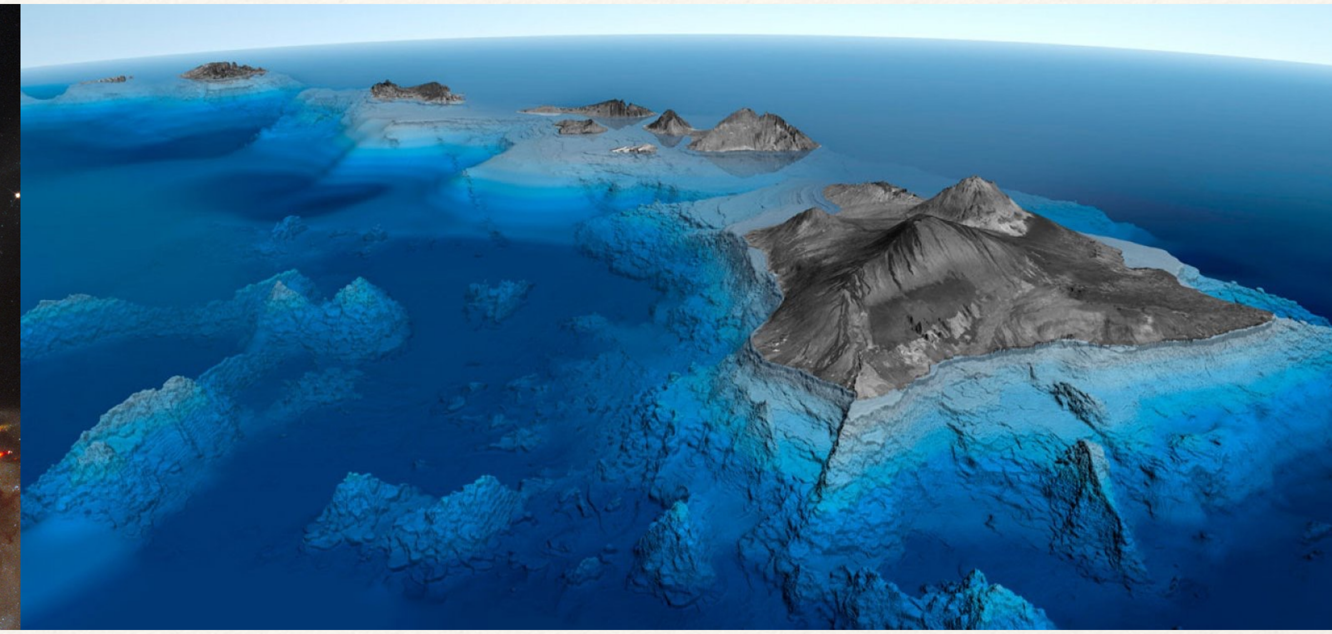


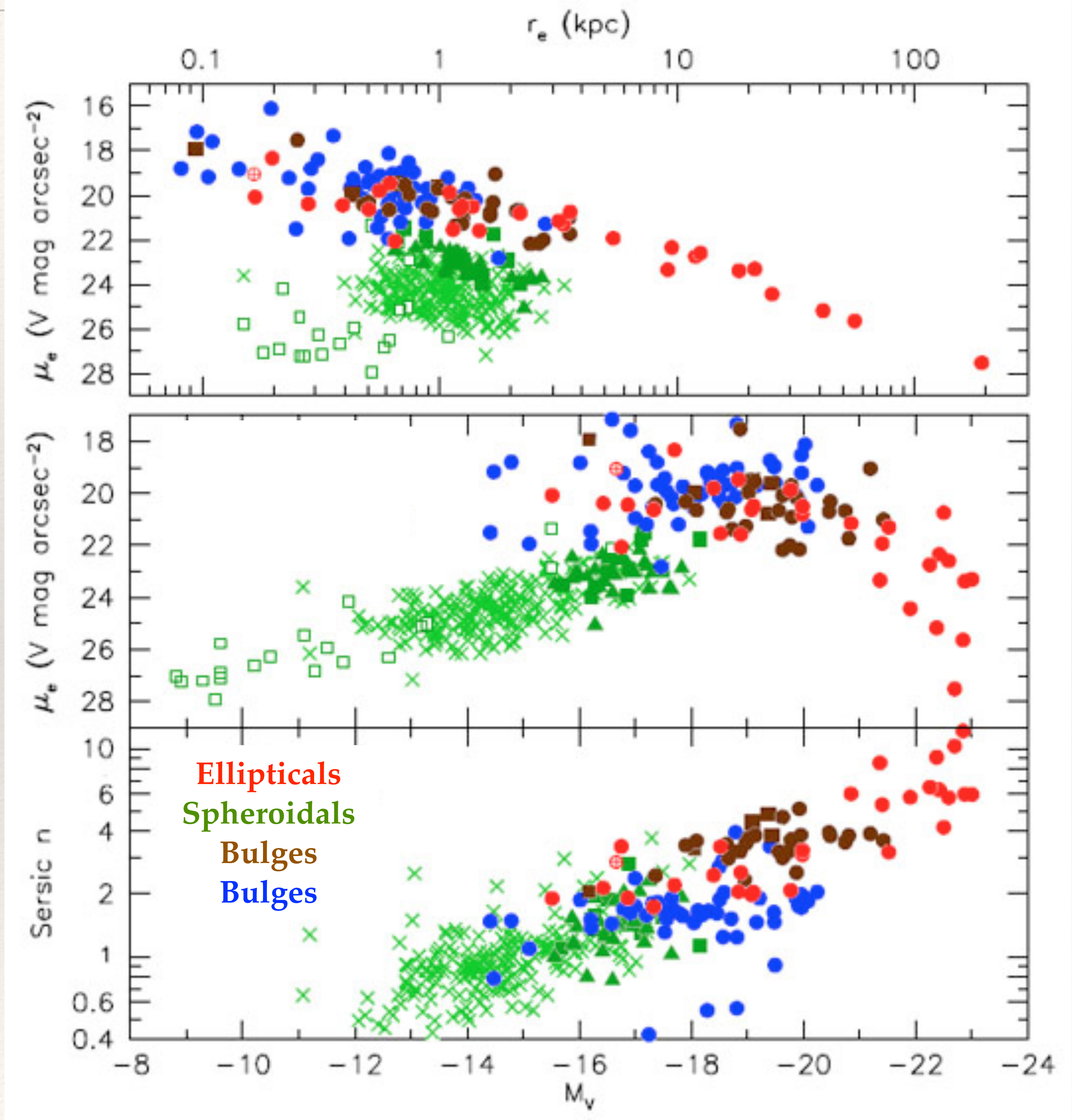
Getting to know the "island universes" out there.

Galaxies I

ASTR 555
Dr. Jon Holtzman

Warm-up

- Two kinds of bulges are indicated in these figures (brown and blue points).
  - Which kind of bulge is which and why?
  - What other observations would be useful to confirm your answer?



Kormendy et al. 2008

Outline for Today

- Galaxy Population - Spirals/Disks:
    - Kinematics
    - Spiral Arms, continued

NGC1232 (ESO)

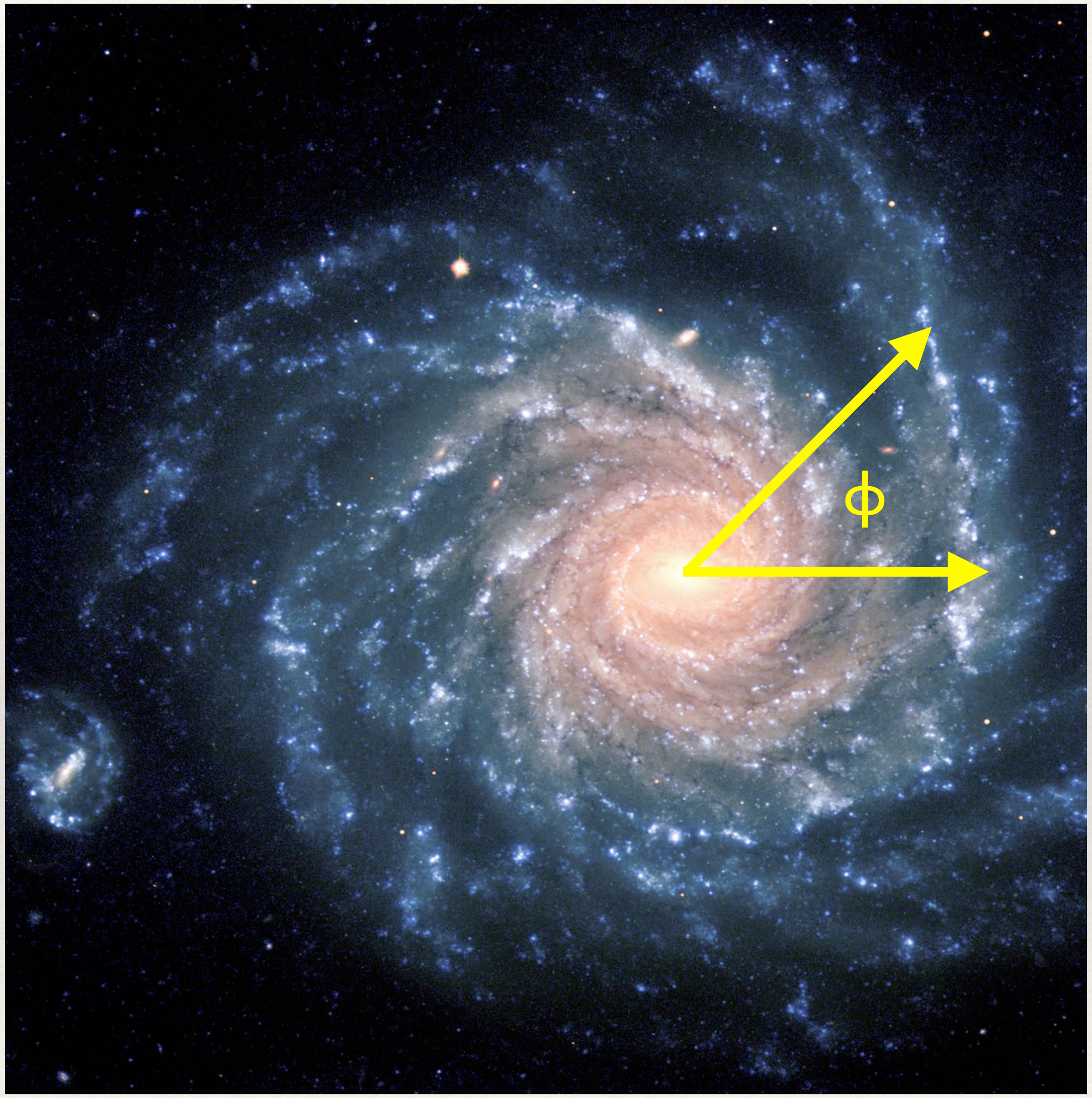
Spirals/Disks: Kinematics

- Spiral galaxies are kinematically “cold”:
  - organized rotational motion is large compared to random motion of stars
  - velocity dispersion low (but not zero)

NGC1232 (ESO)

Spirals/Disks: Kinematics

- Measure galaxy rotation using spectral features:
  - optically, e.g., Hα
  - radio HI 21 cm (unresolved data or spatially resolved, e.g., VLA) generall allows meas rements to signi i antl art er o t



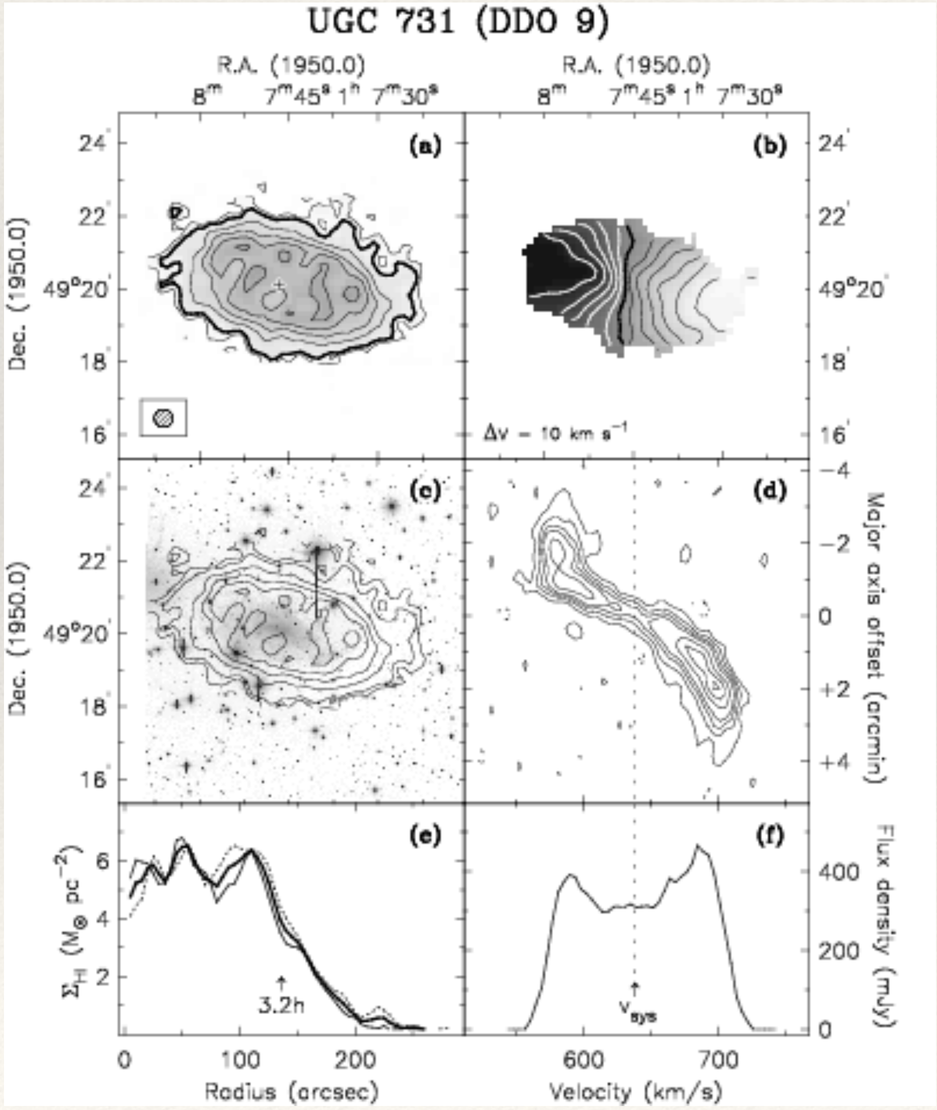
NGC1232 (ESO)

Measure radial (line-of-sight) velocity:

- $\mathbf{V_r(R,i) = V_{sys} + V(R)\ sin(i)\ cos(\phi)}$
- V(R) = rotation velocity at each radius
- V_{sys} = systemic velocity
- i = inclination angle from face-on
- ϕ = azimuthal angle (within disk plane)

Spirals/Disks: Kinematics

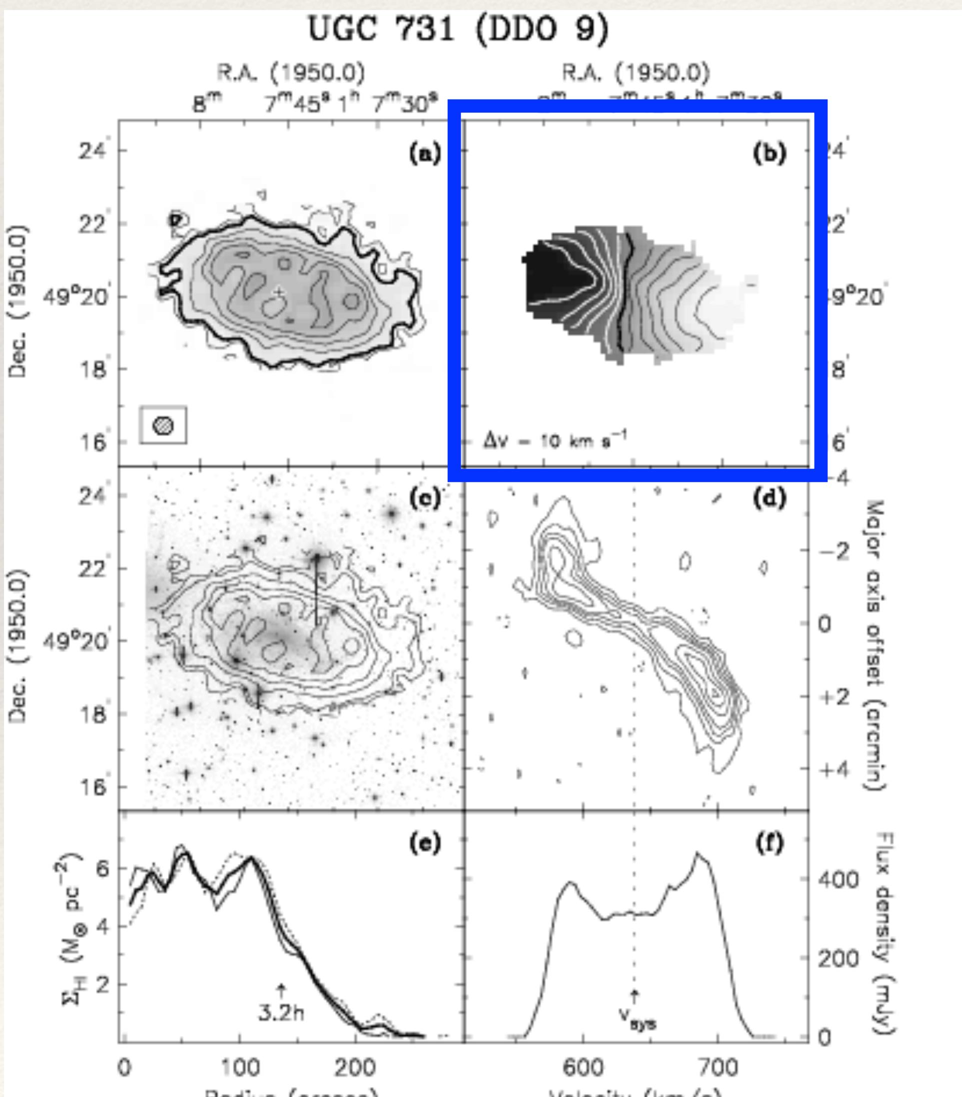
- Many different ways to look at kinematic data:



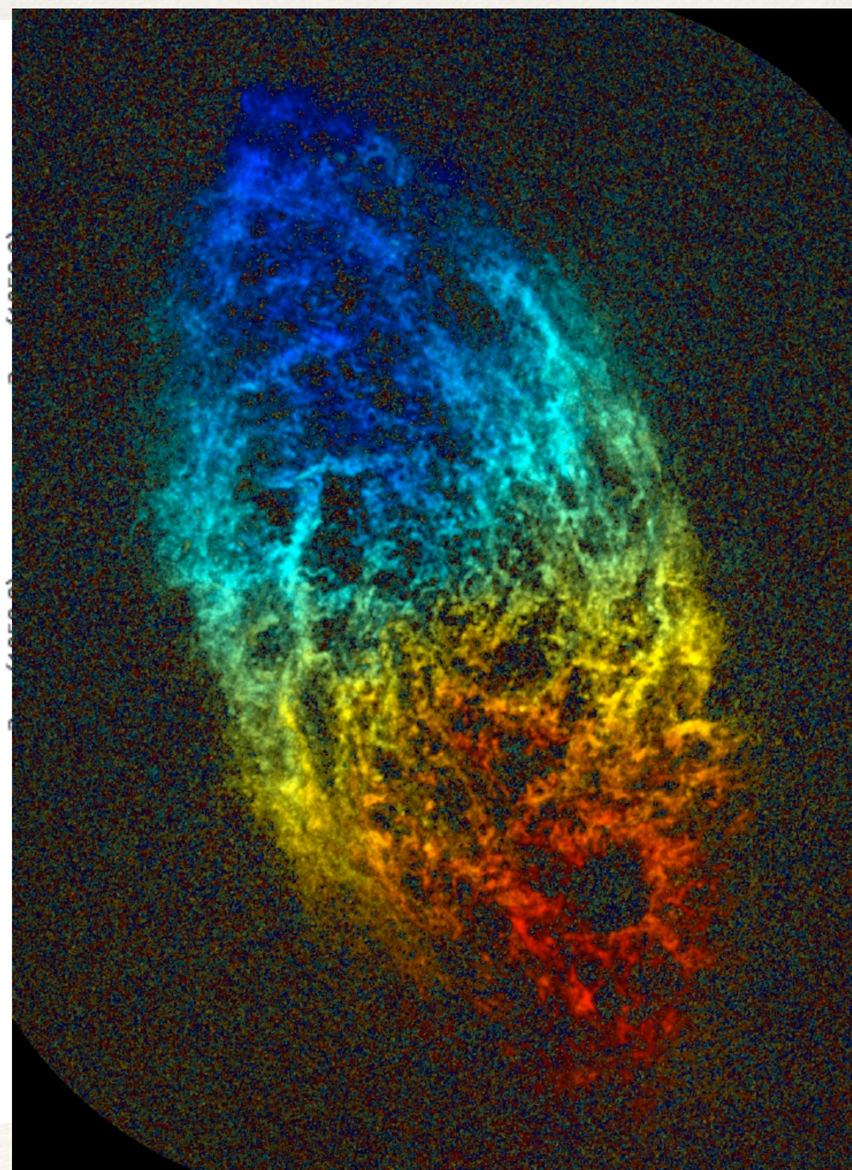
Swaters et al. 2002

Spirals/Disks: Kinematics

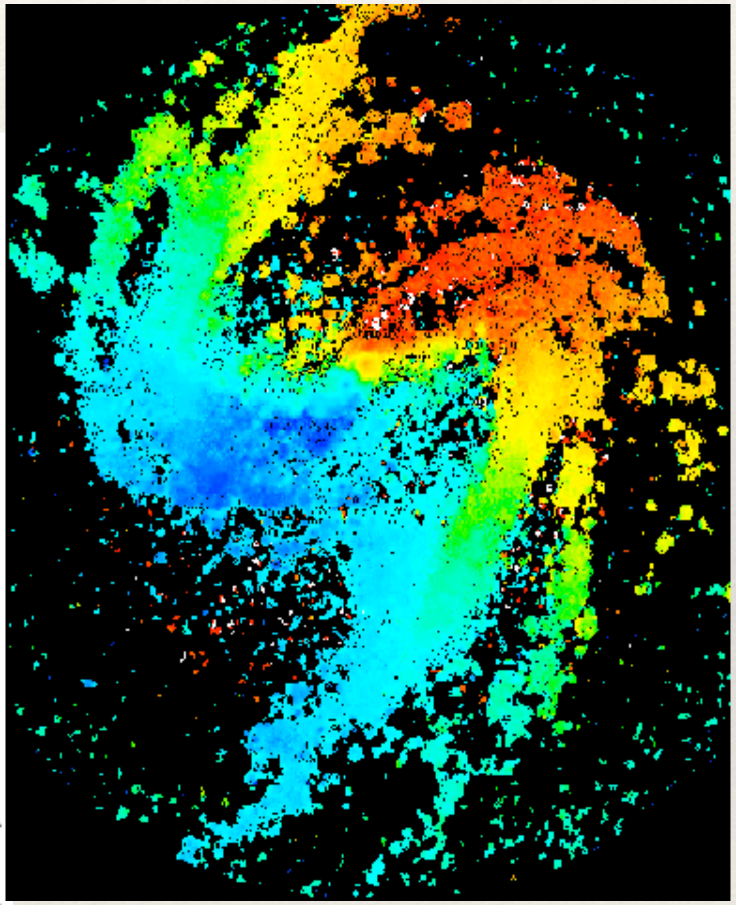
- **Velocity-coded color** — showing blueshift to redshift



Swaters et al. 2002



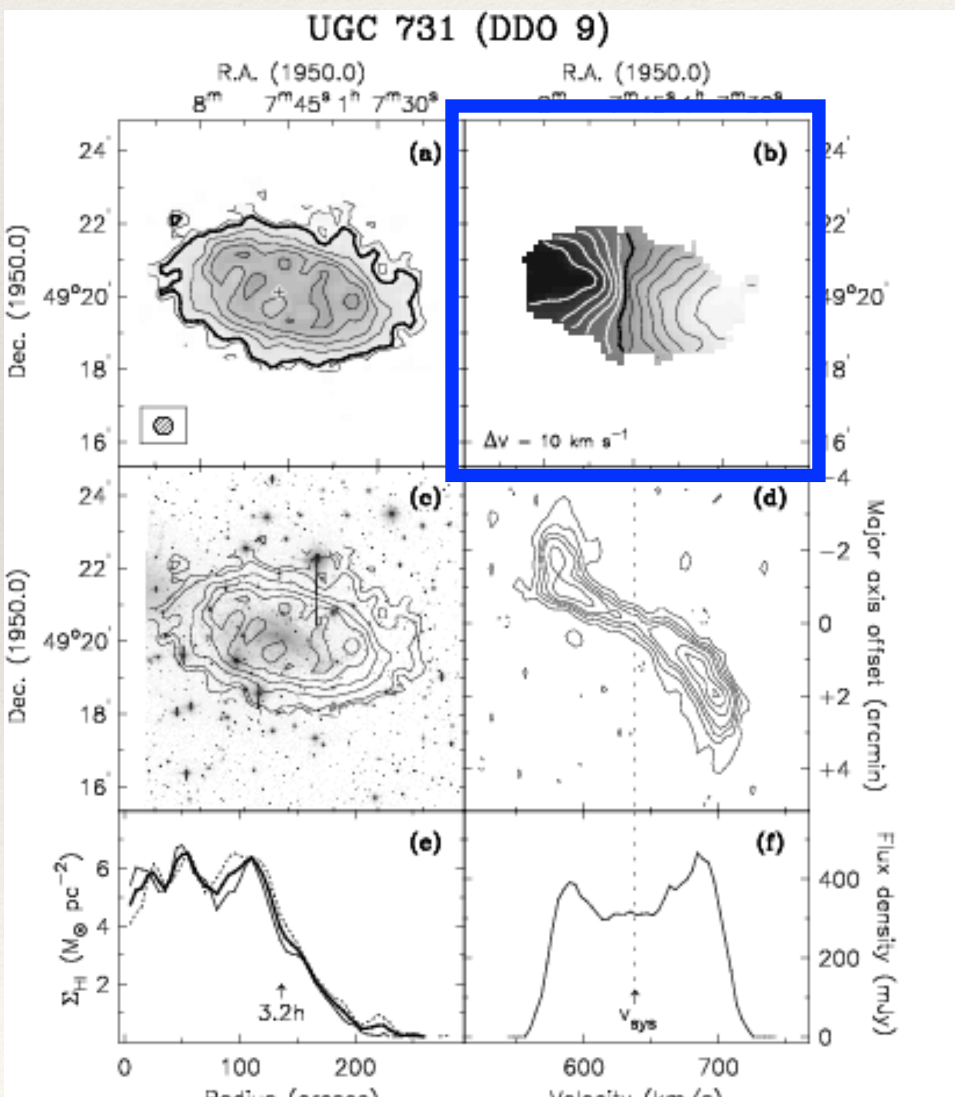
M33 (NRAO)



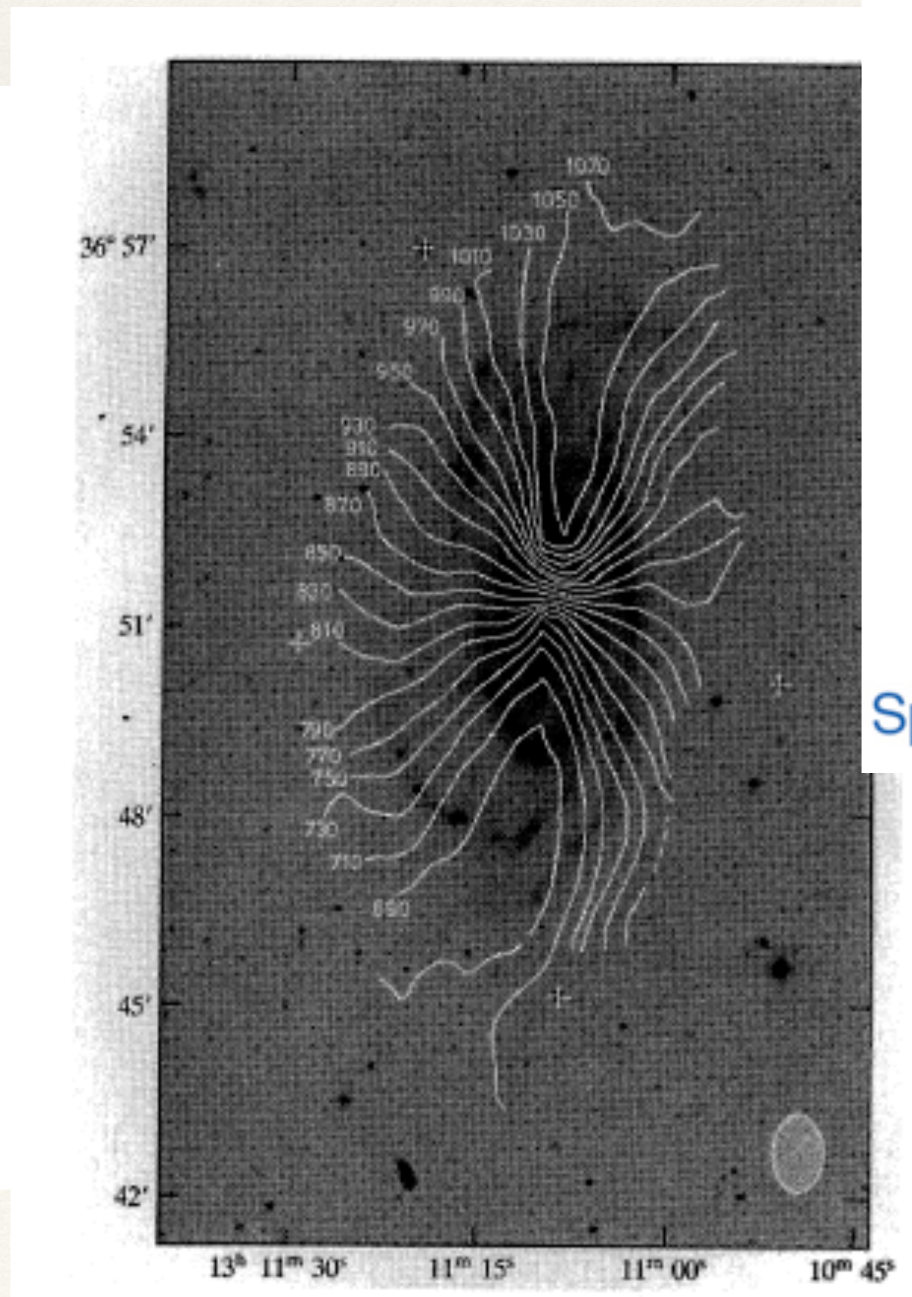
NGC 1365 (Rutgers Astronomy)

Spirals/Disks: Kinematics

- **Spider diagrams** — maps of isovelocity contours



Swaters et al. 2002



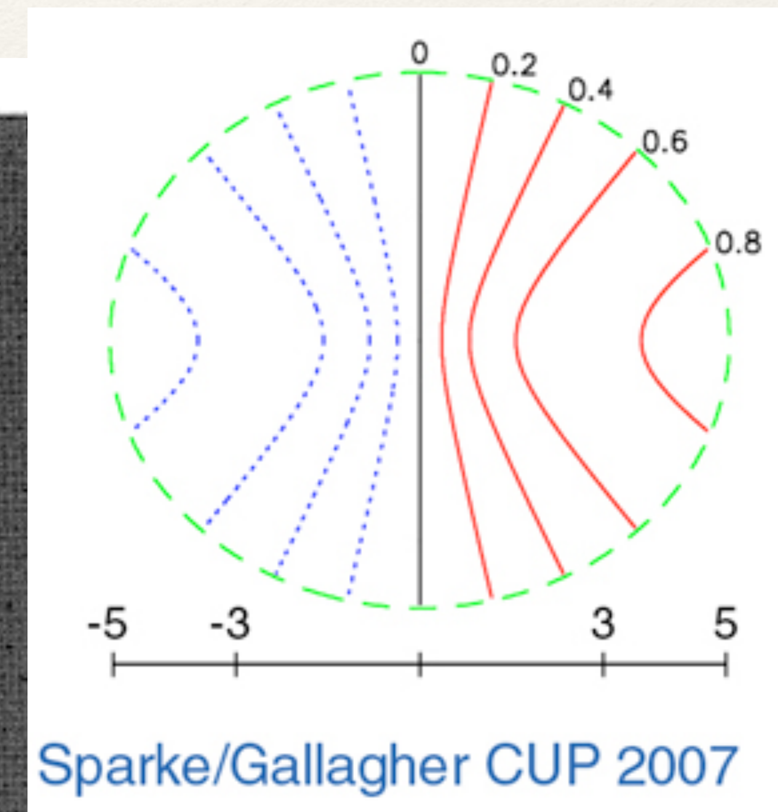
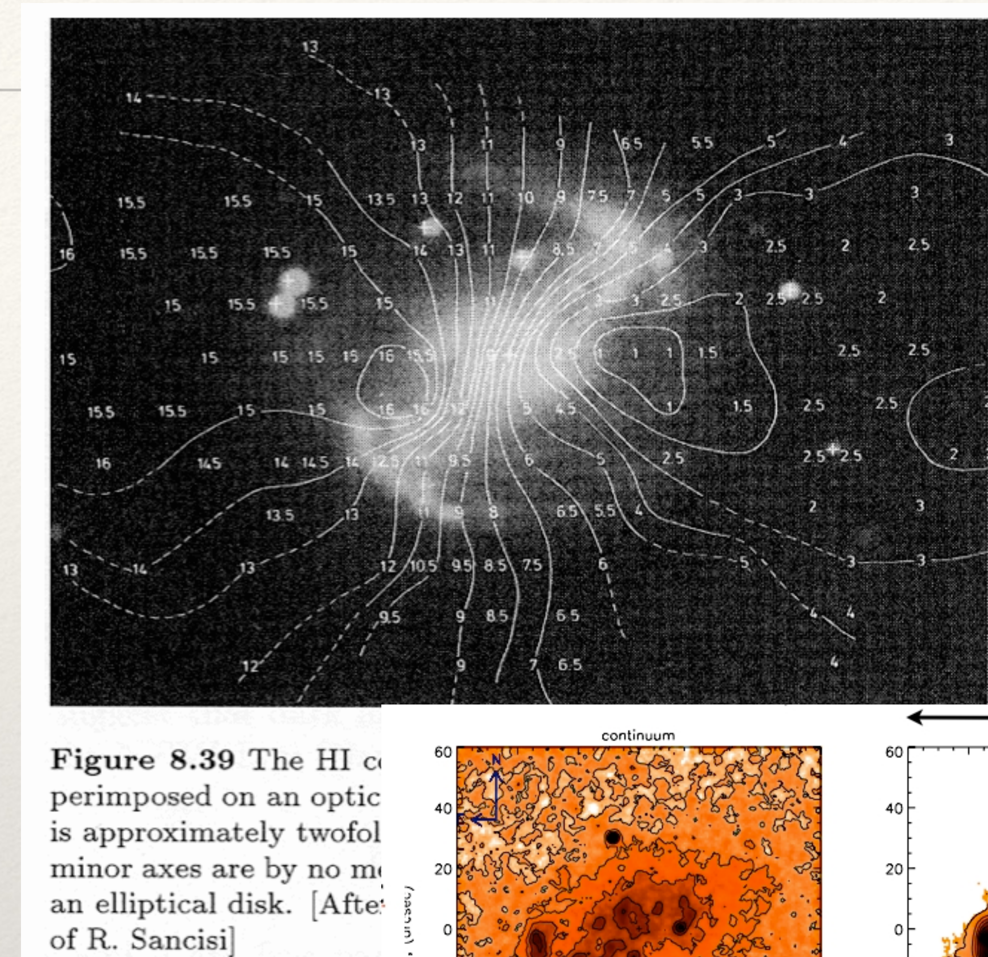


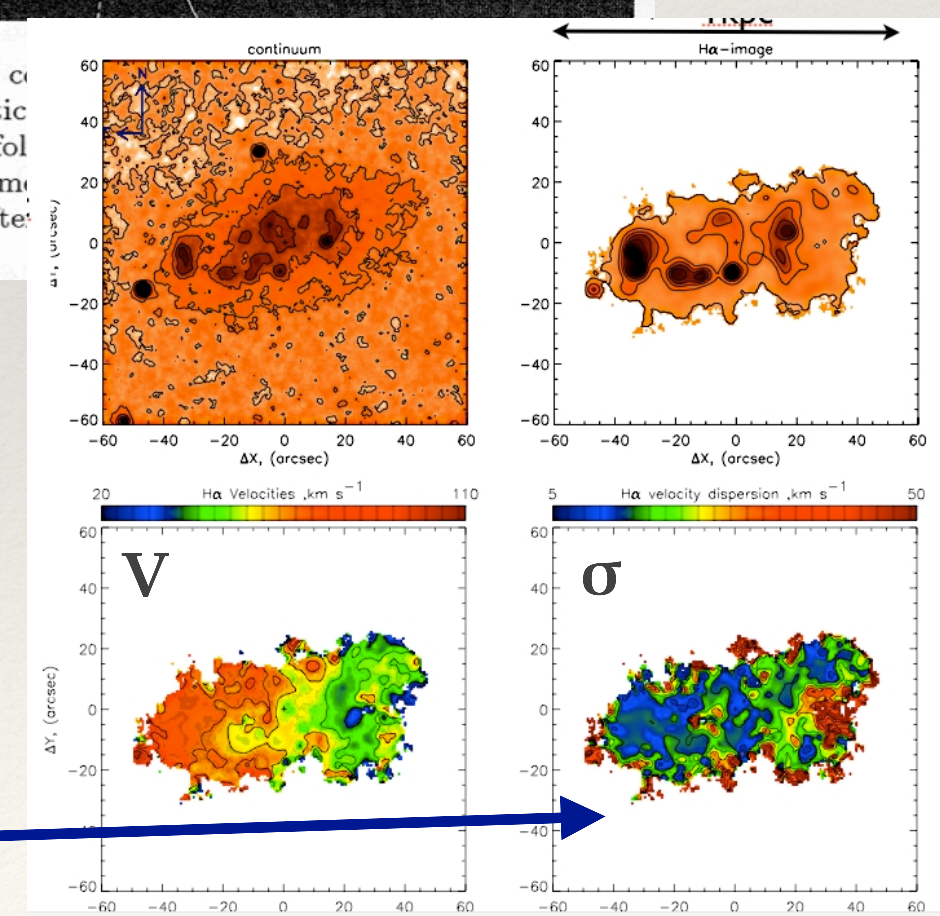
Figure 8.17 Contours of constant HI velocity in NGC 5033. Notice the curvature of the kinematic principal axes. [After Bosma (1978)]

Spirals/Disks: Kinematics

- Spider diagram isovelocity contours aren't always perfectly regular:
    - features related to disk structure
    - motions of gas within disk
    - large scale systematic deviations from rotation, e.g., streaming motions in bars
- Maps of internal velocity dispersion



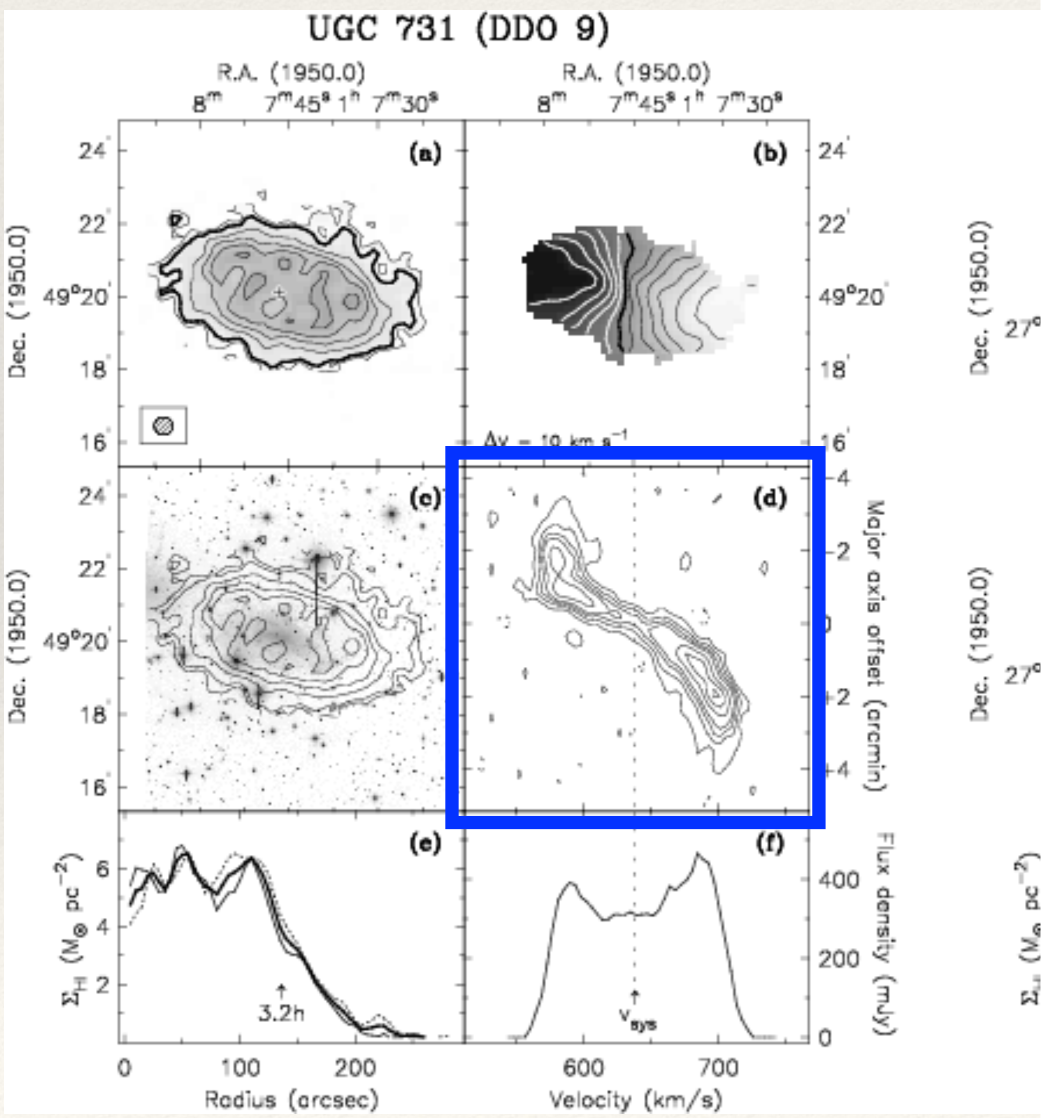
NGC 5383



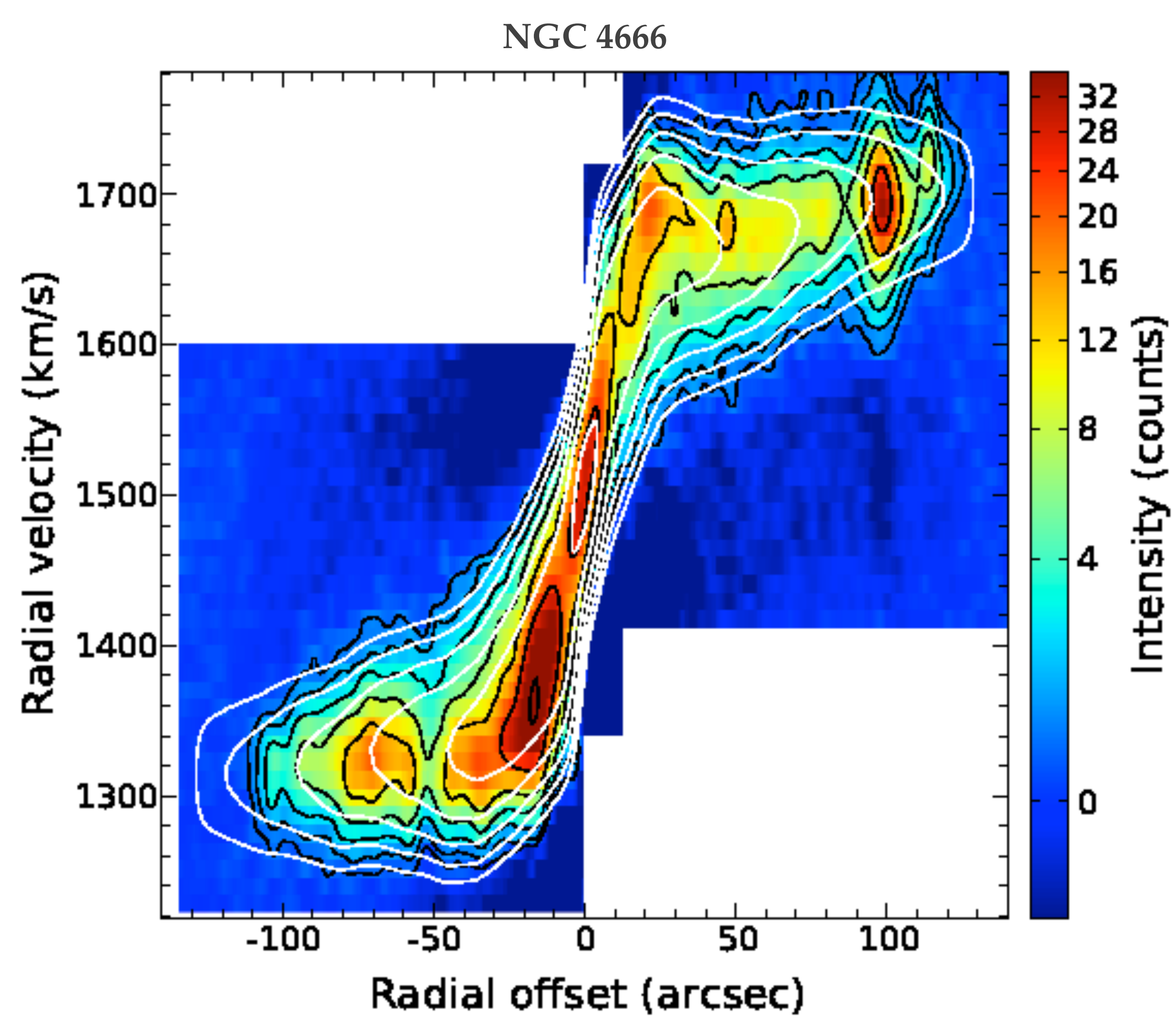
UGC8508

Spirals/Disks: Kinematics

- **Position-Velocity (PV) diagrams** — note spread of velocity at any given position



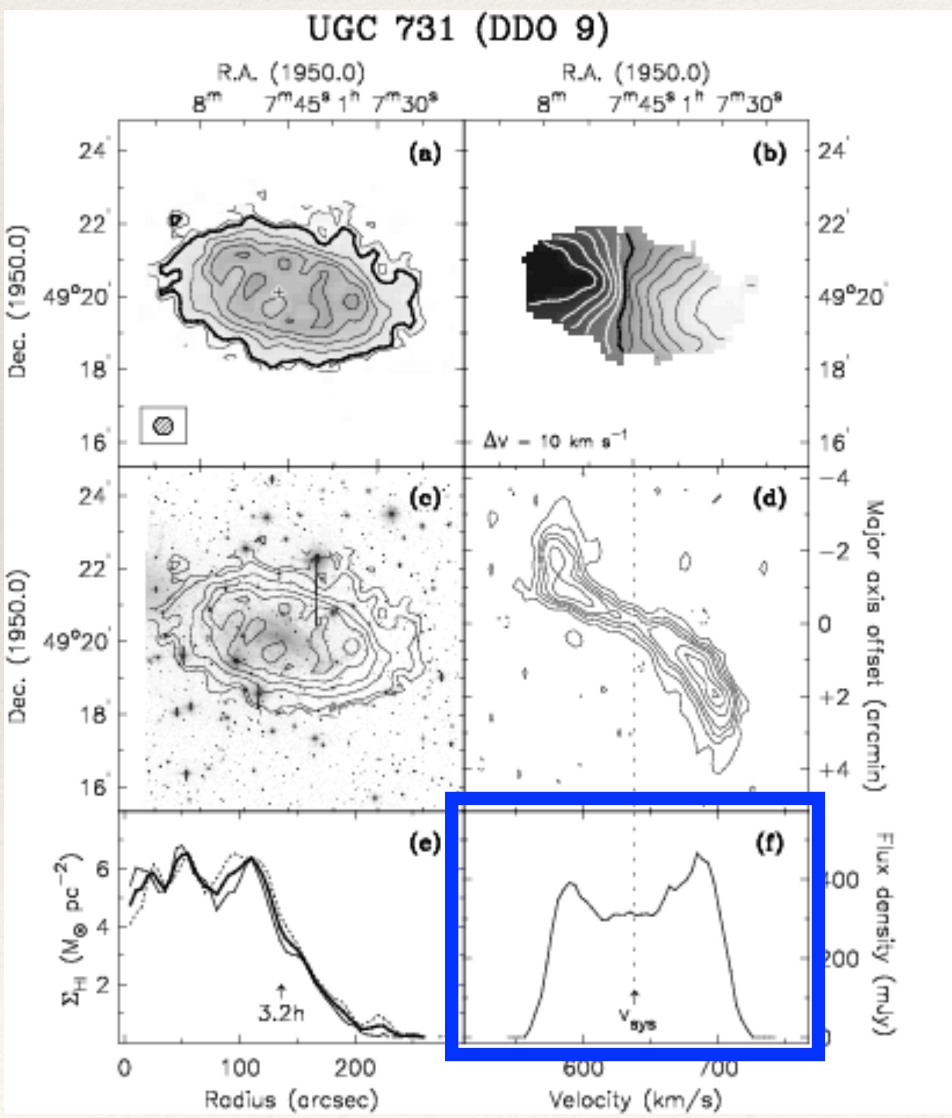
Swaters et al. 2002



Voigtländer et al. 2013

Spirals/Disks: Kinematics

- **Unresolved HI profiles** — rotation characterized by line widths, e.g. W_{50}, W_{20} (width at 50%, 20% of peak line flux)



Swaters et al. 2002

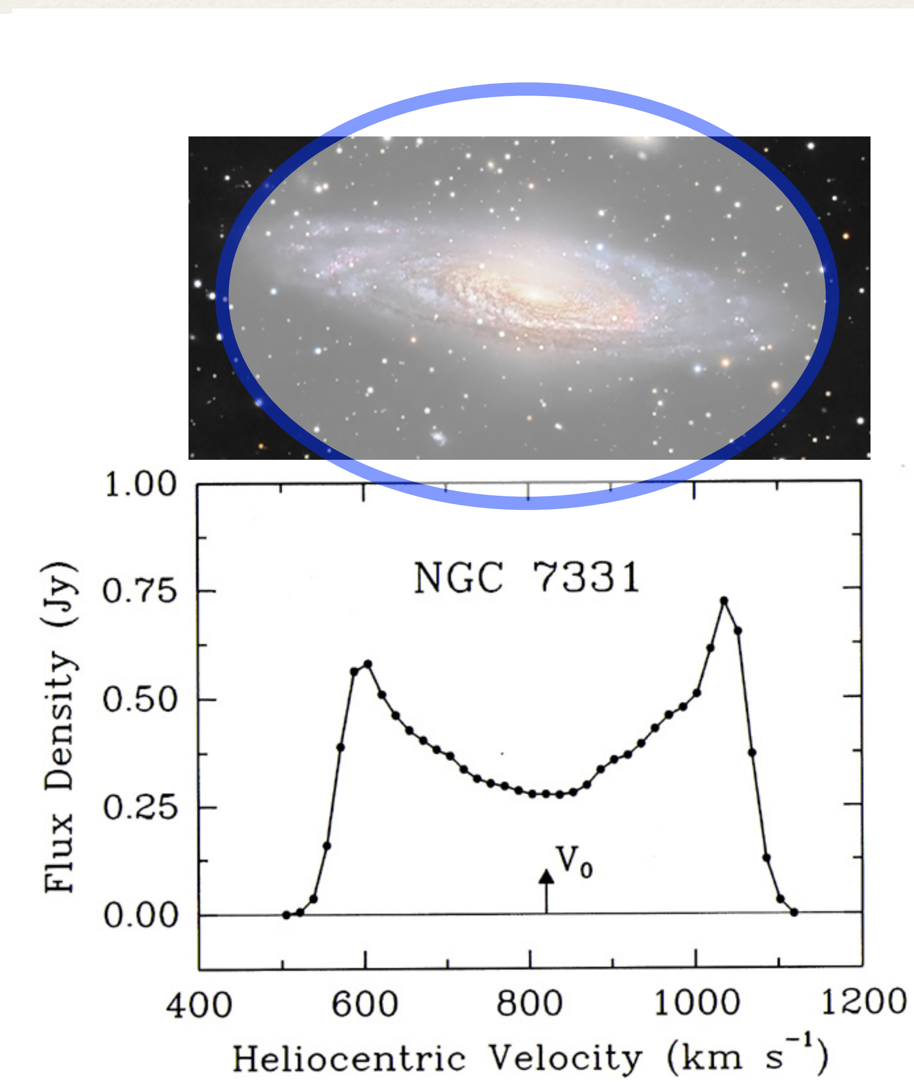
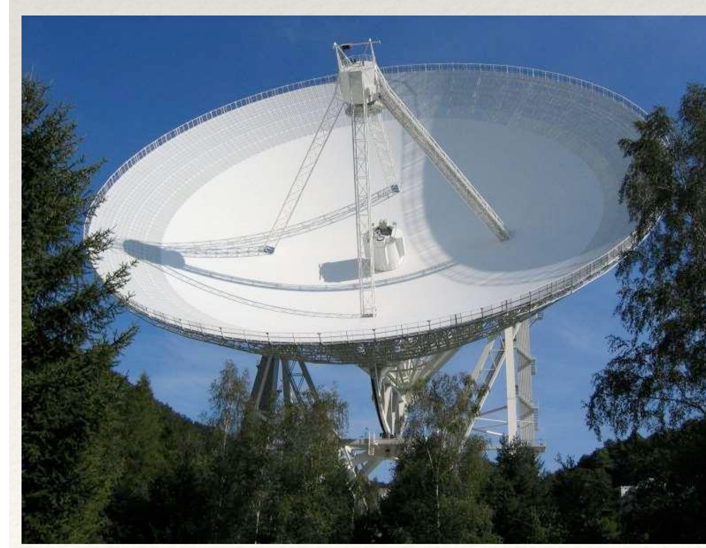


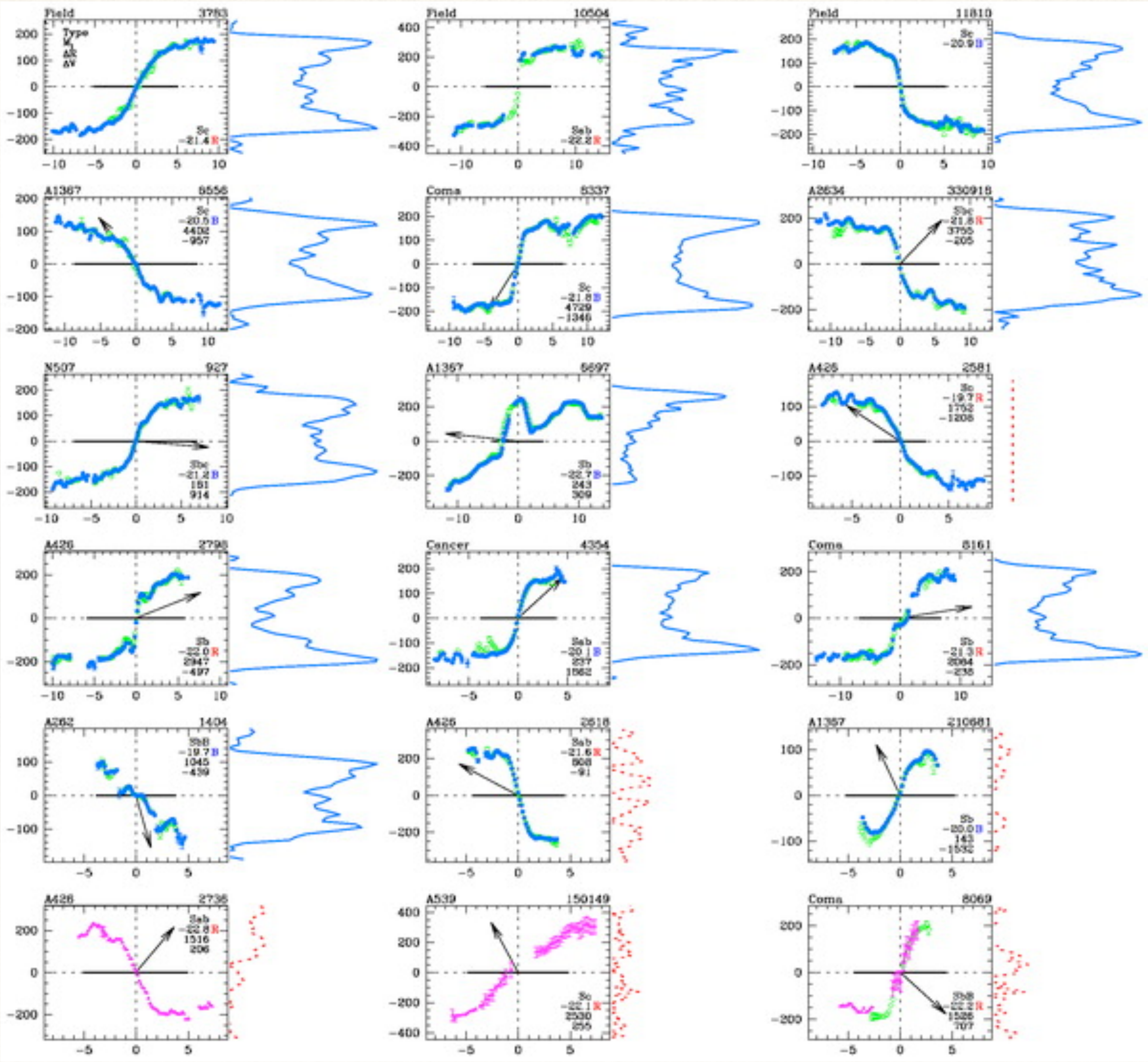
Fig 5.22 (K. Begeman) 'Galaxies in the Universe' Sparke/Gallagher CUP 2007



Effelsberg 100m

Spirals/Disks: Kinematics

- Spirals are often characterized by 1D cut along major axis:
  - **Rotation curve** — maximum rotation velocity as a function of radius
  - Correct for inclination of galaxy, usually based on observed axis ratio



Vogt et al. 2004

Thought Question

- Consider the expected rotation curve of a spiral galaxy:
  - Derive an expression for the rotational velocity versus radius **assuming spherical symmetry and only luminous matter**.
    - *hint* set entripetal a elaration e al to gra itational a eleration
    - w at does t e mass in t e gra itational a eleration e pression re er to?

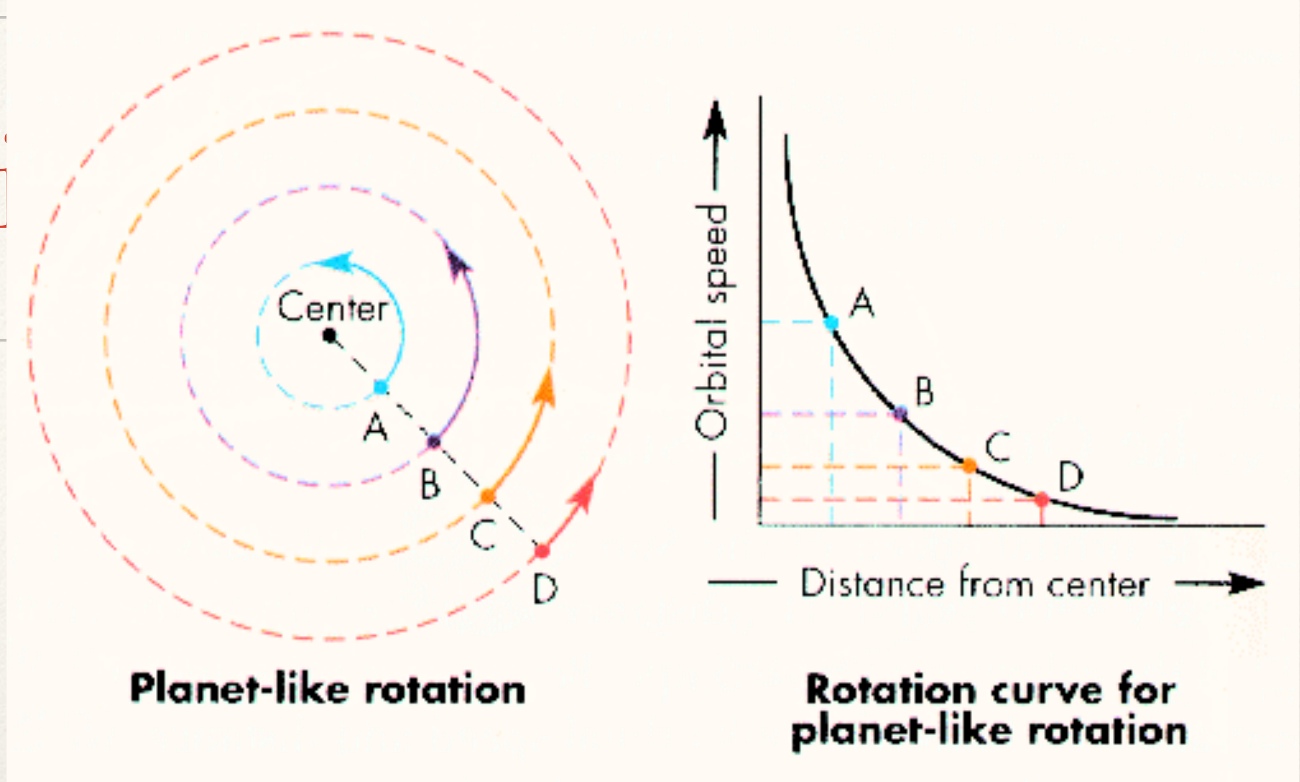
Thought Question

- Consider the expected rotation curve of a spiral galaxy:
  - Derive an expression for the rotational velocity versus radius **assuming spherical symmetry and only luminous matter**.

$$\frac{v(r)^2}{r} = \frac{G\,M(<r)}{r^2}$$

so $$v(r) = \sqrt{\frac{GM(r)}{r}}$$

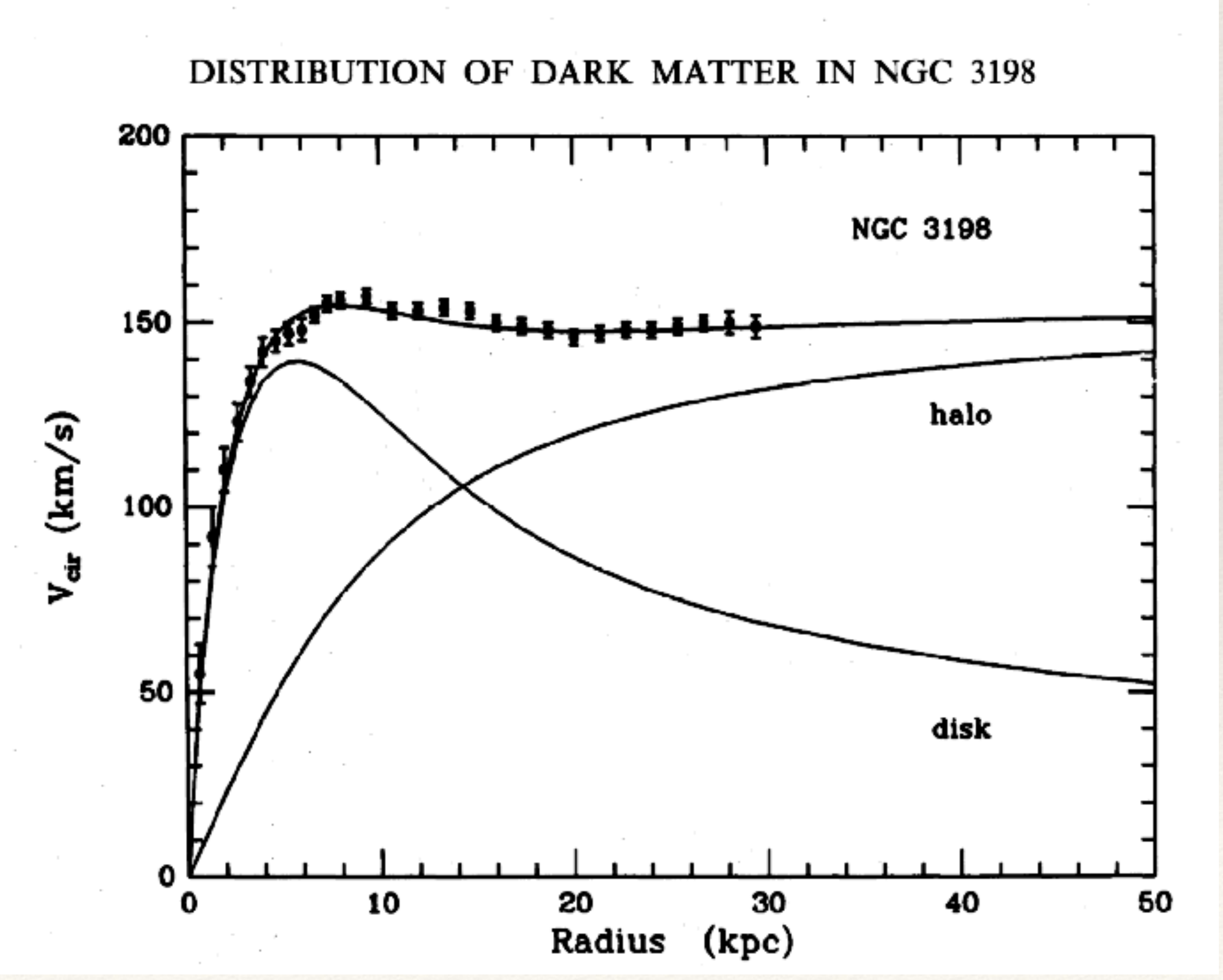
Spirals/Disks: Kinemati



- Rotation velocity scales with radius and mass enclosed:

$$v_{rot} \propto \sqrt{\frac{GM(r)}{r}}$$

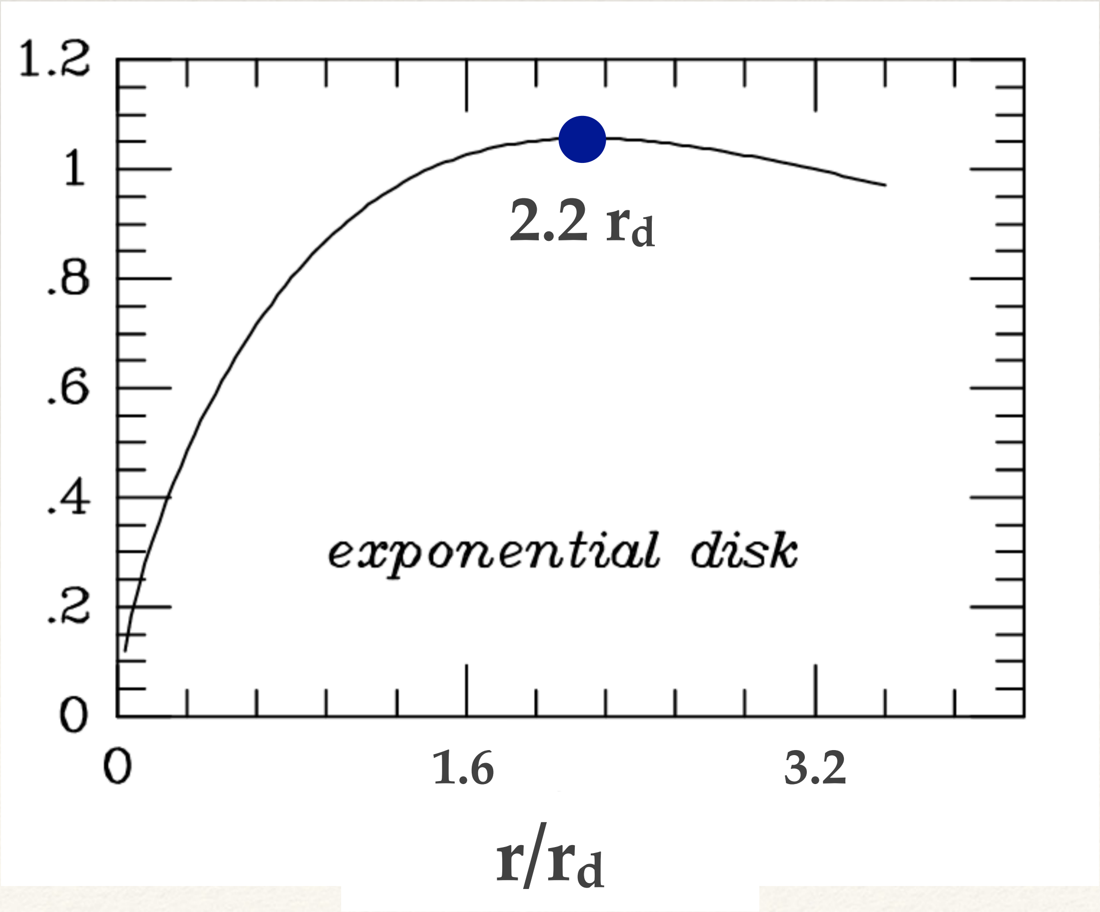
- Flat rotation curves imply **M(r) α r**, i.e. significantly more than implied by exponentially declining stellar component
- A primary indicator of **Dark Matter**!
- What does solid body rotation mean and imply about mass profile?



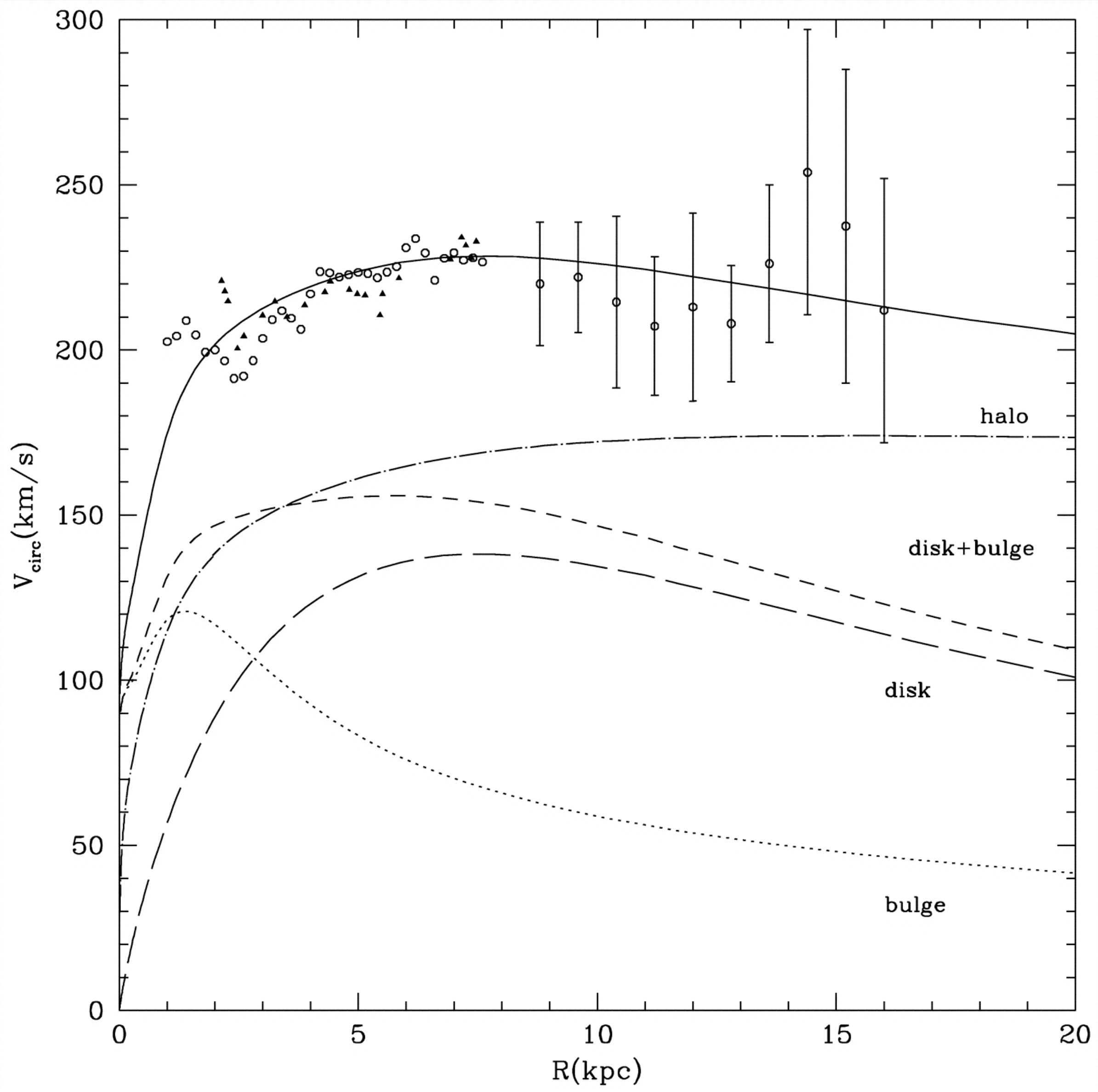
van Albada et al. 1985

Spirals/Disks: Kinematics

- Galaxy often characterized by:
  - V_{max}, i.e., maximum rotation velocity
  - Velocity at specified radius, e.g. 2.2 r_d, radius of maximum velocity for a pure exponential disk



Milky Way Rotation Curve



Klypin et al 2002

- Mass modeling from rotation curves

Galaxy Population - Spirals/Disks: Kinematics

- Amplitude and shape of rotation curve correlated with luminosity, but with significant scatter

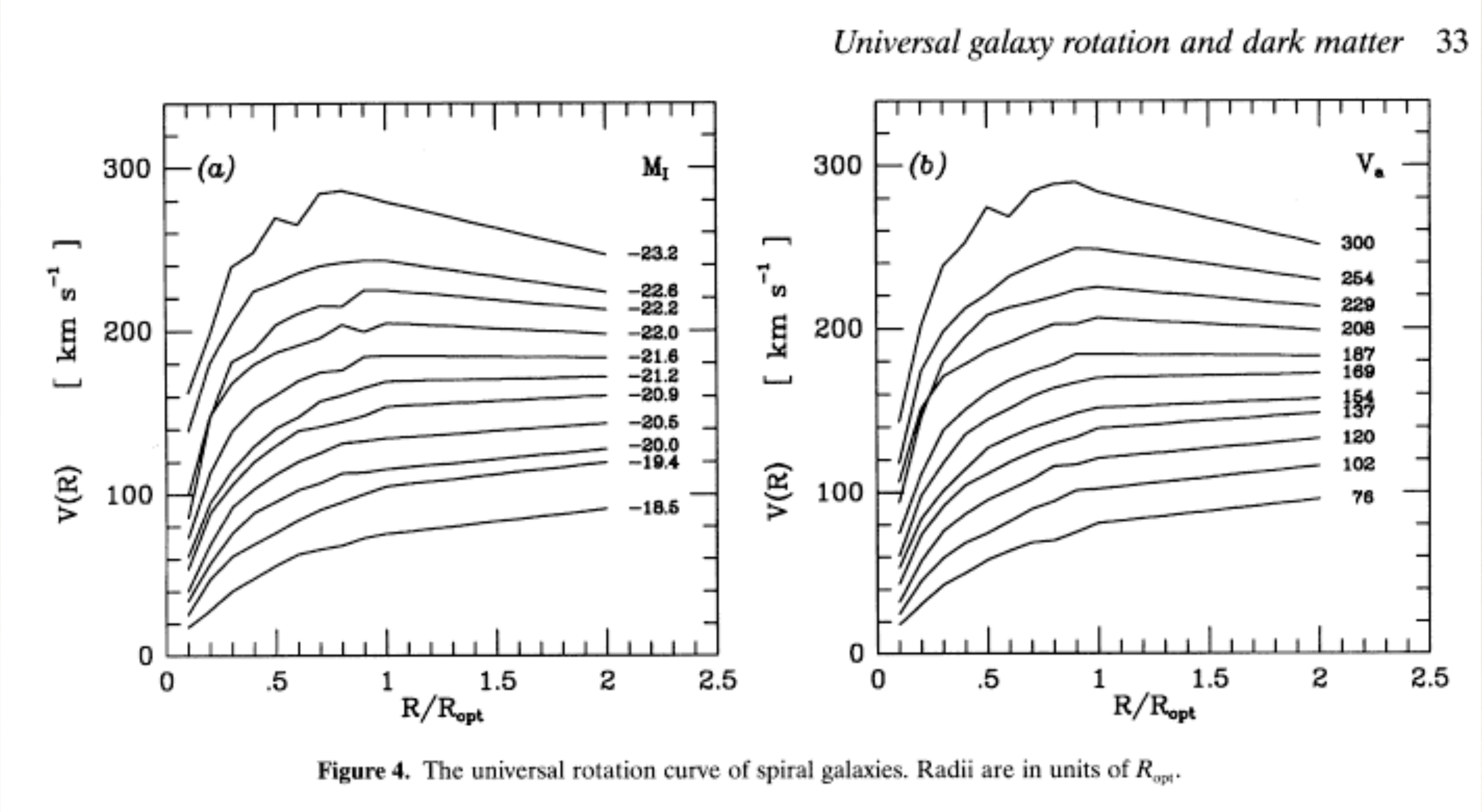


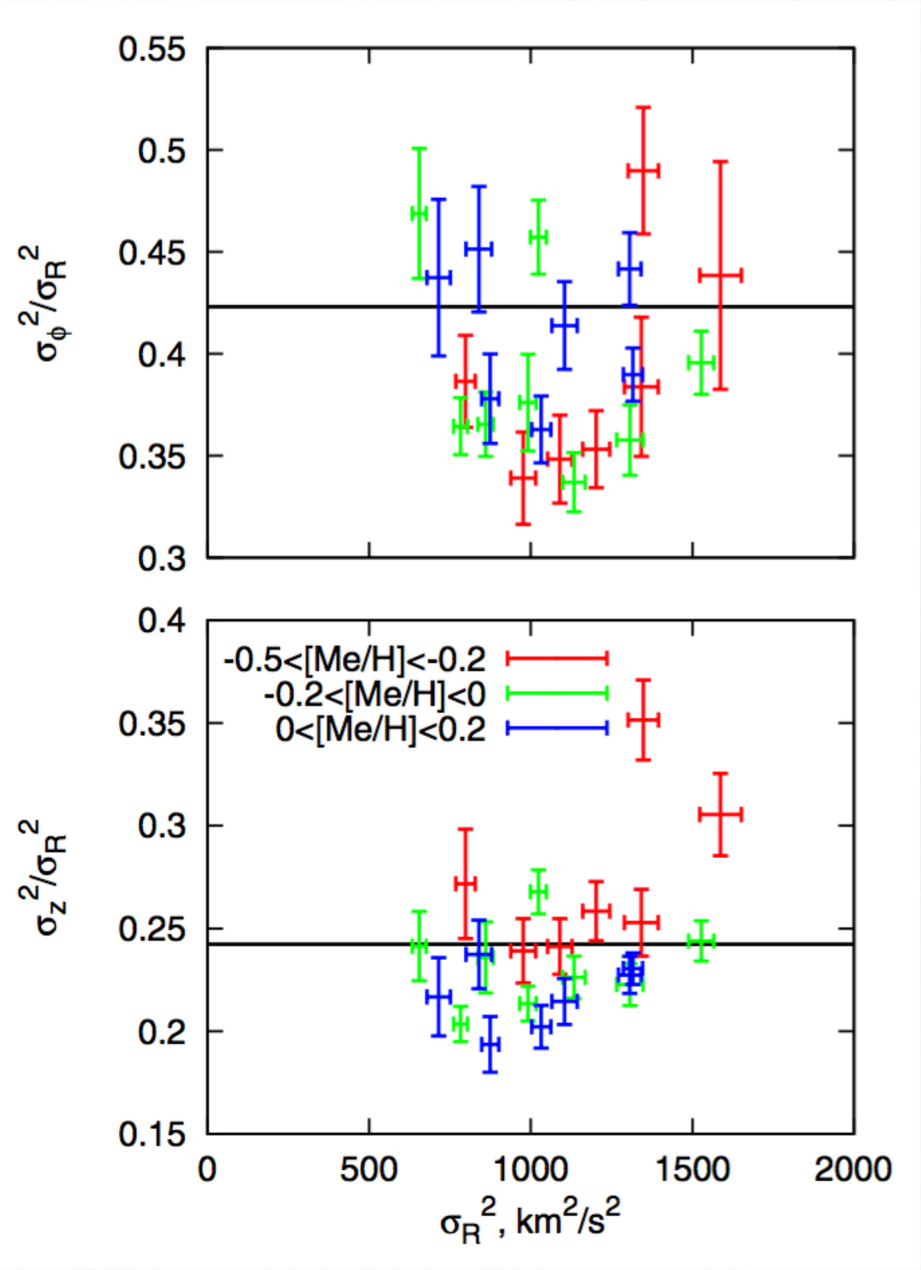
Figure 4. The universal rotation curve of spiral galaxies. Radii are in units of R_{opt}.

Persic, Salucci, & Stel 1996

Spirals/Disks: Kinematics

- Stars also have "random" motions, characterized by velocity ellipsoid:
  - velocity dispersion typically small (~few 10s km/s)
    - hard to observe in external galaxies, but known to exist in the solar neighborhood
  - velocity ellipsoid not isotropic

Solar Neighborhood



Golubov et al. 2013 (Radial Velocity Experiment, RAVE)

Spirals/Disks: Kinematics

- Velocity dispersion increases for redder, more metal-poor (~older) populations:
  - lag in rotation velocity ("**asymmetric drift**")
  - increased ellipticity of orbits ("**radial blurring**")
- Transient spiral structure may play an important role in angular momentum transfer for stars:
  - **radial migration** ("churning")

Solar Neighborhood

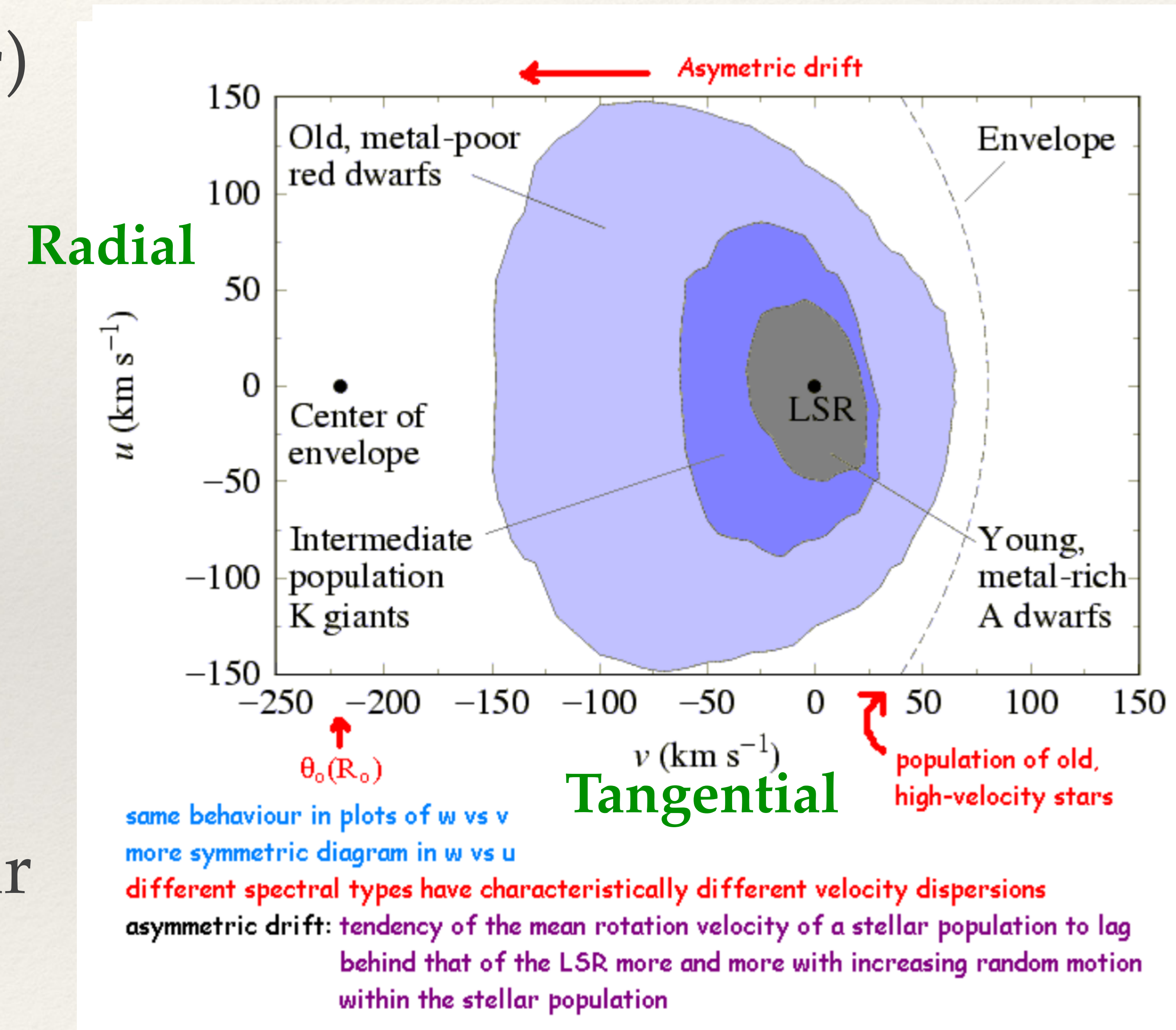


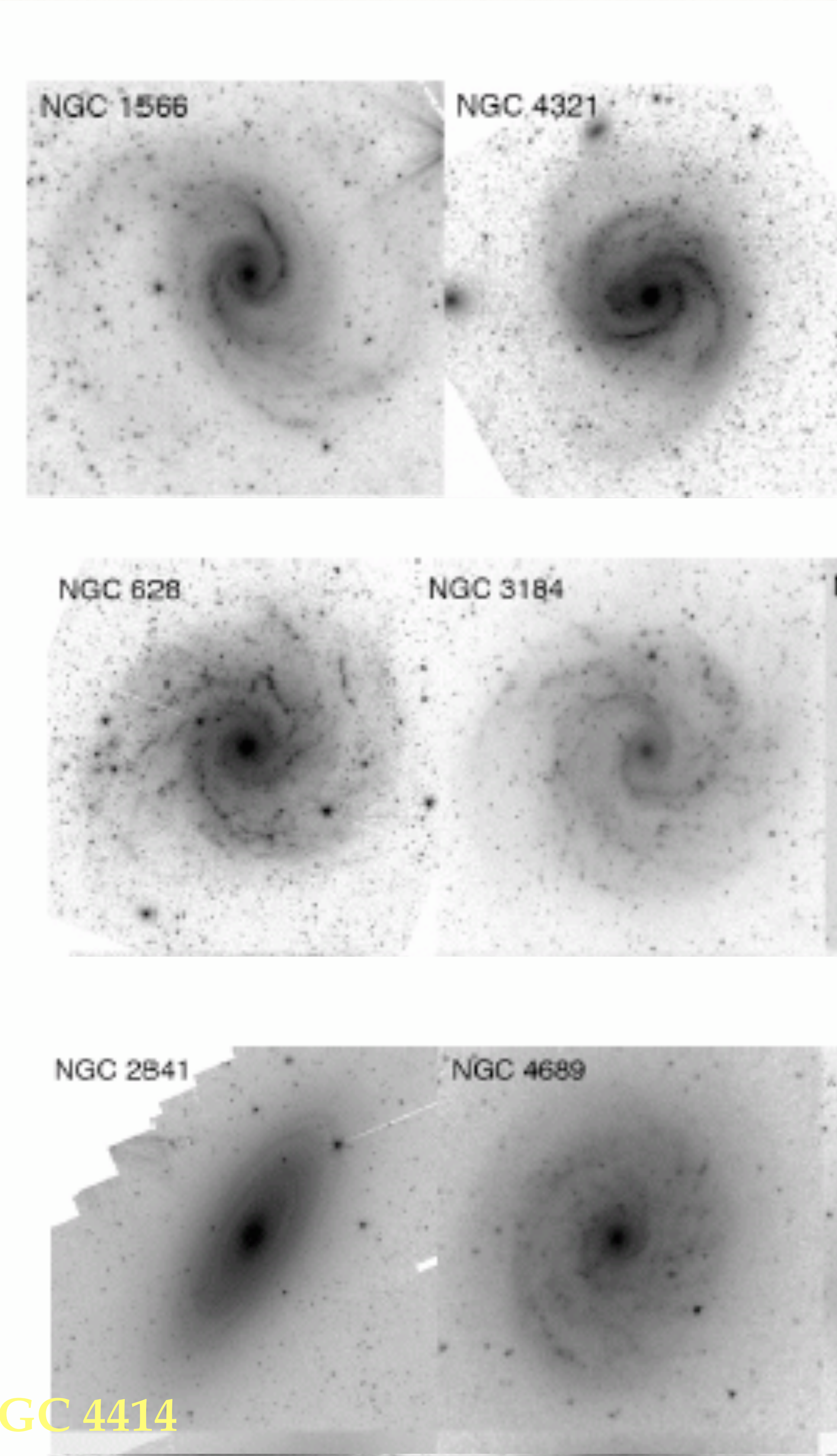
Image Credit: Doohyun Choi

Spirals/Disks: Arms

- How does spiral galaxy rotation affect spiral arms?

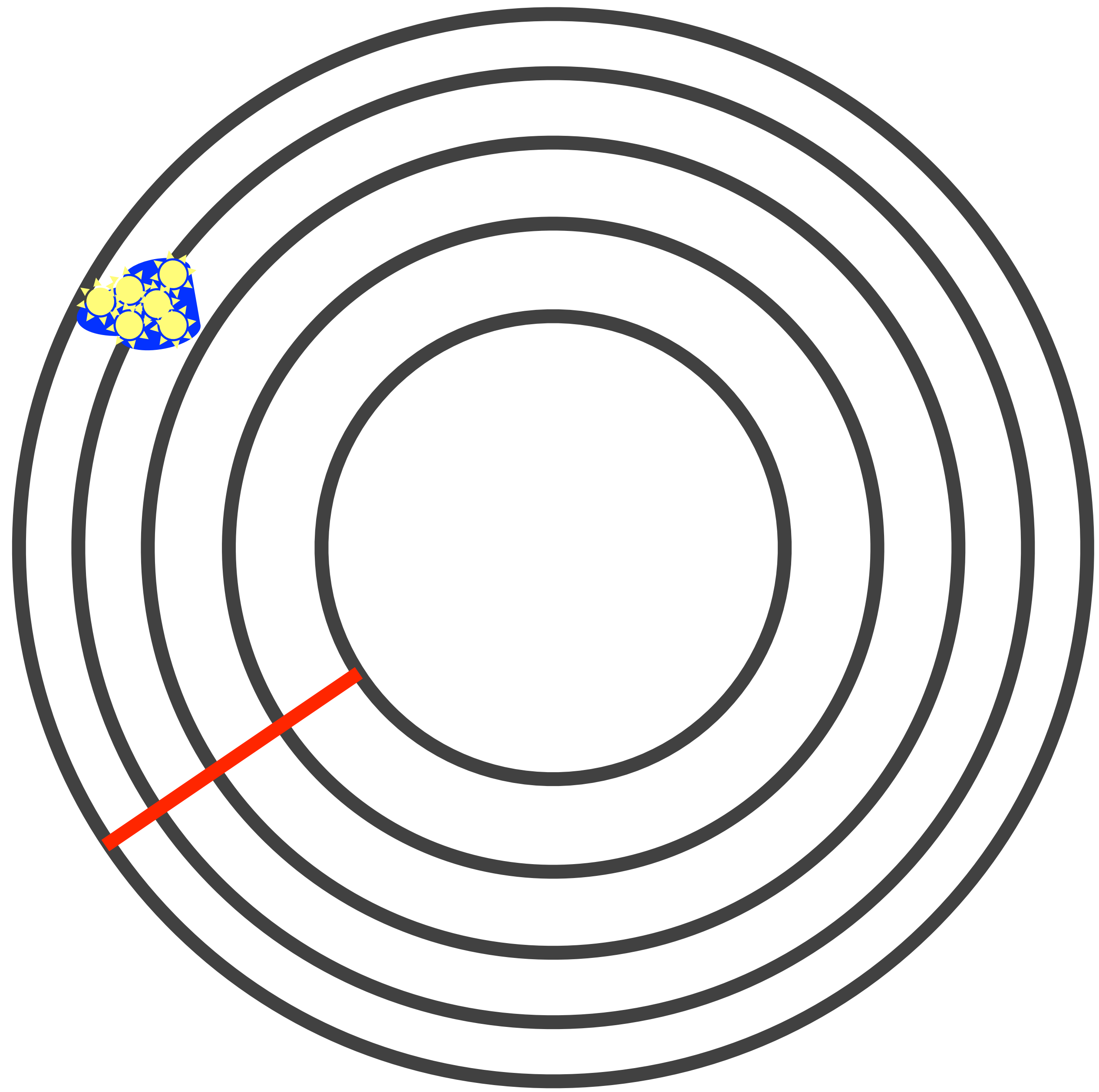
NGC 4414

Elmegreen et al. 2011



Thought Problem

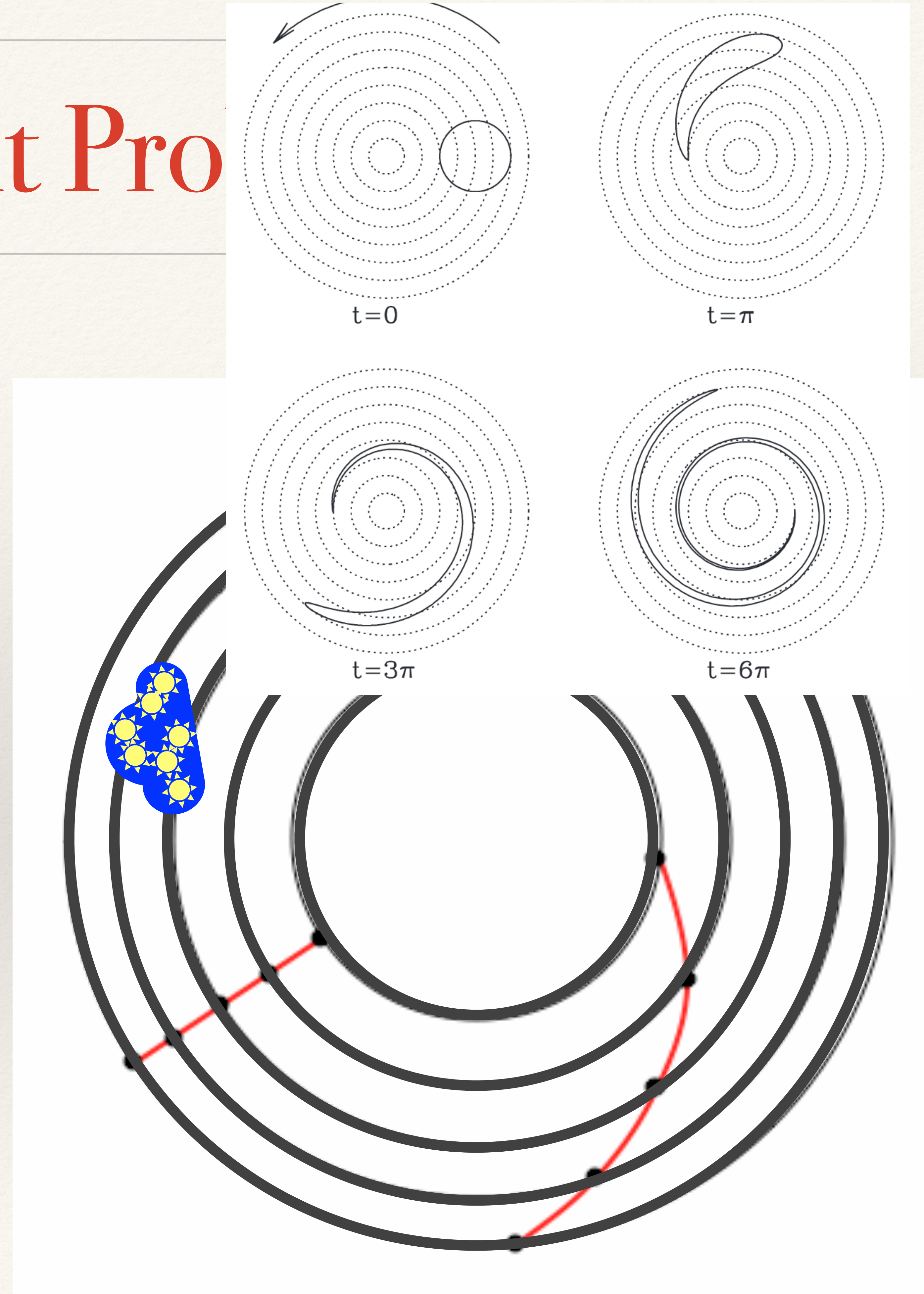
- Consider a simple rotating disk galaxy with a constant rotation velocity at large radii $V(r) = V_{max}$
  - Suppose **patch of stars** formed at a particular location in the disk. What would happen to the appearance of this patch over time?
  - Suppose the disk had a well-defined **arm** moving at $V(r) = V_o$. What would happen after a few rotation periods?



Thought Pro

- Consider a simple rotating disk galaxy with a constant rotation velocity at large radii $V(r) = V_o$
  - Suppose **patch of stars** formed at a particular location in the disk. What would happen to the appearance of this patch over time?
  - Suppose the disk had a well-defined **arm** moving at $V(r) = V_o$. What would happen after a few rotation periods?

Figure 11.7 - Galaxy Formation and Evolution, Mo, van den Bosch, & White

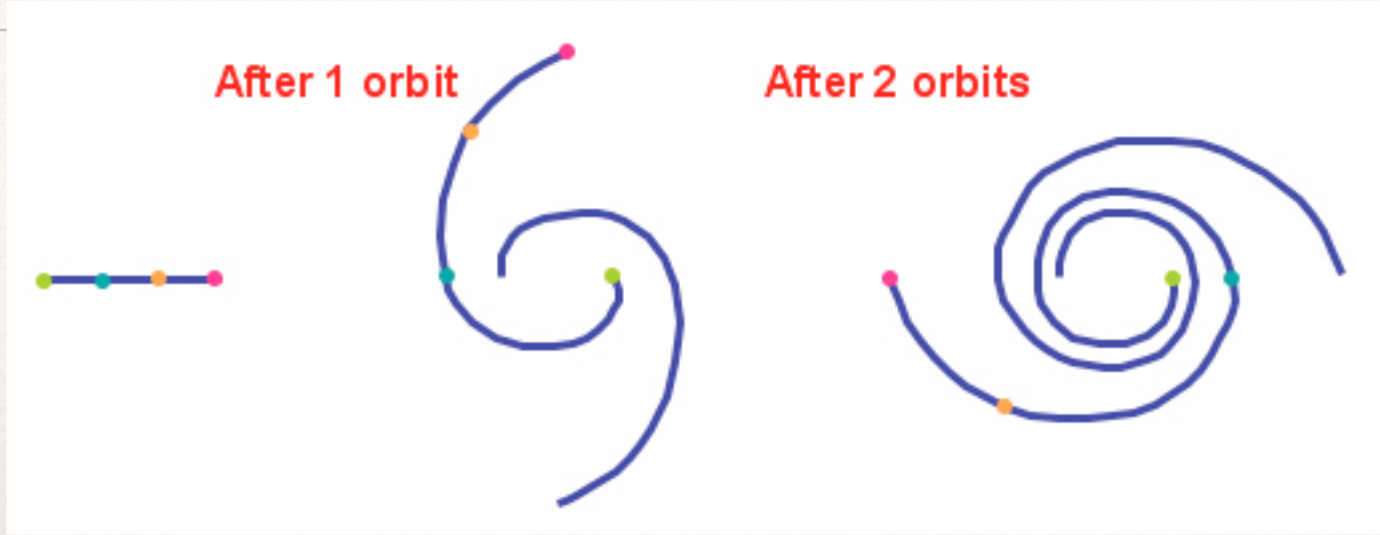


Thought problem

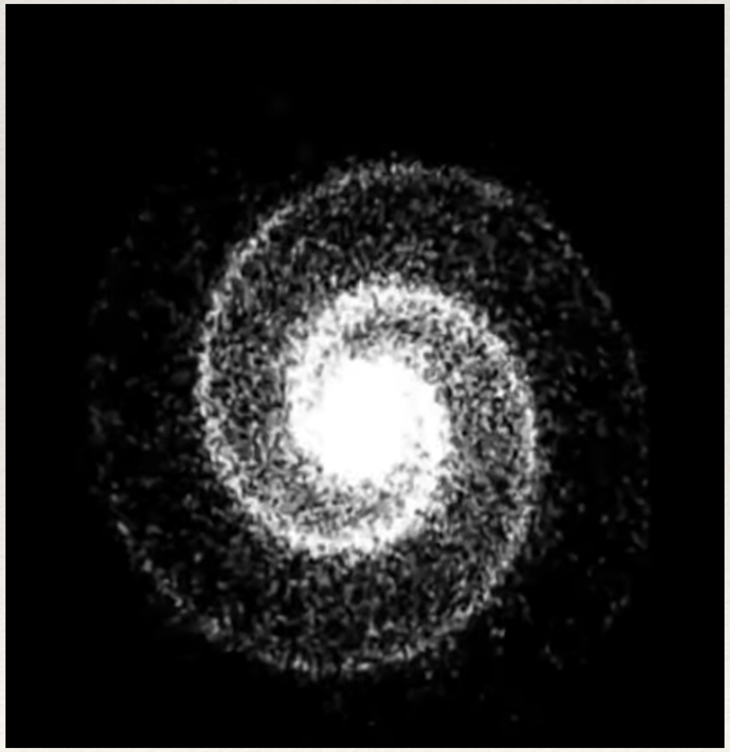
- pi al spiral li e t e il a as lat rotation curve at m s at p
  - p . m
- How long is a rotation period?
- at is t e impli ation or t e e ol tion o a i ed spiral pattern?

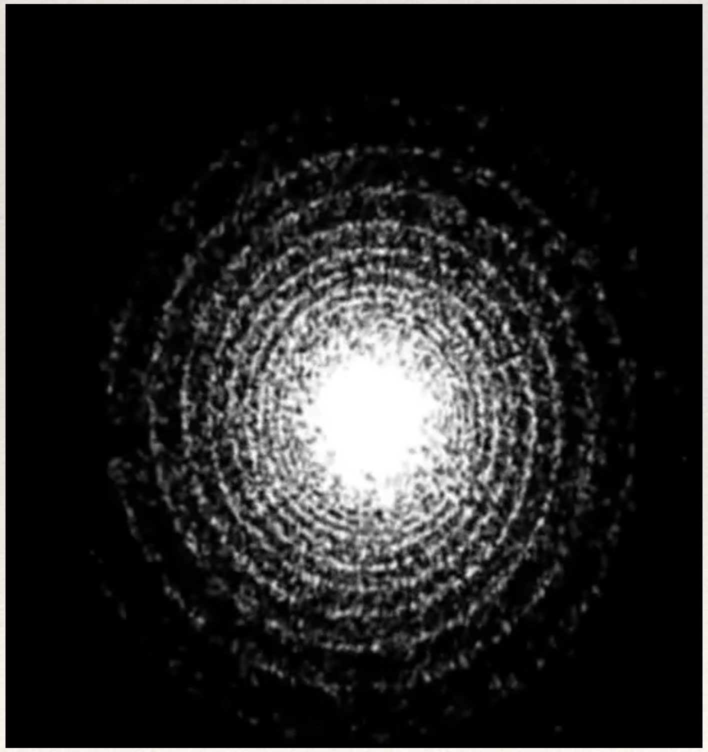
Spirals/Disks: Arms

- Spiral arms can't be a physical spiral
- Material takes longer to orbit at larger radii ("differential rotation")
- Arms would get wound up after just a few orbits ("winding problem")



http://astronomy.swin.edu.au/cosmos/W/Winding+Problem

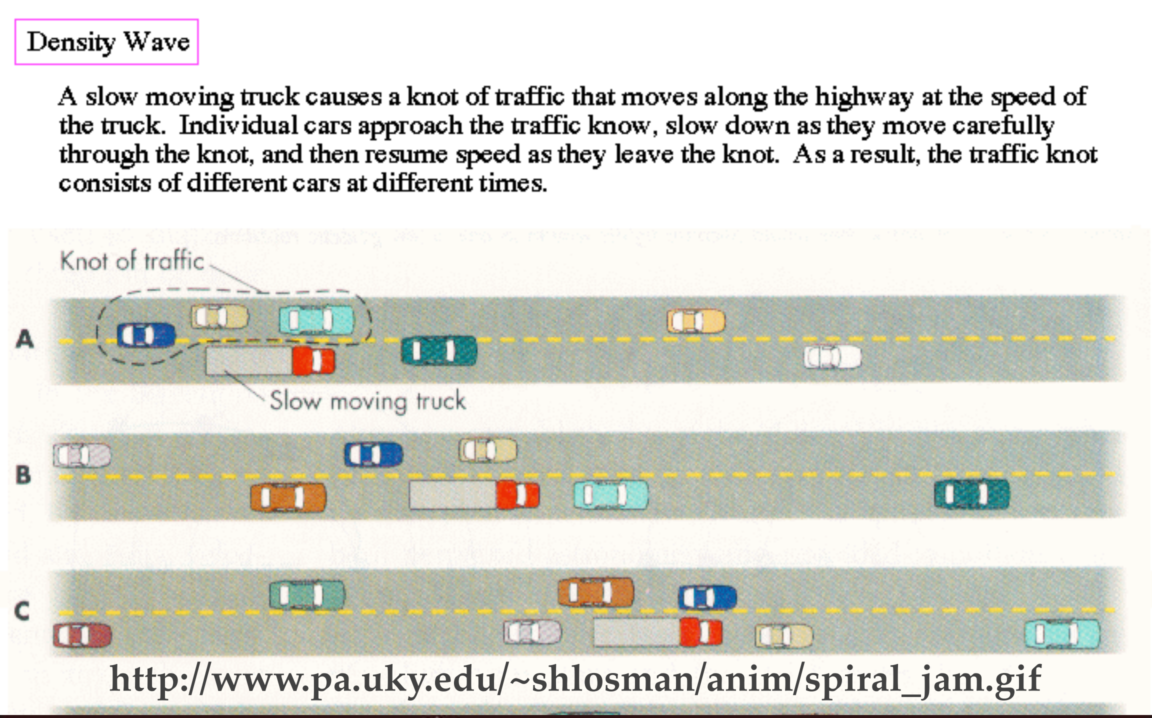


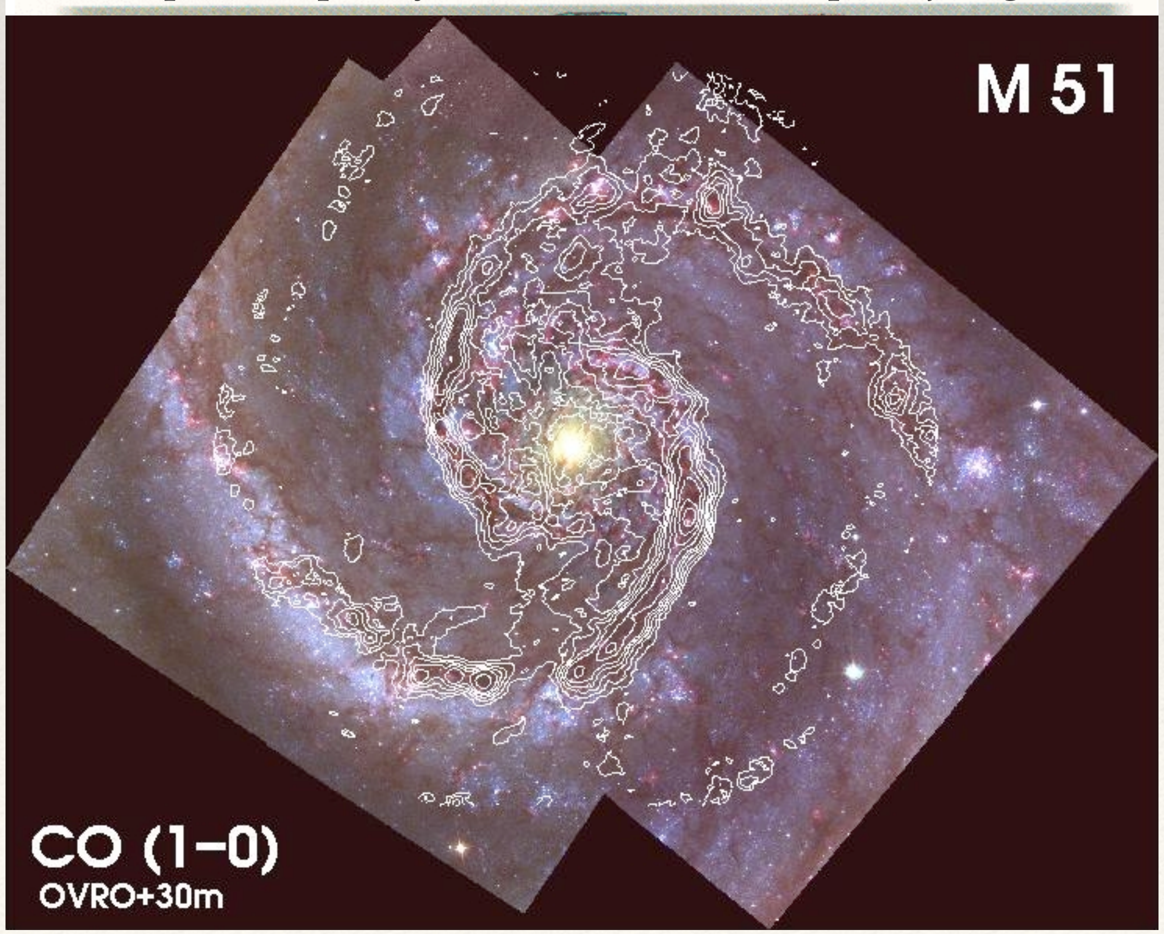


https://www.youtube.com/watch?v=_GNPvYdvZAQ

Spirals/Disks: Arms

- Spiral arms are often a **density wave pattern** moving at a speed different from stars/gas
- Stars/gas move through the arm as they overtake or are overtaken by density wave
- Density waves themselves have a pattern speed, so they will still wrap, but the winding time is longer
- Many inner arms have dust lanes, HII regions, HI/CO concentrated on inside (concave) edge:
    - stars/gas overtaking pattern
    - gas compressed in density wave triggering star formation





Spirals/Disks: Arms

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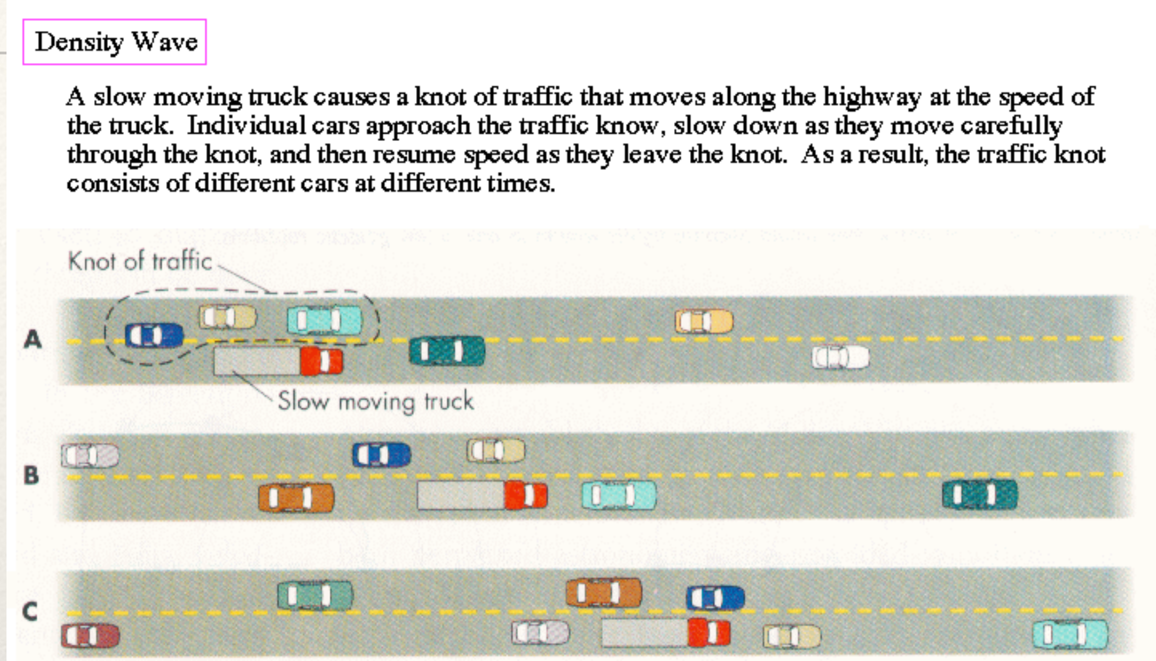
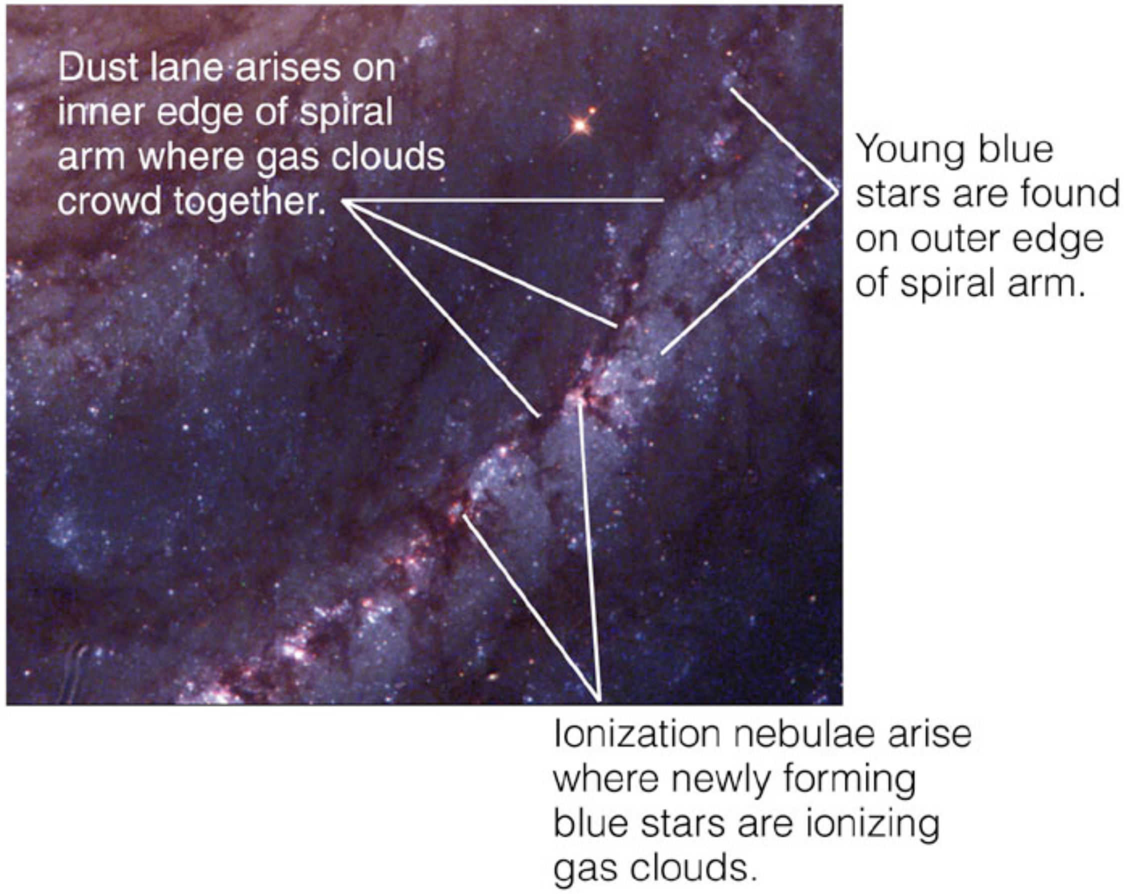
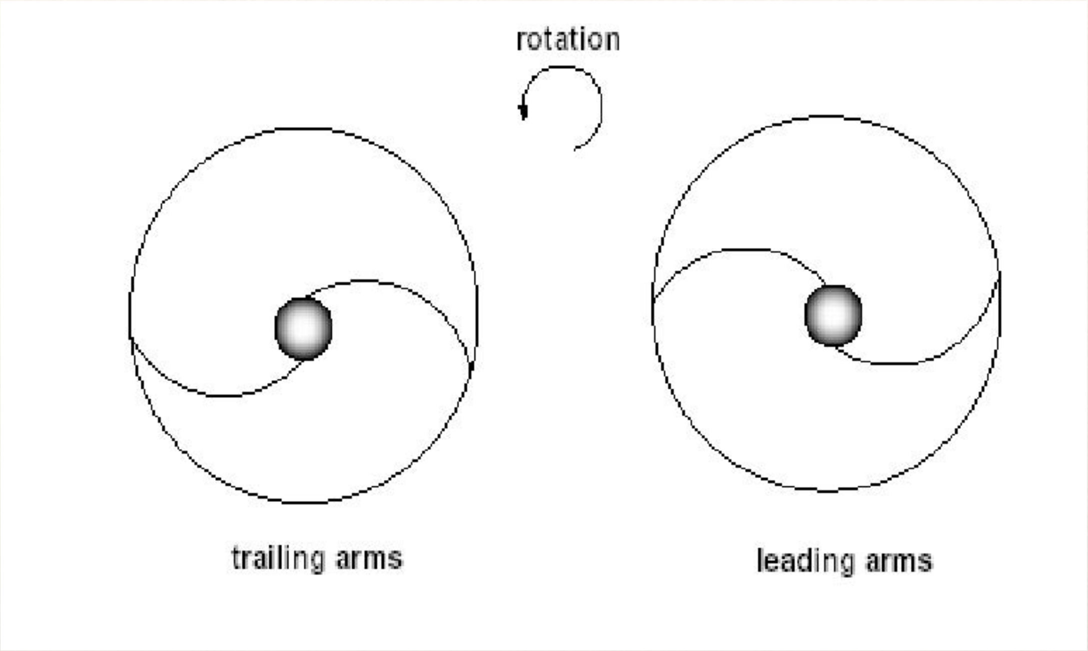


http://www.pa.uky.edu/~shlosman/anim/spiral_jam.gif



Thought Question

- How can we tell if spiral arms are "trailing" (i.e. spiral winds behind the rotation) versus "leading"?

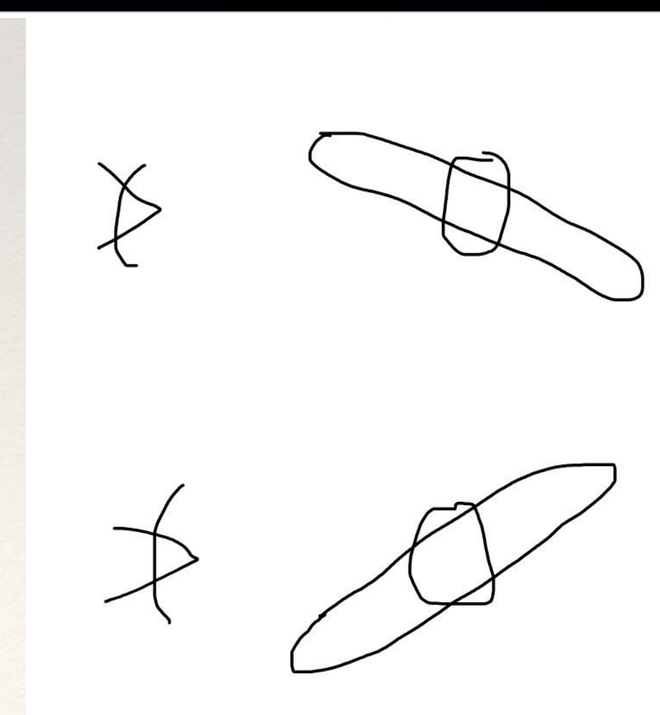


Thought Question

- n an in lined gala , not so eas to tell!

Need to know which way material is moving and which side of galaxy is closer!

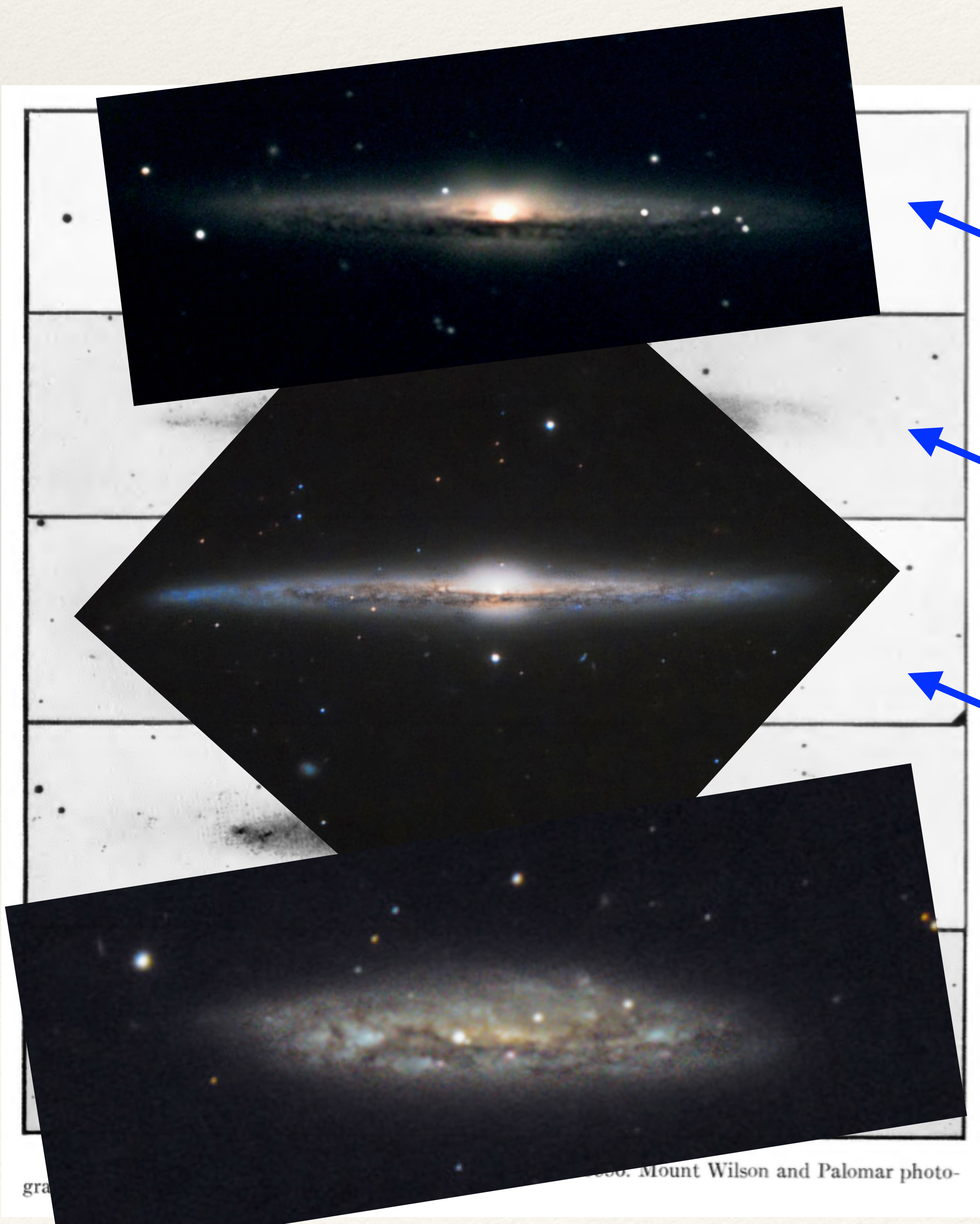
Look for evidence of more prominent dust lanes on near side



Spirals/Disks: Arms

- Edge-on galaxies — easy to tell near side, but hard to see arms

de Vaucouleurs 1958



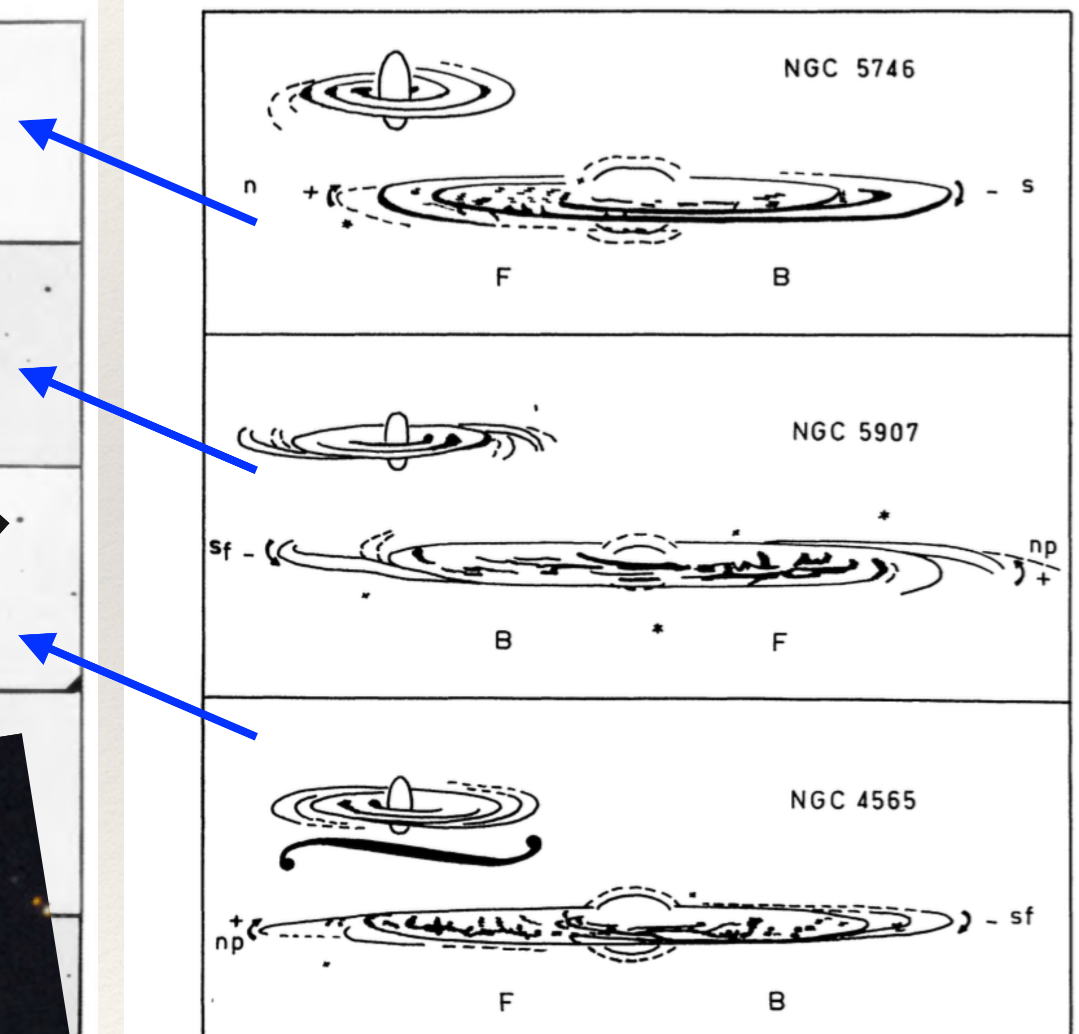


FIG. 2.—Determination of the sense of the spiral pattern in class 1 spirals. The sense of the spiral pattern is directly traceable in NGC 5746; it is indicated by the faint extremities of the arms in NGC 5907 and by the related "twist" of the outline of the disk in NGC 4565. The sense of the spiral pattern is also related to the longitudinal asymmetry of the luminosity distribution as indicated by the letters *B* (bright) and *F* (faint) in each case. The orientation and the direction of the spectroscopic rotation are also marked. All sketches are traced from 200-inch photographs. The insets show schematically the spiral pattern partly deprojected to facilitate the interpretation of the sketches and photographs.

Spirals/Disks: Arms

- Edge-on galaxies — easy to tell near side, but hard to see arms

de Vaucouleurs 1958

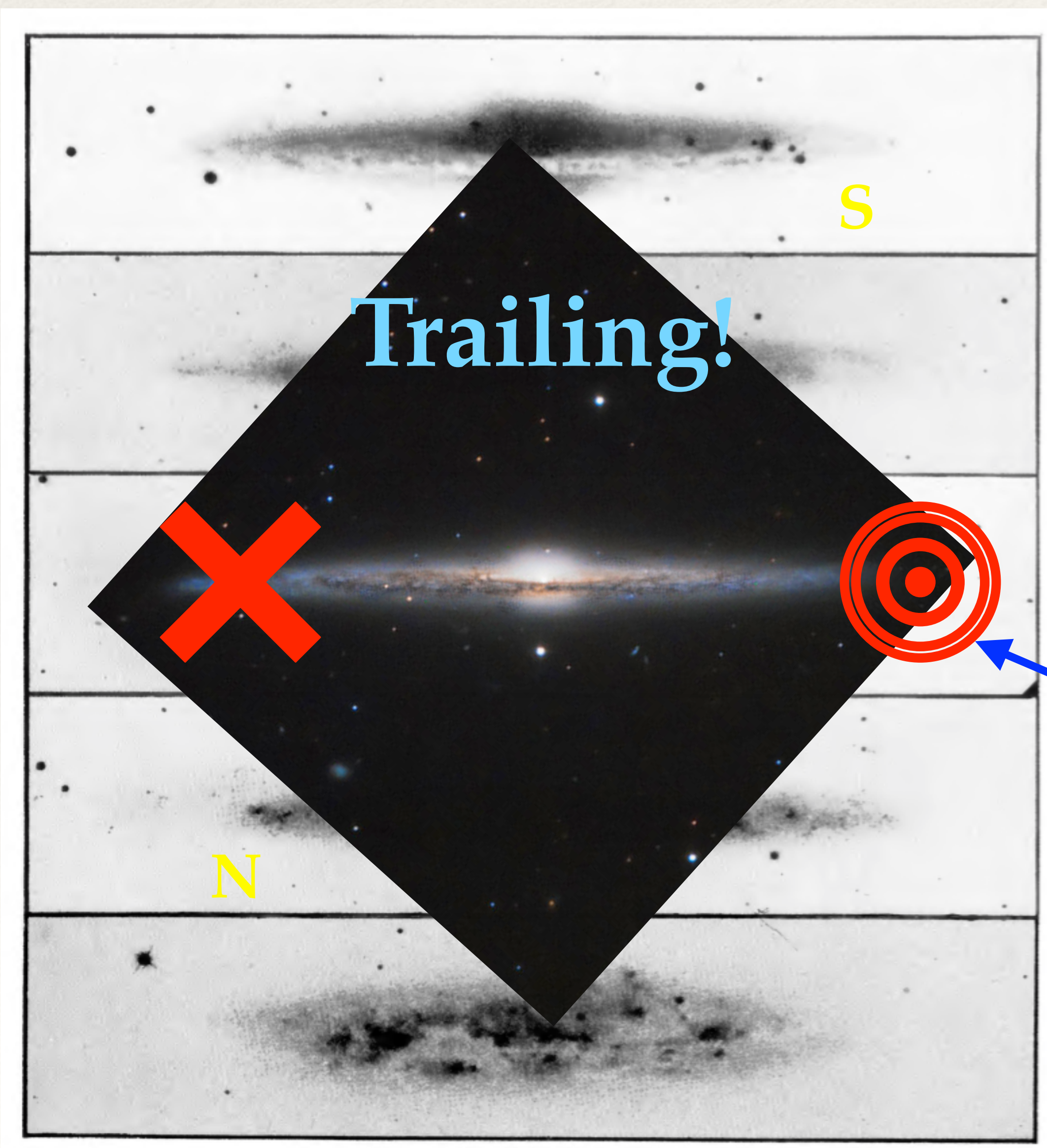
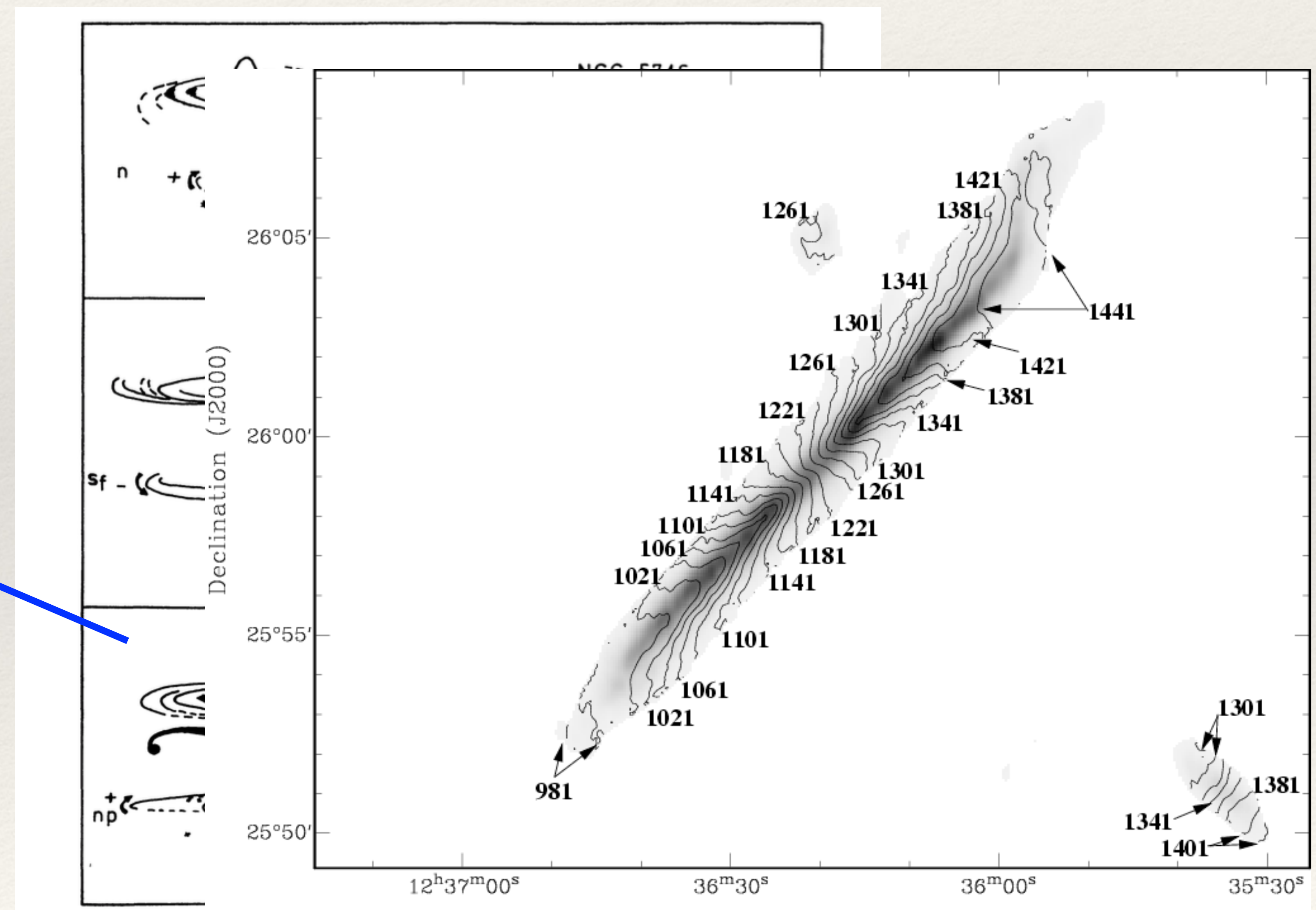


FIG. 3.—Class 1 spirals NGC 5746, 5907, 4565, 4244, and 3556. Mount Wilson and Palomar photographs with the 200-inch reflector.



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Dahlem et al. 2005

Spirals/Disks: Arms

- Moderately inclined galaxies — easy to tell near side, better view of arms

Fig. 5.—Class 2 and class ... and 2841. Mount Wilson and Palomar photographs with the 200-inch ...

de Vaucouleurs 1958

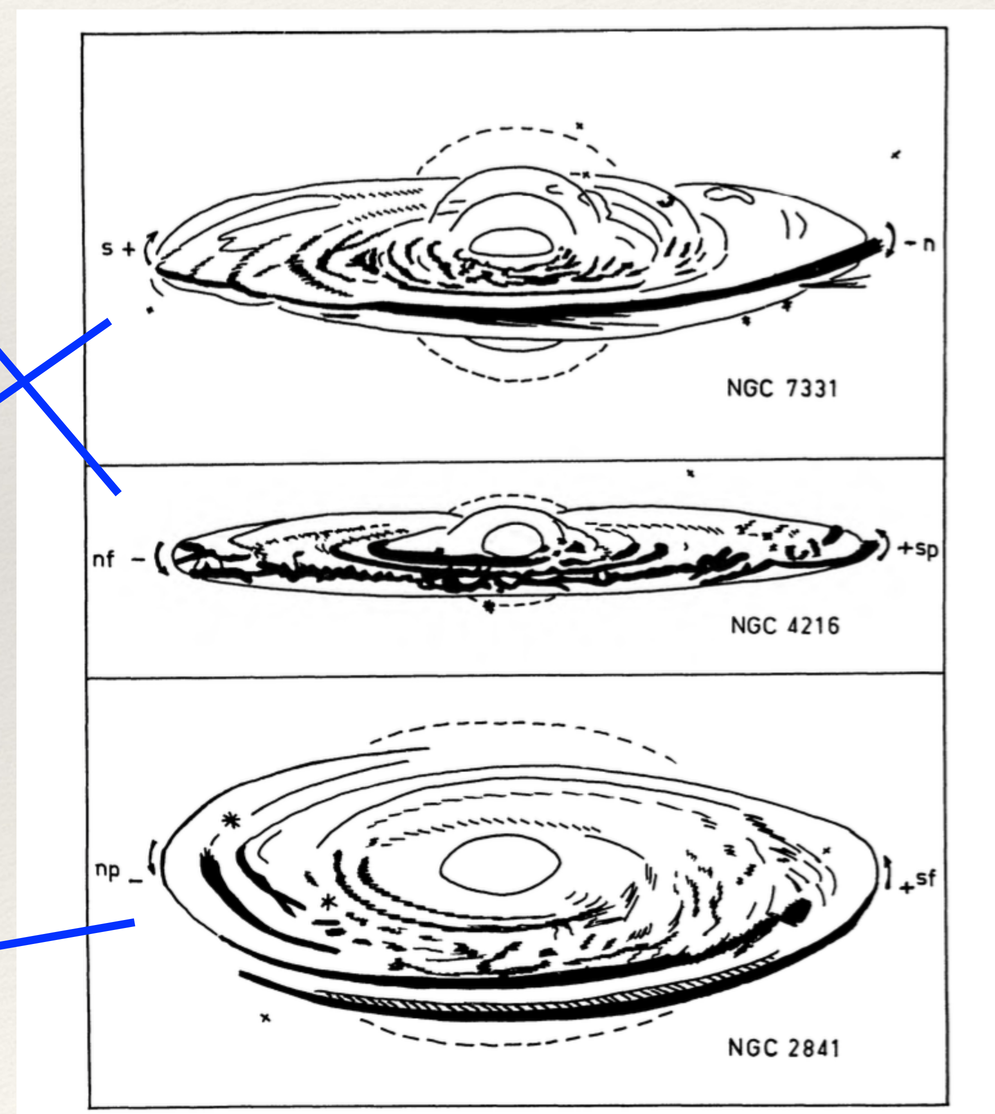
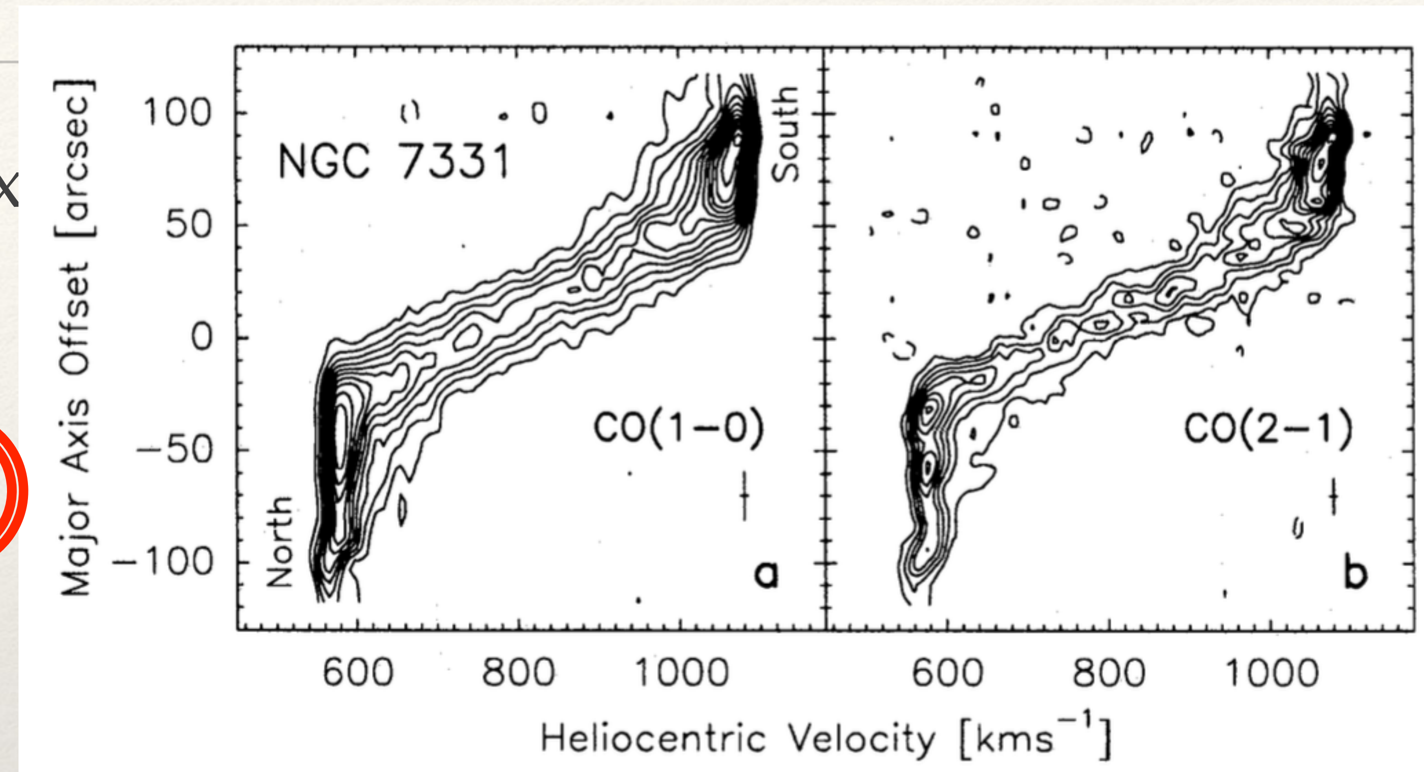


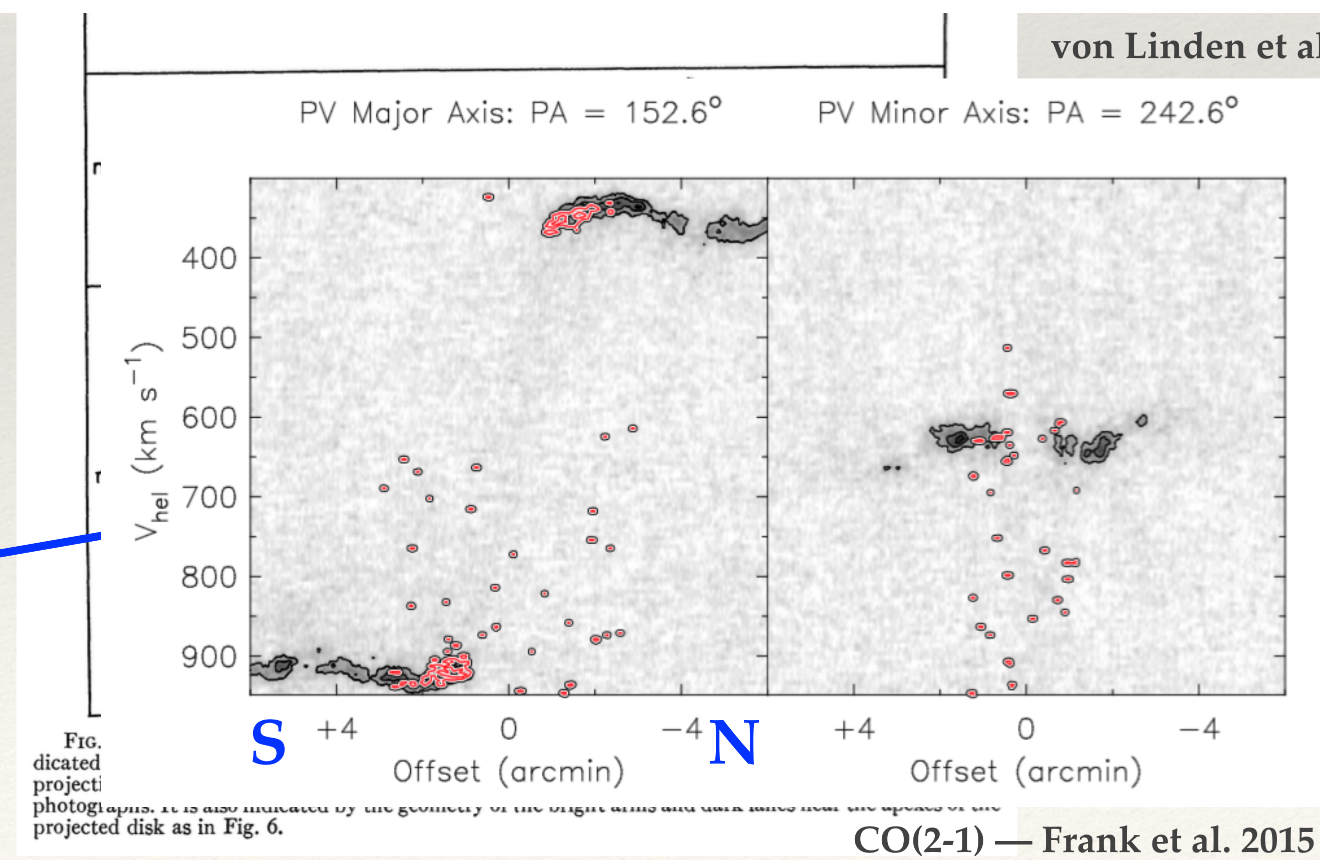
Fig. 4.—Determination of the near side in class 2 and class 3 spirals. The near side of the disk is indicated in NGC 7331, NGC 4216 and possibly NGC 2841 by the primary criterion of tilt, namely, the projection of the outer dark lane against the outer regions of the central bulge traced from 200-inch photographs. It is also indicated by the geometry of the bright arms and dark lanes near the apexes of the projected disk as in Fig. 6.

Spirals/Disks: Arms

- Moderately inclined galax … rms



von Linden et al. 1996



CO(2-1) — Frank et al. 2015

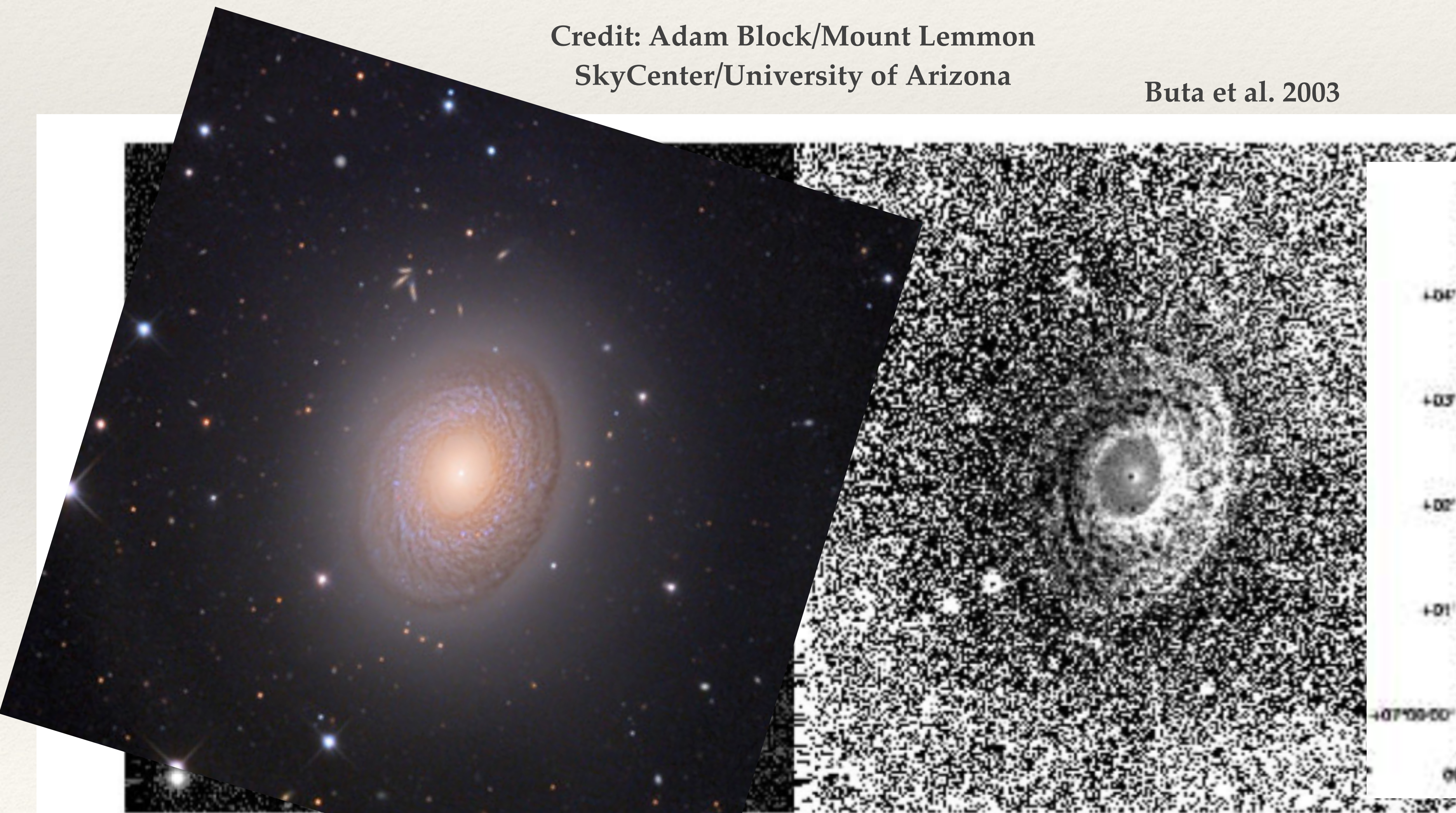
Spirals/Disks: Arms

de Vaucouleurs 1958

- Closer to face-on galaxies — easy to spiral arms, harder to tell near side — but possible with good data!

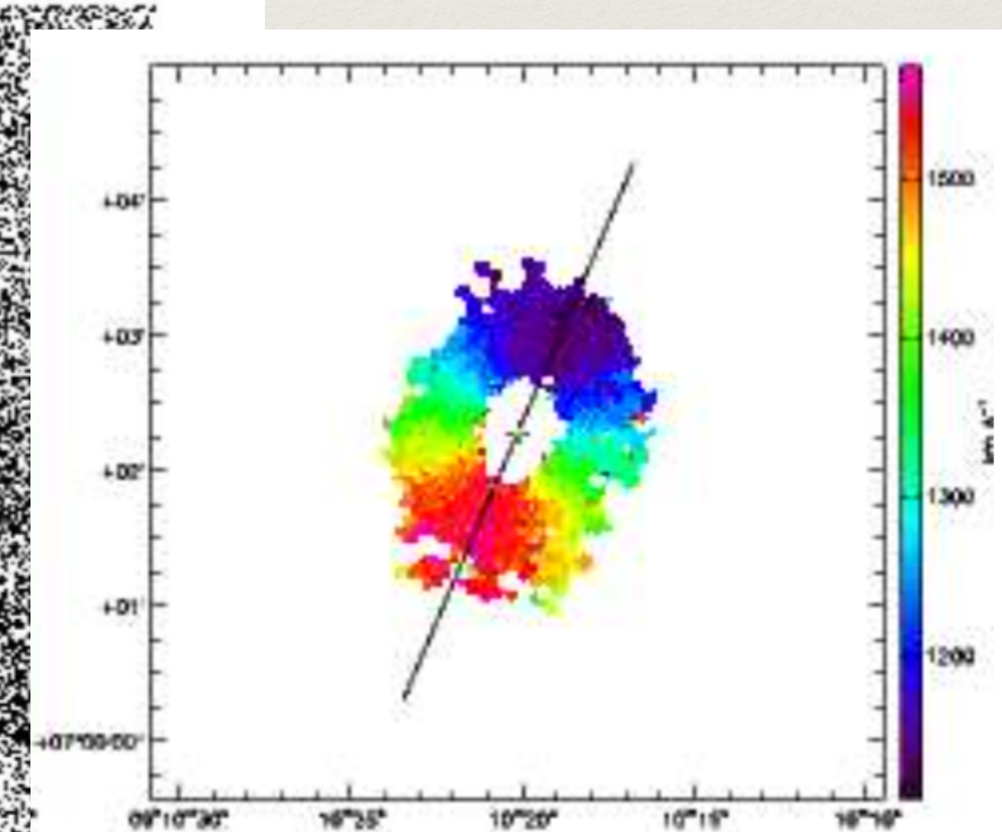
NGC 2775
i~40 degrees

Credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona



Buta et al. 2003

FIG. 19.—*Left*: *B*-band image of NGC 277… …axy Survey. *Right*: *B*–*H* color index map, coded such that redder regions are light and bluer regions are dark. Although the inclination is only … conclusively shows that the west side of NGC 2775 is the near side. The field shown is 6'.4 square. North is to the top, and east to the left.



Epinat et al. 2008

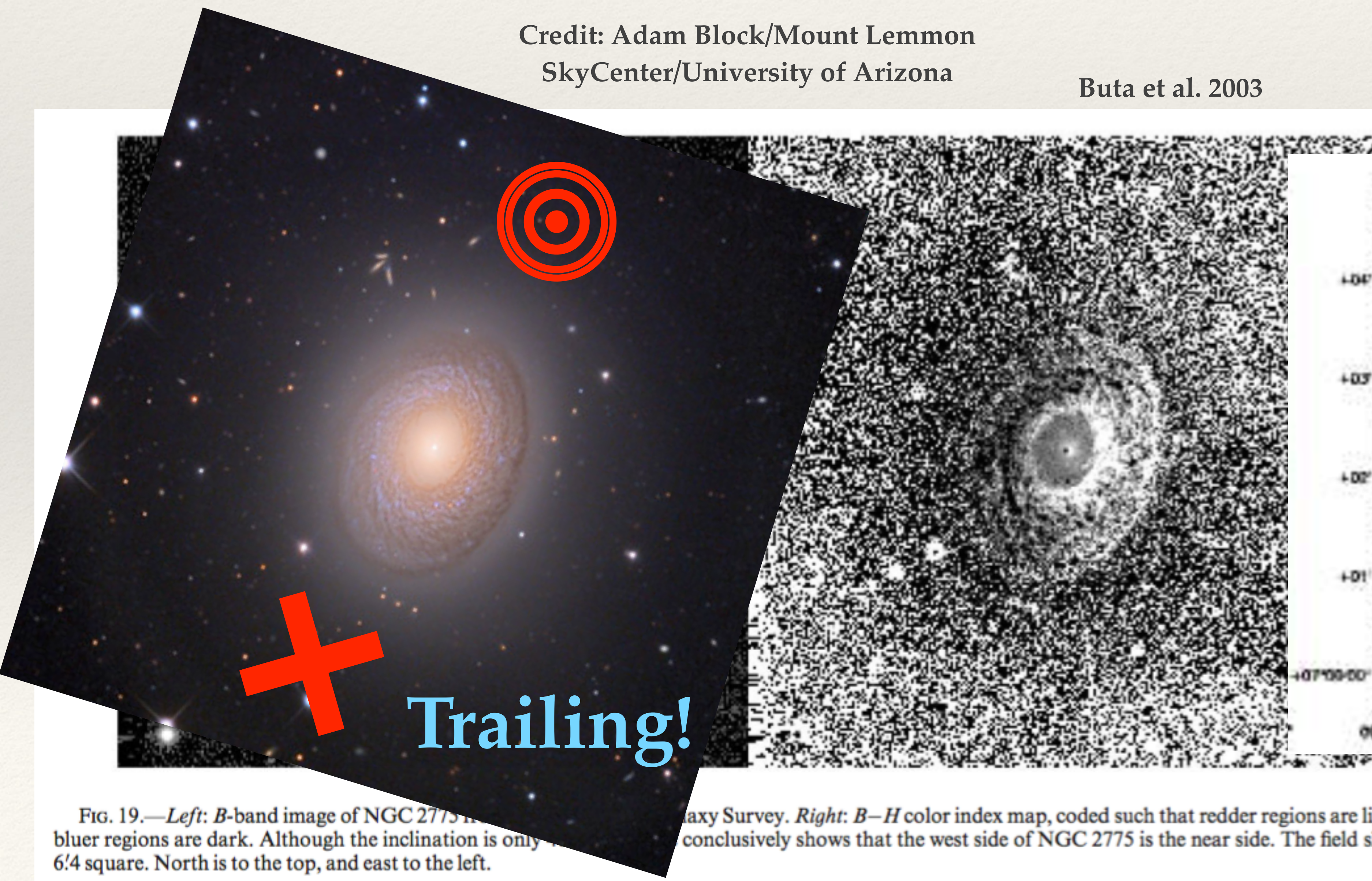
Spirals/disks : arms

de Vaucouleurs 1958

- Closer to face-on galaxies — easy to spiral arms, harder to tell near side — but possible with good data!

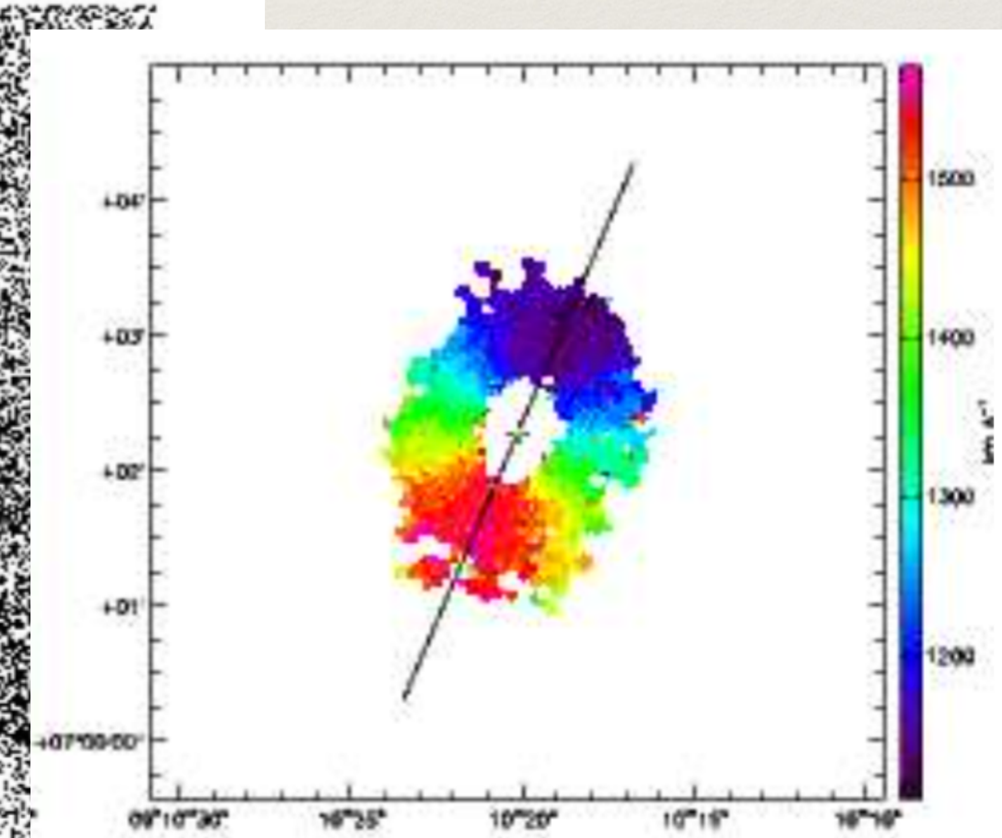
NGC 2775
i~40 degrees

Credit: Adam Block/Mount Lemmon SkyCenter/University of Arizona



Buta et al. 2003

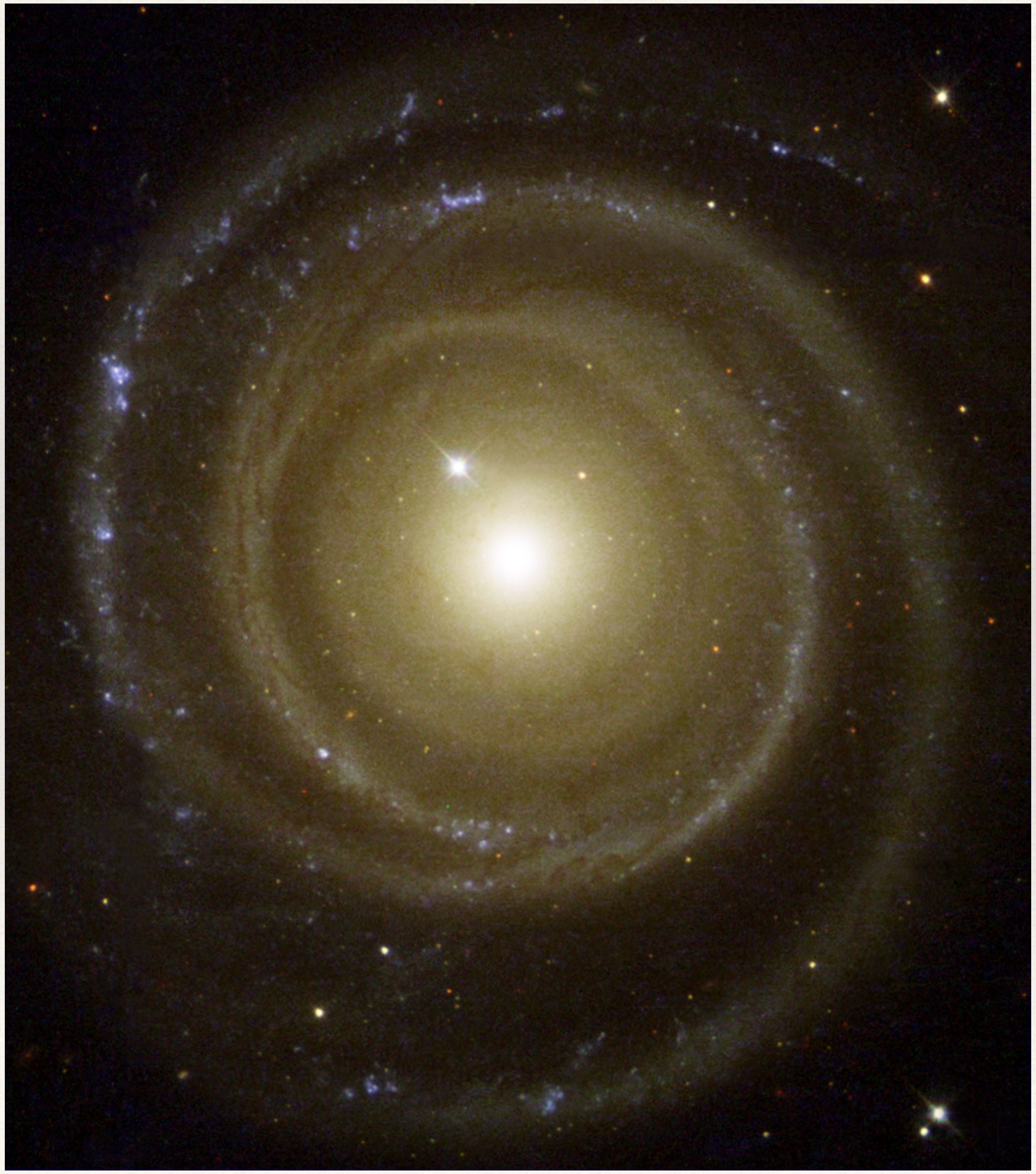
FIG. 19.—*Left*: *B*-band image of NGC 277… …axy Survey. *Right*: *B*−*H* color index map, coded such that redder regions are light and bluer regions are dark. Although the inclination is only … conclusively shows that the west side of NGC 2775 is the near side. The field shown is 6′.4 square. North is to the top, and east to the left.



Epinat et al. 2008

Spirals/Disks: Arms

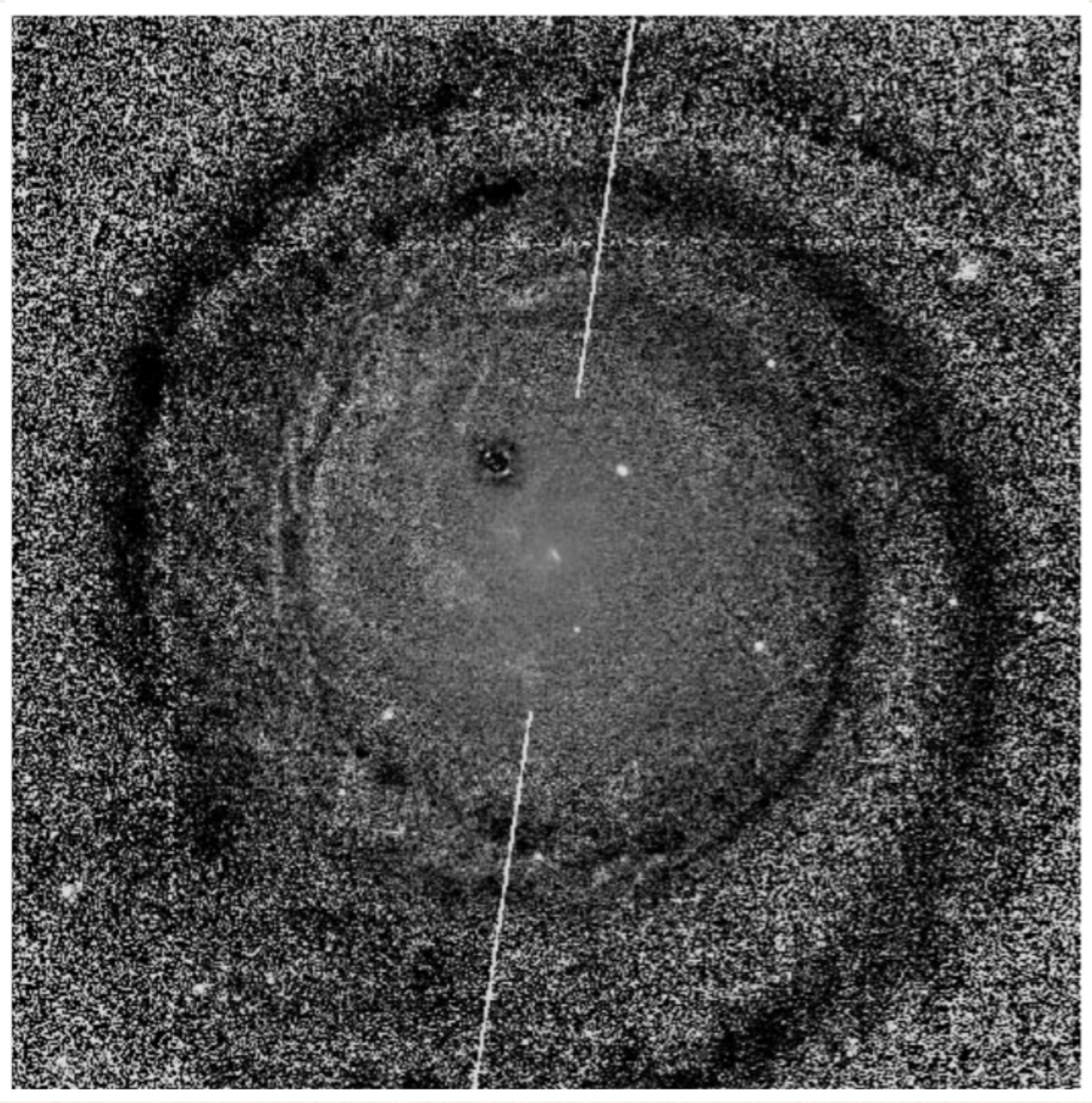
NGC 4622
i~20 degrees



NASA and the Hubble Heritage Team (STScI/AURA)

- Nearly face-on — need high resolution HST imaging

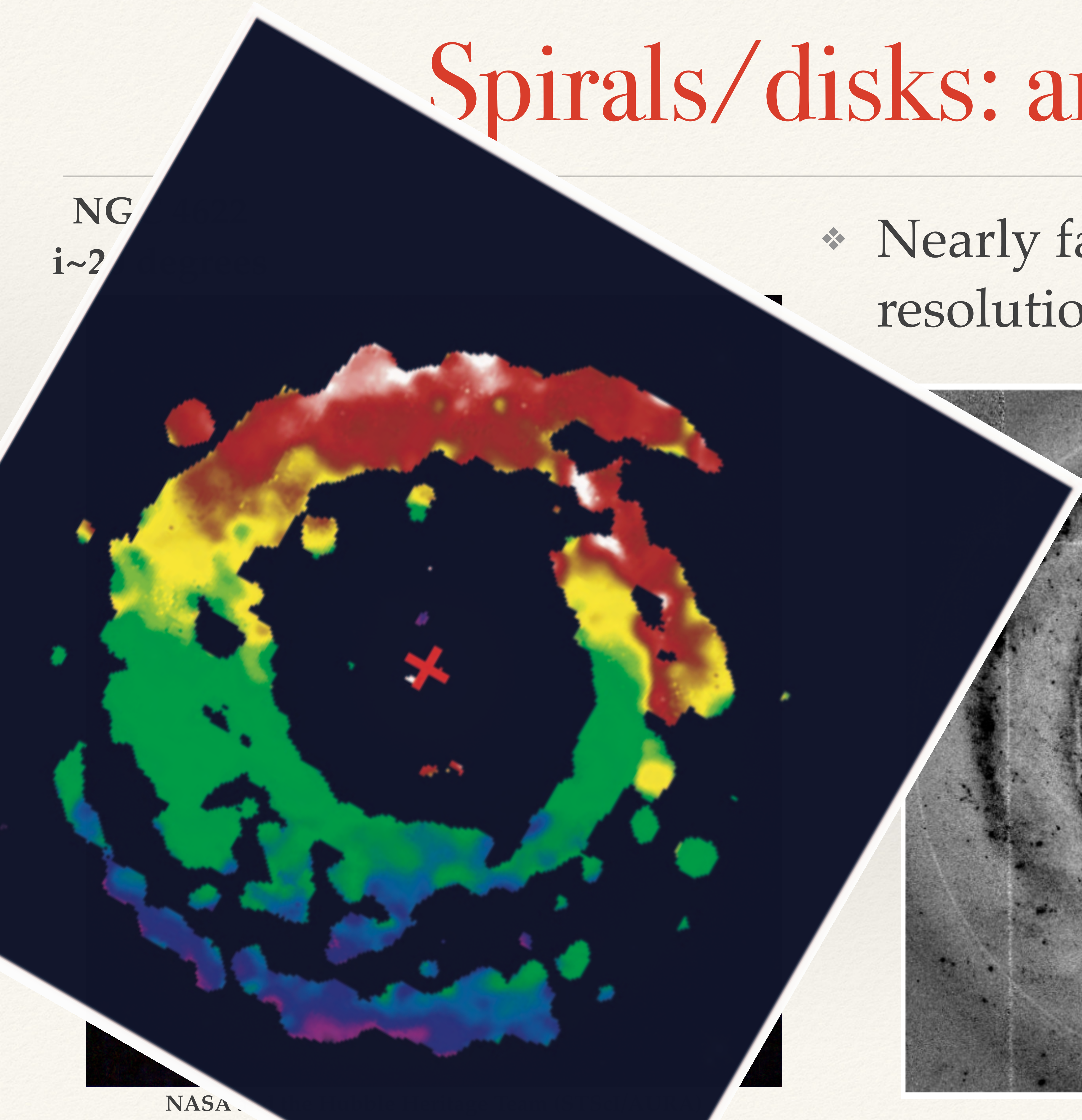
Buta et al. 2003



Spirals/disks: arms

NG

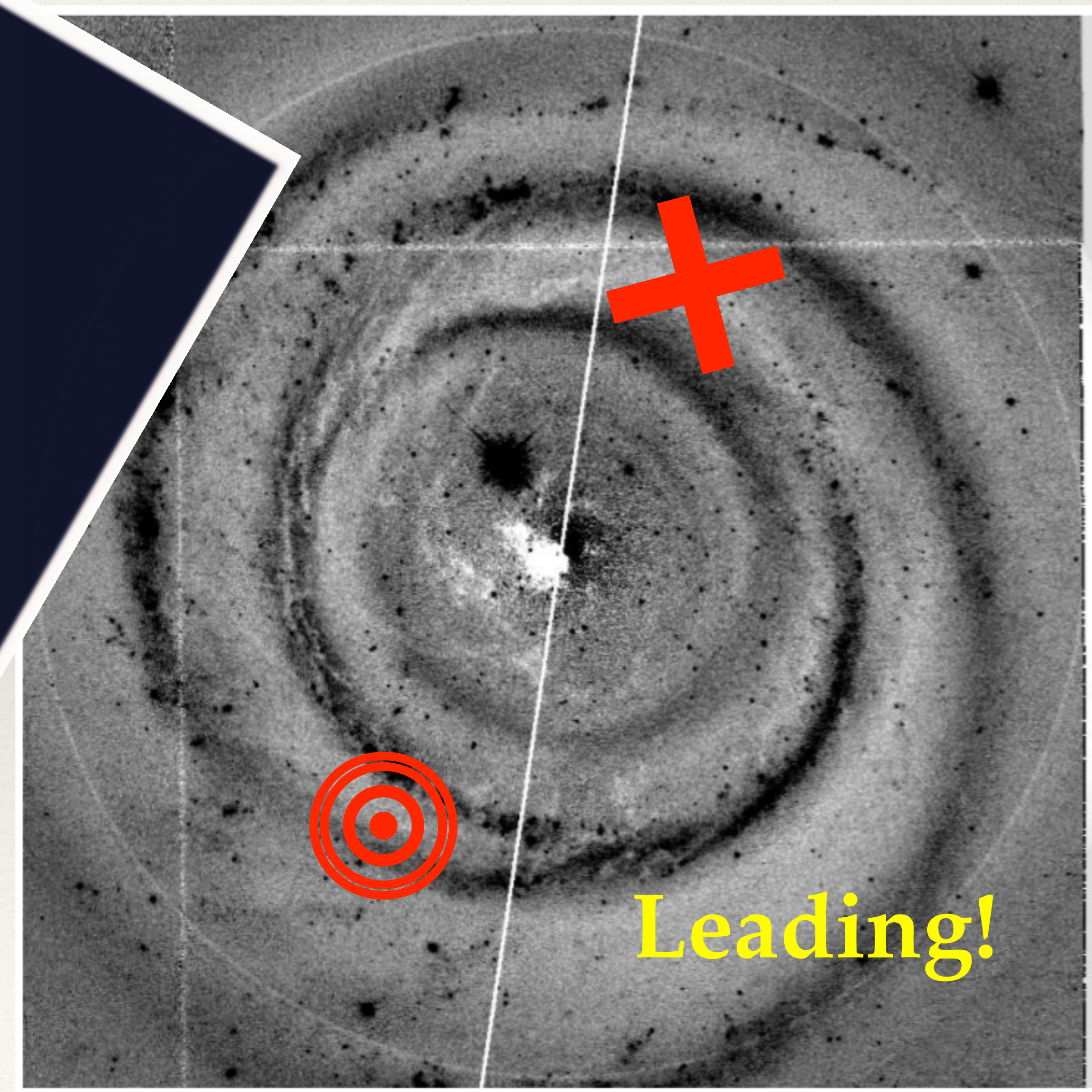
i~2



NASA

- Nearly face-on — need high resolution HST imaging!

Buta et al. 2003

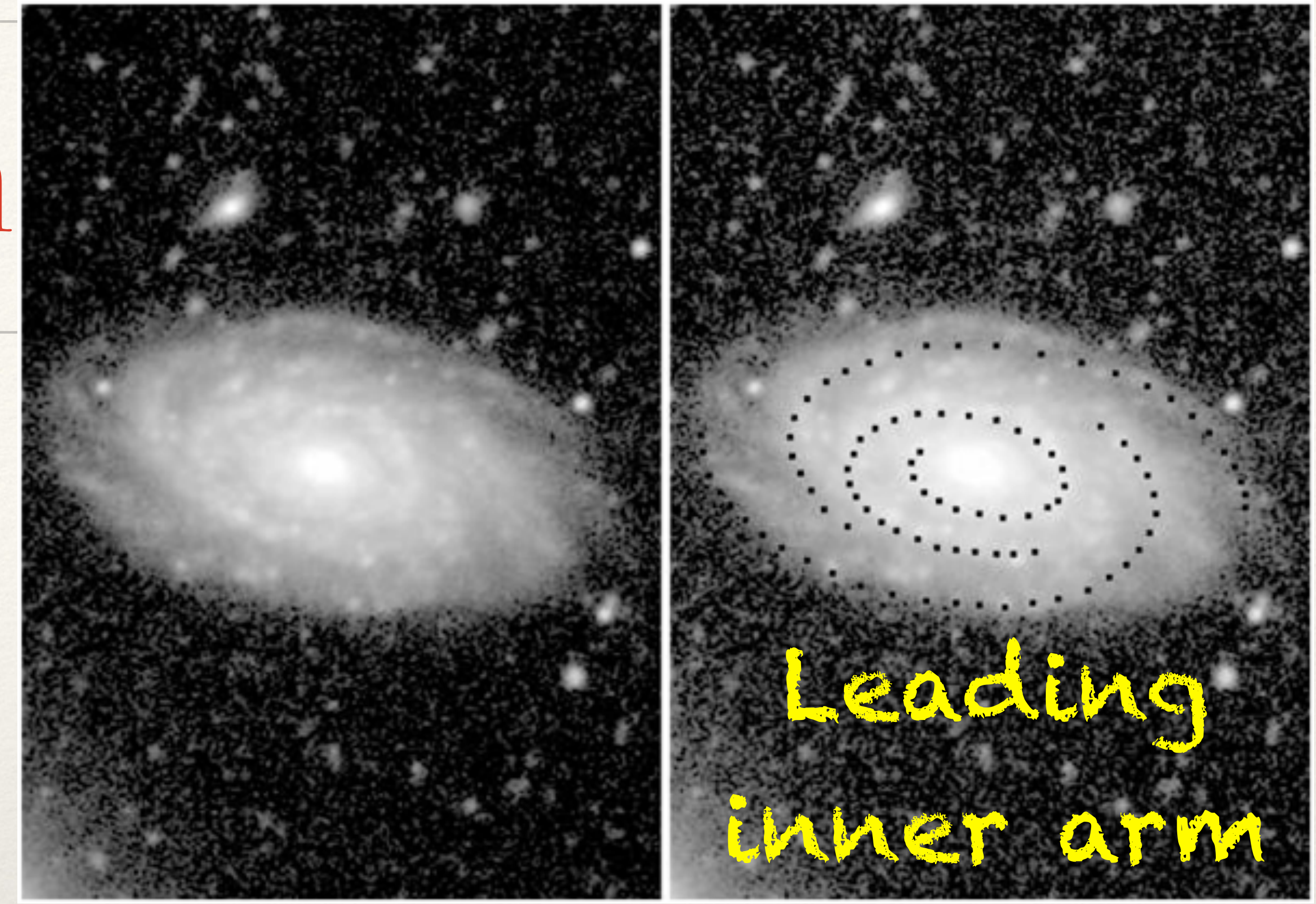


Spirals/Disks: Arm

- "…the central part… turns into the spiral arms as a spring turns in winding up." — Vesto Slipher (1922)
- **Most galaxies have trailing arms — with a few notable exceptions!**

ESO 297-27

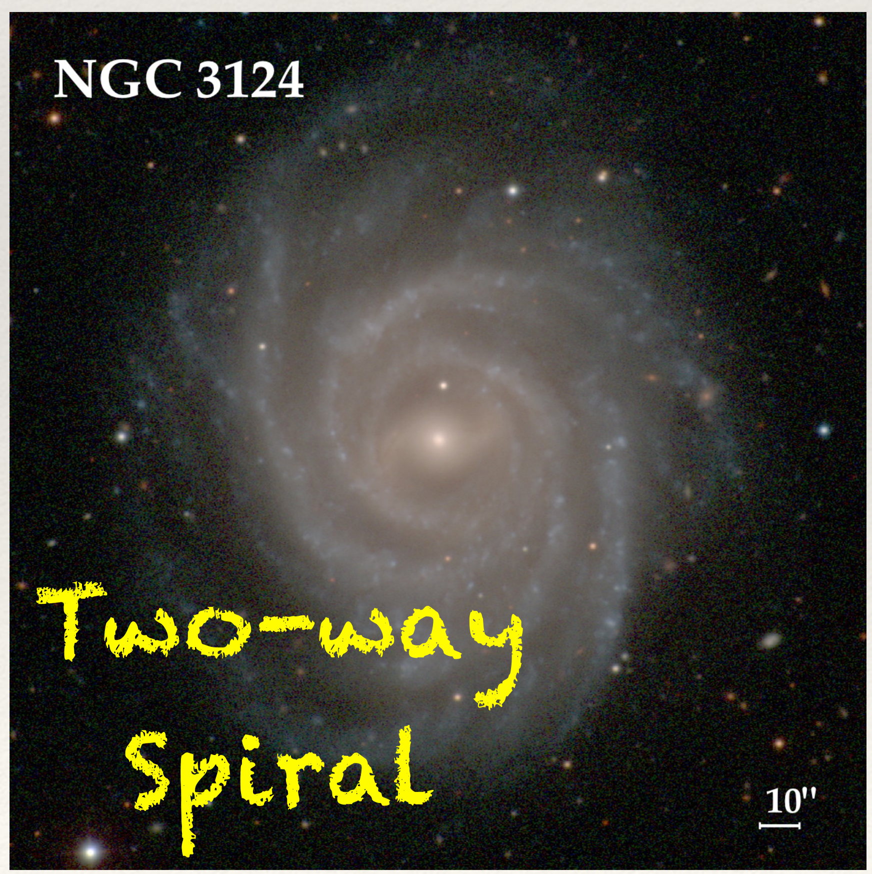
Grouchy & Buta et al. 2003



NGC 4622

Buta et al. 2003

NASA/STScI/AURA



Carnegie Observatories

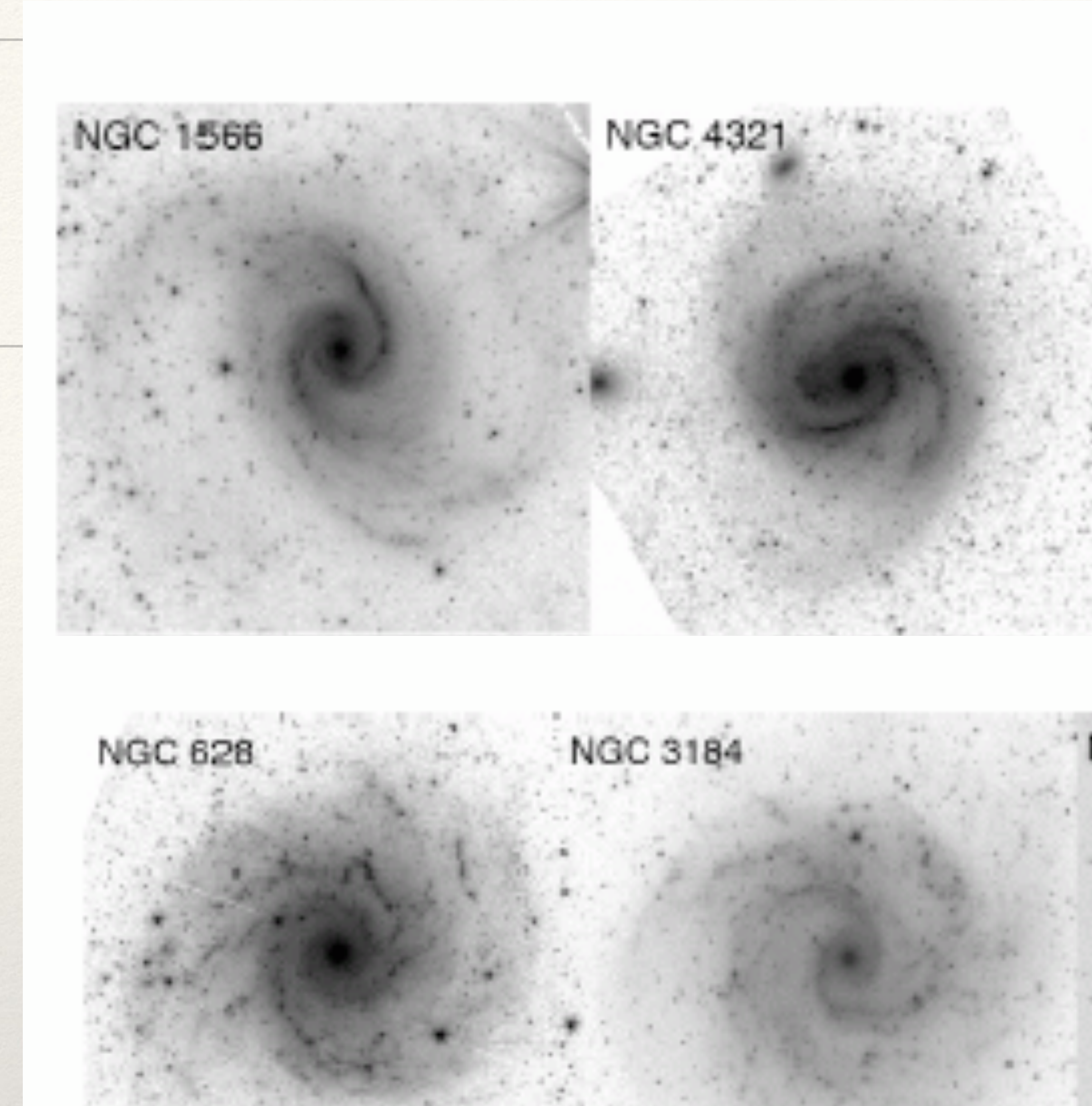
M64 — Black Eye Galaxy

Walterbos et al. 1994

Spirals/Disks: Arms

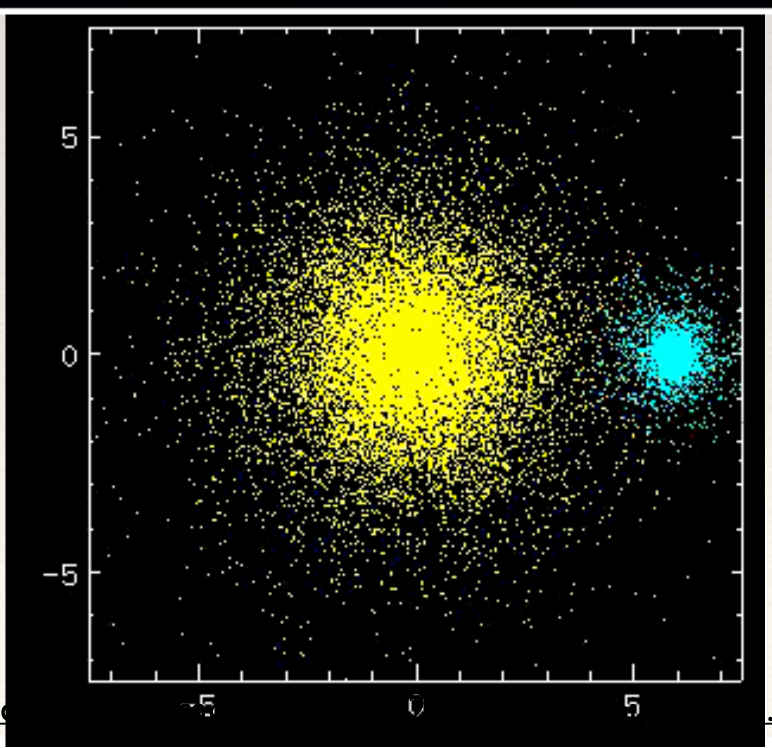
- Instabilities and differential rotation likely drive different types of spiral structure:
  - "flocculent" spirals may be local instabilities sheared by differential rotation
  - "grand design" spirals must be a **density wave pattern**
    - gas and stars move into and out of density wave

Elmegreen et al. 2011



Spirals/Disks: Arms

- What triggers spiral arms to begin with?
    - initial non-axisymmetric properties of disk and halo (intrinsic), e.g. bars
    - galaxy encounters (environmental)
- im lated gala ies de elop spiral arms
- How long do spiral arms last?



http://burro.astr.c .html