INAF

ISTITUTO NAZIONALE DI ASTROFISICA
OSSERVATORIO ASTROFISICO DI ARCETRI

UNIVERSITÀ DEGLI STUDI FIRENZE

Lecture VIII: Fundamental notions of kinematical measurements. Dynamics of galactic disks.

Astrophysics of Galaxies 2019-2020

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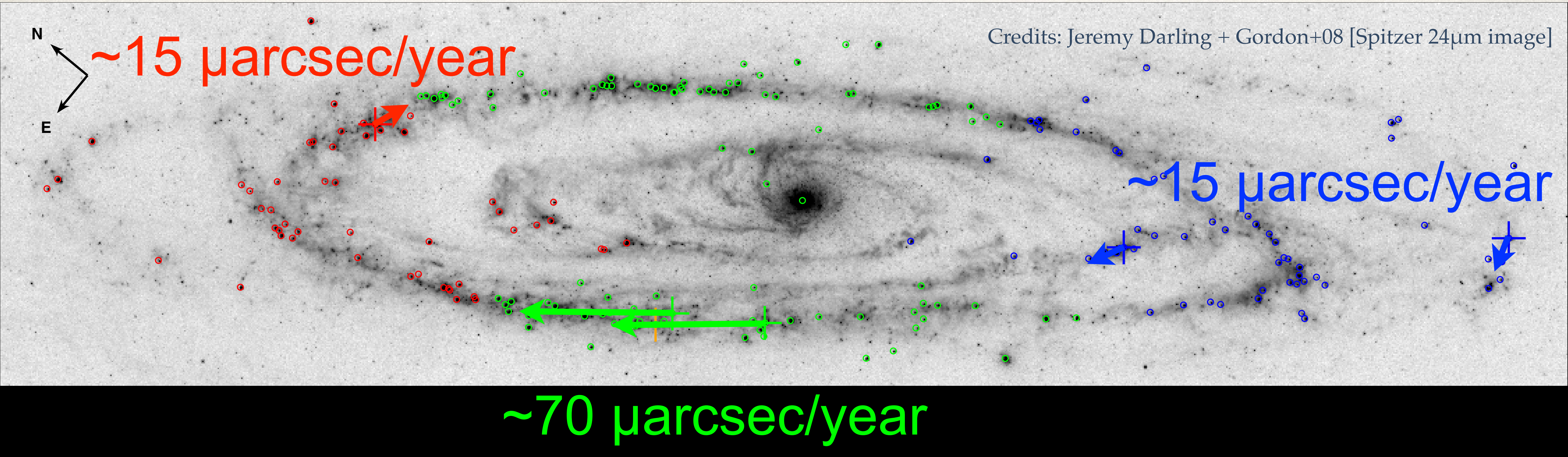
Kinematics from observations

- Doppler effect: radial component only

- lack of two tangential components unless proper motions but...
  - $\mu[\mu\text{arcsec yr}^{-1}] = 21 * v_t\,[100\text{ km s}^{-1}]\ /\ D\,[\text{Mpc}]$
  - becoming accessible in M31 with masers!
  - Out of reach beyond the Local Group



Radial velocities

- Require adequate spectral resolution (and accuracy!)

$$\frac{\Delta\lambda}{\lambda} = \frac{\Delta v}{c} = \frac{1}{R}$$

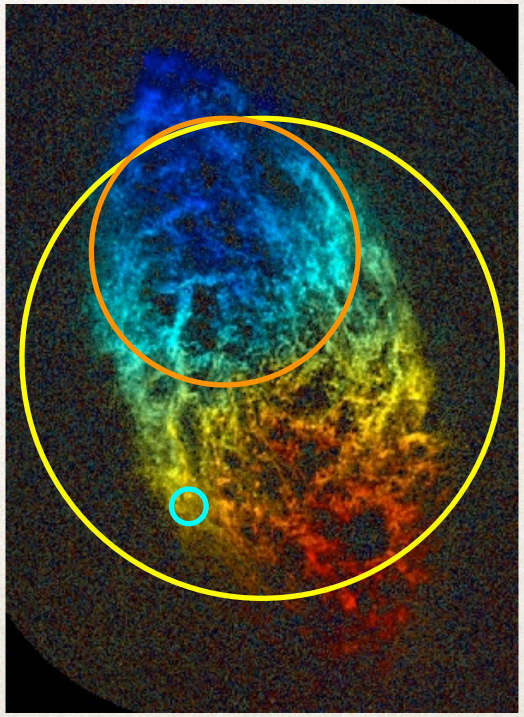
$$R \sim \frac{3{,}000}{v/100\ \mathrm{km\ s^{-1}}}$$

  - At optical wavelengths $\Delta\lambda \sim 1.5$Å
- Must take into account the velocity distribution *f(v)* along the line of sight that is integrated
- Assuming that the spectrum is independent of *v*

$$F_{tot}(\lambda) = \int_{-\infty}^{\infty} dv\, f(v) F(\lambda/(1+v/c))$$

- If F is narrow (almost a δ), the resulting spectrum F_{tot} directly reflects the velocity distribution f(v), with a broadening

$$\Delta\lambda \sim \lambda \frac{\Delta v}{c}$$



Velocity distribution and spectral "smoothing"

- Previous formalism is computationally expensive so normally this is done in velocity space

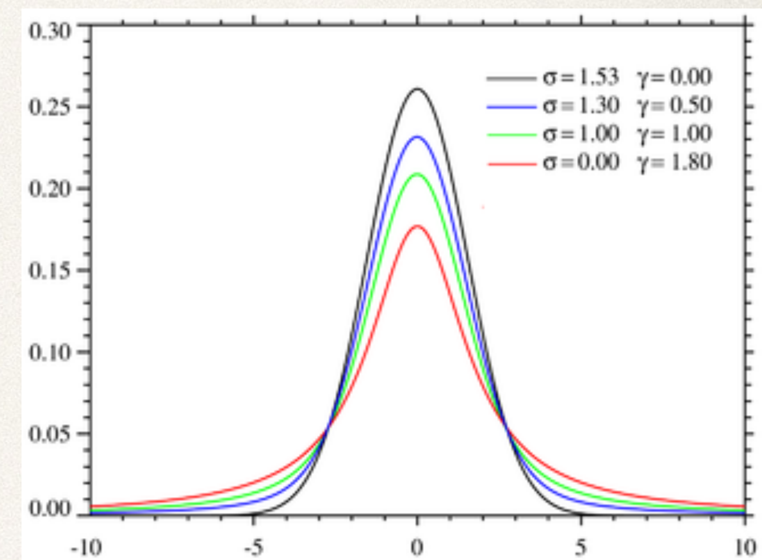
$$\lambda \rightarrow v:$$

$$\frac{dv}{c} = \frac{d\lambda}{\lambda} = d\ln(\lambda) \Rightarrow v = c\ \ln(\frac{\lambda}{\lambda_0})$$

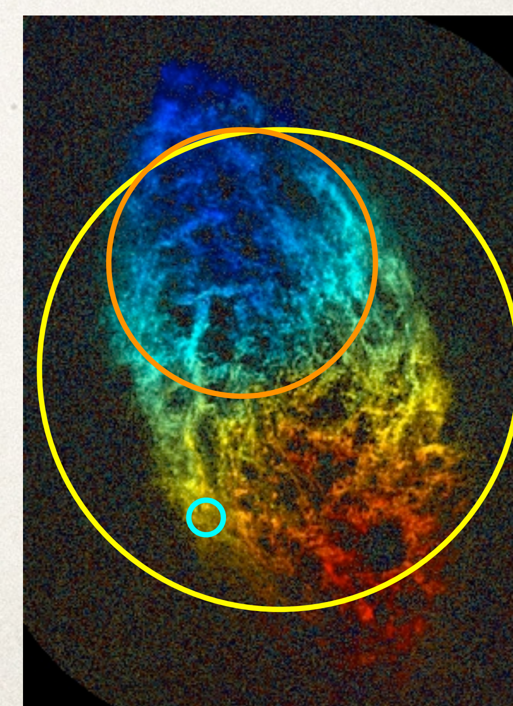
$$F_\lambda d\lambda = F_v dv$$

- The convolution with the velocity distribution becomes "trivial"

$$F_{tot}(v) = \int_{-\infty}^{+\infty} dv'\ \ F_v(v-v')\, f(v')$$

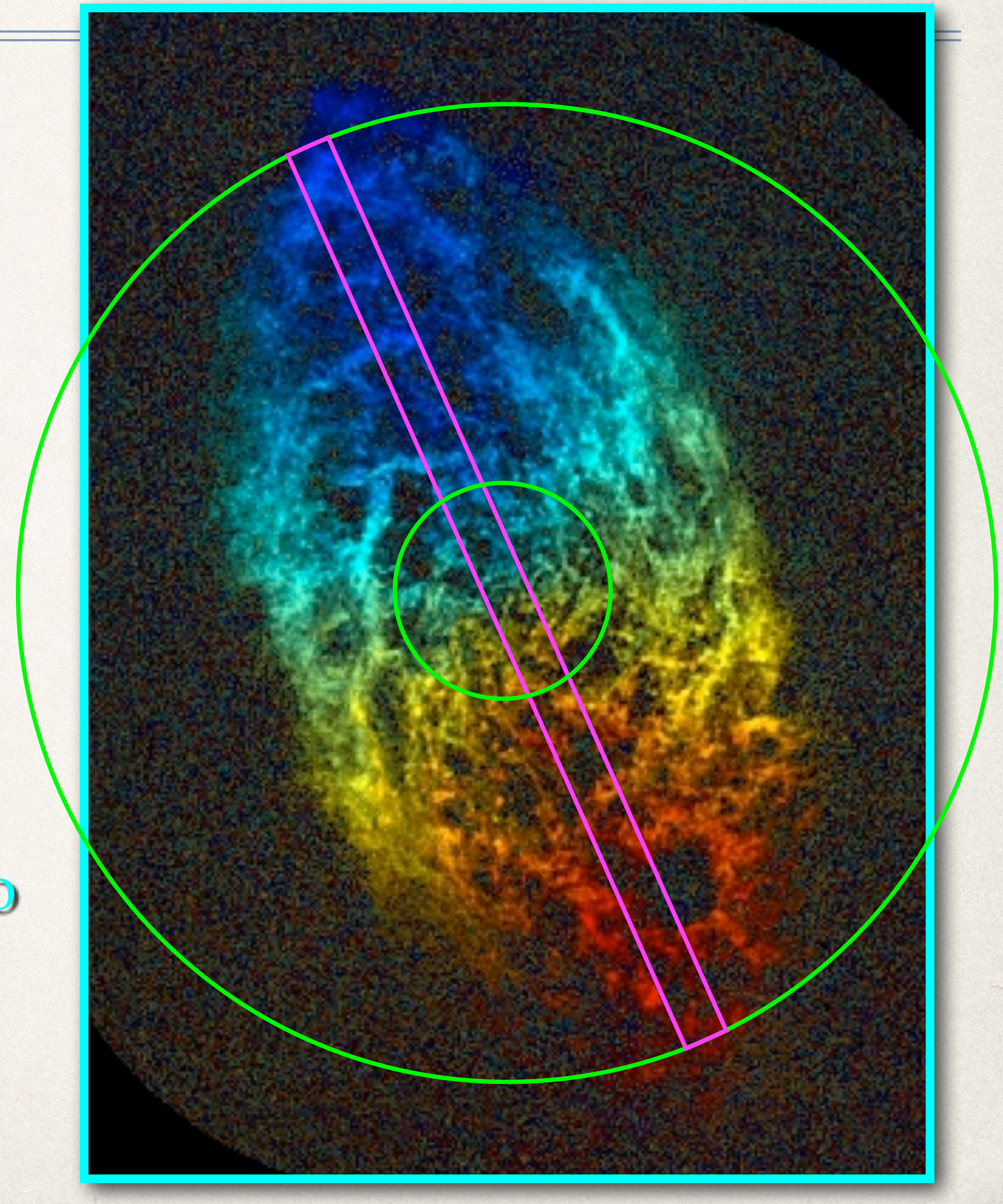


- At 0th order everything is gaussian, but in some cases broadening is not purely gaussian
  - for very strong/high-SNR line observations the profiles are better represented by a Voigt profile: central gaussian (doppler broadened) is convolved with the lorentzian due to natural line-width broadening (uncertainty principle!) (e.g. damping wings!)
  - departures from pure gaussianity are important kinematic diagnostics (h3-h4, skewness and kurtosis)



Kinematics and spatial resolution

- 0D measurements: single beam representative of the entire galaxy
- 1D measurements: long slit spectroscopy
- 2D measurements: integral field spectroscopy, interferometric radio maps



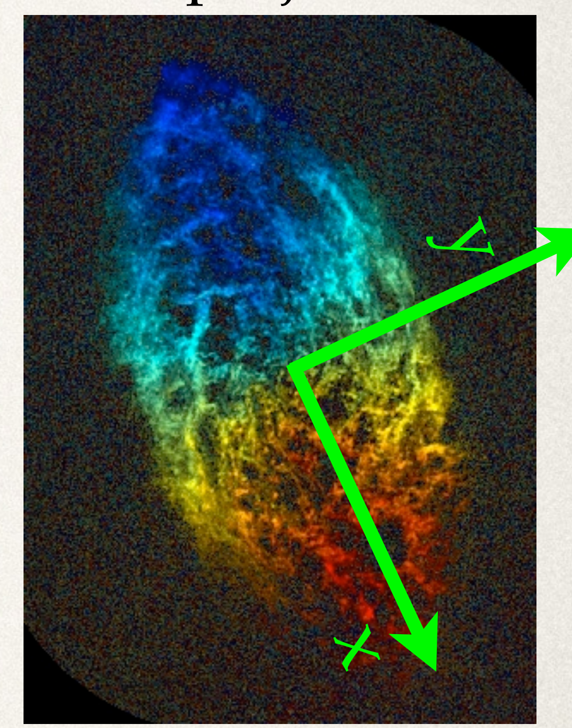
Rotation of disk galaxies

- Best done with (narrow and) strong emission lines: Hα, Hβ, HI-21cm…, but also done with stellar absorption lines for gas poor/passive galaxies
- Measure only the l.o.s. component → tangential (rotational) velocity from de-projection
- Assume axis-symmetry

$$v_{los}(r) = v_{sys} + v_t(r)\sin(i)\cos(\phi)$$

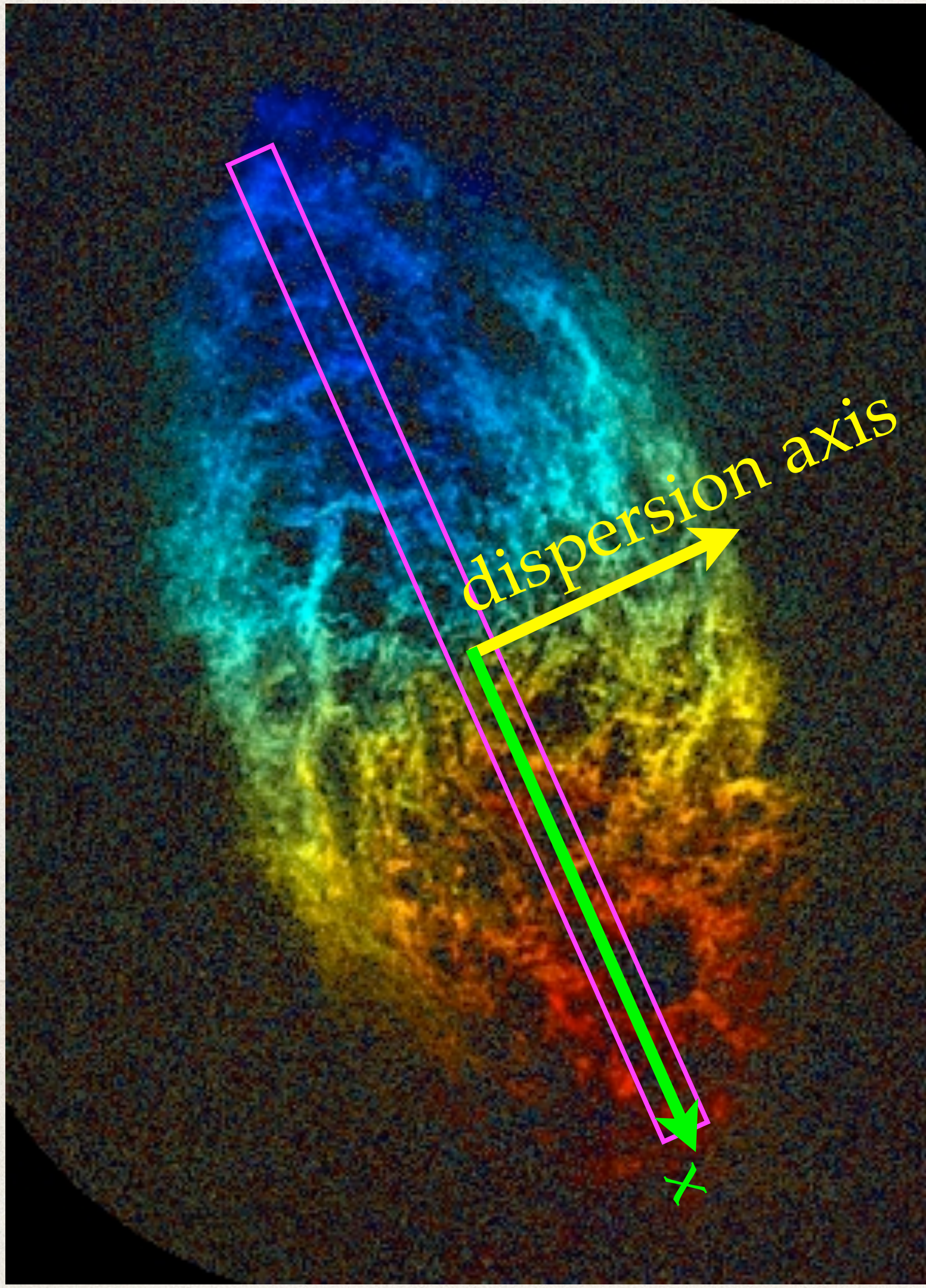
$$i = \arctan\frac{b}{a}$$

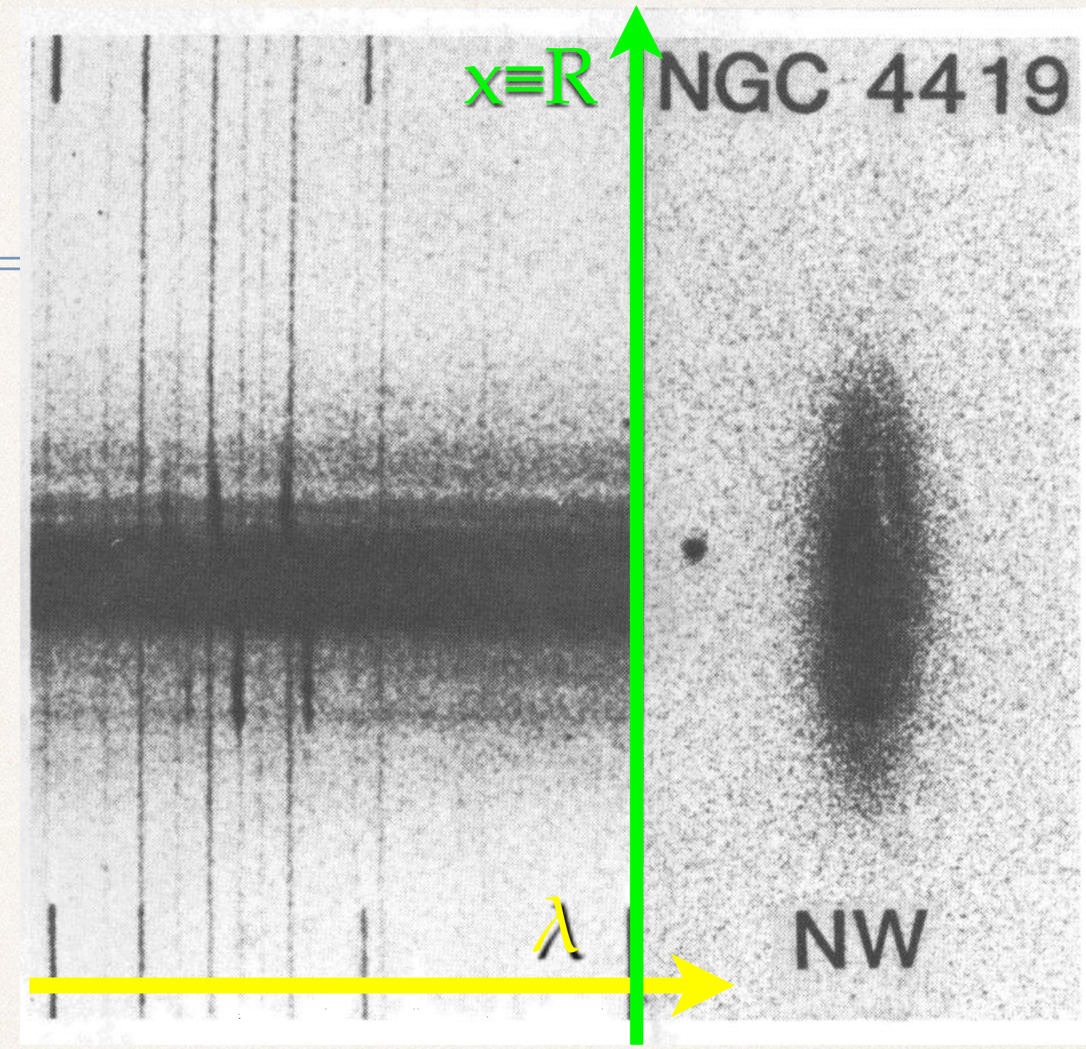
$$\phi = \arctan\left(\frac{y}{\cos(i)}/x\right), \quad r = \sqrt{\left(\frac{y}{\cos(i)}\right)^2 + x^2}$$



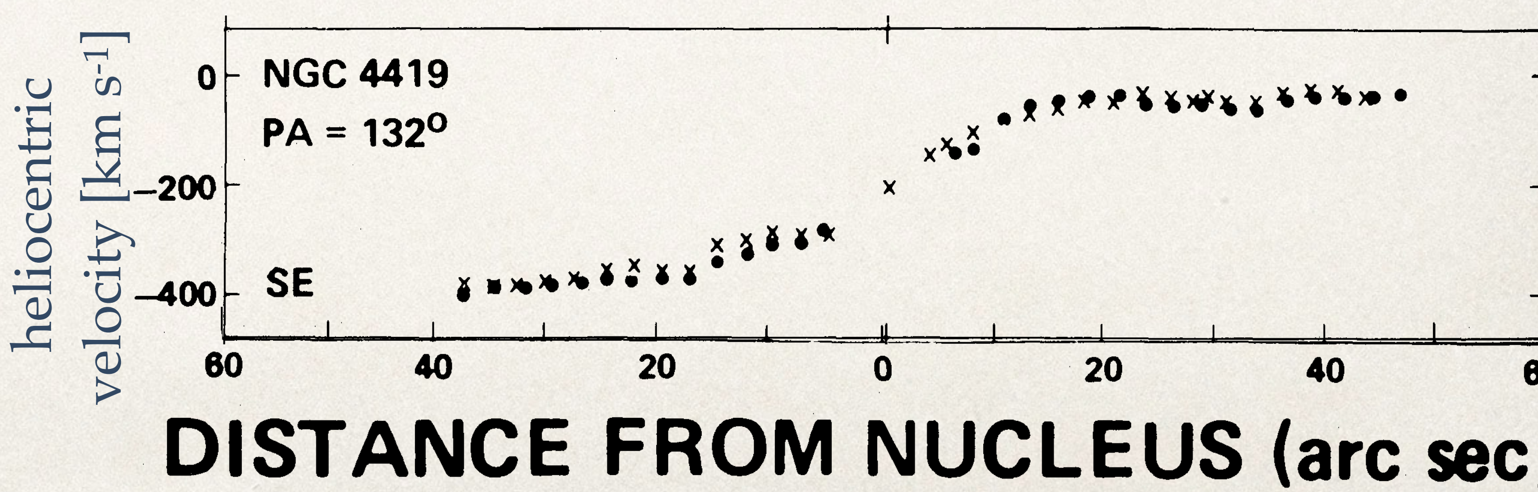
- Inclinations (and PA) derived from images can be quite uncertain and different from those derived from kinematics: bars, oval disks, (asymmetric) spiral arms can bias the estimates!

Long-slit rotation curves





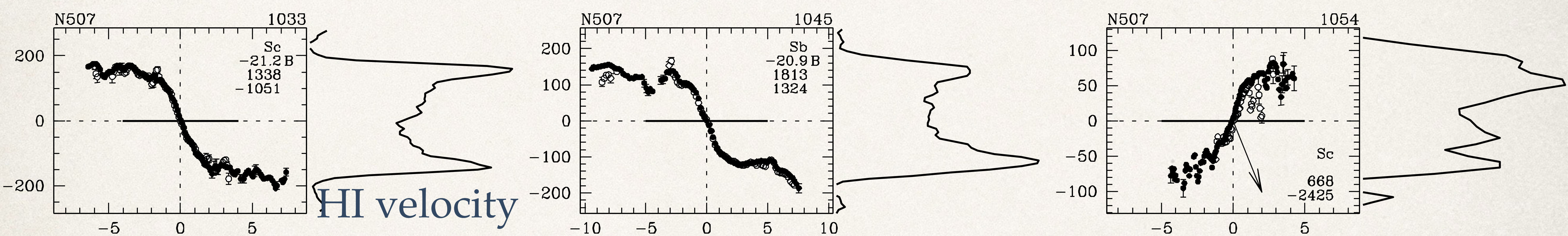
Rubin et al. (1985)



Single-beam measurement

- Velocity profile in the integral of the (covered part of the) galaxy

- Must assume some spatial line intensity profile to interpret!



HI velocity profile

Hα+NII rotation curve

Vogt et al. (2004)

- For classical rotation curves with a flat outer profile, it is easy to derive the maximum rotational velocity ~corresponding to the asymptotic value, i.e. the break in the HI profiles

Rotation curves

- The amplitude and flattening of galaxy rotation curves is inconsistent with pure baryonic disks (well known since pioneering works of Vera Rubin ~50 years ago)

- Systematic variations of the shape of the rotation curve with galaxy luminosity (relevant also to test DM properties and its coupling to baryons): the Universal Rotation Curve (Persic & Salucci 1991)

Persic, Salucci & Stel (1996)

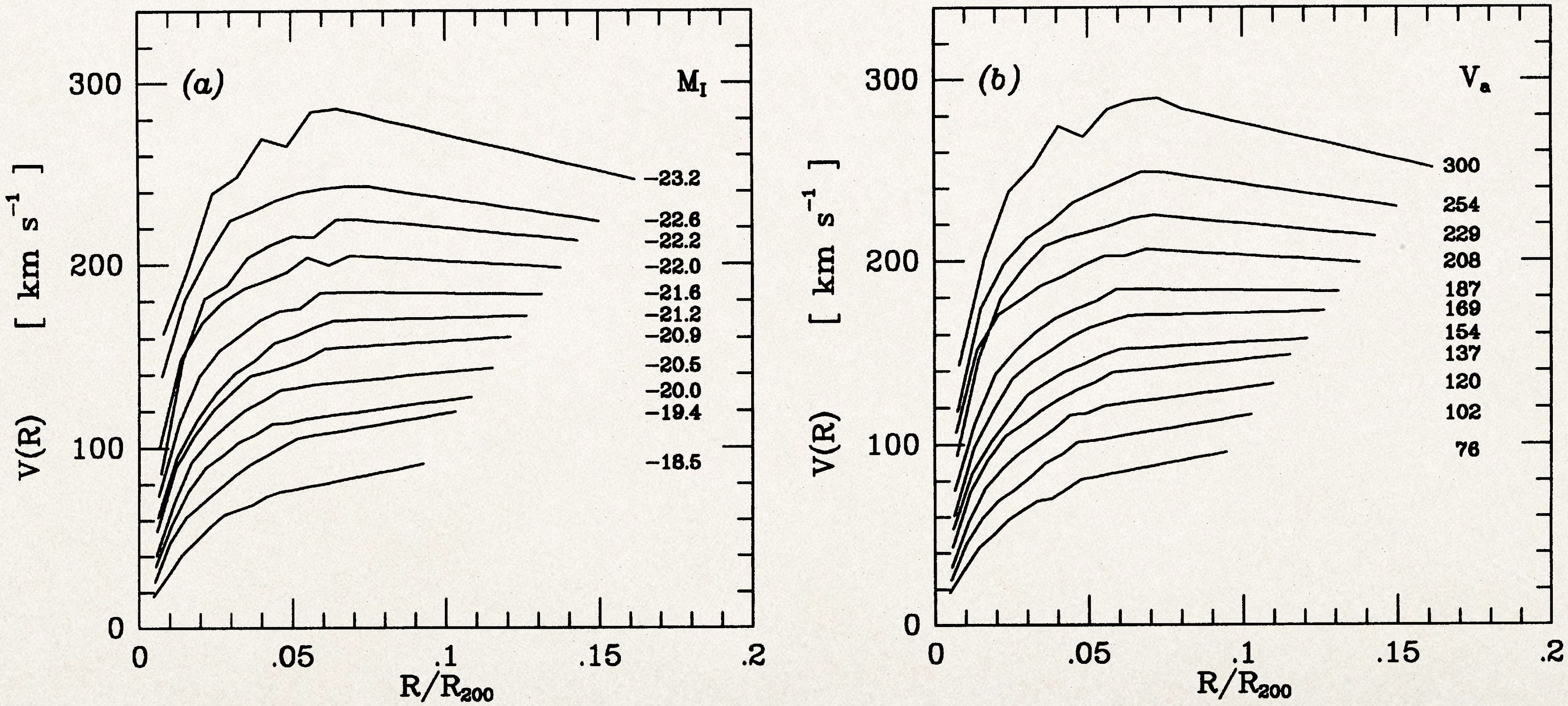


Figure 7. The universal rotation curve of spiral galaxies at different luminosities and velocities [panels (a) and (b), respectively]. Radii are in units of R_{200}, the radius encompassing a mean halo overdensity of 200, which represents the characteristic scalelength of the DM distribution.

The Tully-Fisher relation

- Tight scaling relation between Luminosity and circular velocity discovered by Tully & Fisher (1977)
- Dimensional interpretation

$$\left.\begin{array}{l} \dfrac{v^2}{R} = \dfrac{GM}{R^2} \\ L = M\left(\dfrac{M}{L}\right)^{-1} \\ L \approx\propto R^2 \end{array}\right\} L \propto v^4$$

- Actual slope is generally shallower, yet quite uncertain, ranging from 2.4 to almost 4 (see Pizagno+07)
- Key relation in distance ladder

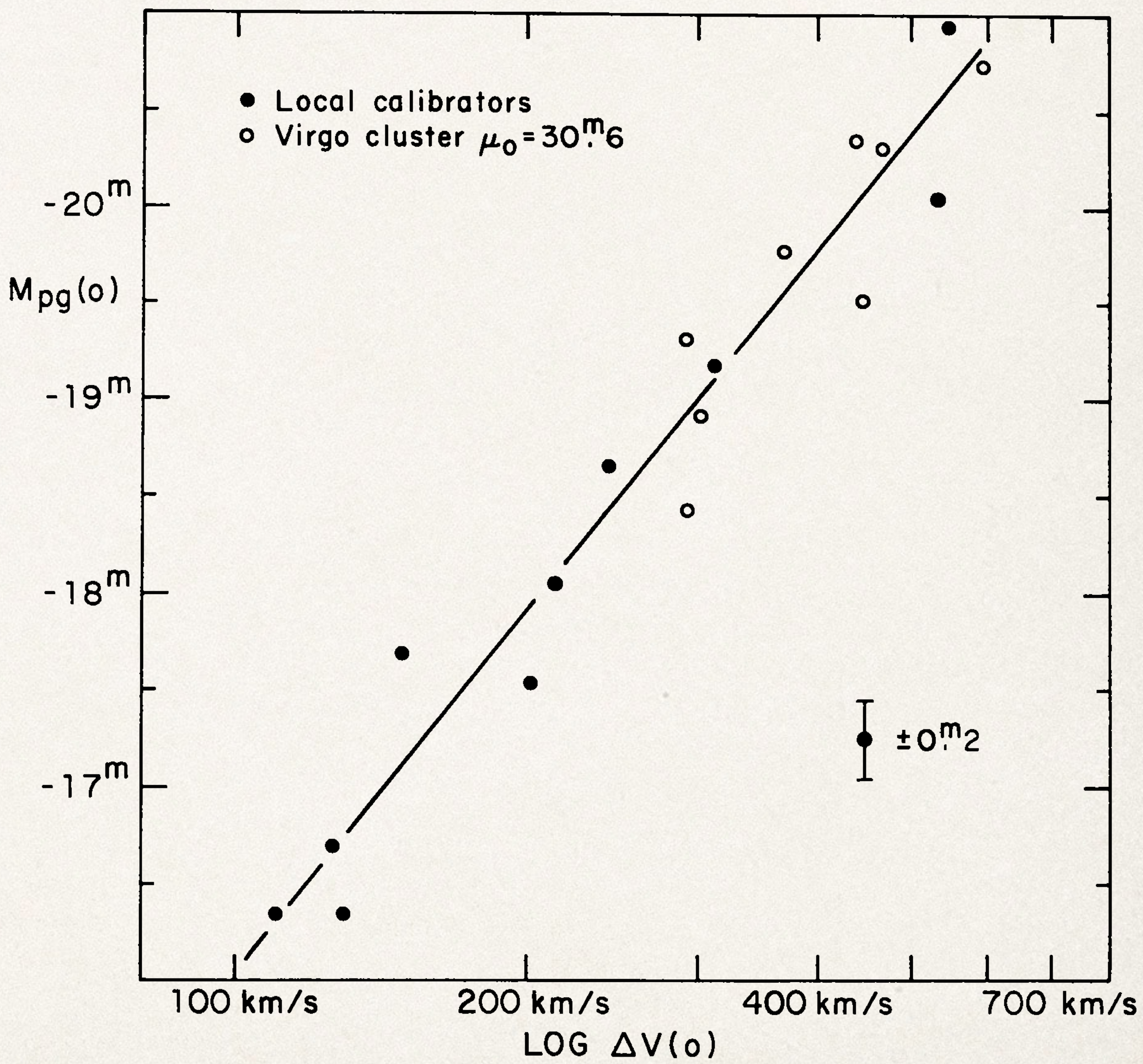
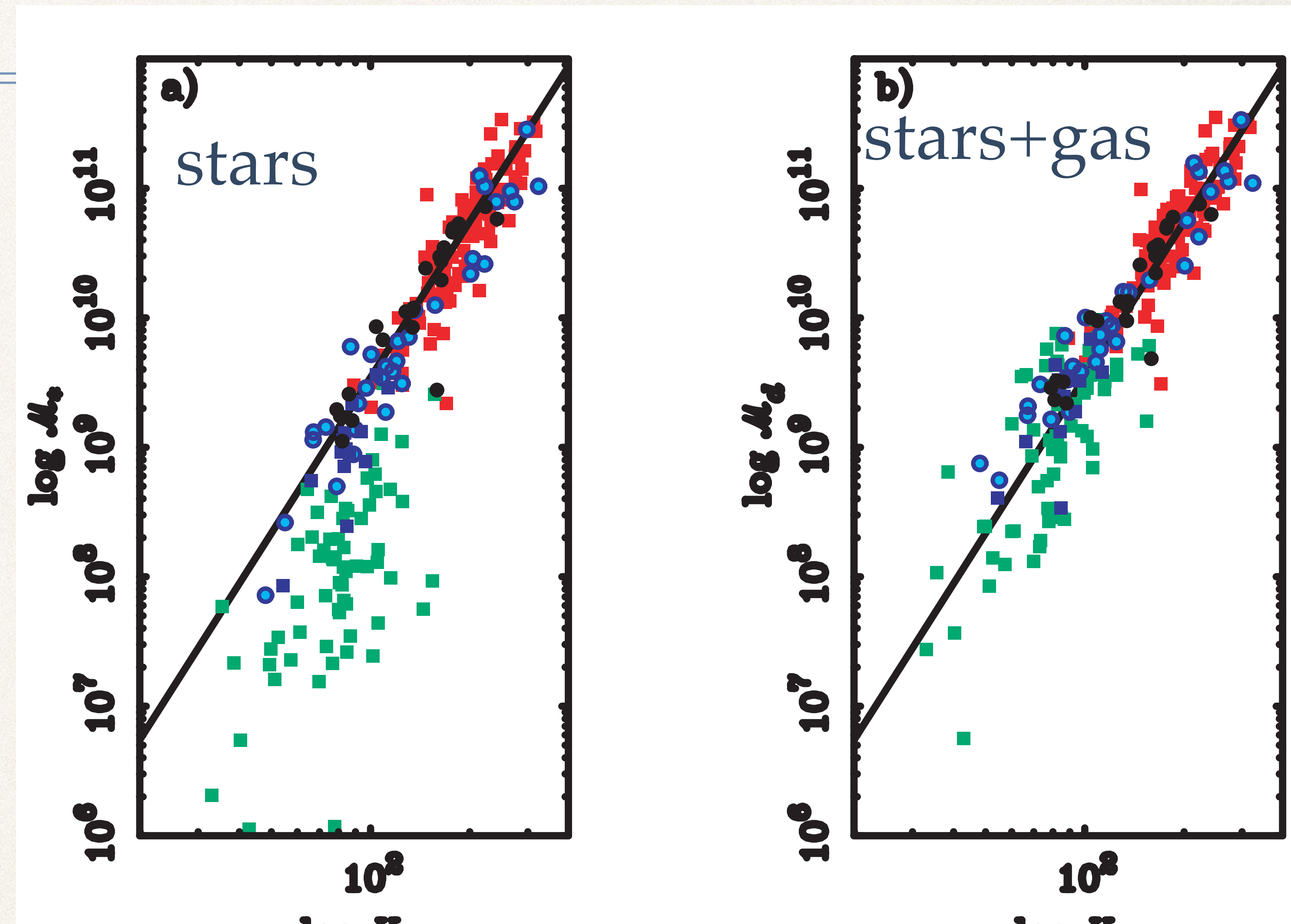


Fig. 5 (a) Absolute magnitude – global profile width relation produced by overlaying Figure 3 on Figure 1, adjusting Figure 3 vertically to arrive at a best visual fit with a distance modulus of $\mu_0 = 30^m\!.6 \pm 0^m\!.2$

Baryonic TF

- Why departure from simplistic expectation?
  - systematic variations in M/L, both baryonic and dark: try to use baryonic mass?
  - systematic variation in the mass and velocity profiles (related: what exactly is the radius in those equations??)



McGaugh et al. (2000)

total baryonic mass in the disk $M_d = \mathcal{A} V_c^b$

$\log \mathcal{A} = 1.57 \pm 0.25$ and $b = 3.98 \pm 0.12$.

Mass decomposition in disk galaxies from rotation curves

- Most spiral/disk galaxies have flat rotation curves for $r \to \infty$ (as traced by HI, which can go out several disk scalelengths >10)
  - pure rotation implies that the gravitational potential is provided by a mass distribution $\varrho \propto R^{-2}$ for large R: DM halo!
- Gravitational potential is additive: total is given by the sum of all components, disk, bulge (if any) and halo ⇒

$$V_{\mathrm{circ}}(R) = \left[V^2_{\mathrm{disk}}(R) + V^2_{\mathrm{bulge}}(R) + V^2_{\mathrm{halo}}(R)\right]^{1/2}$$

  - Decomposition usually not unique, rather degenerate
- Possible complications from non-zero dispersion and deviation from pure rotational dynamics

Dark halos

* Kinematic observations show

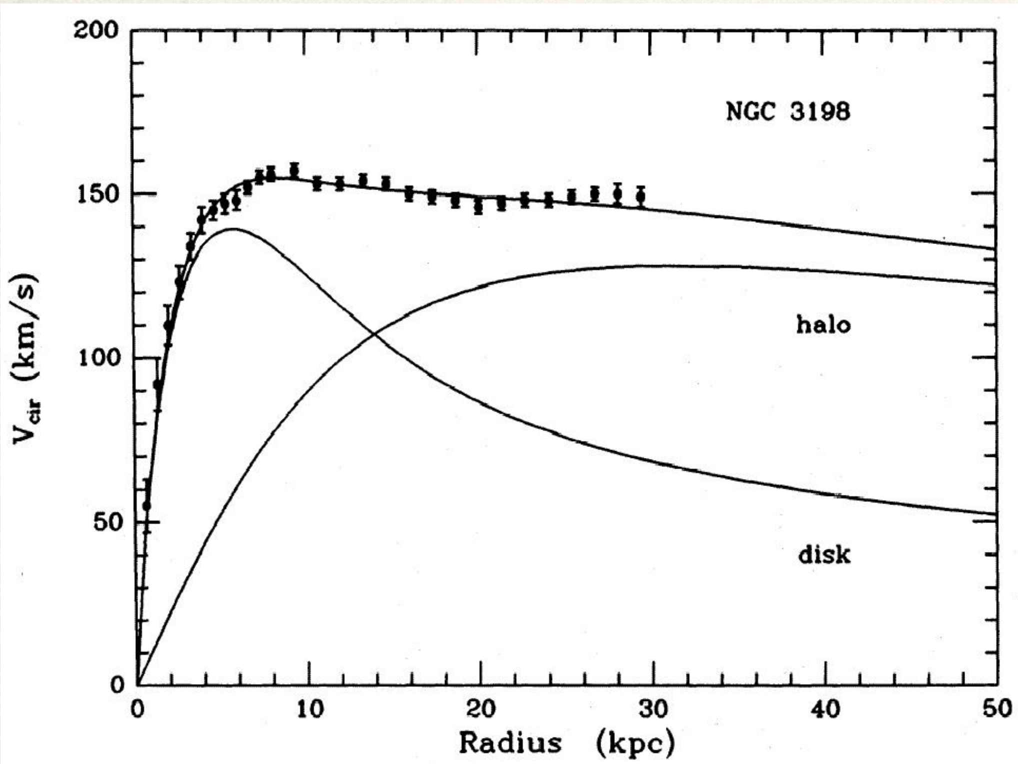
$$V_{circ}(R) \xrightarrow[R\to\infty]{} const$$

$$V_{circ}(R) = \sqrt{\frac{GM(<R)}{R}} = \sqrt{\frac{G}{R}\int_0^R 4\pi r^2 dr\,\rho(r)} \Rightarrow \int_0^R r^2 dr\,\rho(r) \sim R \Rightarrow \rho(r) \sim r^{-2}$$

* Baryonic matter however declines much more steeply, typically as exponential
* Need to introduce an unseen (from electromagnetic radiation) component: the dark matter halo
* Some popular DM halo profiles:
  * Isothermal $\rho(r) = \rho_o \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1}$
  * Navarro, Frenk & White (1996) $\rho(r) = \frac{\rho_{crit}\delta_c}{\left(\frac{r}{r_s}\right)\left(1+\frac{r}{r_s}\right)^2}$
  * Einasto (Merrit et al. 2006) $\rho(r) = \rho_e Exp\left[-d_n\left(\left(\frac{r}{r_c}\right)^{\frac{1}{n}} - 1\right)\right]$ [note it declines exponentially!]

Example of rotation curve decomposition: the bulgeless galaxy NGC 3198

van Albada et al. (1985), slides from Piet van der Kruit's lecture



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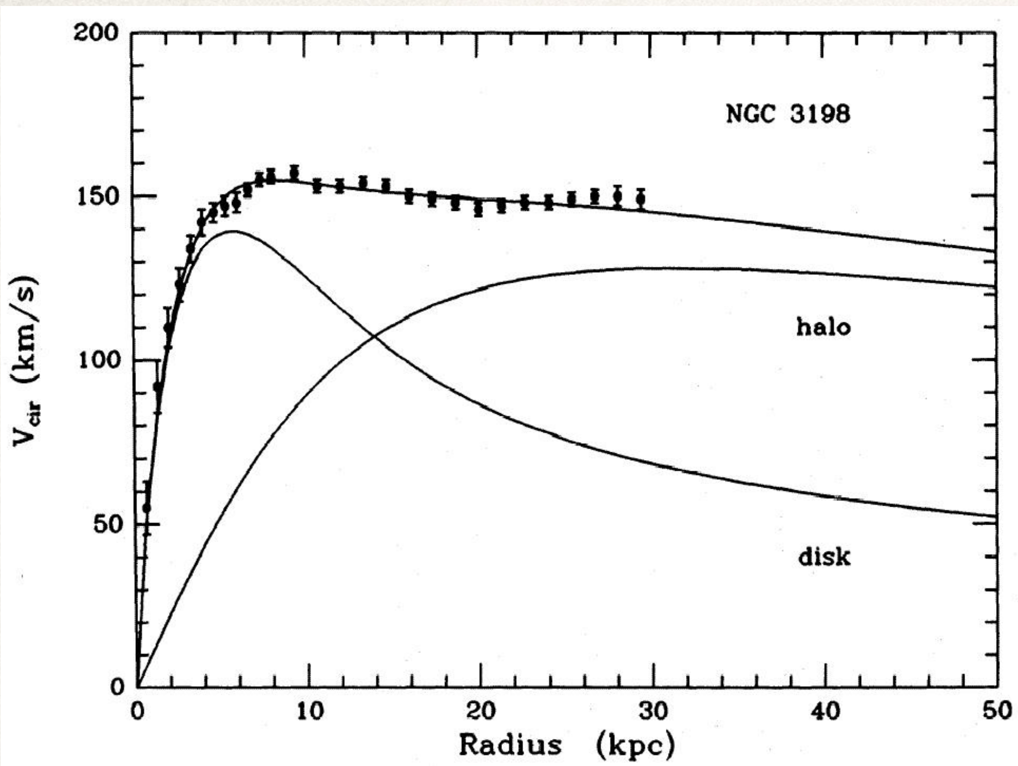

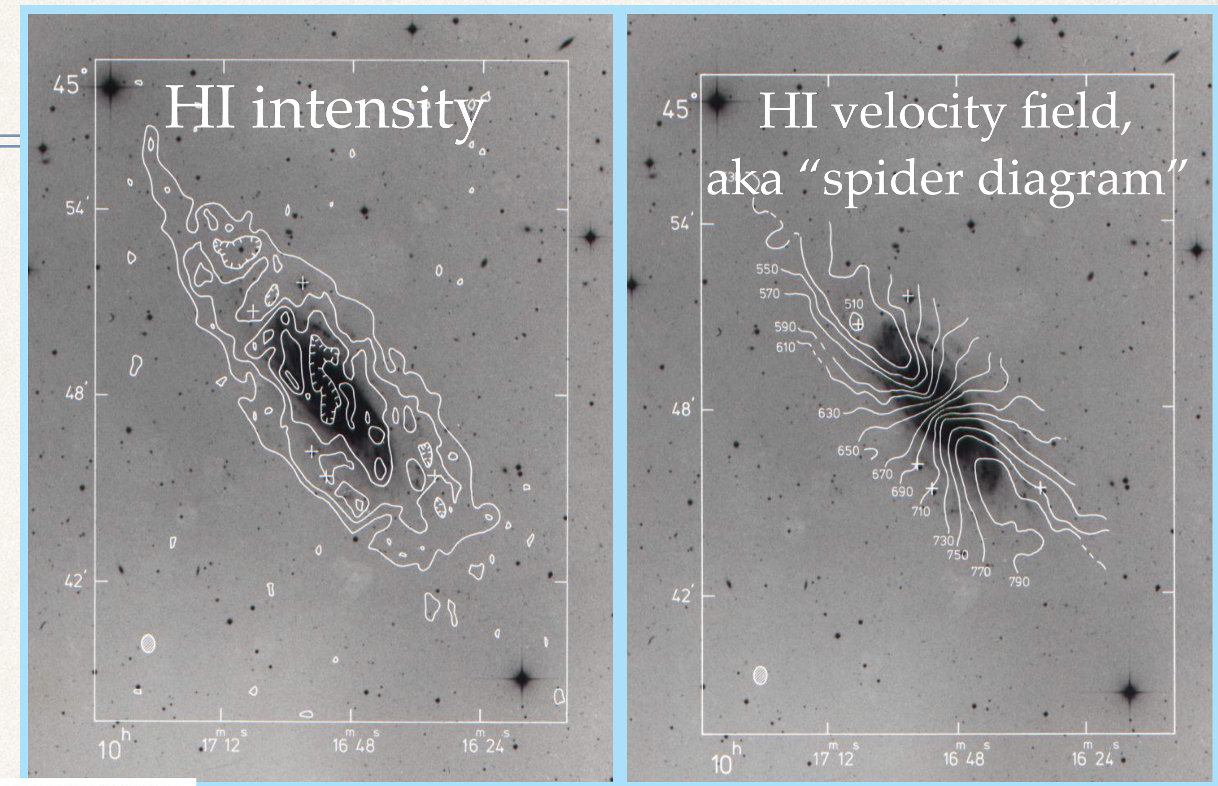

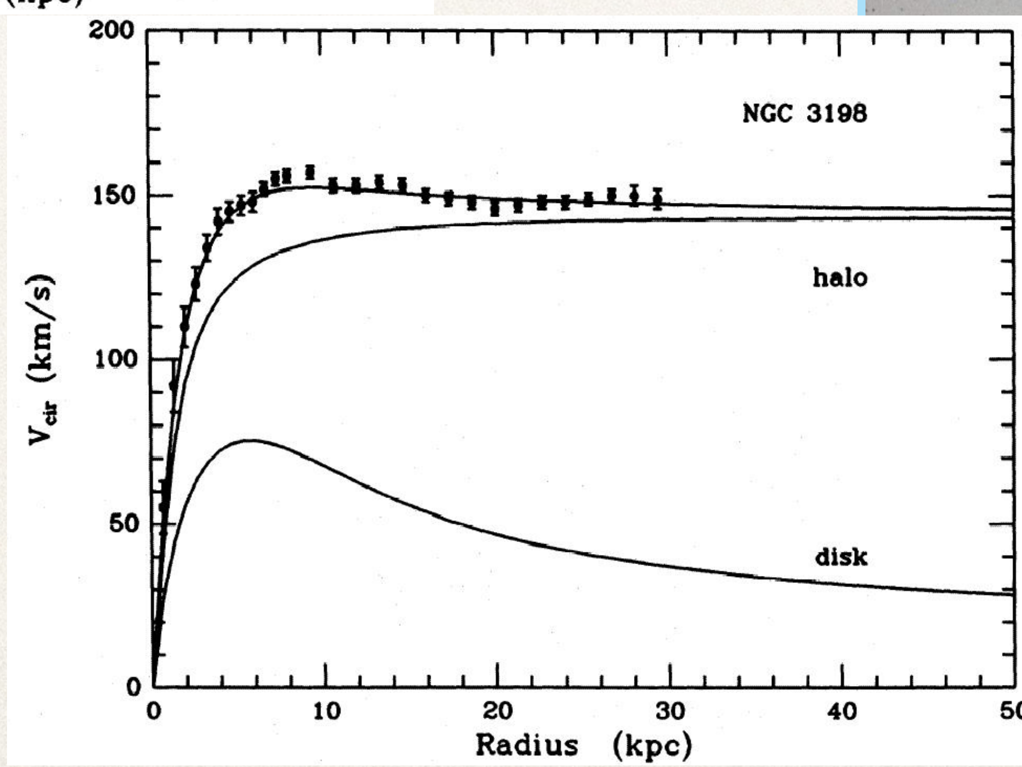

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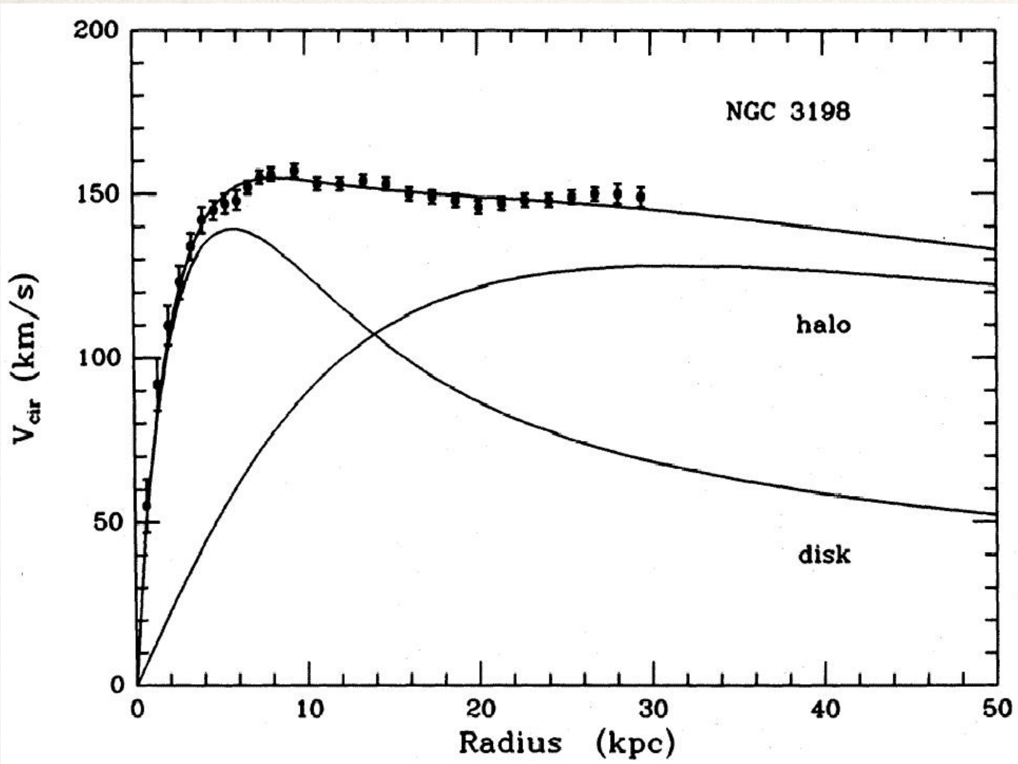

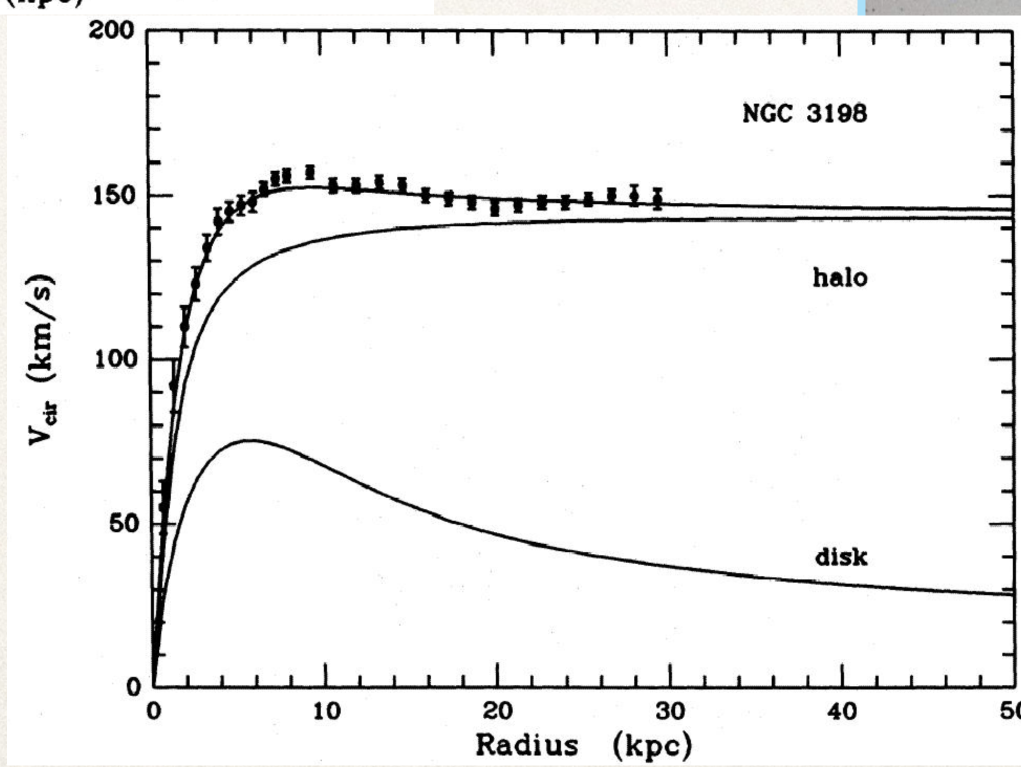

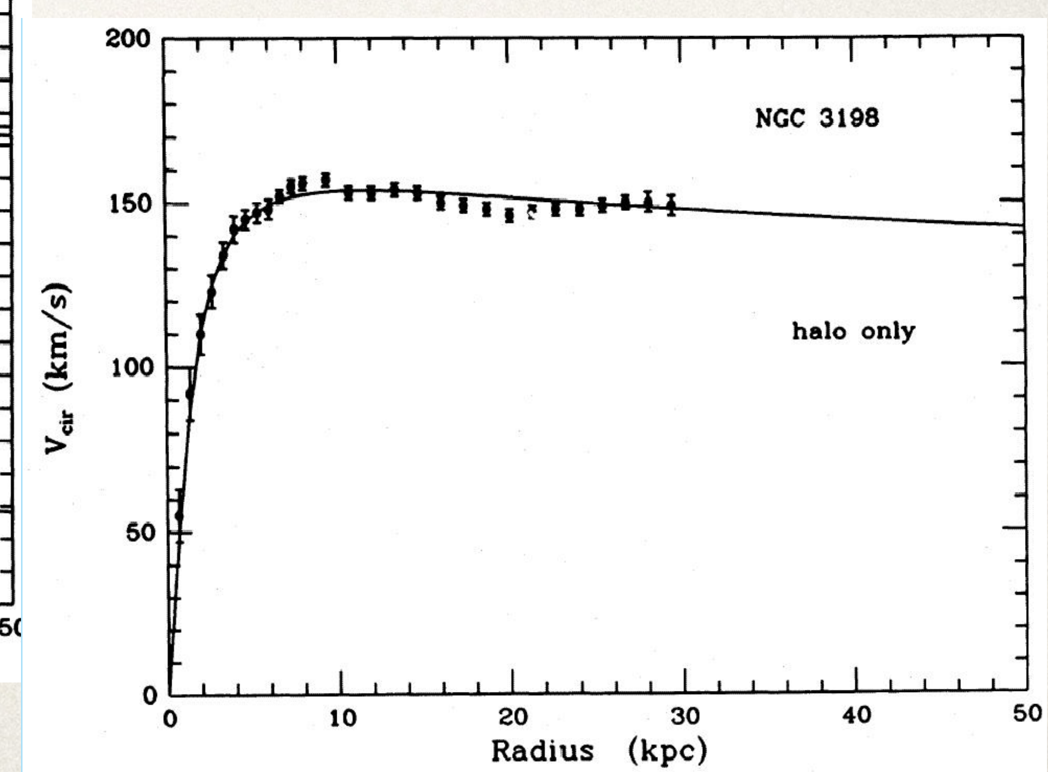

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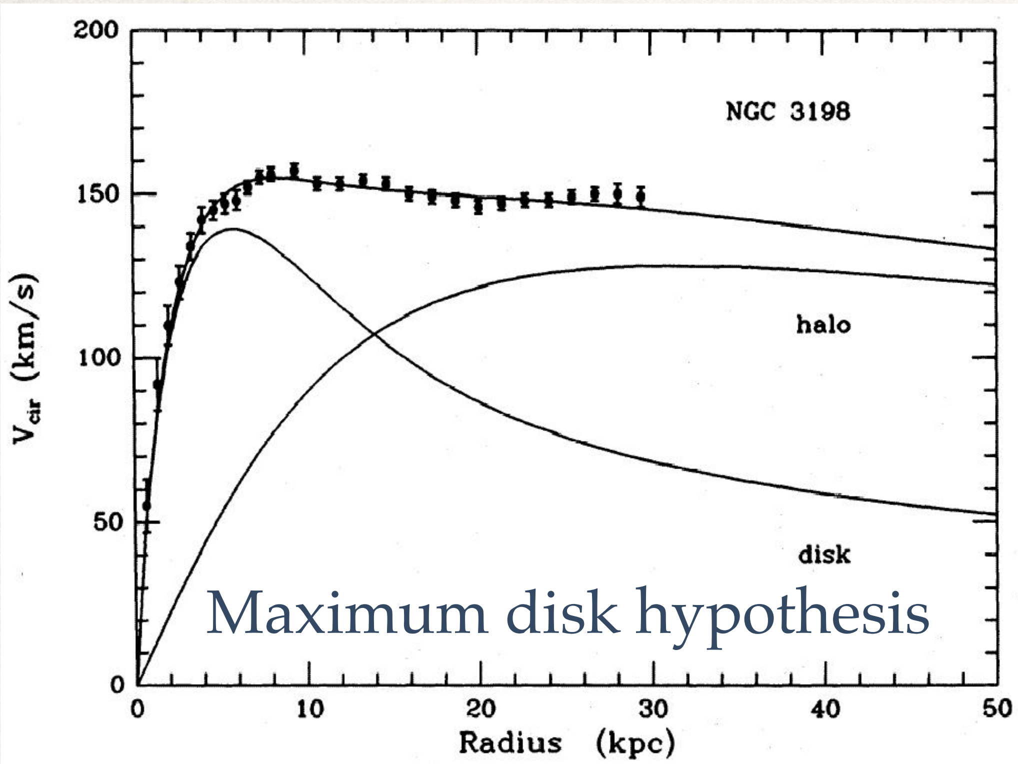
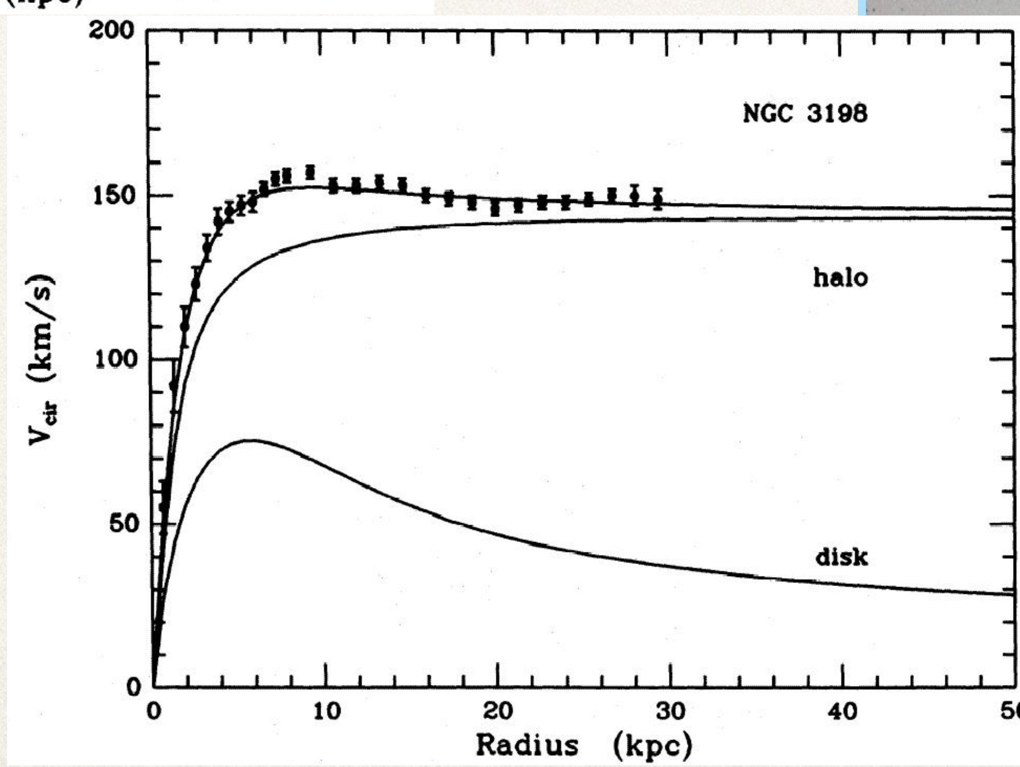
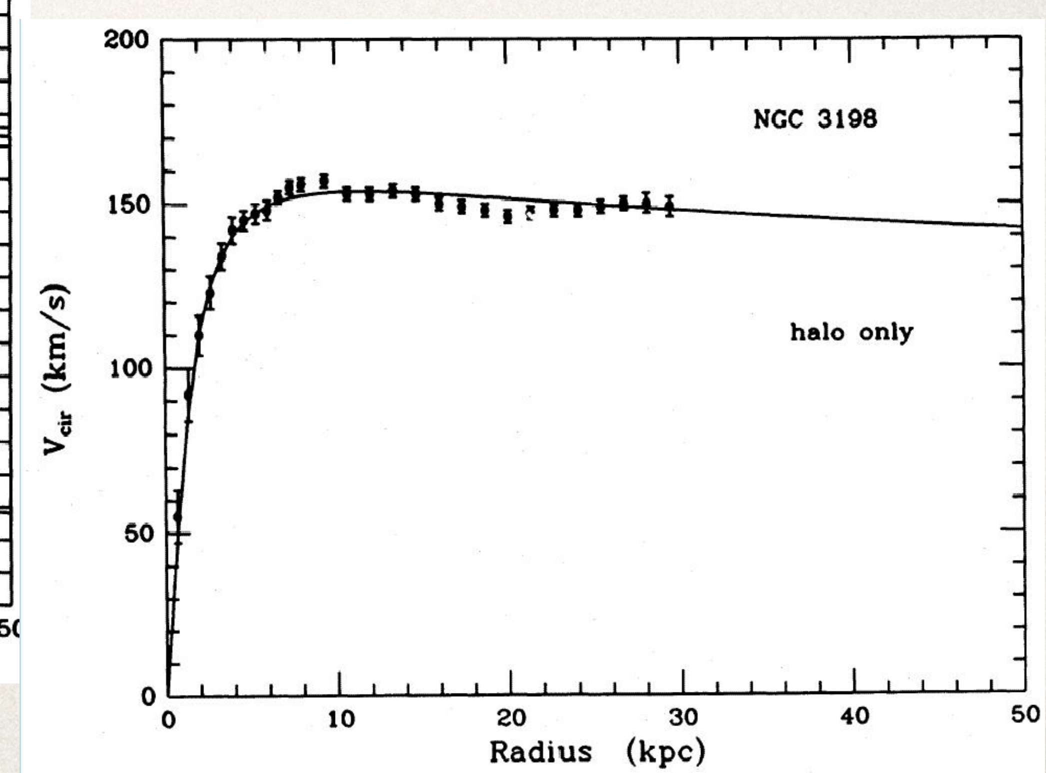






The maximum disk hypothesis

- Put as much mass as possible in the disk, by rescaling the surface brightness profile by a suitably large M/L (constant!)
  - do not overshoot the measured rotation curve!
- check consistency with M/L from stellar estimates
- helps to explain wiggles and truncations reflected from the SB profile in the rotation curves
- Recent results from Verheijen and collaborators show that vertical dispersion in disks is **inconsistent** with the large mass surface density implied by MD

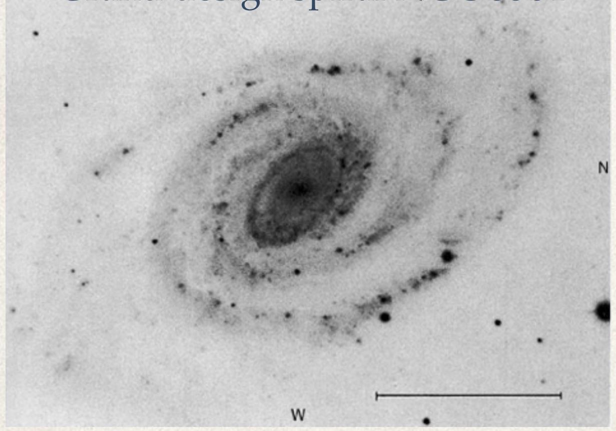
Disk dynamics and spiral structure

(Binney & Tremaine, chap. 6)

Disks and spiral structure

- Key morphological property
  - determines largely the Hubble type
  - related to star formation
- Different kinds of spirals hint at different origins

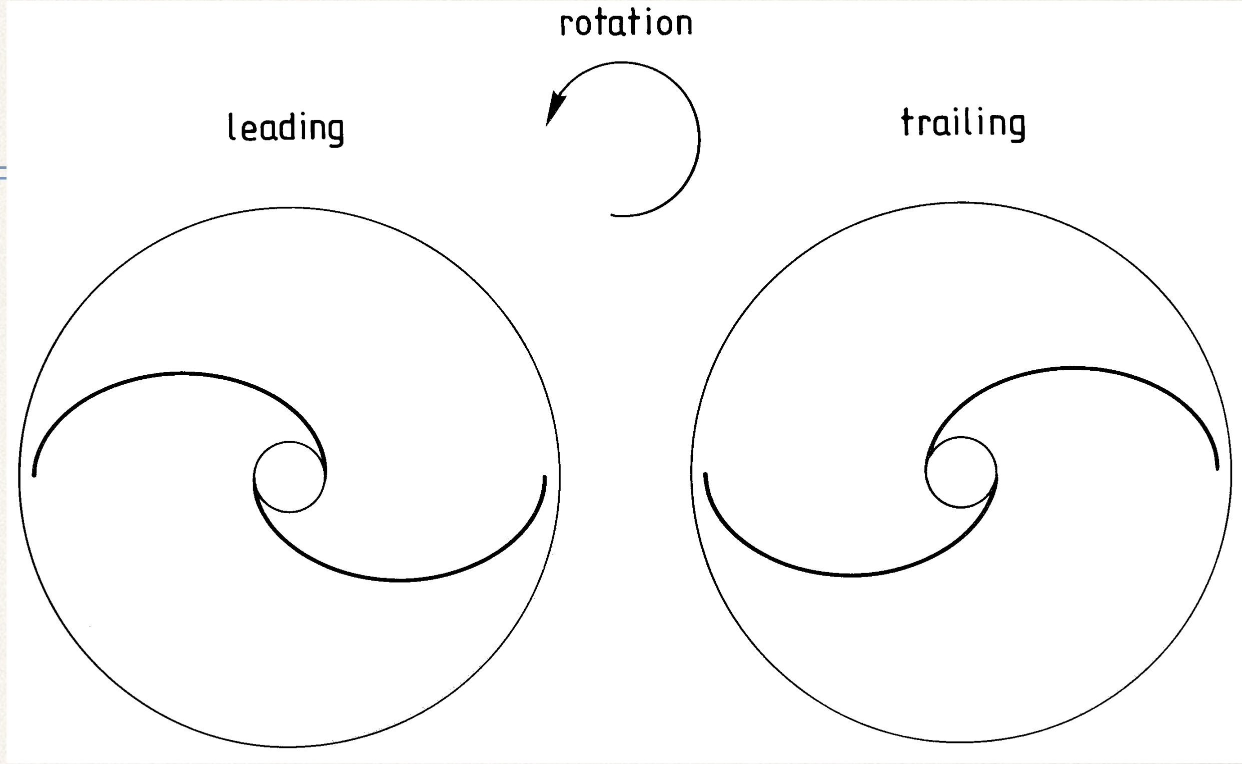

Tidally disturbed spiral M51


Grand design spiral NGC 5364

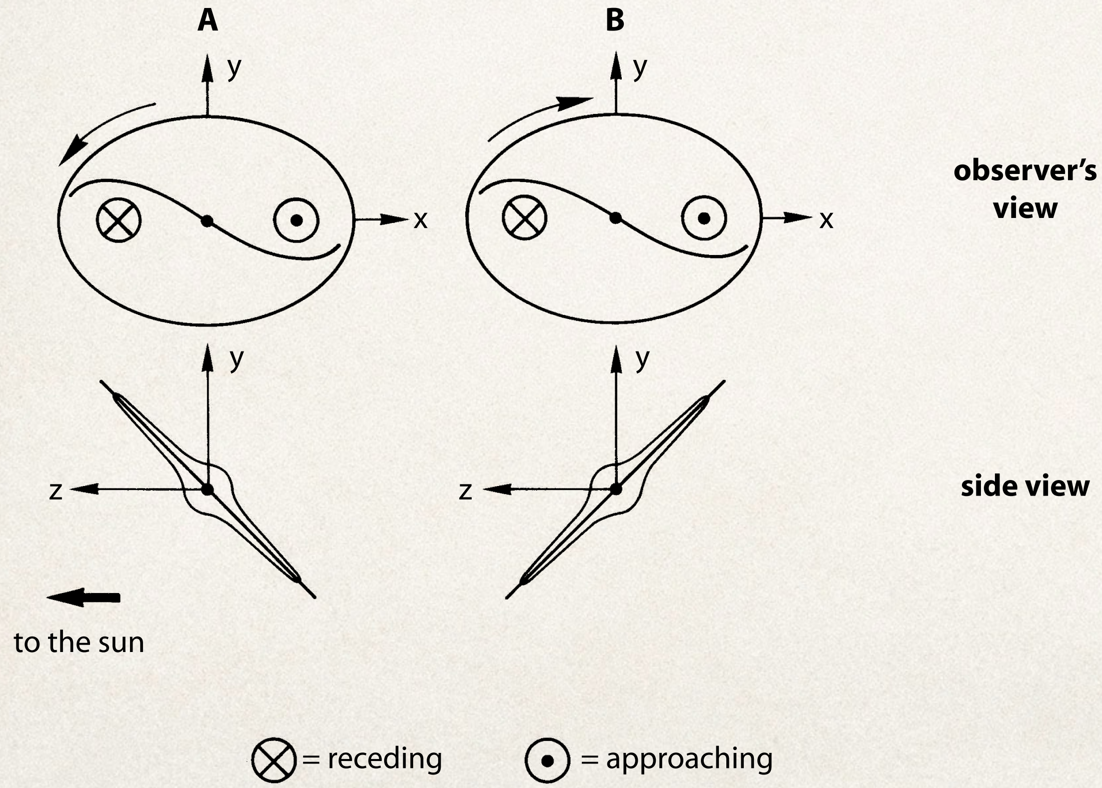

Flocculent spiral M33

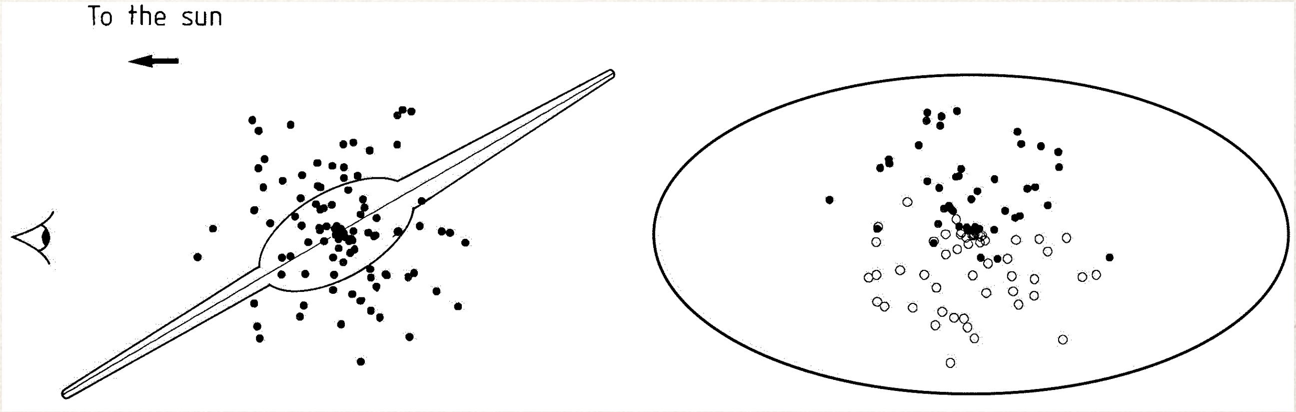
Barred spiral NGC1300

Fundamentals of spiral structure



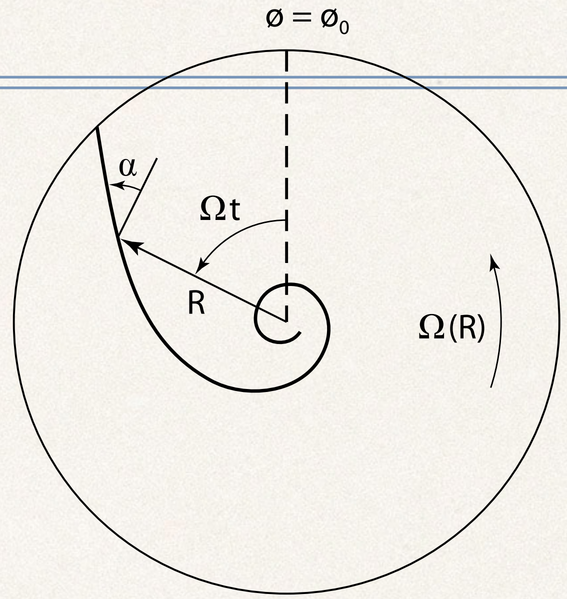
- Leading and trailing arms: most undisturbed grand design spirals are trailing
- Impossible to tell unless one can determine which side is the near one (eg via distribution of globular clusters)

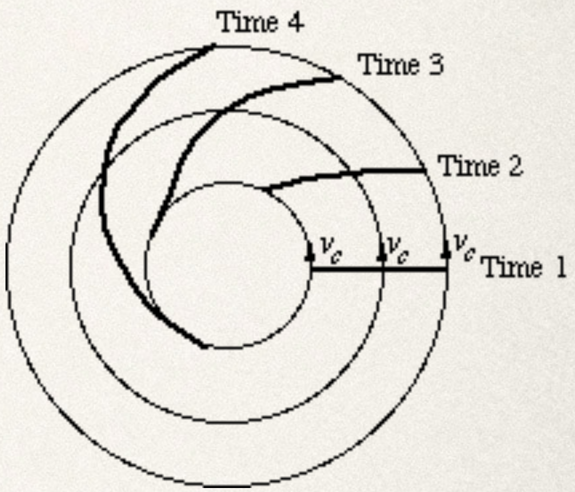


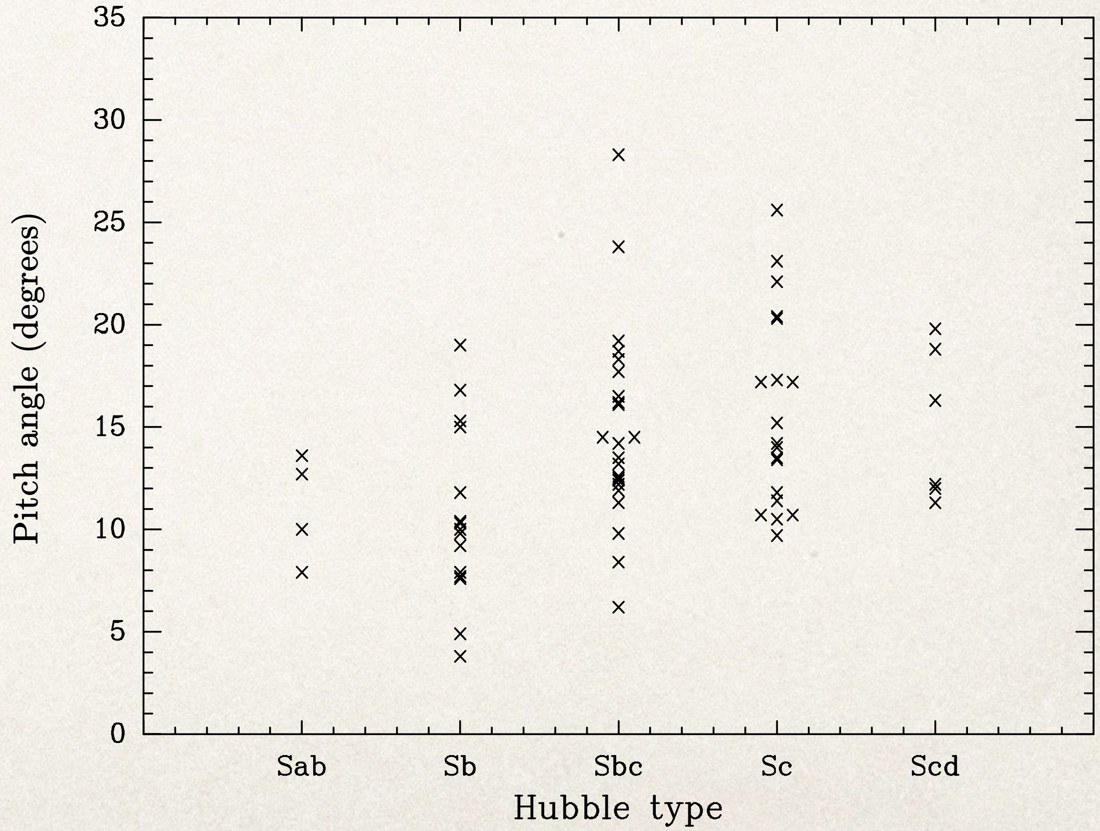


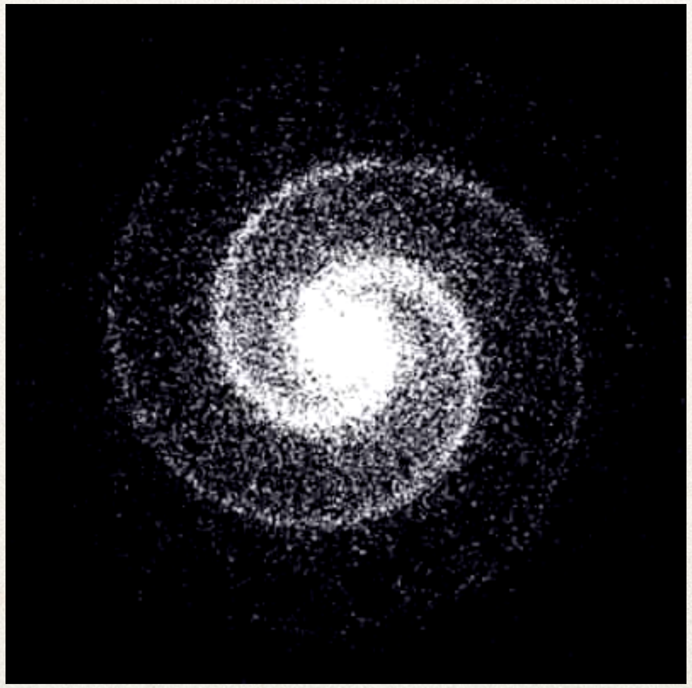
Fundamental of spiral structure

- Pitch angle α
- If spirals were just originally linear structure wound up by the differential rotation, over several Gyr the pitch angle would be <1 deg and arms way too tightly wound









from wikipedia

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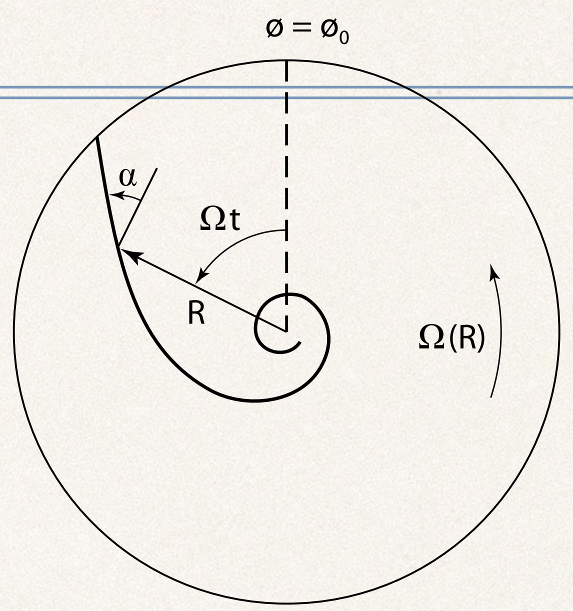
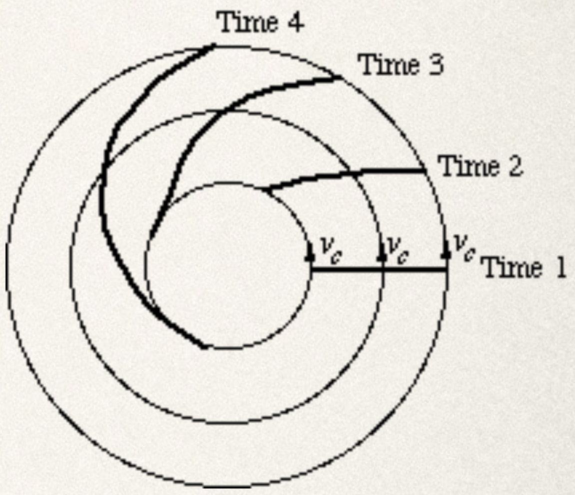
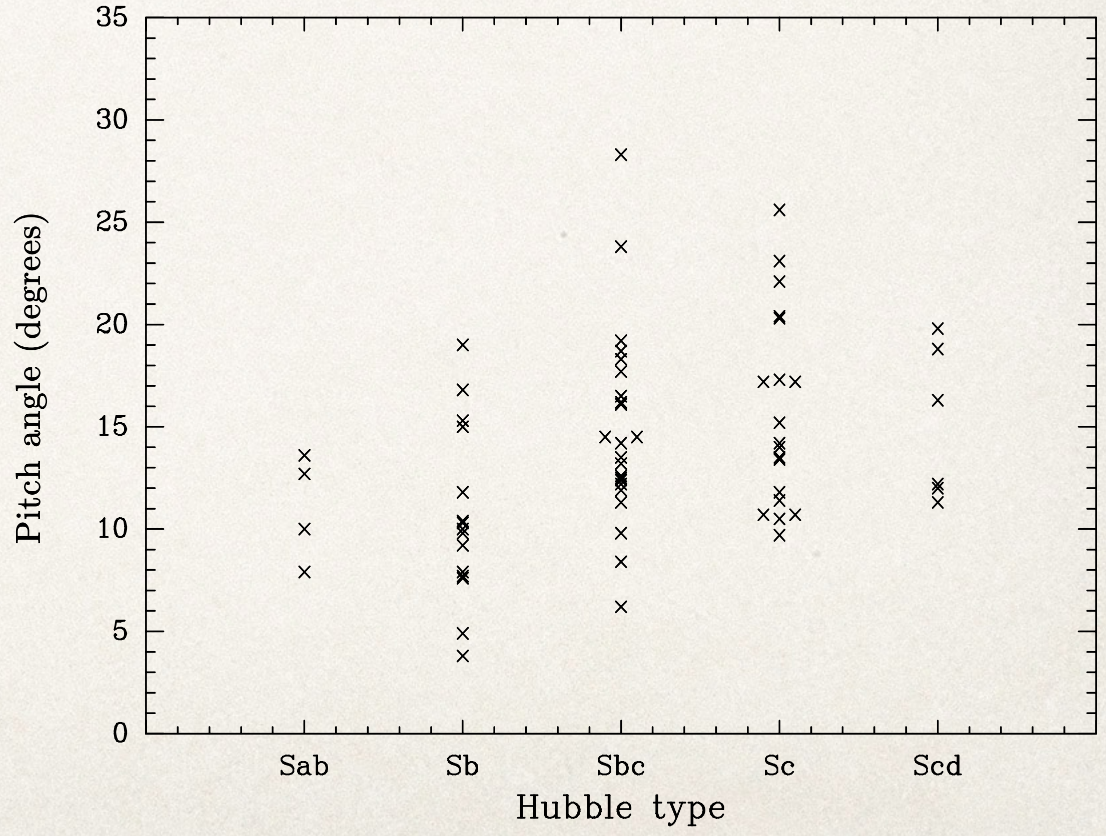
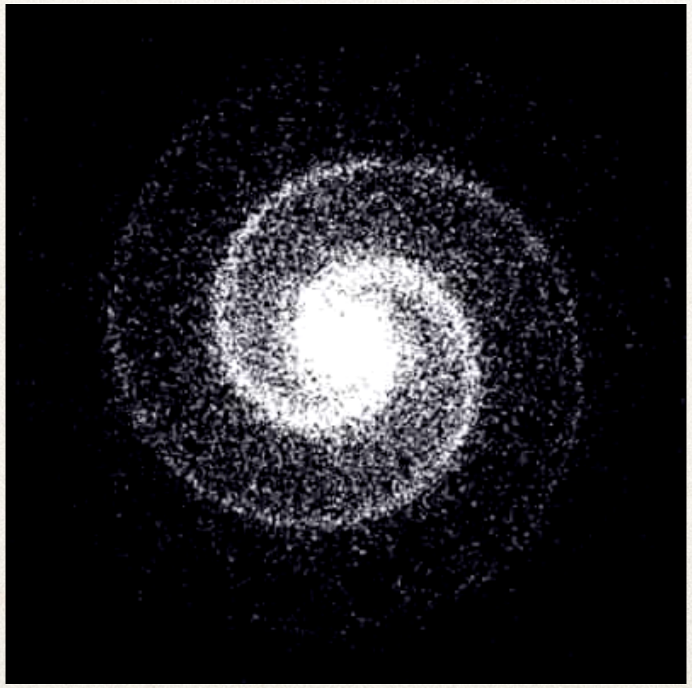








from wikipedia

Resonances in perturbative regime

- Natural frequencies
  - circular orbit Ω
  - epicyclic frequency κ
- In general orbits are rosettae

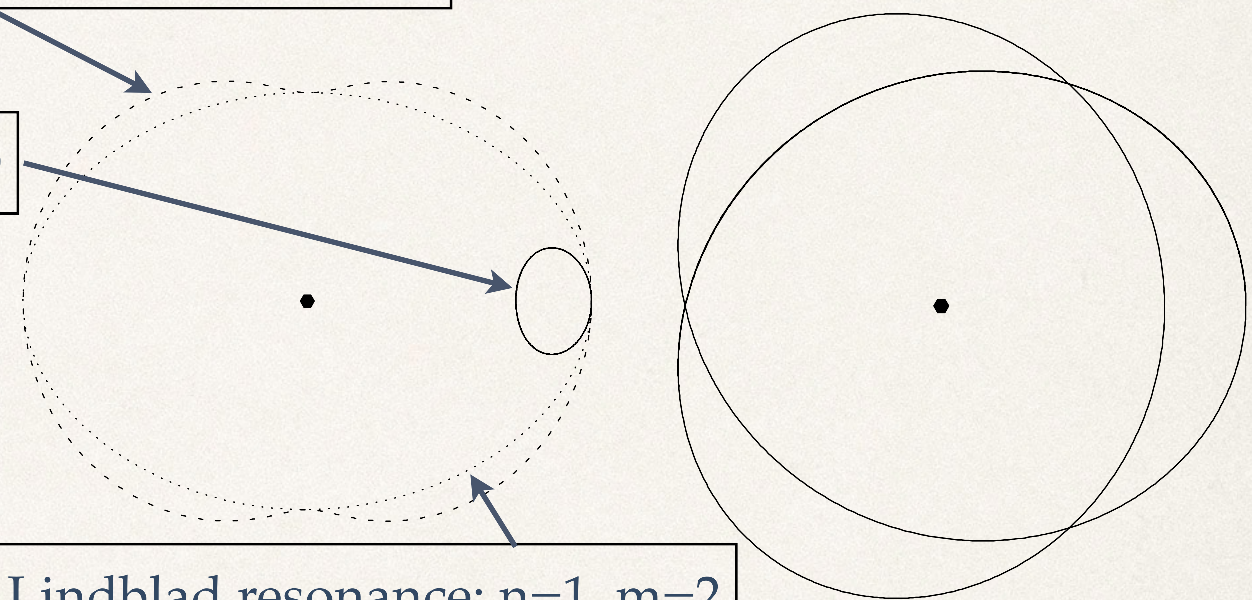


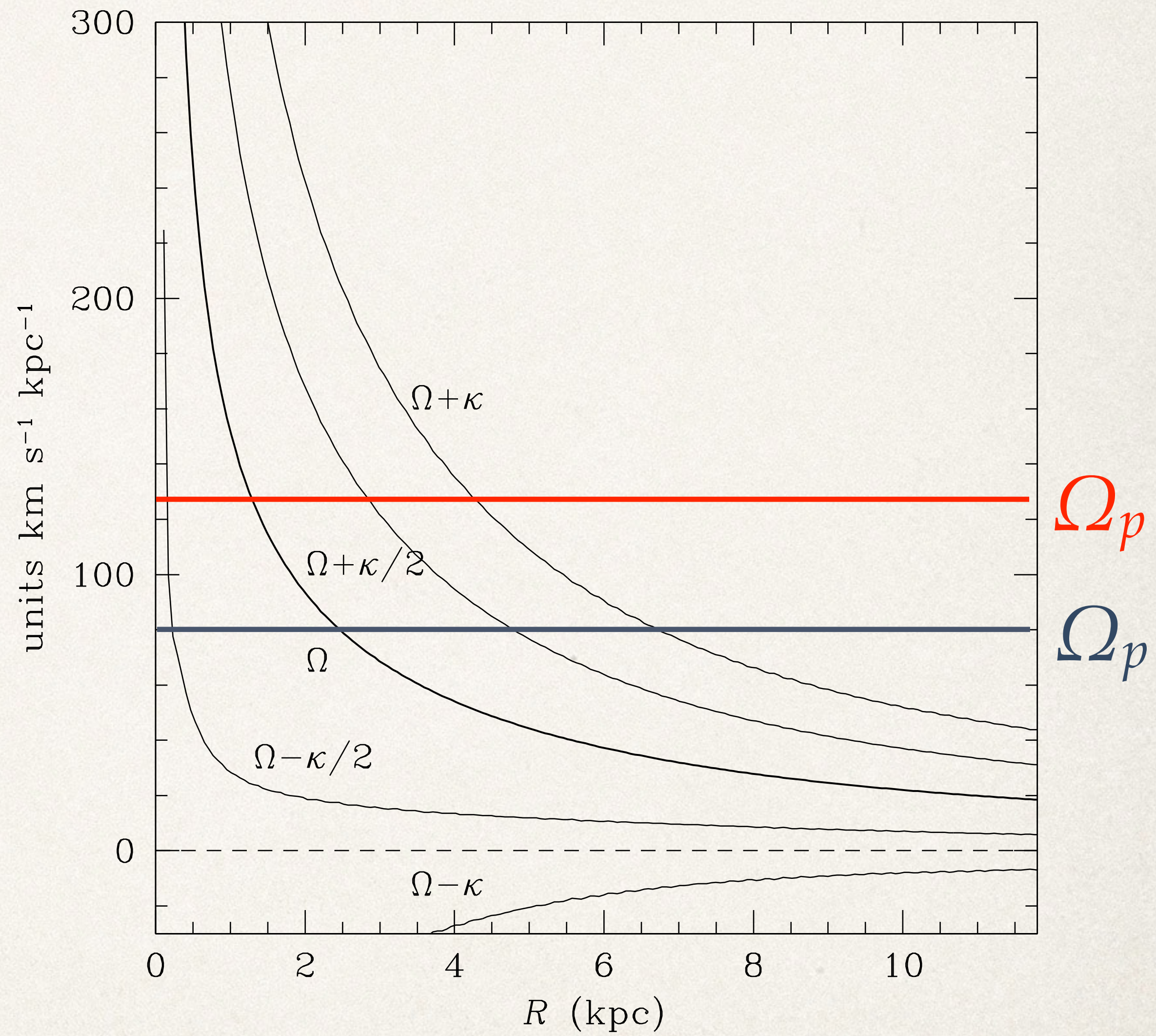
Figure 6.10 The appearance of elliptical orbits in a frame rotating at $\Omega_{\rm p} = \Omega - n\kappa/m$. Left: $(n, m) = (0, 1)$, solid line; $(1, 2)$, dotted line; $(1, -2)$, dashed line. Right: $(n, m) = (2, 3)$.

- By choosing a rotating reference frame with frequency Ωp satisfying the relation $$\Omega_p = \Omega - \frac{n\kappa}{m}$$ *n, m* integers orbits are closed

- If a perturbation is static in one of these frames a resonance occurs

Resonances

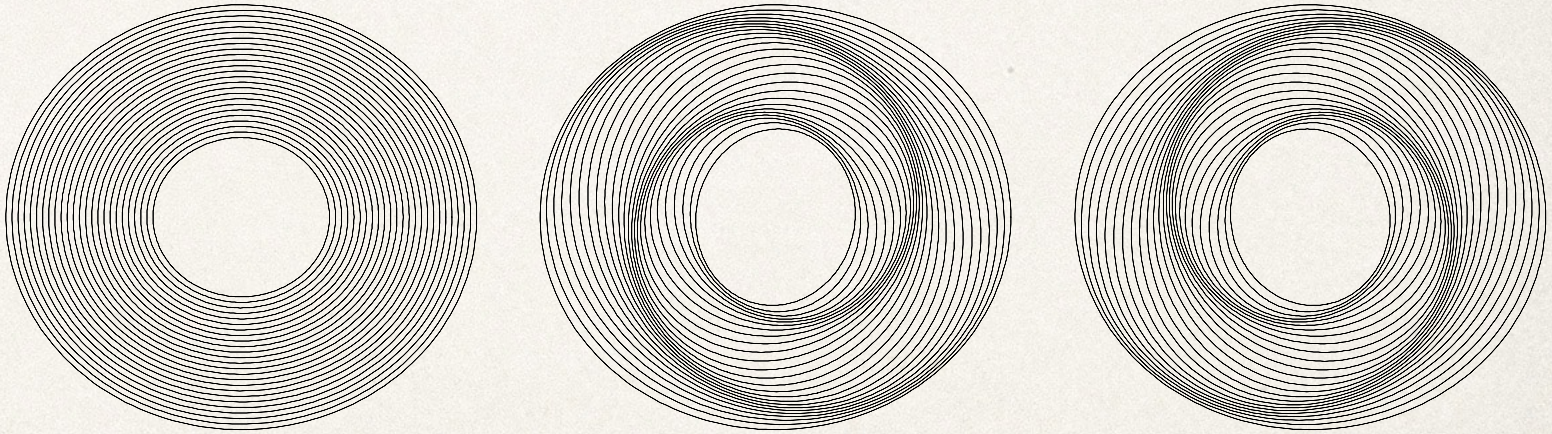
- A perturbation rotating with frequency Ω_p will give rise to various resonances at the radii corresponding to the intersection of the curves



Spirals as kinematic waves?

- Ω-κ/2 is almost constant throughout a galaxy
- The ovals corresponding to the closed orbits will slowly precess with different frequency as a function of radius

- Winding problems is overcome: winding for these waves is much slower
- Explains why m=2 spirals are common
- Needs fine tuning to keep drift rates well behaved after the spirals are formed (growing instability due to density enhancement)



(a) (b) (c)

Figure 6.12 Arrangement of closed orbits in a galaxy with $\Omega - \frac{1}{2}\kappa$ independent of radius, to create bars and spiral patterns (after Kalnajs 1973b).

Wave mechanics of disks

- *In perturbative regime and tightly wound spiral pattern hypothesis* dispersion relations for density waves can be obtained for both stellar disks and gaseous disks (see BT for equations!)
- Notably, at the corotation and Lindblad resonances these relations break down, but in between waves can travel!
- The disk behaves like a resonant cavity between the Lindblad resonances and the edges of the forbidden zone

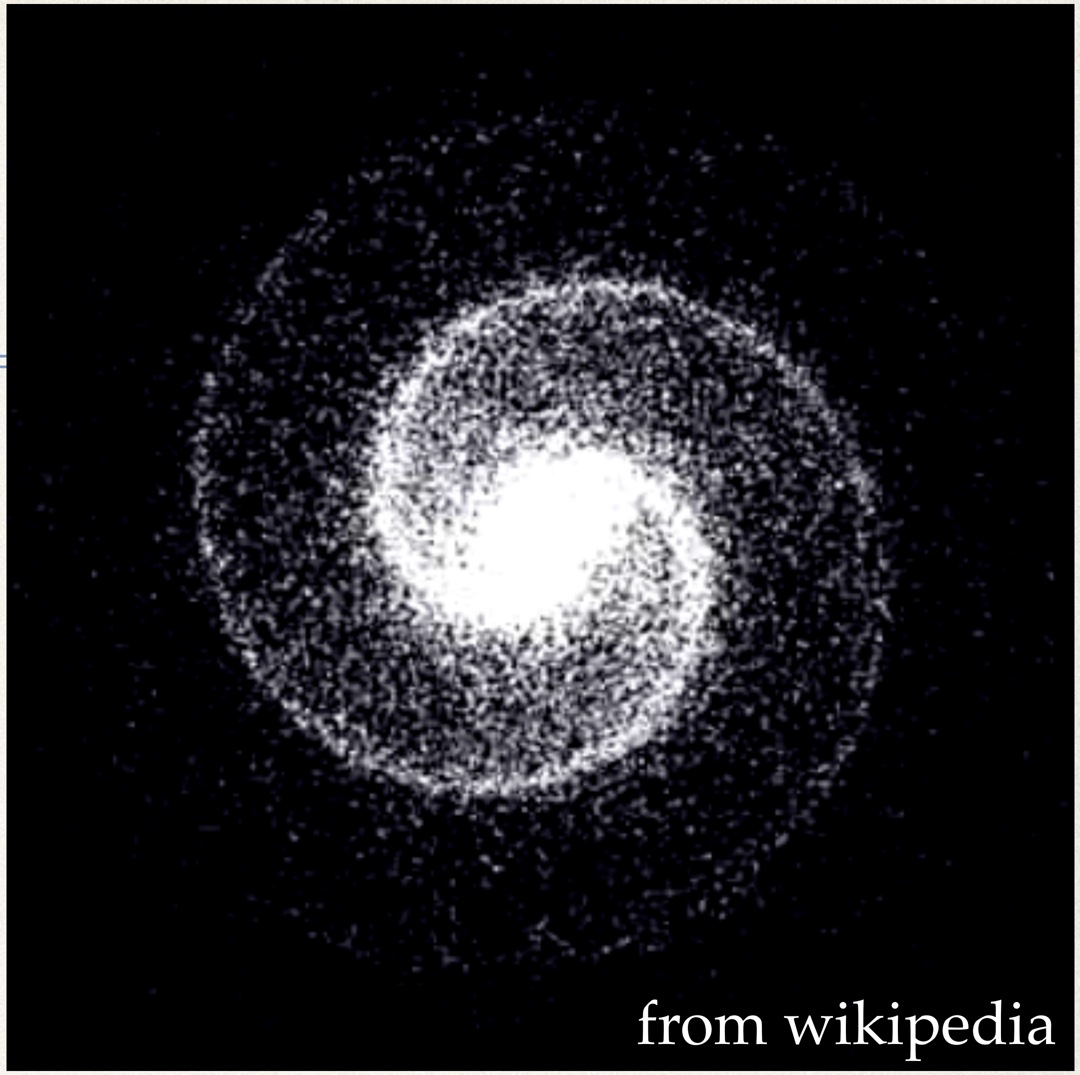
Local Stability and Toomre Q

- For stars $$Q \equiv \frac{\sigma_R \kappa}{3.36 G \Sigma}$$
- For fluid $$Q \equiv \frac{v_{\rm s} \kappa}{\pi G \Sigma}$$
- Stability (=no exponential divergence for wave equation) for a given wavelength requires Q>1

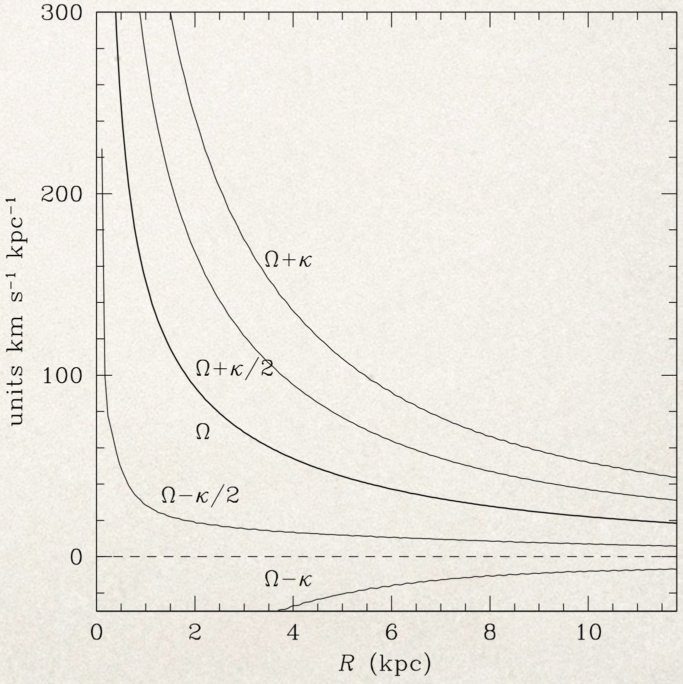
Theories of Spiral Structure

- Lin-Shu (1964-1966): quasi-steady density wave
- Chaotic spiral arms
- Tidal arms
- Driving bars and oval distortions
- detonation waves (self-propagating SF)
- (magnetic fields, obsolete)

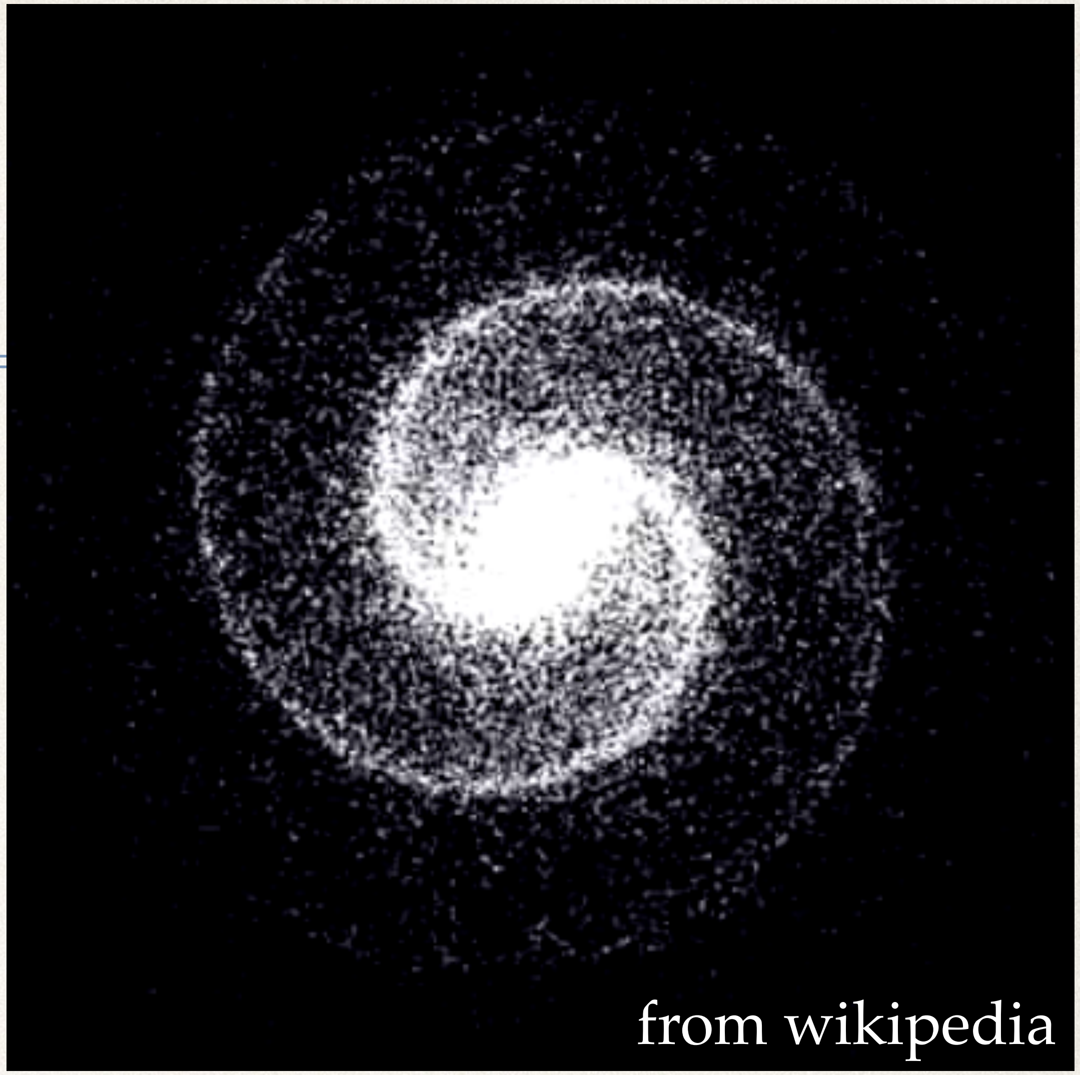
Lin-Shu theory



- Spiral pattern is the most unstable mode of the galactic disk
- As wave amplitude builds, energy dissipation in the interstellar medium leads to damping
- Instability and damping reach an equilibrium
- Predictions
    - ✓ Prevalence of trailing arms due to the "swing amplification" mechanism
    - ✓ m=2 prevails because the region between the Lindblad resonances is the largest
    - ✓ star formation occurs in the narrow high-density arms as a response of the gas/ISM to the density wave
    - ? nobody knows if the spiral pattern is actually stationary in ~Gyr timescale!
    - ? how many grand design spirals are isolated and not barred such that the Lin-Shu theory is actually the explanation for the spiral pattern?



Lin-Shu theory



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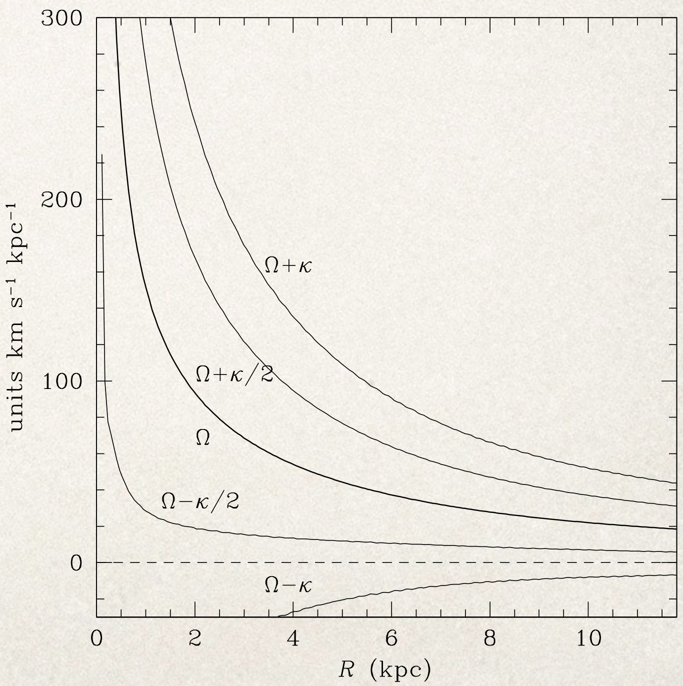


Chaotic spiral arms

- Local instabilities in the gas lead to the formation of new stars in small patches (for Q=1 the typical scale is ~0.2 kpc)
- Patches are sheared by the differential rotation
- Stellar feedback (SNe) heat the gas and re-stabilize the disk

Tidal arms

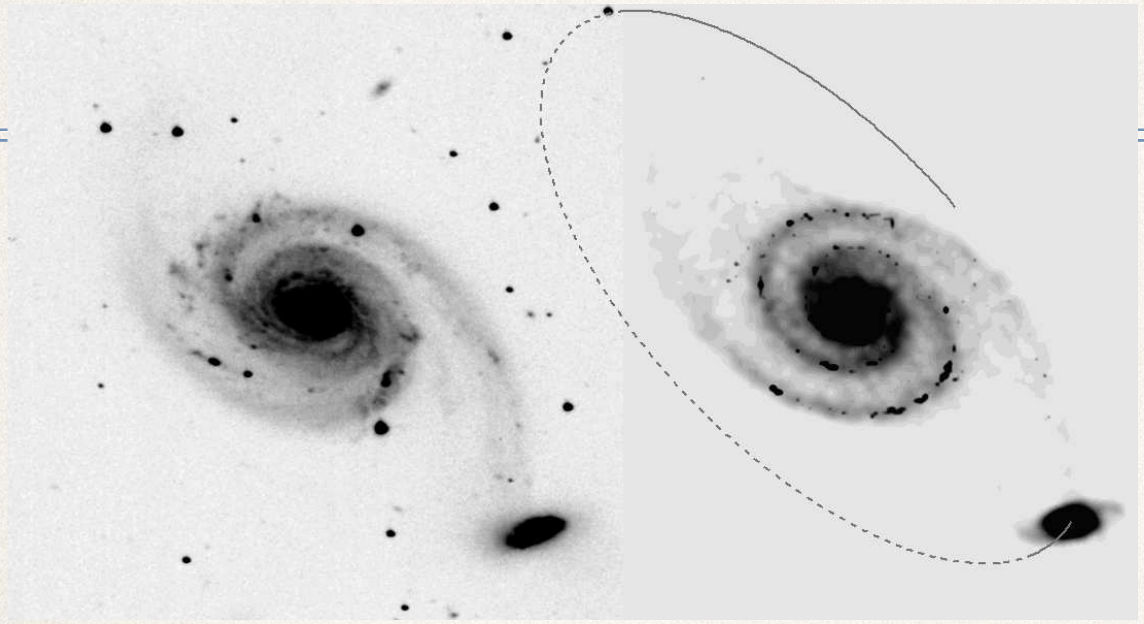


Figure 6.26 Model of the interacting galaxy pair NGC 7753, a large grand-design Sb spiral, and NGC 7752 (the small compact companion at lower right). The left panel shows a negative V-band image and the right panel shows an N-body simulation. The orbit of the companion is marked with a solid line above the disk plane and a dashed line below. The two galaxies are separated by 60 kpc. From Salo & Laurikainen (1993), reproduced by permission of the AAS.

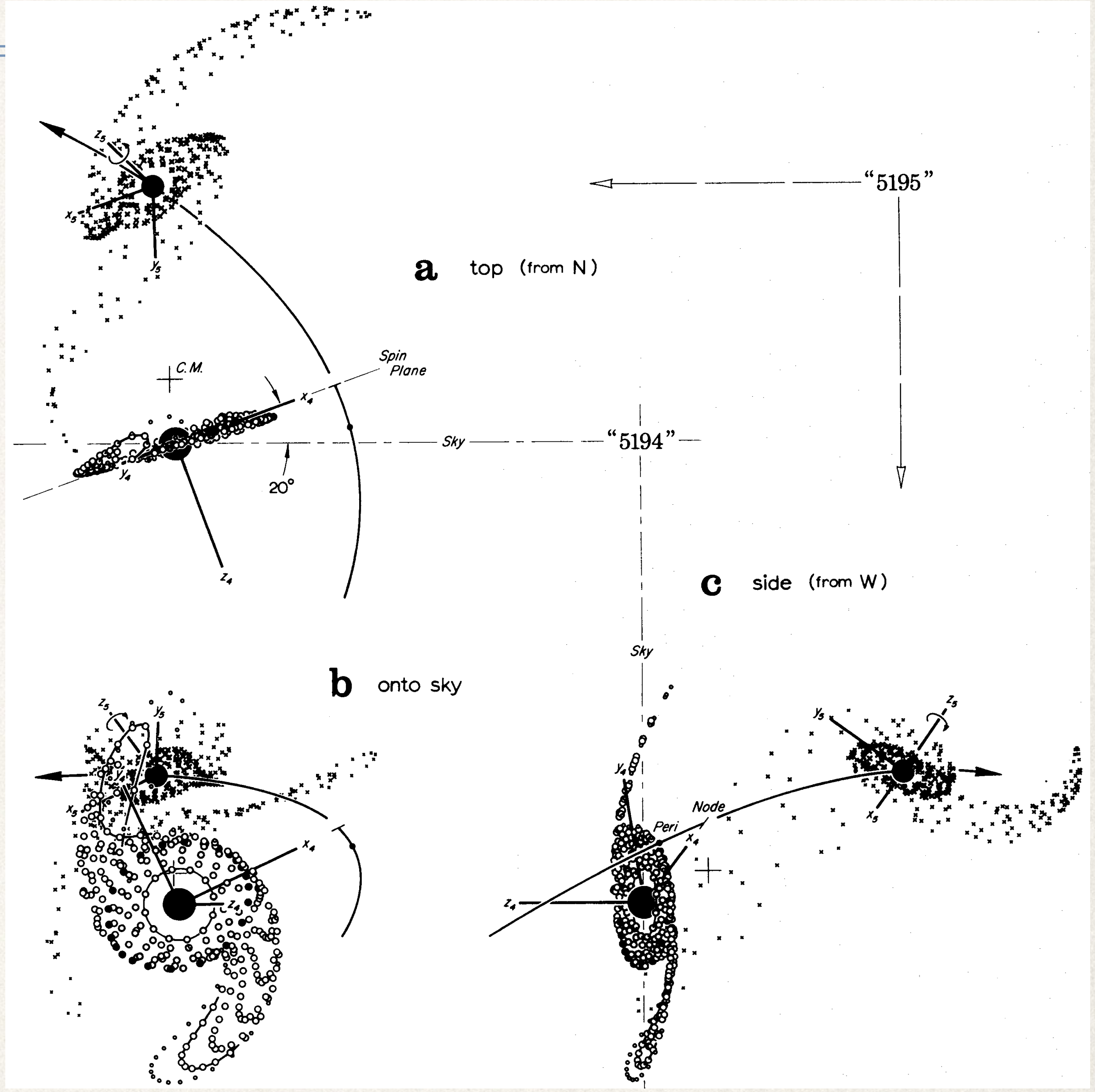
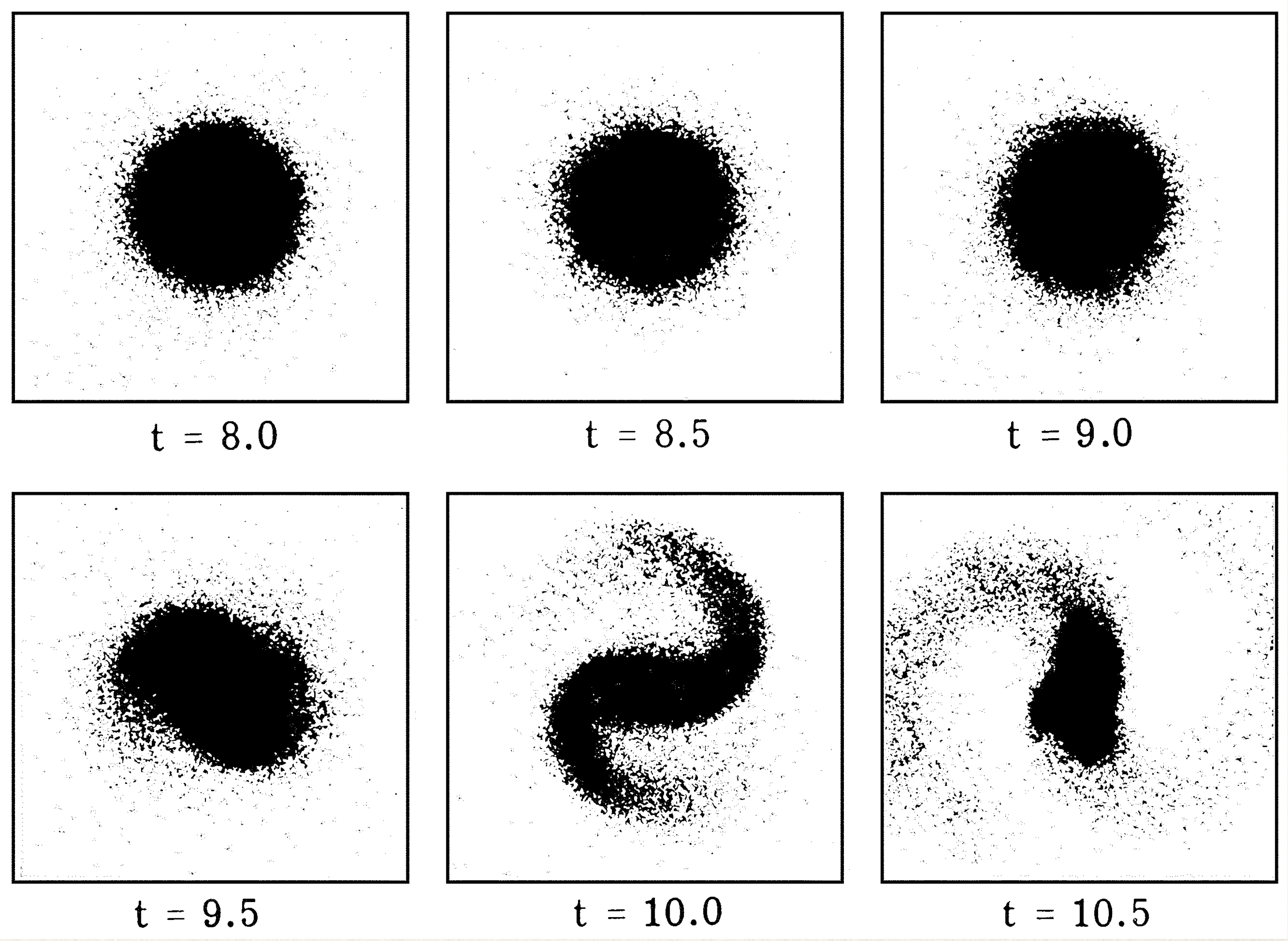


Figure 6.25 Model of the encounter between M51 and NGC 5195, shown in three orthogonal views. The lower left view can be compared with Figure 6.1 or Plate 1. Note that the low-density tidal tail at the 2 o'clock position relative to the center of M51 is similar to a low surface-brightness feature in Figure 6.1. In this pioneering experiment the galaxies were represented as point masses (the filled circles) surrounded by disks of orbiting test particles. From Toomre & Toomre (1972), reproduced by permission of the AAS.

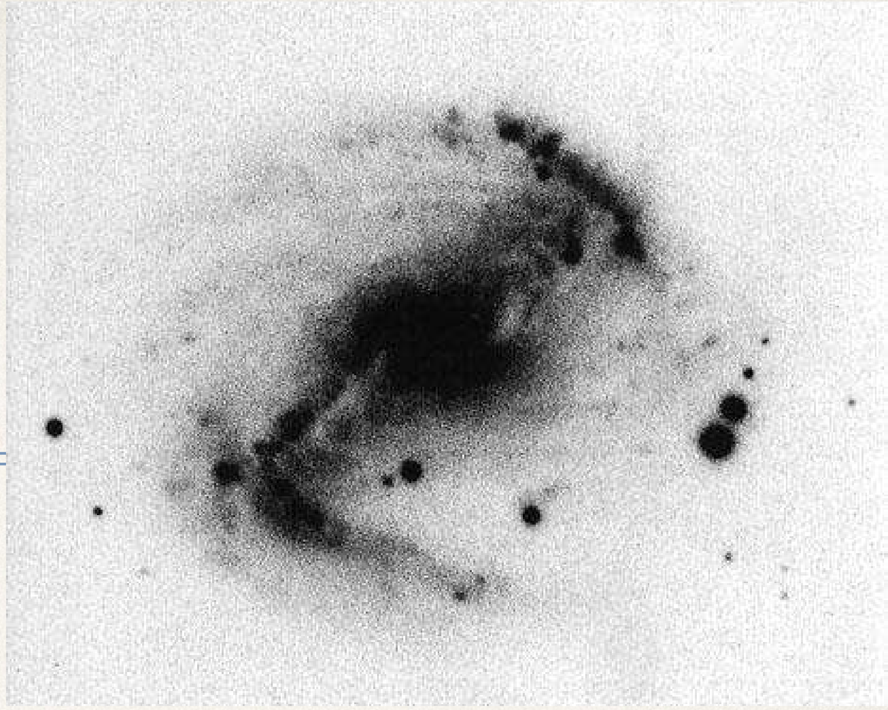
- http://youtu.be/H5KXl4YORYo
- Also possible trigger for steady-density waves

Global disk (in)stability

- Bars!
- Bar instability occurs in cold disks or in absence of a stabilizing halo
- Possible origin?



Bars



- Bars can drive a spiral structure
- Not all spirals have bars though...
- Easily formed in unstable disks
- Bars rotate like solid bodies (constant angular speed)
- Stops at or before corotation
- Gas flows along the bar, shocks at the edges
- Important role in distributing angular momentum