Needles in a Haystack

looking for tiny, faint galaxies in the Local Group

Bill Janesh (Indiana University)

Katherine Rhode (IU), Betsey Adams (ASTRON), Martha Haynes (Cornell), Riccardo Giovanelli (Cornell), John Salzer (IU), John Cannon (Macalester), Steven Janowiecki (ICRAR)

5 October 2017


z = 48.4
T = 0.05 Gyr
500 kpc
Springel+ 2008

Dwarf Galaxies





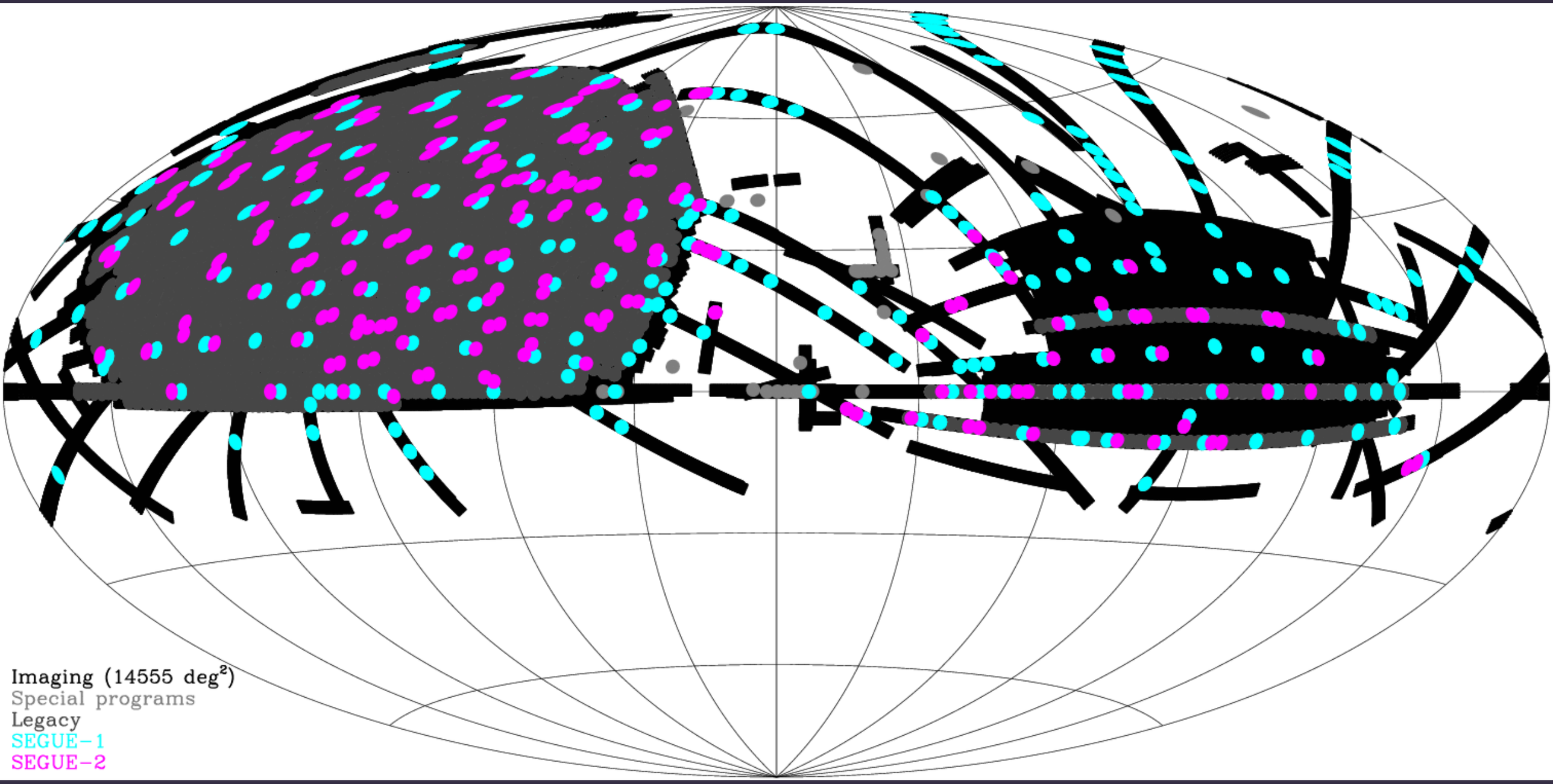






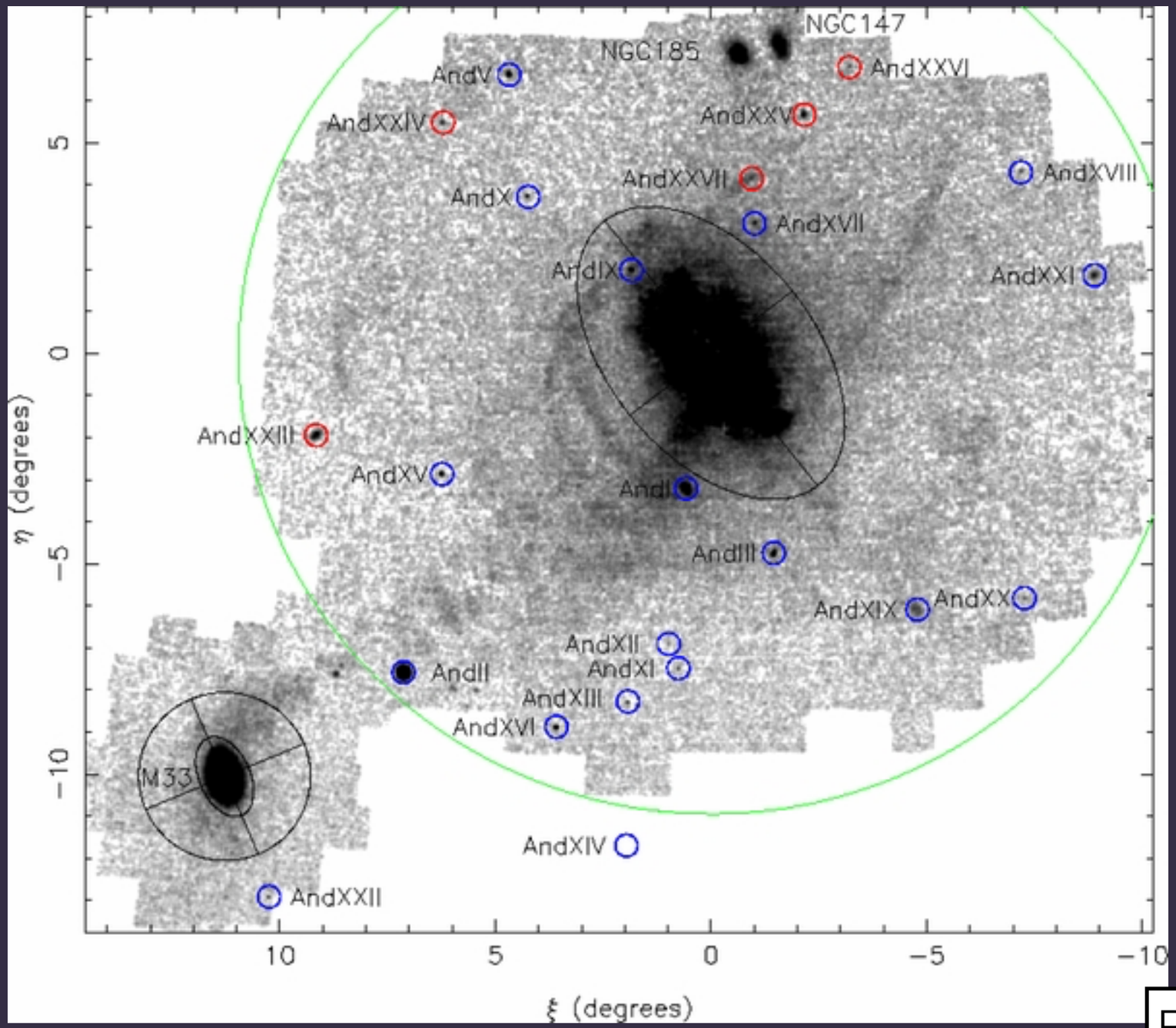



Sloan Digital Sky Survey



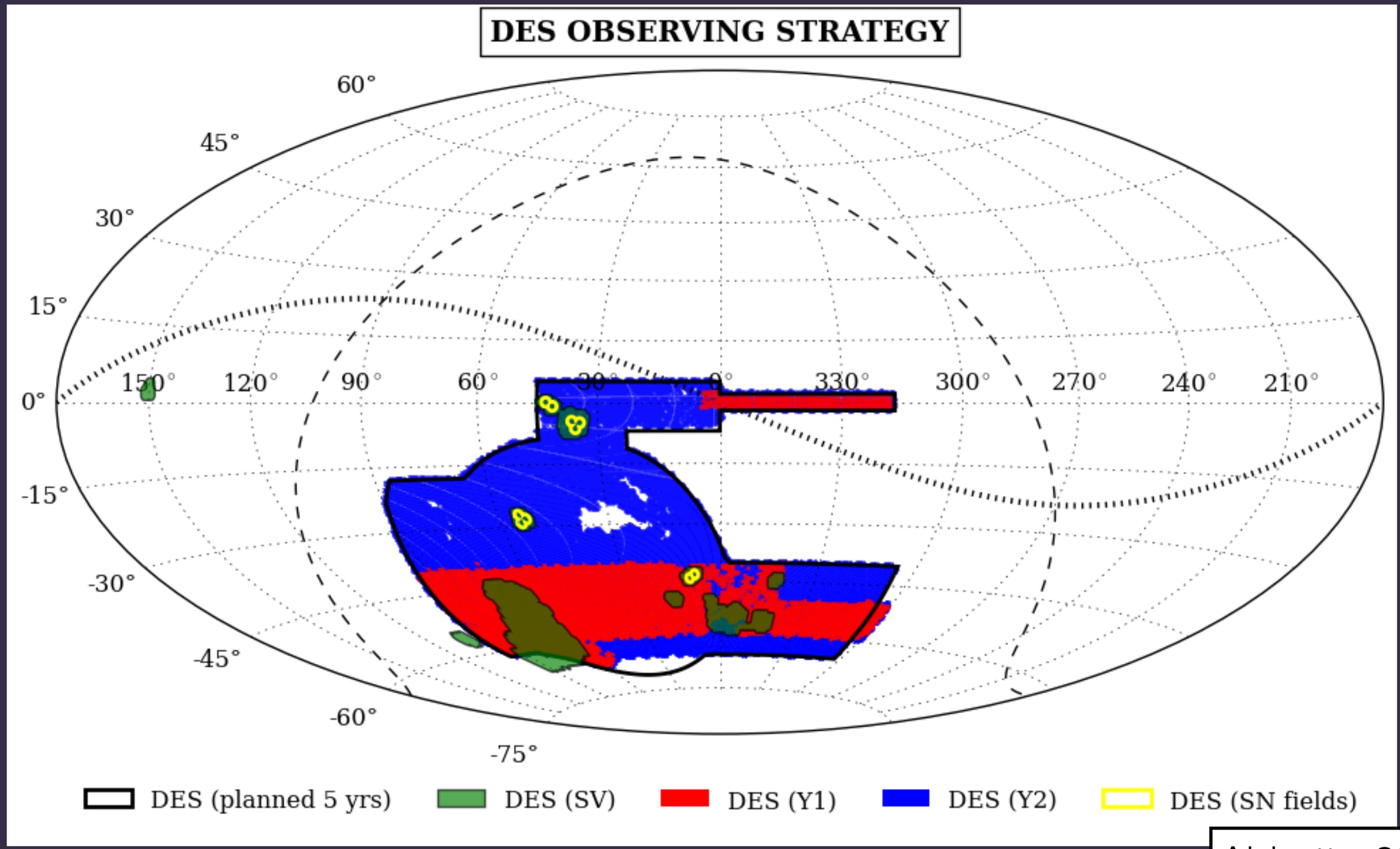
Albareti+ 2016

PanAndromeda Archaeological Survey



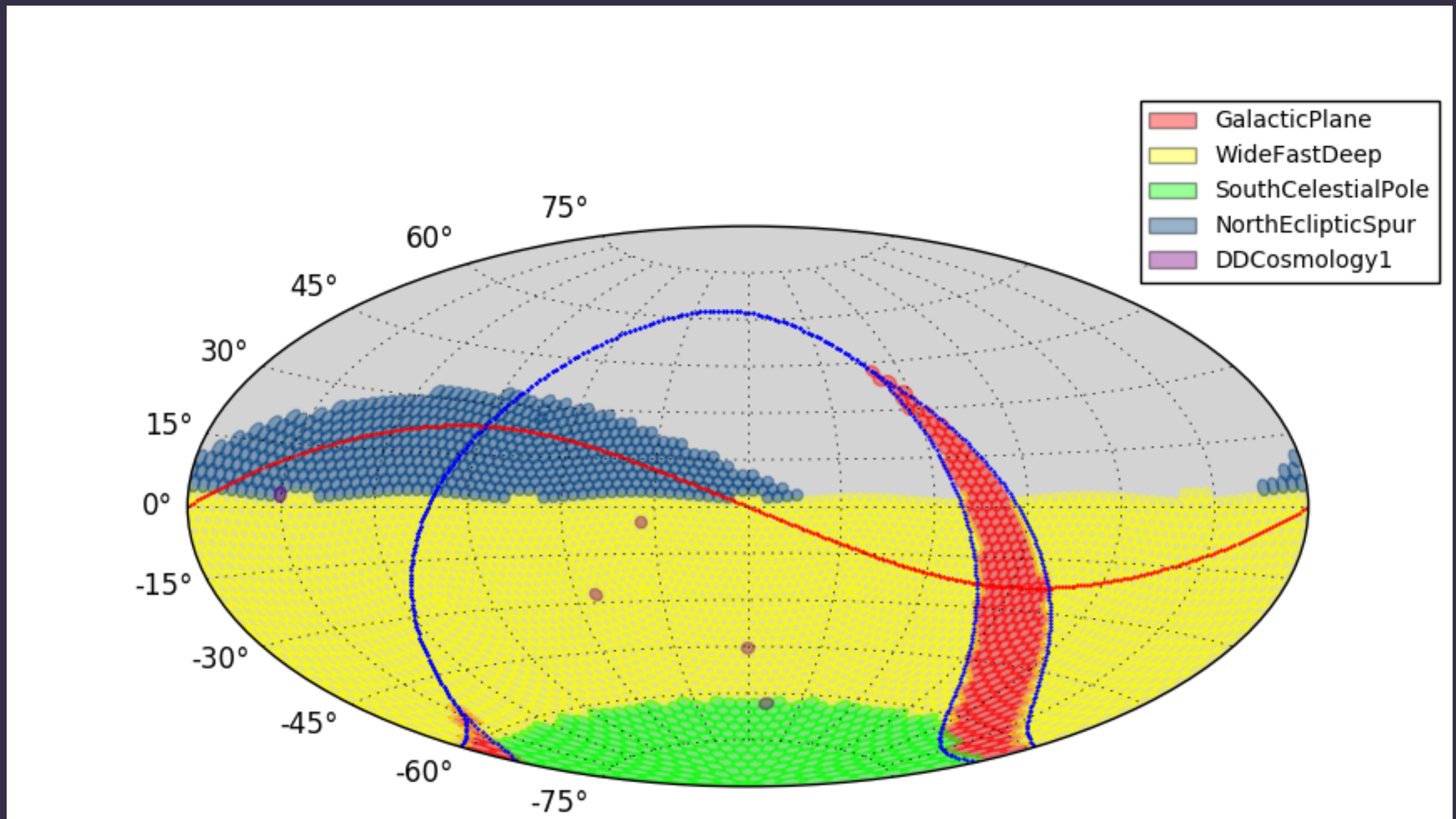
Richardson+ 2011

Dark Energy Survey

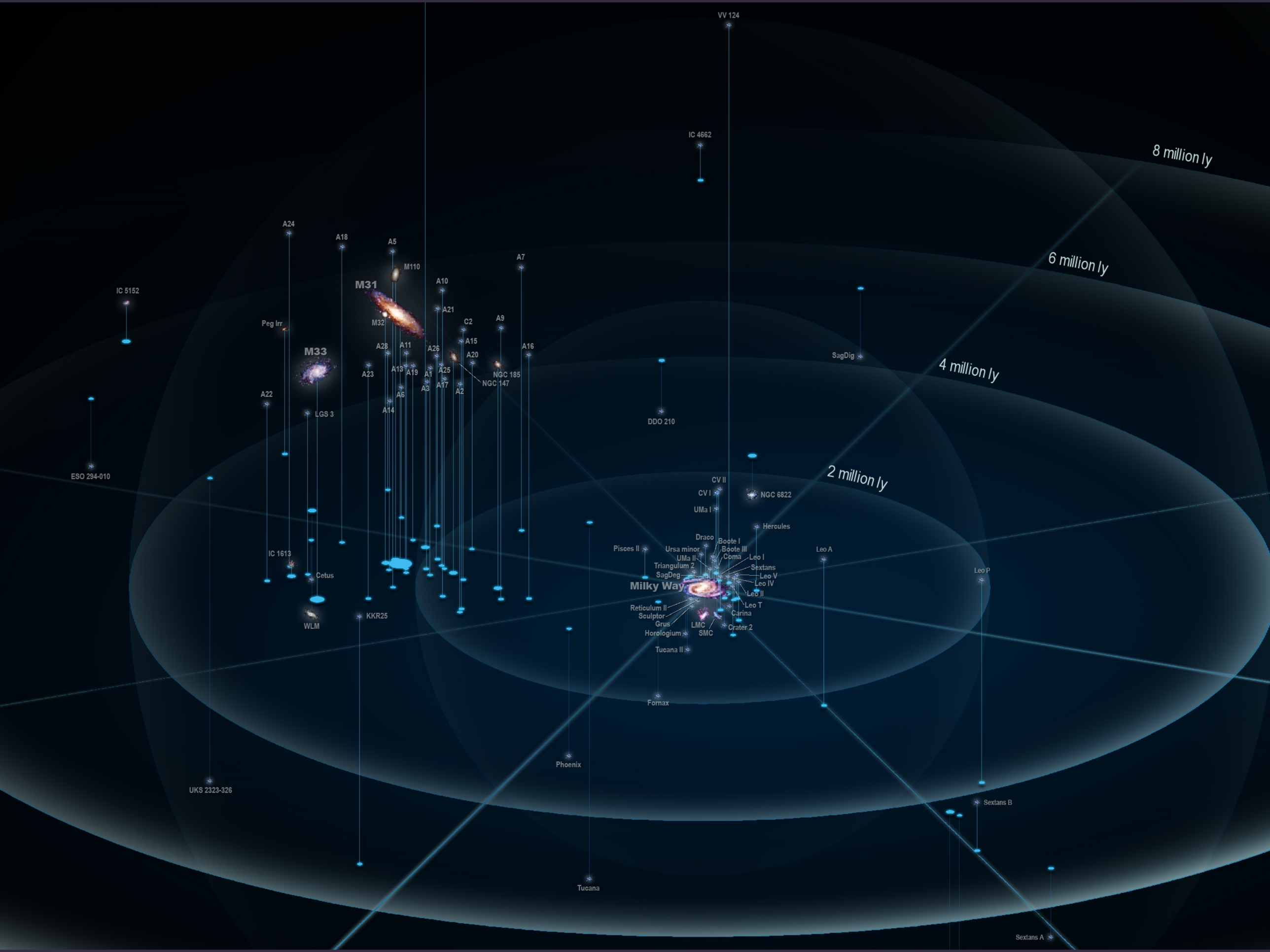


Abbott+ 2016

Large Synoptic Survey Telescope



LSST Consortium


VV 124
IC 4662
8 million ly
6 million ly
4 million ly
2 million ly
A24
A18
A5
M110
M31
A7
A10
IC 5152
A21
C2
A9
Peg Irr
M32
A15
A16
M33
A28
A11
A26
A20
SagDig
A23
A13
A19
A1
A25
NGC 185
NGC 147
A3
A17
A2
A22
A6
A14
LGS 3
DDO 210
ESO 294-010
CV II
CV I
NGC 6822
UMa I
Hercules
Draco
Boote I
Pisces II
Ursa minor
Boote III
Leo A
UMa II
Coma
Leo I
Triangulum 2
Sextans
Leo P
SagDeg
Leo V
IC 1613
Milky Way
Leo IV
Leo II
Cetus
Reticulum II
Leo T
Sculptor
Carina
WLM
KKR25
Grus
LMC
Crater 2
Horologium
SMC
Tucana II
Fornax
Phoenix
UKS 2323-326
Sextans B
Tucana
Sextans A

THE LOCAL GROUP

MEET THE NEIGHBORS: IRREGULARS

WLM; ESO/VLT

Leo A; HST

Sextans B; HST

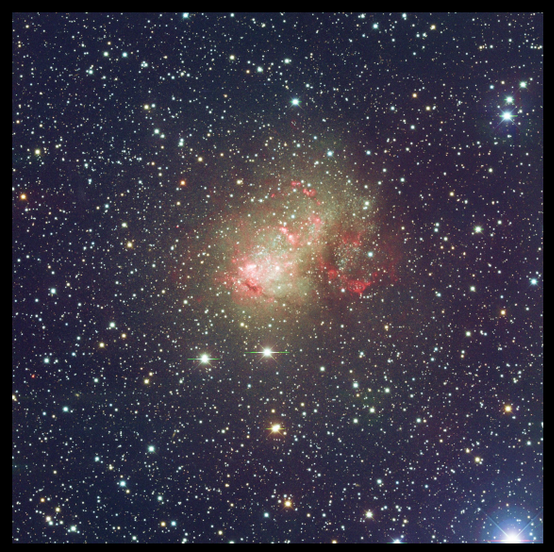
LGS 3; D. Hunter

NGC 3109; GALEX

IC 1613; ESO

Sextans A; van Dyk

IC 10; Lowell Obs.



THE LOCAL GROUP

MEET THE NEIGHBORS: DWARFS

Various; HST, ESO, SDSS

AND DOZENS MORE...

THE LOCAL GROUP

14,000 ly

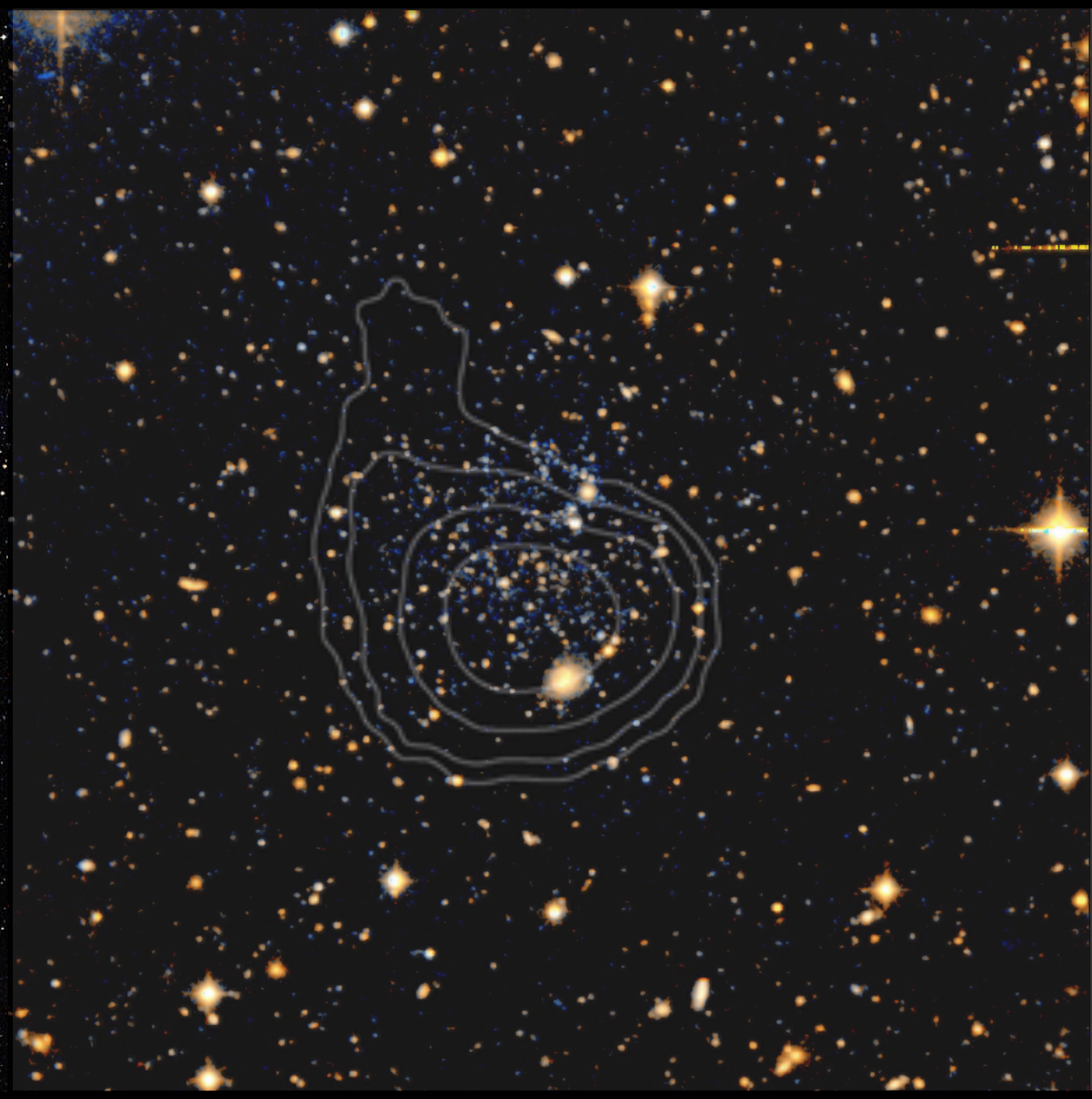
10,000 ly

750 ly

100,000 light-years

FORNAX

DARK MATTER MASS = 56,000,000 M_{SUN}
STELLAR MASS = 20,000,000 M_{SUN}
GAS MASS = <10,000 M_{SUN}
74% DM / 26% STARS
DIAMETER = 10,000 LY



LEO T

DARK MATTER MASS = 6,300,000 M_{SUN}
STELLAR MASS = 100,000 M_{SUN}
GAS MASS = 400,000 M_{SUN}
92.5% DM / 6% GAS / 1.5% STARS
DIAMETER = 750 LY

URSA MINOR

DARK MATTER MASS = 9,500,000 M_{SUN}
STELLAR MASS = 290,000 M_{SUN}
GAS MASS = 0 M_{SUN}
97% DM / 3% STARS
DIAMETER = 600 LY

CARINA

DARK MATTER MASS = 6,300,000 M_{SUN}
STELLAR MASS = 380,000 M_{SUN}
GAS MASS = 0 M_{SUN}
94% DM / 6% STARS
DIAMETER = 800 LY

SEGUE 1

DARK MATTER MASS = 260,000 M_{SUN}

STELLAR MASS = 340 M_{SUN}

GAS MASS = 0 M_{SUN}

99.9% DM / 0.1% STARS

DIAMETER = 100 LY

SEGUE 1

DARK MATTER MASS = 260,000 M_{SUN}

STELLAR MASS = 340 M_{SUN}

GAS MASS = 0 M_{SUN}

99.9% DM / 0.1% STARS

DIAMETER = 100 LY

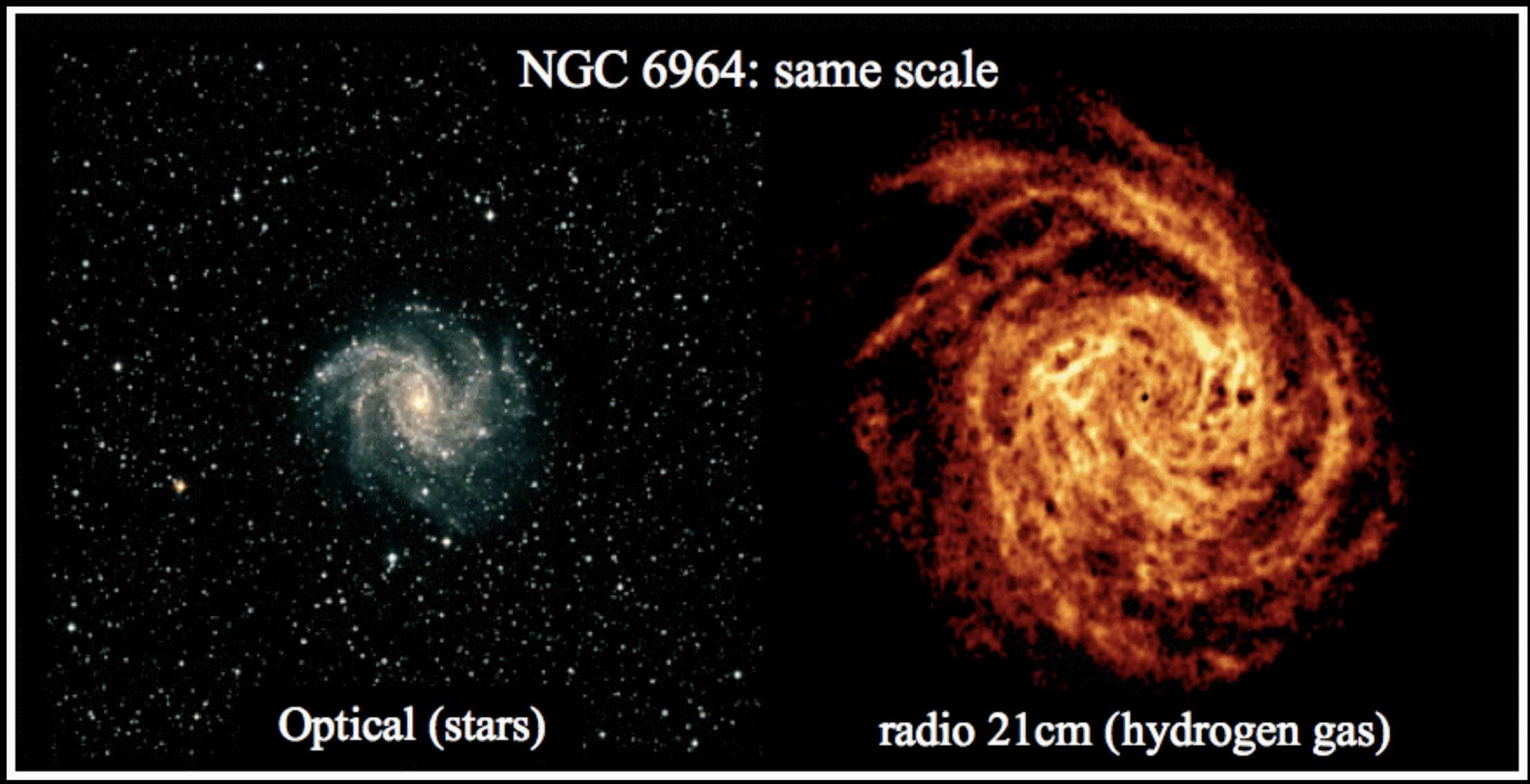
THE LOCAL GROUP

LOOKING FOR NEW DWARF GALAXIES

IF SOME DWARF GALAXIES HAVE GAS, LET'S LOOK FOR NEW ONES WHERE WE SEE A LOT OF GAS!

THE LOCAL GROUP

NEUTRAL HYDROGEN GAS

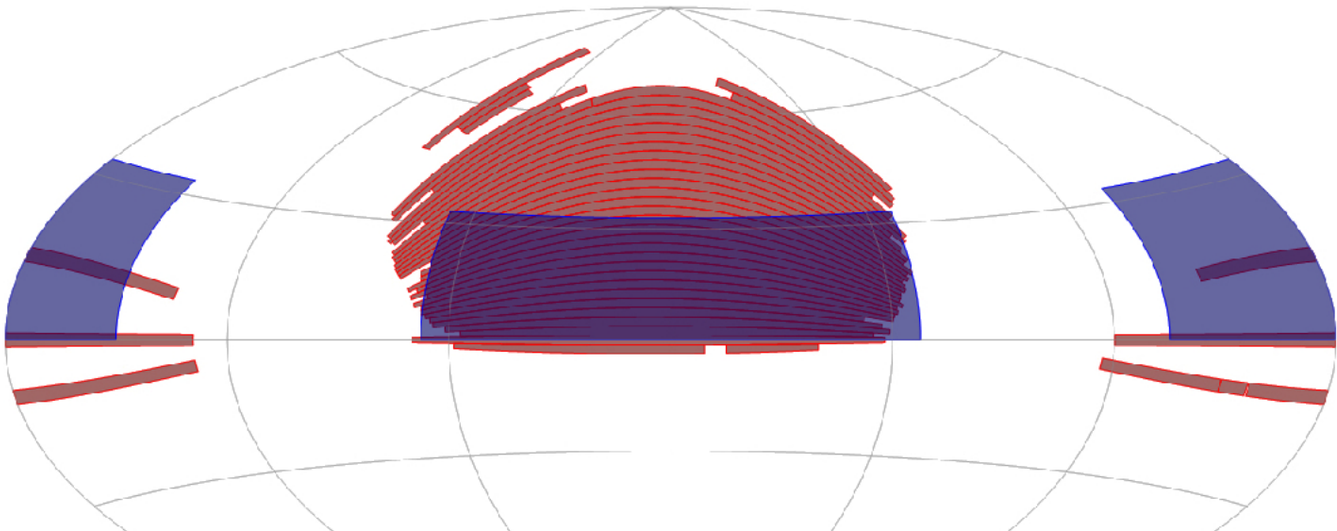


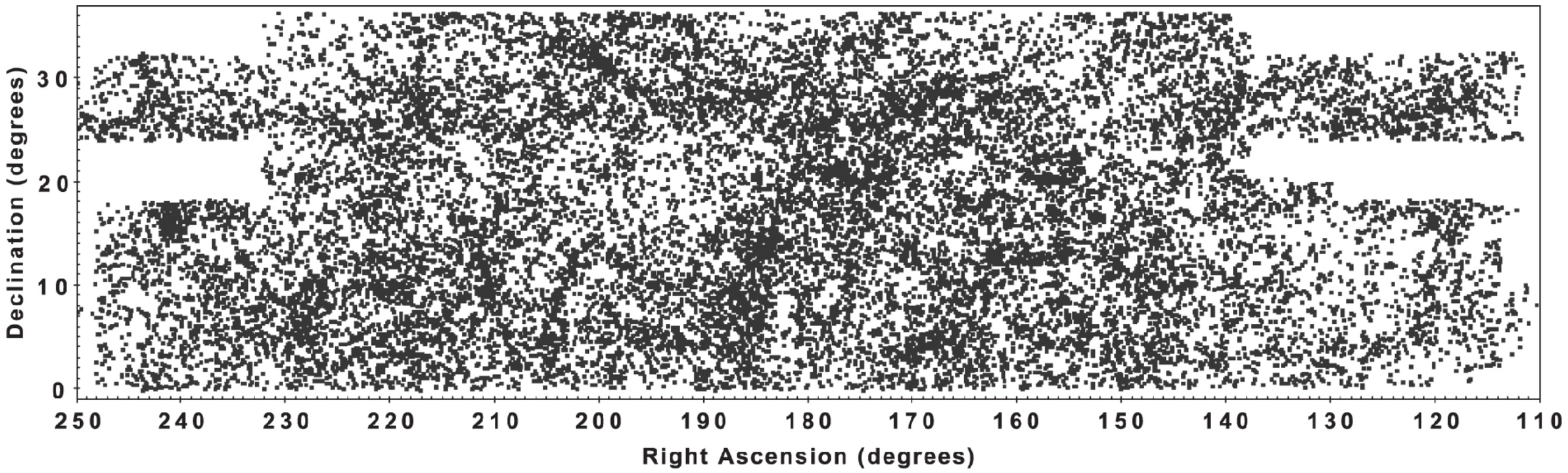
THE LOCAL GROUP

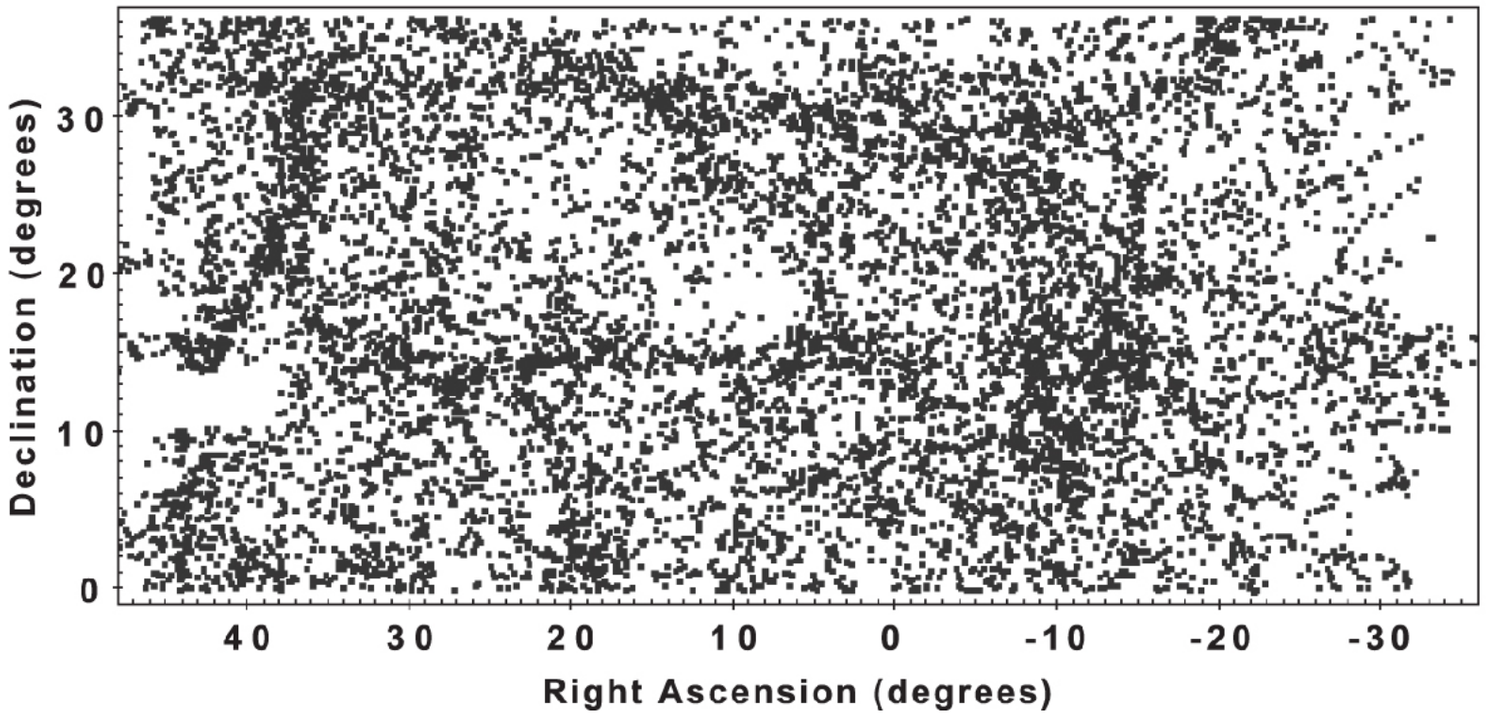
THE ARECIBO RADIO TELESCOPE

ALFALFA

- Arecibo Legacy Fast ALFA Survey
- ALFA: Arecibo L-band Feed Array
- Blind HI survey
- Complete catalog covers ~7000 deg^2 of the sky (Haynes et al. 2018)
- 3.5 arc minute beam makes it possible to detect and resolve compact objects
- Detect sources with 2 x 10^{7} M_{sun} of HI at Virgo Cluster distance, and < 10^{5} M_{sun} in Local Group
- More sensitive and broader coverage than previous blind HI surveys





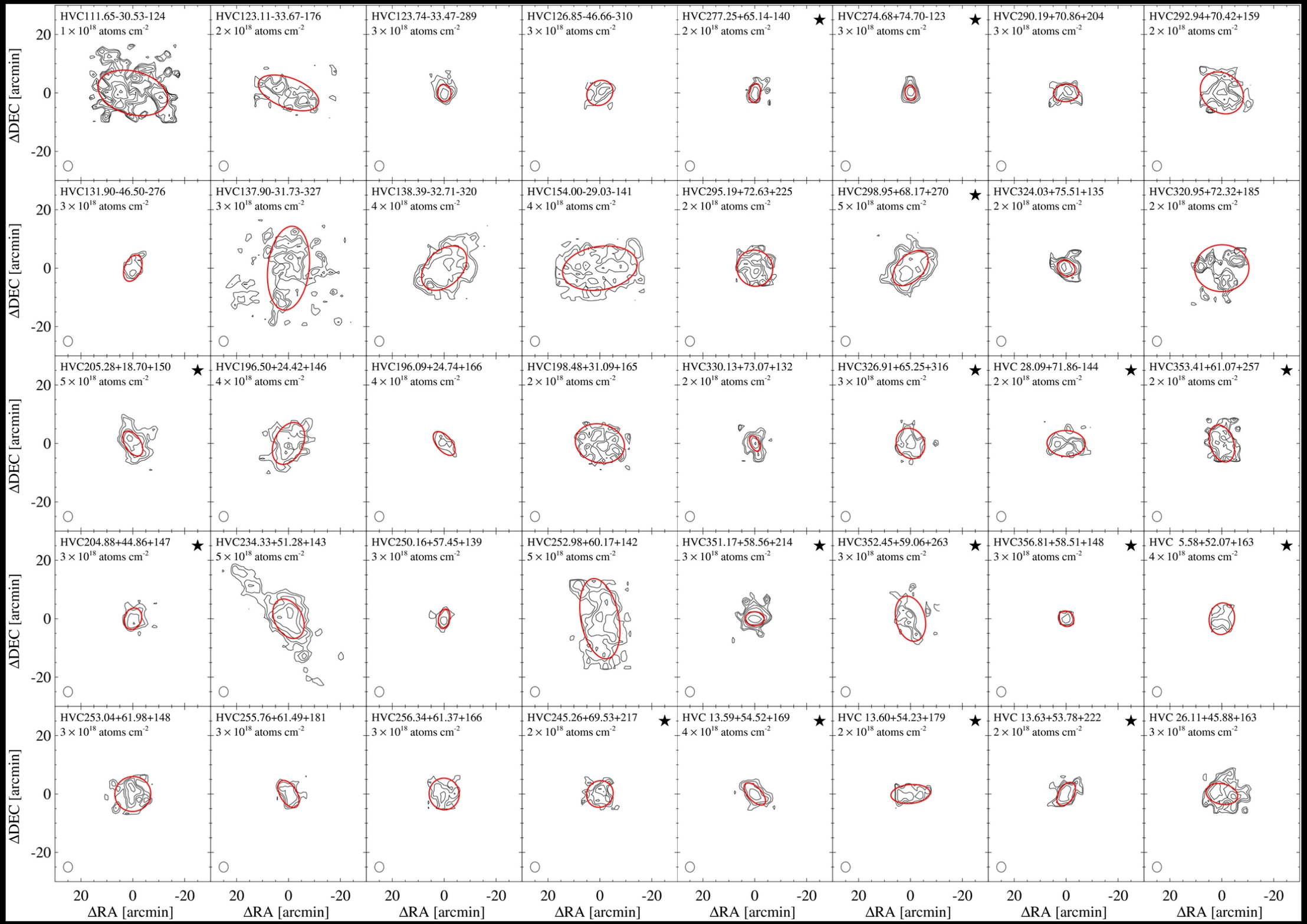


ALFALFA source map (Haynes+ 2018)

~13,500 sources with -2000 km/s < *cz* < 18,000 km/s (*z* < 0.06)

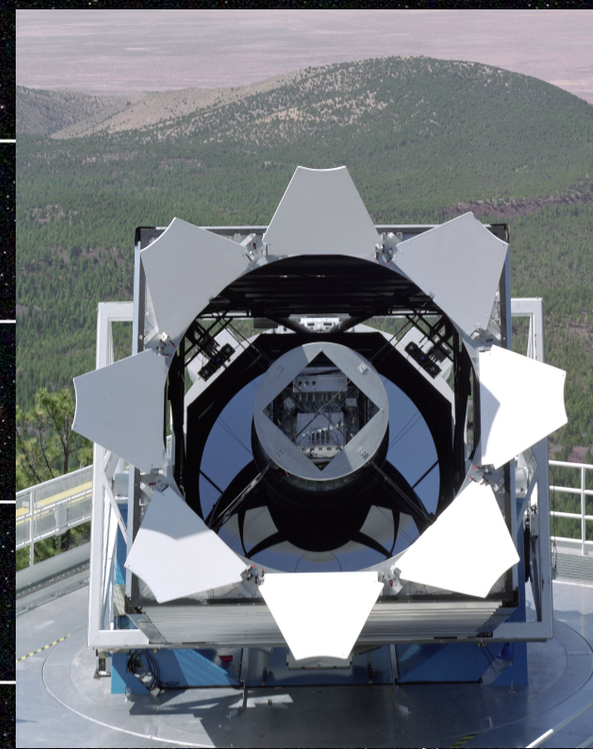
THE LOCAL GROUP

LITTLE BLOBS OF GAS



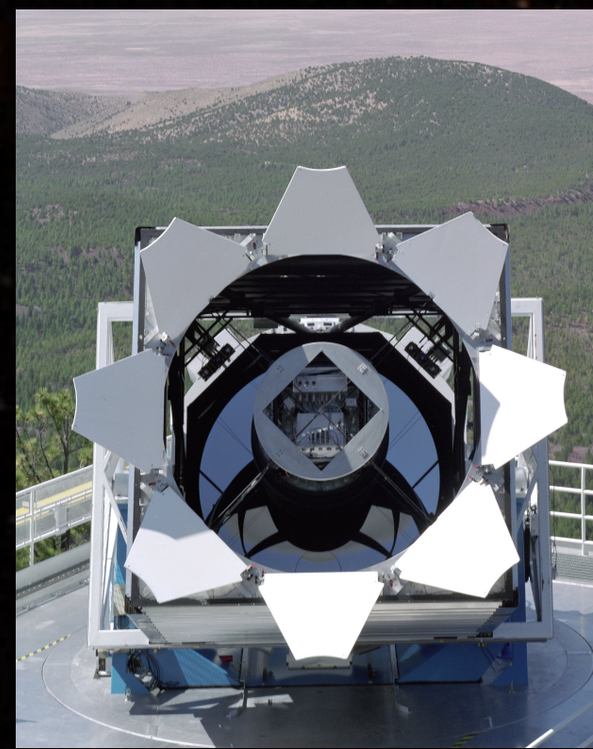
THE LOCAL GROUP

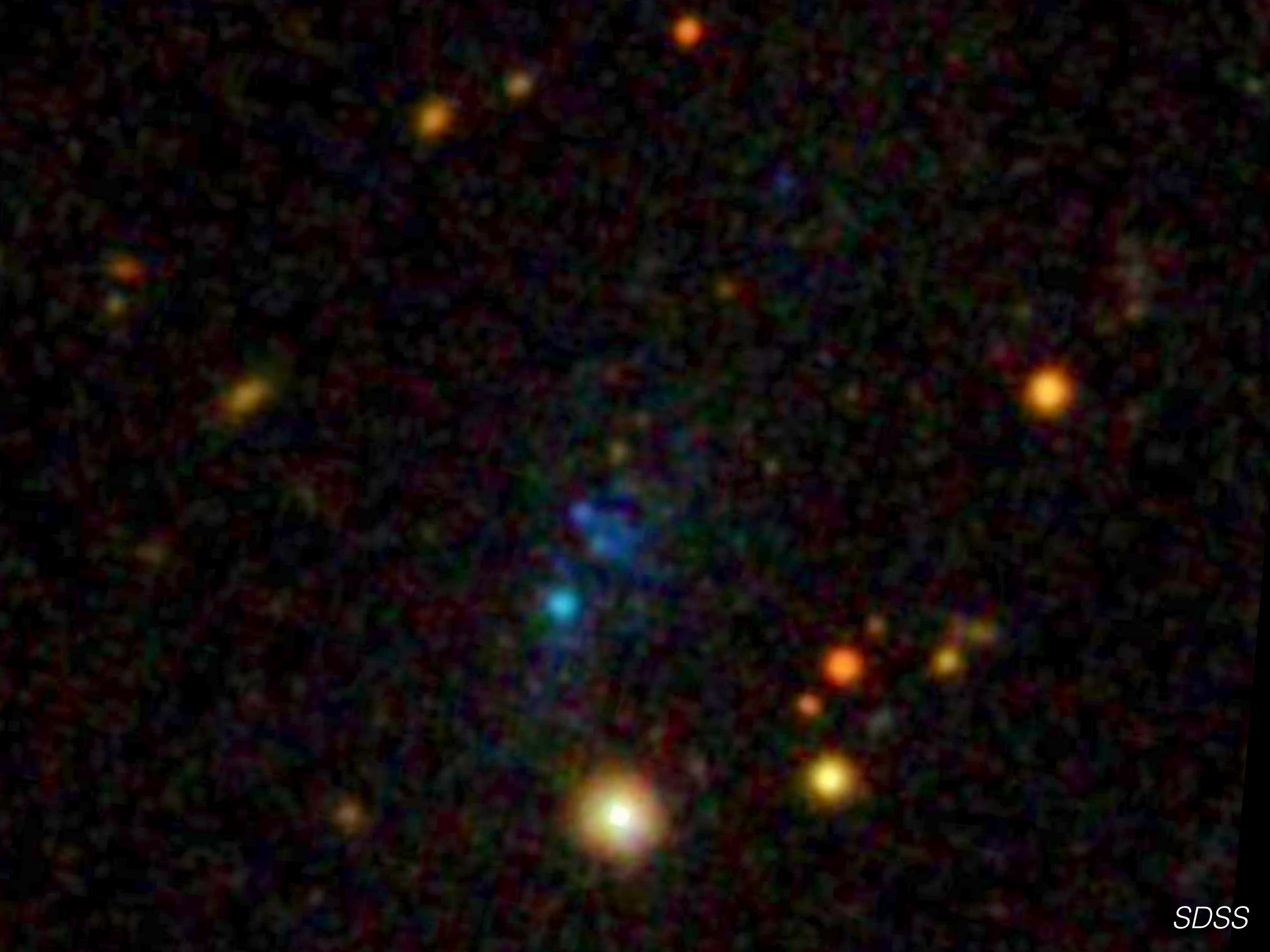
CAN WE SEE ANYTHING THERE?



THE LOCAL GROUP

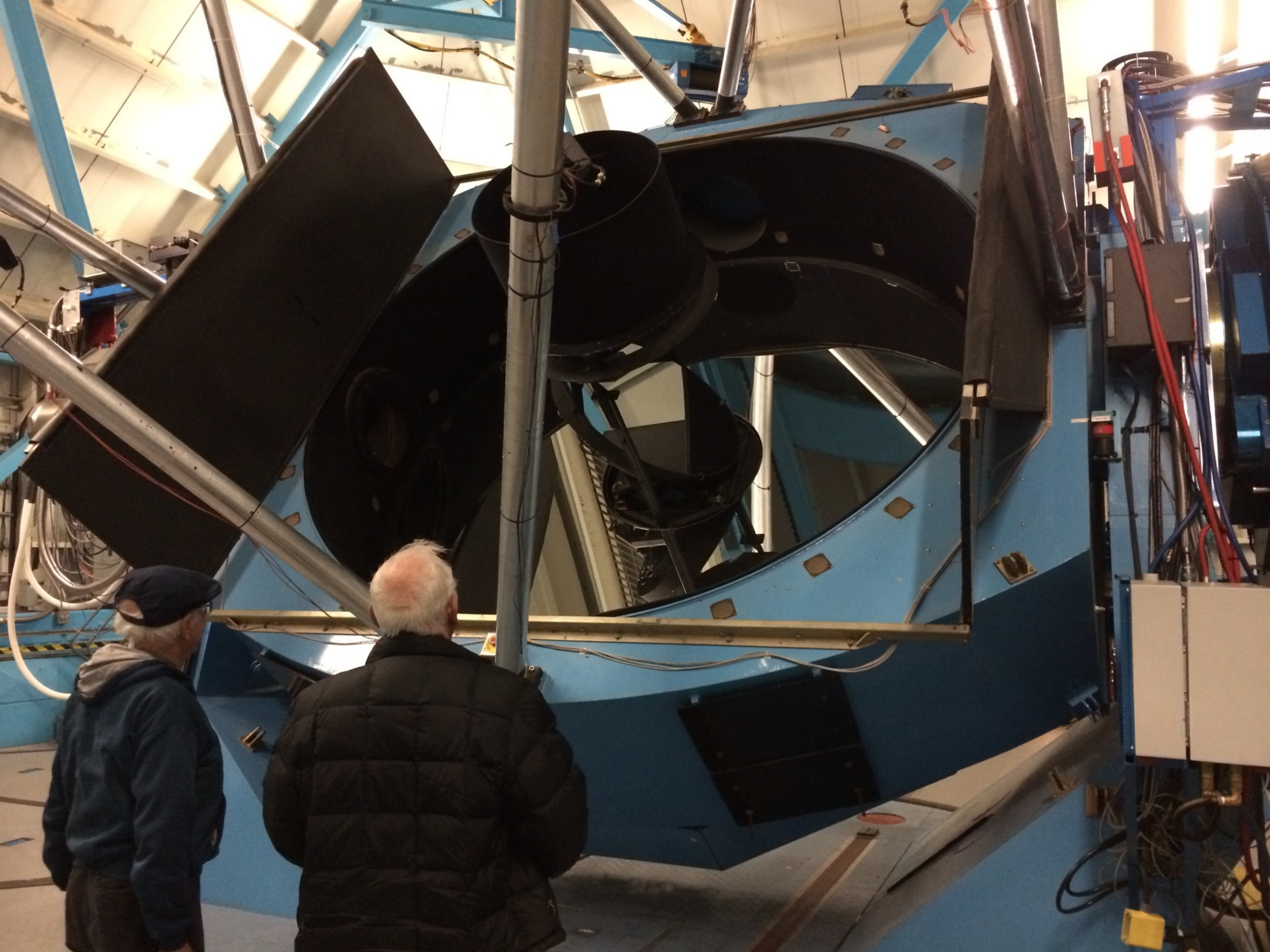
CAN WE SEE ANYTHING THERE?



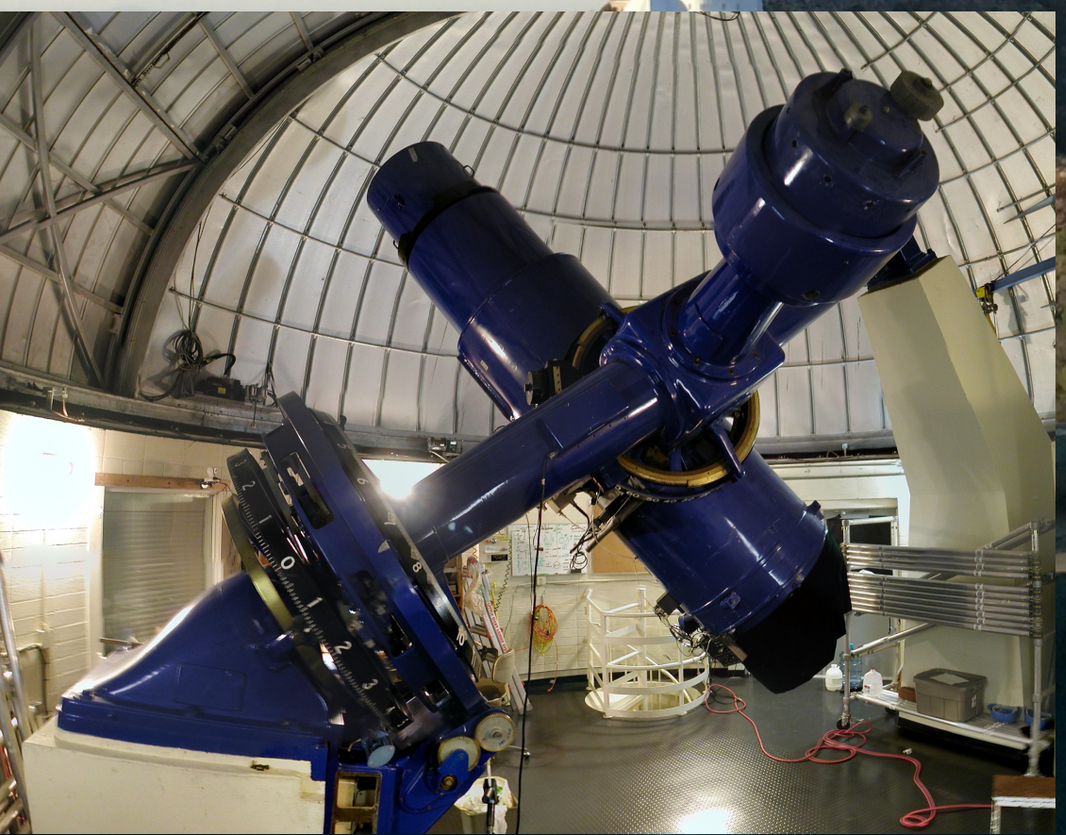

SDSS

THE LOCAL GROUP

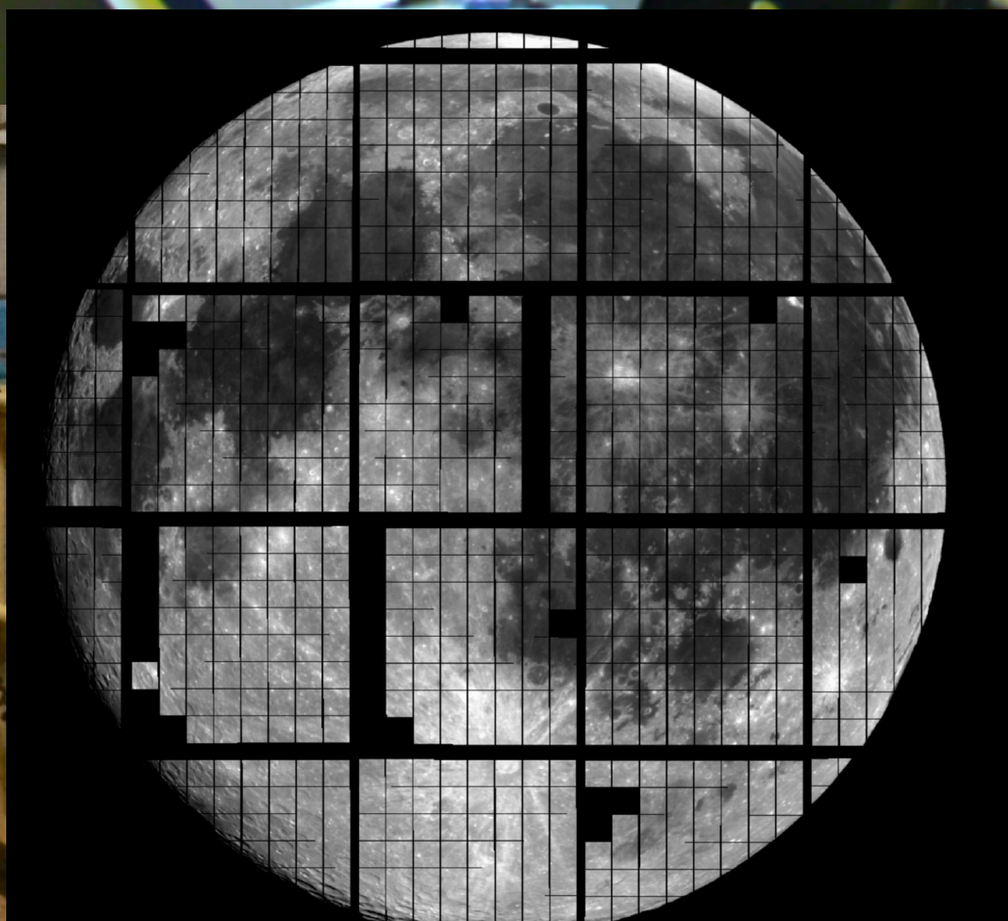
THE WIYN TELESCOPE



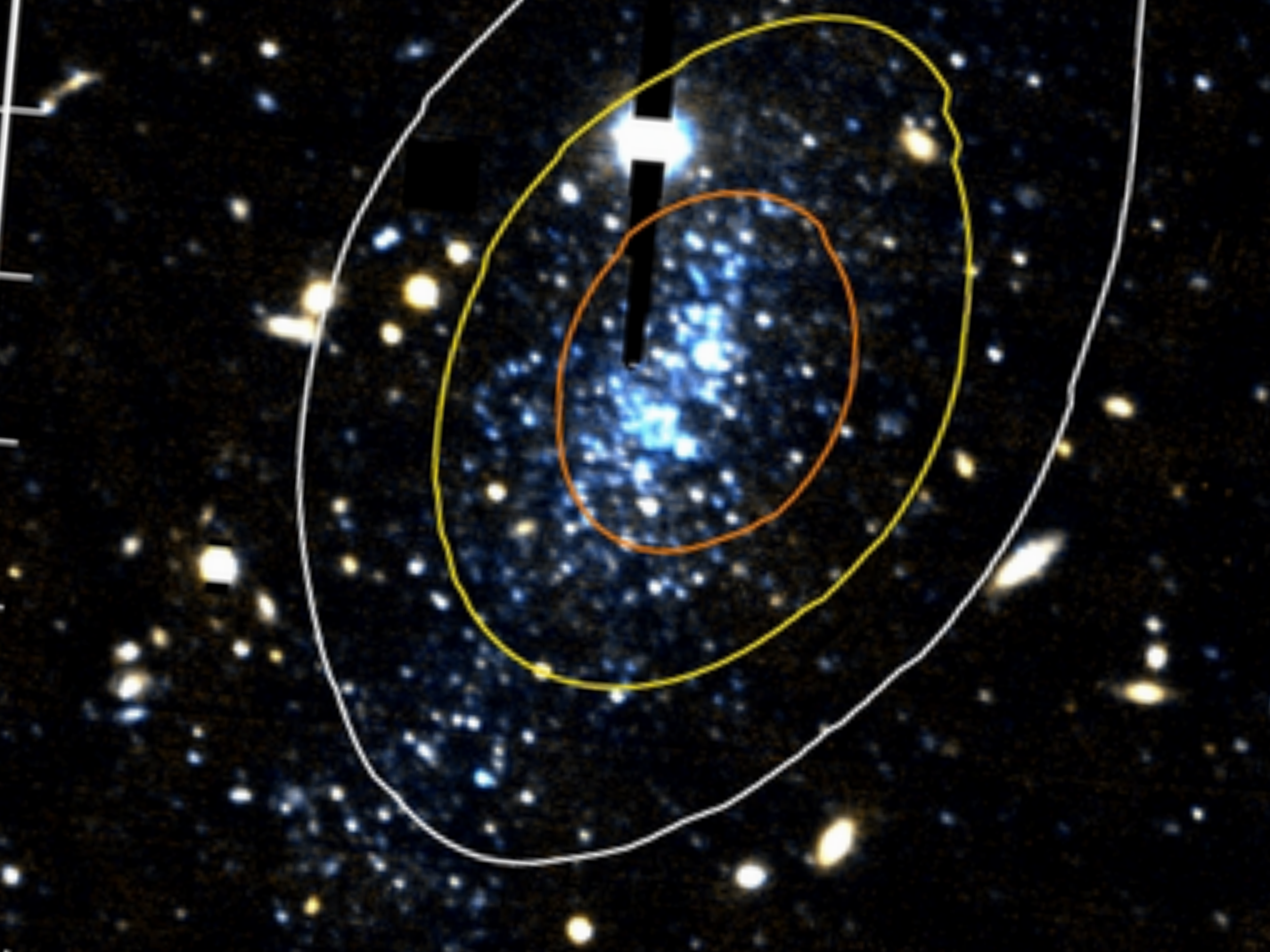
CWRU Burrell Schmidt



500 Megapixel Camera




Rhode+ 2013



galaxies = **dark matter + stars** *+ gas (sometimes)*

active star formation

LEO P

DARK MATTER MASS = 25,000,000 M_{SUN}

STELLAR MASS = 560,000 M_{SUN}

GAS MASS = 810,000 M_{SUN}

95% DM / 3% GAS / 2% STARS

DIAMETER = 1,750 LY

Leo P with HST—McQuinn+ 2015

UC Ultra-Compact

Small <0.5 deg

HV High Velocity

Nearby, but not in the Milky Way

C Cloud

Neutral Hydrogen

Giovanelli+ 2010

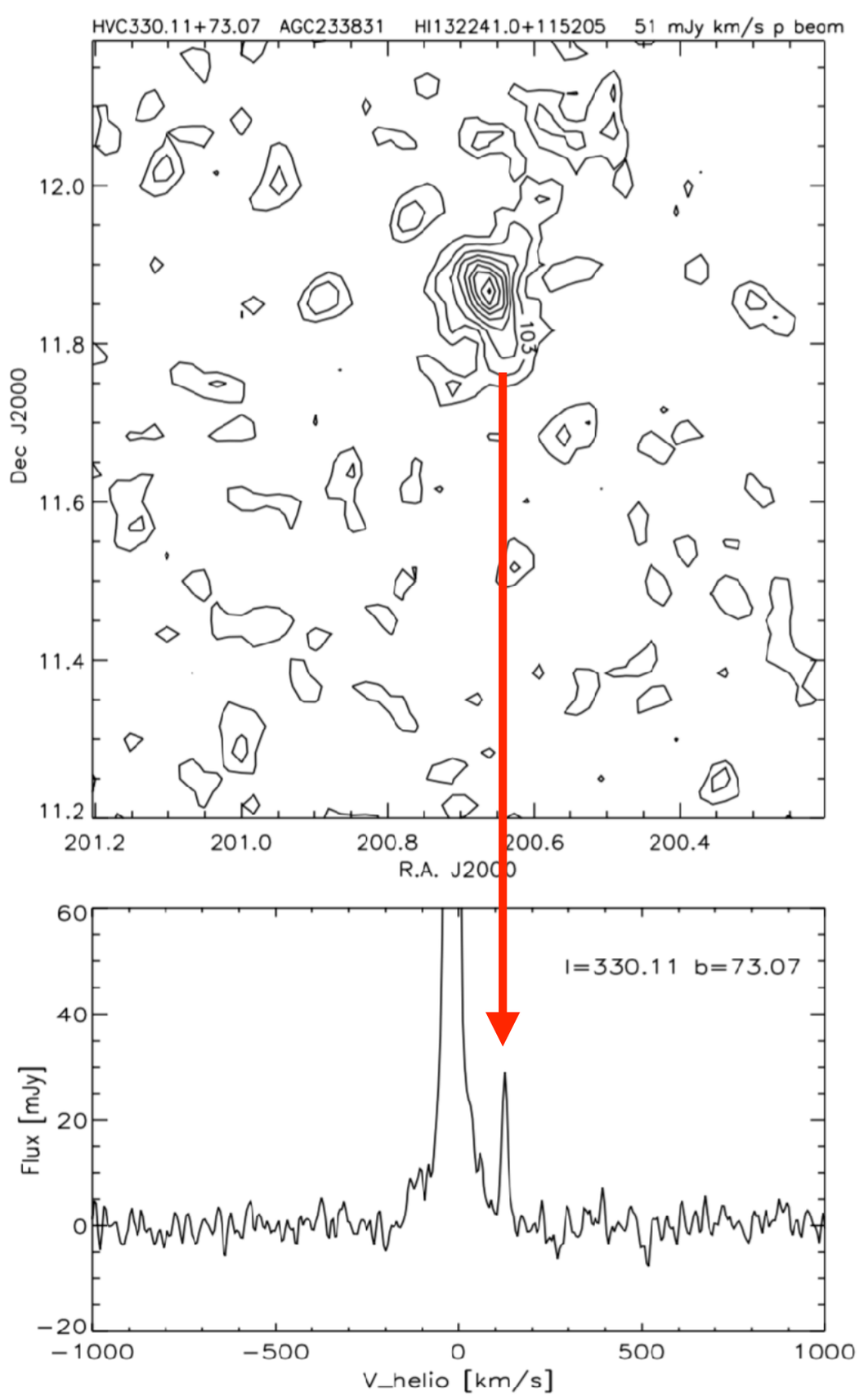
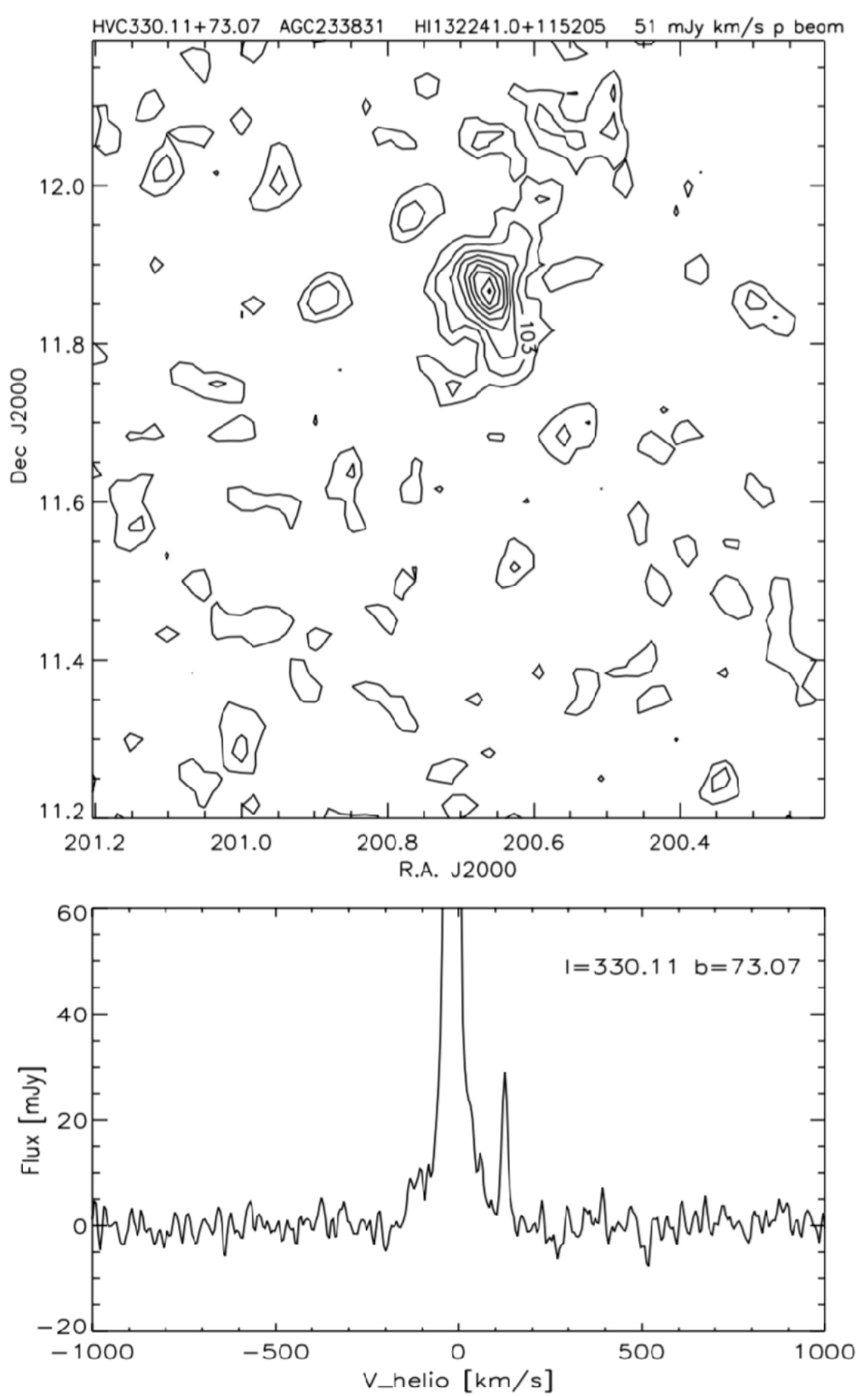


Figure 1. Upper panel: cloud at $l = 330.11$, $b = +73.07$, $cz_{\odot} = 124$ km s^{-1}, $W = 19$ km s^{-1}, angular size of $6' \times 4'$, integrated flux of 0.60 Jy km s^{-1}, $M_{\rm H\,I} = 1.4 \times 10^5 d^2_{\rm Mpc}\, M_{\odot}$, $M_{\rm dyn}[< R_{\rm H\,I}] \simeq 1.1 \times 10^7 d_{\rm Mpc}\, M_{\odot}$. Lower panel: H I line spectrum of the cloud shown above. The strong feature at zero velocity is the MW emission; the cloud is the narrow feature at $cz_{\odot} = 124$ km s^{-1}.

- Cosmological simulations predict low mass dark matter “minihalos”
- UCHVCs match their predicted properties, but don’t appear to have stars in SDSS/DSS/etc.
- gas + dark matter together?

Giovanelli+ 2010



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Selecting a UCHVC sample

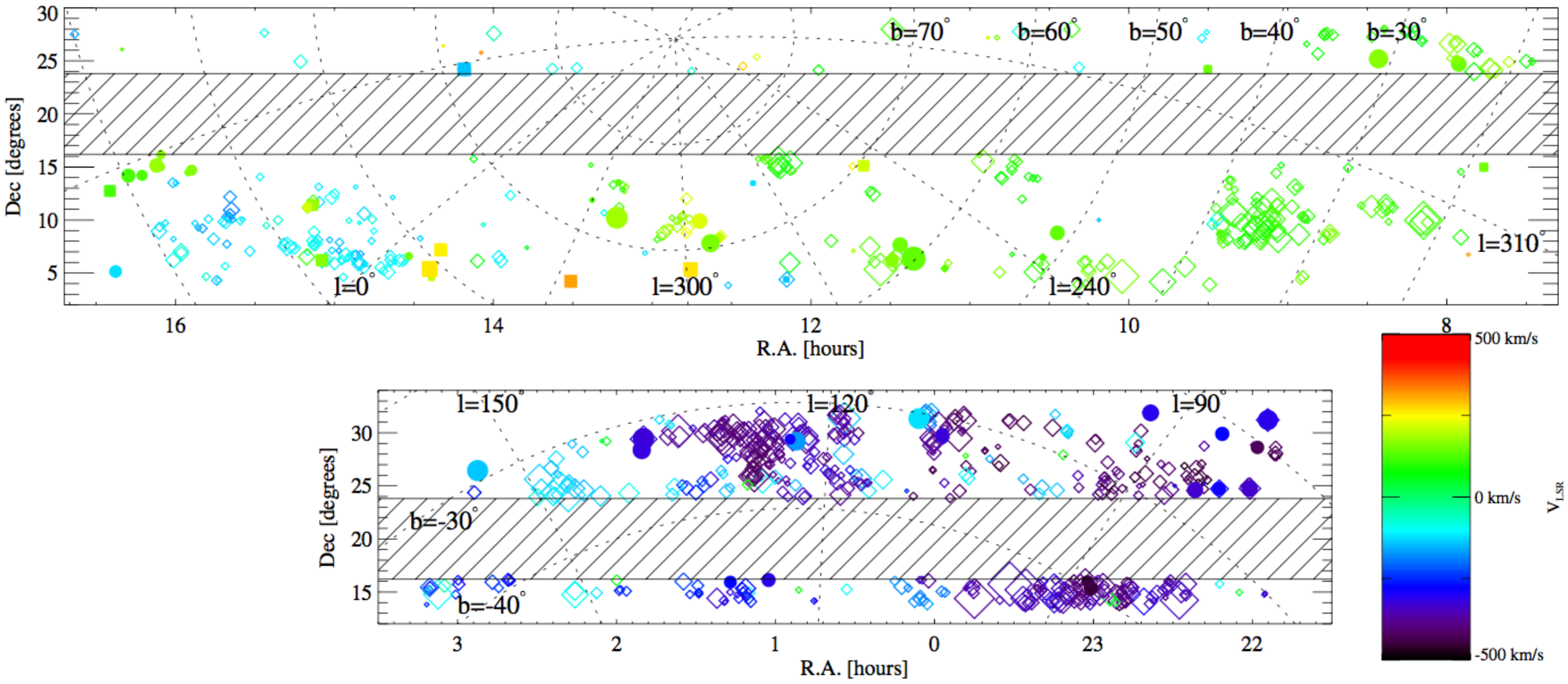


Figure 1. UCHVCs (filled circles) plotted in R.A.–decl. coordinates; gray scale (color in the online version) corresponds to the velocity of the cloud. The solid squares are the most isolated subsample of UCHVCs (see Section 2.4). The open diamonds are the α.40 HVCs shown for reference. The size of the symbols is proportional to the angular sizes of the HVCs in all cases but are not to scale. The top panel is the spring R.A. region, the bottom panel the fall R.A. region. The hashed region corresponds to declination ranges not covered by α.40. The fall sky shows prevalent HVC structure while the spring sky is relatively clear of HVCs.

α.40 sources from Adams+ 2013 & additional ALFALFA sources from subsequent observations (100 total)

SDSS DR14


Rhode+ 2013

Leo P with HST—McQuinn+ 2015

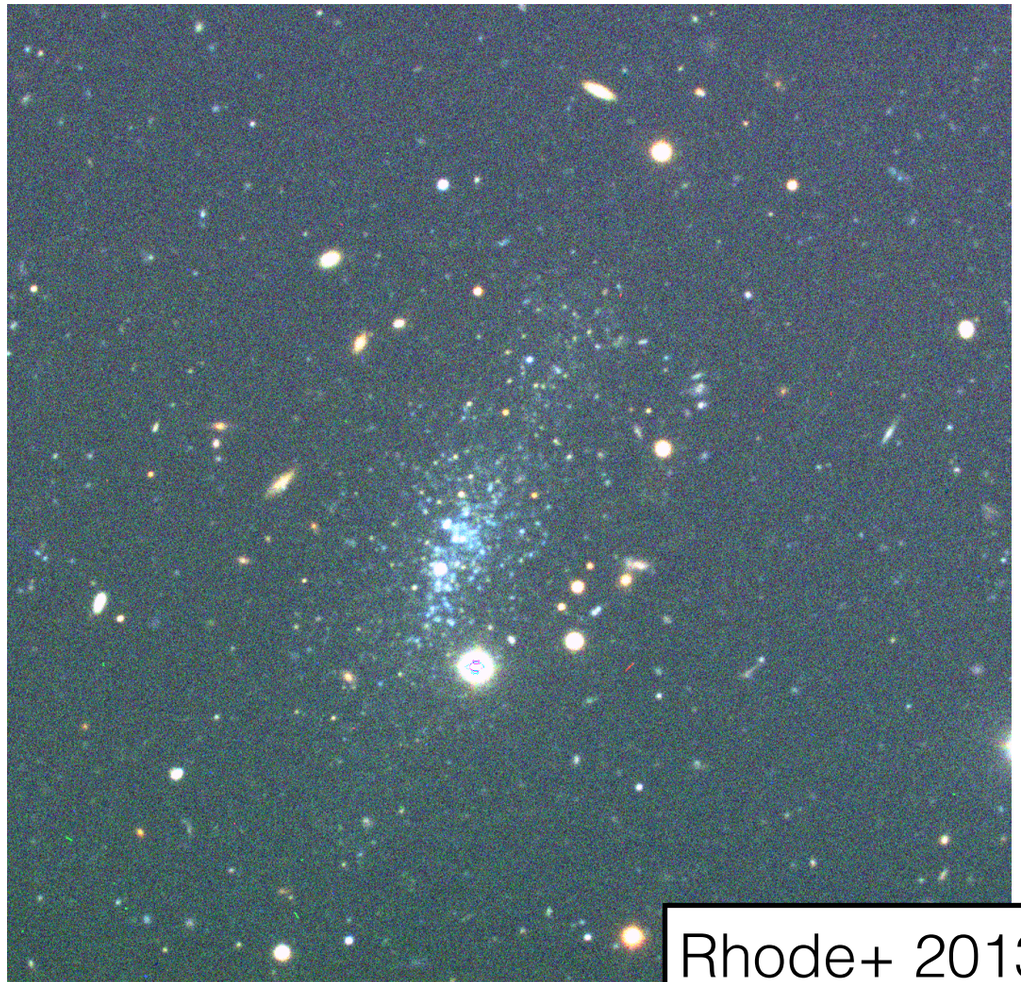
Properties of Leo P

- **Distance:** 1.62 +/- 0.15 Mpc
  M_V = -9.27 +/- 0.2 **Optical Diameter** = 704 pc
  B-V = 0.36+/-0.02, **V-R** = 0.49+/-0.01

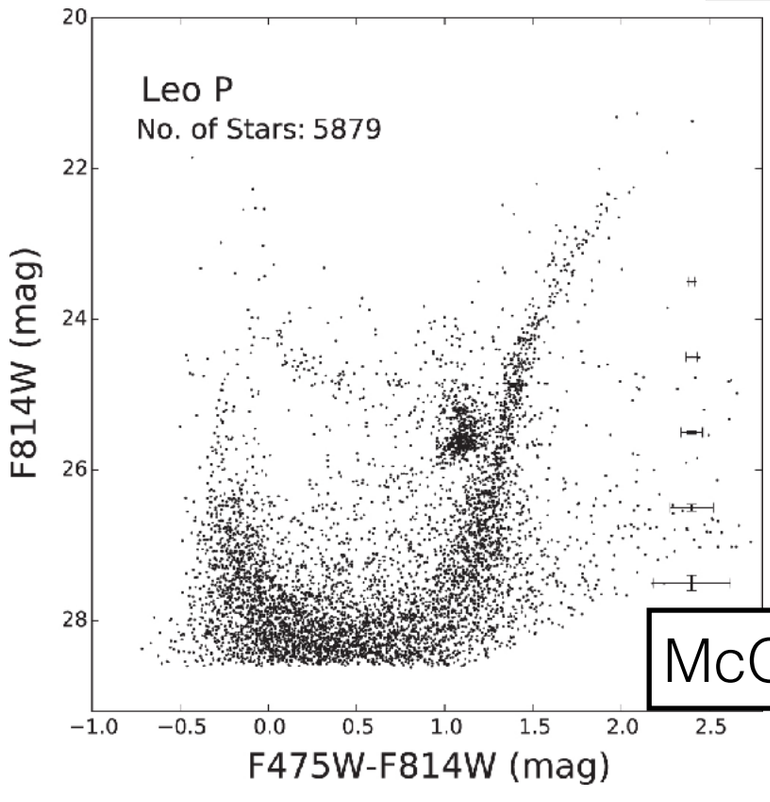
- **Mass:** **M_{stars}** = 5.6 x 10^5 $M_\odot$
  M_{HI} = 8.1 x 10^5 $M_\odot$
  M_{dyn} = 2.5 x 10^7 $M_\odot$ (to HI radius)

- **Abundances:**
log(O/H) + 12 = 7.17 +/- 0.04 (1/42nd solar)
He Abundance (Y) = 0.251 +/- 0.015
(consistent with primordial: Y_P = 0.248)

Table data from Rhode+ 2013, Skillman+ 2013, McQuinn+ 2015



Rhode+ 2013



McQuinn+ 2015

Why study UCHVCs?

- We can learn about lots of things from low mass, gas rich galaxies

star formation
chemical evolution
stellar feedback
galaxy assembly
dark matter
cosmological theories

- and help resolve tensions between models and observations

Leo P (Giovanelli+ 2013; Rhode+ 2013) Image: HST—McQuinn+ 2015

Why study UCHVCs?

- Galaxies
  =
  dark matter
  +
  gas
  +
  stars

Leo P (Giovanelli+ 2013; Rhode+ 2013) Image: HST—McQuinn+ 2015

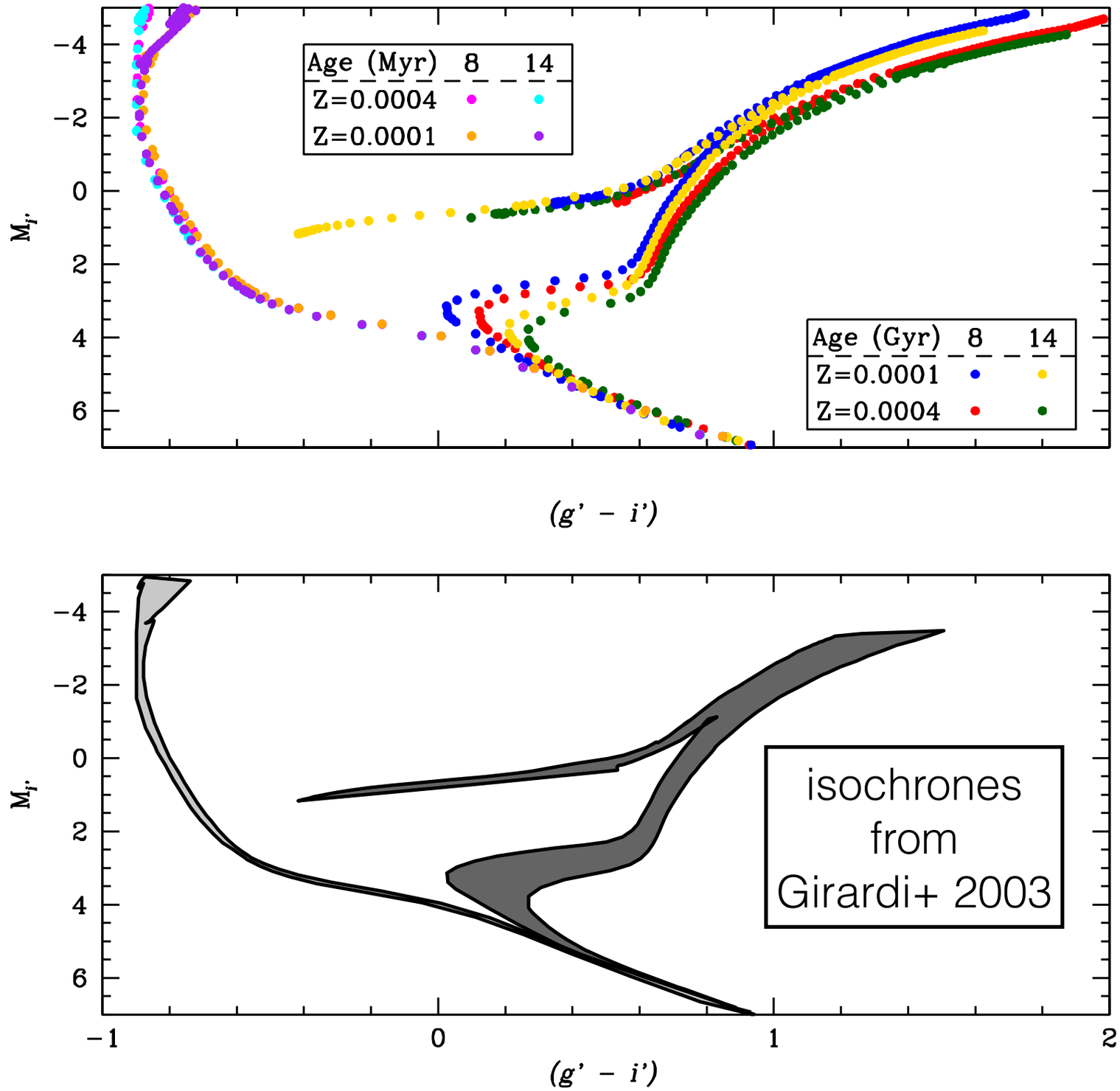
Why study UCHVCs?

- Galaxies
  =
  dark matter
  +
  gas
  +
  stars?

Leo P (Giovanelli+ 2013; Rhode+ 2013) Image: HST—McQuinn+ 2015

Defining a color-magnitude filter

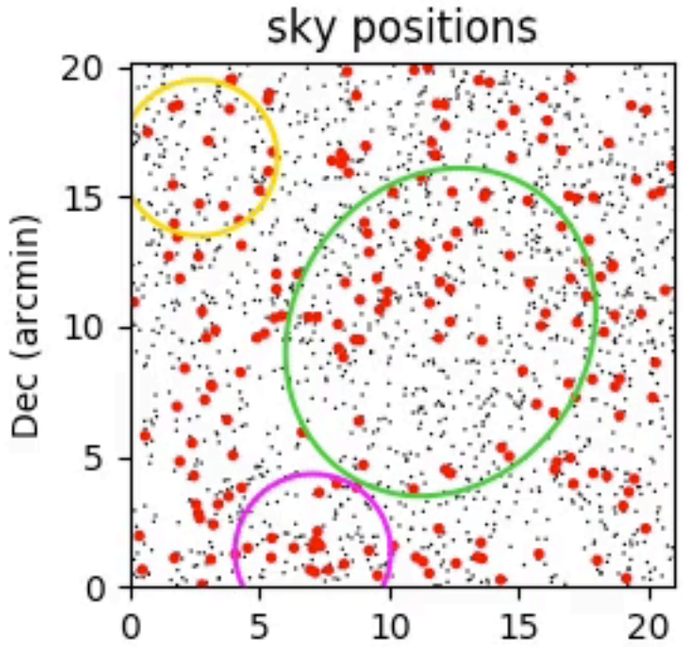
- Select stars likely to belong to a range of stellar populations

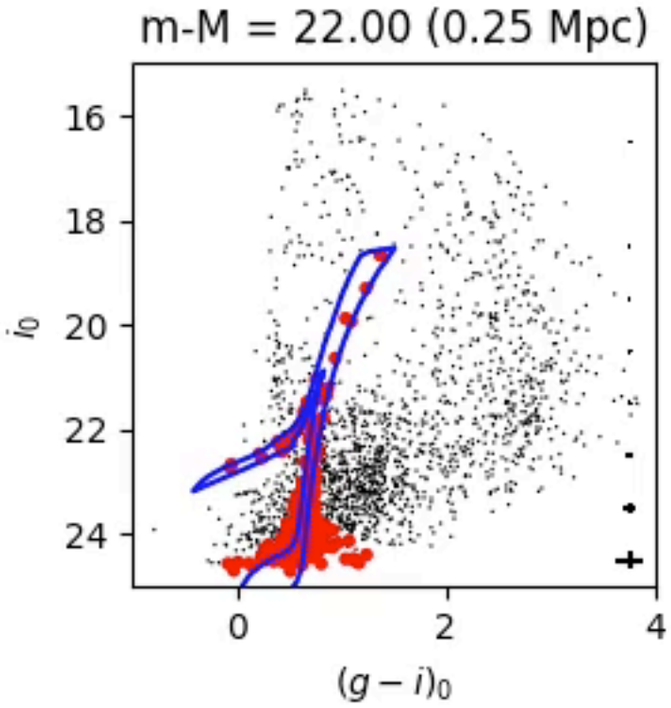


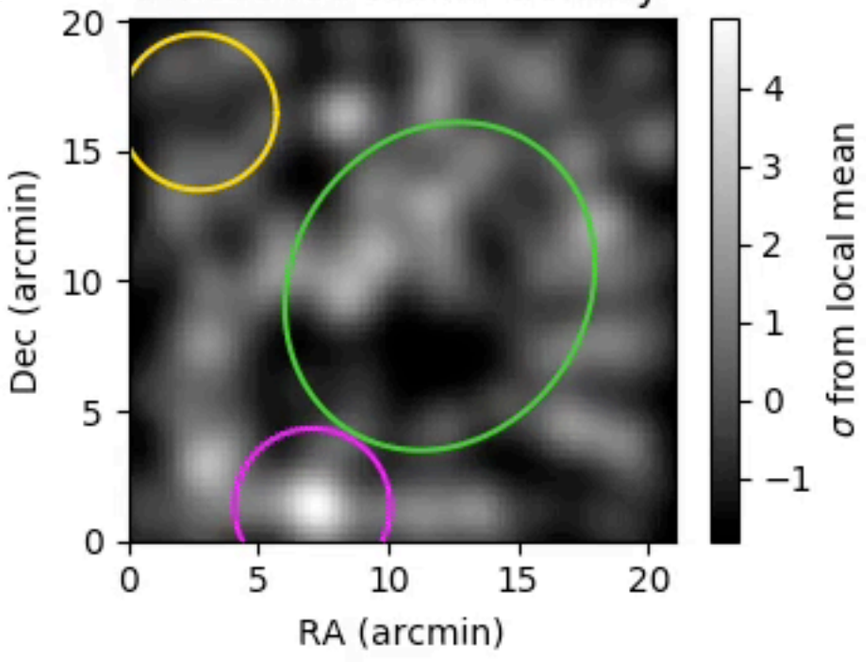
Janesh+ 2015

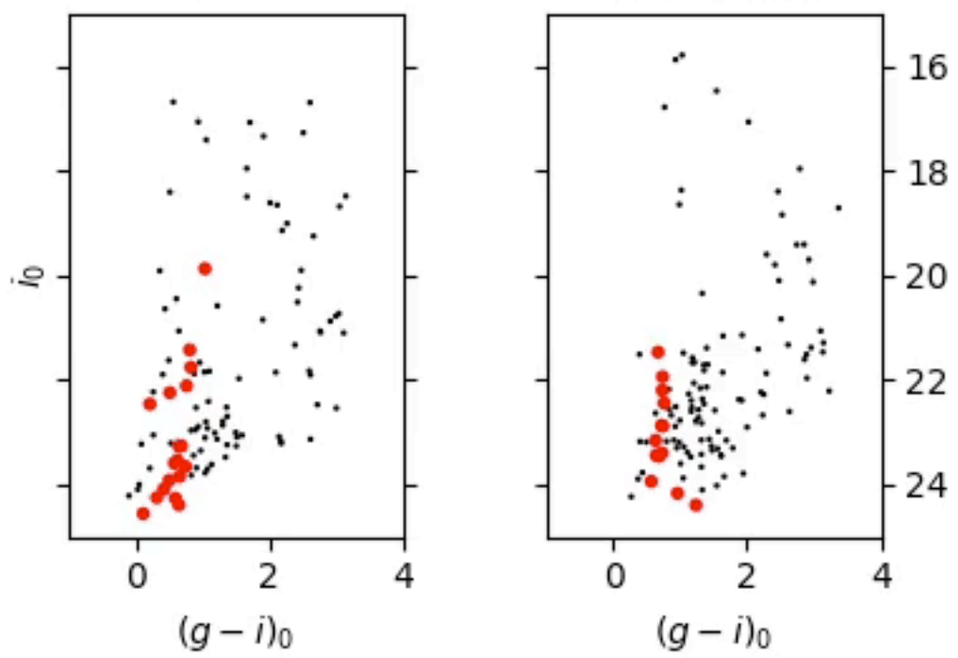
CMD filter technique

- Step filter through range of Local Volume distances (0.25 - 2.5 Mpc)
- Make smoothed density maps of stars selected by CMD filter and normalize to background star counts







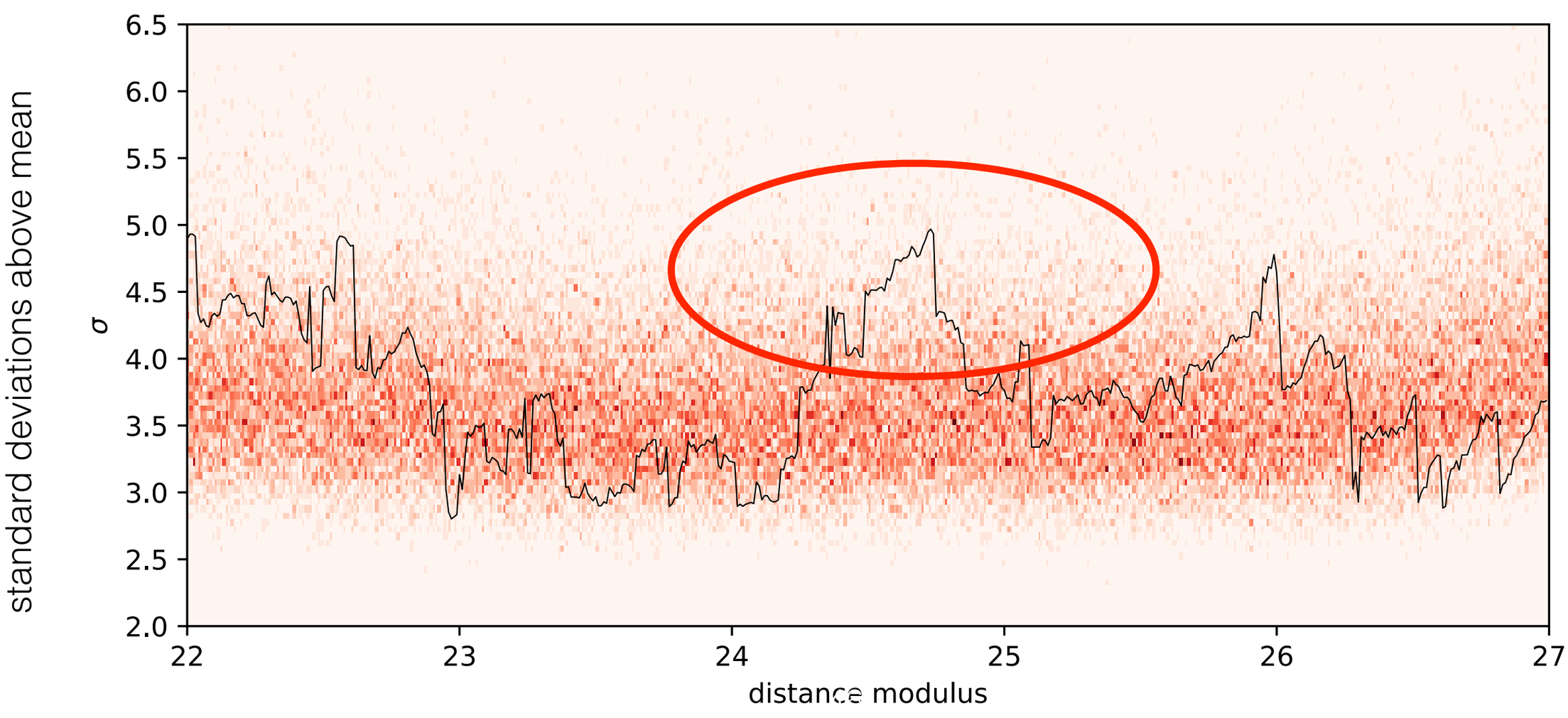


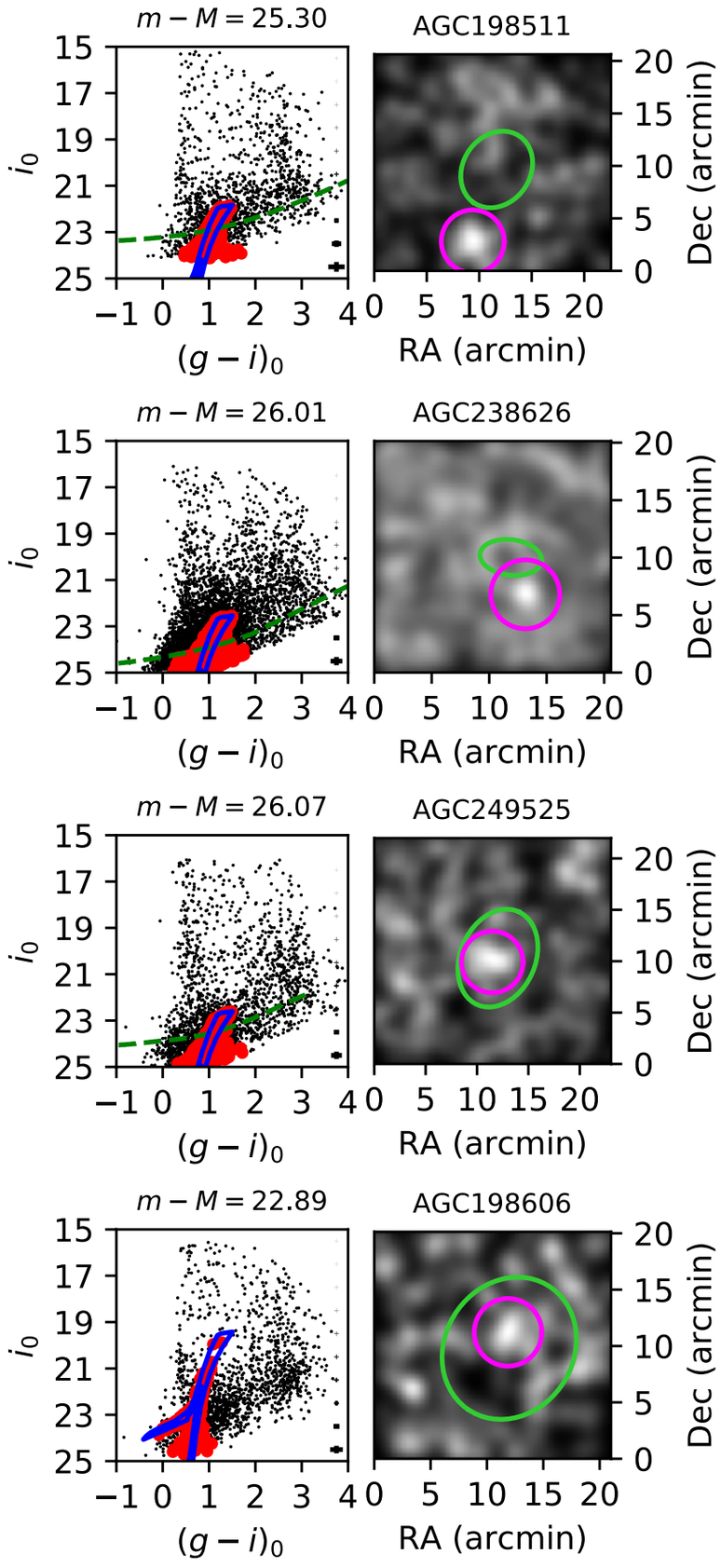
Janesh+ 2019

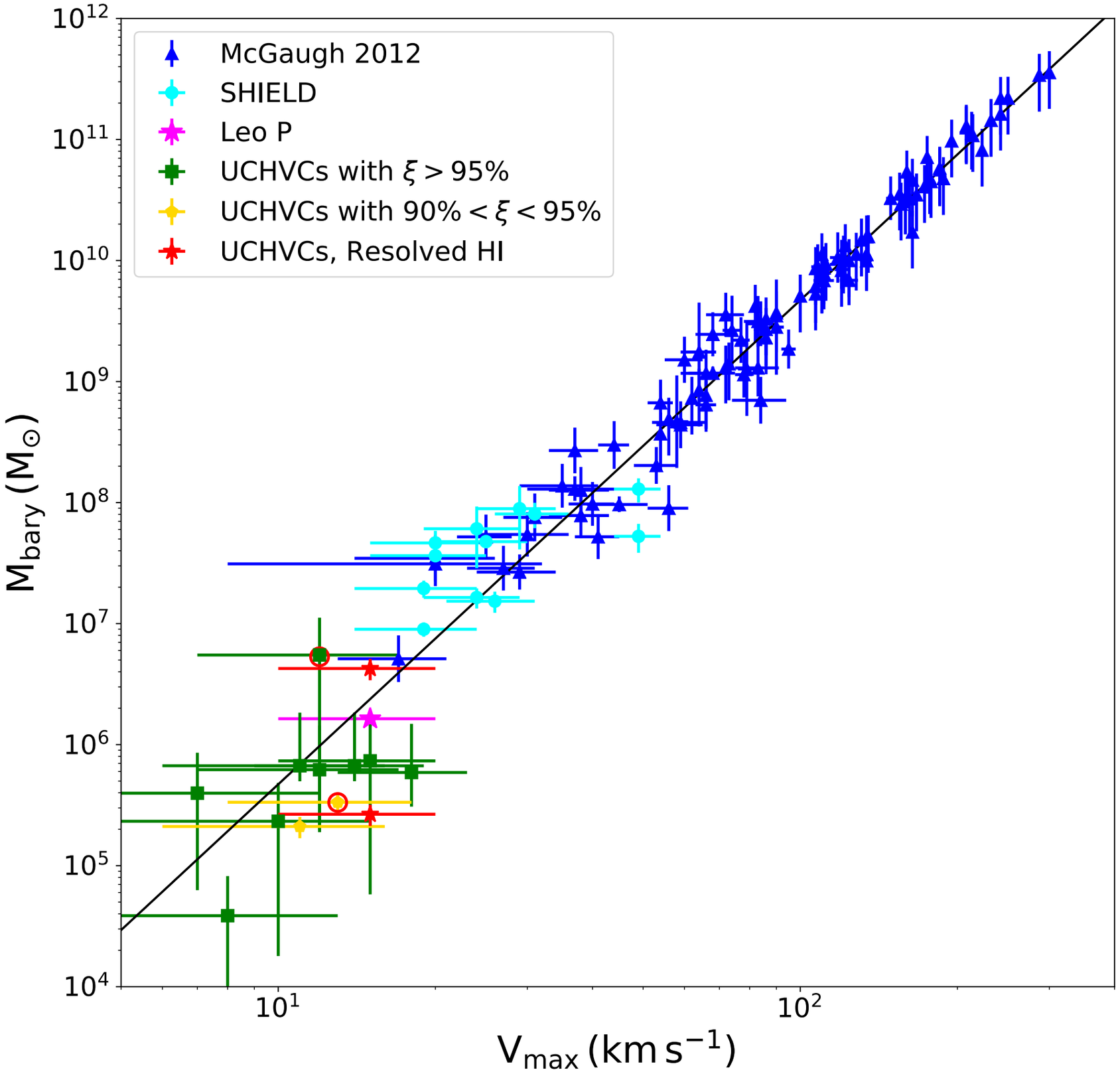
AGC 198606 — *"Friend of Leo T"*

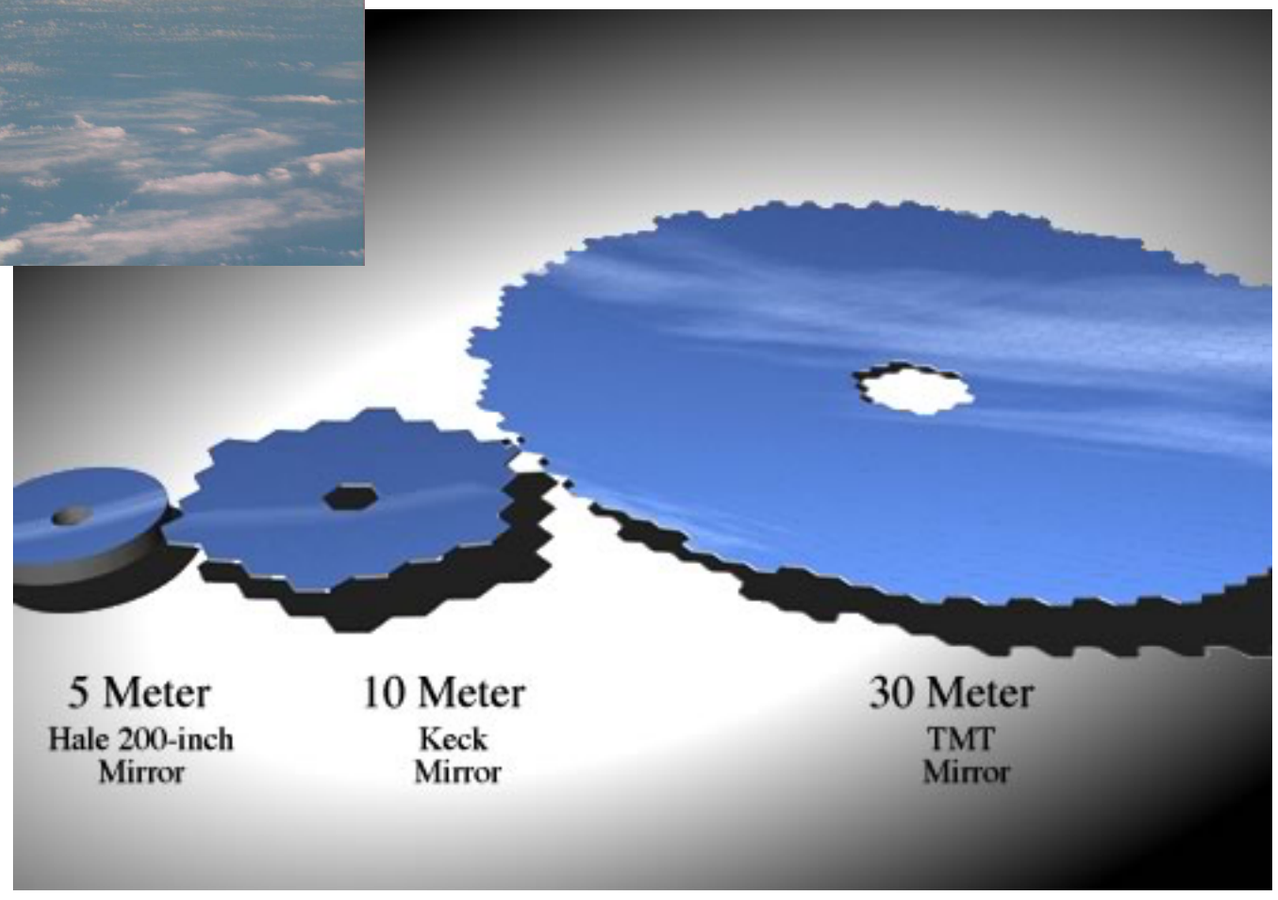
Overdensity significance

- Generate random uniform distributions of stars, track distribution function of highest density; how likely this is a random superposition?




$m-M=25.30$
AGC198511
$m-M=22.72$
AGC215417
$m-M=24.70$
AGC219656
$m-M=26.01$
AGC238626
$m-M=25.30$
AGC249000
$m-M=25.34$
AGC249320
$m-M=26.07$
AGC249525
$m-M=24.02$
AGC258237
$m-M=24.24$
AGC268069
$m-M=22.89$
AGC198606
$m-M=23.08$
HI0959+19
i_0
$(g-i)_0$
RA (arcmin)
Dec (arcmin)


McGaugh 2012
SHIELD
Leo P
UCHVCs with $\xi > 95\%$
UCHVCs with $90\% < \xi < 95\%$
UCHVCs, Resolved HI
10^{12}
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
10^{6}
10^{5}
10^{4}
$M_{bary}\,(M_\odot)$
10^{1}
10^{2}
$V_{max}\,(km\,s^{-1})$


5 Meter
Hale 200-inch
Mirror
10 Meter
Keck
Mirror
30 Meter
TMT
Mirror