Dynamics and large scale star formation in disk galaxies

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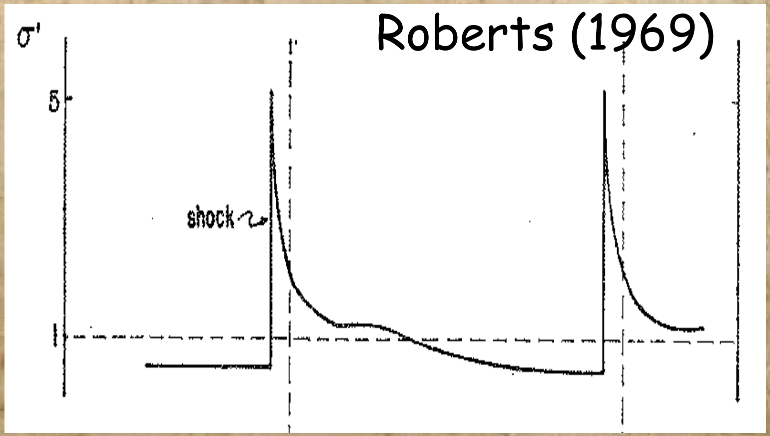
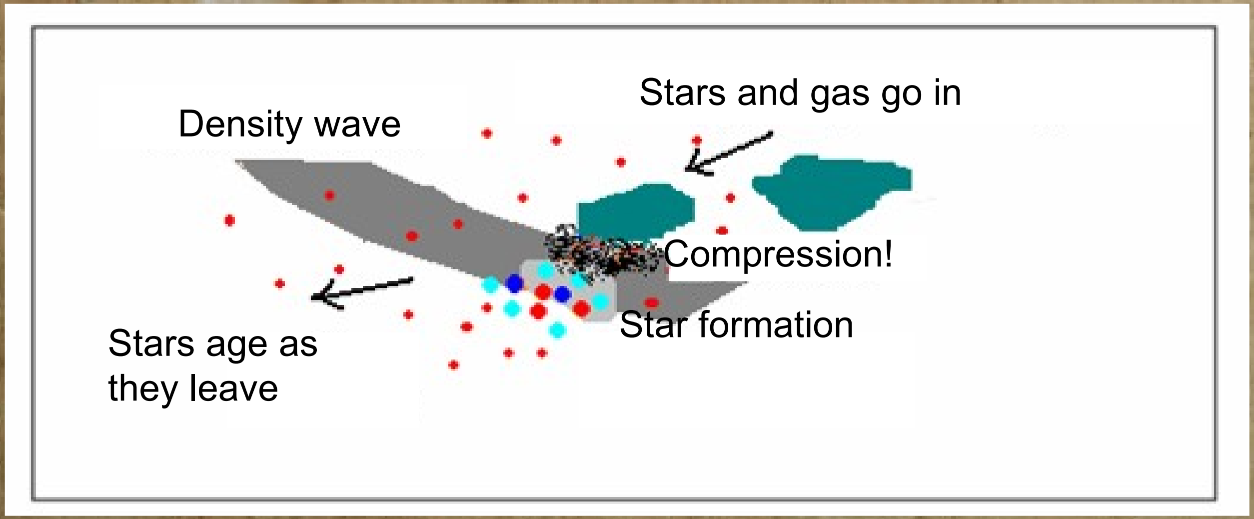
Spiral density waves

- Linblad, Lin & Shu, Roberts, Toomre, Kalnajs, Bertin, Contopoulos, among others.

- The spiral pattern is caused by density waves, i.e., by quasi-stationary and alternate condensations and rarefactions of stars and gas.

Large scale shocks in spiral arm regions.

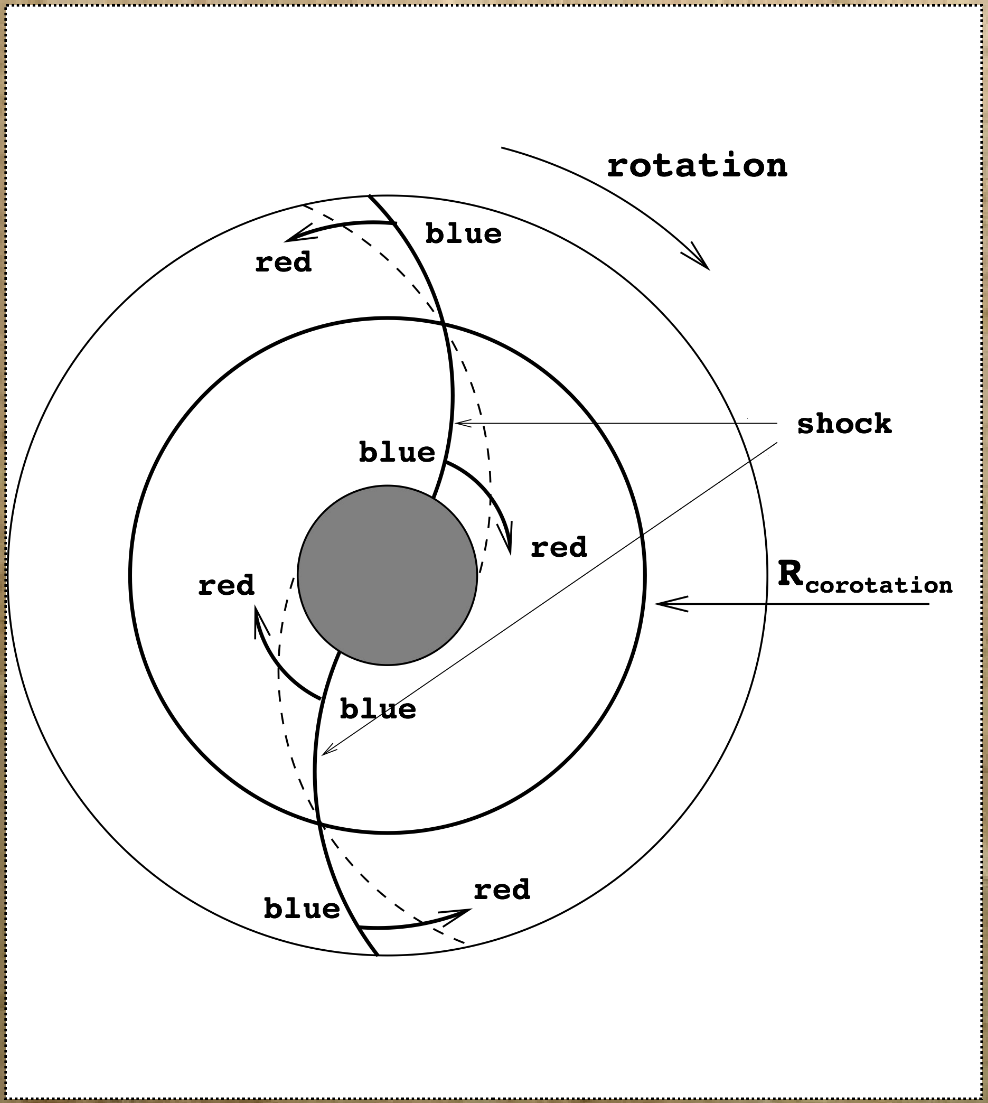




Observed pile-ups of molecular gas and dust in the concave regions of arms

- A consequence of a simple interpretation of these ideas is the prediction of <u>azimuthal and asymmetric stellar color-age gradients.</u>

Azimuthal gradients (age, color).

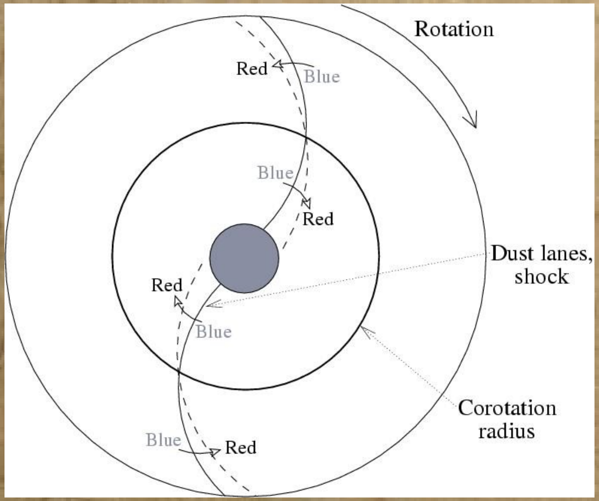


Spiral pattern:

$\Omega_p \cong$ constant

Stars and gas:

Differential rotation



Ω_p constant

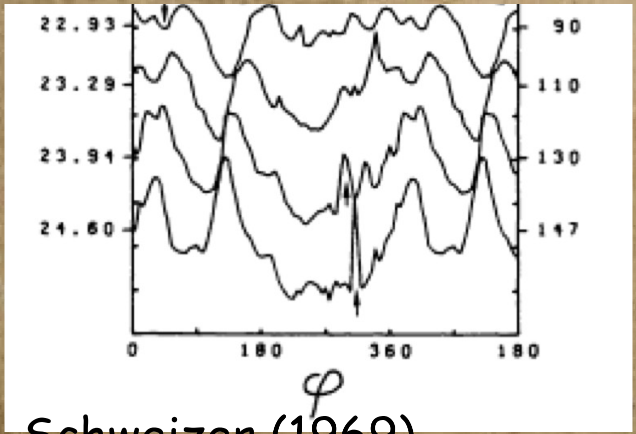
- So far corroborated only through numerical simulations (Thomasson 1990, Zhang 1998) and by the apparent persistence of spiral structure up to a Hubble time (Elmegreen & Elmegreen 1983).

Color gradients:

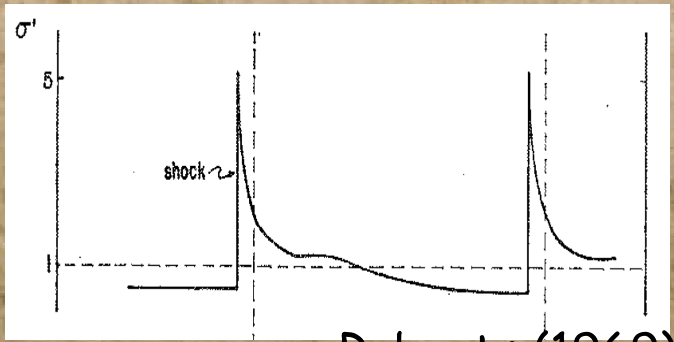
- ✓ Are a dynamical consequence of a constant pattern speed
- ✓ Need star formation triggered by shocks in arms
- ✓ Would be a definitive test of density wave theory

Have gradients been observed?

- Schweizer 1976: hints of asymmetric monochromatic azimuthal stellar light profiles in M99



Schweizer (1969)



Roberts (1969)

- Talbot et al. 1979: regions with and without star formation in M83, no smooth gradient

• Efremov (1985): *age gradient in Cepheids in arm S4 of M31*

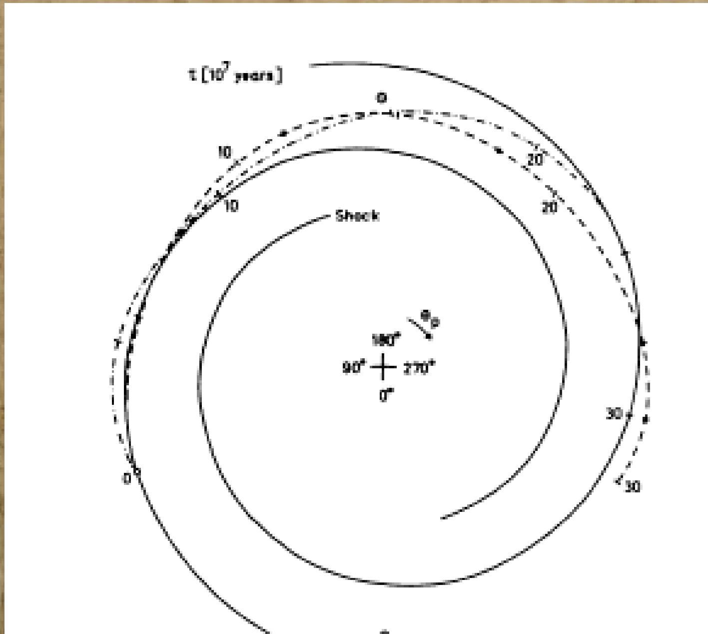
M31 (Robert Gendler)

• Sitnik (1989): massive stars age gradients in various arms around the Sun

• Beckman & Cepa (1990) and Hodge et al. (1990): displacements the size of the "seeing" between blue and red populations.

Yuan (1969), Wielen (1973,1978,1979), Fernández et al. (2008), etc.

Non-circular orbits could prevent observation of gradients



Wielen 1978

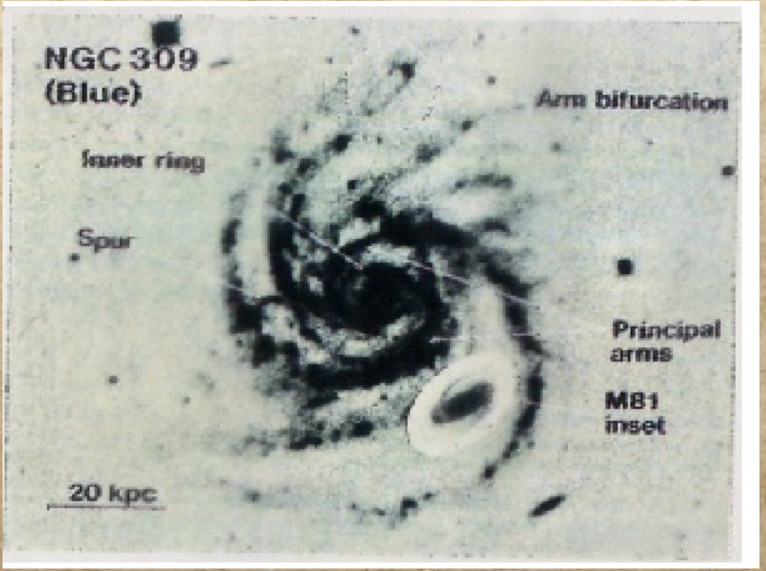
Nearby spirals look different at different wavelengths

Zwicky (1955 PASP,67,232)

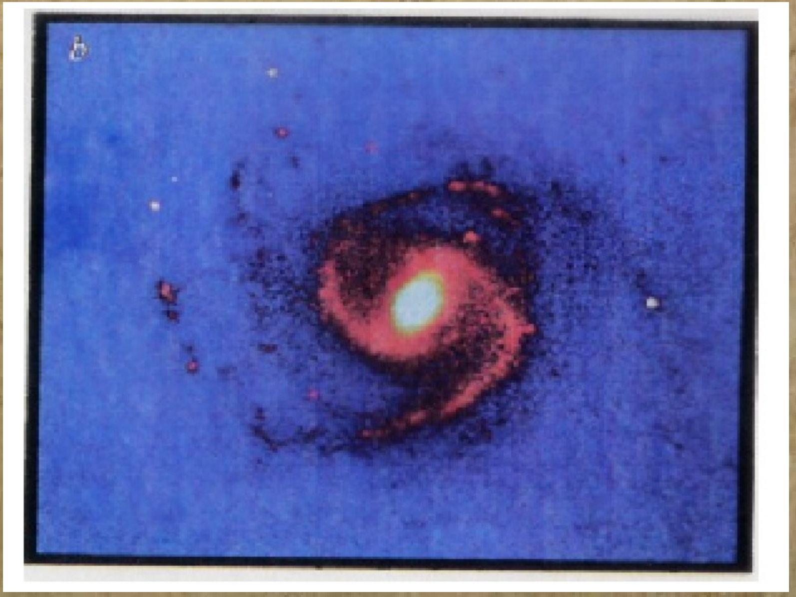
- ***"The blue stars outline extremely irregular and unevenly populated spiral arms, these arms appear surprisingly smoothly streamlined on red bands. The yellow-red stars have a much higher degree of organization than blue stars occupying the same regions of space"***

- ***"It comes to a surprise that populations of different colors occupying the same volumes can have such radically different distributions"***

- Block & Wainscoat (1991)
  - <u>optical</u> : irregular spiral pattern showing lots of substructure.
  - <u>Near-IR</u>: smooth and regular pattern.



- Block, Bertin et al. (1994) suggest that the dynamics of the old disk (the bulk of the mass) and star formation processes are **decoupled**.



Ks Band

Elmegreen & Elmegreen (1986), Elmegreen (1993) :

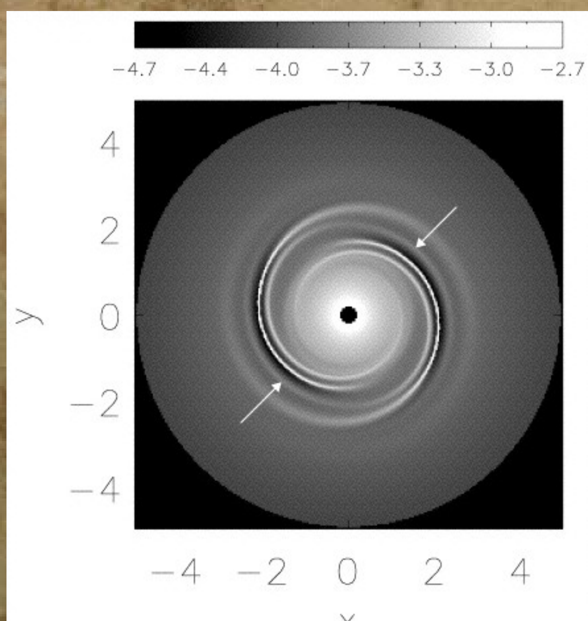
•Global star formation rate (per unit gas mass) is not affected by disk dynamics or the presence of arms (Dopita & Ryder 1994; Ryder & Dopita 1994).

•Density waves do not trigger star formation; they only organize and concentrate ISM and gas in the arms

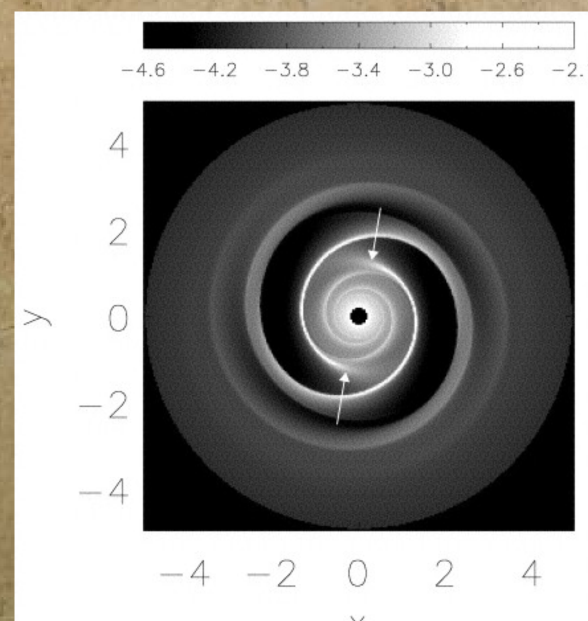
•Density waves do not dominate star formation processes in disk galaxies (instead SNe, stellar winds, expanding HII regions, ISM turbulence, cloud-to-cloud interactions…) .

Substructures (spurs, feathers, branches) and multiarm morphology

- Chakrabarti, Laughlin & Shu (2003) : The response of the gas to the well ordered gravitational field due to the stars in the old disk can be disordered, owing to several nonlinear effects.



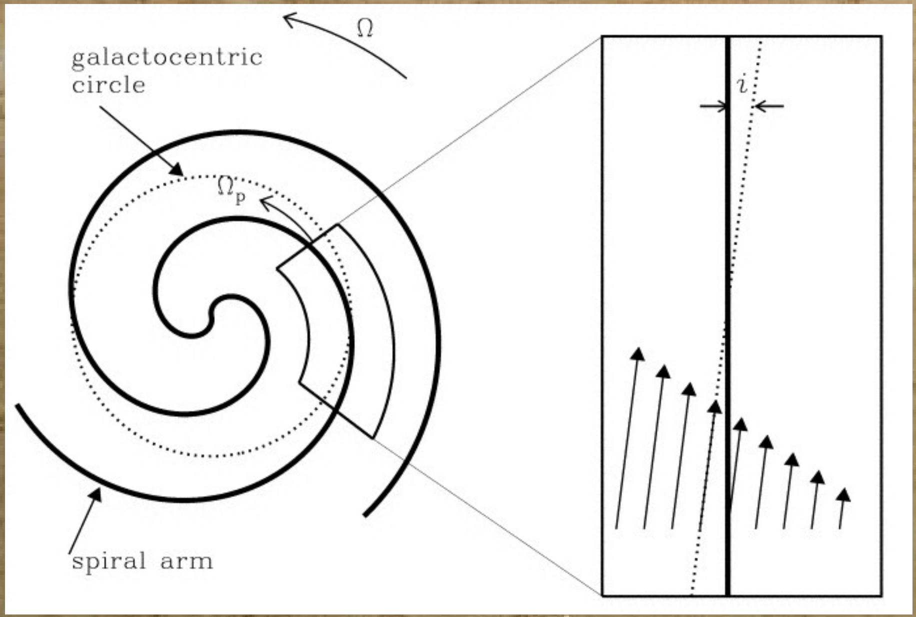
branches

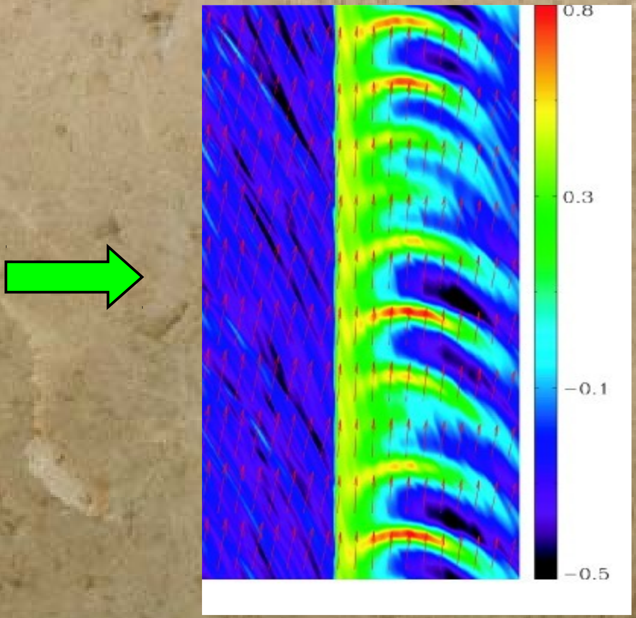


spurs

- Kim & Ostriker (2002; MHD simulations): spurs emerge rapidly in magnetized models of the interaction between the gas and the stellar potential. If Toomre's Q is high (stable disk), B is essential.

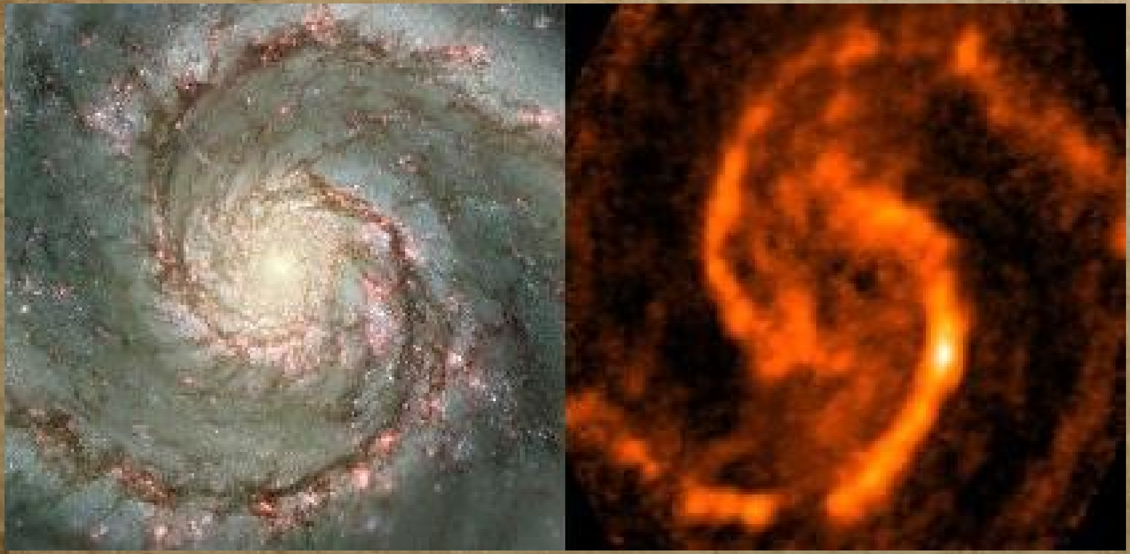
M51 , HST



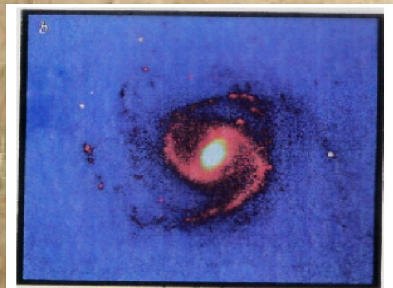


- Seigar & James (2002), Hα and K-band observations:

  local SFR increases close to spiral arms.
- Schinnerer (2004 NRAO), observations of CO radio emission from arms in M51: gas close to the shock is warmer and more turbulent.
- Suggest star formation is triggered there.



HST & Schinnerer

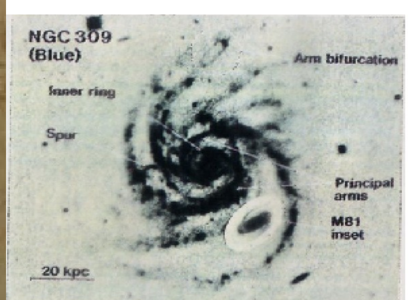


Disk dynamics

Color gradients, the crucial link

Coupled or decoupled?

Star formation



Images Block & Wainscoat 1991.

González & Graham (1996), first detection of a trustworthy extragalactic gradient in M99 ~ 50” (4 kpc)

✓Avoided HII regions

✓Photometric, redefined, Q index; reddening-free and tracer of star formation.

NOAO/AURA/NSF

Photometric Q index (Johnson & Morgan 1953):

$$Q(UBV) = (U - B) - \frac{E(U - B)}{E(B - V)}(B - V)$$

Reddening-free:

$$(U - B) - \frac{E(U - B)}{E(B - V)}(B - V) = (U - B)_0 - \frac{E(U - B)}{E(B - V)}(B - V)_0$$

Redefined in r_s, J, g, i :

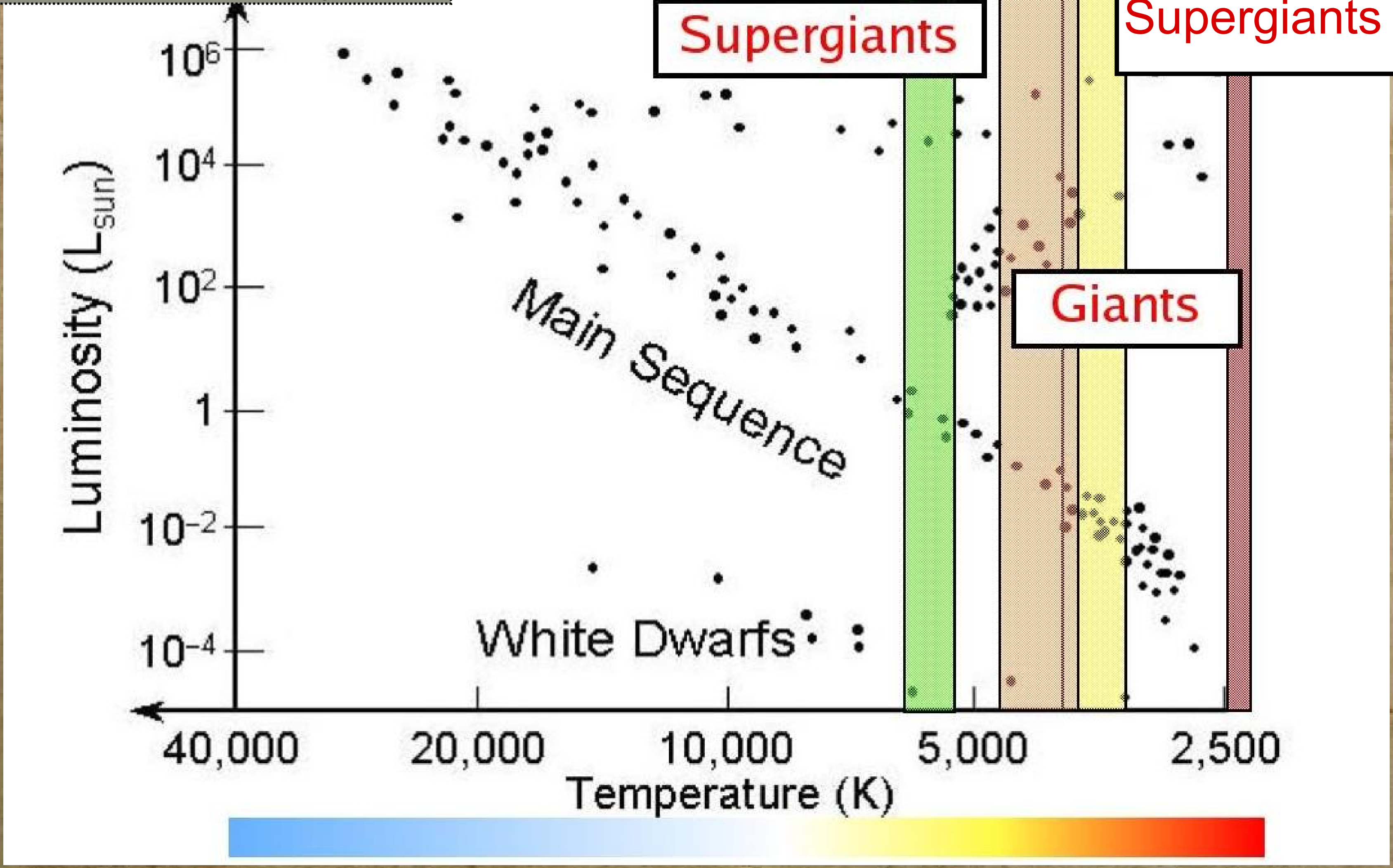
$$Q(r_s Jgi) = (r_s - J) - \frac{E(r_s - J)}{E(g - i)}(g - i)$$

Filter	λ_{eff}	FWHM
g	5000 Å	830 Å
r_s	6800 Å	1330 Å
i	7800 Å	1420 Å
J	1.25 μm	0.29 μm
K_s	2.16 μm	0.33 μm

Do not confuse with Toomre's Q!

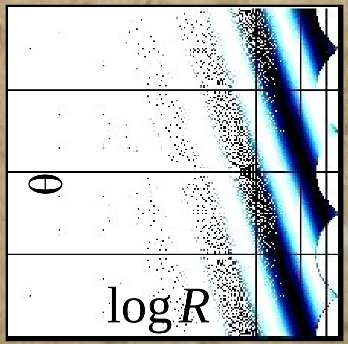
Q traces star formation:

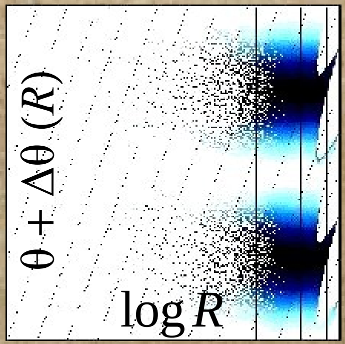
$$Q(r_s Jgi) = \log_{10} \frac{I_g^{2.05} I_J^{2.50}}{I_{r_s}^{2.50} I_i^{2.05}}$$



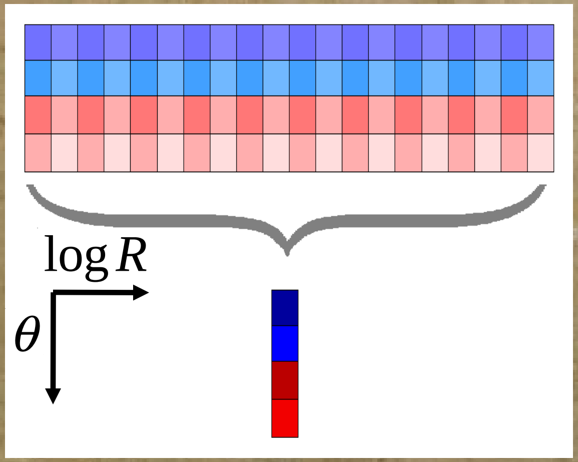
Images were deprojected, with parameters from literature

Spiral arms were unwound (Iye et al. 1982) and straightened

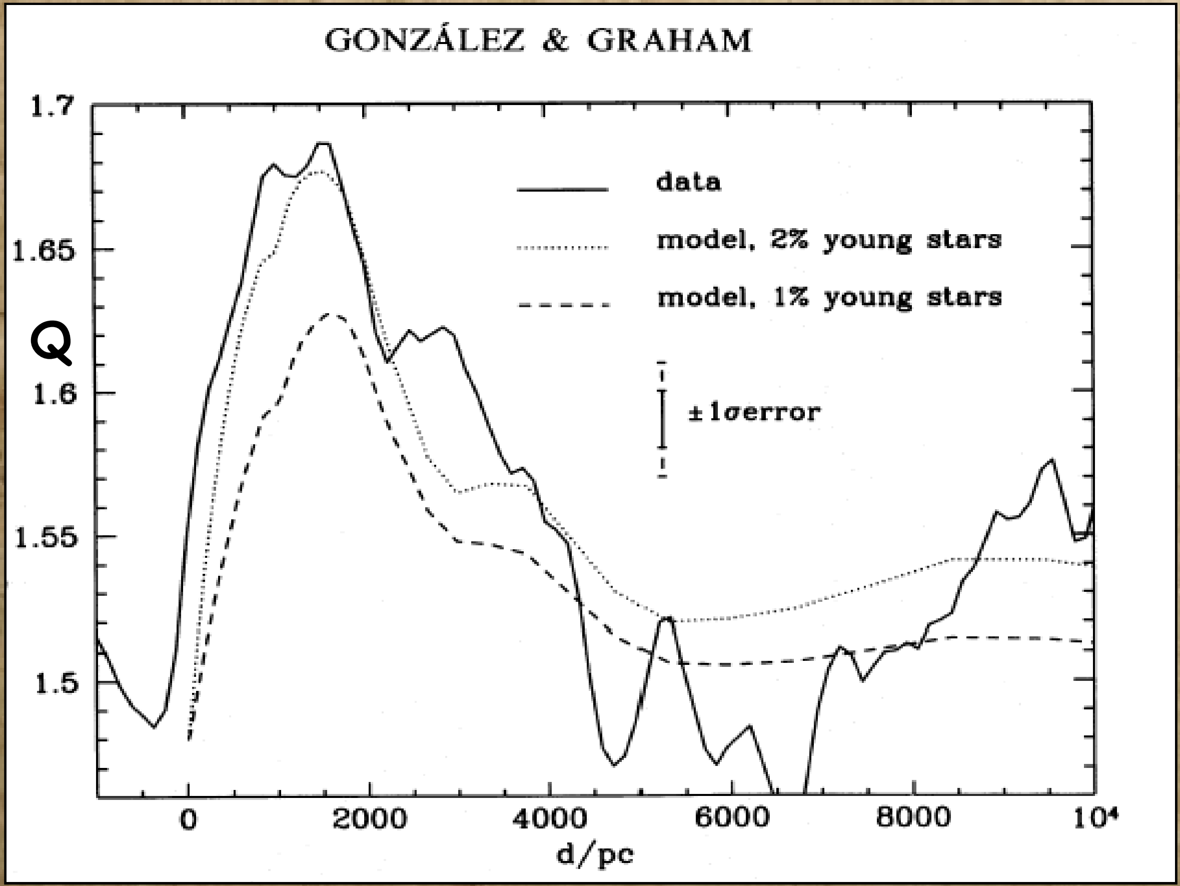




Collapsed in log R to improve S/N ratio



Q. Comparison between data and models.



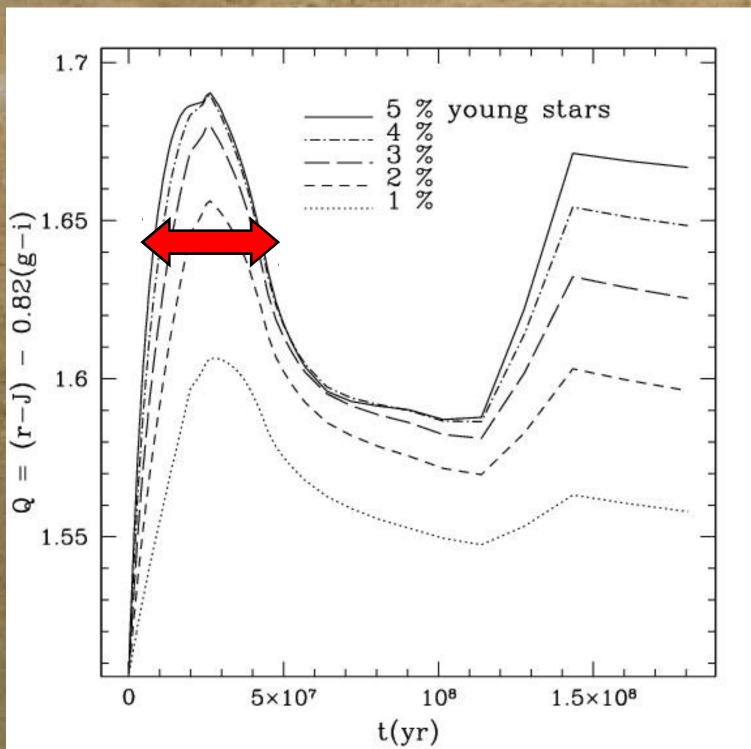
Young star fraction between 0.5 and 2%, in agreement with Schweizer (1976). Bruzual & Charlot 1993 models. M_{upper} = 10 M_{Sun}

✓ Stellar population models: Q function of t.
✓ Data: Q function of d (azimuthal distance).

We can relate age gradients to disk dynamics

➢ The model is “stretched” to obtain Ω_p.

$$\Omega_p \cong \frac{1}{R_{mean}} \left(v_{rot} - \frac{d}{t} \right)$$



V_{rot} , R_{mean} and d functions of inclination angle α

Charlot & Bruzual 2007 models, IMF M_{upper} = 10 $M_{\odot}$.

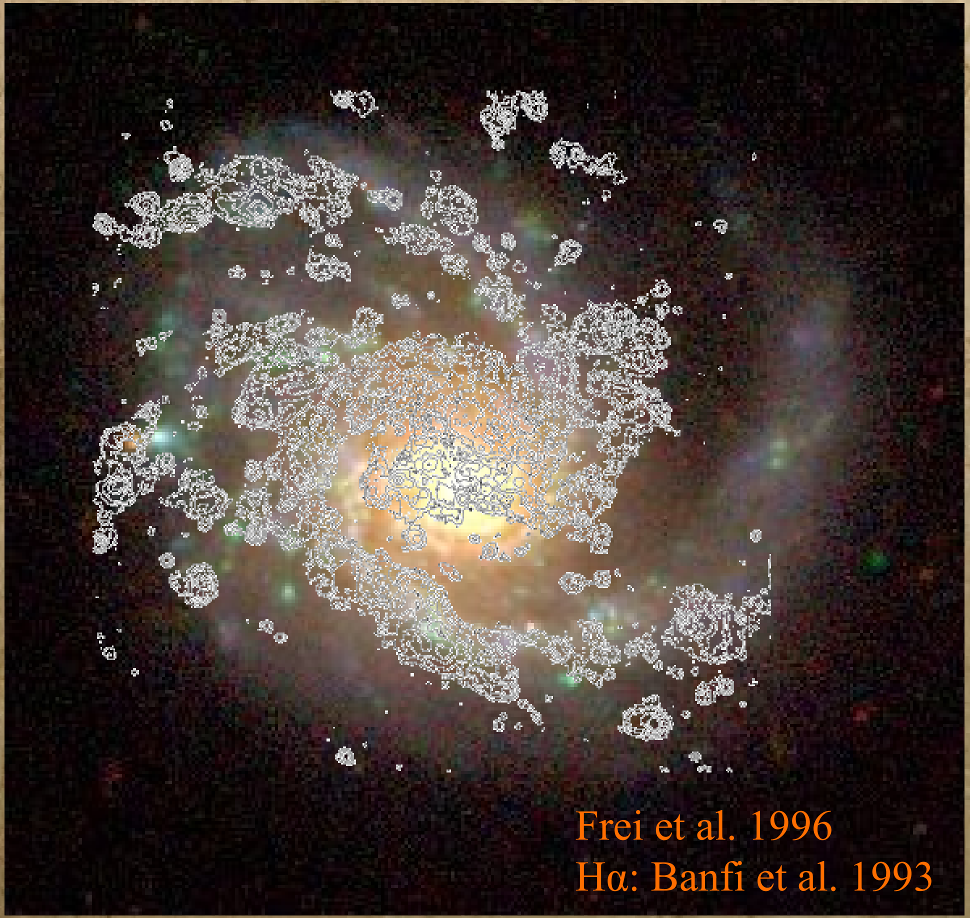
Results for M99 and new questions

Ω_p = 15.7 - 17.2 km s^{-1} kpc^{-1}
R_{mean} = 5.9 kpc

R_{cr} = 8.2 +- 0.6 kpc
= 0.6 - 0.7 R_{25}
$\cong$ 3 r_0 (Bertin et al. 1989)

Coincident with features?

$M_{upper} = 10\ M_{sun}$ and almost no Hα emission



Frei et al. 1996
Hα: Banfi et al. 1993

Just how exceptional M99 really is?

End points of spiral pattern can show link to dynamics

- Early era of linear theory (Lin 1970): corotation.
- Mark 1976; Toomre (1981); Lin & Lau (1979); Donner & Thomasson (1994); Zhang (1996): Outer Lindblad Resonance (OLR).

- Nonlinear analysis of orbits (Contopoulos & Grosbol 1986; Patsis et al. 1991):

"Strong" spirals (Sb & Sc) at 4/1 resonance ($\Omega - \Omega_p = \kappa/4$).

"Weak" spirals (Sa) at corotation

Name	Type
NGC 4939	SA(s)bc
NGC 3938	SA(s)c
NGC 4254	SA(s)c
NGC 7126	SA(rs)c
NGC 1417	SAB(rs)b
NGC 7753	SAB(rs)bc
NGC 6951	SAB(rs)bc
NGC 5371	SAB(rs)bc
NGC 3162	SAB(rs)bc
NGC 1421	SAB(rs)bc
NGC 7125	SAB(rs)c
NGC 918	SAB(rs)c
NGC 578	SAB(rs)c

All non-barred galaxies…

Data

Very deep (30 min in each band: g,r,i,J,K)

1-m and 2-m telescopes at Lick, Kitt Peak, CTIO

1"-2" seeing

0.4" - 2" pixels

Charlot & Bruzual (2007) models

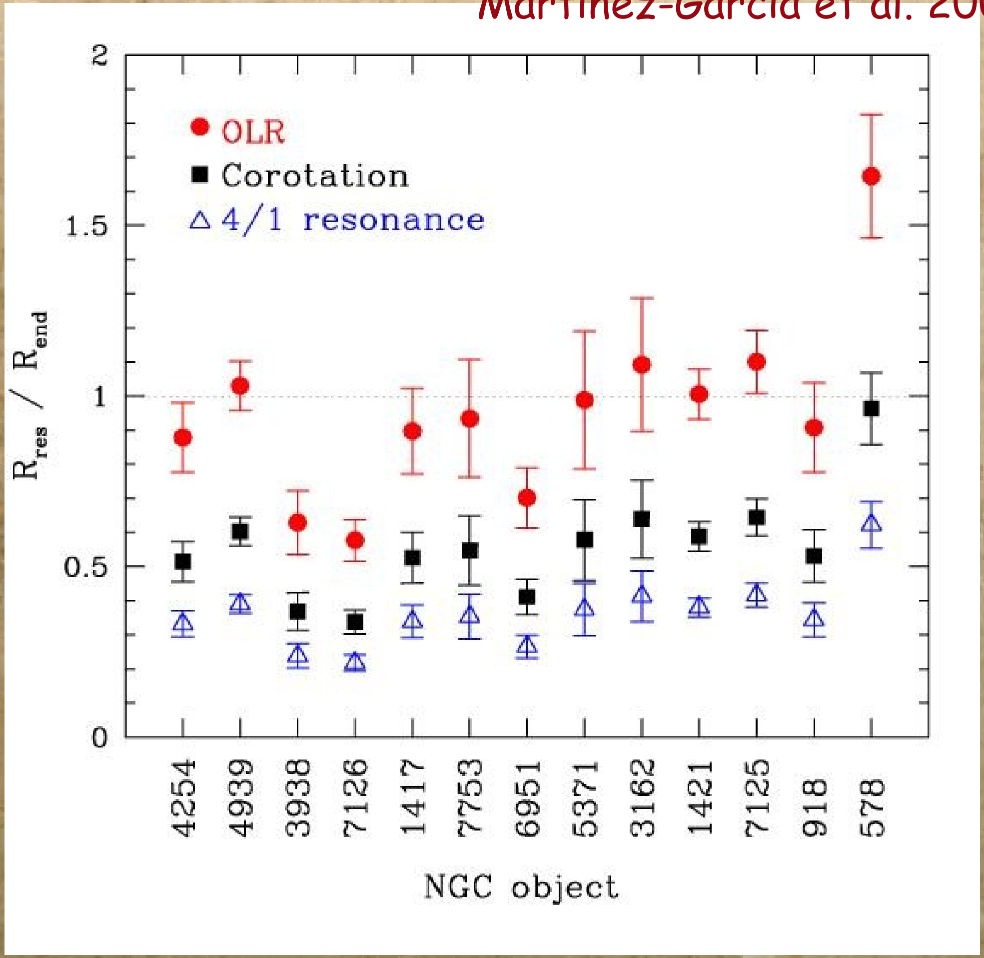
- Burst duration 2×10^{7} yr
- IMF M_{upper} = 10 and 100 $M_{\odot}$
- 2% of young stars, by mass
- Solar metallicity
- Dynamical model: implicit circular orbits (no orbits were calculated)
- (α from RC3; V_{rot} from Paturel et al. 2003)

Gradients in 10 (including M99) out of 13 galaxies

Second gradient in M99 with a different Ω_p

$R_{OLR} / R_{end} \cong 1$

Martínez-García et al. 2009a, ApJ, 694, 512



$\langle R_{OLR} / R_{end} \rangle$ = 0.95+-0.03, χ^2/n = 7.12 ; probability of result by chance 1/10,000

“Strong” (Sb and Sc), open-armed, spirals behave as predicted by linear theory, that supposedly only applies to “weak” (Sa) spirals with tightly wound arms!

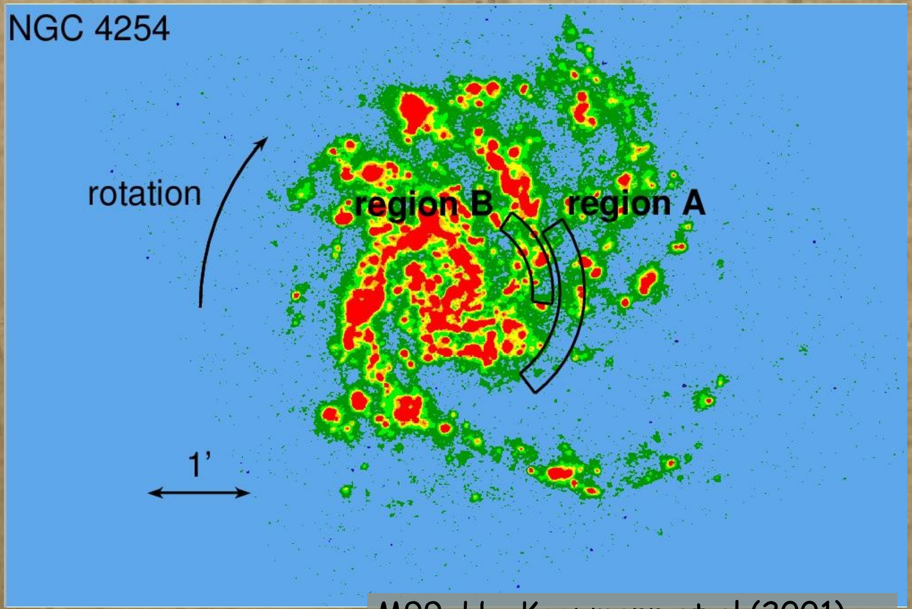
M_{upper} of IMF

For this subsample, models with $M_{upper} = 100\ M_{sun}$ do not work

Best fits are obtained with $M_{upper} = 10\ M_{sun}$

•Inverse correlation between successful detection of color gradients and presence of massive stars

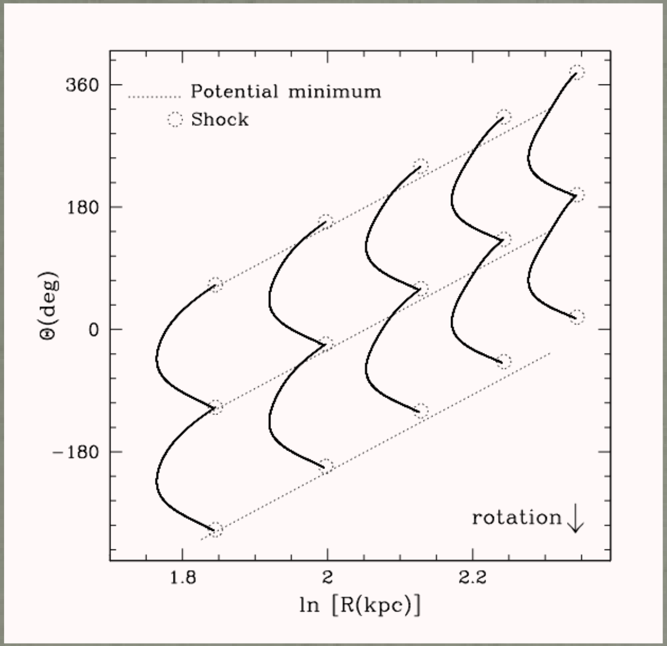
•Contamination by Hα emission from massive stars could be the main reason for the dearth of detected color gradientes up until now!

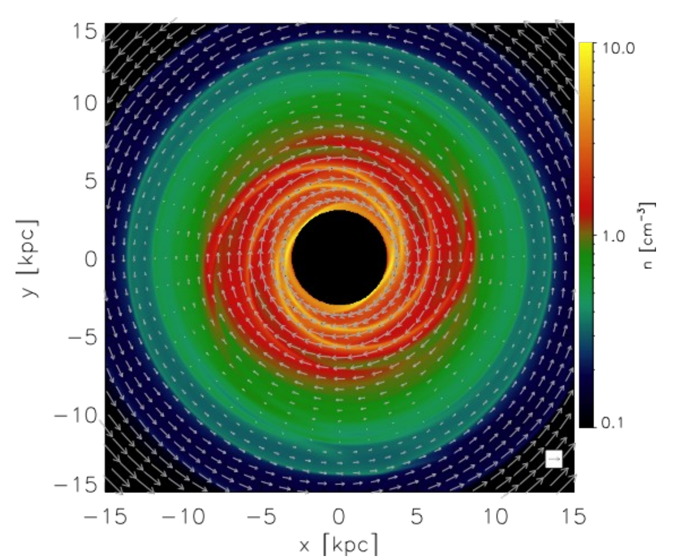


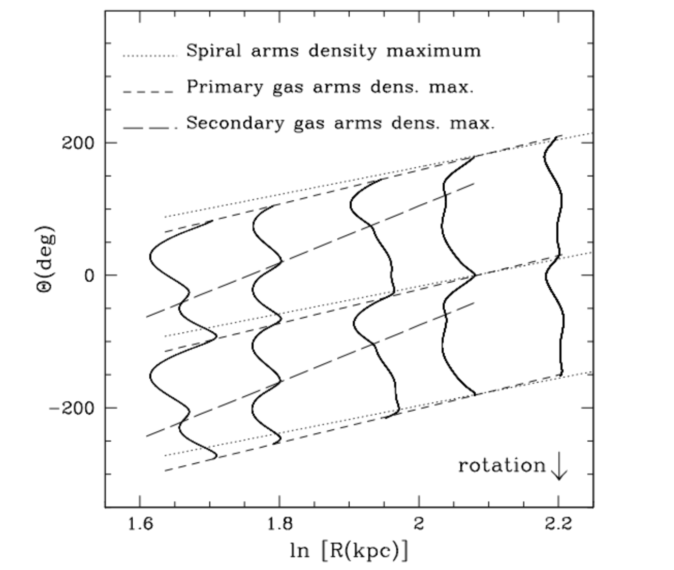
M99, Hα; Koopmann et al.(2001)

Non-circular motions

Martínez-García et al. 2009b, ApJ, 707, 1650

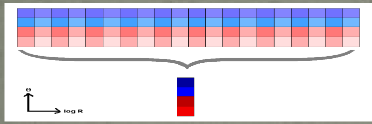


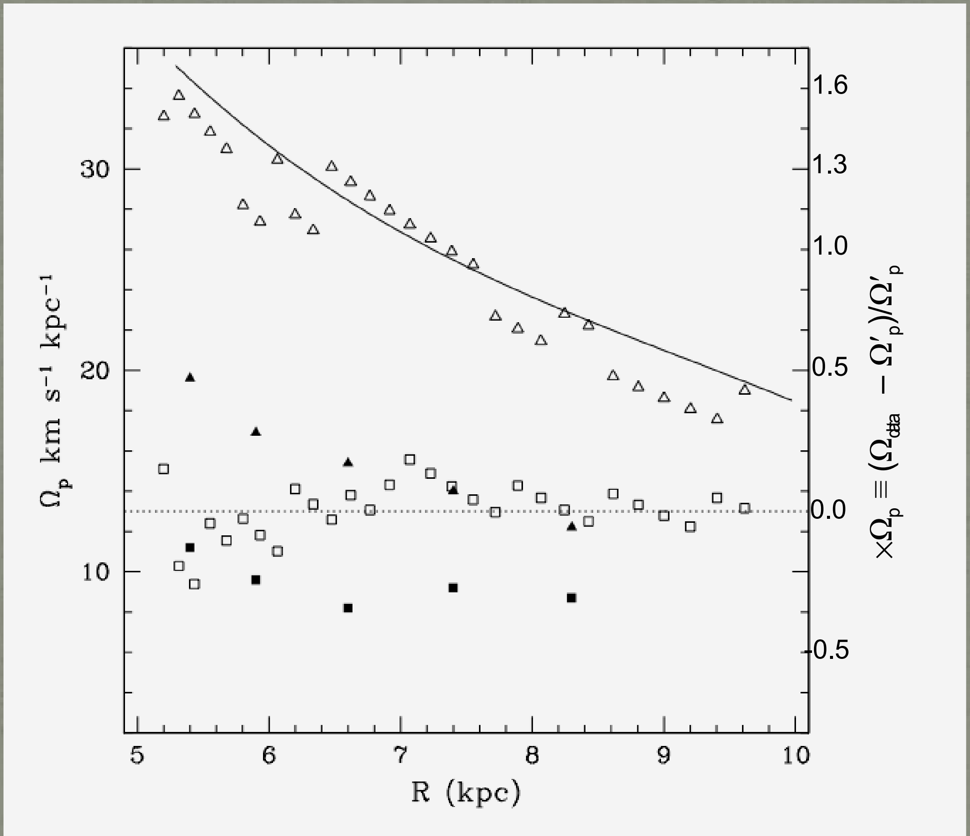




Ω_p measurements (s.a.s.s.)

(one simulated galaxy, different radii)





Data

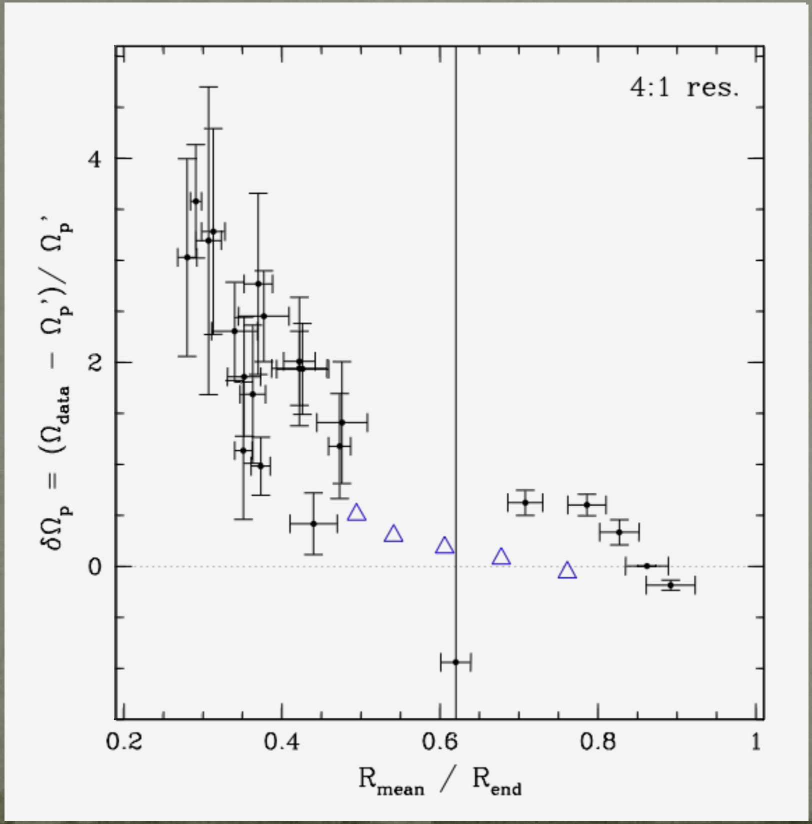
(several galaxies)

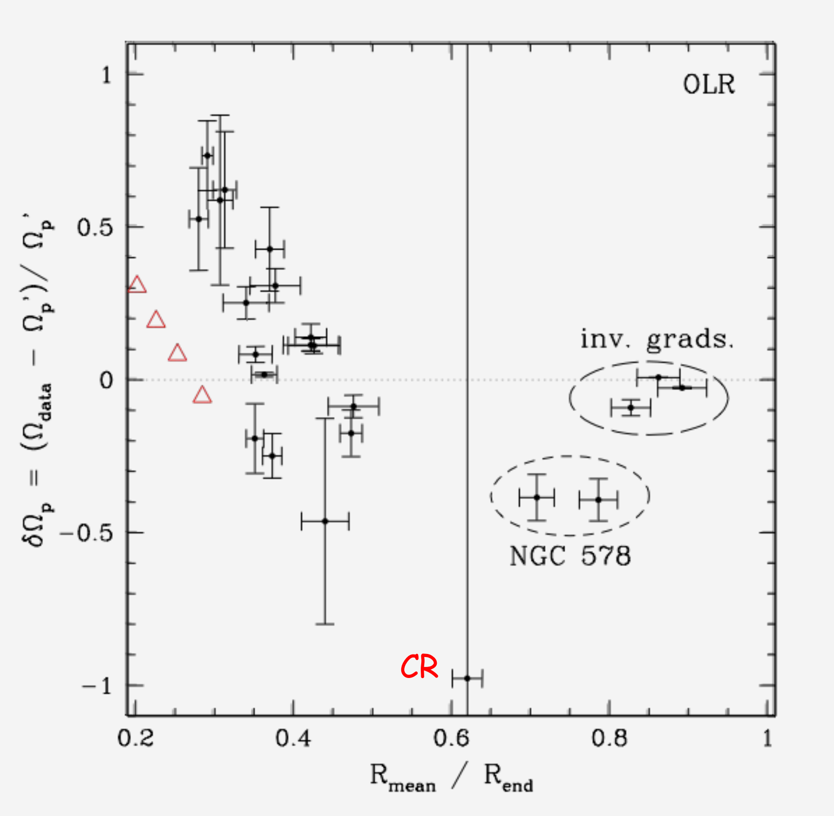
If $R_{end} = R_{4:1}$

$$\Omega'_p \approx \frac{v_{rot}}{R_{4:1}}\left(1 - \frac{\sqrt{2}}{4}\right)$$

If $R_{end} = R_{OLR}$

$$\Omega'_p \approx \frac{v_{rot}}{R_{OLR}}\left(1 + \frac{\sqrt{2}}{2}\right)$$





Conclusions I

- Color gradients in ~ 75% of our sample of A and AB spirals. The number of detections has been multiplied (conservatively) by a factor of 4. M99 is not an oddity.

- Non-circular motions do not prevent detection of gradients. Their imprint (systematic bias of Ω_p measurement with R) further strengthens link between disk dynamics and star formation.

Conclusions II

•Spiral patterns end mostly at the OLR, sometimes at CR, never at the 4/1 resonance. This result is similar to findings by Elmegreen, Elmegreen & Montenegro (1992), Zhang & Buta (2007), and does not support the hypothesis by Contopoulos & Grosbol (1986) about "strong" spirals.

Disk dynamics and star formation ARE coupled.

Ongoing work

- Barred galaxies
- Relative position of shock and potential minimum
- General statistics

THANKS!