

Quasi periodic oscillations



Phd Defence: May 2019, Como, Italy

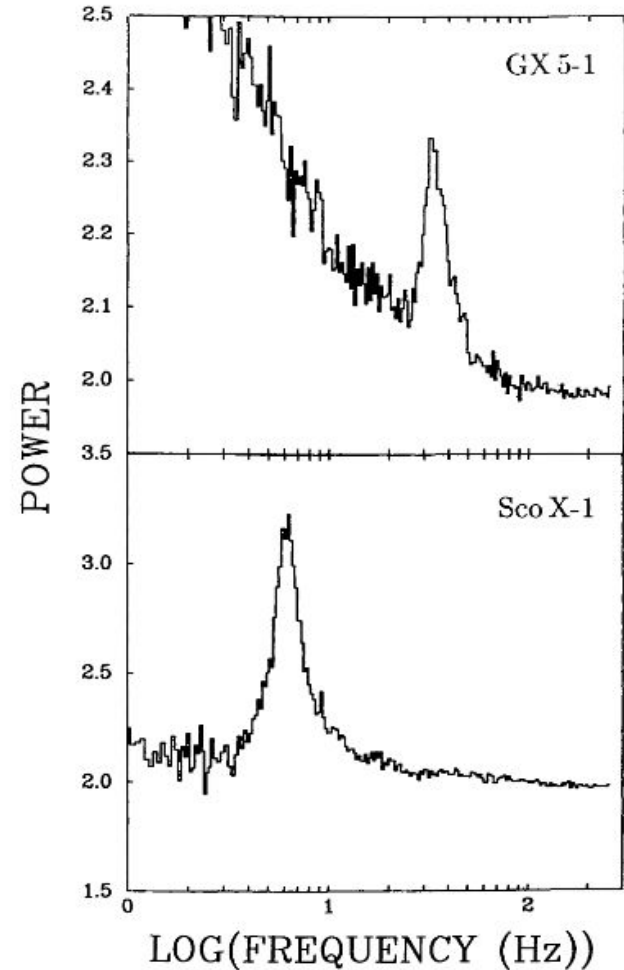
Federico Vincentelli
(Coventry University)

Quasi Periodic oscillations

Broad peaks in the power spectrum of X-ray sources

Known since the 80's

First discovered in bright NSs



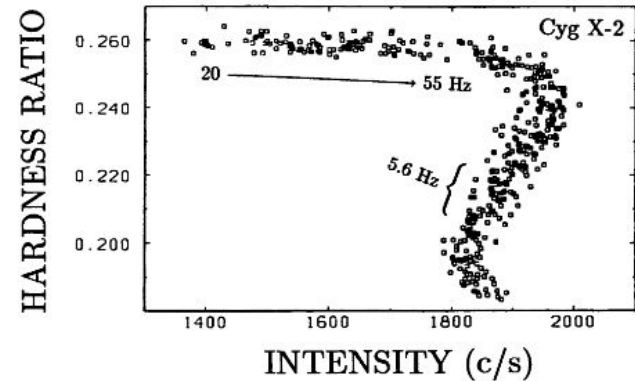
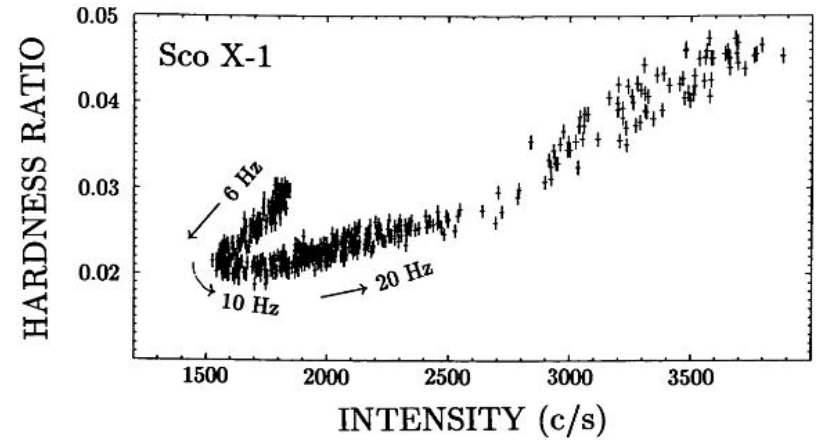
Quasi Periodic oscillations

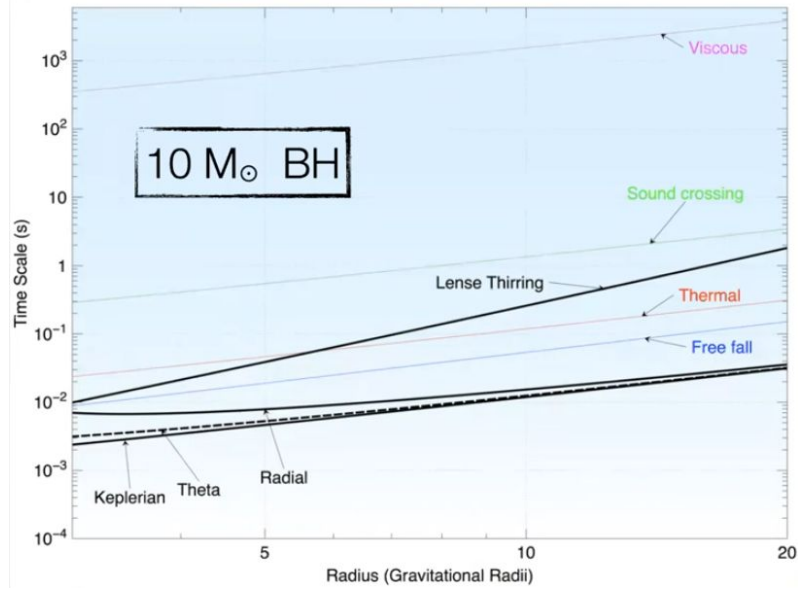
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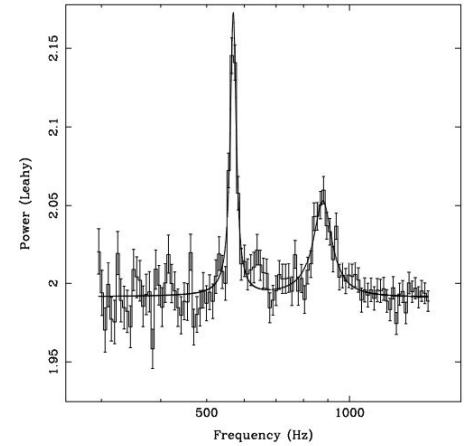
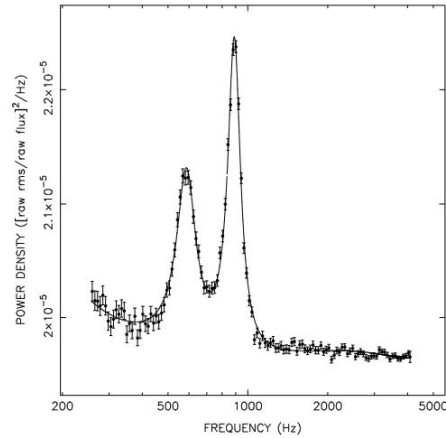
Variable in frequency and associated to different states.





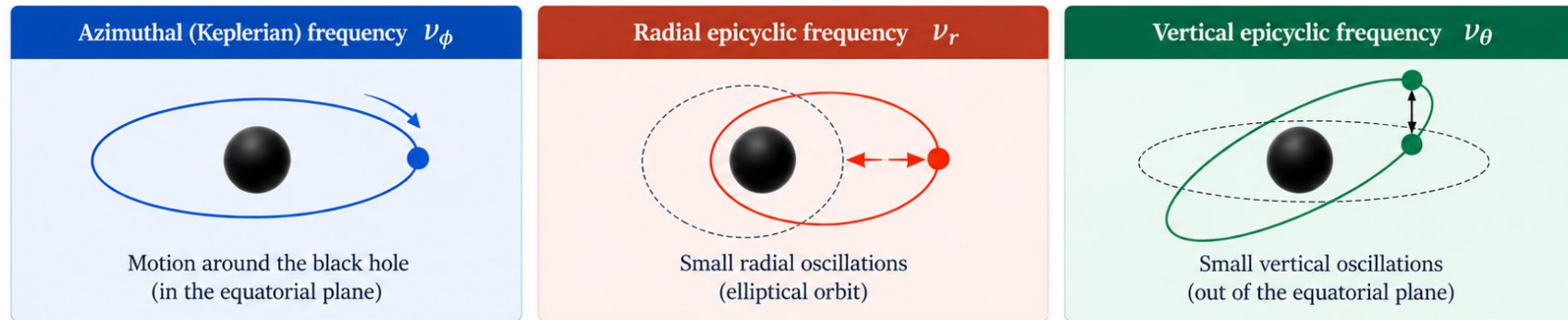
Discovery of k Hz QPOs by RXTE

smoking gun for orbital phenomena

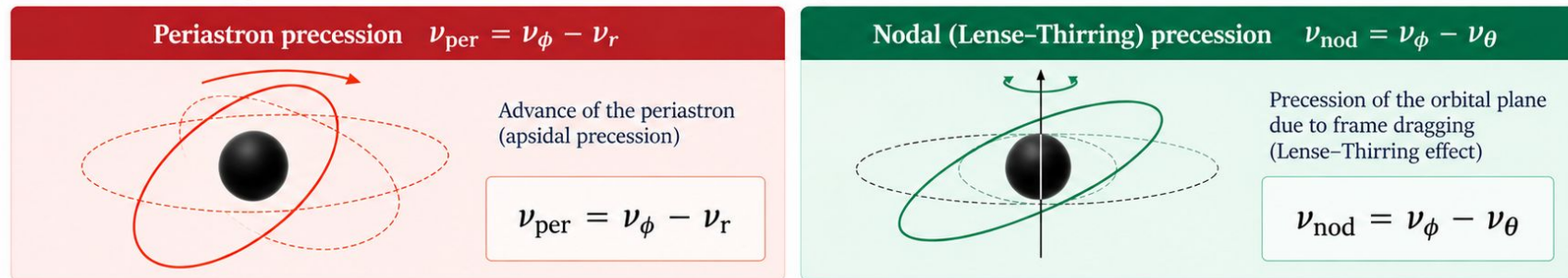


Orbital frequencies and precession in black hole X-ray binaries

1. Test-particle motion at radius r (Kerr spacetime)



2. Precession frequencies (combinations of the fundamental frequencies)

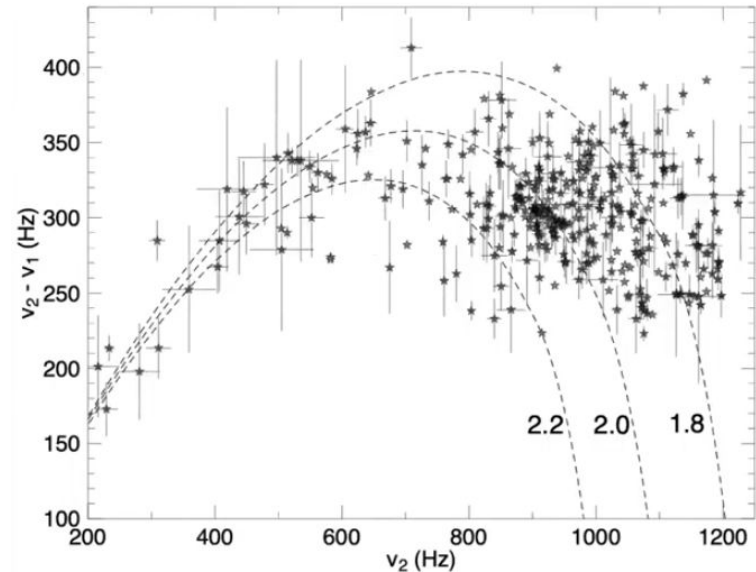
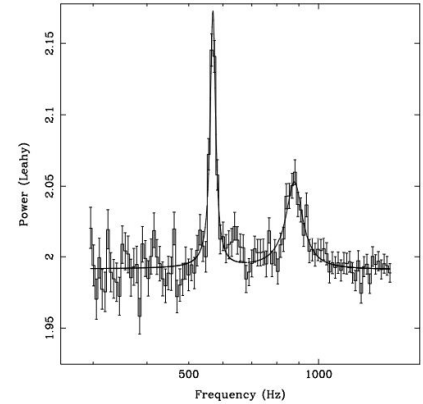
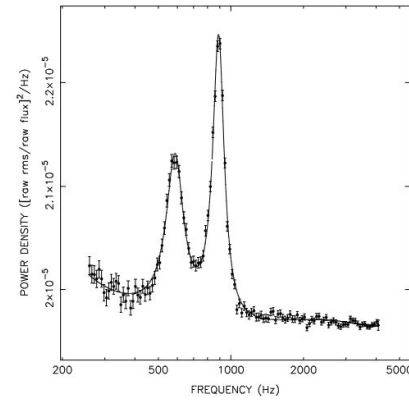


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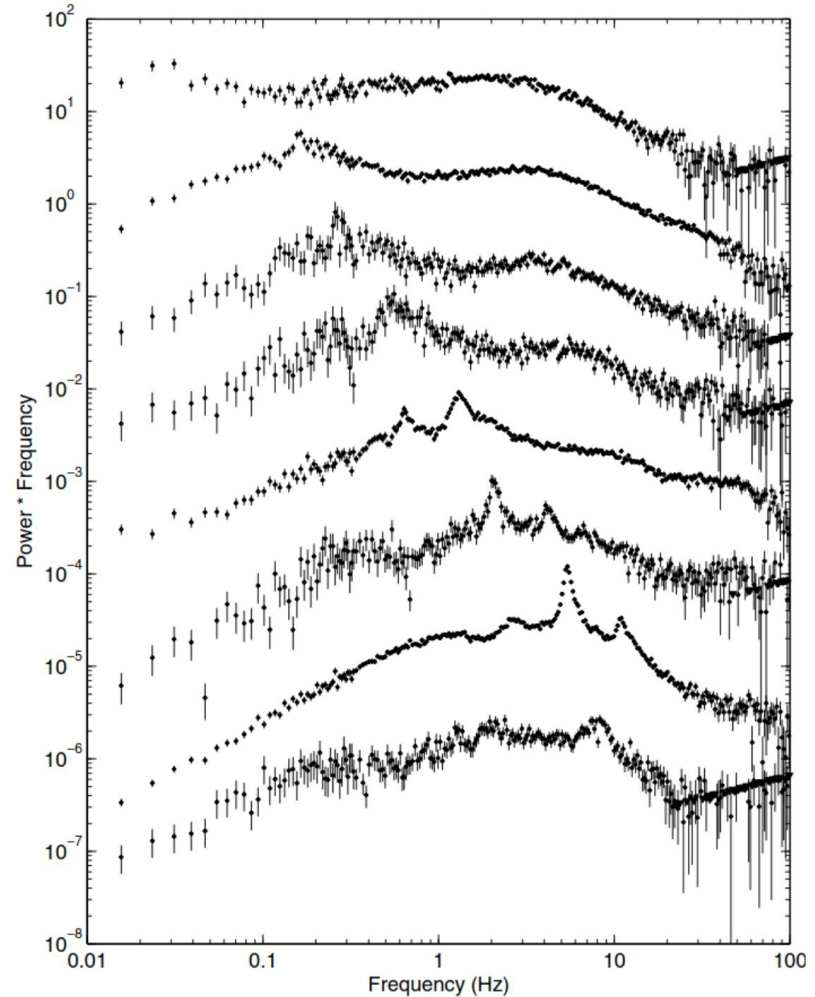
RPM interpretation could explain
most of the evolution in frequency
of the two components

Mendez & Belloni 2021



QPO in BH LMXBs

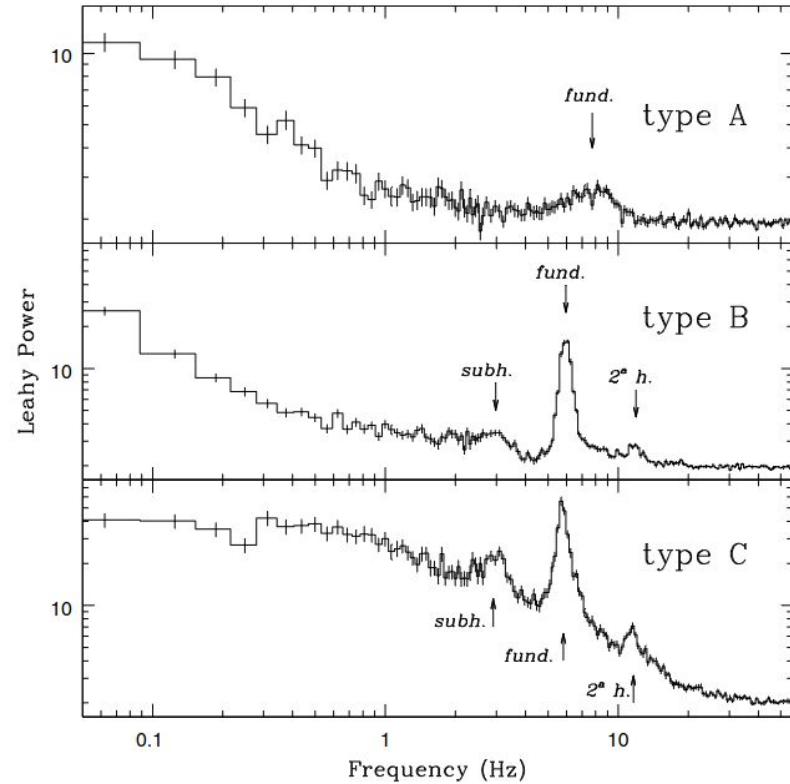
RXTE opened new avenue also for
accreting BHs



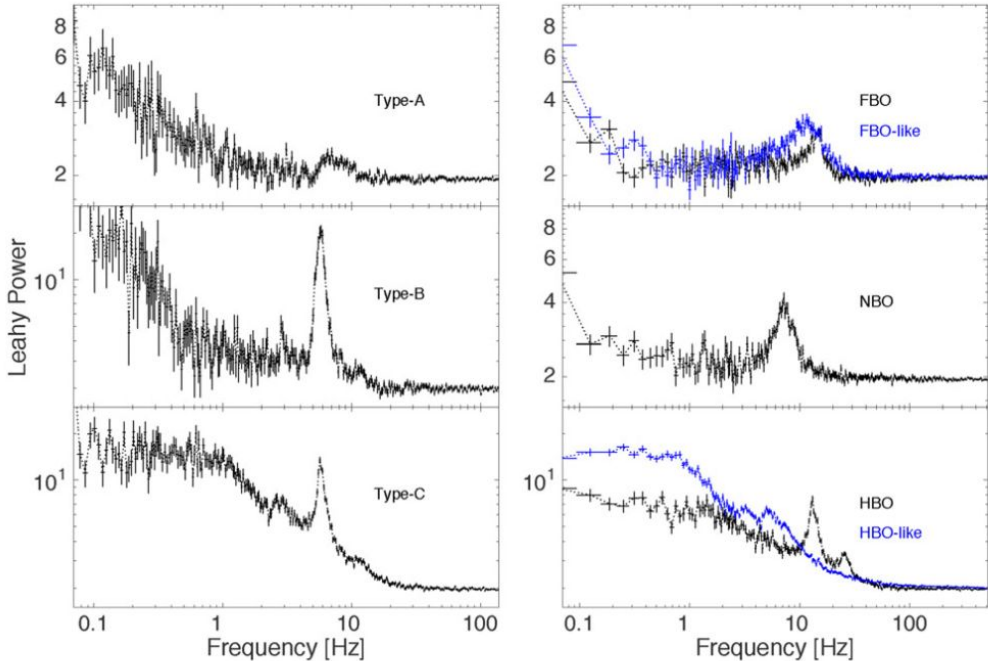
Different type of QPOs appear at different phases of the outburst

Type A/B Intermediate states somehow linked to the transition

Type C Hard state
Evolves in frequency as the geometry evolves



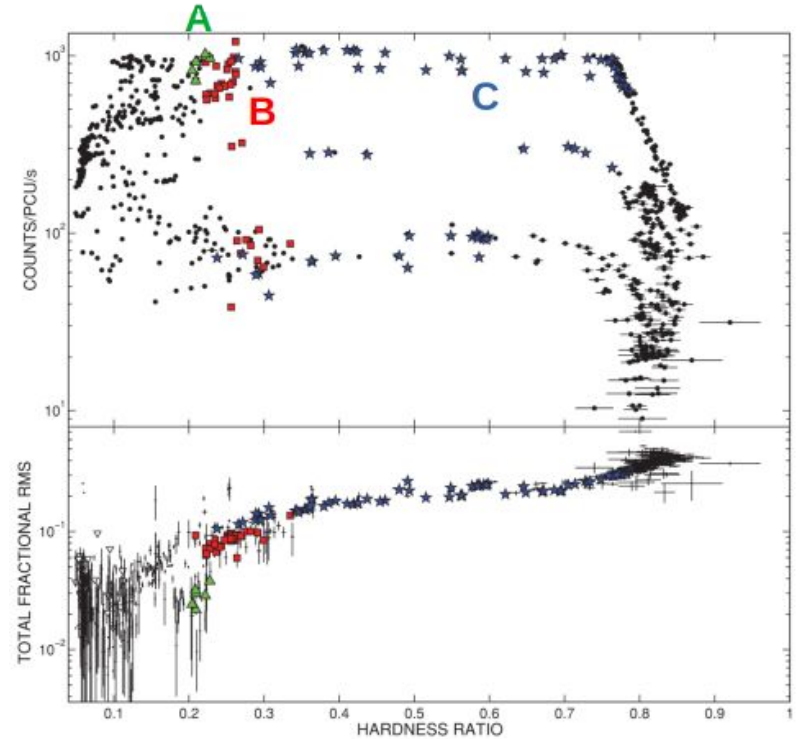
Later systematic analysis confirmed strong links between QPOs in BH and NS behaviour



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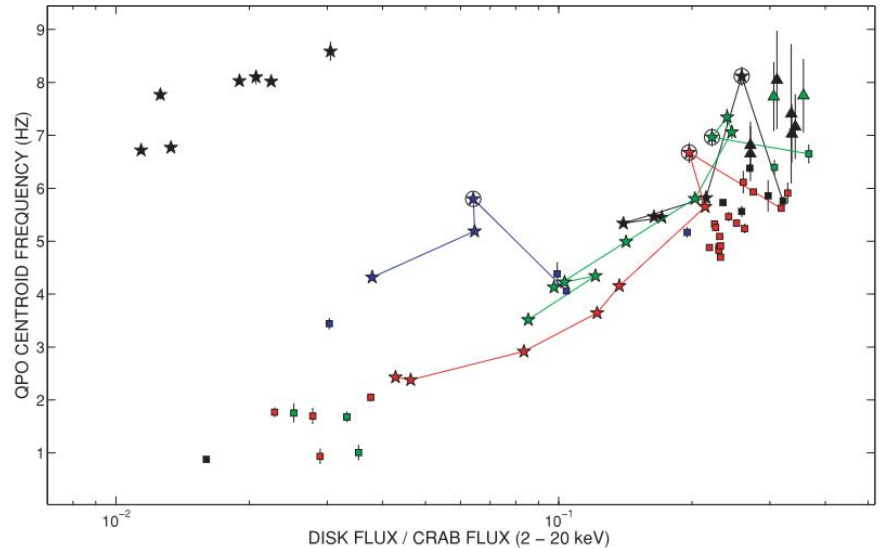
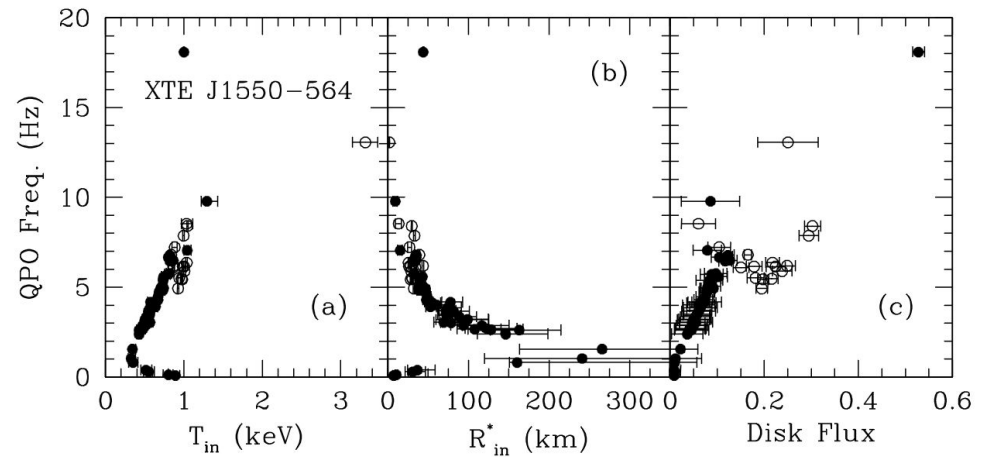
Type C Hard state
Evolves in frequency as the geometry evolves



Type C QPOs show strong correlation with disc evolution

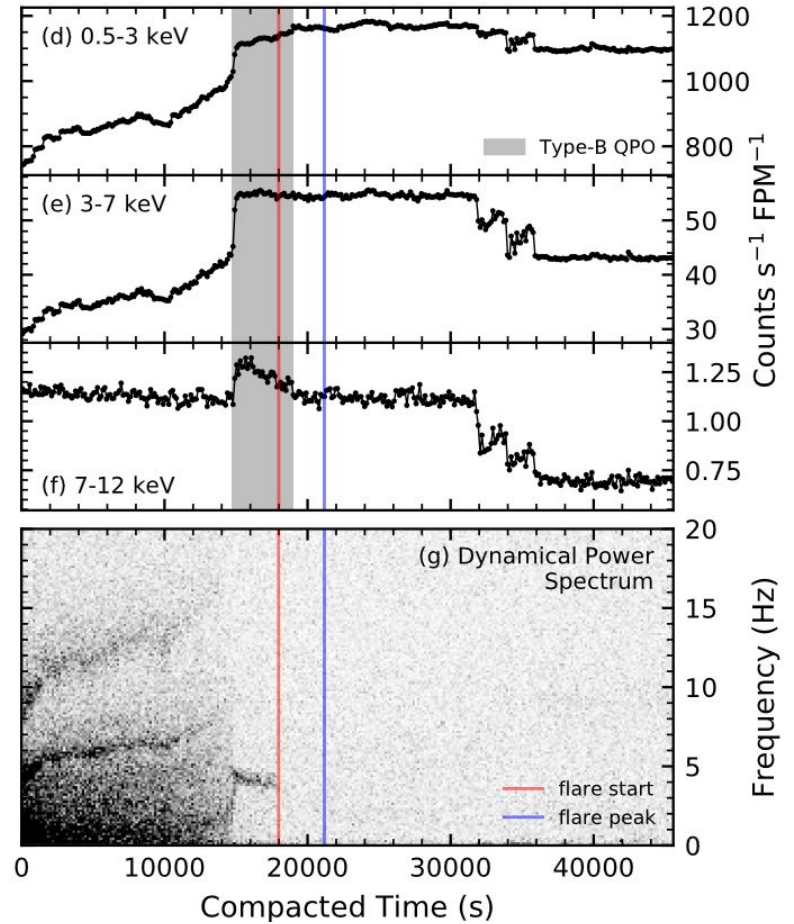
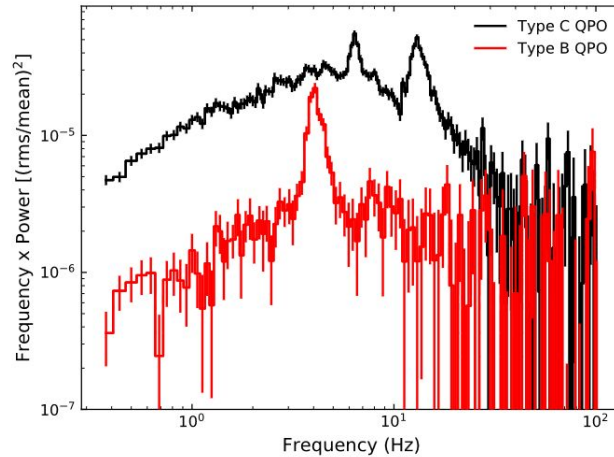
hints that it is related to hot flow truncation radius

Sobczak+2000, Motta+2011



Type C evolves through hard state

Type B related to transition/ejection



High Frequency QPO, opens window on innermost regions to BH.

Discovered only in few systems. Not simultaneously with other QPOs. So RPM hardly applicable...

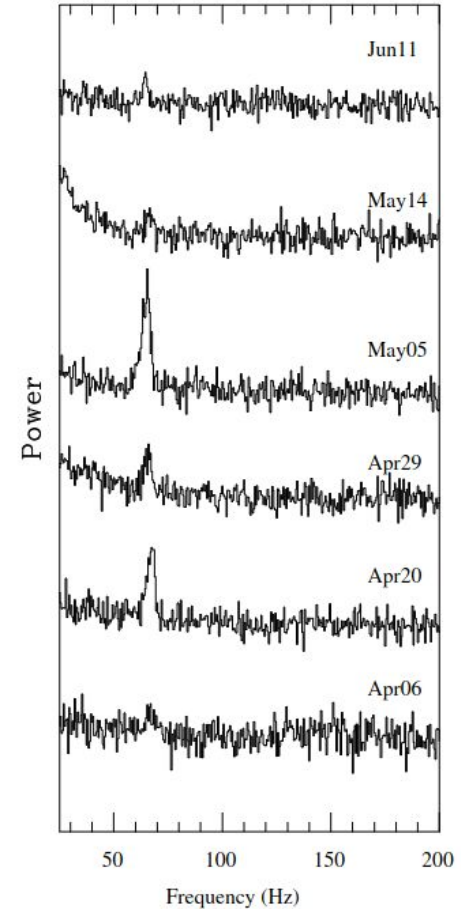
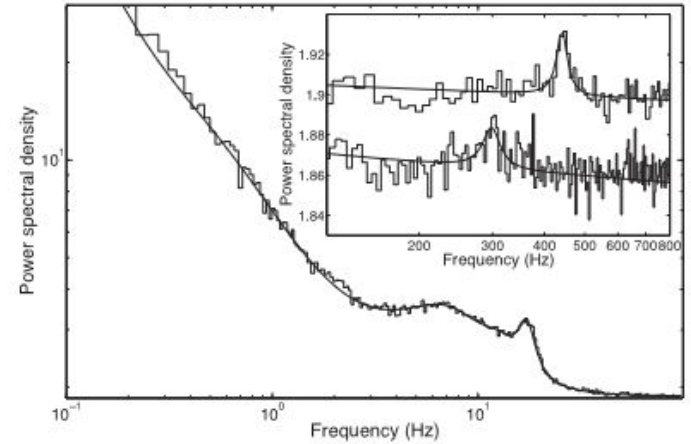
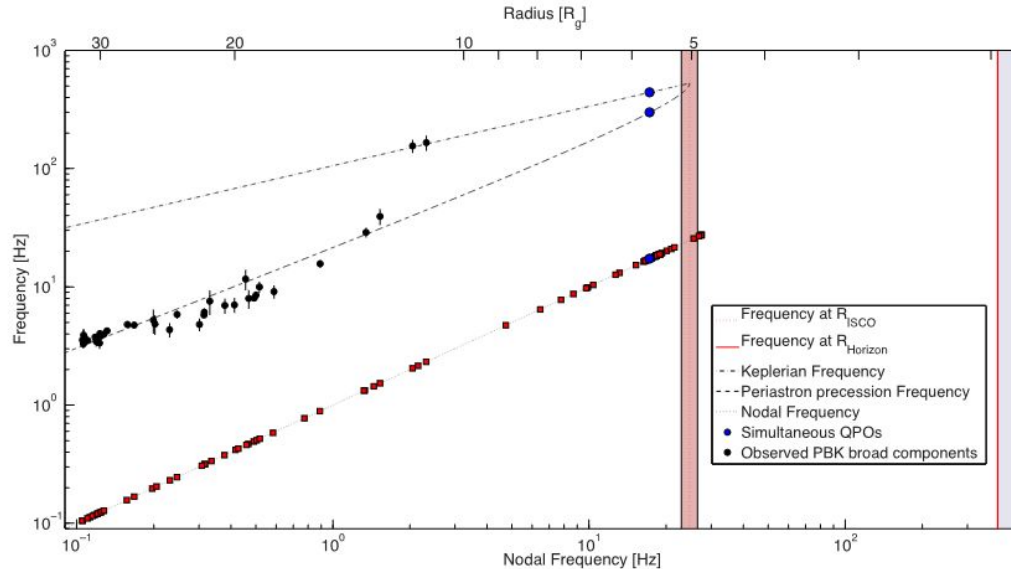


FIG. 6.—Selected power spectra of GRS 1915+105 replotted on a linear scale to display the QPO at 67 Hz. Here the Poisson noise level has not been subtracted.

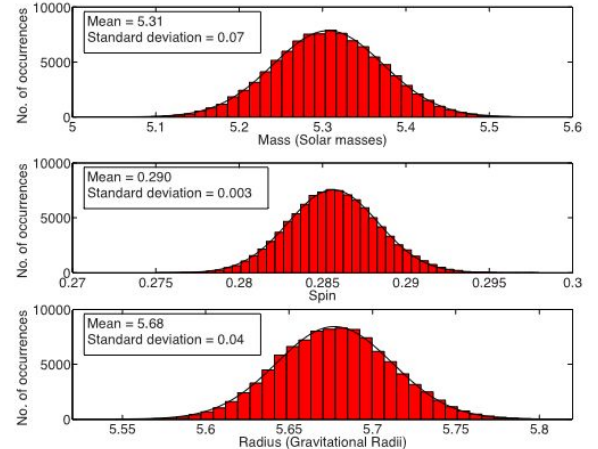
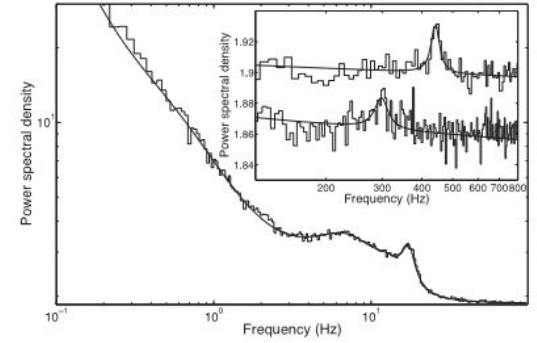
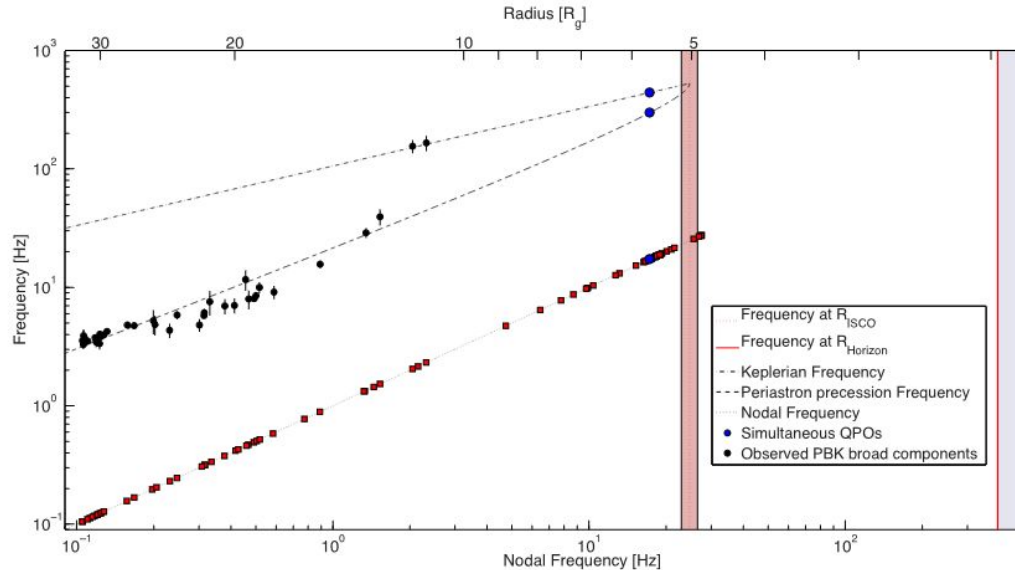
Discovery of 3 frequency simultaneous
allowed to apply RPM

Application to GRO 1655-40



Discovery of 3 frequency simultaneous allowed to apply RPM

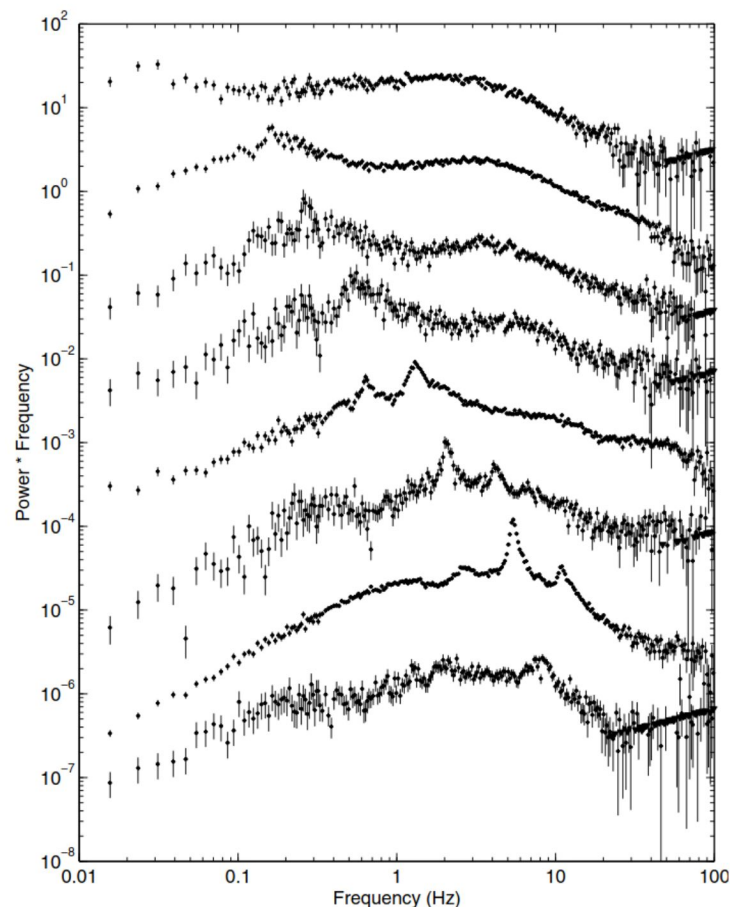
Application to GRO 1655-40



Correlation with broadband noise

Key property of QPO is correlation between frequency of the broadband noise components

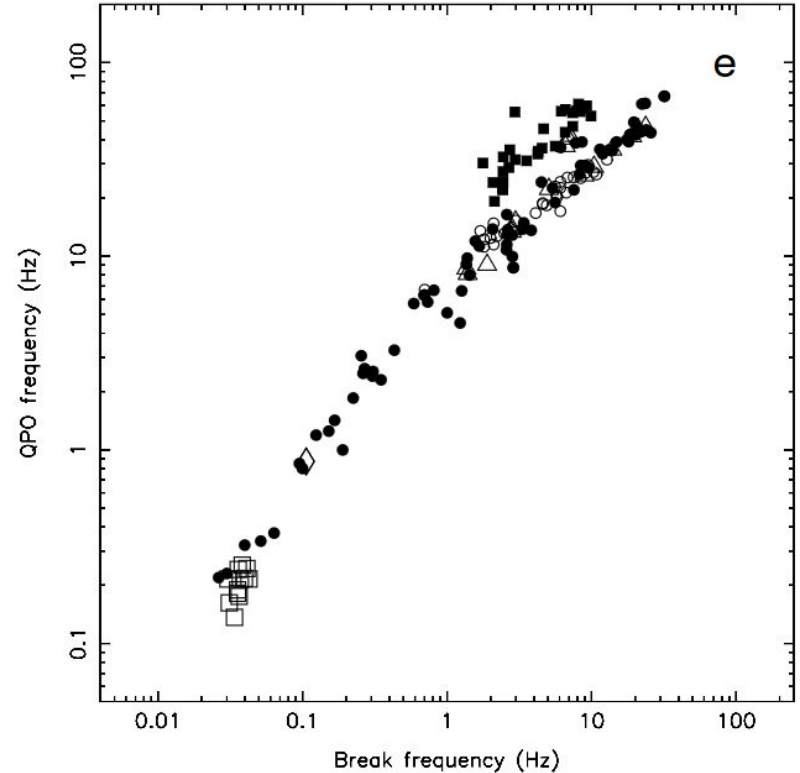
Observed across different orders of magnitudes in both BH and NS!



Correlation with broadband noise

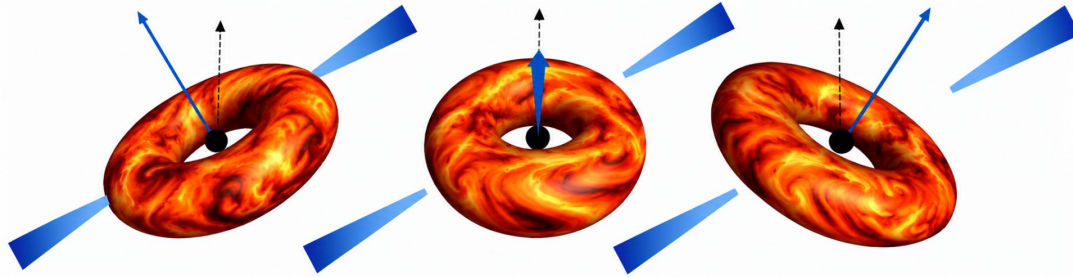
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Connection with broadband noise:

Natural link between LT precession and viscous freq. at truncation radius



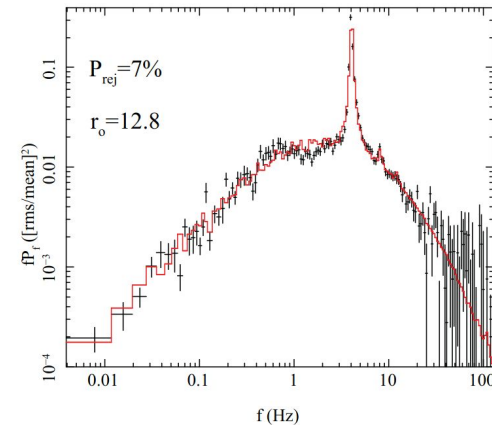
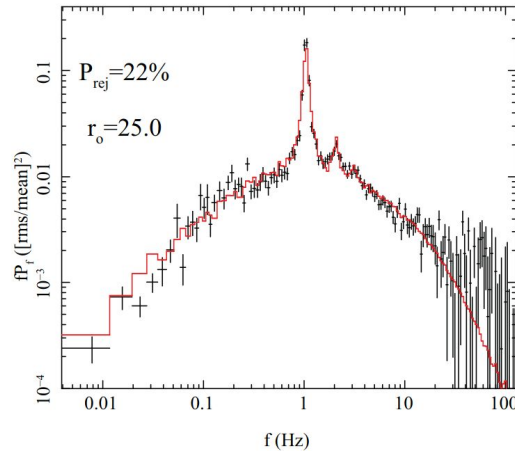
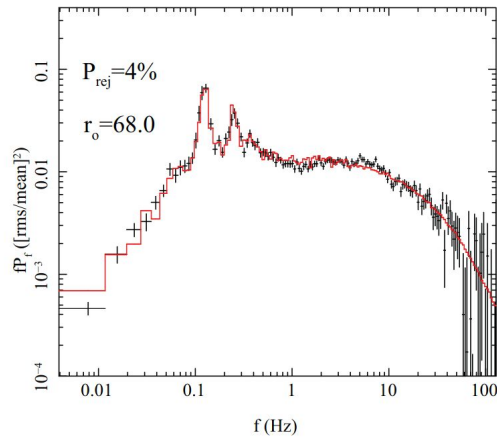
QPO freq. -> LT precession frequency at a given radius

Viscous freq. -> Power spectrum Low frequency break.

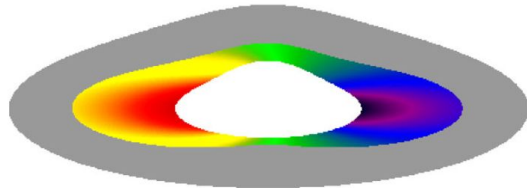
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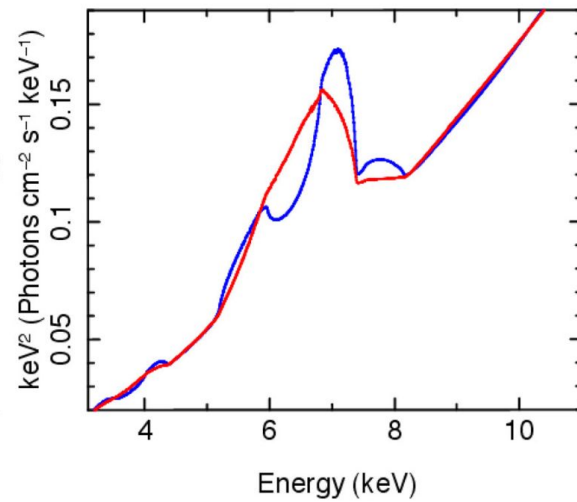
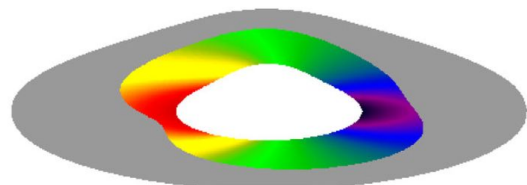
As radius shrinks, both LF break and QPO shift



QPO phase = 0.2 cycles



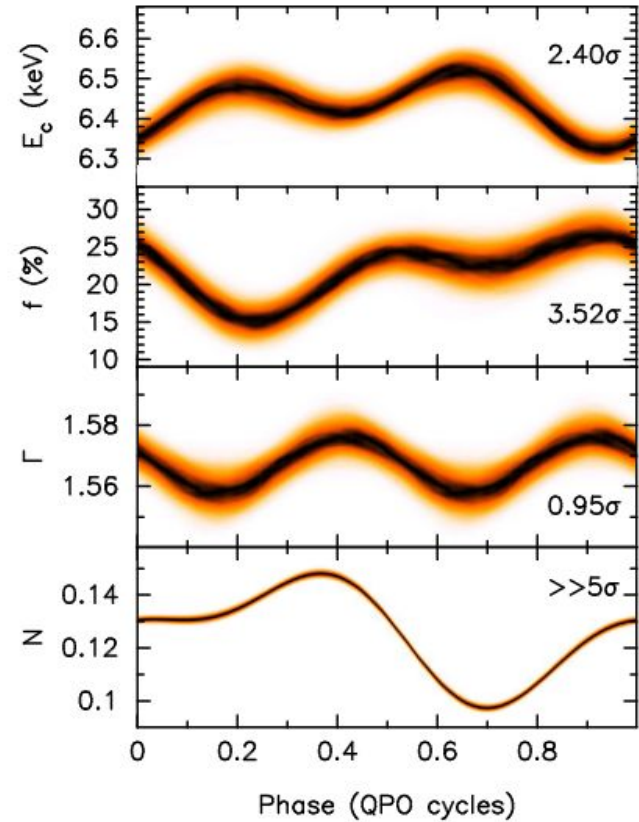
QPO phase = 0.4 cycles



Advanced phase-resolved spectroscopy revealed strong evidence for iron line rocking

Application of same methodology to GRS 1915 required very small truncation radius

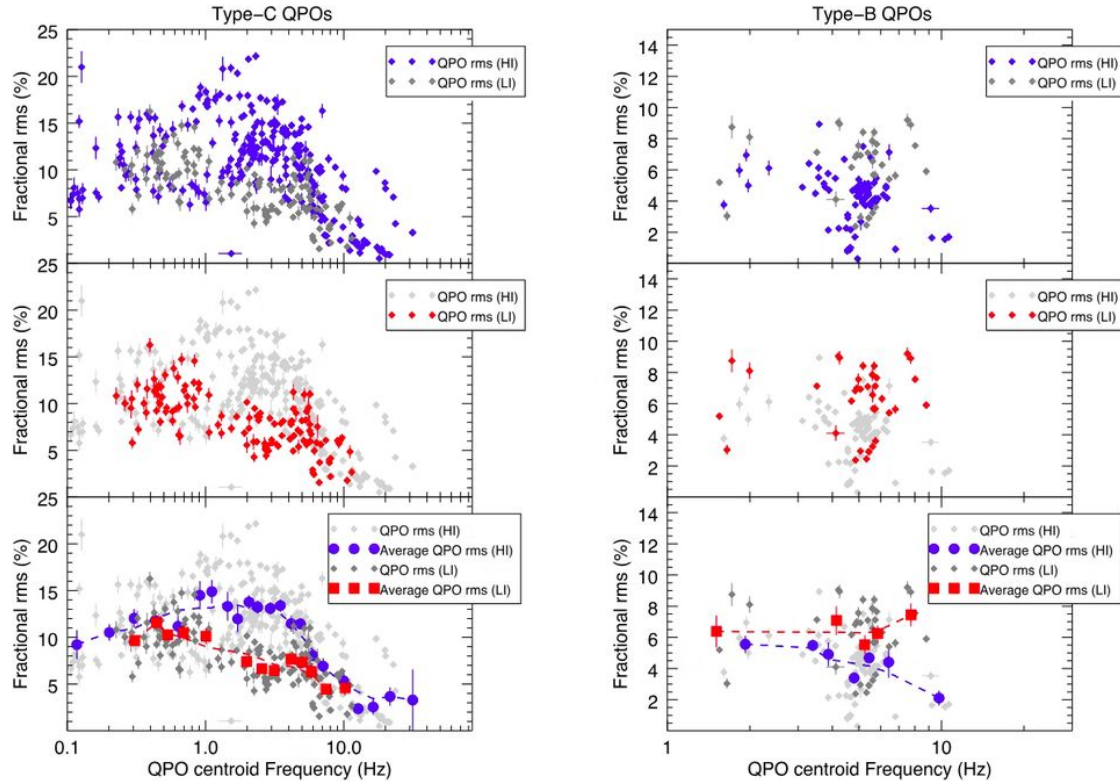
inconsistent with LT precession frequency



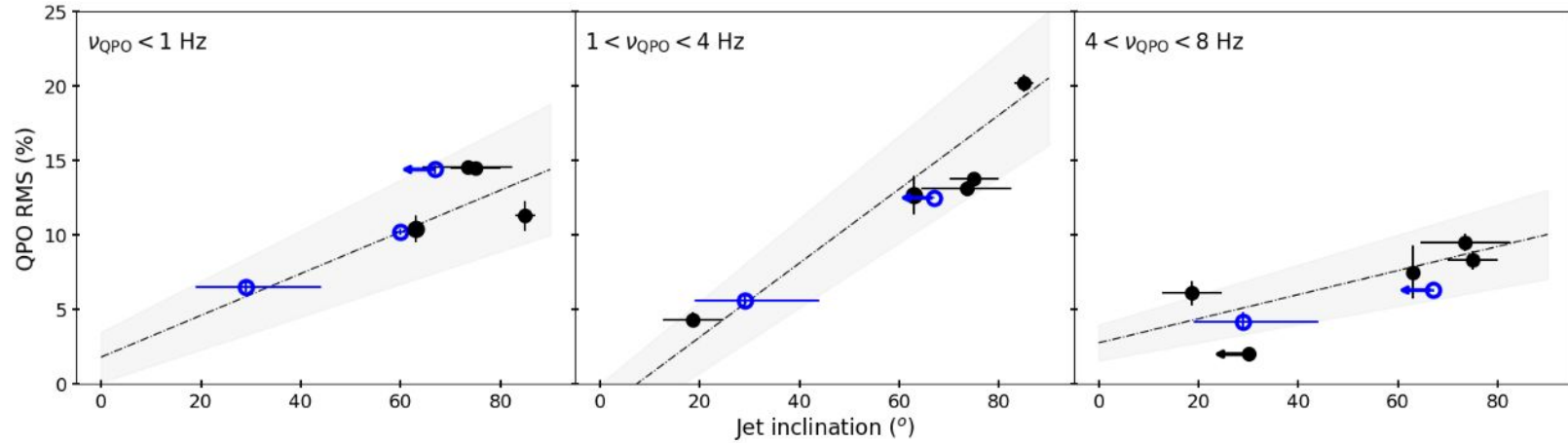
Is it really pression?

Is it really precession?

rms-inclination dependence showed a geometrical effect



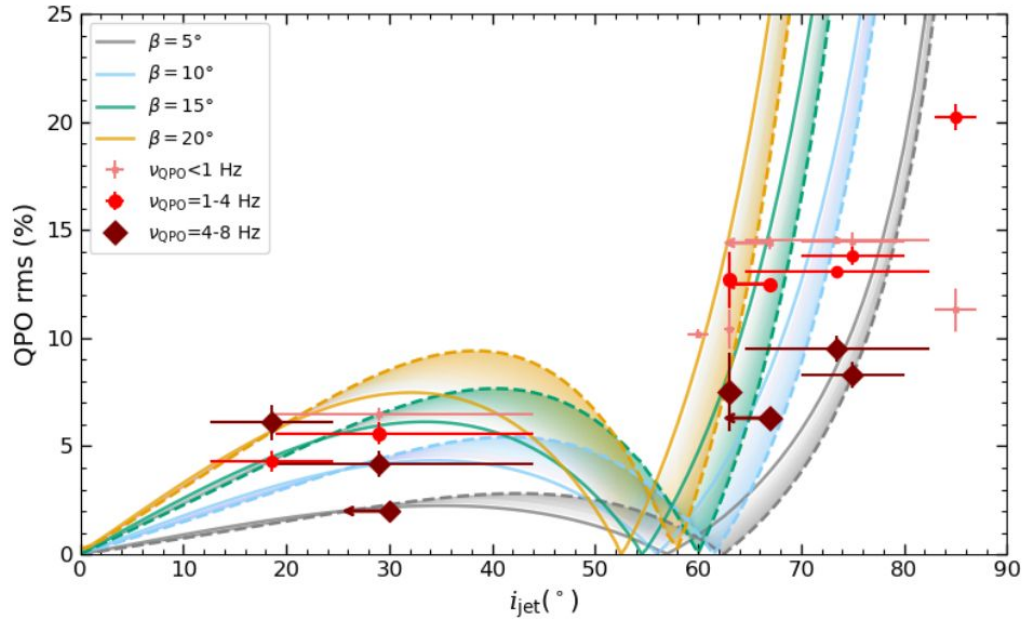
Is it really pression?



Population analysis revealed that rms correlation holds with jet inclination

Requires some asymmetry in the emission

Is it really precession?



Modelling with precessing slab (not LT!) shows good agreement with data

Requires misalignment of at least 10-15 degrees

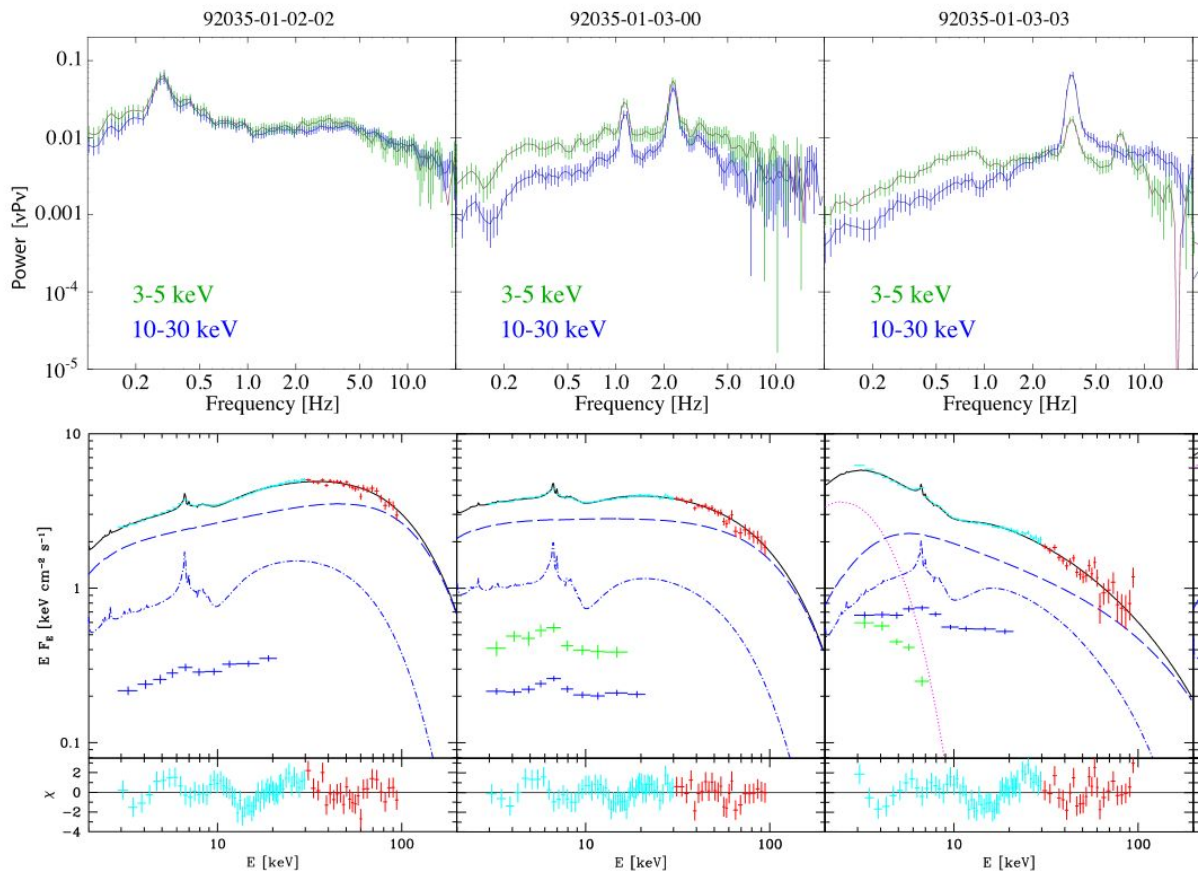
Radiative properties

Rms spectral analysis showed that:

Fundamental + harmonic can be explained with similar spectra

Comptonization + reflection

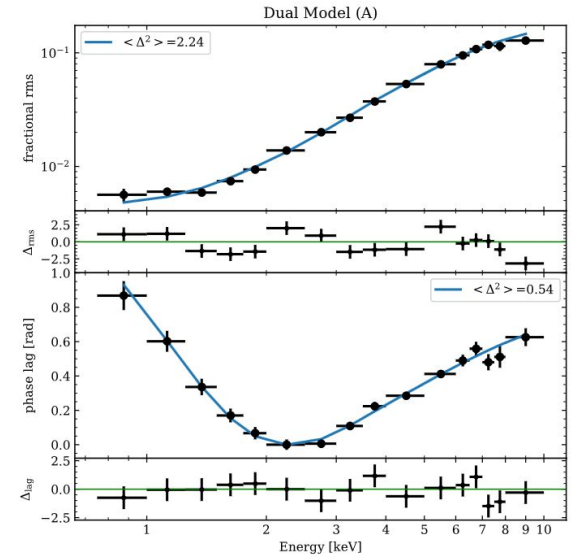
Towards soft state Harmonic shows only soft Comptonization



Radiative properties

Recently lags and spectra of QPOs were modelled through small oscillation of the steady Kompaneets solution

Spherical homogeneous corona + disc seed photons + feedback fraction η returning to the disc



Radiative properties

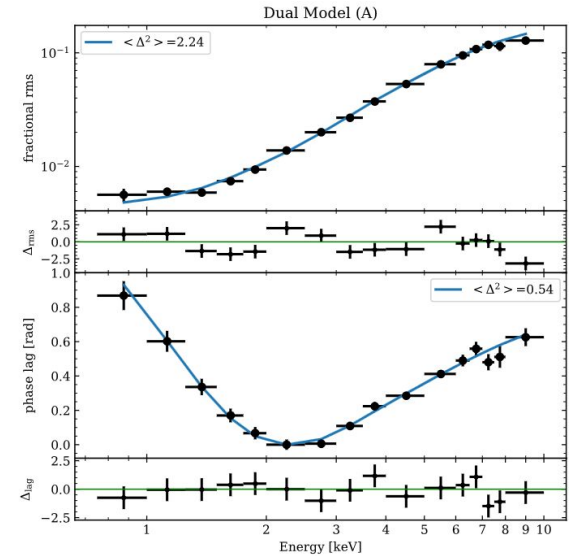
Recently lags and spectra of QPOs were modelled through small oscillation of the steady Kompaneets solution

Spherical homogeneous corona + disc seed photons + feedback fraction η returning to the disc

It has been shown that disk—corona system in BHXRBs can show a limit cycle and give rise to QPO (Mastichiadis+2026)

Unclear if it can really substitute precession.

Karpouzas+2020; Mendez+2022; Bellavita+2022, Garcia+2022,





Observations:

- Multi-wavelength QPOs
- Polarization

Methodology

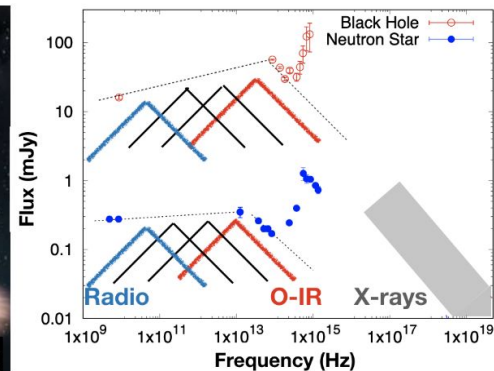
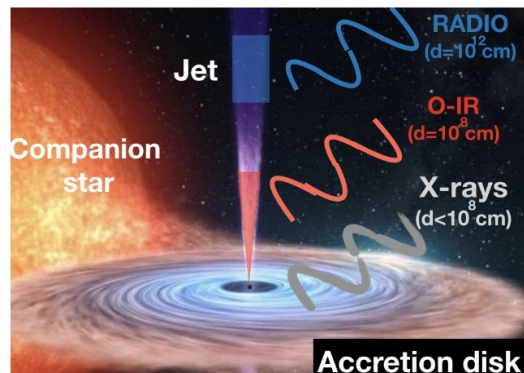
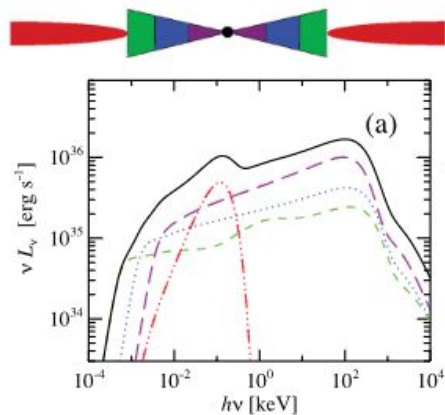
- Bi-spectrum/non-linearity
- “Imaginary QPO”

Two competing models for non-thermal O-IR variability:

PRECESSION OF

Synchrotron from hot flow

vs Synchrotron from jet/outflow



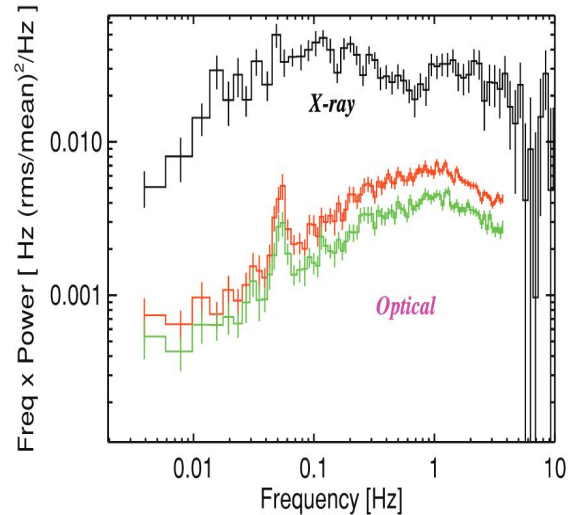
Veledina+2015,2017

Malzac+2014,2018

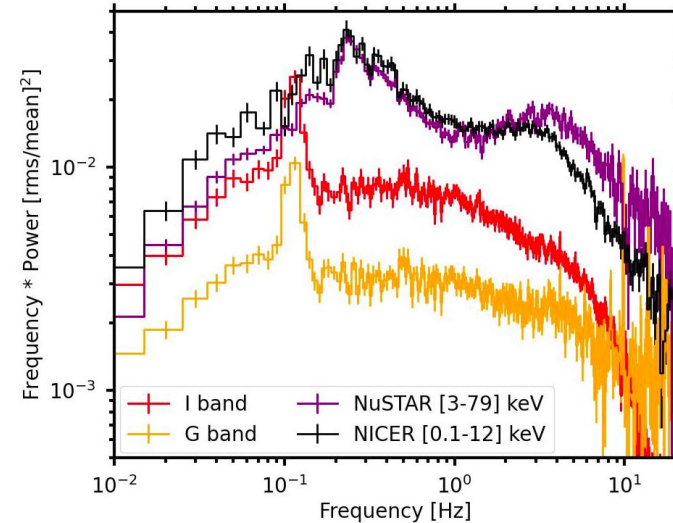
O-IR QPOs: complex relation with the X-rays

Most emblematic case GX 339-4

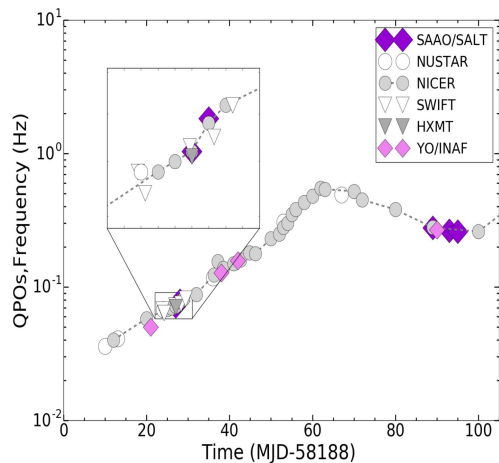
**at low luminosity
only O-IR QPO**



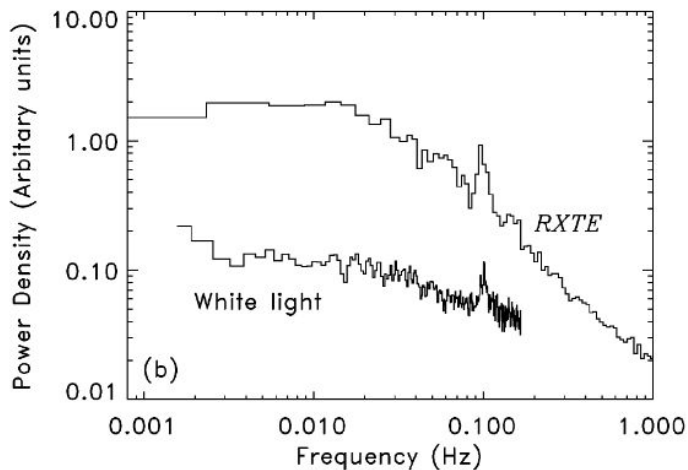
**high luminosity
strong harmonic relation**



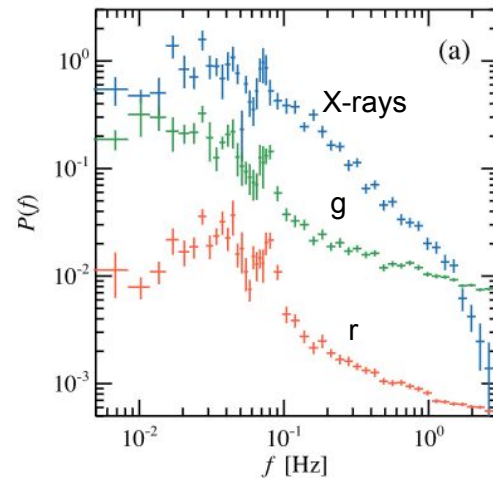
BH LMXB, however, also shows synchronous frequency evolving in time



MAXI J1820+070

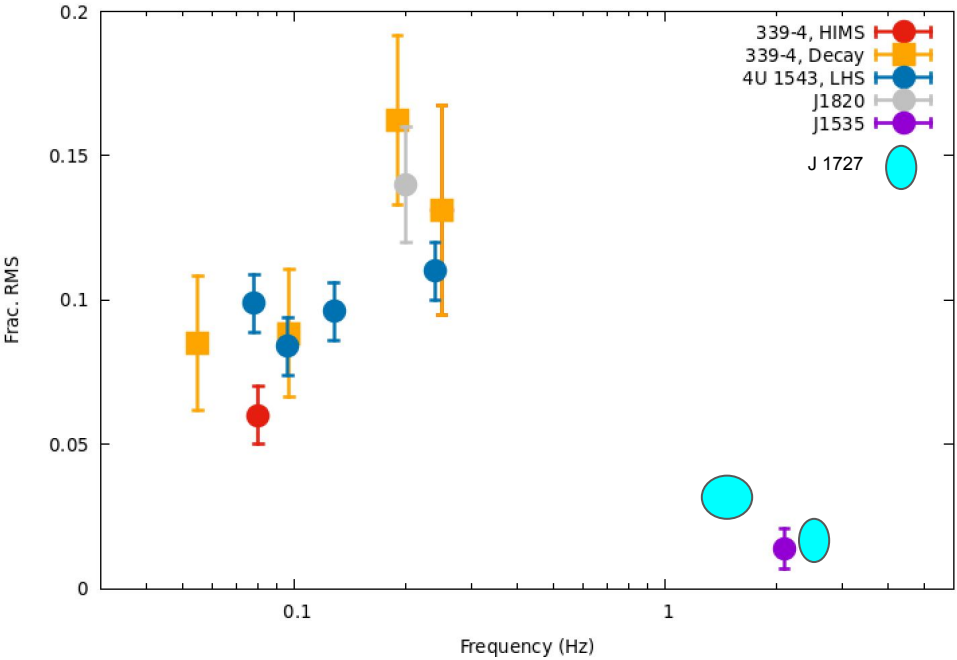


XTE J118+480



SWIFT J1753.5-0127

All together now!



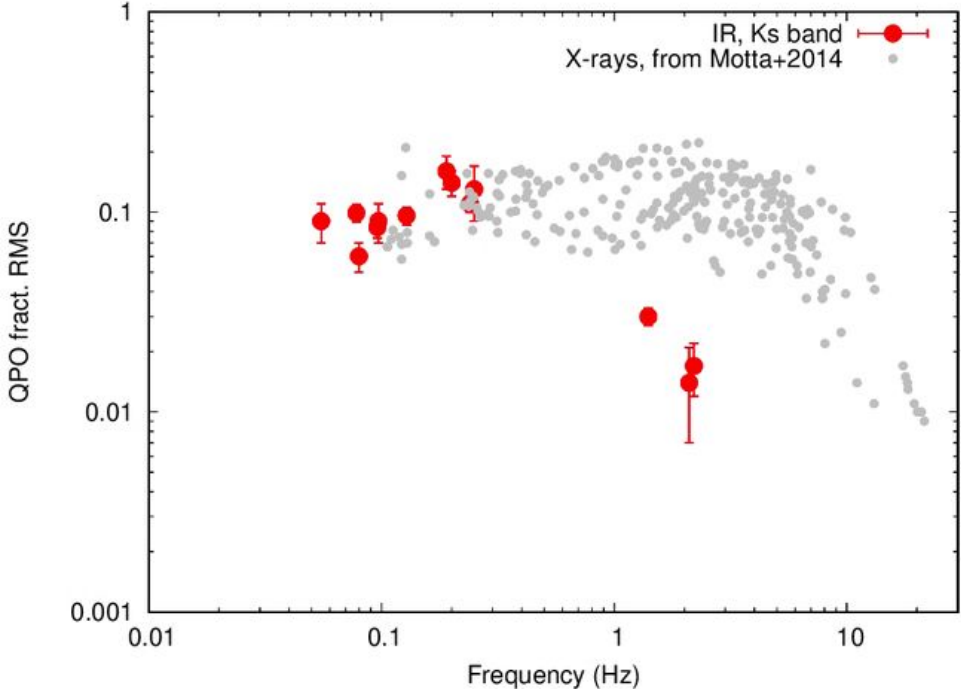
Clear dichotomy. Below 0.5-1 Hz, high rms (10%), above 0.5-1 Hz, rms very low (~few %)

,

Vincentelli+in prep.

Clear dichotomy. Below 0.5-1 Hz, high rms (10%), above 0.5-1 Hz, rms very low (~few %)

What is the relation with the X-rays?

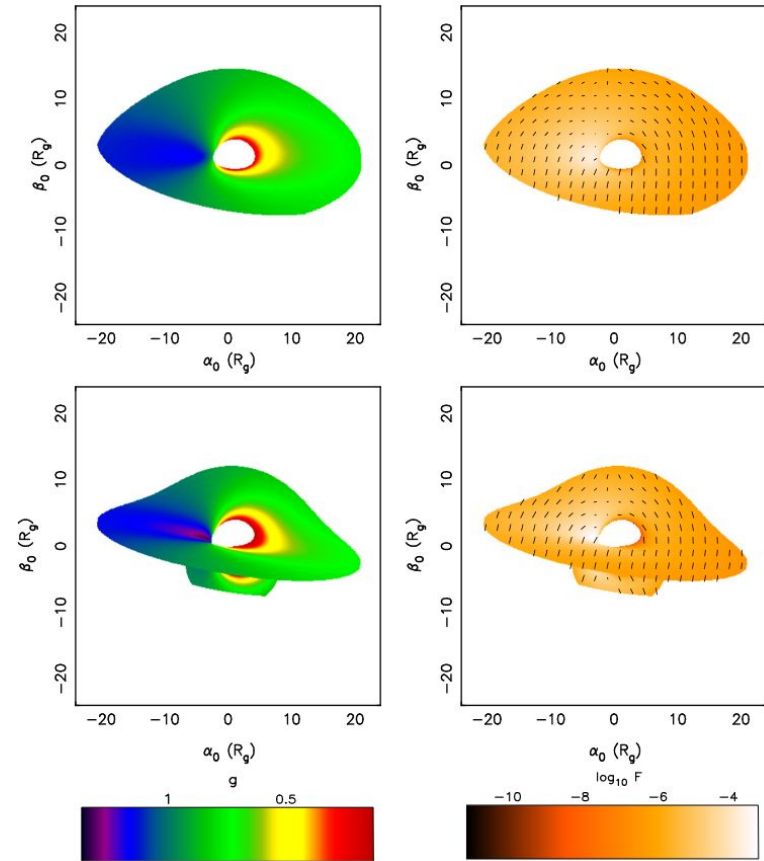


IR QPOs seem to decay earlier in frequencies than the X-rays

Vincentelli+in prep.

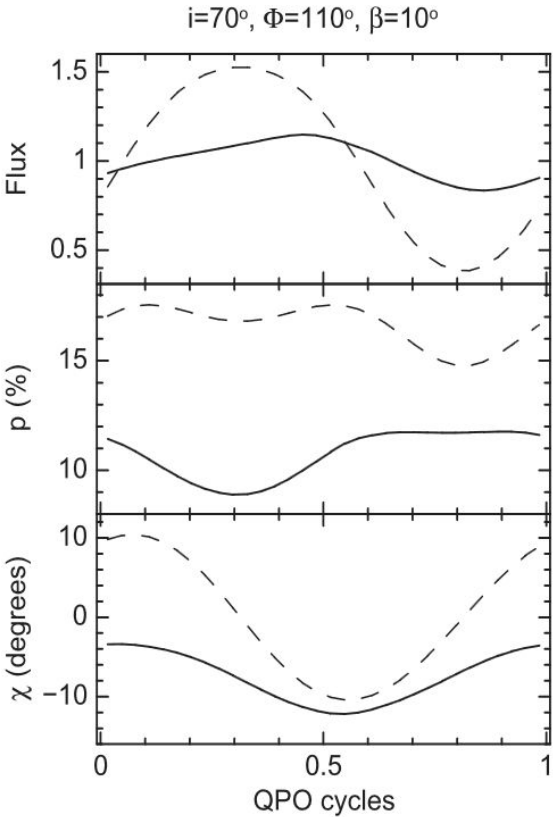
X-ray polarization

Precession models do predict a modulation of X-ray polarization with QPO



X-ray polarization

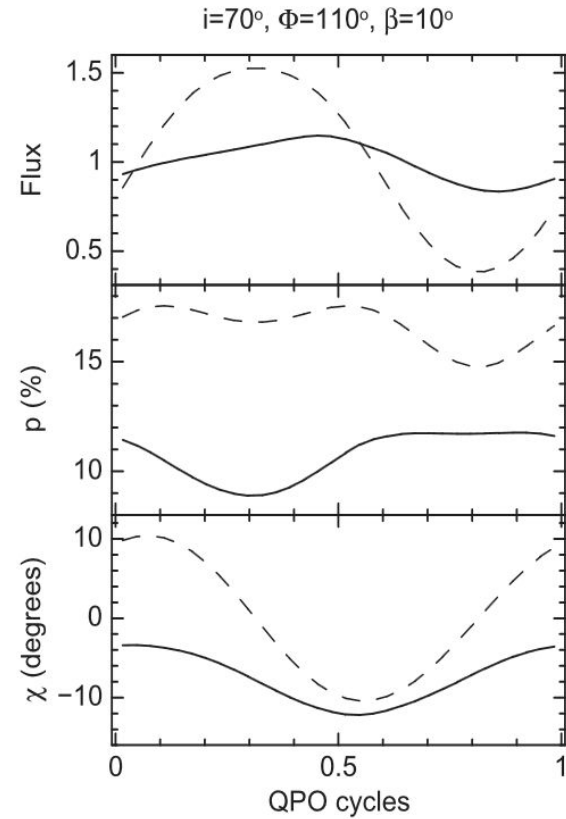
Precession models do predict a modulation of X-ray polarization with QPO



X-ray polarization

Precession models do predict a modulation of both X-ray polarization with QPO

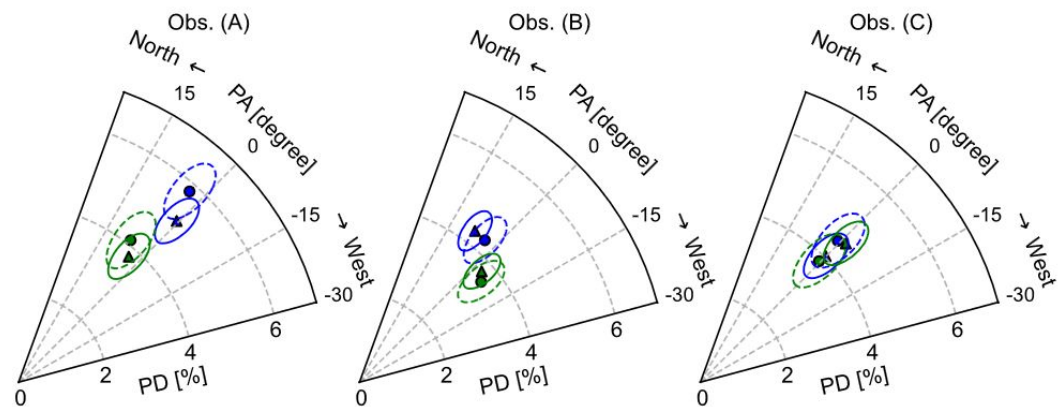
IXPE sensitivity is not enough to perform Phase resolved analysis, but...



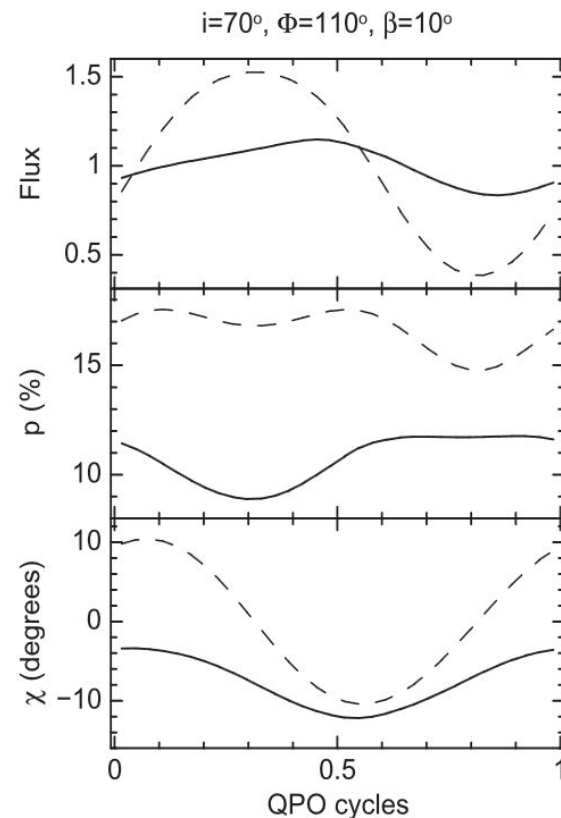
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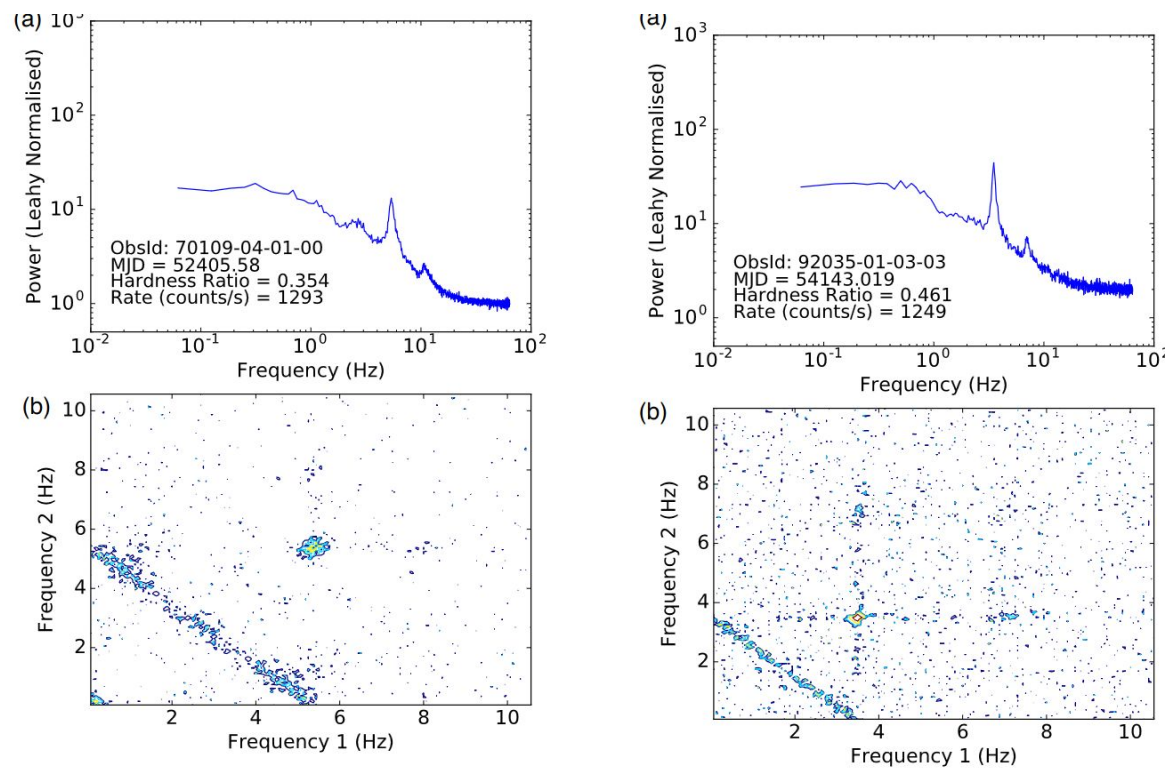
IXPE sensitivity is not enough to perform Phase resolved analysis, but, strong evidence for flux dependent polarization!



Ninoyu+2025

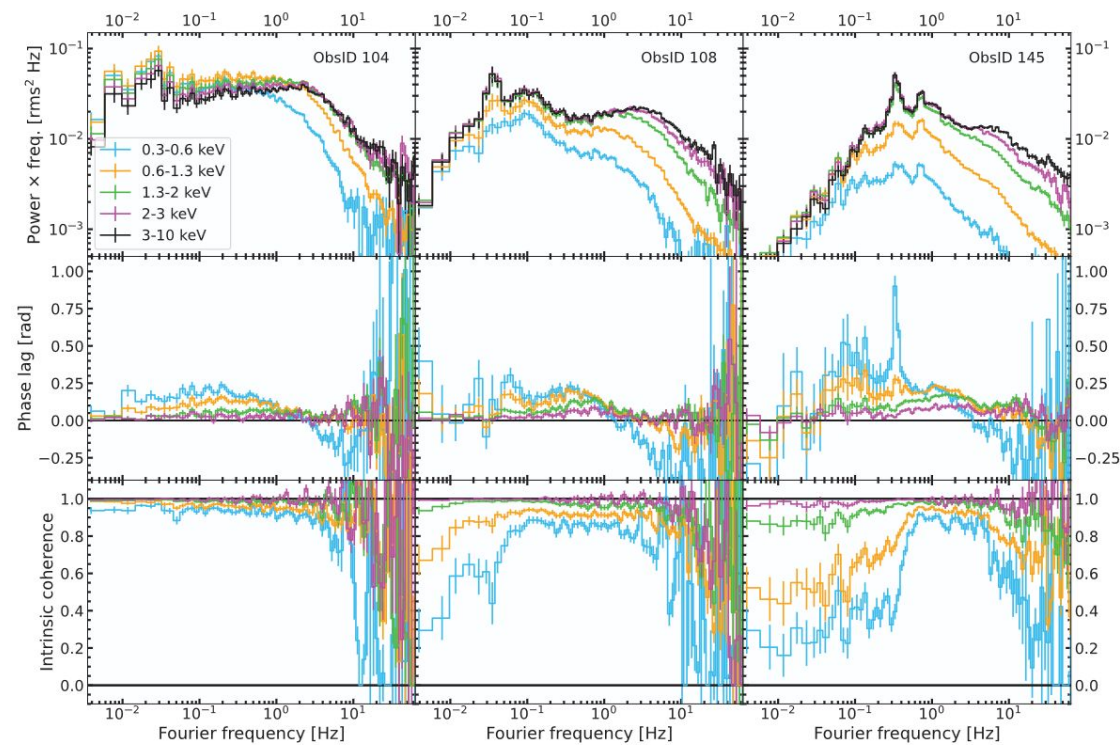


Bi-spectrum/non-linearity



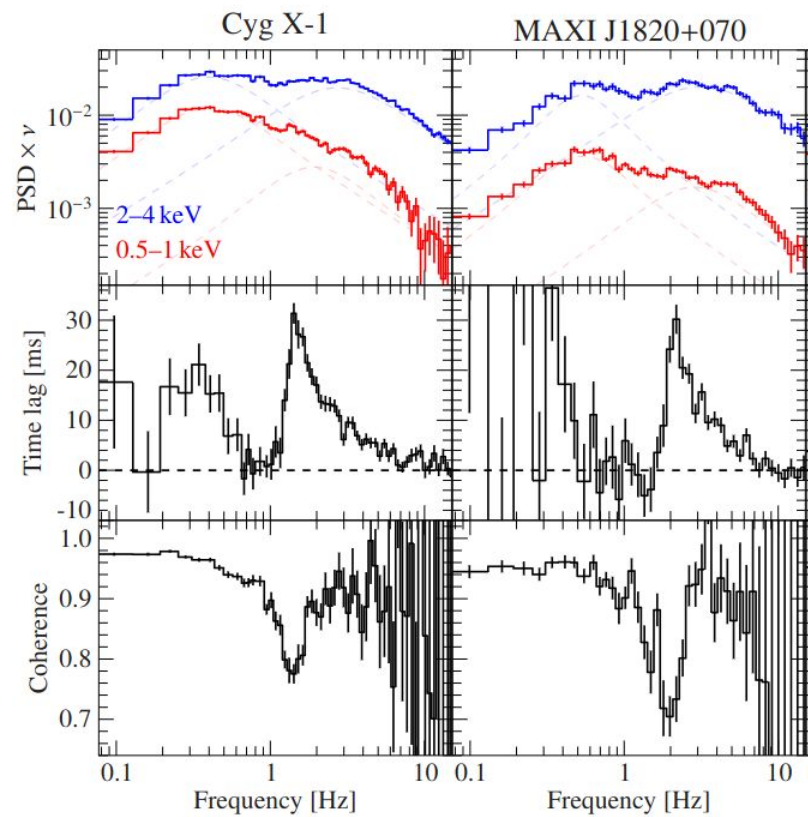
Growing evidence of “cross-talk” between QPO and other components, a lot to explore!

Bi-spectrum/non-linearity



Growing evidence of “cross-talk” between QPO and other components, a lot to explore!

Imaginary QPO



Recent discovery of “hidden” components visible only in the CS

Konig+2024, Bellavita+2025

TAKE HOME MESSAGES:

Evolution in frequency strongly supports precession scenario in both NS and BHs

Study of the amplitude and inclination show need of some structural effect

Results from phase/phase resolved spectral modeling at tension with hot flow precession

Fast MWL variability is opening a new window in understanding all radiative components, including jets

Polarization will open a new avenue in understanding geometry of accretion flow

New methods are unveiling interesting non-linear unexplained phenomenology

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THANK YOU! (and thank you Tomaso!)