Stellar-mass black holes

Tomaso Belloni (INAF - Osservatorio Astronomico di Brera)

Bologna 2006 Sep 29

Thierry Lombry

Osservatorio Astronomico di Brera

Stellar-mass black holes

Tomaso Belloni (INAF - Osservatorio Astronomico di Brera)

Bologna 2006 Sep 29

Thierry Lombry

Outline

- X-ray binaries
- Black holes
- Accretion
- Jet ejection
- GR / Spin

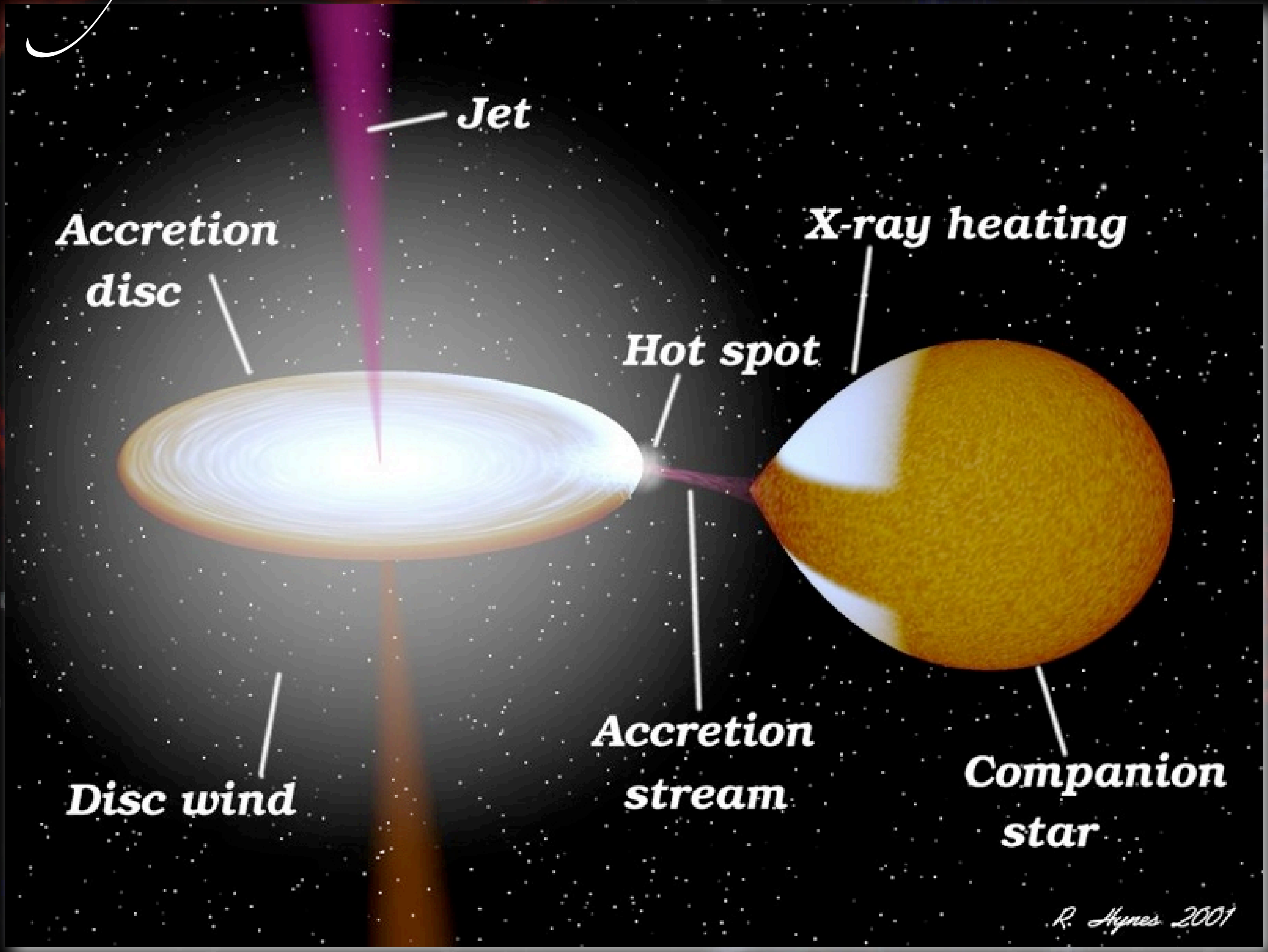
Outline

- X-ray binaries
- Black holes
- Accretion
- Jet ejection
- GR / Spin

→

- Black holes
- Neutron stars
- Accretion disk
- Jet/corona

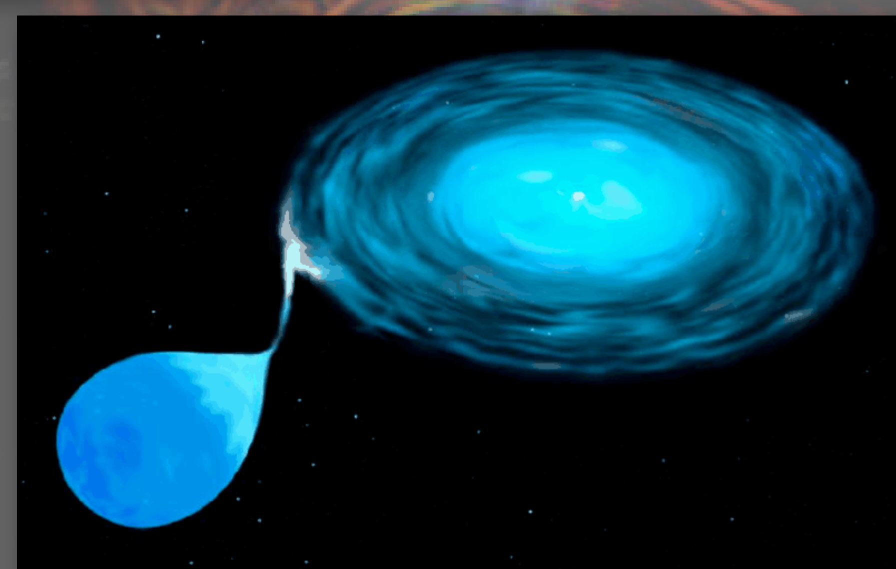
X-ray binaries



BH X-ray binaries

- No magnetic field
- None are pulsars
- Late spectral type companion (but not only)
- Accretion disk extends closer to the BH
- Inner disk region: GR effects

See neutron stars

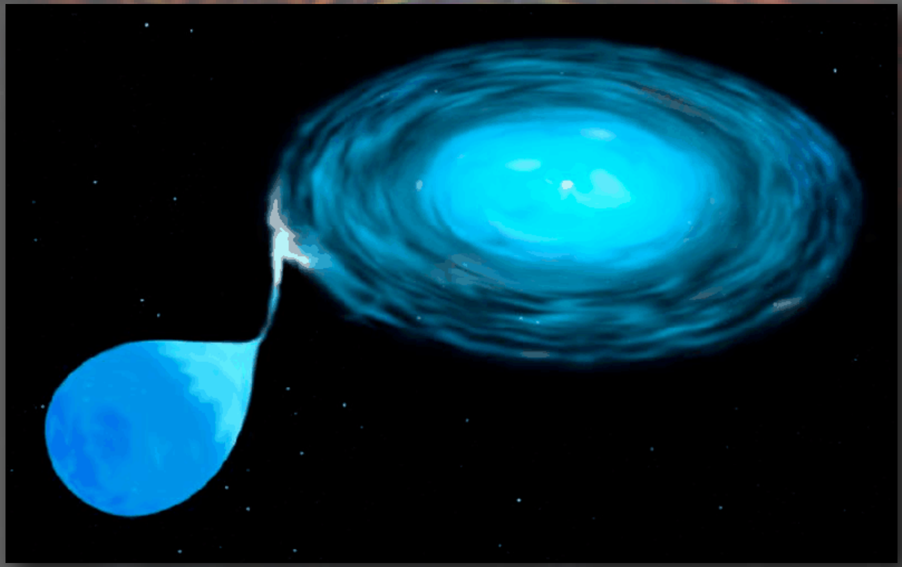


Low-B NS X-ray binaries

Osservatorio Astronomico di Brera

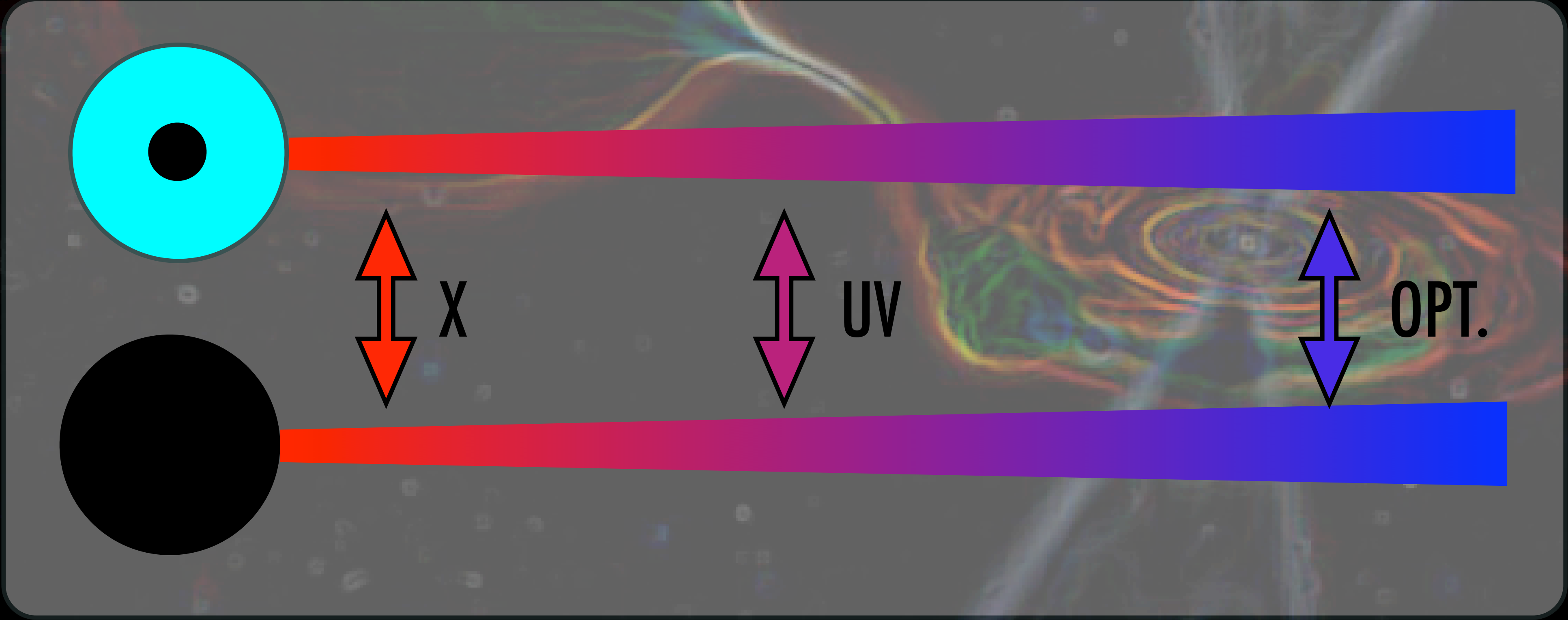
- Magnetic field 10^8-10^9 G
- Some are (ms) pulsars, most are not
- Late spectral type companion
- Accretion disk extends closer to the NS
- Inner disk region: GR effects

See black holes

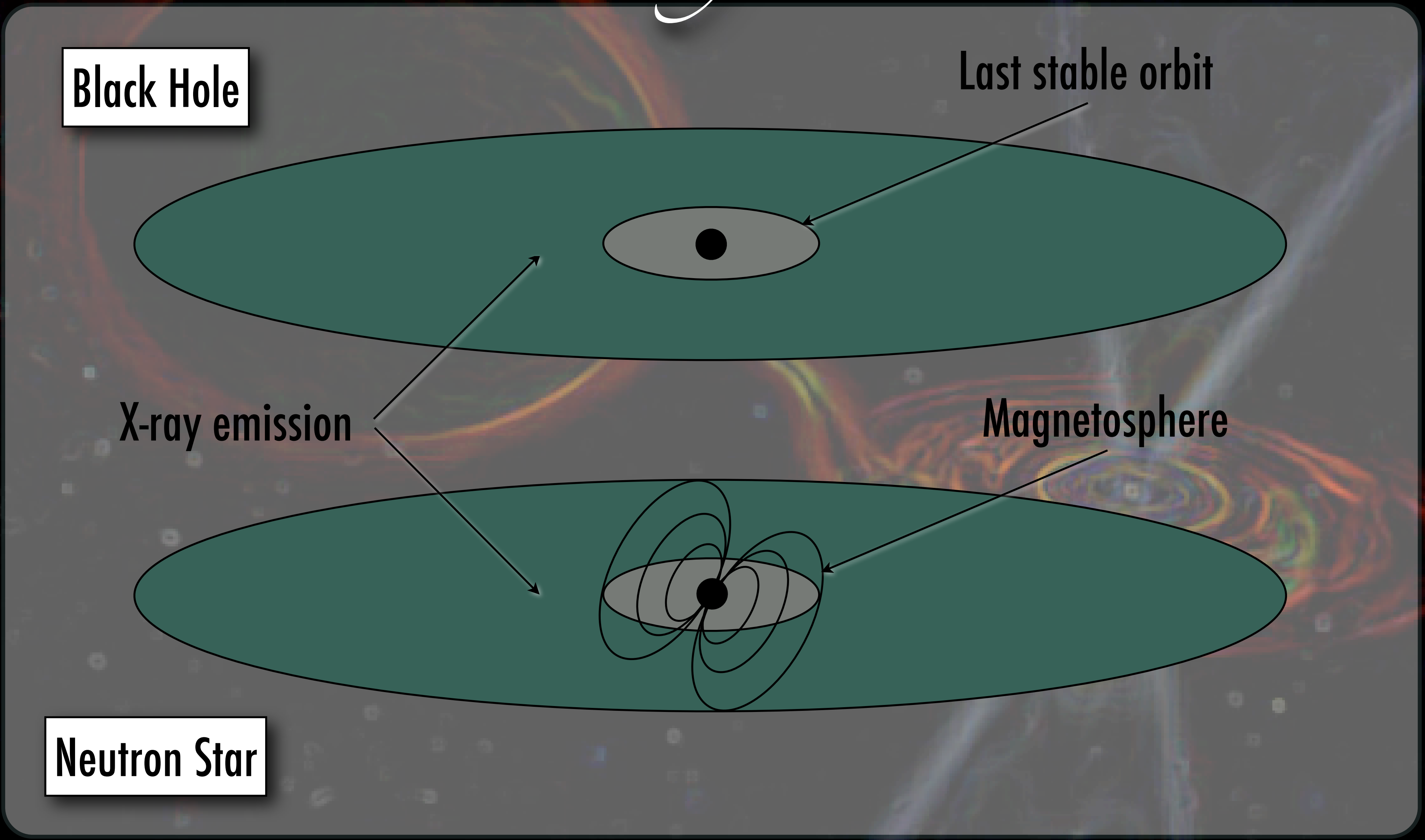


BH / NS X-ray binaries

- Accretion disk structure
- Black hole or neutron star?



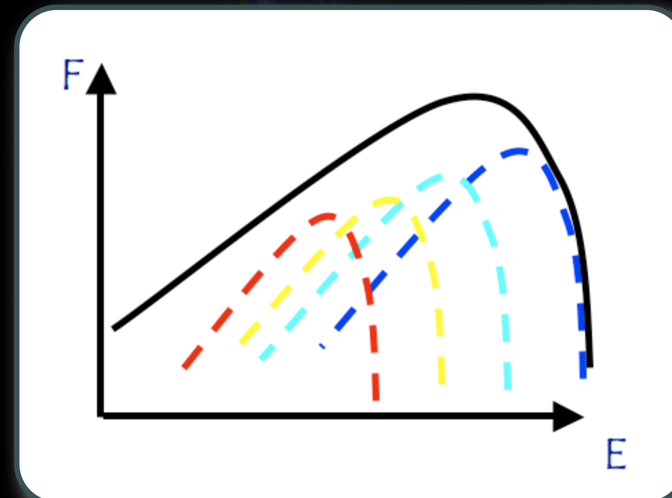
BH / NS X-ray binaries



Thin disk model

- Geometrically thin
- Optically thick
- Quiet
- Approximated as:

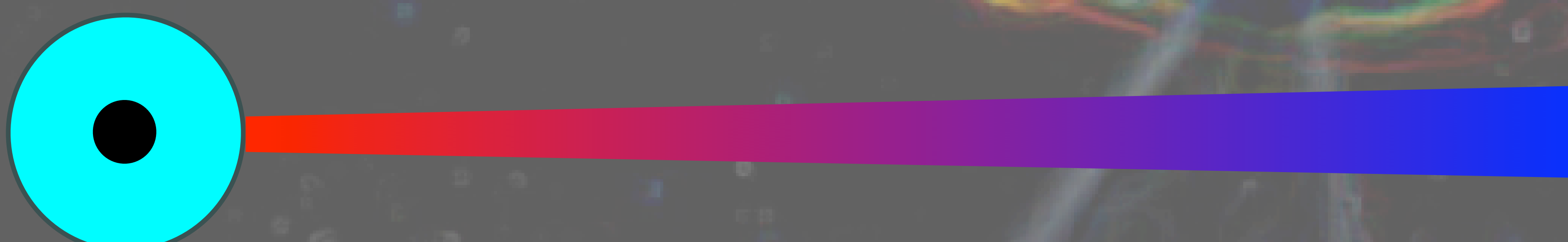
$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \sqrt{\frac{R_*}{R}} \right] \right\}^{1/4}$$



Black Holes in Binary Systems. Observational Appearance

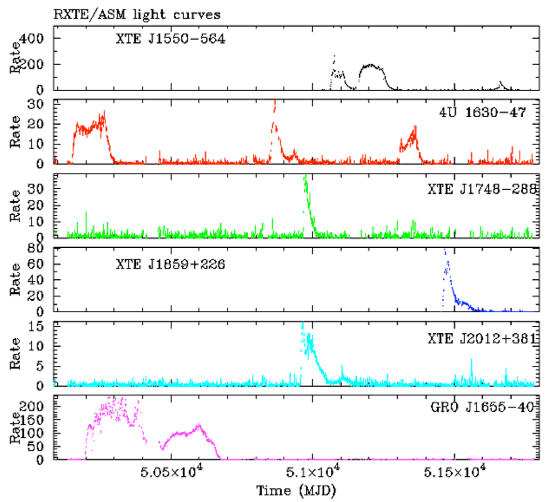
N. I. Shakura
Sternberg Astronomical Institute, Moscow, U.S.S.R.

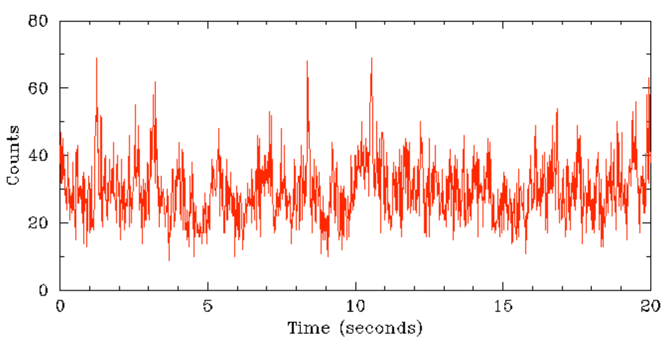
R. A. Sunyaev
Institute of Applied Mathematics, Academy of Sciences, Moscow, U.S.S.R.

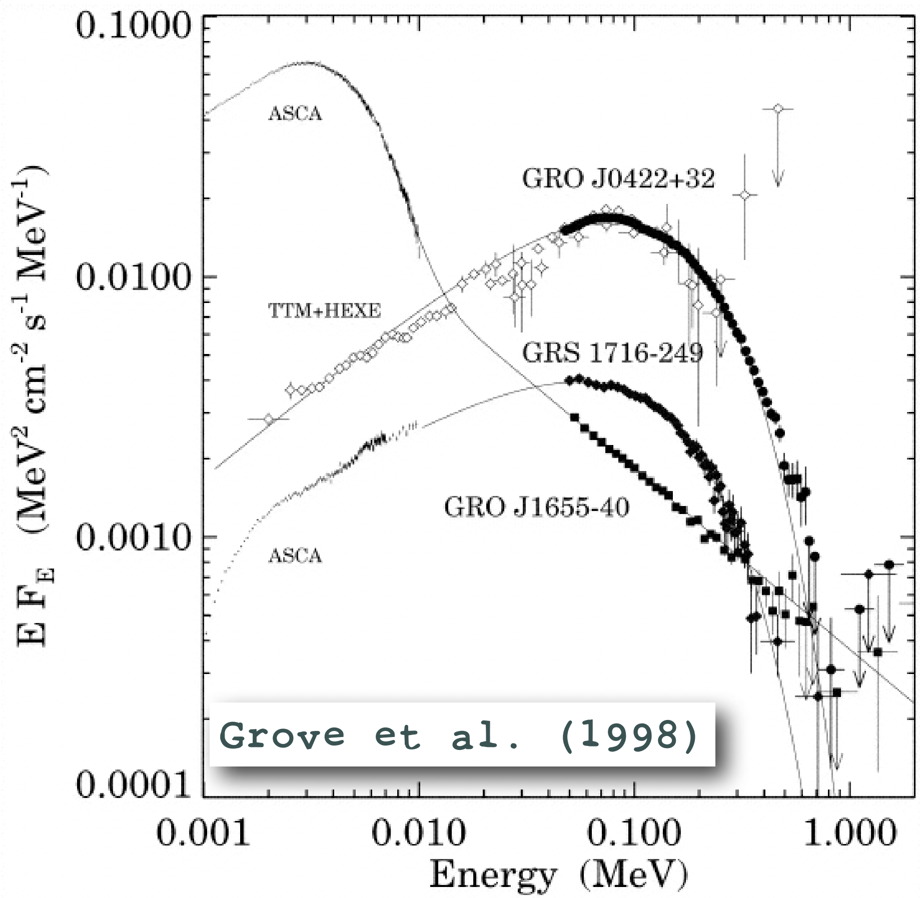


Reality

- High variability on all time scales
- Complex and hard spectrum







Outline

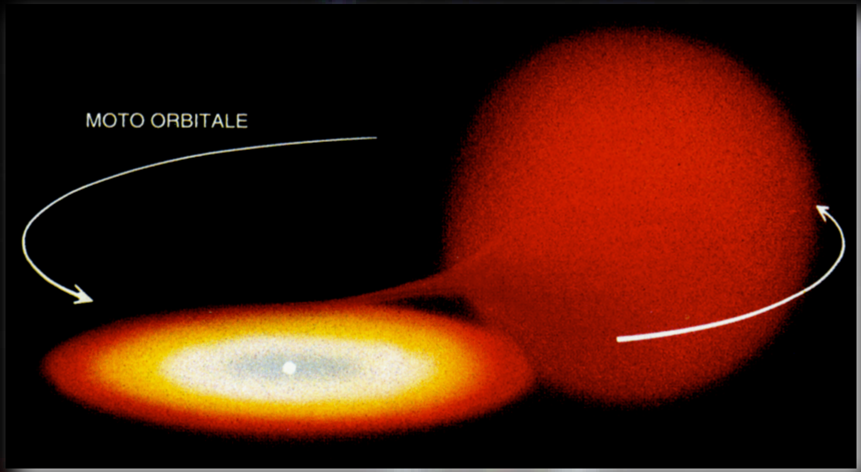
- X-ray binaries
- Black holes
- Accretion
- Jet ejection
- GR / Spin

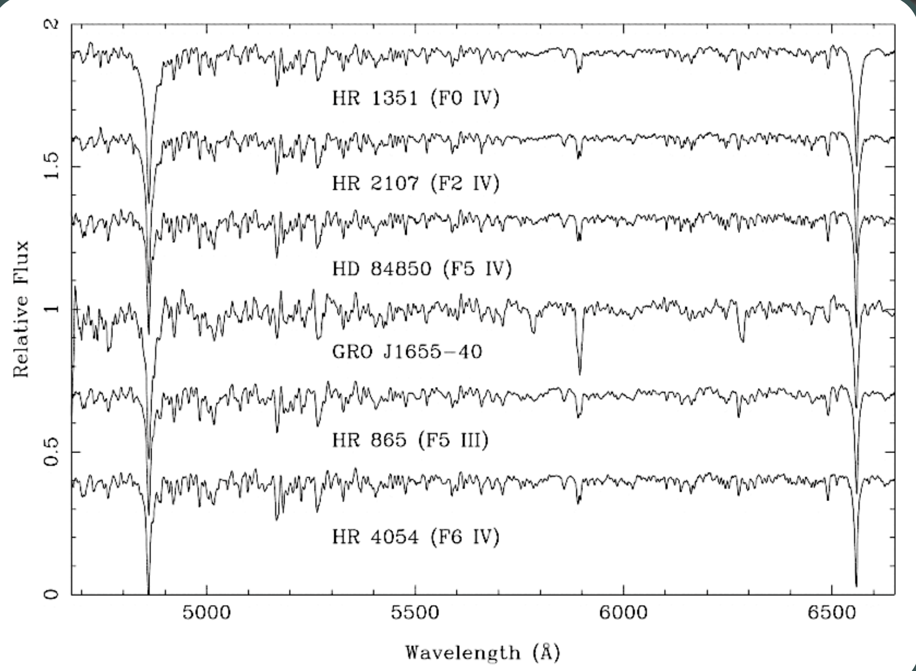
→

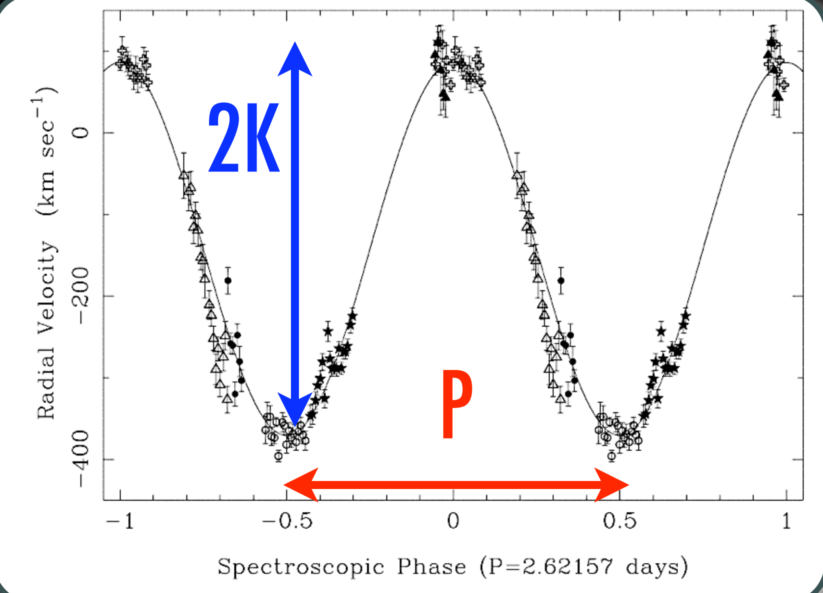
- Black holes?
- Mass
- Dynamical
- Others??

Dynamical mass

- Take a transient system
- Wait for quiescence
- Measure optical spectrum
- Obtain mass function

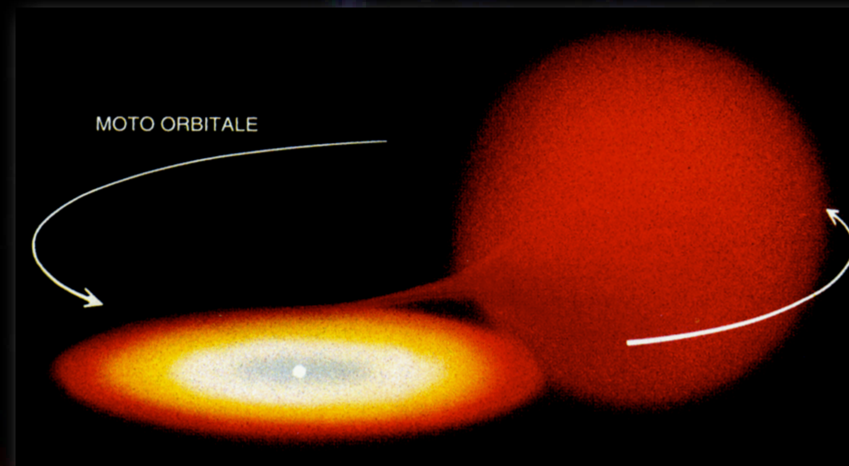


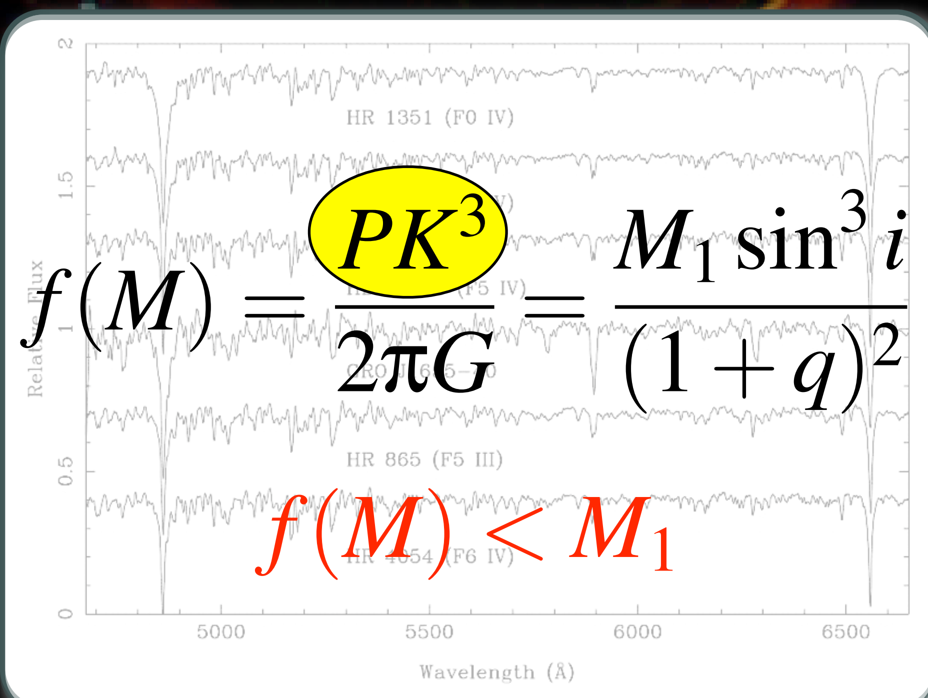




Dynamical mass

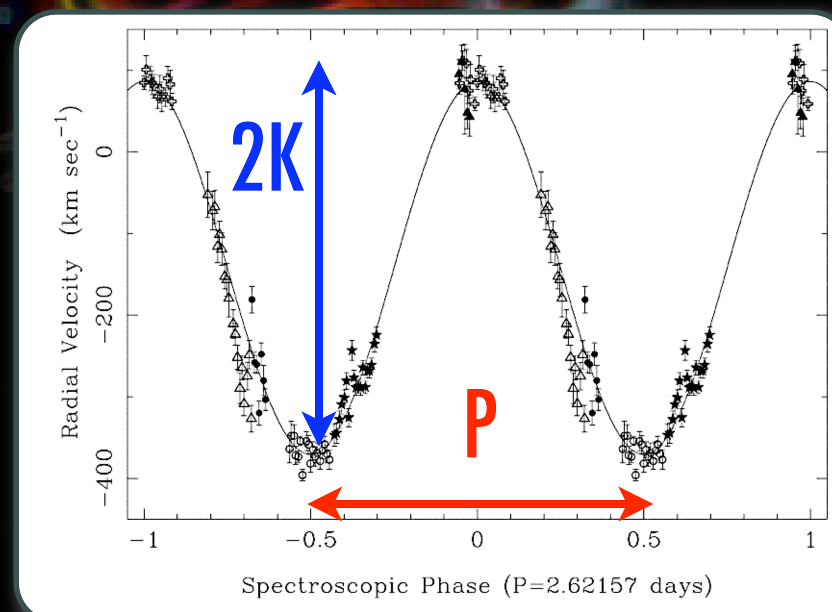
- Take a transient system
- Wait for quiescence
- Measure optical spectrum
- Obtain mass function



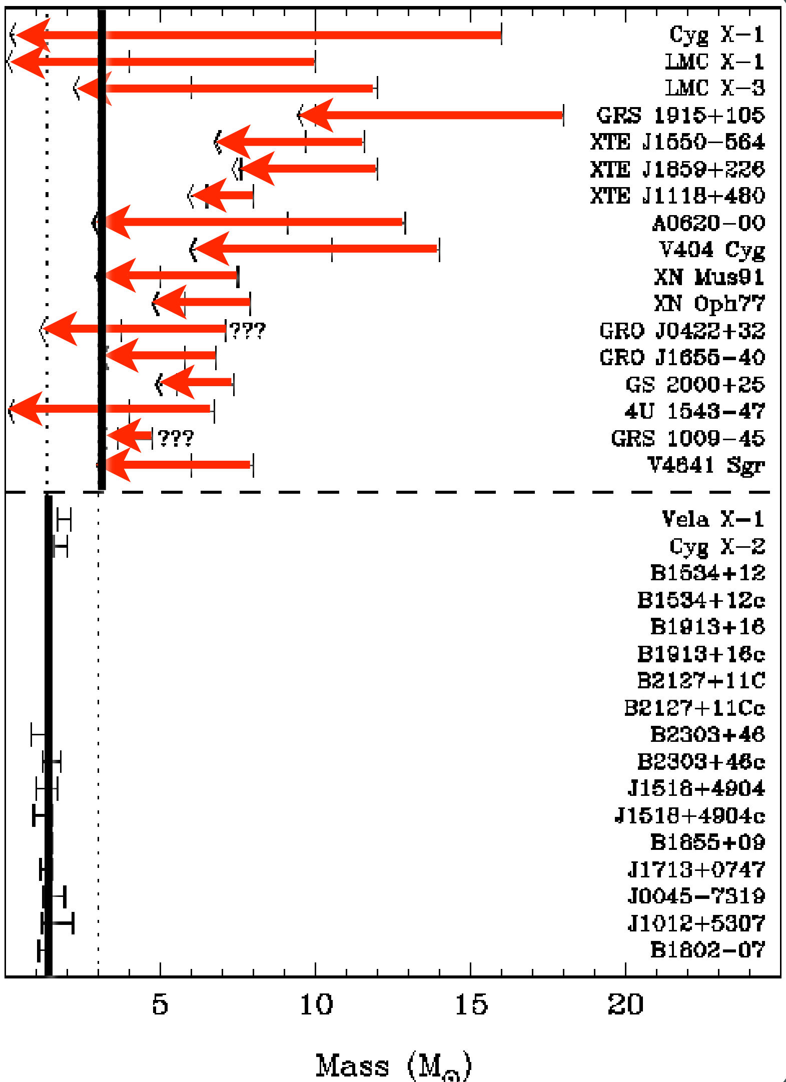


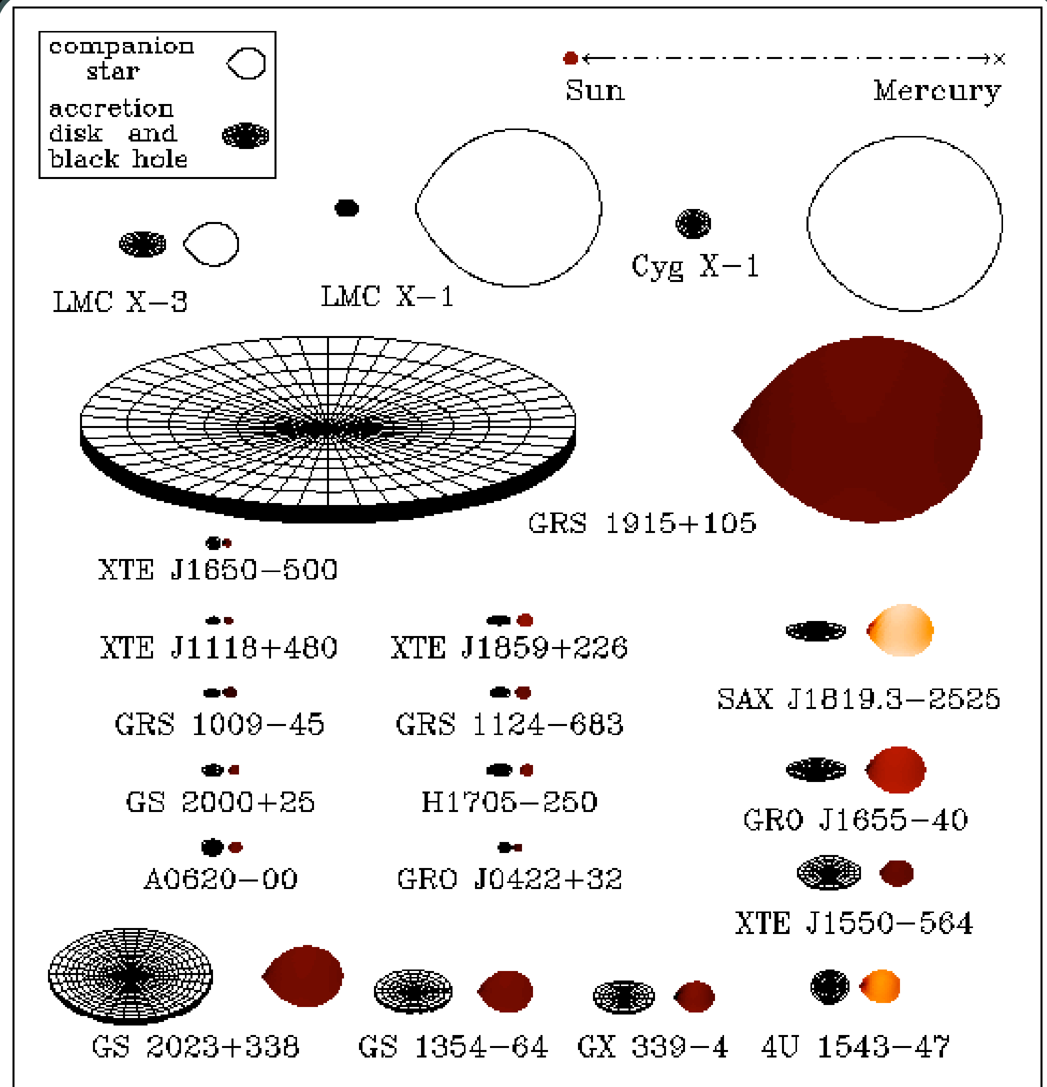
$$f(M) = \frac{PK^3}{2\pi G} = \frac{M_1 \sin^3 i}{(1+q)^2}$$

$$f(M) < M_1$$



Black-hole binaries





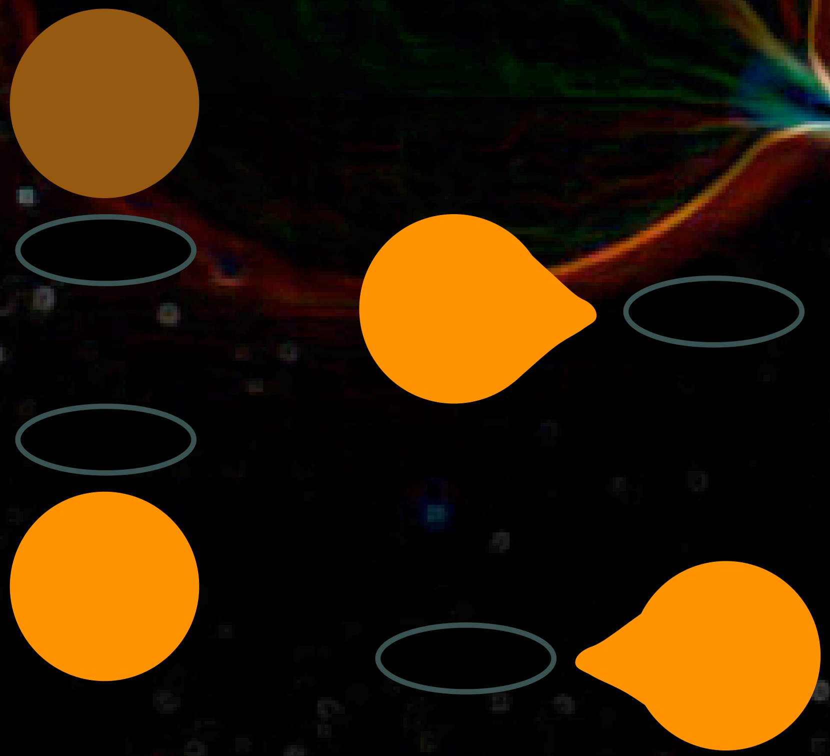
Actual mass measurement

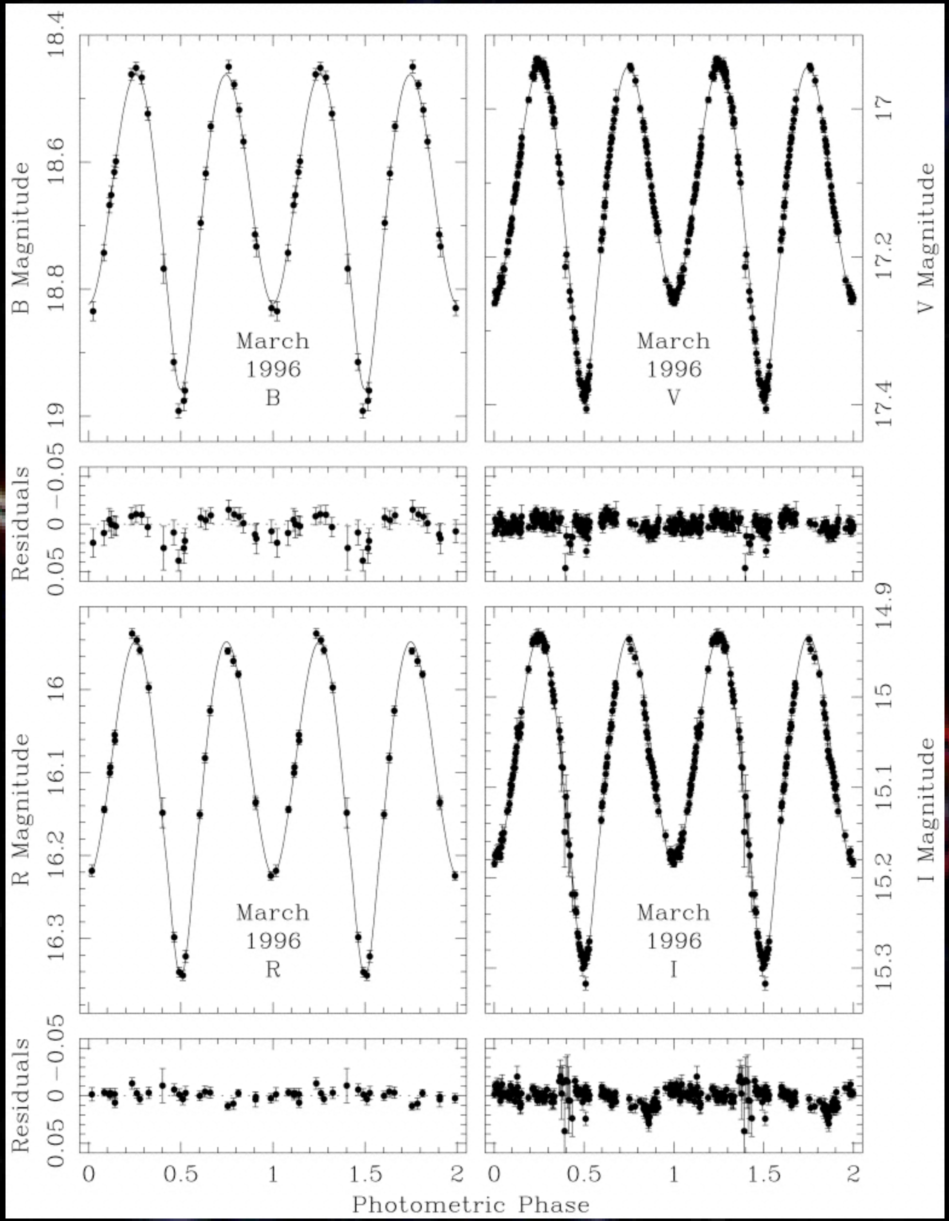
- *q* and *i* needed
- Mass ratio:
  - estimate from spectral type
  - emission lines from accretion disk
  - photometric data
- Inclination:
  - external info (jet inclination?)
  - photometric data

✔ We need photometric data (in quiescence!)

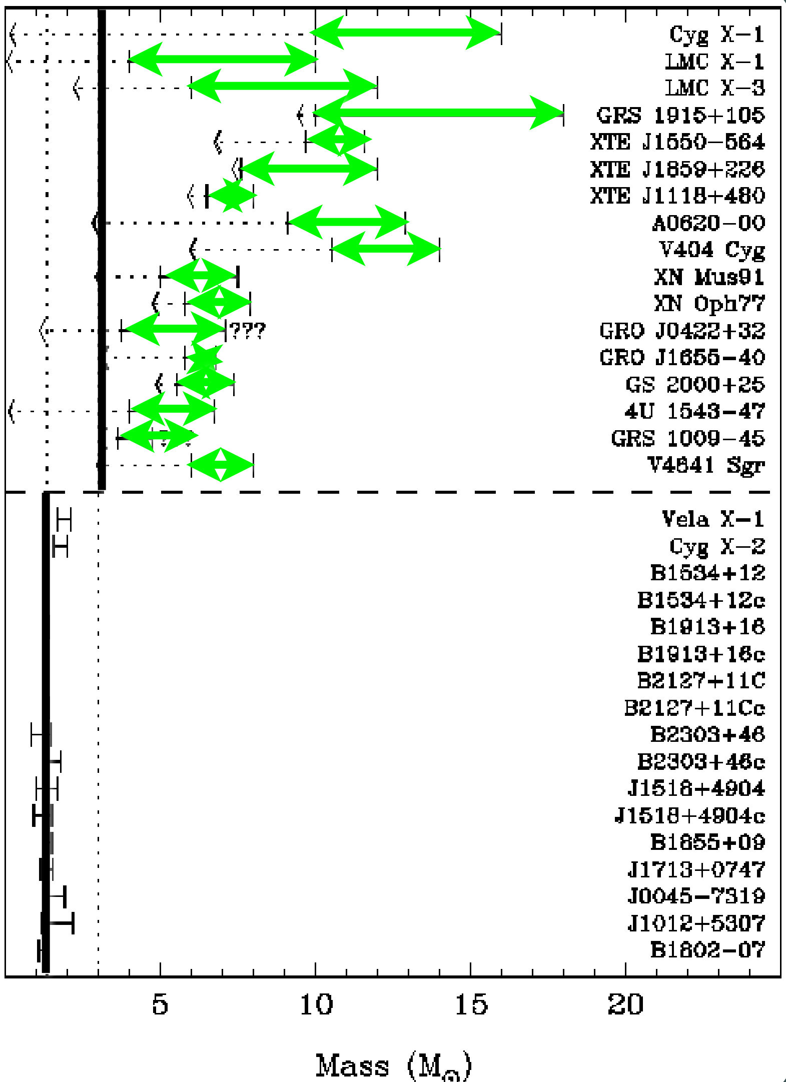
Photometric data

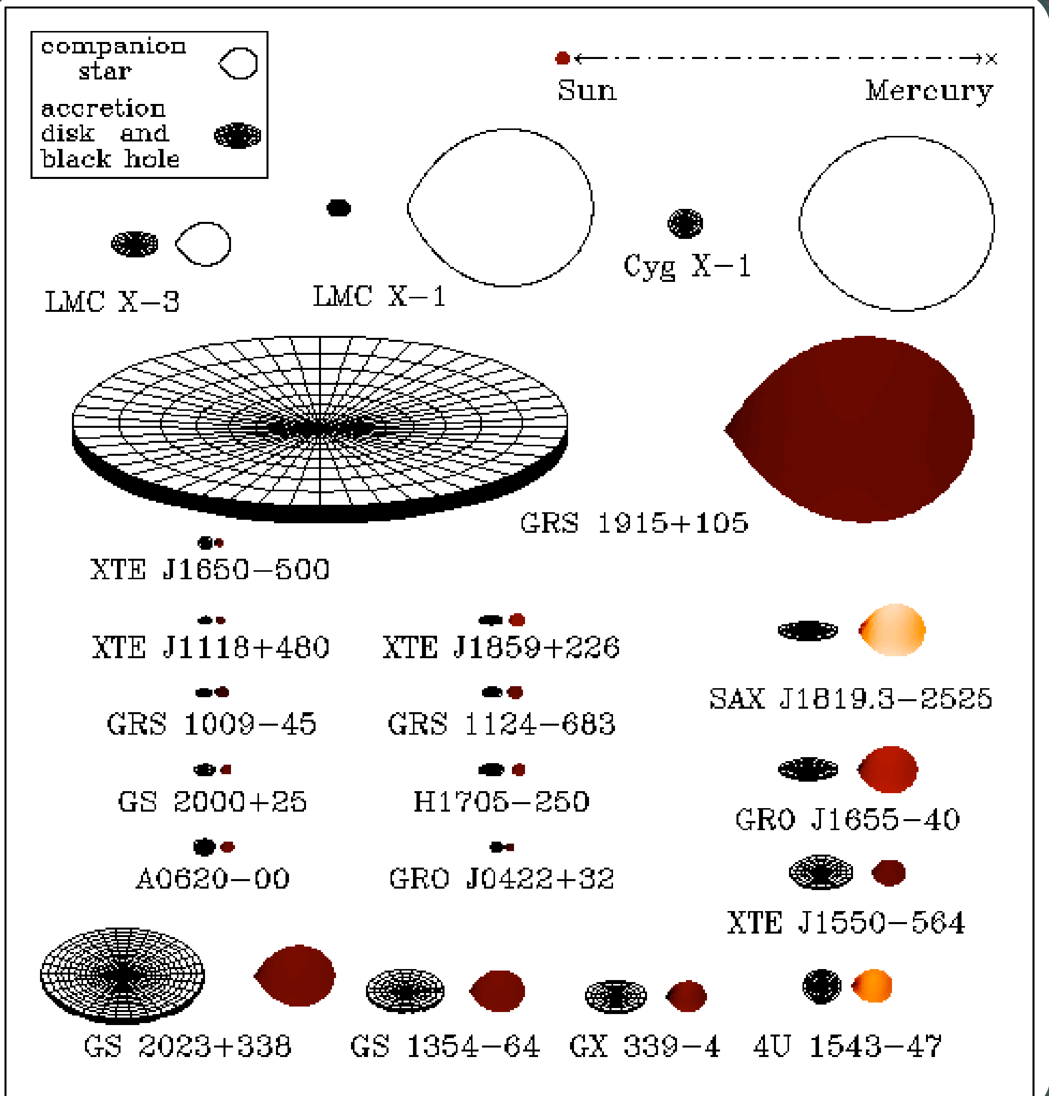
- Optical light curves
- Ellipsoidal variations
- Complications





Black-hole binaries

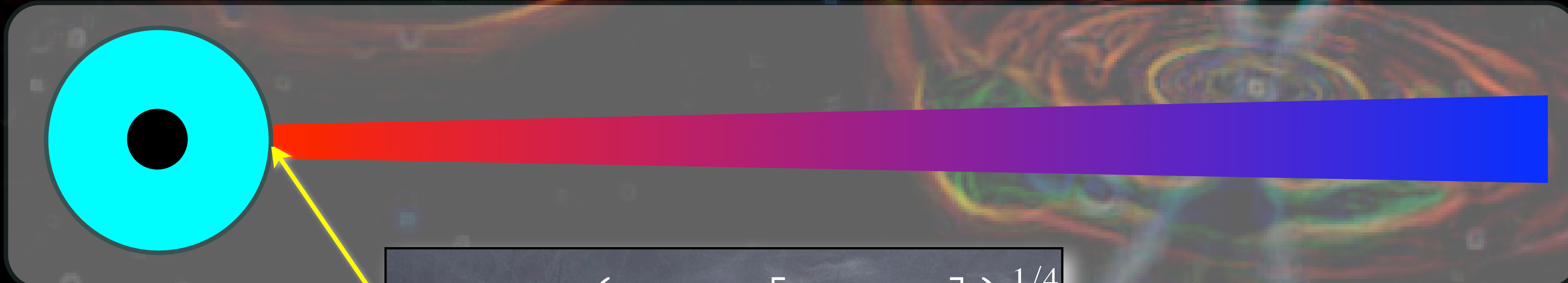




Direct methods

- *Ultra-soft* X-ray spectrum
- Hard spectral tail
- Strong aperiodic noise
- Inner radius of accretion disk

None works!



$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \sqrt{\frac{R_*}{R}} \right] \right\}^{1/4}$$

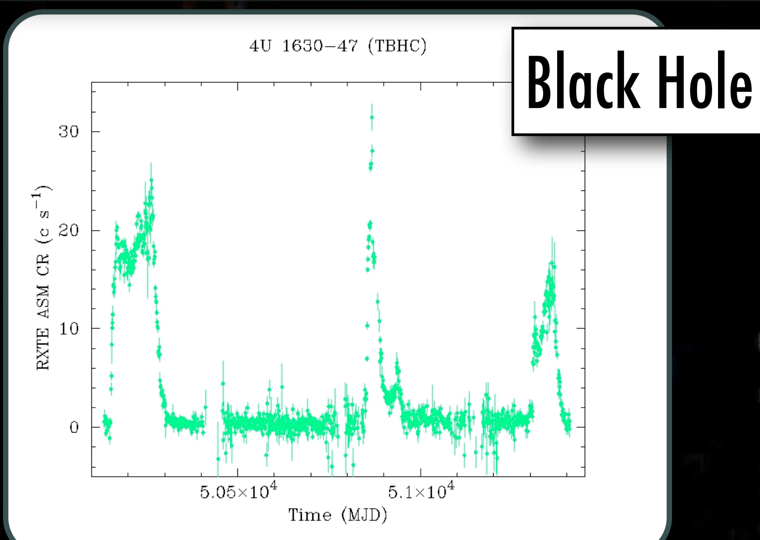
Outline

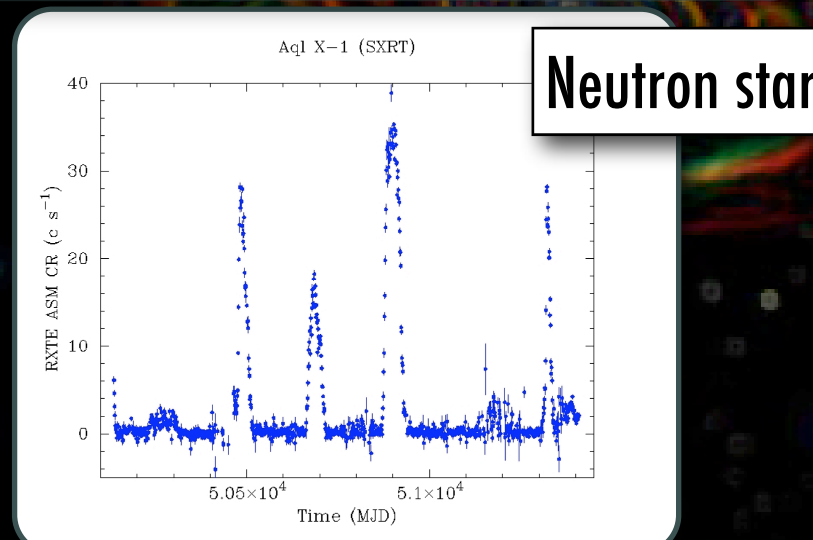
- X-ray binaries
- Black holes
- Accretion
- Jet ejection
- GR / Spin

- Spectra
- Variability
- Radio/X
- States

The role of accretion rate

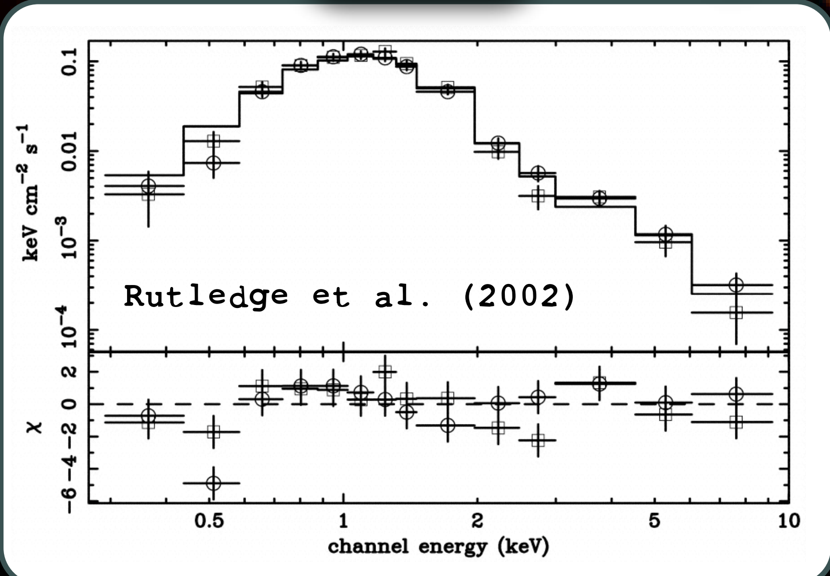
- Accretion rate as main parameter
- Many systems are observed as transients
  - Quiescence: low accretion rate ($L_X = 10^{30\text{-}33}$ erg/s)
  - Outburst: large accretion rate ($L_X = 10^{37\text{-}39}$ erg/s)
  - Important to study accretion rate range





BH/NS in quiescence

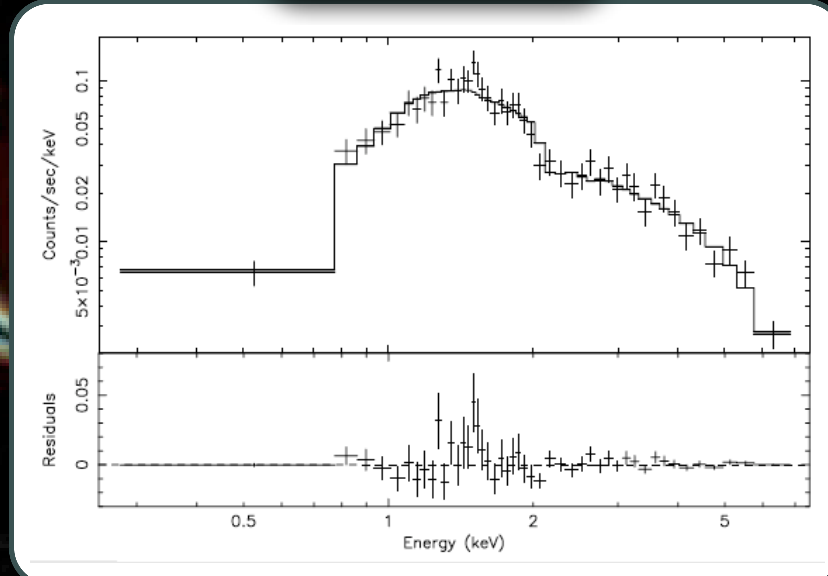
NS: Aql X-1



- "Canonical" NS spectrum
- BB/NS Atm., kT=0.1-0.3 keV

  plus
- Power law, photon index 1-2

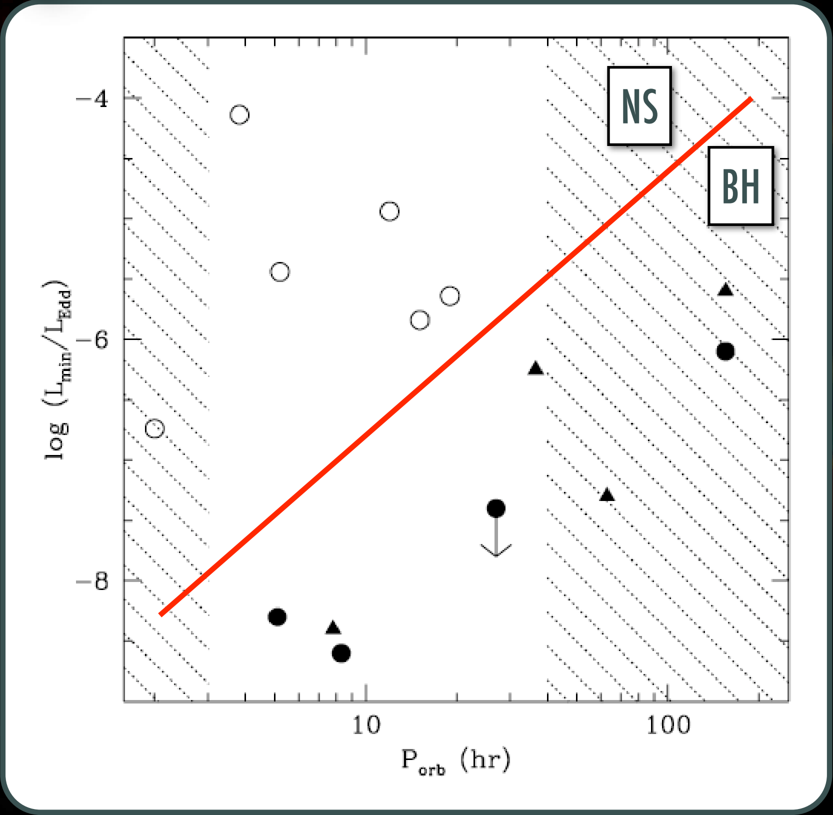
BH: GS 2023+338



- BHC spectrum
- Power law, photon index 1-2

  or
- Optically thin plasma, kT=2-3 keV

Quiescent luminosity

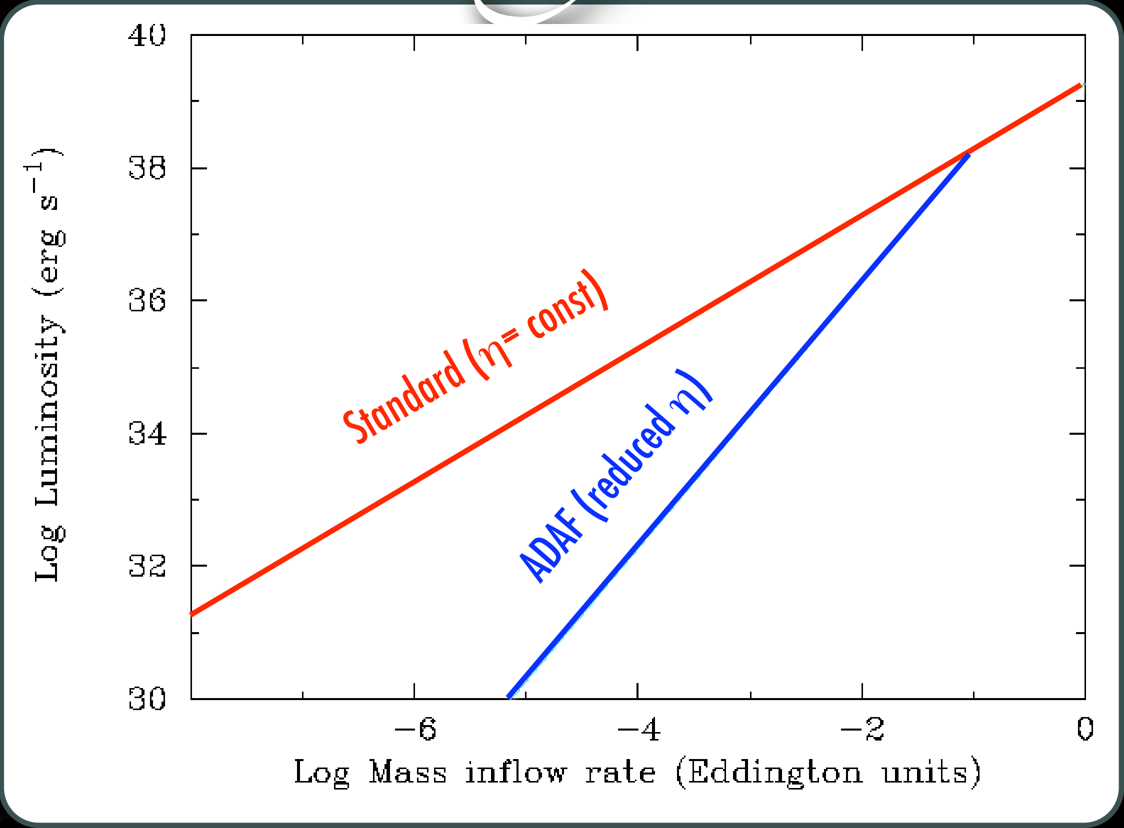


- Clear segregation in L_X
- Larger min-max L swing in BH than NS

Similar binaries: similar swing in mass inflow rate expected

Different mass-to-radiation conversion efficiency?

Advection flows



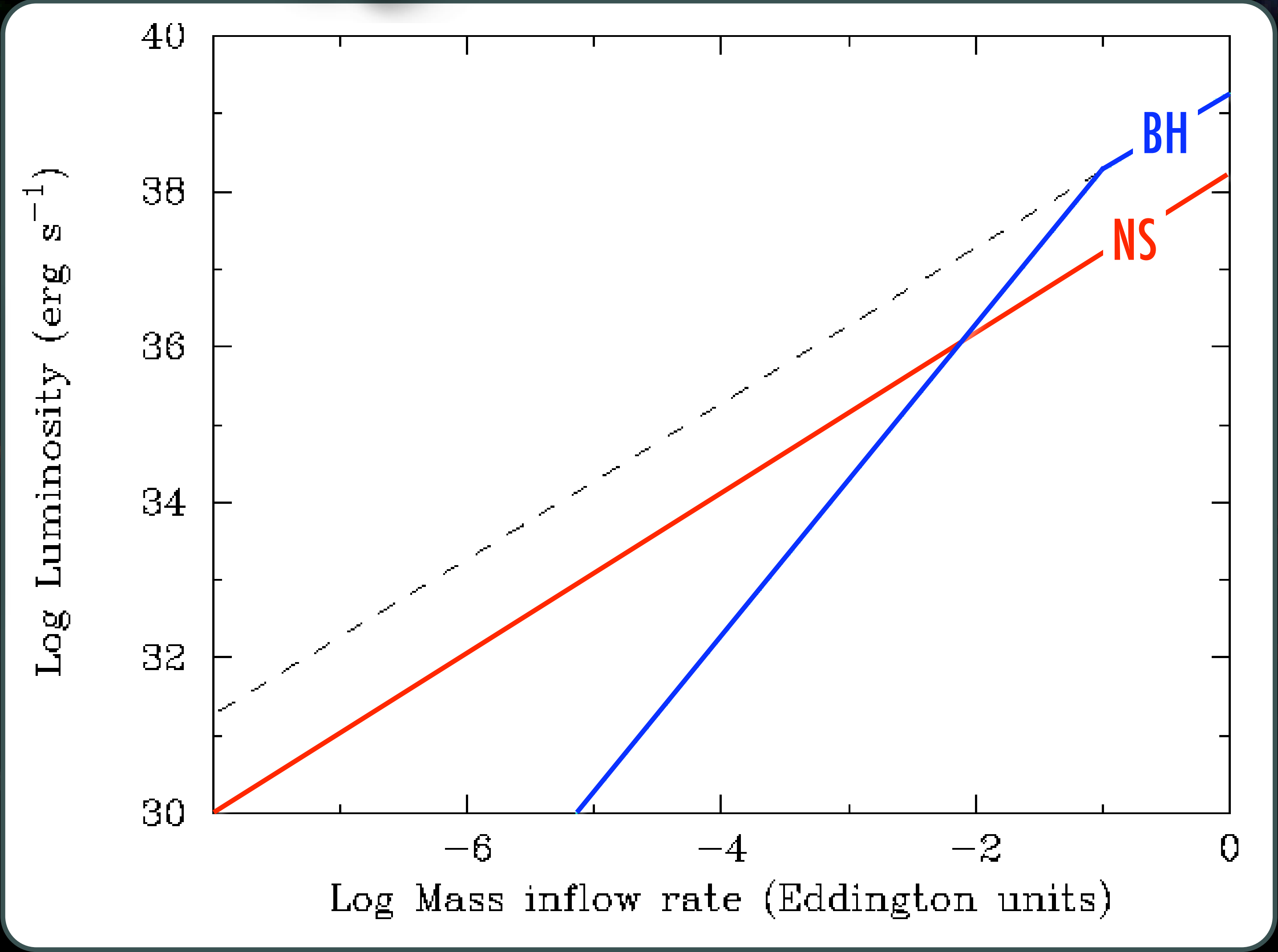
$L = \eta \dot{M} c^2$ mass-to-radiation conversion efficiency

For low rates, increasing fraction of energy stored in the accretion flow

- In BH: energy "lost" in the horizon (reduced efficiency)
- In NS: energy is release at the surface (standard efficiency)

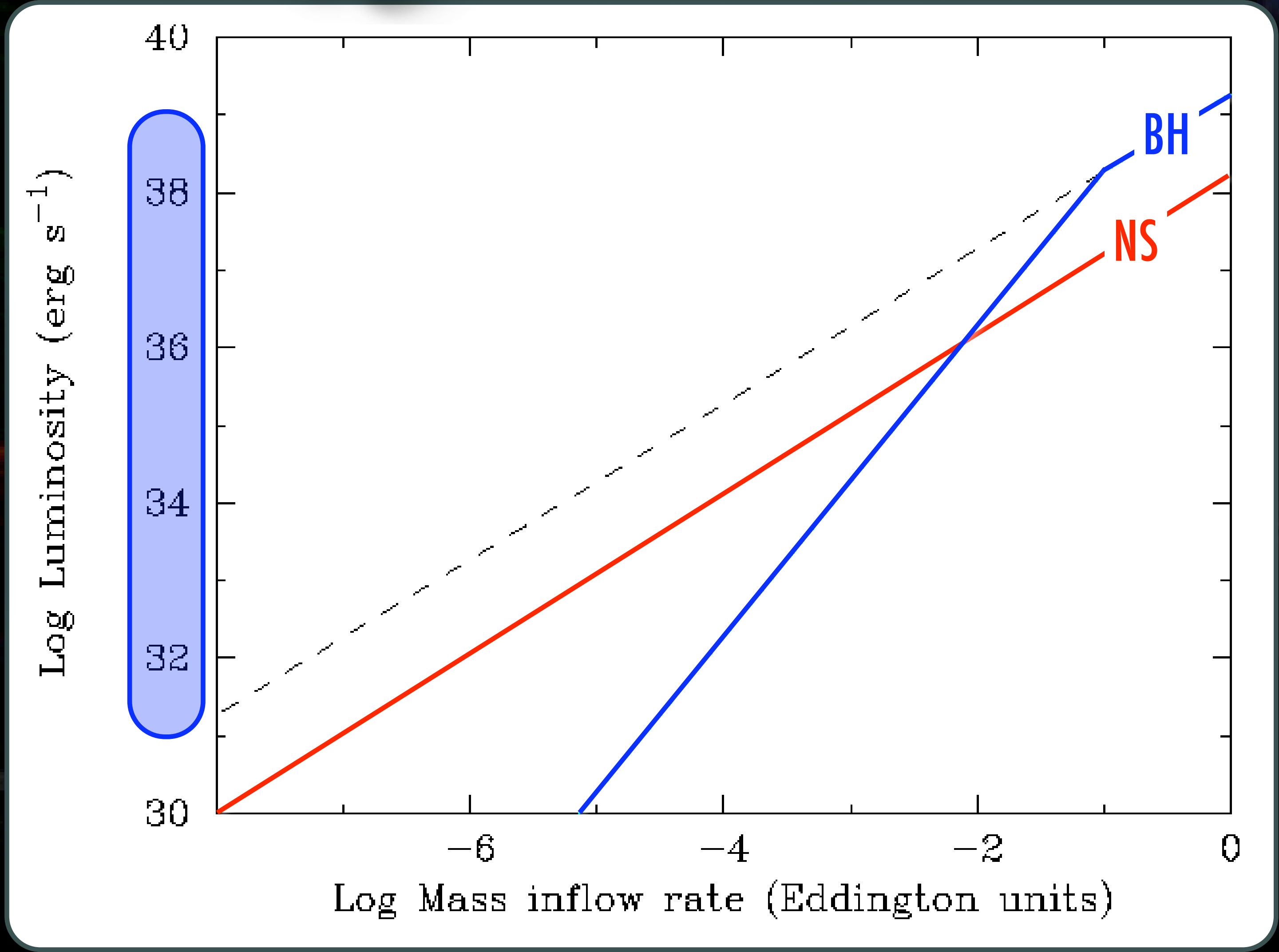
The larger swing for BH

Something more is needed



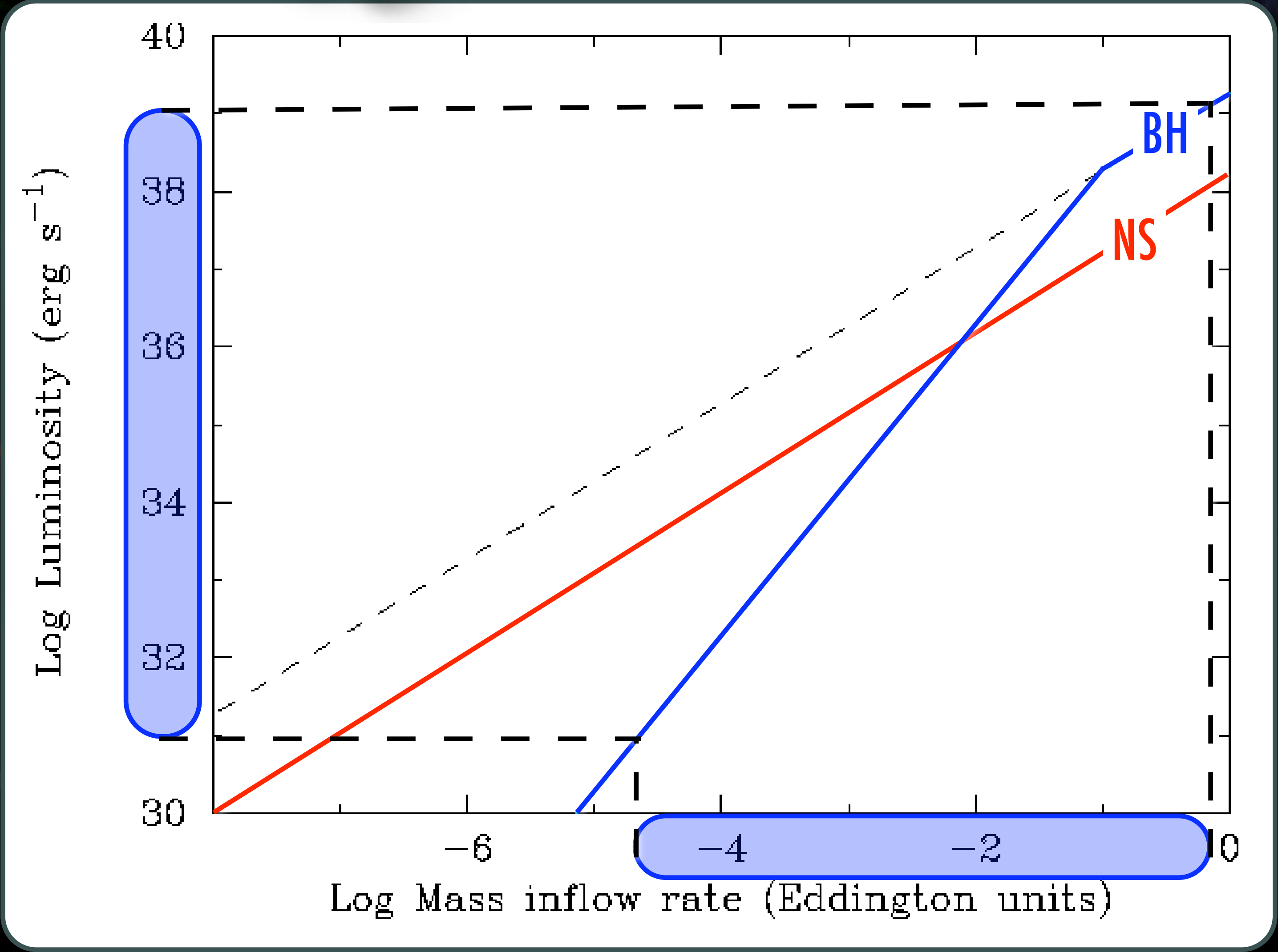
The larger swing for BH

Something more is needed



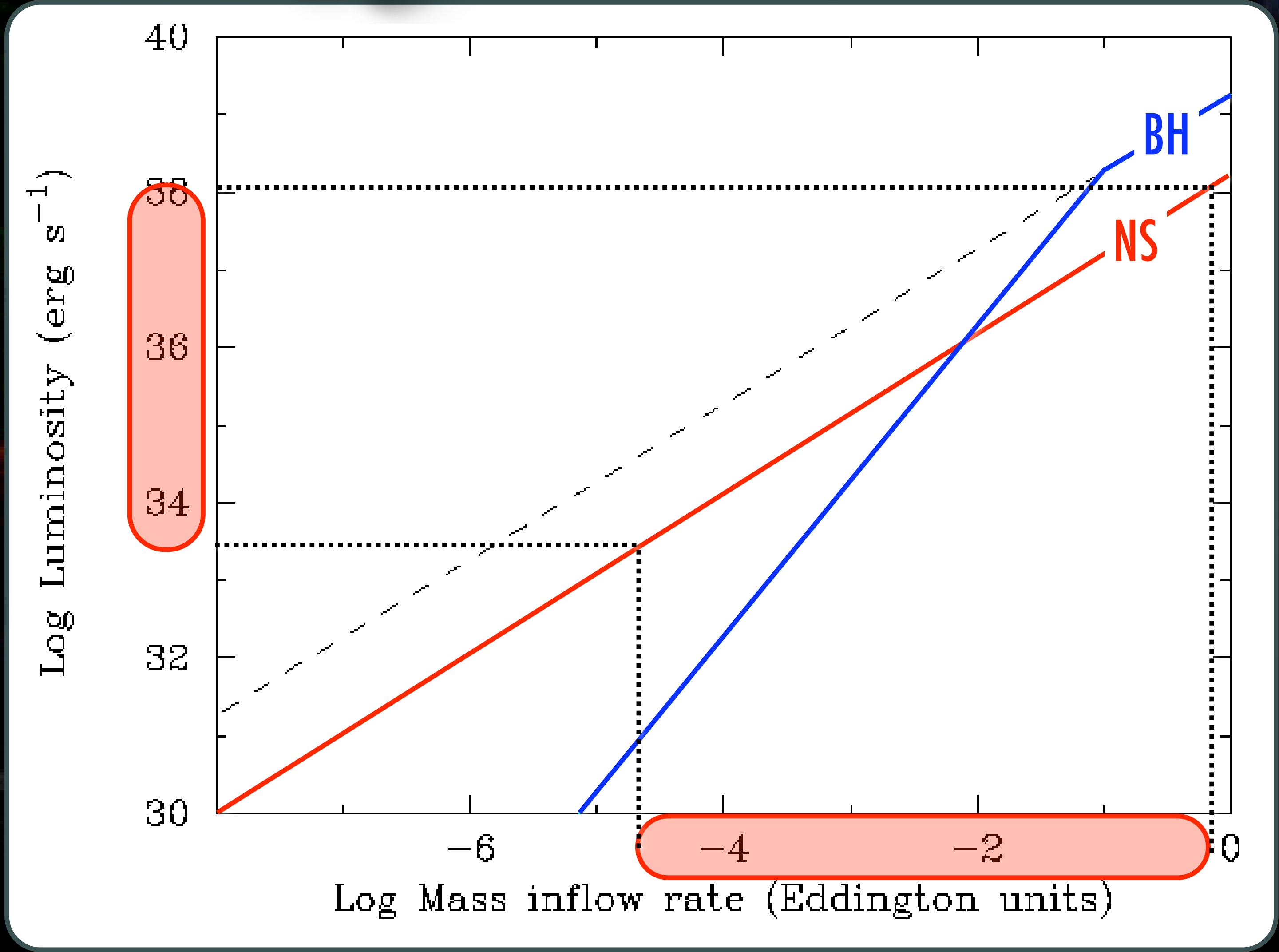
The larger swing for BH

Something more is needed

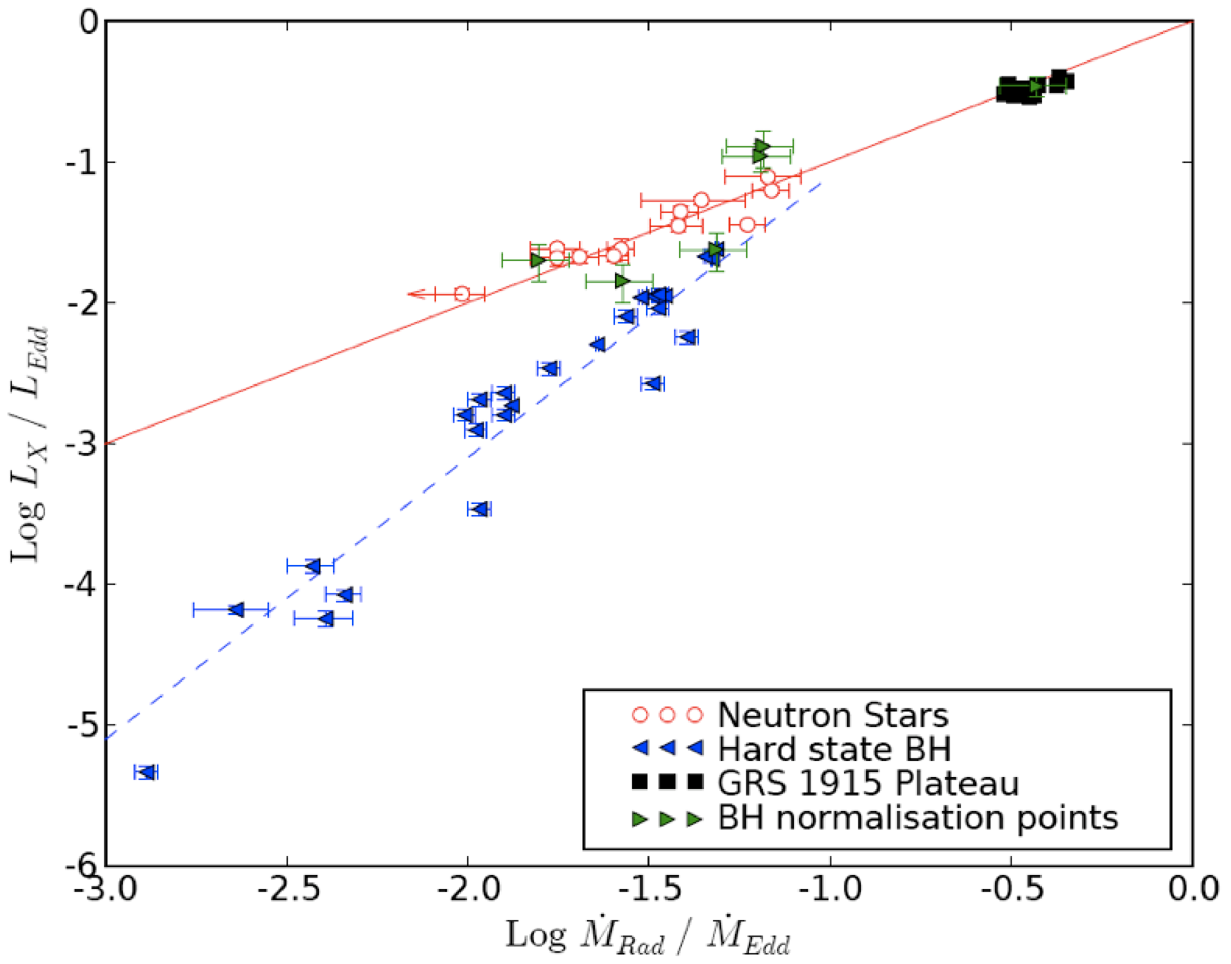


The larger swing for BH

Something more is needed



Jet-dominated advective flows



Körding et al. (2006)

Accretion rate from radio

$$L_{rad} \propto \dot{M}^{1.4}$$

Independent of X rays

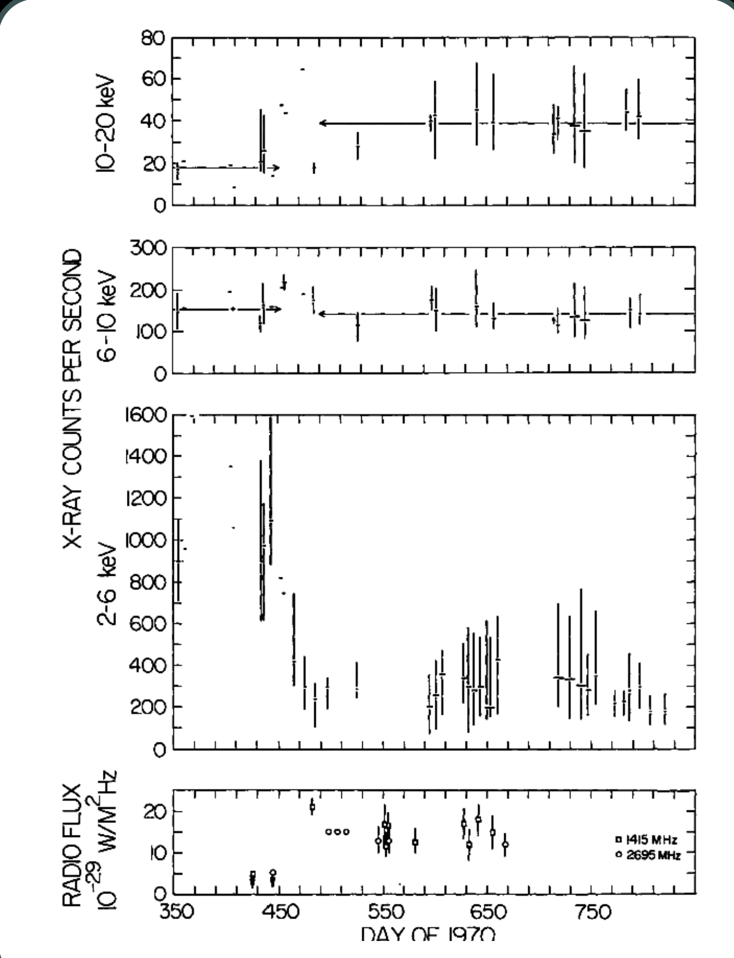
Soft and Hard States

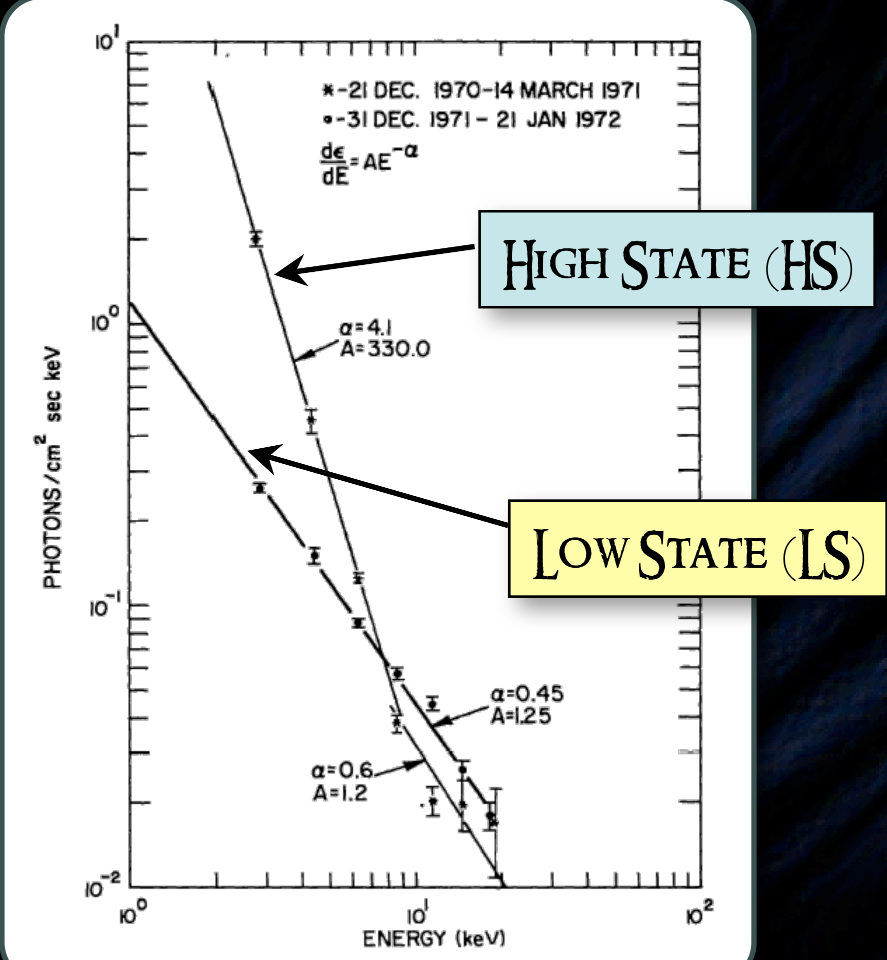
- Two main states are well studied
  - Hard State
  - Soft State
- Do they have anything in common?
- Spectra, variability, jet properties

Soft and Hard States

- Known since Uhuru

Tananbaum et al. (1971)



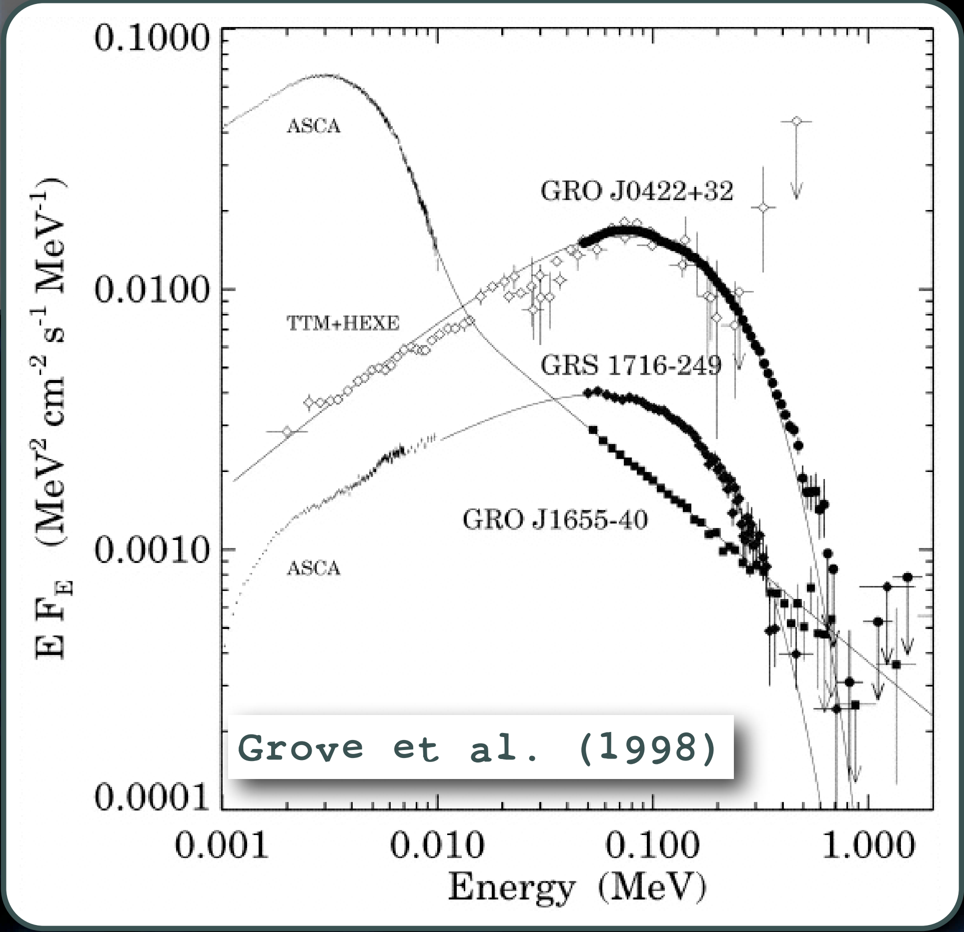


Energy Spectra

- Hard State: hard (Comptonization?) component, very soft (if any) disc
- Soft State: S&S disk + weak steep power law

Cutoff vs. no cutoff

Same component?

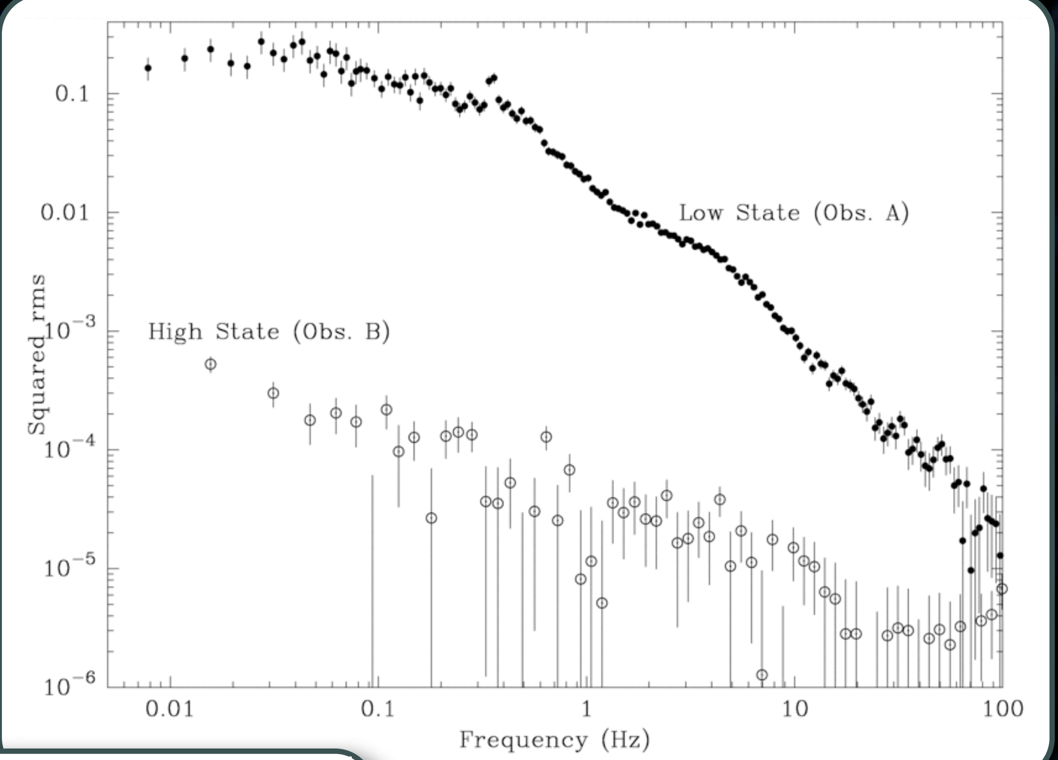


Fast Timing Properties

- Hard State: very strong (30-50%) noise, low-frequency QPOs
- Soft State: weak power law

Disc should not be noisy

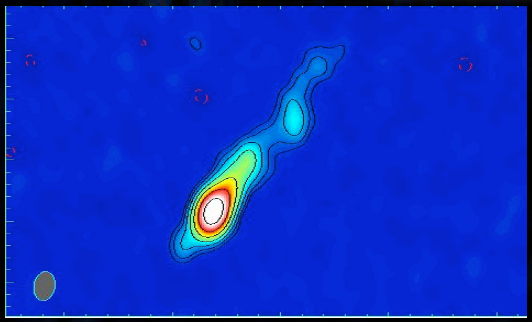
Same component?

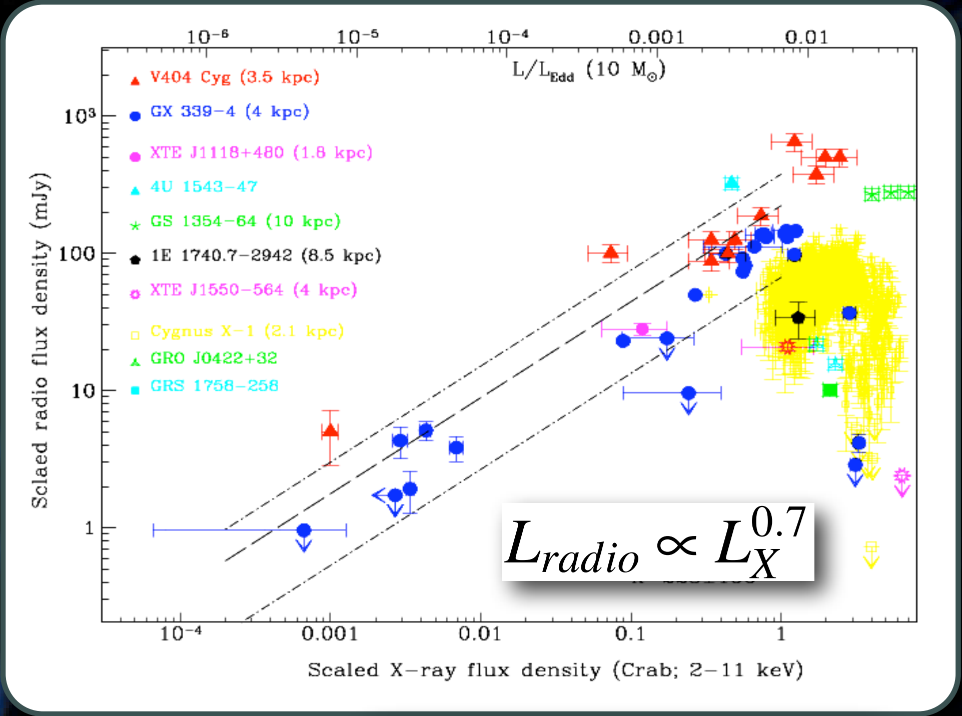


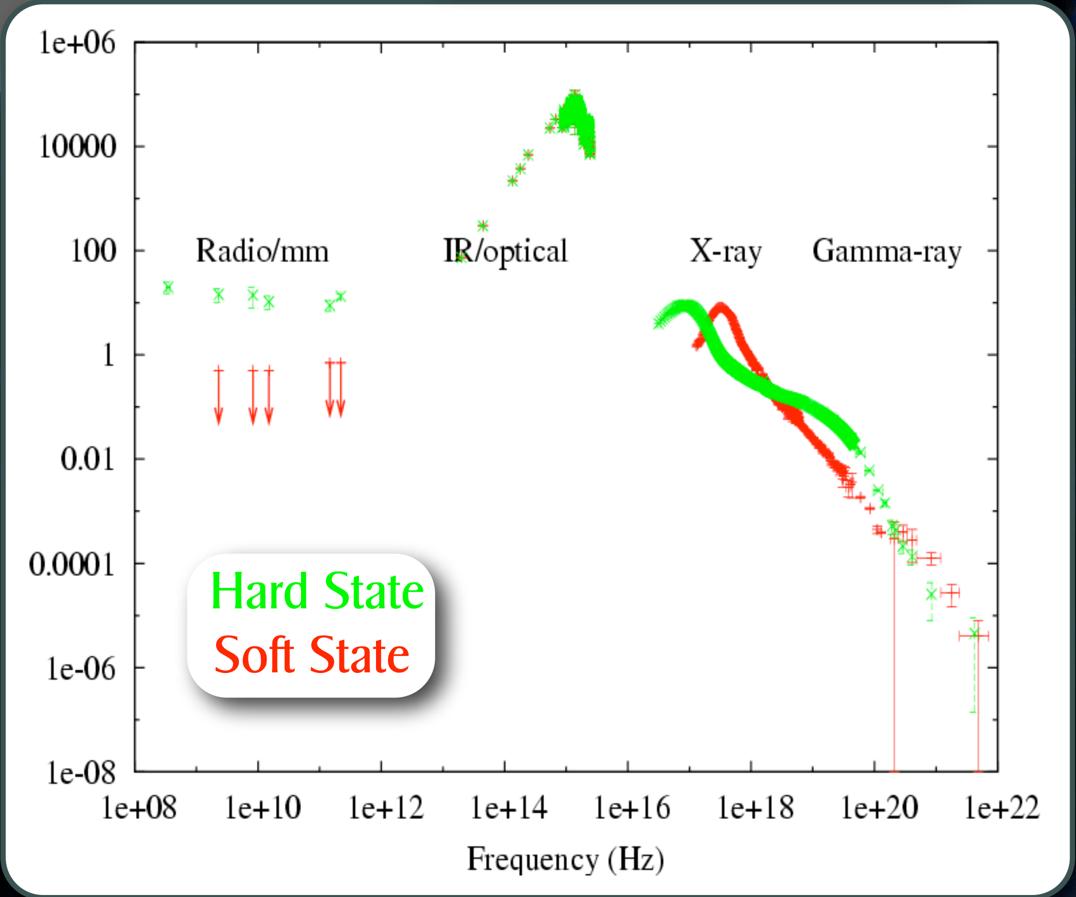
Belloni et al. (1999)

Radio Properties

- Hard State: radio emission, compact jets
- Soft State: radio quiet - no jet?



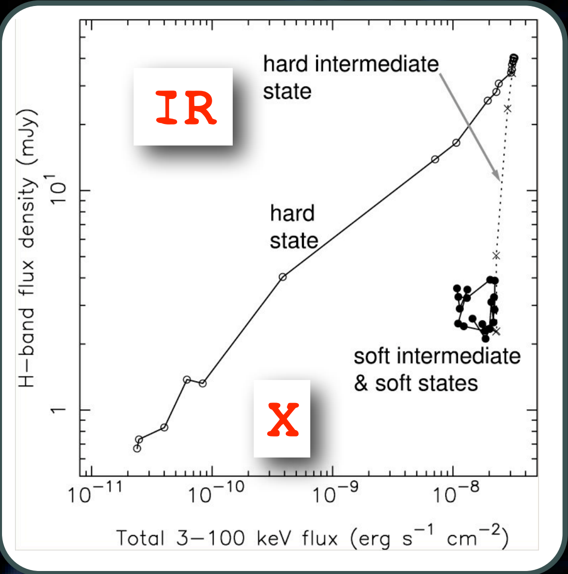




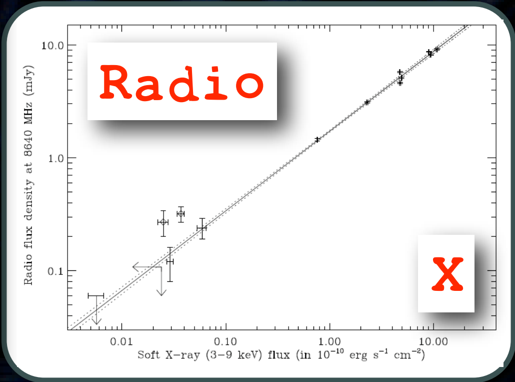
Gallo et al. (2003)

Radio Properties

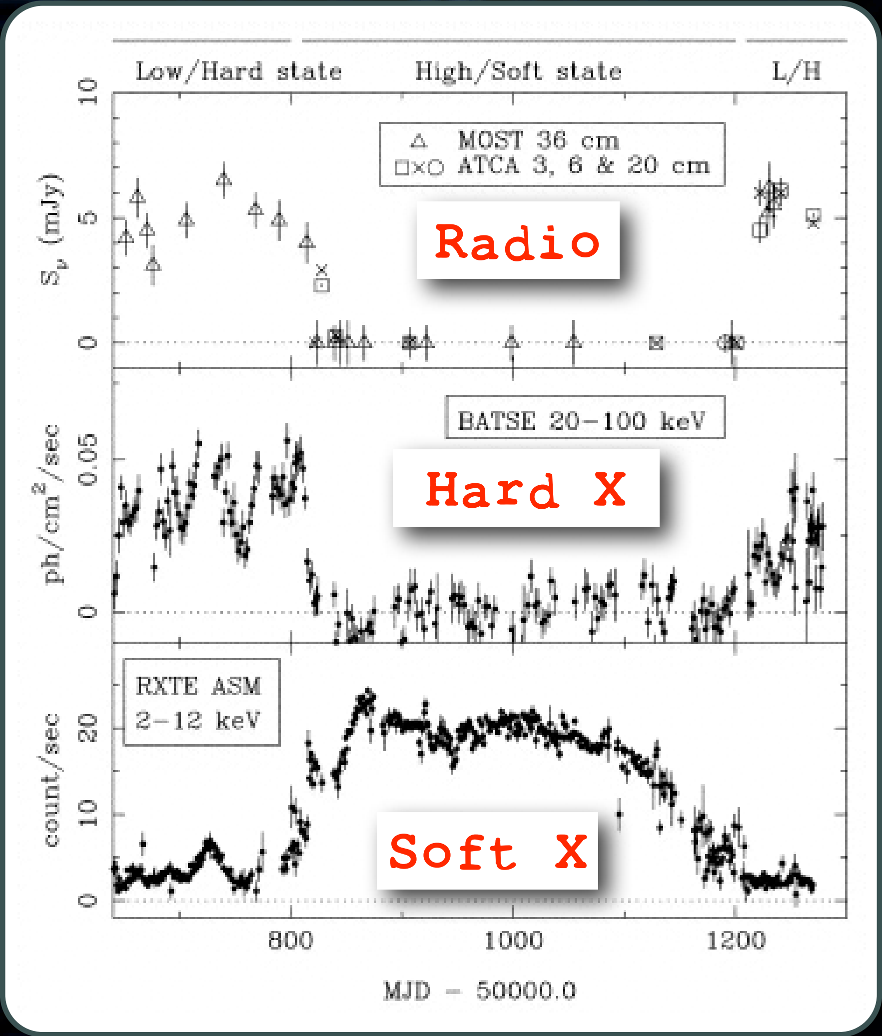
- Hard State: correlations
- Soft State: radio quiet



Homan et al. (2005)



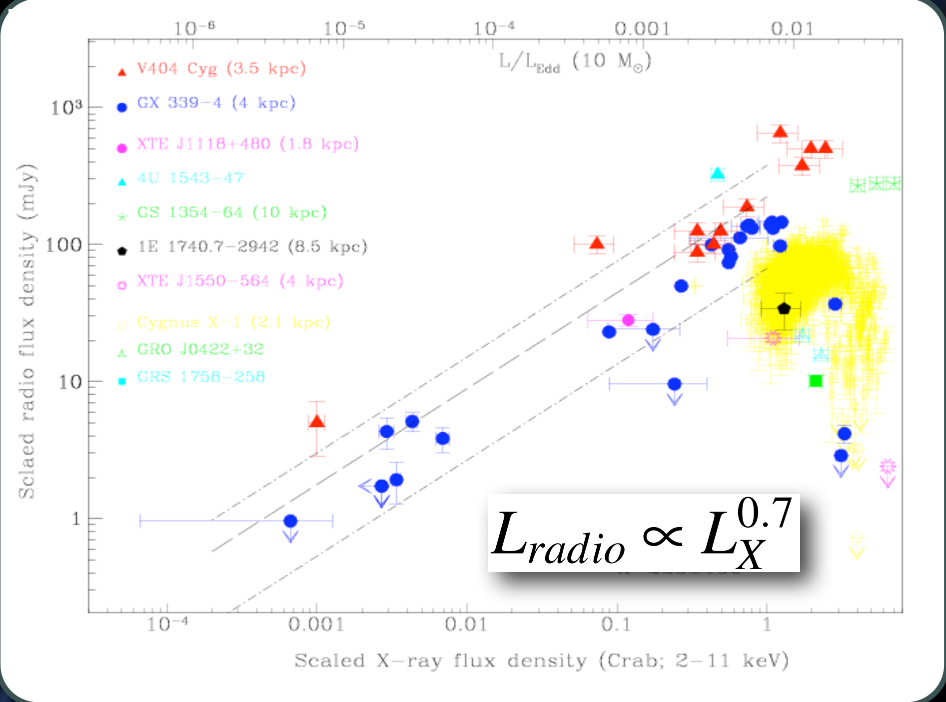
Corbel et al. (2003)

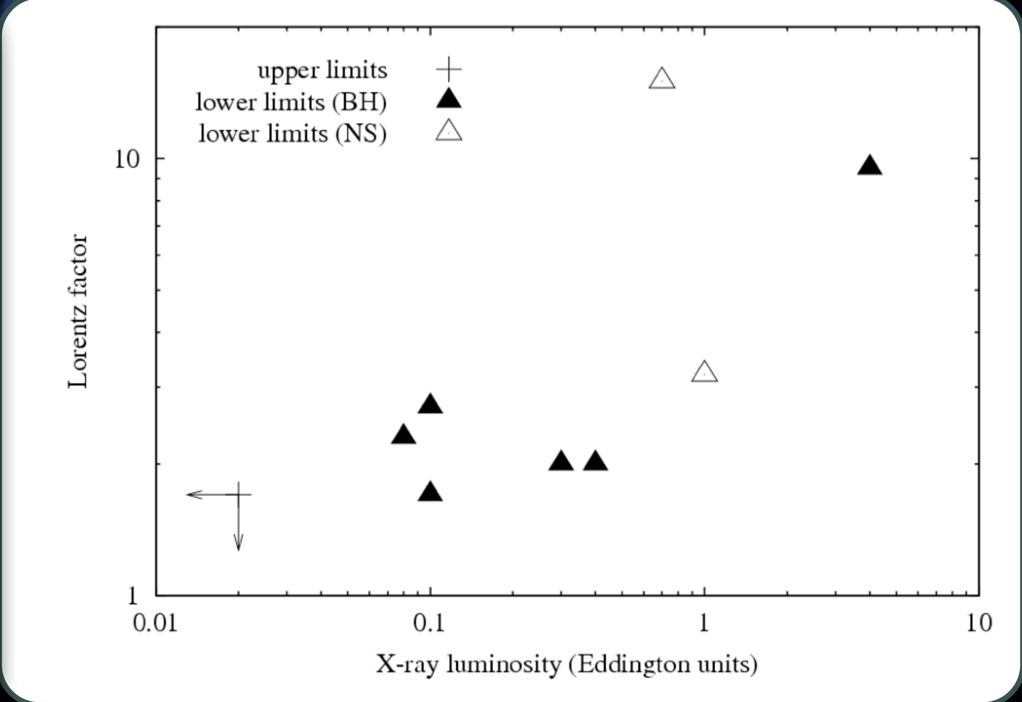


Fender et al. (1999)

Radio Properties

- Hard State: mildly relativistic



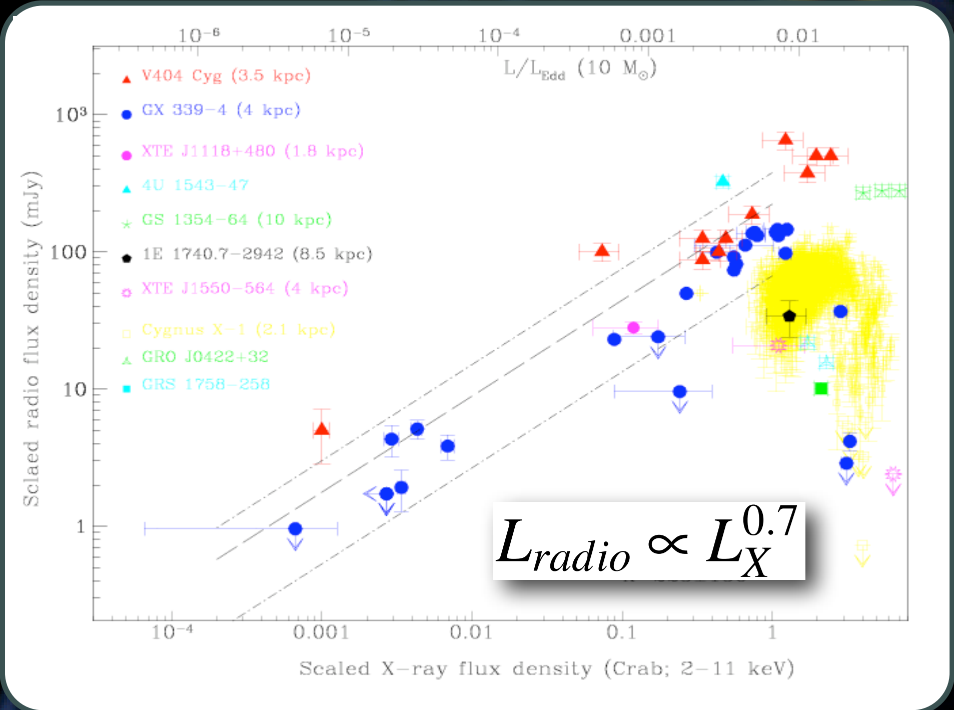


Gallo et al. (2003)

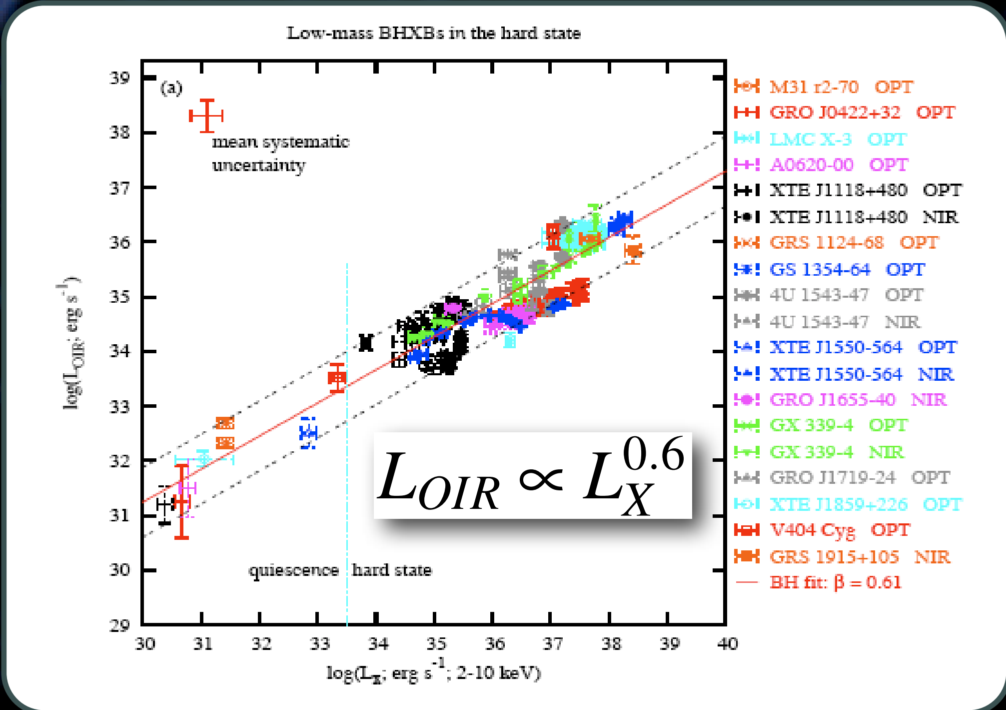
Fender, Belloni & Gallo (2004)

IR-Opt. Properties

- Correlations, correlations...



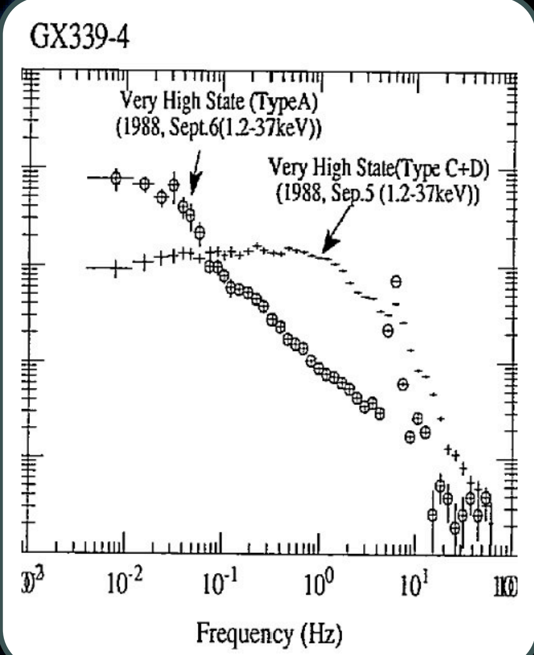
Gallo et al. (2003)



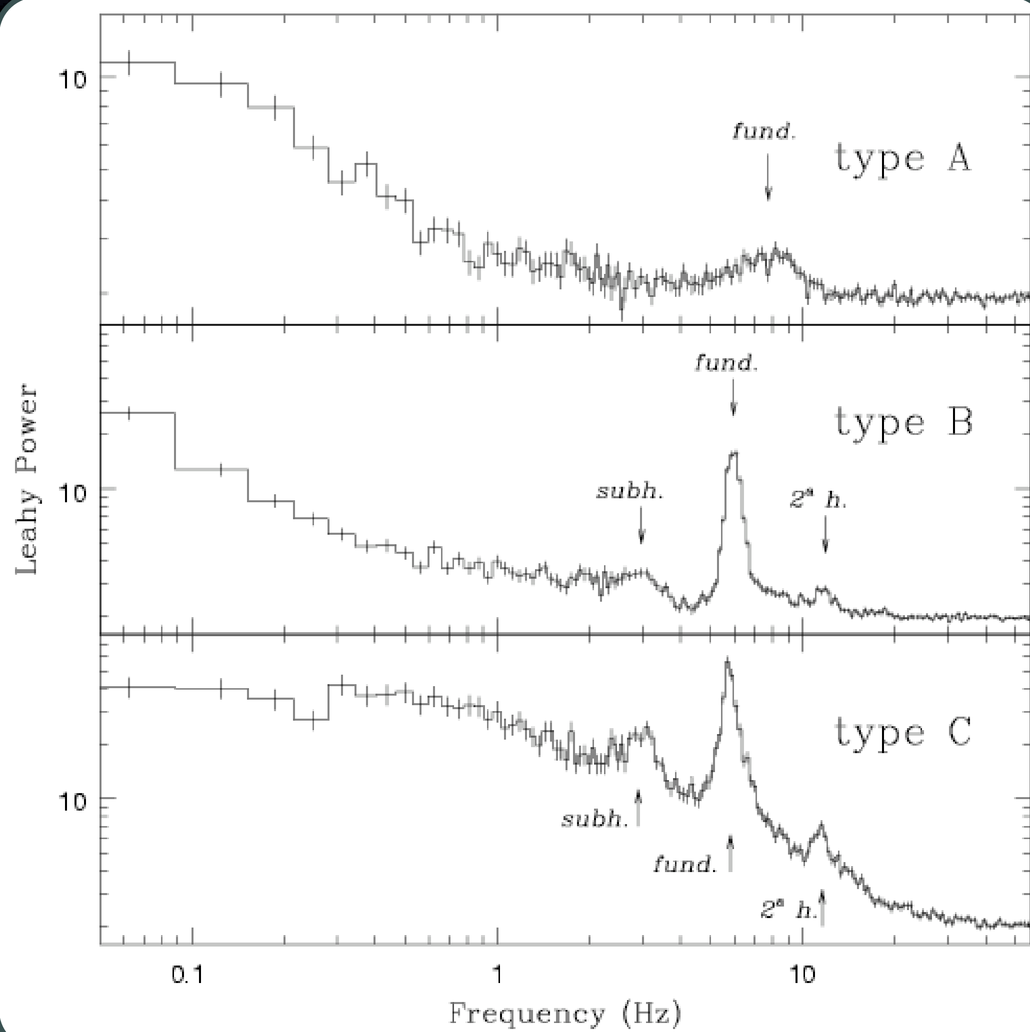
Russell et al. (2006)

Other States

- Very-High State
- Intermediate State
- Steep-Powerlaw State

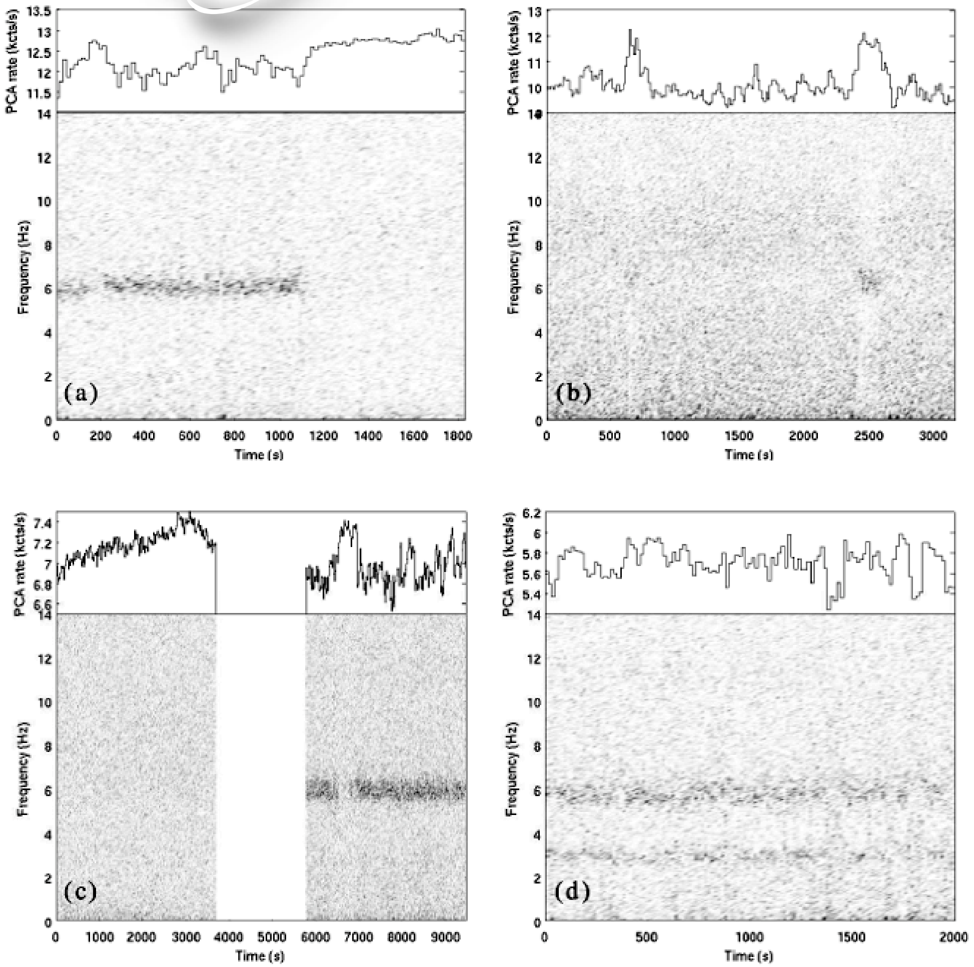


Miyamoto et al. (1991)



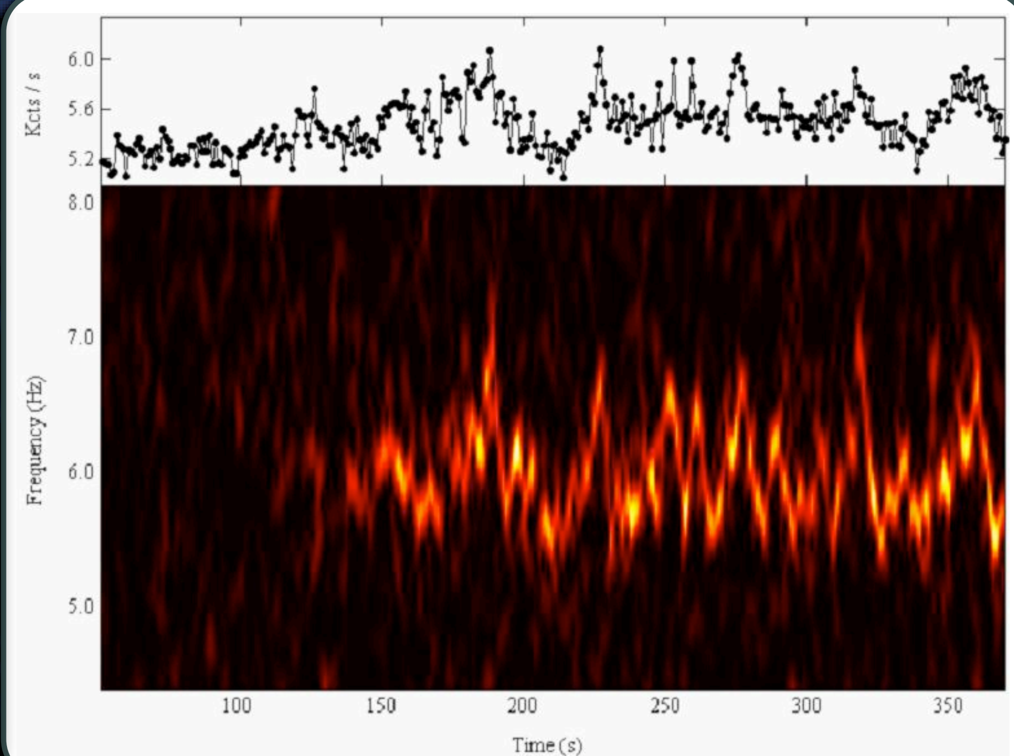
Casella et al. (2004)

Very fast transitions



Casella et al. (2004)

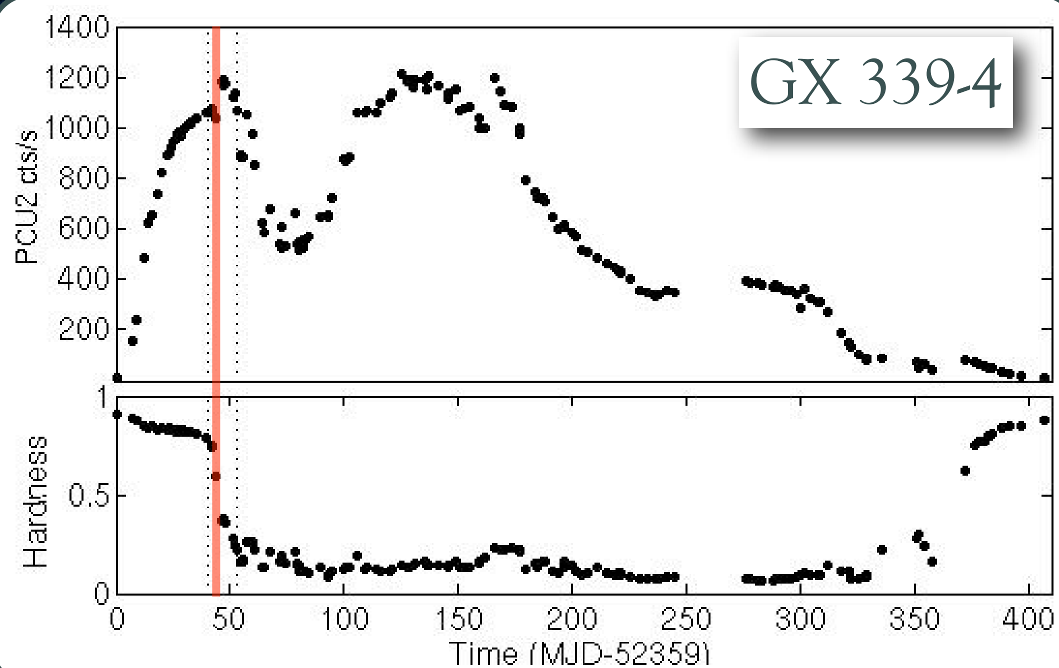
Timing properties



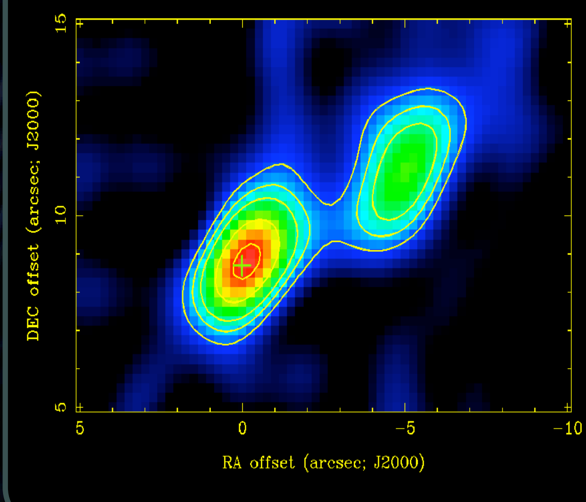
Nespoli et al. (2003)

Powerful ejections

- Related to state transitions
- What happens in between those states?
- Black-hole transients are the key



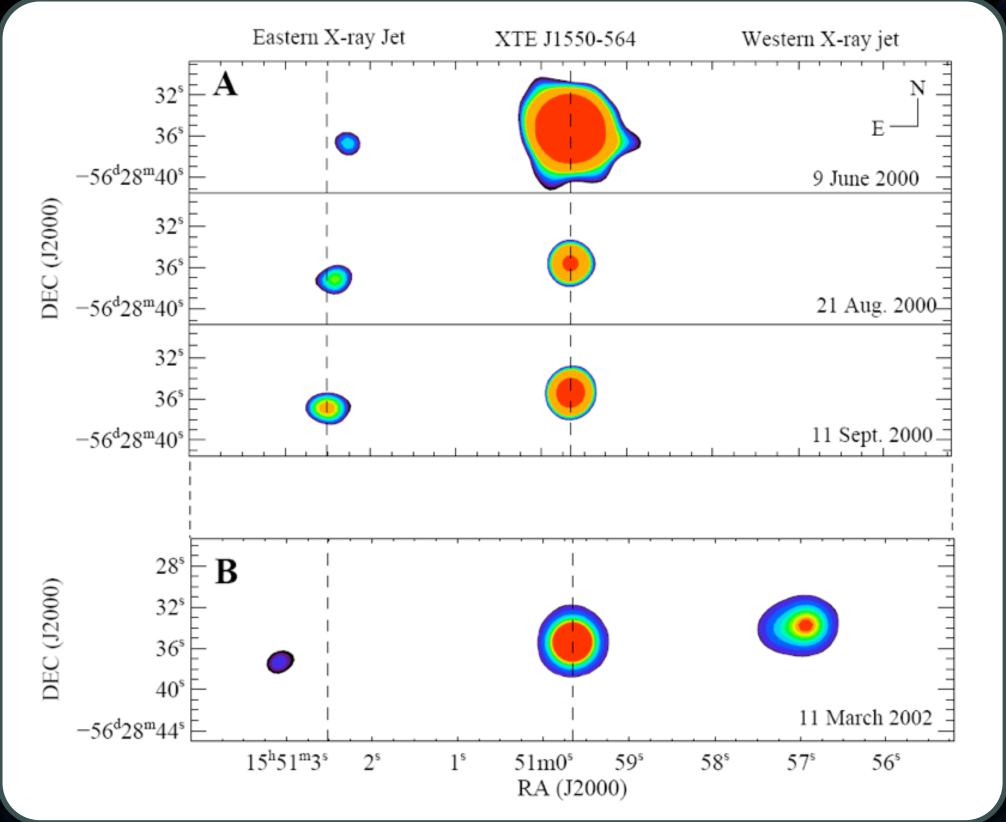
Belloni et al. (2005)

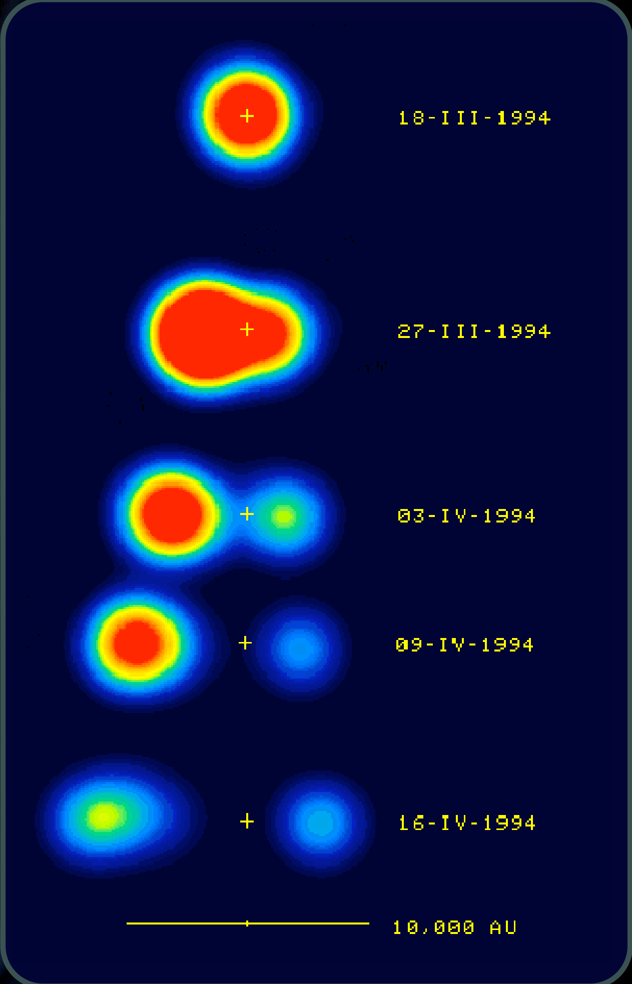


Gallo et al. (2004)

Powerful ejections

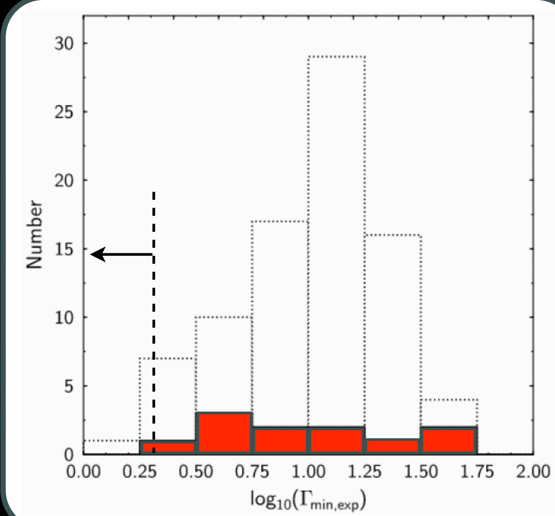
- Superluminal jets
- X-ray jets



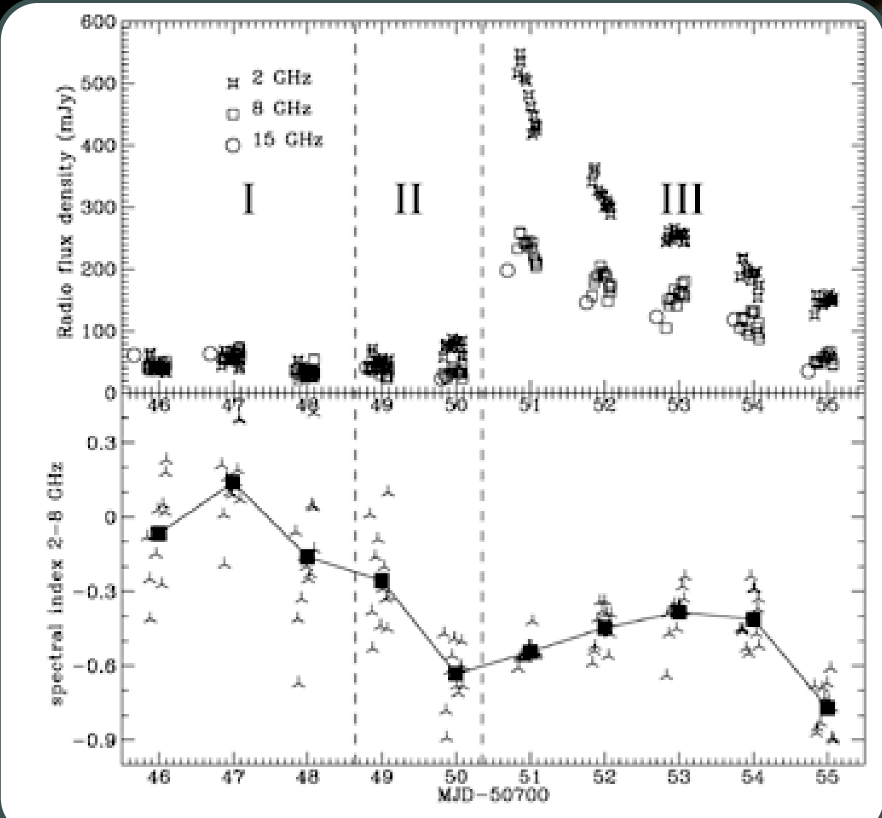


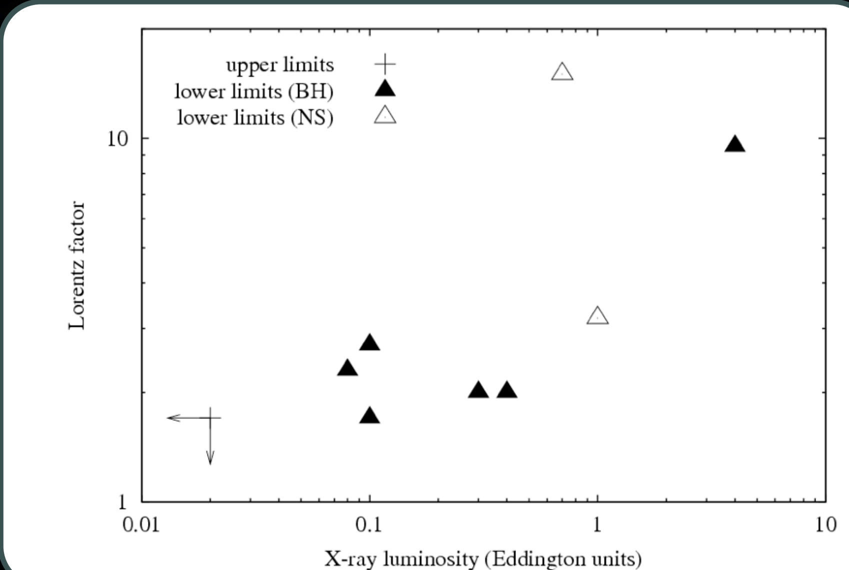
Powerful ejections

- A faster jet
- A different spectrum



Miller-Jones et al. (2006)

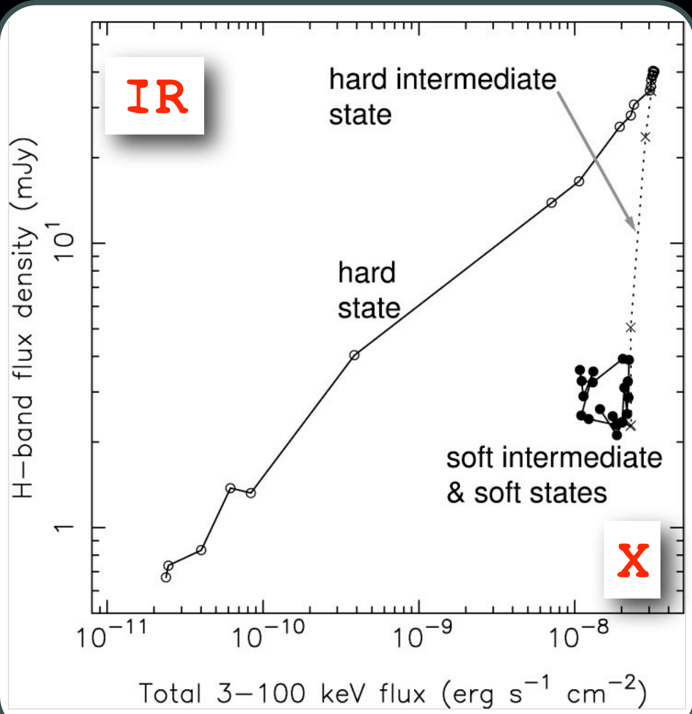




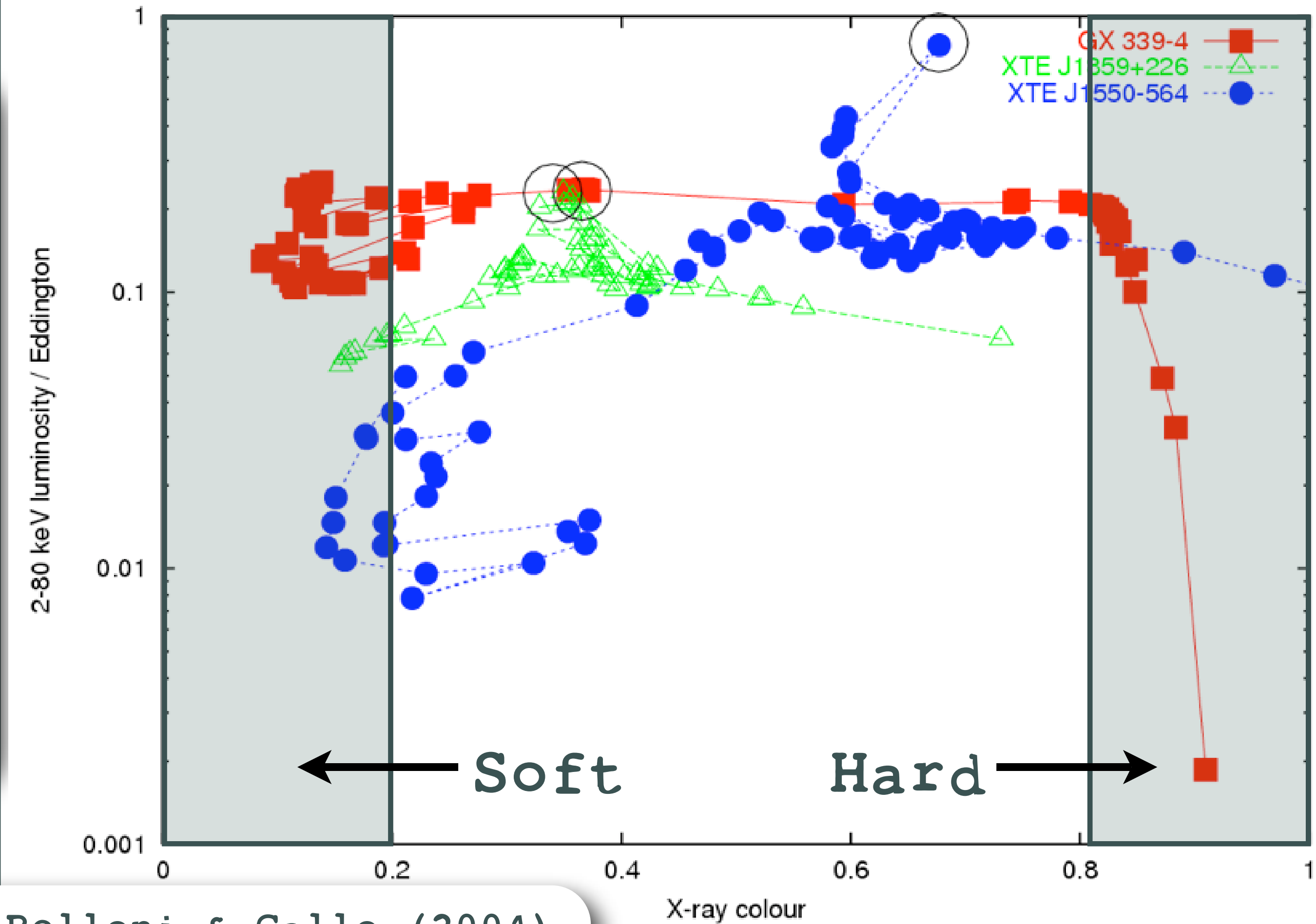
Fender, Belloni & Gallo (2004)

State transitions

- Intermediate states & jet ejections



Homan et al. (2005)



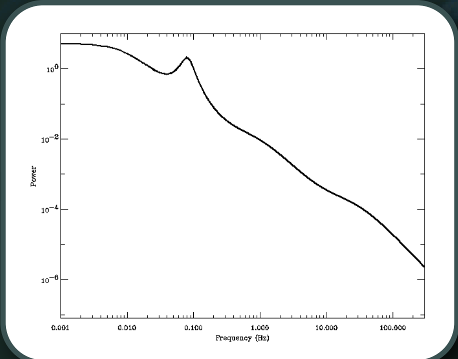
Fender, Belloni & Gallo (2004)

State transitions

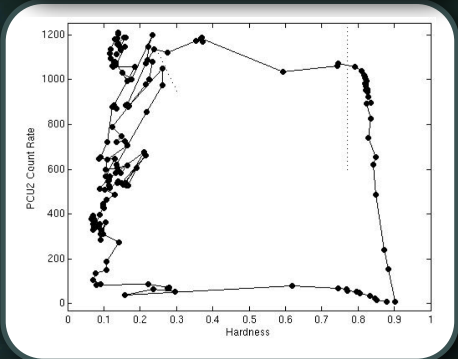
GX 339-4 as template

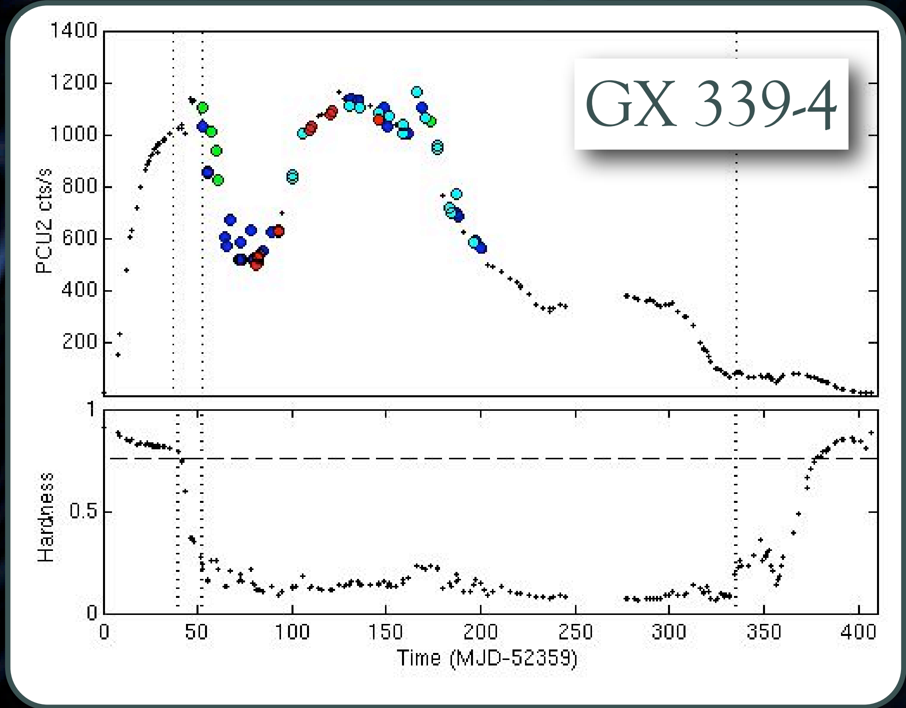
Tools:

Power spectra



Hardness

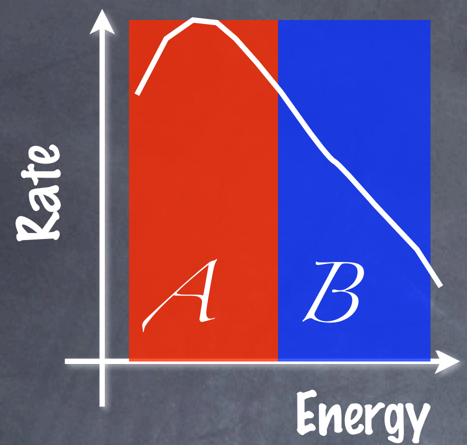




Belloni et al. (2005)

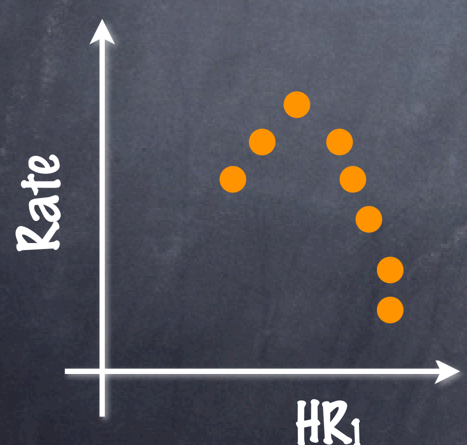
Phenomenology common to many systems

X-ray colors: HID



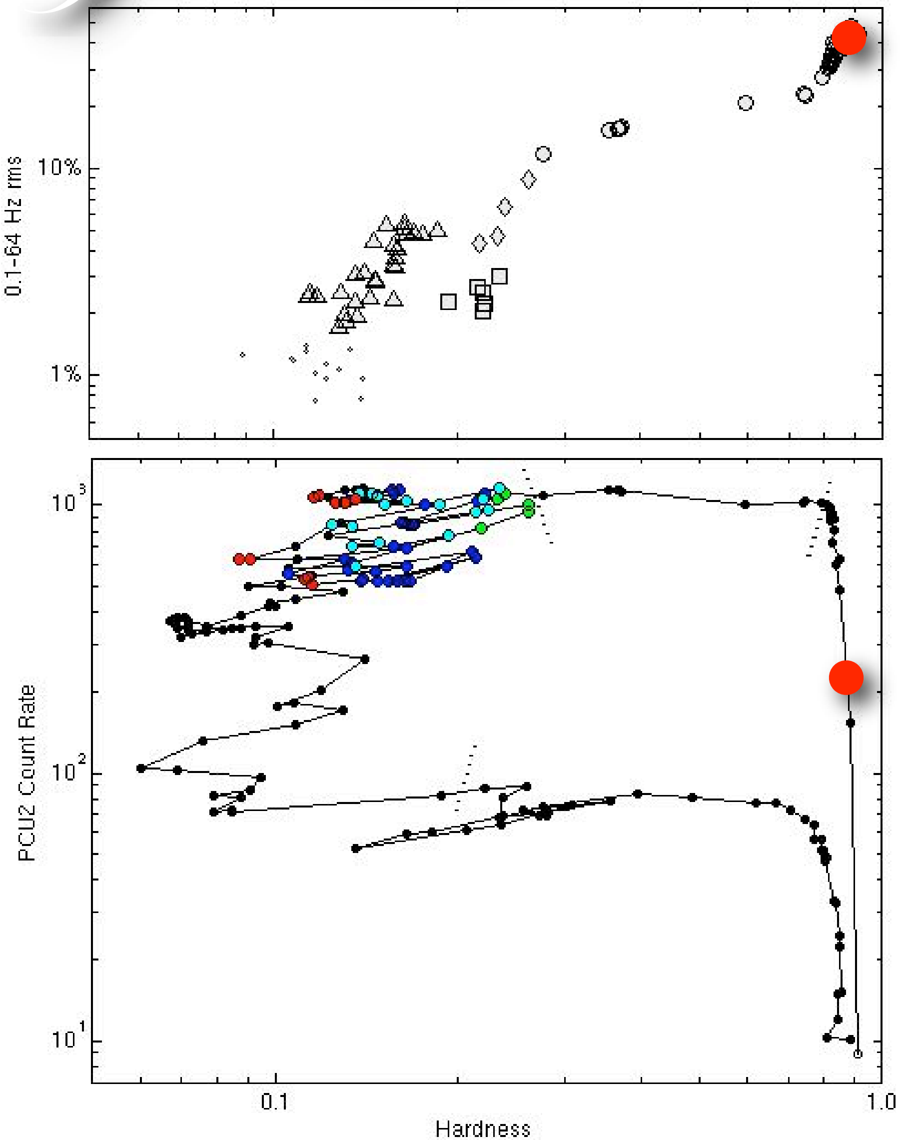
Colors: HR = B/A

Rate: R = A+B

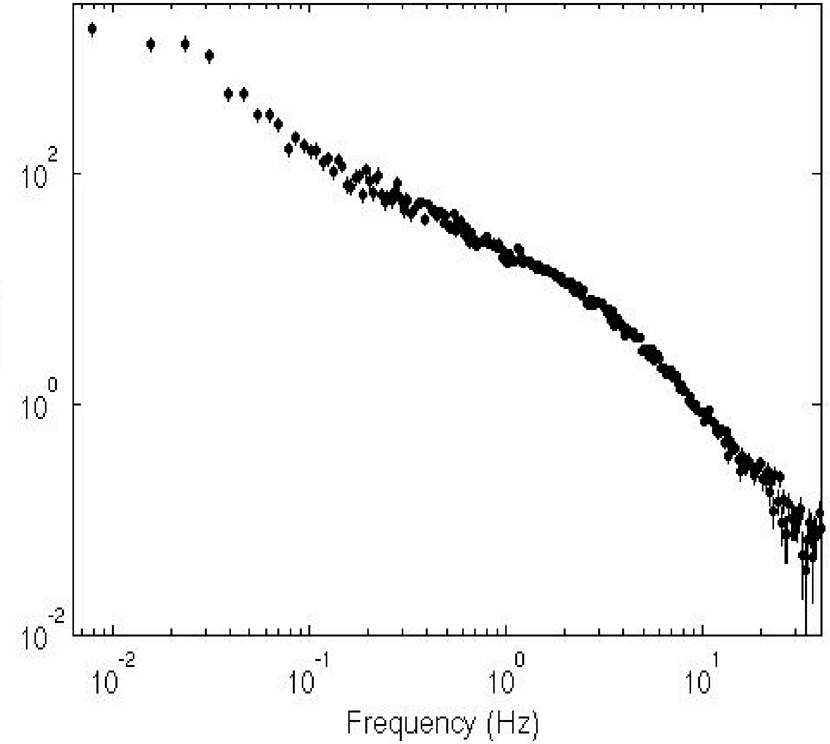


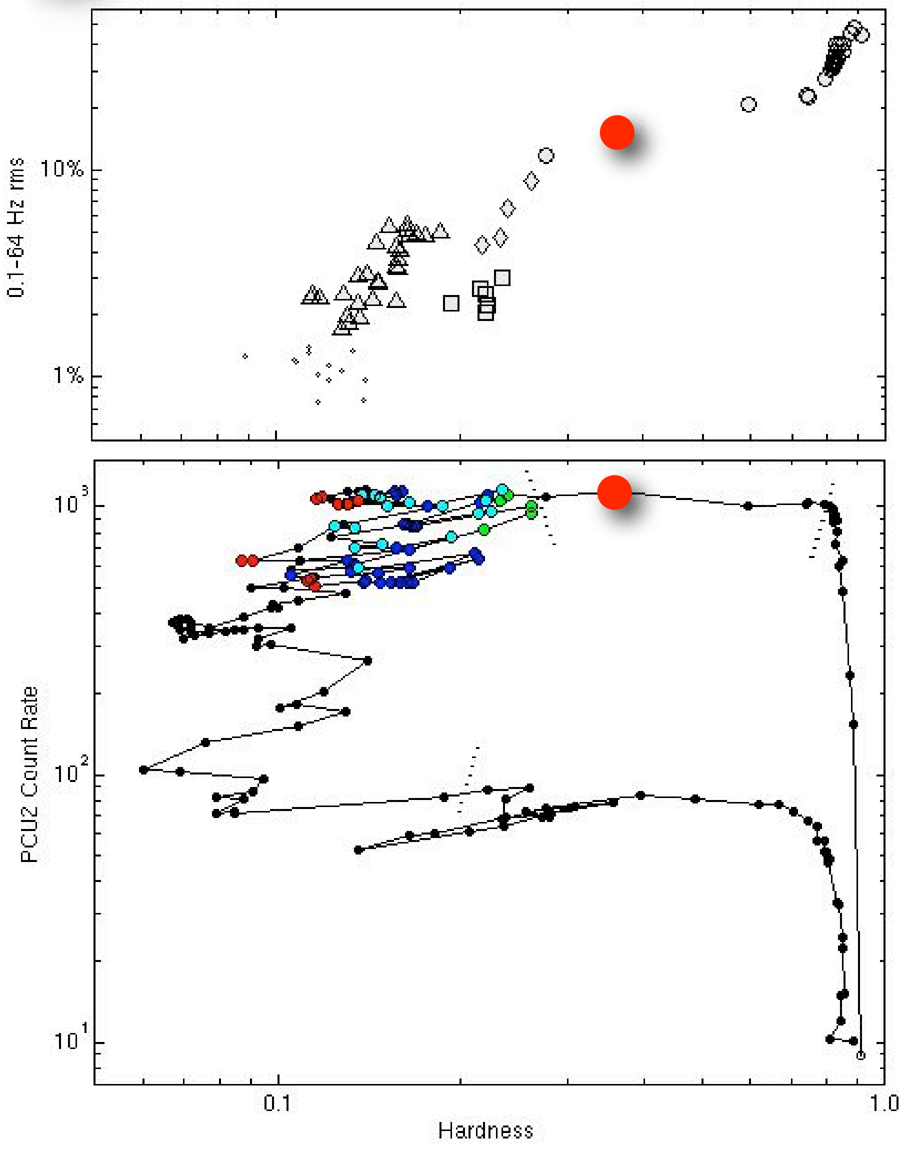
Hardness-Intensiy Diagran

GX 339-4 (2002/3)

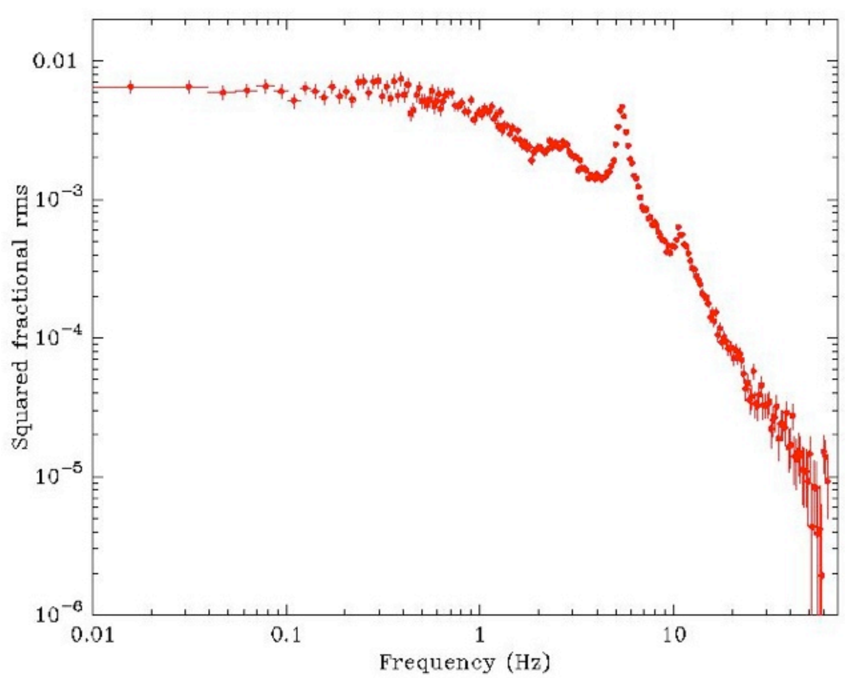


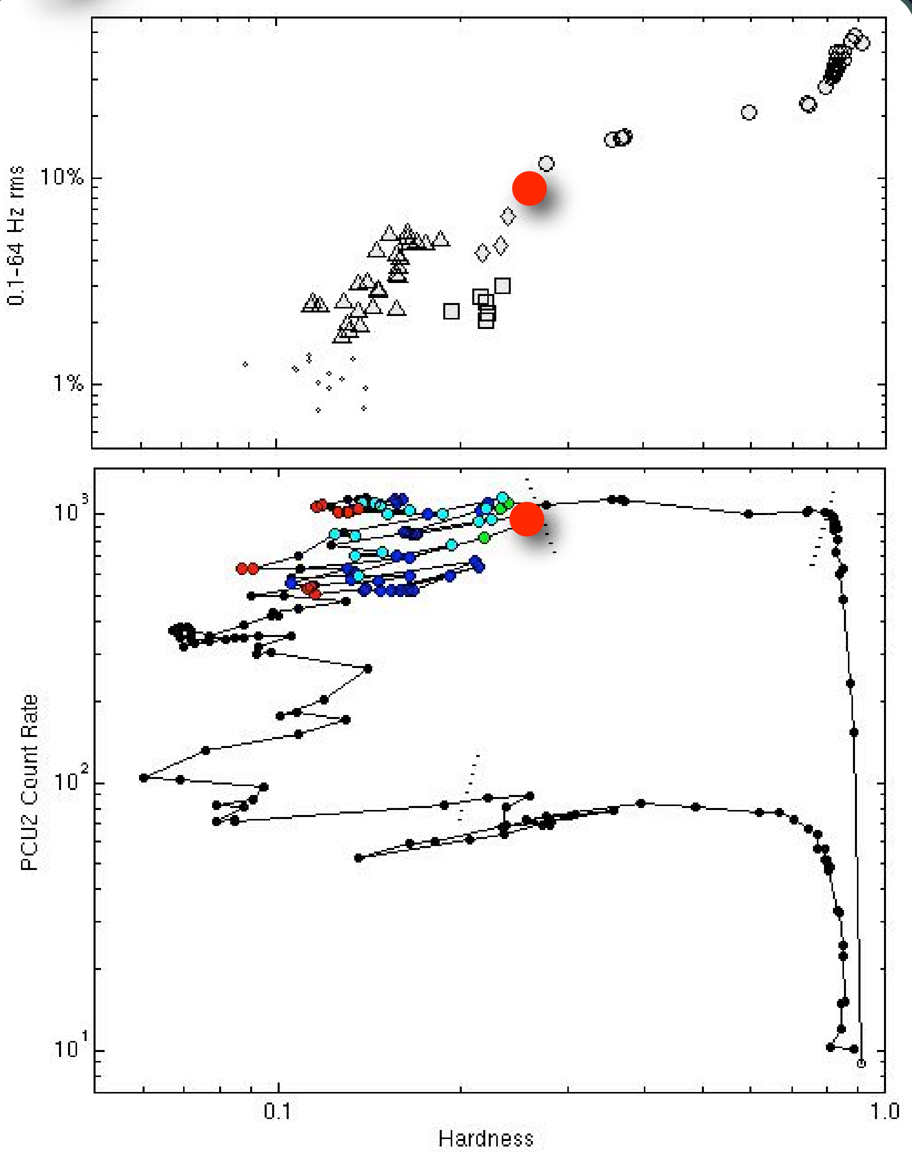
Hard state: noise, high-E cutoff, radio emission, compact jet



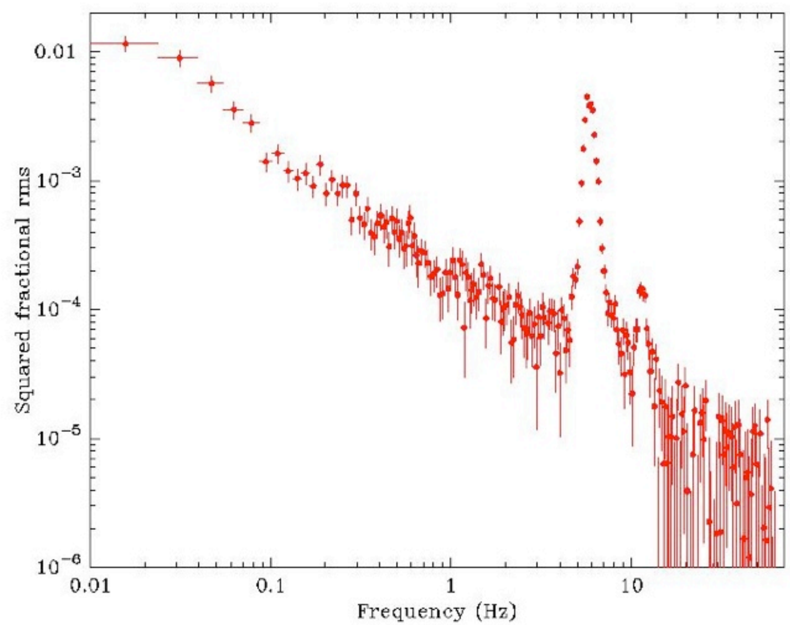


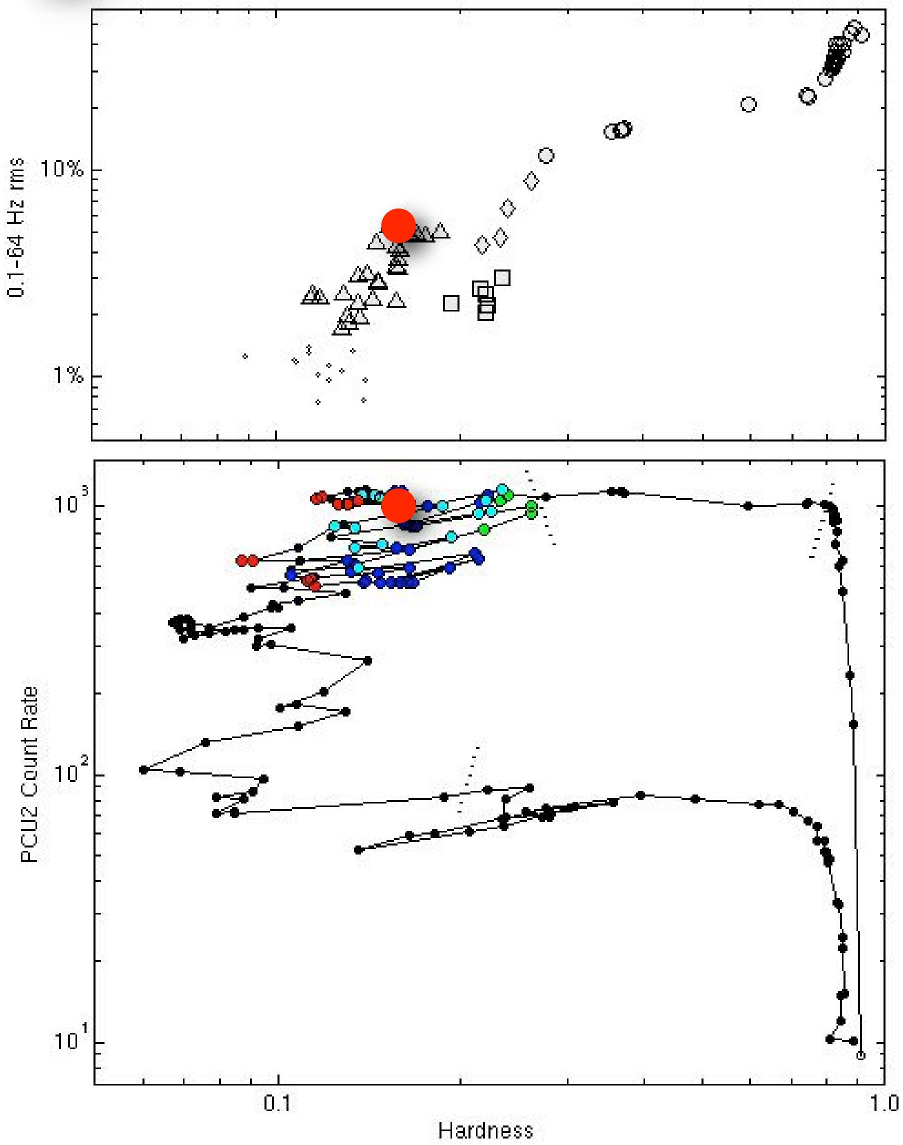
Hard intermediate state: less noise, QPO, high-E cutoff?, radio emission, compact jet



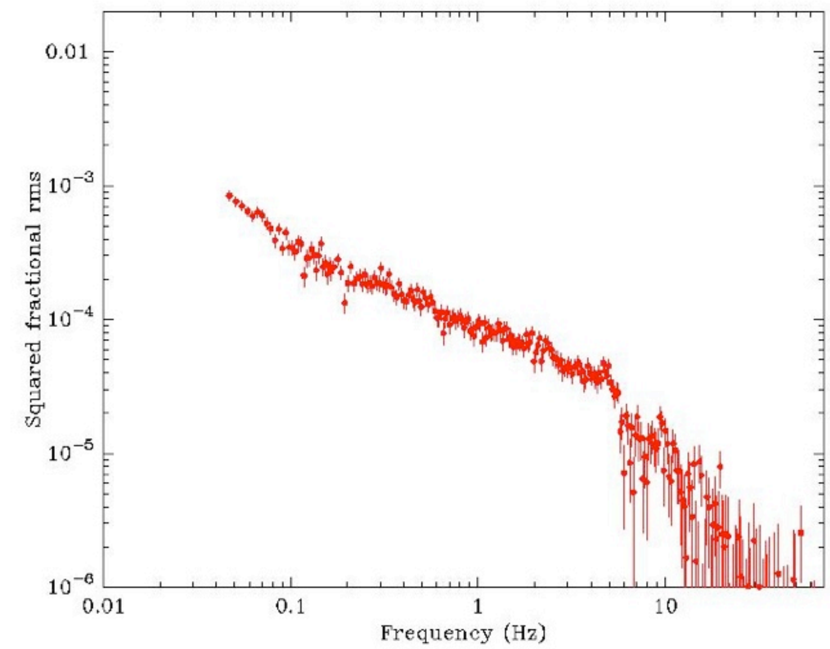


Soft intermediate state: drop in noise, QPO!, high-E cutoff?, no radio emission, jet ejection

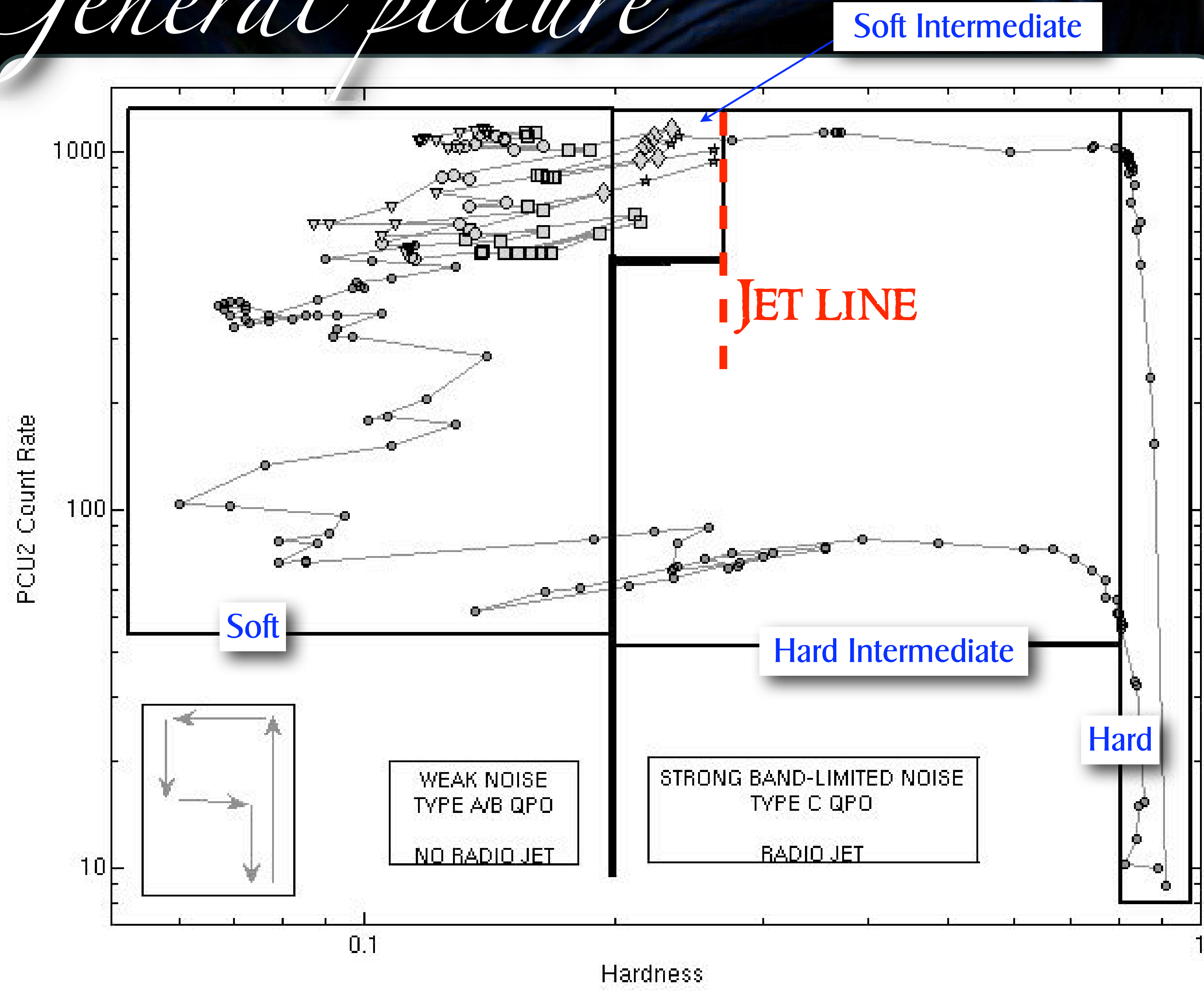




Soft state: little noise, weak QPO, no high-E cutoff, no radio emission



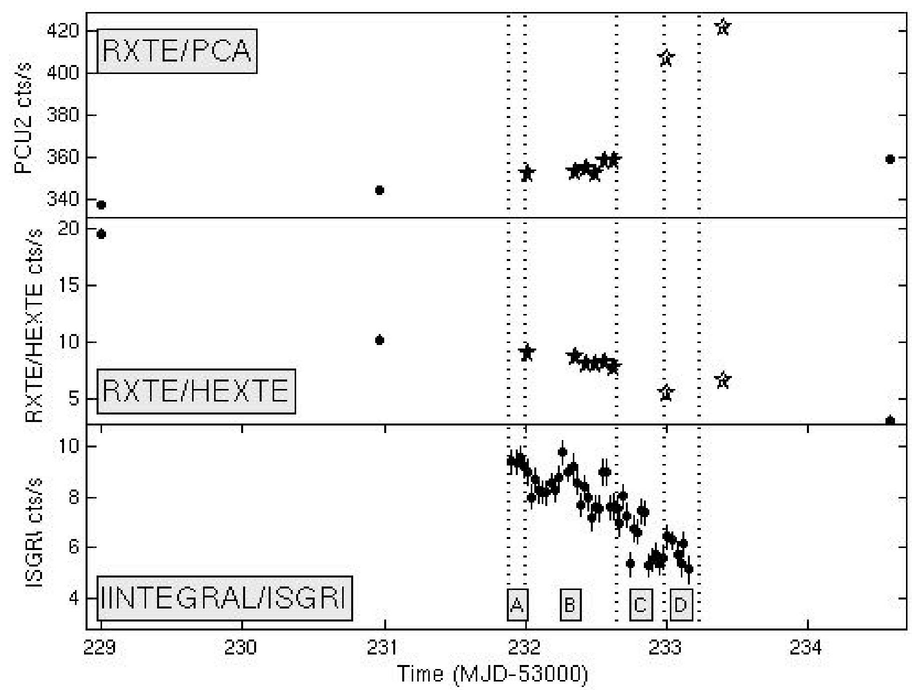
General picture

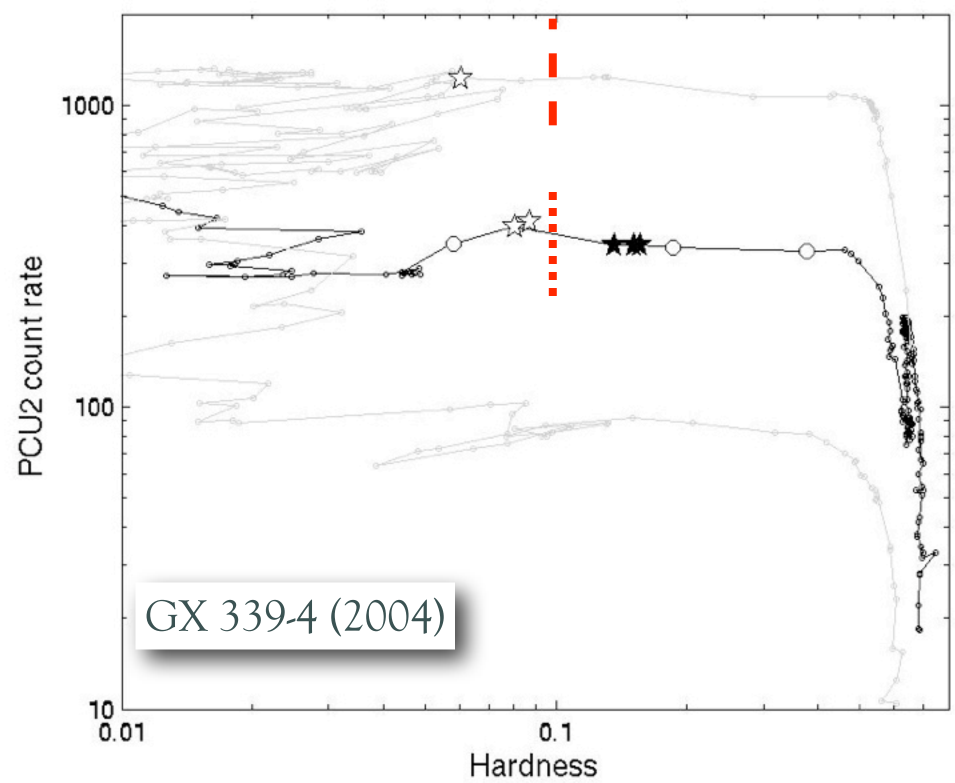


adapted from Belloni (2005)

The Jet Line

- Transitions are fast
- Timing is the tracer
- Jet is the output
- High-energy changes
- Not Mdot driven

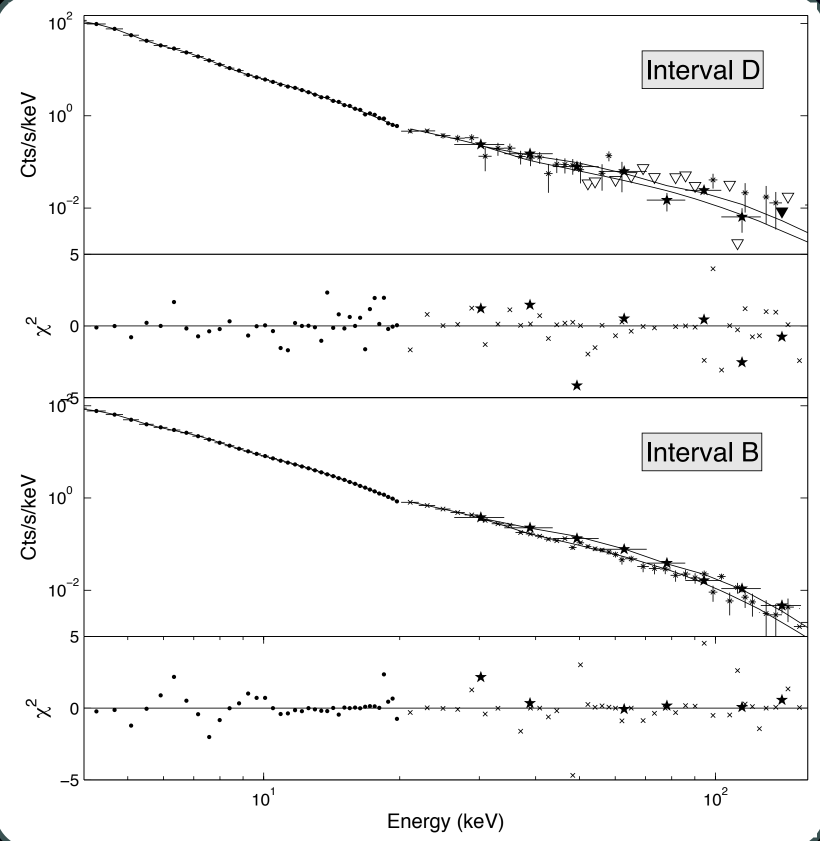


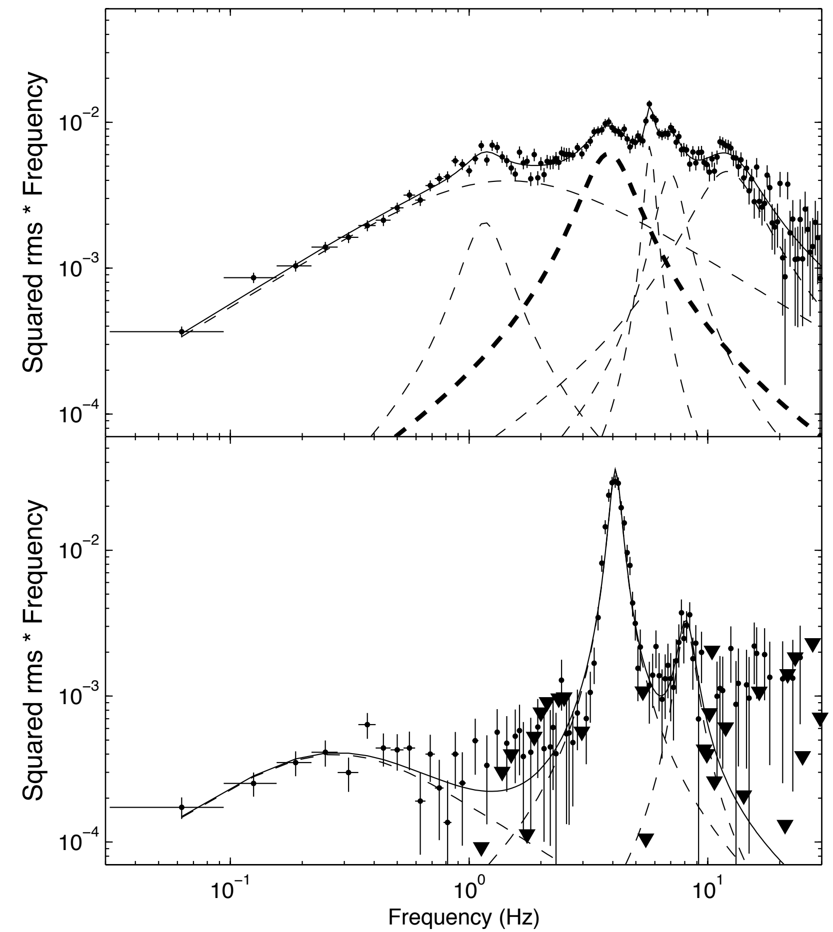


Belloni et al. (2006)

The High-Energy View

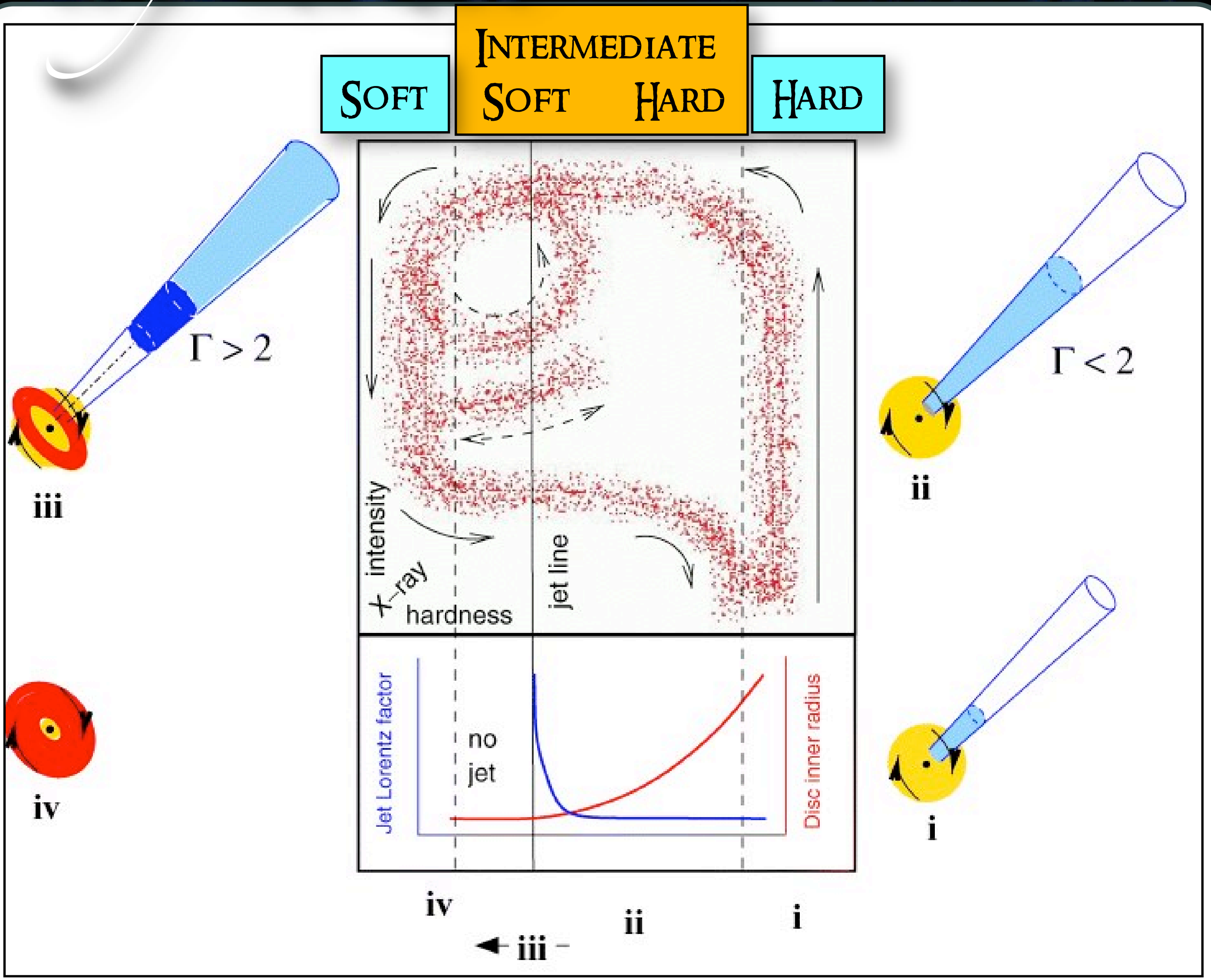
Belloni et al. (2006)





70 keV cutoff disappears

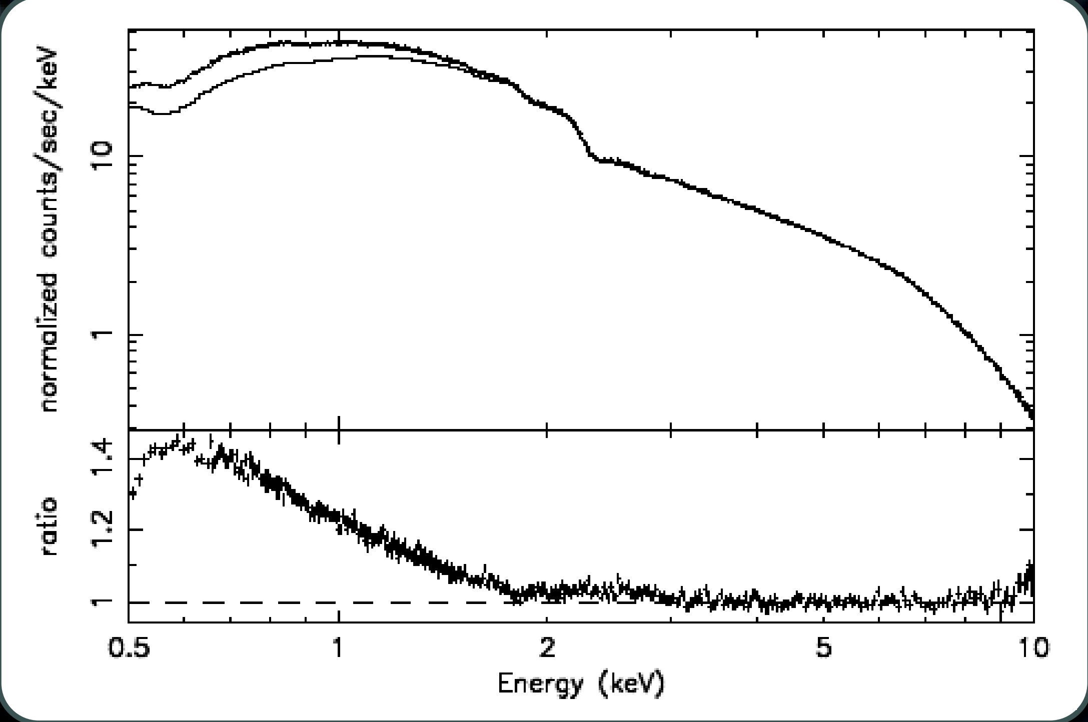
The toy model



Fender, Belloni & Gallo (2004)

Complications...

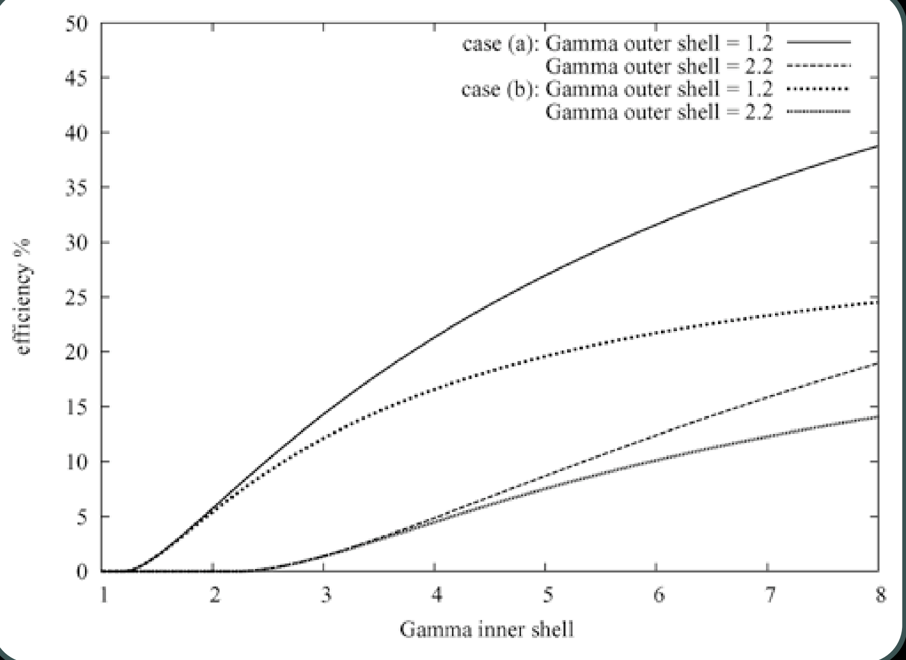
- Disc fully visible
- Hard state
- Sometimes inefficient?
- LS == HS?

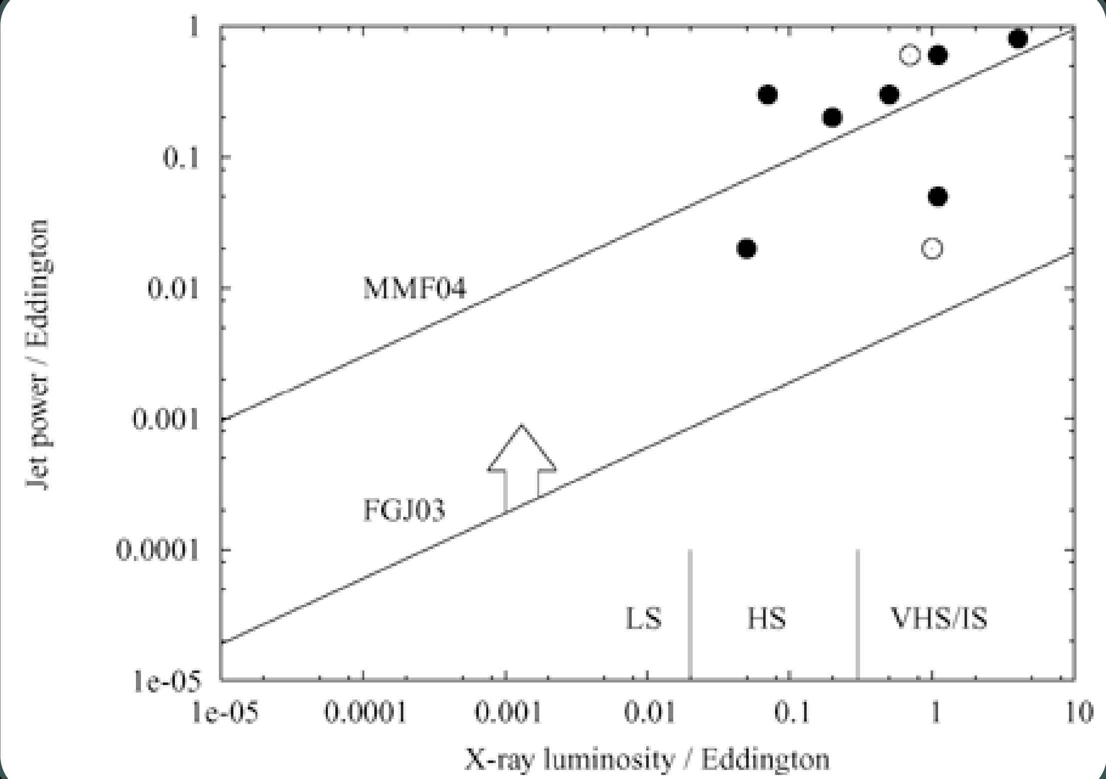


Miller et al. (2006)

The toy model

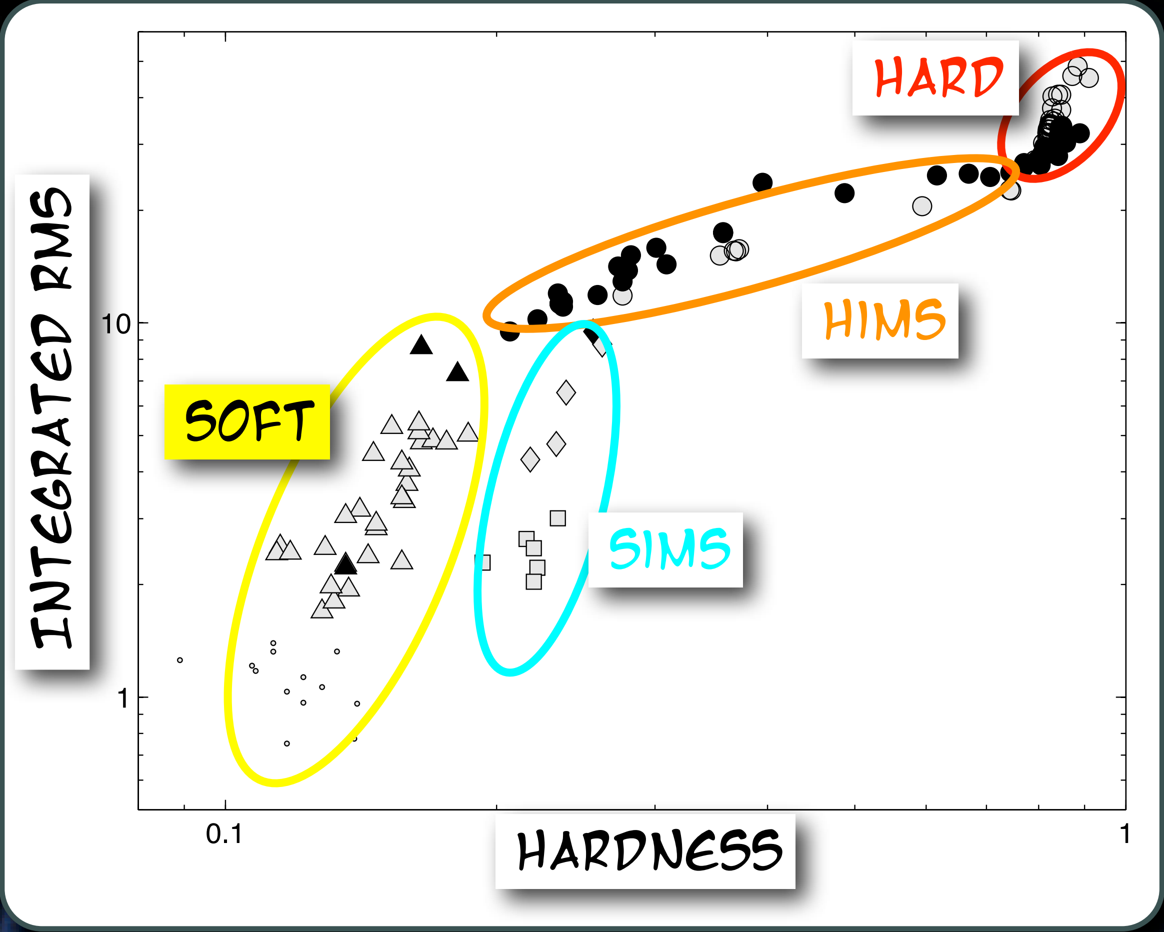
- Continuous evolution of power?
- Internal shocks

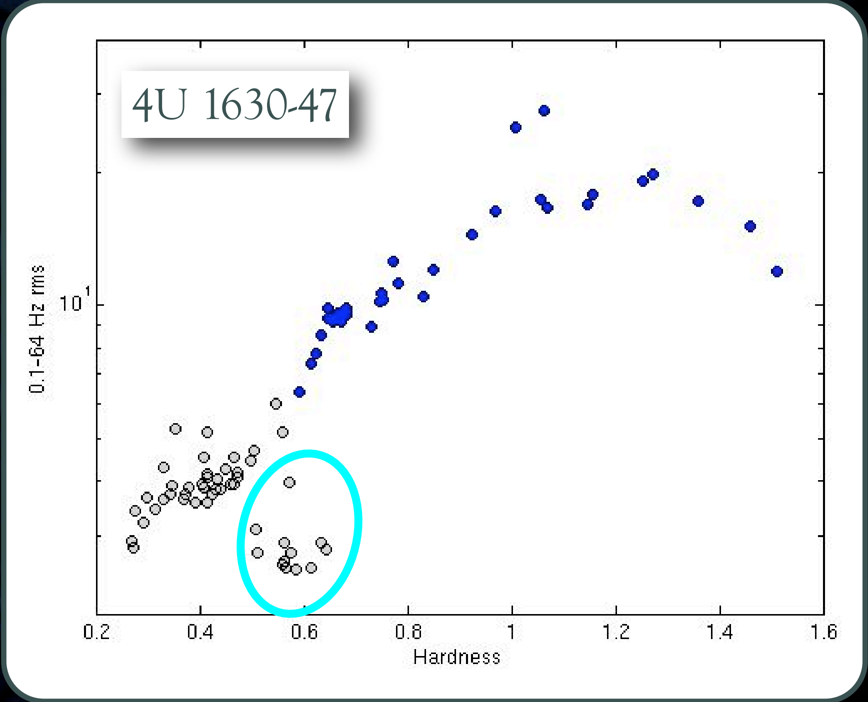




Fender, Belloni & Gallo (2004)

The SIMS region

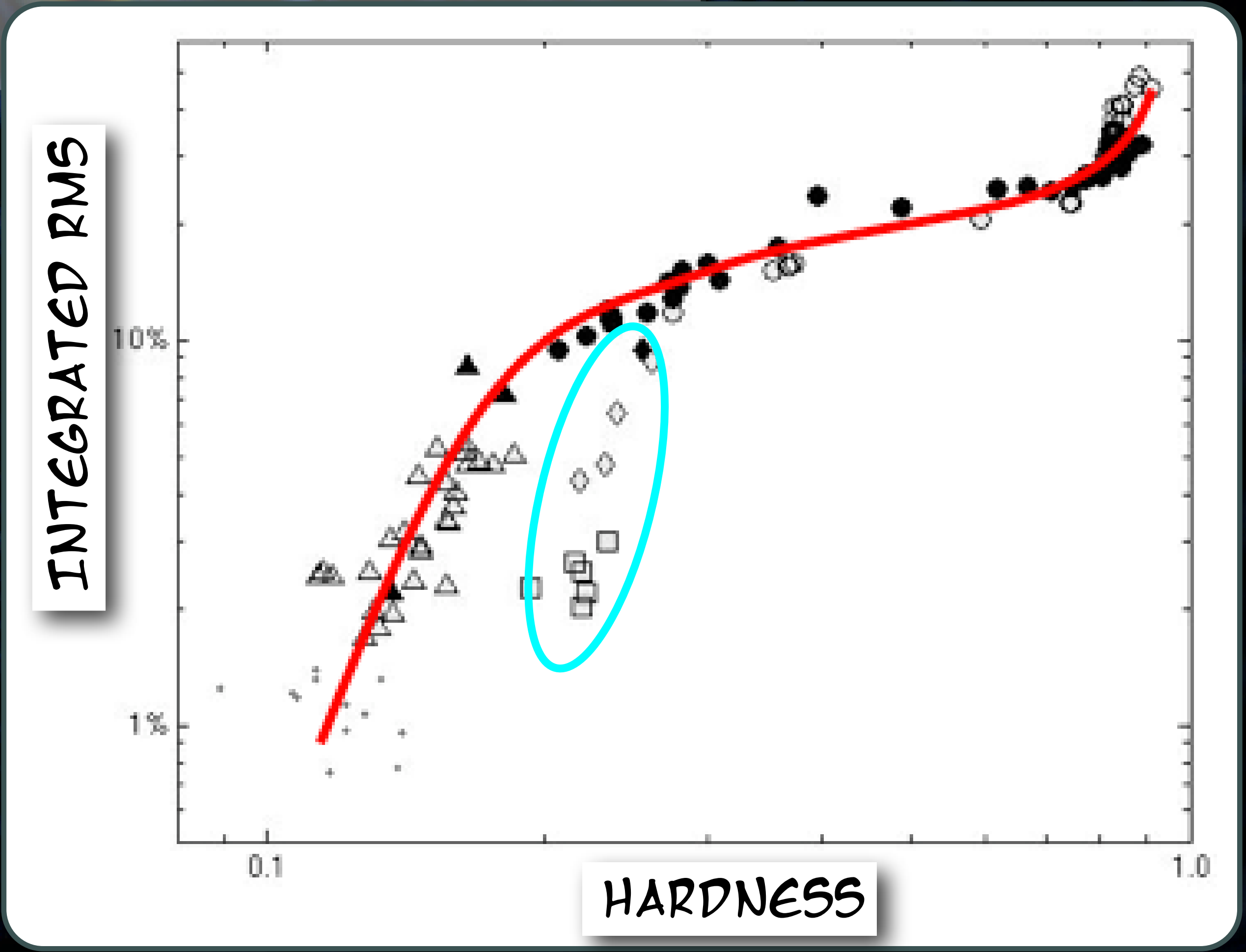




- Different ringing QPO
- Noise drops
- High-frequency QPO
- Not on reverse trans.?

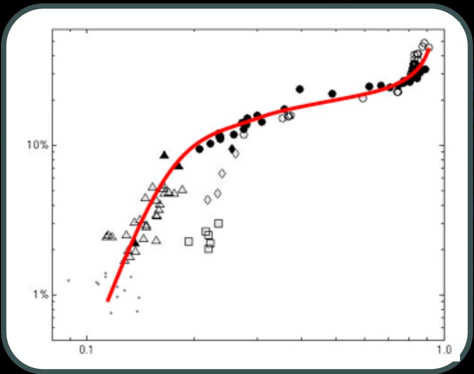
The non-SIMS regions

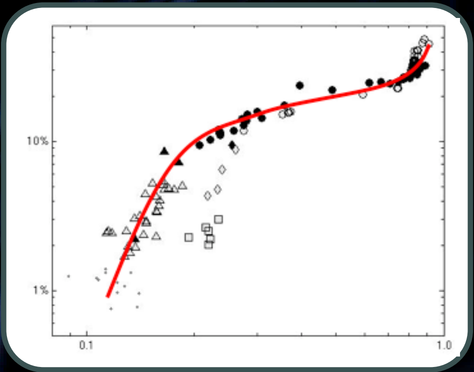
- Timing properties are continuous from hard to soft
- Sharp transitions only involve the SIMS region
- Energy spectra?

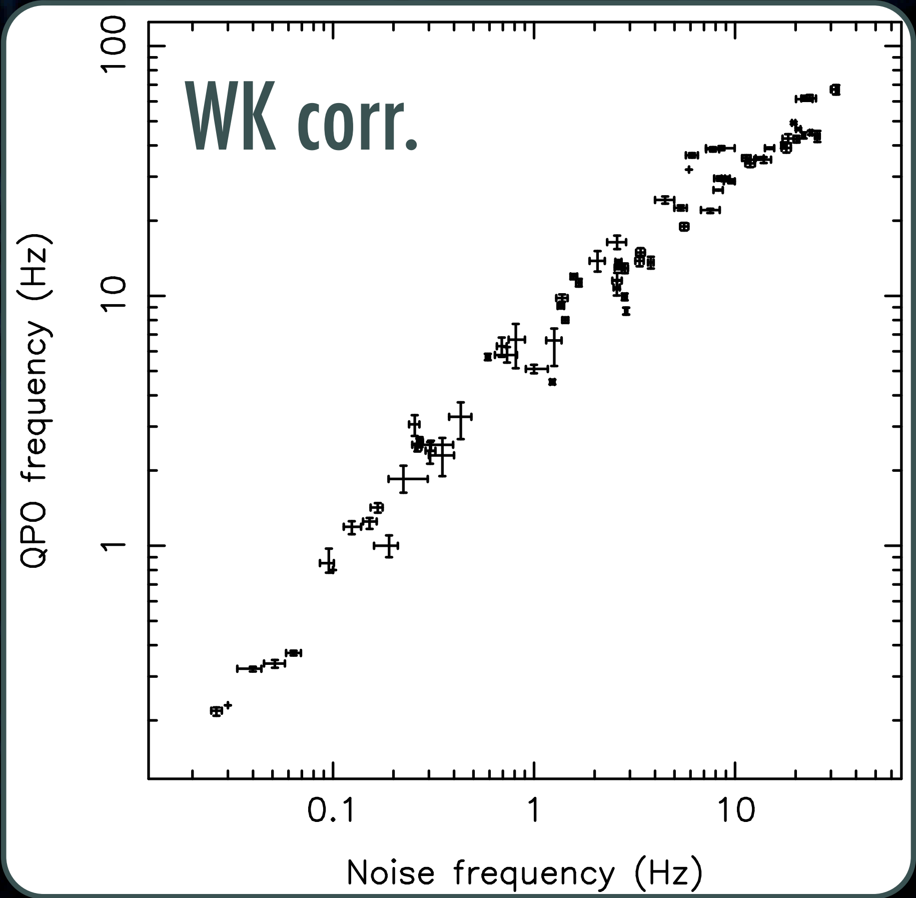


The non-SIMS regions

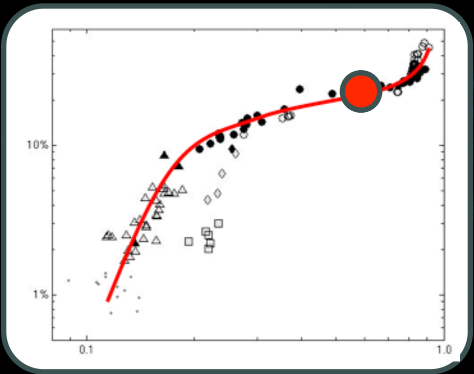
Osservatorio Astronomico di Brera

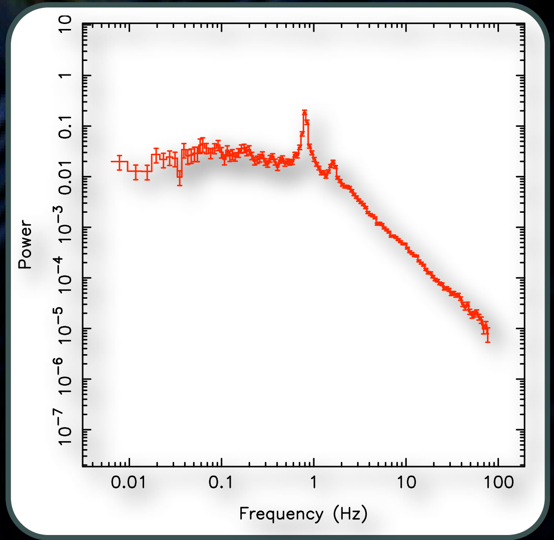


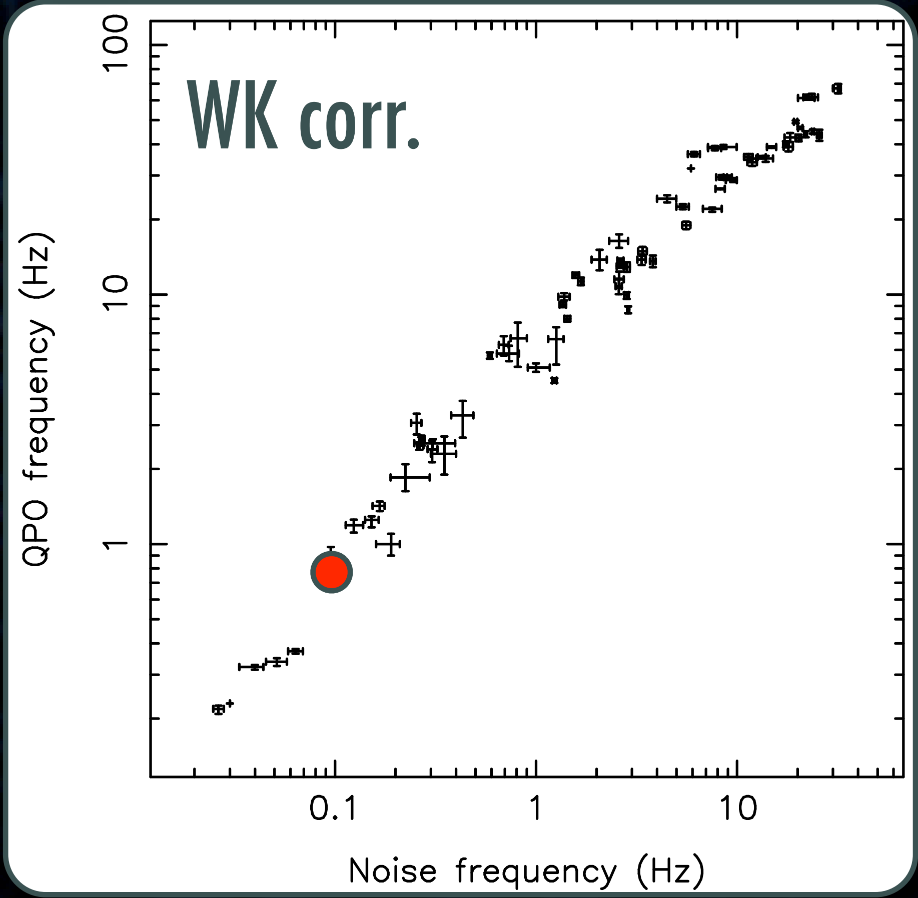


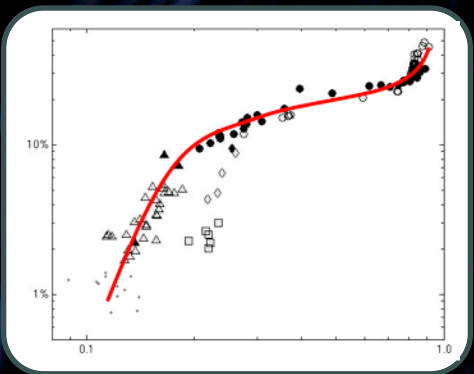


The non-SIMS regions



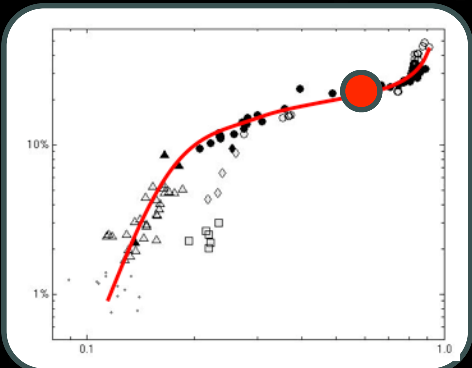


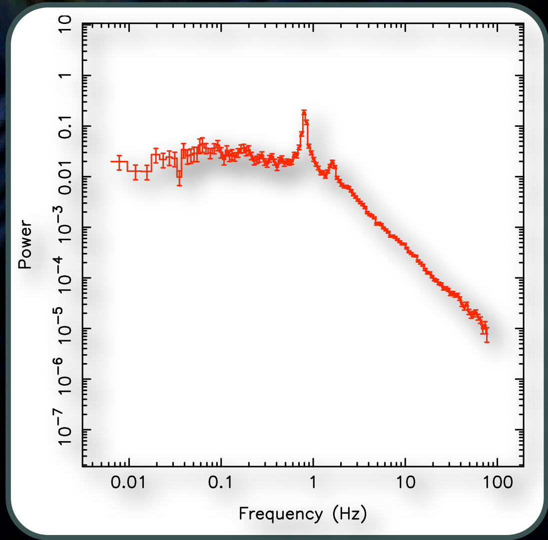


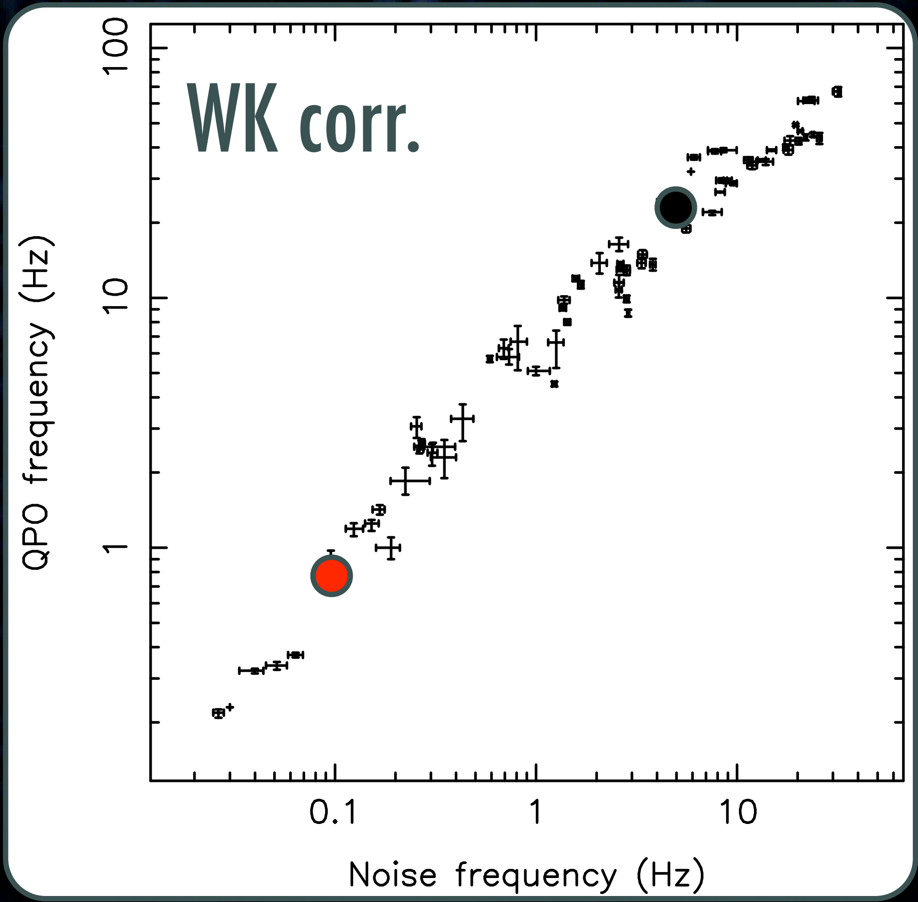


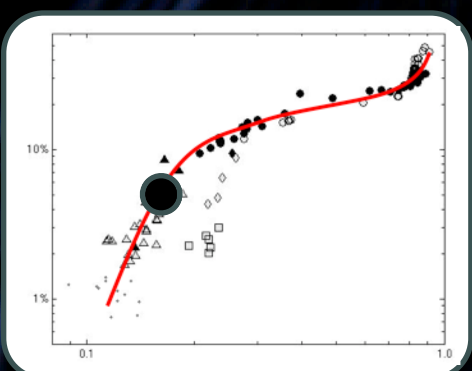
The non-SIMS regions

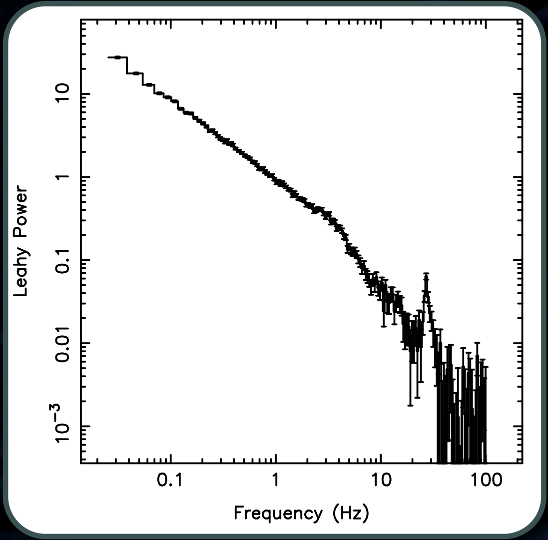
Osservatorio Astronomico di Brera



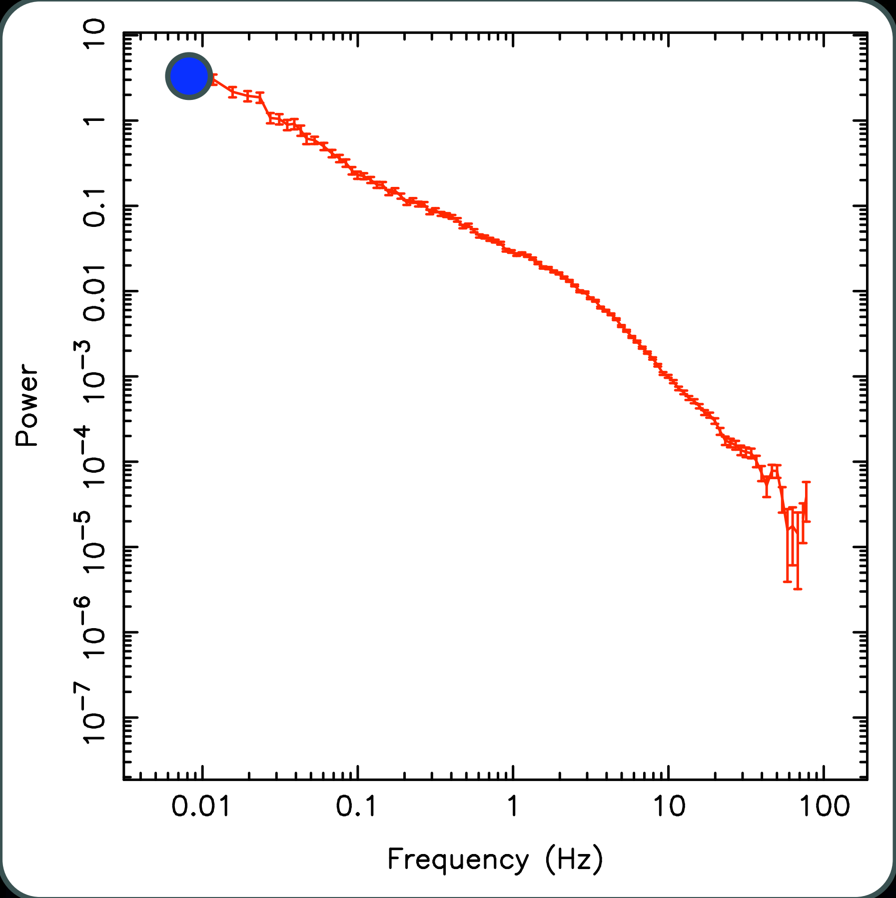


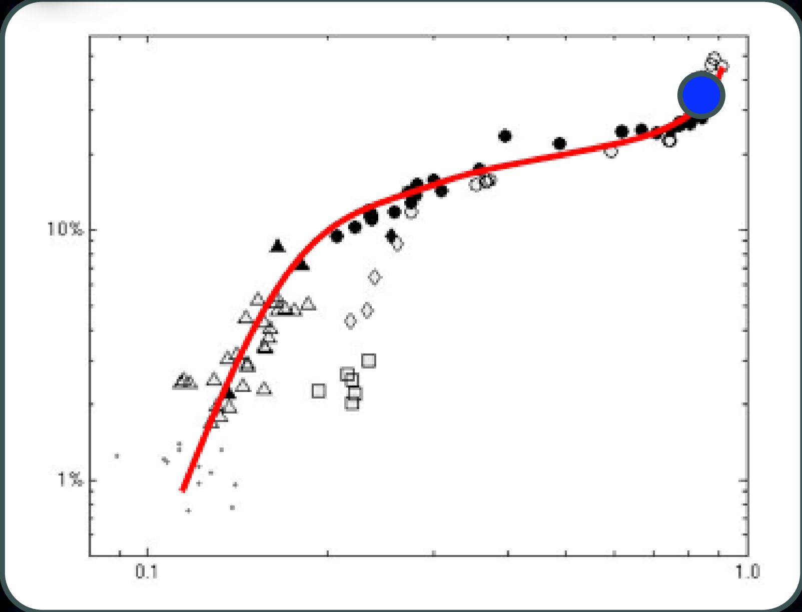






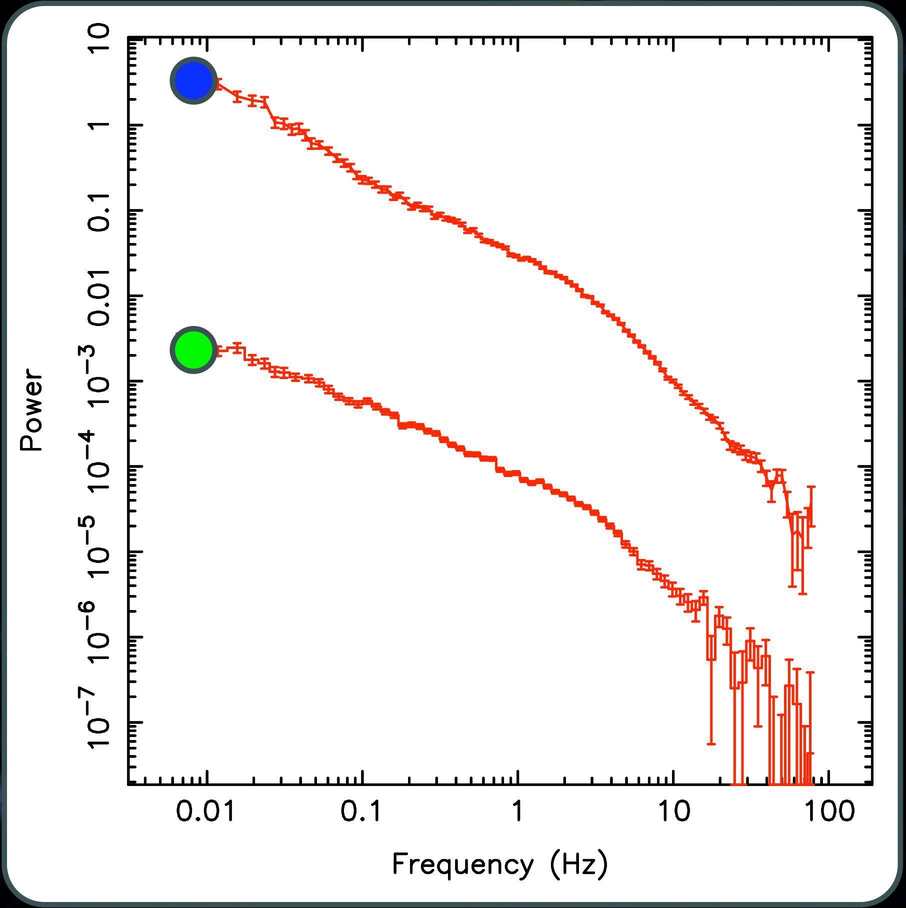
The non-SIMS regions

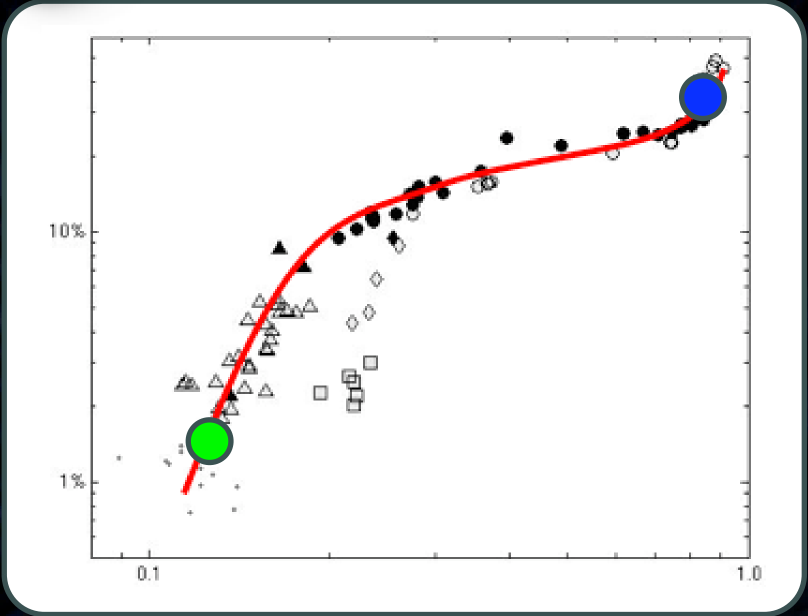




- Continous properties
- Not only frequencies
- Overall noise level
- What connection?

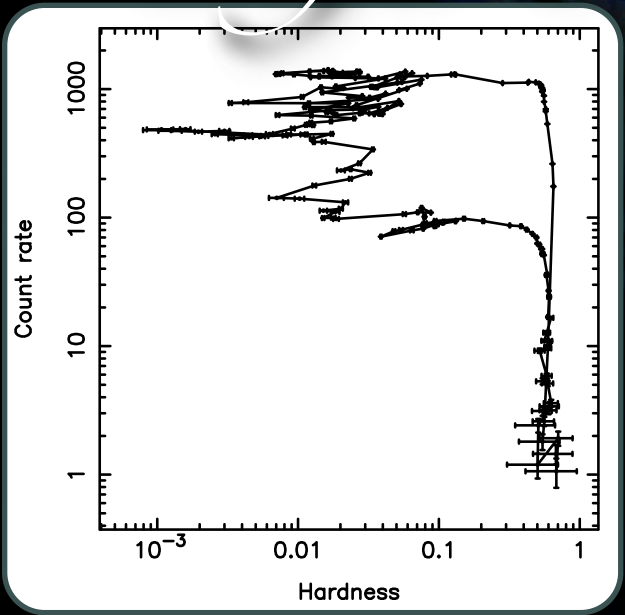
The non-SIMS regions

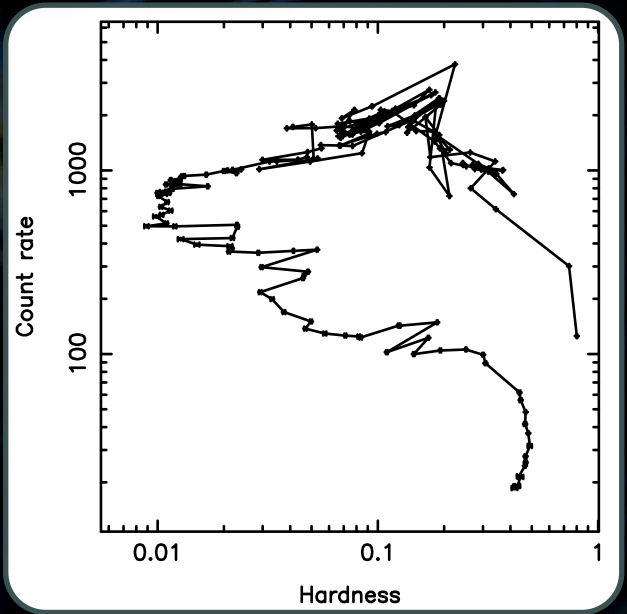


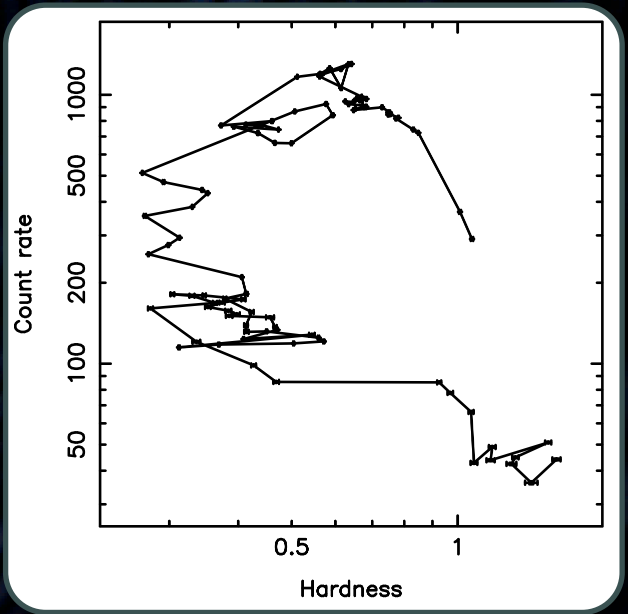


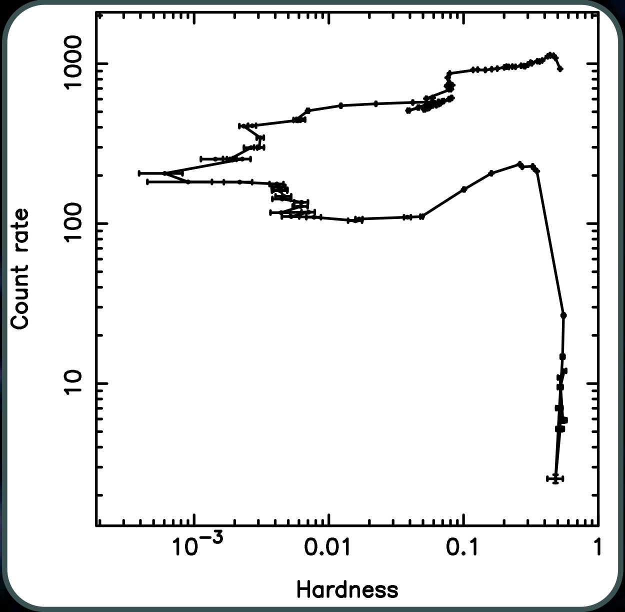
- Continous properties
- Not only frequencies
- Overall noise level
- What connection?

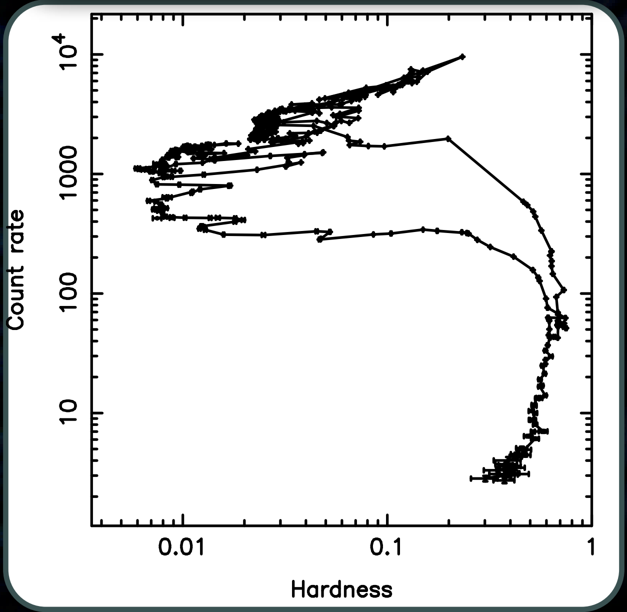
Other Sources

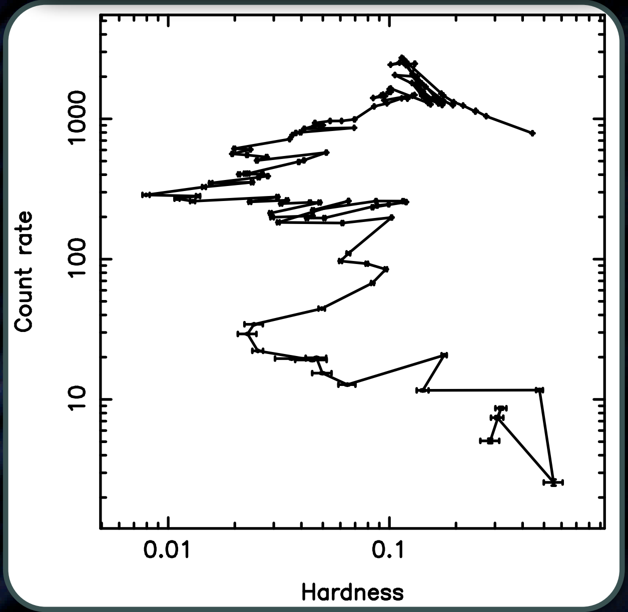




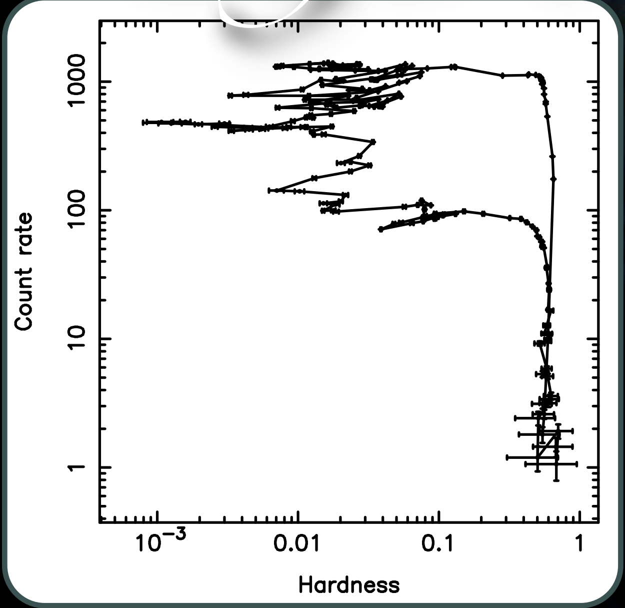


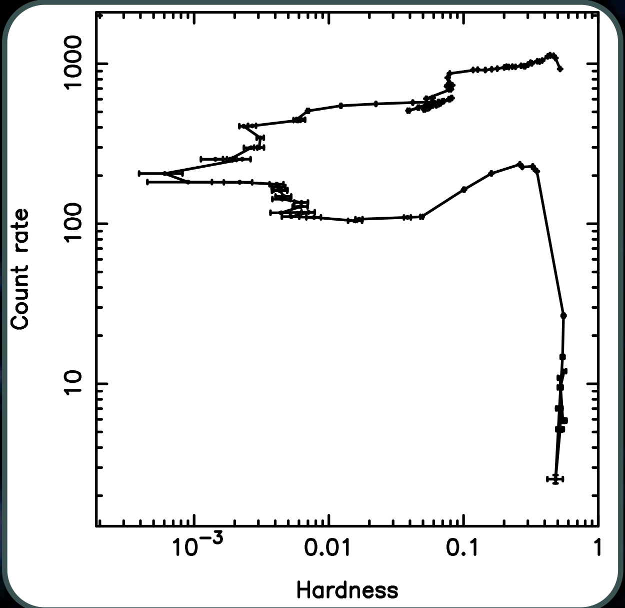


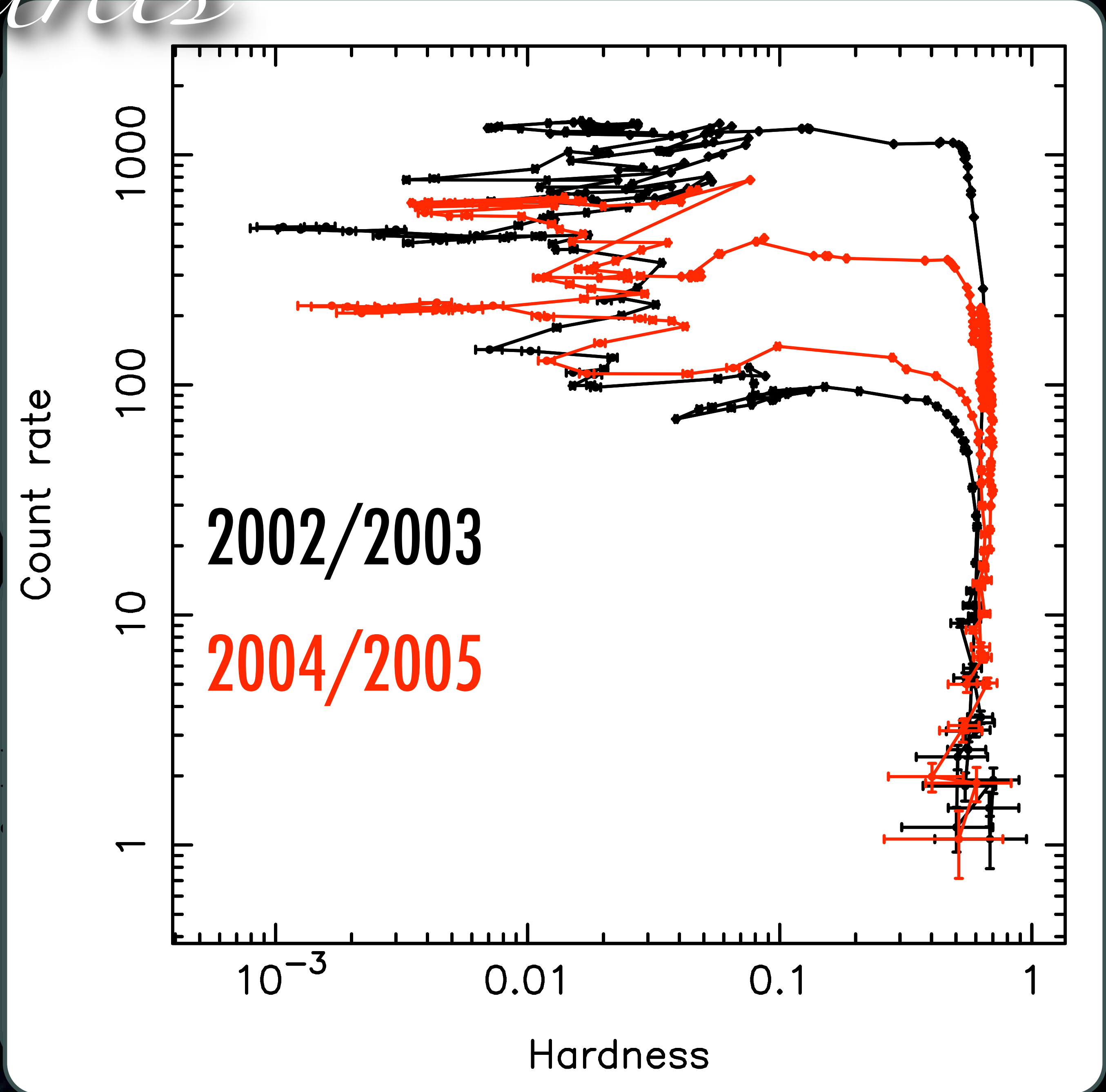




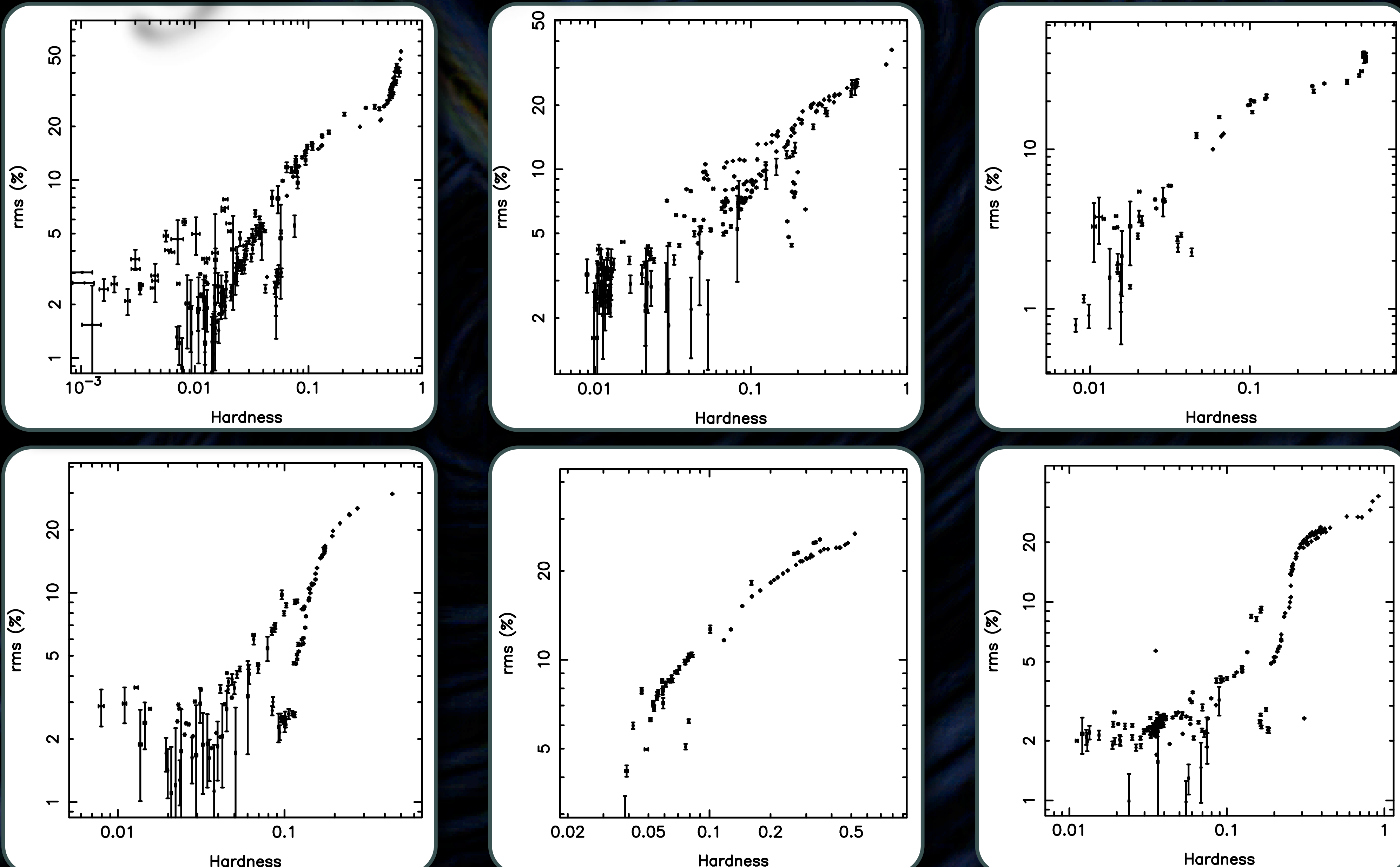
Other Sources

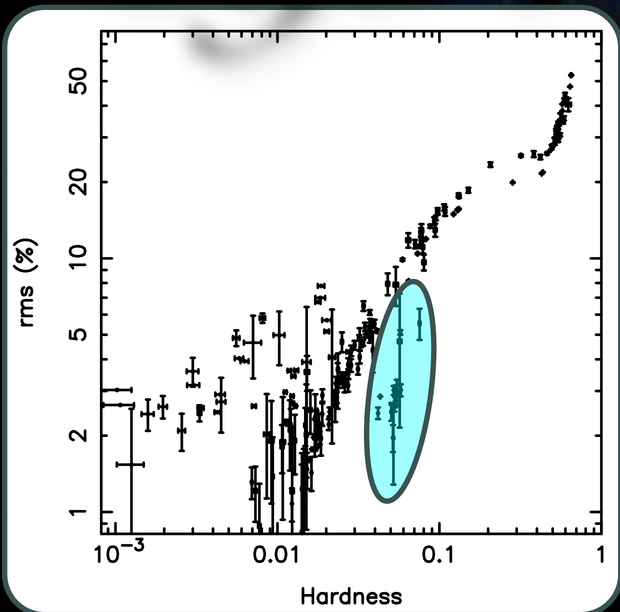


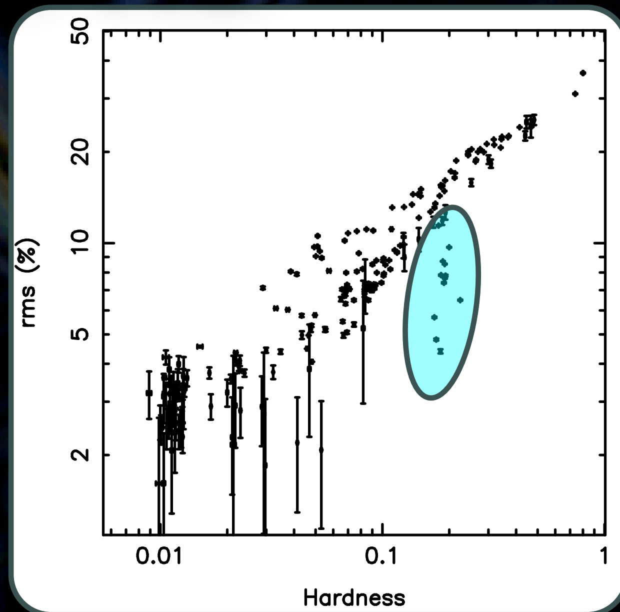


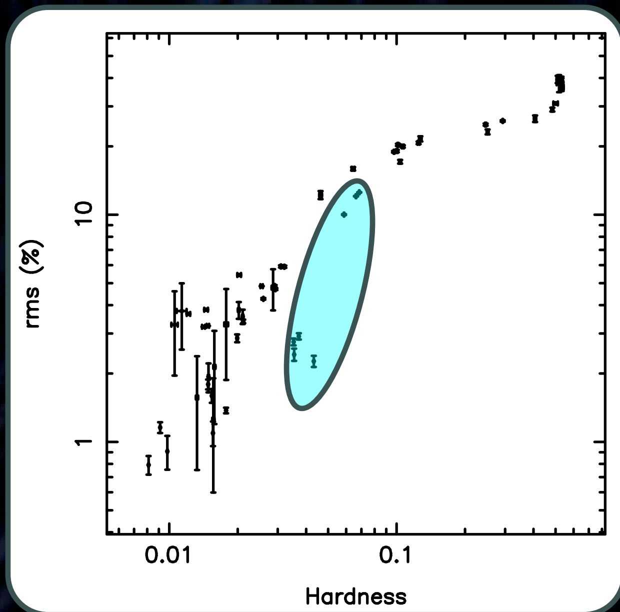


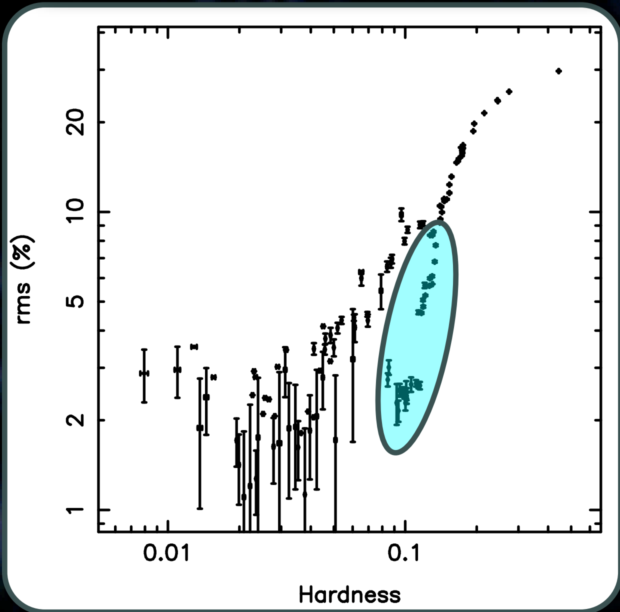
Osservatorio Astronomico di Brera

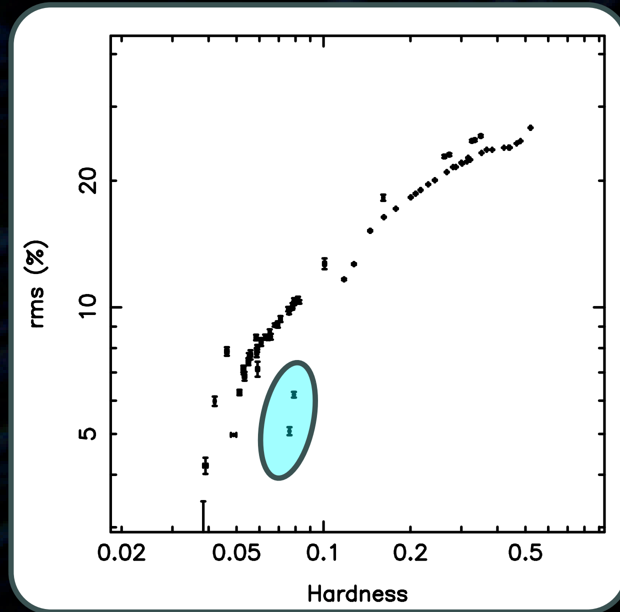


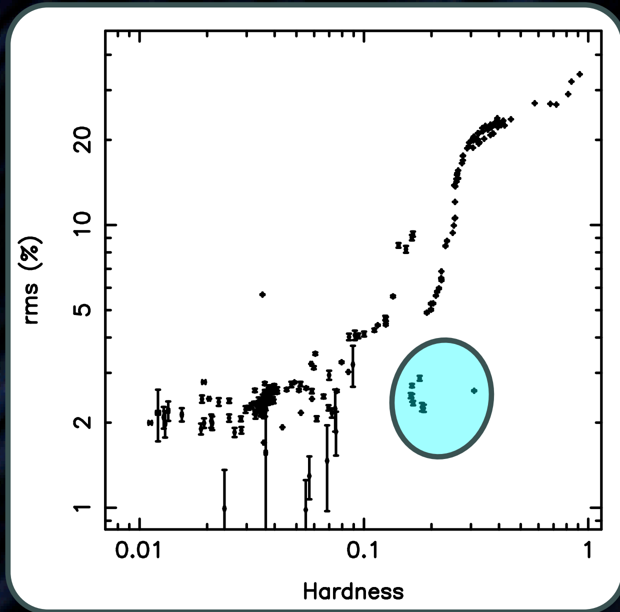

rms (%)
50
20
10
5
2
1
10^{-3}
0.01
0.1
1
Hardness


rms (%)
50
20
10
5
2
0.01
0.1
1
Hardness


rms (%)
10
1
0.01
0.1
Hardness

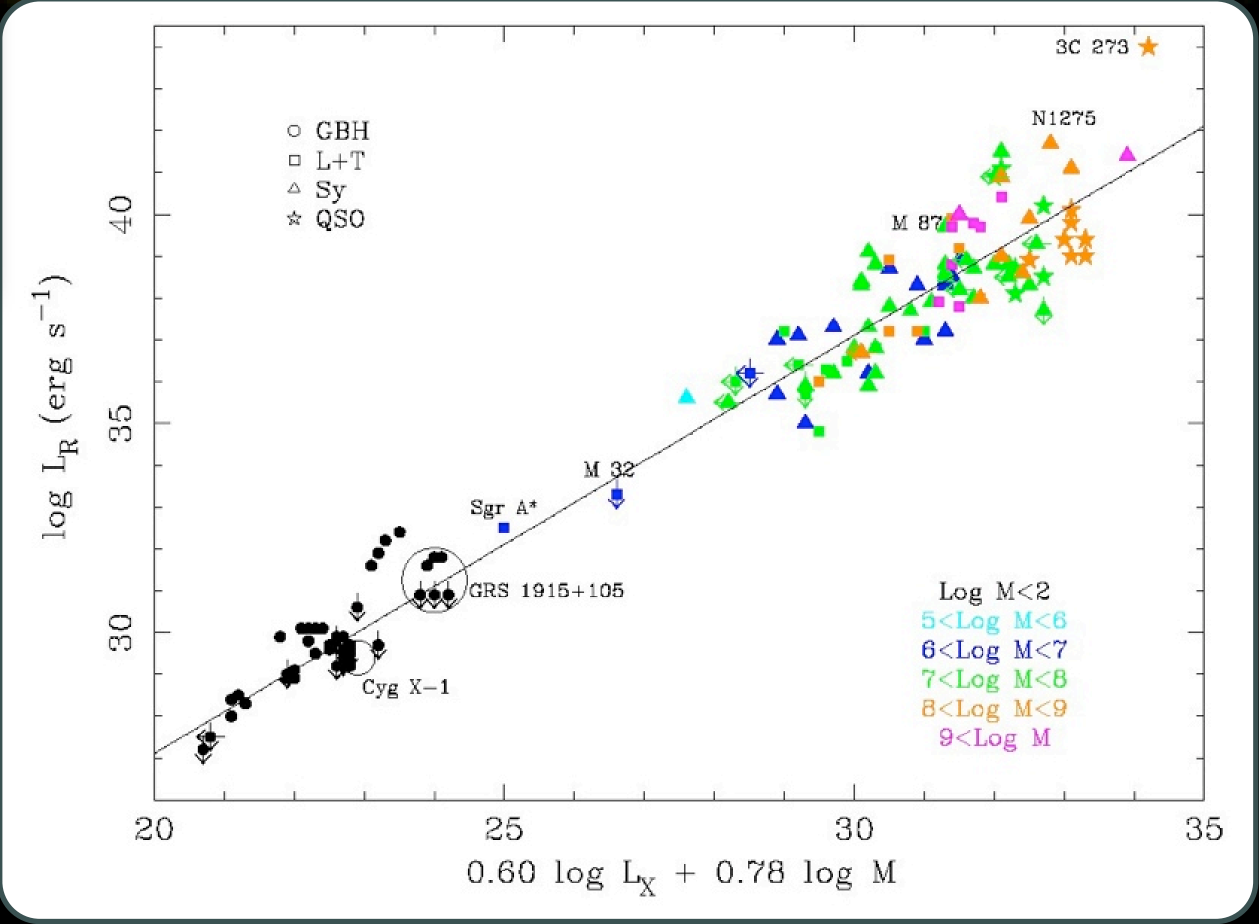

rms (%)
20
10
5
2
1
0.01
0.1
Hardness


rms (%)
20
10
5
0.02
0.05
0.1
0.2
0.5
Hardness


rms (%)
20
10
5
2
1
0.01
0.1
1
Hardness

Comparison with AGN

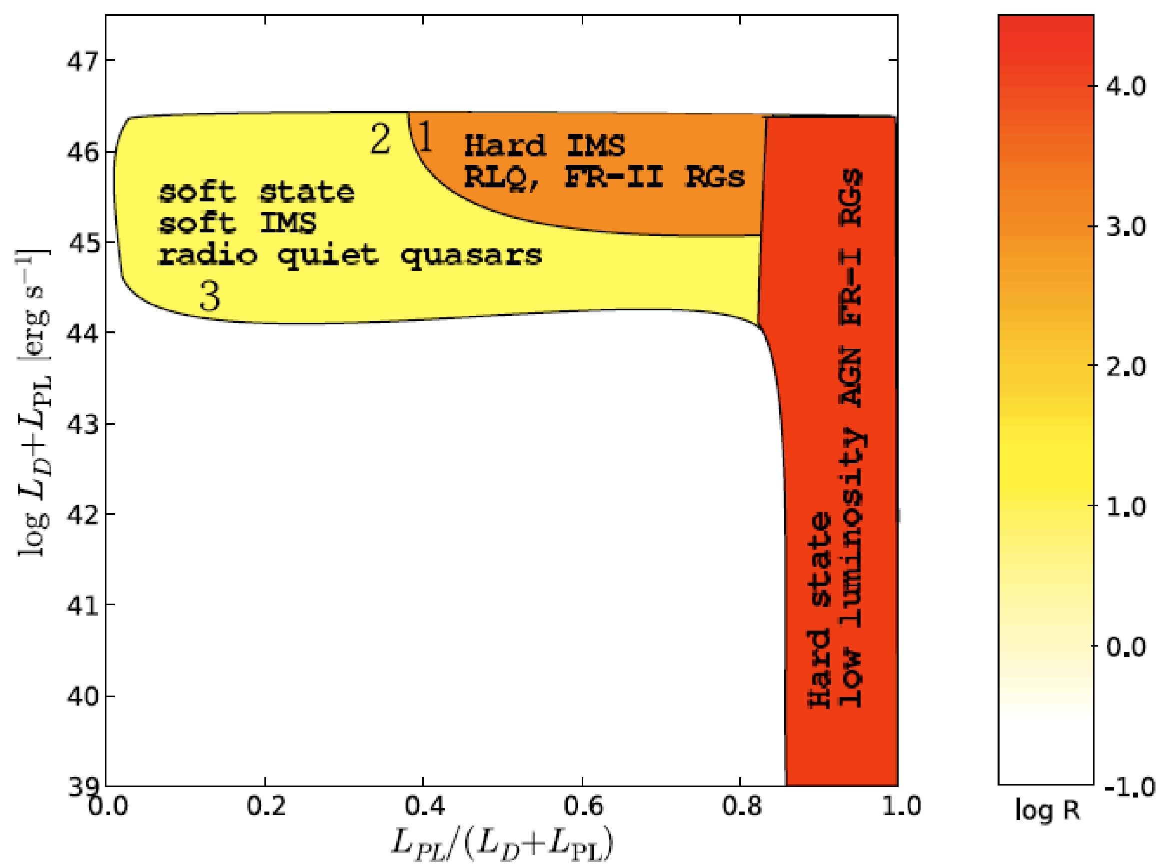
- Global correlations
- Similar behavior?
- Different time scales



Merloni, Heinz & Di Matteo (2003)

Comparison with AGN

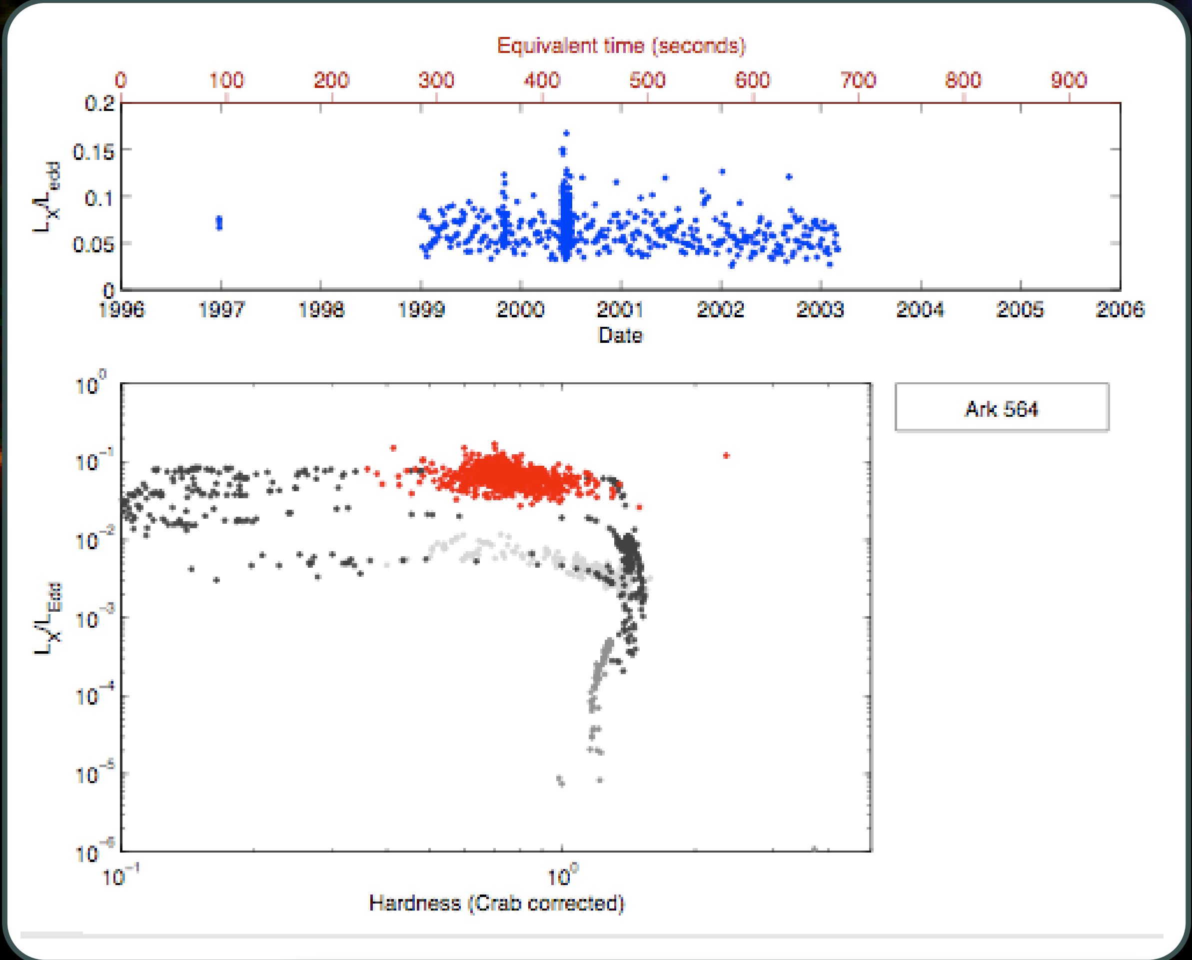
- Global correlations
- Similar behavior?
- Different time scales



Koerding, Jester & Fender (2006)

Comparison with AGN

- Global correlations
- Similar behavior?
- Different time scales



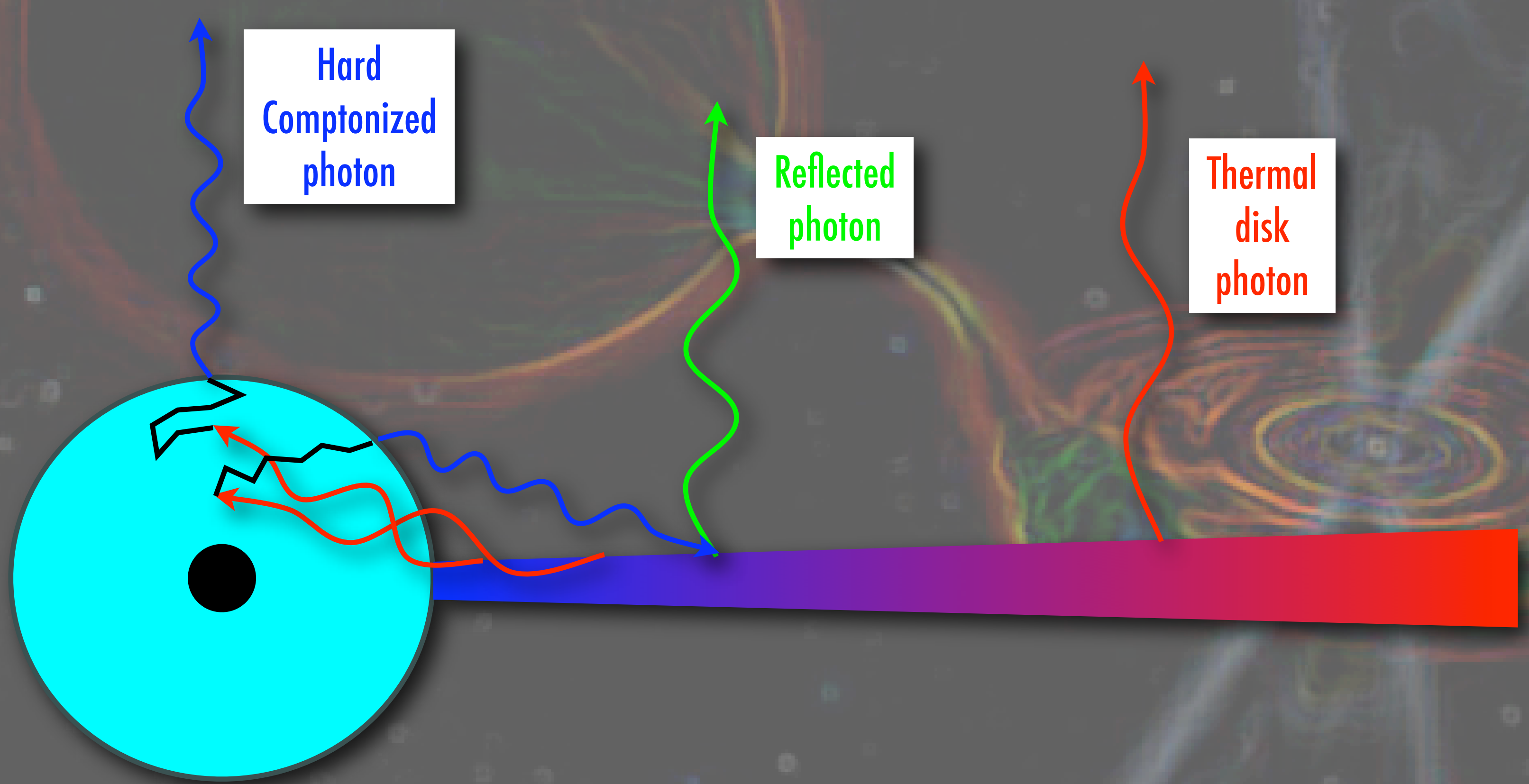
Belloni, Fender & Celotti (2006)

Outline

- X-ray binaries
- Black holes
- Accretion
- Jet ejection
- GR / Spin
  - Emission lines
  - Timing
  - Spectra

Osservatorio Astronomico di Brera

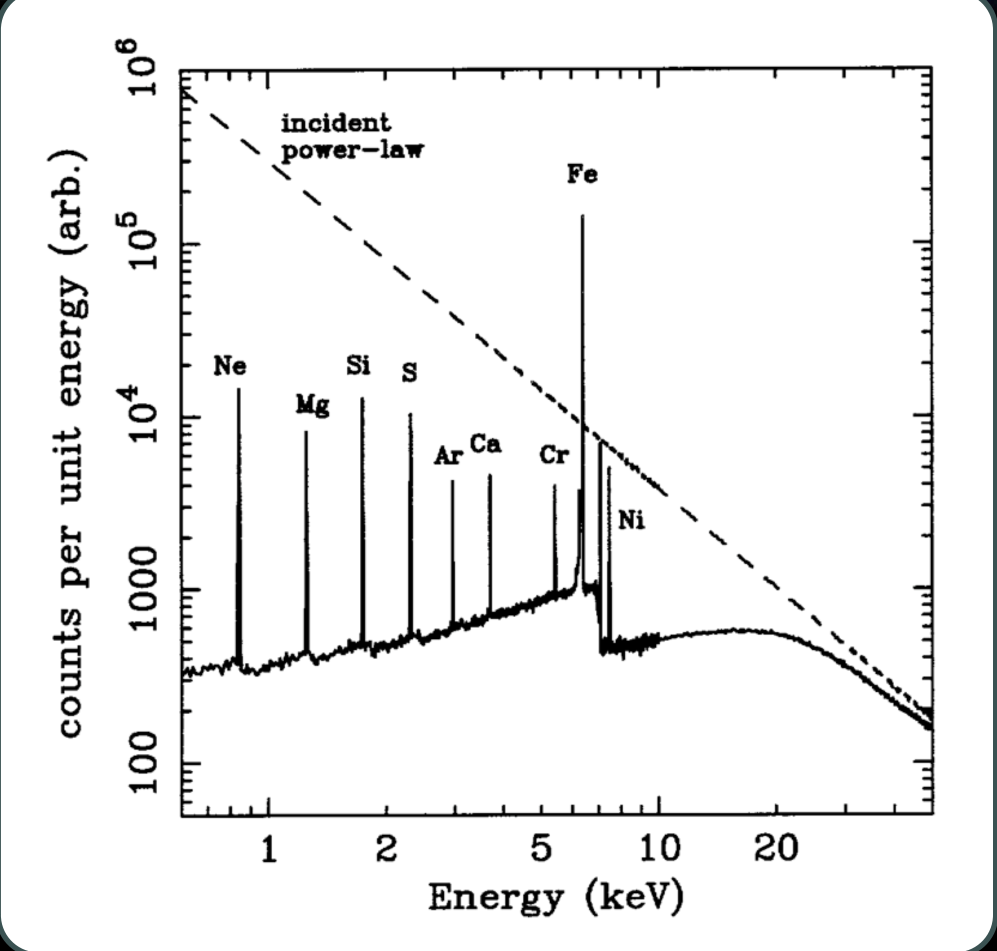
Spin: Emission lines



Reflection component

- Thermal component (disk)
- Hard component (corona, jet)
- Reflection component (disk)

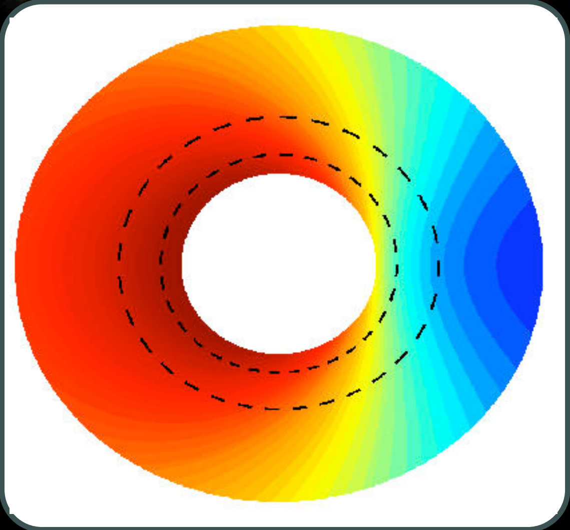
- Fluorescent emission lines
- Iron K_α

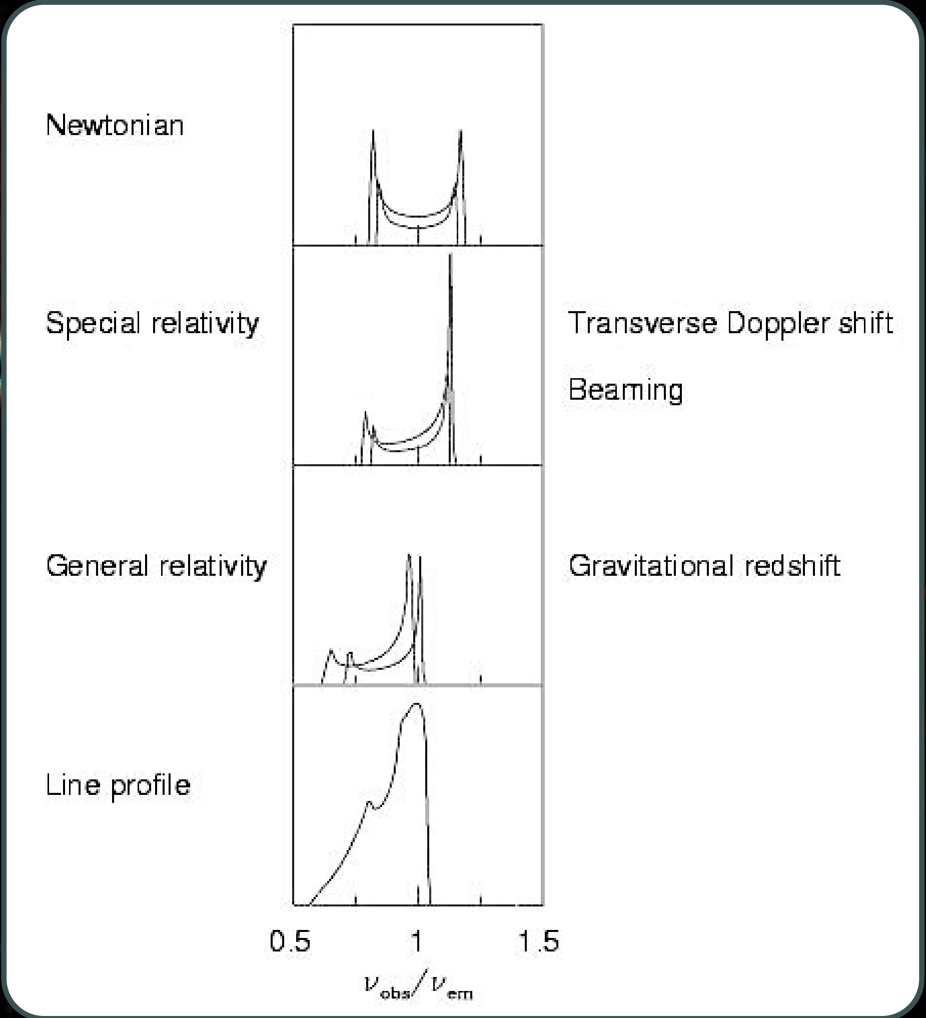


Iron emission line

Relativistic distortions

- Doppler effect
- Relativistic aberration
- Light-bending
- Redshift



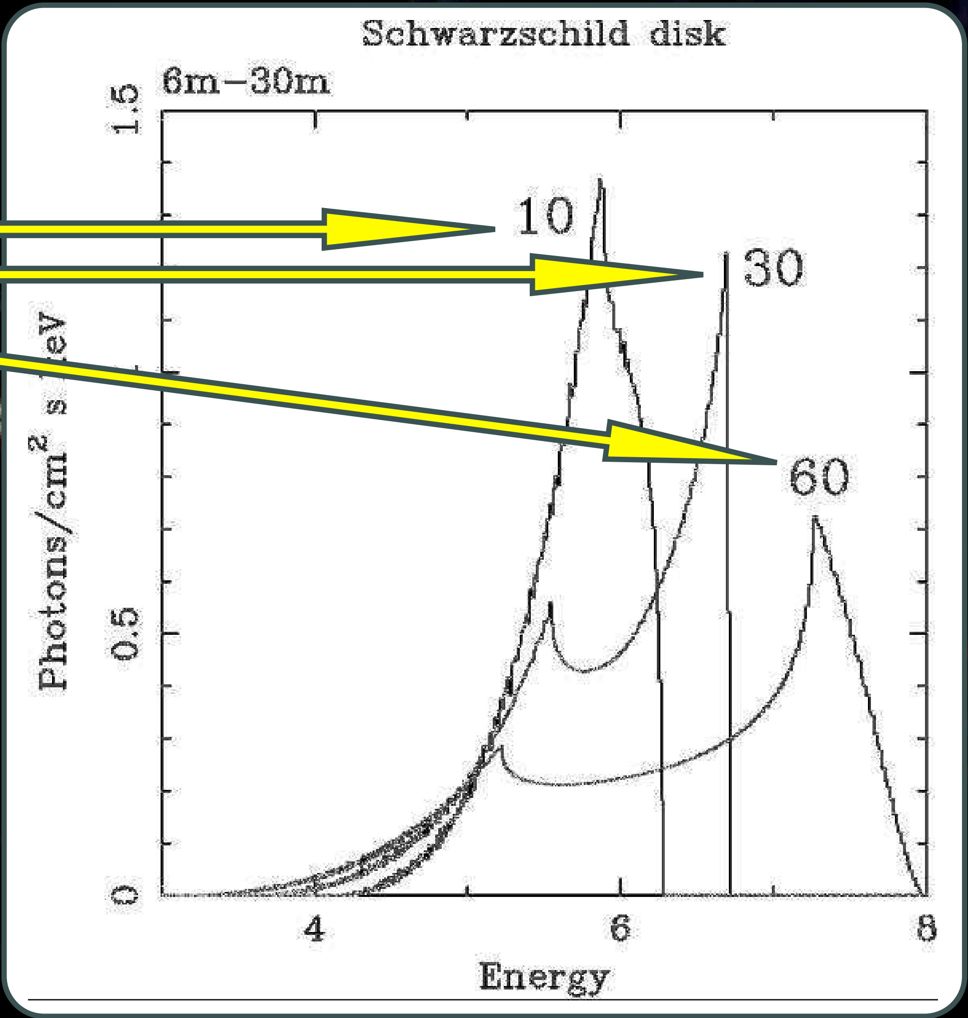


Line (Schwarzschild)

- Three inclinations

Blue wing: strong dependence on angle

Red wing: dependence on inner radius

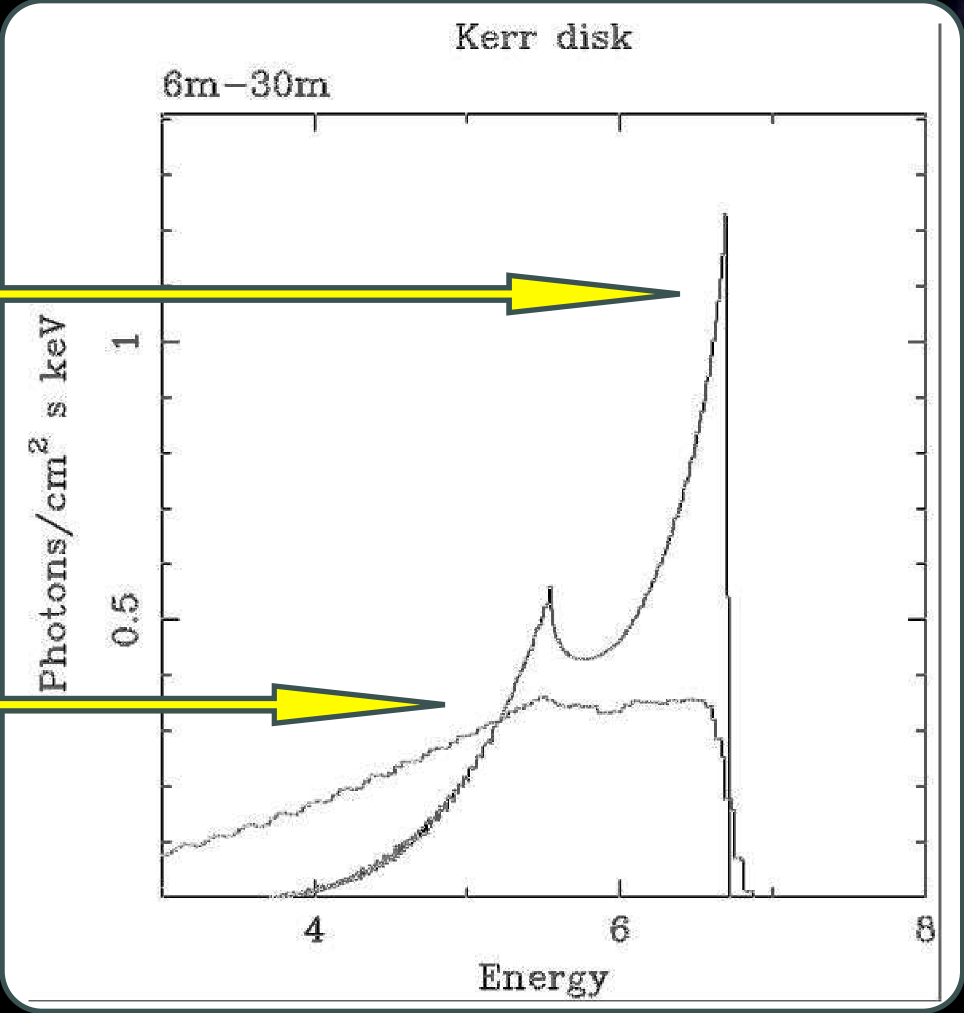


Line (Kerr)

- Three inclinations

Schwarzschild

Kerr

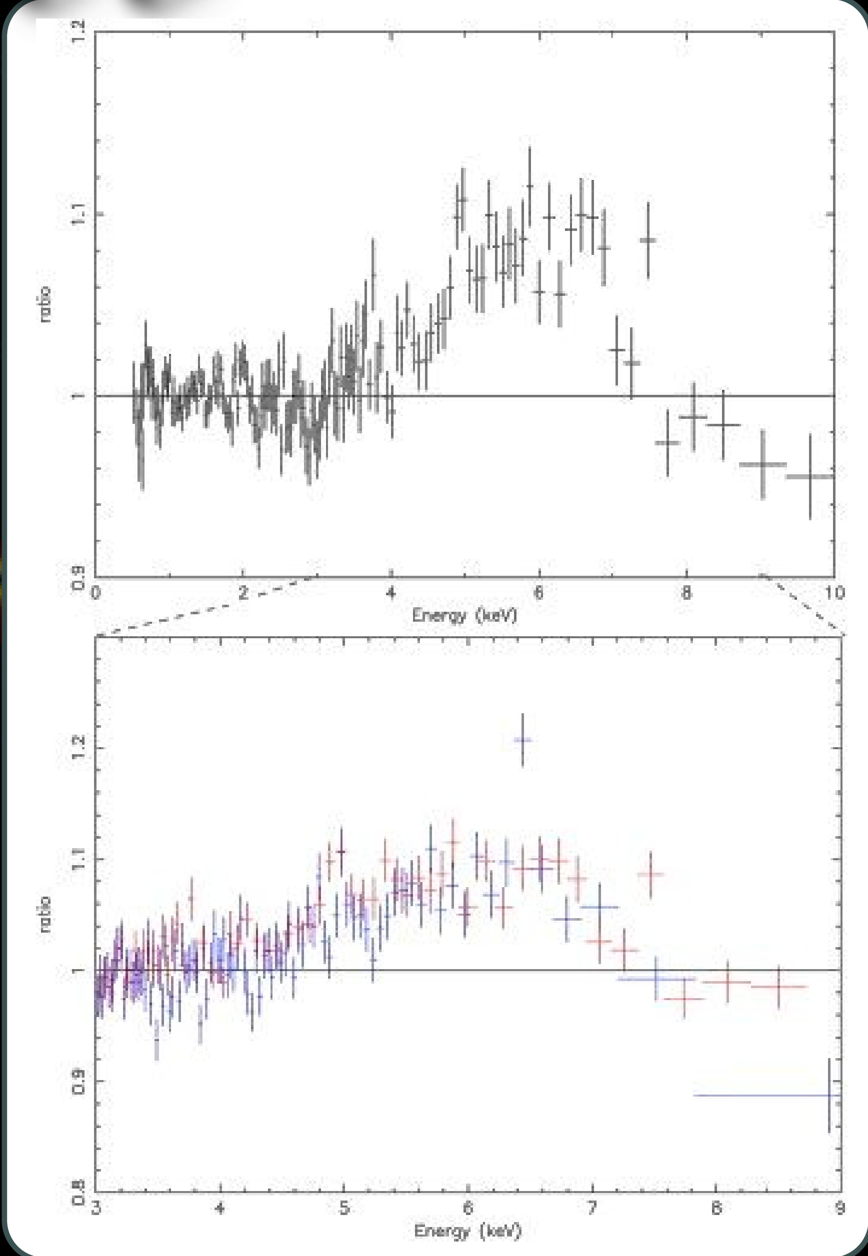


XTE J1650-500

- Broad skewed line

$$R_{in} = 1.24R_g$$

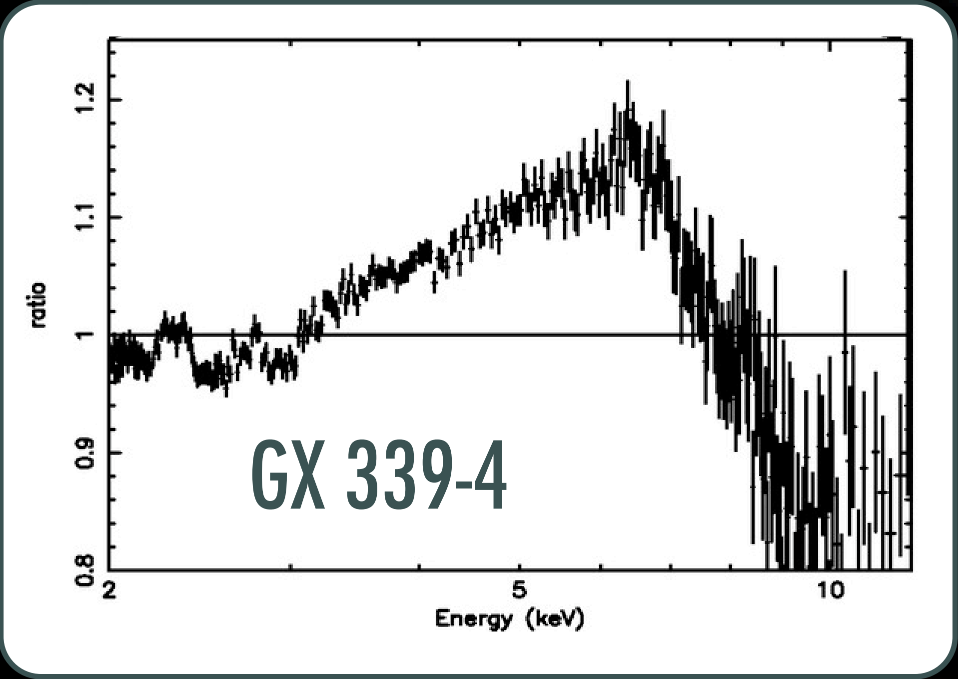
$$a = 0.998$$

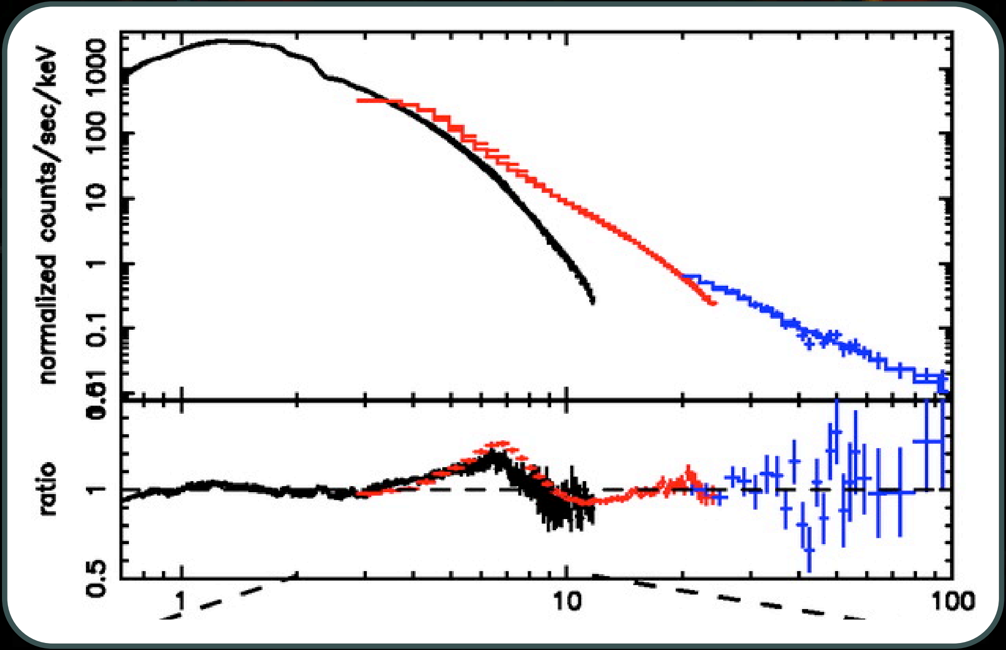


Osservatorio Astronomico di Brera

Problems, problems…

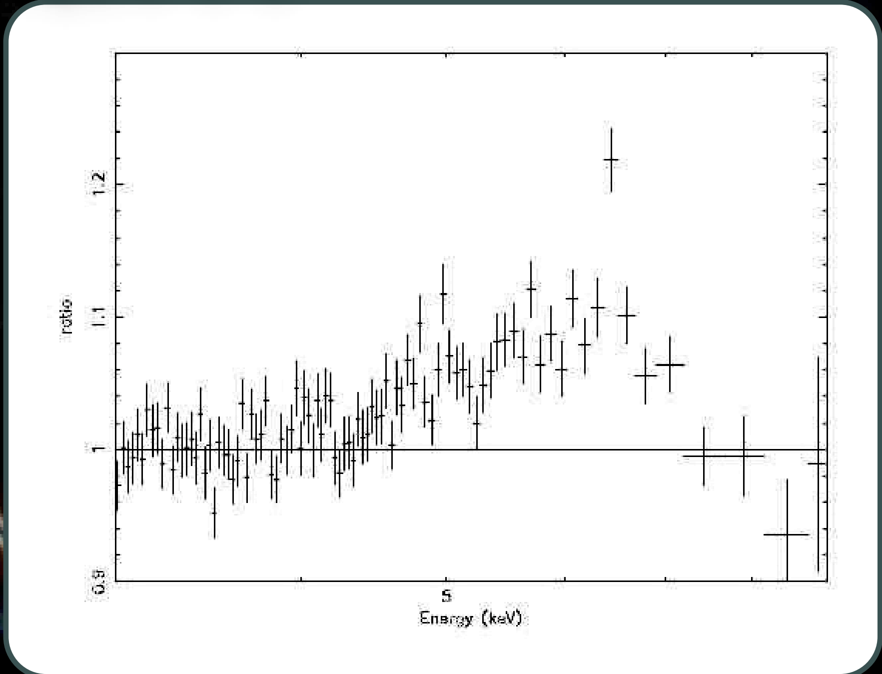
- Need broad-band
- Broad line: continuum
- Warm absorbers

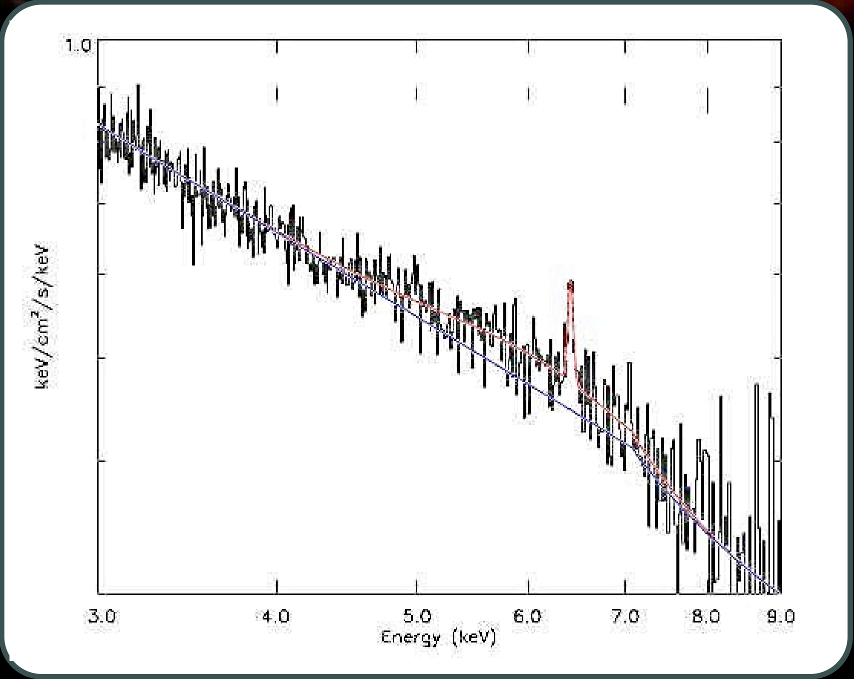




Problems, problems...

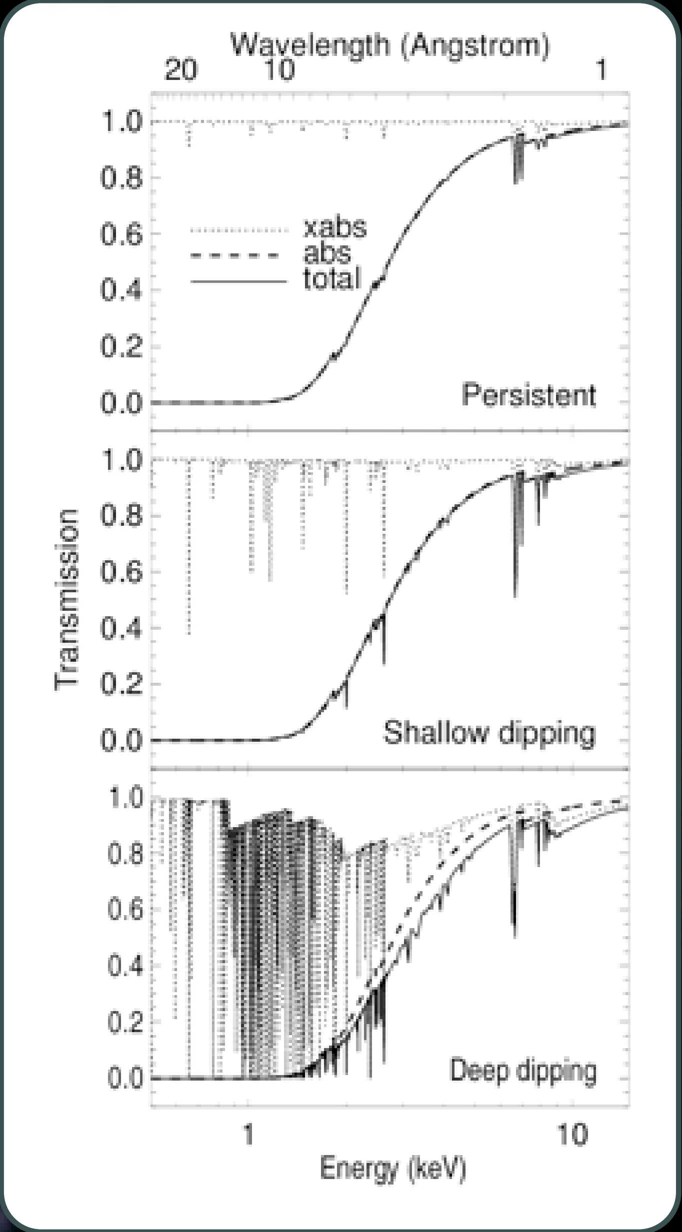
- Need broad-band
- Broad line: continuum
- Warm absorbers



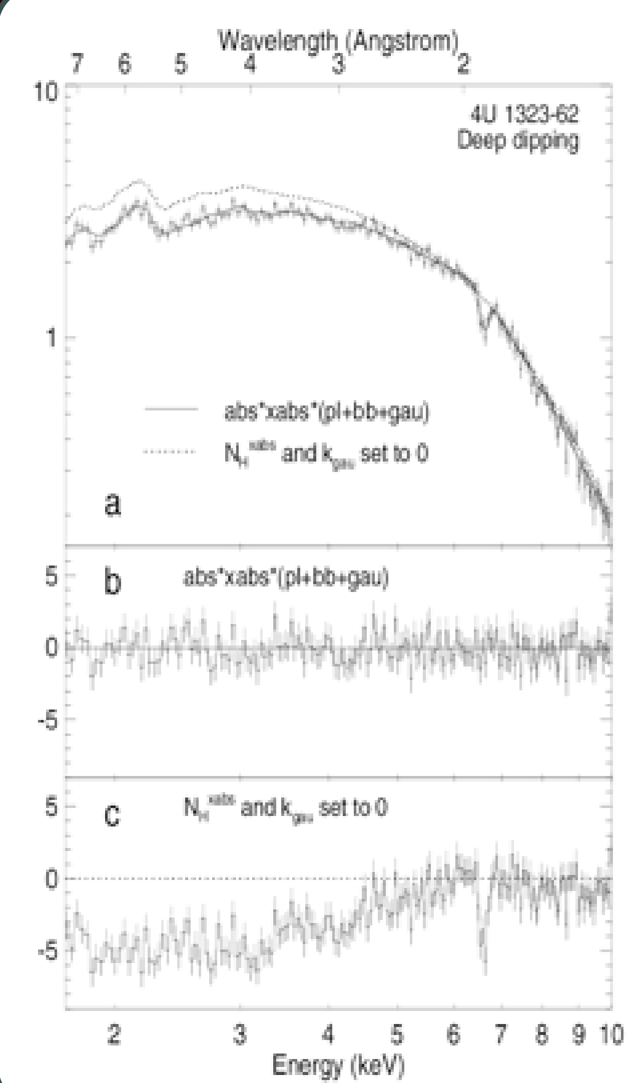


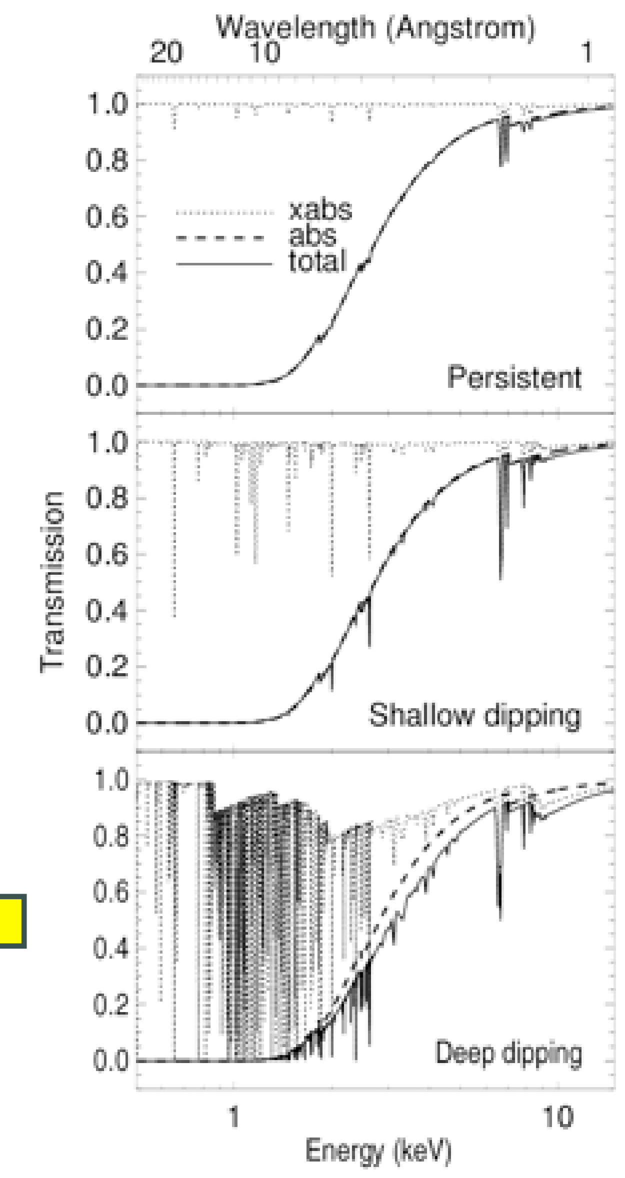
Problems, problems...

- Need broad-band
- Broad line: continuum
- Warm absorbers



Problems, problems...

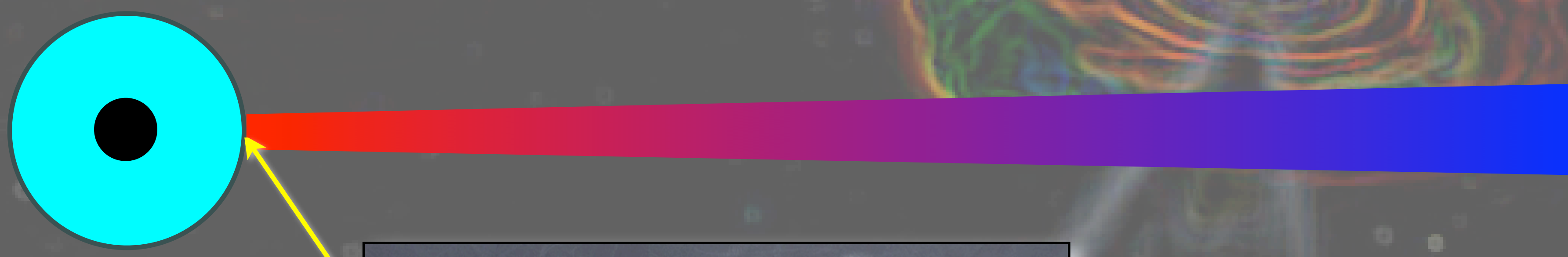




Spin: continuum

- Modeling of accretion disk
- Needs:
  - Data selection
  - Perfect physical model
  - Additional components
  - Absorption

- Based on mass
- Knowledge increase?

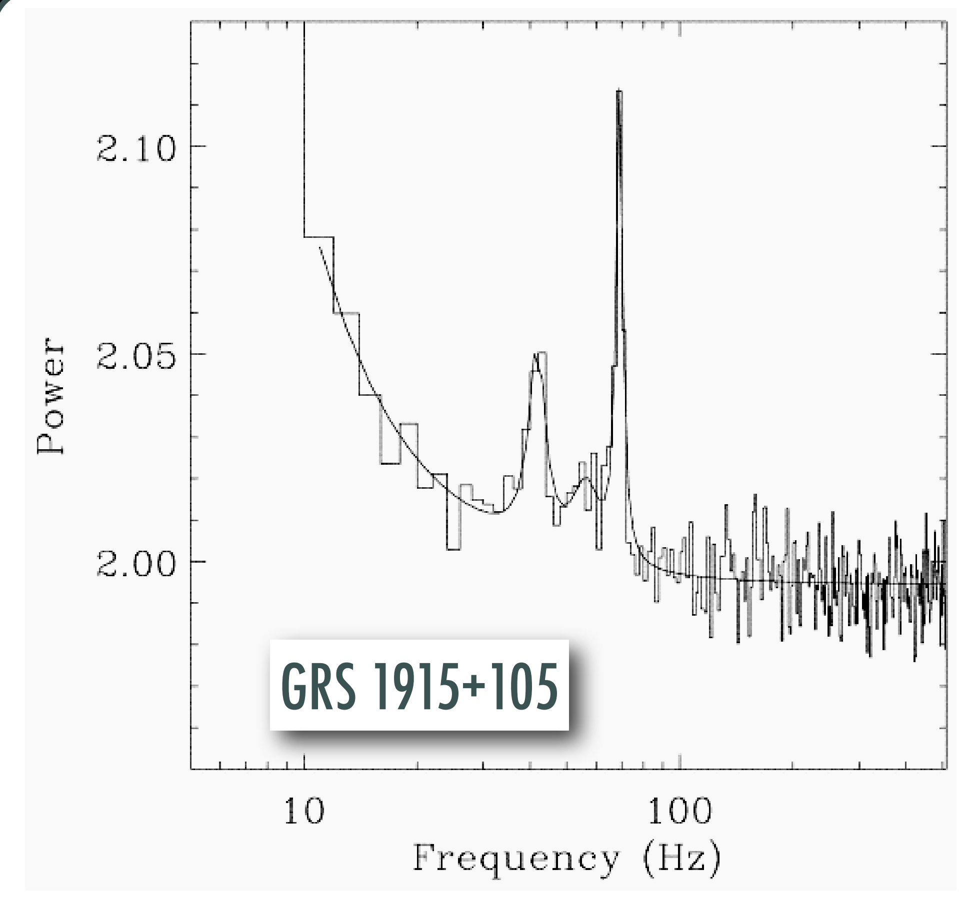


$$T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3 \sigma} \left[1 - \sqrt{\frac{R_*}{R}} \right] \right\}^{1/4}$$

GR:Timing

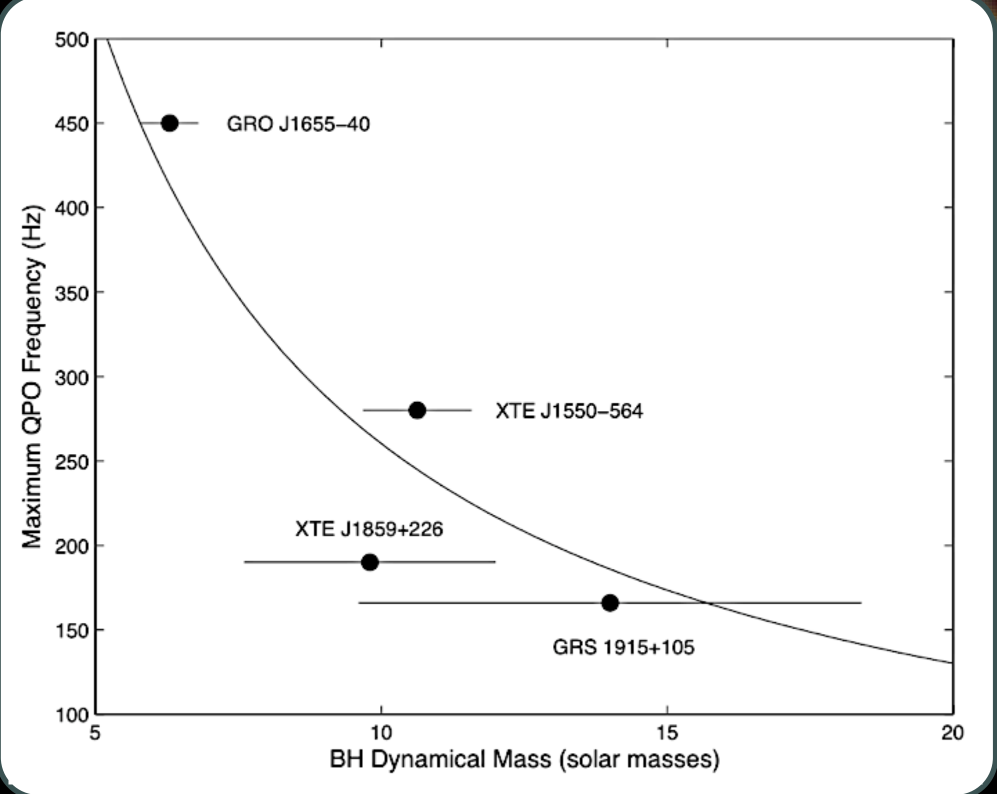
- High-frequency features
- Need physical model
- Only guesses

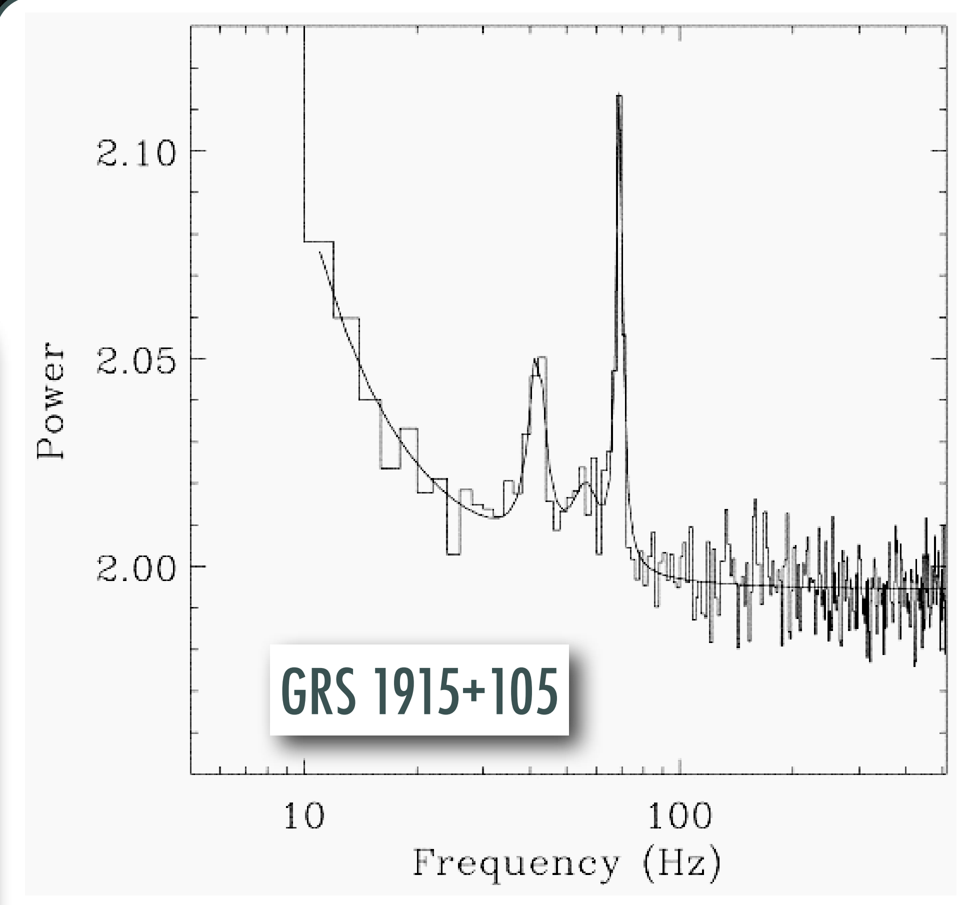
- Highest frequency
- Keplerian?



GR:Timing

- High-frequency features
- Need physical model
- Only guesses

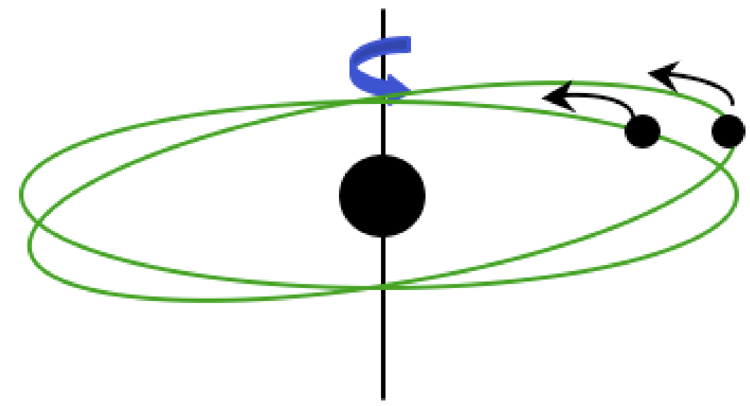


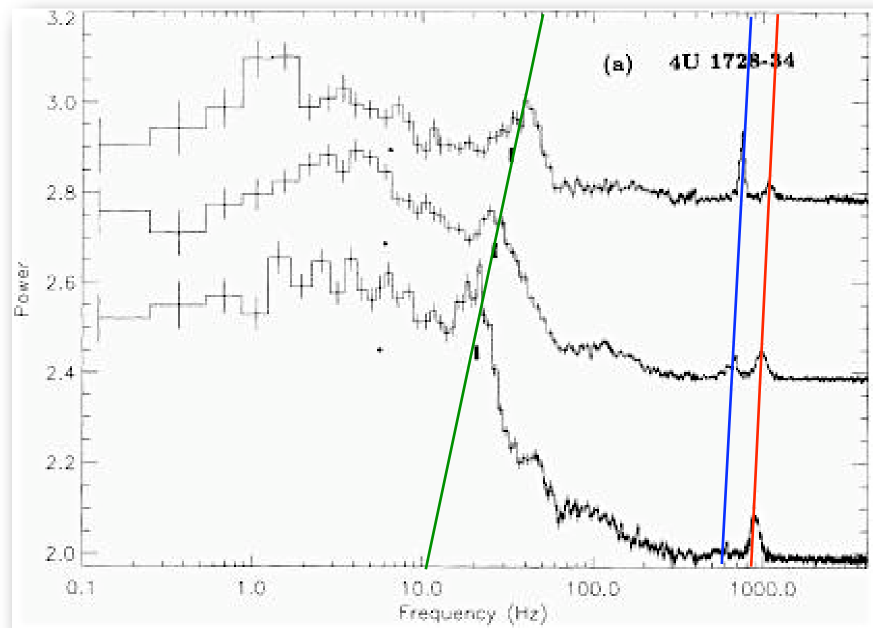


GR:Timing

- Low-frequency features
- RPM model
- Roughly consistent

- Keplerian
- Periastron precession
- Lense-Thirring

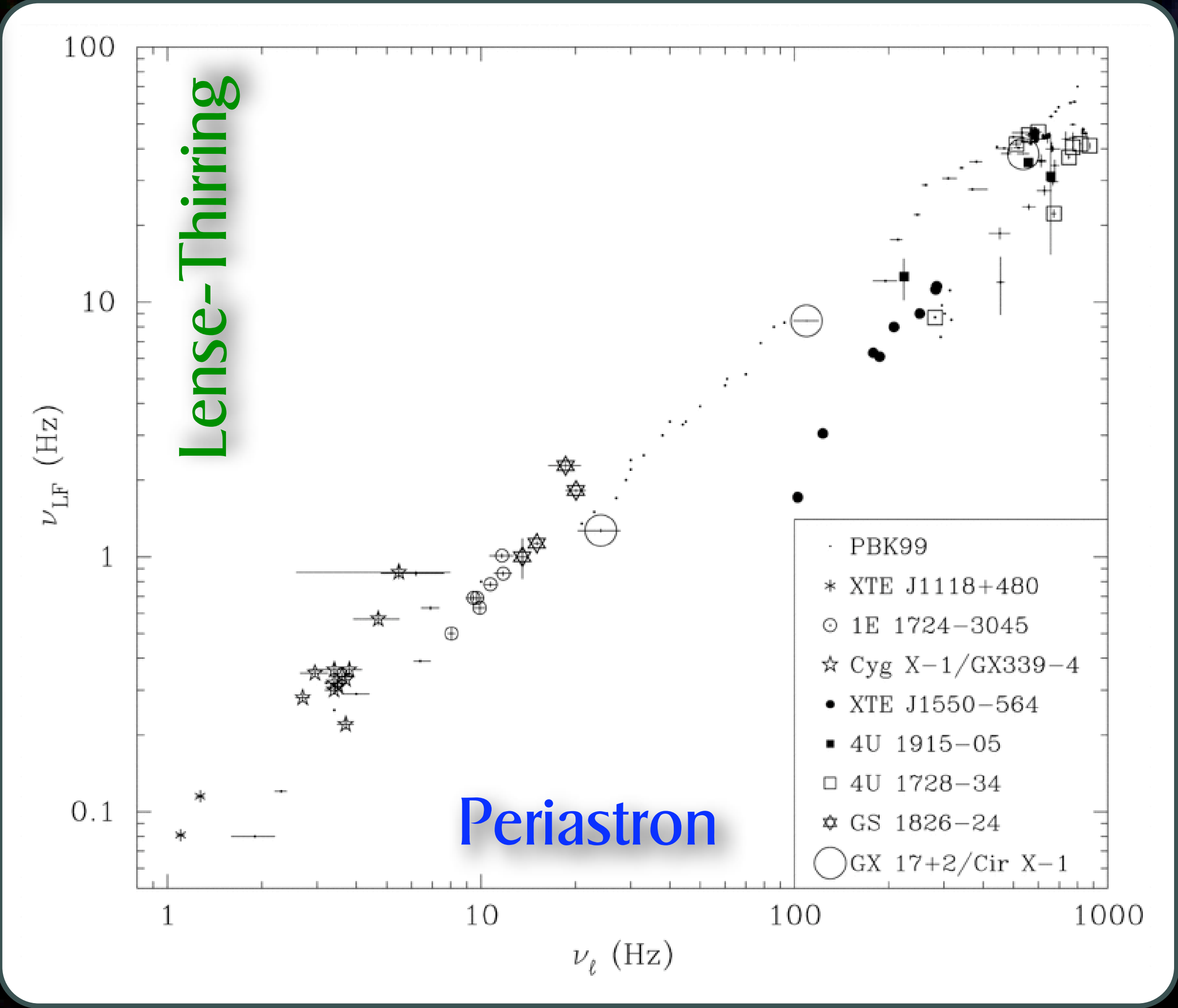




For NS binaries

GR:Timing

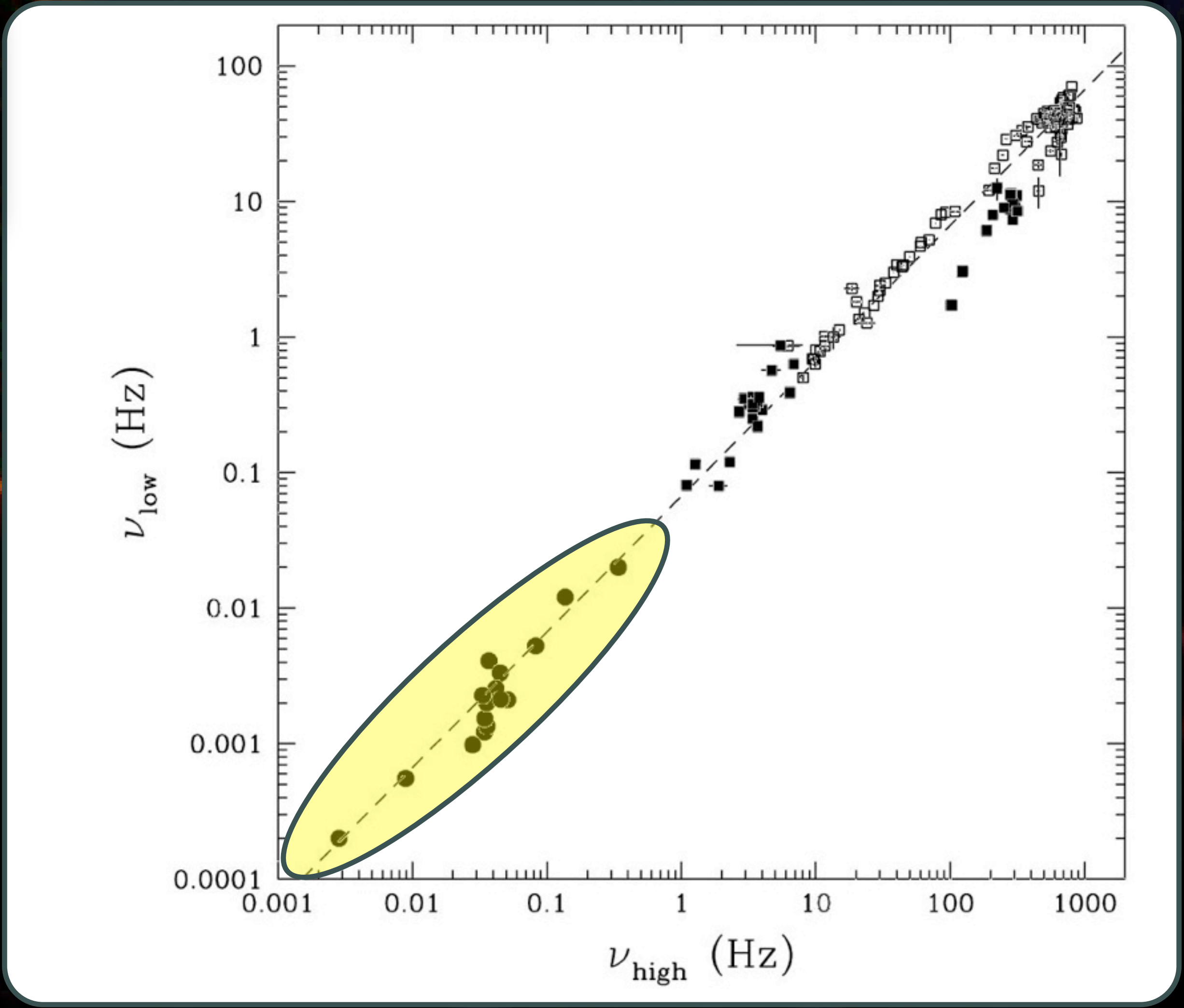
- Works for BH too
- Frequency identification



- Keplerian
- Periastron precession
- Lense-Thirring

GR:Timing

- Works for WD too
- This is a problem



Conclusions

- Masses from optical: black holes
- Accretion/jet: a picture emerges
- AGN connection: getting there
- Spin measurements: tricky
- GR: not yet

Osservatorio Astronomico di Brera