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

Holger Stiele

National Tsing Hua University, Hsinchu

Wenfei Yu (SHAO), Albert K. H. Kong (NTHU)

ApJ, 831, 34

High Throughput X-ray Astronomy in the eXTP Era, Roma, 6. February 2017

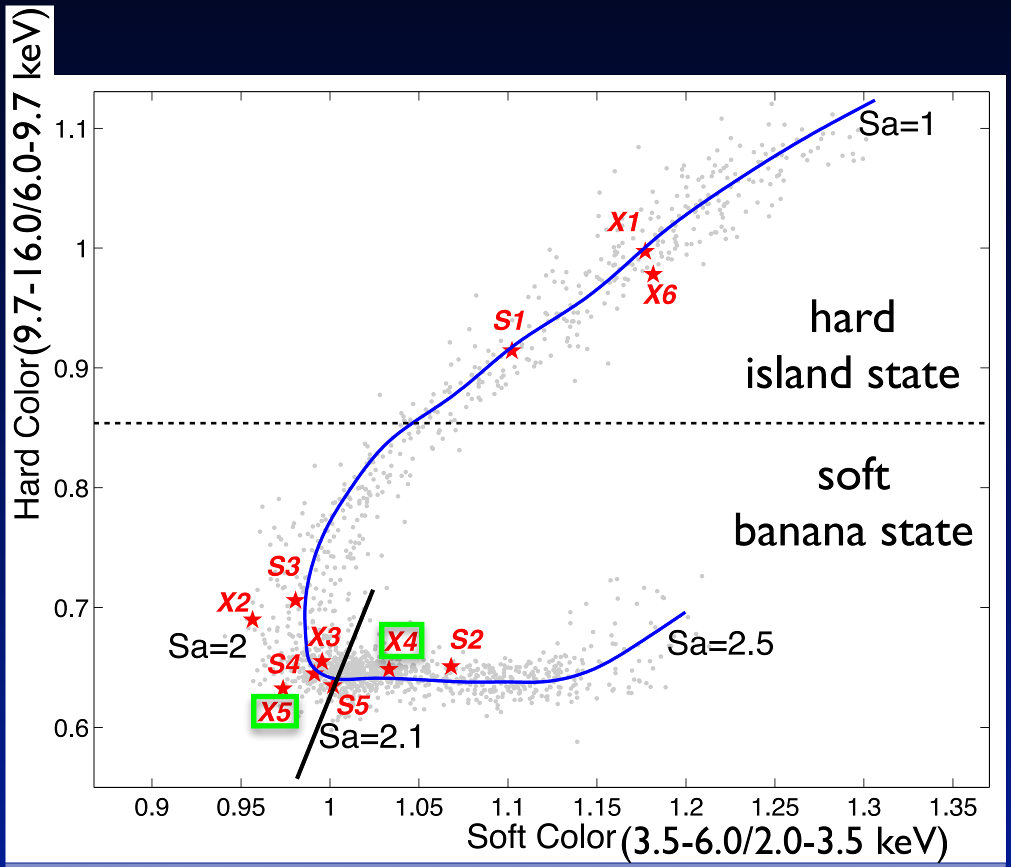
4U 1636-536

- Low-mass neutron star X-ray binary
- Atoll source

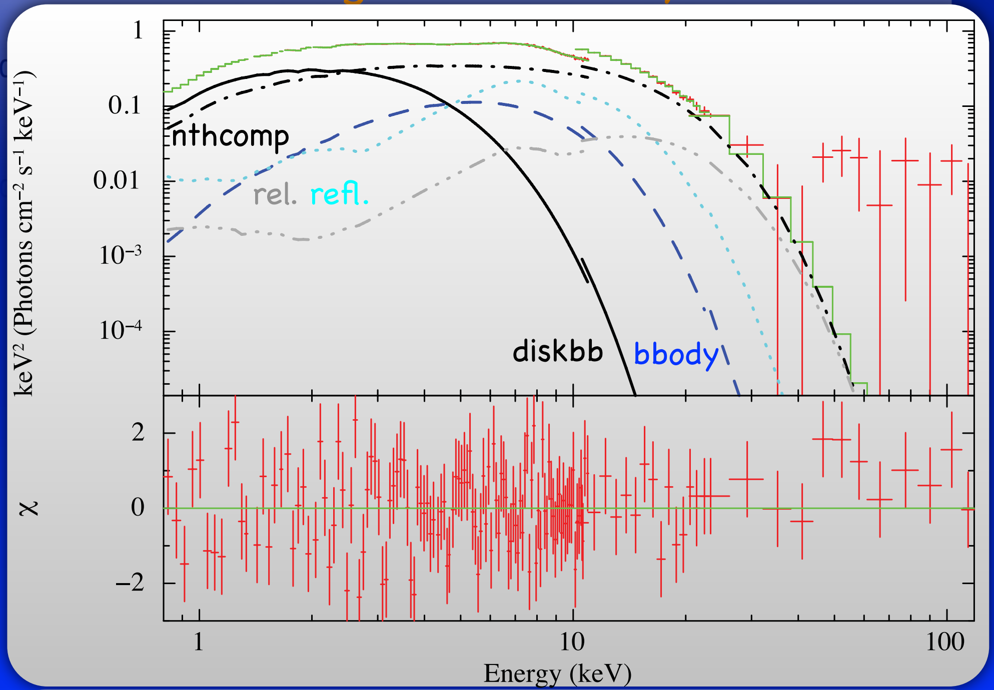
  Hasinger & van der Klis 1989
- Persistent, intensity varies up to a factor 10; ~40 day cycle

  Shih et al. 2005; Belloni et al. 2007; Altamirano et al. 2008
- Discovered 1974 with Copernicus and Uhuru

  Giacconi et al. 1974; Willmore et al. 1974
- Orbital period ~3.8 hr; companion star ~0.5 M⊙; NS ~1.6-1.9 M⊙; distance 6.0±0.5 kpc van Paradijs et al. 1990; Giles et al. 2002; Casares et al. 2006; Galloway et al. 2006



Zhang et al. 2011; Lyu et al. 2014



Sanna et al. 2013

H. Stiele

4U 1636: Timing properties

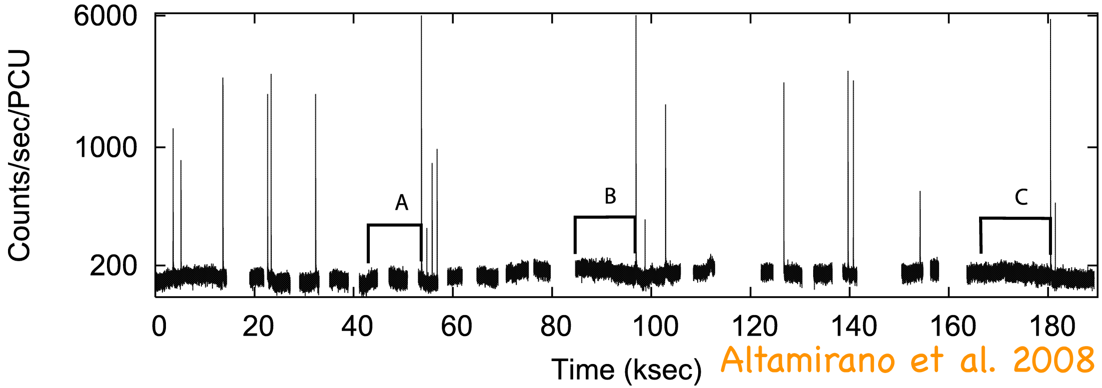
- X-ray burst source

  Hoffman et al. 1977
- Millisecond X-ray pulsar ~518 Hz

  Strohmayer et al. 2002
- Quasi-periodic oscillations on
- kHz
- hHz

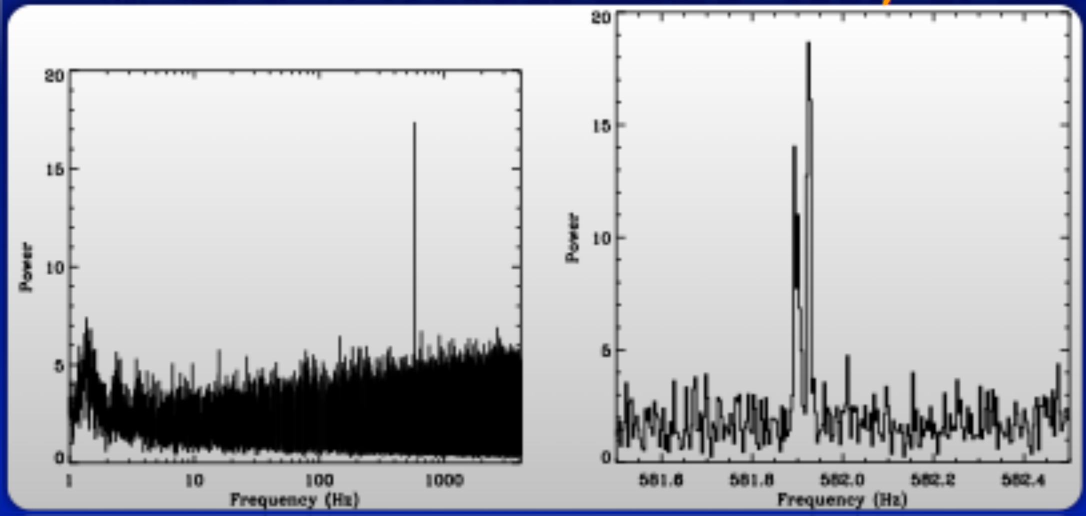
  Wijnands et al. 1997;
  Belloni et al. 2007;
  Sanna et al. 2012;
  Altamirano et al. 2008
- 7-9 mHz

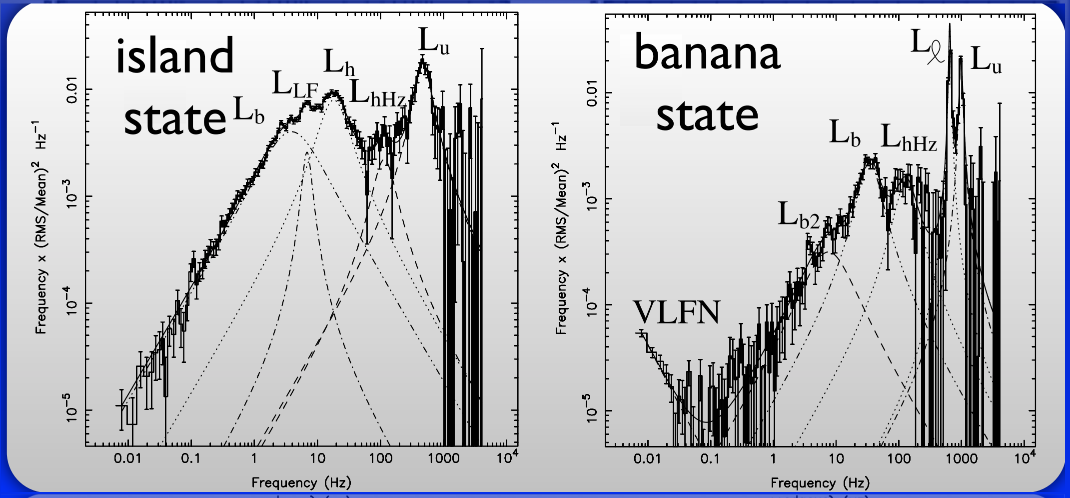
  Revnivtsev et al. 2001;
  Altamirano et al. 2008;
  Lyu et al. 2014; 2015



Altamirano et al. 2008

Strohmayer et al. 2002

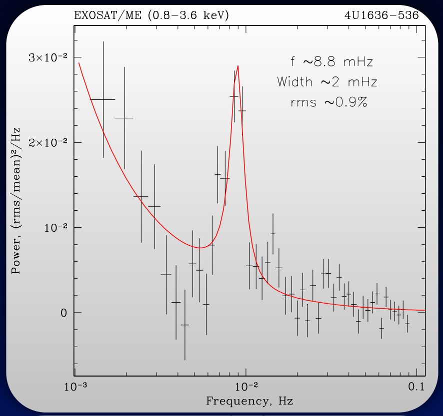




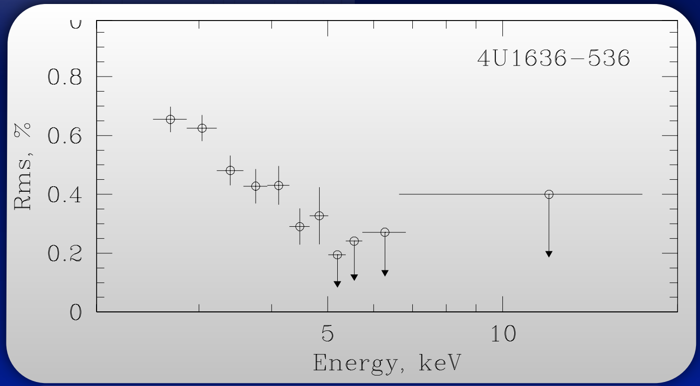
Altamirano et al. 2008

4U 1636: milli-hertz QPOs

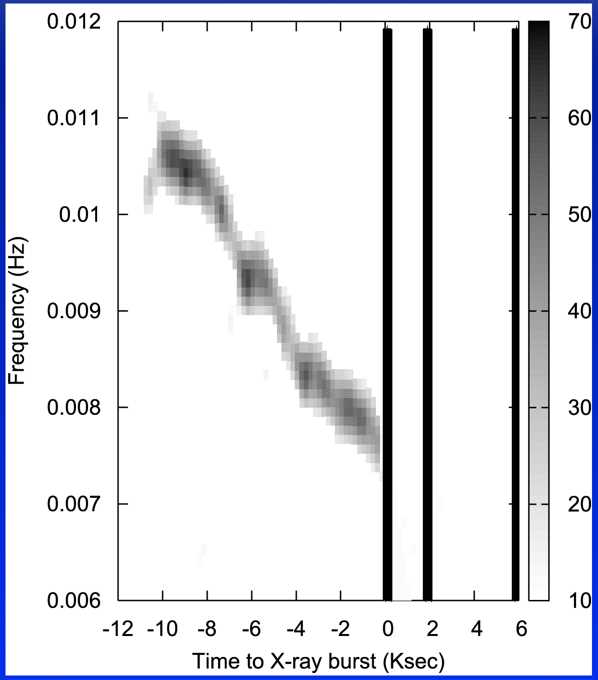
- Detected by Revnivtsev et al. 2001
- Observed at $L_{2\text{-}20\mathrm{keV}} \simeq 5\text{-}11\times10^{36}$ erg s^{-1} close to the transition luminosity between stable and unstable burning
- Fractional rms amplitude strongly decrease with energy
- Possible connection to type I X-ray bursts
- Frequency systematically decrease 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



Revnivtsev et al. 2001



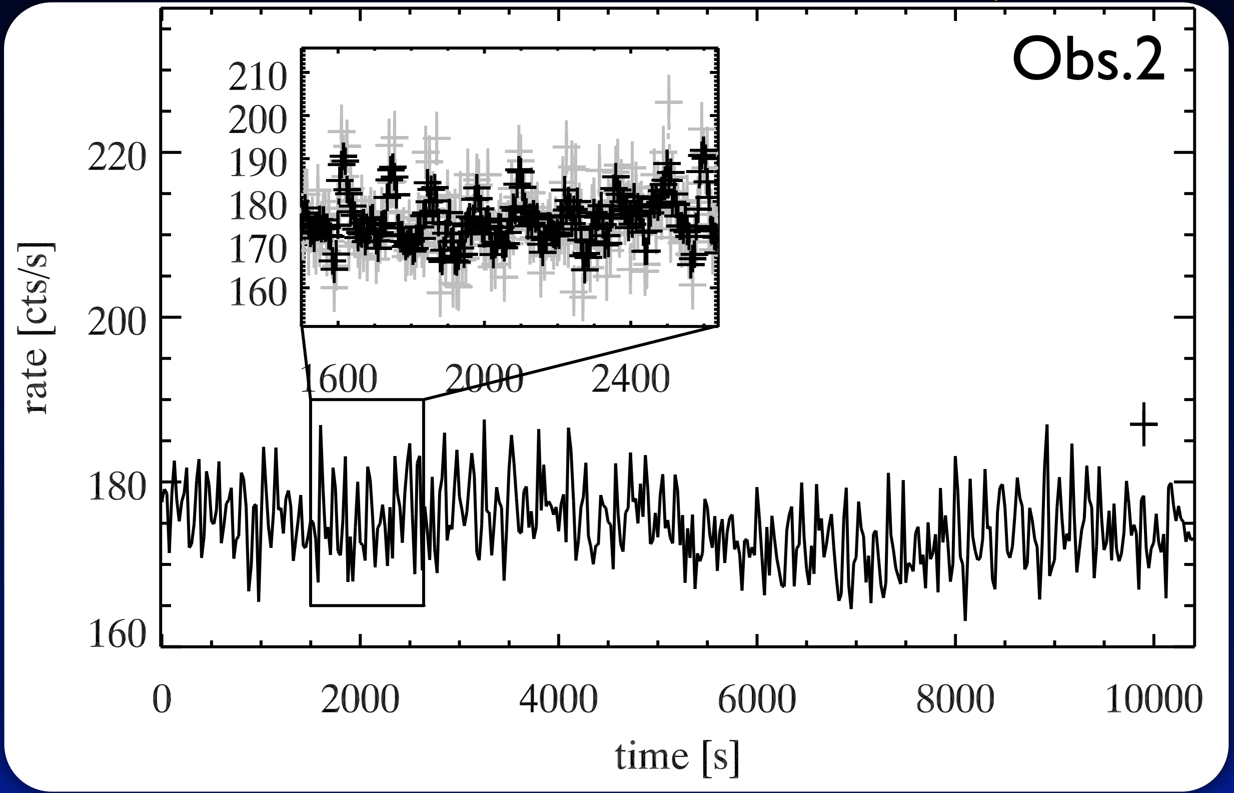
Altamirano et al. 2008

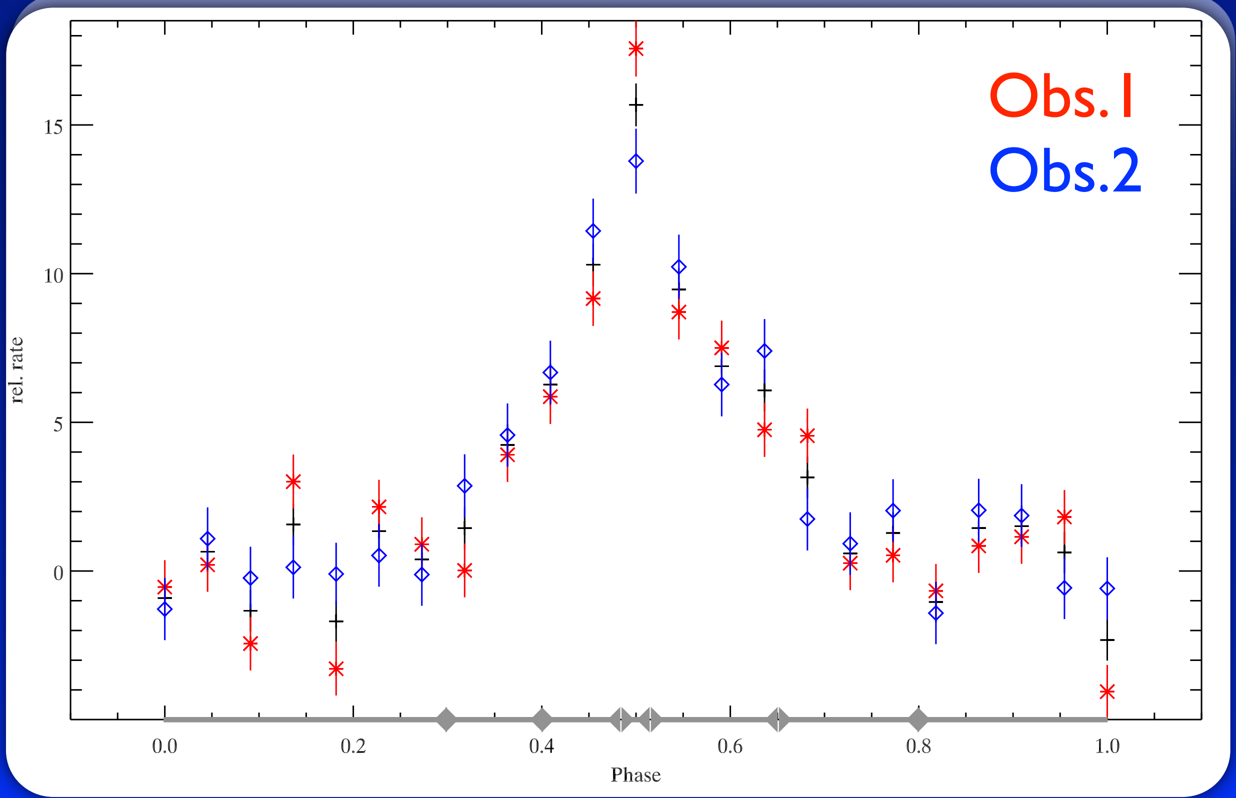


Pulse profile

Stiele et al. 2016, ApJ, 831, 34

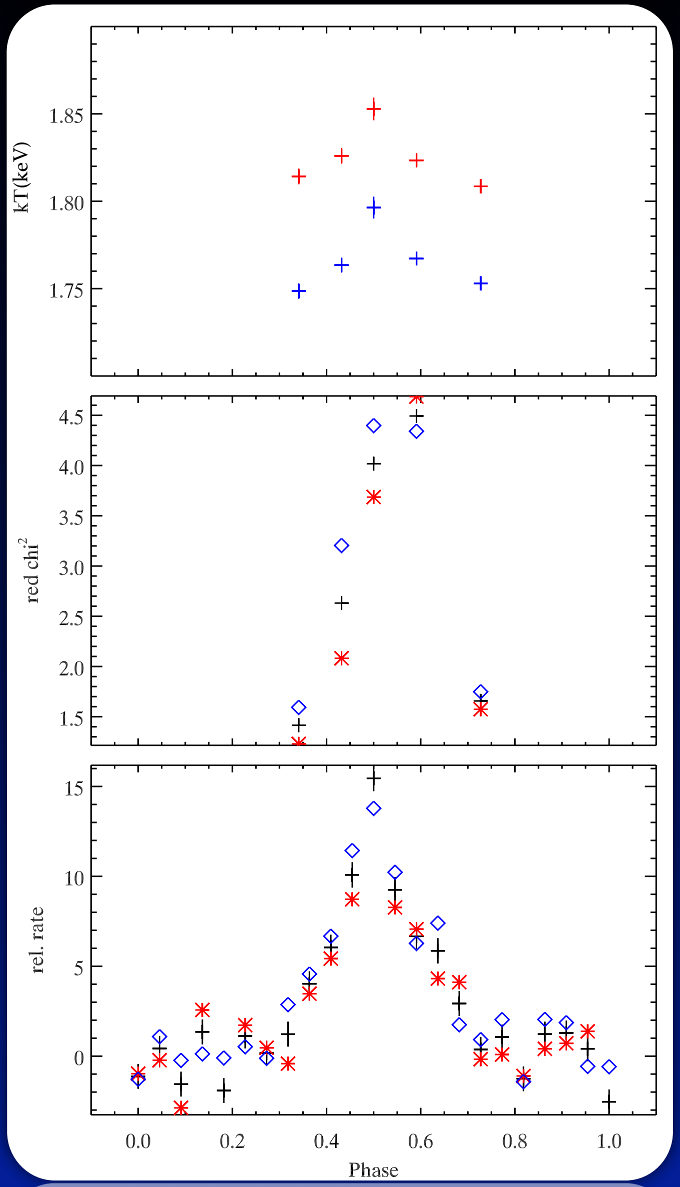
- 2009 March & September XMM-Newton EPIC/pn timing mode observations
- Longest, continuous exposure before type-I X-ray bursts (13.3 & 10.4 ks)
- Full energy range
- Assumption free approach
- Using local maxima and minima to estimate a profile template
- Refining template through correlations



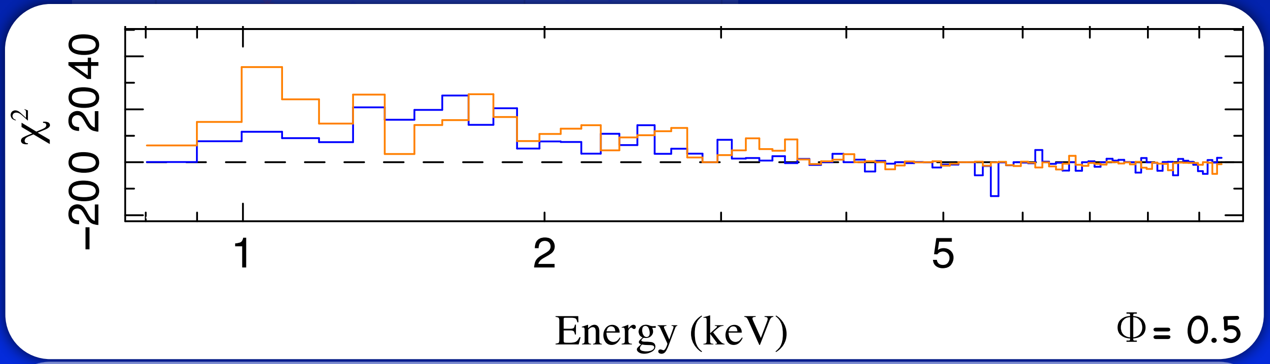


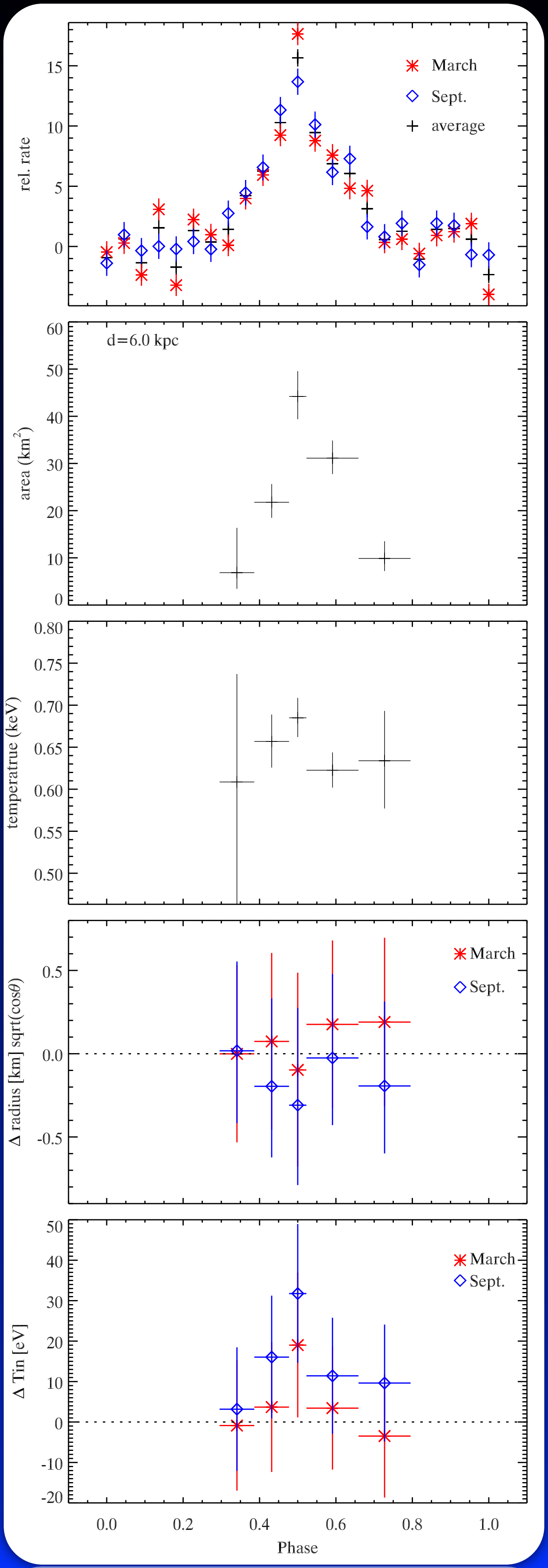
Energy spectrum

- "quiescent" emission ($0.0 \leq \phi \leq 0.3; 0.8 \leq \phi \leq 1.0$): absorbed blackbody + disc blackbody
- Oscillatory burning mode across the whole NS surface Heger et al. 2007, ApJ, 665, 1311
- Variable blackbody temperature:
    - Fix radius (R_{NS}) at "quiescent" value
    - Temperature changes
        - Huge change in $\chi^2_{\rm red}$; $\chi^2_{\rm red}$ substantially larger than 1
            - Fits not acceptable
            - Residuals show additional spectral component



Stiele et al. 2016, ApJ, 831, 34





Energy spectrum

- “quiescent” emission: absorbed blackbody + disc blackbody
- Additional blackbody:
  - constant temperature
  - emission area changes with pulse profile
- Variable disc blackbody:
  - constant inner disc radius
  - negligible change in inner disc temperature

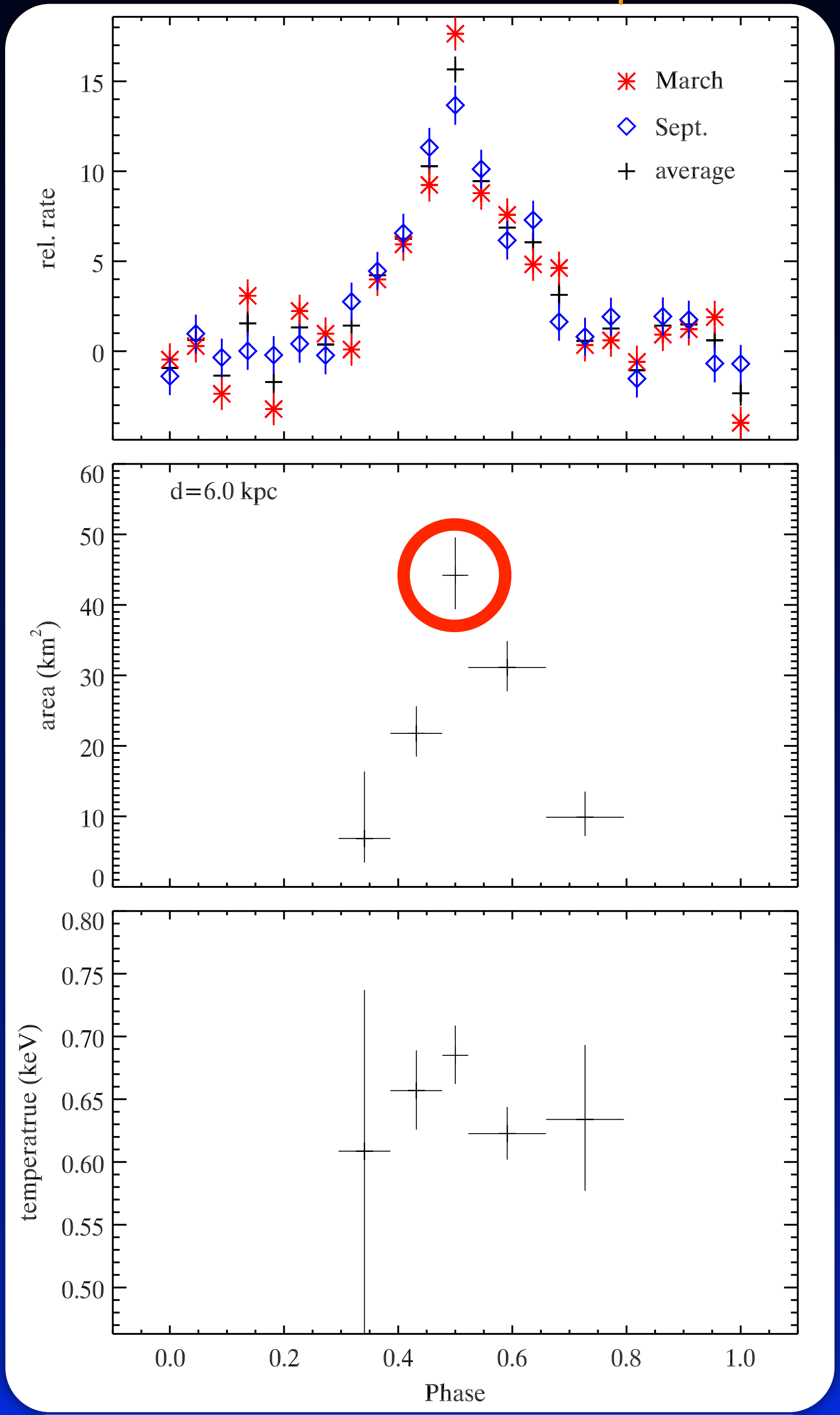
→ mHZ QPO origins on NS surface

Stiele et al. 2016, ApJ, 831, 34

H. Stiele

NS radius

Stiele et al. 2016, ApJ, 831, 34



- Maximum of emission area ➜ lower limit on NS radius

$$R_{\rm BB}^2 = R_\infty^2 \times f_{\rm col}^4 \times \left(1 - 2\frac{M}{R_{\rm NS}}\right)$$

actual area

observed area

hardening factor

$$f_{\rm col} = 1.60^{+0.10}_{-0.15}$$

compactness

$M/R_{\rm NS} = \beta = 0.126 < 0.631$

Nath et al. 2002

Sztajno et al. 1985

G = c = 1

fitting atmosphere spectra for different effective gravity values and He enriched (Lyu et al. 2015) compositions in the 0.5-1.1×10^{37} erg s^{-1} luminosity range (Suleimanov et al. 2012) with a diluted blackbody in the 1-10 keV range, appropriate for EPIC/pn

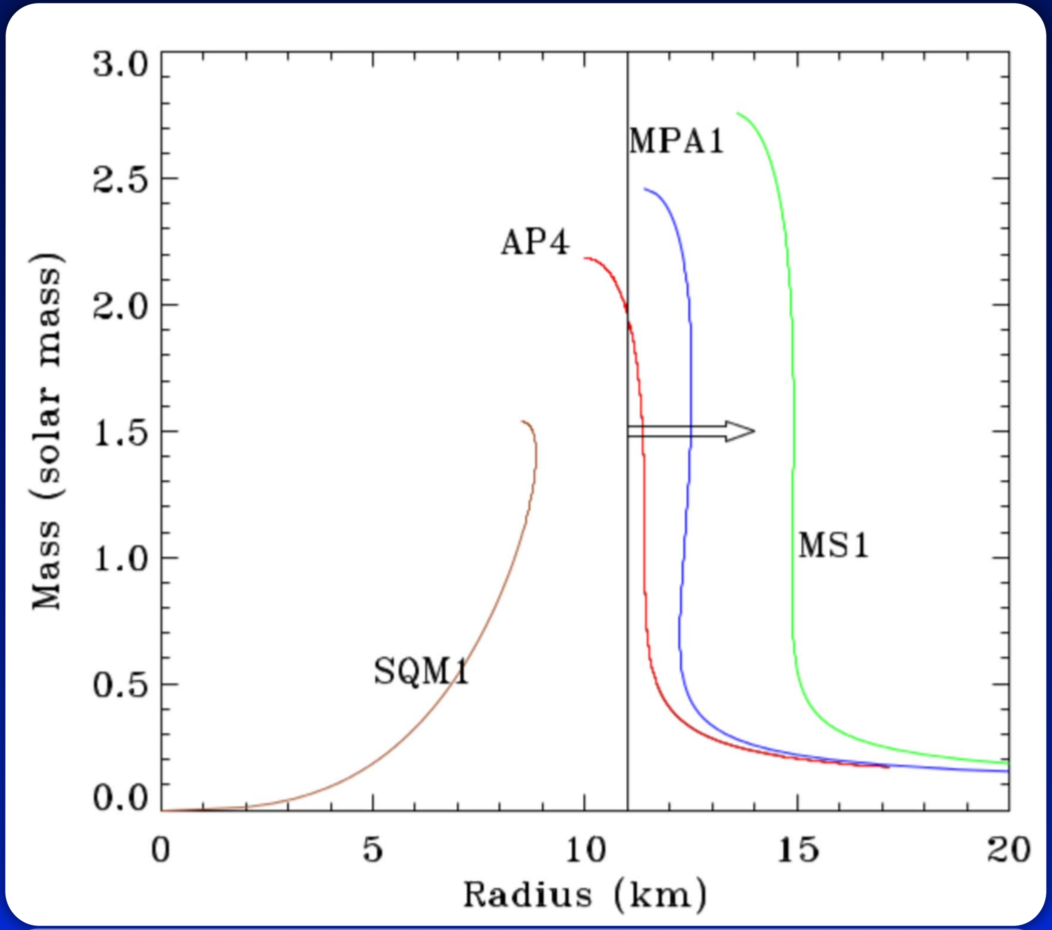
$$R_{\rm BB}^2 = 216.7^{+93.2}_{-86.4}\ {\rm km}^2 \rightarrow R_{\rm BB} = 14.7^{+2.9}_{-3.3}\ {\rm km}$$

H. Stiele

Equation of state

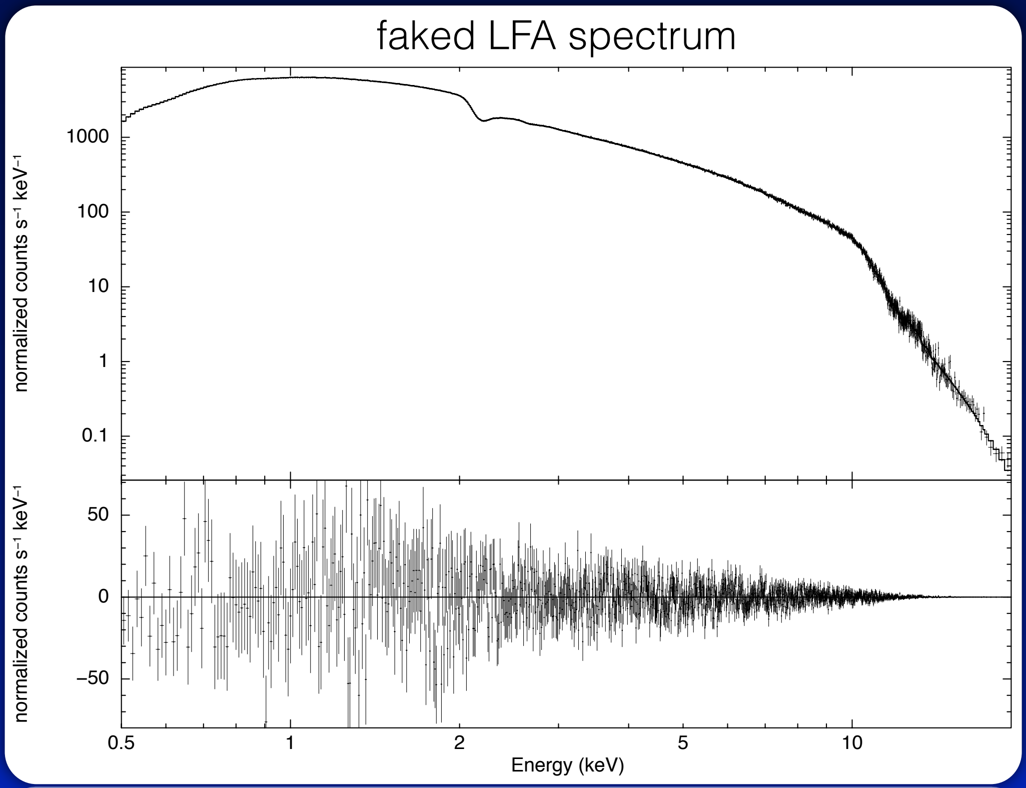
Stiele et al. 2016, ApJ, 831, 34

Ozel & Freire 2016, arXiv:1603.02698



- Lower limit on NS radius: 11 km (2σ)
- Includes uncertainties on the apparent size, hardening factor, and compactness
- Including distance uncertainty lower limit remains above 10 km
- Rules out EoS that favour small NS radius

eXTP: Improving constraints


faked LFA spectrum

- Assume we observe one life cycle of the mHz QPO (19 ks; Lyu et al. 2015) with Low energy Focusing Array
- eXTP can reduce statistical uncertainties in the radius to $\Delta R_{\mathrm{stat.}} \lesssim 0.15$ km
- Constrain NS radius on ±1km using current estimates on distance and hardening factor
- Further improvement achievable as eXTP will improve distance and hardening factors
- Measure emission area for single mHz QPO pulse ➜ push lower limit to larger radii

H. Stiele

Summary

- Phase resolved spectral studies of mHz QPOs in 4U 1636-536
- mHz QPOs are **not** caused by variations in the blackbody temperature of the NS
- Correlation between the change of the count rate during the mHz QPO pulse and the spatial extent of a region emitting blackbody emission ➜ QPO origins on NS surface
- Maximum size of emission region at mHz QPO peak ➜ **lower limit on NS radius ➜ constraints on EoS**
- **eXTP: constrain NS radius on ±1 km + improve distance and hardening factors (constrain R_{NS} on ±0.1 km)**
- **eXTP: measure emission area for single mHz QPO pulse ➜ push lower limit to larger radii**

Thanks for your attention

谢 谢