Wait, So What Is the Low-Mass IMF Doing?:

The Presentation

Wyse et al. (2002) – 'Faint Stars in the Ursa Minor dSph Galaxy'

V.

Geha et al. (2013) – 'The Stellar Initial Mass Function of Ultra-Faint Dwarf Galaxies'

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The Question

- How does the low-mass IMF vary with metallicity, environment, formation time, etc. (if at all), and how can we measure these variations?

- Short answers:
  - Wyse – It doesn't vary at all

  - Geha – It varies with, like everything

- Both papers use sparse, faint objects as probes

Wyse – Argument

- Compare the IMF of the Ursa Minor dSph galaxy and two globular clusters (M15 and M92)
  - The two types could hardly be more different
    - Dense vs. sparse
    - Low M/L (No DM) vs. high M/L (DM-dominated)
    - Low vs. high velocity dispersion
  - But both contain simple stellar populations of old, metal poor stars ([Fe/H] ~ -1.5 – -2.2).
    - Low-mass IMF!

- If even these disparate systems have similar low-mass IMFs, then there might be a universal low-mass IMF.
  - Also implications for dark matter, galaxy formation, galaxy evolution

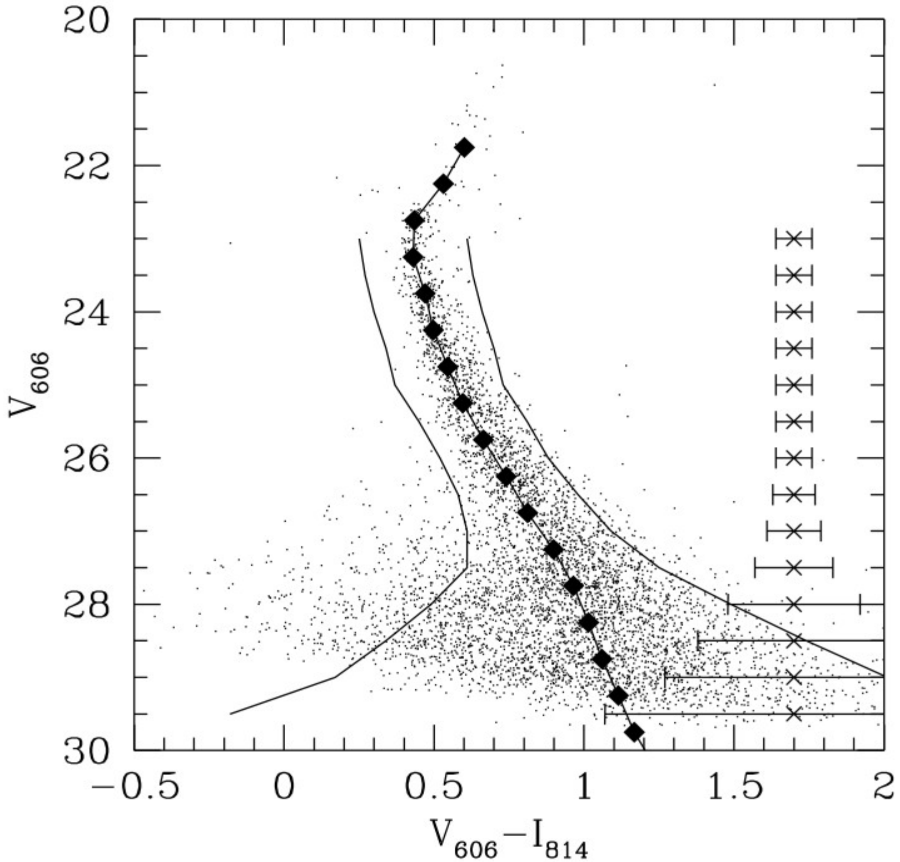
Wyse – The Ursa Minor Dwarf Spheroidal

- Stellar Population non-modal, seems to have occurred in one short era around 12 billion years ago, corresponding to z ~ 2.5
  - Could probe what the IMF looks like at high redshift
  - All one population
  - No apparent mass segregation or dense core

- Utilizes apparently novel HST methodology for the time.

Wyse – Imaging UMi dSph

- Stars of interest (~.4 - ~.7 solar masses) are contaminated by galactic halo stars
- Lots of Hubble images stacked to count stars in Umi dSph and identify interlopers
- Significant population of stars blueward of MS stars in CMD
  - Ignored via brightness cut
- Selections made for luminosity function, binned (with error bars)



Wyse – Luminosity Function Complications

- Paper says (but doesn't explain why) that unresolved binaries cause a red asymmetry of order 1/100 mag
  - Same effect also visible in M92
  - “It is not straightforward to characterize the binary population from the asymmetry in colour, but the similarity in the amplitudes that we find for the fields in the two globular clusters and in the Ursa Minor dSph does suggest that the binary populations are unlikely to be very disparate...”

Wyse – Luminosity Function Complications

- t_{relax}(dSph) >> t_{relax}(glob)
  - There will be mass segregation, evaporation in the globular clusters
  - How are the systems then comparable?
- Luminosity functions in M15 and M92 are remarkably consistent when measuring further from the core
  - Is this good to use?

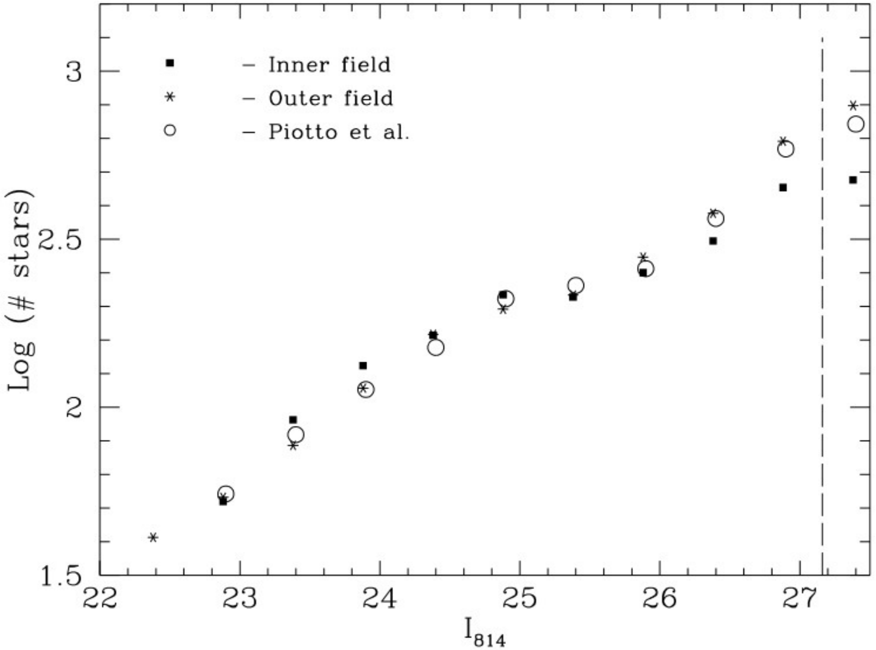


Fig. 31.— Comparison between the luminosity function measured at different projected radii in M92. The inner and outer fields from Andreuzzi et al. (2000) are situated at 13 and 21 core radii, respectively, while the Piotto et al. (1997) field is at 22 core radii. The data have been shifted to match the distance modulus of the Ursa Minor dSph and are normalized at $25 < I_{814} < 26$. The dashed vertical line denotes the equivalent 50% completeness of our Ursa Minor data.

Wyse – LF Comparisons

- “[the UMi dSph LF] is indistinguishable from that of two classical halo globular clusters”
  - Quantification?

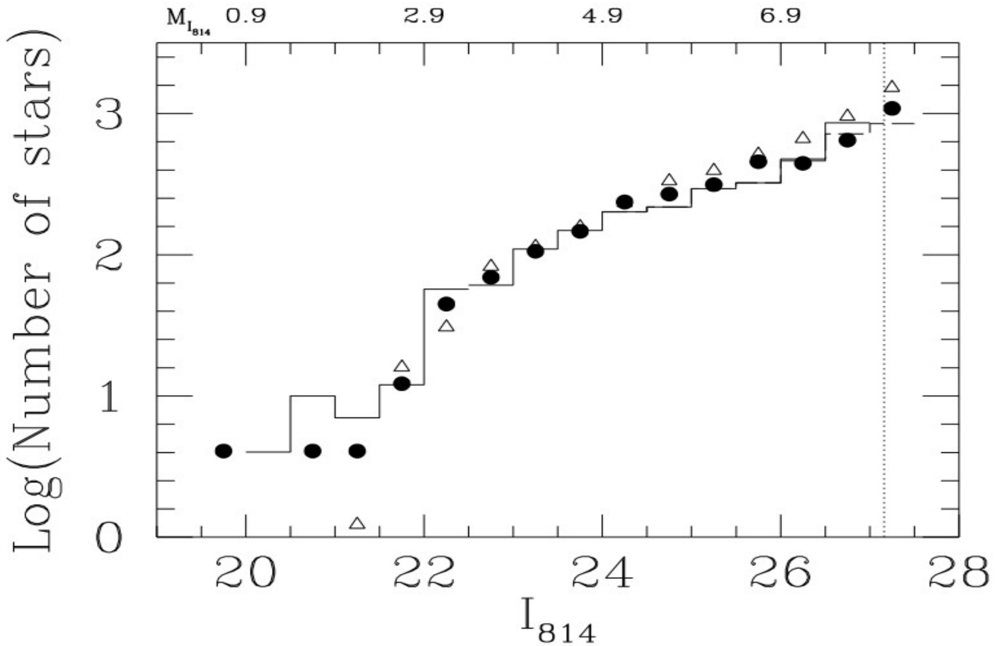


Fig. 24.— I_{814} luminosity function of the Ursa Minor dSph compared to those of M92 (filled circles) and of M15 (open triangles). The dashed line is the UMi luminosity function derived on the basis of the selection criteria of Fig. 23, prior to completeness corrections. The full line includes completeness corrections, with the vertical dotted line indicating the 50% completeness limit. The globular cluster data (Piotto et al. 1997) have been moved to the same distance modulus as the Ursa Minor dSph and normalized to the UMi counts as discussed in the text. The absolute magnitude is given along the upper x-axis.

Wyse – The IMFs

- Using Barrafe et al. (1997) methods to find mass function from UMi dSph data.
  - Spits out a power law slope (-1.8) *with no error bars *faints onto sofa**
  - “clearly an acceptable fit to the observed luminosity functions”

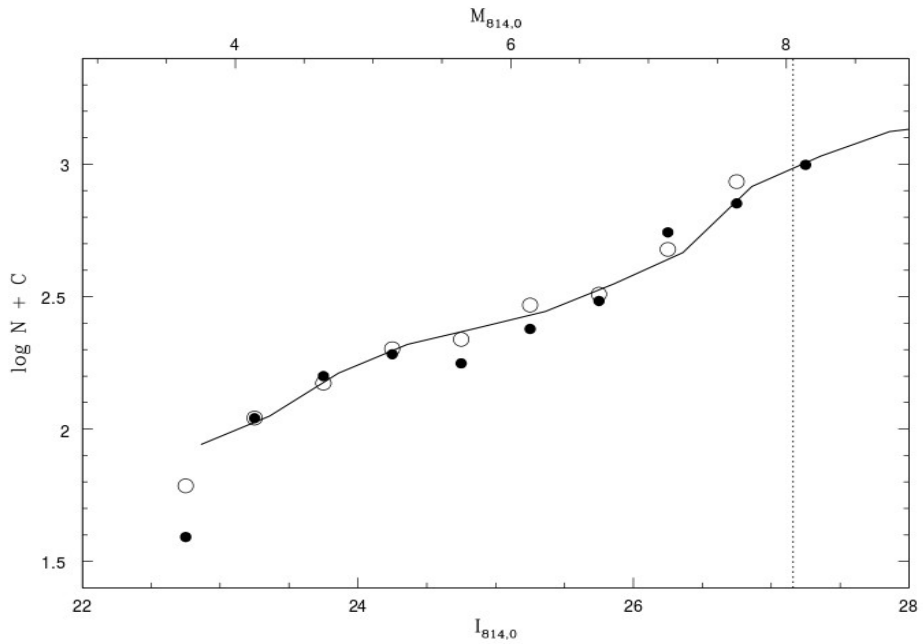


Fig. 33.— The I-band luminosity function for the UMi dSph (solid points, transformed from I_{LP}; open points WFPC2 data). Only bins greater than 50% complete are shown, and the dotted vertical line indicates the 50% completeness of the WFPC2 data. The solid line shows the predicted luminosity function for a low-mass mass function of slope −1.8, based on the Baraffe et al. (1997) models.

Wyse – Implications of Data (DM)

- Implied M/L in the UMi dSph low-mass stars with this IMF slope is only ~2, much lower than the velocity dispersion measurements of ~80.
  - Would require an IMF slope of -3.7 to track that, depending on your methods, and the data do not fit that at all.
  - It seems that baryonic dark matter doesn't track with low-mass stars

Wyse – The Universality of the IMF

- This is only the second luminosity function for dSph, and it is quite interesting that it fits so well with things so different from it as globular clusters
  - The other dSph is in Draco, and the authors say (though do not provide evidence) that those results ($2.1 < \alpha < 2.3$) are consistent with UMi dSph, even though it is brighter with a wider metallicity spread.
- Flattened mass function is also consistent with Galactic bulge observations.
  - These stars are perhaps as old as those in the systems in this paper, but are metal-rich ([Fe/H] ~ 0.0)
  - "Thus, the low-mass IMF of stars that formed at high redshift is apparently independent of metallicity"

Wyse – Further Universality

- UMi dSph star formation period seems to be less than a few Gyrs, but it is possible that the star formation period of globular clusters is ~ 10 Gyrs
  - Additionally, the star formation rate in UMi dSph is thousands of times less than that in the "typical" globular cluster (6e-4 vs. ~.1 M_{sun}/yr)
  - "Thus, the low-mass IMF of stars that formed at high redshift is apparently independent of star formation *rate* also."
- Assessment of the IMF of young field stars is difficult, but, looking at the literature, "the available data are consistent with a mass function again indistinguishable from that of the globular clusters"
  - "Thus, the low mass IMF is apparently invariant with time as well."

Wyse - Conclusions

- Because the low-mass IMF of the disparate high-redshift origin systems examined in this paper agree, the authors infer that the low-mass IMF is independent of basically every factor they could think of
  - Dark matter, environment, formation, and density in this paper's data; formation time, SFR, and metallicity in conjunction with others

- “This allows great simplification in models of galaxy formation and evolution, but begs the question, 'Why?'”

“Woooooah, slow down there”
- Geha et al., a decade later
(I assume)

Geha - Argument

- Examining two ultra-faint dwarf galaxies (Hercules and Leo IV) via direct counts, careful fitting of binary fractions, to find the IMF.
  - Very low luminosity and metal-poor, very long relaxation times
- Ending up with very shallow IMFs.
- Extends into an examination of different Milky Way satellites, finding many variations with velocity dispersion, metallicity, environments, etc.

Geha – Beyond the Milky Way

- Paper assumes basic invariance of IMF within the Milky Way proper
- Uses UFD galaxies similarly to the dwarf spheroidal in Wyse 2002, but even more extreme in terms of metallicity and dimness and distance from the Milky Way.
  - Have the same advantages as the UMi dSph, such as a simple stellar population, sparse stars, very long relaxation time, little contamination, so that the luminosity functions, once found, can be transformed into PDMFs and then IMFs relatively easily.

Geha – Constructing the IMFs

- Fit straight power-law and Chabrier curve to data
  - IMF shape and binary fraction are the only free simultaneous parameters
  - Use metallicity distribution (~.6 dex in both UFDs) as error
- Results in narrow mass band (.52 - .77 solar masses) but is enough to constrain power-law slope and to compare to other objects

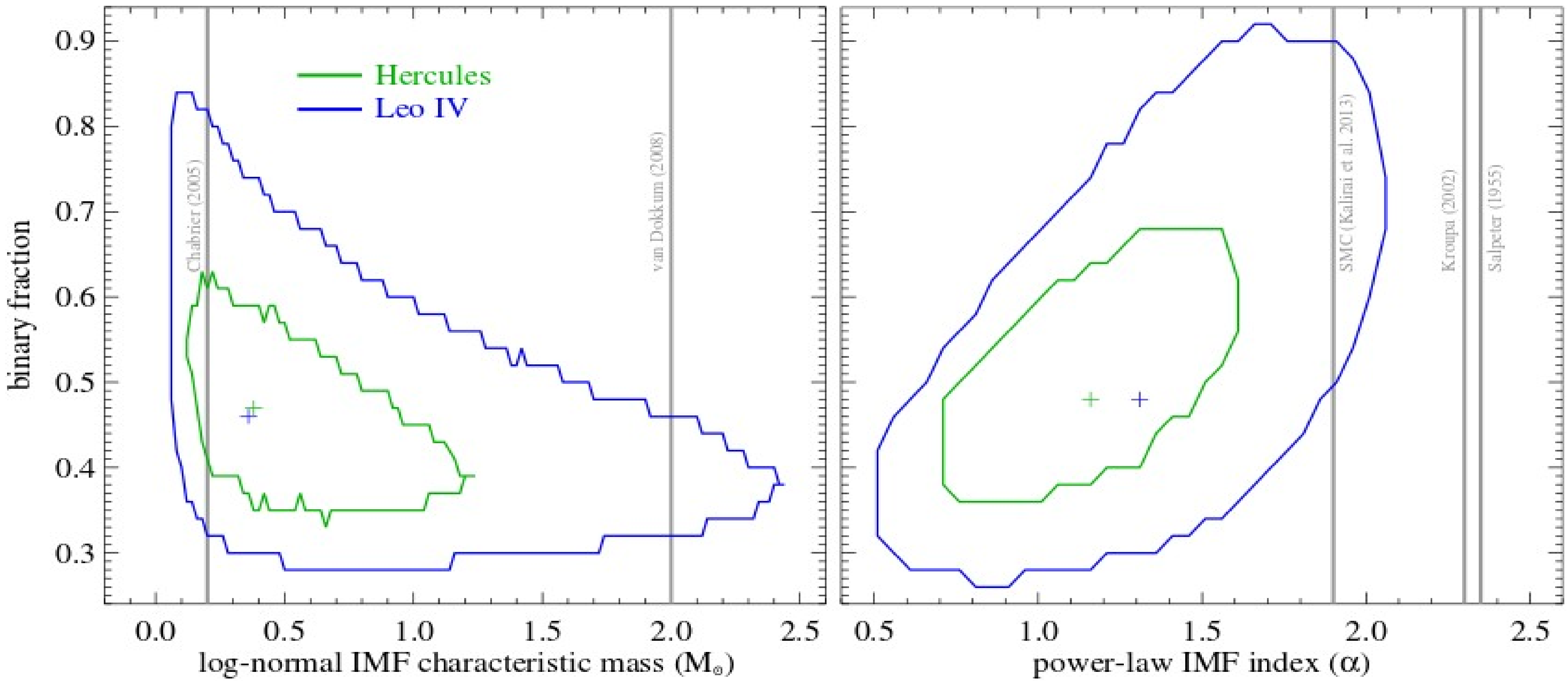


Figure 2. 1σ confidence contours for the Hercules (green) and Leo IV (blue) UFD galaxies. For the mass range probed by our data (0.52–0.77 $M_\odot$), we plot our results for a log-normal IMF (left) and power-law IMF (right). The best fitting combination of characteristic mass (m_c) or slope (α) and stellar binary fraction ($f_{\rm binary}$) are shown as plus symbols. For reference, we indicate values of m_c and α for IMFs in the literature.

(A color version of this figure is available in the online journal.)

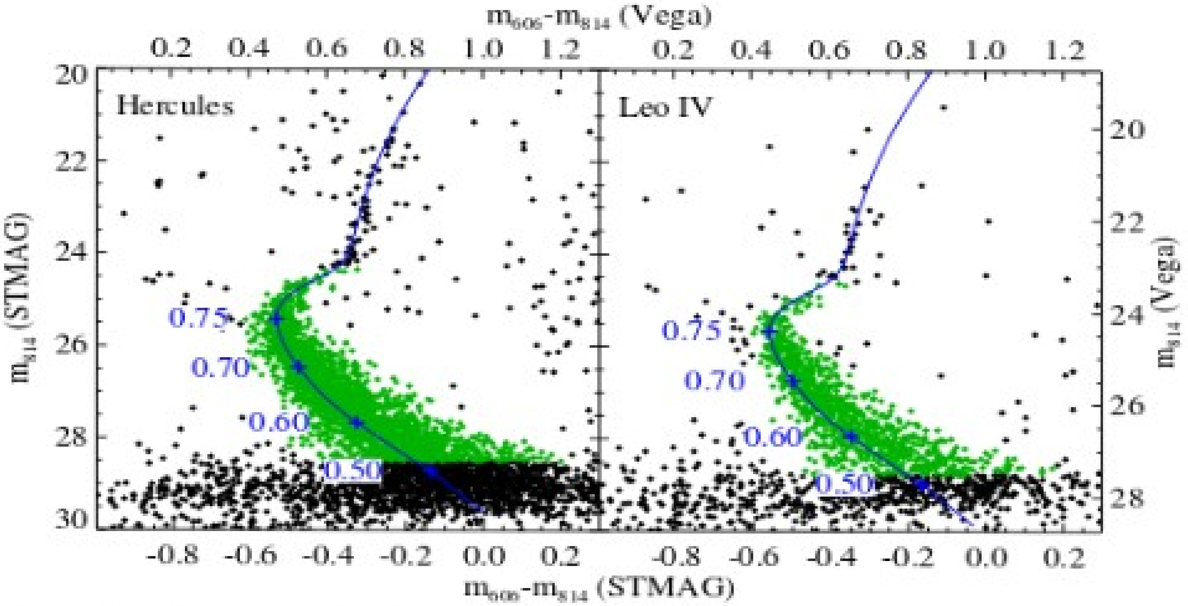


Figure 1. The *HST*/ACS CMDs of two UFD galaxies, Hercules (left) and Leo IV (right). For the IMF analysis, we include stars below the sub-giant branch and above the 66% and 75% completeness limits for Hercules and Leo IV, respectively (green points). The axes are labeled in both STMAG and Vega magnitudes. The blue line is a representative isochrone of 13.6 Gyr and the mean metallicity of each galaxy (Table 1). Blue crosses indicate stellar mass in units of $M_{\odot}$ on the main sequence.

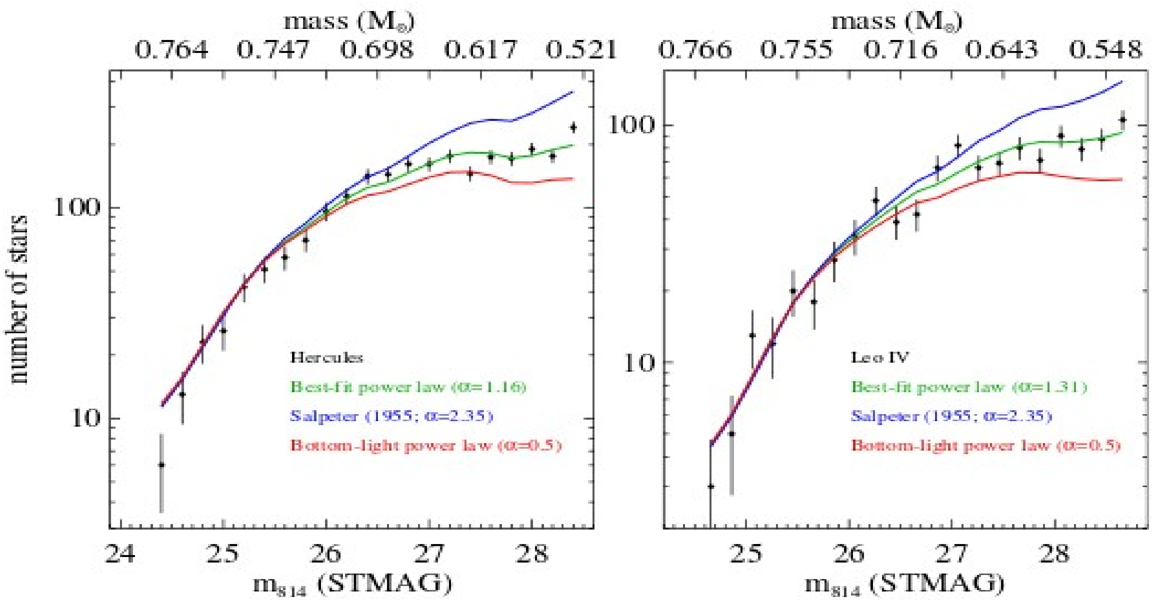


Figure 3. The observed luminosity function for Hercules (left) and Leo IV (right). Errors bars are computed from the observed number of stars in each luminosity bin. For comparison, we plot three theoretical power law IMFs, convolved with our observational errors and photometric completeness. The fits were normalized to reproduce the number of stars in the observed luminosity function, but here they have been normalized at the bright end for clarity. We compare our best-fitting model (green) to a Salpeter IMF ($\alpha = 2.35$, blue) and an extremely bottom-light IMF ($\alpha = 0.5$, red).

(A color version of this figure is available in the online journal.)

Geha – IMF Constraints

- Hercules, $\alpha = 1.2^{+0.4}_{-0.5}$ Leo, $\alpha = 1.3 +/- 0.8$ (.52 - .77 solar masses)
- $f_{binary} = .48^{+0.20}_{-0.12}$ $f_{binary} = .47^{+0.16}_{-0.14}$
  - Fit the Kroupa IMF shallow end (though at too high a mass)
  - What about other derived IMFs?

Geha – Comparing to Other IMFs

- The UFD power-law slopes do not agree with the MW slope or, really the SMC power-law.

- But, why?

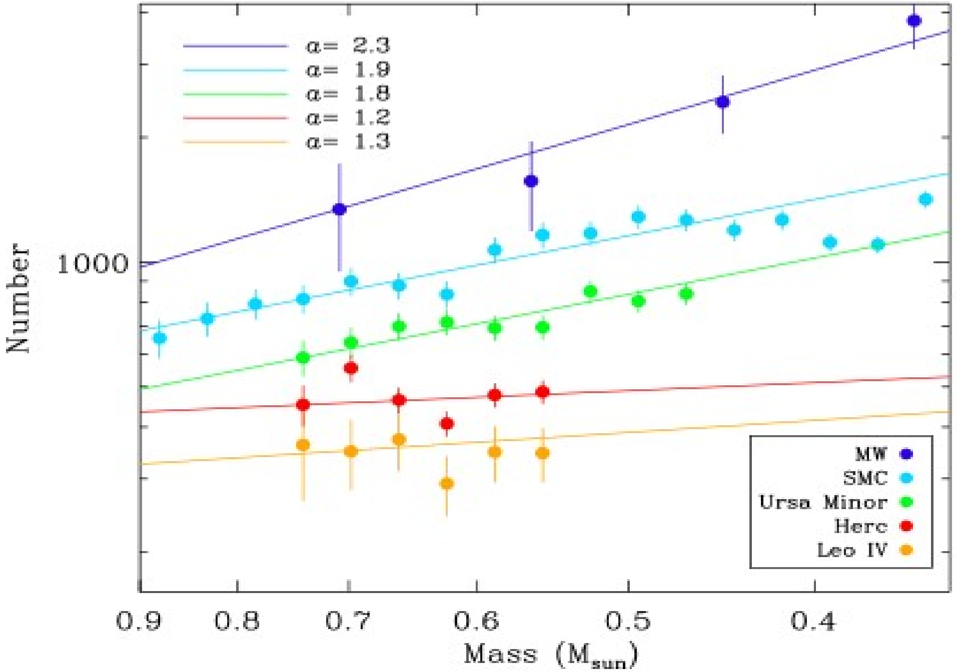


Figure 4. Stellar mass functions for the five galaxies in which the IMF has been measured via direct star counts: the Milky Way (blue; Bochanski et al. 2010), the SMC (light blue; Kalirai et al. 2013), Ursa Minor dSph (green; Wyse et al. 2002), Leo IV (yellow; this work) and Hercules (red; this work). Except for Hercules, the vertical normalization is arbitrary. For reference, the published power law slopes are shown for each dataset, normalized at 0.75 $M_{\odot}$. We note that a power law slope of $\alpha = 1$ is a flat line in this log–log plot. The UFD galaxies show noticeably flatter mass functions in this mass range.

(A color version of this figure is available in the online journal.)

Geha – So Many Relations!

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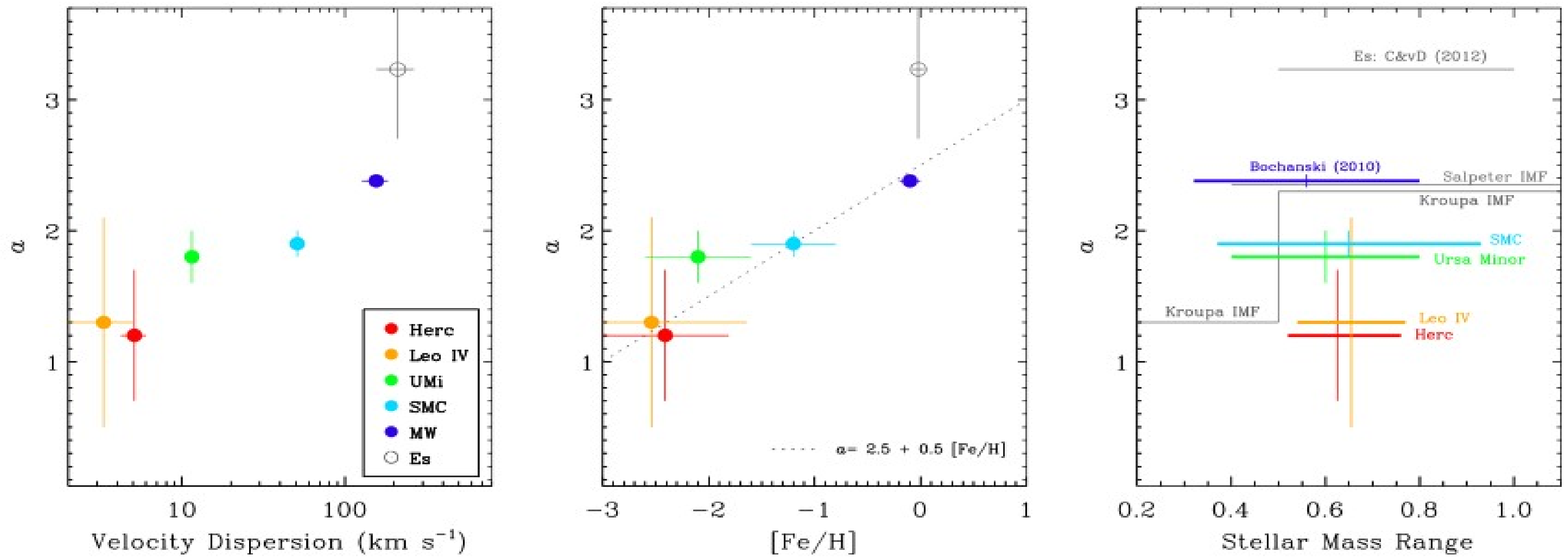

Figure 5. The power law slope, α, plotted against galaxy velocity dispersion (left), metallicity [Fe/H] (middle) and the observed stellar mass range (right). Data are taken from the same sources as Figure 4. The dotted line in the middle panel is an empirical relationship suggested by Kroupa (2001) with a zero-point adjustment to better these data. Indirect measurements are shown for elliptical galaxies from Conroy & van Dokkum (2012). A trend is seen in the sense of shallower, more bottom-light IMF slopes toward less massive and more metal-poor galaxies.

(A color version of this figure is available in the online journal.)