Accretion-Ejection Instability, Quasi-Periodic Oscillations and a Magnetic Floods scenario

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looking for QPO models (1)

Coherence

- => QPO can't be due to blobs
- => global organized motion of the gas
- = normal modes ("global modes")

  = standing waves patterns

looking for QPO models (2)

amplitude

- => QPO can't happen by random process

  (blobs)

- hard to find excitation mechanism
- => must be due to

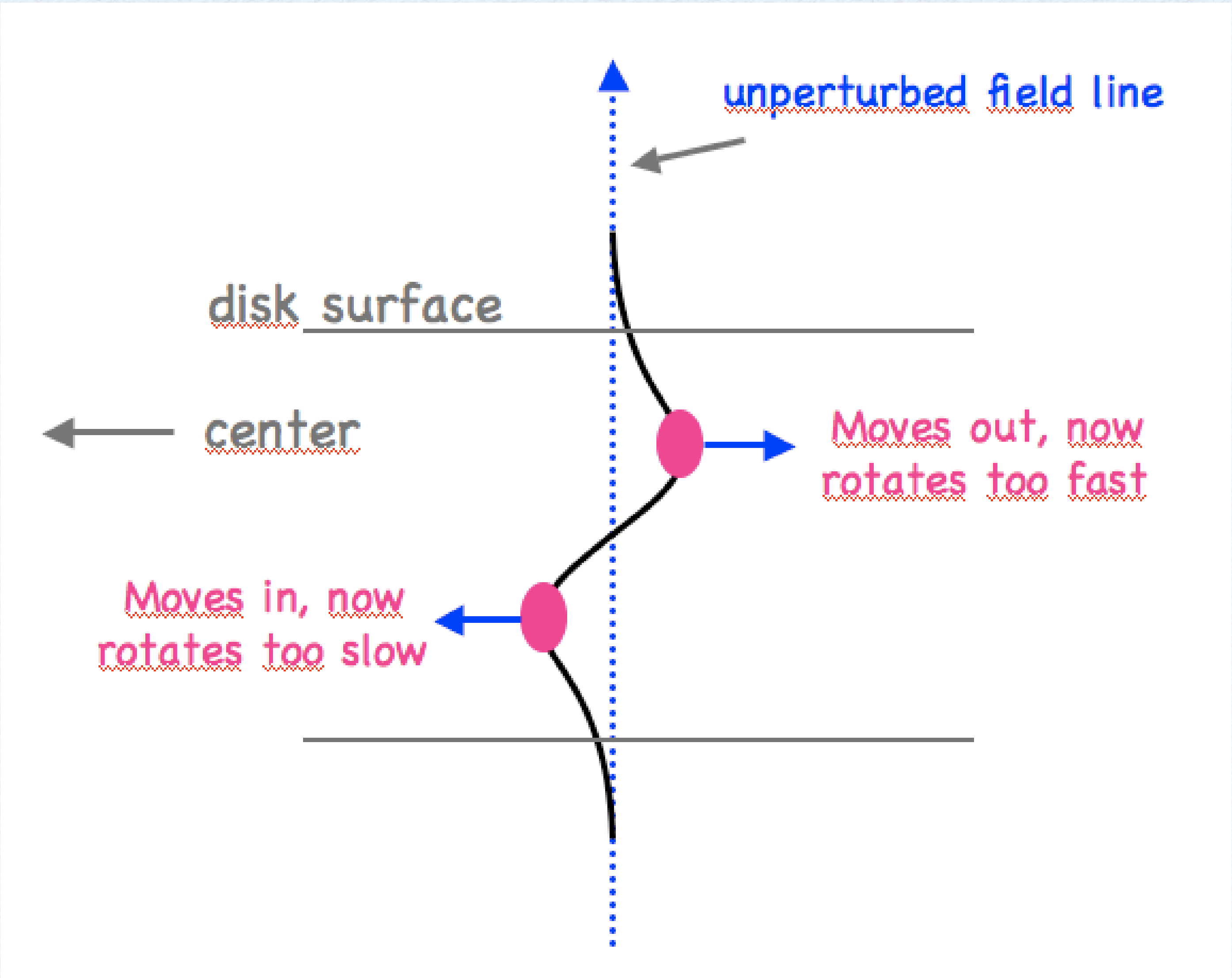
  disk (+ corona ?) instabilities

NGC 1300

unstable normal modes are well known in accretion disks

waves and modes (1)

vertical structure

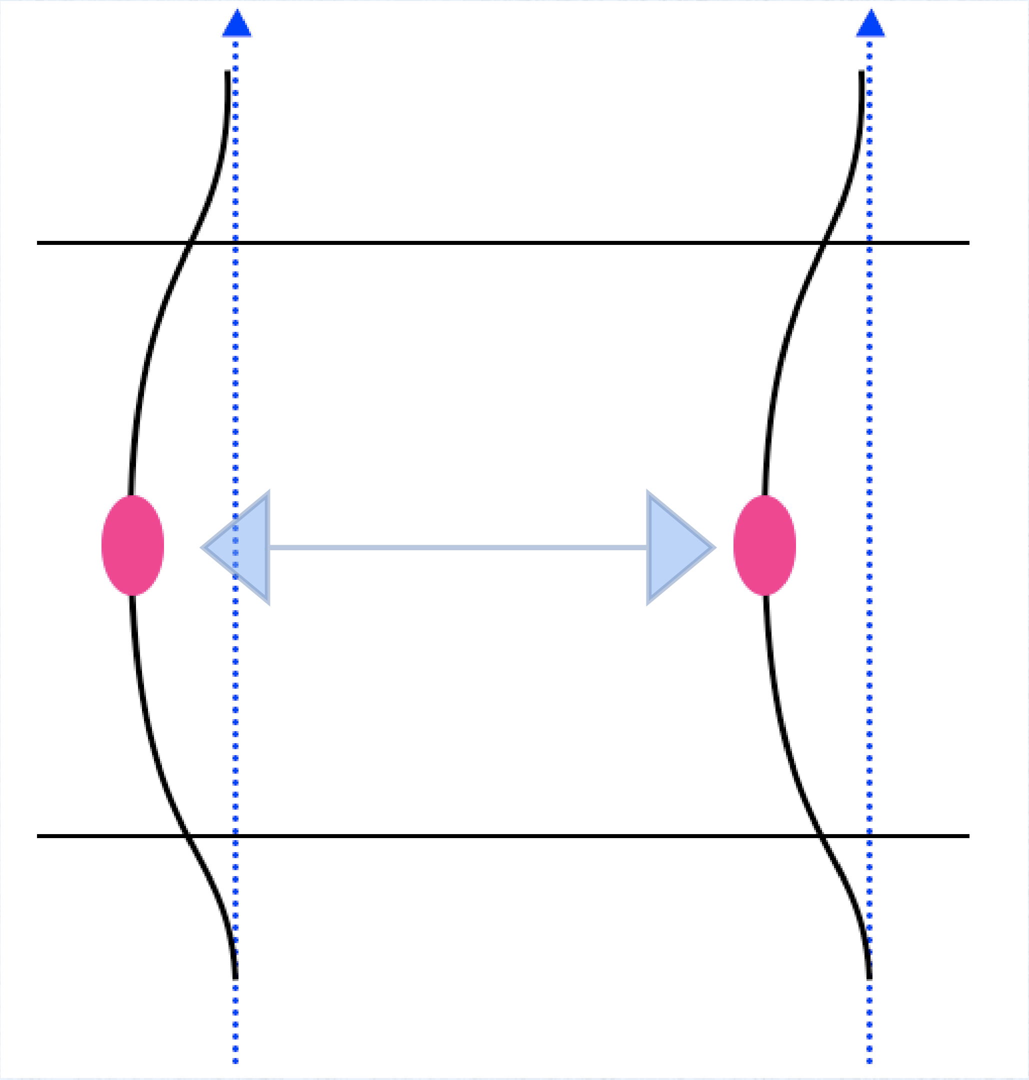


MRI: exchanges energy and angular momentum between fluid particles along field lines

=> needs to vary across the disk thickness

$(k_z h > 1)$

waves and modes (2)



thin disk waves:

perturbations nearly constant across the disk thickness

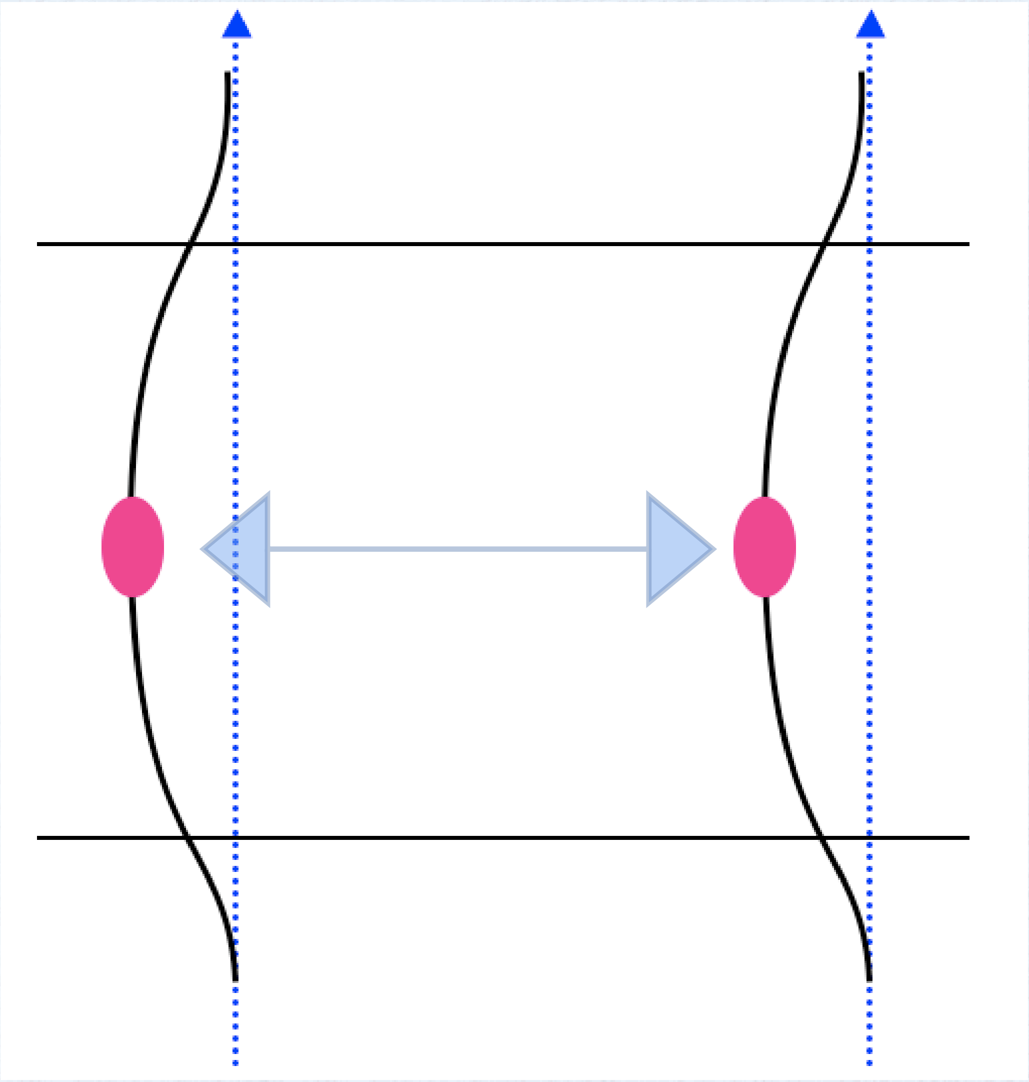
($k_z h \ll 1$)

energy and angular momentum are exchanged at differing radii by the action of forces:

- short-range (pressure):
  -> Papaloizou-Pringle
  (weak, short wavelength)

- long-range:
  self-gravity -> galaxies
  Lorentz -> AEI

waves and modes (3)



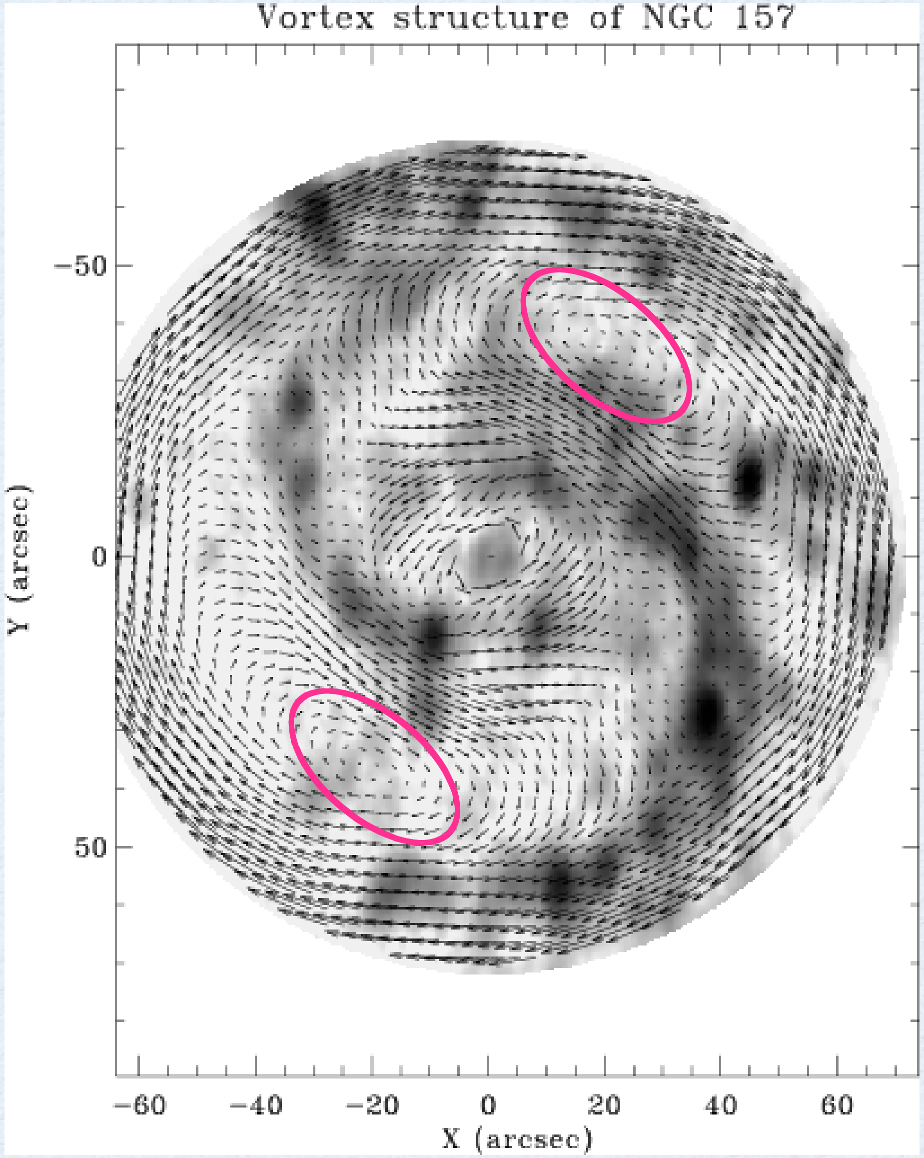
$k_z h \ll 1$

=> thin disk approximation OK (perturbation constant across disk thickness)

=> also allows 2D (r, ϕ) simulations (infinitely thin disk in vacuum)

... this gives the basics, but 3D effects will be important ...

thin disk waves



Fridman et al, 1996

- disks admit spiral density waves (= sound waves modified by diff. rotation, epicyclic motion, self-G, Lorentz...)
- they also admit Rossby waves (propagate vorticity perturbations)
- differential rotation couples these 2 types of waves -> able to exchange energy and angular momentum

instability mechanisms (1)

- waves rotating faster than the gas tend to accelerate it
  -> positive energy and angular momentum flux
- waves rotating slower tend to slow it down
  -> negative energy and angular momentum
- -> corotation radius where $\frac{\omega}{m} = \Omega(r)$
- coupled waves at the same ω inside and outside corotation can grow without changing the total energy and momentum

instability mechanisms (2)

1. coupling two spiral waves inside and outside corotation -> Swing amplification (galaxies)
2. coupling a spiral inside corotation to a Rossby wave at corotation -> corotation resonance

- usually stabilizing for self-G and Pap.-Pringle
- strongly destabilizing in (vertically) magnetized case

-> Accretion-Ejection Instability

3. coupling of two Rossby waves (requires special profiles) -> Rossby Wave Instability

¡ much more efficient with B ∼ equipartition !

3D effects: disk/corona (jet?)coupling

la cherry sur le cake

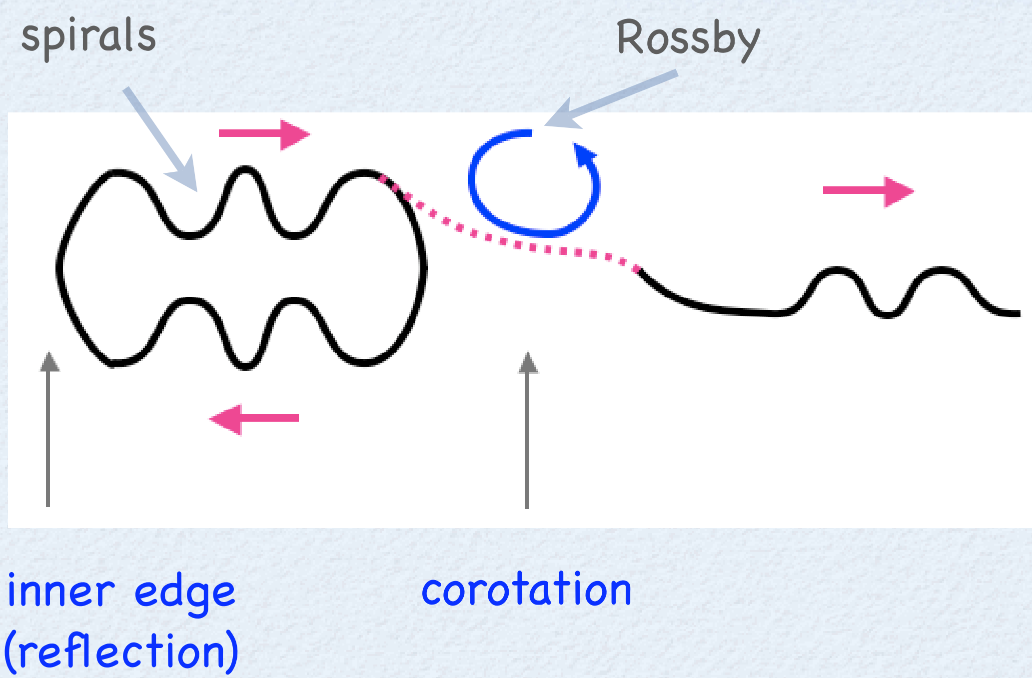
- unmagnetized disks -> Rossby waves are Rossby waves -> store the accretion energy and momentum in a standing (-> saturation?)
- disk threaded by a vertical magnetic field: twisting of the footpoints -> propagate as Alfvén waves

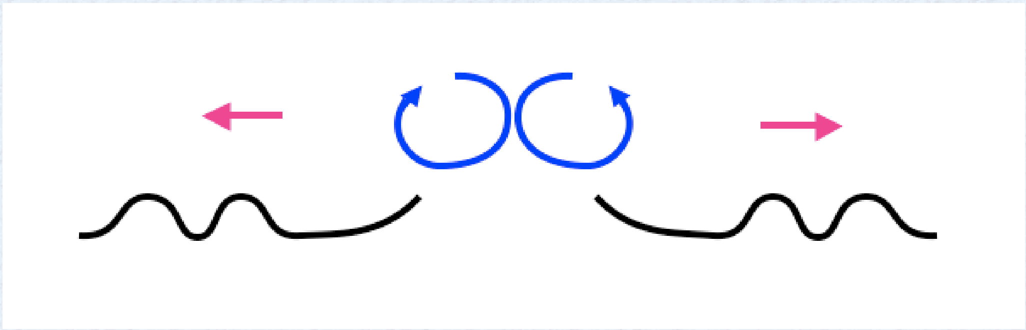
-> a significant fraction of the energy and momentum re-emitted to the corona (see P.V.'s talk)

-> not a jet at this stage

¡ the corona is always active when QPO are present !

two types of modes





- "p-mode" = essentially spirals

  inner spirals extract energy and momentum from inner disk, transfer them to outgoing spiral or vortex

  needs reflection at inner boundary

- "g-mode" (essentially Rossby)

  amplification by coupling vortices of opposite energies

  needs extremum of

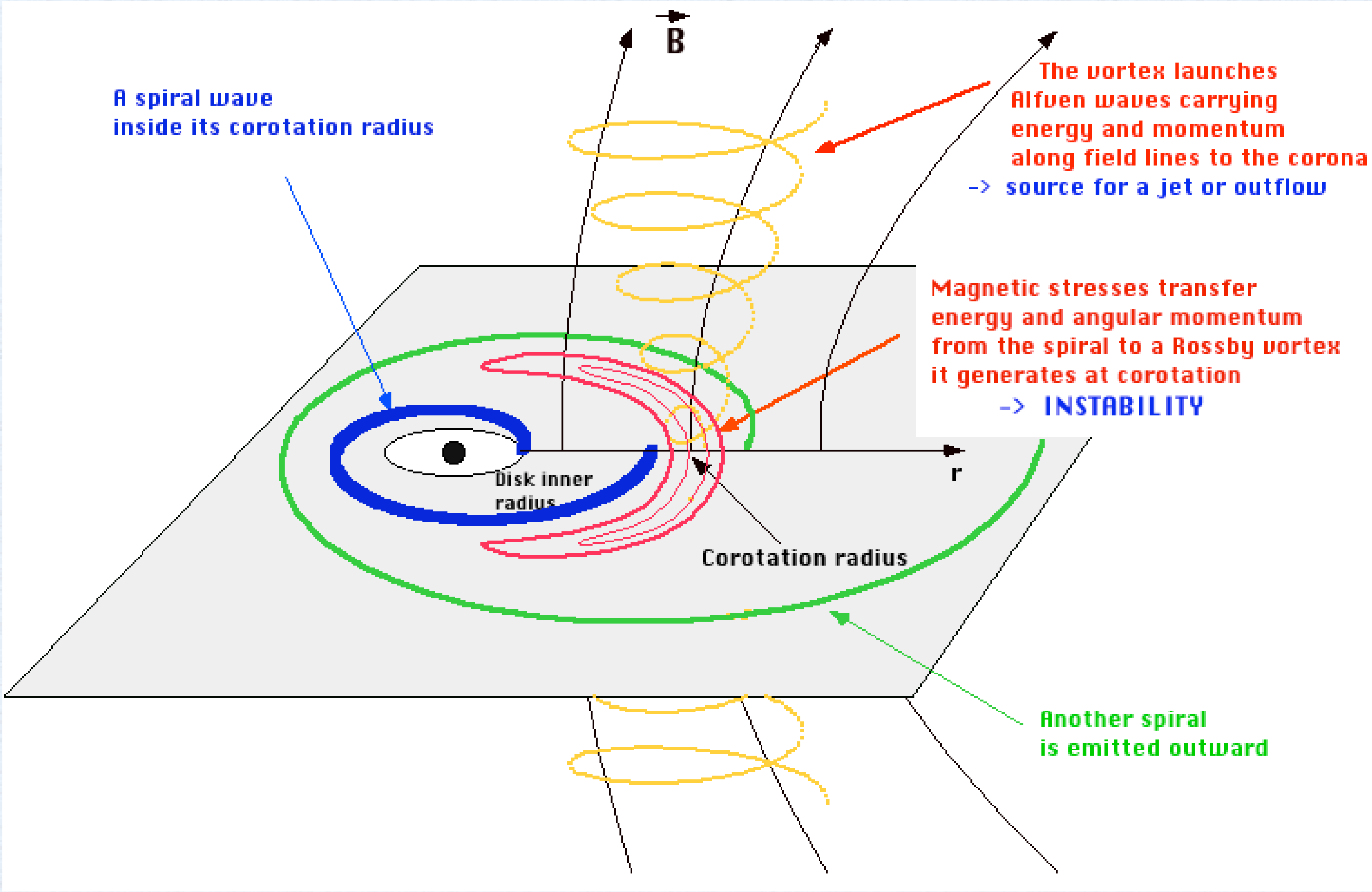
  (magneto)vorticity

  -> extremum of density -> RWI

  OR relativistic rotation curve

(diskoseismology: Nowak & Wagoner)

1: AEI and LF-QPO



- 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: see J.R. and P.V's talks

2: MHD RWI and the quasi-periodicity in Sgr A* flares

with F. Melia

- obs. + models -> flare when a blob from shocks in colliding stellar winds is captured in the disk at a few tens of r_G

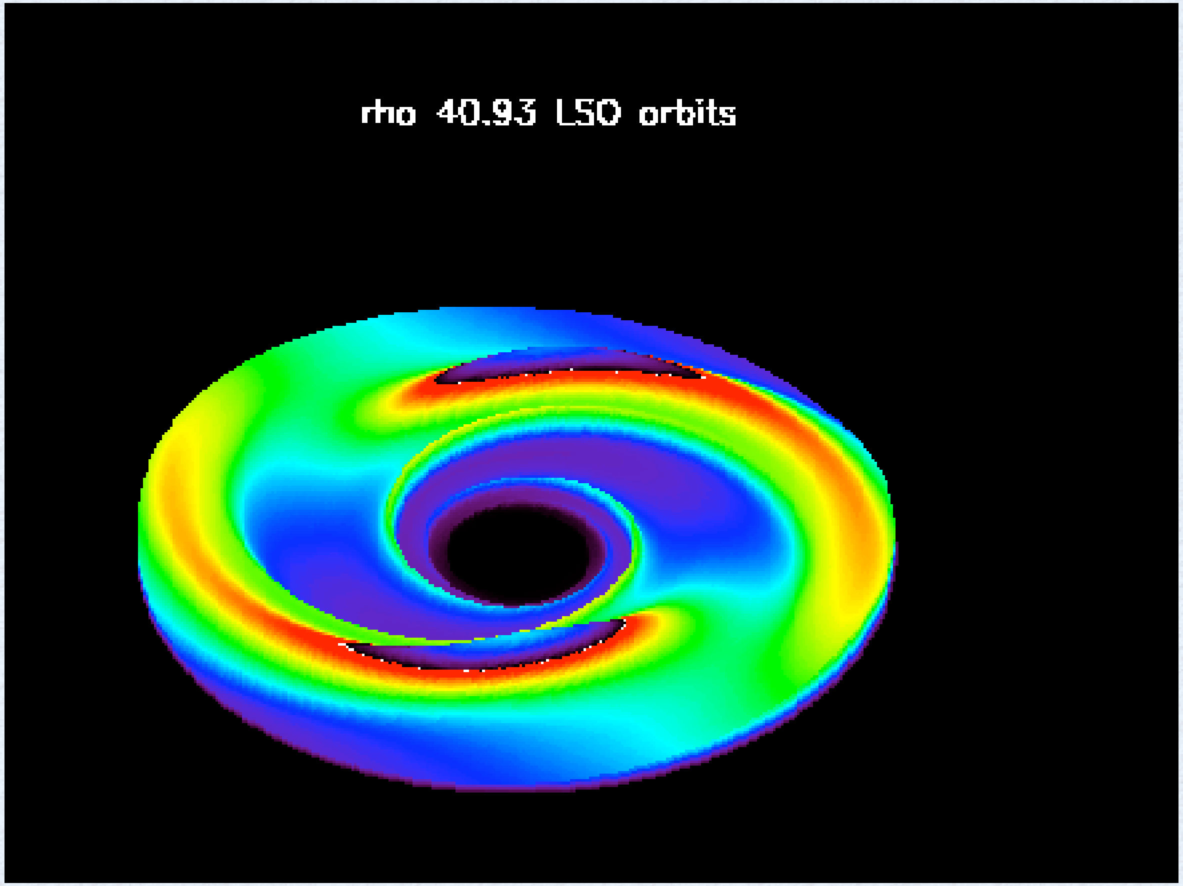
  (see S. Liu's talk)

- our model: the blob circularizes in the disk -> local extremum of $\mathcal{L}_B$ due to density maximum -> strongly unstable to (MHD) RWI

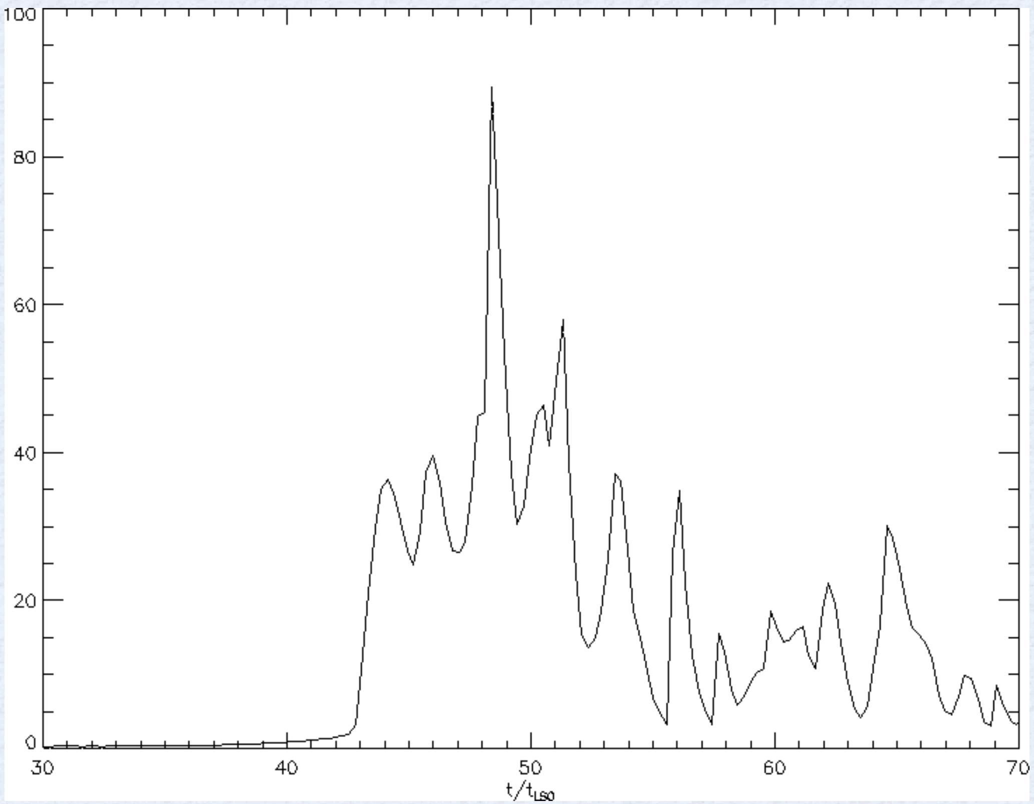
- -> flares and quasi-periodicity, with right order of magnitude

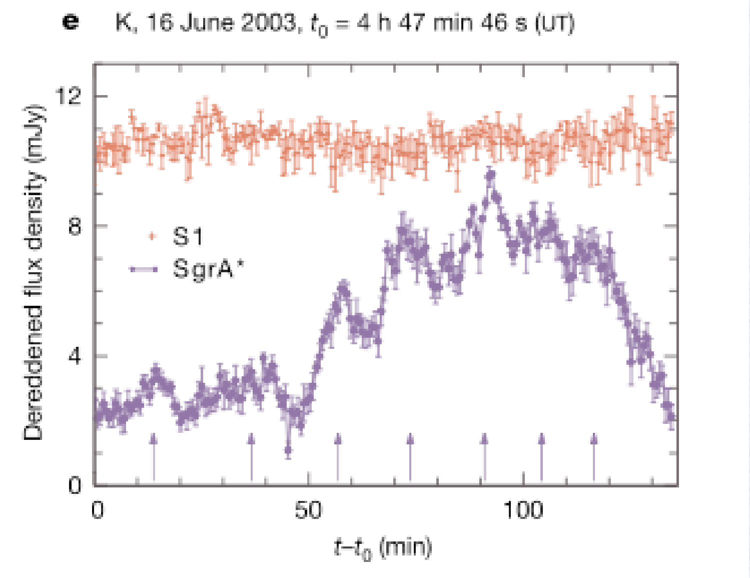
- similar but slower if unmagnetized

flares and quasi-periodicity in Sgr A*

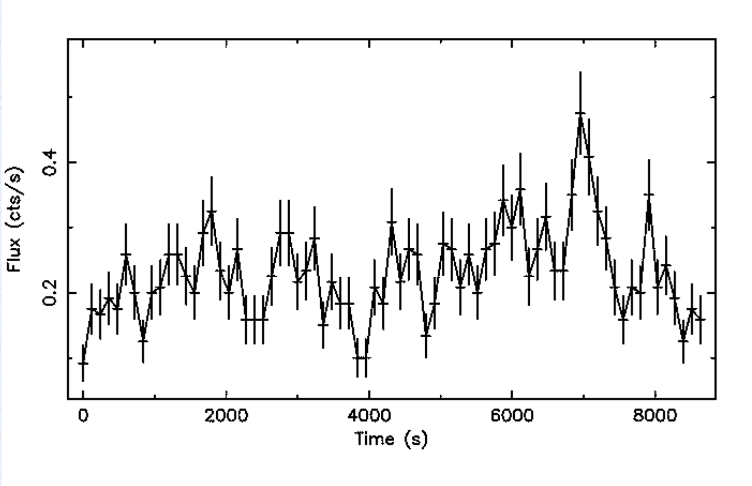


flares and quasi-periodicity in Sgr A*





IR: Genzel et al.



X: Belanger et al.

"light curve"= accretion at MSO

oscillations at ~ .7 Ω_{MSO}

!!! the exact frequency is model-dependant

-> affects spin estimates !!!!

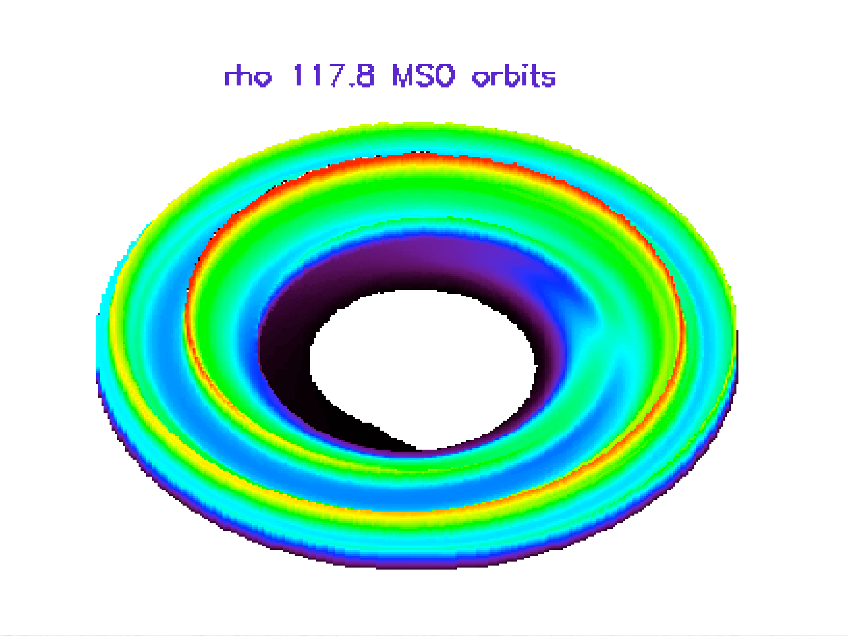
3. HF-QPO

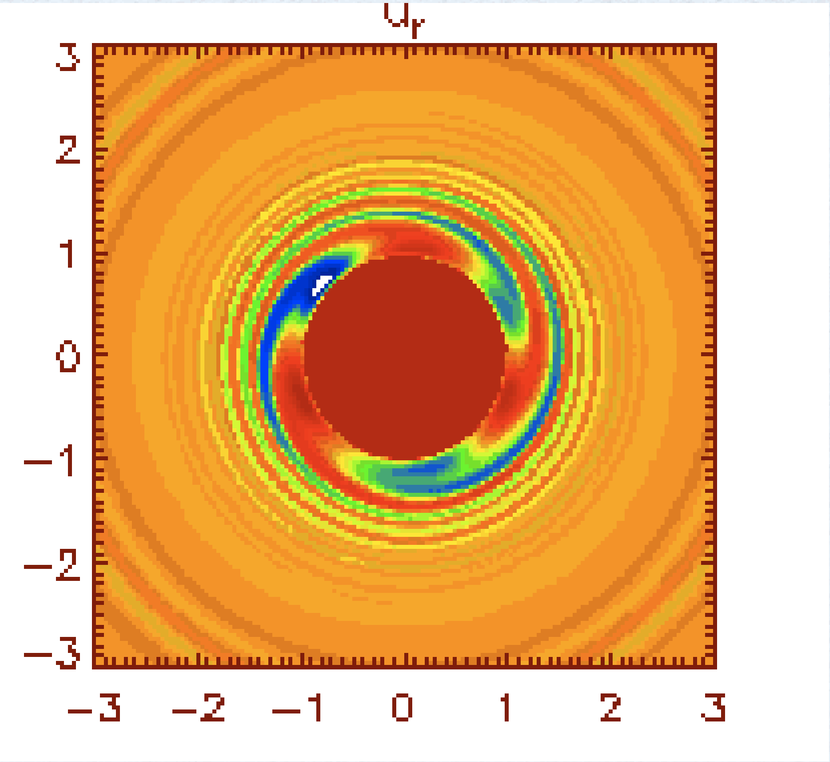
- if the disk extends down to its MSO
- -> modes with relativistic rotation curve
  1. stress-free boundary -> plunging region
     -> $m=1$ mode
  2. assume a magnetosphere (a la B-Z) acting as reflecting boundary to waves
     -> $m=2,3,4$... modes more unstable than $m=1$

-> explains:

- fixed frequencies
- at 2,3,4... an unseen fundamental
- active corona and disk -> SPL state

3. HF-QPO (2)

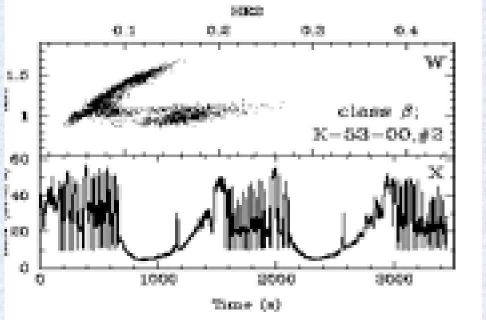




free inner boundary ->
plunging region -> always an
m=1 mode (1-armed spiral)

reflecting boundary ->
unstable m=3
(or 2, or 4, 5...) mode

magnetic floods



first for the β-class cycles of GRS 1915+105

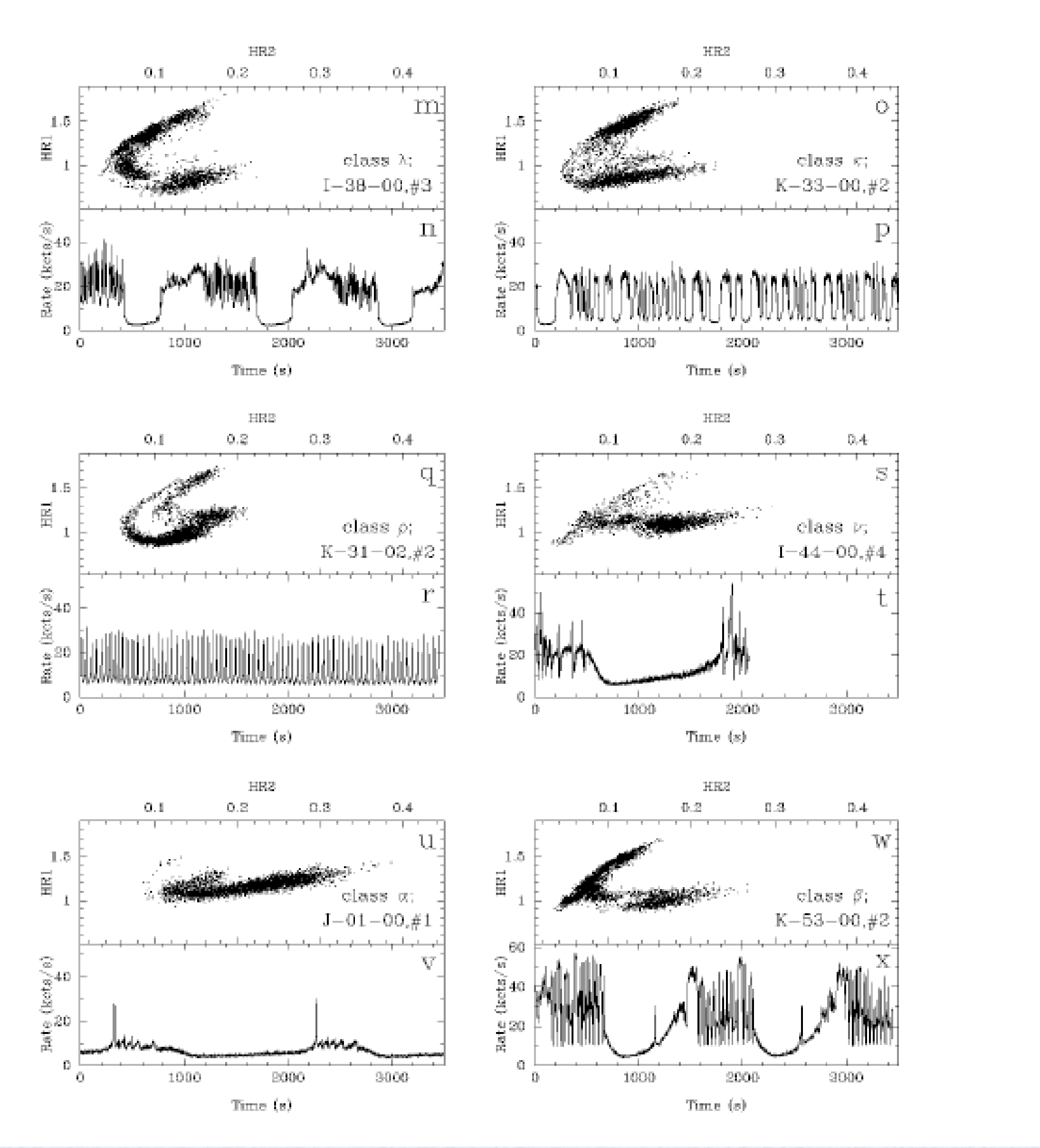
- starting points, assuming the AEI is responsible for the QPO :
  - the transition to the low state must be due to crossing a stability threshold
  - i.e. the MRI exists for $\beta = 8\pi p/B^2 > 1$, the AEI for $\beta \sim 1$
- the AEI does not dissipate locally the accretion energy (-> no more disk heating) but transports it away by waves
  - -> naturally associated with low-hard state
- observations where the QPO appears just before the transition (see J.R.'s talk)

-> LF-QPO = cause rather than effect of the state transition

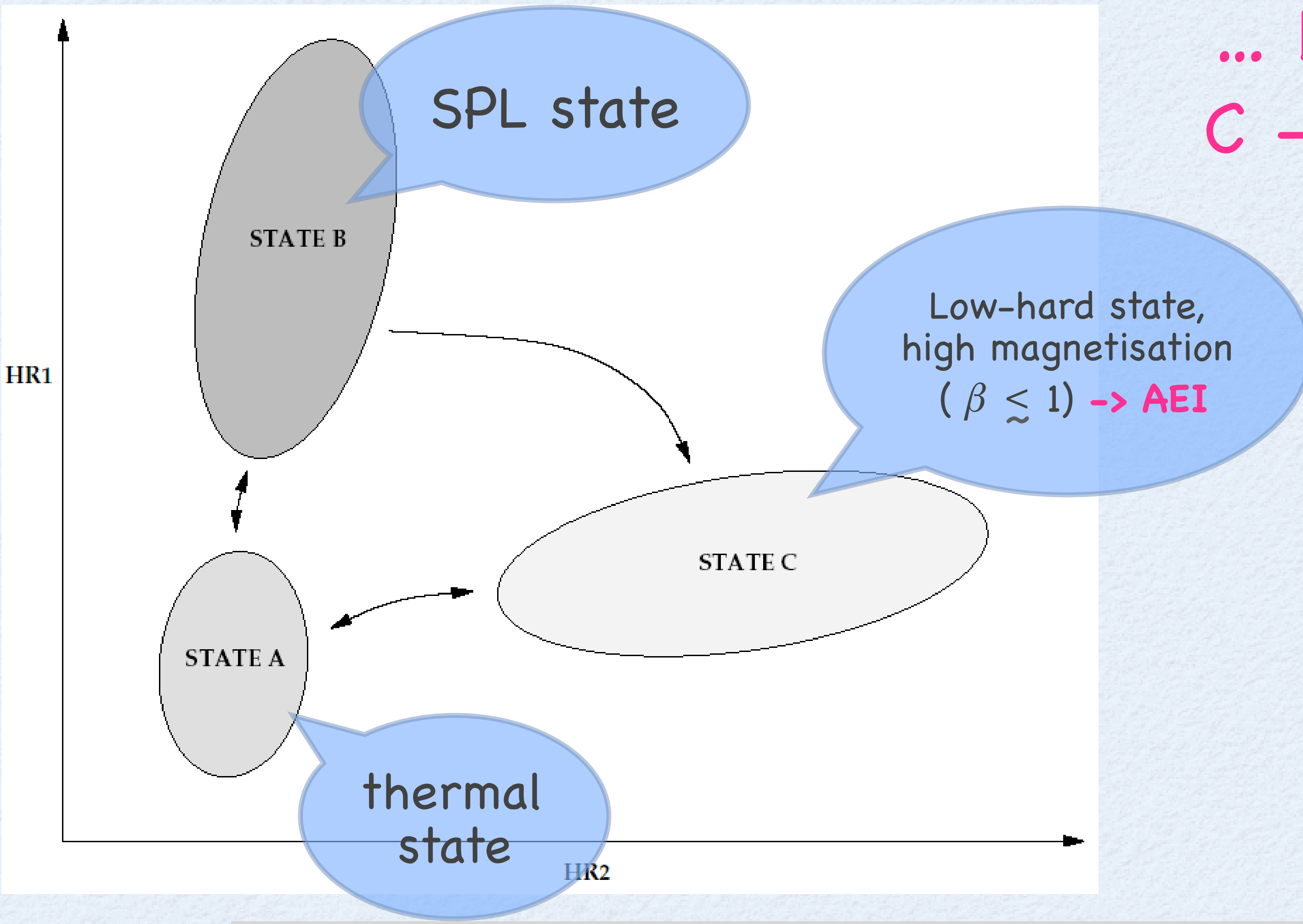
magnetic floods (2)

- our scenario : MRI in the high state -> gradual accumulation of poloidal magnetic flux in the inner disk region until β ~ 1 -> AEI
- => disk cools down => β further decreases (=> sharp transition)
- Intermediate peak : reconnection at inner radius => blob ejection,
- => destruction of magnetic flux => return to high β = high state

Belloni et al.'s 12 classes of variability for GRS 1915+105 …



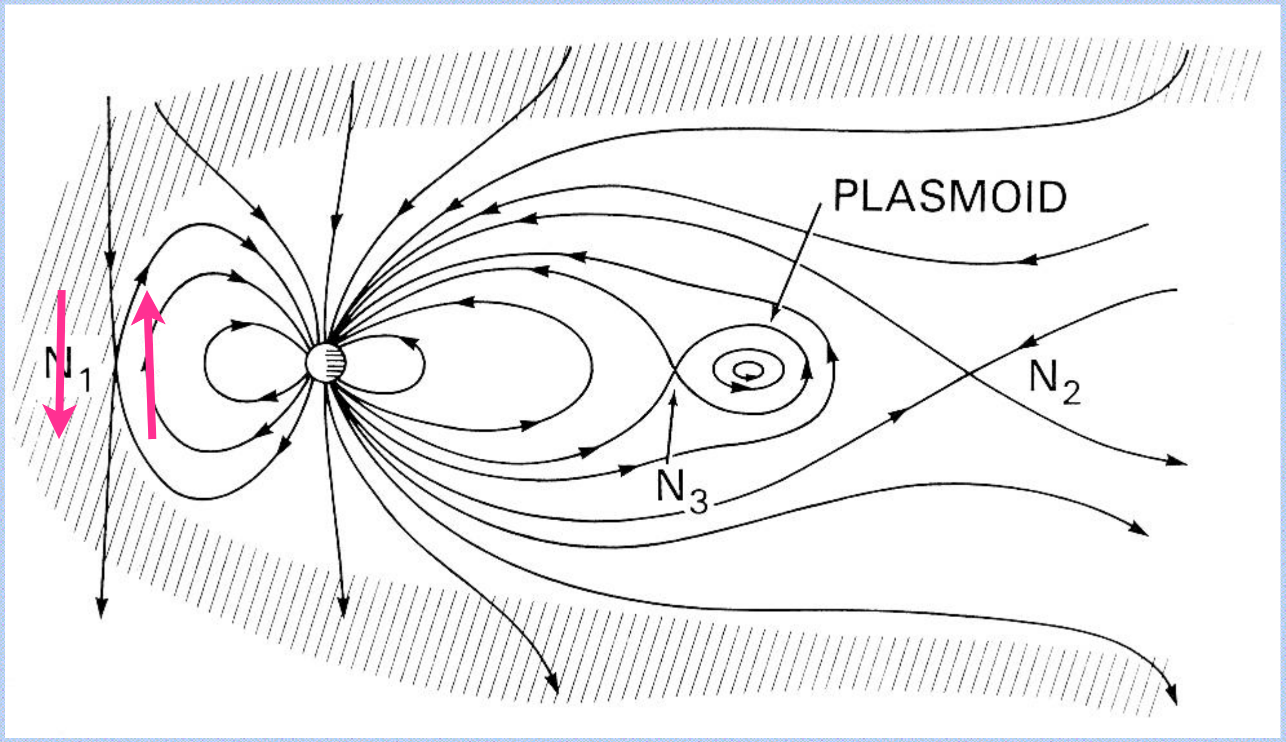
reduced to 3 basic states ...



... but transition C -> B forbidden

Magnetic flood interpretation: Once in state C, reconnection necessary to reduce magnetic flux -> must go through A before return to B

so what about the magnetic flux?



- the magnetophere/solar wind interface has 2 configurations:
  - parallel fields -> complex plasma physics...
  - antiparallel fields -> prone to reconnection events

what about black hole/disk ?

- the horizontal flux in the disk can vary by buoyancy (Parker)

  -> can be expelled from the disk, recreated by dynamo

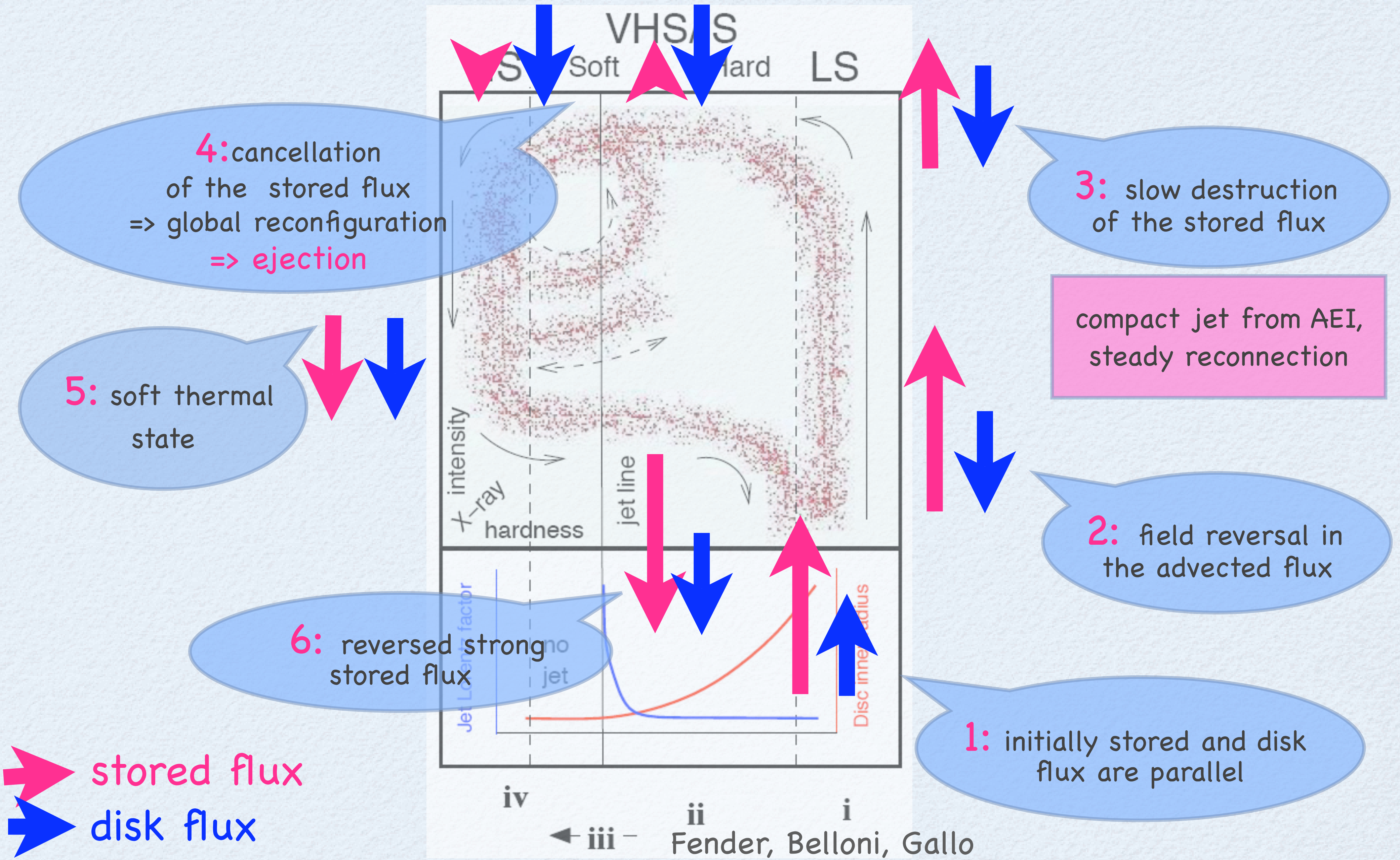
- the vertical flux is advected (although some people believe it isn't, because of magnetic diffusivity)

  (remember that the MRI is ideal MHD!)

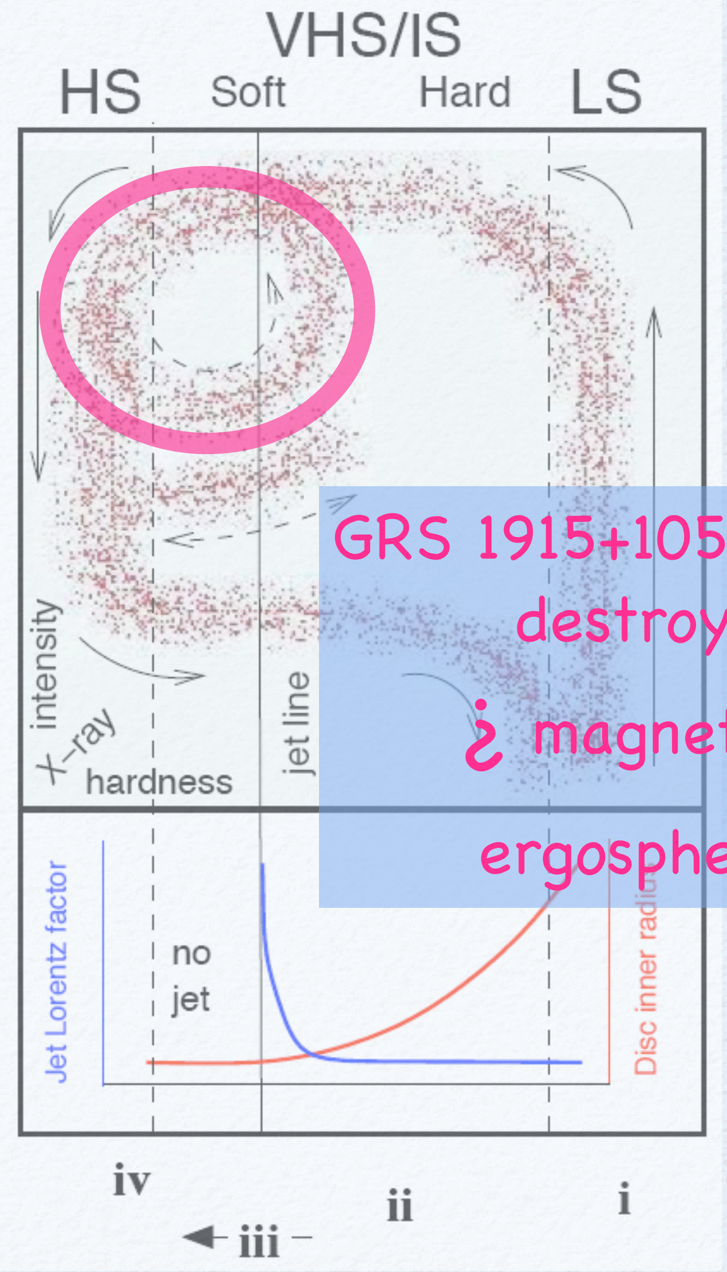
- -> must accumulate in a force-free structure around the BH
- the advected flux comes from the companion (or the disk itself) -> turbulent dynamo -> prone to field reversals
- -> we must expect the same dichotomy
- -> our scenario:

cycles and reconnection/ejection when antiparallel,
quiescent when strong stored flux parallel to the disk flux

generalized magnetic flood



generalized magnetic flood



GRS 1915+105: ejection has not totally destroyed the stored flux

¿ magnetosphere anchored in ergosphere of spinning BH ?

conclusions

- global modes provide the most physical explanation for QPOs: frequencies, coherence, amplitude
- non-axisymmetric modes can be strongly unstable in a variety of conditions
- if well understood, a key diagnostic of the final stages of accretion
- magnetic field plays a key role, especially poloidal flux accumulated in the central cavity between disk and BH
- leads to "Magentic Floods" for GRS 1915+105 and maybe for other microquasars
- B permits transport of accretion energy to the corona
- need full 3D MHD simulations with the relevant magnetic field topology and strength