Observing Density Waves in Spiral Galaxies using Birthplaces and NIR Photometry

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Outline:

- **The Milky Way:**
  - Birthplaces of young stars
  - Direct observations of Perseus arm
- **External Galaxies:**
  - Clusters vs. surface photometry
  - Young stellar clusters
  - Amplitude and shape of spiral arms

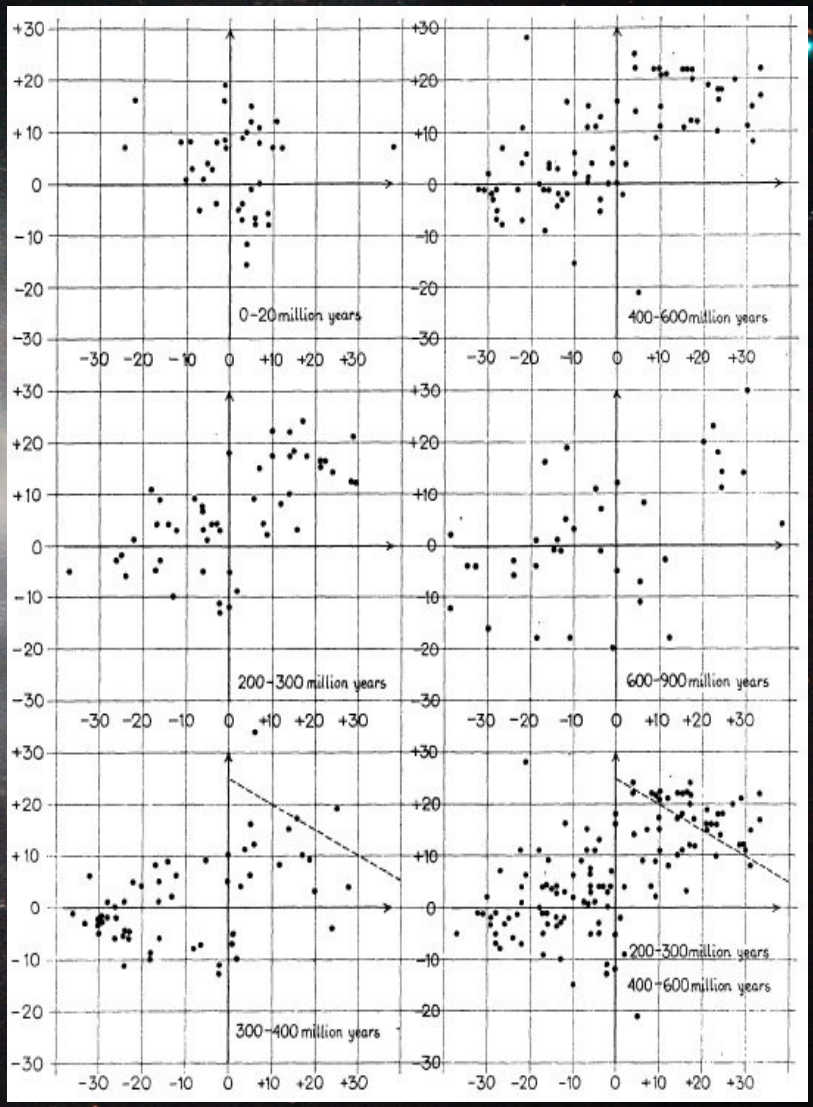
Stellar Birthplaces and Density Waves

Stellar ages and space velocities

- uvby-Hβ photometry → M_v, T_e (Strömgren63)
- M_v, T_e + isochrones → ages (Kushwaha57)
- Stellar distances from photometry
- Space velocities depend on ages
  - Vertex deviation for A-stars
    - Originate in one vast cloud (Lindblad)
    - Or part of spiral arm (Oort)

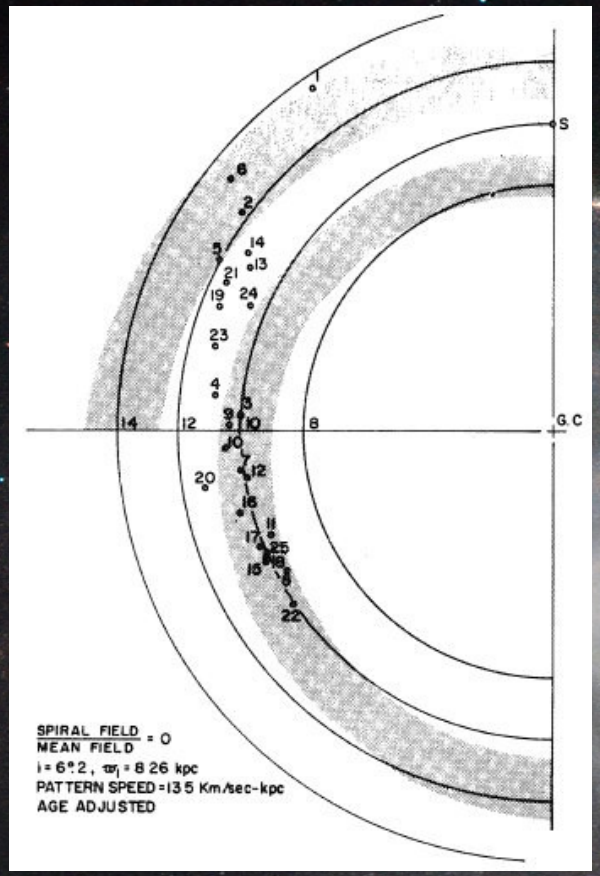
Birthplaces of young stars (Strömgren67)

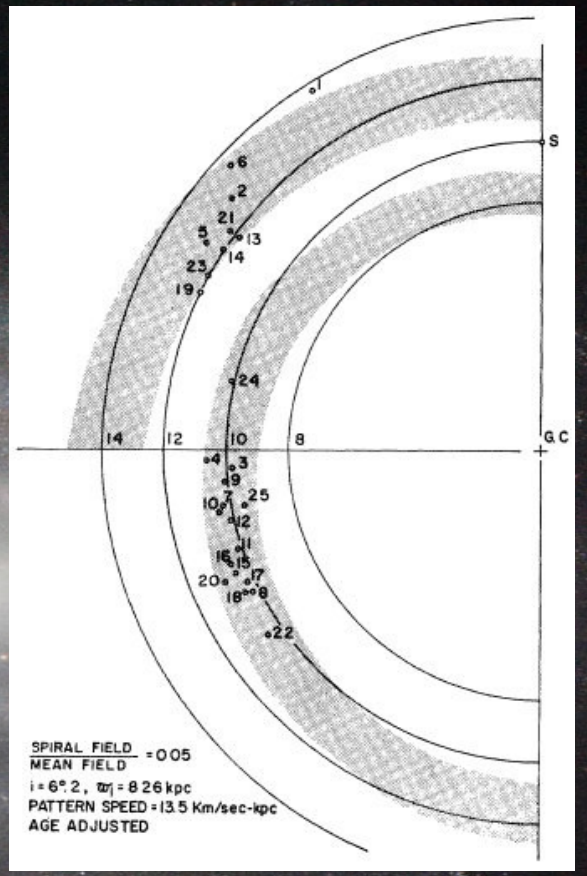
- Stellar data:
  - Space velocities (r, pm, rv)
  - Ages < 300Myr (error 10-20%)
- Galactic potential
  - Axisymmetric potential
  - Spiral perturbation (Lin&Shu64)
- Assume most stars are formed in spiral arms
- Vary perturbation to get best agreement



Strömgren63

First Estimate of Stellar Birthplaces





Yuan69

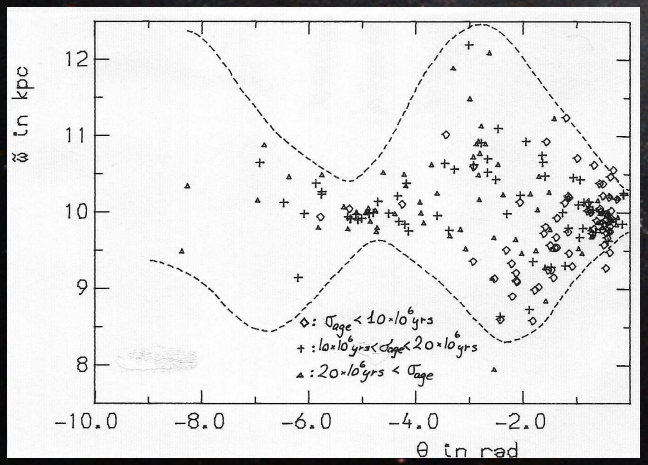
Calculation of birthplaces (Yuan69)

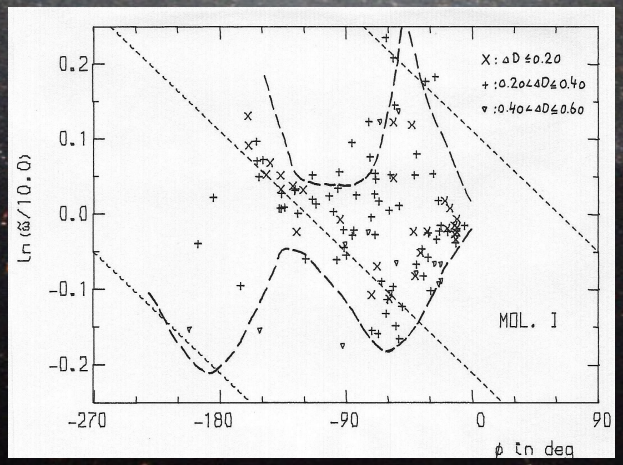
- 25 B/A-stars with ages <300 Myr
- Adjust ages within uncertainties
- Best value for 2-armed spiral perturbation
  - A= 0.05, Ωp = 13.5 km/s/kpc with i = 6.2°

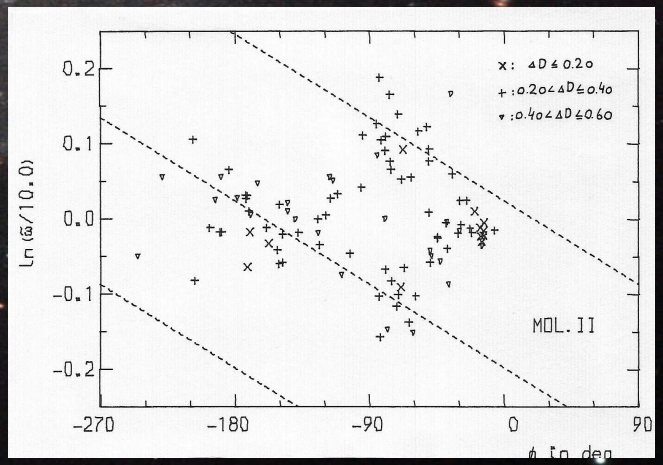
Birthplaces using uvby-Hβ photometry

New uvby-Hβ photometry and proper motions
- 597 B- and A0-stars with space velocities and ages
- 373 in final list rejecting stars with marginal data
- Ages < 300 Myr

Potential models:
- Axisymmetric potential (Contopoulos+Strömgren65)
- Two-armed density wave (Lin+Shu64)
  - Pitch angle 4° < I < 12°
  - Pattern speed 10 < Ω_p < 35 km/s/kpc







Grosbøl76

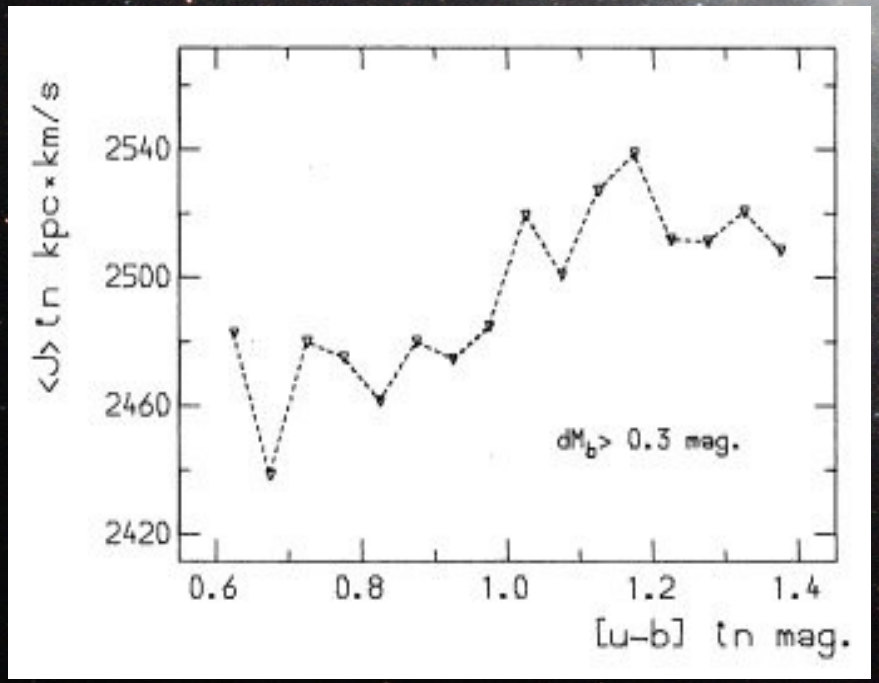
Results and Issues

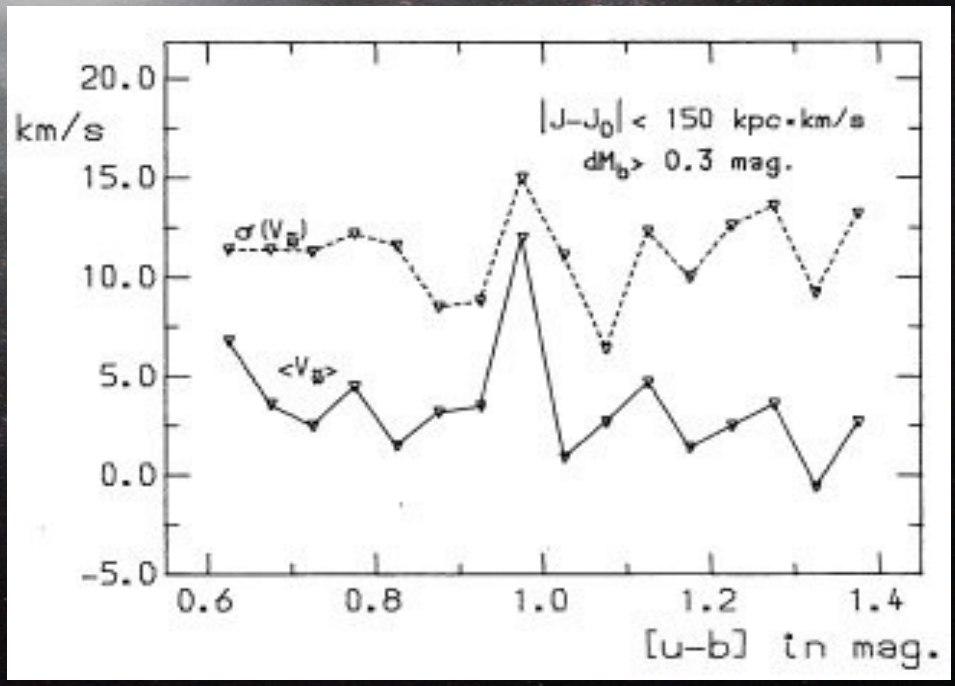
- Best agreement between arms and birthplaces
  - A = 0.04±0.02, i = -6.5°±1.5°, and Ωp = 14±2 km/s/kpc
  - Second maximum local around Ωp = 33 km/s/kpc
  - Issues
    - Many stars formed outside spiral arms
    - Stars in solar neighborhood
      - Limited sensitivity to some spiral configurations
    - Only 2-armed spiral (i.e. Sagittarius and Perseus arms)
    - Potential of Galactic bar not included

Angular Momentum

Angular momentum of nearby B-stars:

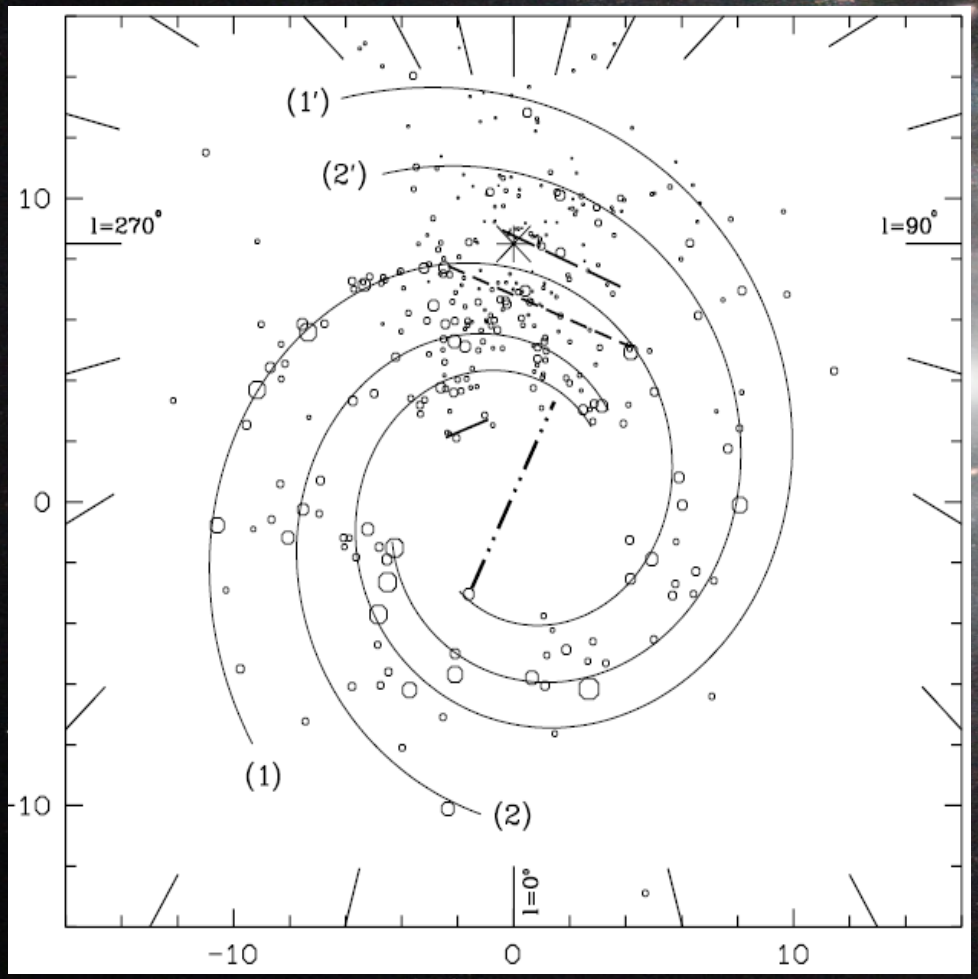
- [u-b] is age indicator for B-stars
  - [u-b] of 0.6..1.4 → age ~ 30..300 Myr
- Average J varies with mean age
  - Suggests change of mean radius of stars formed
  - Possibly due to spiral perturbation
- Peak in radial motion and its dispersion
  - May originate from star with ages close to π/κ



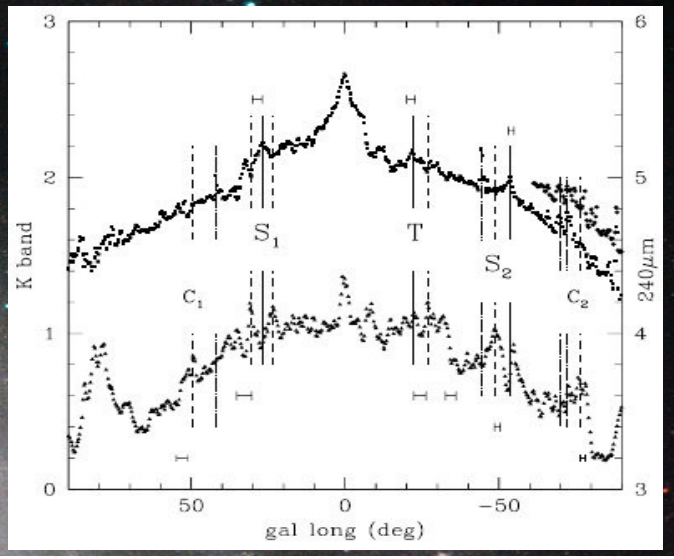


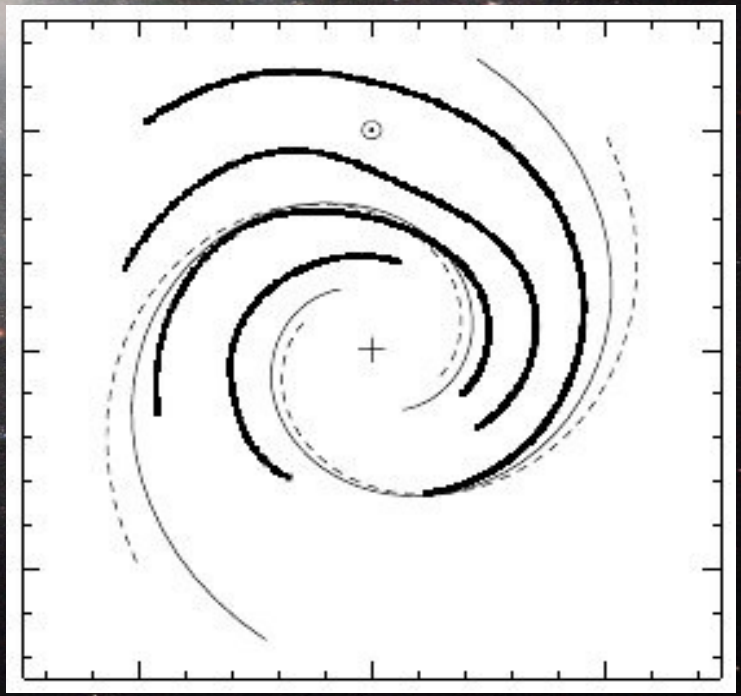
Grosbøl77

Milky Way – 2 or 4 major arms?



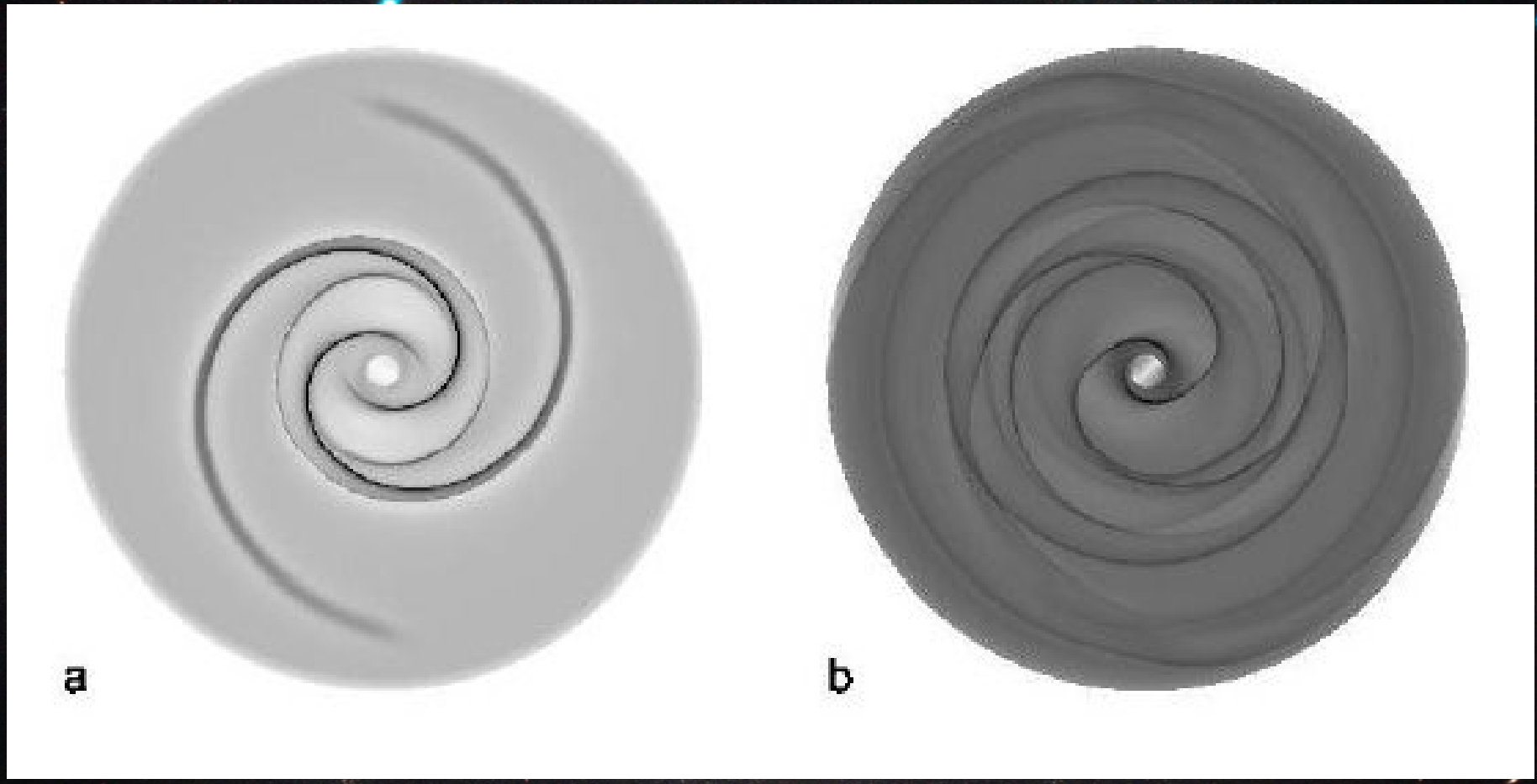
Russeil03





Drimmel00

Two-armed Spiral with 4-armed Gas Response

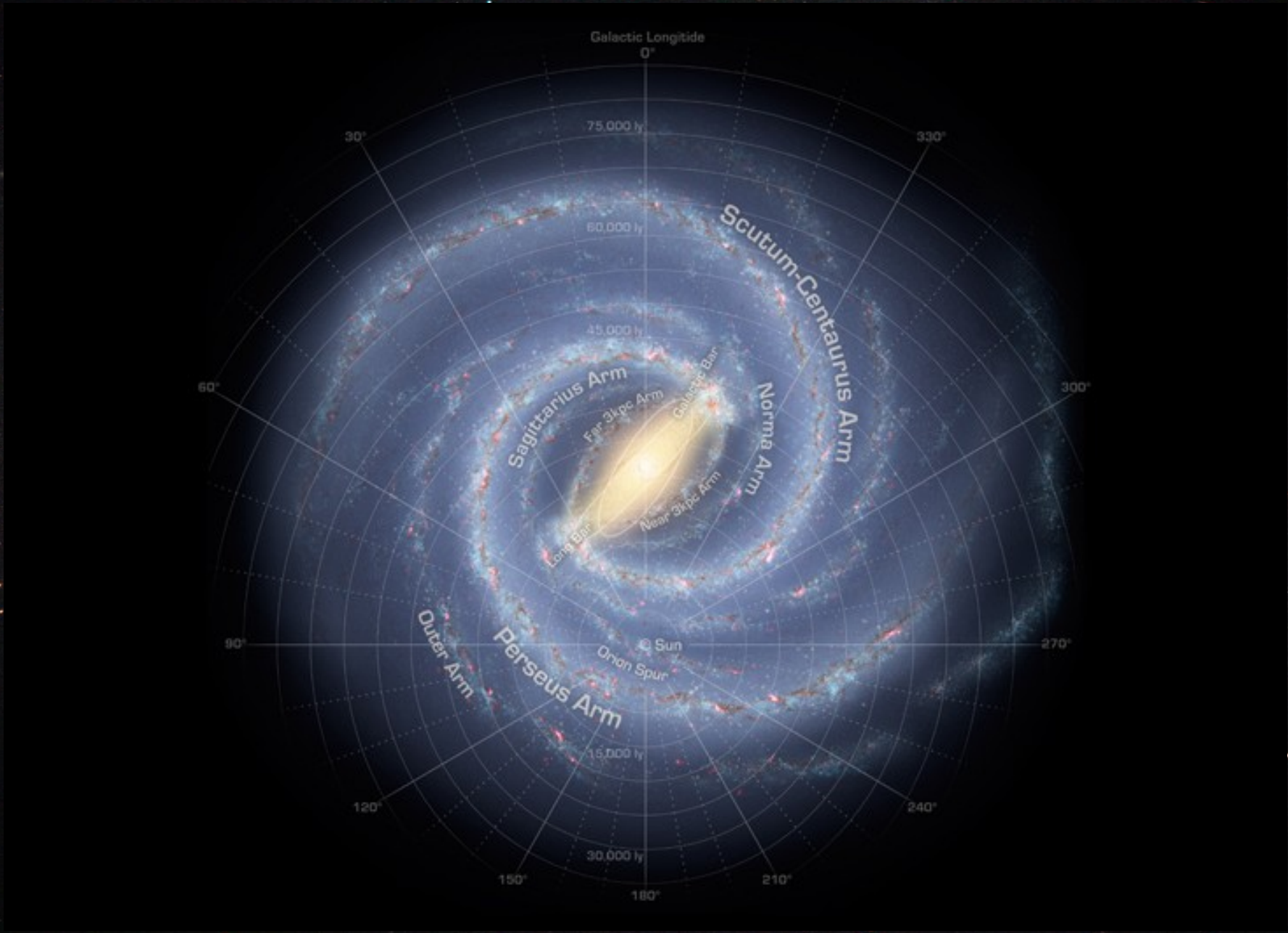


Yanez+08

Additional gas arms may form due to:

- Secondary shock in a 2-armed spiral perturbation (Yanez+08)
- Response to a bar perturbation (Englmaier+99)

Milky Way – Artistic view



Hunt, NASA ©

Anti-center uvby-Hβ survey

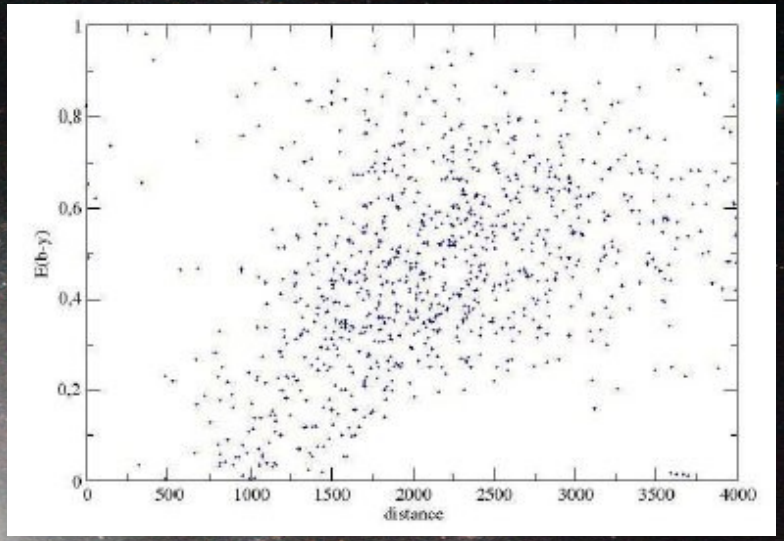
- Main objectives:
  - Determine distance to Perseus arm
  - Estimate its density perturbation
  - Search for associated velocity perturbation
    - Minimum effects of Galactic rotation at anti-center
  - Early type stars
    - Smaller velocity dispersion
  - Test if compatible with a density wave
- Complete census of B5-A3 stars in anti-center direction
  - uvby-Hβ survey to V = 17^m over 8□°
    - Observations at INT/La Palma
  - Derive extinction and distances of individual stars
  - Map surface density of B5-A3 stars as function of distance
  - Observe radial velocities of subset (~400)
    - Observations at WHT/La Palma
  - Thesis of M. Monguio (Barcelona)

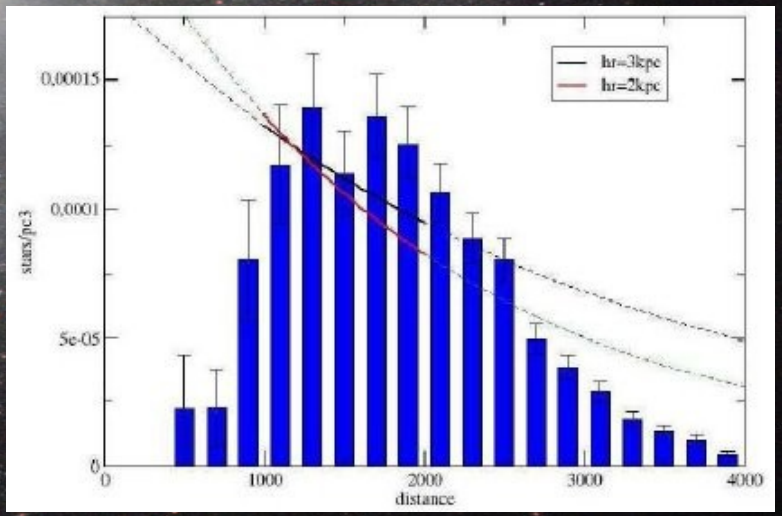
Perseus Arm

Results based on preliminary data:
- 36k stars with full Strömgren photometry
  - ~8k B5-A3 stars
- Extinction and distances estimate
- Surface density calculated

Main result
- Extinctions increase for r<1.5kpc
- Beyond small increase
- Density enhancement around r = 1.7 kpc

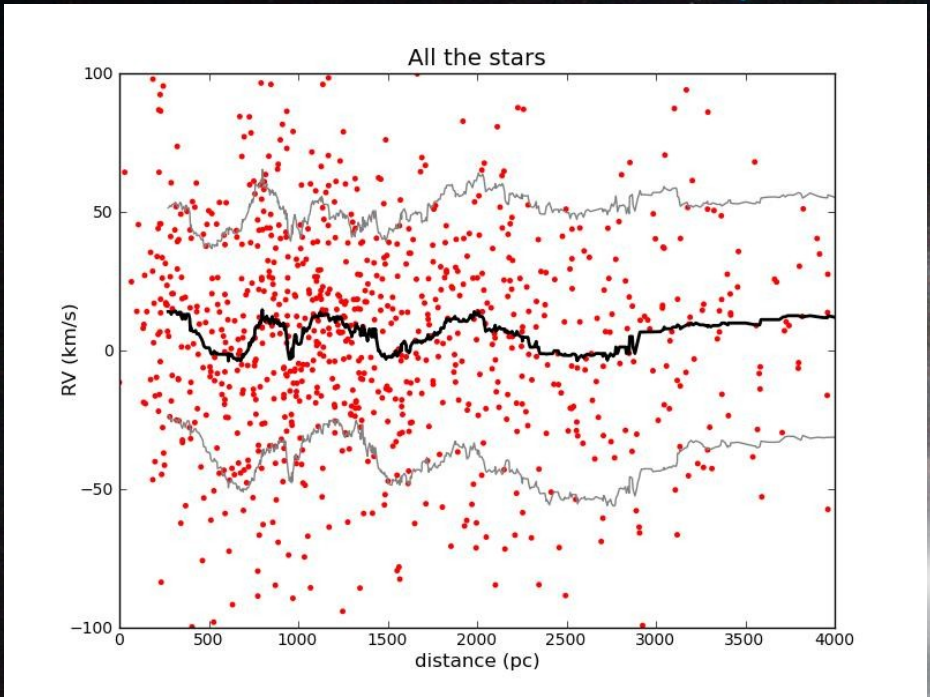
Possible interpretation
- Perseus arm close to 1.7 kpc
- Within co-rotation radius
  - Since main extinction inside arm

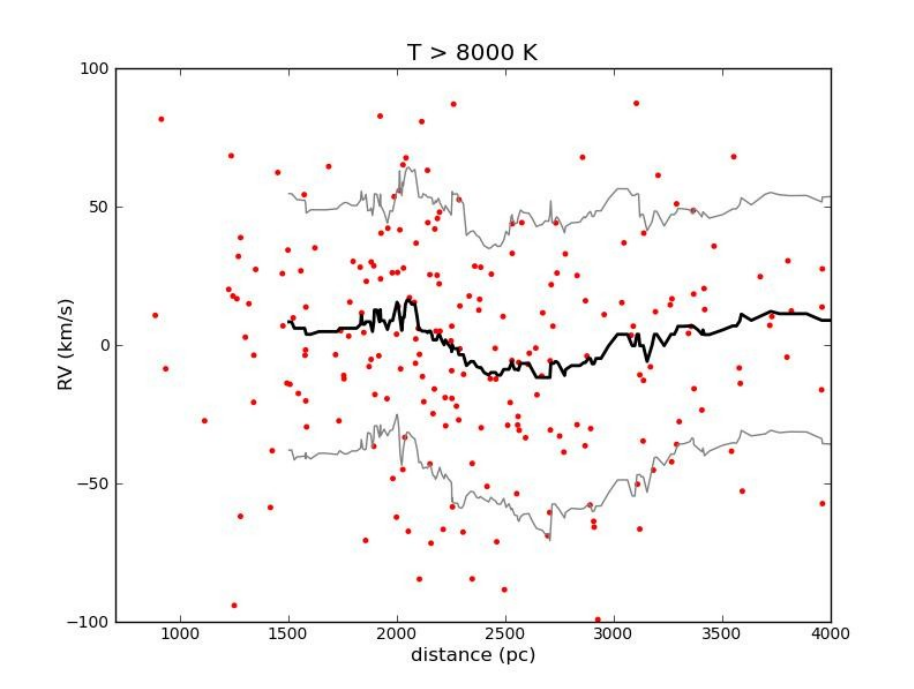




Monguio+13p

Radial Velocities in Anti-center Direction





Luo+12

Star in uvby-Hβ survey with radial velocities

- 1108 observed by LAMOS pilot survey (Luo+12)
  - 292 stars with Te> 8000°K show marginal variation
    - Distance 2.0-2.5 kpc just outside density enhancement
  - Full sample shows little variation due to larger age spread
- Sample of 400 stars observed with WHT/La Palma
  - Two epochs – to identify double stars
  - Analysis in progress

Summary for Milky Way

- Birthplaces of young stars in solar neighborhood
  - Two-armed spirals with Perseus and Sagittarius arms
    - Stars more likely born in arms with spiral perturbation
      - Amplitude a = 0.04 and pattern speed Ωp = 14 km/s/kpc
  - But
    - Different arm configuration not tested e.g. 4-armed
    - Potential of Galactic bar not included
    - Small region in solar neighborhood
    - Many stars may be formed in inter-arm regions
- Location of Perseus arm
  - Survey of B5-A3 stars in anti-center direction
    - Individual extinction, distance , and age using uvby-Hβ
    - Extinction increases to 1.7 kpc but then is more constant
    - Density enhancement is suggested near 1.7 kpc
    - LAMOS data suggest velocity variation
  - Which indicate that the Perseus arm is
    - a major arm at a distance of 1.5-2.0 kpc
    - inside CR

External galaxies – Photometric options

- Optical vs. NIR bands
  - Optical wavelengths
    - Low sky background
    - High attenuation by dust
    - More sensitive to hot, young stars
  - NIR bands
    - High and varying sky background
    - New detectors – NIR observations of spiral galaxies (Block+91)
    - Low extinction Ak = 0.1 x Av
    - Sensitive to old stars (but also to young TP-AGB stars)
- Surface photometry vs. individual sources
  - Surface brightness
    - Provide average of different populations
    - Difficult to separate age and extinction
      - Different mix of stars and dust (Witt+00)
  - Stellar clusters
    - Well defined stellar population
    - Bright sources – upto Mk ~ -15^{m} for masses around 10^{6} M_{o}

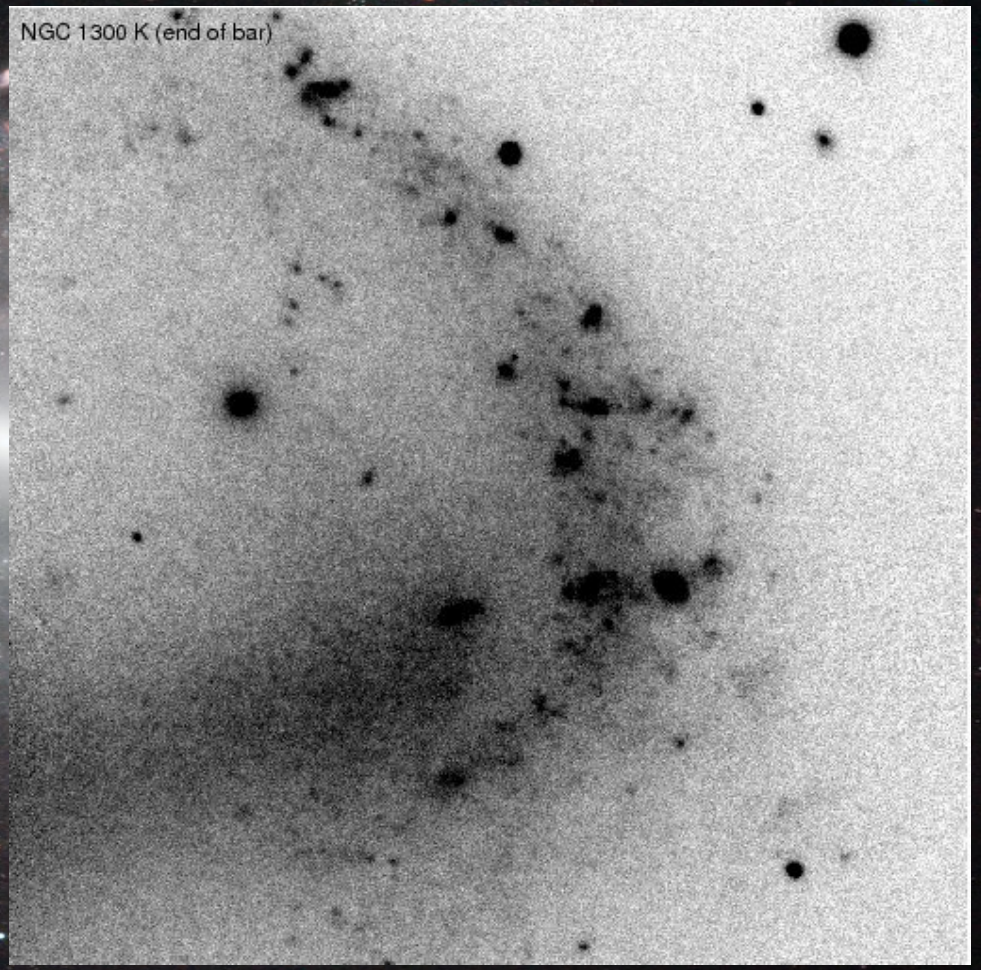
Nearby Grand-design Spirals in NIR

Grosbøl+12

Visual vs. NIR colors

NGC 1300

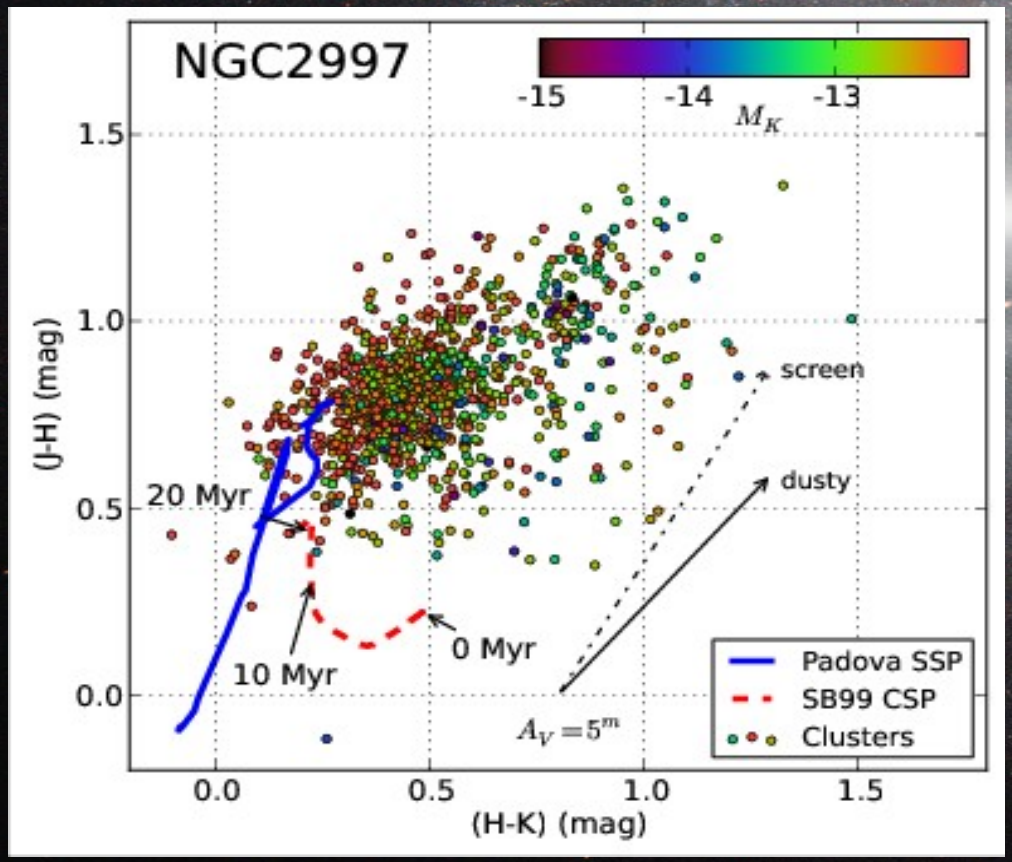
HST

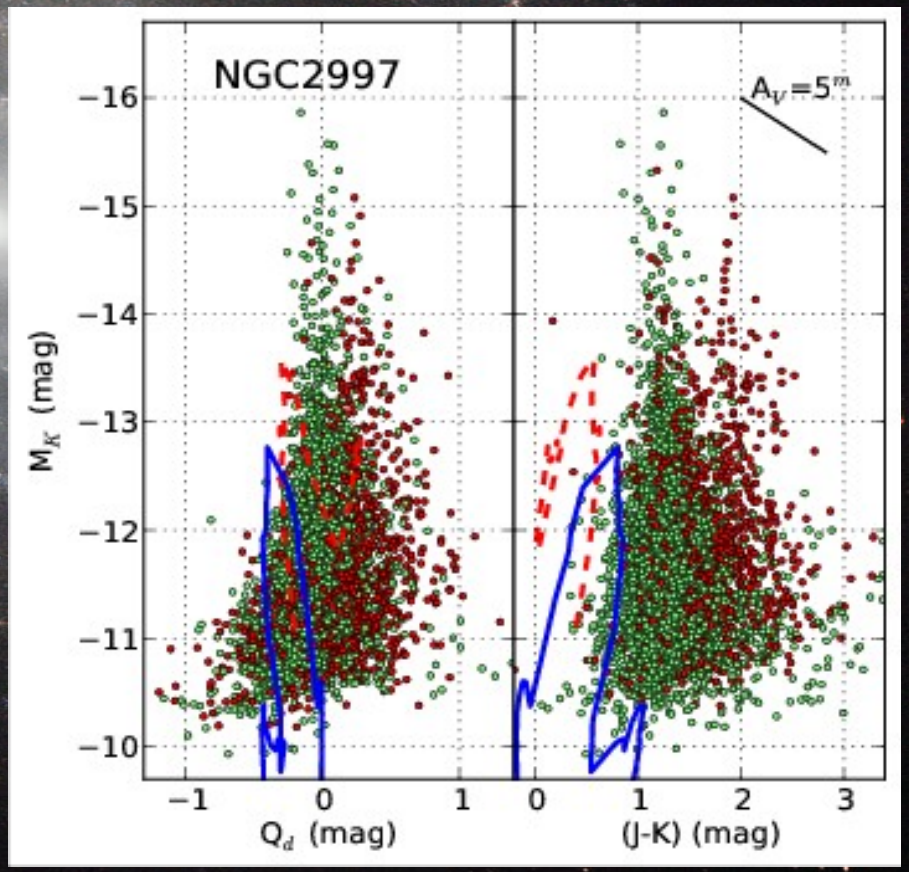


VLT HAWK-I Ks band

NIR Colors of Stellar Clusters

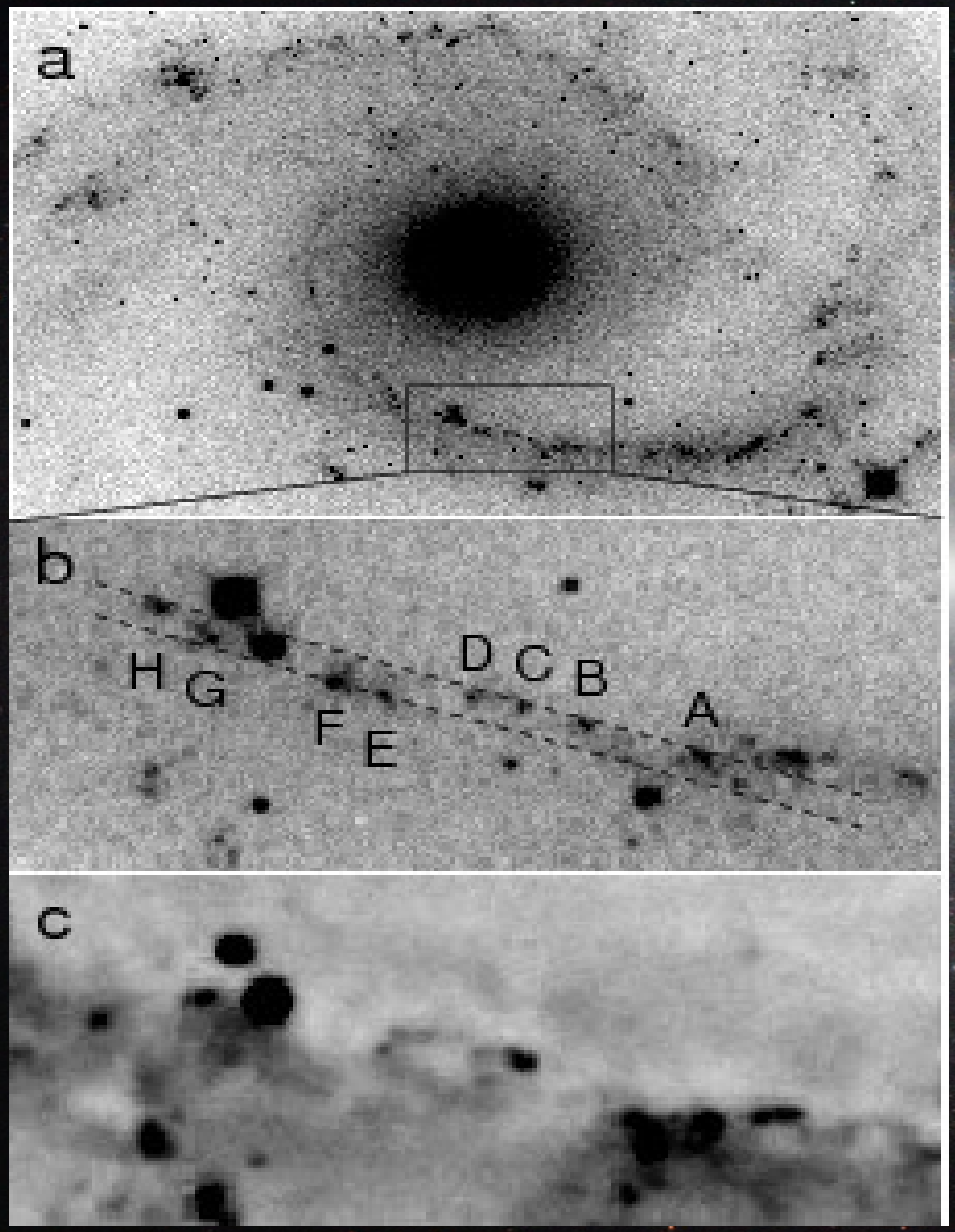
- Two populations of stellar clusters
  - Young clusters (age<7 Myr) with high extinction (Av ~ 5-7^m)
    - Nebular emission important – age indicator
  - Older clusters with low extinction
- Rapid transition between groups (e.g. gas/dust expulsion)

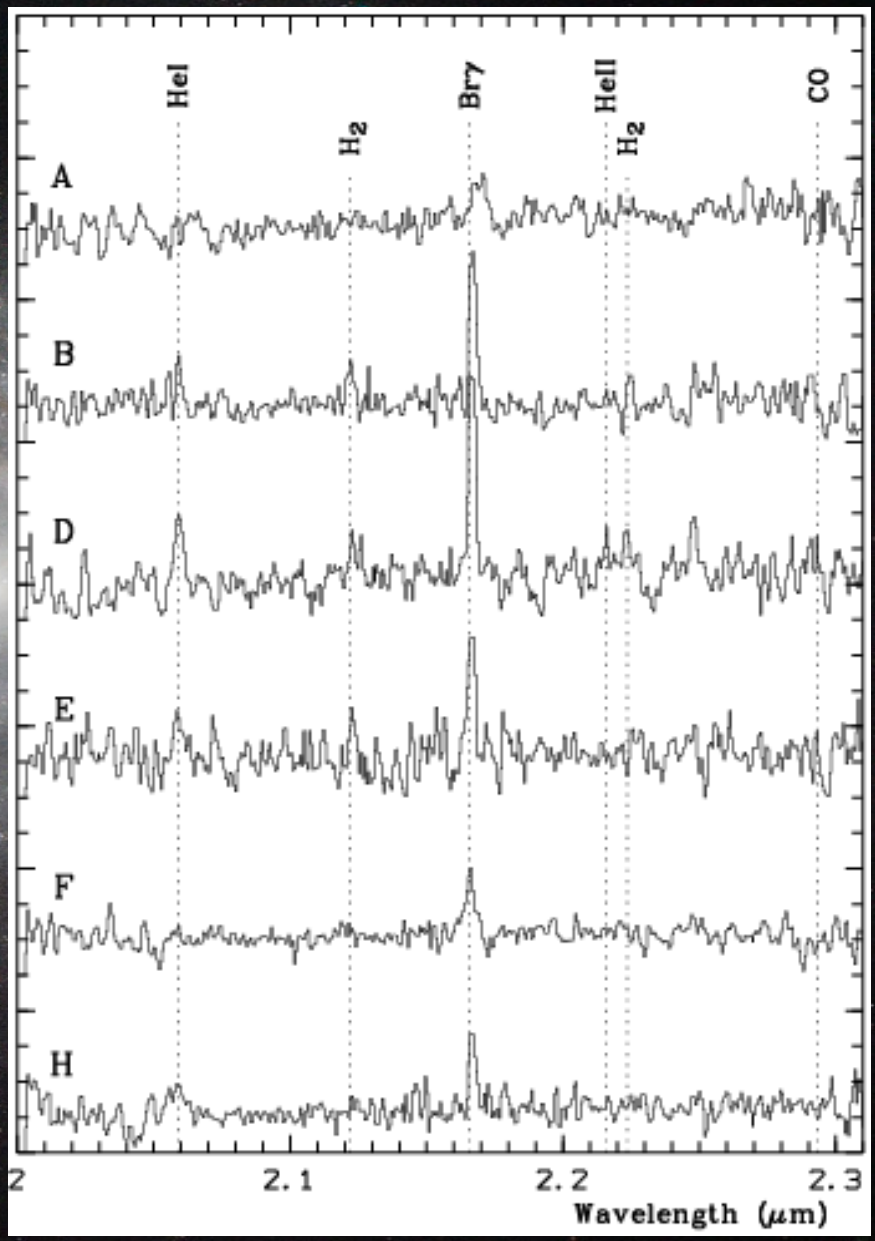




Grosbøl+12

Distribution of Stellar Clusters



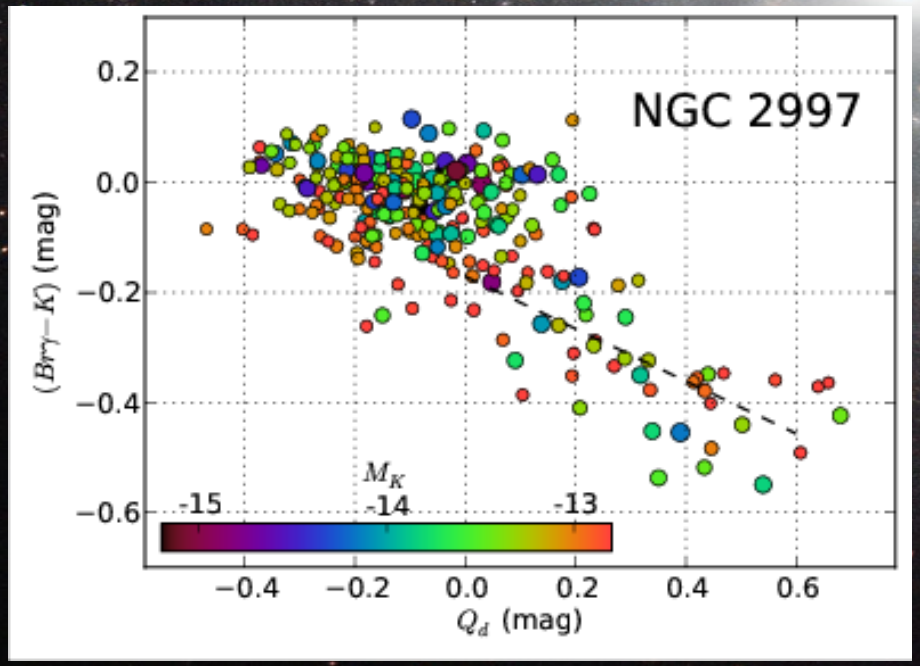


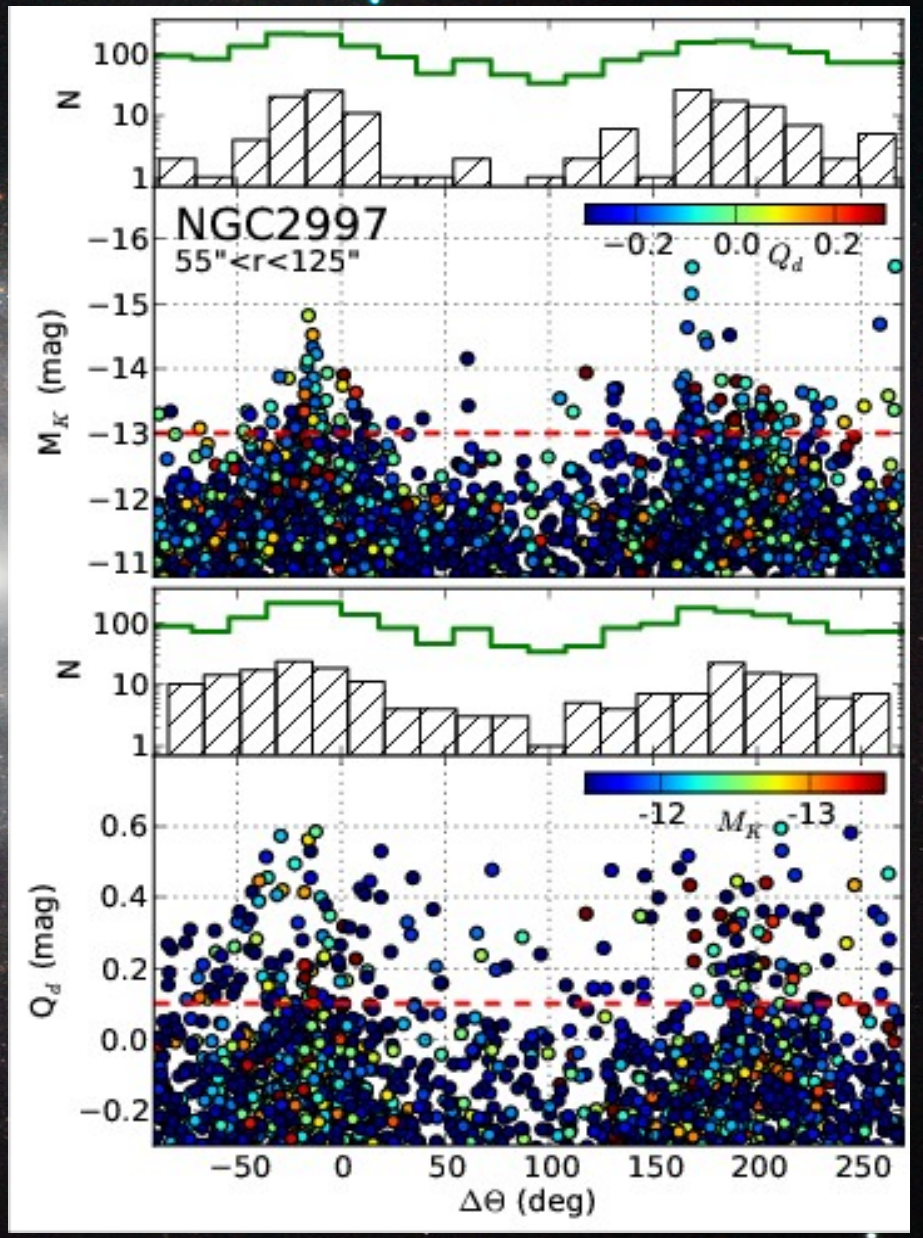
Grosbøl+06

Azimuthal distribution of clusters

Young stellar clusters (<7 Myr):
- Bright clusters are formed in arms
- Fainter clusters also in between

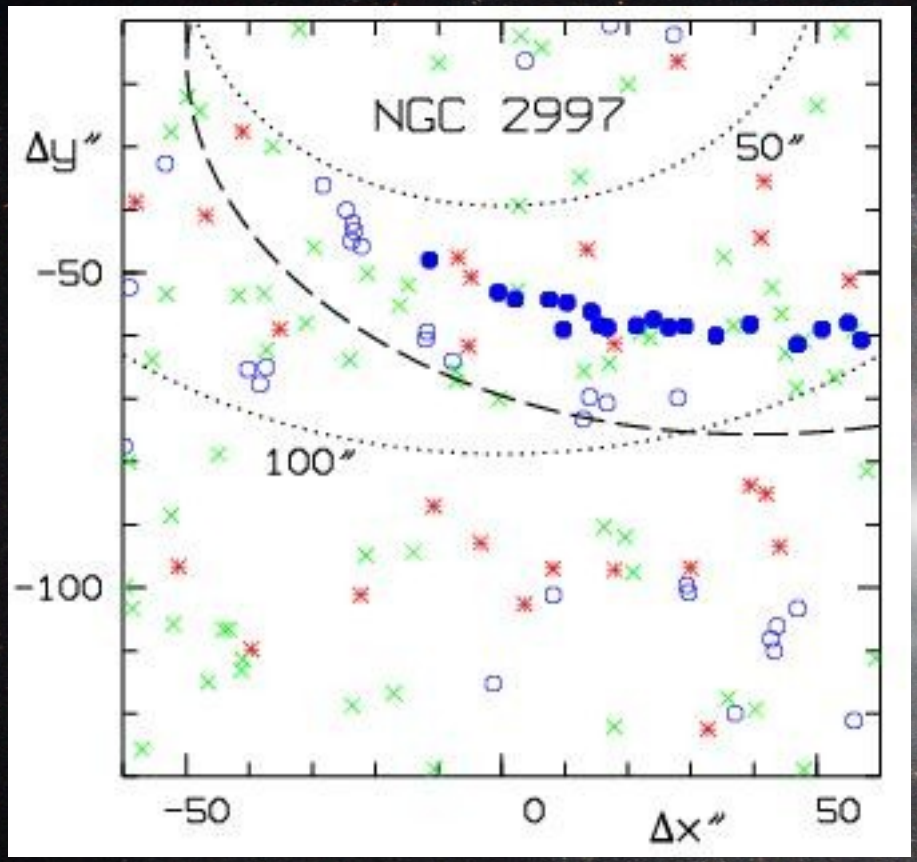
Older clusters:
- Density varies in phase with arms



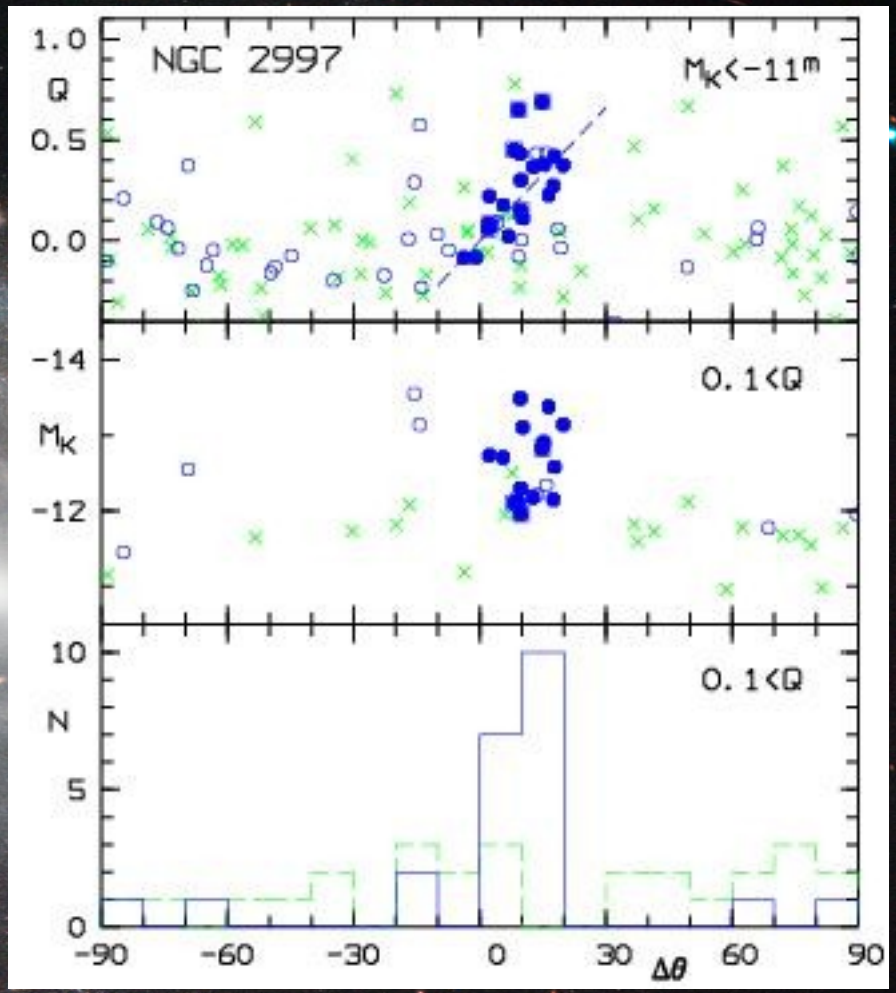


Grosbøl+12

Age Gradient of Clusters



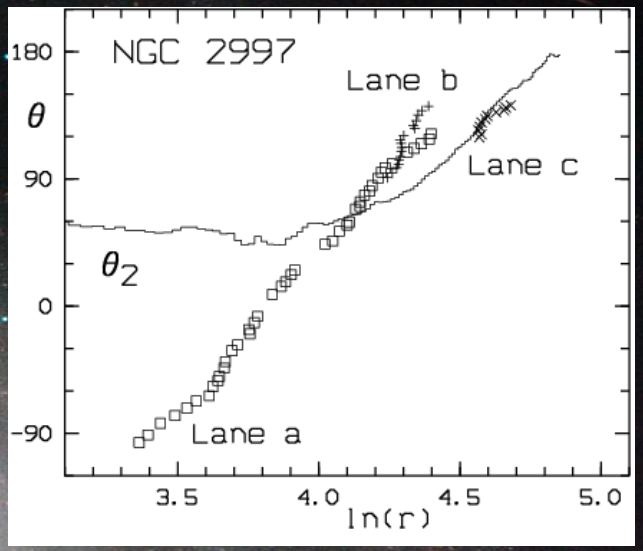
Grosbøl+09

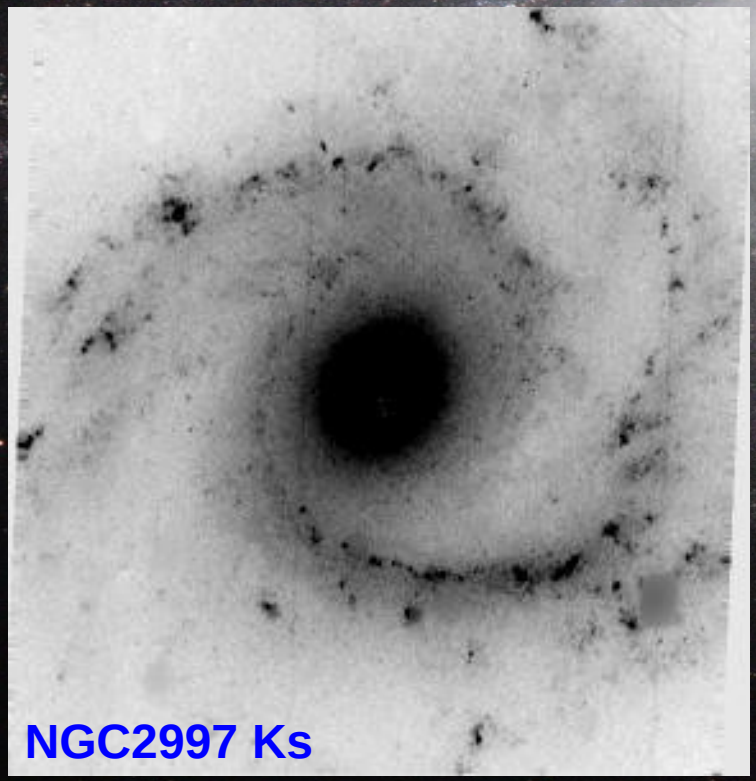


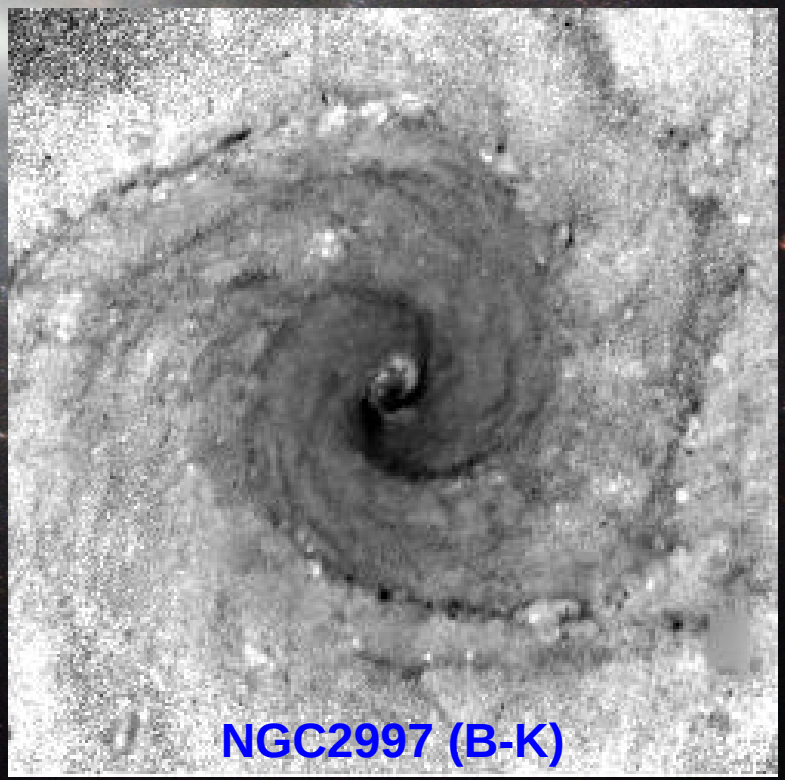
- Young, massive clusters
  - Show azimuthal age gradient: $\Omega p = (Vc - Vr/\tan(i))/r - \delta\theta/\delta age$
  - For Vr = 0, Ωp = 16 km/s/kpc
  - Cluster forming region inside/infront of spiral arm
- Suggest presence of density wave

Dust lanes

- Dust lanes outlined in (B-K) maps
  - Located inside main spiral arms
  - Continue toward center in bar region
    - May suggest double pattern speeds
      - Fast bar with CR near its end
      - Lower spiral Ωp with ILR close to end of bar

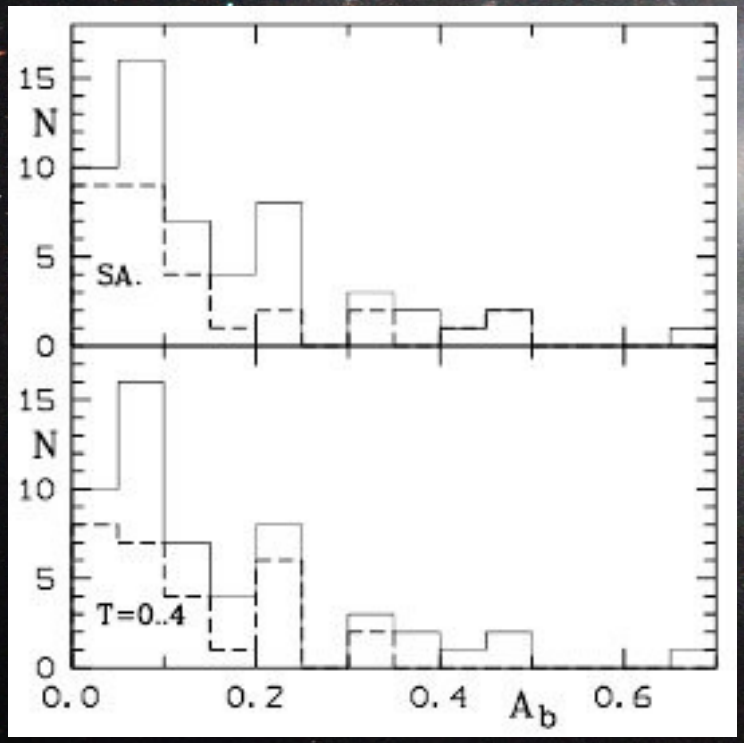


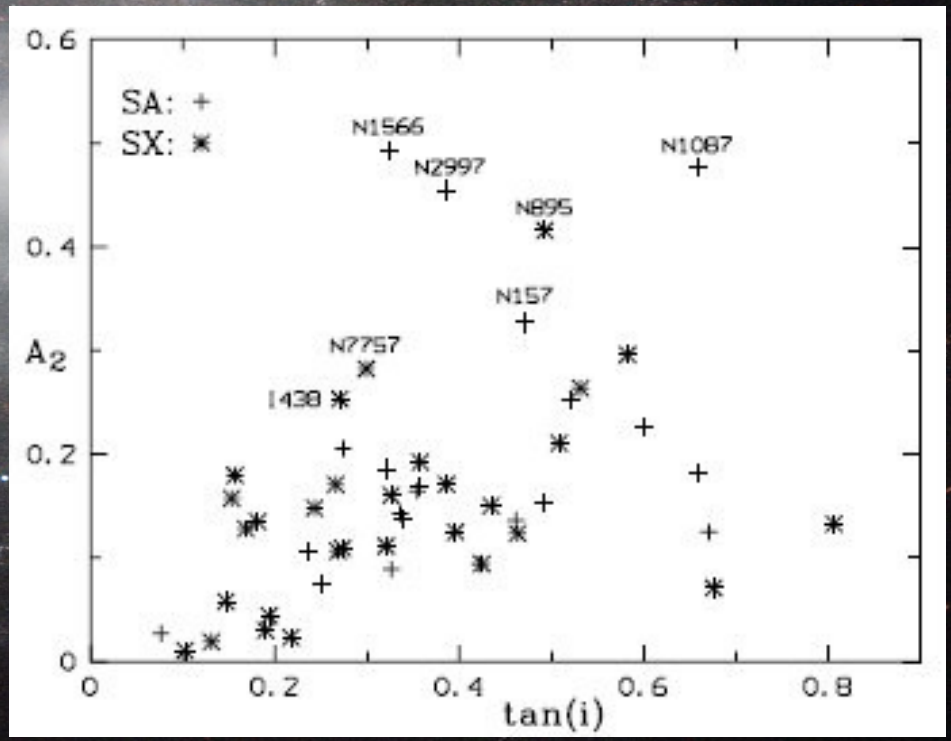

NGC2997 Ks


NGC2997 (B-K)

Amplitudes and pitch angles of spirals

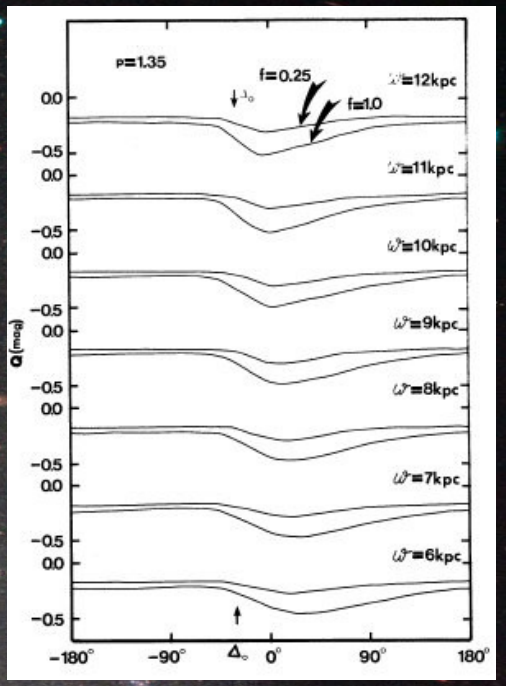
- Ks-band observations of 54 normal spiral galaxies
  - 26 of 30 ordinary spirals had bars with amplitudes >3%
  - 60% display grand-design, 2-armed spiral patterns
  - Tighter spirals have smaller amplitudes
    - Suggesting a limit on relative radial forcing

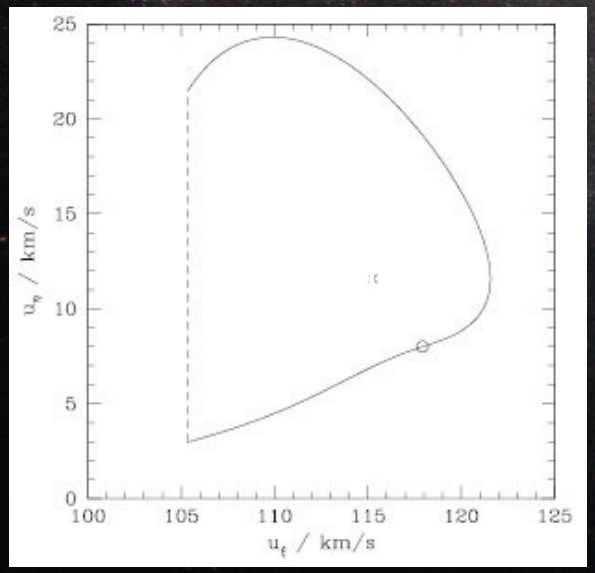




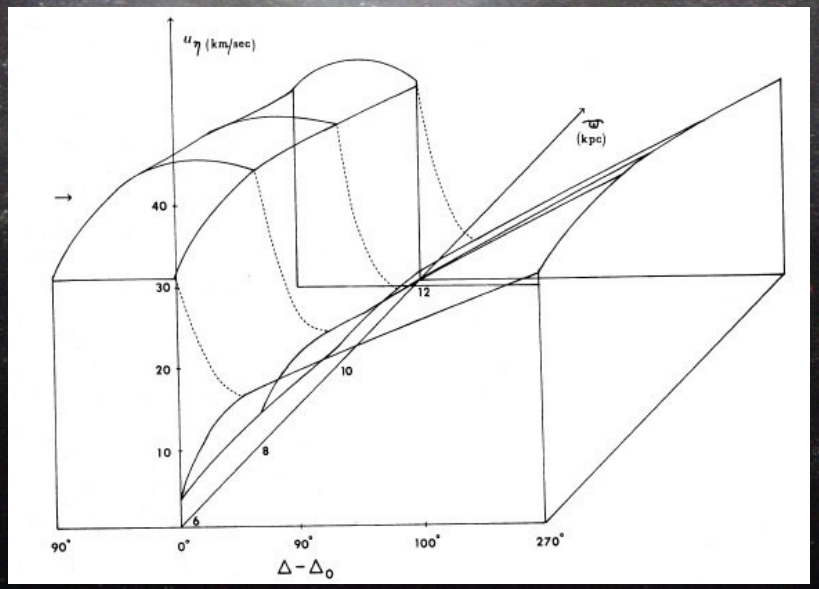
Color gradients across arms

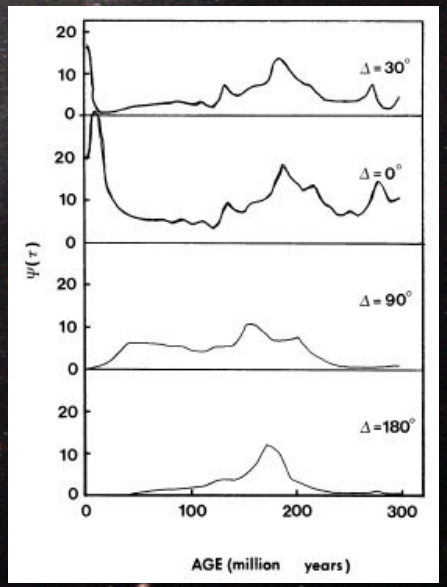
- Star formation after large-scale shock
  - Compute pre-/post-shock velocities
  - Estimate stellar orbits if newly formed stars
  - Derive age distribution vs. azimuth
  - Integrate surface brightness and color
- General results
  - Color variation of 0.1-0.3^{m}
  - Broad color profile due to radial velocities





Gittins+04

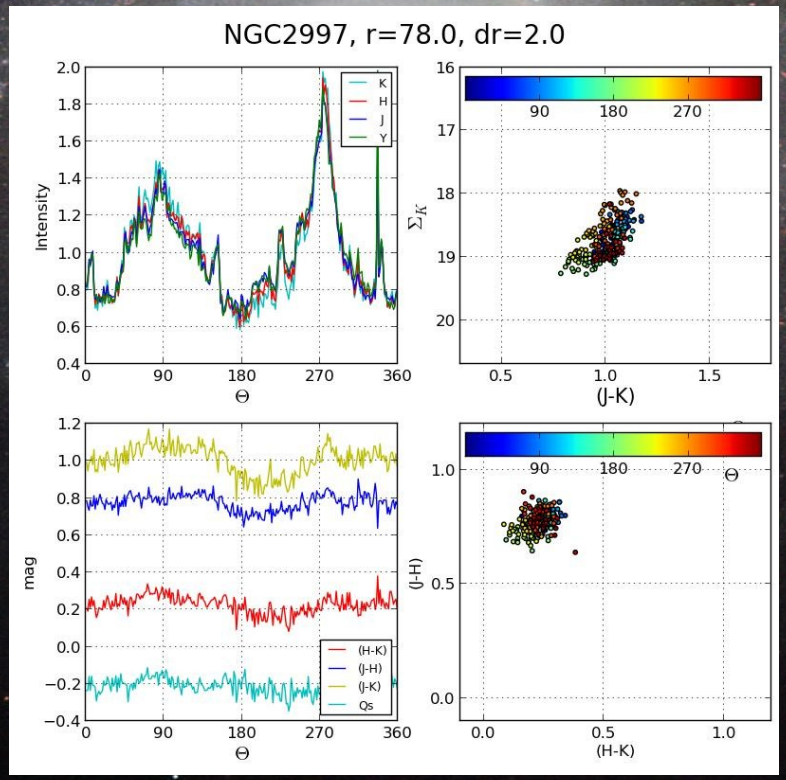




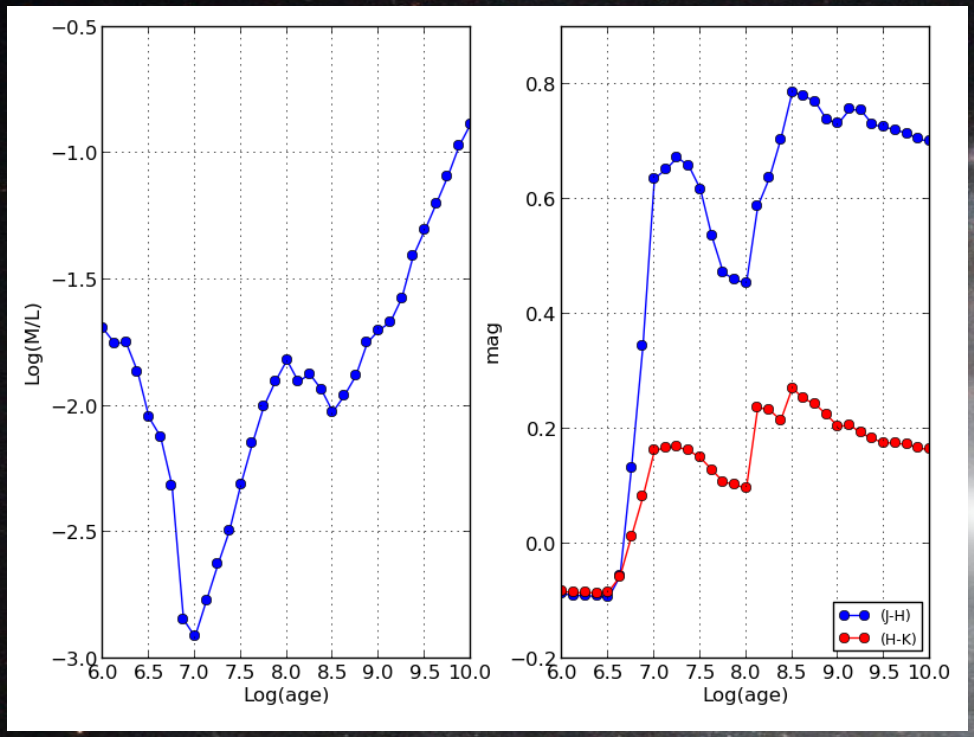
Yuan+81

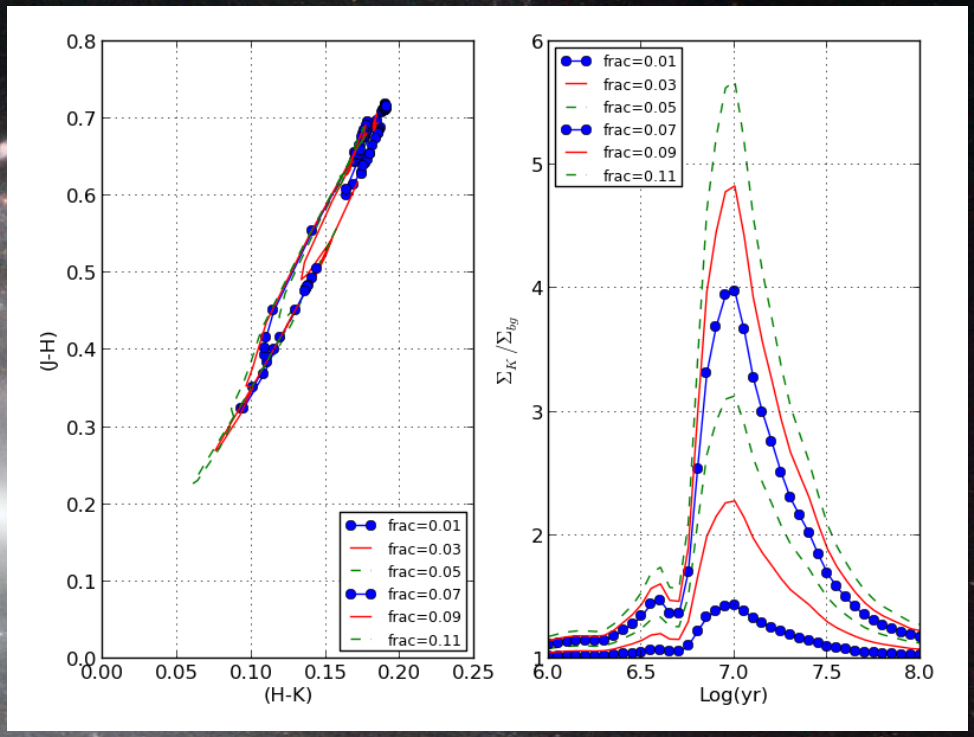
Azimuthal Color Variations in NIR

- NIR color profile after removing clusters
  - 20% typical variation in K
    - Peaks in arm regions – young stars?
  - Main color change in (J-K)
    - Difficult to separate age and extinction effects



K-band M/L ratio variations





M/L ratio of cluster in K-band as function of age

- Variation of more than a factor of 100 (Marigo+08)
- After ~7 Myr significant color change (TP-AGB stars)
- Even a few % young stars with age = 10 Myr can yield factor of 2 in Σk
- Color variation parallel to reddening vector

Summary for Grand-Design Spirals

- Stellar clusters in nearby spiral galaxies
  - Young clusters can be identified due to their nebular emission
  - Massive clusters are formed mainly in arms
    - In front of arms (assuming trailing spirals)
    - Whereas less massive clusters also are formed in inter-arm regions
  - Azimuthal age gradient are seen
- NIR surface photometry
  - Difficult to separate age and extinction effects
    - Mix of stars and gas/dust may vary
  - Small color variation
  - Significant M/L ratio variation in K around age ~ 10 Myr
  - K photometry consistent with 10-20% variation in mass
  - Dust lanes inside main spiral arms
  - Tight spirals have low amplitudes
  - Most ordinary SA spirals has oval distortions

General Conclusions

- Milky Way
  - Estimation of birthplaces may be useful
    - But significant radial range and full potential must be used
  - Indication of Perseus arm being a major arm
    - Extinction suggests that it is inside CR
  - This supports the existence of a density wave
- External grand-design, spiral galaxies
  - K-band images are useful
    - But M/L variation may be a concern
  - Location of young clusters and age gradients
    - Consistent with density waves

Density waves are important in grand-design spirals