Astronomy 730

Disk Galaxies

Outline

- Disk Galaxies
  - Structural properties and trends
    - B/D decomposition
    - Spiral structure
  - Star-formation and feedback (see ISM Notes)
  - Kinematics
  - Scaling relations
  - Evolution:
    - Heating versus cooling
    - Disk heating model

Disk Galaxies

Disk Galaxies: distribution of starlight

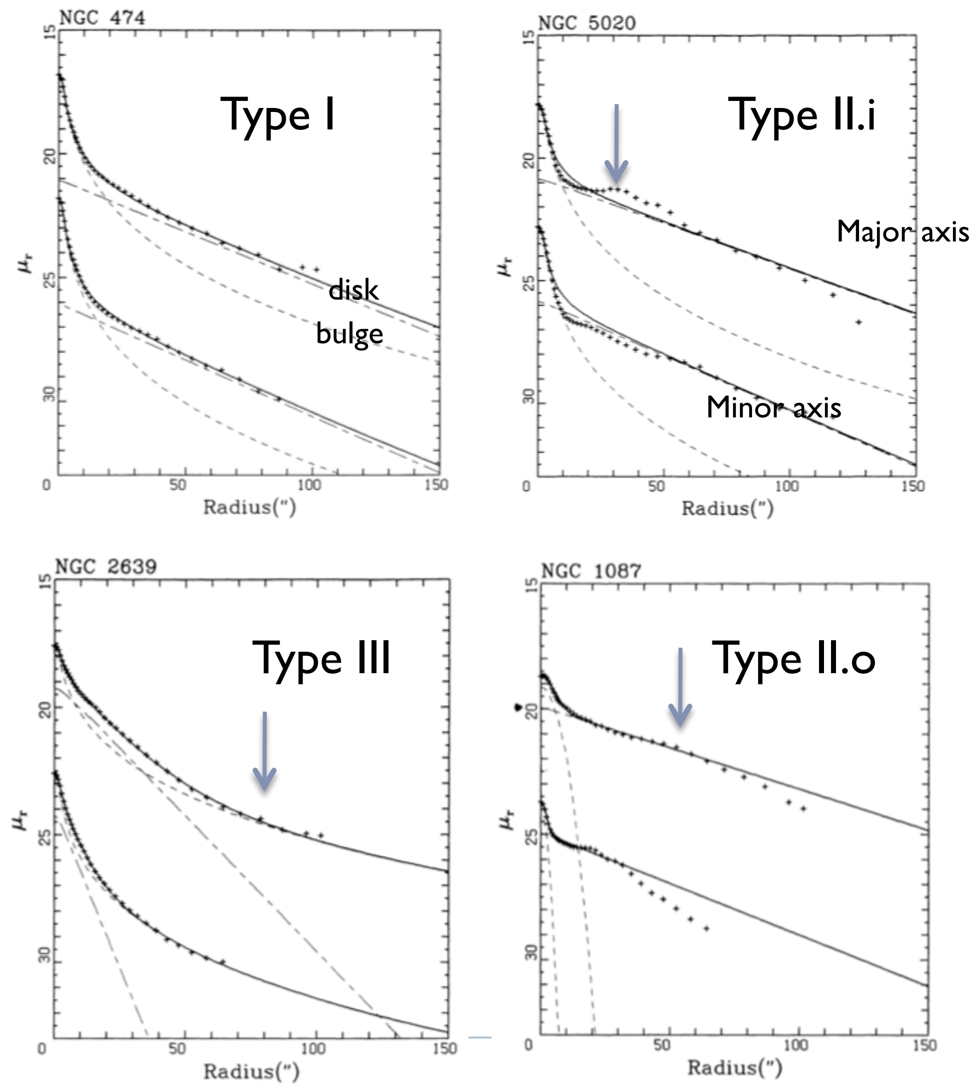
- De-composition of the light profile
  - Disk – generally fit with an exponential or two
    - $I(r) = I_0 e^{-r/hR}$
    - I_0= central surface brightness
    - h_R = scale length of the exponential
  - Bulge – generic function that goes as $r^{1/n}$
    - $I(r)=I_e e^{-k}$ where $k = b_n[(r/r_e)^{1/n} - 1]$
      - Sersic profile: n=4 fits many ellipticals; n=1 is exponential; n=1/2 is Gaussian
    - I_e= effective surface brightness, r_e= effective radius :
      - where half the total light is enclosed
    - $b_n \sim 2n - 0.33$ for $1<n<10$.
    - n = 1.7±0.7 (Balcells et al. 2003)
  - Halo
    - Doesn't contribute much light, treat as extension of bulge

Disk Galaxies: distribution of starlight

- Central surface brightness
  - Usually measured in mag arcsec^{-2} ($\mu = -2.5 \log I + \text{const.}$)
  - *It is independent of distance!* (ignoring cosmological dimming)
- Freeman's law (1970): luminous spirals have nearly constant disk central surface-brightness:
  - $\mu_0 = 21.65$ (*B*-band), 21(*R*-band), 20.65 (*I*-band) ± 0.65 mag arcsec^{-2}
    - Turns out to be a Malmquist-like bias; lower-luminosity systems have lower μ_0
- Central surface-brightness for bulges:
  - typically 10-100 times higher.
  - *Easy to see!*
- Bulge-to-disk (B/D) luminosity ratio a key parameter in describing disk-galaxies

Bulge/Disk decomposition

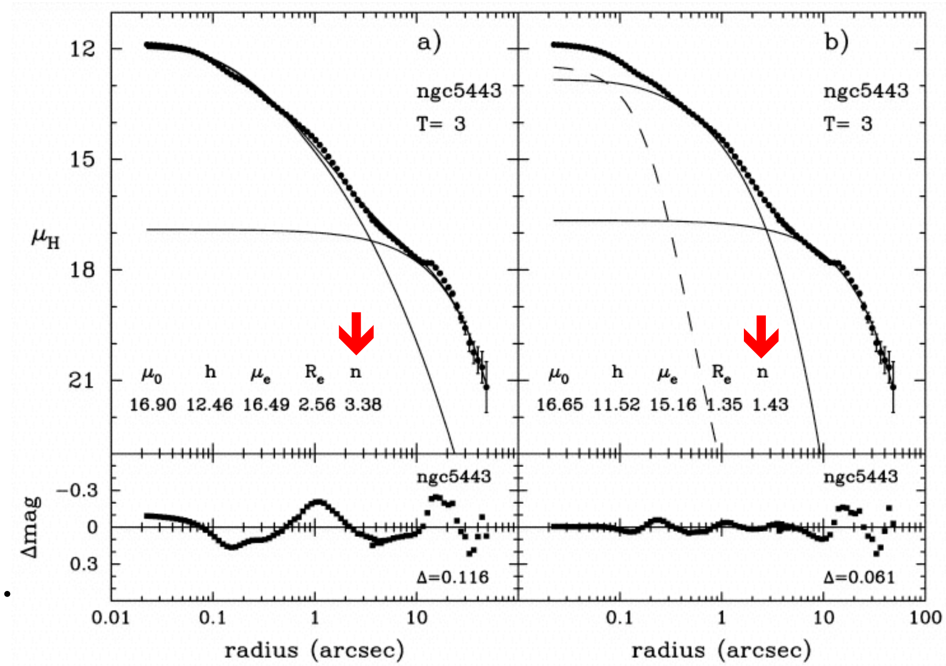
- Traditionally these have been done as 1D fits in radius (Kent 1985, ApJS, 59, 115) ➔
- Several distinct *disk* profile types:
  - Inner breaks (Freeman 1970)
    - Type I, II(.i)
  - Outer breaks (Erwin et al. 2006, Pohlen & Truillo 2006, A&A, 454, 759)
    - Type II.o, III
- Most disks show smooth exponential behavior between $1<R/h_R<4$
- Few extend far beyond $R/h_R=4$ *in starlight*



Bulge/Disk decomposition

- Recent work has focused on high-resolution in the NIR to probe bulge structure
  - HST H-band SB profile: NGC 5443 (Sb).
    - (a) Solid lines = Sersic bulge + exponential disk
    - (b) Adding central point source in leads to a better fit
    - ➔ n = 1.7±0.7
    - w/o central source, overestimate n.
    - *What is the cusp?*
- Bulges have near-exponential radial light-profiles, likes disks, but not highly flattened.
  - *Heated inner disks?*

Balcells et al. 2003



core

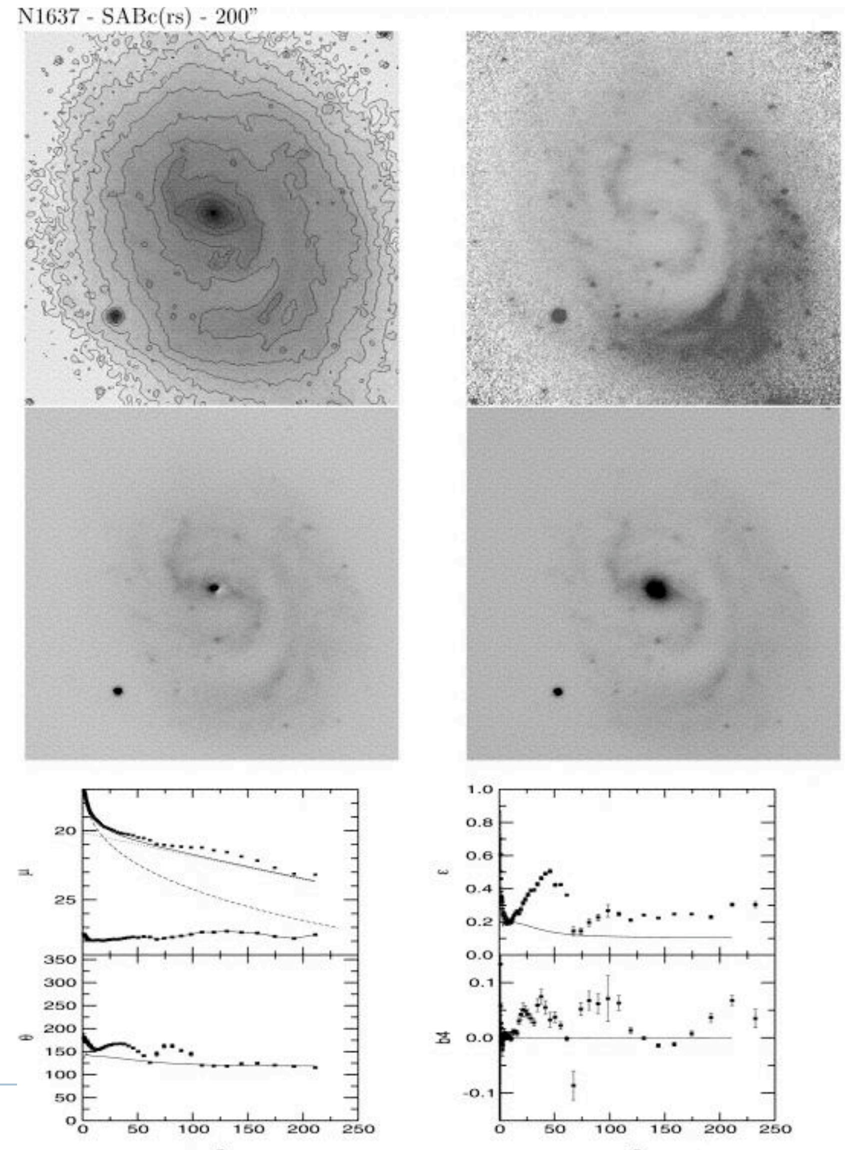
$$\rho_{pseudo-isothermal}(r) = \rho_0[1 + (r/r_c)^2]^{-1}$$
$$\rho_{NFW}(r) = \rho_n(r/a_n)^{-1}[1 + (r/a_n)]^{-2}$$

cusp

Bulge/Disk decomposition

- Best modern methods do simultaneous fits of both *inclined* exponential disk and a Sersic-profile bulge in 2D
  - e.g., De Souza et al. 2004, ApJS, 153, 411
- Reveals wealth of residual structure:
  - Lopsidedness (m=1)
  - Bars, oval distortions (m=2)
  - spiral arms (m=2,3,…)

Fourier modes ↑



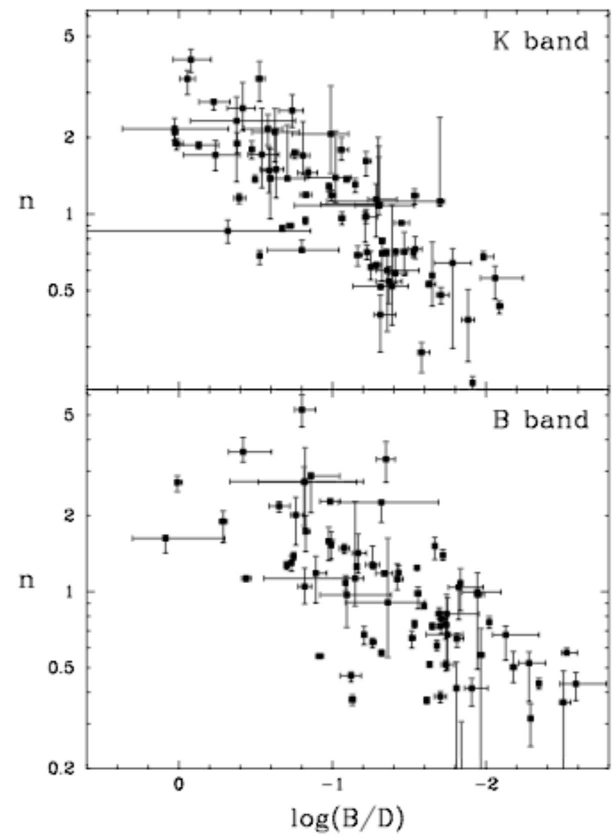
Oval distortions

- 50% of disk galaxies have some sort of oval distortion
  - (bar, linear structure, m=1 Fourier mode at center of galaxy):
    - stars and gas in largely radial orbits, precessing in phase.
  - More easily seen in red light (old stars), but often gas
- Outstanding questions:
  - *Are bars long-lived or short-lived phenomenon?*
    - Investigations of distant samples inconclusive.
      - e.g, Abraham et al. 1999, MNRAS, 308, 569
  - Do bars give rise to bulges?
    - e.g., pseudo-bulges (Kormendy & Freeman 2004)

NGC 1300

Trends along Hubble sequence

- Important structural parameters:
  - μ_0, h_R, n, B/D ratio
- Also gas and stellar content
- Early ➔ Late
  - Decreasing:
    - disk size (h_R), disk surface-brightness μ_0
    - B/D and bulge Sersic index n
    - Overall luminosity, rotation speed
    - metallicity, mean stellar age
  - Increasing:
    - gas content
    - star-formation (per unit mass)
    - disk thickness
    - Lopsidedness, asymmetry (*i.e., irregularity!*)



Graham 2001, AJ 121, 820

Trends along Hubble sequence

- Kent (1985) showed that light-concentration (C) and mean surface-brightness (μ_e) correlated with each other, B/D, and the Morgan spectral type.
  - ➔ Requires no B/D decomposition to characterize disk systems

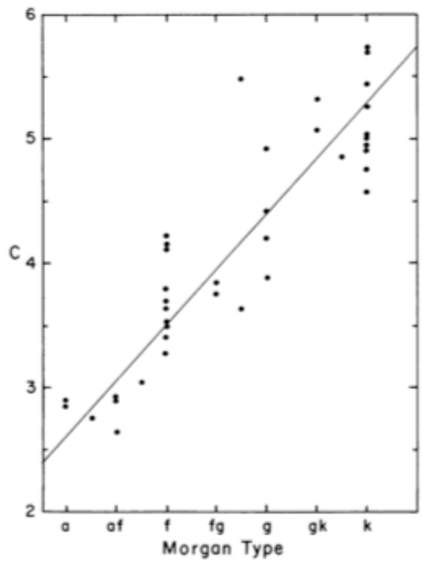


FIG. 9.—Correlation between concentration parameter c and Morgan type. The line drawn is an eyeball fit to the points.

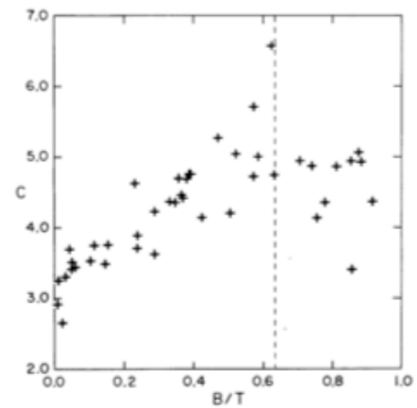


FIG. 10.—Correlation between concentration parameter c and B/T. Dashed line at $B/T = 0.63$ marks the point where bulge/disk decompositions become unreliable.

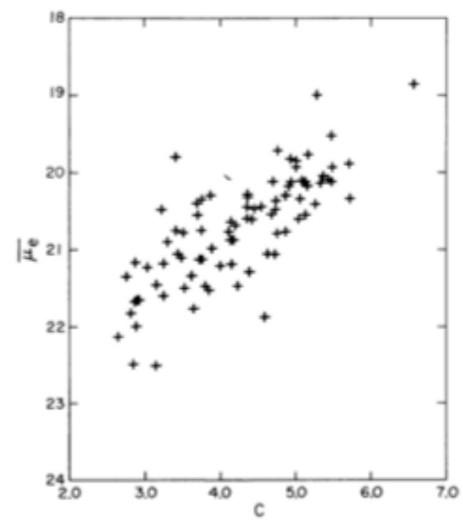
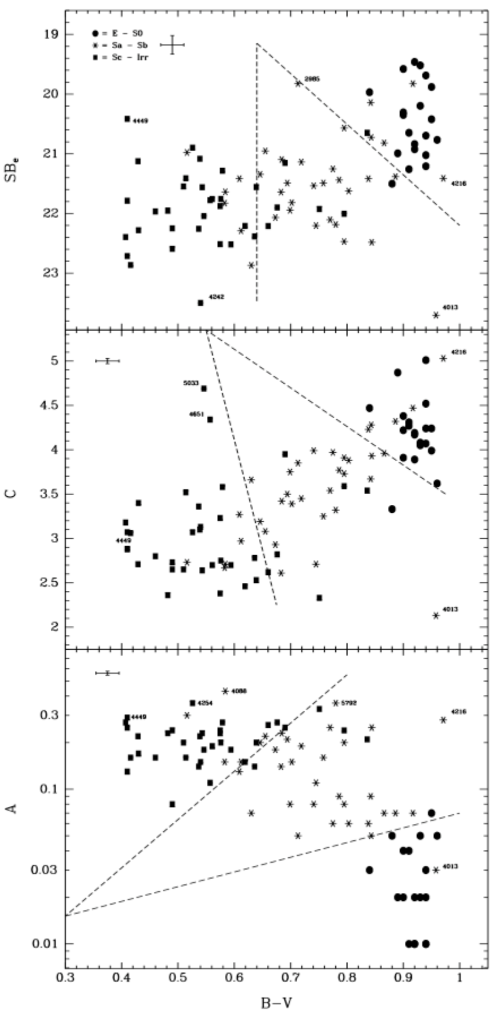
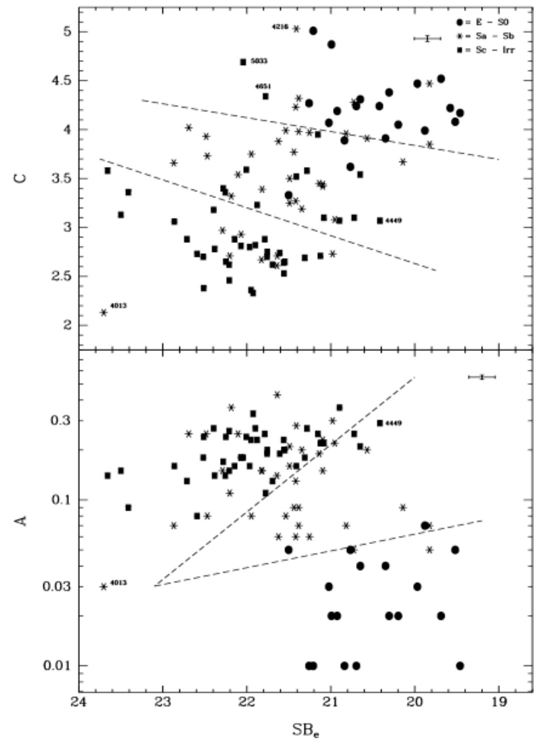


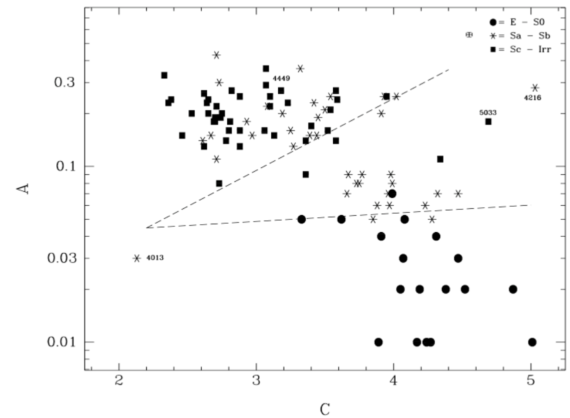
FIG. 12.—Correlation between mean surface brightness $\bar{\mu}_e$ inside effective radius r_e as a function of concentration parameter c.

Alternative classifications





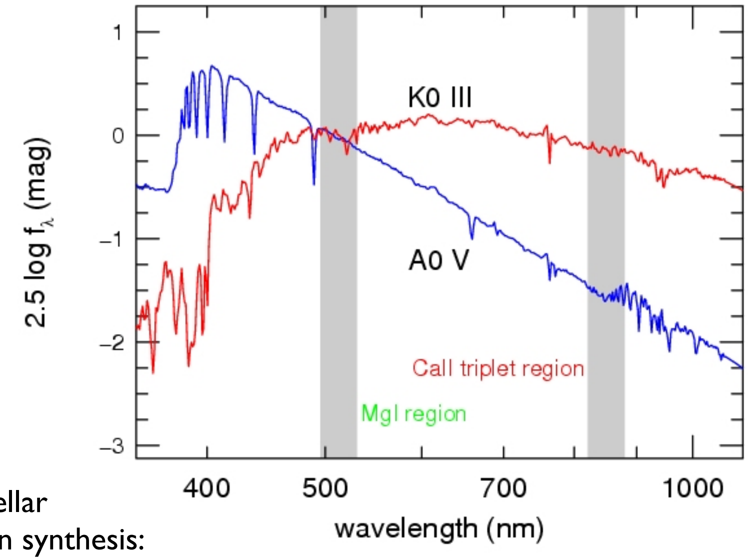
Bershady et al. 2001
Conselice et al. 2001



Mean surface-brightness ($Sb_e = \mu_e$), image concentration (C) and asymmetry (A) correlate with color (stellar populations)

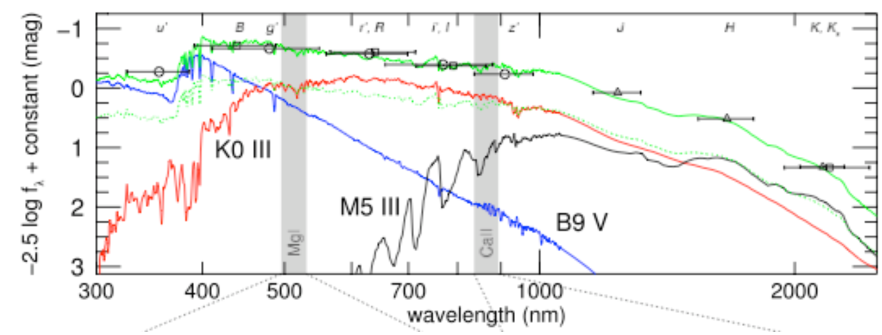
Optical vs NIR view

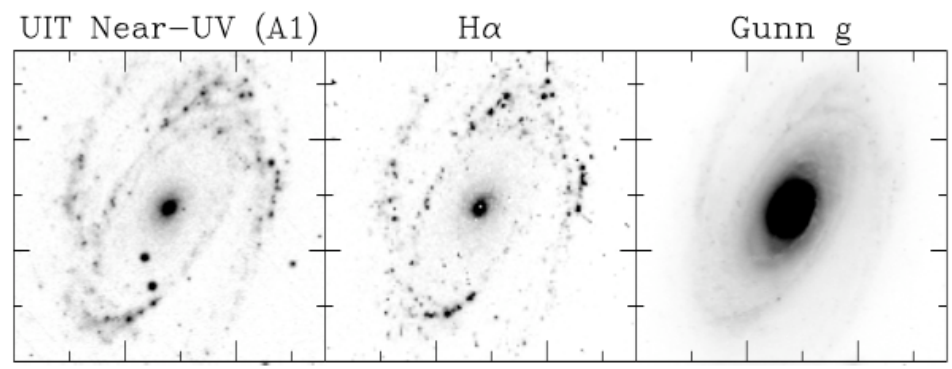
- Modern measurements
  - Digital detectors: CCDs or IR arrays
- Hot stars emit relatively little in the near-IR compared to cool stars of comparable total (bolometric) luminosity.
- Giant stars emit much of their radiation in near-IR
  - ➔ Galaxies appear less "splotchy" in the red and NIR because you see mostly the cool, older stars that are relaxed.
  - Effects of extinction mitigated:
    - $A \equiv -2.5\log(I_{obs}/I_{em}) = 1.065\ \tau$, where τ is optical depth, and goes as $\sim \lambda^{-1}$
    - more accurate view of the stellar distribution.



Simple stellar population synthesis: 2 and 3 star models

Aaronson 1980; Bershady 1995, 2010





M81

Spiral arms

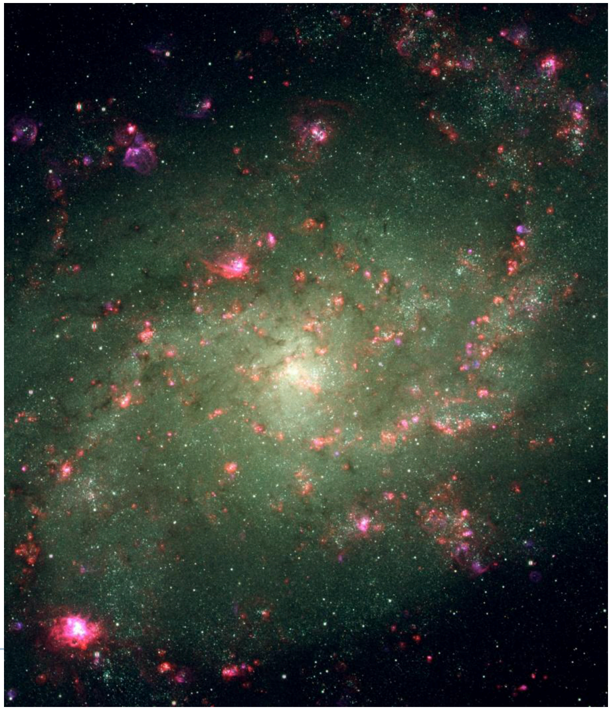
- Recall Hubble's classification criteria
  - Openess of arms
  - Resolution of arms into "stars"
  - Bulge/disk ratio
    - **Sa** - tightly wound, large b/d ratio, some gas, steeply rising rotation curves
    - **Sb** - intermediate
    - **Sc** - open spiral arms, lots of substructure, small bulge, lots of gas, slowly rising rotation curves, lots of HII regions
    - **Sd** - no bulge, open arms, lots of HII regions
    - **Sm** - lopsided (like LMC)

Spiral sequence

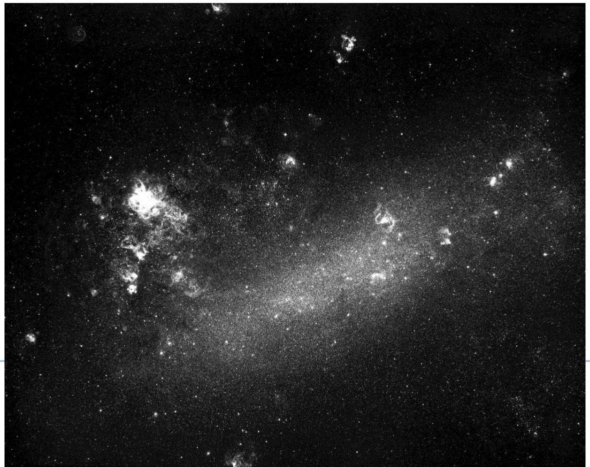
Sb
M31

Sc
M101

Sd
M33

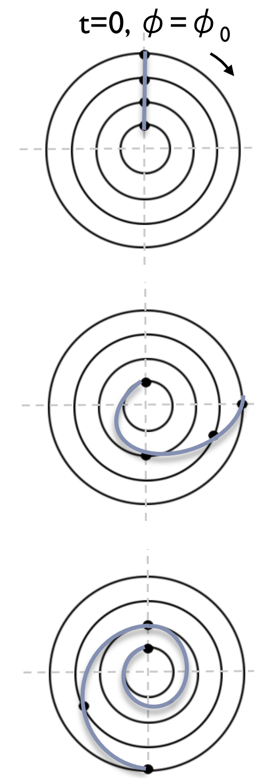


Sm
LMC



Spiral arms: winding problem?

- Assumptions:
  - Start with an arm as a straight radial strip at $t = 0$ and $\phi = \phi_0$.
  - Pattern speed of arm is locked to the rotation of the disk: $\omega_p = \omega(R)$.
  - Disk rotates with $\omega(R) = V(R)/R \neq$ constant
  - In general $V(R) \sim$ constant over most of the disk.
  - ➔Within a few <t_{dyn}>, arms wrap up
    - Recall $t_{dyn} \sim T/4$
    - For $V = 220$ km/s, $R = 8.5$ kpc… $T = 2.4\text{x}10^5$ yr



Winding problem resolutions

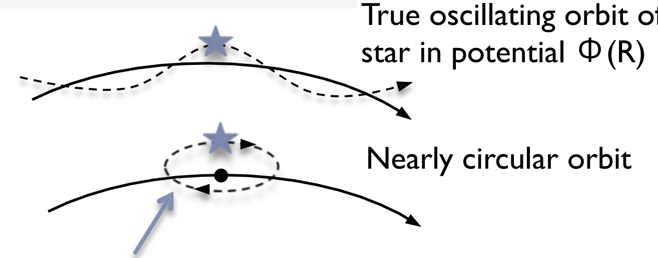
- There is likely no one solution, so the situation is complicated:
  - Arms are constantly regenerated.
    - Transient phenomenon (interactions?)
    - Star-formation generated/stochastic wave
      - Might be a suitable explanation for flocculent spirals
  - Kinematic wave:
    - Nesting of oval orbits (see S&G Figure 5.29)
    - Still a winding problem, but twice as slow as for case where $\omega_p = \omega(R)$.
      - Might be suitable for spirals in gas-free disks
  - "Density wave" arising in the gravitational potential
    - Stars and gas gravitational attraction offset kinematic wave from winding up by making $\omega_p(R)$ = constant.
    - Disk stability must be low:
      - $Q = (\sigma_R \kappa)/3.36\pi G \Sigma \sim 1$ ratio of kinetic : potential energy

Random motions (σ_R) — Epicyclic frequency (κ) — Disk mass surface-density (Σ)

Density waves

- Epicycles: stars oscillations (random motions) about circular orbit described as elliptical epicycles with frequency κ .
  - $\kappa^2(R) = -4B(R)\,\omega(R)$
  - B = (Oort's constant)
- Spiral is strengthened when
  - $m|\omega_p - \omega(R)| < \kappa(R)$
  - m = number of arms
- Continuous wave propagates only between inner and outer Linblad resonances:
  - $\omega_p = \omega(R) - \kappa/m$ (ILR)
  - $\omega_p = \omega(R) + \kappa/m$ (OLR)
- Co-rotation (CR): $\omega_p = \omega(R)$

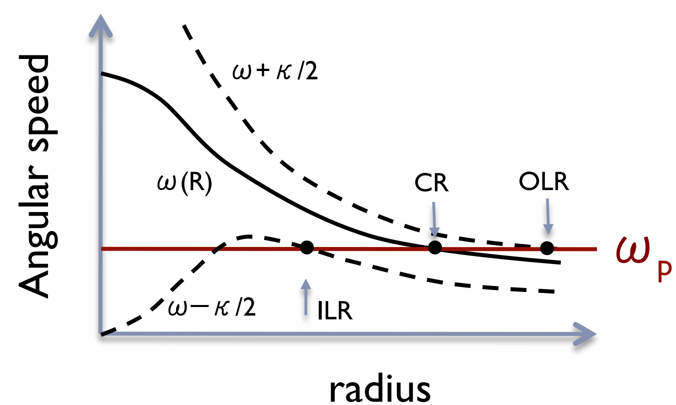
In the disk plane:



Epicycle describing apparent stellar motion from the frame of the LSR – circular orbit with angular speed ω(R).

There's also a component out of the disk plane (z) -- not relevant here.

Schematic for m=2:



Beginning and end of spirals arms indicate location of resonances

Star Formation and Feedback

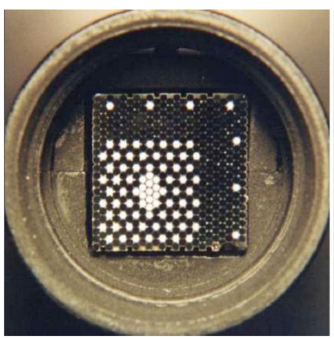
- See ISM Notes.

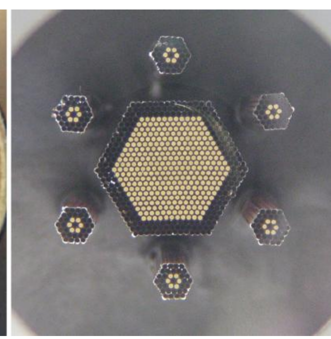
Disk Galaxy Kinematics: 3D

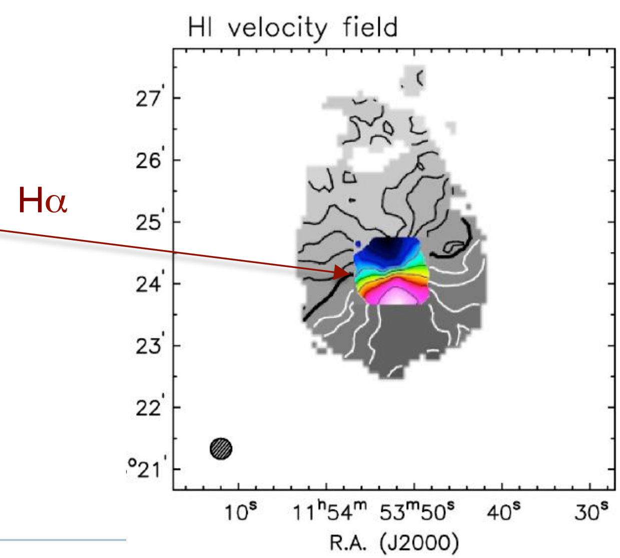
- From easy to hard:
  - Ionized gas kinematics based on centroids of the optical emission lines ([OII], [OIII], Hα).
  - HI kinematics based on radio interferometric studies.
  - Stellar velocity fields and dispersions largely based on centroids and widths of stellar absorption lines.
    - We'll come back to this.

Disk Galaxy Kinematics: 3D

- Optical fibers and image slicers…
  - ….feeding conventional long-slit spectrographs…
  - ….have opened up 2D mapping of disk velocities (3D data = data cube).
- Data cubes:
  - Once only the domain of radio astronomy, where we could probe only neutral or molecular gas
  - We can now probe ionized gas and stars, much more quickly.
- *Why bother with radio ??* Here's just one of several critical reasons:







- WIYN 3.5m/ SparsePak FFU
- 82 fibers, 4."7 diameter
- 72" FOV
- $\lambda/\Delta\lambda$ = 11,000

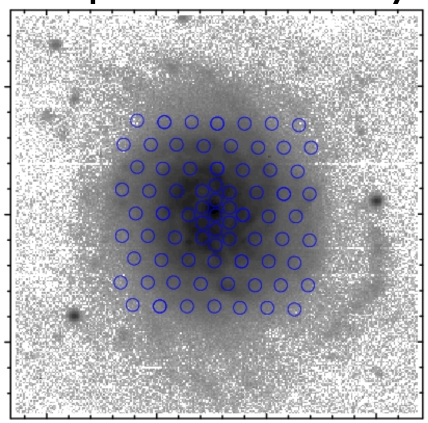
(Bershady et al.'04,'05)

- Calar Alto 3.5m / PPak IFU
- 331 fibers, 2."7 diameter
- 75" FOV
- $\lambda/\Delta\lambda$ = 8000

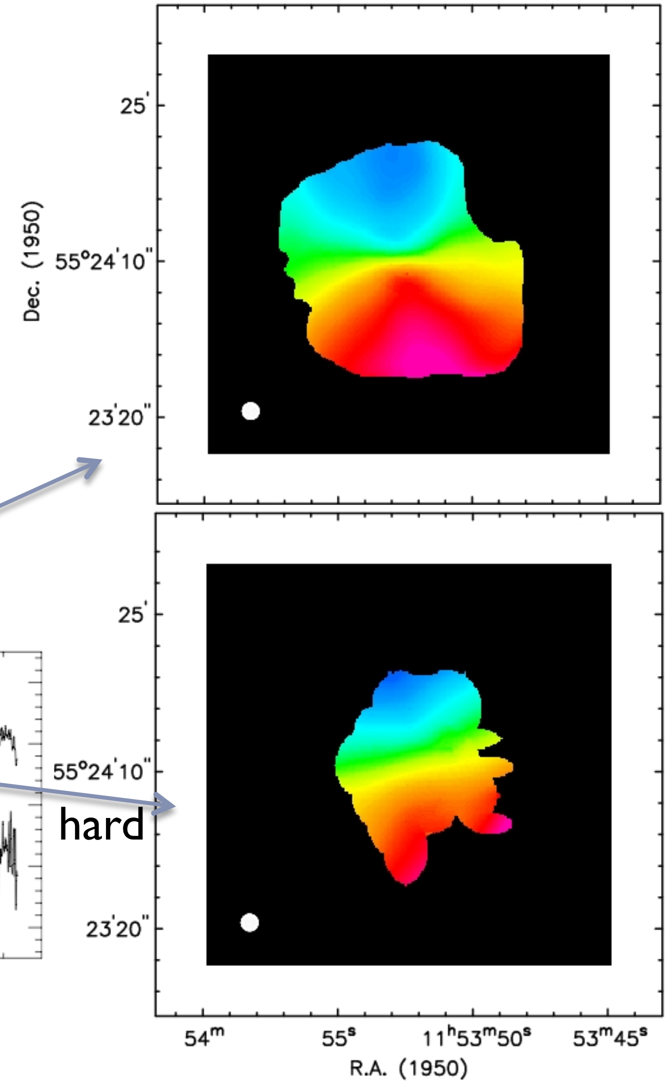
(Verheijen et al.'05)

Disk kinematics: UGC 6918 = NGC 3982

SparsePak overlay



i=26 ± 2°
B-R=1.0
B-K=3.25
h_R=0.94 kpc
$\mu_B(0)$=19.3
M_B=-19.3

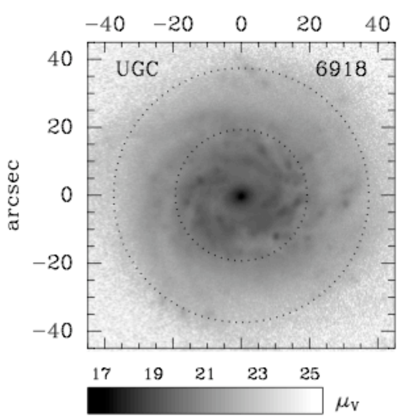


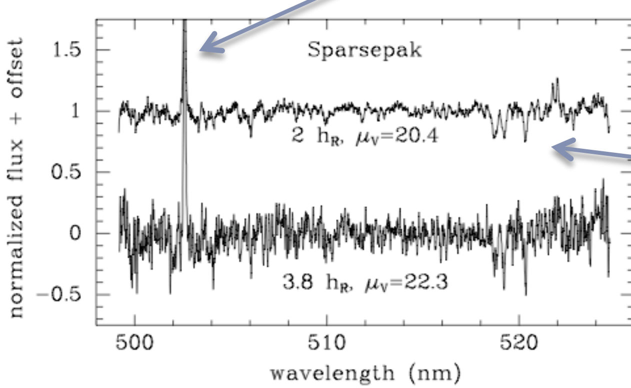
gas

stars

easy

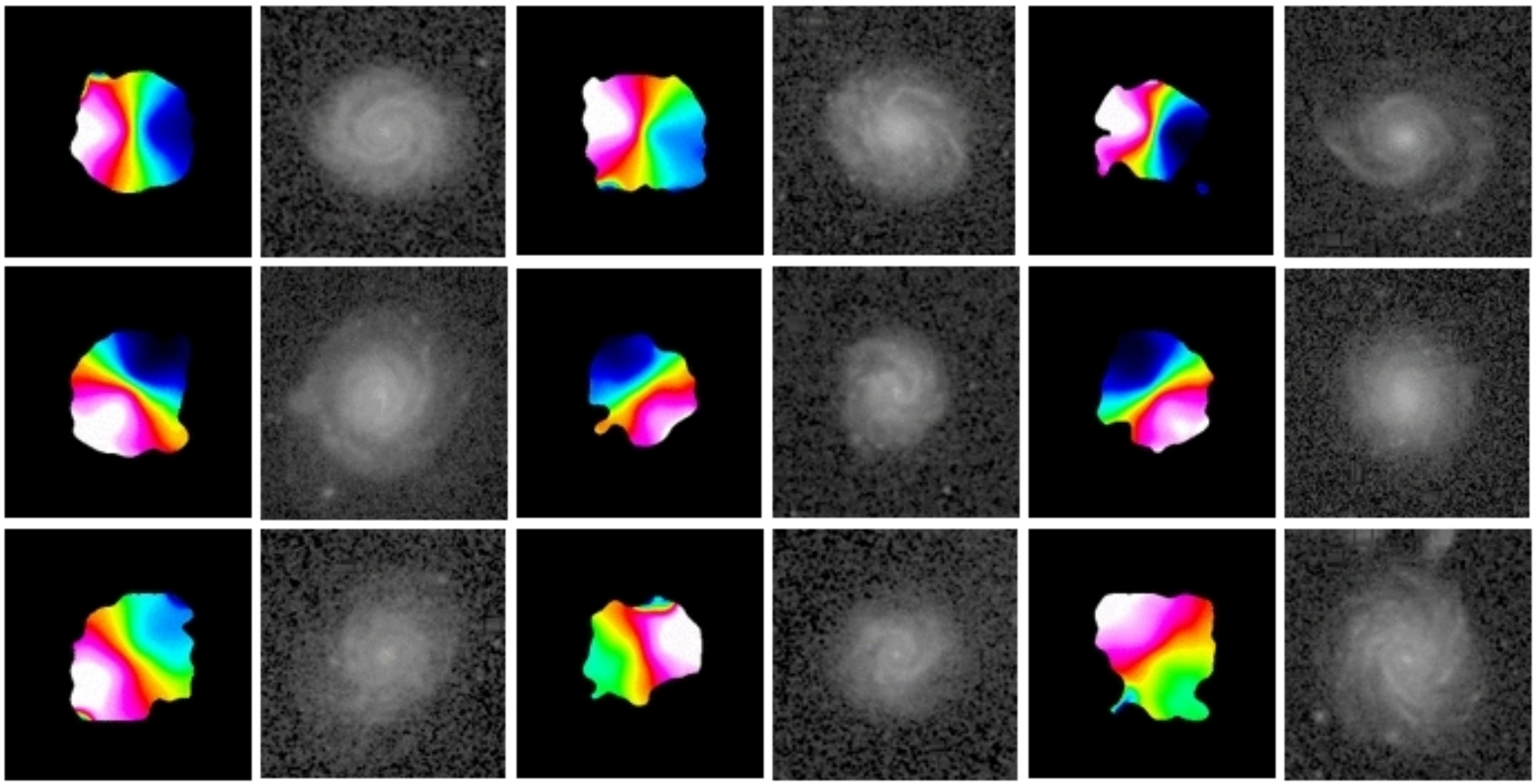
hard





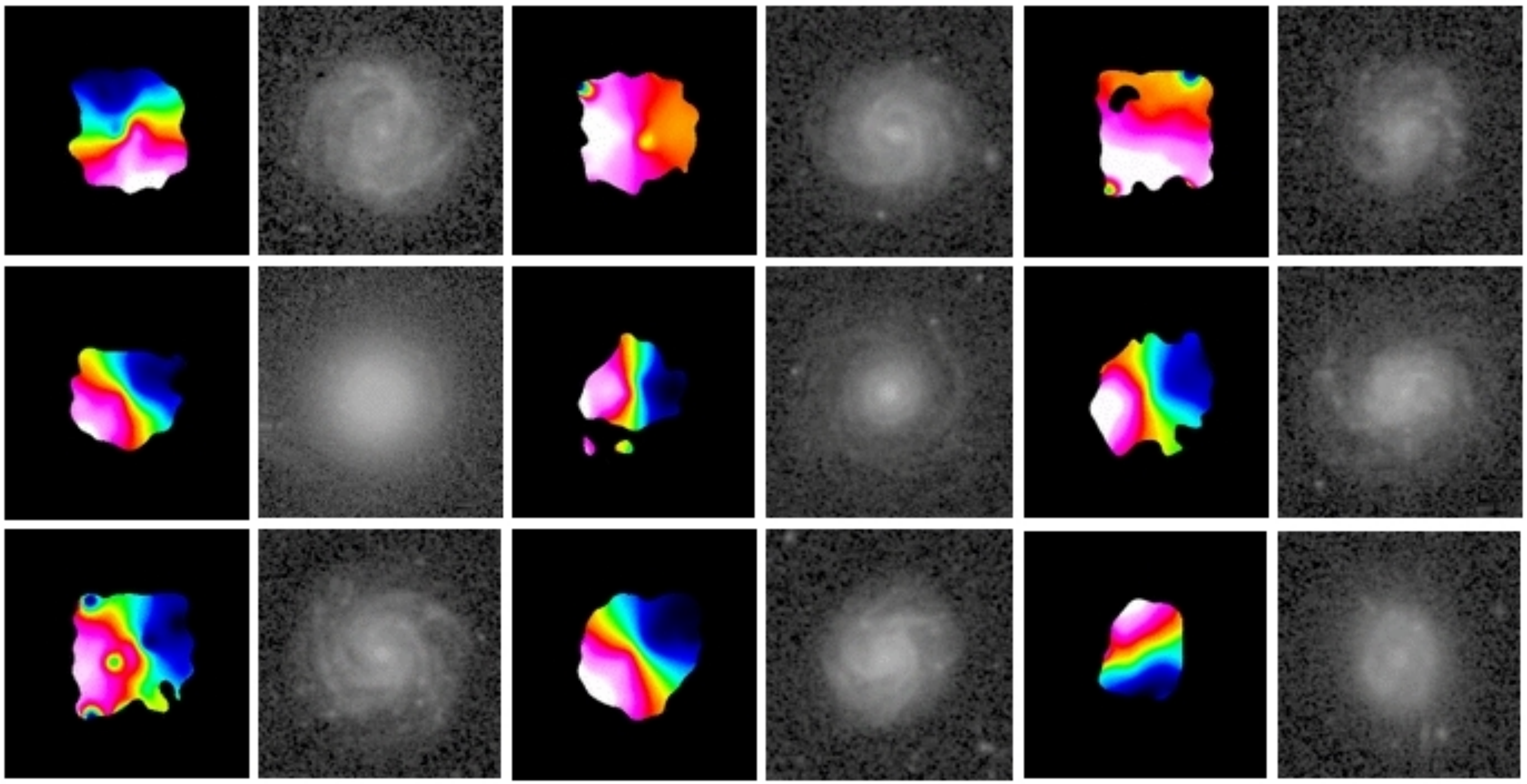
Symmetric, normal galaxies

WIYN/SparsePak Hα velocity fields



Bi-symmetries and Asymmetries

WIYN/SparsePak Hα velocity fields



This is easy: 1hr in bright-time on a 3.5m telescope

Radio Telescopes

Single dish: Green Bank

Interferometers: VLA

HI Kinematics of Disk Galaxies

- Until the last decade, this has been the only source of bi-dimensional kinematics of external galaxies.
- Interferometric observations yield a 3-dimensional map (a data cube) of the distribution and kinematics of HI
  - ➔ x,y,z (RA, DEC, velocity).
    - Moment 0 = total intensity (integrate over v)
    - Moment 1 = velocity field (mean velocity as function of position)
    - Moment 2 = velocity dispersion
    - etc. (skew, kurtosis)

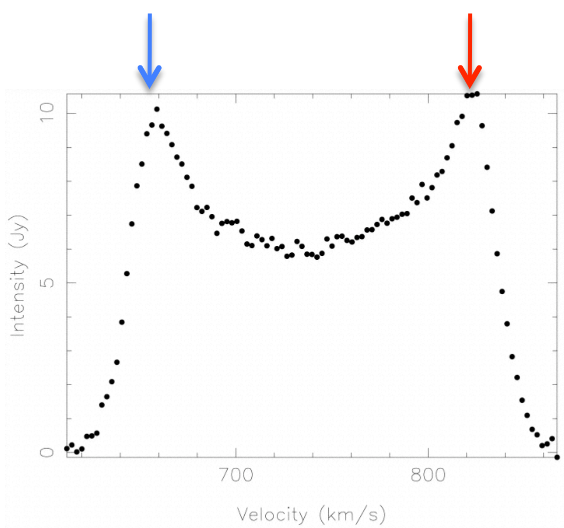
  - These concepts are generic and apply to all line data, e.g., optical emission lines, stellar absorption lines.
  - HI data cubes take 10's of hours to collect on the world's biggest interferometers.

Single-dish vs Inteferometer

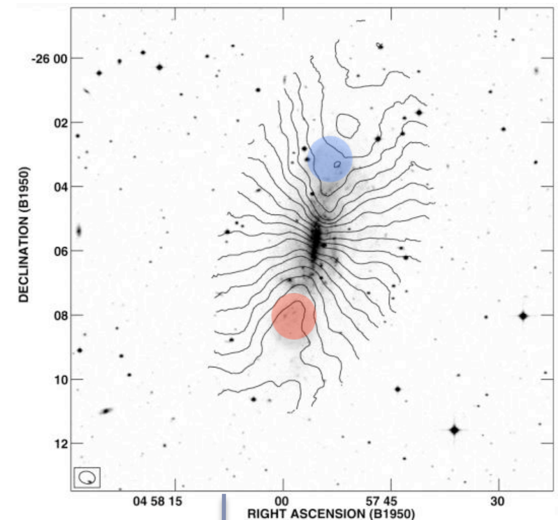
- Sensitivity vs spatial information
- Analogous to single-fiber vs IFU

Inteferomter:

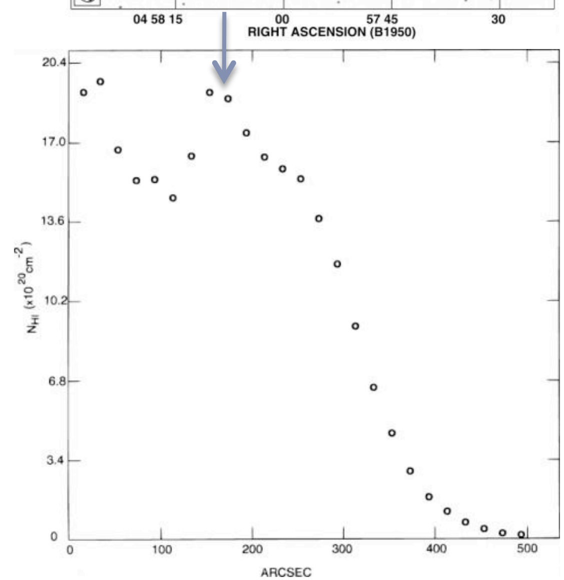
Single dish:



Velocity field:

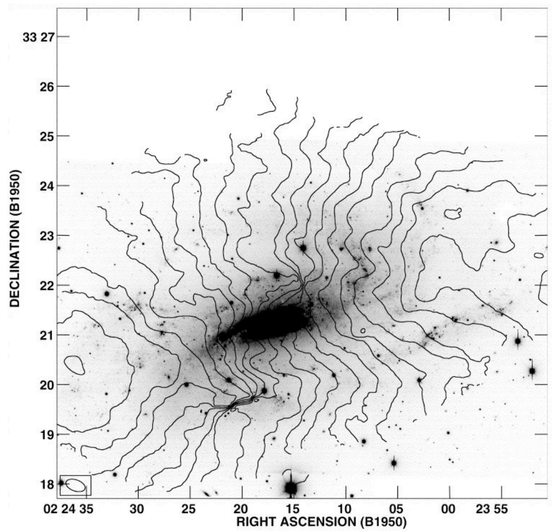


Radial profile:

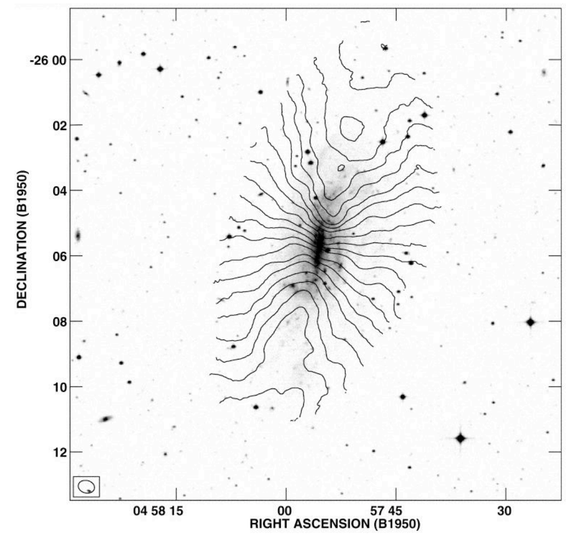


HI spider diagrams

Moderate inclination:
Note beam size relative to optical structure.



NGC 925

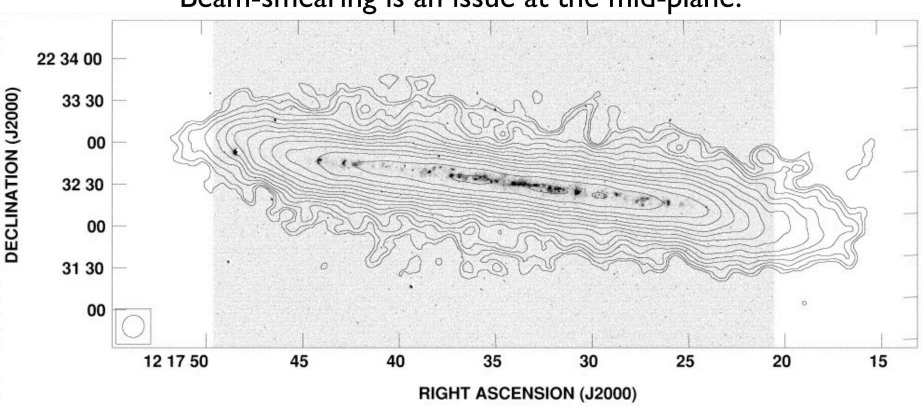


NGC 1744

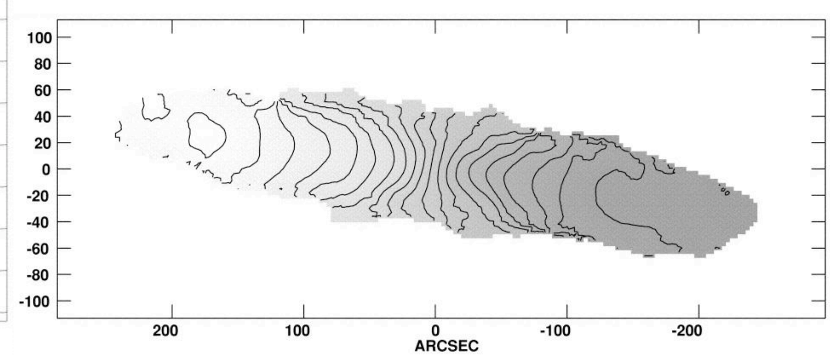
1st moment maps = velocity field

Highly inclined:

0th moment map superimposed on optical image.
Beam-smearing is an issue at the mid-plane.



1st moment map = Velocity field

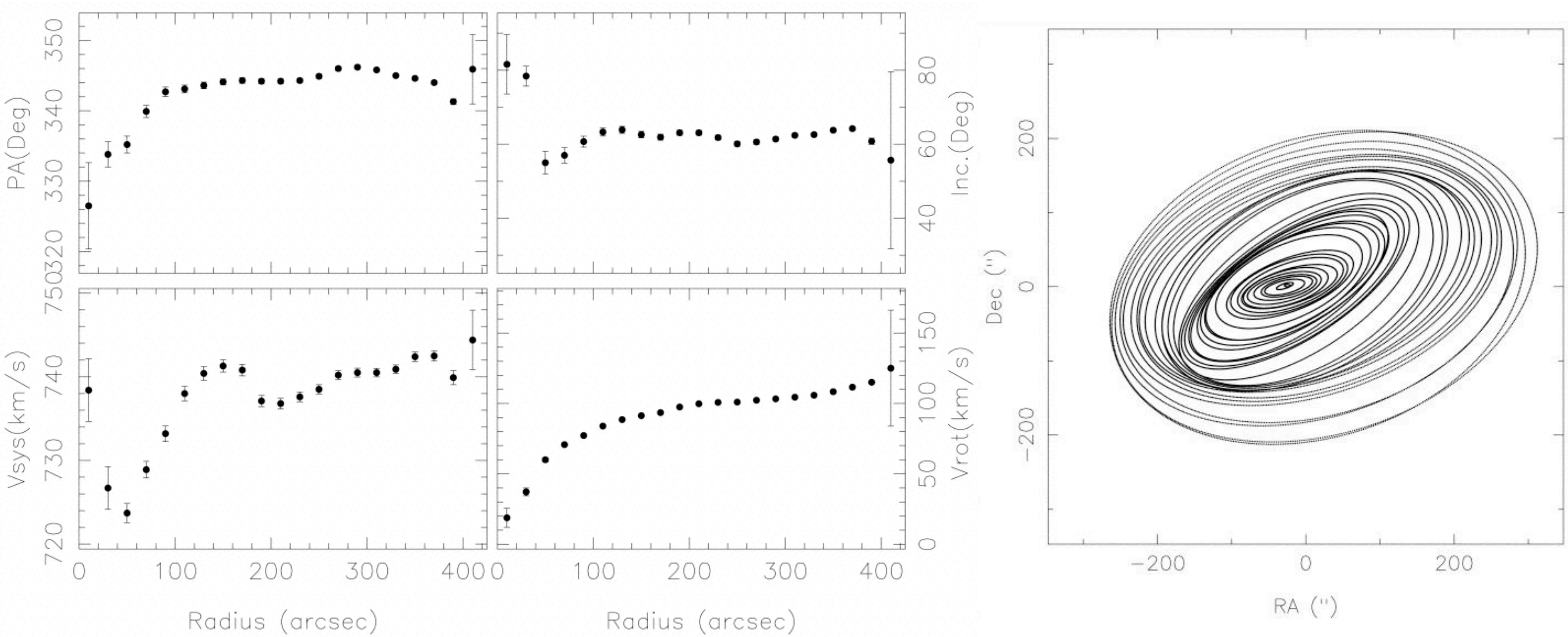


Deriving the rotation curve

- We only measure the radial velocity (i.e. velocity along the line of sight). How do we translate this into a velocity field?
- Components
  - Systemic velocity (e.g. Hubble flow)
  - Inclination, *i*, (i.e. if its face-on we see no rotation)
  - Azimuthal angle (of the major axis)
  - $V_c = V_{SYS} + V(R)(\sin i)(\cos \phi)$

Deriving the rotation curve

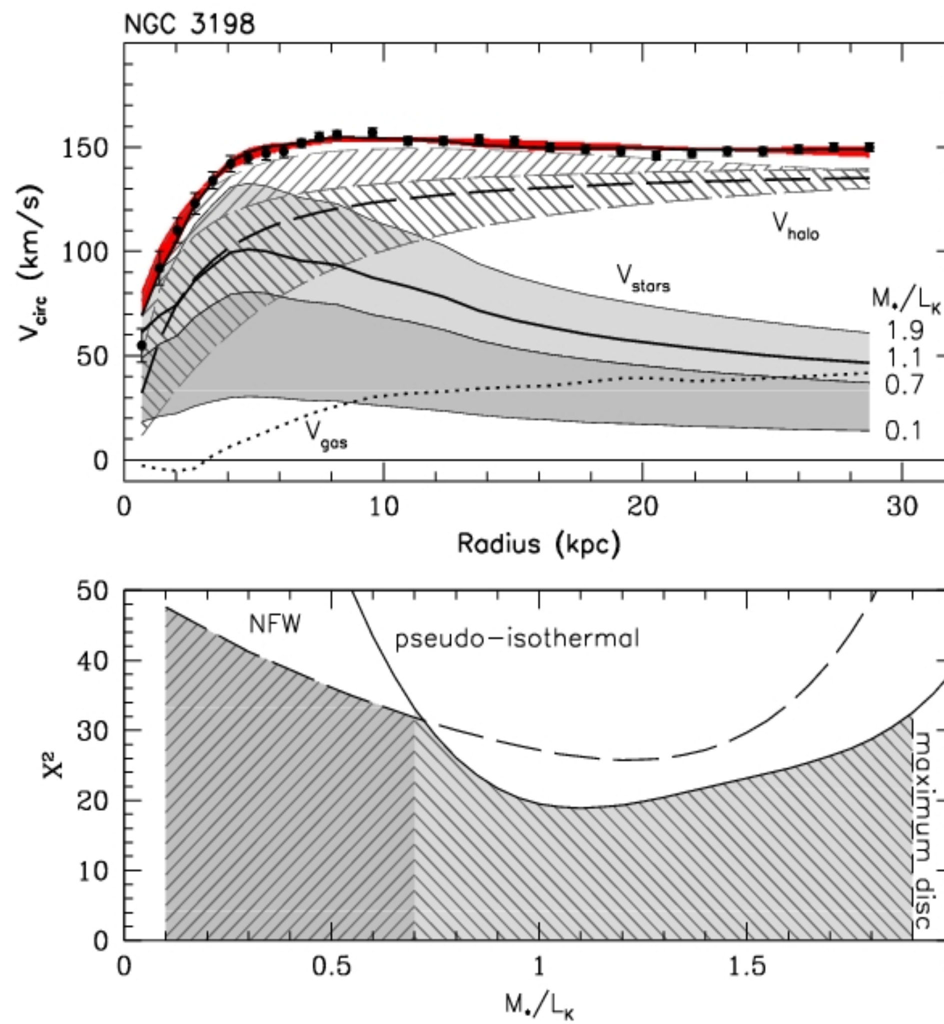
- Tilted ring models allow you to fit the circular velocity, inclination, position angle as a function of radius.



NGC 1744

Deriving the rotation curve

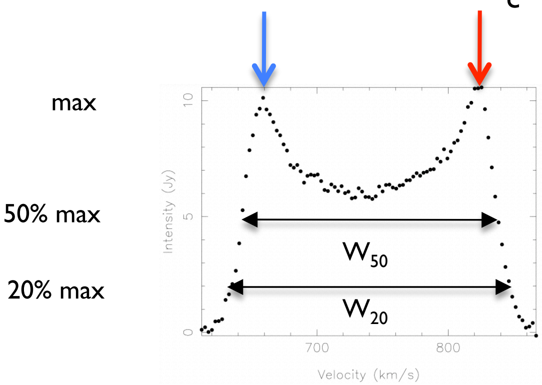
- But it's still just a rotation curve, degenerate to disk+halo, good for estimating total mass only.



Surrogates measures of rotation

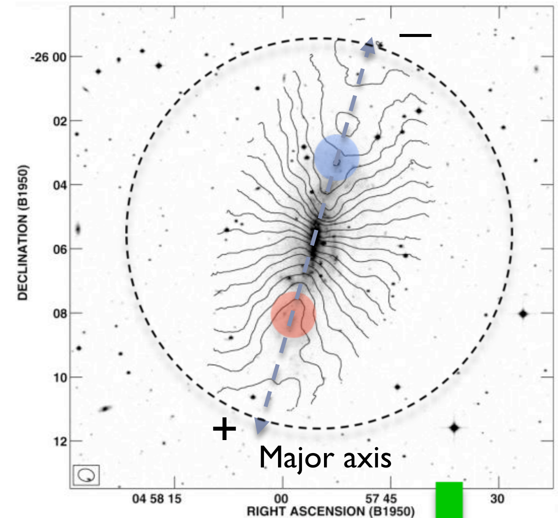
- Spatial information vs sensitivity:

4. Single dish (fiber):
Line width W ~ 2 V_c



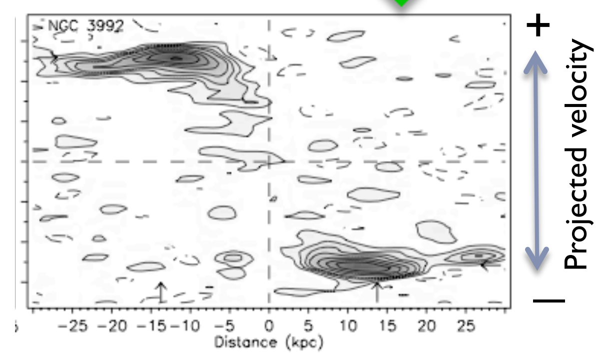
1. Interferometer/IFU:

➔ Velocity field
2D map of velocities, or data cube



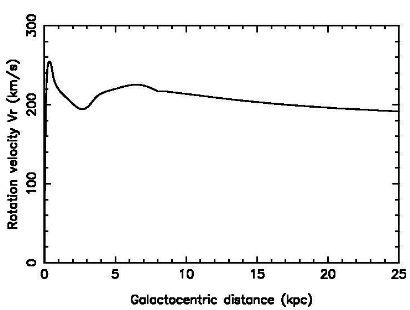
2. Position-velocity diagram (PVD):
Equivalent to long-slit spectrum

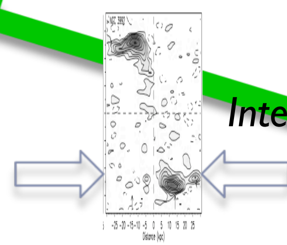
Slice down the major axis



Major axis

3. Rotation curve





Integrate in x (and y)

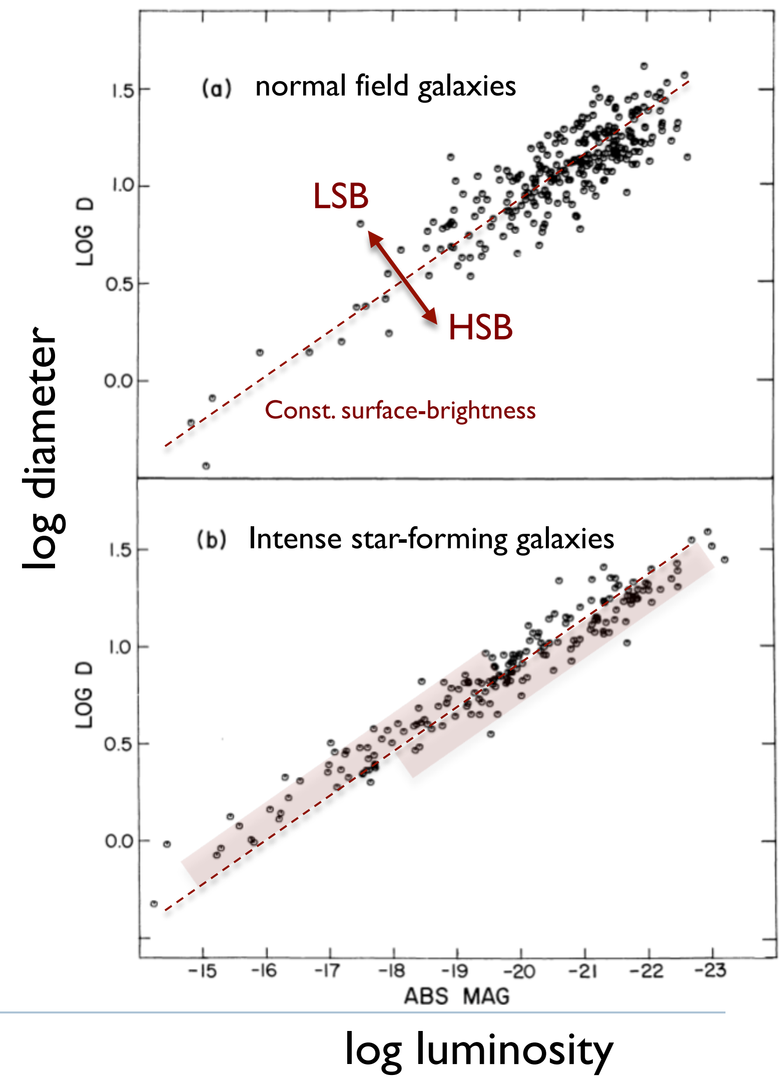
Flip (in V) and fold (in x)

Scaling relations

- V, L, size correlate (the physical *scale* of disk systems)
  - "Larger" systems tend to have higher disk surface-brightness, older stellar populations, less gas, higher metallicity (i.e., the Hubble Sequence)
- Important 2nd-order effect:
  - matter-density increases with V, L, size
    - concentration, surface-brightness
    - ➔ dynamical time-scales decrease
      $t_{dyn} \sim \sqrt{(1/G\rho)}$
    - ➔ SFR, gas consumption and enrichment more rapid
    - ➔ drives Hubble Sequence ???

At some level it must.

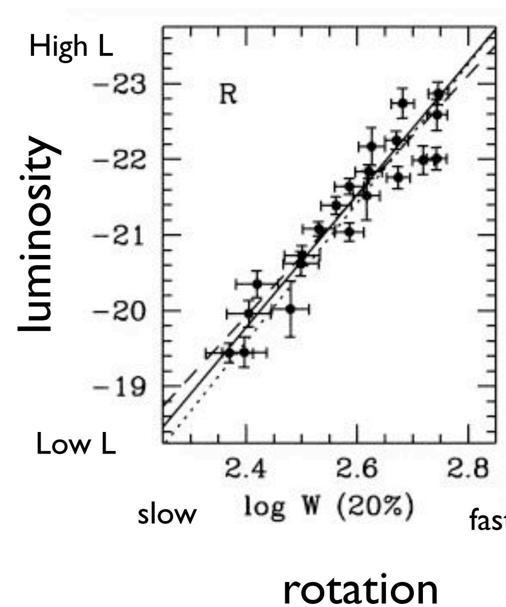
Huchra 1977, ApJ



Scaling relations *continued*

- What about mass?
  - The tightest correlation for disk galaxies is between V and L. This is called the **Tully-Fisher (TF) relation**

R-band (red light) TF:



Tully-Fisher relation: Measurement

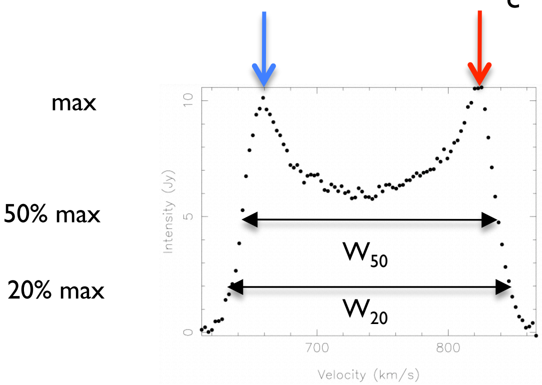
- Details of the measurement
- Velocity:
  - Measure of circular rotation
    - line-width or rotation curve
  - Corrections:
    - *inclination* (1/sin i)
    - turbulent broadening (if line width)
- Luminosity:
  - Corrections:
    - total flux
    - Galactic extinction
    - internal extinction (which depends on *inclination*)
    - distance
      - distance modulous
      - redshifting of band-pass, the so-called "k" correction

- Inclination:
  - Axial ratios of light profile (photometric ellipticity)
    - Correct for disk oblateness
  - Shape of iso-velocity contours (if 2D kinematics are available)

Surrogates measures of rotation

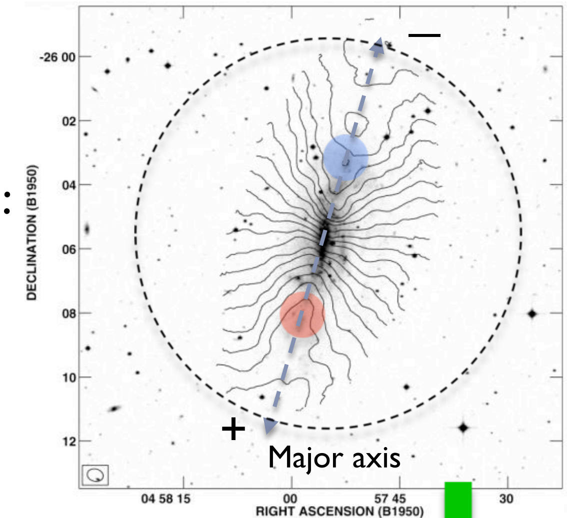
- Spatial information vs sensitivity:

4. Single dish (fiber):
Line width W ~ 2 V_c



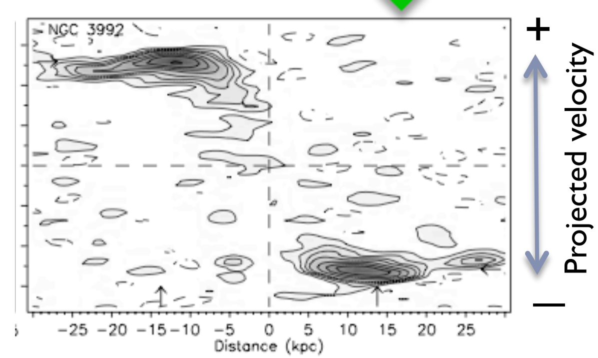
1. Interferometer/IFU:

➔Velocity field
2D map of velocities,
or data cube



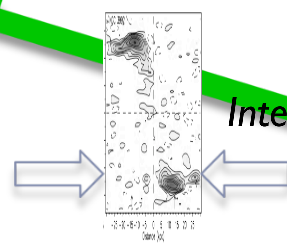
Slice down the major axis

2. Position-velocity diagram (PVD):
Equivalent to long-slit spectrum

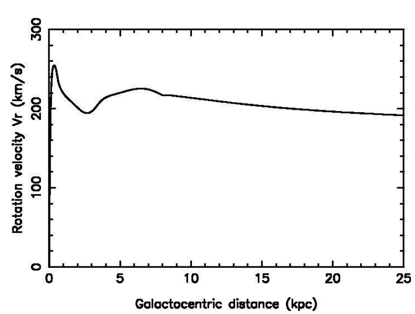


Major axis

Integrate in x (and y)



3. Rotation curve



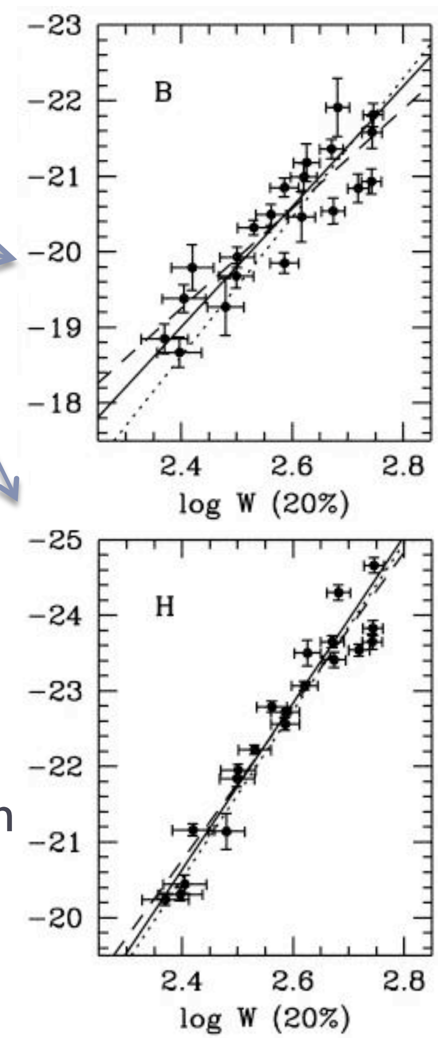
Flip (in V) and fold (in x)

Tully-Fisher relationship: Scatter

- *Small!*
  - 0.5-0.3 mag in blue (B, 0.44 μ m)
  - 0.1 mag in near-IR (H, 1.6 μ m)
  - 0 mag (!) *intrinsic:* K-band for subset of galaxies with rotation curves and flat V(R) (Verheijen 2001)
    - *Too small?*

Why this trend?

gasp!



- Source of dispersion
  - Measurement errors (random)
  - Measurement errors (systematic)
    - Extinction
    - Shape of light-distribution (oblateness)➔inclination
    - Shape of rotation curve➔V_c
  - Cosmic variance
    - Variations in M/L with galaxy type

Tully-Fisher relation: Implications

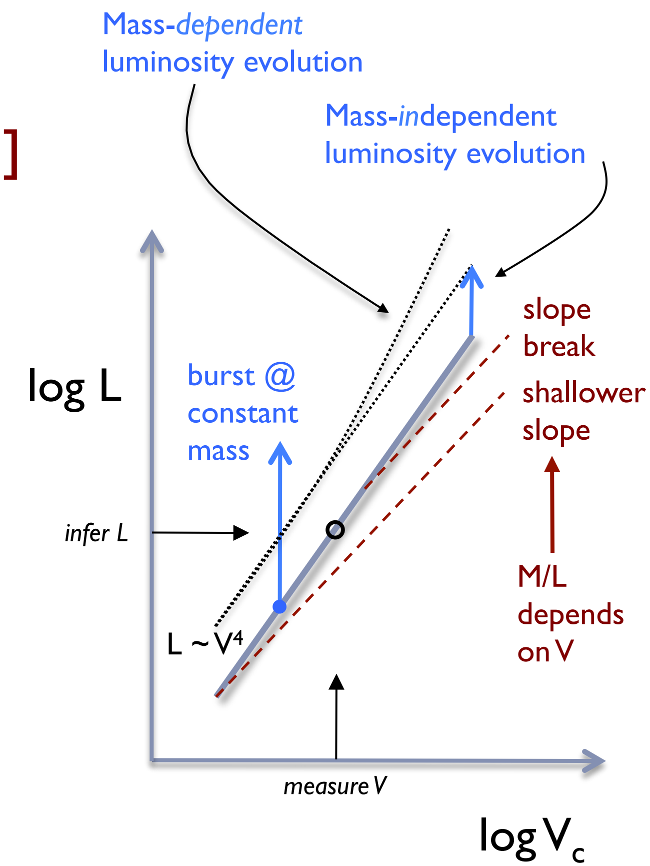
- Why is M/L so constant from galaxy to galaxy?
  - Here we're talking about M/L of the entire galaxy:
    - Mass is dominated by dark halo
    - Luminosity is dominated by disk
  - Total mass: M proportional to $[V^2_{max} h_R]$
  - Total luminosity: L proportional to $[I_0 h_R^2]$ (ignoring bulge)
  - ➔ L proportional to $[V^4_{max} (M/L)^{-2} I_0^{-1}]$
  - A universal M/L implies remarkable constancy of the ratio of dark to luminous matter
    - Or worse, a fine-tuning of the dark-to-luminous mass ratio as the stellar M/L varies.
- What does this tell us about galaxy formation and feedback?

Tully-Fisher relation: diagnostic tool

- Standard candle: V is distance-independent

- Structural probe: slope and scatter
  - Since L is proportional to $[V^4_{max} (M/L)^{-2} I_0^{-1}]$
  - ➔ *M* vs log(V) should have slope of 10
  - and should depend on surface-brightness
    - *Slope is < 10, varies with wavelength*
    - *No dependence on surface-brightness*

- Evolutionary probe
  - Changes in M/L with *time*
    - Assume M roughly constant
      - Secular changes in L: star-formation history
      - Stochastic changes in L (star-formation bursts)
        - Scatter increases with burst duty-cycle



Disk heating in the solar neighborhood

- For a disk in equilibrium the Virial theorem implies σ_z^2/h_z ought to be a constant for any given stellar-population age in the disk

tracer	h_z (pc)	σ_z (km/s)	σ_z^2/h_z
O V	50	6	0.7
B V	60	6	0.8
A V	120	9	0.7
F V	190	13	0.9
G V	350	17	0.8
K V	340	14	0.6
K III	270	16	1.0

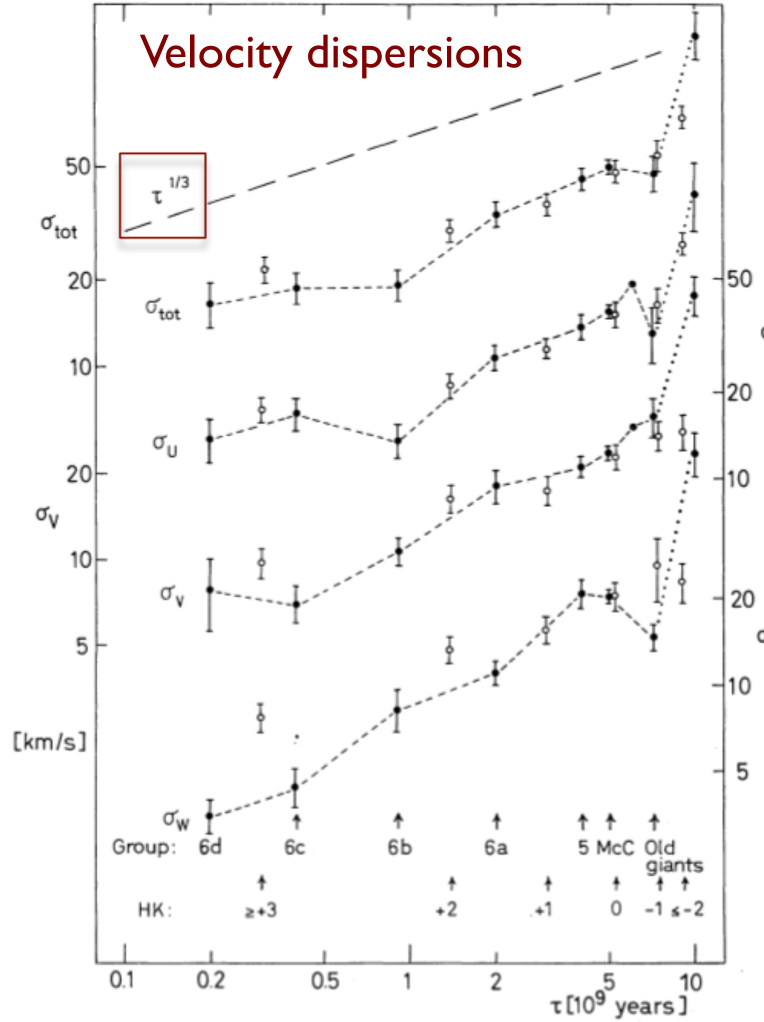


Fig. 4. Velocity dispersions as a function of age.

- Wielen, 1974

How are disk stars heated?

- A number of options…. but:
- Limited constraints
  - Scale-height & vertical velocity dispersion of stars in the solar neighborhood *only*
  - Shape of velocity dispersion ellipsoid:
    - $\sigma_R:\sigma_z:\sigma_\phi \leftrightarrow \langle u^2\rangle^{1/2}:\langle v^2\rangle^{1/2}:\langle w^2\rangle^{1/2}$
  - Constant thickness with radius of external disks
  - Very limited data on a handful (<6) external galaxies: young stars are predominantly near the mid-plane (Seth et al. 2006)

Disk heating options: 1 of 2

- Options 1: Monolithic collapse scenario: early gas disk was thicker
  - This isn't heating!
  - Recent evidence *may* suggest early disks (z~2) were
    - comprised of very large gas clumps (Elmegreen & Elmegren 2006)
    - highly chaotic (smaller V/σ; Förster-Schreiber et al. 2009)
    - Progenitors of today's disk systems or progenitors of today's massive spheroidals?
  - *More fundamentally*: disk heating in MW occurs most rapidly for young ages (recent times). This requires disks to have been a lot thicker in the recent past. *Not observed.*
  - *Thicker gas disks may be relevant for some thick-disk component. TBD!*

Disk heating options: 2 of 2

- Option 2: Gravitational encounters (two-body relaxation)
  - Energy equipartition ➔ star-star encounters not interesting
    - $m_1 v_1^2 = m_2 v_2^2$
  - ➔ requires objects much more massive than single stars:
    - Star—GMC (giant molecular clouds)
      - Encounters naturally due to differential galactic rotation
      - Produces isotropic scattering ➔ $\sigma_R:\sigma_z:\sigma_\phi$ of order unity
    - Star—spiral wave
      - Encounters naturally due to differences between pattern-speed and rotation (what happens at co-rotation?)
      - Produces scattering primarily in plane: $\sigma_z < \sigma_R$ and σ_ϕ ← What is seen in solar neighborhood
    - Star—halo object
      - globular clusters
      - black holes
      - satellites

Apparently cannot account for all of the heating observed in solar neighborhood (Star—GMC and Star—spiral wave)

Outcome depends in detail on orbits (radial or tangential), masses, and spatial distribution (N vs radius) (Star—halo object)

Disk heating via diffusion

- Each encounter delivers an impulse ($\Delta\mathbf{v}$) to a star's velocity $\mathbf{v}$
- Over many (random) encounters $<\Delta\mathbf{v}> = 0$
  - $<\Delta\mathbf{v}> = [\ (1/t)\ \Sigma_{i=1,n}\ \Delta\mathbf{v}_i\ ]_{t\to\infty} = 0$
  - But the sum of the squares does not (direction is randomized, but accelerations are cumulative in an energy sense):
    - $\Sigma_{i=1,n}\ (\Delta\mathbf{v}_i)^2 = D\ t$
    - D is a diffusion coefficient that may, in general depend on t and v

Disk heating via diffusion – Model 1

- Model I:
  - assume diffusion is isotropic, independent of a star's orbit:
    - $d(v^2)/dt = D\ t$
    - For constant $D = D_0$
      - $v^2 = D_0\ t + c$
    - ➔ $v_{rms}(t) = v_{rms}(0)[\ 1\ +\ t/\tau]^{1/2}$

$v_{rms} = \sigma = <v^2>1/2$

τ is something we measure

What about $v_{rms}(0)$?

See Wielen 1977, A&A, 60, 263

Disk heating via diffusion – Model 2

- Model II:
  - From theory of binary encounters (see S&G Ch. 3) D is inversely proprtional to v, i.e., $D(v) = D_0/v$
  - From our initial formulation of diffusion it follows:
    - $d(v^2)/dt = D\ t$
    - $v^3 = 3/2\ D_0\ t + c$
    - $v_{rms}(t) = v_{rms}\ (0)[\ 1 + t/\tau]^{1/3}$

Disk heating via diffusion: conclusions

- From these two models we expect an increase is σ to go as $t^{1/n}$, with $2<n<3$
  - Assuming $v_{rms}(0) = 10$ km s^{-1}, Wielen (1977) estimated from solar neighborhood:
    - $\tau = 2\times10^8$ yr for $n = 2$
    - $\tau = 5\times10^7$ yr for $n = 3$
      - if GMCs ➔ $M_{GMC} \sim 2\times10^6\ M_\odot$, roughly as observed (a bit high)
    - $\sigma_R:\sigma_\phi:\sigma_z \sim 1.0:0.64:0.53$, roughly as observed
      - *even for isotropic diffusion* (don't need spiral arms!)

Disk heating: initial conditions circa 1980

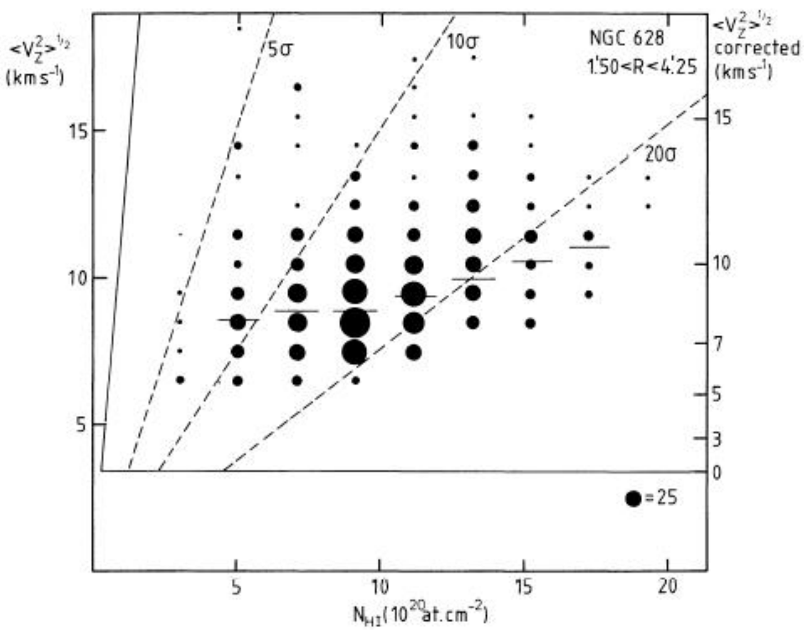
- Vertical velocity dispersions in cold gas

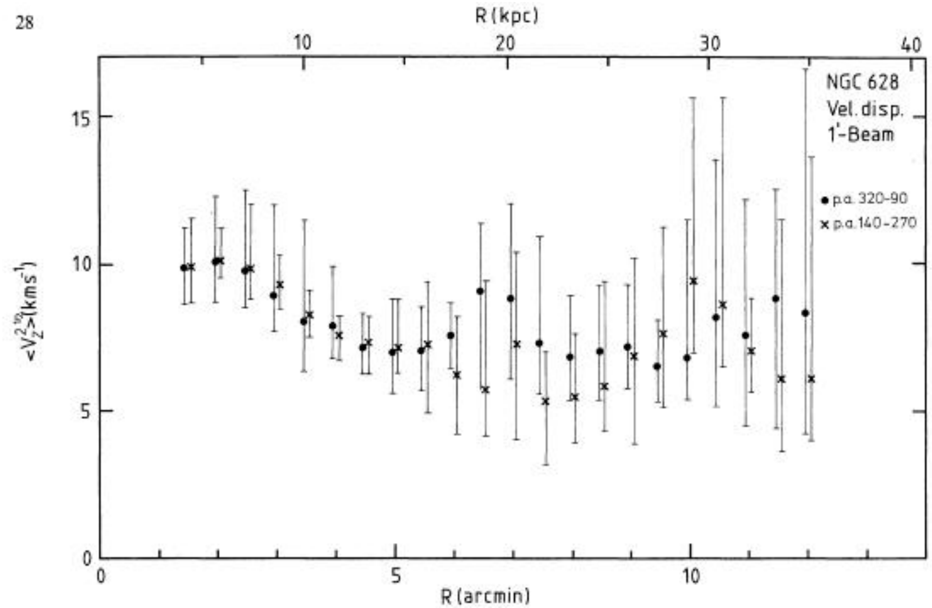
van der Kruit & Shostak (1982, 1984):

σ_{HI} = 6-12 km/s

Combes & Bequaert (1997):

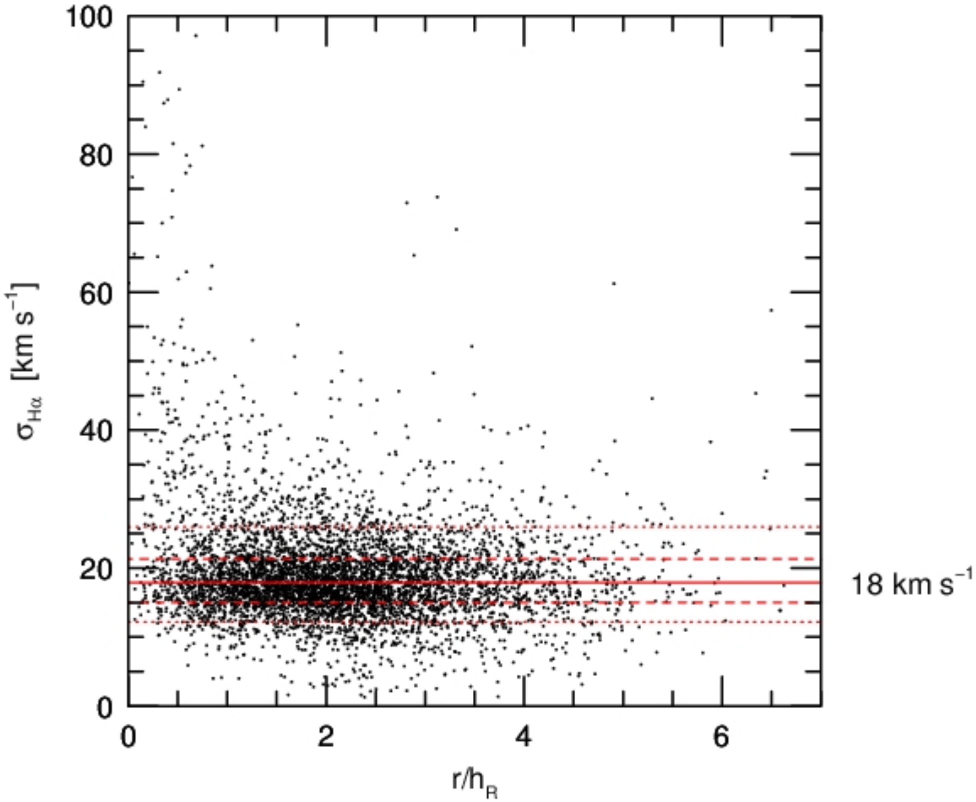
σ_{CO} = 6-9 km/s

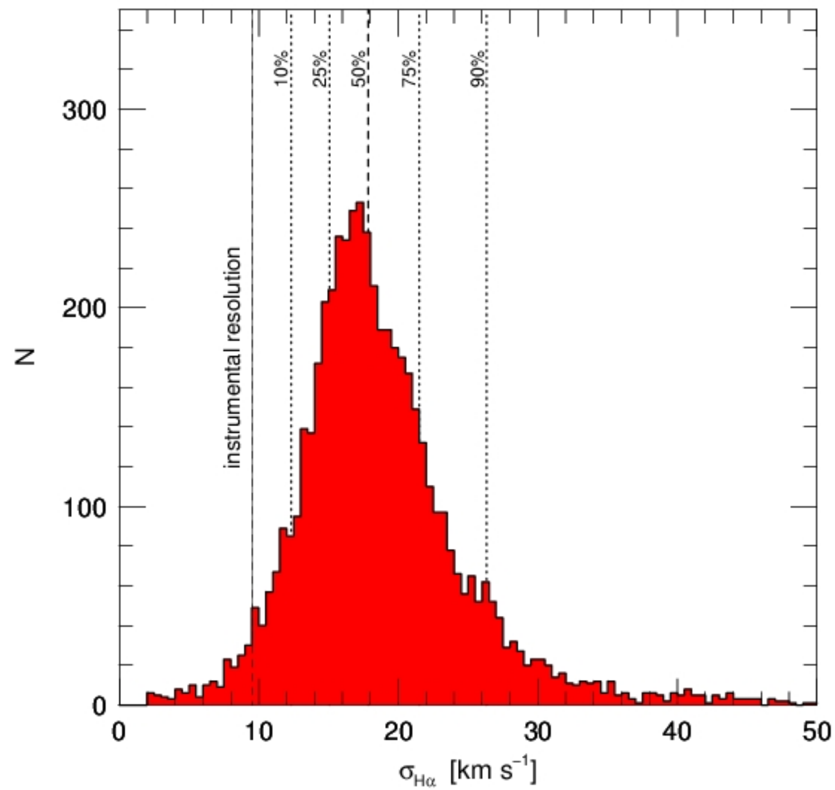




- ~constant with radius -- some density dependence
- Thermal values should be in the 6-8 km/s range

Disk heating: ionized gas (not "initial")

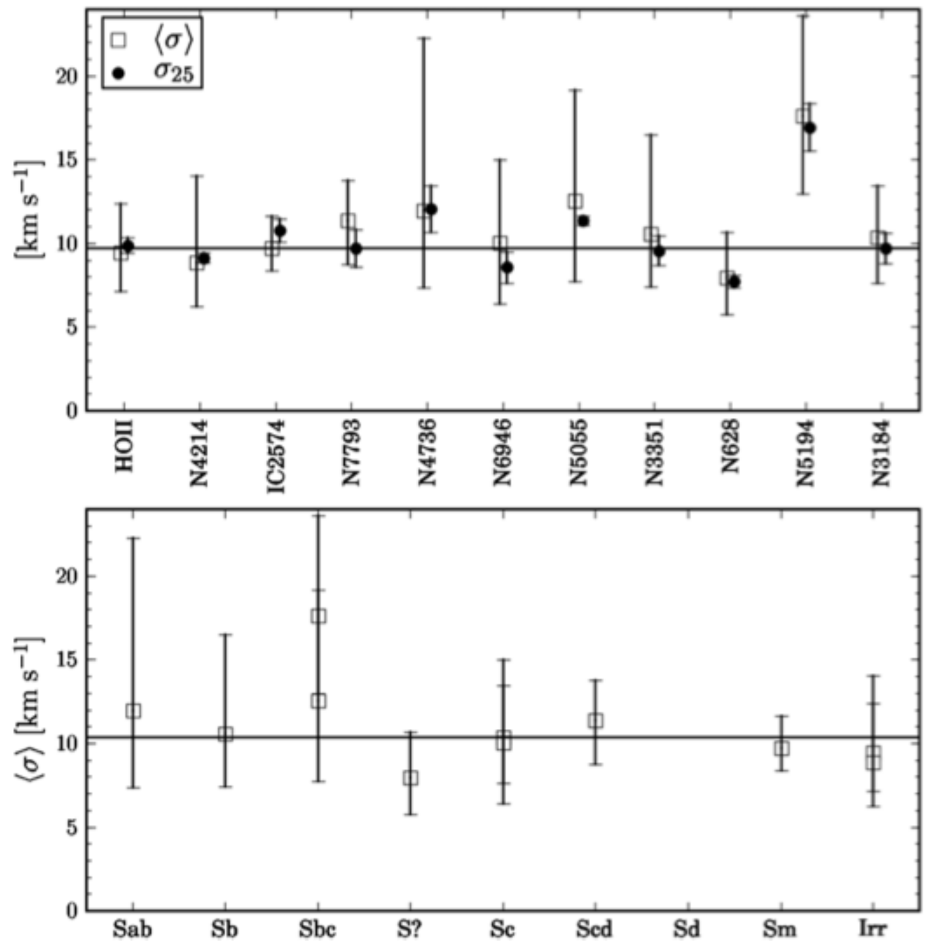




- Median $\sigma_{H\alpha}$ = 18 km/s, appears constant with radius.
- Significant dispersion and galaxy-galaxy variations.

Initial conditions updated:

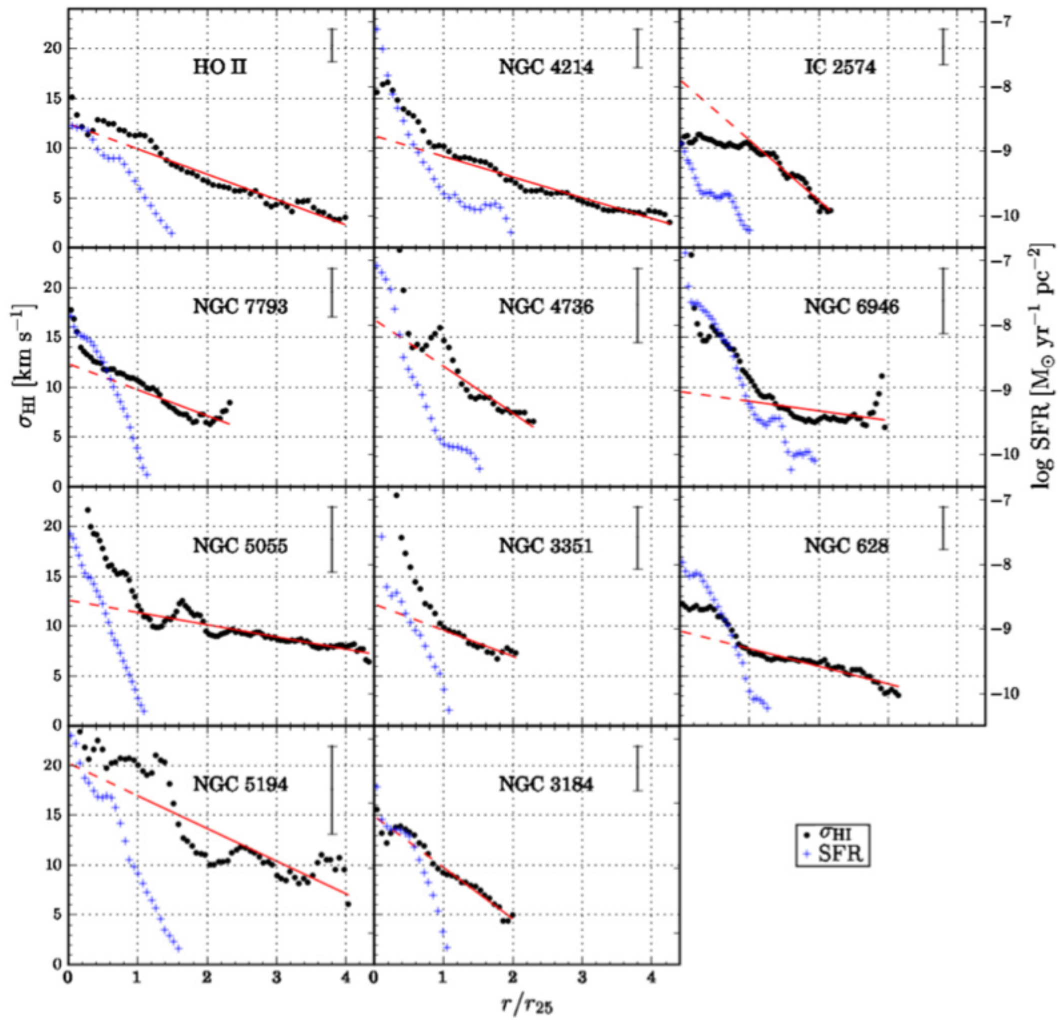
- The good news:
  - The mean σ_{HI} appears very uniform from galaxy to galaxy and across galaxy types.



Tamburro et al. 2009, AJ, 137, 4424

Initial conditions updated:

- The bad news:
  - Almost all galaxies show radial gradients with values of σ_{HI} well above thermal values for warm HI
  - Likely input from star-formation in the form of wind-driven shocks and SNe



Tamburro et al. 2009, AJ, 137, 4424

Disk heating: beyond the solar neighborhood

- While we have a plausible model for how stars heat in the solar neighborhood

  (via diffusion and equipartition from many two-body encounters with massive objects)

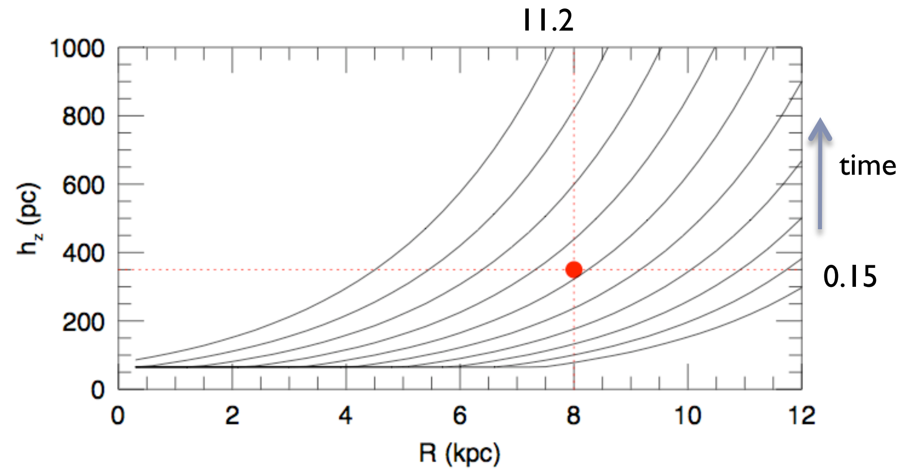
  the picture is incomplete:
  - Diffusion theory doesn't give a good prediction for the time-scale τ
  - GMCs and spiral arms don't appear to heat disk enough
    - Solution: add globular clusters and ubiquitous dark-matter dominated satellites (subhaloes) predicted by ΛCDM structure-formation theory. Ok, but…
  - There has been a lot of work on looking at disk-heating from minor mergers but this tends to lead to disk-flaring in the vertical direction
    - Limits have been placed on the total amount of merging / accretion, e.g., Tóth & Ostriker (1992, ApJ, 389, 5)
  - There hasn't been a study done which includes all of the ingredients
    - **Awesome thesis topic!**

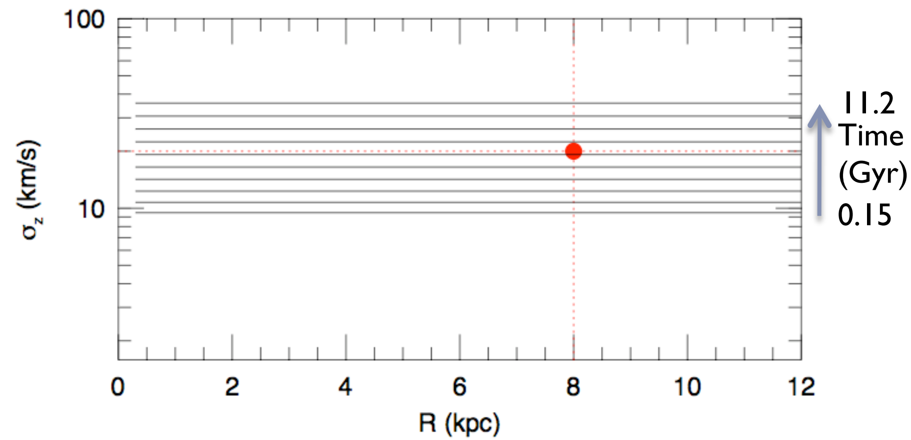
Disk heating: beyond the solar neighborhood

- How well does the model, calibrated in the solar neighborhood match the expectations for the MW and external galaxies overall?
  - Specifically, do we get constant scale-height disks?
- Let's try a few simple calculations for the MW:
  - t_0 = 11 Gyr (age of disk today)
  - $R_\odot$ = 8 kpc
  - $\Sigma = \Sigma_0 \exp(-R/h_R - z/h_z)$
  - h_R = 3 kpc
  - old stars in thin disk in the solar neighborhood:
    - $h_z(R_\odot, t_0)$ = 350 pc
    - $\sigma_z(R_\odot, t_0)$ = 20 km/s
  - Generic assumptions:
    - Disk mass surface-density Σ and scale-length R independent of time

Disk heating: beyond the solar neighborhood

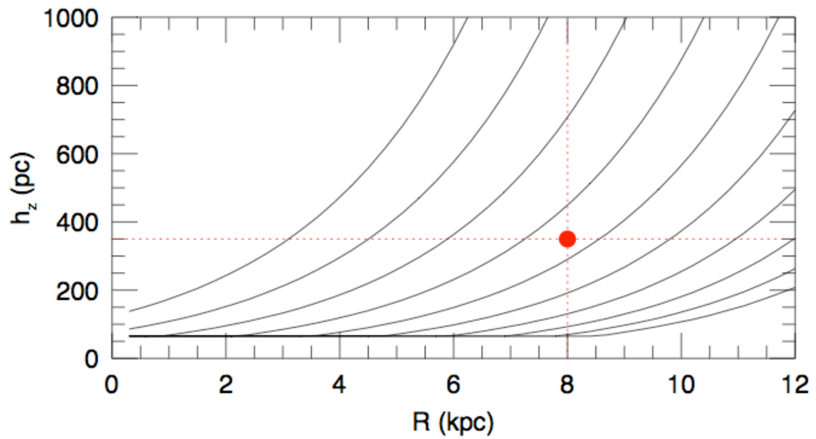
- Model 1:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R independent of time
  - Fixed parameters:
    - n = 2
    - τ= 0.2 Gyr
  - Free parameters: none

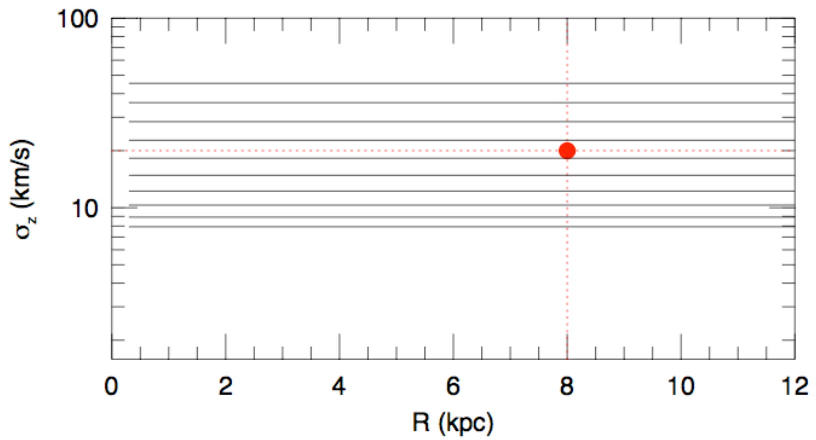




Disk heating: beyond the solar neighborhood

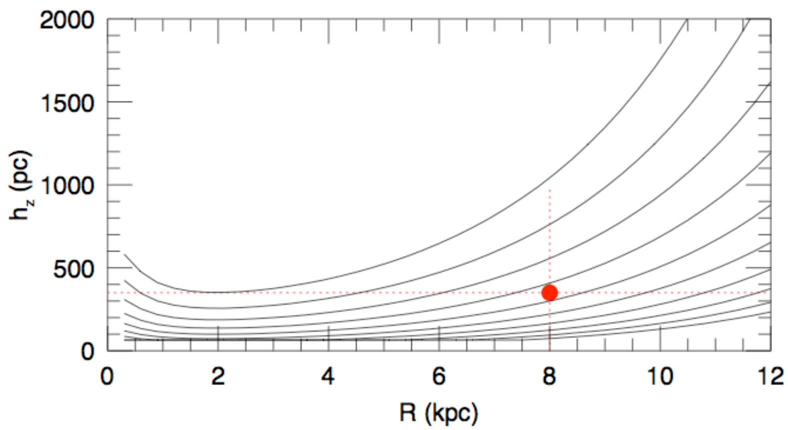
- Model 2:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R independent of time
  - Fixed parameters:
    - n = 3
    - τ= 0.05 Gyr
  - Free parameters: none

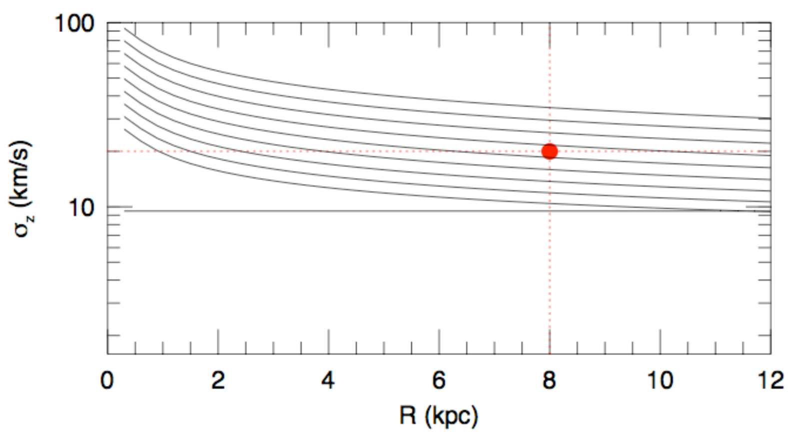




Disk heating: beyond the solar neighborhood

- Model 3:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot, t_0)$ = 350 pc
    - $\sigma_z(R_\odot, t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R independent of time
  - Fixed parameters:
    - n = 3
    - $\tau = t_{dyn} = 2\pi R/V_c$
      - $V_c = V_{flat} \tanh(R/h_{rot})$
      - V_{flat} = 220 km/s
      - $h_{rot} = h_R/10$
  - Free parameters: none

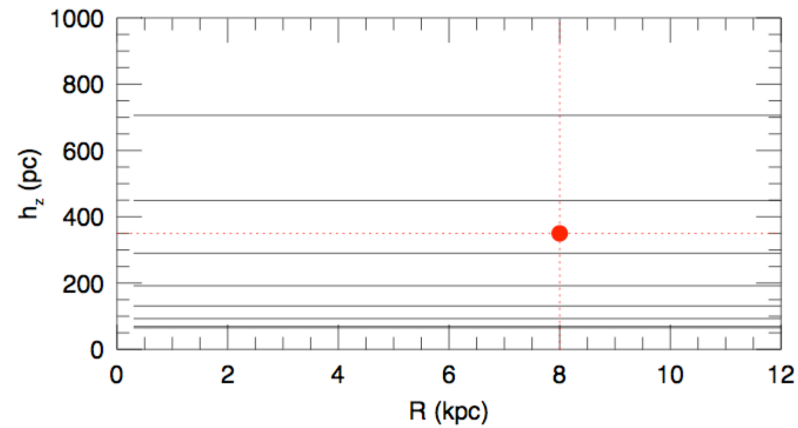


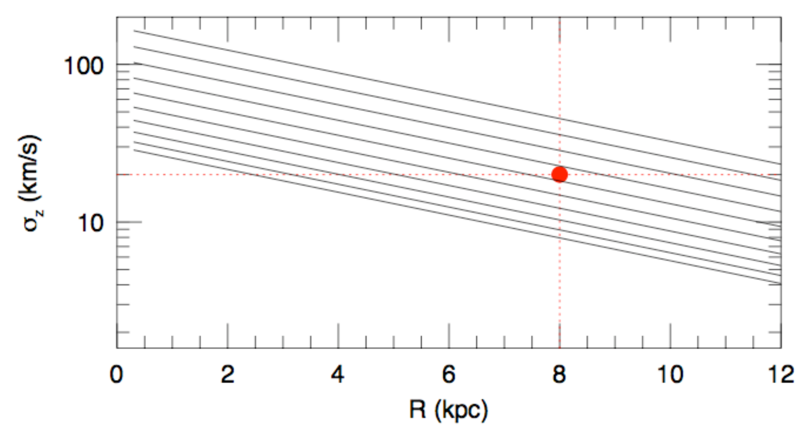


Disk heating: beyond the solar neighborhood

- Model 4:
  - Initial conditions:
    - $\sigma_z\,(R_\odot,t=0)$ = 6 km/s
    - $h_z\,(R_\odot,t=0)$ = 65 pc
    - $\sigma_z\,(R,t=0)$ =

      ** ? ** $\sigma_z\,(R_\odot,t=0)\exp(-R/2h_R)/\exp(-4/h_R)$
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R independent of time
  - Fixed parameters:
    - n = 3
    - τ= 0.05 Gyr
  - Free parameters: none





** Cheating? Recall Tamburro et al. 2009

Disk heating: beyond the solar neighborhood

- Other models:
  - So far we have held n and τ fixed, or held n fixed and set $\tau = t_{dyn}$. The latter looked promising.
  - It is straightforward to find relationships between n and τ such that the final conditions are met for any age population, e.g.,
    - $h_z(R_\odot,t_0) = 350$ pc
    - $\sigma_z(R_\odot,t_0) = 20$ km/s
    - $t_0 = 11$ Gyr (what might be better for old, thin disk?)

    even assuming the initial σ_z and h_z are independent of radius.
  - In this class of models, keeping either n or τ fixed forces the other parameter to change with radius.
  - In all reasonable cases, this yields disks with nearly constant scale-height with radius
  - In the case where n is fixed, $\tau(R)$ is close to t_{dyn}.

Disk heating: beyond the solar neighborhood

Here're examples for fixed n: