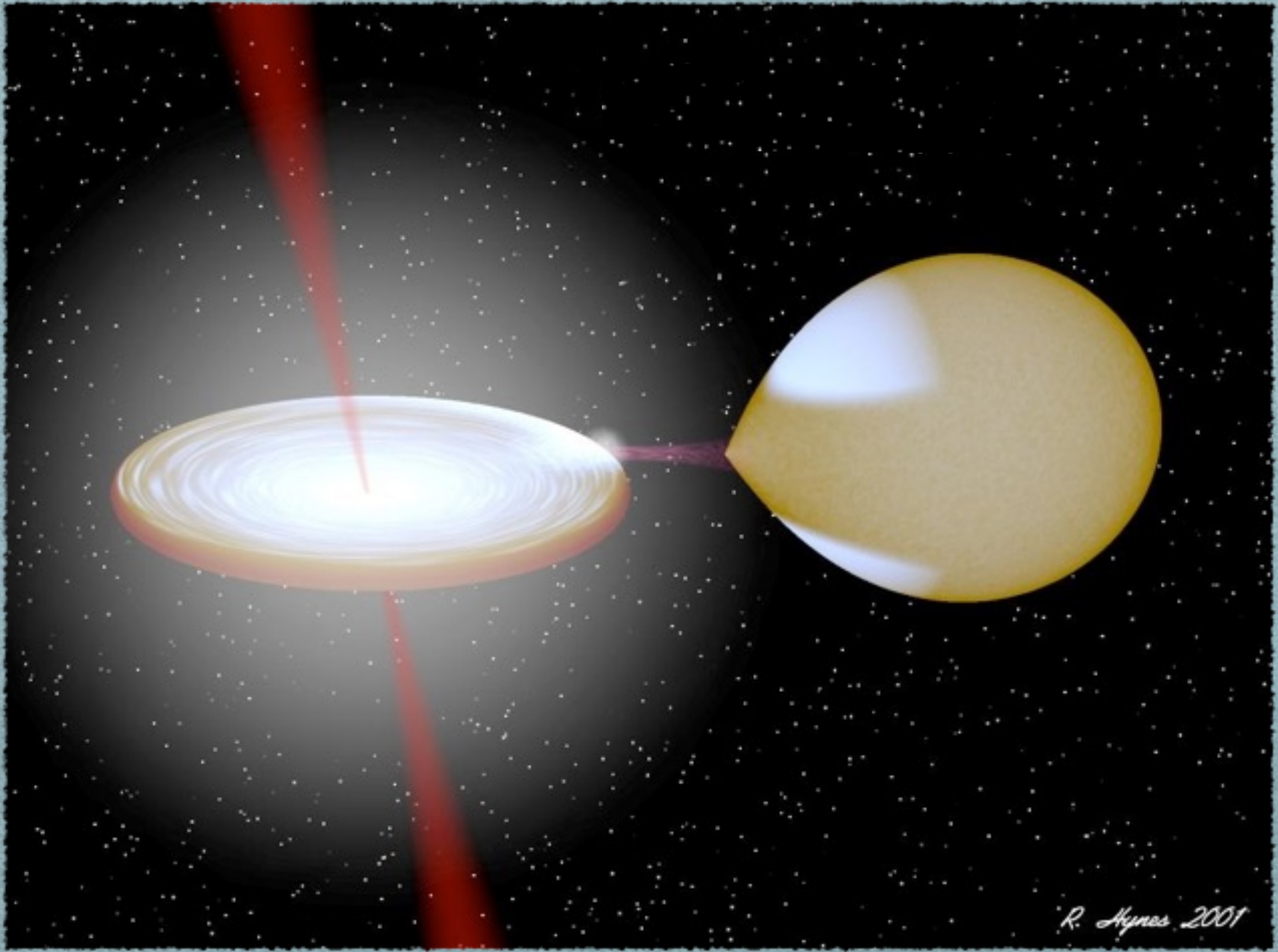


Black-hole binaries

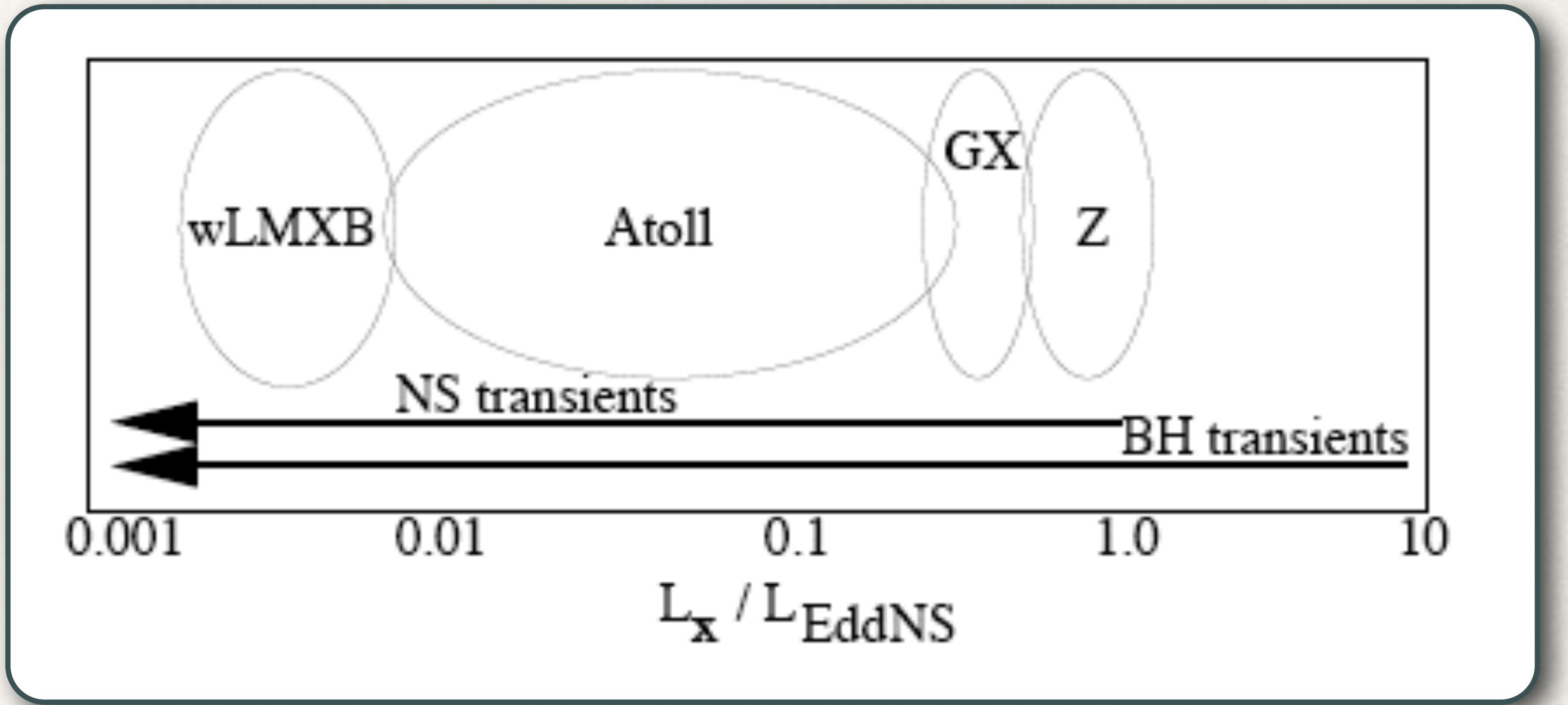
Tomaso M. Belloni
(INAF - Osservatorio Astronomico di Brera)
(Visiting Professor, Univ. of Southampton)

OUTLINE

- Lecture I: Accretion onto compact objects, X-ray binaries, black hole candidates, X-ray pulsars
- Lecture II: High-energy emission and spectra
- Lecture III: Time variability on all scales
- Lecture IV: Radio emission, jets, accretion/ejection
- Lecture V: BH parameters & GR, AGN connection
- **Lecture VI: Neutron-Star binaries + ULX + more**

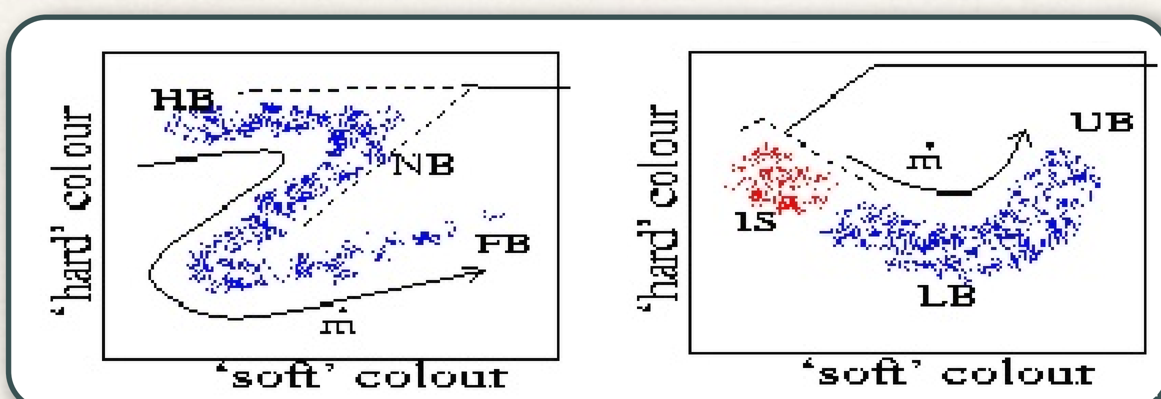
NS LMXBs: source classes

- Z sources
- Atoll sources
- Low-L bursters
- msec X-ray pulsars
- Oddballs (Cir X-1)



NS LMXBs: source classes

- Weakly magnetic systems
- Fast spinning NS (few msec)
- Characteristic phenomena: X-ray bursts
- Fast aperiodic timing
- Source classes



Z source

Atoll source

- Z sources
  - LX 0.1-1.0 LEDD
  - All persistent (?)
- Atoll sources
  - LX 0.01-1.0 LEDD
  - Some transient
  - Type-I bursts
- Low-L bursters
  - LX <0.01 LEDD
  - Some transient
  - Type-I bursts

accretion rate

Timing properties

The Astrophysical Journal, 172:L13–L16, 1972 February 15

DYNAMIC SPECTRUM ANALYSIS OF CYGNUS X-1

M. Oda, M. Wada,* M. Matsuoka, S. Miyamoto,
N. Muranaka, and Y. Ogawara
Institute of Space and Aeronautical Science, University of Tokyo, Tokyo
Received 1971 December 16

ABSTRACT

The oscillatory structure of the counting-rate data trains of Cyg X-1 obtained by the AS&E and the M.I.T. group was studied. Instead of applying the Cooley-Tukey fast Fourier-transform algorithm to the entire data, we obtained the dynamic spectrum by fitting the wave with time sections of the data trains. Also, the Hissagram, which is a quantitative exhibition of the sonagram, was produced for the same train. It was concluded that the oscillation lasts typically for several seconds and its frequency drifts within a few seconds repeatedly.

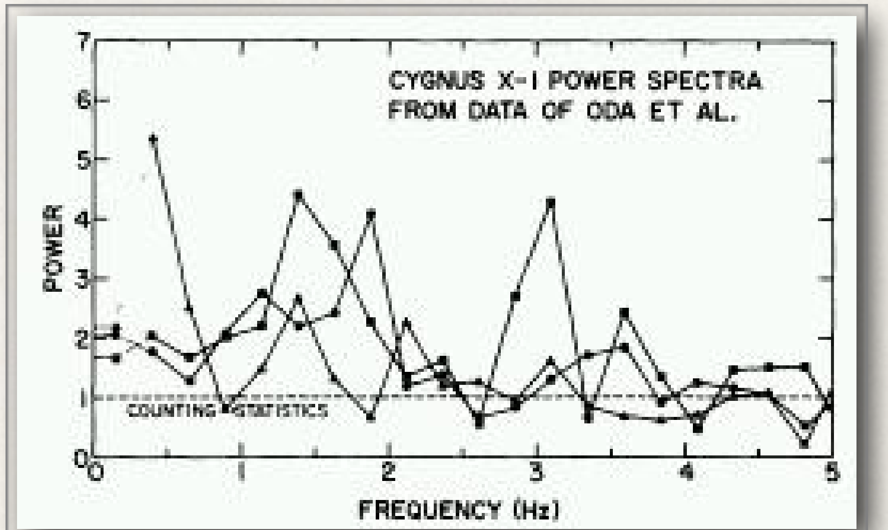
The Astrophysical Journal, 174:L35–L41, 1972 May 15

SHOT-NOISE CHARACTER OF CYGNUS X-1 PULSATIONS*

N. James Terrell, Jr.
University of California, Los Alamos Scientific Laboratory, Los Alamos, New Mexico
Received 1972 February 22

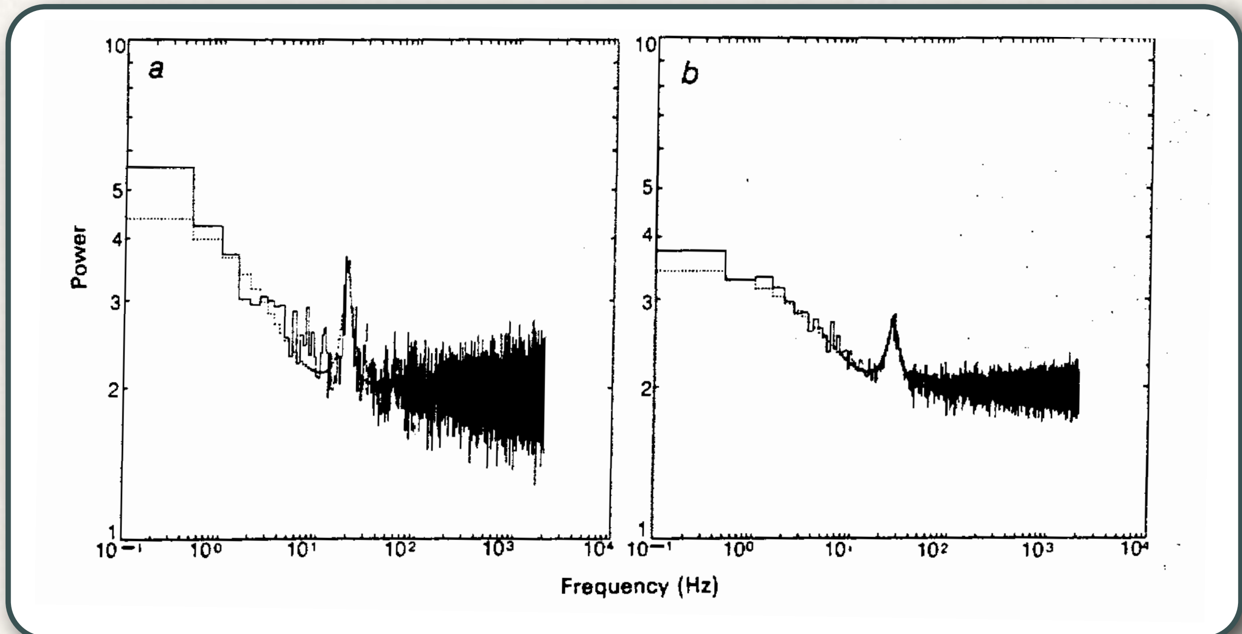
ABSTRACT

The pulsating X-ray source Cyg X-1 has been reported as having various conflicting or changing periodicities, or as being nonperiodic. The reported data have been reanalyzed in an effort to clarify this situation, and are found to be indistinguishable from shot noise due to short overlapping outbursts of X-ray emission, with no true periodicity. Computer-generated shot-noise data have the same appearance and lead to similar power spectra. The observational data are consistent with random pulses which have an effective pulse length of 0.3 ± 0.1 s and occur at varying rates of the order of several hundred per second. The pulse length indicates a maximum source size of $\sim$0.8 light-seconds. It is suggested that some other fluctuating X-ray sources, such as Sco X-1 and Cir X-1, may also have such a shot-noise character.



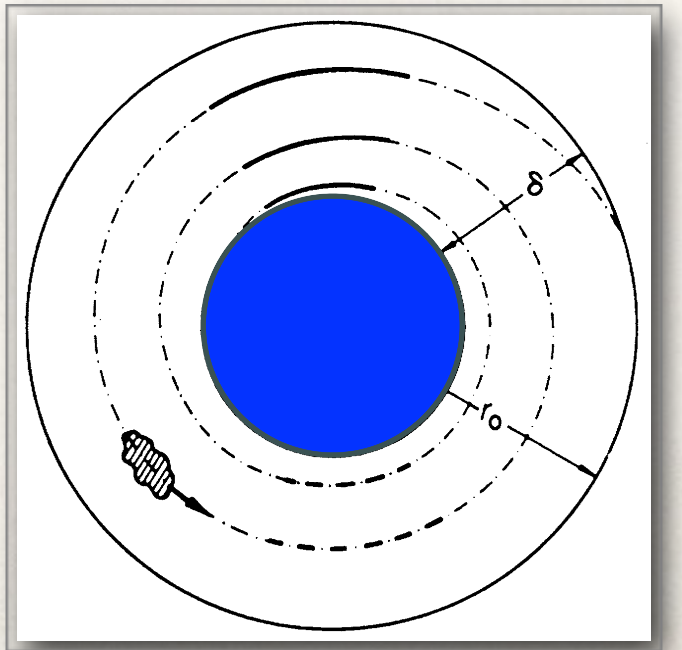
Quasi-Periodic Oscillations (QPO)

- GX 5-1 first source
- Broad and slow features
- Not a pulsar
- No keplerian time scale
- Correlated with count rate (flux?)

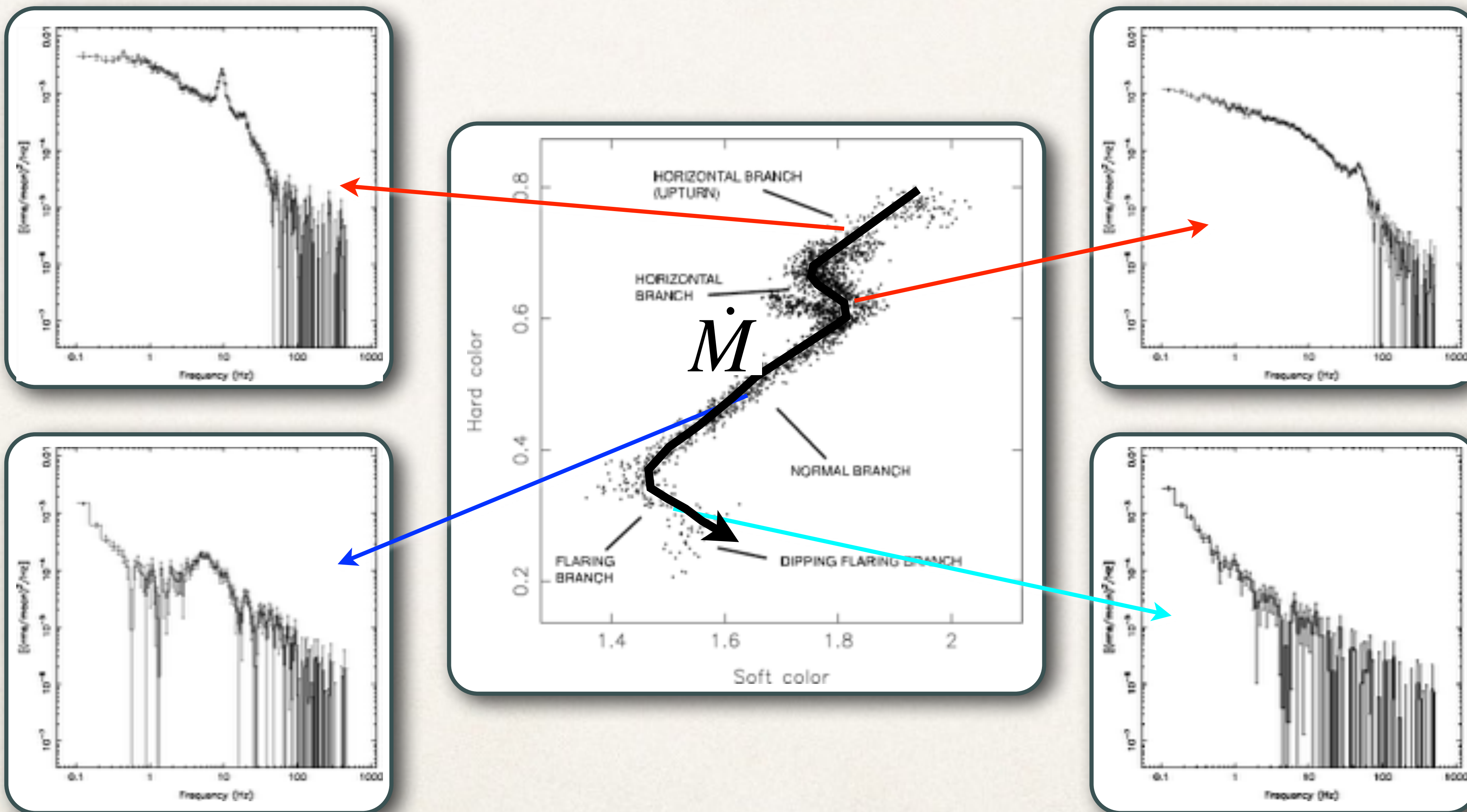


Beat frequency $\omega = \Omega_K(r_A) - \Omega_{spin}$

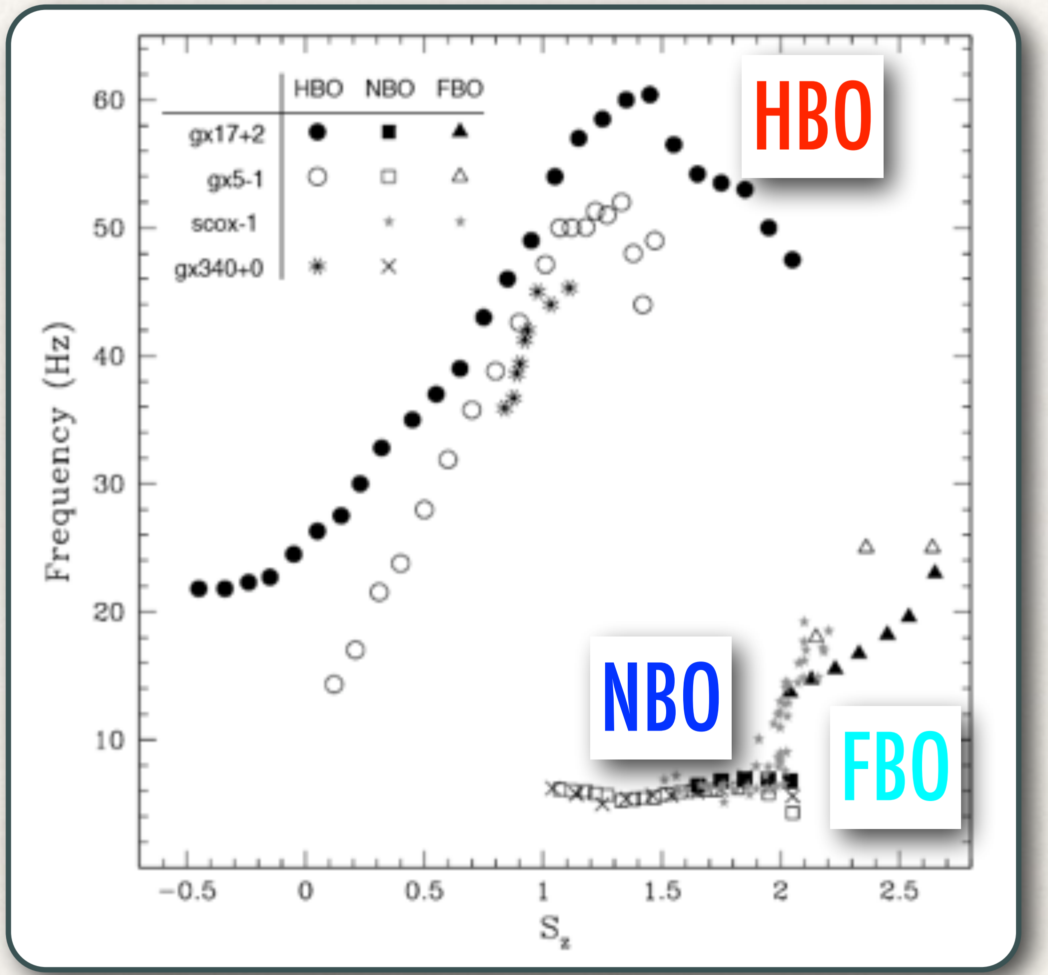
Flux related: $\omega \propto L_{37}^{3/7}$

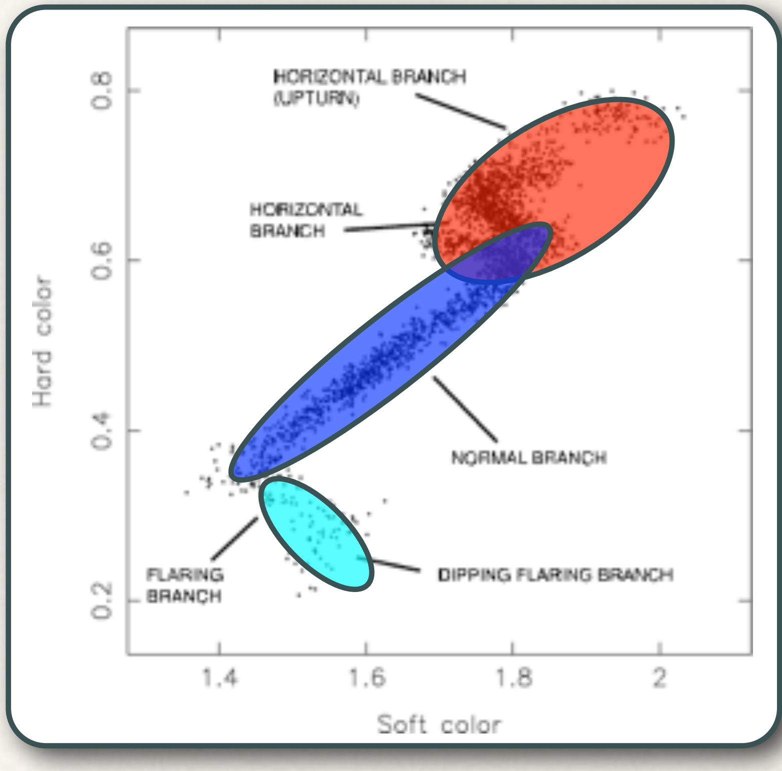


Quasi-Periodic Oscillations (QPO)

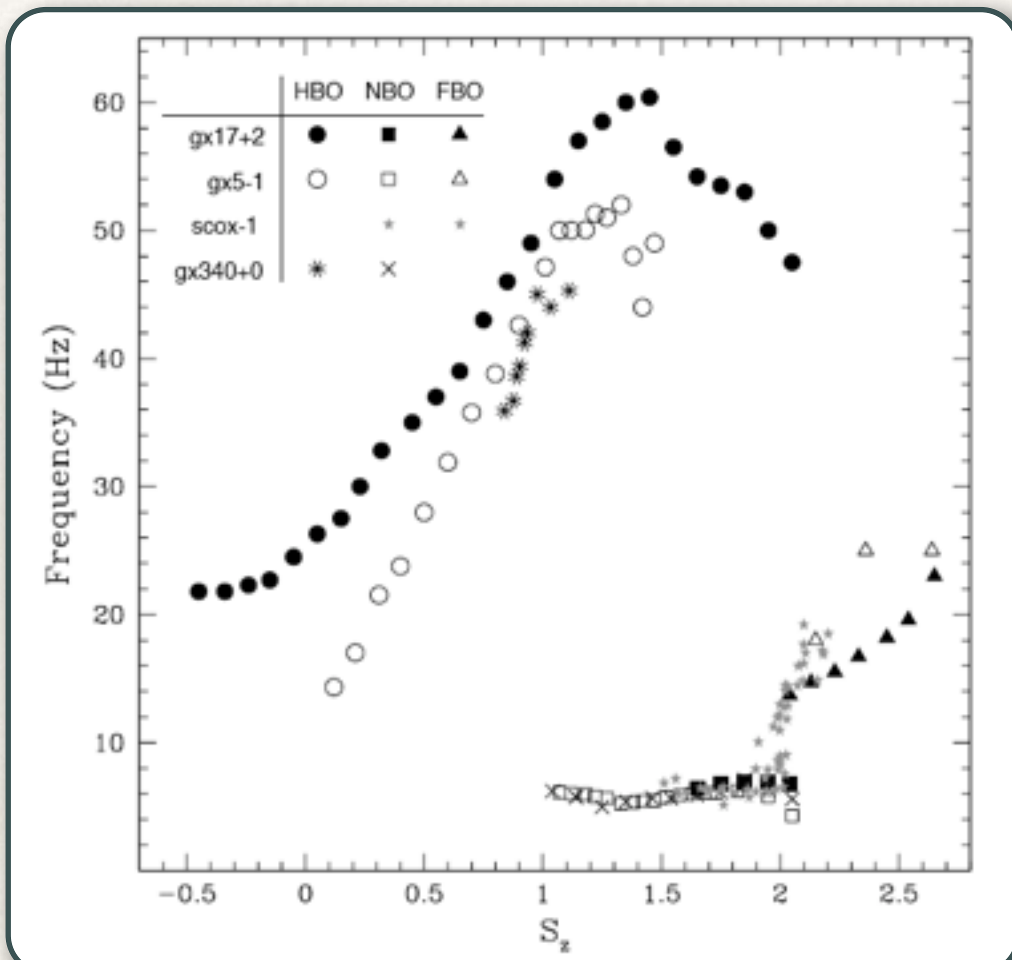


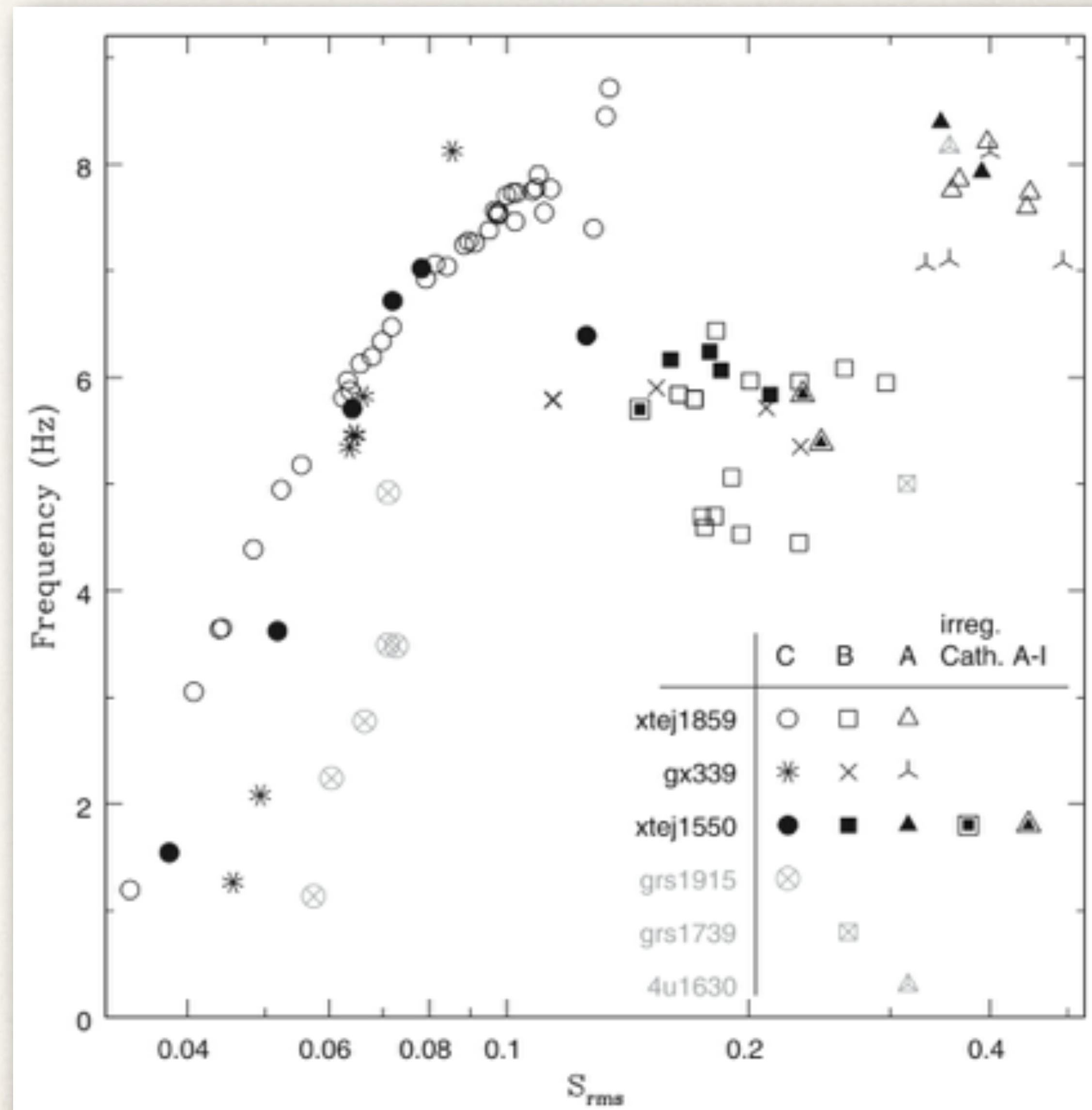
Three QPO types





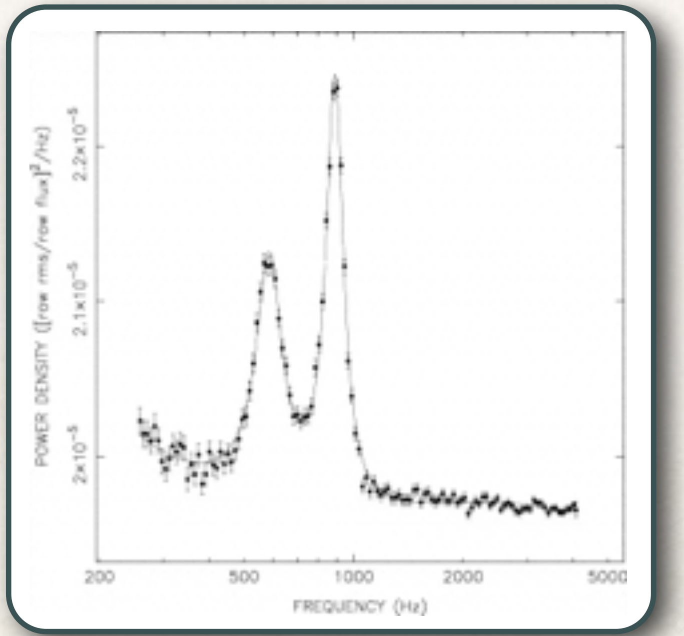
They correspond to BH QPOs

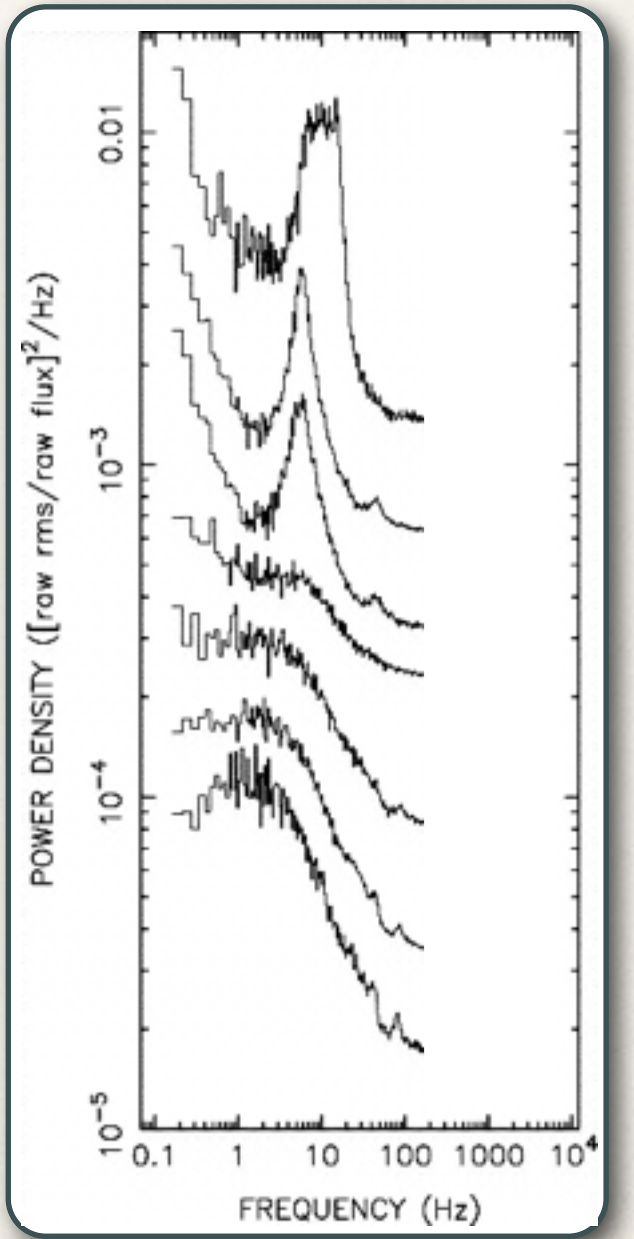




RossiXTE

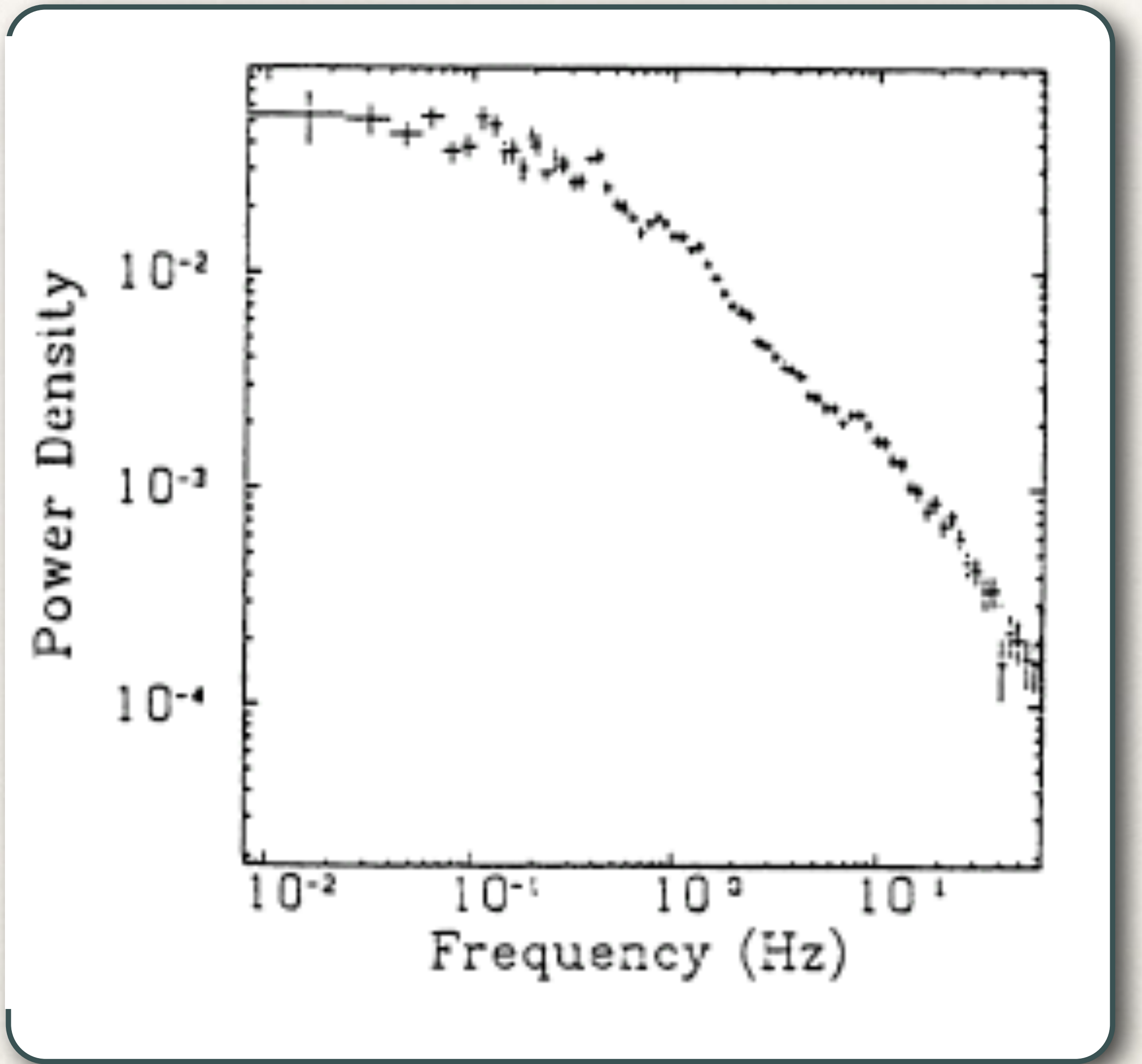
- Double peaks at high frequency
- Expected range for Keplerian
- Frequency changes
- Sco X-1 first, then other Z and atoll



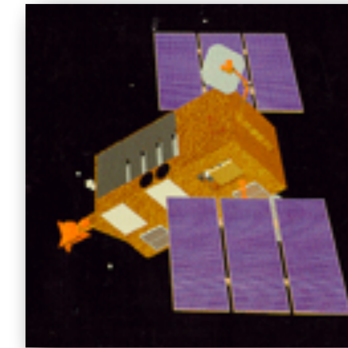


Atoll sources (lower accretion)

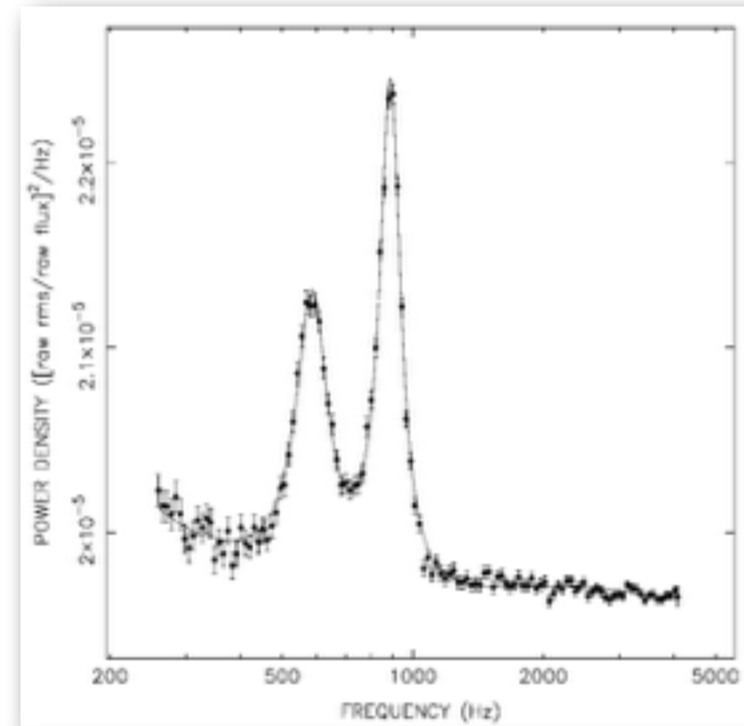
- At low flux: flat-top noise + LFQPO
- Same as low-L bursters

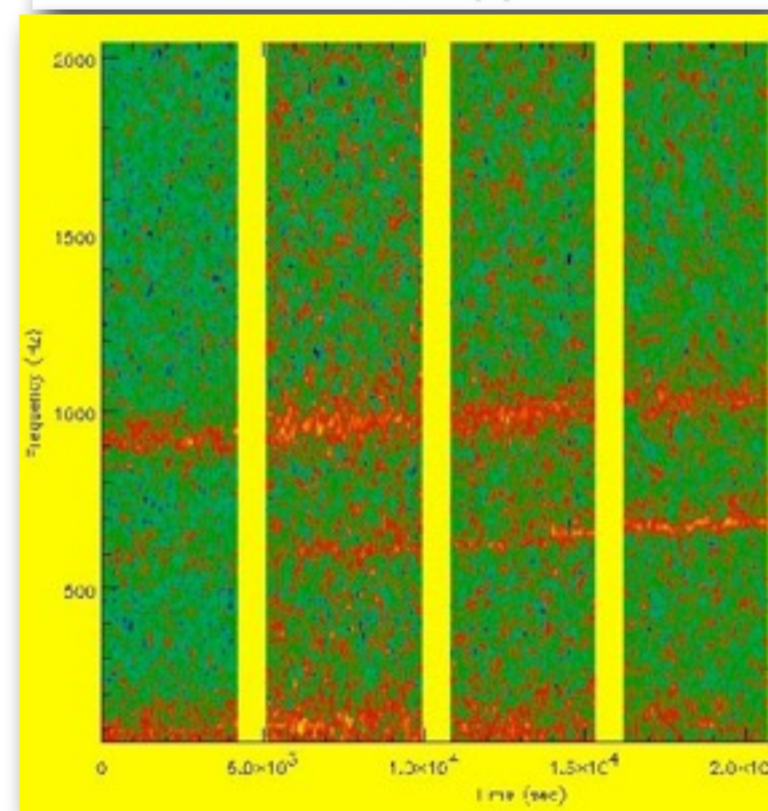


kHz QPO: basic properties



- The RossiXTE satellite
- kHz QPOs in NS: 300-1200 Hz
- 200-1200 Hz, Q up to 200,
- (Often) two peaks, wandering in frequency
- Frequency separation around 300 Hz
- Related to the NS spin?

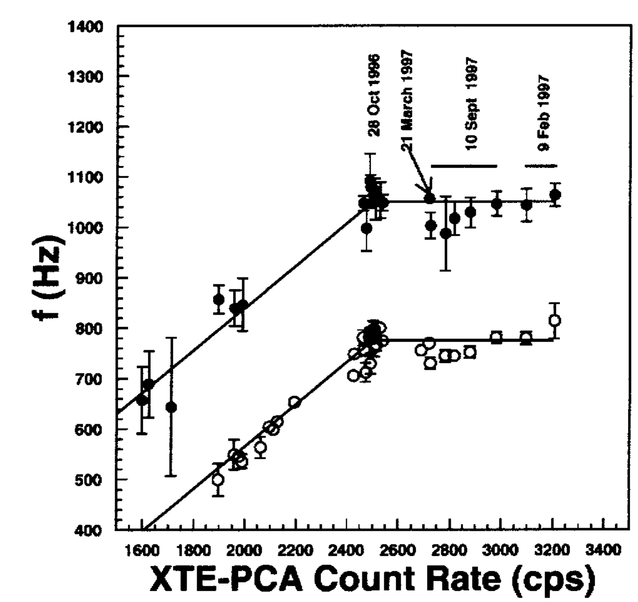


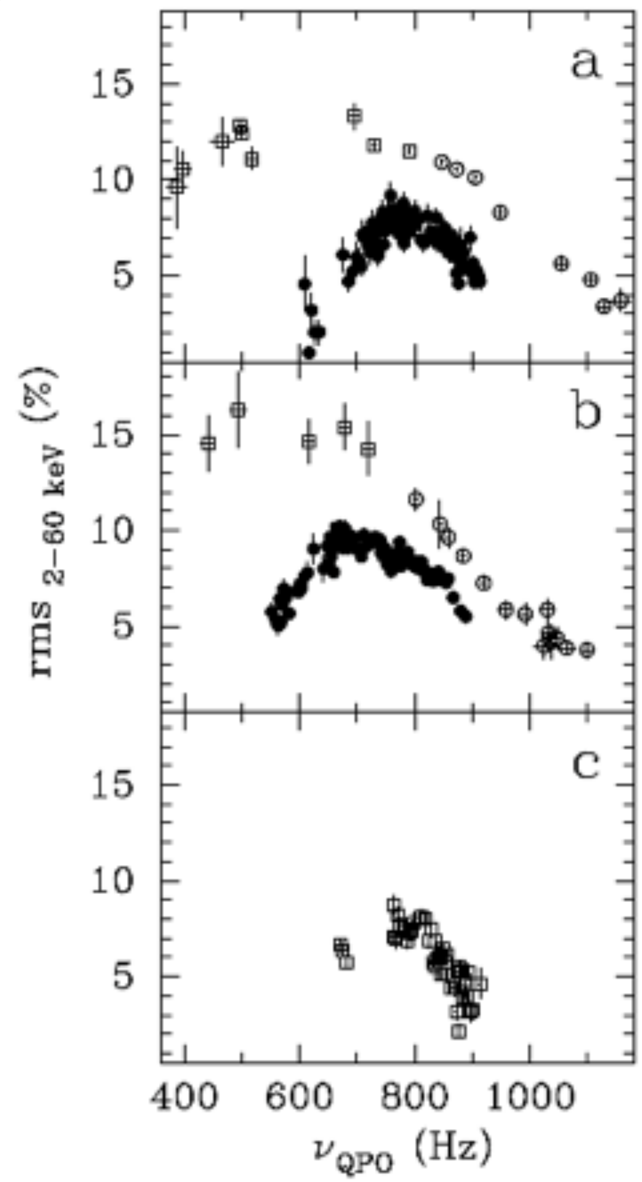


van der Klis et al. (1997)

kHz QPO: basic properties

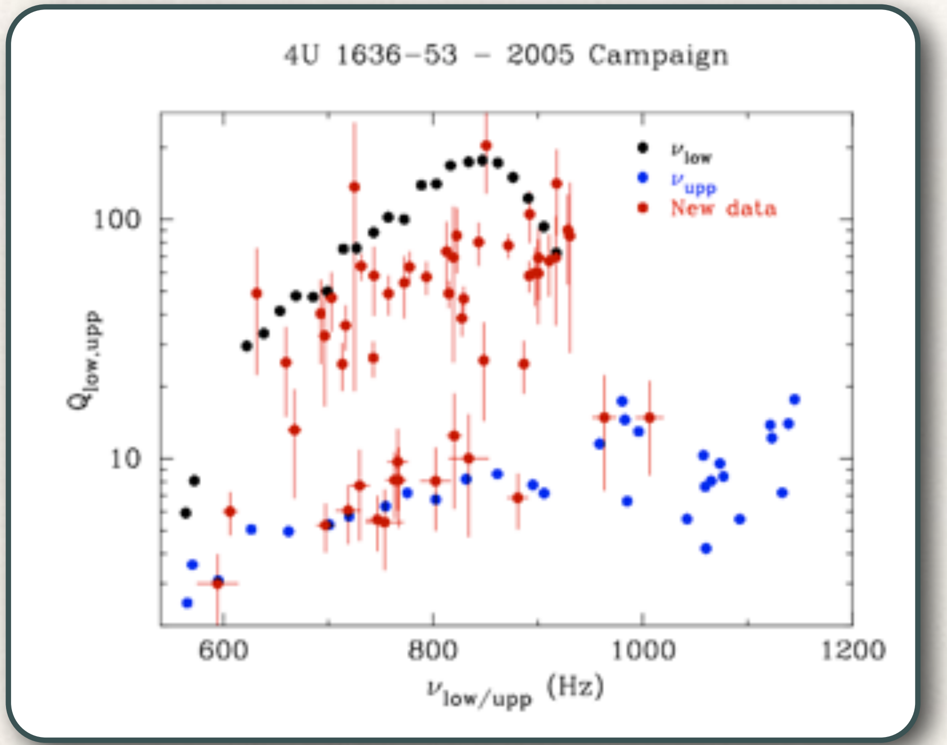
- Seen in nearly all Z and atoll sources
- Twin peaks move in 200-1200 Hz range
- At extreme frequencies, only one peak
- rms is variable

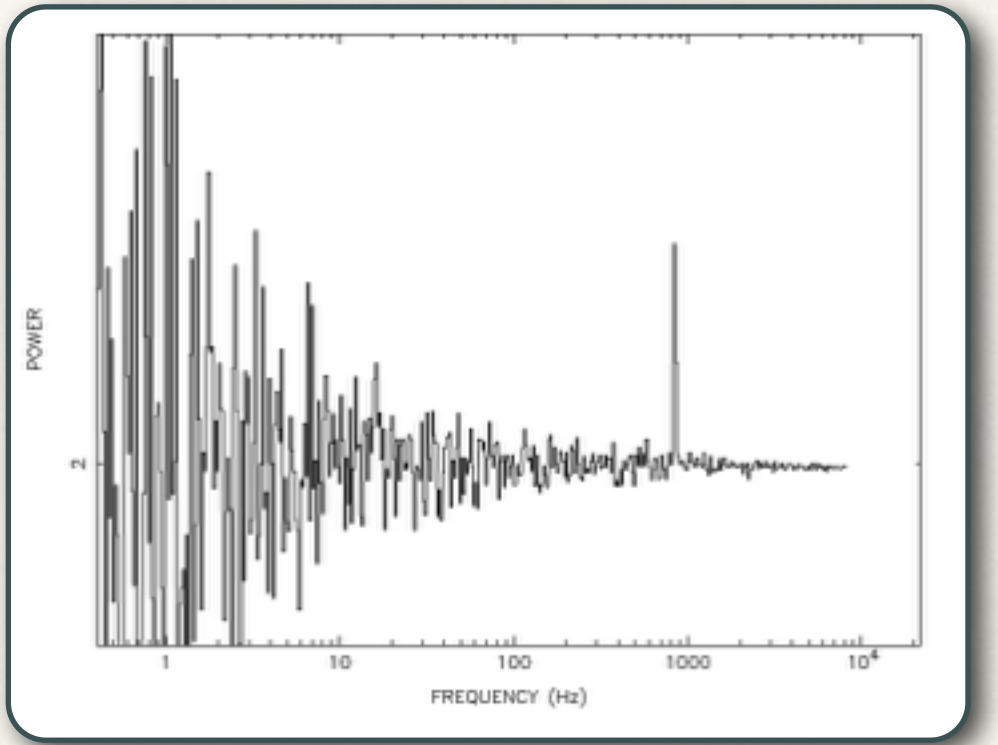




kHz QPO: basic properties

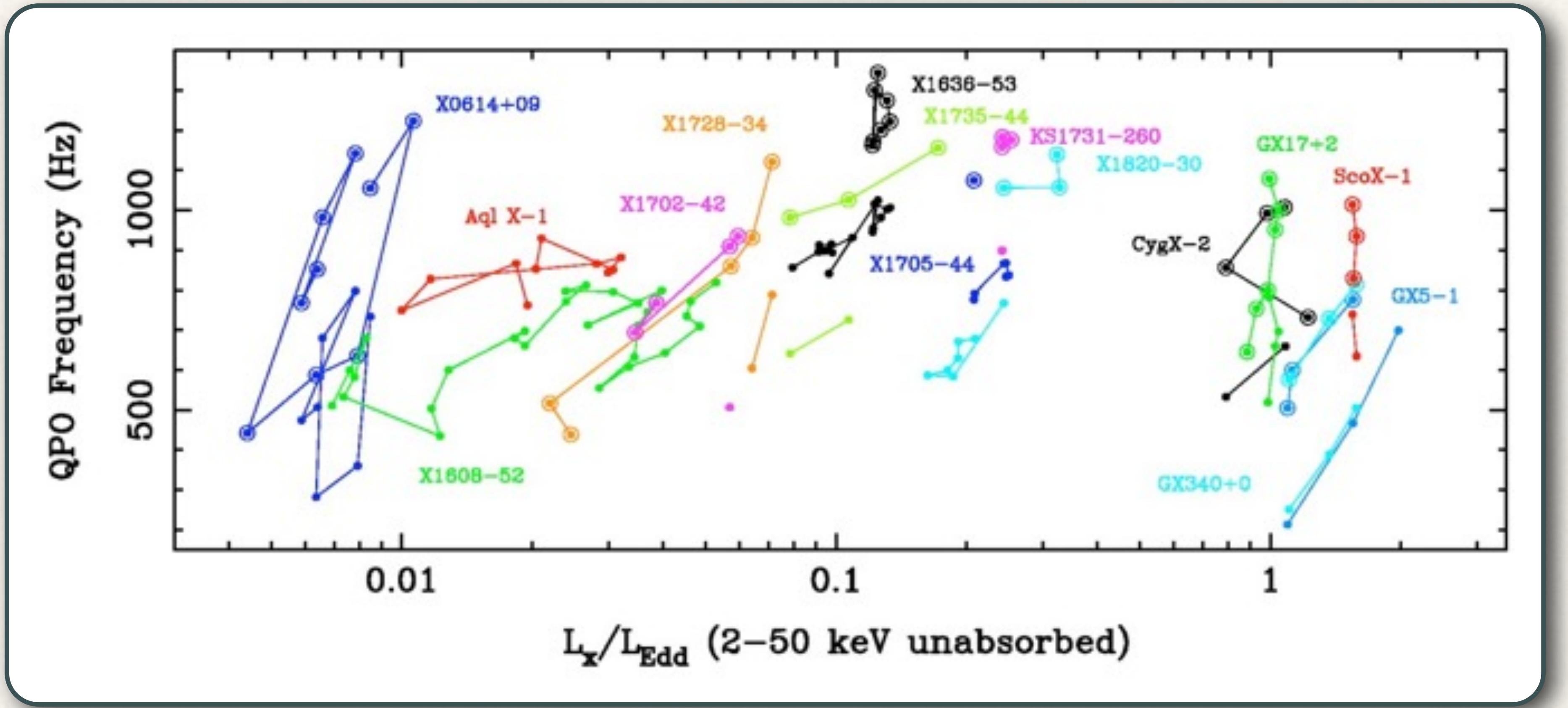
- Q factor can be as high as 200





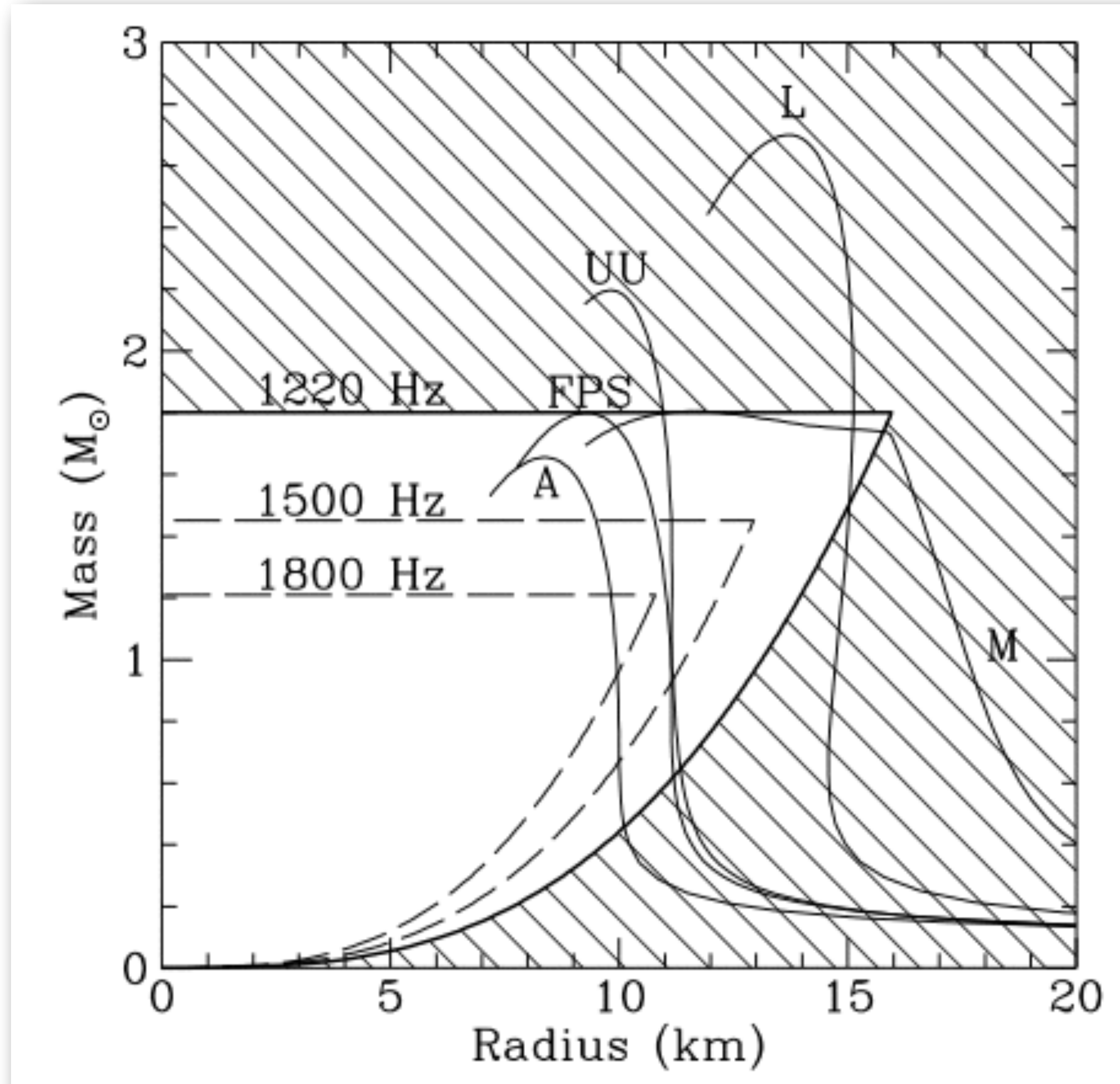
kHz QPO: basic properties

- Frequency shift on “parallel tracks”



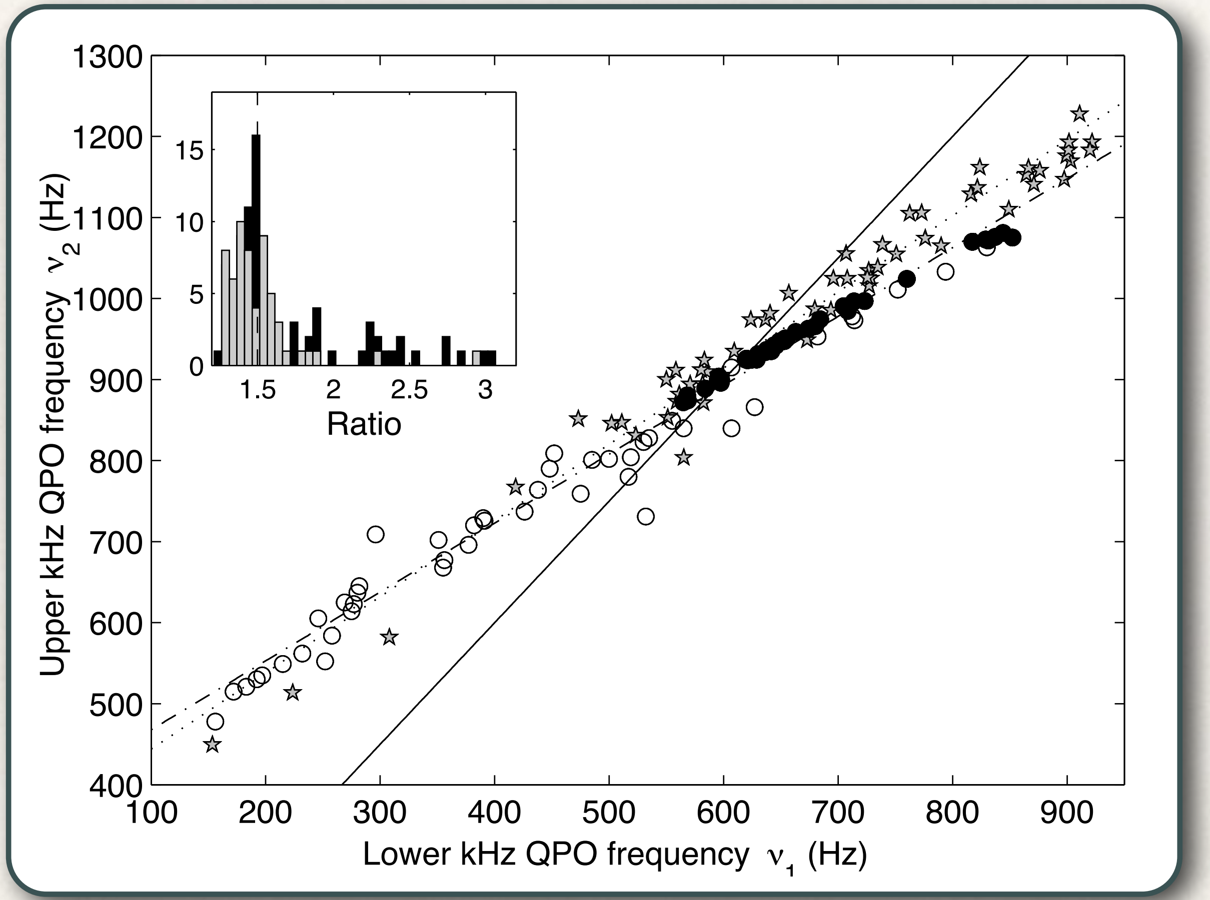
COLLAPSED MATTER

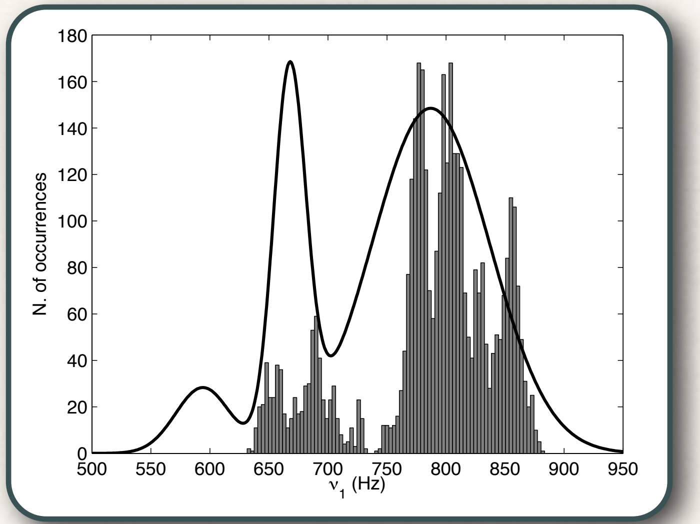
- Keplerian oscillations?
- Limit on EoS

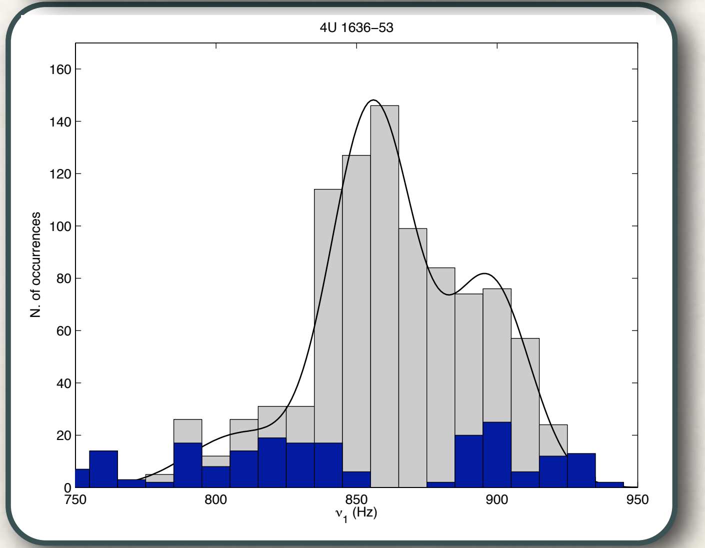


kHz QPO: basic properties

- No preferred frequency or frequency ratio

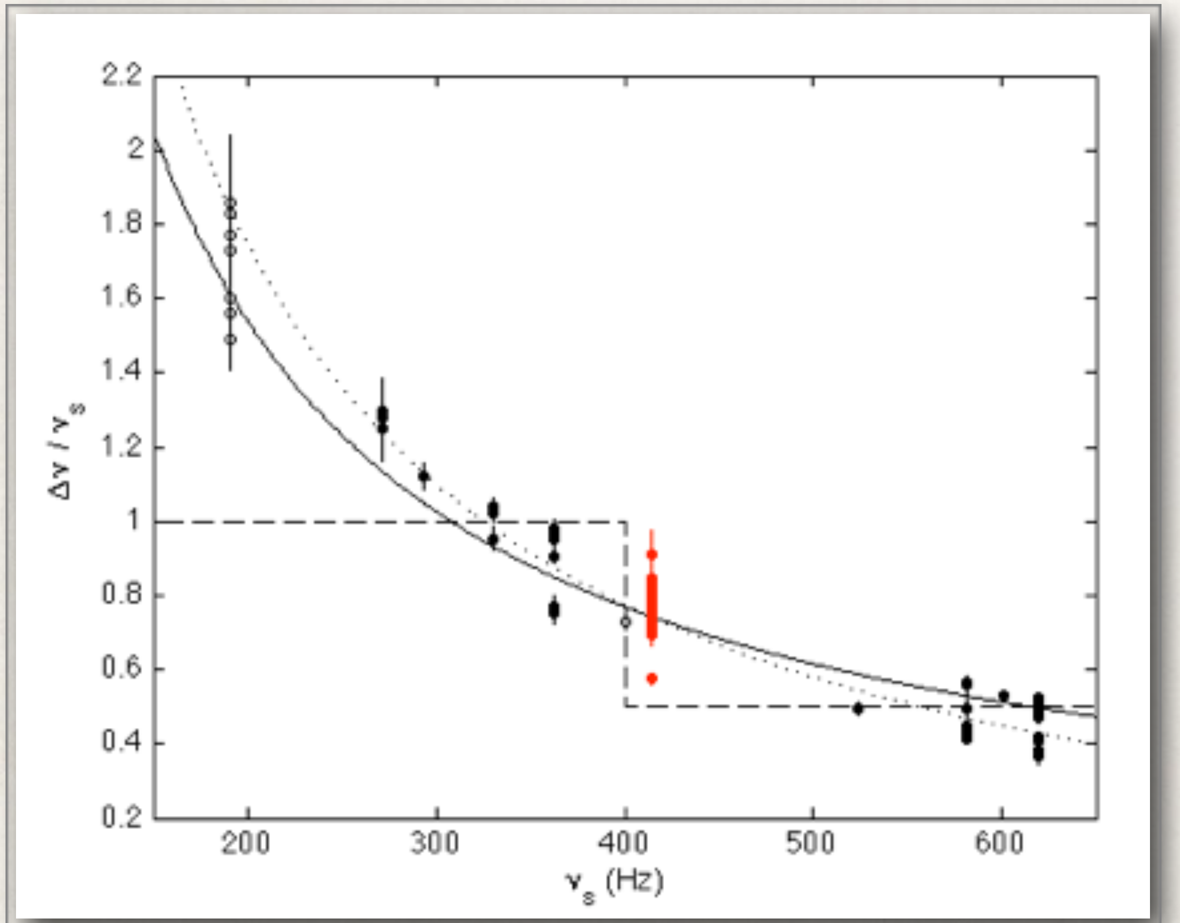


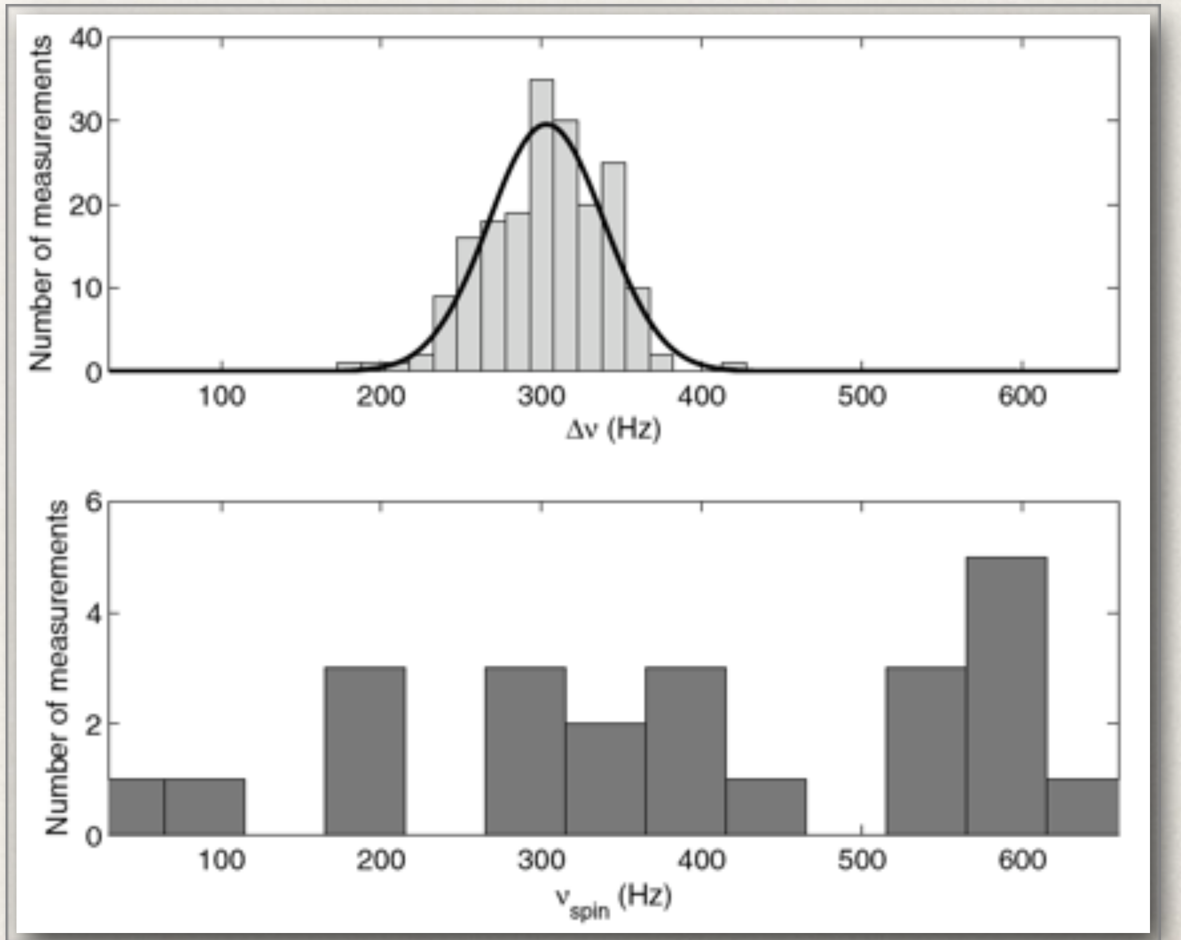




kHz QPO: basic properties

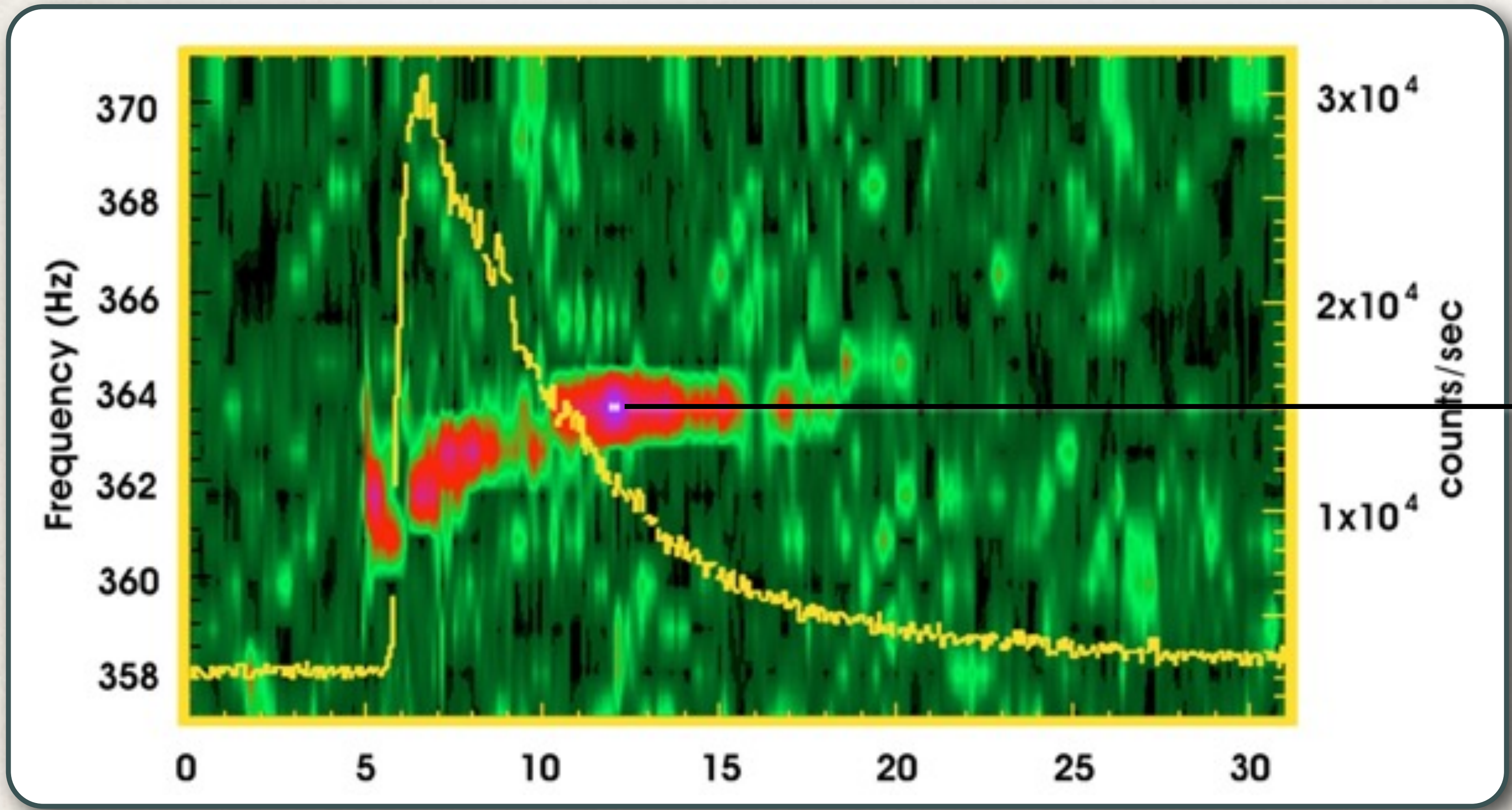
- Relation to source spin?

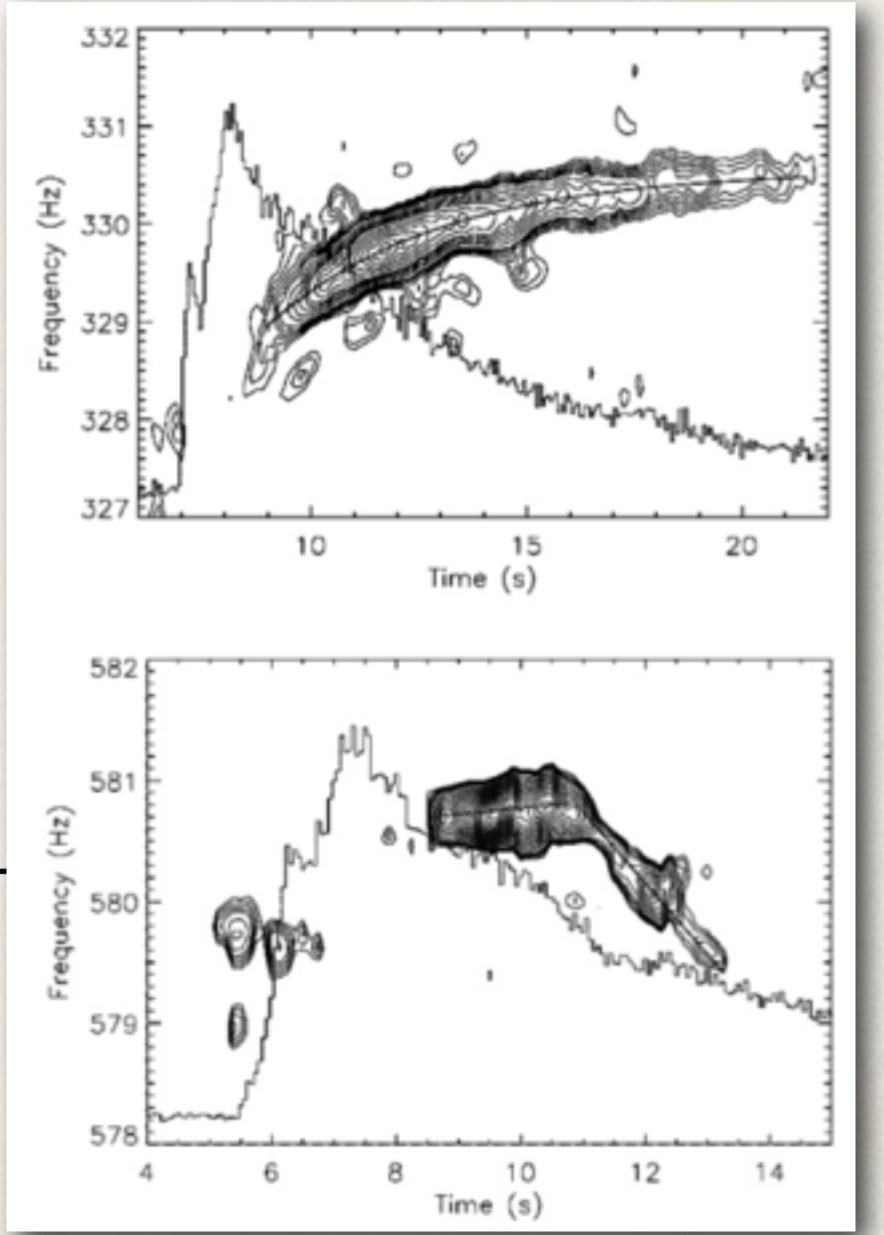




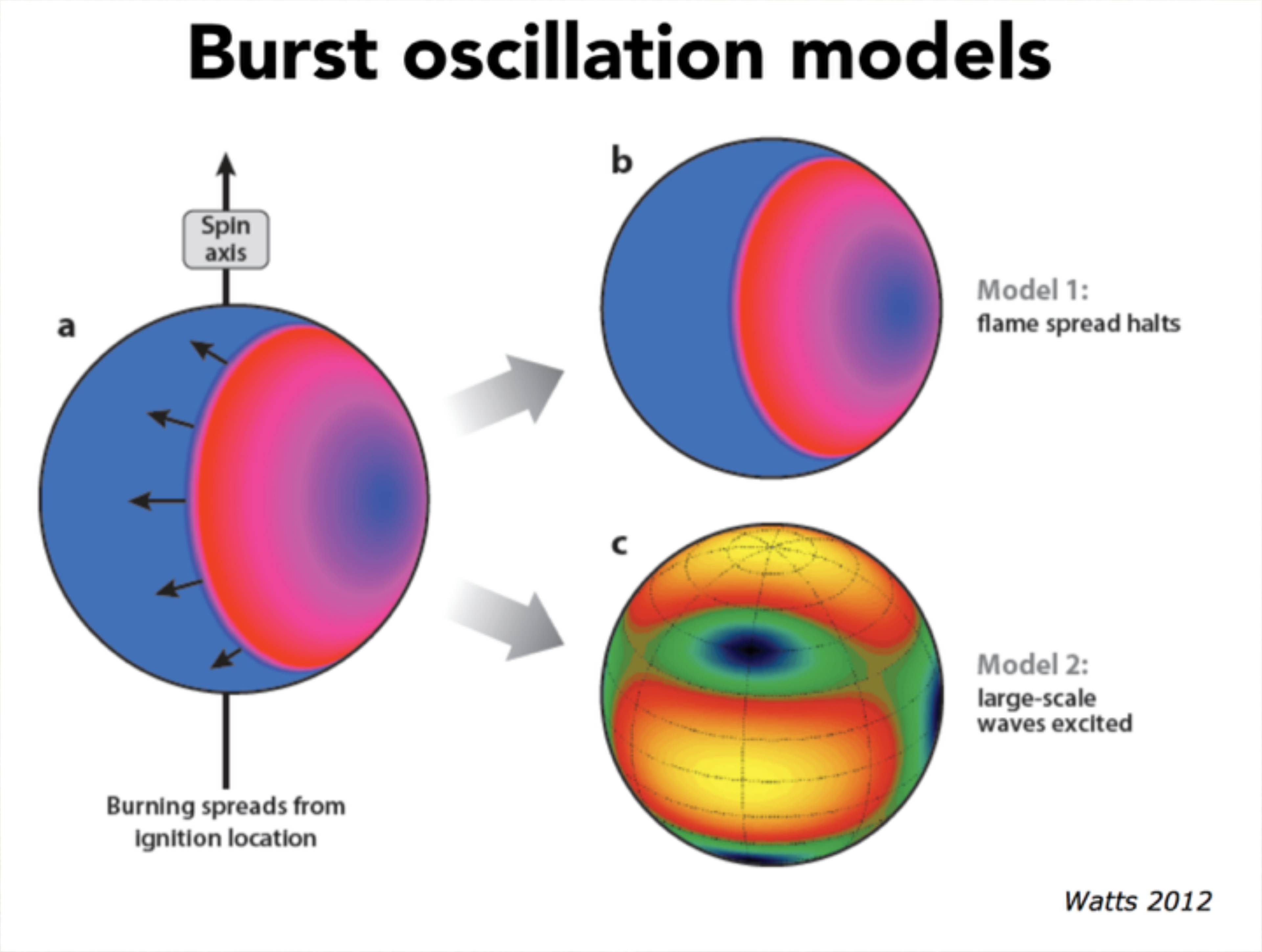
Burst oscillations

- Coherent oscillations
- Give characteristic frequency
- Lot of technical difficulties here



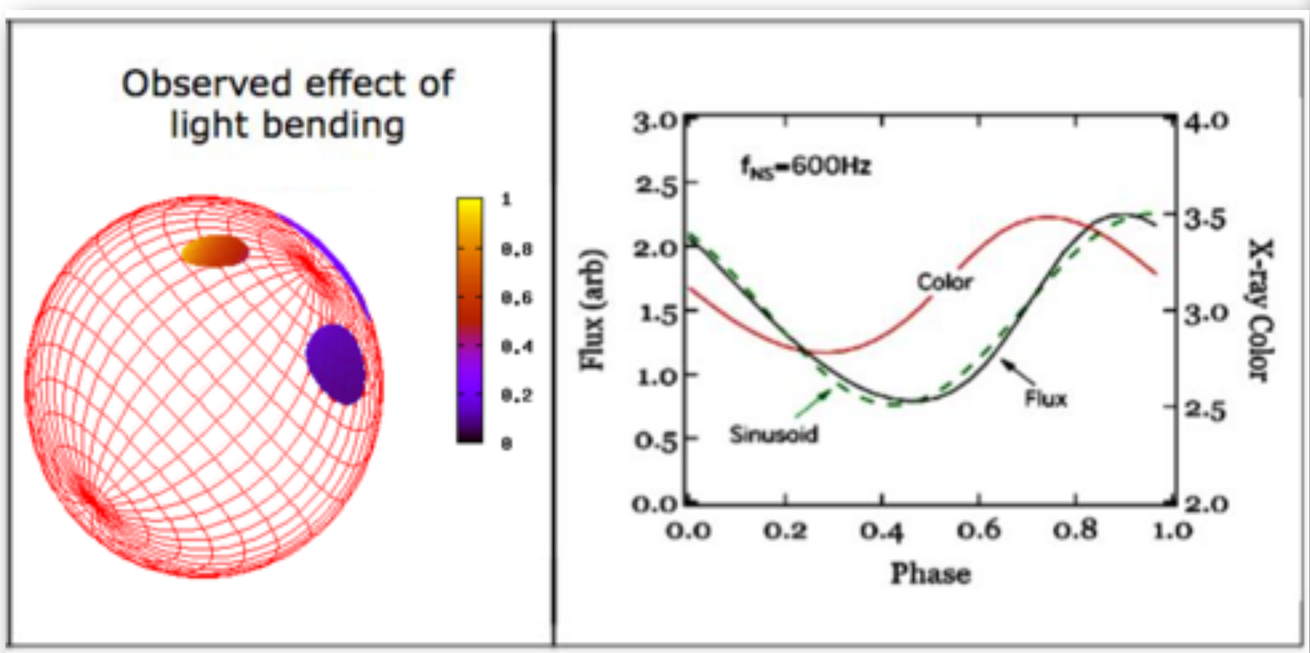


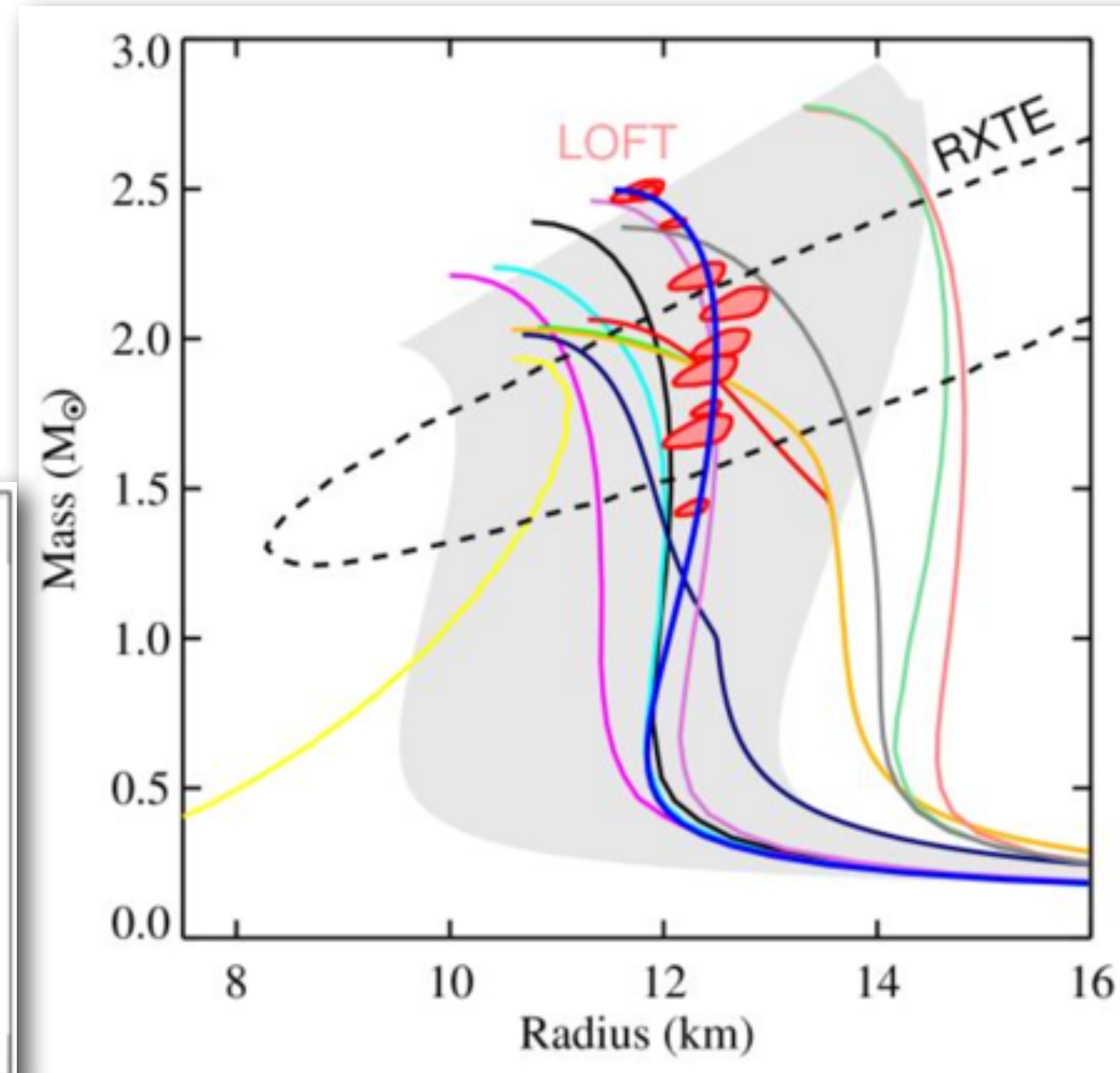
Burst oscillations



COLLAPSED MATTER

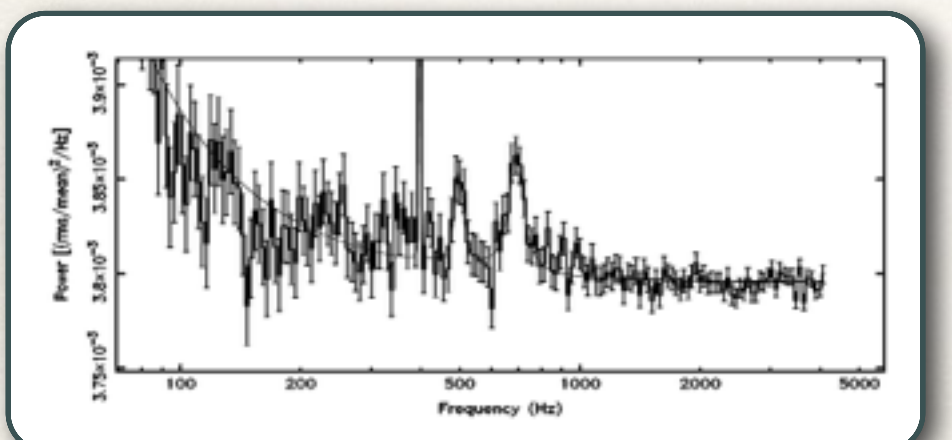
- Burst oscillations
- Limits on M and R
- No LOFT

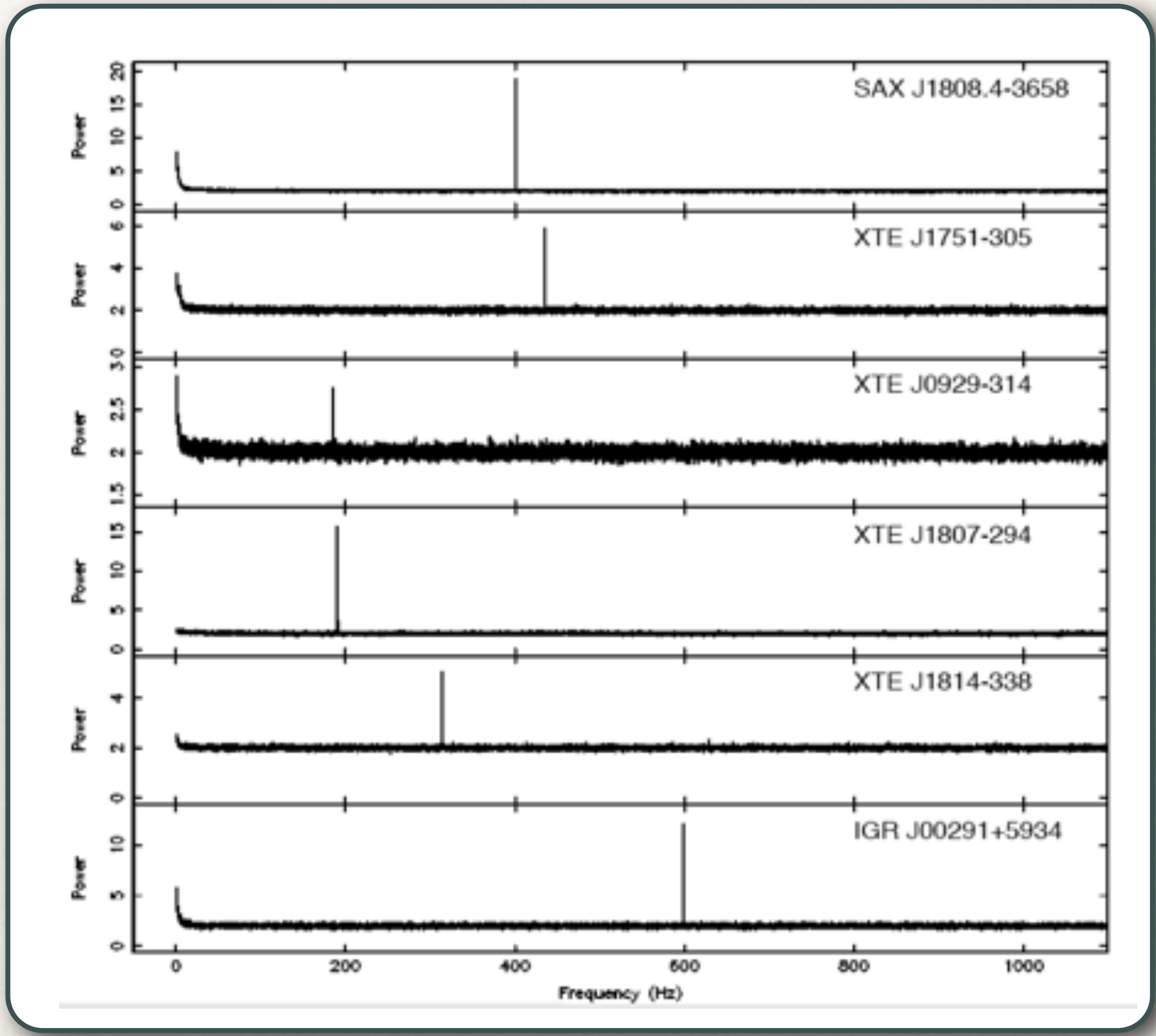




Accreting msec pulsars

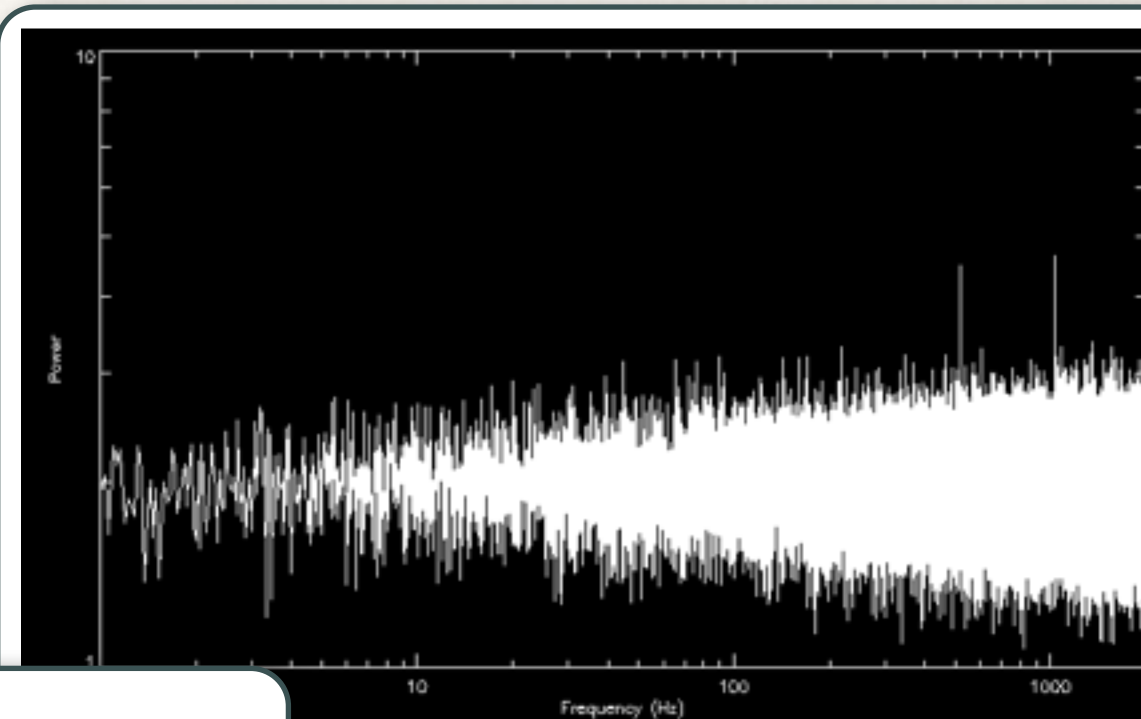
- In 1999 first one found
- 14 known to date
- Faint transients
- 200-600 Hz pulsations

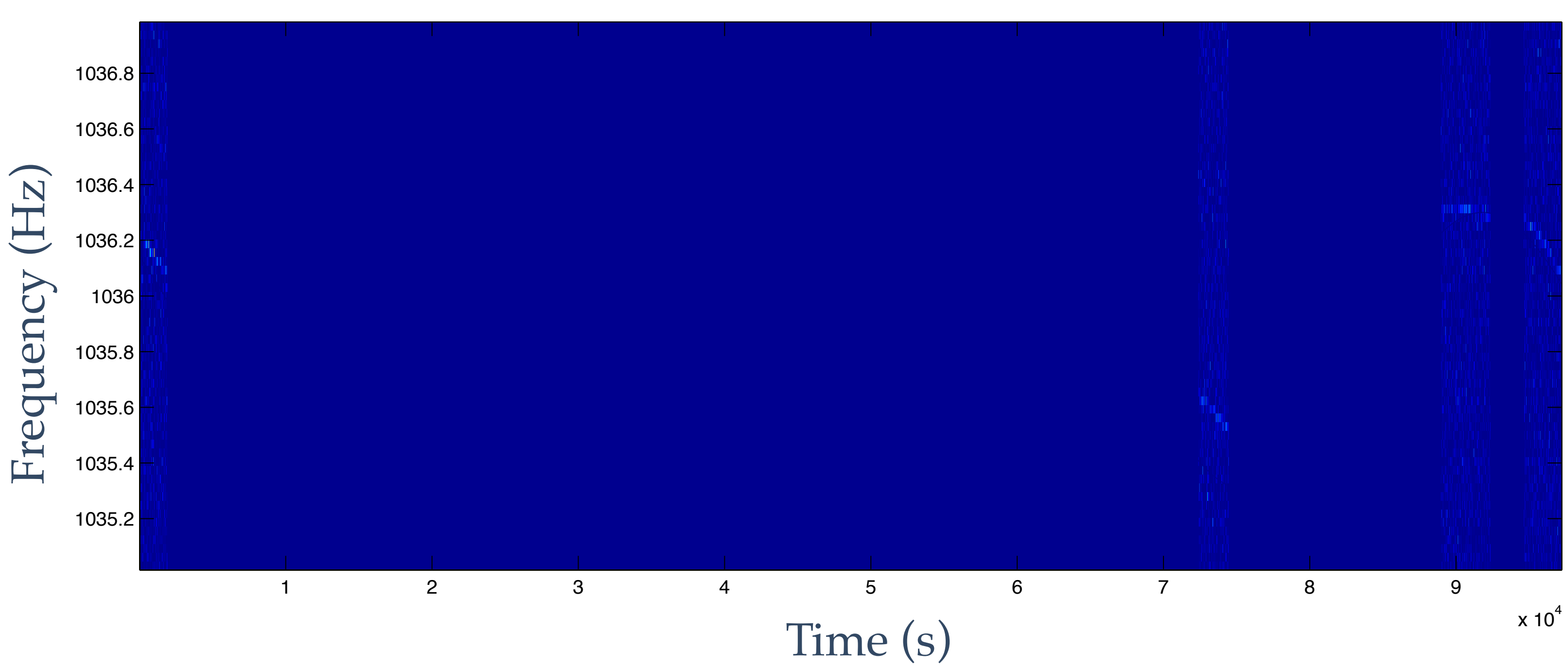




Example: Swift J1749.4-2807

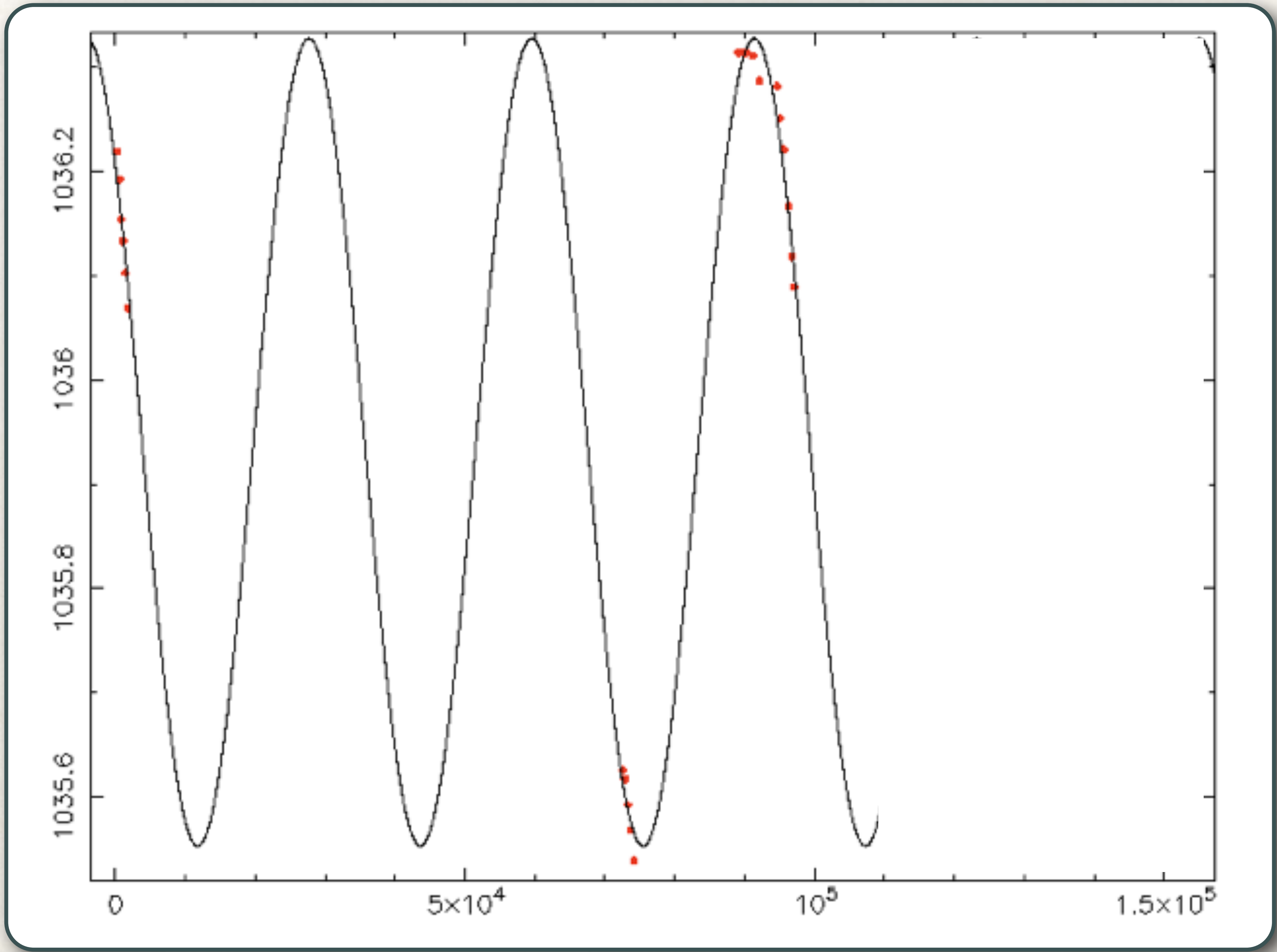
- Pulse: 518 Hz (1036 Hz harmonic)
- Orbit:





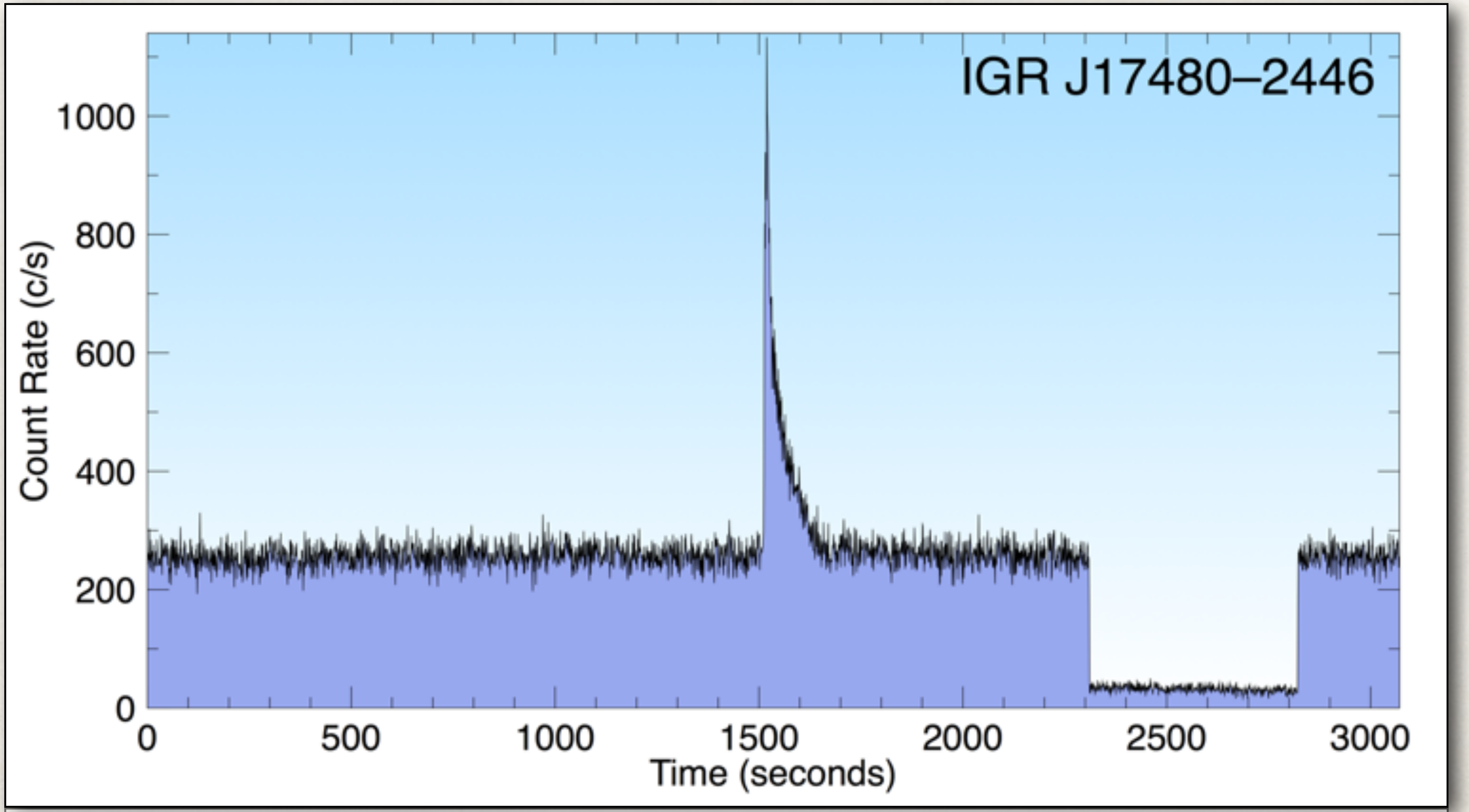
Orbit carpentry

- No barycentric correction



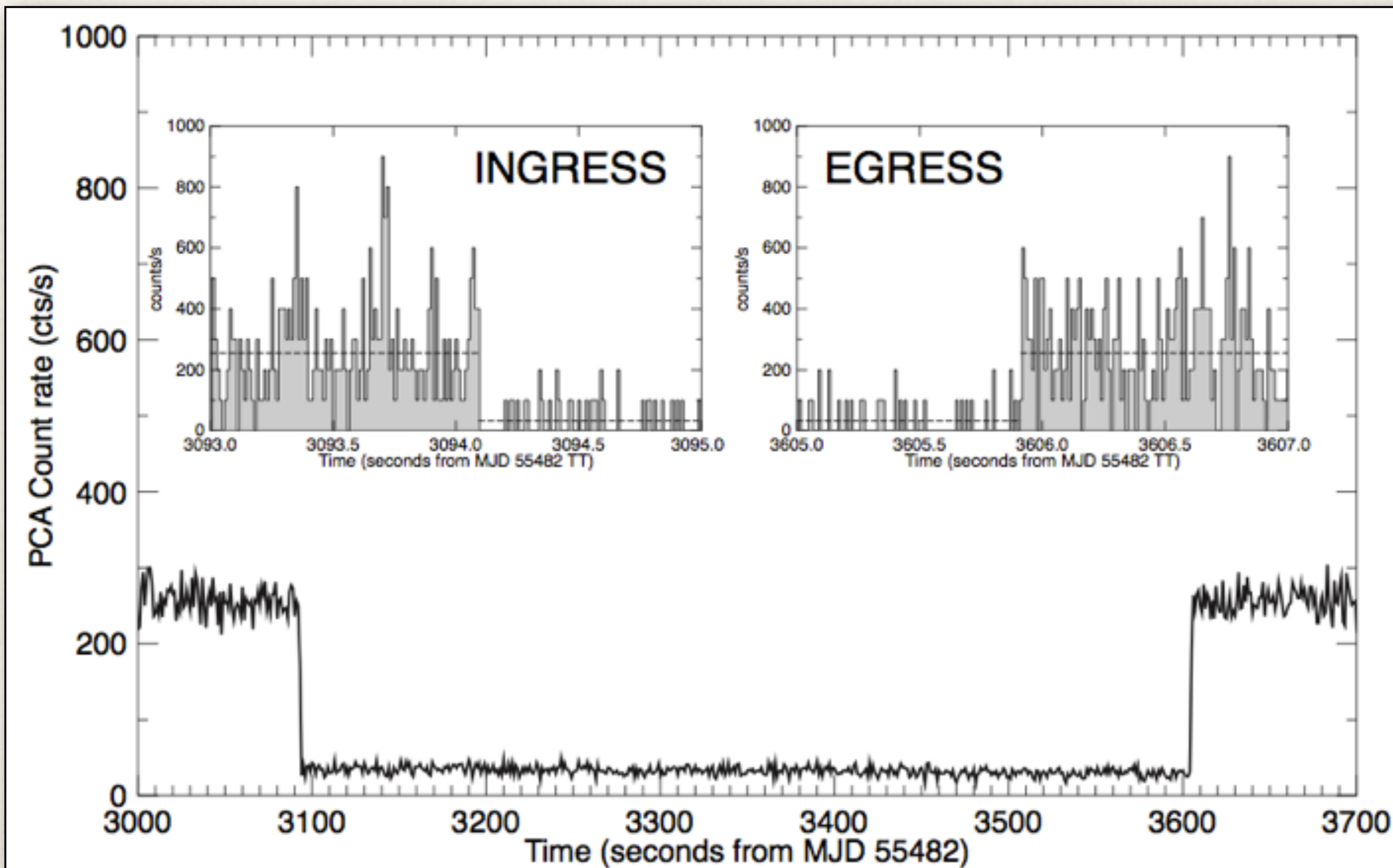
Different timing analysis

- October 2010: a new eclipsing transient accreting ms pulsar

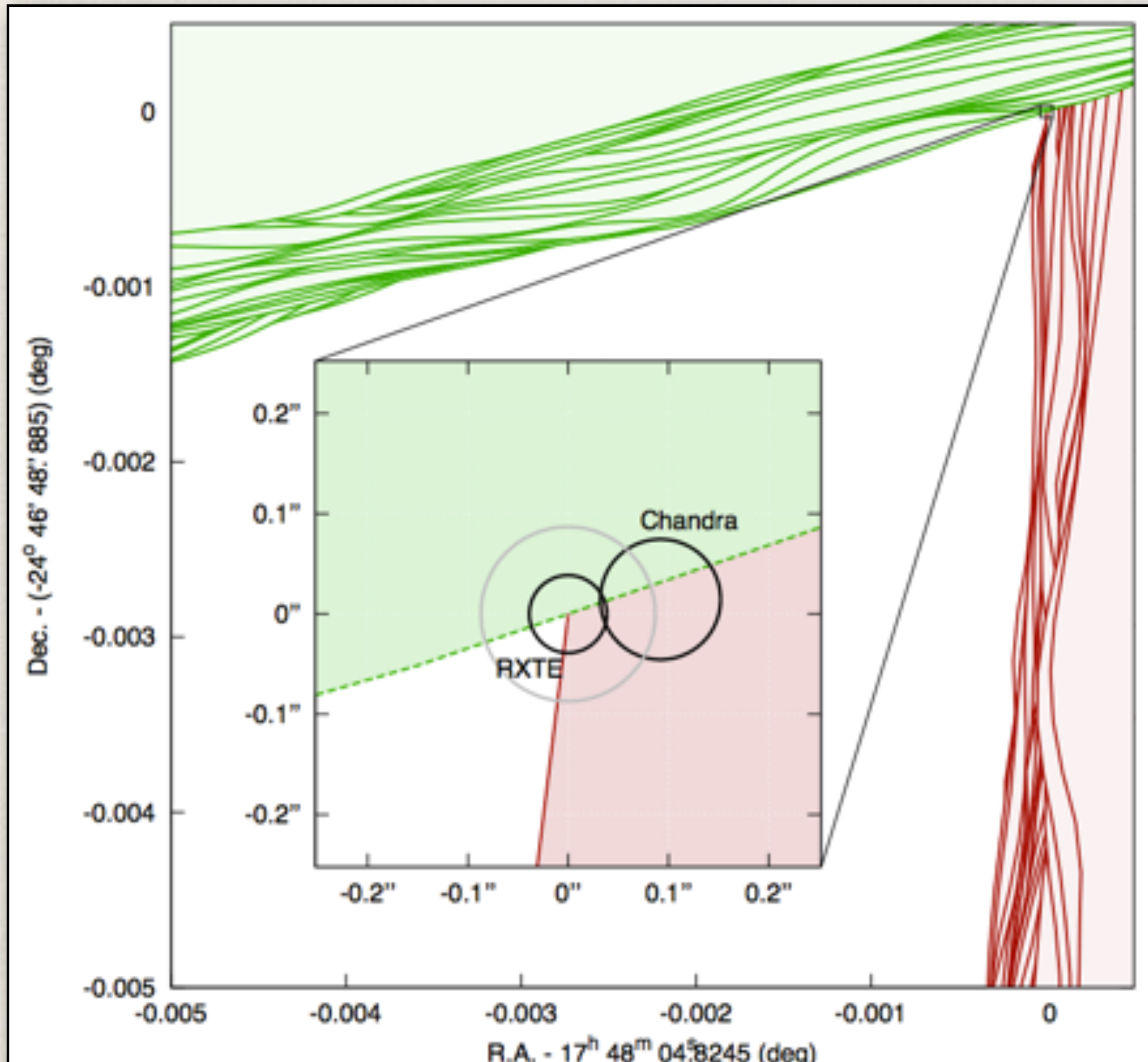


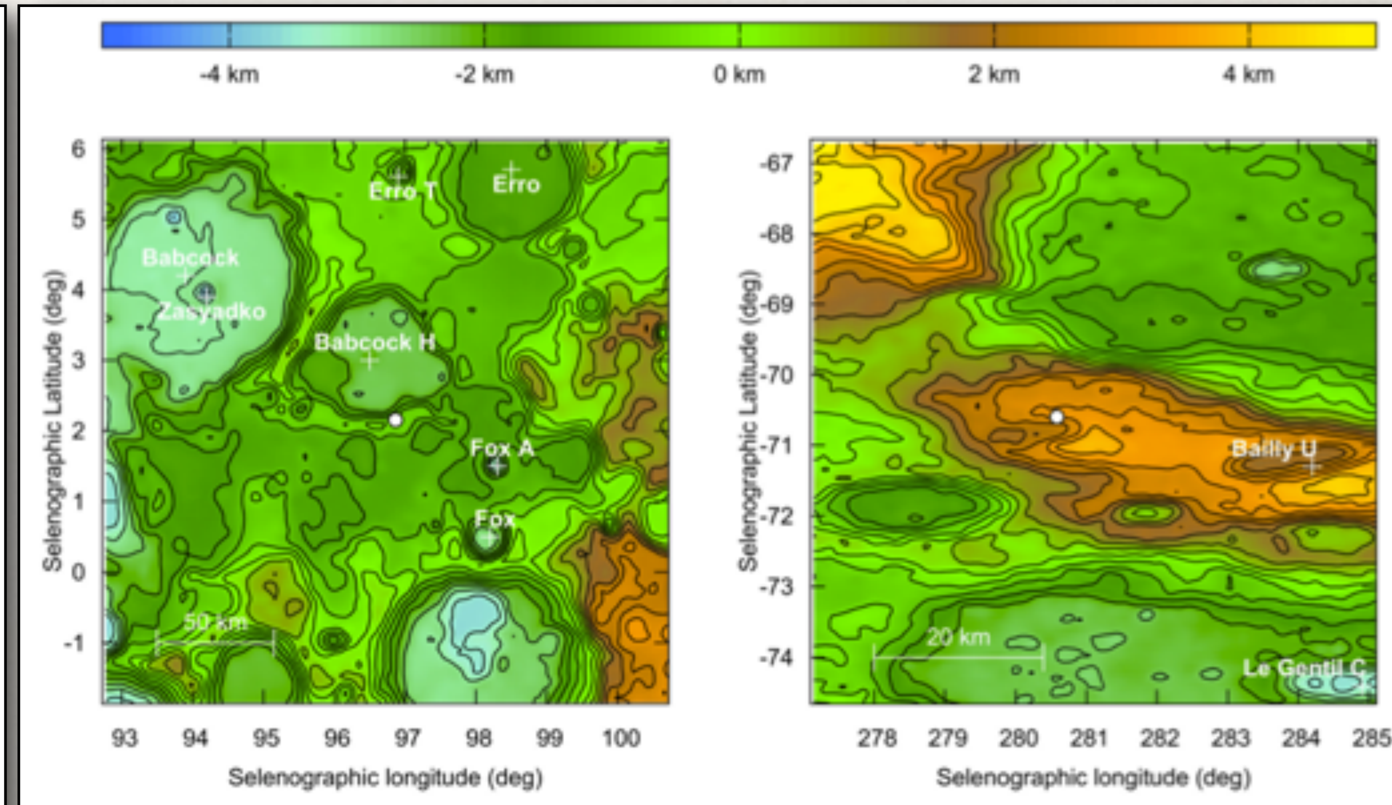
Serendipitous moon occultation

- Requires precise absolute timing



I did not ask for the moon…

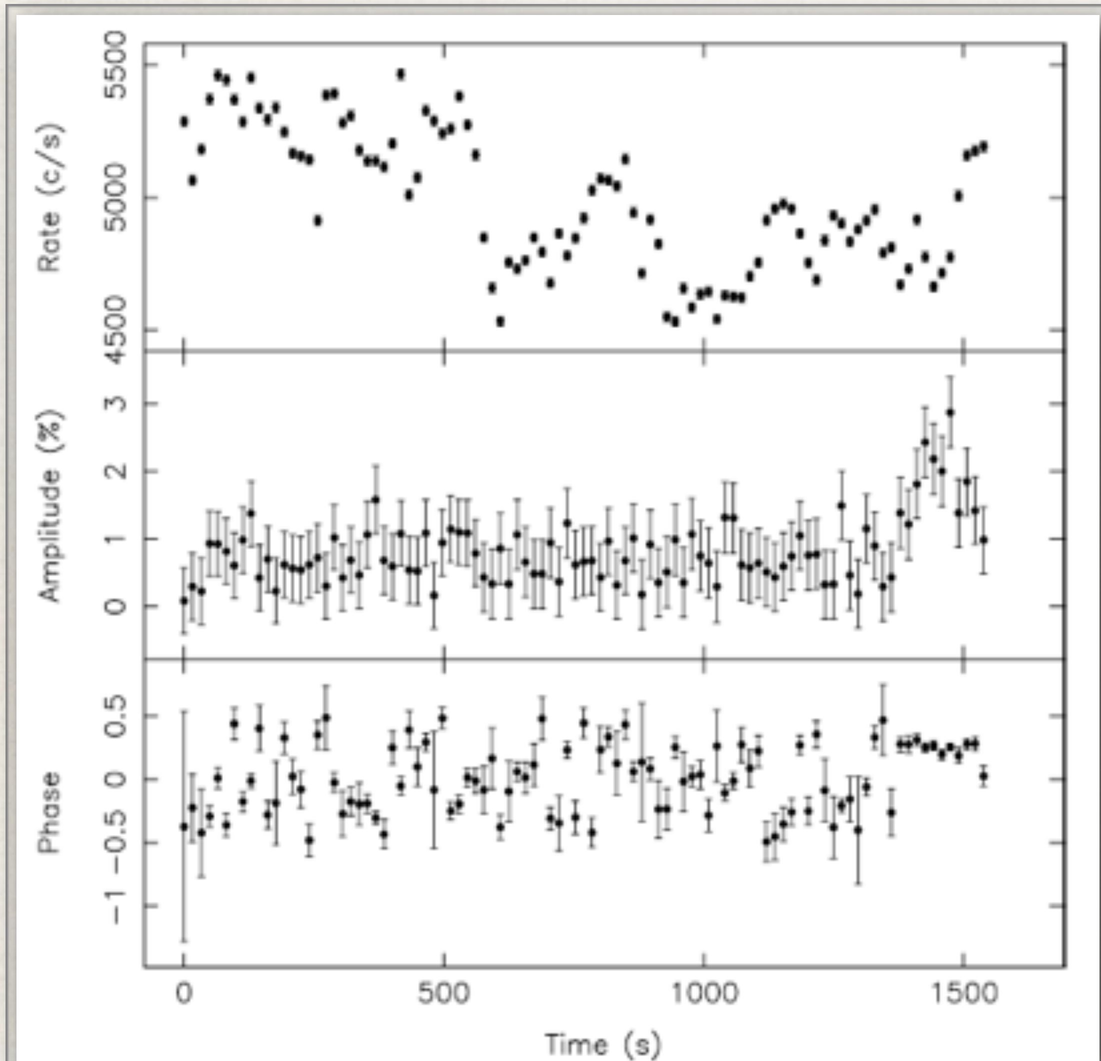


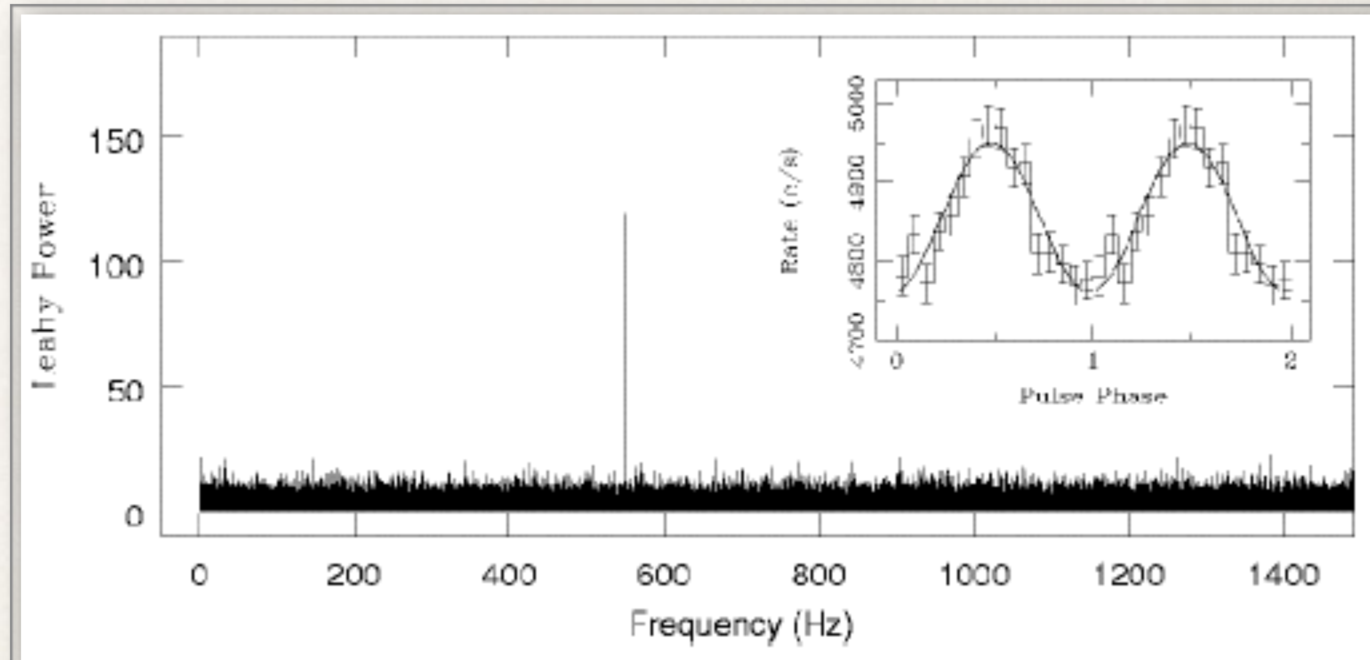


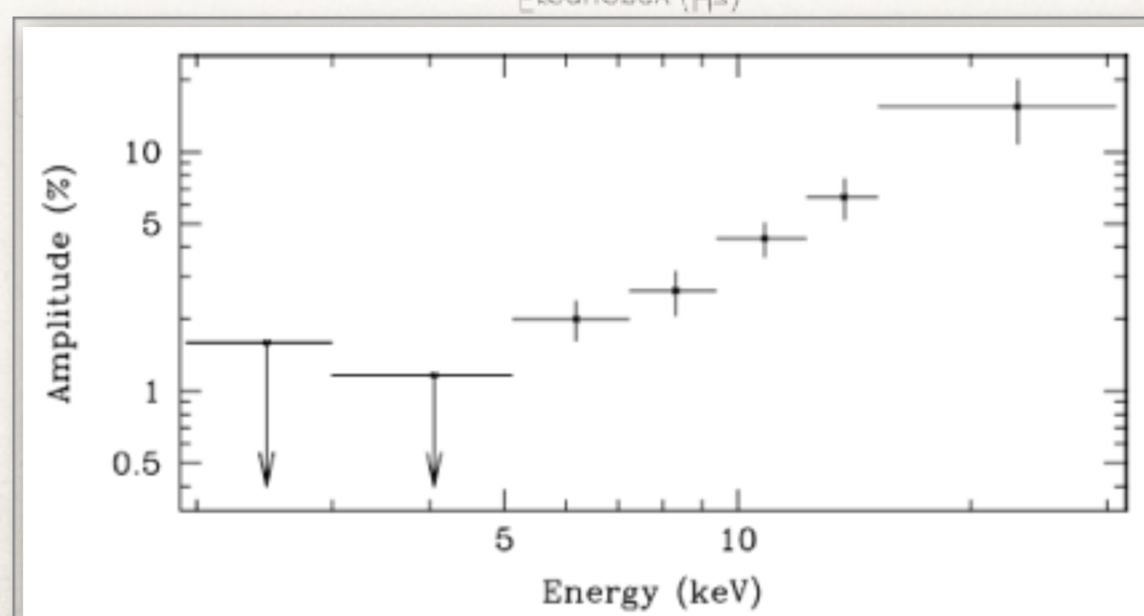
Positional accuracy: 40 μas

Transient pulsations

- Two cases in 2008
- Aquila X-1





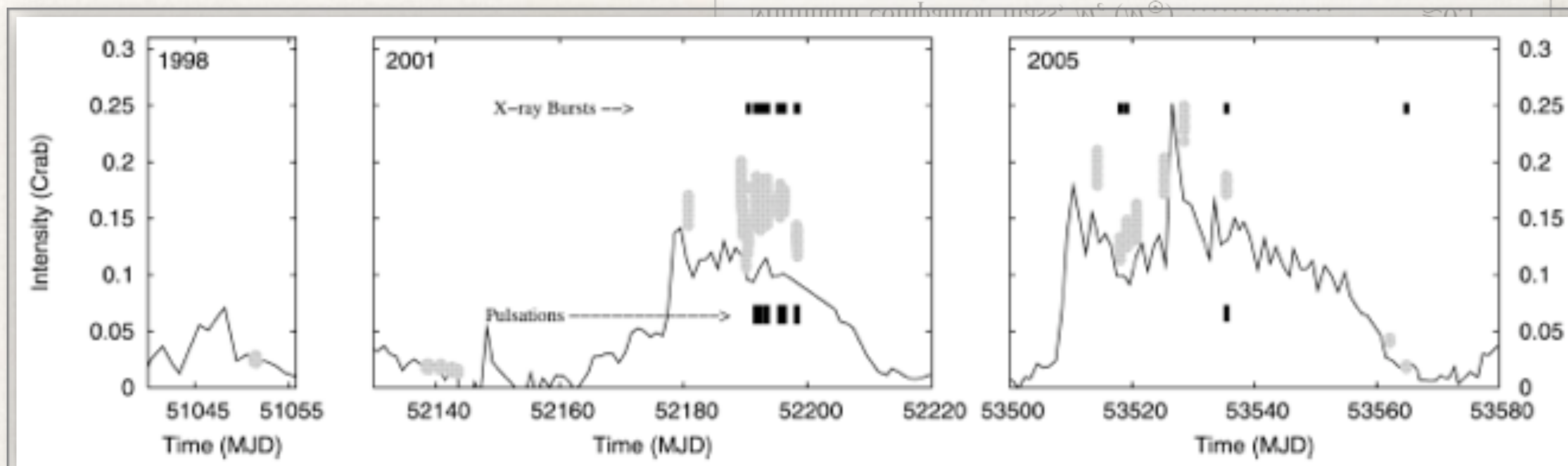


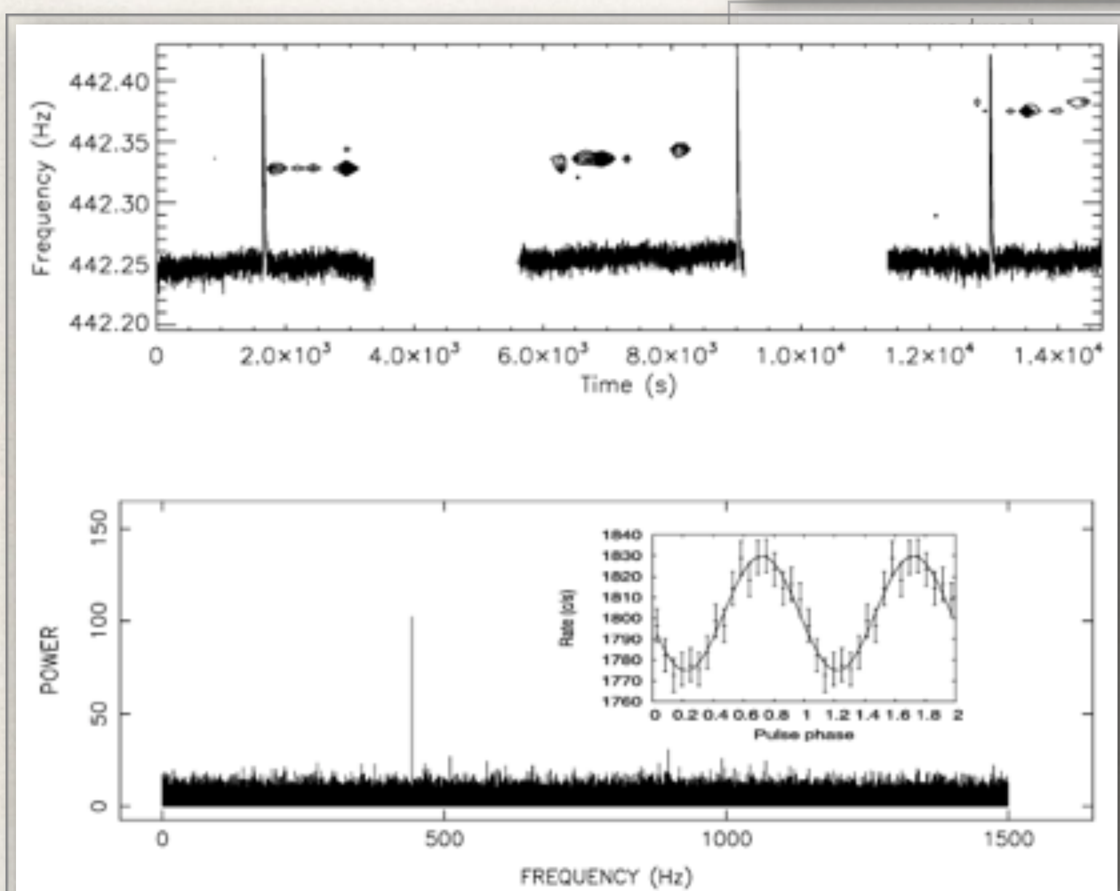
Transient pulsations

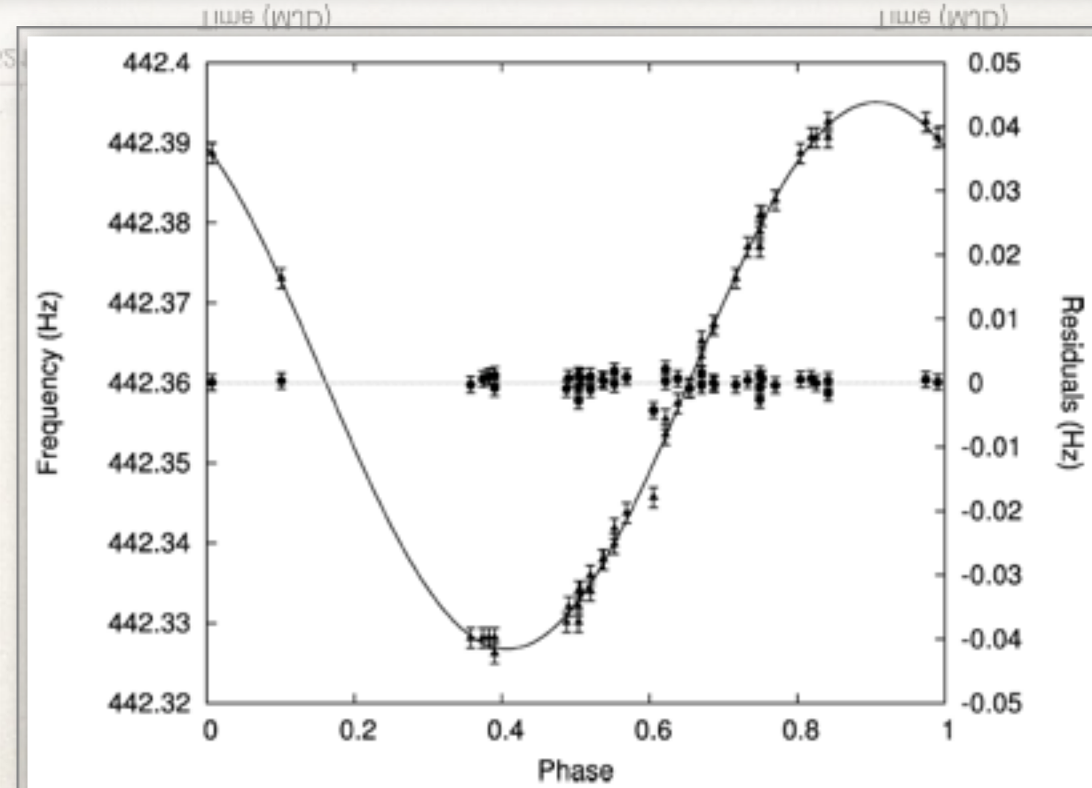
Timing Parameters for NGC 6440

Parameter	Value
Orbital period, P_{b} (hr)	8.764(6)
Projected semimajor axis, $a_x \sin i$ (lt-s)	0.39(1)
Epoch of 0° mean longitude,[a] T_0 (MJD/TDB)	52190.047(4)
Eccentricity, e	<0.001
Spin frequency, ν_0 (Hz)	442.361(1)
Pulsar mass function, f_x ($\times 10^{-4}\ M_{\odot}$)	$\simeq$4.8
Minimum companion mass, M_c ($M_{\odot}$)	$\gtrsim$0.1

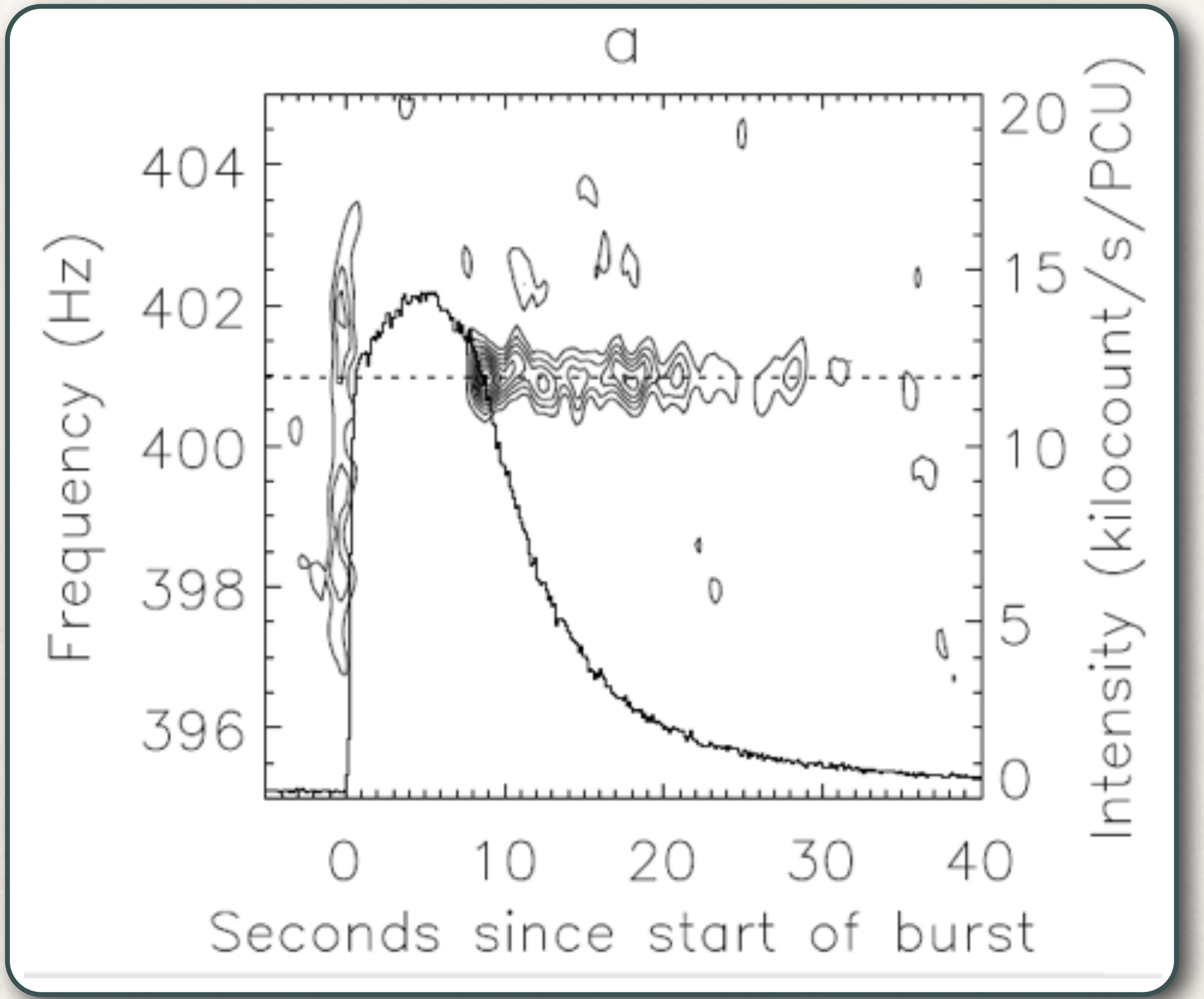
- SAX J1748.9-2021





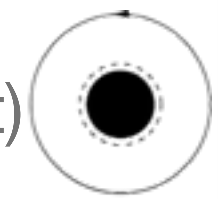


Burst oscillations & spin

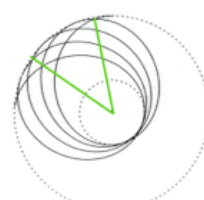


BACK TO GENERAL RELATIVITY

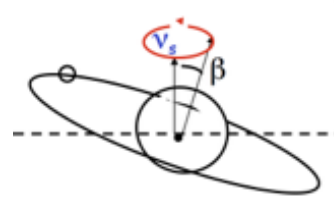
- Three peaks in neutron stars
- One slow, two fast
- Keplerian frequency (fastest)



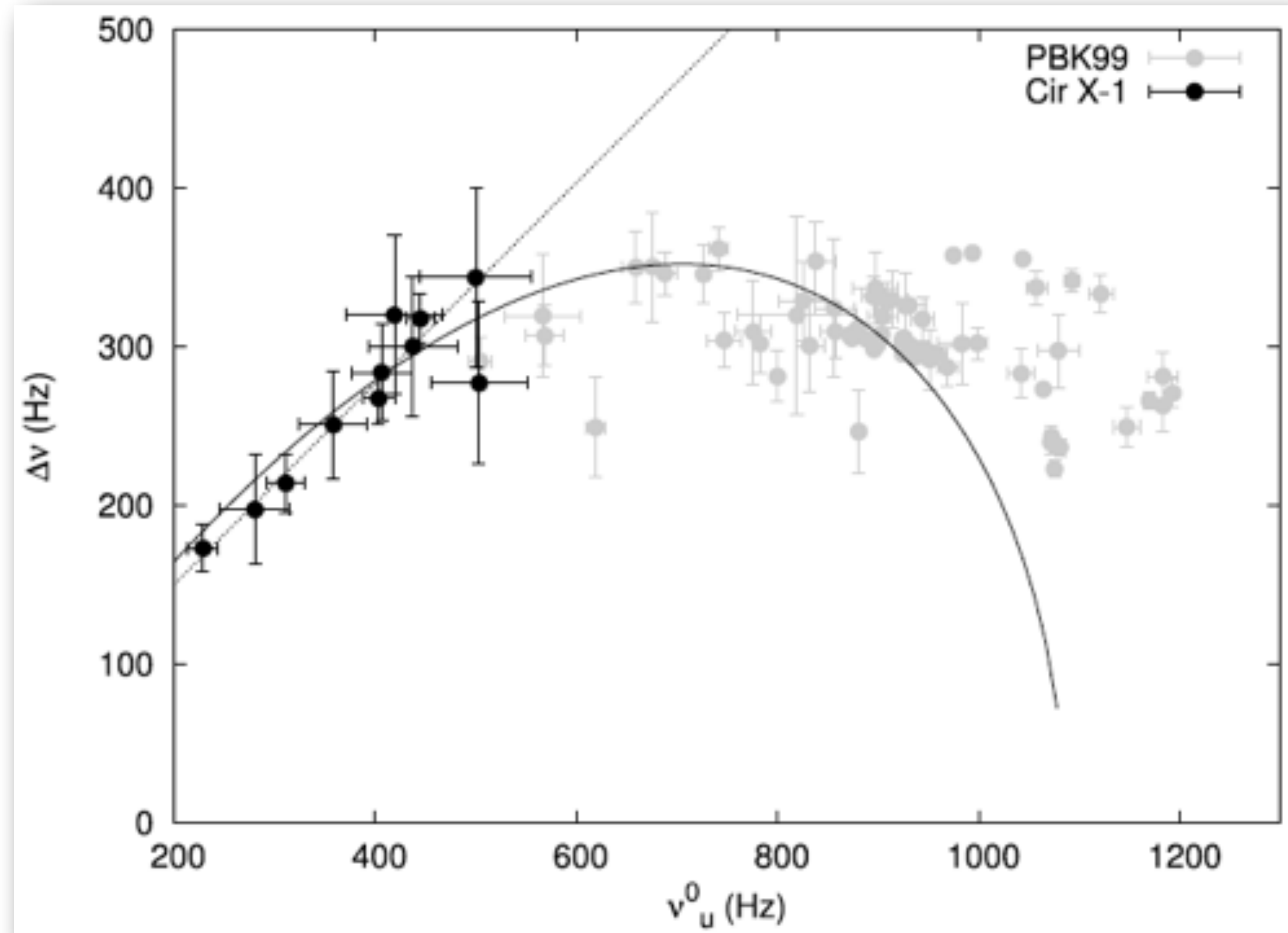
- Periastron precession (fast)



- Lense-Thirring precession (slow)
- @ a certain radius!

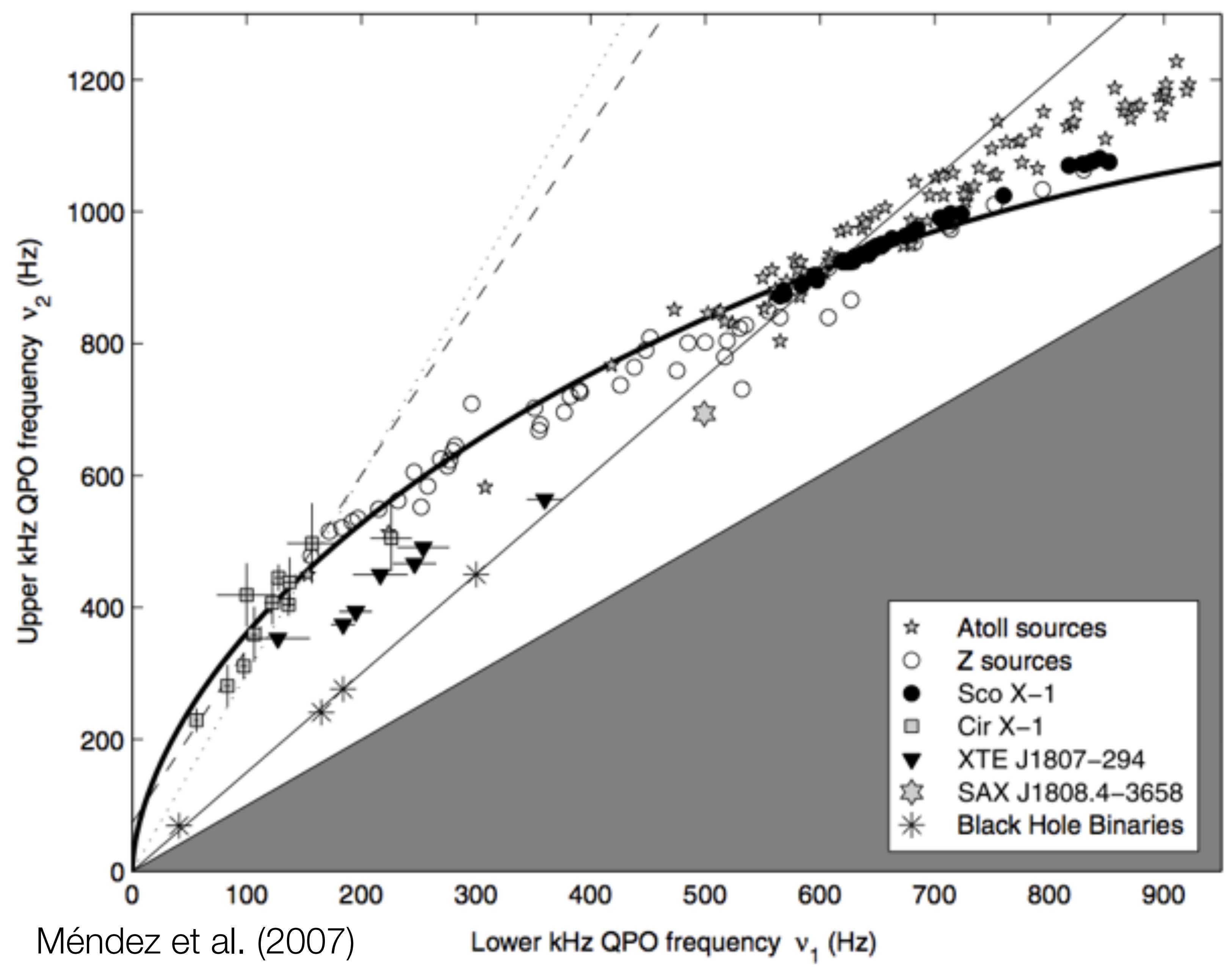


- Amazing agreement, high NS masses



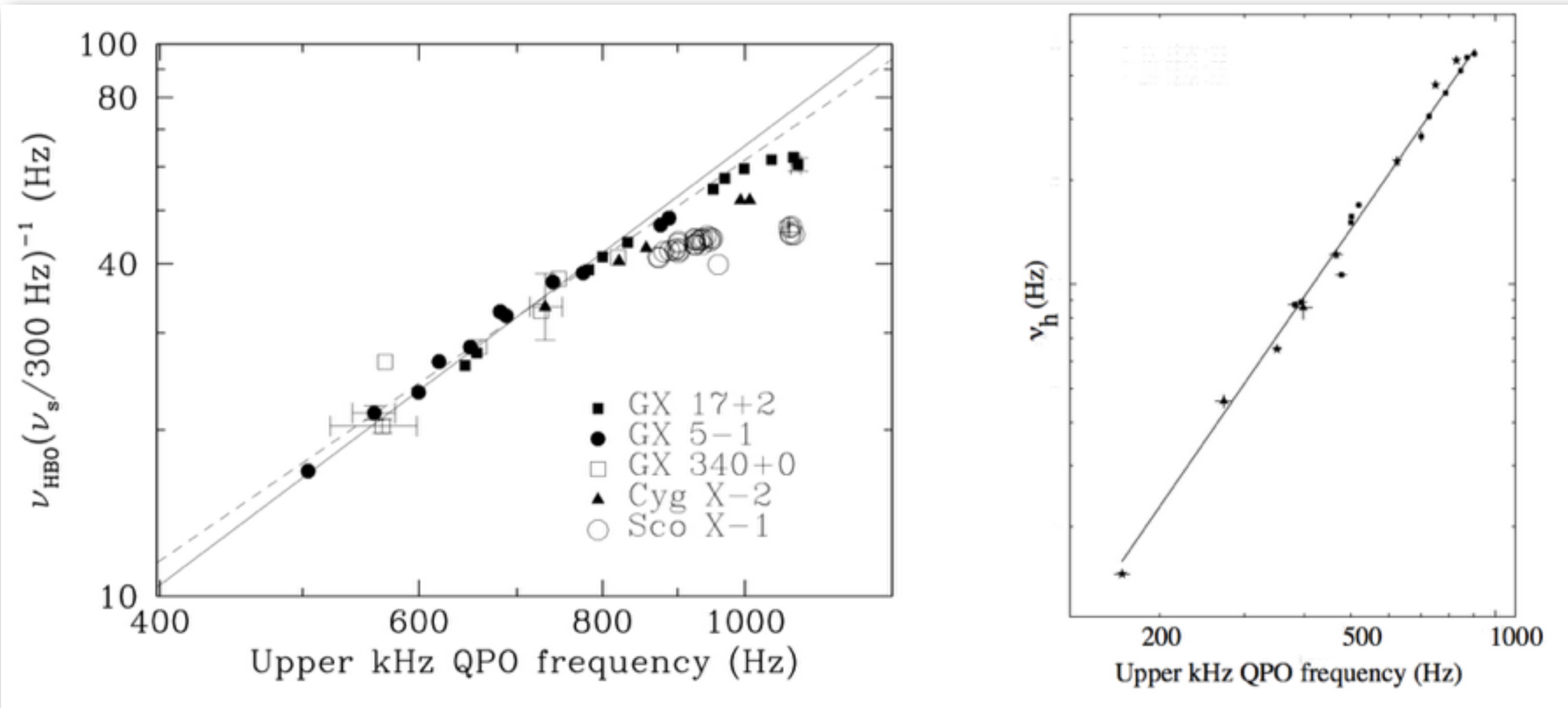
Model by Stella & Vietri (1999)

RELATIVISTIC FREQUENCIES



Méndez et al. (2007)

LOW FREQUENCIES



Psaltis et al. (1999); van Straaten et al. (2003)

see Marieke's poster

Other models for QPOs

- Resonance model   Kluzniak & Abramowicz (2001)
    - Special 3:2 ratio?
    - @ radius where resonance
    - relativistic frequencies
    - requires fixed frequencies (no NS QPO)
    - not much evidence

Other models for QPOs

- Disco-seismic global oscillation model — Nowak & Wagoner (1991)
    - global model
    - trapped g-mode (gravity driven)
- Accretion-Ejection instability — Tagger et al. (1999)
    - similar
    - inner containment radius is poloidal disk
    - Rossby-wave instability

Extension of RPM

- RPM is too simple: only frequencies
- What can give the oscillations?
- Complications and connection to the accretion flow
- Only for LFQPO for the moment

RELATIVISTIC PRECESSION AND TRUNCATED DISK

Lense-Thirring precession & MRI

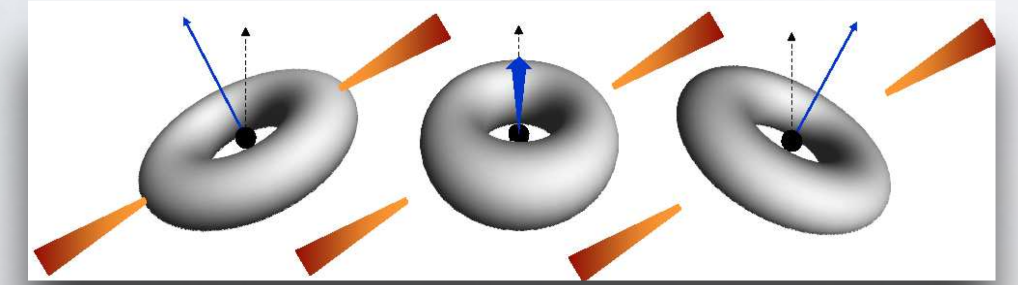
Stella & Vietri 1998a,b, 1999

Ingram et al 2009, Ingram & Done 2010, Ingram & Done 2011

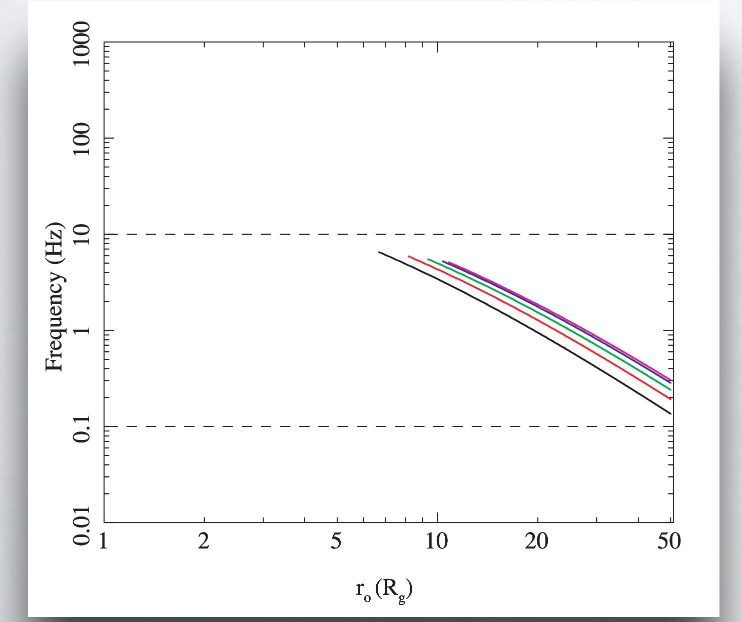
+

Truncated disk model

Done, Gierliński, Kubota 2007



Ingram, Done, Fragile 2009



- spectral evolution: inward-outward movement of inner-disk radius
- Type-C QPOs: Lense-Thirring precession of the inner flow
- broad band noise: Magneto-Rotational Instability (MRI)

RELATIVISTIC PRECESSION AND TRUNCATED DISK

Lense-Thirring precession & MRI

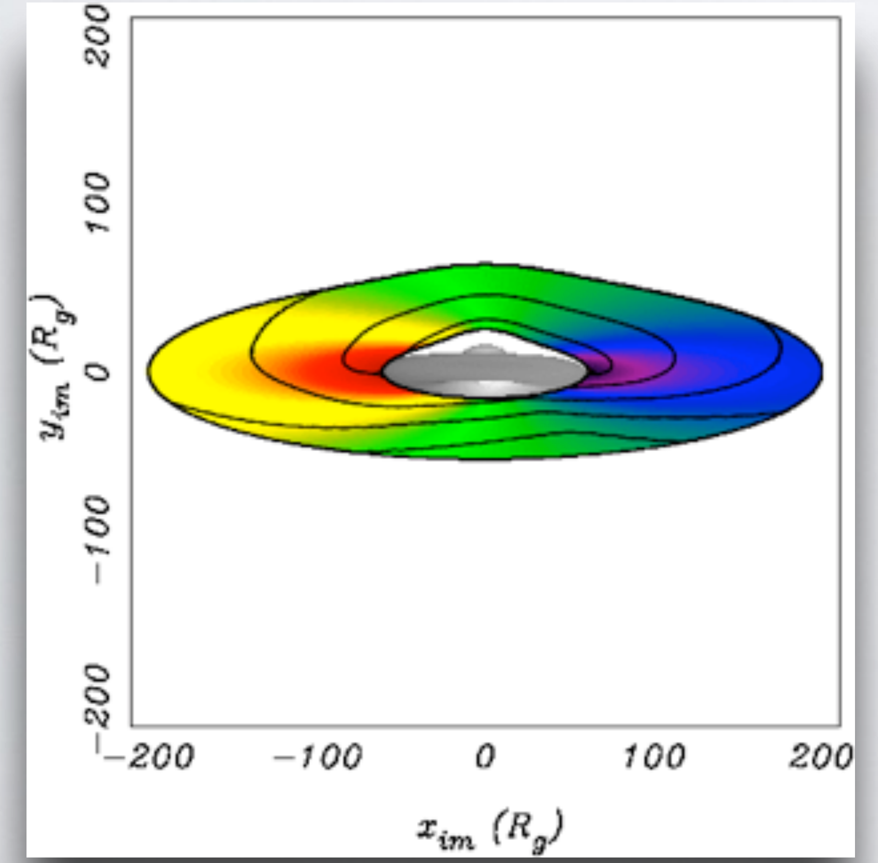
Stella & Vietri 1998a,b, 1999

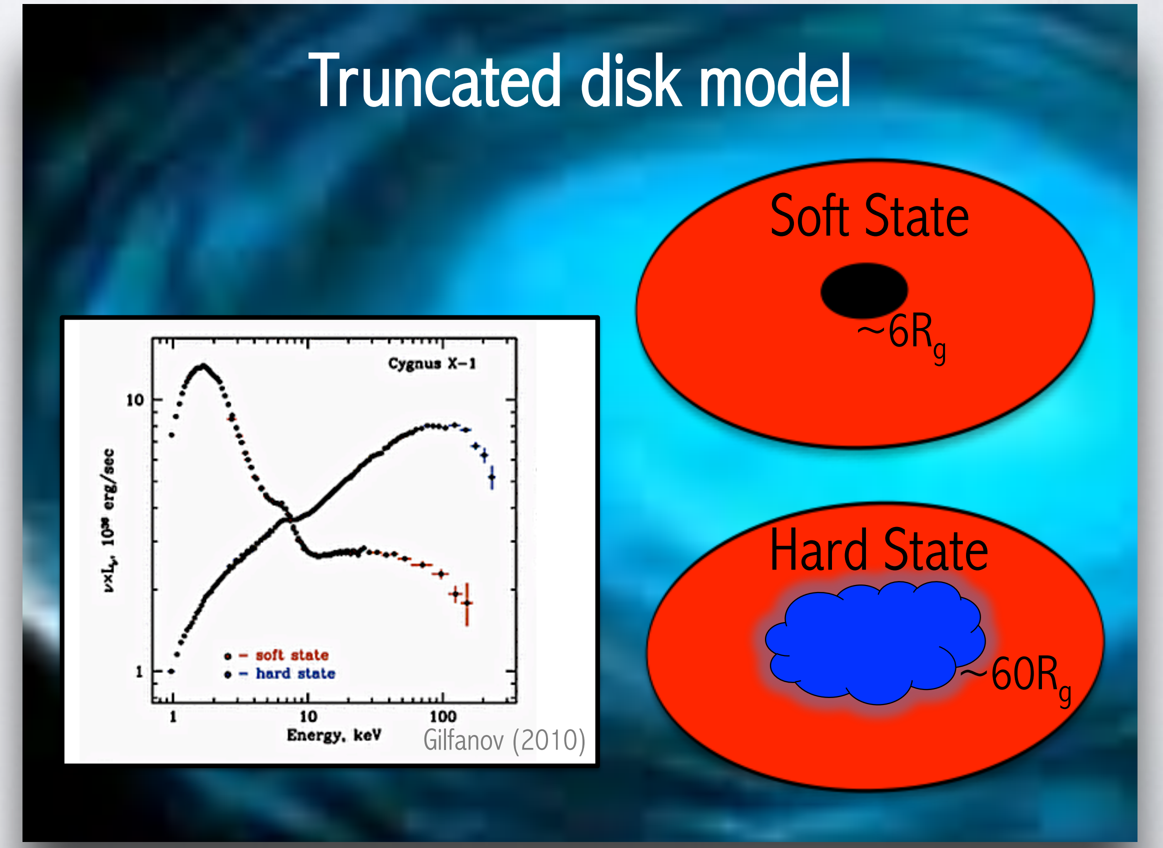
Ingram et al 2009, Ingram & Done 2010, Ingram & Done 2011

+

Truncated disk model

Done, Gierliński, Kubota 2007



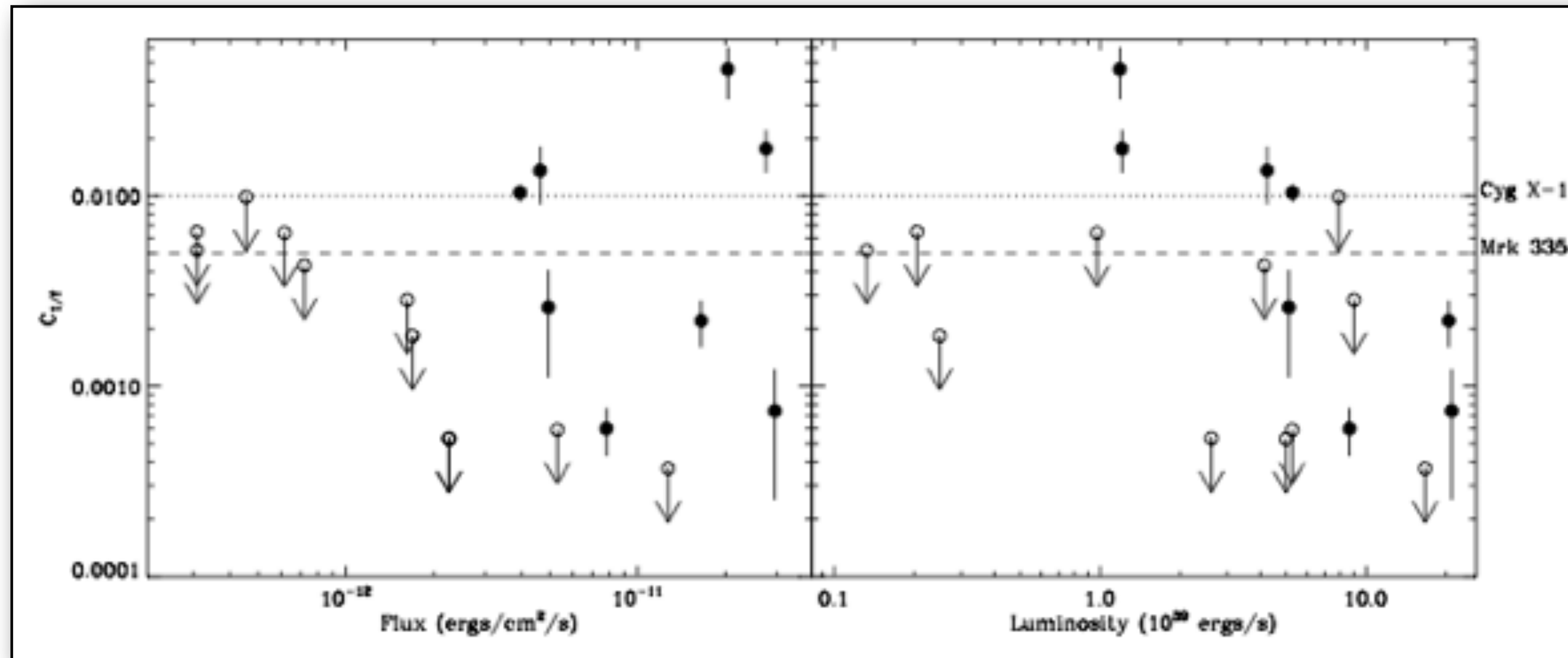


ULXs

- Still the question of mass: IMBH or BHB?
- A lot of discussion on the topic
- Spectral methods, heated discussion
- Timing can be a way
    - Need to identify features
    - Comparison with something we do not know well

ULX: TIMING APPROACH

- Systematic studies (few)
- rms-flux relation (NGC 5408 X-1)

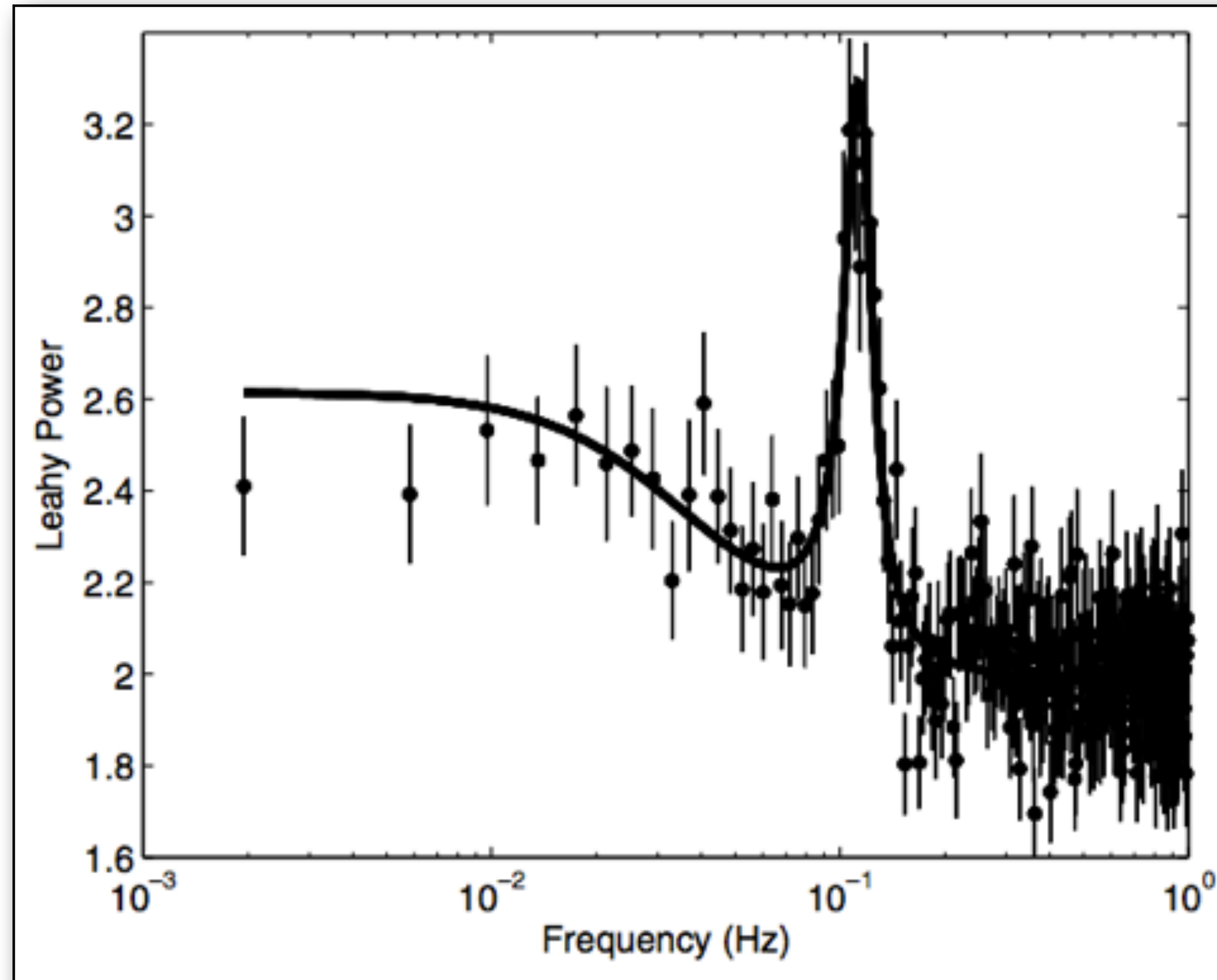


Heil et al. (2009)

- Still missing: hardness-rms diagram - variability hard to measure
- Things will get better in time

ULX: TIMING APPROACH - QPOs

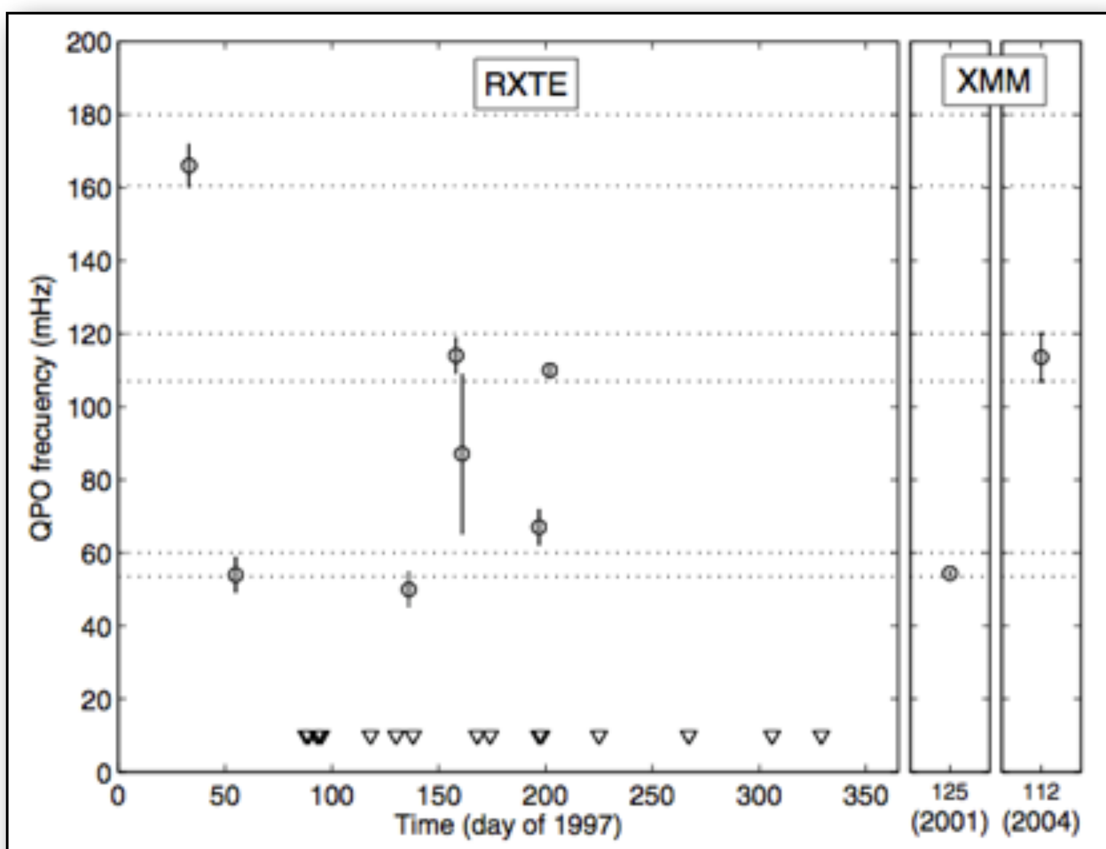
- Precise frequencies
- Typical of galactic binaries
- Direct comparison
- Relatively rare
- M82 X-1 Strohmayer & Mushotsky (2003)
- It has all required signatures

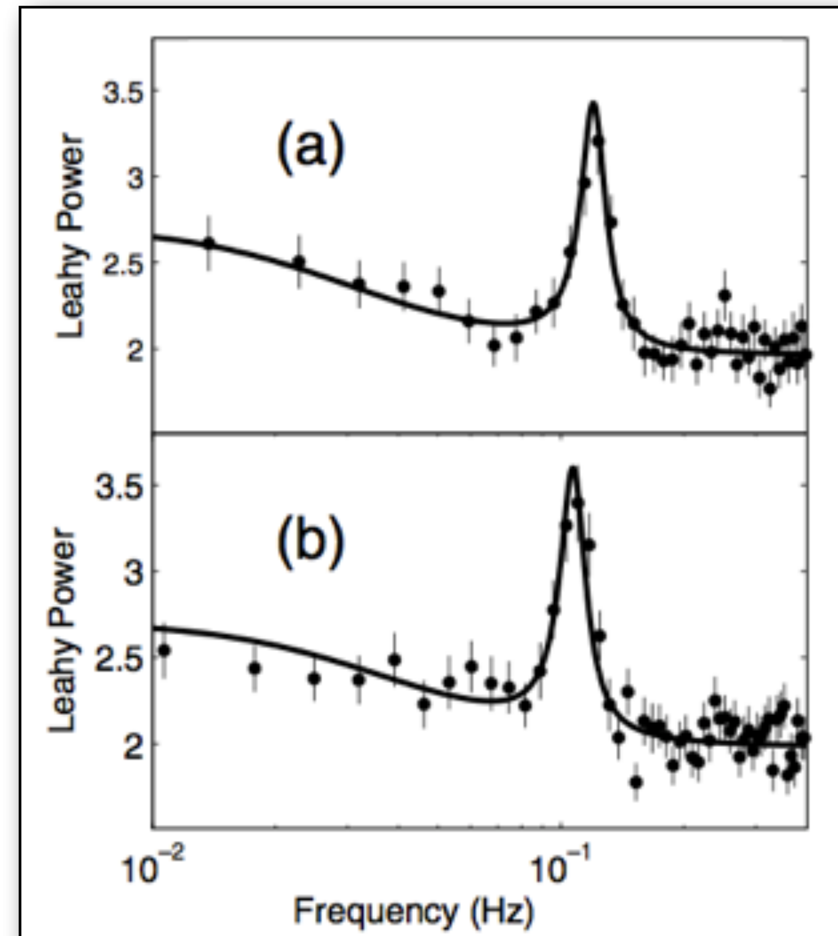


Mucciarelli et al. (2006)

ULX: TIMING APPROACH - QPOs

- Fast frequency variations
- Associated noise (22% rms)
- Long-term changes (?)





Mucciarelli et al. (2006)

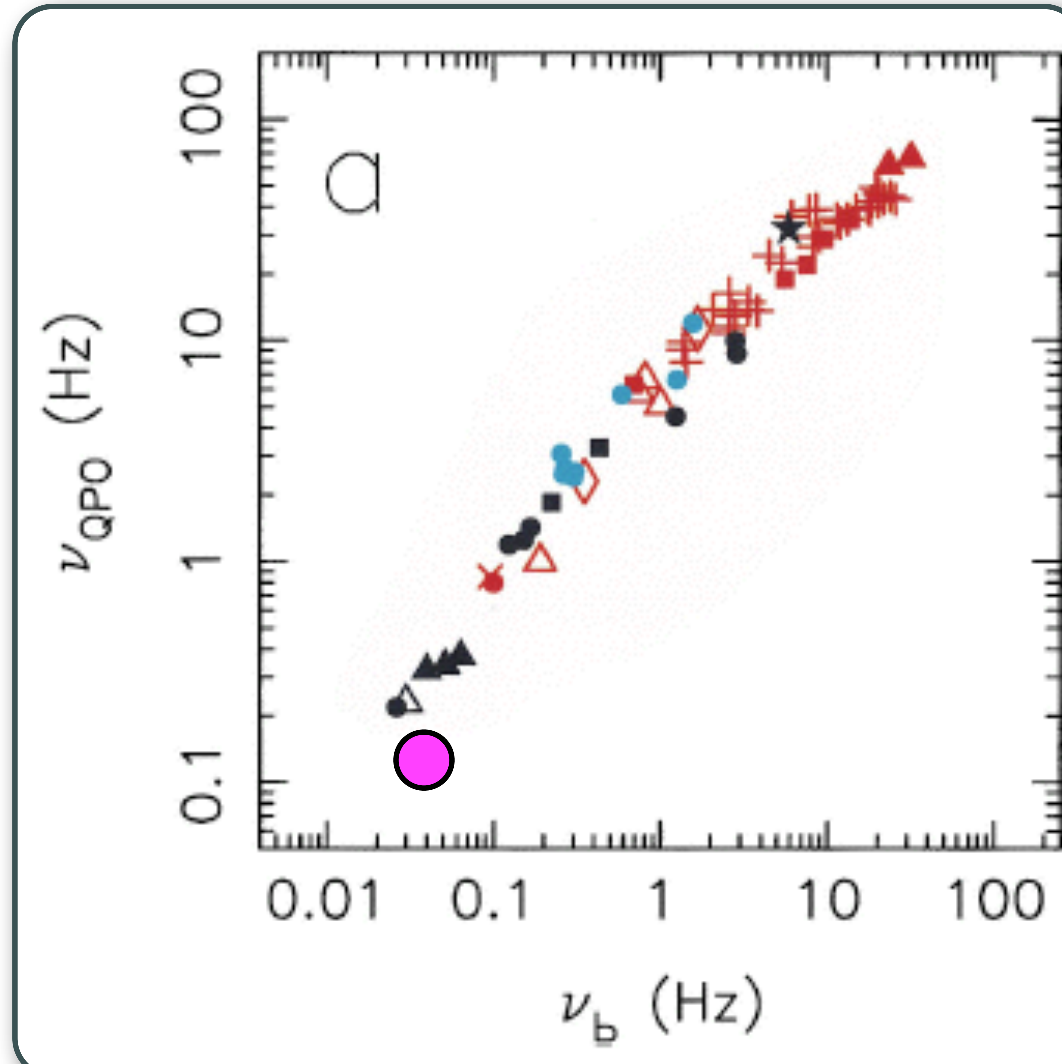
ULX: TIMING APPROACH - QPOs

- Correlation?

- Which QPO?

TABLE 1
SUMMARY OF TYPE-A, -B AND -C LFQPOs PROPERTIES

Property	Type C	Type B	Type A
Frequency (Hz)	~0.1-15	~5-6	~8
Q (ν/FWHM)	~7-12	$\gtrsim$6	$\lesssim$3
Amplitude (%rms)	3-16	~2-4	$\lesssim$3
Noise	strong flat−top	weak red	weak red
Phase lag @ν_{QPO}	soft/hard	hard	soft
Phase lag @$2\nu_{QPO}$	hard	soft	...
Phase lag @$\nu_{QPO}/2$	soft	soft	...



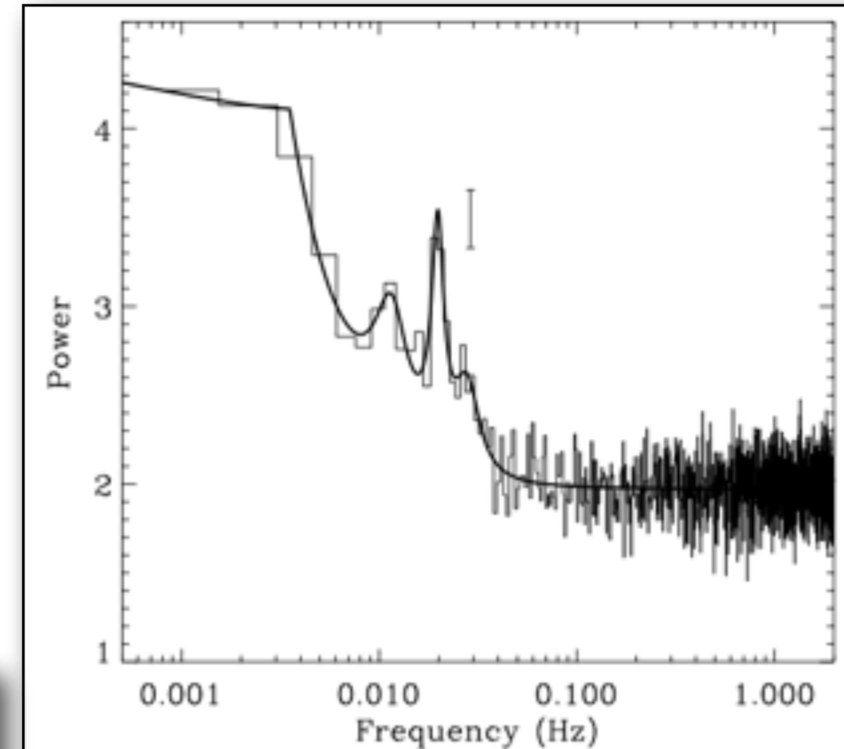
Wijnands & van der Klis (1999)

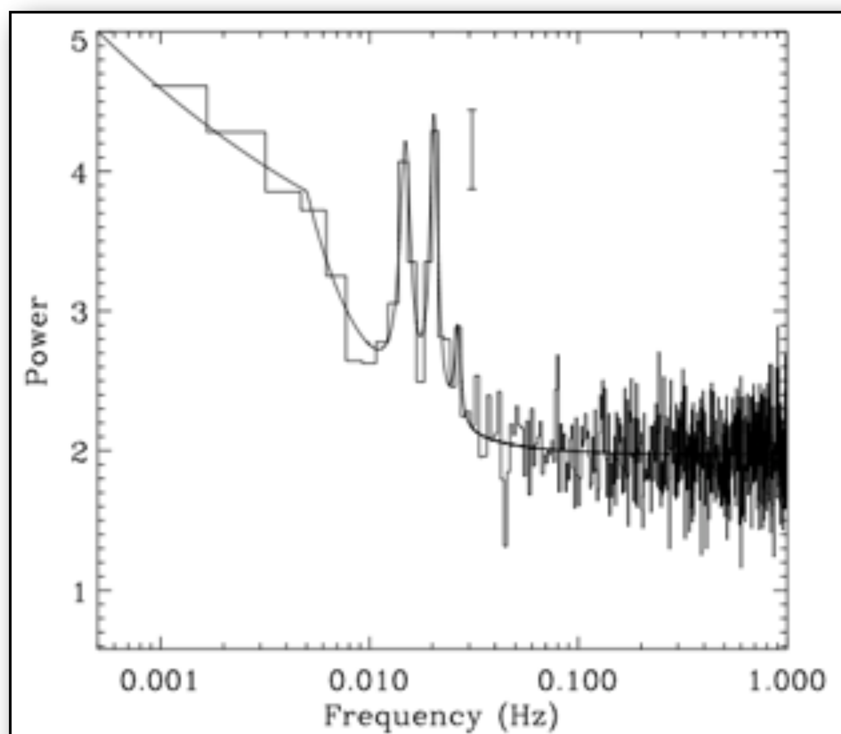
- HFQPO? Does not fit (and yet it moves..!)

- Type C: the worst type for mass estimate

ULX: TIMING APPROACH - QPOs

- NGC 5408 Strohmayer et al. (2007)
- 20 mHz QPO + break 3.5 mHz
- Two peaks?
- Watch out for ratios

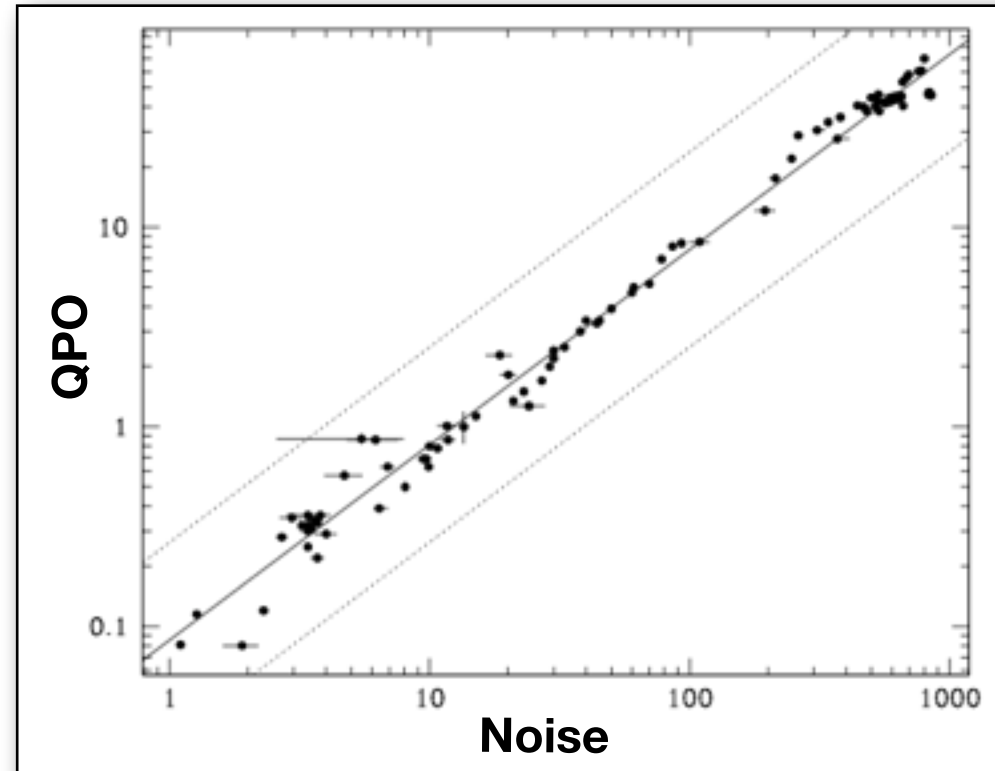




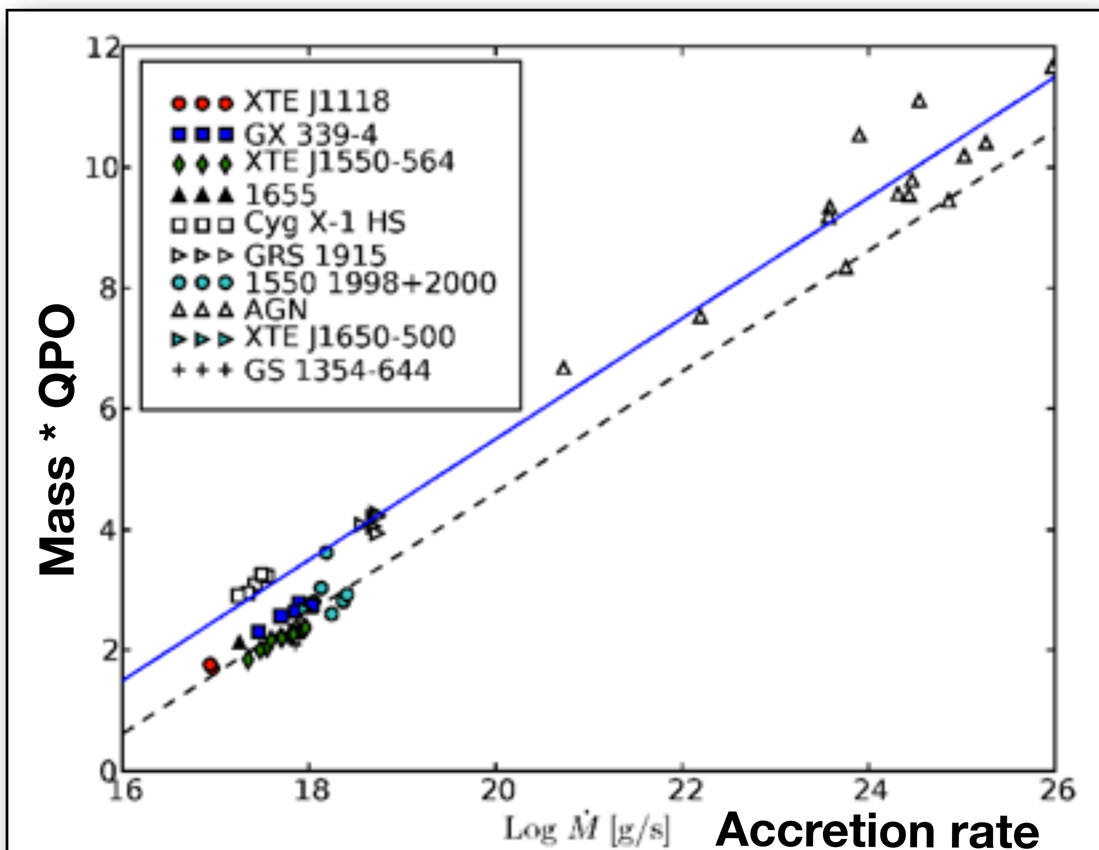
A MULTI-STEP ATTEMPT

- Using correlations:

noise ⇨ QPO
LX ⇨ $\dot{M}$ ⇨ Mass



Belloni et al. (2002)



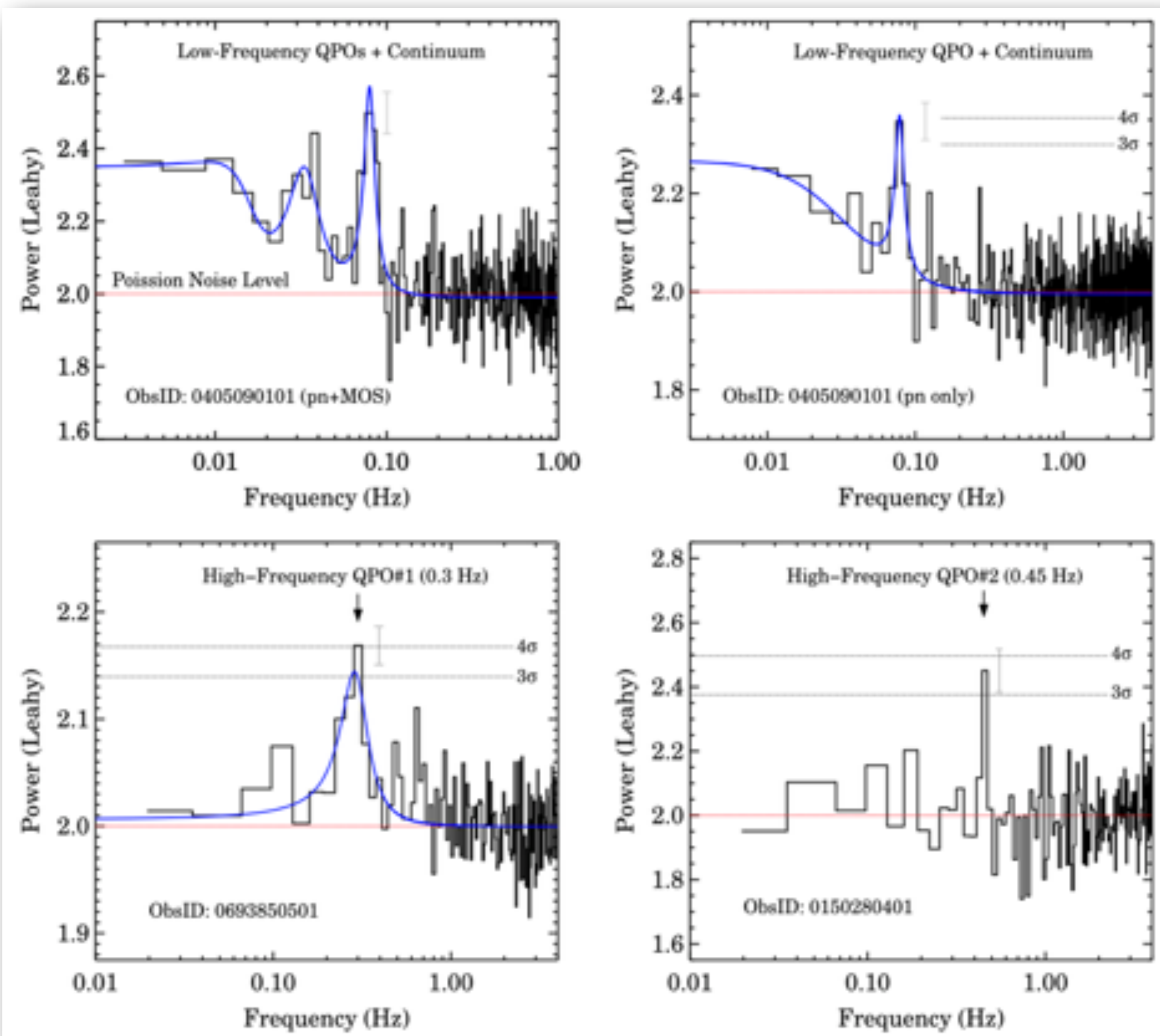
Körding et al. (2007)

Source	ν_{QPO} (mHz)	$L_X{}^a$ (ergs/s)	BH mass ($M_\odot$) Ineff. accr.	BH mass ($M_\odot$) Eff. accr.
M82 X-1 (2001)	54±1	130±13	240^{+380}_{-150}	700^{+905}_{-395}
M82 X-1 (2004)	113±2	170±17	165^{+260}_{-100}	550^{+710}_{-310}
NGC 5408 X-1	20±0.5	30±3	295^{+465}_{-180}	570^{+735}_{-320}

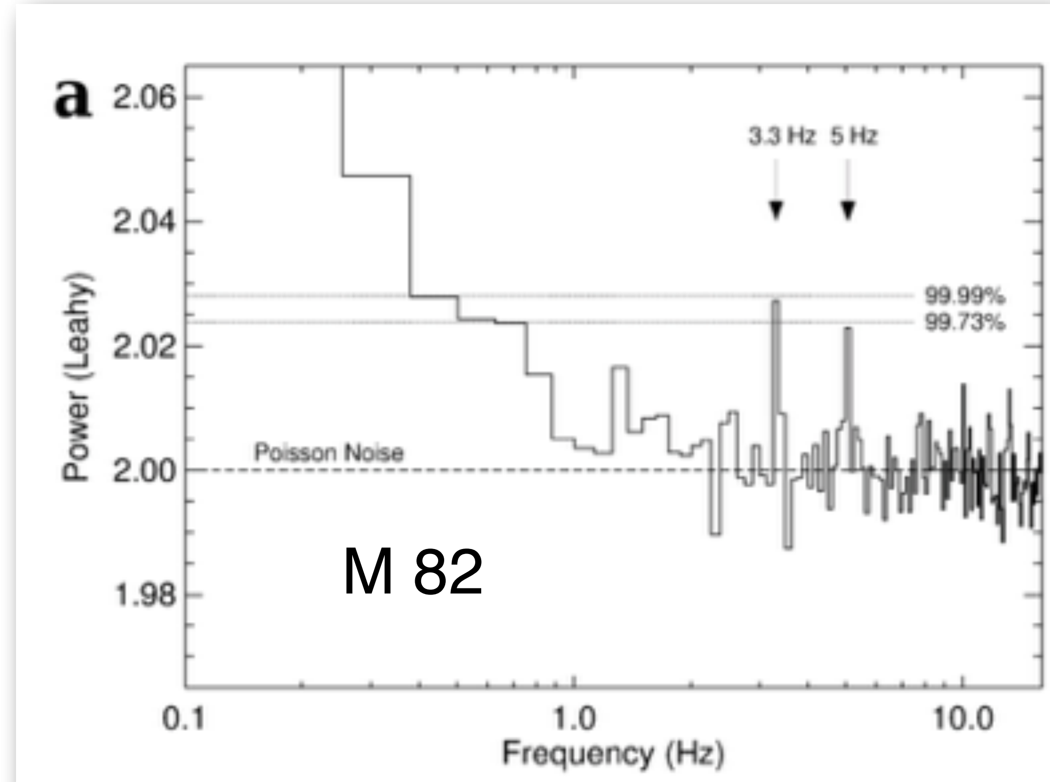
Casella et al. (2008)

NOW MANY MORE CLAIMS

- Dubious detections



NGC 1313



M 82

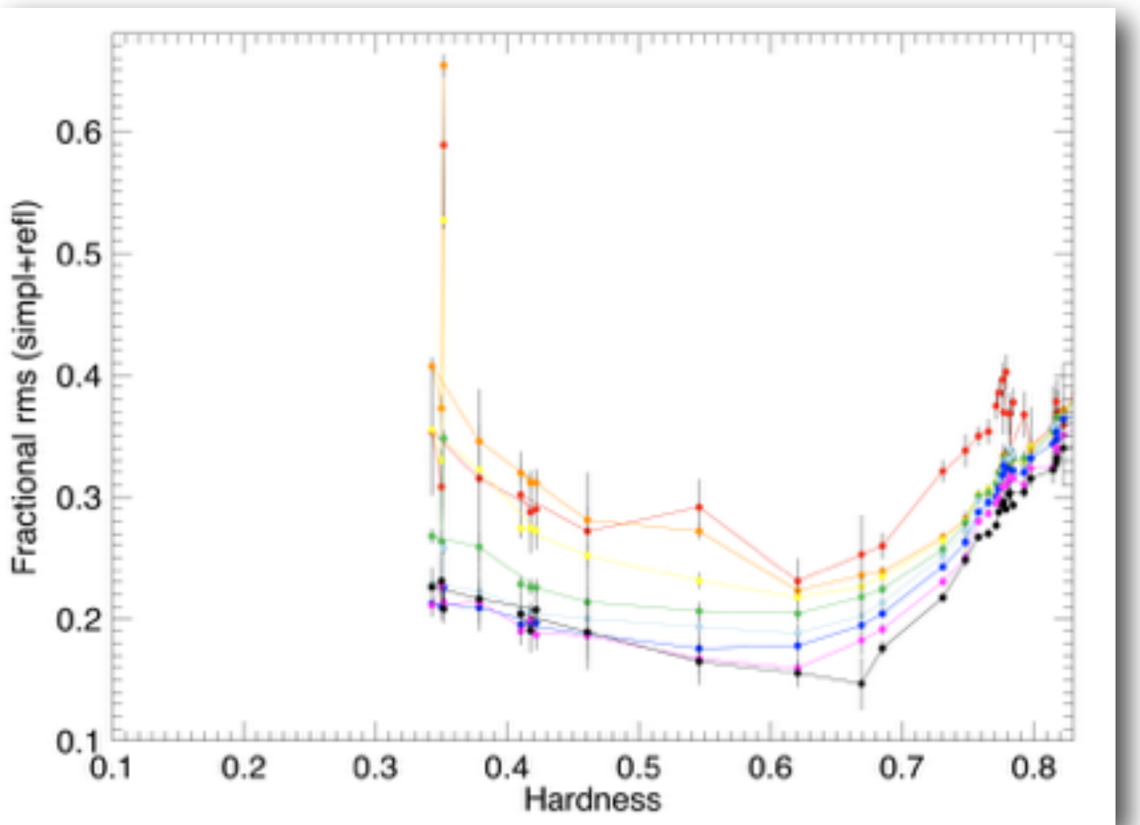
HARD STATE / SOFT STATE

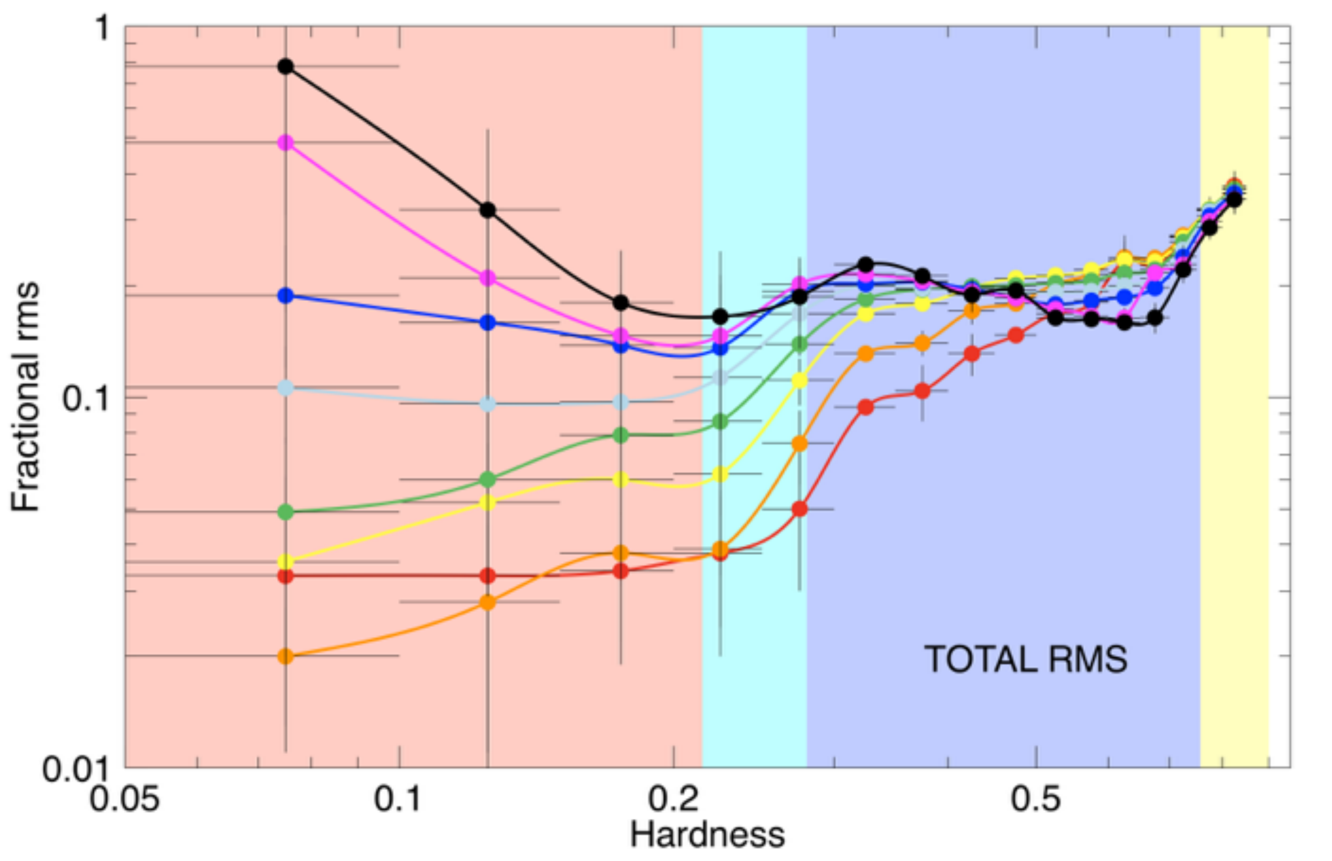
- Hard state: variable
- Soft state: quiet

- Variability in the Compton component
- Disk does not vary
- Closed issue?

SOFT STATE

- Variability is large at high energies
- Disk is not variable
- "Removing it" works

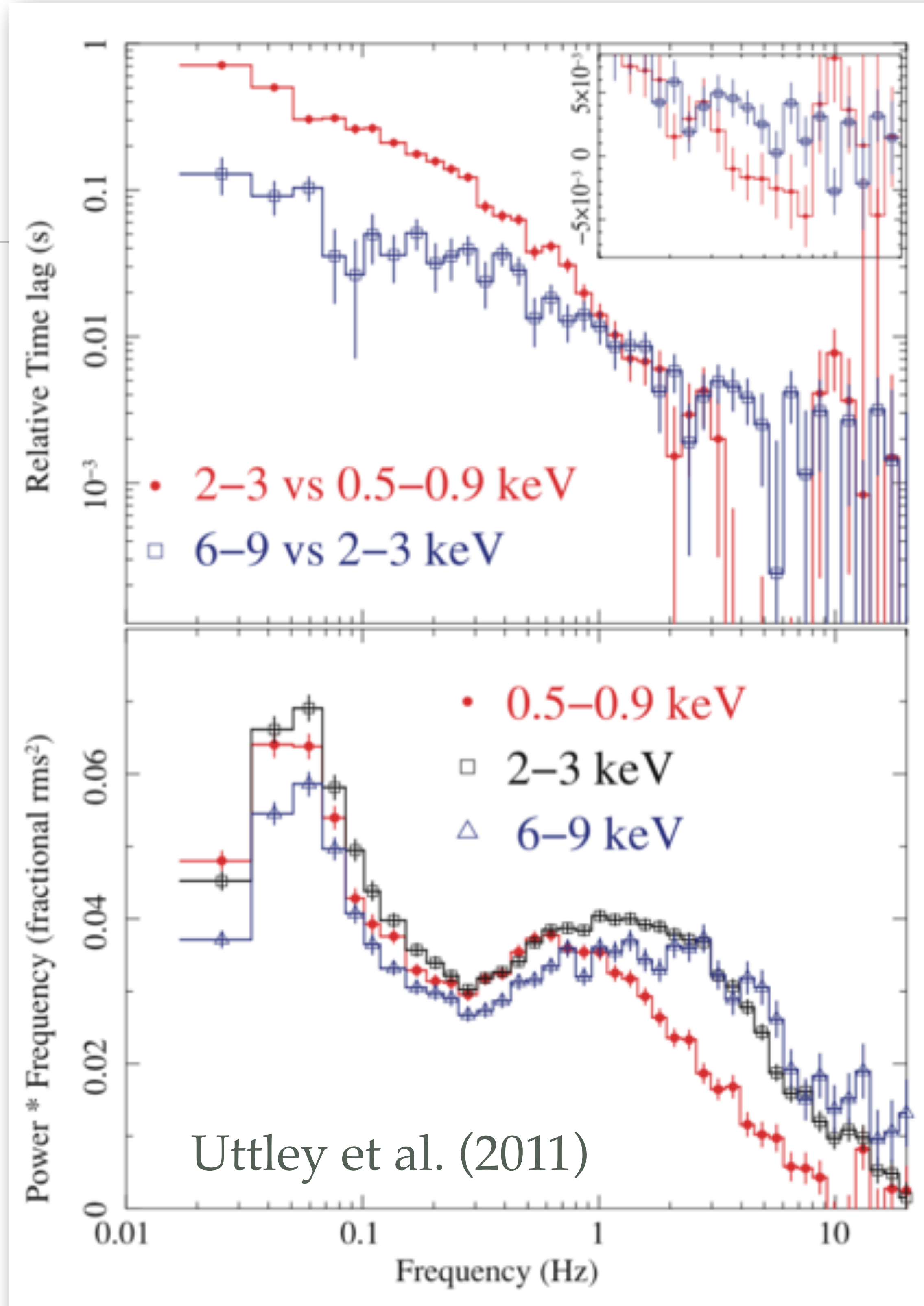




HARD STATE

- Disk is present below 1 keV
- For low N_H we can see it

- Variability is stronger at low ν
- Lags are complex



HARD STATE

- < 1 Hz: disk more variable and leads
  - Long time delay due to viscous propagation

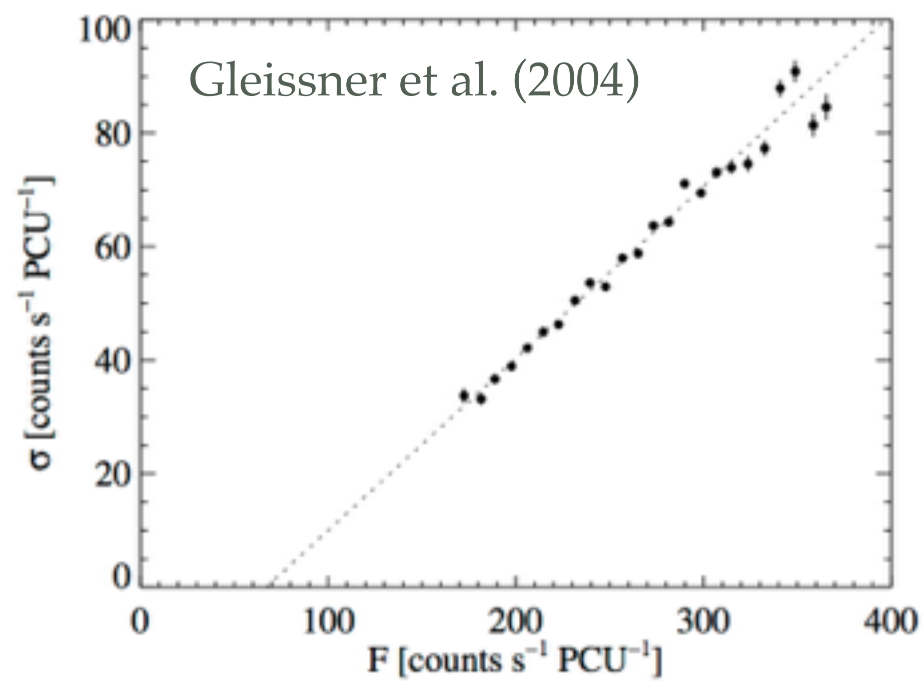
- < 1 Hz: Compton more variable and leads
  - Short time delay due to light travel time

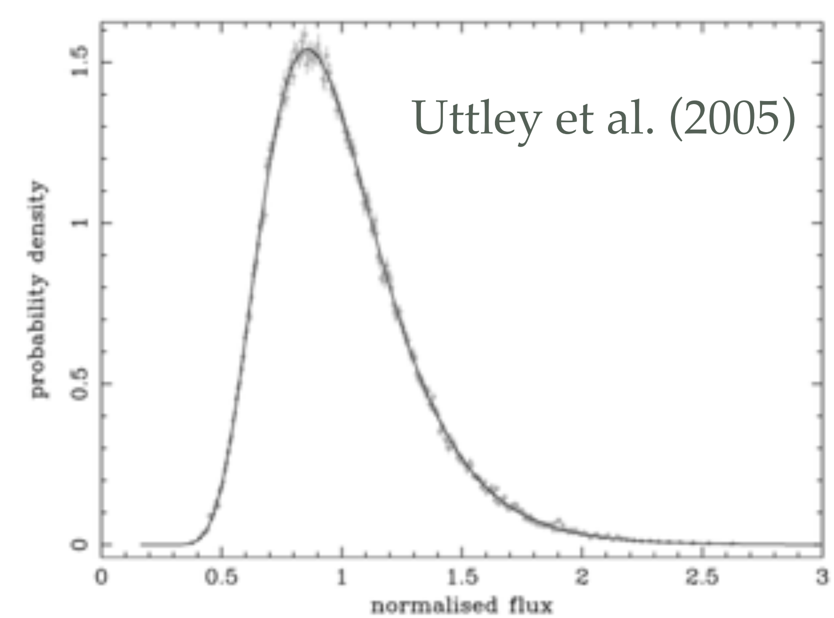
The disk varies only when you don’t see it…

NATURE OF LHS SIGNAL

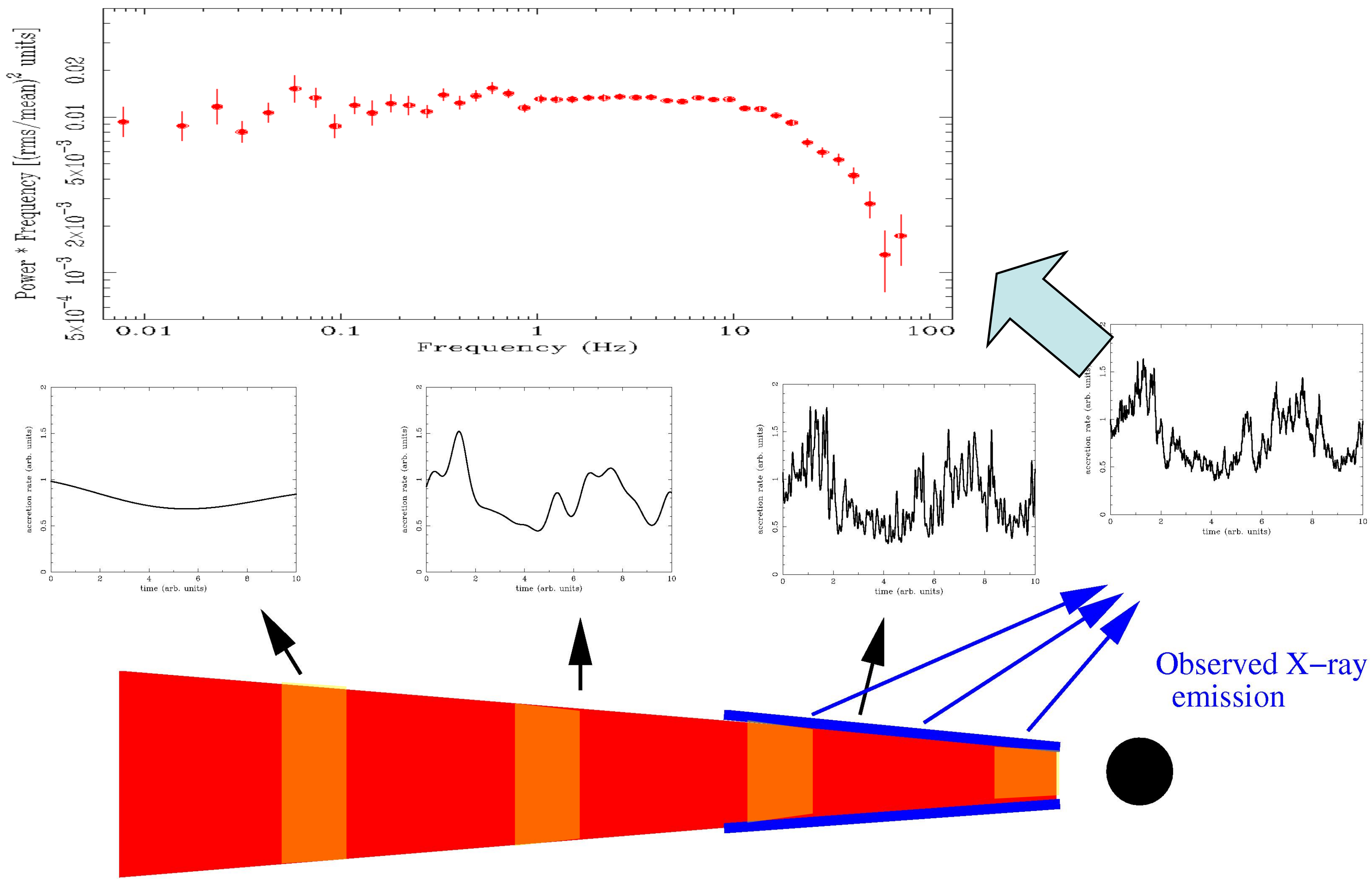
- Shot noise (multiple)?
- res-flux relation
- lognormal distribution

- It cannot be shot noise
- Non-linearity
- Compatible with propagation models

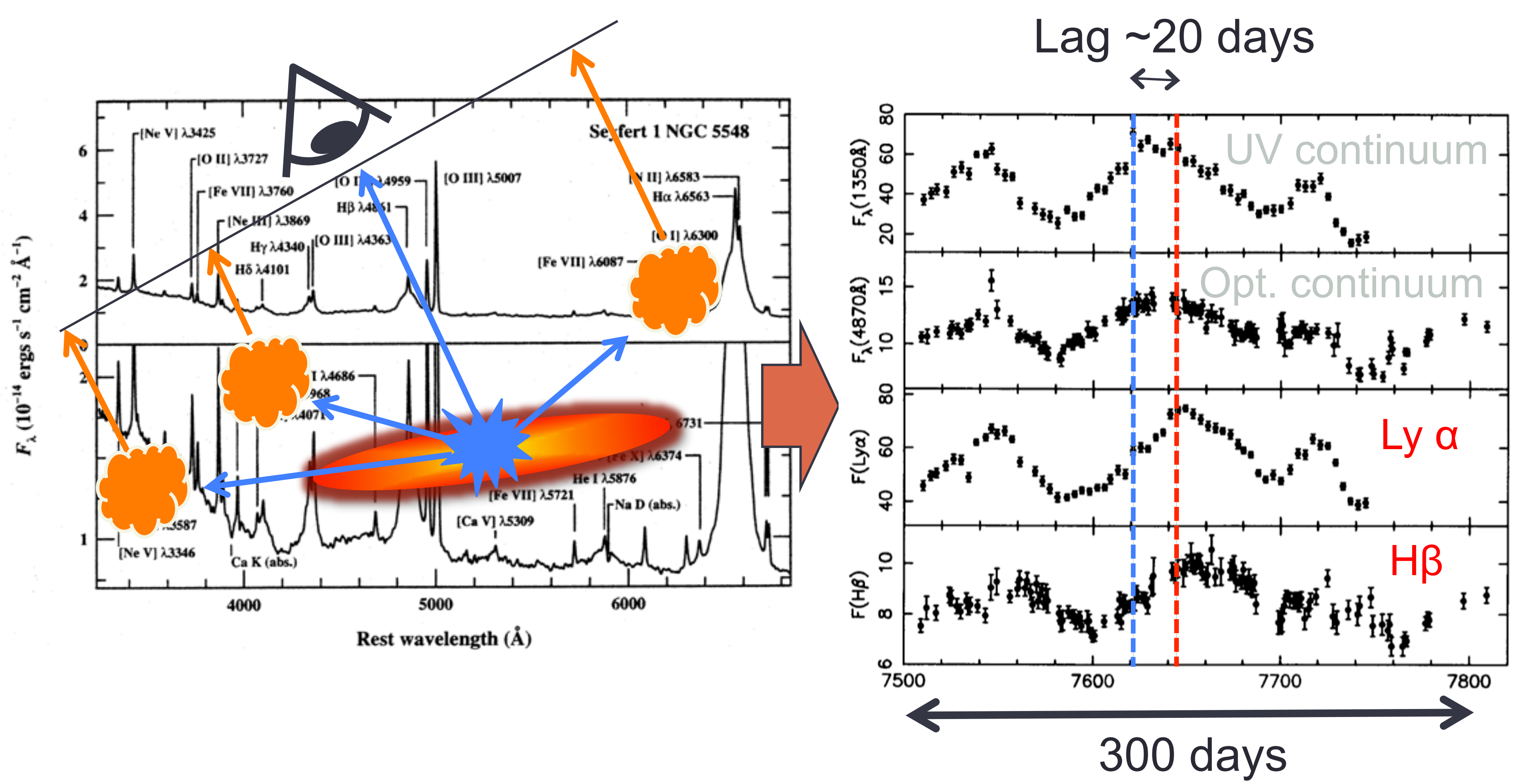




PROPAGATION MODEL



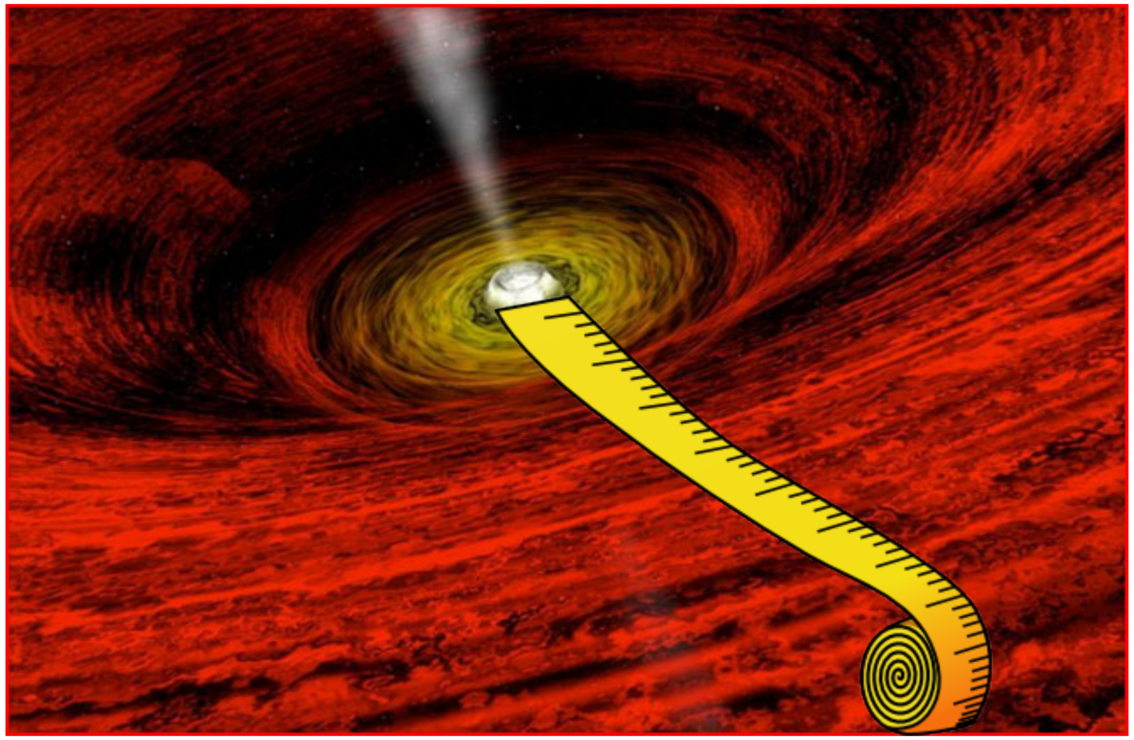
REVERBERATION MAPPING



Optical time lags in AGN can be used to map scales of light-days

X-rays can map <light-mins in AGN, and <light-ms in XRBs!

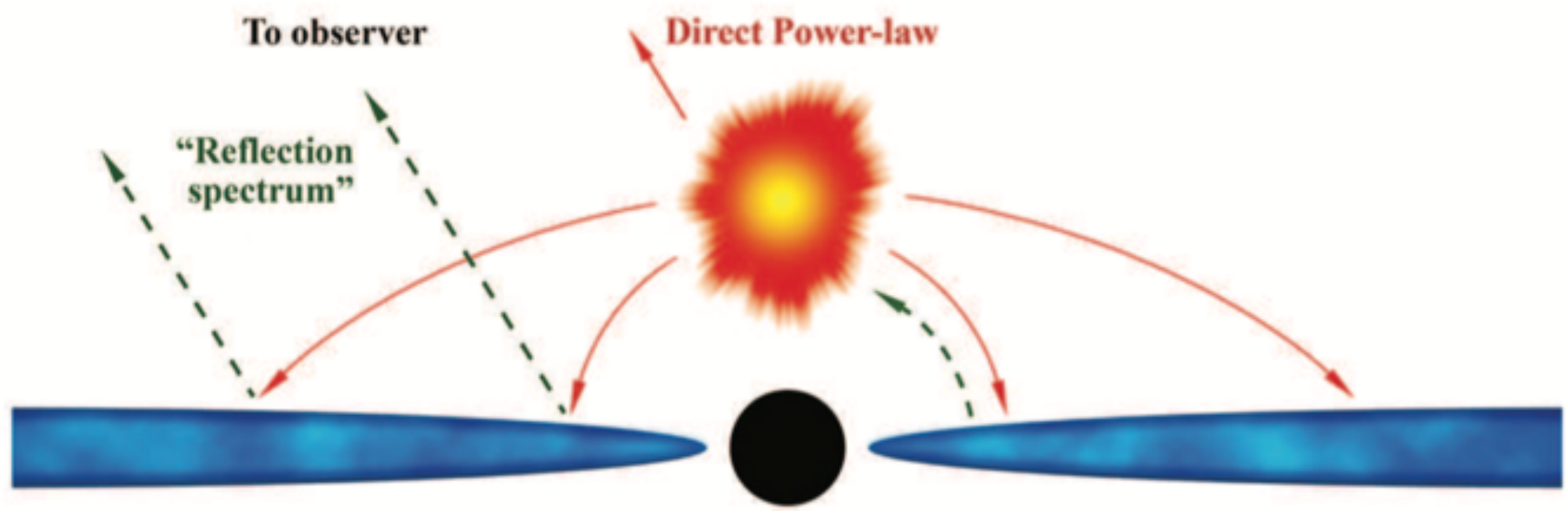
ABSOLUTE DISTANCES



Reverberation allows distances to be measured in km, not R/M: highly complementary to spectral fitting

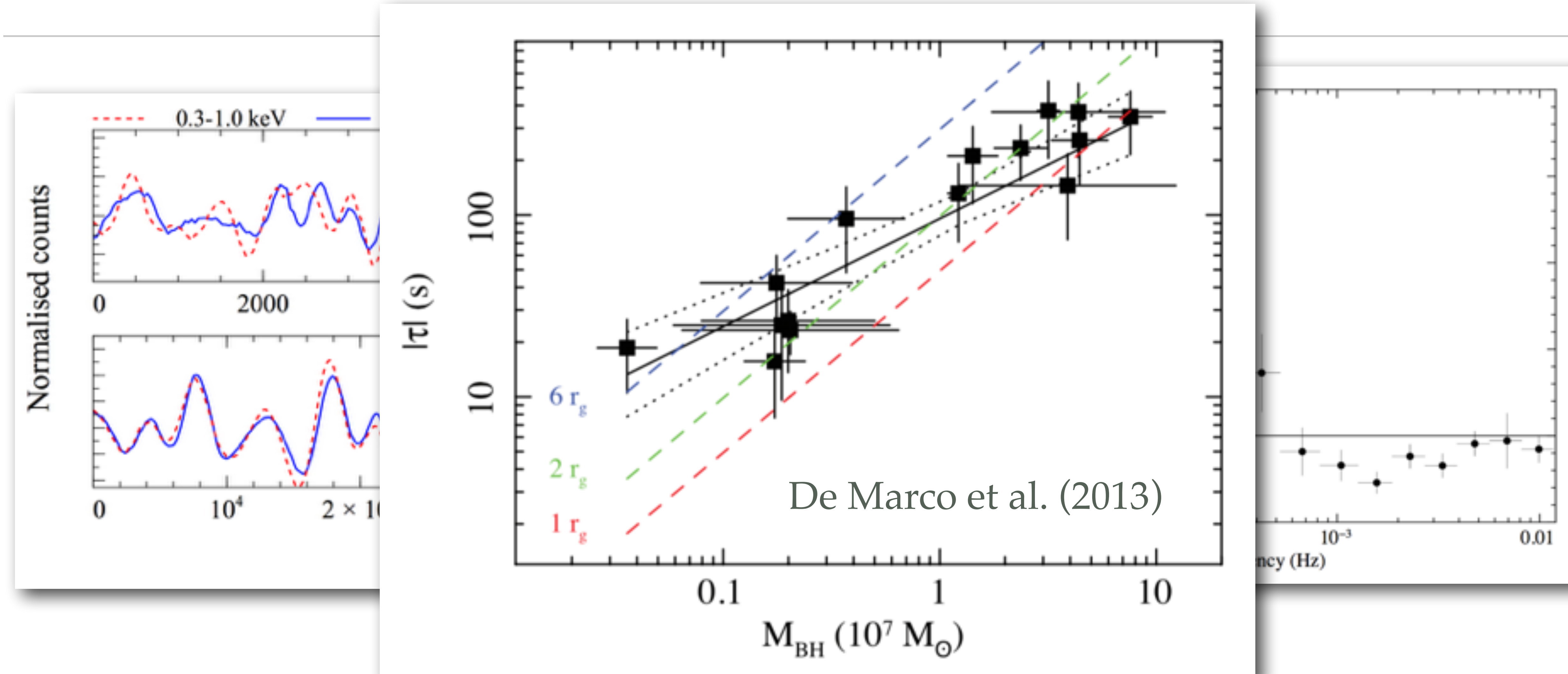
Spectral (i.e. redshift)+lag information can give dynamics of a system

GOING TO THE INNER PARTS



N. of photons over light-crossing time higher for AGN
But for BHBs one can go to lower frequencies
and disk is in X-rays

GOING TO THE INNER PARTS

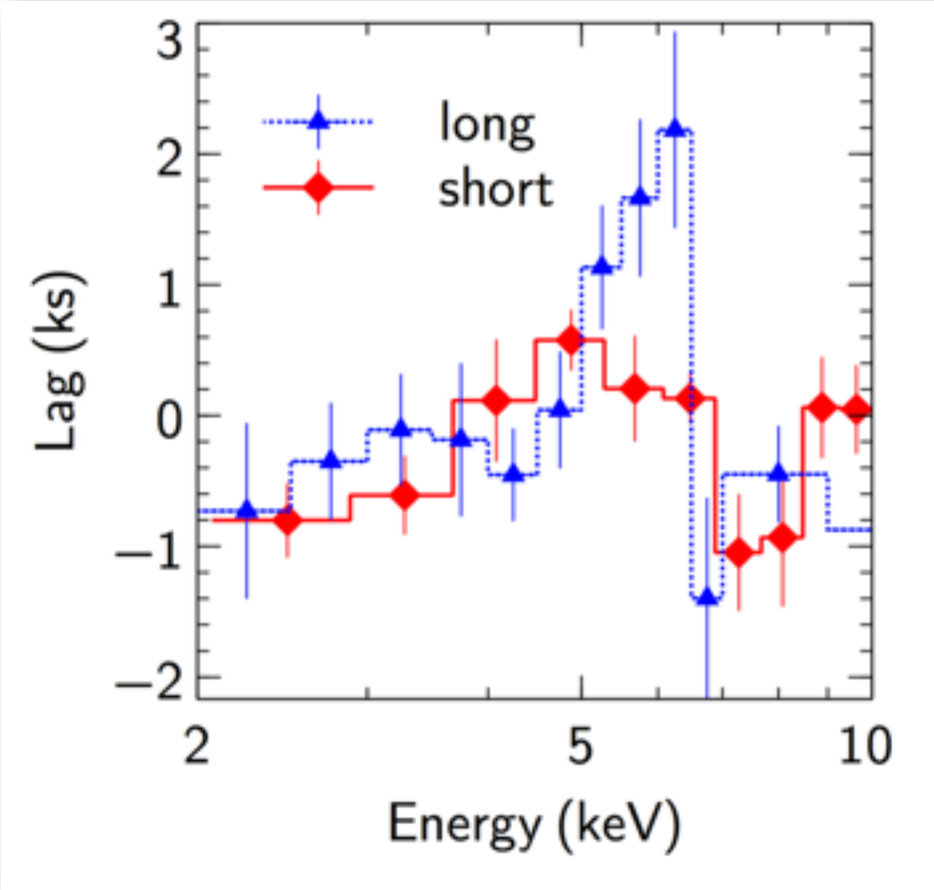


Low frequencies: hard lag ->propagation

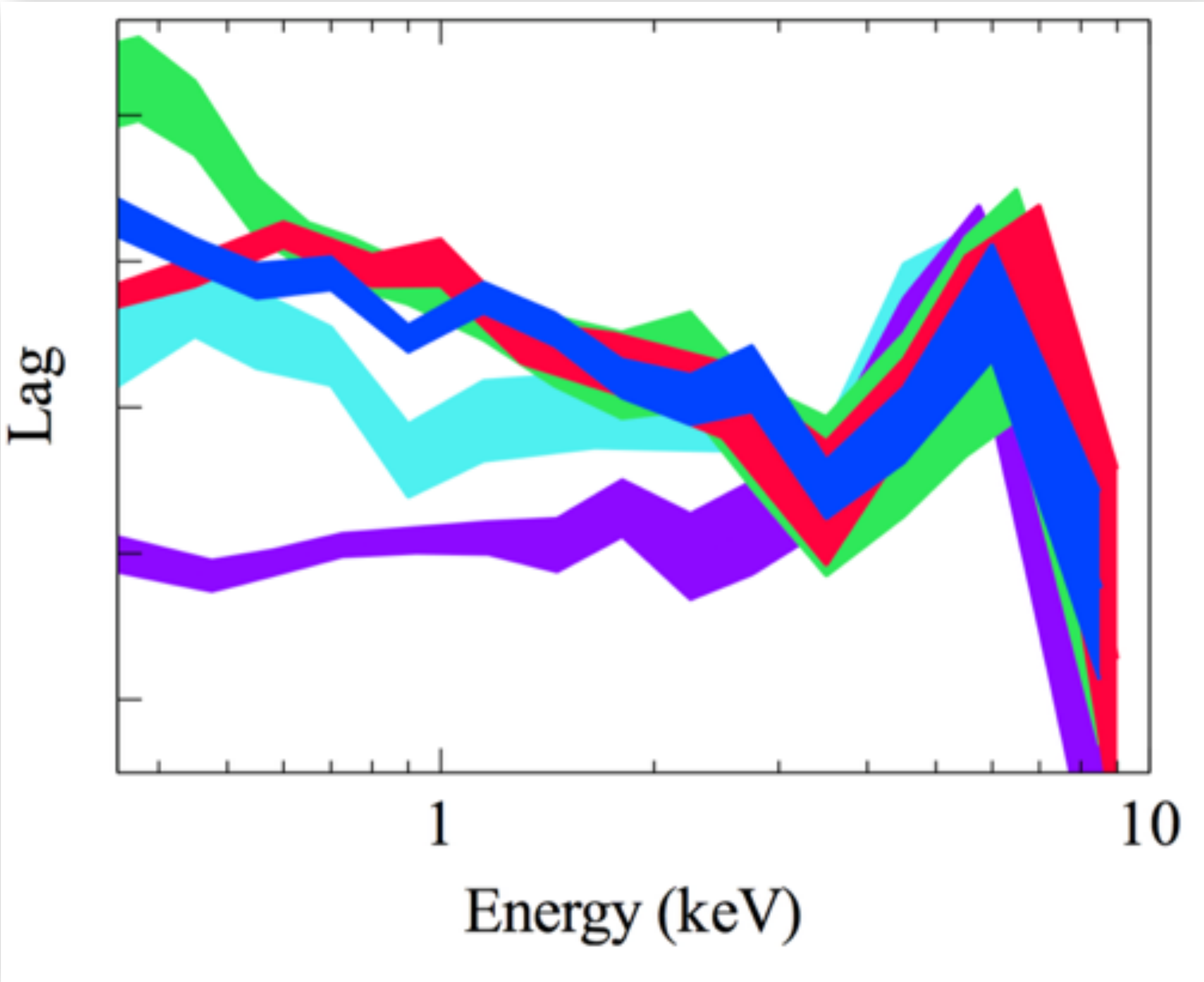
High frequencies: soft lag -> reverberation

IRON LINE COMPLEX

Clean area of spectrum

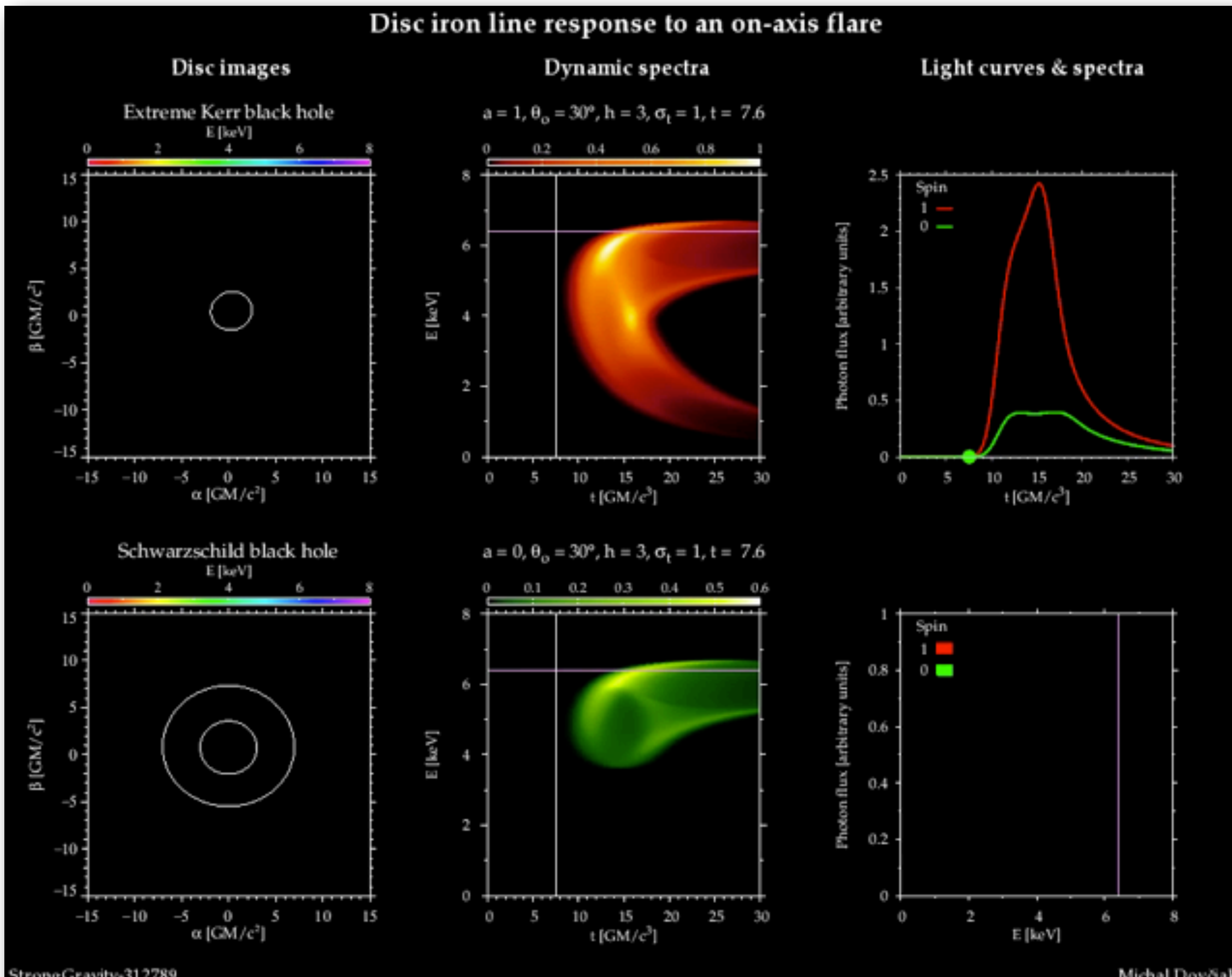


Zoghbi et al. (2012)



Uttley et al. (2014)

RESPONSE TO A FLARE



THE END