

Invisible Galaxies

The background of the slide is a deep space photograph showing a vast field of stars. The stars vary in color, including red, orange, yellow, and blue. Some stars are bright and prominent, while others are faint and numerous. The overall appearance is that of a rich stellar population, likely from a galaxy that is not directly visible in this view.

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

Large Magellanic Cloud

image credit: Yuri Beletsky (ESO) and APOD

~ 1/10 Milky Way luminosity



NGC 205

image credit: www.noao.edu

~ 1/40 Milky Way luminosity

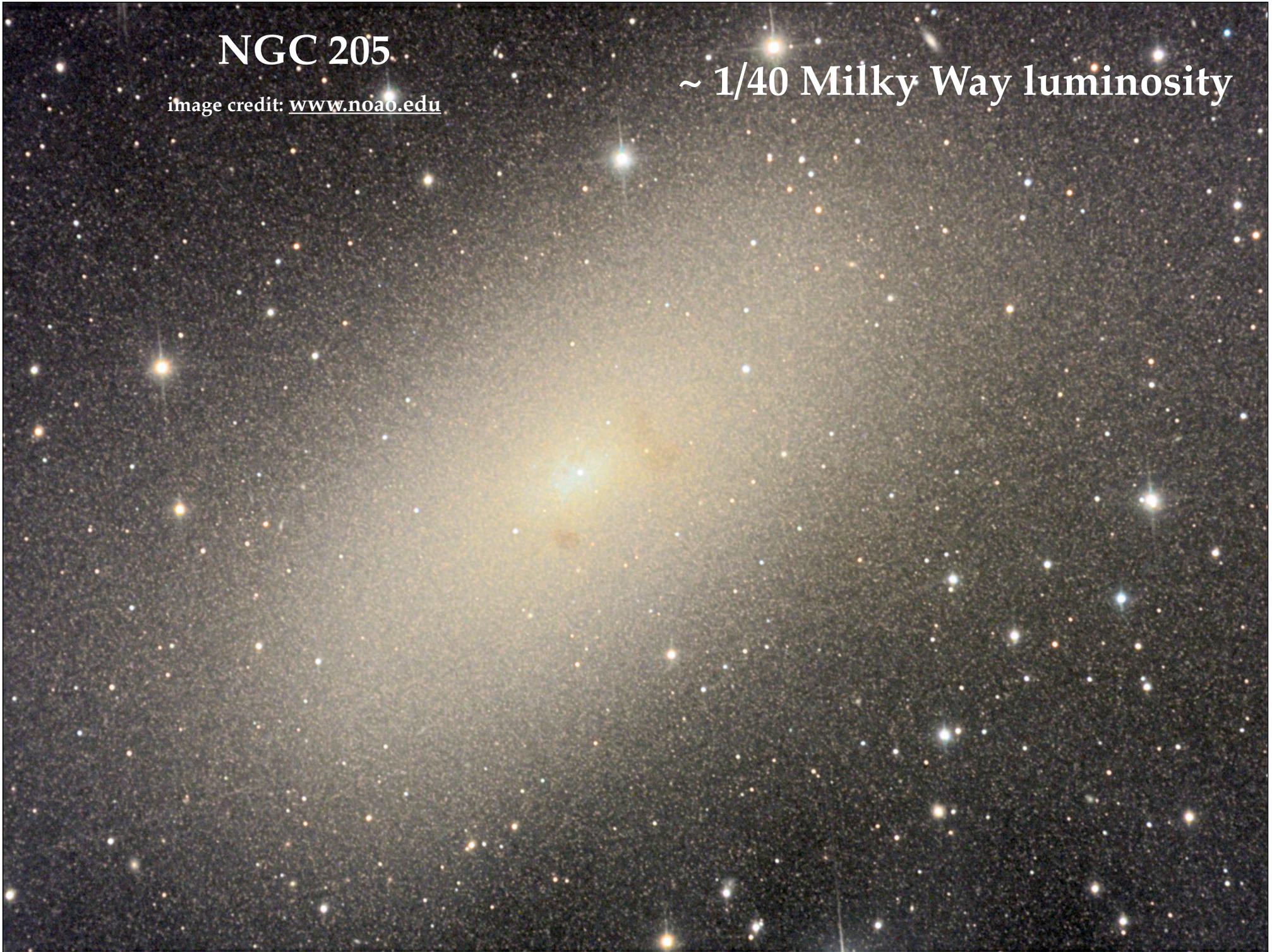


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan
Digital Sky Survey Collaboration

~ 1/300 Milky Way luminosity

Sextans B / UGC 5373 / DDO 70

SDSS *gri* image

2.0 arcmin

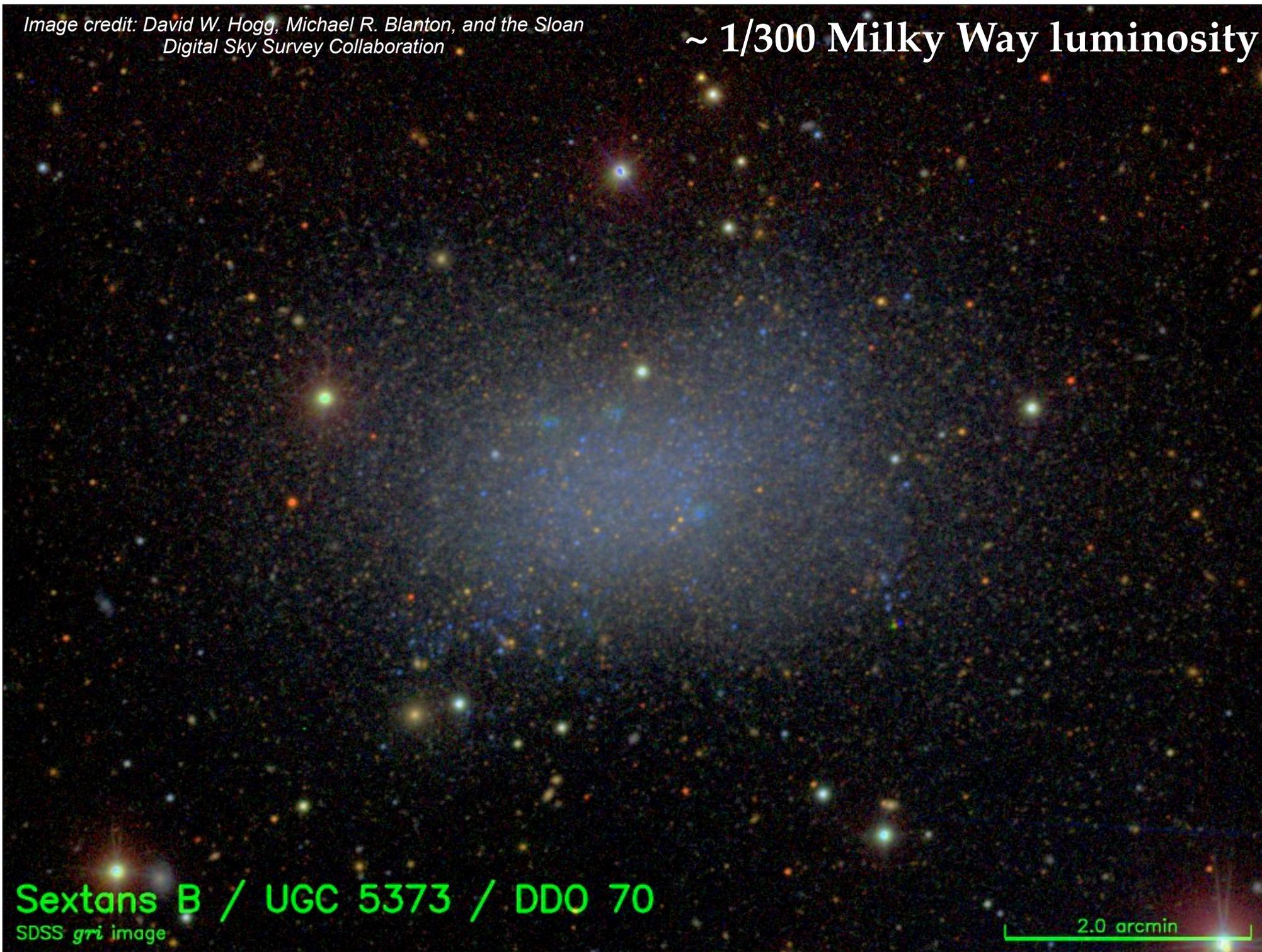


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan
Digital Sky Survey Collaboration

~ 1/2700 Milky Way luminosity

Leo I / UGC 5470 / DDO 74
SDSS *gri* image

5.0 arcmin

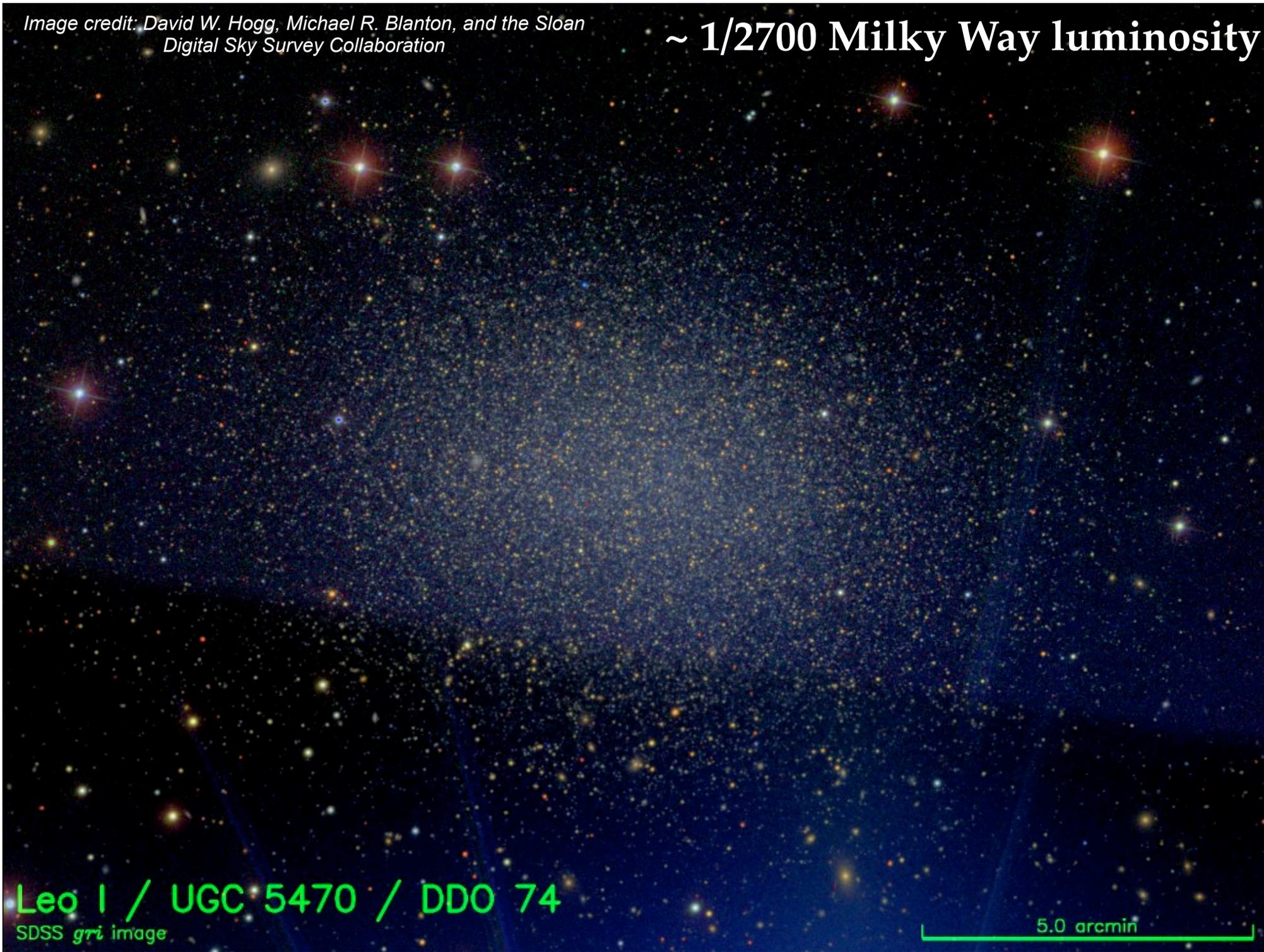
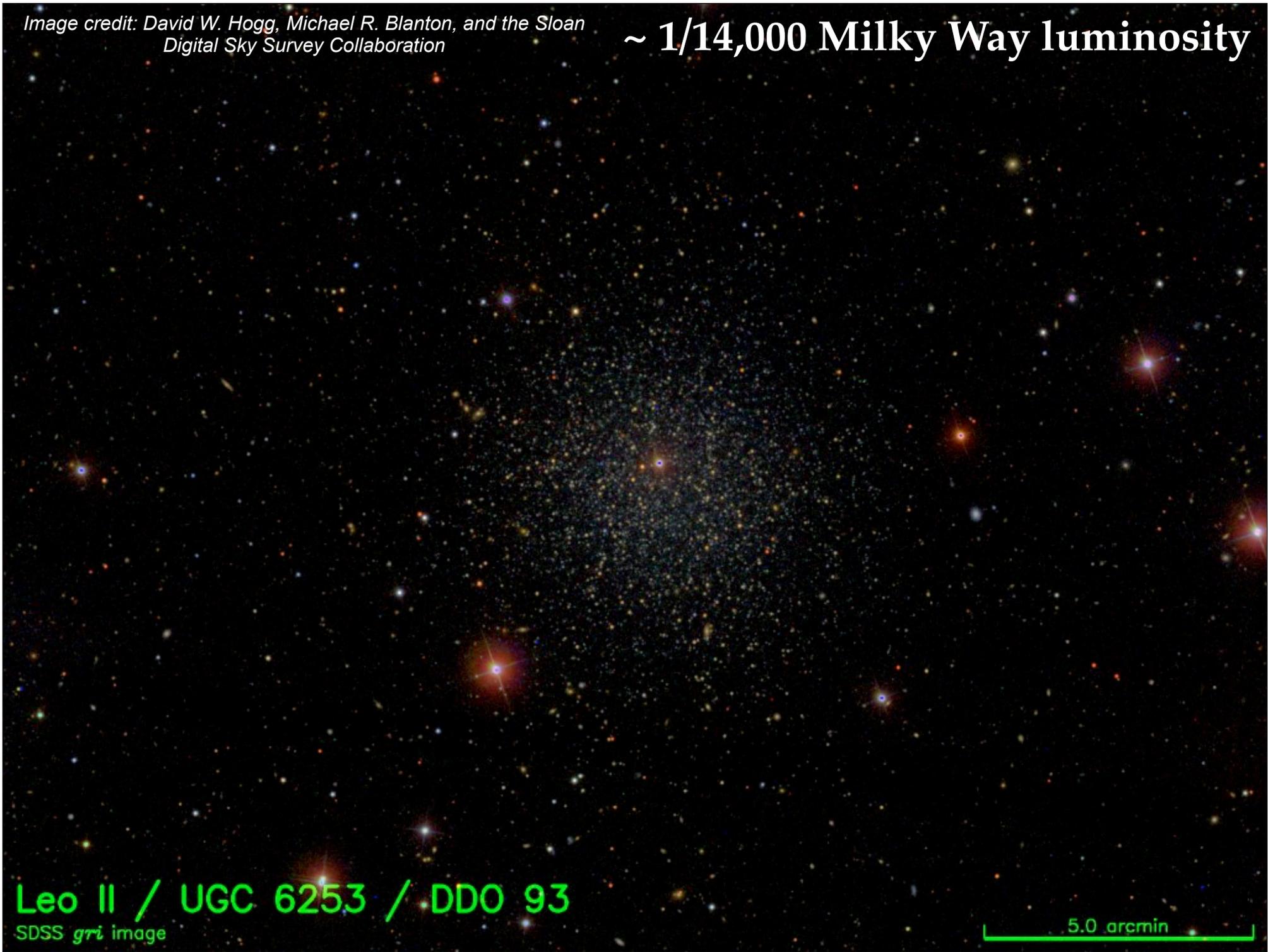


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan
Digital Sky Survey Collaboration

~ 1/14,000 Milky Way luminosity

Leo II / UGC 6253 / DDO 93
SDSS *gri* image

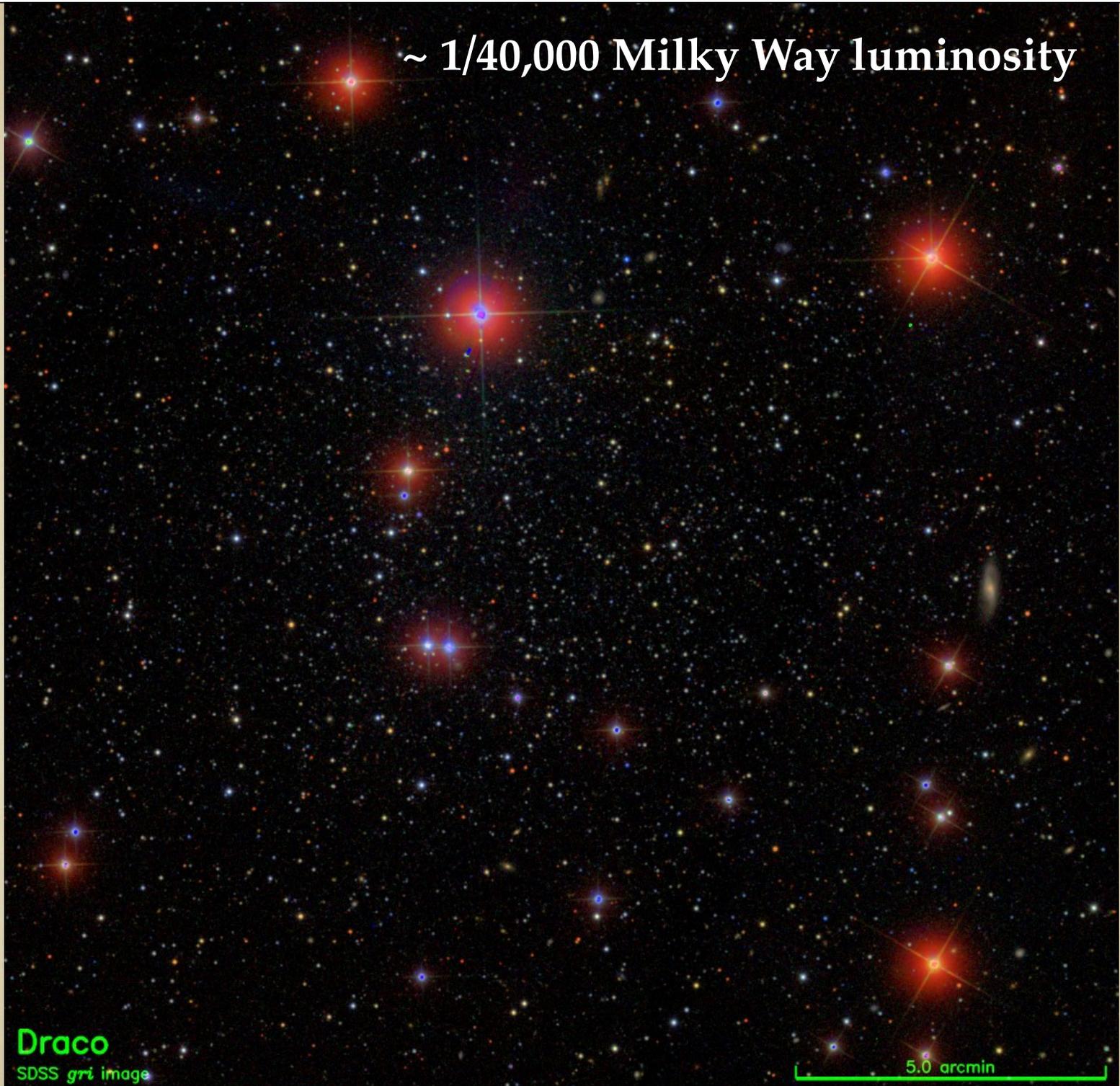
5.0 arcmin



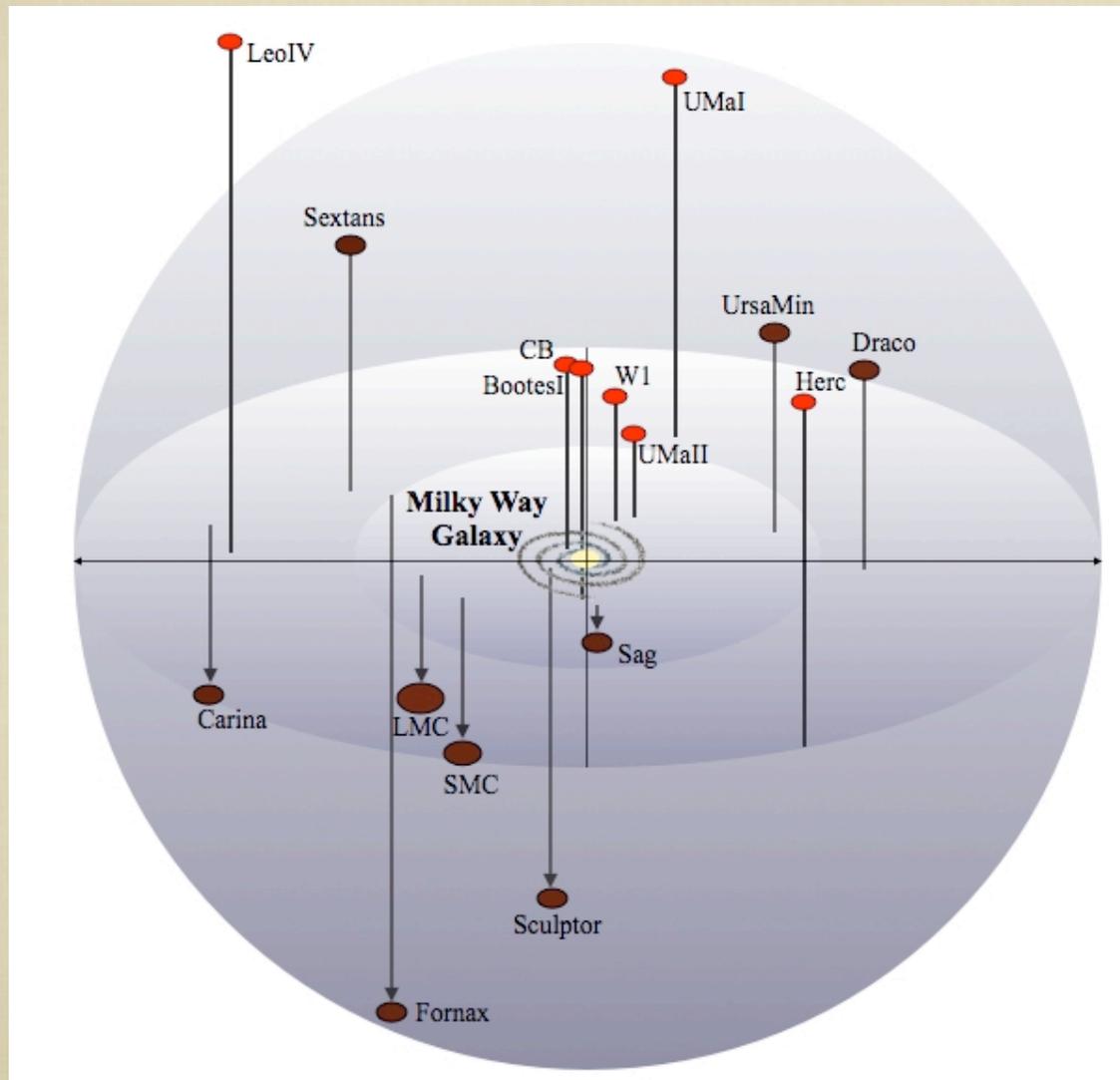
~ 1/40,000 Milky Way luminosity

Draco
SDSS *gri* image

5.0 arcmin



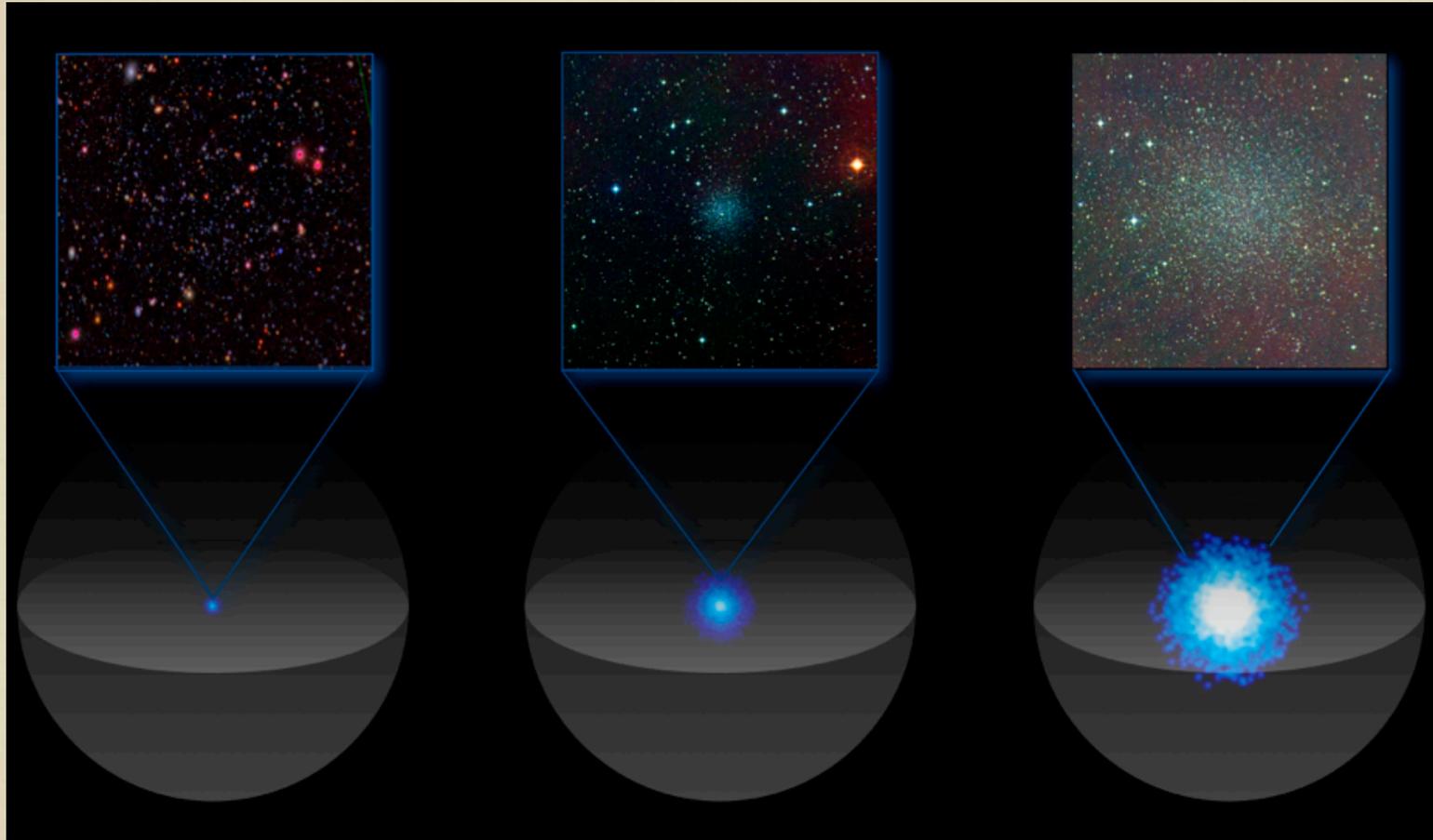
Dwarf galaxies around the Milky Way



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



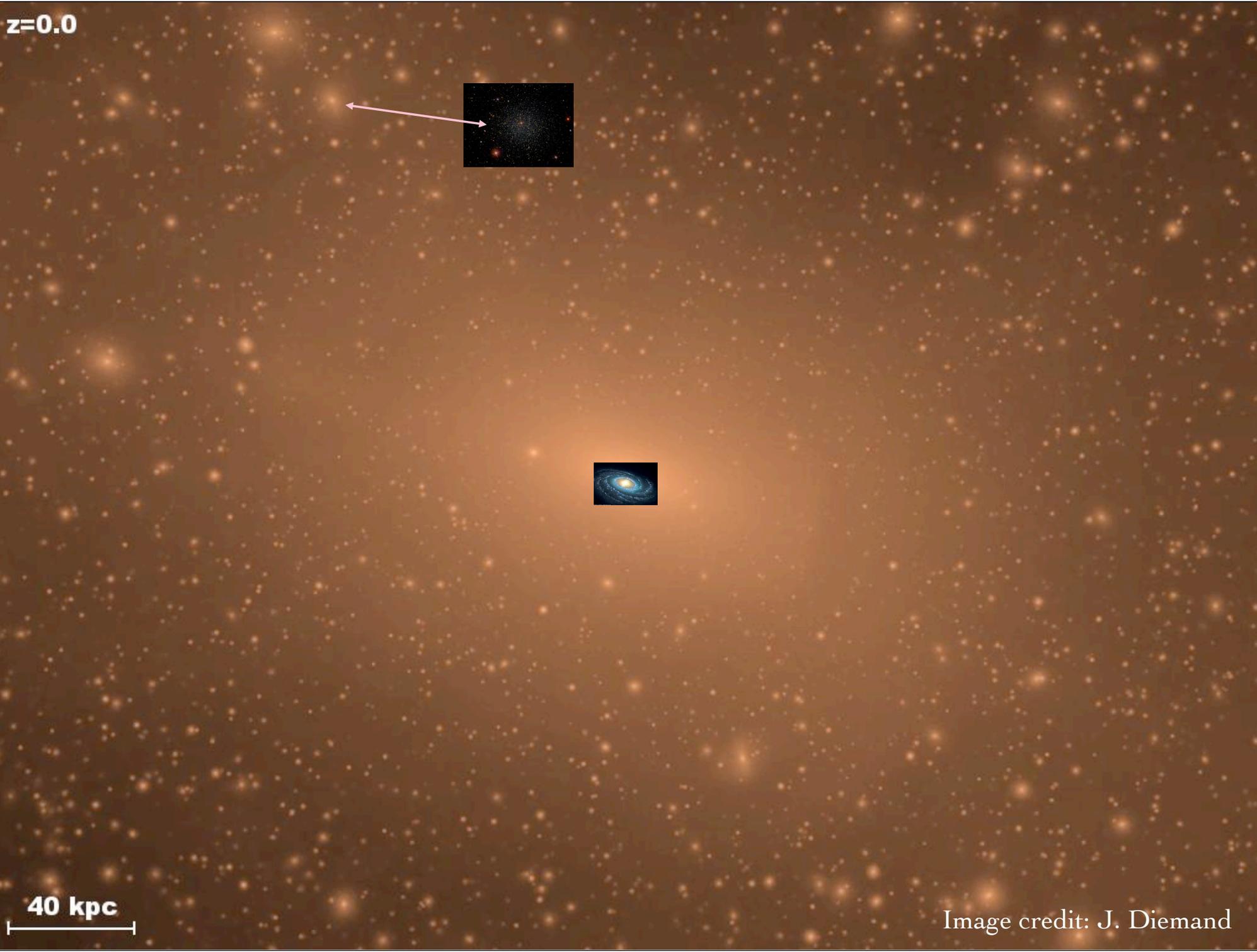
partial solution: We haven't yet found the galaxies

40 kpc



Image credit: J. Diemand

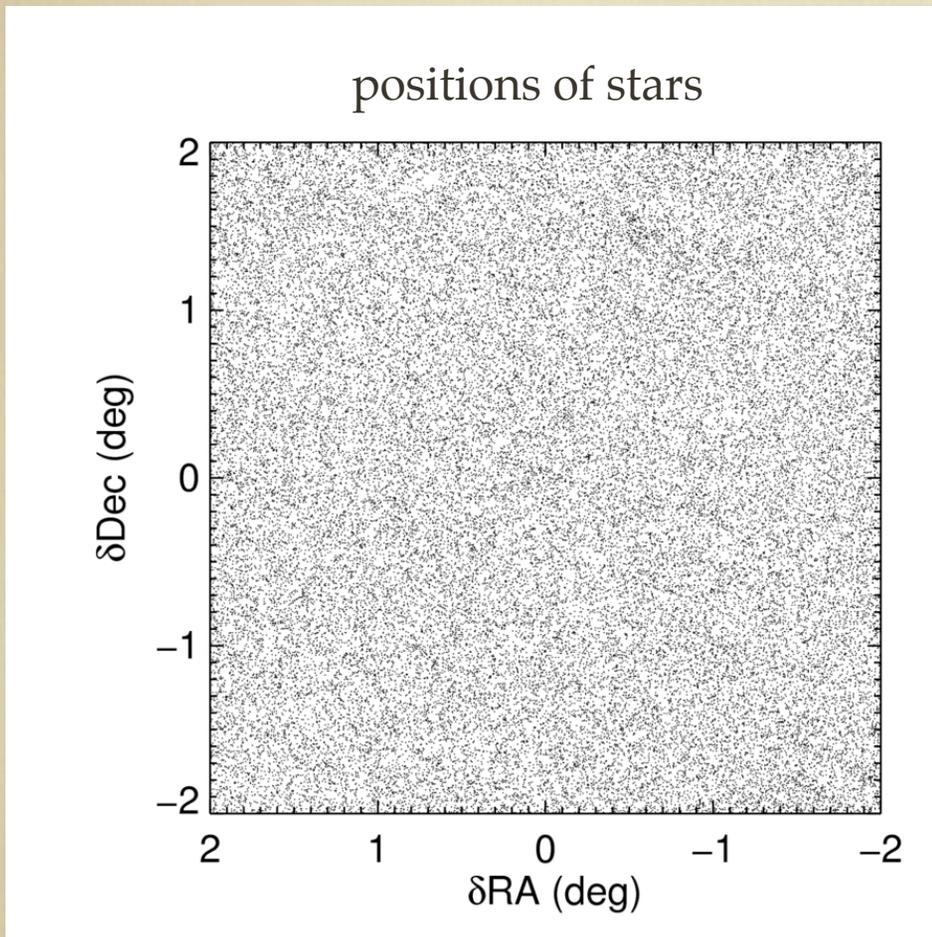
$z=0.0$



40 kpc

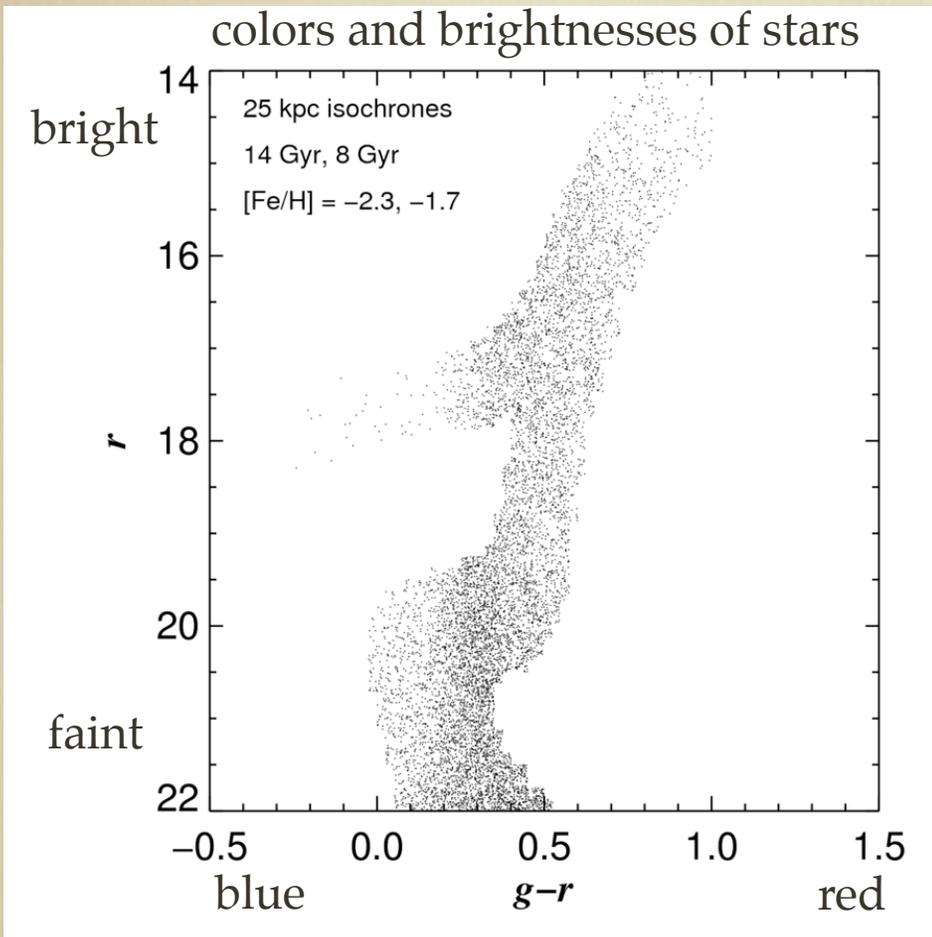
Image credit: J. Diemand

Finding Invisible Galaxies



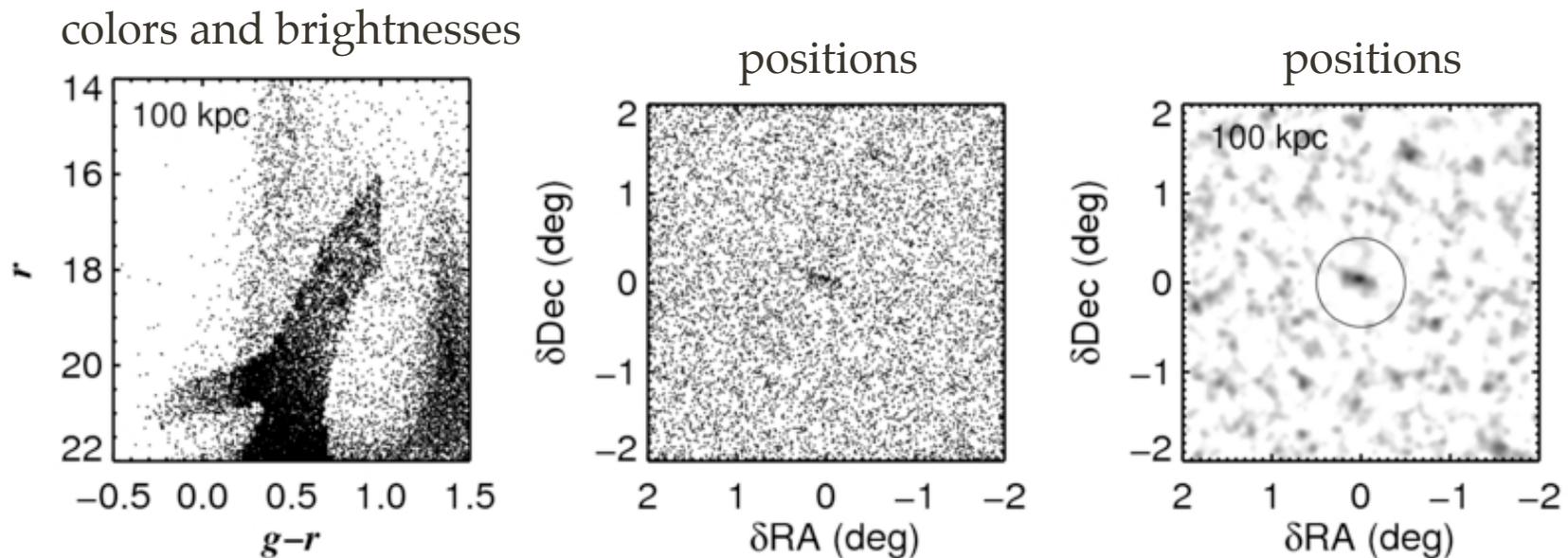
Willman et al 2002, Walsh, Willman & Jerjen 2009; see also e.g. Koposov et al 2008, Belokurov et al.

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



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

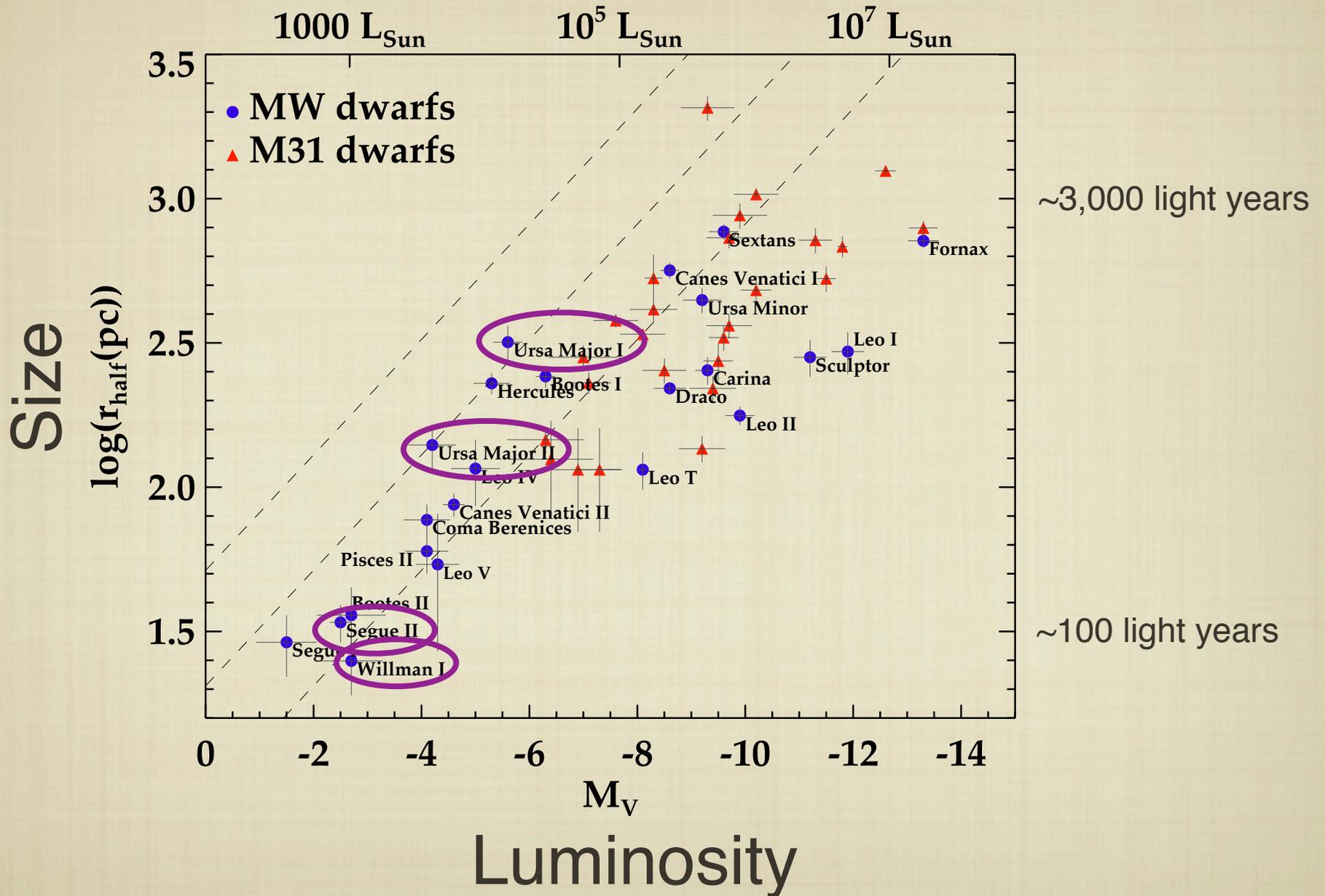
~ 1/10,000,000 Milky Way luminosity

Willman 1

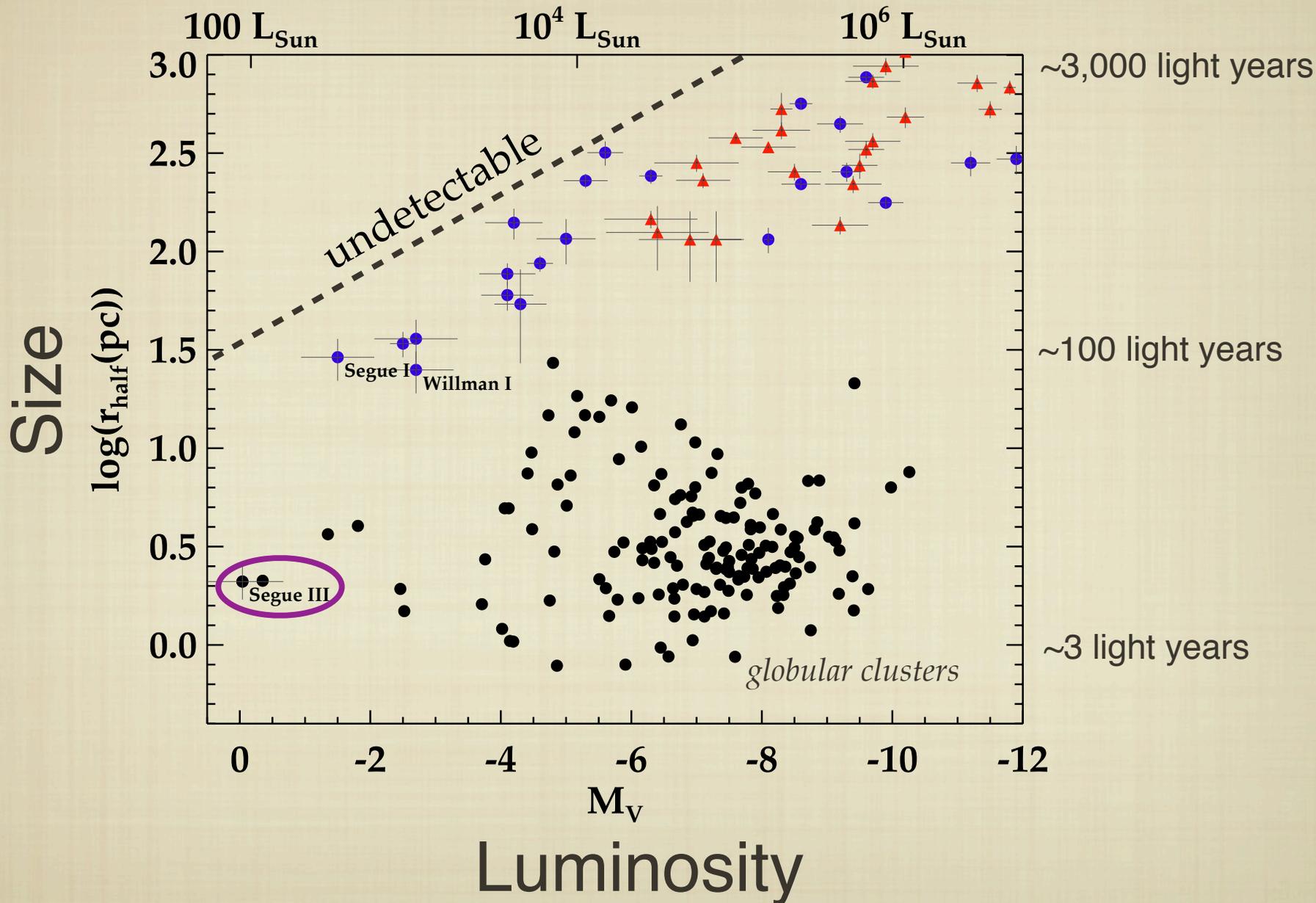
Willman et al 2005



Luminosities and sizes of nearby dwarf galaxies



Luminosities and sizes of dwarfs and star clusters

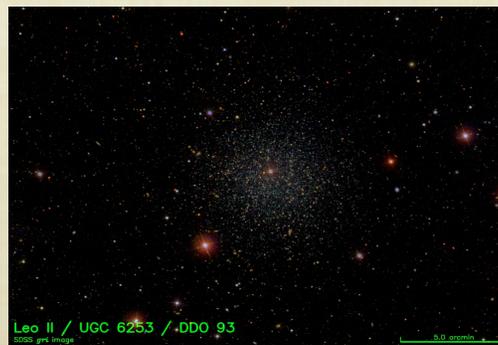


A galaxy is:

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

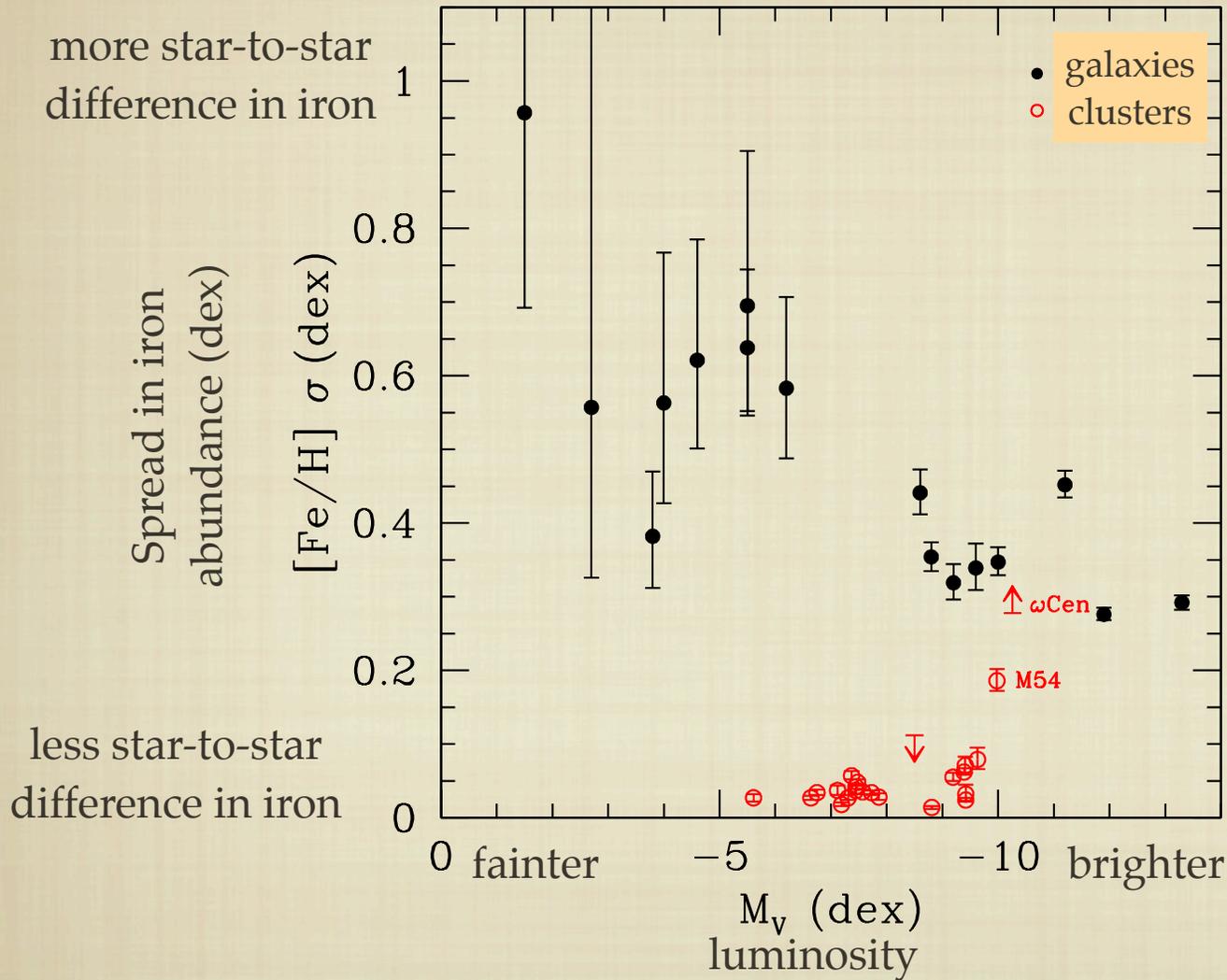


Star cluster:
Weighs what you
expect



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

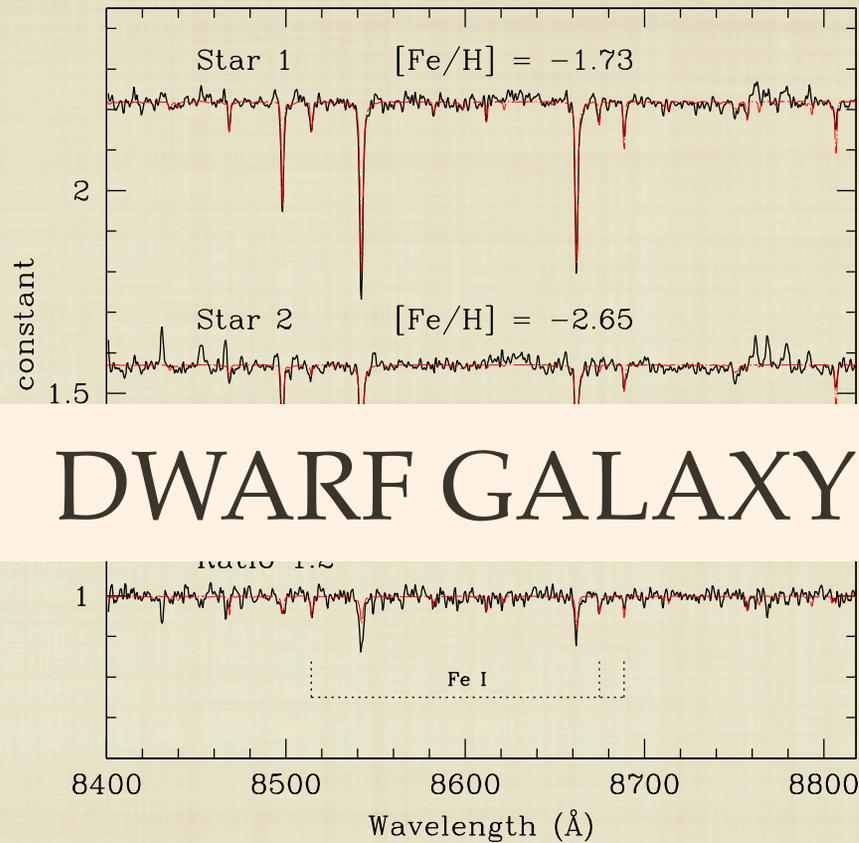
Iron spread can distinguish galaxies from clusters



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



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

DWARF 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...



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



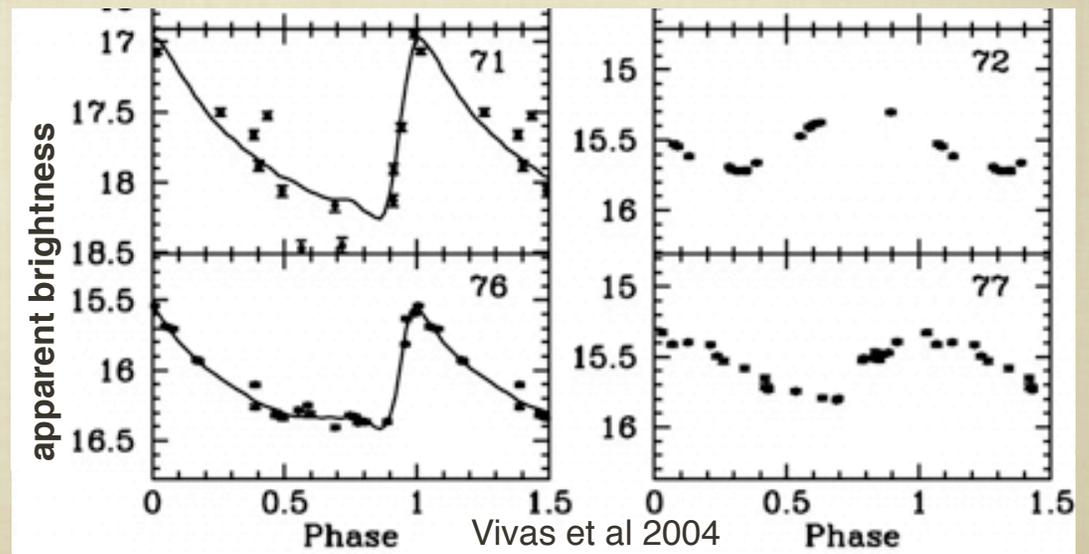
Undergraduates and invisible galaxies

Recent research focus

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

amplitude $\sim 0.2 - 1.5$ mag
period $\sim 0.15 - 0.8$ days

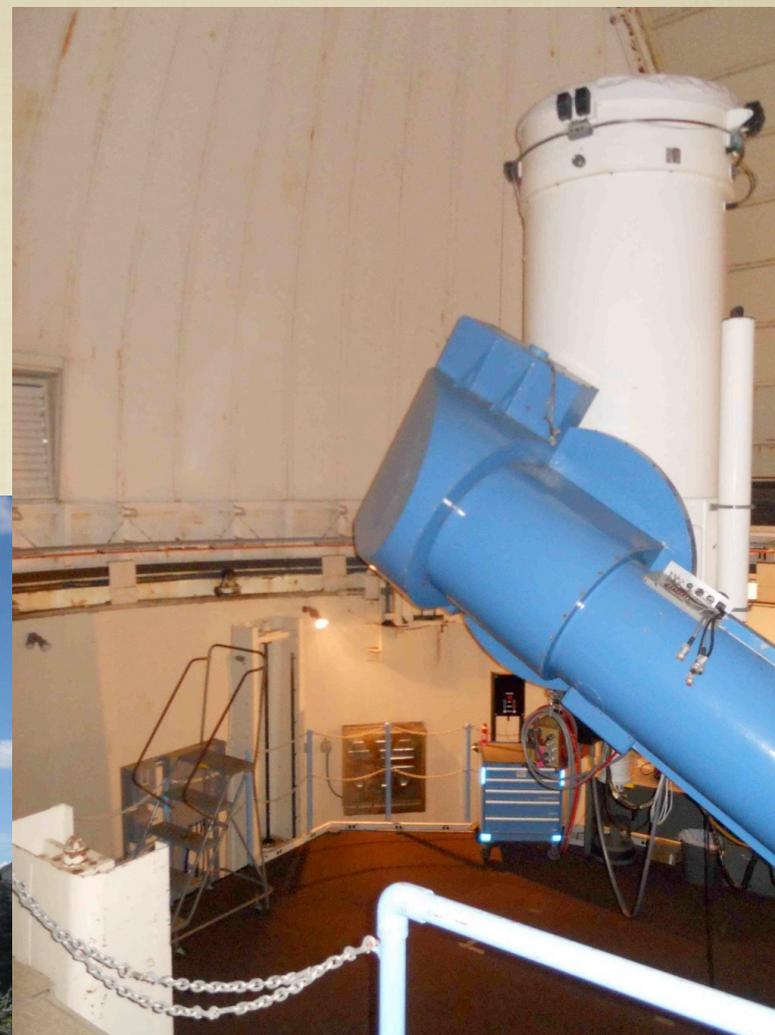
- Standard candles - distances
- Possible discovery tool
- Diagnostic of stellar population



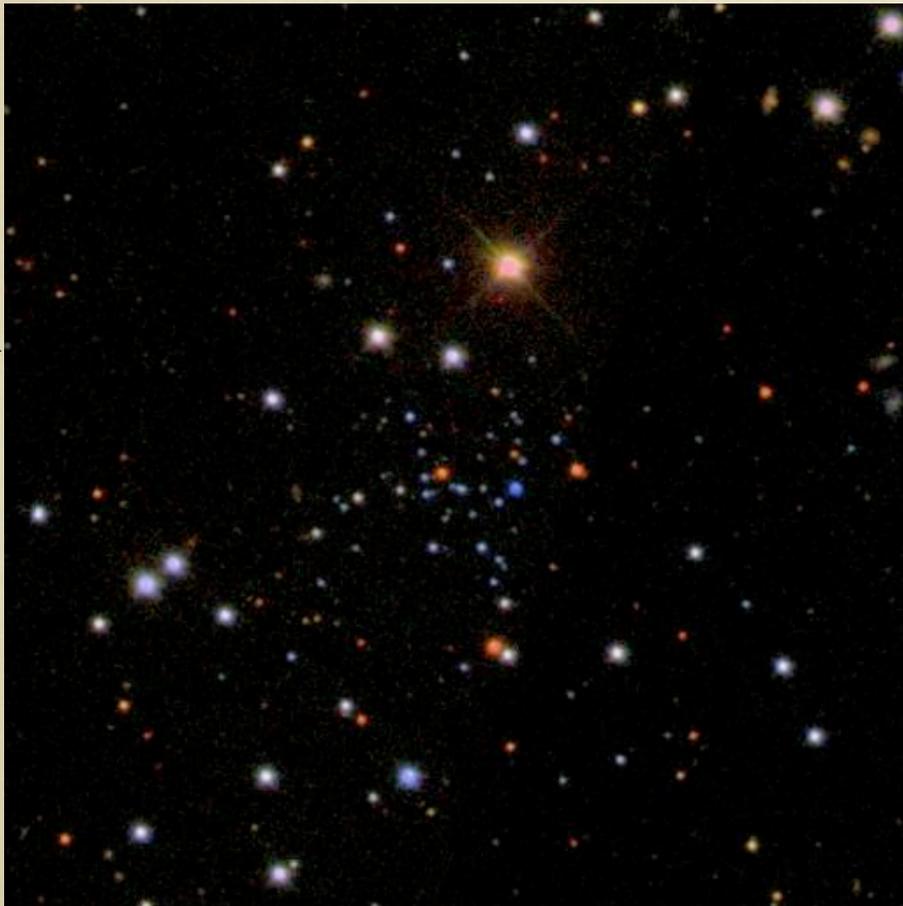
Undergraduates and invisible galaxies

Small aperture telescope
science with undergraduates
KPNO 0.9m consortium





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

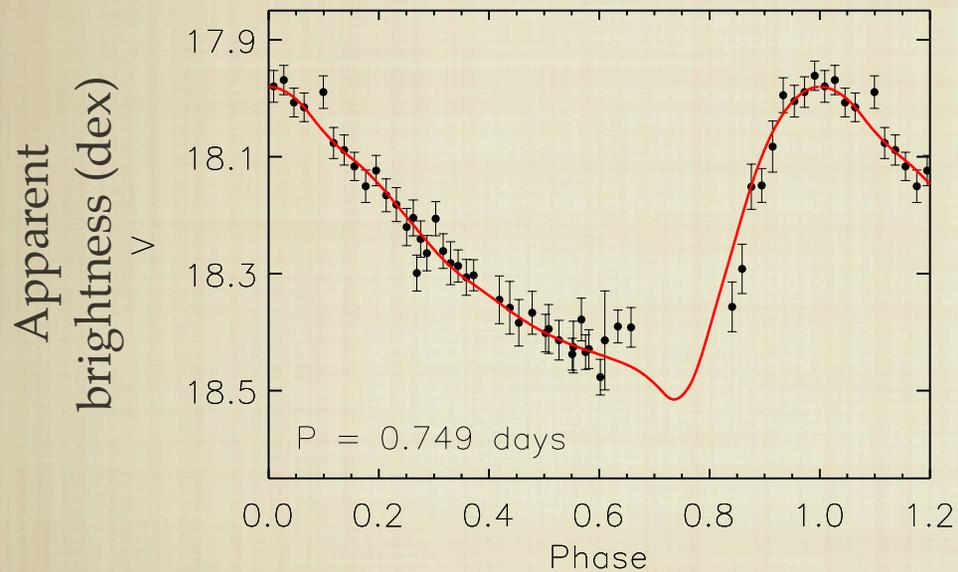


Segue 2 and Segue 3 are both Milky Way satellites located less than 100,000 light years away.

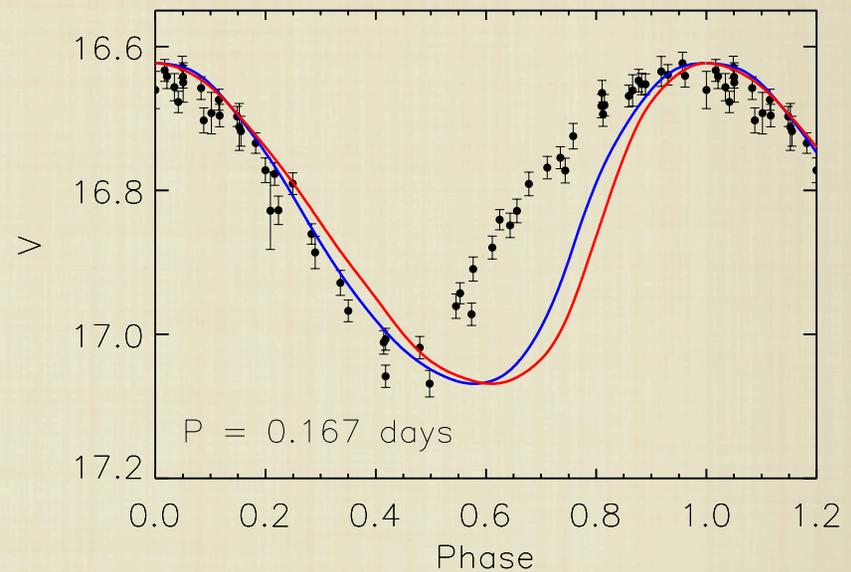
Segue 3 (shown to the left) is the least luminous star cluster known. Segue 2 is one of the least luminous galaxies known.

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

RR Lyrae star in Segue 2

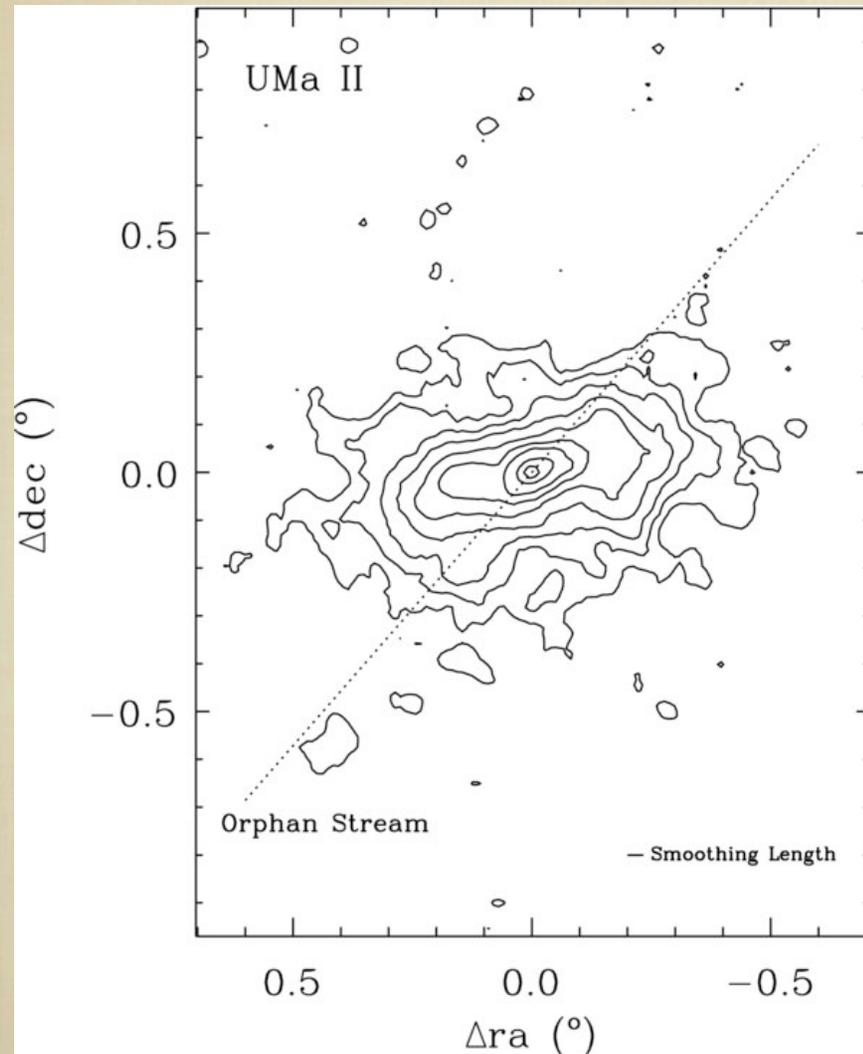


probable eclipsing binary near Segue 3



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

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

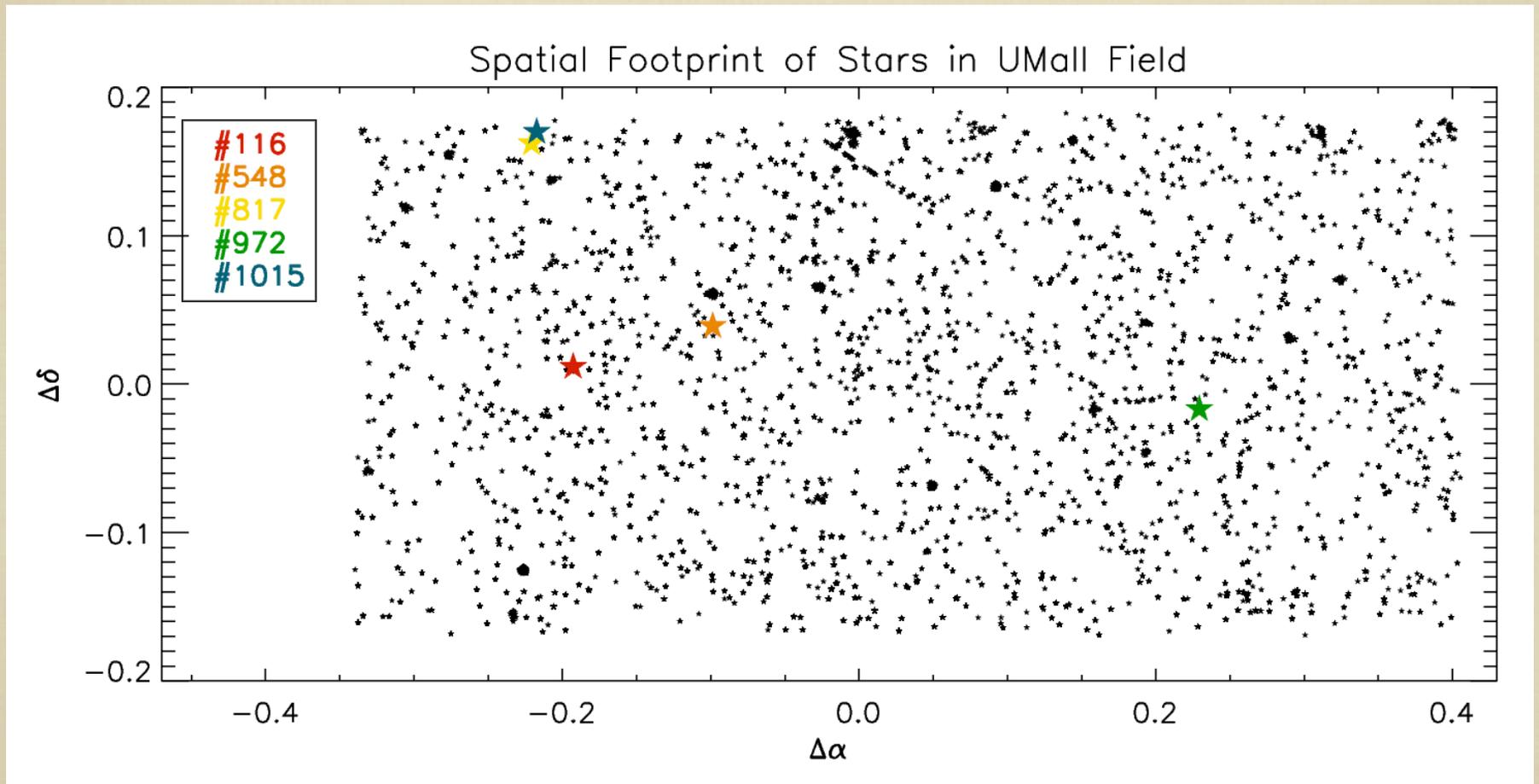


Contour plot showing the spatial
distribution of stars in Ursa Major II

This ultra-faint galaxy has an
unusually high ellipticity

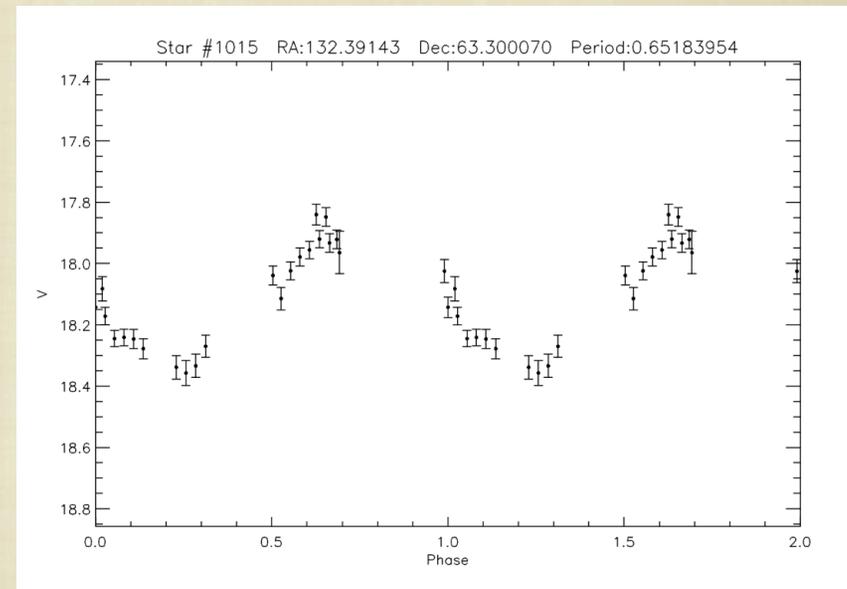
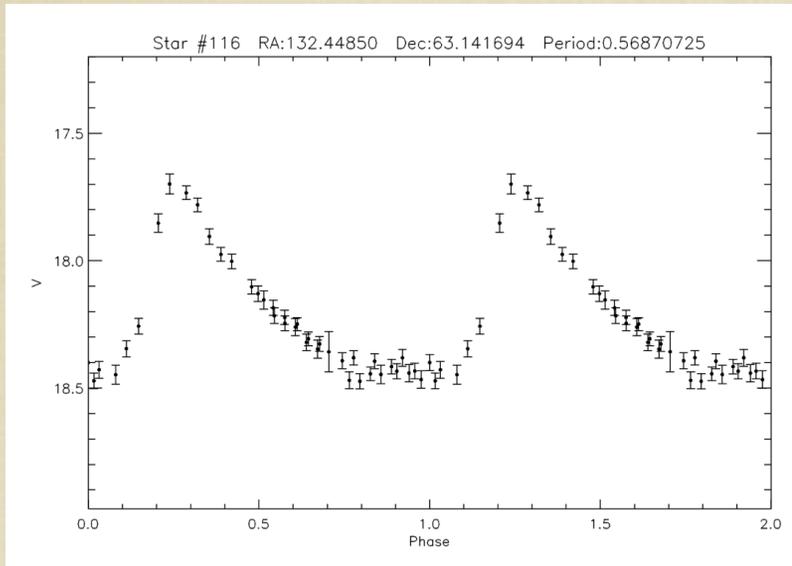
Is it losing stars?

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



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

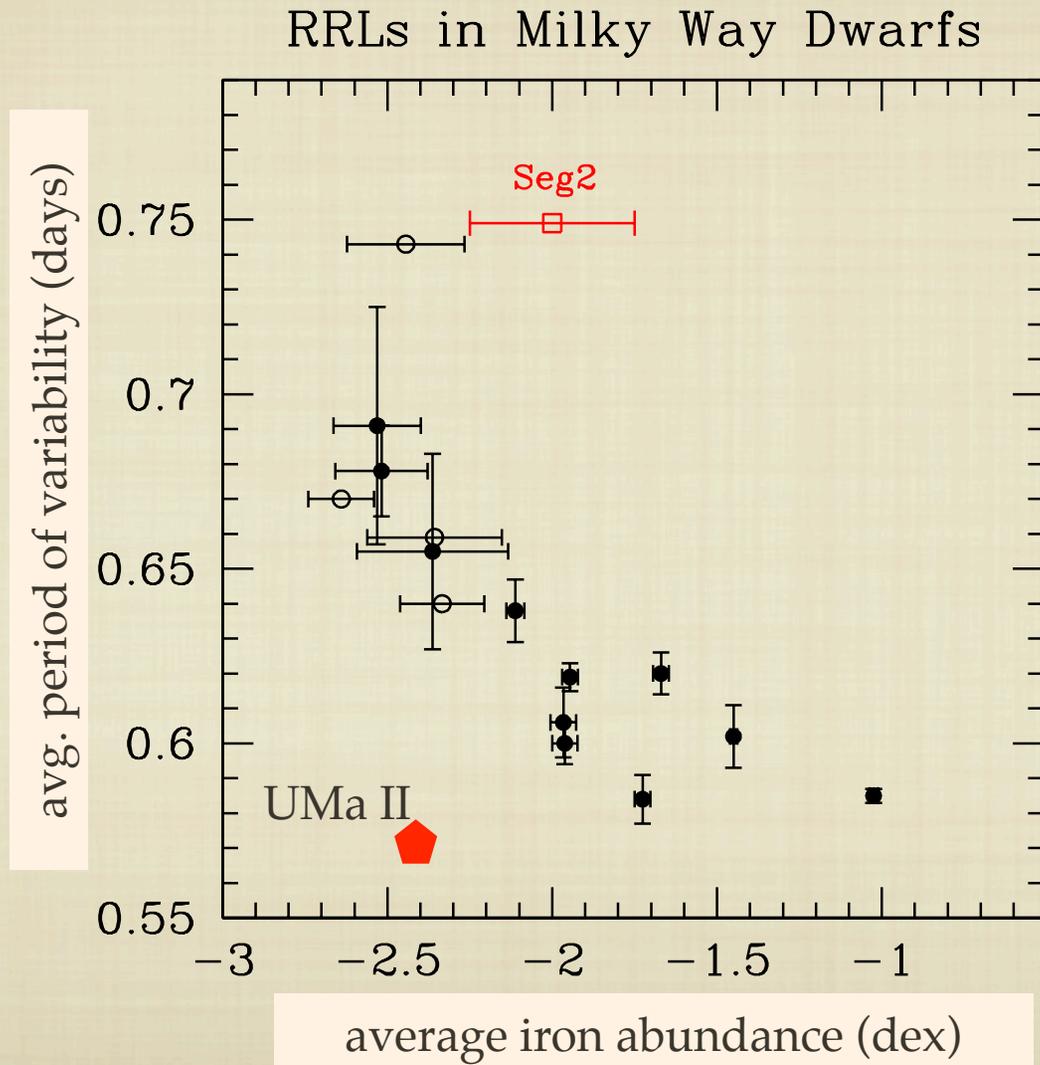
Apparent
brightness (dex)



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

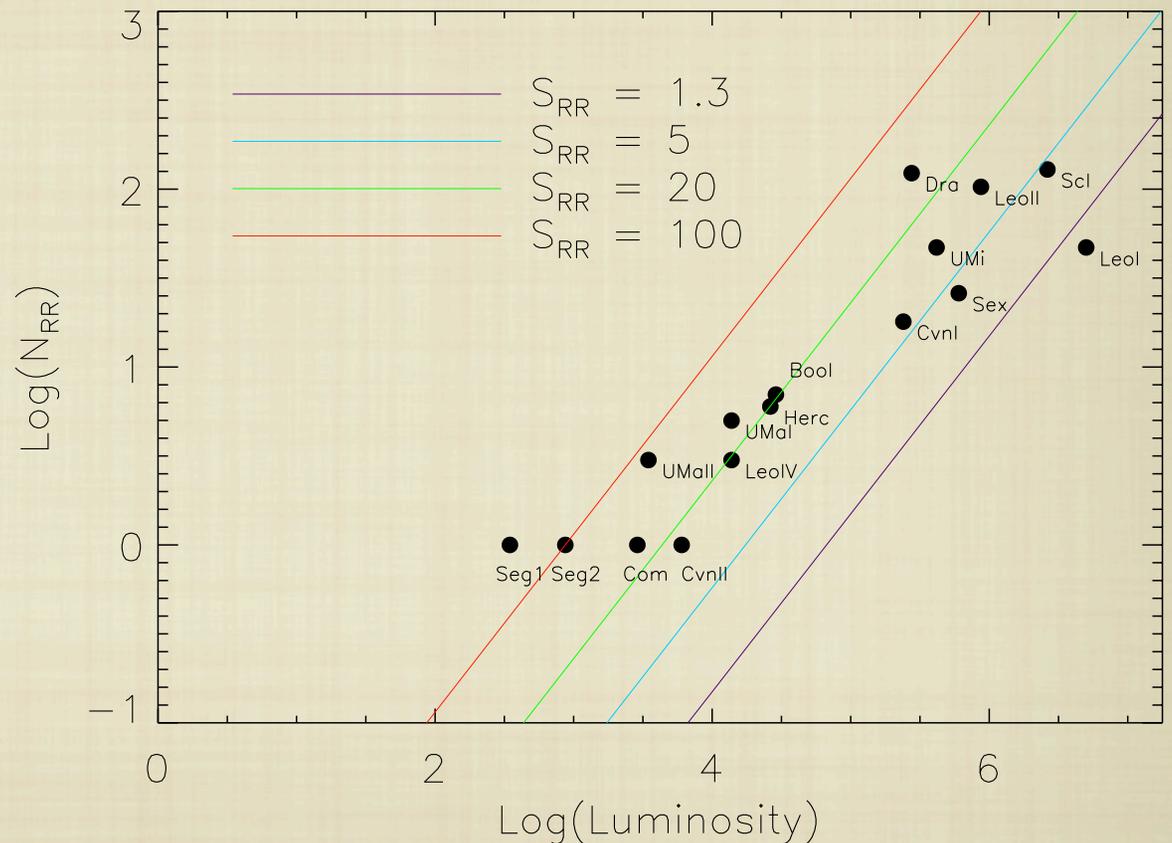
Gaughan et al. in preparation

RR Lyrae in ultra-faint dwarf galaxies

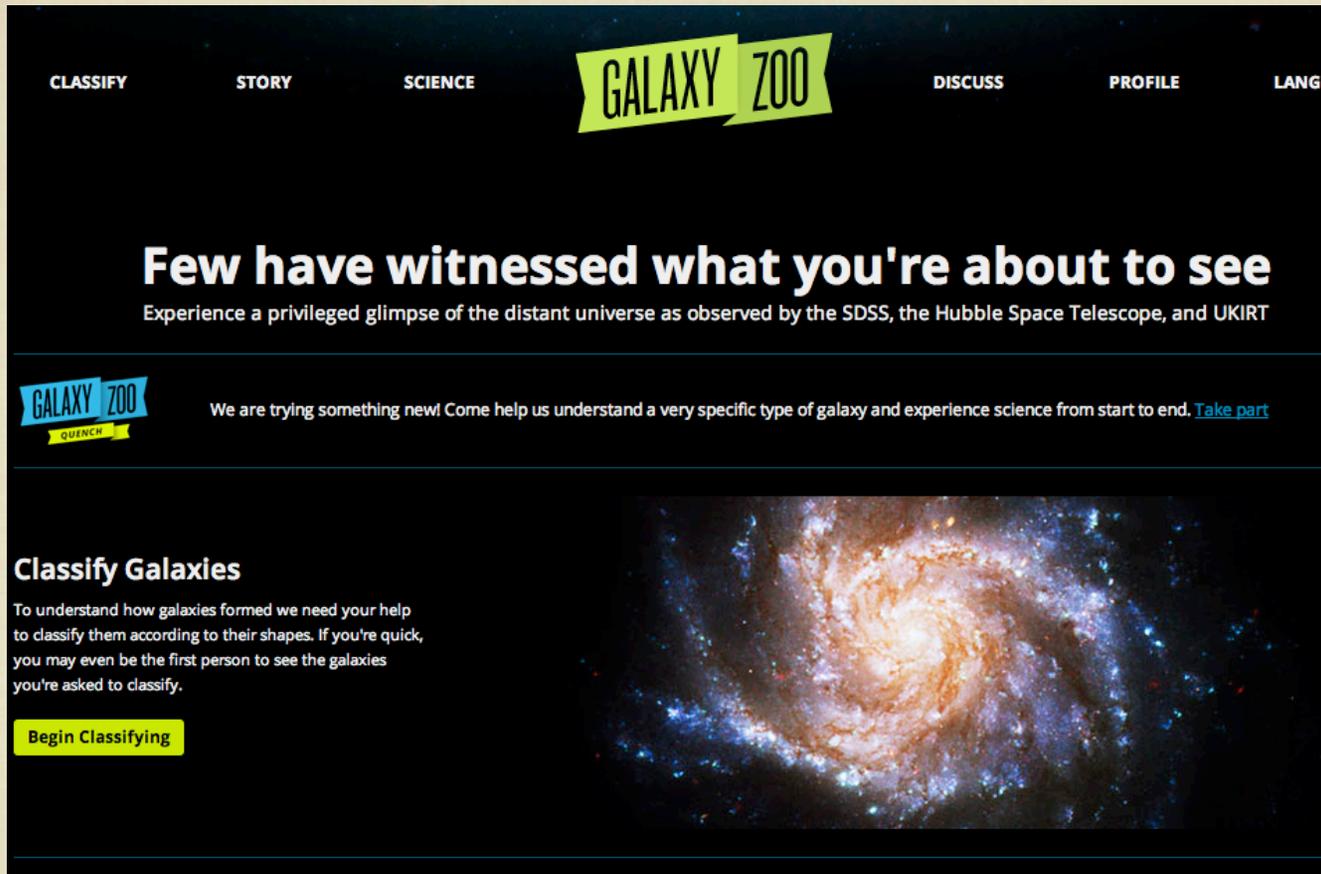


Flip this around: What if we only know where the RR Lyrae are?

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



Galaxies in the classroom



The screenshot shows the Galaxy Zoo website interface. At the top, there is a navigation bar with the following links: CLASSIFY, STORY, SCIENCE, GALAXY ZOO (in a yellow banner), DISCUSS, PROFILE, and LANGU. Below the navigation bar, the main heading reads "Few have witnessed what you're about to see" in white text on a dark background. Underneath this heading is a sub-heading: "Experience a privileged glimpse of the distant universe as observed by the SDSS, the Hubble Space Telescope, and UKIRT".

Below the main heading, there is a section with a blue and yellow banner that says "GALAXY ZOO" and "QUENCH". To the right of this banner is a line of text: "We are trying something new! Come help us understand a very specific type of galaxy and experience science from start to end. [Take part](#)".

Below this section, there is a large image of a spiral galaxy. To the left of the image, the text reads "Classify Galaxies" in bold. Below this is a paragraph: "To understand how galaxies formed we need your help to classify them according to their shapes. If you're quick, you may even be the first person to see the galaxies you're asked to classify." Below this paragraph is a yellow button that says "Begin Classifying".

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

SLOAN DIGITAL SKY SURVEY III
SkyServer DR10

Home | Data | Schema | Education | Astronomy | SDSS | Contact Us | Download | Site Search | Help

Welcome to the **DR10** site!!!

This website presents data from the Sloan Digital Sky Survey, a project to make a map of a large part of the universe. We would like to show you the beauty of the universe, and share with you our excitement as we build the largest map in the history of the world.

News
The site hosts data from **Data Release 10 (DR10)**. What's new in DR10, what's new on this site and known problems. [More...](#)

SDSS-III is supported by

Data Access
Navigate
Quick Look | Explore
Finding Chart
Image List
Search
IQS | SQS | IRSQS
SQL Search
Cross-ID
CasJobs

Education
For Educators
Lesson Plans
Middle School
High School
College Lab Activities
Instructor Guides
Student/Public Research
Galaxy Zoo
Zooniverse

Links
sdss3.org
Data Release 10
SDSS-III Science
Science Archive Server
About Astronomy
About the SDSS
About SkyServer
VAO
Credits

Help
Start Here | FAQ
Glossary
Tool User Guides
Cooking with Sloan
SQL Tutorial
About the Database
Schema Browser
Sample SQL Queries
Data Release Papers

Powered by **Microsoft**

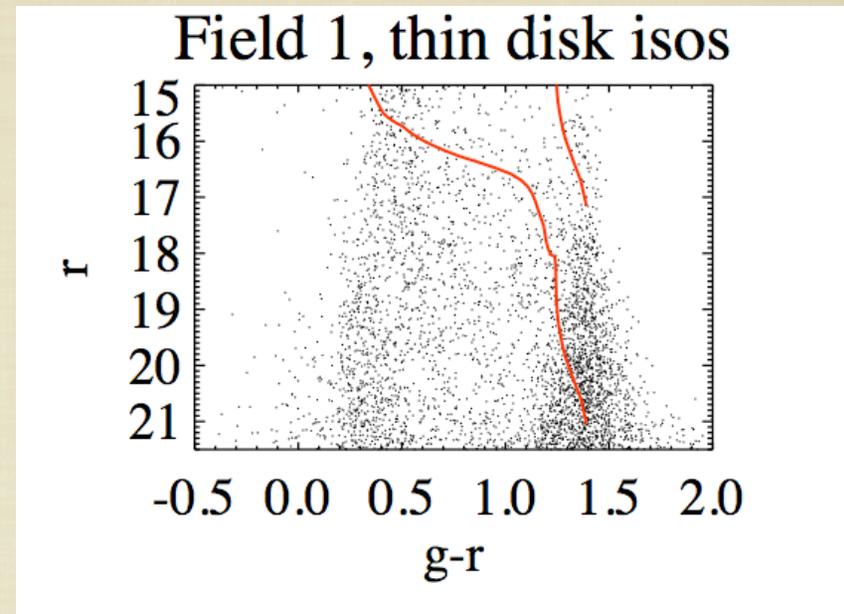
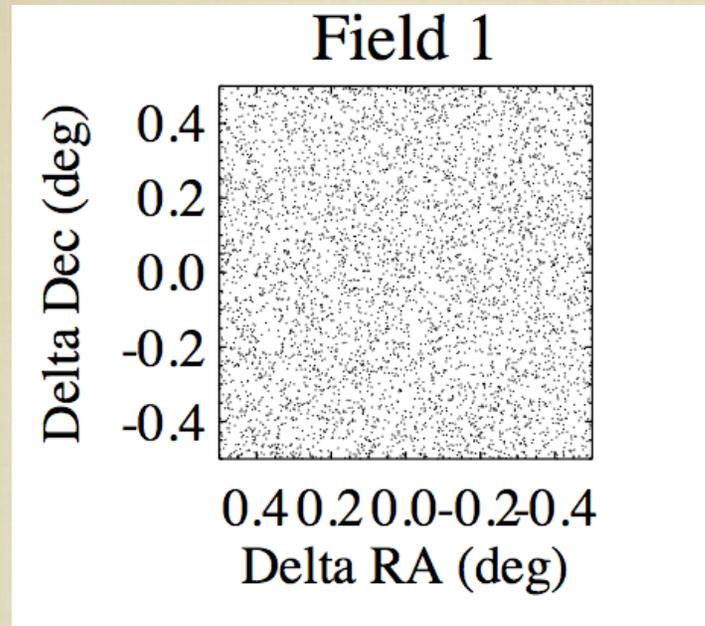
Site Traffic
Privacy Policy

Contact Us

Region	Boundaries	Time	Area	Volume
Galaxy	0.000000	0.000000	0.000000	0.000000
Cluster	0.000000	0.000000	0.000000	0.000000
Group	0.000000	0.000000	0.000000	0.000000
Field	0.000000	0.000000	0.000000	0.000000
Local	0.000000	0.000000	0.000000	0.000000
Local Group	0.000000	0.000000	0.000000	0.000000
Local Group	0.000000	0.000000	0.000000	0.000000
Local Group	0.000000	0.000000	0.000000	0.000000
Local Group	0.000000	0.000000	0.000000	0.000000
Local Group	0.000000	0.000000	0.000000	0.000000

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