STARS2015 @HAVANA, Cuba

The mass and radius of compact star in 4U 1746-37

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Li Chen (Beijing Normal University)
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Outline

- **Motivation**
- **Constrain the *M-R* of NS**

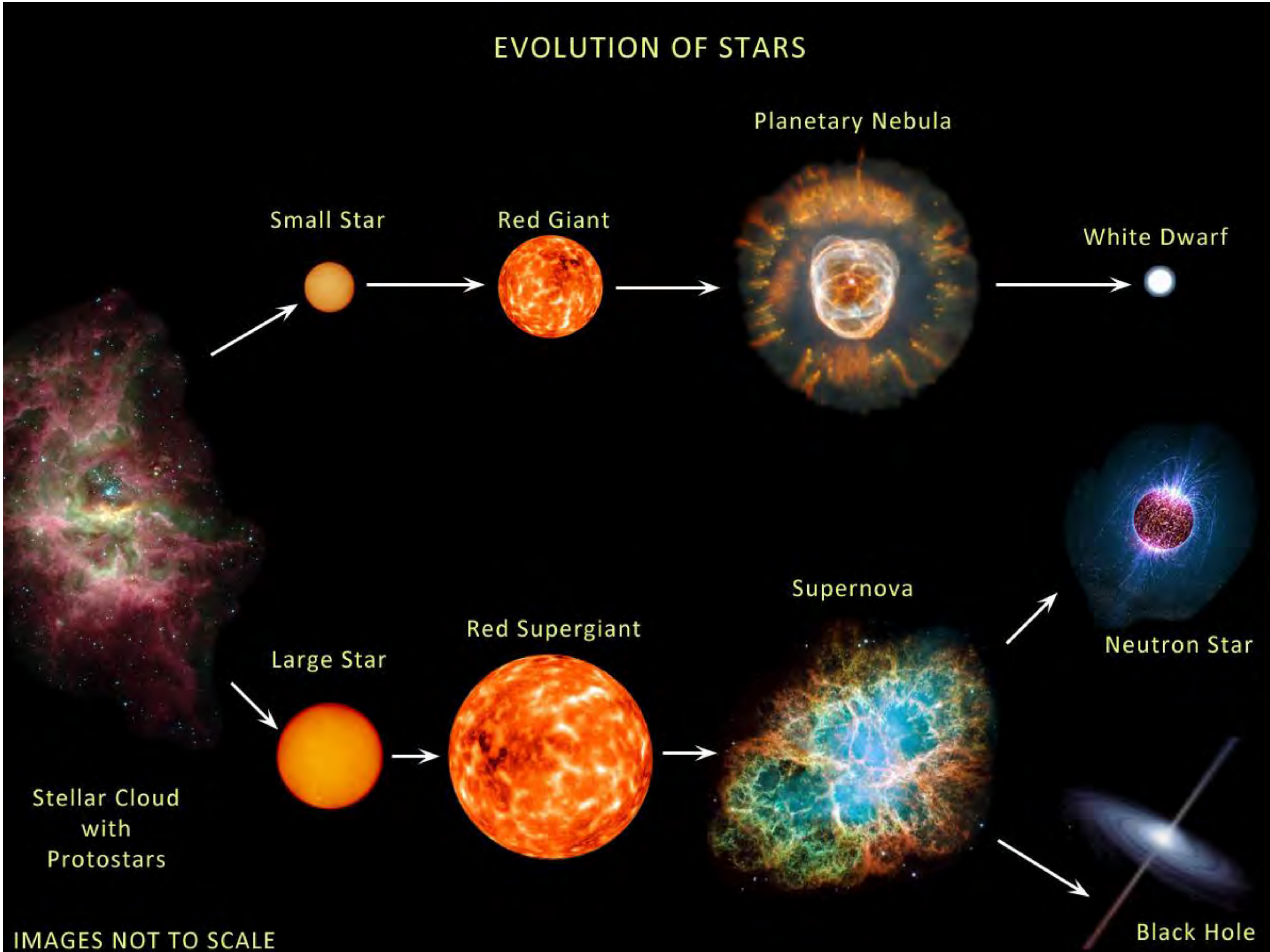
Redshift

Pulse Profile

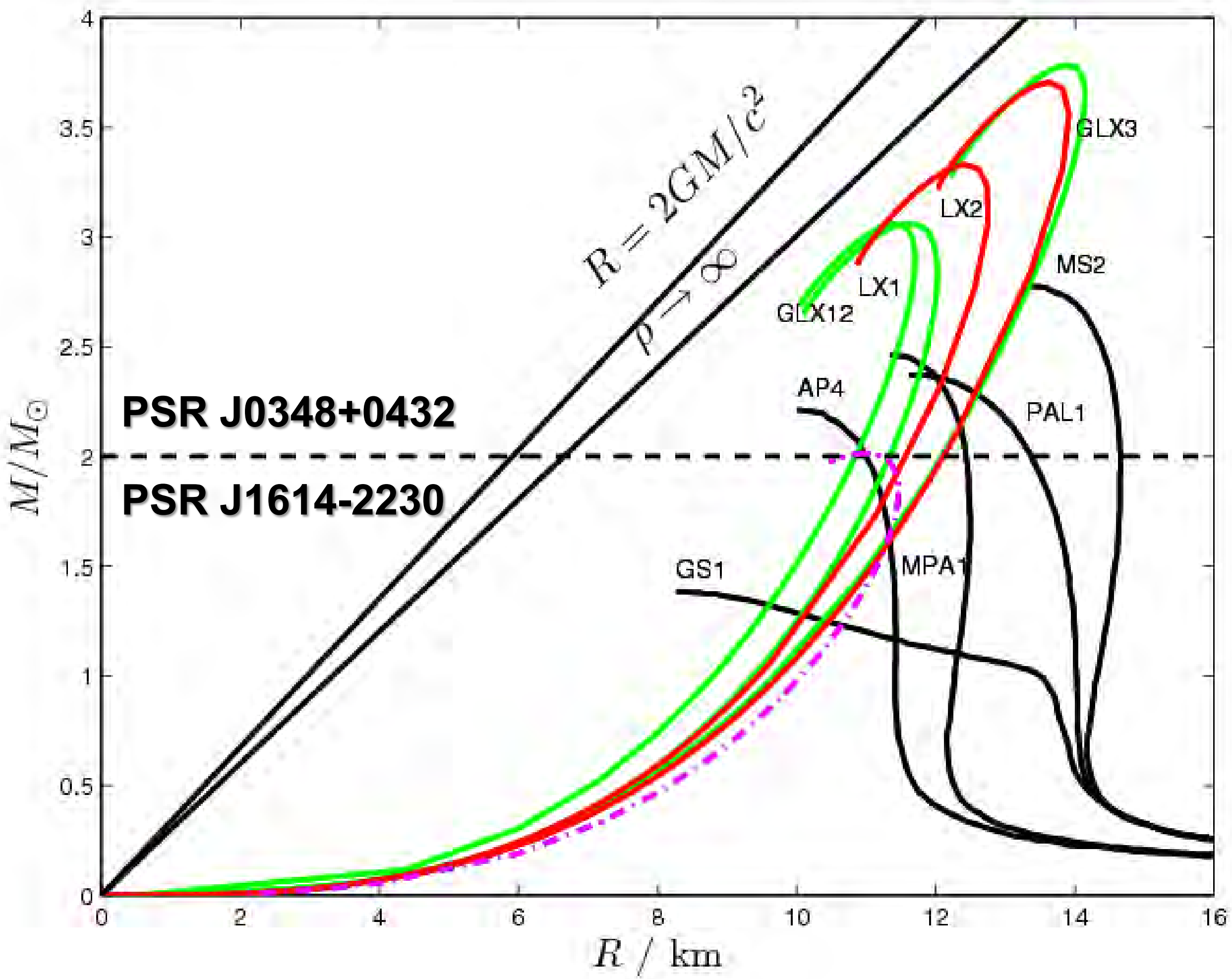
qLMXBs

X-ray Burst

- **The *M* and *R* of NS in 4U 1746-37**


EVOLUTION OF STARS
Planetary Nebula
Small Star
Red Giant
White Dwarf
Supernova
Red Supergiant
Large Star
Neutron Star
Stellar Cloud
with
Protostars
Black Hole
IMAGES NOT TO SCALE

Equation of States



Gravity bound

Hadron star

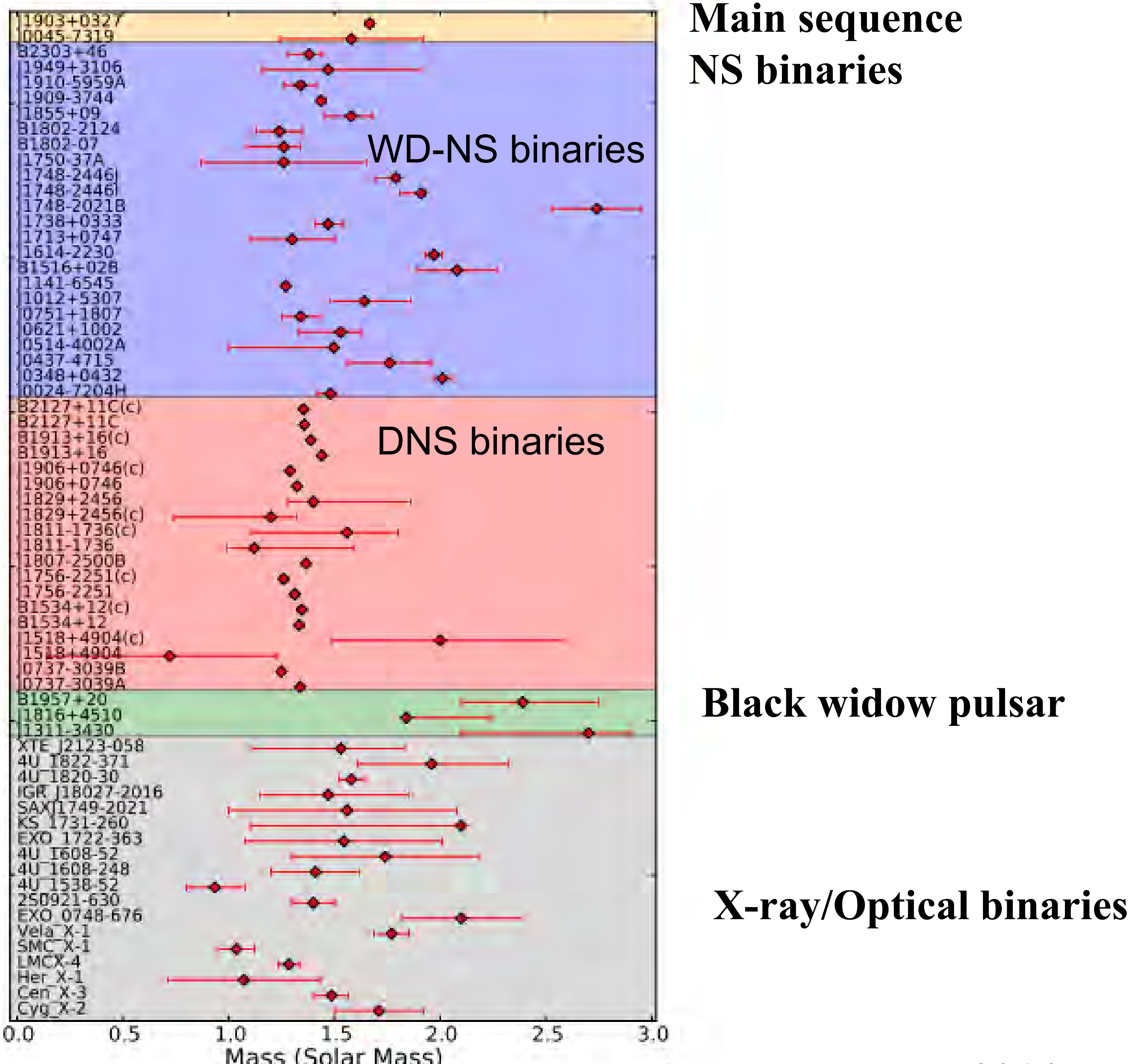
Hybrid star

Self-bound on surface

Quark star

Quark-cluster star

Mass

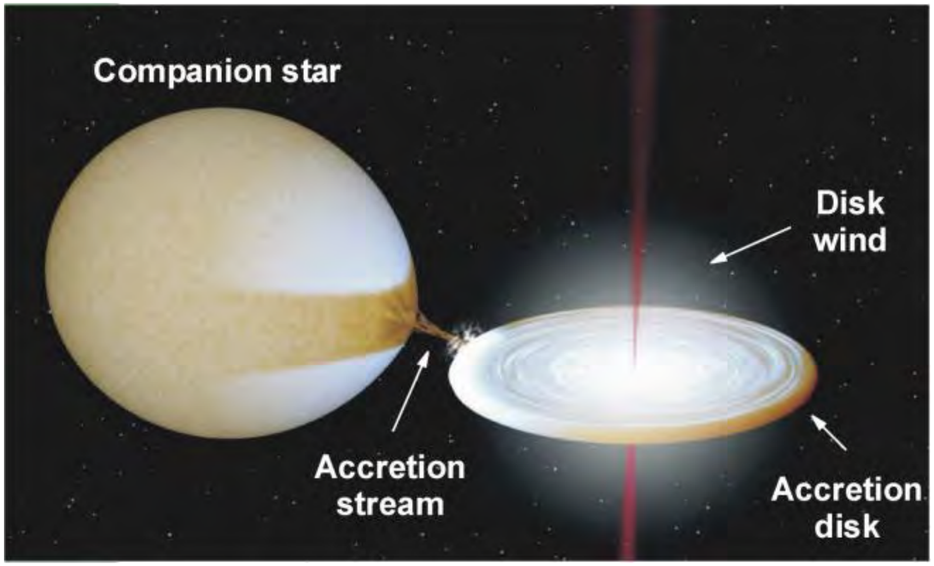


Anna Watts et al.2014

Constrain the *M-R* of NS in LMXBs

- **Redshift measurement**
- **Pulse profile modeling in X-ray pulsars**
- **Atmosphere emission in qLMXBs**
- **X-ray bursts**

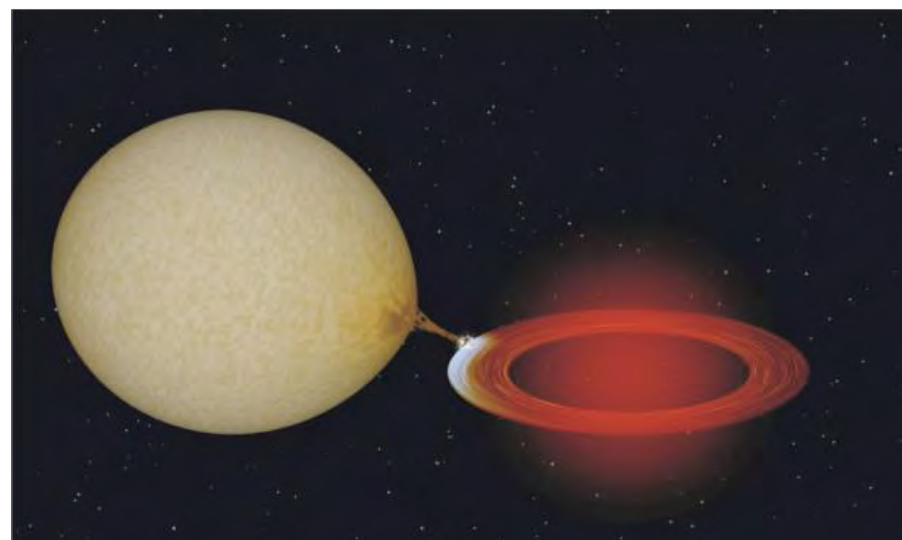
LMXBs



transient source

"Switched on": Accretion induced outburst

"Switched off": Quiescence



Gravitational Redshift

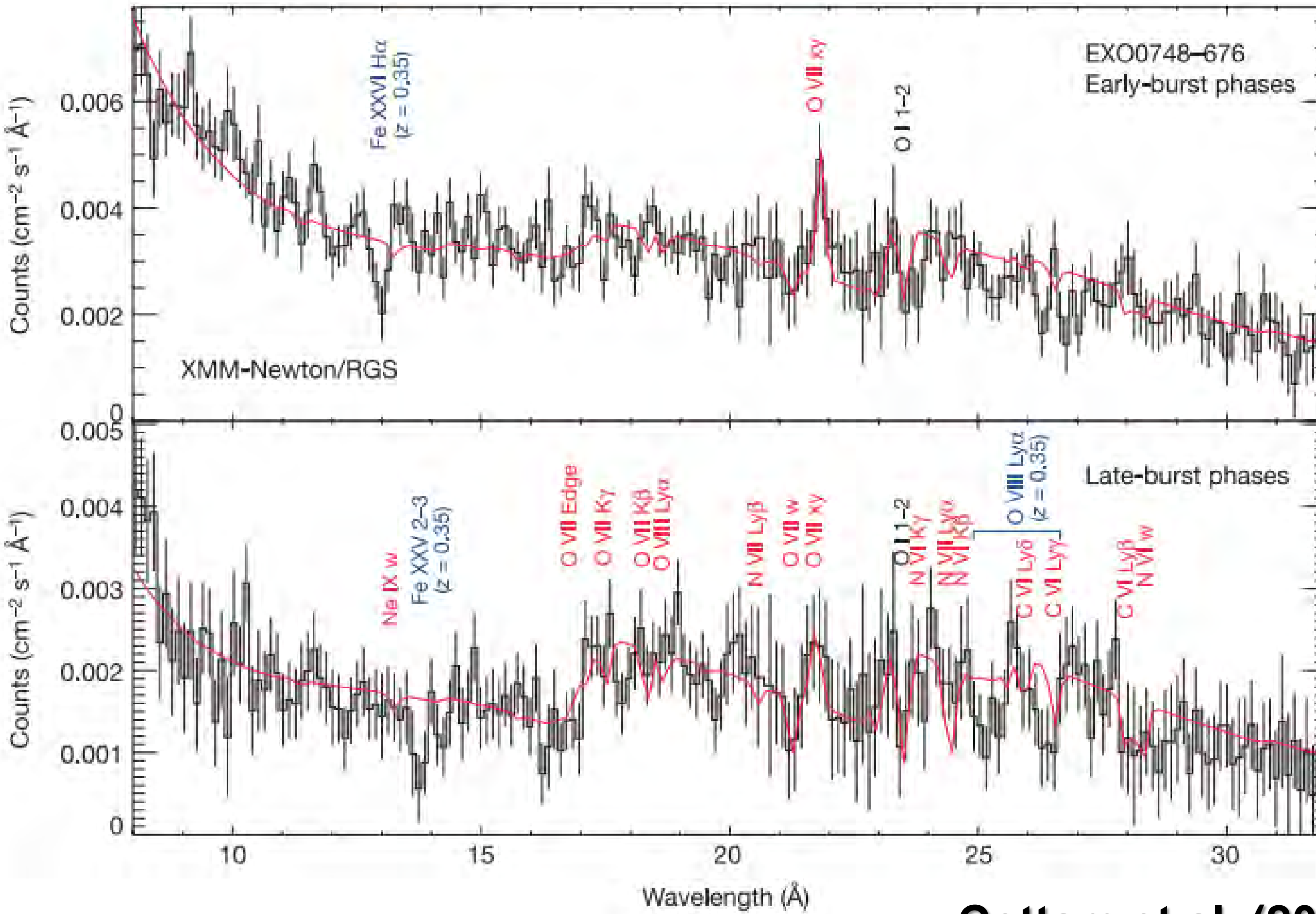
- **EXO 0748-676 (*XMM-Newton*)**

$$1+z(R) = (1-2GM_{\rm NS}/Rc^2)^{-1/2}$$

Z=0.35

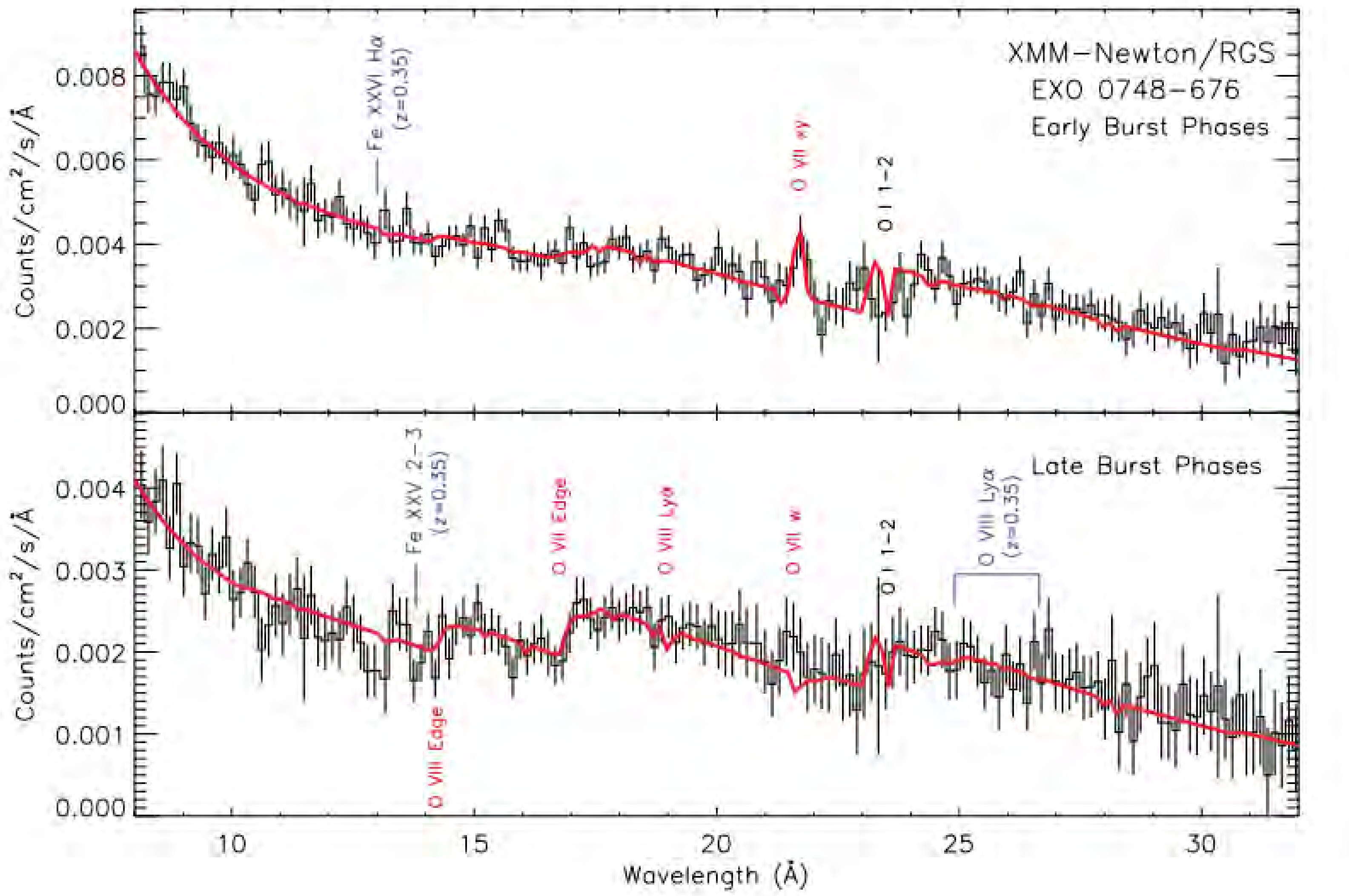
Fe XXVI (Hα)
9.518, 9.533, 9.579
9.675, 9.690,
9.738→13.0

Fe XXV (He-like)
O VIII



Cottam et al. (2002)

Only once in EXO 0748-676

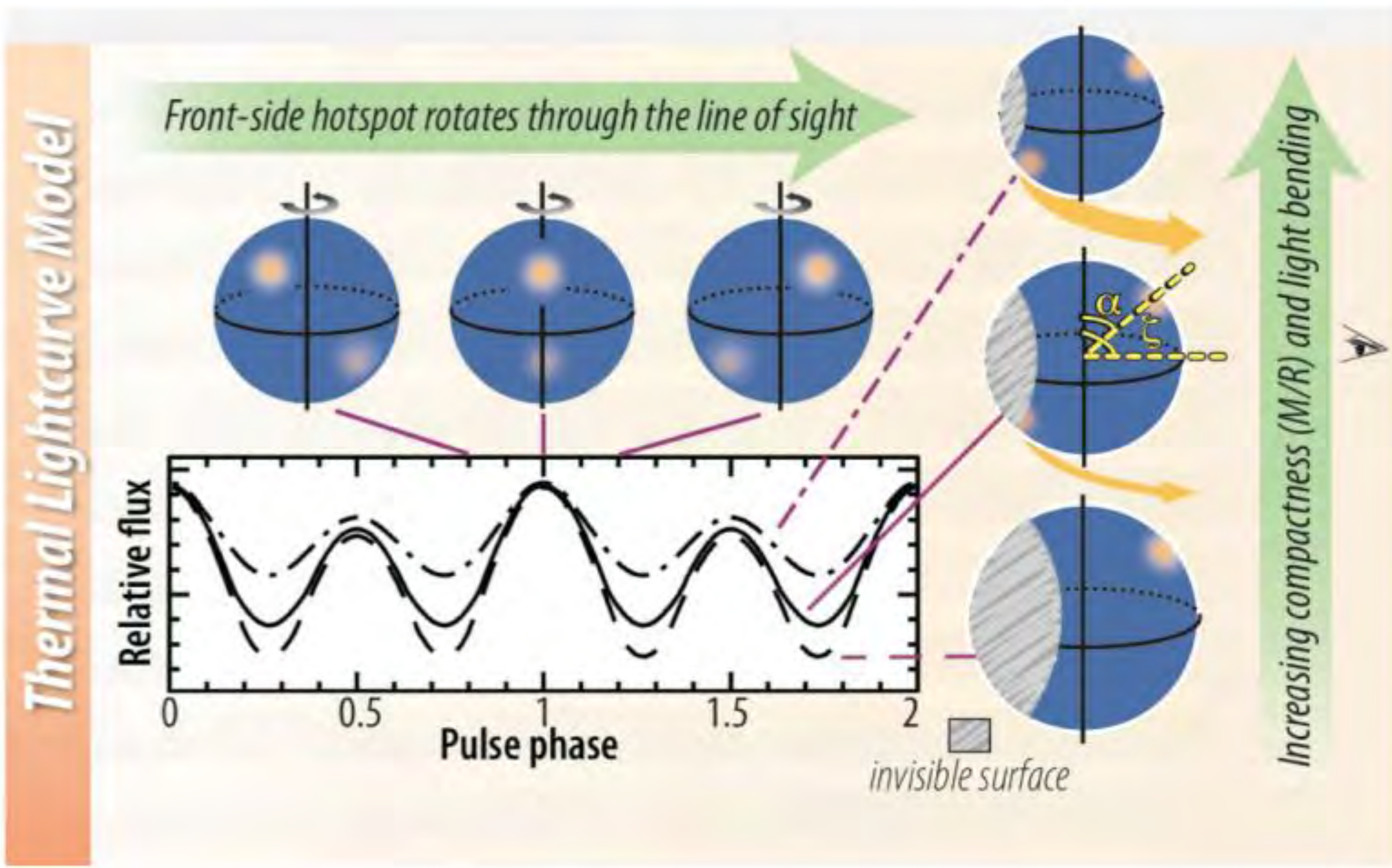


None detection of absorption line!

Cottam et al. (2008)

Pulse profile modeling in X-ray Pulsars

Compactness, *M/R*



NICER, **Gendreau et al. (2012)**

Peculiar pulse profile (Her X-1)

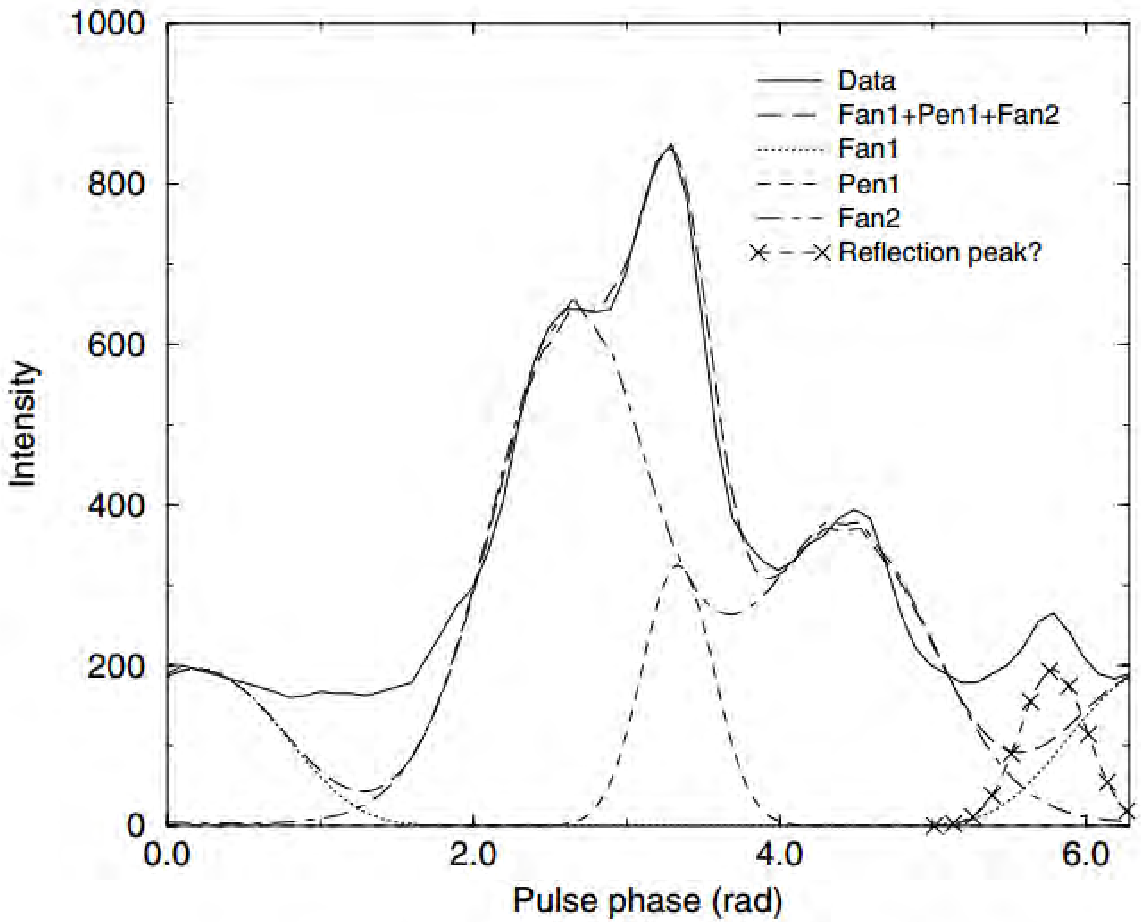


Figure 6. Observed 9–14 keV and model pulse shape for Her X-1.

Fan Beam

+

Pencil Beam

+

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.

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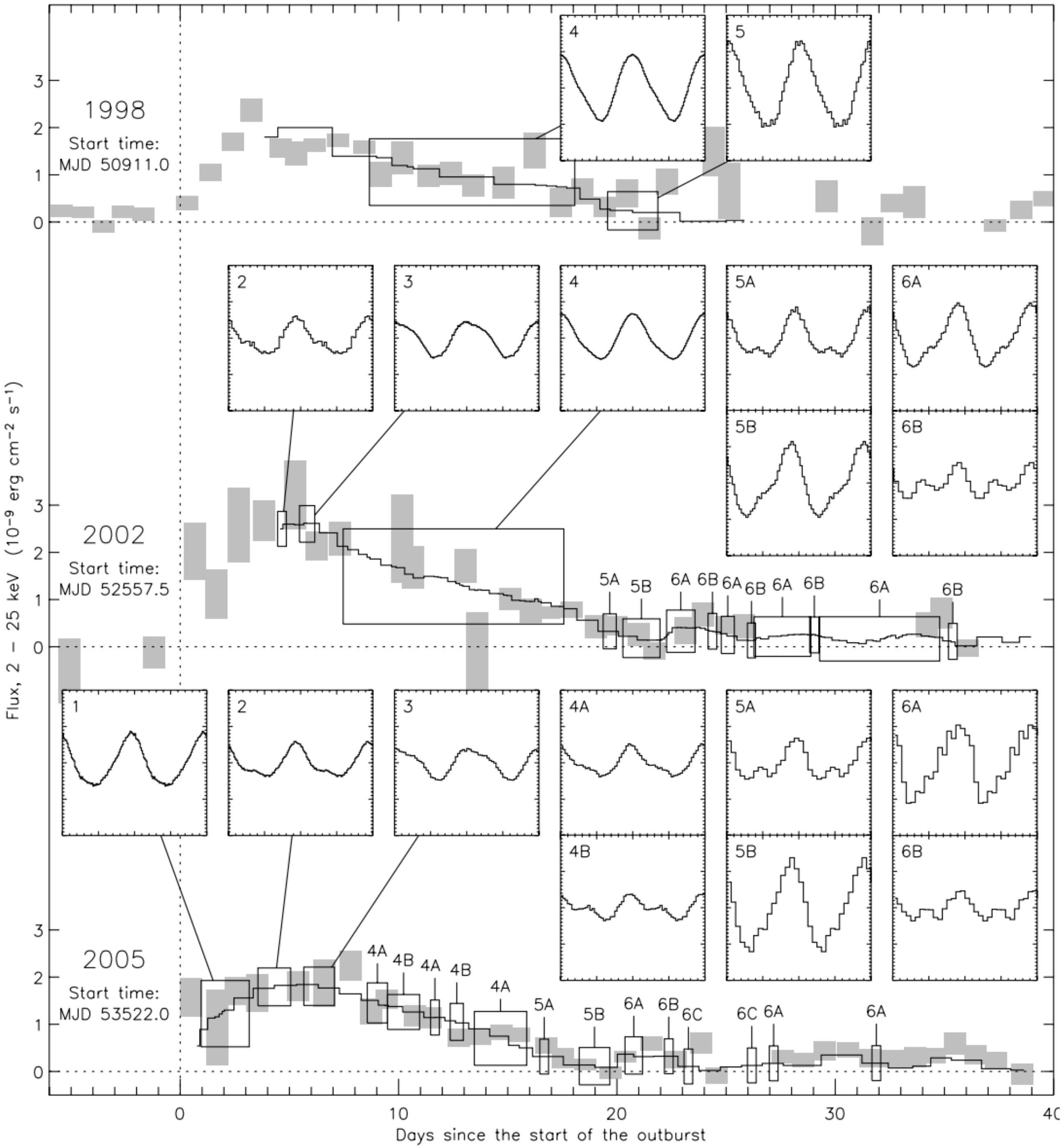
Leahy 2004

Pulse profile variations



Hot spot drifting

SAX J1808.4 -3658

Hartman et al.(2008)

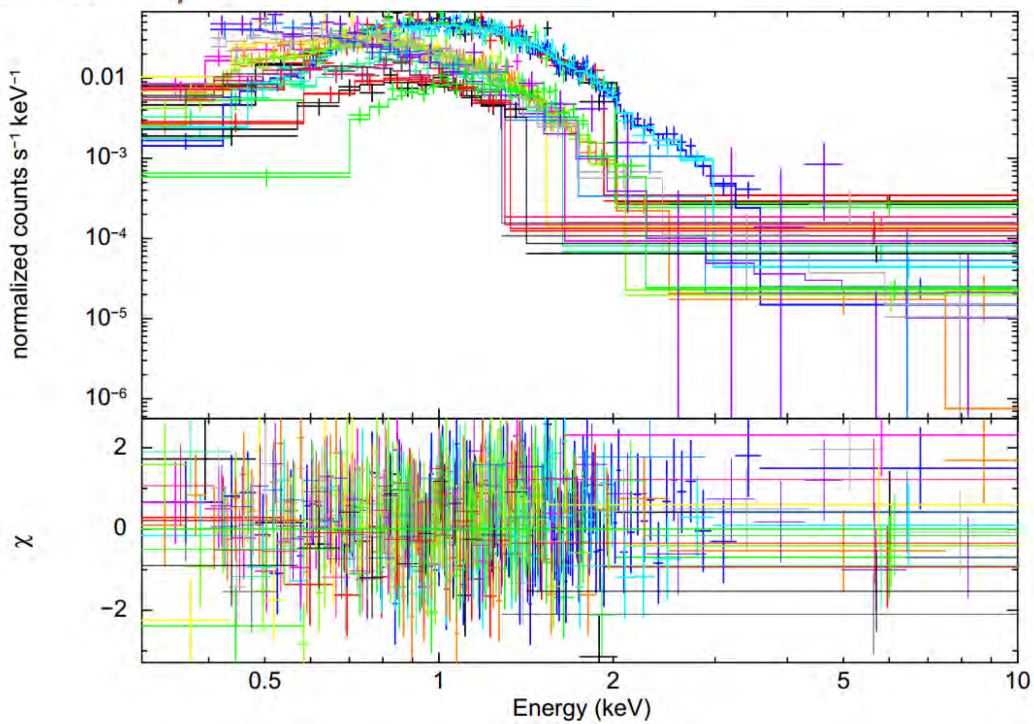
qLMXBs in Globular Clusters

- *Chandra* & *XMM-Newton* ($10^{32} - 10^{33}$ erg/s)

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

Deep Crustal Heating

Brown et al. (1998)



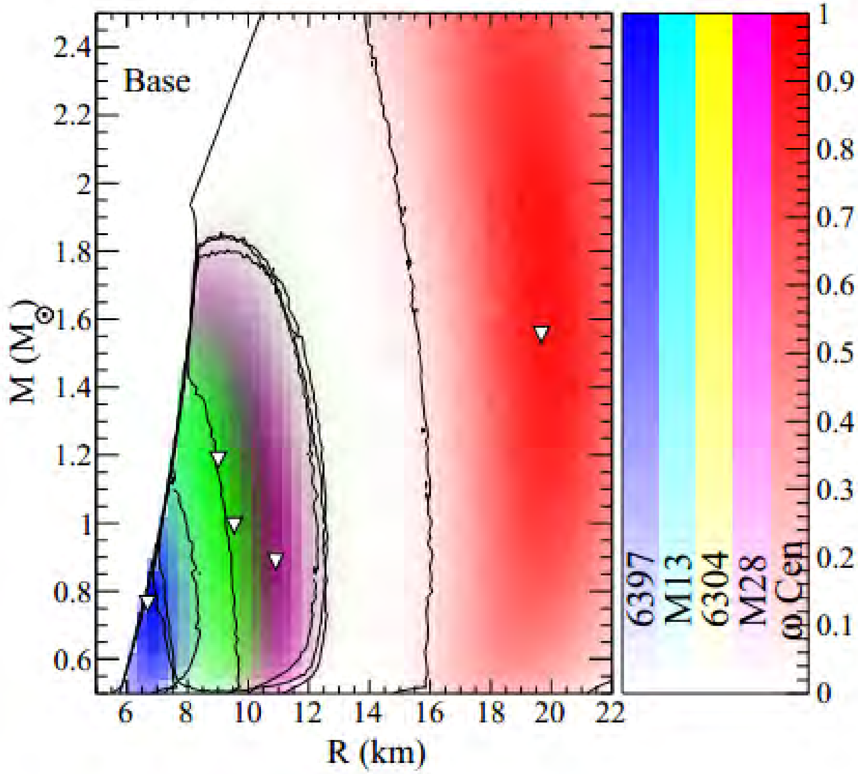
nsatmos

Guillot et al. (2013)

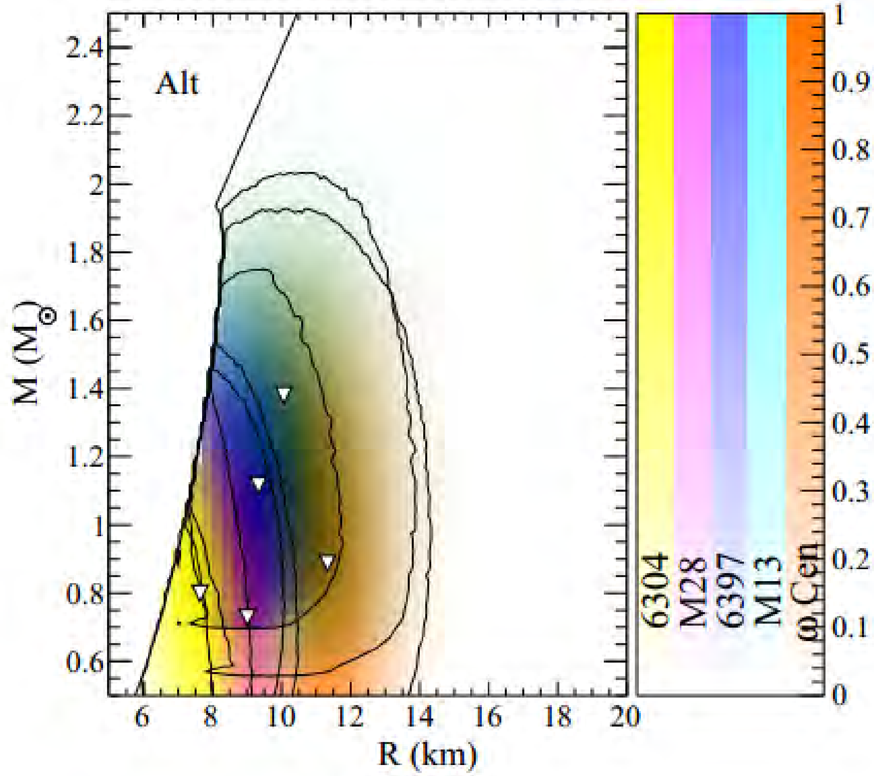
qLMXBs in Globular Clusters

- *Chandra* & *XMM-Newton* ($10^{32} - 10^{33}$ erg/s)

nsatmos



Guillot et al. (2013)

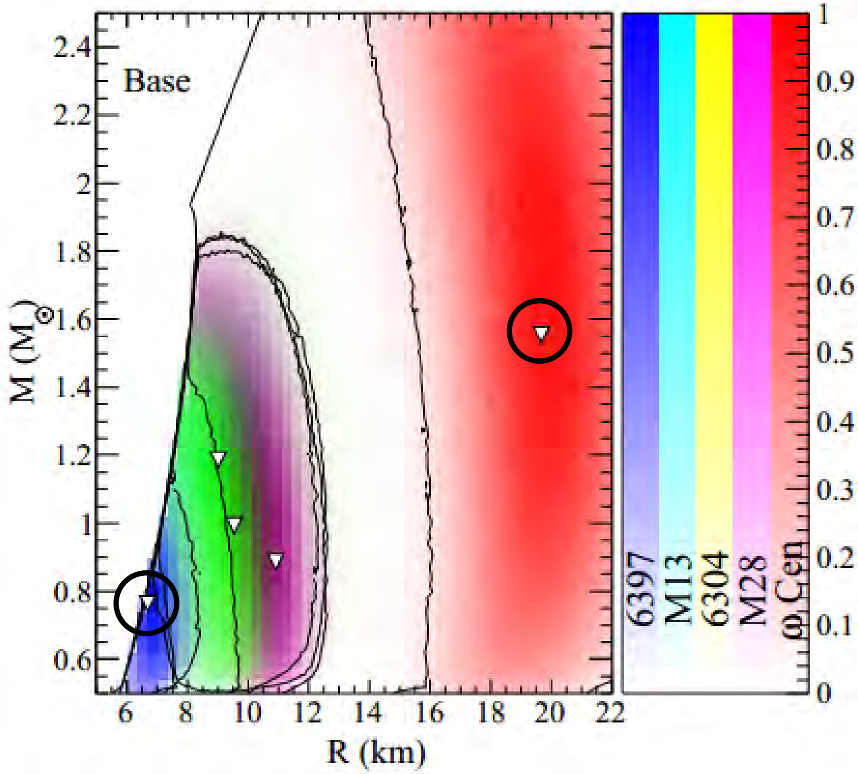


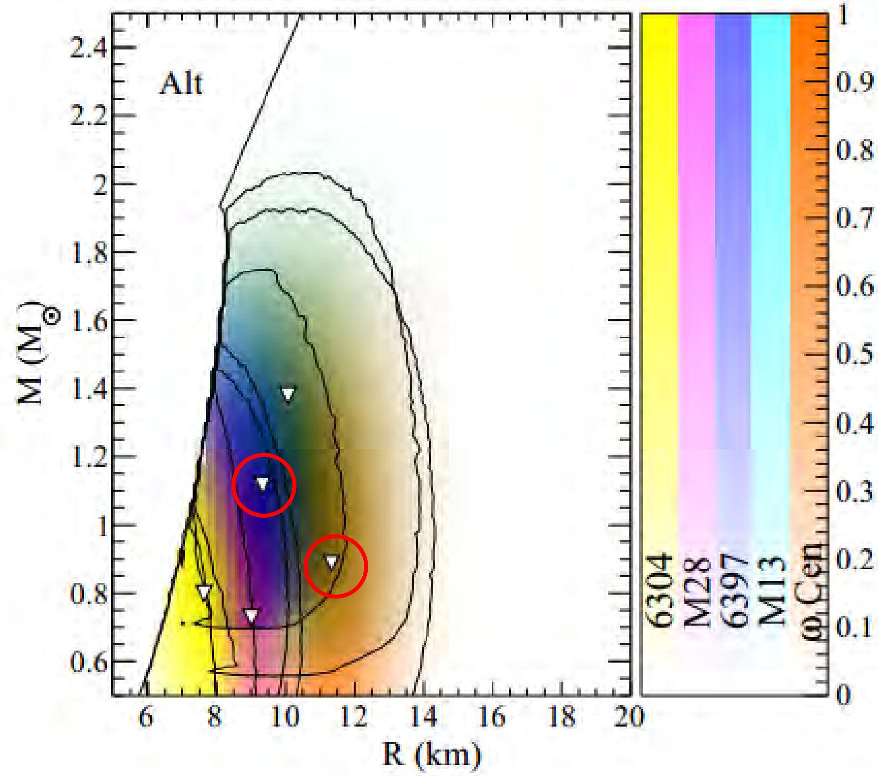
Lattimar & Steiner (2013)

qLMXBs in Globular Clusters

- *Chandra* & *XMM-Newton* ($10^{32} - 10^{33}$ erg/s)

nsatmos





Guillot et al. (2013)

H/He atmosphere

Lattimar & Steiner (2013)

Summary

- **Redshift *M/R***

Not confirmed yet

- **Pulse profile in X-ray pulsars *M/R***

***Peculiar pulse profile* (Her X-1)**

Pulse profile evolution (*SAX J1808.4-3658*)

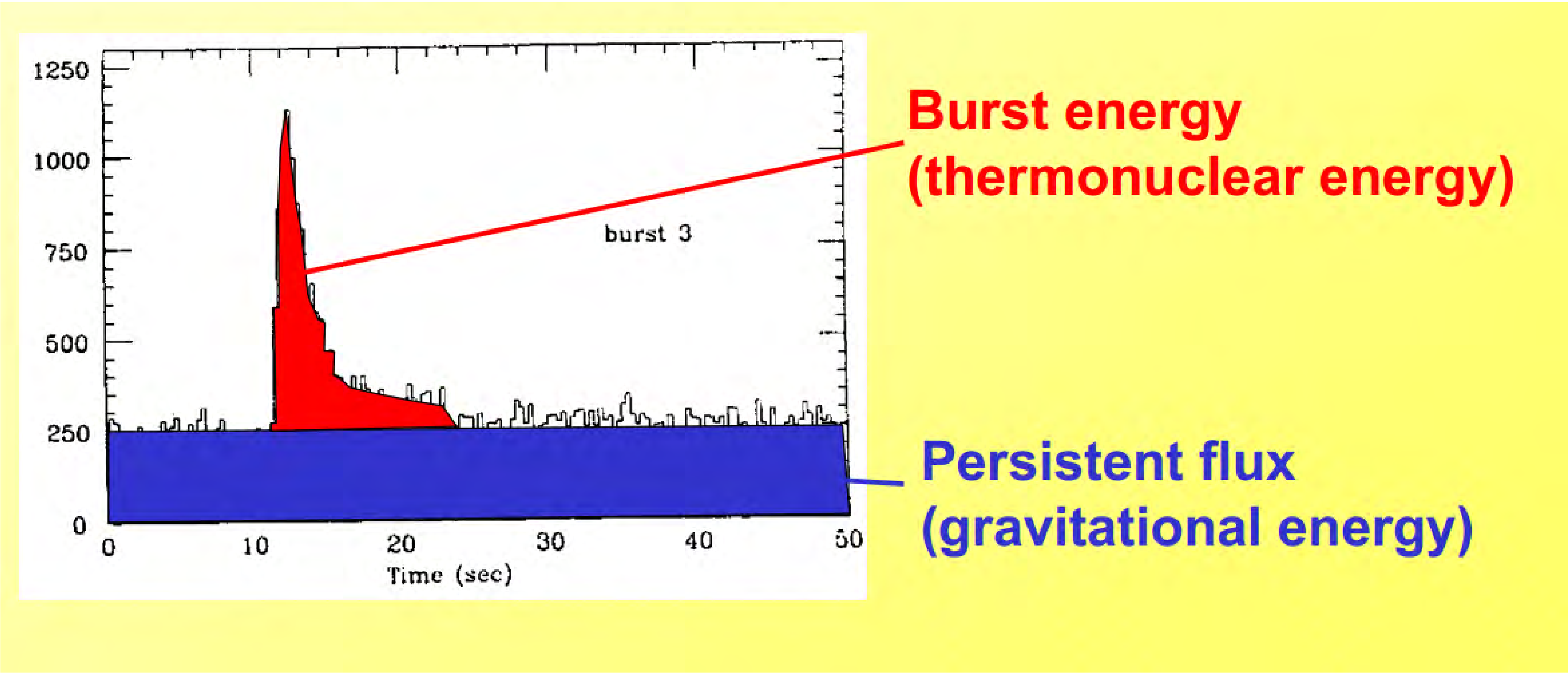
- **Atmosphere emission in qLMXBs *M-R***

Atmosphere composition

- **X-ray bursts**

Type-I X-ray burst

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

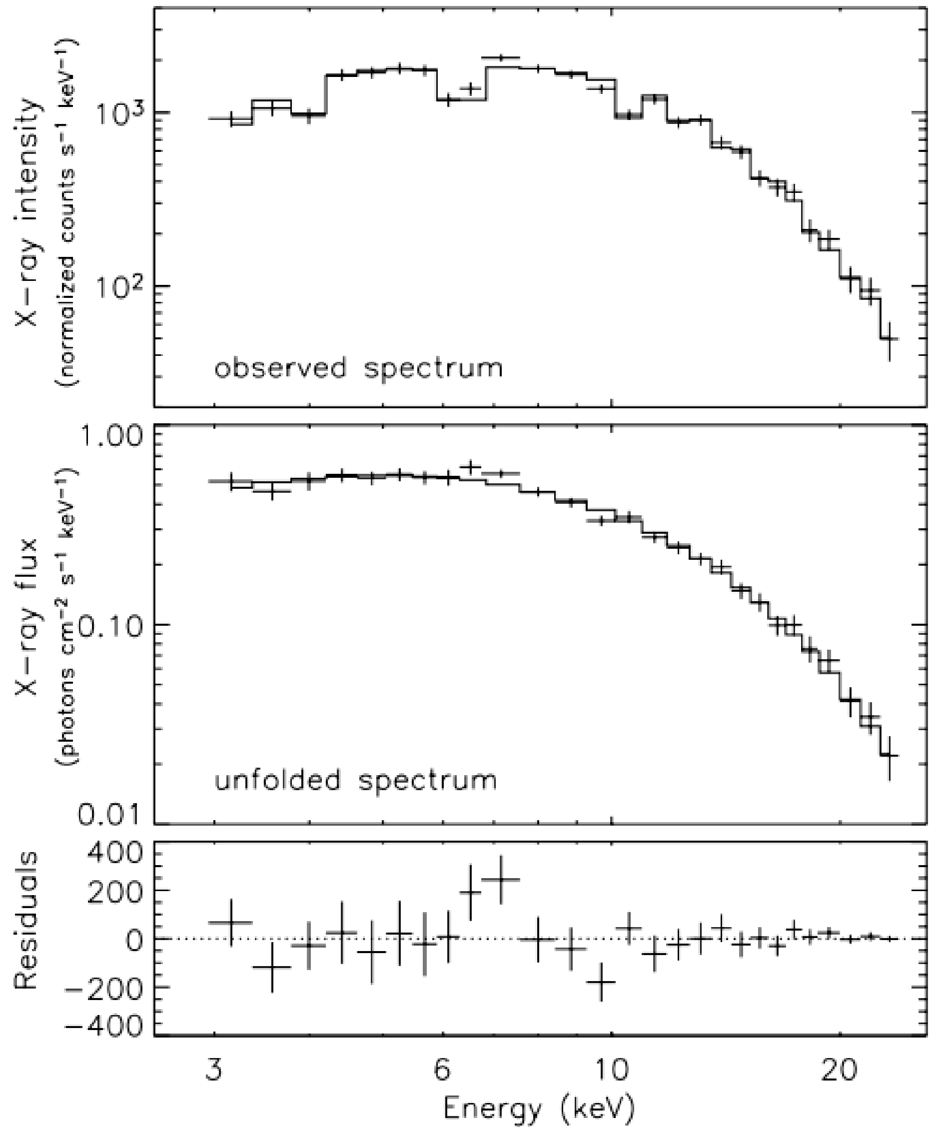


Burst Spectra

- **Emission of hot atmosphere**

- **Black body Temp. ~ 1-3 keV**

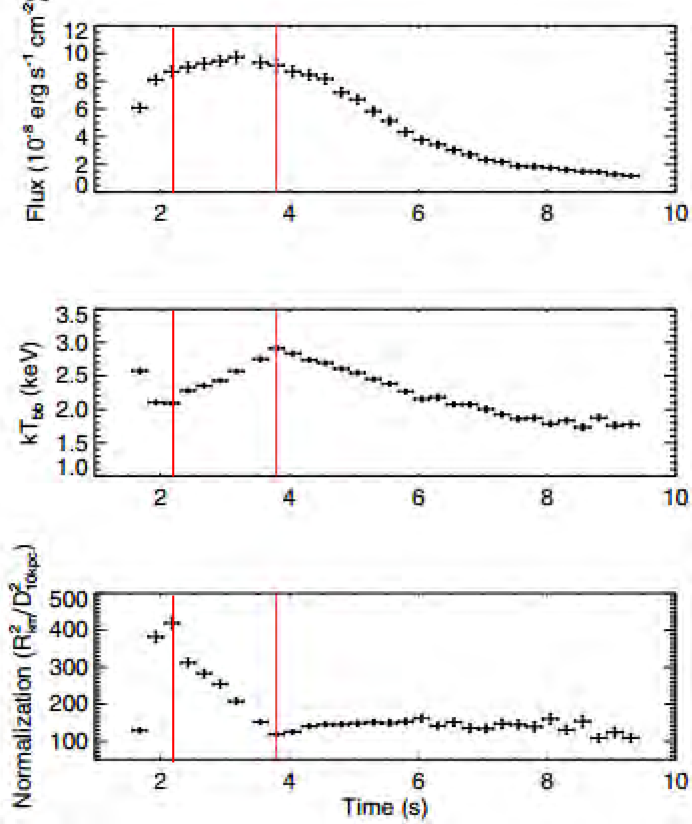
A burst from 4U 1728-34



PRE X-ray Burst

- **Photospheric Radius Expansion Burst**

Expansion->Contraction->Cooling



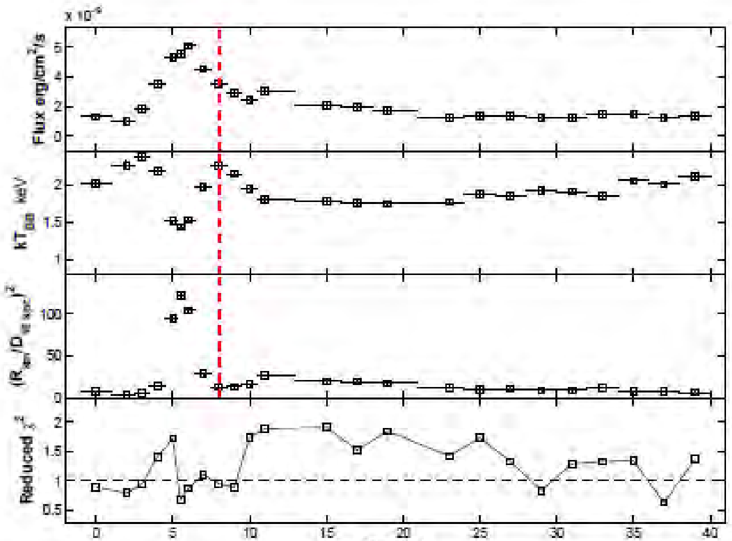
- **The radiation pressure is larger than the gravitational one.**
- **Photospheric layers are lifted off the surface by the radiation pressure.**
- $L \sim L_{\mathrm{Edd}}$ **at touchdown moment**

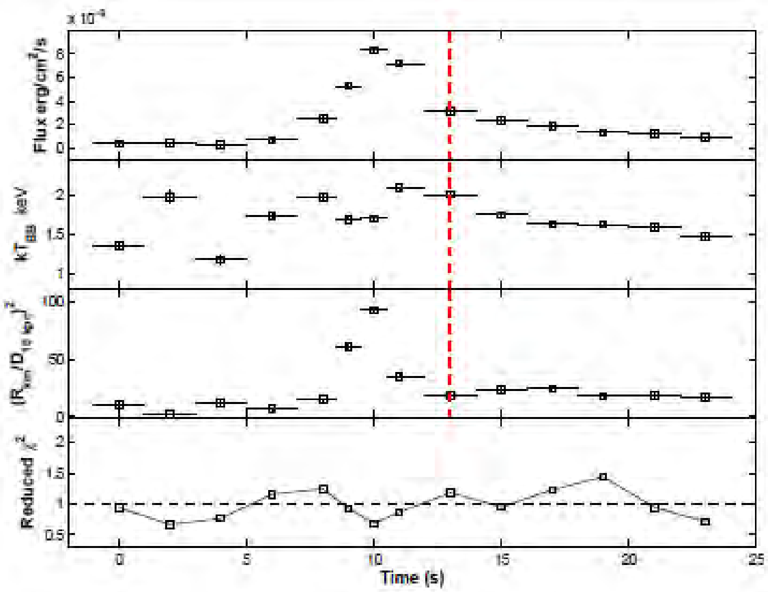
$$F_{\mathrm{TD}} = \frac{GMc}{k_{\mathrm{es}} D^2} (1 - \frac{2GM}{Rc^2})^{1/2},$$

$$A = \frac{R^2}{D^2 f_c^4} (1 - \frac{2GM}{Rc^2})^{-1},$$

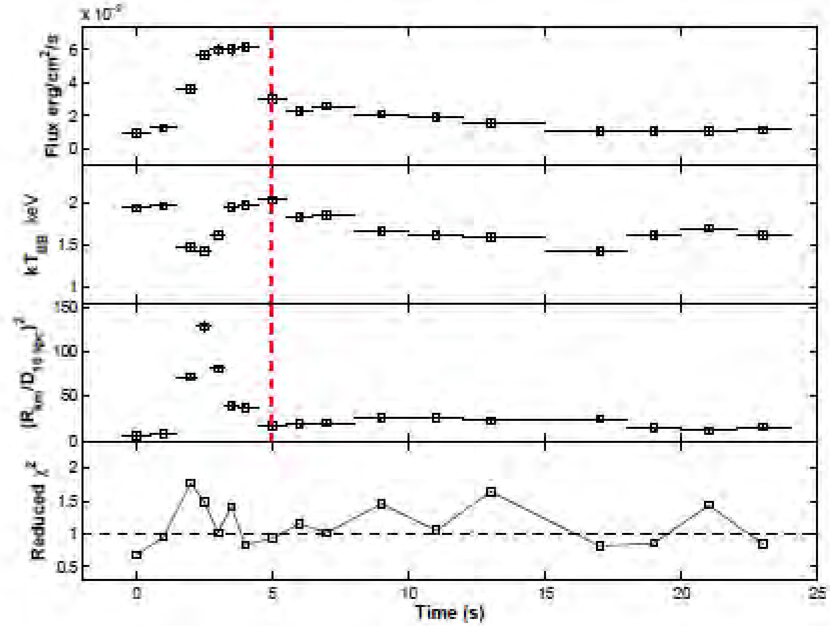
4U 1728-34 **Guver et al. 2012**

RXTE Obs. Of 4U 1746-37/NGC6441





Dipping binary



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

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

Low-mass NS?

Mass-Radius confidence intervals

- **Bayes (Ozel et al.(2009,2010))** $(D,\ f_c, k_{es}, A, F_{TD})$

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

$$A = \frac{R^2}{D^2 f_c^4}(1 - \frac{2GM}{Rc^2})^{-1},$$

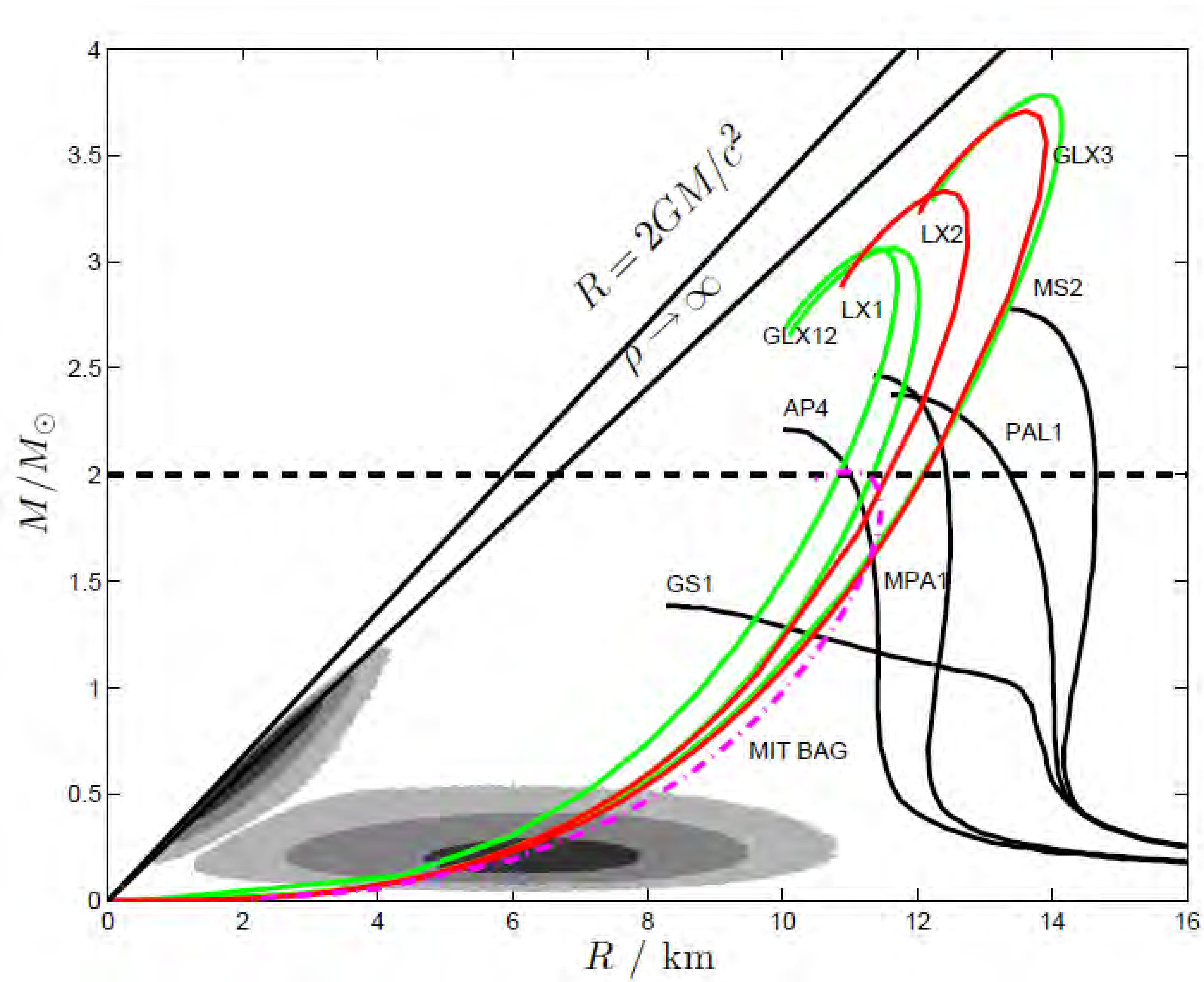
$$k_{es} = 0.2(1 + X)\,\mathrm{cm}^2\ \mathrm{g}^{-1}$$

$$P(D, X, f_c, M, R) = \frac{1}{2}|J(\frac{F_{TD}, A}{M, R})|P(D)P(X) P(f_c)P(F_{TD})P(A)dDdXdf_c dMdR,$$

$$J(\frac{F_{TD}, A}{M, R}) = \frac{2GcR}{k_{es}D^4 f_c^4}(1 - 4\frac{GM}{Rc^2})(1 - \frac{2GM}{Rc^2})^{-3/2}$$

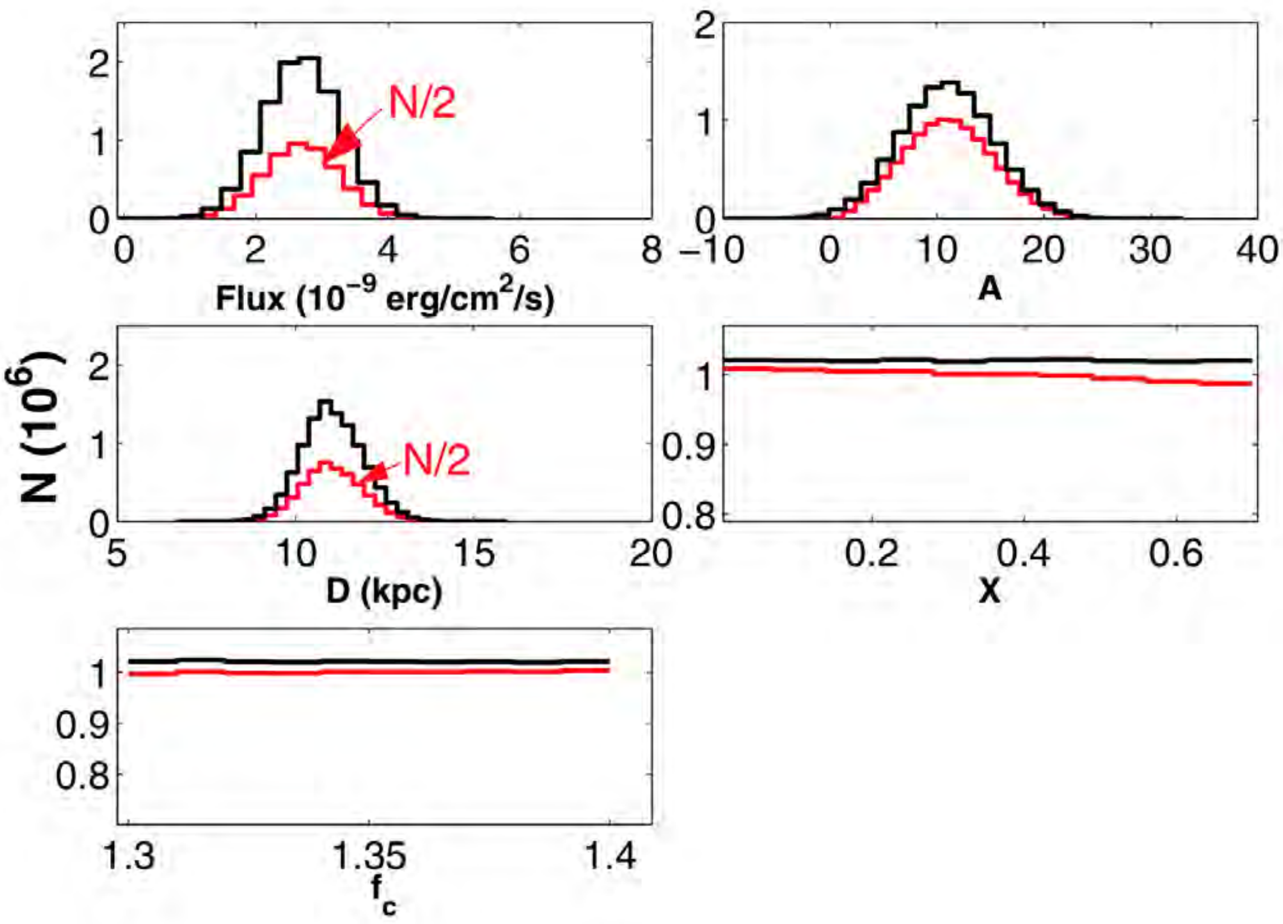
or Monte-Carlo simulation

Results

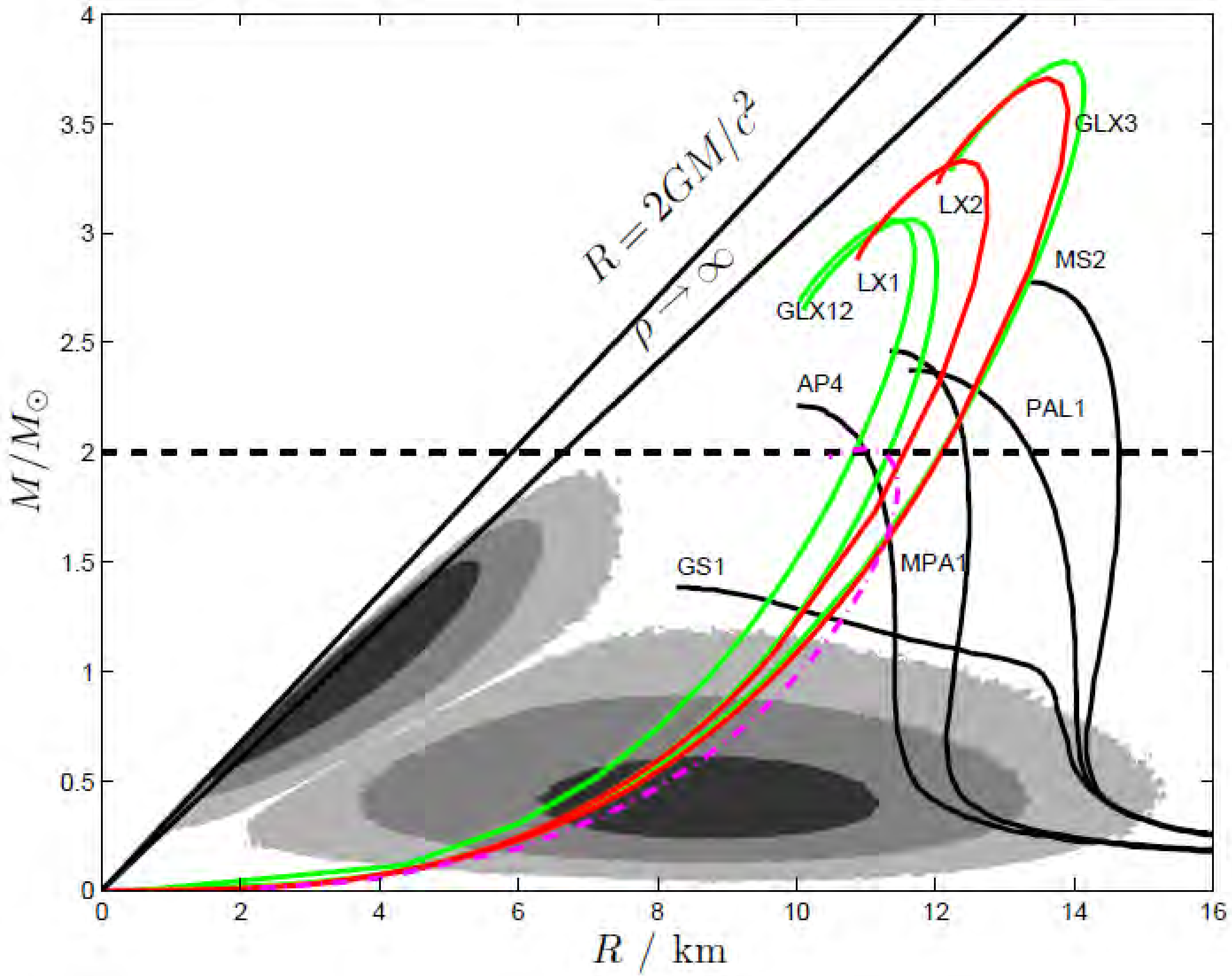


4U 1746-37/NGC 6441

Prior and Posterior Parameter distributions

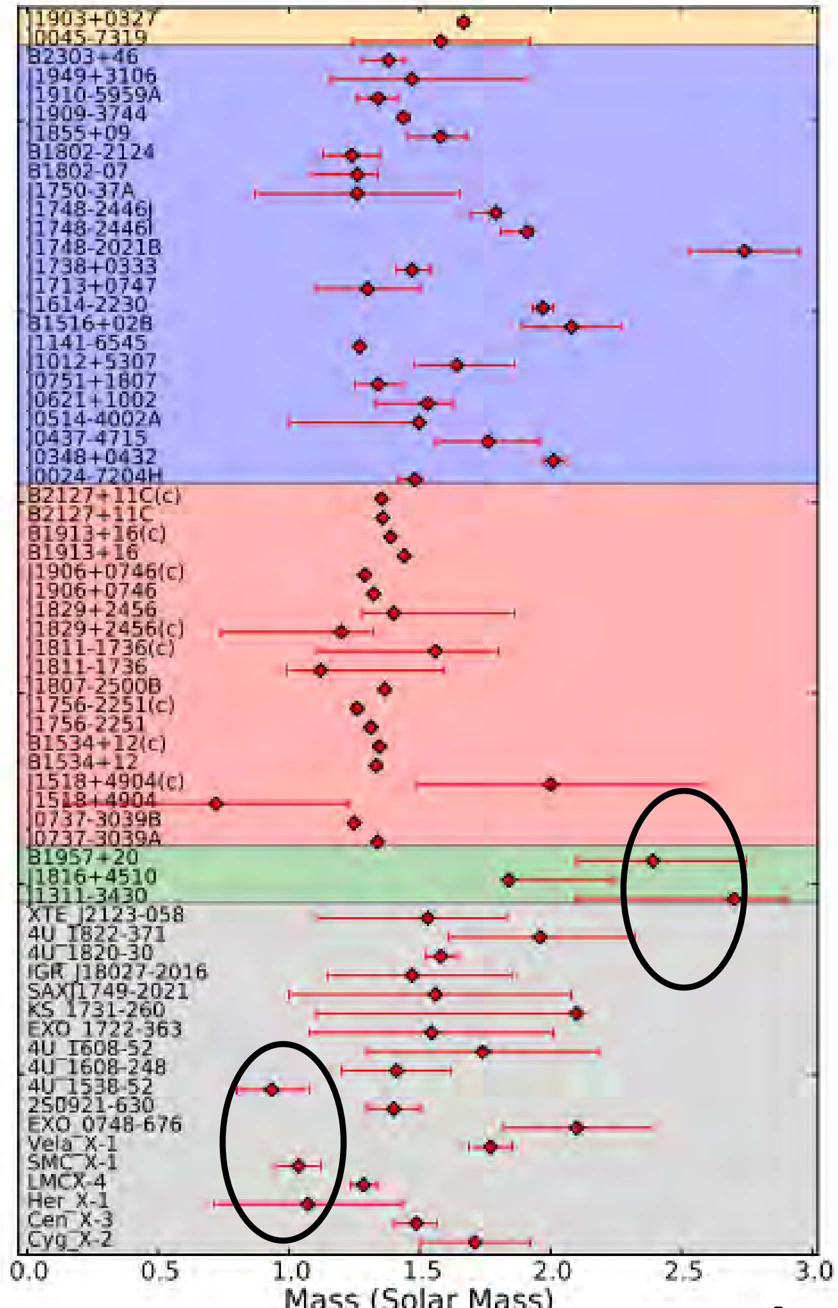


Obscuration



Li et al., ApJ, 2015

Mass



Ultra-high mass Compact Stars ~ 2.5 Msun

Ultra-low-mass Compact Stars ≤ 1 Msun

Anna Watts et al.2014

Why low mass?

- **Large radius gap between gravity bound stars and self-bound stars**

~ 12-14 km vs. ~7 km

- **Formation**

Collapse of a massive star (~0.8-1.0 Msun)

Accretion induced Core-collapse (much lower)

Conclusions and Future Prospects

- **An ultra-low-mass NS may exist in 4U 1746-37**

  < 1.1 Msun

- **EoSs could be effectively tested from low-mass NS**

  Formation (Accretion Induced Core-collapse)

  Radius Gap

- **Multi-method for a single object**

  Pulse profile

  qLMXB

  X-ray Burst …