Spiral Structure in Galaxies

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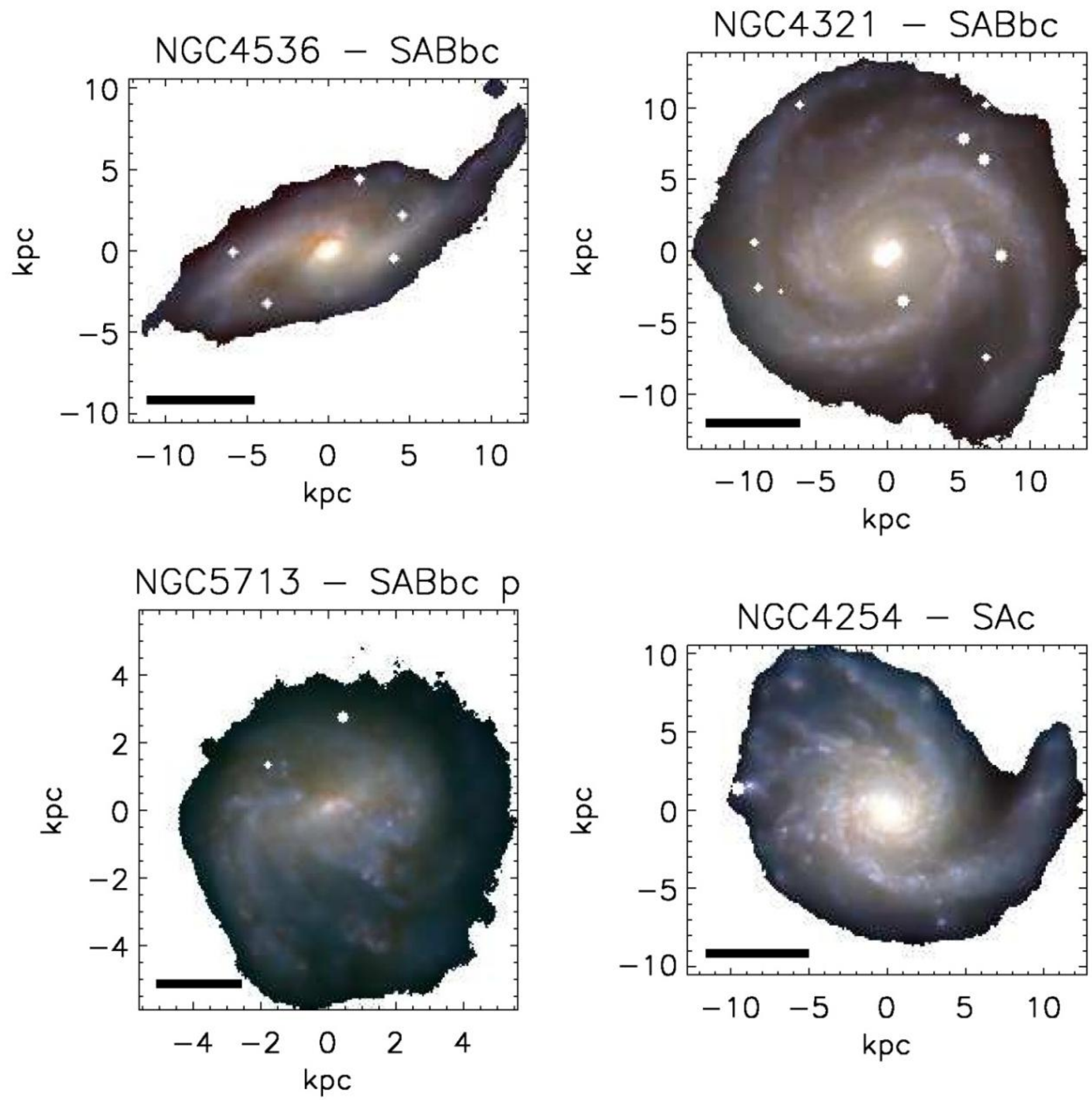
- CITA July 10, 2014

Why spirals matter

- Present structure of a galaxy is not simply the consequence of its formation
- Spirals are major drivers of secular evolution:
  - angular momentum transport (esp. in the gas)
  - age-velocity dispersion relation
  - radial mixing reduces abundance gradients
  - smoothing rotation curves
  - galactic dynamos
  - *etc*.
- How do they work?

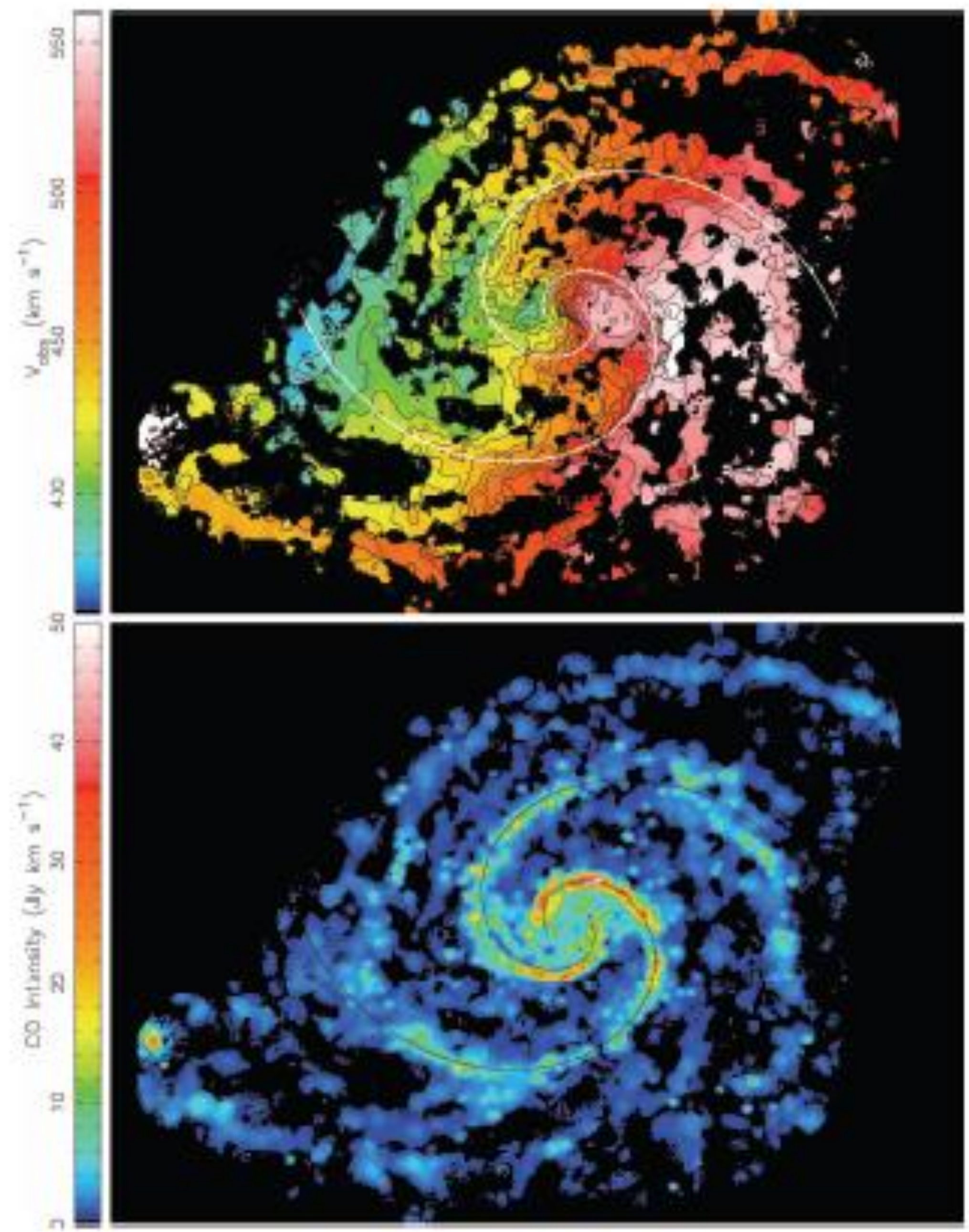
Density waves

- Gravitationally driven waves in the old stellar disk
  - spirals in near IR (Zibetti *et al*. 2009)

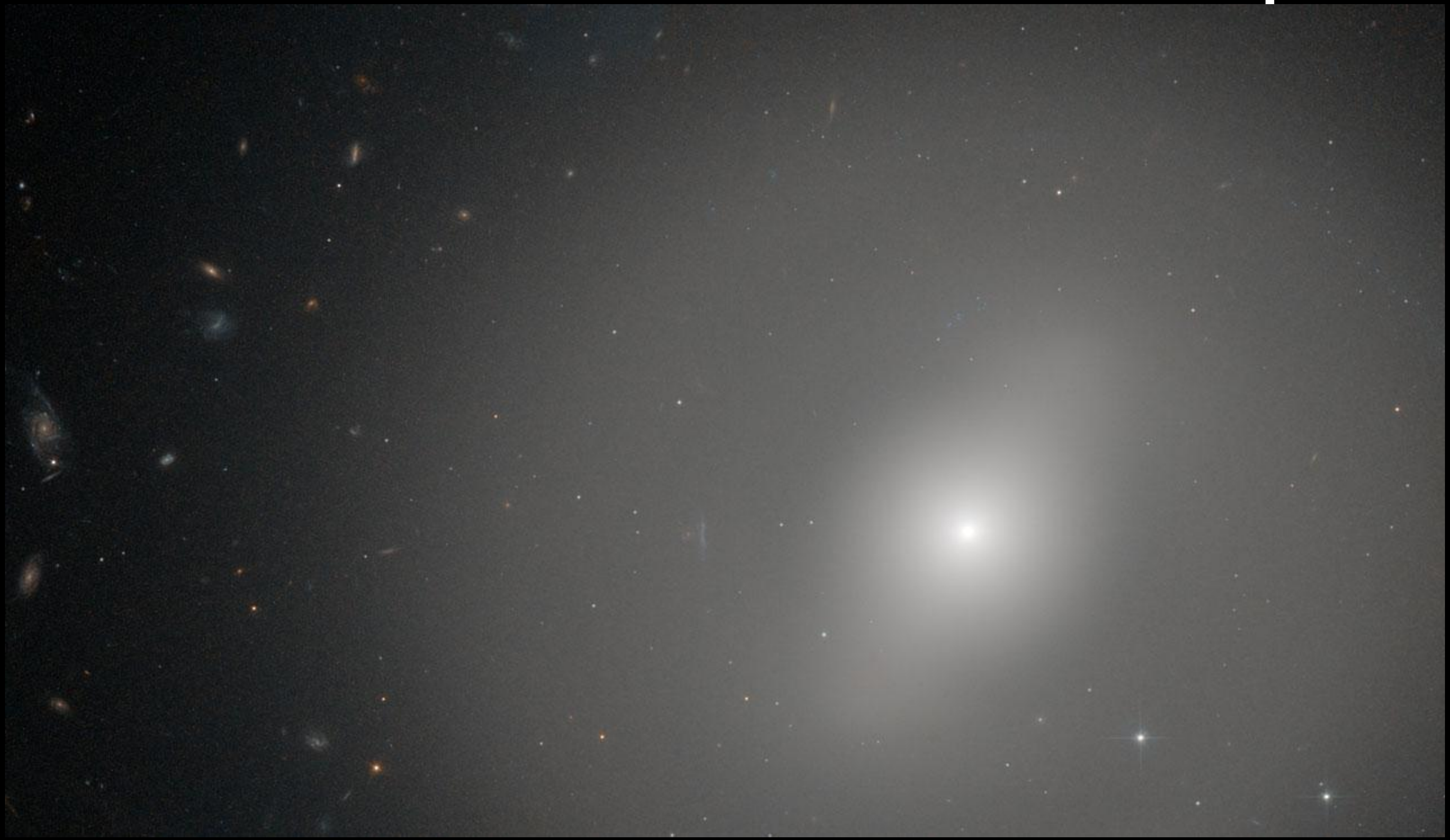


Density waves

- Velocity wiggles also indicate that spiral arms have substantial mass
  – (Shetty *et al.* 2007)
- They are gravitationally-driven waves in the old stellar disk



Gas seems to be essential for spirals

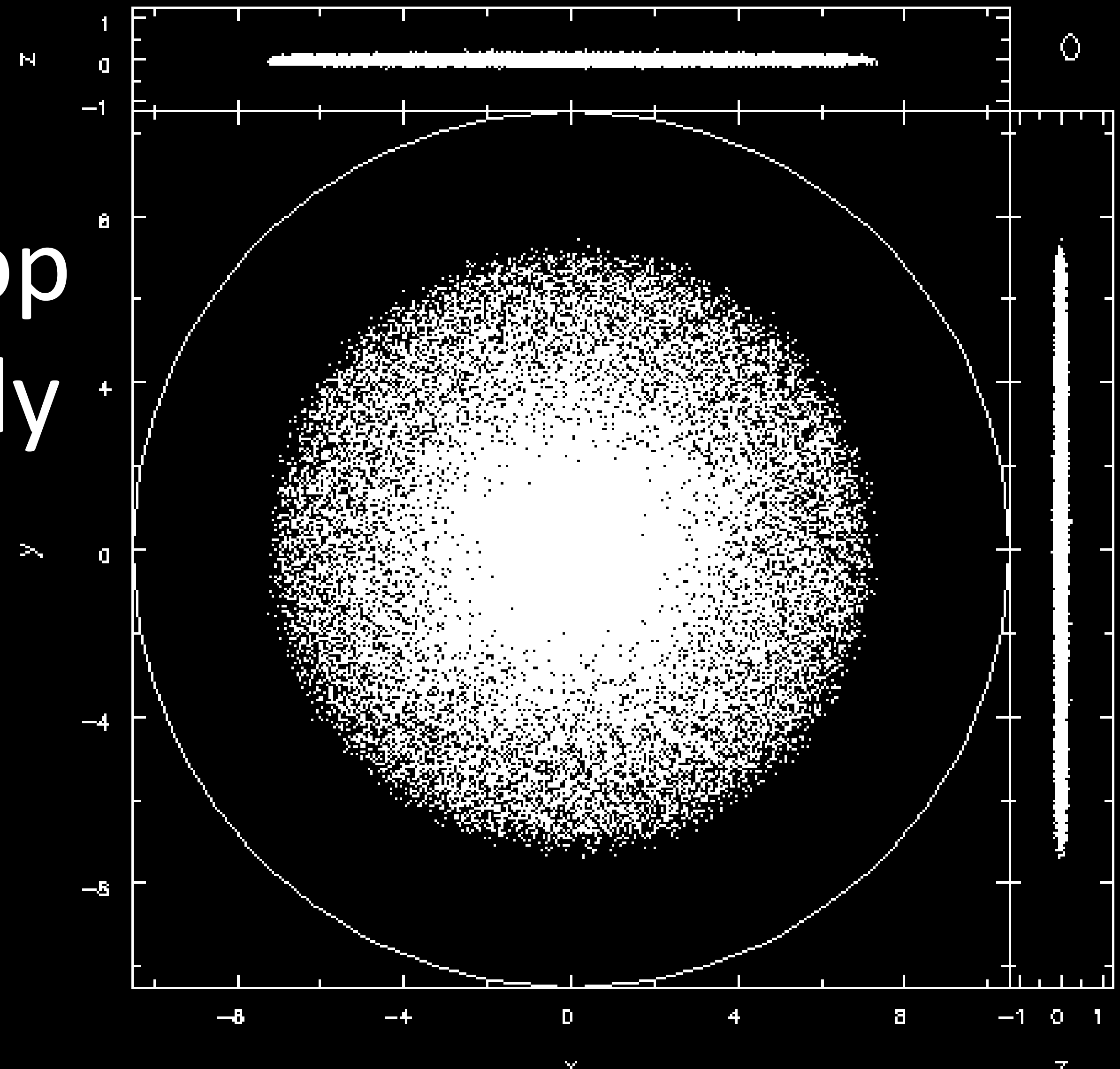


- NGC 1533 – Hubble image
- Misled the community for many years
- Return to this point later

- Some spirals are clearly tidally driven, others may be bar-driven – not the real challenge

M51 & Hubble Heritage NGC 1300

Spirals develop spontaneously



- Always seen in *N*-body simulations of galaxy disks (N=200M, cylindrical polar grid)

Self-excited patterns

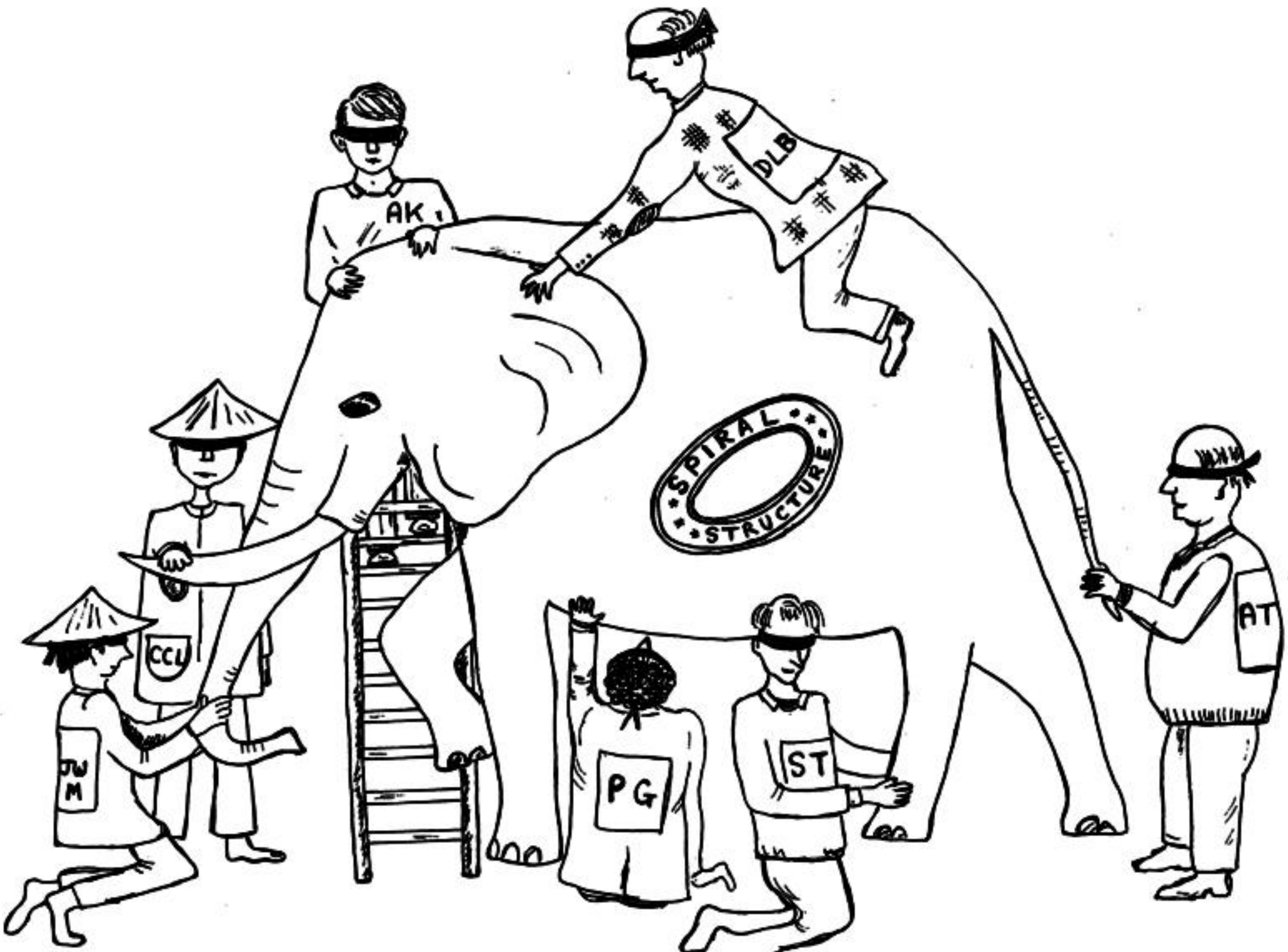
- Spirals develop spontaneously in simulations of cool, isolated, unbarred galaxies

- and they are ubiquitous in galaxies with gas
  - I will explain the importance of gas

- Argues that

most spiral patterns in galaxies are self-excited

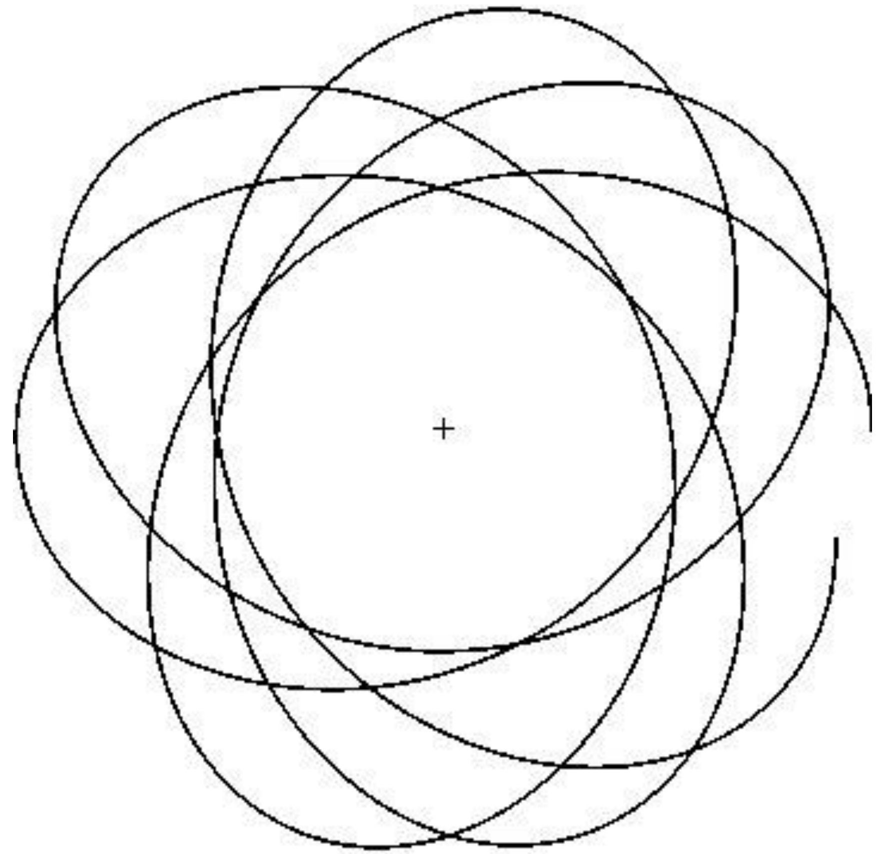
Long-standing challenge



Cartoon, drawn by Janet Sellwood in 1984, based on Toomre's assessment of the state of spiral structure theory in 1980. Apart from a few extra blindfolded individuals, this still seems appropriate today.

Orbit frequencies

- In-plane motion in an axisymmetric potential
- Two principal frequencies: $\Omega_R = 2\pi/\tau_R \rightarrow \kappa$
  - periodic radial oscillation
- and $\Omega_\phi = \Delta\phi/\tau_R$
  - guiding center orbits at const. rate

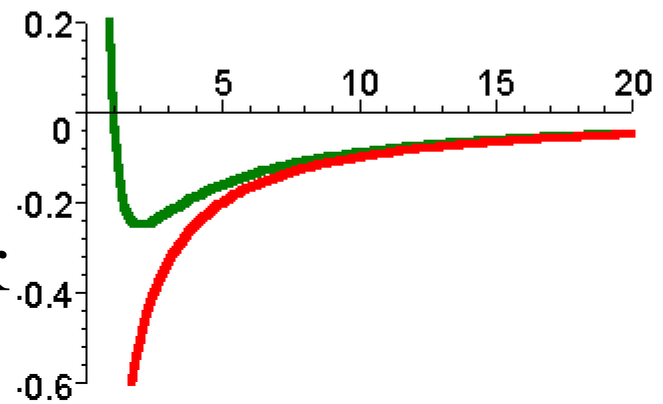


Local stability

- Toomre used WKB (local) approximation for **axisymmetric** stability of a disk of stars
- Short waves are gravitationally unstable in a disk with no random motion
  - rotation stabilizes long waves – surface density Σ

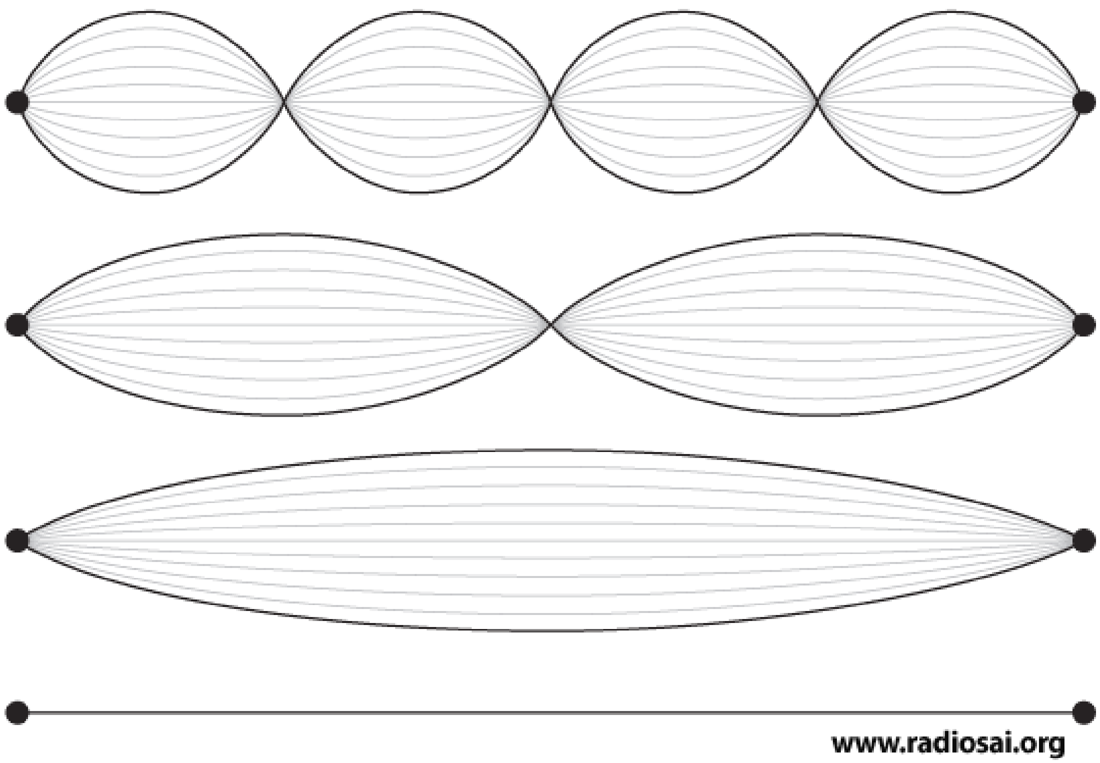
    critical wavelength: $\lambda_{crit} = 4\pi^2 G\Sigma/\kappa^2$
- Random motions stabilize short waves
- Complete stability if: $Q > 1$

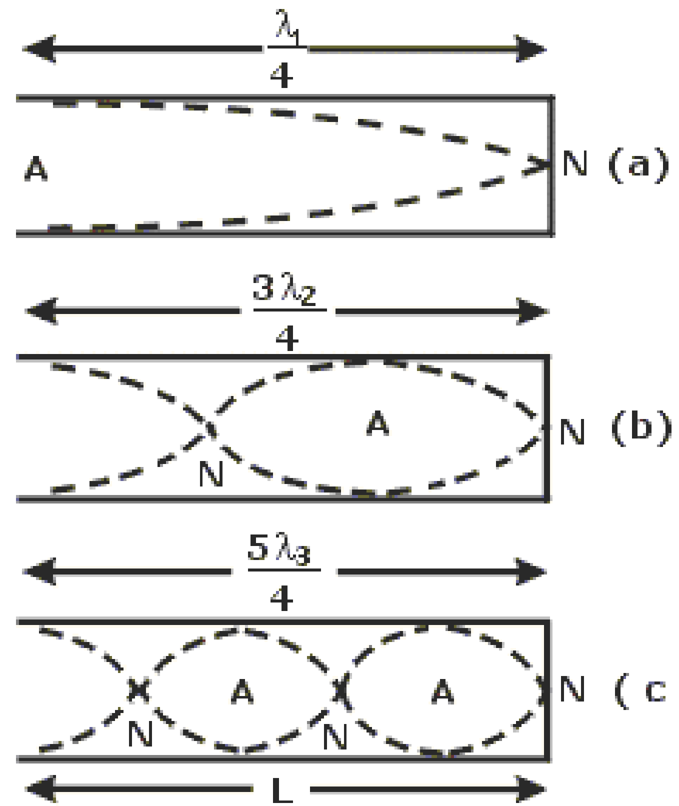
$Q = \sigma_R / \sigma_{R,crit}$ & $\sigma_{R,crit} = 3.36 G\Sigma/\kappa$



Modes

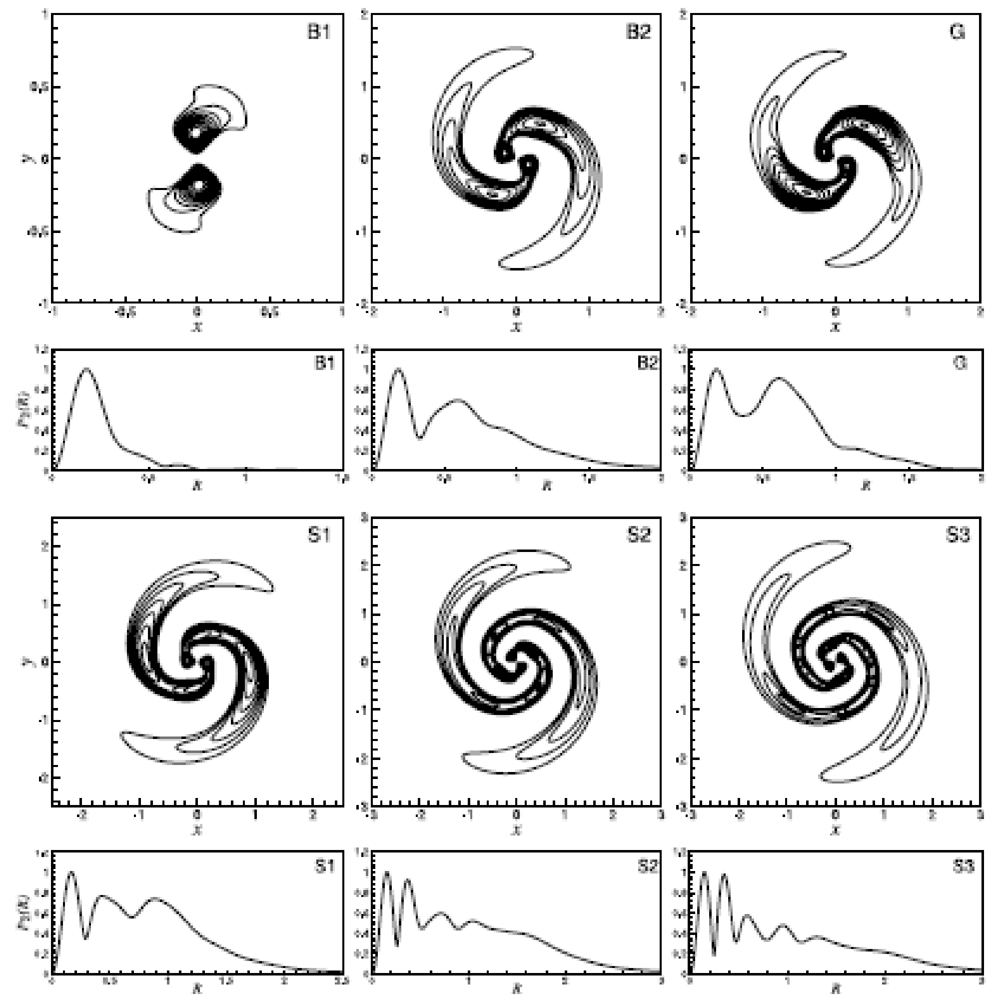
- Standing wave oscillations familiar from guitar strings, organ pipes, *etc*.





Global modes of smooth, rotationally-supported disks

- Growing waves of fixed pattern speed Ω_p *e.g.* Jalali (2007)
- Bar-forming modes usually dominate
  – fastest growing has almost no spirality
  – important for stability
  – not for spiral theory



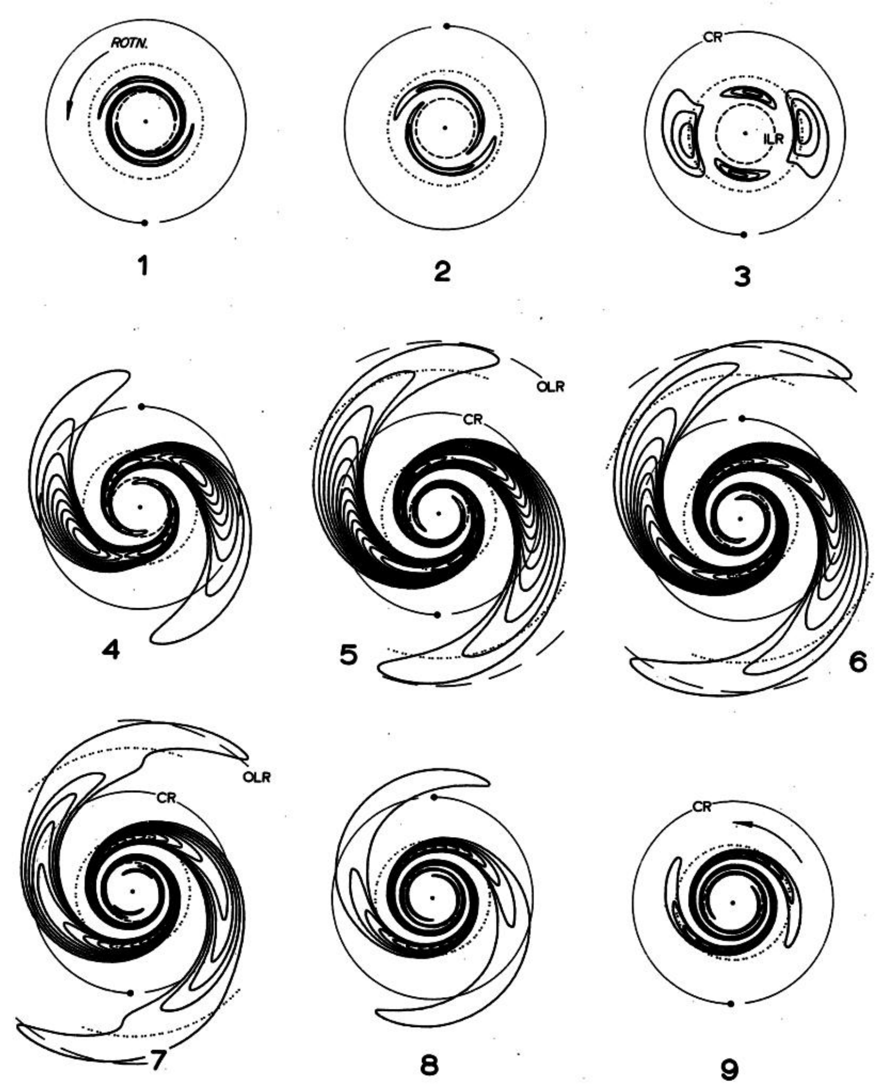
Resonances

- Star orbits at angular rate Ω_ϕ
- An *m*-armed spiral wave rotates at rate Ω_p
- Star encounters the wave crests at the rate

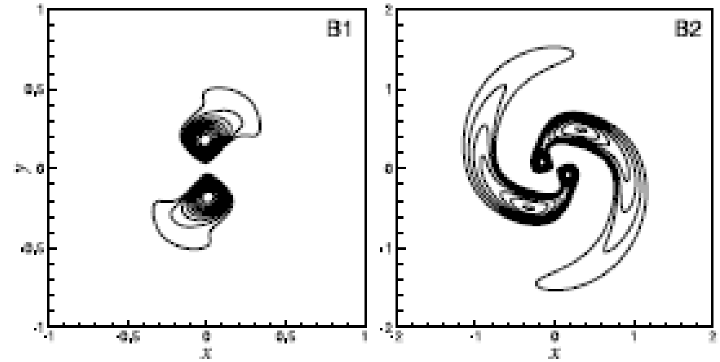
  $m(\Omega_p - \Omega_\phi)$
- Resonances arise where $m(\Omega_p - \Omega_\phi) = l\Omega_R$
  - $l = 0$ – corotation
  - $l = \pm 1$ – Lindblad resonances

Swing Amplification

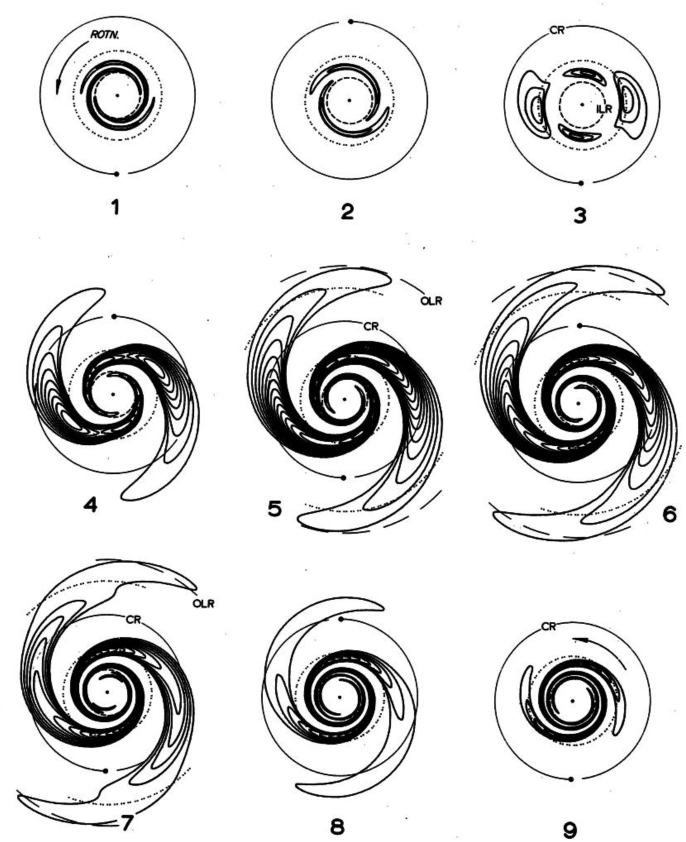
- Figure from Toomre
  - linear calculation
- Transient trailing spiral from input leading wave packet
- Does not persist
  - group velocity
  - damping at LRs
- A vigorous response, not a mode



Mode mechanism



- Feedback loop
- If no inner Lindblad resonance
  - wave propagates to the center
  - reflects into a leading wave
  - propagates back to corotation
  - amplifier with positive feedback
  - unstable standing wave
- Massive galaxies generally have dense centers – stabilized by absorption at ILR

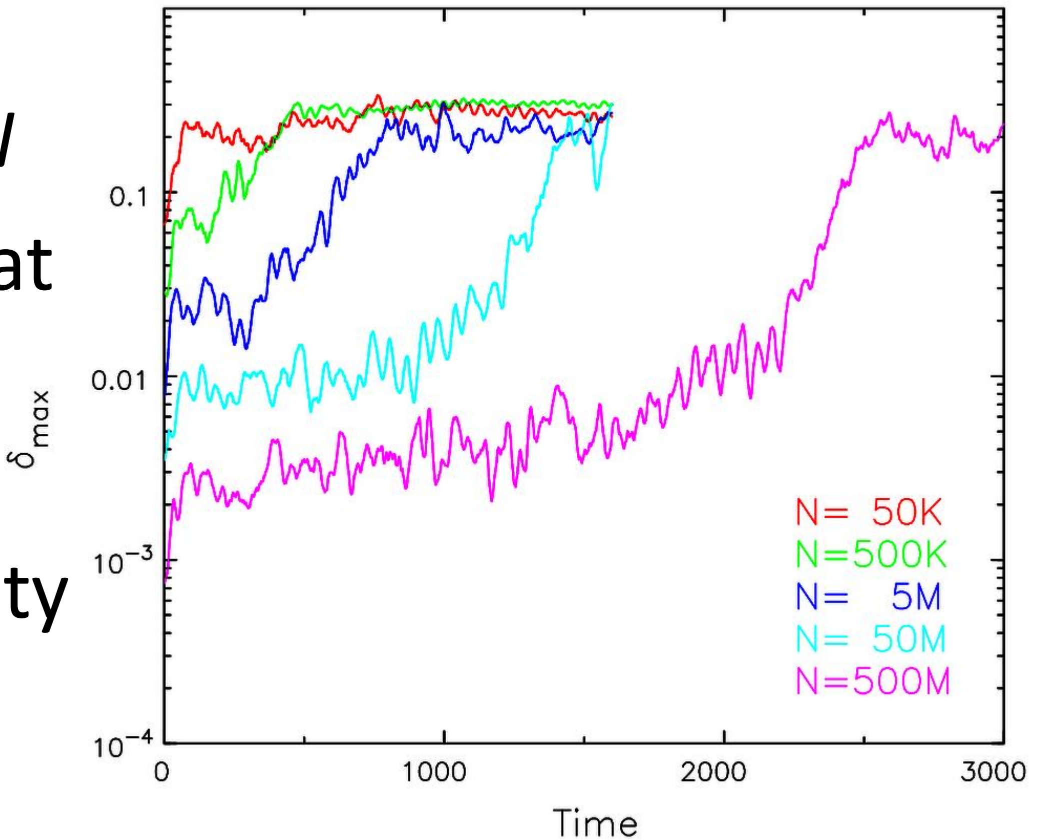


A linearly stable disk

- “Mestel” disk: $\Sigma \propto 1/r$, V_c = const
- Toomre & Zang introduced a central cutout and an outer taper in active density
  - both replaced by rigid mass
- Carried through a global stability analysis of warm disks with a smooth DF
  - confirmed independently (Evans & Read, S & Evans)
- Halve the active mass, in order to suppress a lop-sided instability, and set $Q = 1.5$
- They proved this disk is ***globally stable***

Simulations of the ½-mass Mestel disk

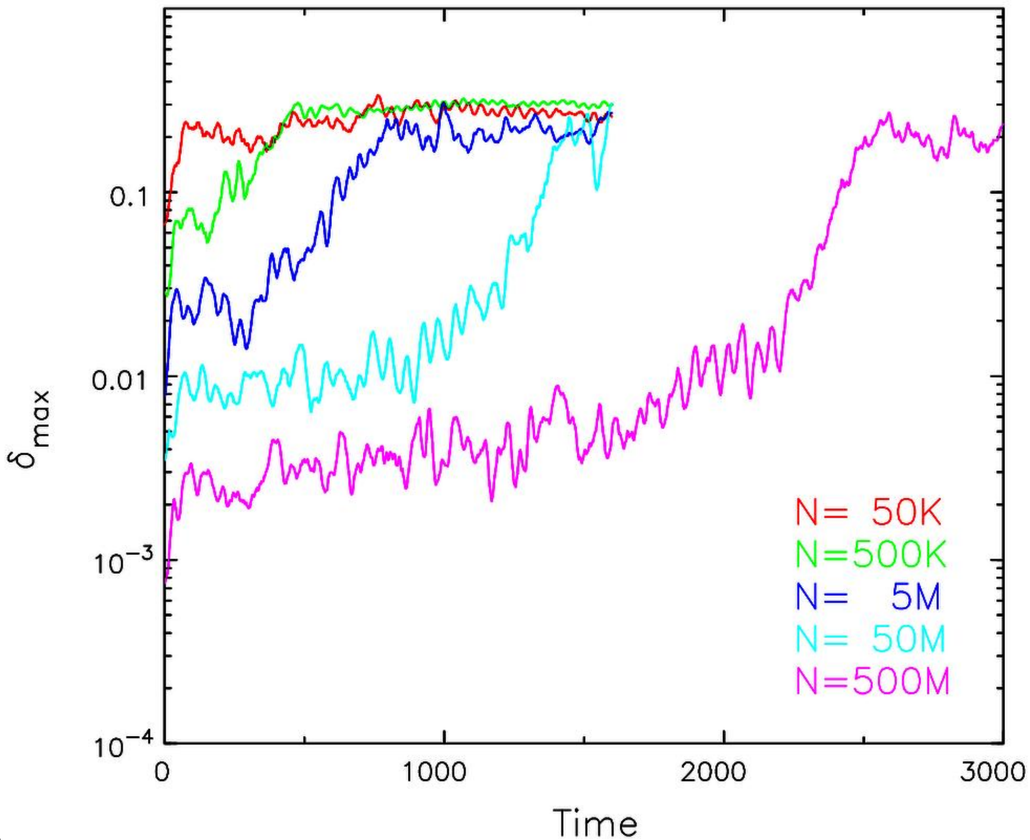
- Peak $\delta = \Delta\Sigma/\Sigma$ from m = 2 with different N
- Amplified shot noise at first
- Always runaway growth of spiral activity
- More and more delayed as N is increased



τ_{rot} = 50 in these units

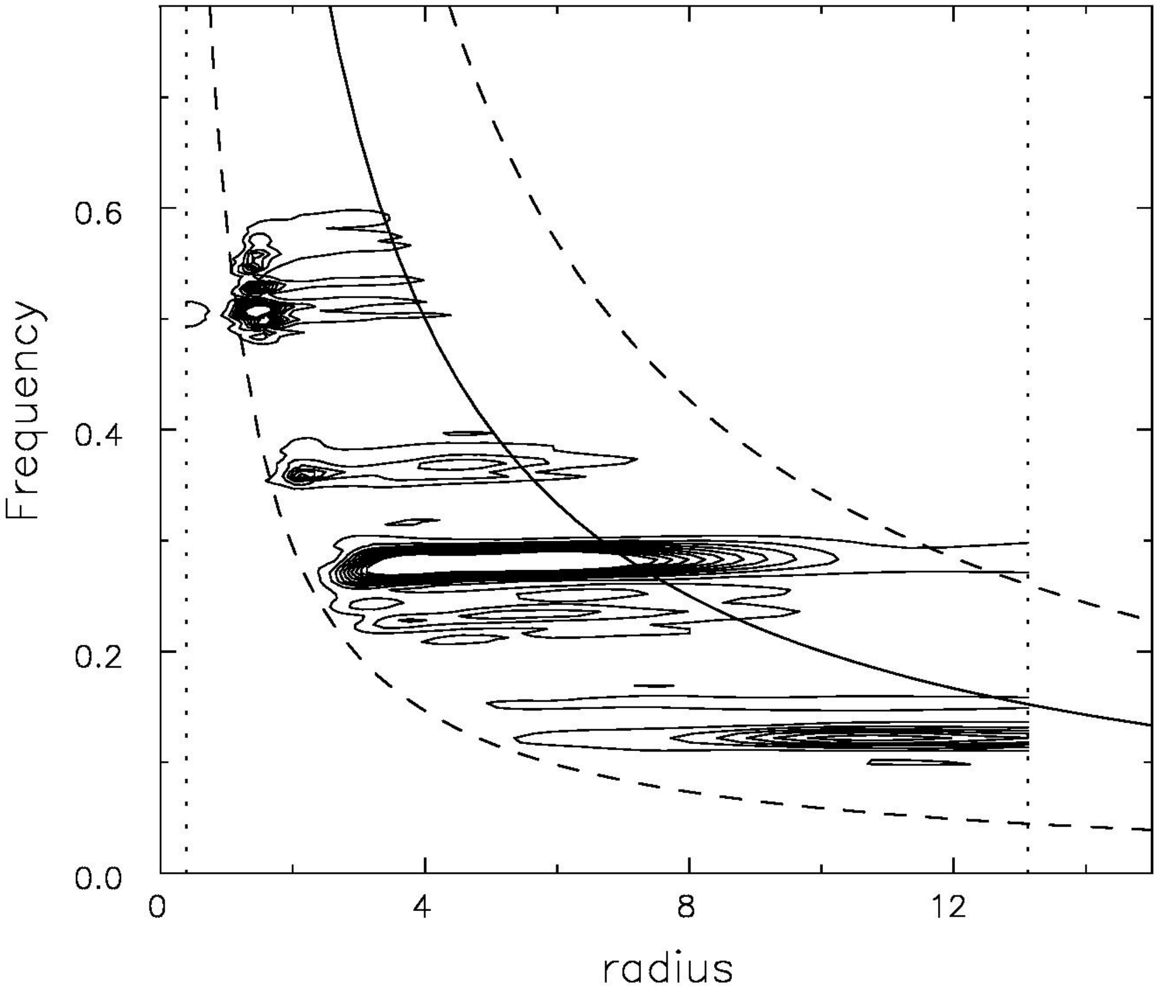
Simulations of the ½-mass Mestel disk

- So what is going on here?
- Rapid growth once $\delta > 2\%$ – non-linear already?
- Real galaxies are not as smooth as N = 500M!
- More detailed analysis



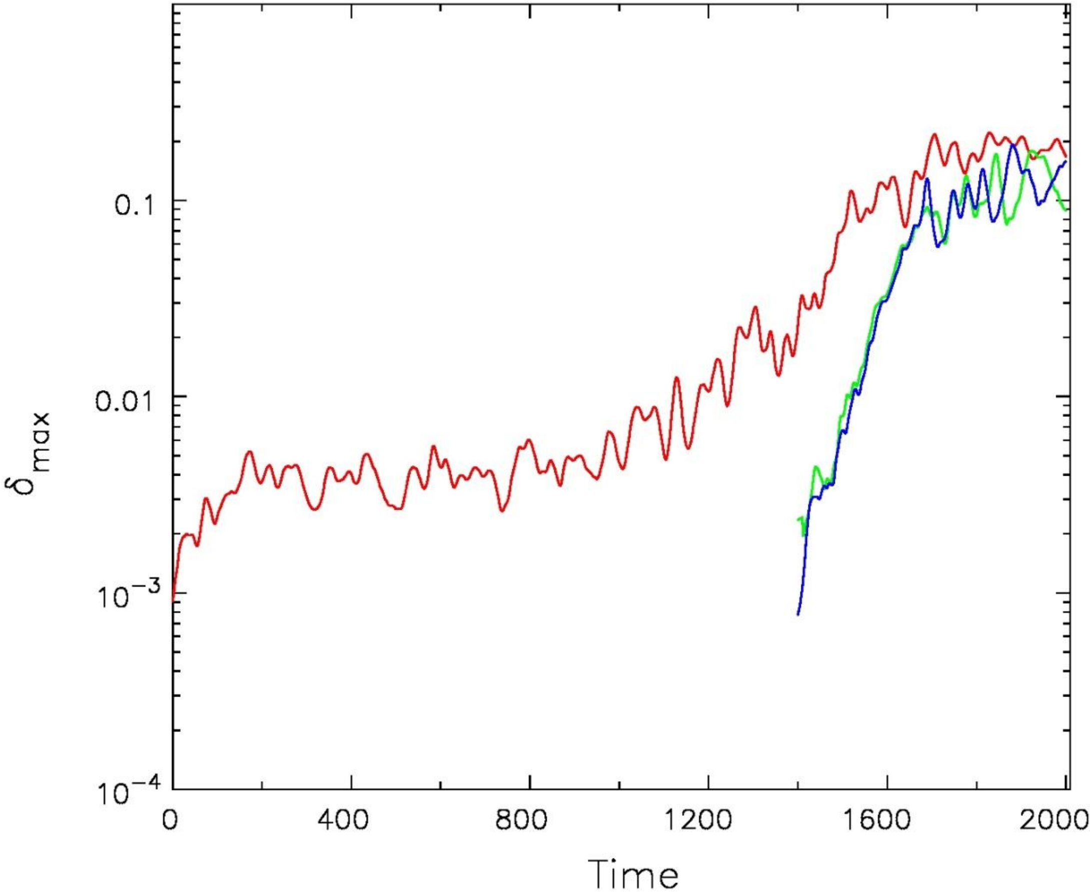
No single coherent wave

- Several separate frequencies as the amplitude rises – *i.e.* not a single mode



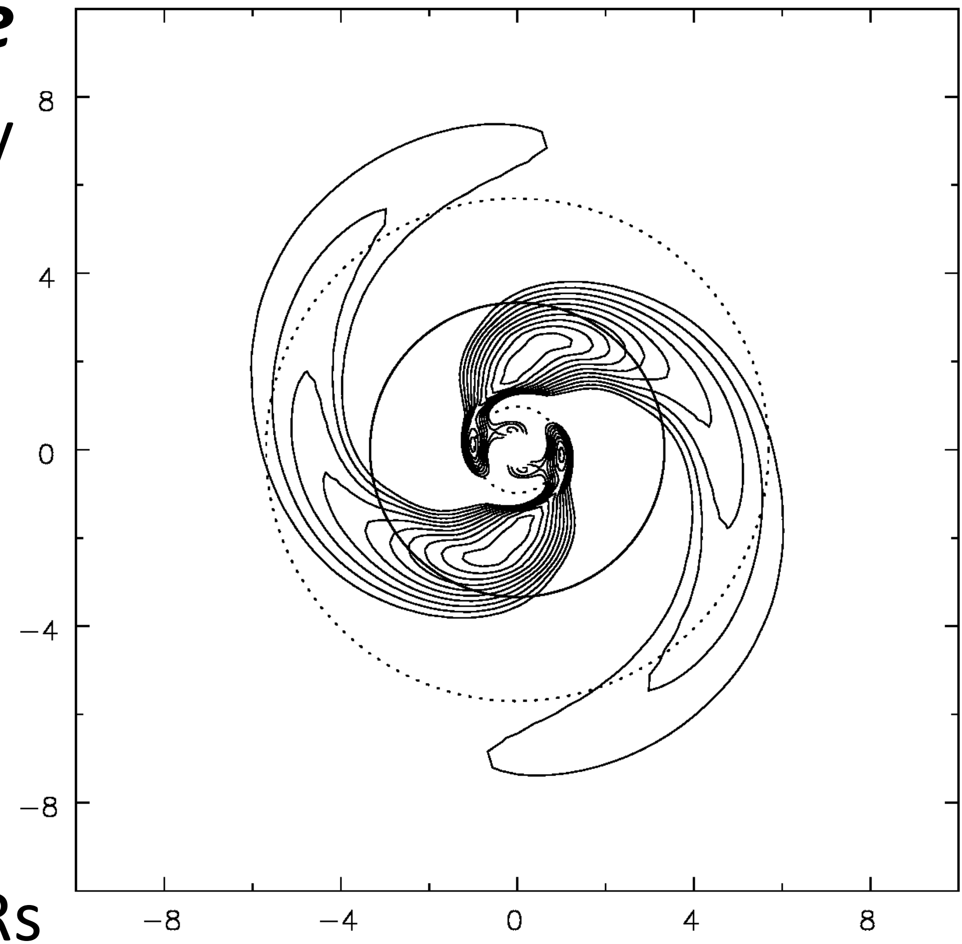
A true instability of the perturbed disk

- Restart from time 1400 with reshuffled phases
  - green: azimuth only
  - blue: both R and ϕ
- No visible spiral by t=1400
- Yet the model now possesses a vigorous instability



A true instability of the perturbed disk

- Vigorously growing ***mode***
  – fixed shape and frequency
- Best fit shape
  – peak near corotation
  – extends to LRs
- Decays after it saturates
  – CR peak disperses
  – "wave action" drains to LRs



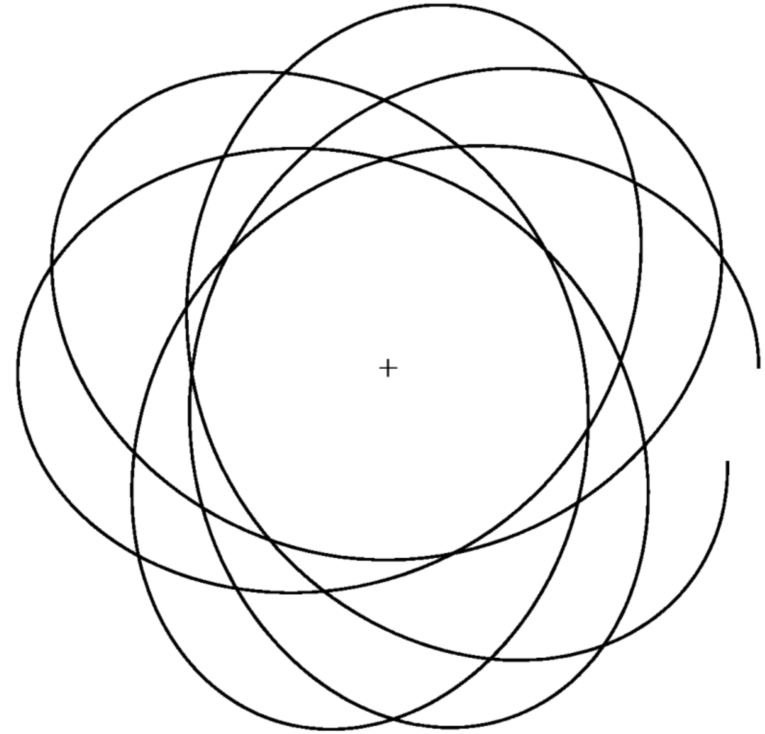
Action-angle variables

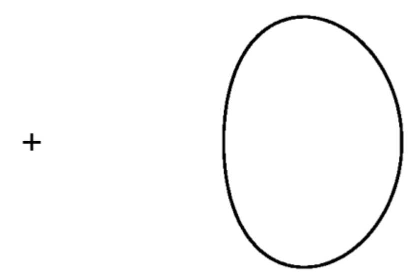
- Rosette orbit
  - uniform angular speed
  - plus a retrograde epicycle
- Actions are

$$L_z \equiv J_\phi \;\;\&\;\; J_R$$

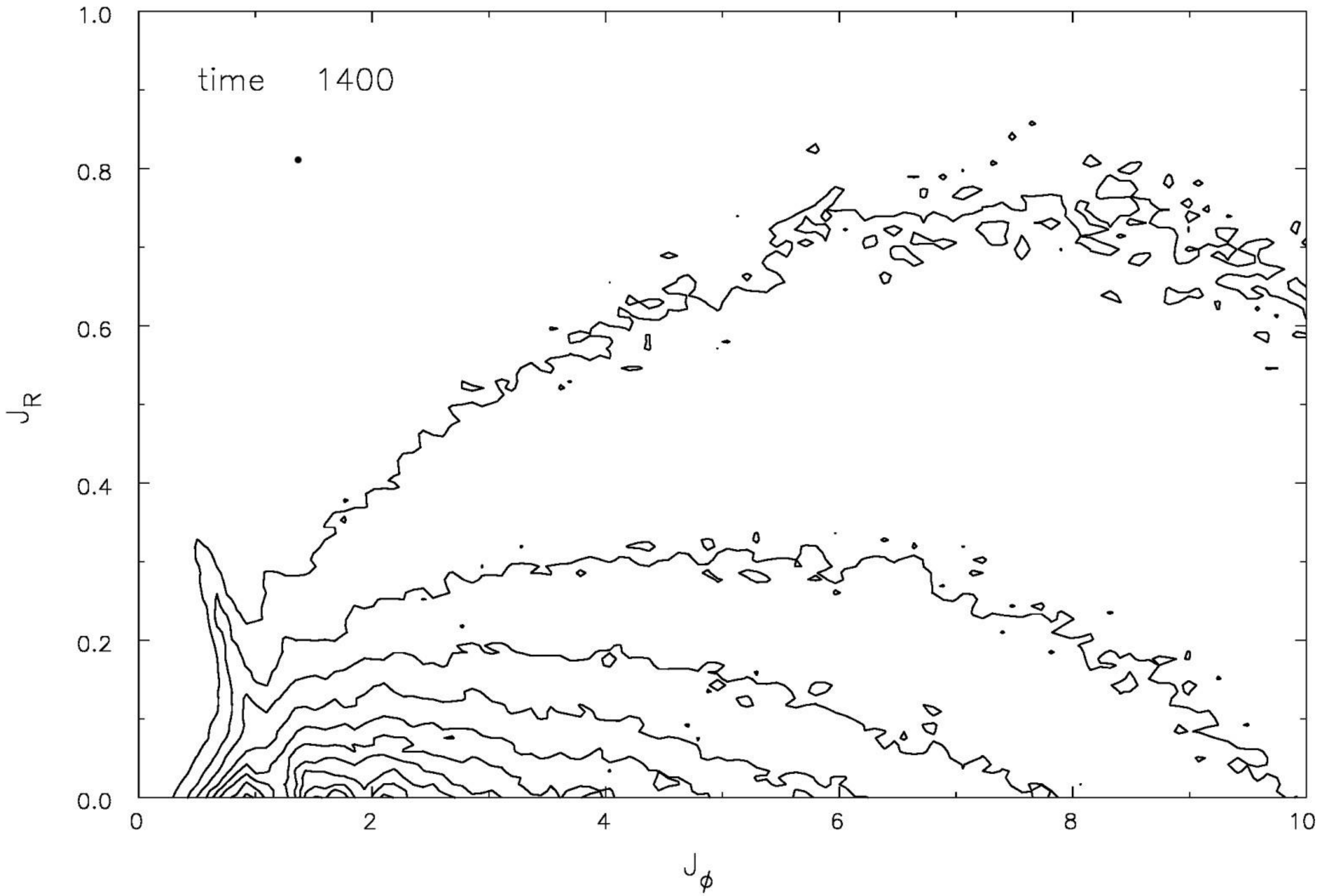
- Angles

$$w_\phi \;\&\; w_R$$



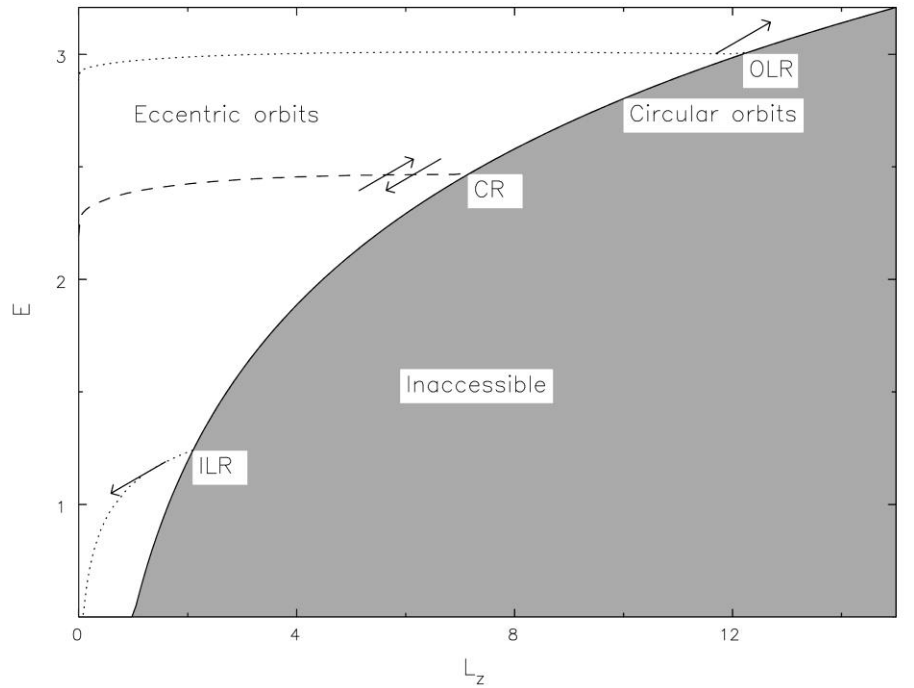


Change to DF



- Density of particles in action space

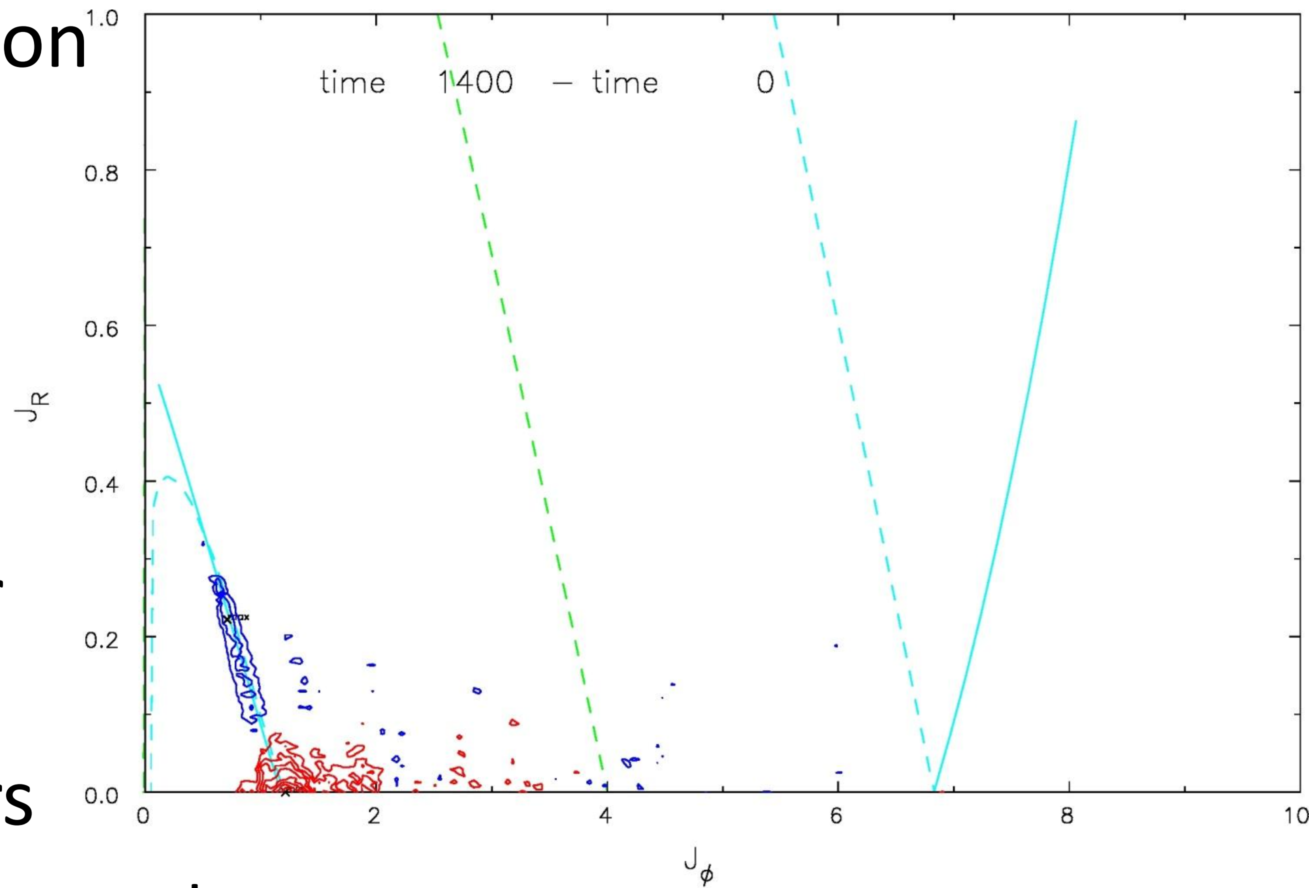
Scattering of stars by a rotating perturbation



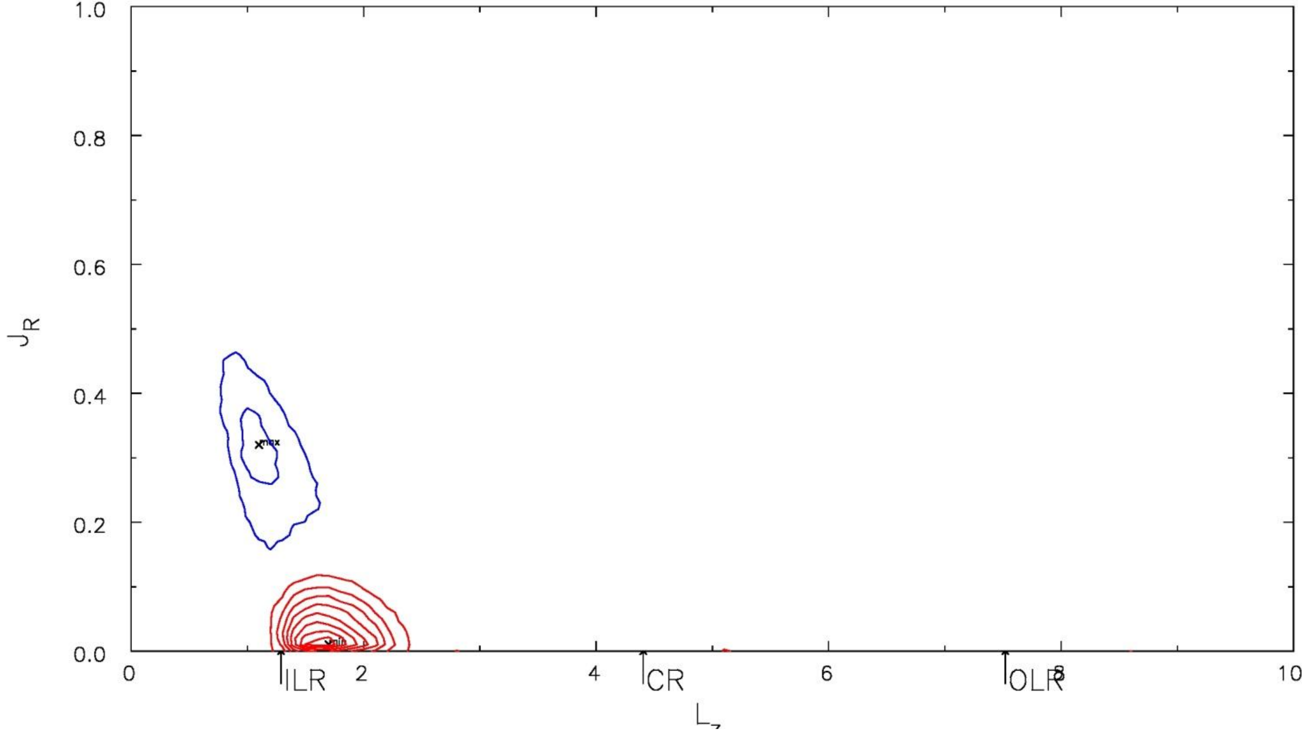
- Lindblad diagram for a flat rotation curve
  - corotation where $\Omega = \Omega_p$
  - Lindblad resonances where forcing freq. = epicycle freq.
- Jacobi's integral: $I_J \equiv E - \Omega_p L_z \rightarrow \Delta E/\Delta L_z = \Omega_p$
- Scattering at LRs $\rightarrow$ heating – well-known (LBK72)
  - & gravity torques extract energy from potential well
- But stars scattered at ILR stay close to resonance!

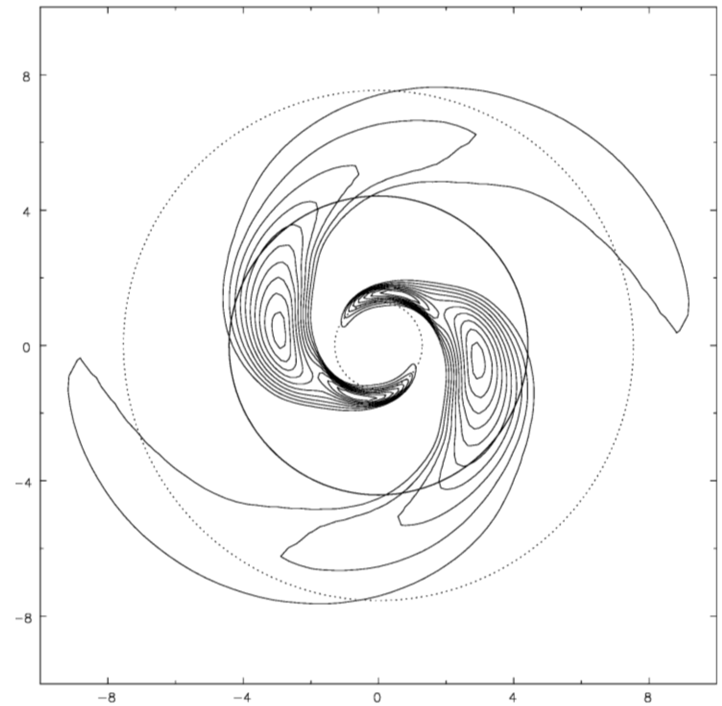
Scattering at the ILR

- Changes in action space density
- Apparently changes at ILR only
- Ω_p from power spectrum – no free parameters
  - dashed – resonance locus
  - solid – scattering direction from J_R=0



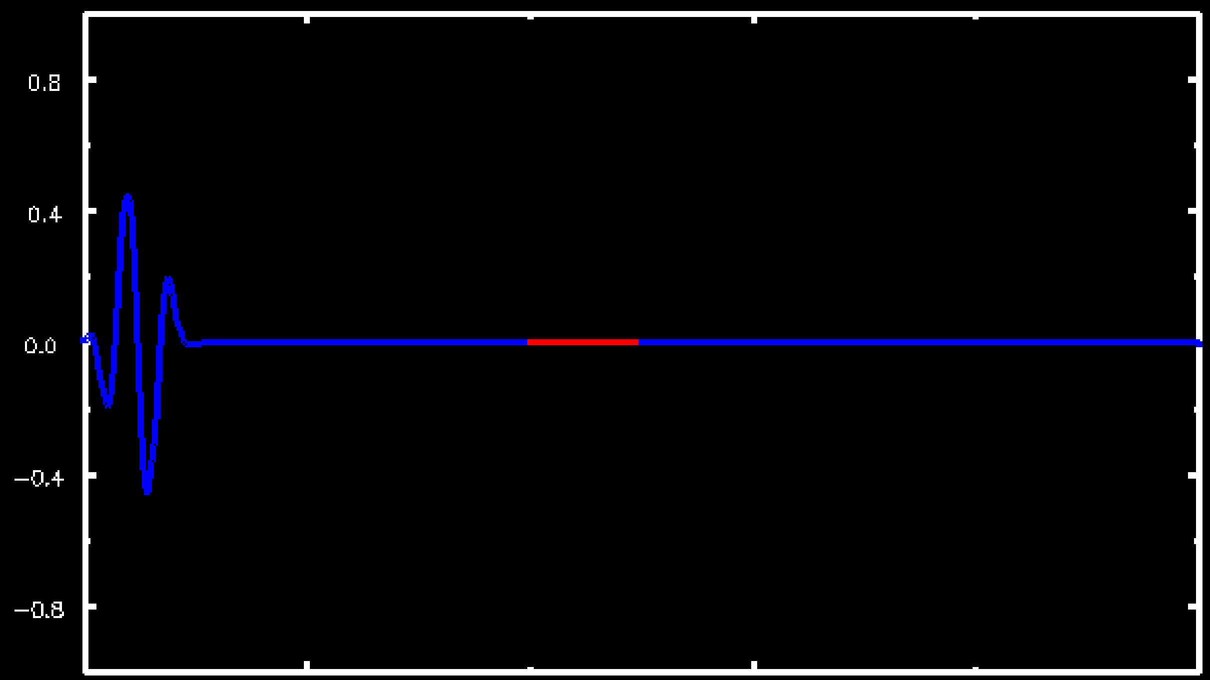
Feature put in "by hand"





- Demonstrates that ILR scattering really does provoke the new instability
  - Mode is vigorous
  - probably of cavity-type with a "hard" reflection near the ILR

A wave in a heavy string

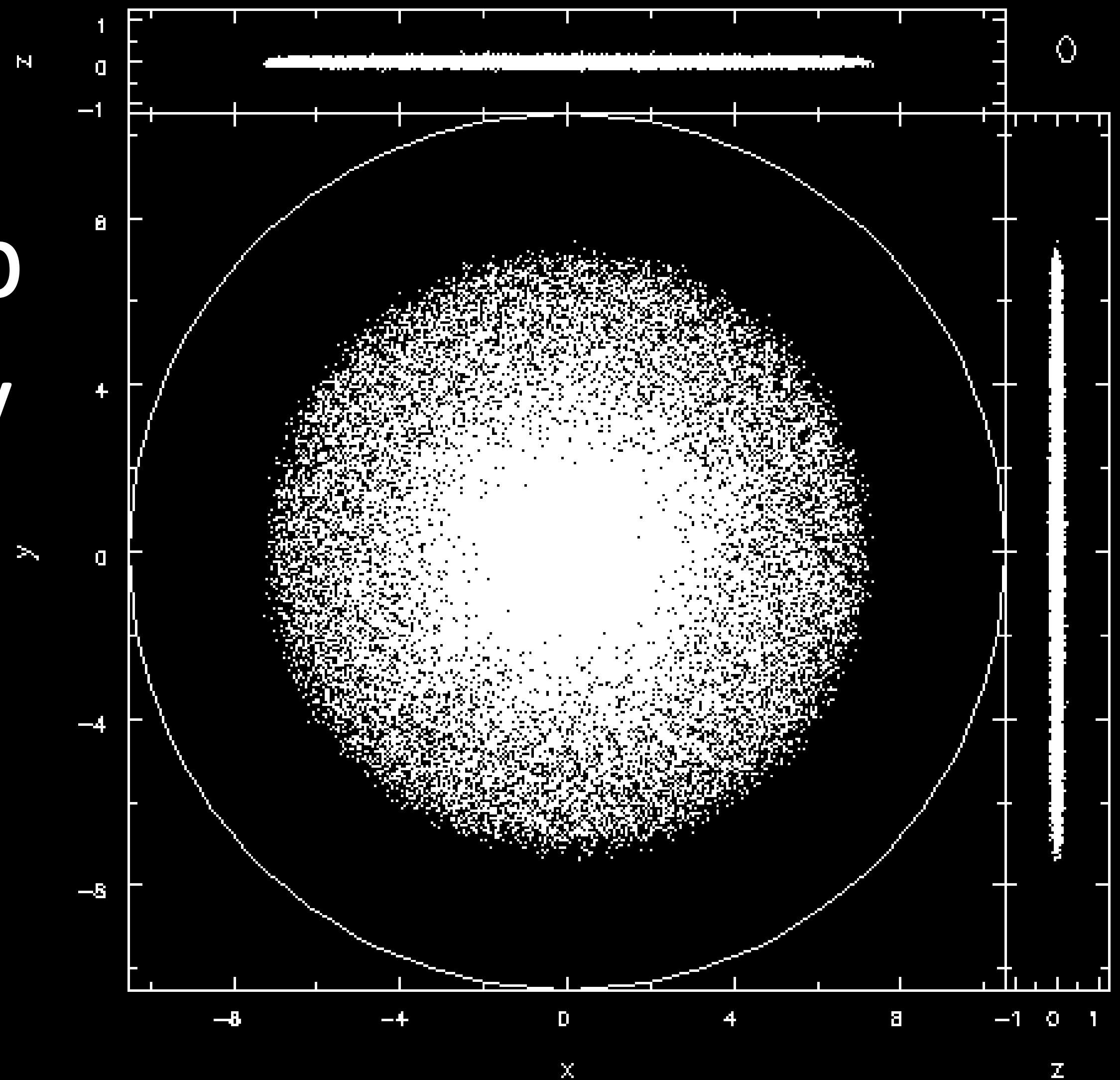


- With a short “frayed” piece – much lighter

Recurrent cycle?

- Each disturbance leaves behind a damaged DF
- Introduces an abrupt change to the impedance of the disk
- Causing partial reflection of waves and creating a new instability
- Perhaps this is the mechanism for spirals in more realistic simulations

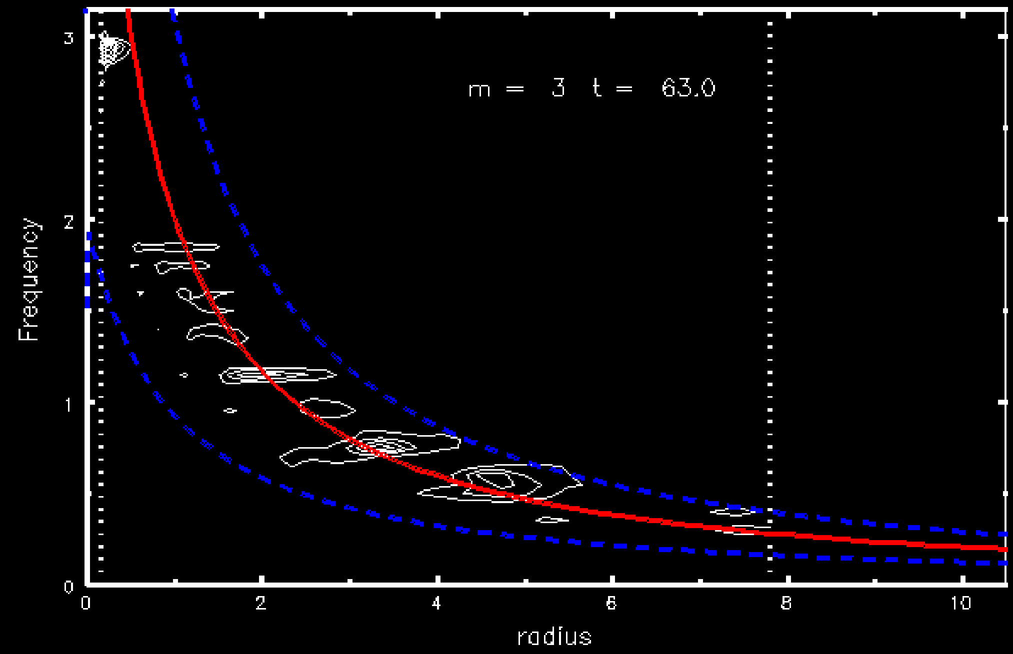
Spirals develop spontaneously

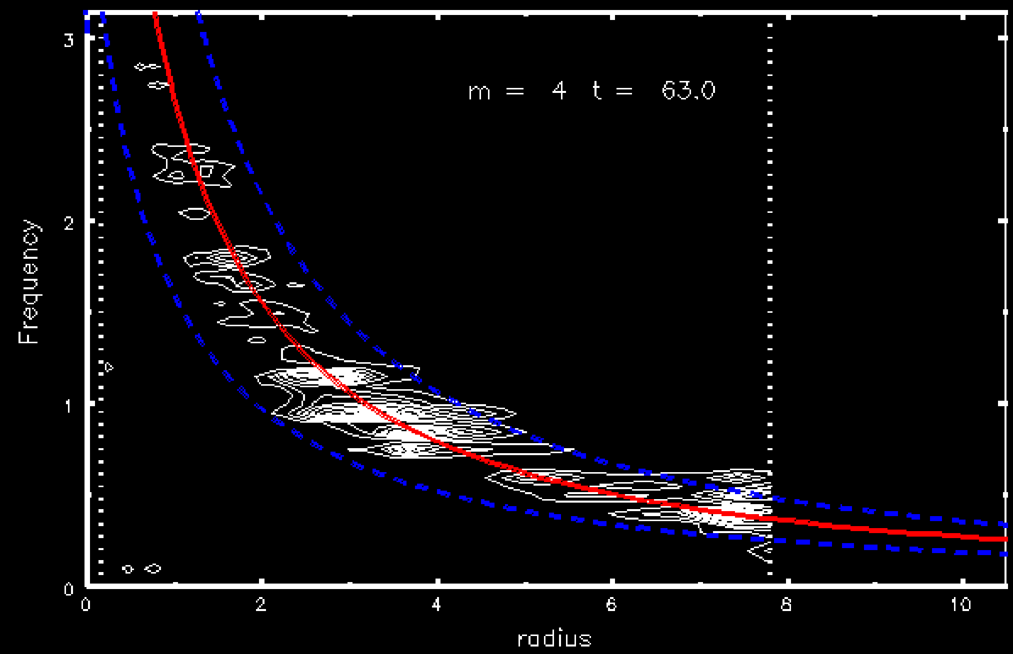


- Always seen in *N*-body simulations of cool, shearing disks

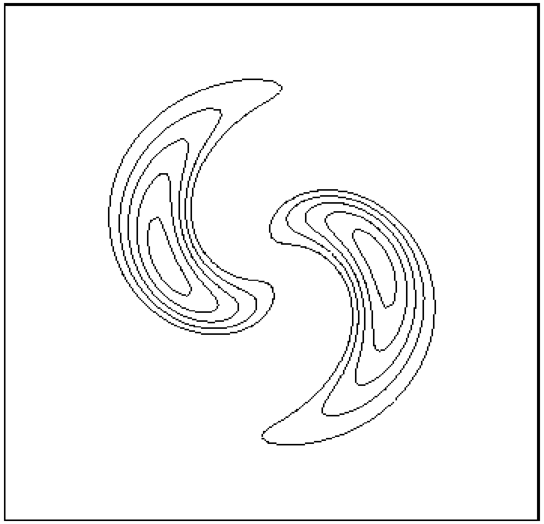
Spiral-forming simulation

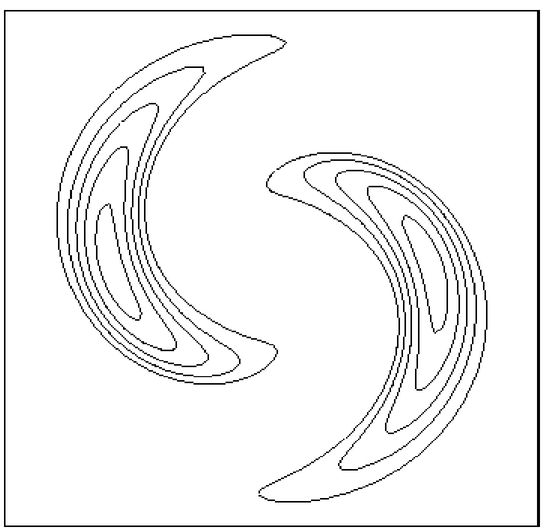
- Lifetime of each pattern is several galactic rotations
- Inner disk heats first and patterns fade
- Suggest that each wave is a spiral mode
  - lifetime a few rotations

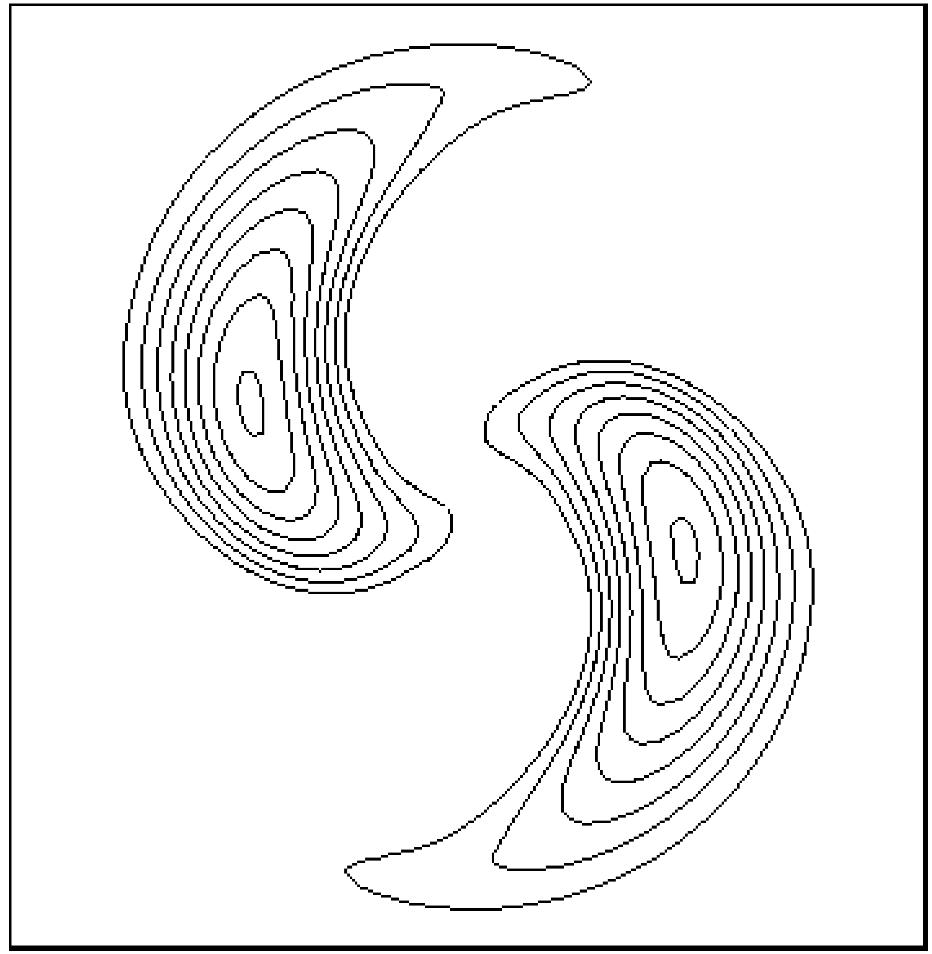




Two superposed steady waves

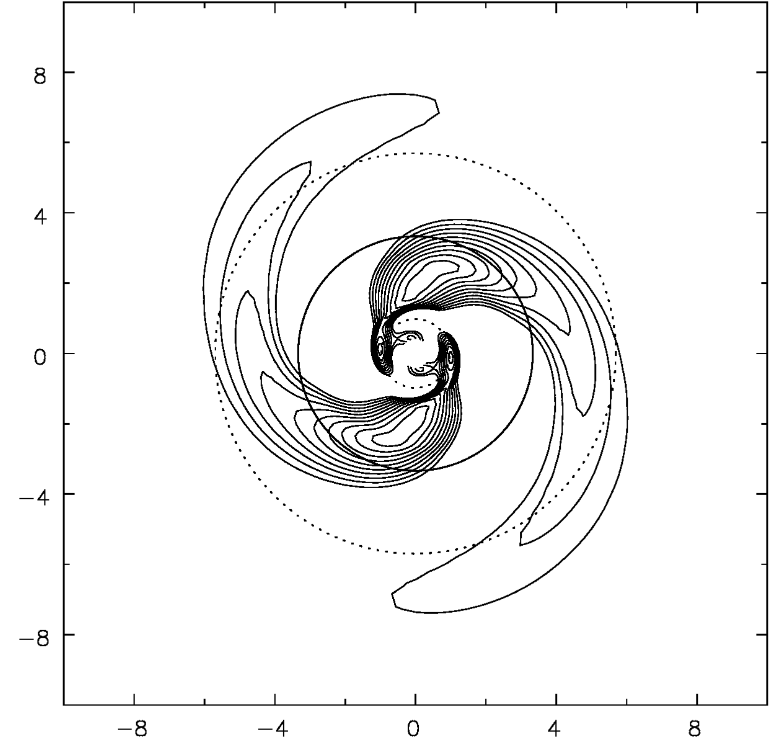






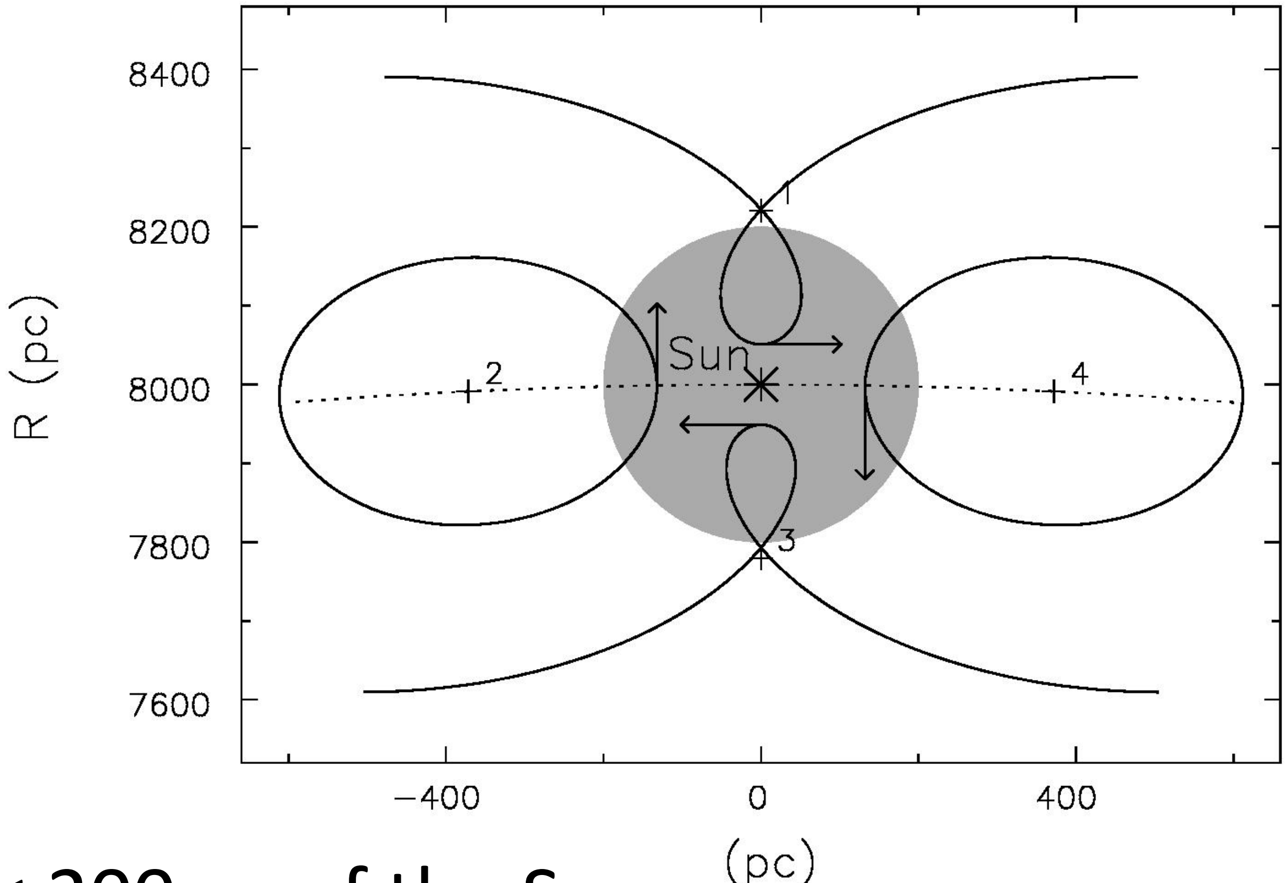
- inner wave has the higher pattern speed

New picture



- Spiral patterns are unstable ***modes*** that grow rapidly, saturate, and decay on time scales of several (5-10) galactic rotations
- New instabilities develop in rapid succession that are neither
  a) long-lived quasi-steady modes (Bertin & Lin), nor
  b) responses to noise (Toomre, Kalnajs, ...)
- Does this happen in nature?

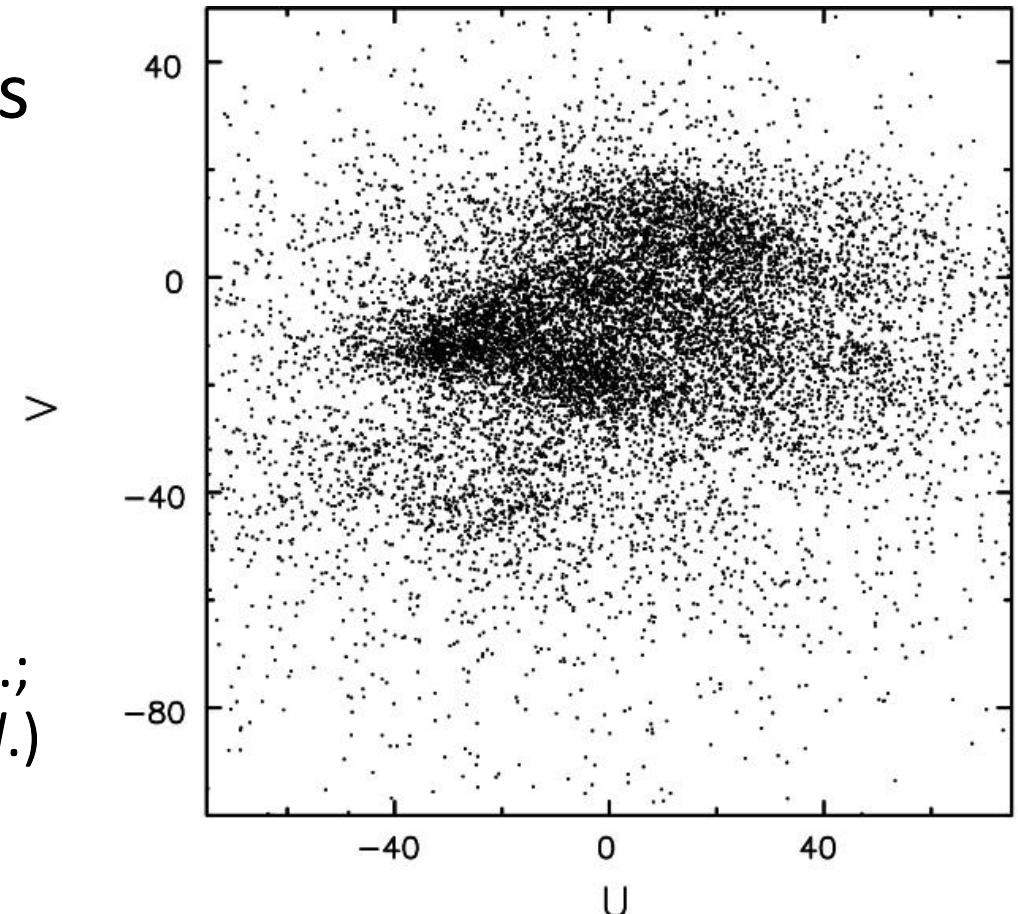
Local samples of stars



- < 200 pc of the Sun
- Most visit from farther afield
- velocities rel. to Sun: V & U (inwards!)

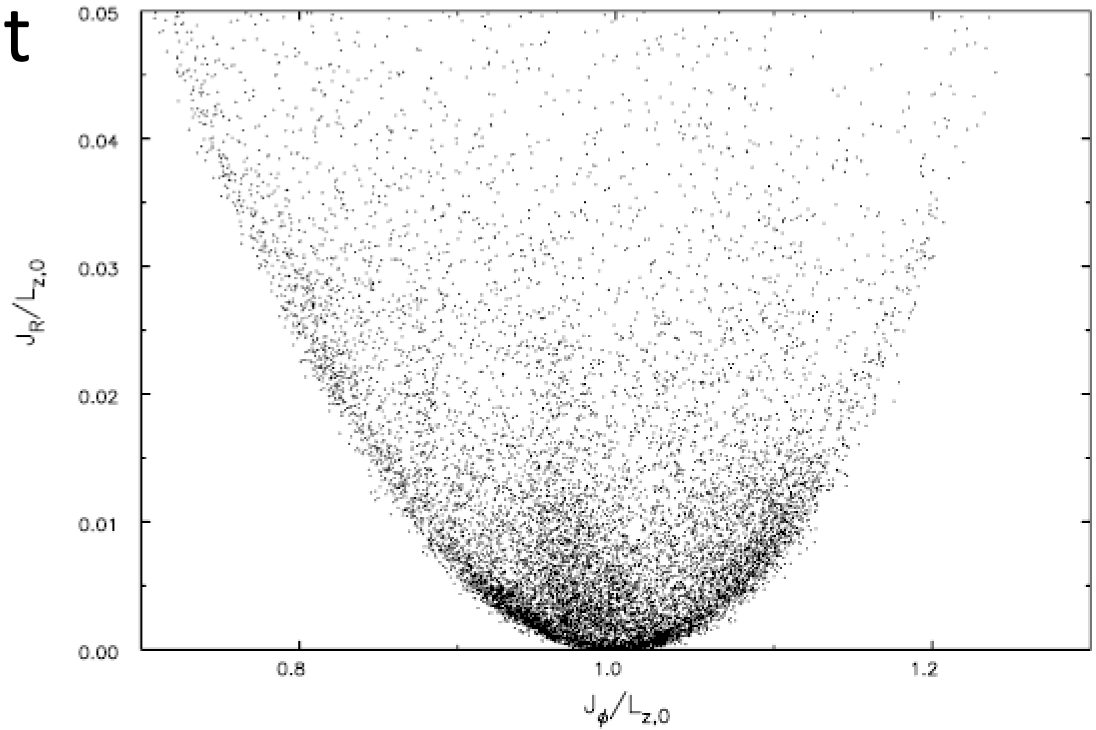
Geneva-Copenhagen survey (Nordström *et al*. 2004)

- Known distances, full space motions and ages of 13,240 local F &G dwarfs
- DF not at all smooth (Dehnen 98)
  - Not dissolved clusters (Famaey *et al*.; Bensby *et al*.; Bovy & Hogg; Pompéia *et al*.)
- Hard to interpret the structure in velocity space



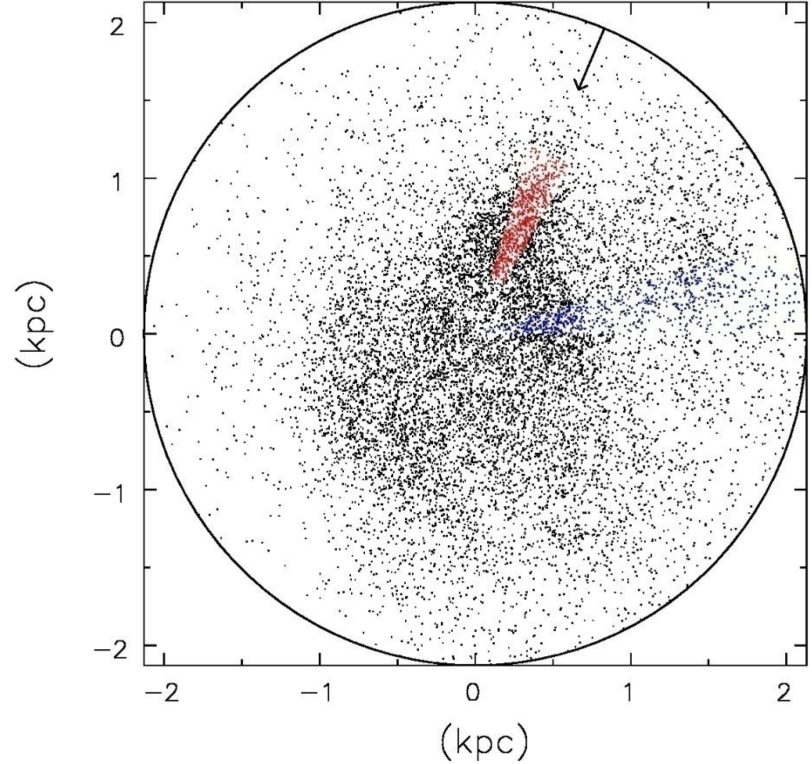
Project into action space

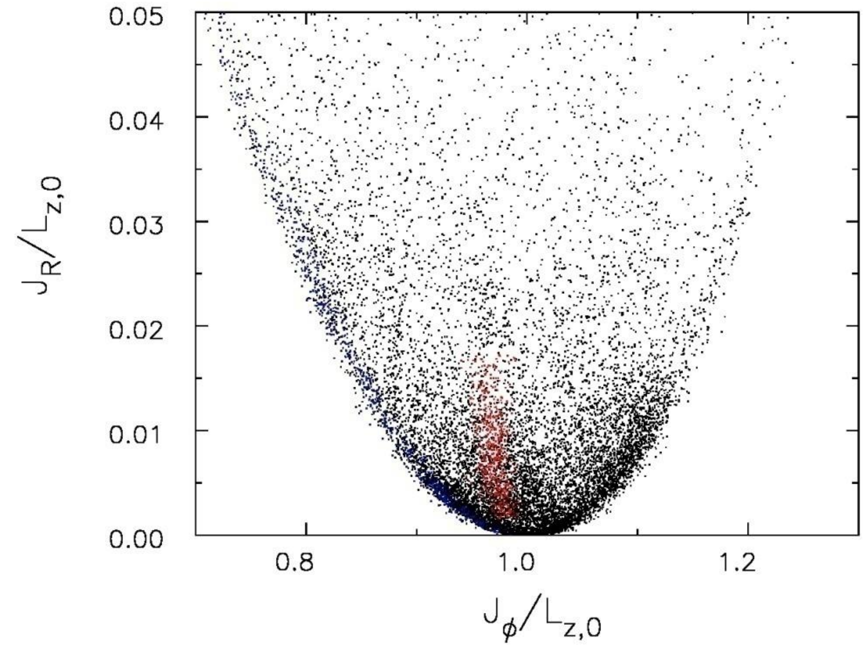
- Scaled by R_0 and V_0 assuming a locally flat RC
  - Lower boundary: selection effect
  - L-R bias: asymmetric drift
- One strong feature
  - (bootstrap analysis)
- Scattering or trapping?



Phases of these stars

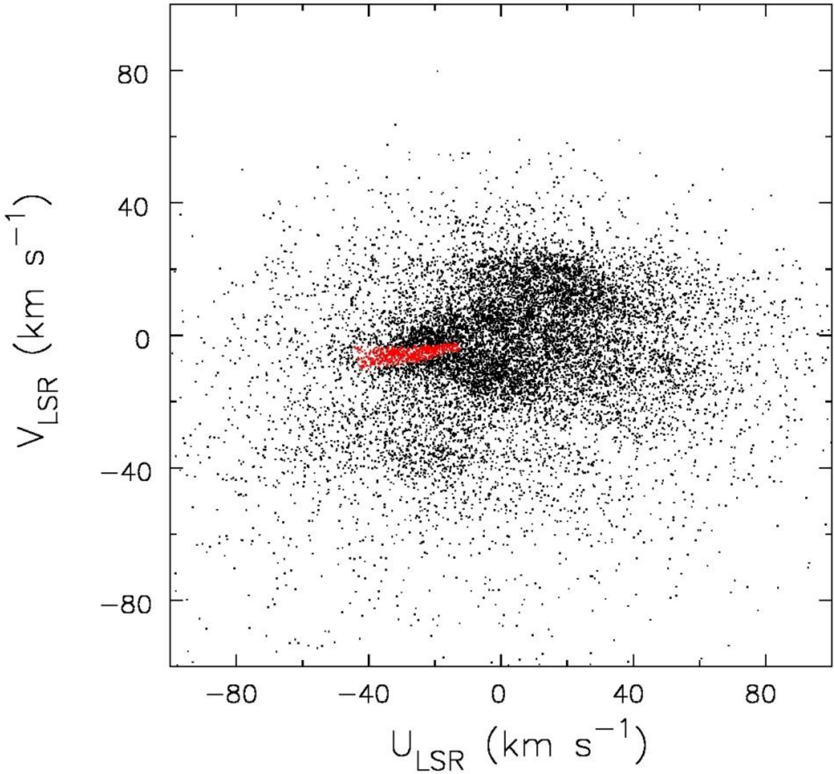
- Action-angle variables
  - radius shows epicycle size – √(2 × J_R)
  - azimuth is $2w_\phi - w_R$
- Concentration of stars at one phase
  - *m* > 2 disturbances are also supported,
  - suggests an ILR
- Exactly the stars (red) in scattering tongue

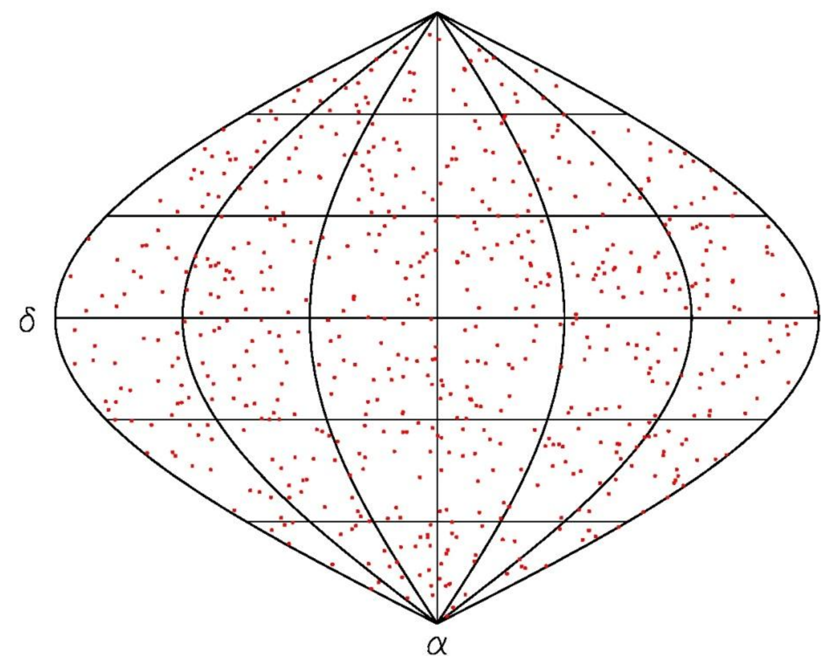




Resonant stars

- Resonant stars are the "Hyades" stream
- Far more than just the Hyades cluster
- Distributed pretty uniformly around the sky
- Hyades cluster (age ~ 650 Myr) is in this resonance

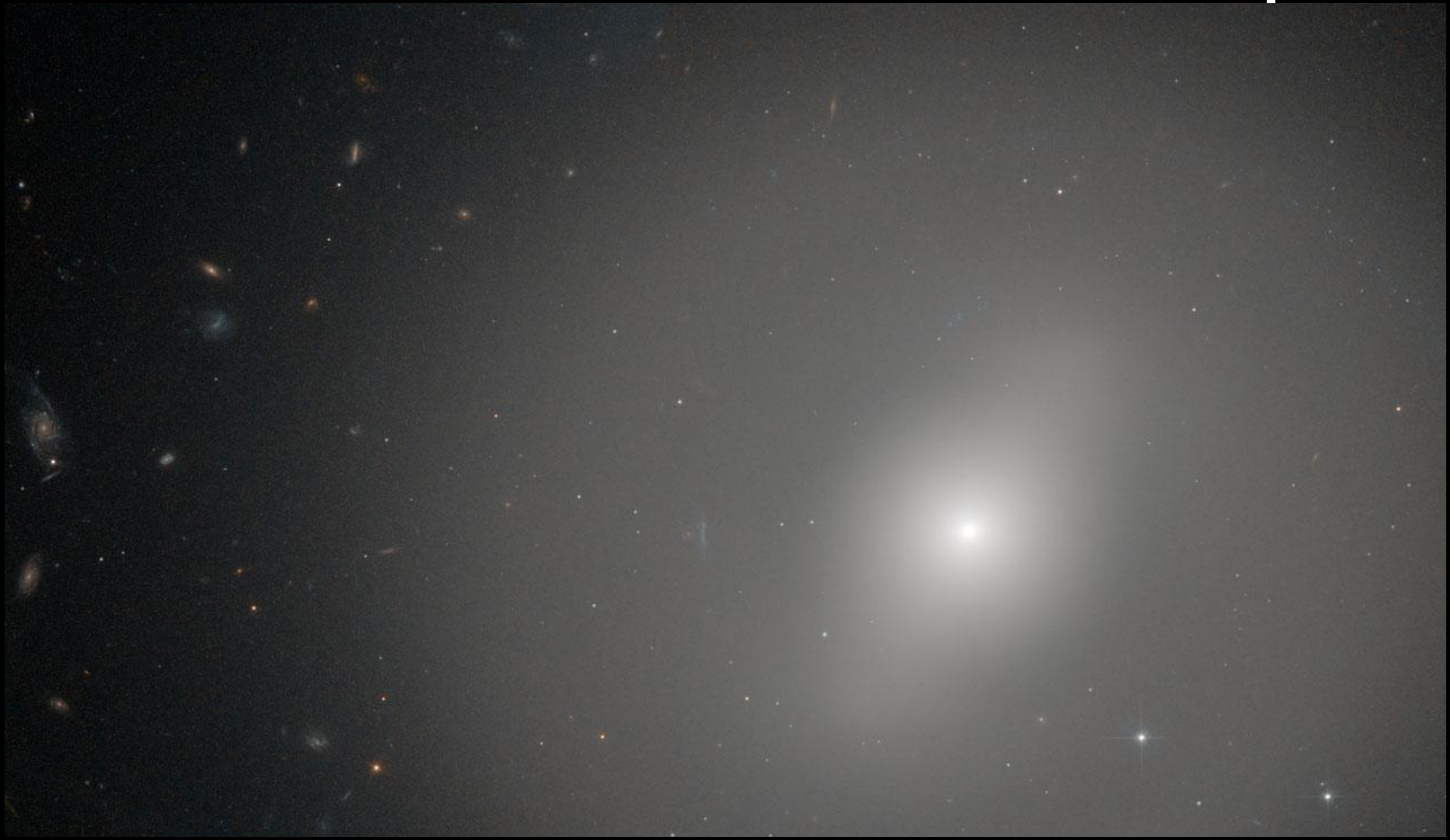




Implications

- Evidence for an LR
  - probably an ILR of an $m = 4$ spiral
- Support for the picture I have been developing from the simulations
  - spirals are transient
  - decay of one pattern seeds the growth of another
  - each is true instability of a non-smooth DF

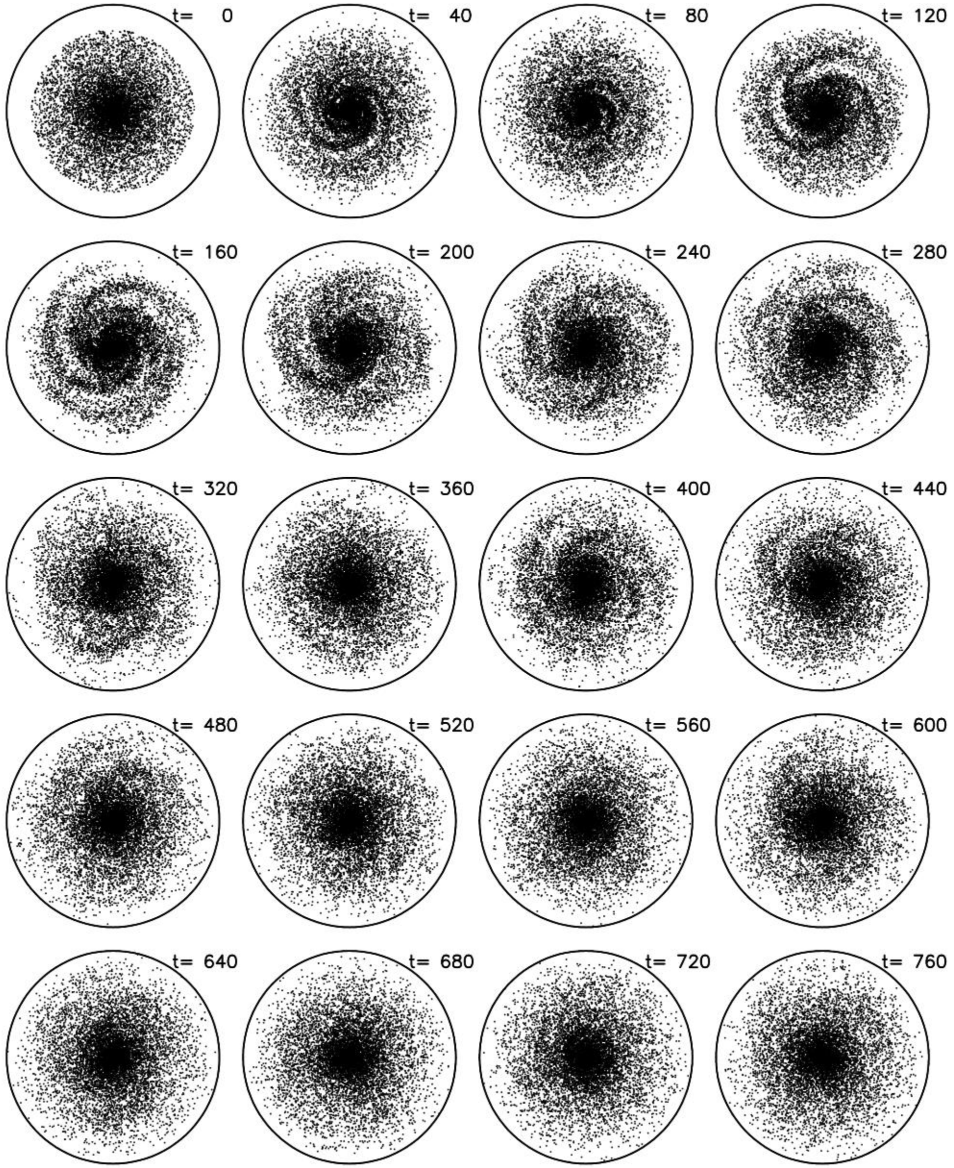
Gas seems to be essential for spirals



- NGC 1533 – Hubble image
- Misled the community for many years

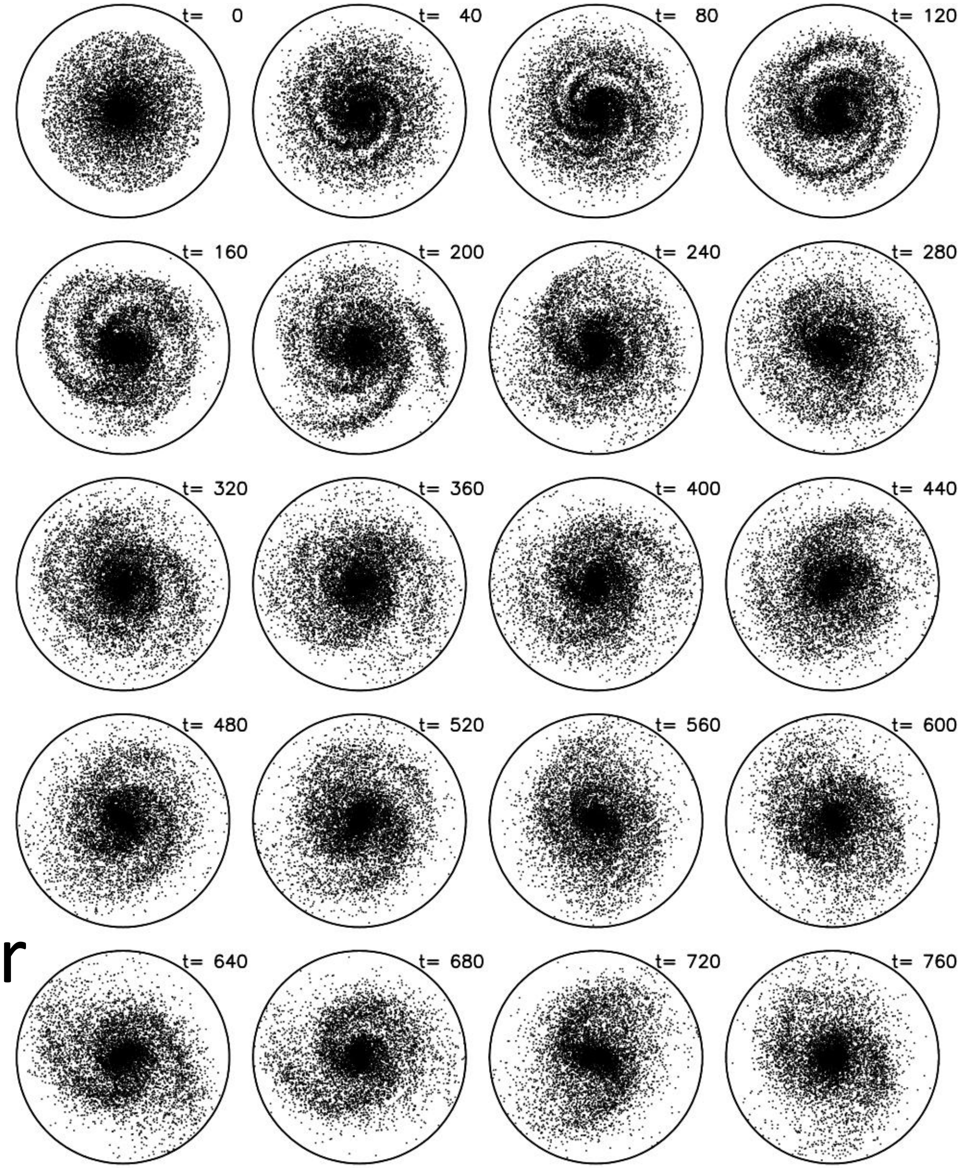
Recurrent transients

- Random motion rises and patterns fade

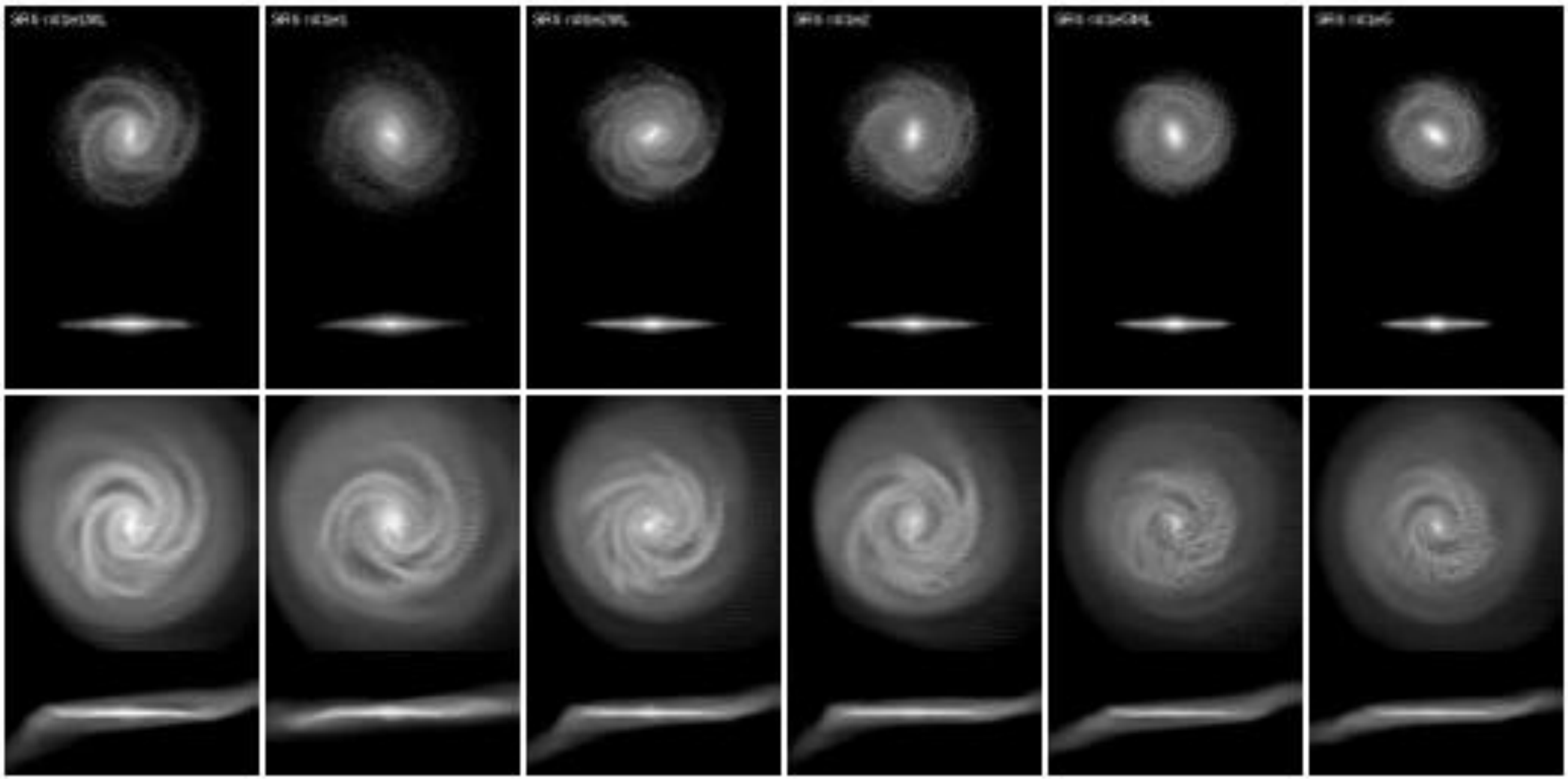


Recurrent transients

- Random motion rises and patterns fade
- Add “gas dissipation” and patterns recur “indefinitely” (SC84)
- A natural explanation for the importance of gas



Galaxy formation simulations



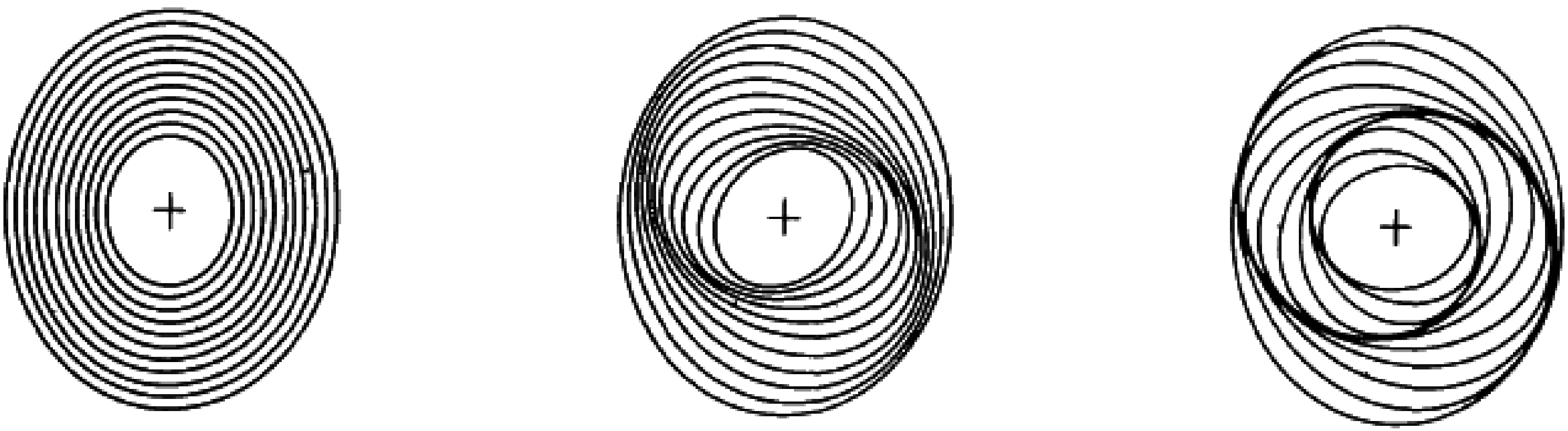
- Agertz *et al*. (2010) – barely a remark!

Conclusions

- Self-excited spirals result from recurrent spiral instabilities
  - decay of one mode seeds the growth of another
  - evidence from both simulations and solar neighbourhood stars
- Transient spirals drive secular evolution
  - gas needed to keep them active
  - age-velocity dispersion relation, radial mixing, metallicity gradients, smoothing rotation curves, galactic dynamo theory, *etc*.

Precessing ellipses

- Orbit construction by Kalnajs



a = 0 a = 5 a = 10