What is a galaxy?

- Traditional galaxies
- Invisible galaxies
- Simulated galaxies

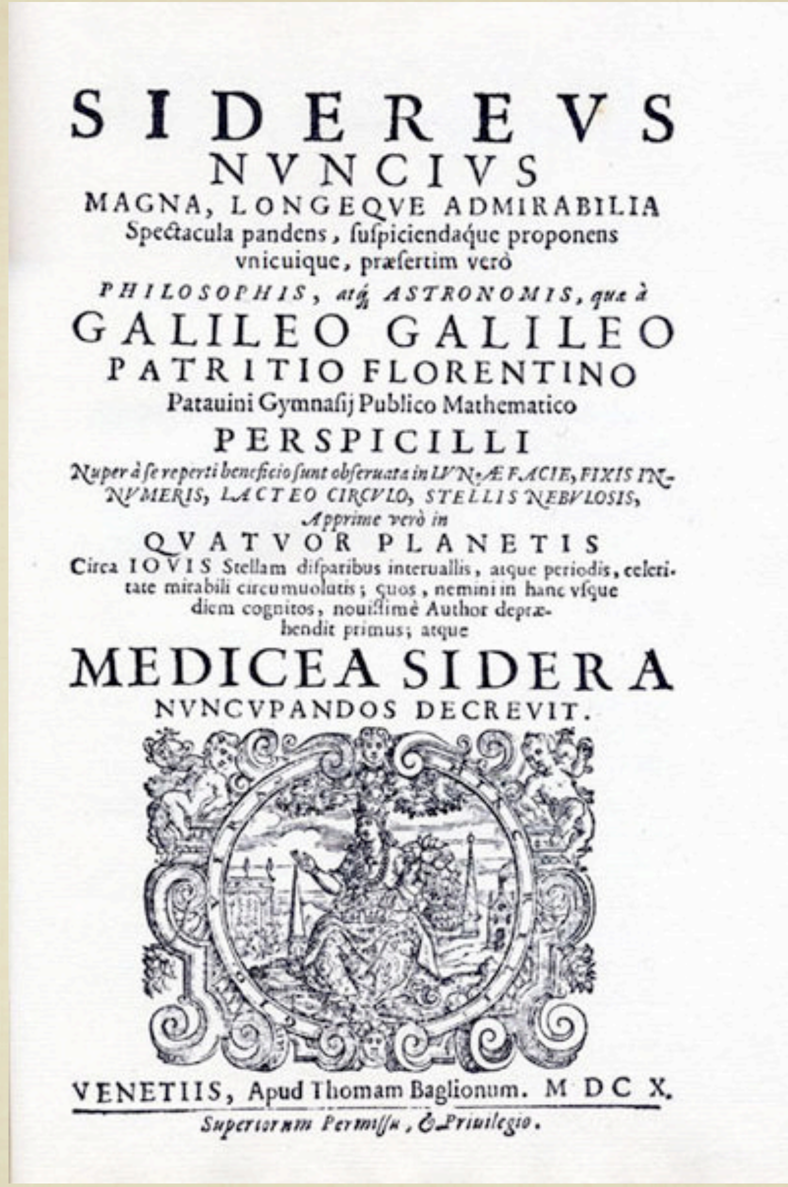
University of Nebraska, October 2013

Beth Willman (Haverford College)

NASA Astronomy Picture of the Day, August 2010; image credit: Alex Cherney (Terrastro)

1610, Galileo makes the first observations of the night sky with a telescope.

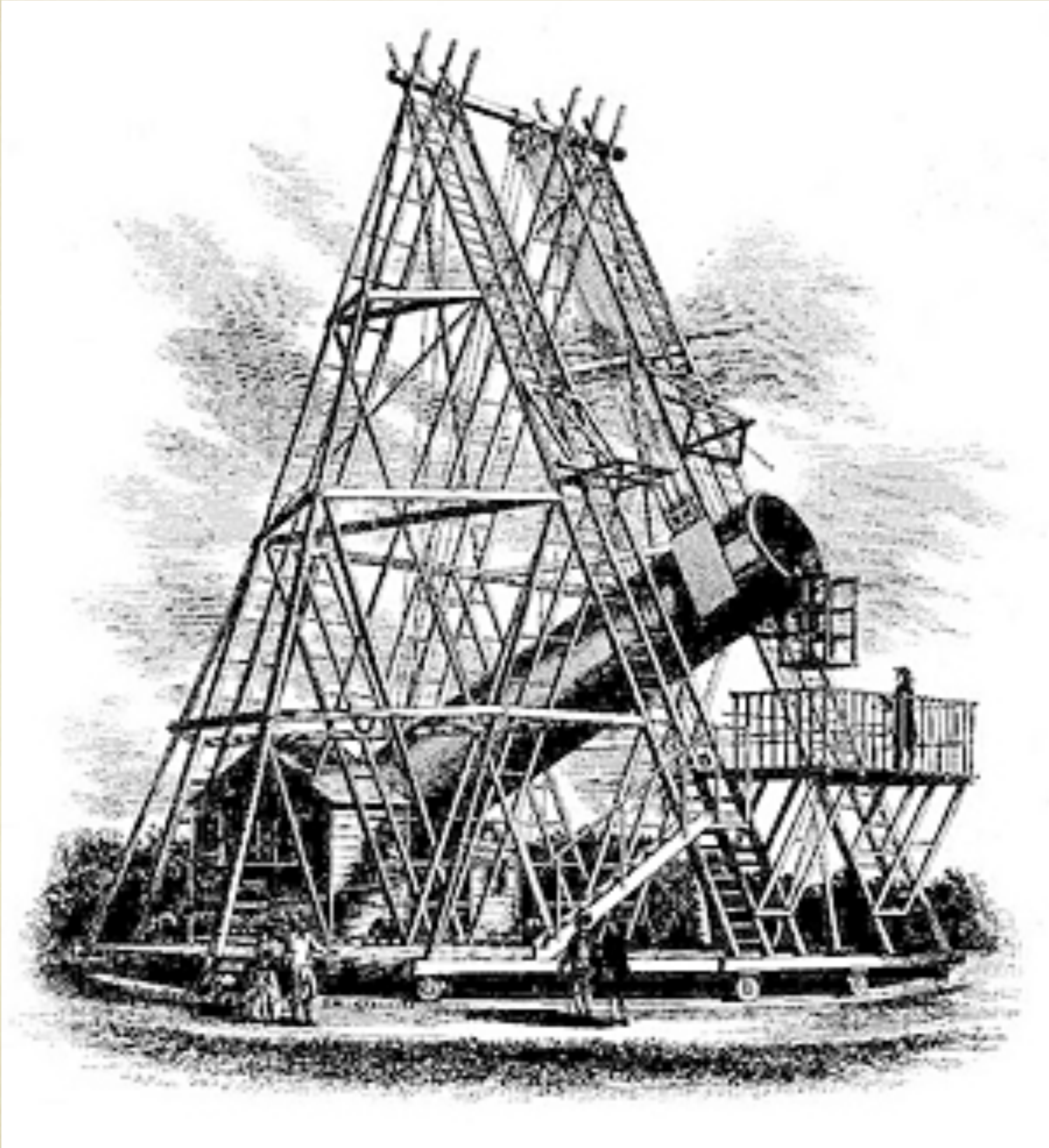
"For the Galaxy is nothing else than a congeries of innumerable stars distributed in clusters"



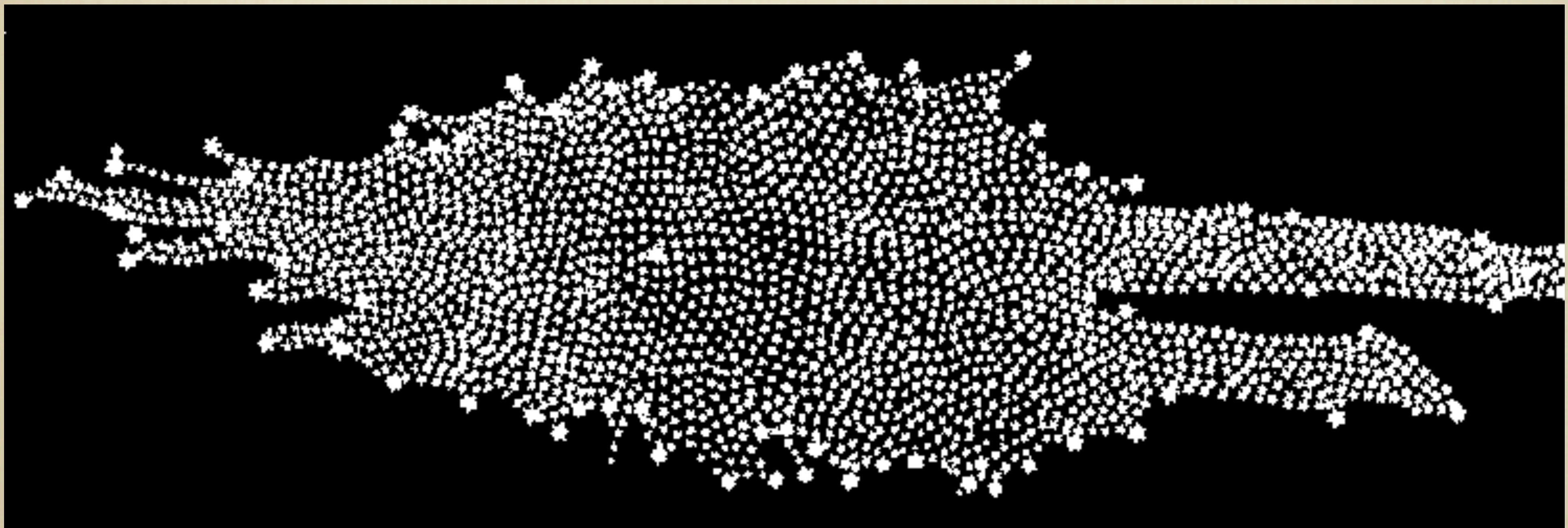
SIDEREVS
NVNCIVS
MAGNA, LONGEQVE ADMIRABILIA
Spectacula pandens, suspiciendaque proponens
vnicuique, præsertim verò
PHILOSOPHIS, atq; ASTRONOMIS, quæ à
GALILEO GALILEO
PATRITIO FLORENTINO
Patauini Gymnasij Publico Mathematico
PERSPICILLI
Nuper à se reperti beneficio sunt obseruata in LVNÆ FACIE, FIXIS IN-
NVMERIS, LACTEO CIRCVLO, STELLIS NEBVLOSIS,
Apprime verò in
QVATVOR PLANETIS
Circa IOVIS Stellam disparibus interuallis, atque periodis, celeri-
tate mirabili circumuolutis; quos, nemini in hanc vsque
diem cognitos, nouissimè Author depræ-
hendit primus; atque
MEDICEA SIDERA
NVNCVPANDOS DECREVIT.

VENETIIS, Apud Thomam Baglionum. M DC X.
Superiorum Permissu, & Priuilegio.

Late 18th century - Caroline and William Herschel counted stars with a 48-inch telescope



The Herschels’ 1785 map of a nearly Sun-centered Milky Way



The Messier catalog was also compiled near the end of the 18th century

M31

M51

Were objects like these part of the Milky Way?

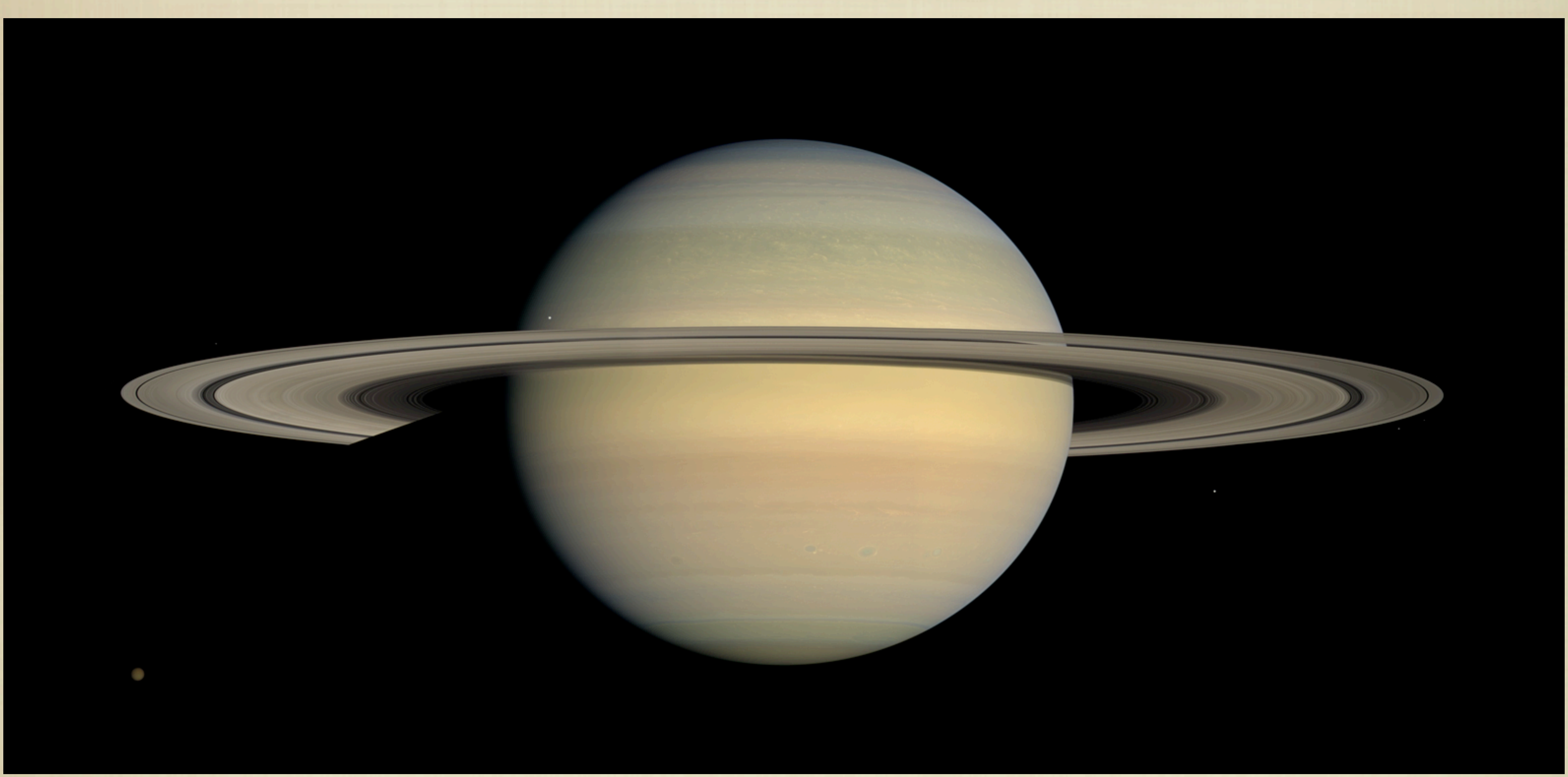
As recently as 100 years ago, the Milky Way was the entire universe

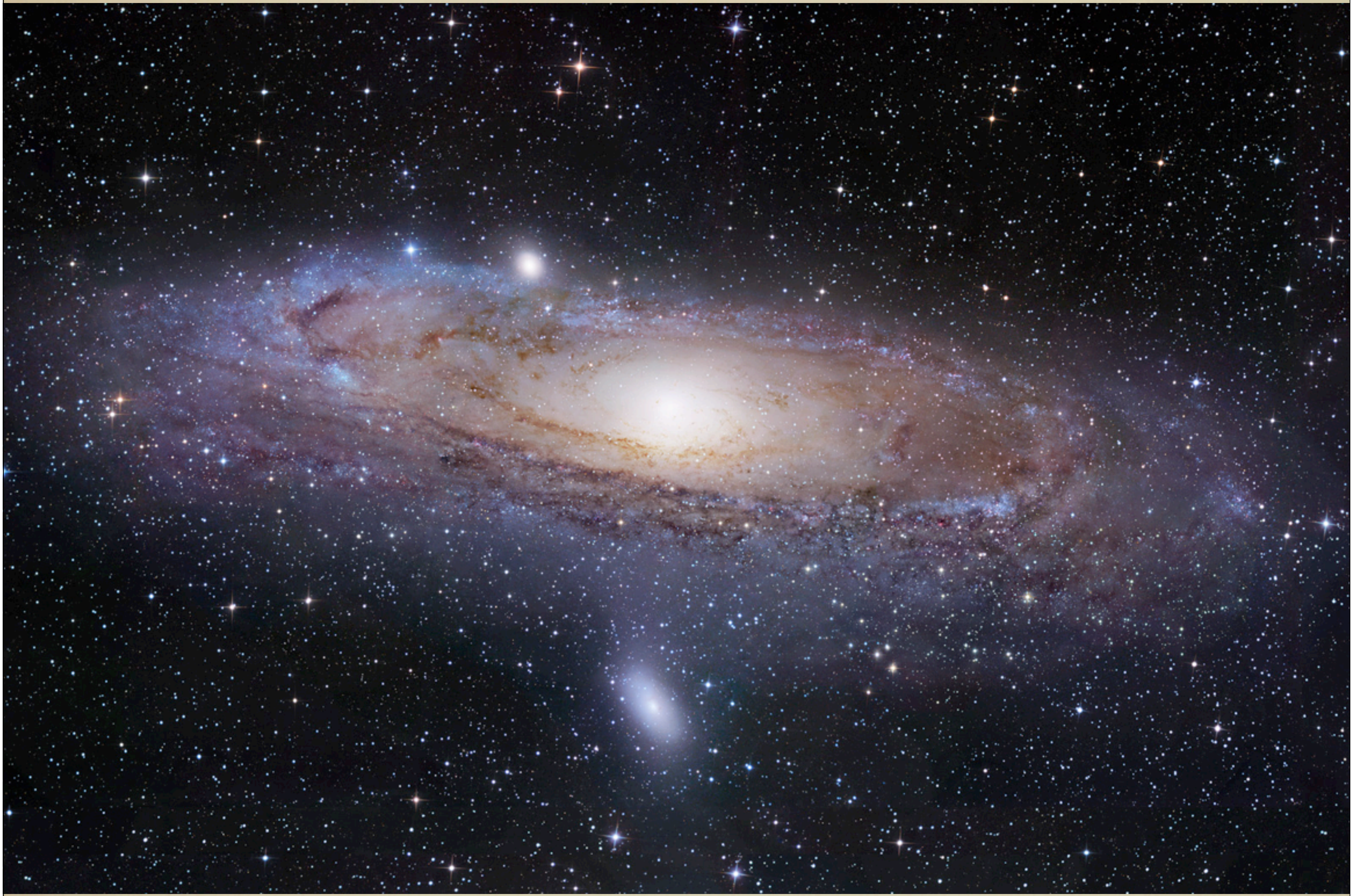
1920's

Edwin Hubble showed that the nebulae in the sky did have larger distances than the size of Milky Way.

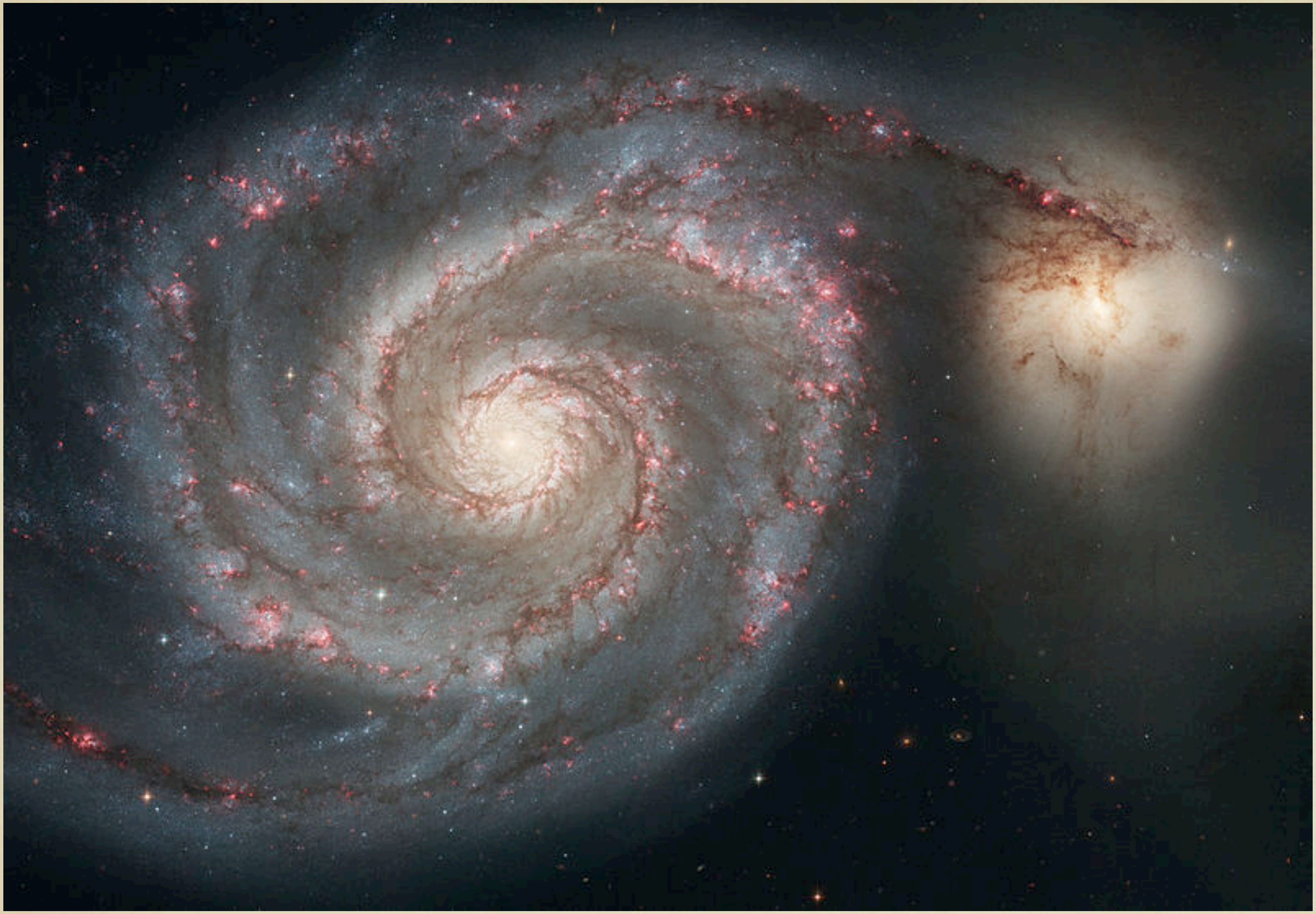
First demonstration of the existence of galaxies (island universes) outside the Milky Way.

Galaxy or Not?

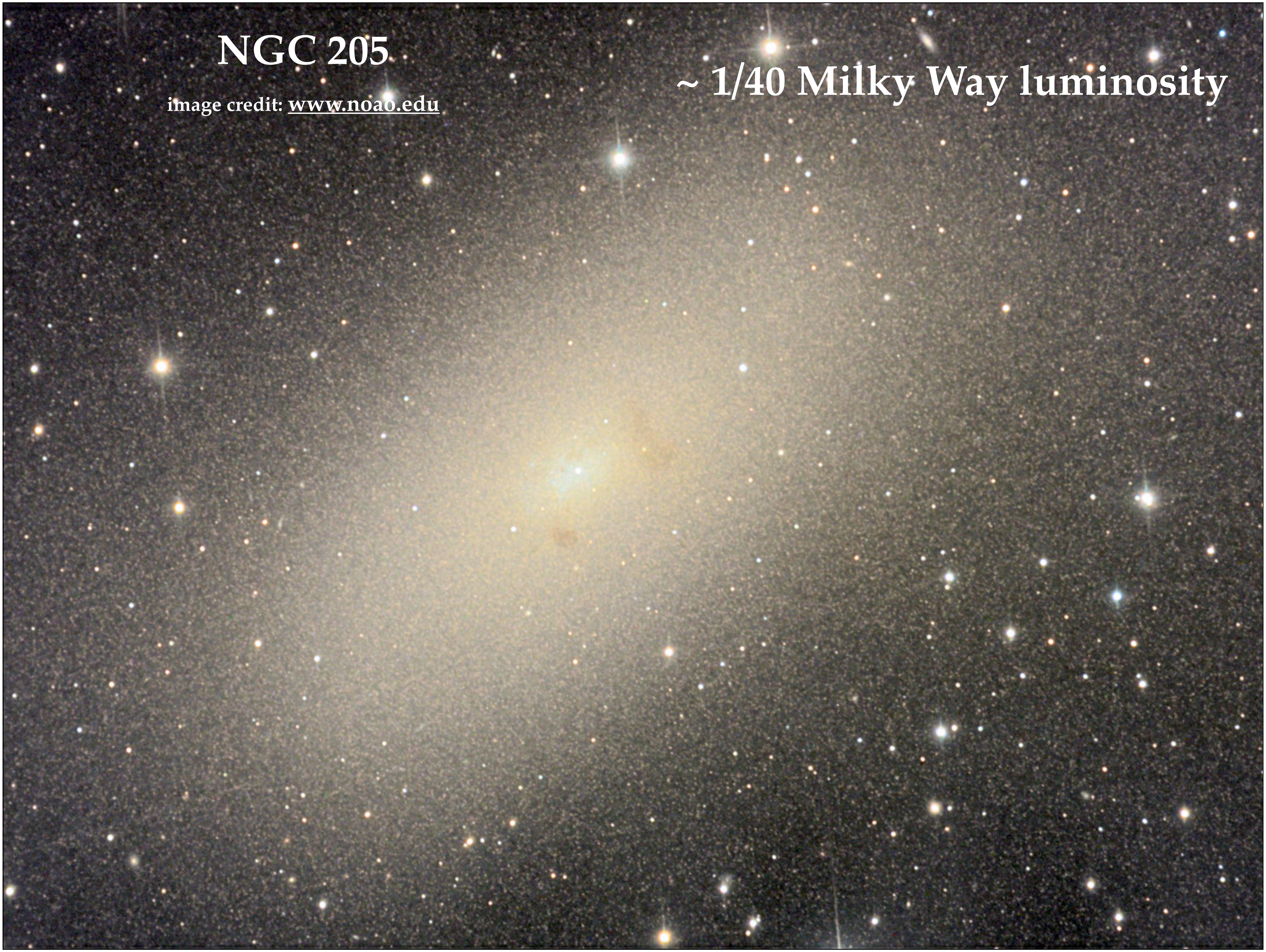




M87




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

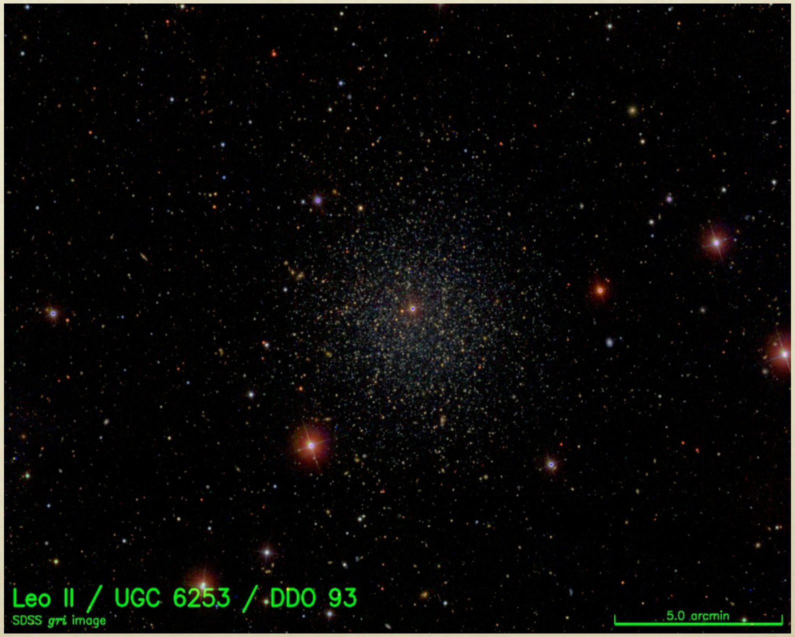
You've seen galaxies with a wide range of appearance and number of stars contained.

What do they have in common?

I know a galaxy when I see it

star cluster: round, compact (< 10 light years across), dense

galaxy: any morphology, large size (thousands of light years across), more diffuse



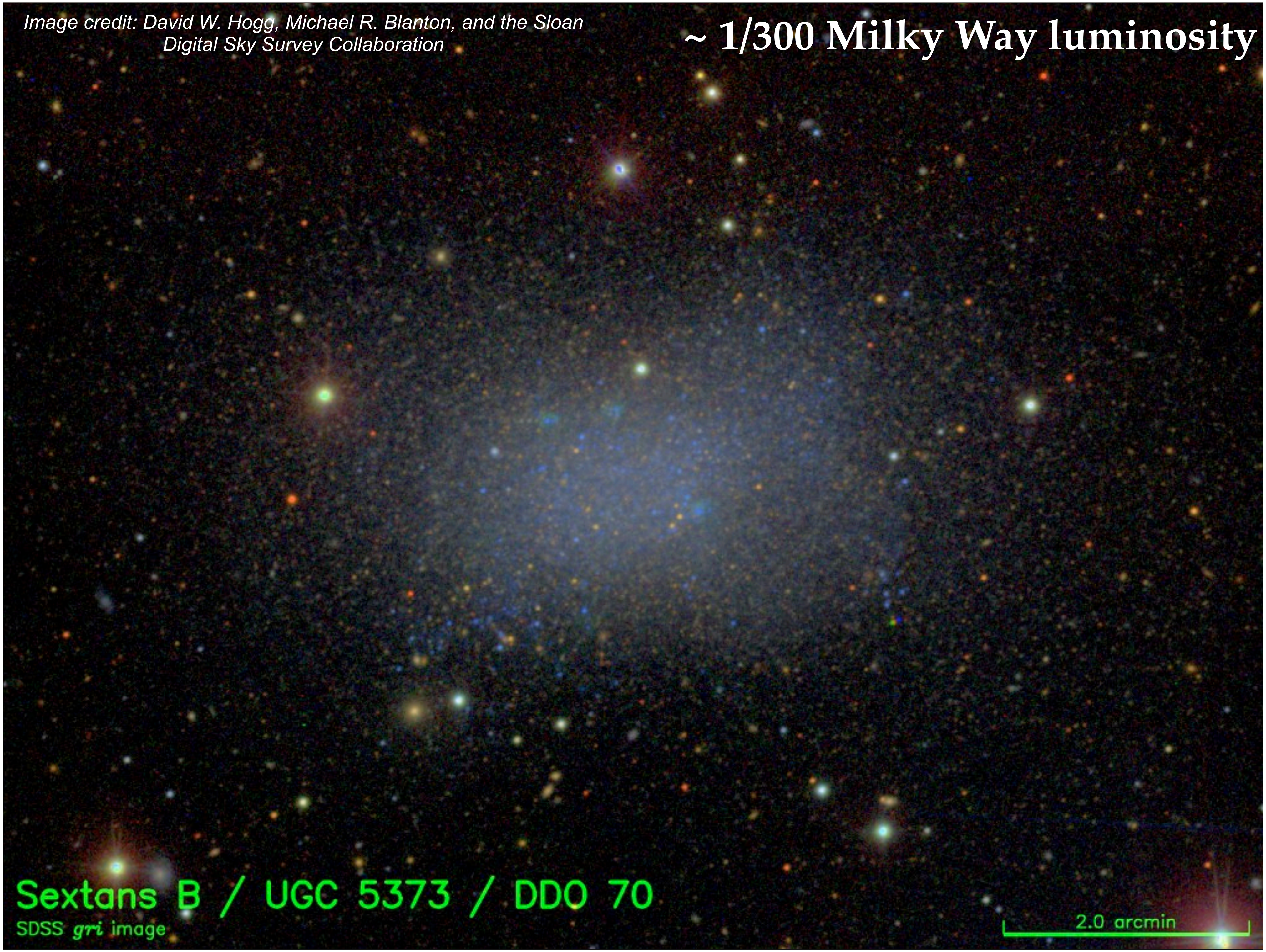


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/300 Milky Way luminosity
Sextans B / UGC 5373 / DDO 70
SDSS gri image
2.0 arcmin

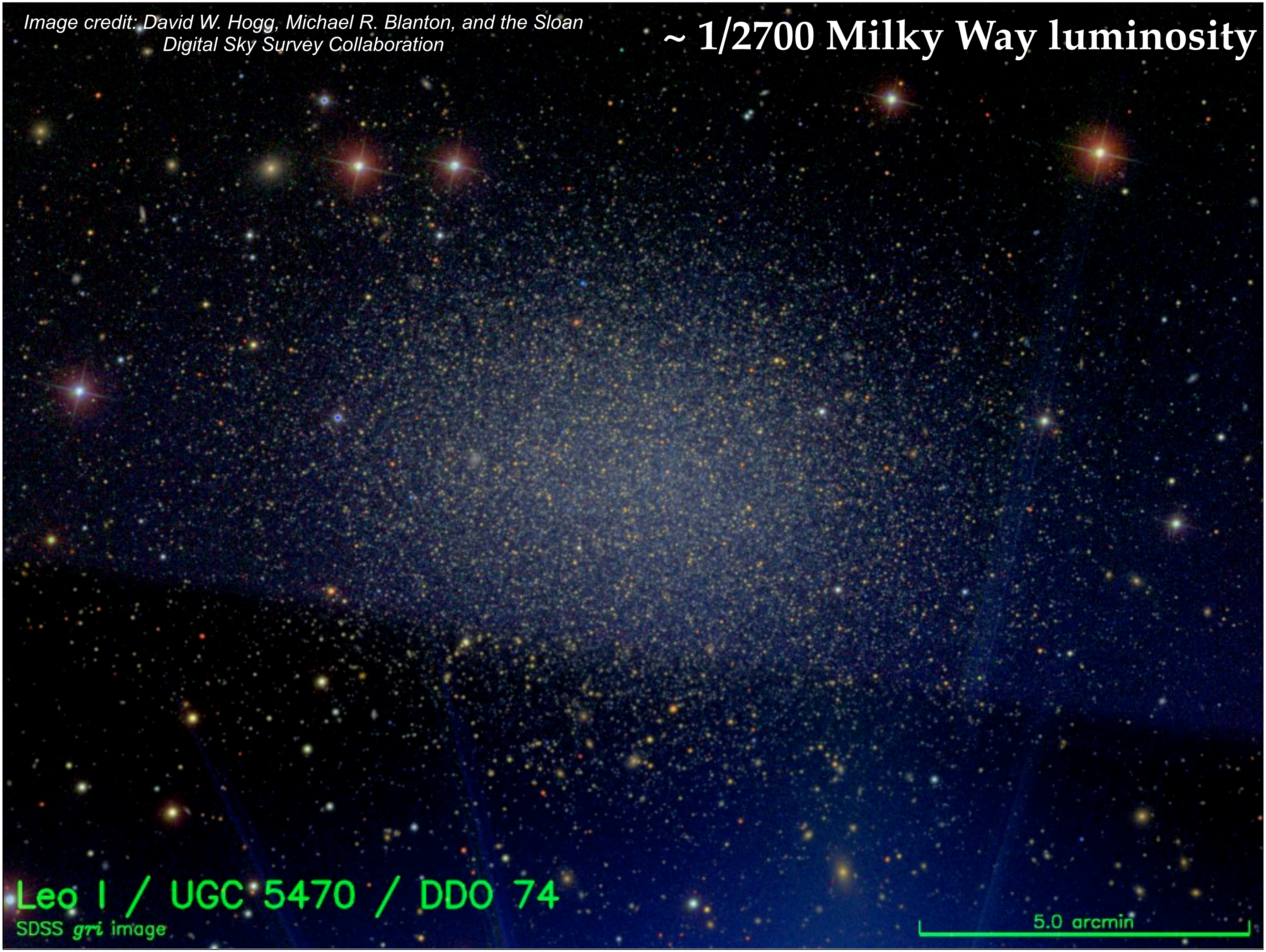


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/2700 Milky Way luminosity
Leo I / UGC 5470 / DDO 74
SDSS gri image
5.0 arcmin

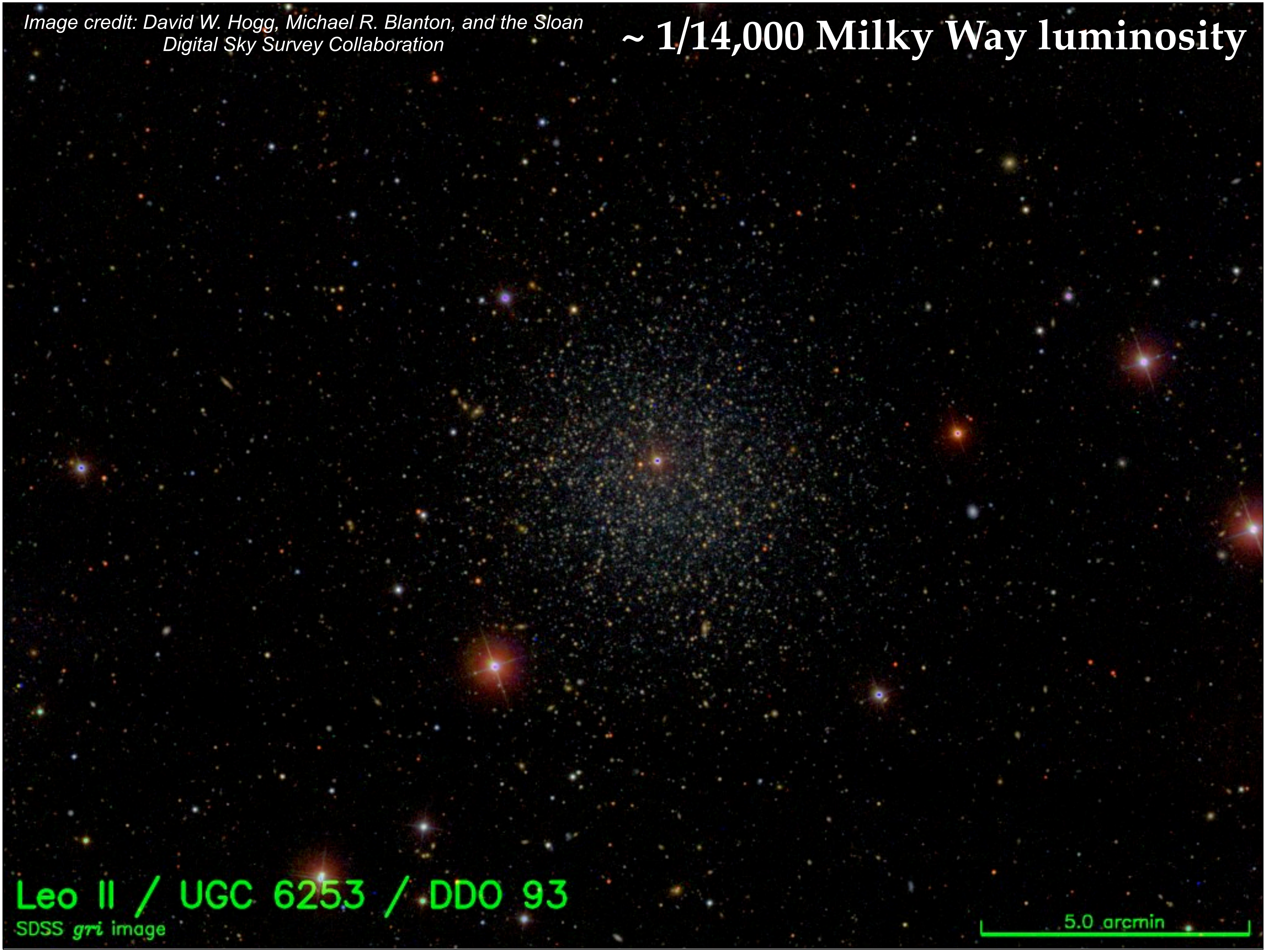


Image credit: David W. Hogg, Michael R. Blanton, and the Sloan Digital Sky Survey Collaboration
~ 1/14,000 Milky Way luminosity
Leo II / UGC 6253 / DDO 93
SDSS gri image
5.0 arcmin

~ 1/40,000 Milky Way luminosity

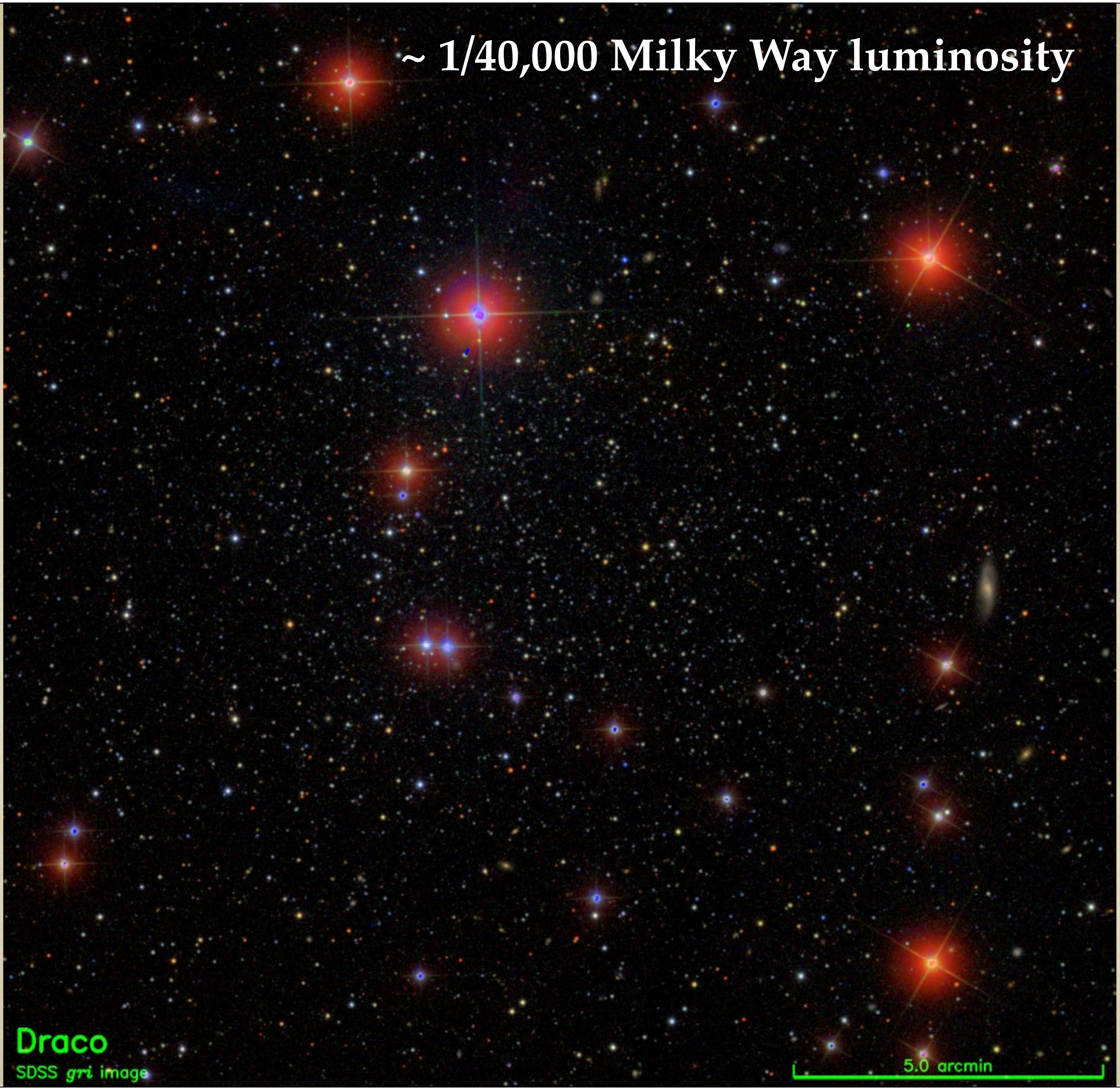
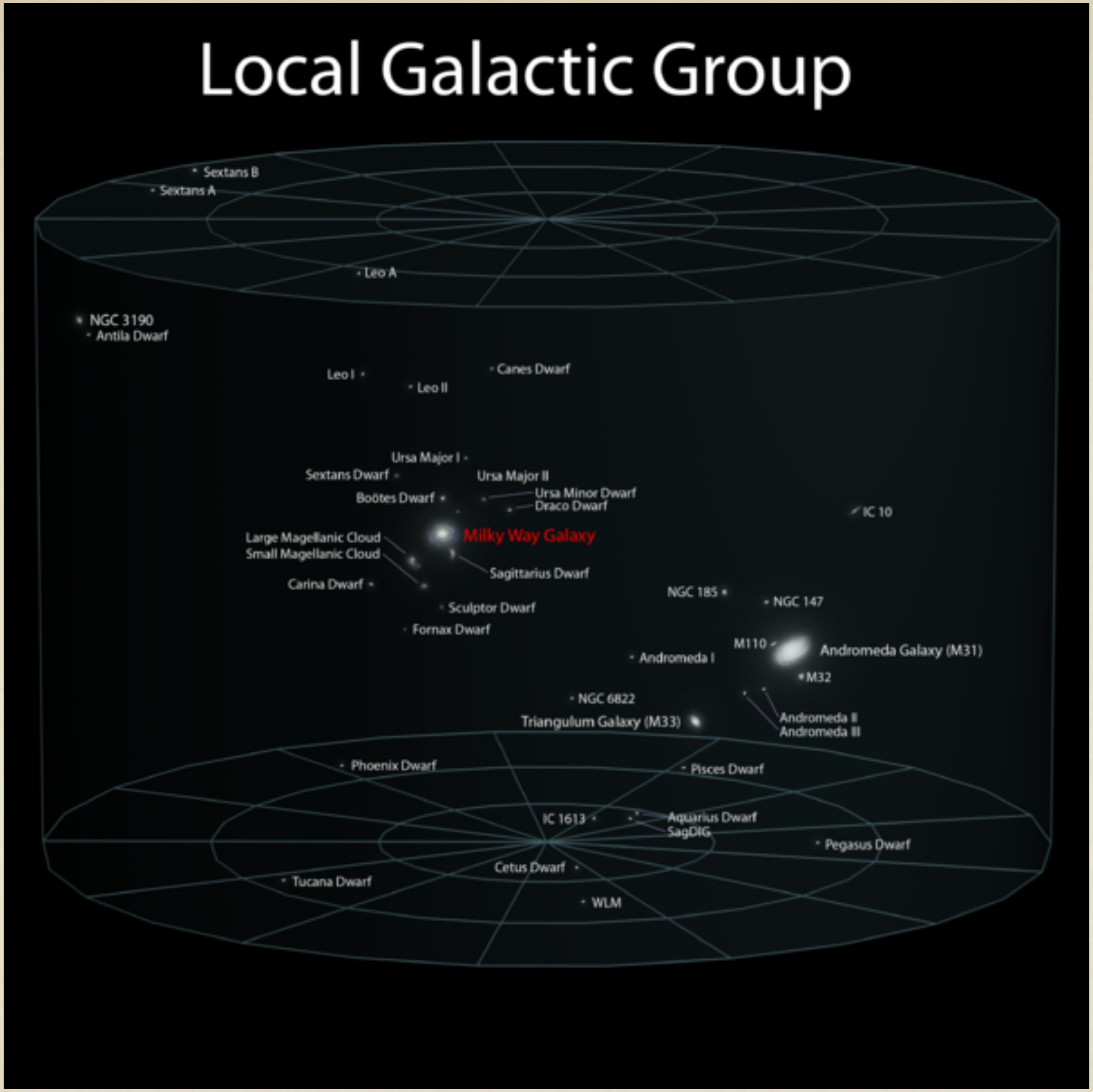
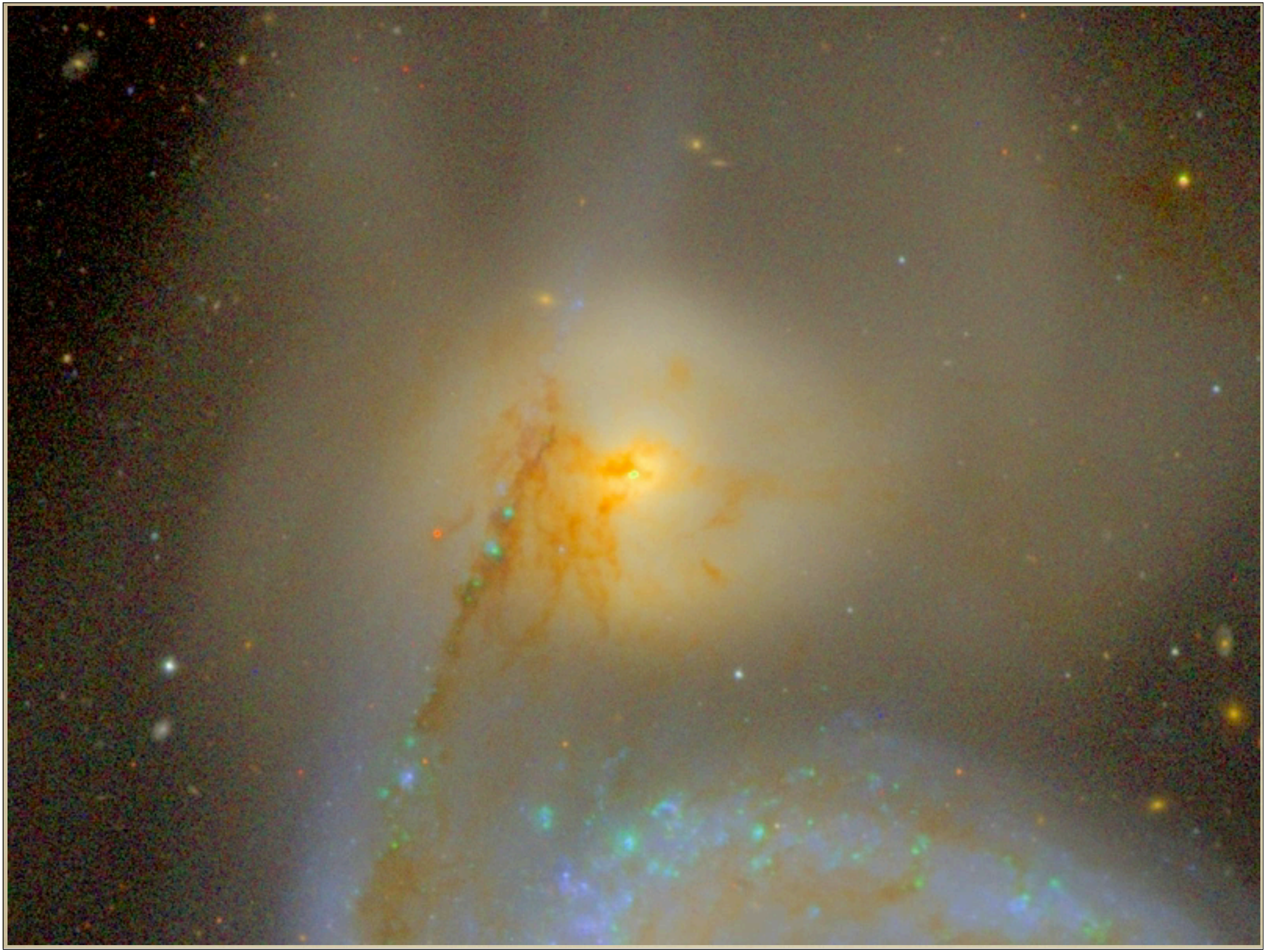


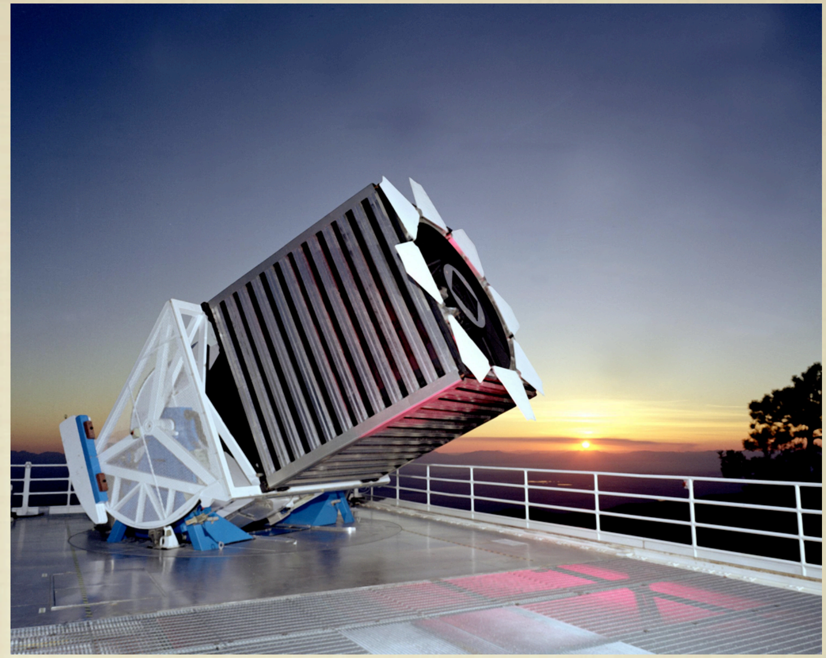
image credit: National Geographic



Are there galaxies so tiny that they evaded detection until the 21st century?

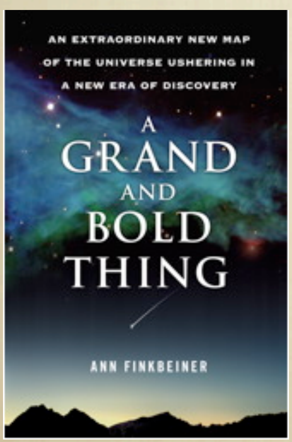


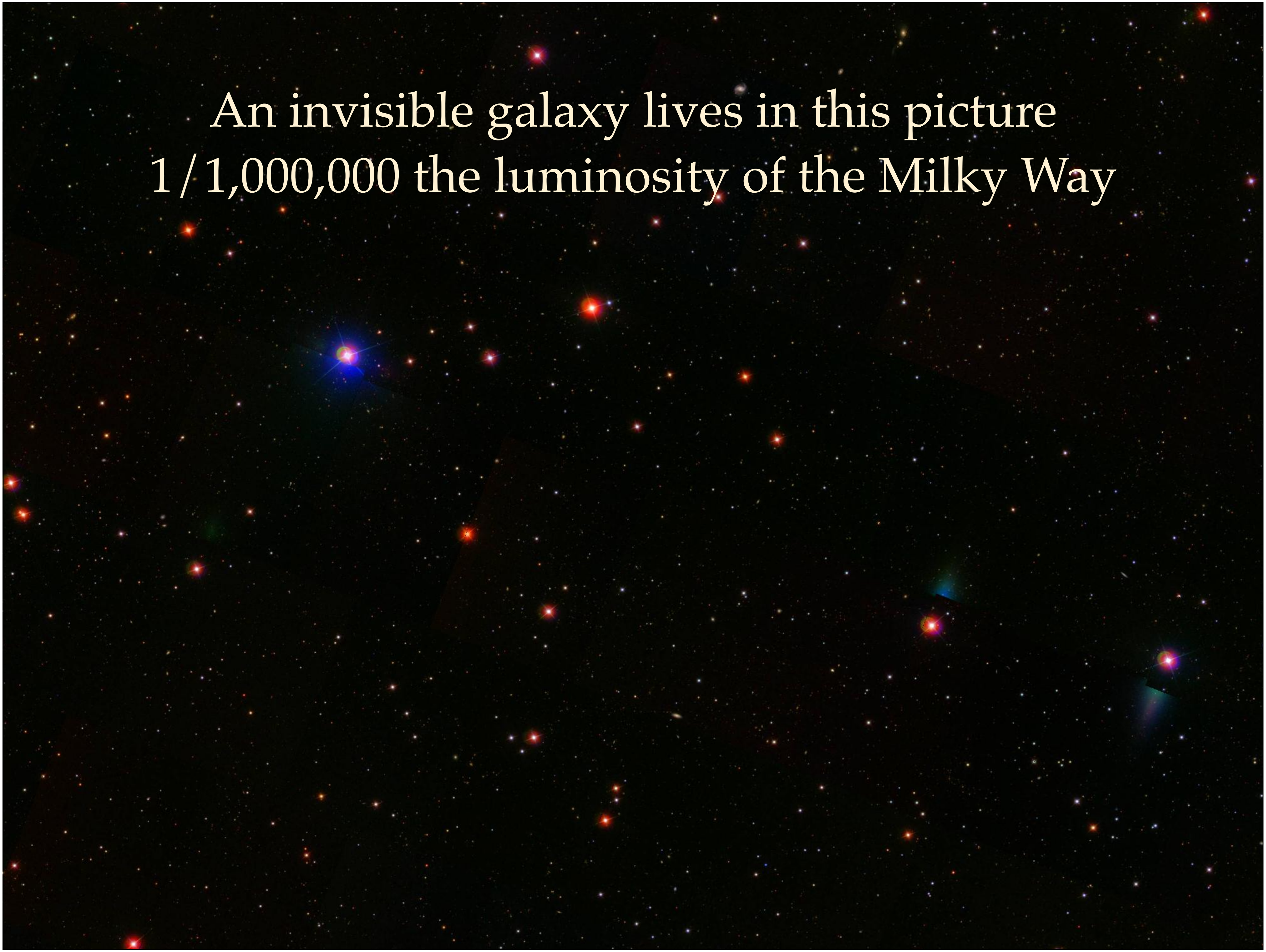
Sloan Digital Sky Survey telescope in New Mexico.



Early Data Release took place in 2001 - 462 deg^2 (1/100) of sky. More than 14,000 deg^2 are now publicly available.

www.sdss3.org



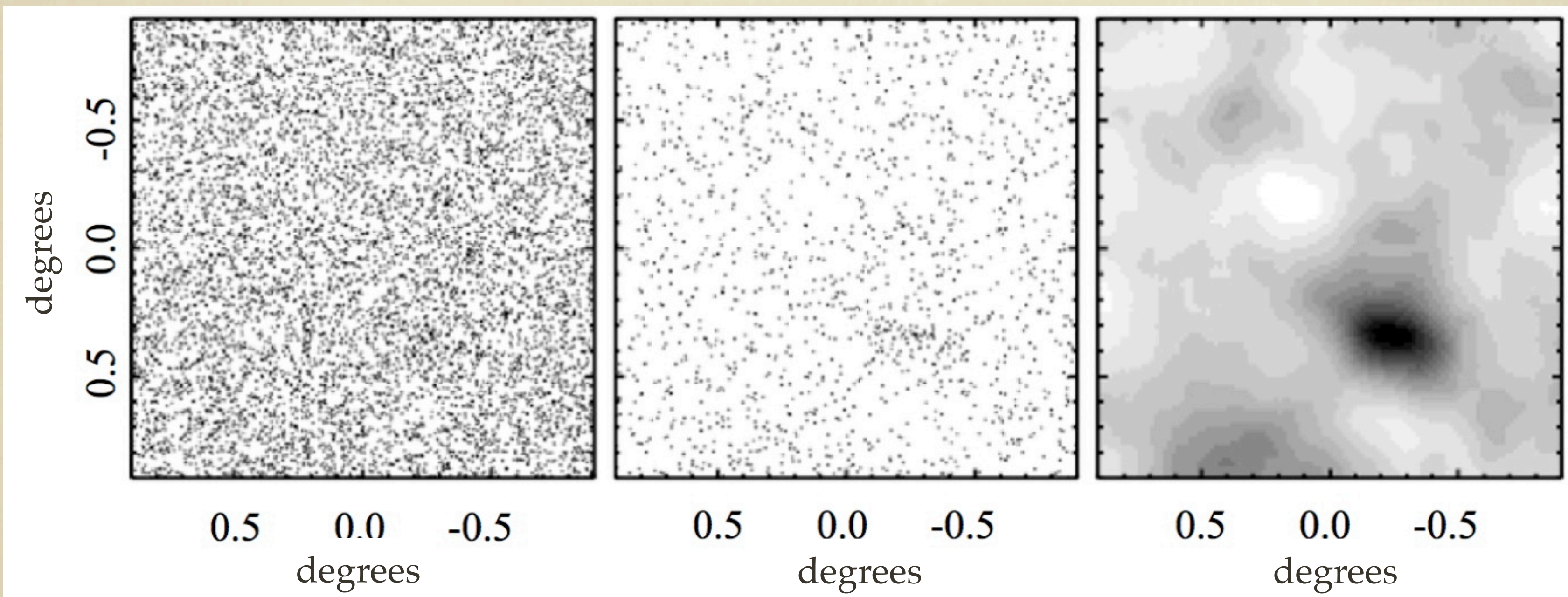

An invisible galaxy lives in this picture
1/1,000,000 the luminosity of the Milky Way

Discovery of an “invisible” galaxy

1 dot = 1 star
before filtering

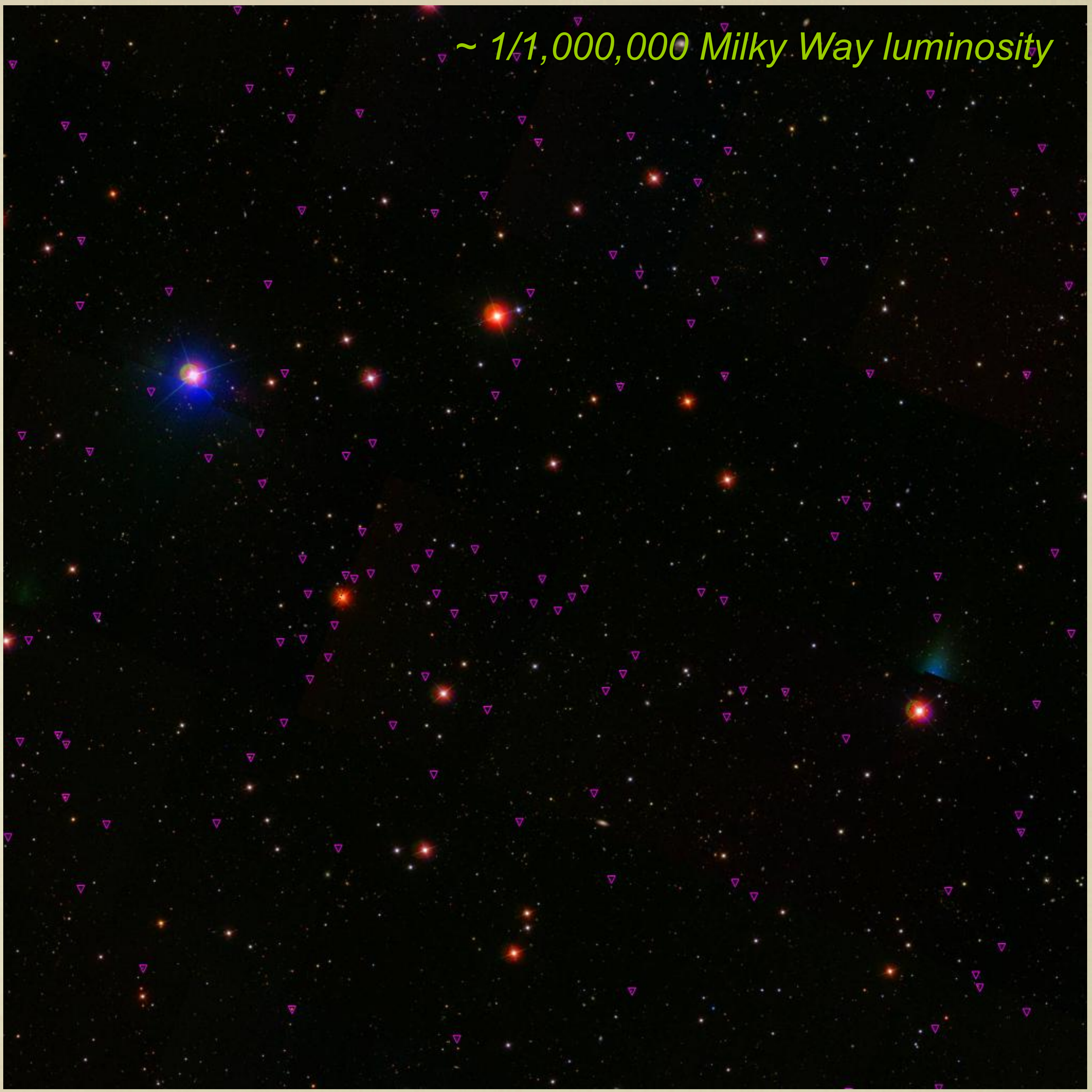
1 dot = 1 star
after filtering

false image



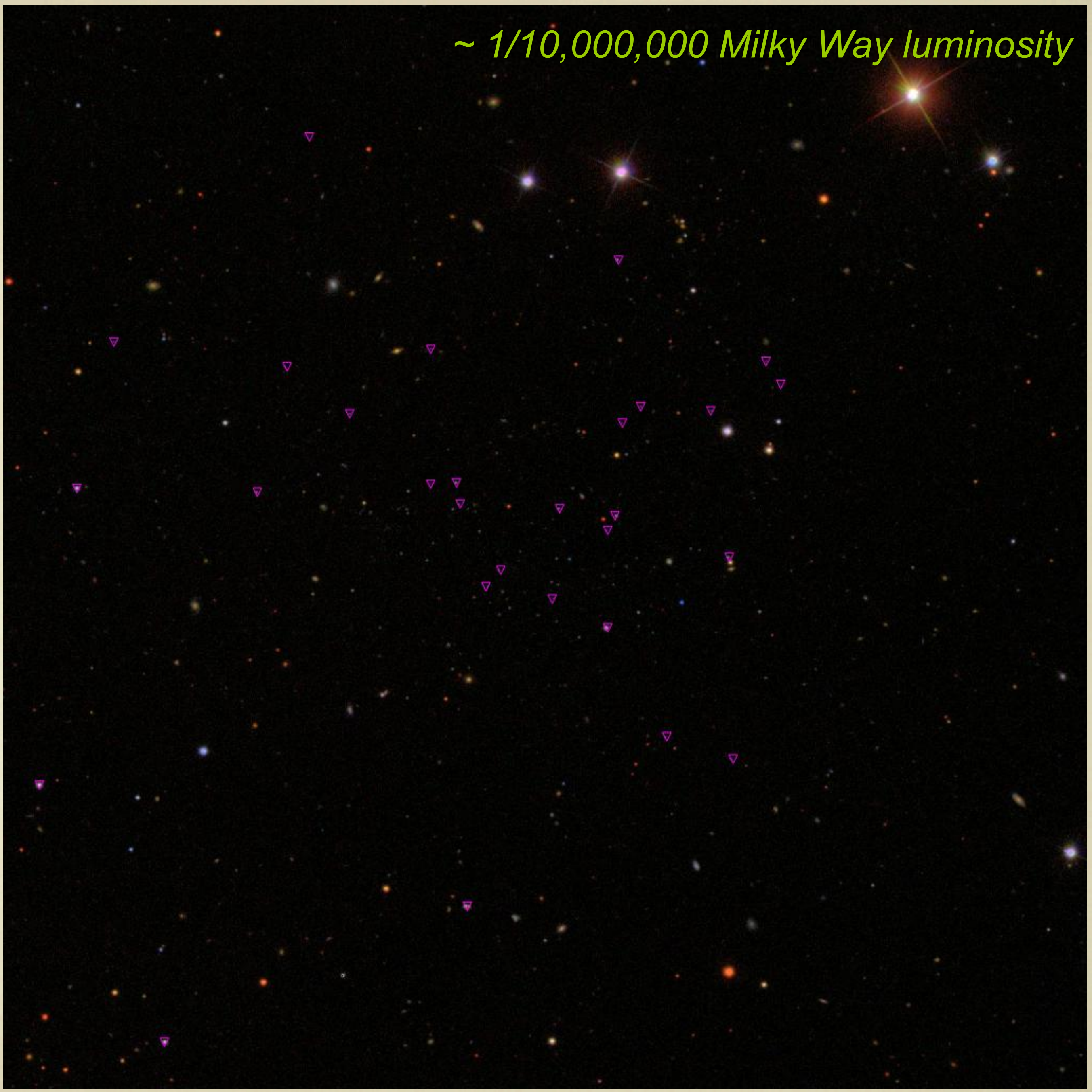
Ursa Major I - discovered in 2005

Ursa Major I



Willman 1

Less light in the entire galaxy than in some individual red giant stars!



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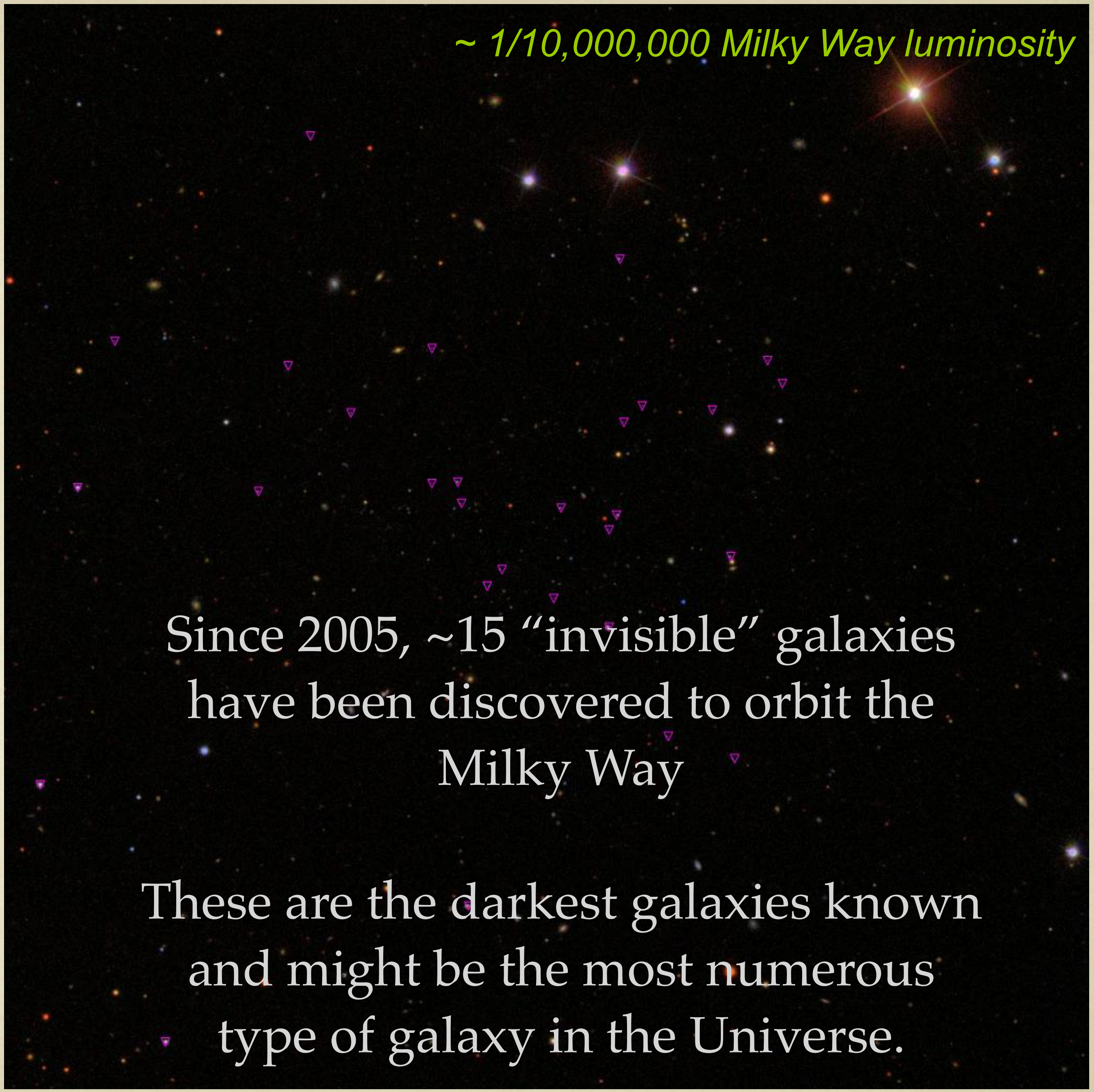
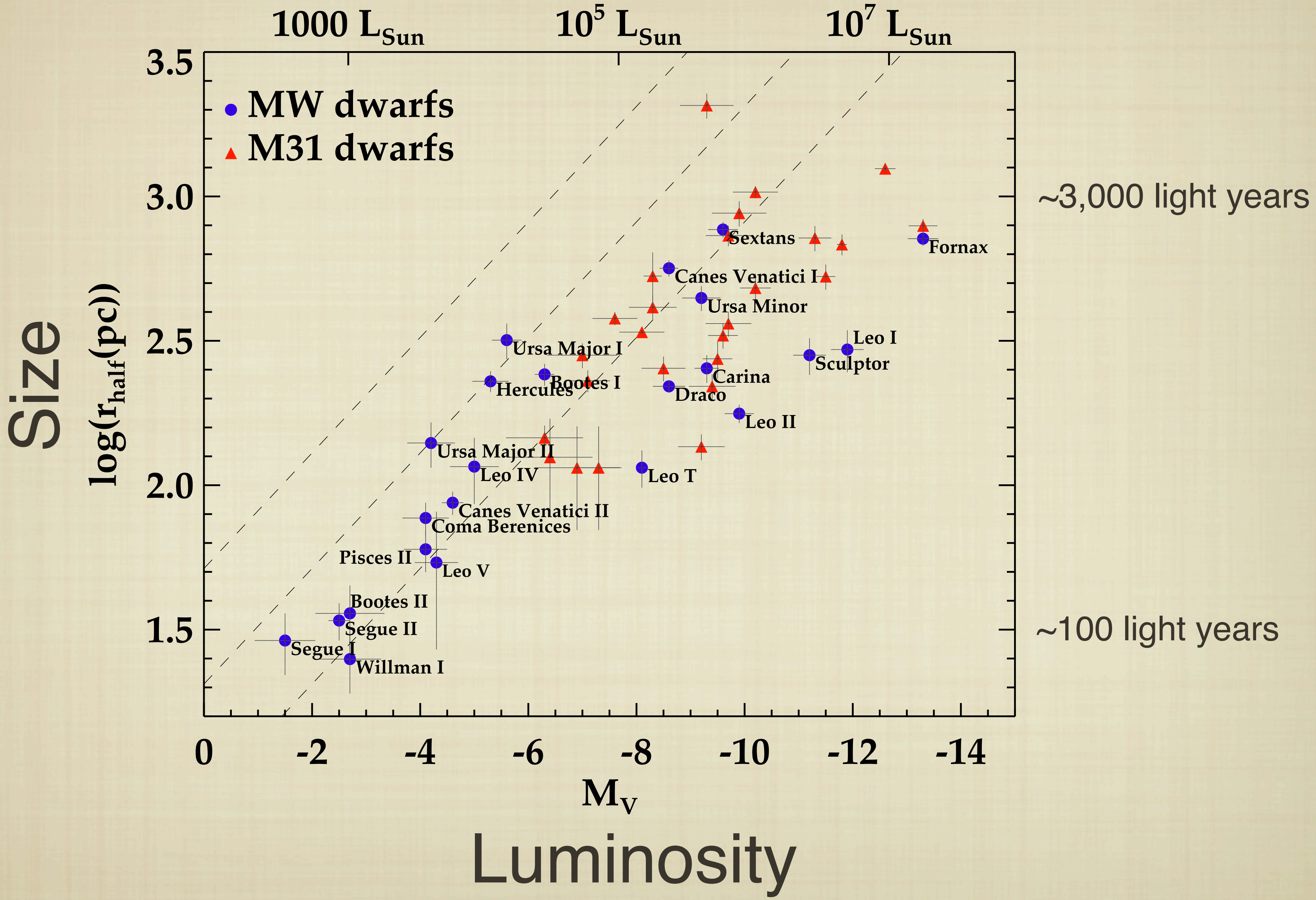


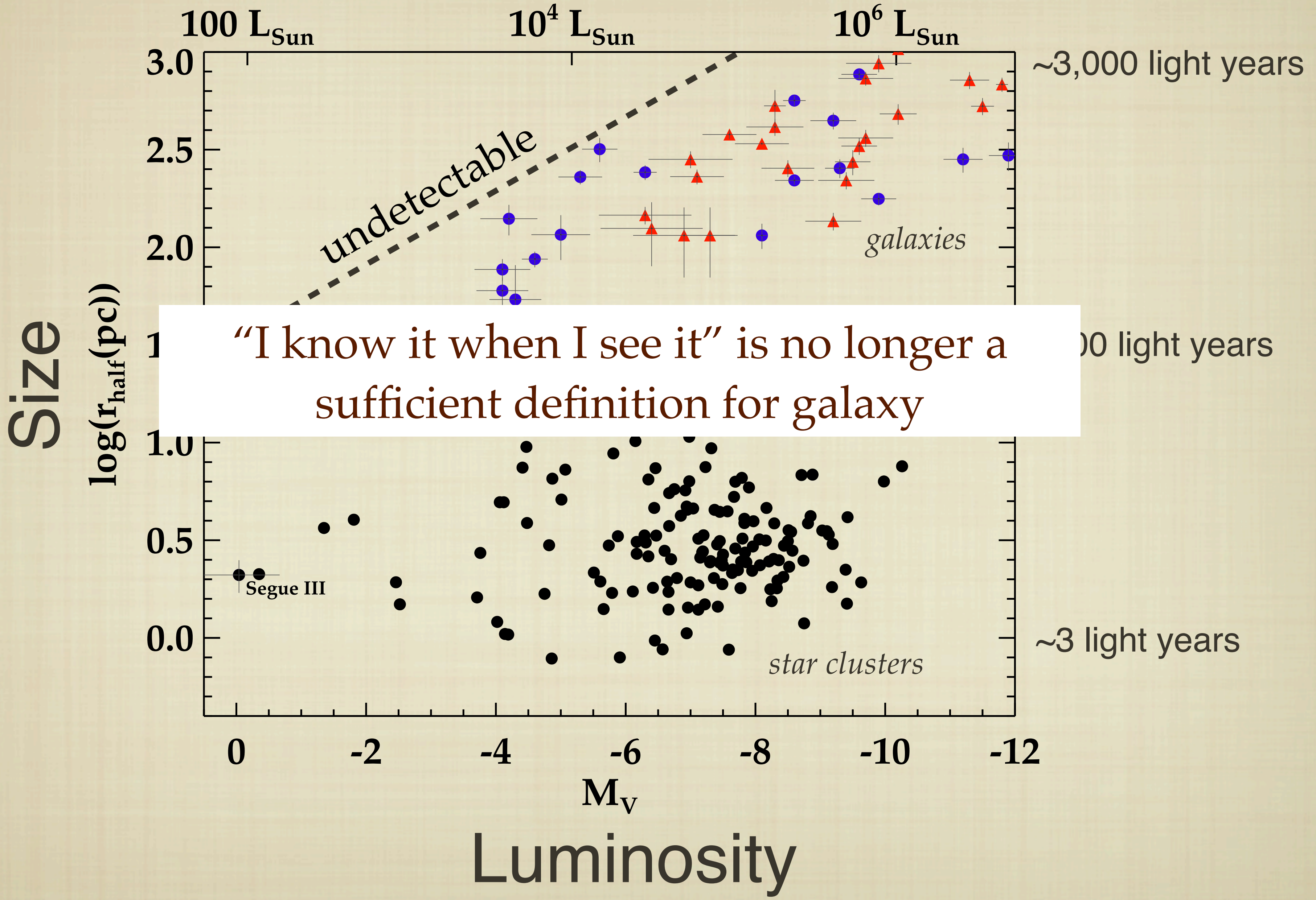
Since 2005, ~15 “invisible” galaxies have been discovered to orbit the Milky Way

These are the darkest galaxies known and might be the most numerous type of galaxy in the Universe.

Luminosities and sizes of nearby dwarf galaxies



Luminosities and sizes of dwarfs and star clusters



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

AJ THE ASTRONOMICAL JOURNAL

The Astronomical Journal > Volume 144 > Number 3

B. Willman and J. Strader 2012 *The Astronomical Journal* **144** 76 doi:10.1088/0004-6256/144/3/76

"GALAXY," DEFINED

B. Willman[1] and J. Strader[2]

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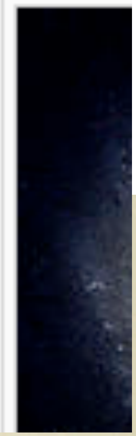
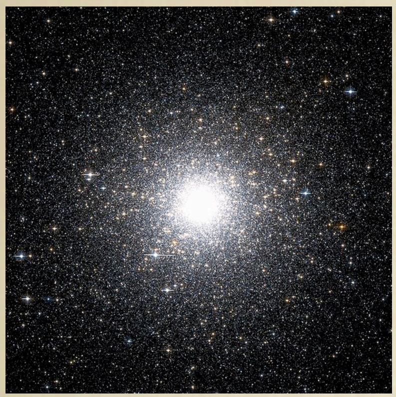


Abstract | References | Cited By | Metrics

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.

Keywords galaxies: dwarf; galaxies: kinematics and dynamics; galaxies: star clusters: general



Star cluster: Weighs what you expect

Galaxy: Heavier than expected.
Dark matter makes up the difference.

Not dark matter

Dark matter

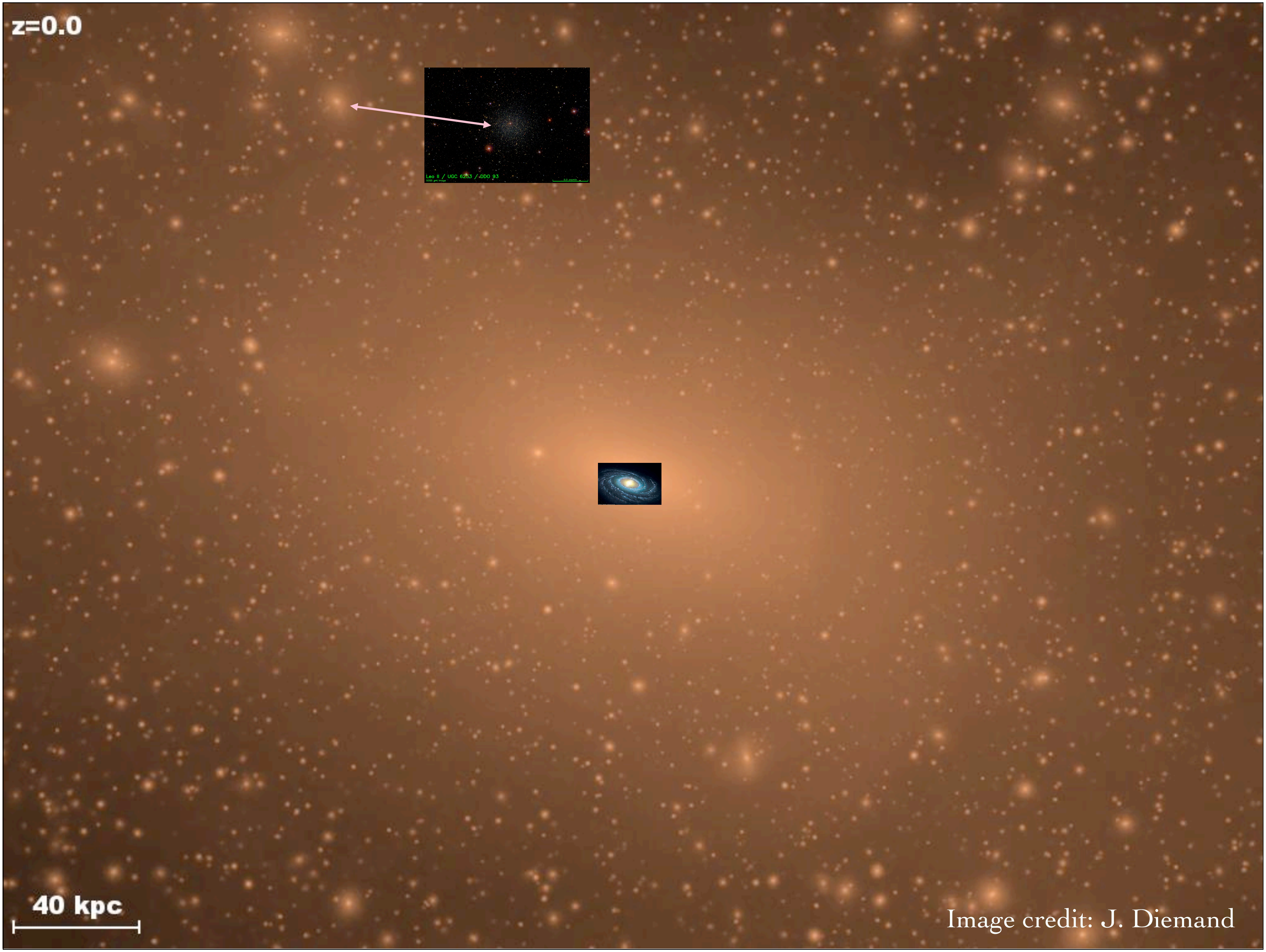
What is Dark Matter?

<u>Normal stuff</u>

- Very dim stars
- Planets
- Black holes
- Dead stars

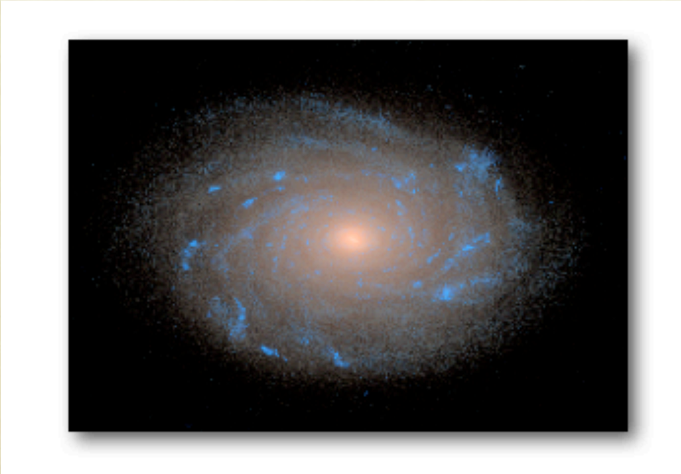
<u>Other stuff</u>

Weakly interacting massive particles (WIMPs)


z=0.0
Leo II / UGC 6253 / DDO 93
SDSS gri image
5.0 arcmin
40 kpc
Image credit: J. Diemand

Ingredients: dark matter + laws of physics
gas + supercomputer

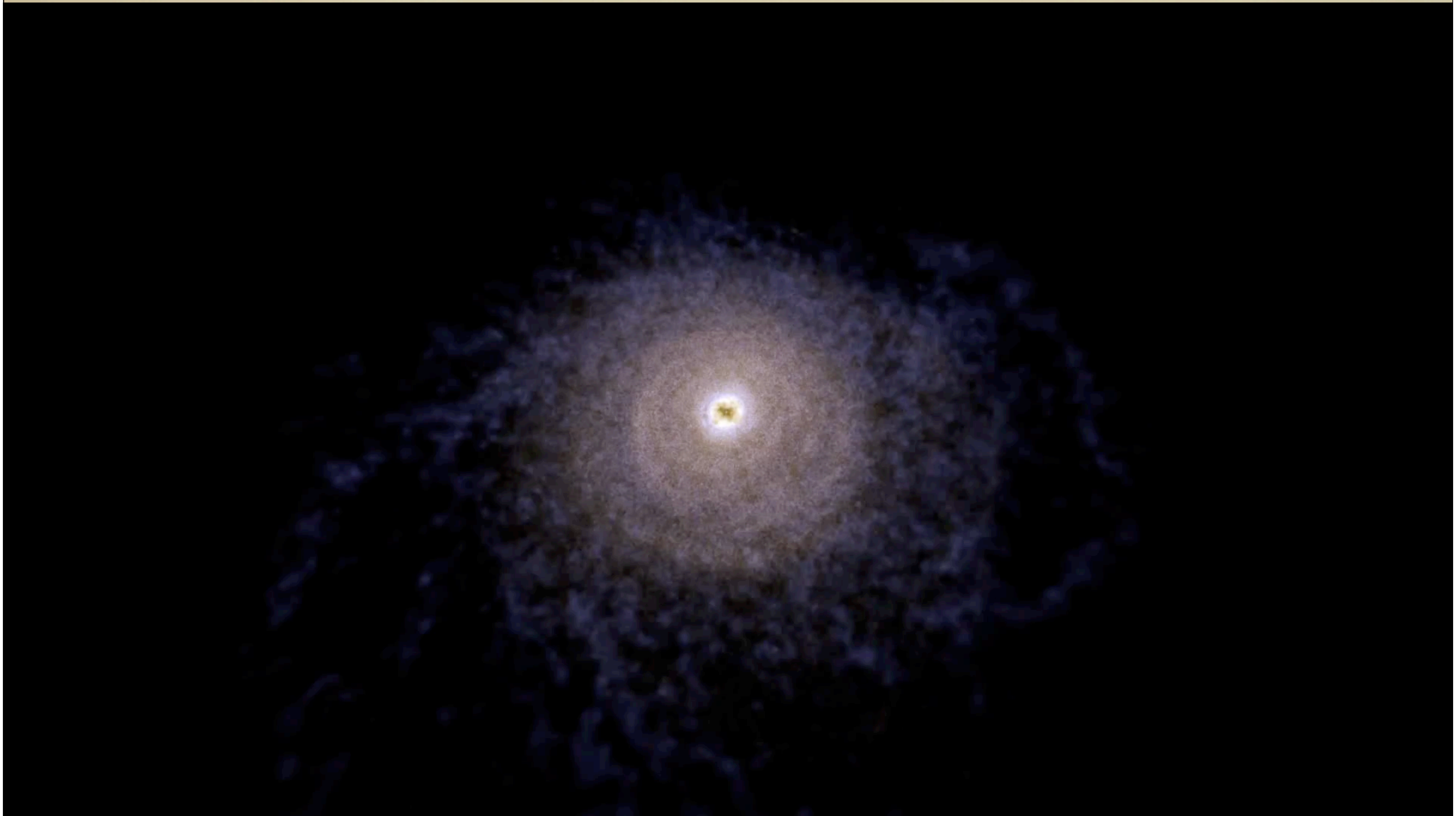
= a simulated galaxy:



We have described "What is a galaxy?"

Do we understand why?

Andrew Pontzen



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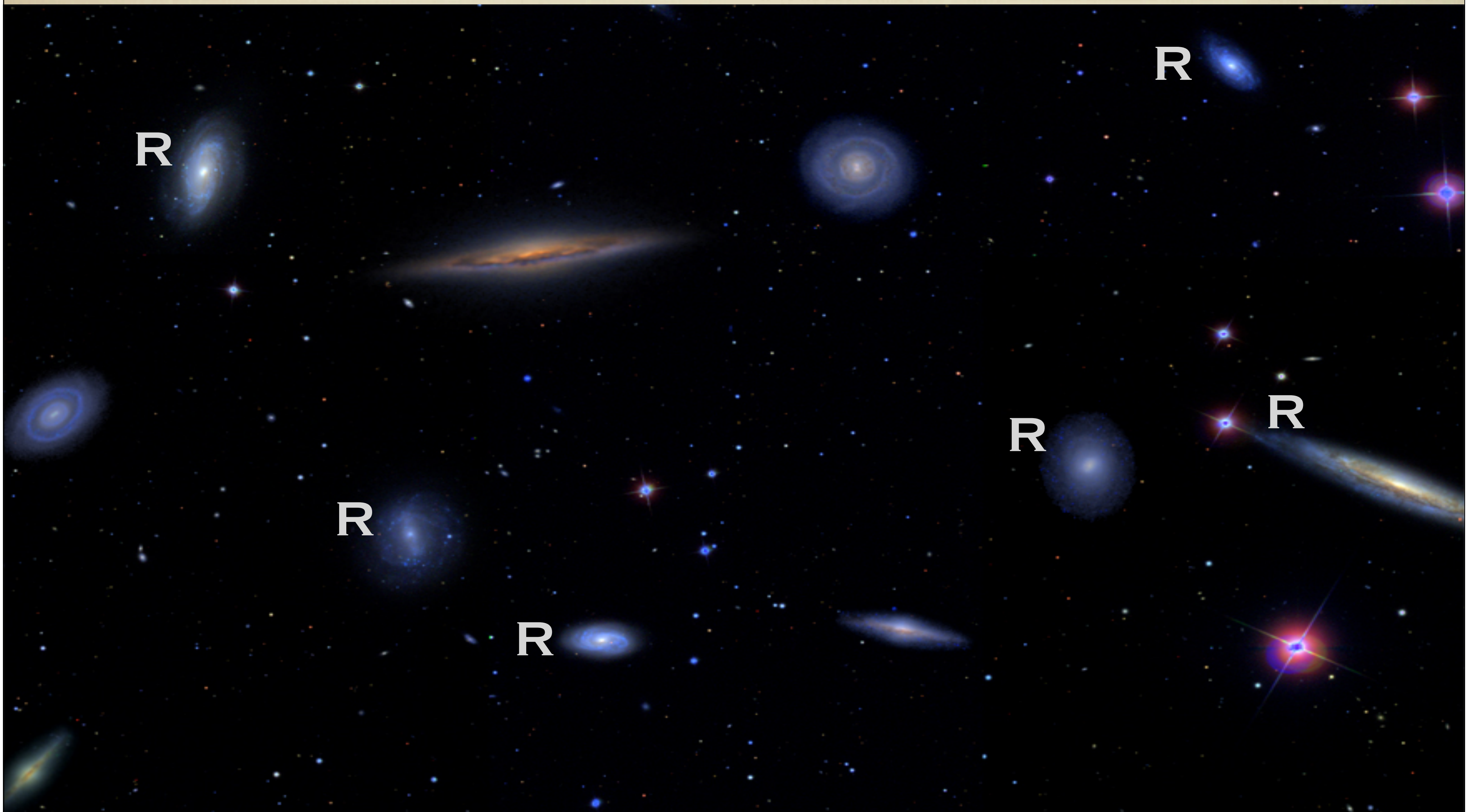
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Large Synoptic Survey Telescope

the widest, fastest, deepest eye of the new digital age

The future

LSST: imaging survey that will make a movie of half of the sky over a ten year period, gathering a half-petabyte of data per month and resulting in the deepest wide-field survey in history.

Search for more invisible galaxies

Study new galaxy simulations to learn what dwarf galaxies may reveal about dark matter

How can *you* study galaxies?

Sloan Digital Sky Survey

Galaxy Zoo

Zooniverse

Interactive Milky Way

The End