Rotation Among High Mass Stars: A Link to Initial Formation Conditions?

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Outline of Talk

- The evidence : Observations of B star rotation speeds
  - Stars in rich, bound clusters
    - Have high median rotation speeds
    - Lack a cohort of slow rotators
  - Stars in unbound associations, field
    - Have a lower median rotation speeds
    - Have a large cohort of slow rotators
- Possible explanations:
  - **Nature**: Rotation could reflect differences between cluster (high-density) and association-forming (low-density) regions in the initial conditions in the star-forming core itself or
  - **Nuture**: Rotational velocity differences could be due to the environment around the core (stellar density; radiation field)

Motivating Observations

- Wolff, Edwards and Preston (1982) observations of Orion B stars
  - Nascent bound cluster (ONC) exhibits
    - Much higher median rotation speed
    - Lack of slow rotators

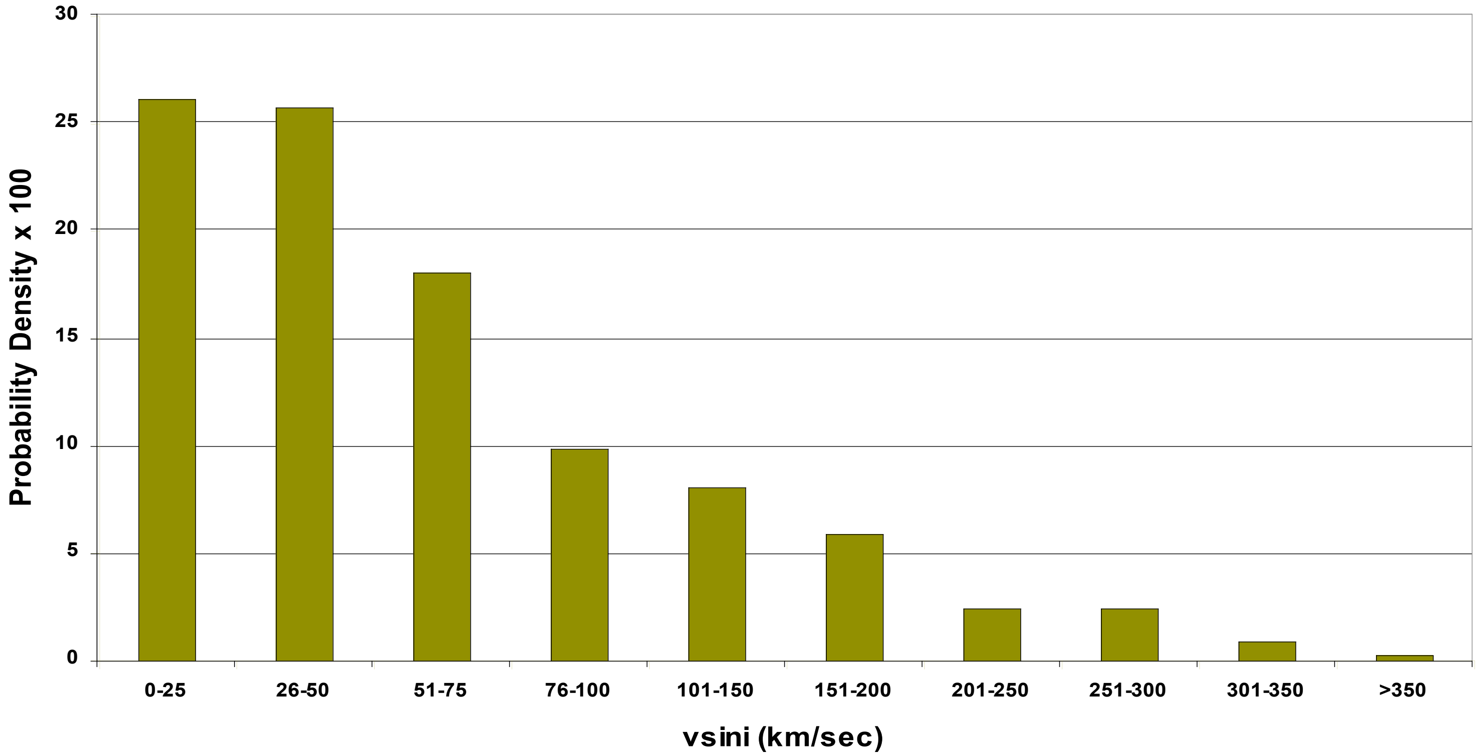
  compared to stars distributed in the surrounding unbound association

- Guthrie (1982) study of late B stars showed that on average field stars rotated more slowly than B stars in clusters

- To test the hypothesis that the distribution of vsini depends on where the stars are located, Strom et al. (2005) compared rotation speeds among late B stars in h and chi Per (bound clusters) to those of comparable age in the field

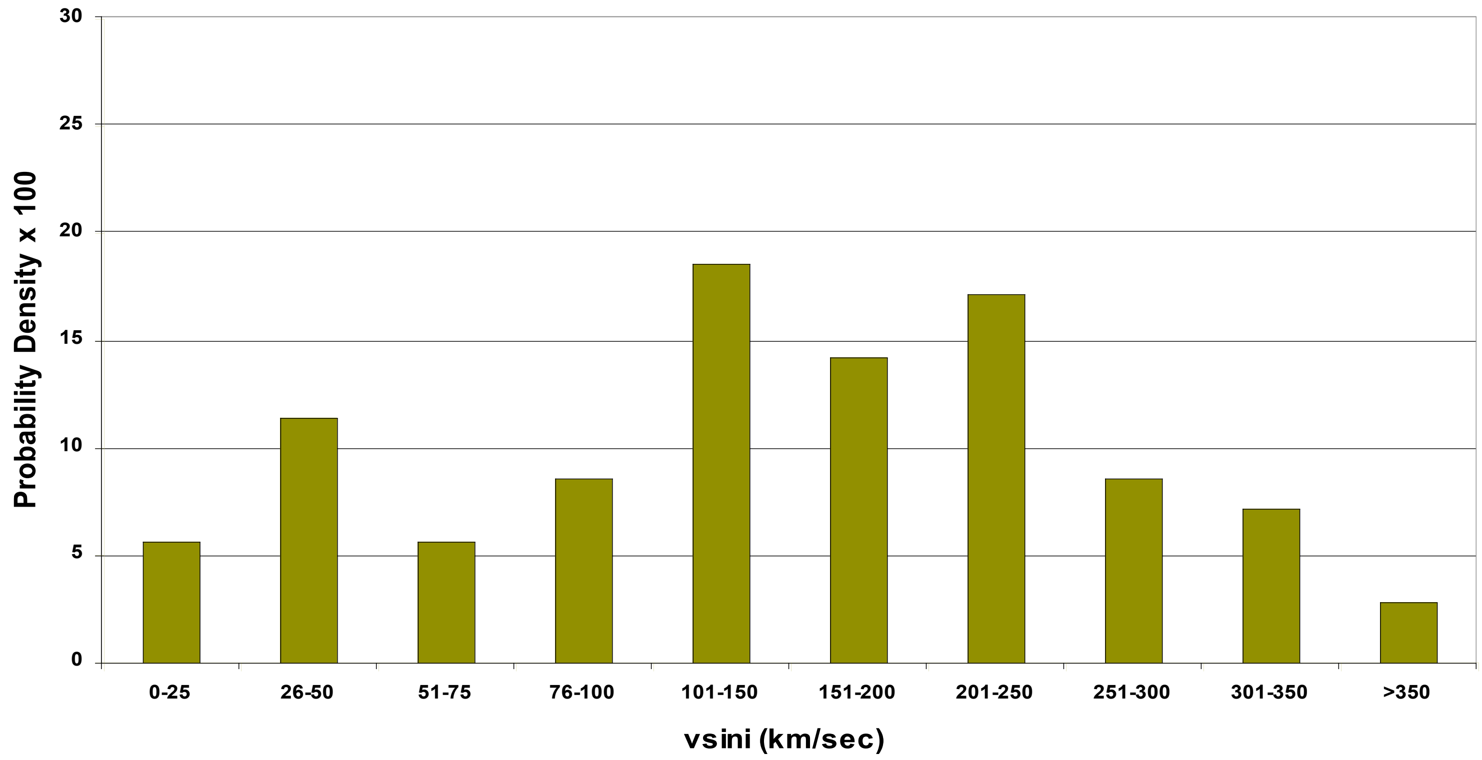
Unevolved Field B Stars

$4 < M/M_{Sun} < 5$



Unevolved B Stars in h and chi Per

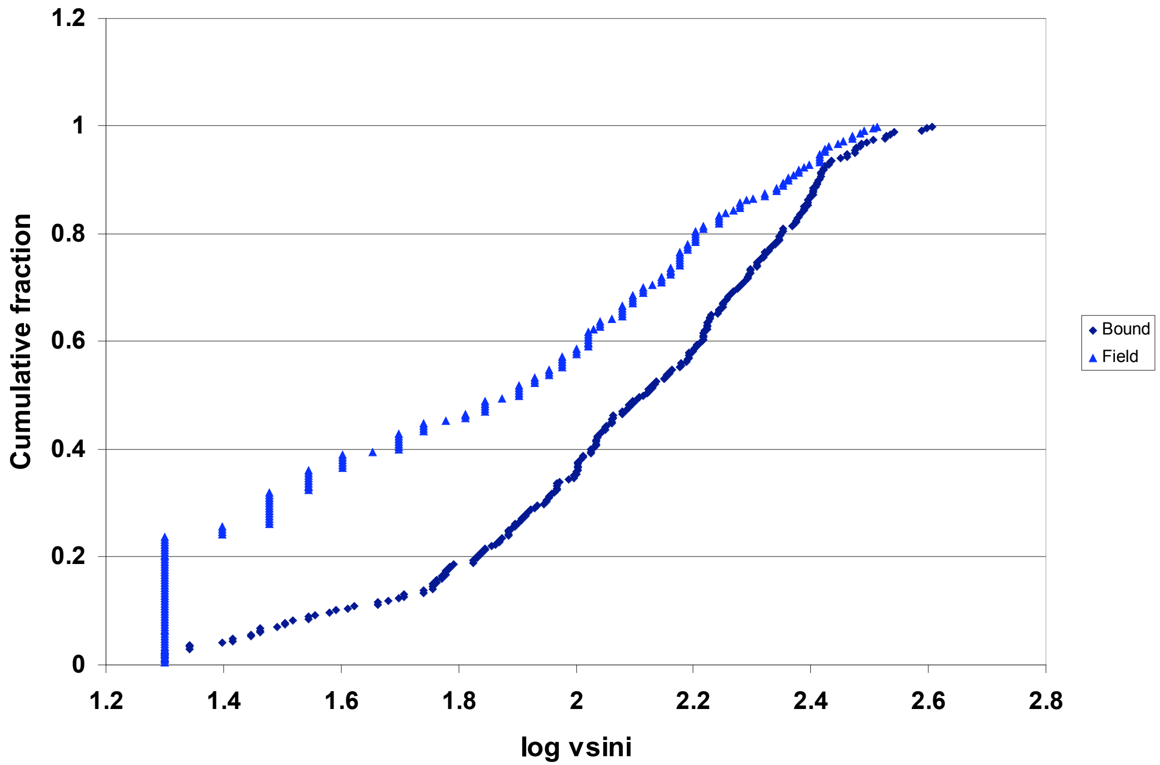
$4 < M/M_{Sun} < 5$



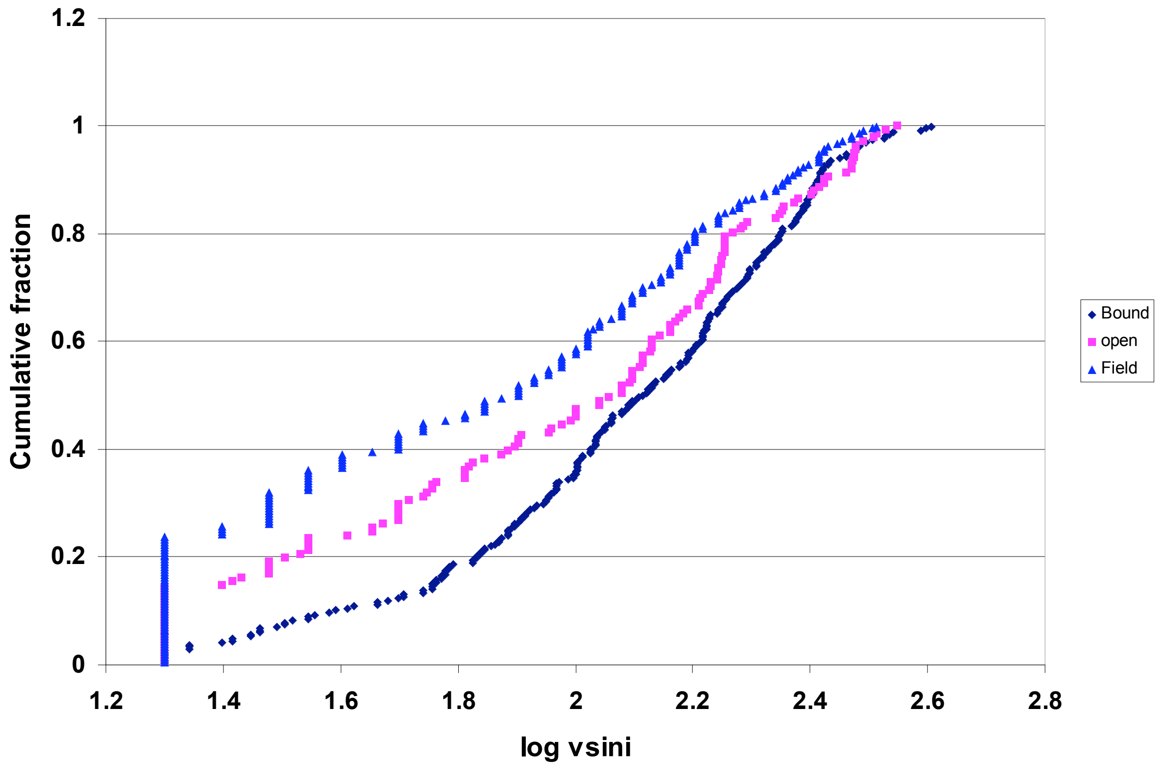
Recent Surveys Offer Strong Confirmation

- Wolff, Strom, Dror, and Venn (2007)
  - Analysis extended to early B stars
  - 4 bound clusters and 3 unbound associations
- Similar results found by Huang & Gies (2006); Dufton et al. (2006)

Cumulative Distribution of vsini
Milky Way 6-12 M_{Sun}



Milky Way 6-12 M_{Sun}
Clusters, Associations, Field Stars

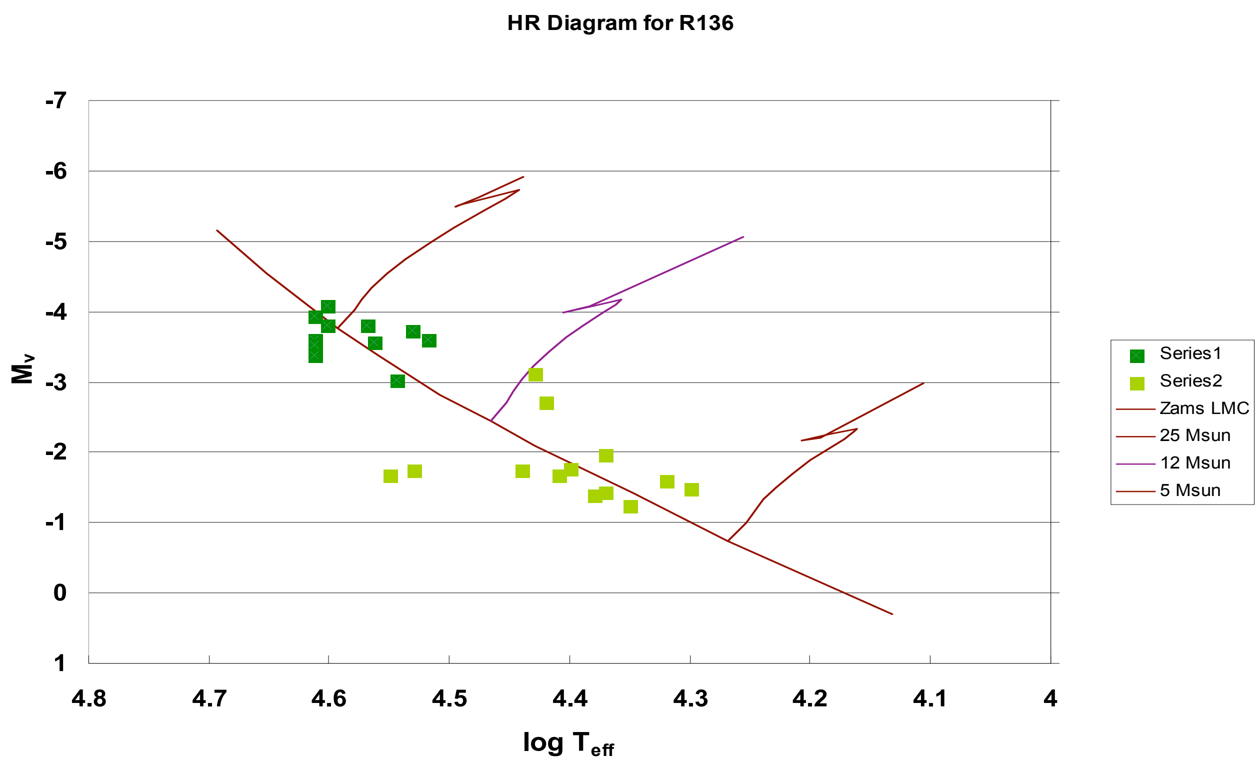


Analysis of Very High Density Region in the LMC: R136

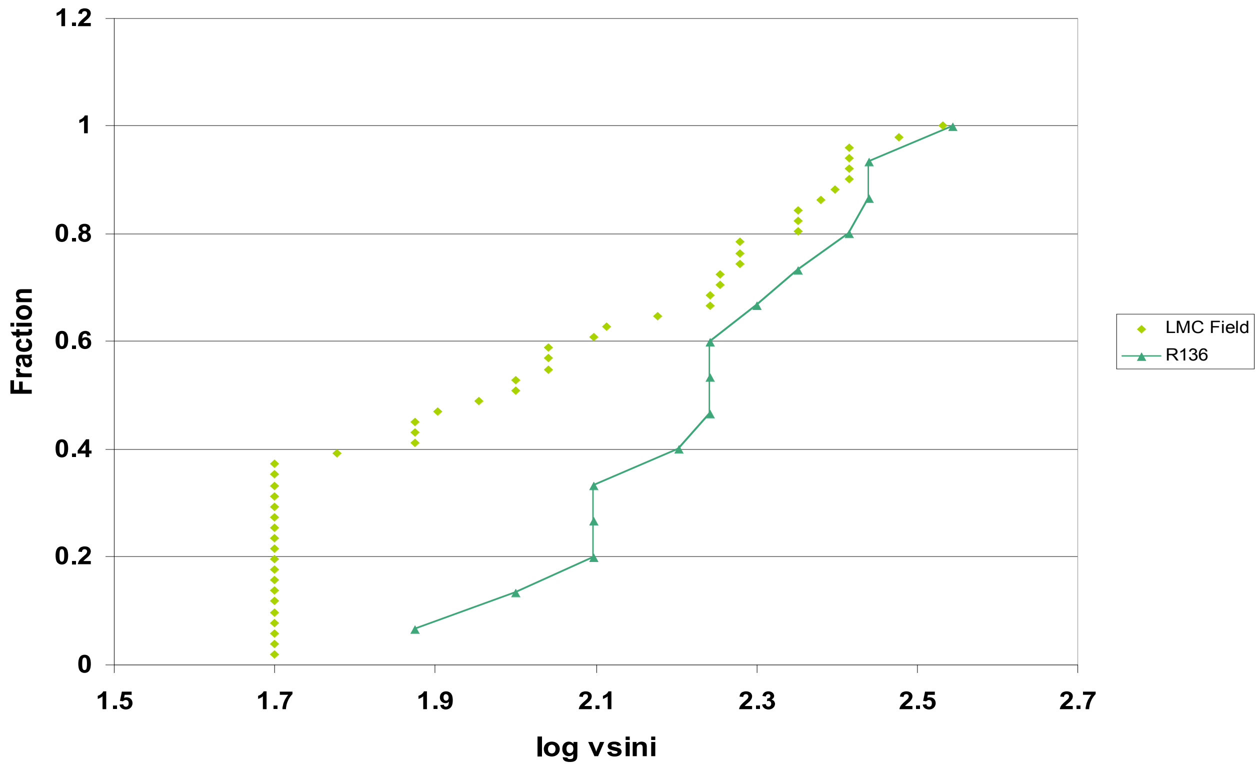
- Q: are the rotation properties even more extreme?
  - Density ~ 3x that of Galactic clusters studied to date

- Observations: 11 O and 15 B stars
  - Data obtained with GMOS on Gemini South
  - Rotations derived via comparison with models (Cunha)
- Comparison sample for B stars
  - Observations of field and bound clusters (lower density) in LMC (Keller 2004)
  - Enables comparison with stars of comparable metallicity

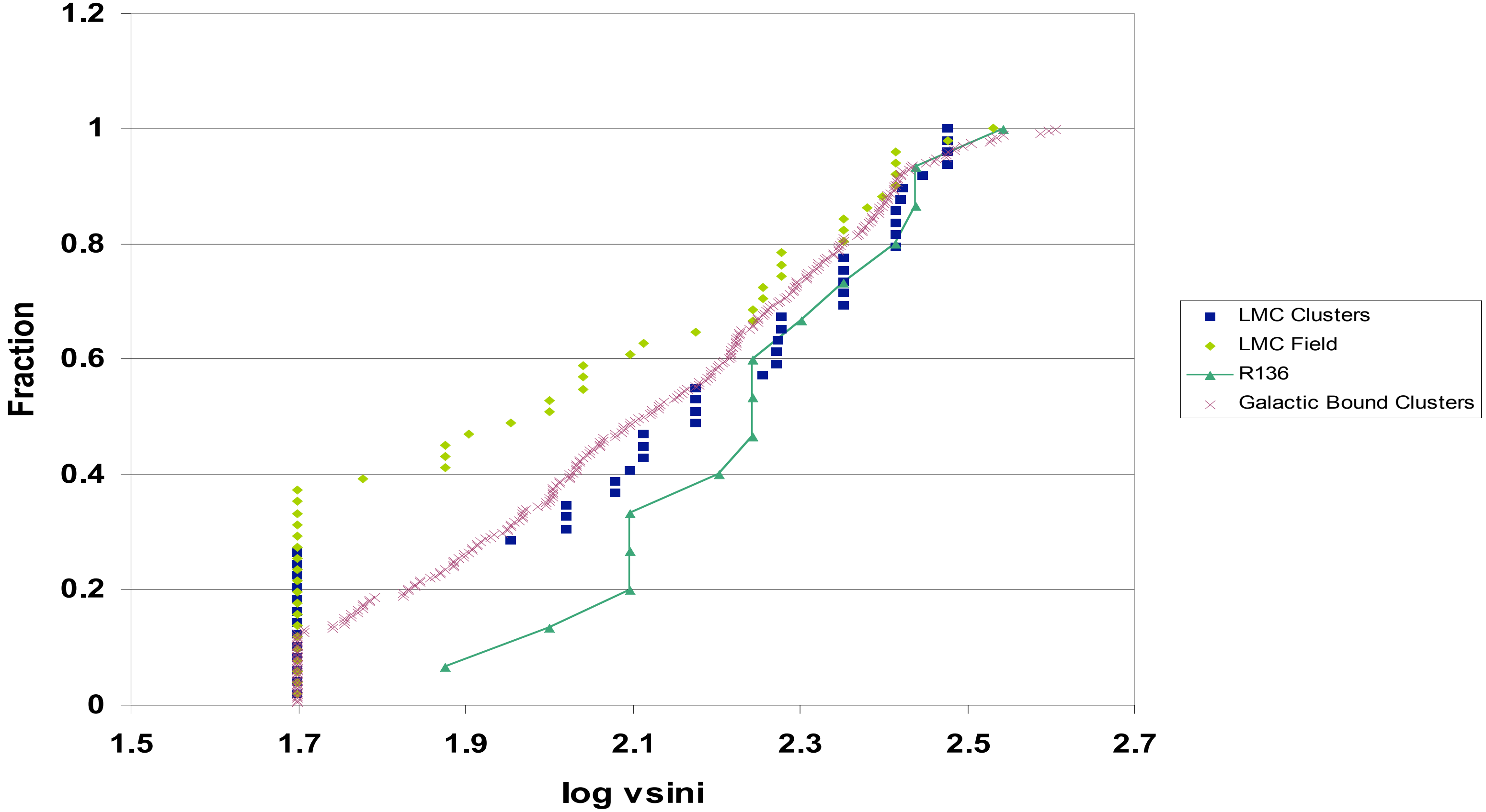
R 136 Observations



Vsini: 6-12 M_{Sun}



Cumulative Distribution of vsini 6-12 M_{Sun}



Conclusions

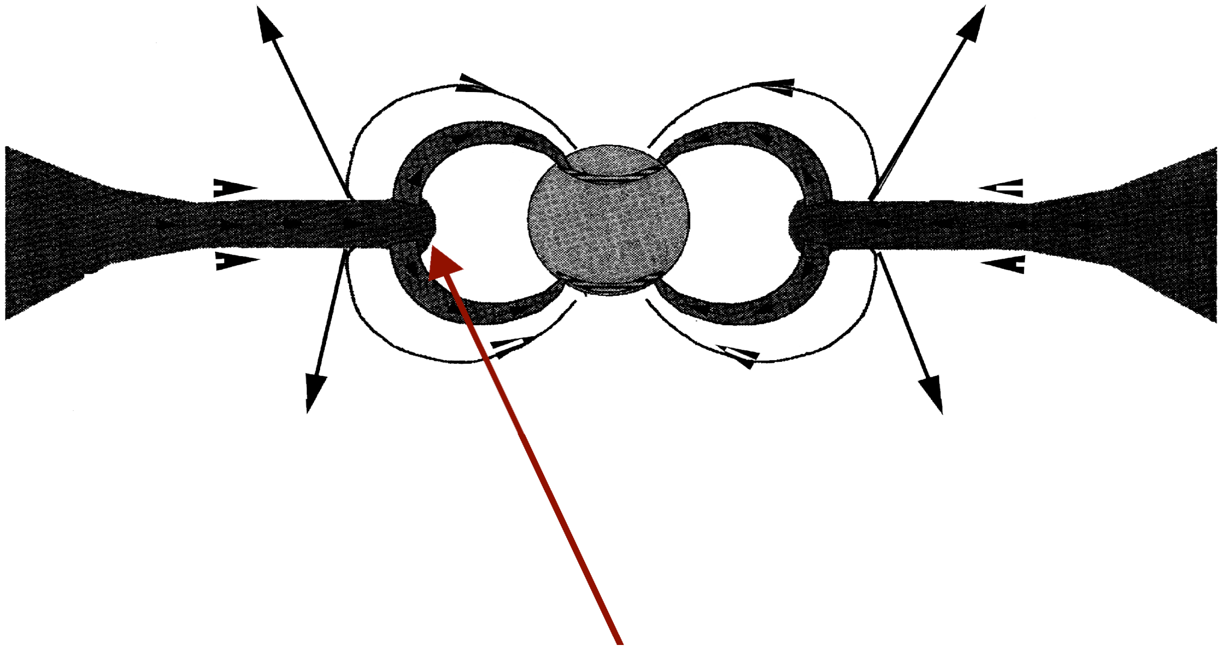
- R136: 15 B Stars (6-12 M_{Sun})
  - Results consistent with studies of regions in Milky Way
  - B stars in R 136 lack cohort of slow rotators
    - R 136: <vsini> = 188 km/sec
    - LMC Field: <vsini> = 116 km/sec
    - LMC Clusters: <vsini> = 147 km/sec
    - MW Clusters: <vsini> = 145 km/sec
  - Effects of metallicity appear small (LMC vs. MW)

NB: While we lack the data needed to establish the EXACT range of ages in all samples, our work on MW clusters and associations shows that evolutionary effects are negligible for ages t < 14 Myr

What Determines Rotation Rates?

Low Mass Stars: Disk-locking

$\Omega \sim (M_{acc}/dt)^{3/7} B^{-6/7}$



Star and disk 'locked' at the co-rotation radius where $P_{dyn} = P_{magnetic}$

$\Omega_{disk} = \Omega_{star}$

Potential Role of Environment Around a Newly Formed Star in Disk-locking Model

- For a low-mass star, the lifetime of the disk plays a major role in determining rotation rate on the main sequence
  - Stars that lose their disks earlier along their PMS convective tracks will spin up more as they contract toward the main sequence and will become rapid rotators
  - Stars that remained locked to their disks until contraction is nearly complete will be slow rotators
- Cluster environments are more conducive to early disk loss
  - Early disruption of disks through tidal interactions in denser, cluster-forming regions
  - Early dissipation of disks through photoevaporation in richer, denser cluster regions containing a number of early-type stars

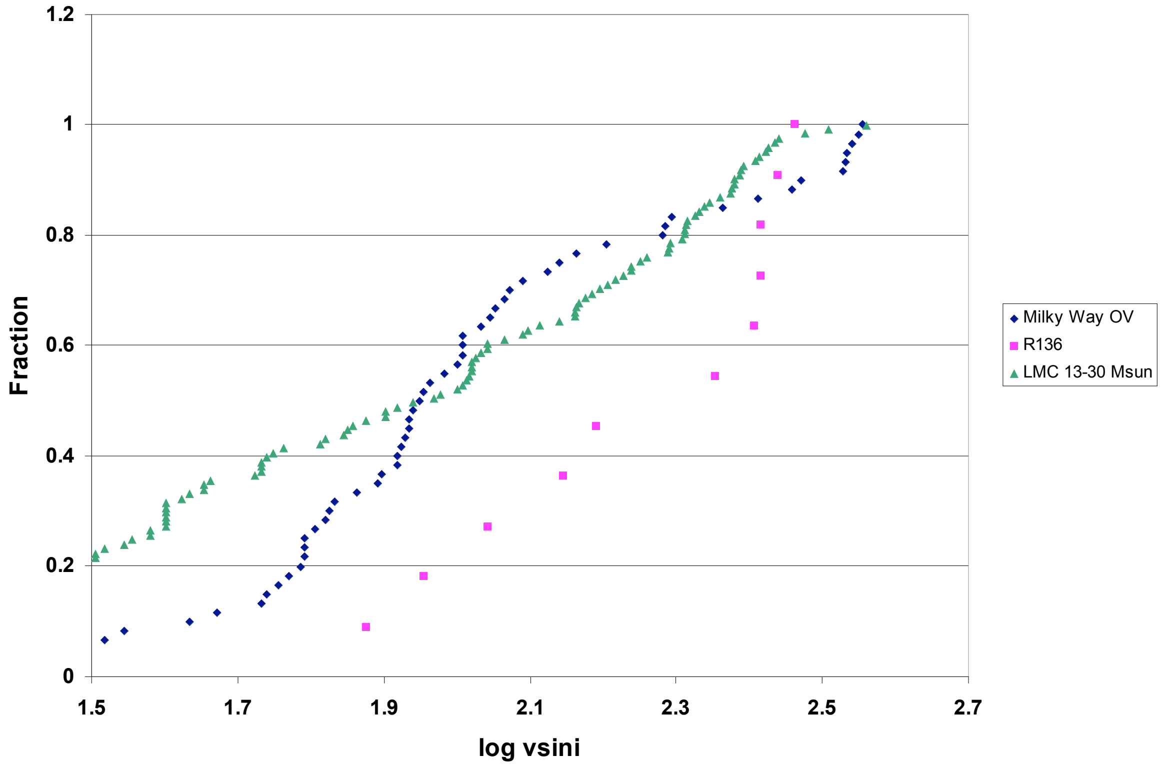
Variations in Disk Lifetime Unlikely to Account for Distribution of B Star Rotation Rates

- In contrast to low mass stars, protostellar B stars have very short lifetimes and
  - Disks less likely to be disrupted prematurely
- Reasons
  - The densities in cluster-forming regions are not large enough to render tidal disruption of disks important
    - Even in the core of R 136, the current distance between stars exceeds 10,000 AU (much larger than expected disk radii)
  - Photoevaporation times are large compared to expected disk lifetimes for B stars
    - In the ONC, the photoevaporation time for a disk of 0.1 Msun (relatively low for a B star disk) is typically 10^6 years
    - Expected lifetime for B star disk is $< 10^5$ years

What About O Stars?

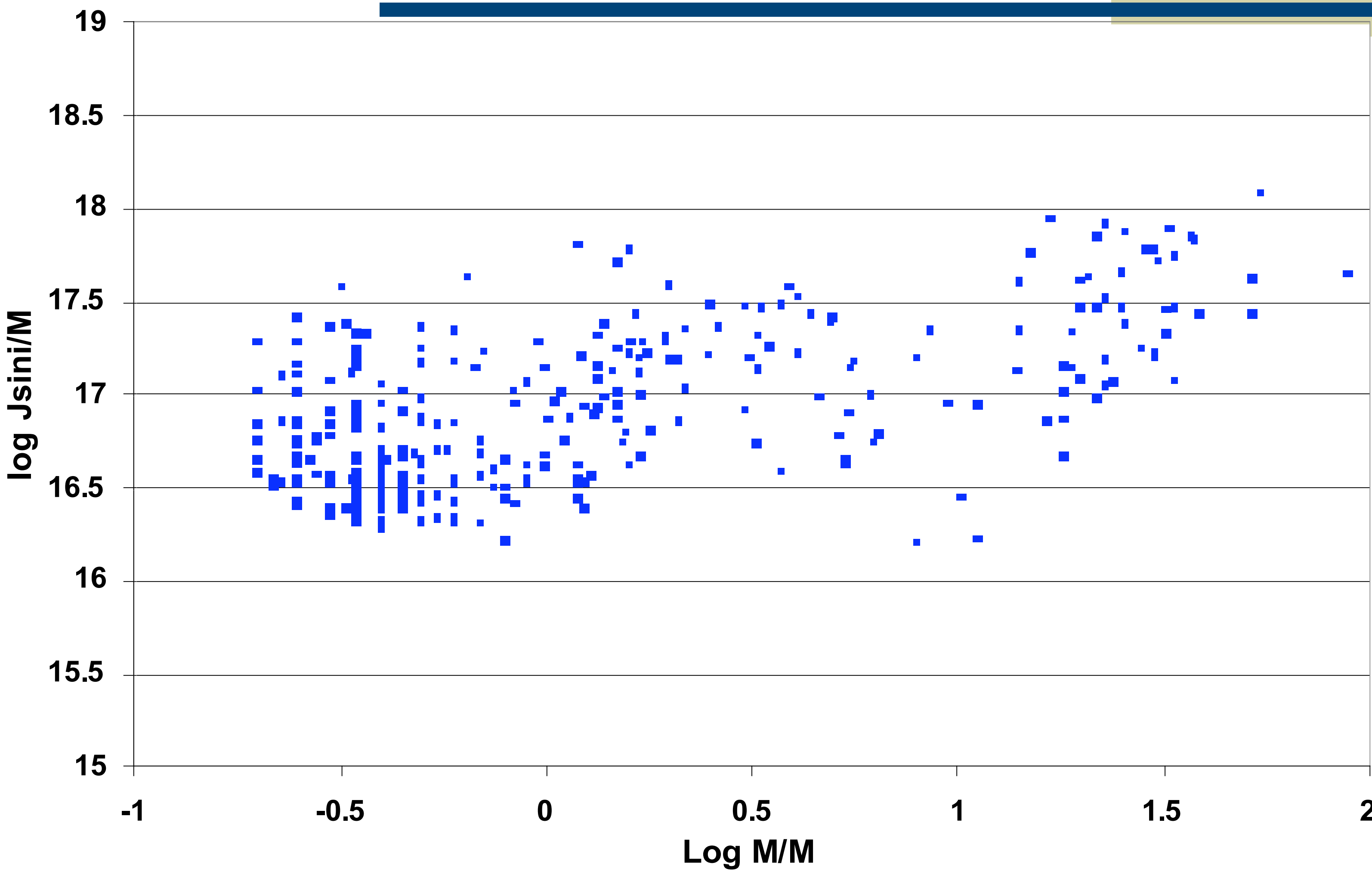
- Stars with M > 10 M_{Sun} are still accreting when they arrive on main sequence
  - Interactions with surrounding stars unlikely to alter rotation after accretion ends
- If distribution of vsini for O stars also depends on density of environment (bound cluster or expanding association), then the cause is likely due to initial conditions in accreting cores
- Observational challenges for O Stars
  - Sample size in given region will be small
  - Difficult to determine accurate ages, and O stars are likely to lose angular momentum as they evolve away from the main sequence

•Stars in R136 13-30 M_{Sun}



Specific Angular Momentum (J/M) vs. Mass

Orion Stars on Near Birthline + Young Massive Stars



Specific Angular Momentum (J/M)

- J/M upper bound continuous (~0.2 V_{esc}) from 0.2-30 M_{Sun}
- Similarity of J/M throughout broad mass range supports the argument that the initial J/M is determined during main accretion phase
  - Some variation of disk-locking during accretion would seem to be required to keep O stars from rotating at breakup
  - Mergers probably do not play a major role in the formation of most massive stars up to about 30 M_{sun} because mergers are expected to produce high angular momentum in product

Rotation: A Probe of Initial Conditions That Govern Accretion?

- Dense, bound stellar clusters form in regions of high gas surface density (McKee and Tan, 2003)

Object	M ($M_\odot$)	$R_{1/2}$ (pc)	Σ (g cm^{-2})
Galactic star-forming clumps.......	3800	0.5	1.0
Orion Nebula Cluster..................	4600	0.8	0.24
Arches cluster	2×10^4	0.4	4
Galactic globular clusters............	2×10^{5a}	3.4	0.8
Taurus			0.03

Potential Influence of Initial Conditions

- Rotation could reflect differences in initial conditions in star-forming core
  - Cluster-forming molecular clumps appear to have higher turbulent speeds (Plume et al. 1997)
  - If higher turbulent speeds also characterize the star-forming cores, then higher initial densities are required in order that self gravity can overcome the higher turbulent pressures
  - Higher core densities lead to shorter collapse times and higher high time-averaged accretion rates (McKee & Tan 2003)
  - In the context of 'disk-locking', higher time-averaged accretion rates lead to higher initial rotation speeds

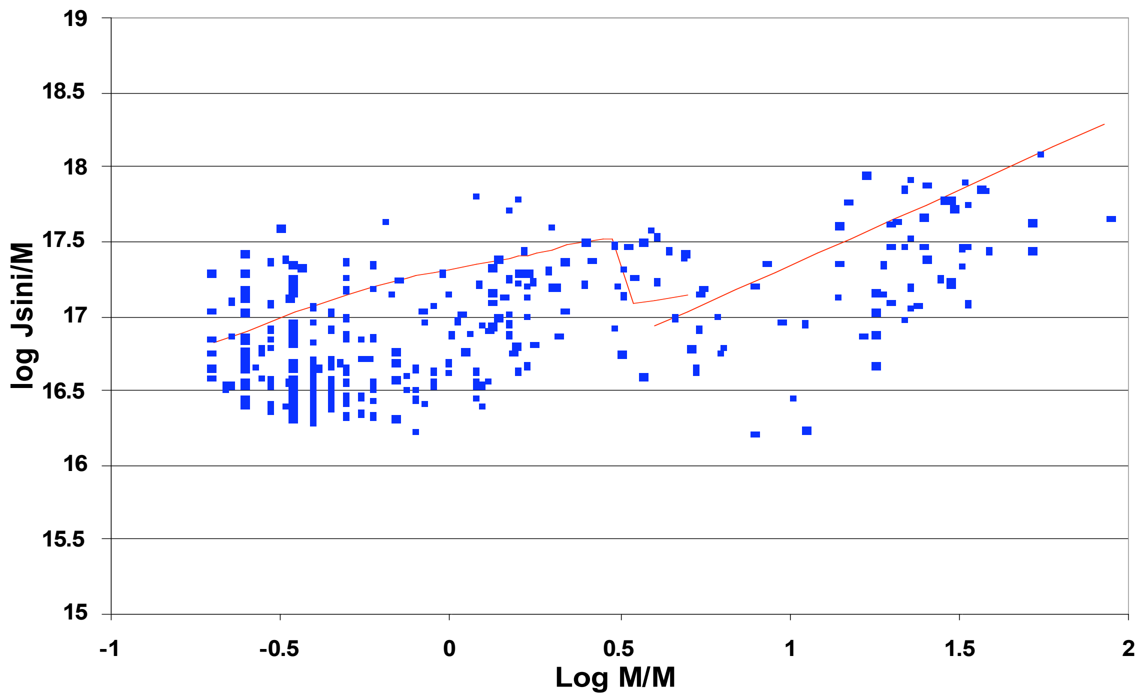
Critical Observations

- While the differences in GLOBAL initial conditions in cluster (high-density)- and association (low-density) - forming molecular clouds are well established, the conditions that obtain in individual star-forming cores are not
- Direct measurements of infall rates are needed
- Requirements:
  - A list of massive stars still embedded within their natal cores
  - Measurements of infall rates
    - Ultimately from ALMA
    - In the near-term, from high resolution mid-IR spectroscopy aimed at deducing the radial distribution of density, temperature and velocity along the line of site through the core to the star-disk system
    - The observations of BN by Kleinmann et al (1983) provide an example of the methodology
    - 8-10m telescopes can make a start on this problem

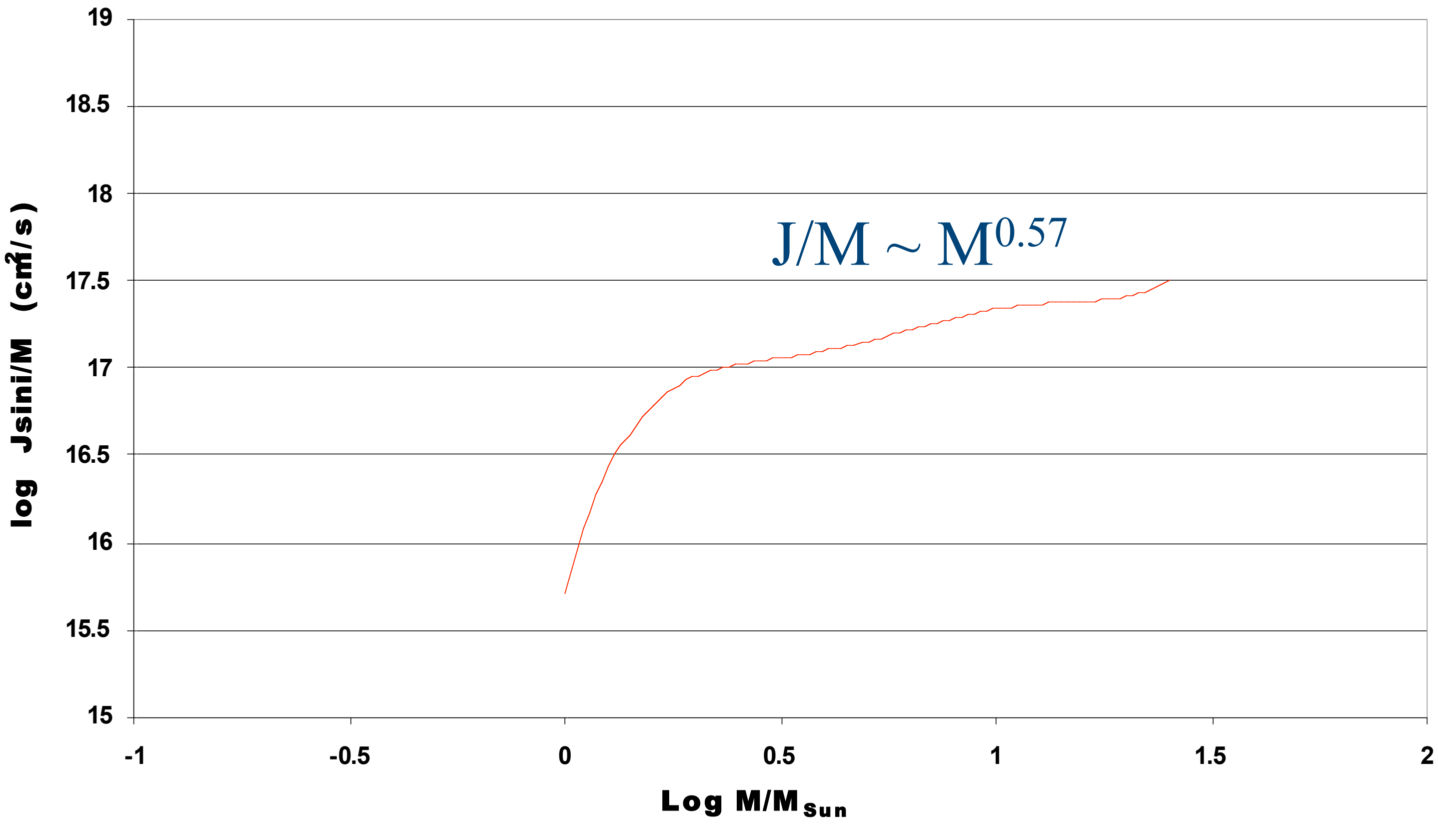
Summary

- Observations now provide robust evidence of a significant difference in rotation properties between cluster- and association- forming regions
  - Higher median rotation in cluster-forming regions
  - Near absence of slow rotators in cluster-forming regions
- R136 observations suggest that in clusters characterized by extremely high densities, mean rotation speeds may be even higher than ‘typical’ MWG clusters
- There are significant differences in initial cloud and stellar environmental conditions between cluster- and association-forming regions
- Initial conditions -- specifically higher turbulent speeds and resulting higher time-averaged accretion rates provide a more plausible explanation for the observed differences in rotation speeds
- Direct measurements of infall rates for individual cores in cluster- and association- forming regions will provide an important test of the ‘hints’ provided by the results of stellar rotation studies

V(Birthline) = 0.2 V(esc)

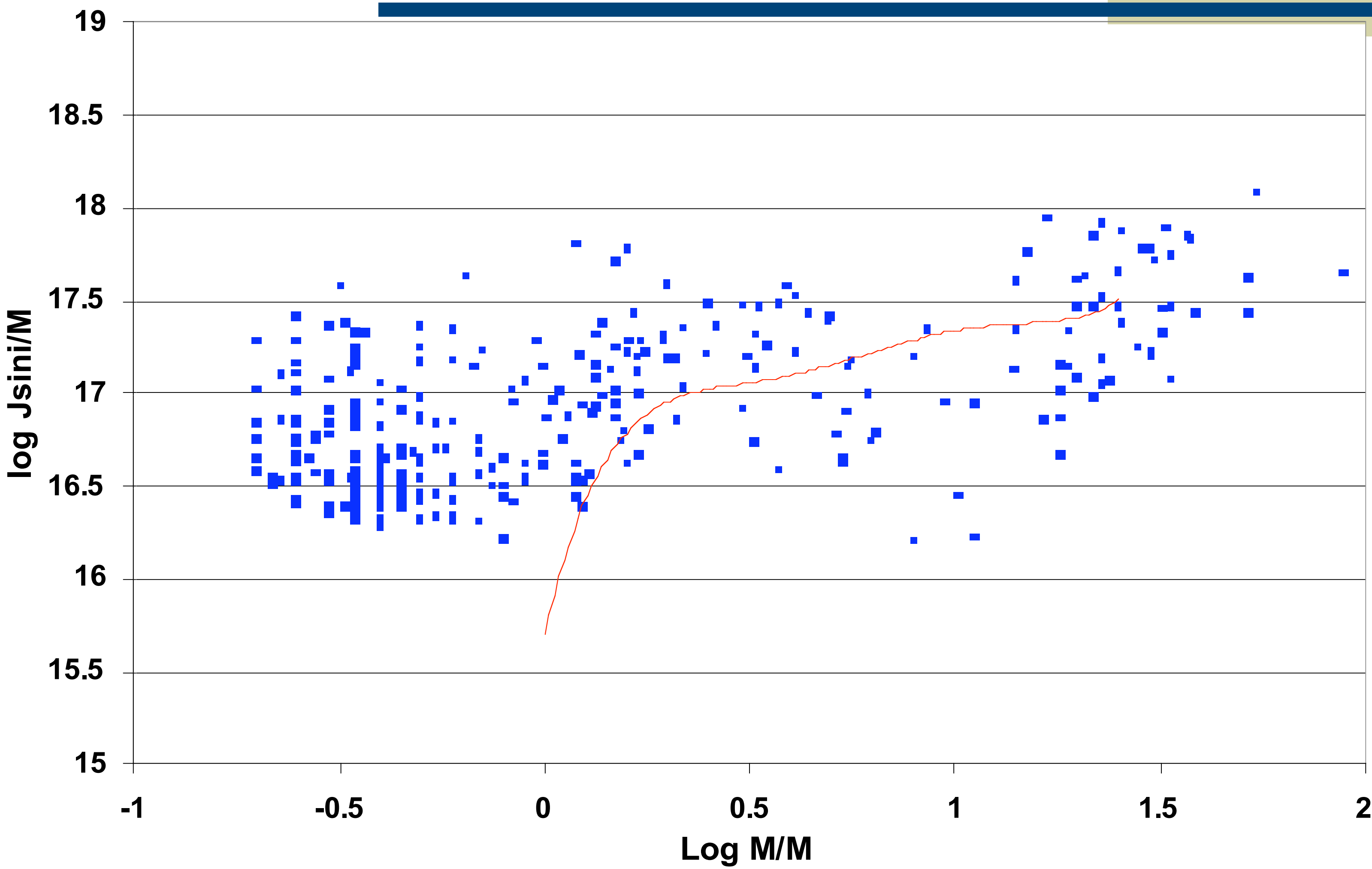


Kraft Curve 1970



Specific Angular Momentum (J/M) vs. Mass

Orion Stars on Convective Tracks + Young Massive Stars



Critical Observations

- 11 O stars in R136; 15-25 M_{Sun})
  - R 136 O stars show higher rotation speeds in comparison with Milky Way O stars and lower density LMC cluster controls
    - R136: <vsini> = 194 km/sec
    - MW : <vsini> = 126 km/sec (Penny 1996)
    - LMC clusters: <vsini> = 111 km/sec (Hunter et al. 2007)