Invisible Galaxies

University of Nebraska, October 2013

Beth Willman (Haverford College)

Invisible Galaxies

- Finding and studying invisible galaxies
- The connection with dark matter
- Contributions of Haverford undergrads to invisible galaxy research
- Current and future sky surveys

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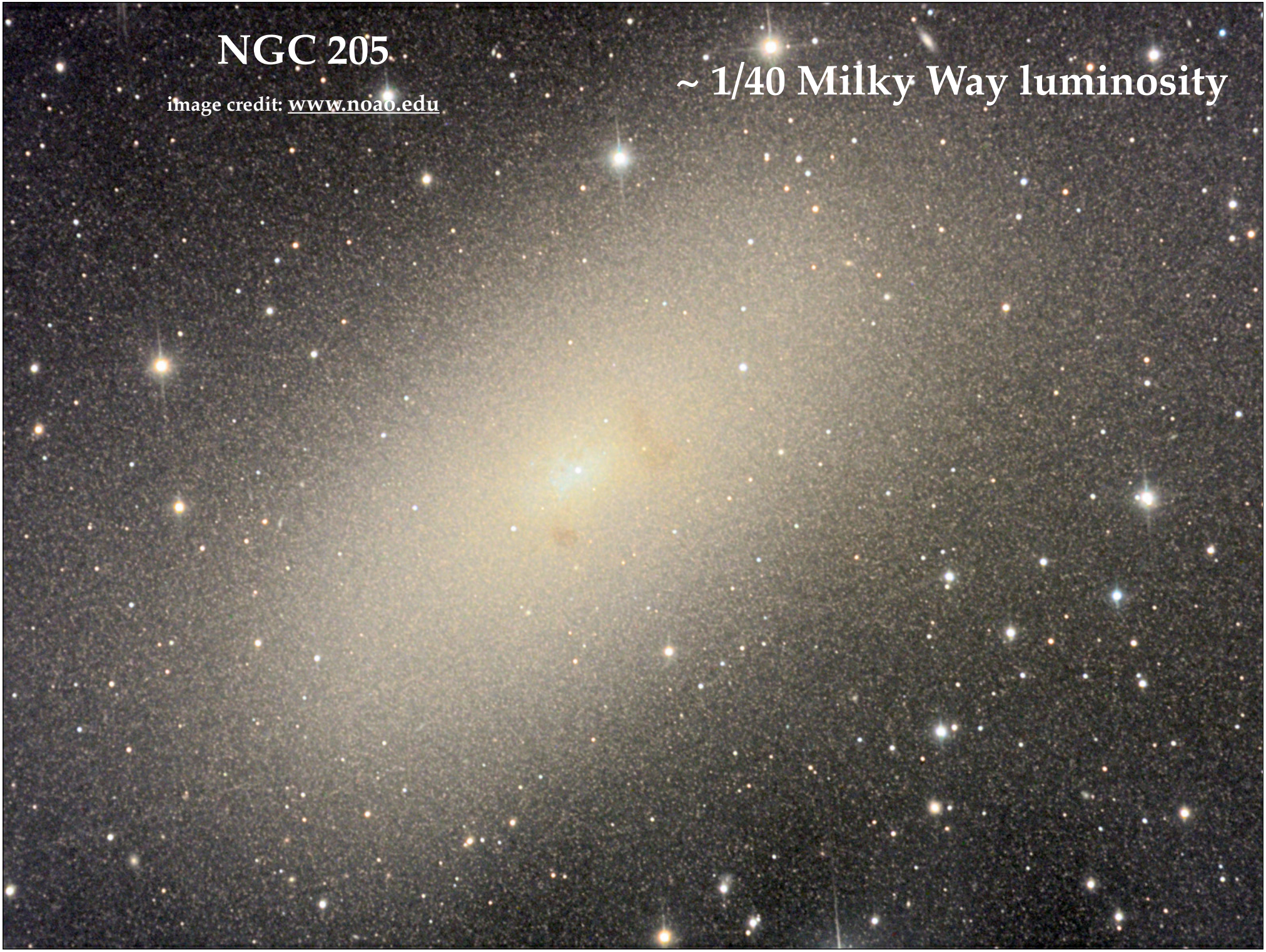
Large Magellanic Cloud
~ 1/10 Milky Way luminosity
image credit: Yuri Beletsky (ESO) and APOD


NGC 205
image credit: www.noao.edu
~ 1/40 Milky Way luminosity

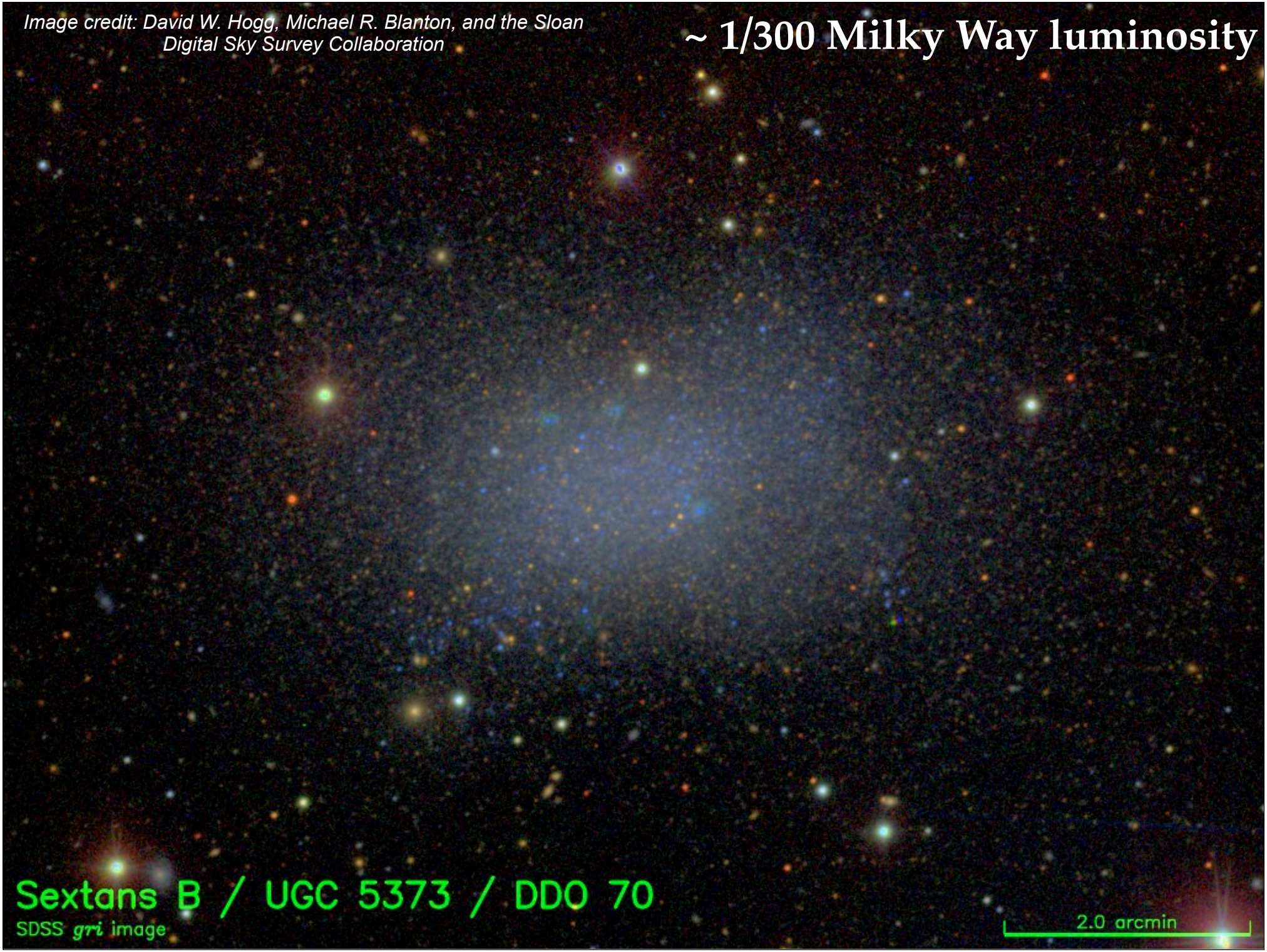


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/300 Milky Way luminosity
Sextans B / UGC 5373 / DDO 70
SDSS gri image
2.0 arcmin


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/2700 Milky Way luminosity
Leo I / UGC 5470 / DDO 74
SDSS gri image
5.0 arcmin

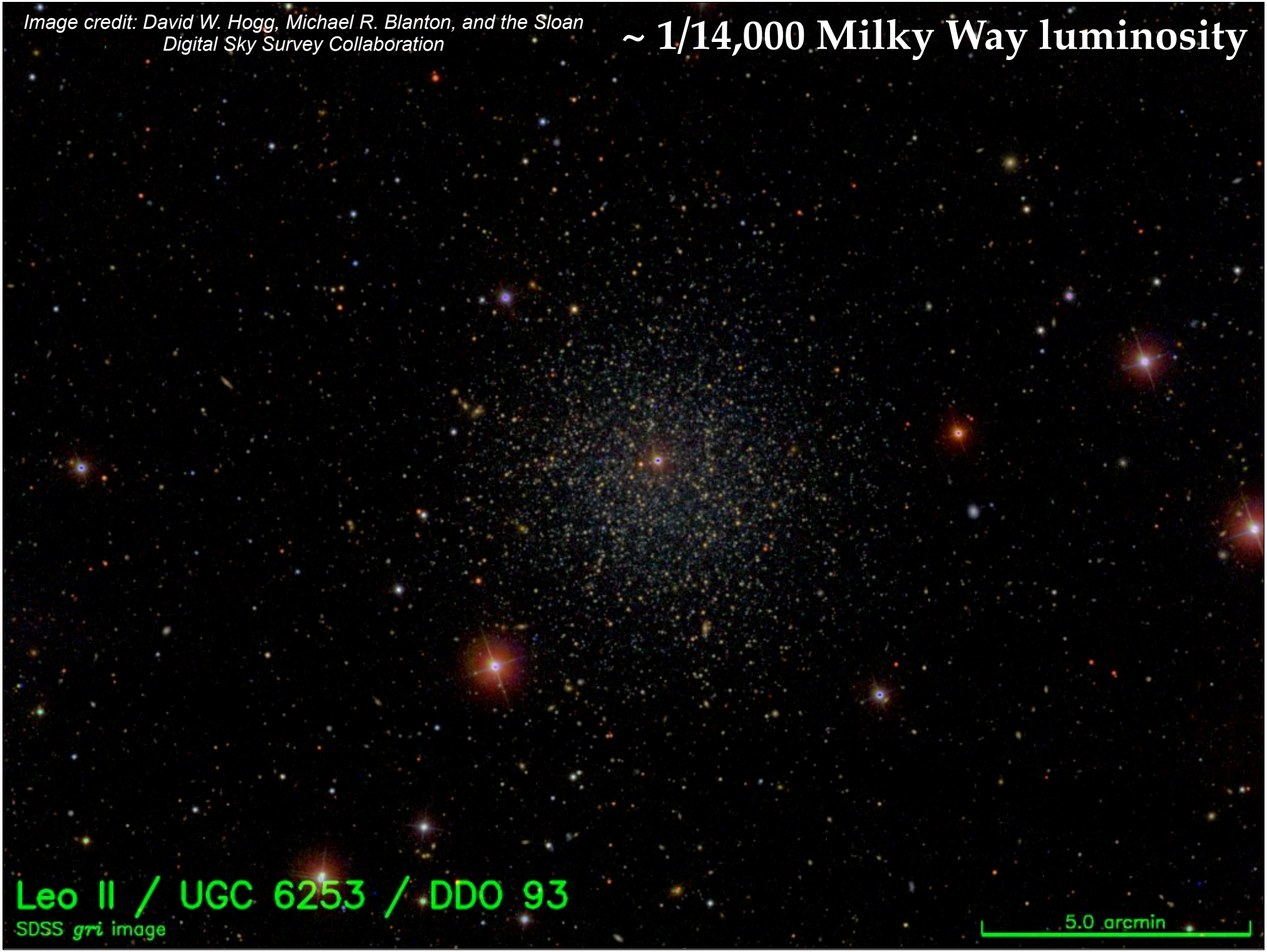
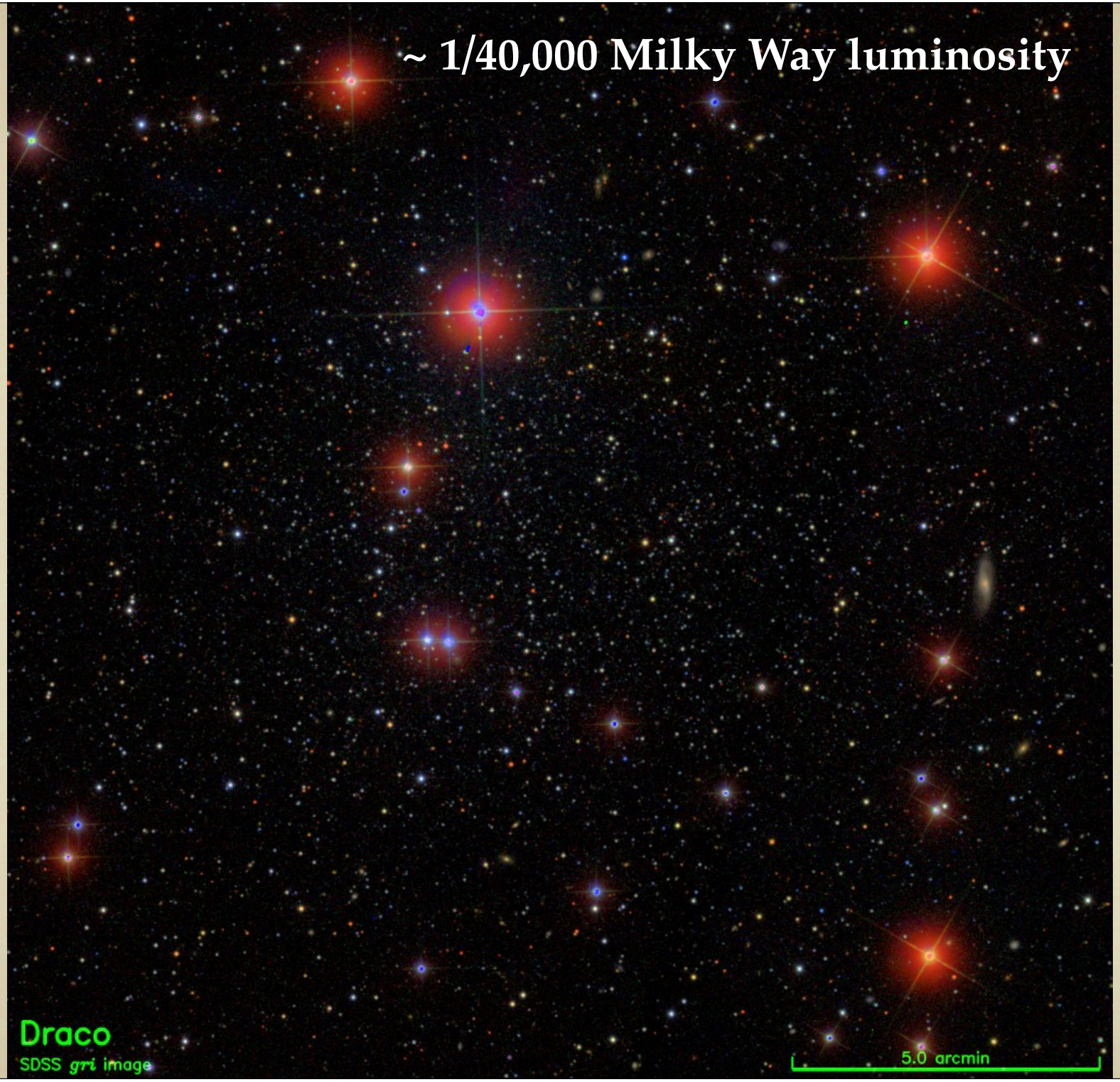
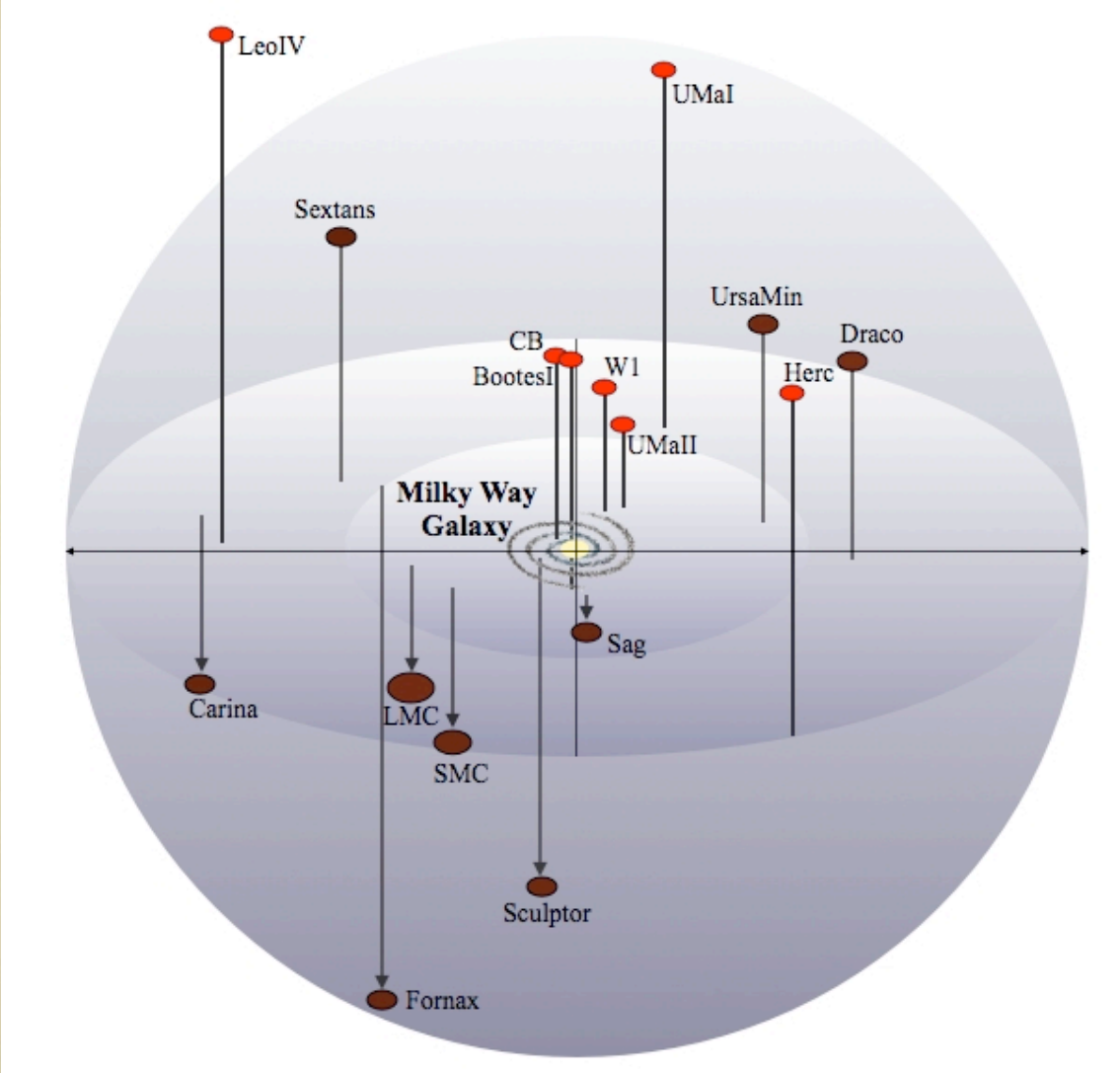


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/14,000 Milky Way luminosity
Leo II / UGC 6253 / DDO 93
SDSS gri image
5.0 arcmin


~ 1/40,000 Milky Way luminosity
Draco
SDSS gri image
5.0 arcmin

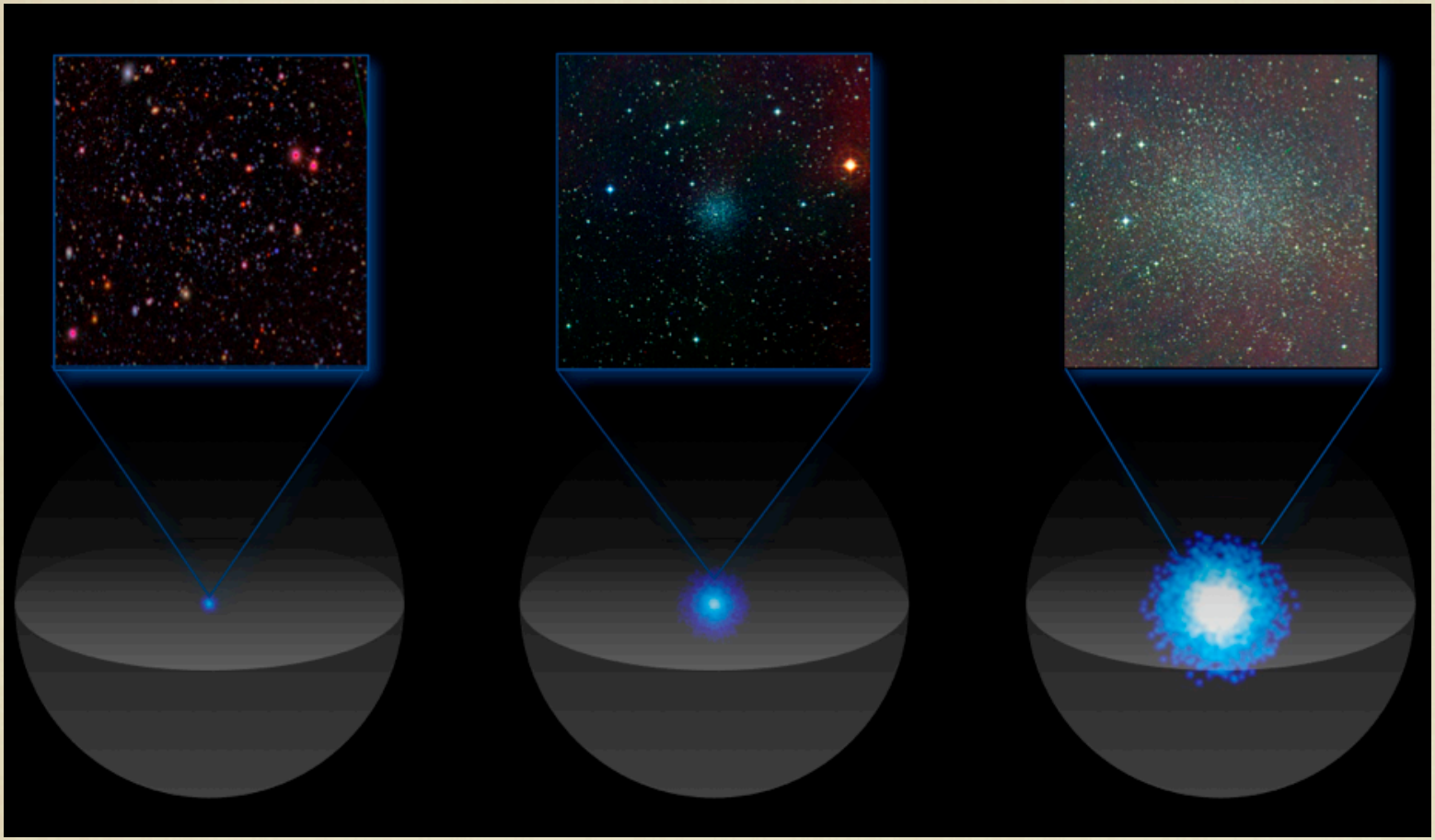
Dwarf galaxies around the Milky Way



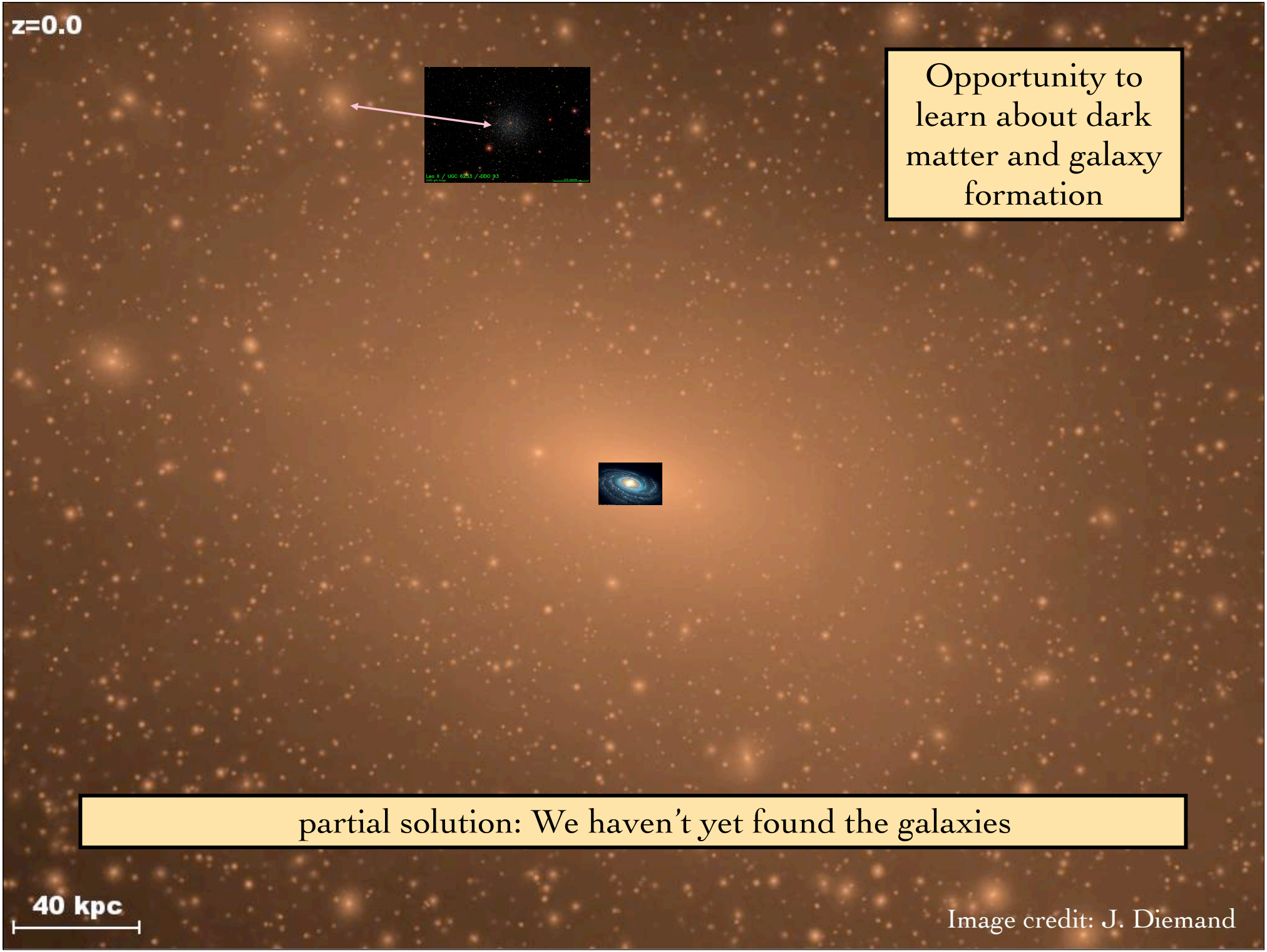
Before 2005: 9 dwarf spheroidal galaxies and 2 dwarf irregular galaxies known around the Milky Way (brown ovals).

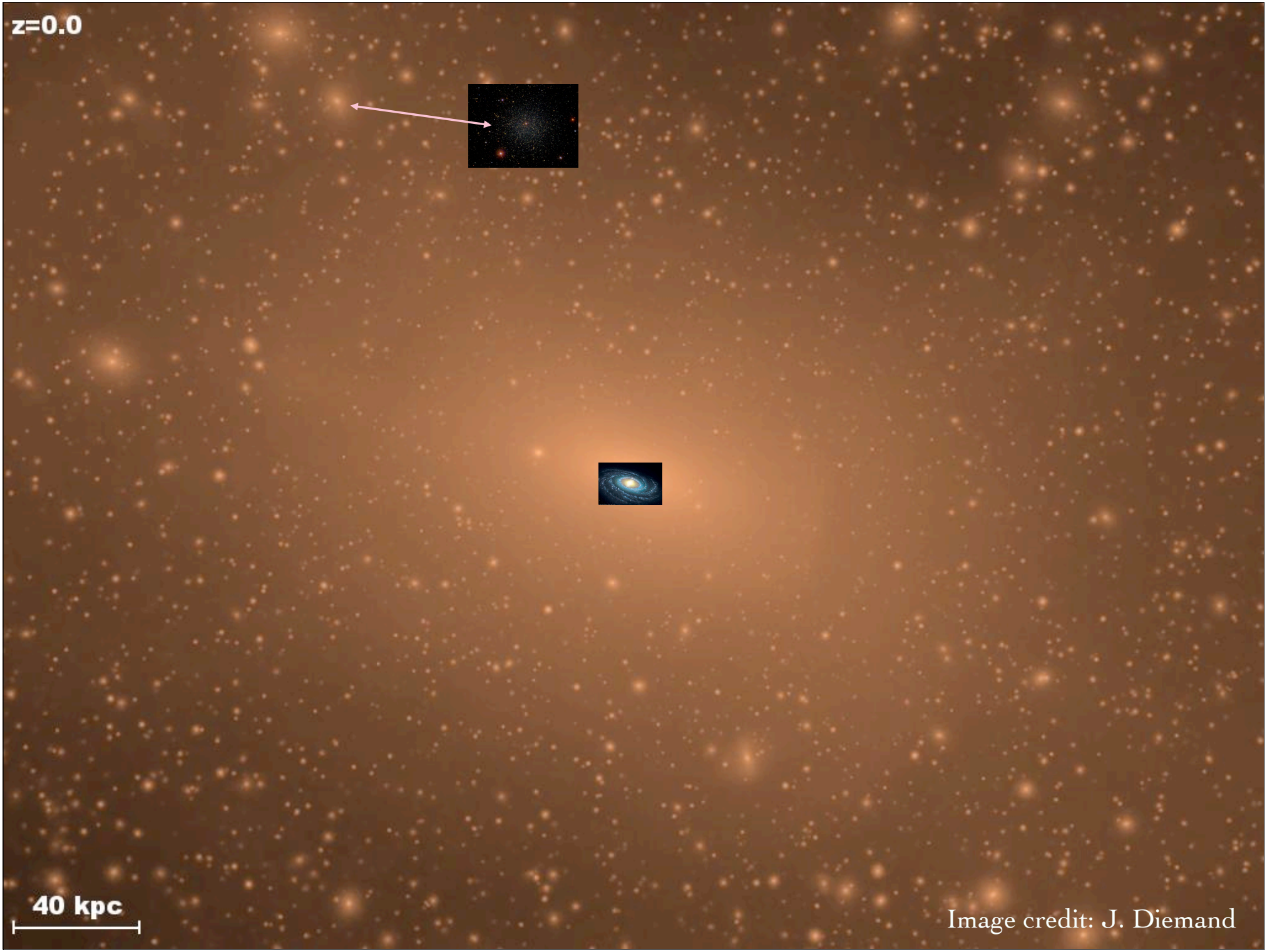
Image from M. Geha's web page.

Observations had previously shown that galaxies weighed a lot more than they appeared to just from their stars.

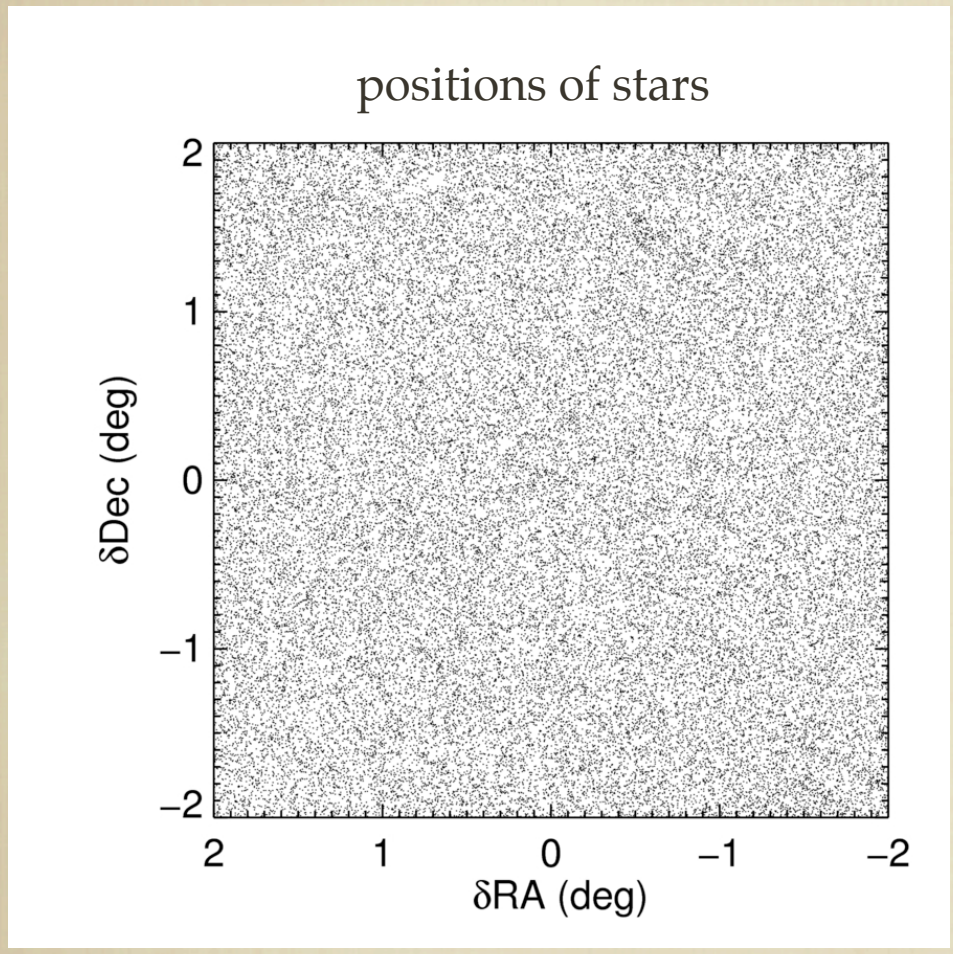


All dwarf satellites of the Milky Way were known to live within clumps of dark matter


z=0.0
Opportunity to learn about dark matter and galaxy formation
partial solution: We haven't yet found the galaxies
40 kpc
Image credit: J. Diemand

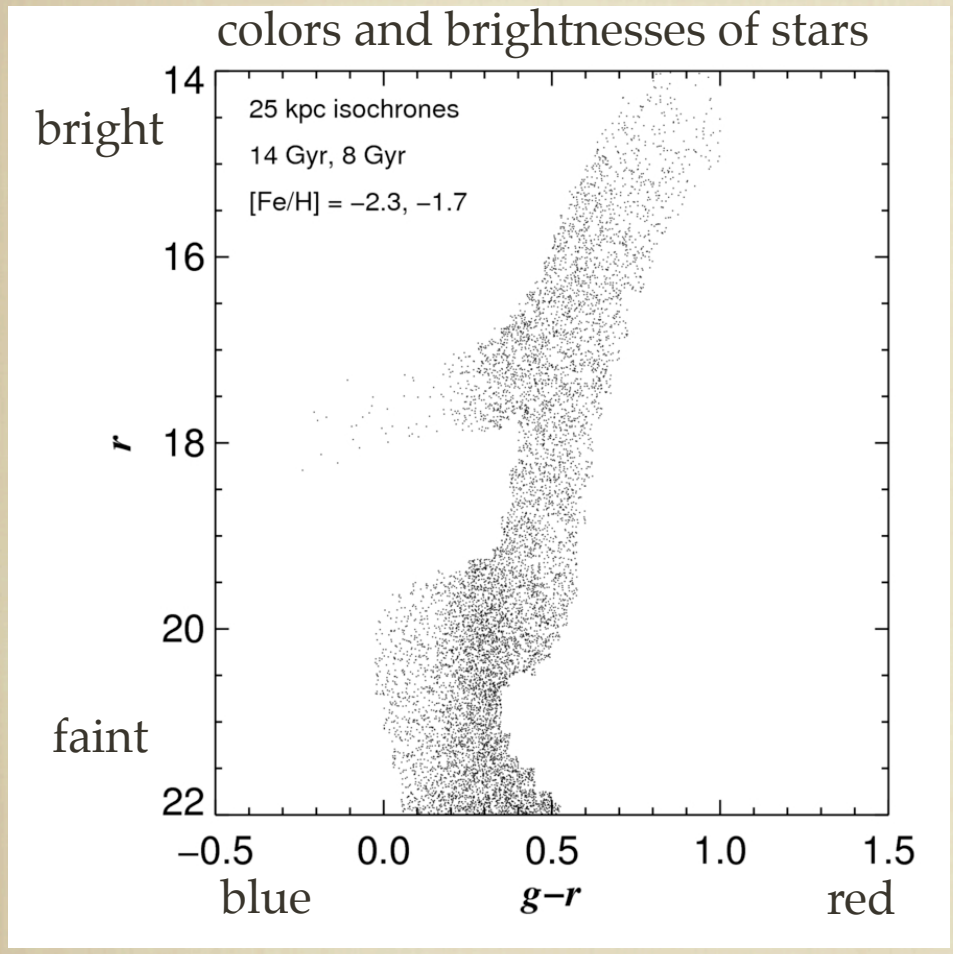

z=0.0
40 kpc
Image credit: J. Diemand

Finding Invisible Galaxies



Willman et al 2002, Walsh, Willman & Jerjen 2009; see also e.g. Koposov et al 2008, Belokurov et al.

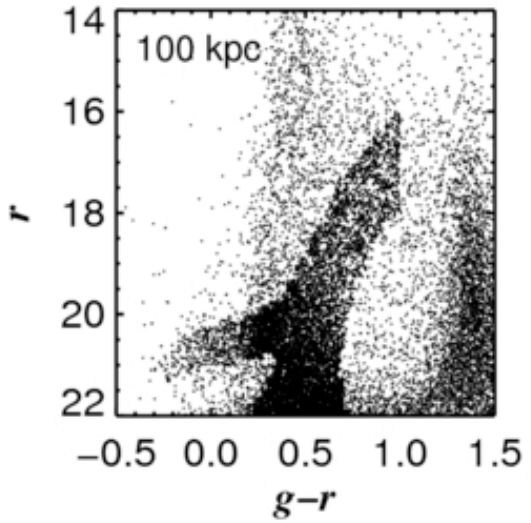
Finding Invisible Galaxies



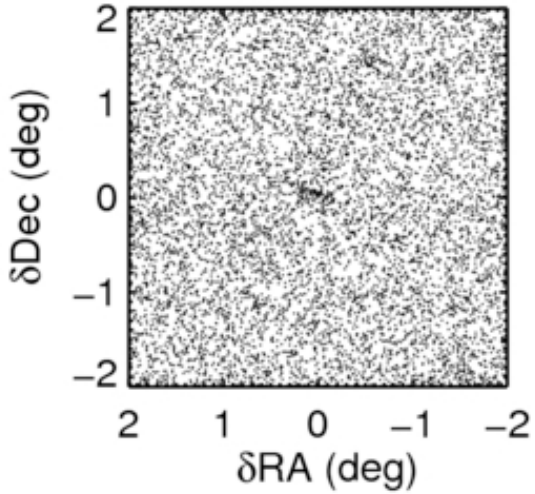
Willman et al 2002, Walsh, Willman & Jerjen 2009; see also e.g. Koposov et al 2008, Belokurov et al.

Finding Invisible Galaxies

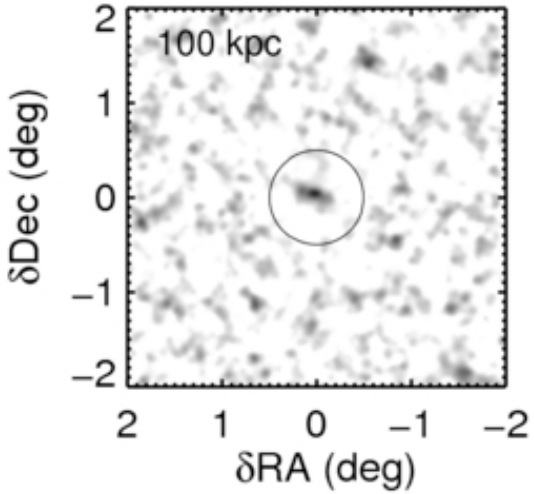
colors and brightnesses



positions



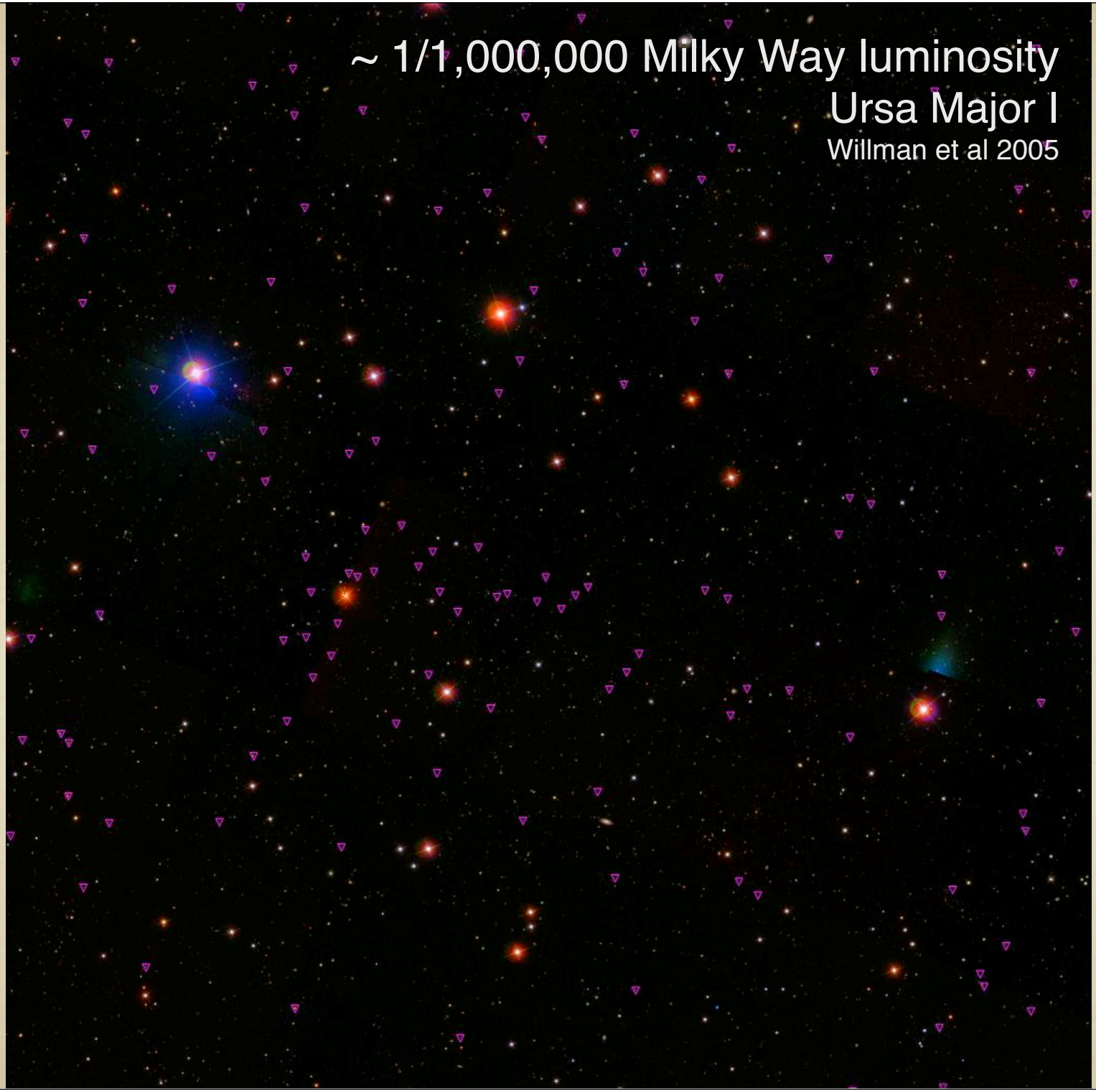
positions



Ursa Major I dwarf

1/1,000,000 MW luminosity

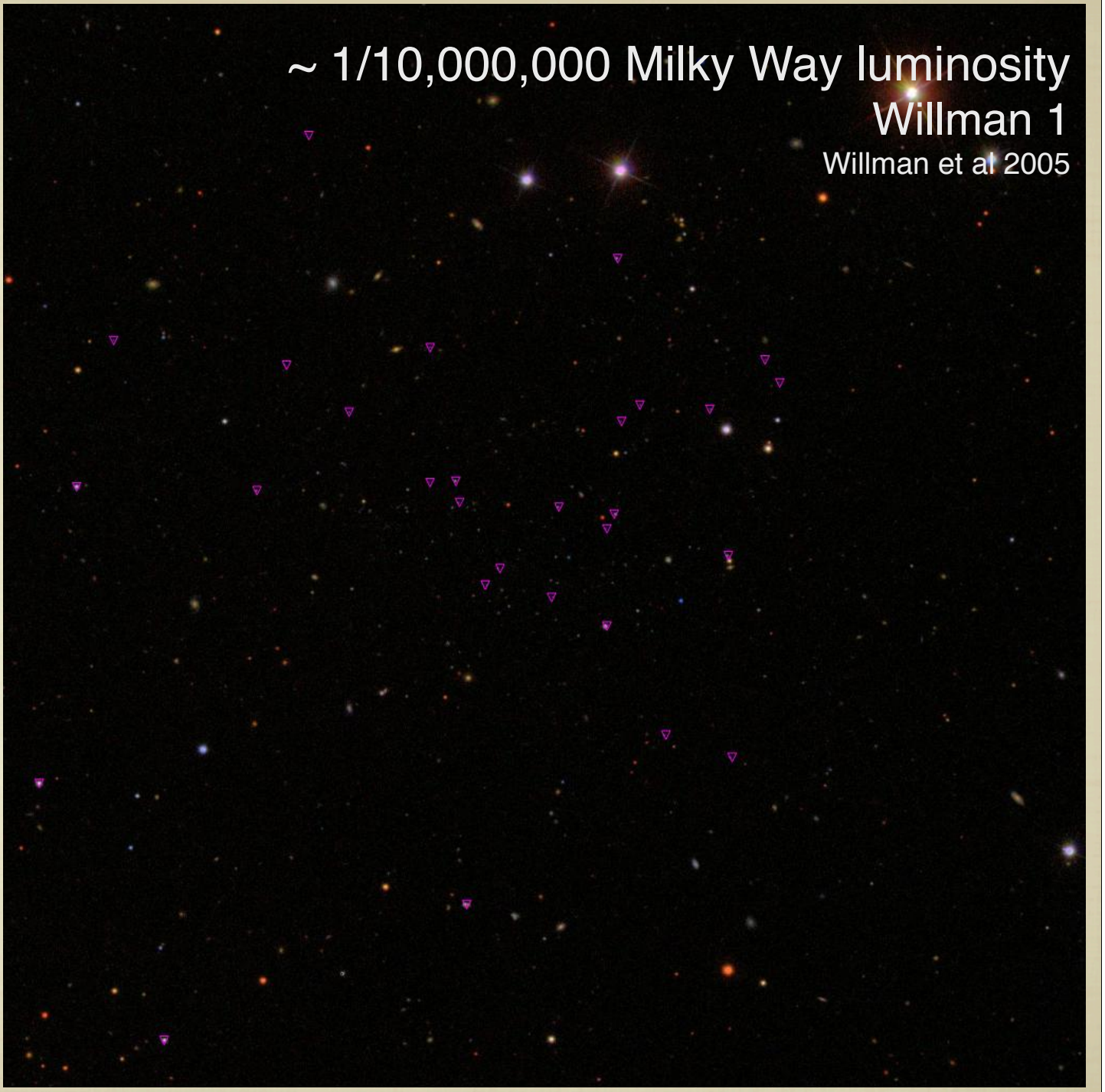
Willman et al 2005


~ 1/1,000,000 Milky Way luminosity
Ursa Major I
Willman et al 2005

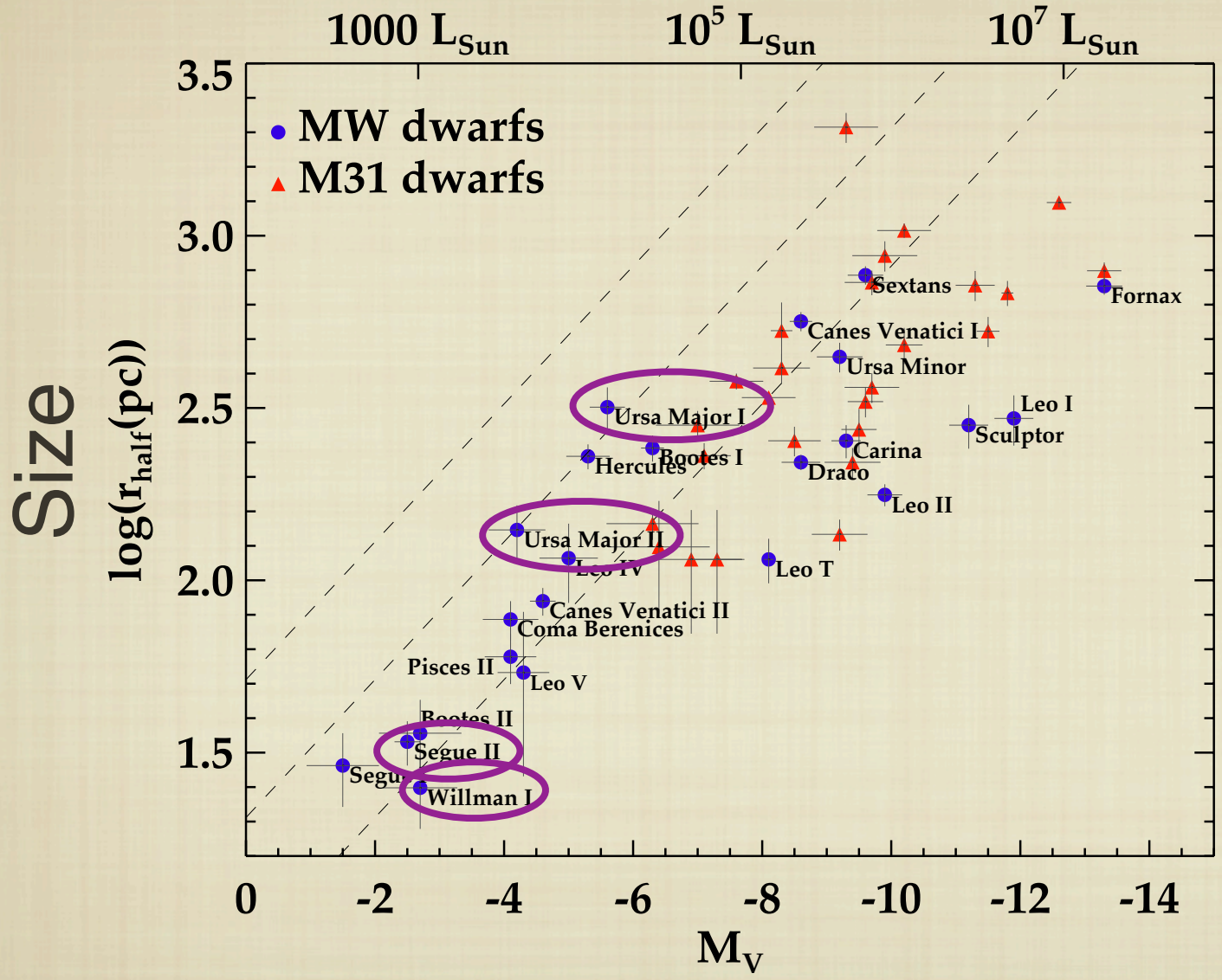
Since 2005, 15 “invisible” galaxies have been discovered to orbit the Milky Way.

This might be the most numerous type of galaxy in the Universe.

MW dwarf galaxy discovery papers: Willman et al 05a,b; Zucker et al 06a,b; Belokurov et al 06,07,08,09,10; Walsh, Jerjen & Willman 07, Irwin et al 07; Detection limits: Walsh, Willman & Jerjen 2009, Koposov et al 2008



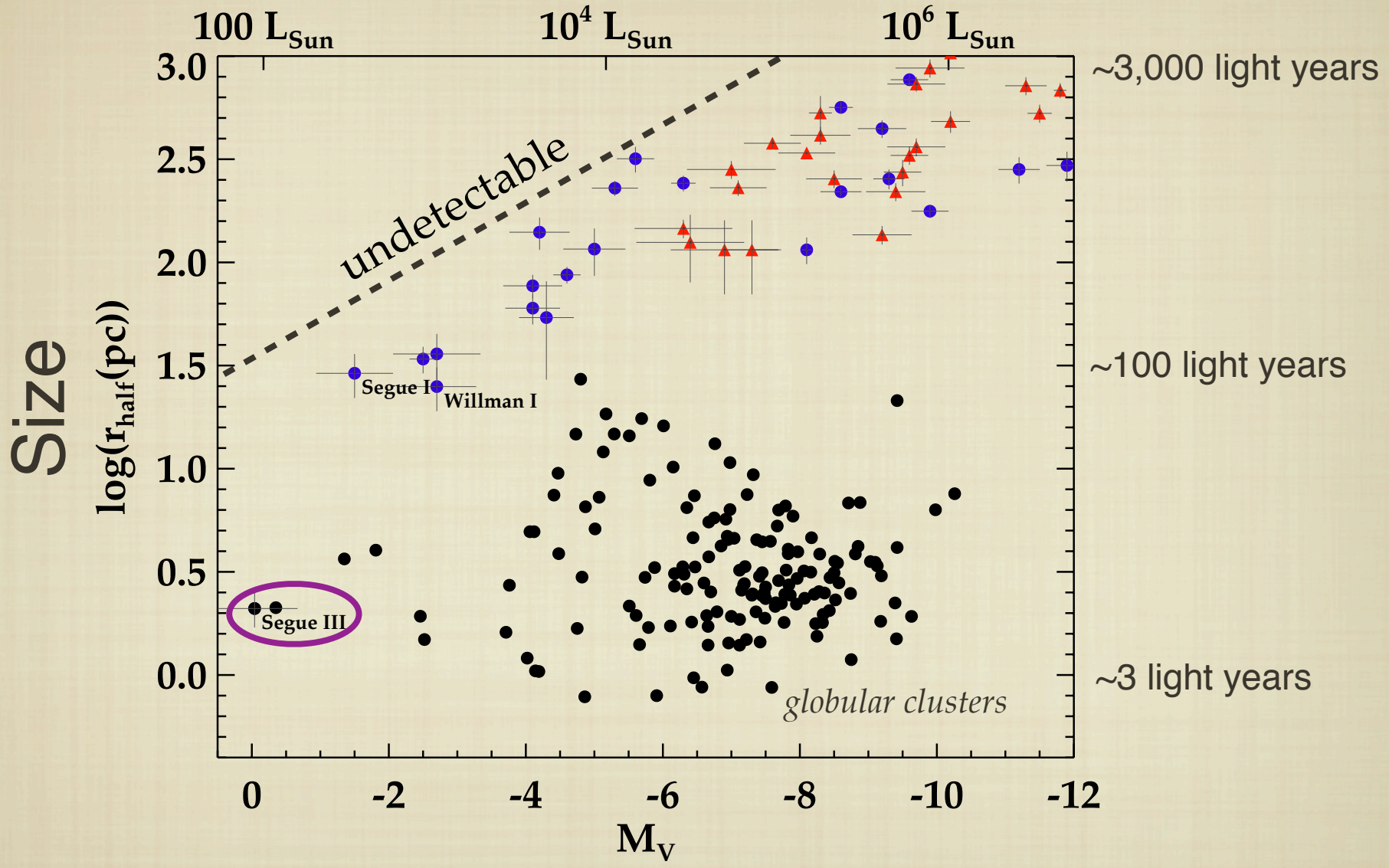
Luminosities and sizes of nearby dwarf galaxies



~3,000 light years

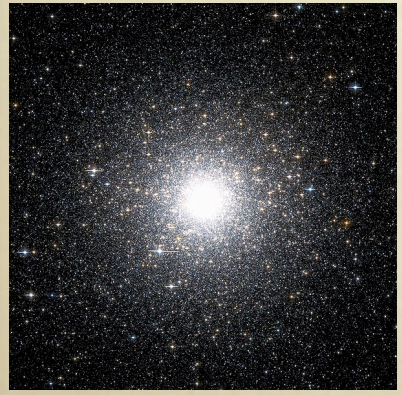
~100 light years

Luminosities and sizes of dwarfs and star clusters

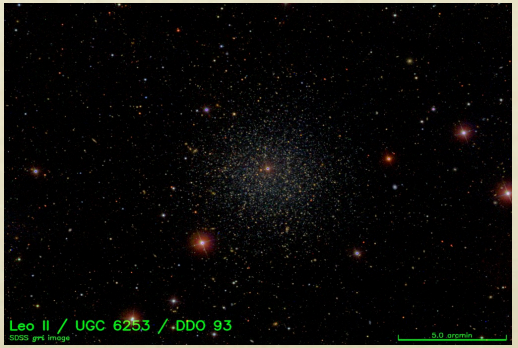


A galaxy is:

A self-bound stellar system whose properties cannot be explained by visible matter + Newton's laws Willman & Strader 2012

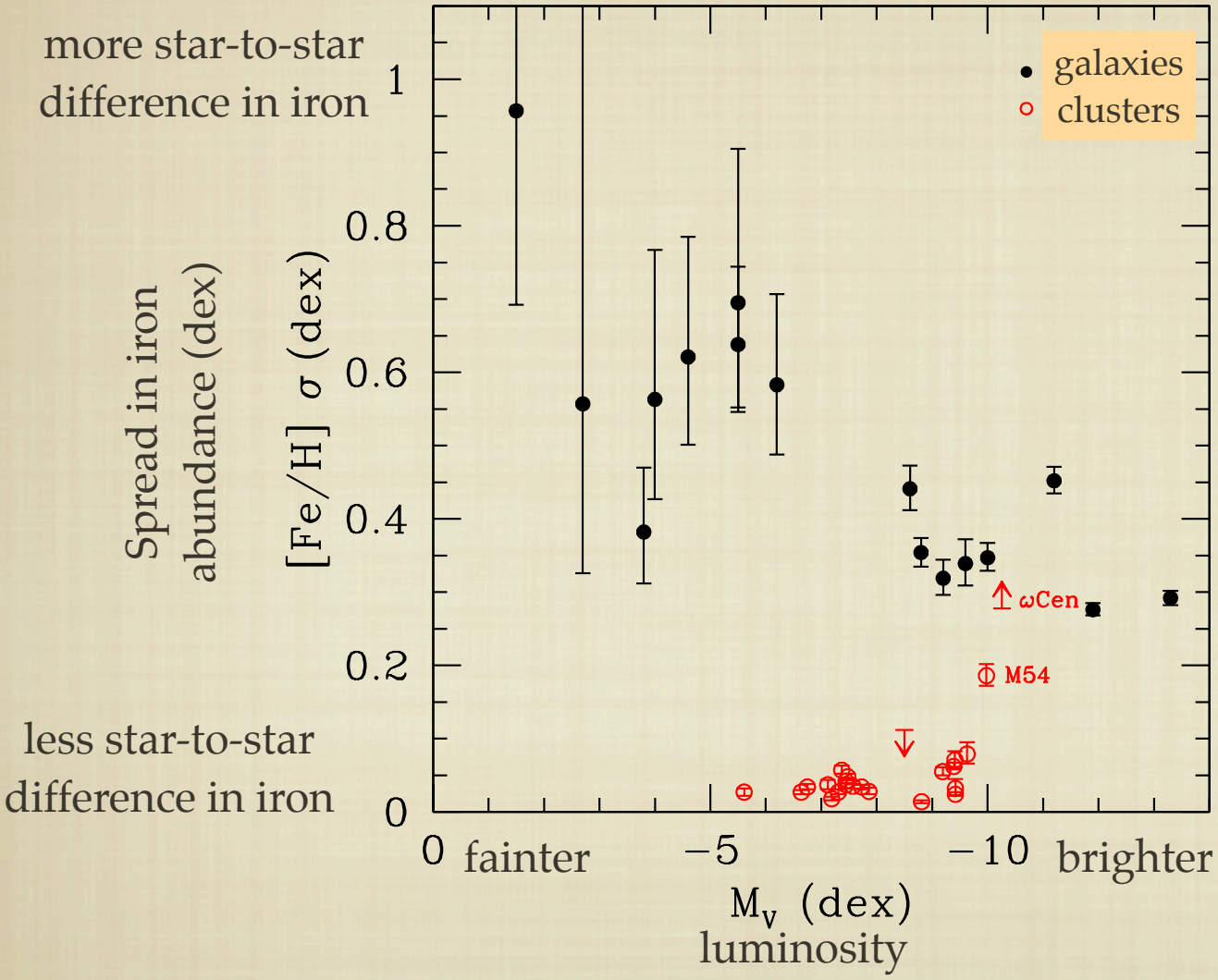


Star cluster: Weighs what you expect



Galaxy: Heavier than expected - dark matter makes up the difference

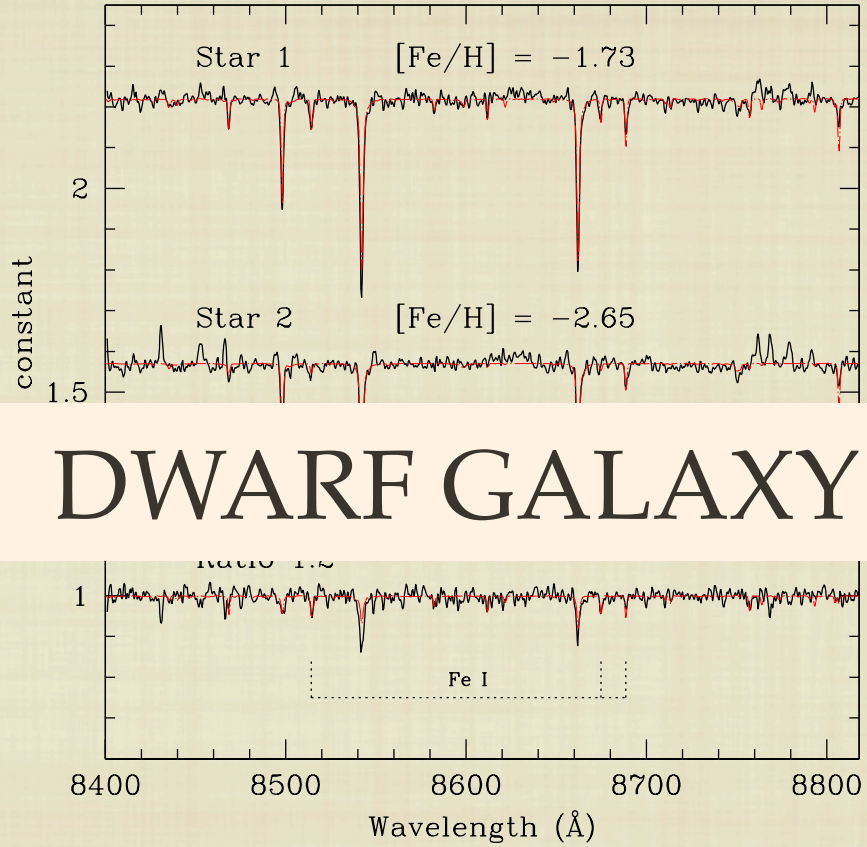
Iron spread can distinguish galaxies from clusters



Willman & Strader 2012

Dwarf data from: Kirby et al 08, 10; Norris et al 10, Simon et al 11, Willman et al 11; GC data from: Carretta et al 06,07,09,10, Johnson & Pilachowski 2010, Cohen et al 2010, Gratton et al 07, Marino et al 11

Iron spread can distinguish galaxies from clusters:
Willman 1



DWARF GALAXY

Factor of ten difference in the iron abundance of two stars belonging to the Willman 1 galaxy

Willman et al (2011)

Keck/DEIMOS spectra

Undergraduates and invisible galaxies

19 students pictured here have either conducted research on ultra-faint dwarf galaxies...


Astro students, spring 2010


Astro students, spring 2013

... or traveled to Kitt Peak National Observatory to observe them.

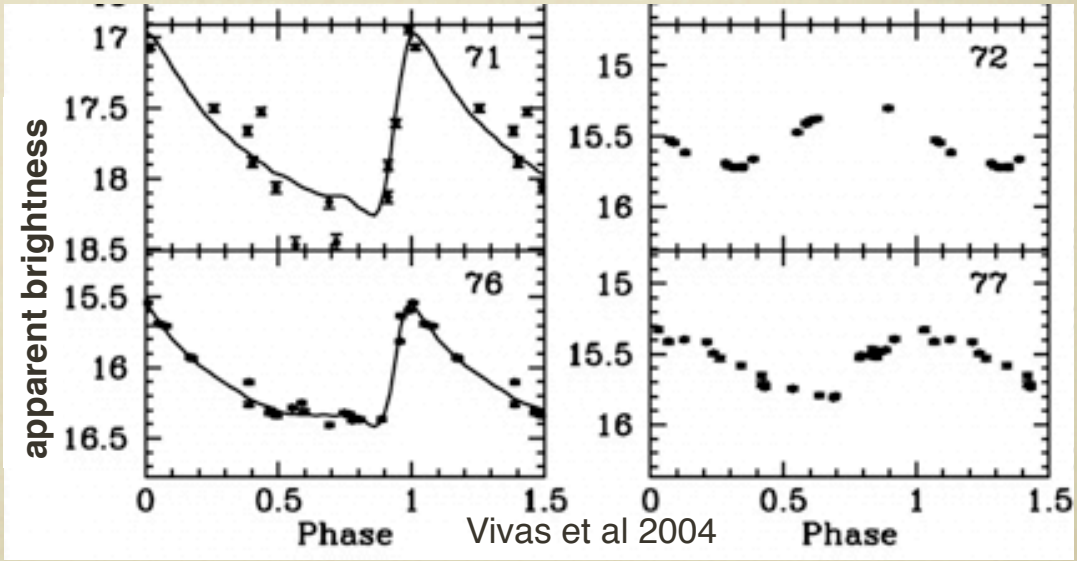
Undergraduates and invisible galaxies

Recent research focus

RR Lyrae (a type of variable star) in ultra-faint dwarfs

amplitude ~ 0.2 - 1.5 mag
period ~ 0.15 - 0.8 days

- Standard candles - distances
- Possible discovery tool
- Diagnostic of stellar population



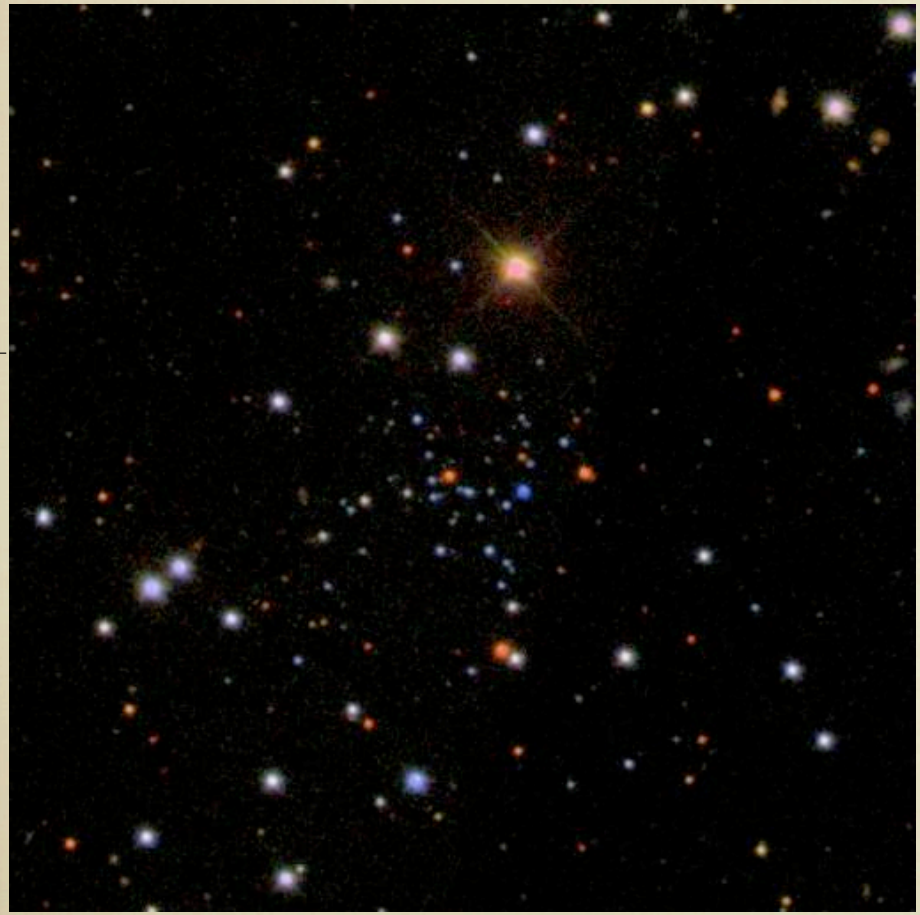
Vivas et al 2004

Undergraduates and invisible galaxies

Small aperture telescope
science with undergraduates
KPNO 0.9m consortium


WALK
ON LEFT
FACING
TRAFFIC

KPNO 0.9m time-series observations of Segue 2 and 3



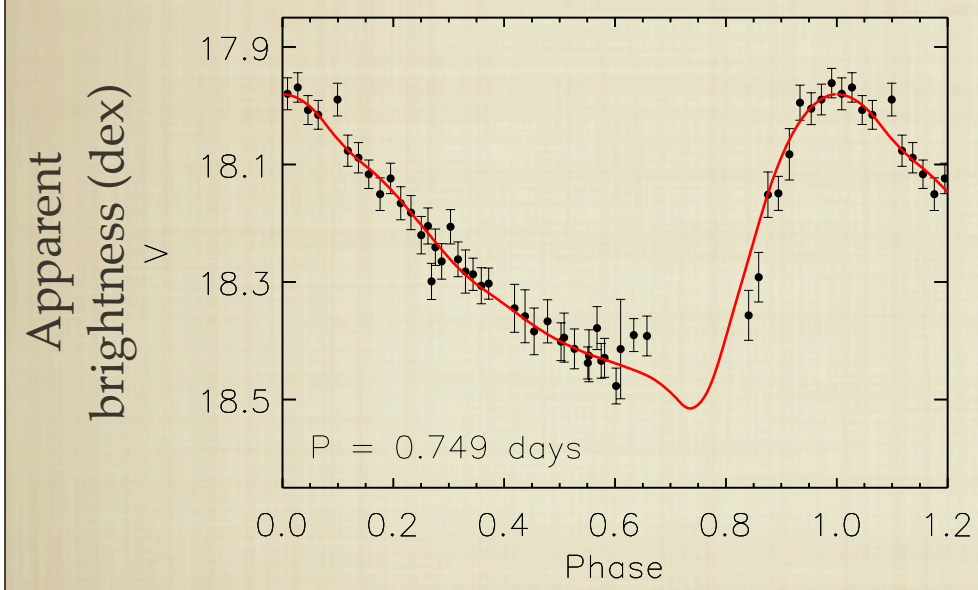
Segue 2 and Segue 3 are both Milky Way satellites located less than 100,000 light years away.

Segue 3 (shown to the left) is the least luminous star cluster known. Segue 2 is one of the least luminous galaxies known.

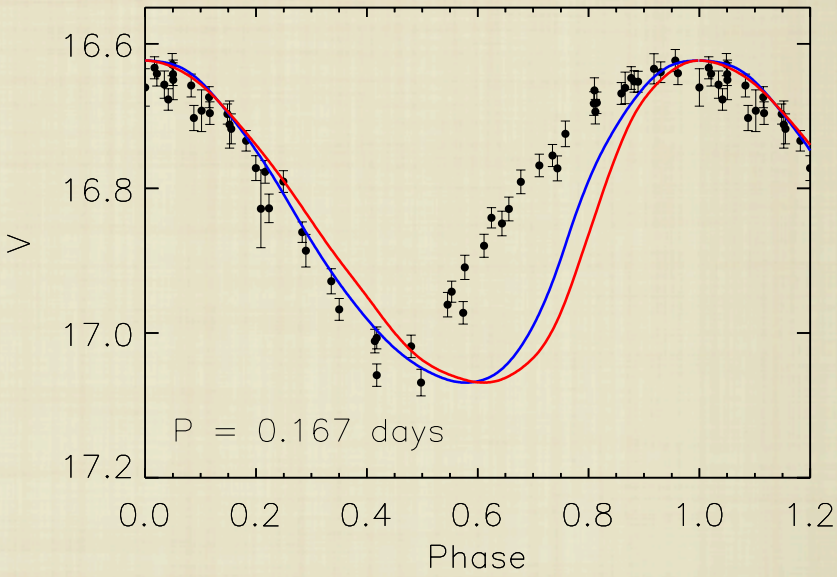
Boettcher et al. 2013

KPNO 0.9m time-series observations of Segue 2 and 3

RR Lyrae star in Segue 2



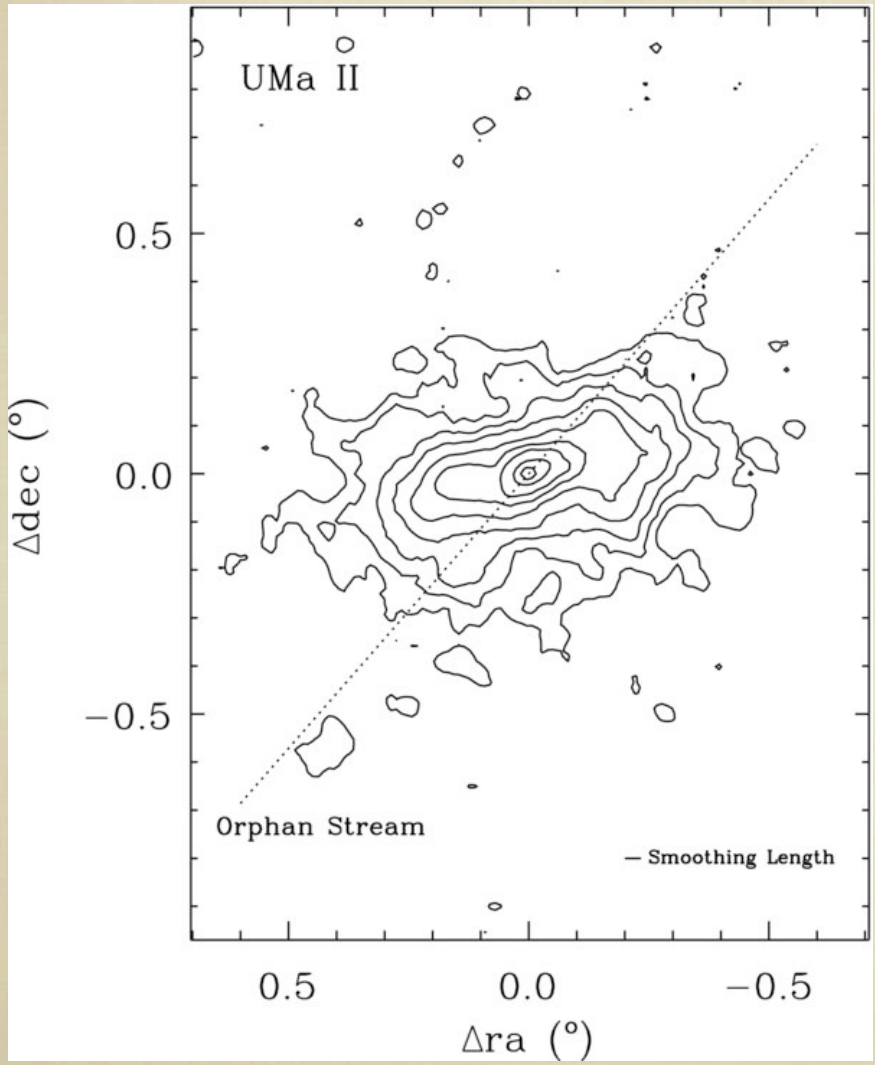
probable eclipsing binary near Segue 3



This star provides a distance measurement to Segue 2 of 37 kpc

Boettcher et al. 2013

KPNO 0.9m time-series observations of Bootes III and Ursa Major II



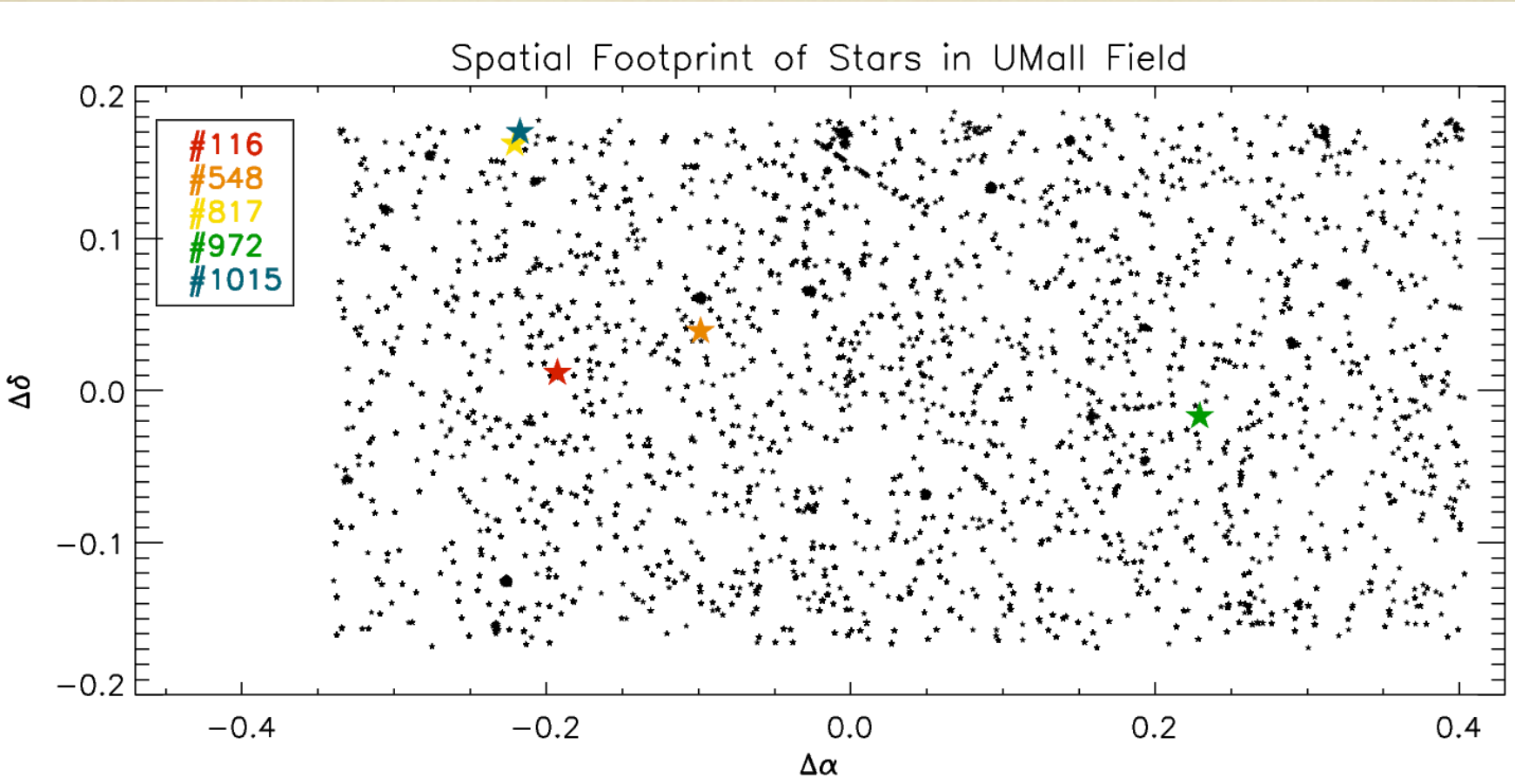
Contour plot showing the spatial distribution of stars in Ursa Major II

This ultra-faint galaxy has an unusually high ellipticity

Is it losing stars?

Gaughan et al. in preparation

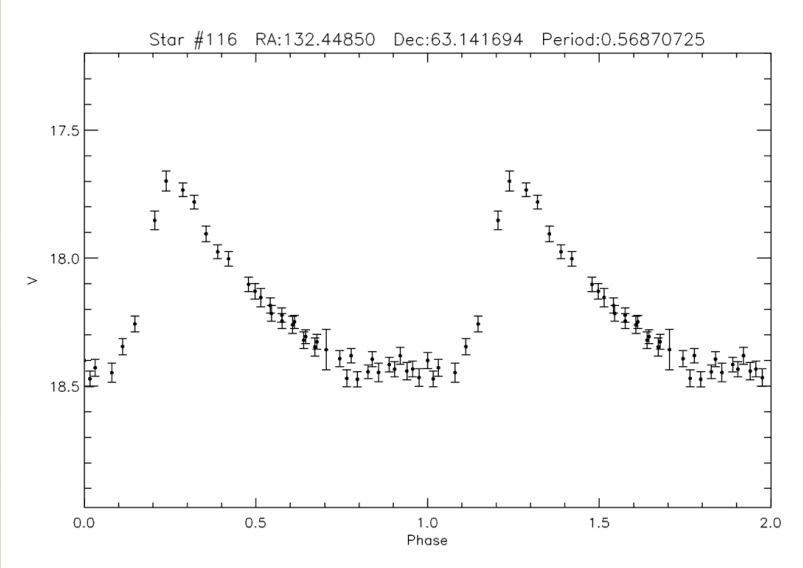
KPNO 0.9m time-series observations of Bootes III and Ursa Major II

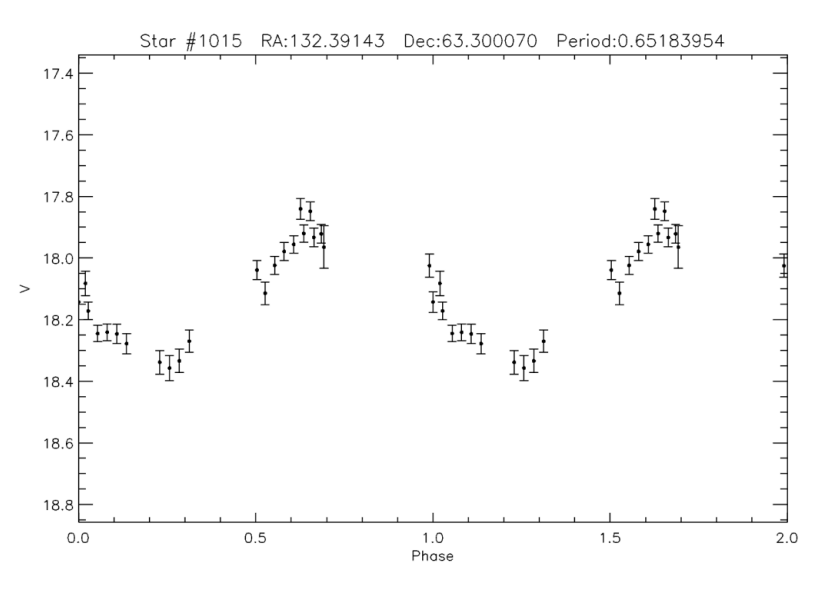


Gaughan et al. in preparation

KPNO 0.9m time-series observations of Bootes III and Ursa Major II

Apparent brightness (dex)

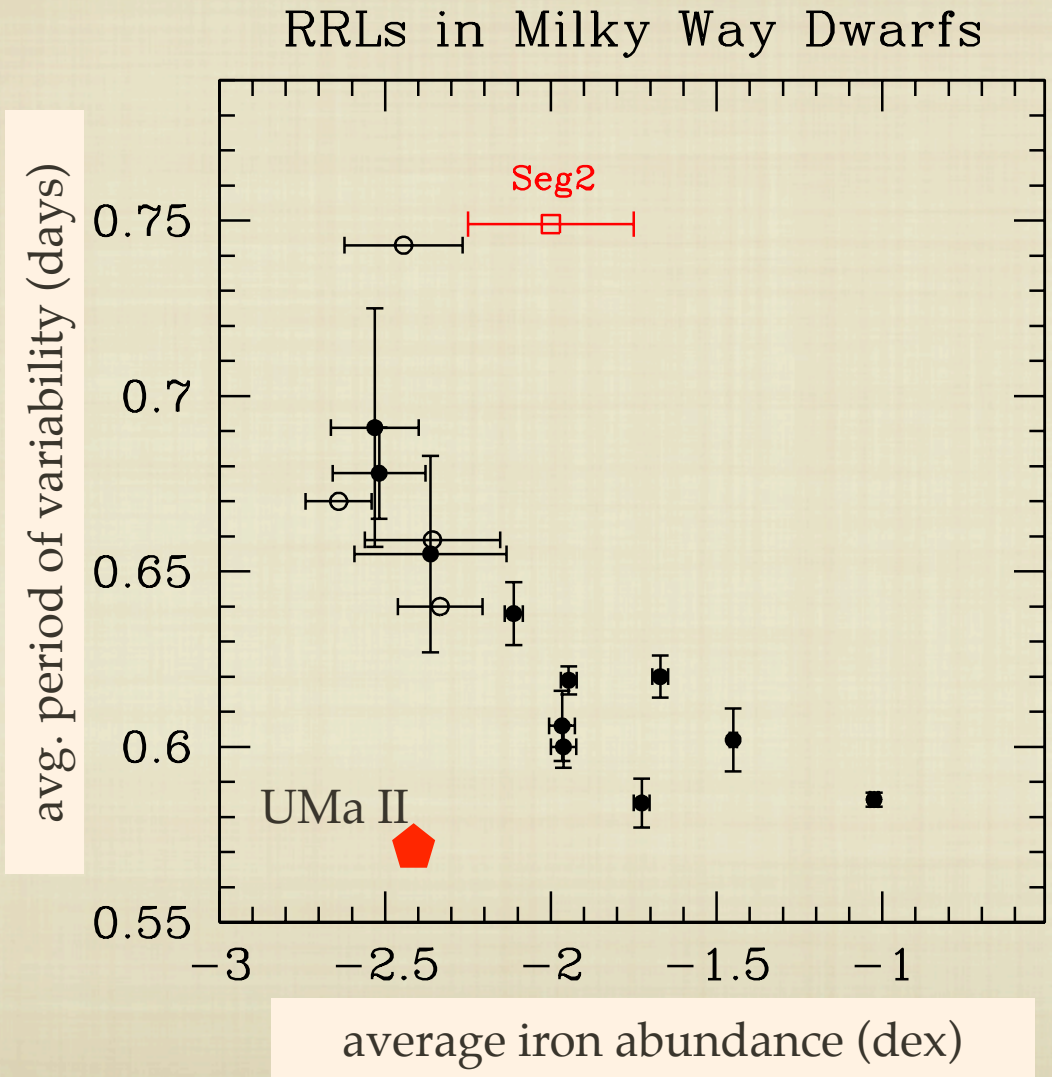




No variable stars found in Bootes III; four candidate RR Lyrae found in Ursa Major II (only 1 previously published)

Gaughan et al. in preparation

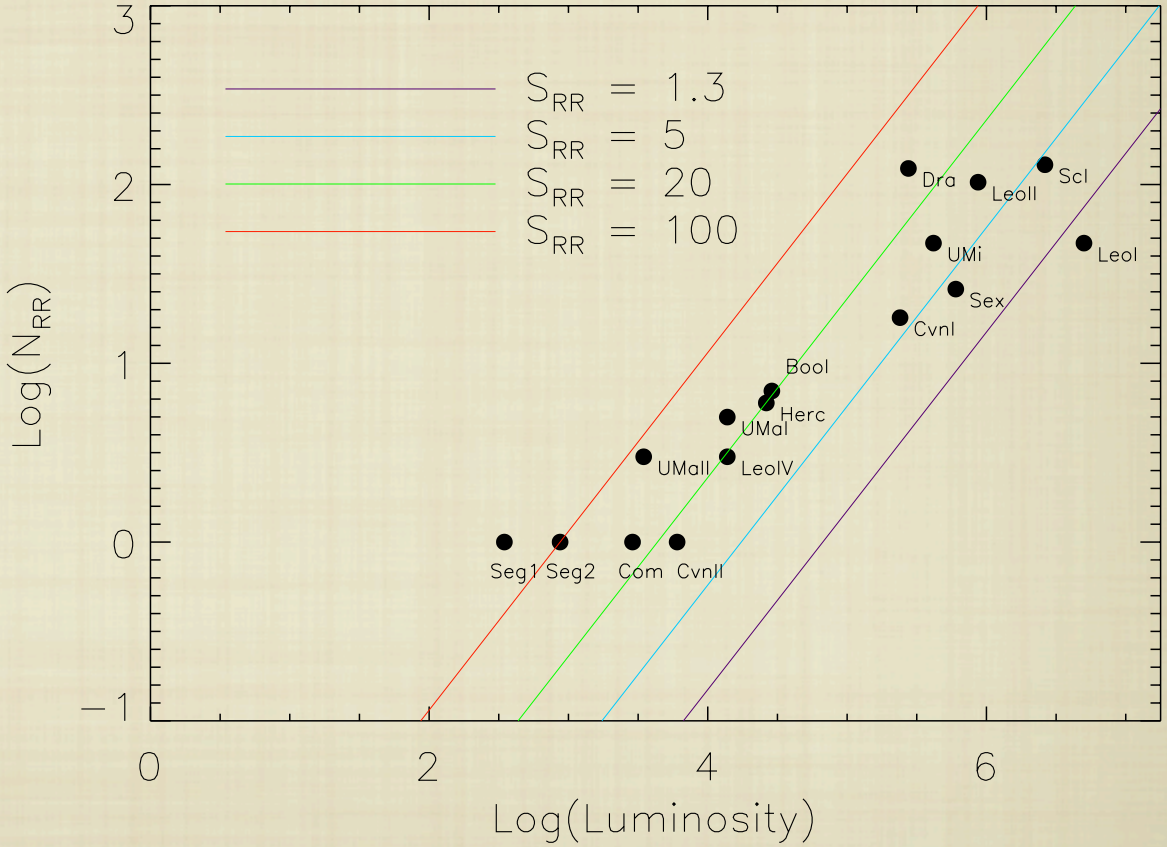
RR Lyrae in ultra-faint dwarf galaxies



Boettcher et al. 2013, Gaughan et al. in prep.

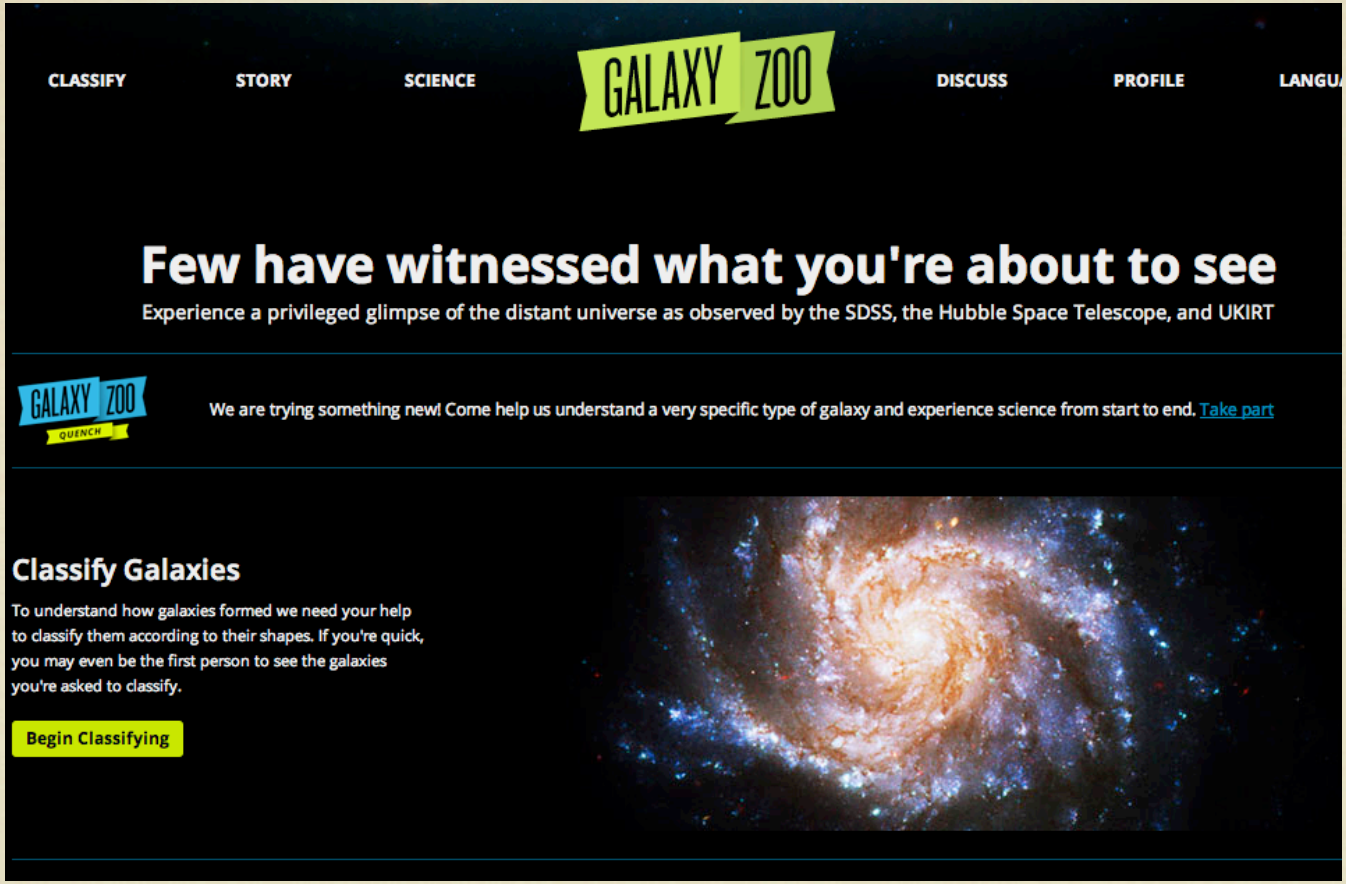
Flip this around: What if we only know where the RR Lyrae are?

Can we use RR Lyrae to discover previously unseen invisible galaxies?



Mariah Baker (class of 2014) & Willman

Galaxies in the classroom



Students at all levels:

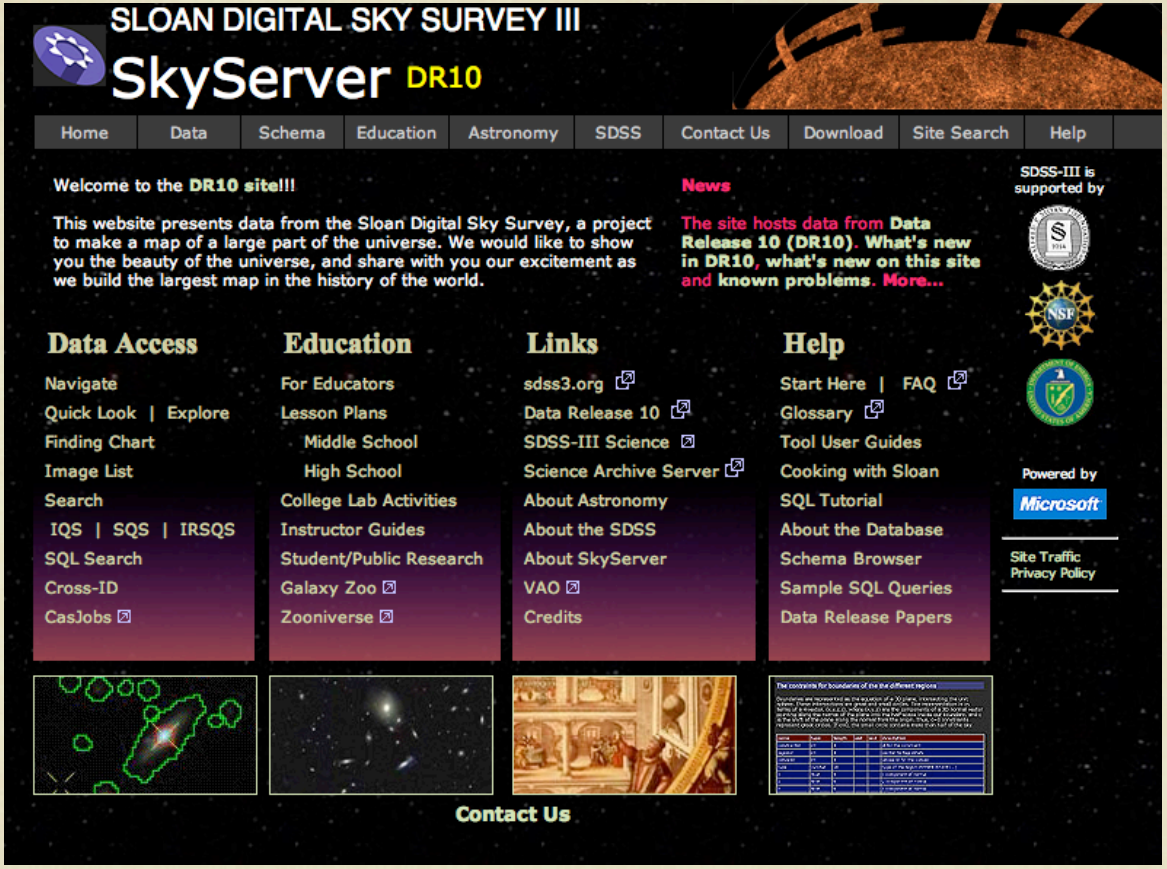
Visually explore galaxy classification, while contributing to actual galaxy research.

Galaxies in the classroom

Students at all levels:

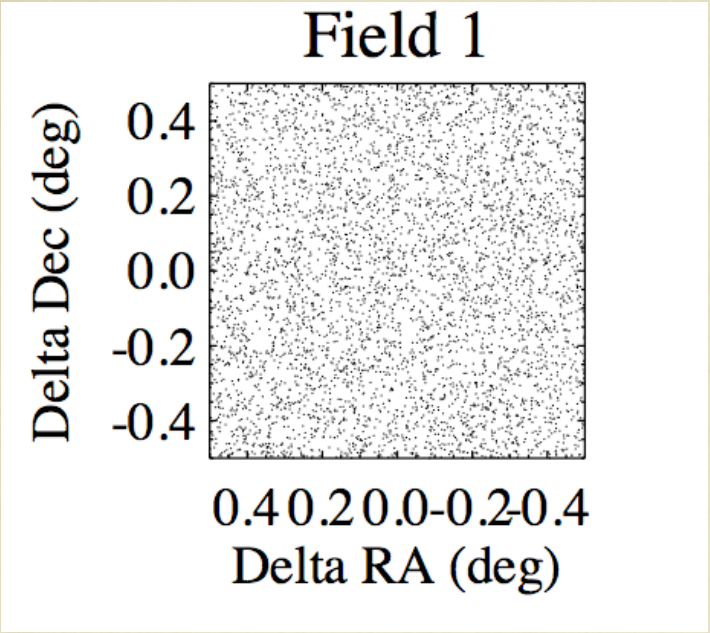
Interactively explore the Milky Way with multi-wavelength maps.

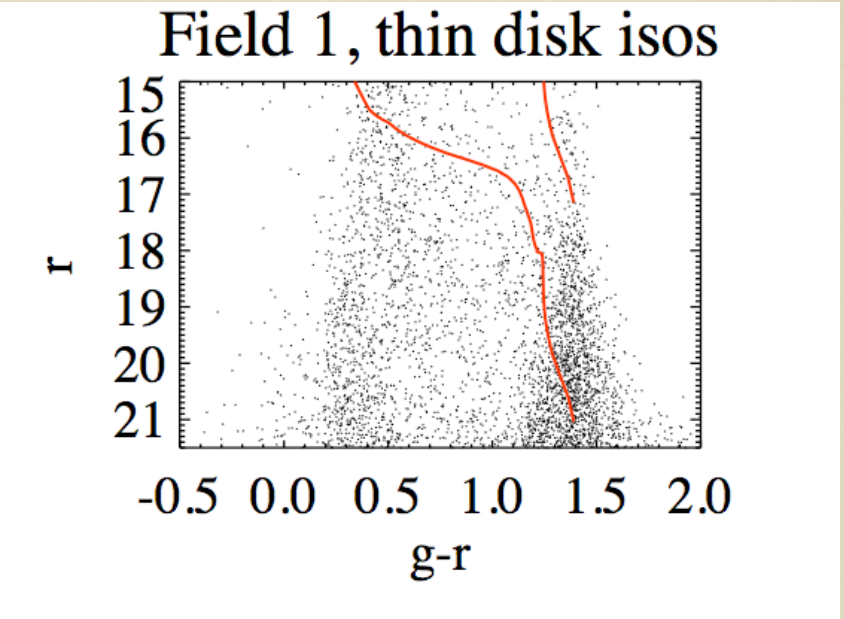
Galaxies in the classroom



Upper-level majors with programming experience:
Introduce students to big data and the SQL database query language.

Galaxies in the classroom





$$M_r = 5.19 + 2.474(r-z) + 0.4340(r-z)^2 + 0.08635(r-z)^3$$

Upper-level majors with programming experience:
Use SDSS data to study Galactic structure, error propagation, observational bias

Final points

1. Invisible galaxies may be the most numerous galaxy in the universe and they hold important clues to the properties of dark matter.

2. To properly compare cosmological predictions with observations requires careful classification of galaxies

3. Undergraduates can meaningfully engage in studies of invisible galaxies, including observations using the KPNO 0.9m telescope

4. There are many ways to bring galaxy research into the high school and college classroom

The End