Observing dwarfs

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Questions

- How many dwarfs are there in the LG now?
- How many dwarfs were accreted and when?
- What are their masses? What were their masses?
- What are their mass profiles? Did they evolve?
- What are their star-formation histories?
- Spatial anisotropy? Group infall?
- What are/were their orbits?
- MW vs M31
- *Your urgent question here*

Contents of a dwarf

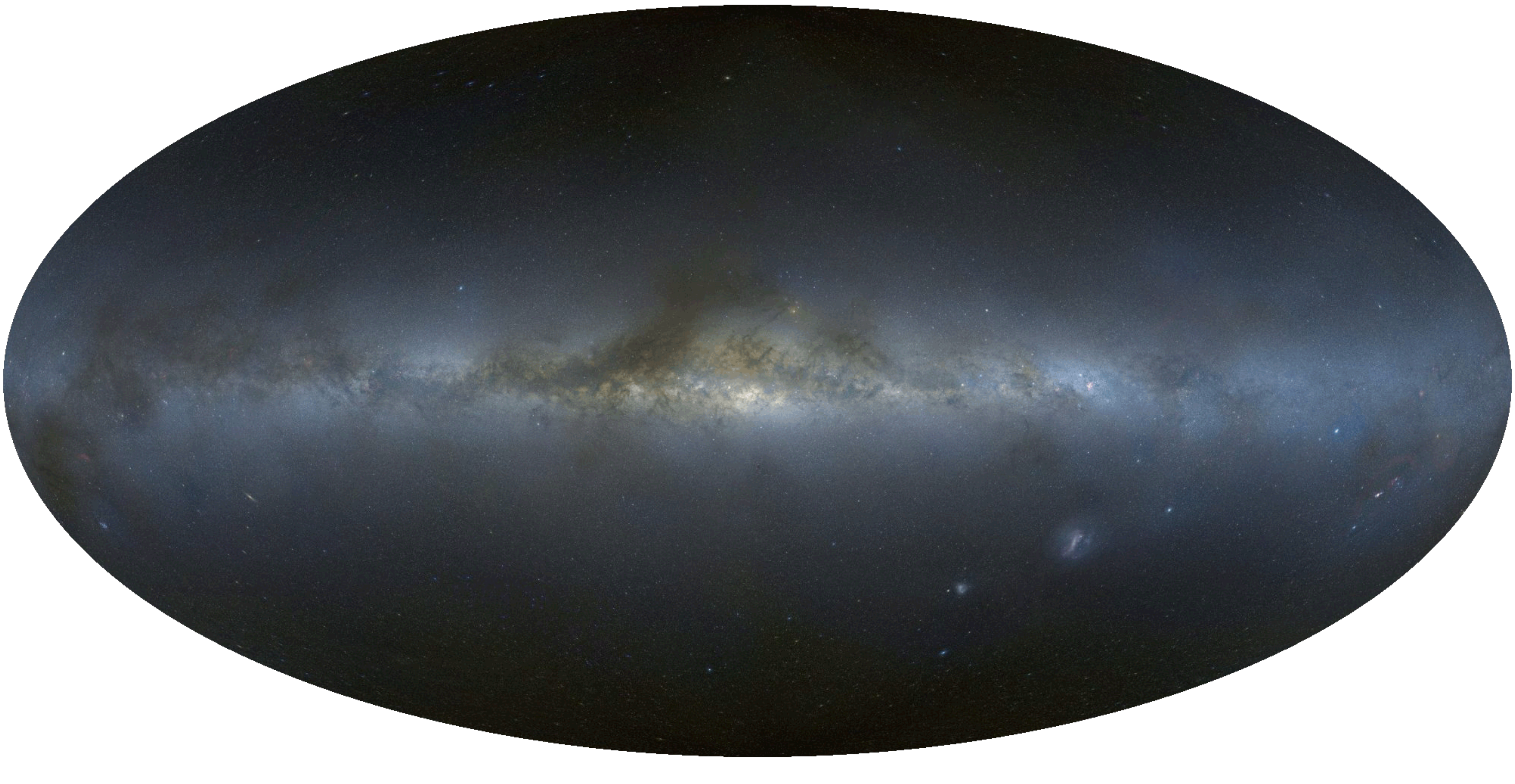
- Dark Matter
- Stars
- Gas
- Dust

3 dwarf types

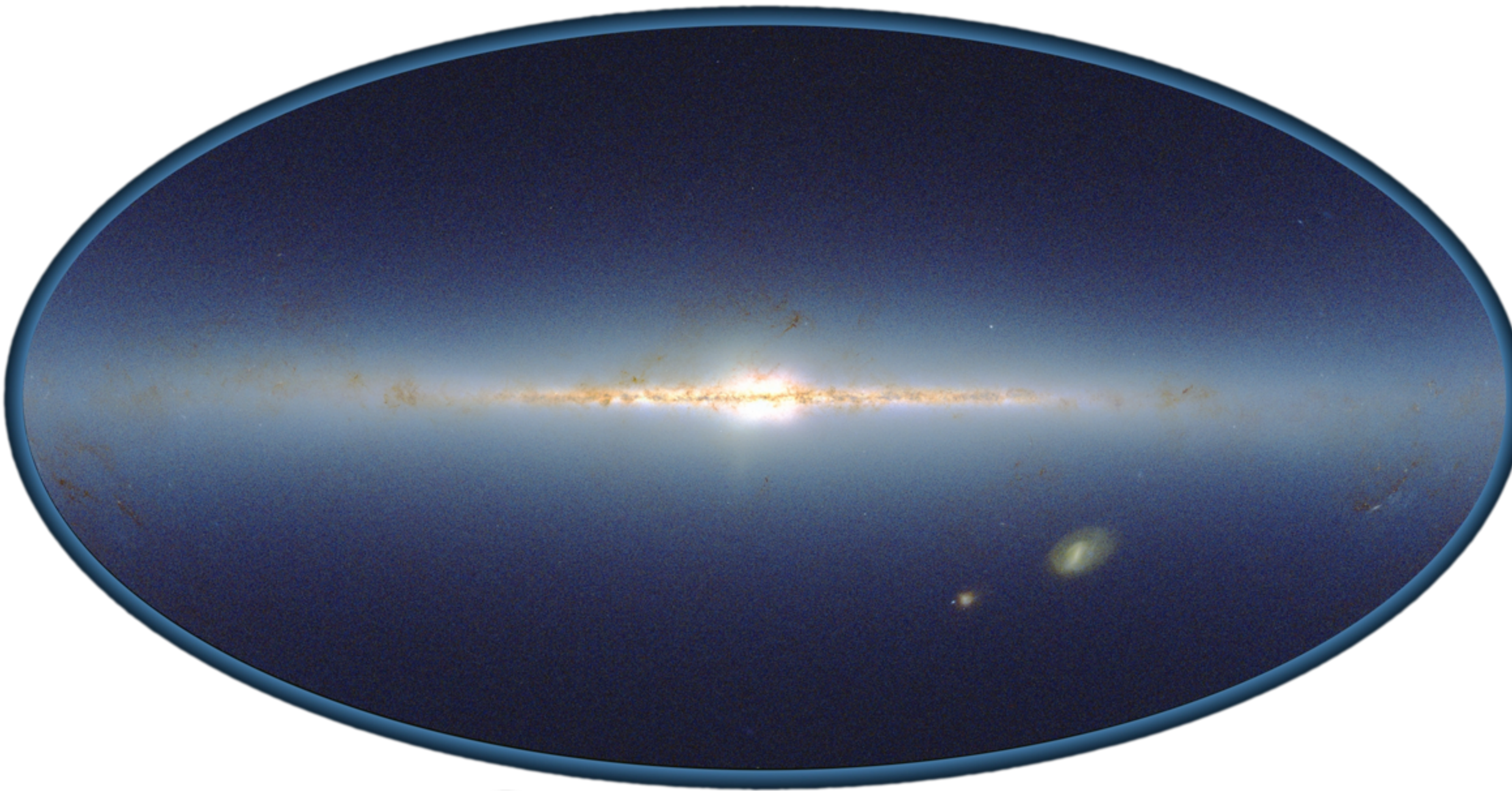
	dSph	dIrr	TDG
dark matter	up to 99%	up to 99%	0%
stars	~1%	~1%	up to 50%
gas/stars	~1/100	up to 10/1	up to to 20/1
rotation	No	Yes	Yes

tidal stirring
(see e.g. Mayer et al 2001)

The three largest dwarfs



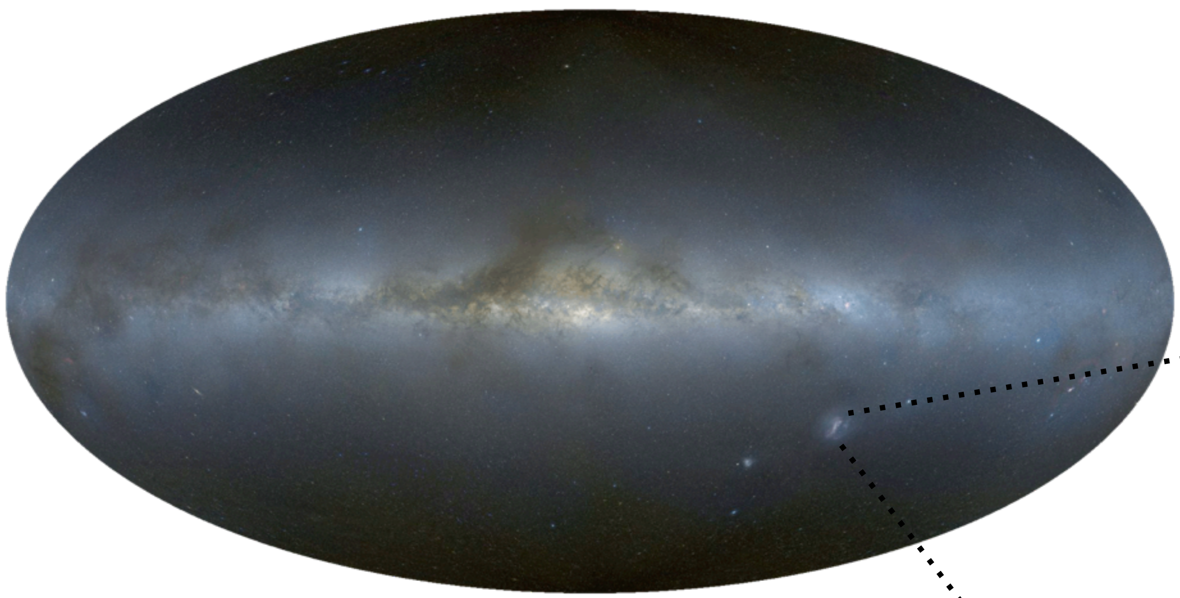
The three largest dwarfs



LMC

Moon

Classical dwarf galaxies



Milky Way

LMC

1/40 L_{MW}

Leo I

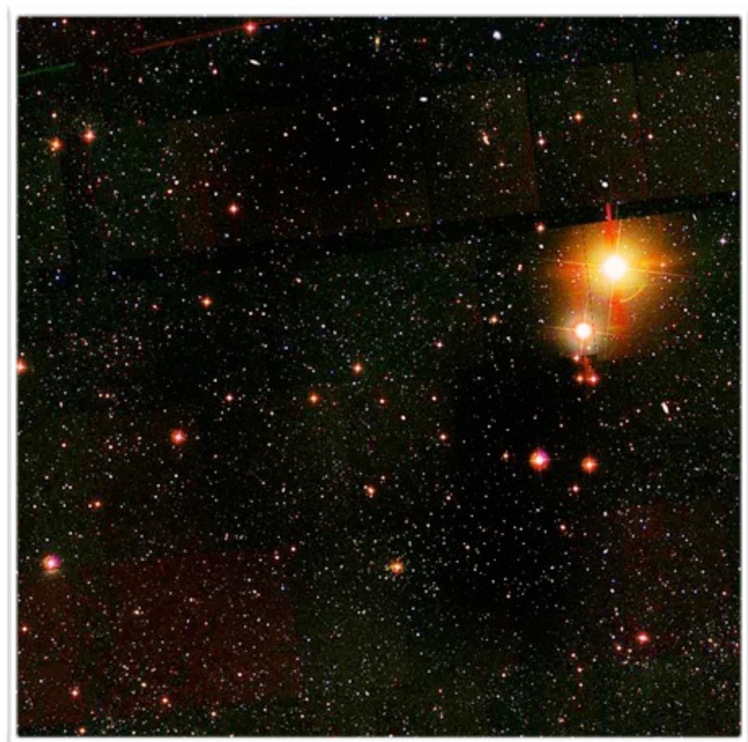
1/8000 L_{MW}

Invisible dwarf galaxies aka Ultra-Faint dwarfs

Leo I

8,000 times fainter then the Milky Way

Bootes I



2,000,000 times fainter then the Milky Way

Horologium I

100,000,000 times fainter then the Milky Way

Invisible dwarf galaxies aka Ultra-Faint dwarfs

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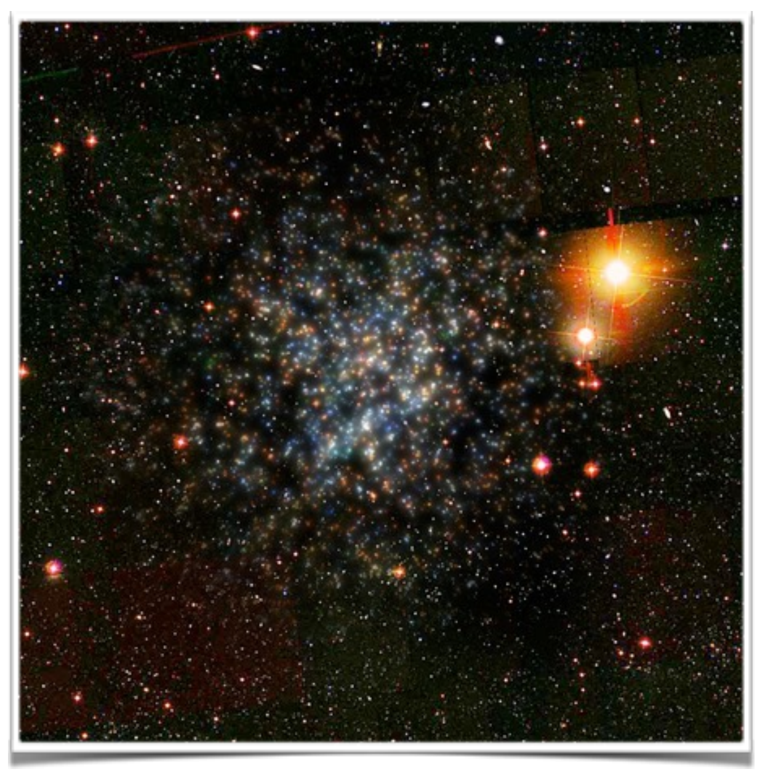
8,000 times fainter then the Milky Way

Bootes I



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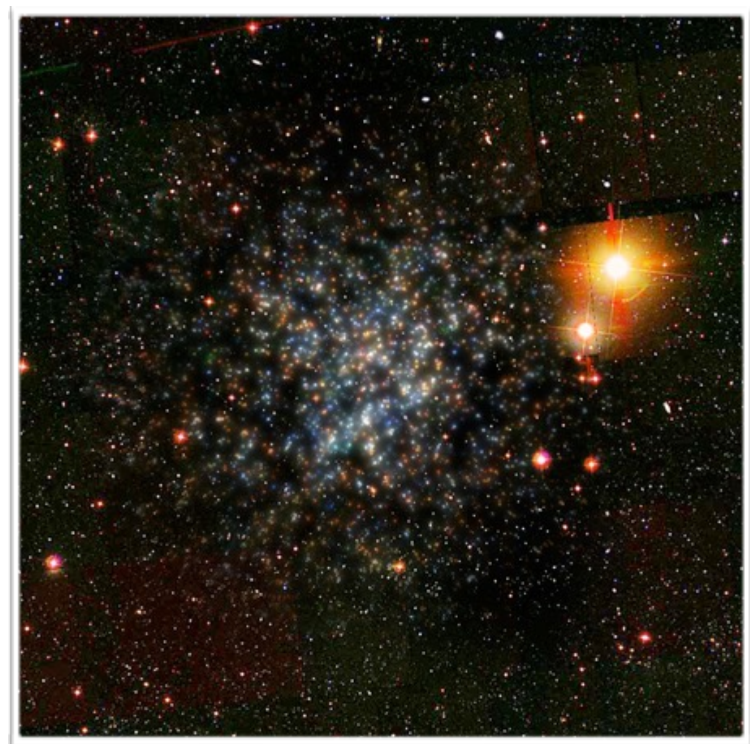

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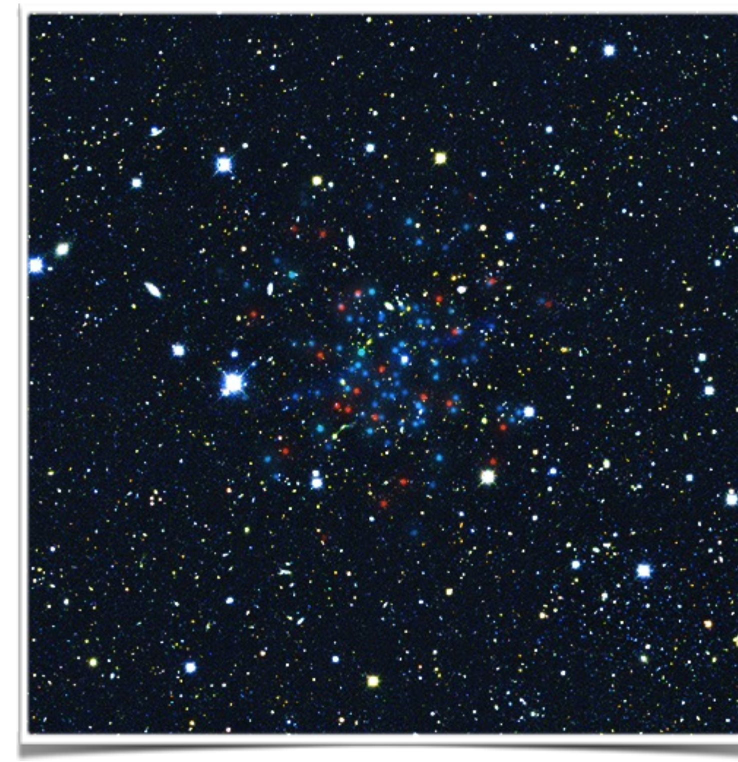
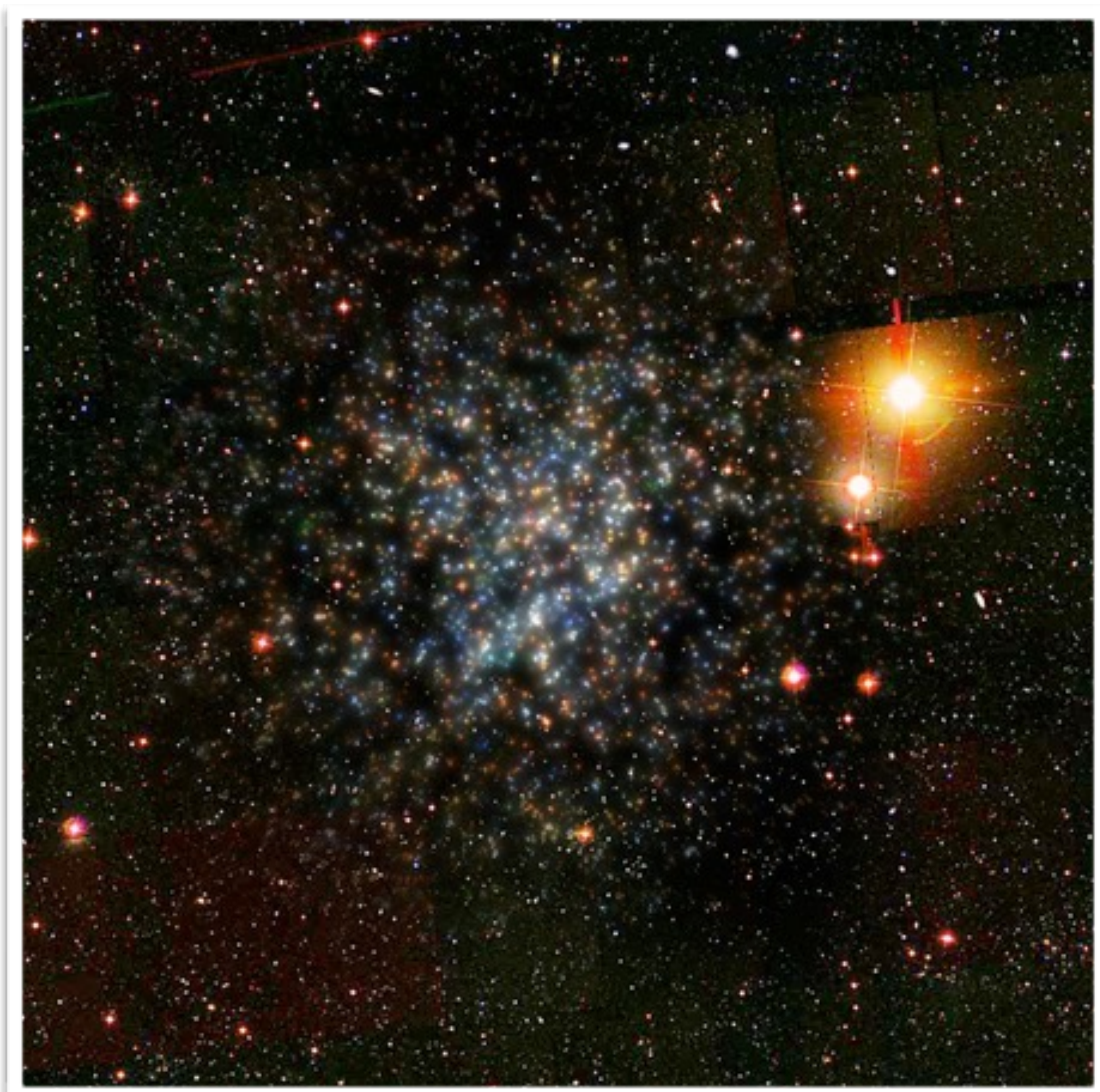
Horologium I



100,000,000 times fainter then the Milky Way

Ultra-faints. Sizes



Bootes I

How many dwarfs are there?

Theoretical predictions

- Current theory has a strong prediction as to the total number and the Mass Function of DM Sub-halos

- Current theory has no strong prediction as to the total number and the Mass Function of Dwarf Galaxies

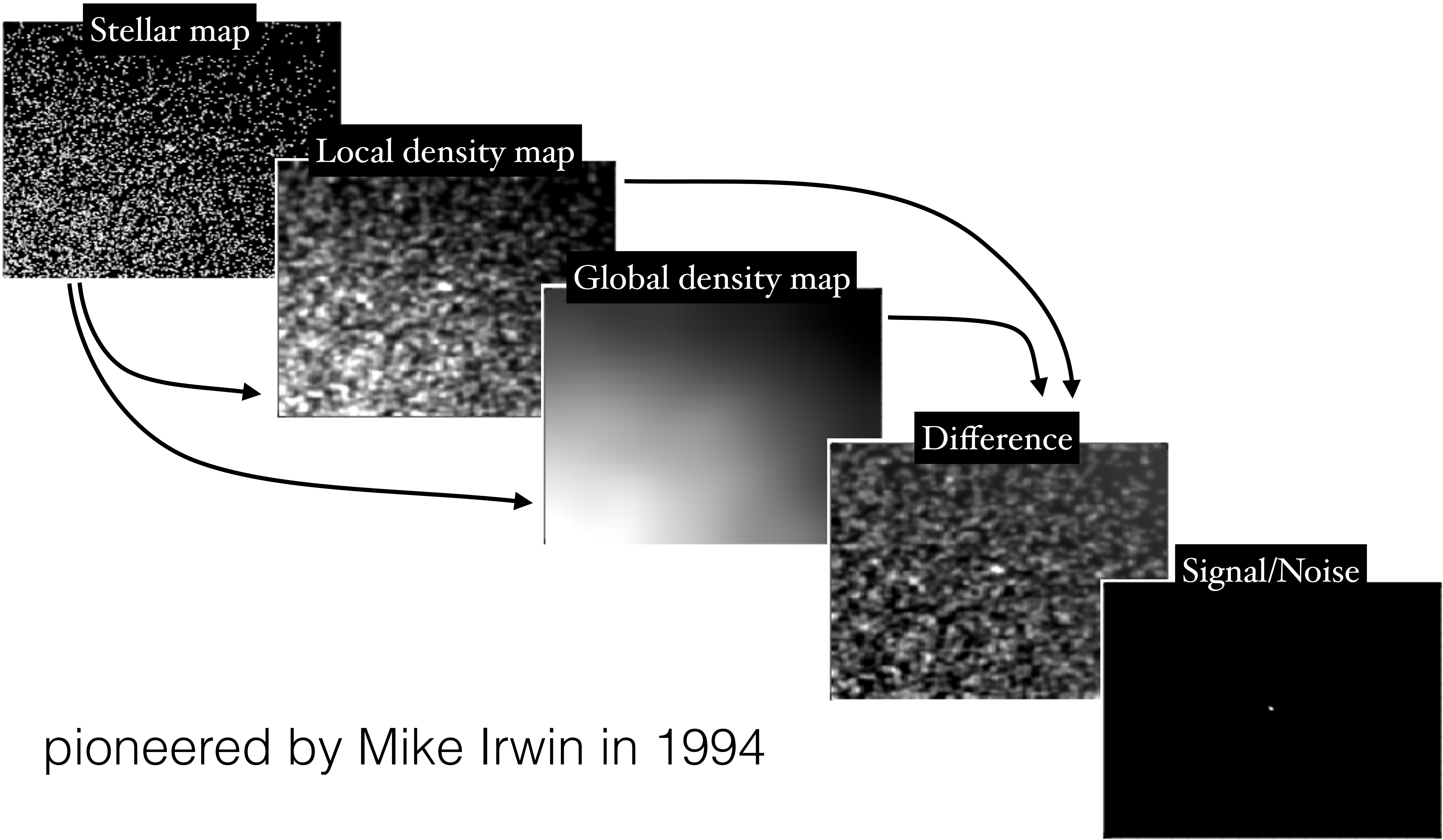
Detection Methods

Dwarf Detection Techniques

- As resolved stellar populations
- As smudges on the images
- As smudges at the locations of HVCs*

*HVC=High Velocity Cloud, a compact HI gas overdensity moving differently to the Galactic foreground

Stellar over-density search

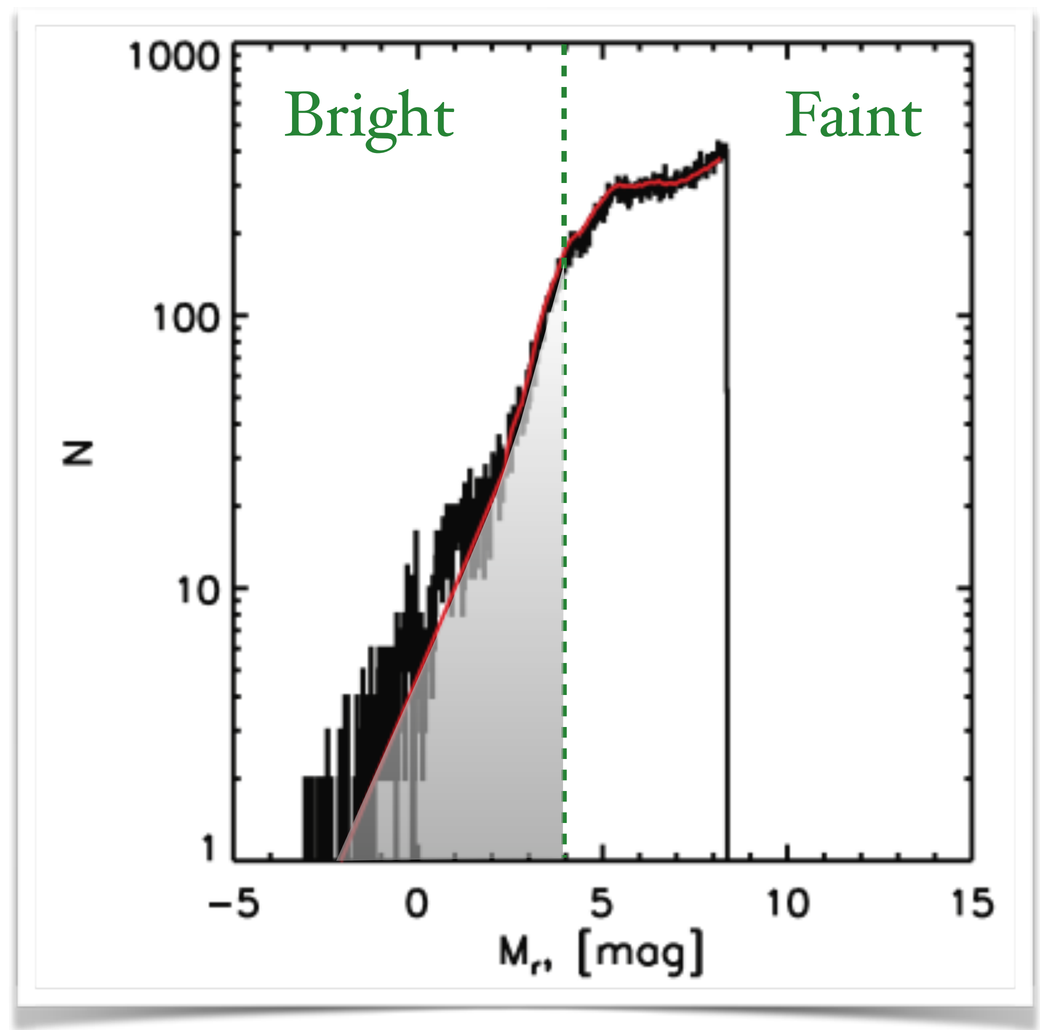


pioneered by Mike Irwin in 1994

Decision Making

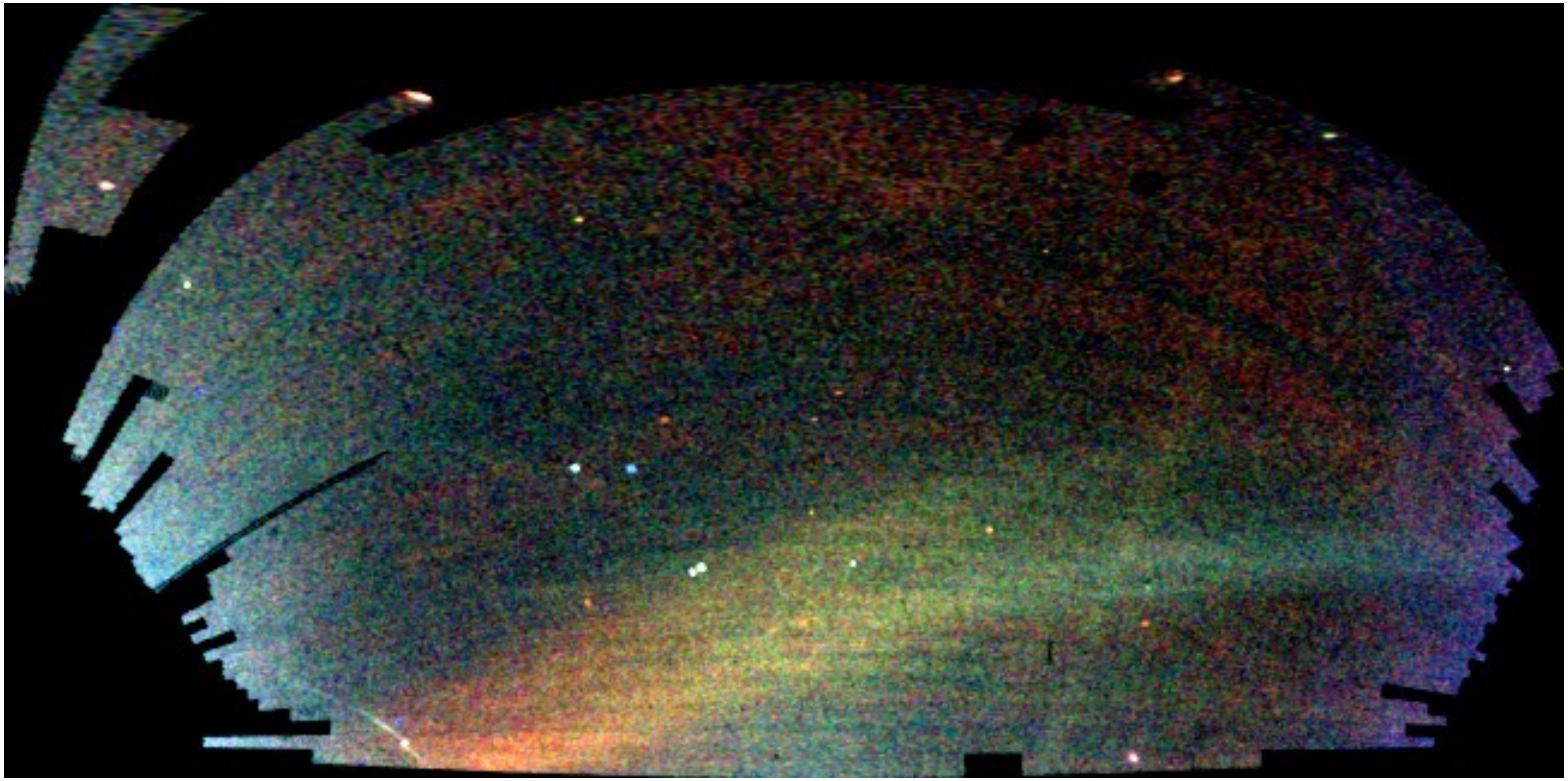
- Noise: smoothly varying background and Poisson statistics
- Signal: dwarf luminosity and distance + survey limiting magnitude

Stellar Luminosity Function



False Positives

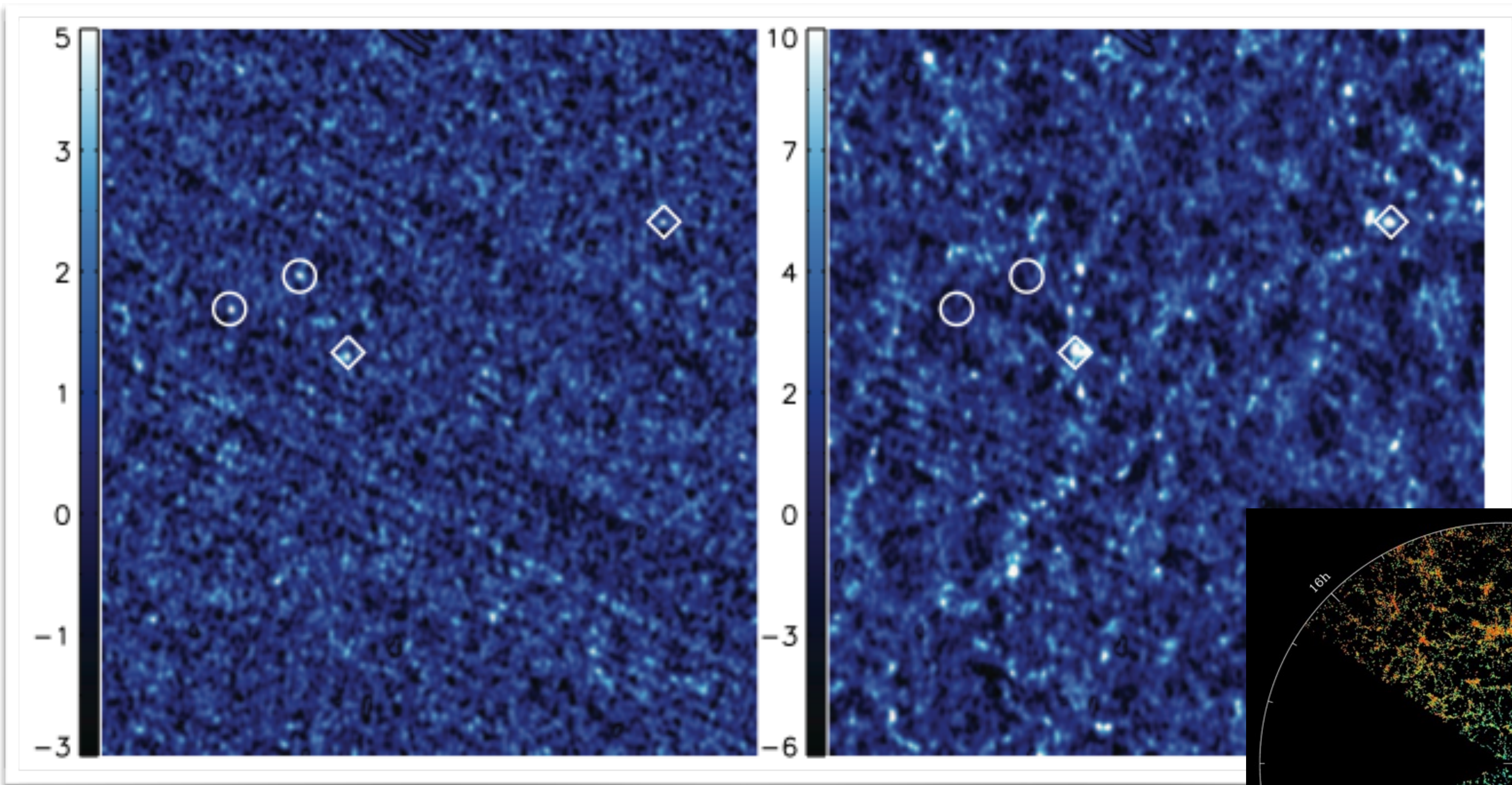
Background is not actually smooth!



Belokurov et al 2006

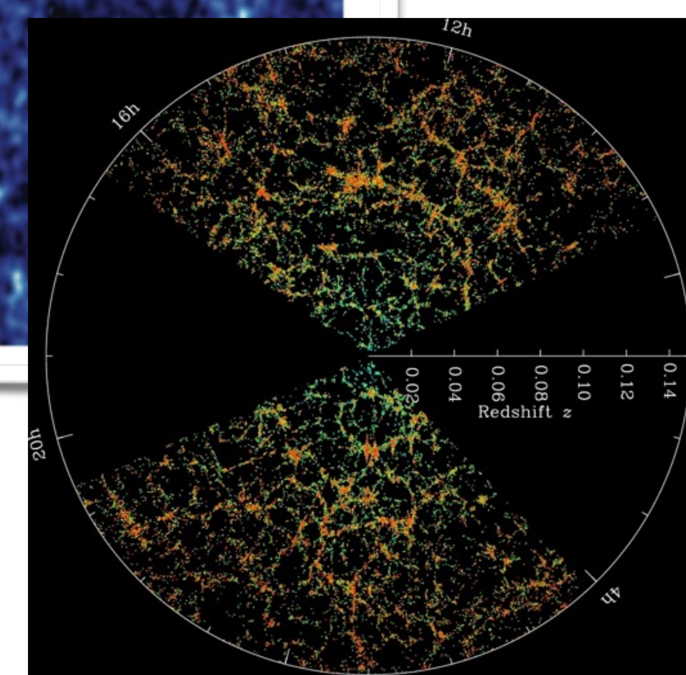
False Positives

Stars Galaxies



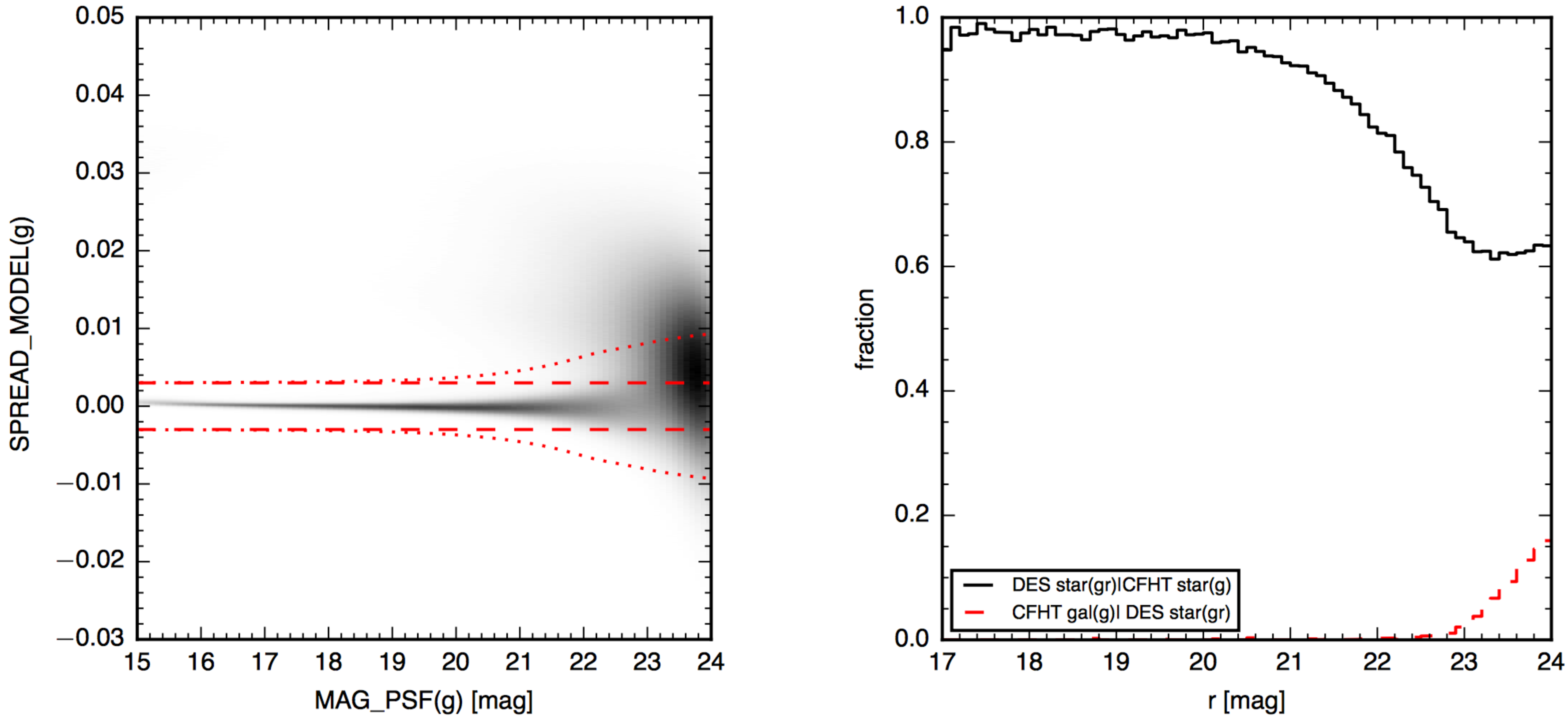
Koposov et al 2008

Large Scale Structure



Star/galaxy separation

comparison with CFHTLS Wide

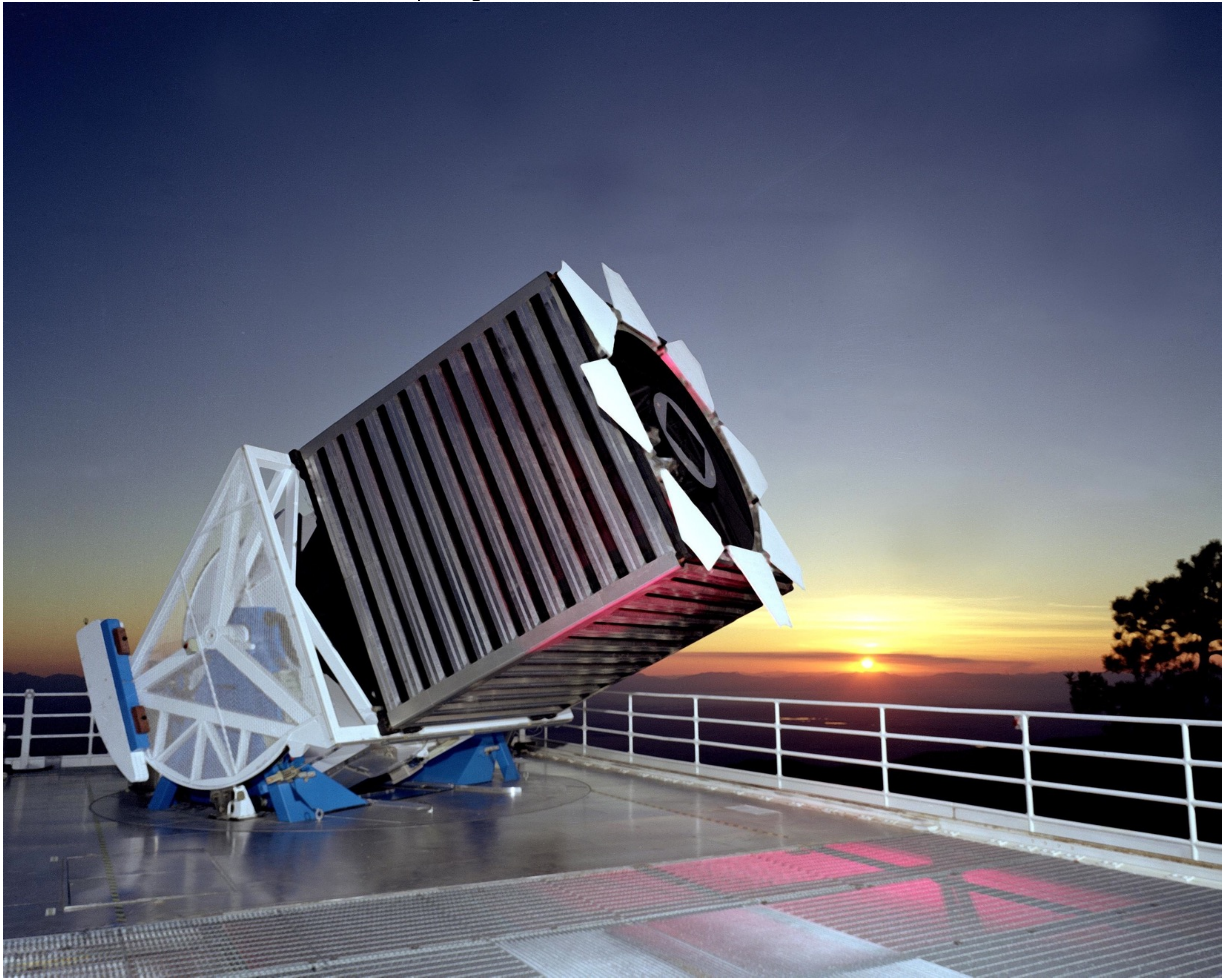


Koposov et al 2015

Detection. Major Players

All-sky imaging surveys

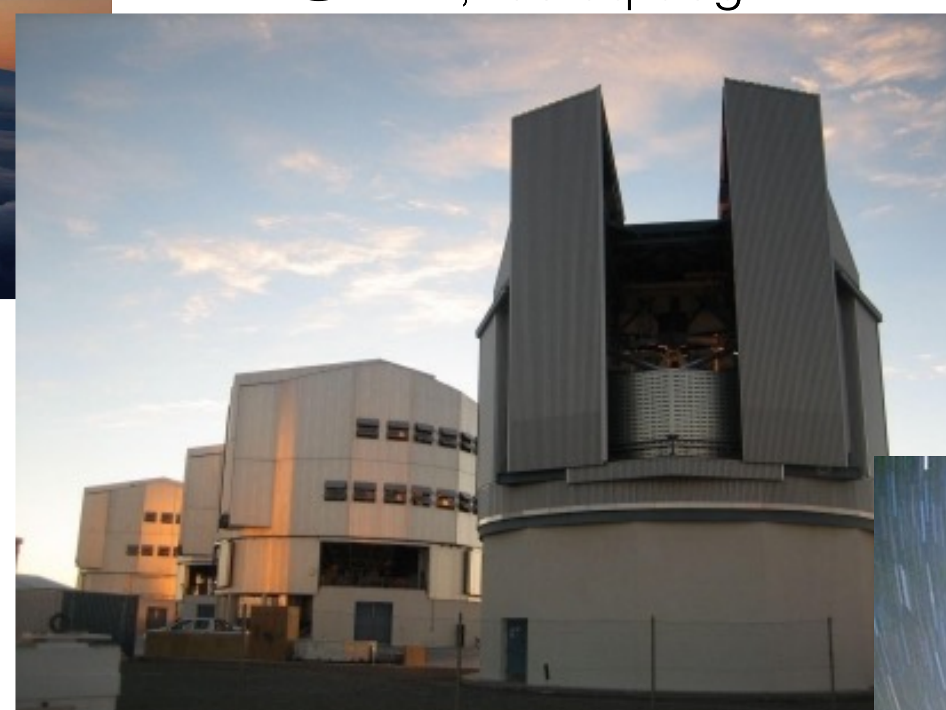
SDSS DR7 11,663 sq deg ~20 satellites discovered



après Sloan

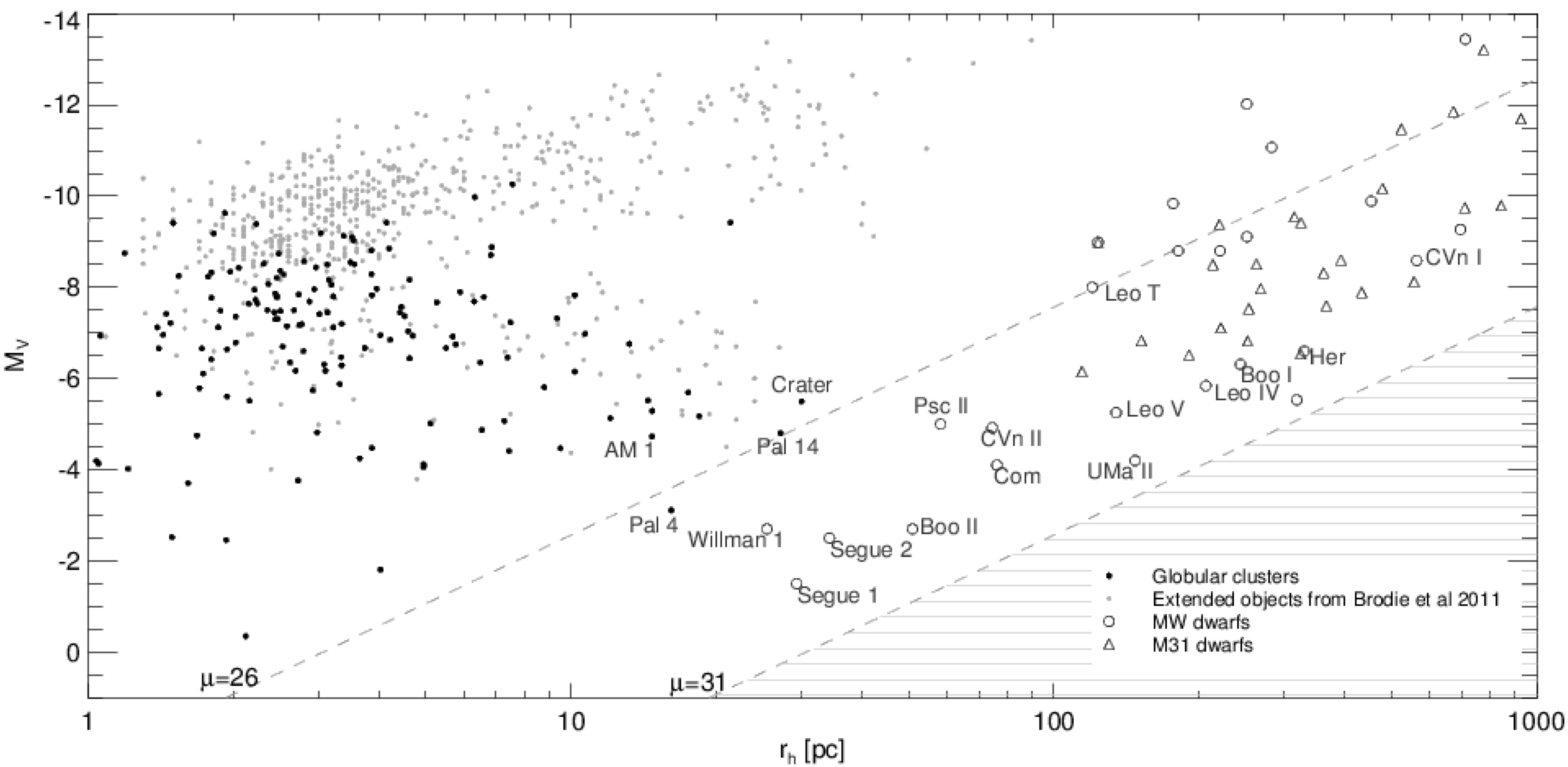
PanSTARRS 30,000 sq deg

VST 2,700 sq deg

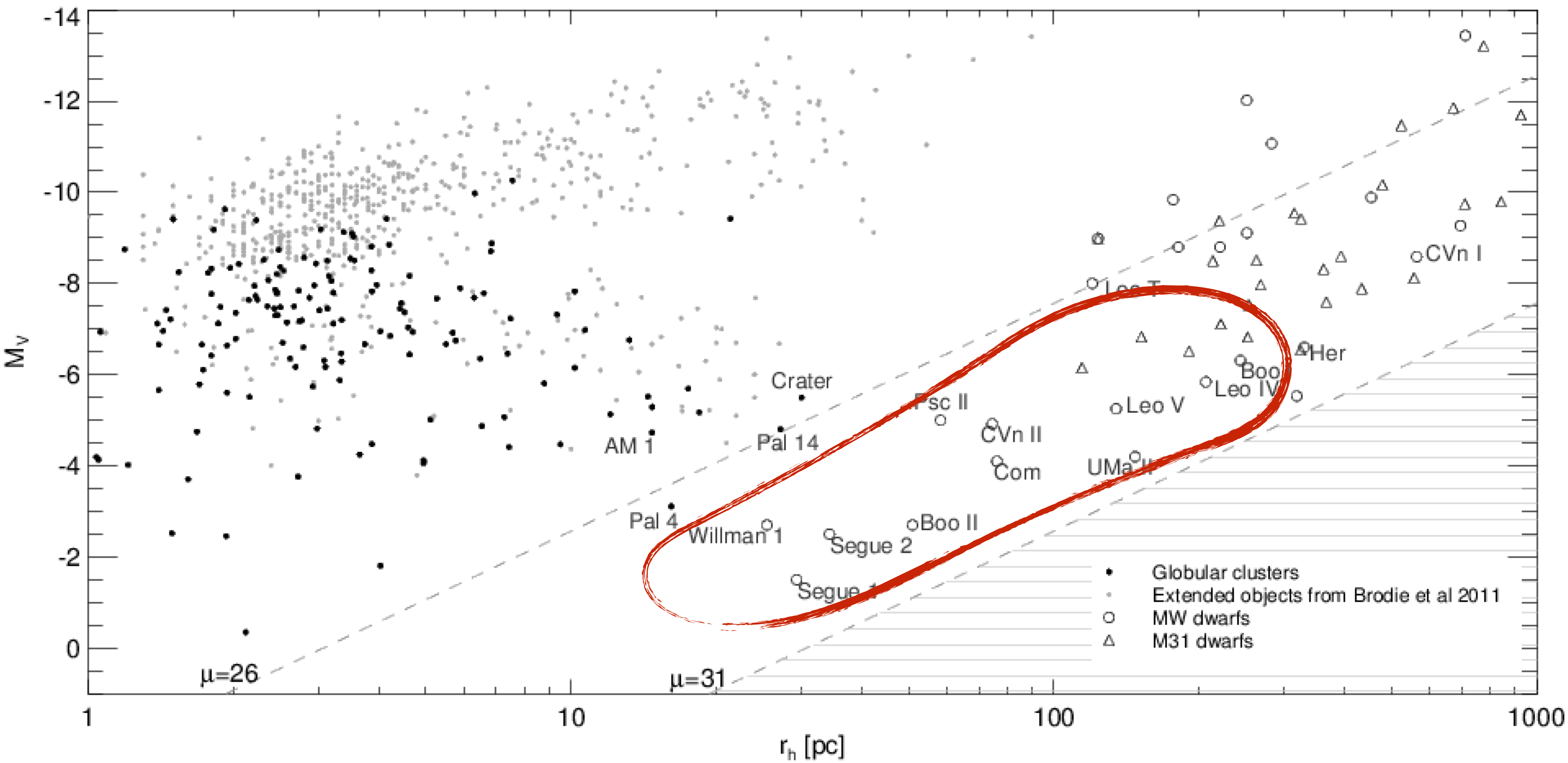


2,100 sq deg DES

Size vs Luminosity



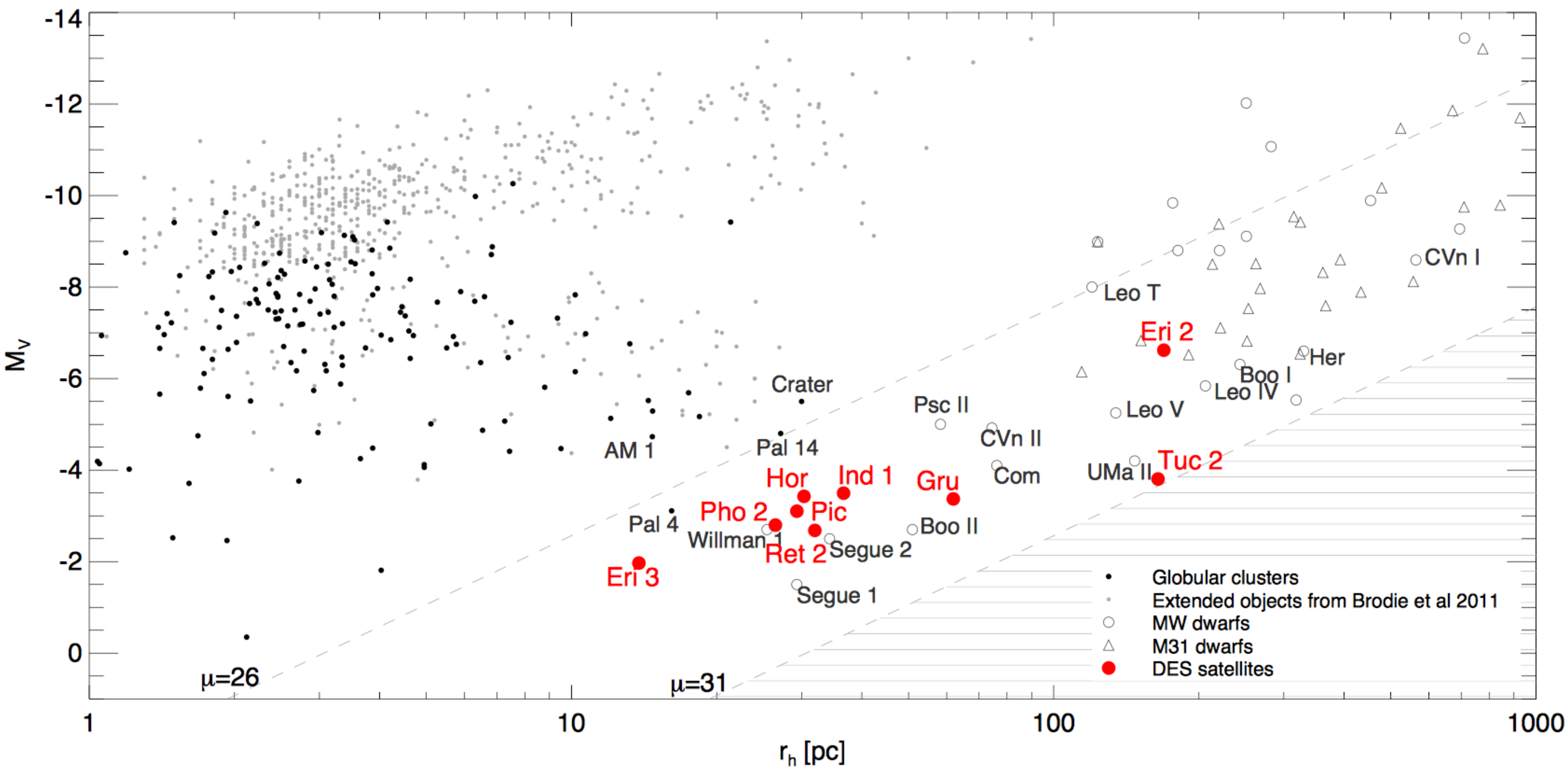
Size vs Luminosity



SDSS: Ultra-Faint Dwarfs

Low luminosities, Low Metallicities
High [Fe/H] spreads, High M/L

Size vs Luminosity



DES Year 1 satellites

What is a galaxy?

THE ASTRONOMICAL JOURNAL, 144:76 (12pp), 2012 September doi:10.1088/0004-6256/144/3/76

"GALAXY," DEFINED

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Received 2012 March 7; accepted 2012 June 28; published 2012 August 2

ABSTRACT

A growing number of low luminosity and low surface brightness astronomical objects challenge traditional notions of both galaxies and star clusters. To address this challenge, we propose a definition of galaxy that does not depend on a cold dark matter model of the universe: a galaxy is a gravitationally bound collection of stars whose properties cannot be explained by a combination of baryons and Newton's laws of gravity. After exploring several possible observational diagnostics of this definition, we critically examine the classification of ultra-faint dwarfs, globular clusters, ultra-compact dwarfs, and tidal dwarfs. While kinematic studies provide an effective diagnostic of the definition in many regimes, they can be less useful for compact or very faint systems. To explore the utility of using the [Fe/H] spread as a complementary diagnostic, we use published spectroscopic [Fe/H] measurements of 16 Milky Way dwarfs and 24 globular clusters to uniformly calculate their [Fe/H] spreads and associated uncertainties. Our principal results are (1) no known, old star cluster less luminous than $M_V = -10$ has a significant ($\gtrsim$0.1 dex) spread in its iron abundance; (2) known ultra-faint dwarf galaxies can be unambiguously classified with a combination of kinematic and [Fe/H] observations; (3) the observed [Fe/H] spreads in massive ($\gtrsim 10^6\ M_\odot$) globular clusters do not necessarily imply that they are the stripped nuclei of dwarfs, nor a need for dark matter; and (4) if ultra-compact dwarf galaxies reside in dark matter halos akin to those of ultra-faint dwarfs of the same half-light radii, then they will show no clear dynamical signature of dark matter. We suggest several measurements that may assist the future classification of massive globular clusters, ultra-compact dwarfs, and ultra-faint galaxies. Our galaxy definition is designed to be independent of the details of current observations and models, while our proposed diagnostics can be refined or replaced as our understanding of the universe evolves.

Key words: galaxies: dwarf – galaxies: kinematics and dynamics – galaxies: star clusters: general

Online-only material: color figure

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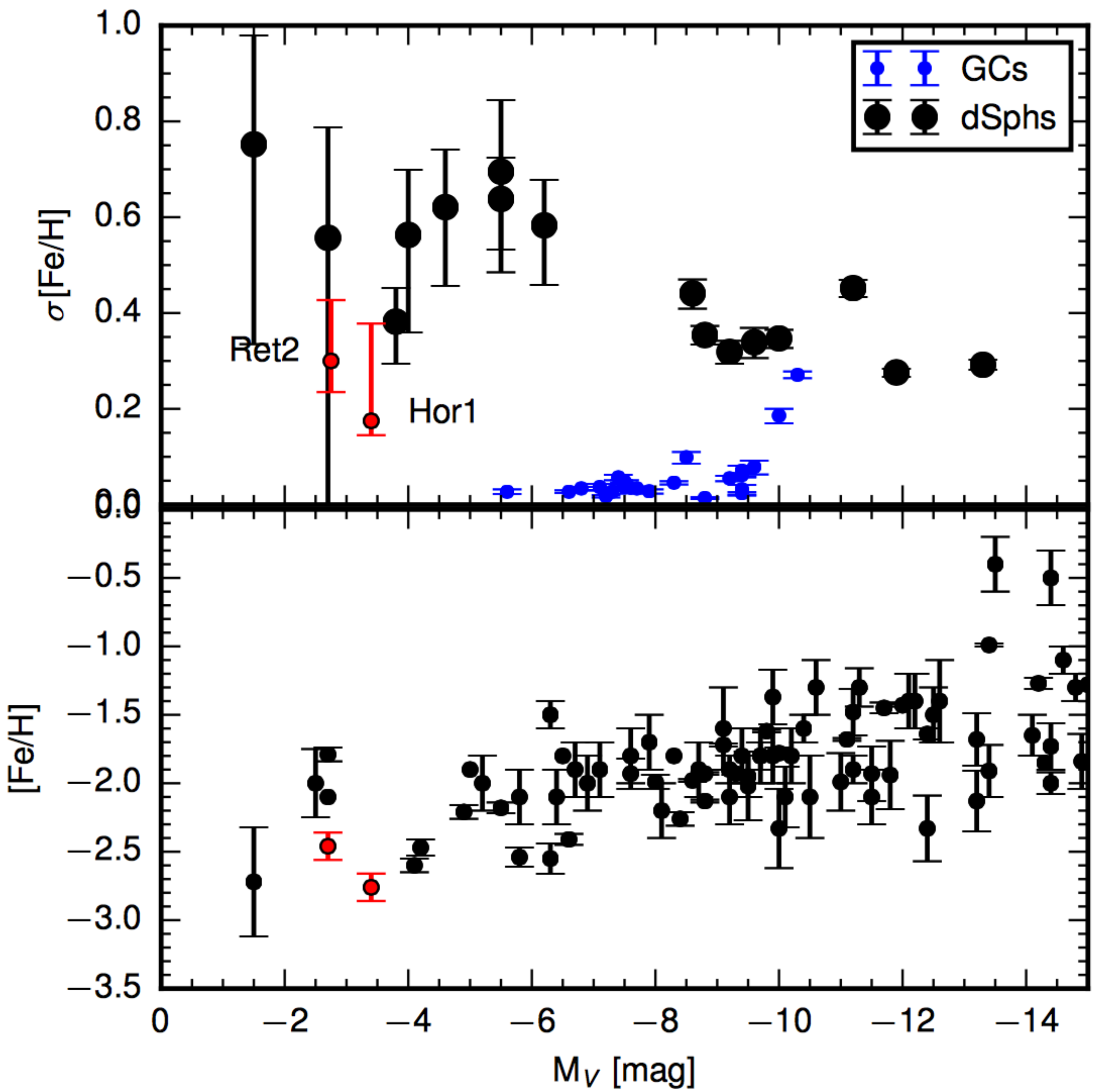
high M/L + metallicity spread

What is a galaxy?



Koposov et al 2015

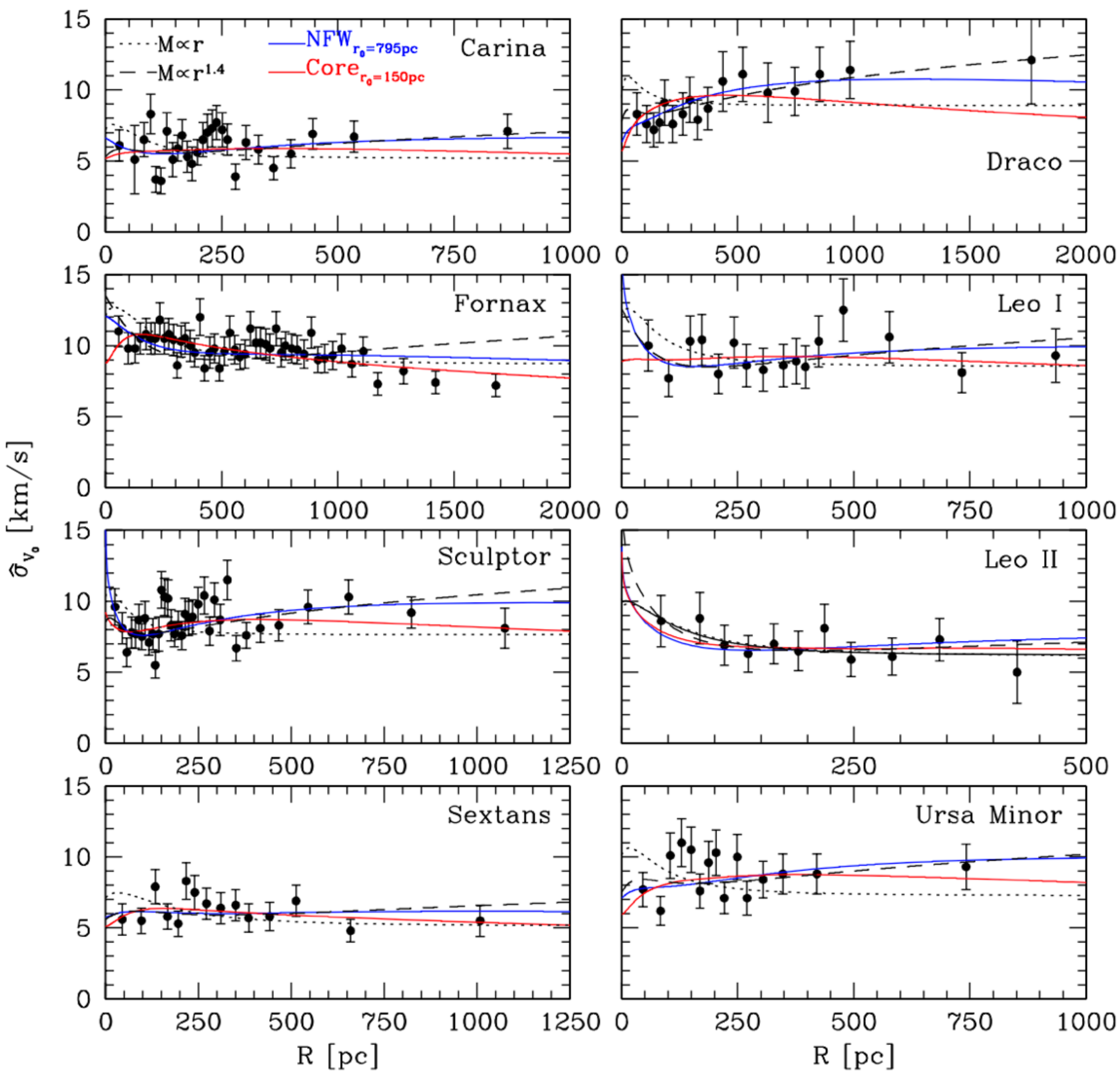
Dwarf Characterisation

Dwarf Follow-up

	structural	M/L	SFH	[Fe/H]	σ[Fe/H]
wide imaging	**required**	beneficial	**required**	-	-
deep hi-res imaging	beneficial	-	**required**	-	-
low-res spectra	-	**required**	beneficial	**required**	beneficial
hi-res spectra	-	-	beneficial	beneficial	**required**

Mass determination

Walker et al 2009



Spherical Jeans Equation

$$\frac{1}{\nu}\frac{\mathrm{d}}{\mathrm{d}r}(\nu \bar{v_r^2}) + 2\frac{\beta_{\mathrm{ani}}(r)\bar{v_r^2}}{r} = -\frac{GM(r)}{r^2},$$

where $\nu(r)$, $\bar{v_r^2}(r)$, and $\beta_{\mathrm{ani}}(r) \equiv 1 - \bar{v_\theta^2}/\bar{v_r^2}$ are the stellar number density, velocity dispersion, and velocity anisotropy, respectively.

$$M(r) = 4\pi \int_0^r \rho_{\mathrm{DM}}(s)s^2\mathrm{d}s$$

solution:

$$\nu \bar{v_r^2} = G r^{-2\beta} \int_r^\infty s^{2\beta-2}\nu(s)M(s)ds.$$

projected along the los:

$$\sigma_{\mathrm{p}}^2(R) = \frac{2}{\Sigma(R)}\int_R^\infty \left(1 - \beta_{\mathrm{ani}}(r)\frac{R^2}{r^2}\right)\frac{\nu(r)\,\bar{v_r^2}(r)\,r}{\sqrt{r^2 - R^2}}\mathrm{d}r$$

Mass modelling problems

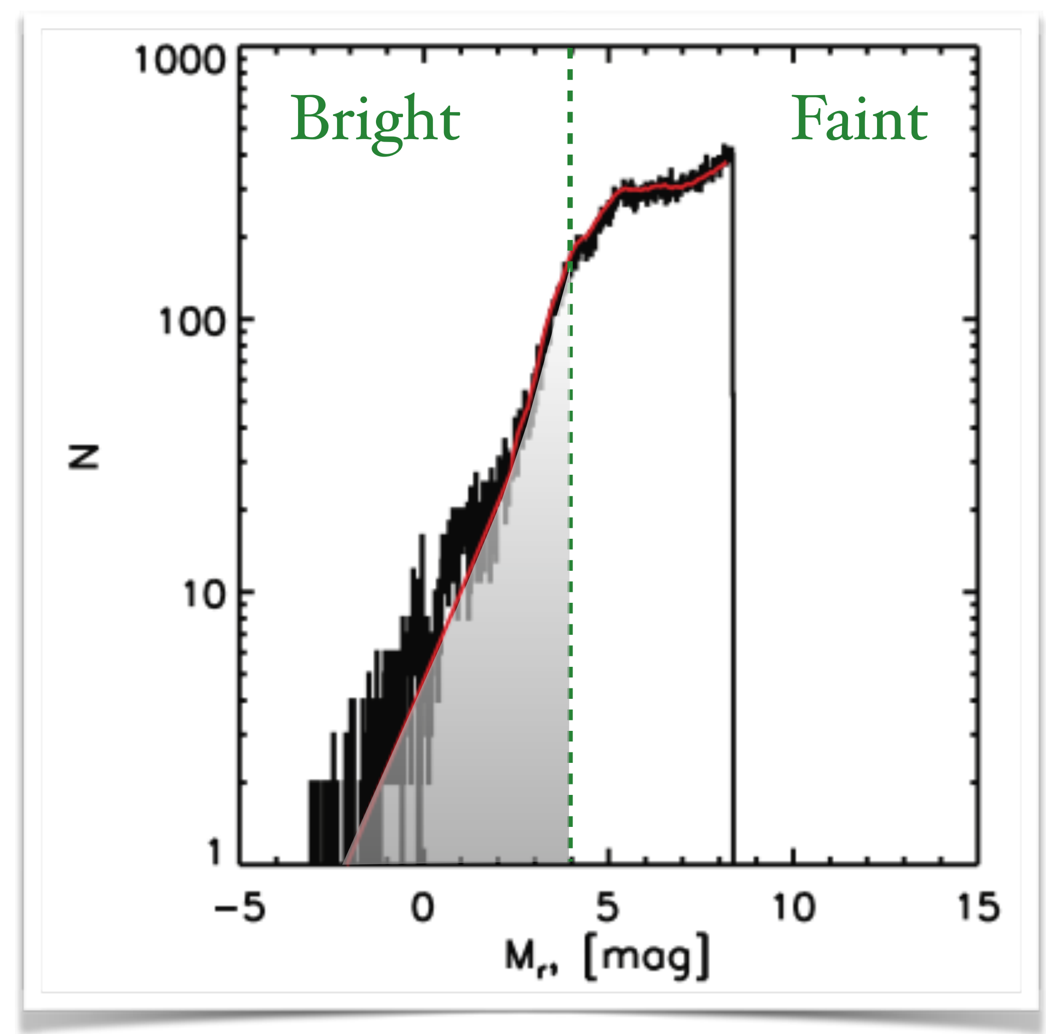
- Low number of stars with velocities measured
- Not enough stars in the centre and on the periphery
- Large and poorly determined velocity errors
- Contamination
- Velocity anisotropy is not known
- DM halos are probably not spherical

Number of stars available

10^4 stars typically available for the spectroscopic follow-up in a "Classical" dwarf galaxy

<**10^2** stars typically available for the spectroscopic follow-up in a "Ultra-Faint" dwarf galaxy

Stellar Luminosity Function



M92 globular cluster

Contamination


The Astronomical Journal, 137:3109–3138, 2009 February doi:10.1088/0004-6256/137/2/3109

CLEAN KINEMATIC SAMPLES IN DWARF SPHEROIDALS: AN ALGORITHM FOR EVALUATING MEMBERSHIP AND ESTIMATING DISTRIBUTION PARAMETERS WHEN CONTAMINATION IS PRESENT

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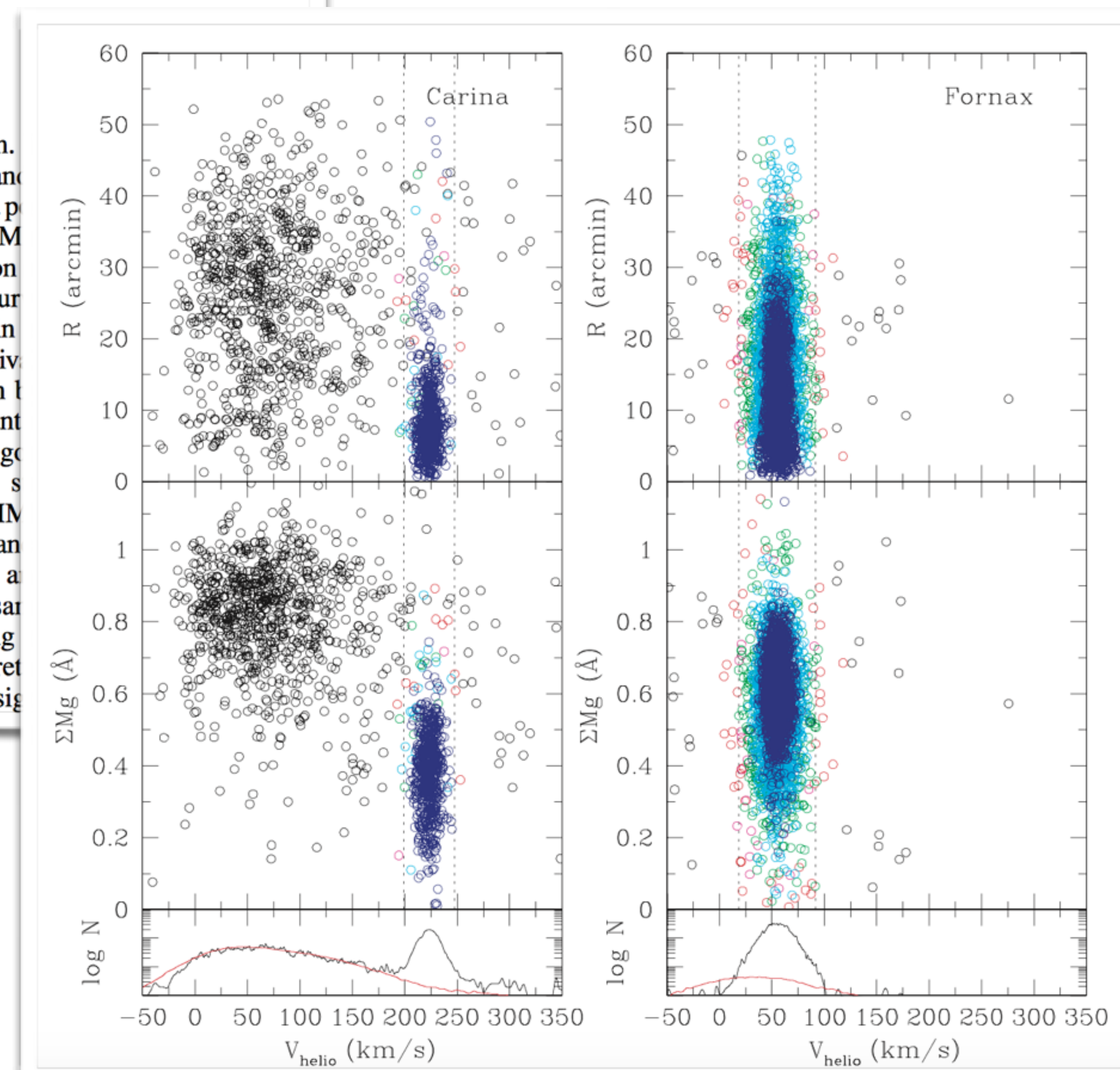
Received 2008 June 10; accepted 2008 November 8; published 2009 January 14

ABSTRACT

We develop an algorithm for estimating parameters of a distribution sampled with contamination. statistical technique known as "expectation maximization" (EM). Given models for both member an populations, the EM algorithm iteratively evaluates the membership probability of each discrete data p those probabilities to update parameter estimates for member and contaminant distributions. The EM wide applicability to the analysis of astronomical data. Here we tailor an EM algorithm to operate on samples obtained with the Michigan-MIKE Fiber System (MMFS) as part of our Magellan sur radial velocities in nearby dwarf spheroidal (dSph) galaxies. These samples, to be presented in paper, contain discrete measurements of line-of-sight velocity, projected position, and pseudo-equiv the Mg-triplet feature, for ∼1000–2500 stars per dSph, including some fraction of contamination Milky Way stars. The EM algorithm uses all of the available data to quantify dSph and contaminant For distributions (e.g., velocity and Mg-index of dSph stars) assumed to be Gaussian, the EM alg maximum-likelihood estimates of the mean and variance, as well as the probability that each s member. These probabilities can serve as weights in subsequent analyses. Applied to our MM EM algorithm identifies more than 5000 stars as probable dSph members. We test the performan algorithm on simulated data sets that represent a range of sample size, level of contamination, a overlap between dSph and contaminant velocity distributions. The simulations establish that for sa from large ($N \sim 3000$, characteristic of the MMFS samples) to small ($N \sim 30$), resembling for extremely faint dSphs), the EM algorithm distinguishes members from contaminants and ret parameter estimates much more reliably than conventional methods of contaminant removal (e.g., sig



Probability of membership can be estimated by modelling the distribution of the background and the members in the space of observables

Impact of interlopers

Segue 1: Bonnivard et al 2015

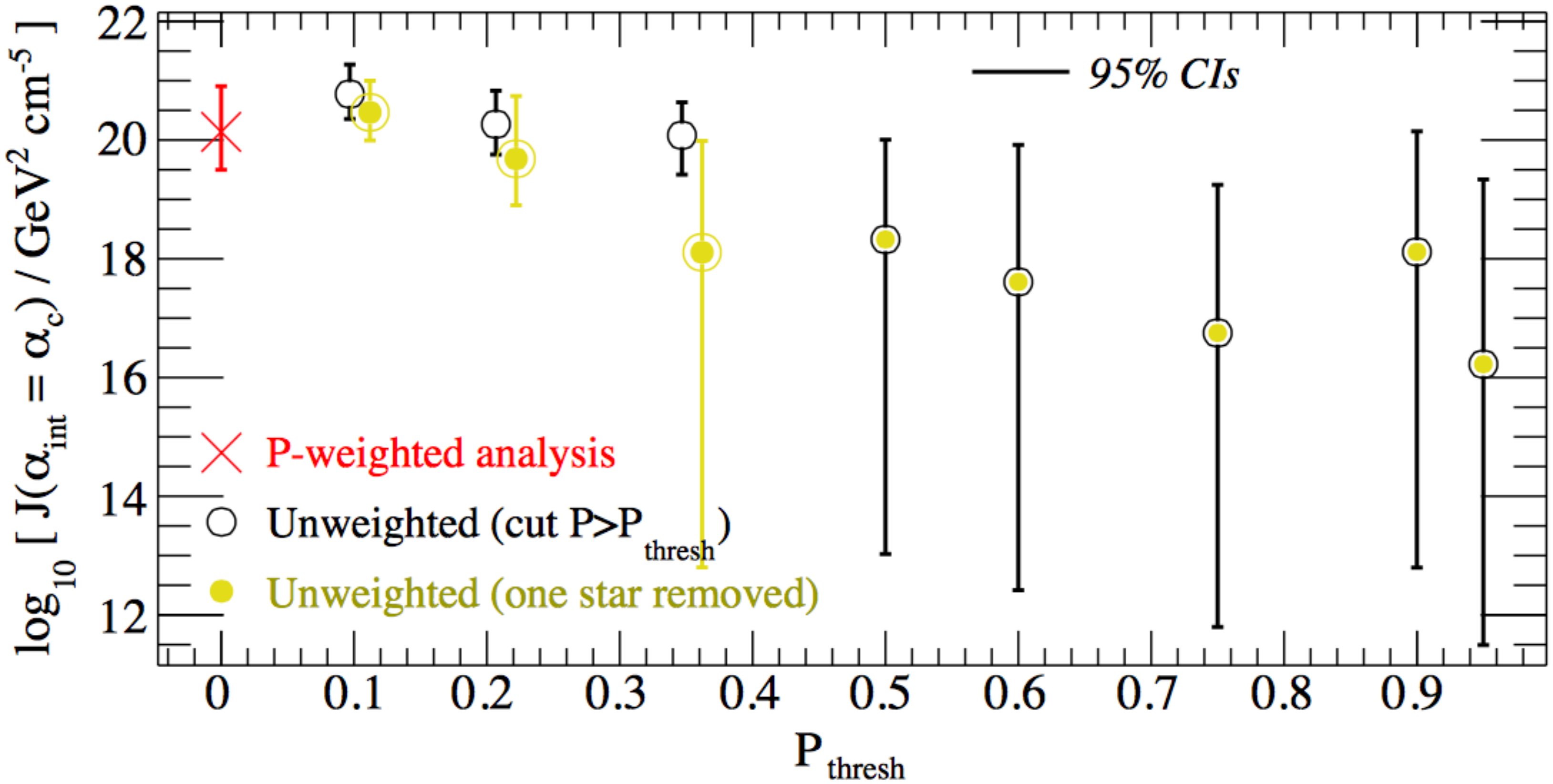


Figure 7. $J(\alpha_{\rm int} = \alpha_c = 0.14°)$ and 95% CIs from P-weighted (red cross) and P-unweighted MCMC analyses as a function of $P_{\rm thresh}$, the threshold for which stars with $P < P_{\rm thresh}$ are discarded from the analysis. The difference between filled yellow circles and black circles is the removal of a single star shown with a similar symbol in the bottom panel of Figure 6 (star at $R = 5.5$ pc and with $P = 0.39$).

Accurate kinematics at faint magnitudes

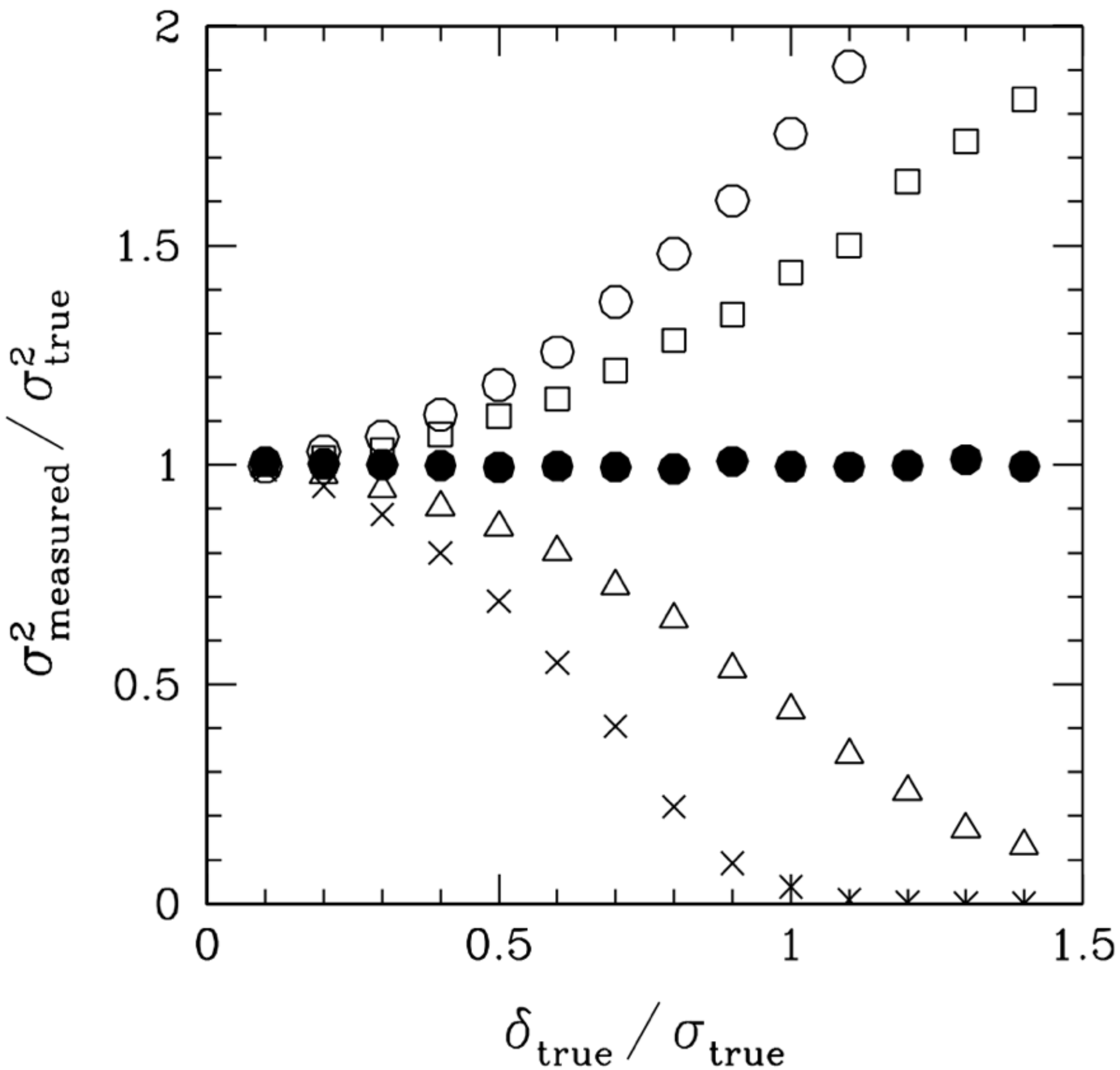


Figure 1. Accuracy of simulated velocity dispersion estimates as a function of the ratio of measurement errors to the true velocity dispersion. Filled circles represent cases in which the measurement errors are known perfectly. Open circles and open squares represent cases in which the errors used in the analysis are underestimated (optimistic) by a factor of 0.5 and 0.75, respectively. Open triangles and crosses represent cases in which the adopted errors are overestimated (pessimistic) by a factor of 1.25 and 1.5, respectively.

Accurate kinematics at faint magnitudes

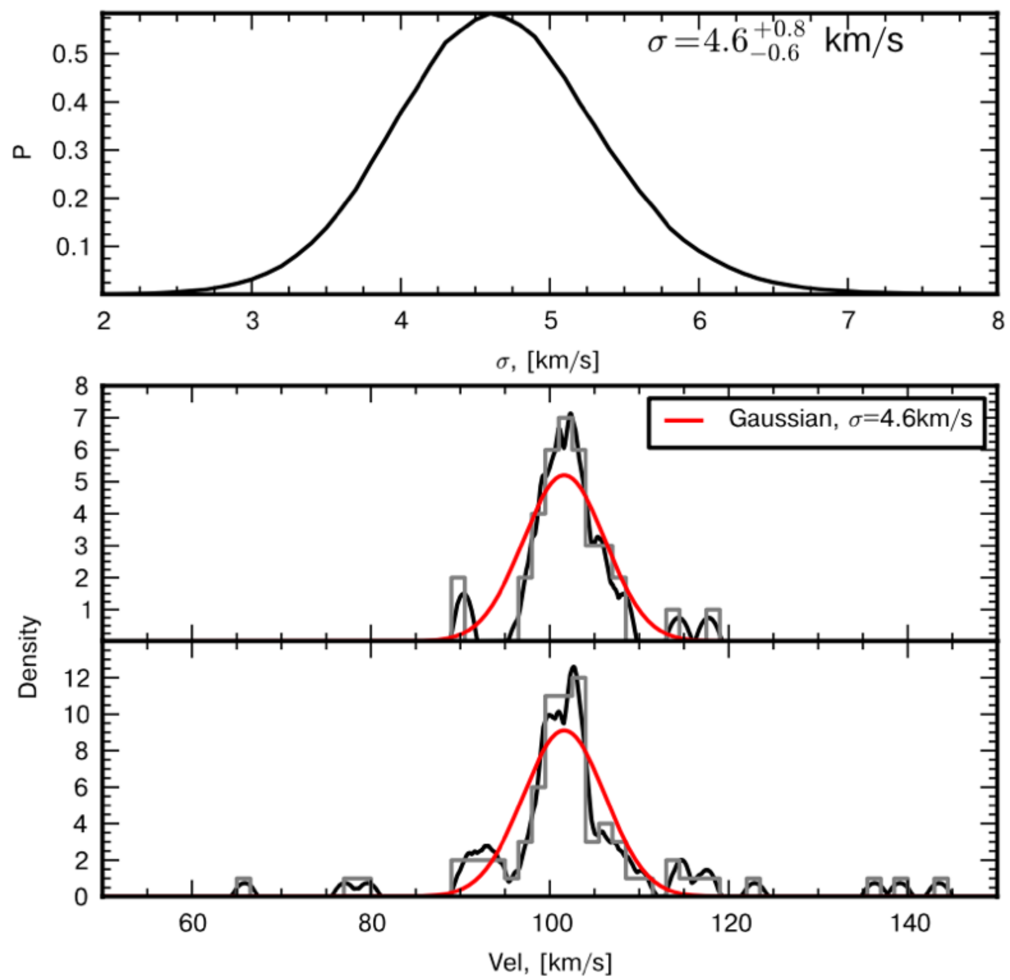


Figure 13. Top panel: the probability distribution of the internal Boötes I Gaussian velocity dispersion, determined from an MCMC fit to our velocity data for our full 100 star non-variable sample, when the velocity distribution is assumed to be consistent with a single Gaussian. Middle panel: the MCMC fit Gaussian, with dispersion 4.6 km s^{-1}, overlaid on the kinematic data. Lower panel: to illustrate that the derived MCMC fit is robust to data selection, we show the derived Gaussian with dispersion 4.6 km s^{-1} overlaid on the subset of 37 stars from Figure 12, those which are highly probable Boötes I members, i.e., those with [Fe/H] < -1.5, $\log(g) < 3.5$, small velocity error $\sigma_v < 2.5$ km s^{-1}, and no significant velocity variability.

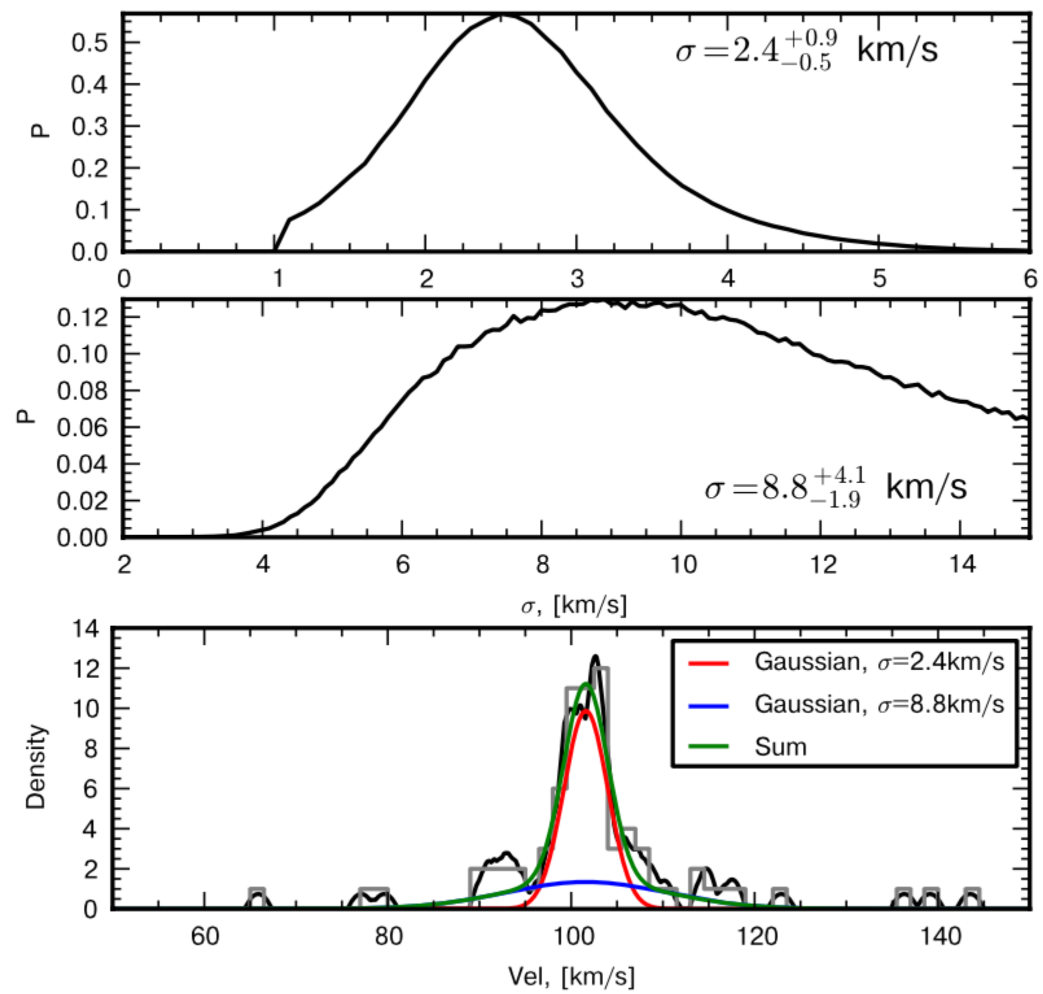
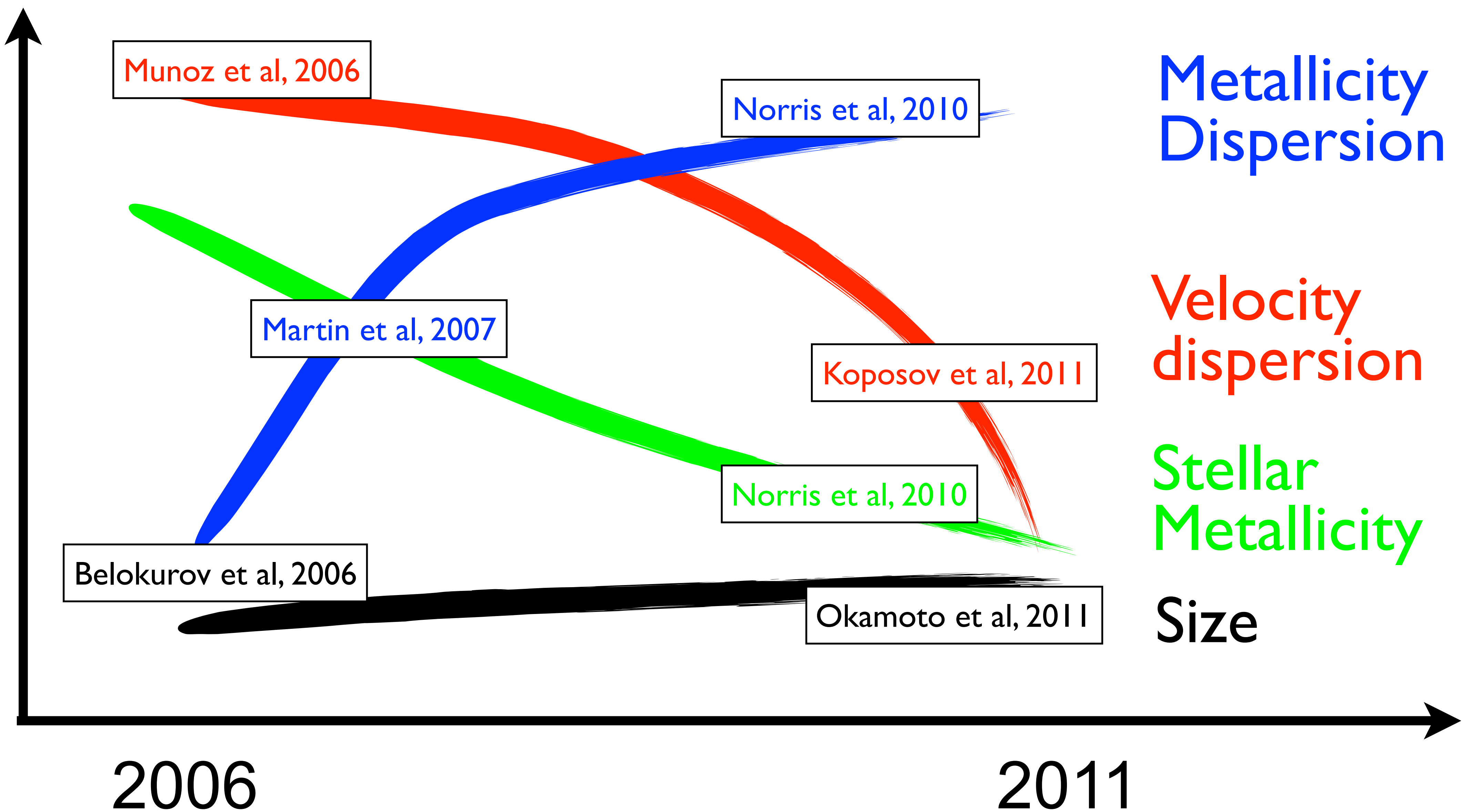


Figure 14. Top two panels: the probability distributions of the internal Boötes I Gaussian velocity dispersion, determined from an MCMC fit to our 100 star non-variable velocity data, when the velocity distribution is assumed to be consistent with two Gaussians. The top panel shows the probability distribution for the lower dispersion component, while the bottom panel shows the probability distribution for the higher-dispersion component. The MCMC analysis allocated 70% of the stars to the 2.4 km s^{-1} dispersion component, and 30% of the stars to the 9 km s^{-1} dispersion component. Lower panel: the corresponding two-Gaussian distribution overlaid on the kinematic data.

Koposov et al 2011

Ultra-Faint: Difficult

Bootes 1



Ultra-Faint: Difficult

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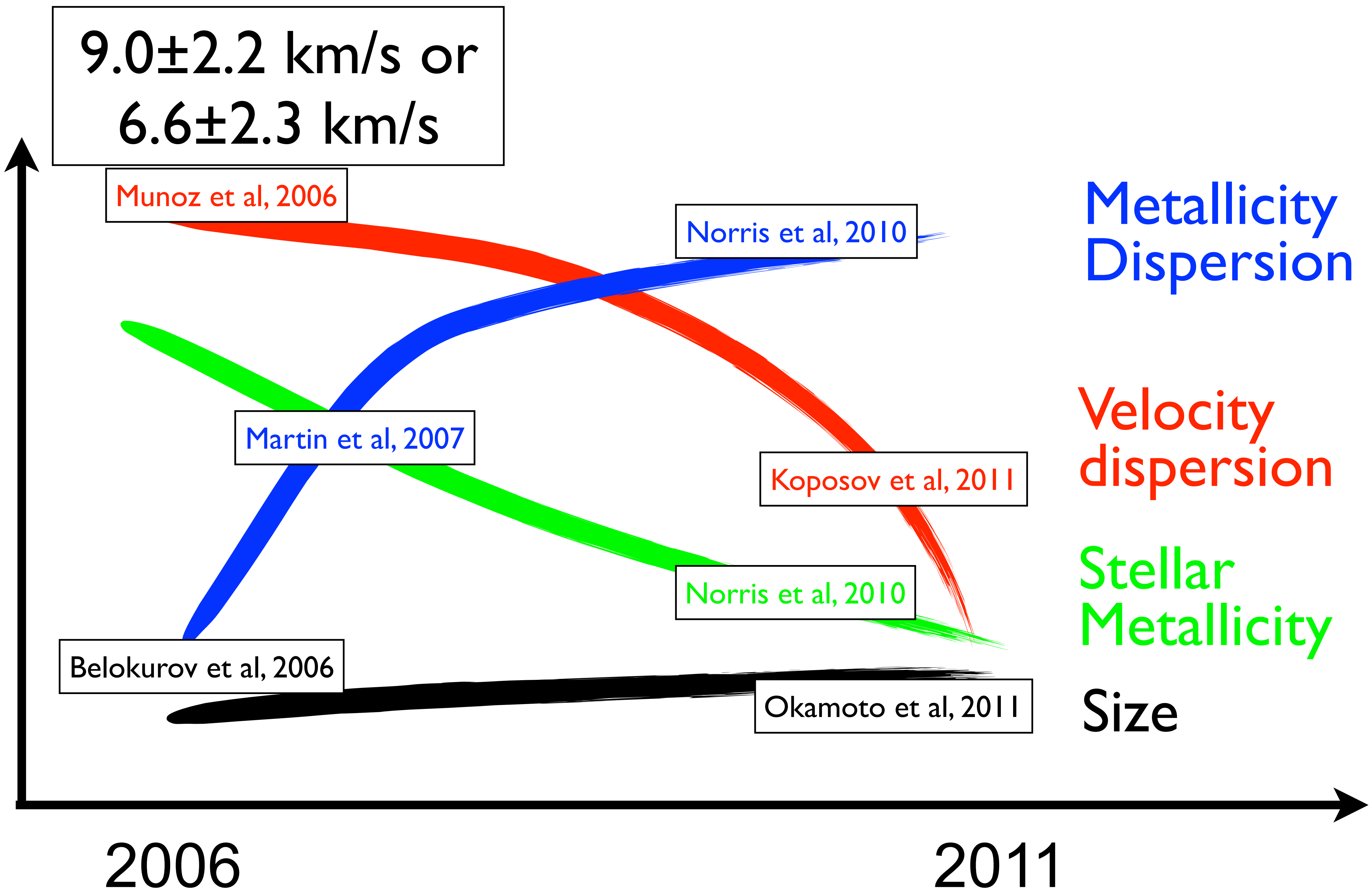
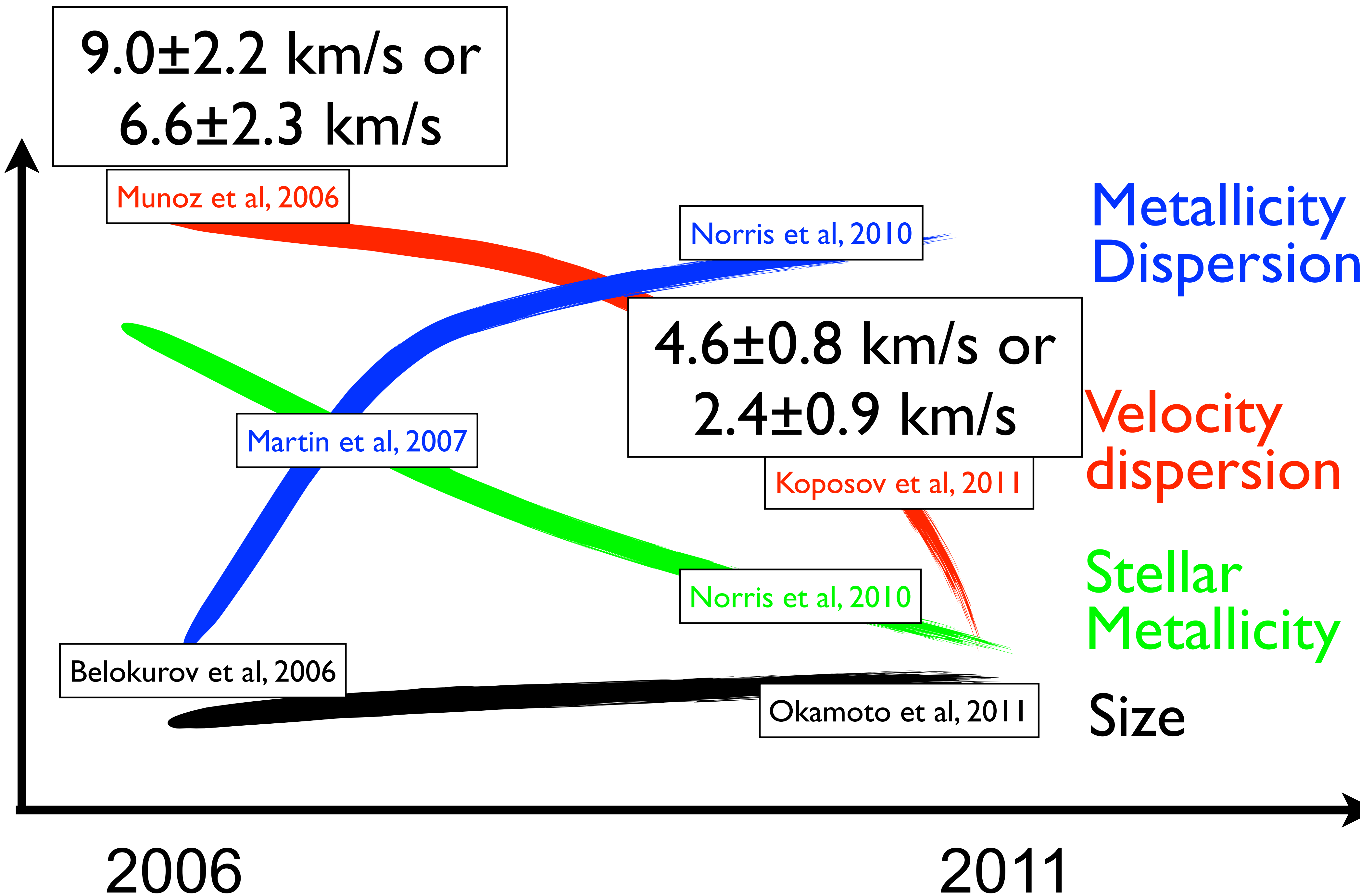


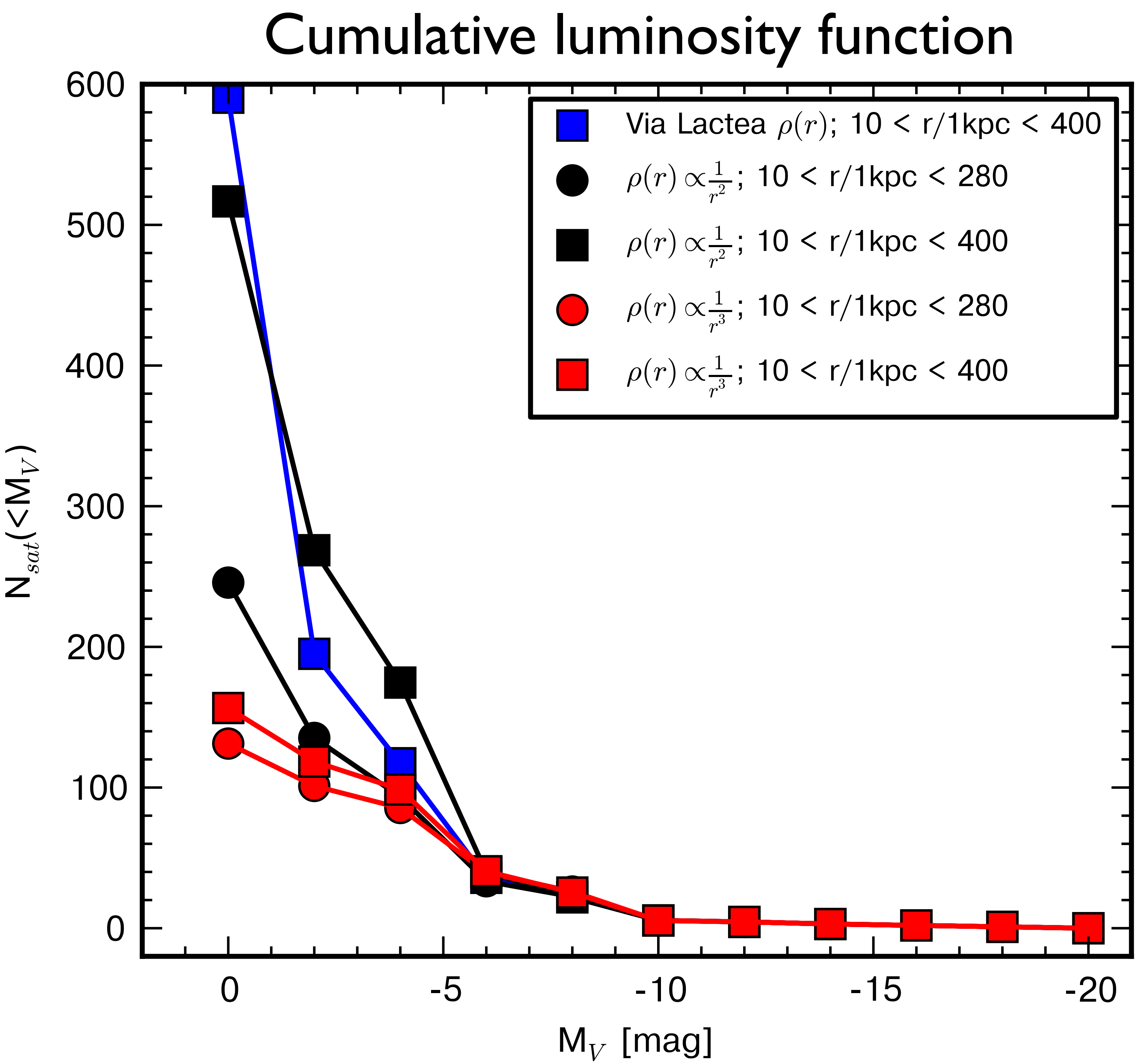
Ultra-Faint: Difficult

Bootes 1

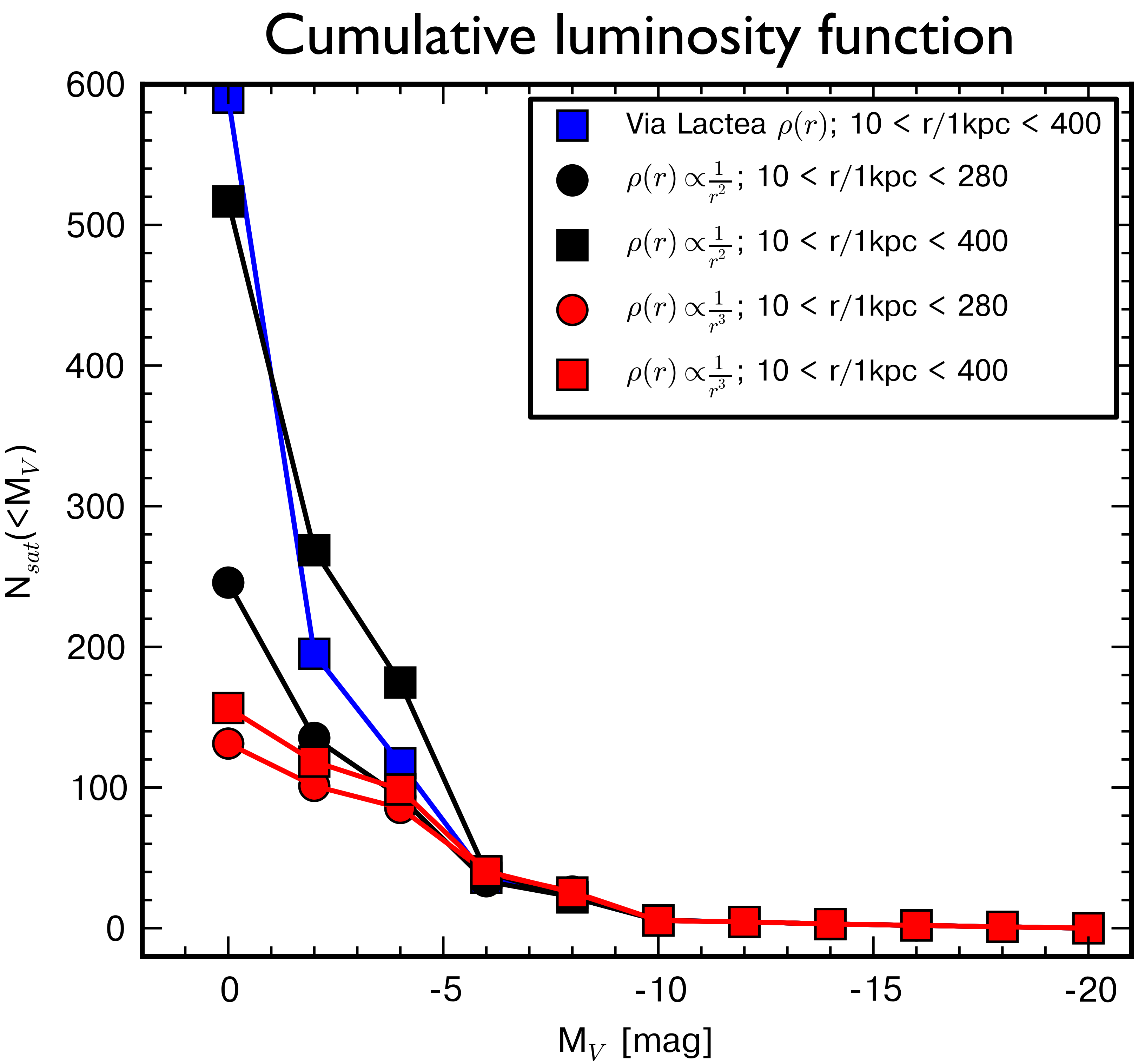


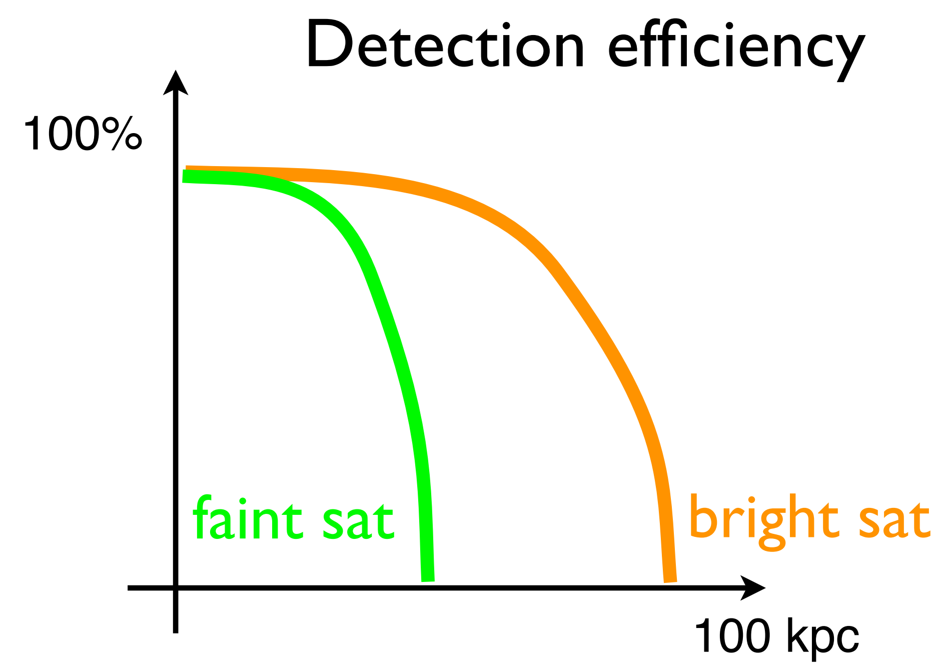
Dwarf counts.
Theory vs Observations

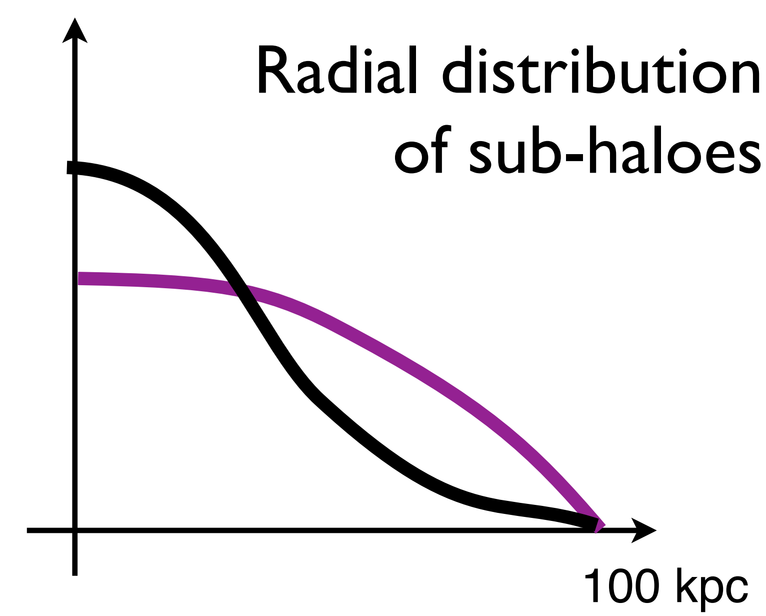
The dwarf census



The dwarf census





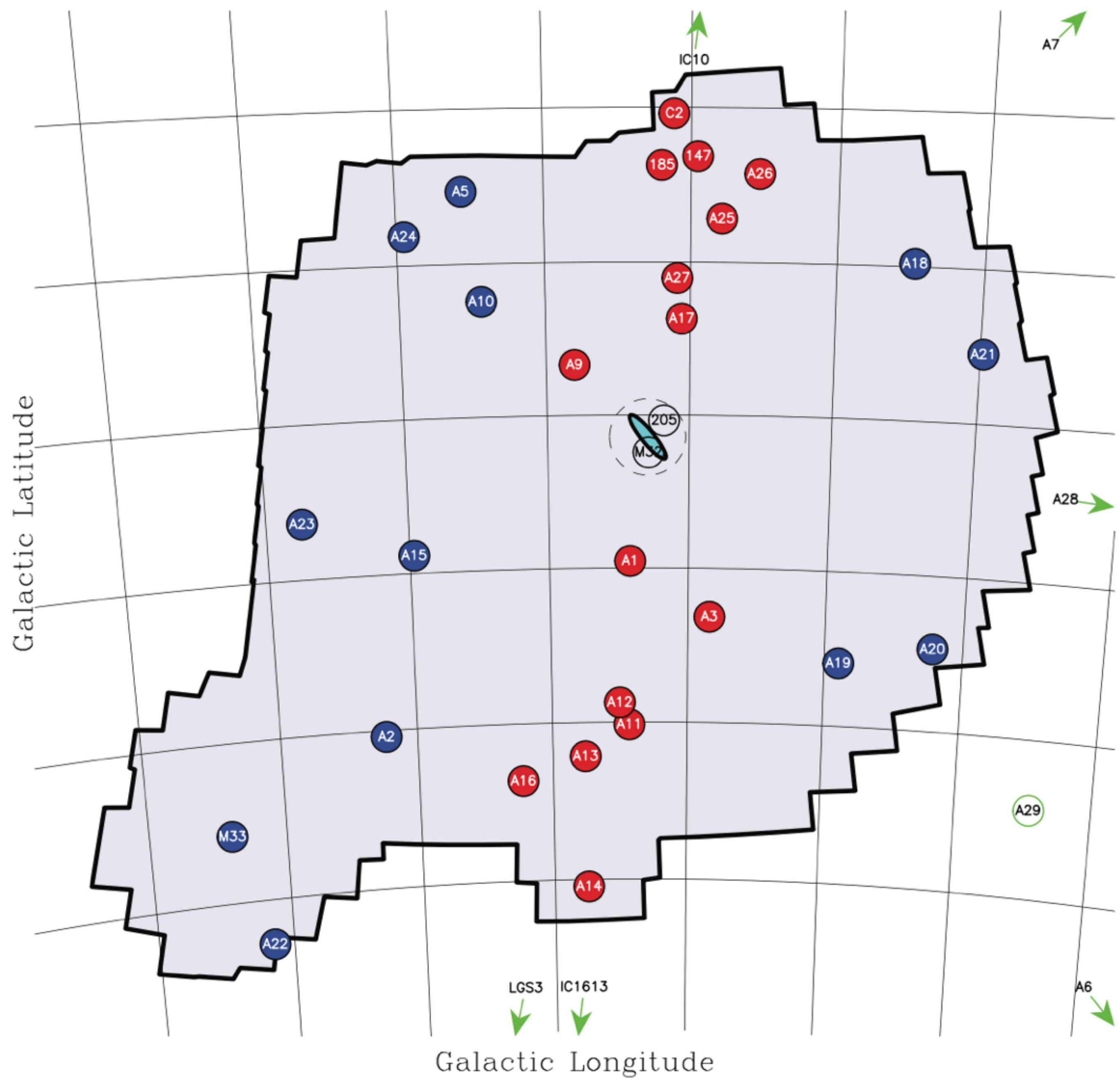


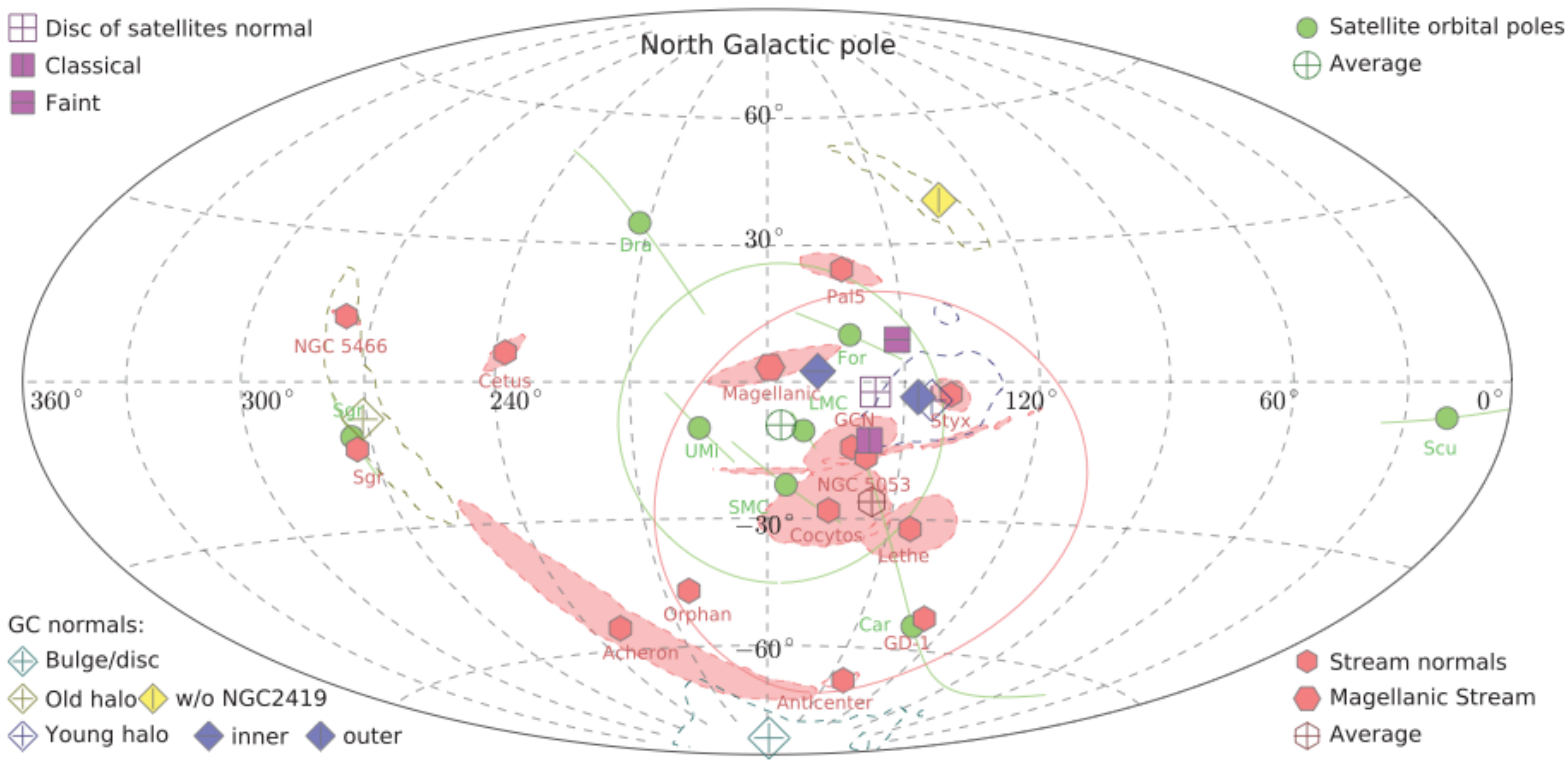
Spatial anisotropy?

Planes of satellites

Observational Evidence

M31, Ibata et al 2013




Disc of satellites normal
Classical
Faint
North Galactic pole
Satellite orbital poles
Average
60°
30°
−30°
−60°
360°
300°
240°
120°
60°
0°
Dra
Pal5
NGC 5466
Cetus
Magellanic
For
LMC
GCN
Styx
Sgr
UMi
NGC 5053
SMC
Cocytos
Lethe
Scu
Orphan
Acheron
Car
GD-1
Anticenter
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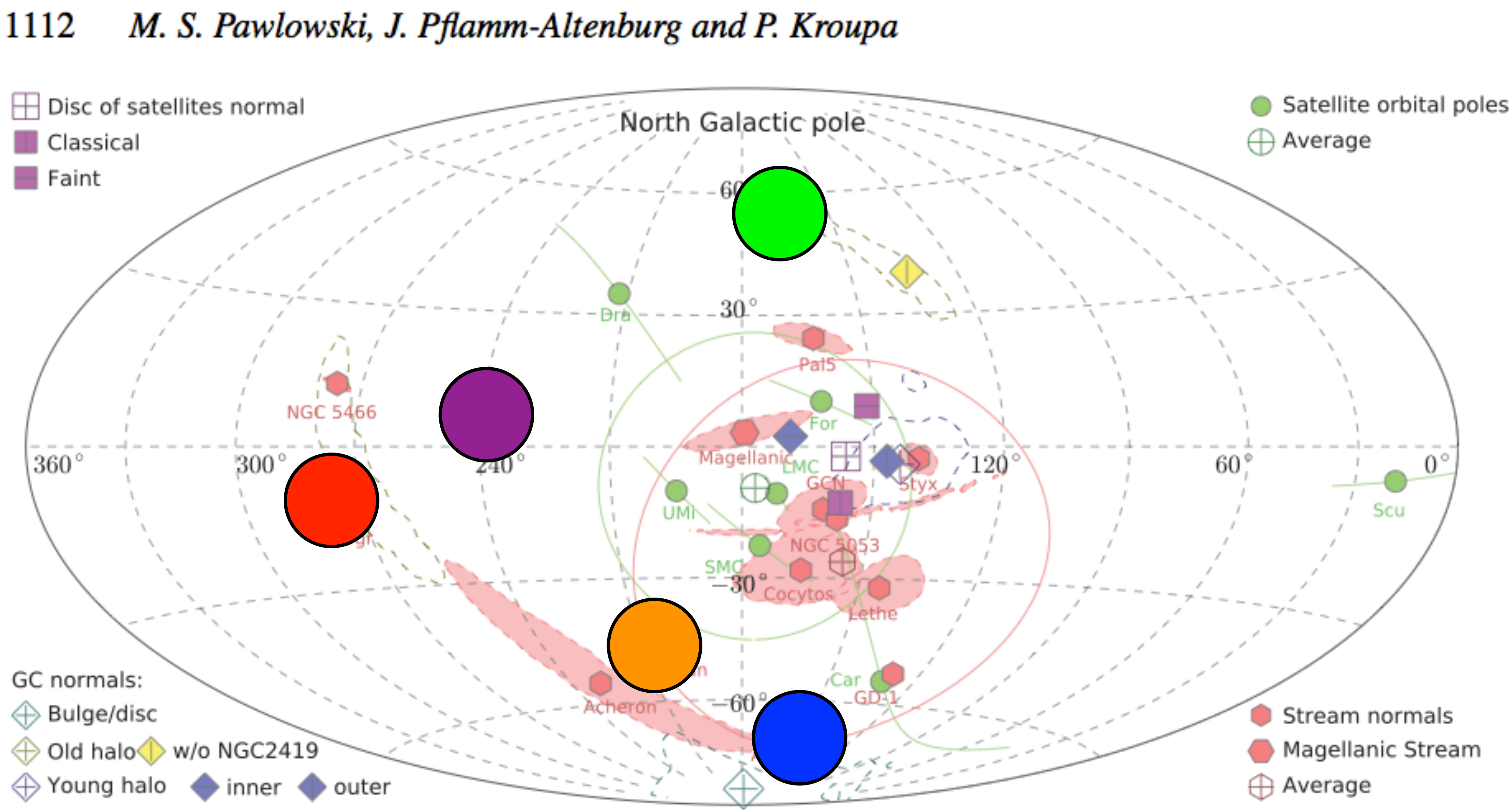
Young halo
inner
outer
Stream normals
Magellanic Stream
Average



7 known dwarf galaxy stellar streams:

Sagittarius, Tri-And, Monoceros, Her-Aquila, Cetus, Virgo, Orphan

none aligned with the so-called VPOS!

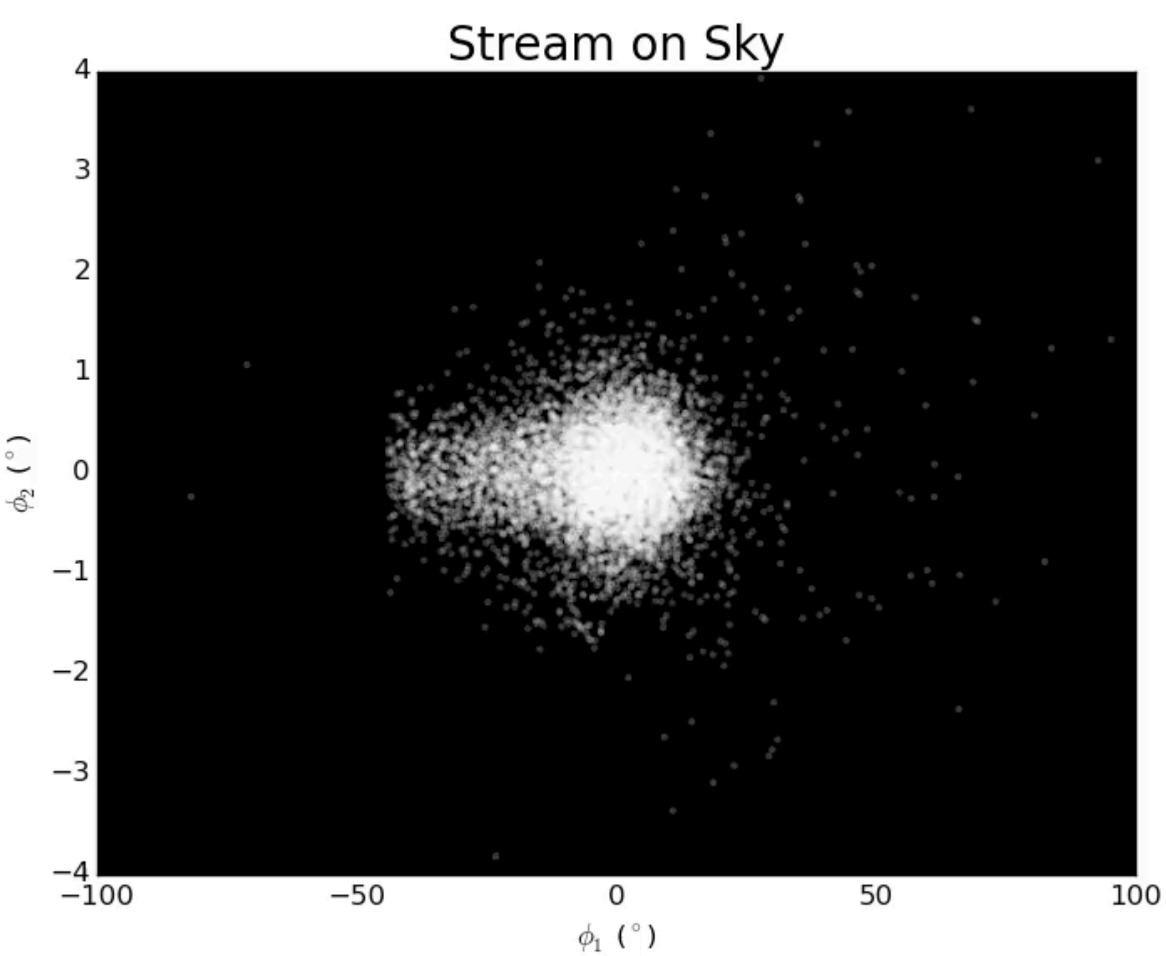
Future Prospects

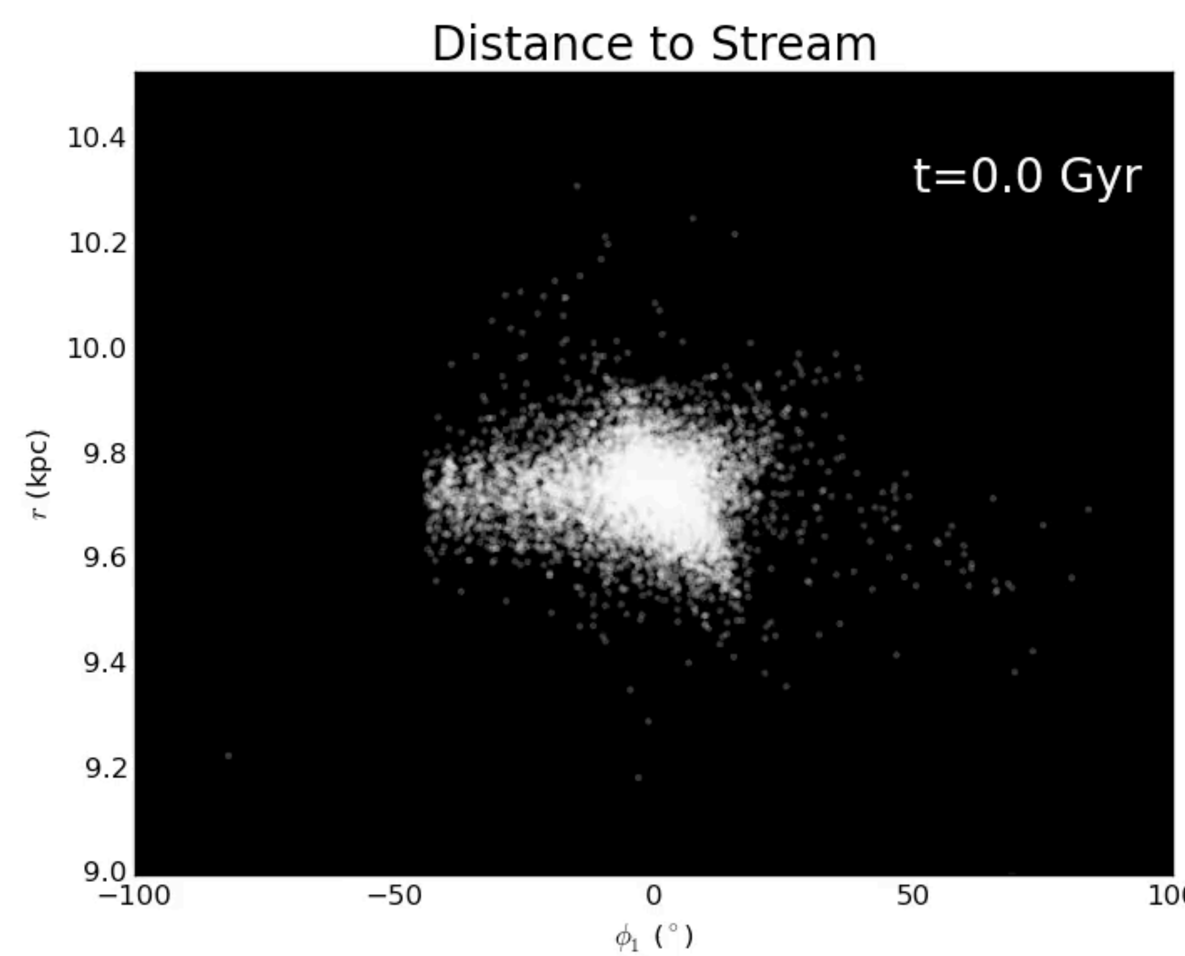
The not so distant future

- Proper motions of individual stars in some of the dwarfs with Gaia and HST
- New closer and fainter dwarfs with Gaia (new detection window)
- The complete Galactic dwarf census with LSST
- The 100 Mpc census with LSST and Euclid
- Proper motions of dwarfs with Gaia+LSST
- En-masse spectroscopy with new multi-fiber instruments: WEAVE, 4MOST, DESI, SuMIRe

Why not look instead directly at the DM halos?

- Forensics of stellar stream perturbations allows to recover the **complete set of properties** for a DM sub-halo, including its mass, size and orbit! See Erkal & Belokurov 2015a,b





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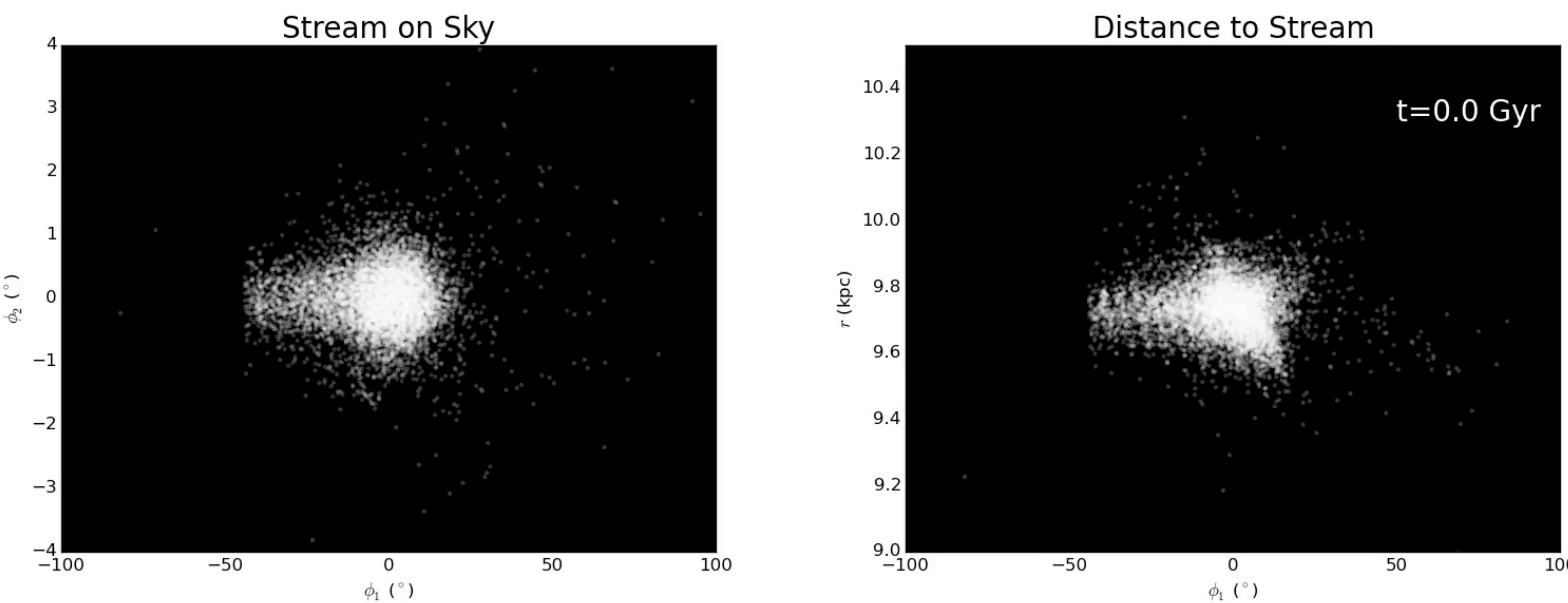
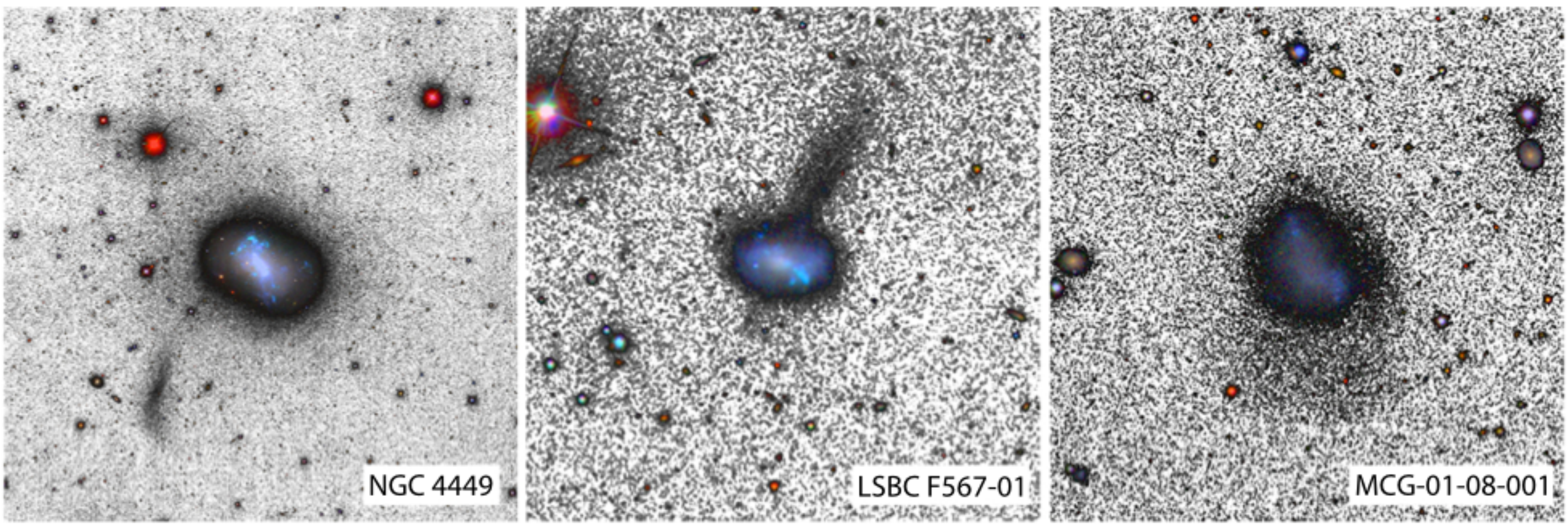


The End

Extra slides

Accretion of dwarfs onto dwarfs

Belokurov 2013



Local Volume examples of SMC-like dwarf accreting a dwarf satellite with mass ratio in the range 10:1 - 100:1

Tidal dwarfs