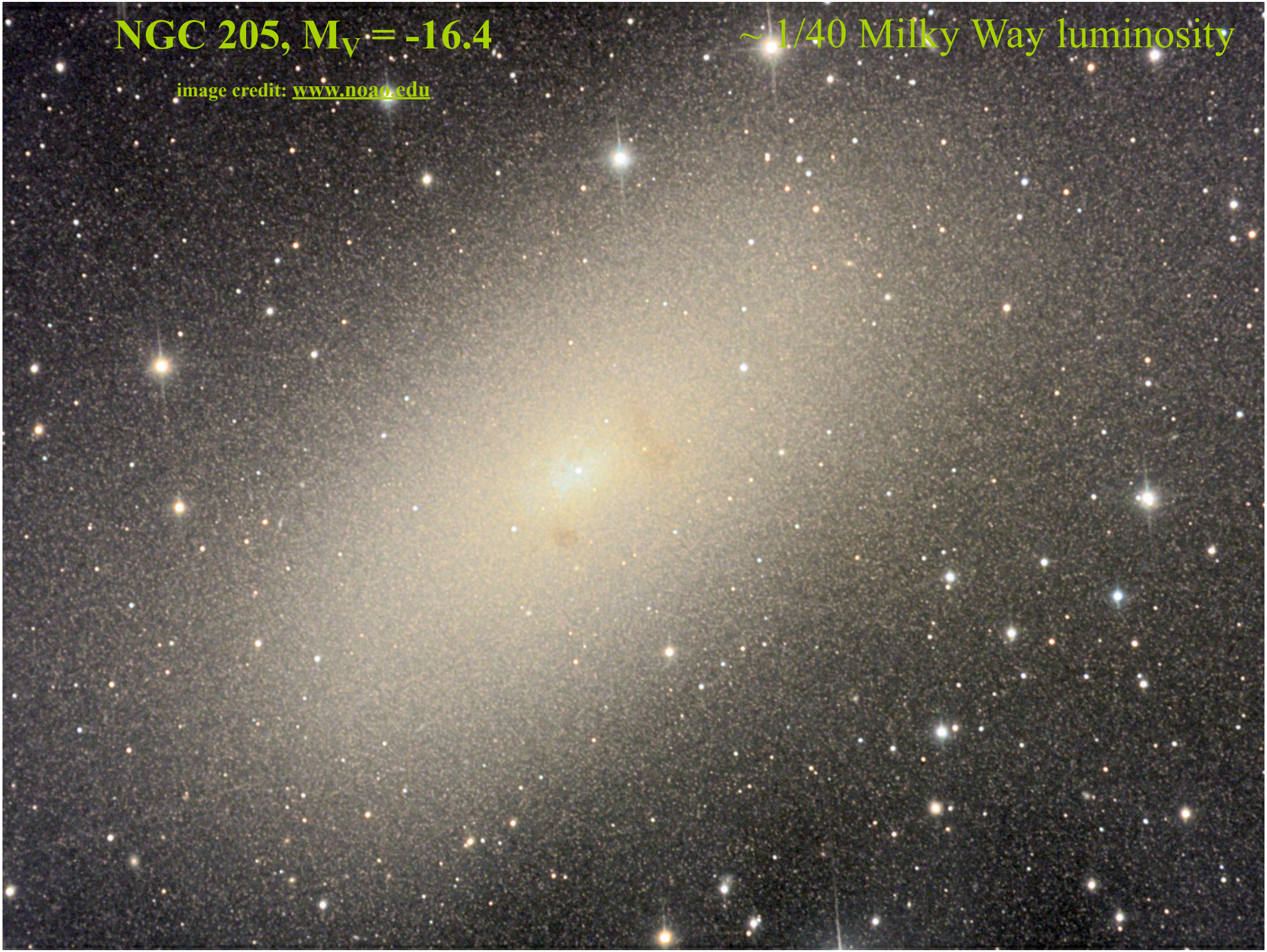
UCSB KITP Feb 16 2012

Beth Willman (Haverford College)


Large Magellanic Cloud, $M_V = -18$
image credit: Yuri Beletsky (ESO) and APOD
~ 1/10 Milky Way luminosity


NGC 205, $M_V = -16.4$
~1/40 Milky Way luminosity
image credit: www.noao.edu

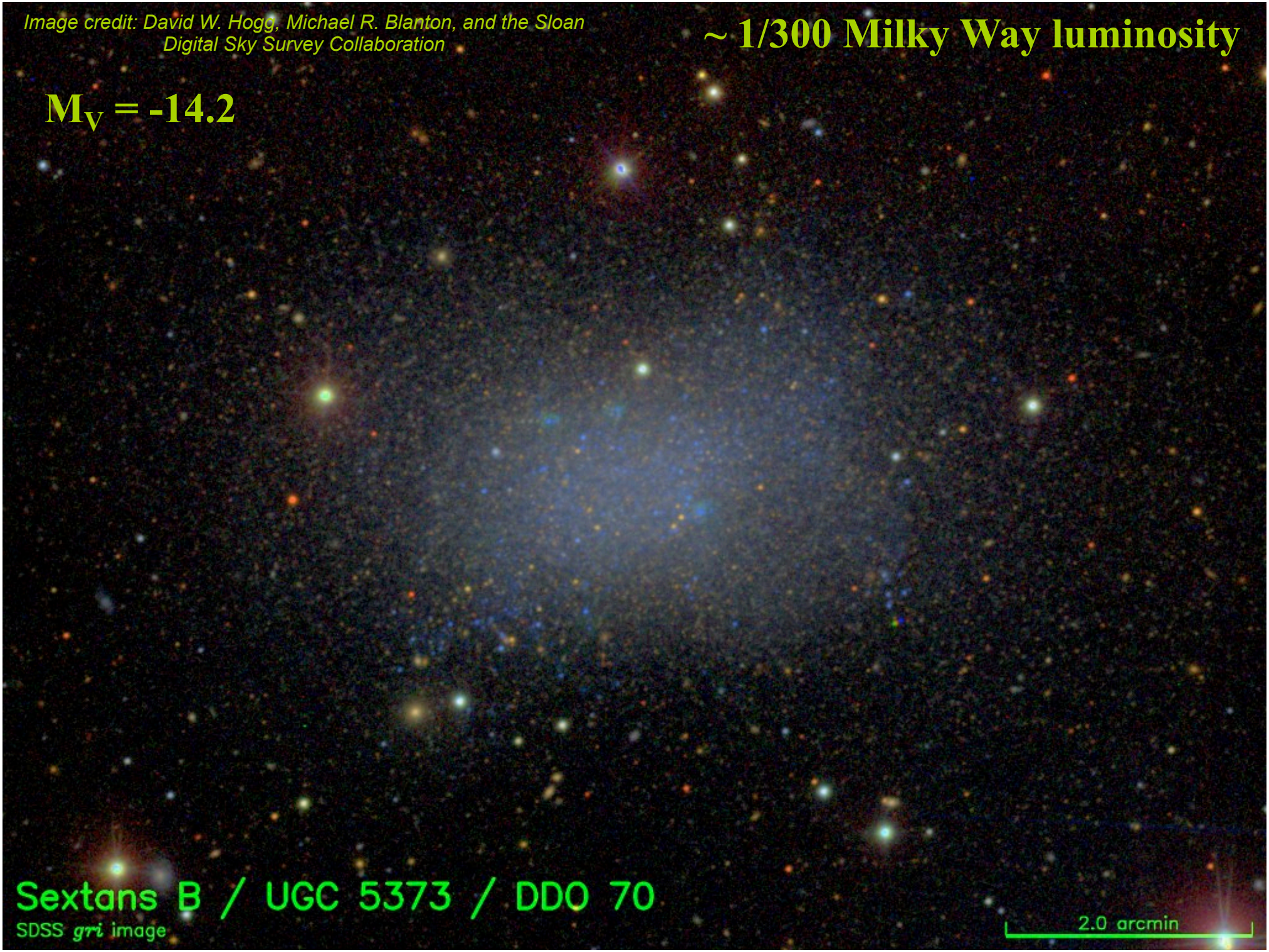


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/300 Milky Way luminosity
$M_V = -14.2$
Sextans B / UGC 5373 / DDO 70
SDSS gri image
2.0 arcmin

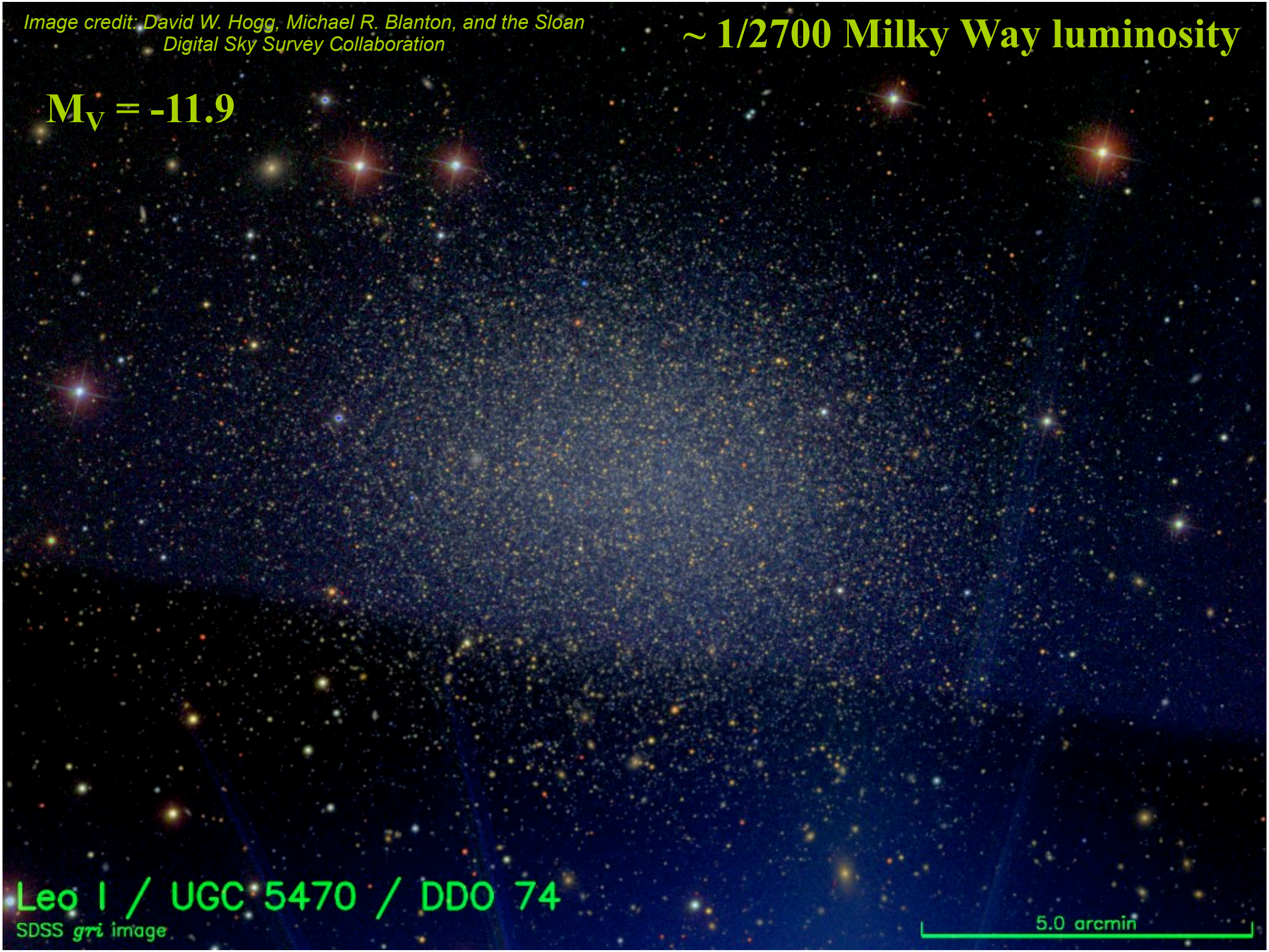


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/2700 Milky Way luminosity
M_V = -11.9
Leo I / UGC 5470 / DDO 74
SDSS gri image
5.0 arcmin

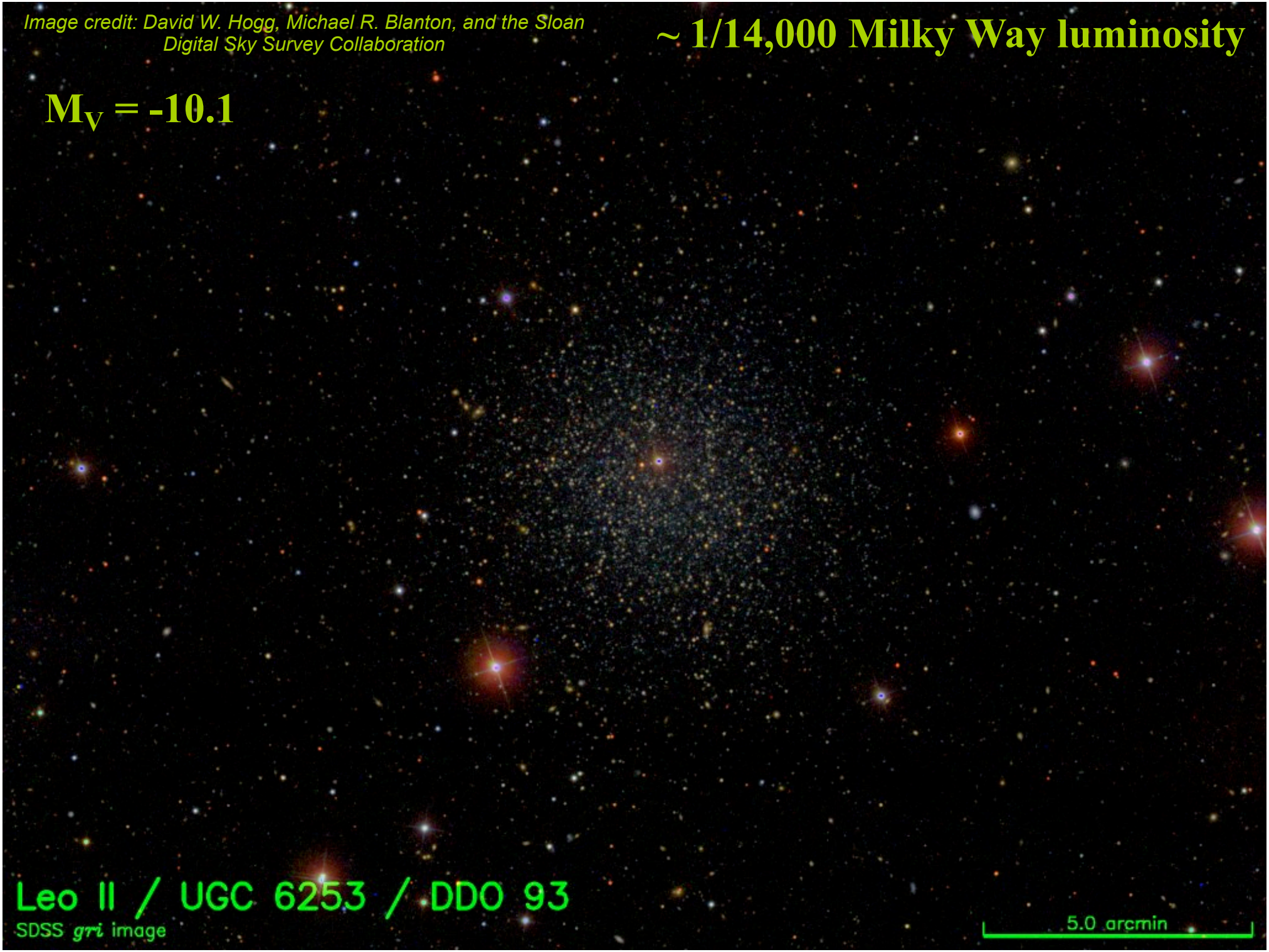
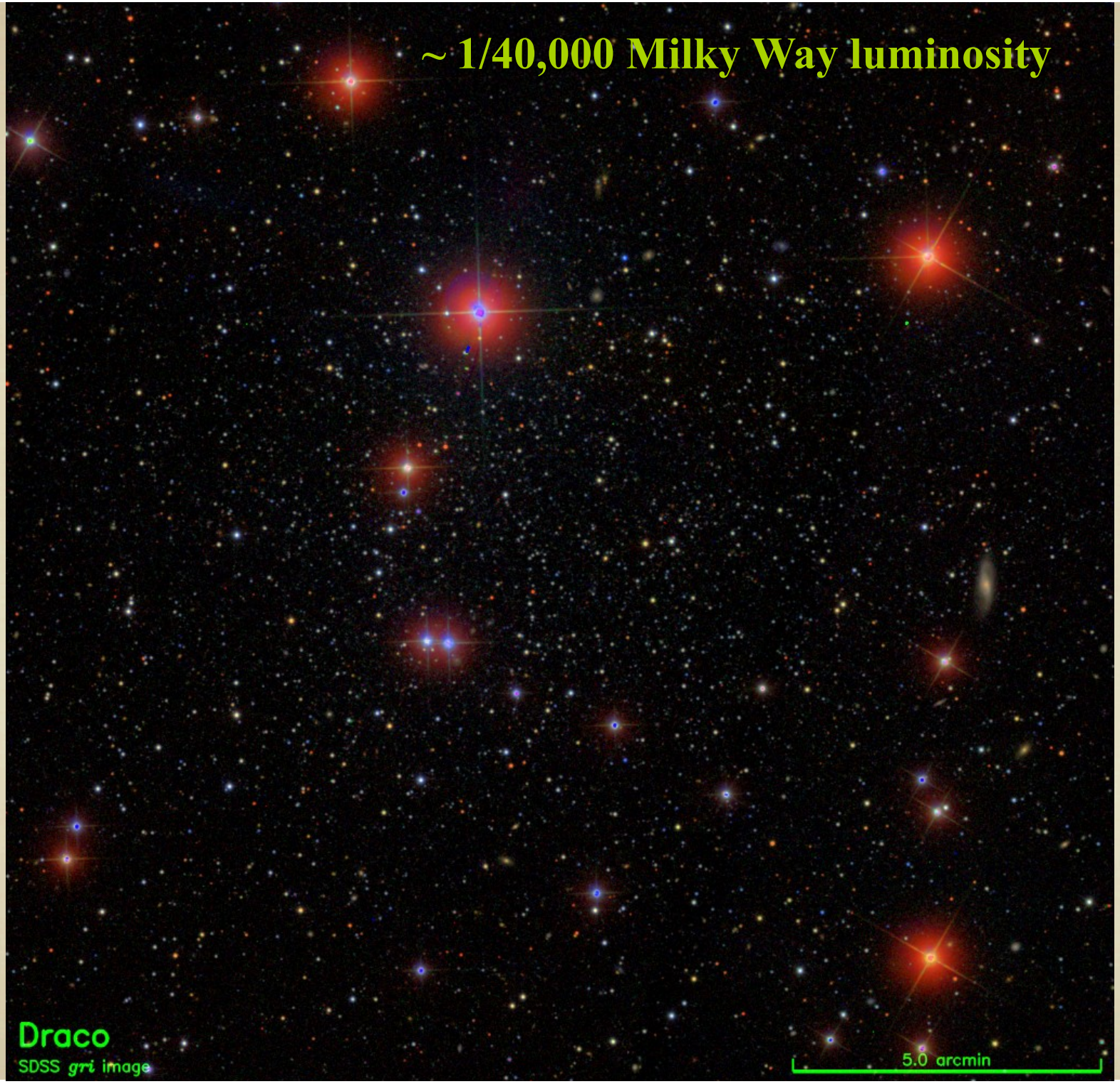
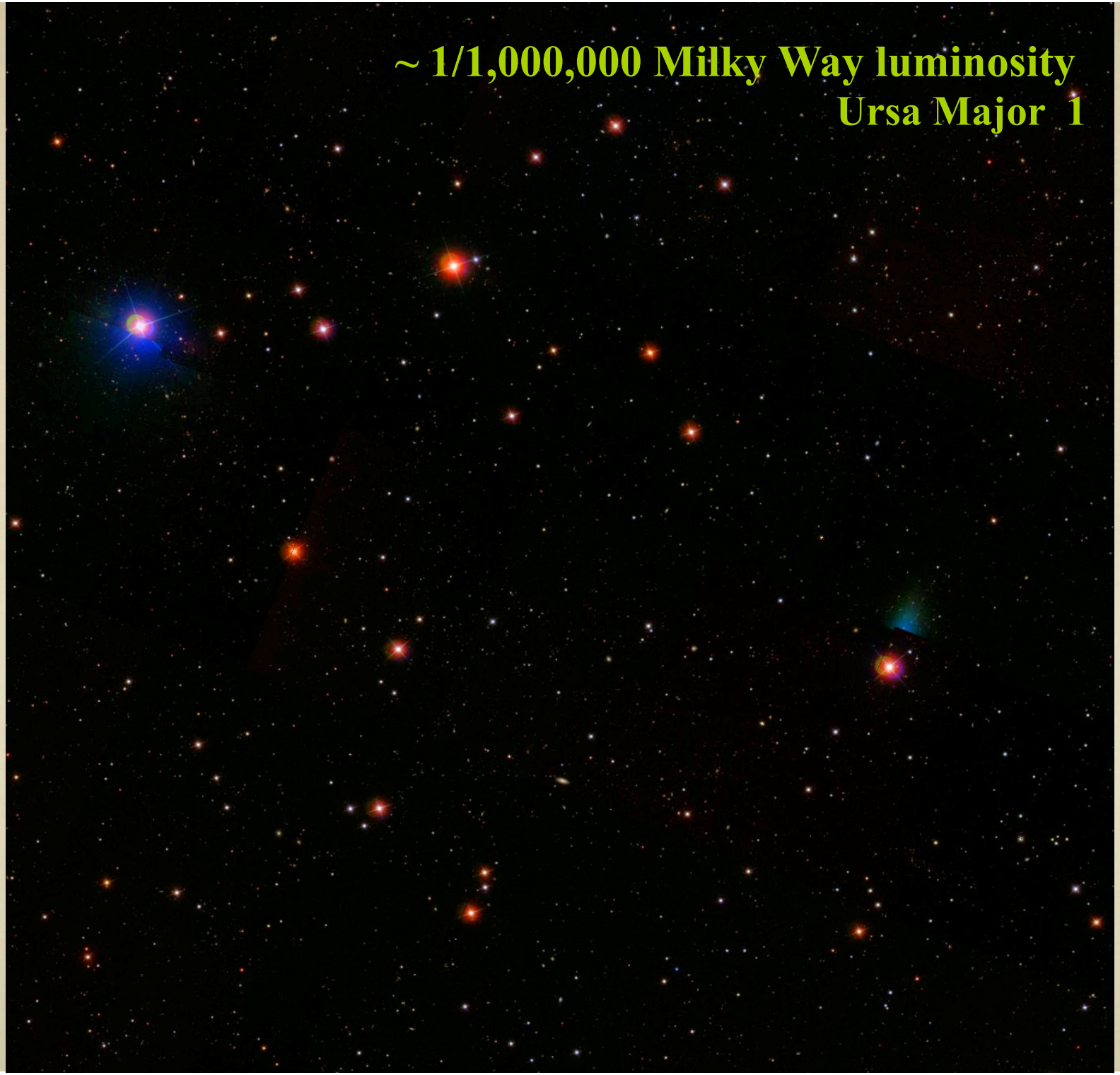
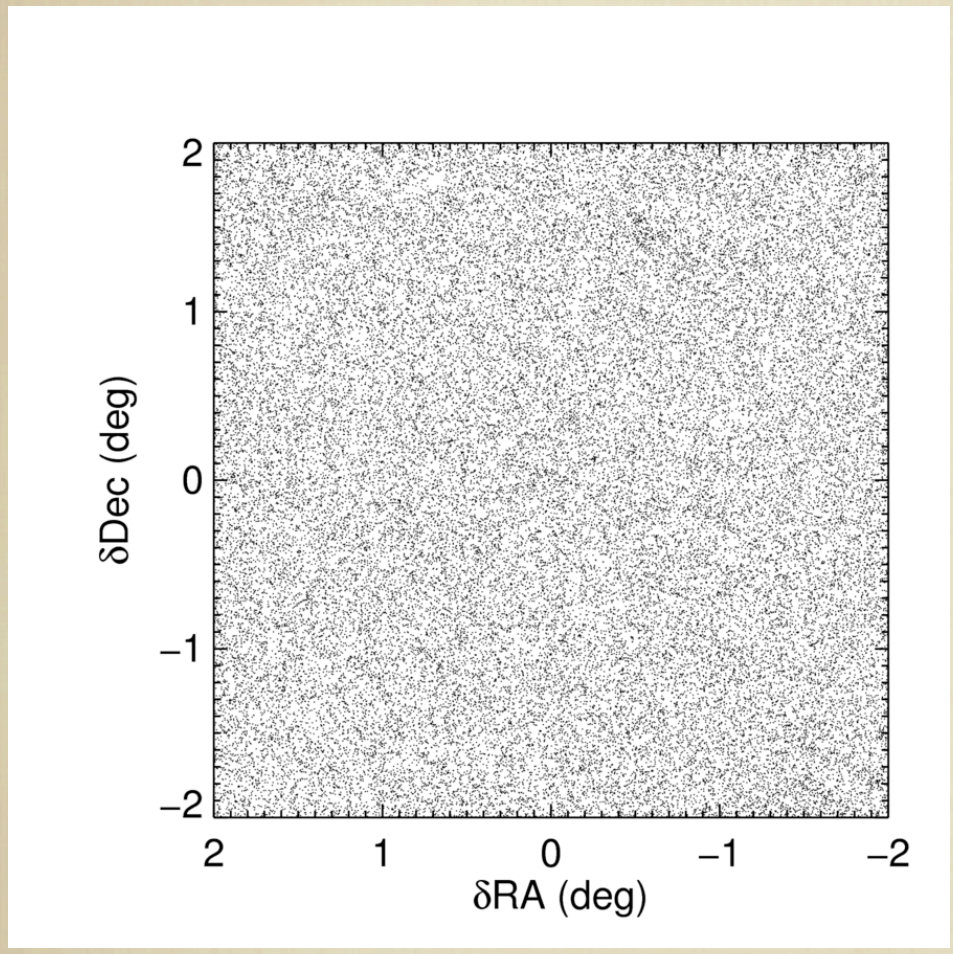


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/14,000 Milky Way luminosity
M_V = -10.1
Leo II / UGC 6253 / DDO 93
SDSS gri image
5.0 arcmin


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

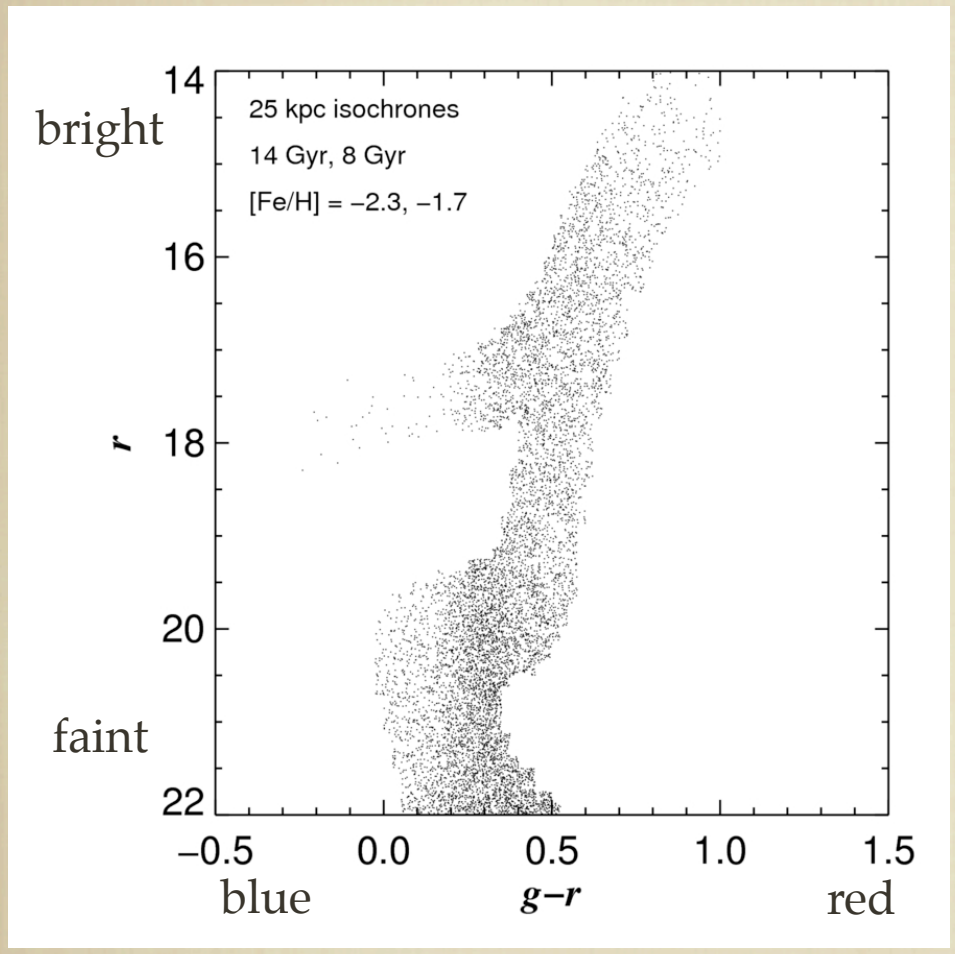

~ 1/1,000,000 Milky Way luminosity
Ursa Major 1

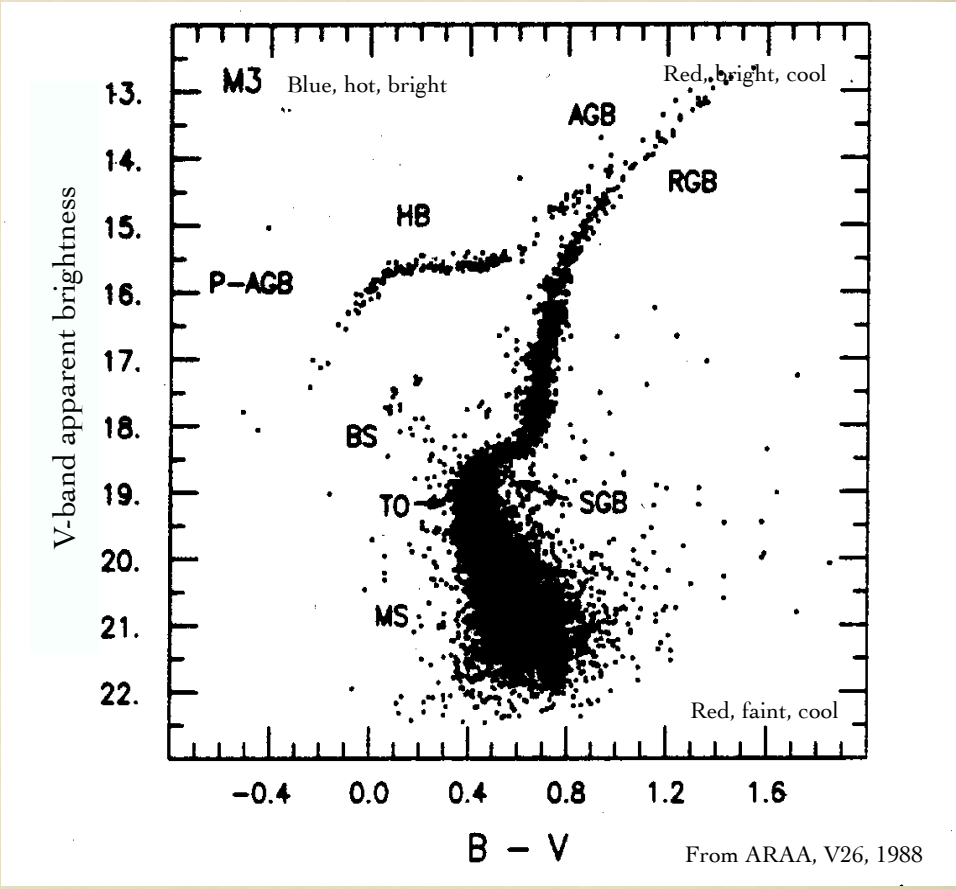
Finding Invisible Galaxies



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

Finding Invisible Galaxies





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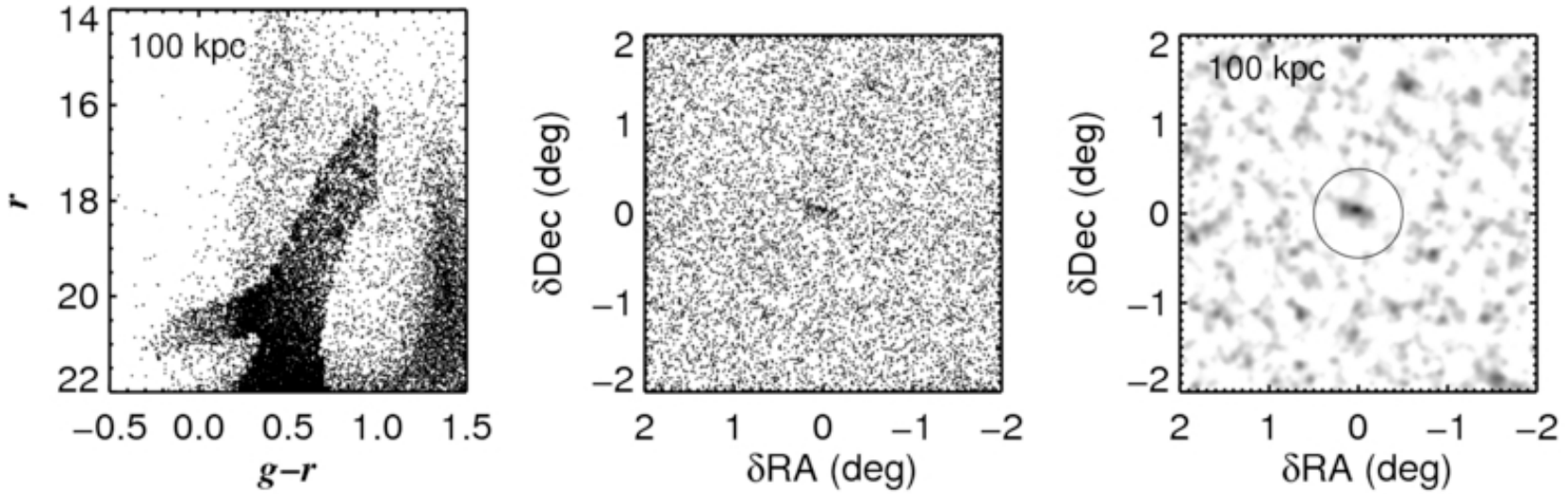


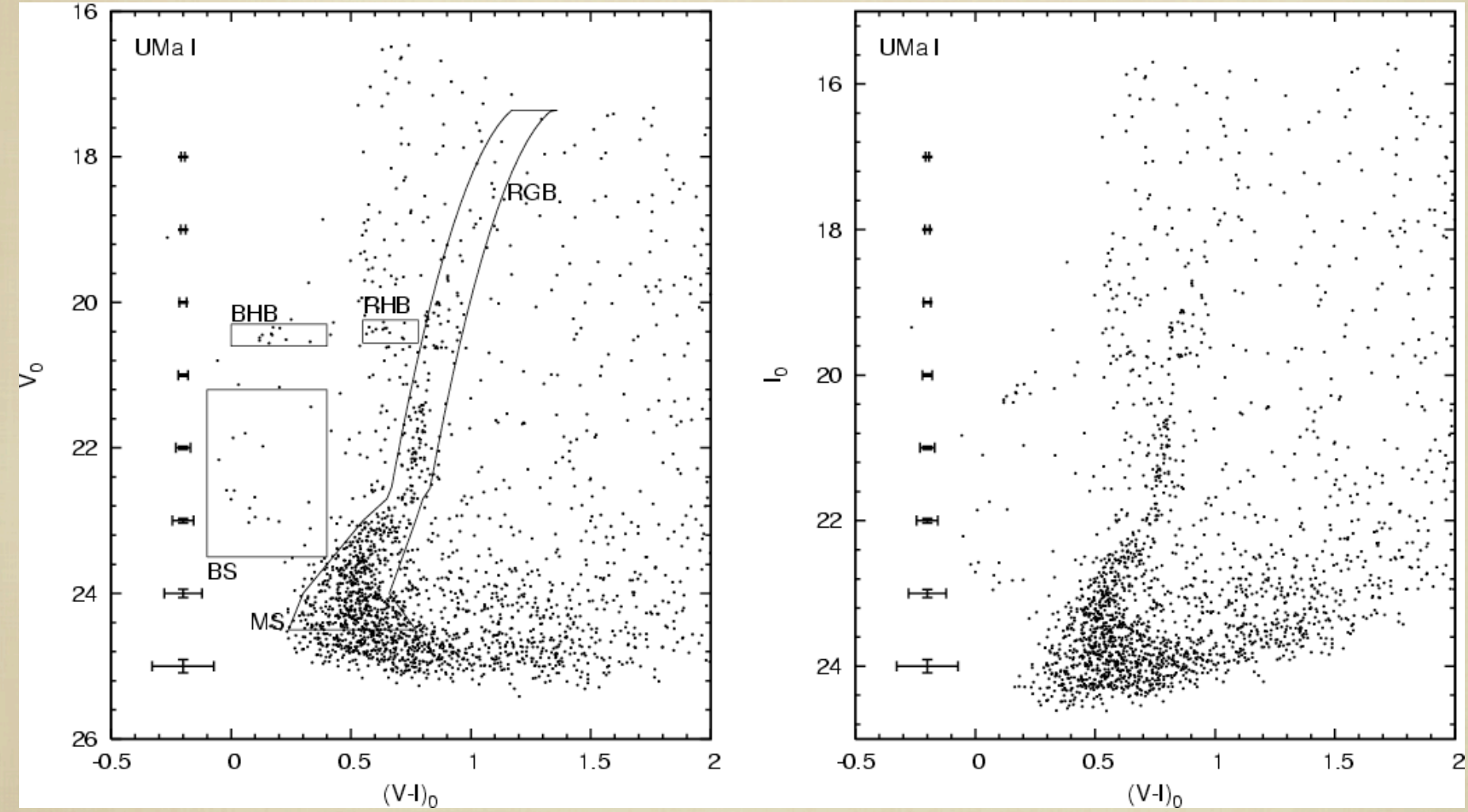
Ursa Major I dwarf

1/1,000,000 MW luminosity

Willman et al 2005

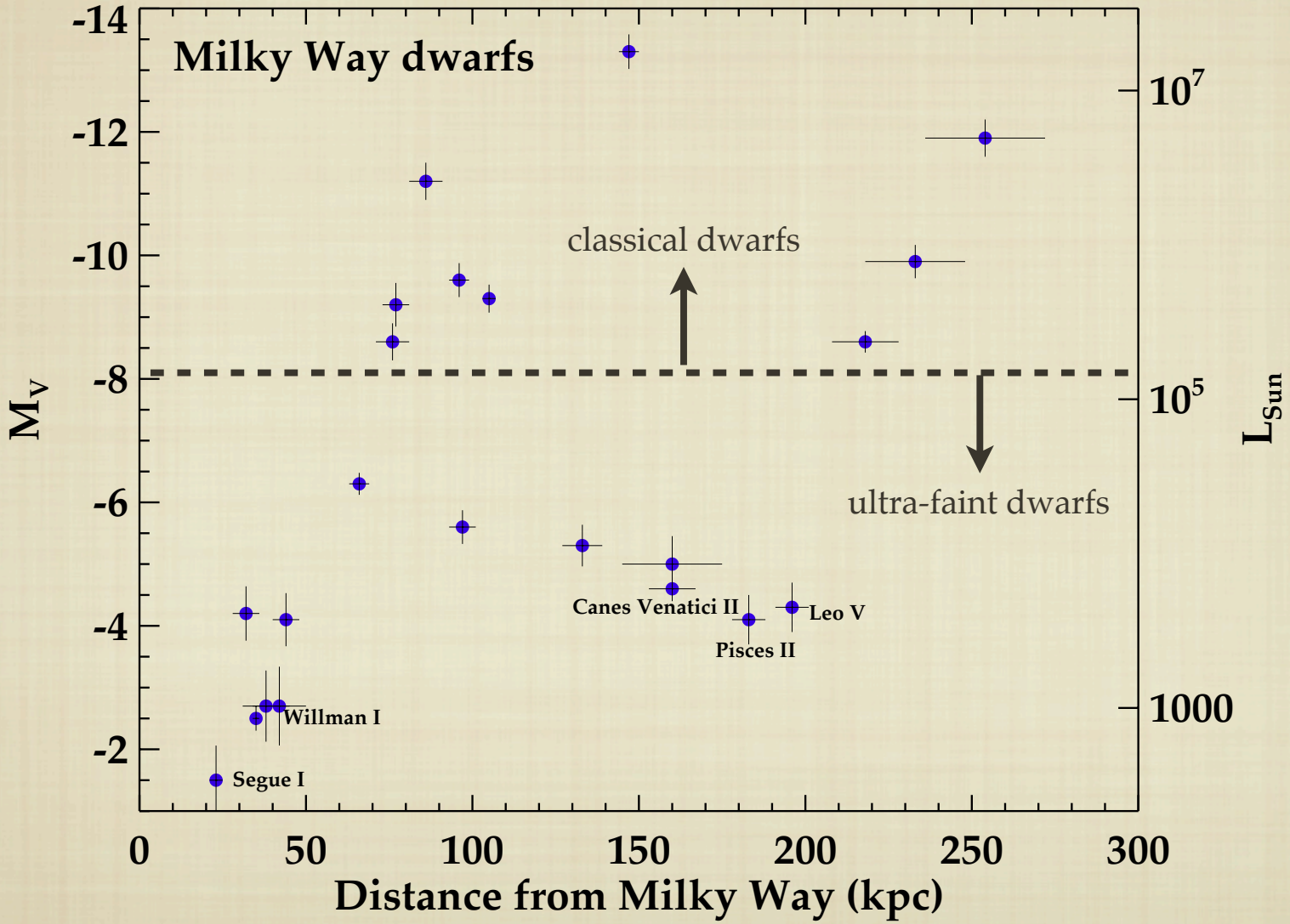

~ 1/1,000,000 Milky Way luminosity
Ursa Major 1

CMD of Ursa Major I

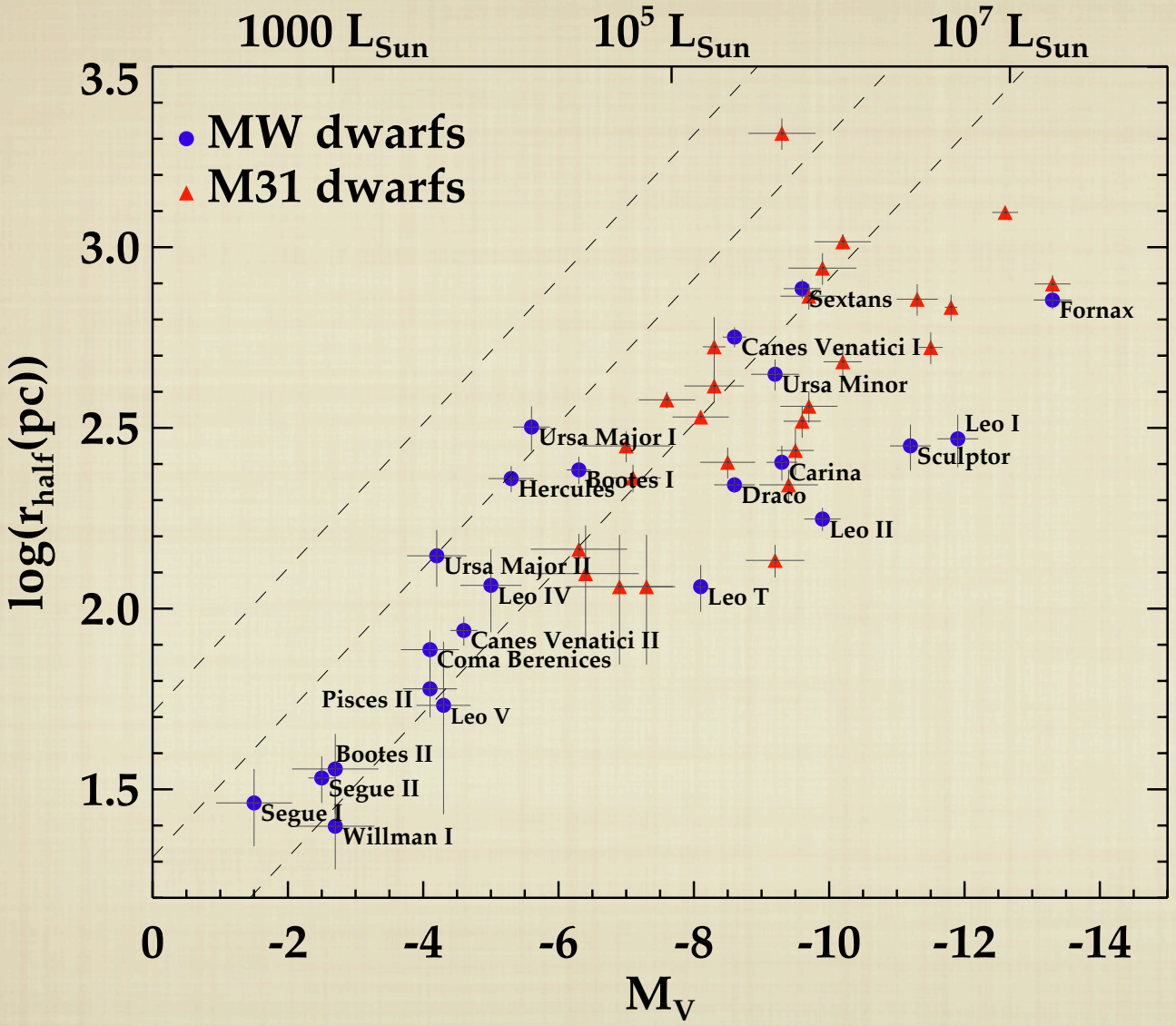


Okamoto et al 2008

Distribution of the Milky Way's dwarfs

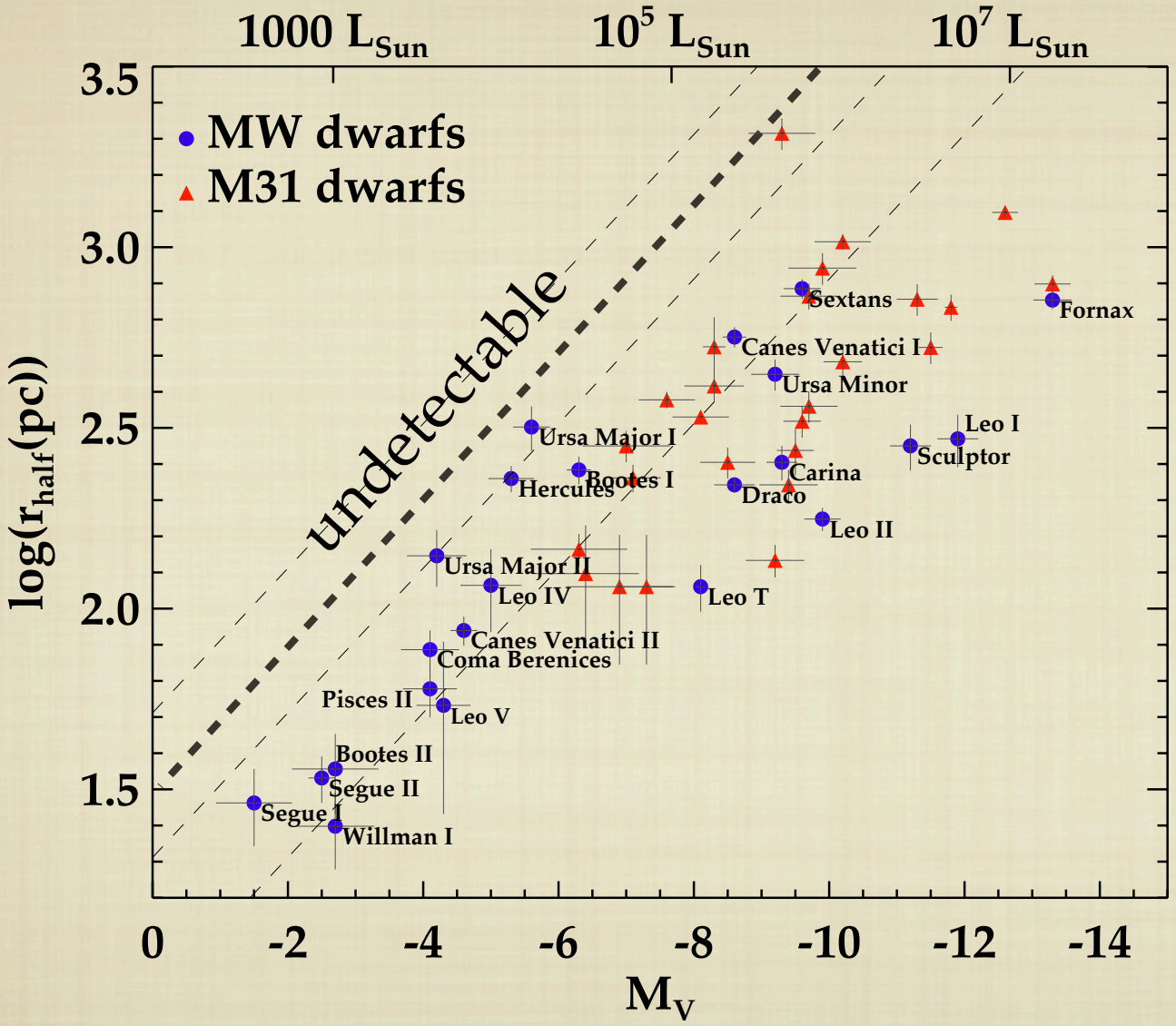


Luminosities and sizes of nearby dwarf galaxies



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

Luminosities and sizes of nearby dwarf galaxies



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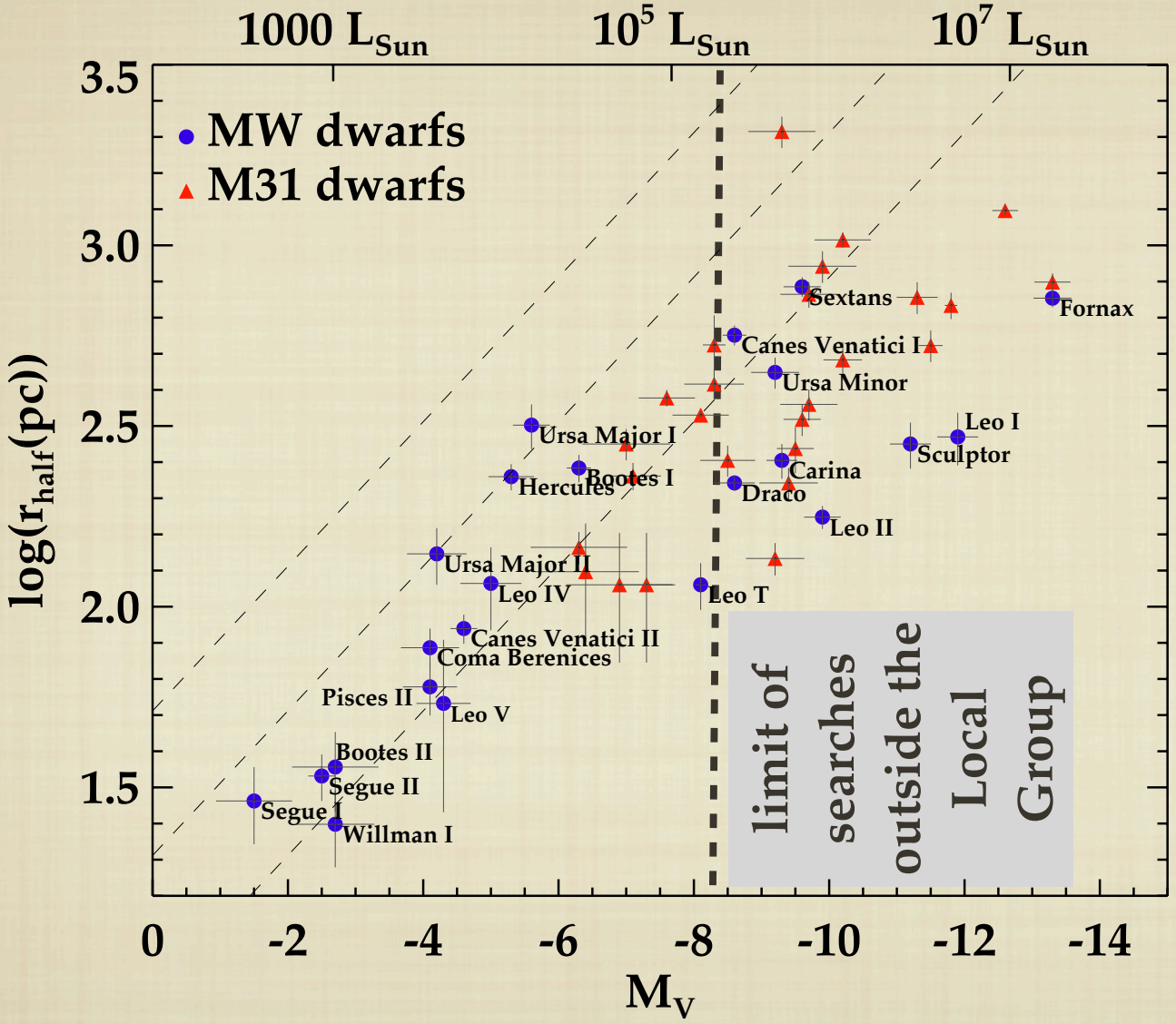

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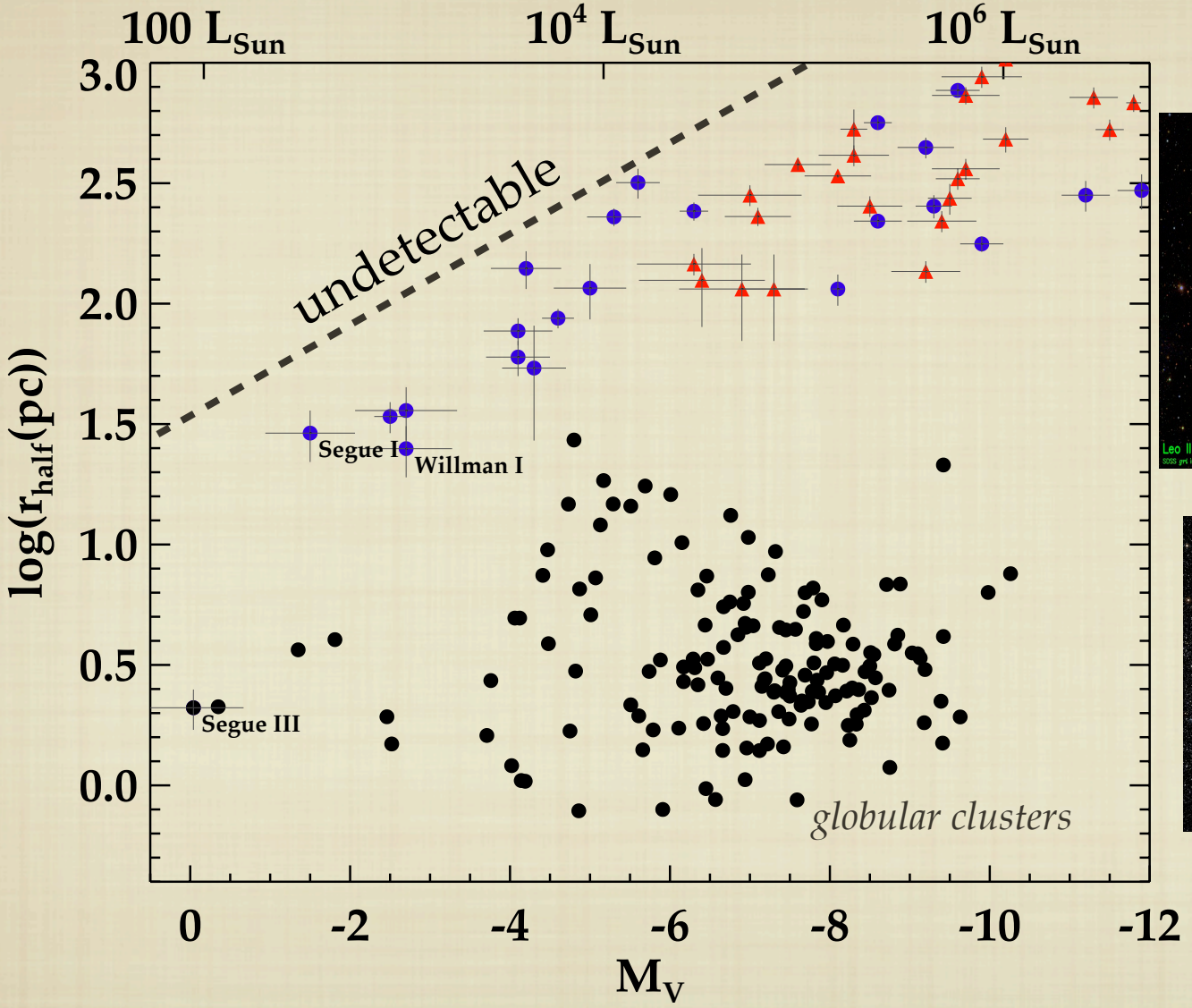
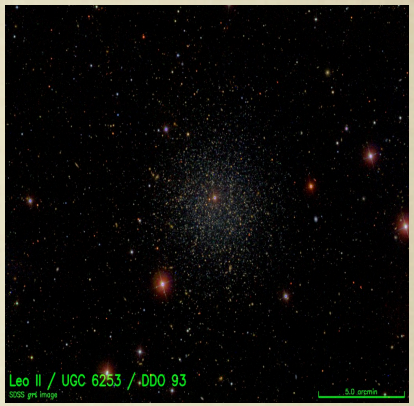
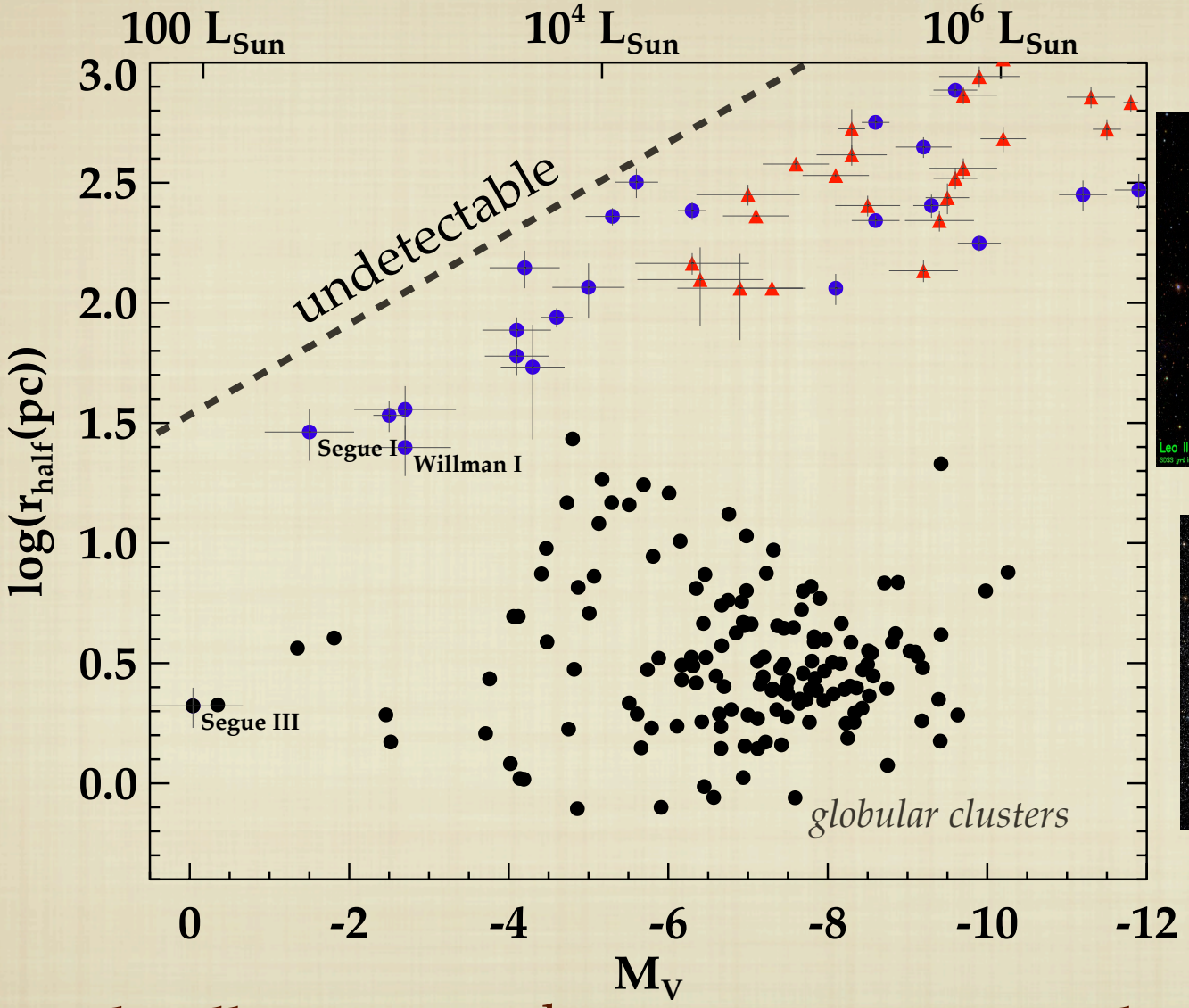
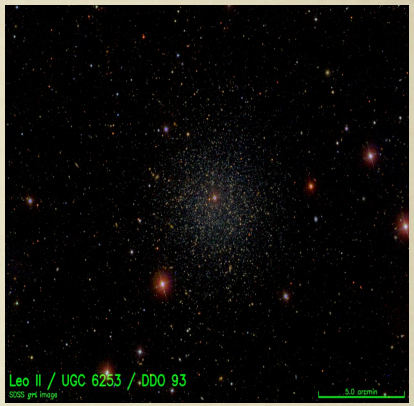




"I know it when I see it" is no longer a sufficient definition for galaxy

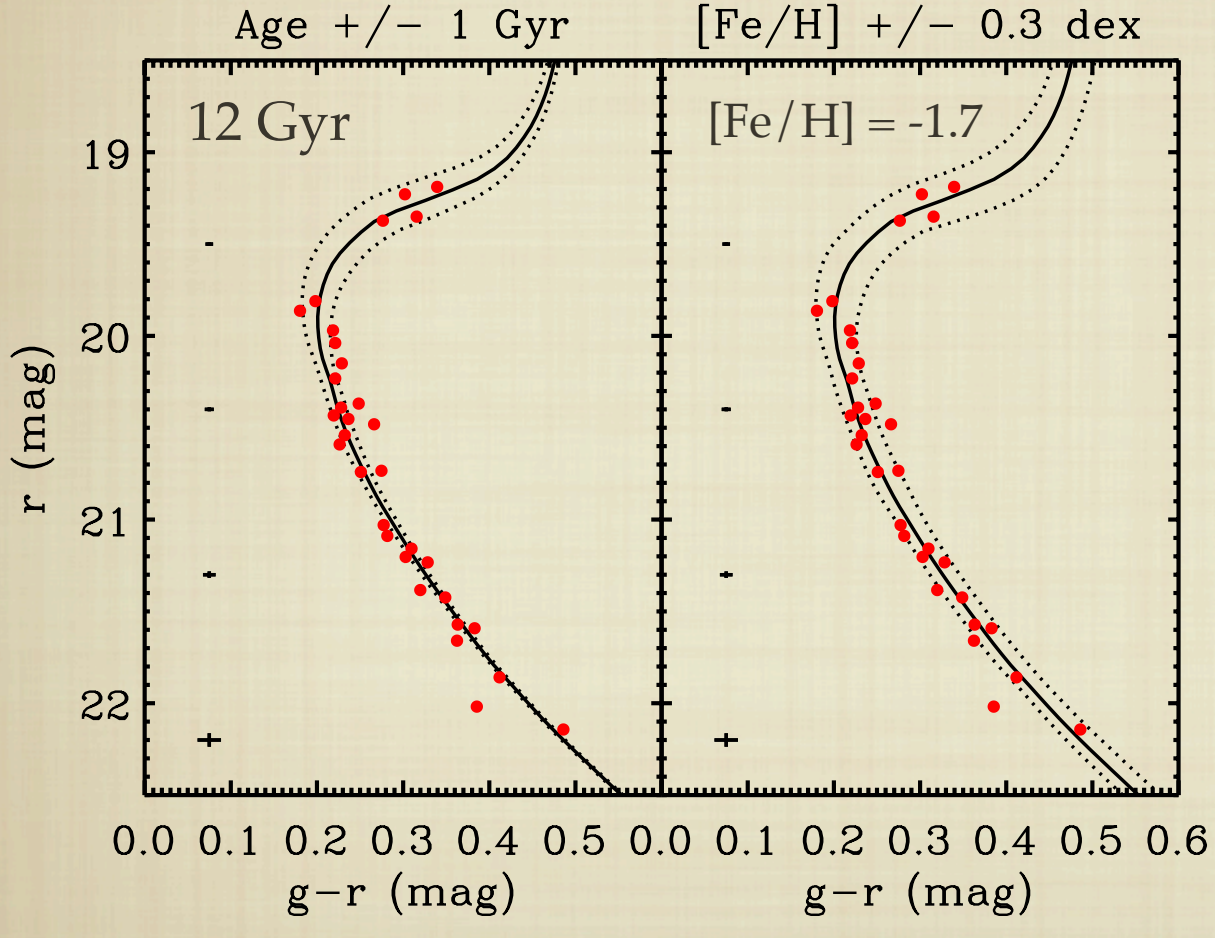
Luminosities and sizes of nearby dwarf galaxies





A self-bound stellar system whose properties cannot be explained by baryons + Newton's laws Willman & Strader in prep

Kinematics don't reveal huge dark matter reservoirs



Segue 3: Magellan/IMACS photometry + Keck/DEIMOS spectroscopy

d ~ 17 kpc, M_V ~ -0.1, r_{half} ~2 pc

$\sigma_{vel} = 1.5^{+1.5}_{-1.0}$ km/sec

Fadely, Willman, Geha, Walsh et al 2011

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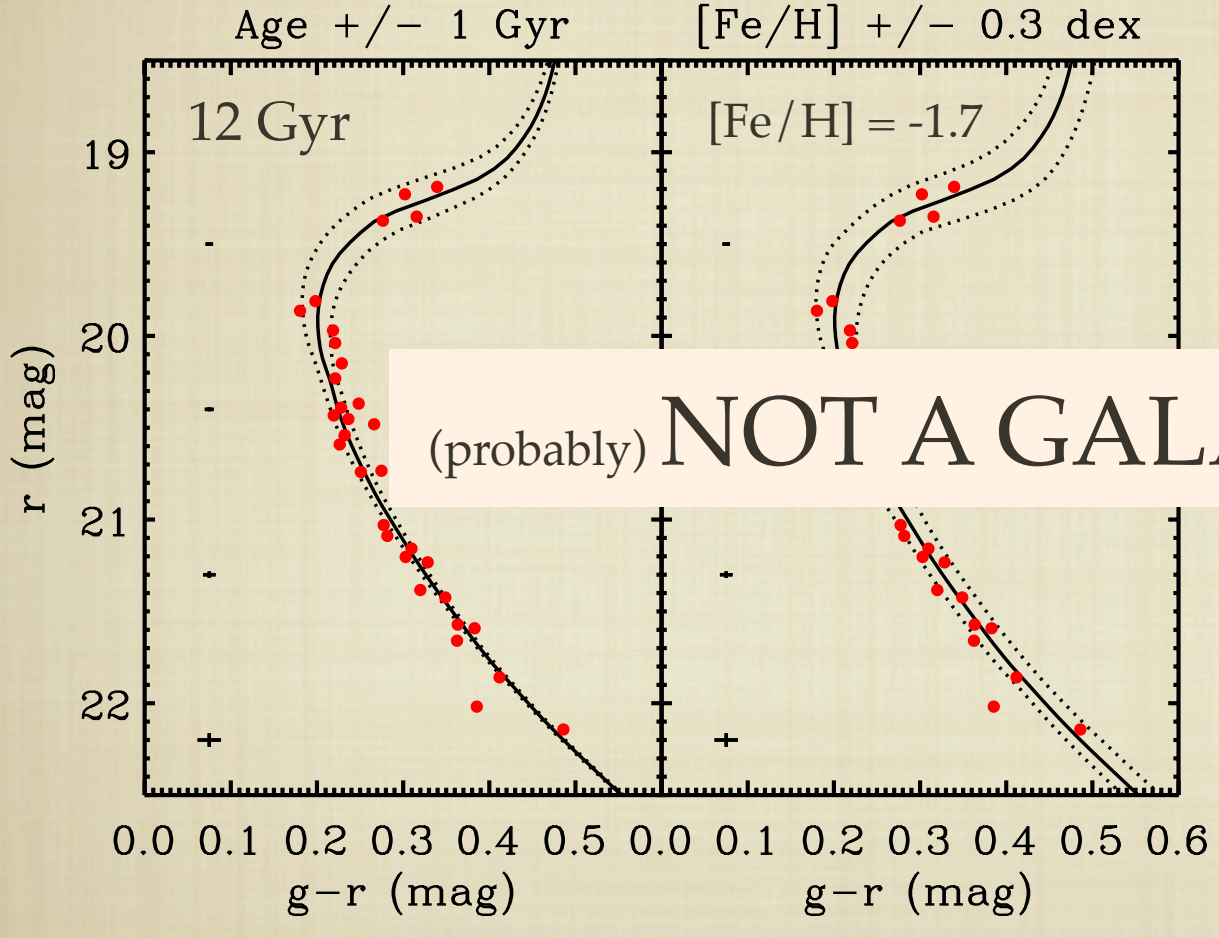

(probably) NOT A GALAXY

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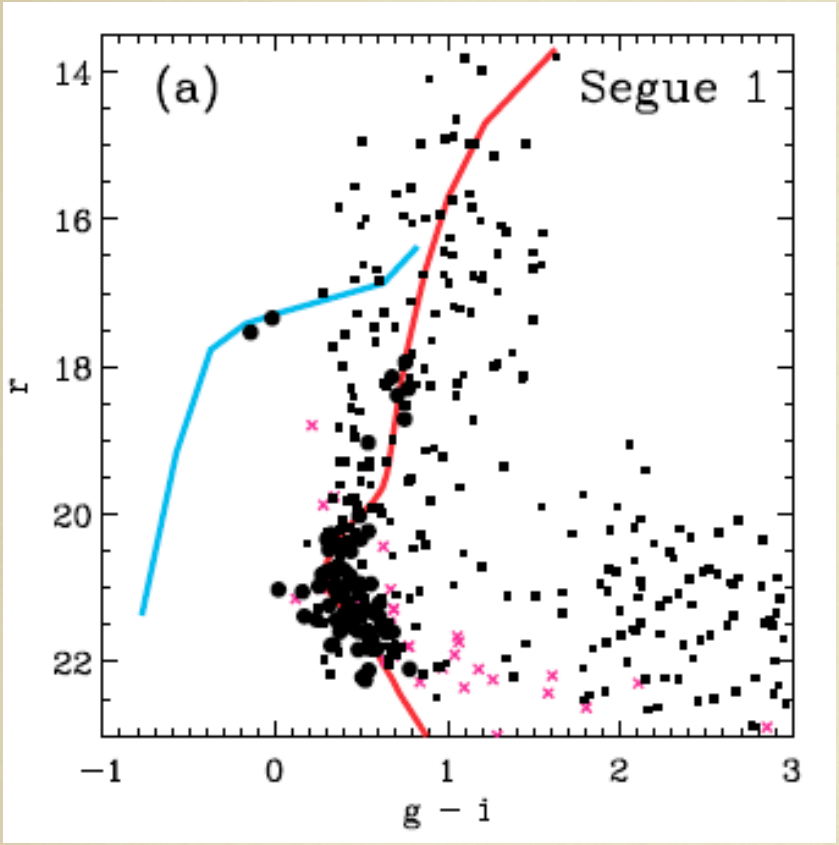
Kinematic studies reveal huge dark matter reservoirs



$\sigma = 3.7\ ^{+1.4}_{-1.1}$ km/sec (incl. binary correction)

Mass within 30 pc ~ 6 x 10^5 M_{Sun}, M/L ~ 3000

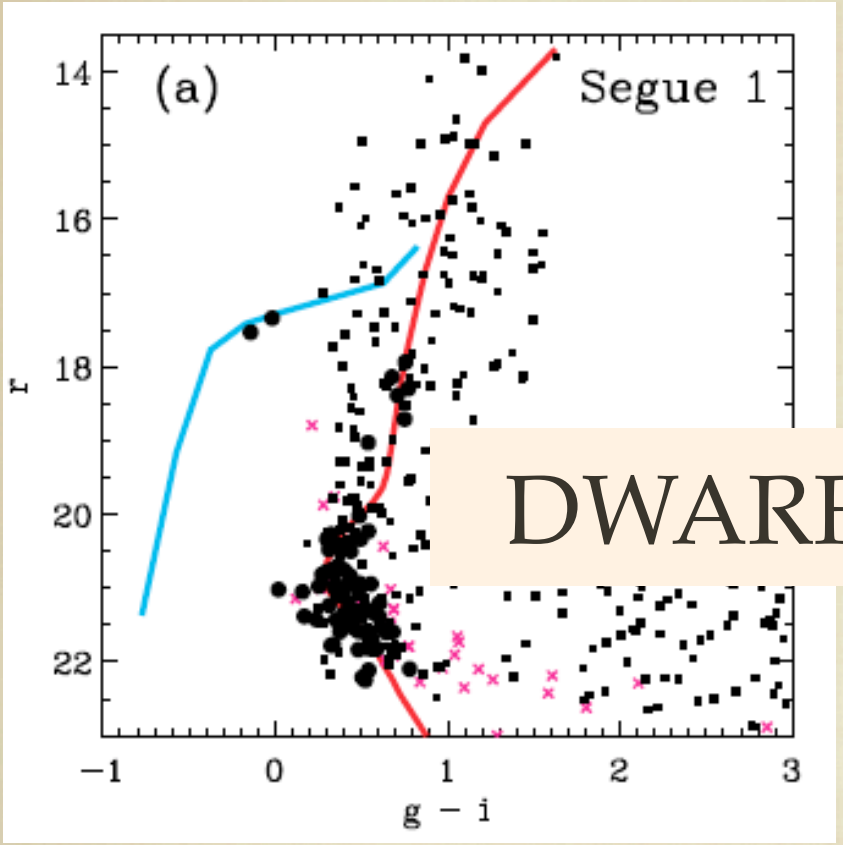
6 stars with [Fe/H] estimates from -1.7 to -3.3

Keck/DEIMOS observations of Segue 1

99% complete sample of stars with r < 22 within 2 r_{eff} (60 pc)

Simon, Geha ... Kirby...
Willman et al (2011)

Kinematic studies reveal huge dark matter reservoirs



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DWARF GALAXY

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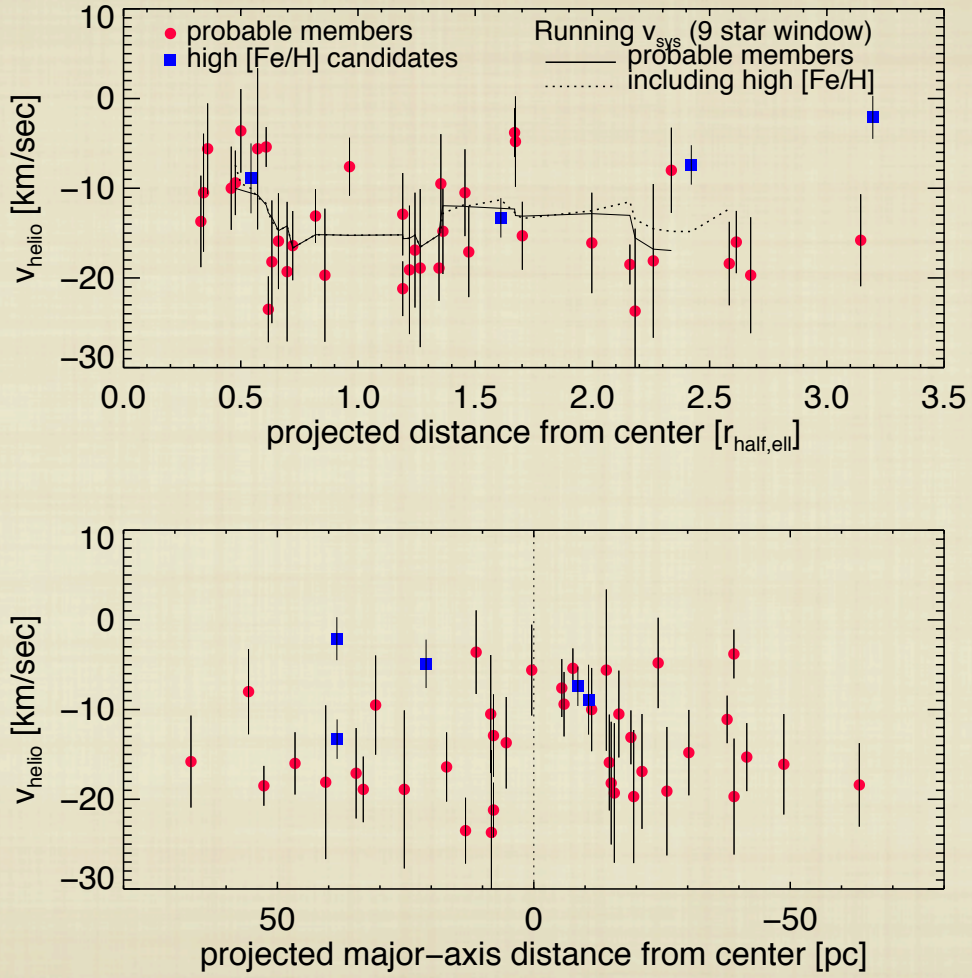
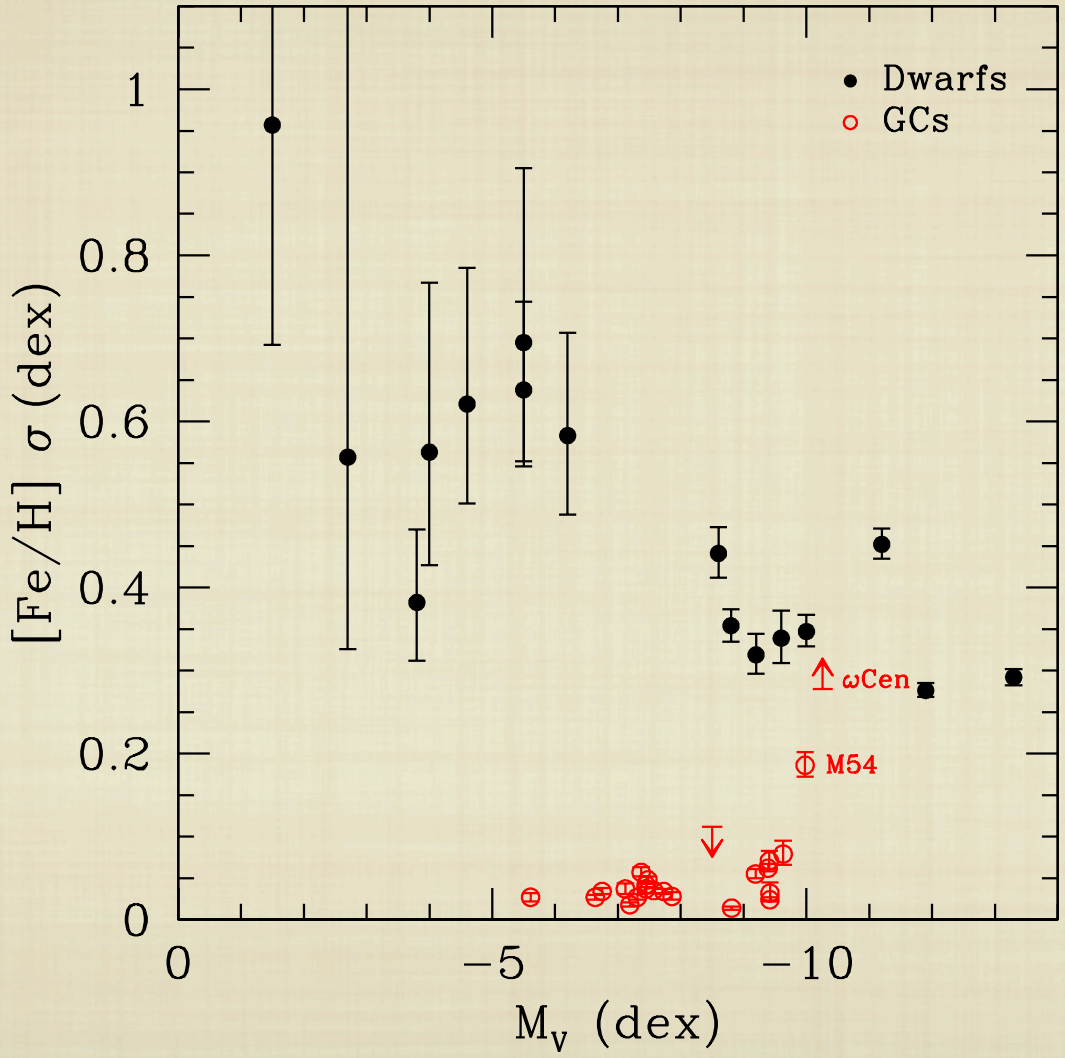
Kinematic studies complicated by irregular dynamics



Keck/DEIMOS and KPNO observations of Willman I (M_V ~ -2, d ~ 38 kpc)

Willman, Geha... Simon, Kirby et al (2011)

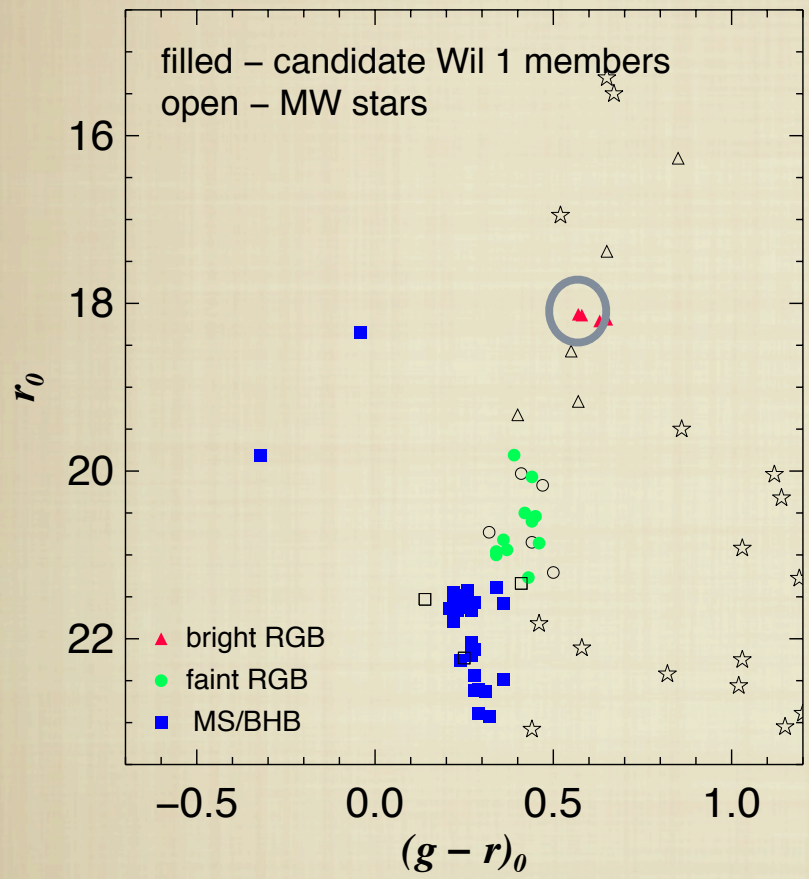
[Fe/H] spread can distinguish galaxies from clusters

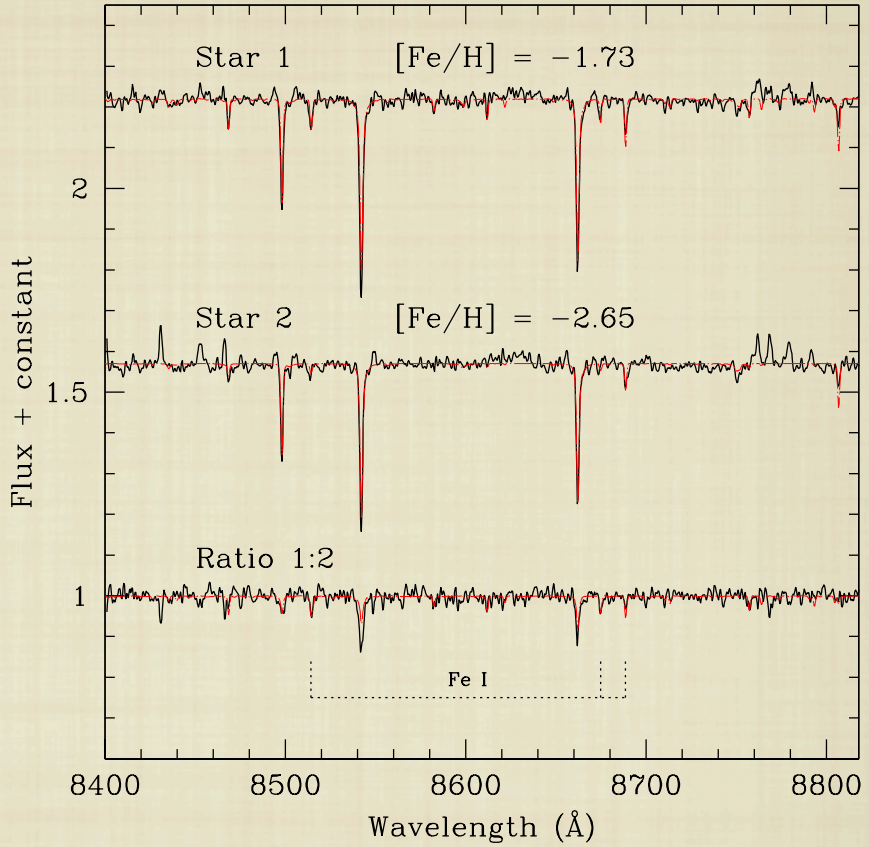


Willman & Strader
in preparation

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

[Fe/H] spread can distinguish galaxies from clusters: Willman 1





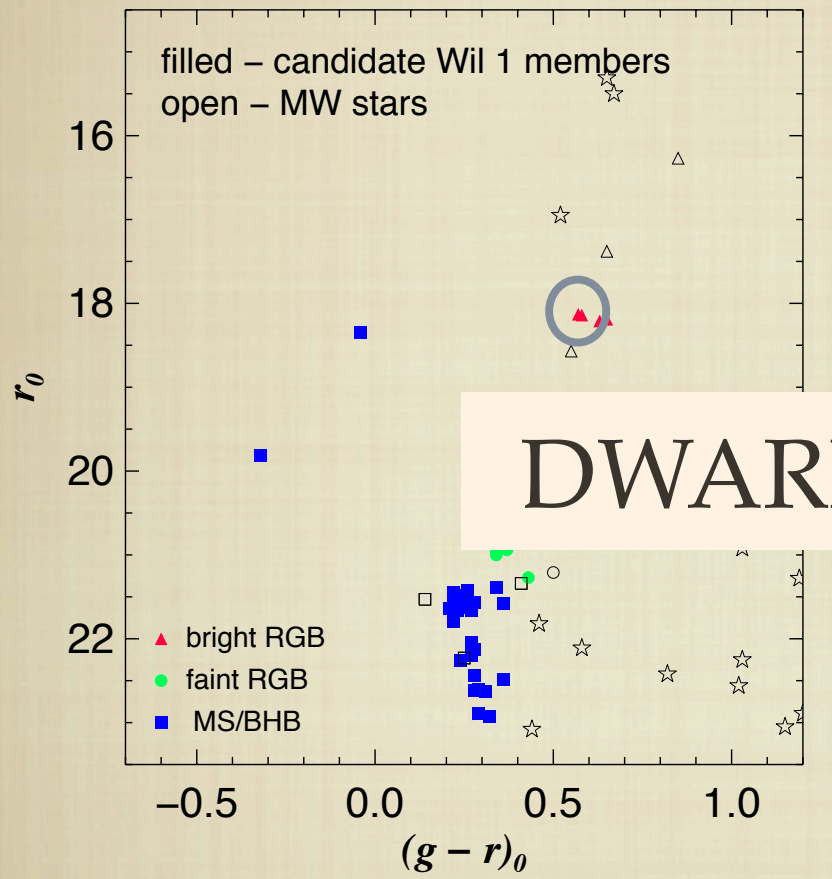
Willman, Geha... Simon, Kirby et al (2011)

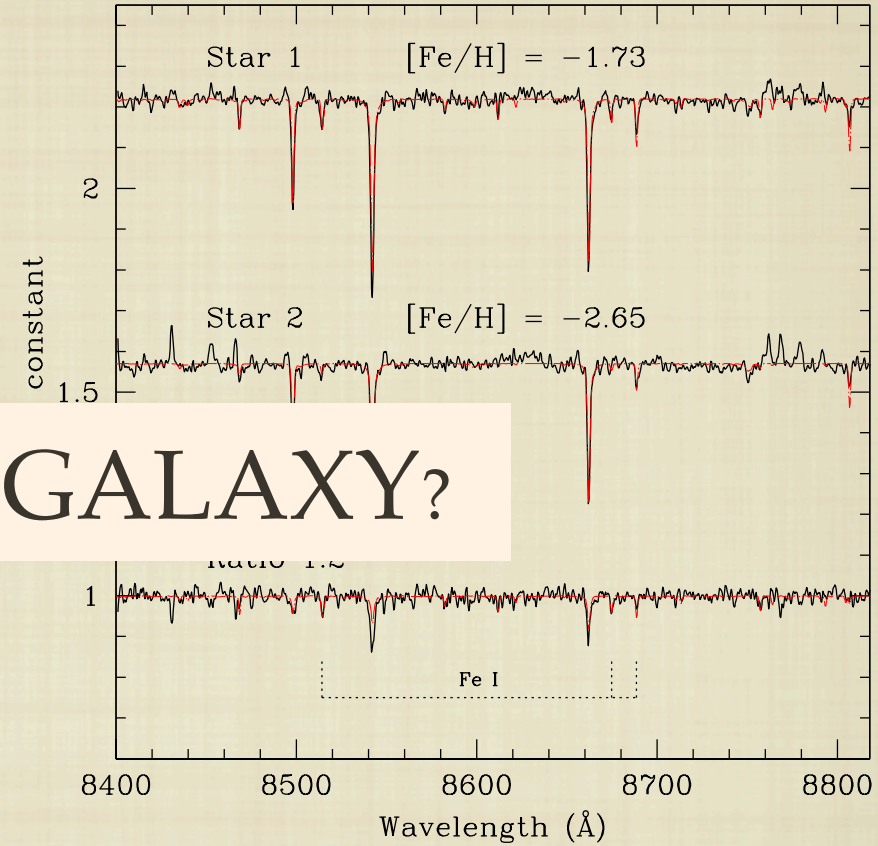
Keck/DEIMOS and KPNO observations of Willman I (M_V ~ -2, d ~ 38 kpc)

Two red giant branch star members

There is an [Fe/H] ([Ca/Fe]) spread: -1.7 and -2.7 (-0.4 and +0.1)

[Fe/H] spread can distinguish galaxies from clusters: Willman 1





DWARF GALAXY?

Willman, Geha... Simon, Kirby et al (2011)

Keck/DEIMOS and KPNO observations of Willman I (M_V ~ -2, d ~ 38 kpc)

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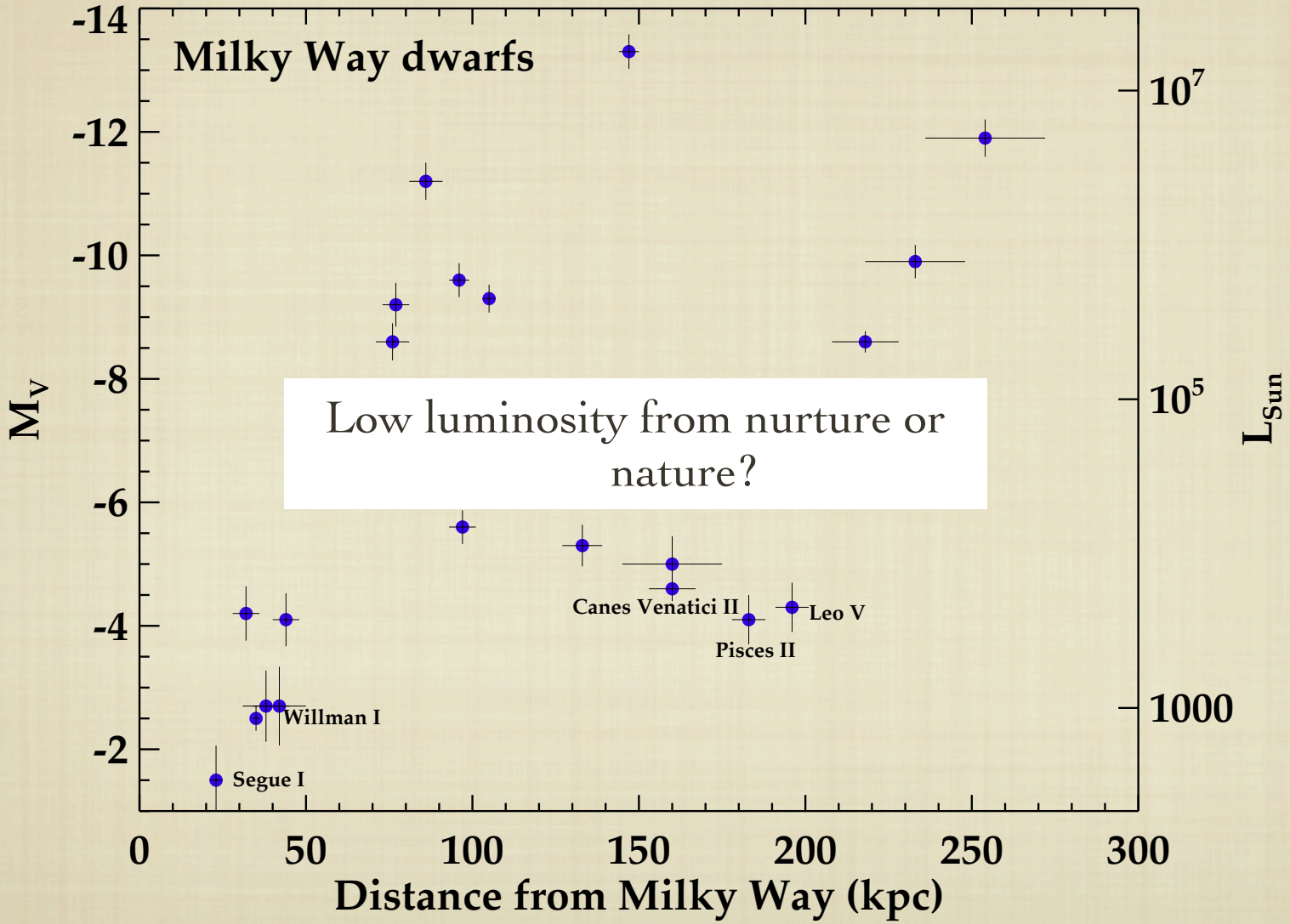
Distribution of the Milky Way's dwarfs



see e.g. Willman et al 2002; Walsh, Willman & Jerjen 2009

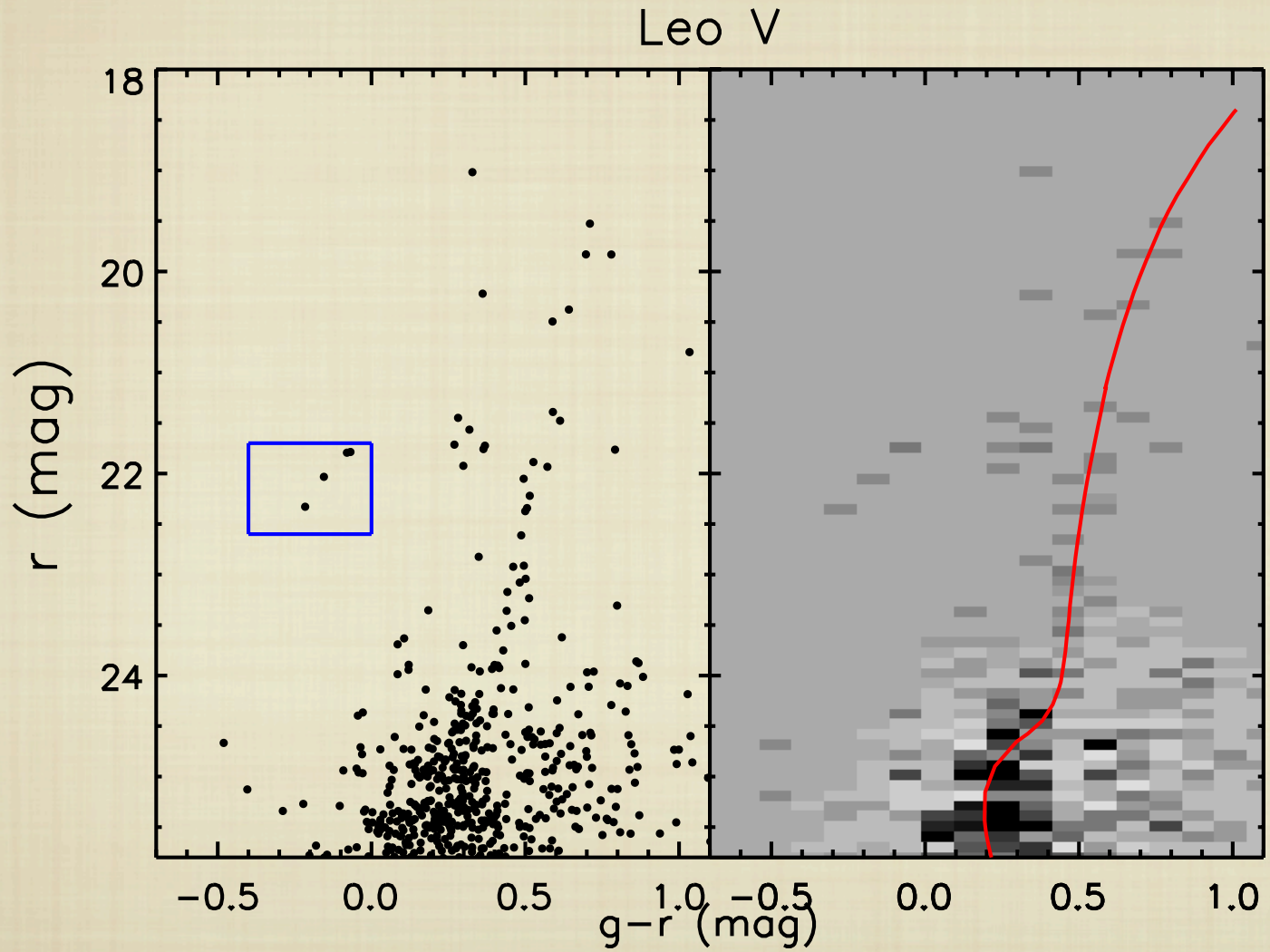
Outer halo dwarfs: Nature vs Nurture

Leo V, Pisces II, CVn II

- Morphological evidence for tidal evolution?

Sand, Strader, Willman et al submitted

Hints of disturbed structure: 2d distribution



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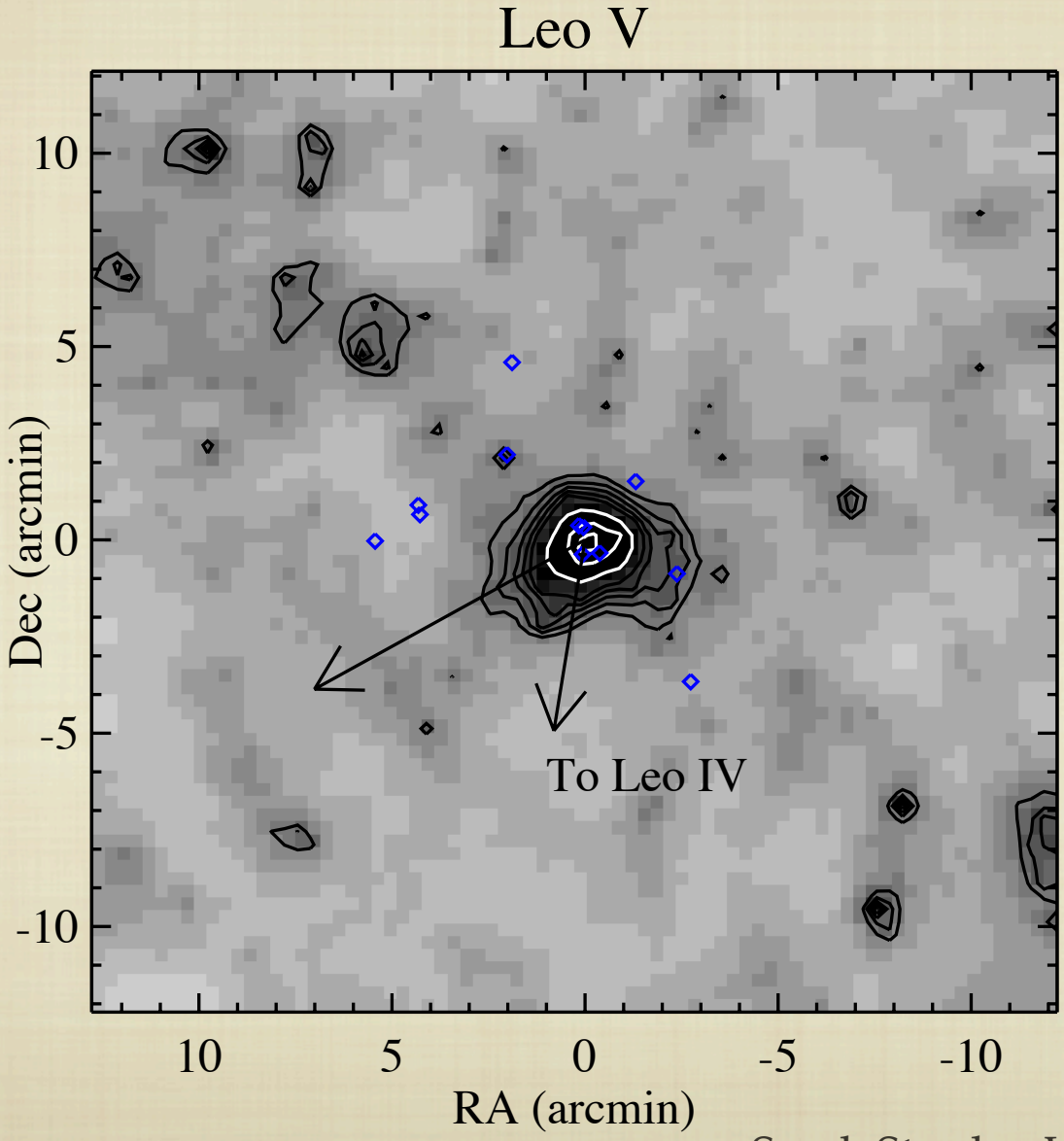
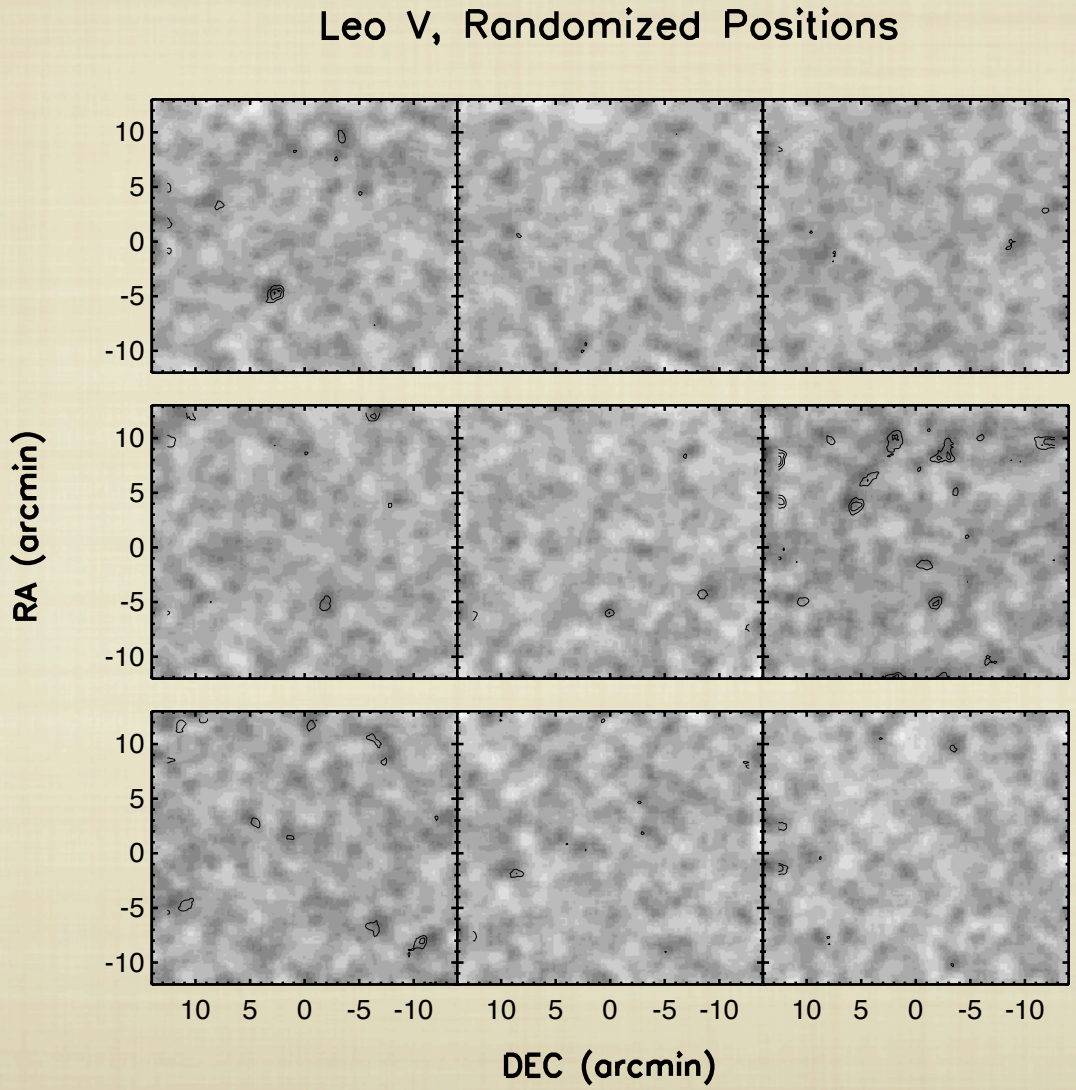


d ~ 190 kpc

Sand, Strader, Willman et al submitted

Hints of disturbed structure: 2d distribution



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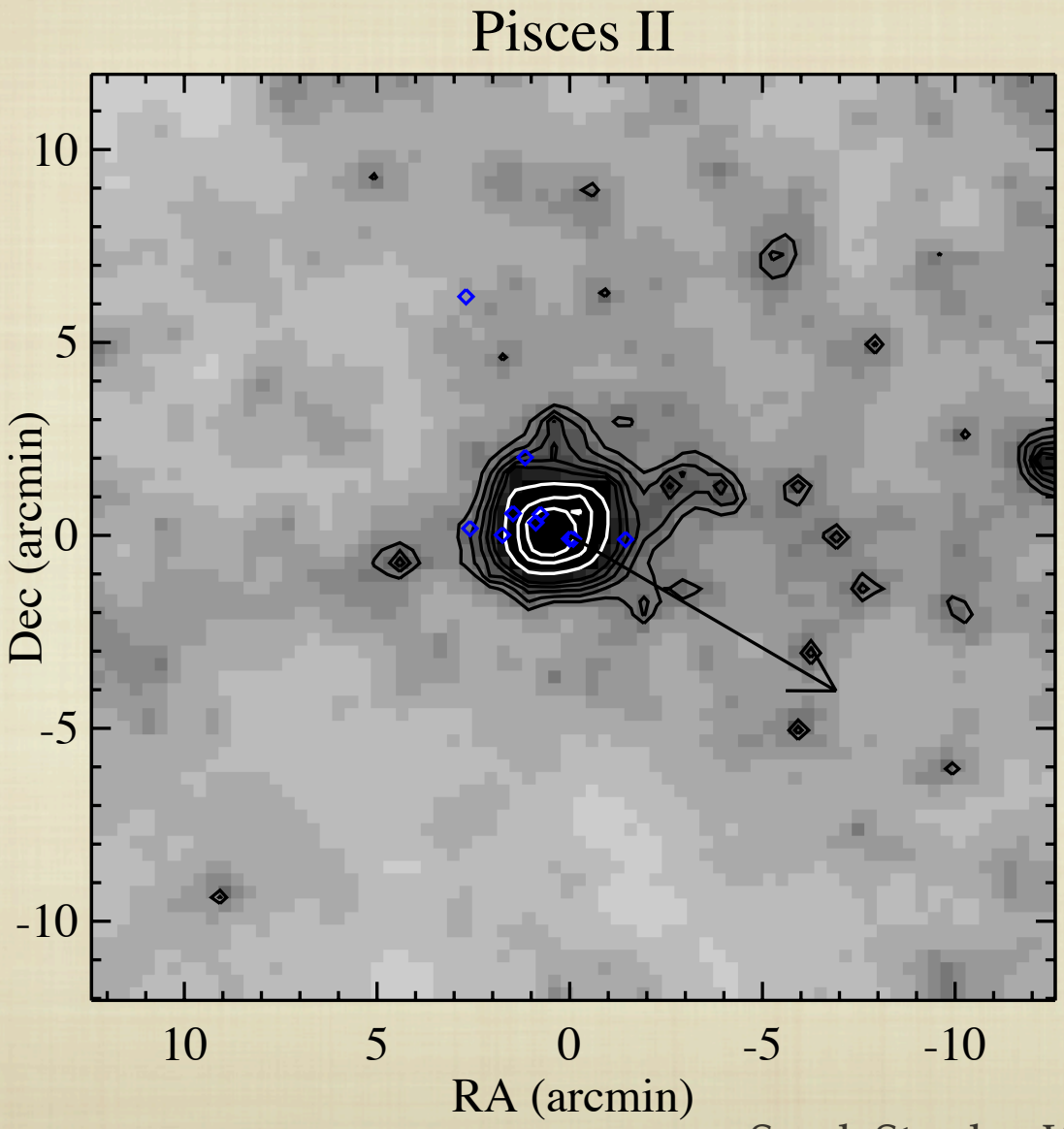
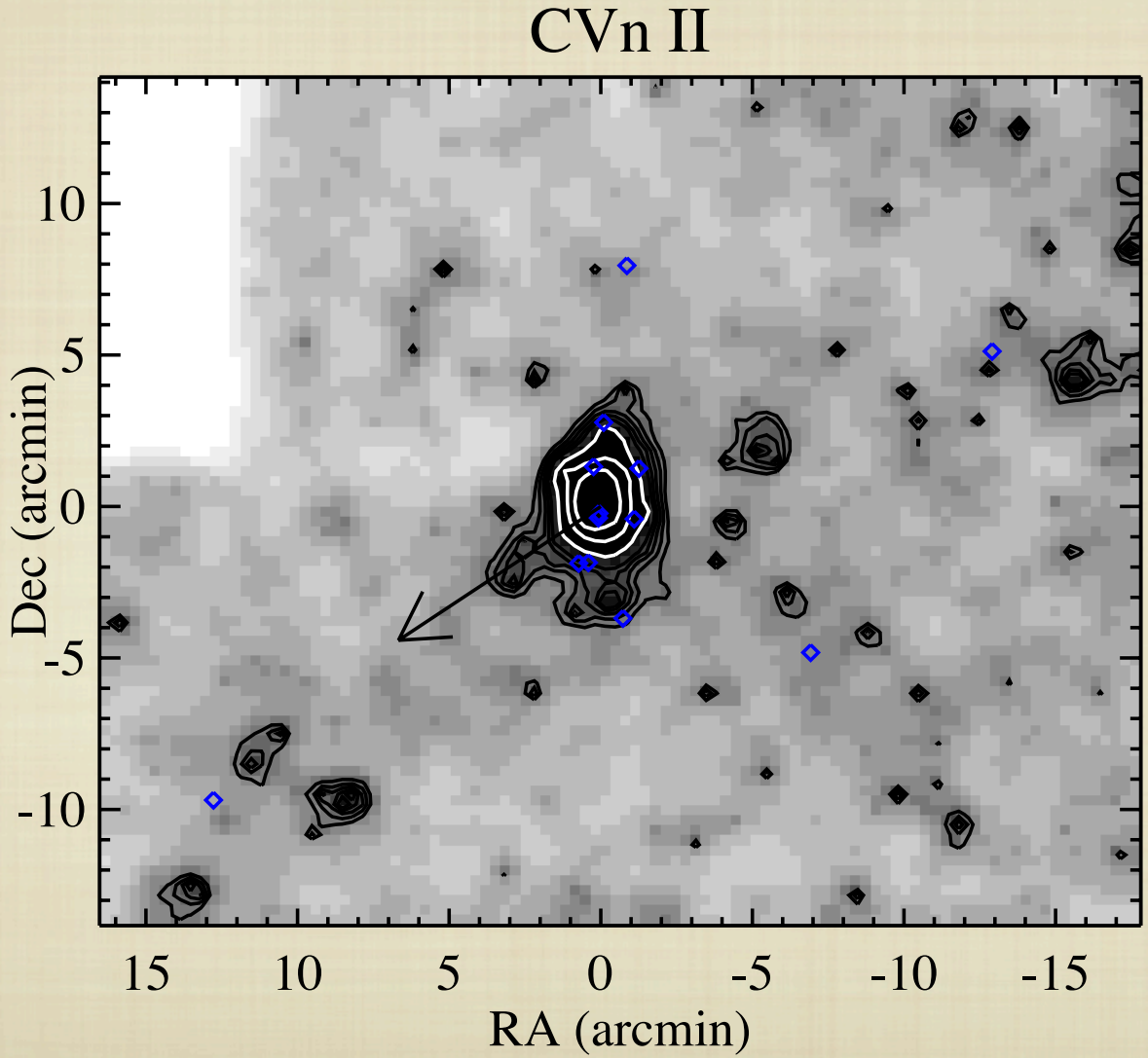


d ~ 170 kpc

Sand, Strader, Willman et al submitted

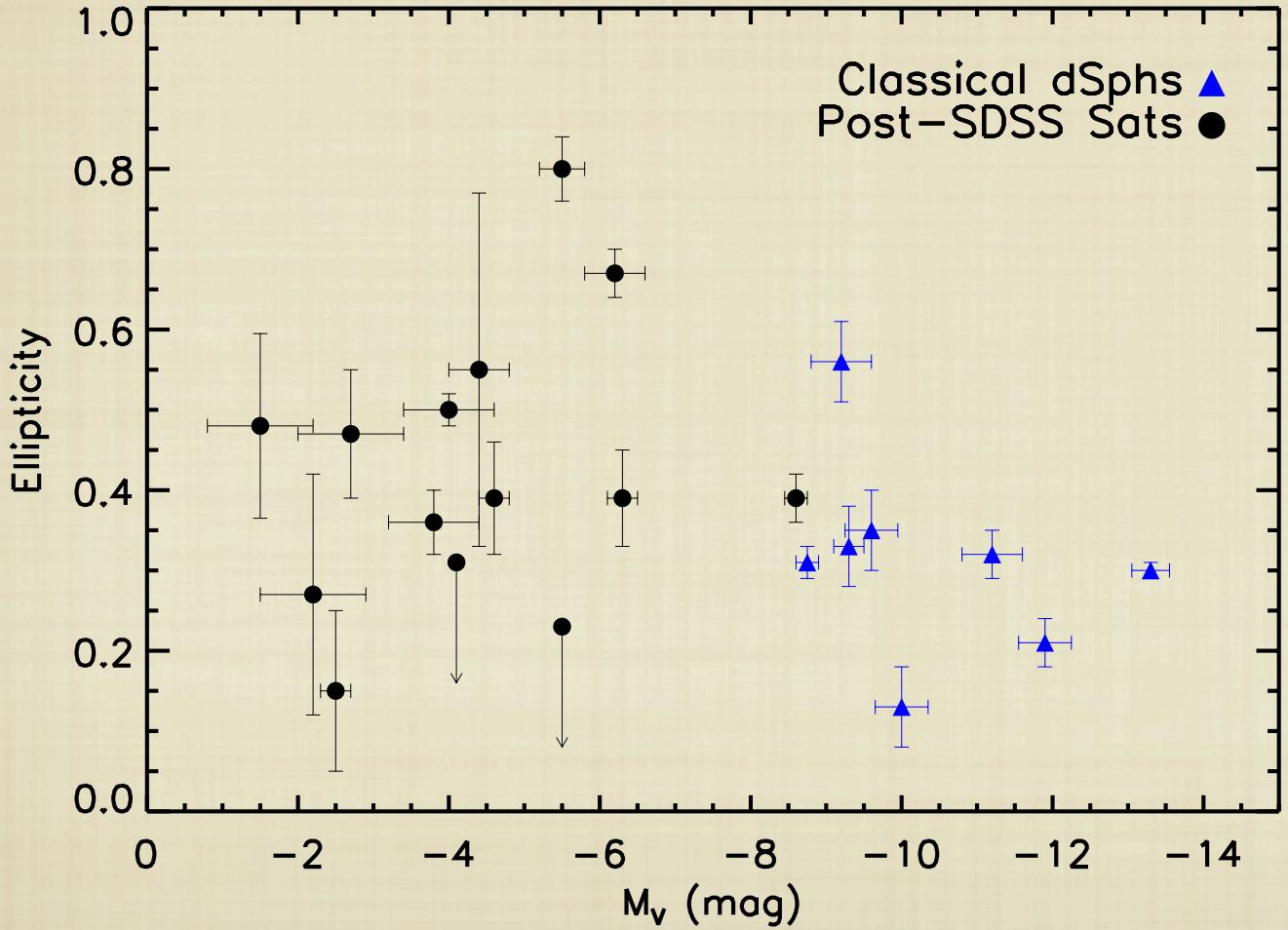
Hints of disturbed structure: 2d distribution



d ~ 160 kpc

Sand, Strader, Willman et al submitted

Hints of disturbed structure: Ellipticity

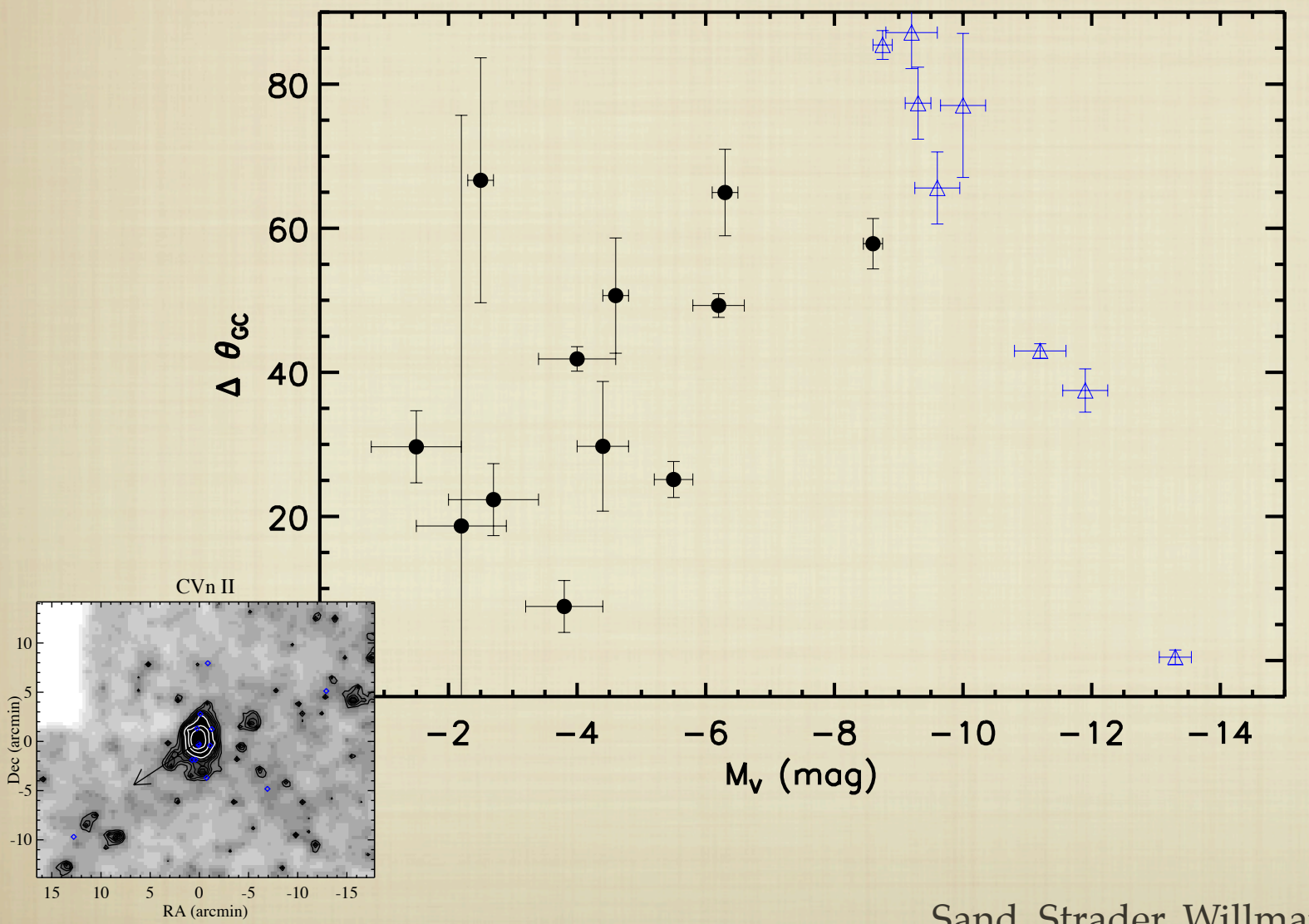


e_{SDSS} = 0.44 +/- 0.05

$e_{classical}$ = 0.32 +/- 0.03

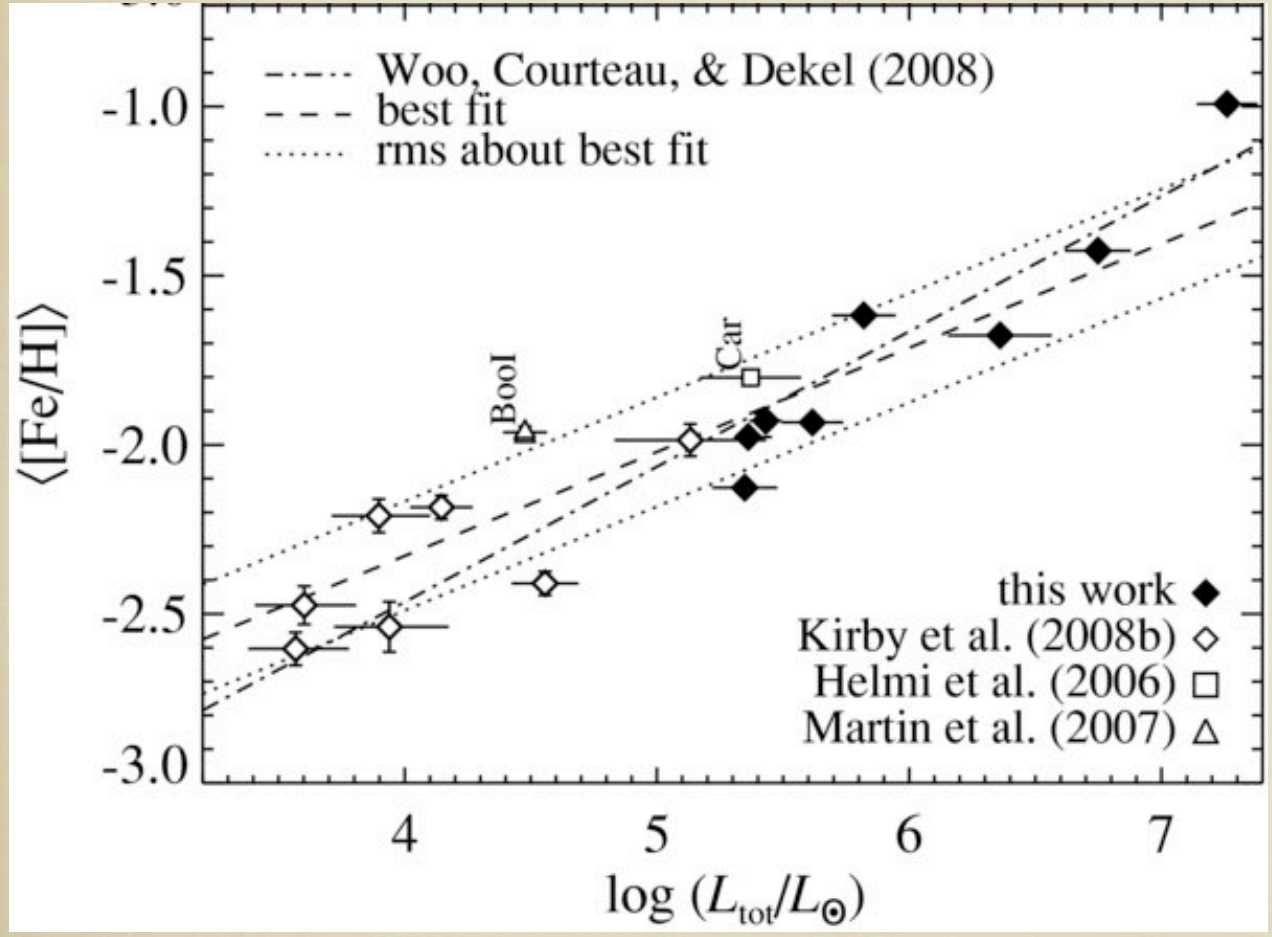
Sand, Strader, Willman et al submitted

Hints of disturbed structure: Orientation



Sand, Strader, Willman et al submitted

Challenging pathological explanations: Luminosity-[Fe/H] relation



Segue 1 (7 stars):
-2.7 +/- 0.4 dex

Wil 1 (3 stars):
-2.1 +/- 0.4 dex

Kirby et al 2011

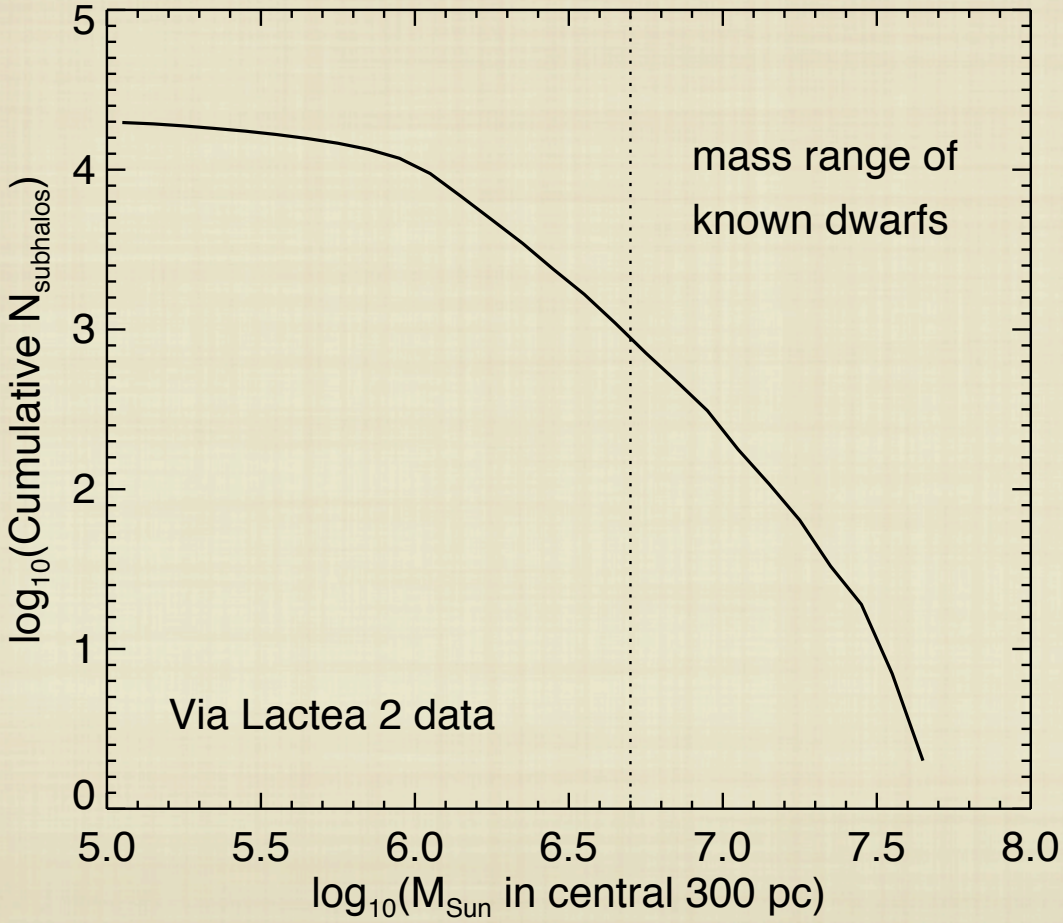
Connecting observations to theory: How many dwarfs vs subhalos

Corrections for SDSS footprint and luminosity bias suggest ~100-300 dwarfs

(e.g. Tollerud et al 2008, Koposov et al 2008; loads of assumptions and caveats)

The devil is in the details (e.g. densities, spatial distributions)

Connecting observations to theory: How many dwarfs vs subhalos



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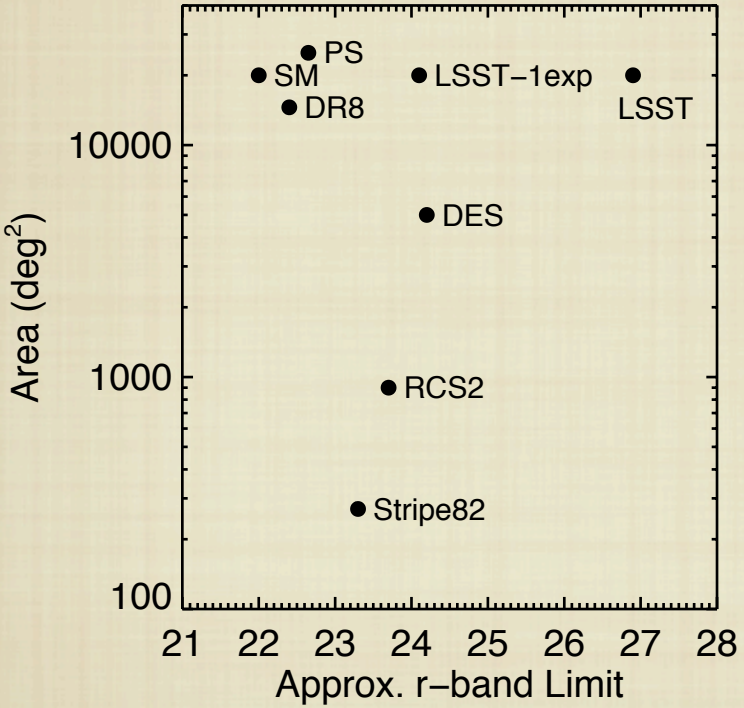
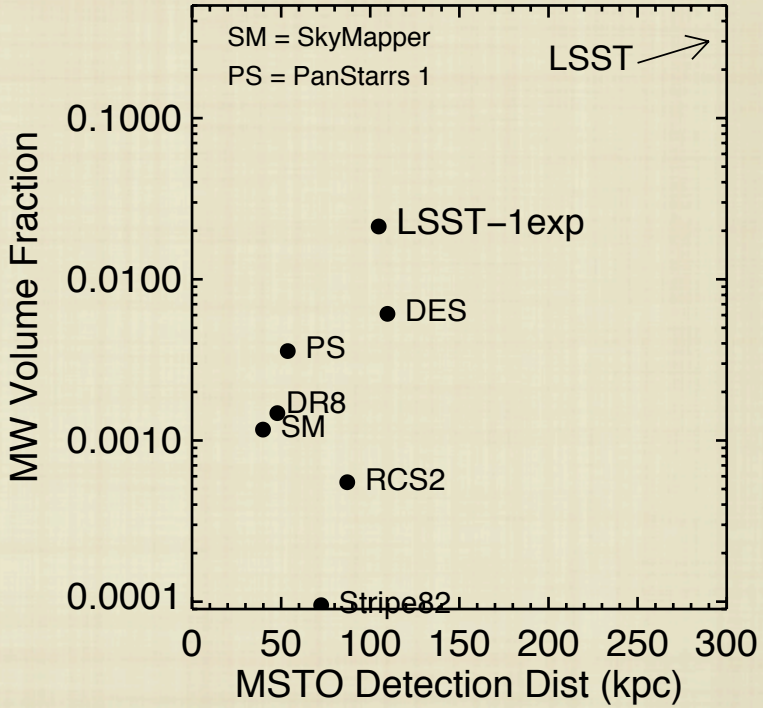
Current and Future Optical Surveys





What we have learned since 1999

- A large number of Milky Way dwarf galaxies remain to be found
- Galaxies exist with mere hundreds of Solar luminosities
- Complexities of their stellar populations and morphologies yield vital clues to the origin of these objects

Open questions

- The very least luminous objects: tip of the iceberg or tidal remnants?
- How faint is the faintest galaxy?
- What is the spatial distribution, luminosity function, mass function of the least luminous galaxies?

The End