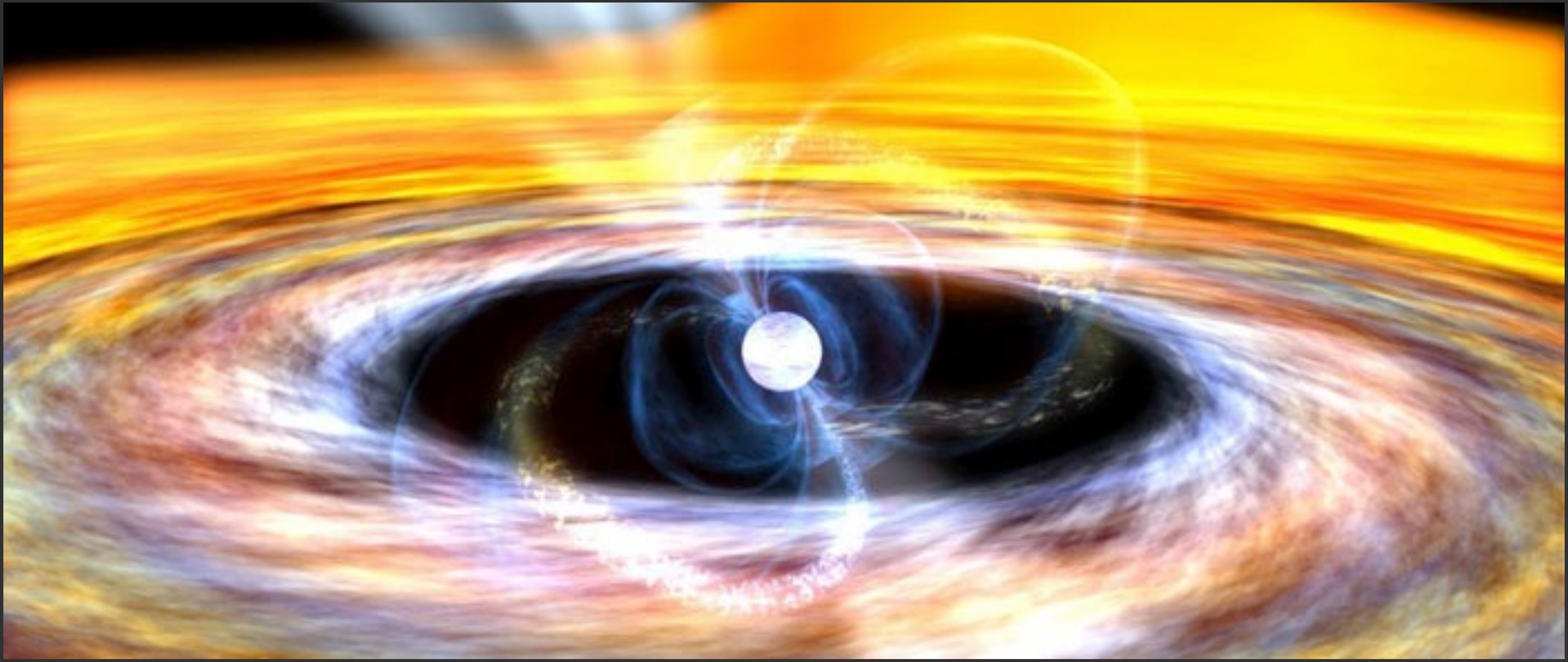
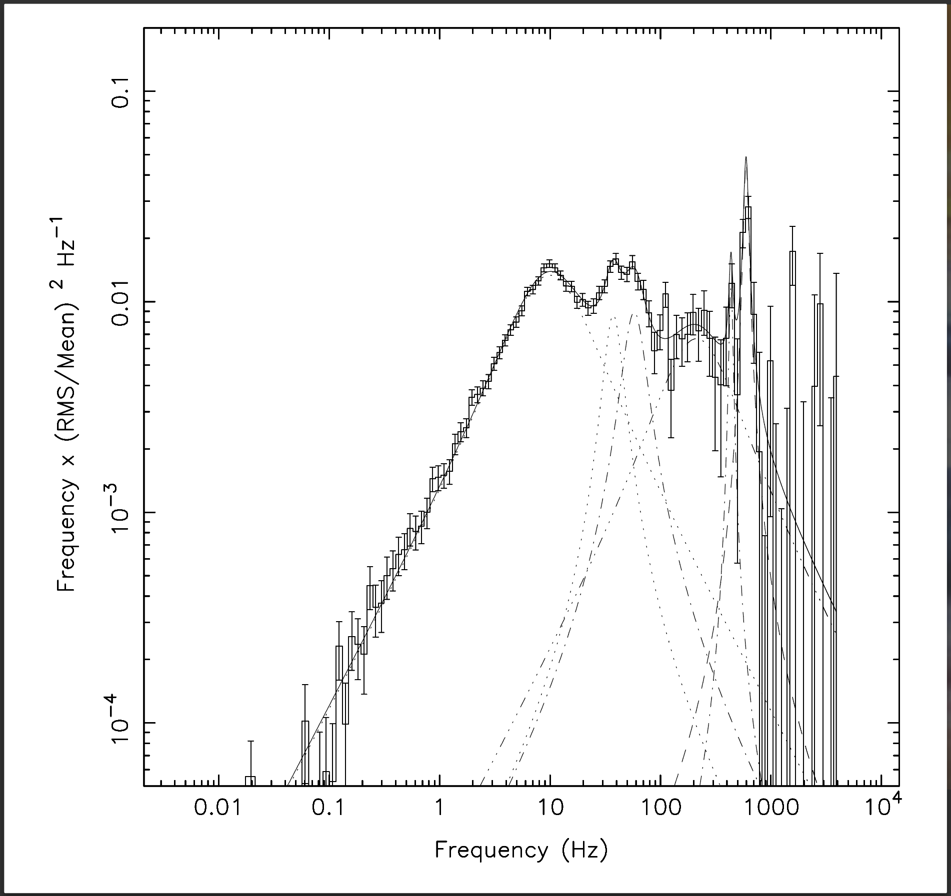
Quasi-periodic modulation of accreting millisecond pulsars

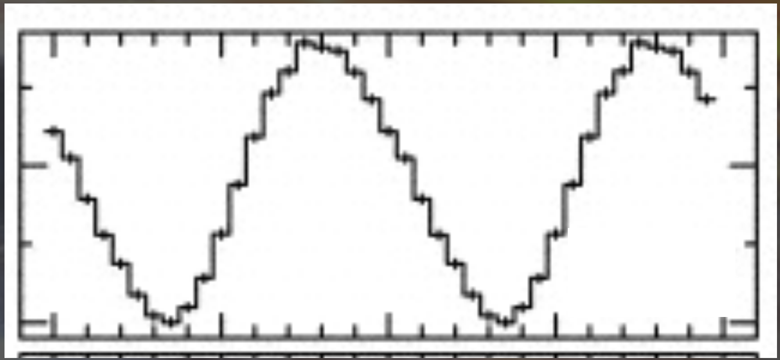
Peter Bult

QPO/Pulse coupling



QPO/Pulse coupling



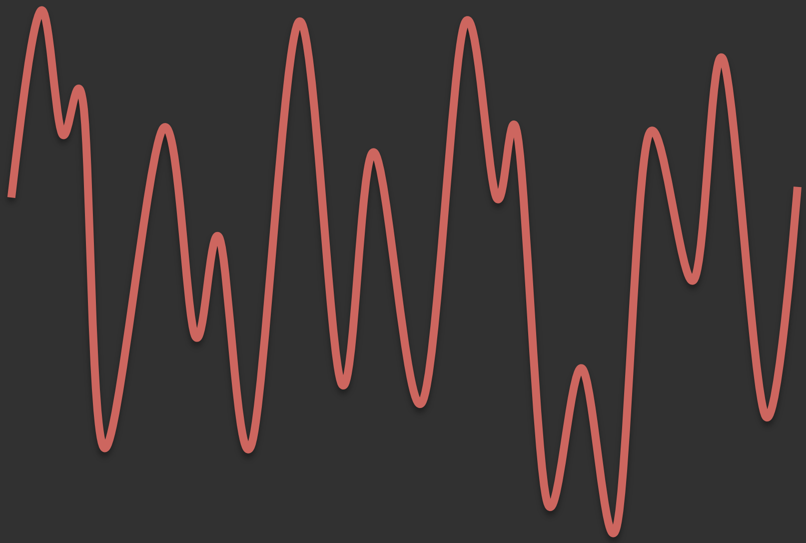


QPO/Pulse coupling

- Tells us something about the pulsar emission
  - Hotspot shape
  - Beaming angle
- Tells us something about the aperiodic emission
  - Accretion geometry
- Complementary to spectral timing type studies

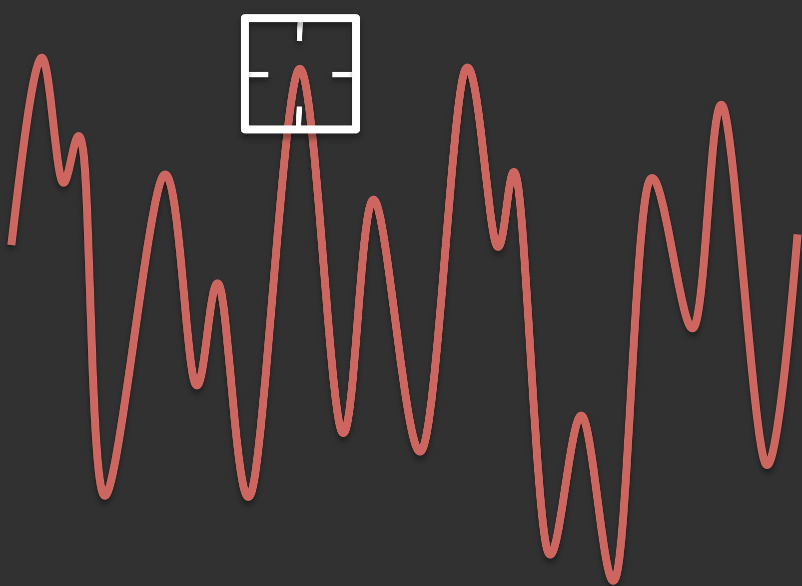
traditional approach

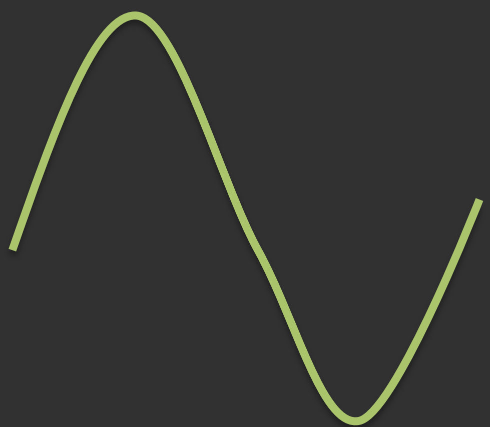
Consider a light curve with a prominent QPO



traditional approach

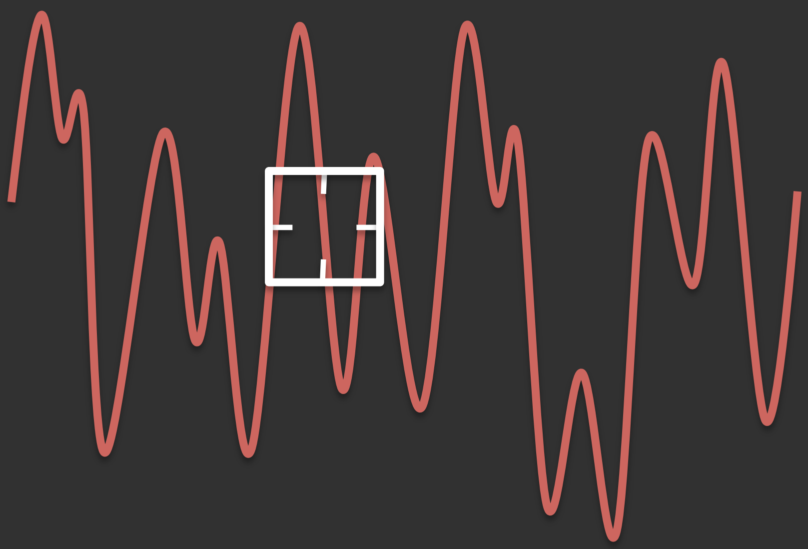
Fold a pulse profile for
potions of the light curve

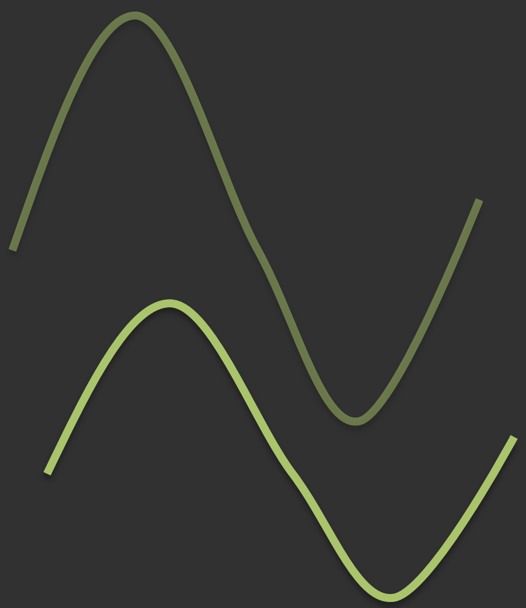




traditional approach

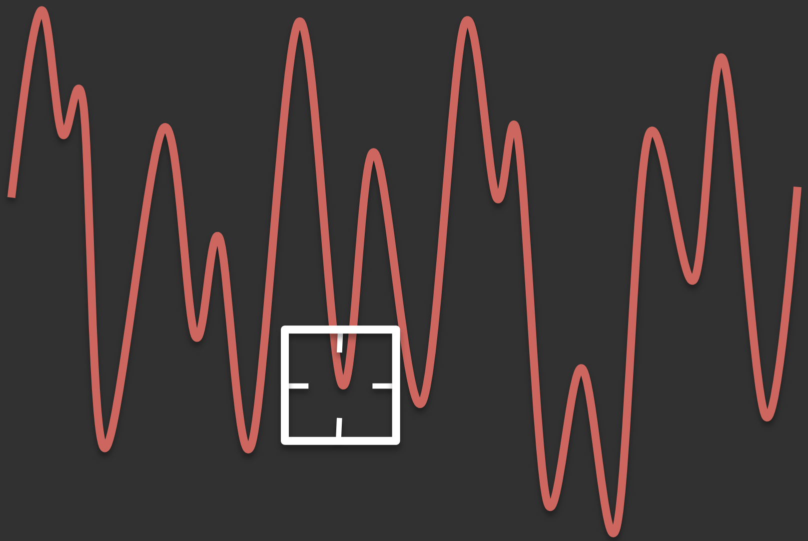
See how the pulse changes
with QPO phase

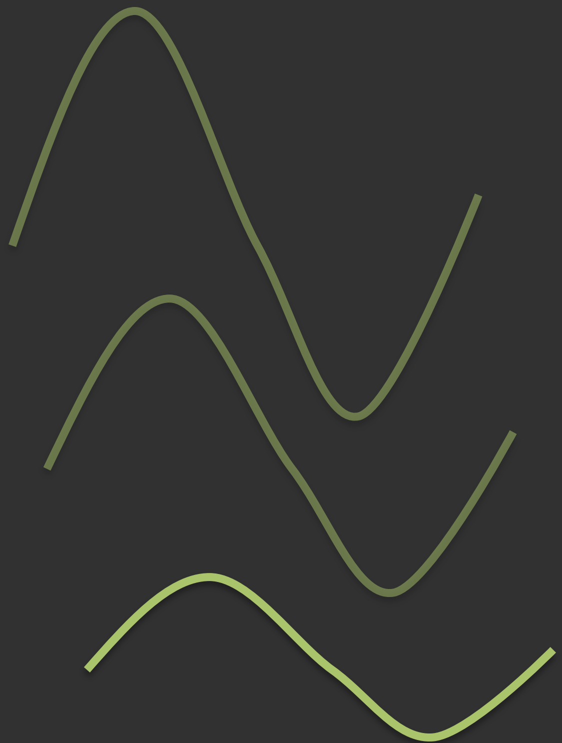




traditional approach

See how the pulse changes with QPO phase





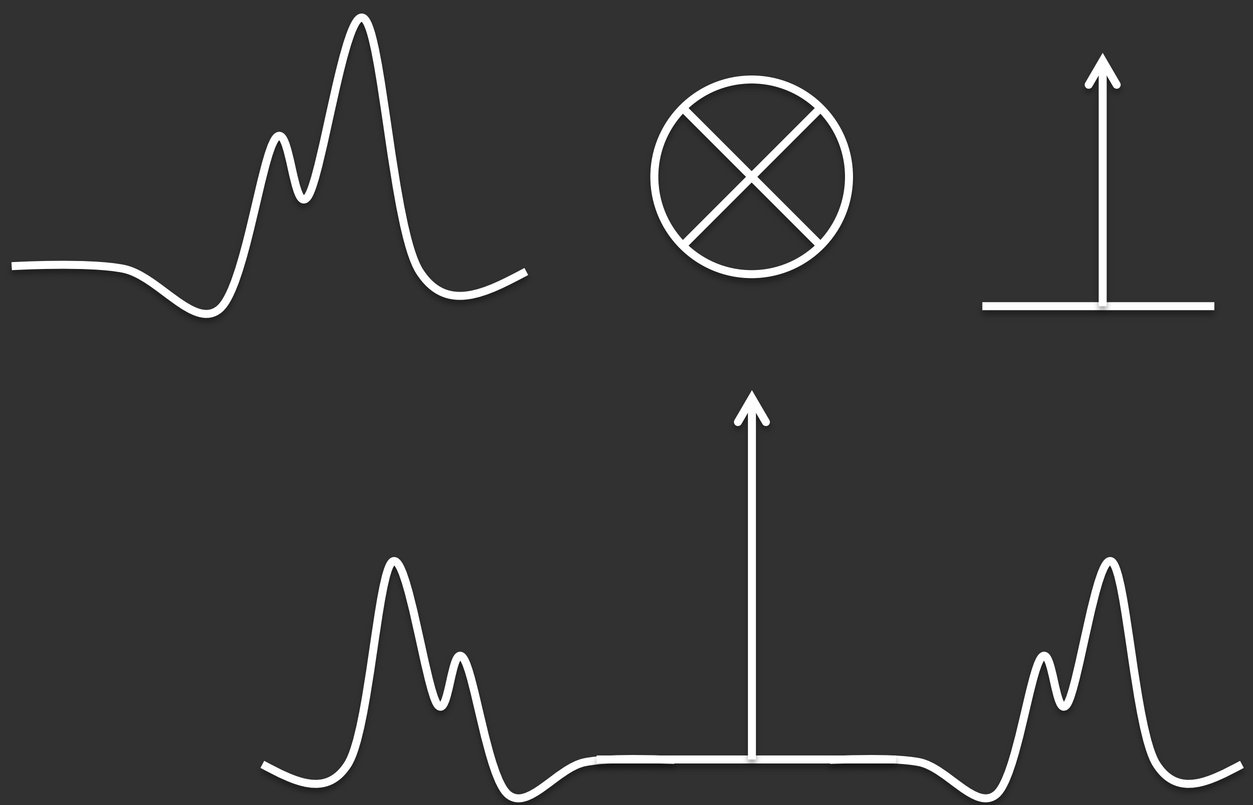
traditional approach

- Heuristic
- Time domain selection needed
- Qualitative
  - statistics not well defined
  - not clear what fit parameters mean

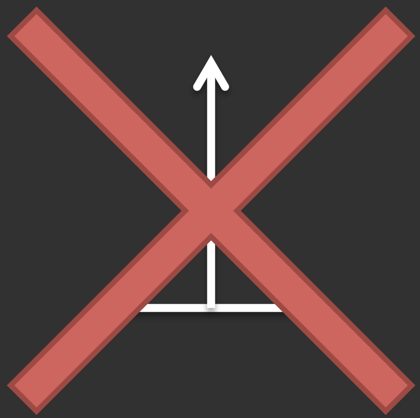
a better way?

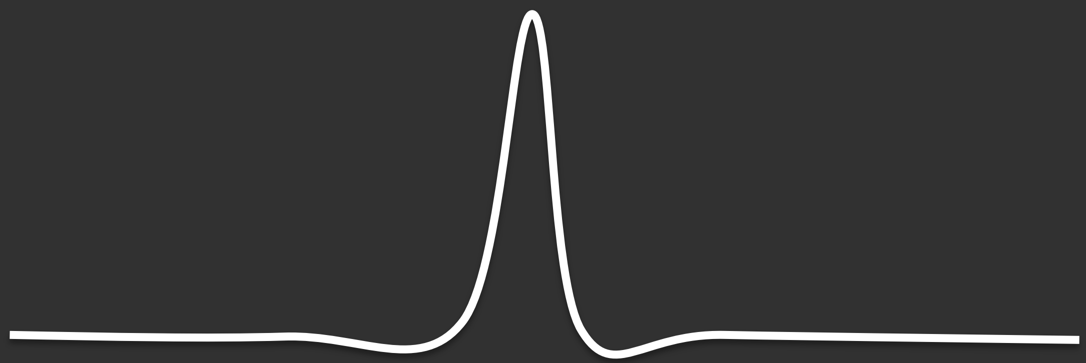
- All information exists in the Fourier Domain
- Multiplied signals are Fourier Domain convolutions
- Convolution with a pulse spike is easy!

pulsar sidebands



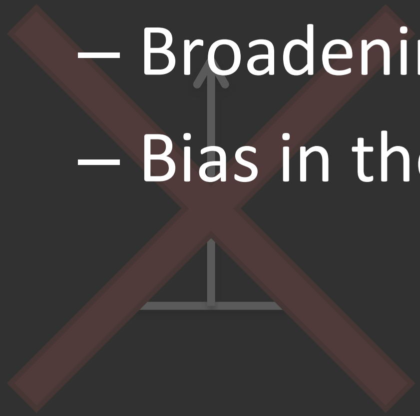
FFT Sampling distorts the profile

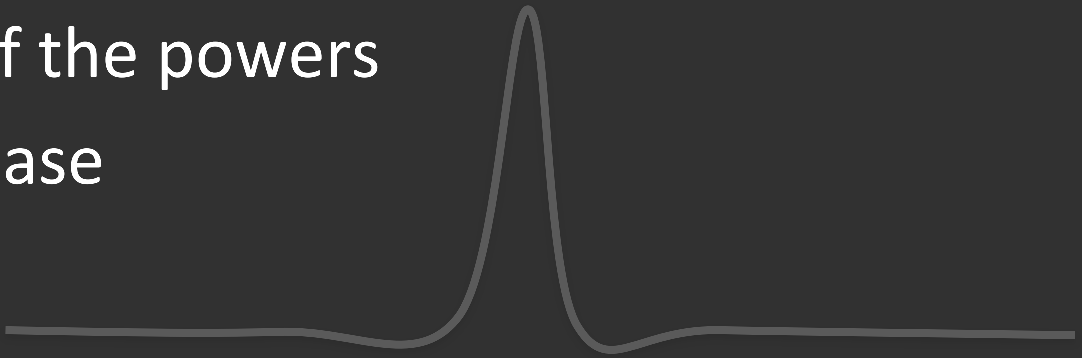




FFT Sampling distorts the profile

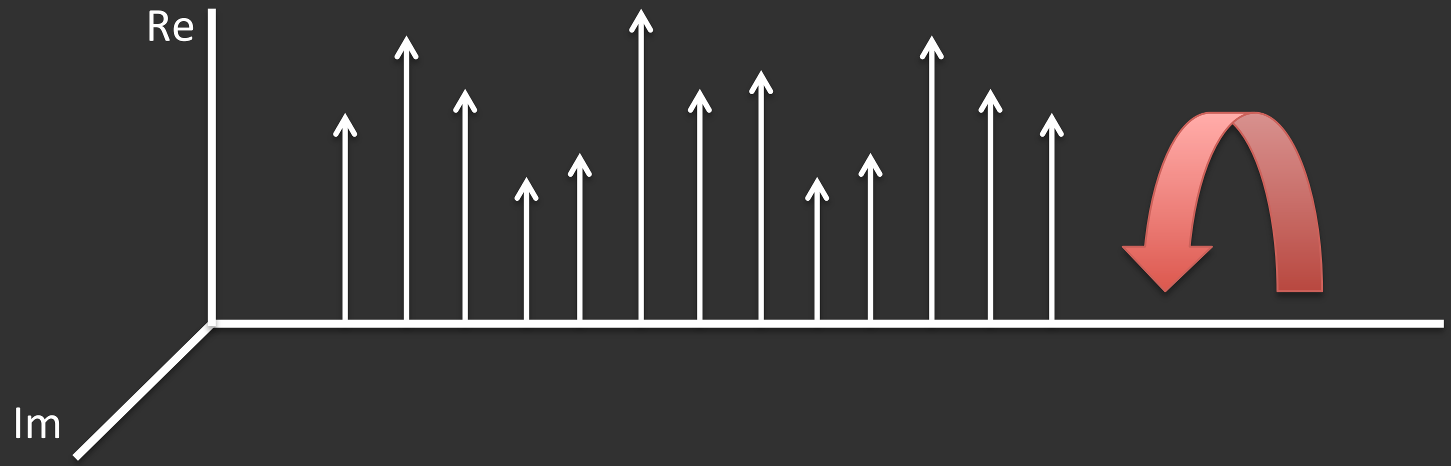
- Spectral leakage
  - Broadening of the powers
  - Bias in the phase



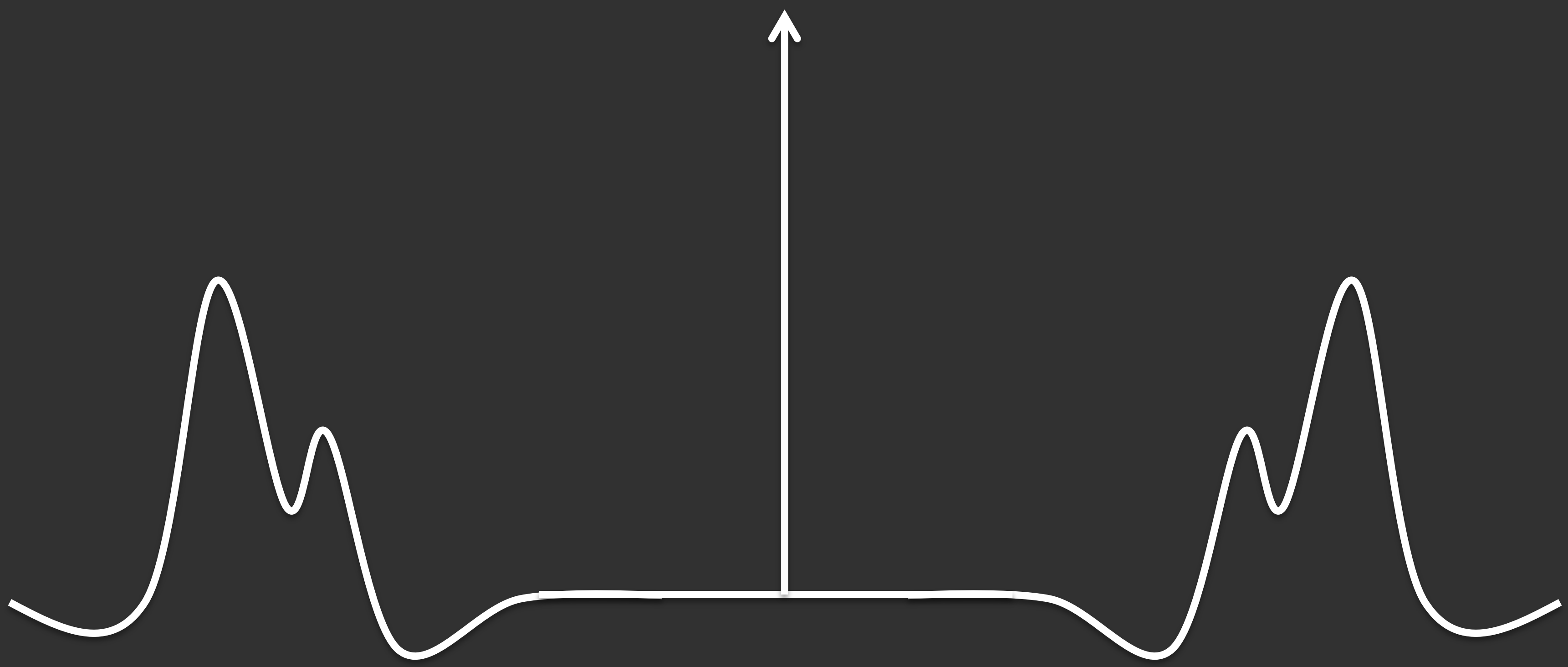


correcting the distortion

- Take the light curve
- Rotate into the complex domain
- Then FFT

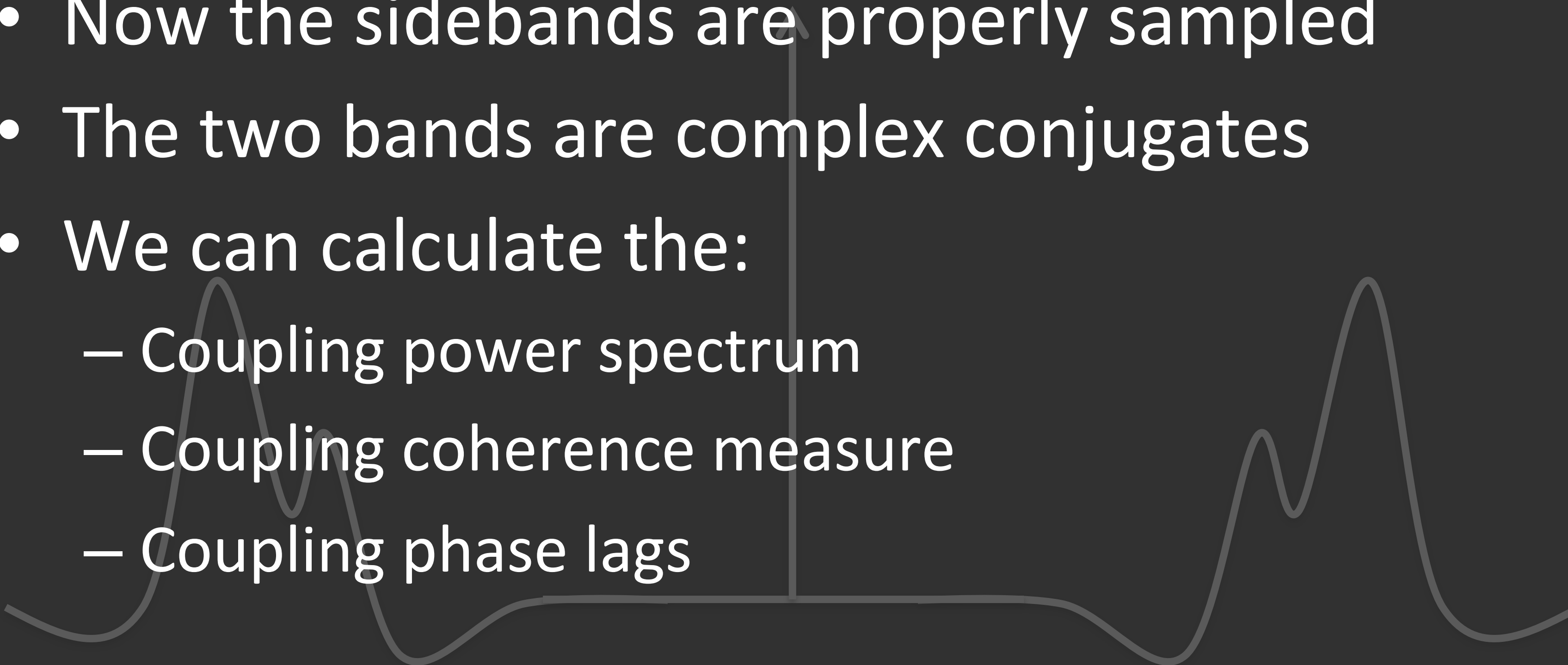


pulse amplitude modulation

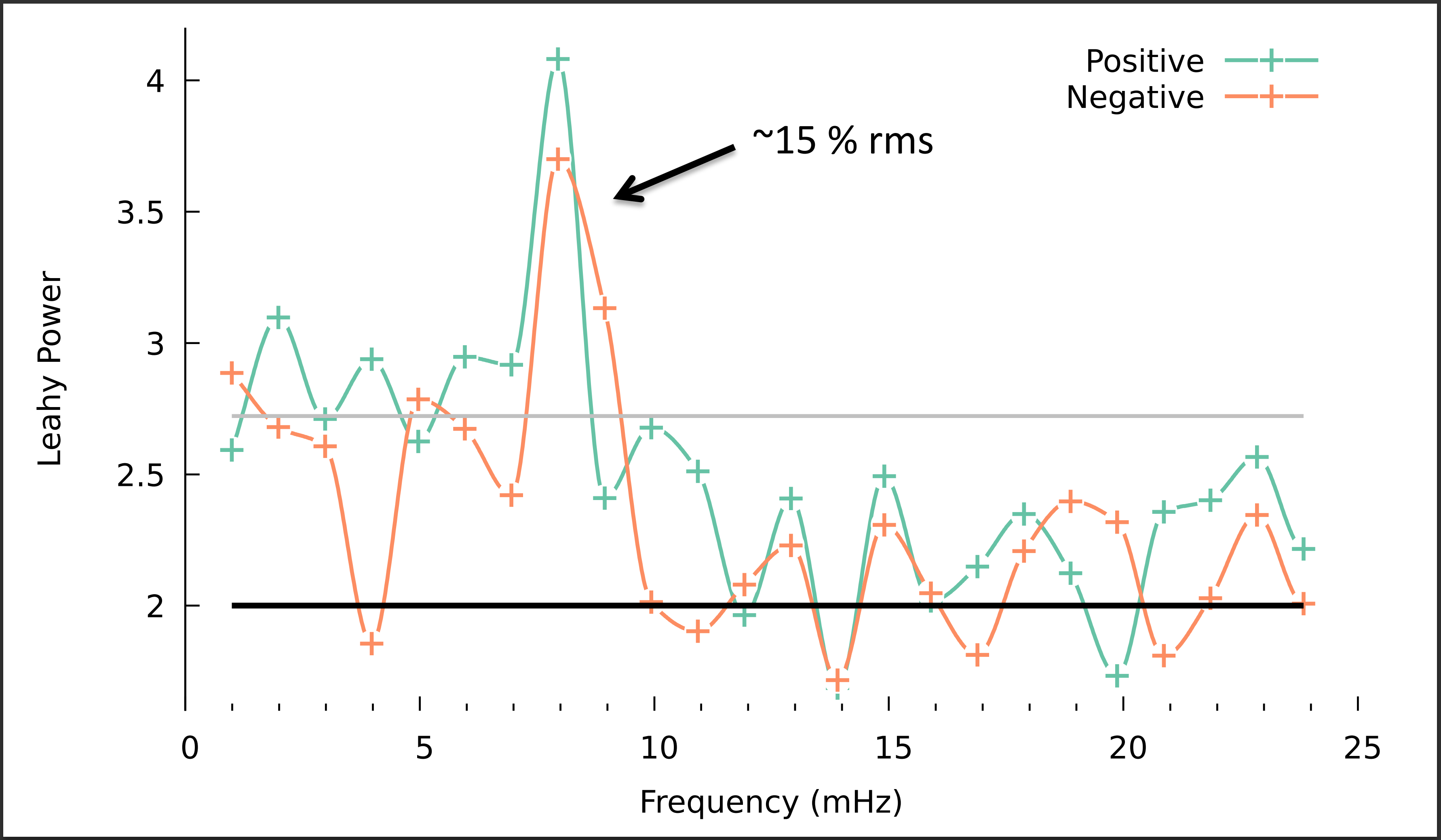


pulse amplitude modulation

- Now the sidebands are properly sampled
- The two bands are complex conjugates
- We can calculate the:
  - Coupling power spectrum
  - Coupling coherence measure
  - Coupling phase lags



IGR J00291



Positive
Negative
~15 % rms
Leahy Power
4
3.5
3
2.5
2
0
5
10
15
20
25
Frequency (mHz)

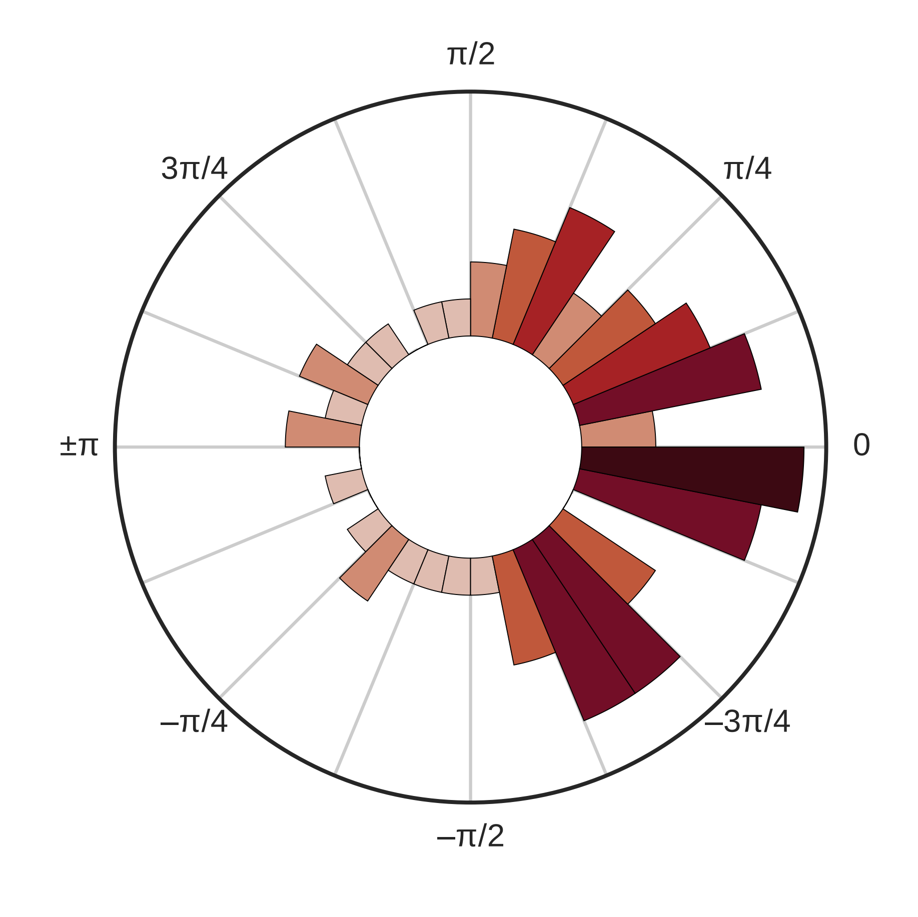
IGR J00291

Phase distribution between sidebands

$S_+(f)\, S_-(f)$

$= A_+ A_-\, e^{2\pi i\,(\Phi_+ + \Phi_-)}$

$= A^2\, e^{2\pi i\,(\Phi\ -\ \Phi)}$



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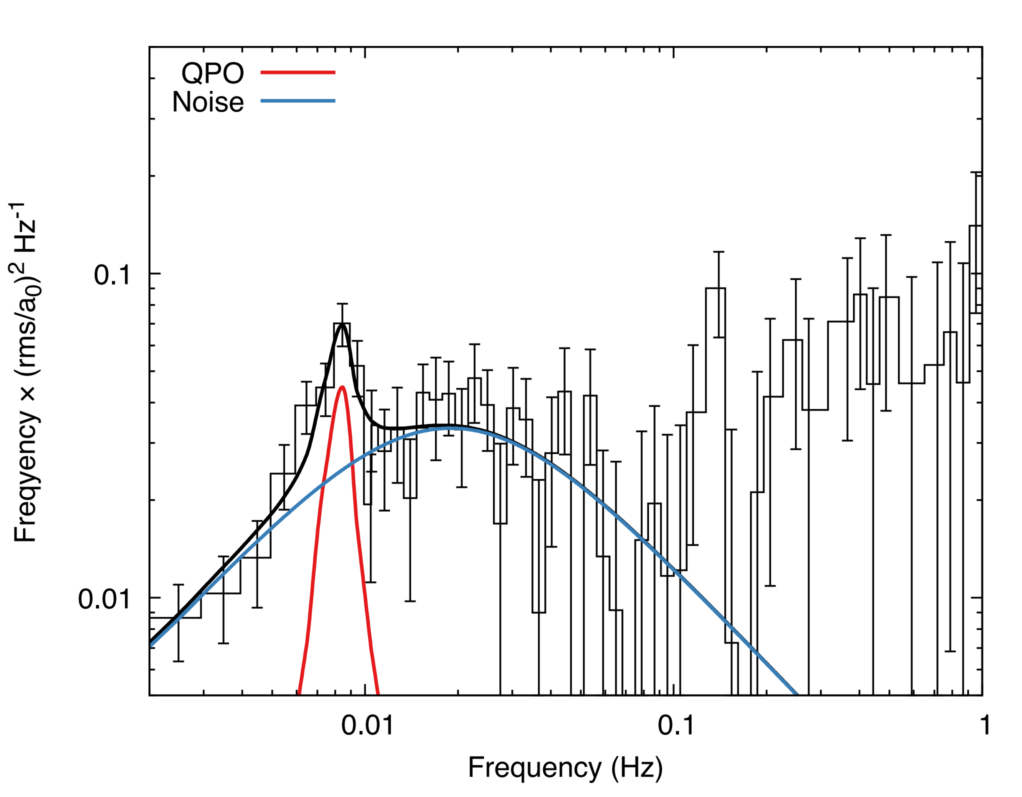
A coupling pds.

Both the QPO and the noise are modulating the pulsations.



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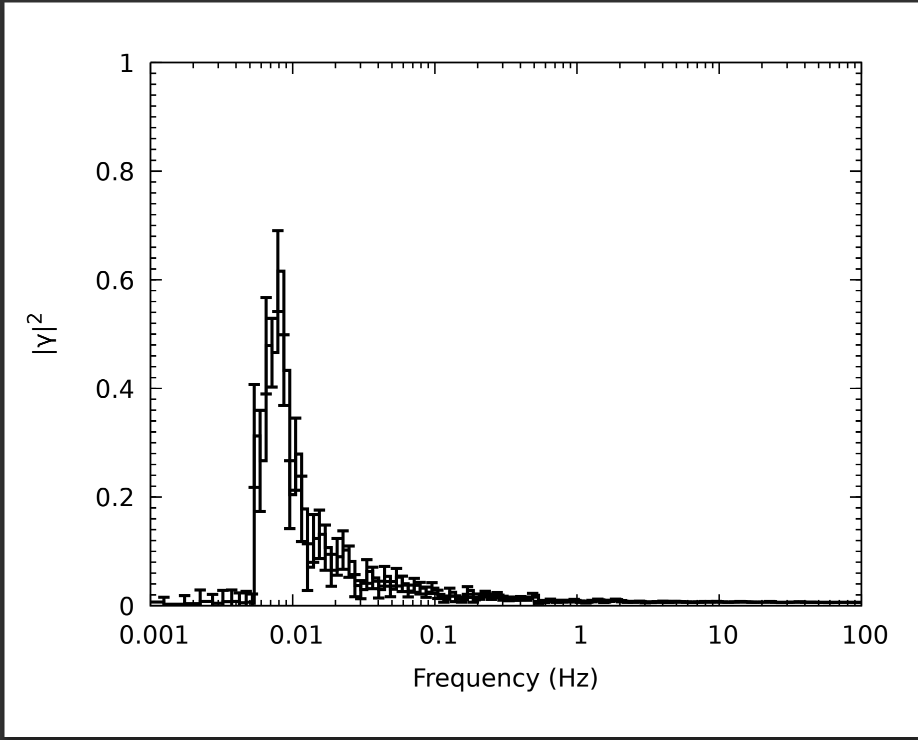
Coupling coherence.

Knowing the sideband complex Fourier samples, we can now calculate cross coherence measures



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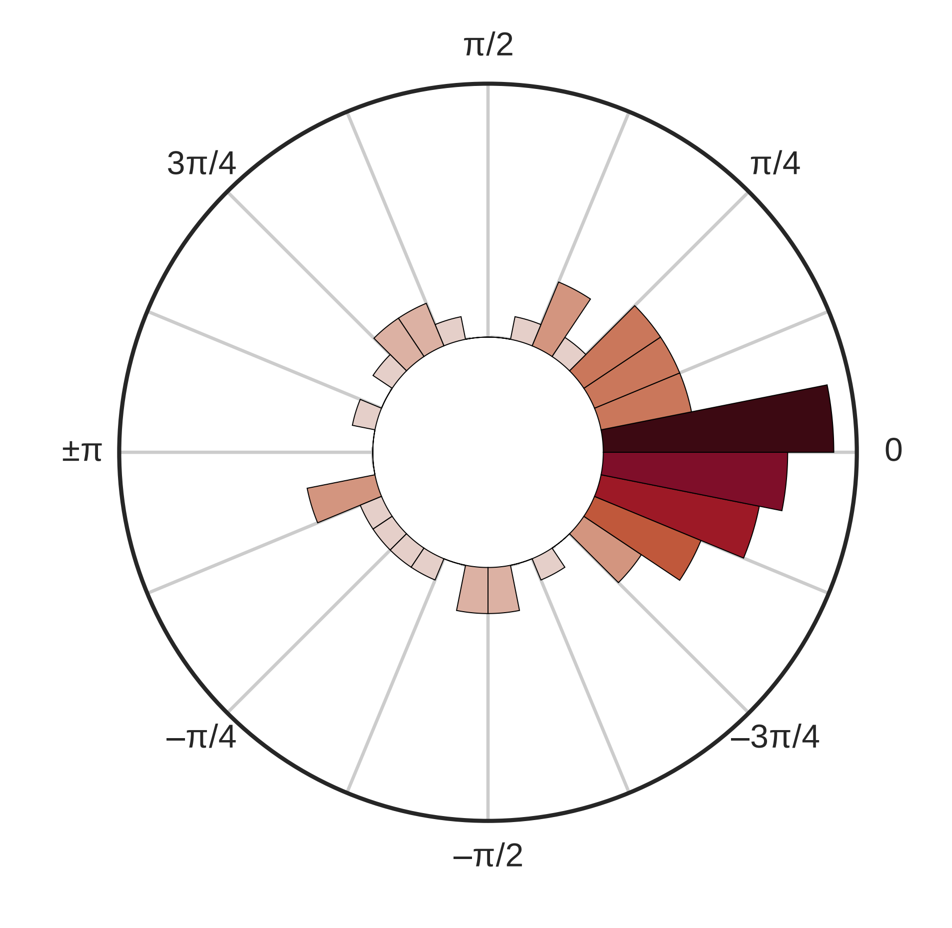
Coupling phase lag

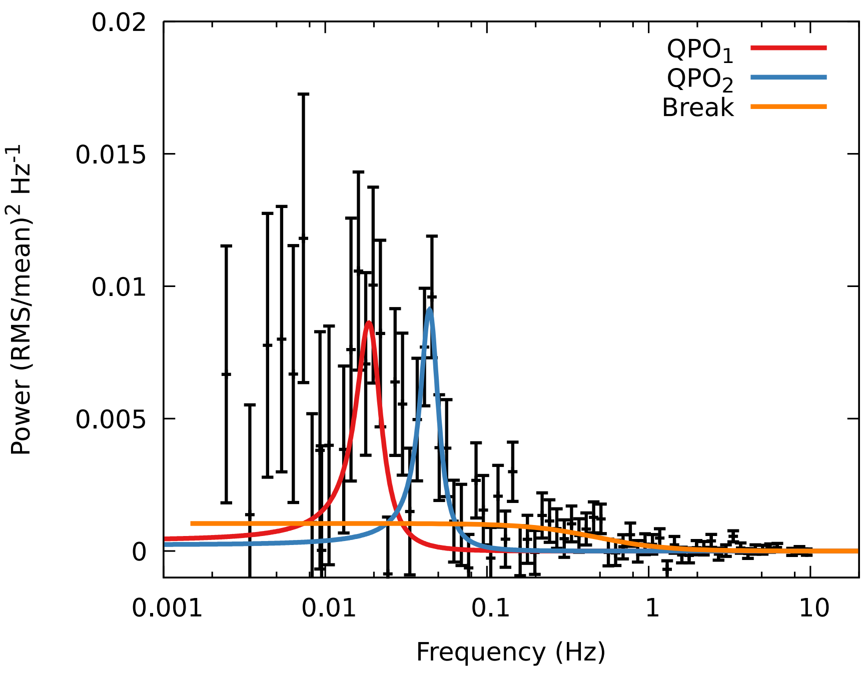
Phase distribution between sideband and the direct low frequency spectrum

$S_{QPO}(f)\ S_{Pulse}(f)^*$
$= A_Q A_P\ e^{2\pi i\ (\Phi_Q - \Phi_P)}$



IGR J00291

Works even for weak QPOs that are not visible in the the light curve directly.



RXTE mHz QPOs in IGR J00291

high throughput x-ray timing

- The obvious improvements apply
  - Higher count rates means faster convergence
  - Less phase smearing
  - Better energy resolution (higher s/n)
  - Energy spectra for QPO, Pulse AND coupling separately

Summary

- A Fourier domain framework for QPO/Pulse coupling studies
- Meaningful measures of coupling and interaction
- Well defined statistics