Using mHz QPOs to put constraints on neutron star size and equation of state

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We performed a variability study of archival XMM-Newton data of 4U 1636-536, a neutron star (NS) low mass X-ray binary, and investigated the energy dependence of its low frequency variability. Here we present the results of our waveform analysis and phase resolved spectral investigations of the mHz quasi-periodic oscillations (QPOs). Our study showed that the oscillations are not caused by variations in the blackbody temperature of the NS, but revealed a correlation between the change of the count rate during the mHz QPO pulse and the spatial extent of a region emitting blackbody emission. The maximum size of the emission area allowed us to obtain a lower limit on the size of the NS that rules out equations of state that prefer small NS radii.

milli-hertz QPOs

- Detected by Revnivtsev et al. (2001)
- Fractional rms amplitude decreases strongly with energy

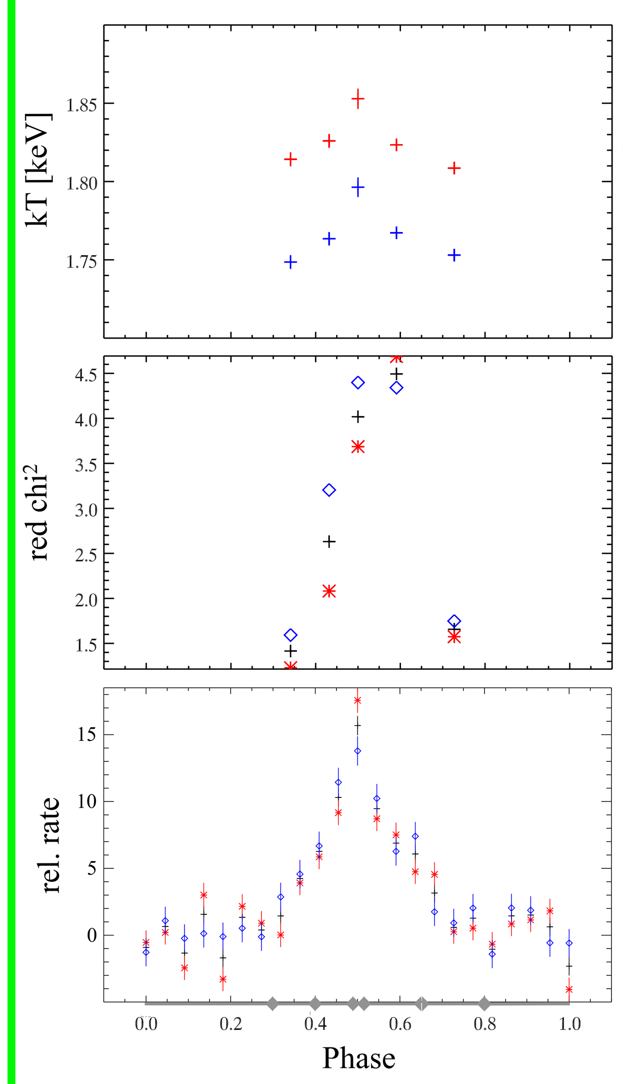
  ➜ possible connection to type I X-ray bursts
- Frequency systematically decreases with time, until oscillations disappear & a type I burst occurs (Altamirano et al. 2008, Lyu et al. 2014, 2015)

  ➜ supports connection to type I X-ray bursts

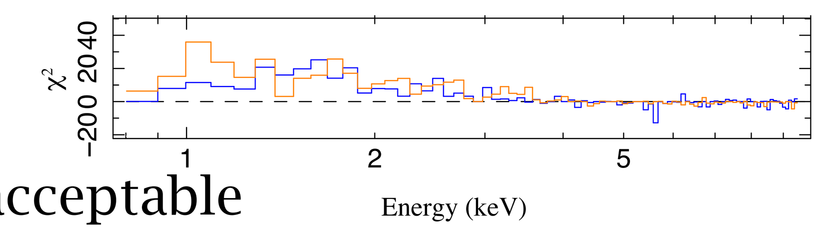
Introduction

- In X-ray binaries (XRBs) a multitude of periodic and quasi-periodic phenomena has been observed (van der Klis 2006; Belloni & Stella 2014)
- Variability mostly associated with orbiting material in the accretion flow (Done et al. 2007; Gilfanov 2010)
- In case of neutron star (NS) accretor matter can accumulate on the NS surface ➜ variability phenomena can originate form the NS surface
- Depending on the properties of the layer of accreted material the ignition conditions for hydrogen or helium fusion can be reached ➜ stable or unstable thermonuclear burning
- Conditions largely set by the mass accretion rate; transition of unstable to stable burning close to ten percent of the Eddington limit (Fujimoto et al. 1981; Bildsten 1998; van Paradijs et al. 1988; Cornelisse et al. 2003)
- At the transition occurs marginally stable burning; thought to be the source of milli-hertz quasi-periodic oscillations (Heger et al. 2007)

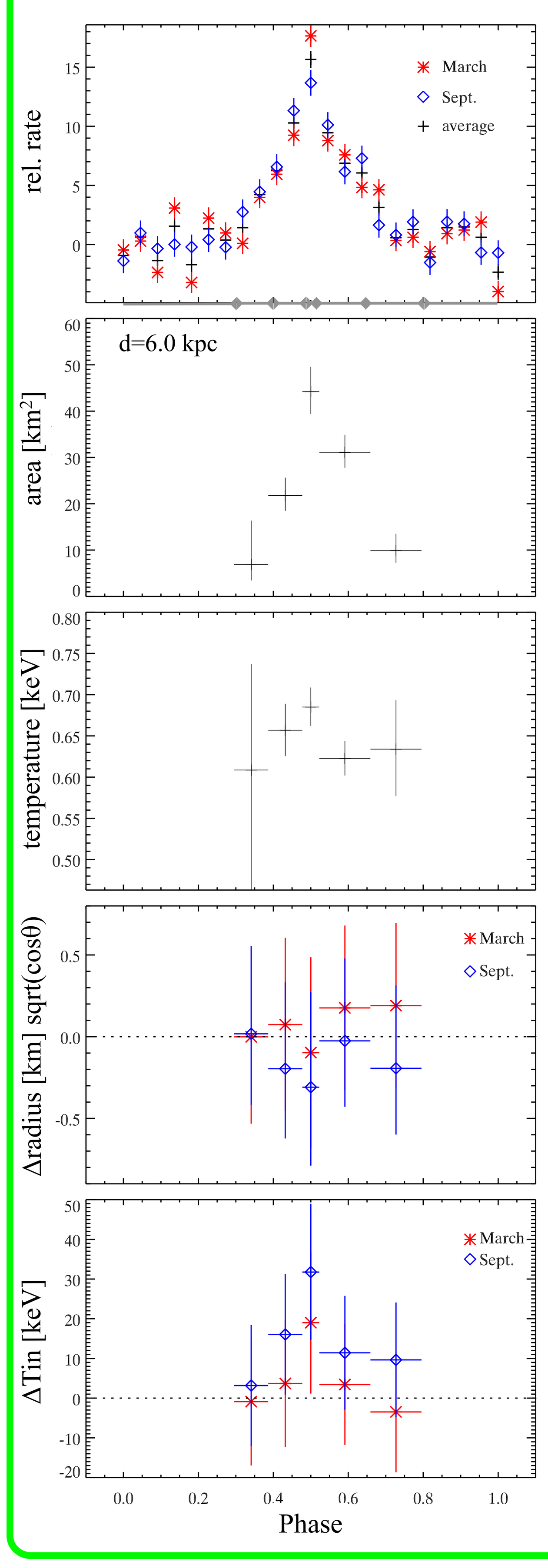
Phase-resolved spectra of mHz QPO



- Spectrum of "quiescent" emission ($\Phi < 0.3$ and $\Phi > 0.8$): blackbody + disc blackbody
- **Interpreting mHz QPO as an oscillatory burning mode across the whole NS surface (Heger et al. 2007):**
  - Neutron star radius (R_{NS}) is fixed
  - Blackbody temperature varies
  - Huge change in χ^2_{red}; χ^2_{red} substantially larger than 1



  - Fits not acceptable
  - Residuals show existence of additional spectral component



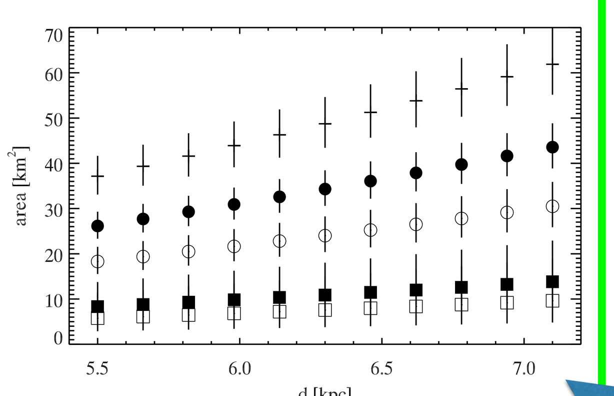
- **Assuming mHz QPO is caused by an additional blackbody:**
  - Fit gives constant temperature
  - Emission area changes with pulse profile
  - Apparent area (R^2_∞) is related to area measured at the NS surface (R^2_{BB}) by (Sztajno et al. 1985):

$$R^2_{BB} = R^2_\infty \times f^4_{col} \times \left(1 - 2\frac{M}{R_{NS}}\right) \quad G = c = 1, \; f_{col} = 1.60^{+0.10}_{-0.15}, \; M/R_{NS} = \beta_{avg} = 0.126 < 0.163$$

Nath et al. (2002)

f_{col} is based on Suleimanov et al. (2012) and has been adapted to XMM-Newton's 1–10 keV range

distance: $6.0^{+1.1}_{-0.5}$ kpc (Galloway et al. 2006)



Dependence of the apparent emission area on the distance. □: $0.3 \leq \varphi < 0.4$; ○: $0.4 \leq \varphi < 0.5$; +: $\varphi = 0.5$; ●: $0.5 < \varphi \leq 0.65$; ■: $0.65 < \varphi \leq 0.8$

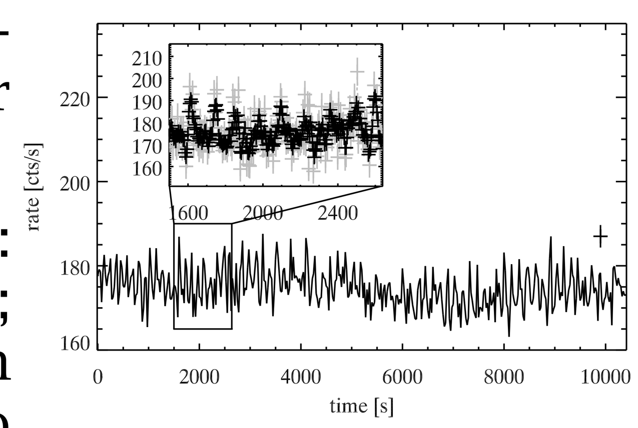
Emission area at peak ➜ lower limit of 11 km on the neutron star radius

- **Assuming mHz QPO is caused by a variable disc blackbody:**
  - Constant inner disc radius
  - Negligible changes in inner disc temperature

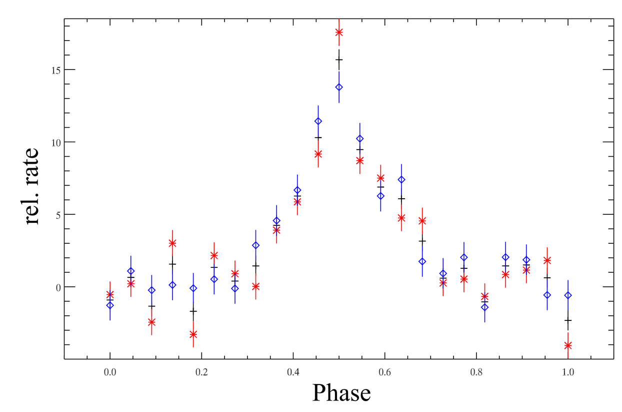
➜ mHz QPO origins on NS surface

mHz QPO waveform

- Derive waveform through a multi-step process (similar to Yu & van der Klis 2002)
- Create template of waveform: smooth light curve by a factor of 3; search local maxima and minima in windows of 140 s; aline maxima to obtain template
- Refine template through correlation with not smoothed light curve in steps of one bin width; new set of extrema from best correlations in windows of 140 s; aline maxima to obtain refined template
- Advantage: do *not* need to assume a specific waveform

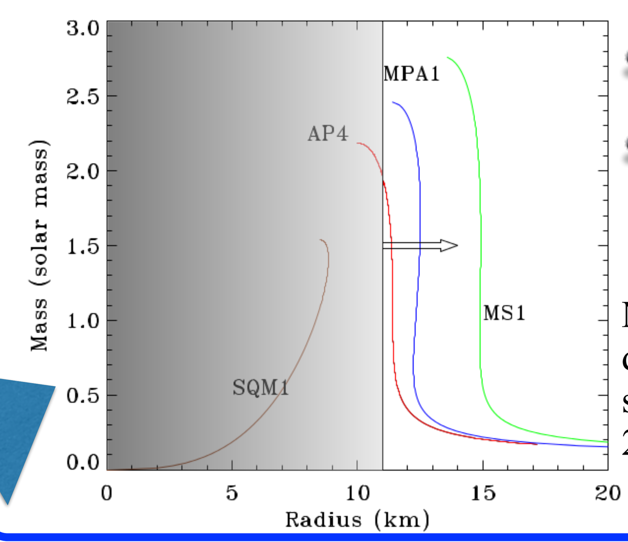


Light curve of the September observation. Bin time 25s (inset 5s)



mHz QPO waveform

Constraints on the equation of state



Mass-radius curves for different equation of states (Ozel & Freire 2016)

- Lower limit (2σ) on NS radius: 11 km
- **Rules out EoS that favour small NS radius**
- NICER and eXTP can improve constraints ($\Delta R_{stat.}$ = 0.3; 0.15 km)

4U 1636-536

- Persistent neutron star low-mass X-ray binary
- Belongs to the class of atoll sources
- Shows intensity variations up to a factor of 10 on an ~ 40 day cycle (Belloni et al. 2007)
- Spin frequency: ~ 581 Hz (Strohmayer & Markwardt 2002)

Observations

- XMM-Newton EPIC/pn timing mode
- March & September 2009
- mHz QPO at similar frequency with upper harmonic
- Continuous exposure: 13.3 & 10.4 ks

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