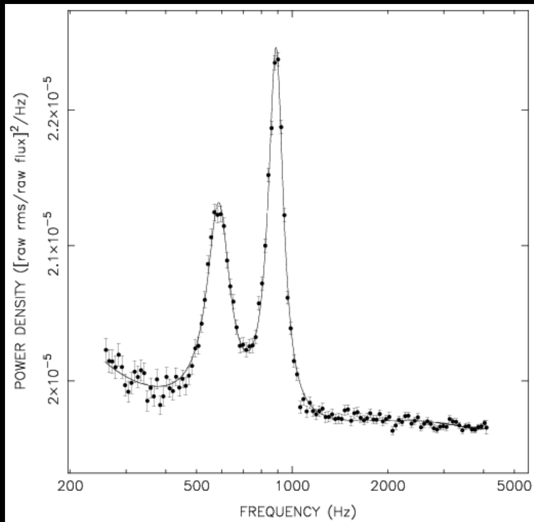

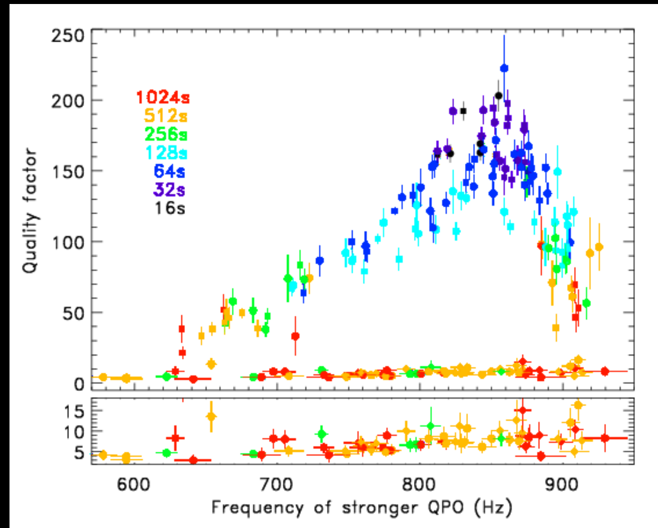

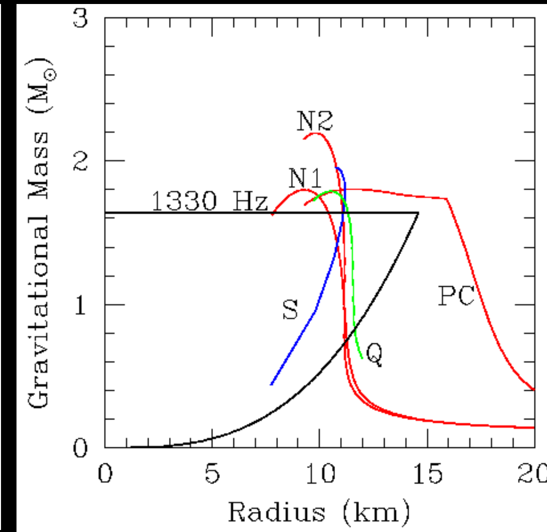

The Implications of kHz QPOs

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Outline

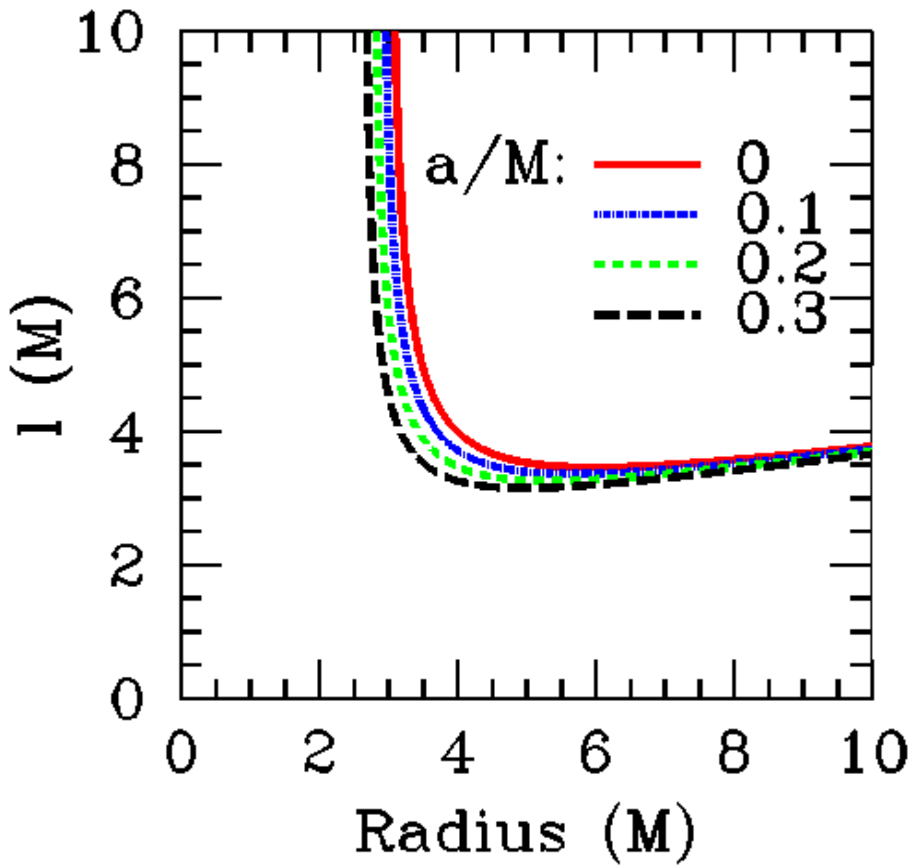
- Why the model matters
- The essential properties of kHz QPOs
- Models for high Q and tuneability
- Is $\nu_{upper} \sim \nu_{orb}(r_{special})$?
- Have we seen the ISCO?

Why does the model matter?

- Much as I like QPOs for themselves, it is their implications that are important!
  Strong gravity
  Dense matter
- High frequencies suggest we can access these, but only with a generally accepted model.

Strong Gravity

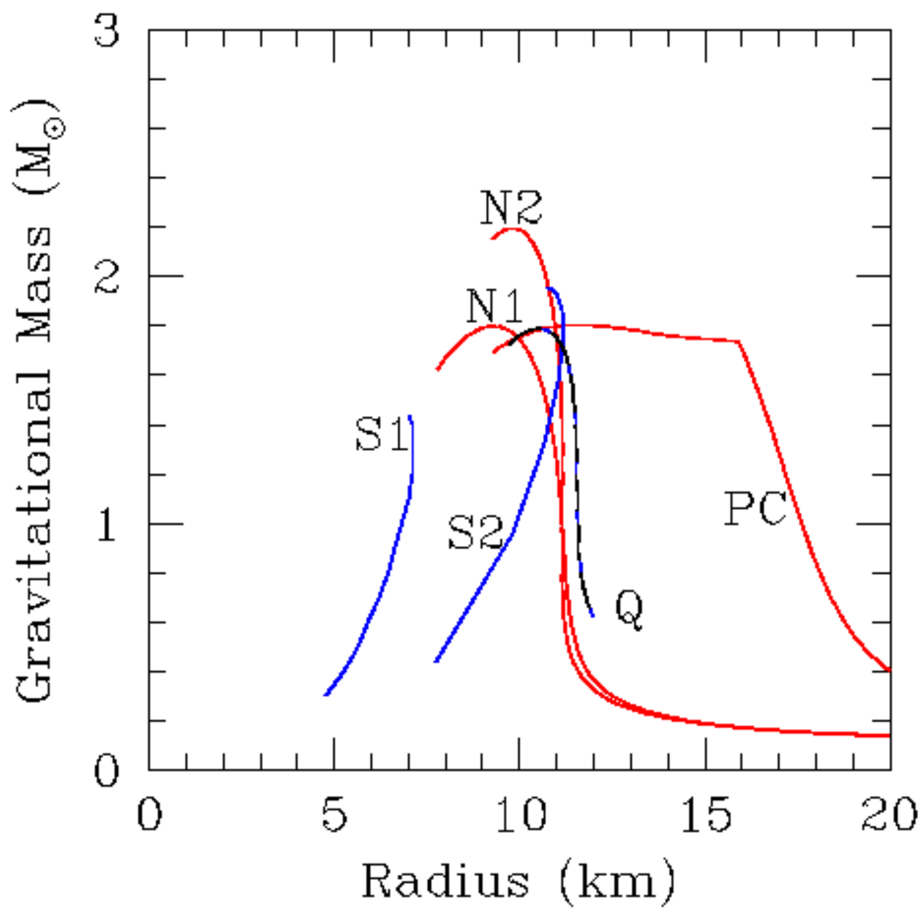
- GR "pit in the potential": gravity is stronger than Newtonian
- Minimum in L
  Unstable for $r<r_{ISCO}$
- Matter should fall in rapidly
- Lower limit to disk inner radius



Specific angular momentum vs. radius, for different spin parameters

Dense Matter

- Matter in NS core is several x nucl. density
  Only nucleons?
  Quark matter?
  Strange matter?
  Condensates?
- NS mass vs. radius, maximum mass would provide clues



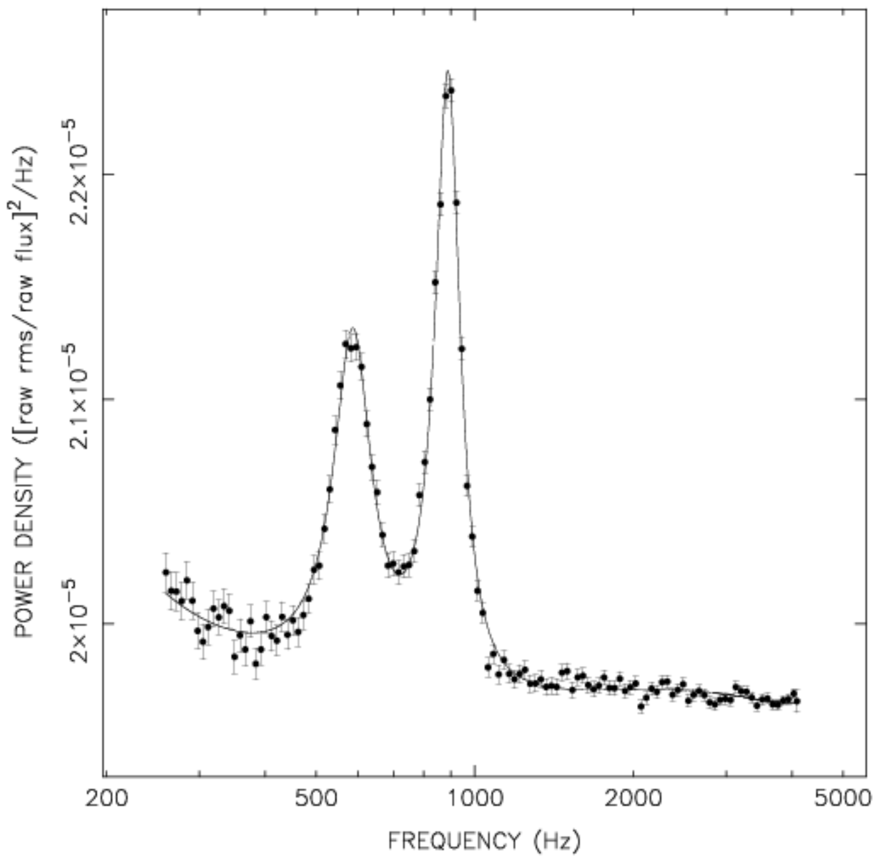
Theoretical curves: NS mass vs. radius

A Position Statement

- Models of kHz QPOs are currently unsettled.
- They will remain that way until first-principles numerical simulations produce QPOs like those observed; future large-area missions will also be essential to refine our knowledge, exclude some models, and point to others.
- In the meantime, we can draw some guidance from the most important trends obtained using RXTE's remarkable capabilities.

Feature 1: High Frequencies

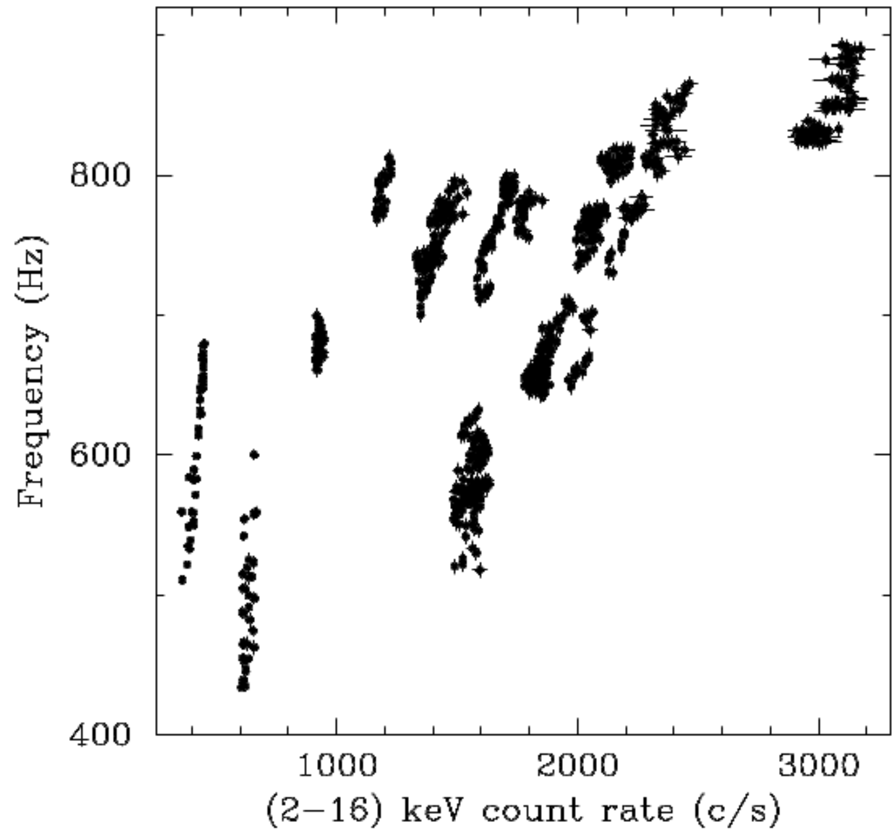
- Pair commonly seen
- Frequencies up to ~1200-1300 Hz
- Compare: ISCO for non-rot 1.4 M_{sun} NS has ν_{orb}~1600 Hz
- For higher masses, max freq could be close to ν_{ISCO}



Sco X-1: van der Klis et al. 1996

Feature 2: Tuneability of QPOs

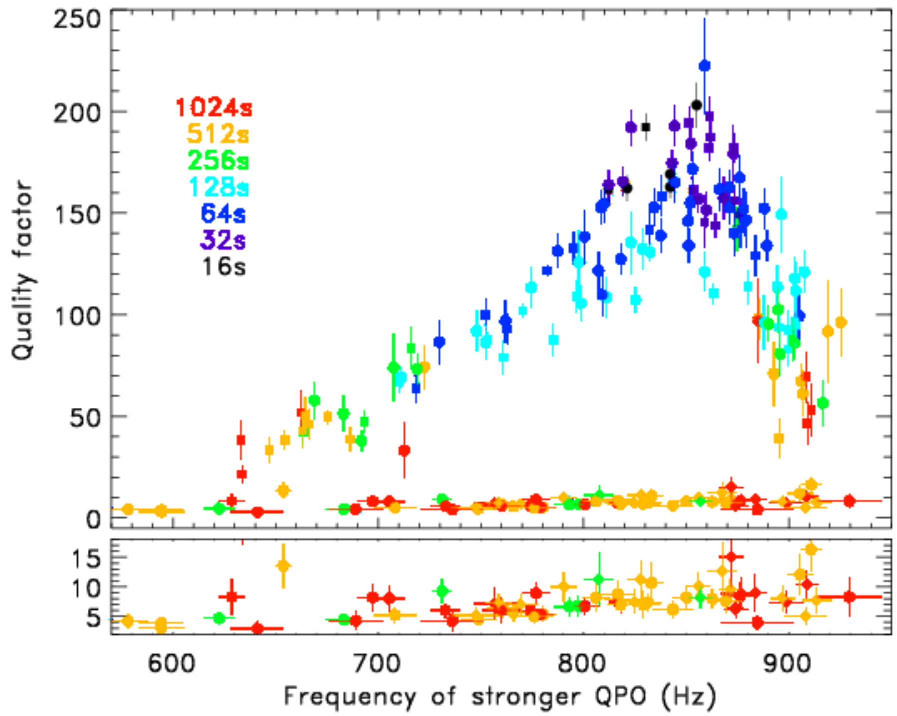
- Frequencies can change by factor >2 in a given source
- Initially thought to correlate well with flux or colors, but behavior is complicated



Mendez et al. 1999
4U 1608-52

Feature 3: Sharp Peaks

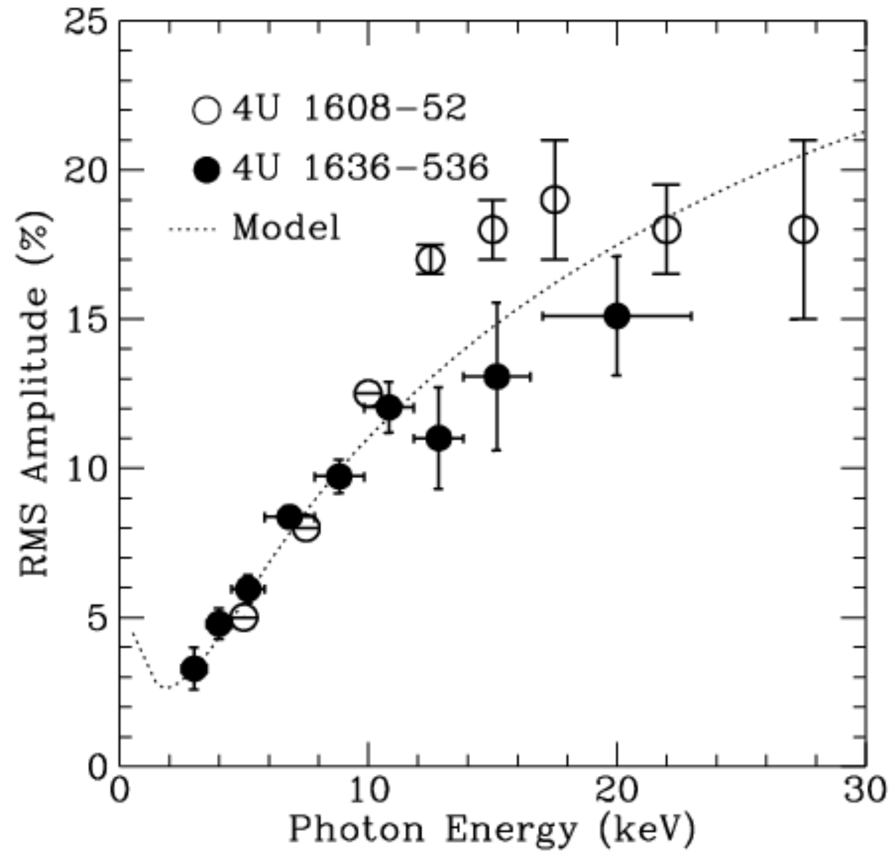
- Quality factor ν/FWHM can exceed 200
- Most often true for the lower peak
- True Q could be higher; not yet possible to detect on coherence time (AXTAR, LOFT, NICER)



4U1636: Barret et al.
Lower peak can have Q>200

Feature 4: High Amplitudes

- Many sources have 2-60 keV rms>10%
- Fractional rms tends to be larger at higher photon energy
- High rms, high Q means most promising (only?) possibility is oscillating emission from NS surface, not disk



Miller, Lamb, Psaltis 1998

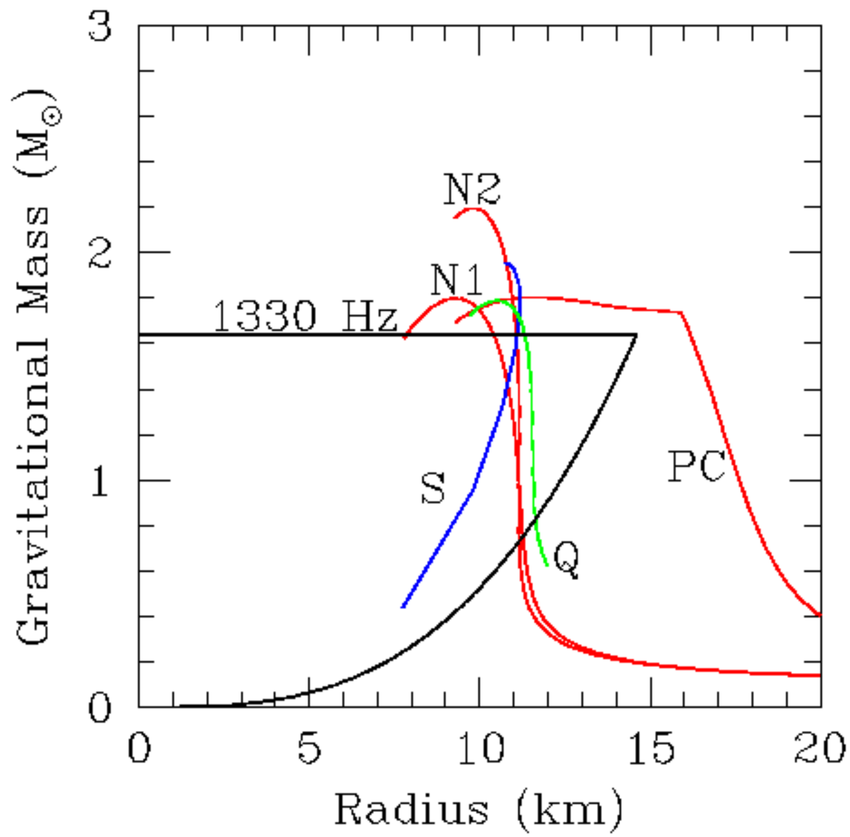
Model Ingredients

- Accretion disk
  Could be warped, lumpy, have modes, ...
- Neutron star
  Surface, radiation from star, ...
- Stellar magnetic field
  Can be strong enough to affect matter
- General relativity

What models satisfy these trends?

So What Can We Say?

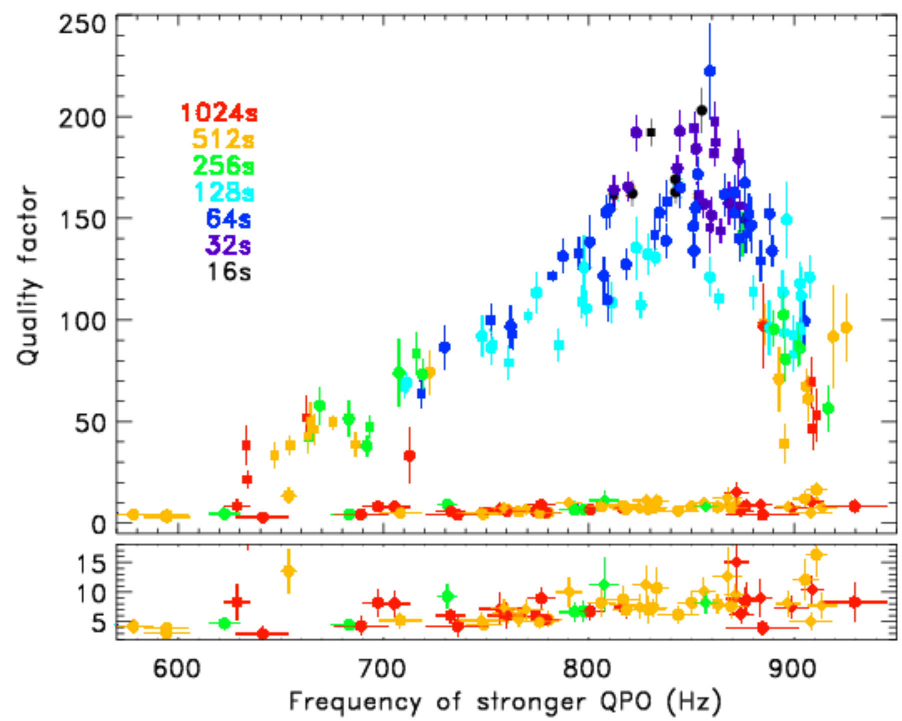
- In my opinion, $\nu_{upper} \sim \nu_{orb}$ is still the best bet.
  Good freq, amp, Q
- This, and this alone, gives us some constraints on M, R
- Inferring more (e.g., ISCO) requires more details



Miller, Lamb, Psaltis 1998

Have we seen the ISCO?

- Expected: hard max on frequency, sharp drop in Q near ISCO
- Zhang et al. (1998) saw max, but doubt cast by parallel tracks
- D. Barret et al.: evidence for Q drop in several sources
- Mendez, Belloni: plasma effects?



4U1636: sharp drop in Q at fixed frequency, as expected for ISCO

Conclusions

- $\nu_{upper} \sim \nu_{orb}$ consistent with data
- Accounts for high Q, high frequencies and tuneability, and location of emission
- First-principles numerical simulations are essential
- The ISCO may have been detected; if so, it stands as one of the most important discoveries with RXTE, and is a testament to Rossi's unique capabilities