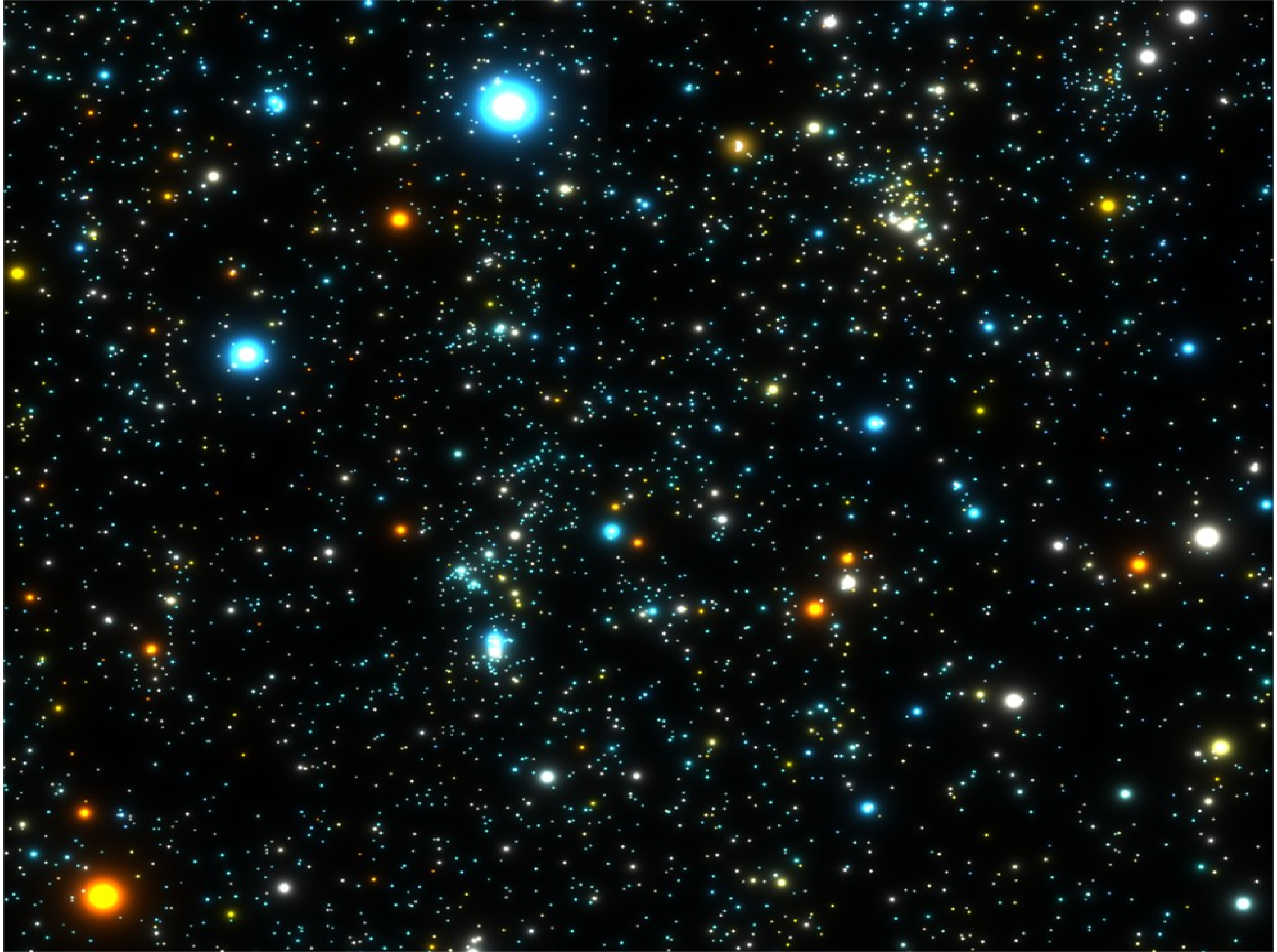
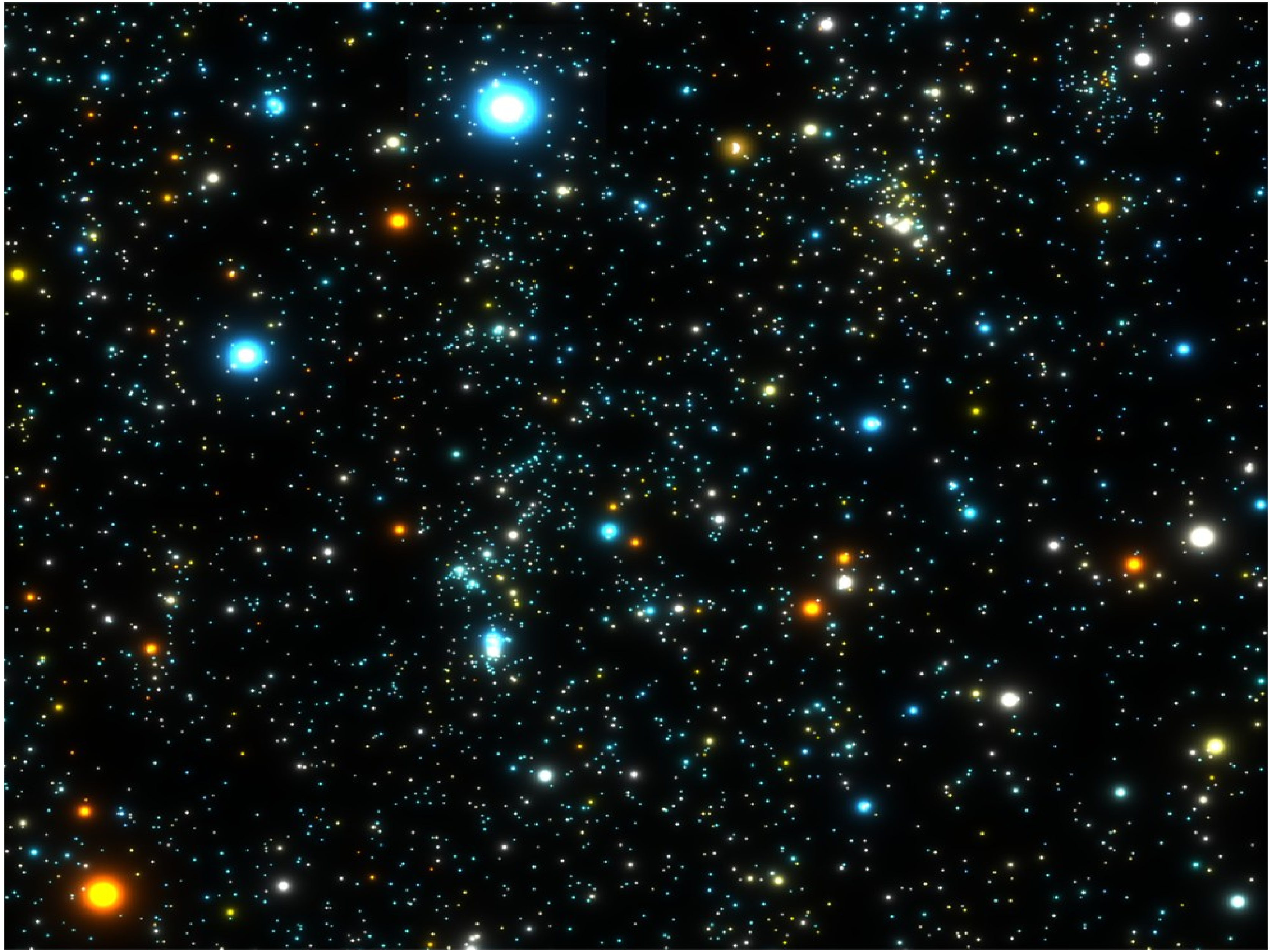


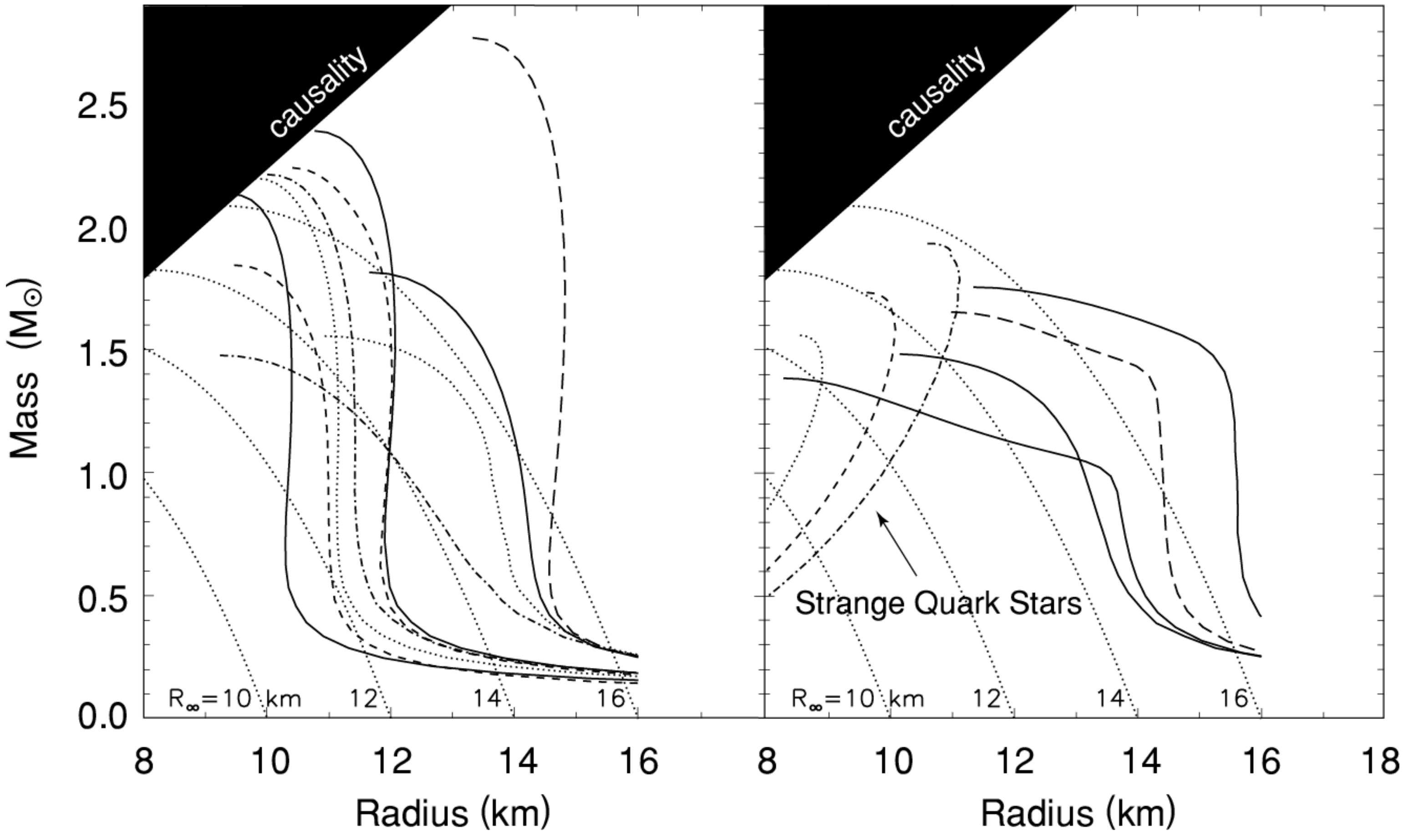
The X-ray Sky

25 square degrees, viz. 0.06 %, of the whole ROSAT sky survey



Mass-Radius Relations for Different Equations of State

Lattimer & Prakash 2001

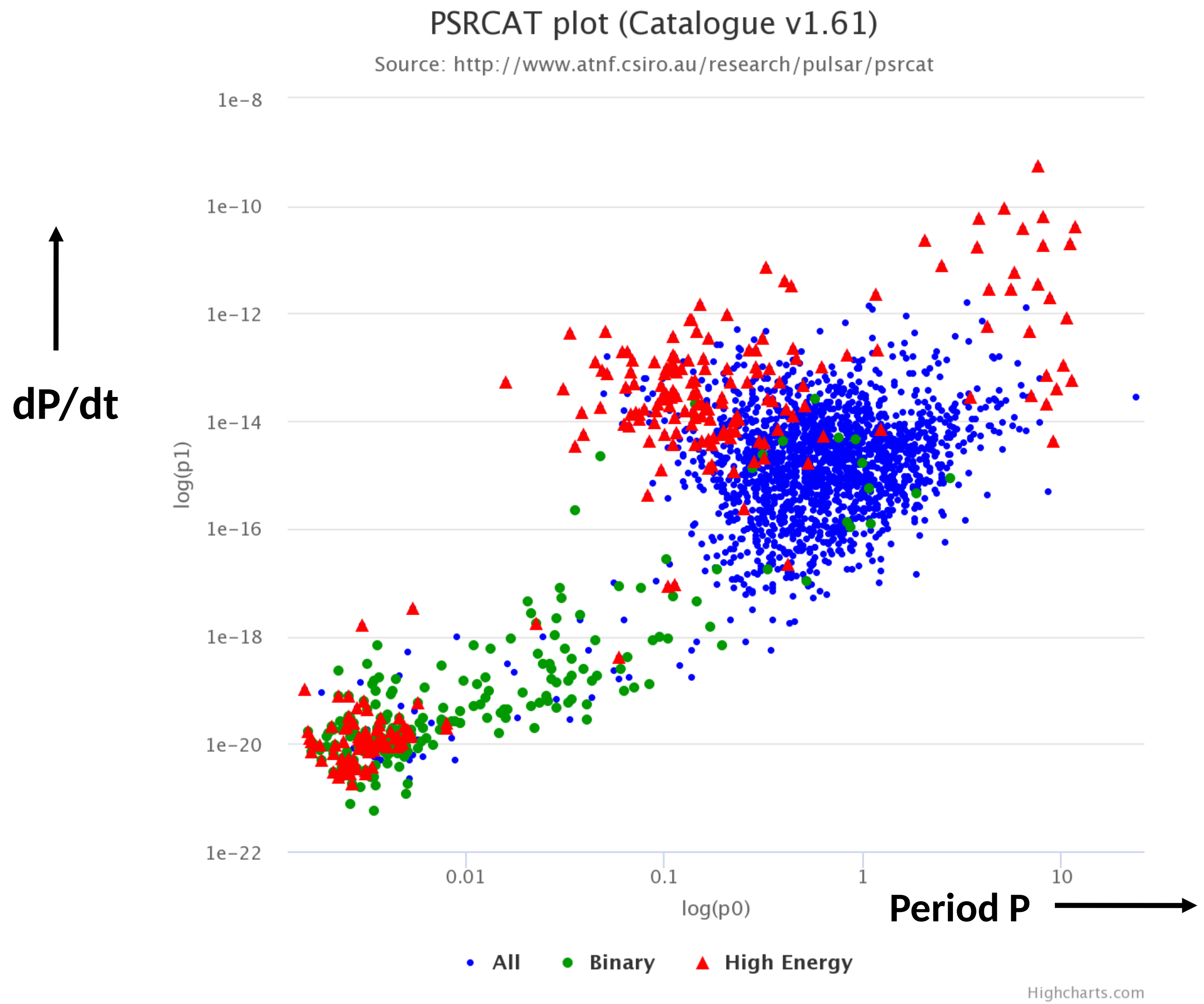


nucleon / hyperon stars

kaon condensates & strange quark stars

The Zoo of neutron stars: P, dP/dt - diagram from the Pulsar catalogue

(Manchester et al. 2005, updated 2019)



Shown are all 2796 rotation driven neutron stars:

2703 radio only pulsars

93 radio, optical, X-ray pulsars

Pulsars in binary system

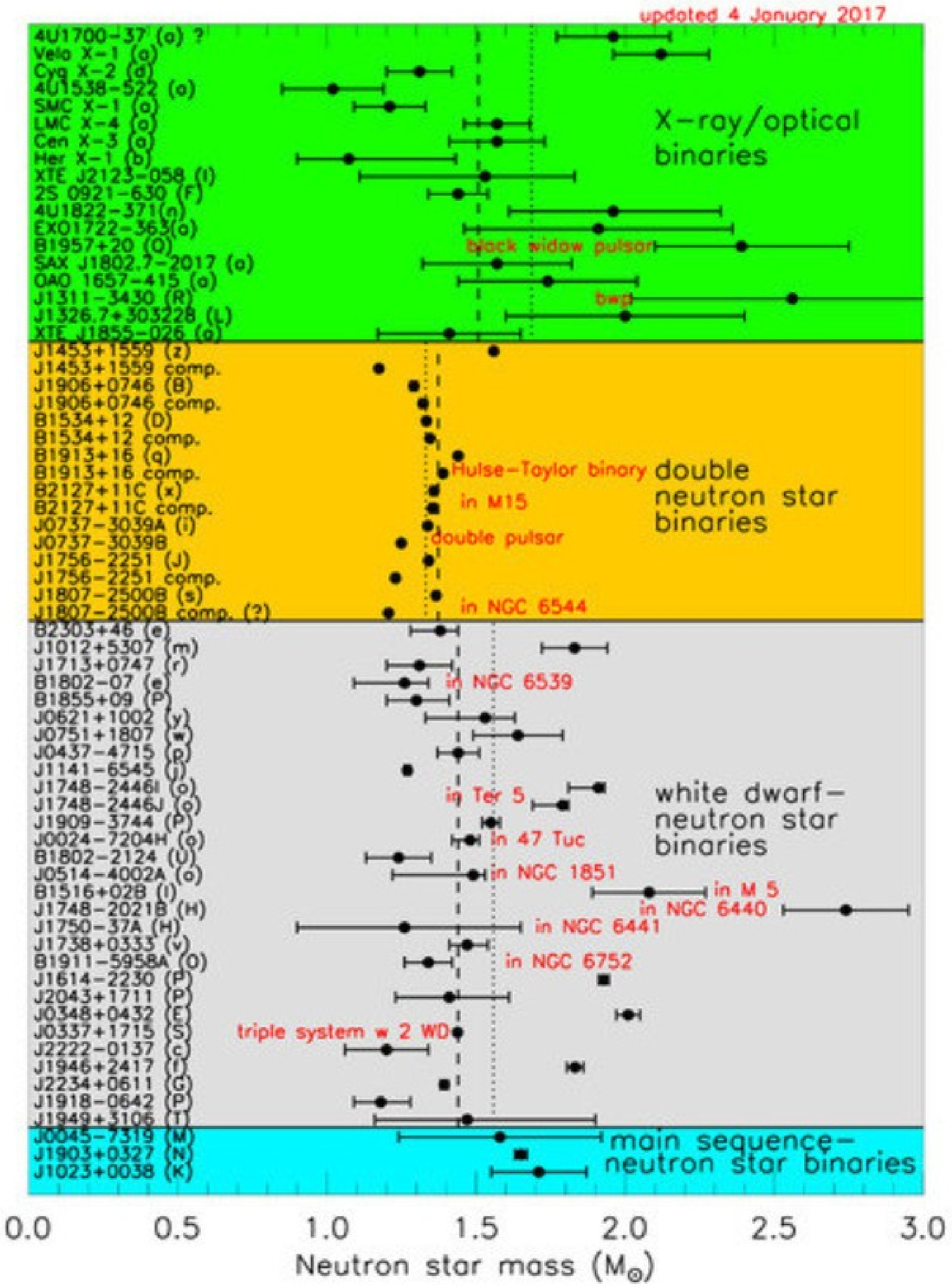
Not shown are accreting neutron stars in binary systems:

~ 200 HXMBs

~ 130 LMXBs

Neutron Star Masses

Compilation by
Lattimer 2019



Average mass = 1.4 – 1.5 M_o
(error weighted / unweighted)

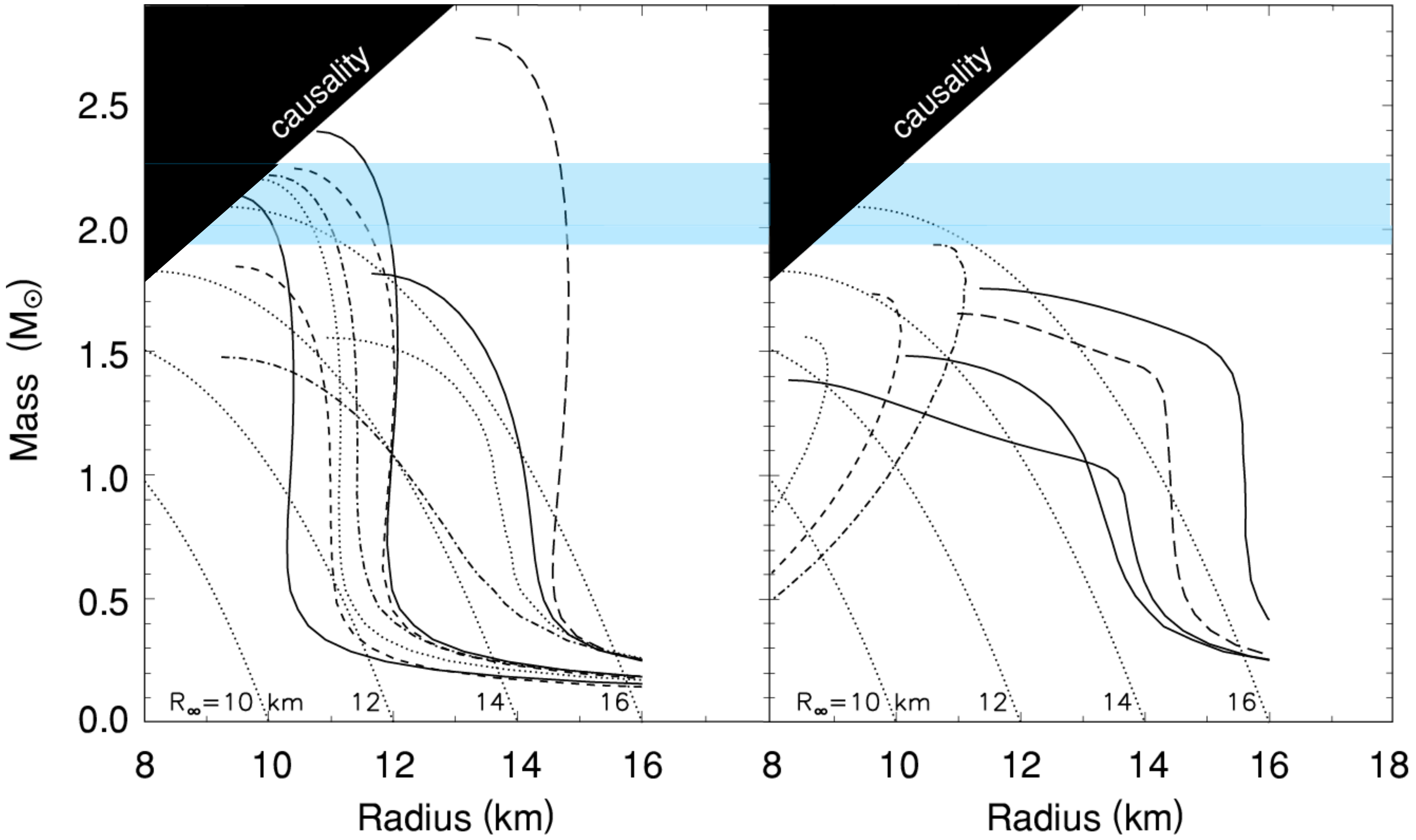
Largest observed Masses:

M = 1.97 +- 0.04 M_o (Demorest + 2010)

M = 2.01 +- 0.04 M_o (Antoniadis + 2013)

M = 2.17 +- 0.10 M_o (Cromartie + 2019)

The EOS of neutron stars should cross the blue band



Pulsars near the centrifugal limit

The maximum rotational frequency of a spherical star is

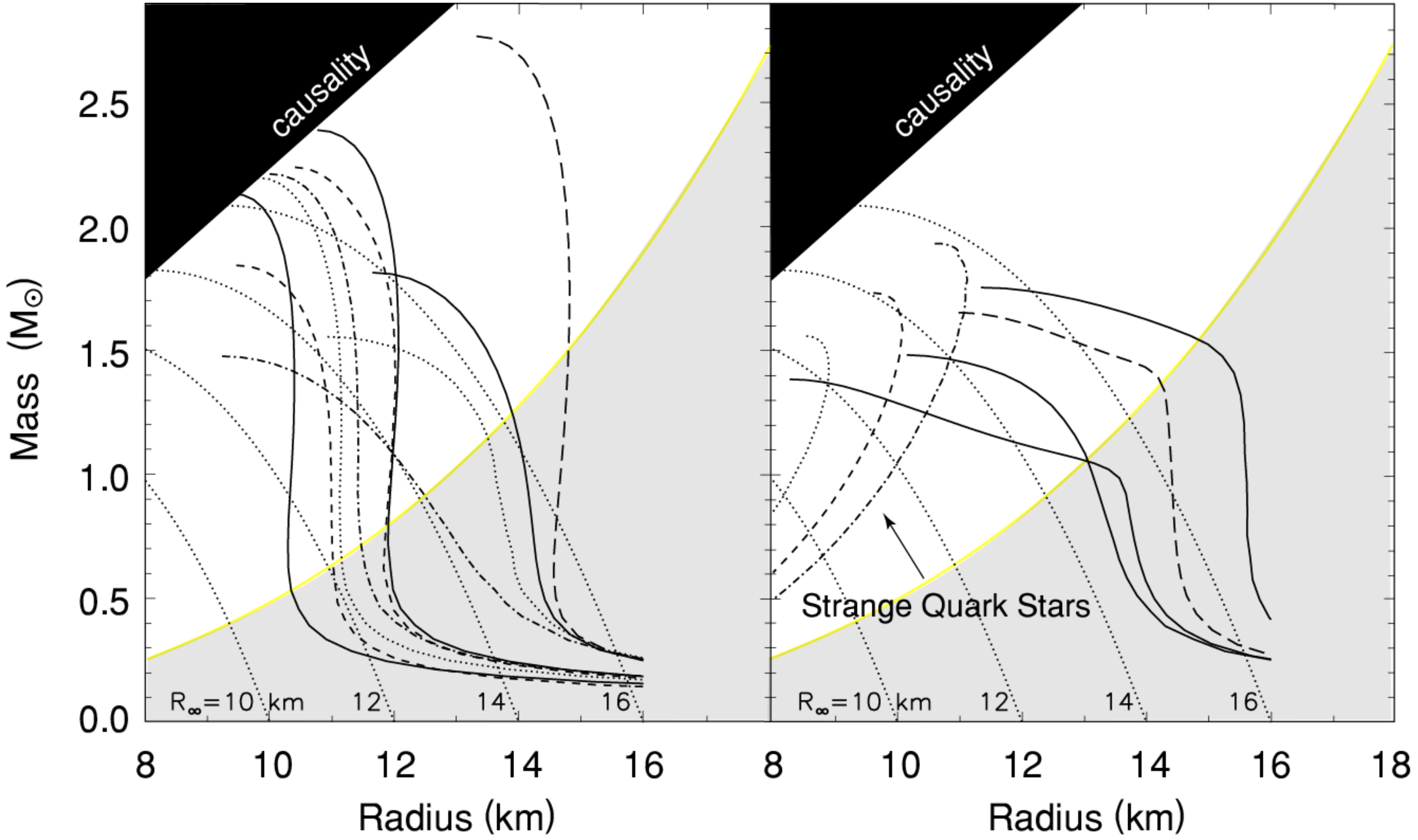
$$\nu_{max} = 1/2\pi\, (GM/R^3)^{1/2}$$
$$= 1833\, (M/M_o)^{1/2}\, (10km/R)^{3/2}\ \mathrm{Hz}$$

because of the centrifugal deformation and general relativistic effects the critical spin frequency is reduced (Lattimer & Prakash 2004) **:**

$$\nu_{max} = 1045\, (M/M_o)^{1/2}\, (10km/R)^{3/2}$$

The record holder is PSR J1748-244ad in the globular cluster Terzan 5 (Hessels et al. 2006):

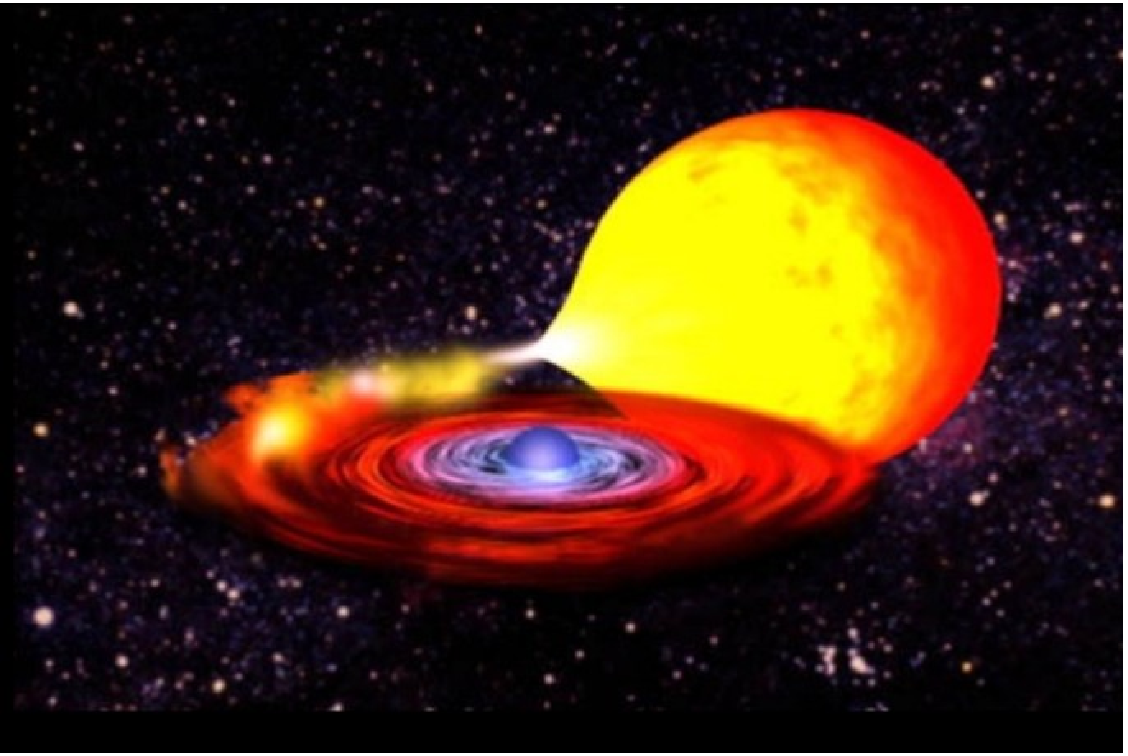
ν = 716.35556 Hz (43.000 revolutions/min!), P = 1.4 millisec

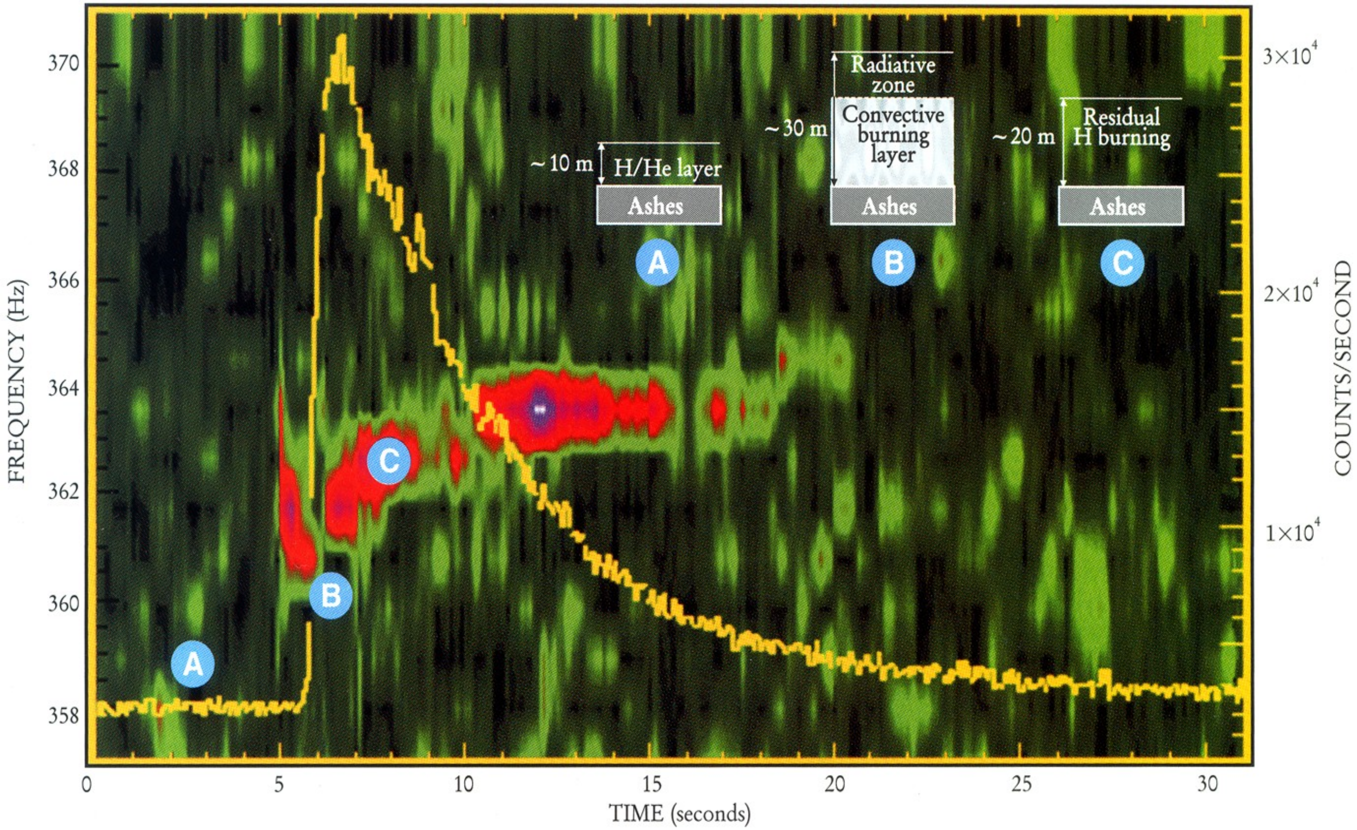


J. Trümper, 2013

Low Mass X-ray Binaries - X-ray burster

Burst Oscillations

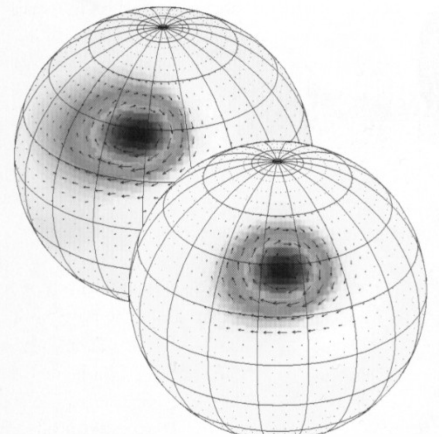


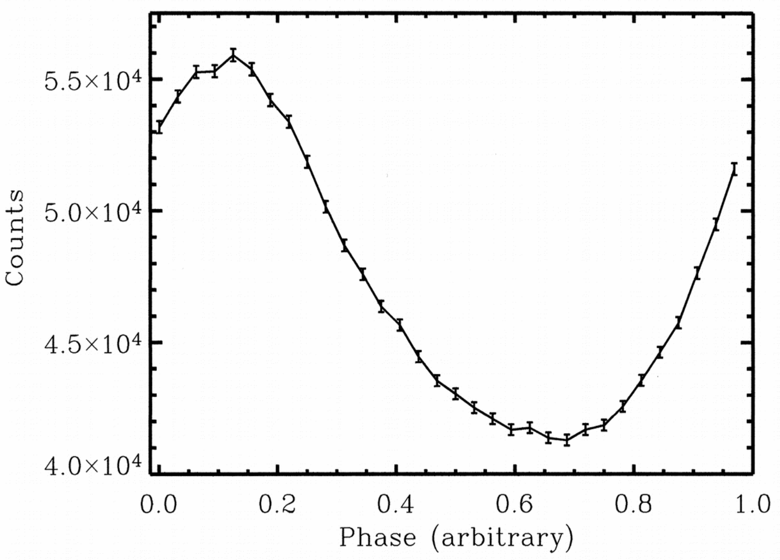


J. Trümper, 2013

X-Ray Burst Oscillations

Modelling the Light Curve of XTE J1814-338 of a hot spot on the surface modulated by rotation (Bhattacharyya et al. 2005)





P = 3.18 millisec

model parameters:

- radius of the spherical star
- latitude of the hot spot
- angular size of the hot spot
- beaming I $(\psi) \sim \cos^n \psi$ in the neutron star rest frame
- inclination of the spin axis vs. line of sight

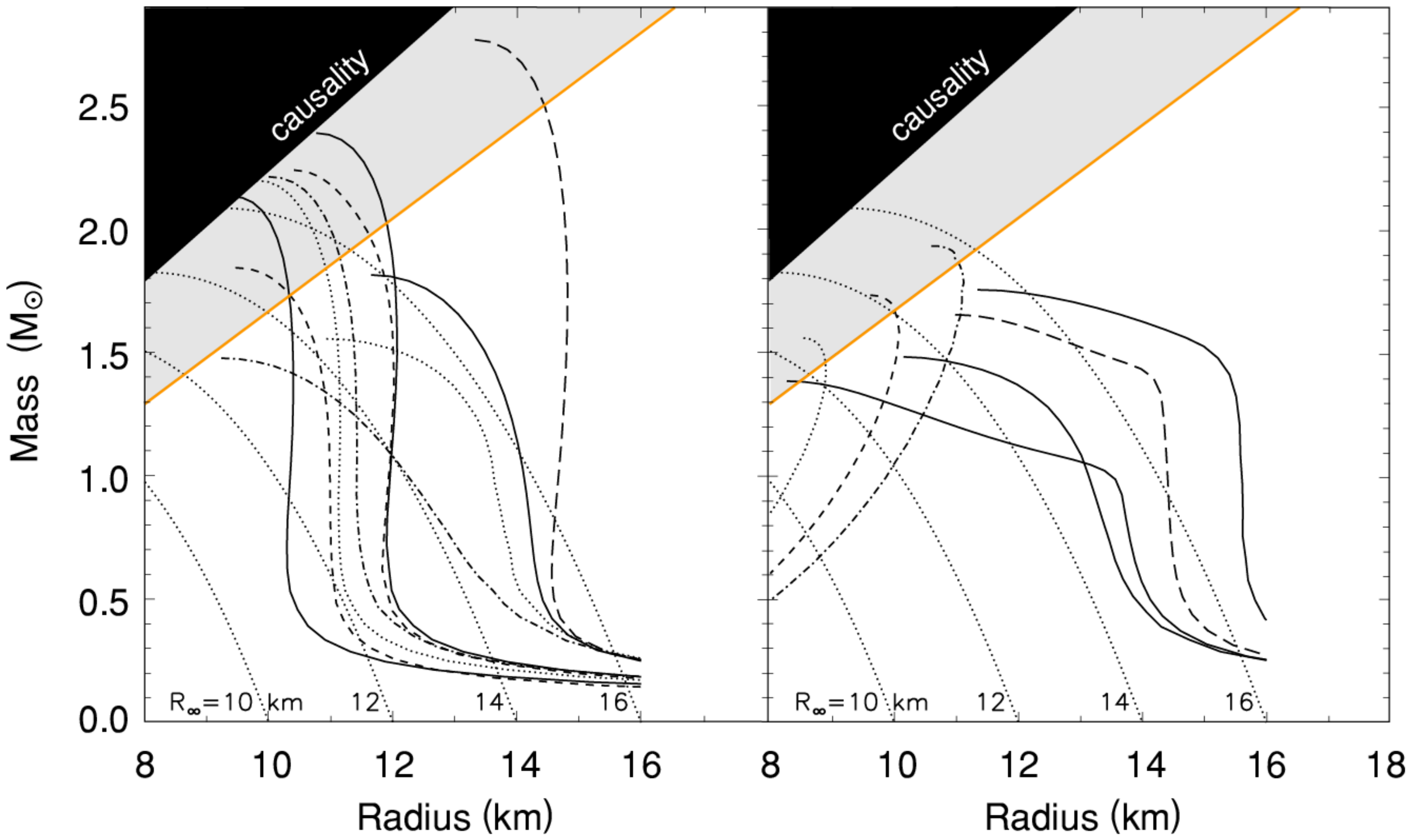
effects considered:

- general relativistic light bending,
- frame dragging

$$\Rightarrow \frac{GM}{R c^2} = \frac{R_S}{2 R} \leq 0.24$$

$$\Rightarrow R > 8.7 \text{ km for } M = 1.4 M_\odot$$

Limit from Burst Oscillations

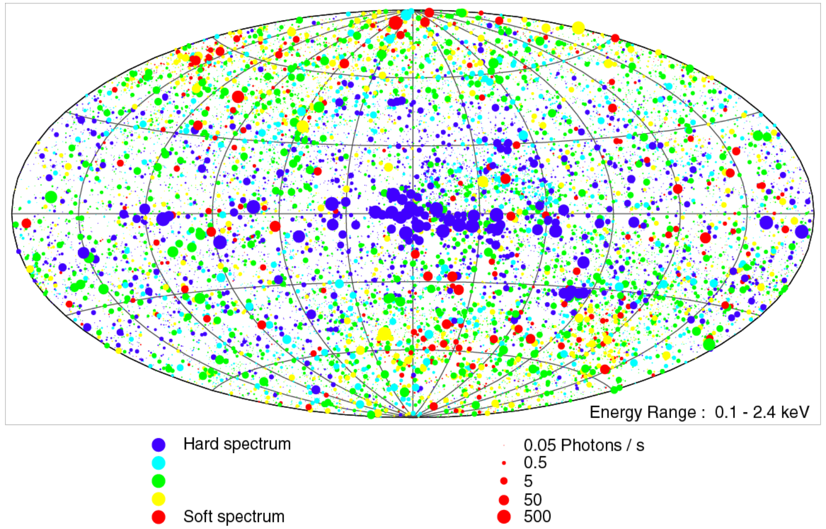


Light curve of coherent burst oscillations of XTE J1814-338 : R / R_s > 2.1 (Bhattarcharyya et al. 2005)

Discovery of 7 neutron stars showing purely thermal emission - XTINS or “The Magnificent Seven”

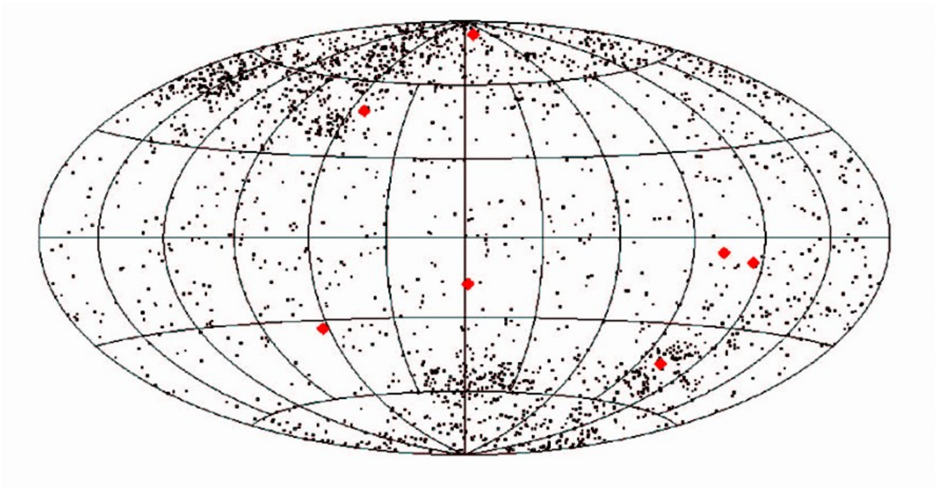
ROSAT Bright Survey

(~ 20 000 Sources)



Soft X–ray spectrum + faint in optical

The „Magnificent Seven“



Hubble Space Telescope:
m = 25,7
Astrometric distance 120 pc

J. Trümper, 2019

I. Radii fromThermally emitting isolated neutron stars (XTINS)

Compilation by F. Haberl 2018

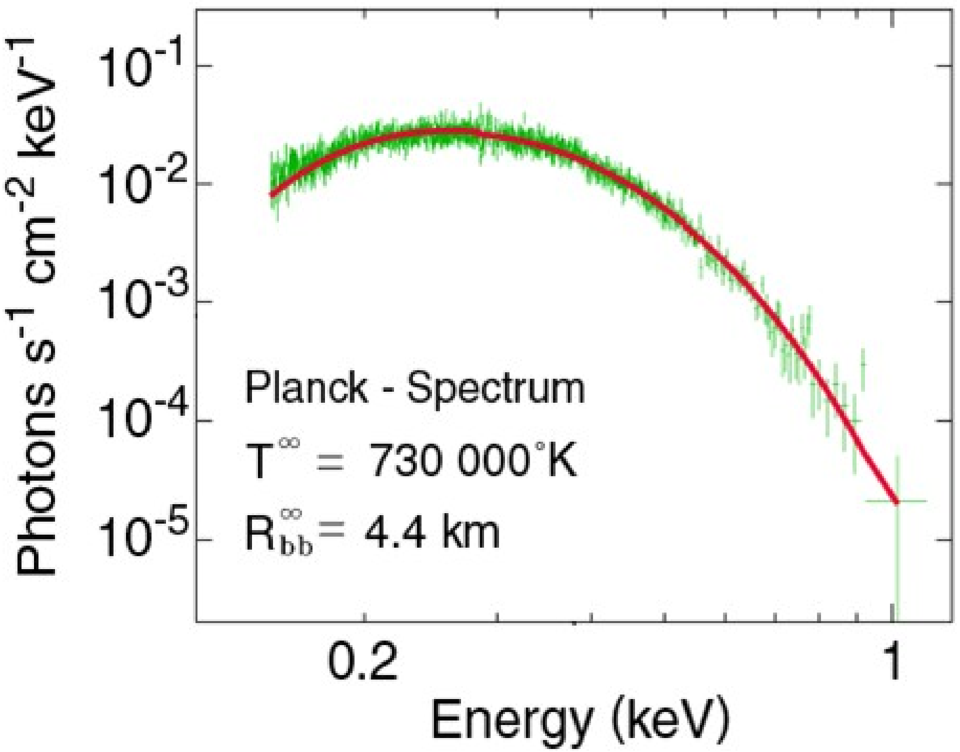
Object	kT_∞ (eV)	P (s)	p.f.[a] (%)	$\dot{P}$ (s s^{-1})	$B_{\rm dip}$ (10^{13} G)	τ (Myr)	$t_{\rm kin}$ (Myr)	m_B[b] (mag)	d[c] (pc)
RX J0420.0−5022	48	3.45	17	-2.8×10^{-14}	1.0	1.95	?	26.6	$\sim$345
RX J0720.4−3125	84–94	16.78	8–15	-1.40×10^{-13}	5.0	1.91	0.85	26.6	286^{+27}_{-23}
RX J0806.4−4123	95	11.37	6	-5.50×10^{-14}	2.5	3.24	?	$>$24	$\sim$250
RX J1308.6+2127	100	10.31	18	-1.12×10^{-13}	3.5	1.45	0.55/0.90/1.38	28.4	?
RX J1605.3+3249	100	?	$<$2	?	?	?	0.45	27.2	$\sim$390
RX J1856.5−3754	61	7.06	1	-2.97×10^{-14}	1.5	3.80	0.42–0.46	25.2	120^{+11}_{-15} *)
RX J2143.0+0654	104	9.43	4	-4.00×10^{-14}	1.9	3.72	?	$>$26	$\sim$430

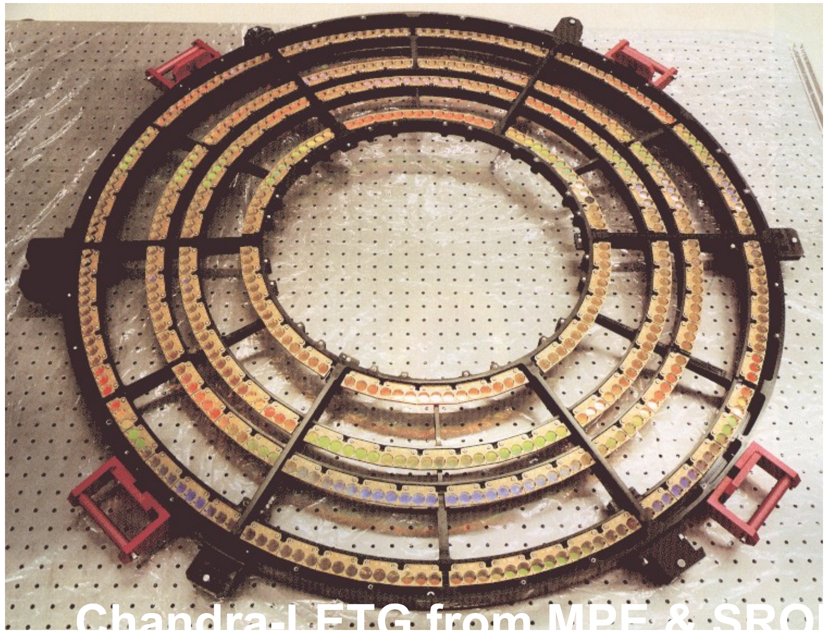
***) currently the best distance to RX J1856-3754 is 120^{+8}_{-10} pc**

(combining observations of two HST instruments)

High Resolution CHANDRA-LETG X-ray spectrum of RX J1856-3754

Burwitz, Trümper, Haberl & Zavlin, 2004





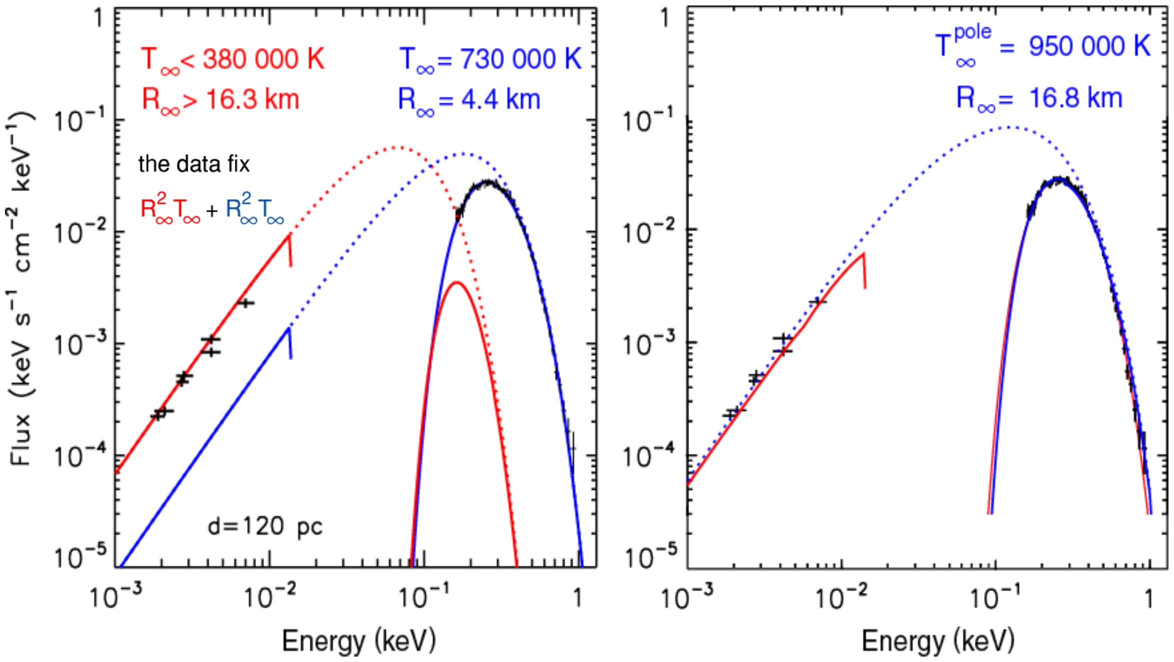
Energy resolution 2 %

An excellent blackbody with a very small radius!

A quark star?

However….

The optical VLT/HST - spectrum of RX J1856-3754 is a blackbody (Rayleigh-Jeans - type) as well (Walter et al. 2001, 2002)



Trümper, Burwitz, Haberl & Zavlin 2004,
based on Chandra LETG data

Two temperature model:
- **hot polar cap**
- **larger cooler surface**

⇒ R_∞ 16.9 km × d/120pc

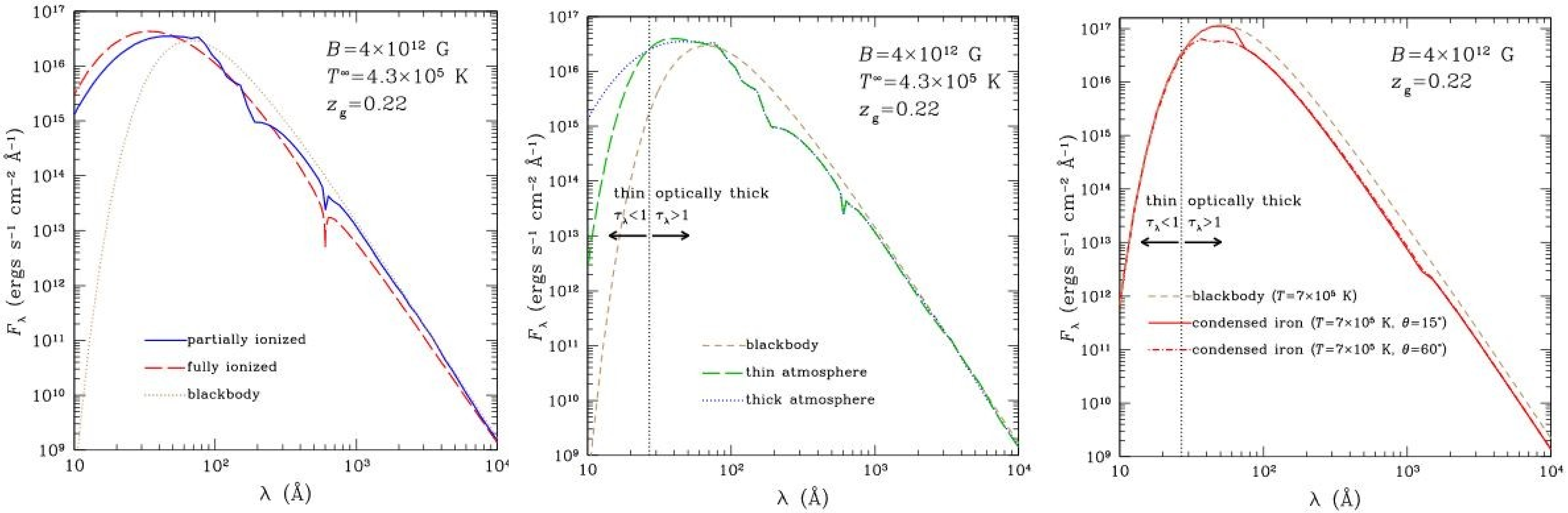
Temperature distribution:

$$T = T_{pole} \left(\frac{1}{1 + (\theta/\theta_0)^2} \right)$$

⇒ R_∞ 16.8 km × d/120pc σ(d) ~ 10%

Magnetic hydrogen atmosphere models for RX J1856-3754 (Ho et al. 2007)

assuming an isothermal atmosphere and a constant magnetic field over the whole surface



Result: $R_\infty \sim$ 14 km → R ~ 10 km for M = 1.4 M_o , viz. smaller than the double blackbody radius

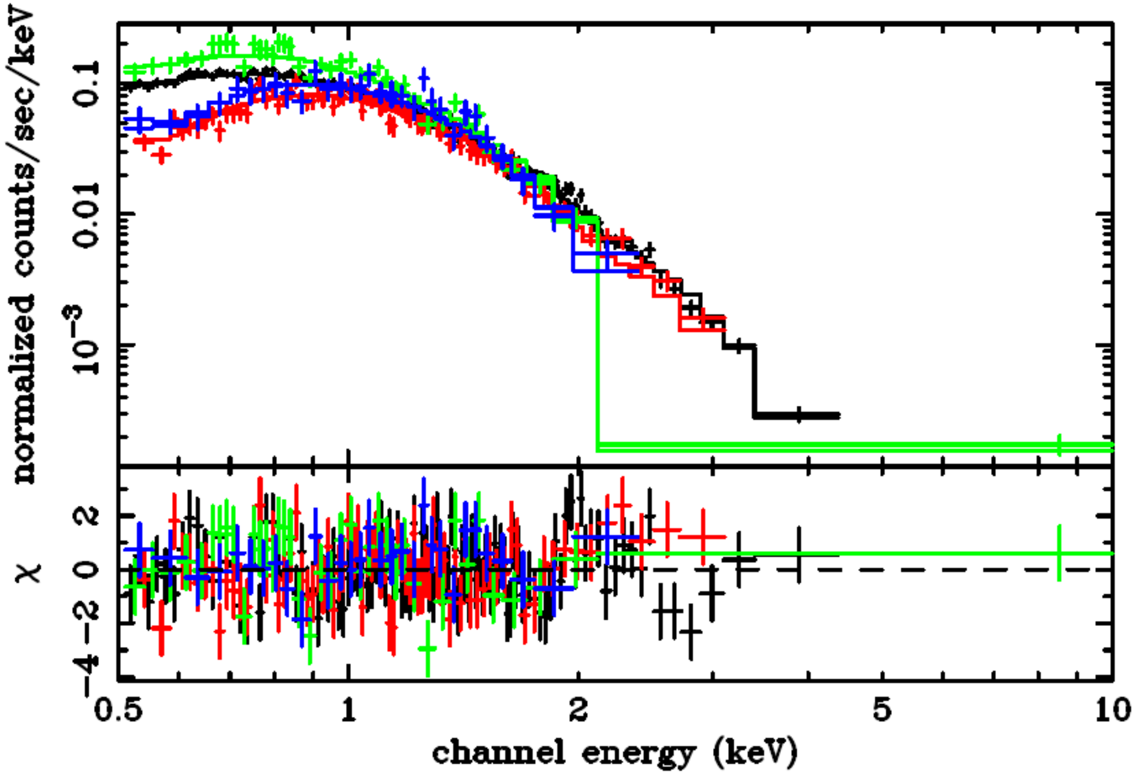
Comment: The above assumptions are unrealistic.
In 2007 the pulsations (7.1 s) were discovered, confirming a hot spot model.
The BB – model is unrealistic as well; a thin atmosphere and a strong magnetic dipole field should be included...

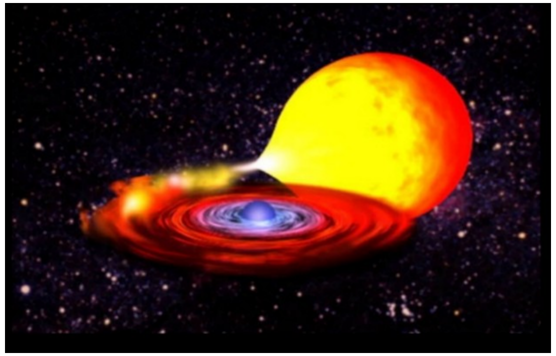
Such a realistic model is still pending – 12 years later

II. Radii of low mass X-ray binaries in quiescence (qLMXB)

The neutron star X7 in the globular cluster 47 Tuc (Heinke et al. 2006)

The distance of the globular cluster 47 Tuc is well known: 4.85 +/- 0.18 kpc





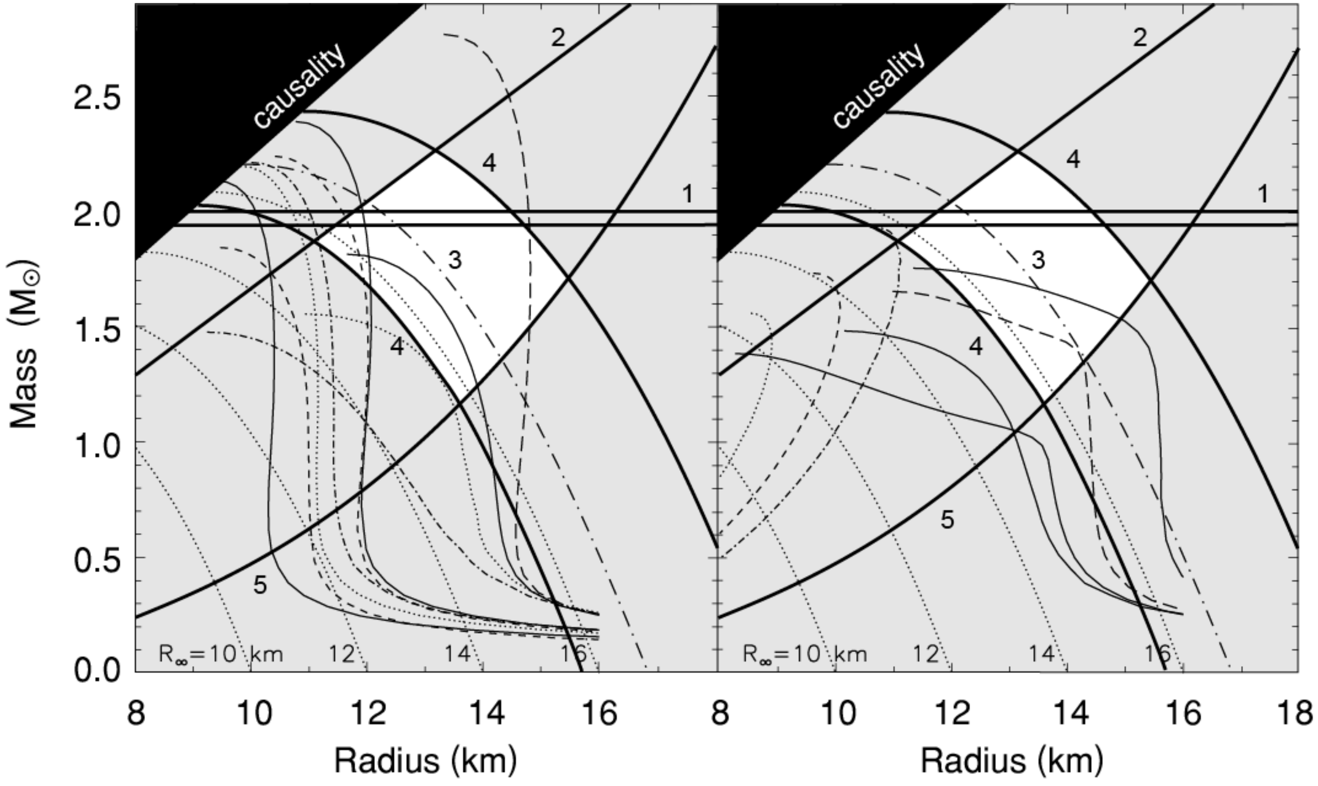
qLXMB
temporalily no accretion disk
A naked neutron star in orbit

Chandra spectra fitted by a standard nonmagnetic hydrogen model (McClintock et al. 2004)

For a mass of 1.4 $M_{\odot}$ the radius is R = 14.5 +1.8/-1.6 km

Caveat: No optical spectrum of the neutron star available because that is dominated by the light of the bright companion star (thus R is a lower limit)

Summarizing all early (< 2007) constraints:



1 Largest mass J1614 - 2230
(Demorest et al. 2010)

2 Maximum gravity XTE 1814 – 338
(Bhattacharyya et al. 2005)

3 Minimum radius RXJ1856 - 3754
(Trümper et al. 2004)

4 Radius, 90% confidence limits LMXB 47 Tuc
(Heinke et al. 2006)

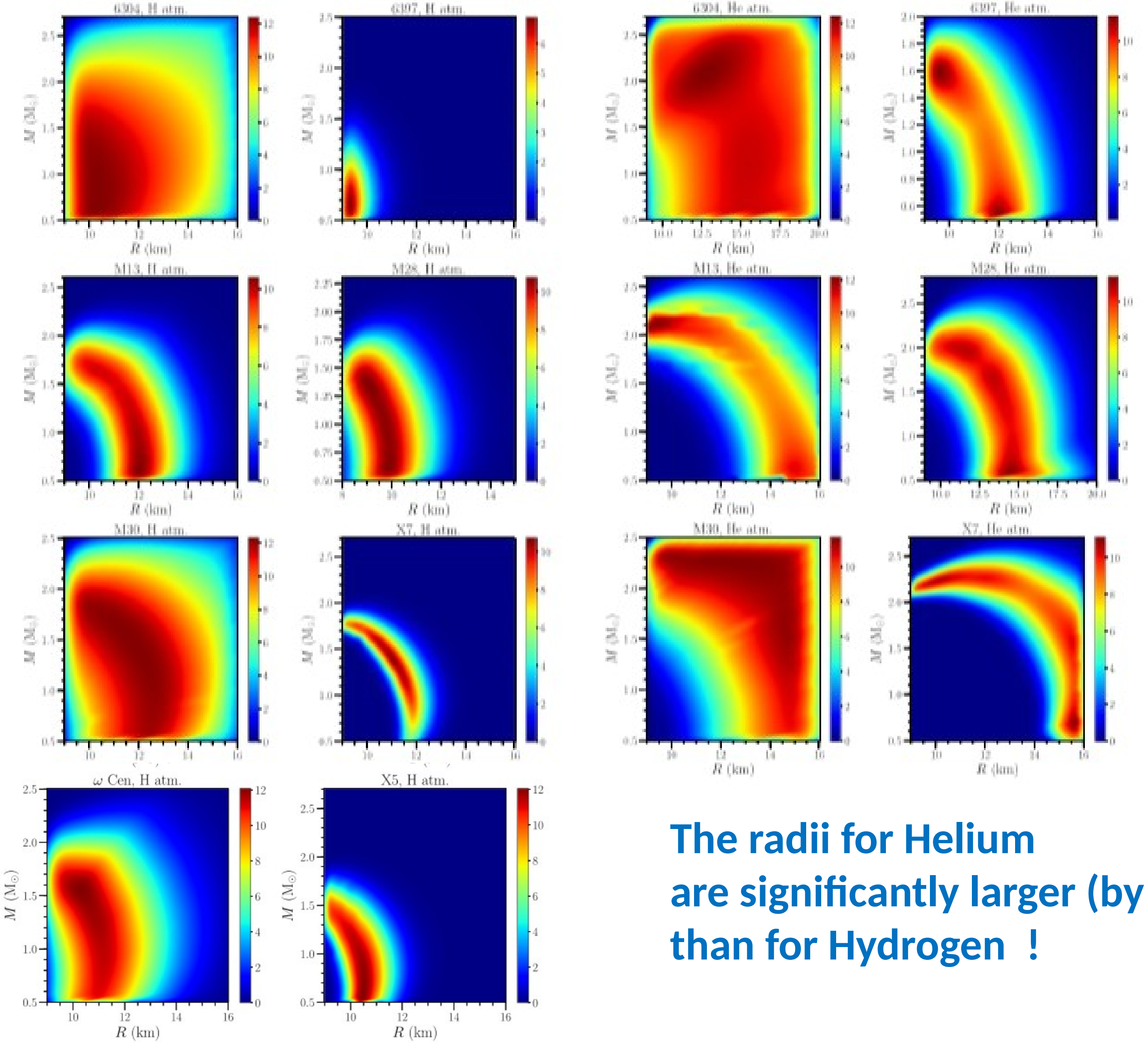
5 Largest spin frequency J1748 – 2446
(Hessels et al. 2006)

The constraints favour a stiff equation of state

Recent work on qLMXBs in globular clusters

(Steiner, Heinke, Bogdanov, Ho et al. 2018)

8 qLMXBs Hydrogen Atmospheres assumed



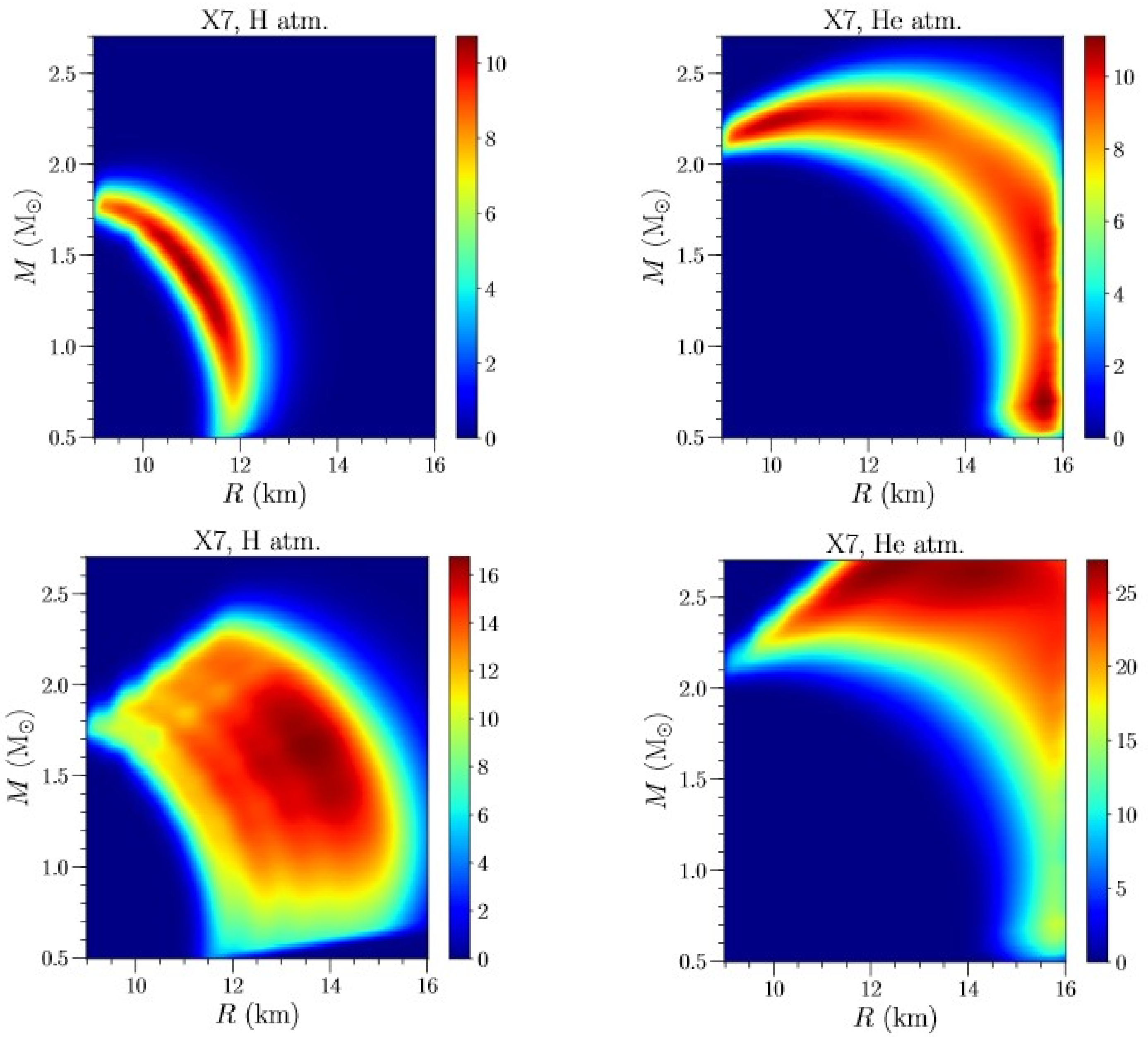
6 qLMXBs Helium Atmospheres assumed

The radii for Helium are significantly larger (by ~ 4km) than for Hydrogen !

Hydrogen **Atmosphere** **Helium**

Neutron star X7 in the globular cluster 47 Tuc

(the brightest one)



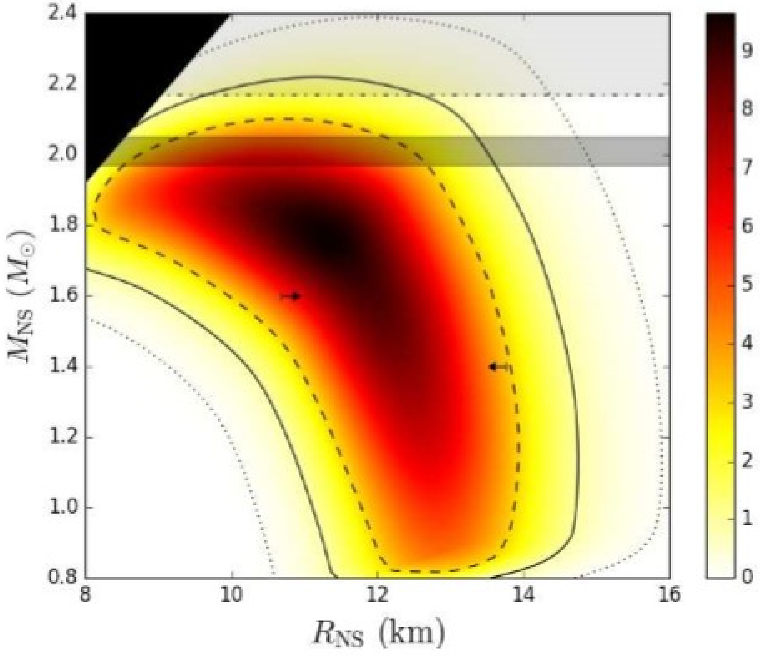
Isotropic radiation

Assuming a hot spot is present

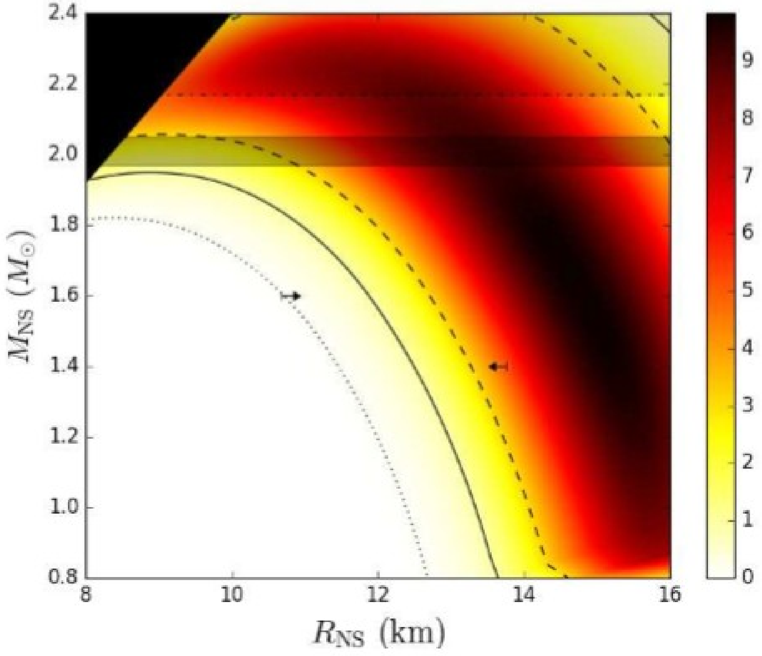
Radius of the quiescent neutron star in the globular cluster M13

(Shaw, Heinke, Steiner, Ho et al. 2018)

Hydrogen



Helium

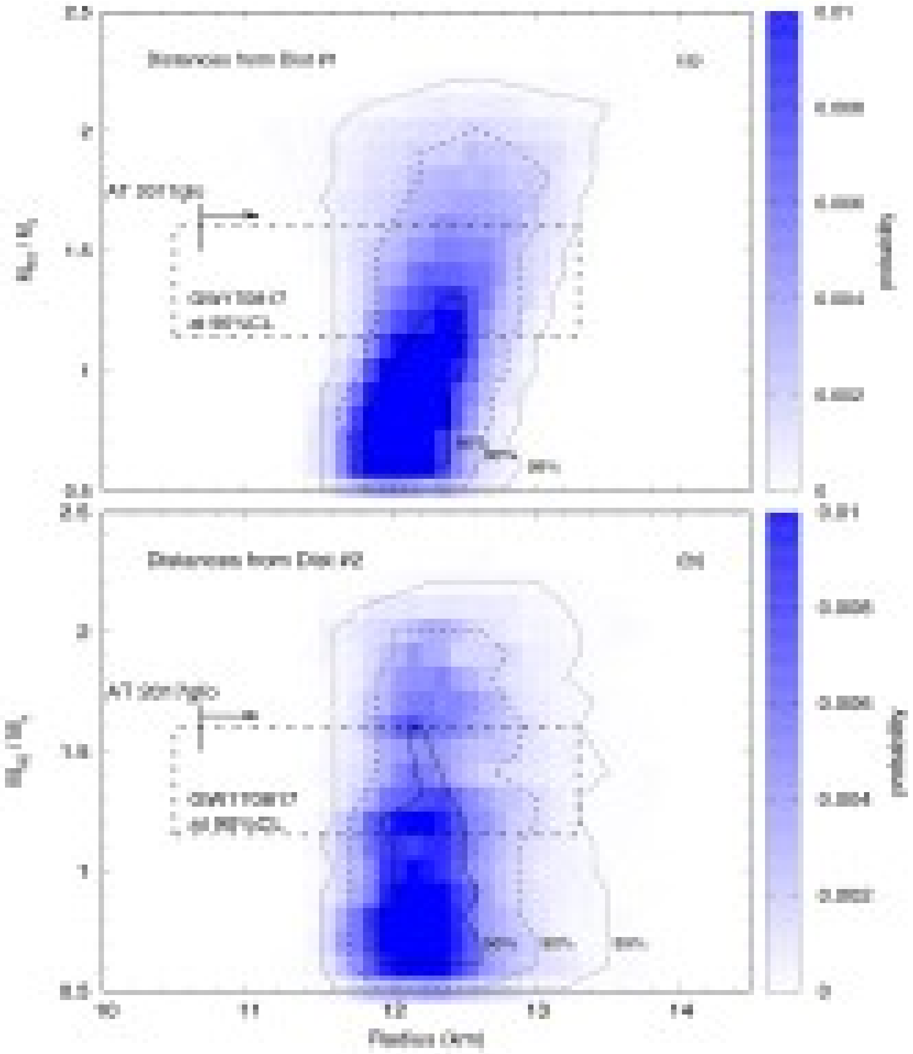


„To verify the nature of the atmosphere of the neutron star spectroscopy of the optical counterpart is required, which has not been discovered“

JWST(NASA) and ELT (ESO) will help!

M,R probability distribution for seven qMXLBs (Baillot D'Etivaux et al. 2019)

It is generally accepted that the atmosphere of a qLMXB is composed of pure hydrogen, because matter accreted before quiescence will contain some hydrogen and that will float on top of the atmosphere



III. Radii from X-ray bursts

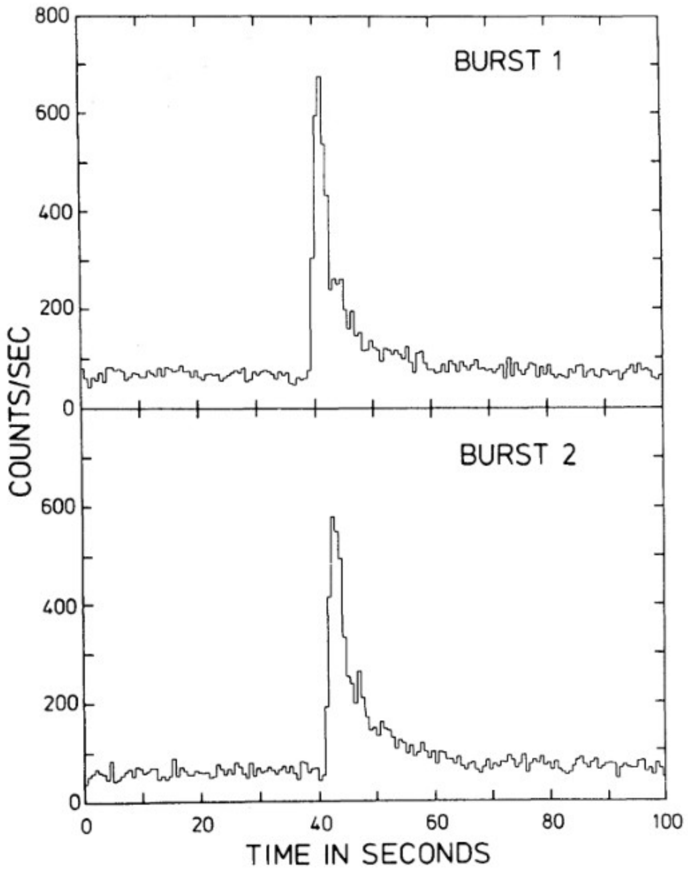
X-ray bursts were discovered in 1976 in the globular cluster NGC 6624 with the ANS satellite

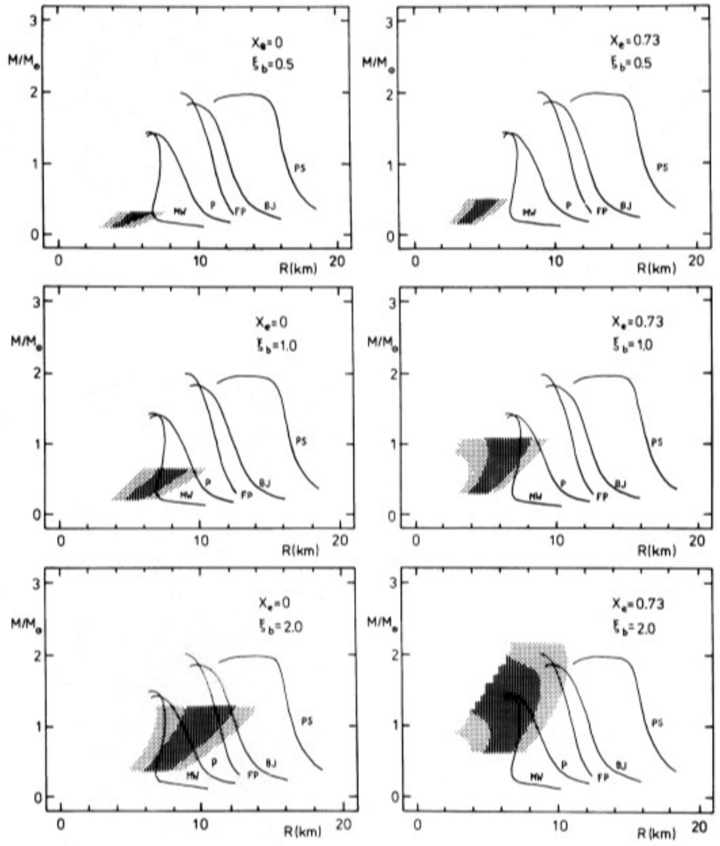
(Grindlay et al. 1976)

In the 1980's a lot of bursts were harvested with EXOSAT, e.g. from

4U 1746 -37 in NGC 6441
2 bursts in 12 hours

BB spectra taken at maximum and low level
yield M and R/d

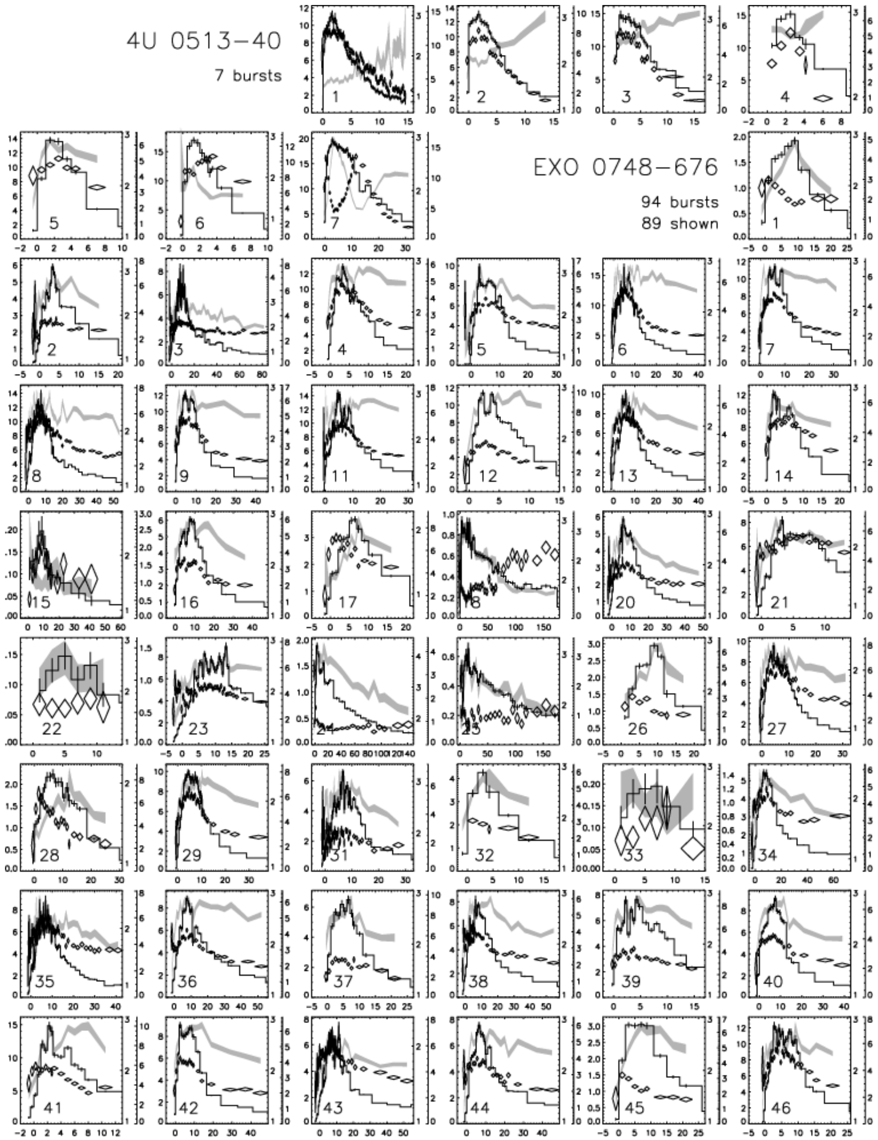




The early measurements yielded low values for R (< = 10 km)

Thermonuclear X-ray bursts observed with the Rossi X-Ray Timing Explorer

Galloway et al. 2008



A sample of 1187 bursts from 48 accreting NSs show a variety of burst shapes and amplitudes.

The typical scatter in amplitude and shape is >/~ 50 %.

35 sources exhibiting „radius expansion bursts“ show constant peak fluxes within +- 13%

Such bursts have been used to measure M, R using the toughdown method

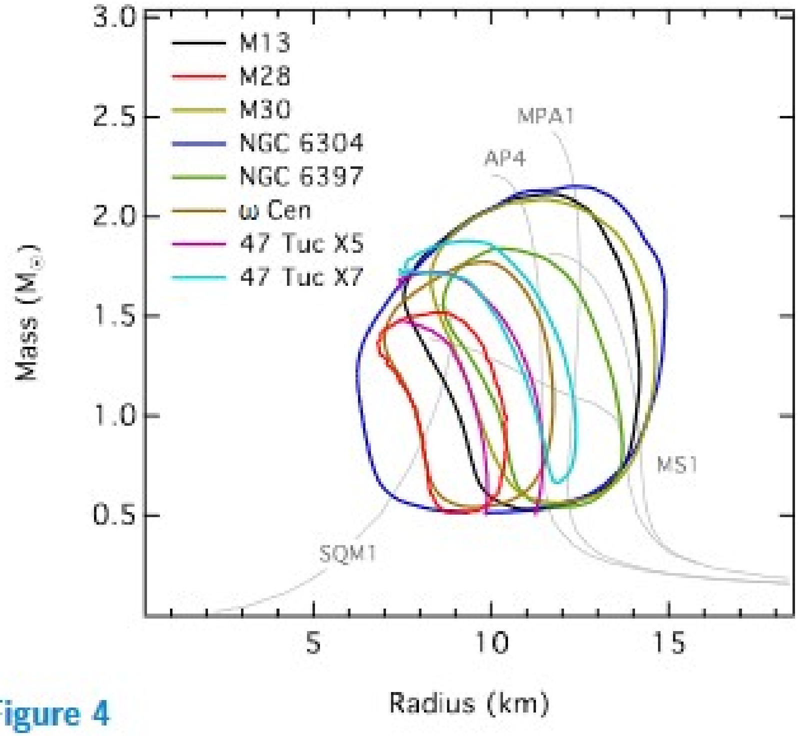
Many papers – wide dispersion of radii

J. Trümper, 2019

Masses, Radii of neutron stars in low mass X-ray binaries

Özel and Freire 2016)

8 qLMXBs in globular clusters



6 X-ray burster in globular clusters

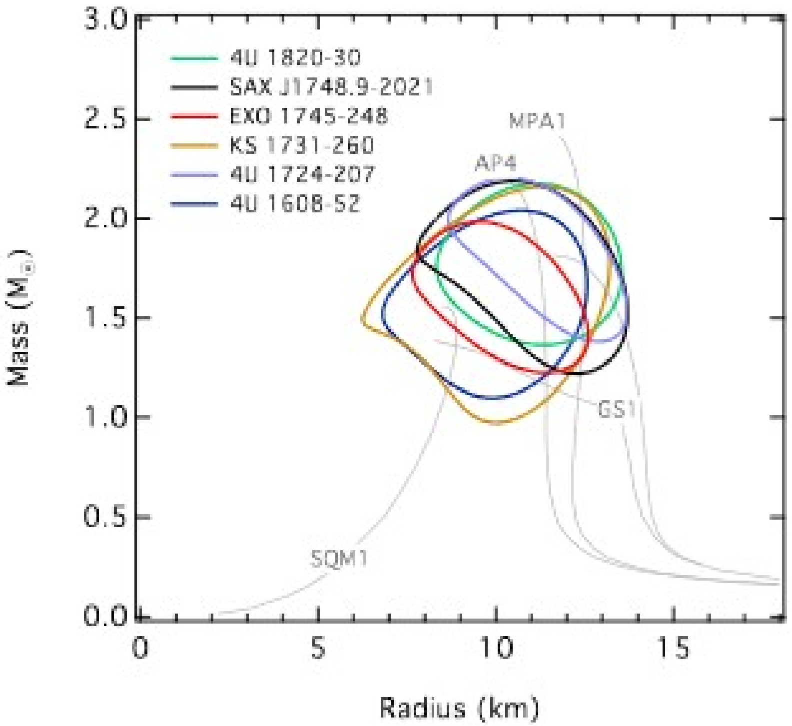


Figure 4

Hydrogen atmospheres are assumed except for the qLMXB in NGC 6397

Hydrogen atmospheres. Helium would yield radii larger by 3 – 5 km

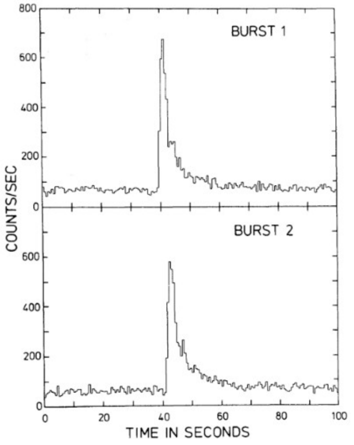
The modeling burst data using the touchdown method is quite complicated
- a rapidly spinning neutron star and a rapidly rotating disk

1. The exploding matter is freshly accreted material from the low mass companion having an unknown composition

2. The accreted material settles in two rings at high latitudes, despite the
- succeeding spreading ist efficient accumulation occurs in these zones
- (Inogamov & Sunyaev 1999)

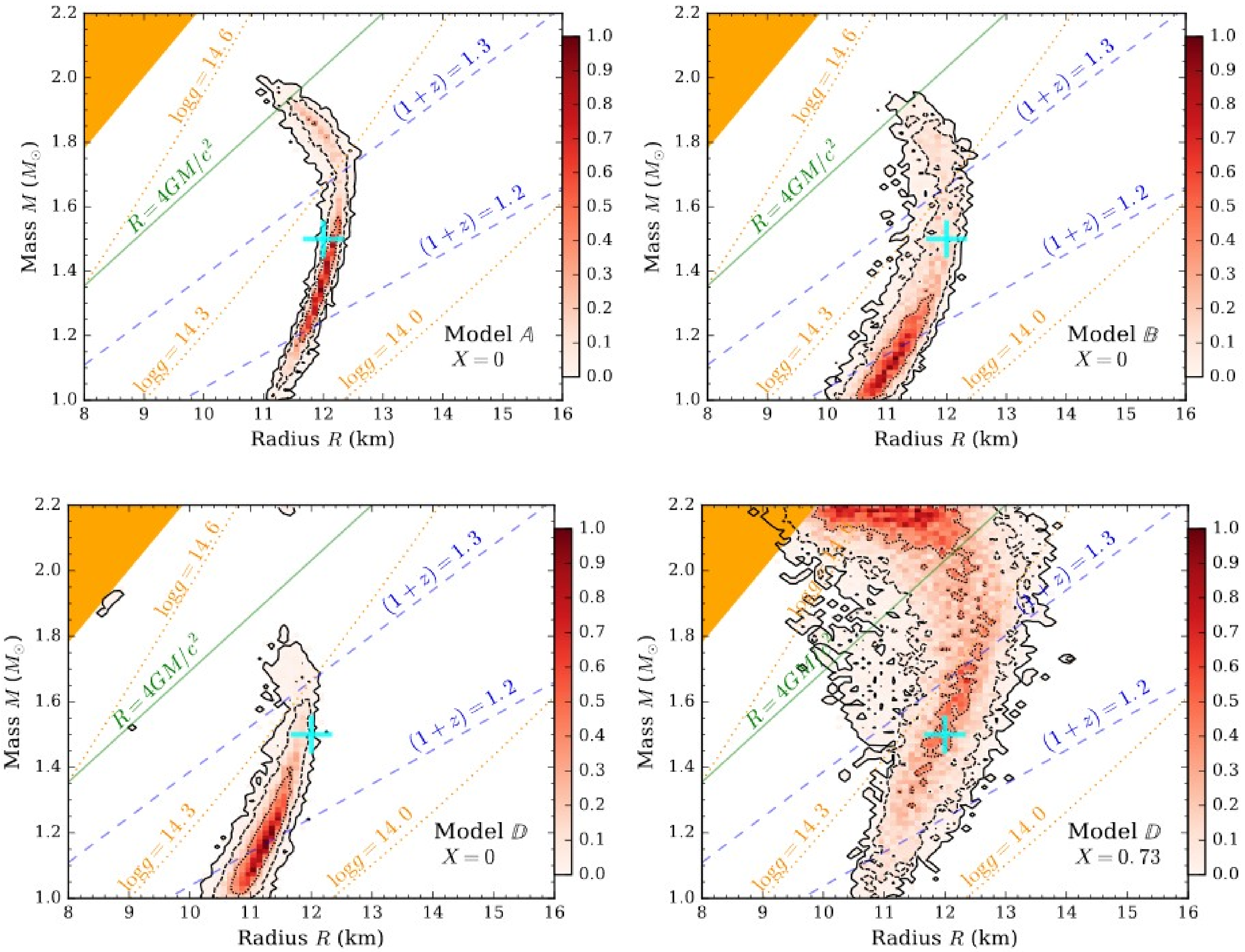
3. The conditions favourable for thermonuclear ignition will occur in these zones –
- double bursts, triple bursts etc. The burst emission may be anisotropic
- (Grebenev 2019)

- An alternative, more gentle method
- is to use cooling tail spectra
- (e.g. Suleimonov et al. 2011)



M,R constraints from atmospheric models using X-ray burst cooling tail spectra

(Nattilä, Miller et al. 2017)



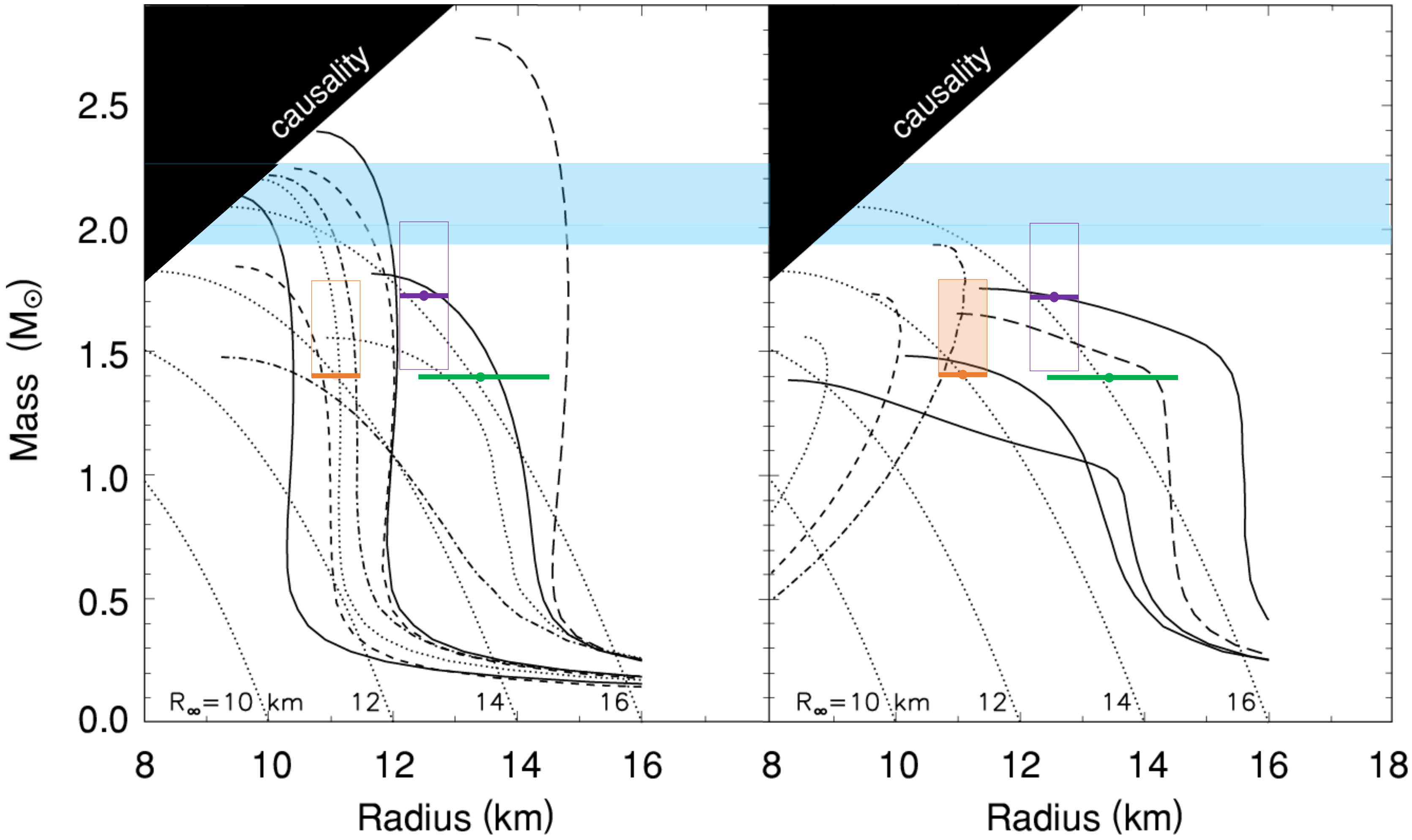
4U 1702-429

Result:
Hydrogen mass fraction X < 0.09

R = 12.4 +/- 0.4 km

M is ill constrained!

Summary of constraints from XTIN RX J1856-3754 and LMXBs in globular clusters



Burwitz et al. 2003, Trümper et al. 2004 — RX J1856-3754

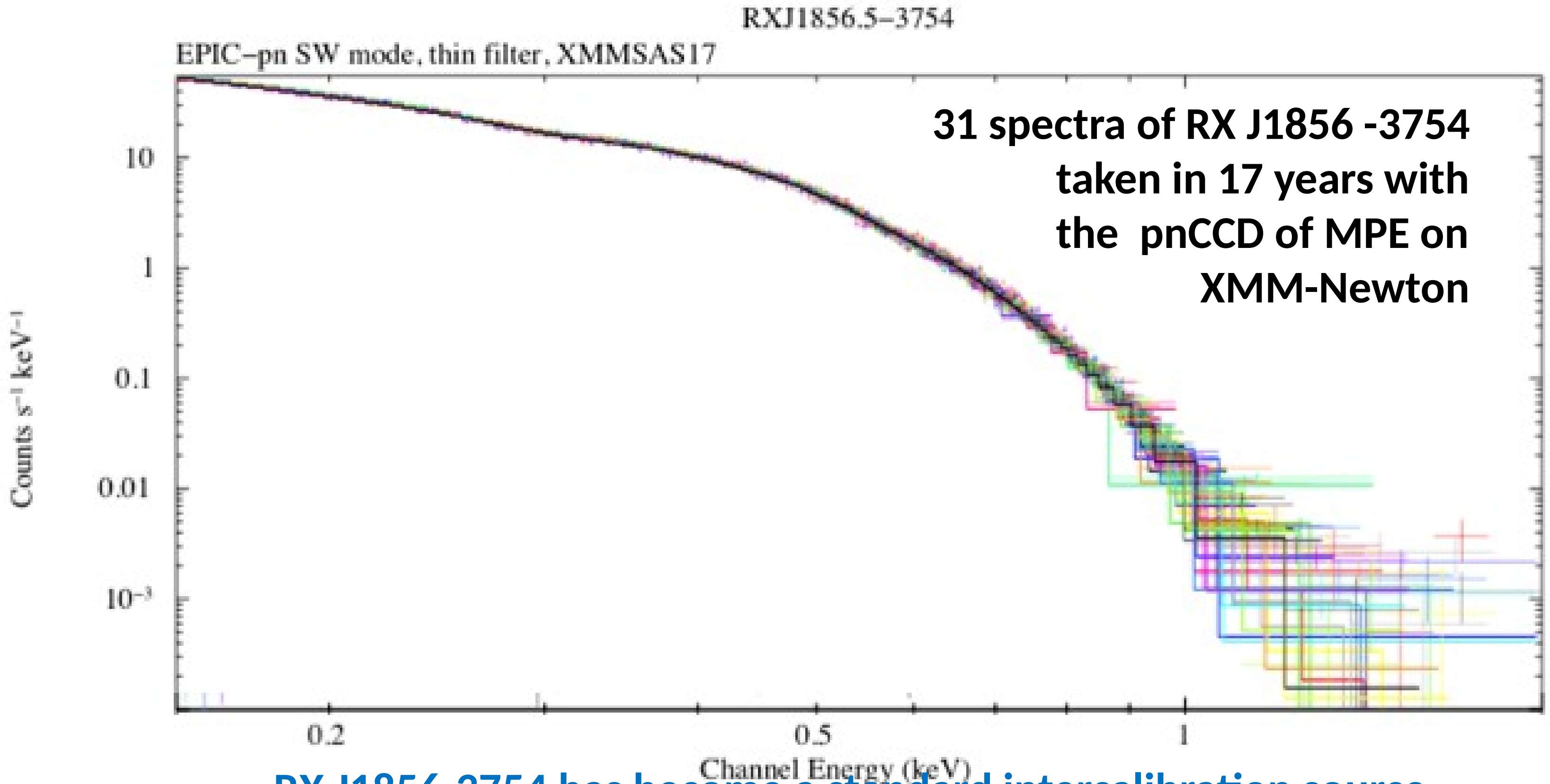
Nattilä et al. 2017, D'Etivaux 2019 — 5 bursts of 4U 1702 – 429 using cooling tails

Steiner et al. 2018 — 8 qLMXBs in globular clusters

J.Trumper 2019

Back to XTINs and their advantages

- Optical observations allow to see the cool parts of the surfaces (this is not possible for LMXBs)
- XTINs are slow rotators (1000 x slower than LMXBs)
- They have extremely stable spectra:

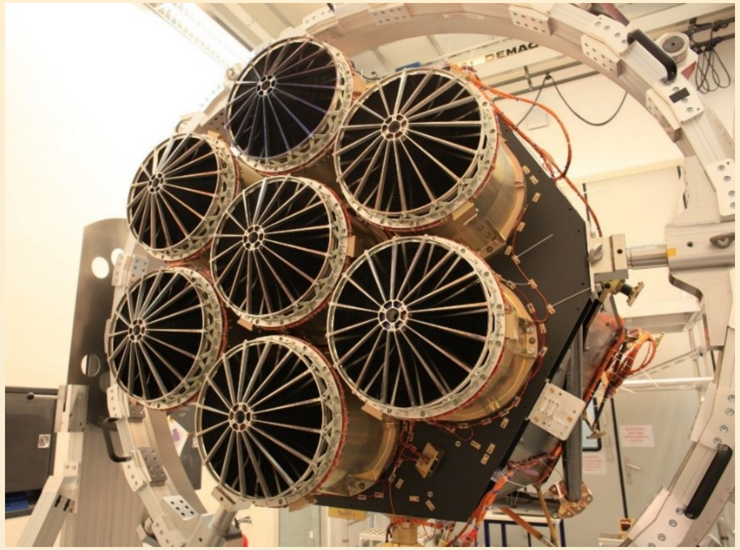


31 spectra of RX J1856 -3754 taken in 17 years with the pnCCD of MPE on XMM-Newton

RX J1856-3754 has become a standard intercalibration source for all current X-ray telescope missions

J. Trümper 2019

eROSITA (MPE) on SRG - First Light last Sunday!



The Future

4 years All-Sky Survey

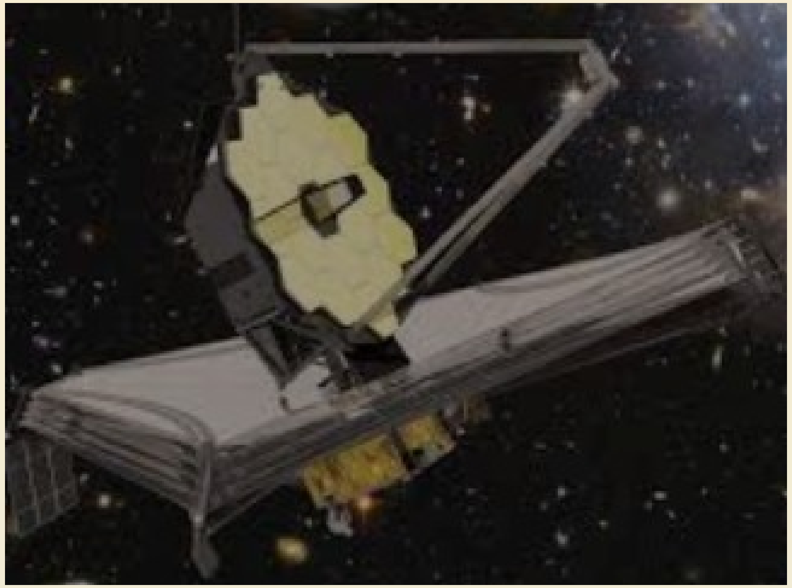
Sensitivity ~ 25 x ROSAT

A few million sources and

50-100 XTINs !

5-10 may be bright enough for detailed investigations

JWST (NASA) launch 2021



IR, optical, UV observations of XTINs:

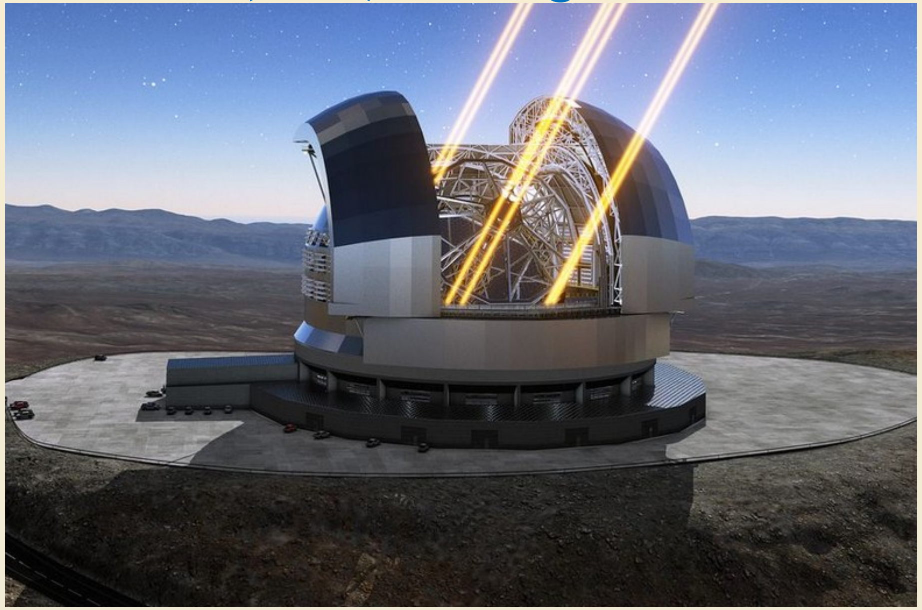
JWST: Distances!

Do they have residual disks?

LMXBs:

ELT& JWST: Atm. composition?

ELT (ESO) first light 2025



Summary

- Observations show that the neutron star stellar radius is larger than the canonical 10 km for $M = 1.4\ M_{o}$, probably between 10 – 14 km

The EOS of high density nuclear matter is probably stiff.

In the next 5-10 years observations in X-rays, visible light and IR and and improvements in model fitting will allow to sharpen conclusions.

Thank you!