Dynamics and large scale star formation in disk galaxies
(an observer's perspective)

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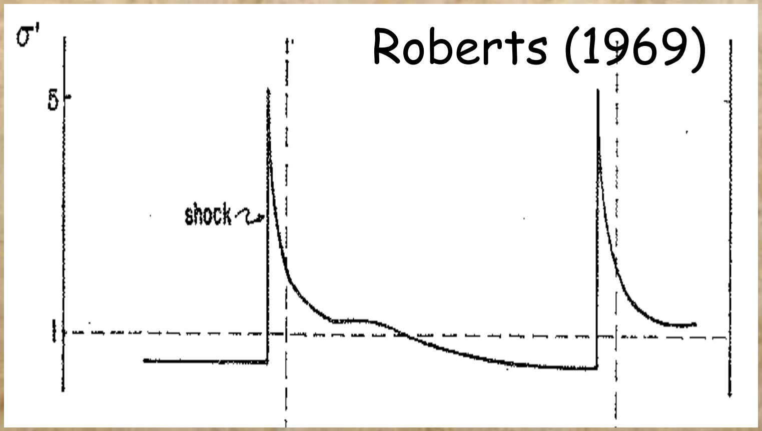
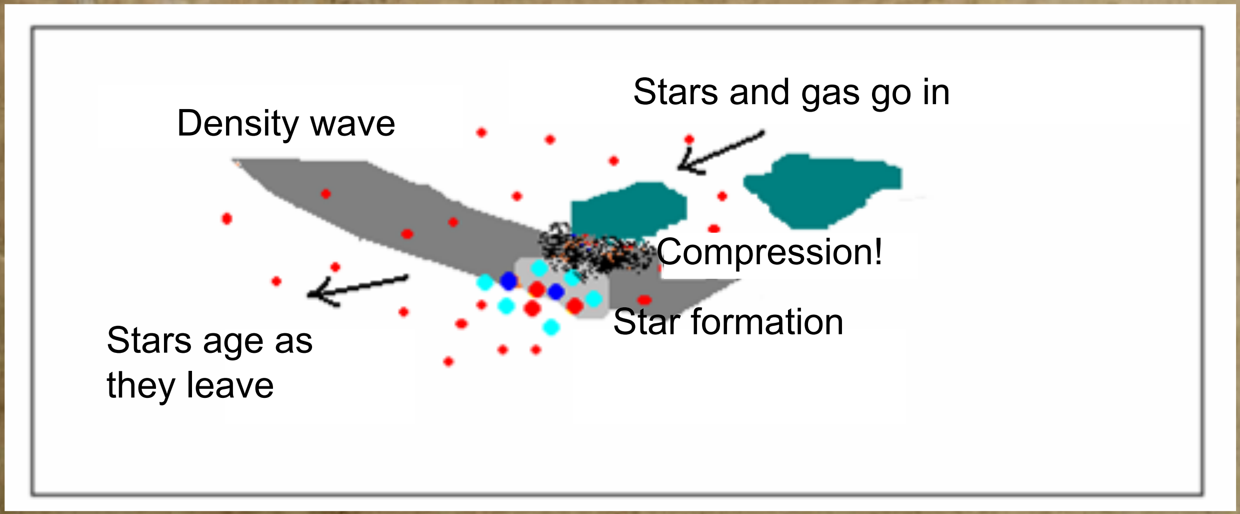
Spiral density waves

•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

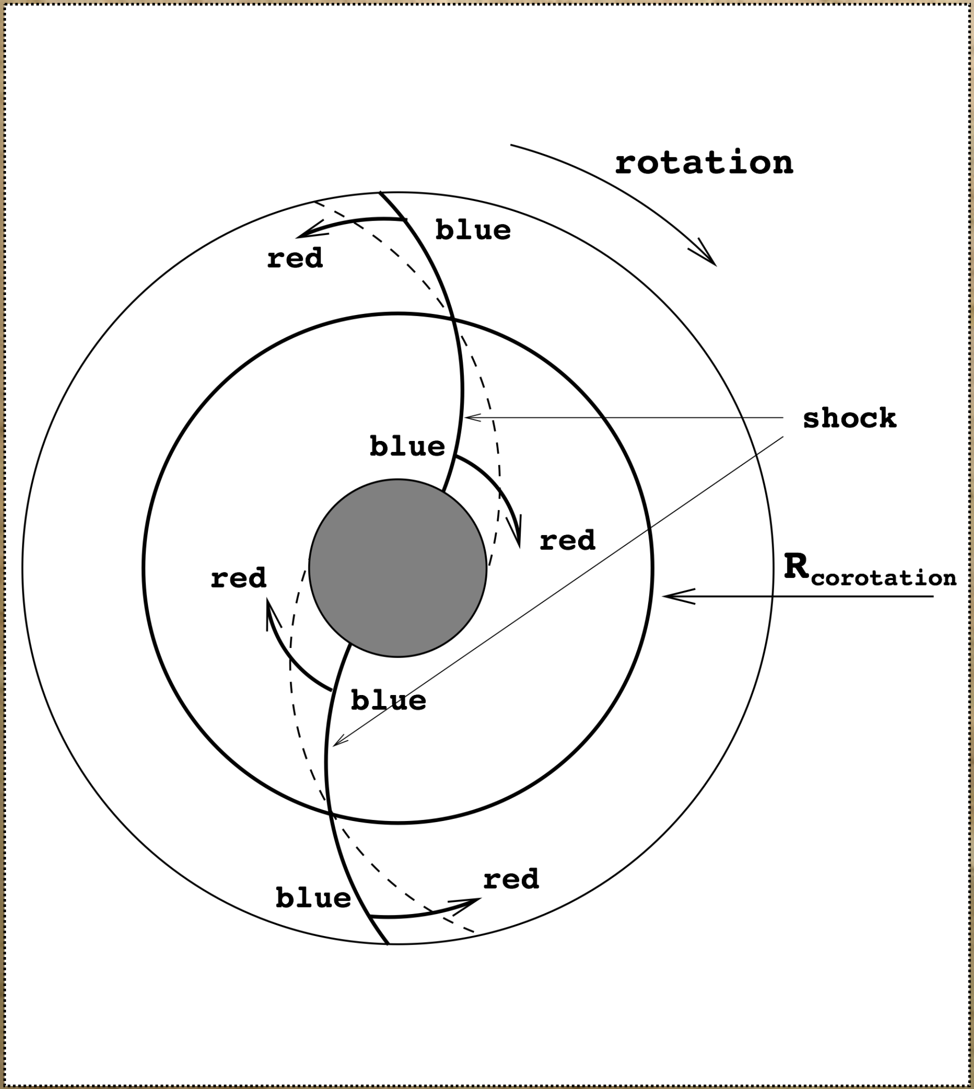




Observed pile-ups of molecular gas and dust in the concave regions of arms

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

Azimuthal gradients (age, color).

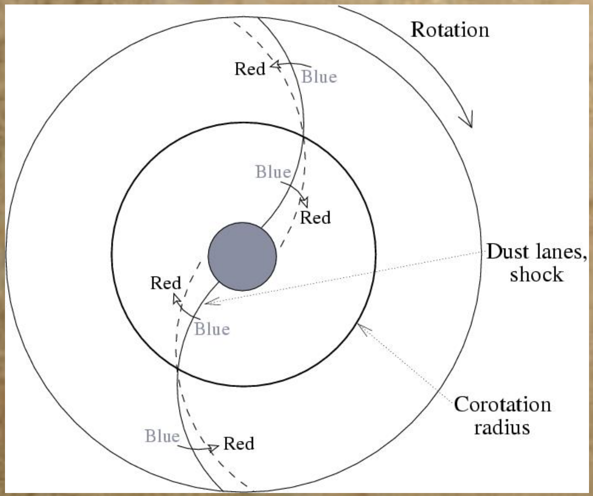


Spiral pattern:

$\Omega_p \cong$ constant

Stars and gas:

Differential rotation



Ω_p constant

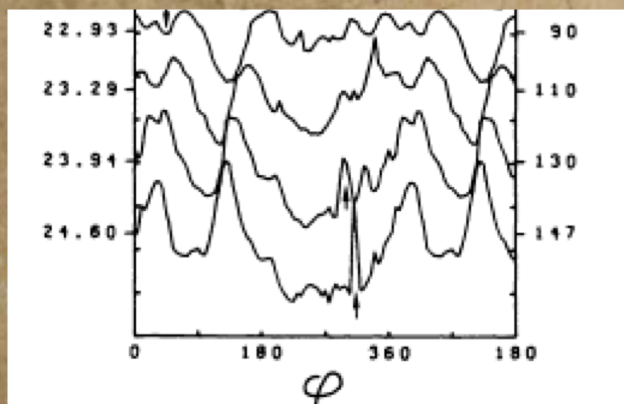
- So far corroborated only through numerical simulations (Thomasson 1990, Zhang 1998, Roca-Fàbrega+ 2013) and by the apparent persistence of spiral structure up to a Hubble time (Elmegreen & Elmegreen 1983).

Color gradients:

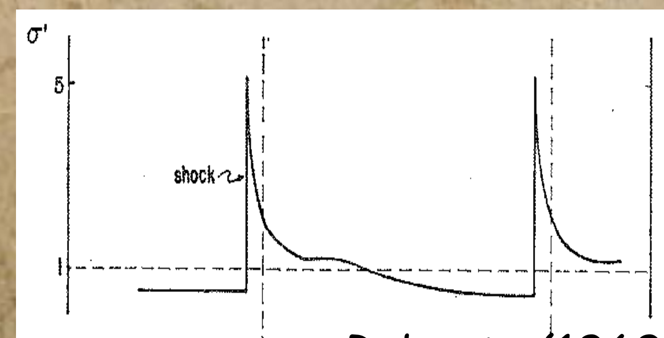
- ✓ Are a dynamical consequence of a constant pattern speed
- ✓ Need star formation triggered by shocks in arms
- ✓ Would be a definitive test of density wave theory

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 SW of arm S4 of M31

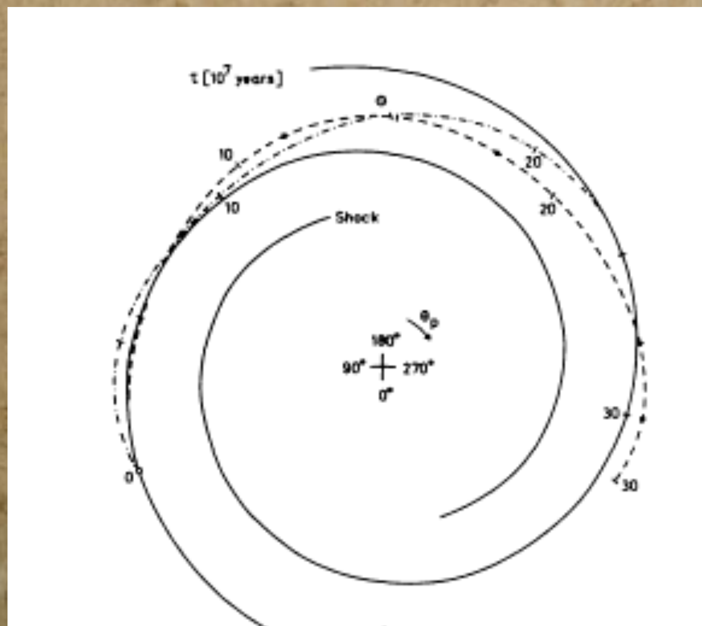

M31 (Robert Gendler)

• 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

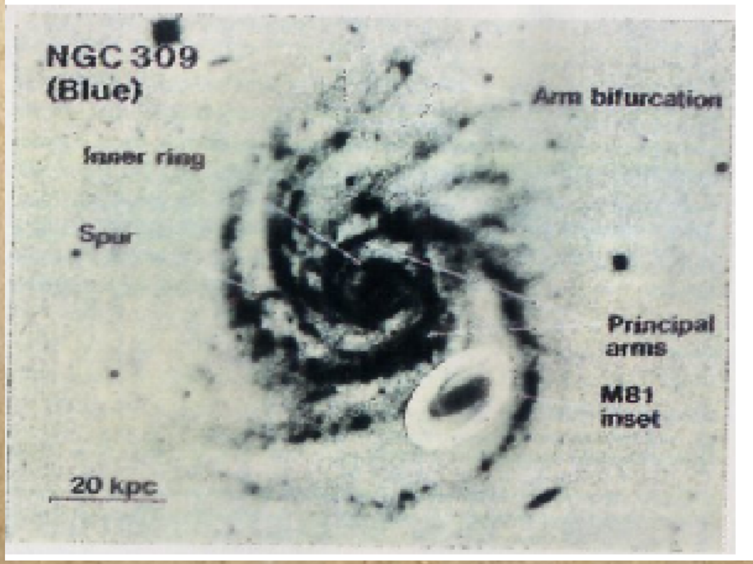
Nearby spirals look different at different wavelengths

Zwicky (1955 PASP,67,232)

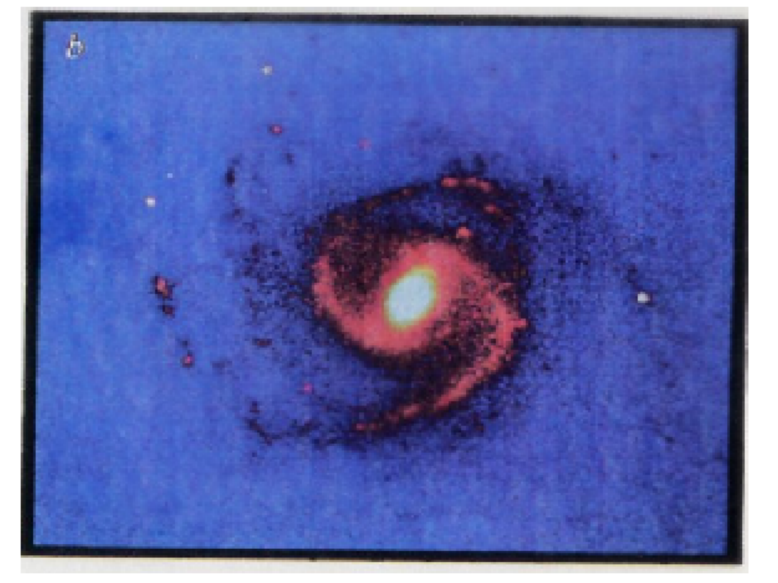
- ***"The blue stars outline extremely irregular and unevenly populated spiral arms, these arms appear surprisingly smoothly streamlined on red bands. The yellow-red stars have a much higher degree of organization than blue stars occupying the same regions of space"***

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

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



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



Ks Band

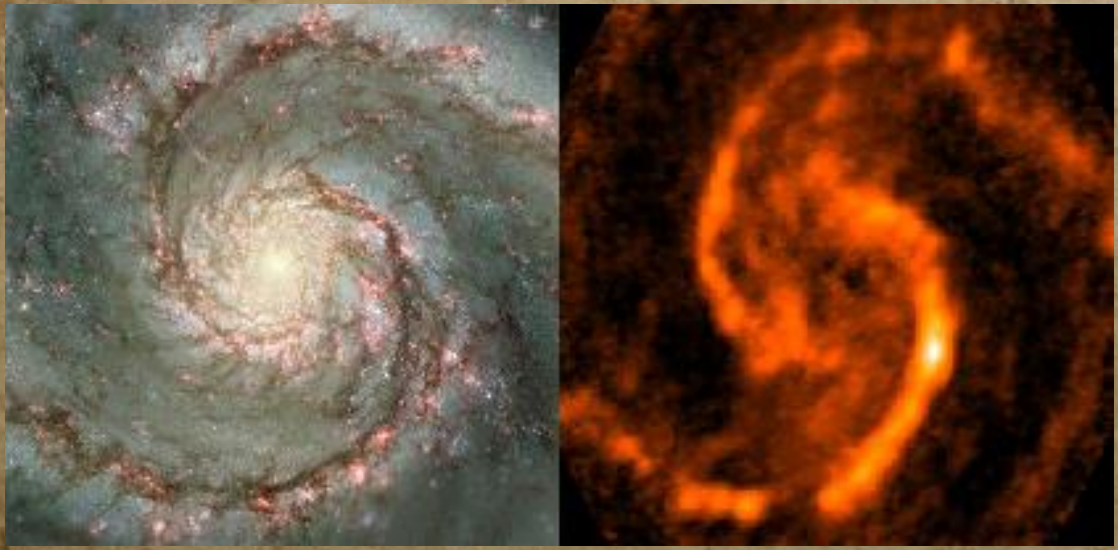
Elmegreen & Elmegreen (1986), Elmegreen (1993) :

- 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…) .

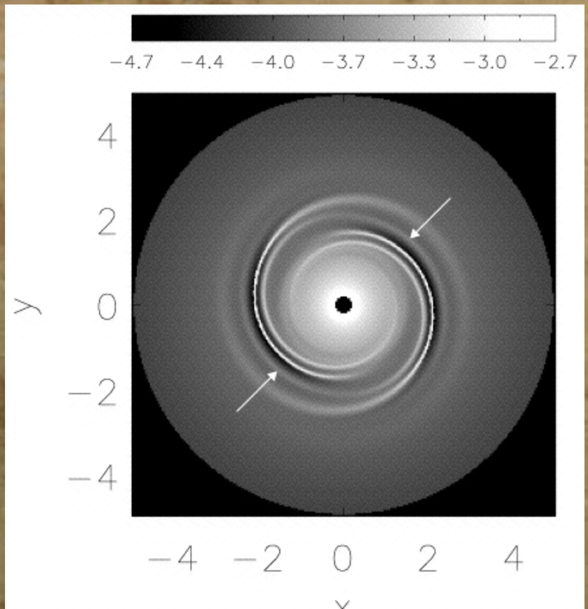
- Seigar & James (2002), Hα and K-band observations: local SFR increases close to spiral arms.
- Schinnerer (2004 NRAO), observations of CO radio emission from arms in M51: gas close to the shock is warmer and more turbulent.
- Suggest star formation is triggered there.



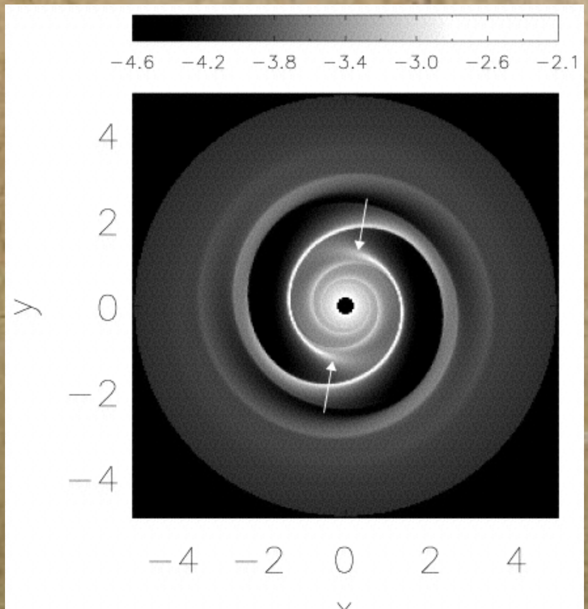
HST & Schinnerer

Substructures (spurs, feathers, branches) and multiarm morphology

- Chakrabarti+ 03: 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.



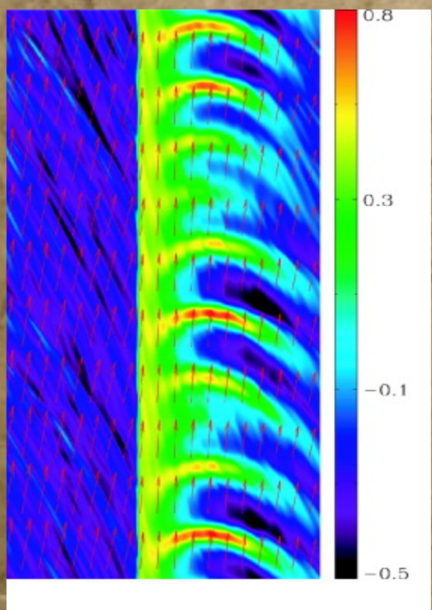
branches

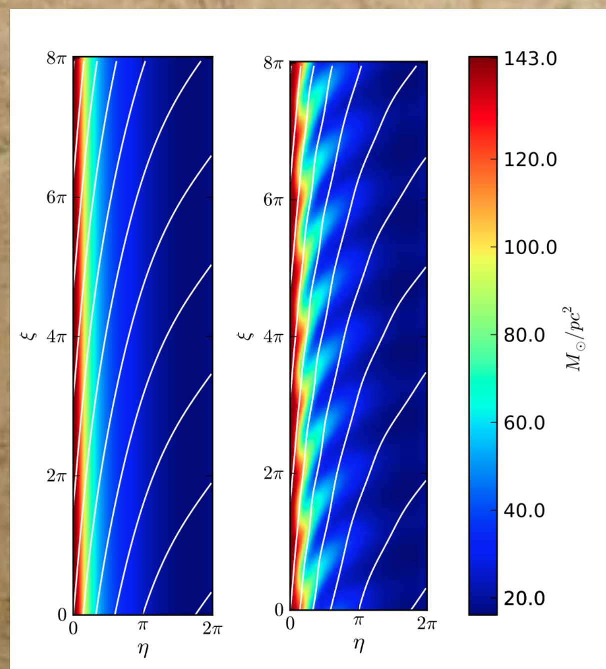


spurs

With B (essential if Q is large)

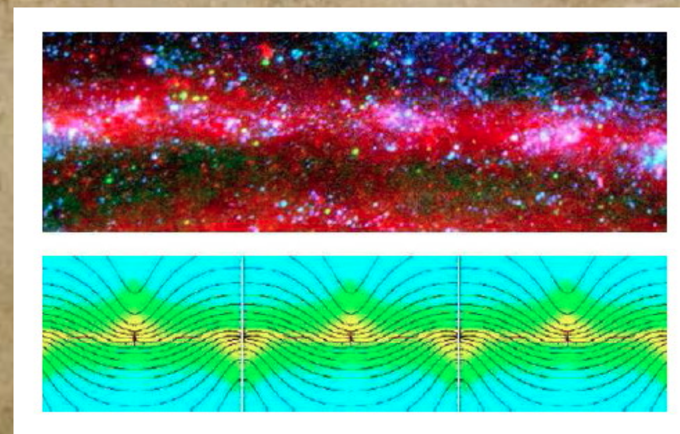
Spurs
(Kim & Ostriker 2002)

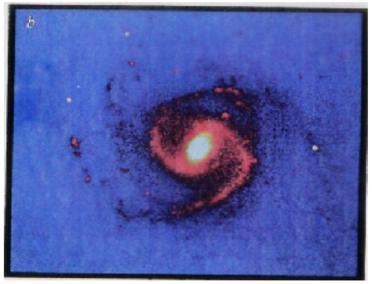




Feathers
(Lee & Shu 2012)

Beads on a string
NW of arm S4 (!) of M31
(Efremov 2010)



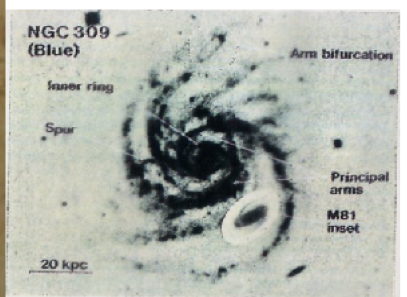


Disk dynamics

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.

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 :

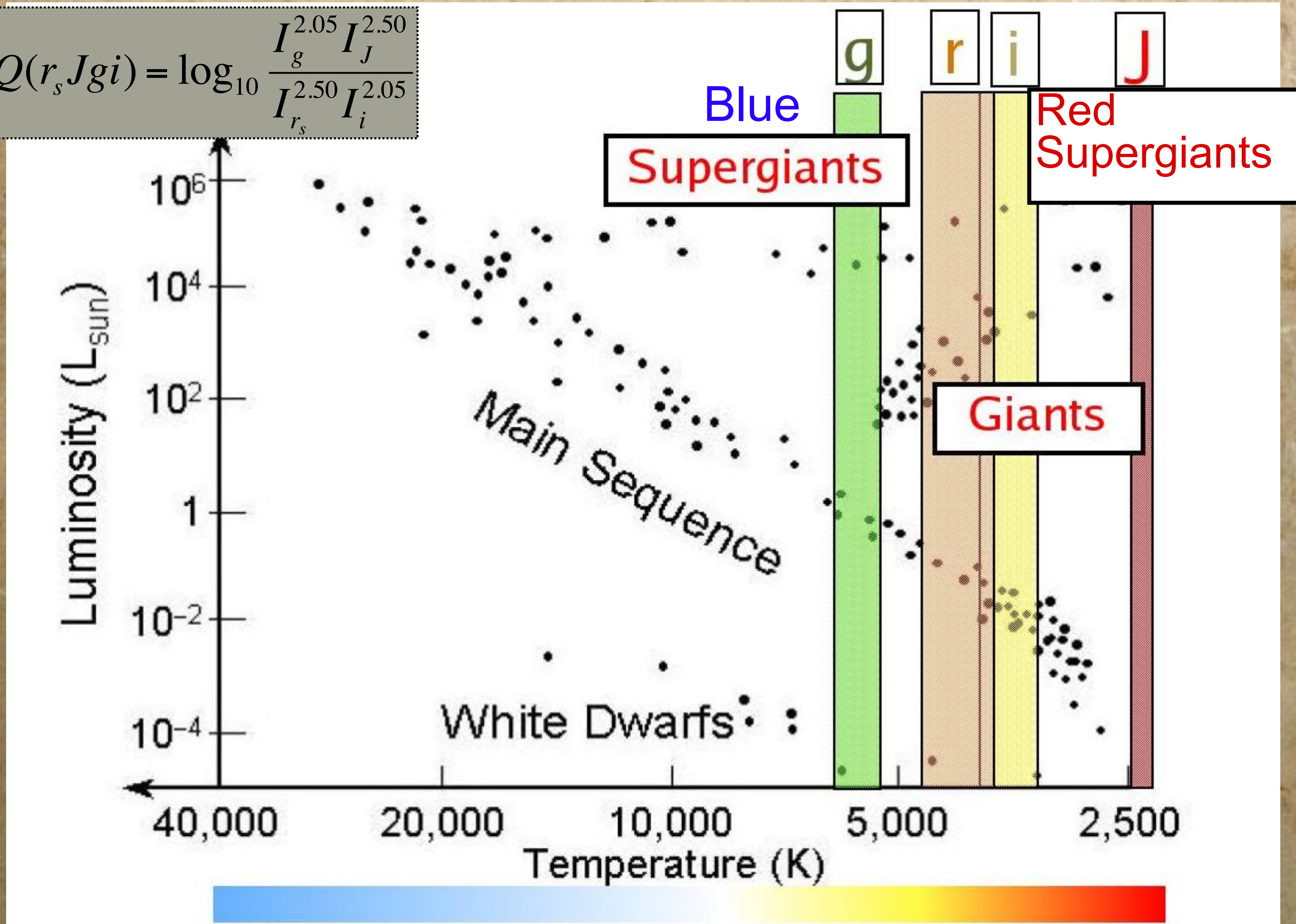
$$Q(r_s Jgi) = (r_s - J) - \frac{E(r_s - J)}{E(g-i)}(g-i)$$

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

Not to be confused with Toomre's Q!

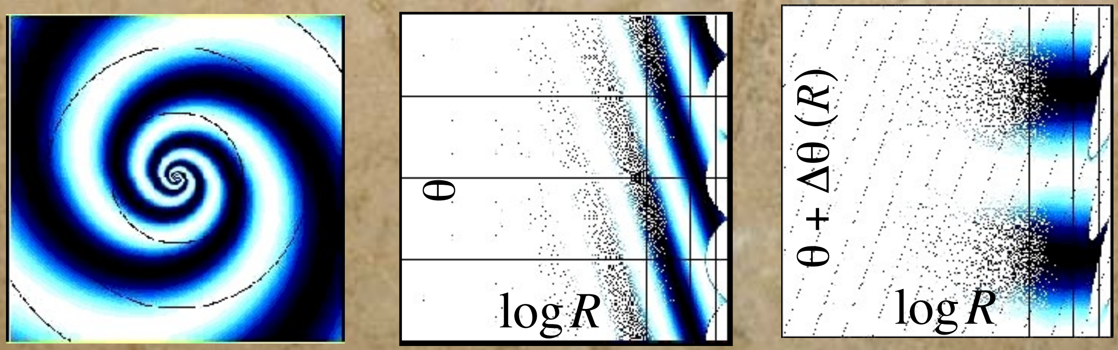
Q traces star formation:

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

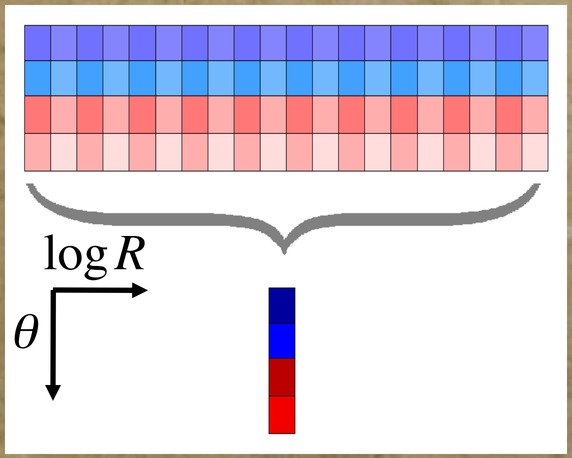


Images were deprojected, with parameters from literature

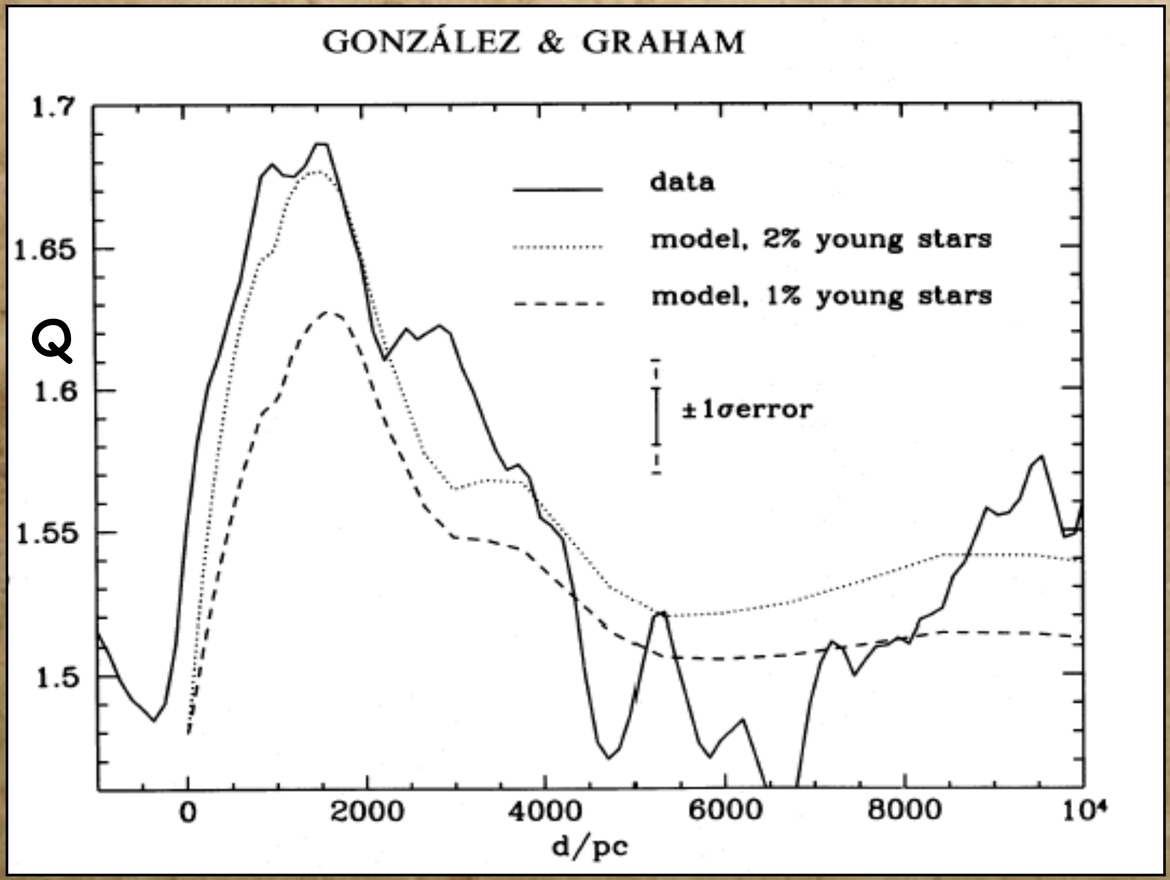
Spiral arms were unwound (Iye et al. 1982) and straightened



Collapsed in log R to improve S/N ratio



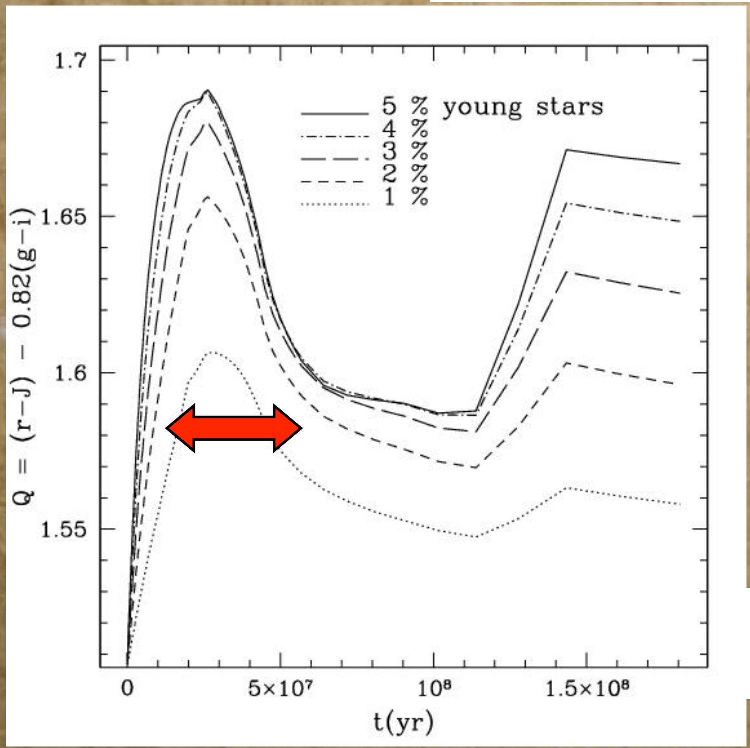
Q. Comparison between data and models.



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).
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_{Sun}.

We can relate age gradients to disk dynamics

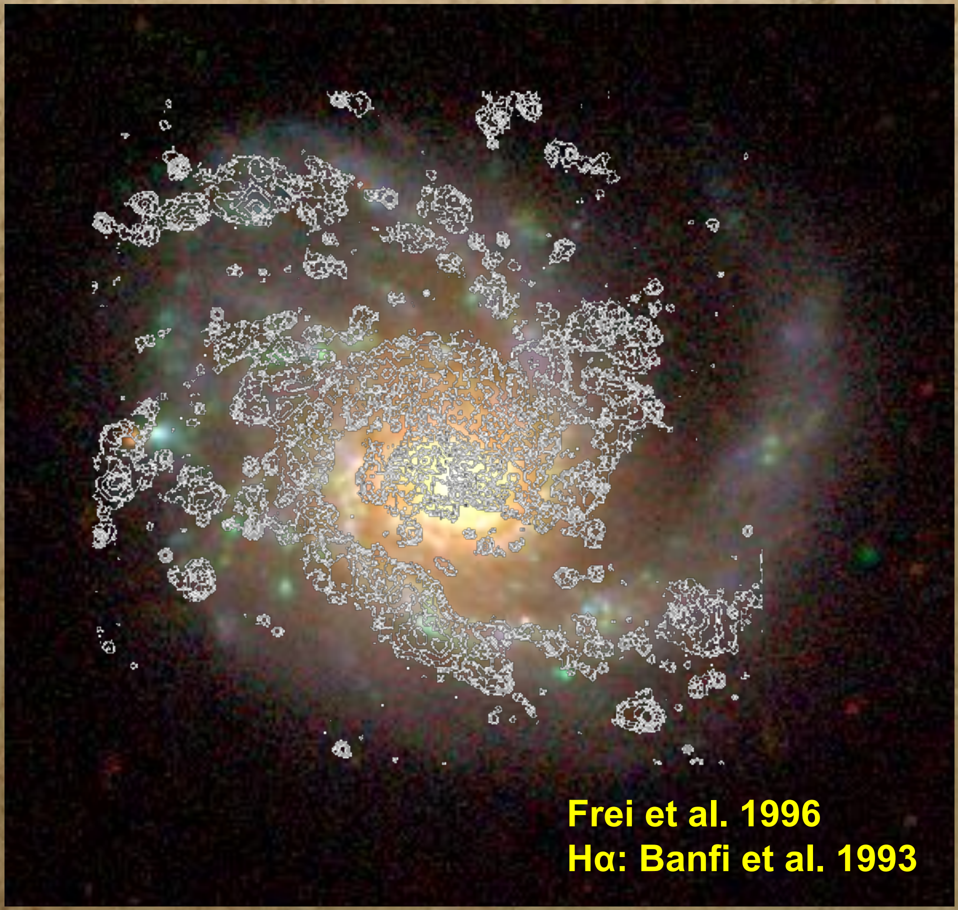
Results for M99 and new questions

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}
≅ 3 r_0 (Bertin et al. 1989)

Gradient where almost no Hα emission

$$M_{upper} = 10\ M_{sun}$$



Just how exceptional M99 really is?

Non-barred galaxies

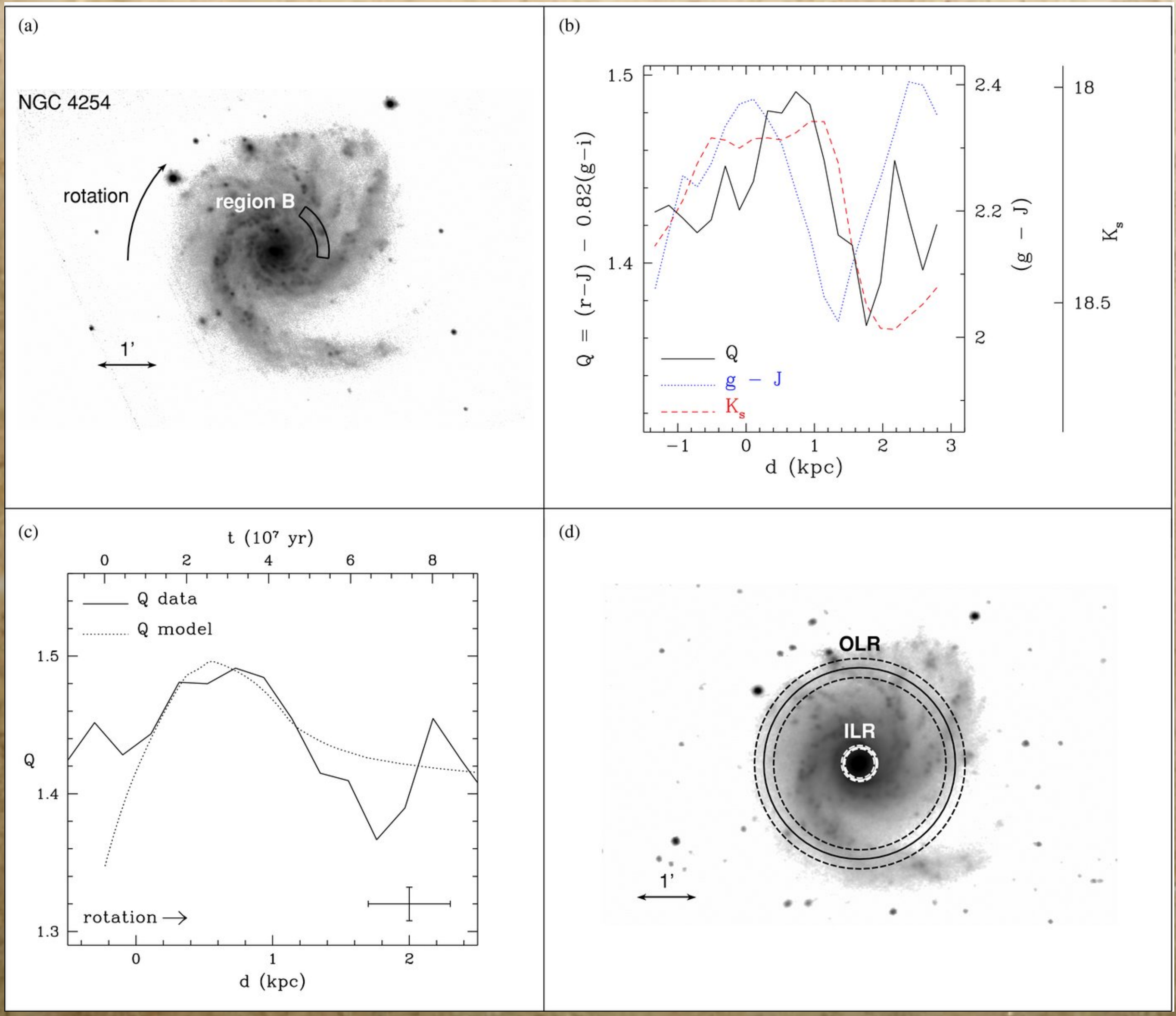
Name	Type
NGC 4939	SA(s)bc
NGC 3938	SA(s)c
NGC 4254	SA(s)c
NGC 7126	SA(rs)c
NGC 1417	SAB(rs)b
NGC 7753	SAB(rs)bc
NGC 6951	SAB(rs)bc
NGC 5371	SAB(rs)bc
NGC 3162	SAB(rs)bc
NGC 1421	SAB(rs)bc
NGC 7125	SAB(rs)c
NGC 918	SAB(rs)c
NGC 578	SAB(rs)c

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 $2x10^7$ yr
- IMF M_{upper} = 10 and 100 M_{Sun}
- 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


(a)
NGC 4254
rotation
region B
1'
(b)
Q = (r−J) − 0.82(g−i)
(g − J)
K_s
d (kpc)
Q
g − J
K_s
(c)
t (10^7 yr)
Q data
Q model
Q
rotation →
d (kpc)
(d)
OLR
ILR
1'

Results for non-barred galaxies

Gradients and Ω_p in 10 (including M99) out of 13 galaxies.

M99 is *not* unique!

Q(rJgi) constitutes the right technique for gradient search

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, $\Omega - \Omega_p = -\kappa/2$).

$\kappa^2 = 2\Omega/R \times d(R^2\Omega)/dR$; $\kappa = \Omega\sqrt{2}$ for flat rotation curve.

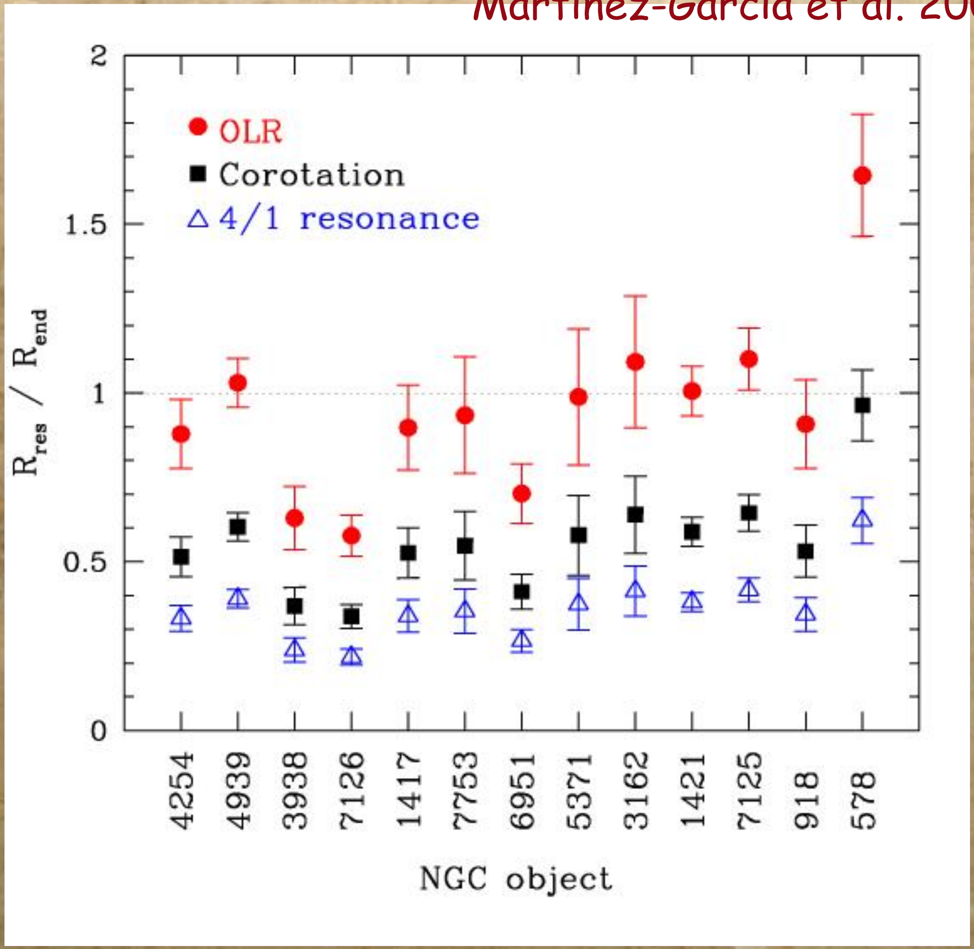
- Nonlinear analysis of orbits (Contopoulos & Grosbol 1986; Patsis et al. 1991):

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

"Weak" spirals (Sa) at corotation.

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

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



$\langle R_{OLR}/R_{end} \rangle = 0.95 \pm 0.03$, $\chi^2/n = 7.12$; 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 (WKB approximation)!

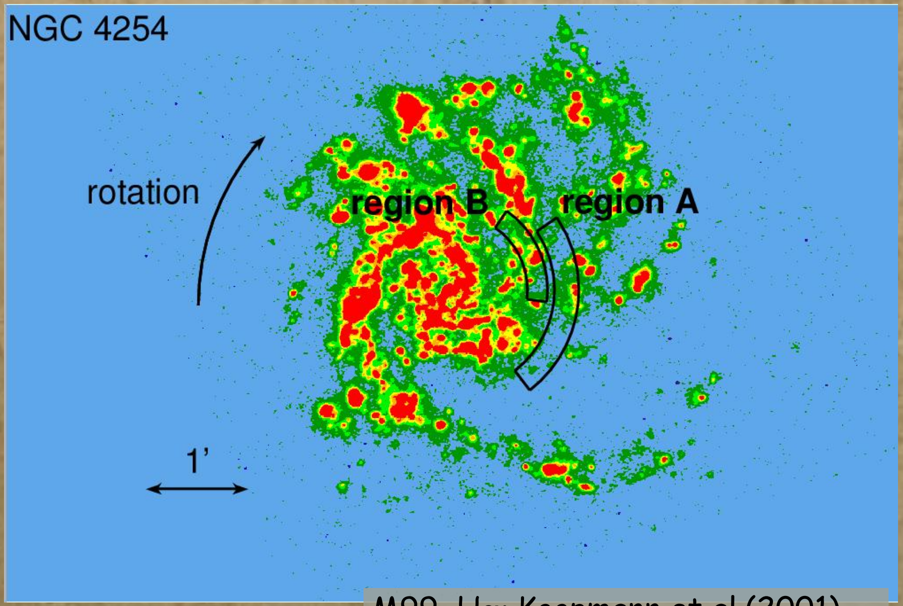
M_{upper} of IMF

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

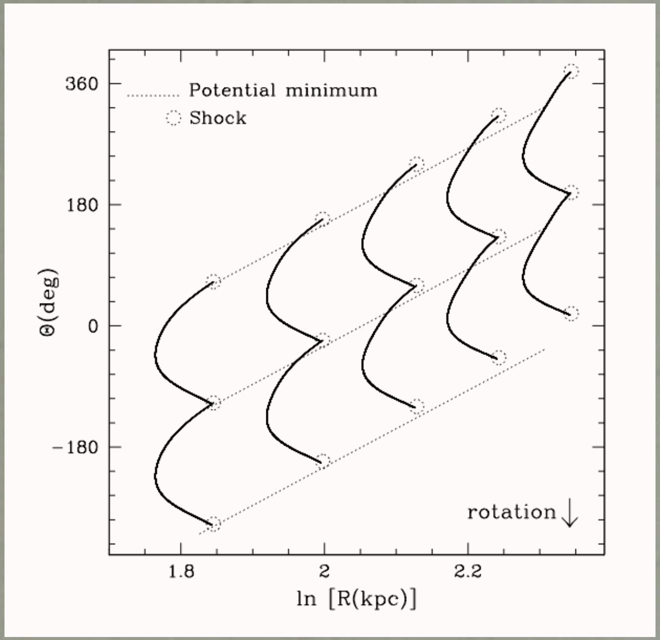
Contamination by patchy Hα emission from massive stars or destruction of an ordered front by SN explosions could be causes behind the dearth of detected color gradientes up until now (besides non-linear/chaotic effects/instabilities)!

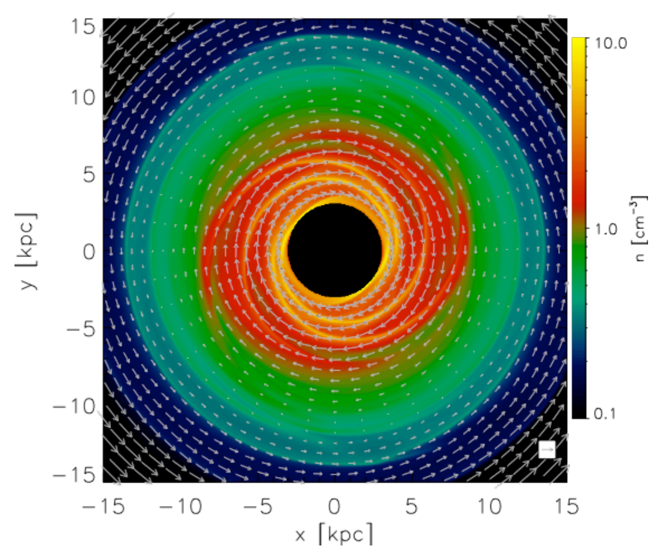


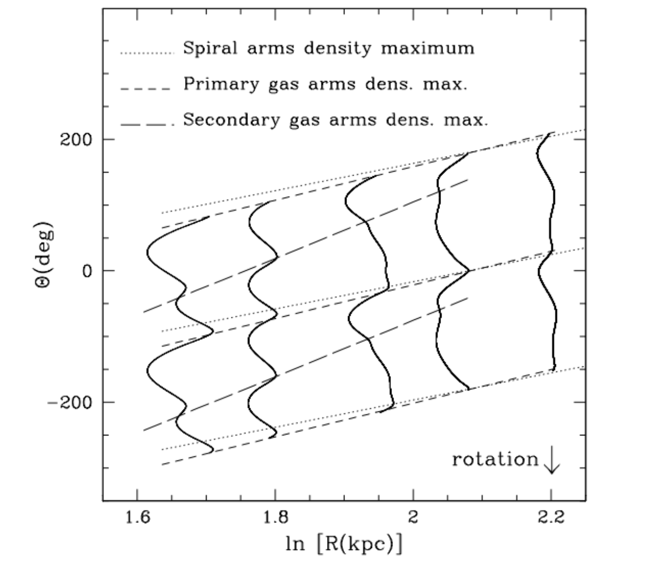
M99, Hα; Koopmann et al.(2001)

Non-circular motions

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

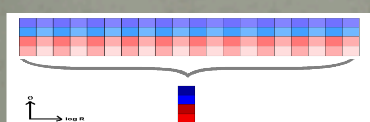


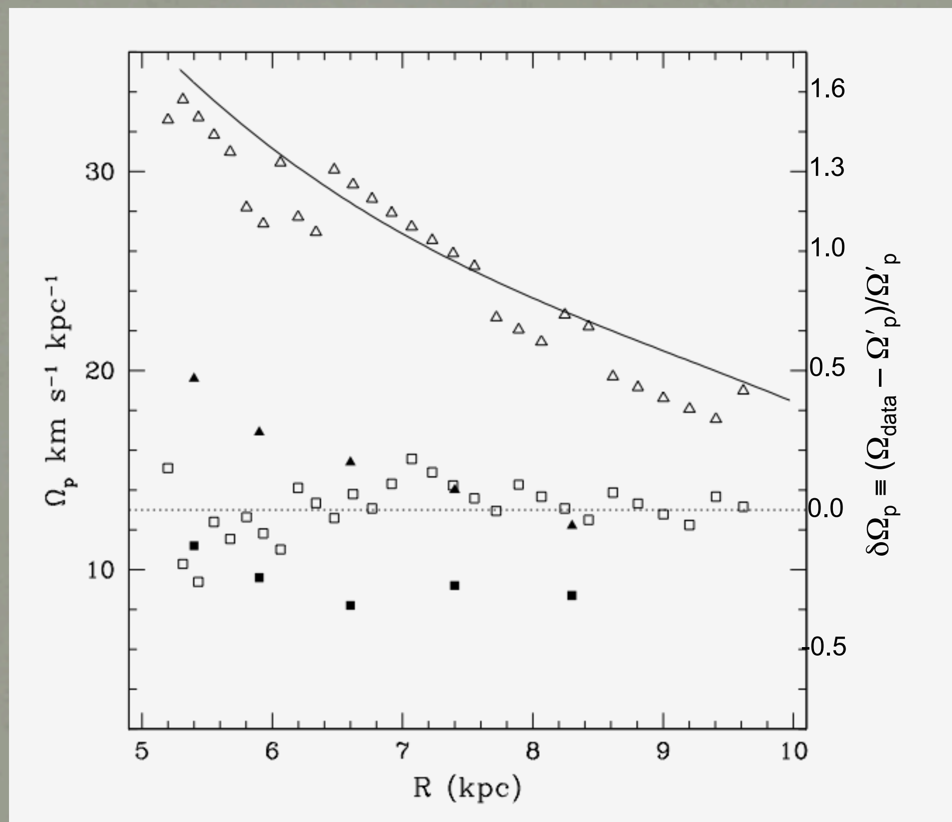




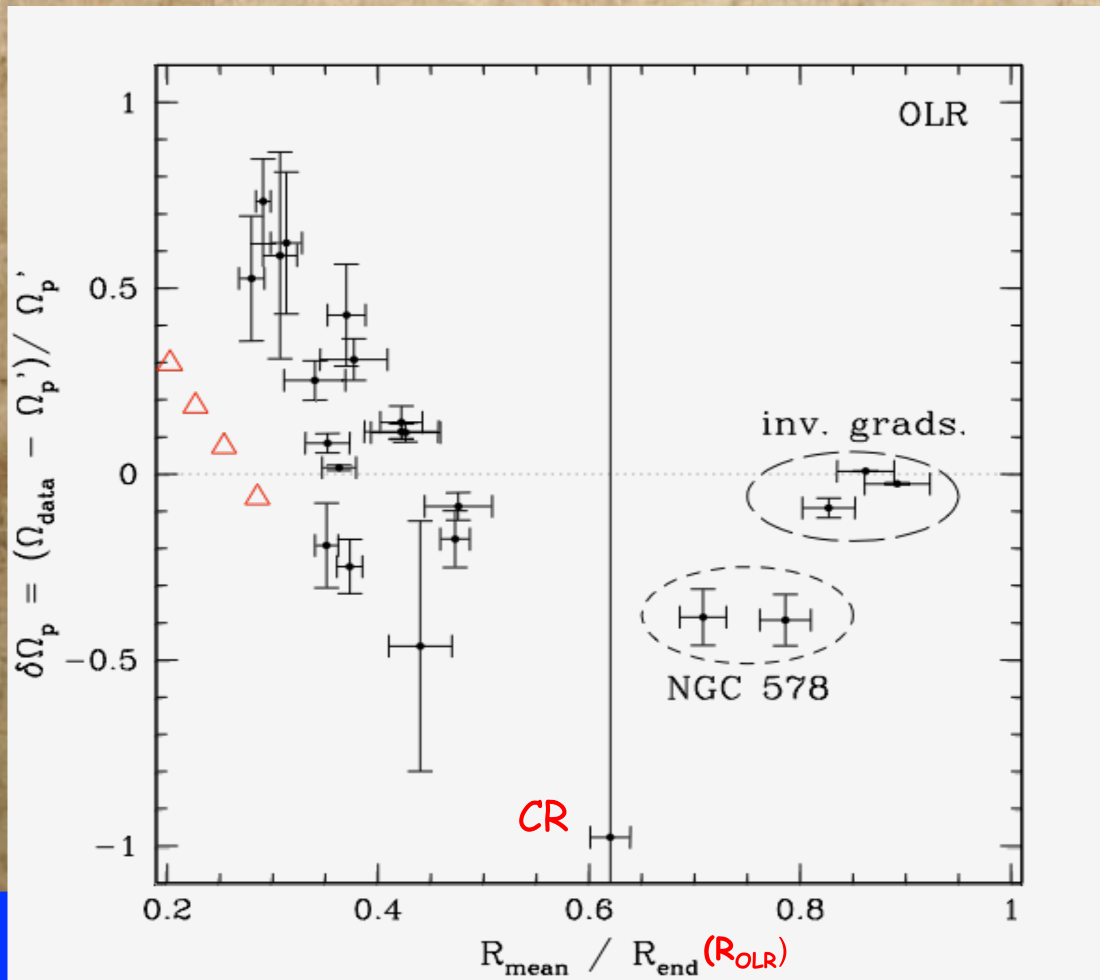
Ω_p measurements (s.a.s.s.)

(one simulated galaxy, different radii)



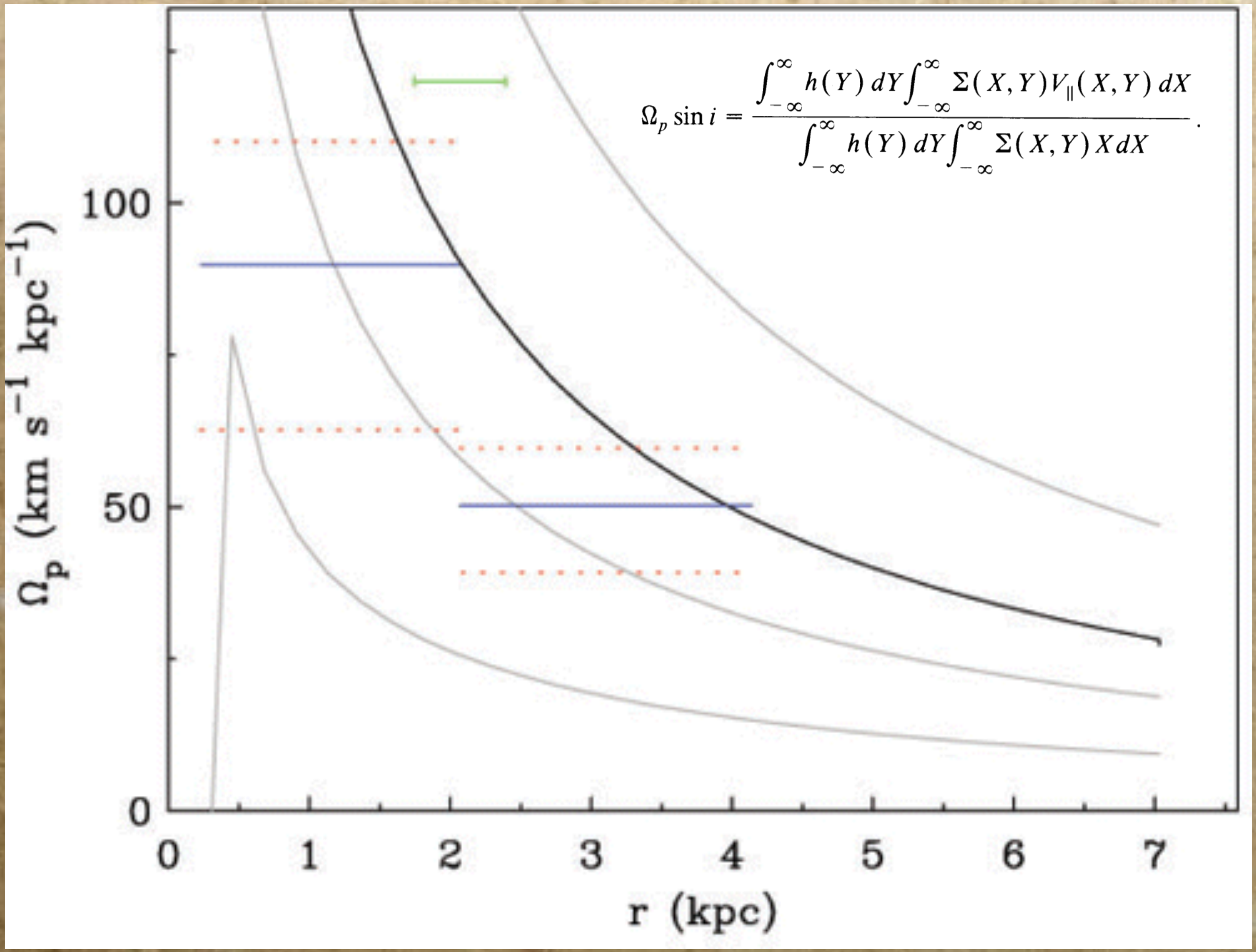


Data
(several galaxies)



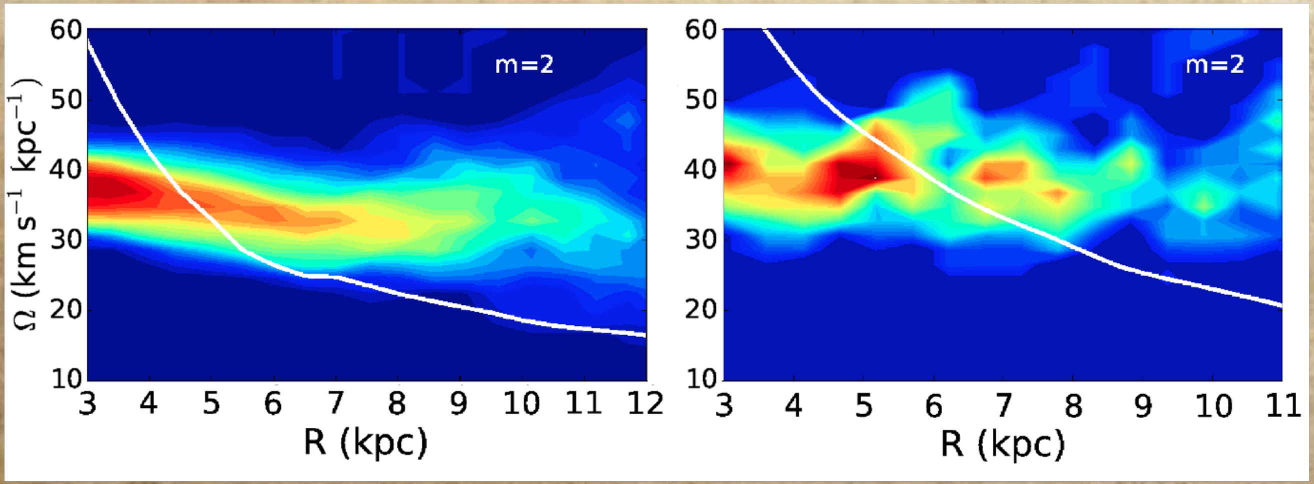
$$\Omega'_p \approx \frac{v_{rot}}{R_{OLR}}\left(1 + \frac{\sqrt{2}}{2}\right)$$

M51, radial Tremaine-Weinberg (TWR) method

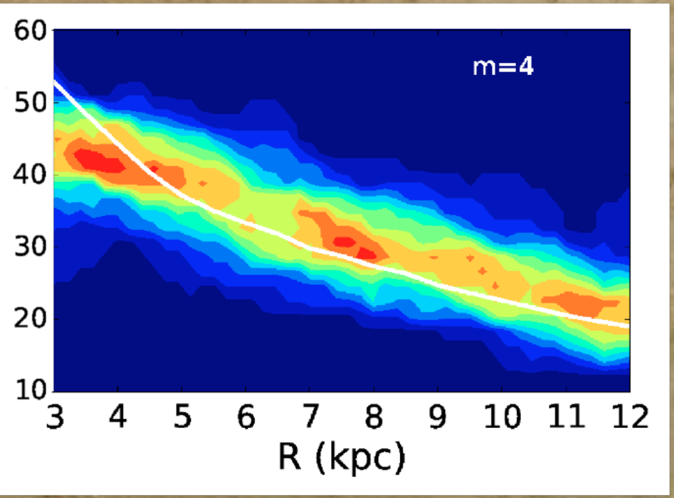


Meidt+ 08

Barred N-body simulations, corotating arms and bars



Unbarred N-body simulation, flocculent arms

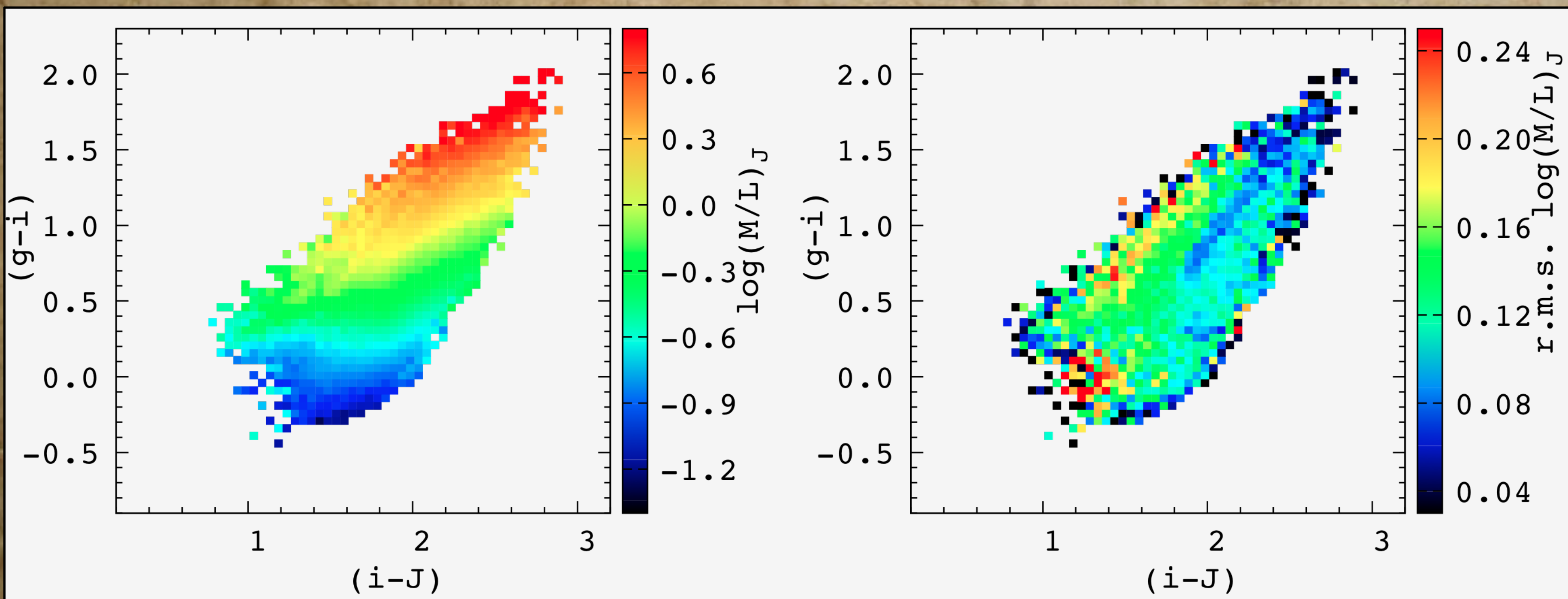


Roca-Fàbrega+ (2013)

Evidence of radially extended azimuthal gradients

Fourier analysis of mass arms

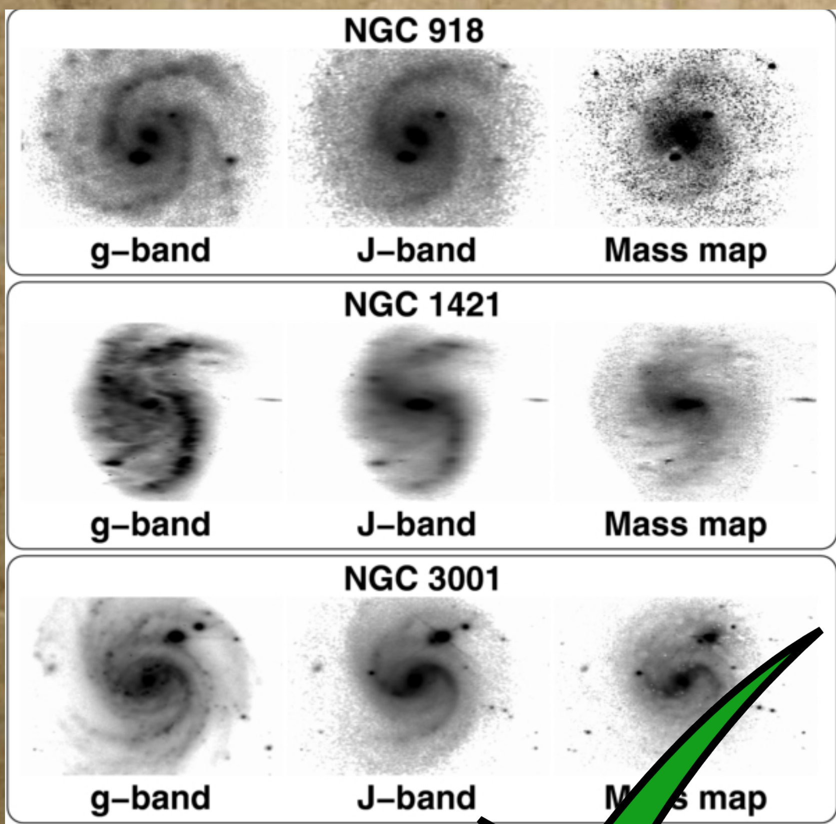
SFH, Z, τ

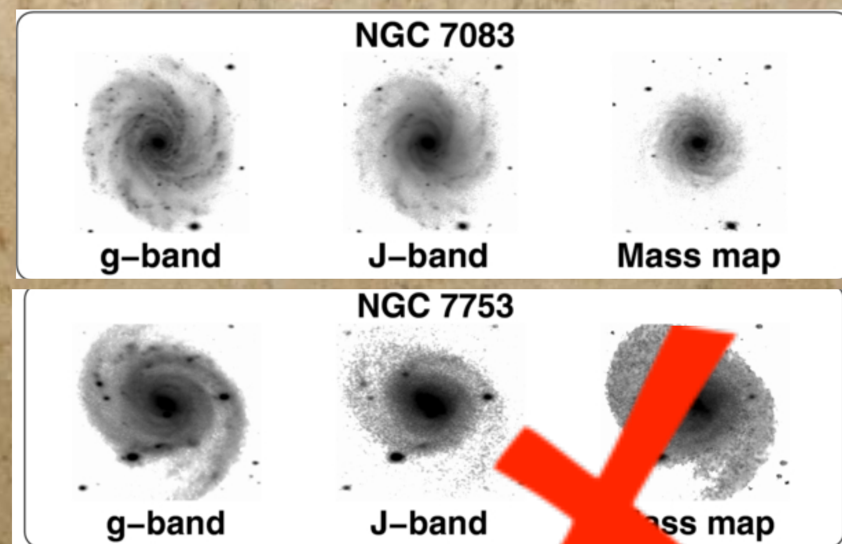


Martínez-García & González-Lópezlira (2012), after da Cunha+ 08 and Zibetti+ 09

Evidence of radially extended azimuthal gradients

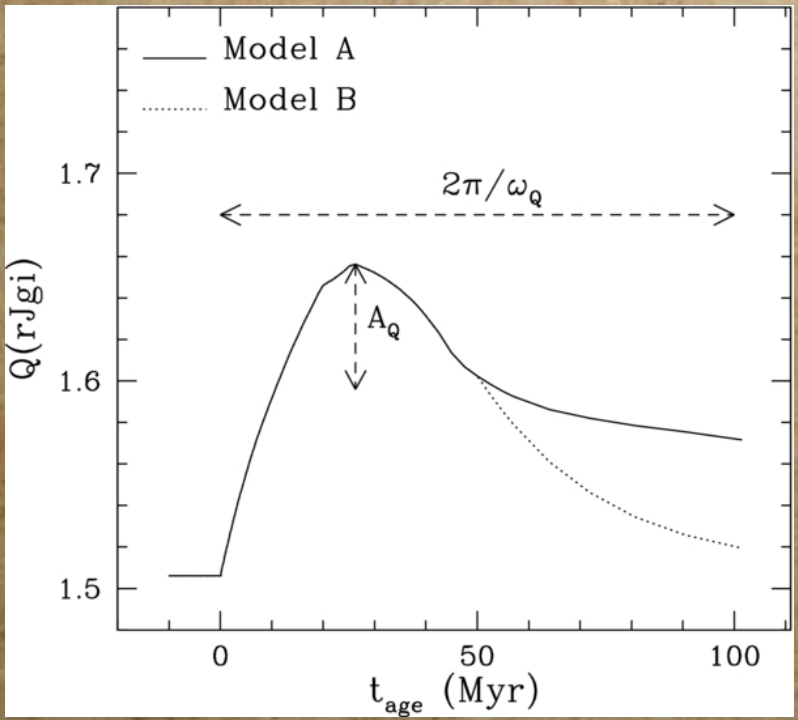
Fourier analysis of mass arms

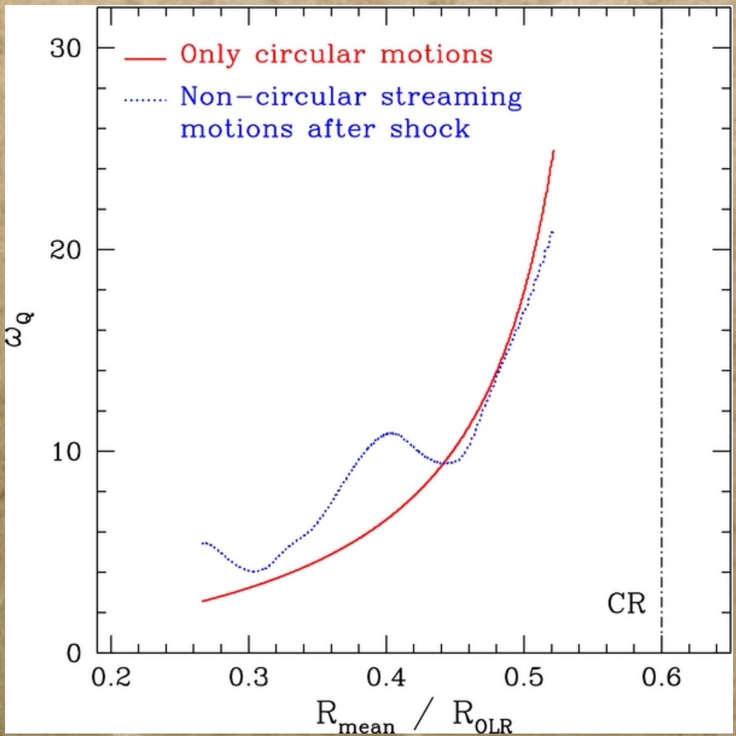




13 out of 19 spirals
(non- or weakly barred)

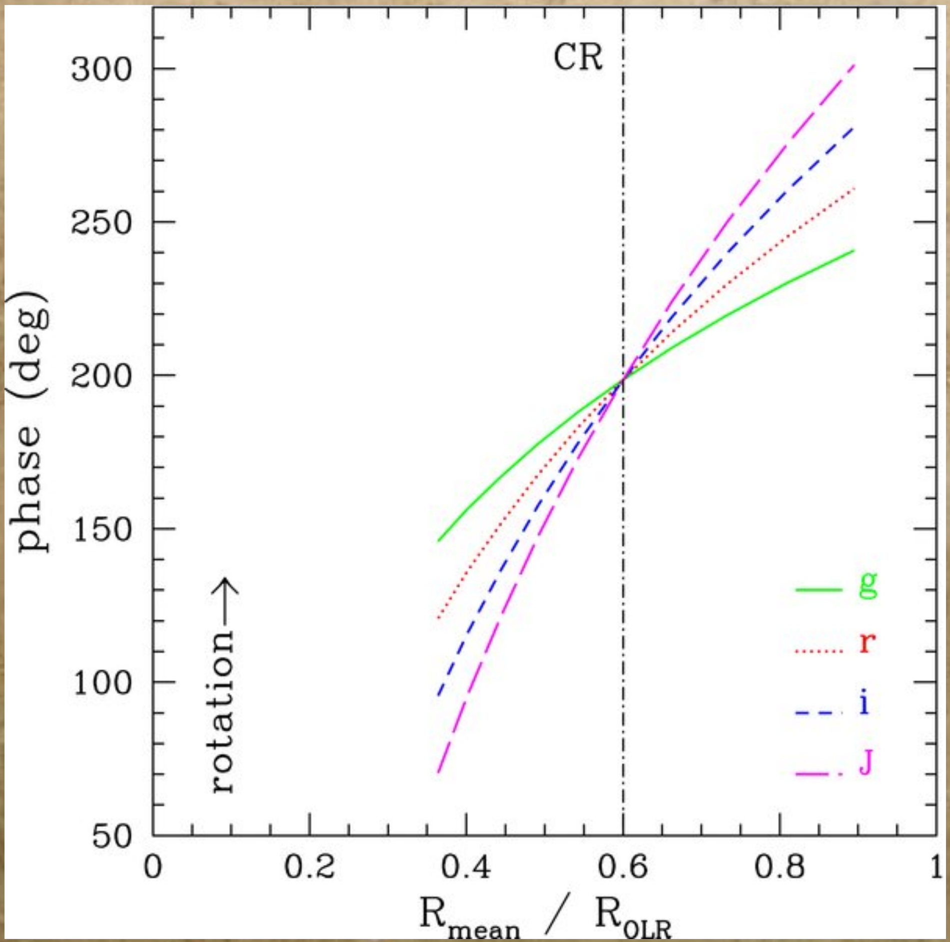
Gradient frequency ω_Q



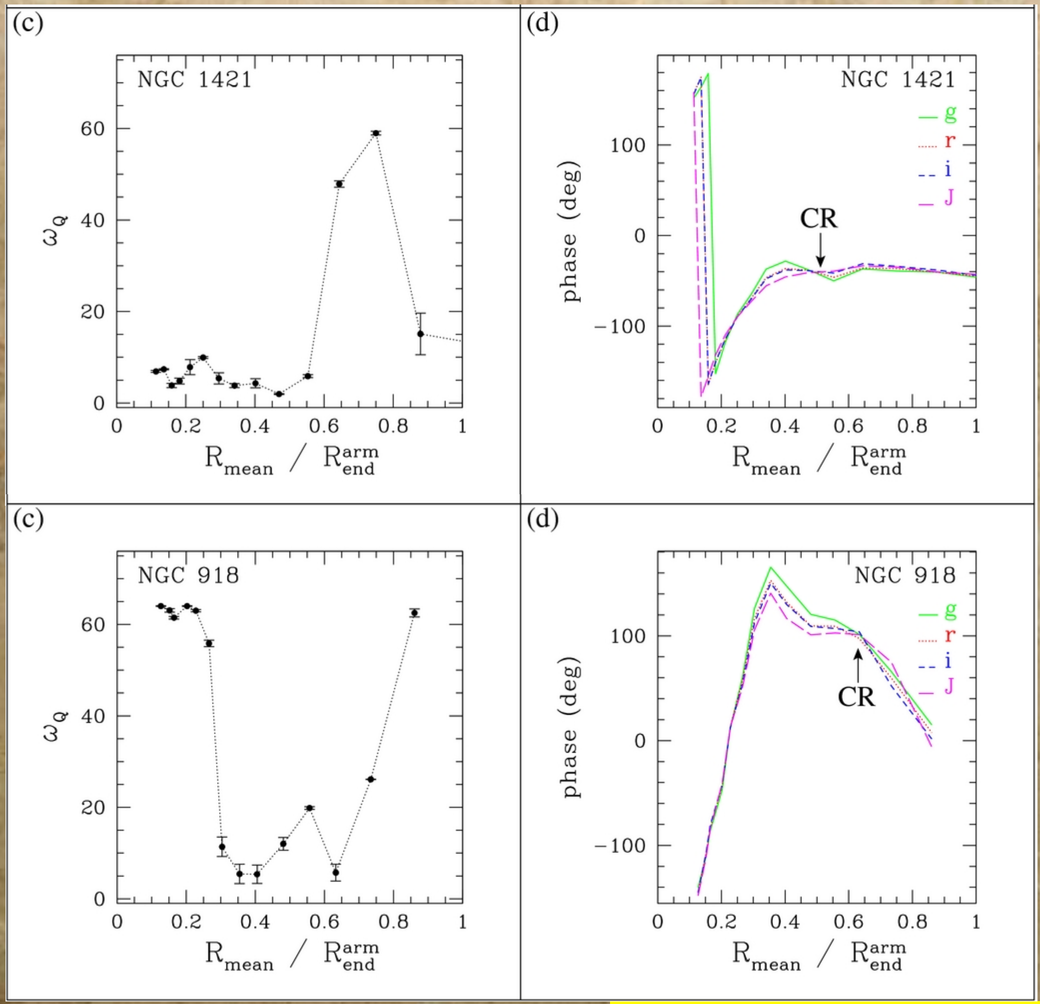


Gradient phase as a function of R and λ

(e.g., Puerari & Dottori 1997)

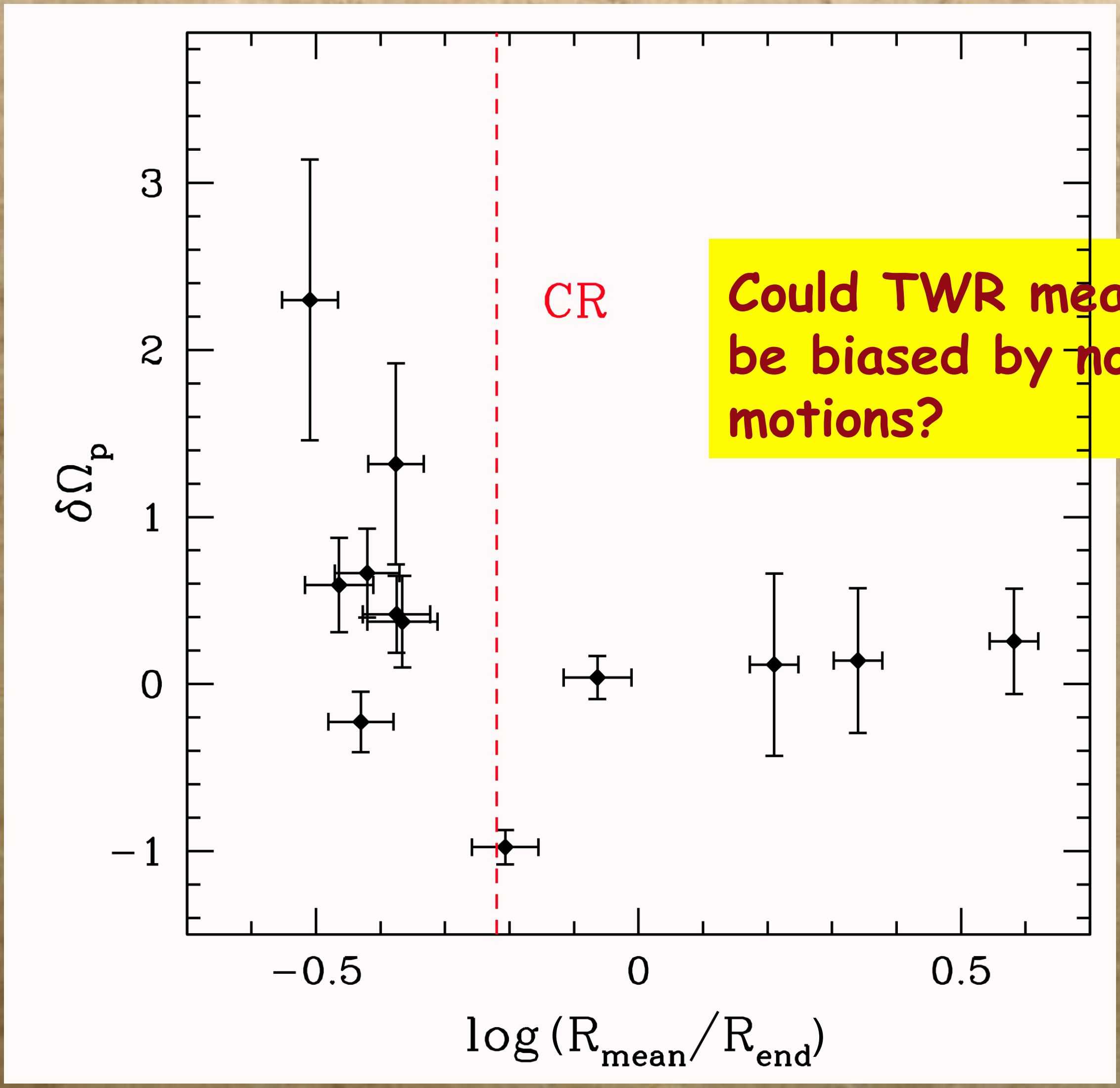


A couple of (positive) examples



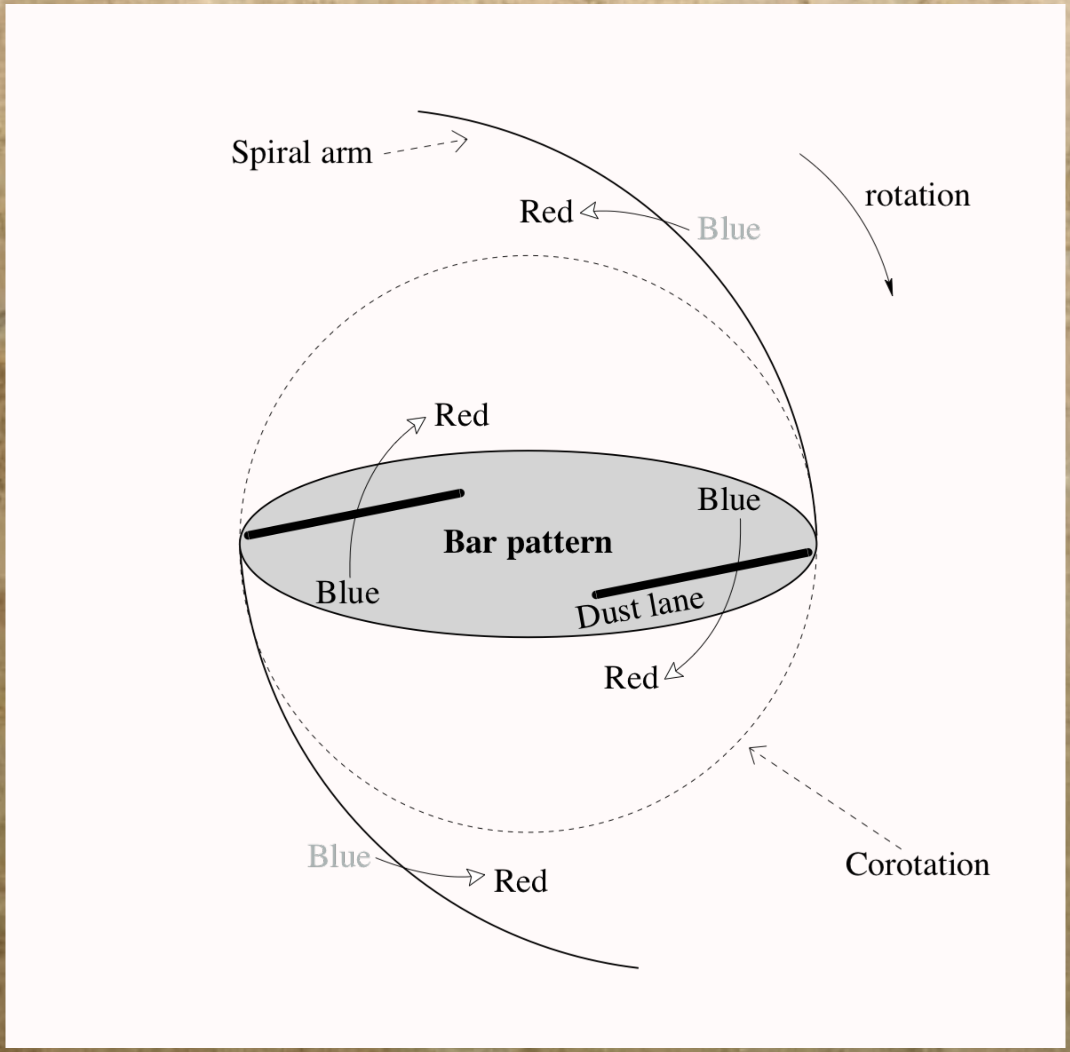
7 or ≈50% of galaxies with mass arms

$\delta\Omega_p$ for 5 spirals with mass arms and radially extended gradients (REG)



Could TWR measurements be biased by non-circular motions?

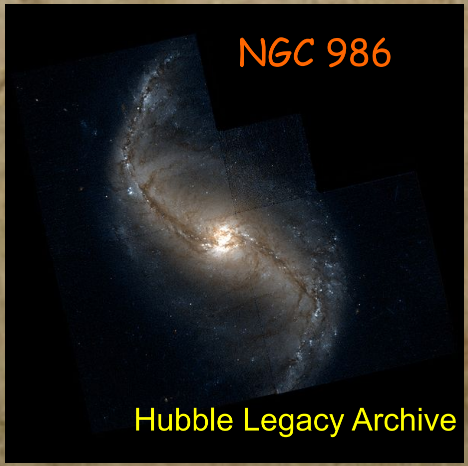
Barred galaxies



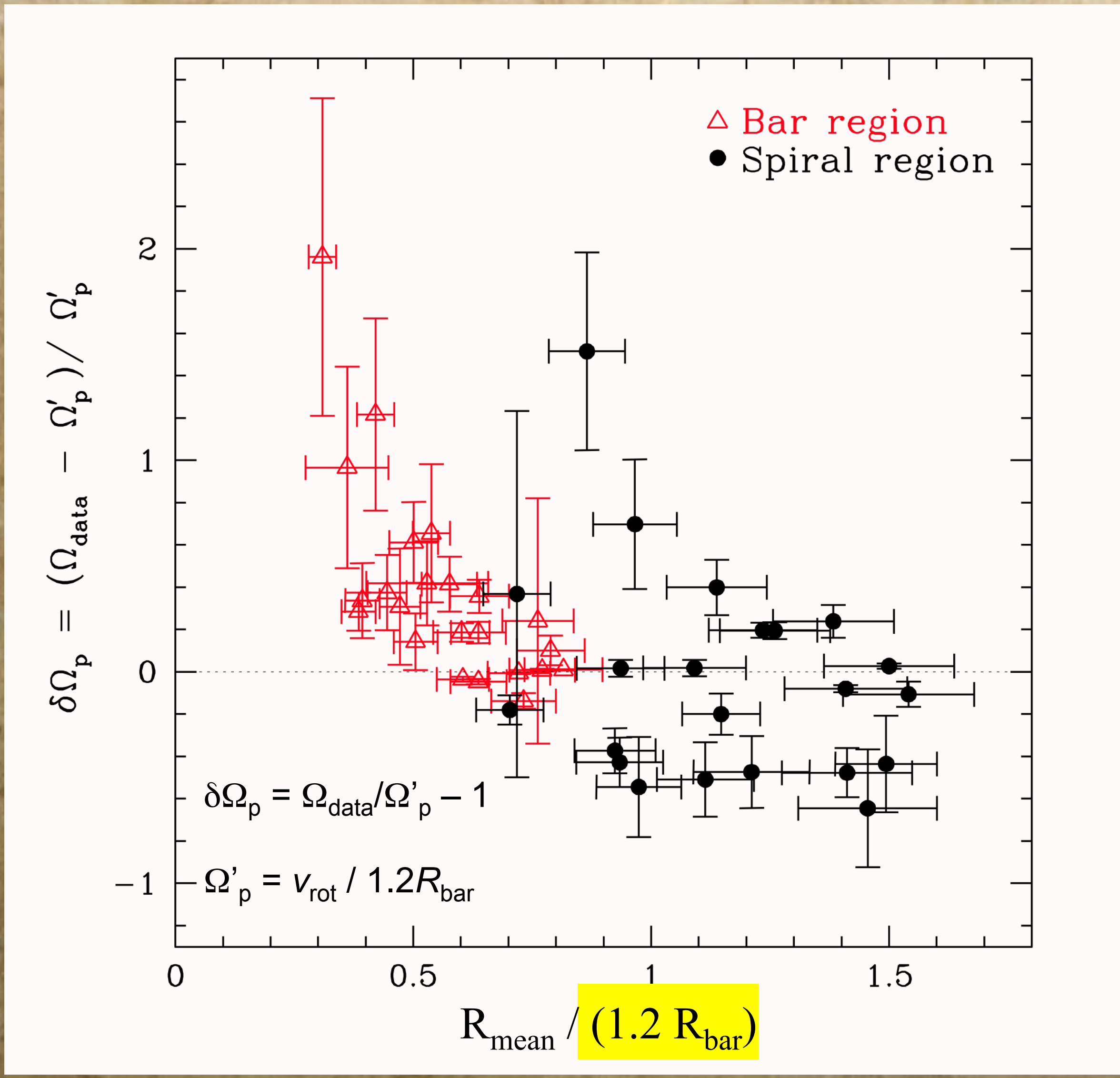
Barred galaxies

Martínez-García & González-Lópezlira 2011, ApJ, 734, 122

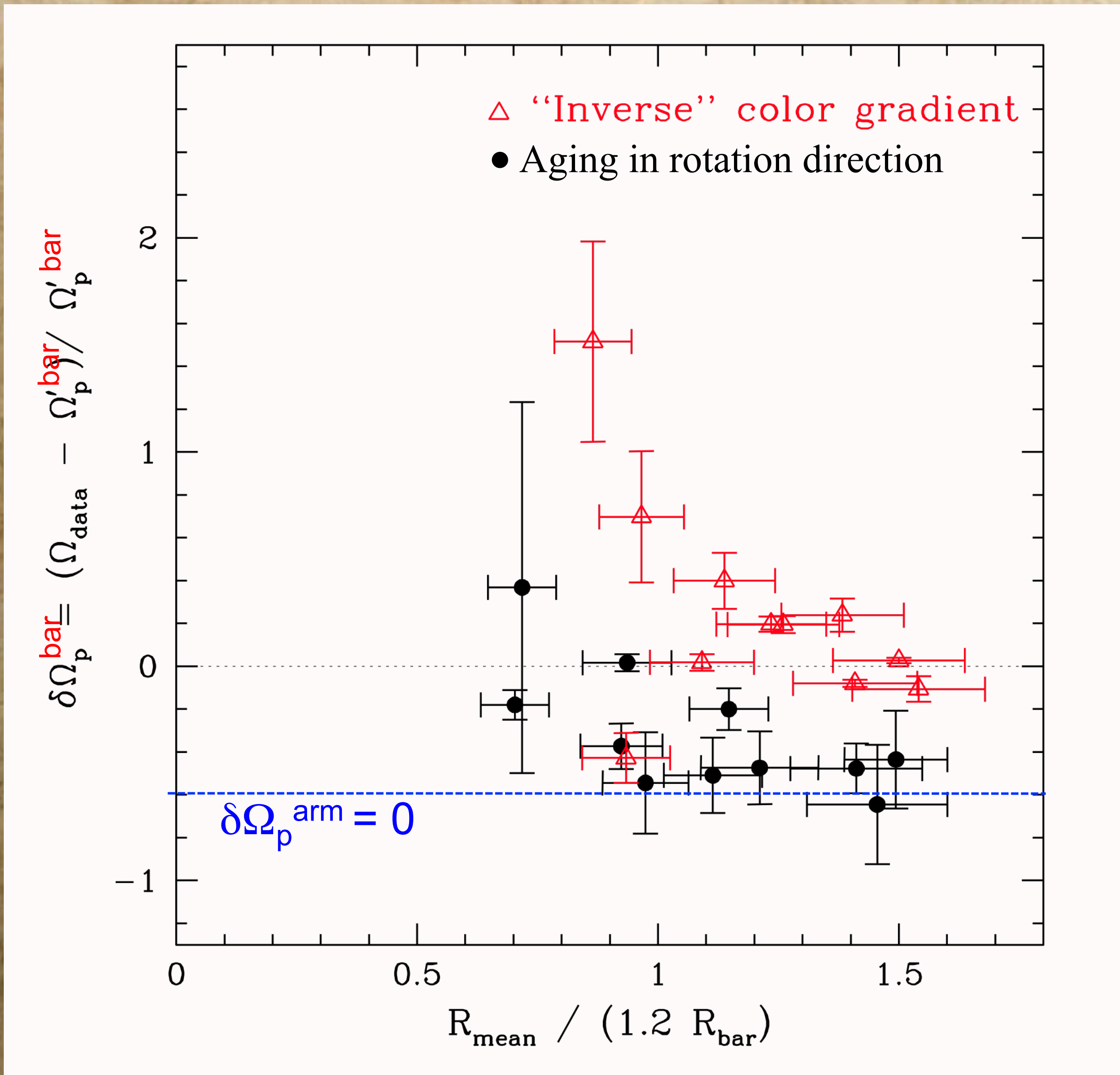
Name	Type
NGC 718	SAB(s)a
NGC 864	SAB(rs)c
NGC 4314	SB(rs)a
NGC 266	SB(rs)ab
NGC 986	SB(rs)ab
NGC 7496	SB(s)b
NGC 5383	SB(rs)b
NGC 4593	RSB(rs)b
NGC 3059	SB(rs)bc
NGC 7479	SB(s)c
NGC 3513	SB(rs)c



Gradients in barred galaxies

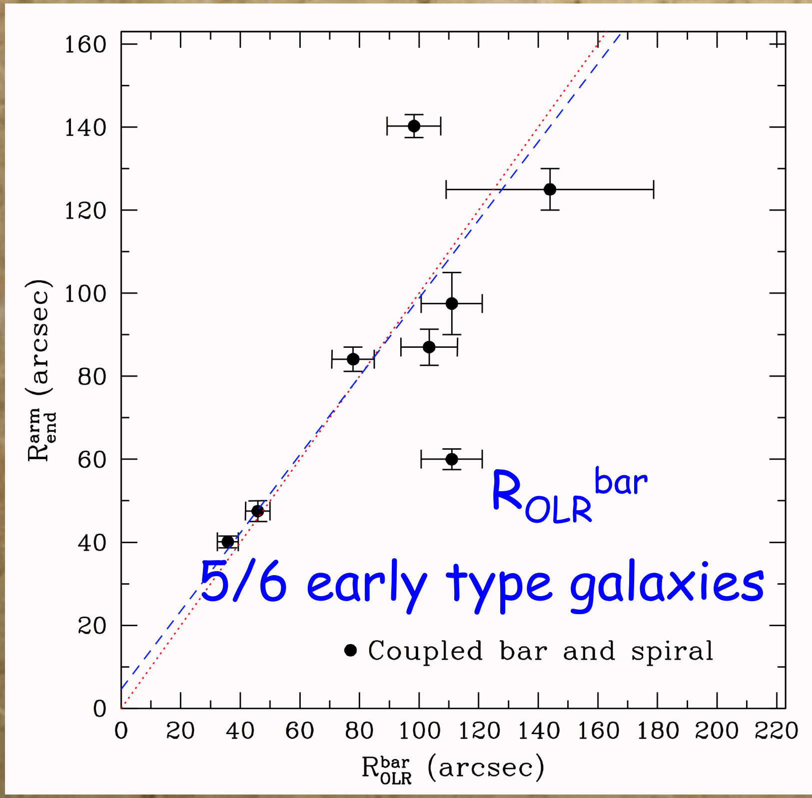


Gradients in arms of barred galaxies

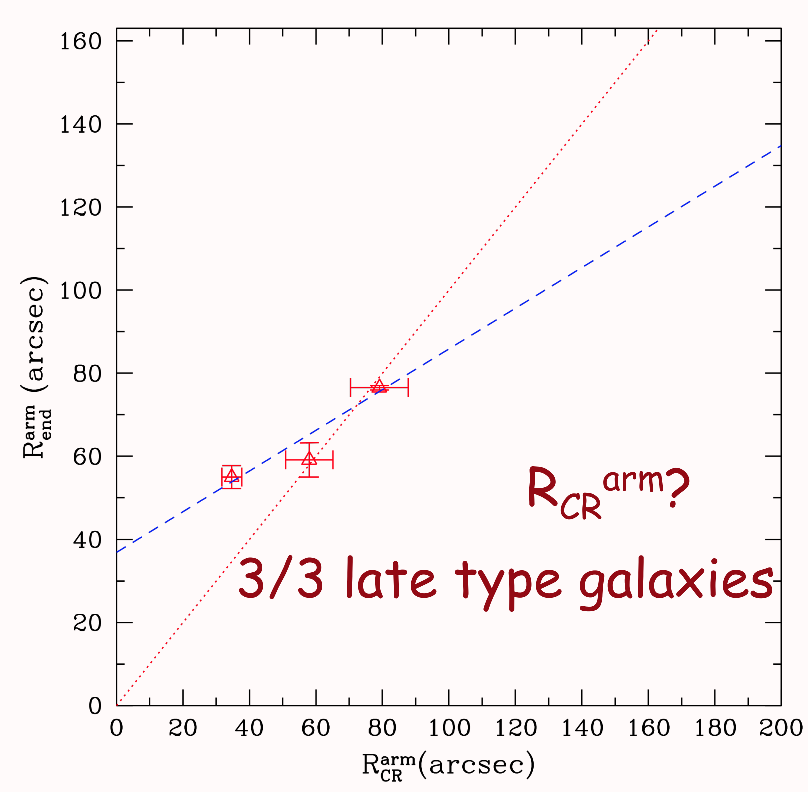


Arm end points in barred galaxies

Coupled bar and spiral



Uncoupled bar and spiral



Conclusions I

•Color gradients in ~ 75% of our sample of non-barred and weakly barred spirals, and in 100% of barred galaxies. The number of galaxies with detected gradientes has increased (conservatively) by a factor of 7. M99 is not an oddity.

•Contrary to common wisdom, gradients are detected away from patchy emission of hot young stars and ionized gas.

•Non-circular motions do not prevent detection of gradients, but can mimic absence of pattern speed. Also paradoxically, the systematic bias of Ω_p measurement with R further strengthens link between disk dynamics and star formation.

Conclusions II

•Non- or weakly barred galaxies with mass arms, and signatures of radially extended gradients also show a radial change of $\delta\Omega_p$.

•Different kinds of galaxies, different kinds of arms, different kinds of arm ***segments***!

•Spiral patterns in non-barred galaxies 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); may be due to stabilizing effect of halo.

Conclusions III

•Bars end at their own CR radius

•Spiral arms in early-type barred galaxies are coupled to the bar and end at the bar's OLR.

•Spiral arms in late-type barred galaxies are uncoupled to the bar and may end at their own corotation
(more data are needed).

•Disk dynamics and star formation ARE coupled.

Ongoing and future work

- Apply TWR to spirals with mass arms and REG
- Where do arms start in barred galaxies?
- Are arms different in late and early type barred galaxies?
- SFR, SFE and gradients

THANKS!