Astronomy 330

Lecture 20

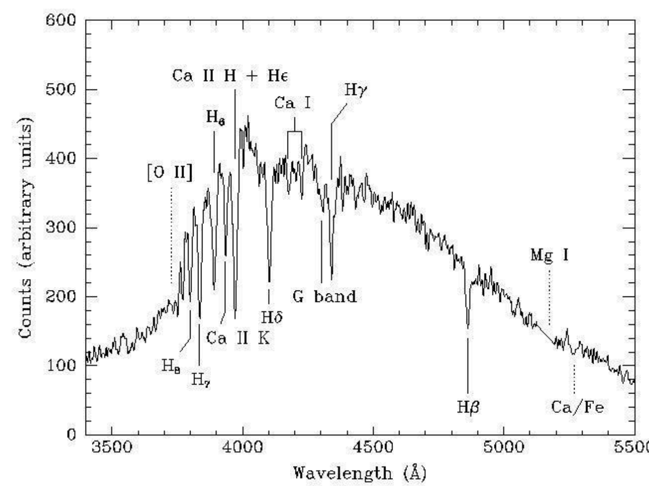
17 Nov 2010

Outline

- Review:
  - Ellipticals: major-mergers & cannibalism
    - Minor mergers: disk heating but not destruction
  - Stellar populations
    - Fuel consumption theorem
    - Direct approach (Pickles)
    - Modern SPS (BC03)
      - Spectra vs age and SFR
- Stellar populations continued
  - Simple models
- Disk heating

Elliptical galaxies

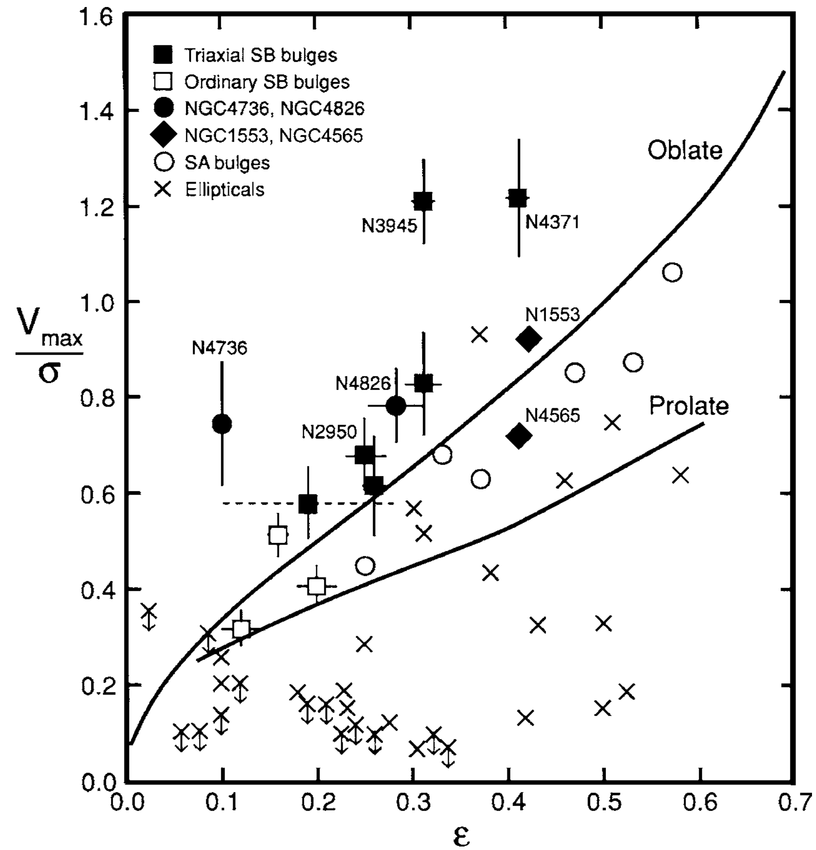
- Formation via major mergers & cannibalism
  - (what's the difference?)
- Major mergers:
  - Destruction of disks
    - Kinematic redistribution of stars
      - dynamical heating: V/σ is lowered
    - Spatial redistribution of stars
      - Simulated merger remnants ~follow $r^{1/4}$ law
  - quenching of star formation
    - E+A galaxies look like merger remnants
  - Heating of gas
    - Ellipticals typically lack cold gas
    - But have x-ray haloes



Update: Dynamical Temperature

Where are spiral disks?

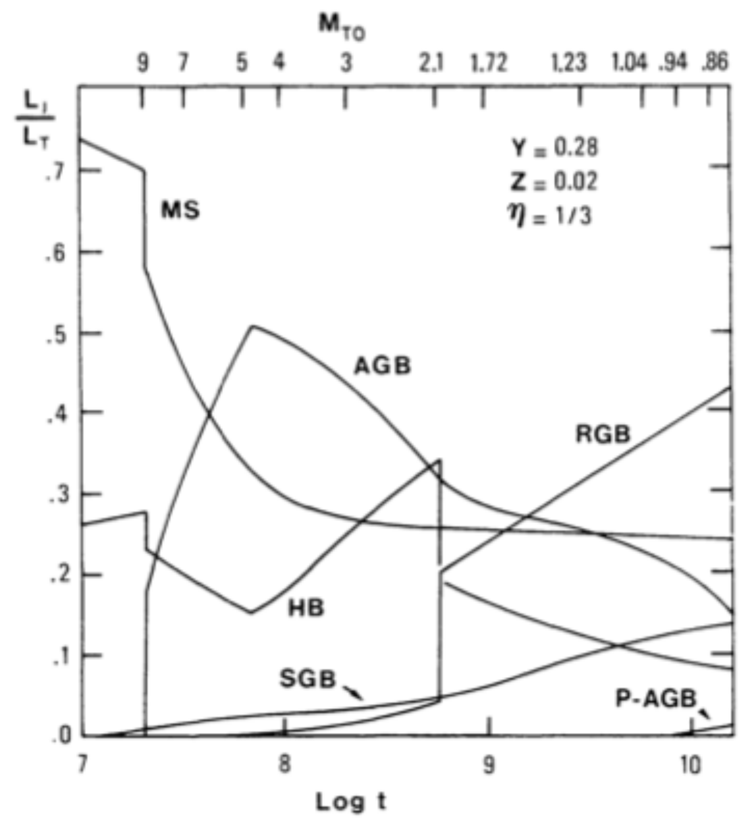
- **The relative dynamical importance of rotation and random motions as a function of observed ellipticity for various kinds of stellar systems.**
  - V_{max}/σ *is the* ratio of maximum rotation velocity to mean velocity dispersion interior to the half-light radius and
  - *ε = 1 — axial ratio.*
  - *The "oblate" line describes oblate-spheroidal systems* that have isotropic velocity dispersions and that are flattened only by rotation; it is a consequence of the tensor virial theorem (Binney&Tremaine 1987).
  - The "prolate" line is one example of how prolate spheroids can rotate more slowly for a given *because* they are flattened partly by velocity dispersion anisotropy.



Kormendy & Kennicutt (2004, ARAA, 42, 603)

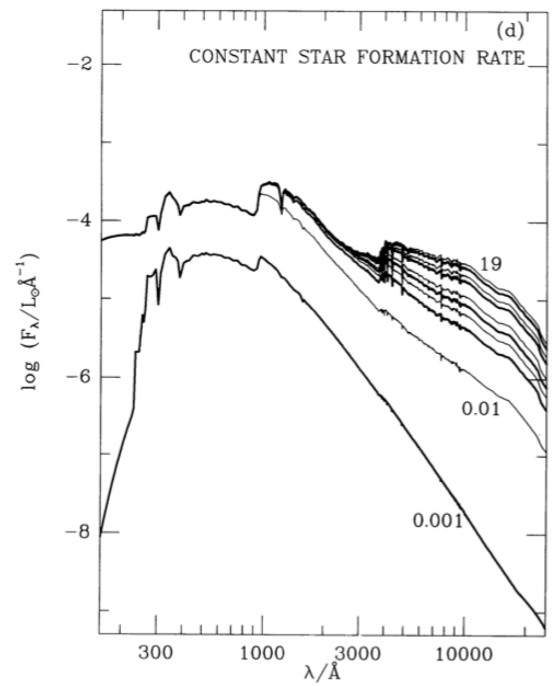
Review: Stellar populations

- Fuel Consumption theorem
  - The relative *bolometric* contribution of stars (L_j) in any evolutionary phase (j) is equal to the relative amount of fuel (F_j) that each evolving star burns during that phase

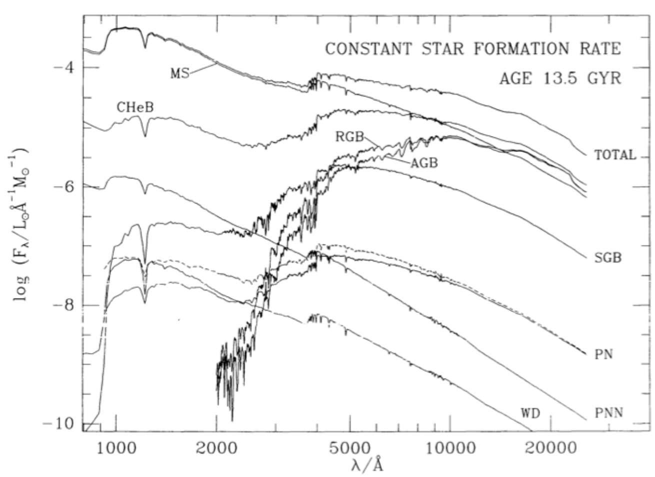


Stellar populations

- Modern SPS ingredients:
  - IMF
  - SFR
  - Chemical enrichment
  - Isochrones (log L, T_e)
  - Stellar atmospheres (M_V, B-V)



↑ Evolution over time



← Contributions at curent time

Ancient isochrones (you can't get this on iTunes)

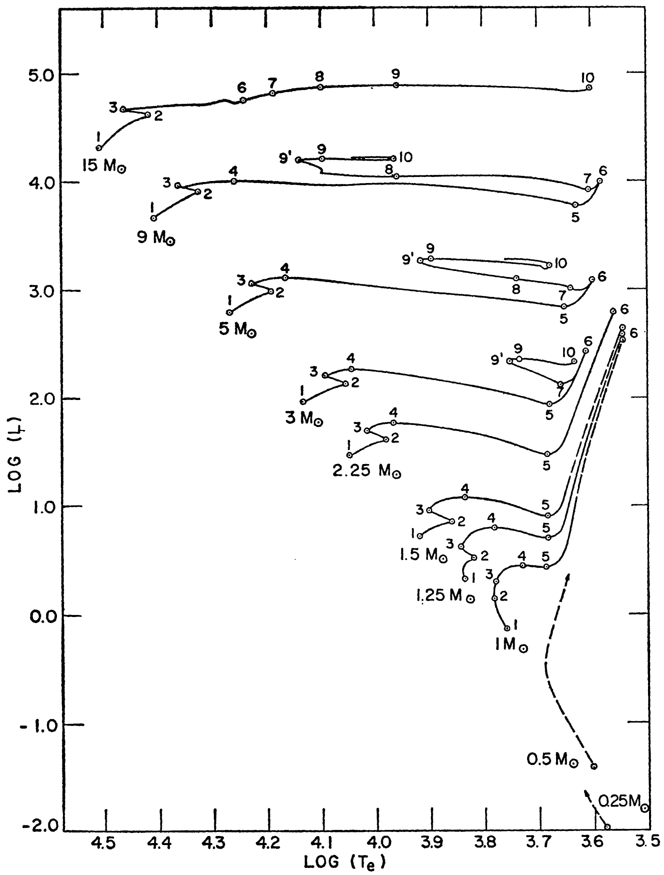


FIG. 3. Paths in the H-R diagram for metal-rich stars of mass $(M/M_{\odot})=15$, 9, 5, 3, 2.25, 1.5, 1.25, 1, 0.5, 0.25. Units of luminosity and surface temperature are the same as in Figure 1. Traversal times between labeled points are given in Tables III and IV. Dashed portions of evolutionary paths are estimates.

TABLE III

STELLAR LIFETIMES (yr)[a]

Mass ($M_{\odot}$) \ Interval ($i-j$)	(1–2)	(2–3)	(3–4)	(4–5)	(5–6)
15	1.010 (7)	2.270 (5)		7.55 (4)	
9	2.144 (7)	6.053 (5)	9.113 (4)	1.477 (5)	6.552 (4)
5	6.547 (7)	2.173 (6)	1.372 (6)	7.532 (5)	4.857 (5)
3	2.212 (8)	1.042 (7)	1.033 (7)	4.505 (6)	4.238 (6)
2.25	4.802 (8)	1.647 (7)	3.696 (7)	1.310 (7)	3.829 (7)
1.5	1.553 (9)	8.10 (7)	3.490 (8)	1.049 (8)	≥2 (8)
1.25	2.803 (9)	1.824 (8)	1.045 (9)	1.463 (8)	≥4 (8)
1.0	7 (9)	2 (9)	1.20 (9)	1.57 (8)	≥1 (9)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

TABLE IV

STELLAR LIFETIMES (yr)[a]

Mass ($M_{\odot}$) \ Interval ($i-j$)	(6–7)	(7–8)	(8–9)	(9–10)
15	7.17 (5)	6.20 (5)	1.9 (5)	3.5 (4)
9	4.90 (5)	9.50 (4)	3.28 (6)	1.55 (5)
5	6.05 (6)	1.02 (6)	9.00 (6)	9.30 (5)
3	2.51 (7)	4.08 (7)		6.00 (6)

[a] Numbers in parentheses beside each entry give the power of ten to which that entry is to be raised.

Iben 1967, ARAA, 5, 571 (same year as Sgt. Pepper's and Magical Mystery Tour)

Evolution of an intermediate-mass star

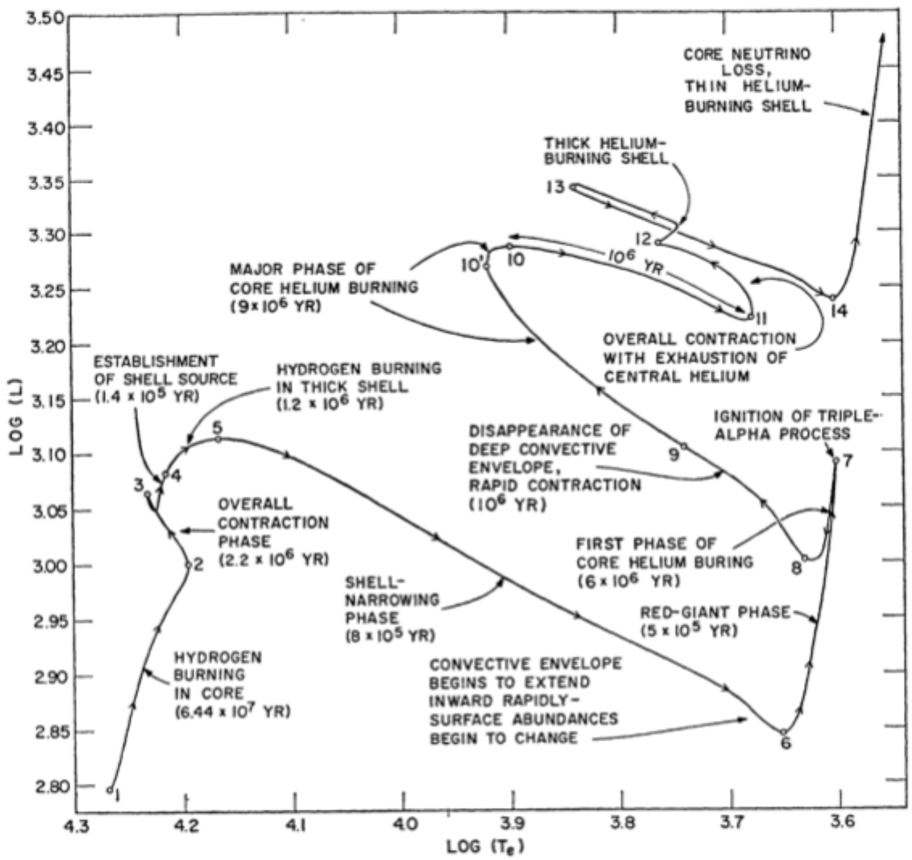
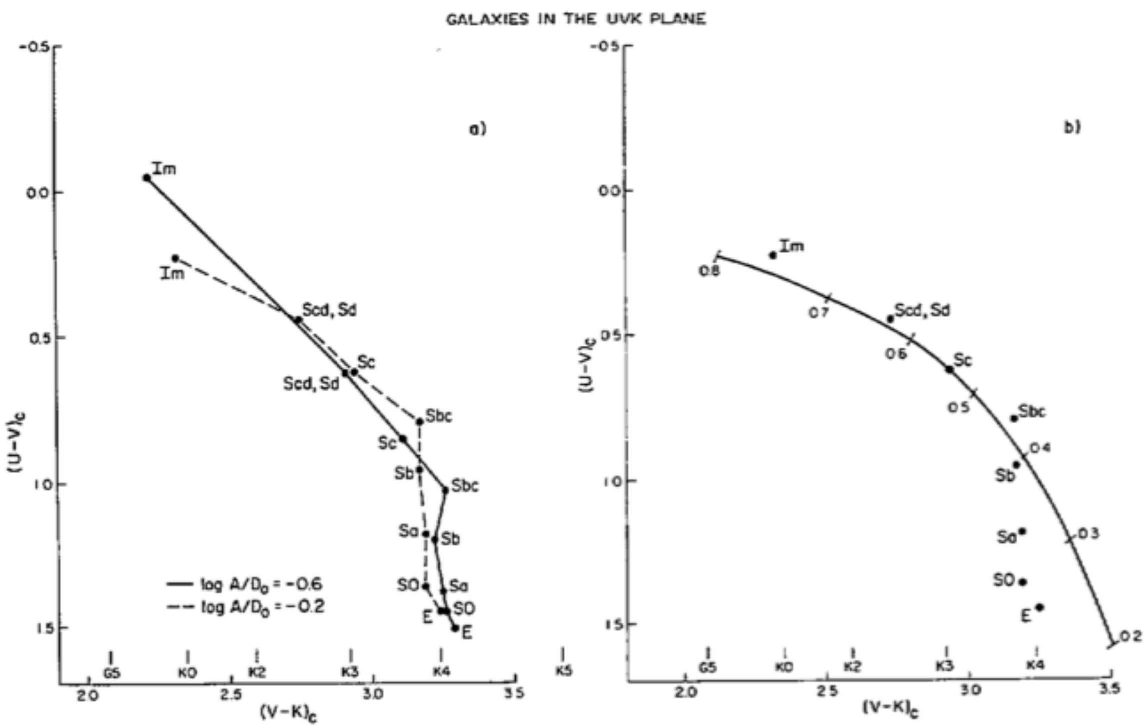


FIG. 1. The path of a metal-rich $5M_{\odot}$ star in the Hertzsprung-Russell diagram. Luminosity is in solar units, $L_{\odot}=3.86\times10^{33}$ erg/sec, and surface temperature T_e is in deg K. Traversal times between labeled points are given in years.

- Iben 1967, ARAA, 5, 571 (Paul Martin didn't edit this volume)

Simple population synthesis: the UVK plane

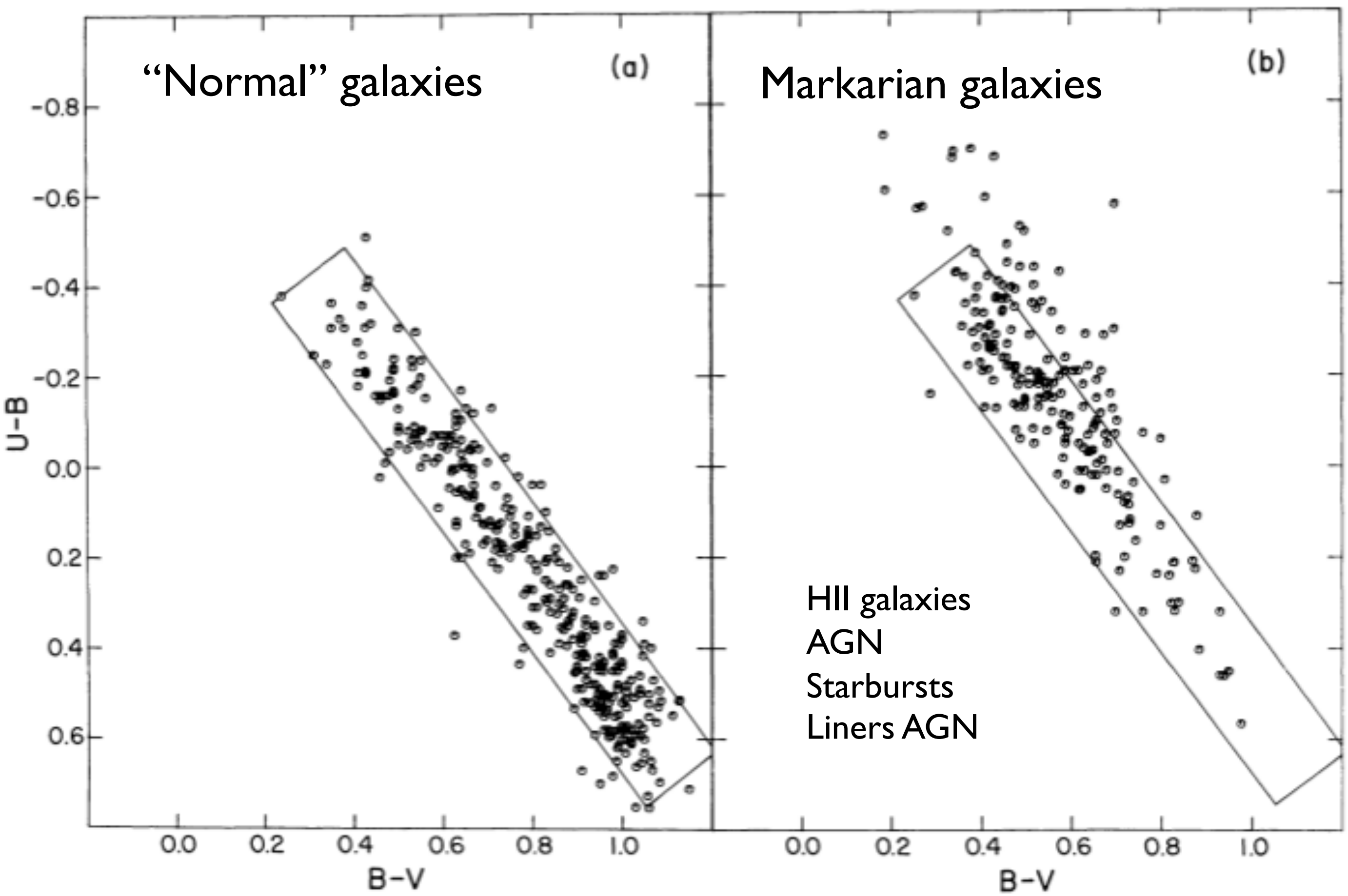


U: 370 nm
V: 550 nm
K: 2200 nm

Galaxies can be well-modeled by an admixture of A0V and M0III in U-V vs V-K

- Aaronson 1980 ApJ, 221, L103

Galaxies in the UBV plane



Markarian:
Russian astronomer

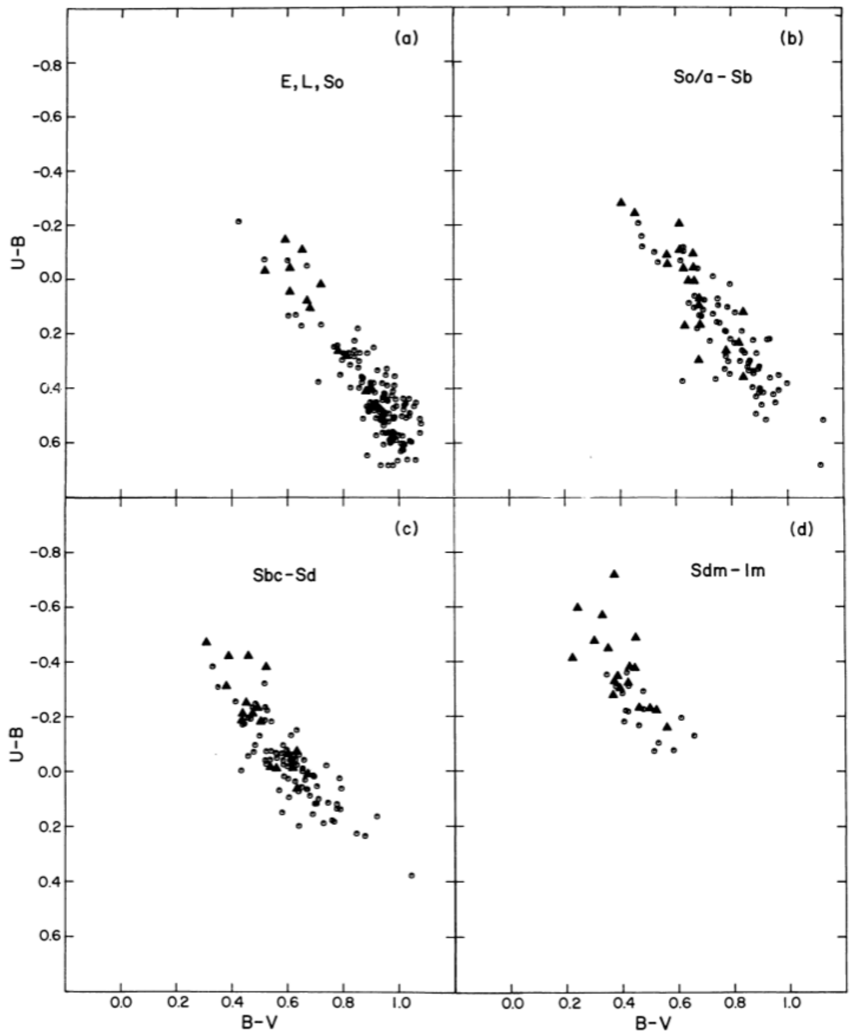
U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

- Huchra 1977, ApJS, 35, 171

Galaxies in the UBV plane by Type



U: 370 nm
B: 440 nm
V: 550 nm

What's the color of an A0V?

What does this tell us about Aaronson's simplification of A0V+M0III for the UVK plane?

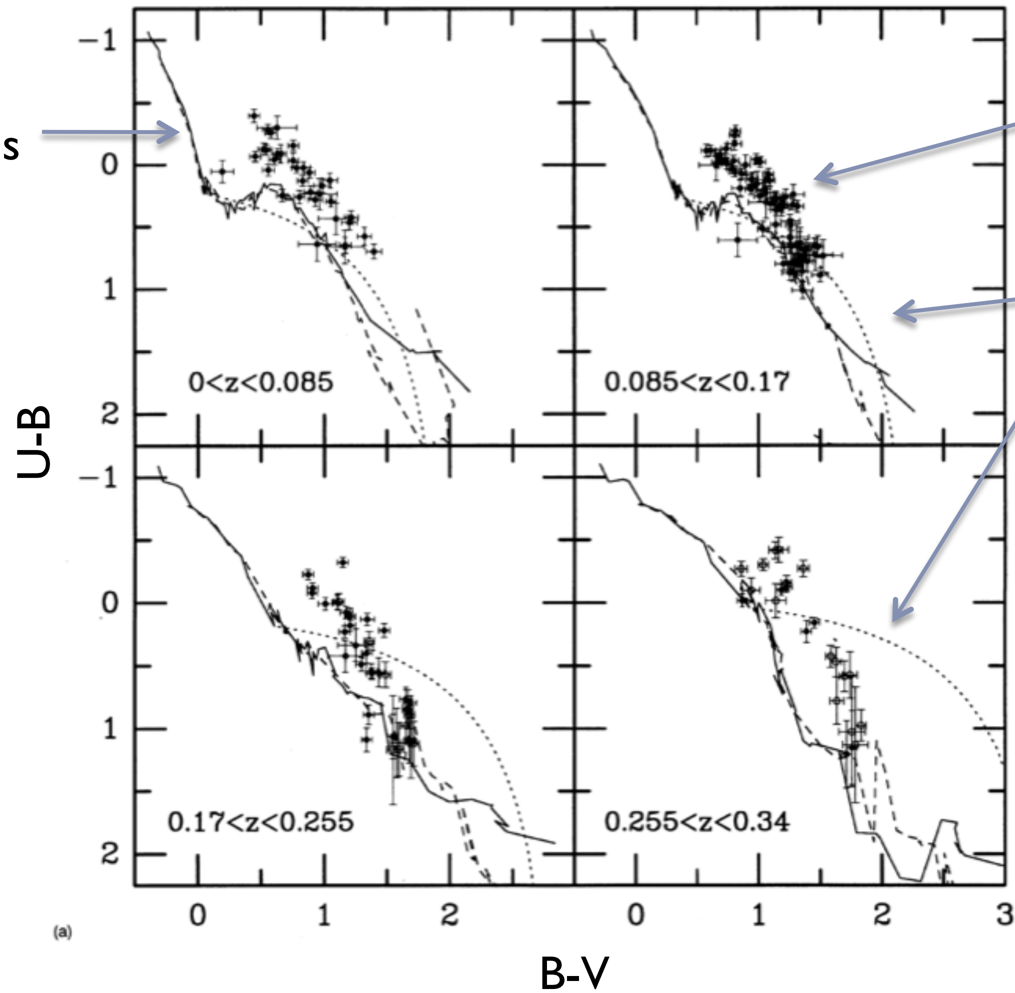
Why is it more complicated when you look in more detail in the blue? (U-V ➔ U-B,B-V)

What are the implications for spectra?

- Huchra 1977, ApJS, 35,171

Galaxies: UBVRIK multi-colors

Stellar locus



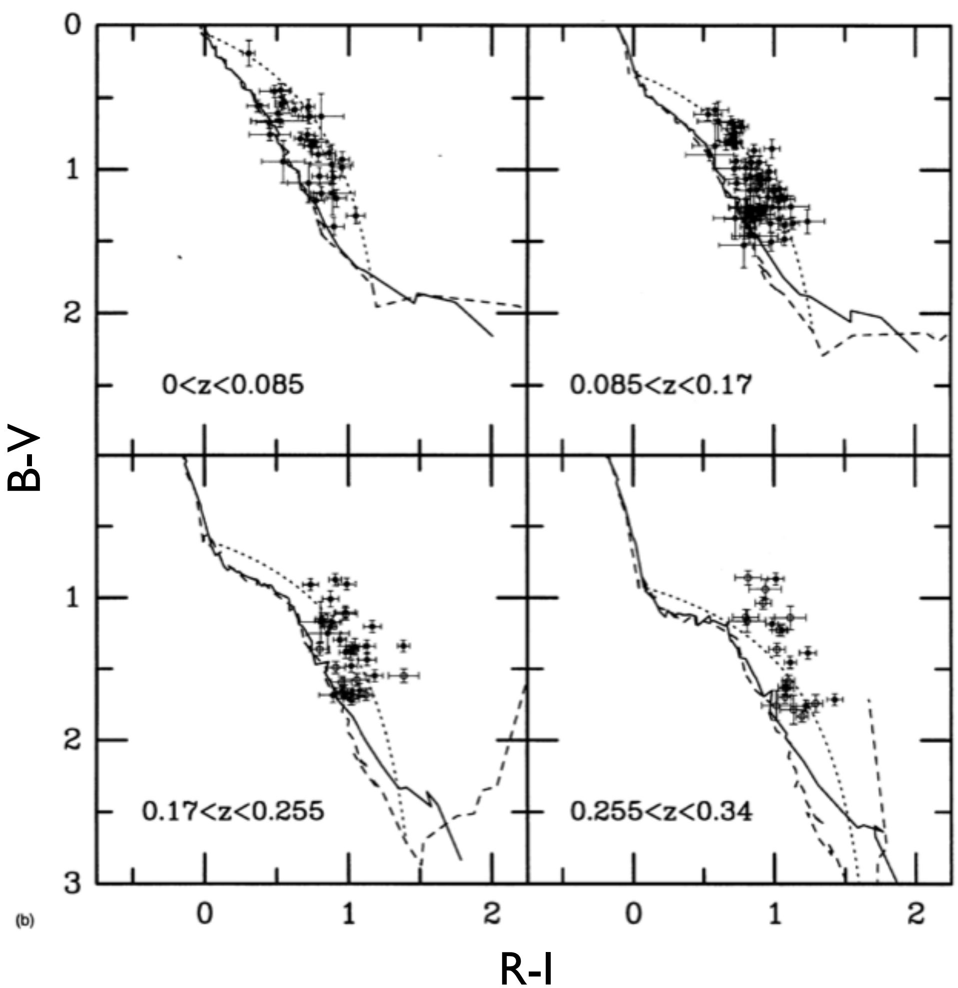
Individual galaxies

Aaronson's A0V+M0III model

The effect of redshift:
By z ~ 0.3 UBV samples 280, 330, 420 nm (near-UV)

- Bershady 1995, AJ, 109, 97

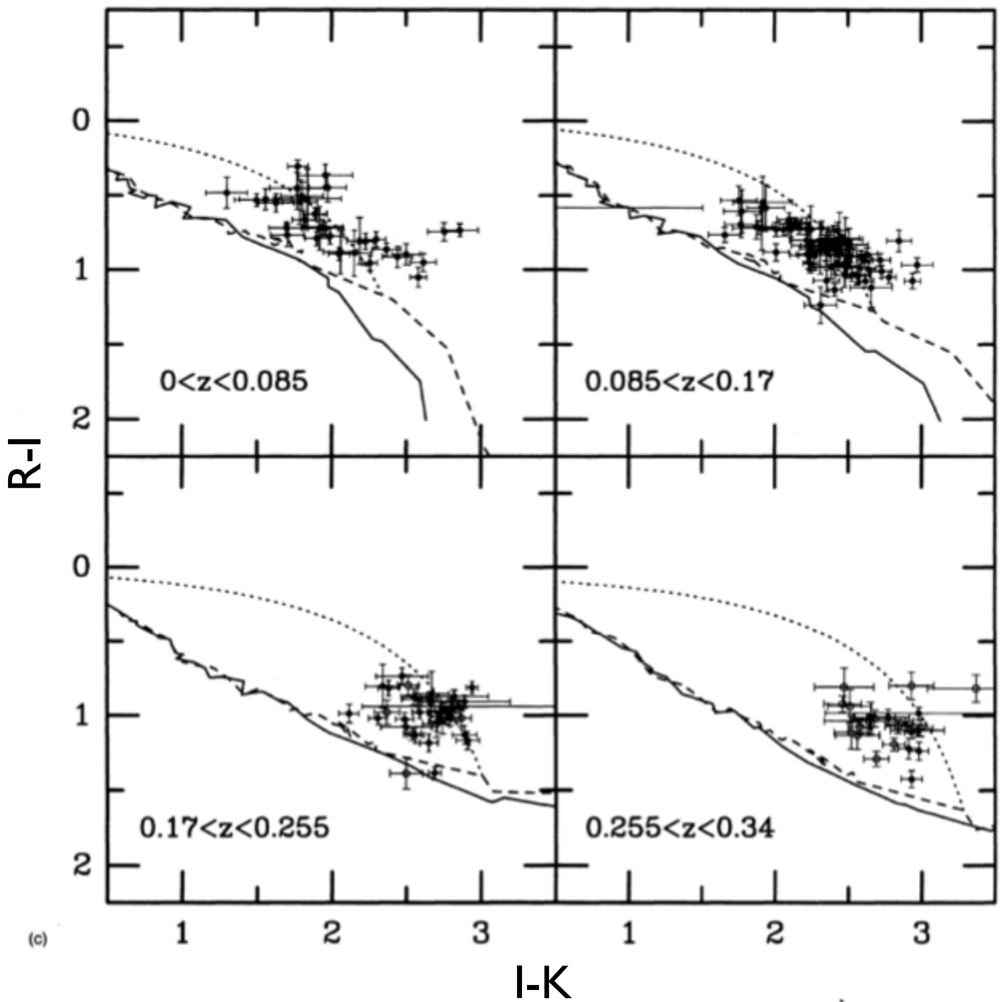
Galaxies: UBVRIK multi-colors



R: 650 nm
I: 800 nm

- B95

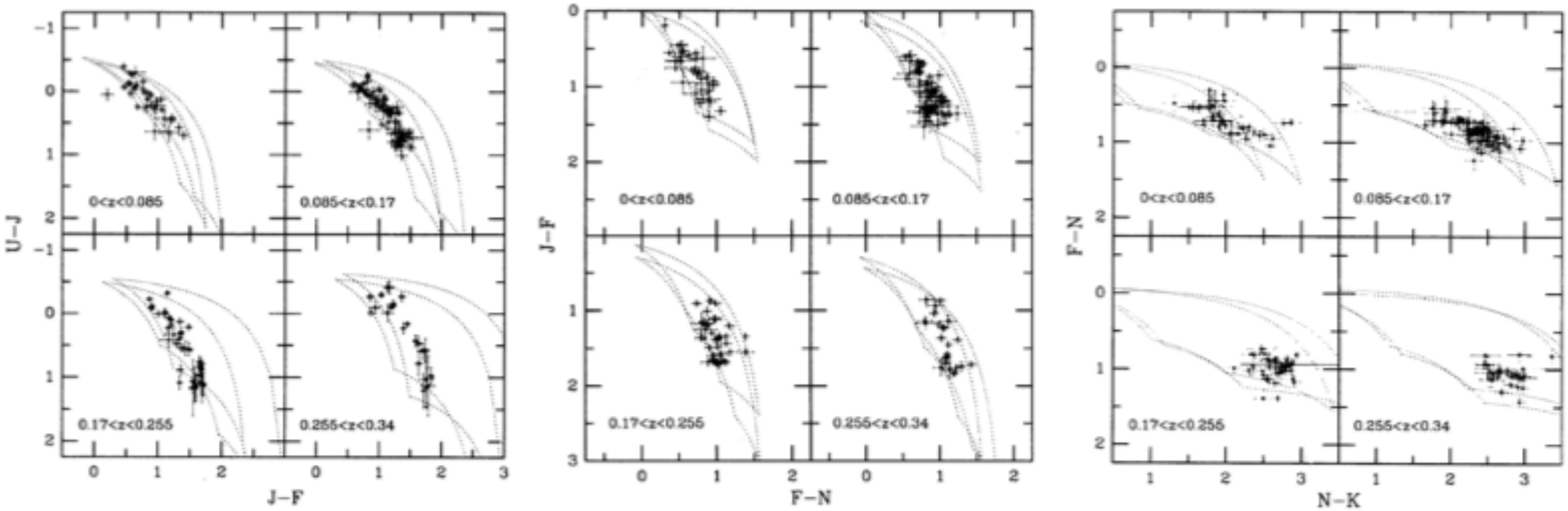
Galaxies: UBRIK multi-colors



- B95

Simple model: 4 stars in UBRIK

Linear combinations of B V, G V, K III, M III



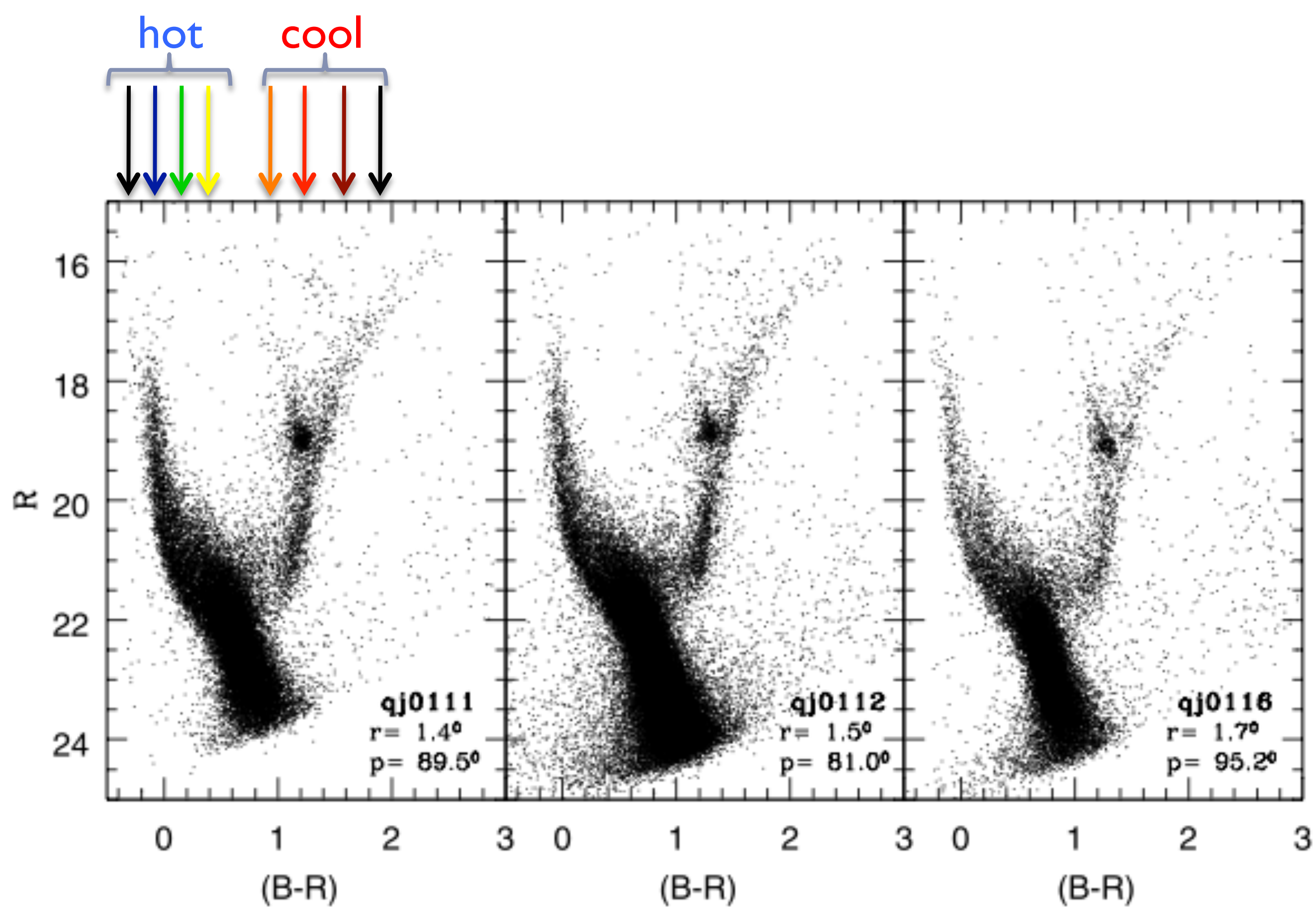
Alternatively, use linear combinations of 2 *stars*, but don't fix type:

○ One star is hot (ranging from B to G) – assume luminosity class V

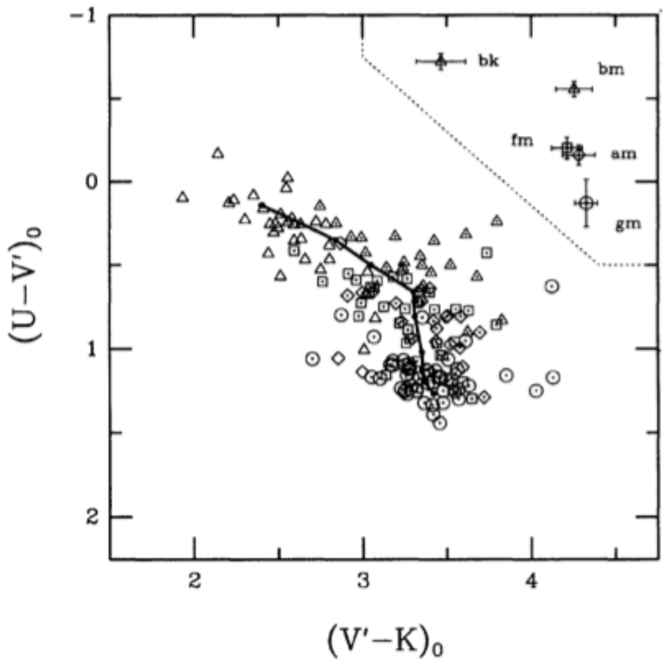
○ The second star is cool (ranging from G to M) – assume luminosity class III

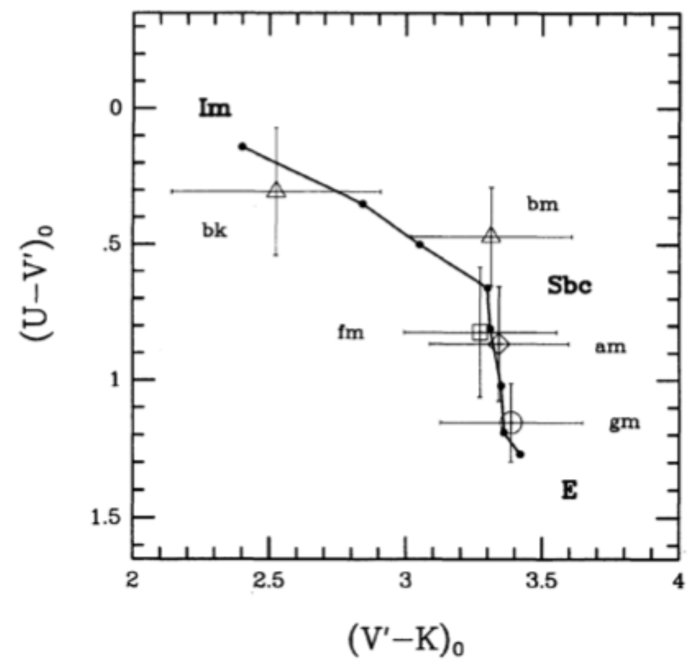
Thinking in terms of CMDs, why does this make sense?

CMD for the SMC at 60 kpc OMG



UVK plane revisited: a 2-star model

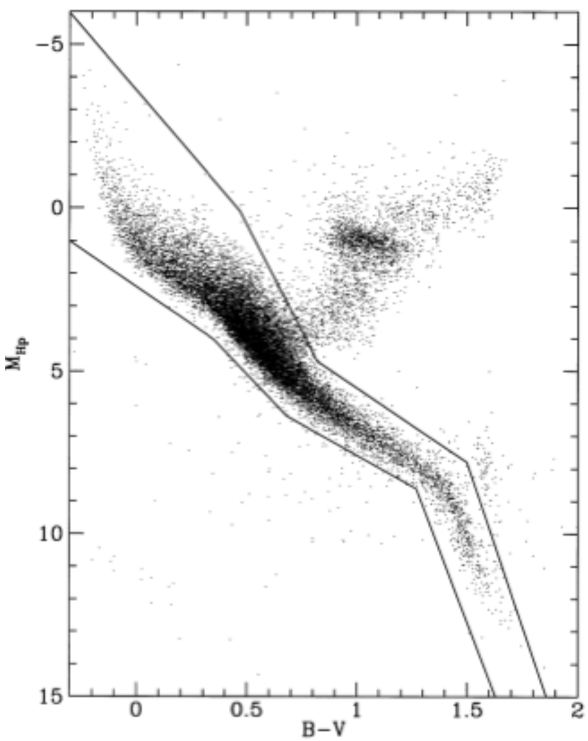




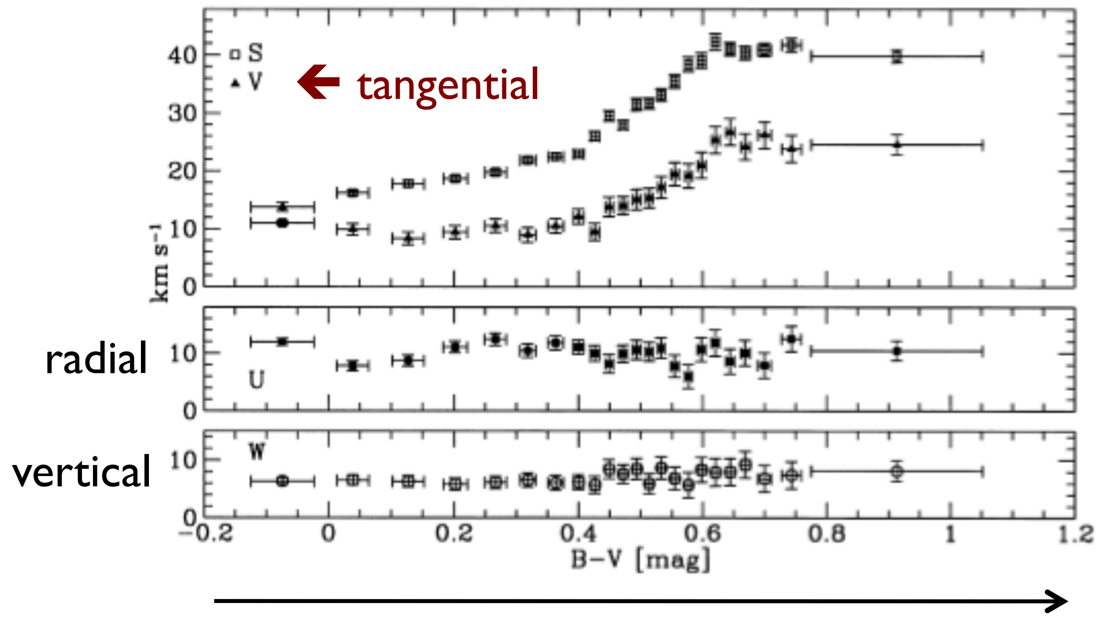
- Galaxies classified by two-star models required to fit UBVRIK multicolors
- Reminiscent of Morgan spectral-types, extended to red and NIR

Disk heating: recall Parenago's Discontinuity

Clues to disk evolution: old disk stars rotate more slowly



Hipparcos catalogue: geometric parallax and proper motions



τ_{ms} → mean age

Binney et al. (2000, MNRAS, 318, 658)

$S = S_0\,[1+(t/\mathrm{Gyr})^{0.33}]$ ← random grav. encounters

$S_0 = 8$ km s^{-1} ← why might this be?

See also Wielen 1977, A&A, 60, 263

Disk heating: kinematics – solar neighborhood

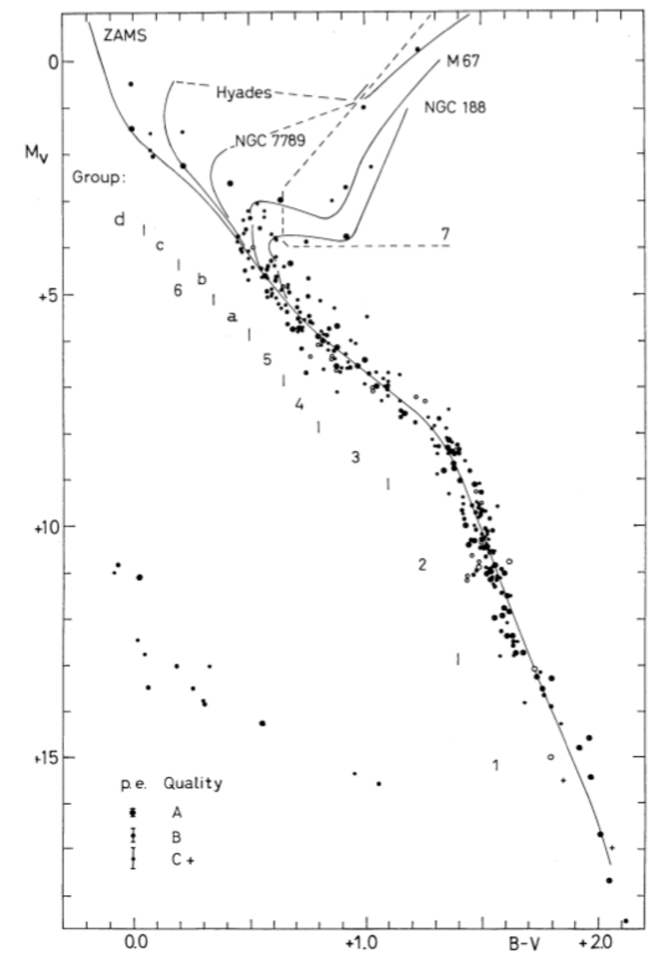


Fig. 2. Colour-magnitude diagram for Gliese's stars with accurate trigonometric parallaxes

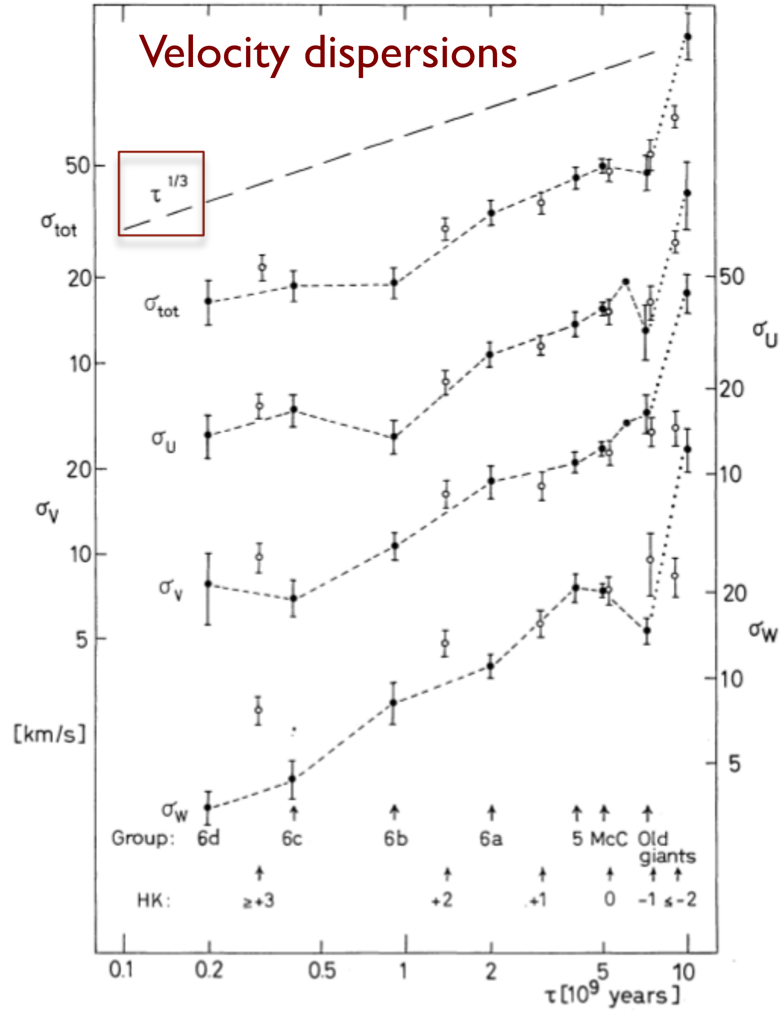


Fig. 4. Velocity dispersions as a function of age.

- Wielen, 1974

Disk heating: scale-heights – solar neighborhood

- There is a correlation between the scale-height of stars near the Sun in the MW and their spectral type:
  - Crudely: the thin-disk is young and the thick disk is old
  - Both scale-height and vertical velocity dispersion change with spectral type. *Why*?
- What would you expect for a disk in dynamical equilibrium?
  - Virial theorem: KE = −1/2 PE
  - In the vertical dimension, per unit surface-area:
    - KE ~ ½ $\Sigma\ \sigma_z^2$
    - PE ~ $-G\Sigma/h_z$
- Similarly, recall:

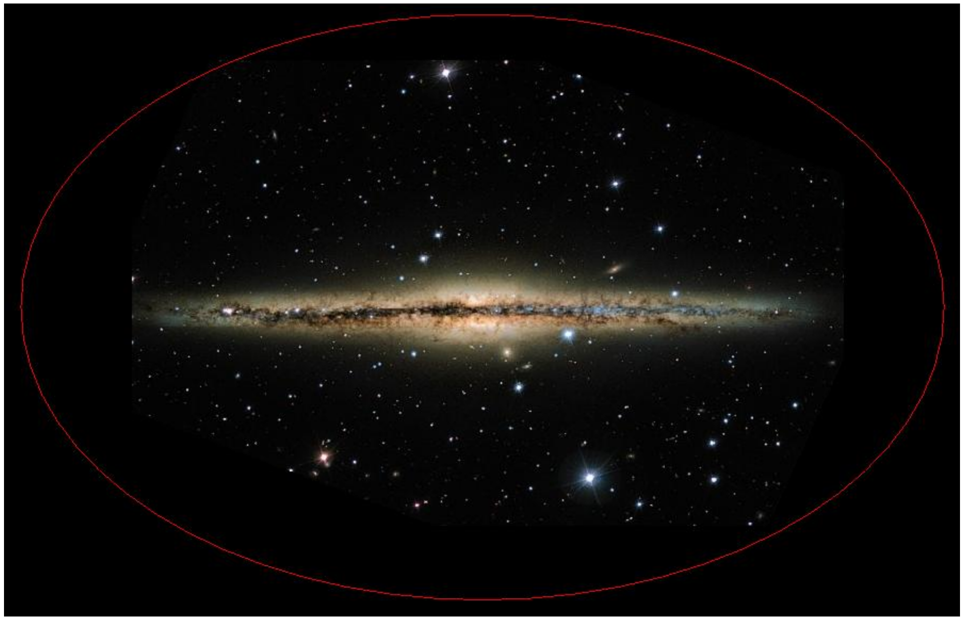
$$\Sigma = 100\left(\frac{k}{3/2}\right)^{-1}\left(\frac{h_z}{444\ \mathrm{pc}}\right)^{-1}\left(\frac{\sigma_z}{30\,\mathrm{km/s}}\right)^{2} \mathrm{M_{sol}\ pc^{-2}}$$

- This means σ_z^2/h_z ought to be a constant
  - What are the assumptions?

Disk heating in the solar neighborhood

- Take these numbers with a grain of salt (they are old; Mihalas & Binney compilation circa 1981)
- Is there a trend?
- Anything weird?
  - If so, why?

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



$$\Sigma = 100 \left(\frac{k}{3/2}\right)^{-1} \left(\frac{h_z}{444\ \mathrm{pc}}\right)^{-1} \left(\frac{\sigma_z}{30\ \mathrm{km/s}}\right)^{2} \mathrm{M_{sol}\ pc^{-2}}$$

How are disk stars heated?

- A number of options
- 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)

- 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!*

How are disk stars heated?

- 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
    - Star—halo object
      - globular clusters
      - black holes
      - satellites

What is seen in solar neighborhood➔ (pointing to: Produces scattering primarily in plane)

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 and impulse ($\Delta \mathbf{v}$) to a star's velocity $\mathbf{v}$
- Over many (random) encounters $<\Delta \mathbf{v}> = 0$
  - $<\Delta \mathbf{v}> = [\ (1/t)\ \Sigma_{i=1,n}\ \Delta \mathbf{v}_i\ ]_{t \rightarrow \infty} = 0$
  - 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
- Model 1:
  - assume diffusion is isotropic, independent of a star's orbit:
    - $d(v^2)/dt = D\ t$
    - For constant $D = D_0$
      - $v^2 = D_0\ t + c$
    - $\rightarrow v_{rms}(t) = v_{rms}(0)[\ 1\ +\ t/\tau]^{1/2}$

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

τ is something we measure

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

- See Weilen 1977, A&A, 60, 263

Disk heating via diffusion

- 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:
    - $d(v^2)/dt = D\ t$
    - $v^3 = 3/2\ D_0\ t + c$
    - $v_{rms}(t) = v_{rms}(0)[\ 1 + t/\tau]^{1/3}$
- So we expect an increase is σ to go as $t^{1/n}$, with $2<n<3$
  - Assuming $v_{rms}(0) = 10$ km s^{-1}, Weilen (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

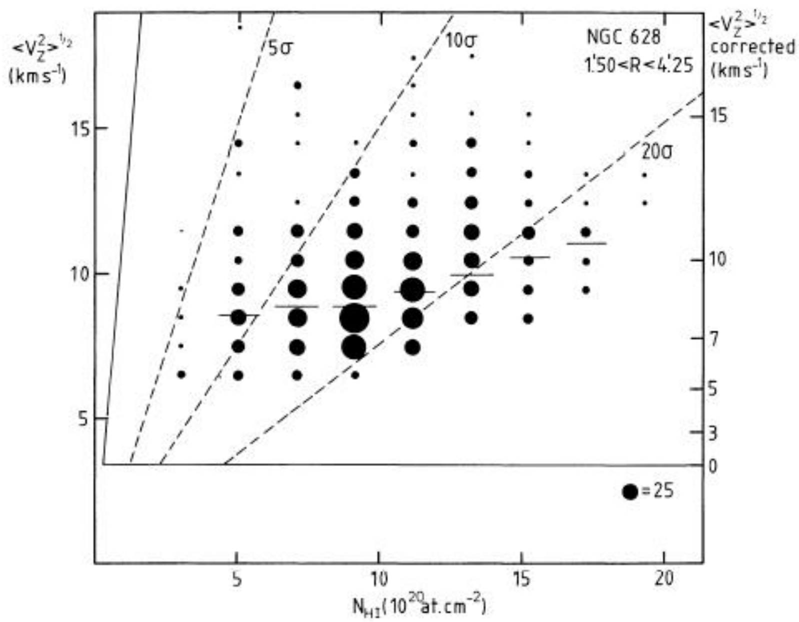
- Vertical velocity dispersions in cold gas

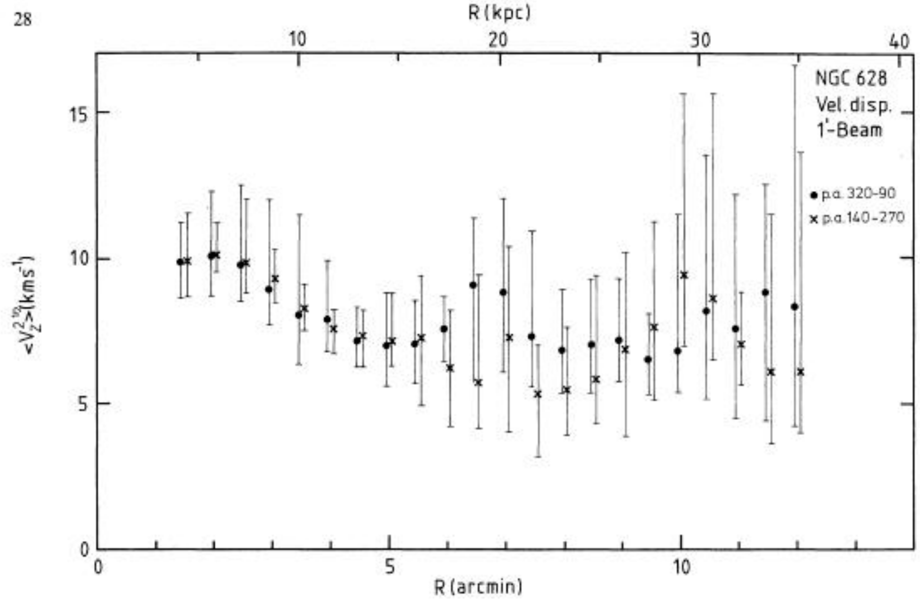
van der Kruit & Shostak (1982, 1984):

σ_{HI} = 6-12 km/s

Combes & Bequaert (1997):

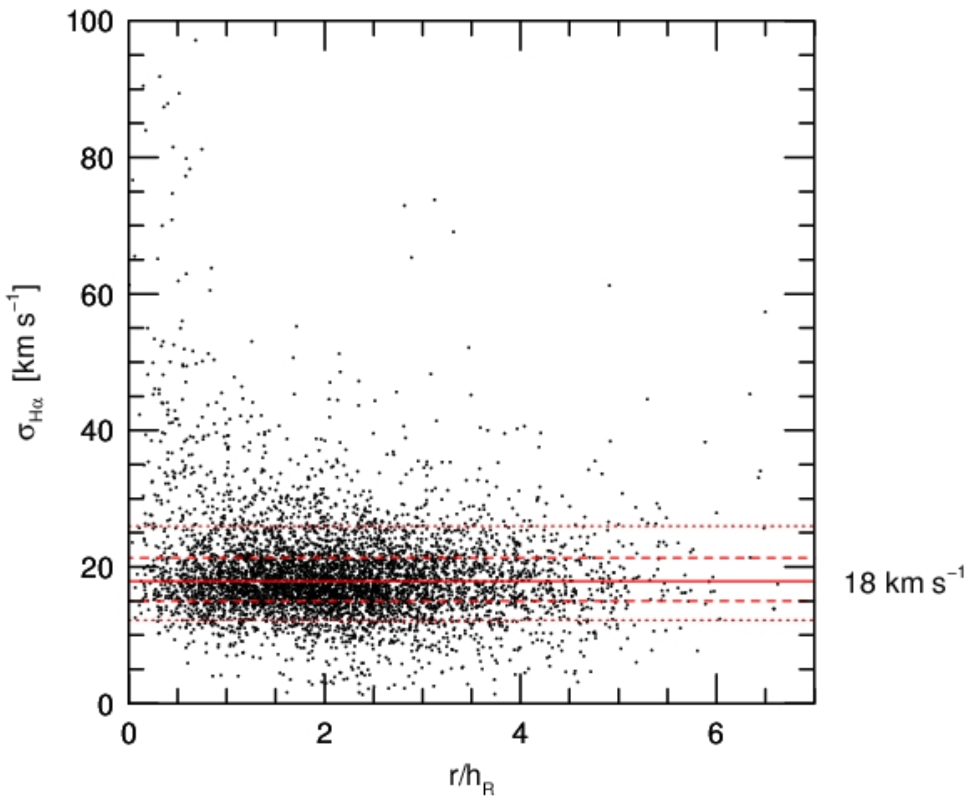
σ_{CO} = 6-9 km/s

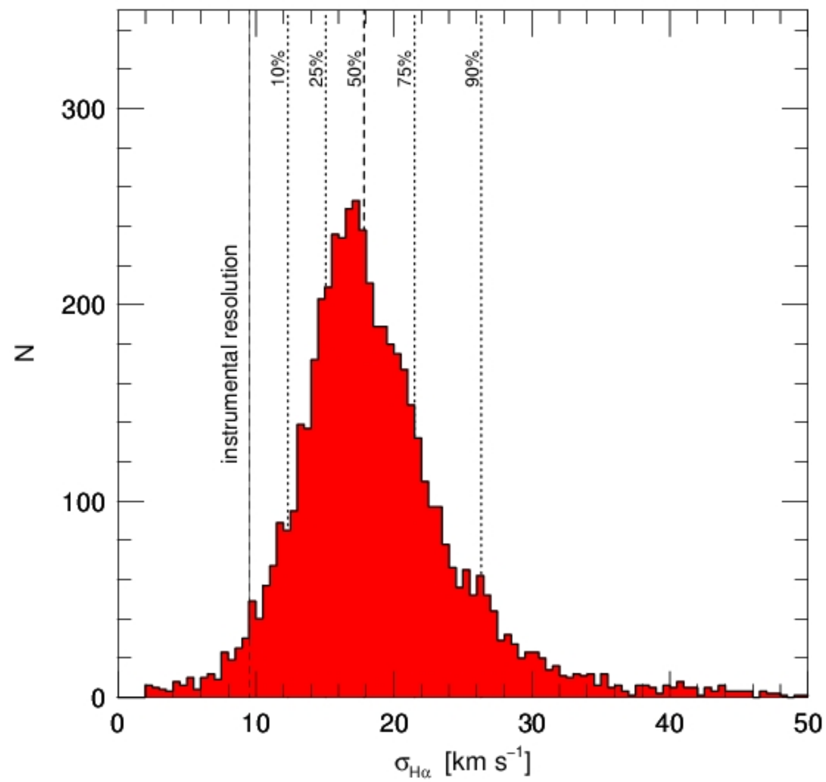




- ~constant with radius -- some density dependence
- Thermal values should be in the 6-8 km/s range

Disk heating: ionized gas (not "initial")

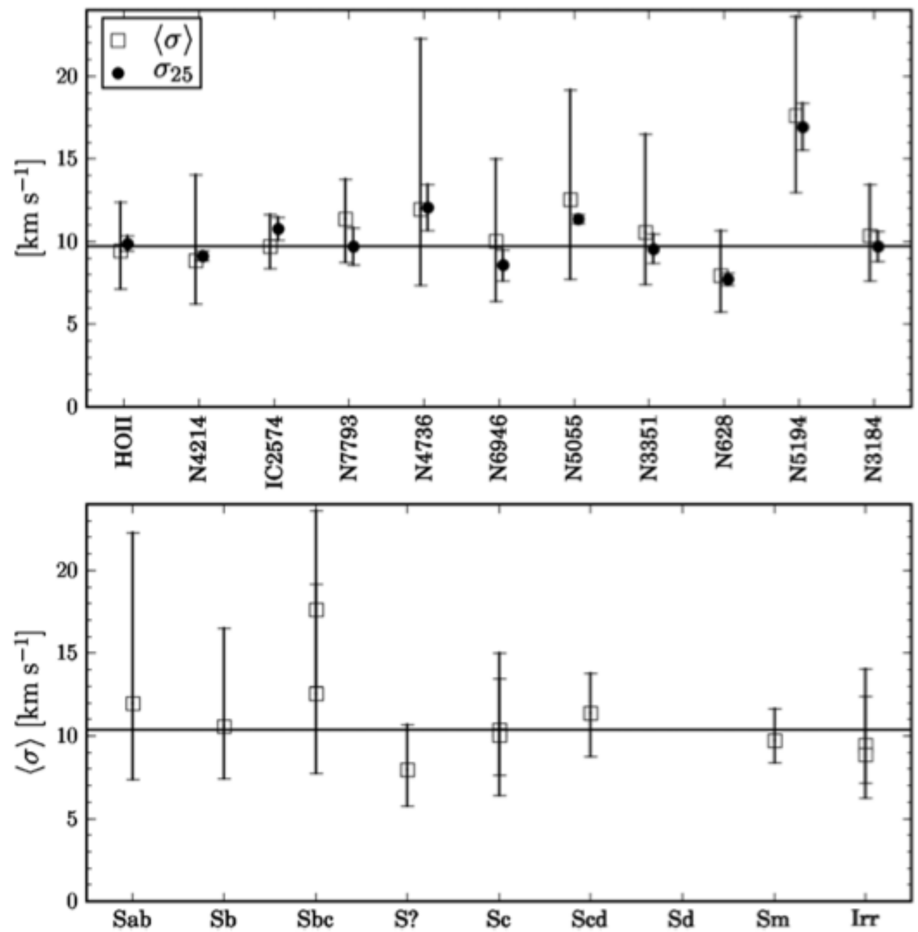




- Median $\sigma_{H\alpha}$ = 18 km/s, appears constant with radius.
- Significant dispersion and galaxy-galaxy variations.

Initial conditions updated:

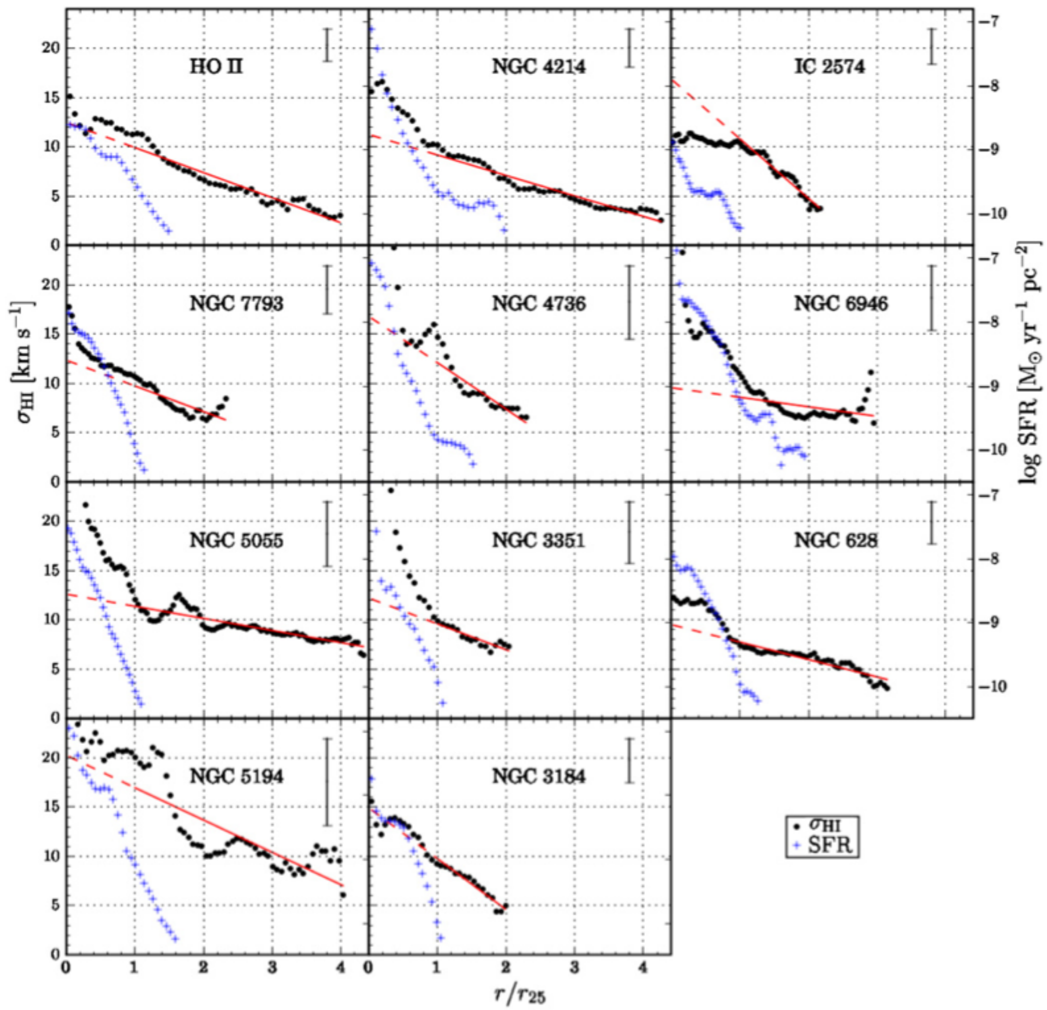
- The good news:
  - The mean σ_{HI} appears very uniform from galaxy to galaxy and across galaxy types.



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:
- 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
- Simple diffusion theory doesn't give a good prediction for the time-scale τ
- How well does the model, calibrated in the solar neighborhood match the expectations for the MW overall?
  - Specifically, do we get constant scale-height disks?