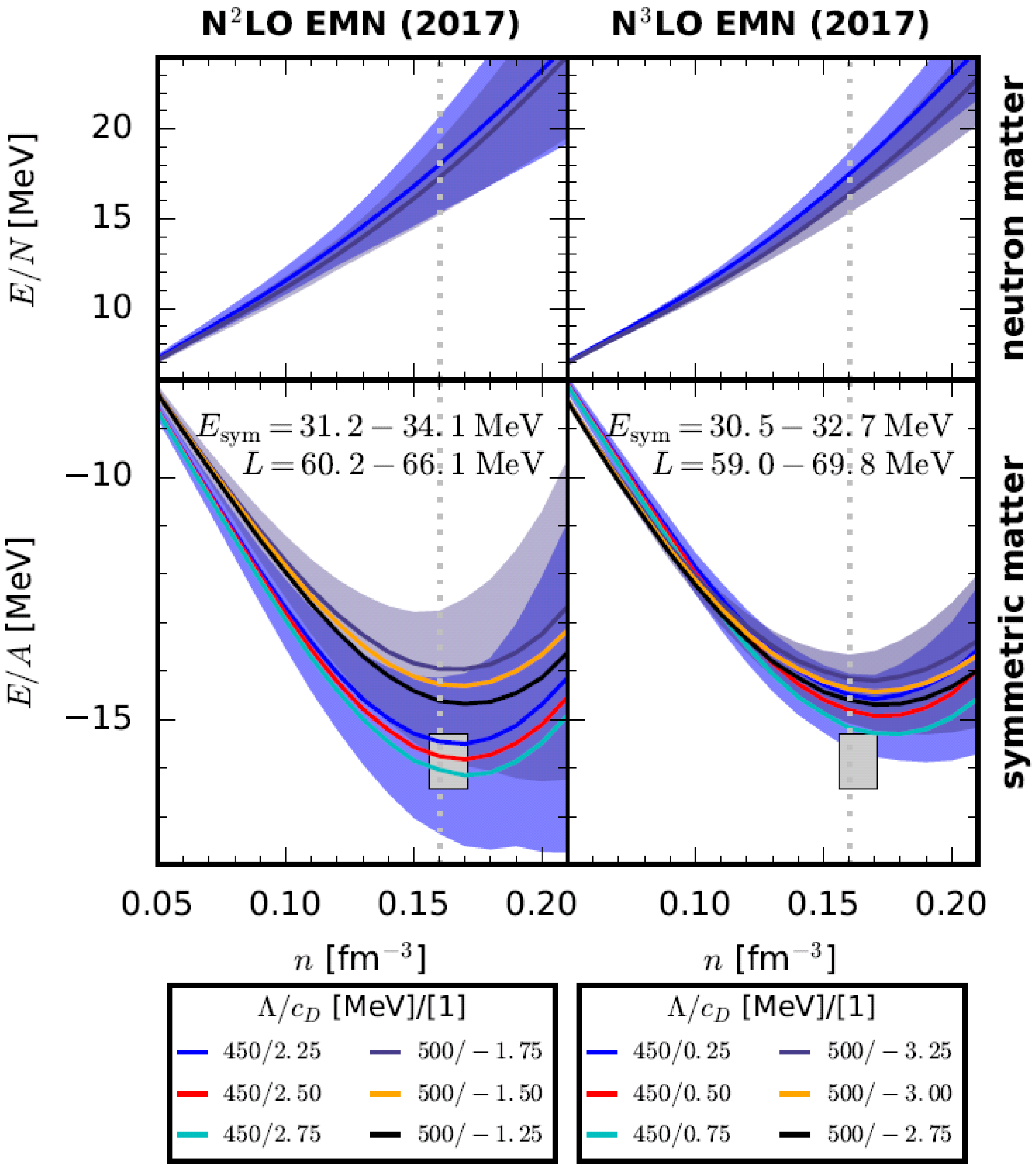
1^{st}, 2^{nd} order pp contributions due to 3N and 4N interactions:



Ref. Krüger, Tews, Hebeler, & Schwenk, PRC **88** (2013) 025802.

Many-body perturbation calculations with chiral 2N, 3N, 4N interactions

Up to 4[th] order:



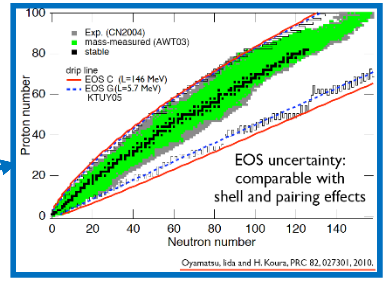
3N interaction parameters fitted to the empirical saturation region and triton binding energy

Ref. Drischler, Hebeler, & Schwenk, arXiv:1710.08220.

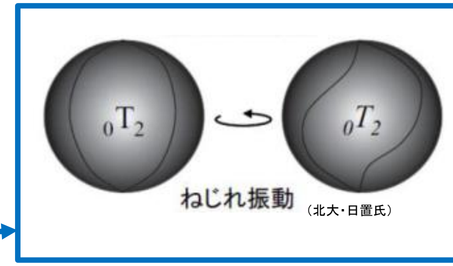
Ref. Iida & Oyamatsu, EPJA **50** (2014) 42.

これまでの核物質研究のまとめ

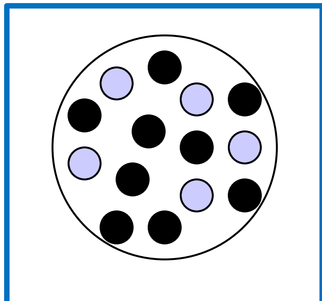
中性子ドリップ線



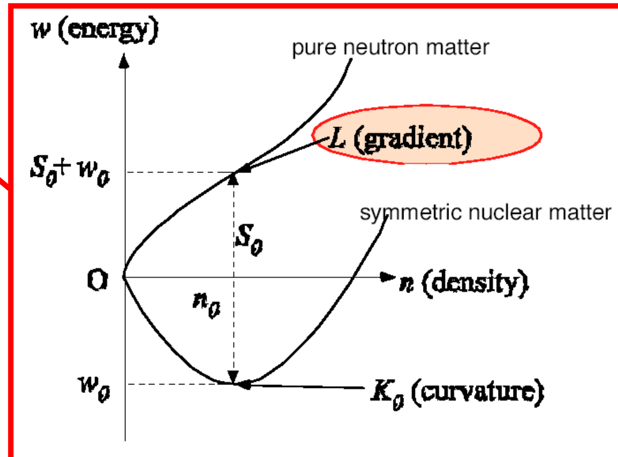
中性子星クラストのずりモード



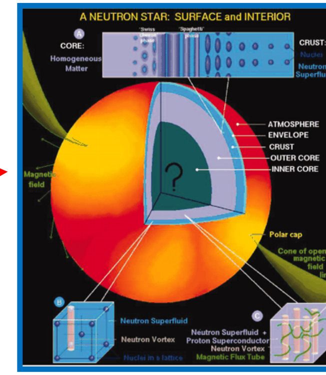
中性子過剰核の半径・質量



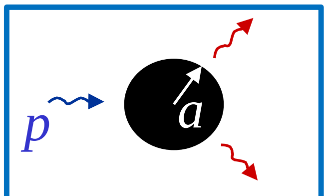
核物質の状態方程式



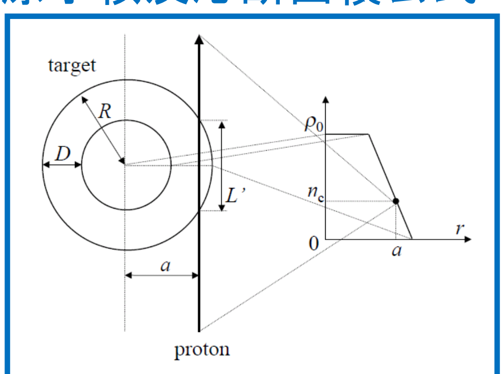
軽い中性子星の質量・半径



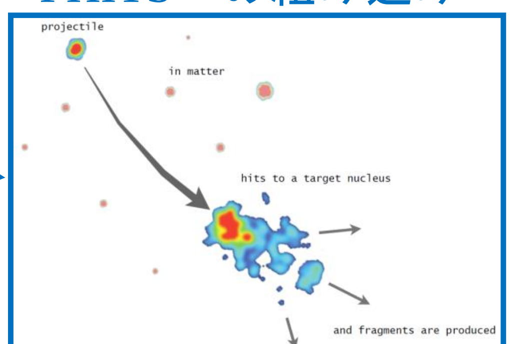
原子核のくろたま模型



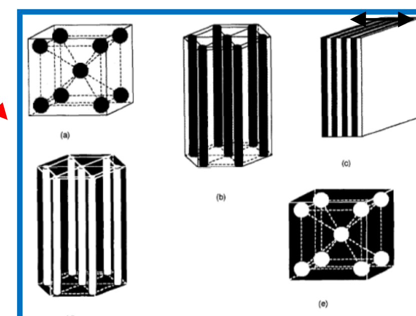
原子核反応断面積公式

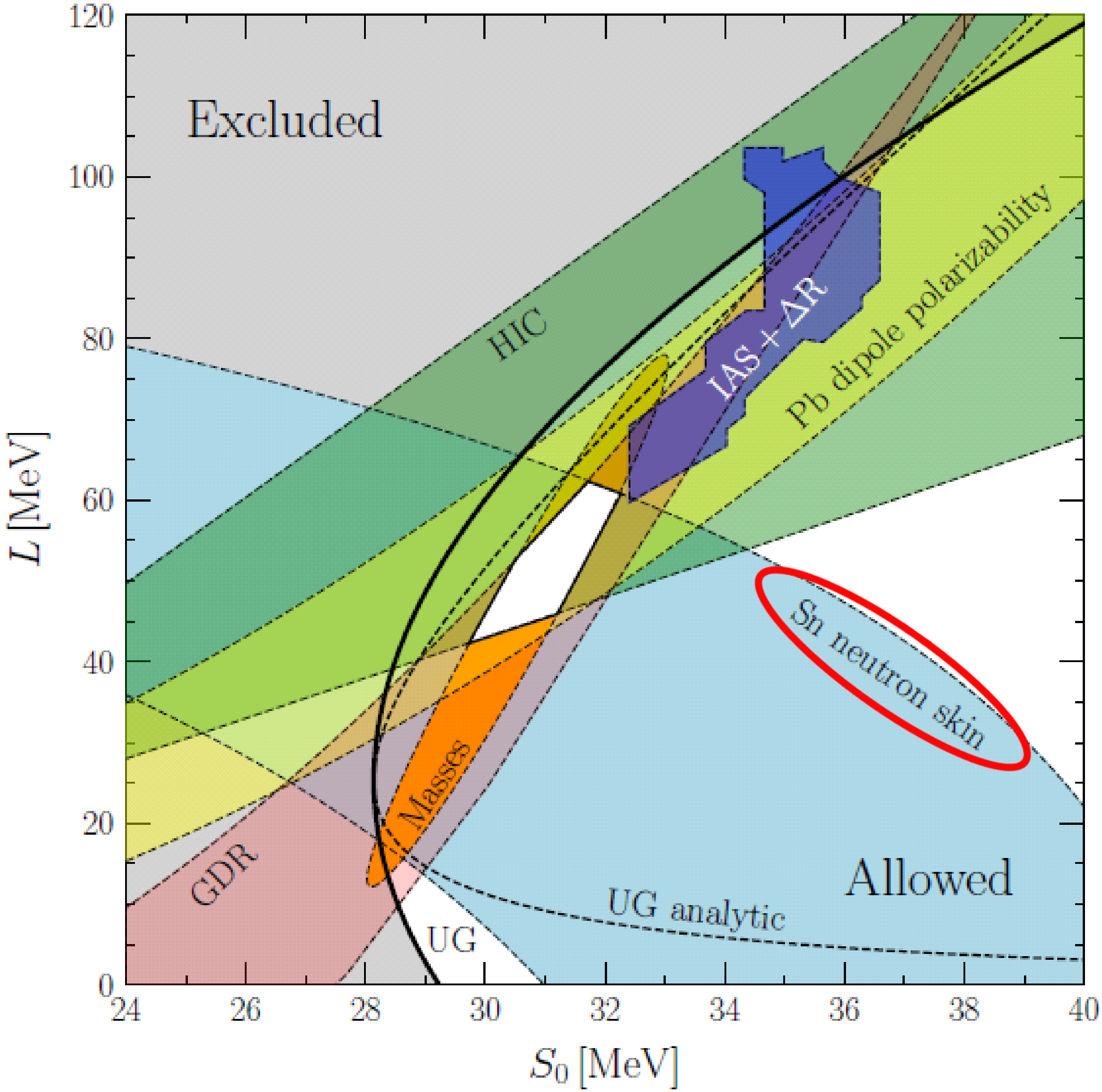


PHITSへの組み込み



中性子星クラスト中での パスタ原子核の存在領域





Ref. Tews, Lattimer, Ohnishi, & Kolomeitsev, arXiv:1611.07133.

Compressible liquid-drop model

Ref. Iida & Oyamatsu, PRC **69** (2004) 037301.

Semi-empirical mass formula: $-E_B = E_{vol} + E_{sur} + E_{Coul}$

For a spherical nucleus ($R_p \approx R_n$),

$$E_{vol} = Aw(n_{in}, \delta_{in})$$

$$w(n,\delta) \xrightarrow{\delta\approx 0,\, n\approx n_0} w_0 + \frac{K_0}{18n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\delta^2$$

n_0, $w_0 \approx 0.14\text{-}0.17\ \mathrm{fm}^{-3}, -16$ MeV   saturation point of symmetric nuclear matter

$S_0 \approx 25\text{-}40$ MeV   symmetry energy coefficient

$K_0 \approx 180\text{-}360$ MeV   incompressibility

$L \approx 0\text{-}200$ MeV   density symmetry coefficient

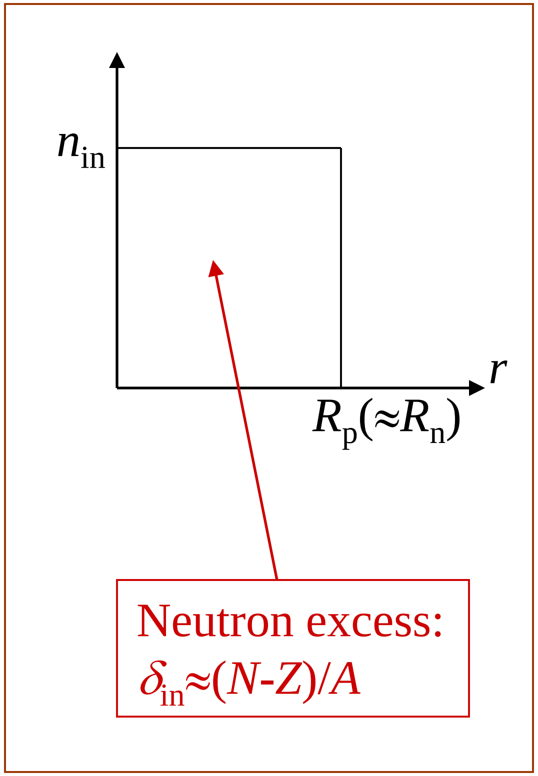
$$E_{sur} = 4\pi\sigma(n_{in}, \delta_{in})R_p^2$$

$$\sigma(n,\delta) \xrightarrow{\delta\approx 0,\, n\approx n_0} \sigma_0\left[1 - C_{sym}\delta^2 + \chi\left(\frac{n-n_0}{n_0}\right)\right]$$

$\sigma_0 \approx 1\ \mathrm{MeV\ fm}^{-2}$ surface tension at $\delta = 0$ and $n = n_0$

$C_{sym} \approx 1.5 - 2.5$ surface symmetry energy coefficient

$$E_{Coul} = \frac{3Z^2e^2}{5R_p}$$



$\chi=0$ Myers & Swiatecki (1969)
$\chi \approx 1/2$ Yamada (1964)
$\chi=4/3$ Fermi-gas model

Nucleon density in the nuclear interior

Ref. Iida & Oyamatsu, PRC **69** (2004) 037301.

Pressure equilibrium: $\delta E_B|_{A,Z} = 0$, i.e., $P_{vol} + P_{sur} + P_{Coul} = 0$

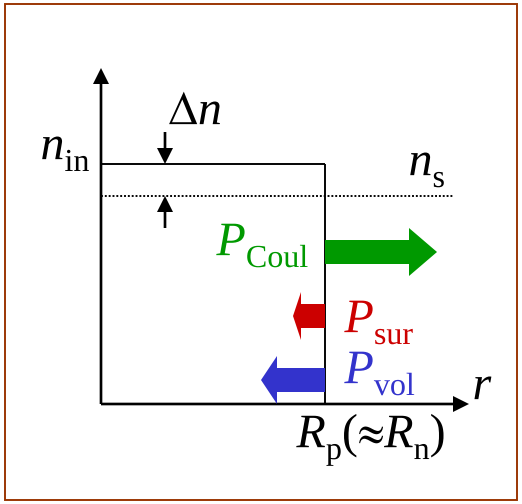
$$P_{vol} \approx \frac{K_0}{9}(n_{in} - n_0) + \frac{L}{3} n_0 \delta_{in}^2 \equiv \frac{K_0}{9}(n_{in} - n_s)$$

$$w(n,\delta) \xrightarrow{\delta\approx 0,\, n\approx n_0} w_0 + \frac{K_0}{18 n_0^2}(n-n_0)^2 + \left[S_0 + \frac{L}{3n_0}(n-n_0)\right]\delta^2$$

$$P_{sur} \approx -\frac{2\sigma_0}{R_p}\left(1 - \frac{3}{2}\chi\right) \quad =0 \ \text{ at } \chi=2/3 \ !$$

$$\sigma(n,\delta) \xrightarrow{\delta\approx 0,\, n\approx n_0} \sigma_0\left[1 - C_{sym}\delta^2 + \chi\left(\frac{n-n_0}{n_0}\right)\right]$$

$$P_{Coul} = \frac{Z^2 e^2}{5VR_p}, \quad V = A n_{in}^{-1}$$



Saturation density of uniform matter at neutron excess δ_{in}: $n_s = n_0 - \frac{3n_0 L}{K_0}\delta_{in}^2$ $(\leftarrow P_{vol}=0)$

Density difference:

$$\Delta n \equiv n_{in} - n_s \approx -\frac{9}{K_0}(P_{sur} + P_{Coul}) \sim 0.1 n_0 \quad \text{for } \chi = 0$$

$$\sim -0.1 n_0 \quad \text{for } \chi = 4/3$$

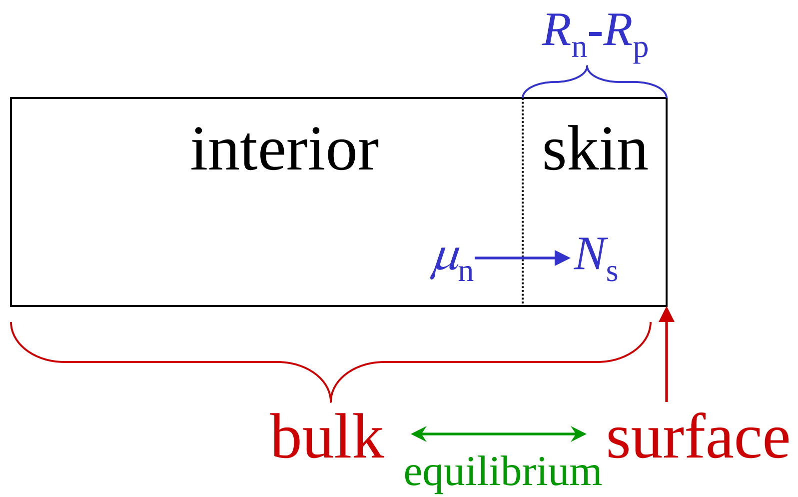
Neutron skin thickness

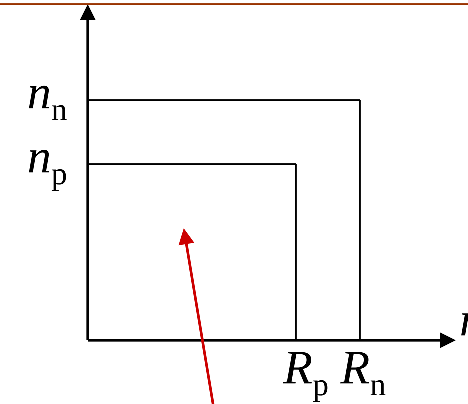
Ref. Iida & Oyamatsu, PRC **69** (2004) 037301.

——— a quantity useful for deduction of the value of χ

Thermodynamic description of the nuclear surface

Ref. Pethick & Ravenhall, NPA **606**(1996)173.





Neutron excess:
$\delta_{in} = (n_n - n_p)/(n_n + n_p)$
$\approx (N-Z)/A - 3(R_n - R_p)/2R_p$

Small change in δ_{in} → $\Delta\Omega = -N_s \Delta\mu_n$

Surface tension:
$s = (\Omega_{tot} - \Omega_{bulk})$ / (area of the surface)

Neutron skin:
adsorbed neutrons at the surface

In the absence of Coulomb energy,

$$R_n - R_p \approx C\frac{N-Z}{A}\left(1+\frac{3C}{2R_p}\right)^{-1}, \quad C \equiv \frac{2\sigma_0}{S_0 n_0}\left(C_{sym}+\frac{3L\chi}{K_0}\right)$$

Neutron skin thickness (contd.)

Ref. Iida & Oyamatsu, PRC **69** (2004) 037301.

Coulomb effects

Ref. Myers & Swiatecki, NPA **336**(1980)267.

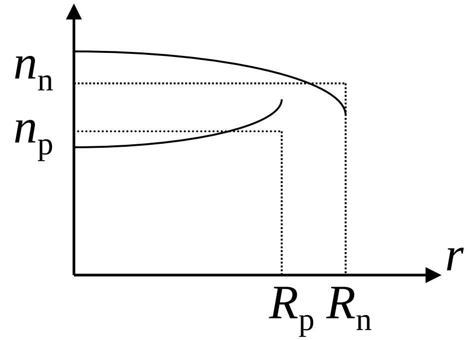
· Reduction of the neutron-skin driving force

$$R_n - R_p \propto \frac{N-Z}{A} \quad \Rightarrow \quad R_n - R_p \propto \frac{N-Z}{A} - \frac{Ze^2}{20 R_p S_0}$$

proton skin at $N=Z$

· Polarization of the nuclear interior

$$R_n - R_p \Rightarrow R_n - R_p - \frac{Ze^2}{70 S_0}$$



Eventually,

$$R_n - R_p \approx C\left(\frac{N-Z}{A} - \frac{Ze^2}{20 R_p S_0}\right)\left(1 + \frac{3C}{2R_p}\right)^{-1} - \frac{Ze^2}{70 S_0}, \; C \equiv \frac{2\sigma_0}{S_0 n_0}\left(C_{sym} + \frac{3L\chi}{K_0}\right)$$

Poorly known

Cf. The diffuseness correction is ignored.

Diffuseness correction to neutron skin thickness

$$\Delta r_{np}^{\mathrm{surf}} \simeq \sqrt{\frac{3}{5}}\frac{5}{2R}(b_n^2 - b_p^2)$$

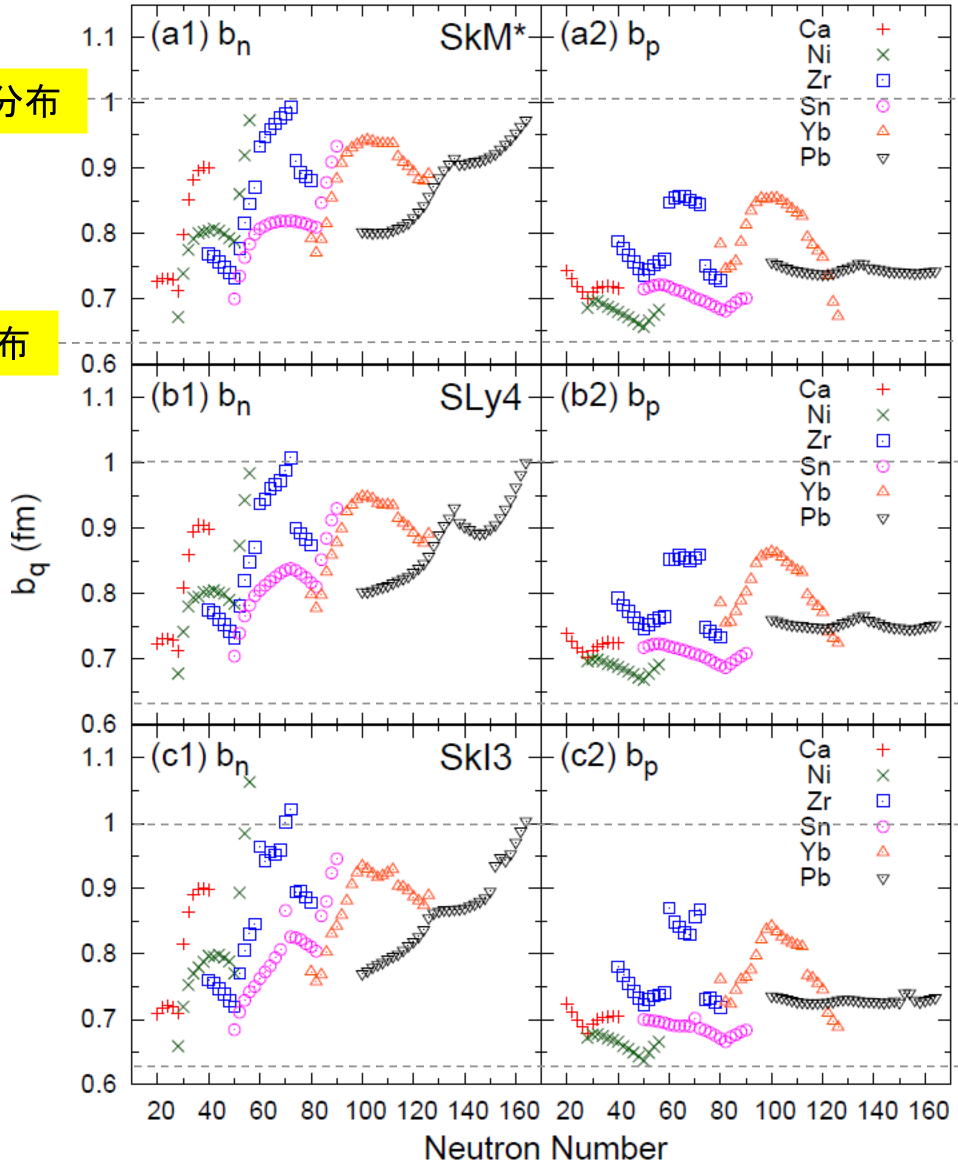
フェルミ分布

台形分布

with

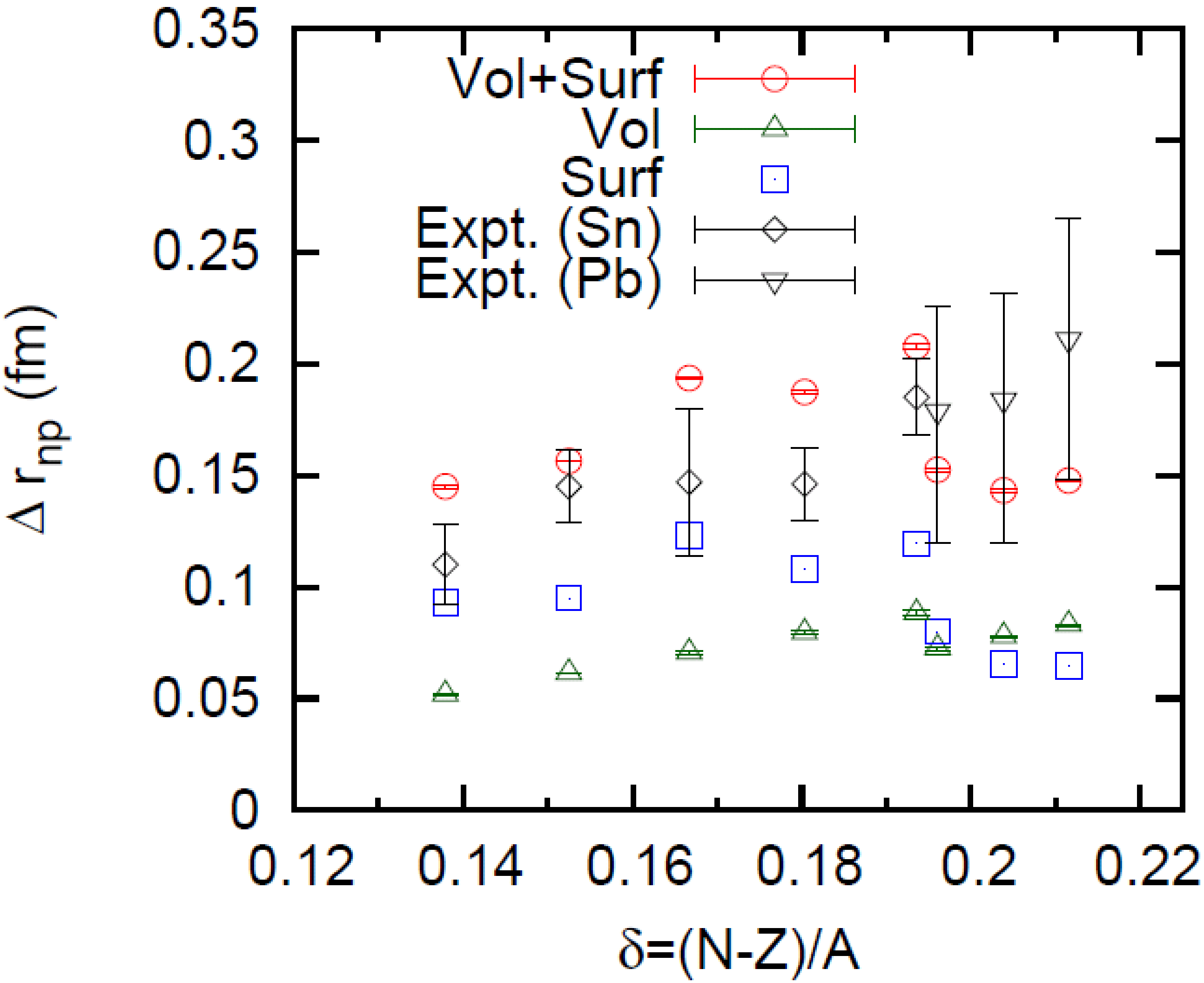
$$b_q^2 = \frac{2\int_{c_q}^{\infty}(r-c_q)^2[(r-c_q)^2+c_q^2]\,\rho_q'(r)dr}{\int_0^{\infty} r^2\rho_q'(r)dr}$$

$$c_q = \frac{4\pi\int_0^{\infty} r^3\rho_q'(r)dr}{4\pi\int_0^{\infty} r^2\rho_q'(r)dr}$$



Ref. Horiuchi, Ebata, & Iida, PRC **96** (2017) 035804.

Why the EOS dependence of neutron skin thickness is so elusive?

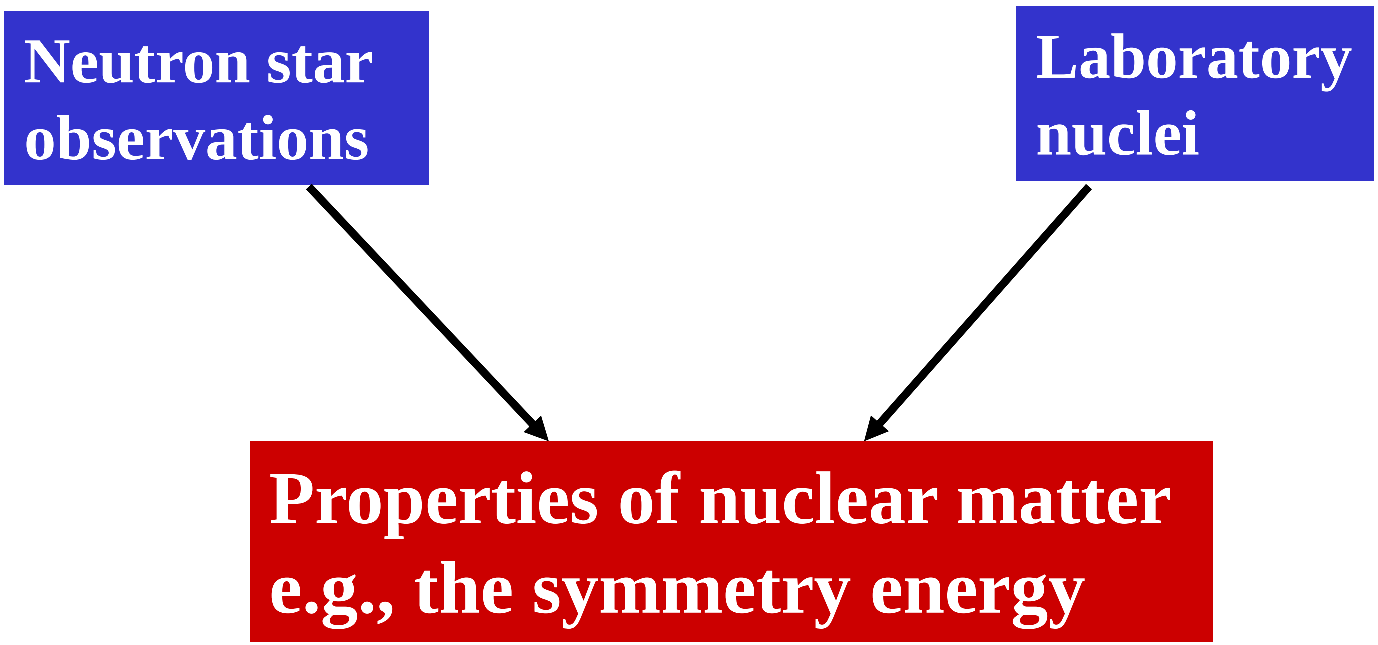


Only *C* is empirically determined as ∼1.06.

The diffuseness correction is of the order of the liquid-drop contribution.

Ref. Horiuchi, Ebata, & Iida, PRC **96** (2017) 035804.

Conclusion



Neutron star observations
Laboratory nuclei
Properties of nuclear matter e.g., the symmetry energy