QCS2023@2023.09.24

2023 YANGZHOU CHINA

Neutron Star Properties from Low-Mass X-ray binary (LMXB)

Chang-Hwan Lee / Pusan National University

focused on Astronomy & Astrophysics 650, A139 (2021)

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

Contributions to QCS

- QCS2014: *Supercritical Accretion in the Evolution of Neutron Star Binaries and its Implications*
- QCS2017: *Strangeness in Neutron Star Cooling*
- QCS2019: *Chair of Organizing Committee*
- QCS2023: *Neutron Star Properties from Low-Mass X-ray Binary*

Astro-Hadron Physics *my main interests in Neutron Star related problems*

Hadron Physics | *Astrophysics*

1990s
- Hadron Physics: Kaon Condensation in Dense Stellar Matter (with **D.P.Min**, **M.Rho** & **G.E.Brown**)
- Astrophysics: NS Binary as a source of GW (with **G.E.Brown**@Stony Brook)

2003
- Astrophysics: **Korean Gravitational Wave Group**
  Nuclear physics + Astrophysics + Mathematics + Artificial Intelligence

2006
- Hadron Physics: **Science-Business-Belt Project** initiated by **D.P. Min**

2009
- Hadron Physics: **RAON project** was approved
- Astrophysics: **KGWG** joined LIGO Scientific Collab.

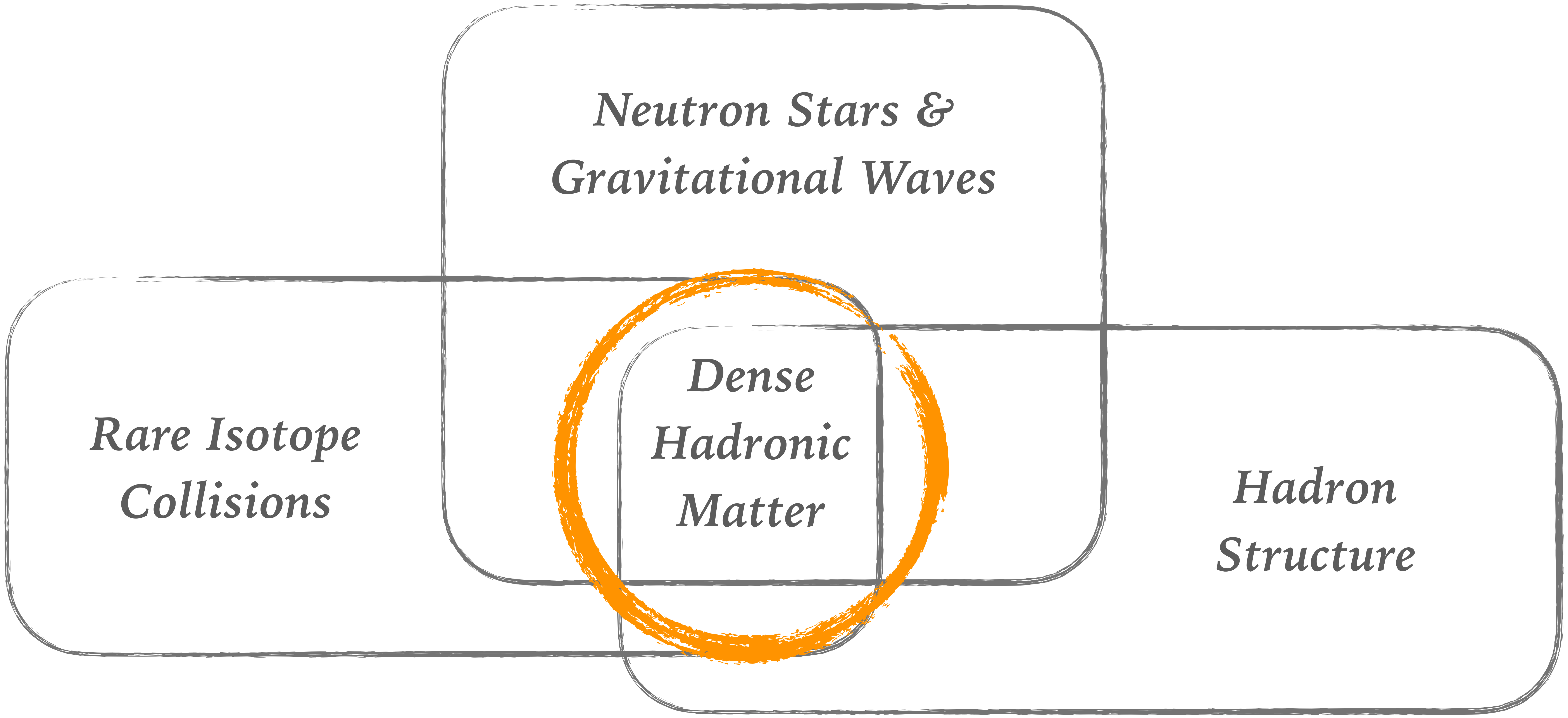
2017
- Hadron Physics: **Transport Studies**
  DJBUU (new transport code)
  BUD^2-McGill Collaboration
- Astrophysics: **GW from NS-NS mergers** (Multi-messenger Astrophysics)
  Tidal deformability of NS

2022
- Hadron Physics: **First Beam of RAON** 2022.10.07

2023

for Astro-Hadron Physics

Astro-Hadron Physics Group@PNU



Dense Nuclear & Stellar Matter Studies

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

***BUD**^{2} Collaboration*

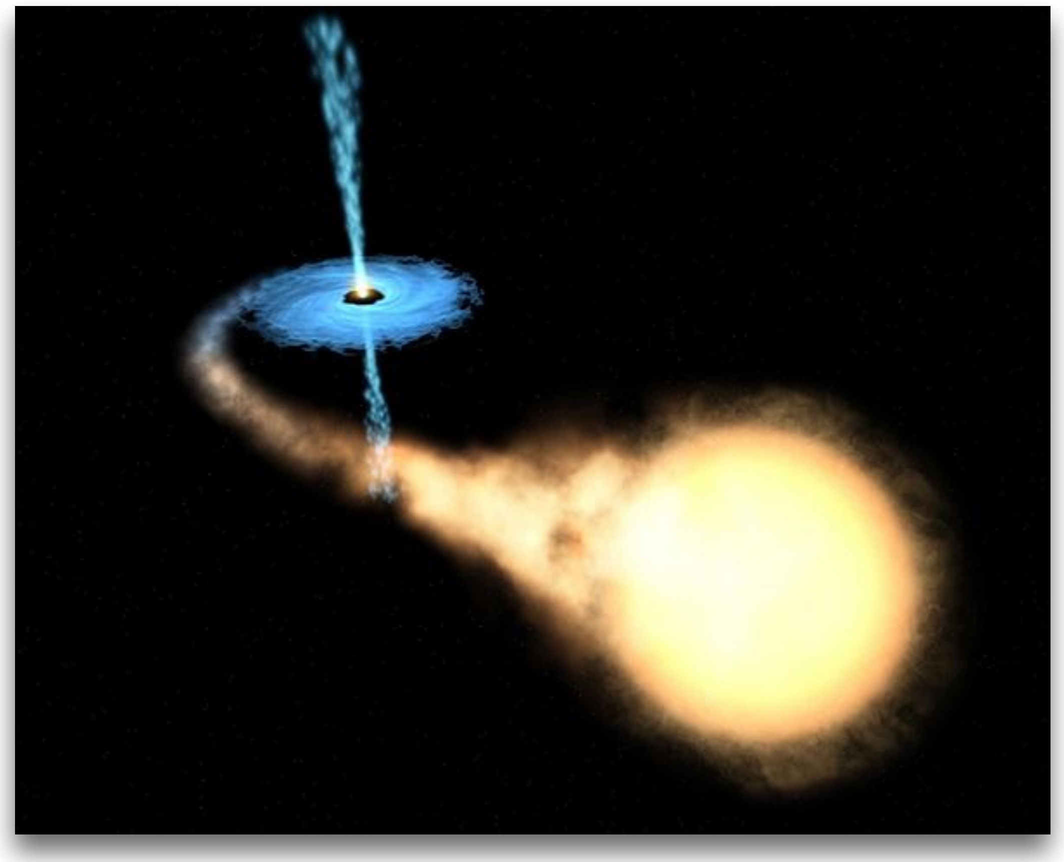
***B**usan (CHL, H.S. CHO, … …)*
***U**lsan (K. KWAK, Y.-M. KIM, M. KIM, … …)*
***D**aegu (Chang Ho HYUN)*
***D**aejeon (**Youngman KIM**, … …)*
Montreal (Sangyong JEON, McGill)

Contents

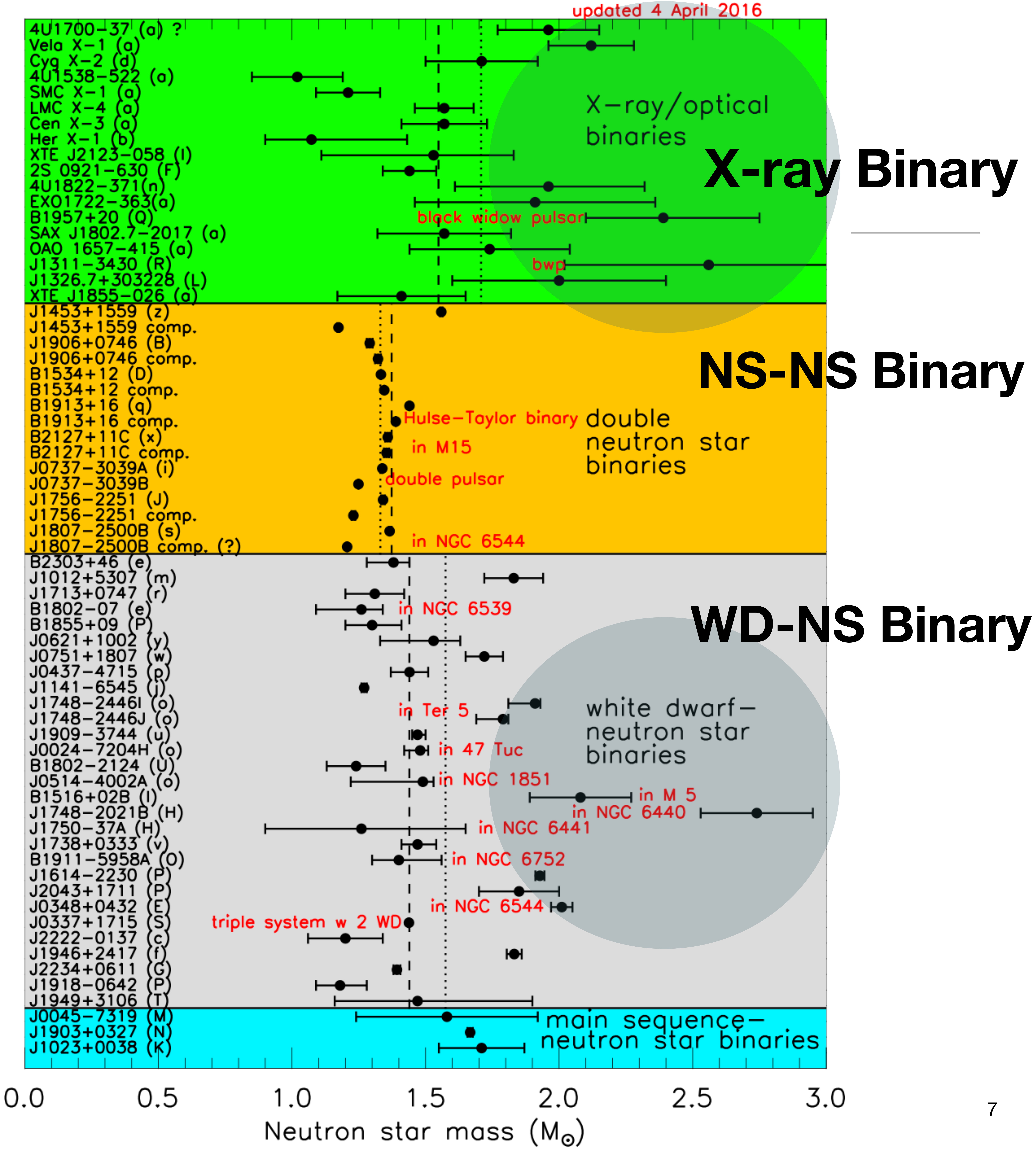
- Introduction & Motivation
- Mass & Radius of NS from Low-Mass X-ray binary (LMXB)
  - Monte Carlo sampling
  - Bayesian analysis
- Discussion

By EM observations before GW

- High-mass neutron stars in X-ray binaries have been reported
- But, they are not considered as evidences of the existence of high-mass NS due to large uncertainties

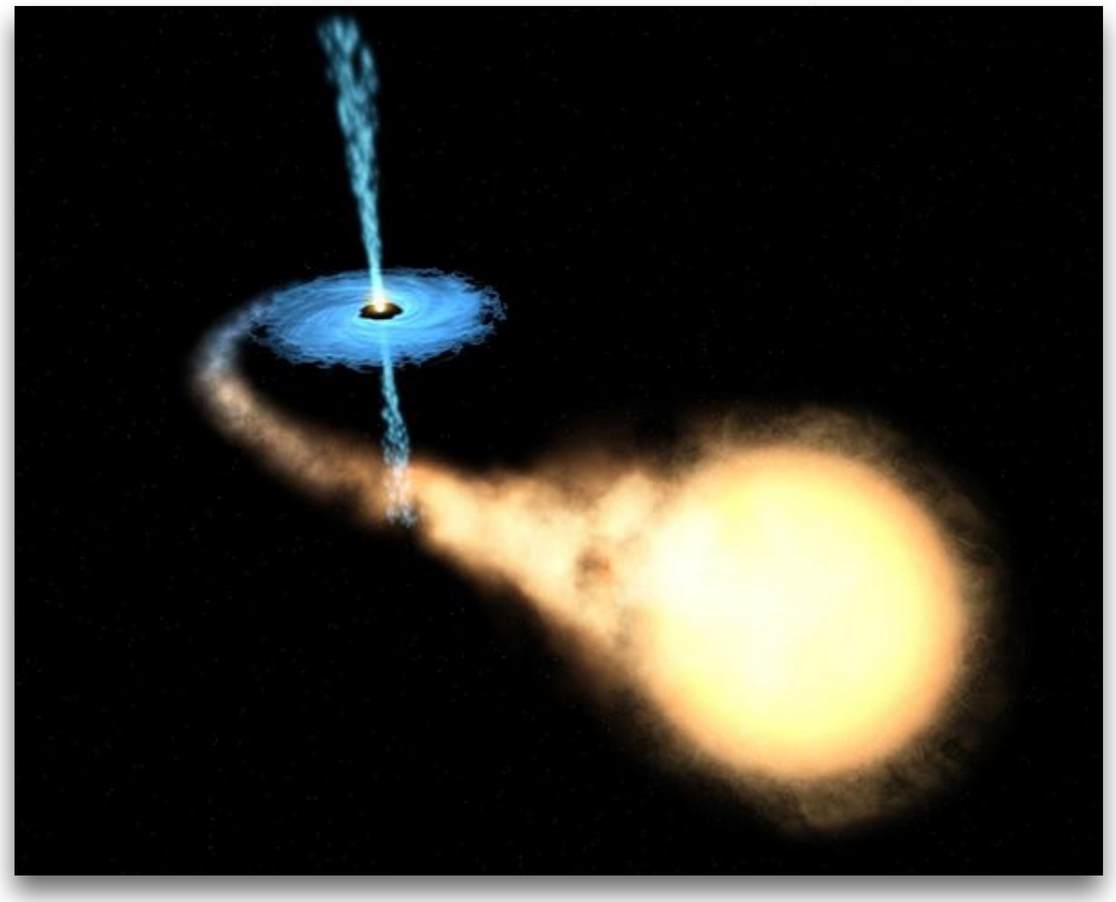


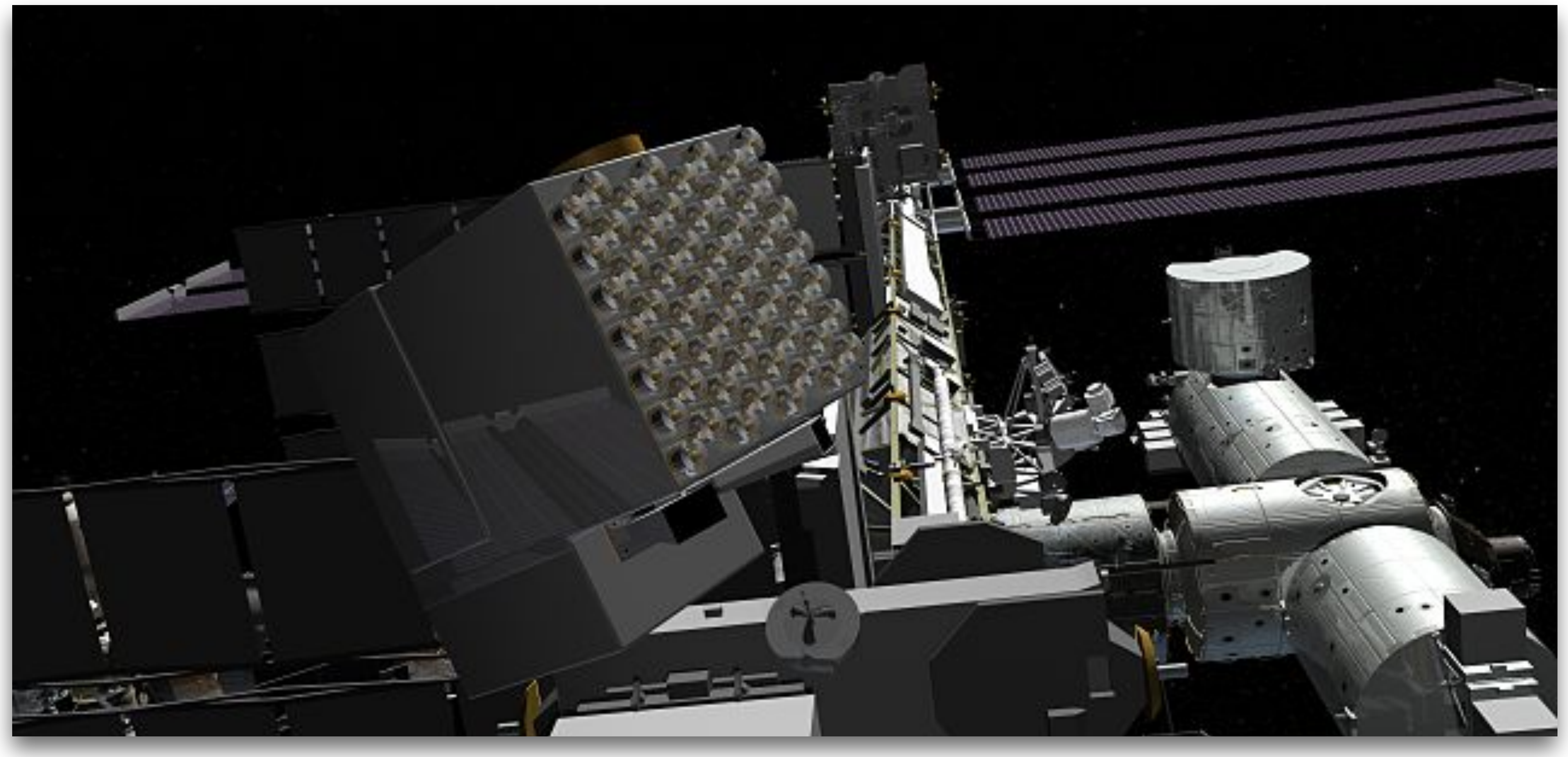
J. Lattimer



NICER Neutron star Interior Composition ExploreR

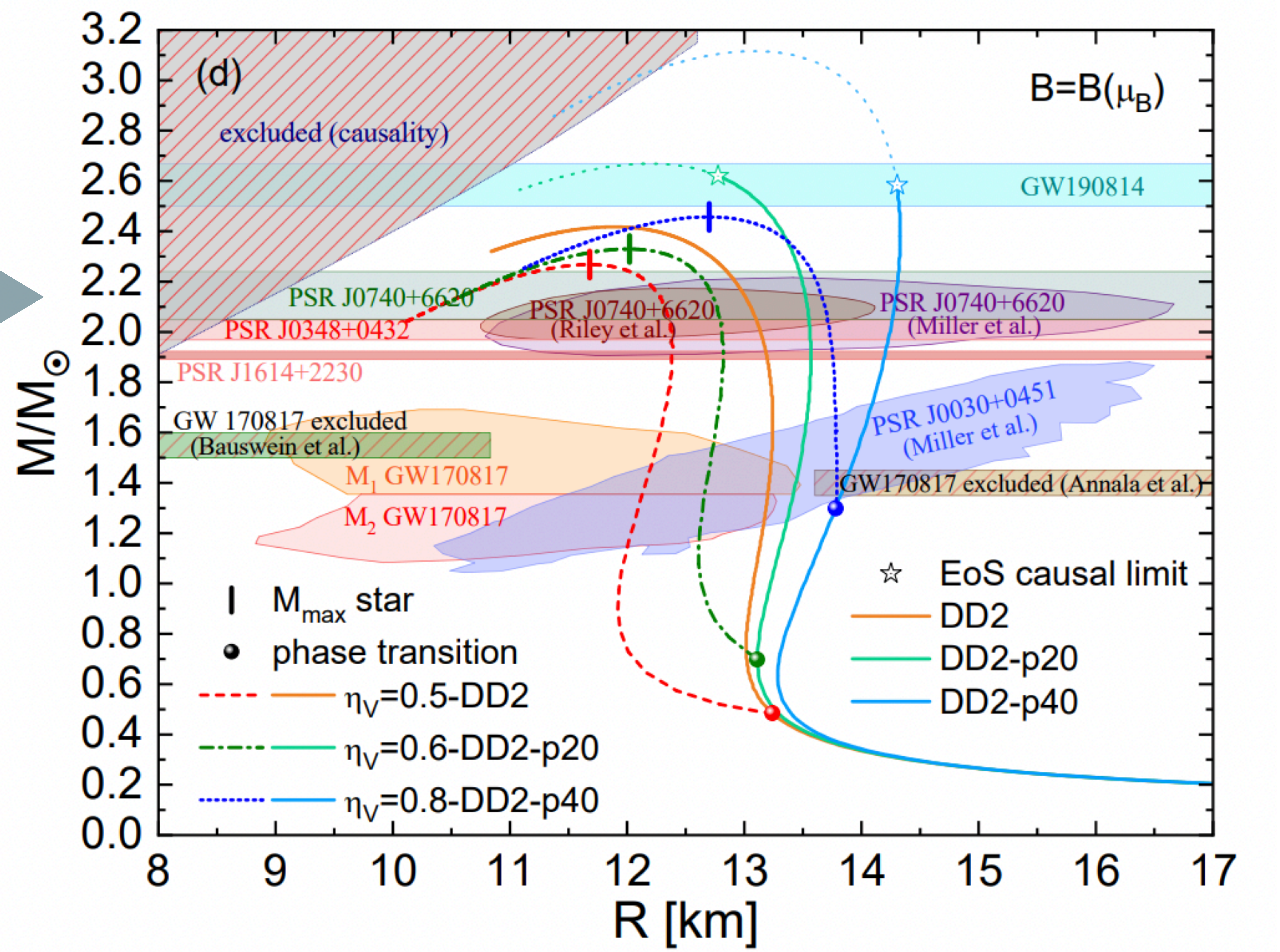
- **launch**: June 2017, SpaceX
- **platform**: ISS ELC (ExPRESS Logistics Carrier)
- **instrument**: **X-ray (0.2-12 keV)**
- **objective**
  - ***structure***: neutron star radii to 5%, cooling timescales
  - ***dynamics***: stability of pulsars as clocks, properties of outbursts, oscillations, and precession
  - ***energetics***: intrinsic radiation patterns, spectra, and luminosities





High-mass NS by NICER (X-ray : 0.2-12 keV)

WD-NS Binary (radio/Shapiro delay)

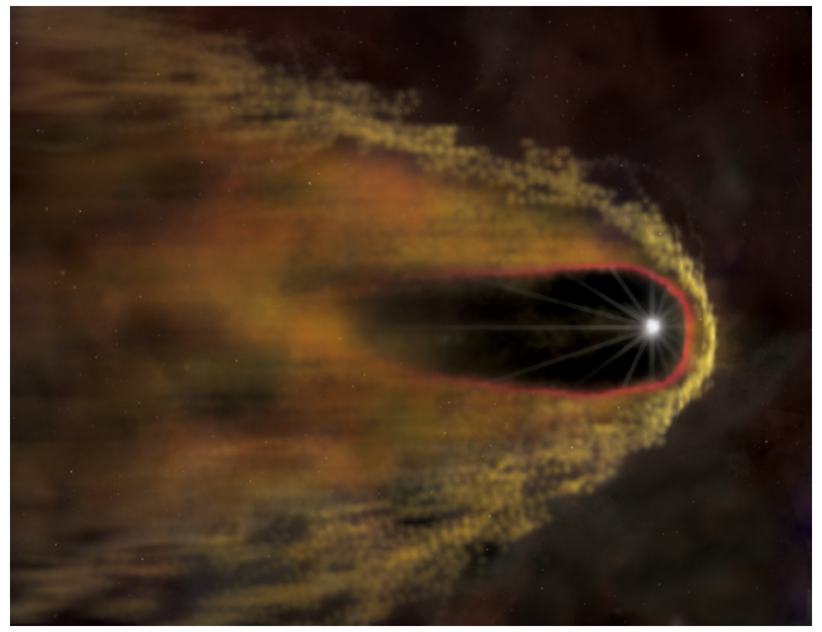


arXiv:2201.00477

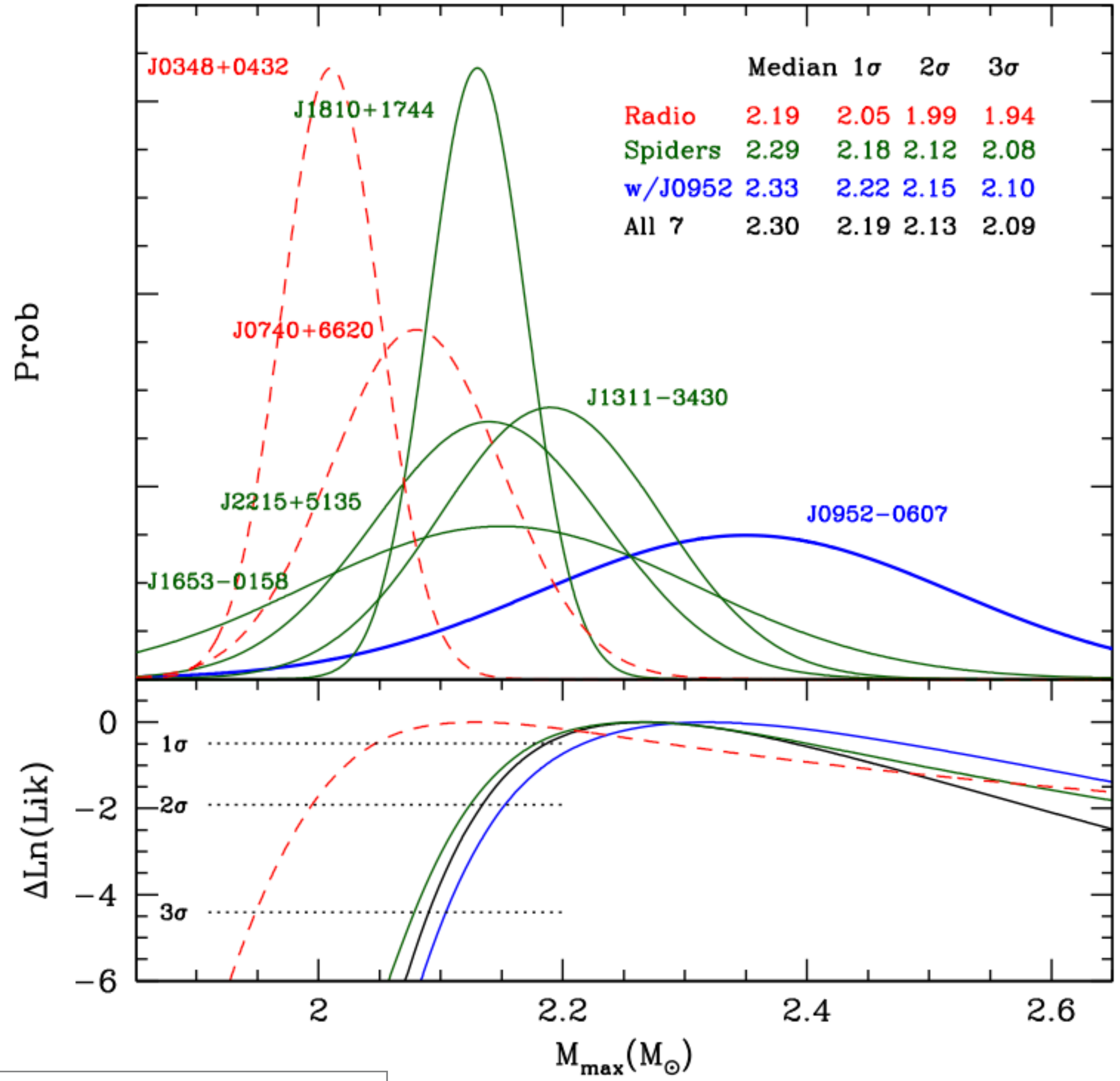
Contrera, Blaschke, Carlomagno, Grunfeld, Liebbing

Black Widow Pulsar

Companion is destroyed
by the strong powerful outflows, or winds,
of high-energy particles caused by the neutron star



$$M_{NS} = 2.35 \pm 0.17\, M_{\odot}$$



THE ASTROPHYSICAL JOURNAL LETTERS, 934:L17 (6pp), 2022 August 1 https://doi.org/10.3847/2041-8213/ac8007

CrossMark

PSR J0952−0607: The Fastest and Heaviest Known Galactic Neutron Star

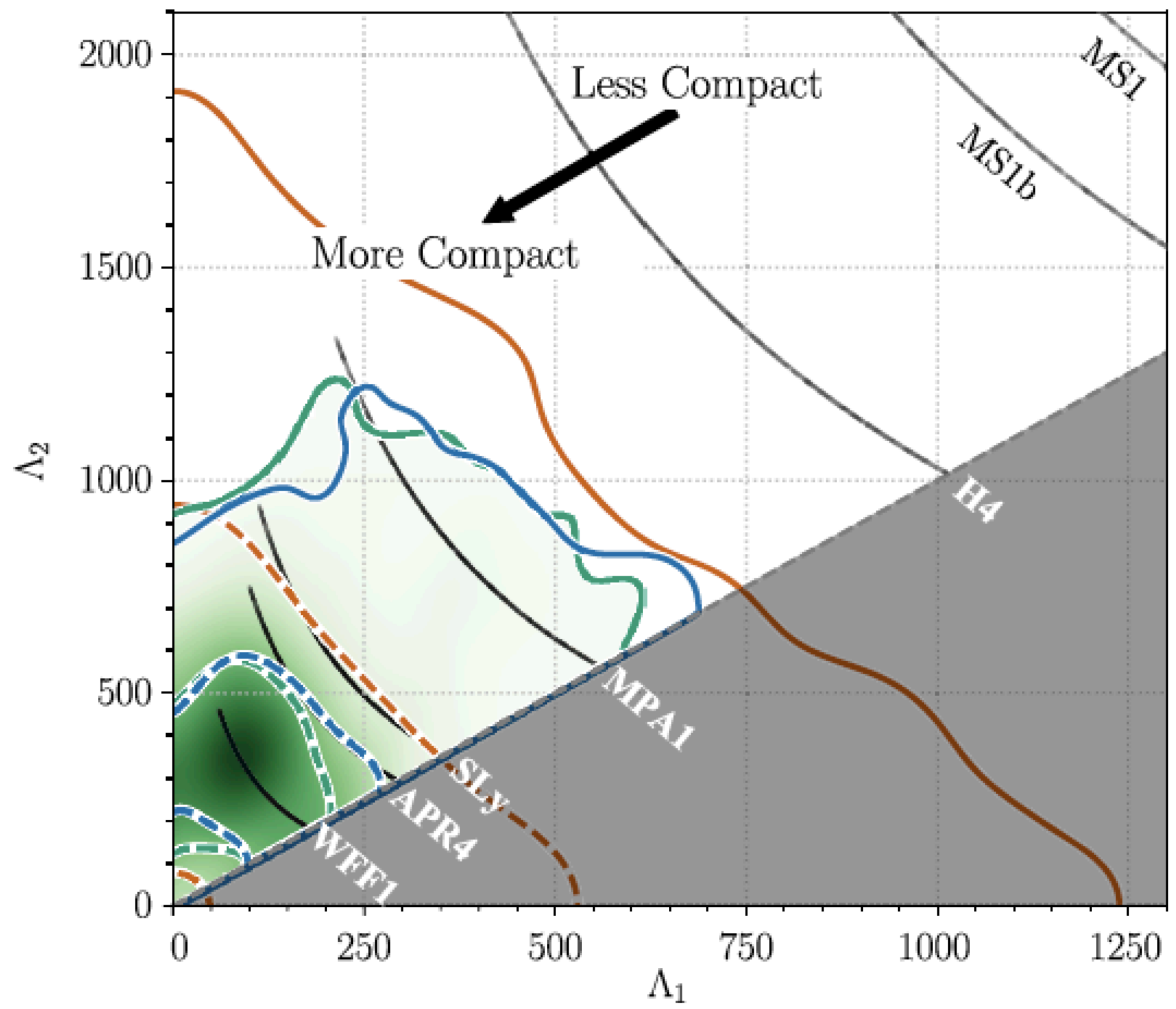
Roger W. Romani[1], D. Kandel[1], Alexei V. Filippenko[2], Thomas G. Brink[2], and WeiKang Zheng[2]

GW 170817 (**d=40 Mpc**)
GRB 170817A by Fermi-GBM
Kilonova/X-ray/Optical Afterglows

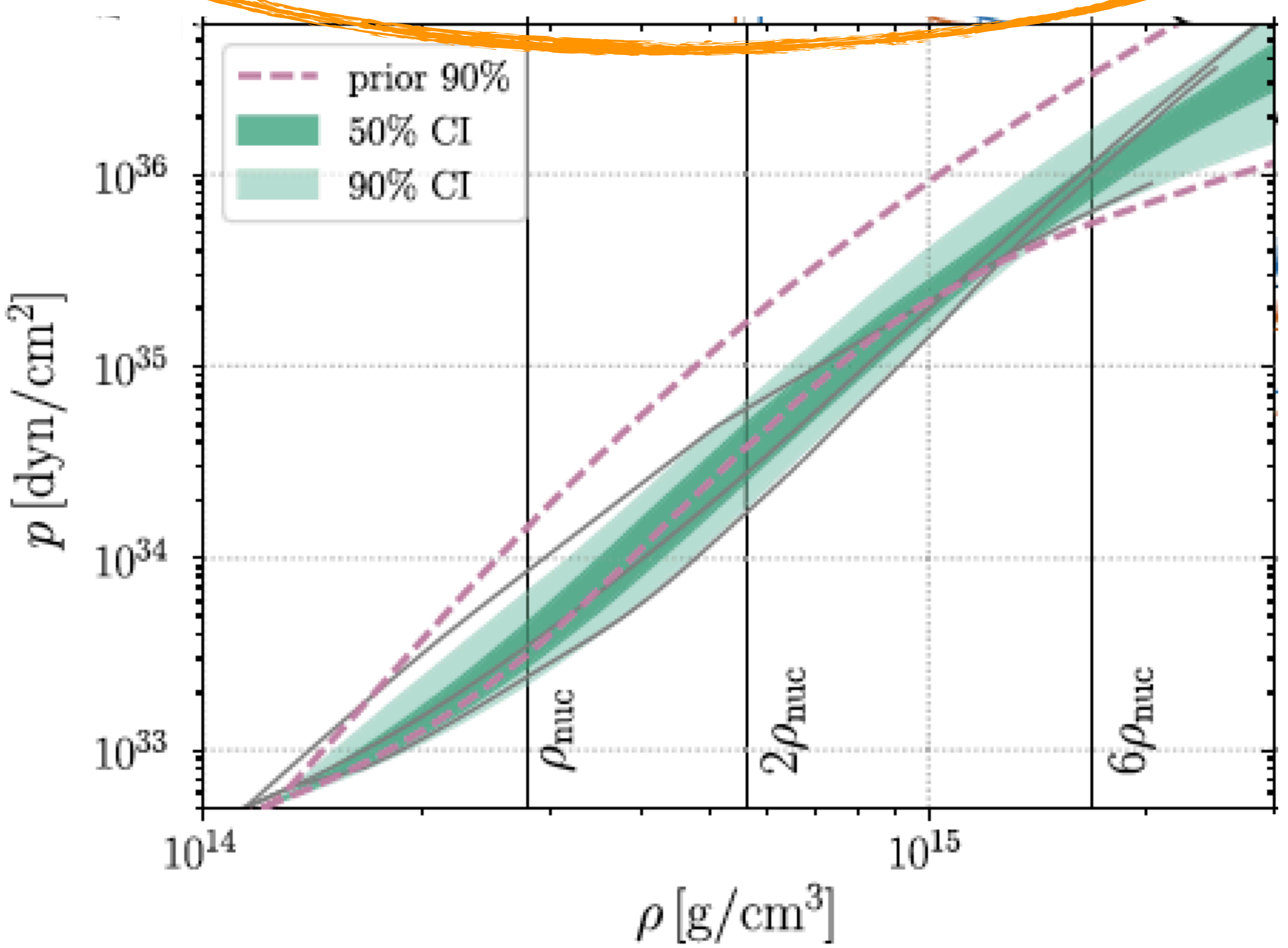
A new constraints by GW observations

$$P_{2\rho_{\rm nuc}} = 3.5^{+2.7}_{-1.7} \times 10^{34}\ {\rm dyne/cm^2}$$
$$P_{6\rho_{\rm nuc}} = 9.0^{+7.9}_{-2.6} \times 10^{34}\ {\rm dyne/cm^2}$$

$$\Lambda_{1.4M_\odot} = 190^{+390}_{-120}$$



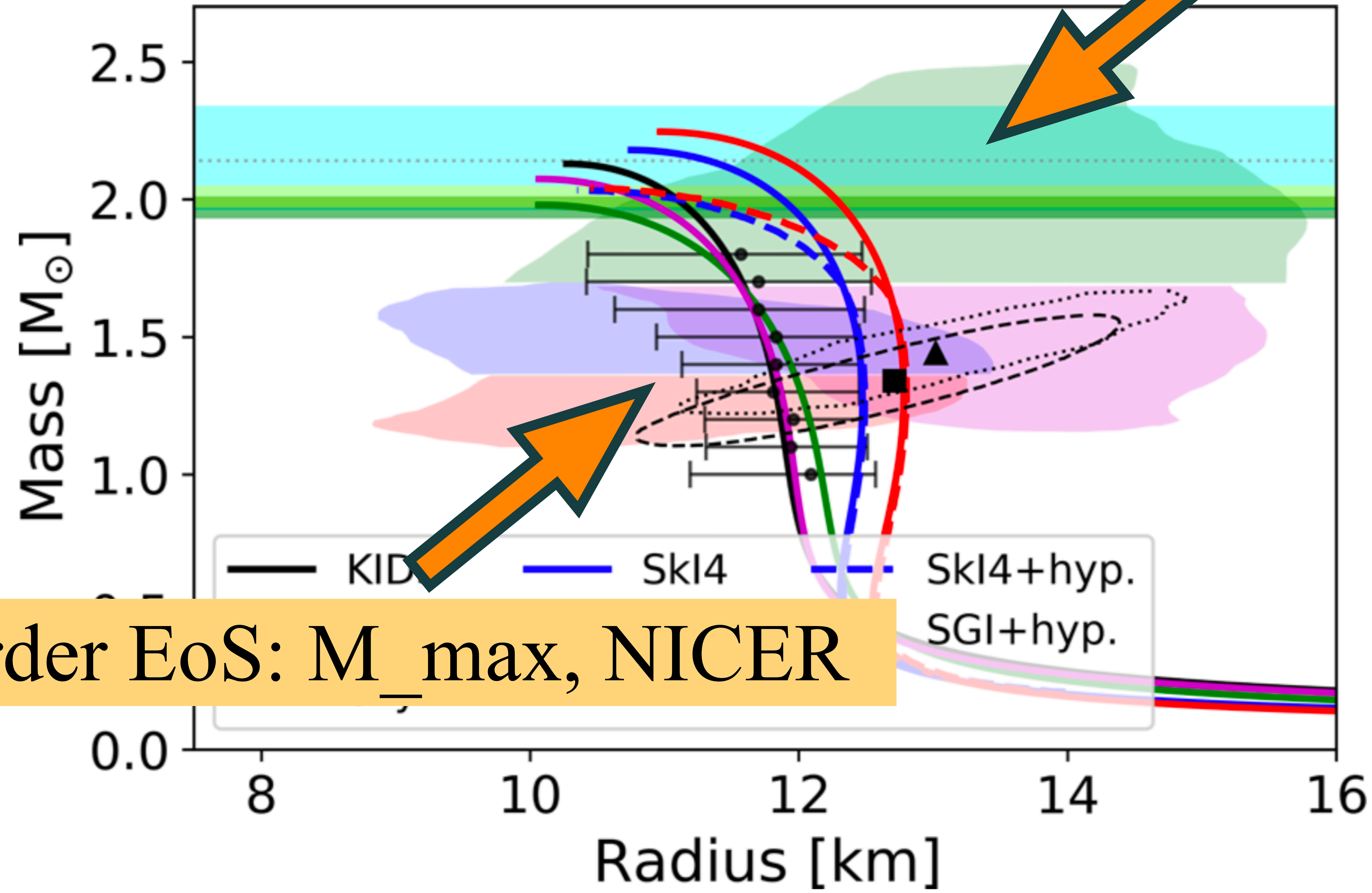
LSC and Virgo, PRL 121, 161101 (2018)



$$\rho_{\rm nuc} = 2.8 \times 10^{14}\ {\rm g/cm^3}$$

Constraints on Equation of State

prefer soft EoS: GW170817, strangeness



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

prefer harder EoS: M_max, NICER

M. Kim et al. (IJMPE 2020)

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

- **Light Black Hole**
  - *e.g., Yang et al., ApJL 901, L34 (2020)*
  - Tidal deformability of GW170817 **prefers soft EOS**
  - 2.6 solar mass NS is **inconsistent with soft EOS** (requires hard EOS)
  - 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
- … …

Low-Mass X-ray Binaries

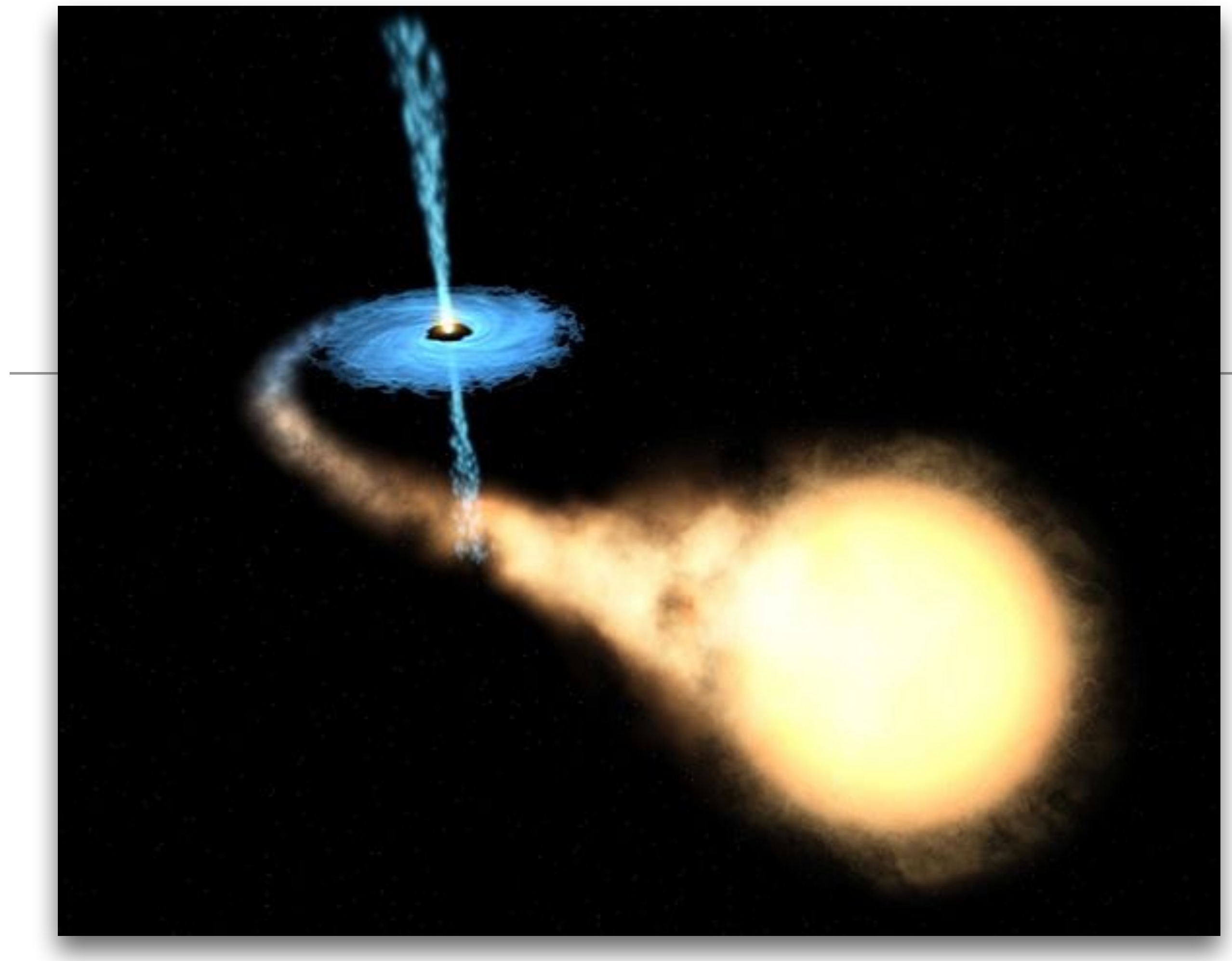
With Myungkuk Kim, Young-Min Kim, Kyujin Kwak

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

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]



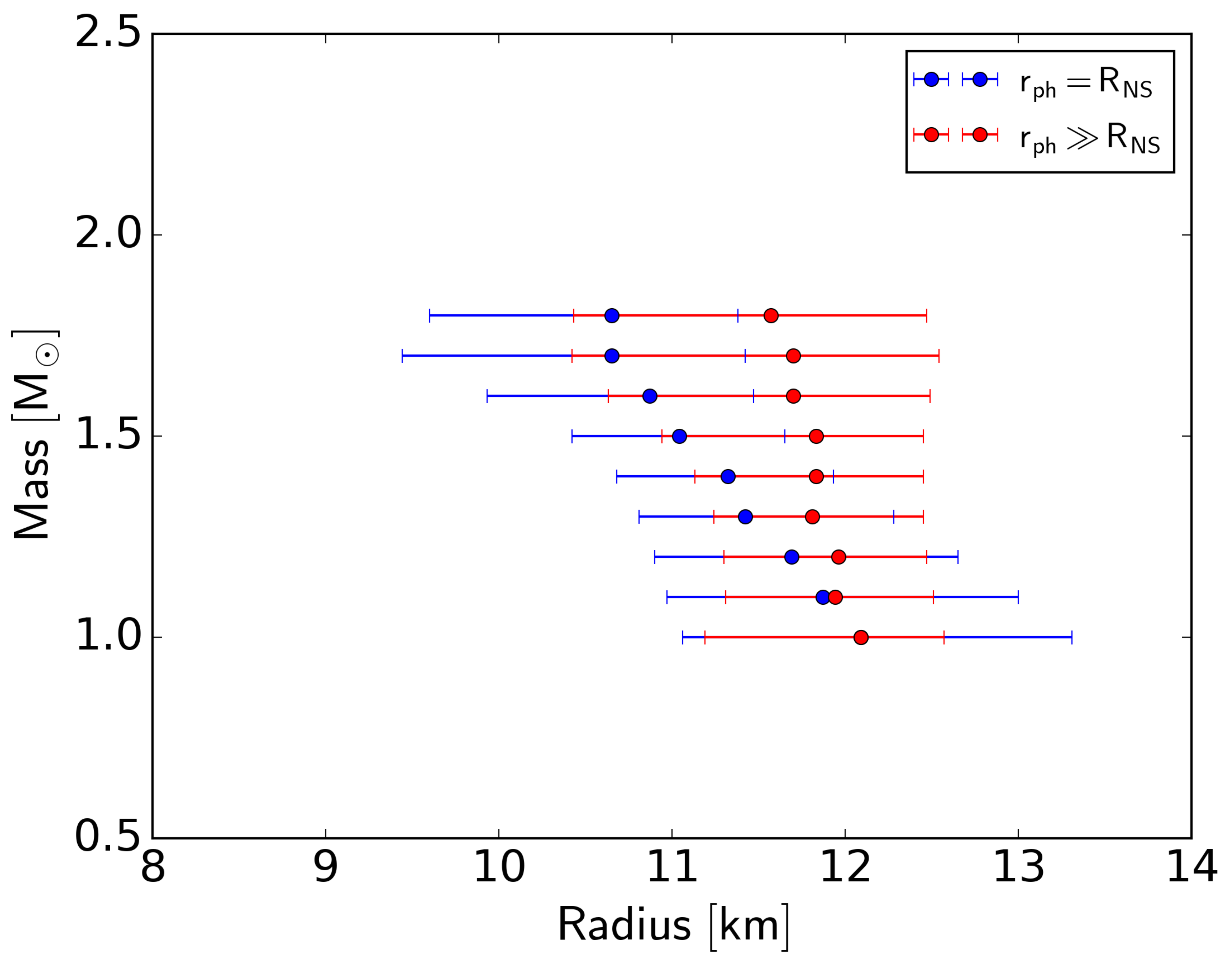
Low-Mass X-ray binary (low-mass companion)

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

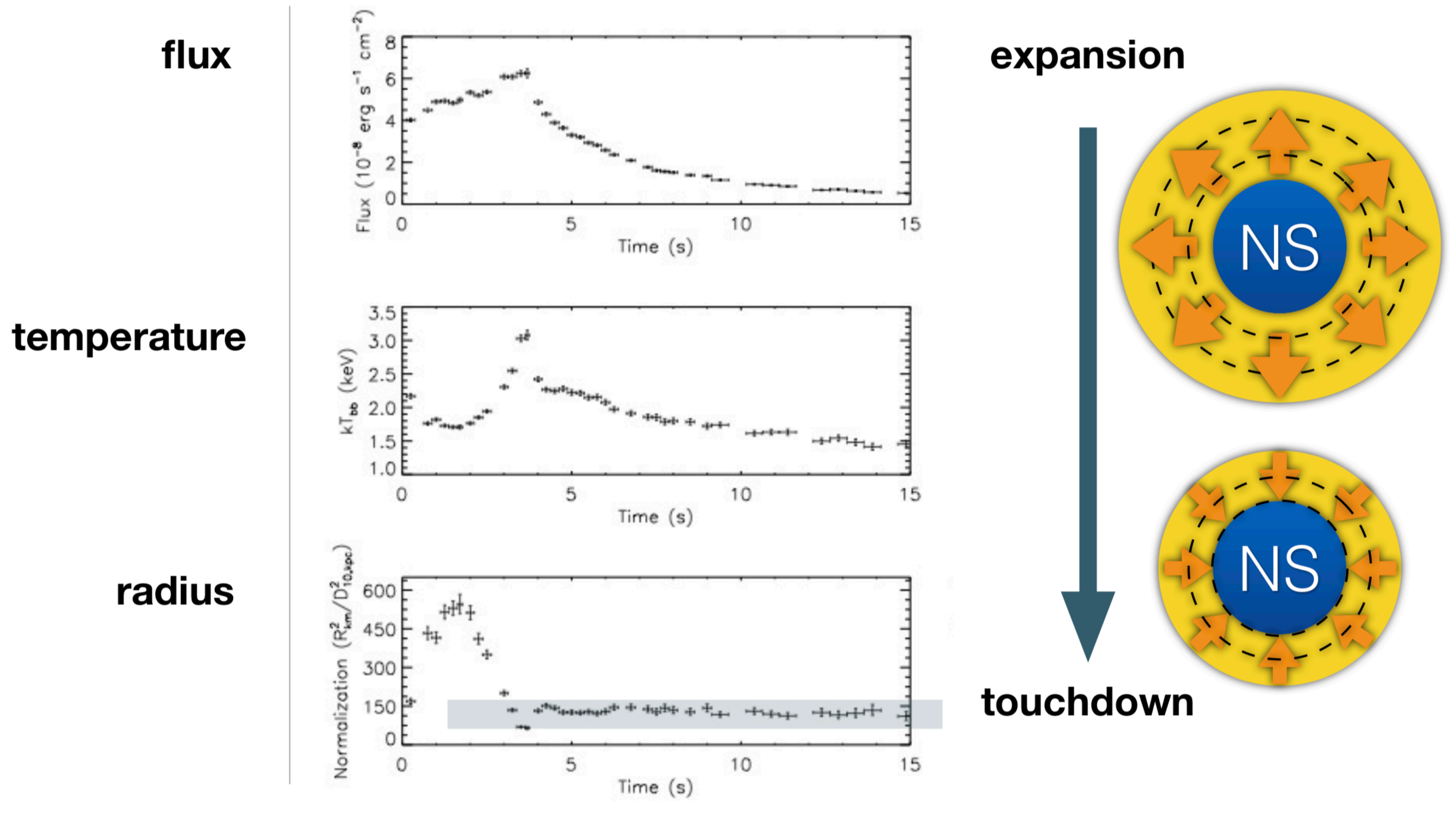
95% confidence limits by using MC sampling (for fixed NS mass)



In this talk, I will focus on

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

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*

Flux, Color temperature, Apparent area $(r_{\mathrm{ph}} = R)$

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1-\frac{2GM}{Rc^2}\right)^{1/2} \left[1+\left(\frac{kT_{\mathrm{c}}}{38.8\,\mathrm{keV}}\right)^{a_g}\left(1-\frac{2GM}{Rc^2}\right)^{-a_g/2}\right],$$

where

$$a_g = 1.01 + 0.067\log\left(\frac{g_{\mathrm{eff}}}{10^{14}\,\mathrm{cm\,s^{-2}}}\right),$$

$$g_{\mathrm{eff}} = \frac{GM}{R^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1/2},$$

$$T_{\mathrm{c}} = f_{\mathrm{c}}\left(\frac{g_{\mathrm{eff}}c}{\sigma\kappa}\right)^{1/4} = f_{\mathrm{c}}\left(\frac{GMc}{\sigma\kappa R^2}\right)^{1/4}\left(1-\frac{2GM}{Rc^2}\right)^{-1/8}.$$

$$A = f_{\mathrm{c}}^{-4}\frac{R^2}{D^2}\left(1-\frac{2GM}{Rc^2}\right)^{-1}\left\{1+\left[\left(0.108-0.096\frac{M}{M_\odot}\right) +\left(-0.061+0.114\frac{M}{M_\odot}\right)\frac{R}{10\,\mathrm{km}}-0.128\left(\frac{R}{10\,\mathrm{km}}\right)^2\right] \left(\frac{f_{\mathrm{NS}}}{1000\,\mathrm{Hz}}\right)^2\right\}^2.$$

$r_{\mathrm{ph}} \neq R$

$$F_{\mathrm{TD},\infty} = \frac{GMc}{\kappa D^2}\left(1 - \frac{2GM}{r_{\mathrm{ph}}c^2}\right)^{1/2} \left[1 + \left(\frac{kT_{\mathrm{c}}}{38.8\,\mathrm{keV}}\right)^{a_g}\left(1 - \frac{2GM}{r_{\mathrm{ph}}c^2}\right)^{-a_g/2}\right],$$

where

$$a_g = 1.01 + 0.067\log\left(\frac{g_{\mathrm{eff}}}{10^{14}\,\mathrm{cm\,s^{-2}}}\right),$$

$$g_{\mathrm{eff}} = \frac{GM}{{r_{\mathrm{ph}}}^2}\left(1 - \frac{2GM}{r_{\mathrm{ph}}c^2}\right)^{-1/2},$$

$$T_{\mathrm{c}} = f_{\mathrm{c}}\left(\frac{g_{\mathrm{eff}}c}{\sigma\kappa}\right)^{1/4} = f_{\mathrm{c}}\left(\frac{GMc}{\sigma\kappa {r_{\mathrm{ph}}}^2}\right)^{1/4}\left(1 - \frac{2GM}{r_{\mathrm{ph}}c^2}\right)^{-1/8}.$$

Modifications

touchdown radius parameter

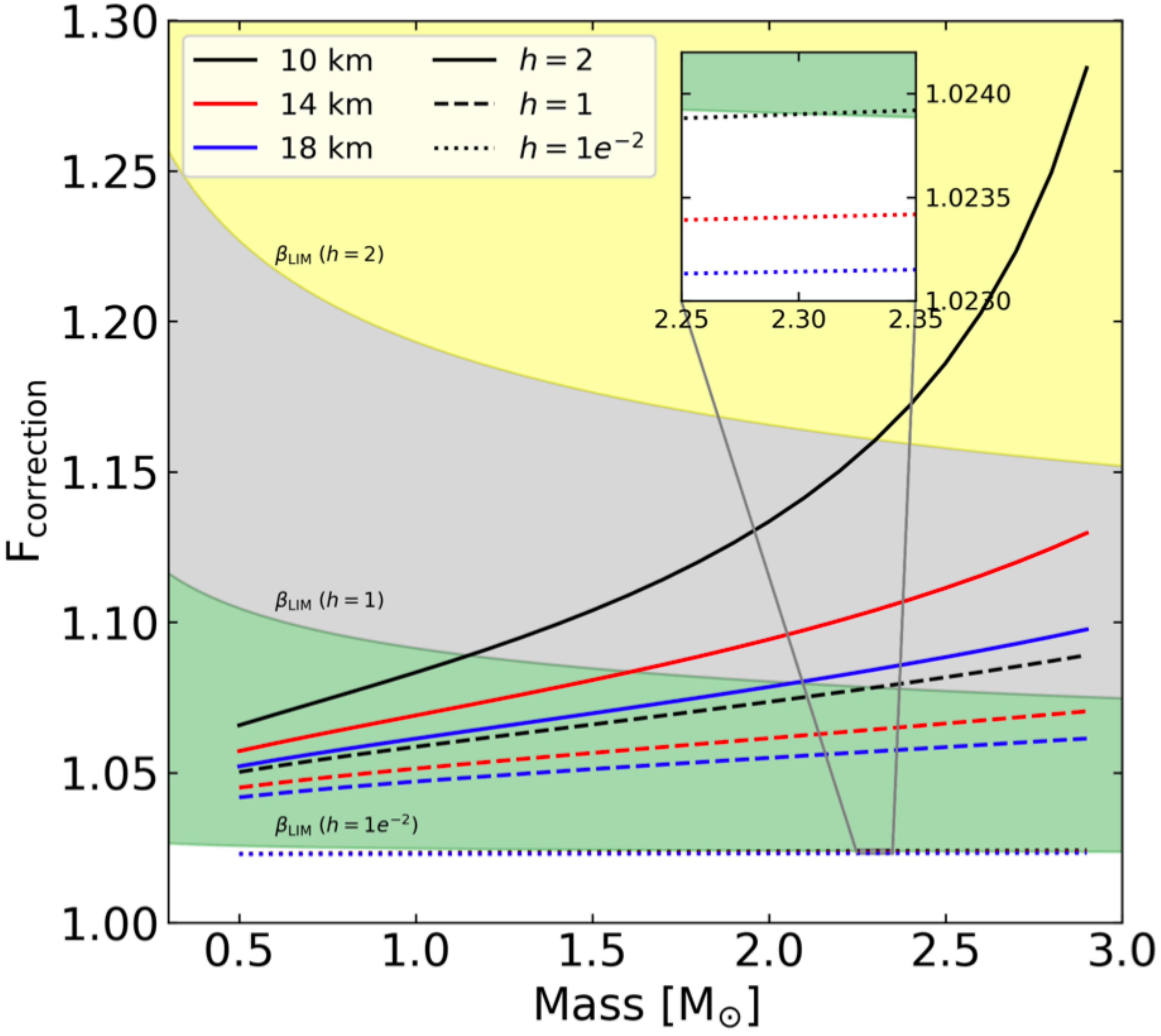
$$h = \frac{2R_{\rm NS}}{r_{\rm ph}}$$

causality limit

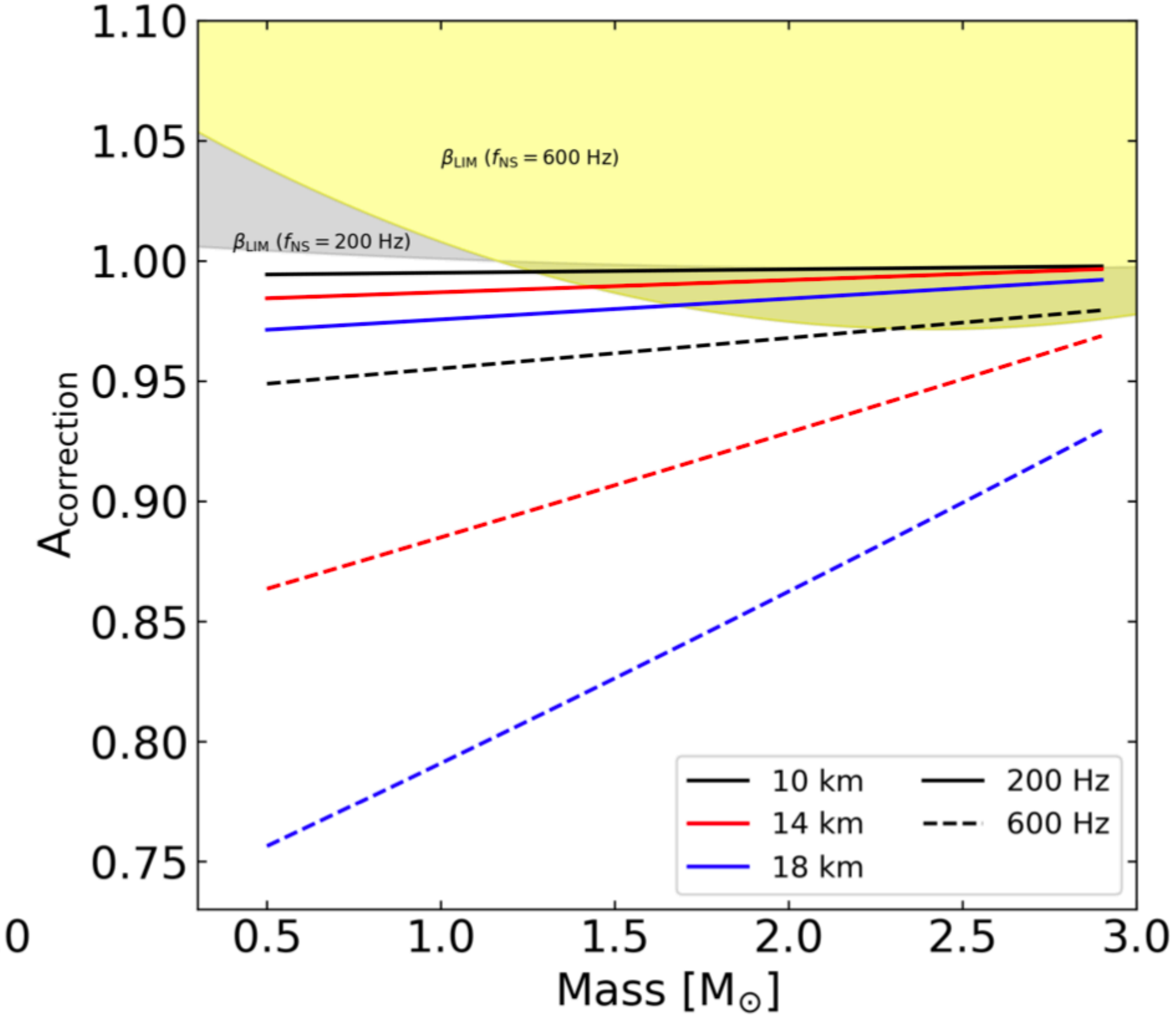
$$\beta = \frac{M_{\rm NS}}{R_{\rm NS}} < \frac{1}{2.94}$$

NS spin frequency

$$f_{\rm NS}$$

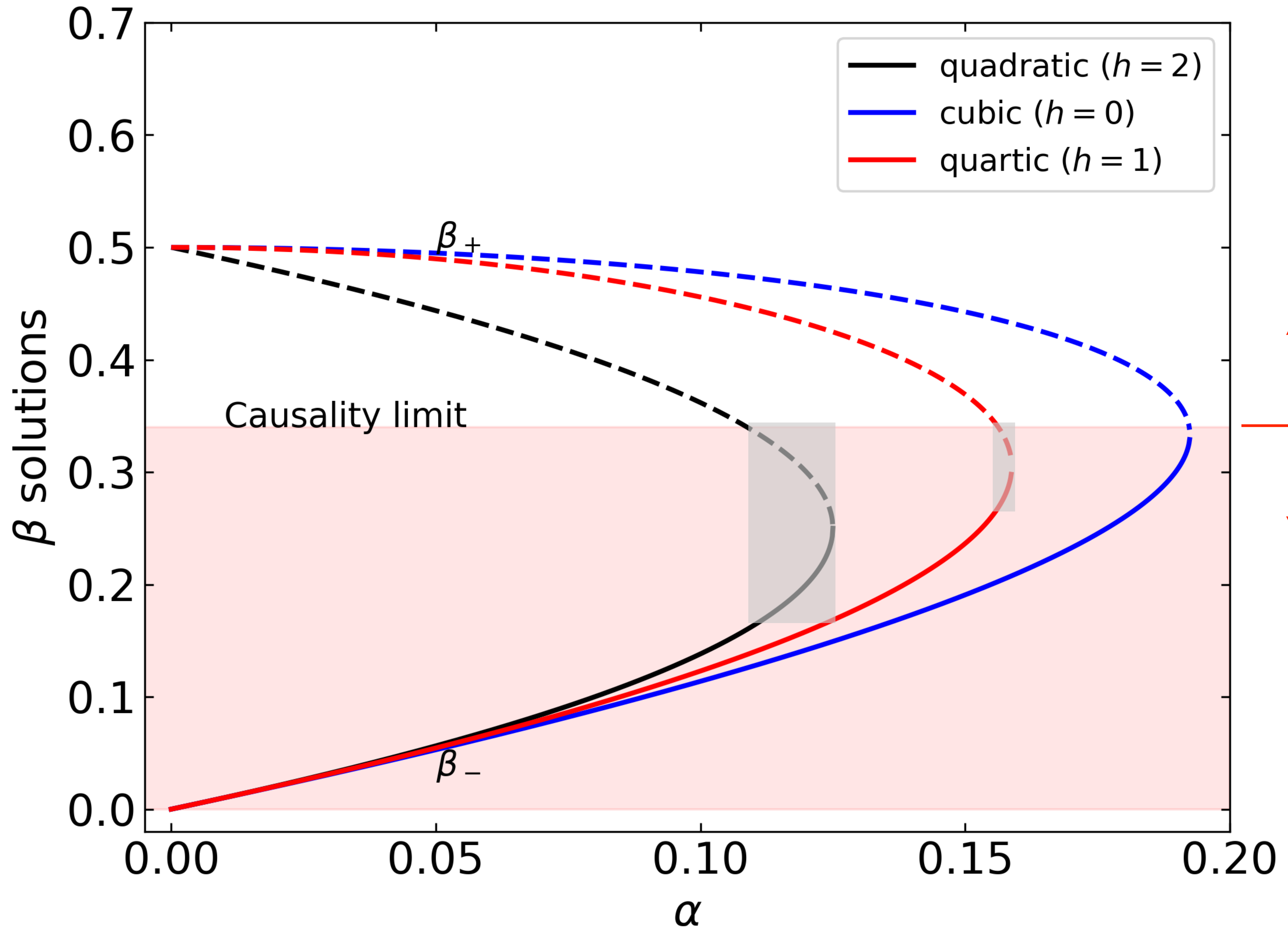


Touchdown Flux (ratio)



Apparent angular area (ratio)

Double solutions are allowed in MC sampling



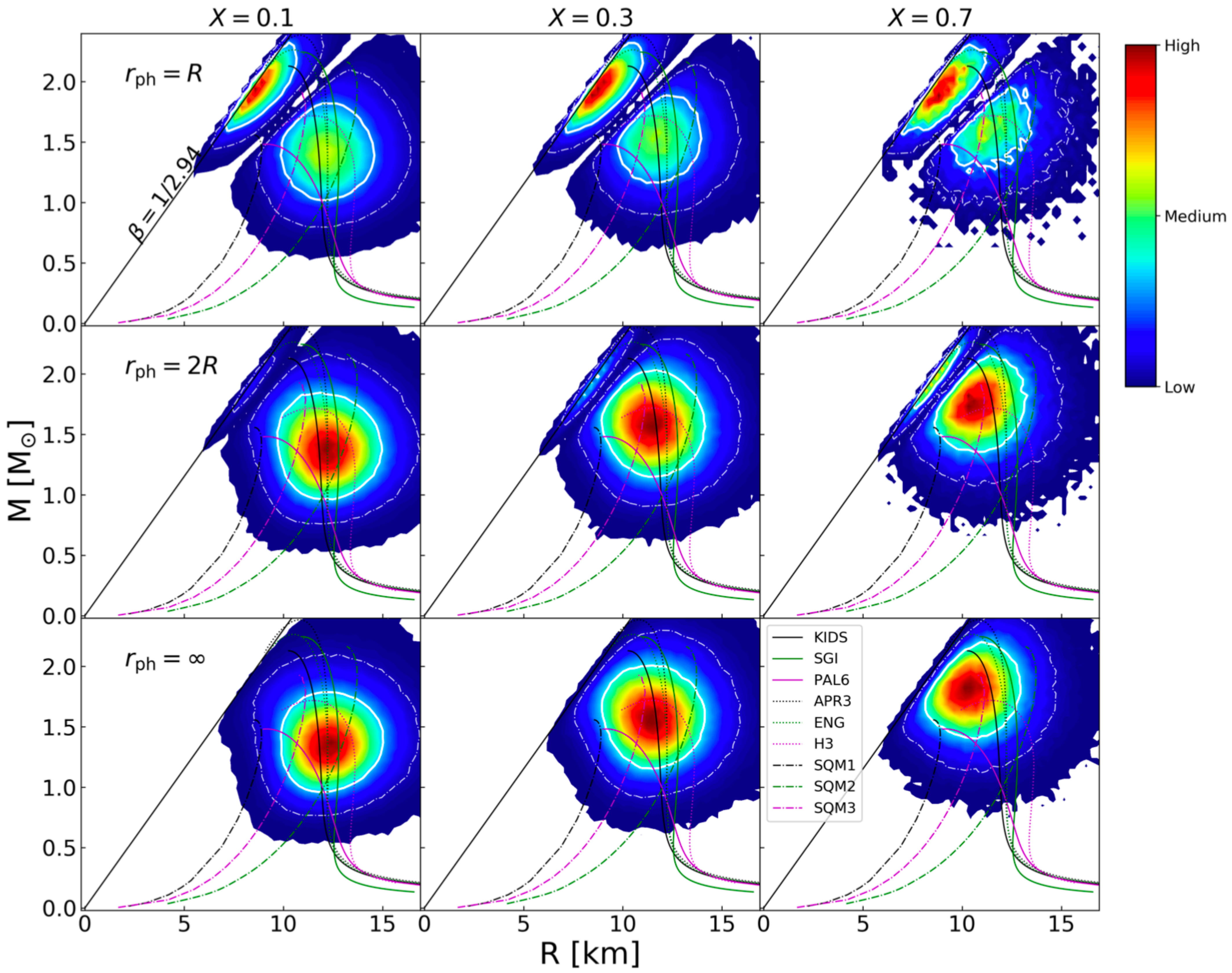
$$h = \frac{2R_{\rm NS}}{r_{\rm ph}} \qquad \beta = \frac{M_{\rm NS}}{R_{\rm NS}}$$

unphysical/unstable region

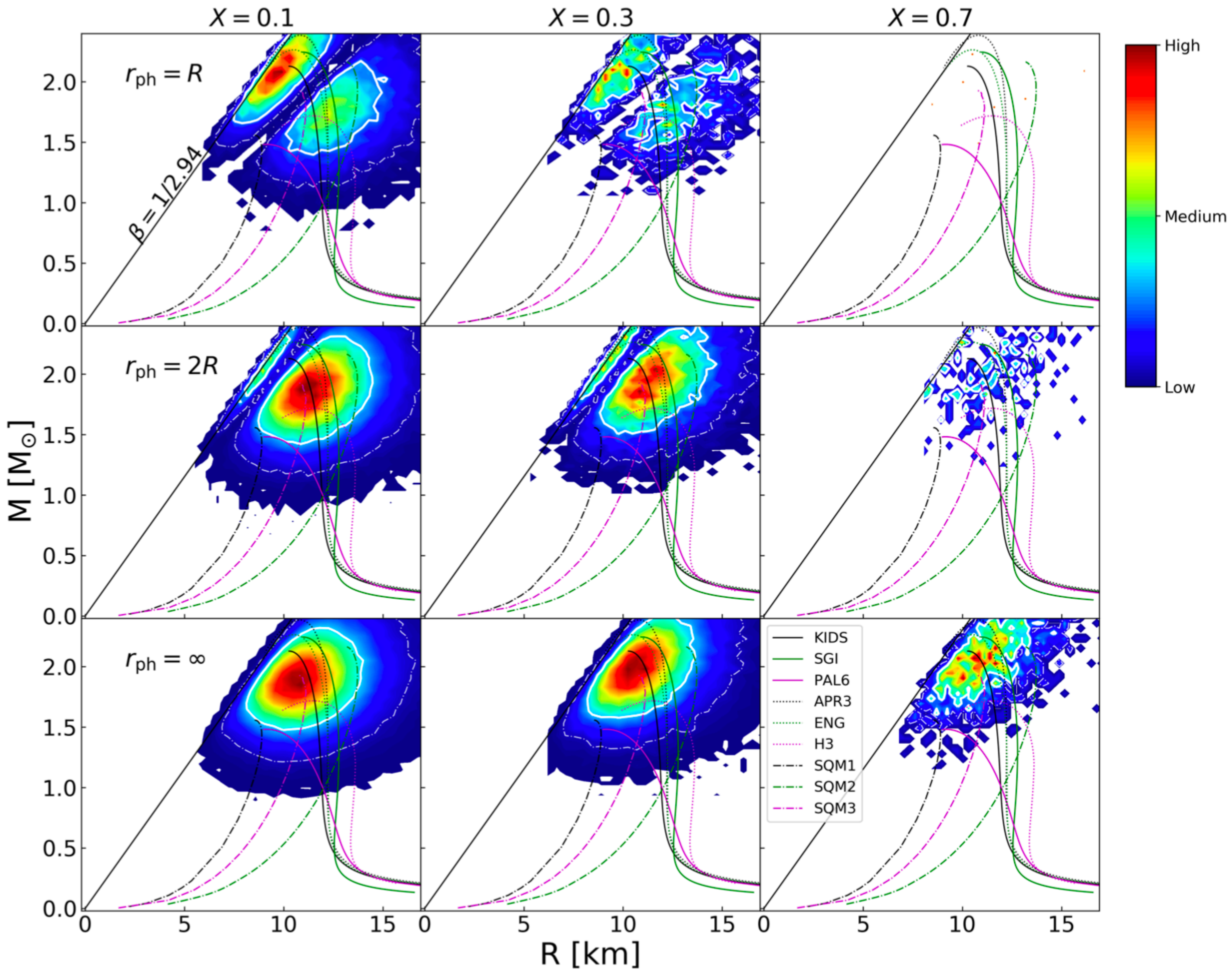
allowed region

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

X: hydrogen mass fraction



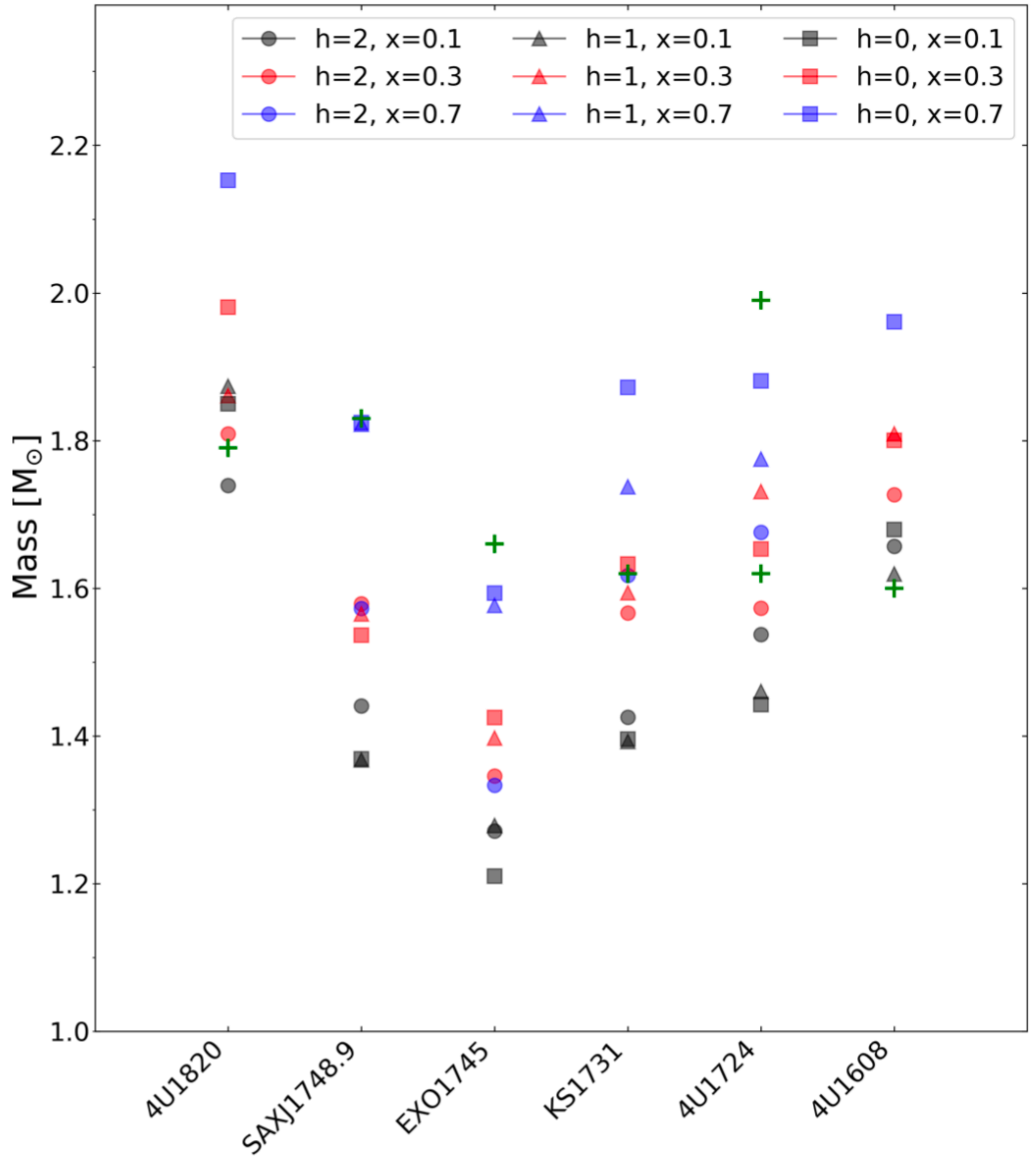
SAX J1748.9-2021

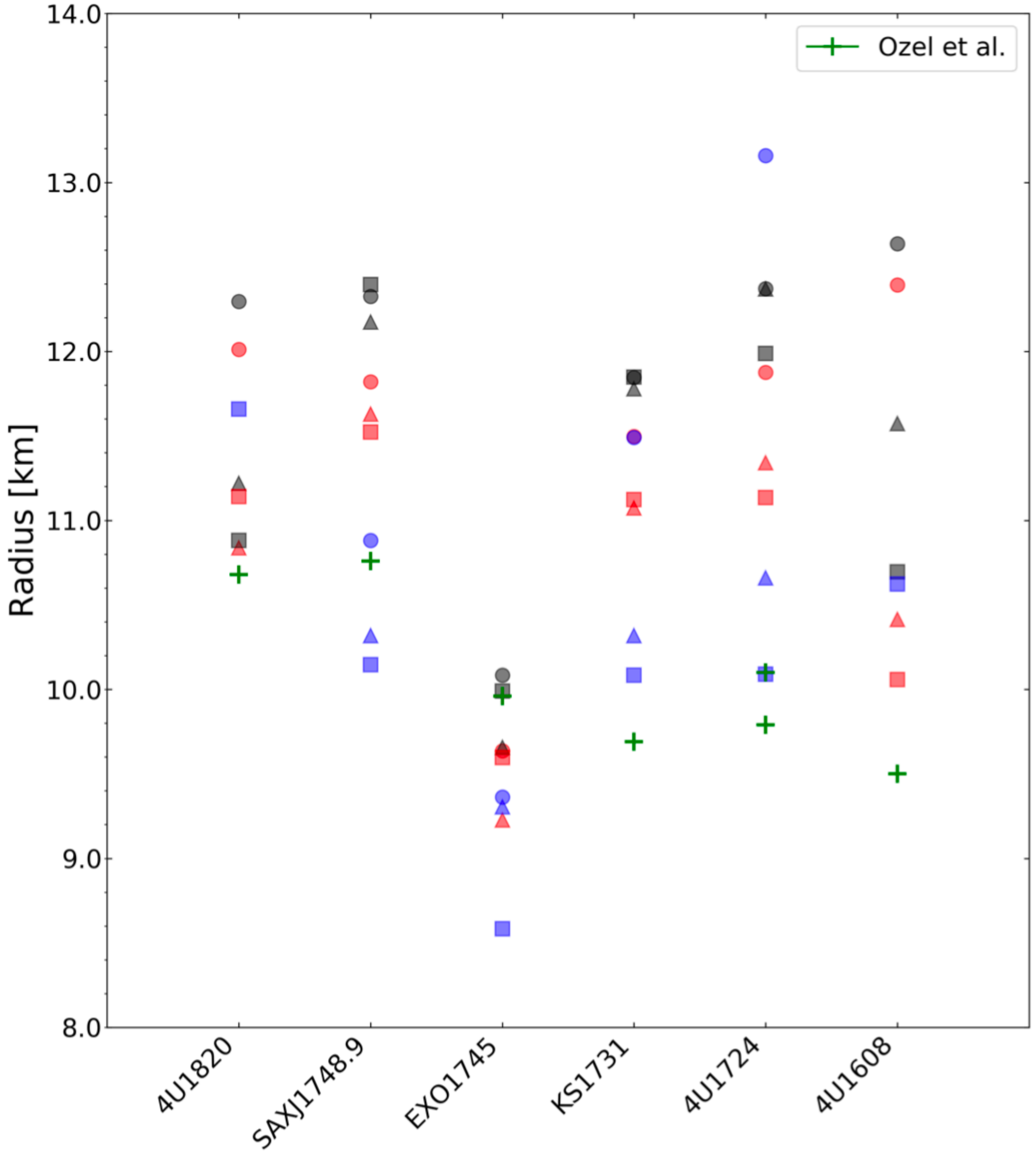


4U 1820-30

Most probable values of M & R

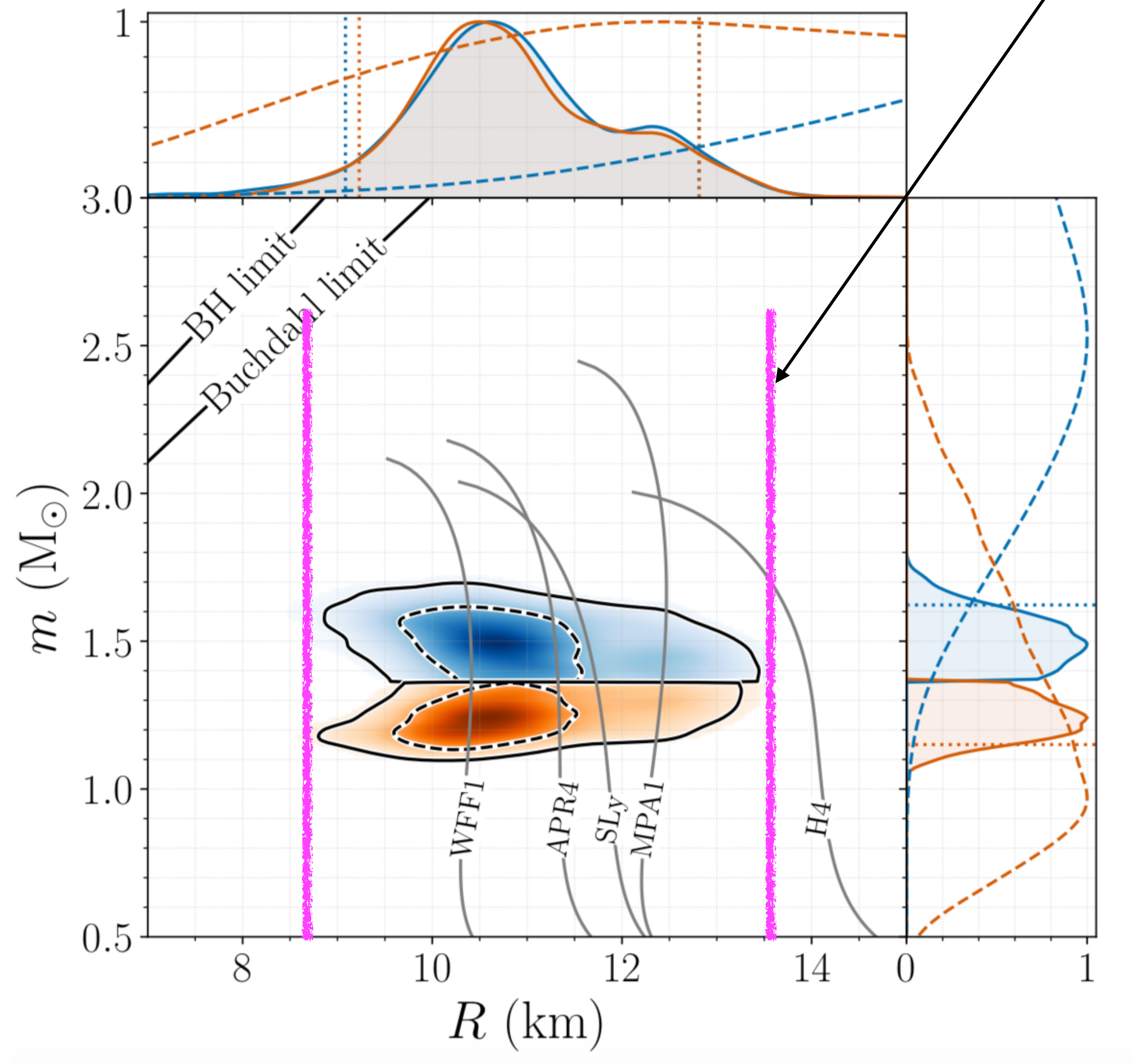
M. Kim, Y.-M. Kim et al. (A&A 2021)



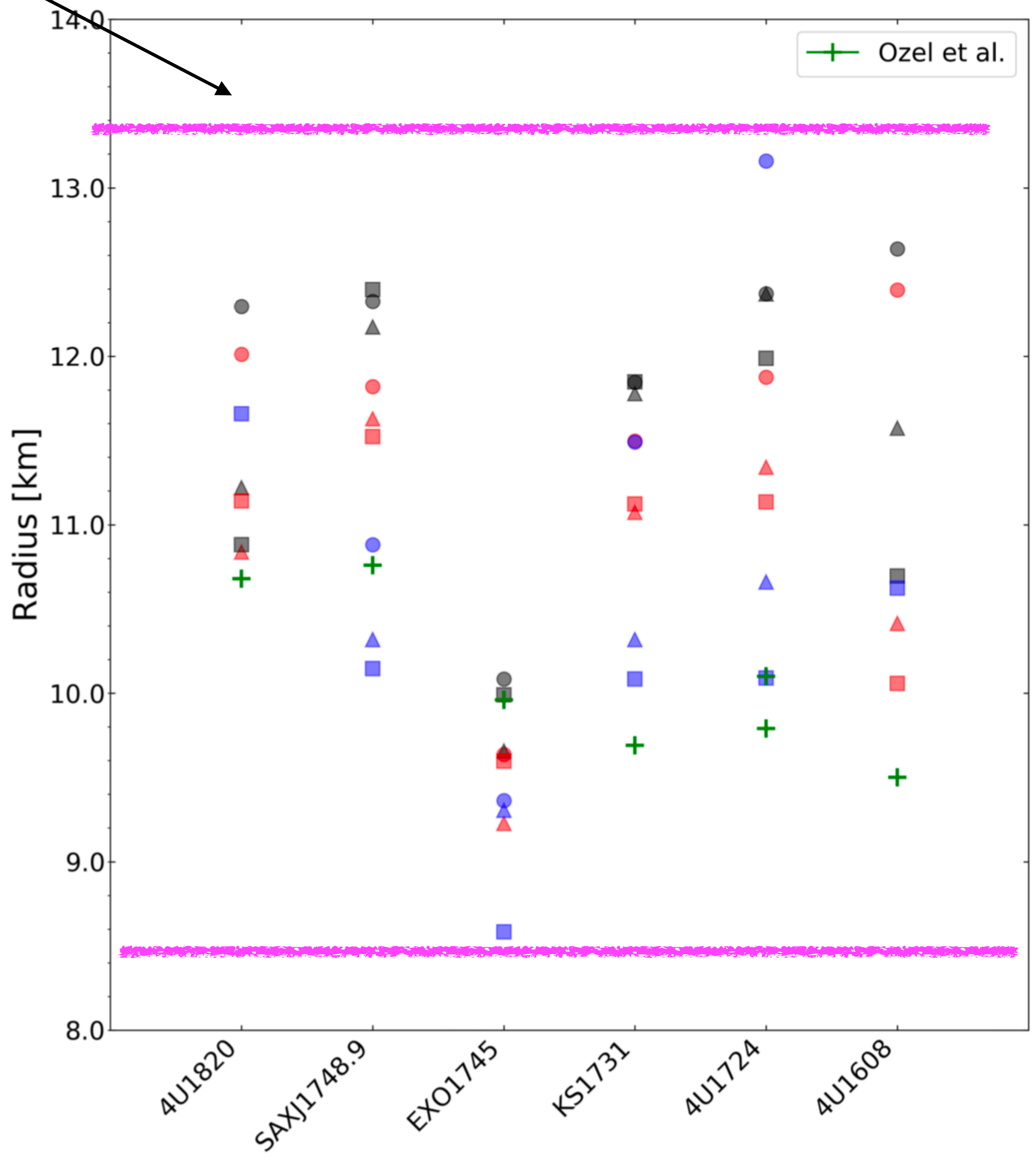


Most probable M,R

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

$$P(\theta)$$

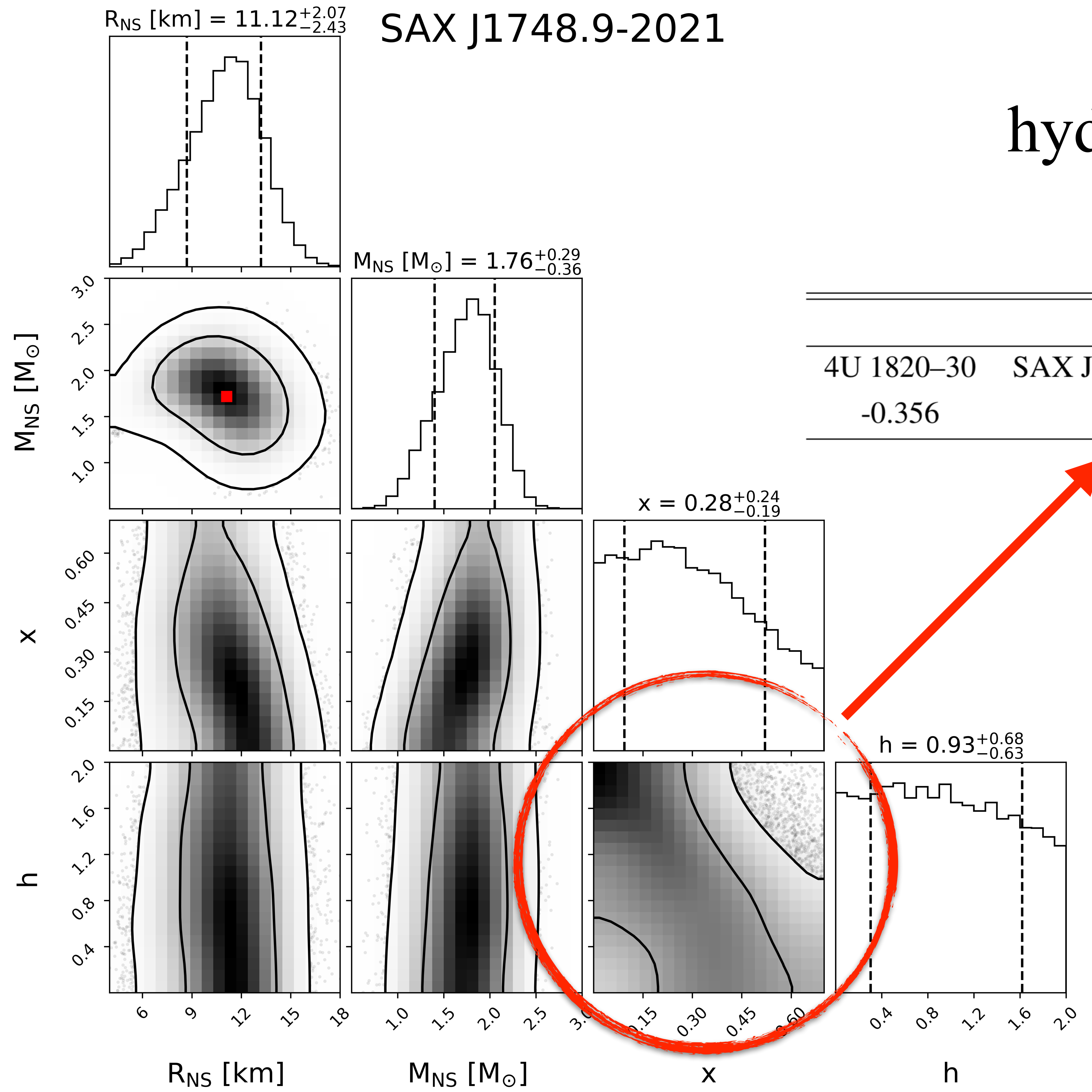
Prior of the parameter set of the model

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

(flat distribution for unknown quantities without using EOS)

Mass-Radius estimation by Bayesian.

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



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.
  - Bounds of NS radius is consistent with the results of 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.

Symmetry

yangzhou@2023.09.22