Mass formula for low-mass neutron stars and its application

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collaborated with

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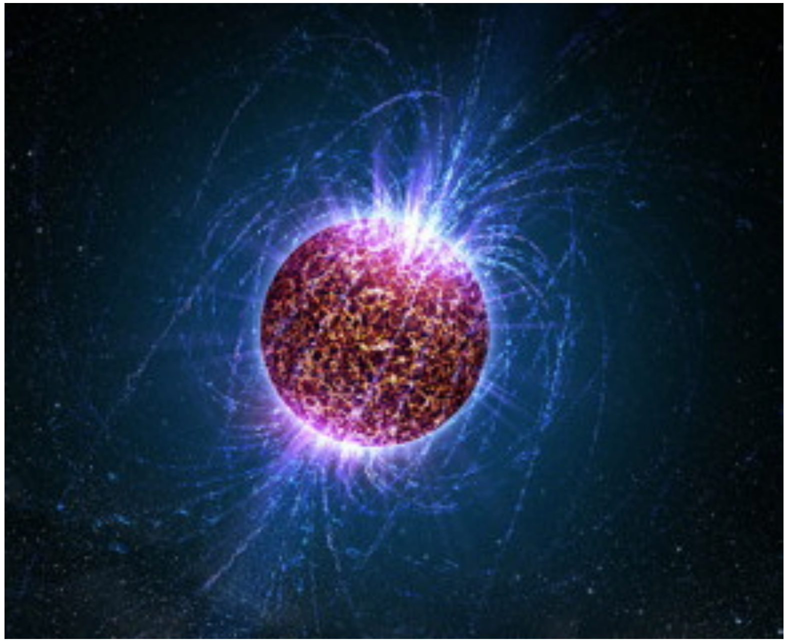
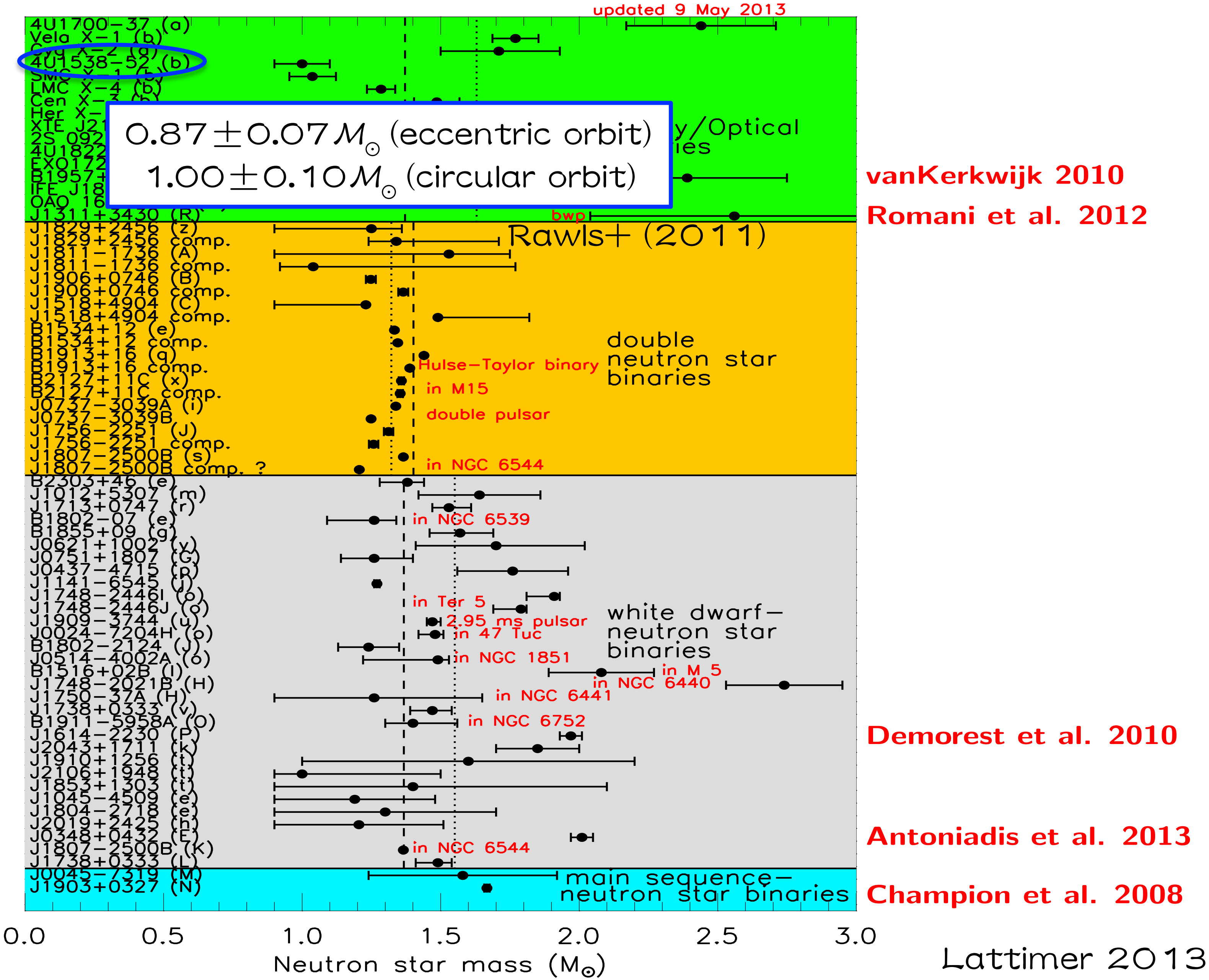
NS - EOS



- physics in NS crust
- low-mass NSs

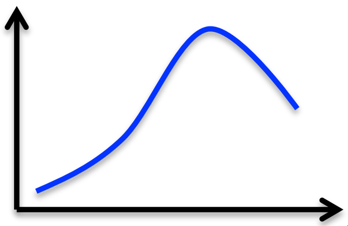
(1) TOV equation
(2) equation of state
- model
- nuclear interaction
- composition

constraints from the terrestrial
nuclear experiments
≀≀
properties around
the saturation density



updated 9 May 2013
4U1700−37 (a)
Vela X−1 (b)
4U1538−52 (b)
SMC X−1 (b)
LMC X−4 (b)
Cen X−3 (b)
y/Optical
ies
0.87±0.07$M_\odot$ (eccentric orbit)
1.00±0.10$M_\odot$ (circular orbit)
J1311+3430 (R)
bwp
Rawls+ (2011)
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
J0045−7319 (M)
J1903+0327 (N)
main sequence−
neutron star binaries
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Neutron star mass ($M_\odot$)
vanKerkwijk 2010
Romani et al. 2012
Demorest et al. 2010
Antoniadis et al. 2013
Champion et al. 2008
Lattimer 2013

low-mass NS models



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

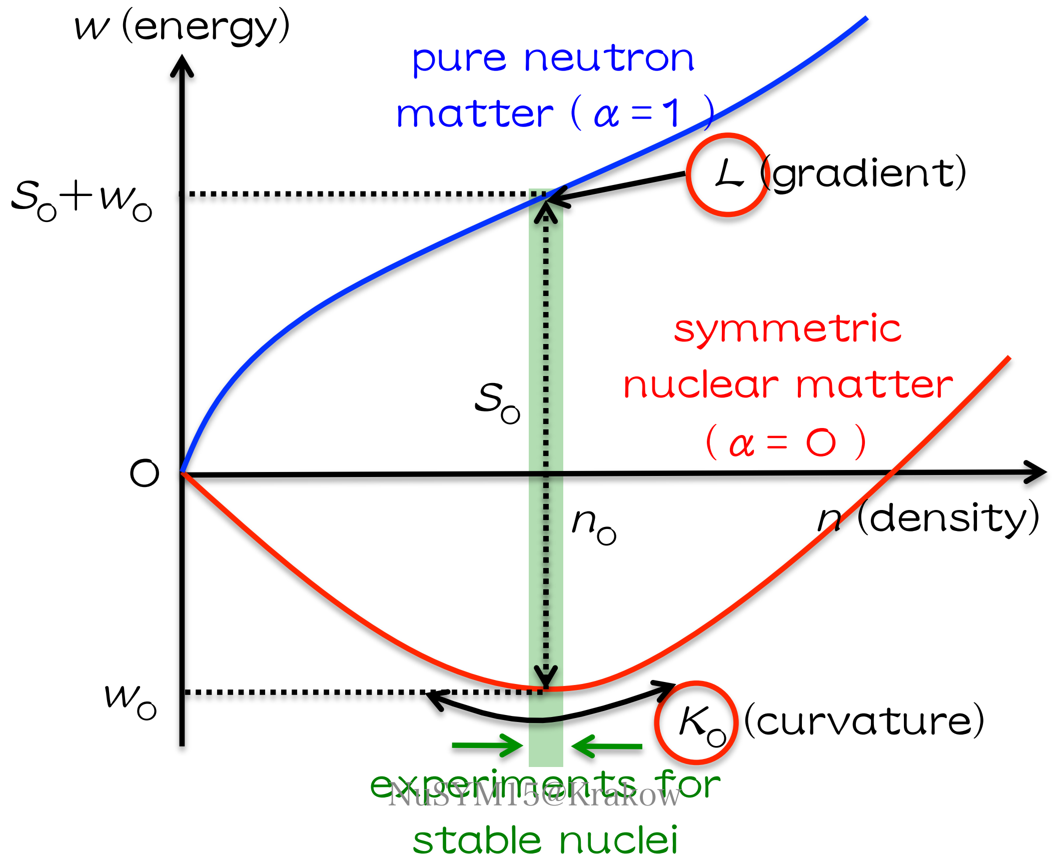
⇒ we focus on the NS models for $\rho \lesssim 2\rho_0$

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
  - 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
  - describing both the crustal and core regions of NS

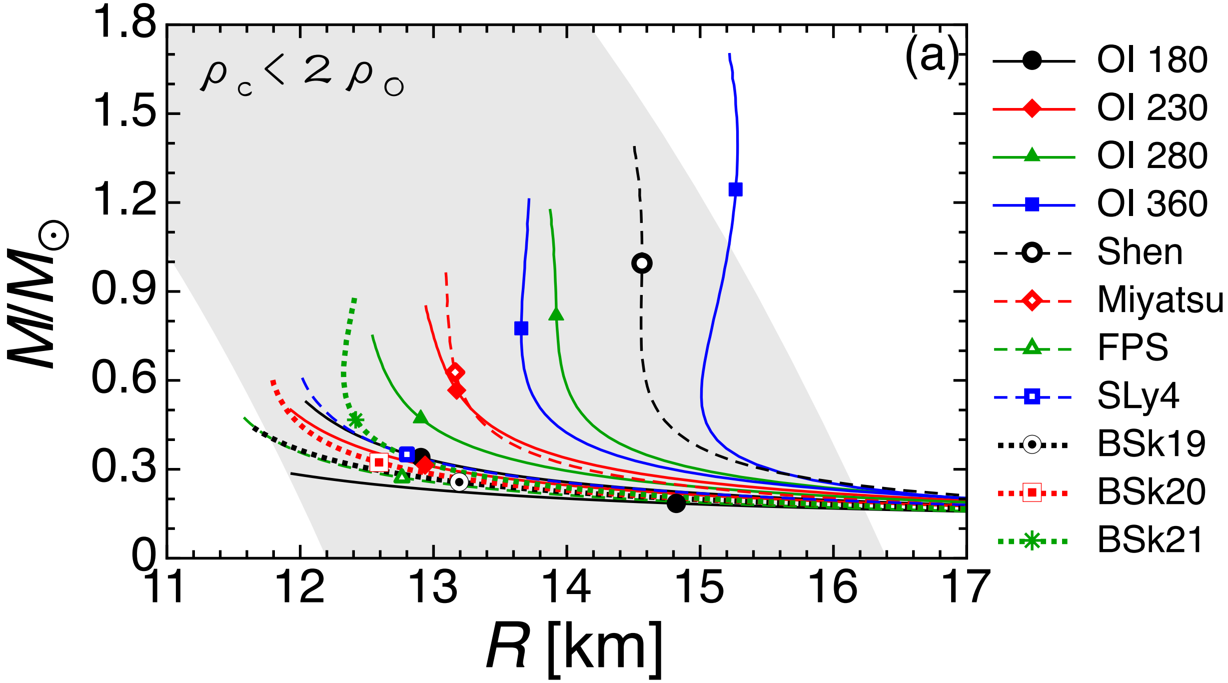
- we especially focus on
  - phenomenological EOS with various K_0 & L (Oyamatsu & Iida 2003; 2007)
  - EOSs based on relativistic mean field models
    - Shen EOS (Shen+ 1998)
    - Miyatsu EOS (Miyatsu+ 2013)
  - Skyrme-type effective interaction
    - FPS (Pethick+ 1995),
    - SLy4 (Douchin & Haensel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

EOSs based on the different theoretical models

MR relations

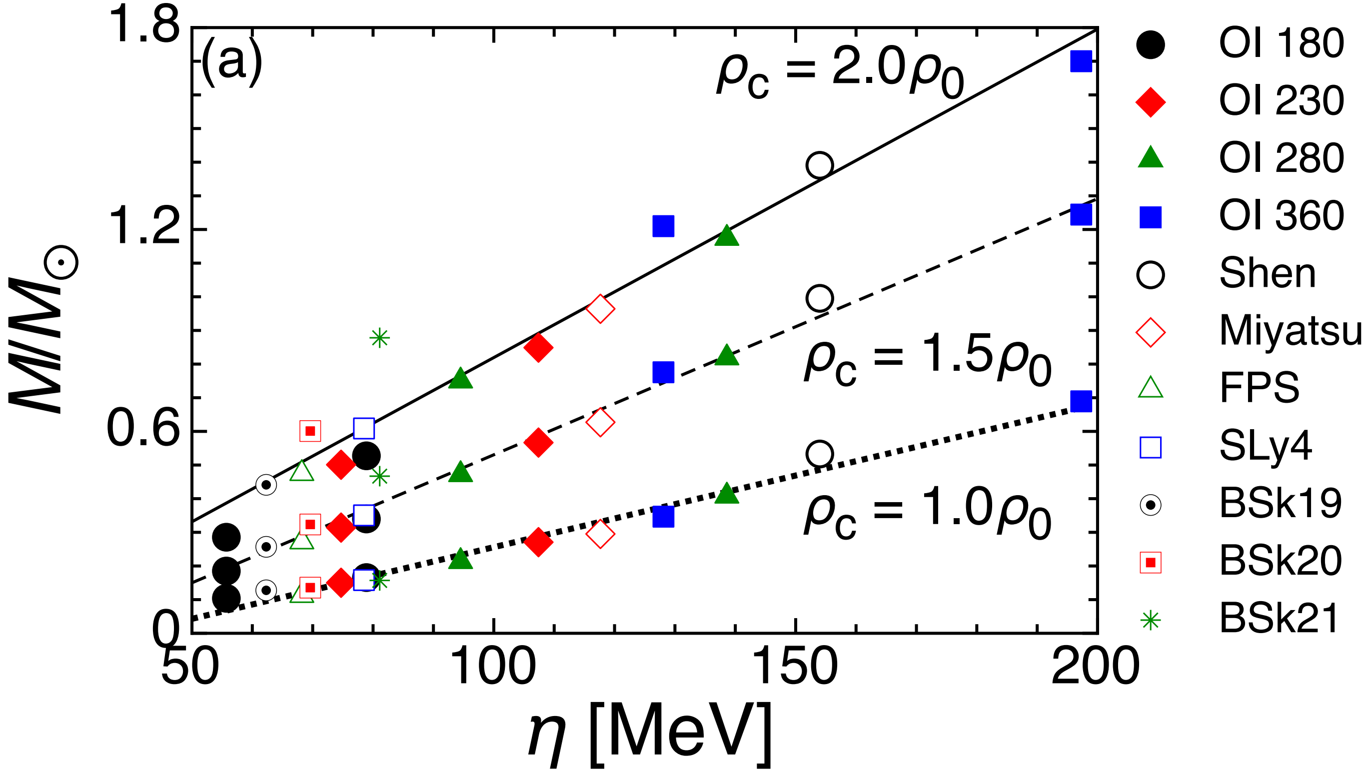
- NS models are constructed with various sets of K_0 & L
- We can find the specific combination of K_0 & L describing the low-mass NSs,

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

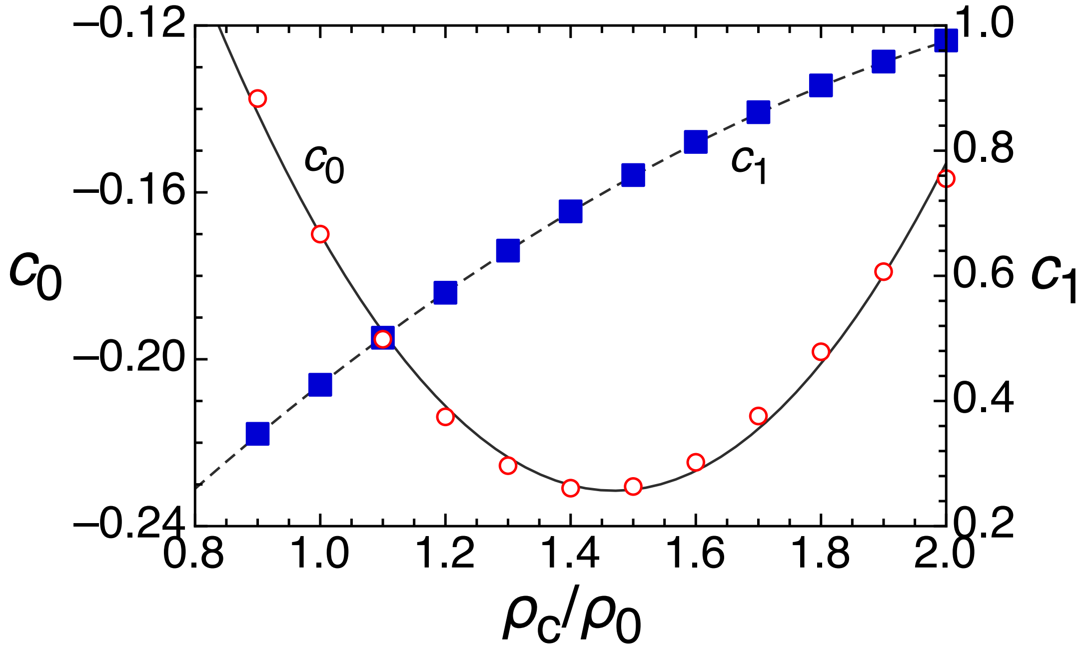


EOS	K_0 (MeV)	L (MeV)	η (MeV)
OI-EOS	180	31.0	55.7
	180	52.2	78.9
	230	42.6	74.7
	230	73.4	107.4
	280	54.9	94.5
	280	97.5	138.6
	360	76.4	128.1
	360	146.1	197.3
Shen	281	114	154.0
Miyatsu	274	77.1	117.7
FPS	261	34.9	68.2
SLy4	230	45.9	78.5
BSk19	237	31.9	62.3
BSk20	241	37.4	69.6
BSk21	246	46.6	81.1

mass formula



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



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

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

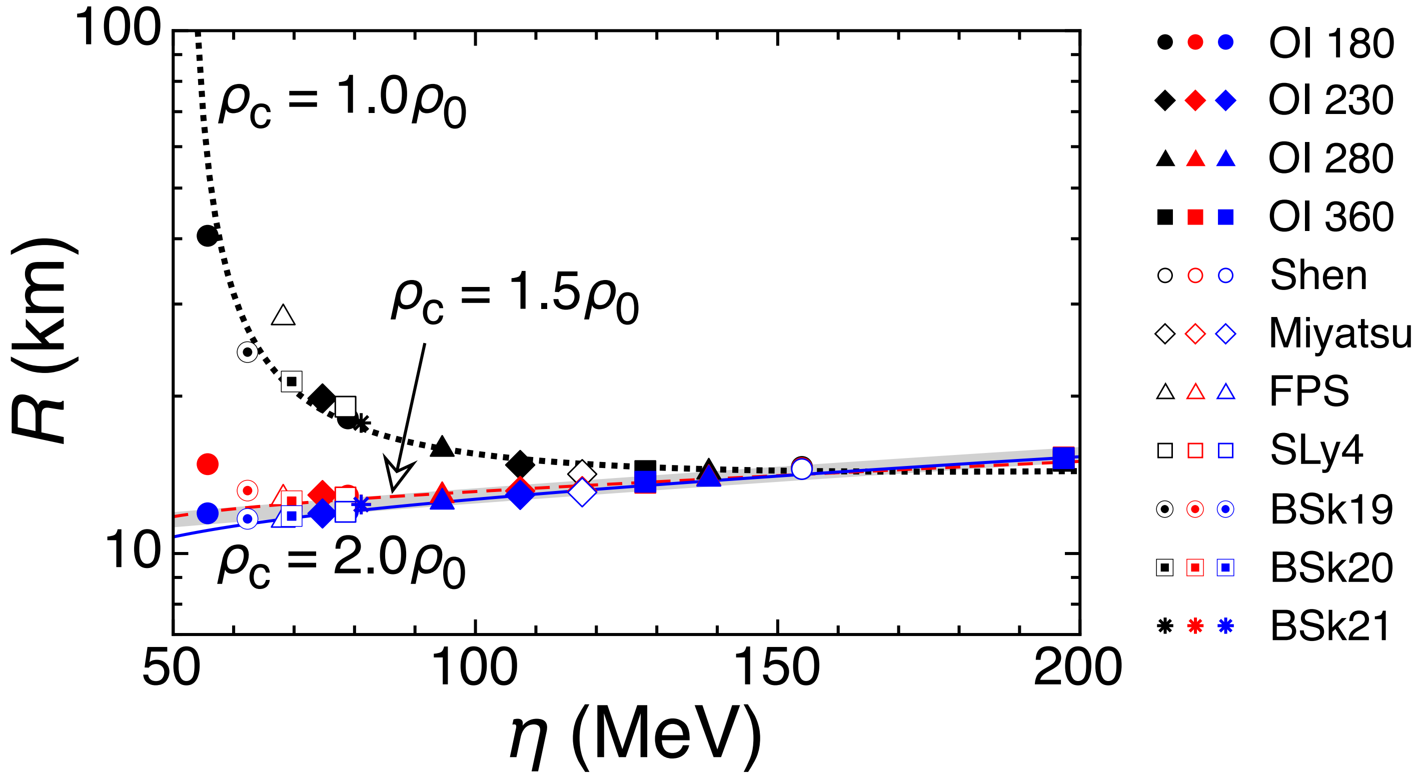
$$z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

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

- 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

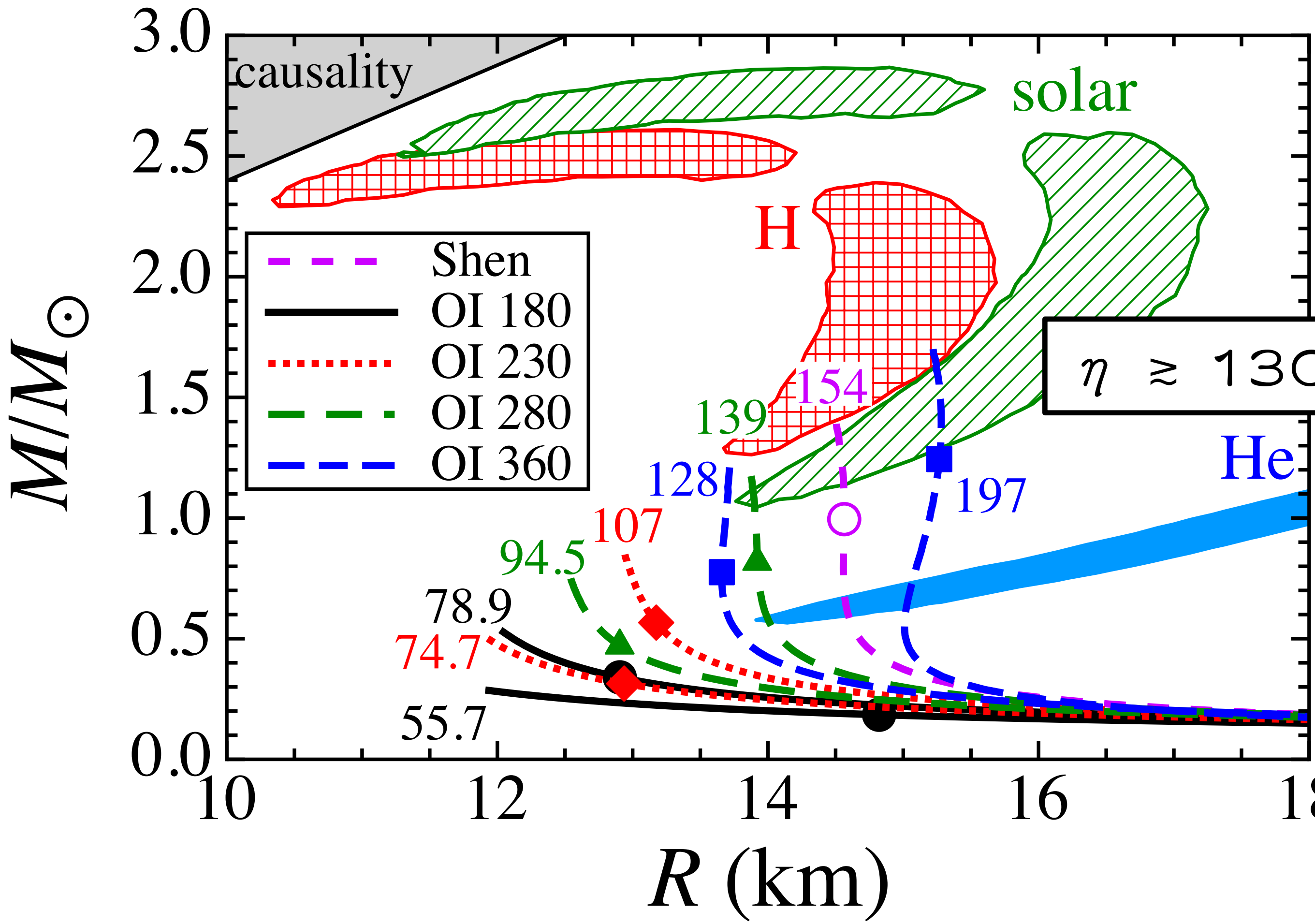
- with using the formulas of mass and gravitational redshift, one can also predict the radius of NS.



application of η

- Unlike M, R is generally much more difficult to determine
- Thermal emission from NS surface must be one of the good chances to obtain the information associated with R.
  - thermonuclear X-ray bursts at NS surfaces
  - photospheric radius expansion
  - quiescent low-mass X-ray binaries
- we adopt the constraints on (M,R) obtained by Suleimanov et al. (2011), because their results are minimized the theoretical uncertainties.
  - they adopt three different atmosphere model, i.e., H, He, & $Z = 0.3Z_\odot$
  - they adopt the whole cooling track

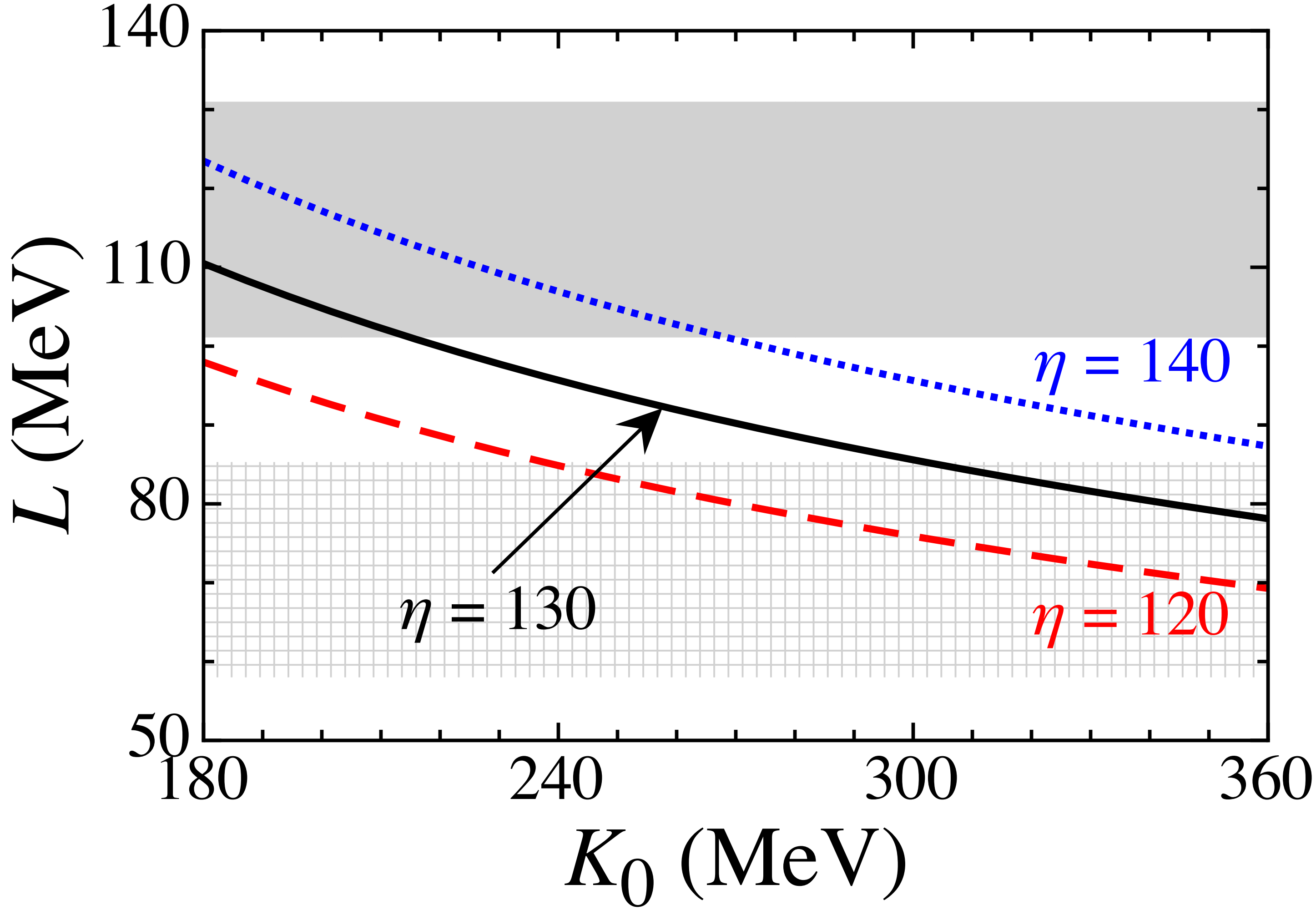
allowed region in MR relation



$\eta \gtrsim 130$ MeV

- $R \geqq 13$ km for NS in 4U 1608-52, if masses are in the range of 1.2-2.4$M_\odot$ (Poutanen et al. arXiv:1405.2663)

constraint on (L, K_0)



summary

- M & R of (low-mass) NSs are becoming to determine observationally.
  - low-mass NSs are 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
  - probably, independent of the EOS models
  - this is direct connection between the nuclear physics & astrophysics.
- we show a prospect to constrain the saturation parameters via the direct observations of NSs.