低質量中性子星における質量公式

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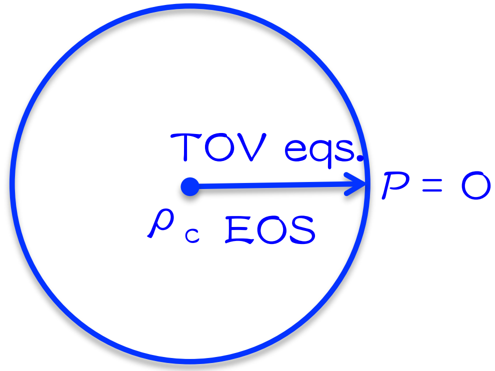
mass formula

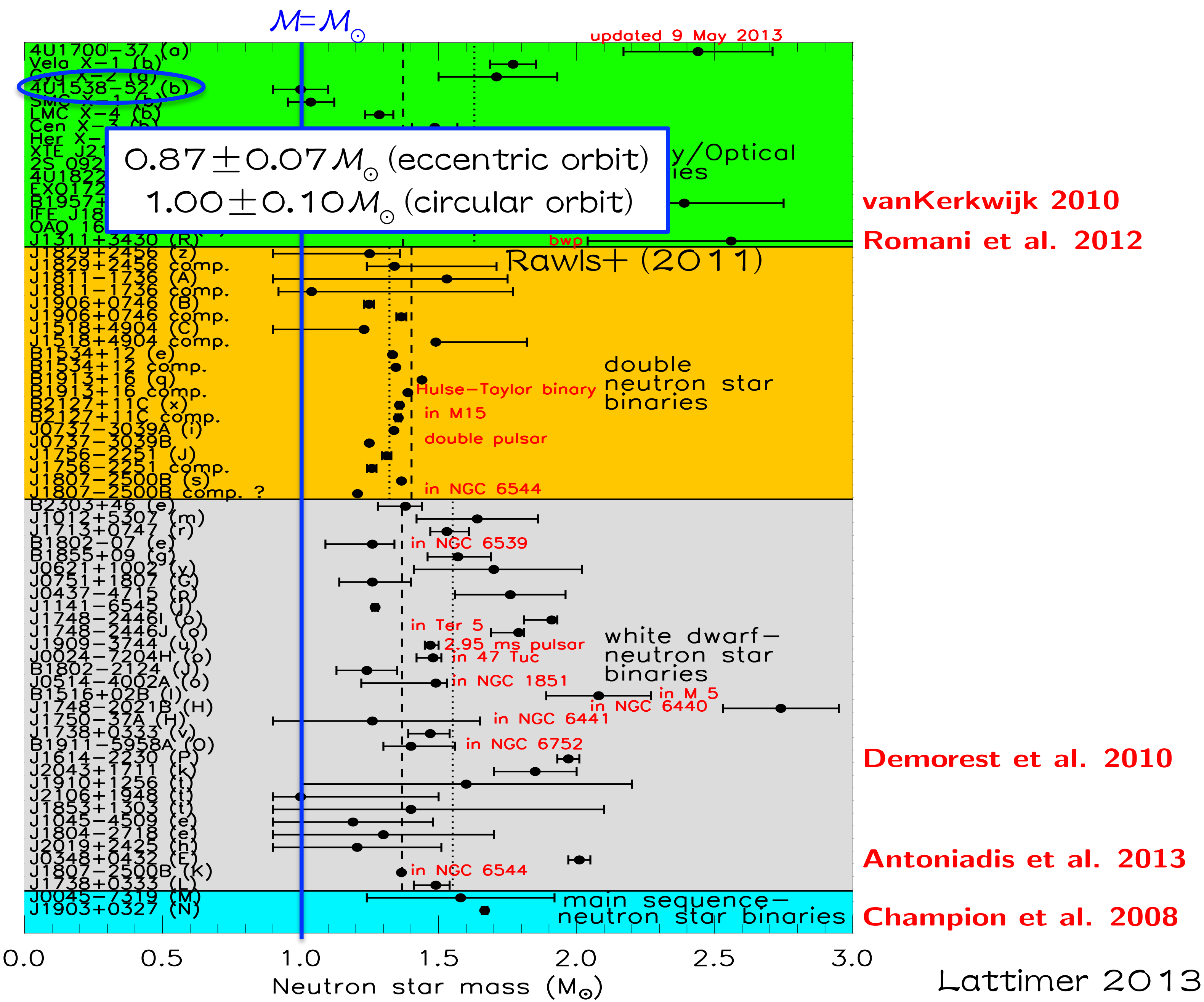
- well-known mass formula of stable nuclei
  - Bethe-Weizacker mass formula
  - due to the density saturation



you can get a NS model !!

- How about NSs ?
  - structure of NS is determined as a result of balance of gravity & pressure gradient.
  - in general, not so simple…

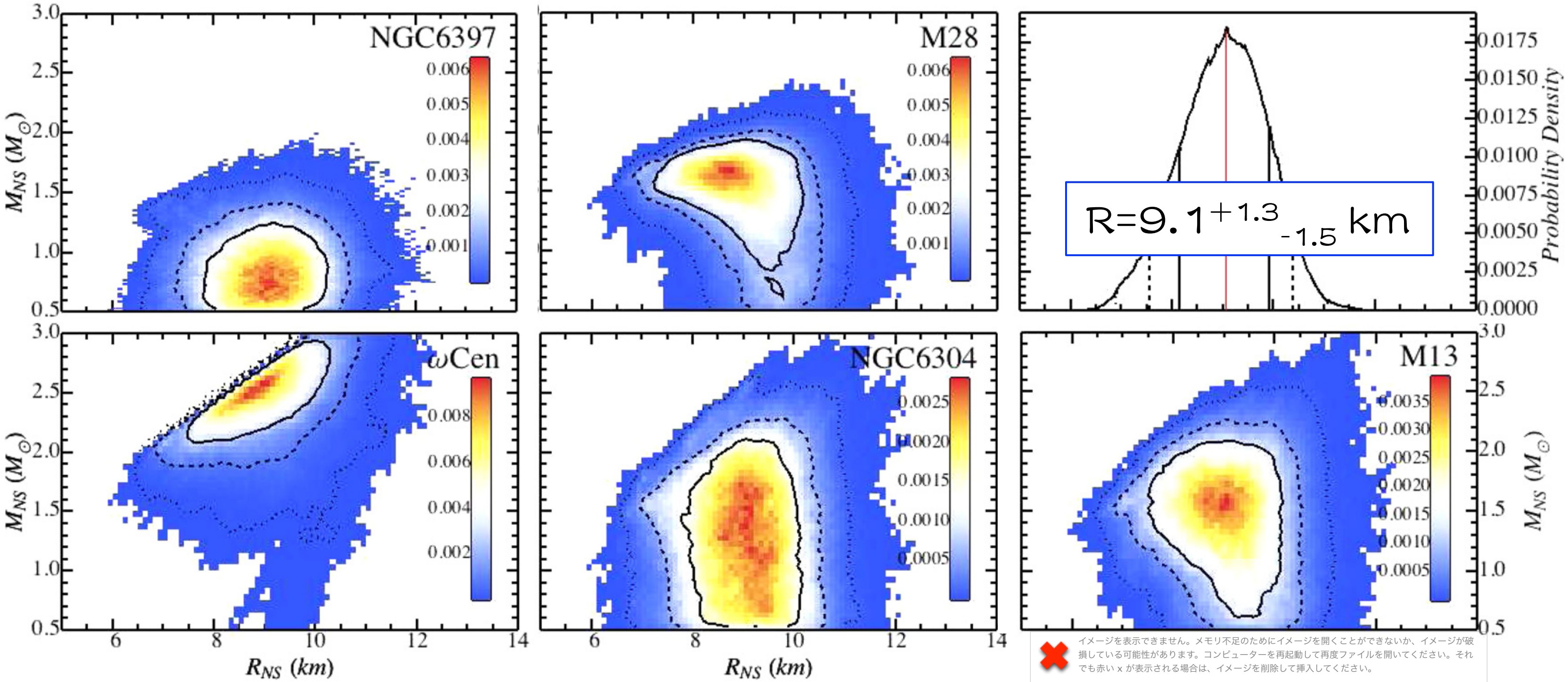
- we are successful to derive a mass formula of low-mass NS
  - as functions of nuclear **saturation parameter** η & central density
  - probably, independent of the EOS models



$M = M_\odot$
updated 9 May 2013
$0.87 \pm 0.07 M_\odot$ (eccentric orbit)
$1.00 \pm 0.10 M_\odot$ (circular orbit)
4U1700−37 (a)
Vela X−1 (b)
4U1538−52 (b)
SMC X−1 (b)
LMC X−4 (b)
Cen X−3 (b)
J1311+3430 (R)
bwp
Rawls+ (2011)
vanKerkwijk 2010
Romani et al. 2012
J1829+2456 (z)
J1829+2456 comp.
J1811−1736 (A)
J1811−1736 comp.
J1906+0746 (B)
J1906+0746 comp.
J1518+4904 (C)
J1518+4904 comp.
B1534+12 (e)
B1534+12 comp.
B1913+16 (q)
B1913+16 comp.
B2127+11C (x)
B2127+11C comp.
J0737−3039A (i)
J0737−3039B
J1756−2251 (J)
J1756−2251 comp.
J1807−2500B (s)
J1807−2500B comp. ?
Hulse−Taylor binary
in M15
double pulsar
in NGC 6544
double neutron star binaries
B2303+46 (e)
J1012+5307 (m)
J1713+0747 (r)
B1802−07 (e)
B1855+09 (g)
J0621+1002 (y)
J0751+1807 (G)
J0437−4715 (p)
J1141−6545 (j)
J1748−2446I (o)
J1748−2446J (o)
J1909−3744 (u)
J0024−7204H (o)
B1802−2124 (J)
J0514−4002A (o)
B1516+02B (I)
J1748−2021B (H)
J1750−37A (H)
J1738+0333 (v)
B1911−5958A (O)
J1614−2230 (P)
J2043+1711 (k)
J1910+1256 (t)
J2106+1948 (t)
J1853+1303 (t)
J1045−4509 (e)
J1804−2718 (e)
J2019+2425 (h)
J0348+0432 (E)
J1807−2500B (K)
J1738+0333 (L)
in NGC 6539
in Ter 5
2.95 ms pulsar
in 47 Tuc
in NGC 1851
in M 5
in NGC 6440
in NGC 6441
in NGC 6752
in NGC 6544
white dwarf−neutron star binaries
Demorest et al. 2010
Antoniadis et al. 2013
J0045−7319 (M)
J1903+0327 (N)
main sequence−neutron star binaries
Champion et al. 2008
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
Lattimer 2013

observations of NSs

- candidates of <u>low-mass NSs</u> have been also discovered in binary system (Lattimer & Prakash 2011)
- radiation radius of X-ray source (Rutledge+ 2002)
  e.g.) R_∞ = 14.3±2.1km : CXOU 132619.7-472910.8 in omega Cen
- M & R from thermal spectra from quiescent low-mass X-ray binaries (Guillot+ 2013; Lattimer & Steiner 2013)



イメージを表示できません。メモリ不足のためにイメージを開くことができないか、イメージが破損している可能性があります。コンピューターを再起動して再度ファイルを開いてください。それでも赤い x が表示される場合は、イメージを削除して挿入してください。

Guillot+ 2013

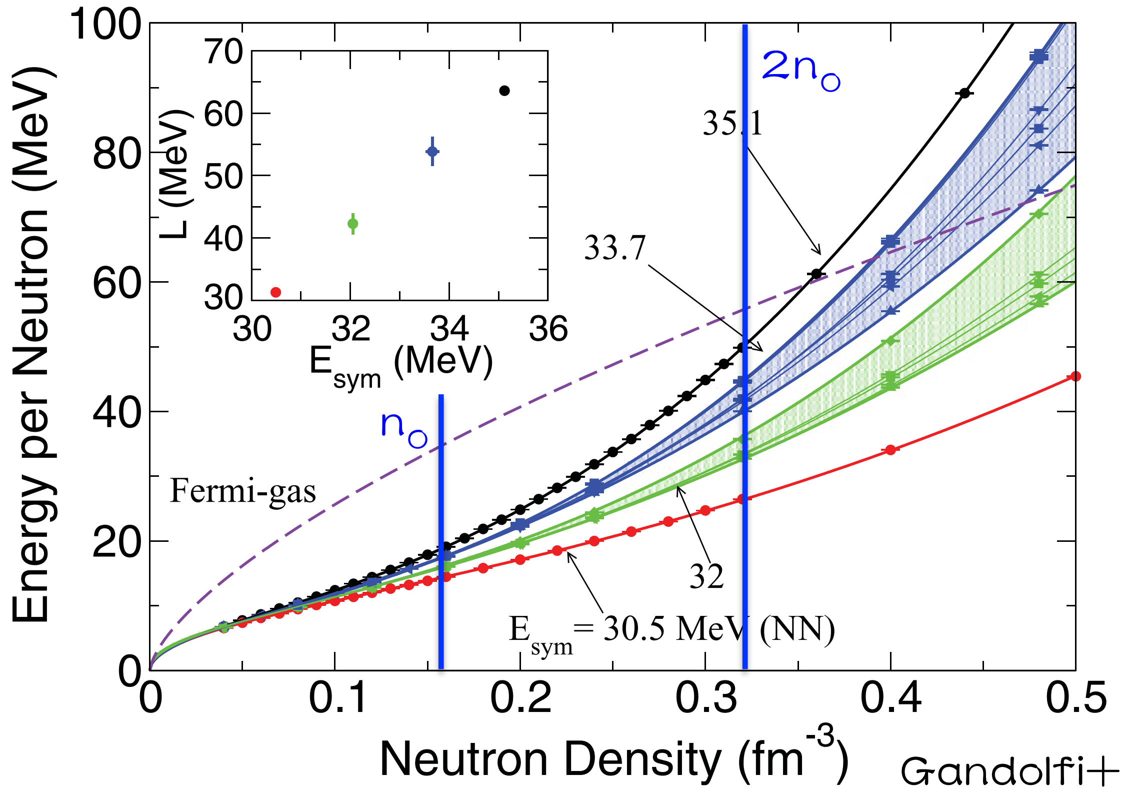
low-mass NS models

- low-mass NSs
  - low-central density
  - importance of EOS for low-density region
  - may be able to discuss the stellar models without the core EOS
- EOS of nuclear matter for $\rho \lesssim \rho_0$ (normal nuclear density) would be determined with reasonable accuracy by terrestrial nuclear experiments.
- For $\rho \lesssim 2\rho_0$, one can almost neglect an uncertainty of three nucleon interaction (Gandolfi+ 2012) and contribution from hyperon (or quark etc...).

→ we focus on the NS models for $\rho \lesssim 2\rho_0$

three-nucleon interactions

- for $\rho \lesssim 2\rho_0$, the uncertainty from three-nucleon interactions in EOS is not so relevant.



Gandolfi+ 2012

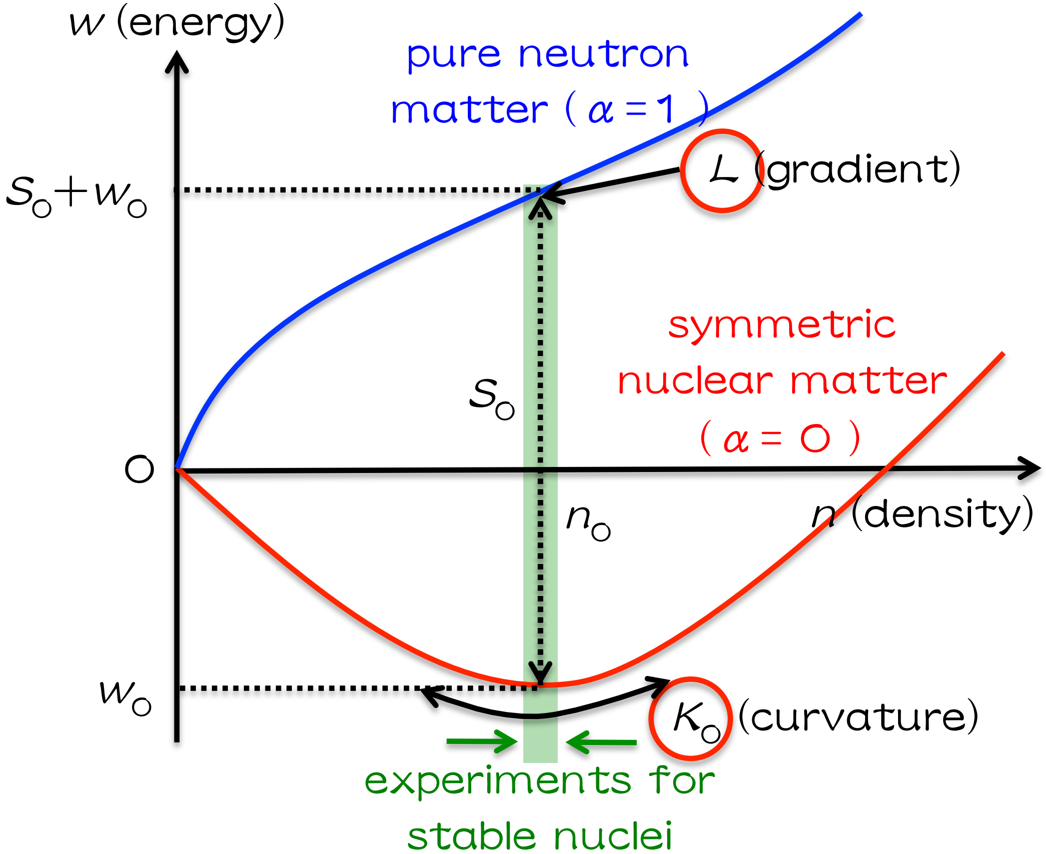
EOS near the saturation point

- Bulk energy per nucleon near the saturation point of symmetric nuclear matter at zero temperature;

incompressibility

symmetry parameter

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



unified EOS modes

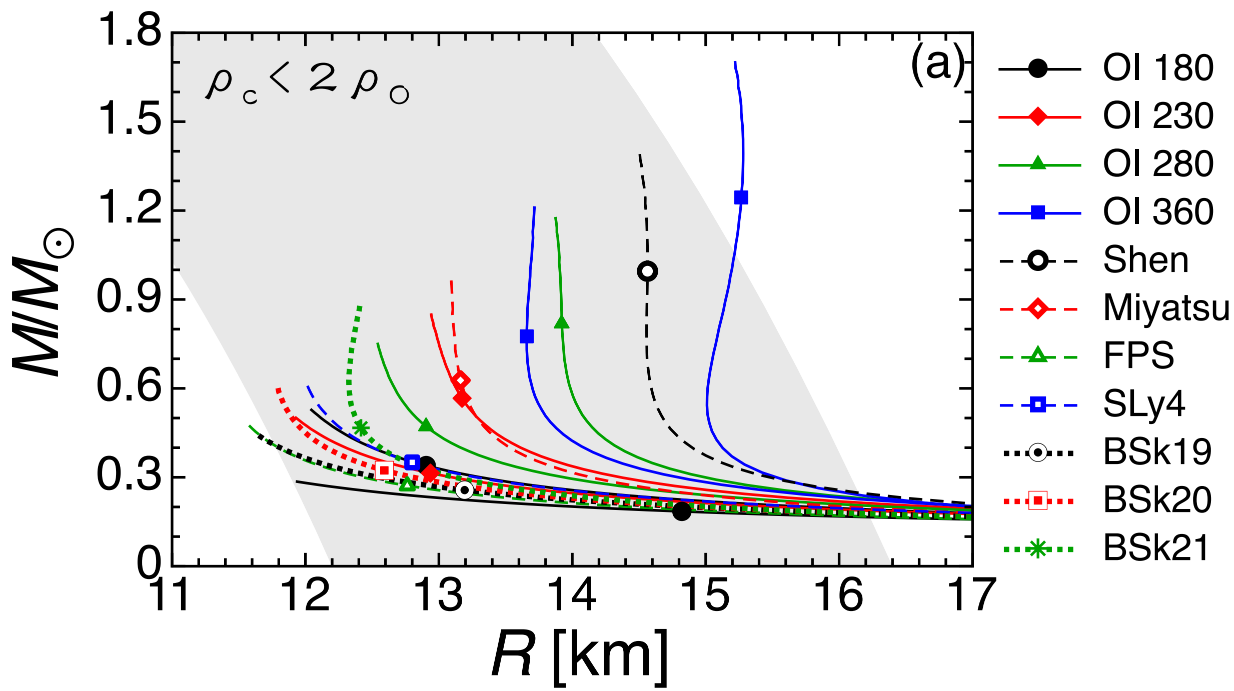
- unified-EOS models
  - describing both the crustal and core regions of NS
  - based on the EOSs of nuclear matter with specific values of K_0 & L
  - consistent with empirical data of masses and radii of stable nuclei

- we especially focus on
  - phenomenological EOS with various K_0 & L (Oyamatsu & Iida 2003; 2007)
  - EOSs based on relativistic mean field models
    - Shen EOS (Shen+ 1998)
    - Miyatsu EOS (Miyatsu+ 2013)
  - Skyrme-type effective interaction
    - FPS (Pethick+ 1995),
    - SLy4 (Douchin & Haensel 2001)
    - BSk19, BSk20, BSk21 (Potekhin+ 2013)

MR relations

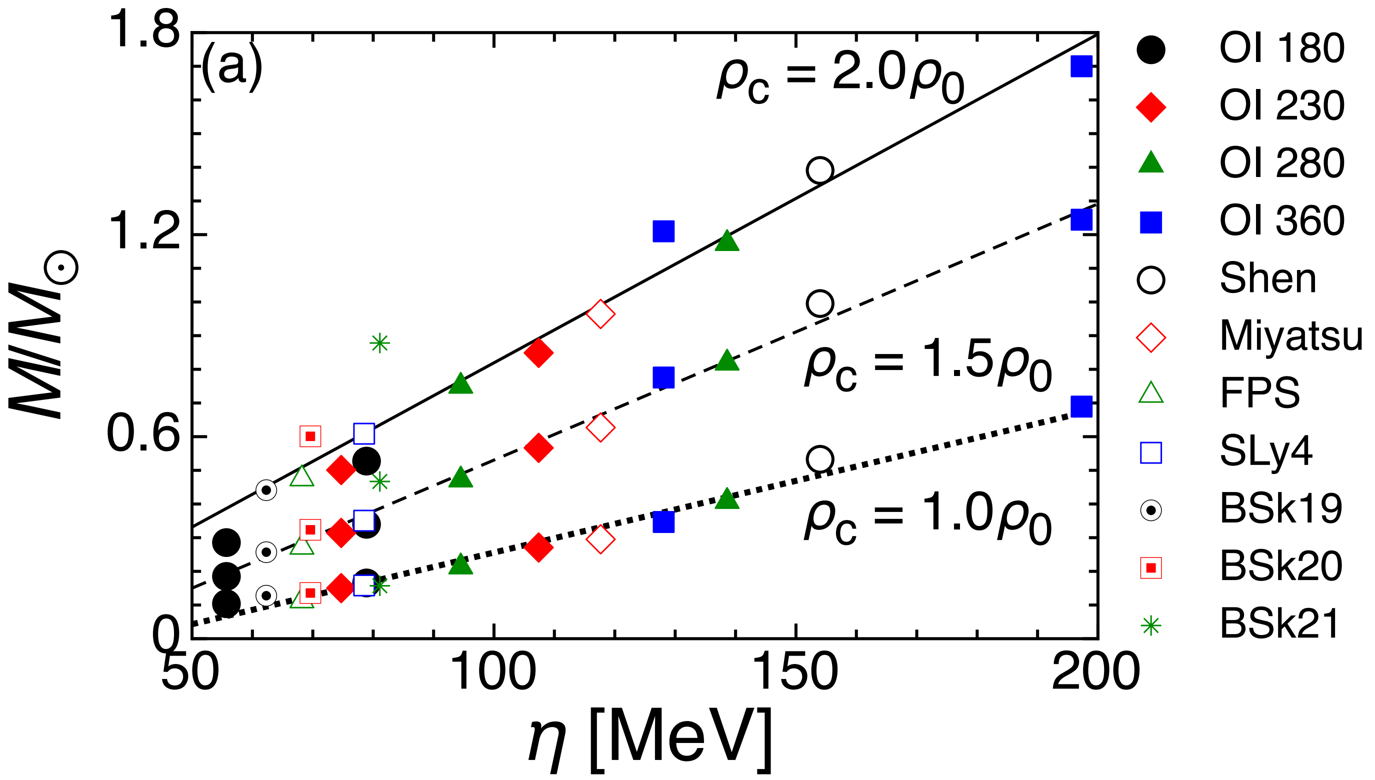
- NS models are constructed with various sets of K_0 & L
- We can find the specific combination of K_0 & L describing the low-mass NSs,

$$\eta = (K_0 L^2)^{1/3}$$

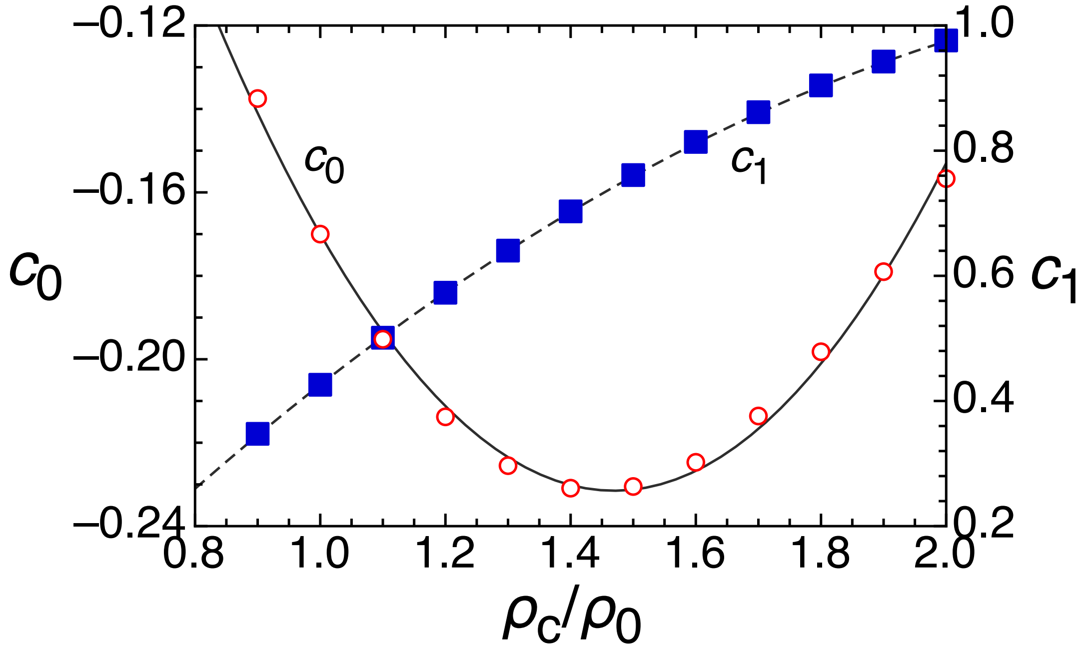


EOS	K_0 (MeV)	L (MeV)	η (MeV)
OI-EOS	180	31.0	55.7
	180	52.2	78.9
	230	42.6	74.7
	230	73.4	107.4
	280	54.9	94.5
	280	97.5	138.6
	360	76.4	128.1
	360	146.1	197.3
Shen	281	114	154.0
Miyatsu	274	77.1	117.7
FPS	261	34.9	68.2
SLy4	230	45.9	78.5
BSk19	237	31.9	62.3
BSk20	241	37.4	69.6
BSk21	246	46.6	81.1

mass formula



$$\frac{M}{M_\odot} = c_0 + c_1 \left(\frac{\eta}{100\,\mathrm{MeV}} \right)$$



$$u_c \equiv \rho_c/\rho_0$$

$$\boxed{\frac{M}{M_\odot} = 0.371 - 0.820u_c + 0.279u_c^2 - (0.593 - 1.254u_c + 0.235u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)}$$

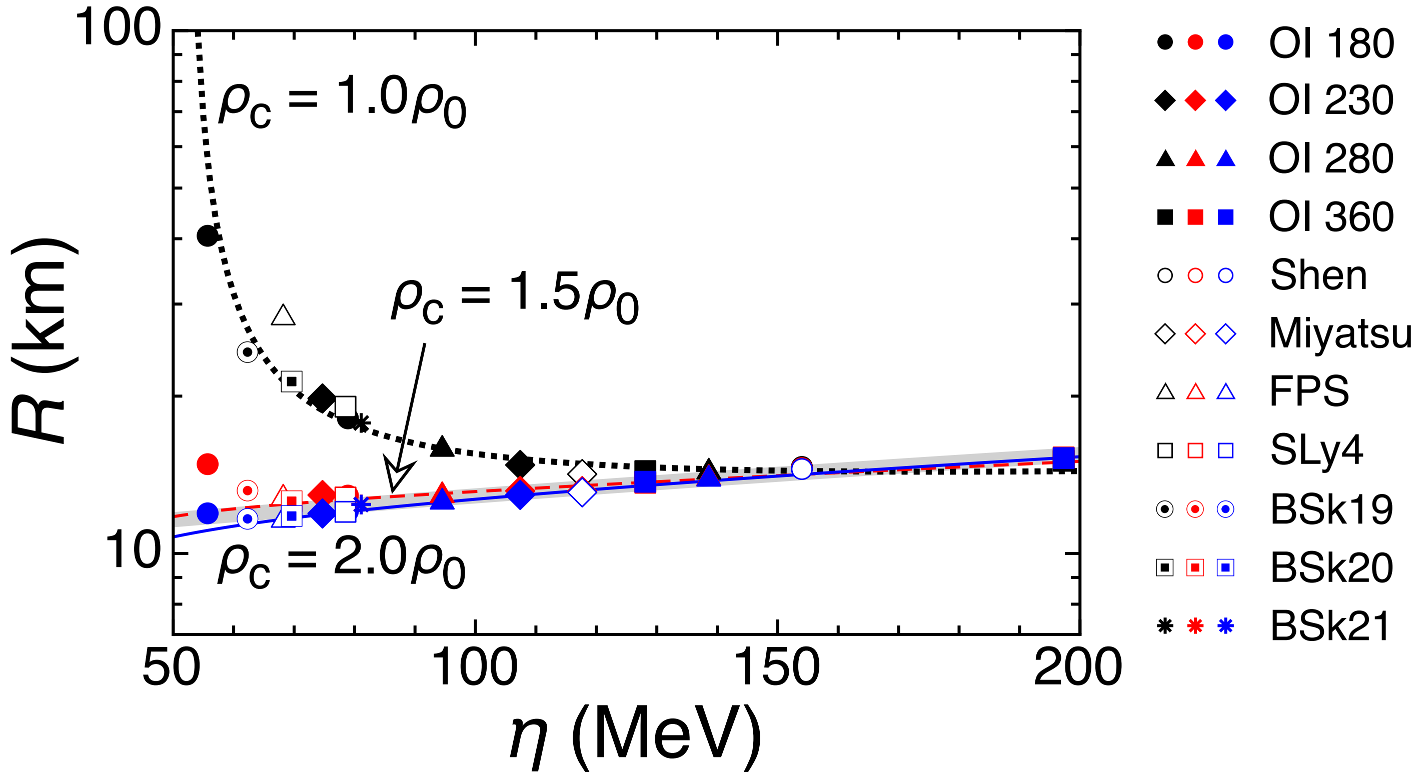
$$\boxed{z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)}$$

$$z = 1/\sqrt{1 - 2GM/Rc^2} - 1$$

- via the simultaneous observations of M & z (or R or R_∞), one could extract the values of η & ρ_c !!

radii of low-mass NSs

- with using the formulas of mass and gravitational redshift, one can also predict the radius of NS.



summary

- M & R of low-mass NSs are becoming to determine observationally.
  - strongly associated with the EOS for low-density region
- we focus on the NS models with $\rho \lesssim 2\rho_0$, adopting the unified EOS models.
- we are successful to derive the formulas of mass and gravitational redshift for low-mass NS, as functions of NS central density and a new nuclear matter parameter.
  - also predict the stellar radius
  - this is direct connection between the nuclear physics & astrophysics.