Astronomy 330

Lecture 21

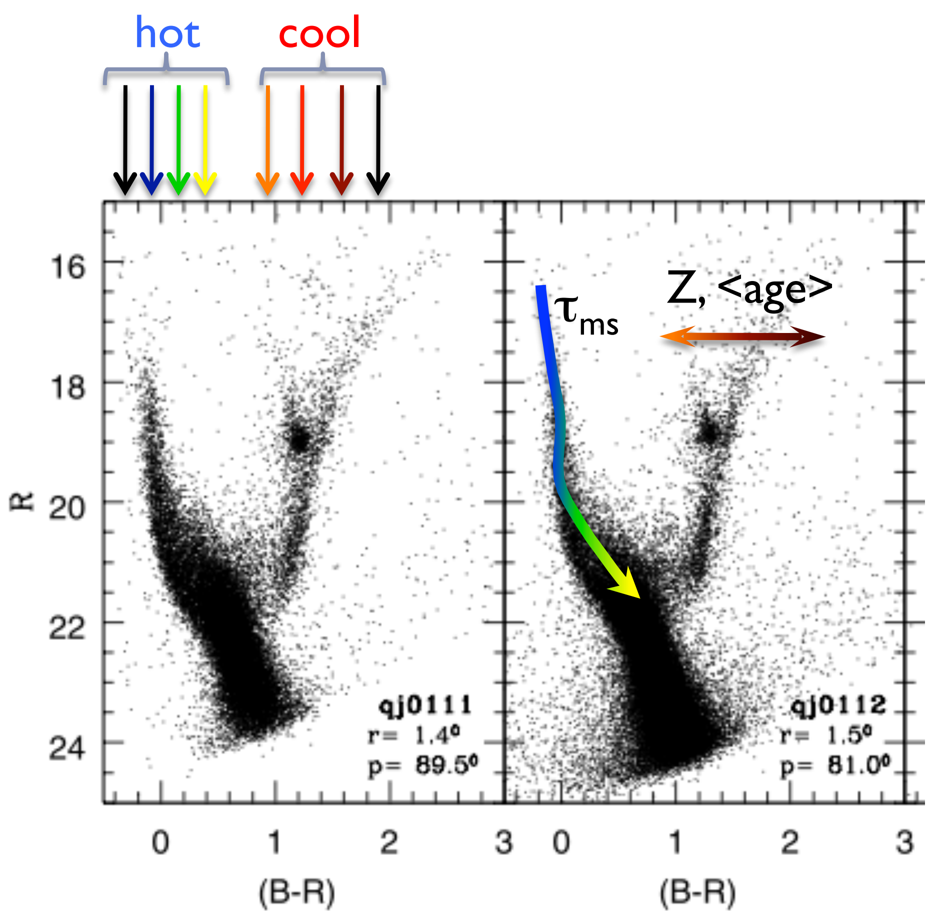
19 Nov 2010

Outline

- Review:
  - Stellar populations continued
    - Simple models
  - Disk heating in the solar neighborhood
    - Parenago's discontinuity
    - Scale-height – velocity-dispersion relation for disk stars
- Disk heating models
- Dwarf galaxies
  - Context of galaxy formation
  - Content of Local Group

CMD for the SMC at 60 kpc OMG

Why we might expect a *flexible* 2-star model will work:



- What's *flexible*?
- How many total stars (taken two at a time) are needed to describe a composite stellar population over time?
- What does *composite* mean?

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

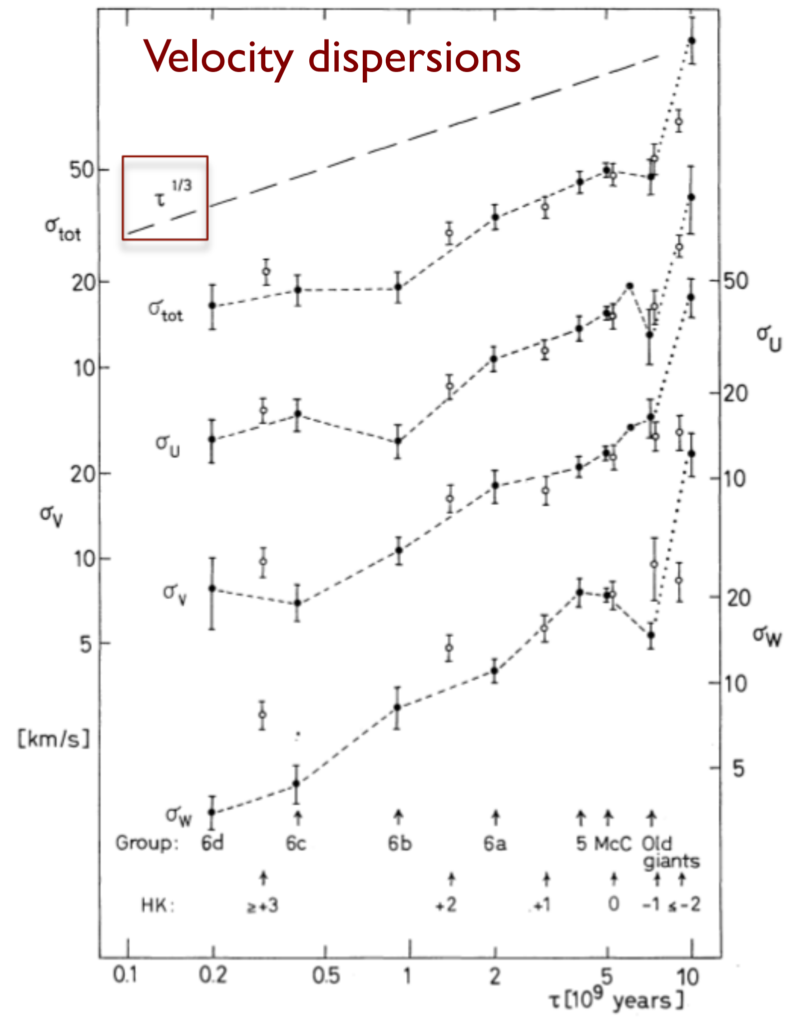


Fig. 4. Velocity dispersions as a function of age.

- 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➔ (Produces scattering primarily in plane)

Apparently cannot account for all of the heating observed in solar neighborhood

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

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

Disk heating via diffusion

- Each encounter delivers an impulse ($\Delta \mathbf{v}$) to a star's velocity $\mathbf{v}$
- Over many (random) encounters $\langle \Delta \mathbf{v} \rangle = 0$
  - $\langle \Delta \mathbf{v} \rangle = [\, (1/t) \, \Sigma_{i=1,n} \, \Delta \mathbf{v}_i \,]_{t \rightarrow \infty} = 0$
  - 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

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 $D = D_0$
    - $v^2 = D_0\ t + c$
  - ➔ $v_{rms}(t) = v_{rms}(0)[\ 1 + t/\tau]^{1/2}$

$v_{rms} = \sigma = \langle v^2 \rangle 1/2$

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

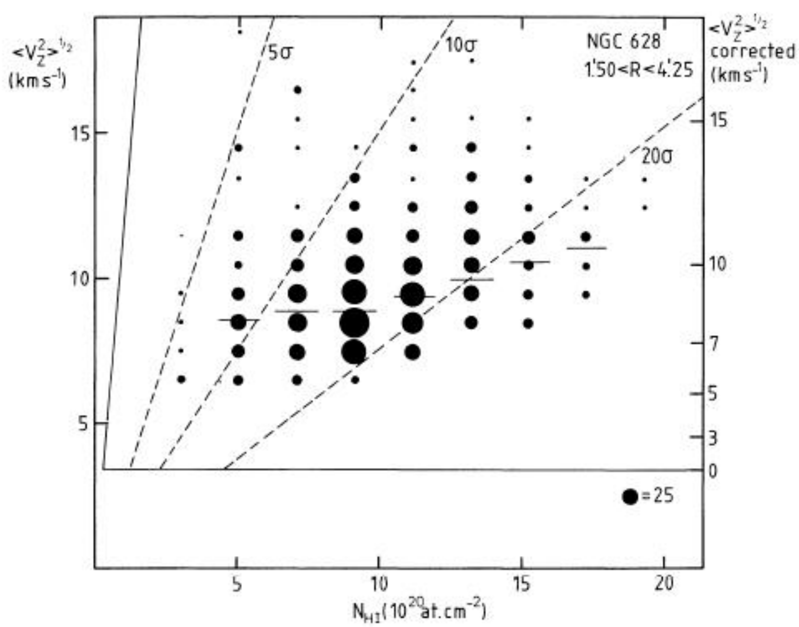
- Vertical velocity dispersions in cold gas

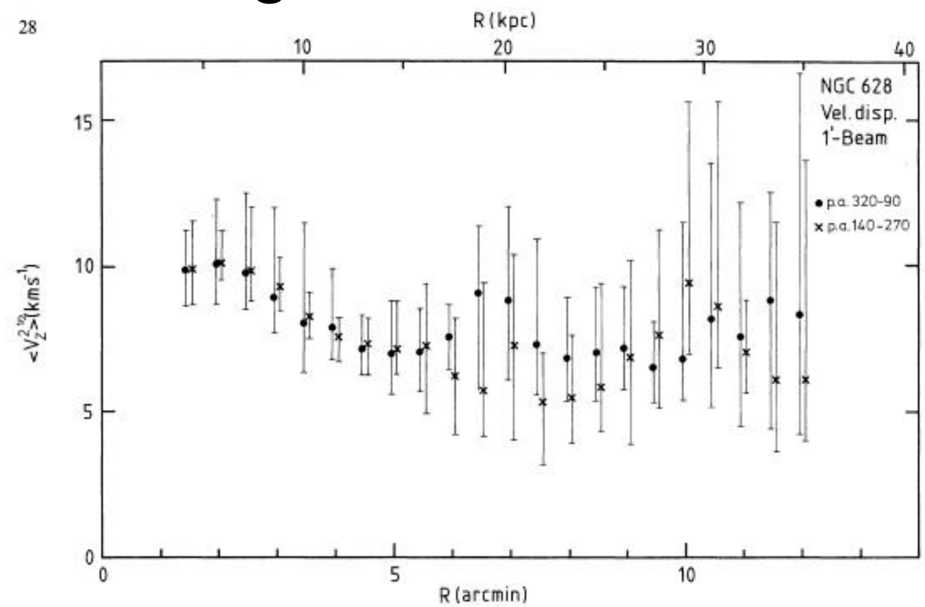
van der Kruit & Shostak (1982, 1984):

σ_{HI} = 6-12 km/s

Combes & Bequaert (1997):

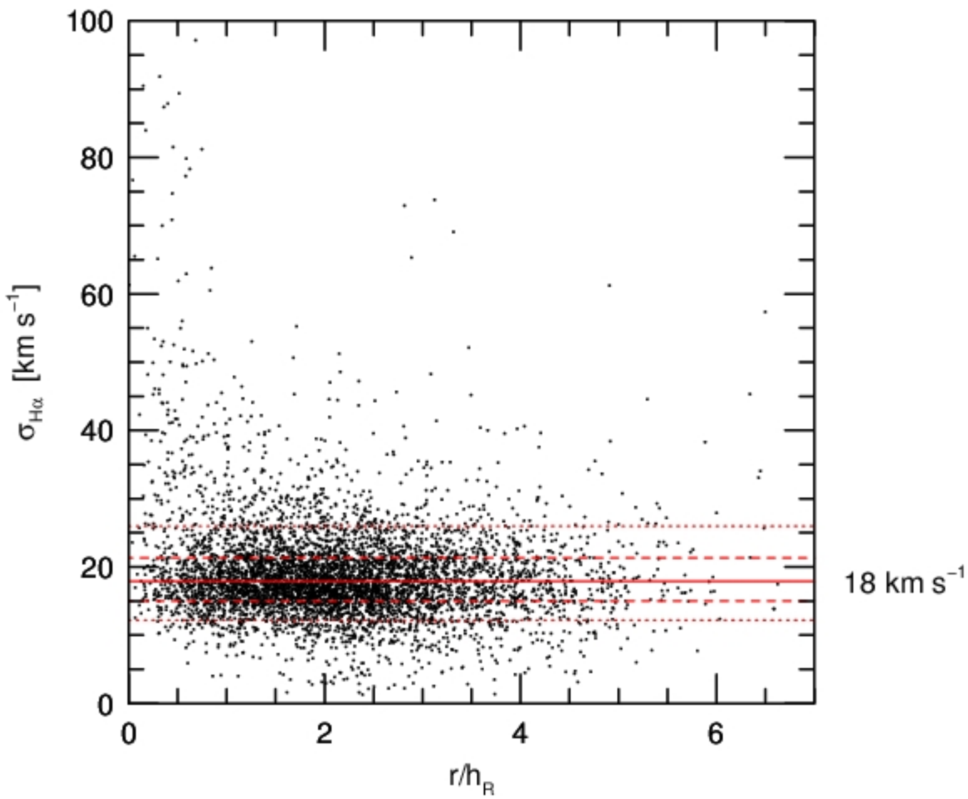
σ_{CO} = 6-9 km/s

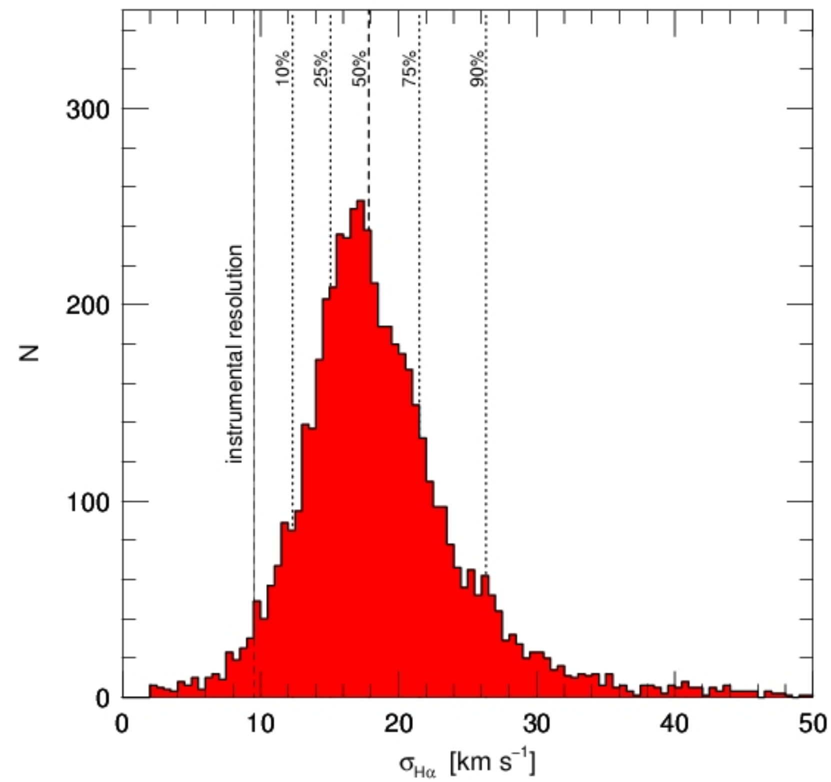




- ~constant with radius -- some density dependence
- Thermal values should be in the 6-8 km/s range

Disk heating: ionized gas (not "initial")

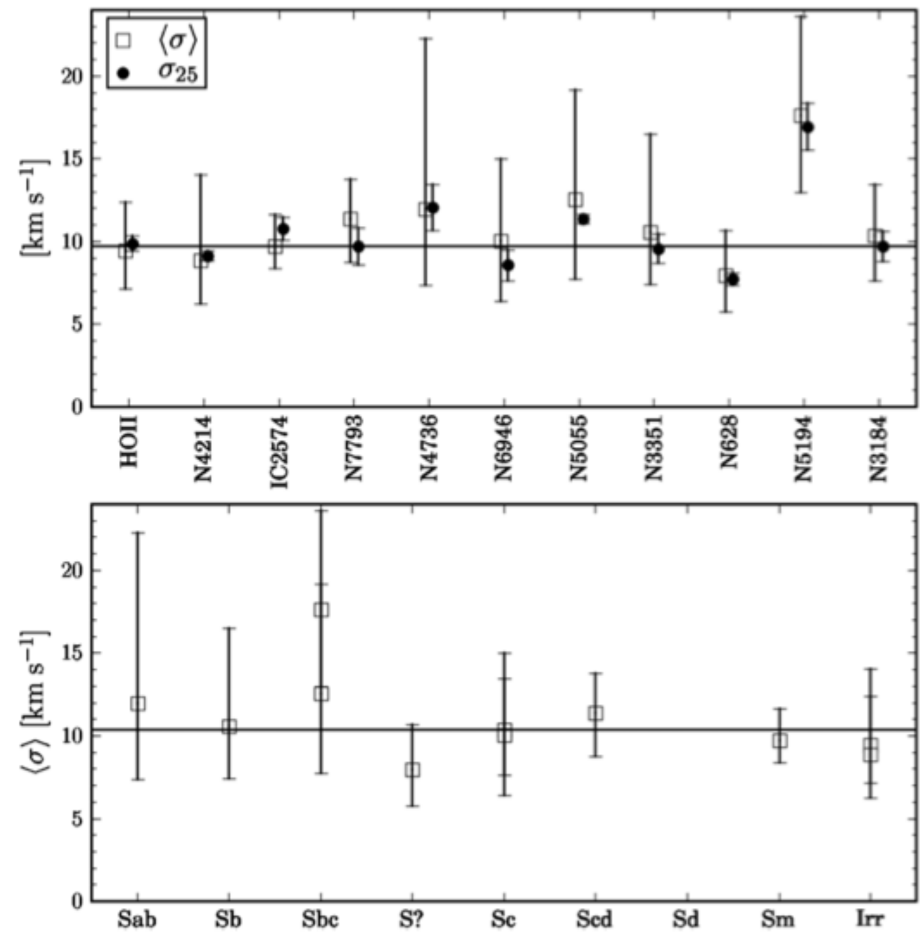




- Median $\sigma_{H\alpha}$ = 18 km/s, appears constant with radius.
- Significant dispersion and galaxy-galaxy variations.

Initial conditions updated:

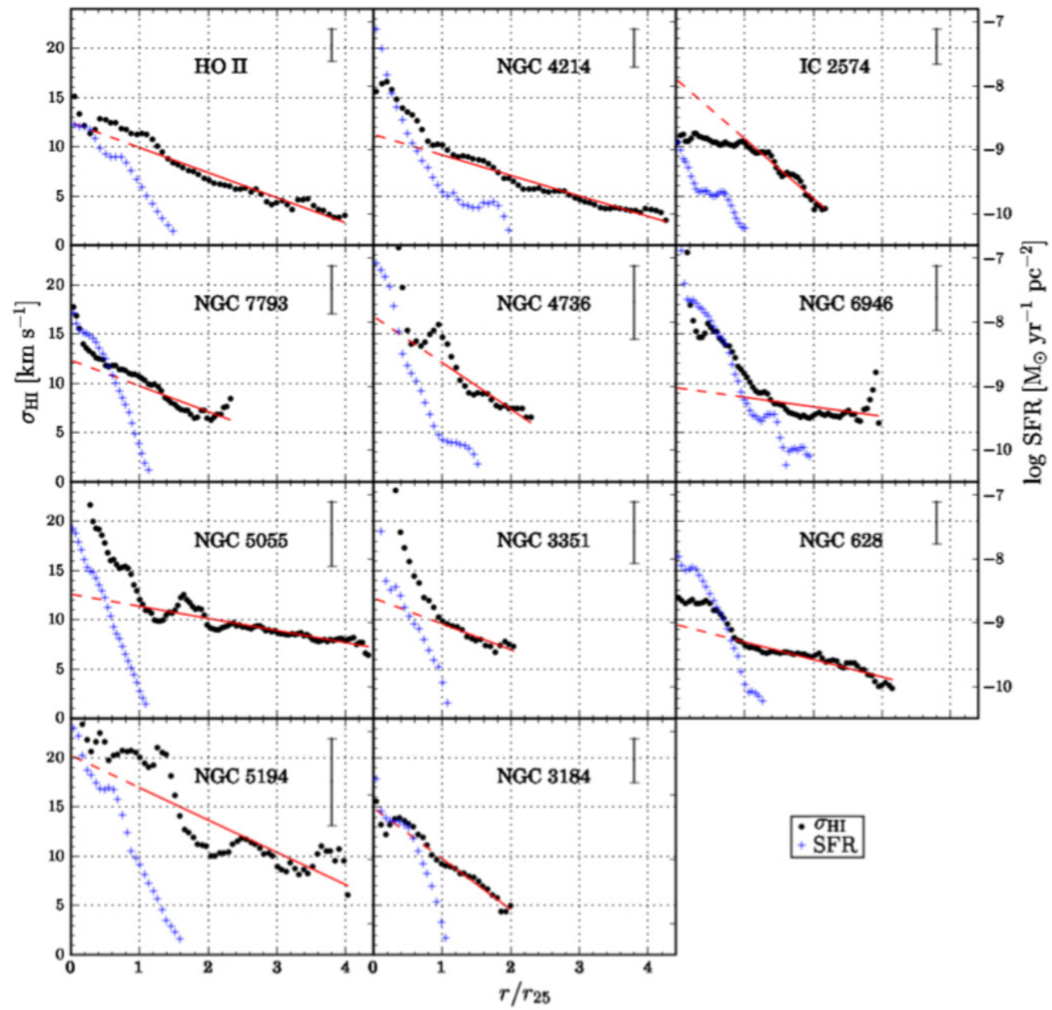
- The good news:
  - The mean σ_{HI} appears very uniform from galaxy to galaxy and across galaxy types.



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)

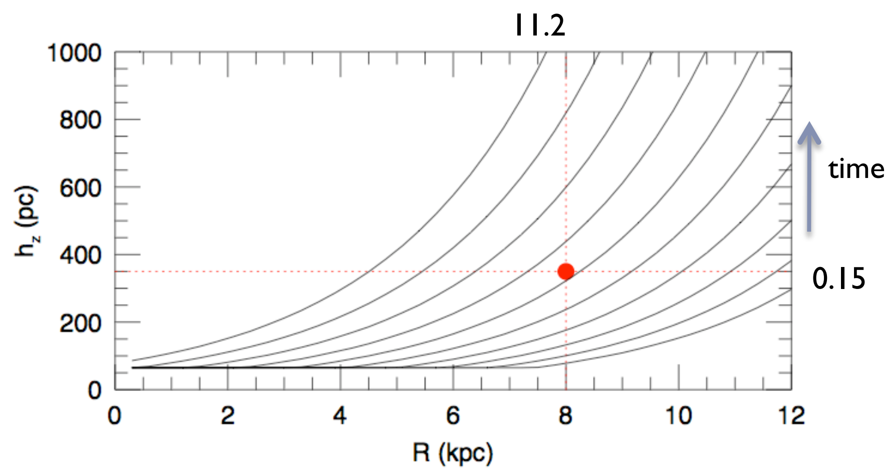
  the picture is incomplete:
  - Diffusion theory doesn't give a good prediction for the time-scale τ
  - GMCs and spiral arms don't appear to heat disk enough
    - Solution: add globular clusters and ubiquitous dark-matter dominated satellites (subhaloes) predicted by ΛCDM structure-formation theory. 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!**

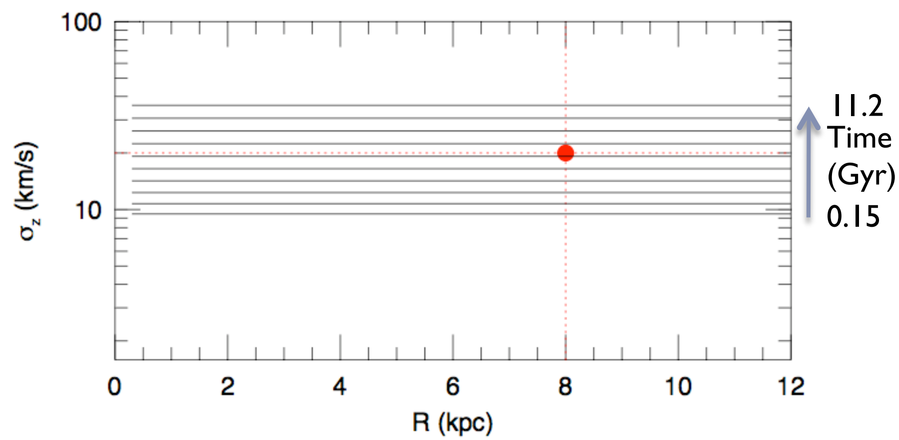
Disk heating: beyond the solar neighborhood

- 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

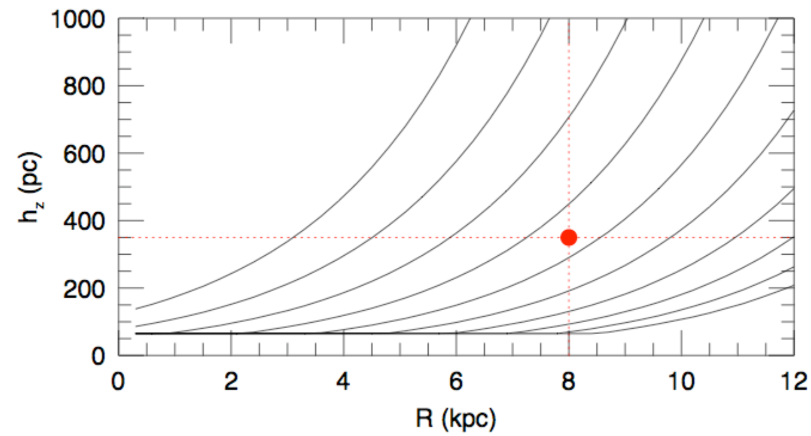
- Model 1:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R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

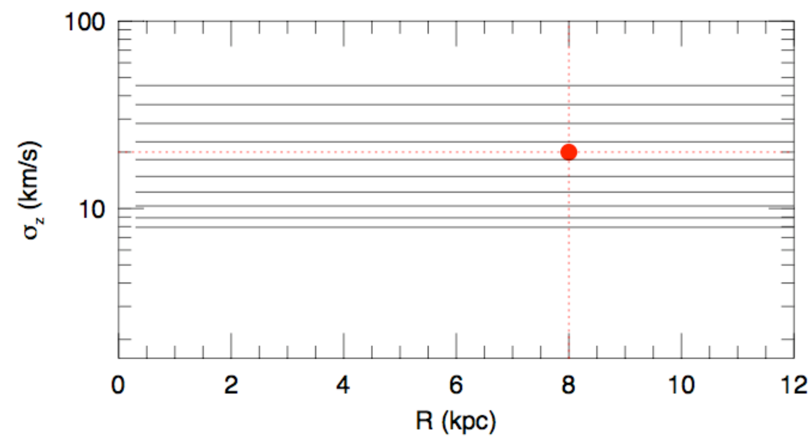




Disk heating: beyond the solar neighborhood

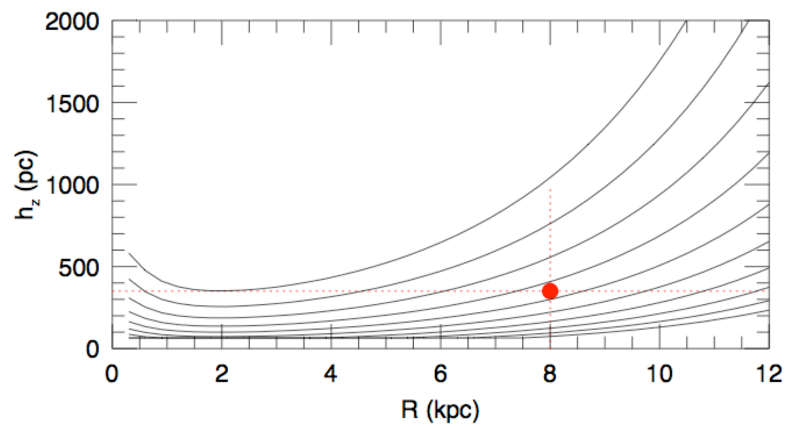
- Model 2:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R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

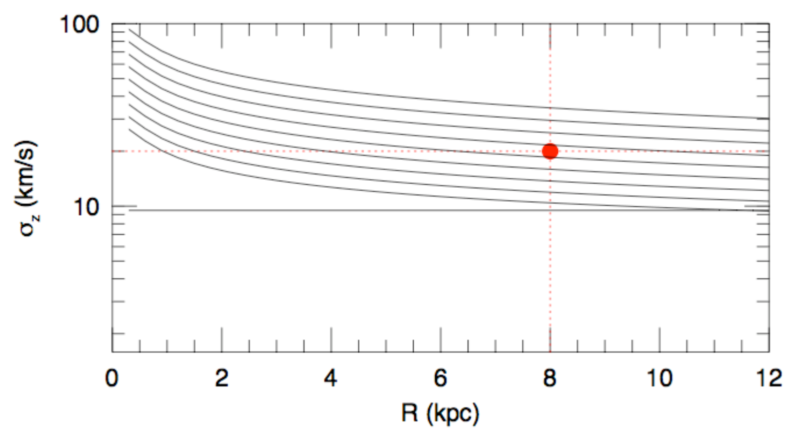




Disk heating: beyond the solar neighborhood

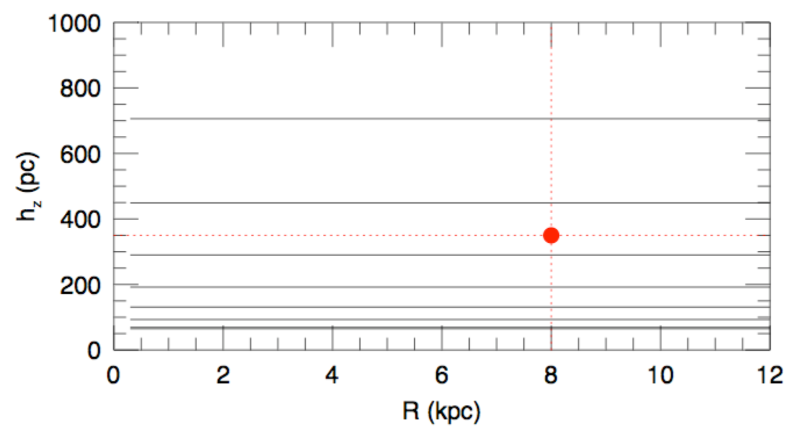
- Model 3:
  - Initial conditions:
    - σ_z (t=0) = 6 km/s , independent of radius
    - h_z (t=0) = 65 pc, independent of radius
  - Final conditions:
    - $h_z(R_\odot,t_0)$ = 350 pc
    - $\sigma_z(R_\odot,t_0)$ = 20 km/s
  - Other conditions:
    - Disk mass surface-density Σ and scale-length R 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

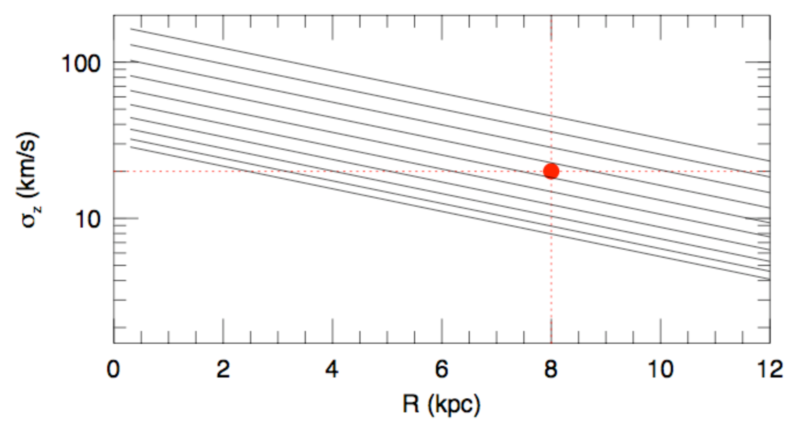




Disk heating: beyond the solar neighborhood

- 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

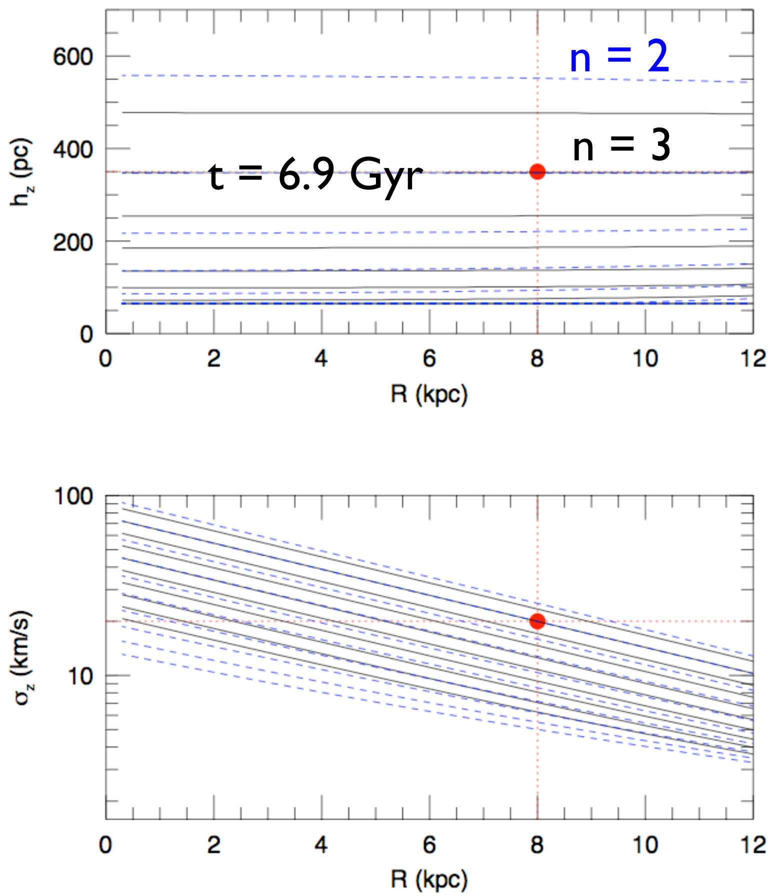
Disk heating: beyond the solar neighborhood

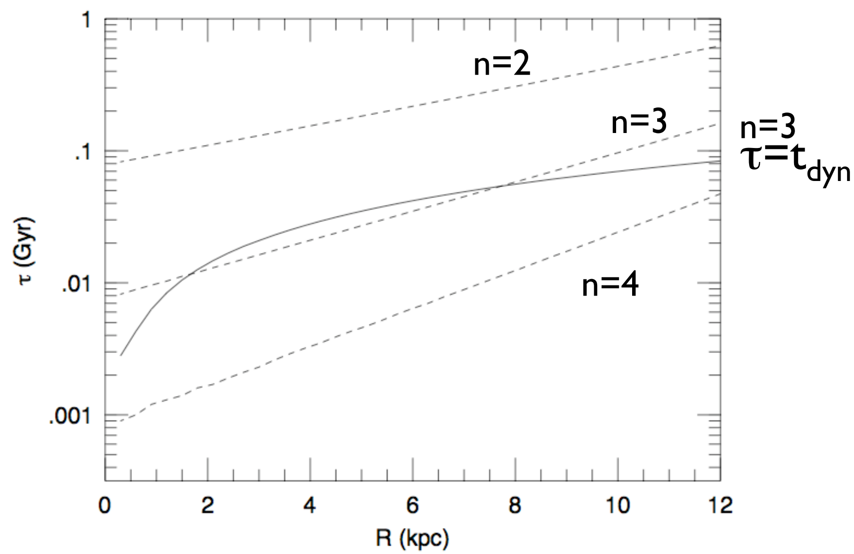
- Other models:
  - So far we have held n and τ fixed, or held n fixed and set $\tau = t_{dyn}$. The latter looked promising.
  - It is straightforward to find relationships between n and τ such that the final conditions are met for any age population, e.g.,
    - $h_z(R_\odot, t_0) = 350$ pc
    - $\sigma_z(R_\odot,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





Dwarf Galaxies

Dwarf Galaxies: Galaxy formation context

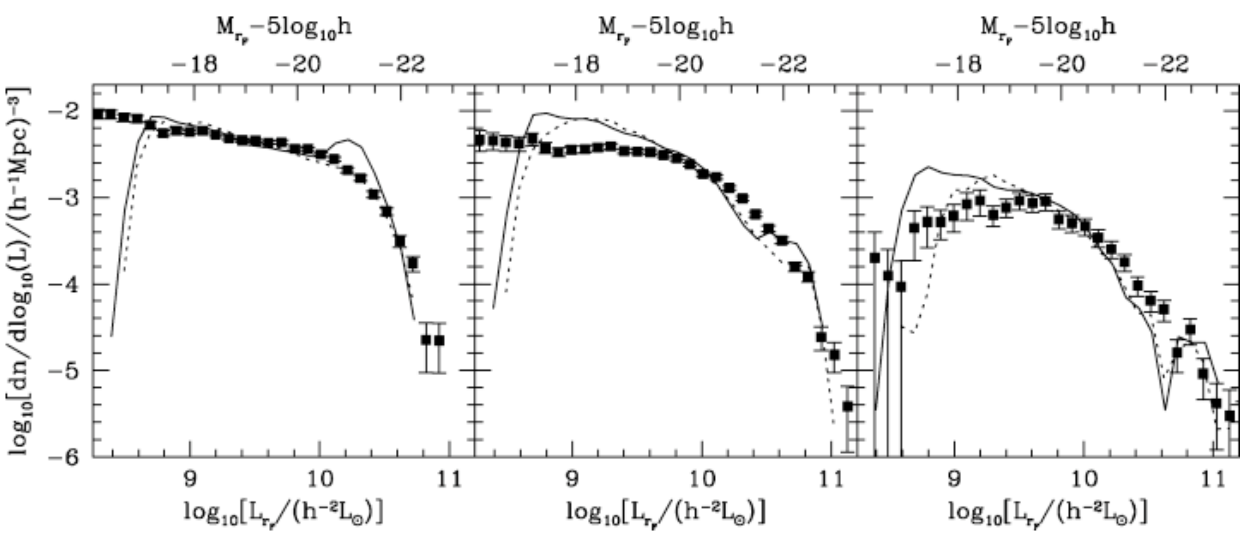
- Galaxy Formation I
  - Begin with some fluctuations…
    - Max. scale: $\lambda_J = 2\pi/k_J = c_s(\pi/G\rho)^{1/2}$
    - Freq. of perturbations: $\omega = [4\pi G\rho(\lambda_J^2/\lambda^2) - 1]^{1/2}$
    - For perturbations smaller than Jeans length
  - Imagine a sphere with the Jeans length
    - $M_J = (\pi\lambda_J^3/6)\rho$
    - In radiation dominated era: $M_J = 10^{11} M_\odot$
    - In matter dominated era: $M_J = 10^6 M_\odot$
- Cold Dark Matter
  - 1^{st} structures are low mass halos
  - Larger structures form via hierarchical merging

Galaxy formation (continued)

- Cooling
  - Initial fluctuations are warm post-recombination (1000's of degrees)
  - What does the cooling?
    - No metals, so it must be some form of H
    - In situ formation of H_2
  - Results (e.g. Hutchings et al. 2002)
    - 1st structures to cool have $M_{virial} \sim 9 \times 10^5 M_\odot$
- Simulations/Semi-Analytic Models
  - Remember "cosmology" yields a spectrum of density fluctuations
  - Fluctuations = regions of overdensity → growth of dark matter halos →baryon infall →make stars →feedback →result is a prediction of the distribution/population of galaxies at high redshift

Why Dwarf Galaxies are so important

- Dwarfs
  - are 1st to form and the most numerous objects in the early Universe;
  - dominate faint galaxy counts in any deep survey;
  - should dominate local galaxy luminosity function;
  - Are the building blocks of larger galaxies.
- But…
  - They do not contain most of the stars and baryonic matter

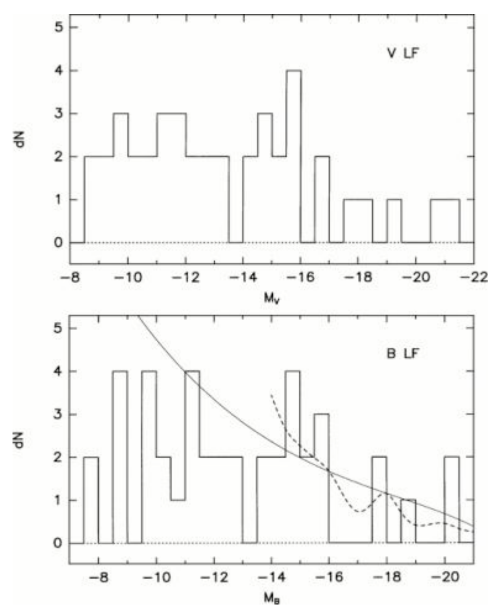


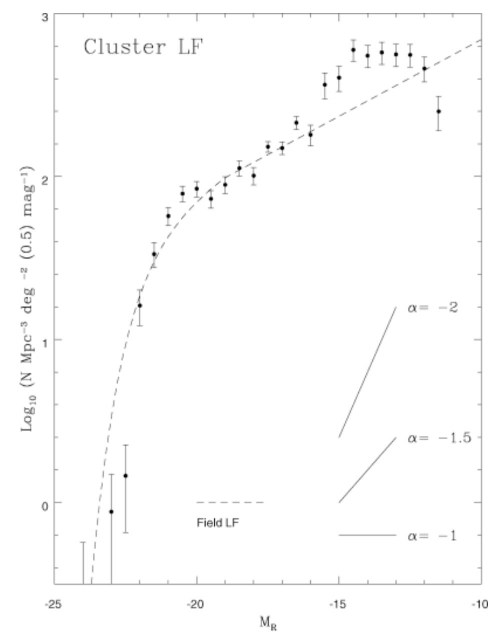
Luminosity function

Rising slope at faint luminosities ➔lots of dwarf galaxies

Galaxy luminosity function

- LF varies a bit with environment
  - Virgo: faint end slope is steep ➔ dEs are > 50% of all galaxies (Trentham et al)
  - Local Group: steeply rising at low luminosities (Mateo)
- HI mass function is similar



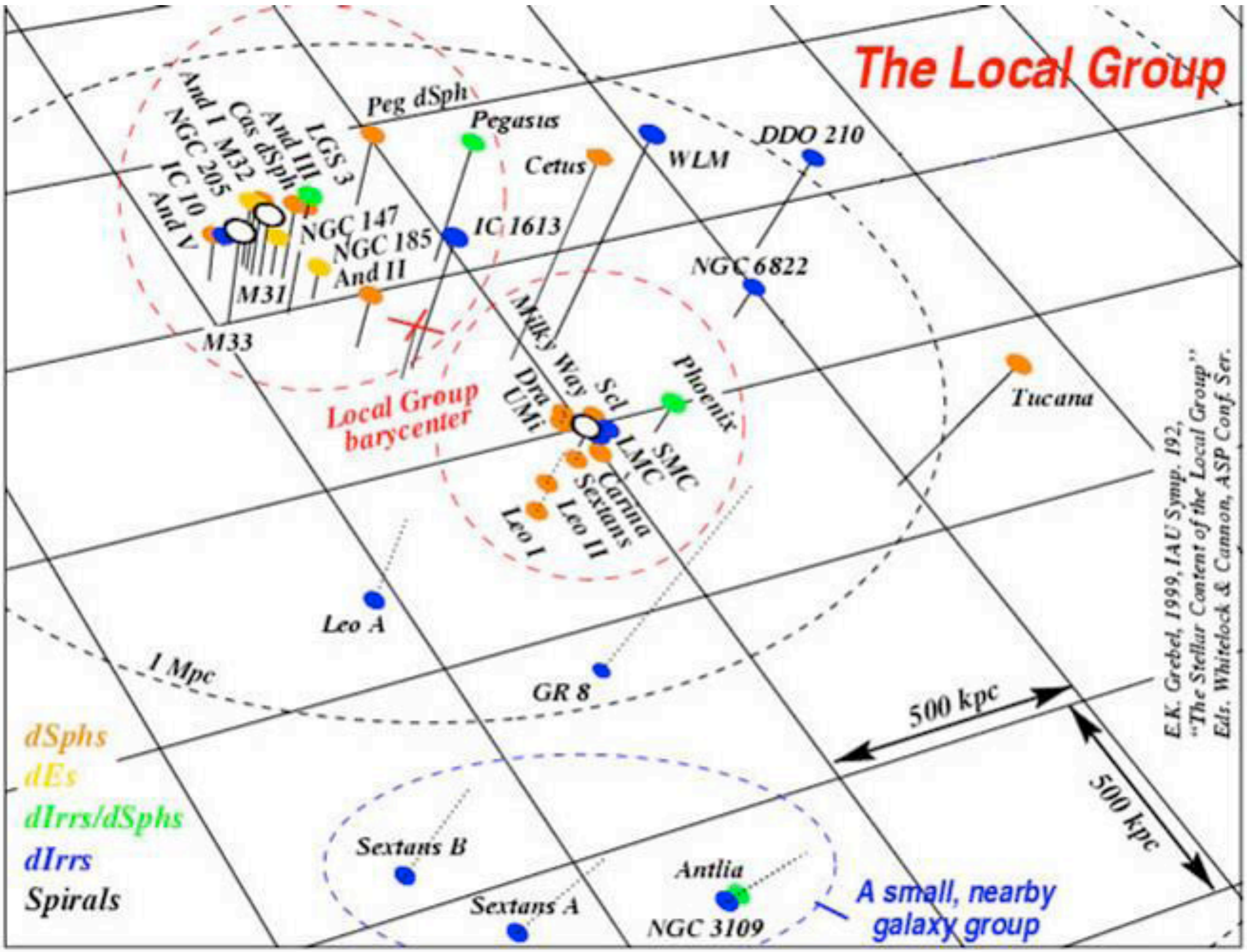


Dwarf Census in the Local Group

- Mateo (1998) ARAA, 36, 435
- Total number of dwarfs: ~40
  - Magnitude limits: (fainter than ~ −18)
    - Ursa Minor ~ −7.6
    - NGC 205 ~ −16.0
  - Mass (dynamical)
    - DDO 210 ~ $5.4 \times 10^6 M_\odot$
    - M32 ~ $2.1 \times 10^9 M_\odot$
  - M_{HI} / M_{TOT}
    - Several < 0.001
    - Leo A ~ 0.72
- Morphology – Distribution Correlation

Distribution of Dwarfs in the Local Group

- Dwarf Ellipticals
  - concentrated around M31
  - M32, N147, N205, N185
  - Little gas, old stellar pops
  - N147, N185, N205 rotationally supported
- Dwarf Irregulars
  - All over, even at outskirts
  - Lots of gas (HI), mixed stellar pops
  - Rotationally supported
- Intermediate/Transition
  - Some gas, some SF, some with very few old stars
  - Probably not rotationally supported
- Dwarf Spheroidal (dSphs)
  - Satellites of MWG, M31
  - Complex SFH
  - gas?
  - Glorified globular clusters, but with dark matter
  - High σ/Vrot


The Local Group
Peg dSph
Pegasus
Cetus
WLM
DDO 210
And V
IC 10
NGC 205
And I
M32
Cas dSph
And III
LGS 3
NGC 147
NGC 185
IC 1613
And II
M31
M33
NGC 6822
Local Group barycenter
Milky Way
Dra
UMi
Scl
Phoenix
LMC
SMC
Carina
Sextans
Leo II
Leo I
Tucana
Leo A
GR 8
1 Mpc
500 kpc
500 kpc
dSphs
dEs
dIrrs/dSphs
dIrrs
Spirals
Sextans B
Sextans A
Antlia
NGC 3109
A small, nearby galaxy group
E.K. Grebel, 1999, IAU Symp. 192, "The Stellar Content of the Local Group" Eds. Whitelock & Cannon, ASP Conf. Ser.