湘潭大学 XIANGTAN UNIVERSITY

To measure the mass and radius of neutron star

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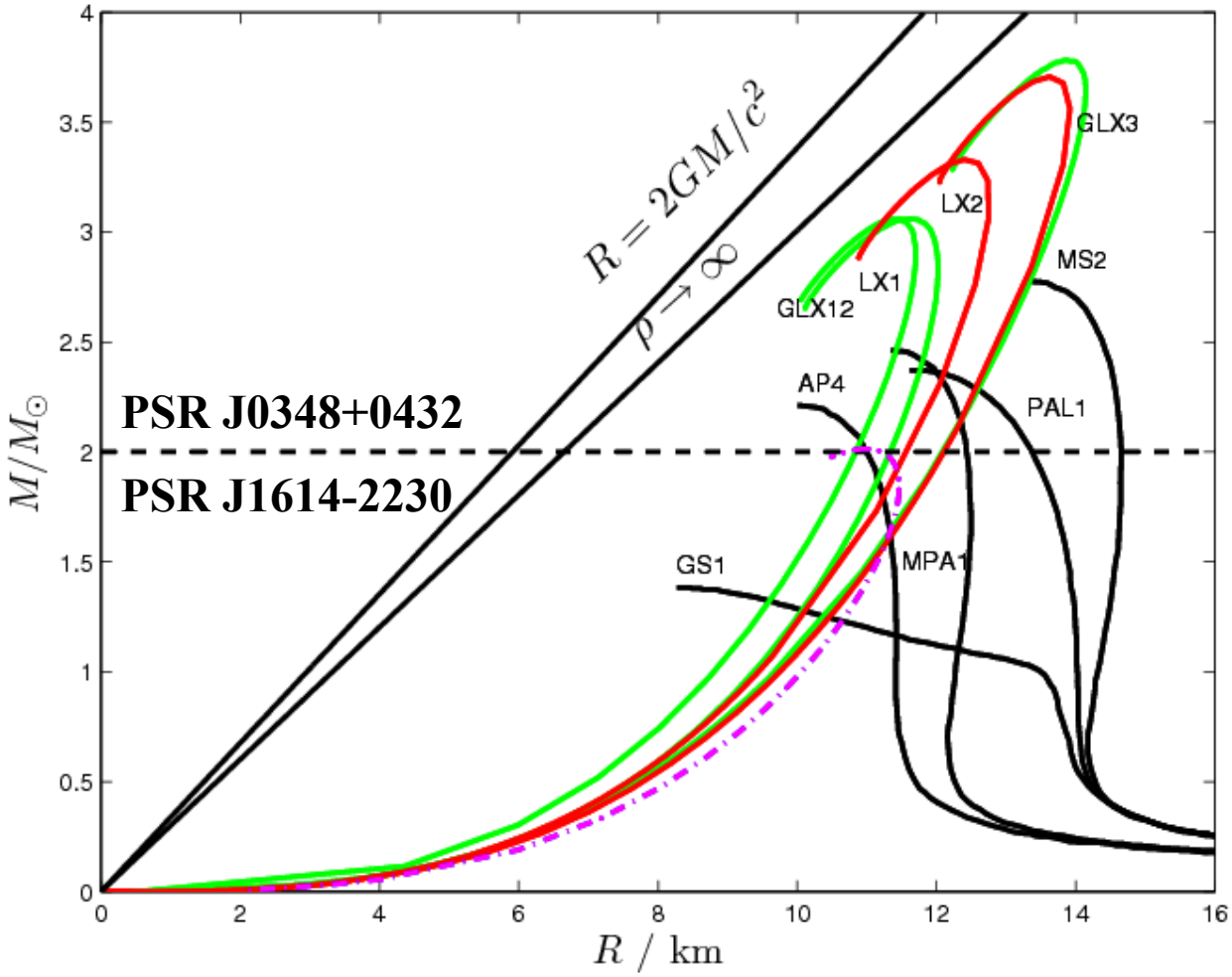
Equation of States



Gravity bound

Hadron star

Hybrid star

Hyperon Core

(R > 13 km)

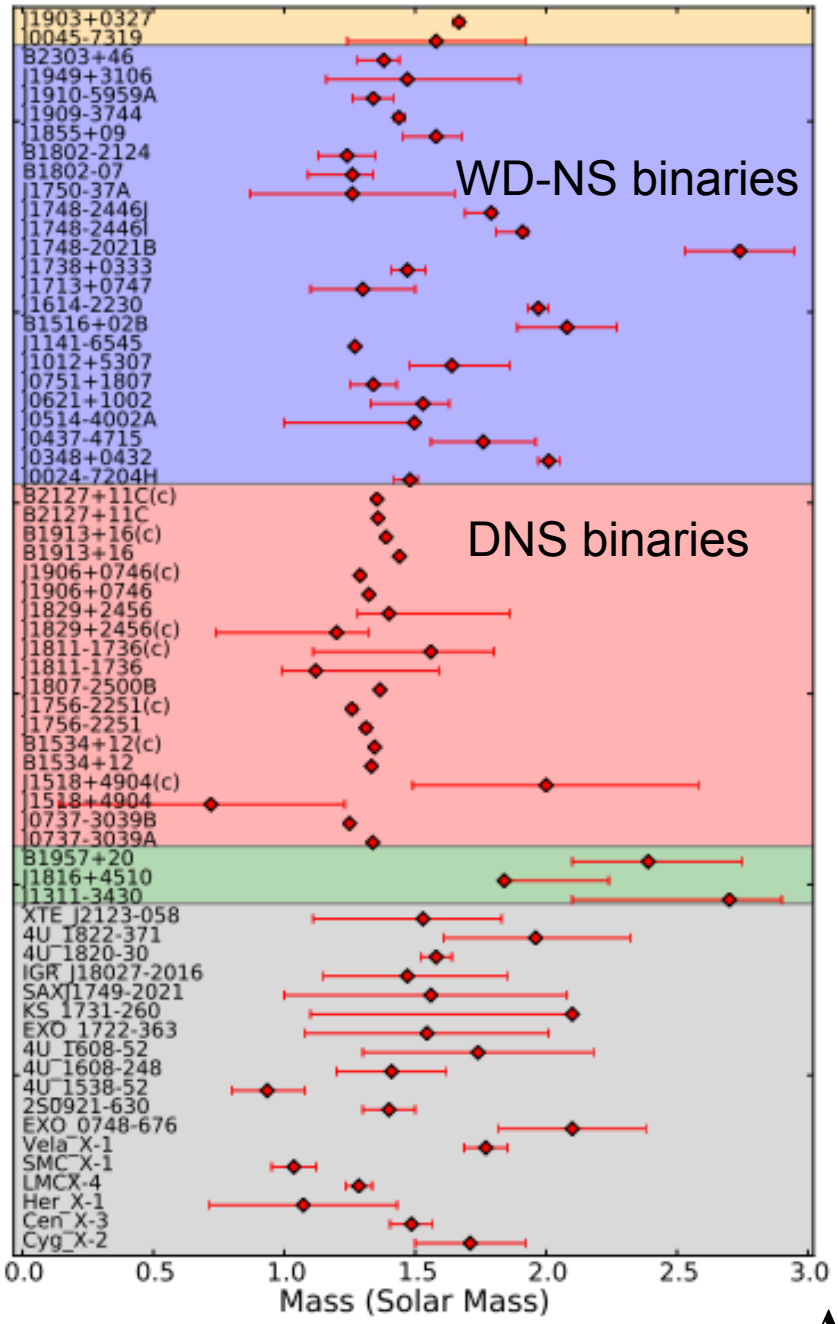
Fortin et al.(2014)

Self-bound on surface

Quark star

Quark-cluster star

Mass



Main sequence NS binaries

Black widow pulsar

X-ray/Optical binaries

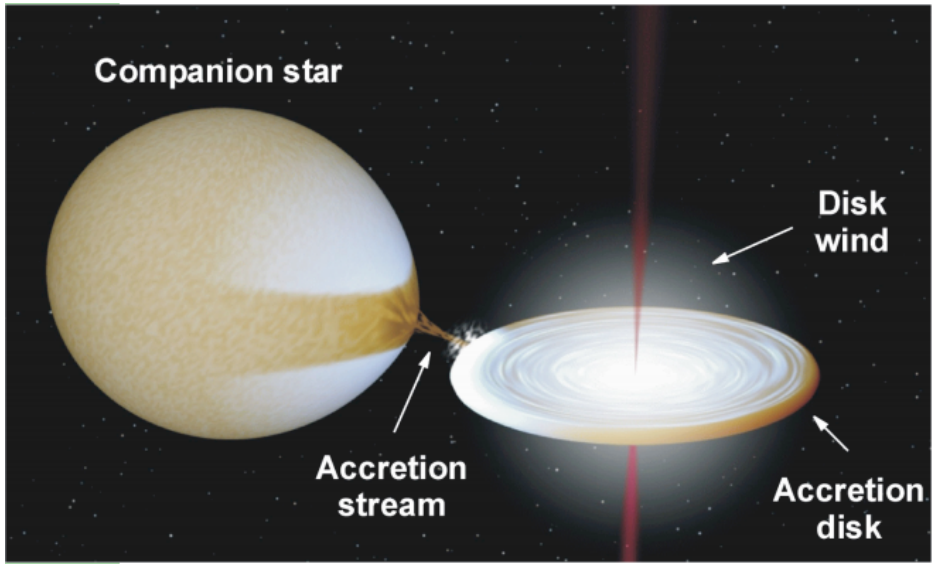
Anna Watts et al. (2014)

Outline

How to measure the mass and radius of NS?

- **Gravitational Redshift**
- **Pulse Profile Modeling**
- **X-ray bursts (4U 1746-37)**
- **qLMXBs thermal emission (Aql X-1)**

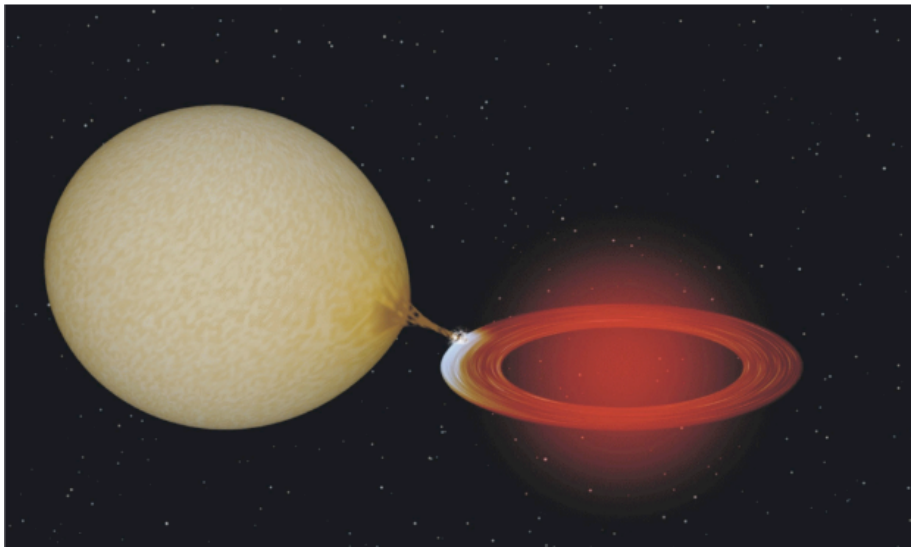
LMXB



Transient source

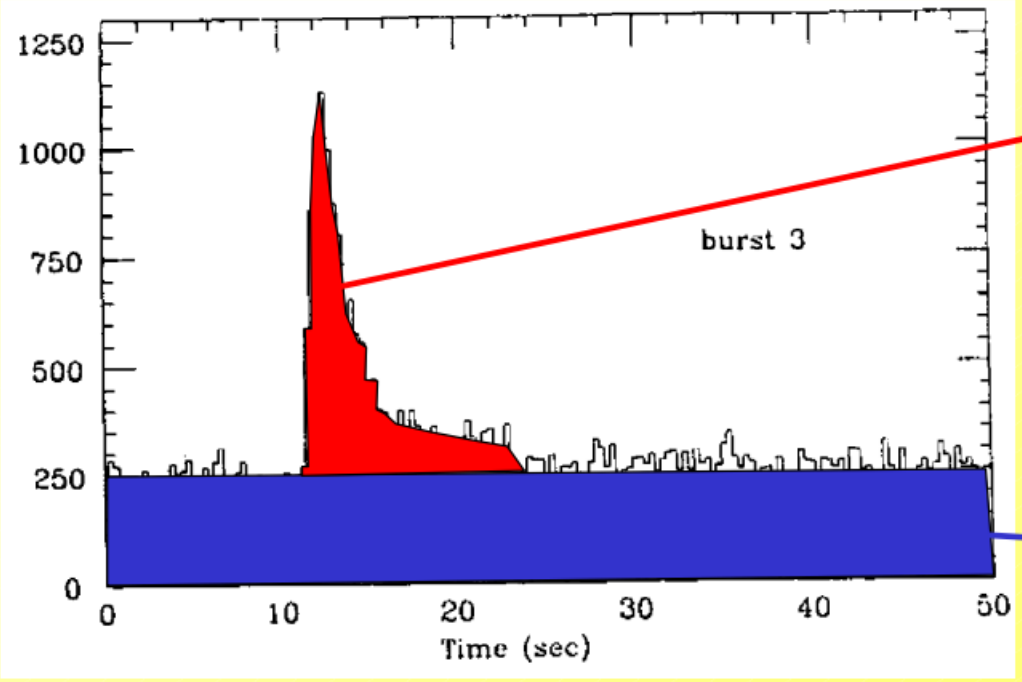
“Switched on”: Accretion induced outburst

“Switched off”: Quiescence



Type I X-ray burst in LMXB

- **H burning via: CNO cycle** **6.7 MeV/u**
- **He burning via:** $\alpha + \alpha + \alpha \rightarrow {}^{12}\mathrm{C}$ **0.6 MeV/u**

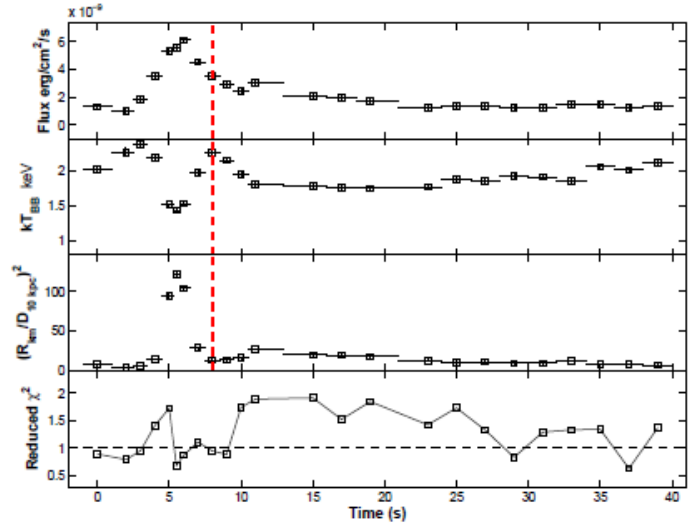


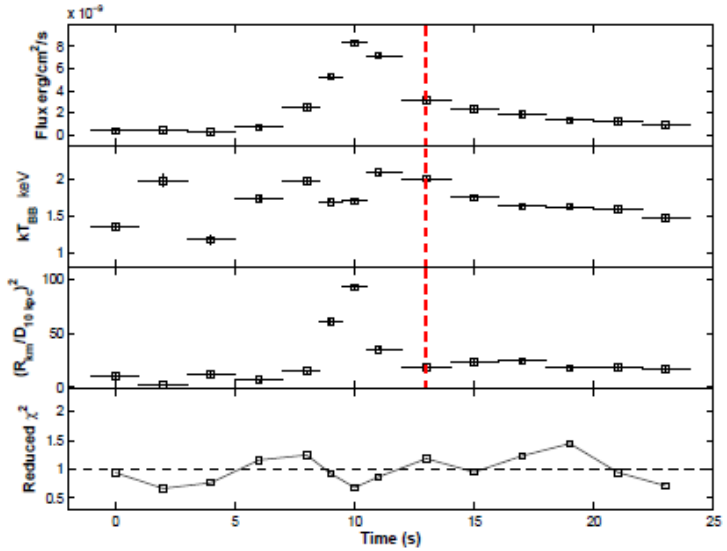
Burst energy (thermonuclear energy)

Persistent flux (gravitational energy)

PRE bursts in Dipping binary 4U 1746-37

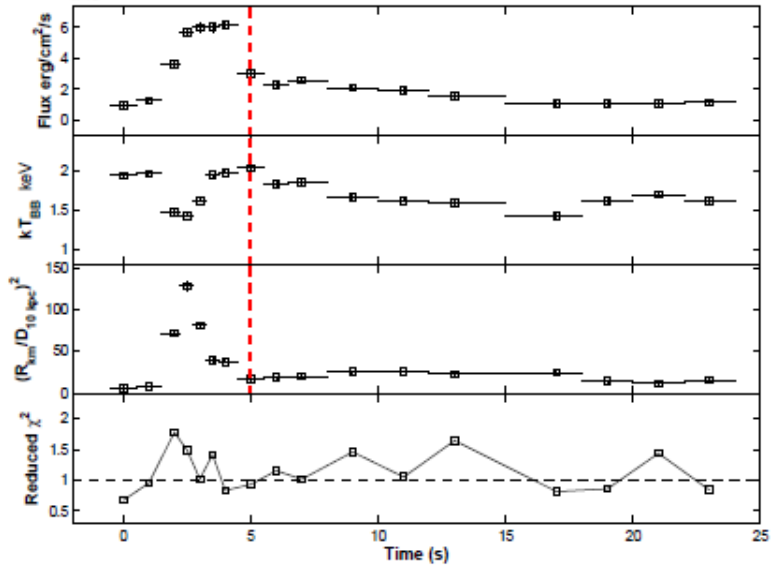
Photospheric Radius Expansion Burst





$$F_{\rm TD} = \frac{GMc}{k_{\rm es} D^2}\left(1 - \frac{2GM}{Rc^2}\right)^{1/2},$$

$$A = \frac{R^2}{D^2 f_{\rm c}^4}\left(1 - \frac{2GM}{Rc^2}\right)^{-1},$$

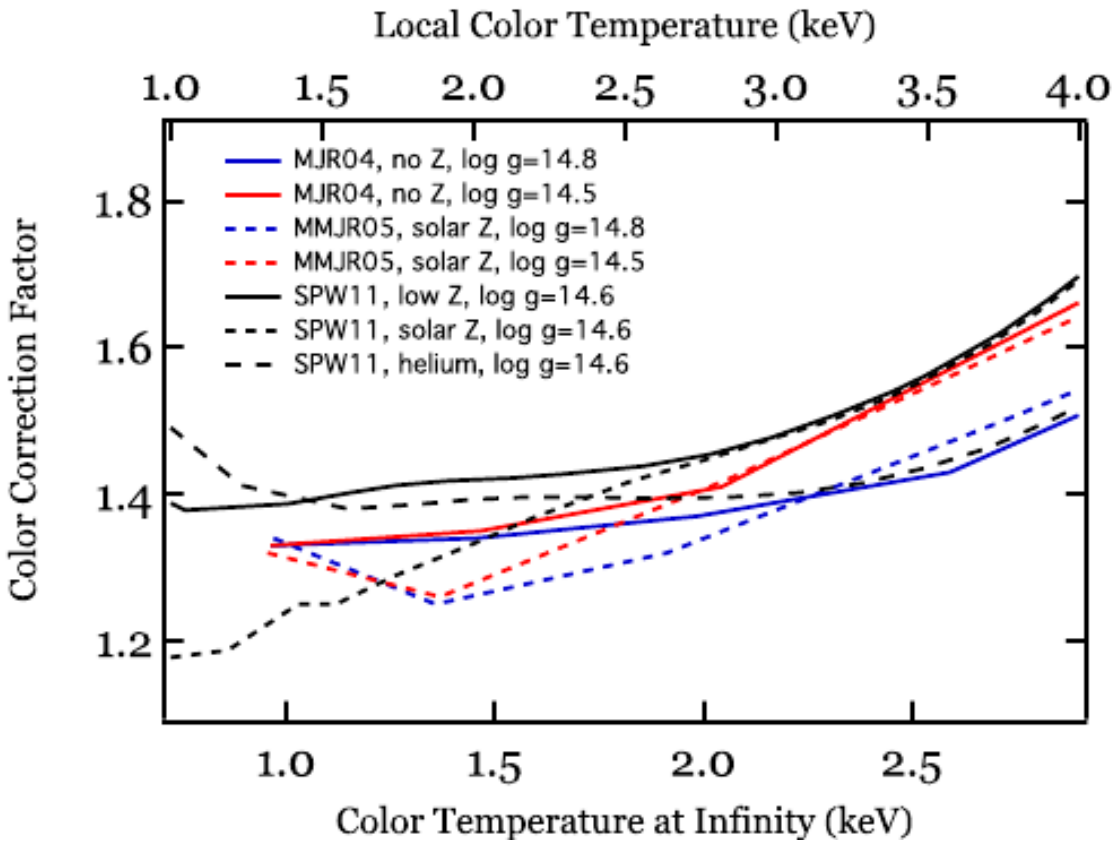


Low touchdown flux (luminosity) $11^{+0.9}_{-0.8}$ kpc

$(2.69 \pm 0.57) \times 10^{-9}$ erg/cm^{2}s

Low-mass NS?

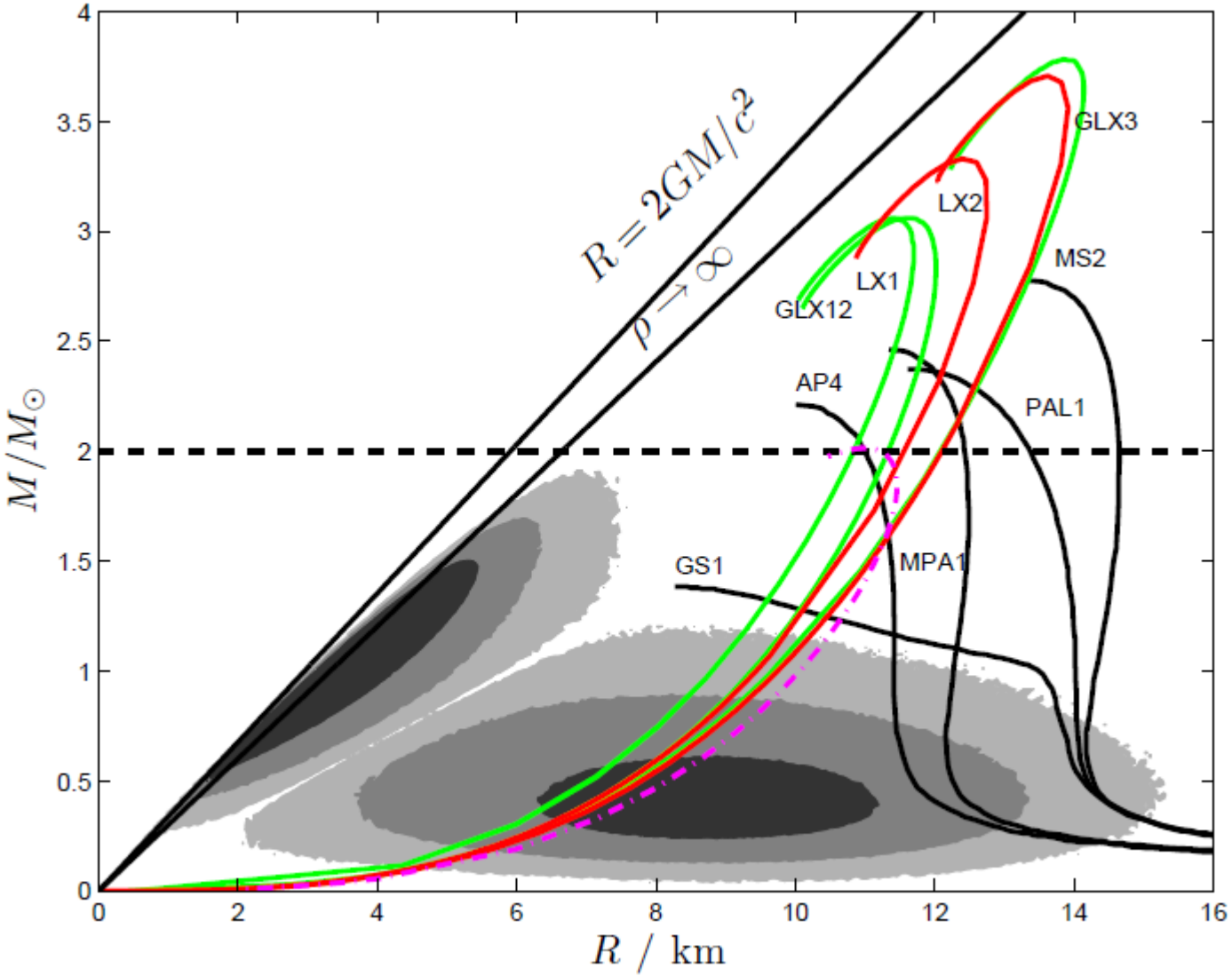
Color Correction Factor



$f_c \sim 1.3 - 1.4$

Güver et al. 2012a

M-R of NS in 4U 1746-37



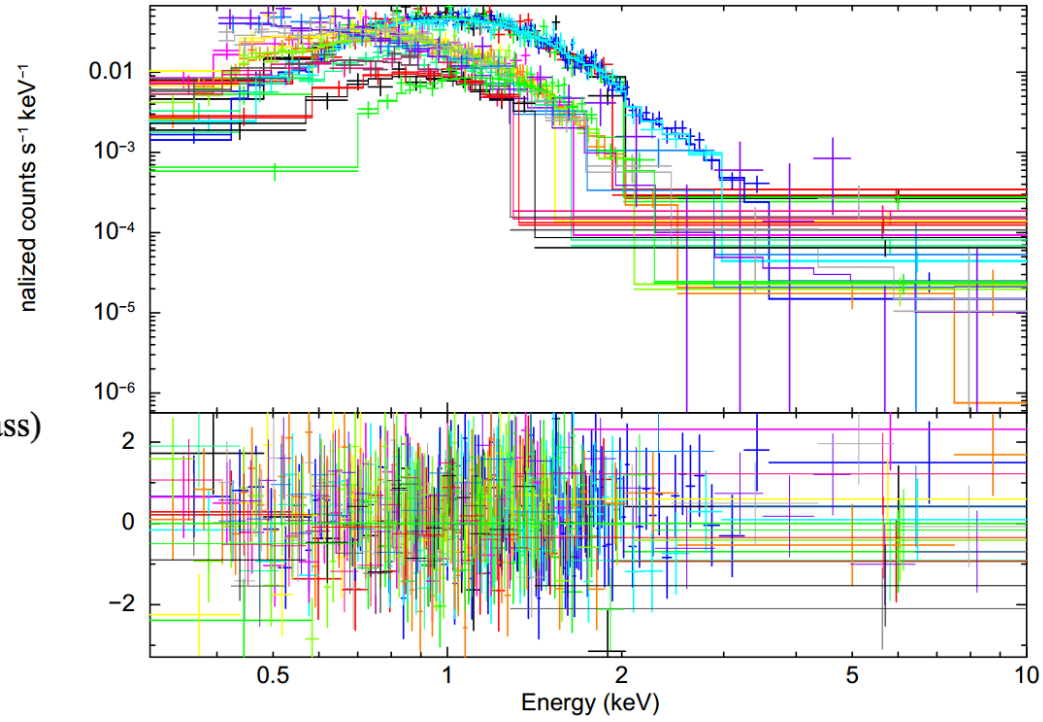
Z.S. Li et al. (2015), ApJ

qLMXBs in Globular Clusters

- *Chandra* & *XMM-Newton* (10^{32} – 10^{33} erg/s) **Deep Crustal Heating**

$$\langle L \rangle = 9\times10^{32} \frac{\langle \dot{M} \rangle}{10^{-11}\ M_\odot\ \mathrm{yr}^{-1}} \frac{Q}{1.5\,\mathrm{MeV/amu}}\ \mathrm{erg\ s}^{-1}$$

Brown et al. (1998)



Log T_{eff} : (unredshifted) effective temperature

M_{ns} : neutron star gravitational mass (in units of Solar mass)

R_{ns} : "true" neutron star radius (km)

dist : distance to the neutron star (in kpc)

fraction of the neutron star surface emitting

nsatmos **Guillot et al. (2013)**

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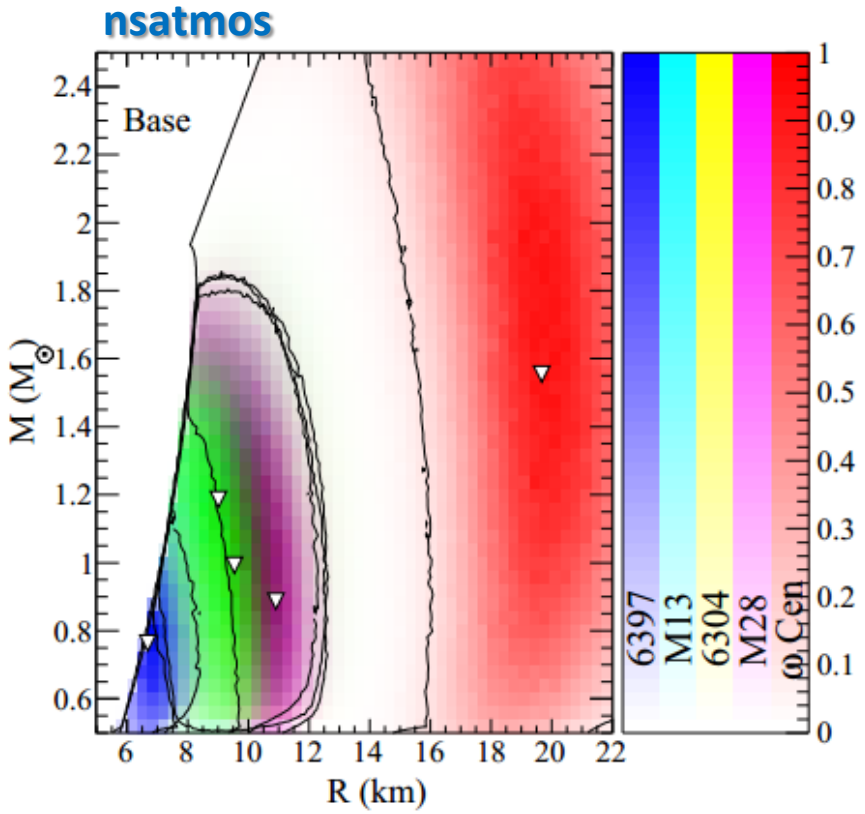
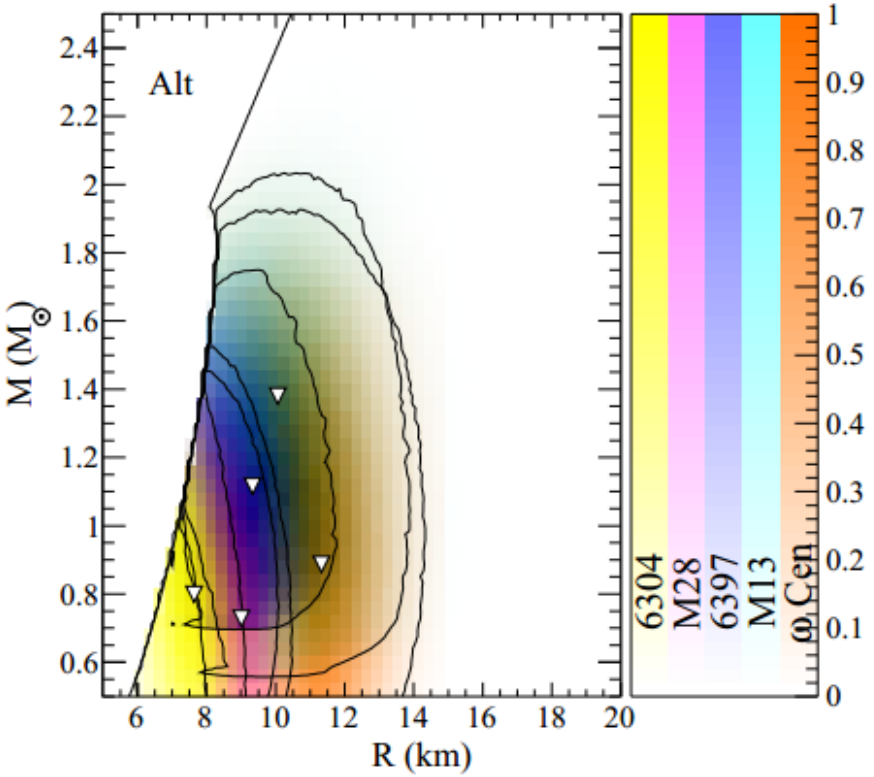


Guillot et al. (2013)



Lattimar & Steiner (2013)

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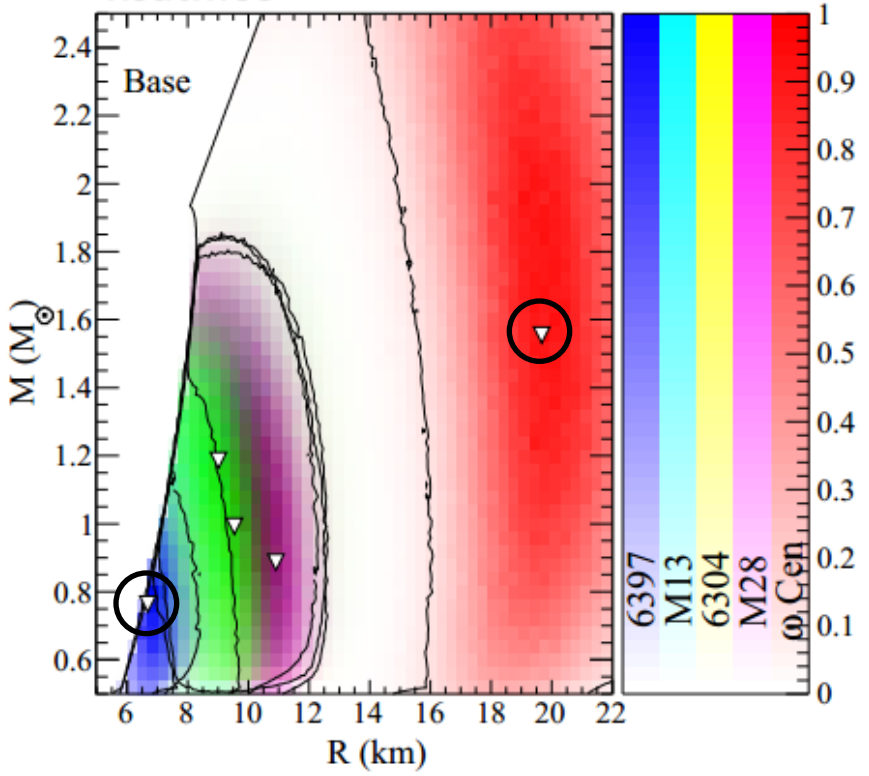
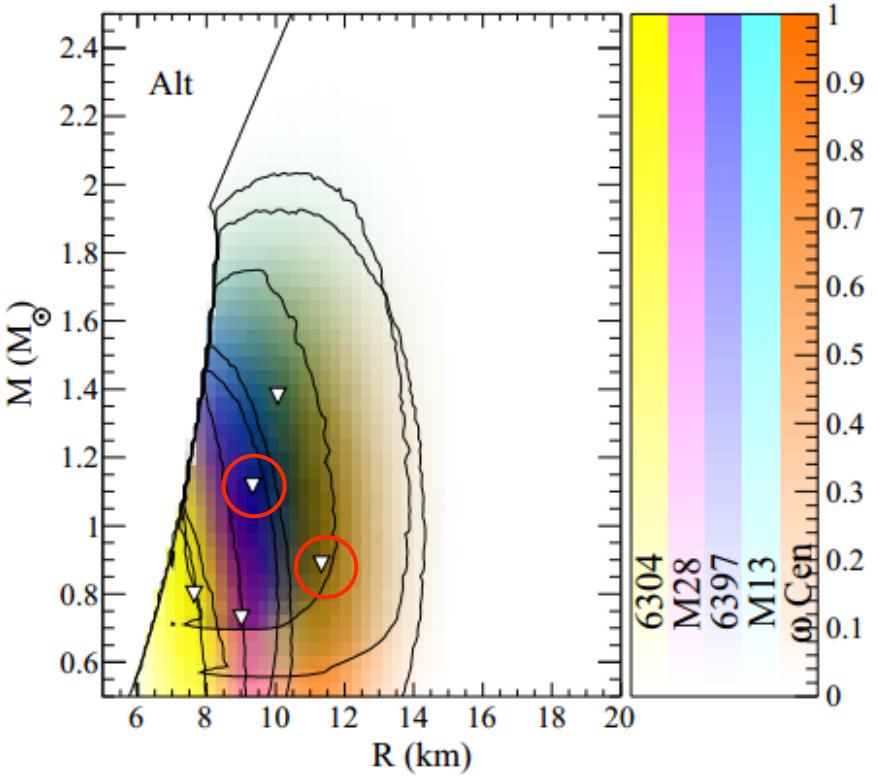
nsatmos



Guillot et al. (2013)

H/He atmosphere



Lattimar & Steiner (2013)

Aql X-1

- **Companion**

Spectral type K7 main sequence star

4-6.5 kpc (Chevalier et al. (1999))

- **Quiescent**

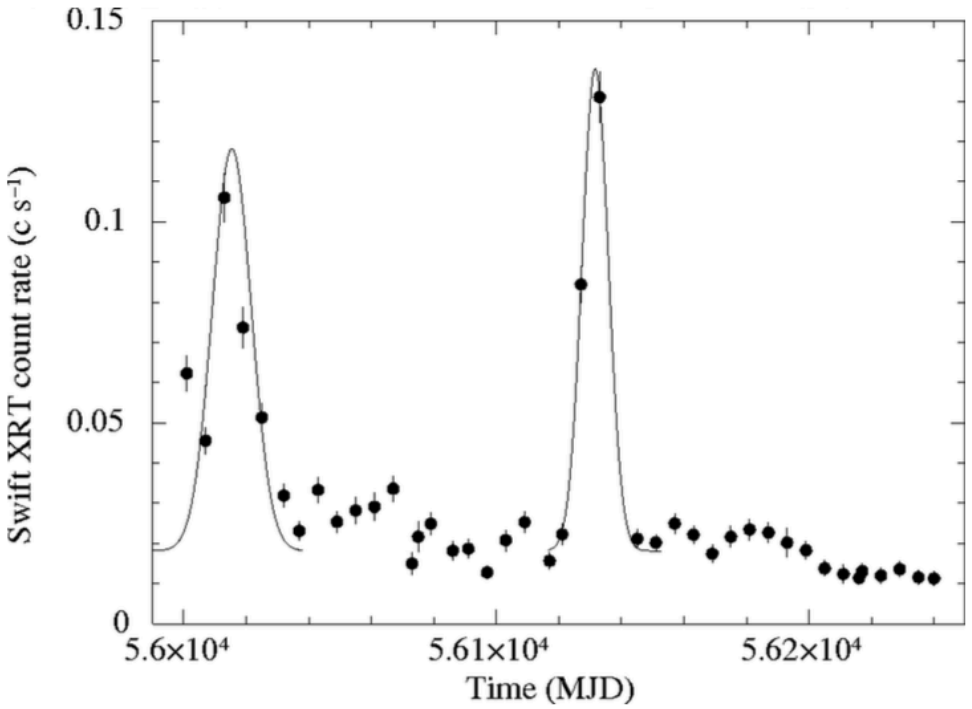
Chandra, XMM-Newton, Swift

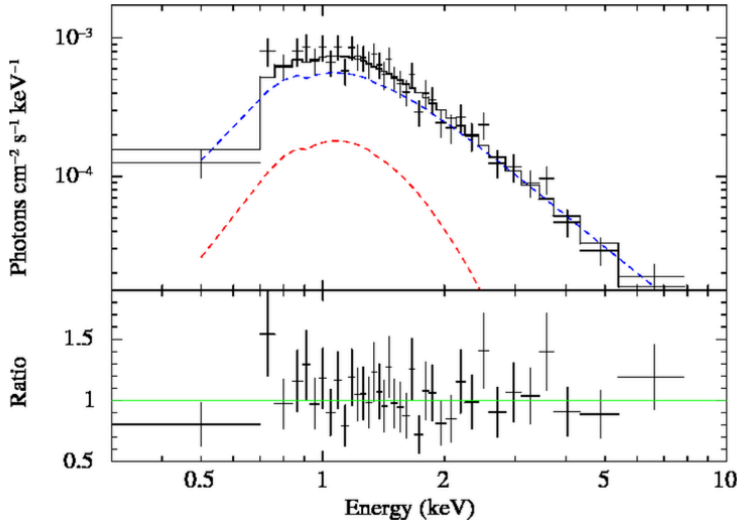
(Rutledge et al. (2001), Zelati et al. (2011, 2014)

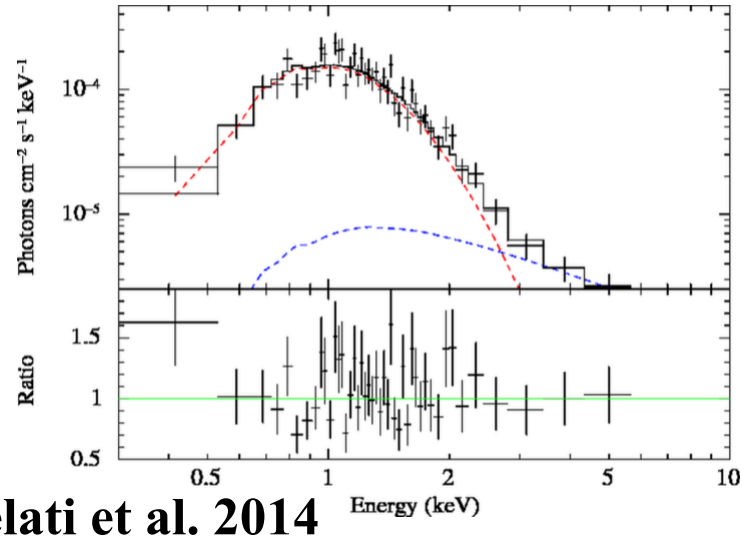
- **PRE bursts**

RXTE, Galloway (2008)

Aql X-1 variability







Two X-ray flares during quiescence

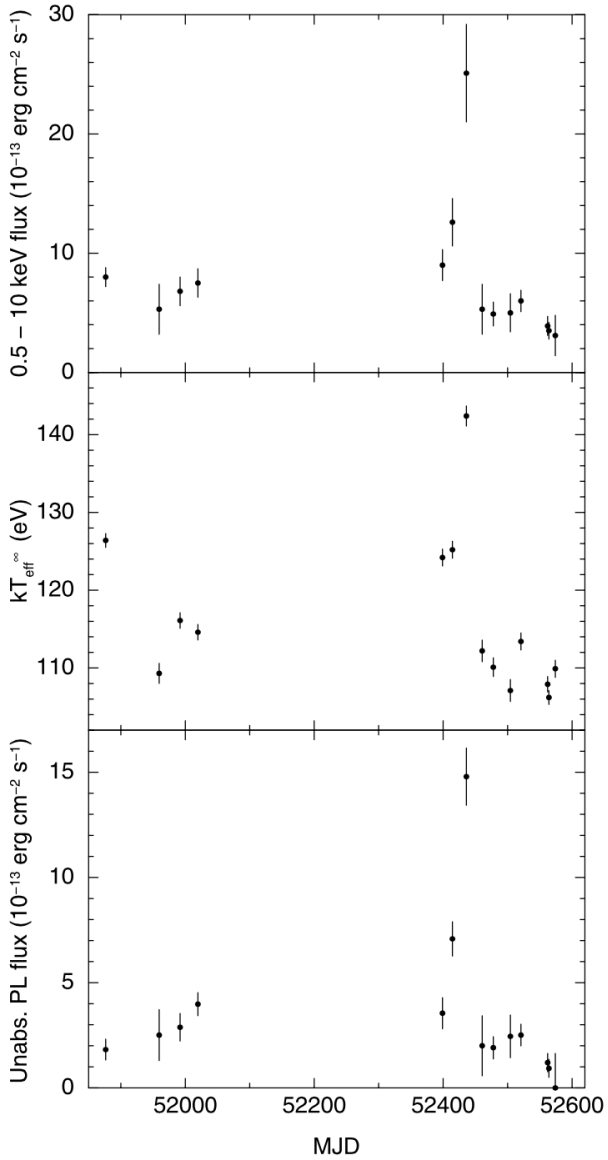
F. Coti Zelati et al. 2014

Consequence of accretion

- Heating the atmosphere
- Enhanced the power

low component

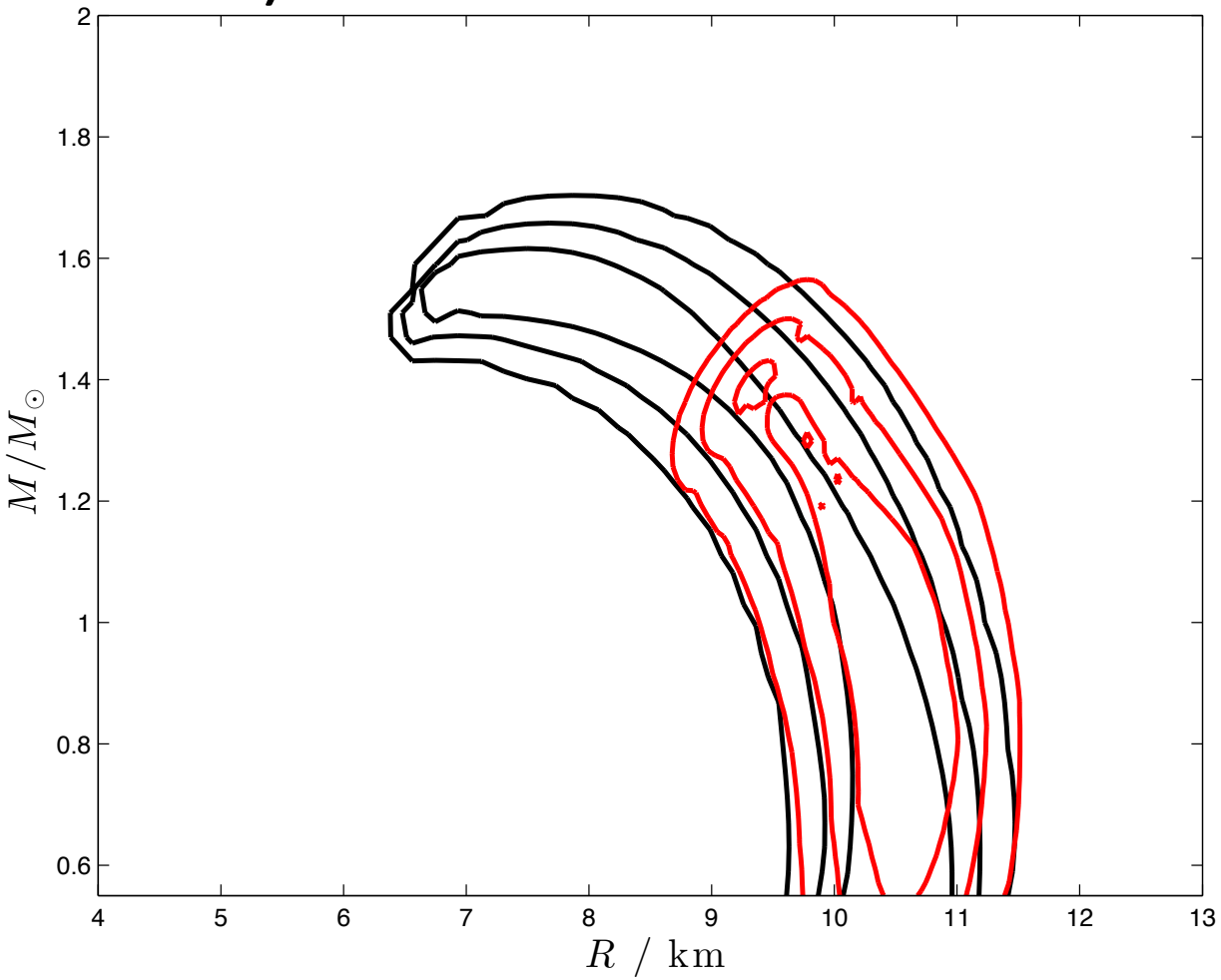
- No evidence of affect *M-R*



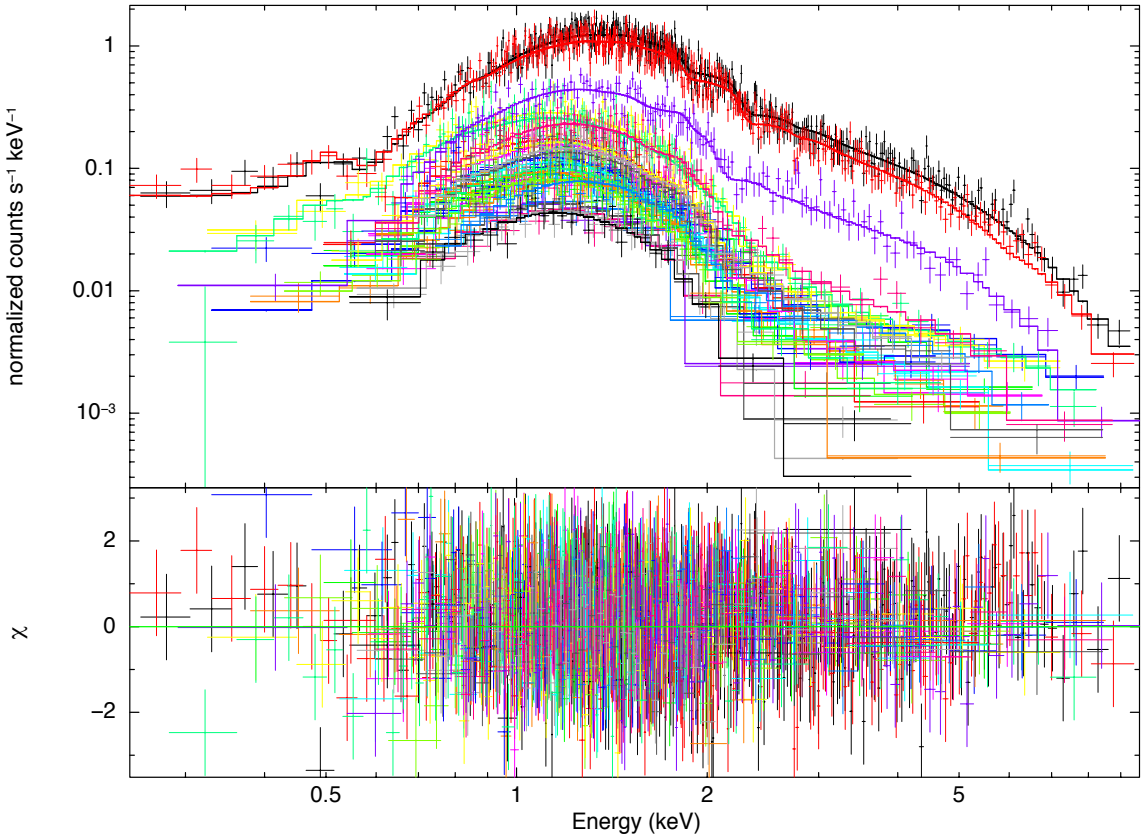
F. Coti Zelati et al. 2011, 2014

Chandra vs. Newton

Flux calibration and response calibration (Güver et al. 2015)



Quiescent spectra

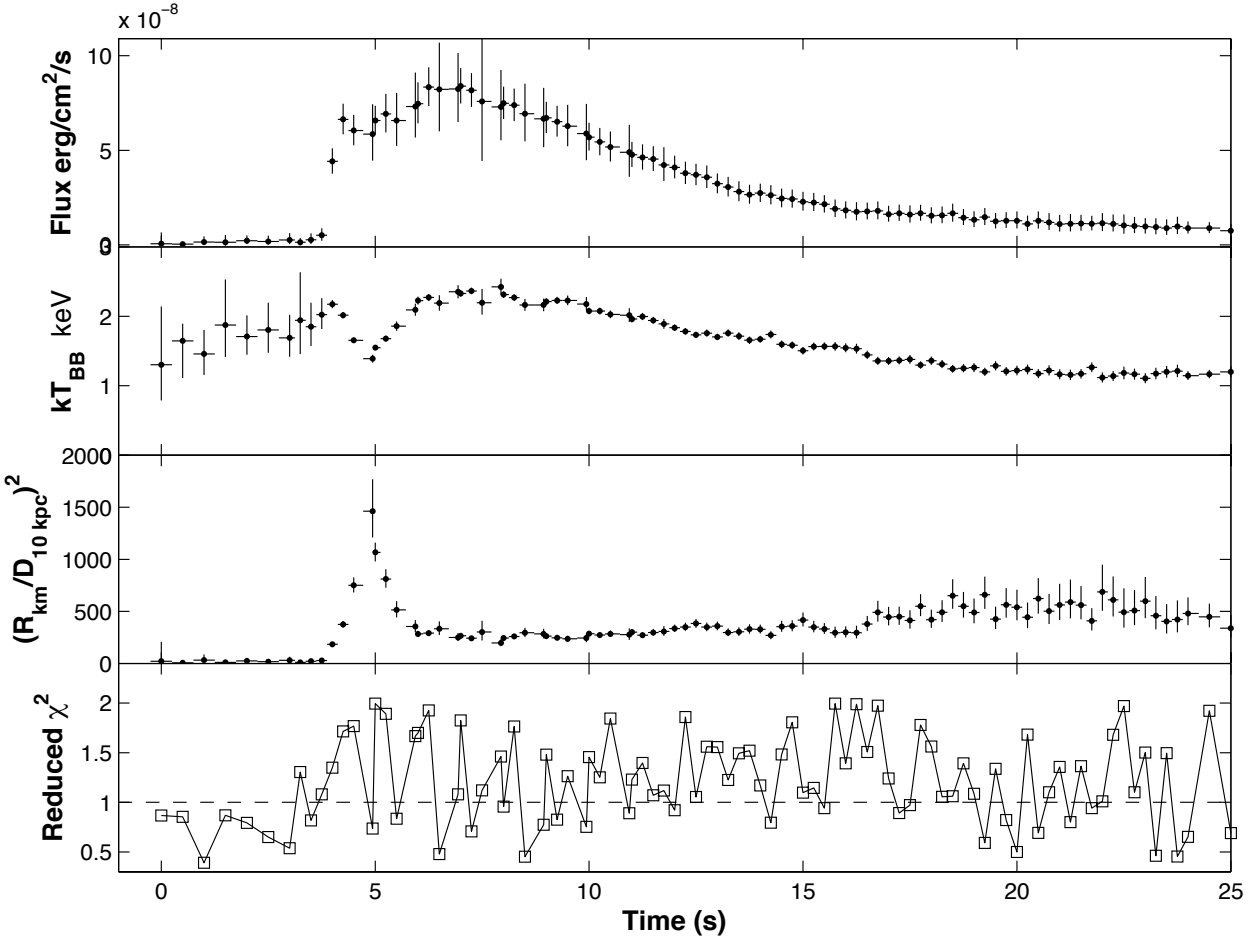


Chandra+Newton quiescent Obs.

tbabs(nsatmos+powerlaw)

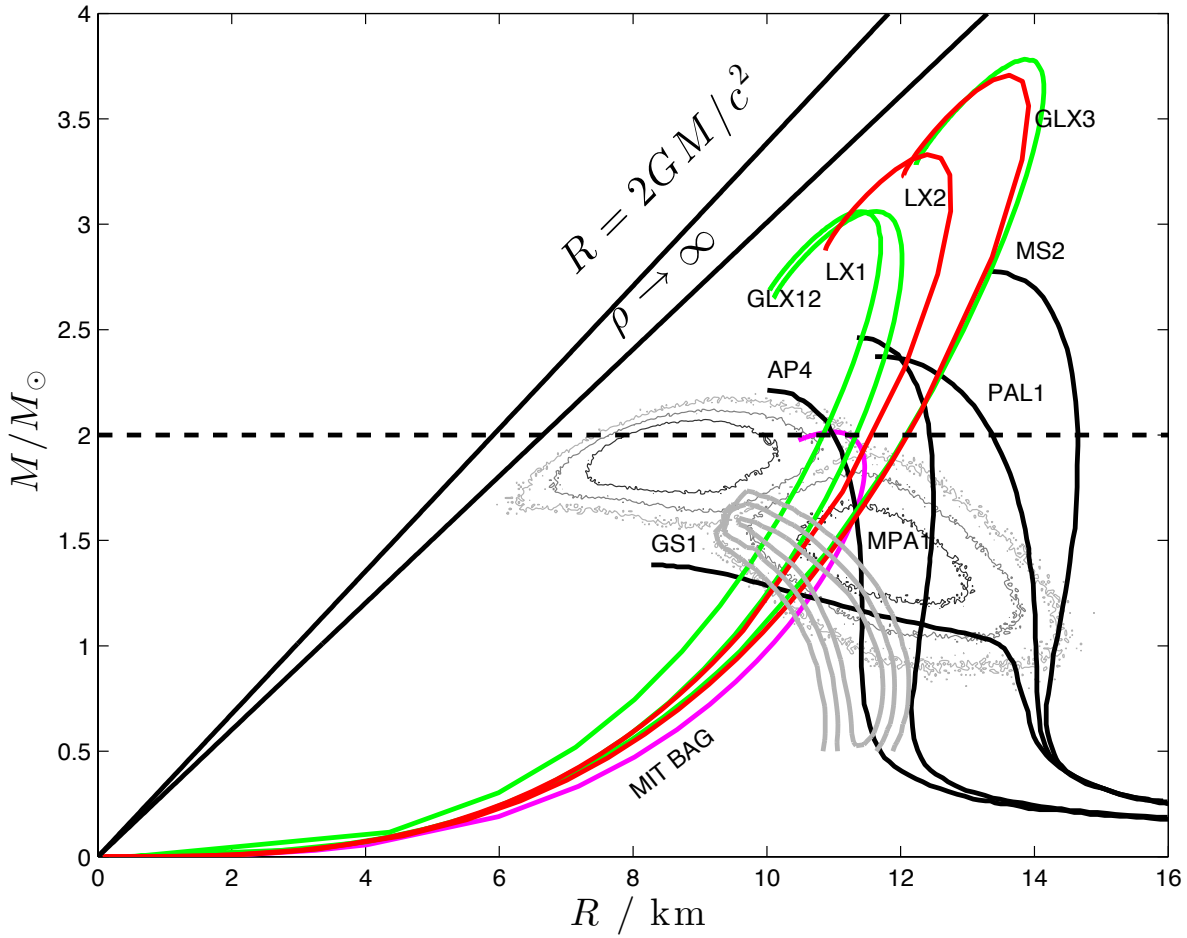
Hydrogen atmosphere

PRE bursts

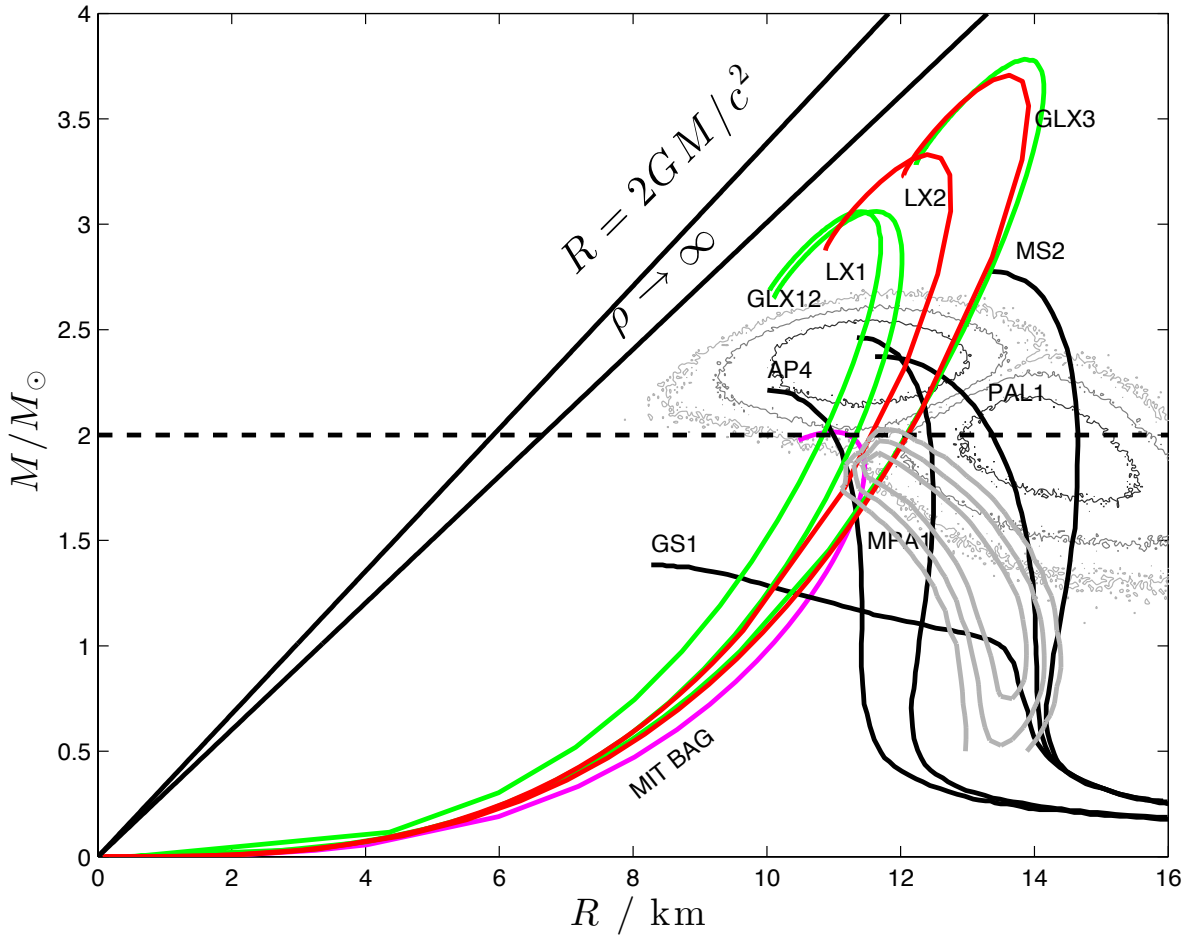


50049-02-13-01

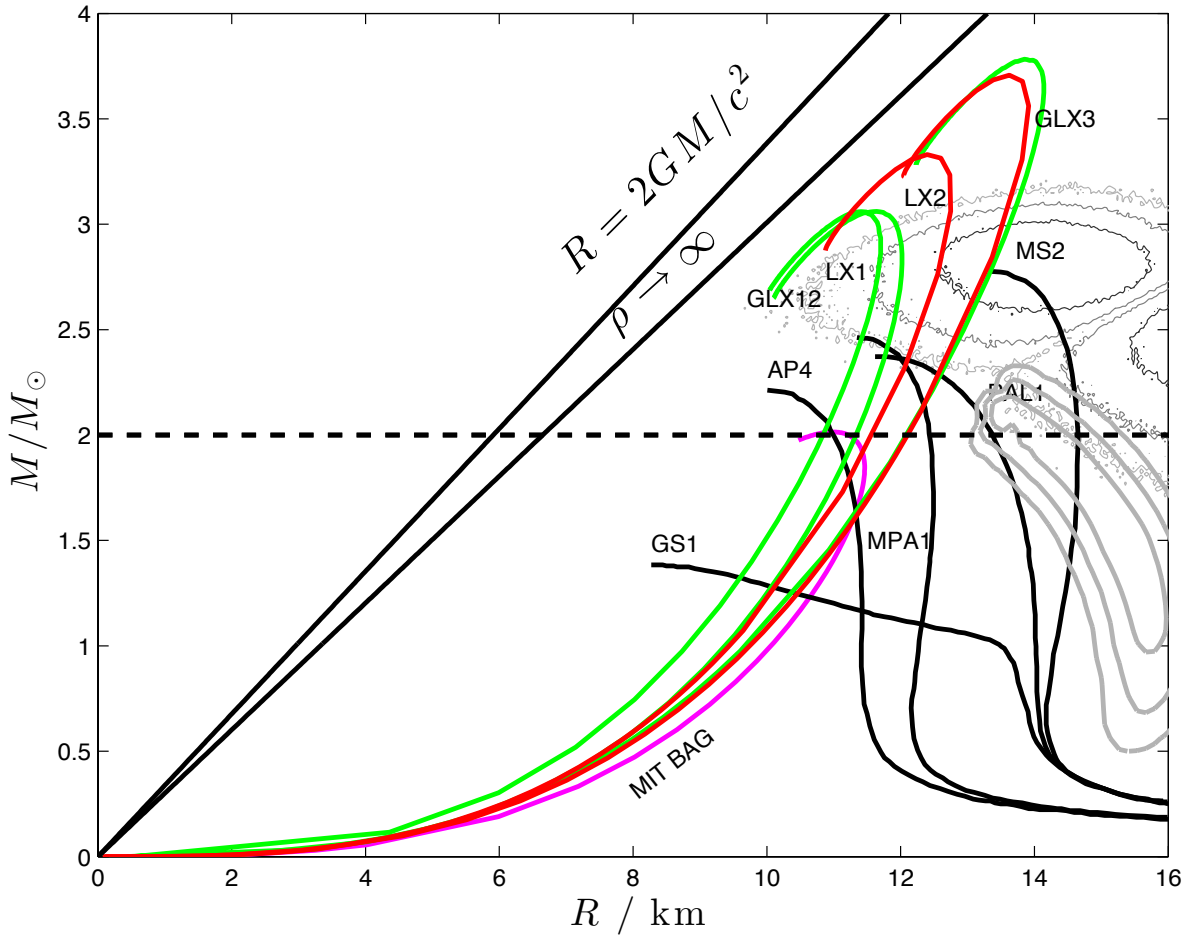
The *M-R* of Aql X-1



D=4.5 kpc


$R = 2GM/c^2$
$\rho \to \infty$
GLX3
LX2
MS2
LX1
GLX12
AP4
PAL1
GS1
MPA1
MIT BAG
$M/M_\odot$
R / km
0
0.5
1
1.5
2
2.5
3
3.5
4
0
2
4
6
8
10
12
14
16

D=5.5 kpc



D=6.5 kpc

Z.S. Li 2015, in prep.

Conclusions

- **4U 1746-37: an ultra-low-mass compact star**

< 1.1 Msun

- **EoSs can be effectively tested**

Formation (Accretion Induced Core-collapse)

Low mass compact star (self-bound or gravity bound)

- **Aql X-1**

Quiescent & X-ray burst