THE DARK ENERGY SURVEY

Fermilab

Milky Way Satellite Galaxies with DES

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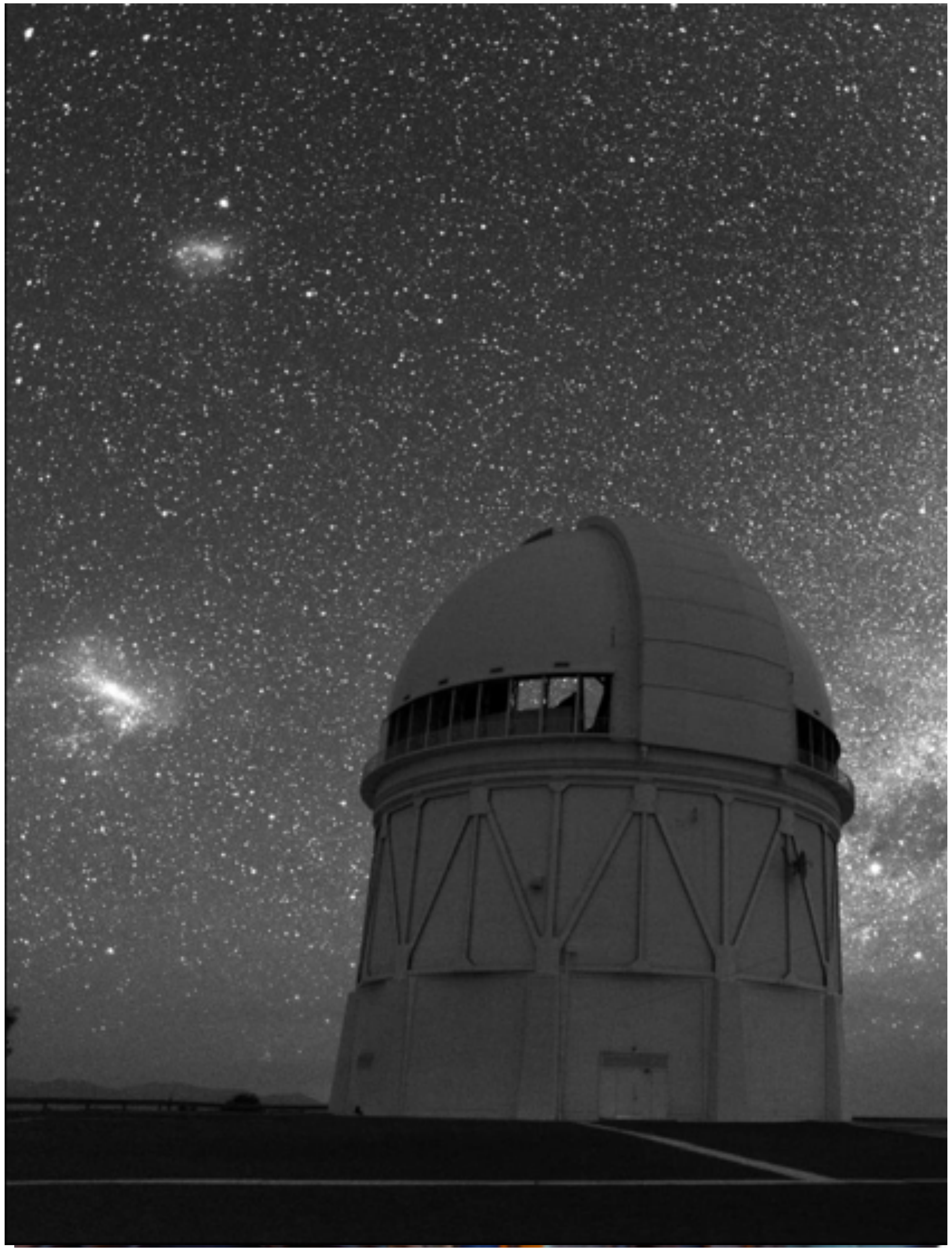
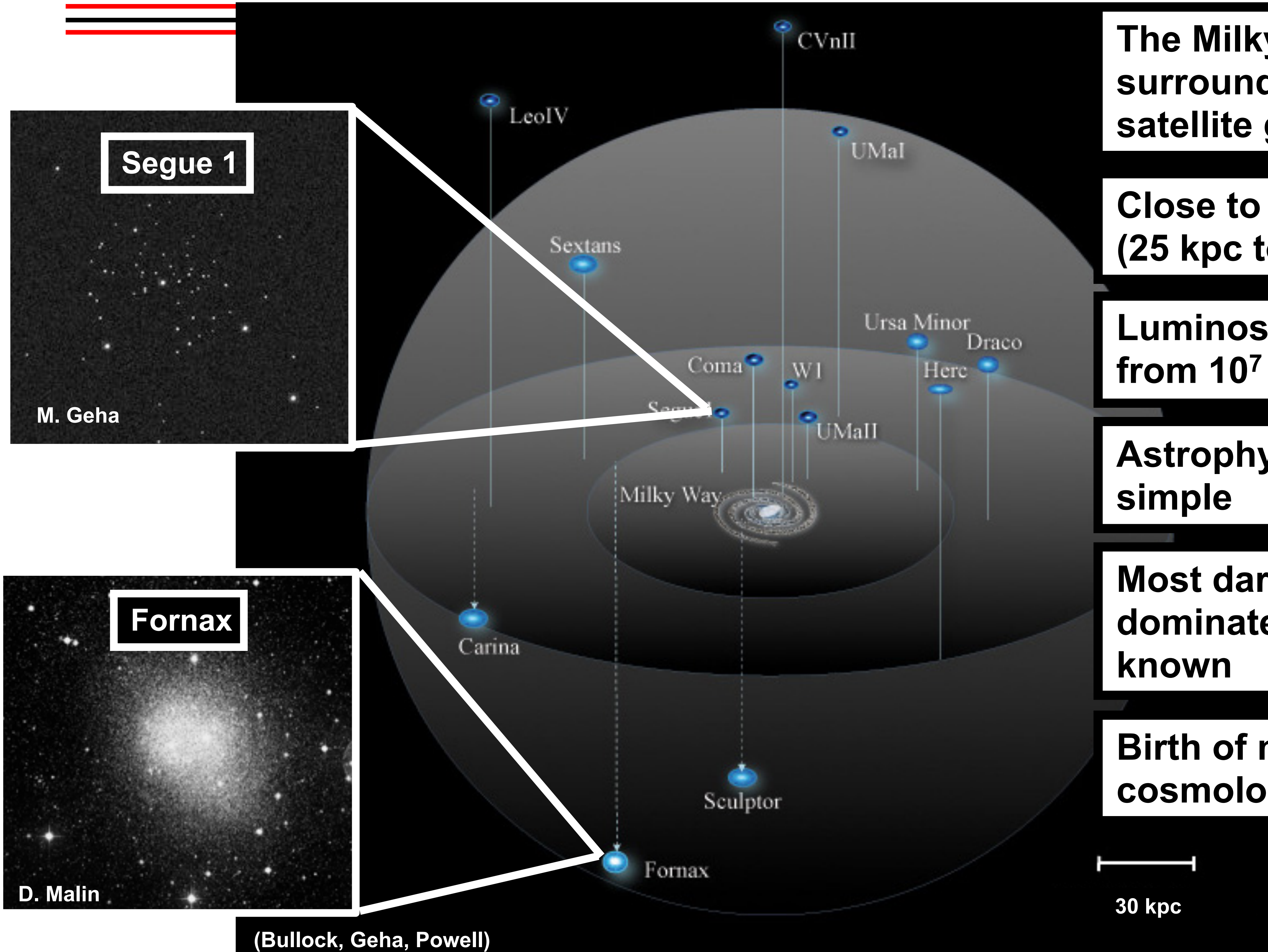
Fermilab | Center for Particle Astrophysics



Milky Way Satellite Galaxies

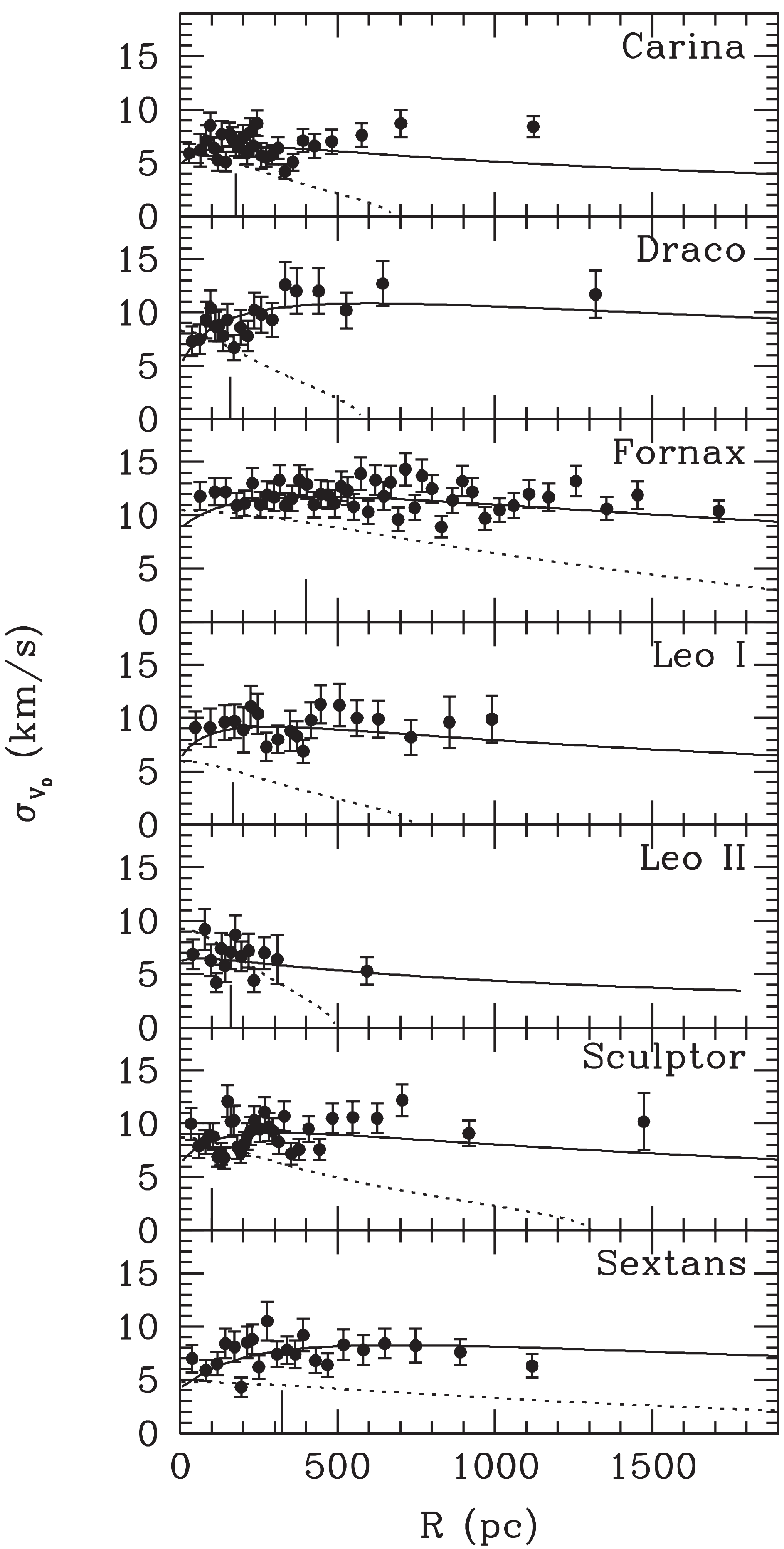


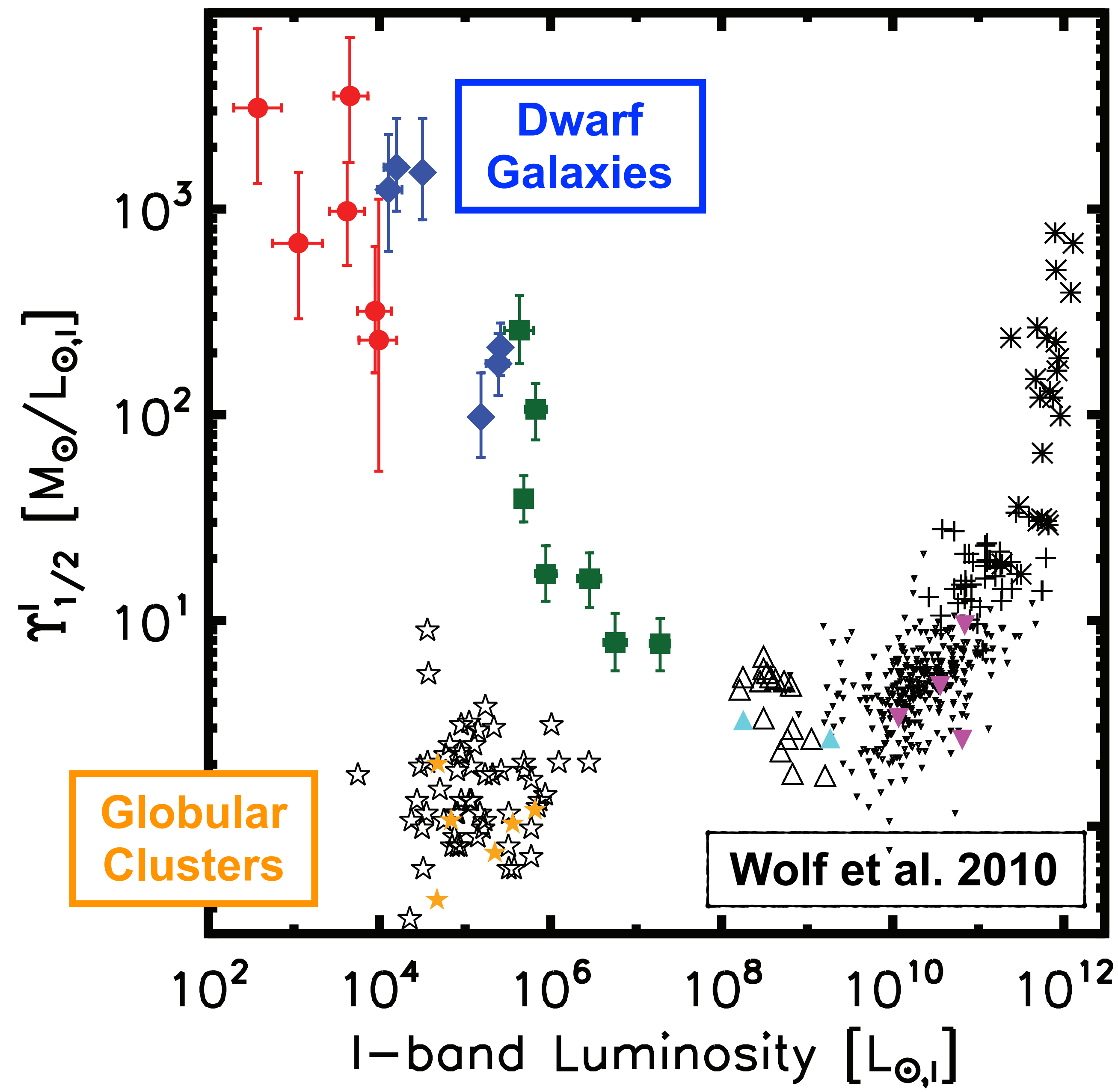
- The Milky Way is surrounded by small satellite galaxies
- Close to Earth (25 kpc to 250 kpc)
- Luminosities range from $10^7\ L_\odot$ to $10^3\ L_\odot$
- Astrophysically simple
- Most dark matter dominated objects known
- Birth of near-field cosmology

Dark Matter Dominated

The stars in dwarf galaxies are moving too fast to be explained by visible mass alone

Walker et al. 2007





Finding Milky Way Satellite Galaxies

Finding Milky Way Satellite Galaxies

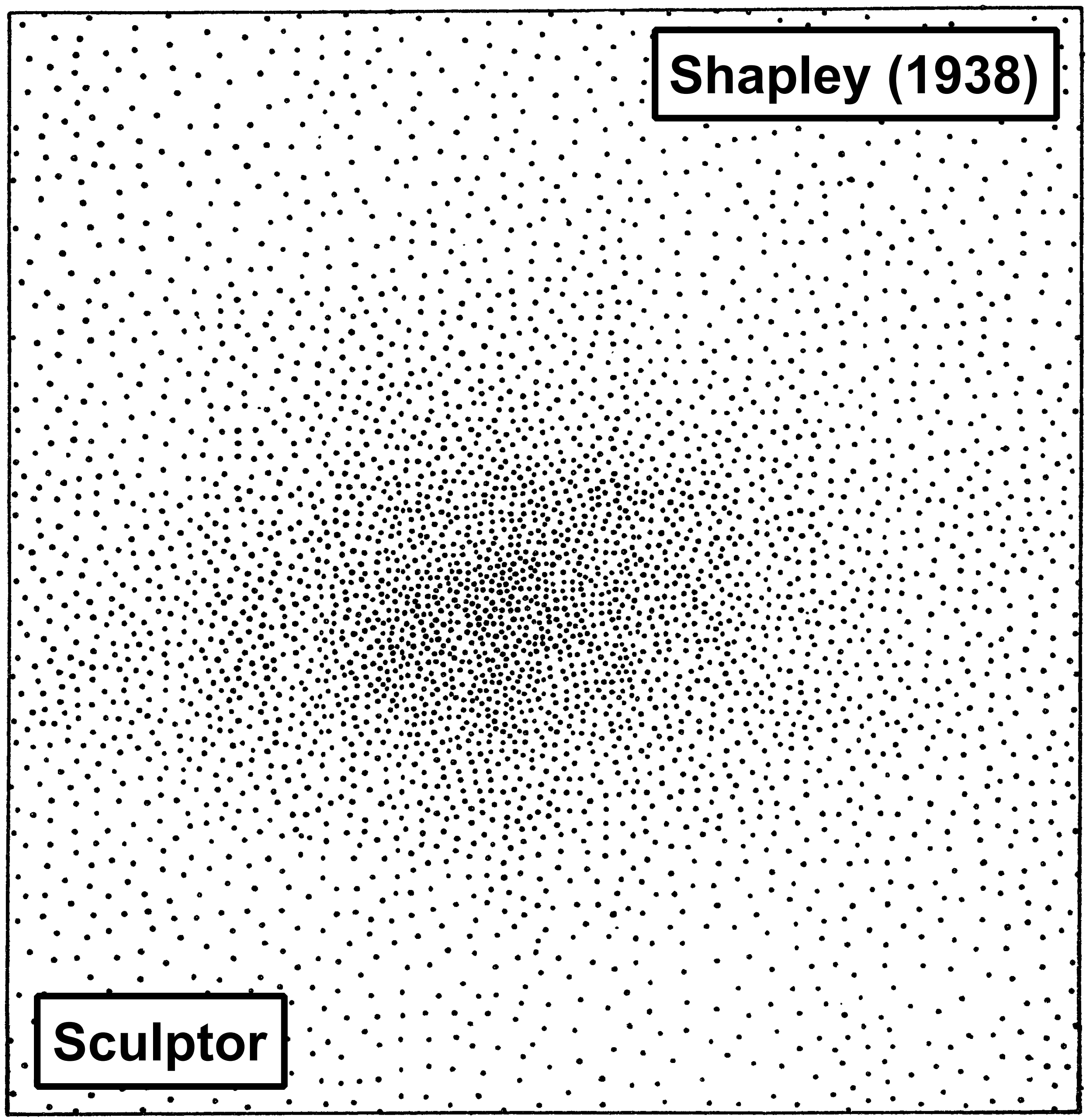


FIGURE 2.– DISTRIBUTION OF STARS IN CENTRAL SQUARE DEGREE

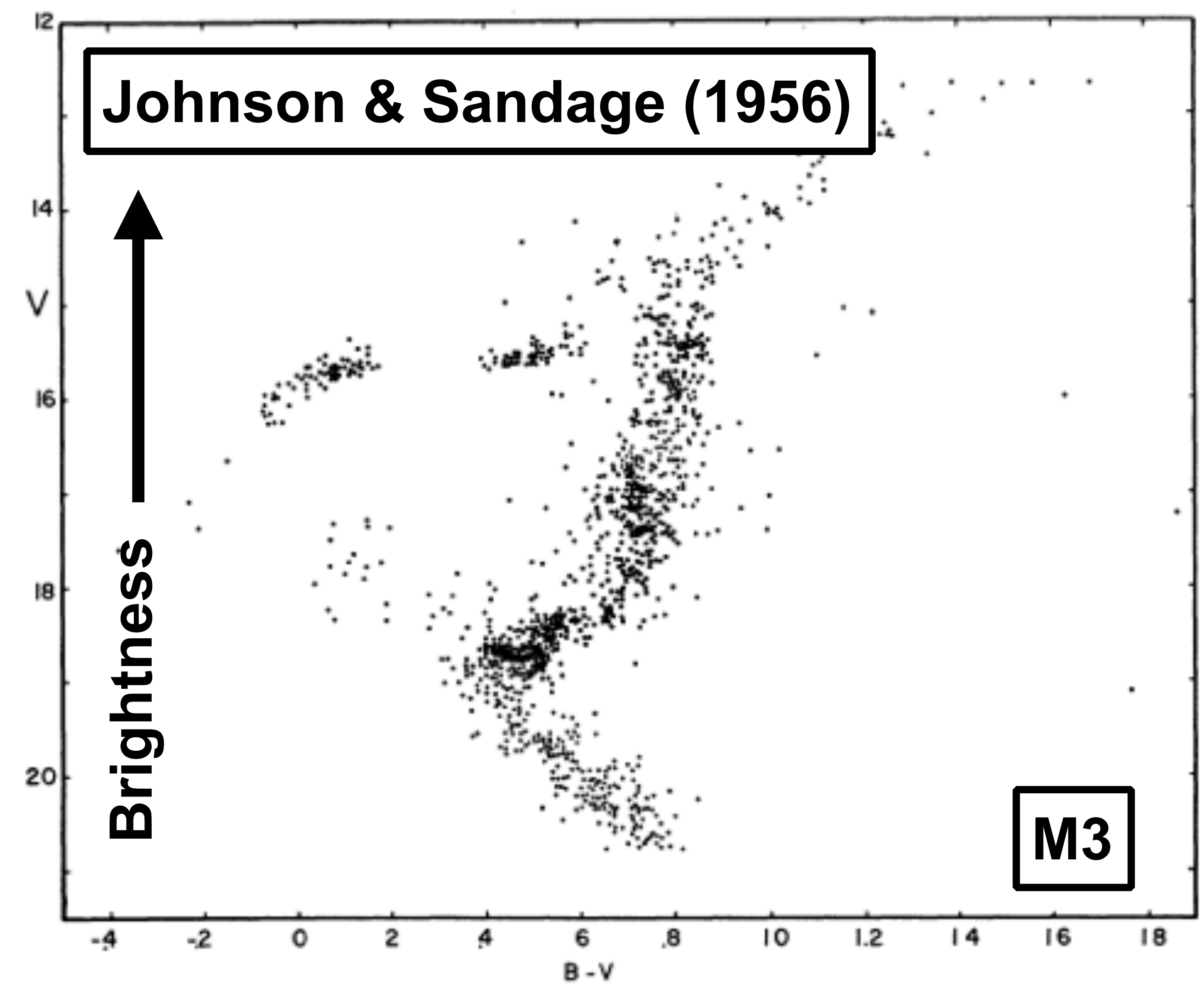
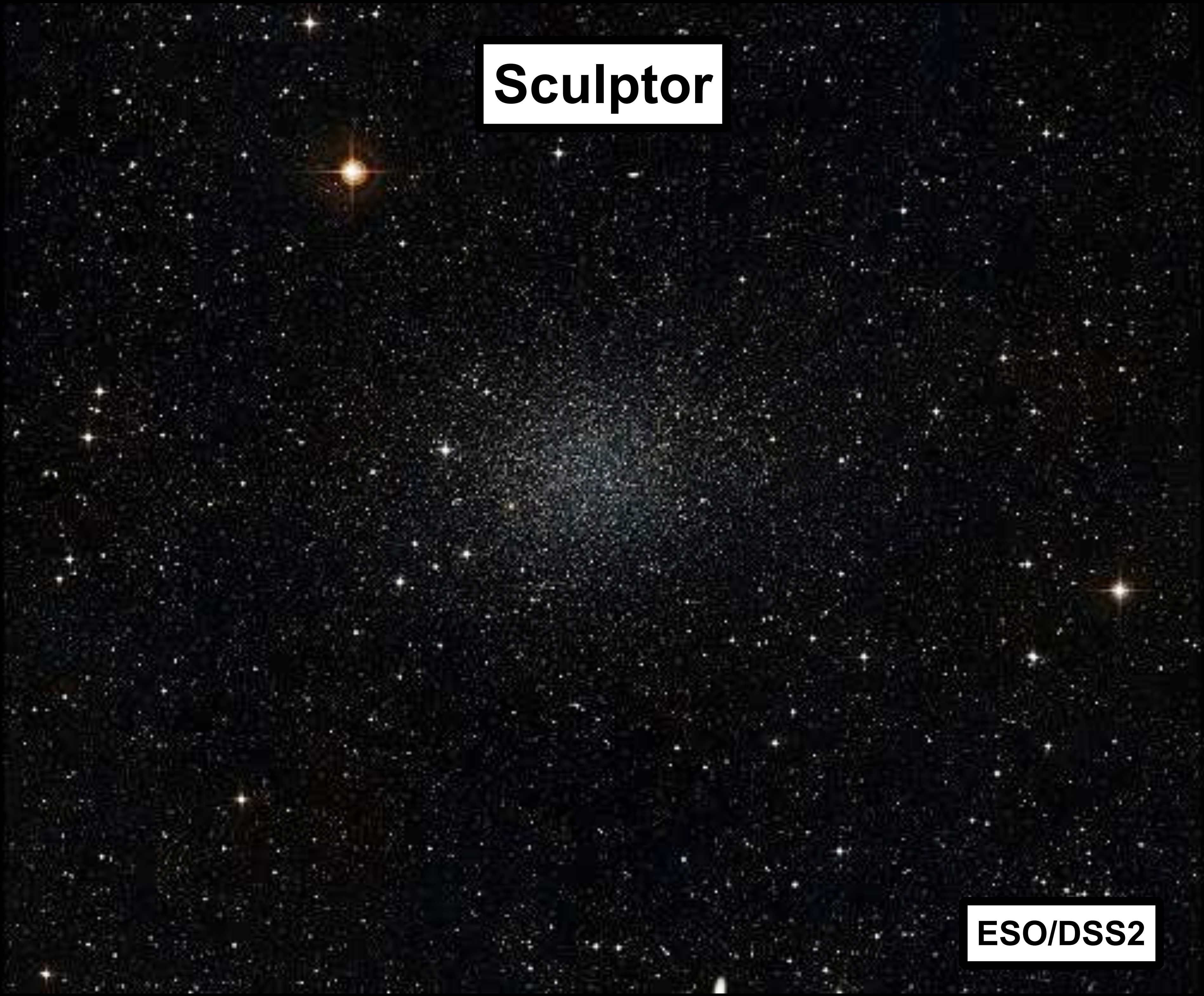
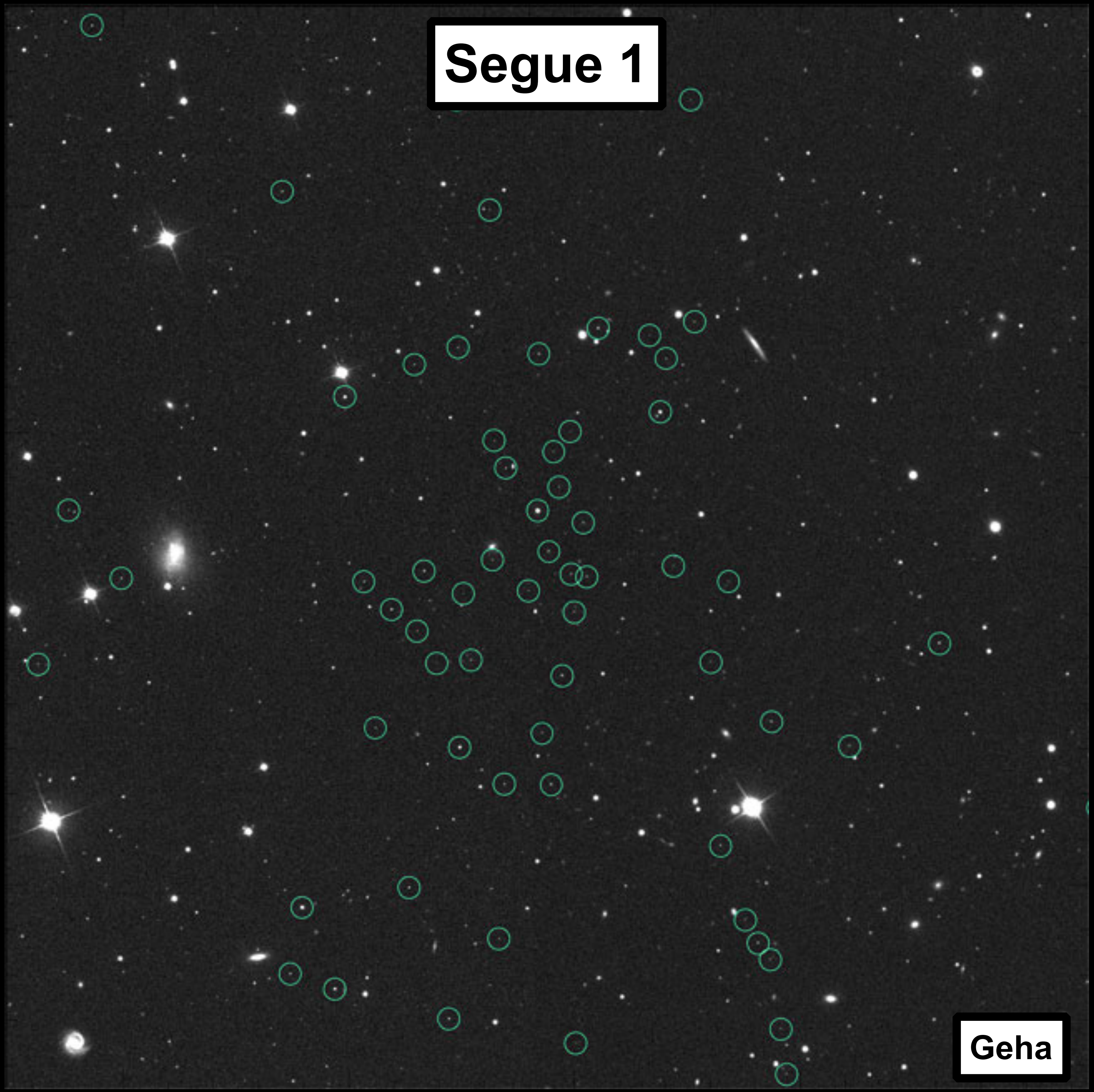


FIG. 5.—Color-magnitude diagram for M3 stars in the arguments V and $B - V$

“Redness”


Sculptor
ESO/DSS2

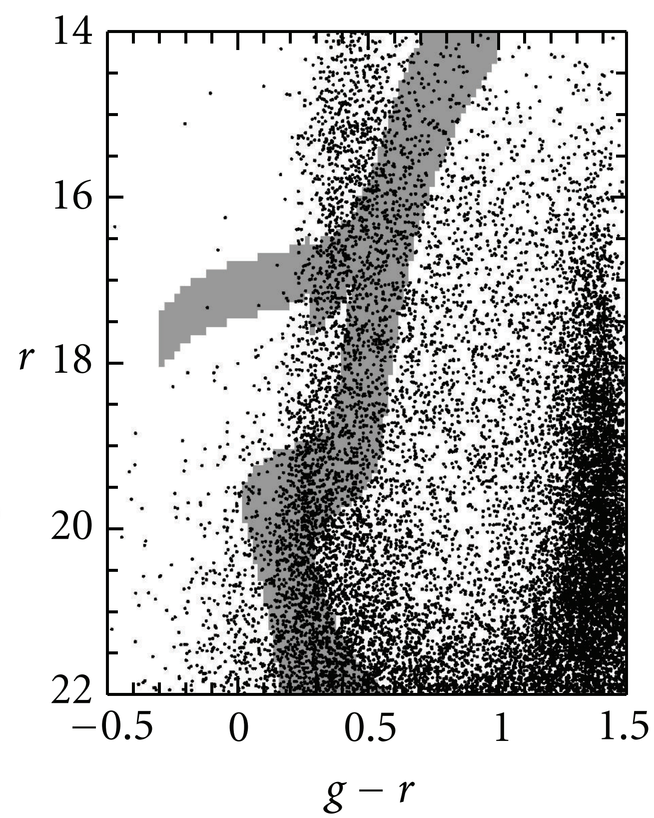

Segue 1
Geha


Segue 1
Geha

Finding Milky Way Satellite Galaxies

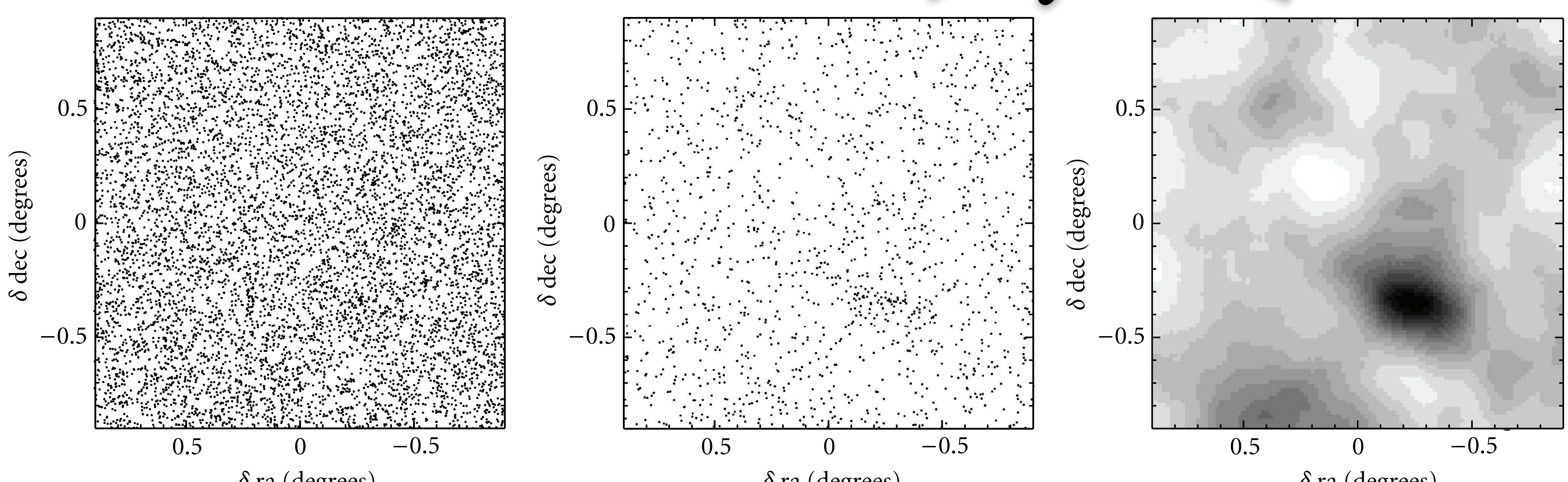
Koposov et al. (2008)
Walsh et al. (2009)
Willman et al. (2010)

Select Stars with a Characteristic Age and Metallicity

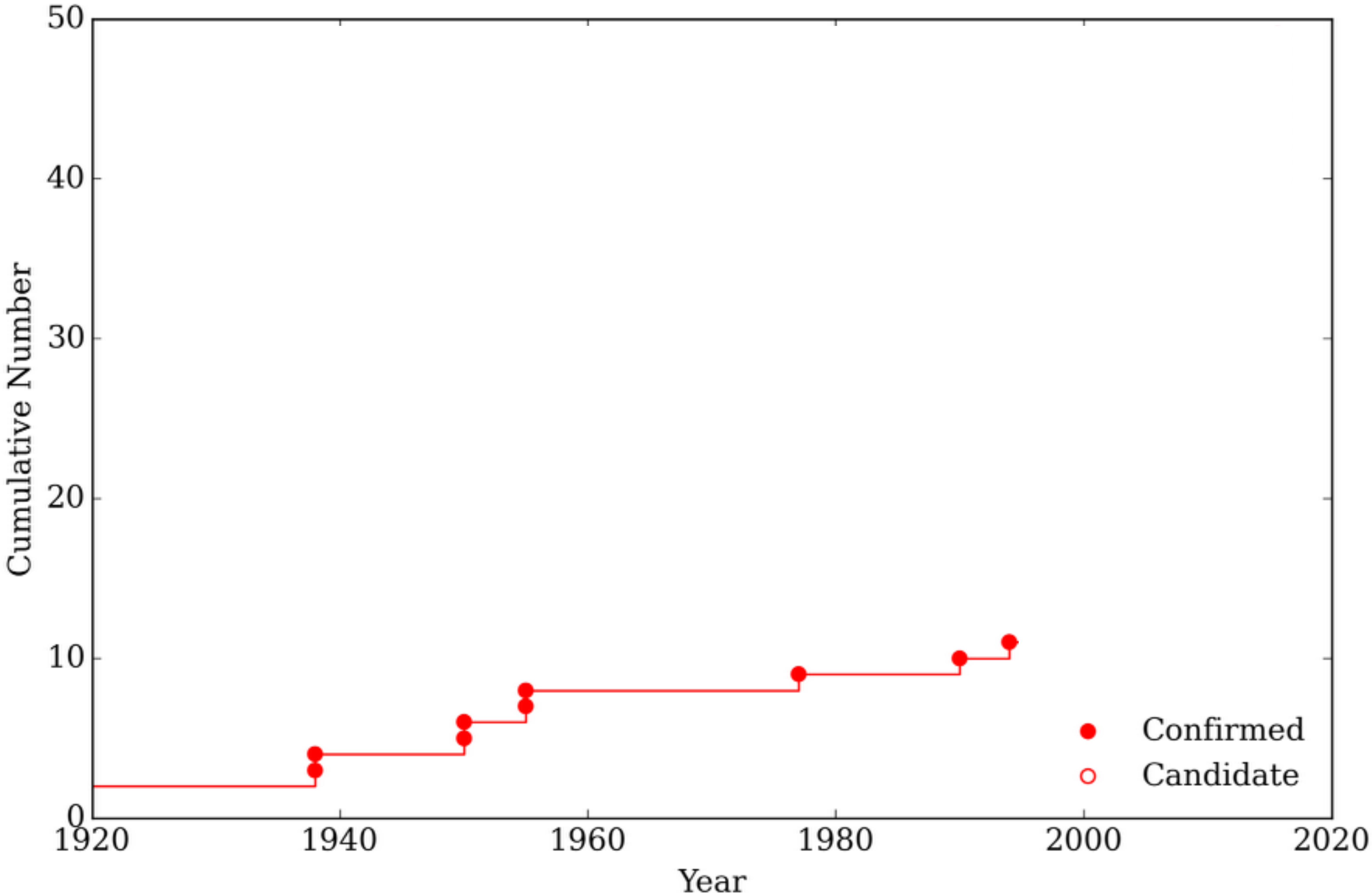


Convolve with Spatial Kernel

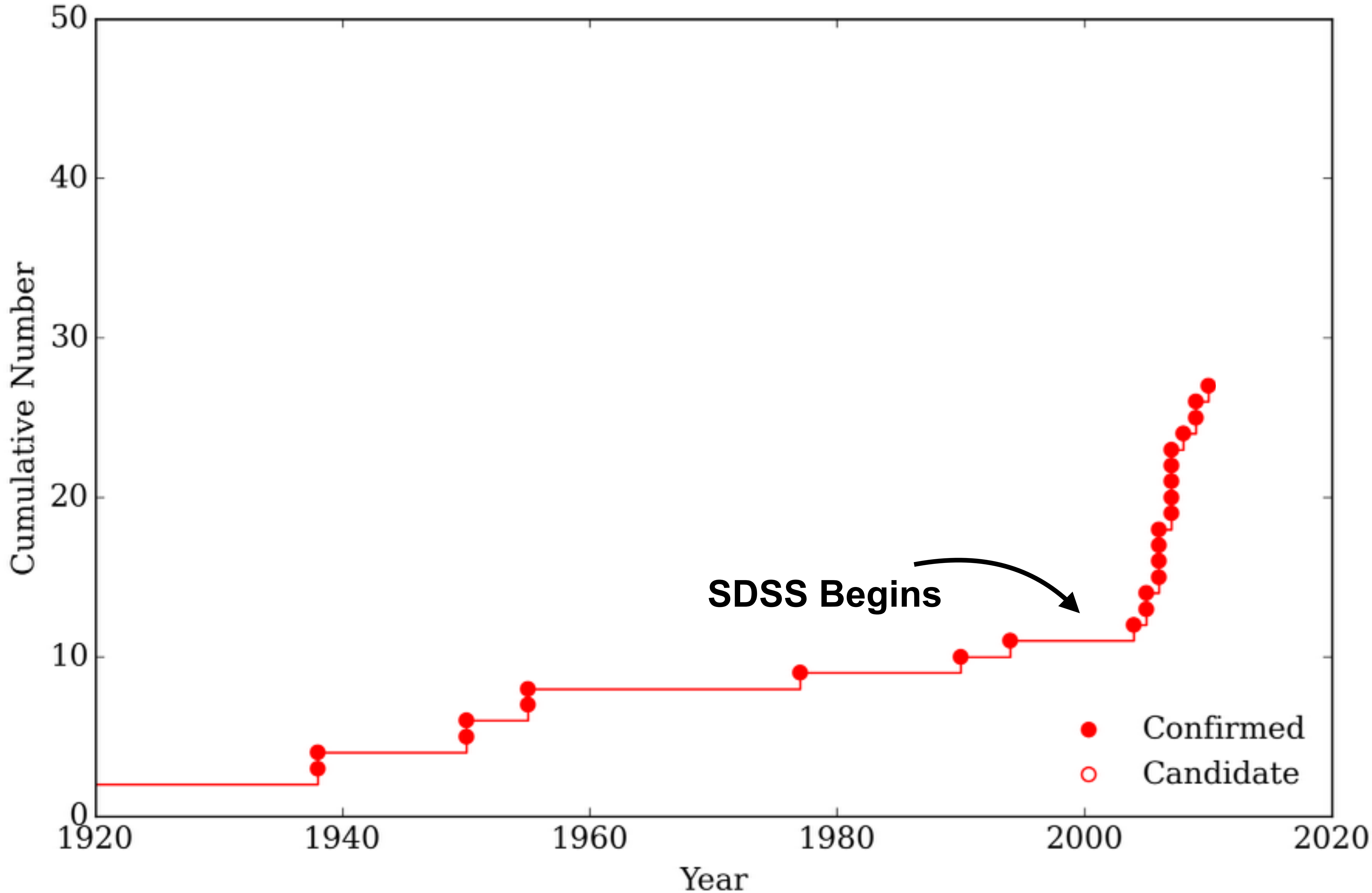
Stellar Field



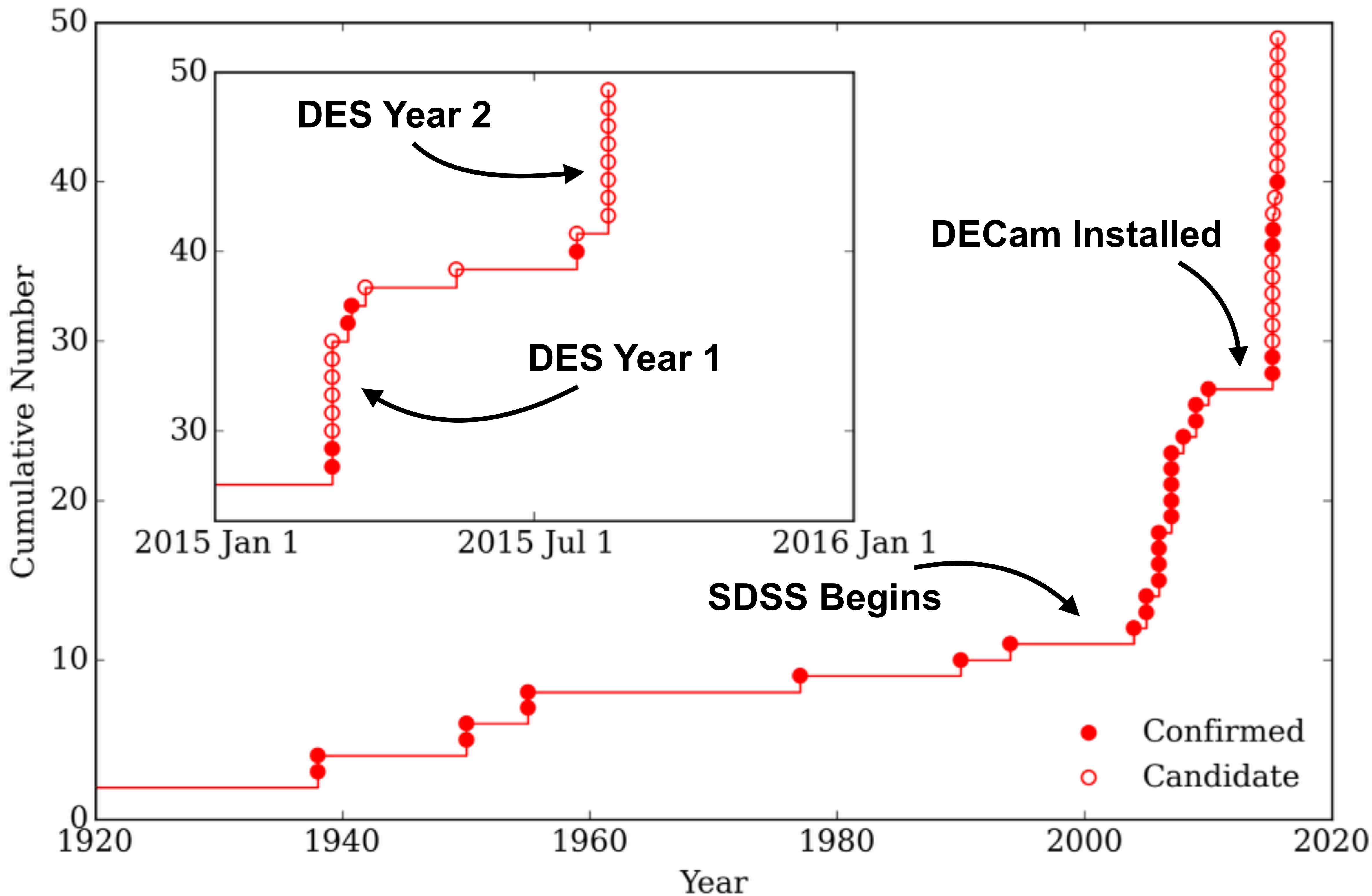
Discovery Timeline



Discovery Timeline



Discovery Timeline



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SDSS DR10 + DES Y2

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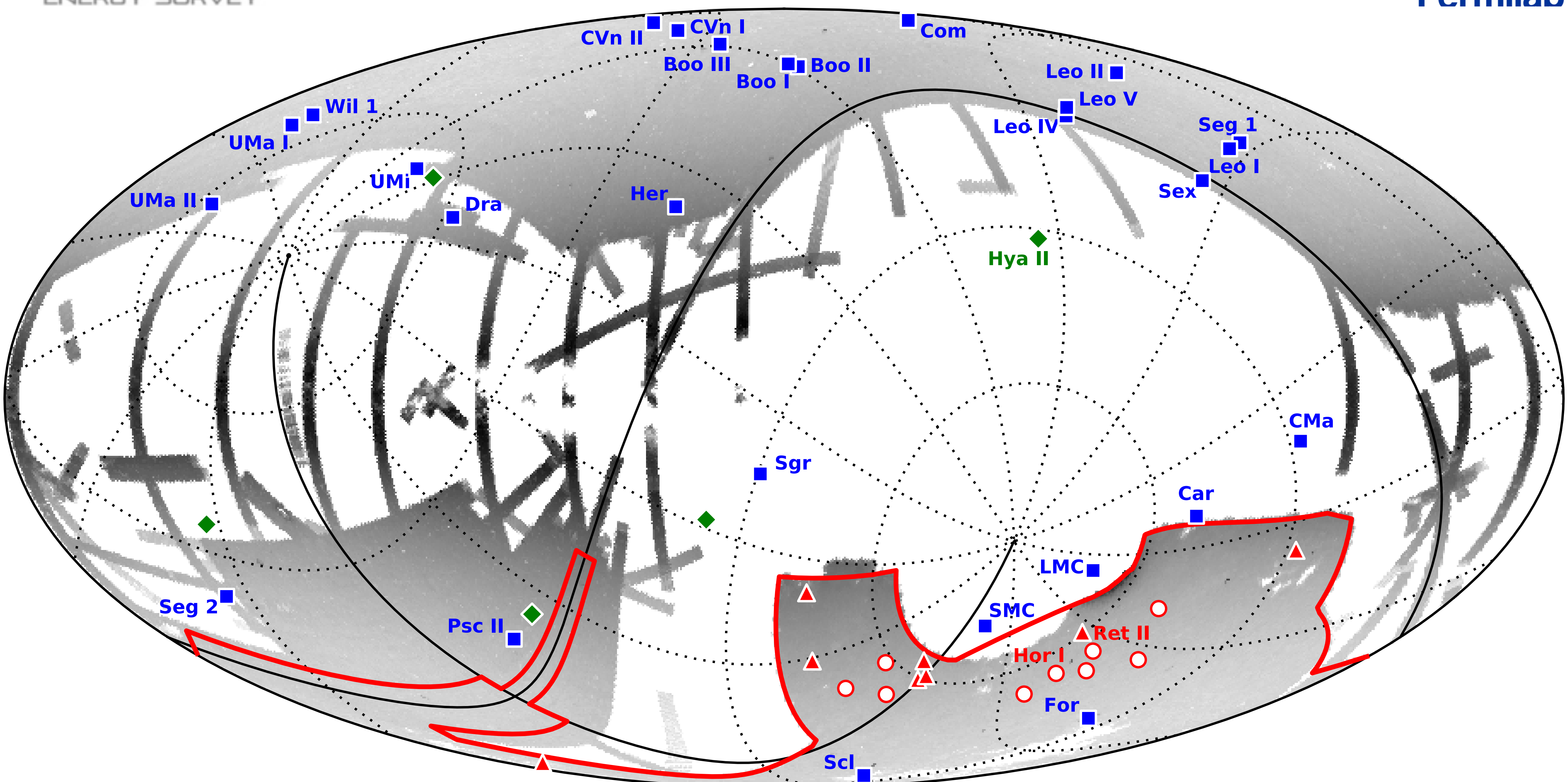


Blue - Previously discovered satellites

Green - Discovered in 2015 with PanSTARRS/SDSS

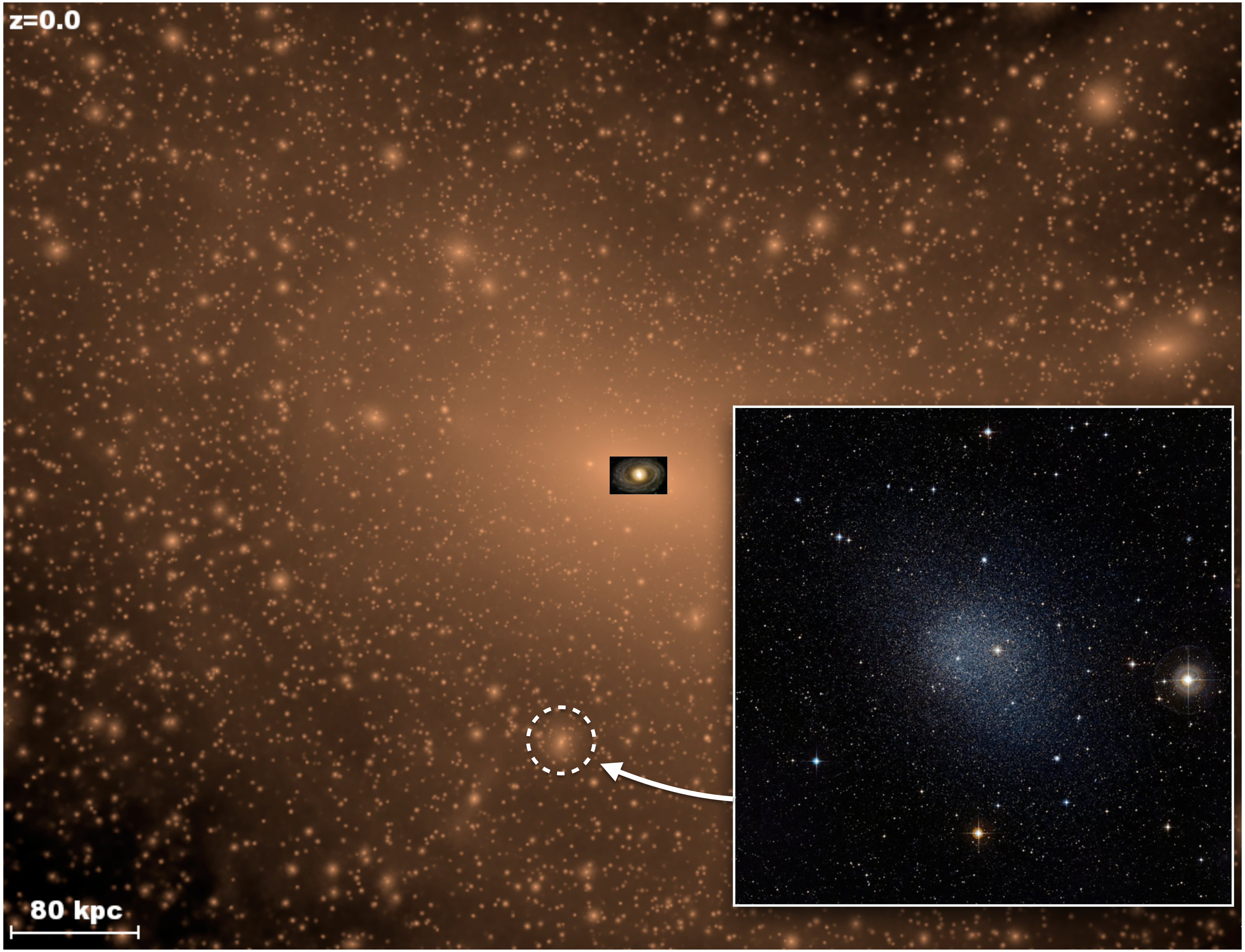
Red outline - DES footprint

Red circles - DES Y1 satellites

Red triangles - DES Y2 satellites

Open Questions

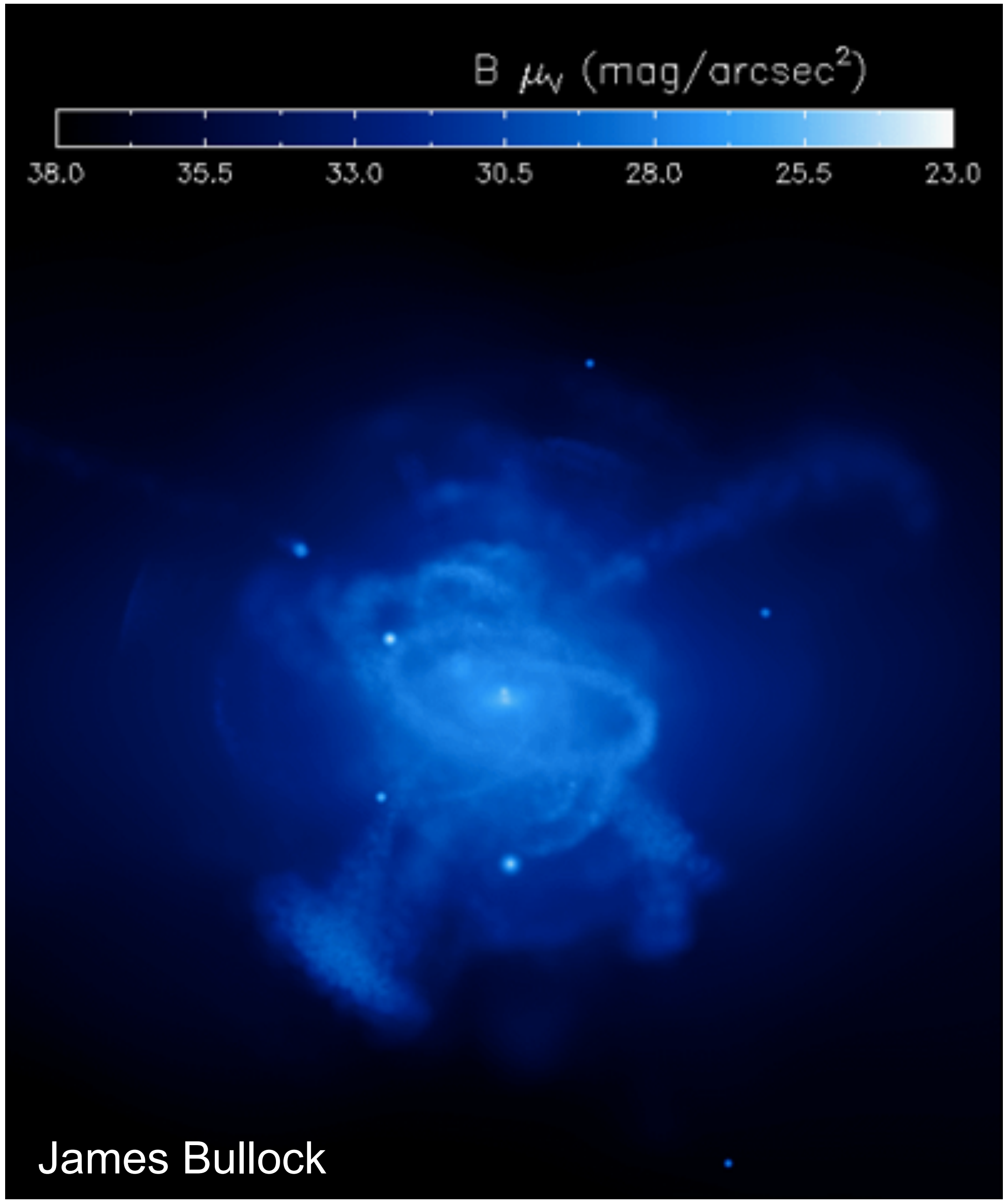
Missing Satellites



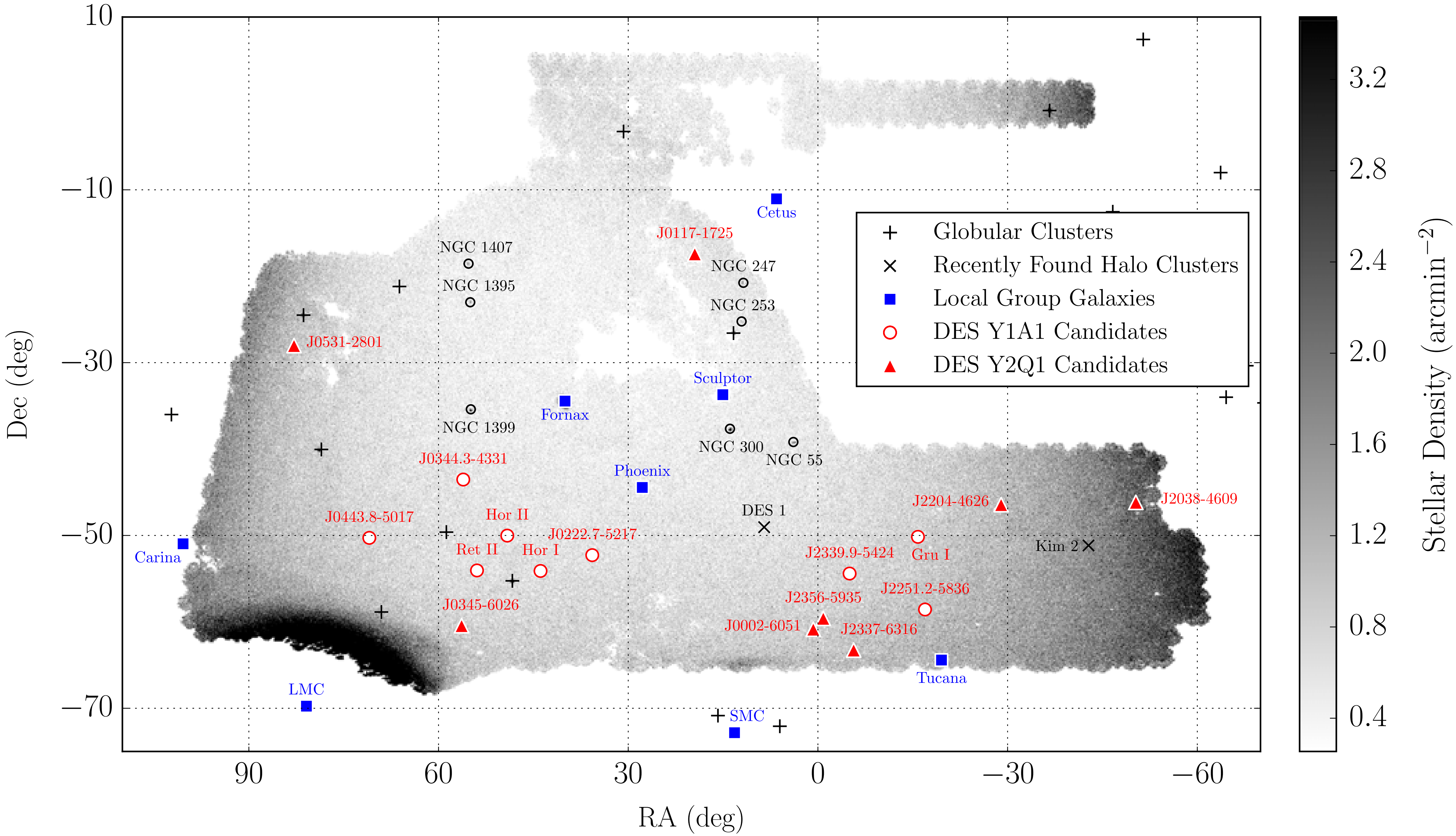
Missing Satellites

- Galaxies inhabit dark matter halos
- Simulations predict that the Milky Way halo should contain thousands of dark matter subhalos
- We only "see" dark matter halo that are traced by baryons, and we only know of several dozen dwarf galaxies.
- Where are the missing satellites?
- What can we learn about galaxy formation and the nature of dark matter?

- Combine large photometric surveys (DES, SDSS, Pan-STARRs, etc.)
- Opportunities to work with Big Data, data mining, and statistics!
- Understand the galaxies that we *don't see*.

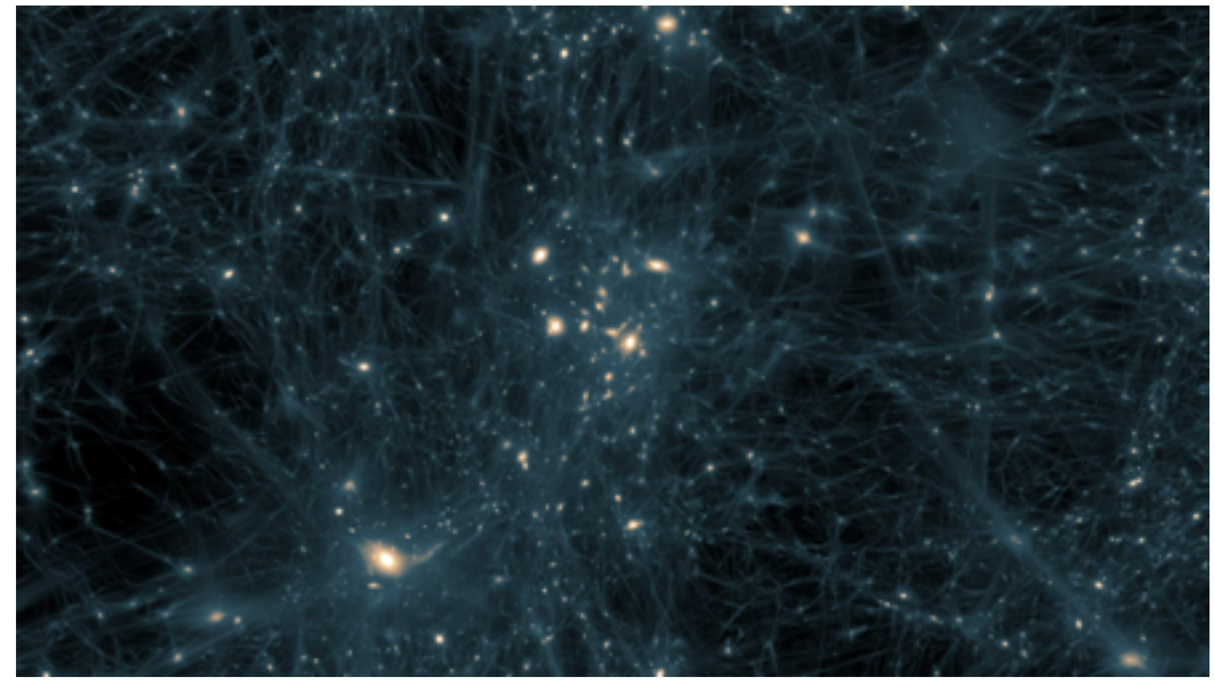


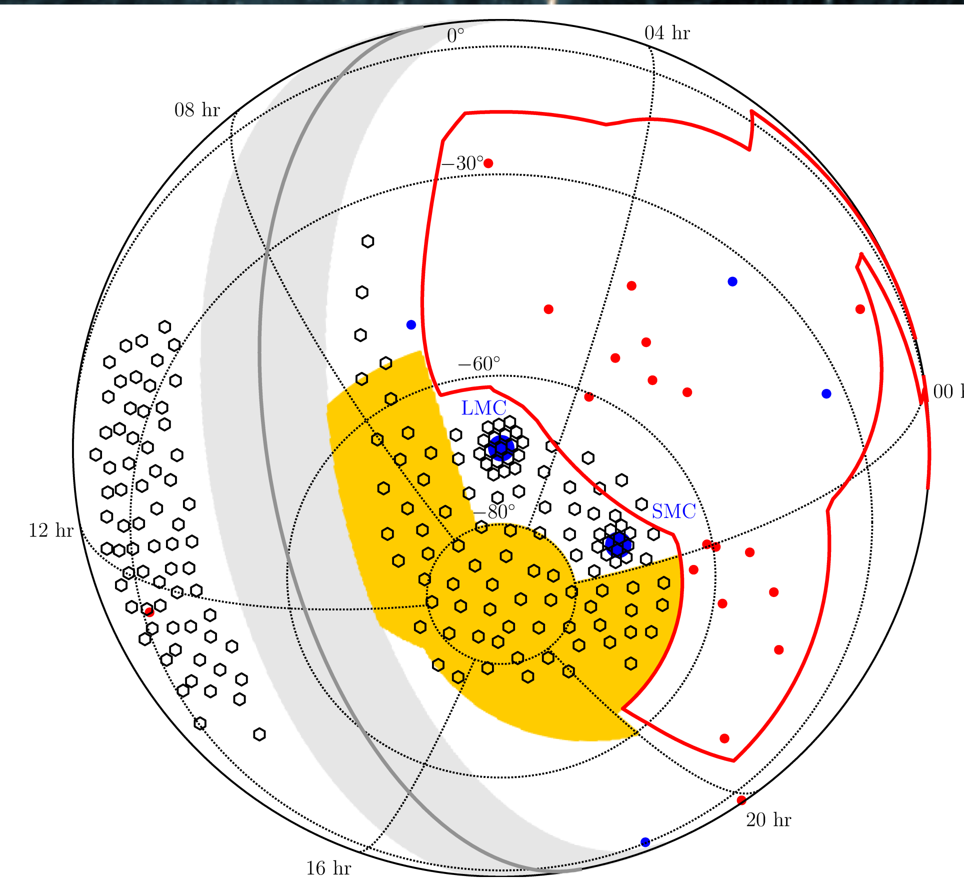
Galaxy Formation



Galaxy Formation

- The Milky Way satellites found in DES are not distributed uniformly
- Is the observed distribution of satellites consistent with LCDM?
  - Biases from the Solar position?
  - Accretion as satellites of the Magellanic Clouds?
  - Accretion along the same filament as the Magellanic Clouds?
  - A plane of satellites?
- Need larger photometric coverage to test these various hypotheses (new Magellanic Satellites Survey)
- Need spectroscopy and proper motions to determine the dynamics of satellite systems.
- Lots of opportunities to do photometry and spectroscopy!





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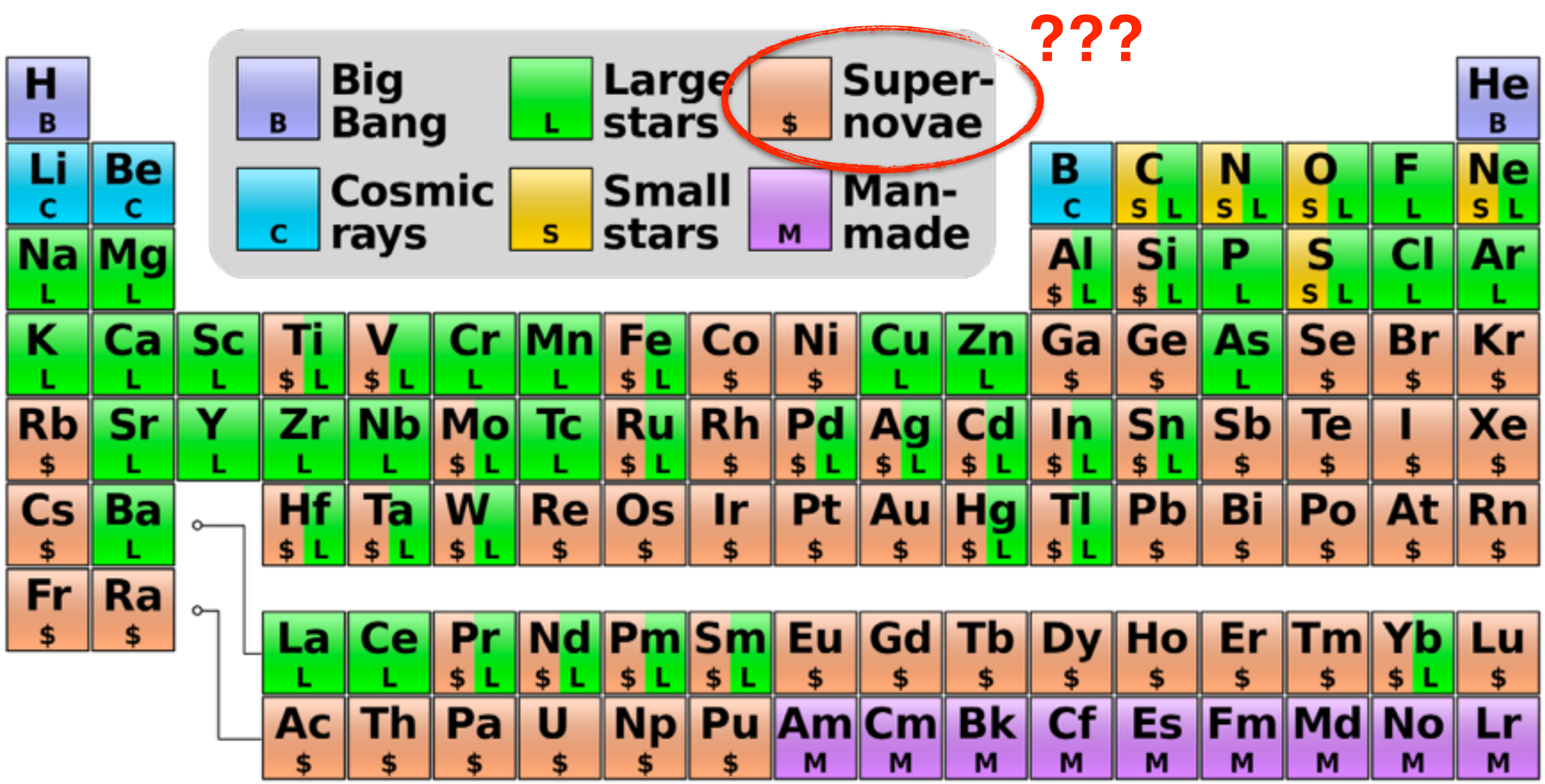
Origin of Heavy Elements

Rapid absorption of free neutrons during explosive event

Possible sites: core-collapse SNe, neutron star mergers

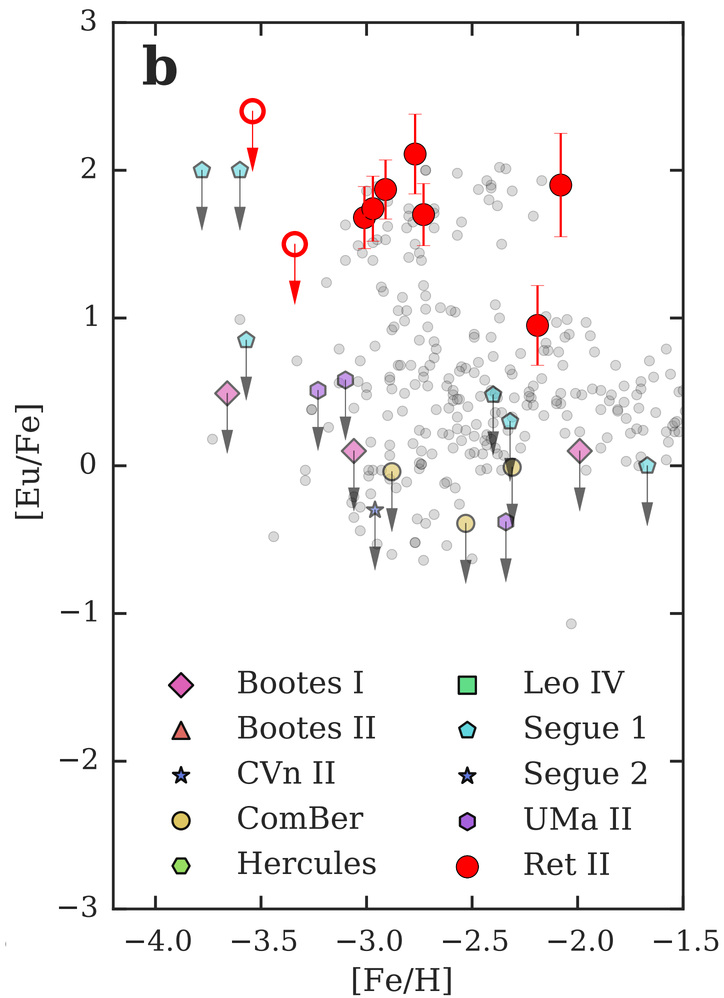
Observed excess of r-process elements in Ret II relative to other ultra-faint dwarfs (by factor >100) suggests enrichment by a single (rare) event

→ Consistent with neutron star merger hypothesis

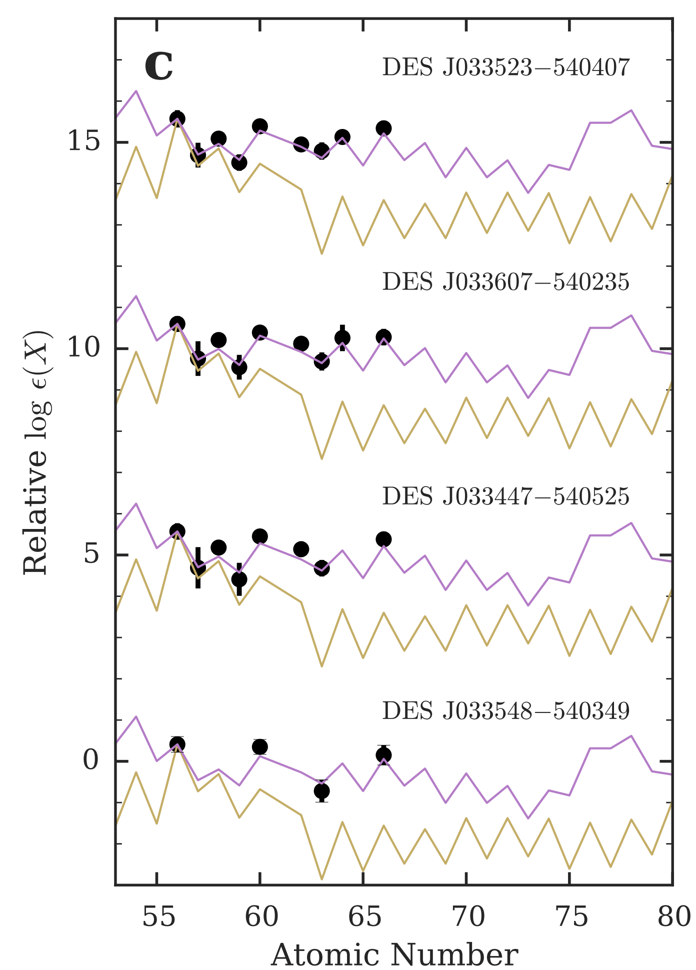


Origin of Heavy Elements

- Heavy elements are formed in extreme conditions through (r)apid and (s)low neutron capture processes
- Satellite galaxies are nearby relics of the early universe
- Are r-process elements created continuously by core-collapse supernova or in rare events like neutron star mergers?



Ret II Stars enriched in Eu

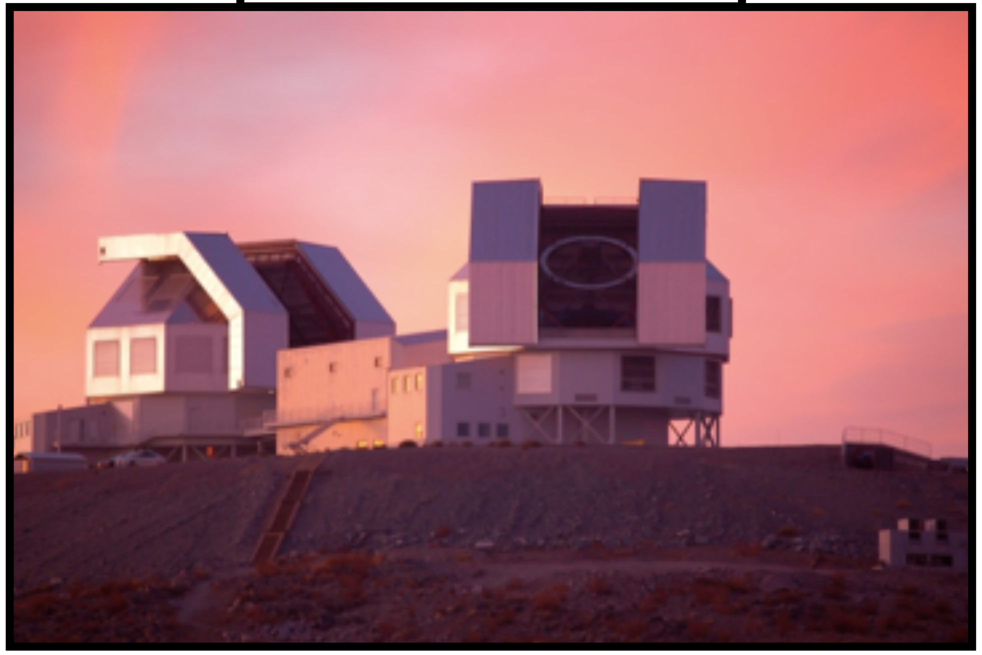


r-process
s-process

Ji et al. 2015 (1512.01558)

Origin of Heavy Elements

Magellan/M2FS



Gemini/GMOS

VLT/GIRAFFE

AAT/AAOmega

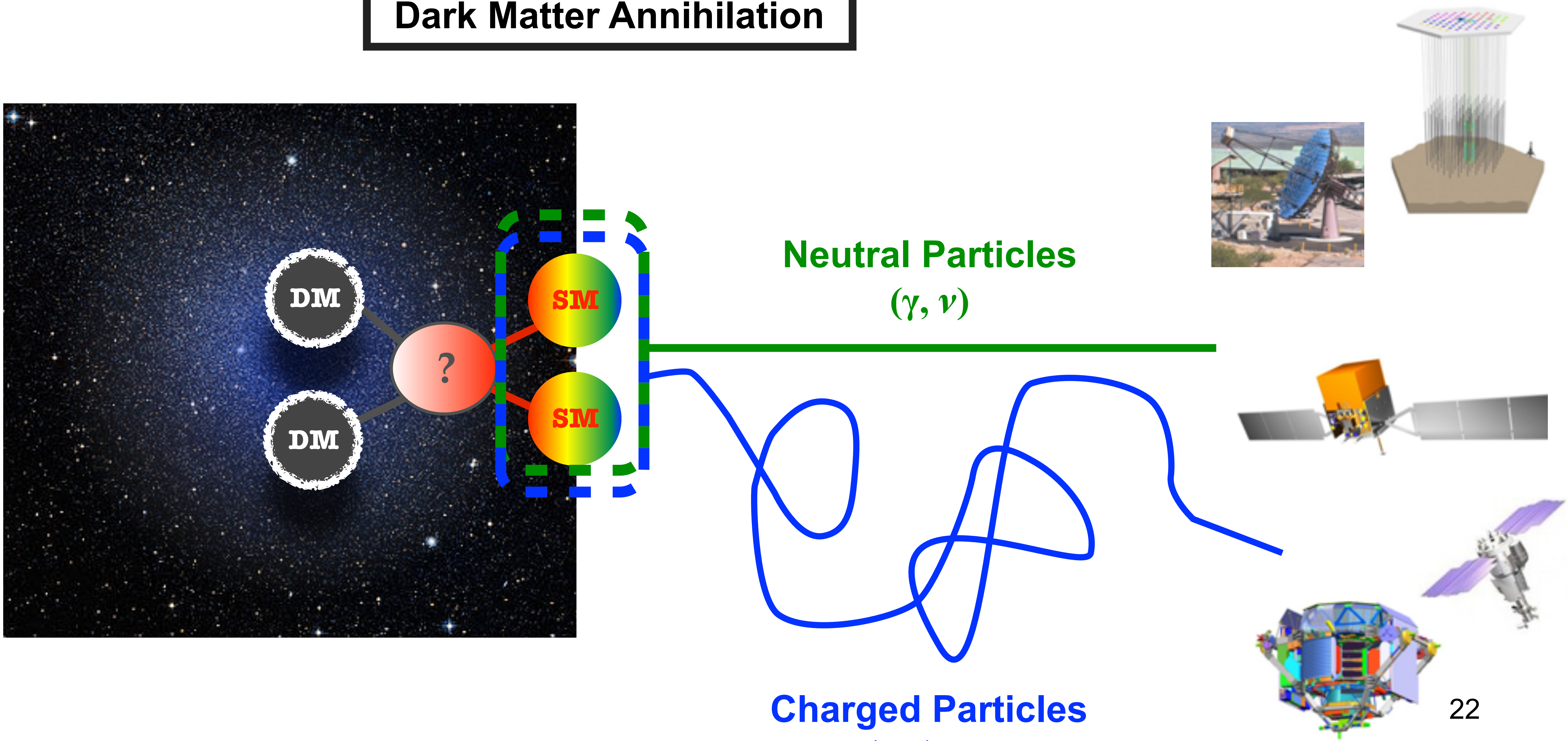
Nature of Dark Matter

Dark Matter Distribution

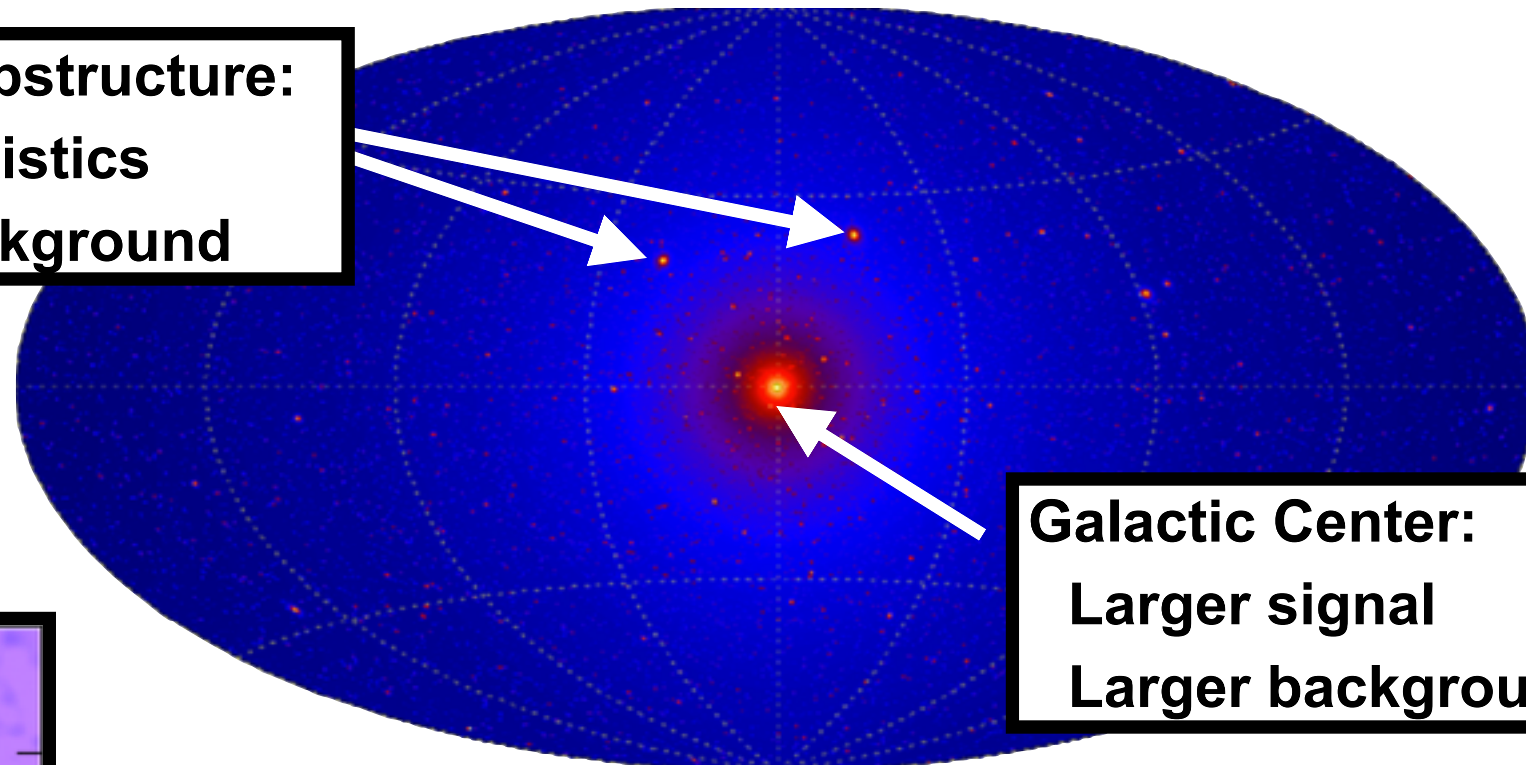
Particle Propagation

Particle Detection

Dark Matter Annihilation

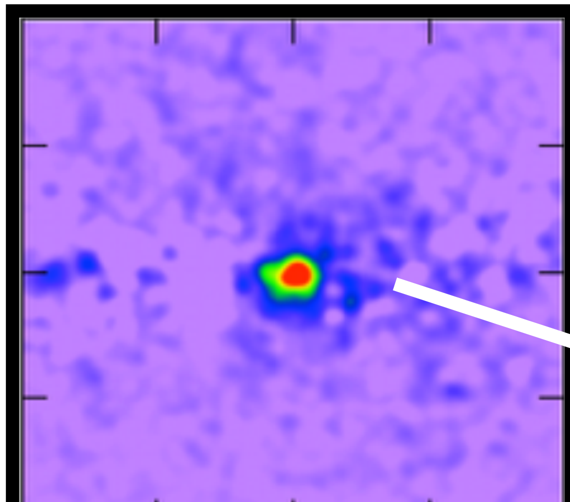


Nature of Dark Matter

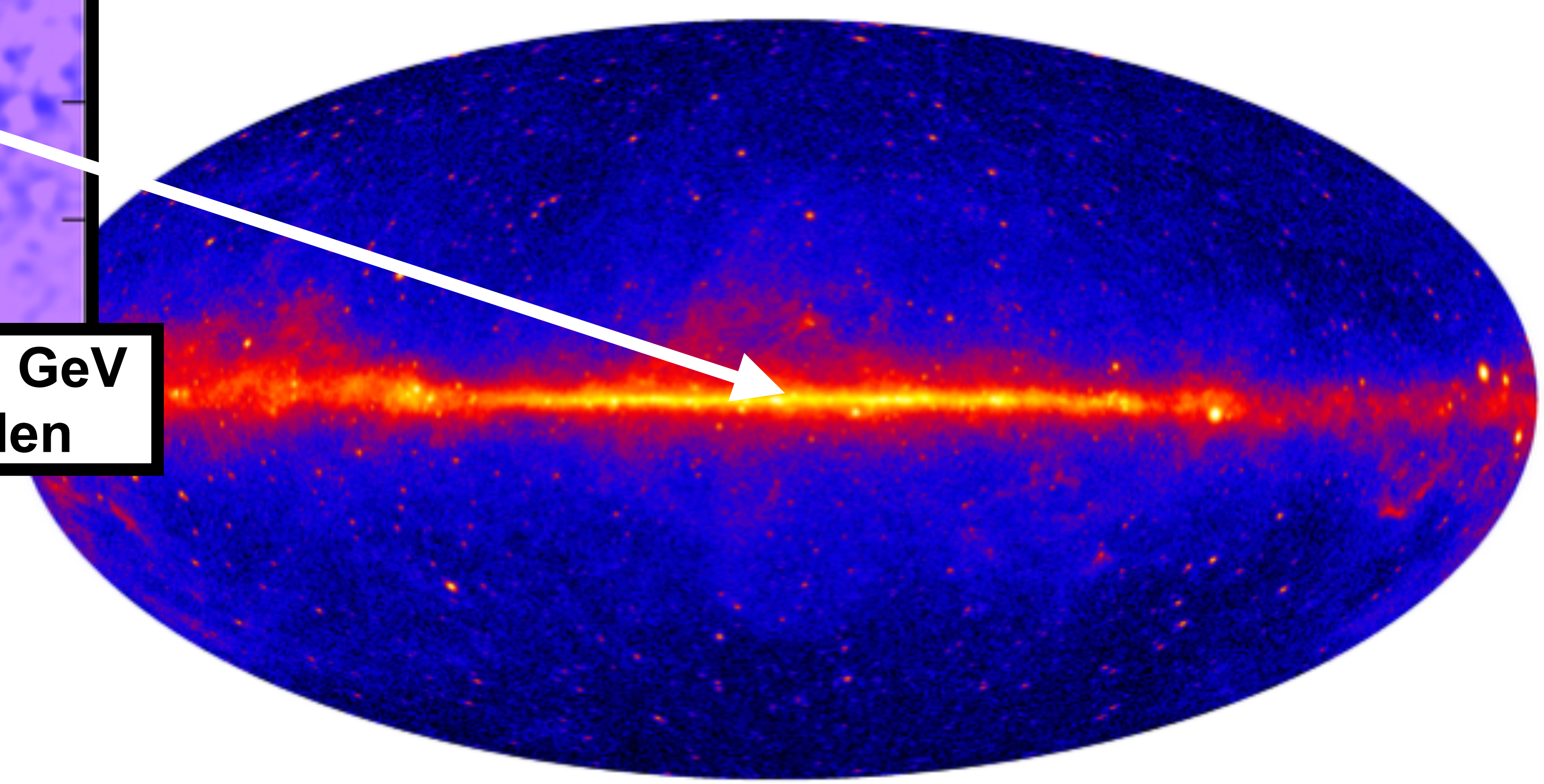


Galactic Substructure:
- Lower statistics
- Lower background

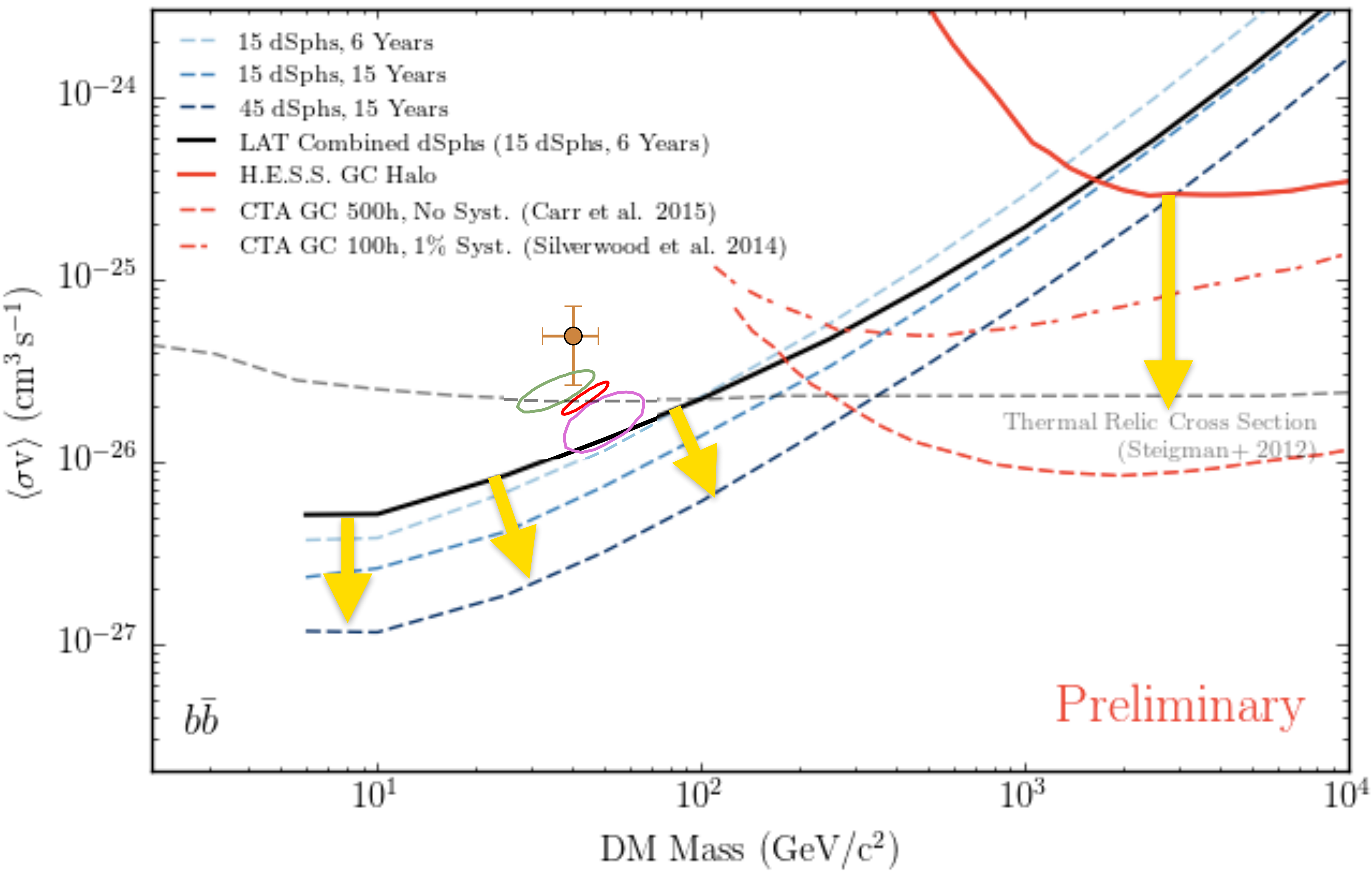
Galactic Center:
- Larger signal
- Larger background



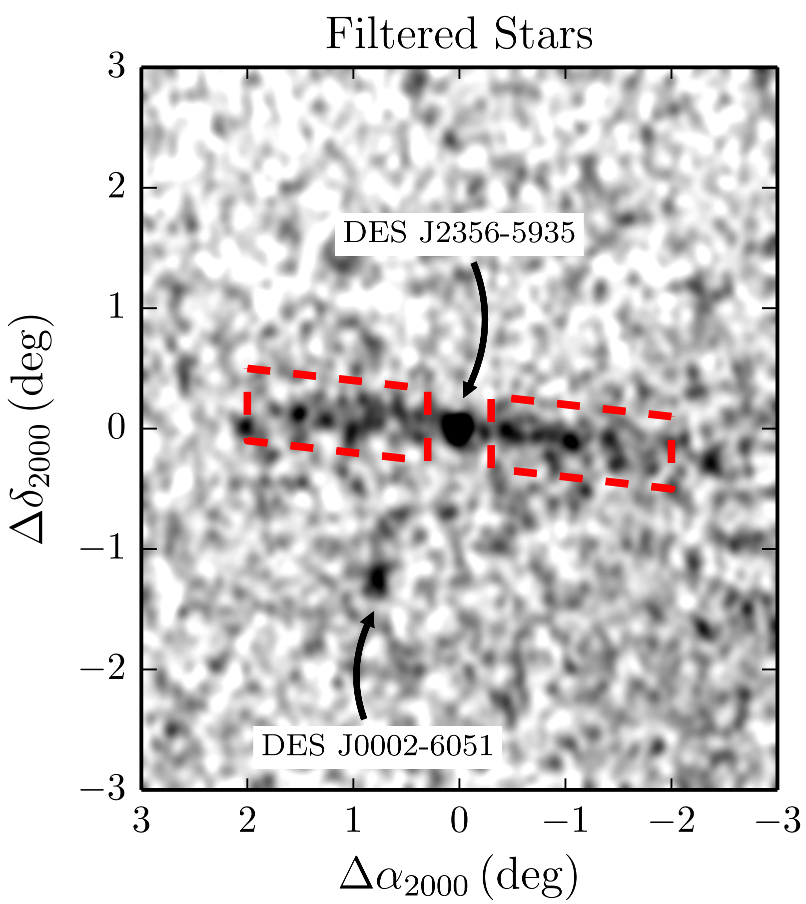
Residual Map: 1-3 GeV
Credit: Tim Linden



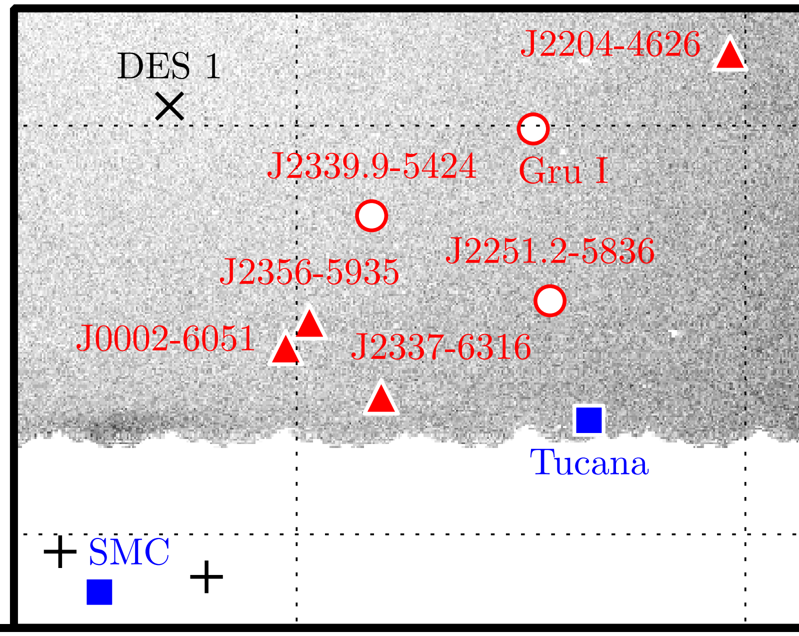
Nature of Dark Matter



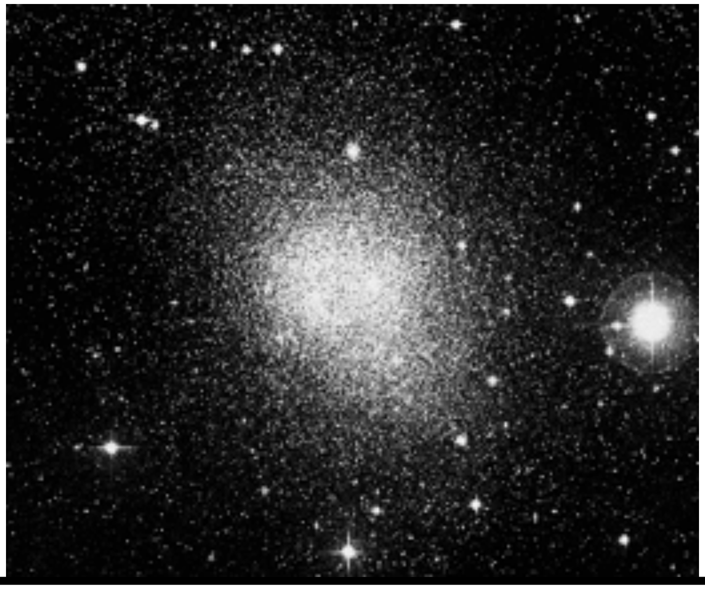
Shorter Term Projects



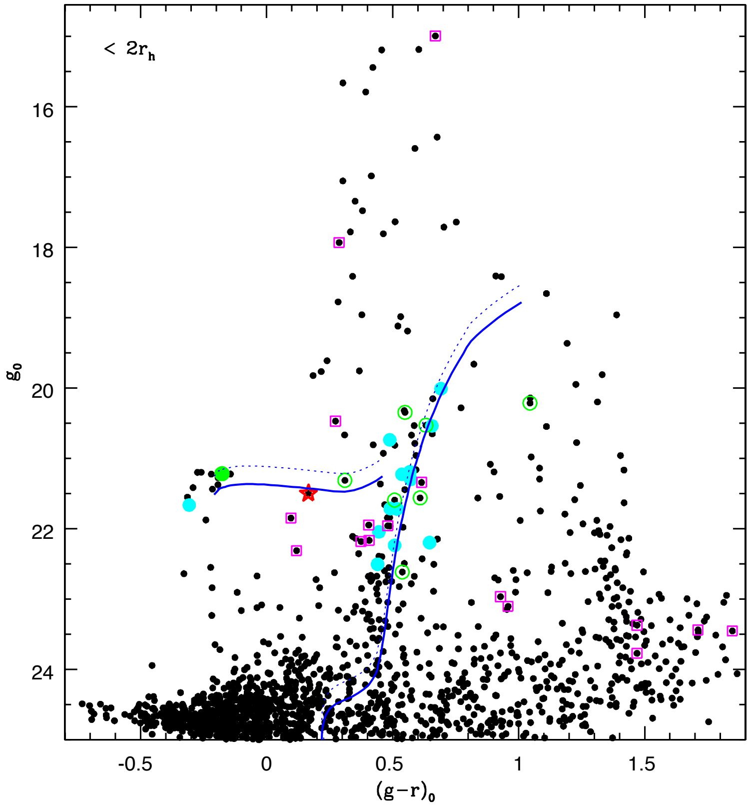
Tidal tails around Tucana III (deeper photometry)



Tucana group of satellites (Magellan observing this semester)



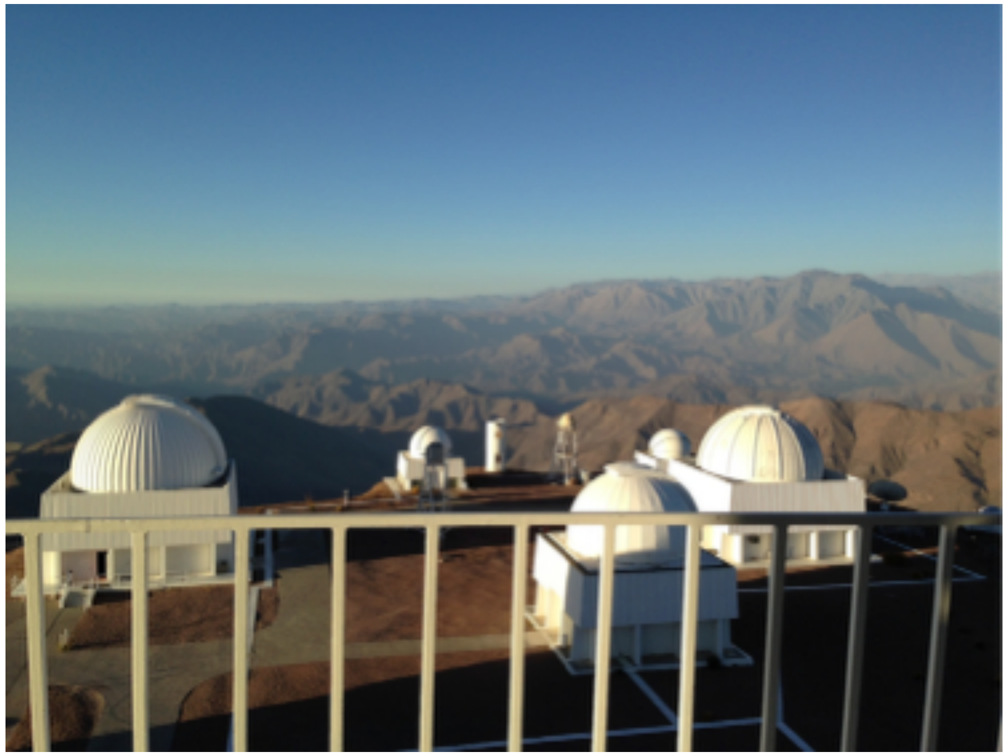
Satellites and stream around Fornax & Sculptor (Y3 DES data)



RR Lyrae stars in DES Y2 dwarfs (SOAR observing this semester)

Scientific Skills

- These projects will develop a wide range of skills.
- Observing Experience
  - Photometry: DECam, SOAR, Gemini
  - Spectroscopy: Magellan, VLT, AAT
- Astronomical Tools
  - Photometry of large survey data sets (DES, SDSS, DECaLs, Pan-STARRs,…)
  - Medium resolution spectroscopy for velocity determination
  - High resolution spectroscopy and spectral synthesis for elemental abundances
- Computational Tools
  - Parallelized processing of big data
  - Machine learning and data mining
  - Statistical modeling with frequentist and bayesian techniques



Working in DES

- The DES Collaboration provides an extensive support structure.
- Opportunities to meet and interact with scientists around the world.
- Opportunities in other science areas, public outreach, etc.
- Milky Way science is undersubscribed in DES — DES provides a large audience, a lot of support, and little competition.

- Chicago is at the heart of DES
  - Josh Frieman (FNAL/UChicago)
  - Rich Kron (UChicago)
  - Brian Yanny (FNAL)
  - Scott Dodelson (FNAL/UChicago)
  - … and many other faculty, staff, post-docs and students!

Even More Questions

- Optimized searches for low-luminosity dwarf galaxies beyond the MW virial radius.
- Satellite systems of nearby galaxies
- Understanding the structure of the Milky Way halo using various stellar tracers (i.e., MSTO stars, HB stars, etc.)
- High resolution spectroscopy of Carbon-enhanced metal poor (CEMP) stars.
- Identifying high proper motion stars in DES (white dwarfs?)
- Using internal proper motions to understand the dark matter distribution of Milky Way satellite galaxies.
- many, many more…