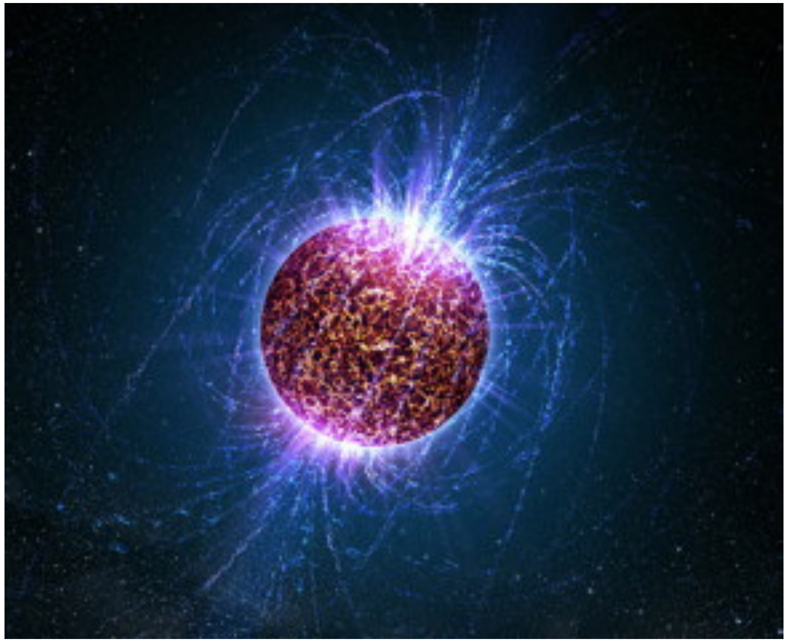
Constraints on the nuclear saturation parameters via neutron star observations

Hajime SOTANI (NAOJ)

K. Iida, K. Oyamatsu, K. Nakazato, & A. Ohnishi

NS - EOS



- physics in NS crust
- low-mass NSs

(1) TOV equation

(2) equation of state

- model
- nuclear interaction
- composition

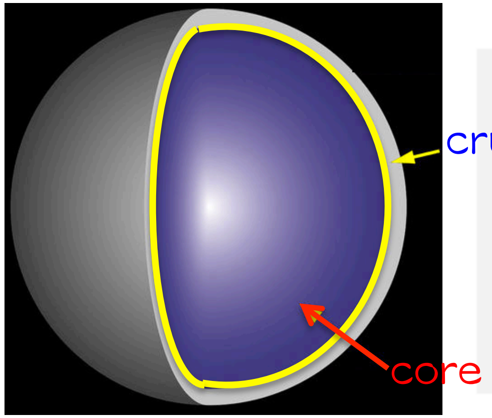
constraints from the terrestrial
nuclear experiments
≀≀
properties around
the saturation density

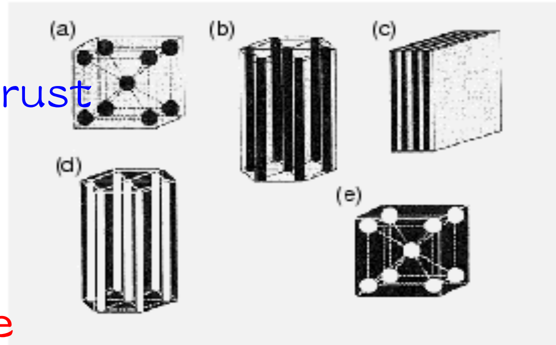
Crust in NSs

neutron stars

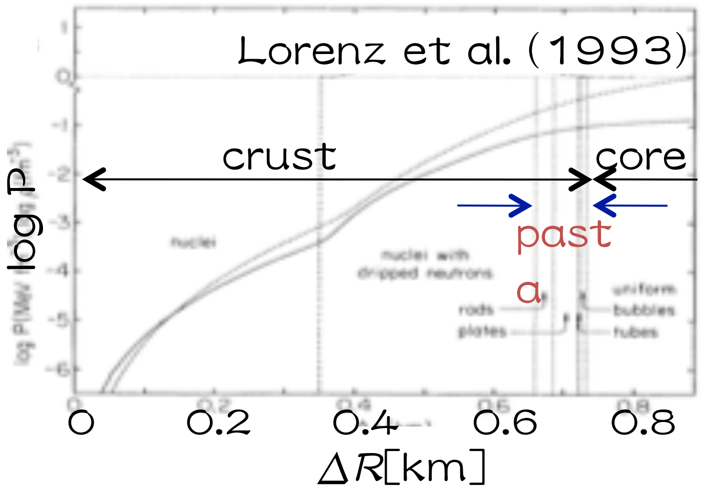
- Structure of NS
  - solid layer (crust)
  - nonuniform structure (pasta)
  - fluid core (uniform matter)
- Crust thickness ≲ 1km
- Determination of EOS for high density (core) region could be quite difficult on Earth
- Constraint on EOS via observations of neutron stars
  - stellar mass and radius
  - stellar oscillations (& emitted GWs)

  "(GW) asteroseismology"





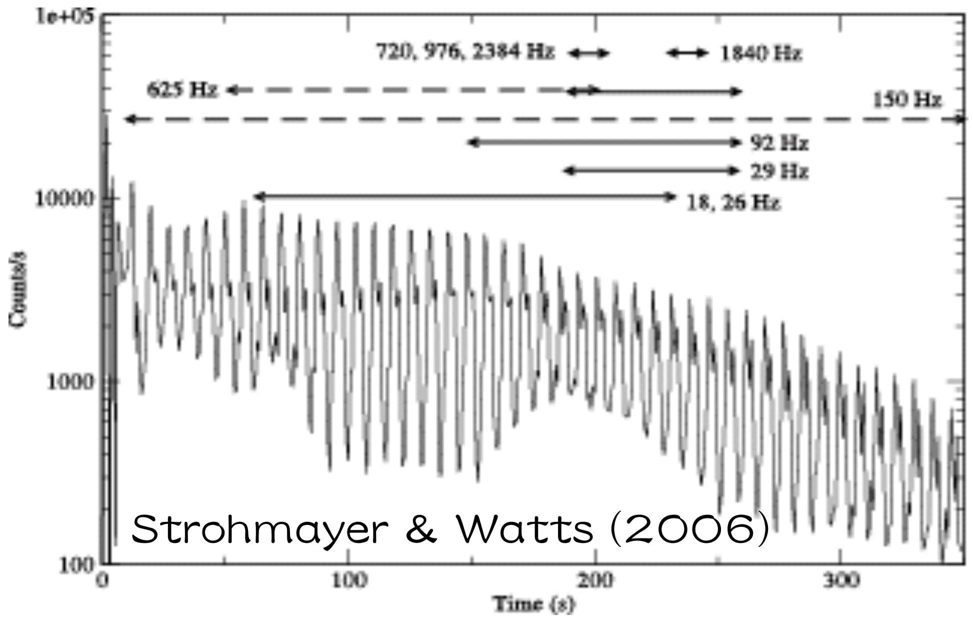
Oyamatsu (1993)



QPOs in SGRs

- Quasi-periodic oscillations (QPOs) in afterglow of giant flares from soft-gamma repeaters (SGRs)
  - SGR 0526-66 (5^{th}/3/1979) : 43 Hz
  - SGR 1900+14 (27^{th}/8/1998) : 28, 54, 84, 155 Hz
  - SGR 1806-20 (27^{th}/12/2004) : 18, 26, 30, 92.5, 150, 626.5, 1837 Hz

(Barat+ 1983, Israel+ 05, Strohmayer & Watts 05, Watts & Strohmayer 06)



- Crustal torsional oscillation ?
- Magnetic oscillations ?
- Asteroseismology
  → stellar properties
  (M, R, B, EOS ...)

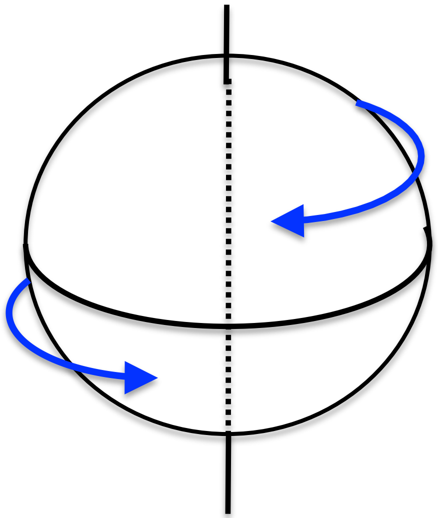
torsional oscillations

- axial parity oscillations
  - incompressible
  - no density perturbations
- in Newtonian case (Hansen & Cioffi 1980)

$$ {}_\ell t_0 \sim \frac{\sqrt{\ell(\ell+1)\mu/\rho}}{2\pi R} \sim 16\sqrt{\ell(\ell+1)}\ \mathrm{Hz} \qquad {}_\ell t_n \sim \frac{\sqrt{\mu/\rho}}{2\Delta r} \sim 500 \times n\ \mathrm{Hz} $$

  - μ : shear modulus
  - frequencies ∝ shear velocity $v_s = \sqrt{\mu / \rho}$
  - overtones depend on crust thickness
- one can consider torsional oscillations independently of core EOS
- effect of magnetic field
  - frequencies become larger

(Sotani+07, Gabler+12,13)

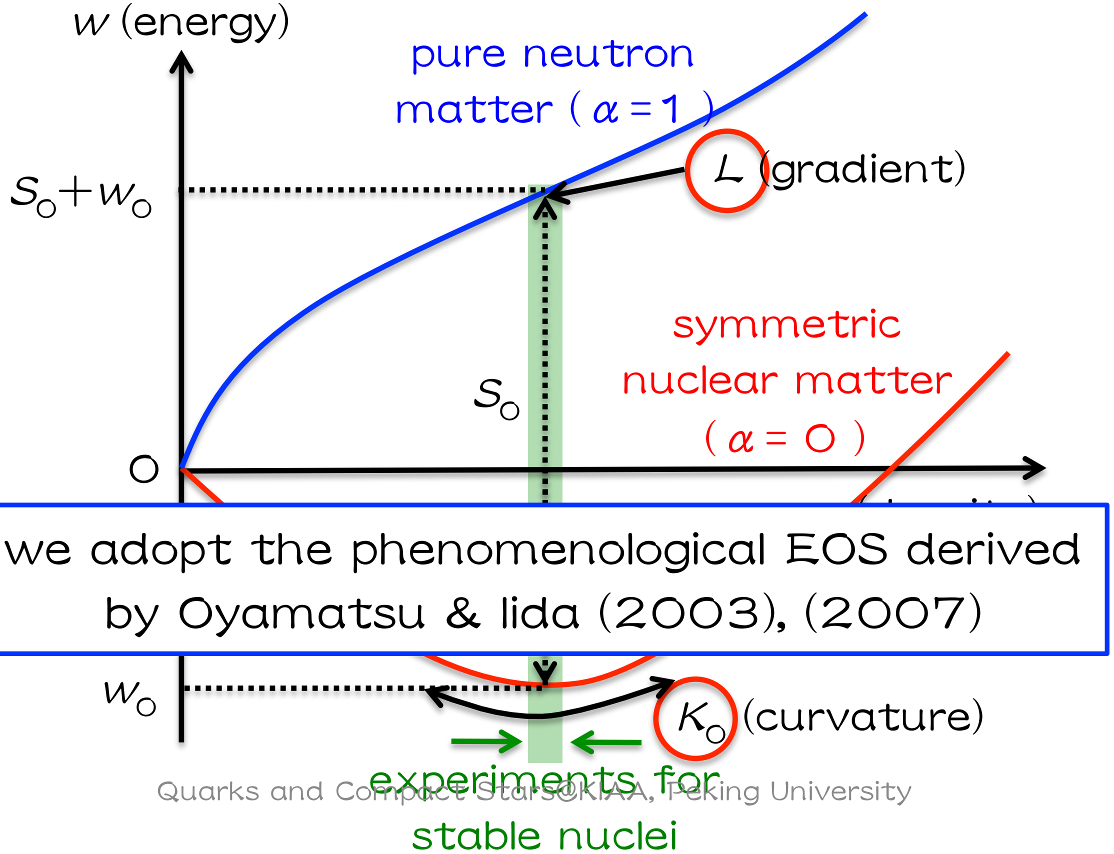


EOS near the saturation point

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

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

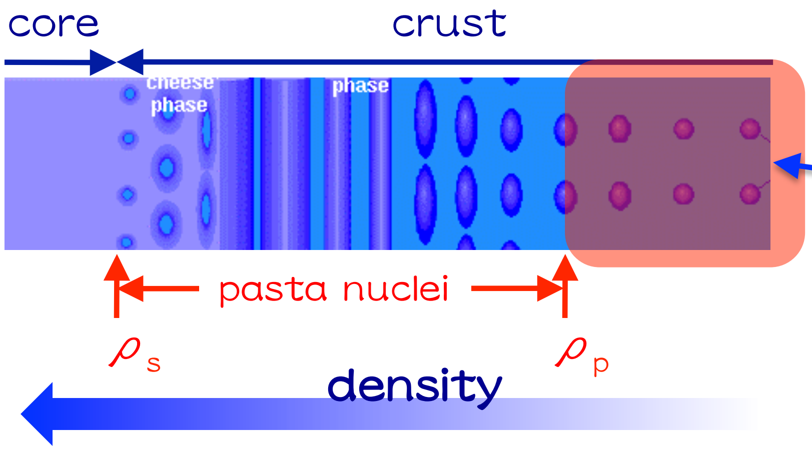
incompressibility — symmetry parameter



we adopt the phenomenological EOS derived by Oyamatsu & Iida (2003), (2007)

What we do

- EOS for core region is still uncertain.
- To prepare the crust region, we integrate from $r=R$.
  - M, R : parameters for stellar properties
  - L, K_0 : parameters for curst EOS (Oyamatsu & Iida (2003), (2007))
    - → For $L \gtrsim$ 100MeV, pasta structure almost disappears
- In crust region, torsional oscillations are calculated.
  - considering the shear only in spherical nuclei.
  - frequency of fundamental oscillation $\propto v_s$ ($v_s^2 \sim \mu / H$)
  - calculated frequencies could be lower limit



for bcc lattice

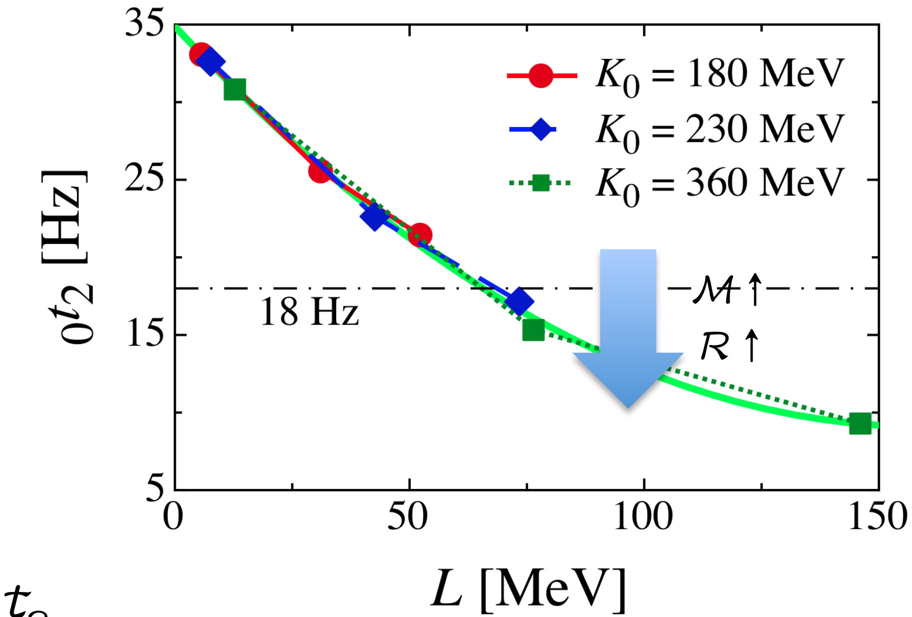
$$\mu = 0.1194 \frac{n_i (Ze)^2}{a}$$

n_i : number density of quark droplet
Z : charge of quark droplet
a : Wigner-Seitz radius

${}_0t_2$ without superfluidity

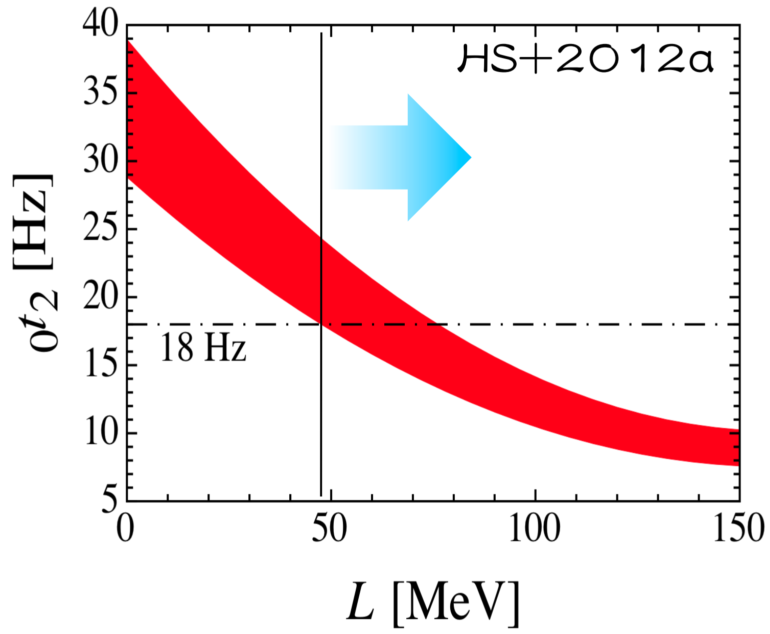
HS+2012a

- For M=1.4$M_\odot$ & R=12km, calculated frequencies ${}_0t_2$
- ${}_0t_2$ is almost independent of the value of K_0
- For R=10~14 km and $M/M_\odot$=1.4~1.8, similar dependence on K_0
- One can write fitting line
- Focus on L dependence of ${}_0t_2$
- ${}_0t_2$ becomes smaller with larger R and M.



Constraint on L

- For R=10km~14km & $M/M_\odot$=1.4~1.8, ${}_0t_2$ are calculated
- Assuming that the observed QPOs would come from torsional oscillations
- ${}_0t_2$ is the smallest frequency among a lot of torsional oscillations
  - ${}_0t_2$ should be equal to or smaller than the smallest observed QPOs frequency



- Consequently, $L \gtrsim$ 50 MeV.
  - For $L \gtrsim$ 50 MeV, pasta region could be very narrow
  - Modification due to the pasta effect should be small
  - This is first constraint in the symmetry parameter with astronomical observations

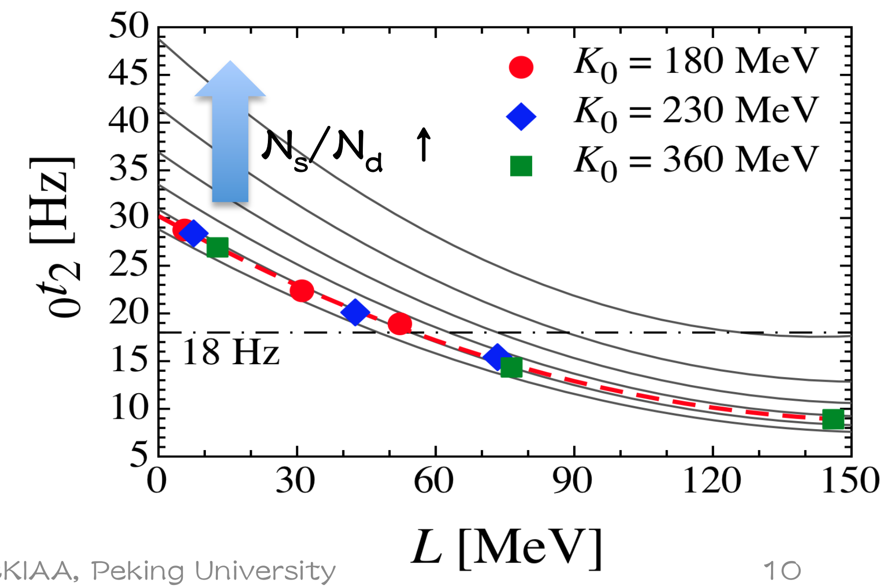
Effect of superfluidity

HS+2012b

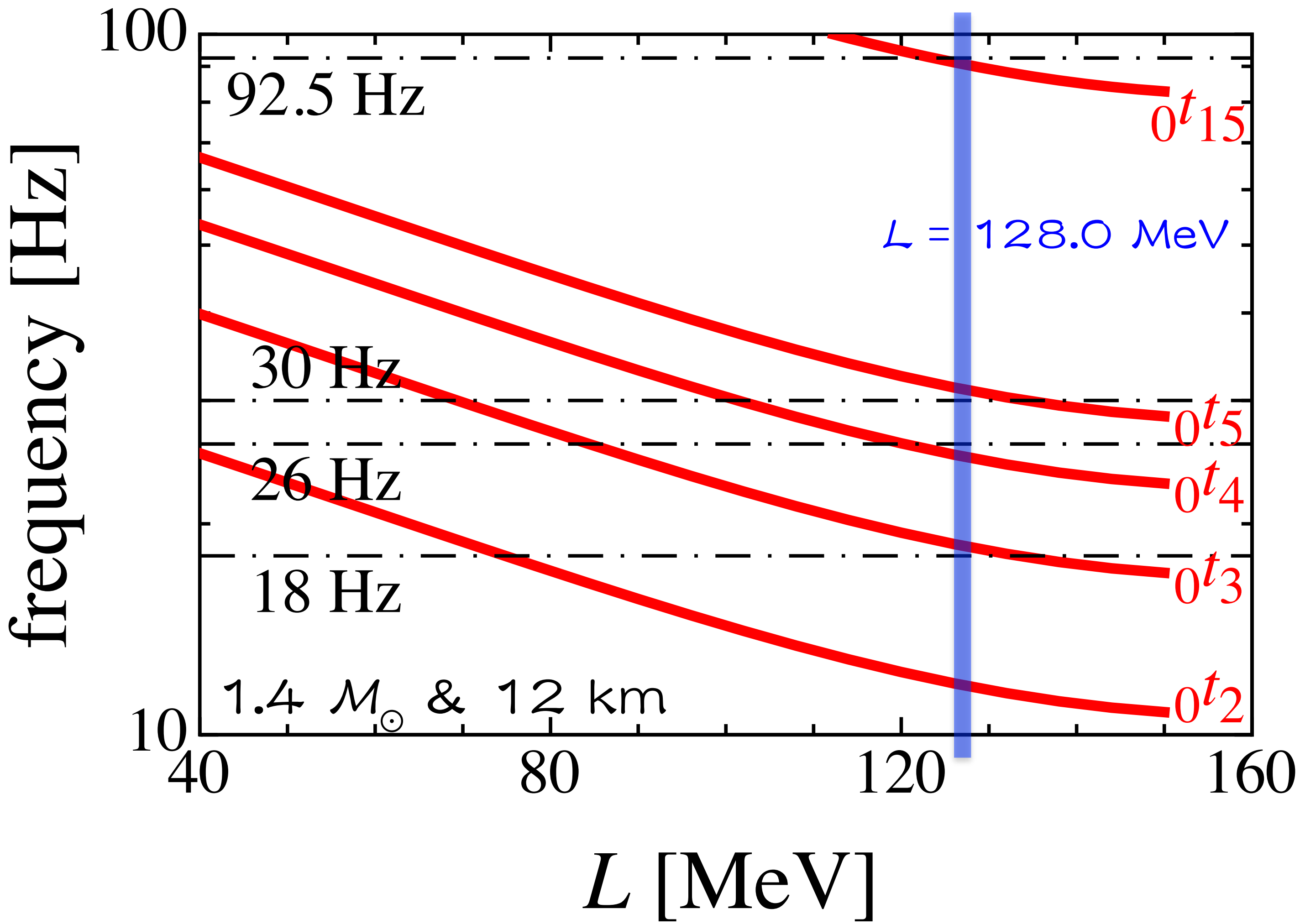
- For $\rho \gtrsim 4 \times 10^{11}$ g cm^{-3}, neutron could drip from nuclei
- Some of dripped neutron play a role as superfluid
- Effective enthalpy affecting on the shear oscillations could be reduced
  - shear speed ($v_s^2 \sim \mu / H$) increases due to the effect of superfluidity

$$\mathcal{Y}'' + \left[\left(\frac{4}{r} + \Phi' - \Lambda'\right) + \frac{\mu'}{\mu}\right]\mathcal{Y}' + \left[\frac{\epsilon + p}{\mu}\omega^2 e^{-2\Phi} - \frac{(\ell+2)(\ell-1)}{r^2}\right] e^{2\Lambda}\mathcal{Y} = 0.$$

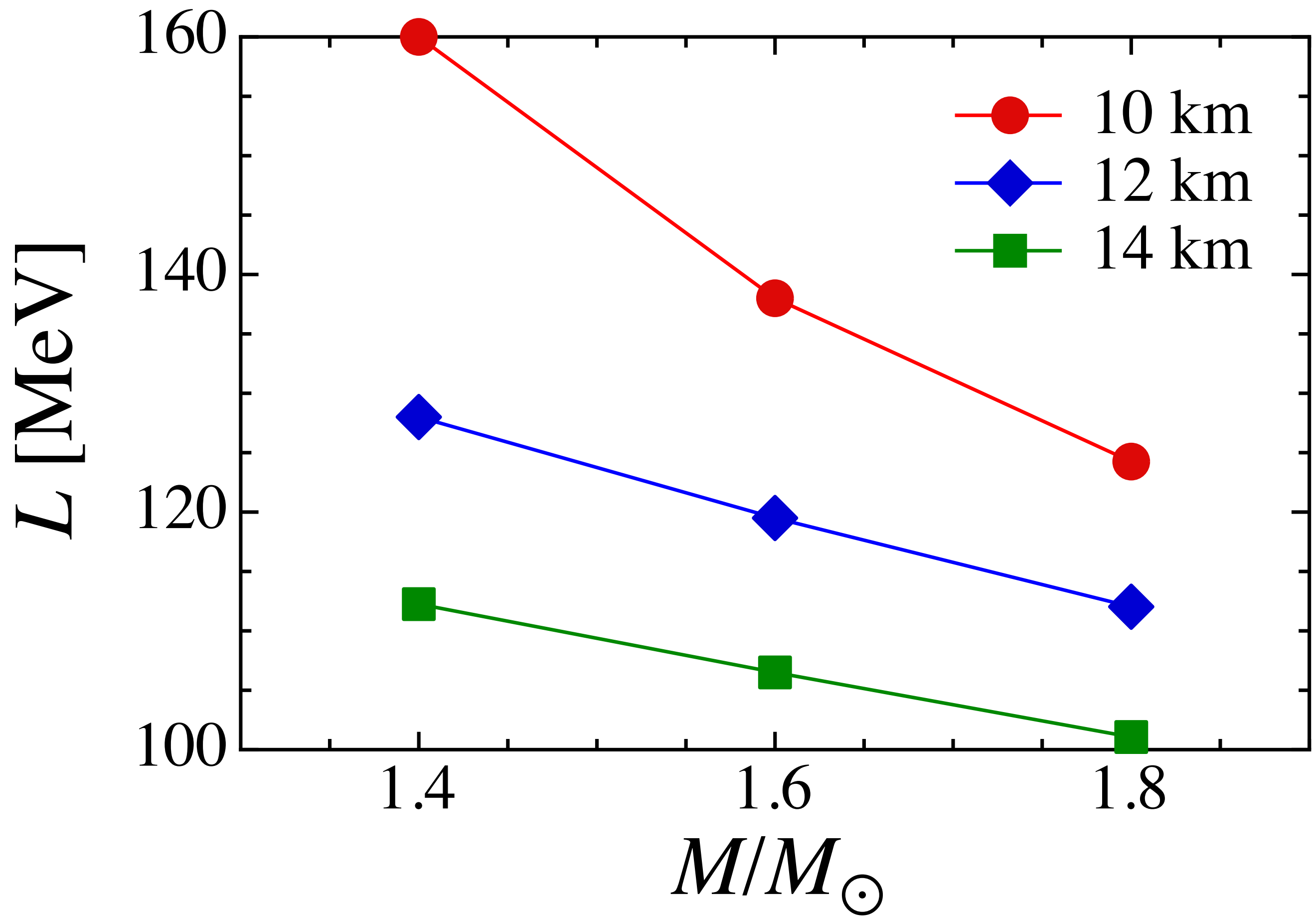
- ${}_0t_l$ could also increase due to the effect of superfluidity
- While, the fraction of superfluid neutron in dripped neutron is still unknown…
  - Chamel (2012): superfluid neutron are not so much (~10-30%?)
- ${}_0t_l$ with using a parameter of N_s/N_d for R=14km & M=1.8$M_\odot$



identification of SGR 1806-20

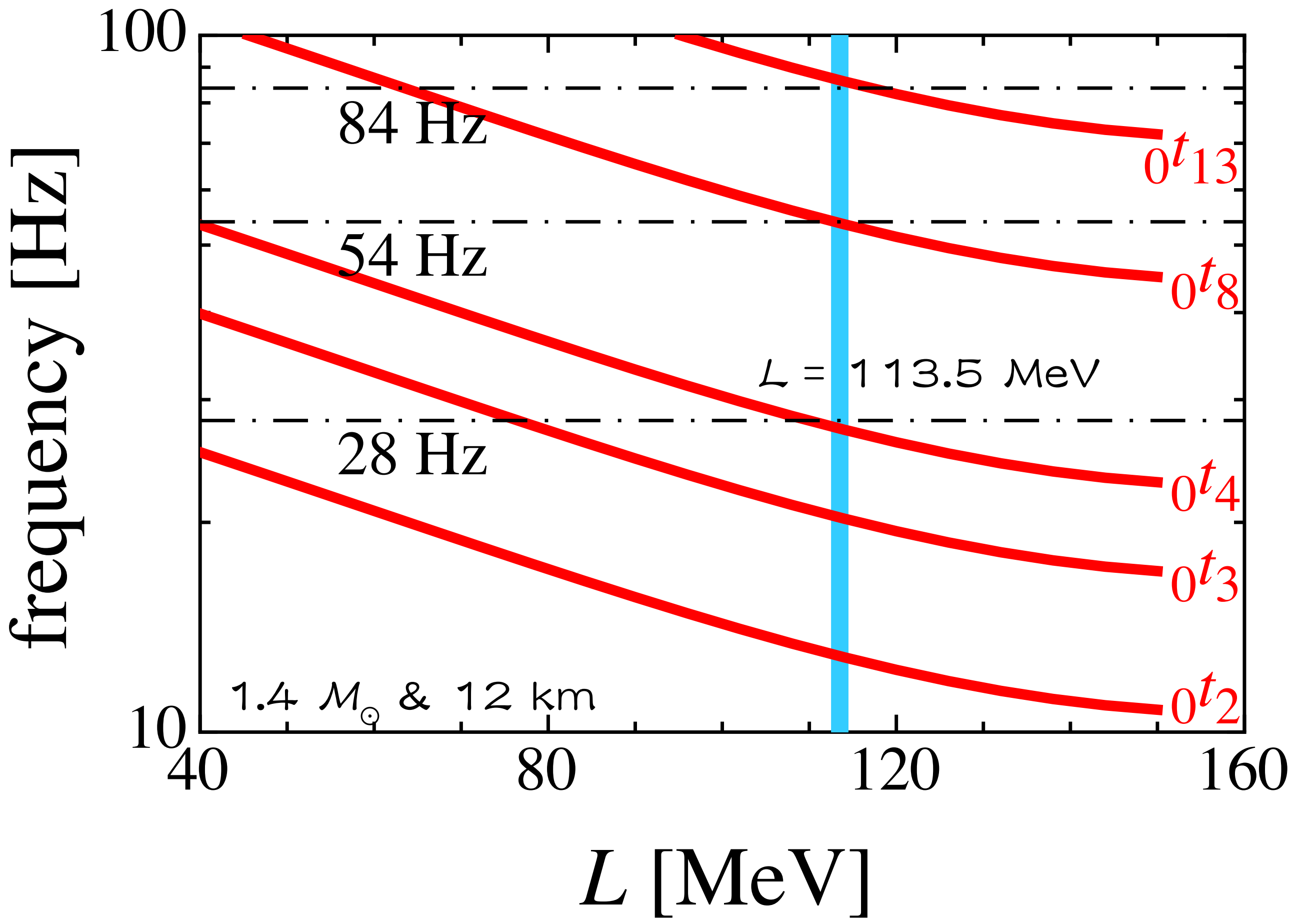


constraint on L via SGR 1806-20

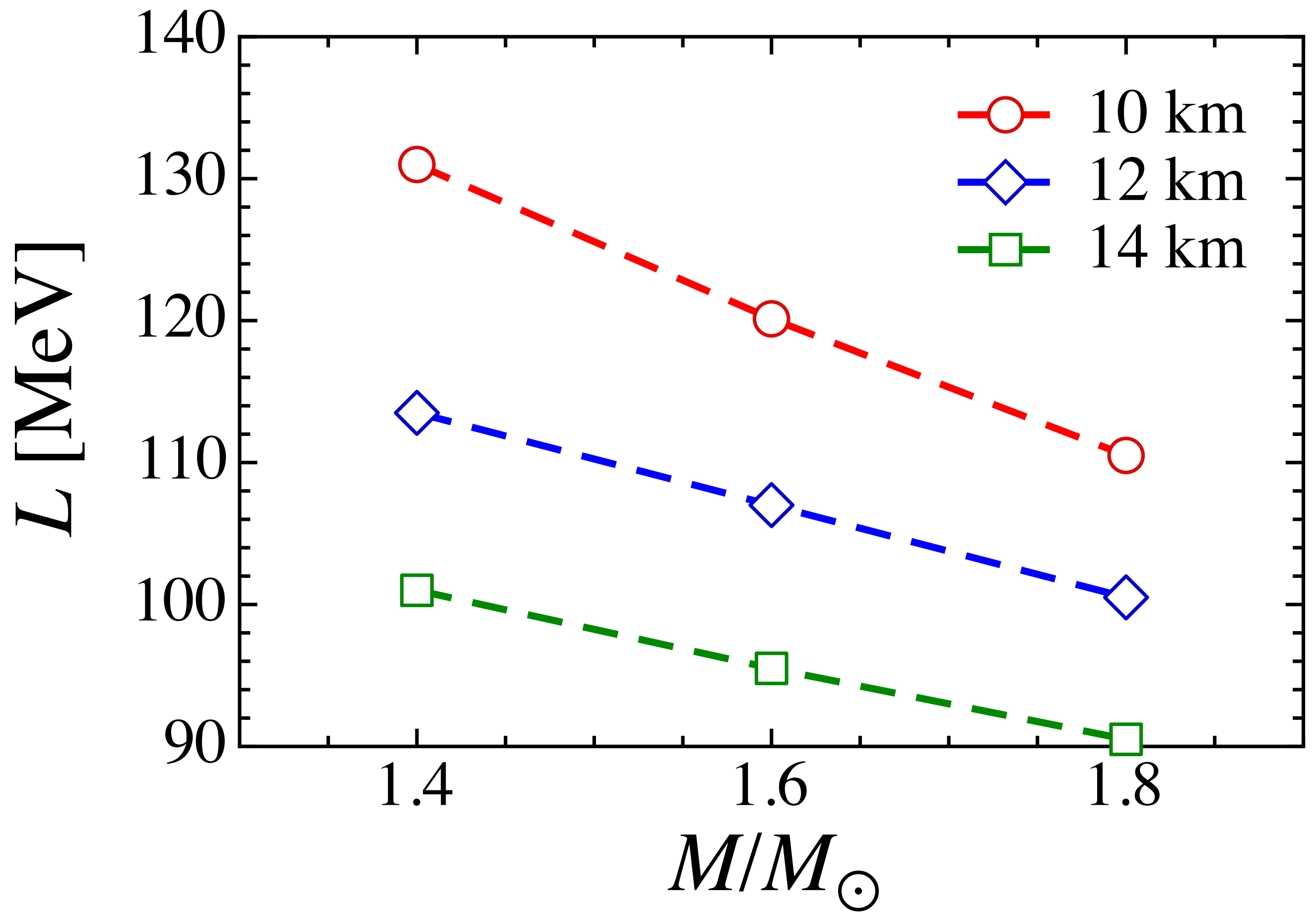


➡ 101.1 MeV $\leqslant L \leqslant 160.0$ MeV

identification of SGR 1900+14

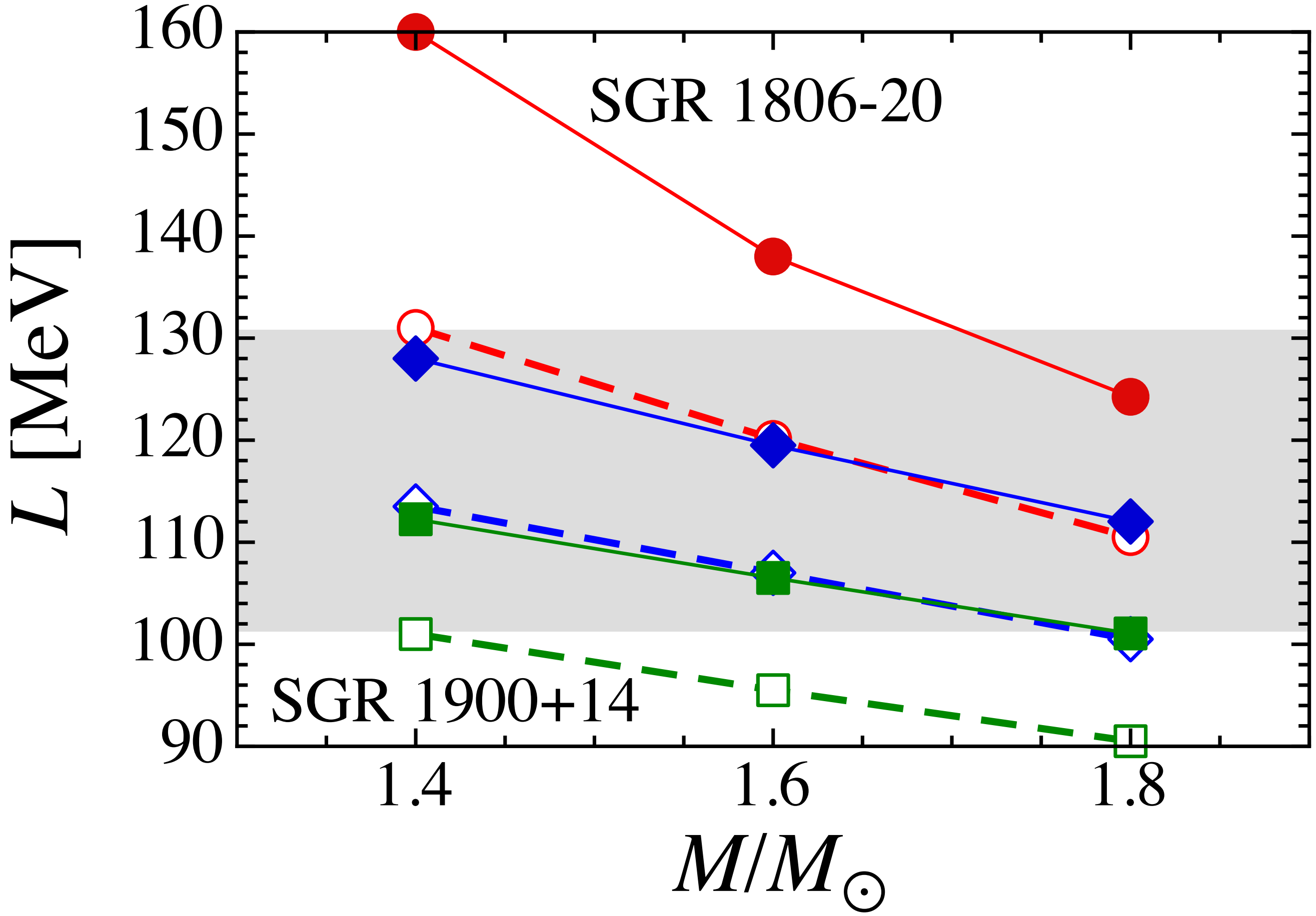


constraint on L via SGR 1900+14



➡ $90.5\ \mathrm{MeV} \leq L \leq 131.0\ \mathrm{MeV}$

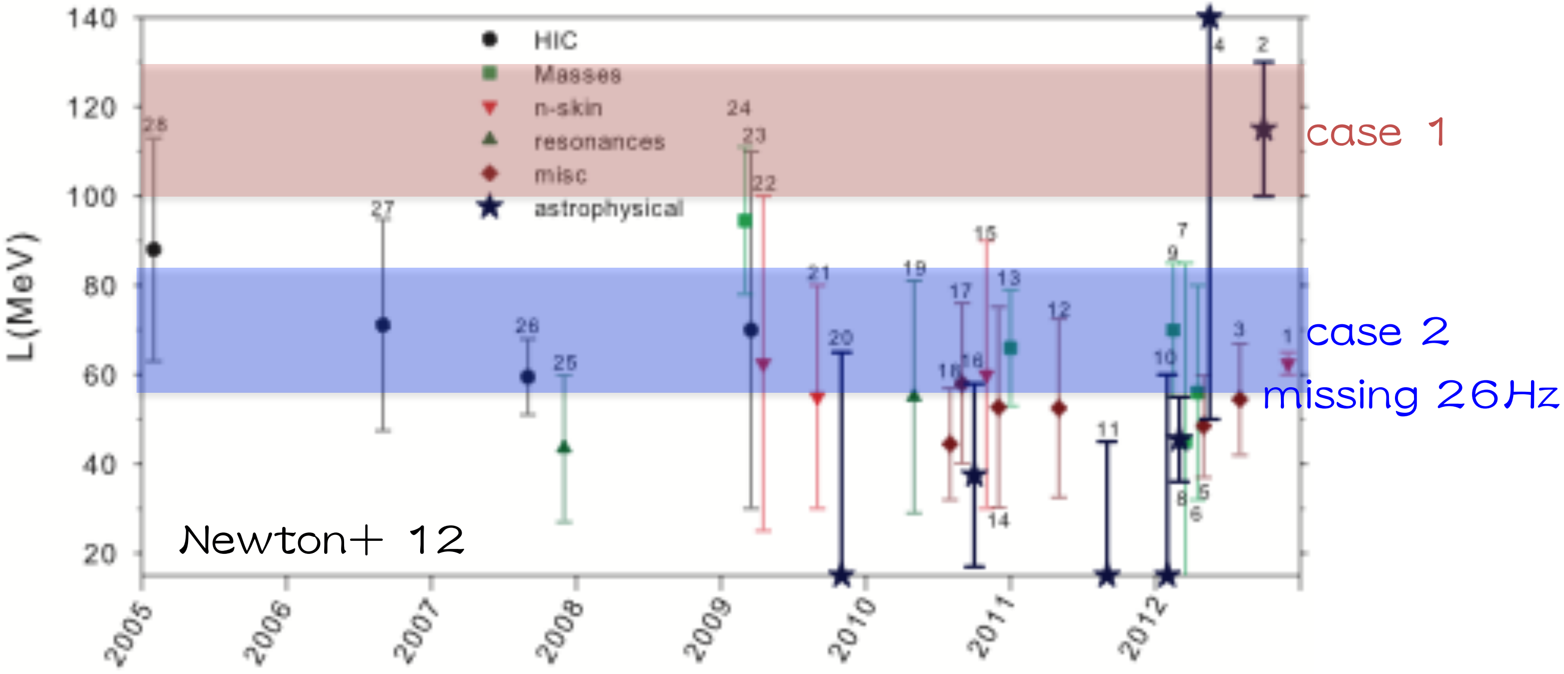
allowed region for L



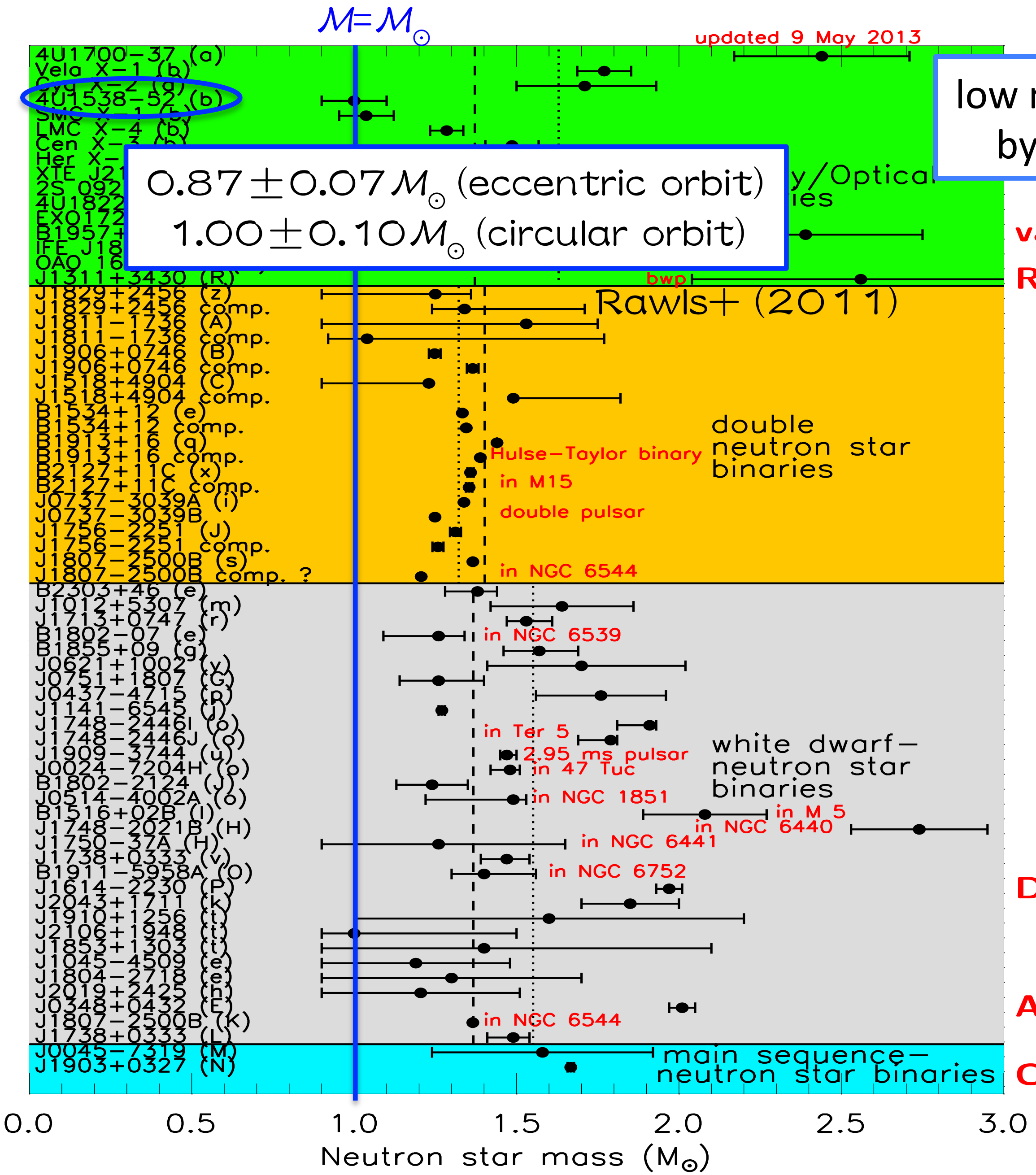
➡ 101.1 MeV ≤ L ≤ 131.0 MeV

other constraints on L

- other constraints suggests $L \sim 60 \pm 20$ MeV ?
  - our results may be larger than the previous experimental constraints.



Low-mass NSs



$0.87 \pm 0.07 M_\odot$ (eccentric orbit)
$1.00 \pm 0.10 M_\odot$ (circular orbit)

low mass NS in 4U 1746-37
by Li's talk on Monday

vanKerkwijk 2010

Romani et al. 2012

Demorest et al. 2010

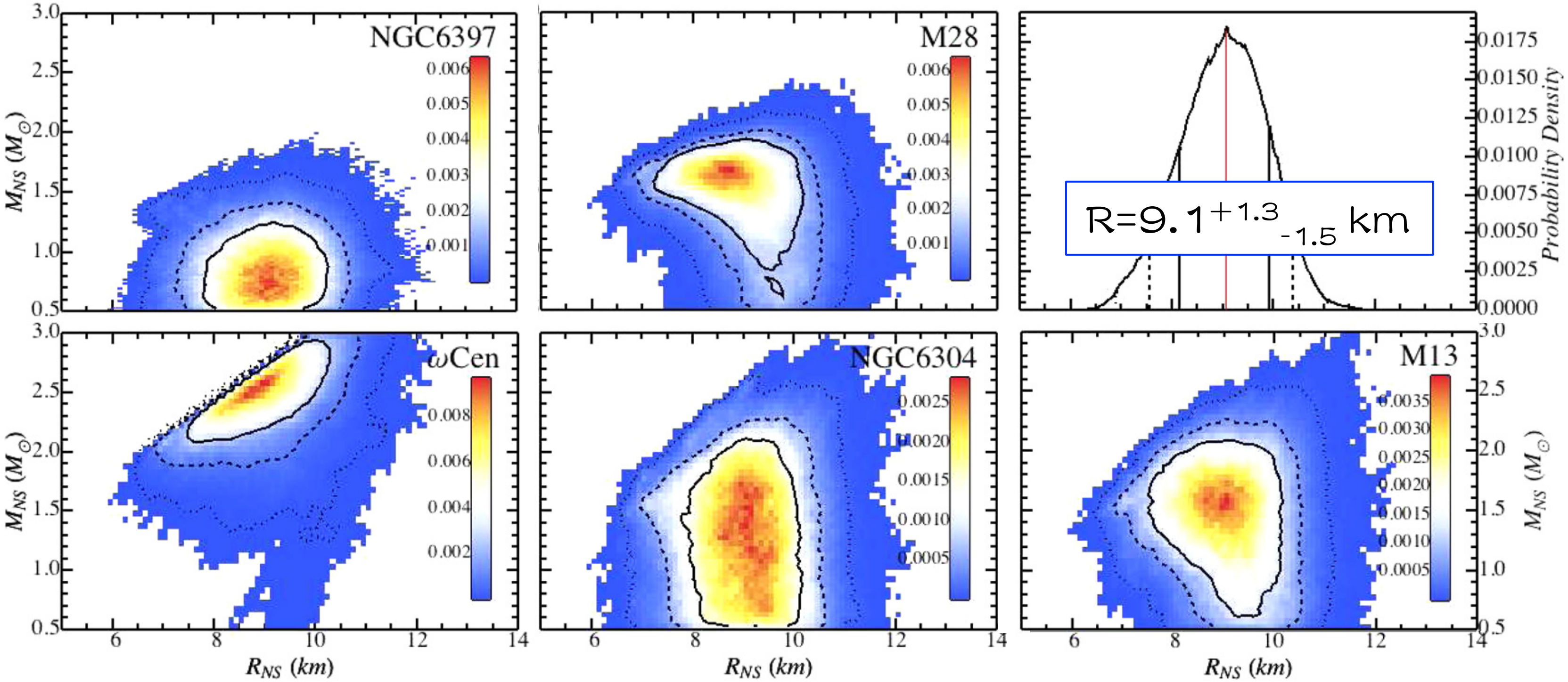
Antoniadis et al. 2013

Champion et al. 2008

Lattimer 2013

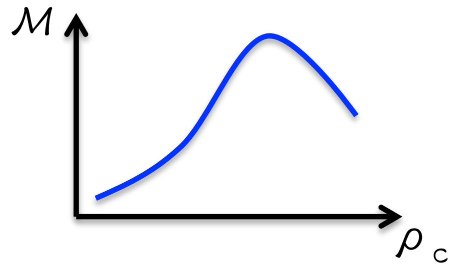
observations of NSs

- candidates of low-mass NSs 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)



Guillot+ 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 → this is an advantage to consider low-mass NSs!
- 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 an uncertainty of three nucleon interaction (Gandolfi+ 2012) and contribution from hyperon (or quark etc…).

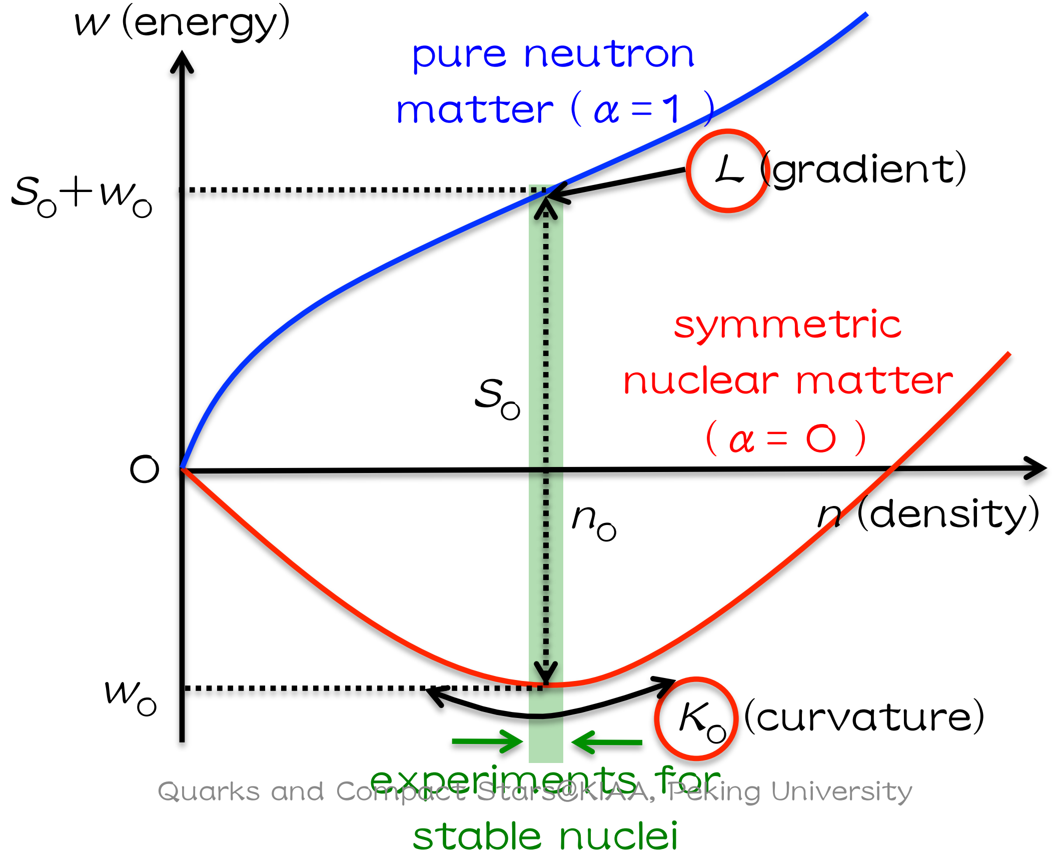
→ we focus on the NS models for $\rho \lesssim 2\rho_0$

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

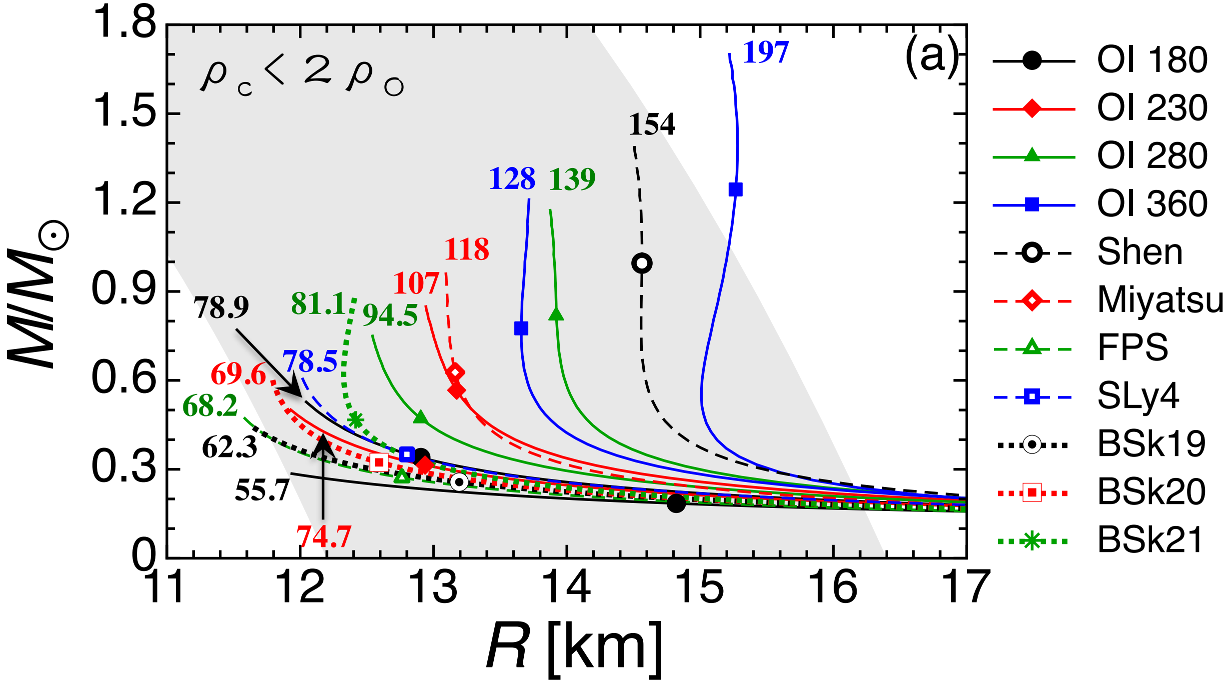
- we especially focus on
  - phenomenological EOS with various K_0 & L (Oyamatsu & Iida 2003; 2007)
  - EOSs based on relativistic mean field models
    - Shen EOS (Shen+ 1998)
    - Miyatsu EOS (Miyatsu+ 2013)
  - Skyrme-type effective interaction
    - FPS (Pethick+ 1995),
    - SLy4 (Douchin & Haensel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

EOSs based on the different theoretical models

MR relations

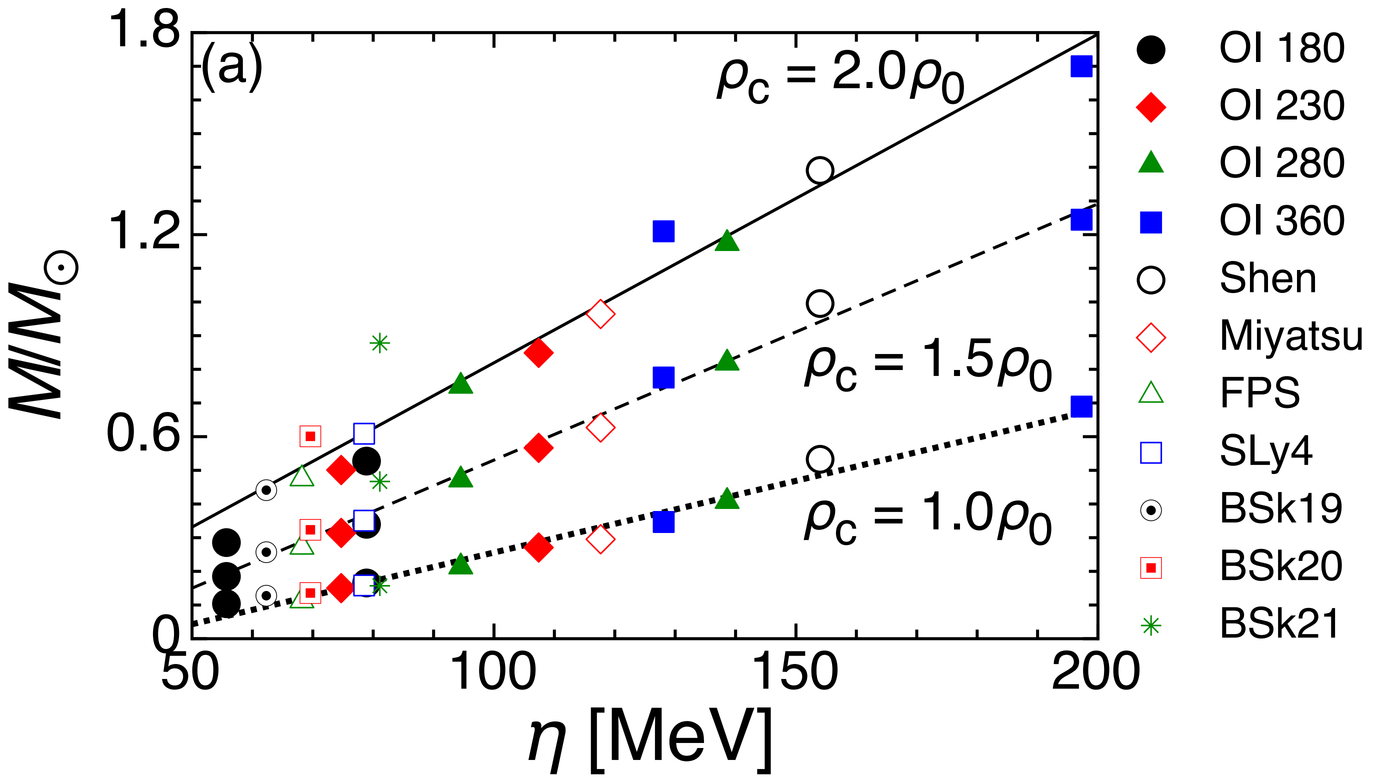
- NS models are constructed with various sets of K_0 & L
- We can find the specific combination of K_0 & L describing the low-mass NSs,

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

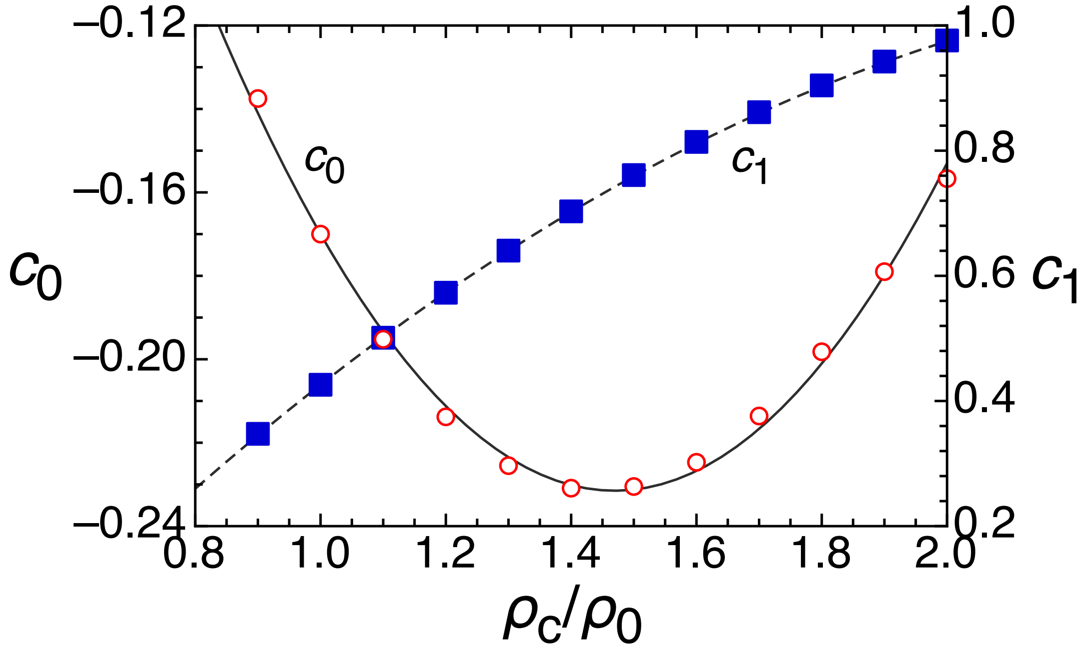


EOS	K_0 (MeV)	L (MeV)	η (MeV)
OI-EOS	180	31.0	55.7
	180	52.2	78.9
	230	42.6	74.7
	230	73.4	107.4
	280	54.9	94.5
	280	97.5	138.6
	360	76.4	128.1
	360	146.1	197.3
Shen	281	114	154.0
Miyatsu	274	77.1	117.7
FPS	261	34.9	68.2
SLy4	230	45.9	78.5
BSk19	237	31.9	62.3
BSk20	241	37.4	69.6
BSk21	246	46.6	81.1

mass formula



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



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

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

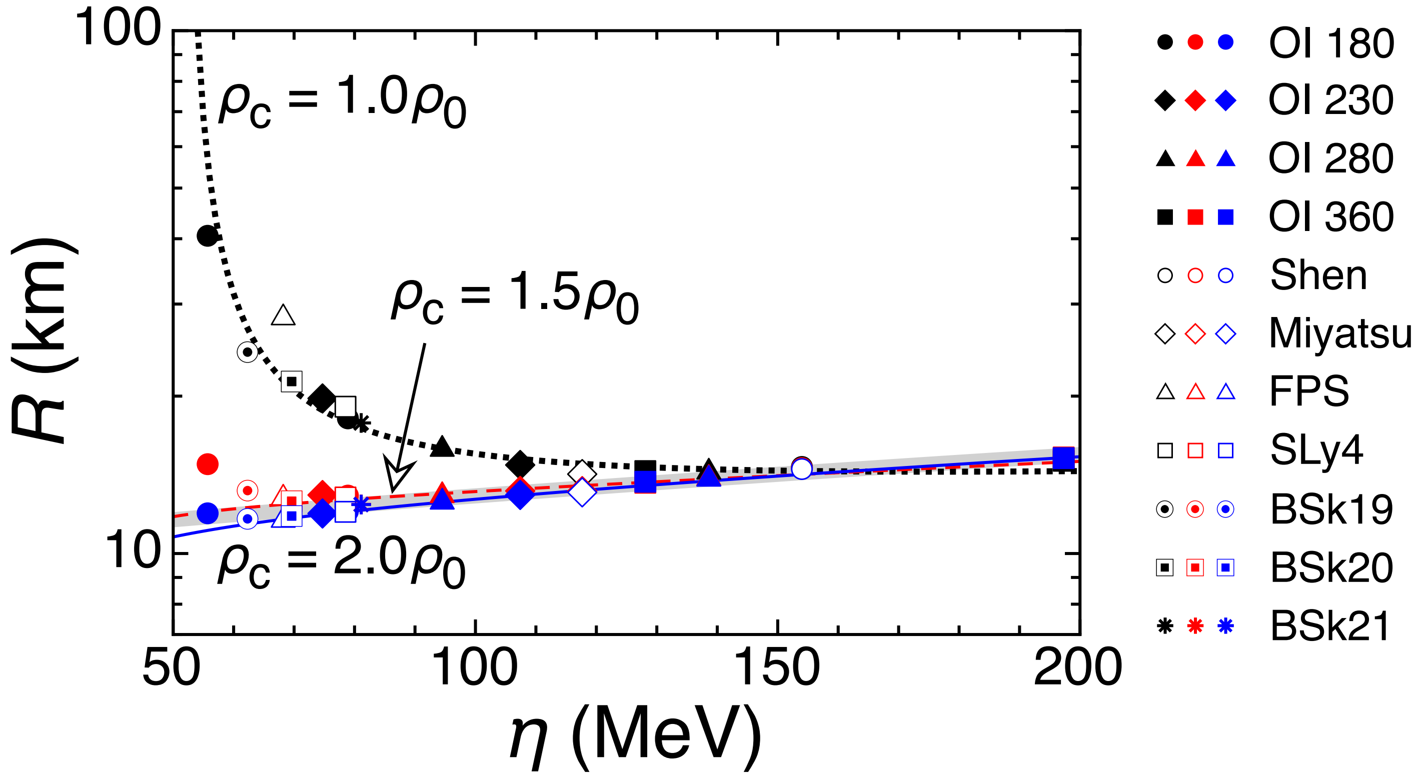
$$z = 0.00859 - 0.0619u_c + 0.0255u_c^2 - (0.0429 - 0.108u_c + 0.0120u_c^2)\left(\frac{\eta}{100\,\mathrm{MeV}}\right)$$

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

- 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.



how to determine R

- 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

how to determine (*M*, *R*) 1

- Assuming that Eddington limit reaches at the stellar surface…
- Eddington luminosity

$$L_{\rm Edd} = \frac{4\pi GMc}{\kappa_{\rm e}}(1+z) = 4\pi R^2 \sigma_{\rm SB} T_{\rm Edd}^4 \qquad 1+z = (1-2GM/Rc^2)^{-1/2}$$

$\kappa_{\rm e} = 0.2(1+X)\ {\rm cm}^2\ {\rm g}^{-1}$ electron Thomson scattering opacity

X : hydrogen mass function

$$F_{\rm Edd} = \frac{L_{\rm Edd,\infty}}{4\pi D^2} = \frac{GMc}{\kappa_{\rm e} D^2}\frac{1}{1+z} \qquad L_\infty = \frac{L}{(1+z)^2}$$

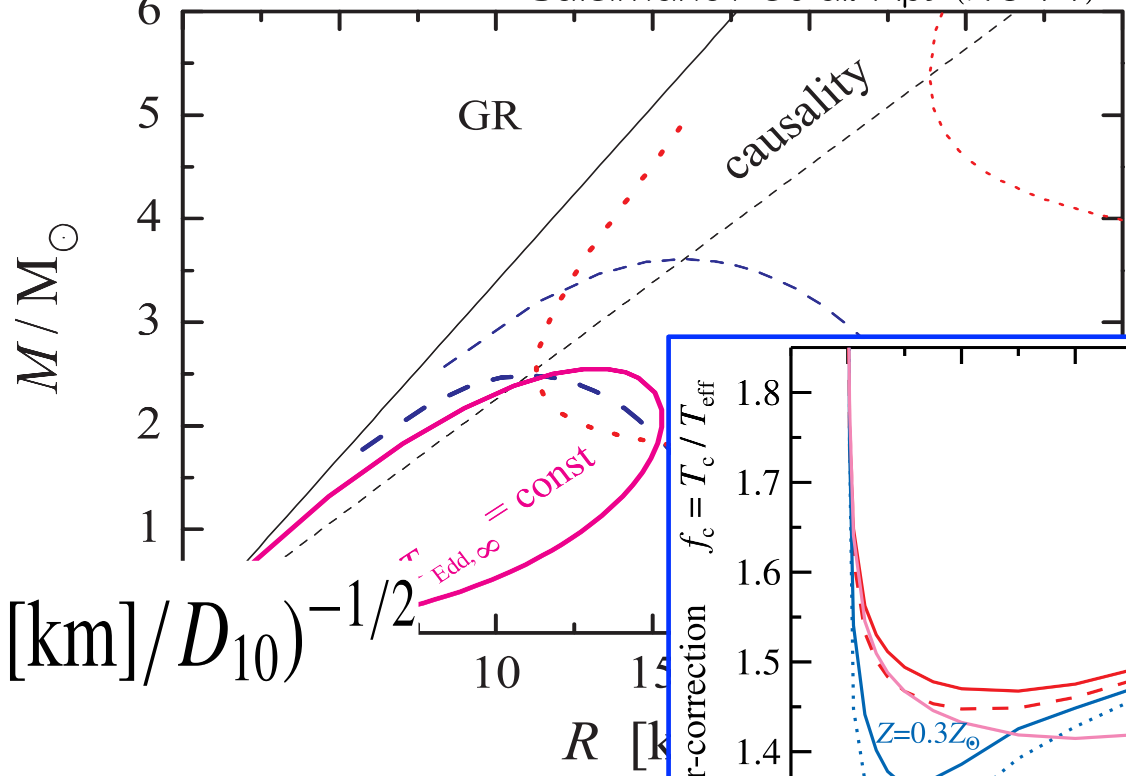
observed Eddington flux

- X depends on an atmosphere model
  - pure hydrogen: X = 1
  - pure helium: X = 0
  - solar H/He + Z=0.3$Z_\odot$: X = 0.74, where $Z_\odot$= 0.0134

how to determine (M, R) 1

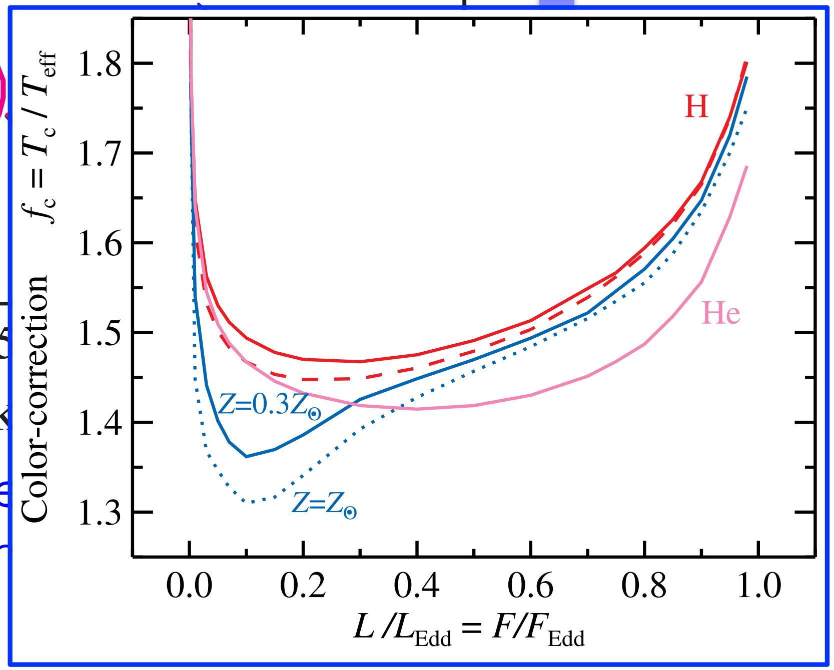
- if D would be known…

Suleimanov et al. ApJ (2011)



$$A = (R_\infty[\mathrm{km}]/D_{10})^{-1/2}$$

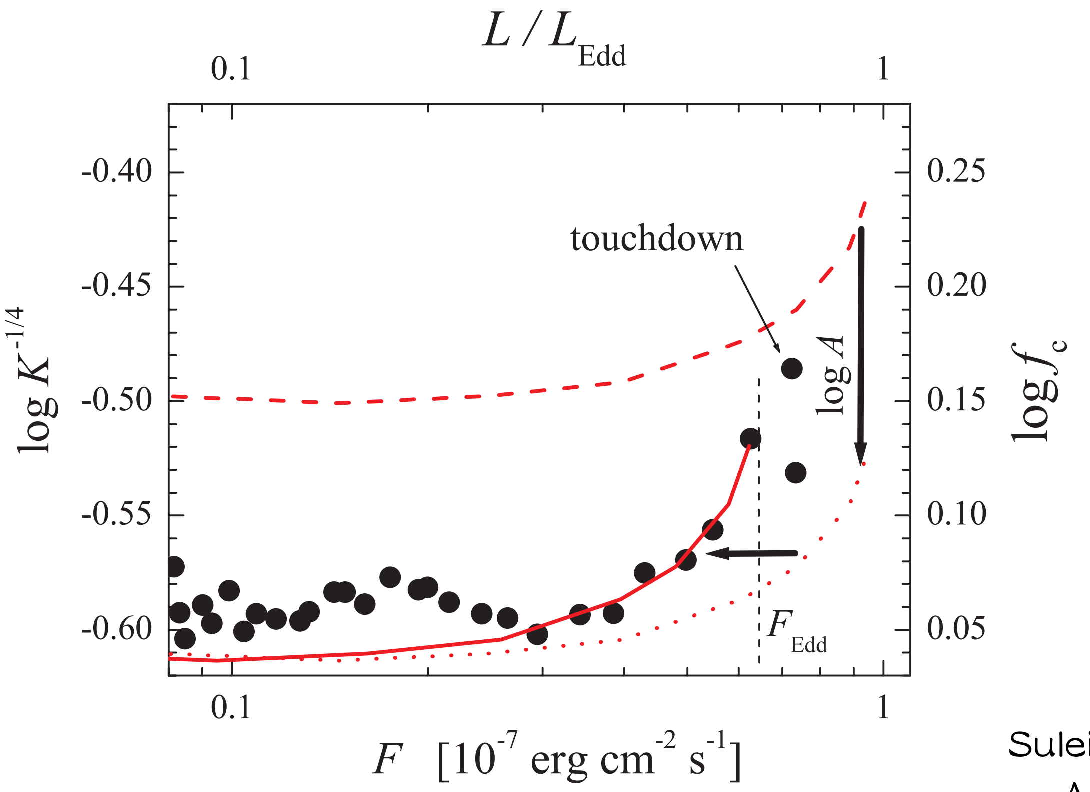
large



- BUT, the determination of the e
luminosity reaches Eddington lim
quite uncertain…

Suleimanov idea

- in order to minimize the theoretical uncertainties, the whole cooling track is adopt to determine the values of F_{Edd} & A

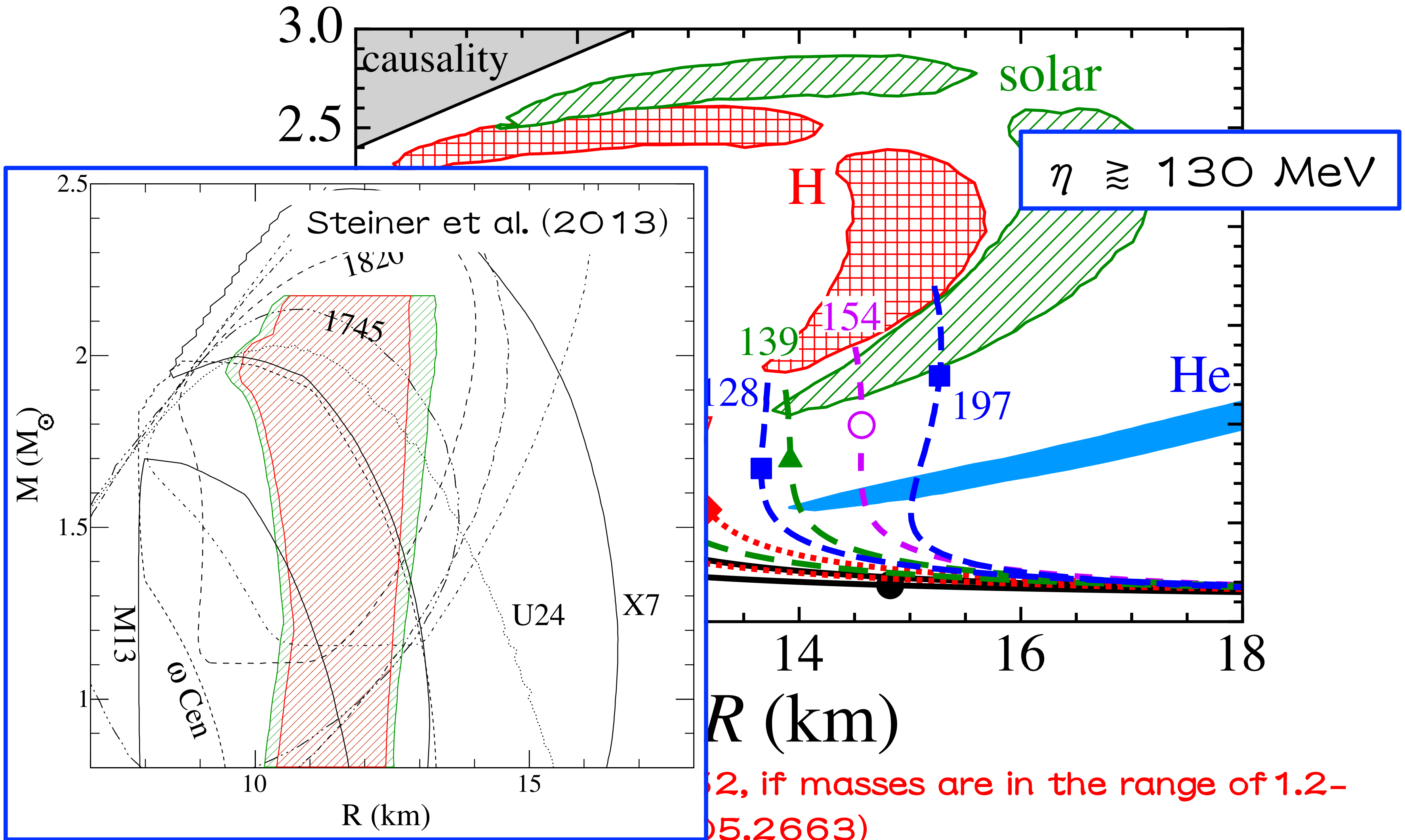


Suleimanov et al. ApJ (2011)

X-ray burster 4U 1724-307

- in the globular cluster Terzan 2
  - solar H/He + subsolar metal abundance $Z = 0.3Z_{\odot}$ (Ortolani et al. 97)
- Distance
  - $D = (5.3 - 7.7) \pm 0.6$ kpc (Kuchinski et al. 95, Ortolani et al. 97)
- data observed by Rossi X-ray Timing Explorer (RXTE)

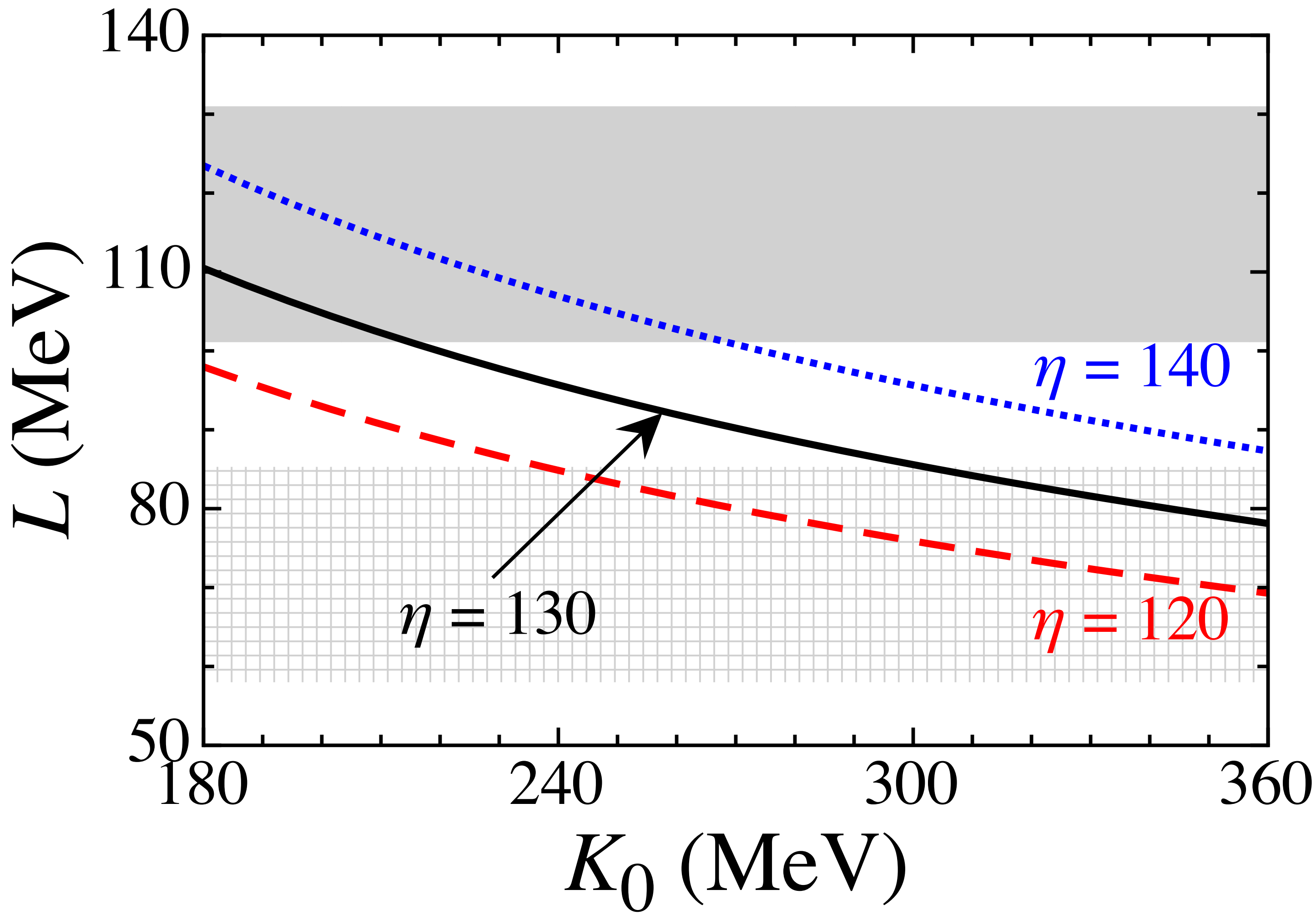
allowed region in MR relation



2, if masses are in the range of 1.2-

05.2663)

constraint on (L, K_0)



summary

- neutron stars are good candidates to examine the physics under the extreme state.
  - QPOs in SGRs may be good examples to adopt the asteroseismology
- compering the torsional oscillations to the observational evidences, we can get the constraint on L as $L \gtrsim 50$ MeV.
- superfluid effect enhances the frequencies of torsional oscillations.
  - $100 \lesssim L \lesssim 130$ MeV, if all QPOs come from torsional oscillations
  - $58 \lesssim L \lesssim 85$ MeV, if QPOs except for 26 Hz QPO coms from torsional oscillation
- we find a good parameter to describe a low-mass NS
  - using the mass-radius constraint obtained by Suleimanov et al., we show a possibility to make a constraint on the nuclear saturation parameters
  - consistent with the constraints obtained from the QPO frequencies observed from the giant flares in soft-gamma repeaters