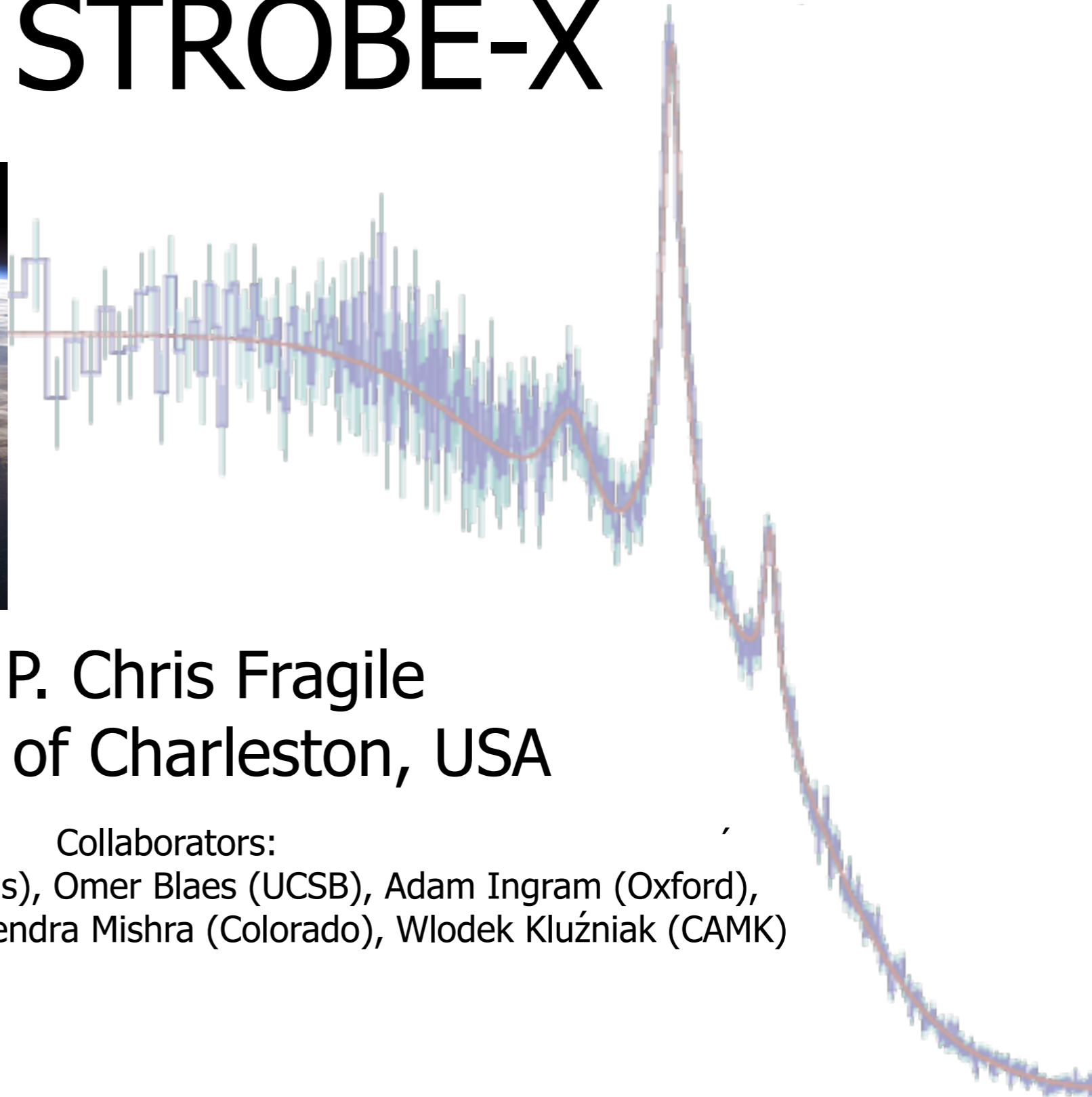
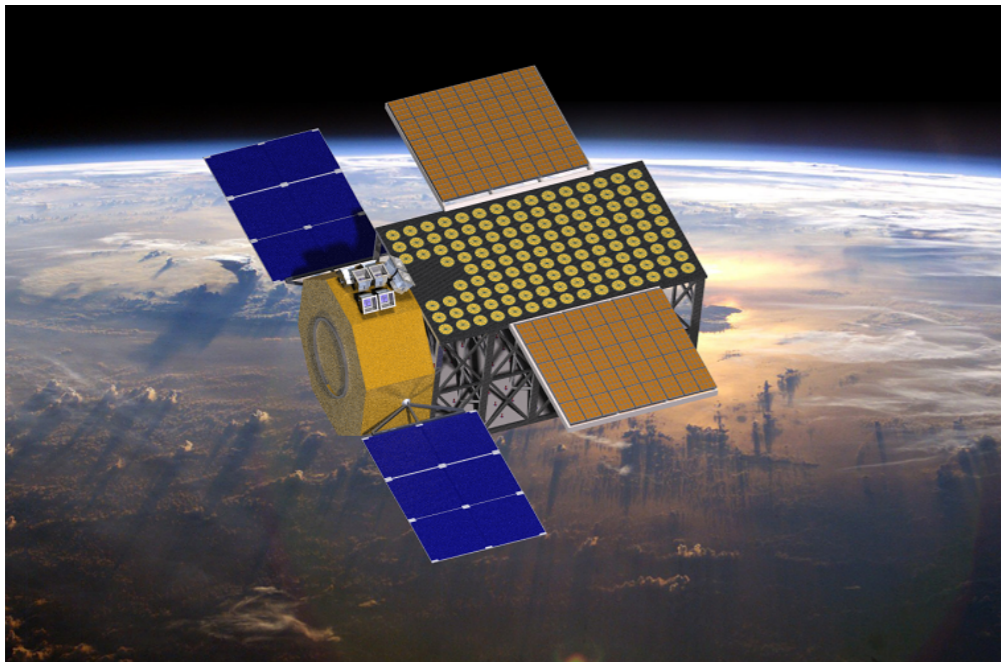


# Quasi-Periodic Oscillations with STROBE-X



Dr. P. Chris Fragile  
College of Charleston, USA

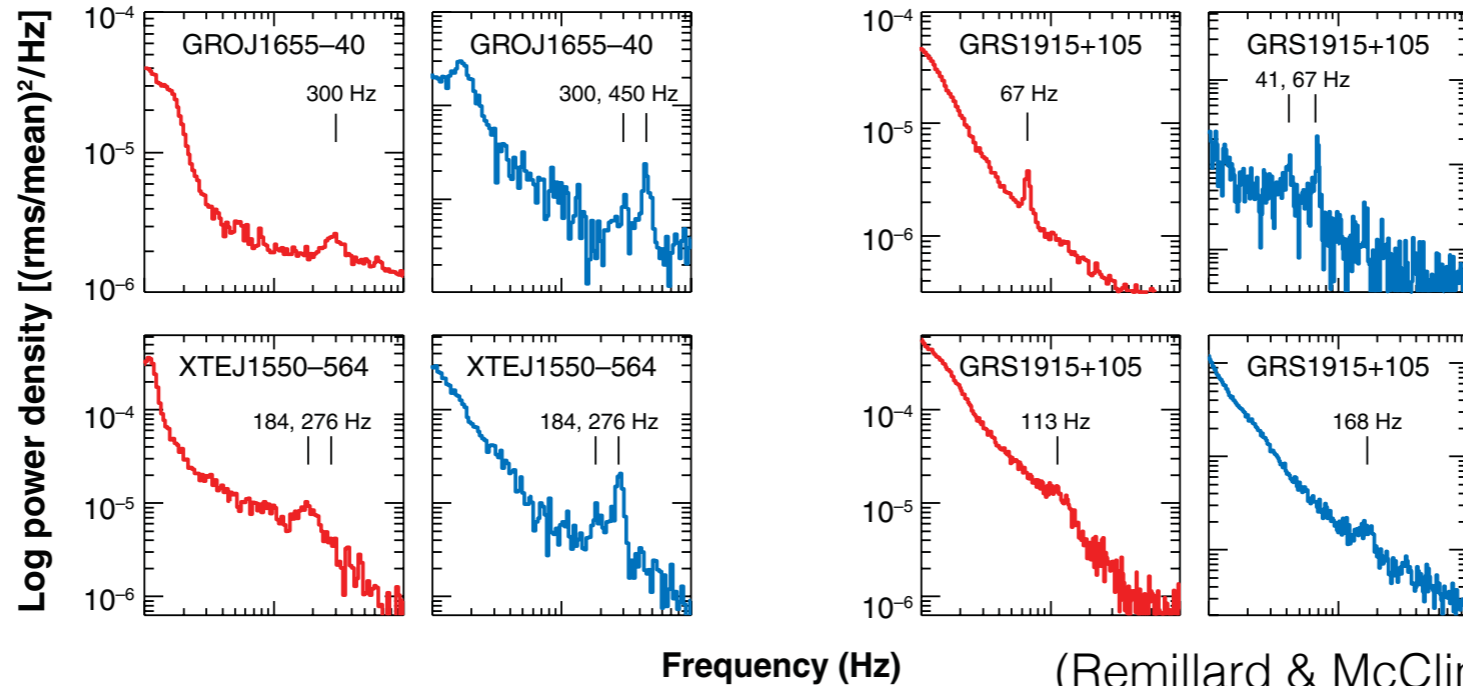
Collaborators:

Odele Straub (Obs. de Paris), Omer Blaes (UCSB), Adam Ingram (Oxford),  
Chris Done (Durham), Bhupendra Mishra (Colorado), Wlodek Kluźniak (CAMK)



# Quasi-Periodic Oscillations (QPOs)

- Peaks in Power Density Spectra of some XRBs



- Why they are interesting

- Tell us something about accretion physics
- Allow measurement of BH spin
- Probe spacetime geometry

(Almost certain)

(Possible)

(Speculative)

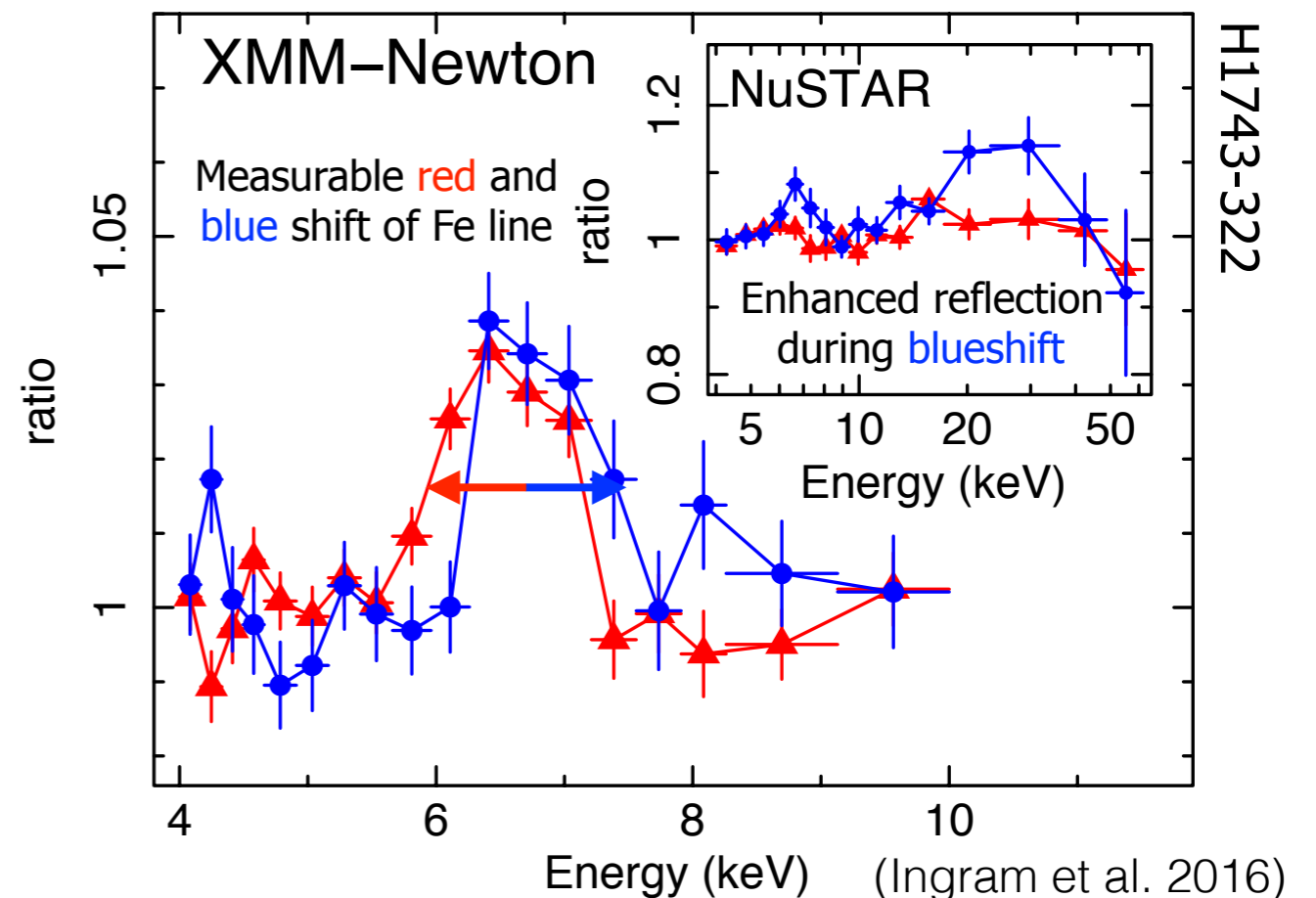
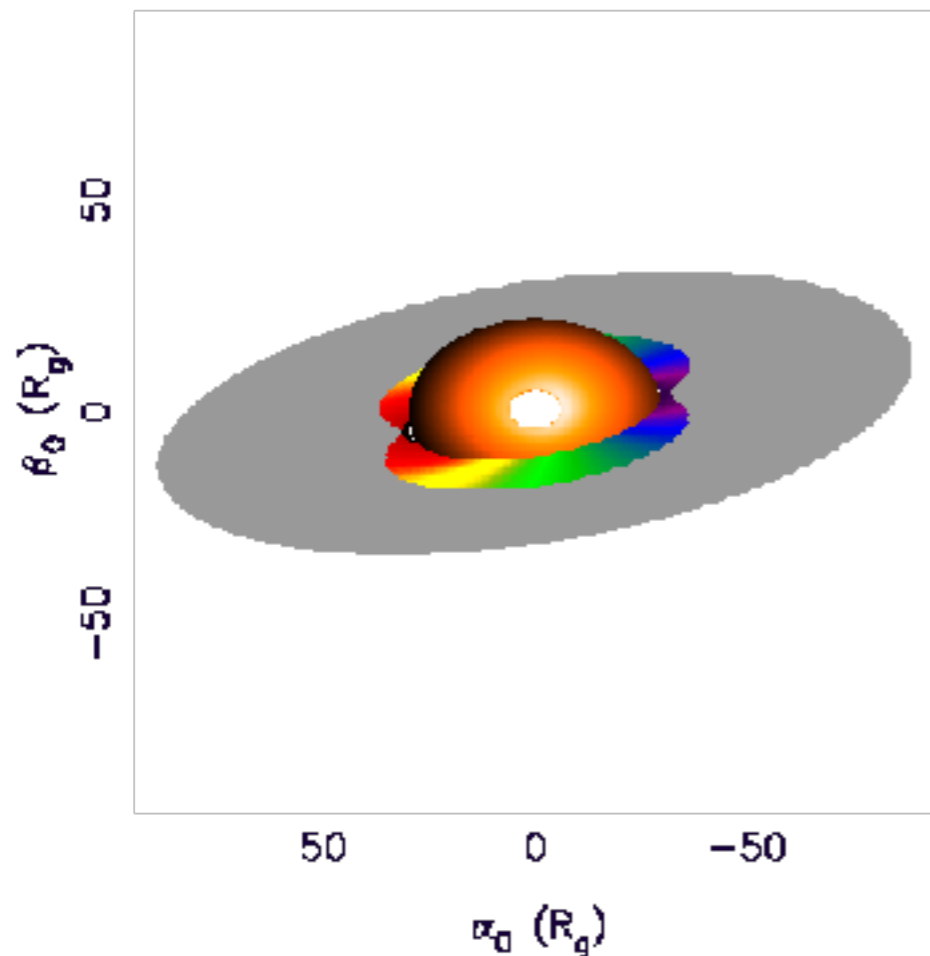
- Focus on two types

- Type-C Low-Frequency QPO (LFQPO)
- High-Frequency QPO (HFQPO)
  - $\gtrsim 100$  Hz
  - 3:2 frequency ratio



# Type-C QPO as precession

- Right frequency range (0.01-10 Hz)
  - Stella & Vietri (1998); Stella et al. (1999); Ingram et al. (2009)
- Fits in with the truncated disk interpretation of Hard state
  - Ingram et al. (2009);
- Explains association of QPO with high inclination sources
  - Homan (2012); Motta et al. (2015)
- Consistent with phase-resolved spectroscopy of Fe-line
  - Ingram & Done (2012); Ingram & van der Klis (2015); Ingram et al. (2016)

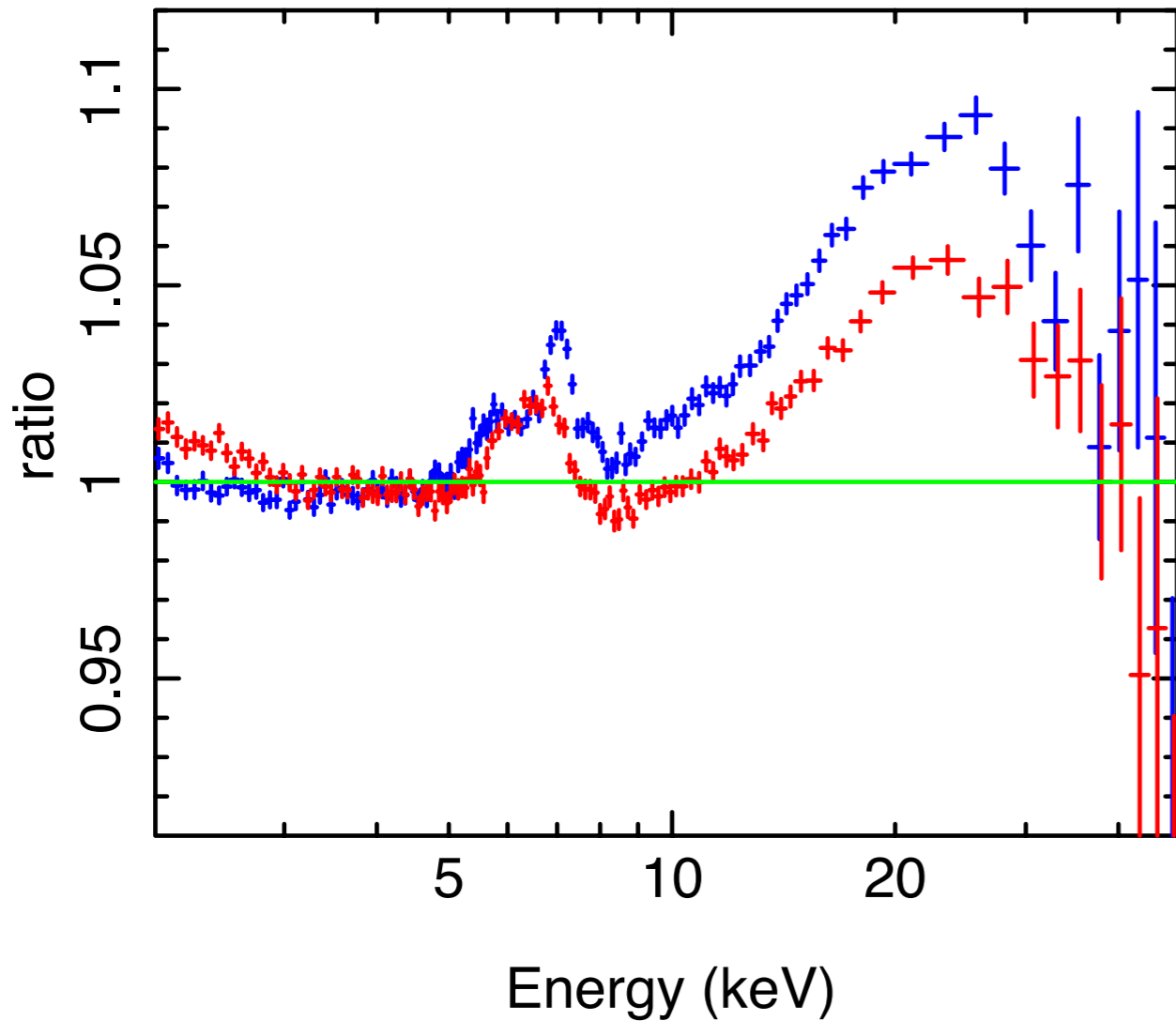




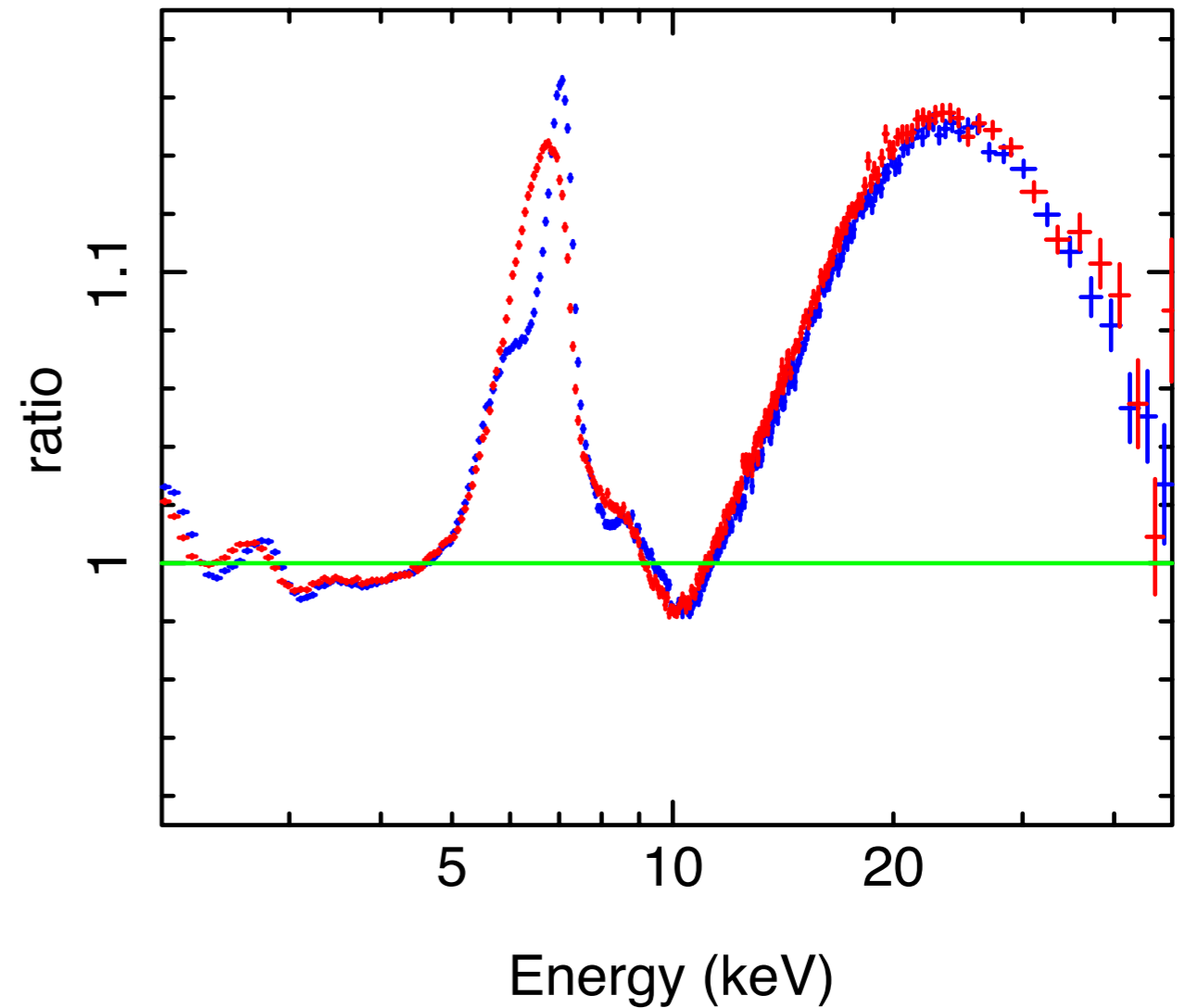
# Type-C QPO as precession

- What could STROBE-X do?

### H1743-322



### GX 339-4



Figures courtesy of Adam Ingram



# Models to explain HFQPOs

- Relativistic Precession Model (RPM)

- Stella & Vietri (1998); Stella et al. (1999)

- Diskoseismic Modes

- Wagoner (1999); Kato (2001); Kato et al. (2008)

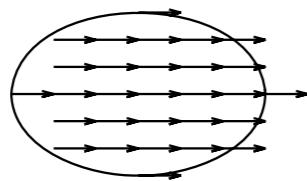
- Resonance Models

- Kluźniak & Abramowicz (2001; 2002); Kluźniak et al. (2004)

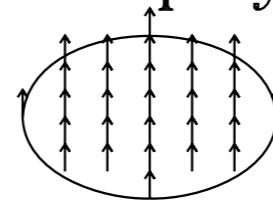
- Global Oscillation Modes

- Rezzolla et al. (2003); Blaes et al. (2006); Török et al. (2016)

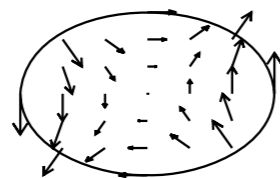
Radial Epicyclic (-+01)



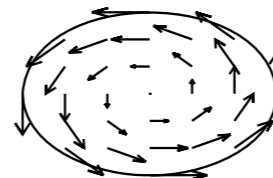
Vertical Epicyclic (+-01)



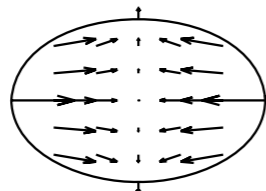
× Mode (- -02)



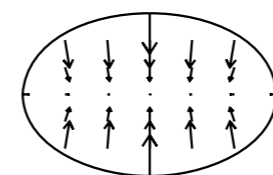
Inertial Mode (- -02)



+ Mode (+ +02)



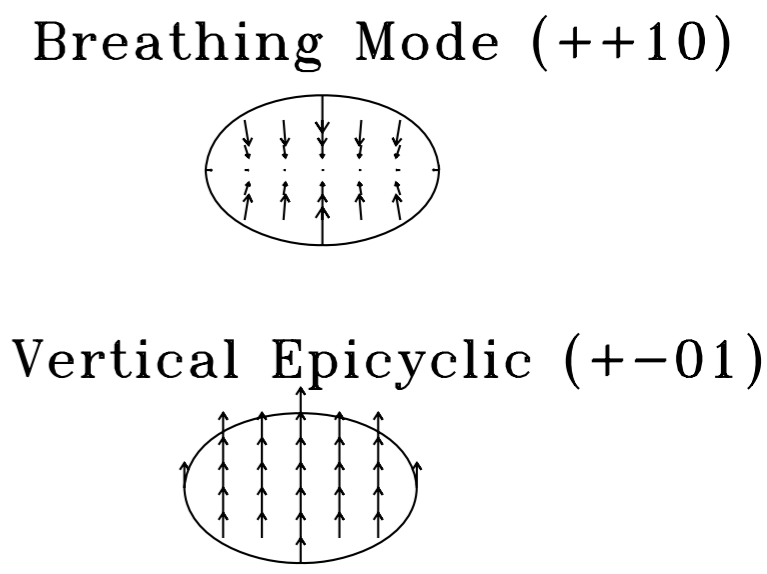
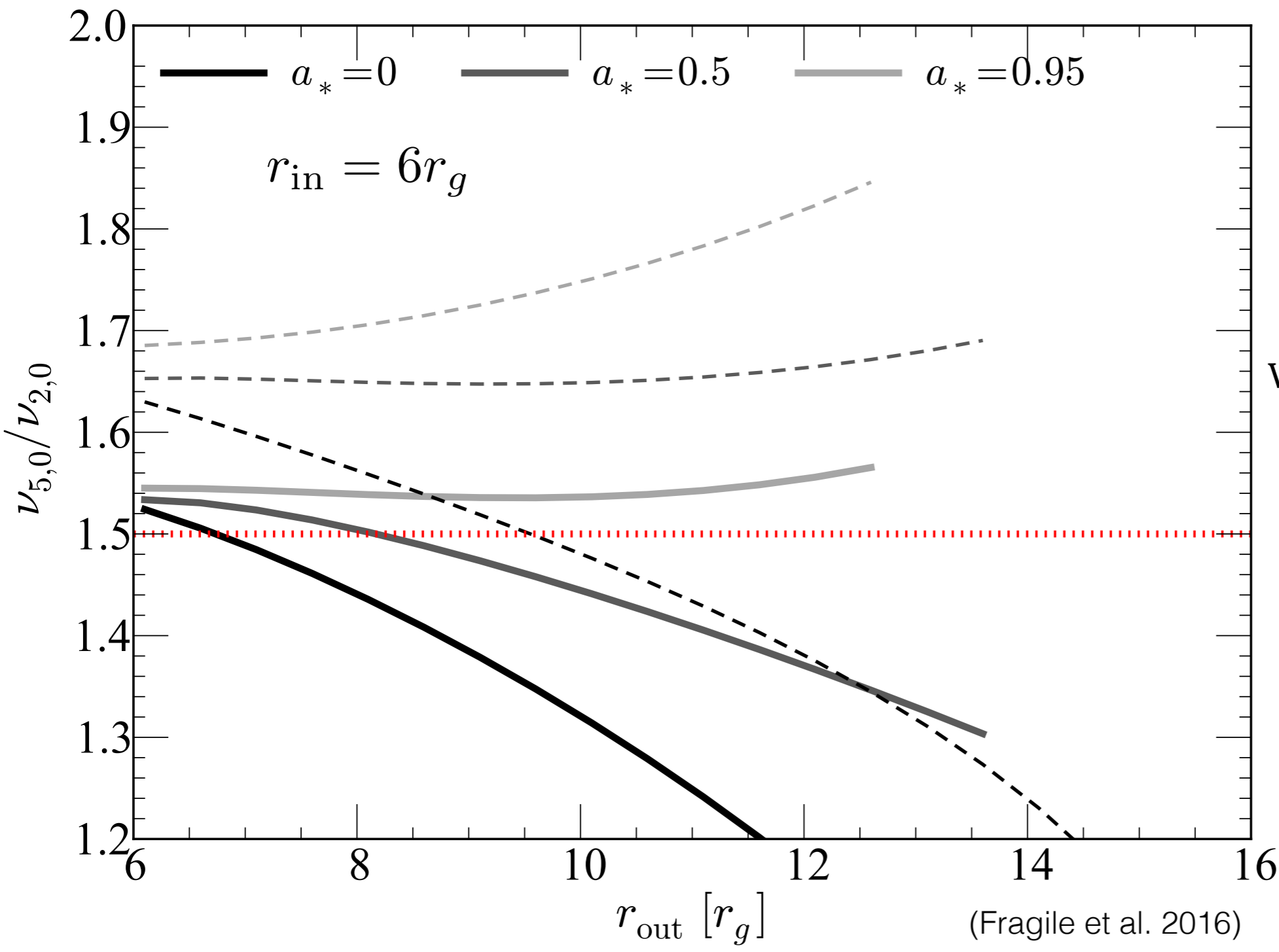
Breathing Mode (+ +10)





# Global modes in near 3:2 ratio

## ● Breathing & vertical epicyclic (Blaes et al. 2006)





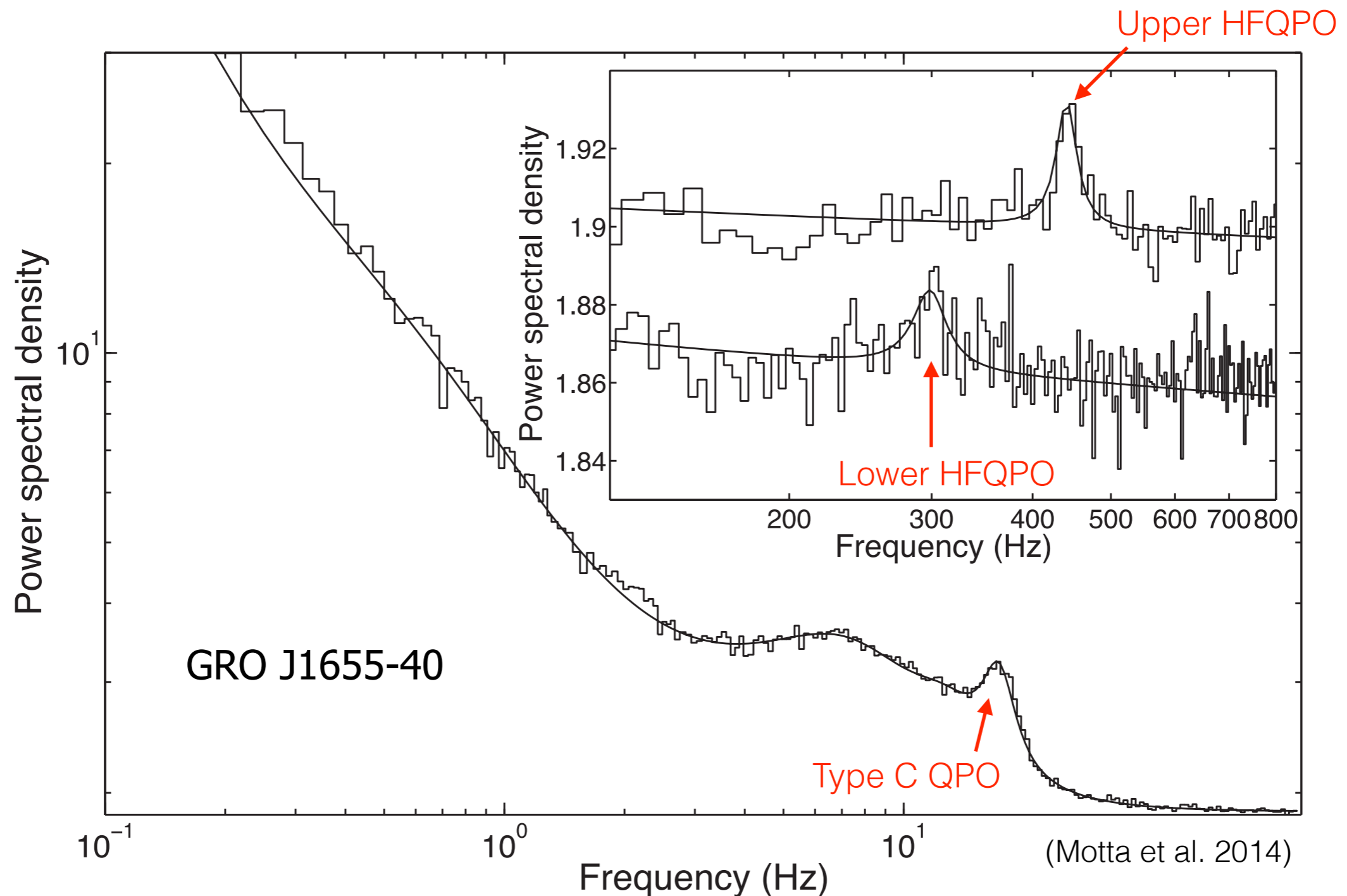
# Simultaneous High Frequency & type-C QPOs

- GRO J1655-40, XTE J1550-564 & H1743-322

- Motta et al. 2014a; Motta et al. 2014b; Homan et al. 2005

- M82 X-1 & NGC 1313 X-1

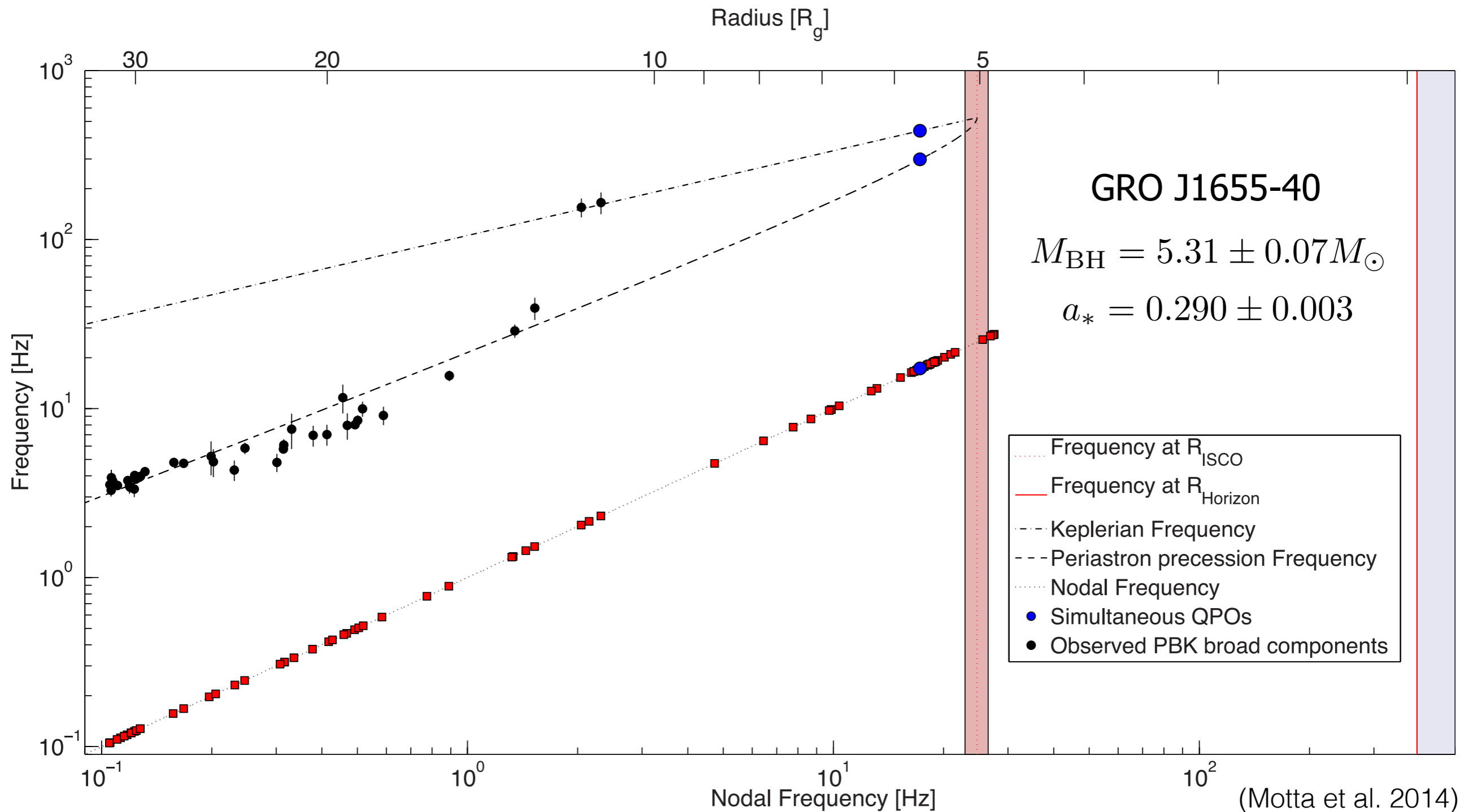
- Pasham et al. 2014; Pasham et al. 2015





# QPO frequency correlation

- Can be fit with Relativistic Precession Model
  - Stella & Vietri 1998; Stella et al. 1999
- Based on test particle frequencies

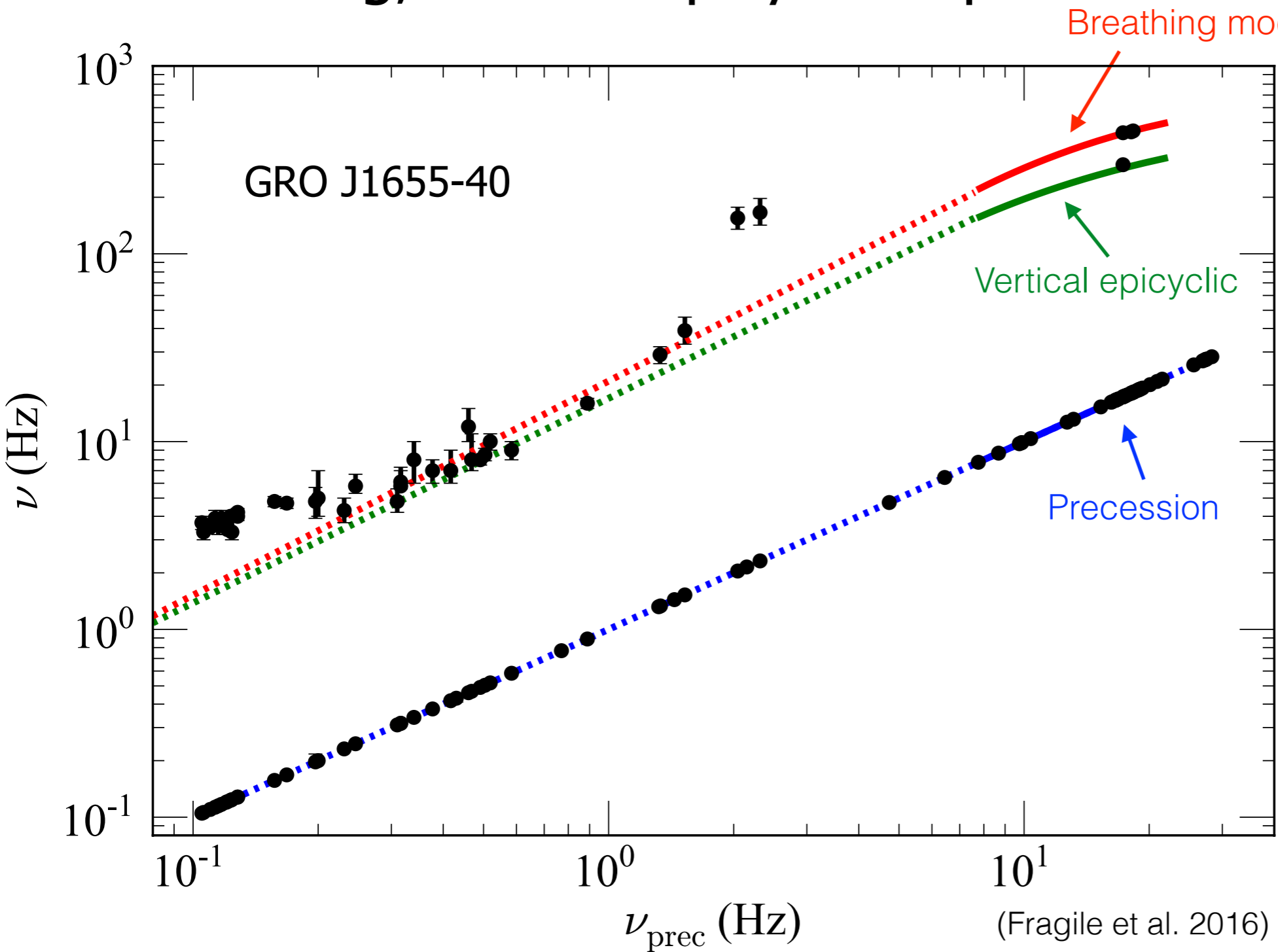




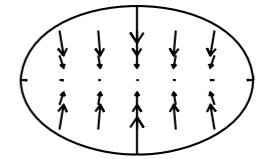


# QPO frequency correlation

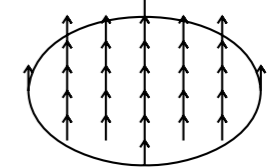
- Breathing, vertical epicyclic & precession (Blaes et al. 2006)



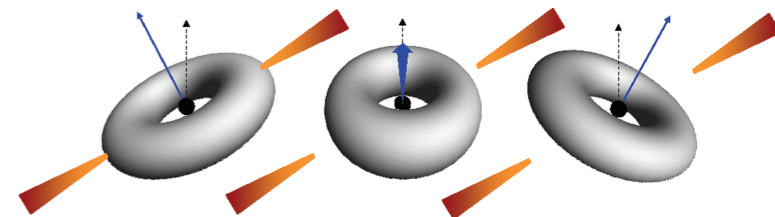
Breathing Mode (++10)



Vertical Epicyclic (+-01)



Precession



- GRO J1655-40

$$M_{\text{BH}} = 5.4 M_{\odot}$$

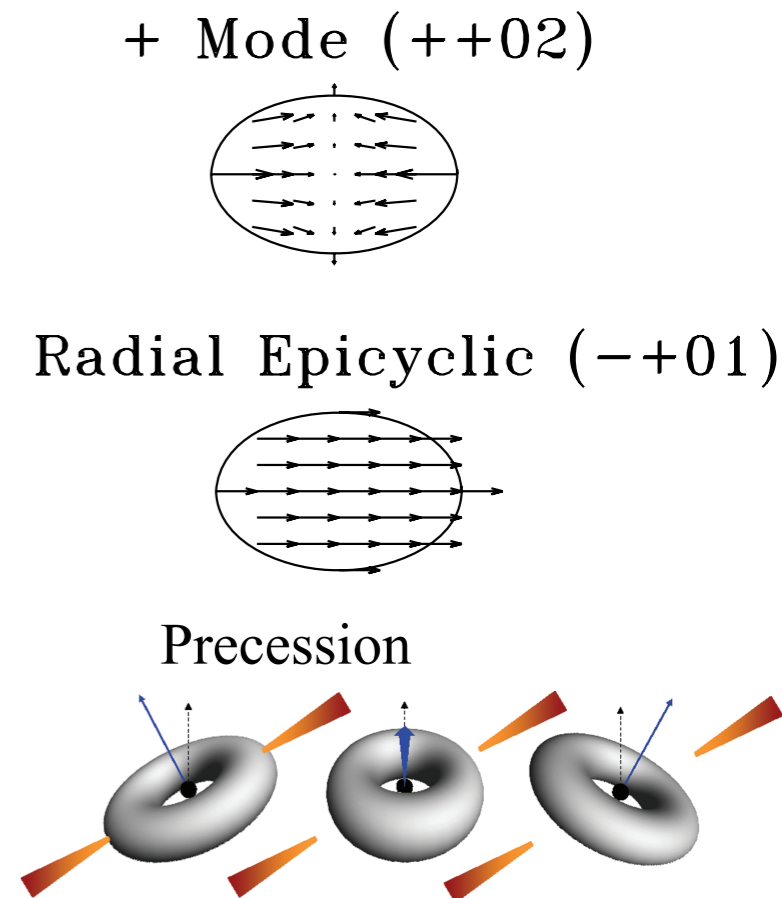
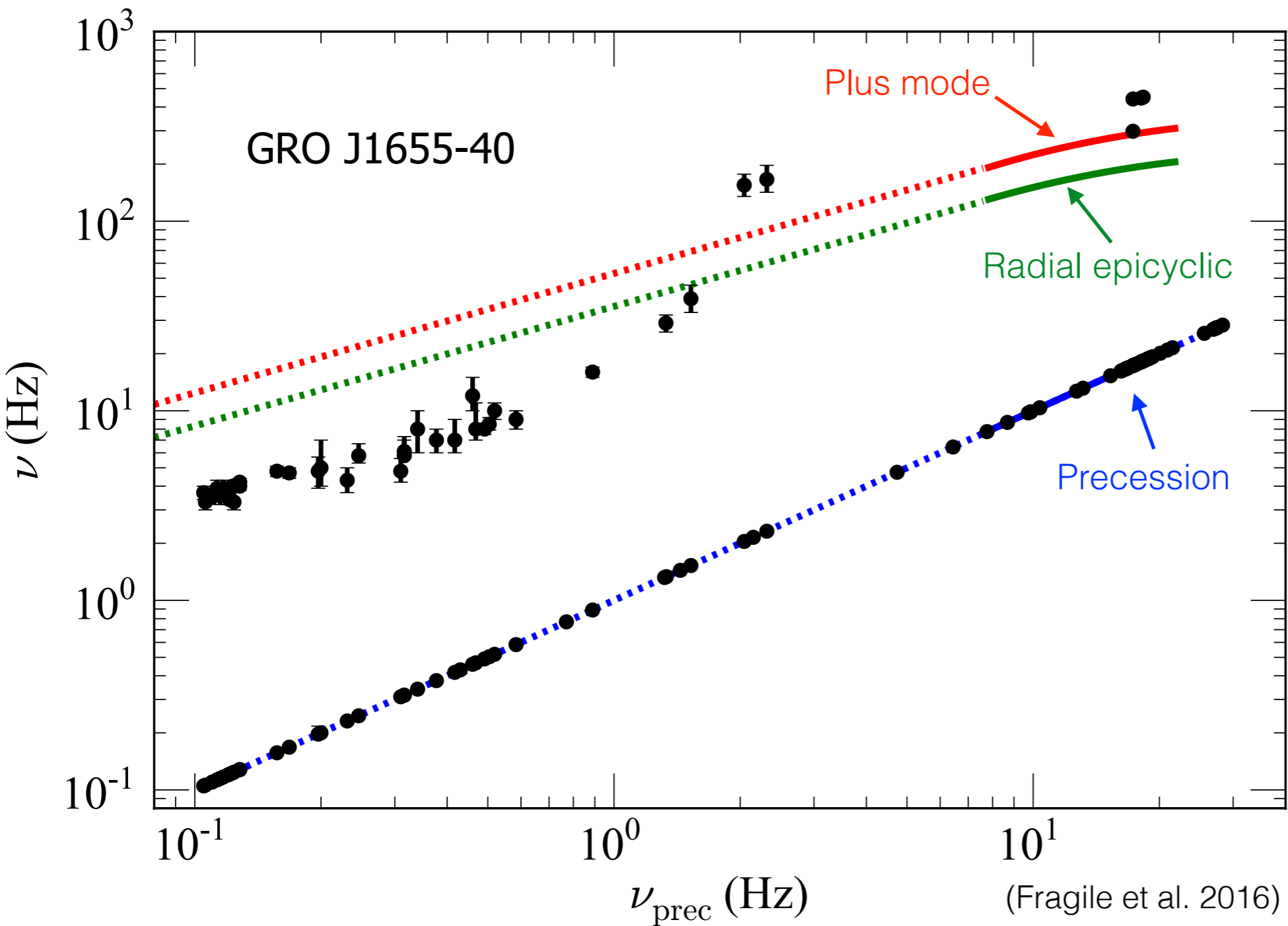
$$a_* = 0.63 \pm 0.12$$

$$r_{\text{in}} = 6.5 \pm 0.6 r_g \quad r_{\text{in}} + 0.2 \leq r_{\text{out}}/r_g \leq r_{\text{in}} + 2.9$$

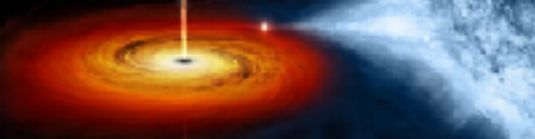


# QPO frequency correlation

- Plus, radial epicyclic & precession (Rezzolla et al. 2003)

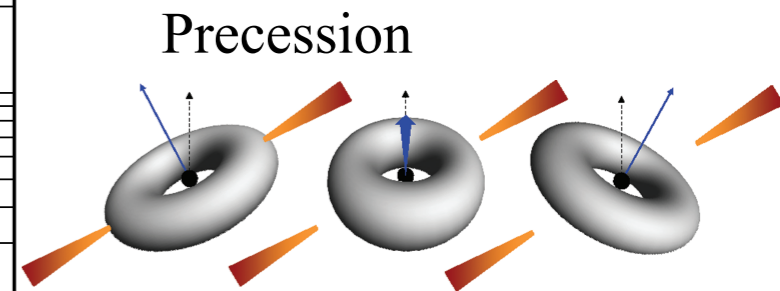
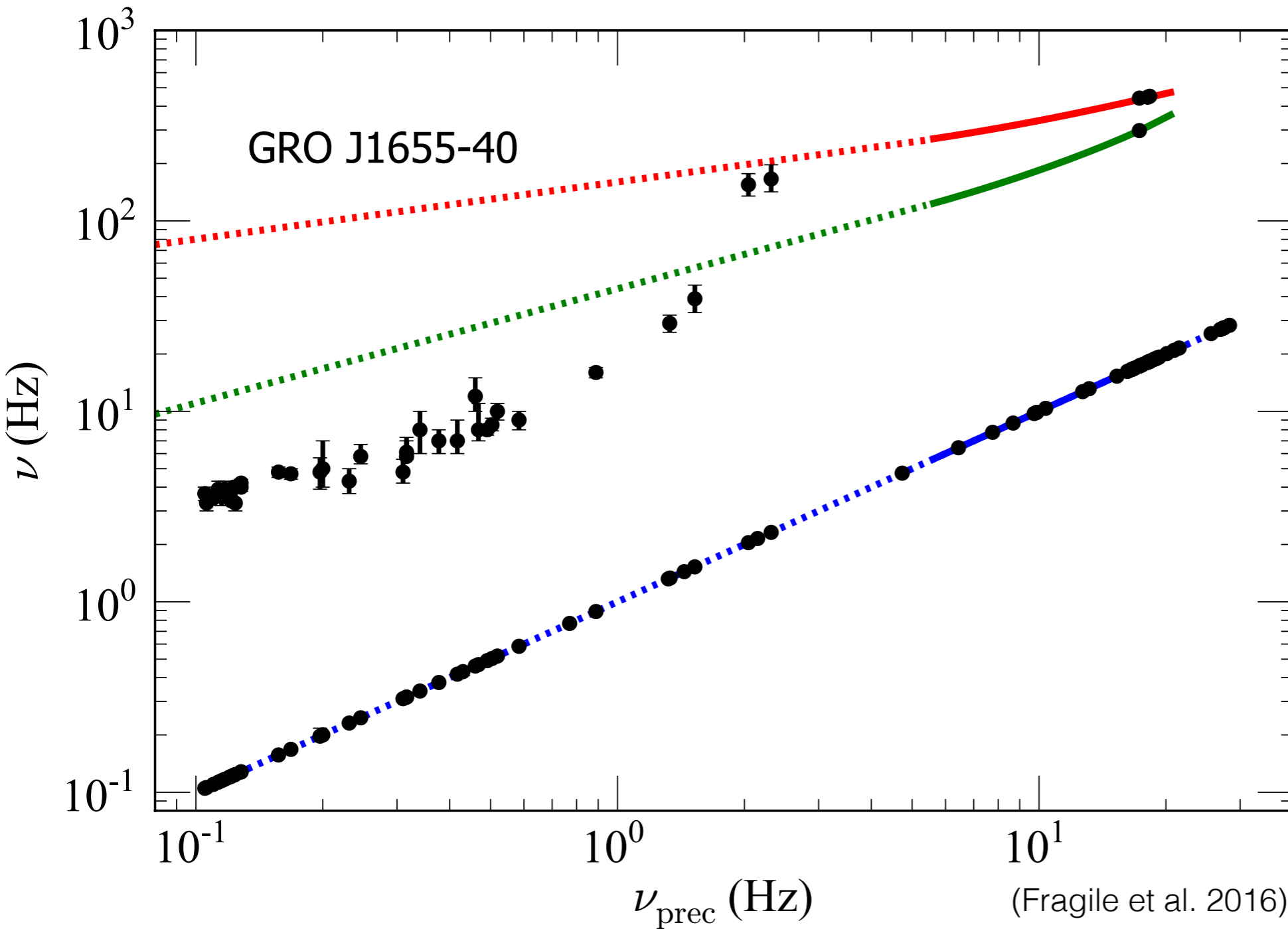


- Can't simultaneously fit all 3 QPOs in GRO J1655-40



# QPO frequency correlation

- Keplerian,  $m=-1$  radial epicyclic & precession (Török et al. 2016)



- GRO J1655-40

$$M_{\text{BH}} = 5.4 M_{\odot}$$

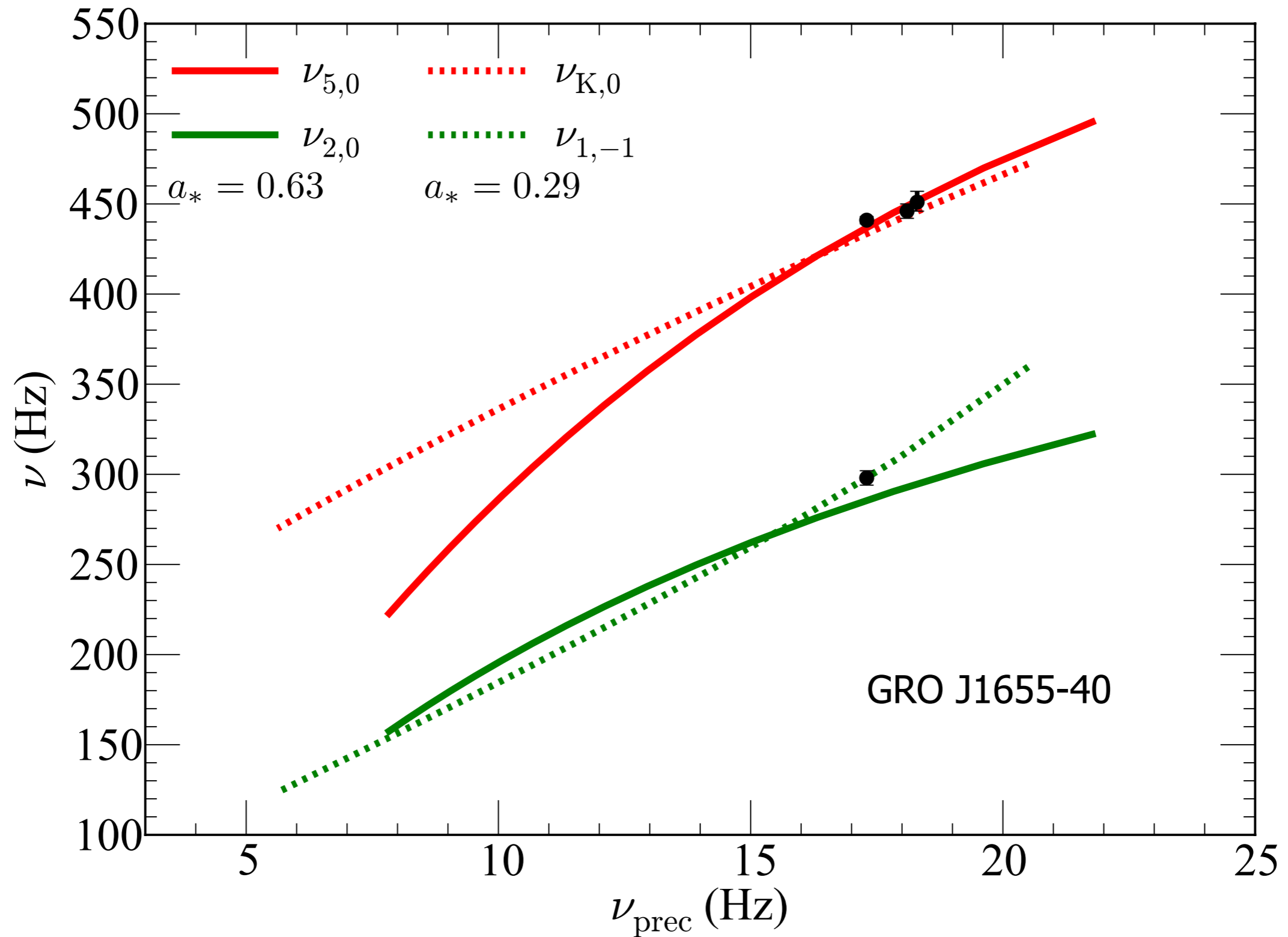
$$a_* = 0.29 \pm 0.03$$

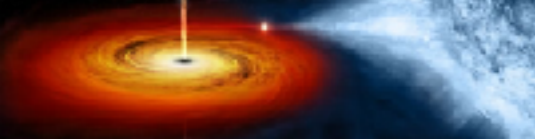
$$r_{\text{in}} = 5.3 \pm 0.3 r_g \quad r_{\text{in}} + 0.3 \leq r_{\text{out}}/r_g \leq r_{\text{in}} + 1.5$$



# QPO frequency correlation

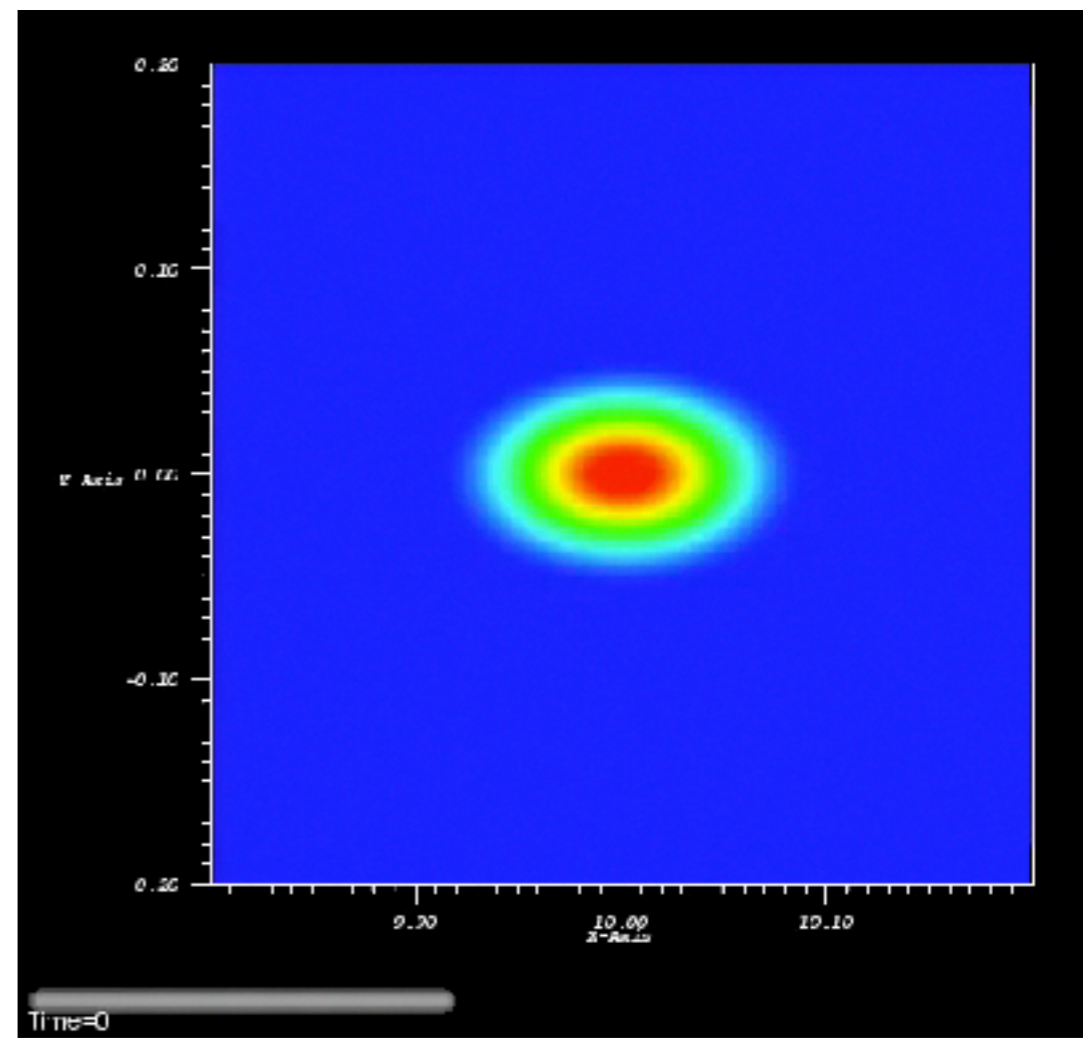
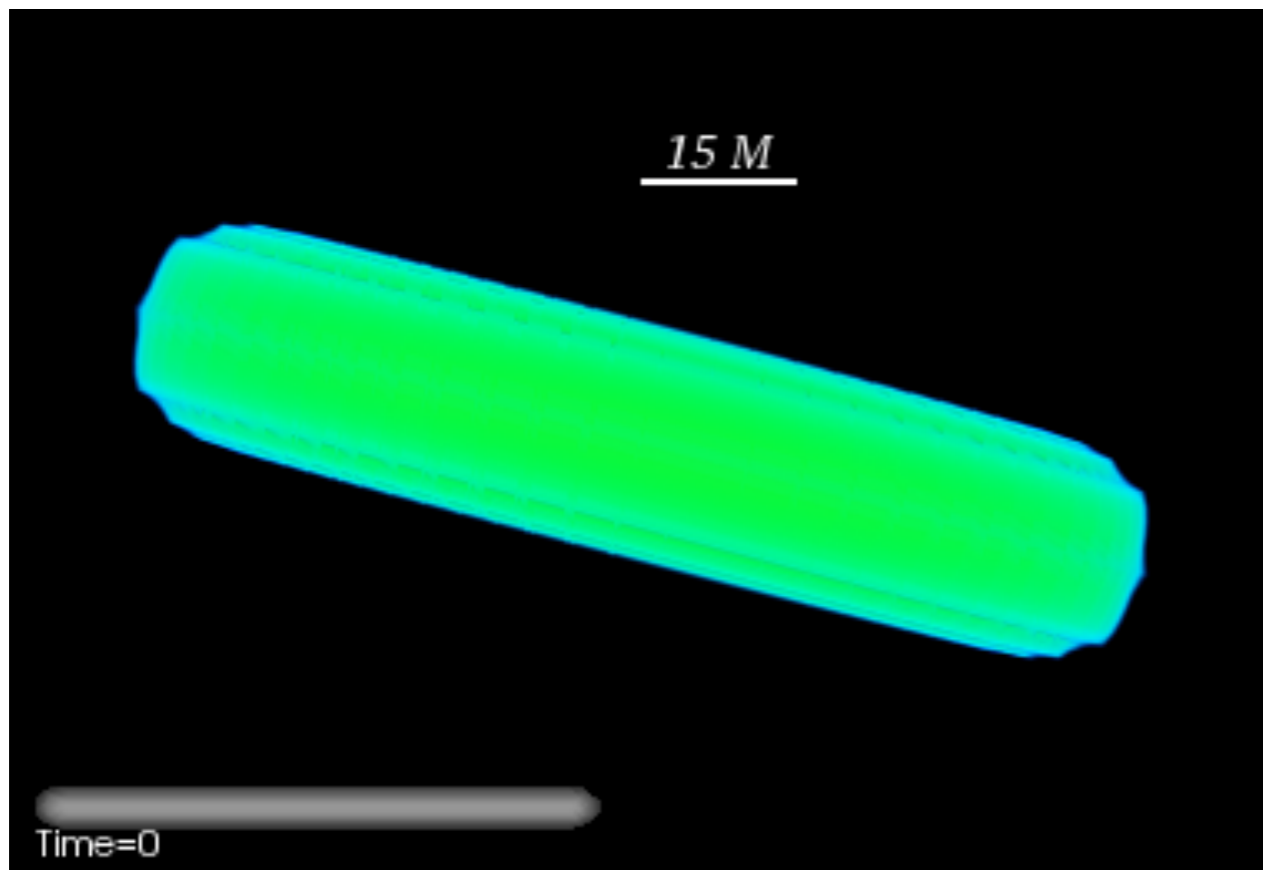
- Could STROBE-X distinguish models?



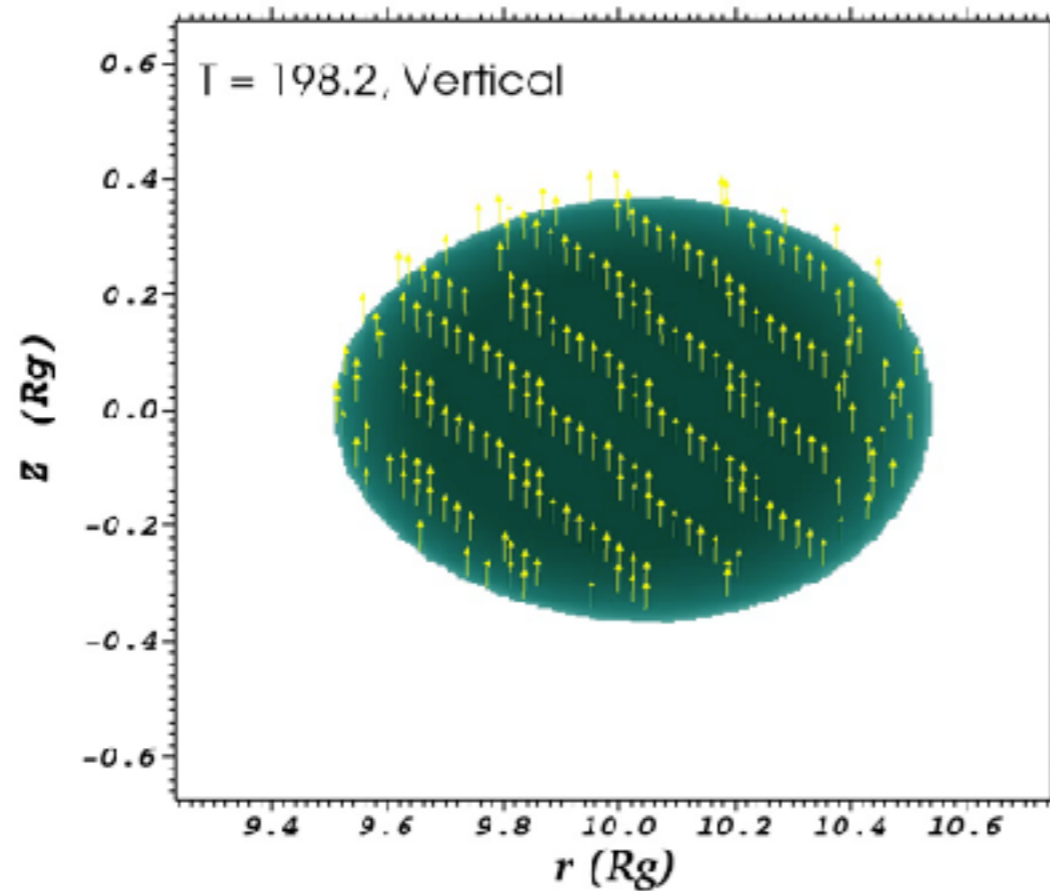


# Simulations of oscillating tori

(Fragile & Blaes 2008)



(Blaes et al. 2006)

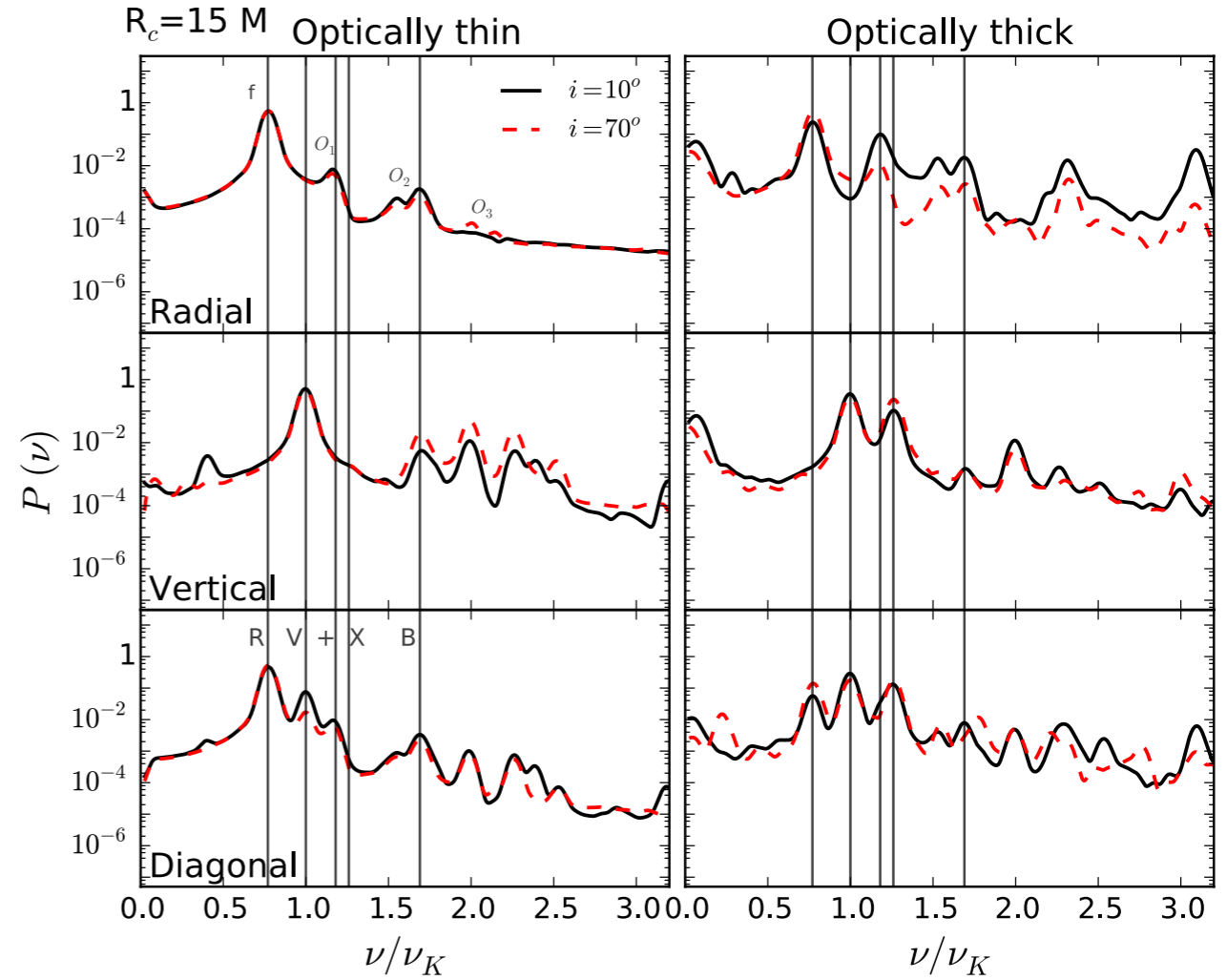
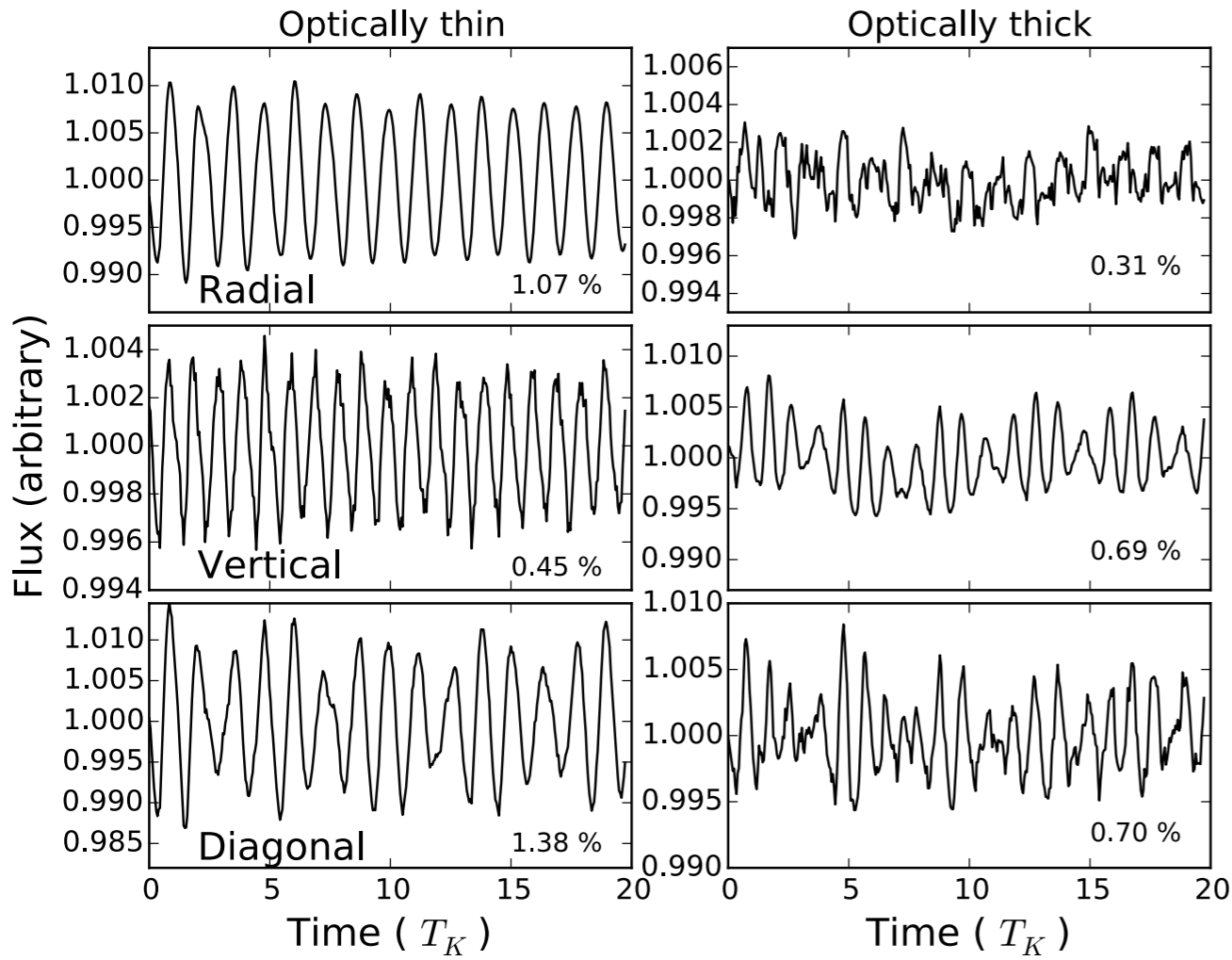


(Mishra et al. 2017)

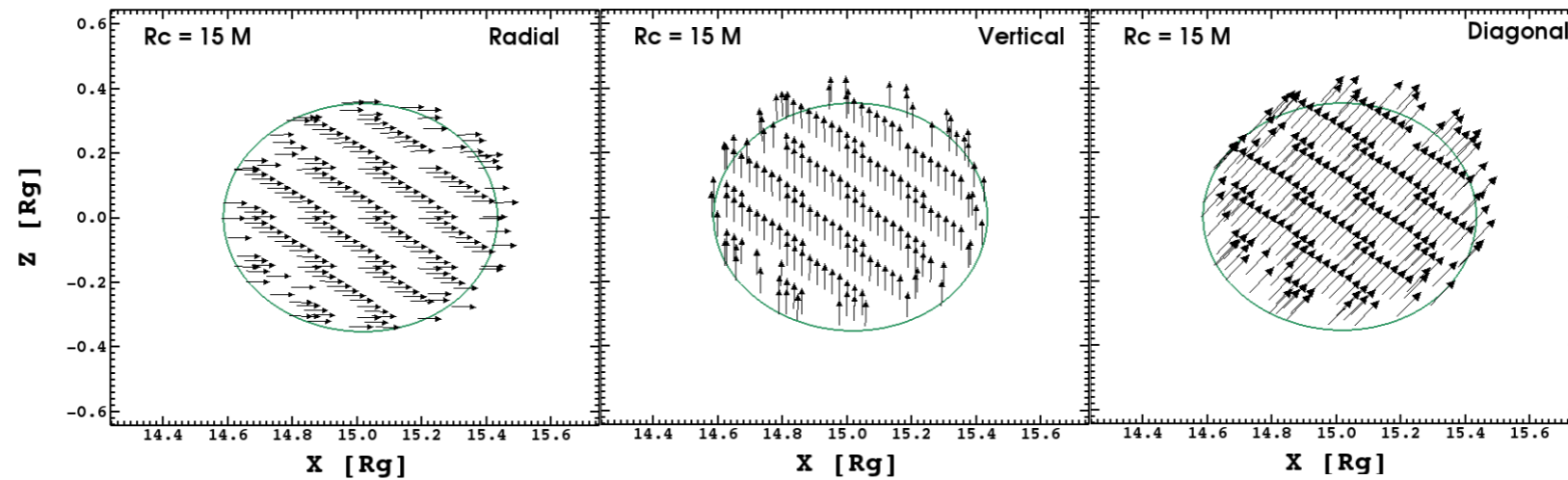


# Light curves & Power spectra from simulations

$i = 10^\circ$



(Mishra et al. 2017)





# What can STROBE-X do for QPOs?

- Phase-resolved spectroscopy for LFQPOs
  - Huge gain in Signal-to-Noise
  - Eliminates problems with pile-up (can look at sources like GX 339-4)
- Possibly differentiate HFQPO models
  - Need to be able to follow HFQPO during rise of outburst
  - Or definitively show that QPO only appears at certain discrete time intervals during outburst

