Neutron Star Properties from Astrophysical Observations

Chang-Hwan Lee / Pusan National University

focused on Astronomy & Astrophysics 650, A139 (2021)

in collaboration with
***Myungkuk Kim, Young-Min Kim**, **Kyujin Kwak** (UNIST)*

Contents

Astro-Hadron Physics in Korea *my personal point of view*

Hadron Physics		*Astrophysics*
NS EoS with **Effective Field Theories** (with D.P.Min, **M.Rho** & G.E.Brown)	**1990s**	NS Binary as a source of GW (with **G.E.Brown**@Stony Brook)
	2003	**Korean Gravitational Wave Group** Nuclear physics + Astrophysics + Mathematics + Artificial Intelligence
Science-Business-Belt Project initiated by **D.P. Min**	**2006**	
RAON project was approved	**2009**	**KGWG** joined LIGO Scientific Collab.
New Transport DJBUU Nuclear Structure DRHBc New EDF KIDS … …	**2017**	**GW from NS-NS mergers** (Multi-messenger Astrophysics) Tidal deformability of NS … …
	2021	

Astro-Hadron Physics

Dense Nuclear & Stellar Matter Studies

for **RAON** New Rare Isotope Accelerator & **MMA** Multi-Messenger Astrophysics

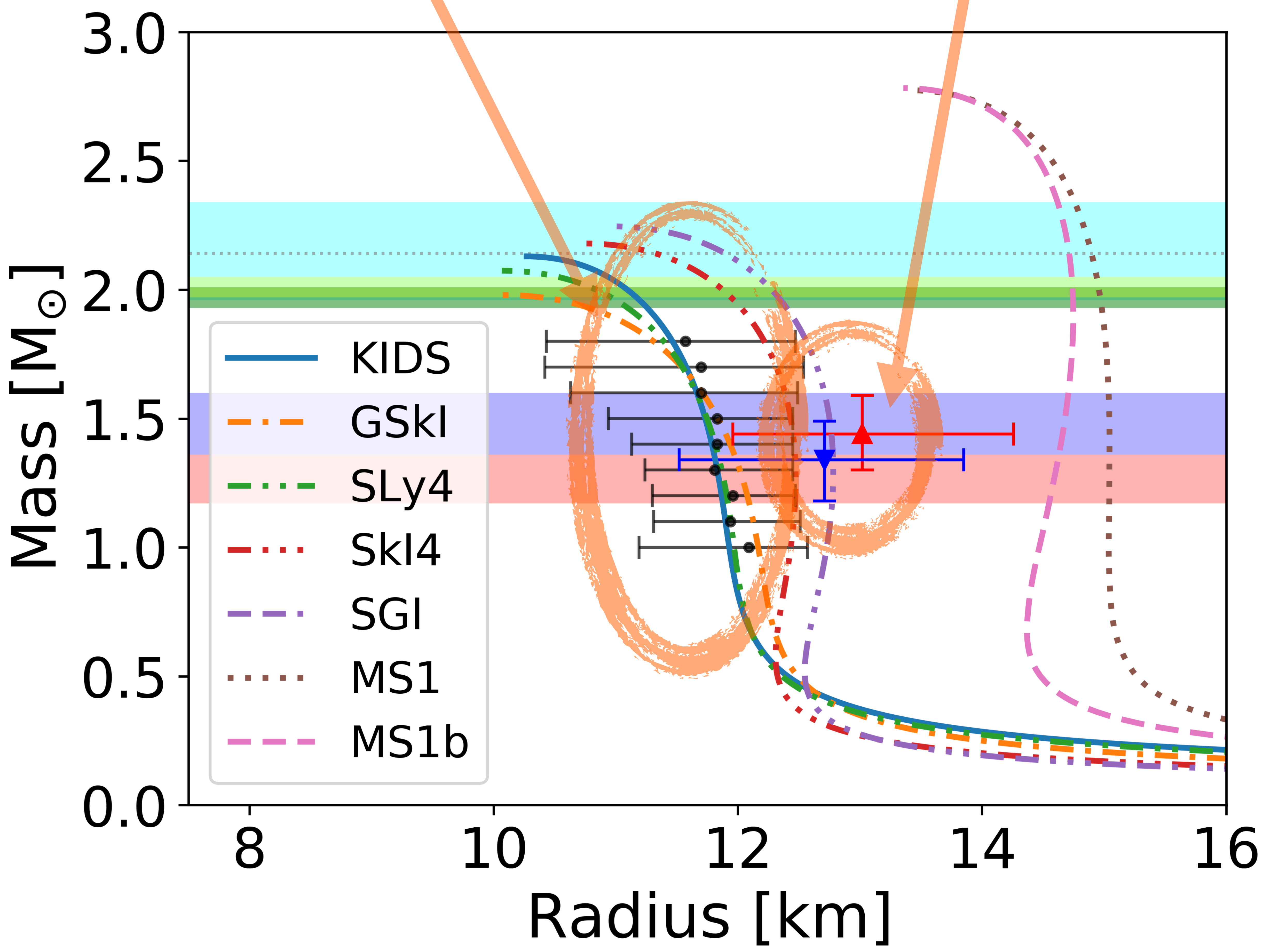
BUD*² *Collaboration

***B**usan (**CHL**, H.S. CHO, … …)*
***U**lsan (**K. KWAK, Y.-M. KIM, M. KIM**, … …)*
***D**aegu (Chang Ho HYUN)*
***D**aejeon (Youngman KIM, … …)*
Montreal (Sangyong JEON, McGill)

Single NS (better constraint) *J0030+0451 by NICER*

Low-mass X-ray binary (NS binary)

Riley 2019 vs. Miller 2019



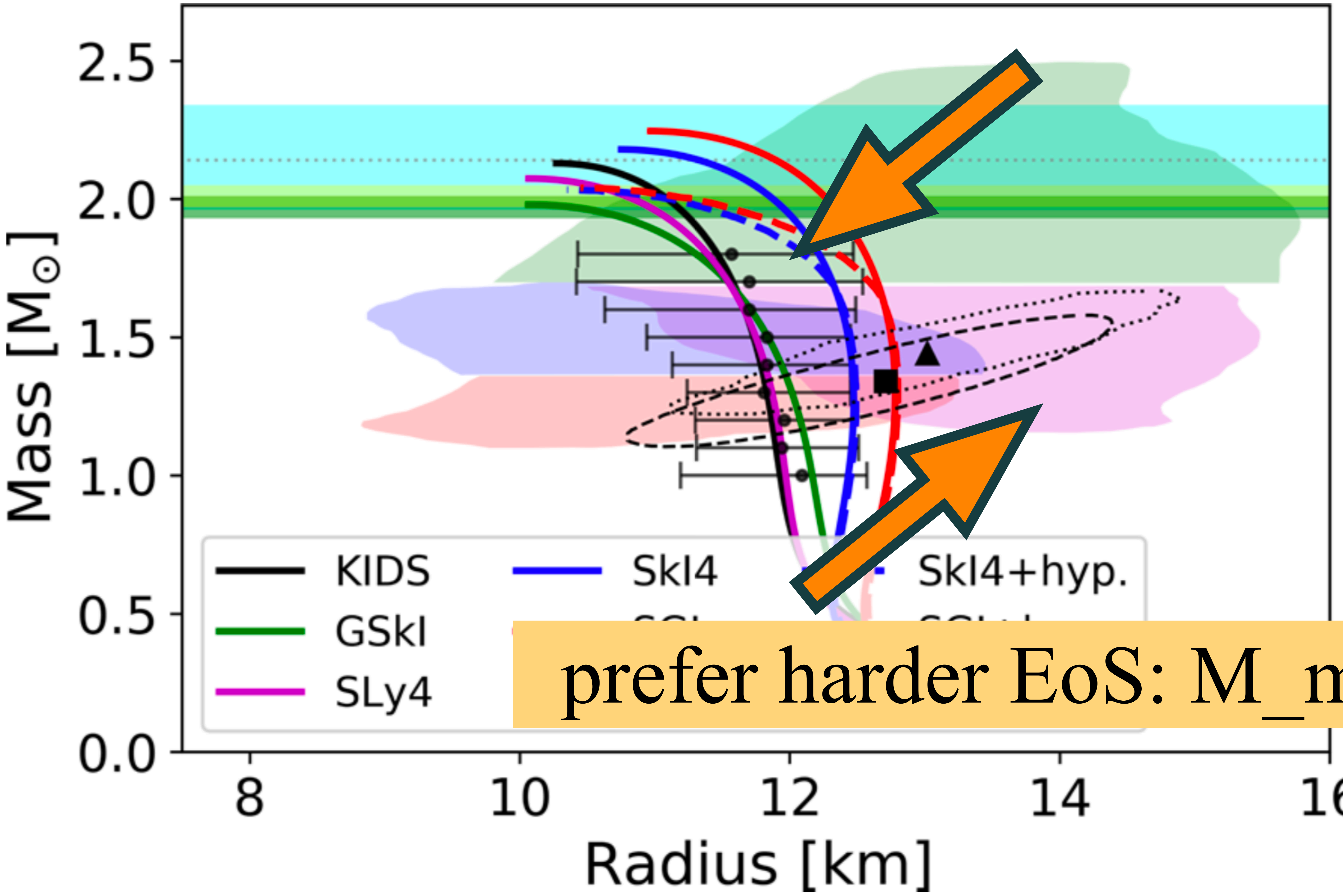
$2.14^{+0.20}_{-0.18} M_\odot$

H. T. Cromartie, *et al.*, Nature Astronomy (2019).

Kim et al., EPJA 56, 157 (2020)

Constraints on Equation of State

prefer soft EoS: GW170817, strangeness



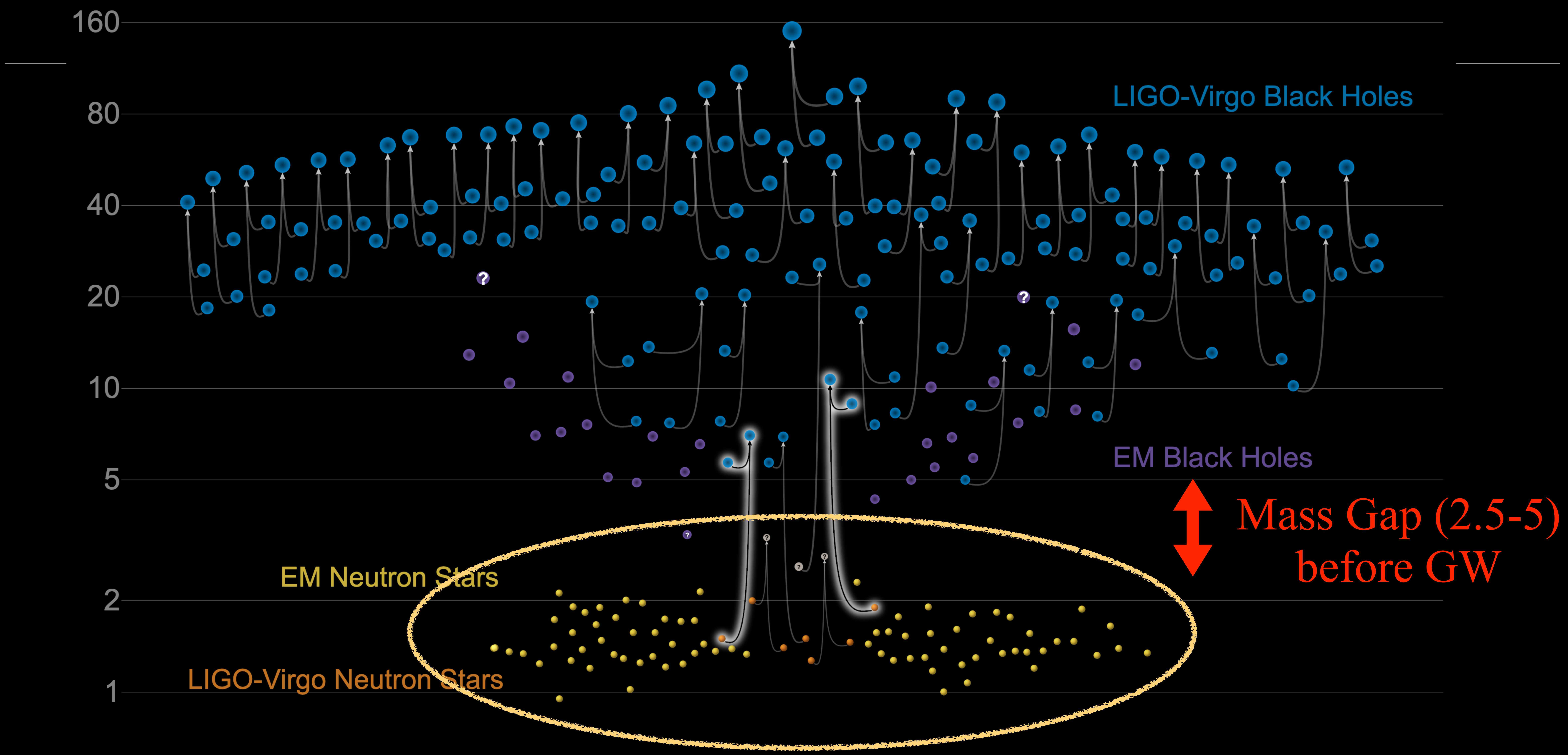
$2.14^{+0.20}_{-0.18} M_{\odot}$

M. Kim et al. (IJMPE 2020)

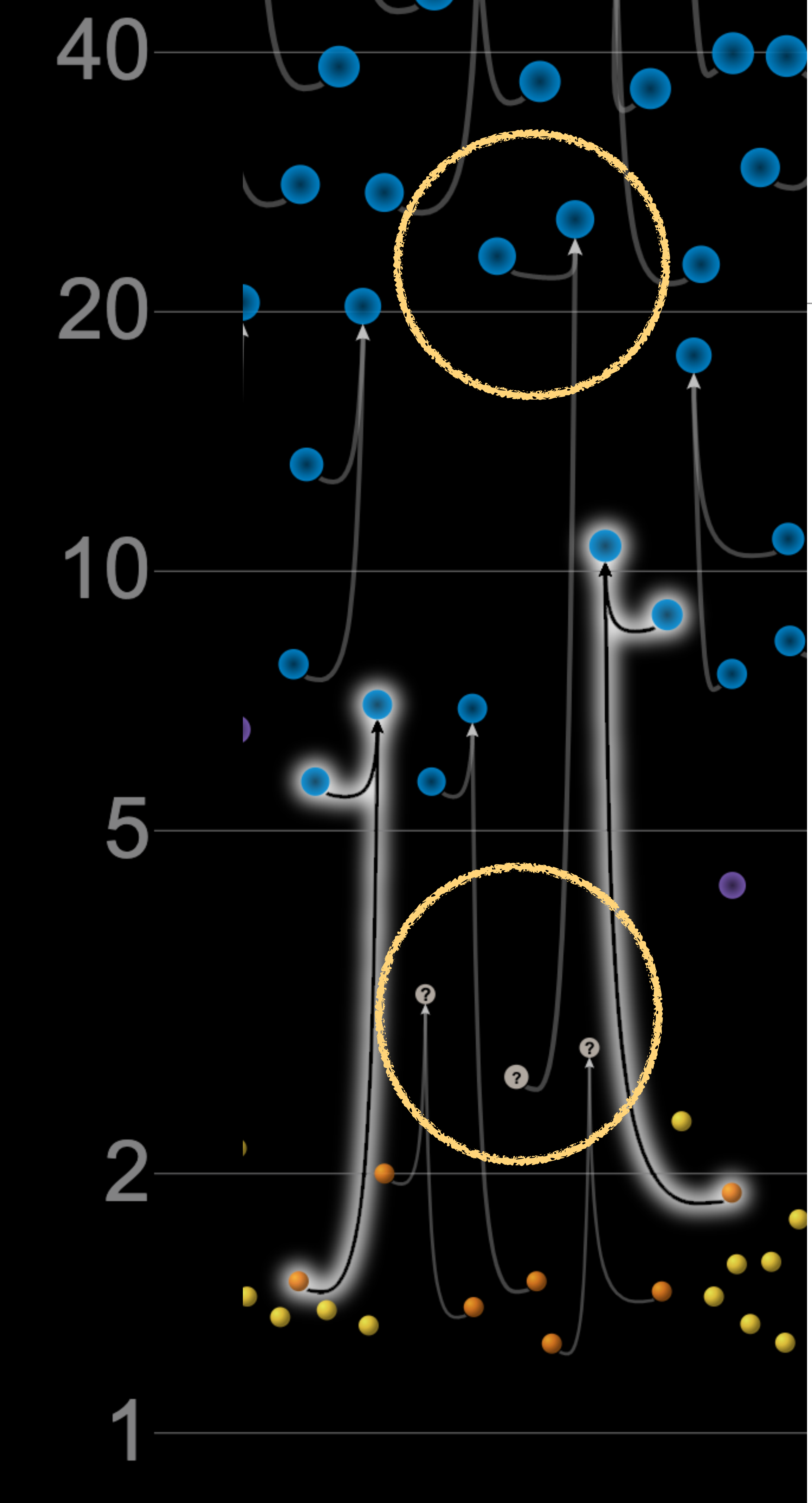
prefer harder EoS: M_max, NICER

Masses in the Stellar Graveyard

in Solar Masses



GWTC-2 plot v1.0
LIGO-Virgo | Frank Elavsky, Aaron Geller | Northwestern



The Astrophysical Journal Letters, 896:L44 (20pp), 2020 June 20
https://doi.org/10.3847/2041-8213/ab960f
© 2020. The American Astronomical Society.
OPEN ACCESS

GW190814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object

mass gap $(2.5\ M_\odot < M < 5\ M_\odot)$

- Probability of NS formation from core collapse SN is low
- What is the origin of 2.6 solar mass compact object ?

$2.6M_\odot$ ***Black Hole*** *or* ***Neutron Star*** *or* ***Quark Star*** *?*

- **Light Black Hole**
  - *e.g., Yang et al., ApJL 901, L34 (2020)*
  - Tidal Love number of GW170817 prefers **soft EOS**
  - 2.6 solar mass NS required **hard EOS (inconsistent with GW170817)**
  - Light BH may be formed **by accretion** (not from direct collapse of giant stars)
- **Strange Quark Star**
  - *e.g., Bombaci et al., PRL 126, 162702 (2021)*
    Drago & Pagliara, PRD 102, 063003 (2020)
  - Two track scenario
  - NS and QS may coexist
- … …

Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW D **81,** 105021 (2010)

Cold quark matter

Aleksi Kurkela,[1] Paul Romatschke,[2] and Aleksi Vuorinen[3,4,5]

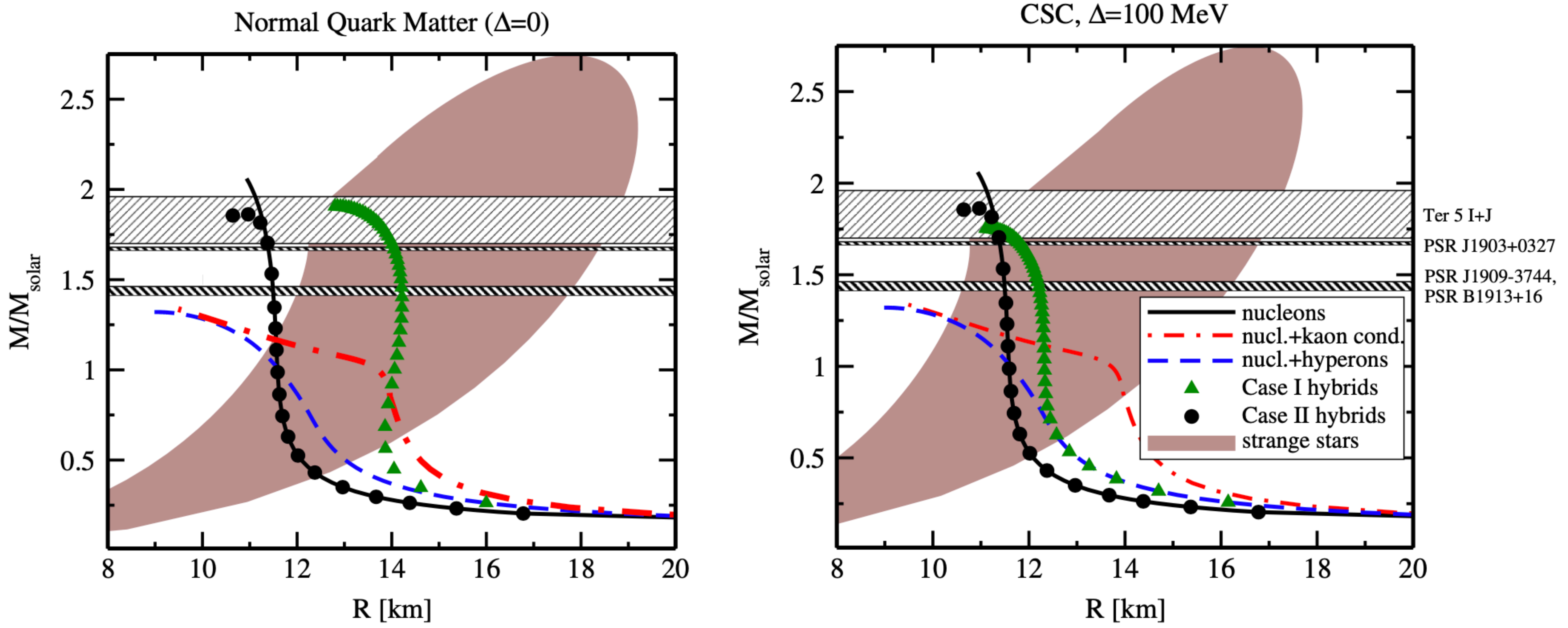


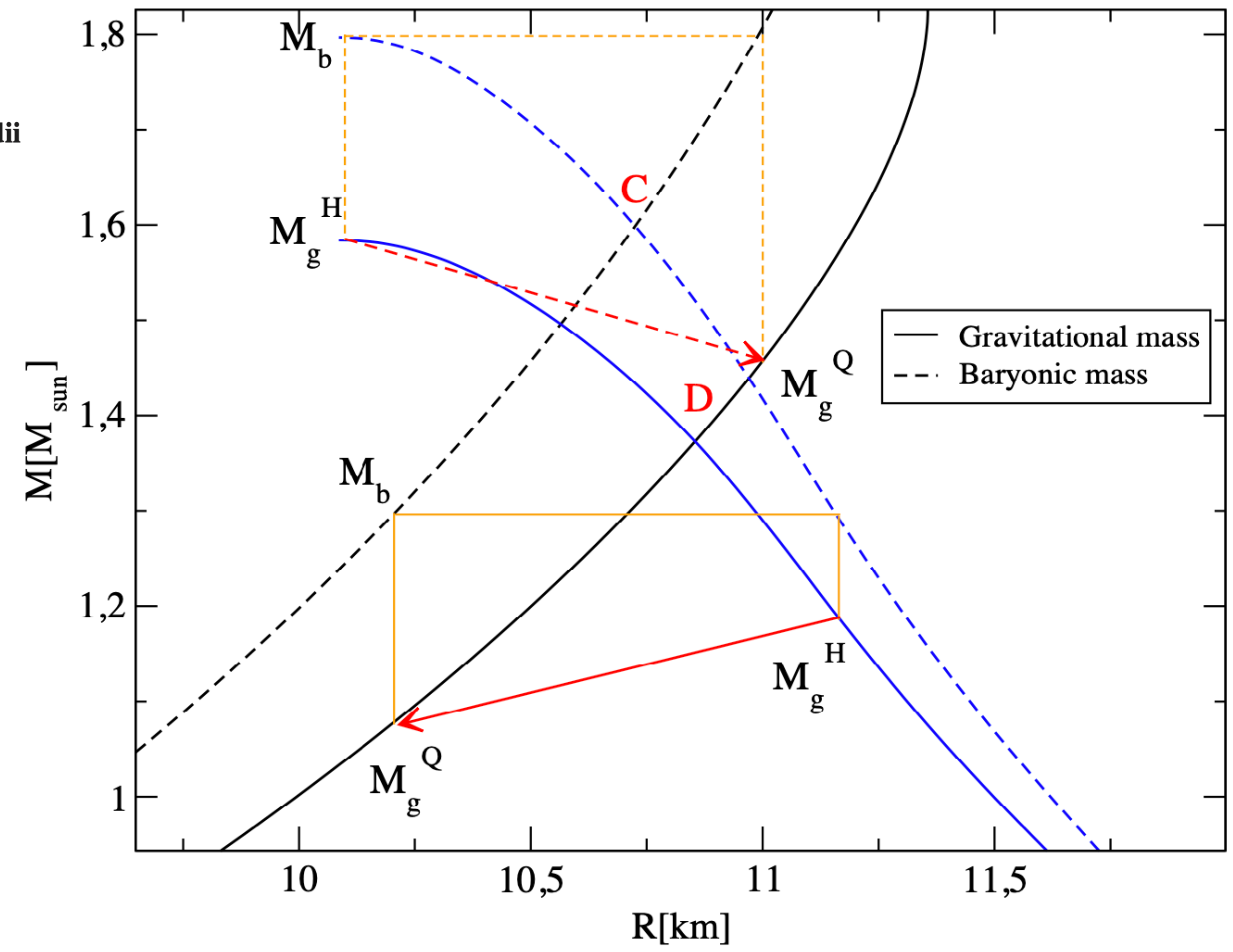
FIG. 10 (color online). The mass-radius relation for compact stars, obtained using $\Delta = 0$ (left) and $\Delta = 100$ MeV (right) in the quark matter EOS. We display the results for purely hadronic stars (containing only nucleons [69], nucleons with kaon condensation [70], or nucleons and hyperons [71]), pure quark matter stars (strange stars, cf. Sec. V A) and hybrid stars including both hadronic and quark matter (see text for details). Also shown in the plots are compact star mass observations from Refs. [81–85].

Open questions

PHYSICAL REVIEW D **102**, 063003 (2020)

Why can hadronic stars convert into strange quark stars with larger radii

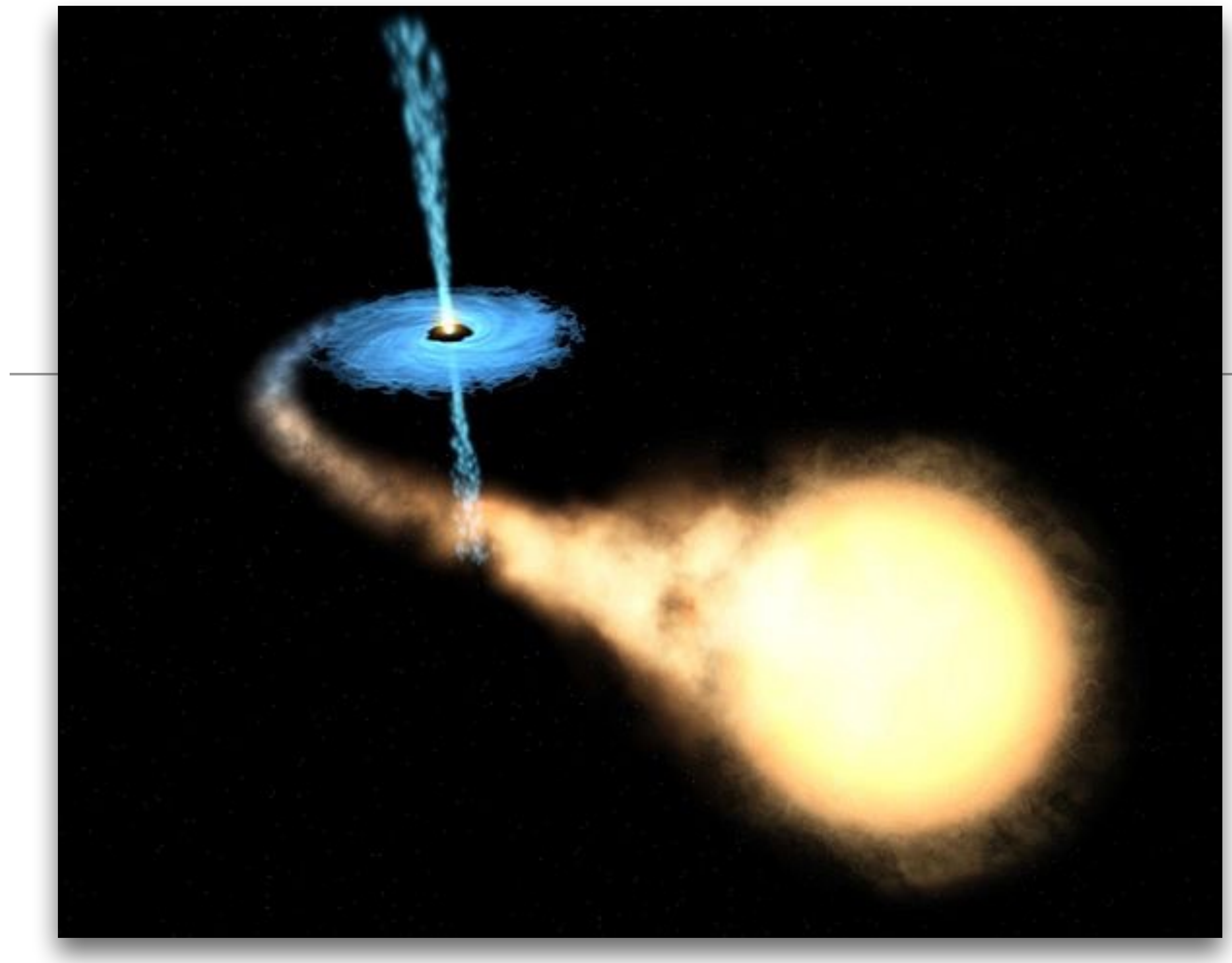
Alessandro Drago and Giuseppe Pagliara



Observations of both M & R of NS are important !!

Low-Mass X-ray binary (LMXB)

- Mass & Radius of Neutron Star
  - Monte Carlo sampling
  - Bayesian analysis



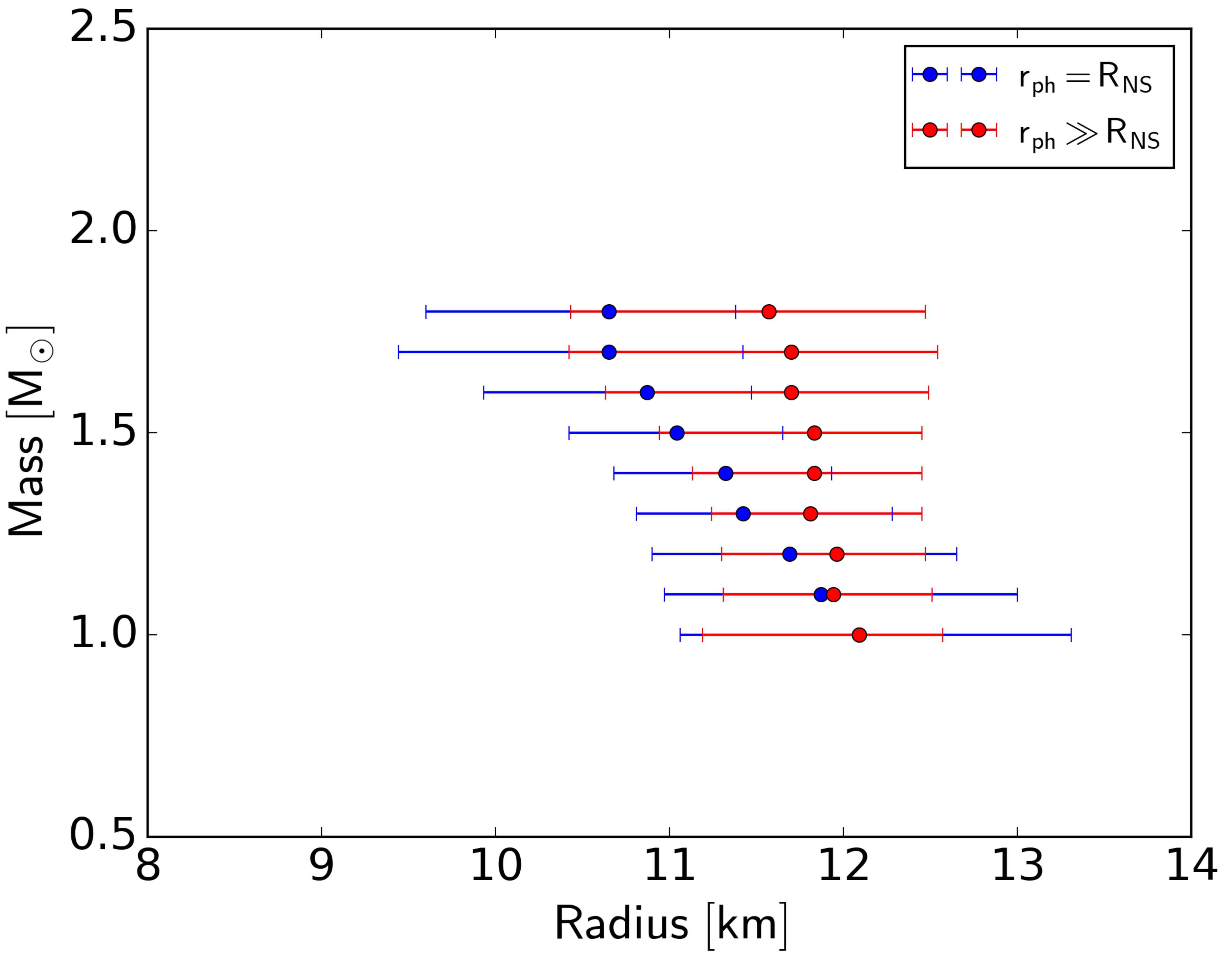
Low-Mass X-ray binary (low-mass companion)

Table 9
Most Probable Values for Masses and Radii for Neutron Stars Constrained to Lie on One Mass Versus Radius Curve

Object	M ($M_\odot$)	R (km)	M ($M_\odot$)	R (km)
	$r_{ph} = R$		$r_{ph} \gg R$	
4U 1608–522	$1.52^{+0.22}_{-0.18}$	$11.04^{+0.53}_{-1.50}$	$1.64^{+0.34}_{-0.41}$	$11.82^{+0.42}_{-0.89}$
EXO 1745–248	$1.55^{+0.12}_{-0.36}$	$10.91^{+0.86}_{-0.65}$	$1.34^{+0.450}_{-0.28}$	$11.82^{+0.47}_{-0.72}$
4U 1820–30	$1.57^{+0.13}_{-0.15}$	$10.91^{+0.39}_{-0.92}$	$1.57^{+0.37}_{-0.31}$	$11.82^{+0.42}_{-0.82}$
M13	$1.48^{+0.21}_{-0.64}$	$11.04^{+1.00}_{-1.28}$	$0.901^{+0.28}_{-0.12}$	$12.21^{+0.18}_{-0.62}$
ω Cen	$1.43^{+0.26}_{-0.61}$	$11.18^{+1.14}_{-1.27}$	$0.994^{+0.51}_{-0.21}$	$12.09^{+0.27}_{-0.66}$
X7	$0.832^{+1.19}_{-0.051}$	$13.25^{+1.37}_{-3.50}$	$1.98^{+0.10}_{-0.36}$	$11.3^{+0.95}_{-1.03}$

Steiner, Lattimer, Brown, ApJ 2010

95% confidence limits by using MC sampling (for fixed NS mass)



In this talk, we will focus on

- Low-Mass X-ray Binaries (LMXB) with Photospheric Radius Expansion (PRE)
- Simultaneous measurement of neutron star Mass & Radius

A&A 650, A139 (2021)
https://doi.org/10.1051/0004-6361/202038126
© ESO 2021

Astronomy & Astrophysics

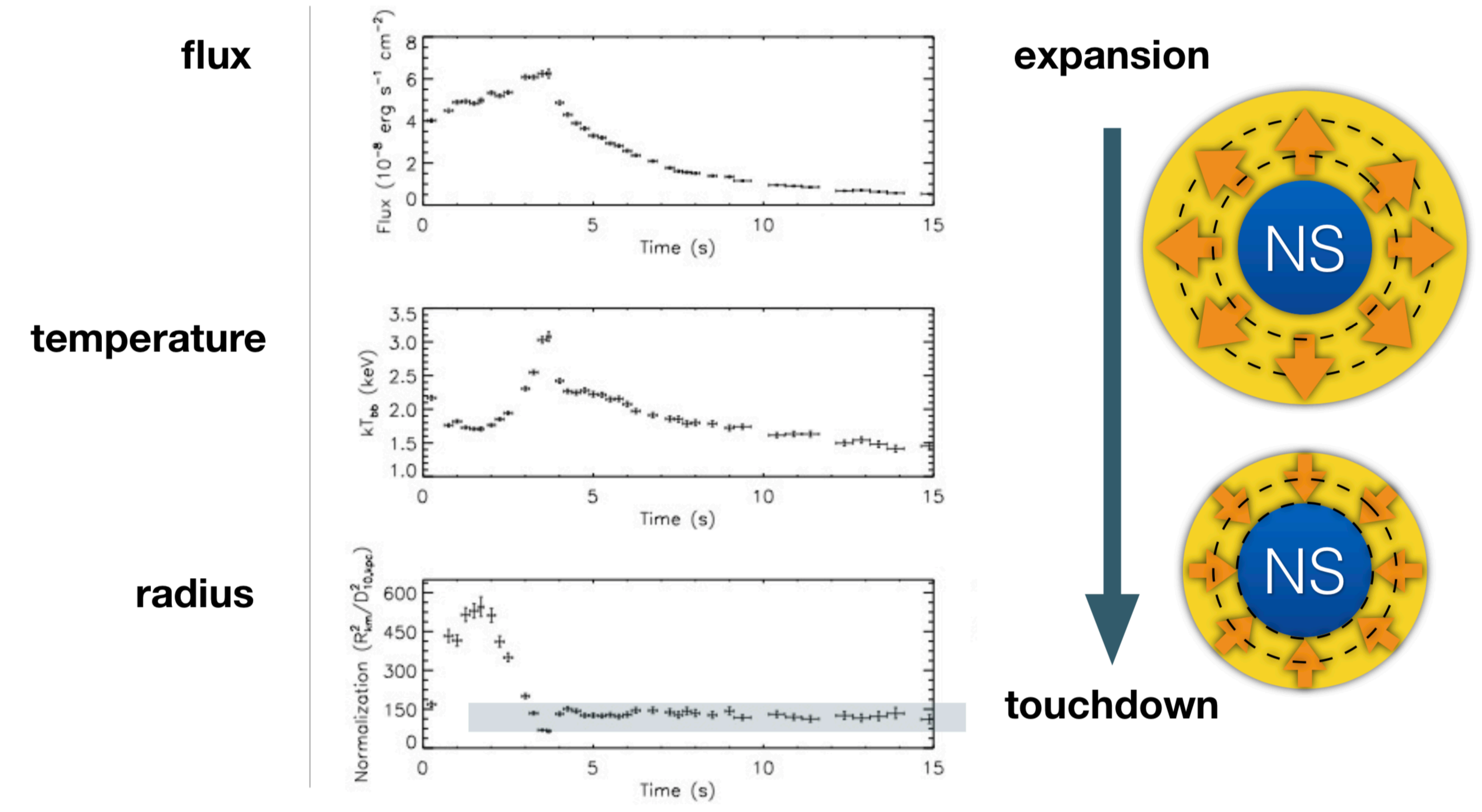
Measuring the masses and radii of neutron stars in low-mass X-ray binaries: Effects of the atmospheric composition and touchdown radius

Myungkuk Kim[1], Young-Min Kim[1], Kwang Hyun Sung[1], Chang-Hwan Lee[2], and Kyujin Kwak[1]

[1] Department of Physics, Ulsan National Institute of Science and Technology, Ulsan 44919, Korea
e-mail: myungkkim@unist.ac.kr; ymkim715@unist.ac.kr; kkwak@unist.ac.kr
[2] Department of Physics, Pusan National University, Busan 46241, Korea

Received 9 April 2020 / Accepted 26 March 2021

Photospheric Radius Expansion (PRE) XRB



Ozel et al. 2009

Observations

(F_D, T; *distance*)

(M, R)

Equations of state

LMXBs considered in our work

Table 1. Observational properties of six LMXBs that show PRE XRBs.

Source	App. angular area $(\mathrm{km}/10\ \mathrm{kpc})^2$	Touchdown flux $(10^{-8}\ \mathrm{erg\ cm^{-2}\ s^{-1}})$	Spin freq. [a] (Hz)	Distance [a] (kpc)
4U 1820–30	89.9 ± 15.9	5.98 ± 0.66	…	7.6 ± 0.4 (4)
				8.4 ± 0.6 (5–6)
SAX J1748.9–2021	89.7 ± 9.6	4.03 ± 0.54	410 (1)	8.2 ± 0.6 (4, 5, 7)
EXO 1745–248	117.8 ± 19.9	6.69 ± 0.74	…	6.3 ± 0.63 [b] (8–9)
KS 1731–260	96.0 ± 7.9	4.71 ± 0.52	524 (2)	7–9 [c] (10)
4U 1724–207	113.8 ± 15.4	5.29 ± 0.58	…	7.4 ± 0.5
4U 1608–52	314 ± 44.3	18.5 ± 2.0	620 (3)	4.0 ± 2.0, $D_{\mathrm{cutoff}} > 3.9$ [d]

Our strategy

Observations

(F_D, T; *distance*)

Steiner et al., ApJ 722, 33 (2010)

Ozel et al., ApJ 820, 28 (2016)

Method 1

Monte Carlo sampling

(M. Kim)

Method 2

Bayesian analysis (*NS EOS is used*)

(Y.-M. Kim)

(M, R)

Method 1: Monte Carlo sampling *(by M. Kim)*

Basic observations : flux, spectrum (blackbody temperature)

before corrections

Touch down flux

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2}$$

Apparent angular area

$$A \equiv \frac{F_\infty}{\sigma T^4_{\mathrm{bb},\infty}} = f_{\mathrm{c}}^{-4}\frac{R^2}{D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1}$$

Opacity $\kappa = 0.2(1+X)\ \mathrm{cm}^2\ \mathrm{g}^{-1}$

X : *hydrogen mass fraction in H-He plasma*

Systematic treatments

- ***Color-correction factor***
  - Change of the effective area due to the atmospheric effect
- ***Cooling tail method***
  - Spectral evolution during the cooling phase due to the atmosphere of NS (surface gravity & chemical composition)
- ***Chemical composition of the photosphere***
  - H-He plasma

$$\kappa = 0.2(1 + X)\ \mathrm{cm}^2\ \mathrm{g}^{-1}$$

X : *hydrogen mass fraction in H-He plasma*

Modifications

touchdown radius parameter

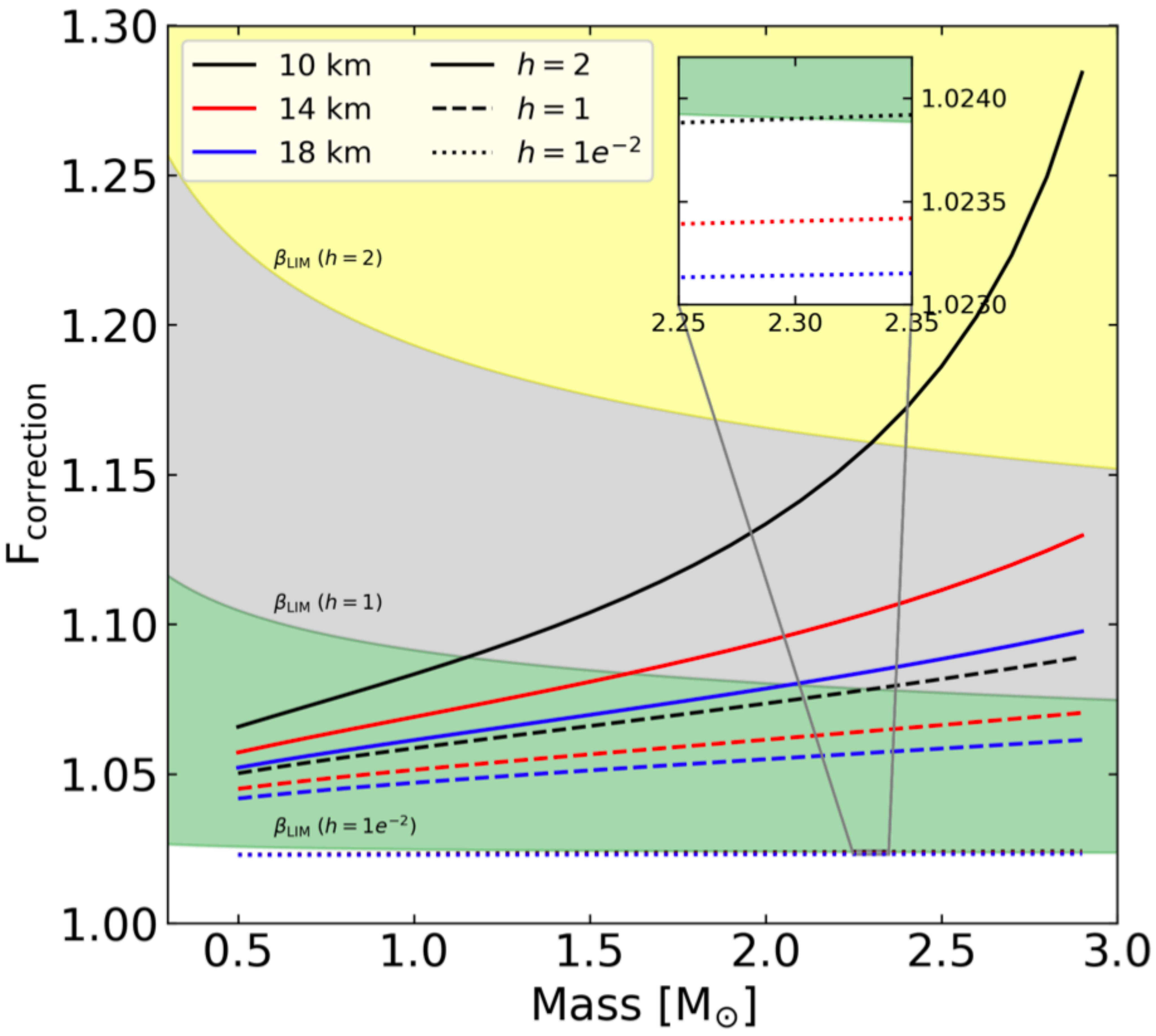
$$h = \frac{2R_{\rm NS}}{r_{\rm ph}}$$

causality limit

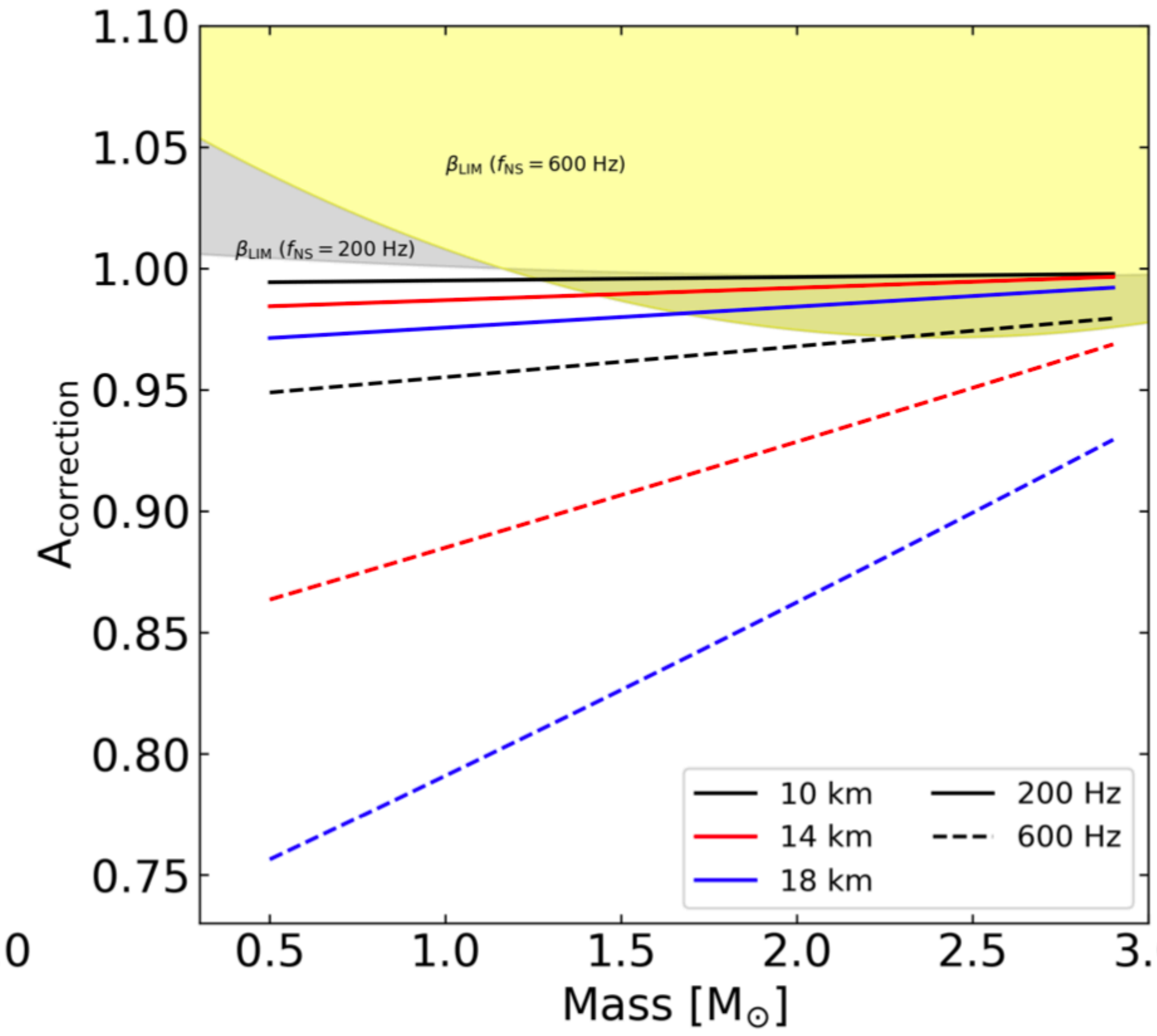
$$\beta = \frac{M_{\rm NS}}{R_{\rm NS}} < \frac{1}{2.94}$$

NS spin frequency

$$f_{\rm NS}$$

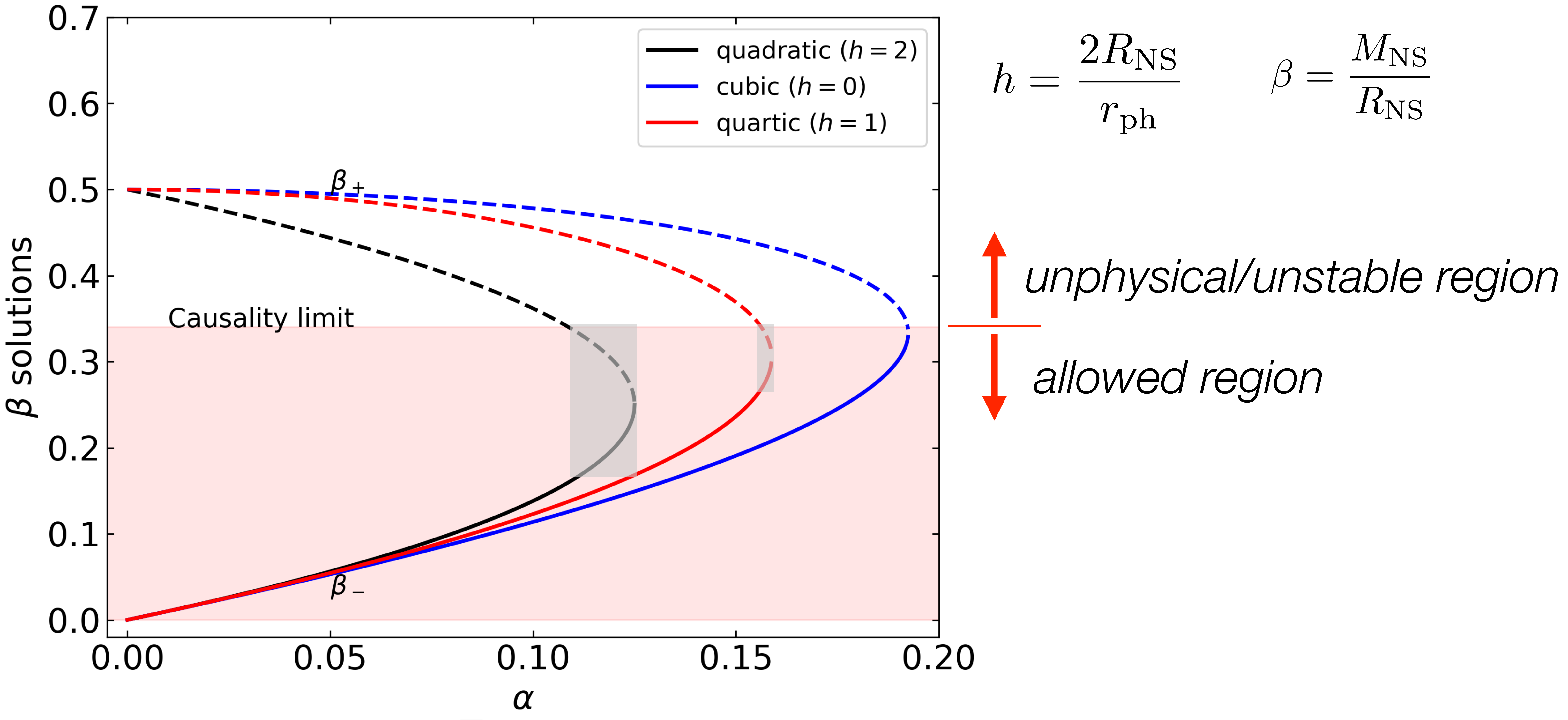


Touchdown Flux (ratio)



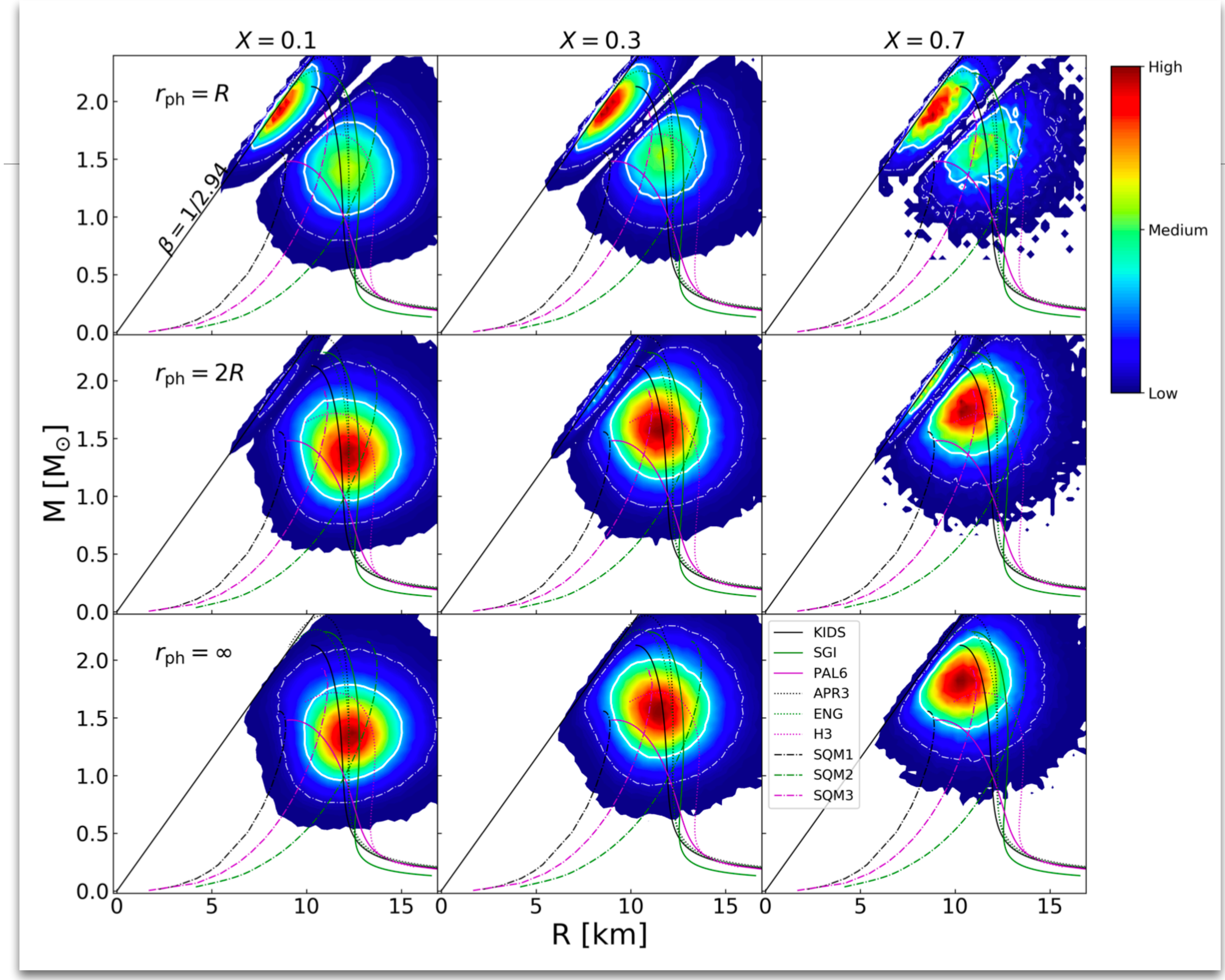
Apparent angular area (ratio)

Double solutions are allowed in MC sampling



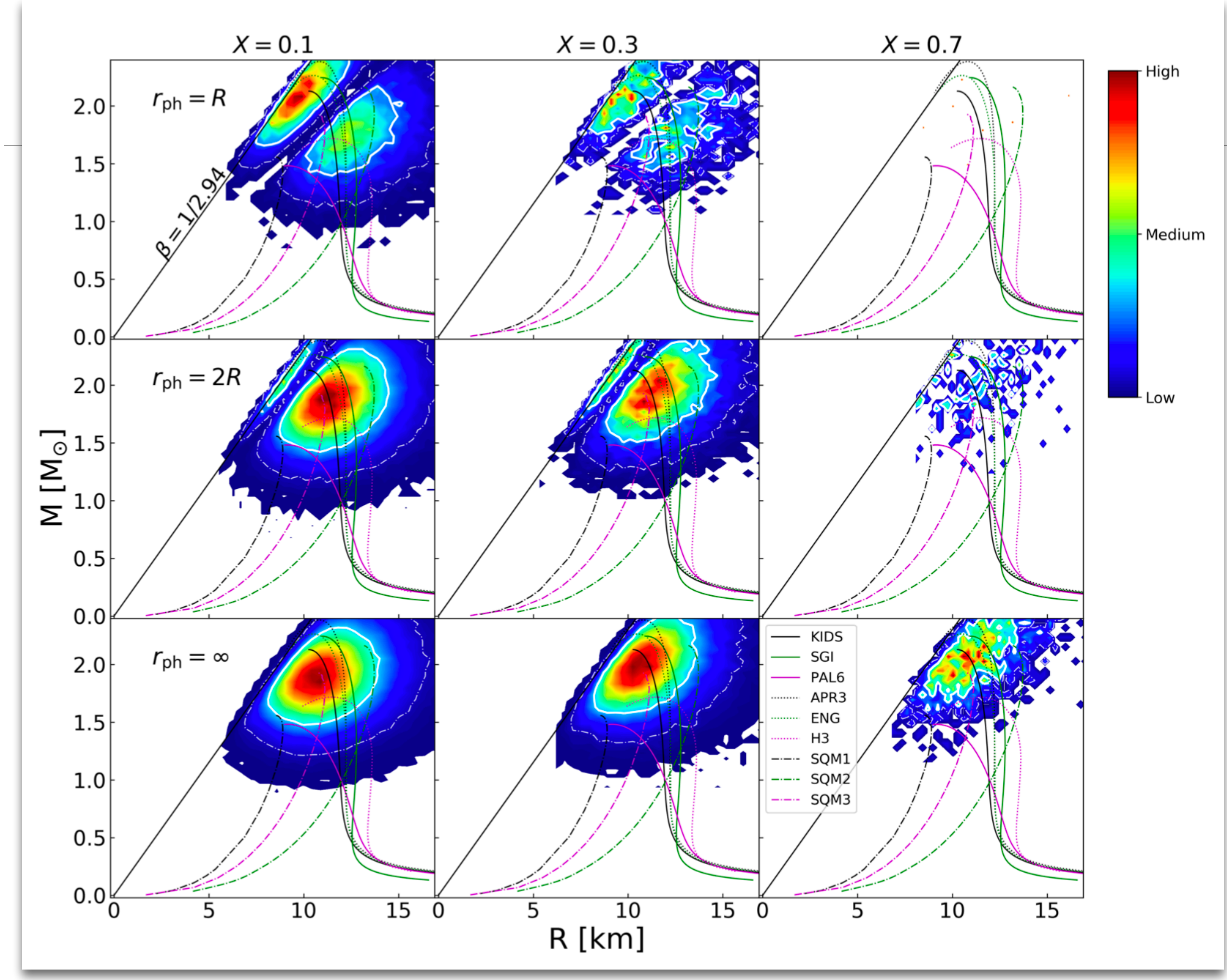
$$h = \frac{2R_{\rm NS}}{r_{\rm ph}} \qquad \beta = \frac{M_{\rm NS}}{R_{\rm NS}}$$

$$\alpha \equiv \frac{F_{\rm TD,\infty}}{\sqrt{A}} \frac{\kappa D}{c^3 f_c^2}$$



SAX J1748.9-2021

X: hydrogen mass fraction

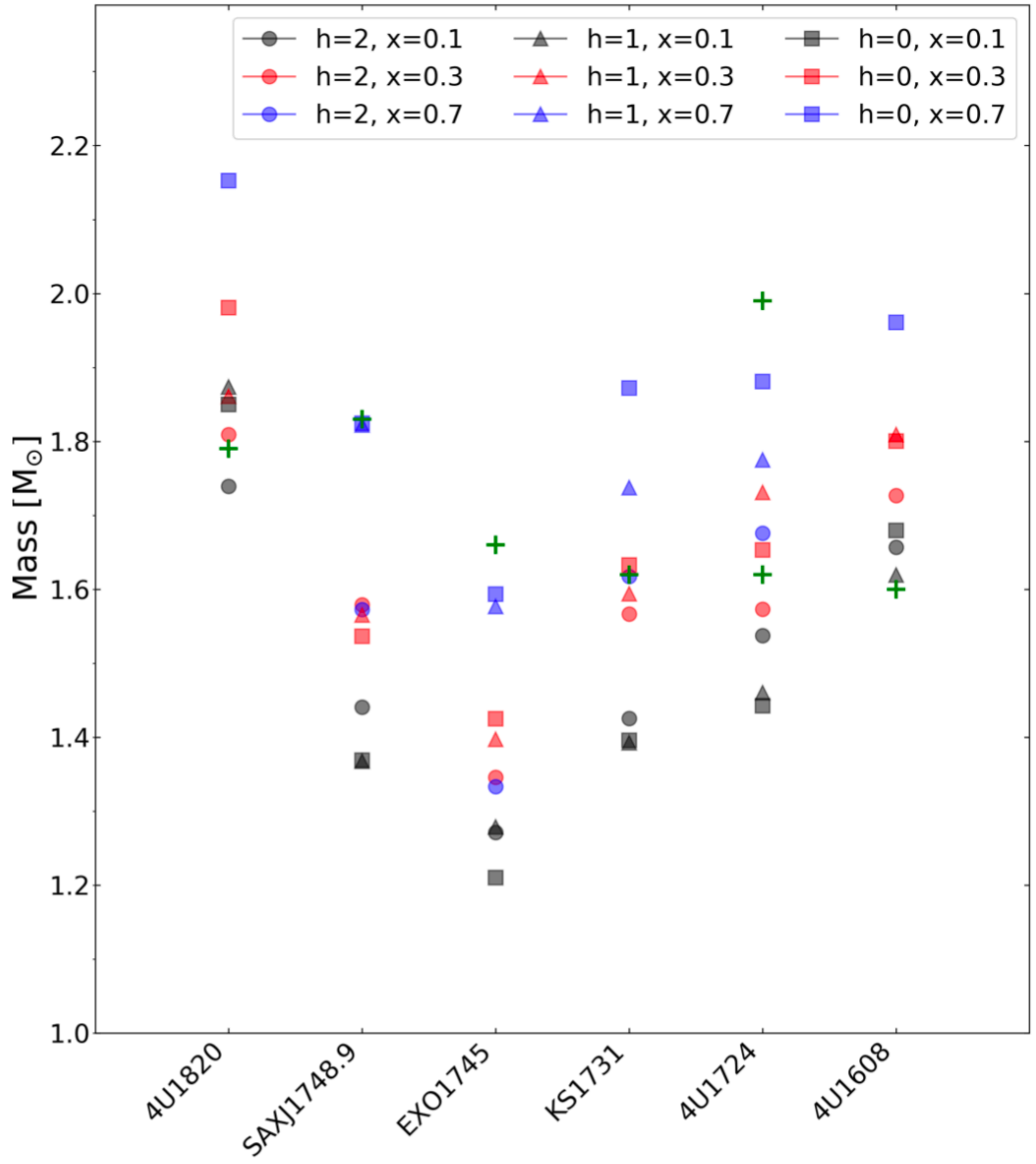


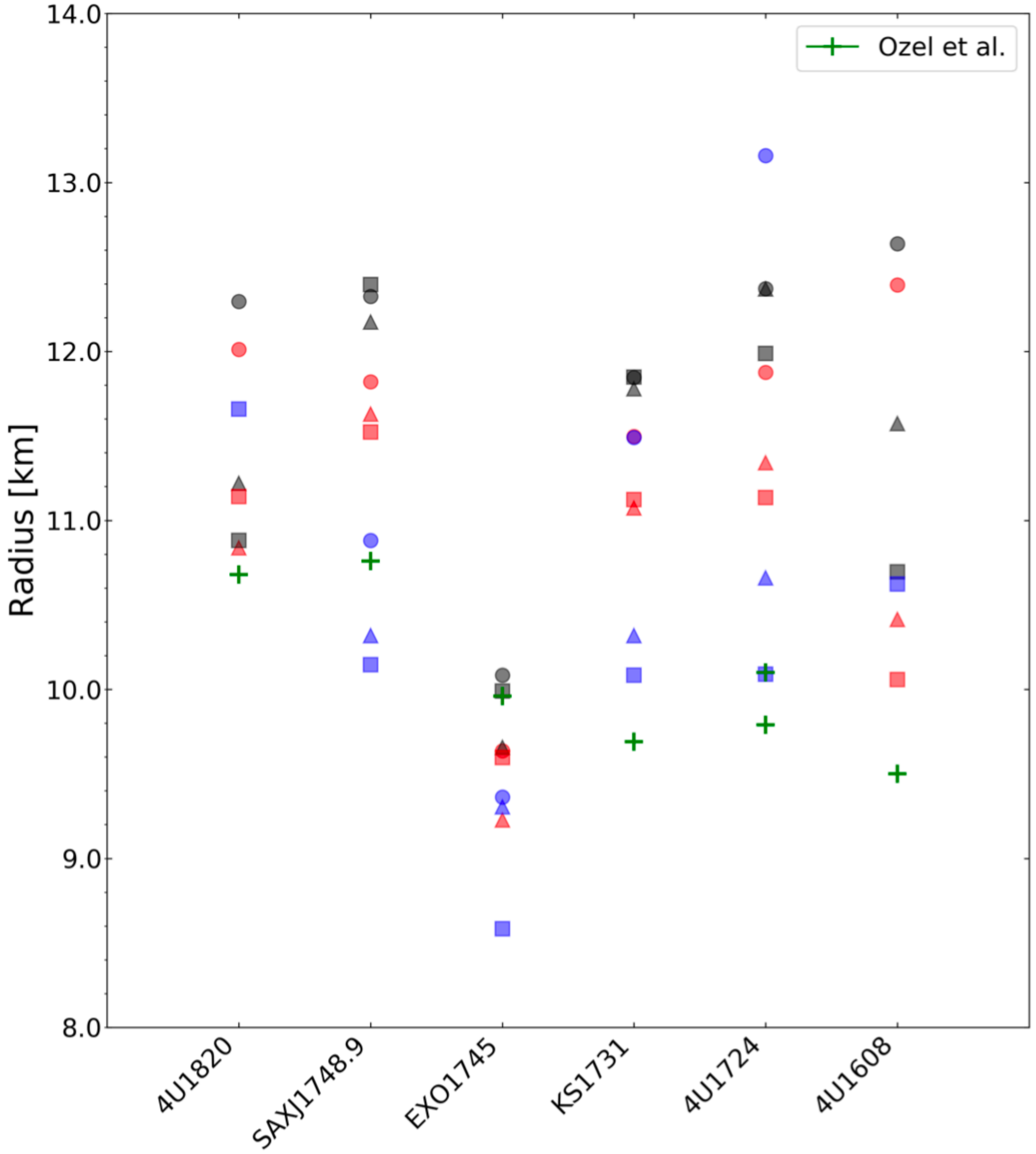
4U 1820-30

X: hydrogen mass fraction

Most probable values of M & R

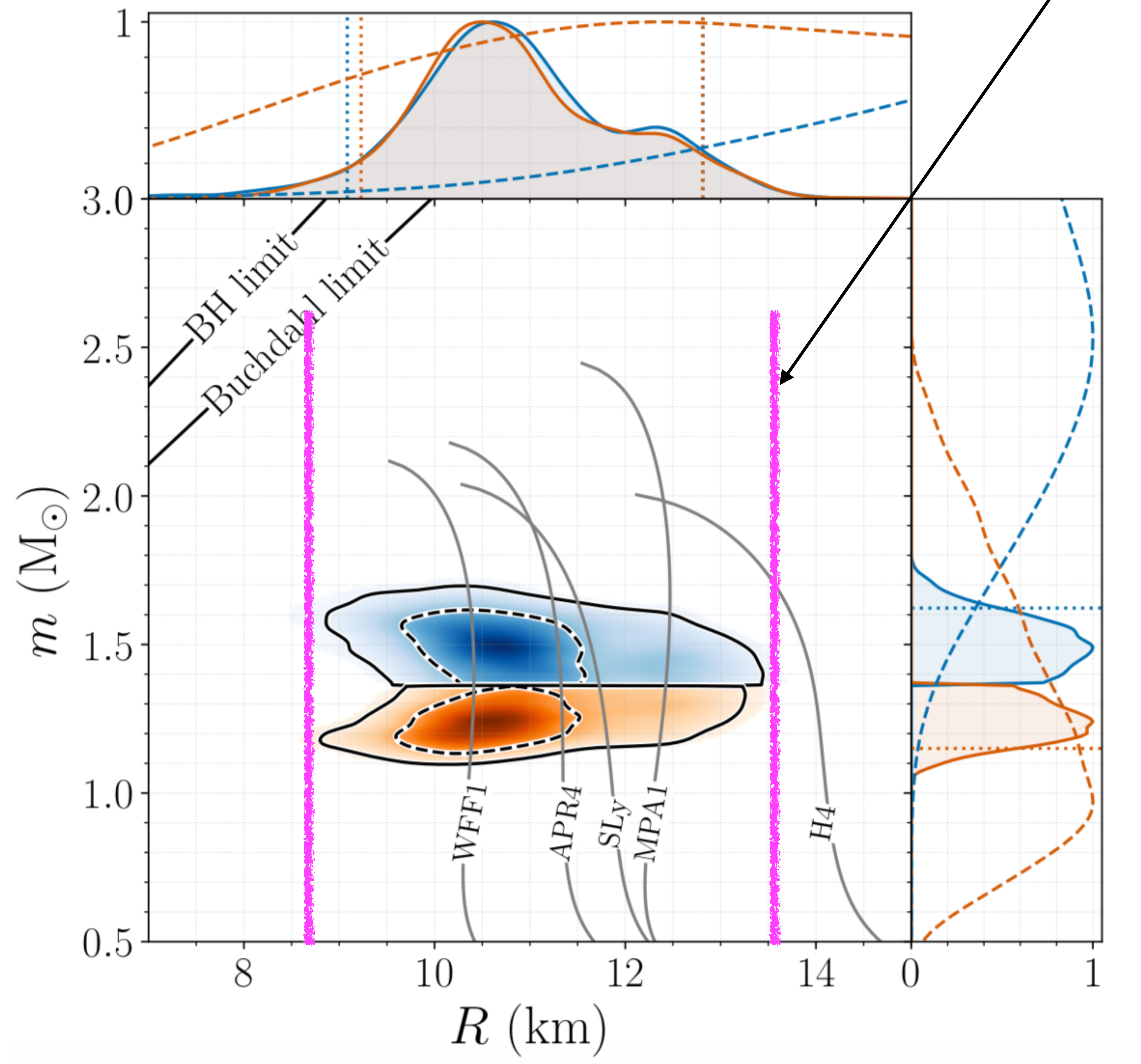
M. Kim, Y.-M. Kim et al. (A&A 2021)



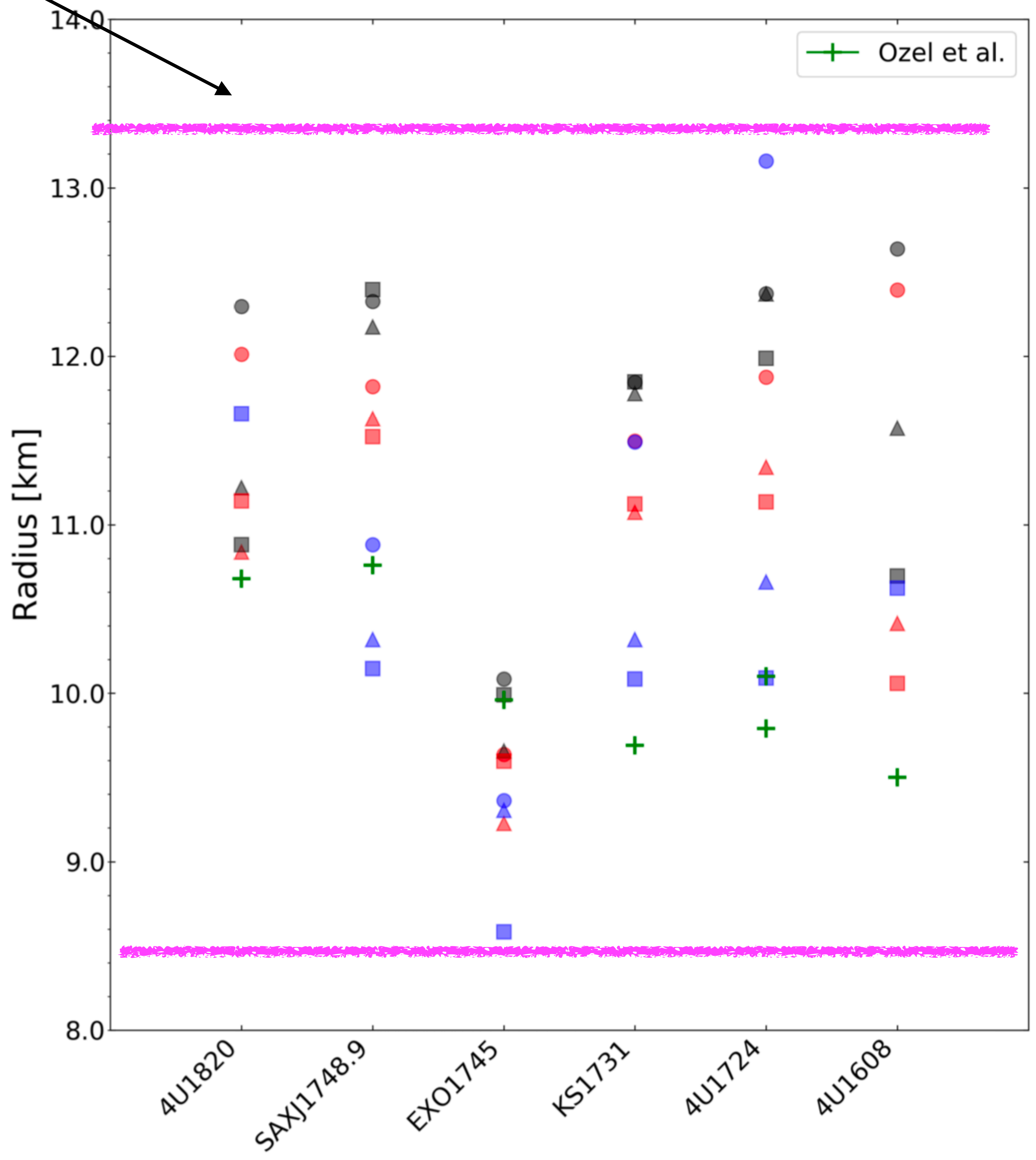


Most probable M,R

Consistent



Abbott et al. (LSC and Virgo), PRL 121.161101



M. Kim, Y.-M. Kim et al. (A&A 2021)

Method 2: Bayesian analysis *(by Y.-M. Kim)*

$$P(\boldsymbol{\theta}|\text{data}) = \frac{P(\text{data}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{P(\text{data})}$$

Posterior probability distribution

$$\boldsymbol{\theta} = \{R, M, D, f_{\text{NS}}, f_{\text{c}}, X, h\}$$

Parameter set

$$P(\text{data}|\theta)$$

Likelihood

$$P(\theta)$$

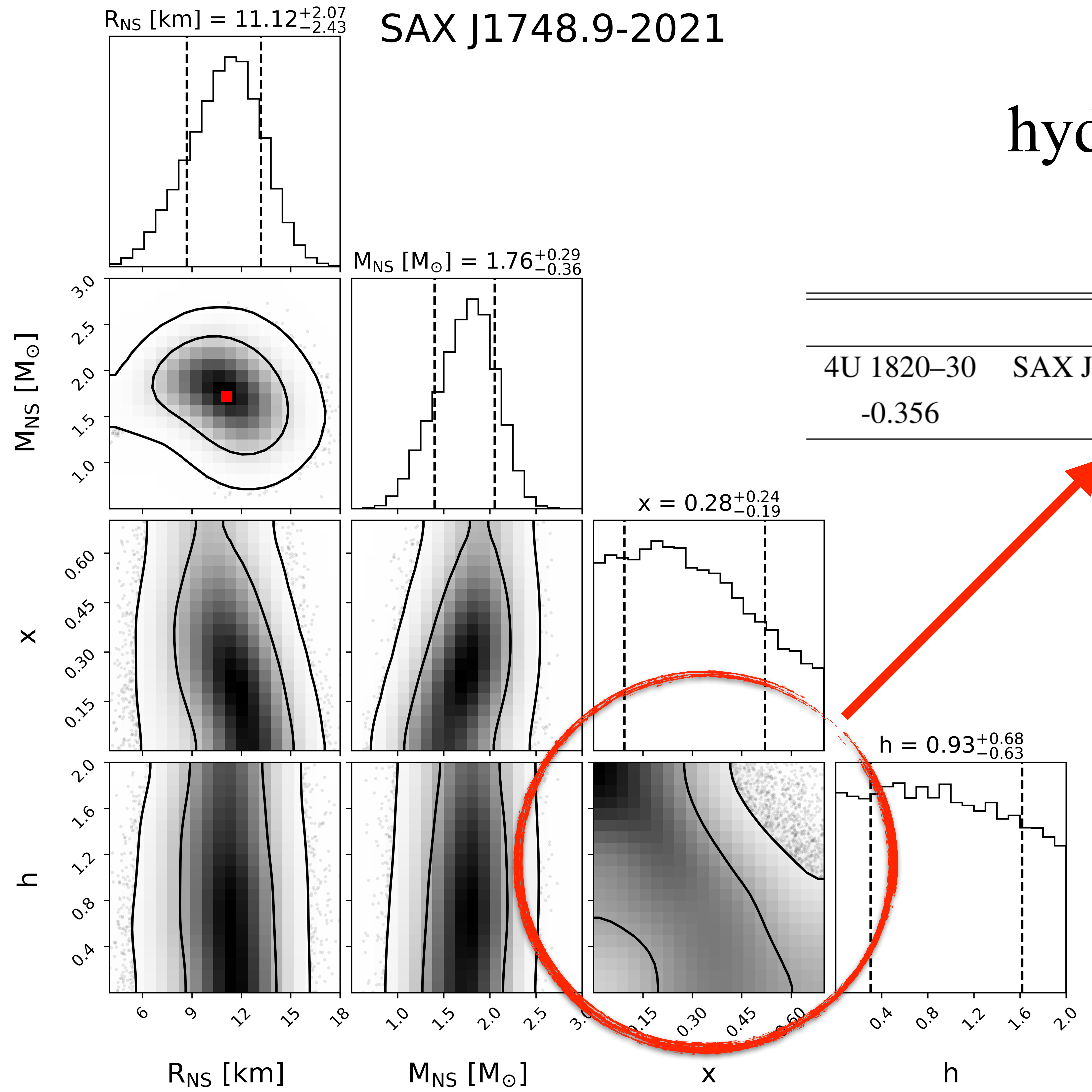
Prior of the parameter set of the model

$$P(\boldsymbol{\theta}) = P(R)P(M)P(D)P(f_{\text{NS}})P(f_{\text{c}})P(X)P(h)$$

(flat distribution for unknown quantities without using EOS)

Mass-Radius estimation by Bayesian.

$$h = \frac{2R_{NS}}{r_{ph}}$$



Correlation of hydrogen mass fraction, x Photosphere size, h

Pearson correlation coefficient (R)					
4U 1820–30	SAX J1748.9–2021	EXO 1745–248	KS 1731–260	4U 1724–207	4U 1608–52
-0.356	-0.622	-0.526	-0.539	-0.631	-0.529

M. Kim, Y.-M. Kim et al. (A&A 2021)

Discussions on LMXBs

- LMXBs are good laboratories for NS physics
  - Photosphere is likely to be H-poor regardless of the energy generation mechanism below.
  - Touchdown is likely to occur away from the neutron star surface.
  - Upper bound of NS radius is consistent that by LIGO/Virgo (based on tidal deformability of GW170817).
- Future observations of LMXBs will be able to give more constraints on NS masses & radii, and check the possibilities of Quark Stars.
- Effects of accretion disk in LMXBs are in progress.

Thanks

Binary interactions
are always interesting

Ssireum (Korean Wrestling)
Hong-Do Kim (1745 ~ ?)