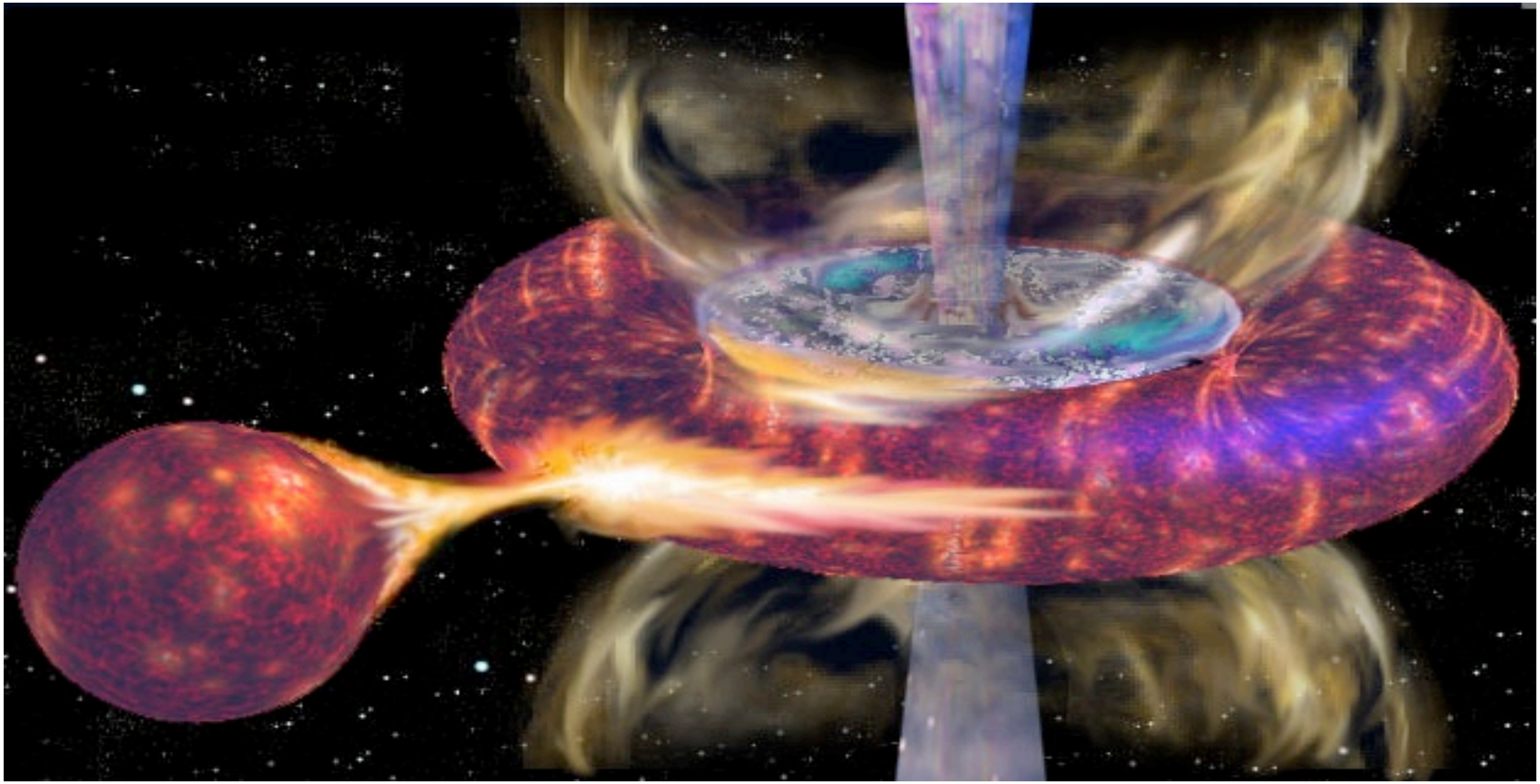
A disk instability based classification for microquasars

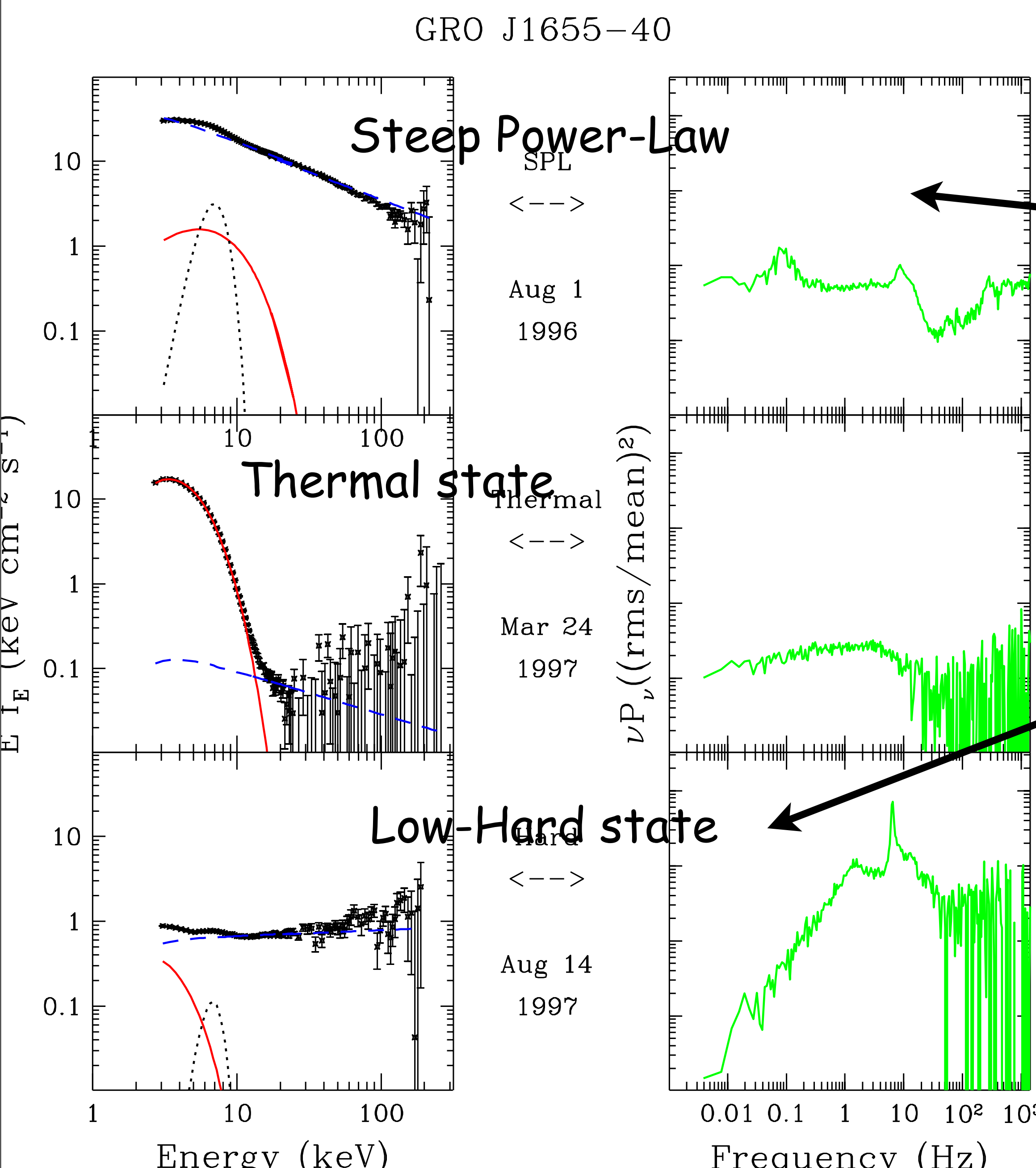


P. Varniere, M.Tagger, J.Rodriguez

Microquasar observations

a microquasar is a binary system hosting a black-hole of a few tens of solar masses being “fed” an accretion disk and emitting relativistic jets.

Microquasars appear to transit between several states, here we are mainly interested in the ones displaying timing variability known as Quasi-Periodic Oscillations (QPOs)



The Steep Power-Law state involves

- disk and power-law emissions are both present
- Low Frequency Quasi Periodic Oscillation (LFQPO)
- and High Frequency Quasi Periodic Oscillation (HFQPO)

The low-hard state involves

- mostly power-law spectrum
- emission of a steady jet
- and Low Frequency Quasi Periodic Oscillation

large variety of observations (X-rays, Gamma rays, Infra-Red, radio,...) and techniques (timing, lags)

➜ many constraints on theories

AEI and LFQPO

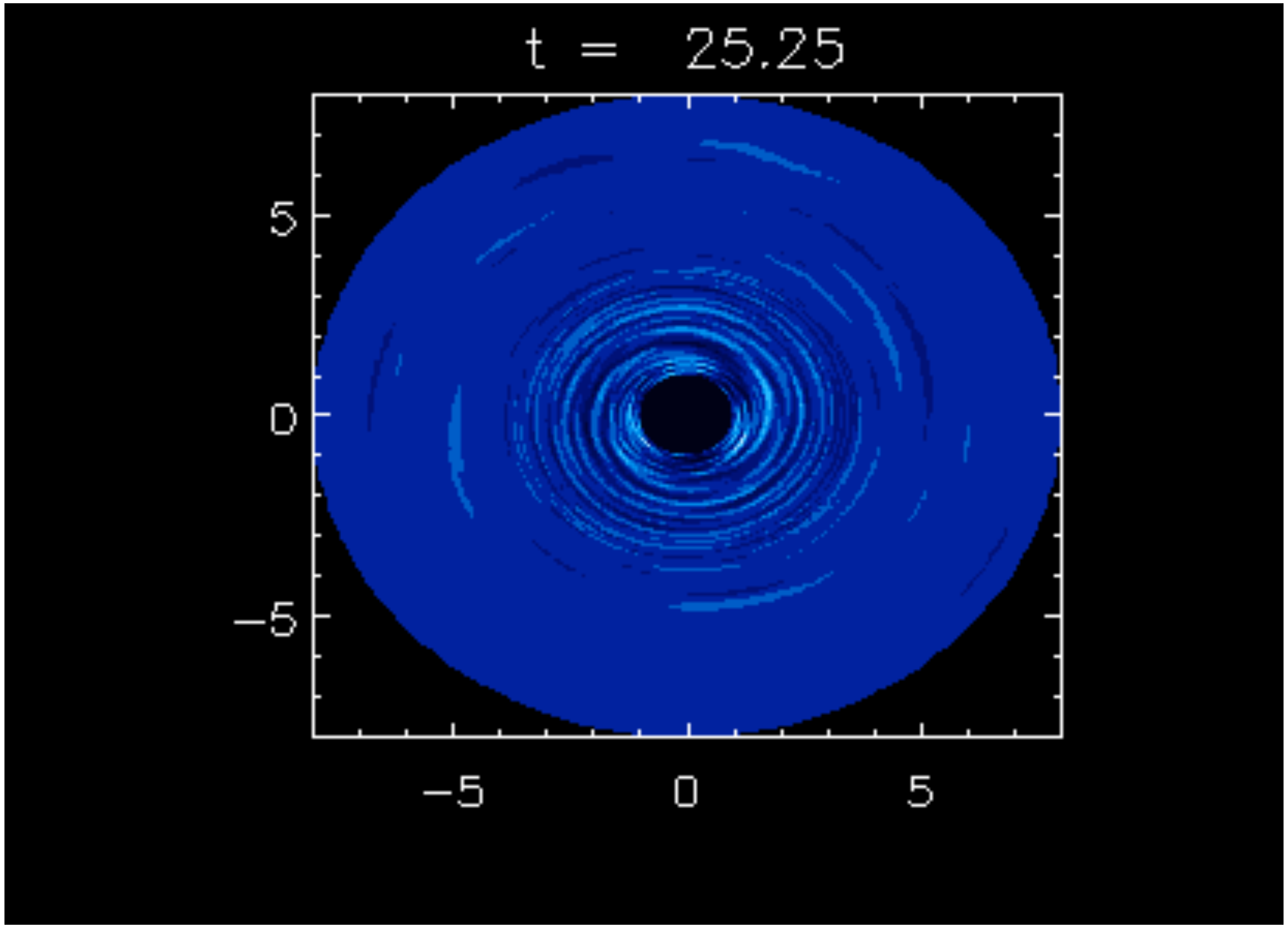
in a disk threaded by a vertical B $\sim$ equipartition

needs positive gradient of magneto-vortensity:

$$\mathcal{L}_B = \frac{\kappa^2}{2\Omega}\,\frac{\Sigma}{B^2}$$

➔ application to LF-QPO: frequency/radius, correlation with jet/radio, global properties...

AEI and LFQPO



in a disk threaded by a vertical B ~ equipartition

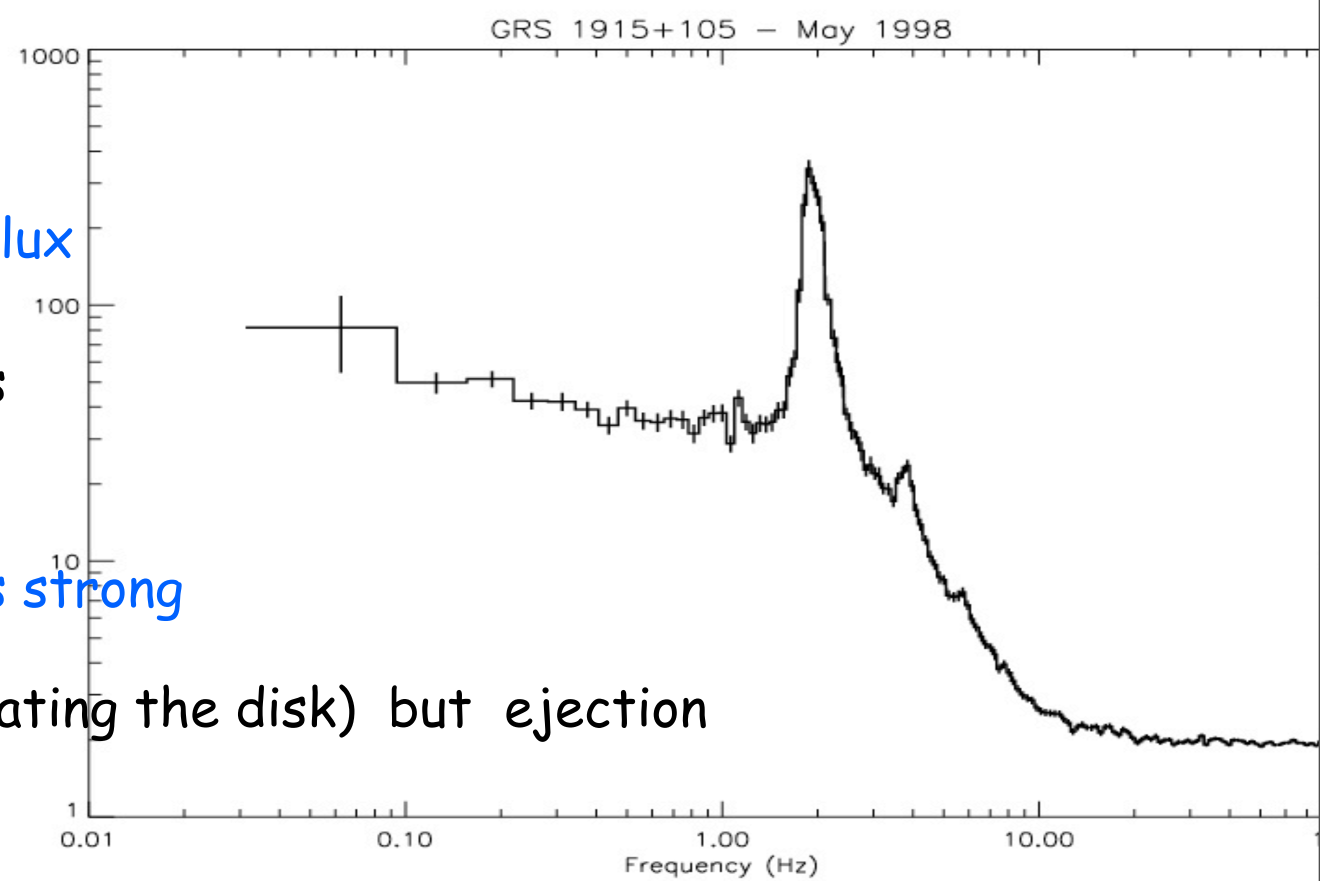
needs positive gradient of magneto-vortensity:

$$\mathcal{L}_B = \frac{\kappa^2}{2\Omega} \frac{\Sigma}{B^2}$$

➔ application to LF-QPO: frequency/radius, correlation with jet/radio, global properties...

Looking for a LFQPO model

- variable frequency between 1-30 Hertz, with a fast change
  - ➥ the frequency of the spiral wave is a few time the rotation frequency at the inner edge of the disk
- coherence ⇒ QPO can't be due to blobs ⇒ global organized motion of the gas = normal modes
- rms amplitude as much as 30% ⇒ QPO can't happen by random processes (blobs) ⇒ must be due to strong disk (+ corona ?) instabilities
- correlation of the LFQPO frequency with the soft flux
  - ➥ comparison with observation of several objects
- QPO associated with a state where the power-law is strong
  - ➥ accretion energy not deposited locally (not heating the disk) but ejection through Alfven Waves emission



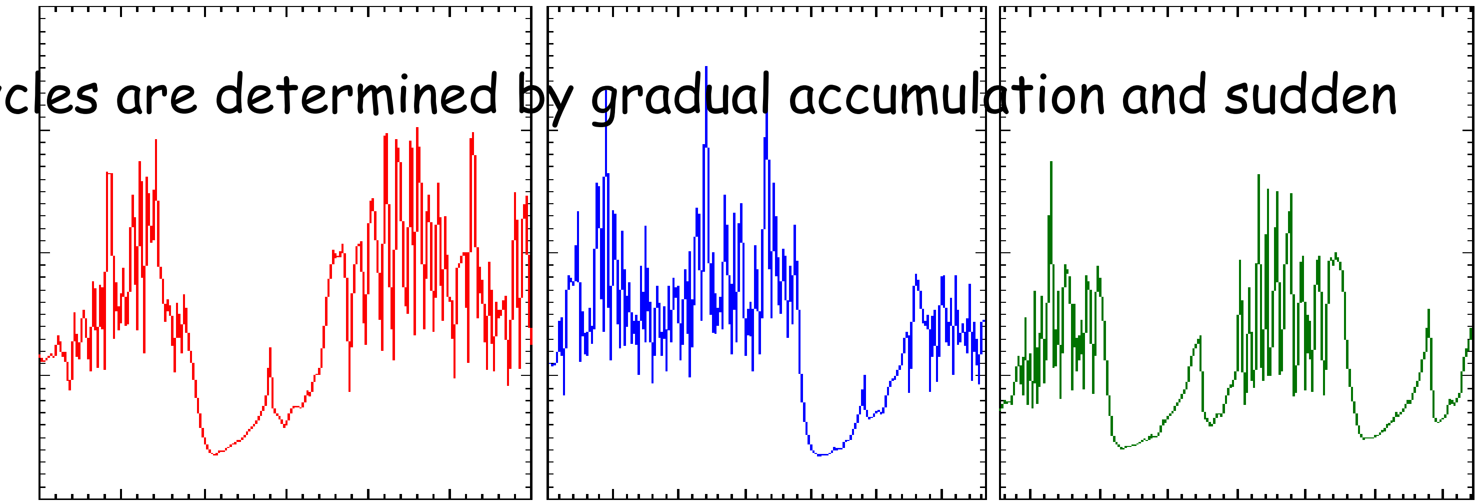
- the existence of several "types" of LFQPO with distinct characteristics (A, B and C)
- lag sometimes changing sign, sub-harmonic structure...

The Magnetic Flood Scenario

the AEI is a candidate to explain the LFQPO and can also be linked with ejection.

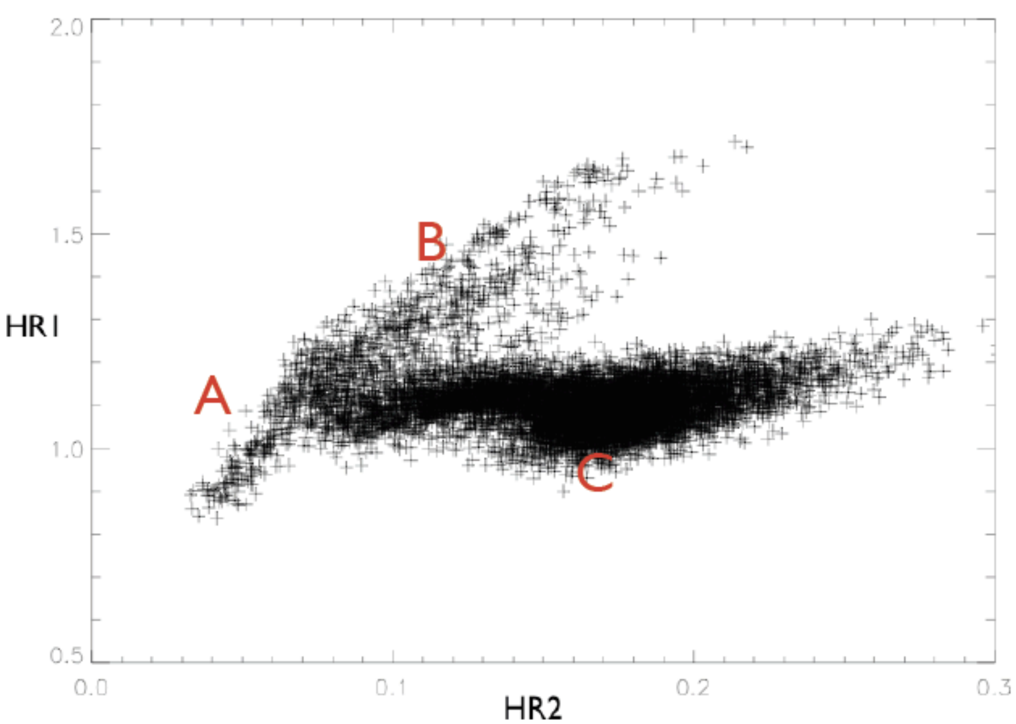
next step : assume that AEI ⇔ QPO … then try to understand ….

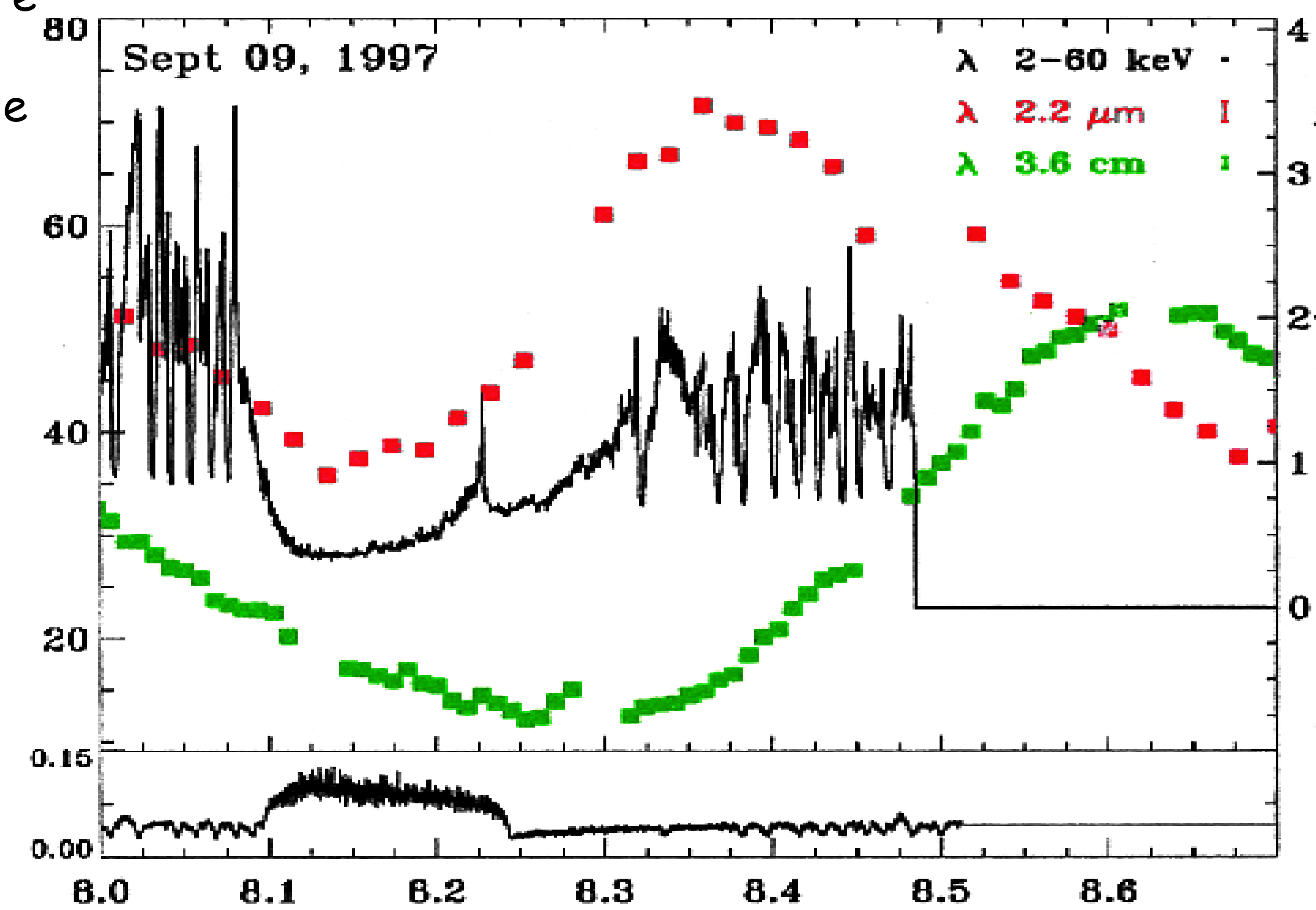
➜ "Magnetic Floods" scenario : the cycles are determined by gradual accumulation and sudden destruction of magnetic flux



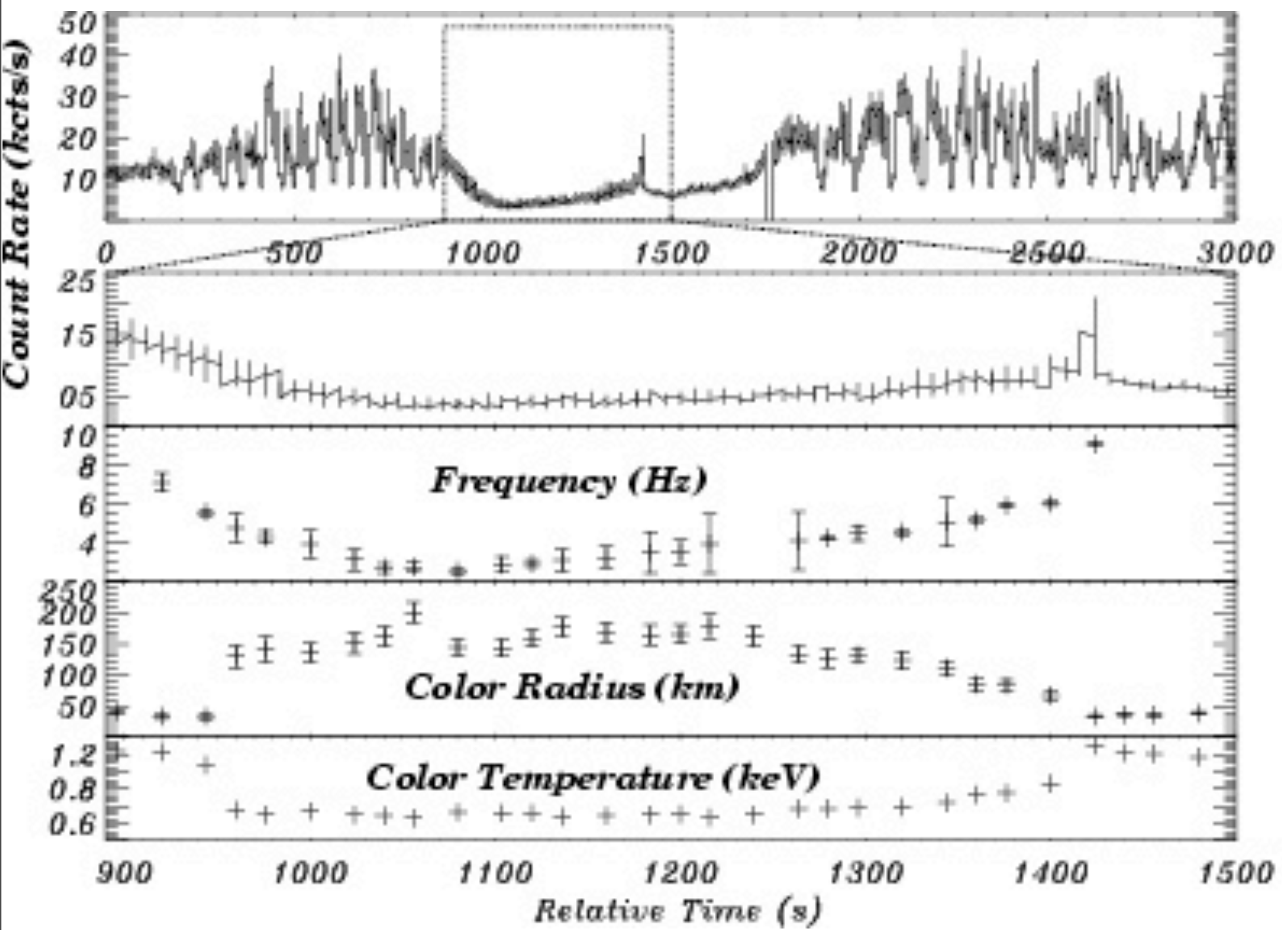
we looked at the cycles of GRS 1915+105 because:

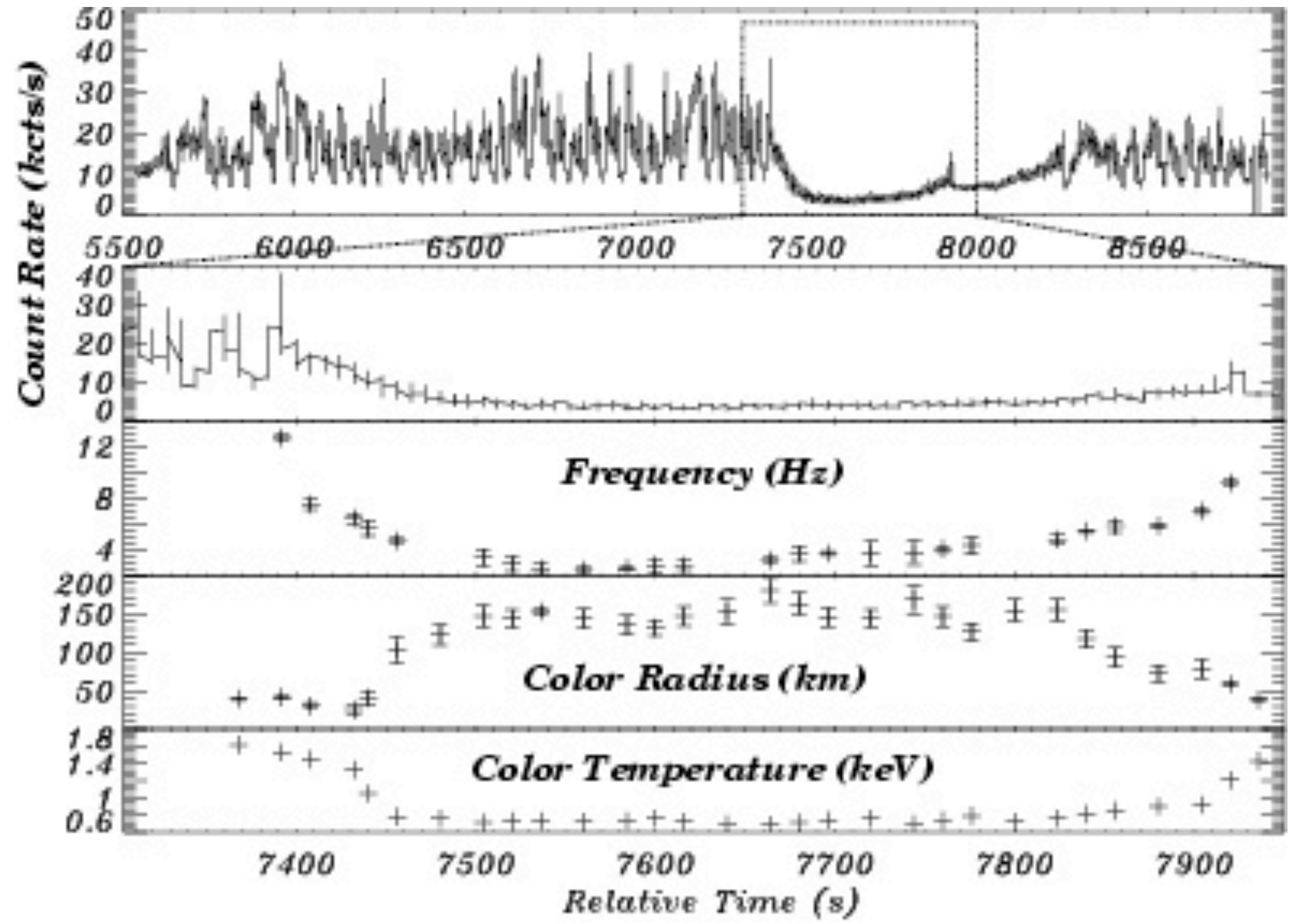
- we had already worked on that source before
- multi-wavelength observations were available
- it has known (and highly repeatable) cycles between state C, A and B (Belloni et al 2000)





The Magnetic Flood Scenario





The cycle begins in the “high/soft -thermal state” during which magnetic field is accumulated in a turbulent disk (possibly driven by the MRI) → B becomes of the order of equipartition

➜ the disk becomes unstable to the AEI, LFQPO appears. it is in the“Low-Hard state”

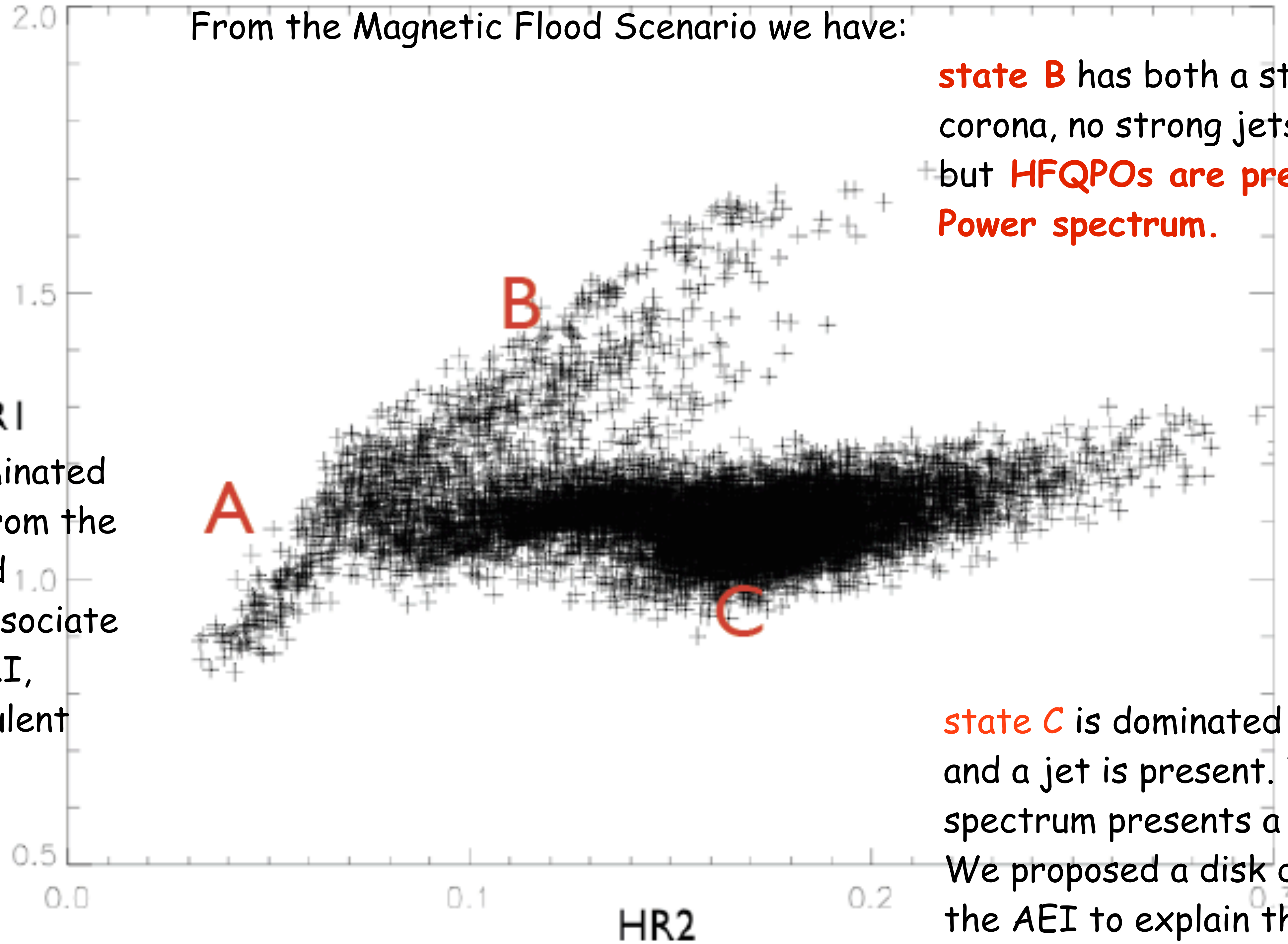
➜ at the intermediate peak we have reconnection of the magnetic field, causing an ejection and the plasma β to increase ending the AEI and the LFQPO causing the disk to go back to a softer state

➜ we linked instabilities occurring in the disk with observational states

What is at the origin of the three states?

All the observations from GRS 1915+105 can be classified in 12 classes made of three states labeled A, B and C as shown on the color-color diagram.

From the Magnetic Flood Scenario we have:

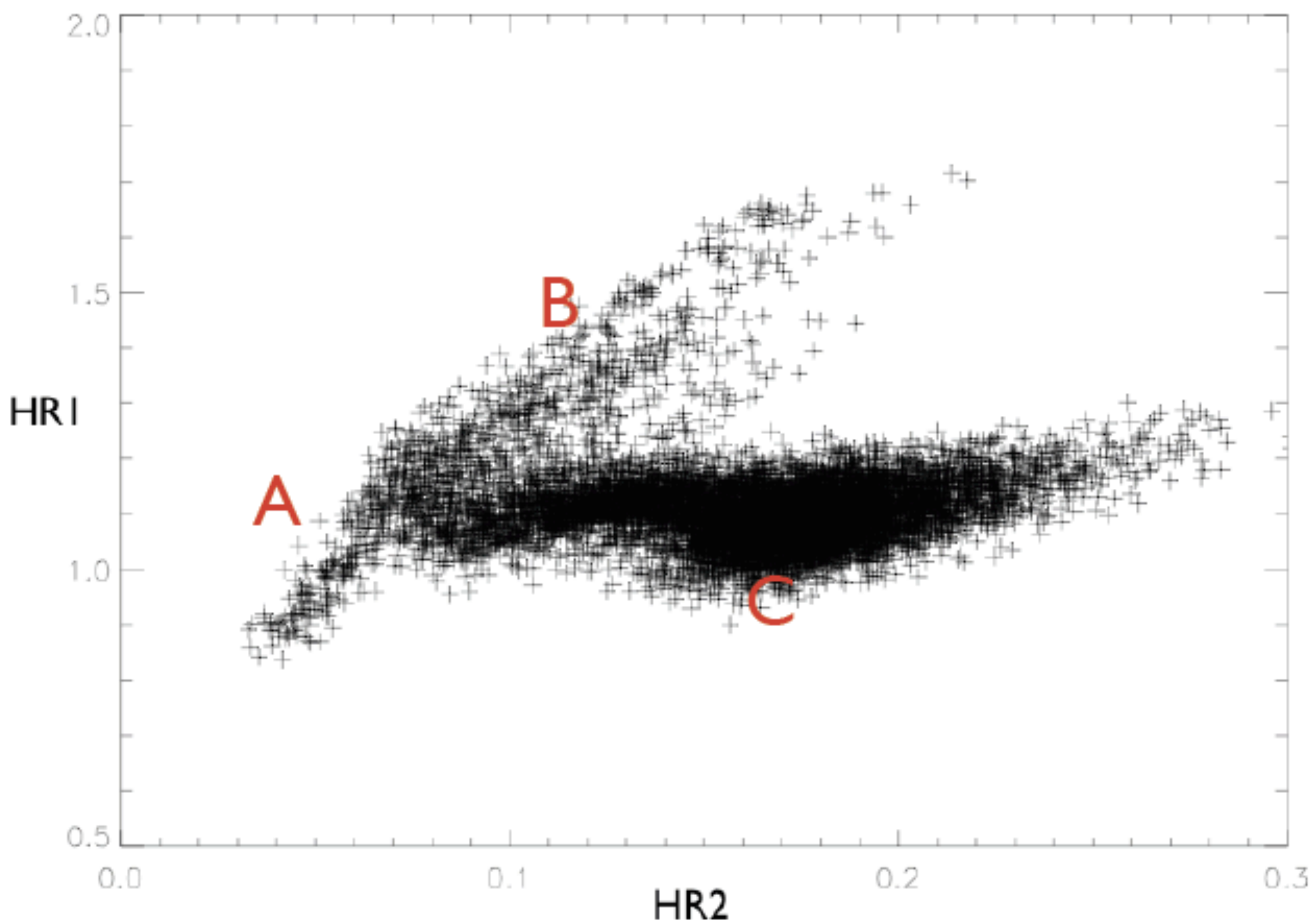


state B has both a strong disk and a corona, no strong jets are observed but **HFQPOs are present in the Power spectrum.**

state A is dominated by the disk; from the magnetic flood scenario we associate it with the MRI, namely a turbulent disk.

state C is dominated by the corona and a jet is present. The Power spectrum presents a LFQPO.
We proposed a disk dominated by the AEI to explain those features.

What is at the origin of the three states?



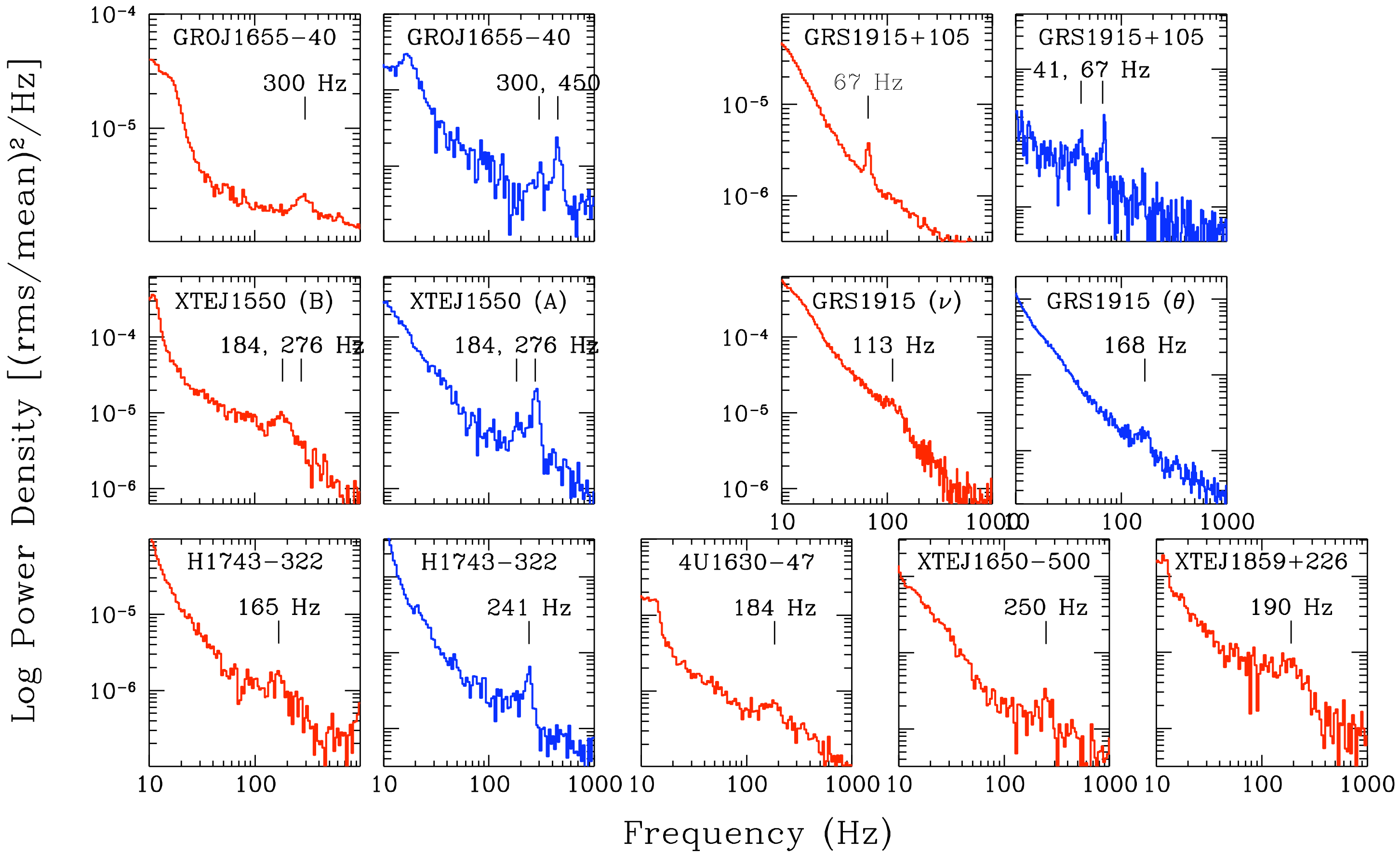
In 2006 we proposed the Rossby Wave Instability (RWI) to be at the origin of HFQPOs in black hole systems.

This instability requires an extremum of vortensity which exists in disks with their inner edge close to the last stable orbit.

One interesting characteristic of this instability is that the m=1 mode is not dominant but it is rather a mix of the m=2 and m=3 modes that dominates.

➜ this instability was the last piece of the puzzle and we now have three disk instabilities which properties make them good candidates to explain the three states

Looking for a HFQPO model: what we need to explain



- ✳ small variations in the observed frequency (maximun change in frequency of about +/- 15%)

➥ **the existence of the RWI is linked to the position of maximun of vortensity**

- ✳ HFQPOs appear alone or in "pairs" (with related frequencies, most of the time in a 2:3 ratio, sometimes 1)

  ⇒ need one mechanism that can select several linked frequencies depending on the disk conditions

➥ **depending on the inner boundary, the dominant mode of the RWI is the m=2 / m=3, or the m=1**

- ✳ HFQPOs can occur in the absence of LFQPOs
- ✳ when they co-exist we have "unusual" LFQPO (type A and B)
- ✳ HFQPOs rms amplitudes are much lower than LFQPO and seem anti-correlated with the LFQPO rms

  ⇒ the HFQPO models need to be coherent with a LFQPO model as they have to co-exist in the disk

while being independent

The 3 instabilities at the origin of 3 states

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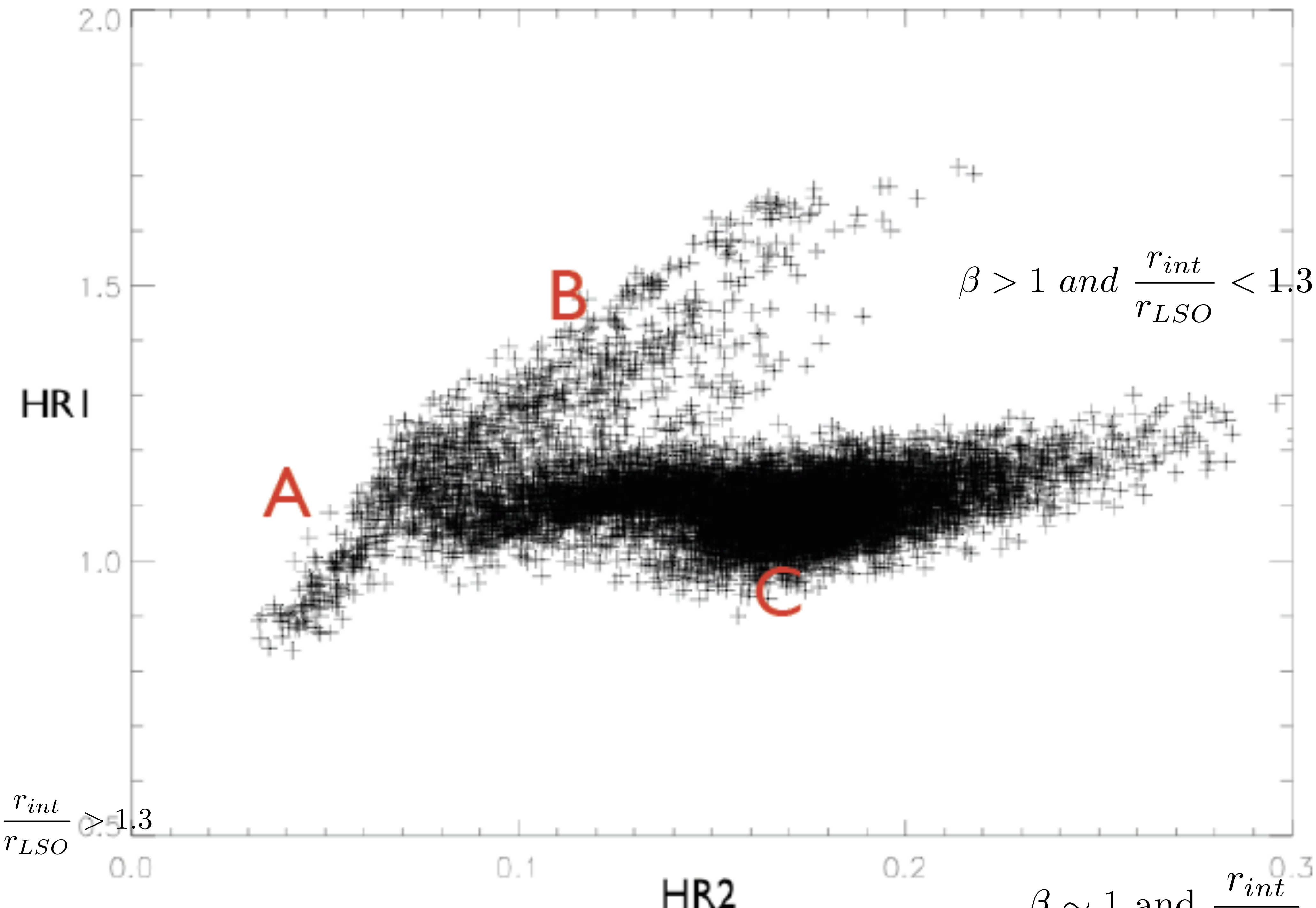

$\beta > 1 \; and \; \frac{r_{int}}{r_{LSO}} < 1.3$

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➜ this can explain the observed 3 states of GRS 1915+105 but not the presence of both HFQPO and LFQPO

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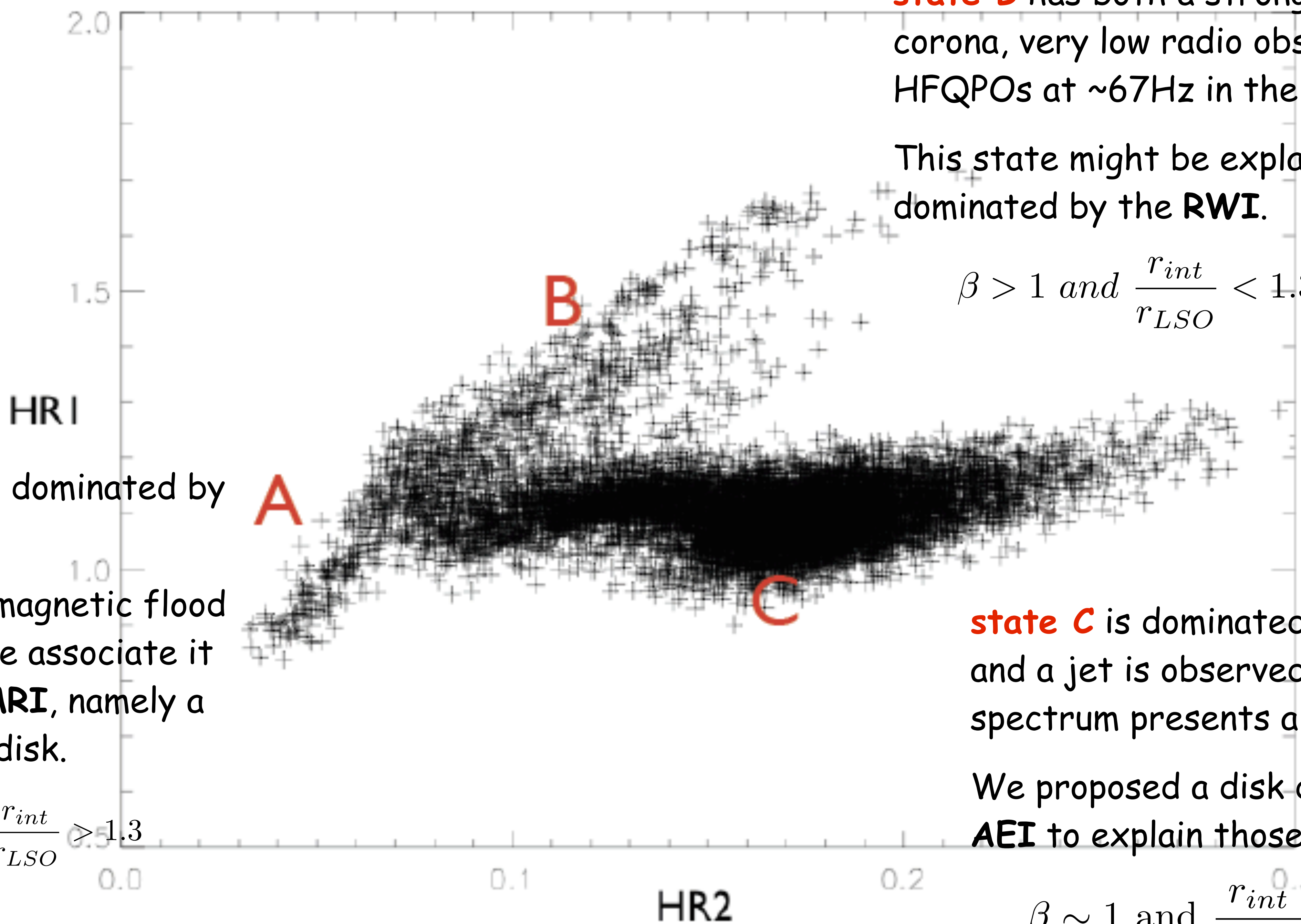

state B has both a strong disk and a corona, very low radio observed and HFQPOs at ~67Hz in the Power spectrum

This state might be explained by a disk dominated by the **RWI**.

$$\beta > 1 \; and \; \frac{r_{int}}{r_{LSO}} < 1.3$$

state A is dominated by the disk.

From the magnetic flood scenario we associate it with the **MRI**, namely a turbulent disk.

$$\beta > 1 \; and \; \frac{r_{int}}{r_{LSO}} > 1.3$$

state C is dominated by the corona and a jet is observed. The Power spectrum presents a LFQPO.

We proposed a disk dominated by **AEI** to explain those features.

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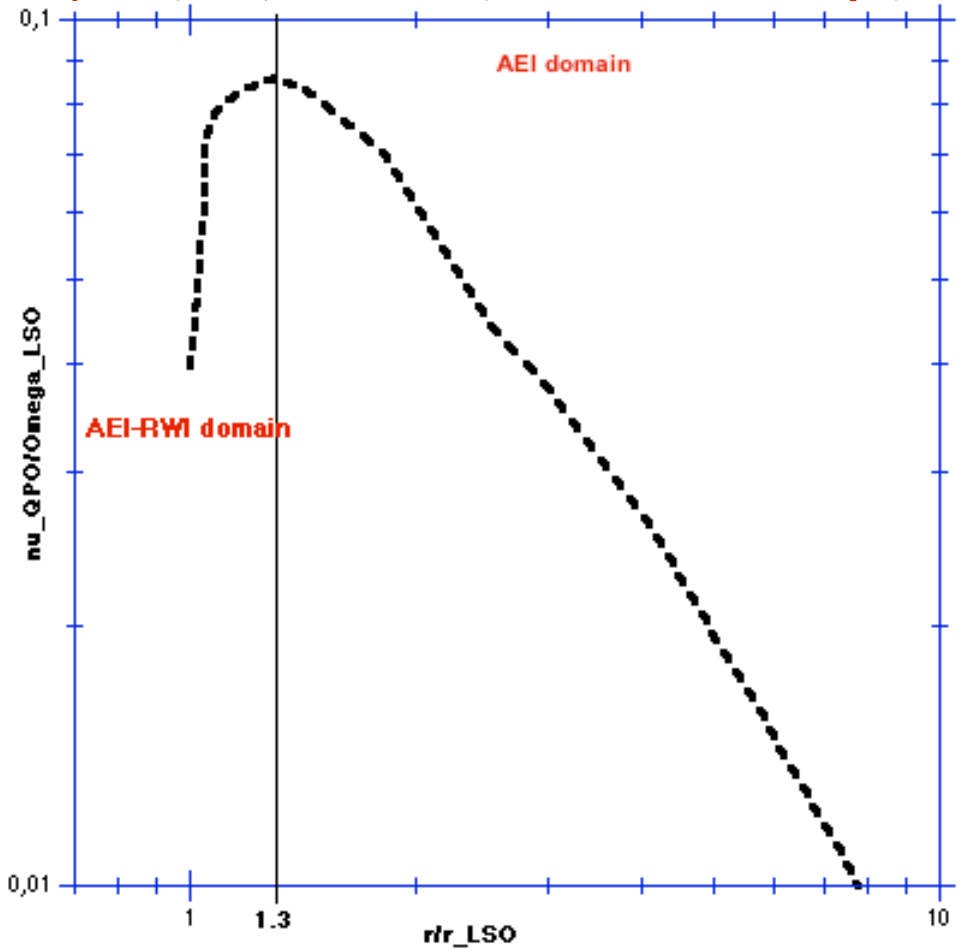
3 instabilities but 4 states

We see that there is a domain where both the AEI and the RWI can be active in the disk.

The inner edge is close to the last stable orbit and the disk is at the equipartition.

In that state we have both the LFQPO and the HFQPOs



validity

RWI: inner edge of the disk close to the last stable orbit and an extremun of:

$$\mathcal{L}_B = \frac{\kappa^2}{2\Omega}\frac{\Sigma}{B^2}$$

AEI: equipartition between gas pressure and magnetic field and

$$\frac{\partial}{\partial \ln r}\ln\left(\frac{\kappa^2\Sigma}{2\Omega B^2}\right) > 0$$

we get the following four possible states with our three instabilities:

- MRI: turbulent disk, similar to the A state, high/soft state, thermal state...
- RWI: hot disk, HFQPO, very low radio, similar to B state, other?
- AEI: cold disk, LFQPO, jet, BLN, similar to the C state, low-hard state
- AEI-RWI: warmer/hot disk, low radio, HF + LFQPOs, steep power-law, VHS

➜ The fourth state exhibits both LF and HF QPOs, which occurs frequently in sources like XTE J1550-564.... It has since been observed GRS 1915+105 has become the first object to show all 4 states. The RWI alone state has not been observed yet in other microquasars.

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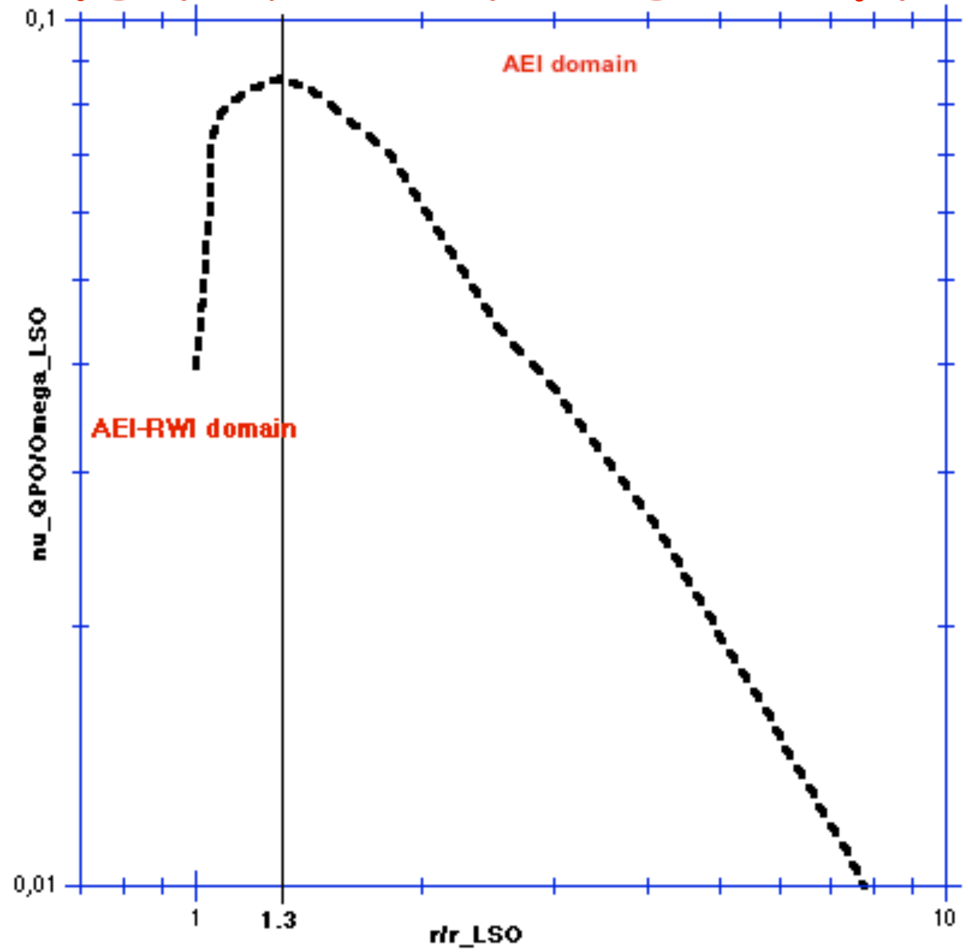

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we get the following four possible states with our three instabilities:

- MRI: $\beta > 1 \; and \; \frac{r_{int}}{r_{LSO}} > 1.3$ turbulent disk, similar to the A state, high/soft state, thermal state...
- RWI: $\beta > 1 \; and \; \frac{r_{int}}{r_{LSO}} < 1.3$ hot disk, HFQPO, very low radio, similar to B state, other?
- AEI: $\beta < 1 \; and \; \frac{r_{int}}{r_{LSO}} > 1.3$ cold disk, LFQPO, jet, BLN, similar to the C state, low-hard state
- AEI-RWI: $\beta < 1 \; and \; \frac{r_{int}}{r_{LSO}} < 1.3$ warmer/hot disk, low radio, HF + LFQPOs, steep power-law, VHS

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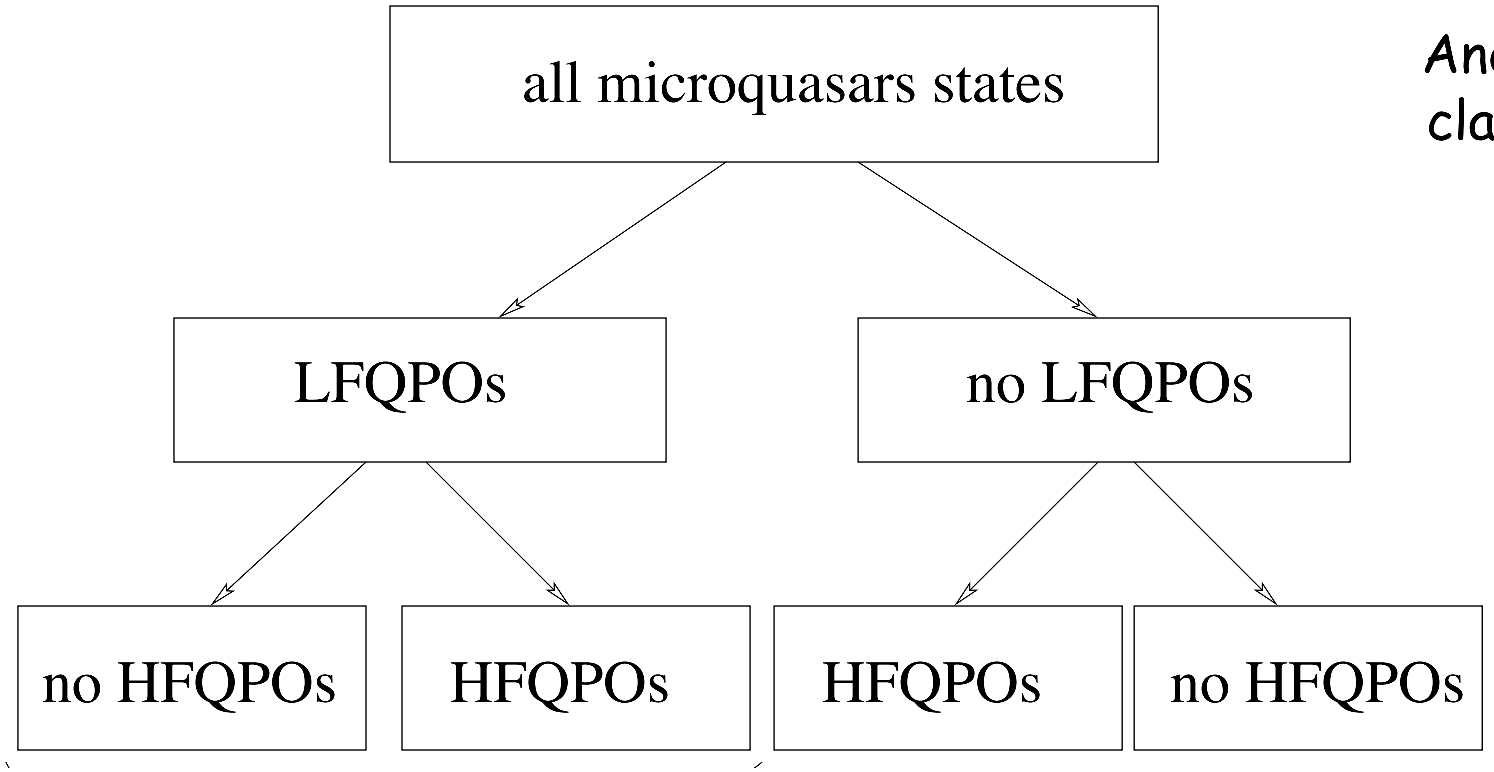
Variability based classification



Another way to look at the previously described classification is through the variability

Is there a LFQPO?

is the AEI active in the disk?

Is there an HFQPO?

is the RWI active in the disk

This way to look at the classification is model-independent. It is not important what instability is at the origin of the LFQPO and the HFQPO as long as they can operate simultaneously in the disk as required by observation

➜ another requirement for both LF and HF QPOs model

An interesting by-product of this classification is that it links together the behavior of the LFQPO with the HFQPO and could explain the LFQPO types in microquasars like XTE J1550-564.

A quick look at LFQPOs type

When we are in a state where both the RWI and the AEI exist, it is actually the relativistic AEI which is present. The R-AEI has slightly different properties.

We did numerical simulations of a disk having both the AEI and the RWI and it appears that the dominant mode is always the same for both of the instabilities.

In that picture we have

C-type is the "regular AEI"   A and B-type is the R-AEI with higher modes dominating

- link between the type of LFQPO and the HFQPO mode

  ➜ both instabilities (AEI and RWI) are in the same disk, the same modes are dominant for both instabilities.

- (sub)-harmonic content (A- and B-types sometimes present sub-harmonics or "almost harmonics")

  ➜ contrary to the non relativistic case, it is not the m=1 mode of the AEI which always dominates when the disk gets close to the last stable orbit. The non-dominating m=1 could be taken for a sub-harmonic. Also, the different modes of the AEI are in close-harmonic relationship, not exact.

- the frequency of the A- and B-type seems to have a small range (compared to the C-type)

  ➜ to be in the AEI-RWI state, the inner edge of the disk needs to be close to the last stable orbit so the LFQPO cannot change frequency as much as in the C-type case

Conclusion

- ℘ using a consistent model : control by the gradual accretion of vertical magnetic flux, stored in the BH magnetosphere and destroyed in reconnection events (= ejections) when disk magnetic flux and stored flux are opposite

➜ we proposed a new classification based on which instability dominates the disk: equivalent to a variability based classification

➜ studying the instability behaviour in that new state gives a possible explanation for LFQPO types which needs to be further tested

- ℘ the next step is to look at the consequences of the different instabilities on ejection to also link the four states with the radio emission observed.

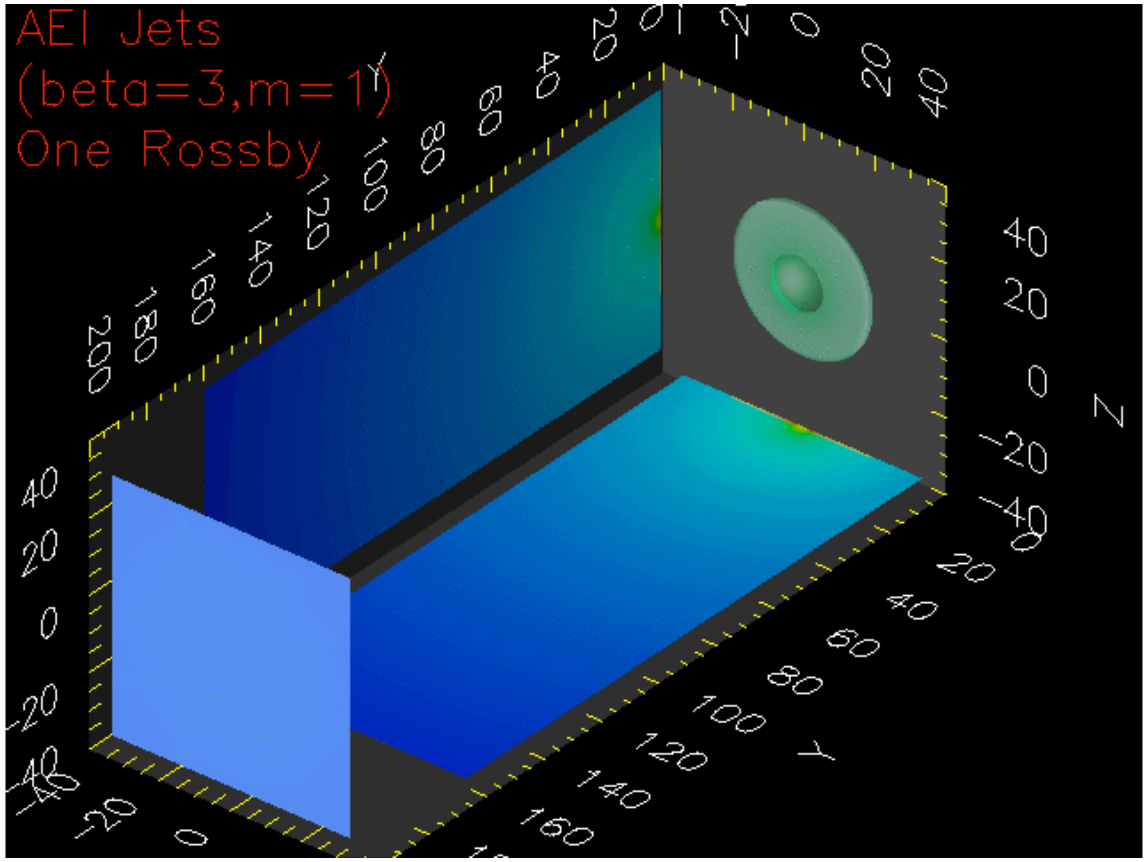
- ℘ we are also working on making a list of observational constraints against which to test both LFQPO and HFQPO models

Alfven Wave Emission Toward the Corona

The Rossby vortex twists the footpoint of the field lines threading the disk. If the disk has a low density corona:

twisting ➜ emission of Alfven Waves

- energy and angular momentum extracted from the disk will be transfered to the corona where they can power a wind or a jet



We describe this via a variational form: ➜

F = energy of the waves + i (outgoing spiral

+ coupling with the vortex + kz Alfven Waves)

imaginary term ⇔ amplification or damping of the wave

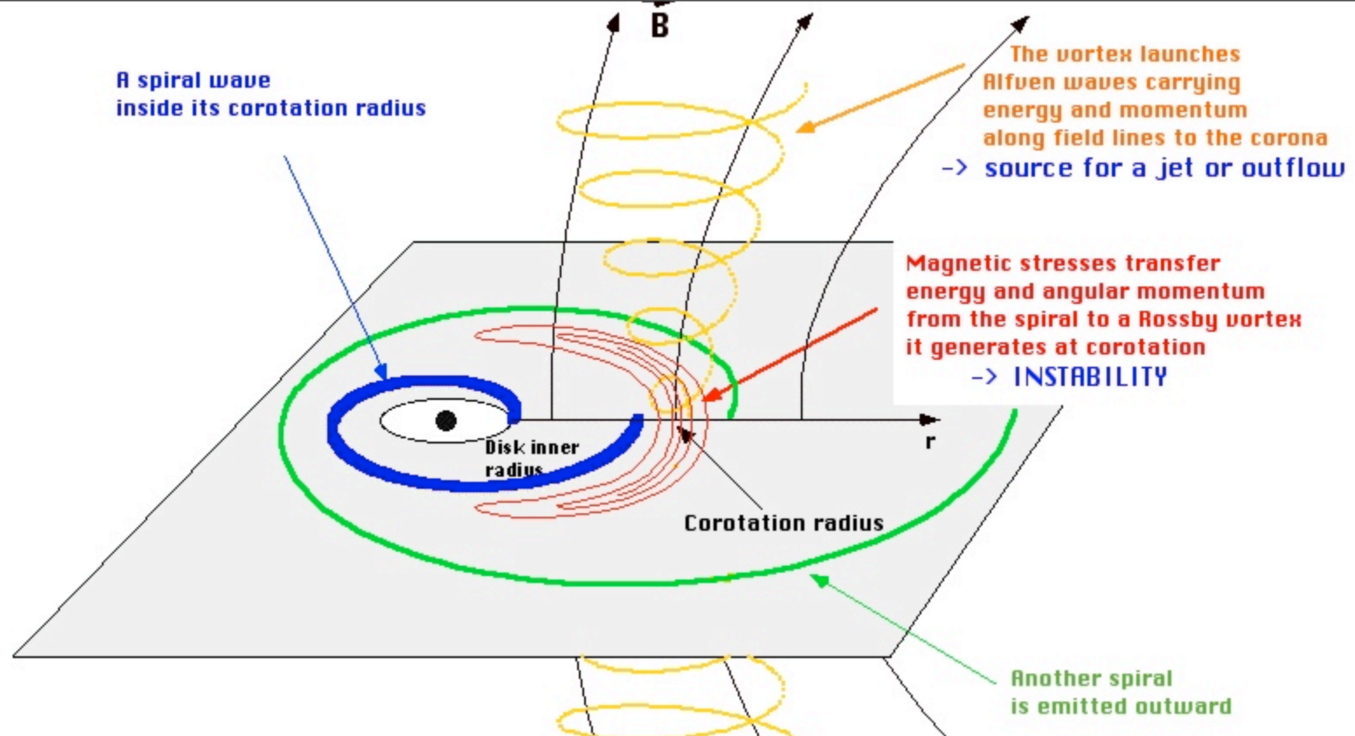
the Alfven terms are singular at the vortex radius

Efficiency of the mecanism: we compute the ratio of the flux emitted toward the corona as Alfven waves to the energy removed from the inner region (flux at the corotation radius)

$$\frac{F_{Alfven}}{F_{disk}} \sim \left(\frac{\rho_{corona}}{\rho_{disk}}\right)^{1/2} \left(\frac{r}{h}\right)^{3/2}$$

Typical Xray Binary aspect ratio $h/r \sim 10^{-2}$

➜ $F_{Alfven}/F_{disk} \sim 1$ very efficient mecanism if the density gets $\rho_{corona}/\rho_{disk} \sim 10^{-6}$



Basics of the AEI

- properties of the spiral

➔ most often the m=1 (one armed spiral) with $\omega \sim 0.1 - 0.3\ \Omega_{int}$ (rotation frequency at the inner edge of the disk)

- differential rotation + differential vorticity

➔ unstable by coupling to a Rossby vortex (~ great red spot of Jupiter)

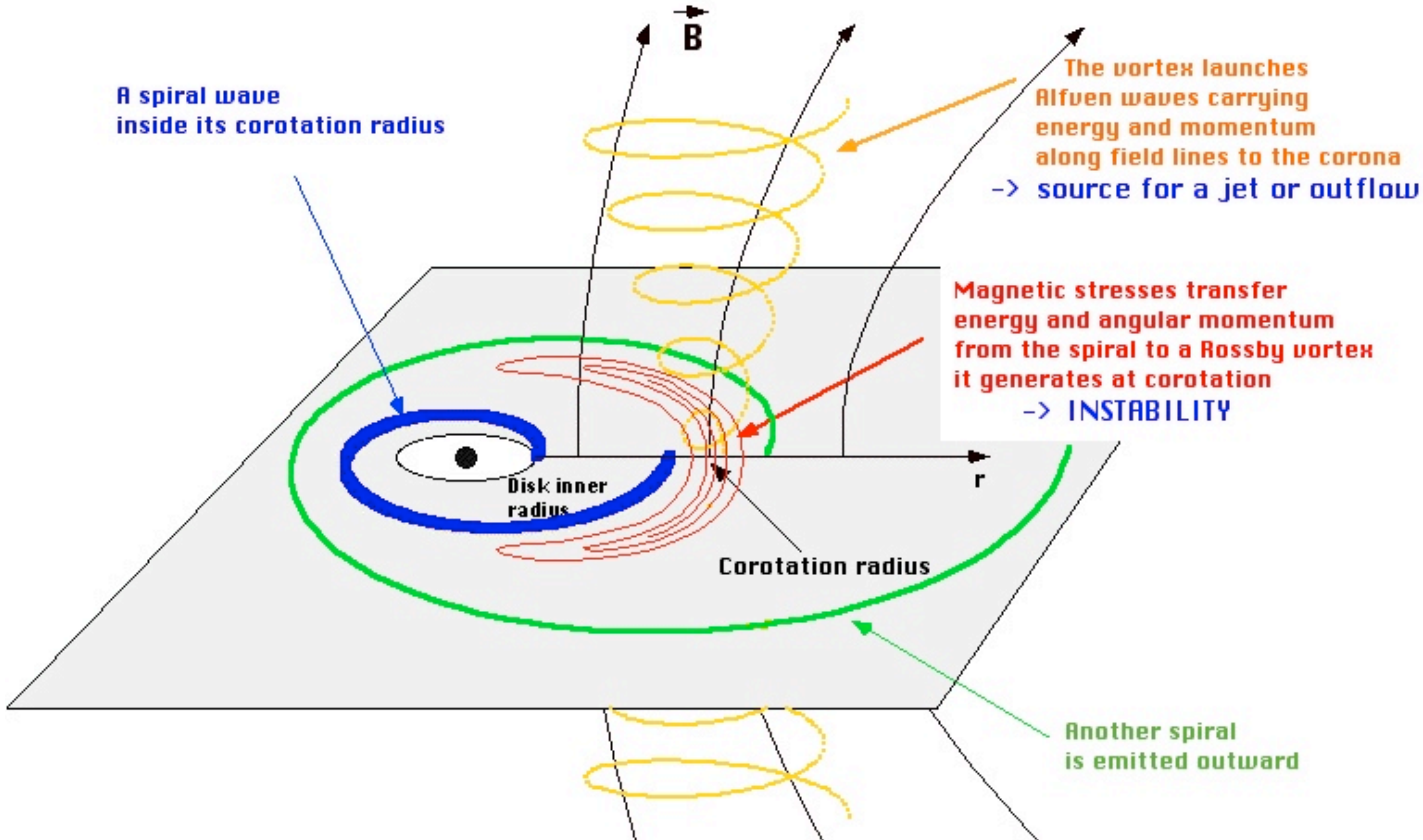
- extracts energy and angular momentum from the disk (➔ accretion) and stores them in the Rossby vortex

- if the disk has a low density corona

energy and angular momentum from the vortex are transfered upward as Alfven waves to the corona

➔ power for a jet or a wind

Basics of the AEI



a disk threaded by a vertical magnetic field ~ equipartition

➔ large scale instability

a spiral wave ~ galactic spirals but driven by magnetic stresses rather than self-gravity

same structure of large scale normal modes (= standing patterns) as in galaxies

The perturbation is almost constant across the disk height

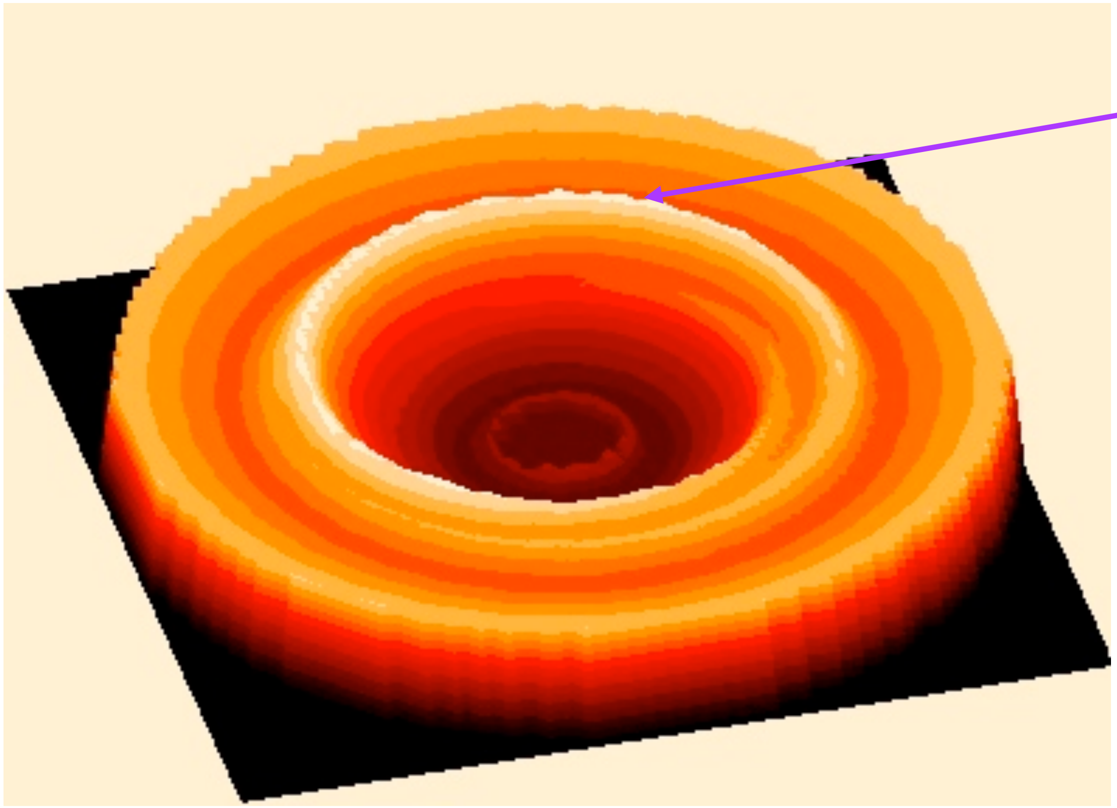
➔ 2D simulation possible

All self similar MHD jet models (Blandford & Payne, Pelletier & Pudritz, ...) are unstable

a modulation of the disk emission

work done with M.Muno, L.Prat

The effects of the spiral shock is the creation of a hot-point in the disk



→ and also a thickenning of the disk

From 2D non-linear MHD simulation we get the following thickness (with a simplistic model for disk height and temperature)

Computing the X-ray emission from such an accretion disk **shows a modulation in the flux** of a few percent (5 to 10%)

➜ we need to improve the computation of the disk thickness to obtain a better estimate of the rms

what does it gives:

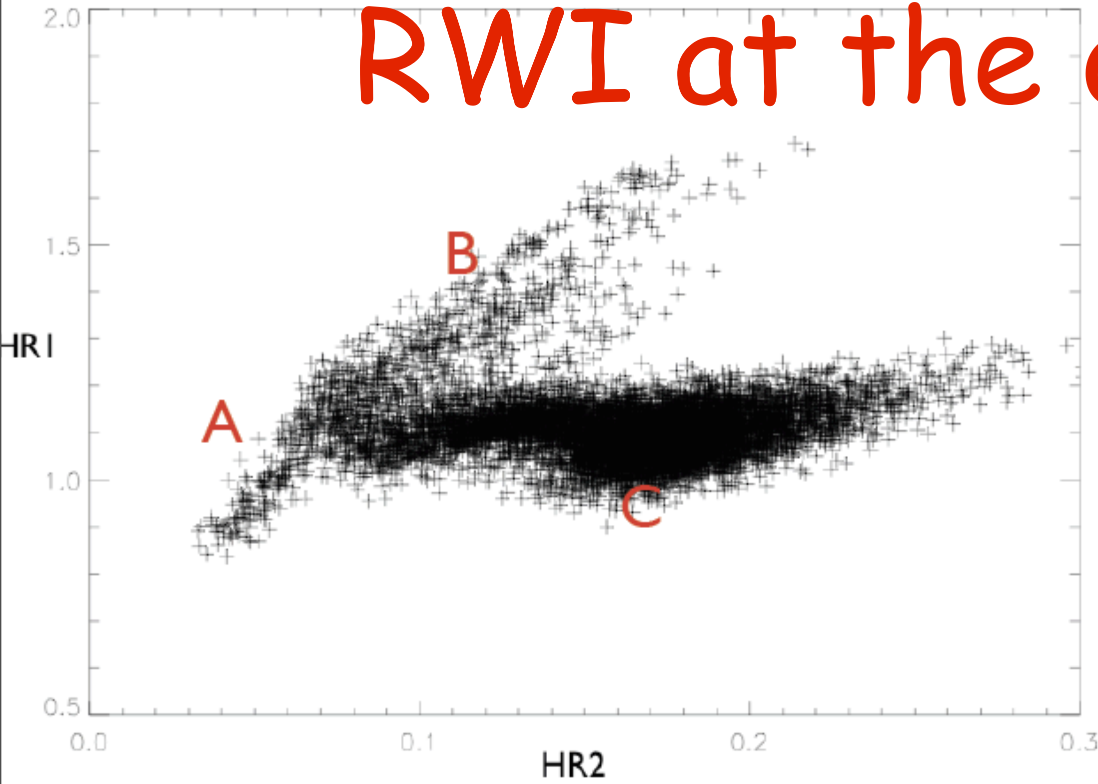
- geometric modulation of the flux
- hot region in a warn disk → growth of the rms amplitude with energy
- not only the disk but the jet will obscur the hot-point

→ a way to explain the reverse time lag

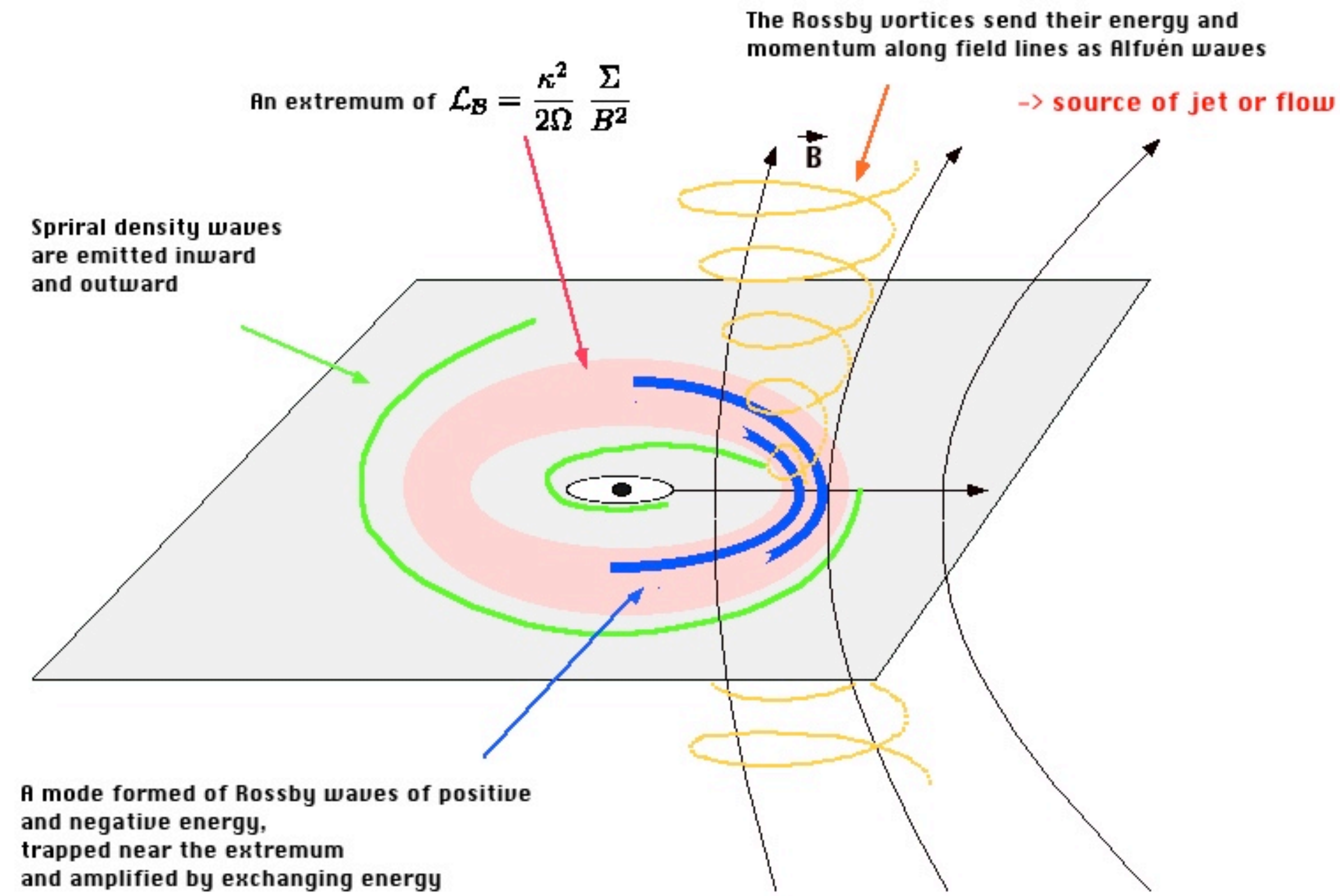
The AEI as a model for the LFQPO

- ✳ frequency between 1-10 Hertz
  - ➥ frequency of the spiral wave $\omega \sim 0.1 - 0.3\ \Omega int$ (rotation frequency at the inner edge of the disk)
- ✳ stability in time
  - ➥ large scale structure as in galaxies (quasi-standing spiral structure)
- ✳ rms amplitude as much as 30%
  - ➥ we observed in the simulation as much as 10% in a oversimplified model, working on a better approximation
- ✳ correlation with the soft flux
  - ➥ comparison with observation in Varniere et al A&A 2002 and Mikles et al. ApJ 2009
- ✳ QPO associated with a state where the power-law always dominates
  - ➥ accretion energy not deposited locally (not heating the disk) but ejection through Alfven Waves emission
- ✳ lag sometimes changing sign, sub-harmonic structure
  - ➥ possibility of geometrical effects from the jet

RWI at the origin of the state B?



state B has both a strong disk and a corona, no strong radio emission are observed and **HFQPOs are present in the Power spectrum** (the 67Hz) **but no LFQPOs.**



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One interesting characteristic of this instability is that, depending on the inner boundary, the m=1 mode is not dominant but it is rather a mix of the m=2 and m=3 modes that dominates.

a disk with an extremum of $\mathcal{L}_B = \frac{\kappa^2}{2\Omega}\frac{\Sigma}{B^2}$ is necessary

possibility of emitting Alfven waves in presence of a low density corona above the disk

➜ we need to see if that instability is a good candidate for the HFQPOs in microquasars and therefore a candidate to explain the state B of GRS 1915+105

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RWI: toward a model for the HFQPO?

- ✳ small variation in the observed frequency
  - ➥ the existence of the RWI is linked to the position of maximun of vortensity
- ✳ seems to select pairs of frequencies, in a 3:2 ratio
  - ➥ depending on the inner boundary, the dominant mode of the RWI is the m=2 / m=3, or the m=1
- ✳ the HFQPO model need to be coherent with a LFQPO model
  - ➥ the condition for the magnetized RWI are similar to the one of the relativistic AEI
- ✳ link with the appearance of unusual (type A and B) LFQPO
  - ➥ We proposed an explanation for the different types of LFQPO based on the behavior of the relativistic AEI

✳ we still have several points to work on before being able to compare the RWI-HFQPO model to observations, especially the computation of the observed rms amplitude, the Alfven wave emission, the variation of frequency and 3D MHD simulation...

⇒ We are also working on better understanding the constraints from observations.

➜ this instability was the last piece of the puzzle and we now have three disk instabilities which could explain the three states

generalized magnetic flood