Fundamental Physics with the Smallest Galaxies

Alex Drlica-Wagner

LIneA Webinar
August 18, 2016

THE DARK ENERGY SURVEY

Fermi Gamma-Ray Space Telescope

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DES-Brazil
Dark Energy Survey
LIneA

Also see Keith Bechtol talk at AAS
(several slides borrowed)

THE DARK ENERGY SURVEY

Fermi Gamma-Ray Space Telescope

- Introduction to Dwarf Galaxies
- Finding New Dwarf Galaxies
- Our Newest Neighbors
- Dwarf Galaxies and Dark Matter
- Future Prospects

- **Introduction to Dwarf Galaxies**
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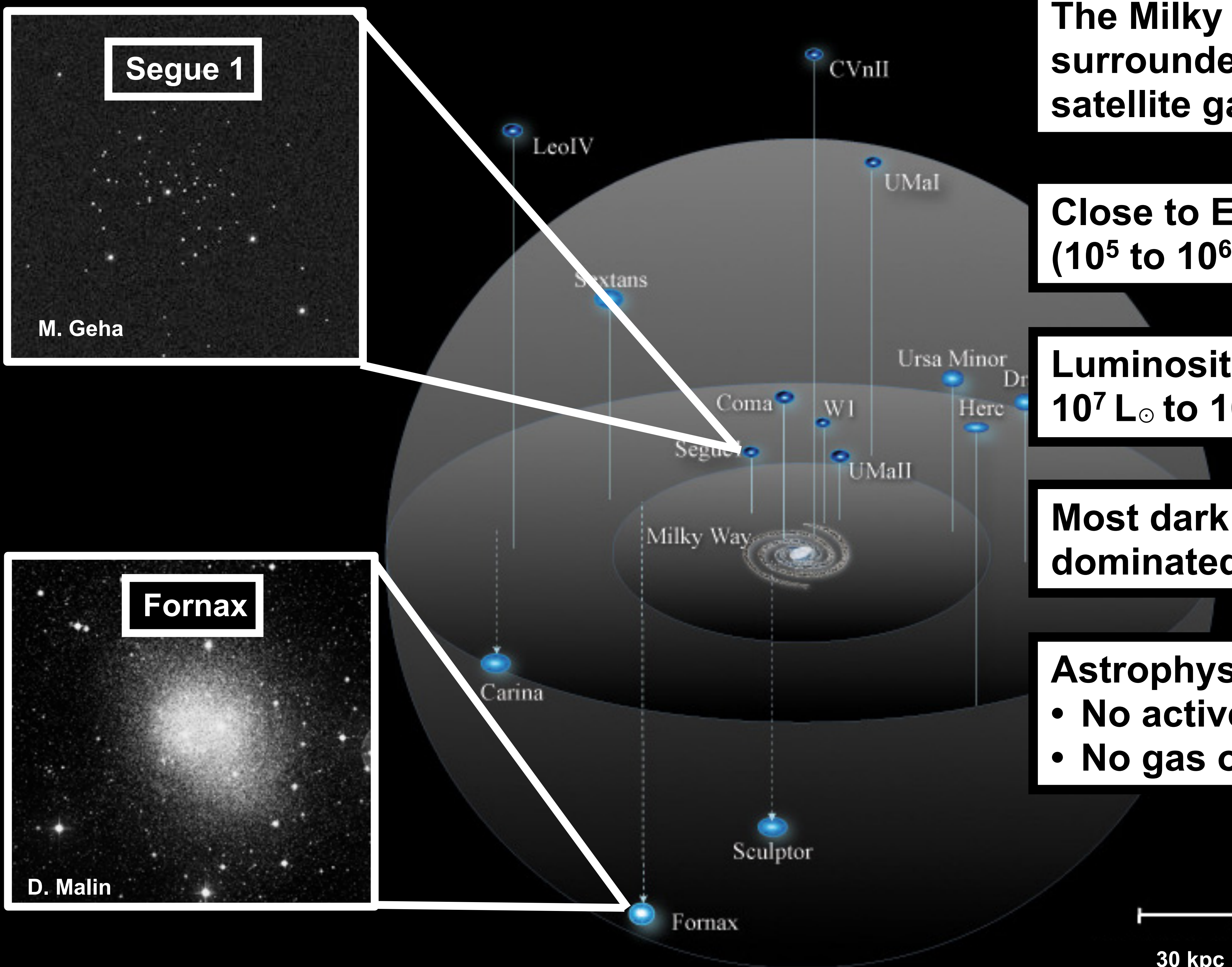
Milky Way Satellite Galaxies



The Milky Way is surrounded by small satellite galaxies

Close to Earth (10^5 to 10^6 ly)

Luminosities range from $10^7 L_{\odot}$ to $10^3 L_{\odot}$

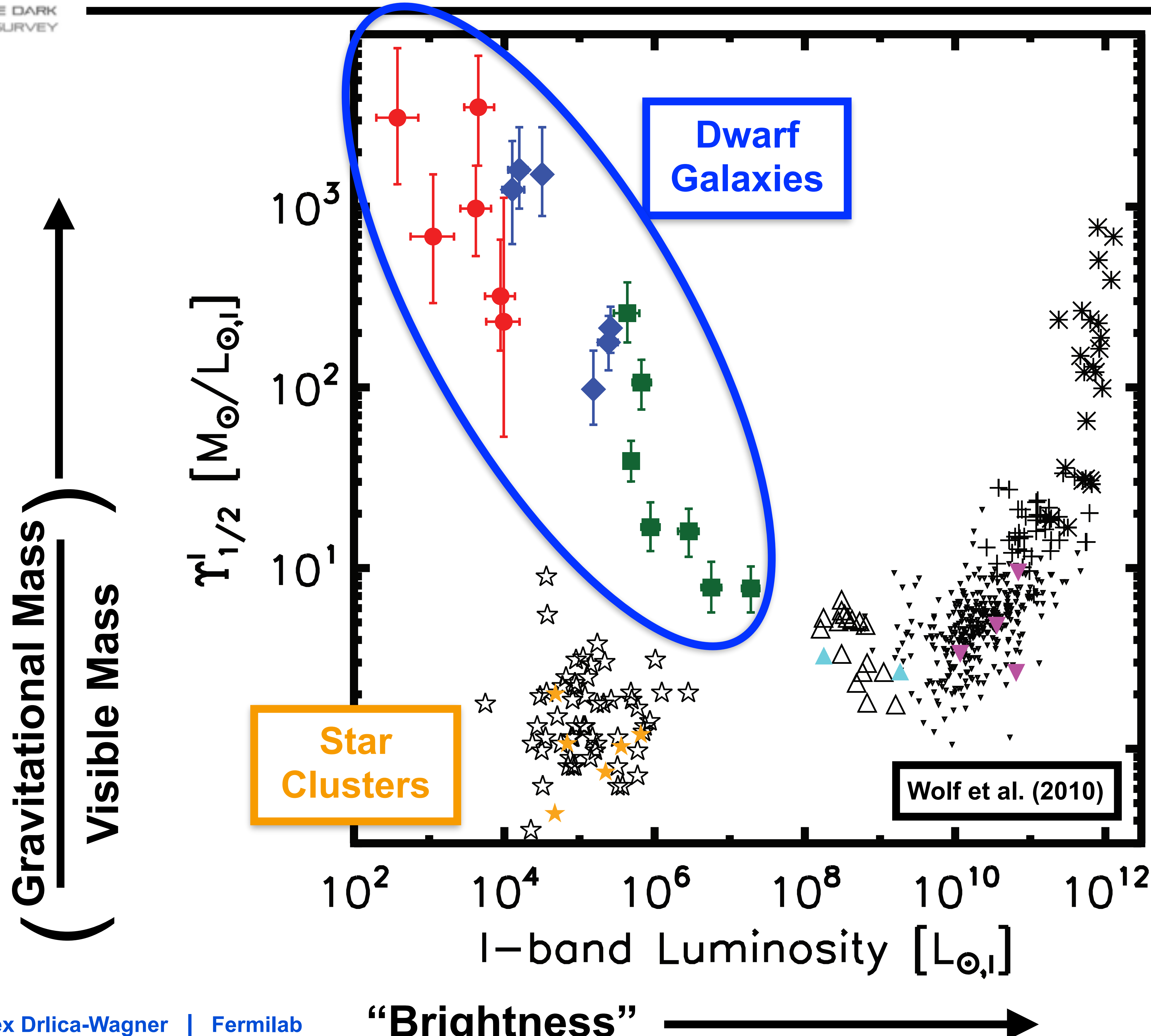
Most dark matter dominated objects known

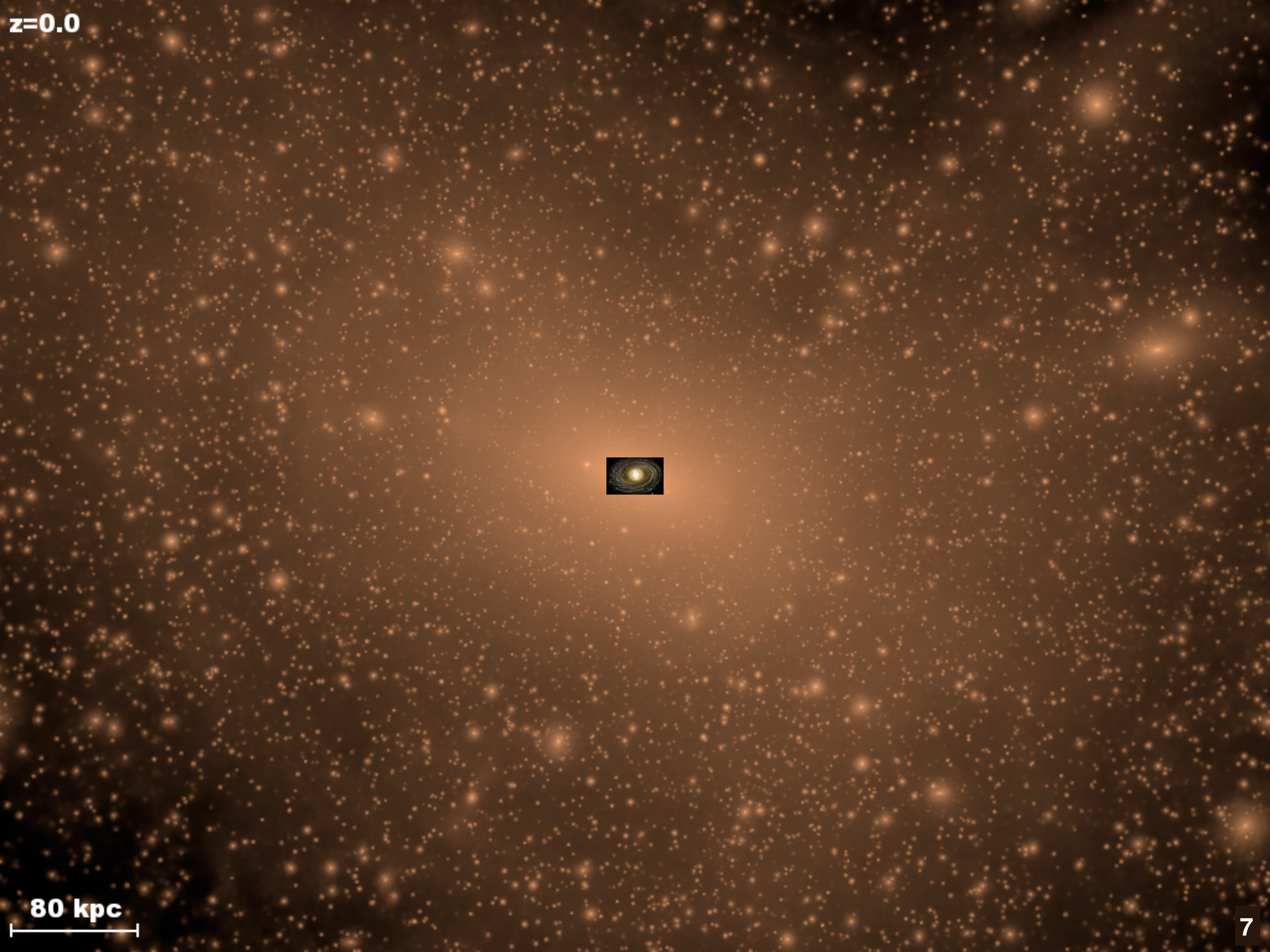
Astrophysically simple
- **No active star formation**
- **No gas or dust**

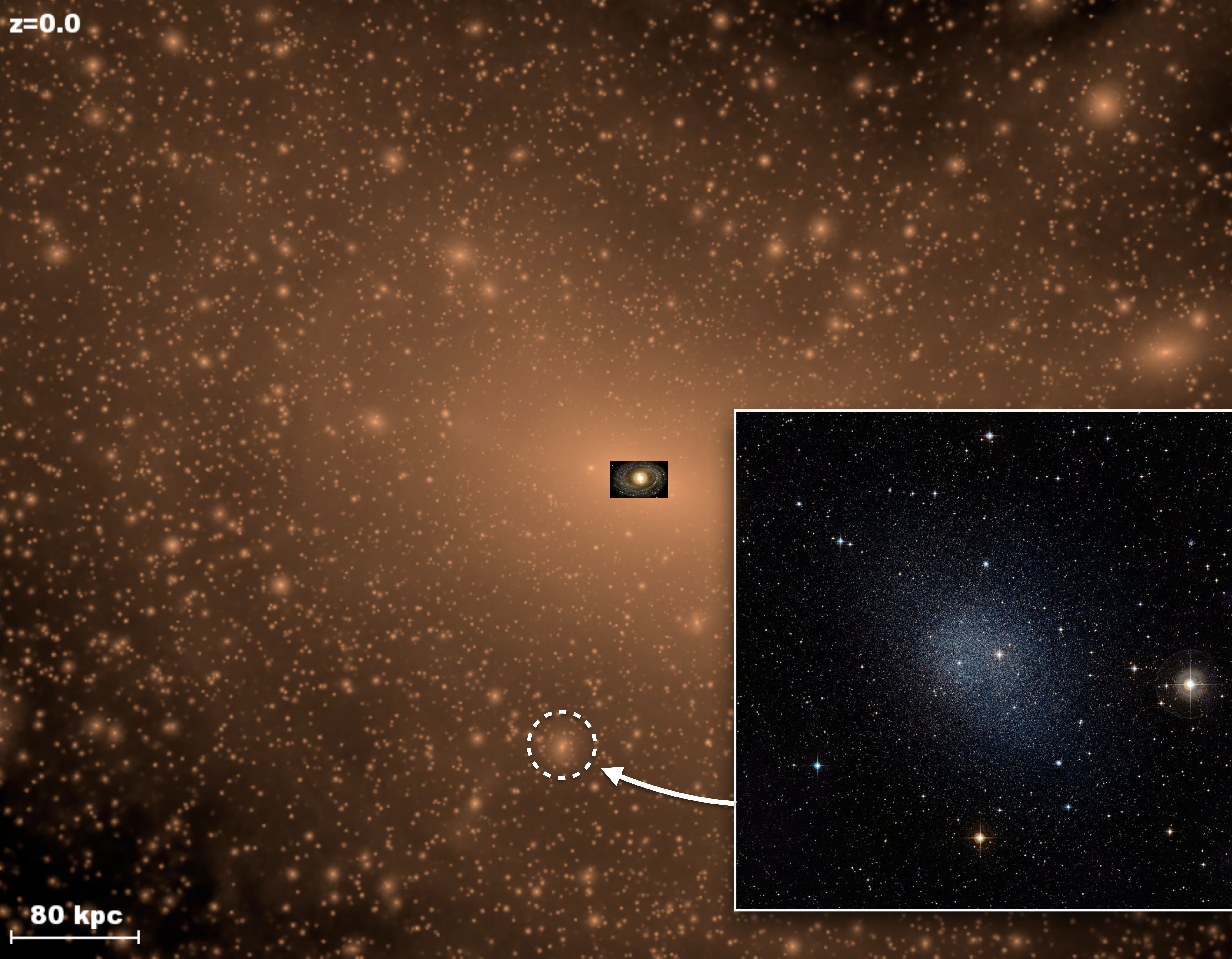
(Bullock, Geha, Powell)

c. 2014

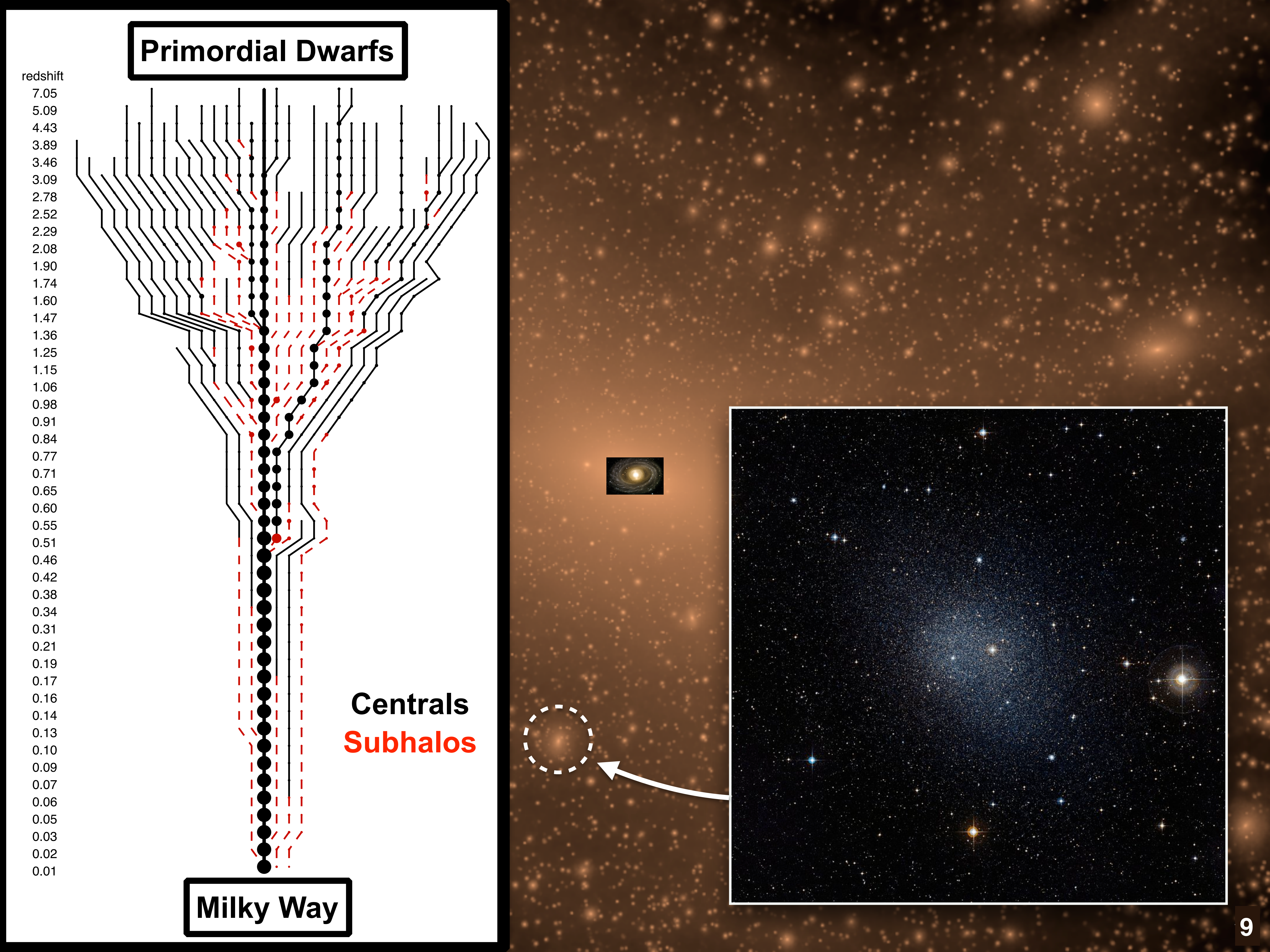
Milky Way Satellite Galaxies



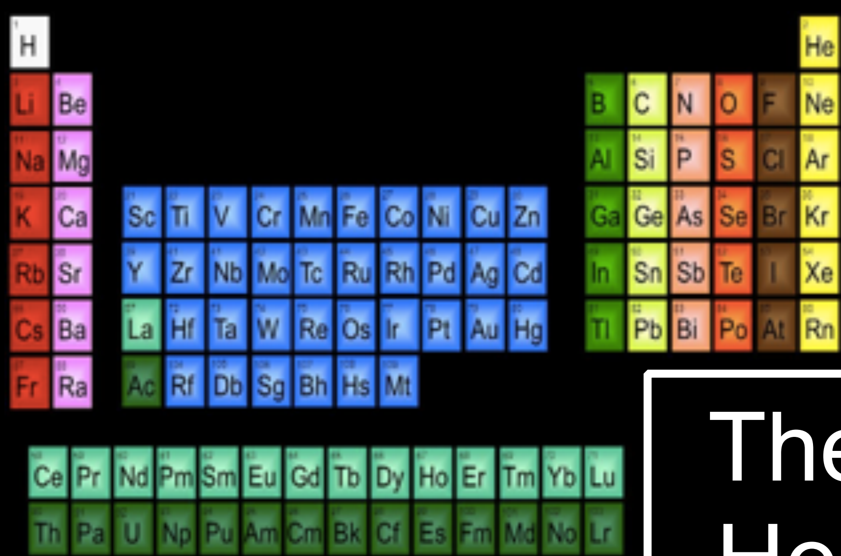

z=0.0
80 kpc



z=0.0
80 kpc

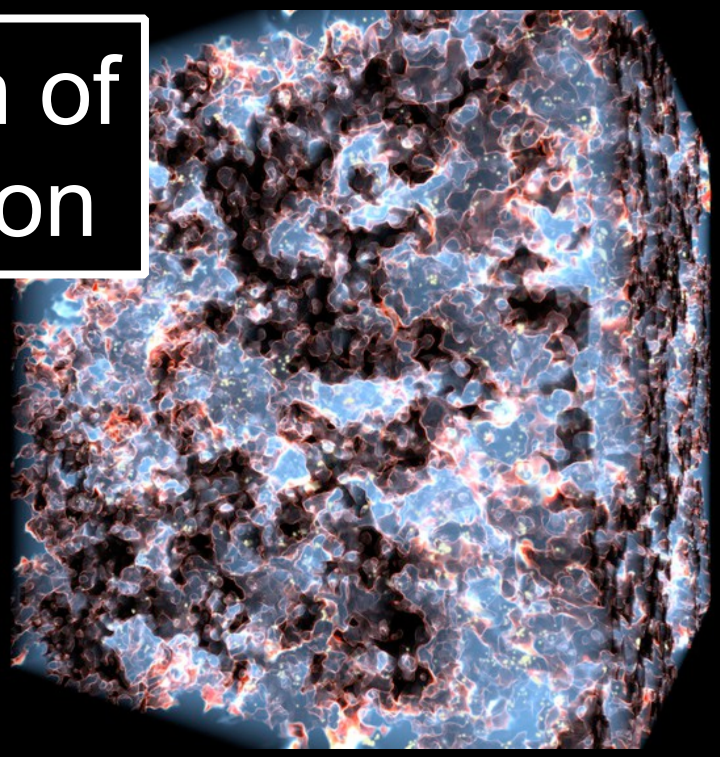

Primordial Dwarfs
redshift
7.05
5.09
4.43
3.89
3.46
3.09
2.78
2.52
2.29
2.08
1.90
1.74
1.60
1.47
1.36
1.25
1.15
1.06
0.98
0.91
0.84
0.77
0.71
0.65
0.60
0.55
0.51
0.46
0.42
0.38
0.34
0.31
0.21
0.19
0.17
0.16
0.14
0.13
0.10
0.09
0.07
0.06
0.05
0.03
0.02
0.01
Centrals
Subhalos
Milky Way

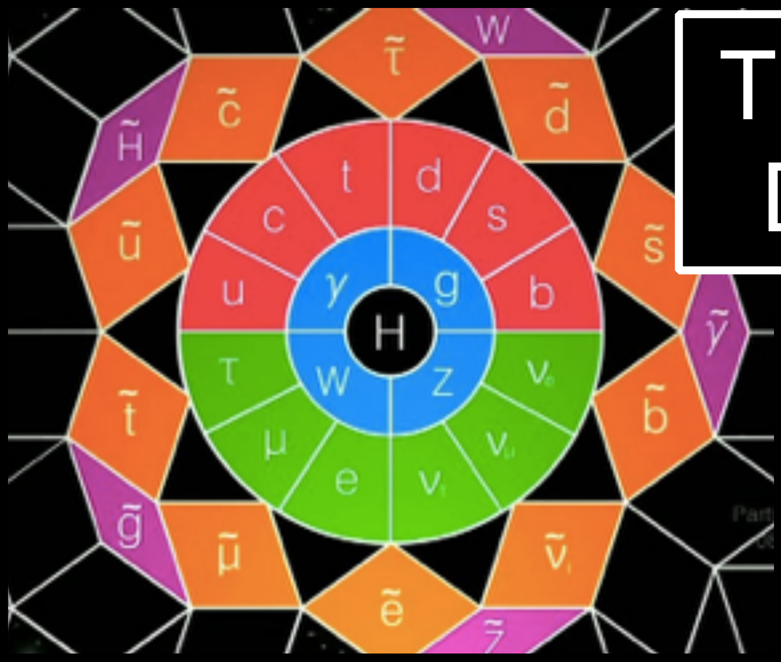
Ultra-faint galaxies are the most numerous, ancient, chemically pristine, and dark matter dominated galaxies.



The Origin of the Heavy Elements

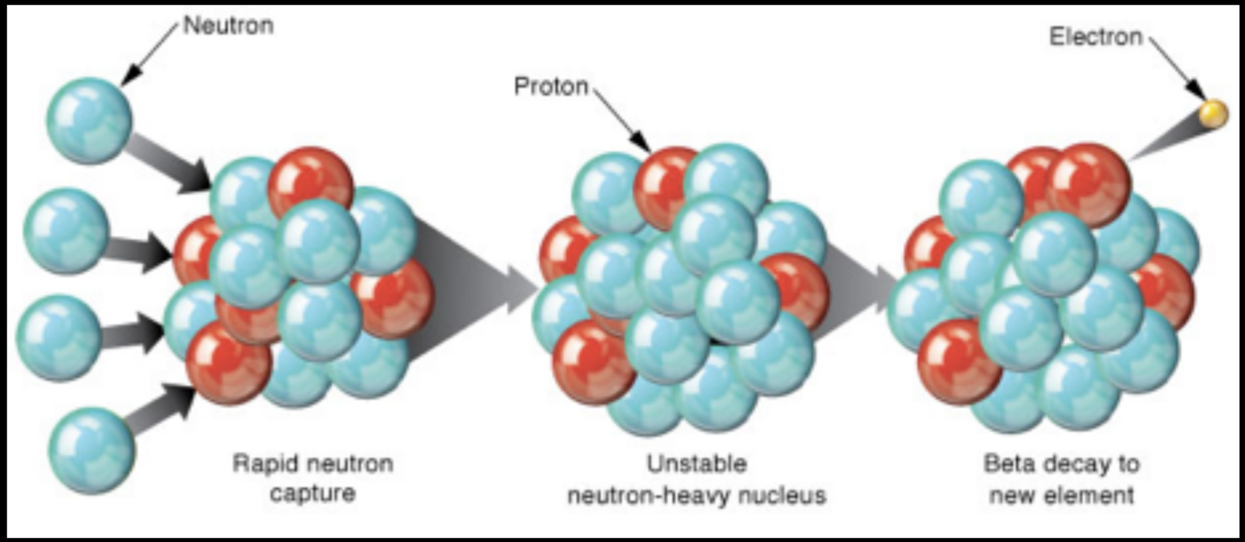
The Epoch of Reionization





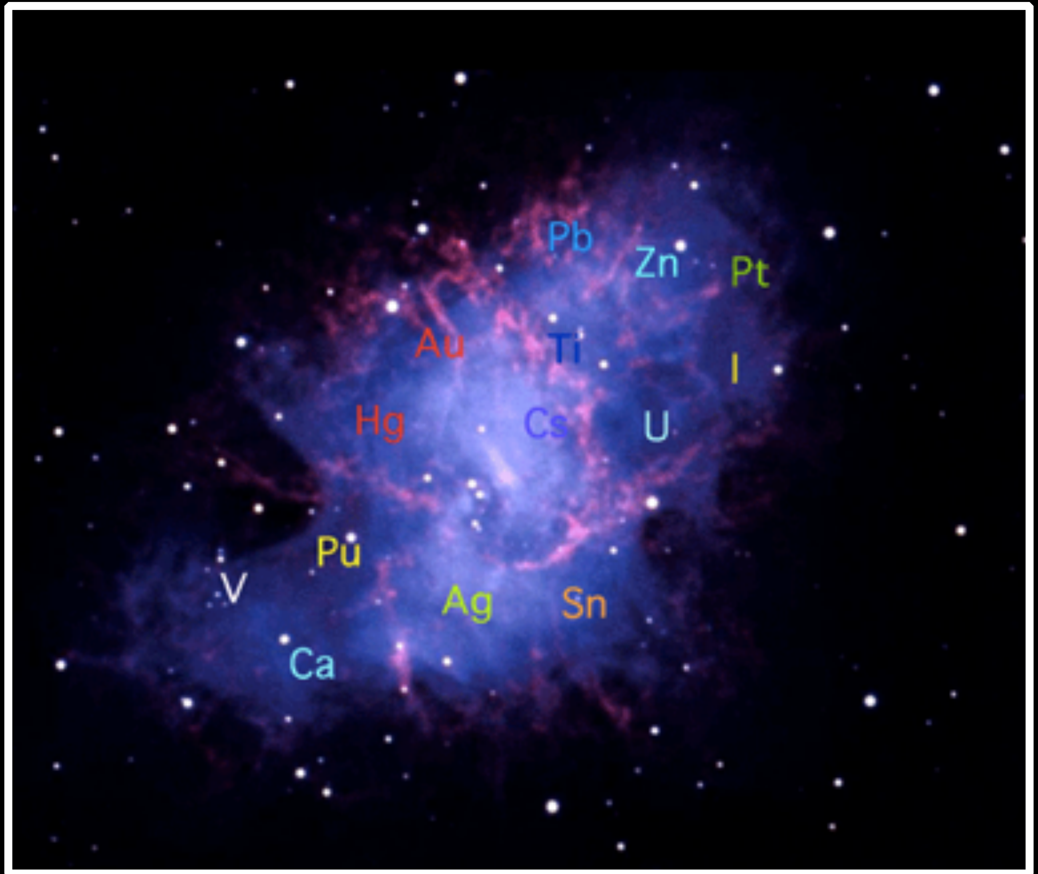
The Nature of Dark Matter

Origin of r-process Elements



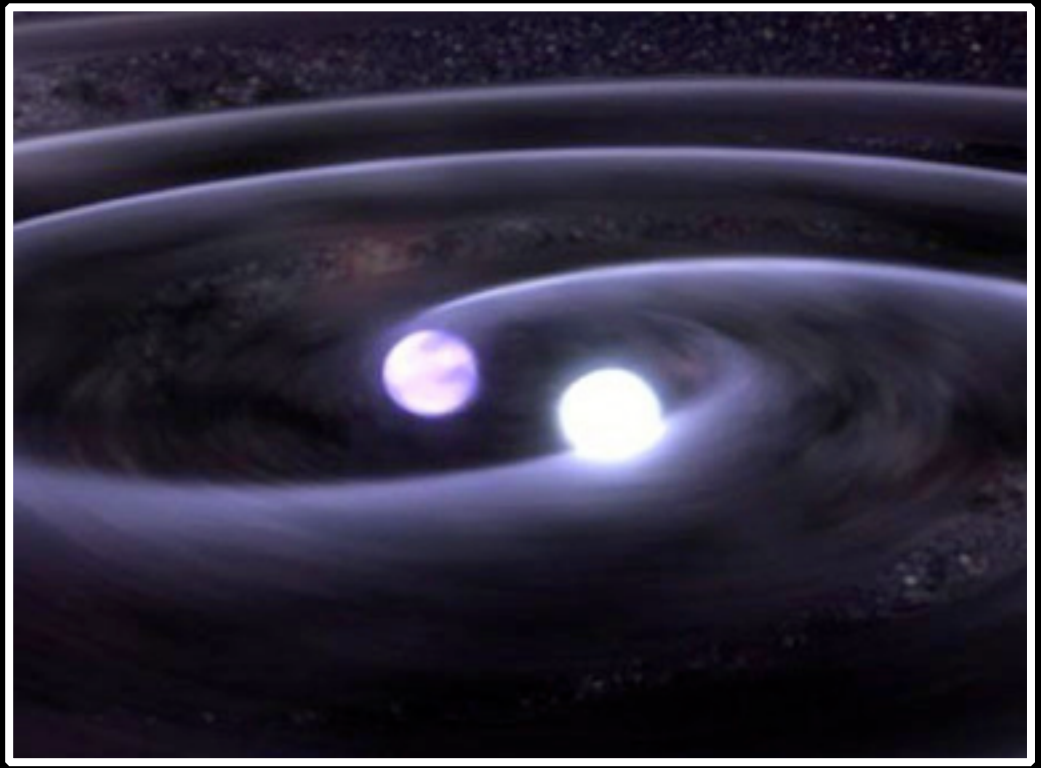
Supernovae

(~$10^{-7.5}$ $M_\odot$ of Eu per event)



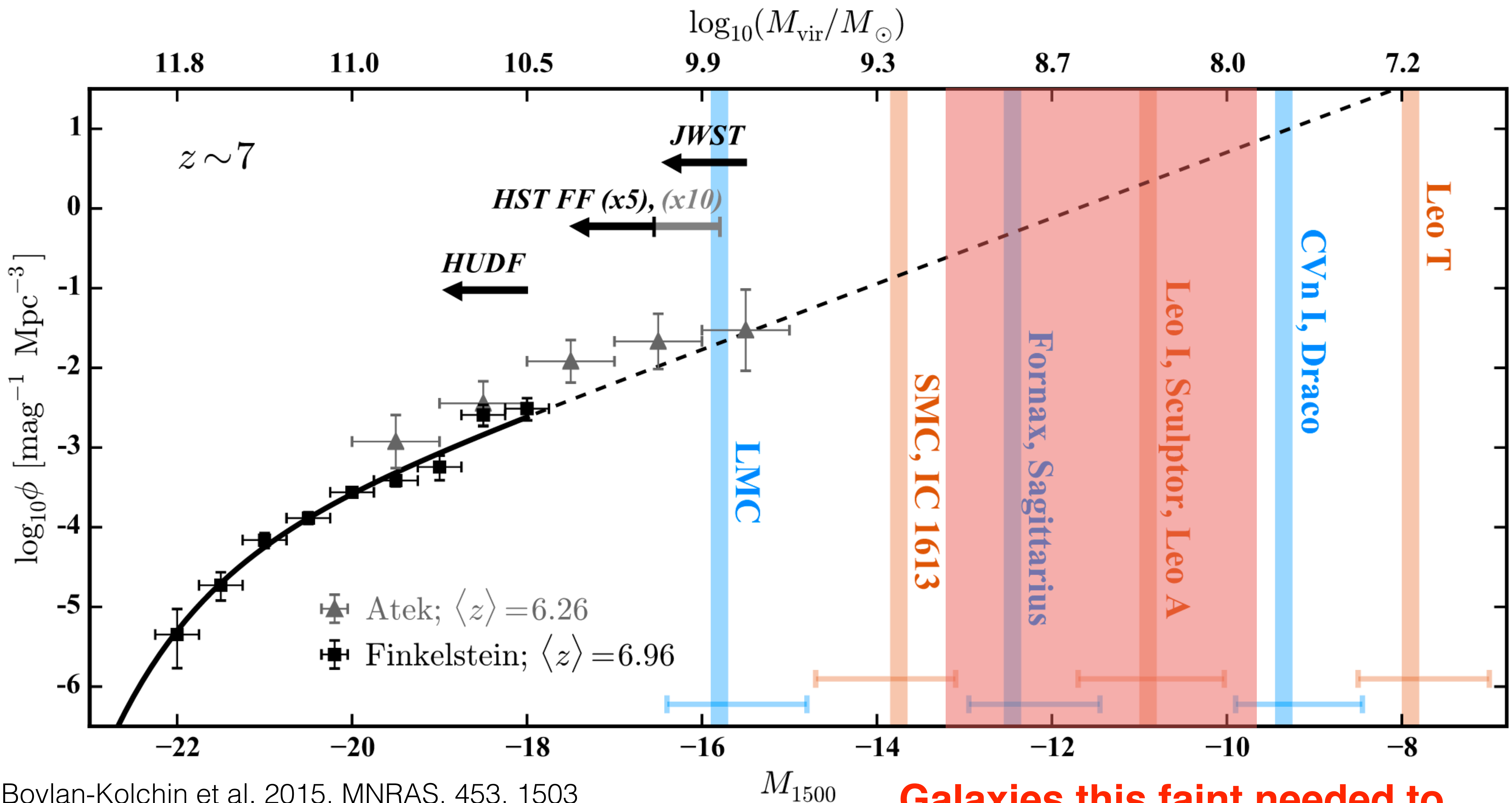
Neutron Star Mergers

(~$10^{-4.5}$ $M_\odot$ of Eu per event)



Local Connection to High-Redshift Universe

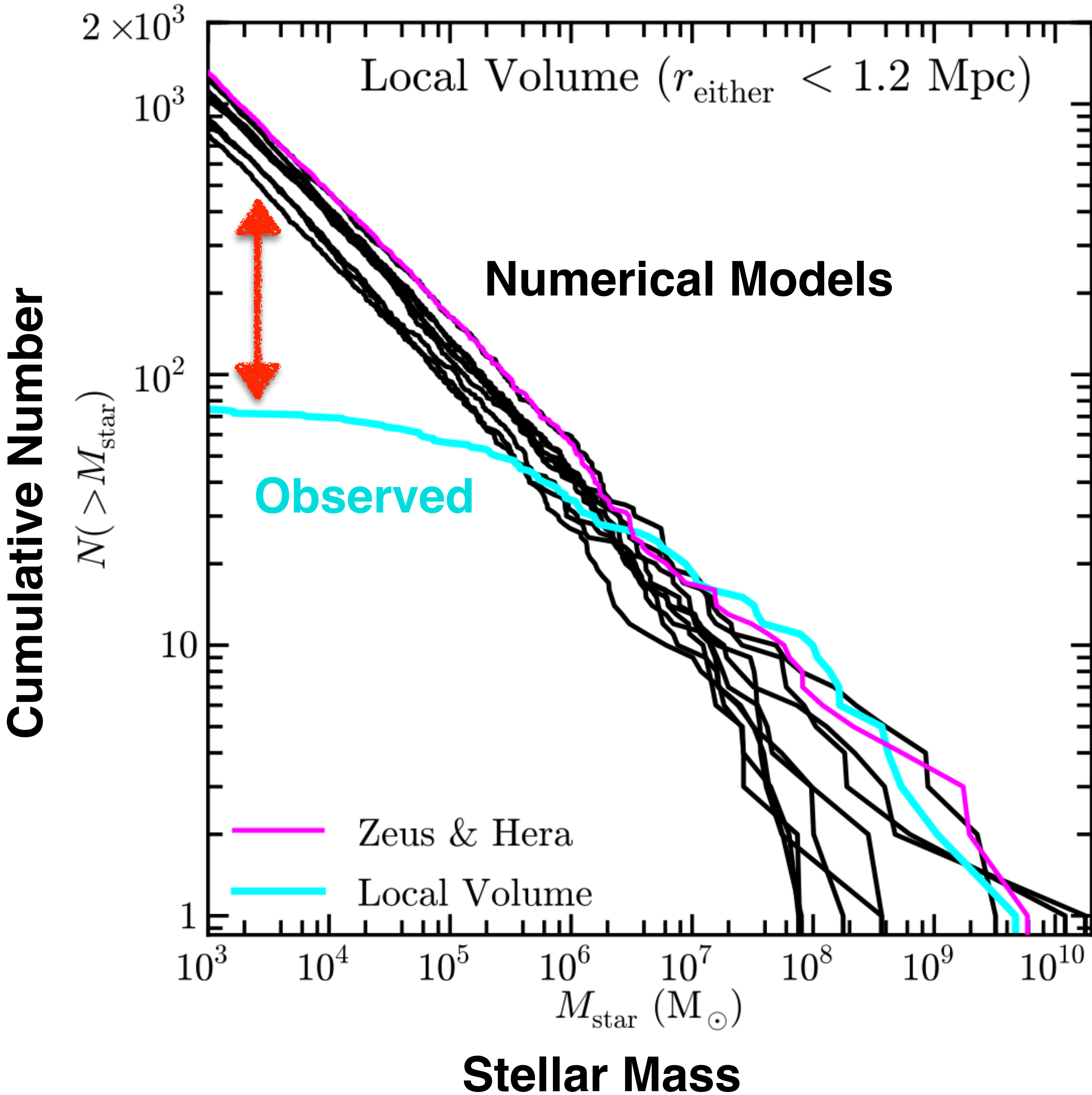
Star-formation histories of Local Group galaxies constrain faint end of UV luminosity function during epoch of reionization



Boylan-Kolchin et al. 2015, MNRAS, 453, 1503

Galaxies this faint needed to provide ionizing radiation

Open Issues for Cold Dark Matter Paradigm at Smallest Scales



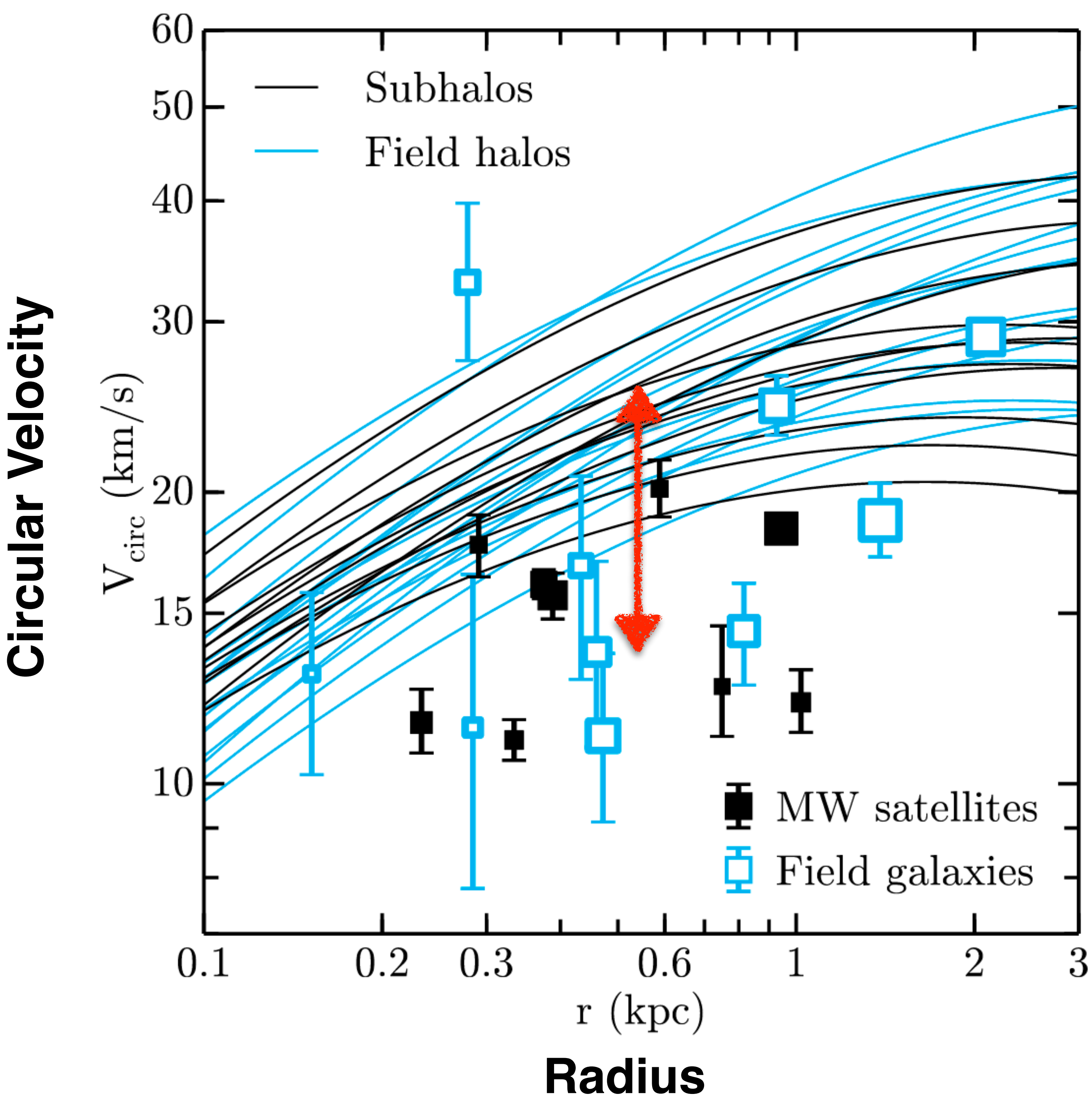
"Missing Satellites Problem"

Expect ~1000 luminous subhalos in Local Group, but only ~100 detected so far (includes Andromeda)

Klypin et al. 1999
Moore et al. 1999

Recent example from ELVIS simulations
Garrison-Kimmel et al. 2014, MNRAS, 438, 2578

Open Issues for Cold Dark Matter Paradigm at Smallest Scales



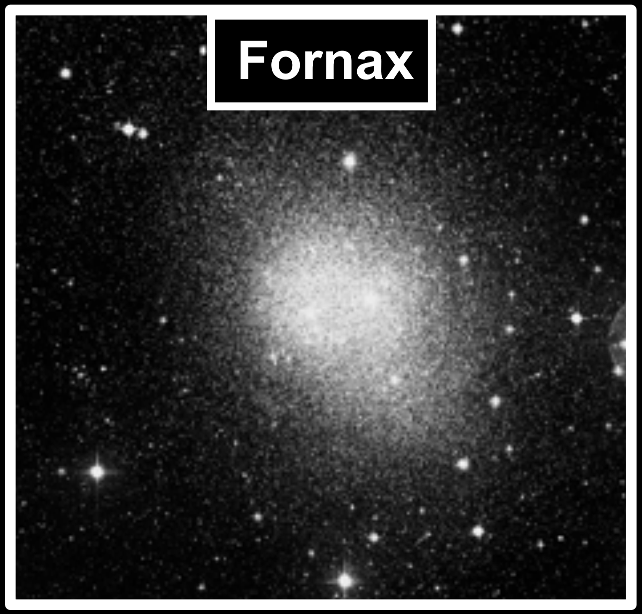
Garrison-Kimmel et al. 2014, MNRAS, 444, 222

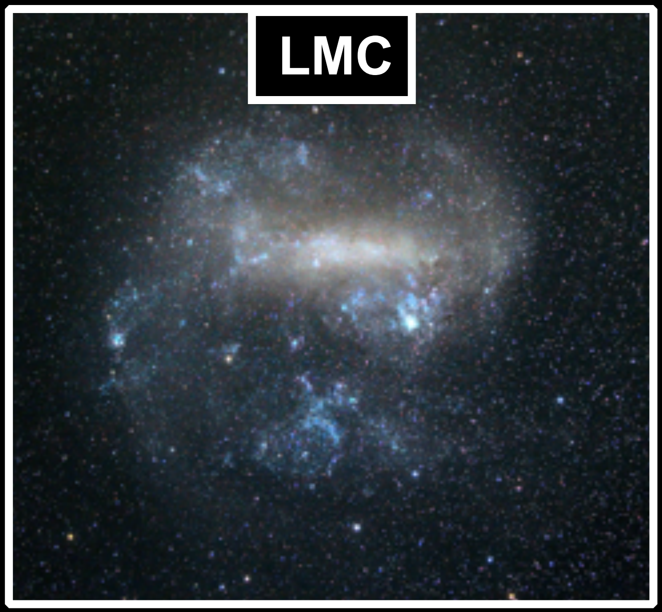
"Central Density Problem"

Numerical simulations with CDM only predict the existence of subhalos with higher central densities than observed in known Milky Way satellites (and isolated dwarfs)

"Core-cusp"
"Too big to fail"

Flores & Primack 1994
Moore 1994





Lower Luminosity

More Dark Matter Dominated

Cleaner Probes of Fundamental Physics

- Introduction to Dwarf Galaxies
- **Finding New Dwarf Galaxies**
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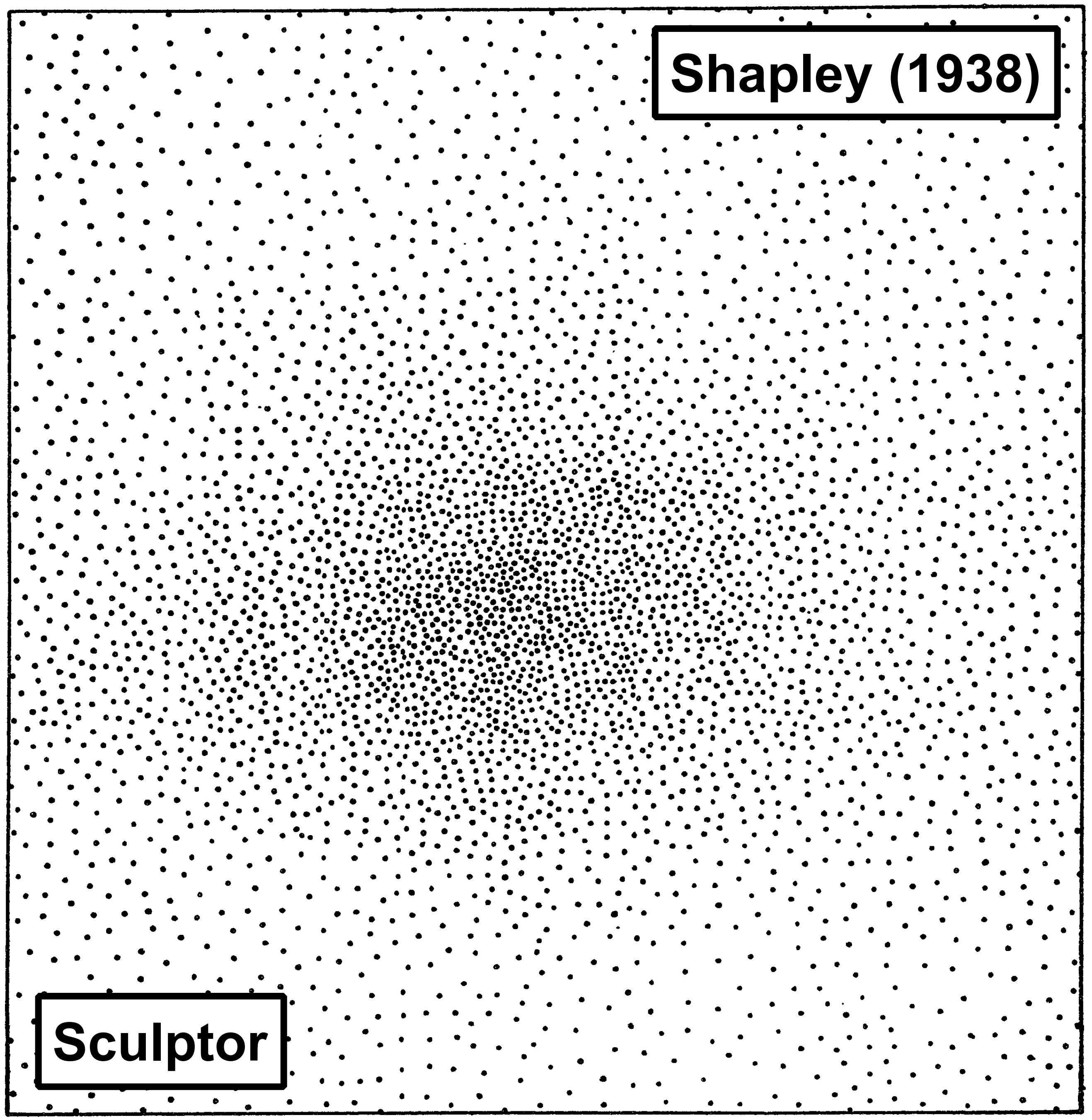
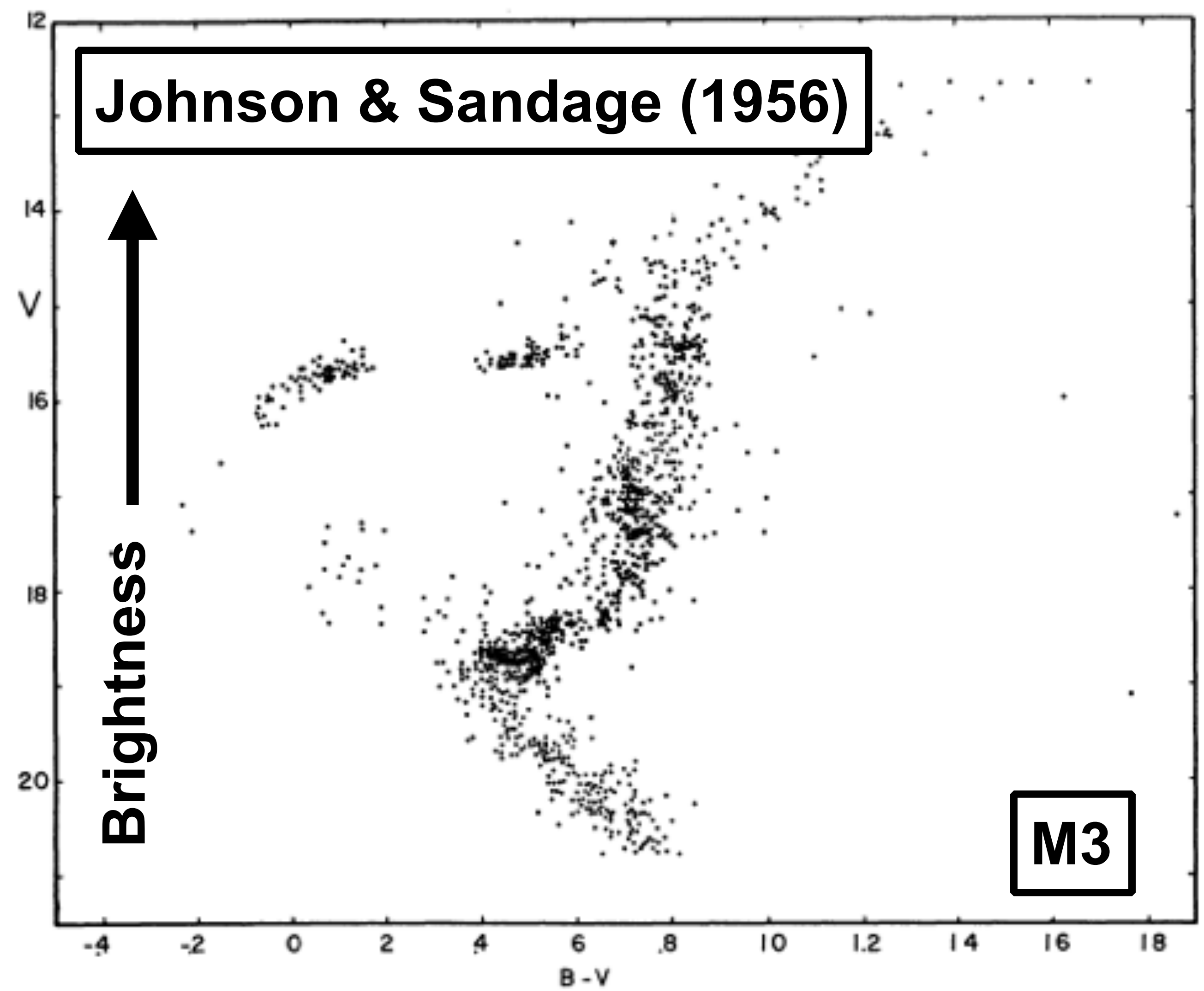
Finding Milky Way Satellite Galaxies

Detectors Drive Discoveries

Visual Searches

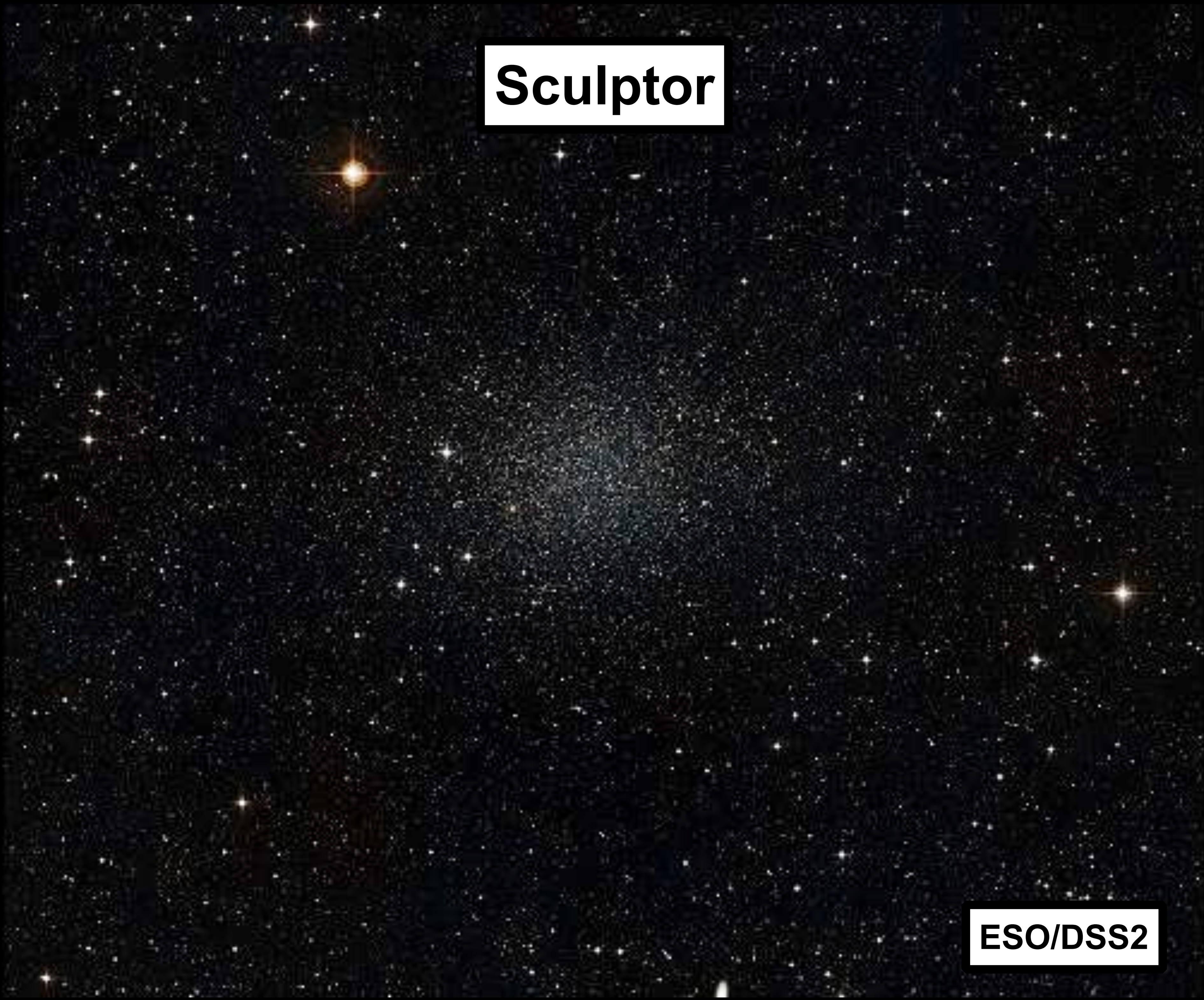
- **First objects discovered by visual scans of photographic plates**





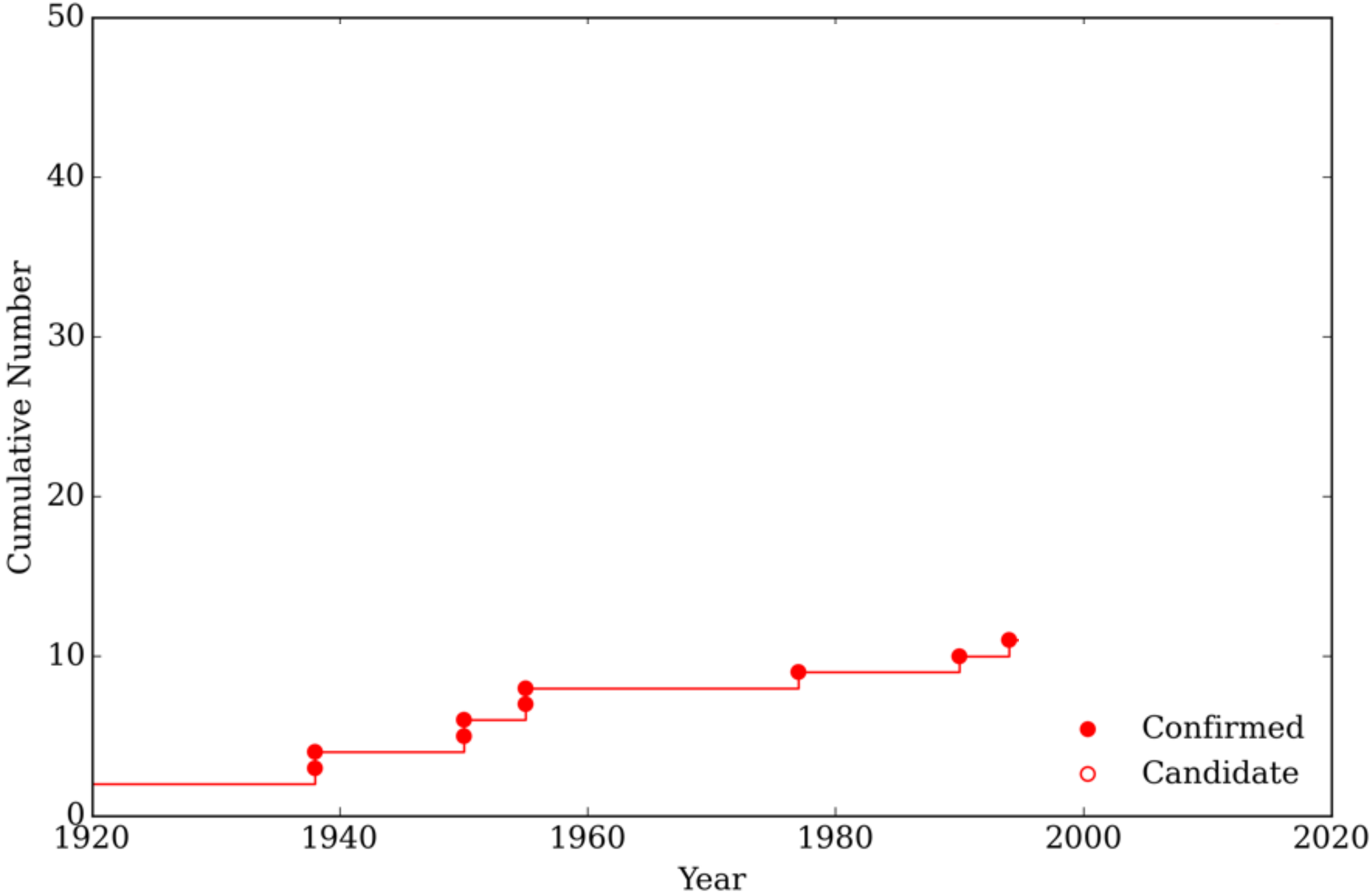
Blue ← **Color** → **Red**

24-inch Telescope
Photographic Plates



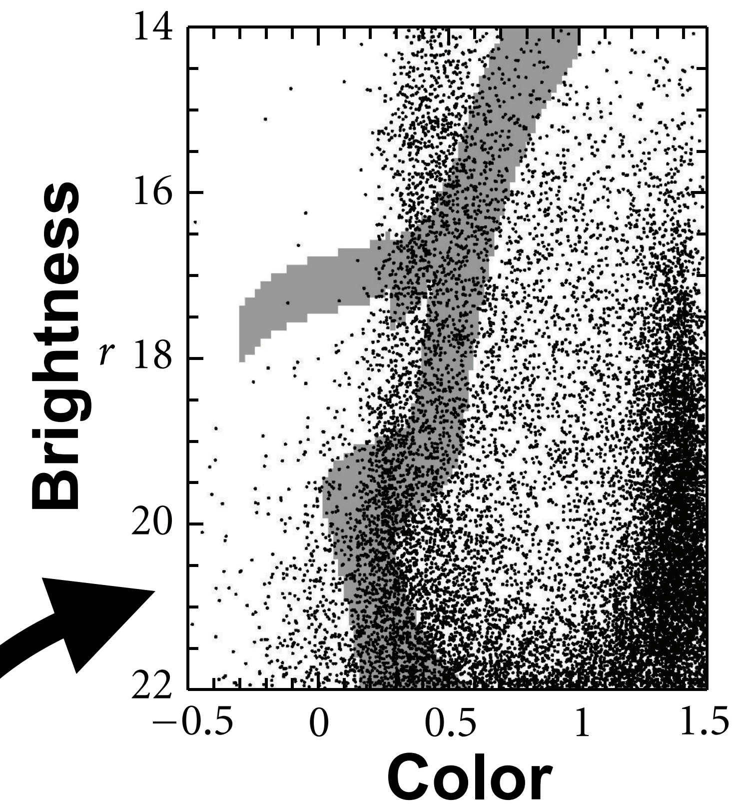
1.2m Telescope
Photographic Plates

Discovery Timeline



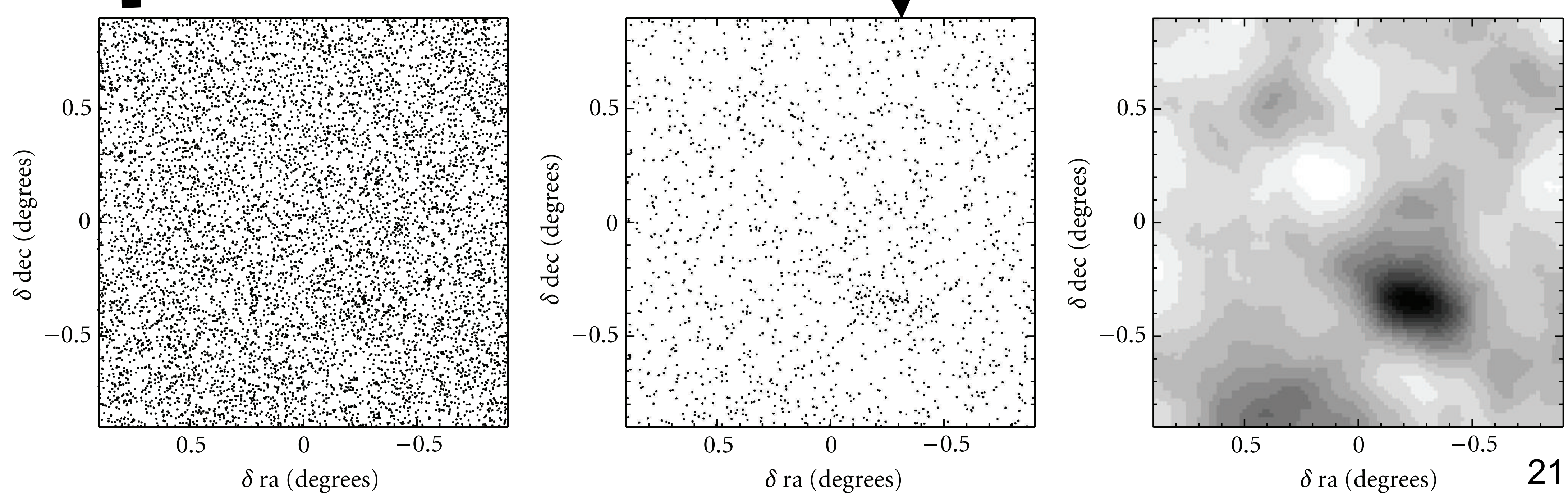
Matched-Filter Searches

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

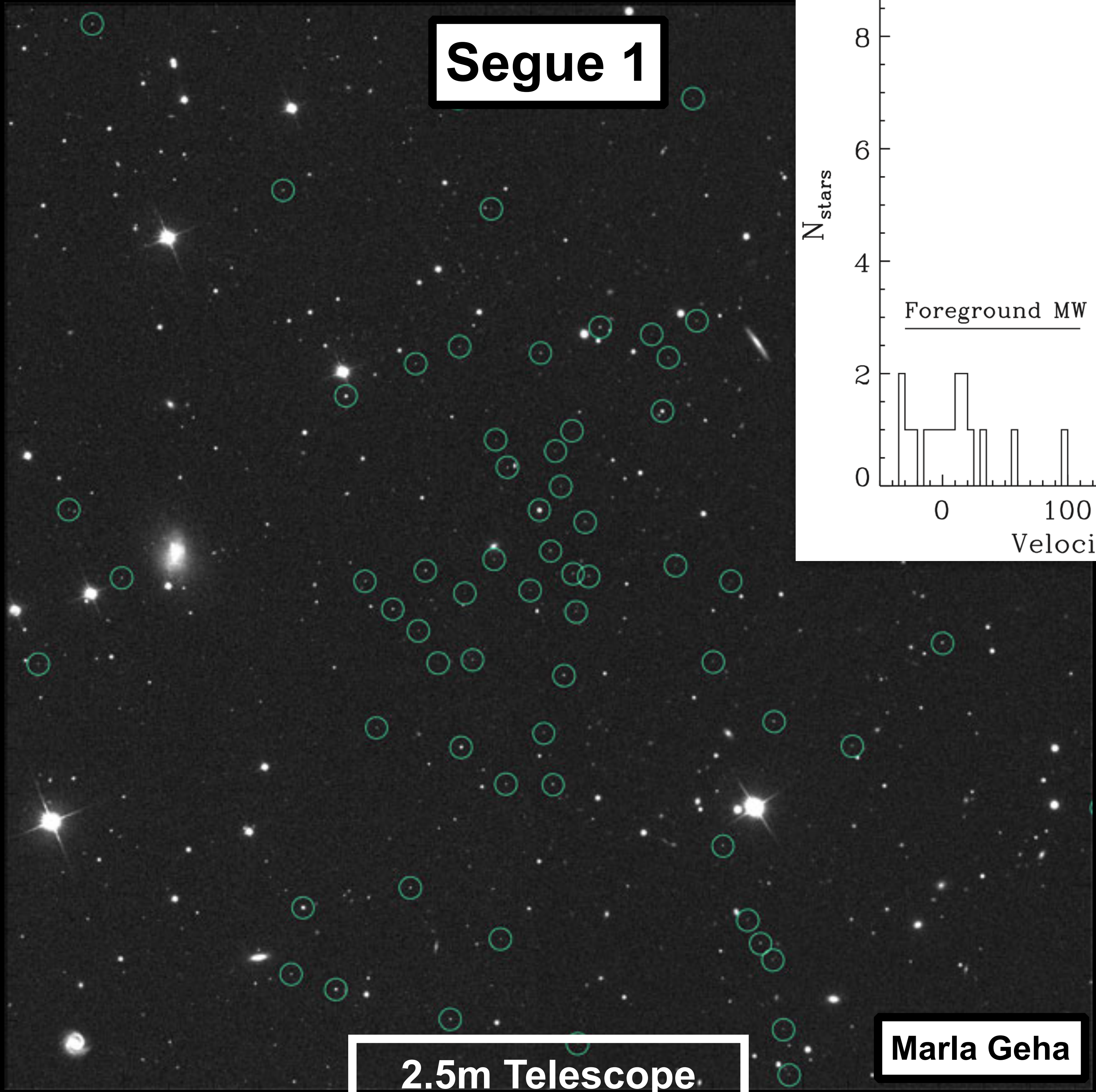


Color-Magnitude Domain

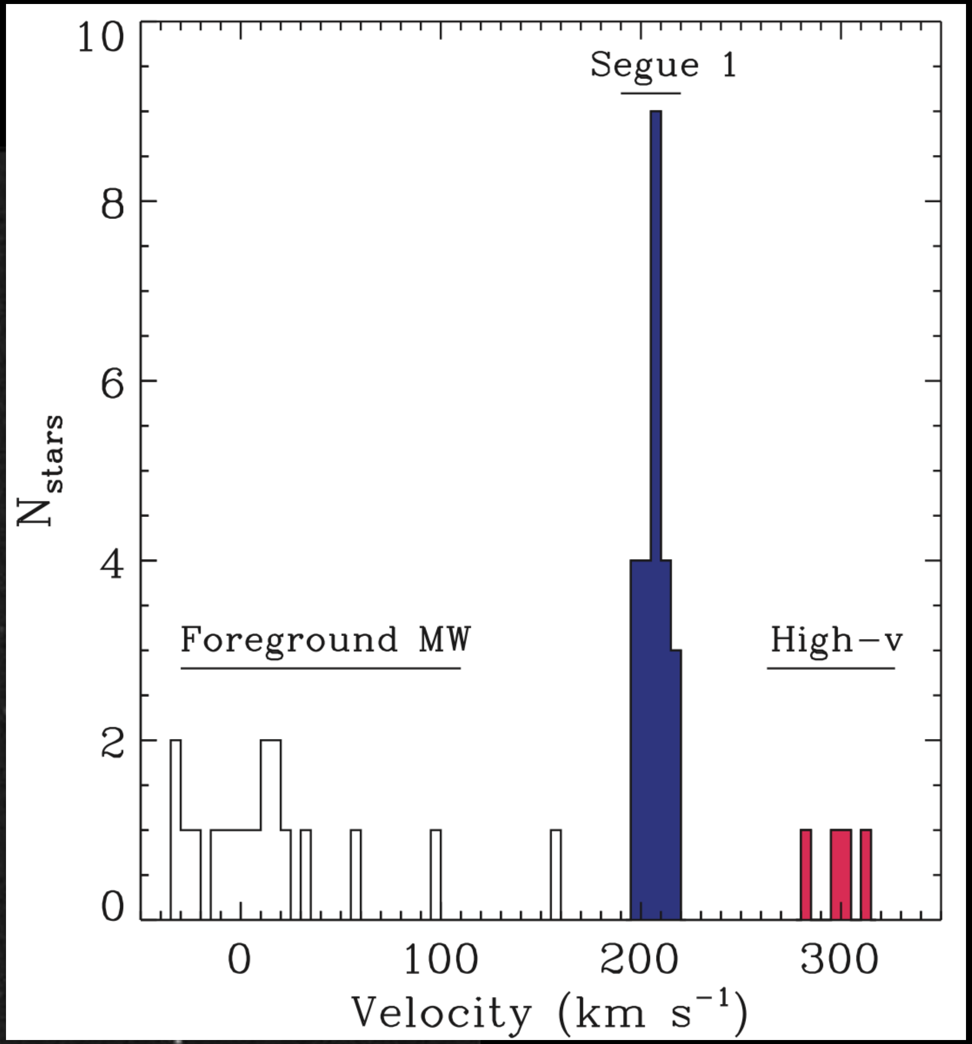
Spatial Domain




Segue 1
Marla Geha
2.5m Telescope
SDSS CCD Camera

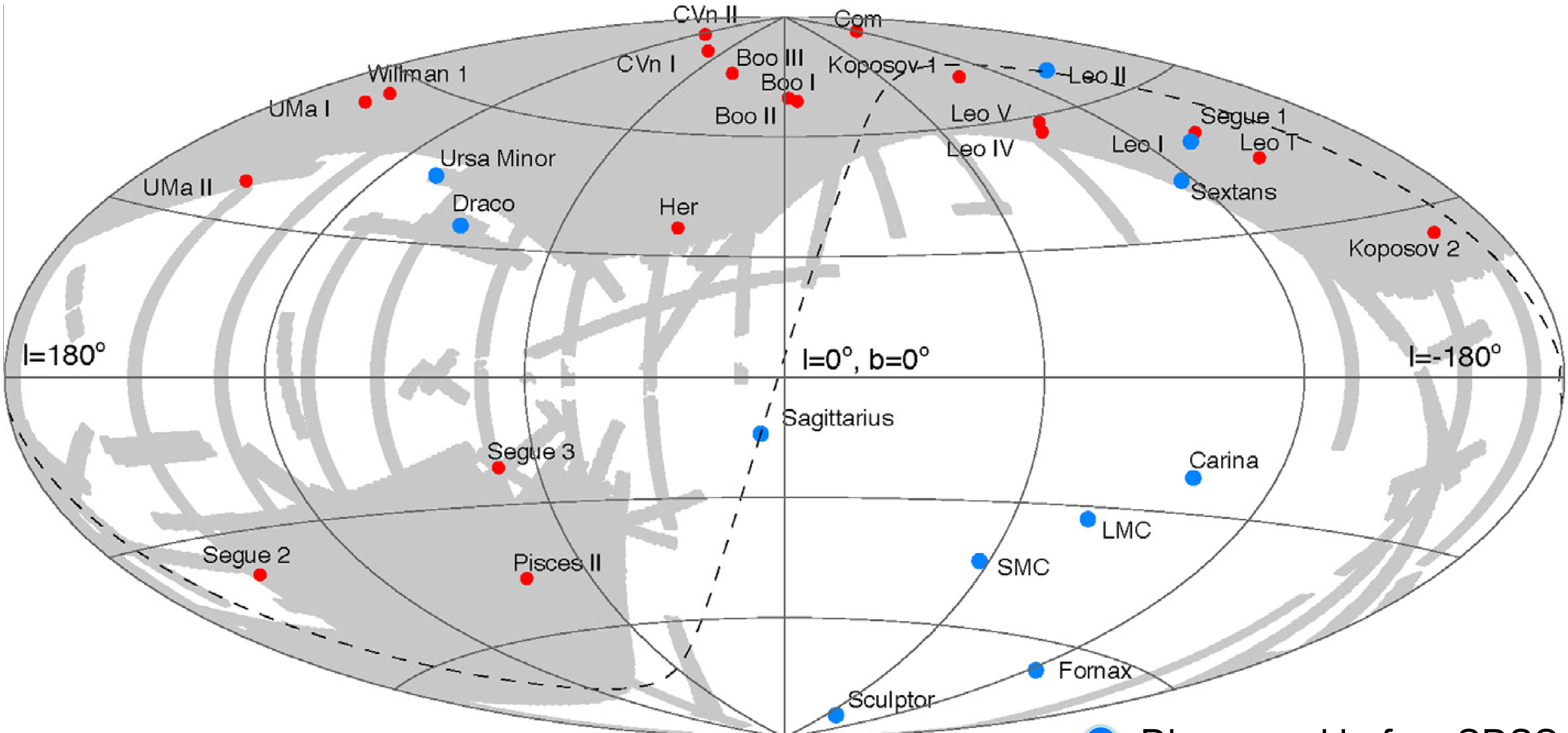


Segue 1
2.5m Telescope
SDSS CCD Camera
Marla Geha



Segue 1
Foreground MW
High−v
N_{stars}
Velocity (km s^{-1})
0
100
200
300
0
2
4
6
8
10

SDSS DR10



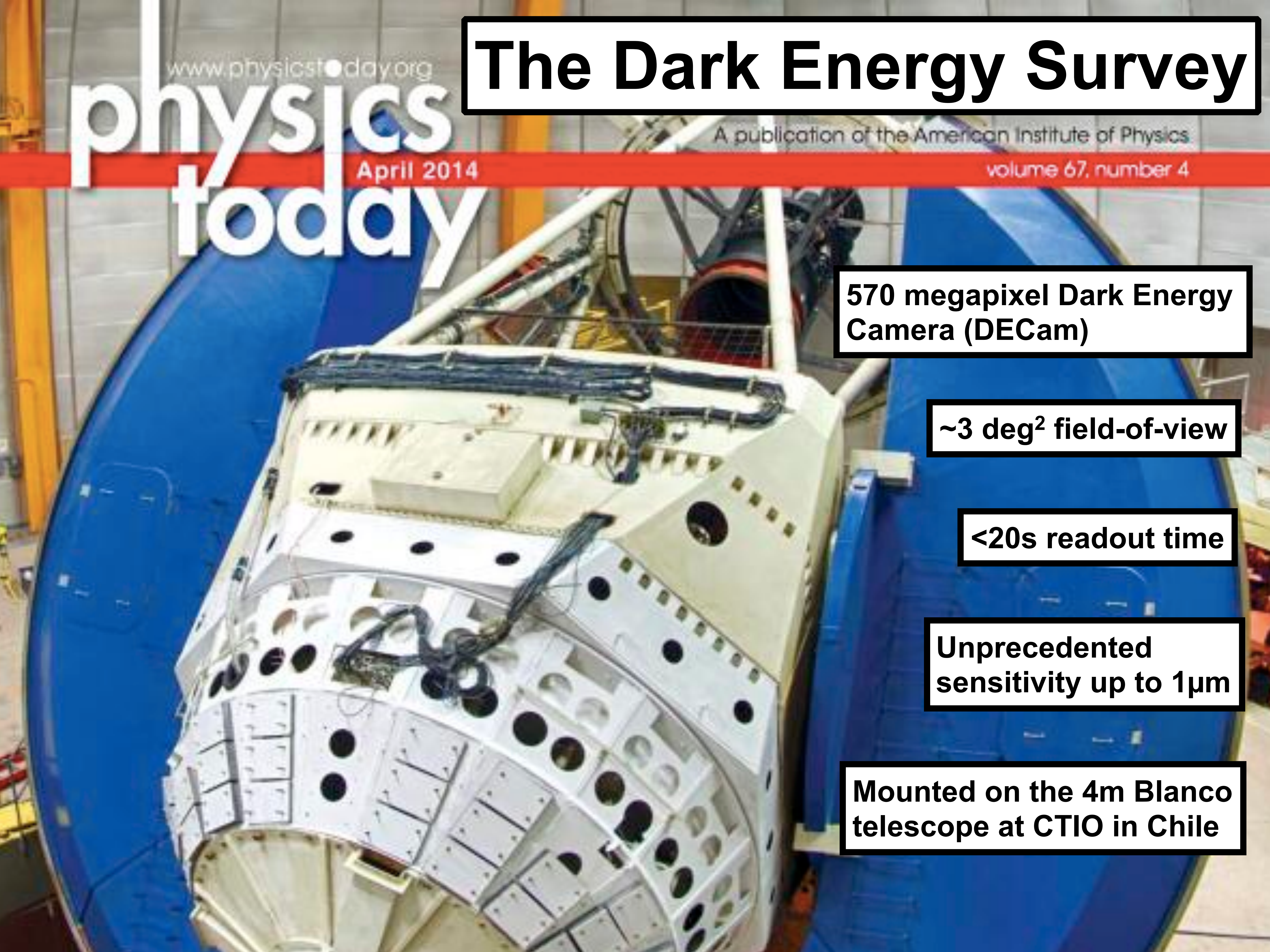
Sky Covered by SDSS

Discovered before SDSS (classical dwarfs)

Discovered with SDSS (ultra-faint dwarfs)

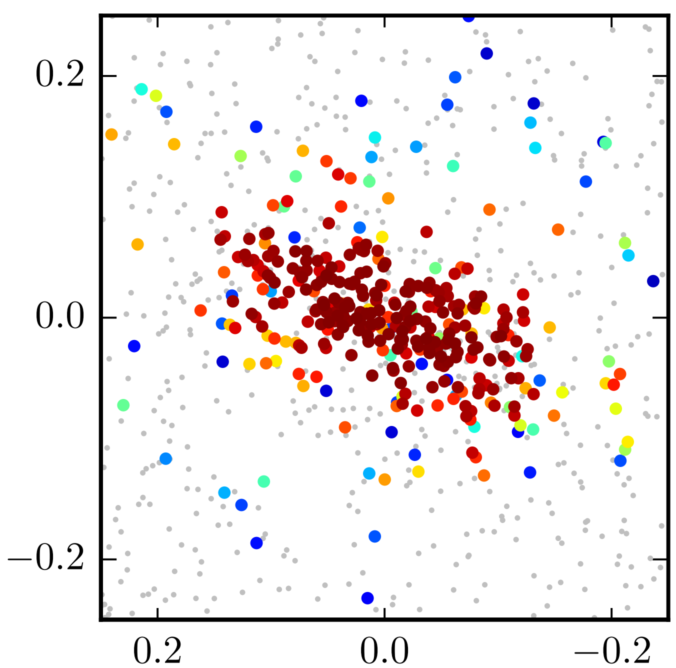
(Belokurov 2013)

The Dark Energy Survey

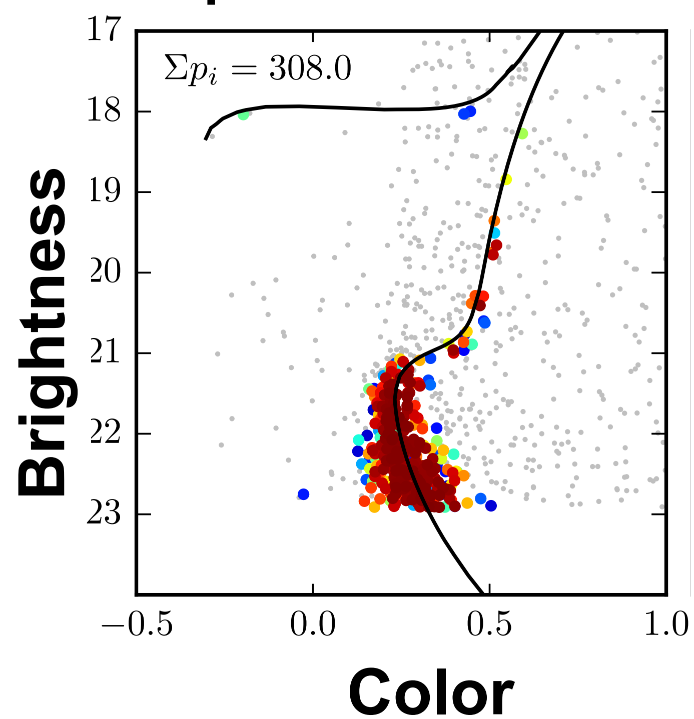


Maximum-Likelihood Searches

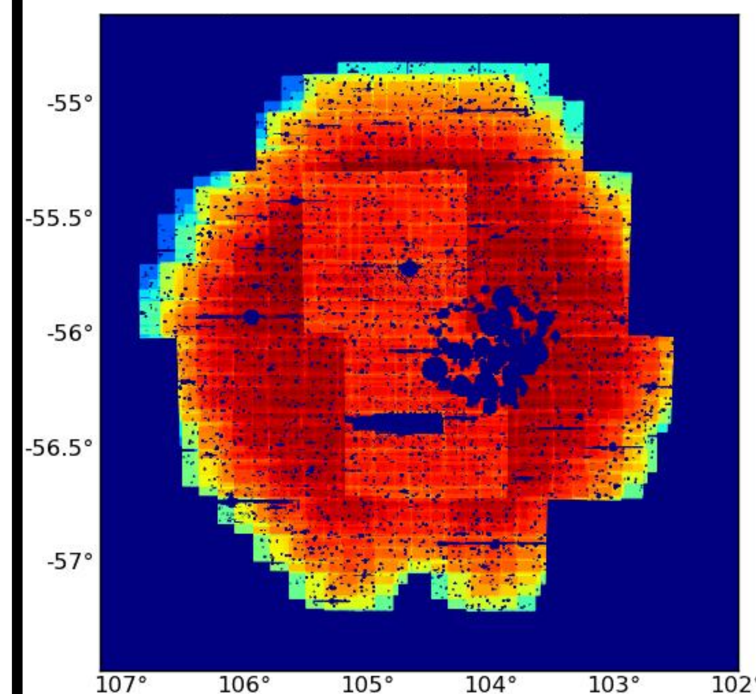
Spatial Model



Spectral Model



Survey Sensitivity



$$p_i = \frac{\lambda u_i}{\lambda u_i + b_i}$$

$$\lambda = \frac{1}{f} \sum_{i \in \mathrm{Stars}} p_i$$

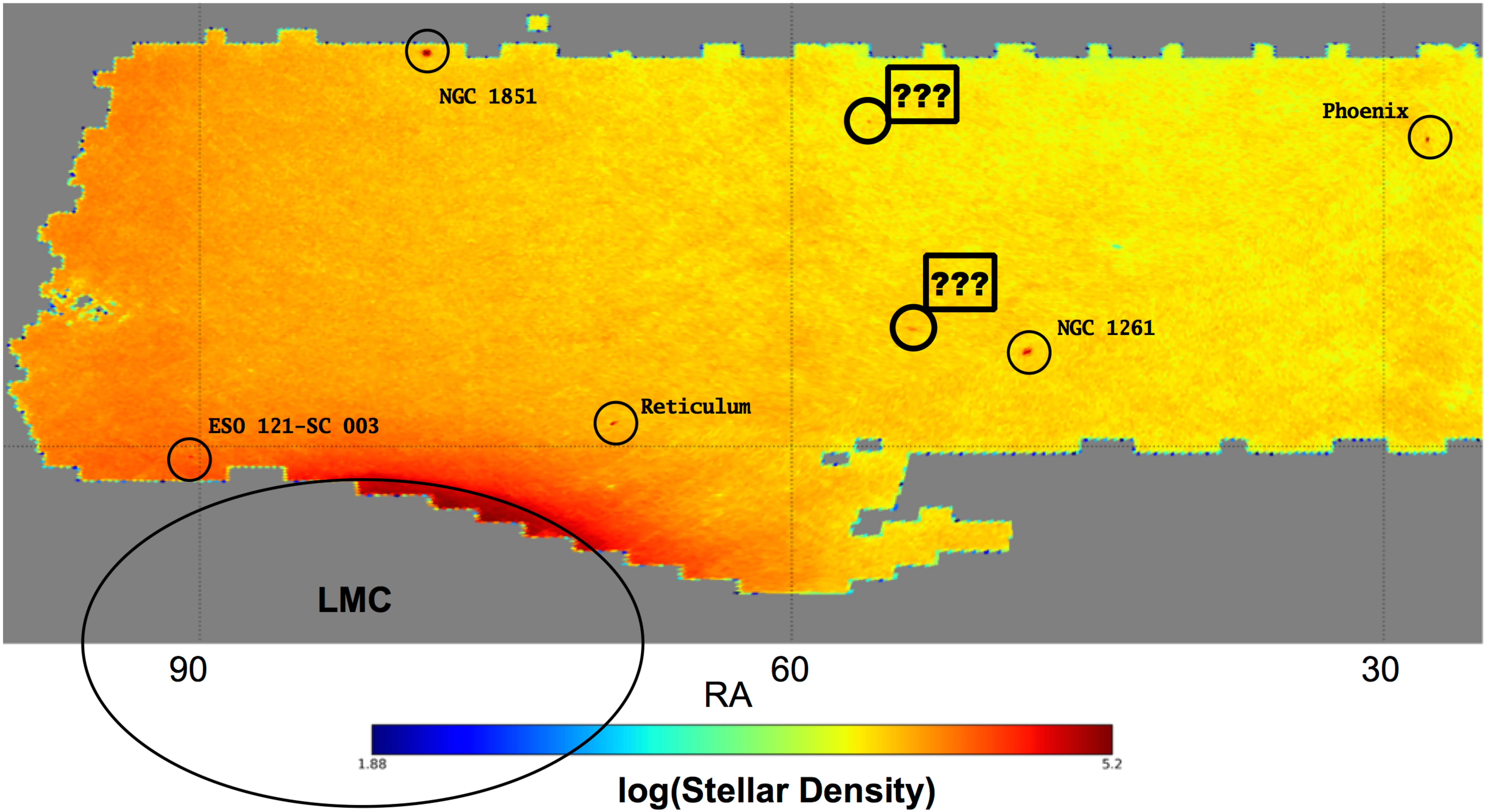
$$\log L = -\sum_{i \in \mathrm{Stars}} \log(1 - p_i) - f\lambda$$

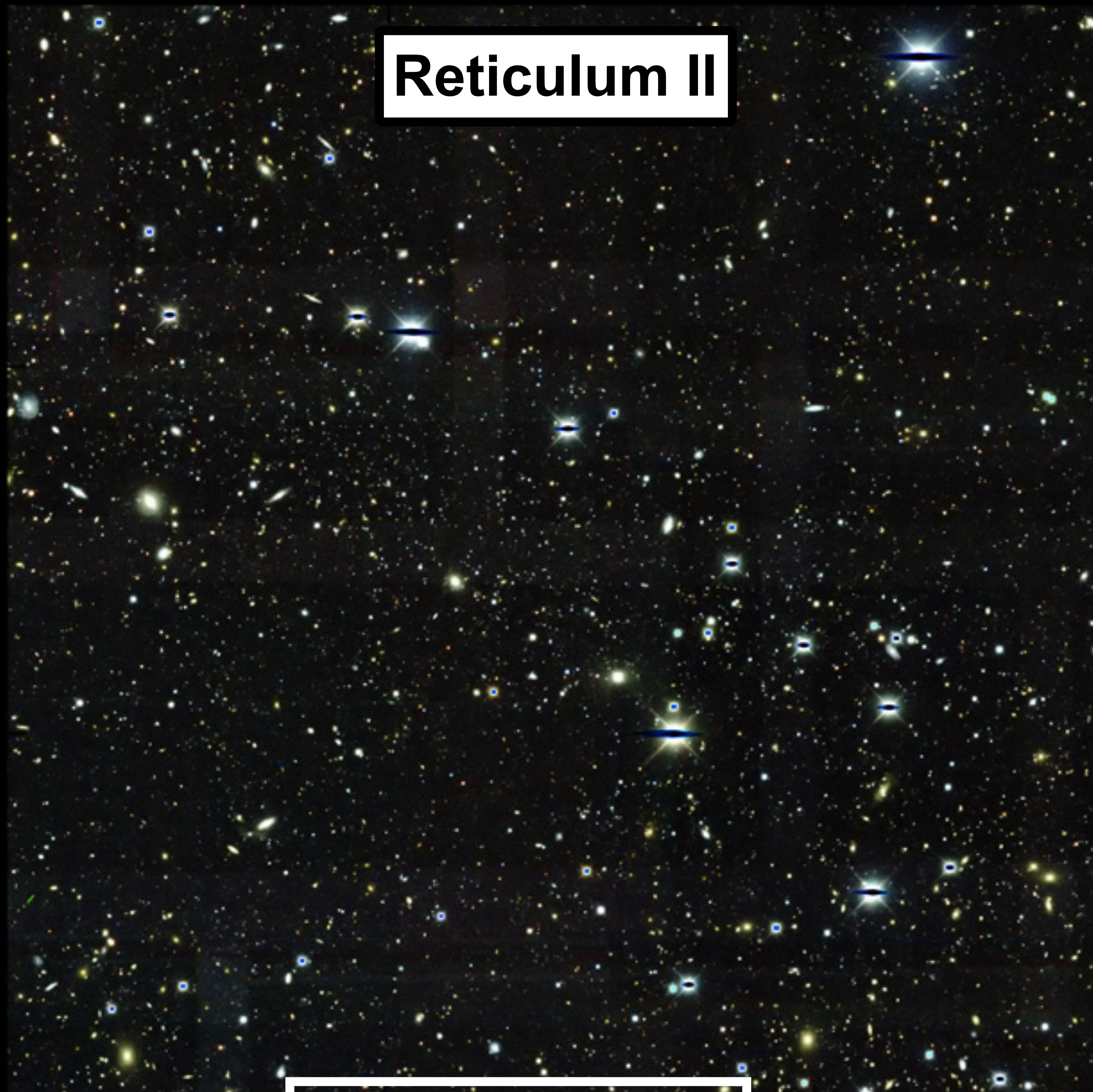
A likelihood analysis to simultaneously combines spatial and spectral information

u_i = sig prob
b_i = bkg prob
λ = normalization = number of stars
f = observable fraction

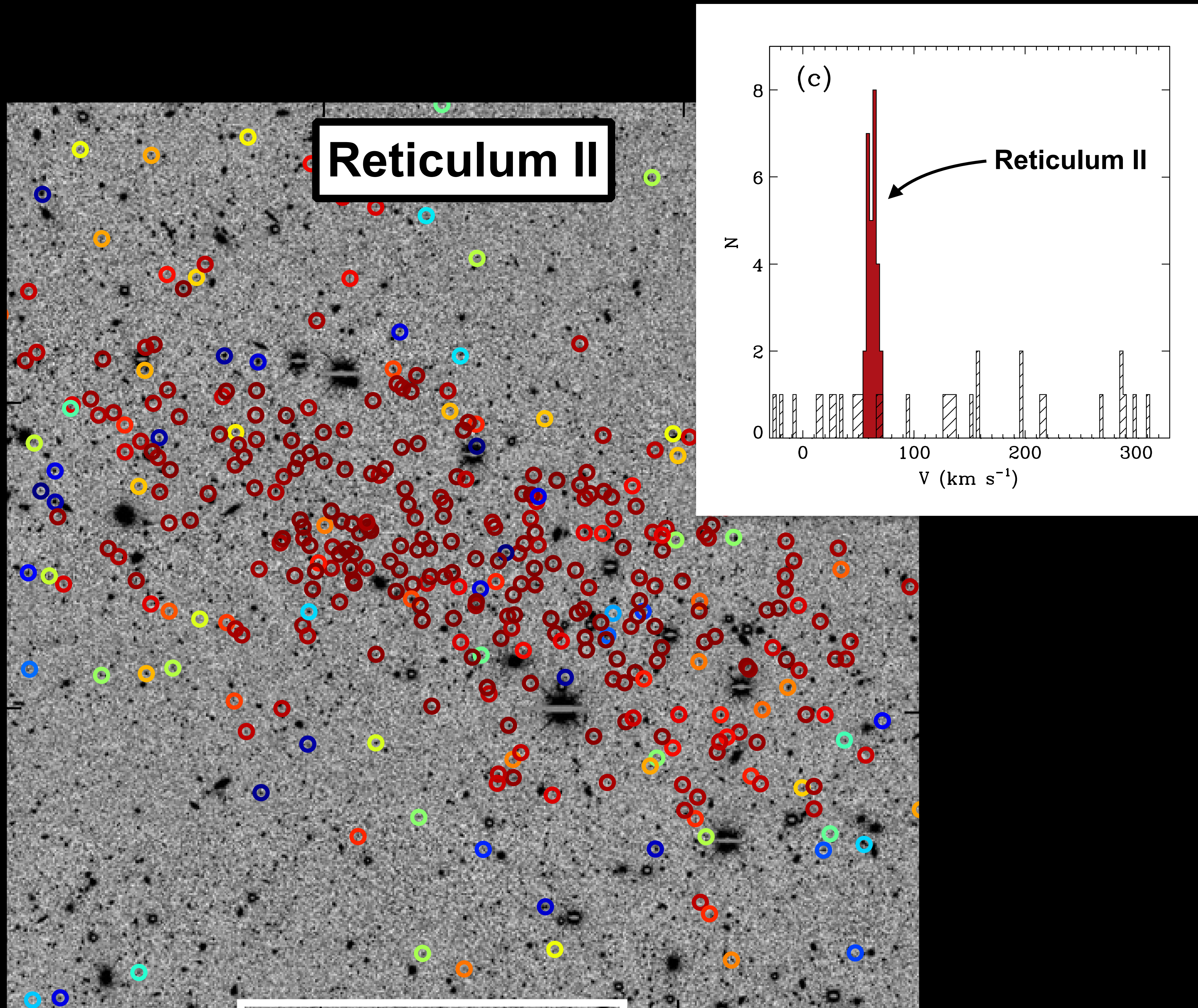
This approach naturally yields a membership probability for each star; important for spectroscopy

A Very First Look…





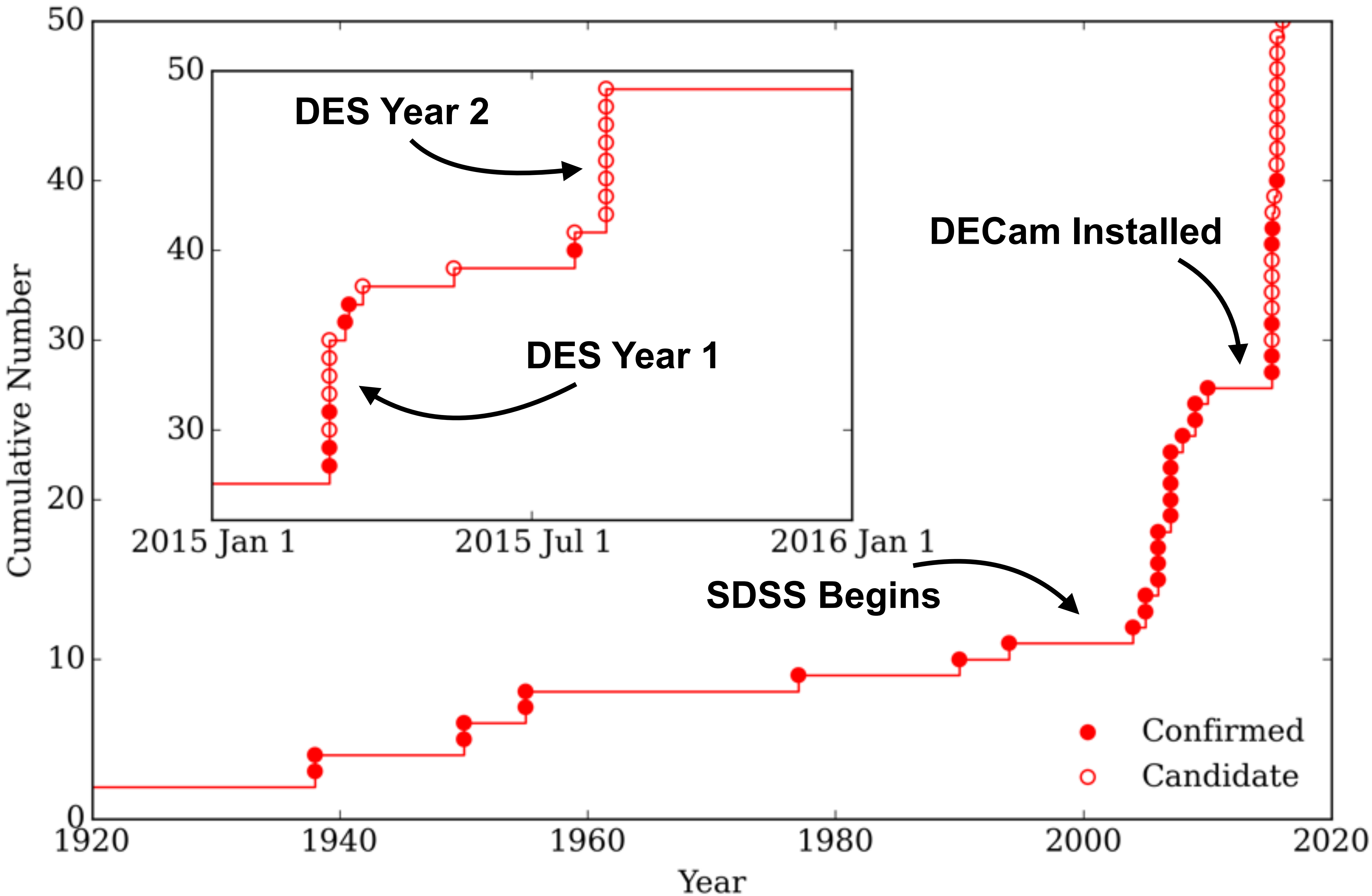
DES Collaboration



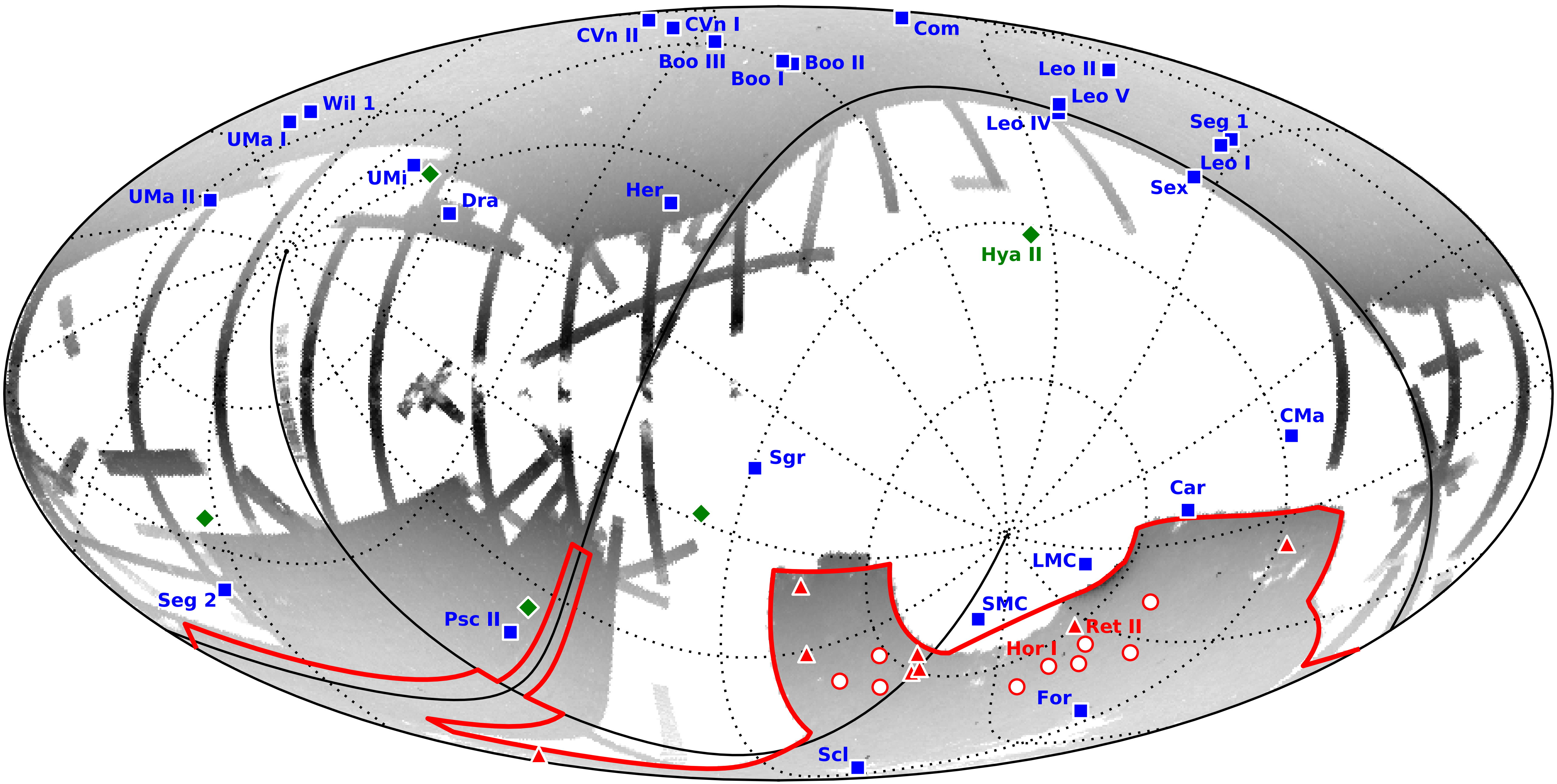
4m Telescope
DECam CCD Camera

DES Collaboration

Discovery Timeline



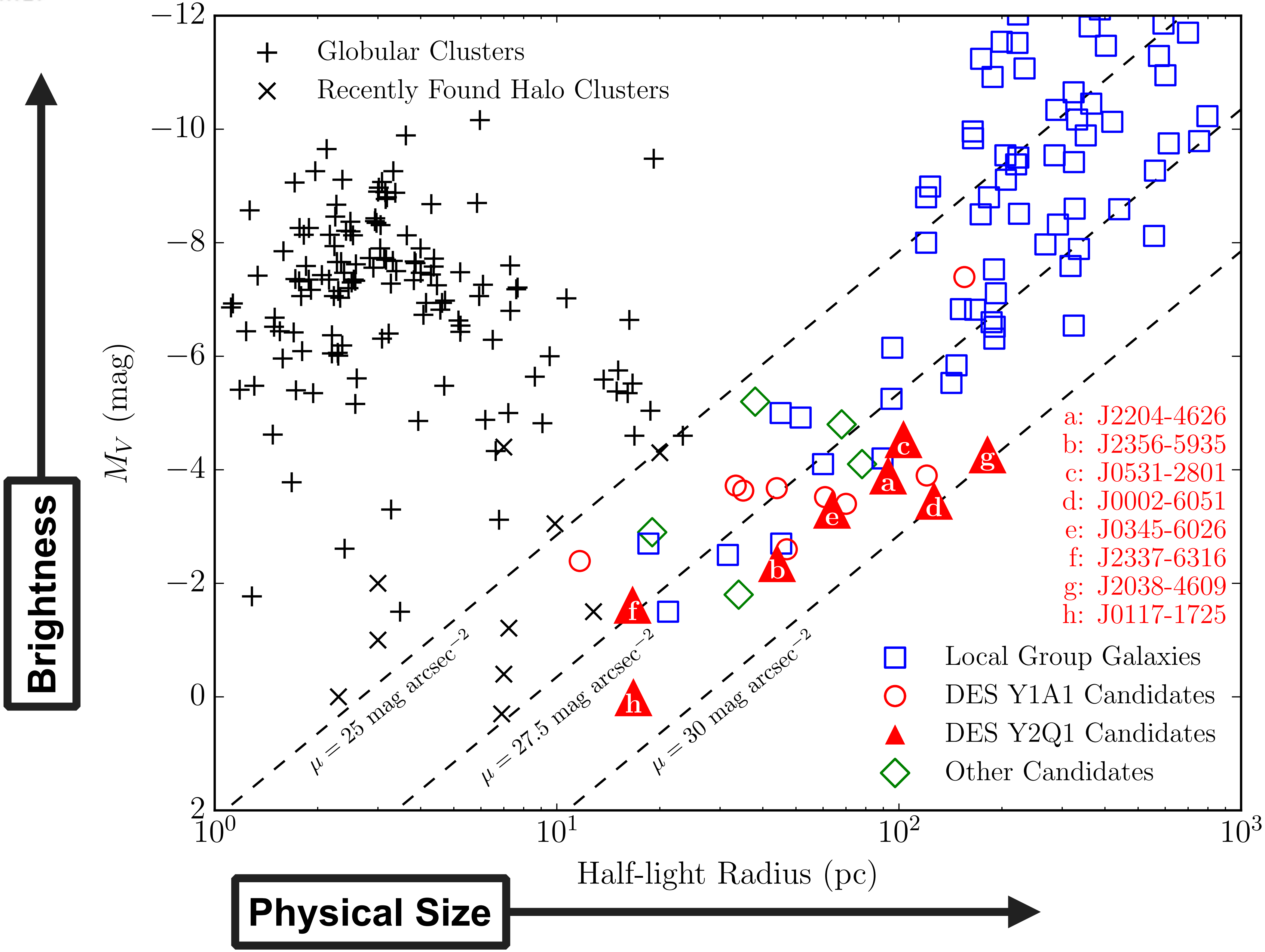
SDSS DR10 + DES Y2



Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS, SDSS, etc.

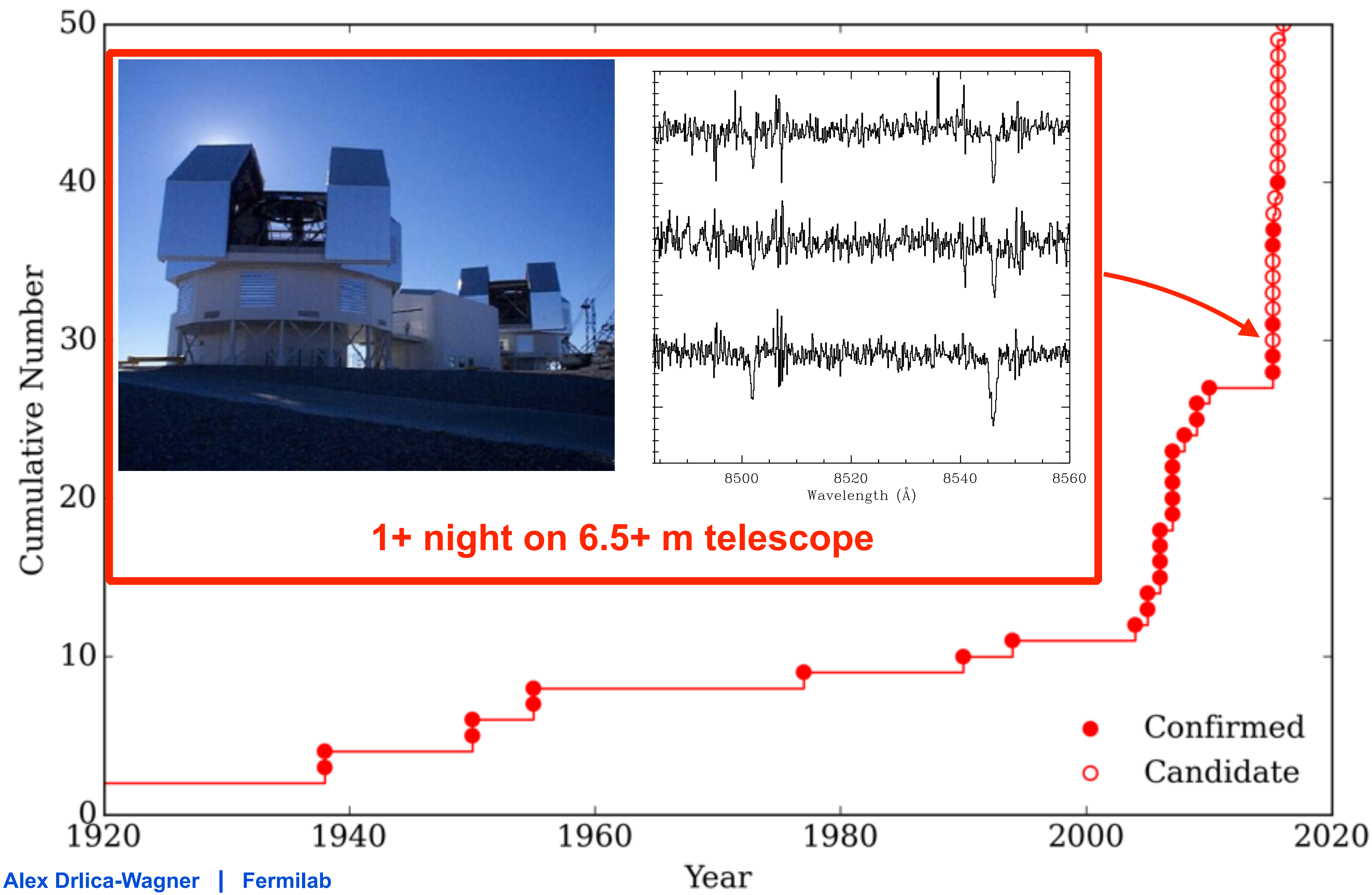
Red outline - DES footprint
Red circles - DES Y1 satellites
Red triangles - DES Y2 satellites

Galaxies or Star Clusters?



DES Collaboration, ApJ 813, 109 (2015)

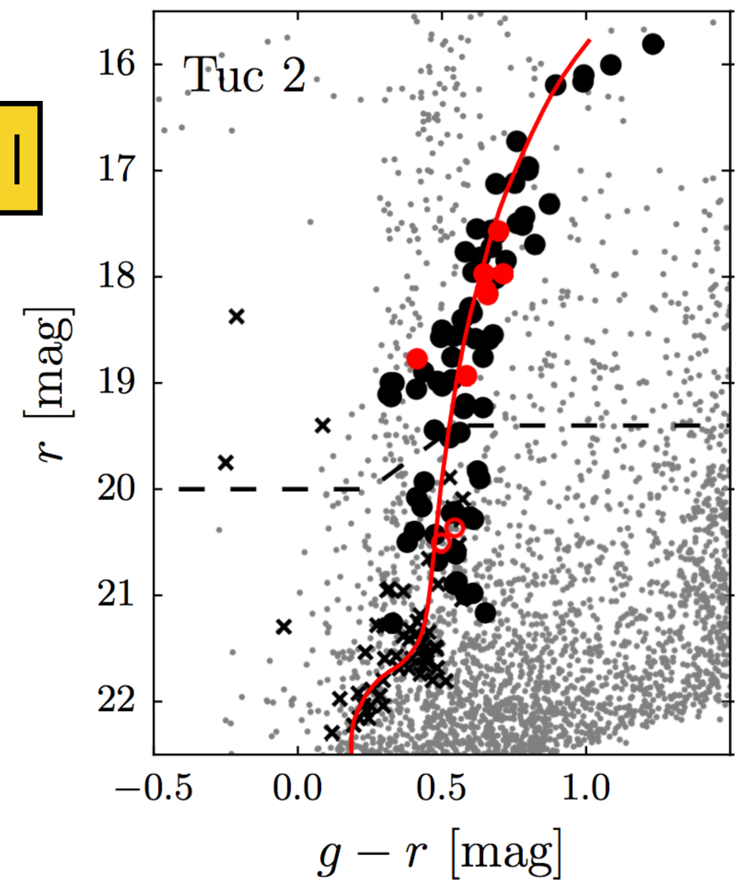
Discovery Timeline

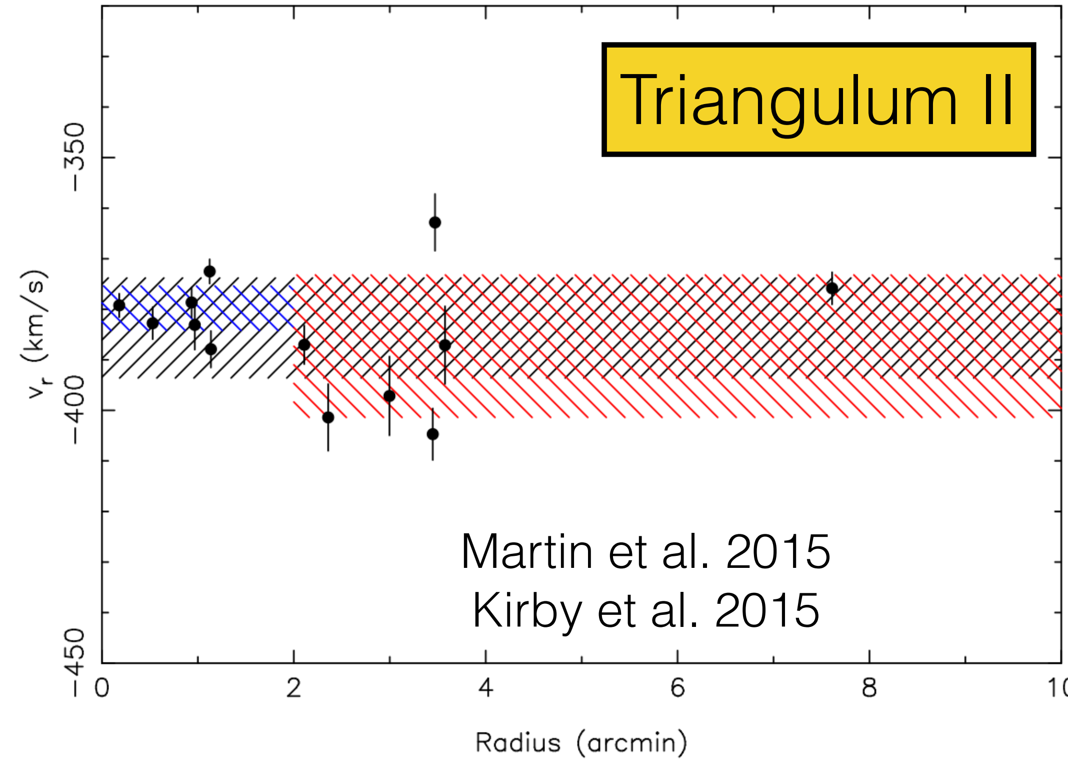


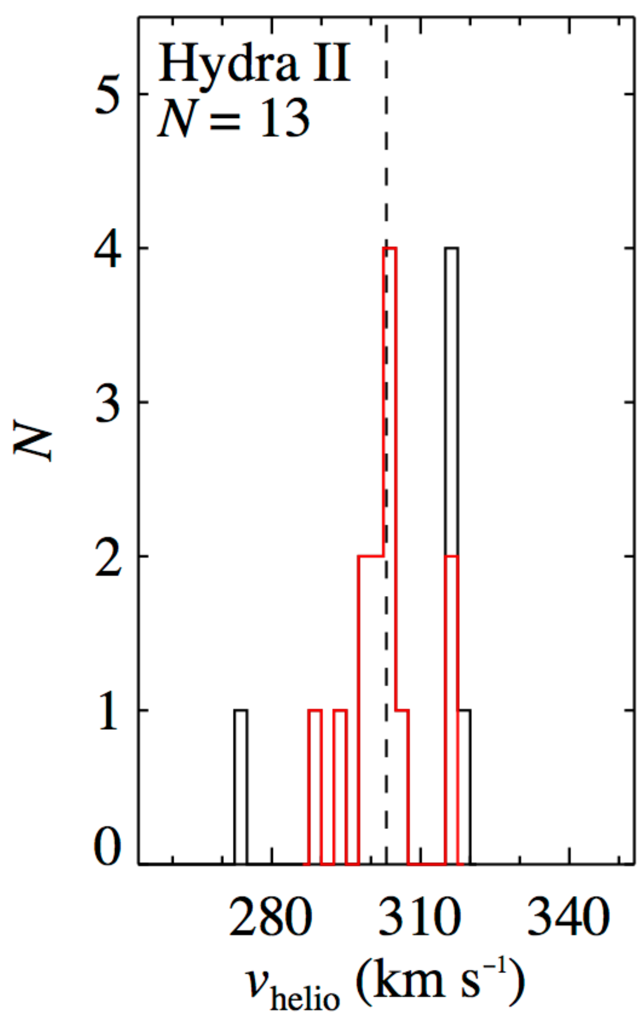
Spectroscopic Follow-up

Tucana II

Walker et al. 2015





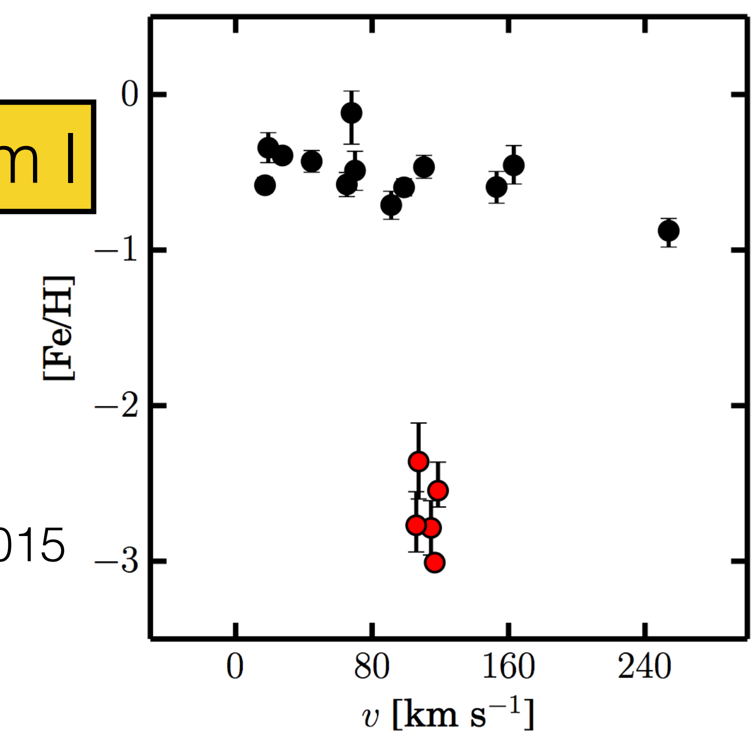


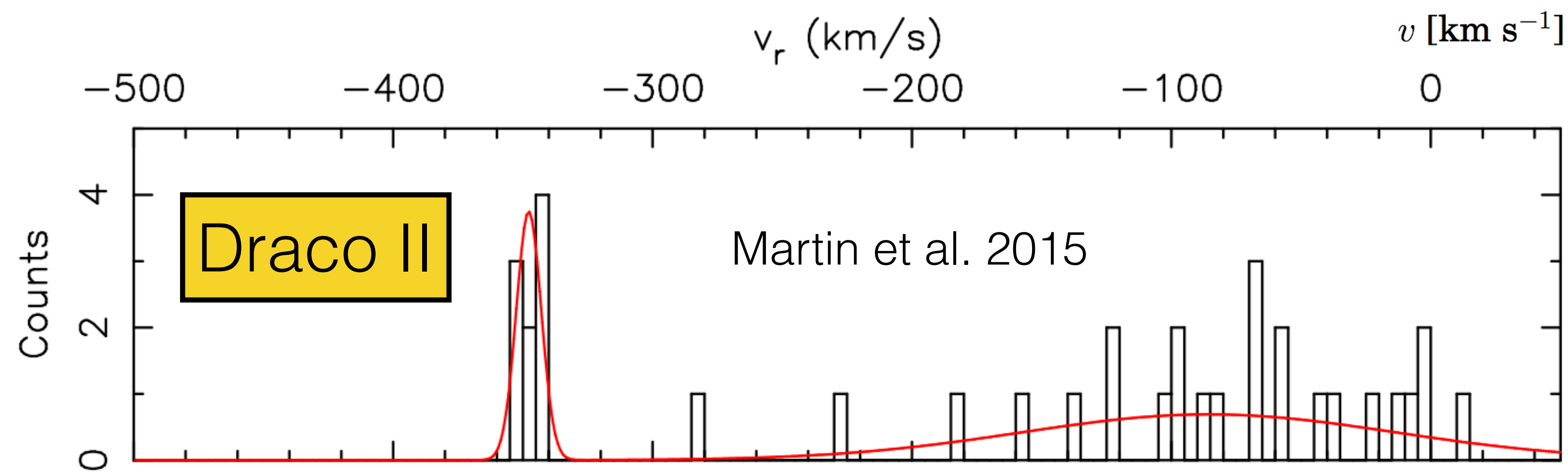
Kirby et al. 2015

Hydra II

Horologium I

Koposov et al. 2015





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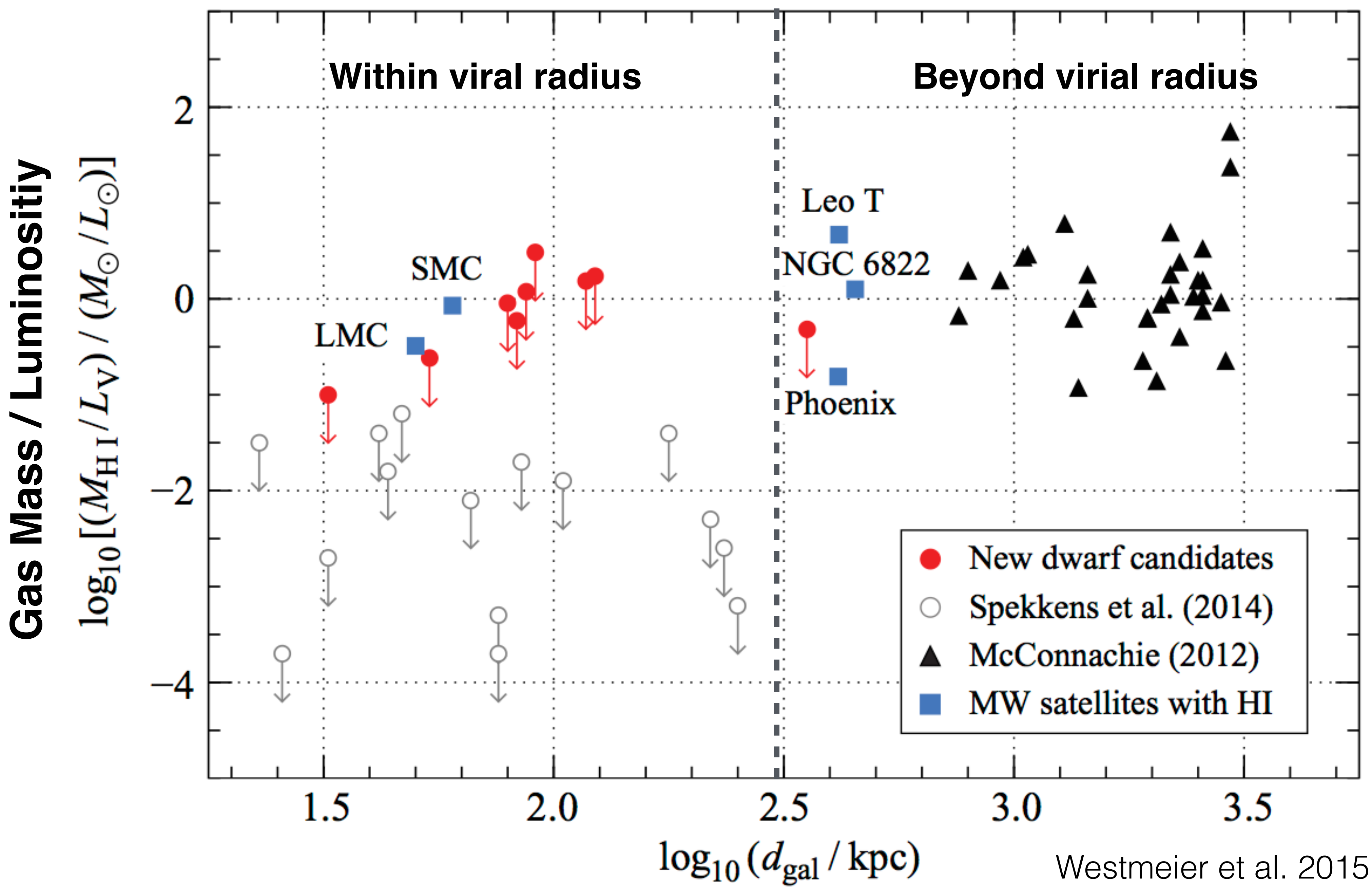
Low Neutral Gas Content

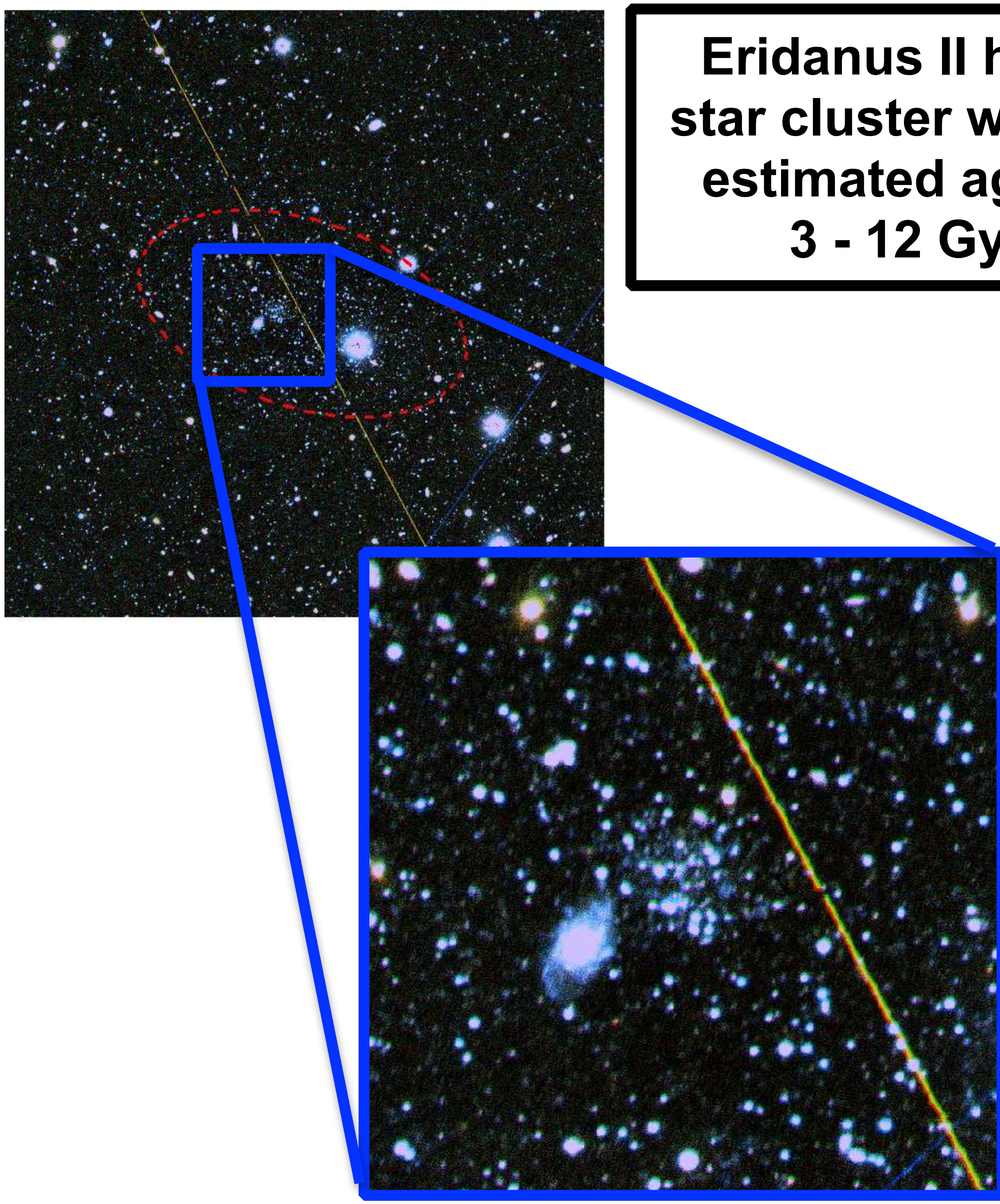
Nine dSphs found in first-year DES data found to have low neutral gas content, similar to previously known dSphs around the Milky Way



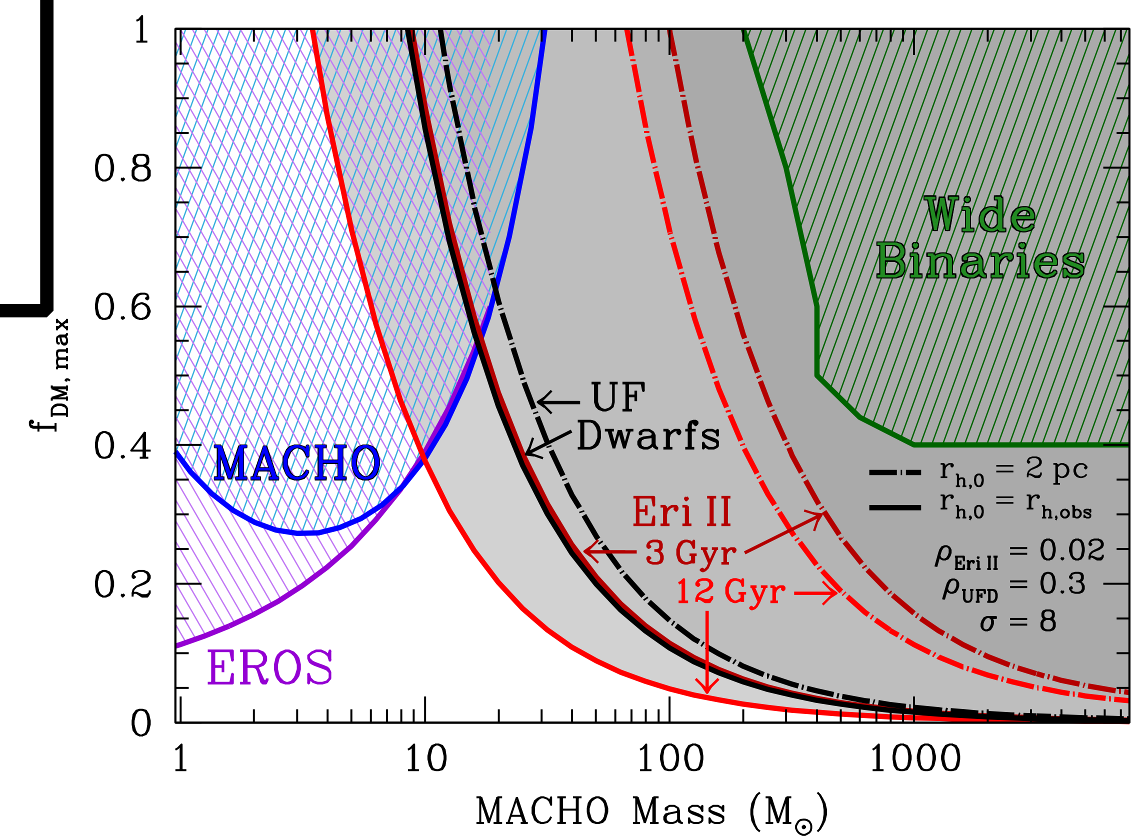
Westmeier et al. 2015, MNRAS, 453, 338

Galaxies beyond Milky Way virial radius tend to be more gas rich than those within

MACHOs in Eridanus II



Eridanus II has a star cluster with an estimated age of 3 - 12 Gyr



MACHO dark matter would disrupt this cluster by dynamical heating.

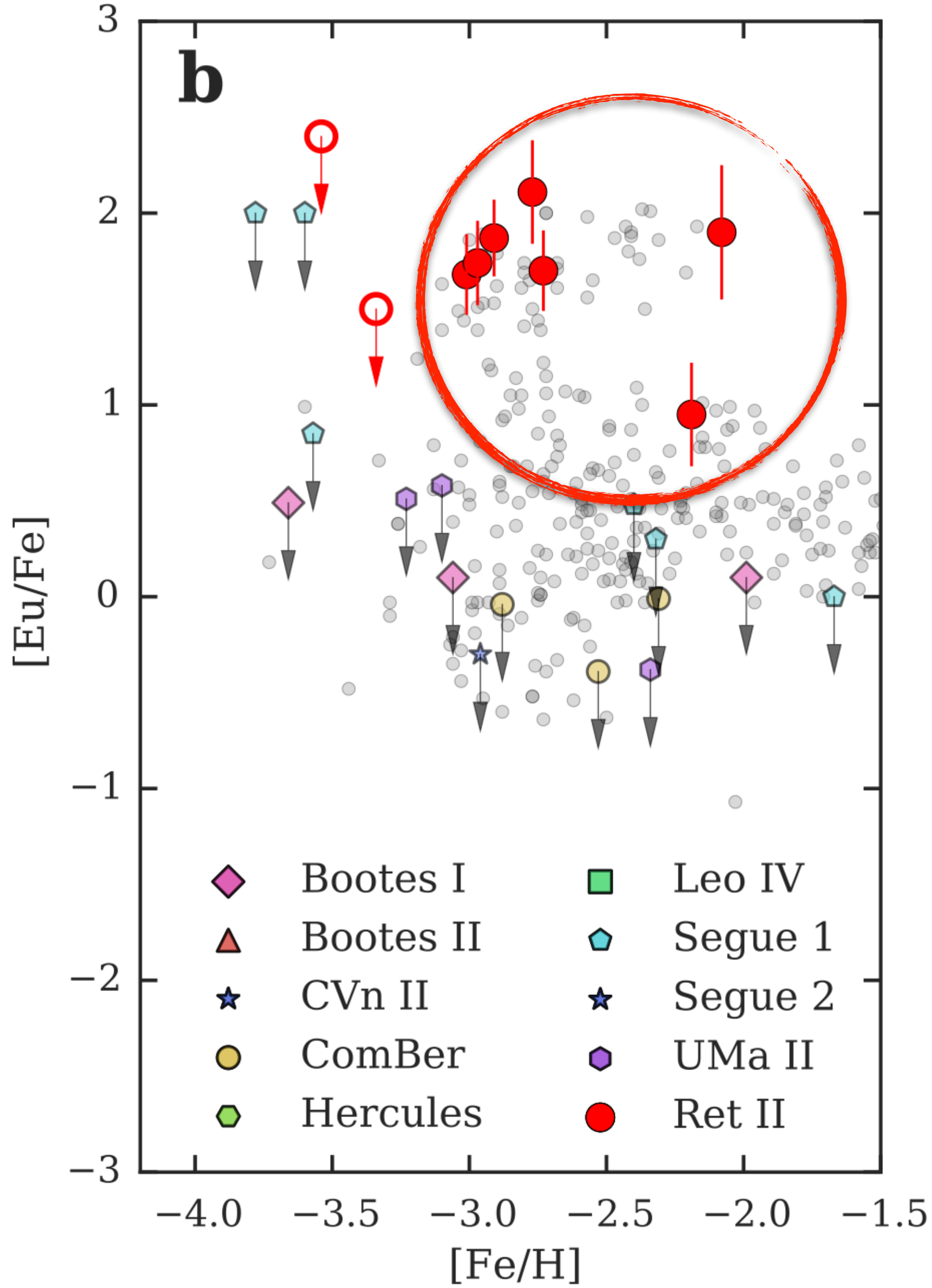
The existence of the star cluster can place limits on the fraction of MACHO dark matter

Crnojevic et al. [1604.08590]

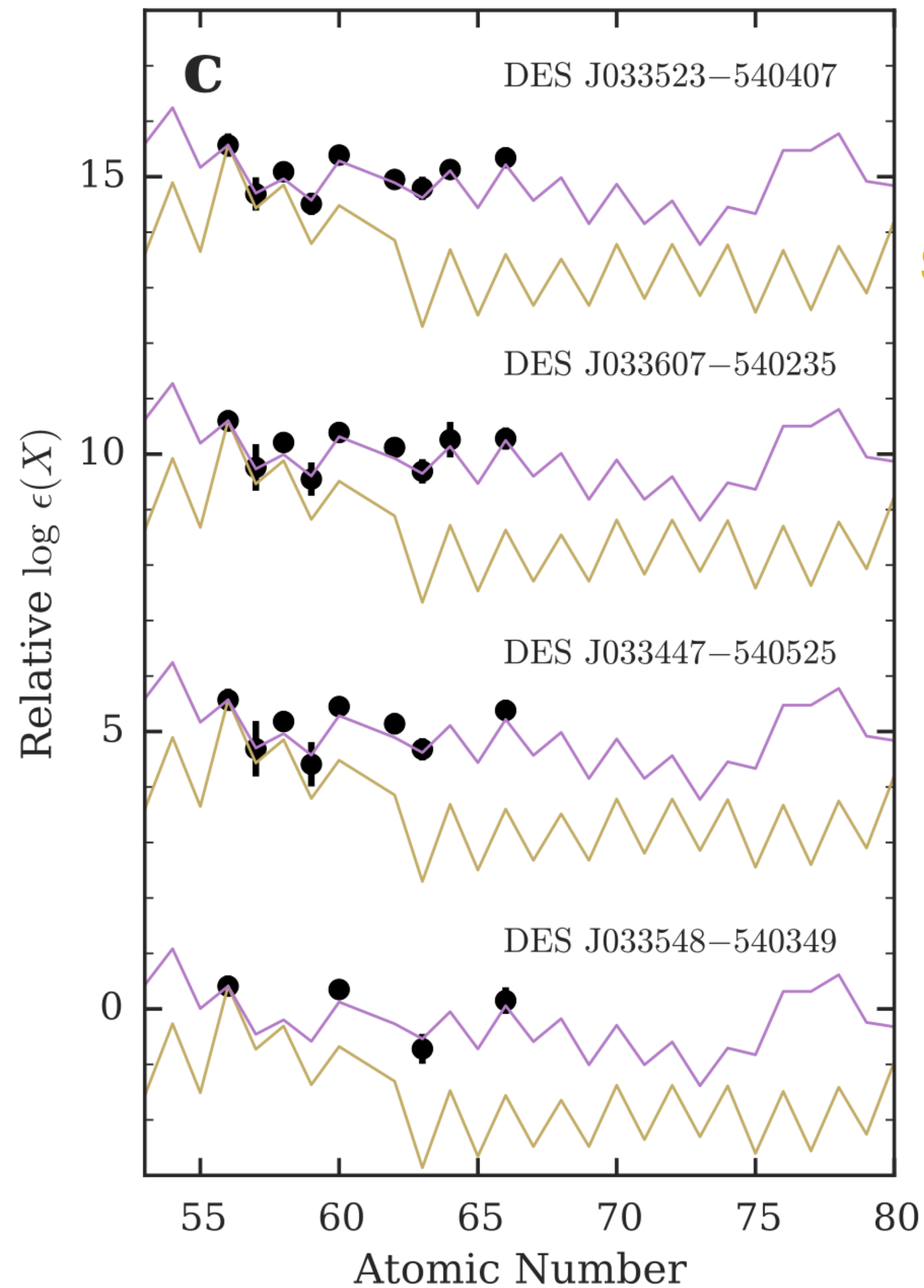
Brandt [1605.03665]

Heavy Elements in Reticulum II

Using europium as representative r-process element

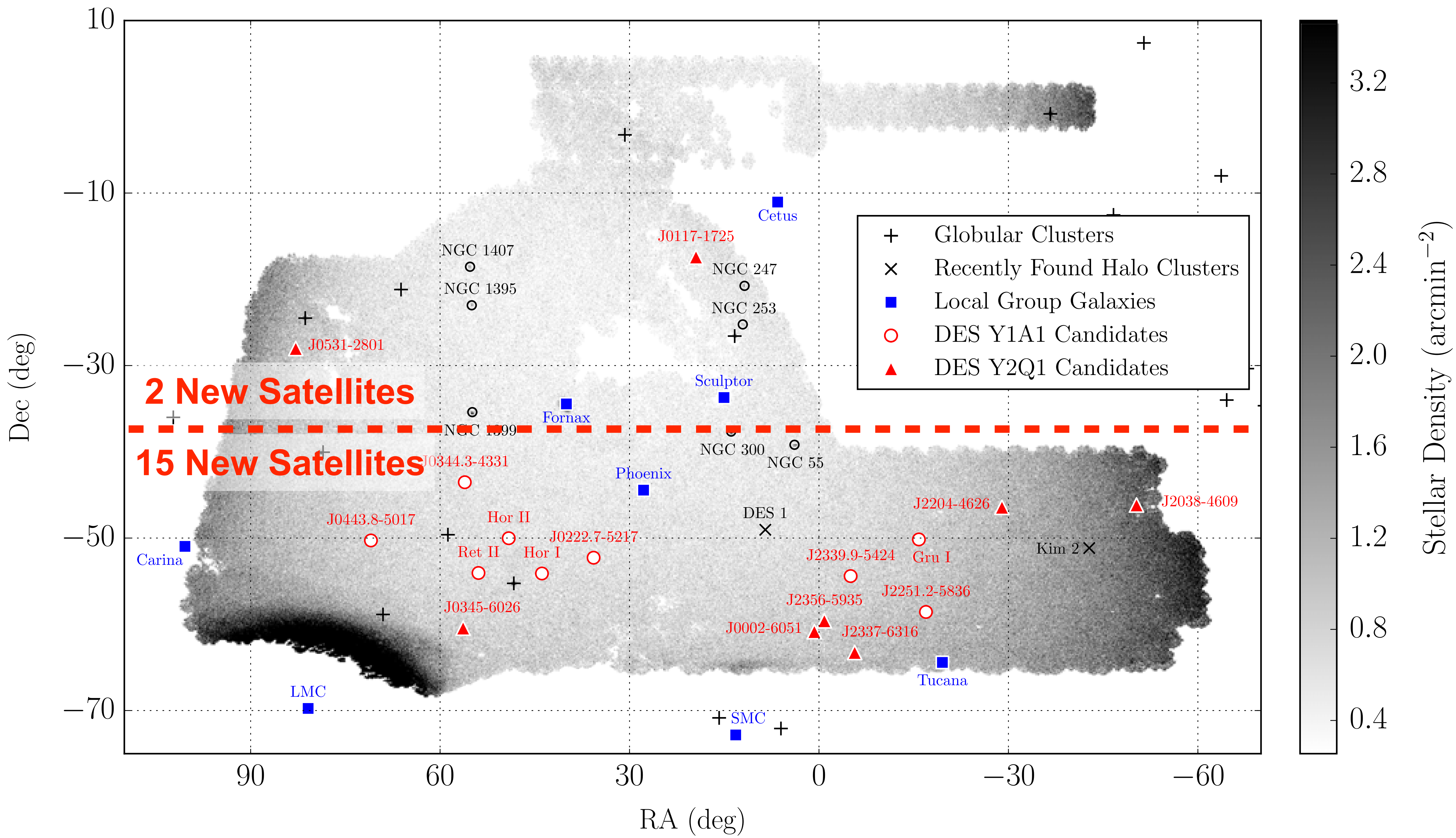


Neutron-capture abundance patterns for 4 brightest Ret II stars



Ji et al. (2015) [arxiv:1512.01558]
also see Roederer et al. (2016) [1601.04070]

DES Satellite Distribution

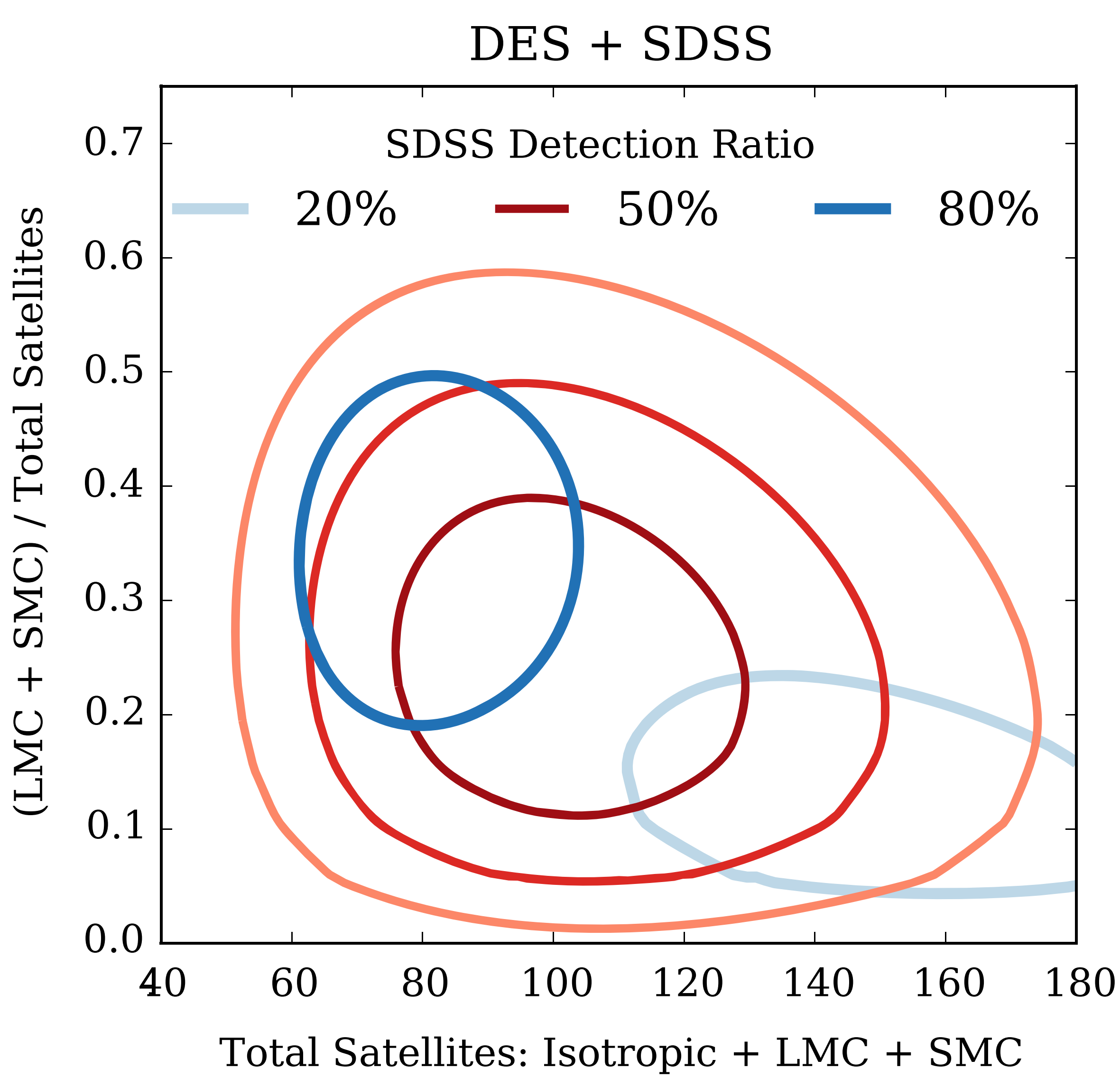


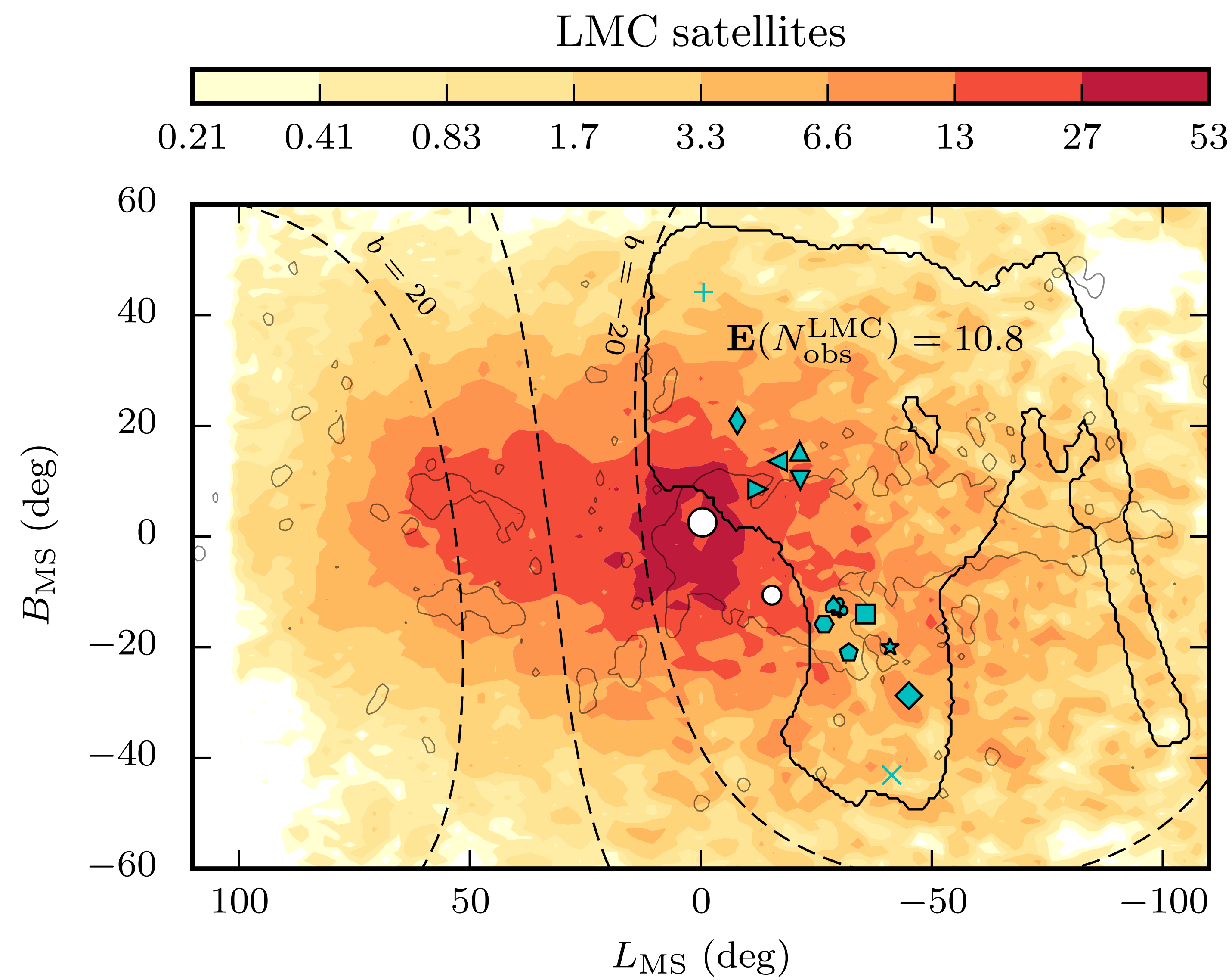
DES Collaboration, ApJ 813, 109 (2015)

Magellanic Satellites?

With DES sensitivity expect 100+ satellites over the entire sky

30+ of these satellites contributed by the LMC/SMC





DES Collaboration [1503.02584]

Jethwa et al [1603.04420]

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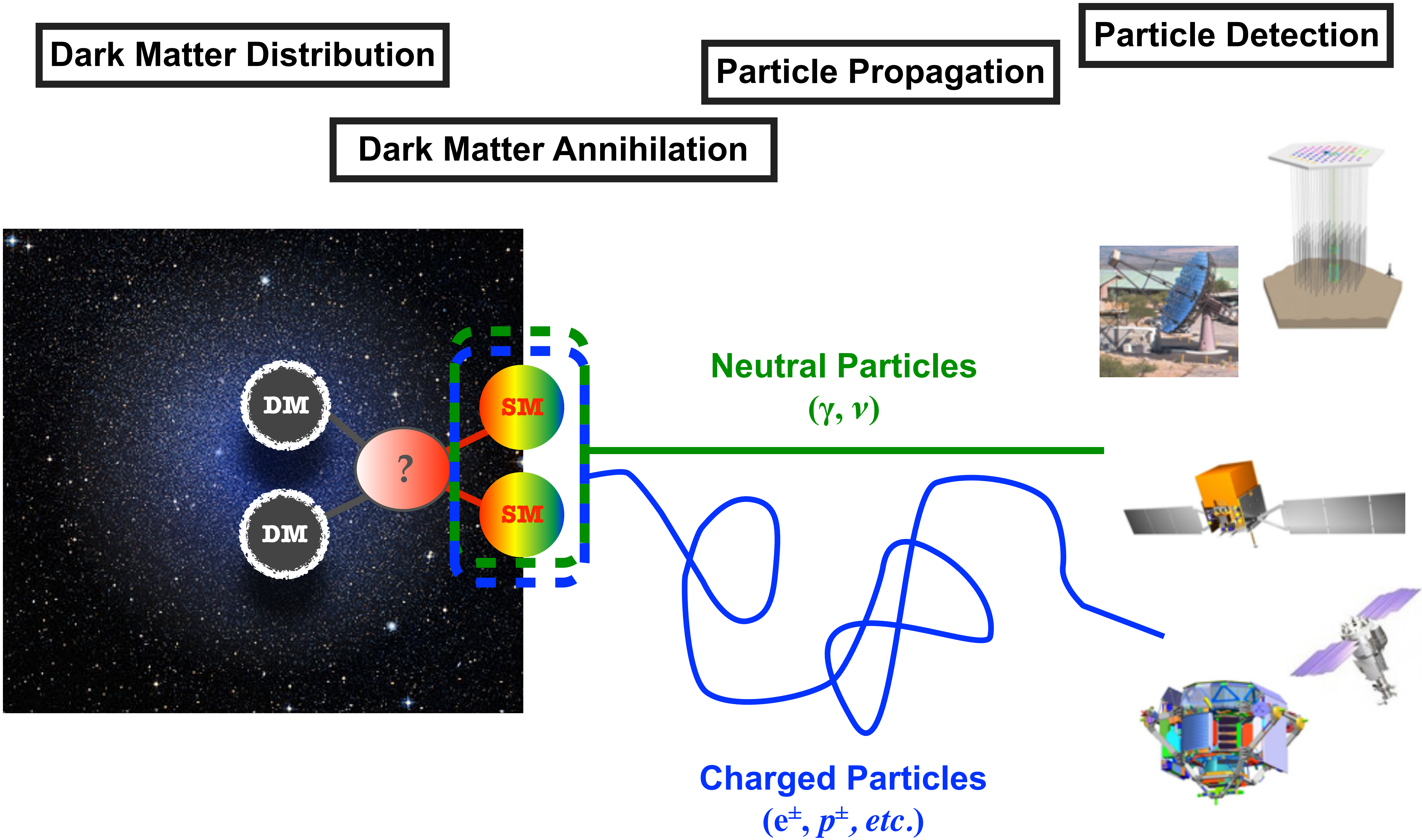
- ❖ **Dwarf Galaxies and Dark Matter**
- ❖ Future Prospects

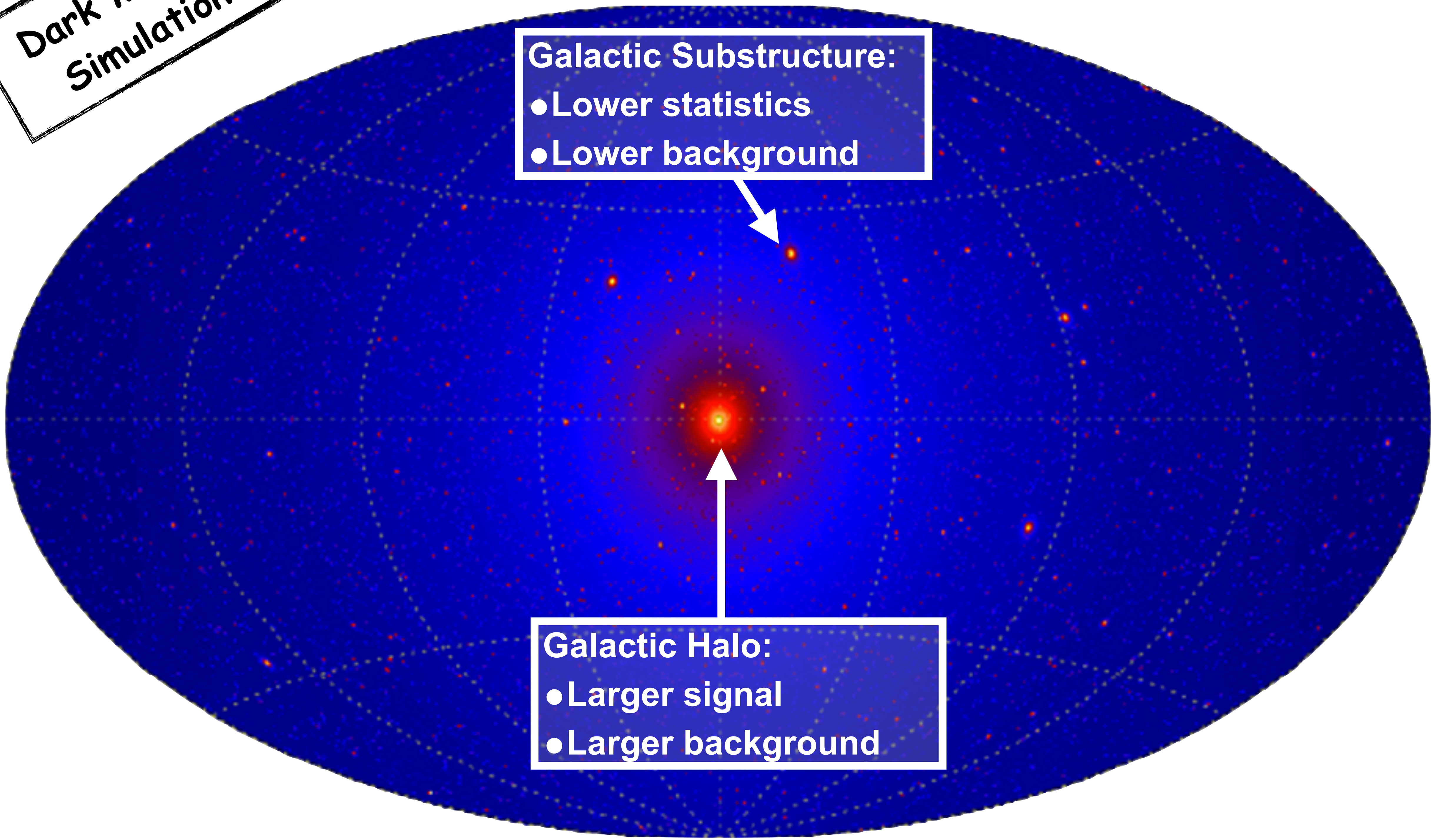
Indirect Detection



Dark Matter Distribution

Dark Matter Simulation

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



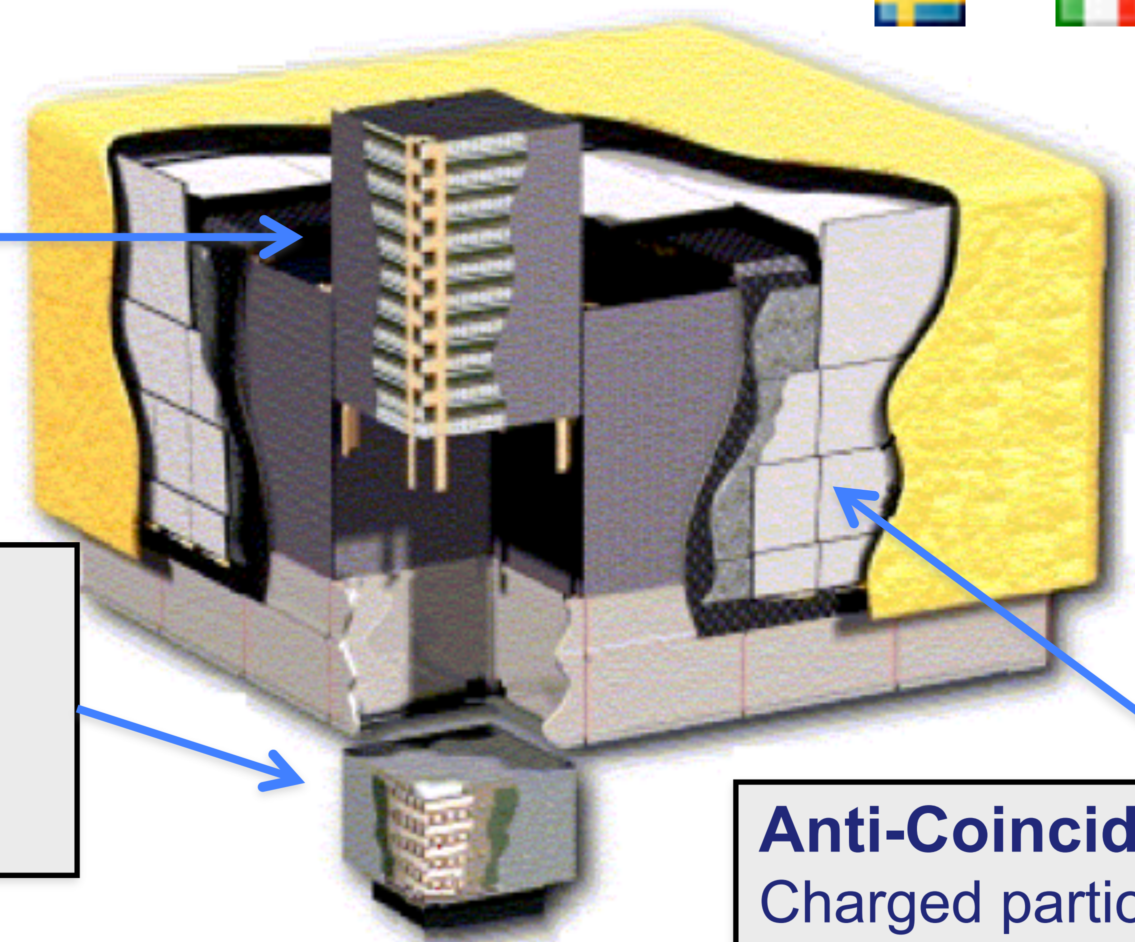
Pieri et al. Phys Rev D83, 023518 (2011)

The Fermi Large Area Telescope

Fermi LAT Collaboration:
~400 Scientific Members,
NASA / DOE & International Contributions

Public Data Release:
All γ-ray data made public within 24 hours (usually less)

Si-Strip Tracker:
convert $\gamma \rightarrow e^+e^-$
reconstruct γ direction
EM vs. hadron separation



No Magnet

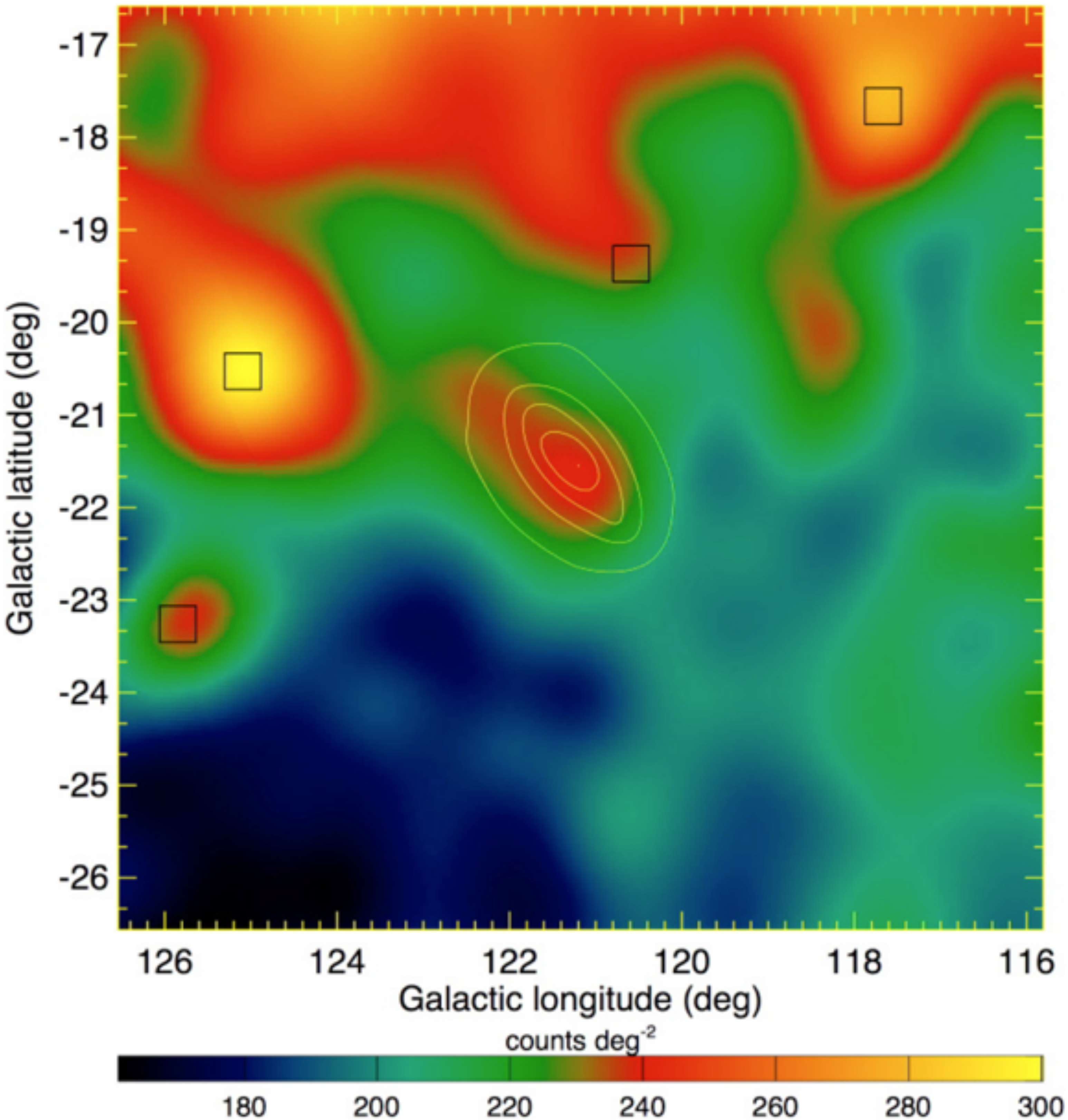
Hodoscopic CsI Calorimeter:
measure γ energy
image EM shower
EM v. hadron separation

Anti-Coincidence Detector:
Charged particle separation

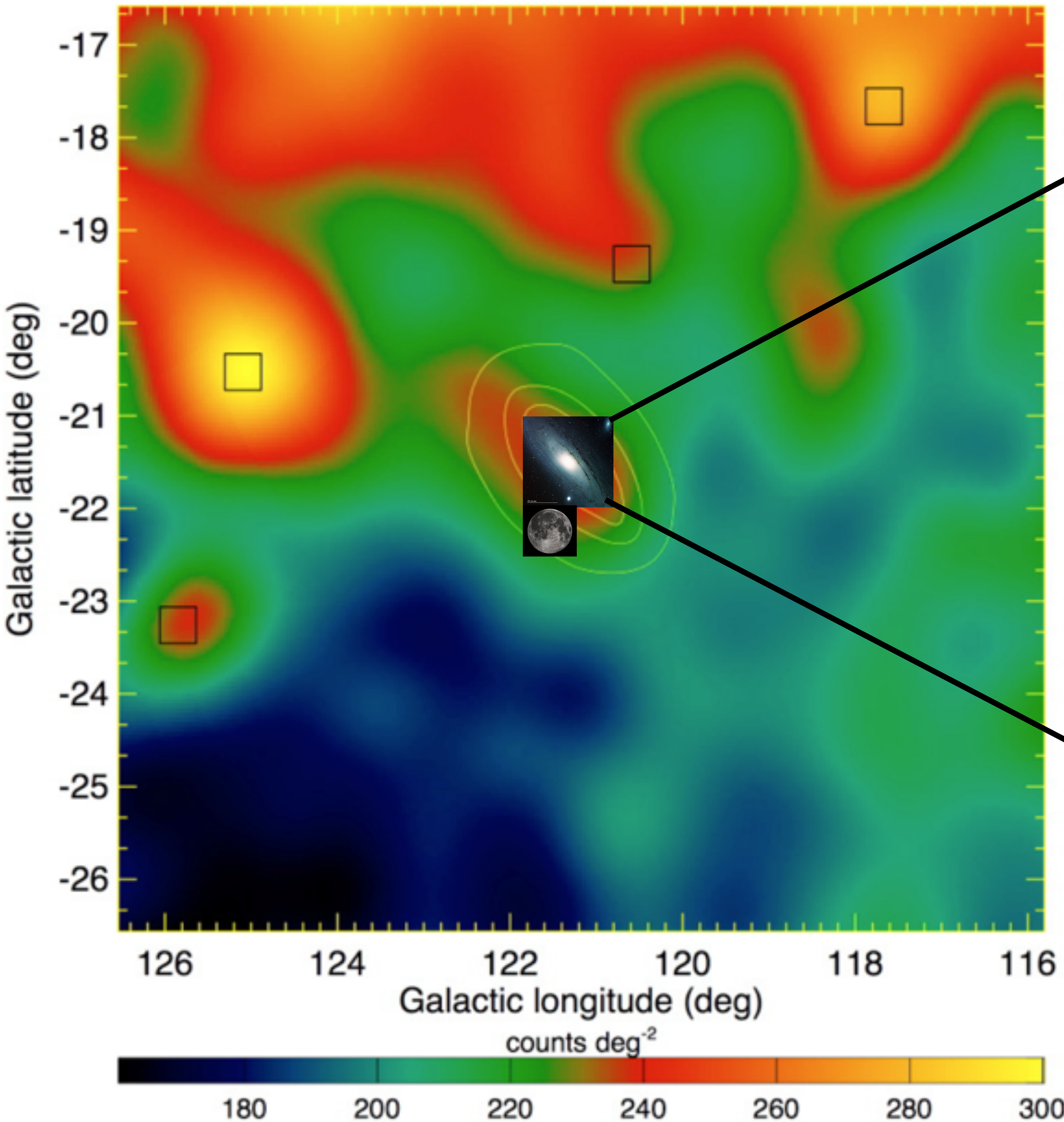
Sky Survey:
The LAT observes the whole sky every 3 hours (2.5 sr FOV)

Trigger and Filter:
Reduce data rate from ~10kHz to 300-500 Hz

Fermi-LAT Performance

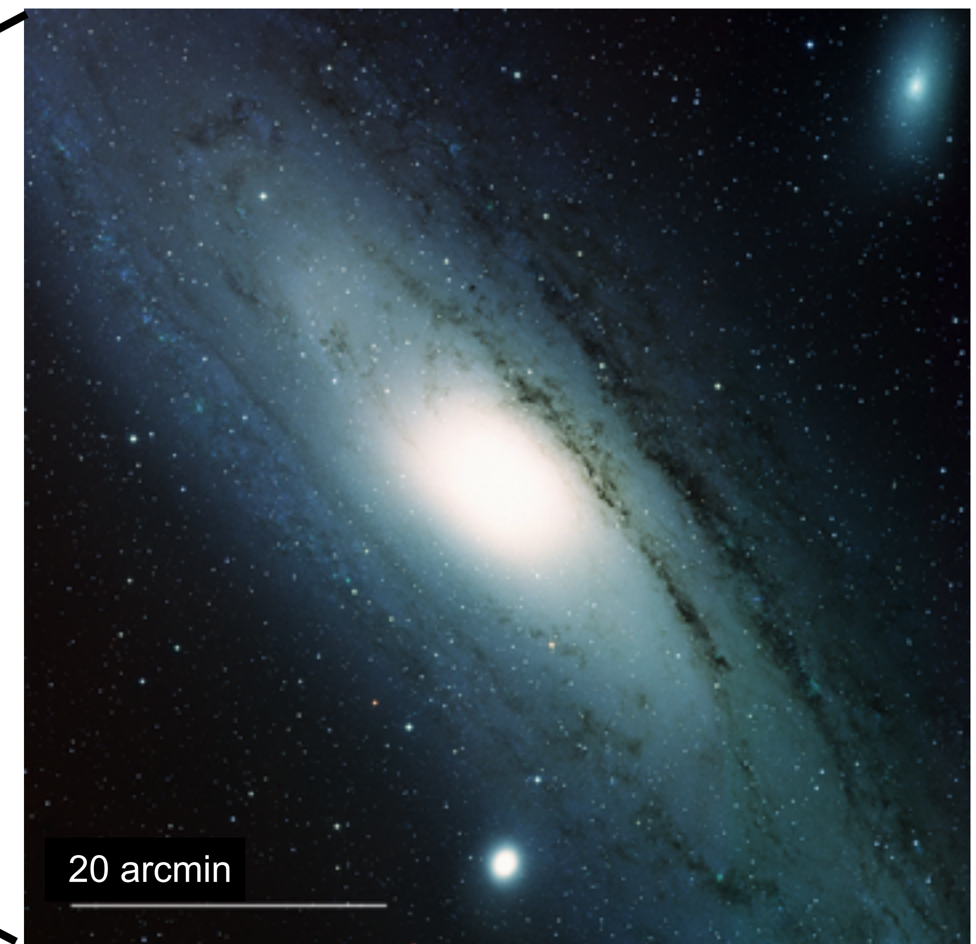


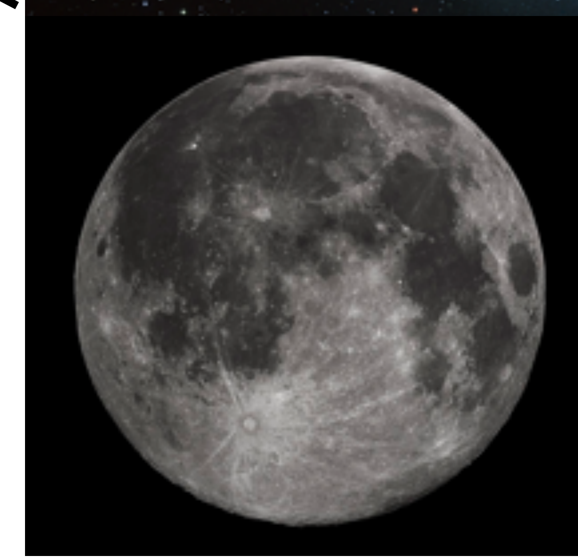
Fermi-LAT Performance



Andromeda (M31)

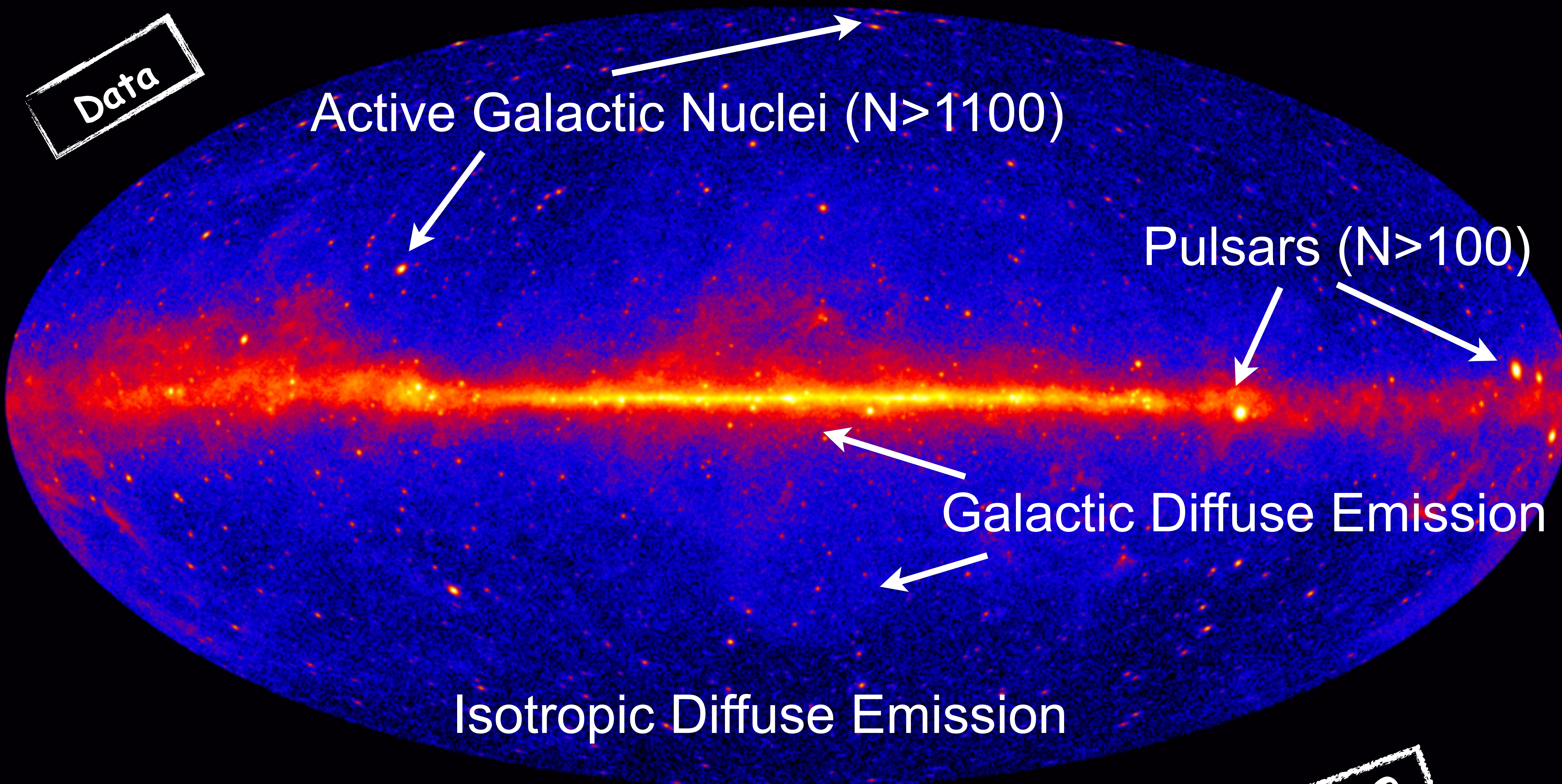
Optical DSS Image





Gamma-Ray Data ($E_\gamma > 1$ GeV)

Data



+ a lot of additional astrophysics …

+ Dark Matter?

The Galactic Center

The Galactic Center is an appealing target for dark matter searches

- Rich in dark matter
- Relatively nearby

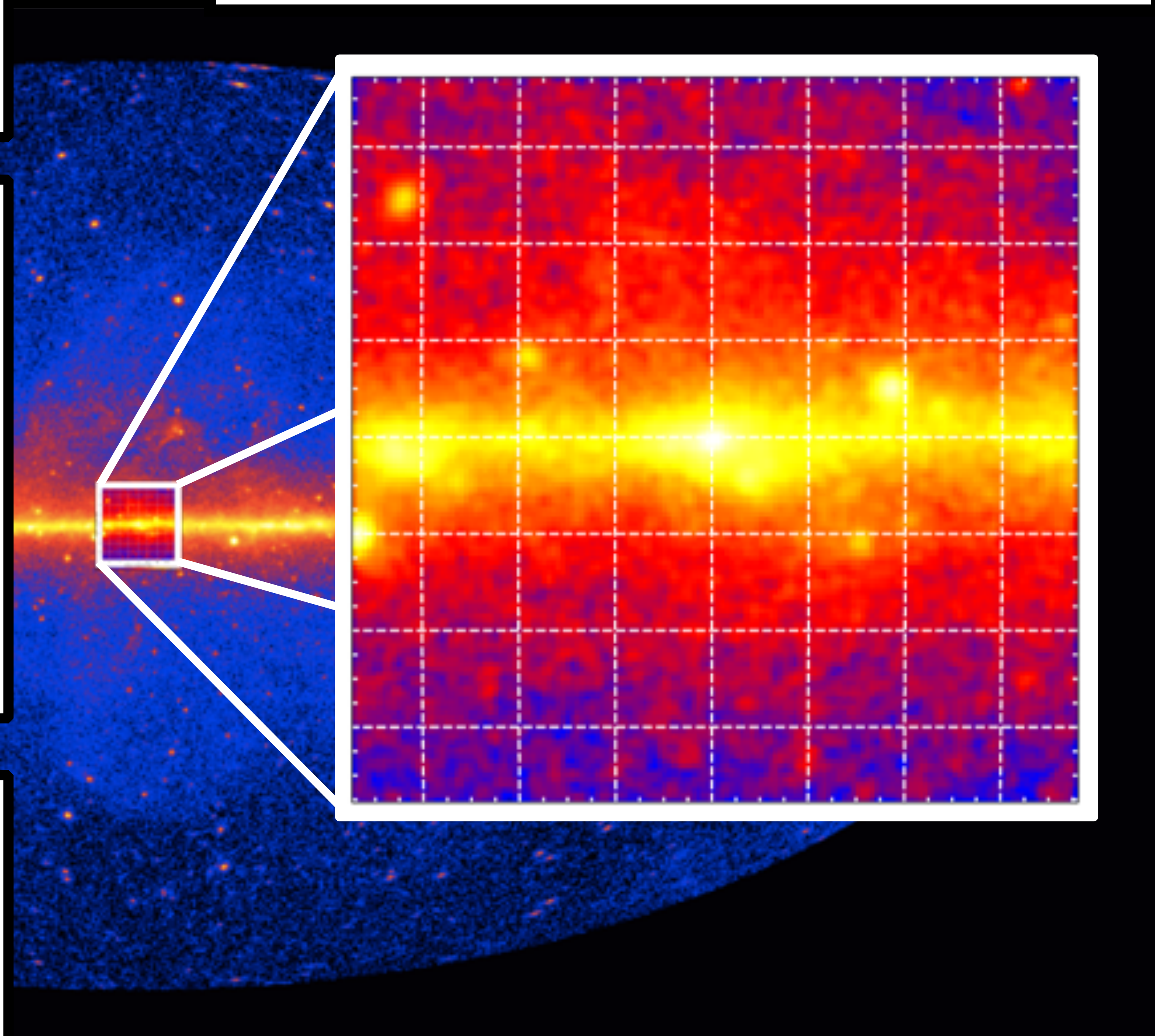
However, the Galactic Center is astrophysically complicated

- Diffuse emission from cosmic-ray interactions with Galactic gas and dust
- Densely populated by astrophysical sources (e.g., pulsars, SNR), which are detected in other wavelengths (e.g., radio, X-ray, TeV)

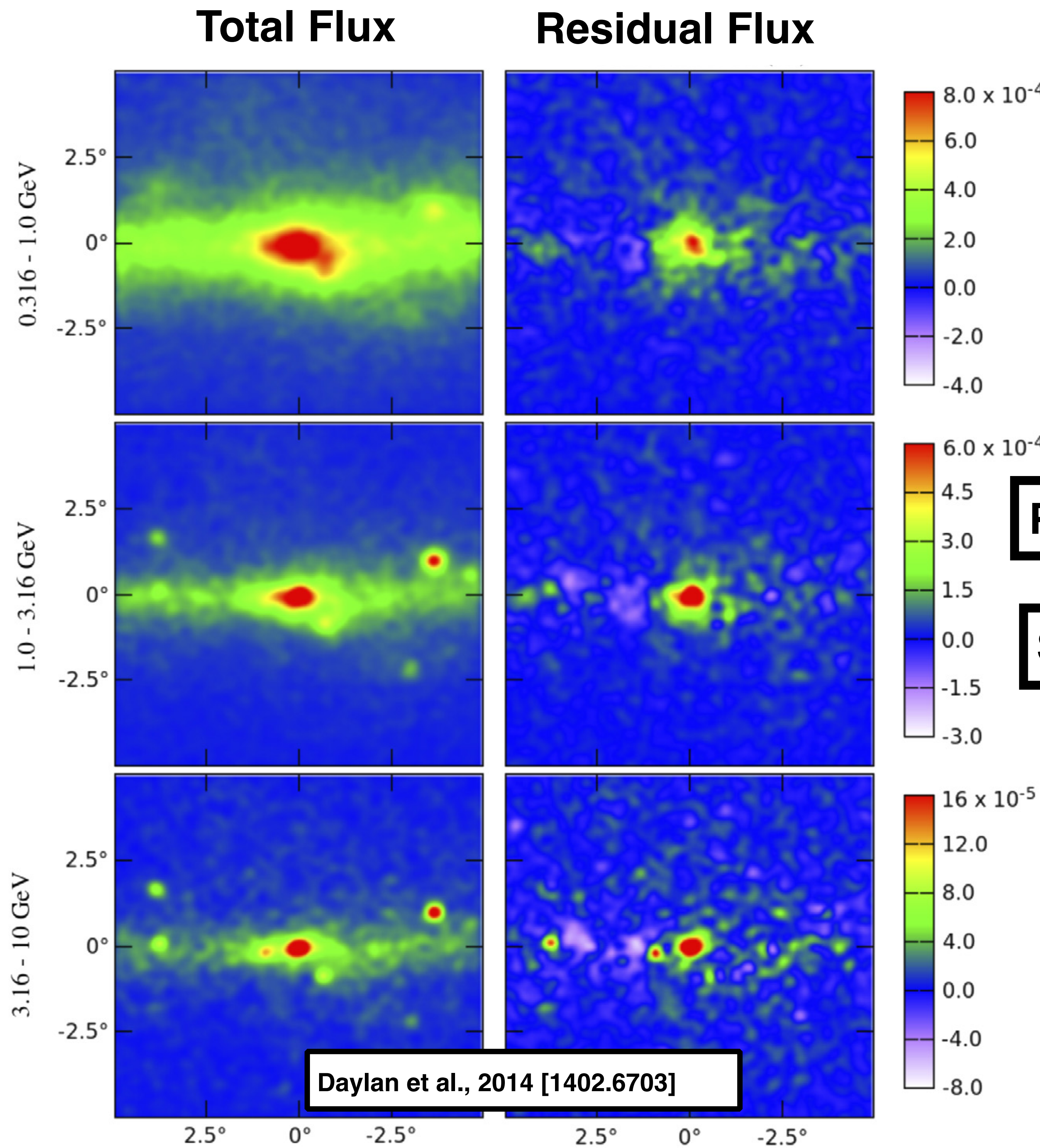
Topic of extensive recent research (much led here at Fermilab)…

- Hooper & Linden (2011); Boyarski et al. (2011); Abazajian & Kaplinghat (2012); Gordon & Macias (2013); Huang et al. (2013); Abazajian et al. (2014); Daylan et al. (2014); Calore et al. (2014); Lee et al. (2015); Bartels et al. (2015) Ajello et al. (2015); etc.

Gamma-ray Data ($E_\gamma > 1$ GeV)



The Galactic Center



Peaks at a few GeV

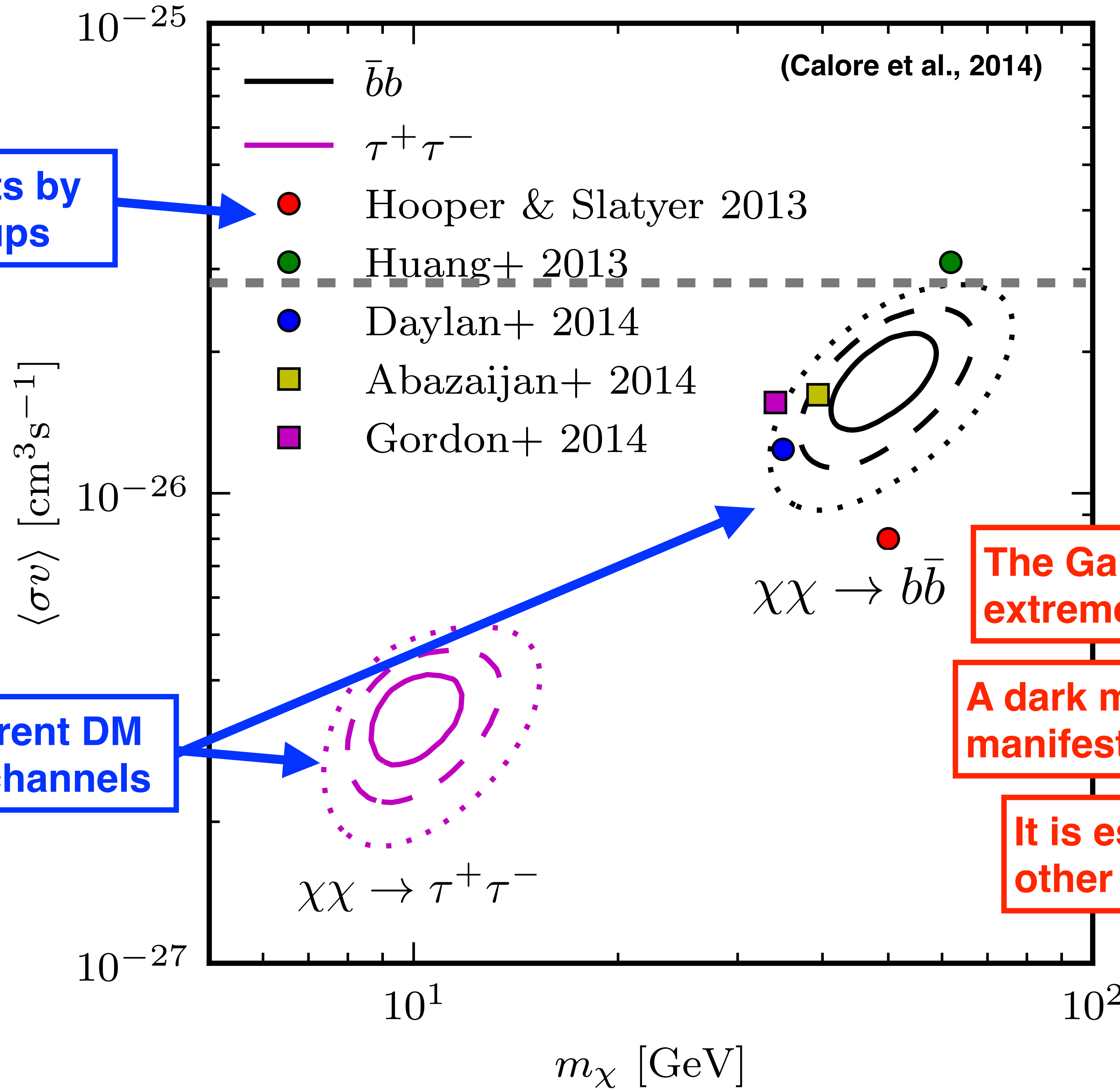
Spatially extended

Daylan et al., 2014 [1402.6703]

The Galactic Center

Measurements by different groups

Assume different DM annihilation channels



Thermal Relic Cross Section

The Galactic Center is an extremely complicated region

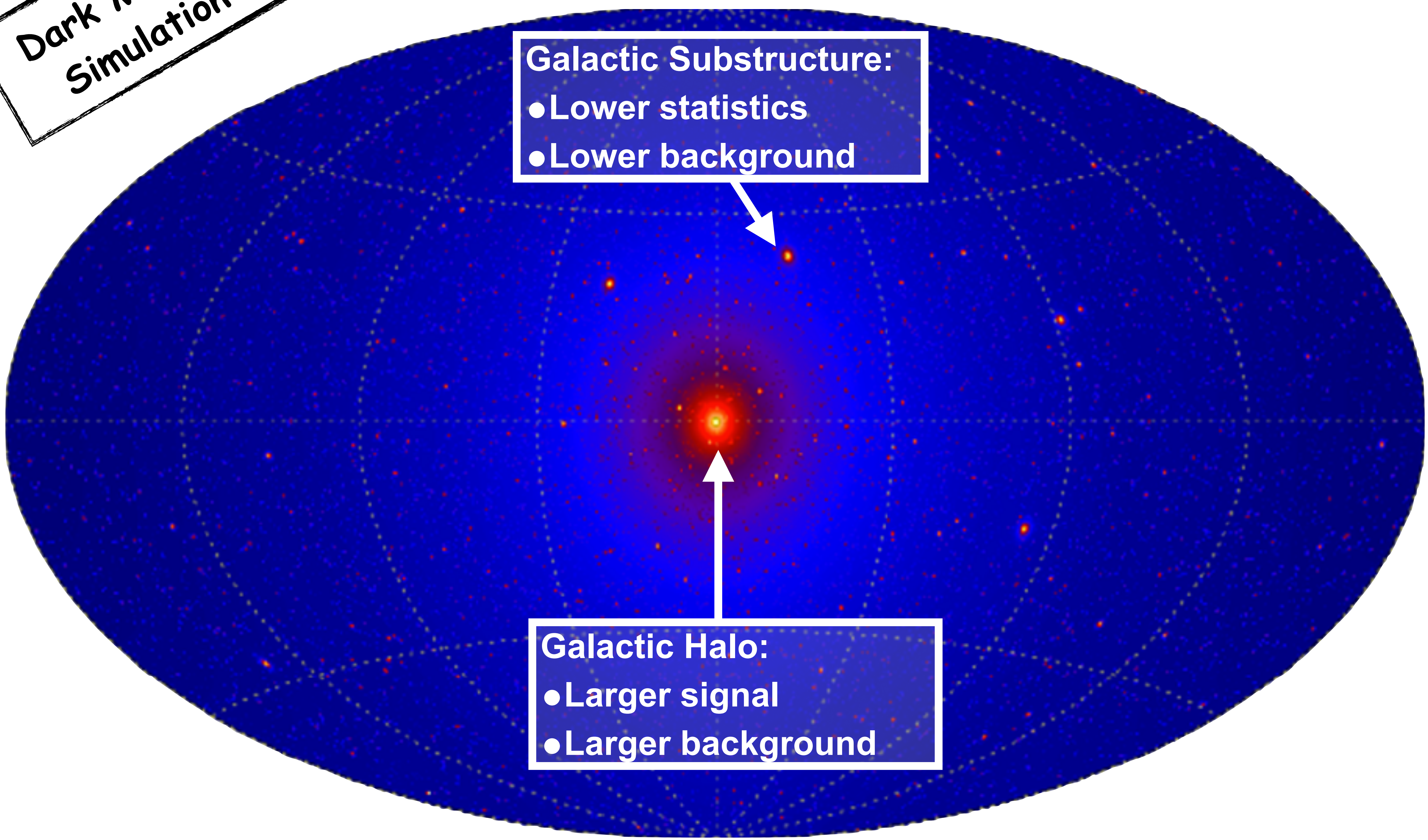
A dark matter signal should manifest itself in other regions

It is essential to investigate other dark matter targets

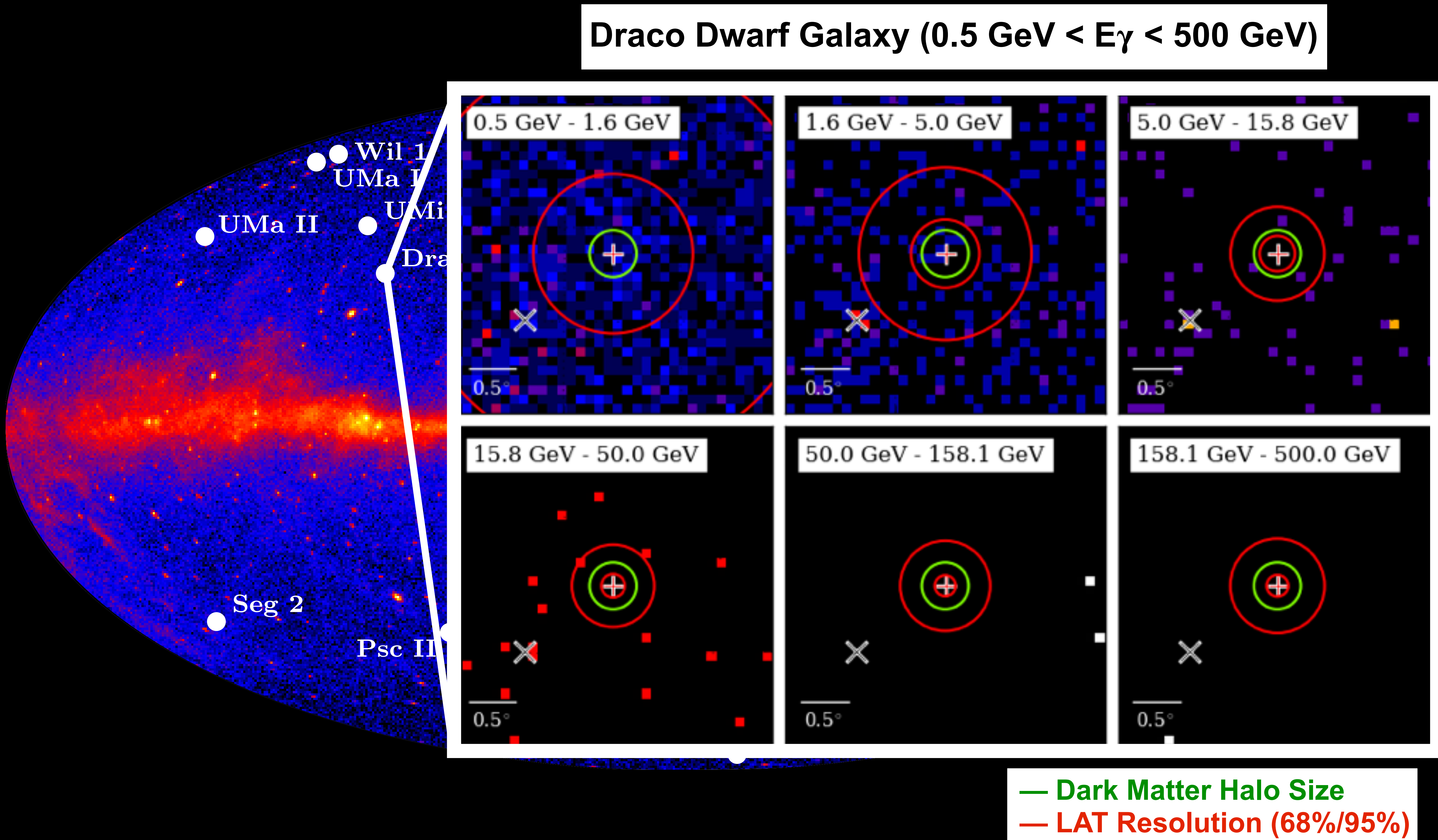
Dark Matter Distribution

Dark Matter Simulation

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$



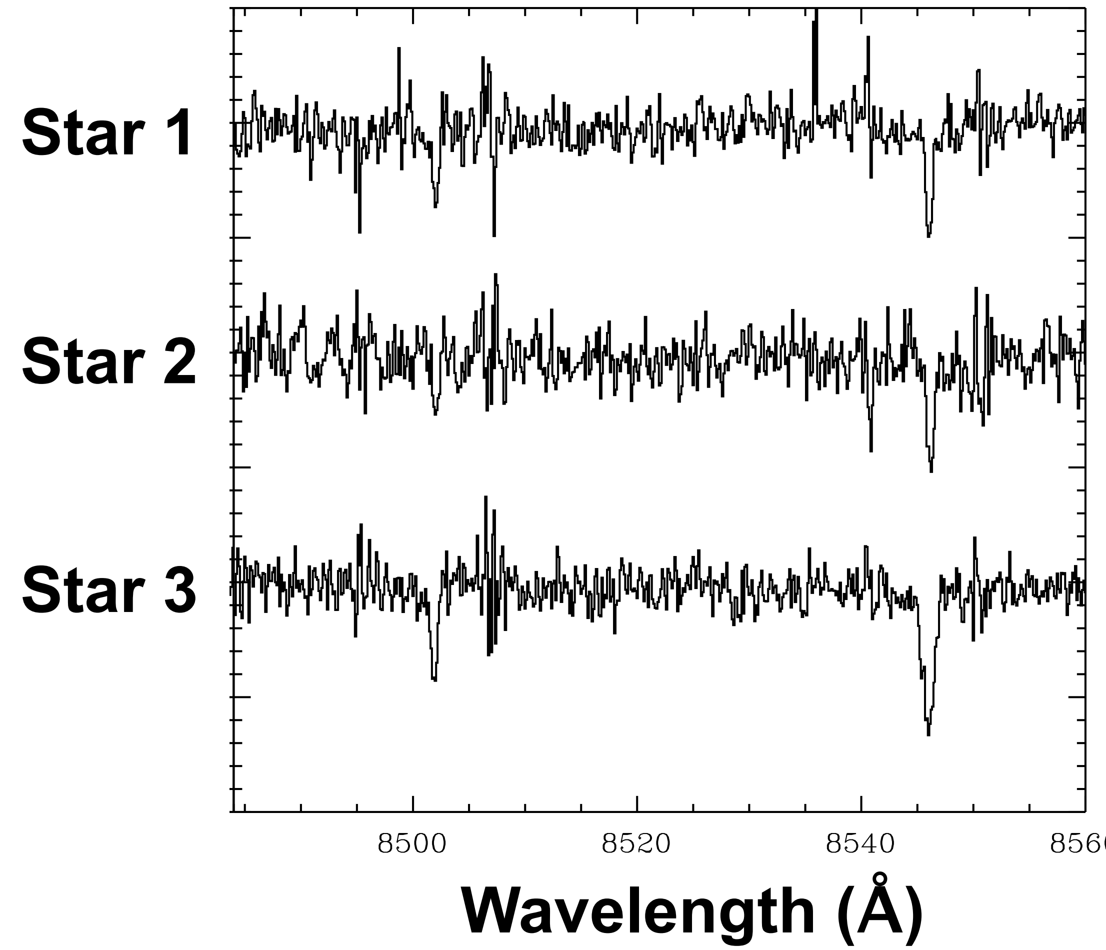
Milky Way Satellite Galaxies

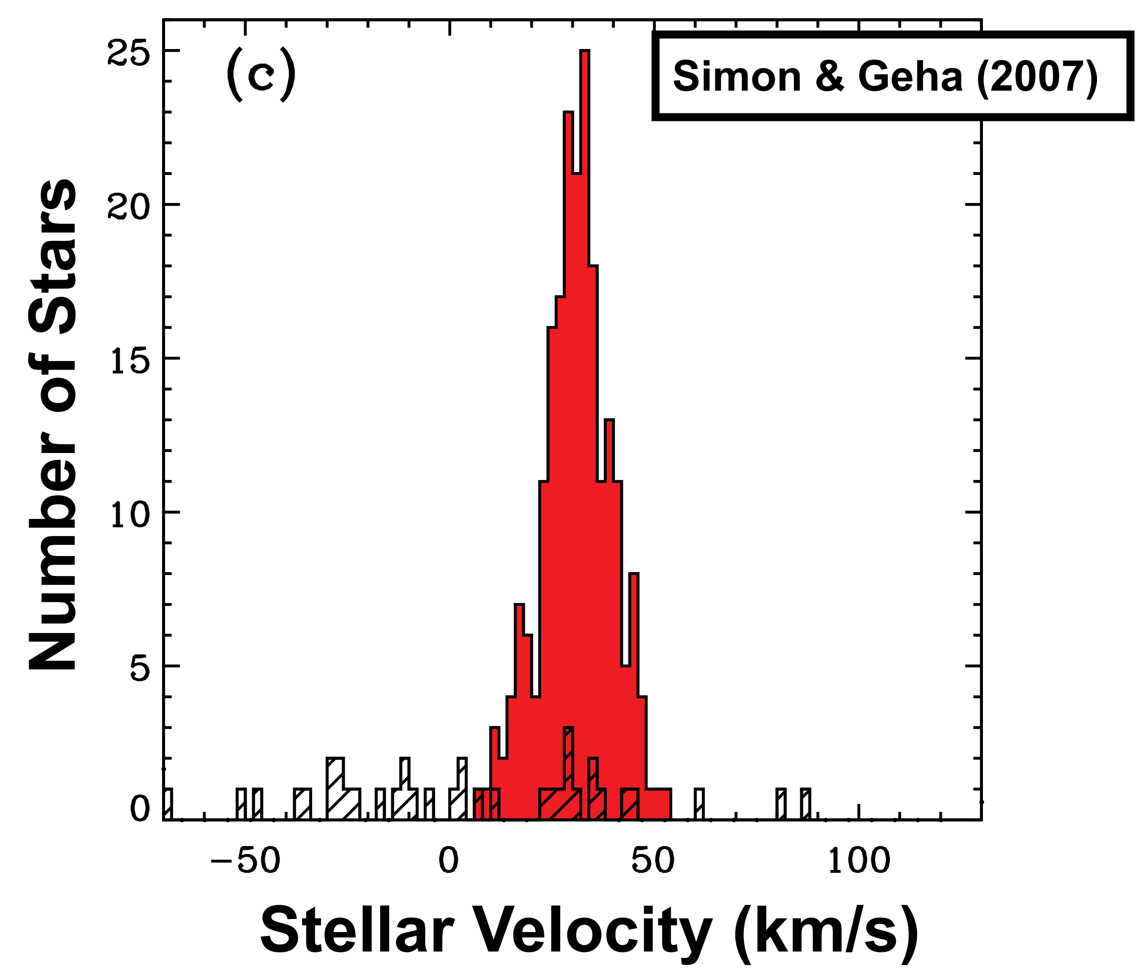


Dark Matter Content (J-Factor)

$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

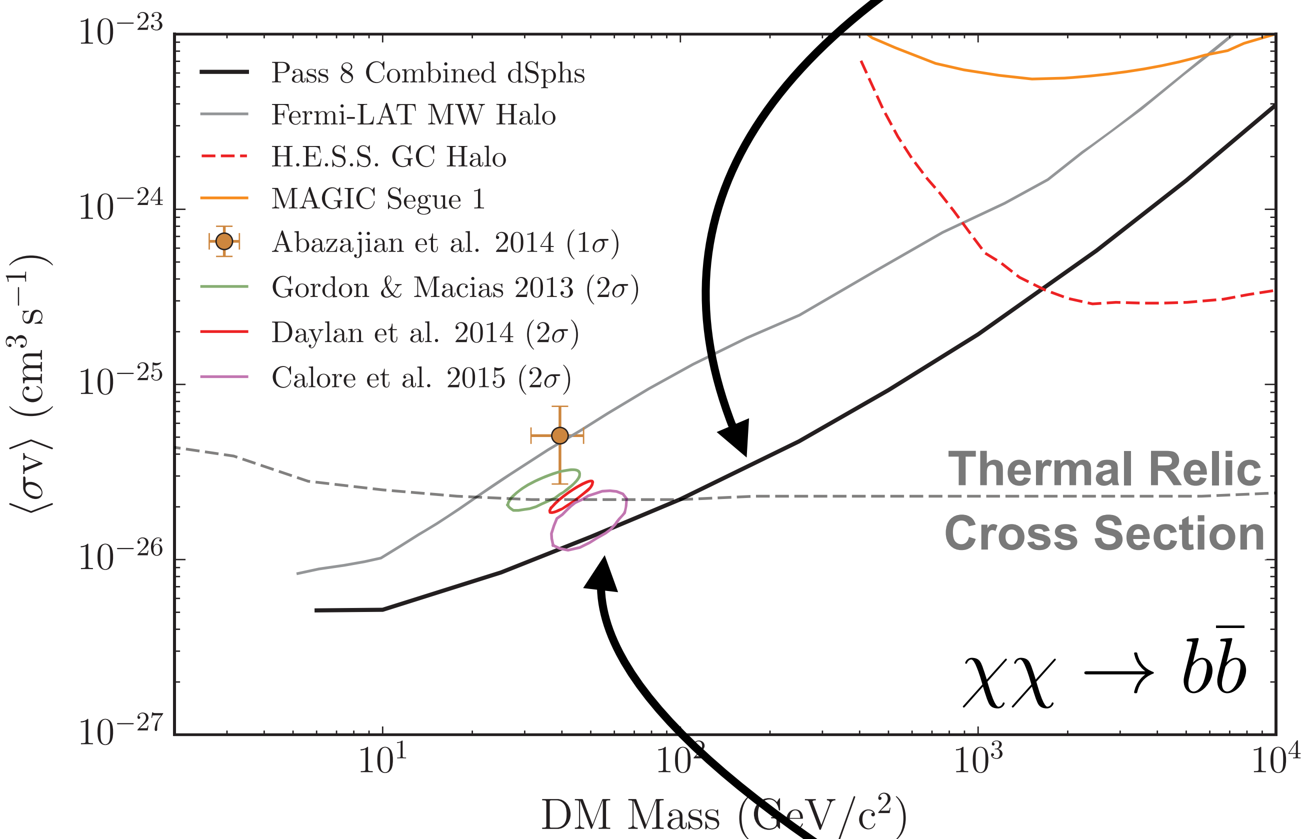
- The dark matter content of dwarf galaxies can be determined from the velocities of their stars
- Measure the Doppler shift of atomic lines in stellar spectra
  - Bright dwarf galaxies: velocities for thousands of stars
  - Faint dwarf galaxies: velocities for fewer than one hundred stars
- A large dispersion of stellar velocities requires a large gravitational binding force

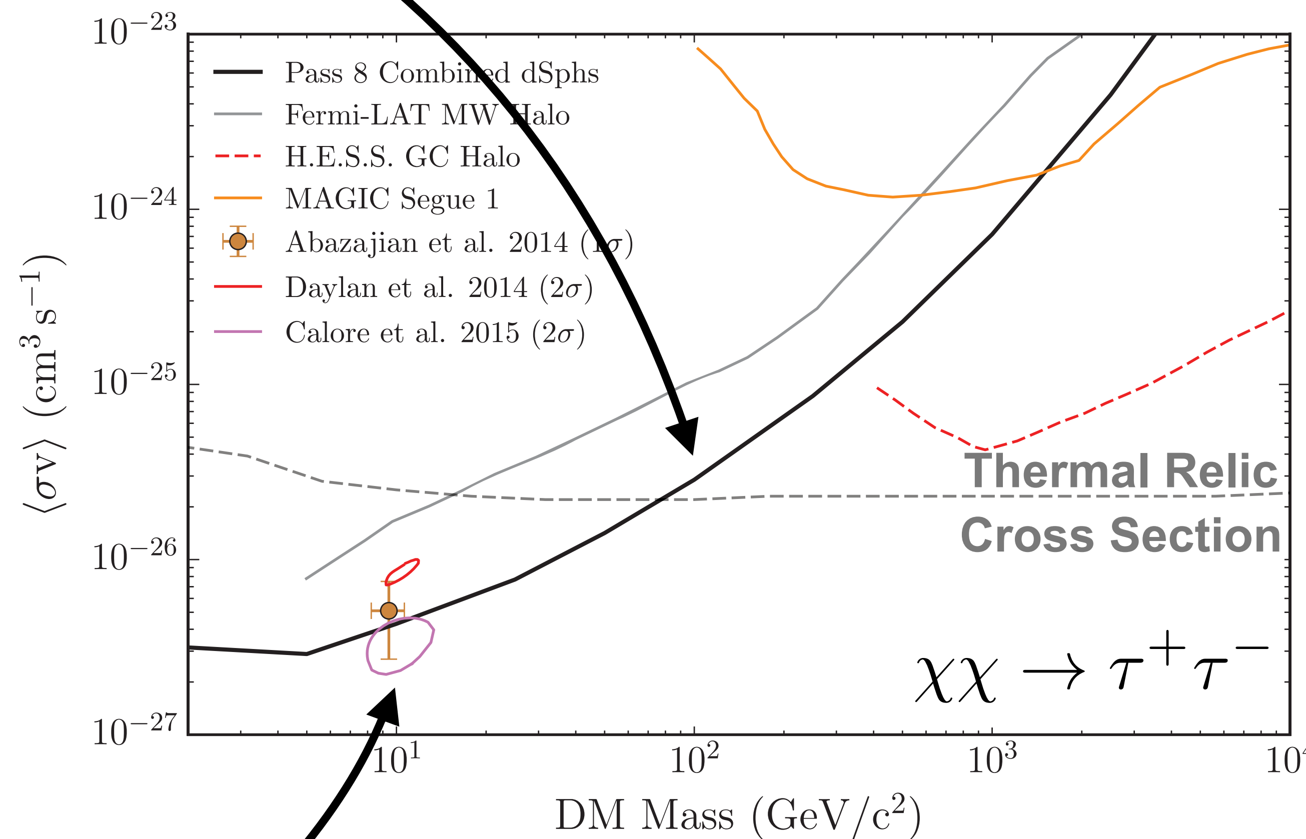




Dwarf Galaxy Constraints

Combined upper limits from observations of 15 dwarf galaxies





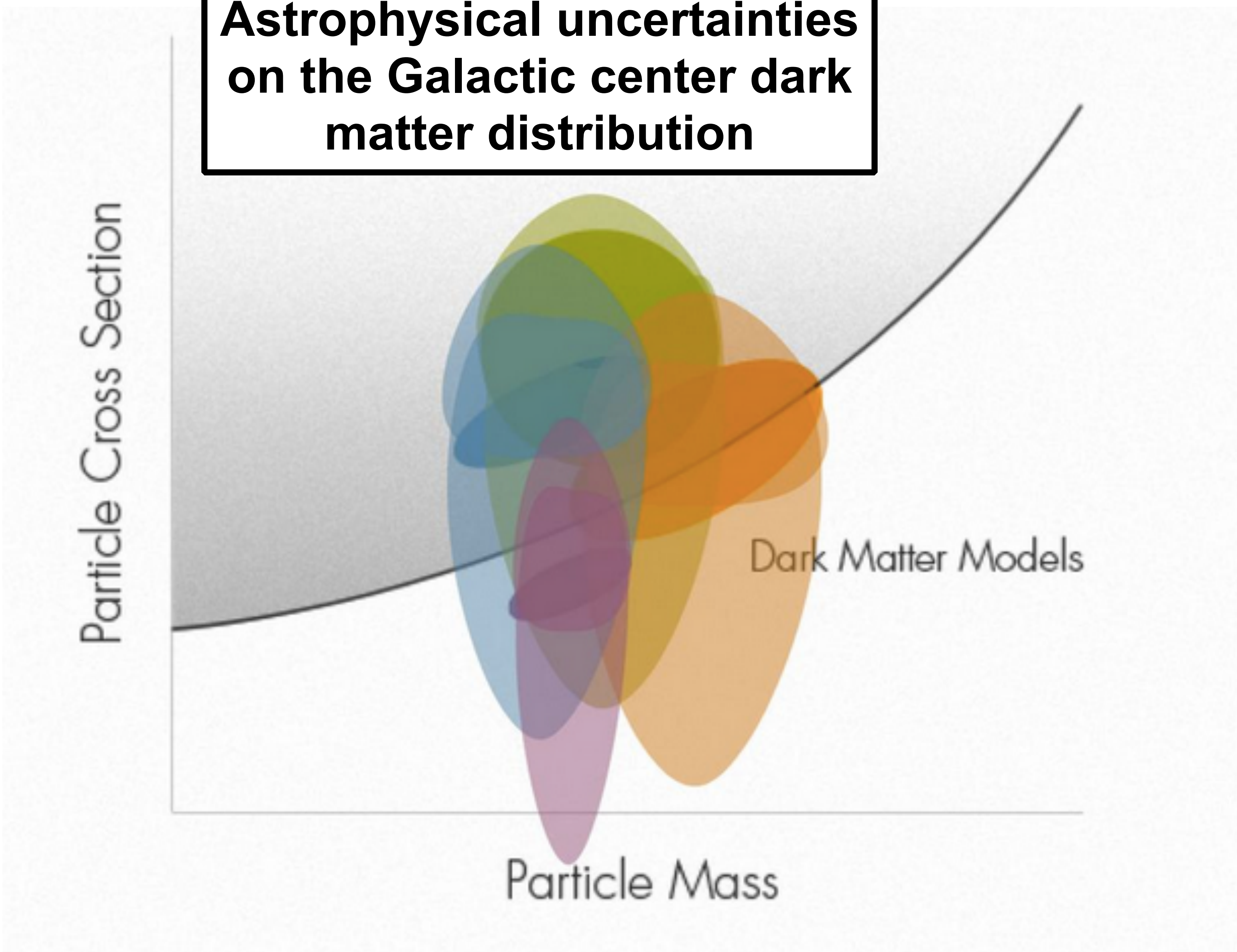
Dark matter interpretations of the Galactic Center excess

Ackermann et al. 2015 (1503.02641)

Galactic Center Comparison

CARTOON

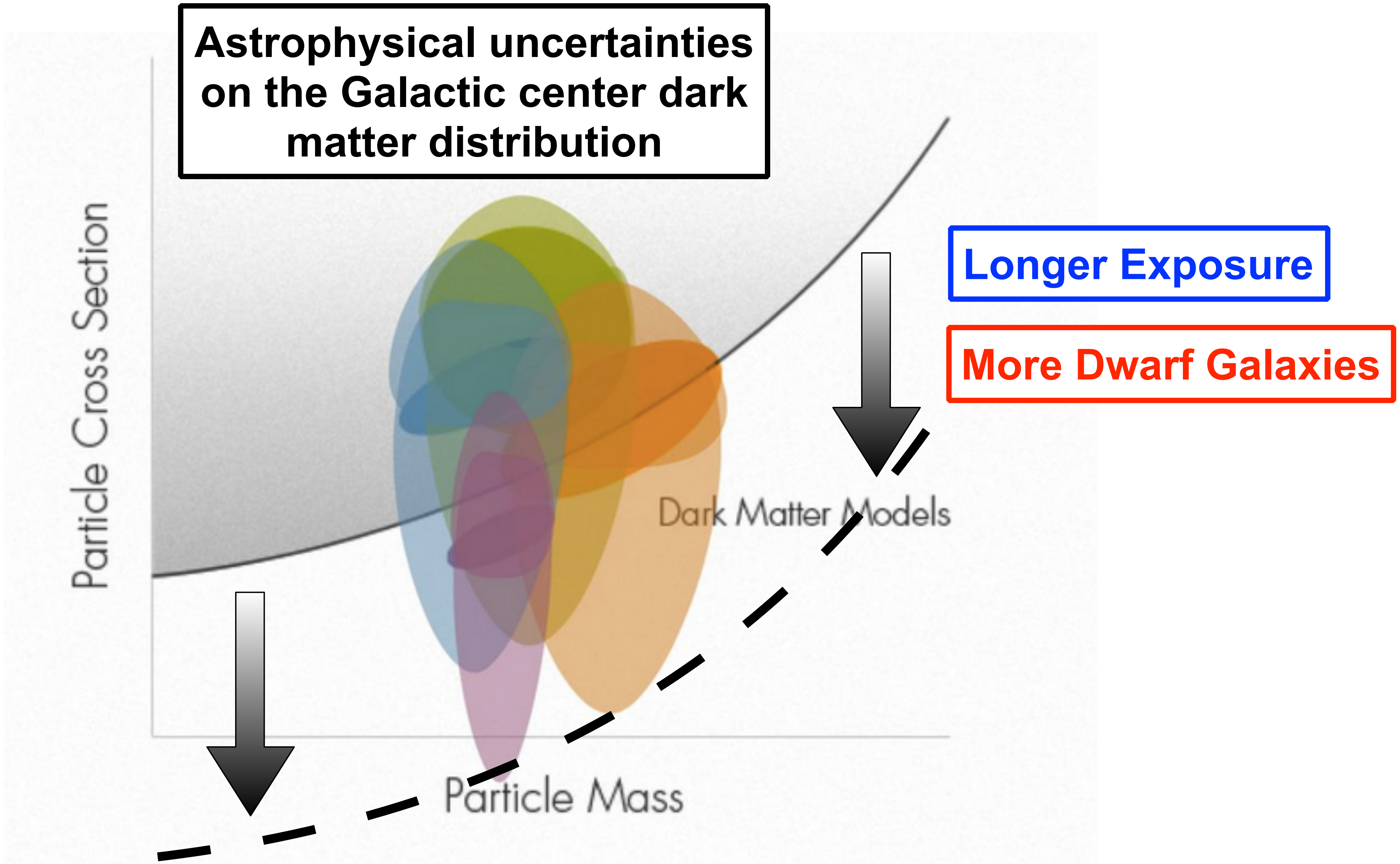
Astrophysical uncertainties on the Galactic center dark matter distribution



Quanta Magazine & Kev Abazajian

Galactic Center Comparison

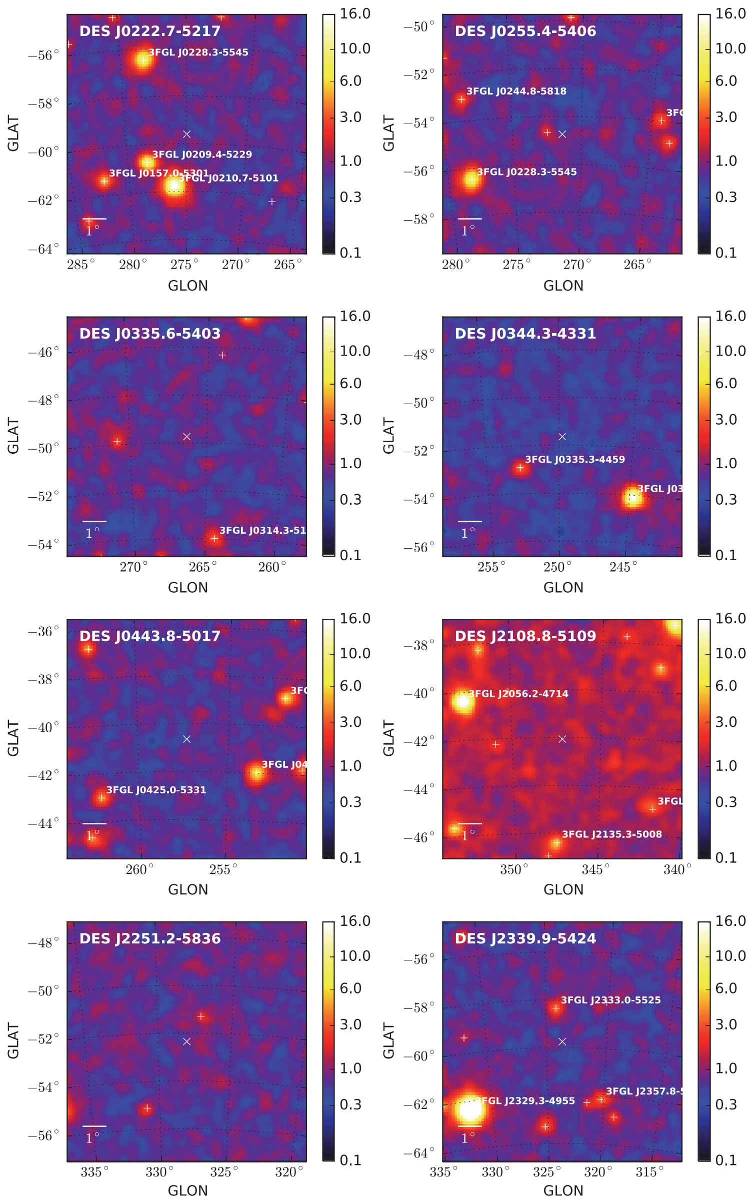
CARTOON



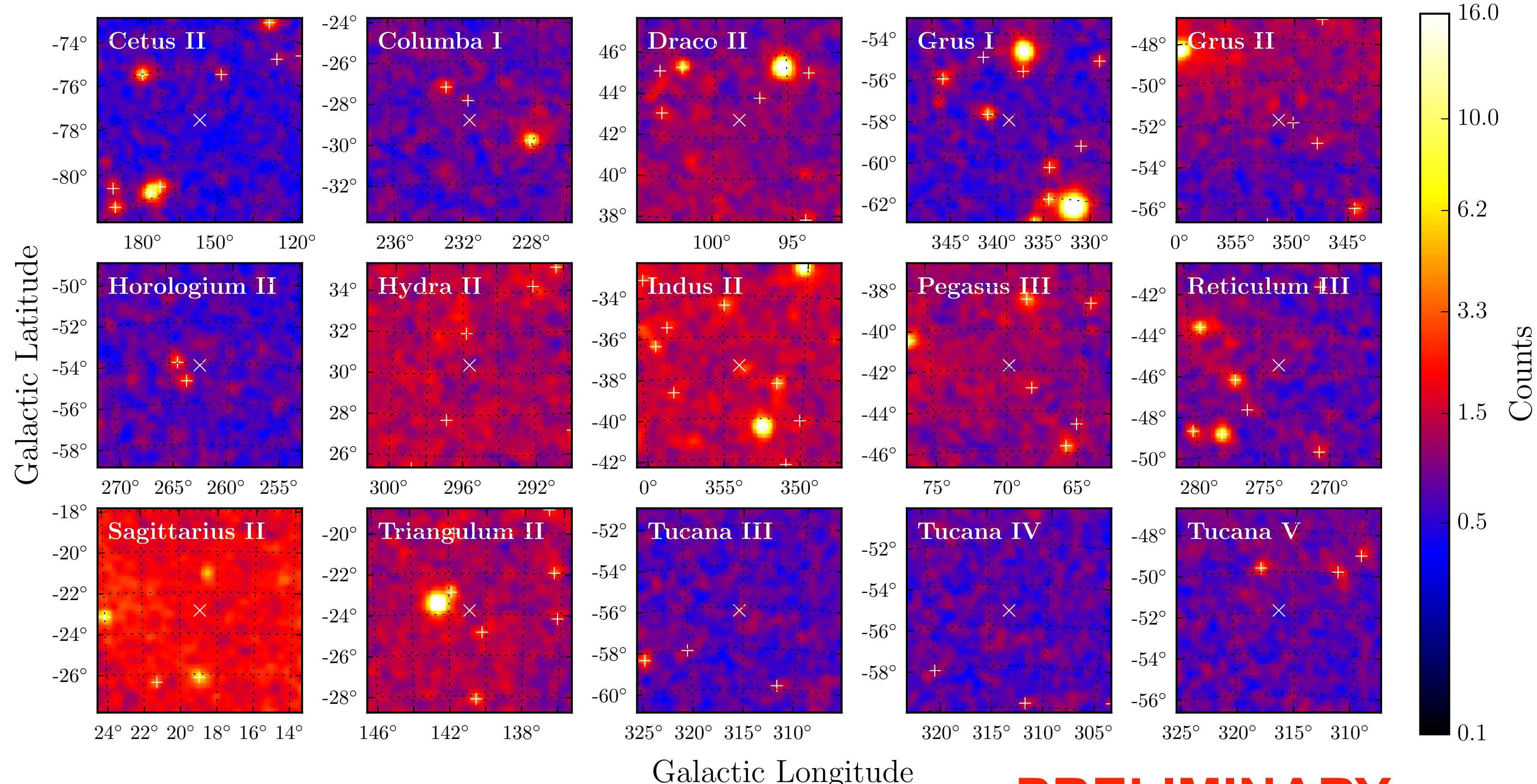
Quanta Magazine & Kev Abazajian

Search for Gamma Rays

Gamma-ray data are already available for newly discovered dwarf galaxies



+



PRELIMINARY

+

23 other dSphs…

Search for Gamma Rays

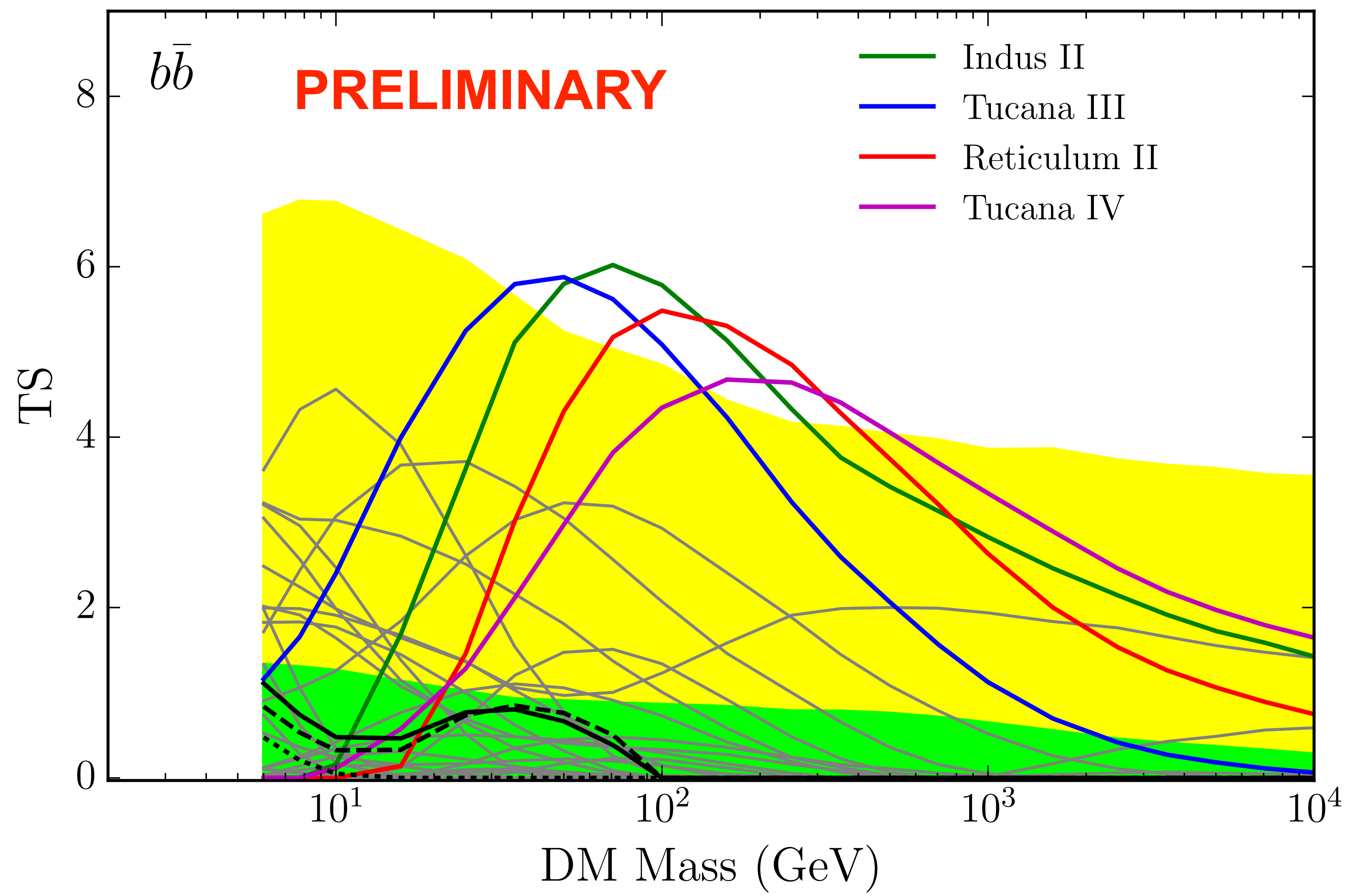
Target 45 confirmed and candidate dSphs

Four targets show ~2 sigma (local) gamma-ray excesses

Two of these targets are nearby: Ret II and Tuc III (D < 35 kpc)

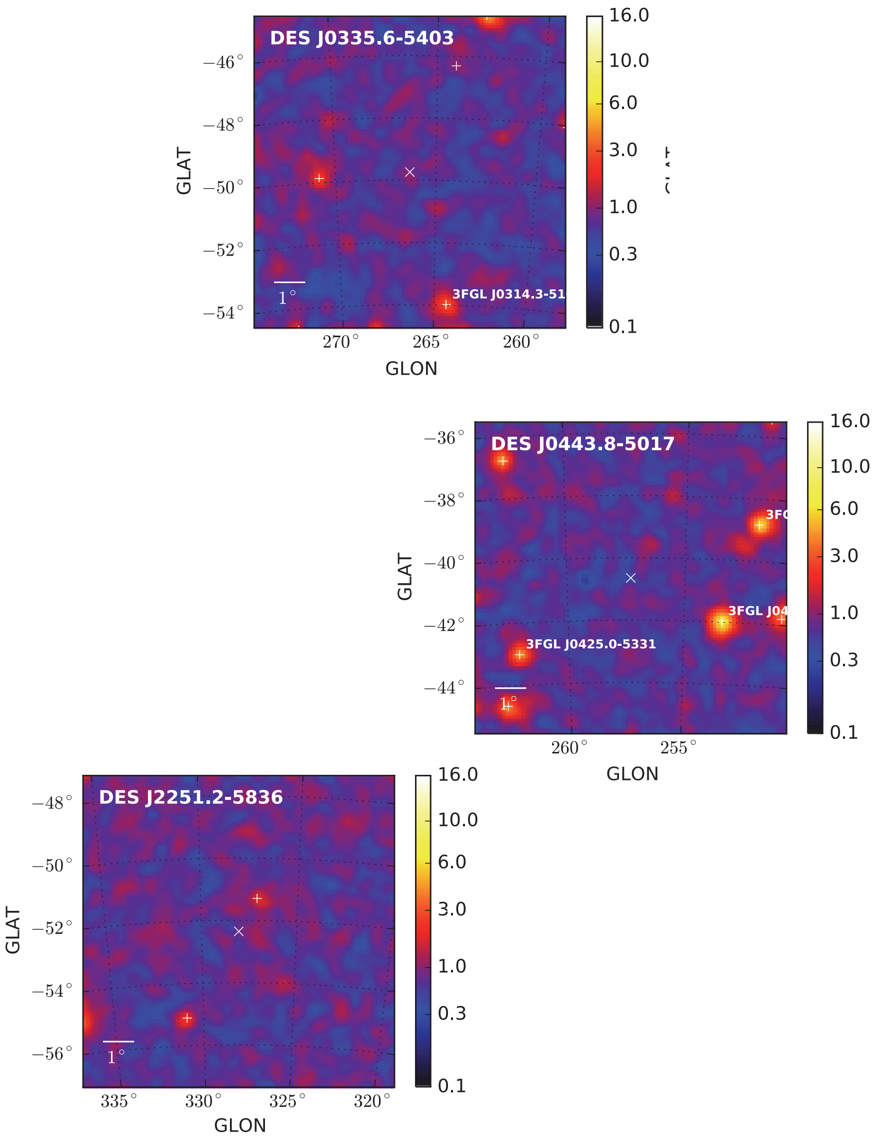
Composite analysis depends on J-factor and uncertainty

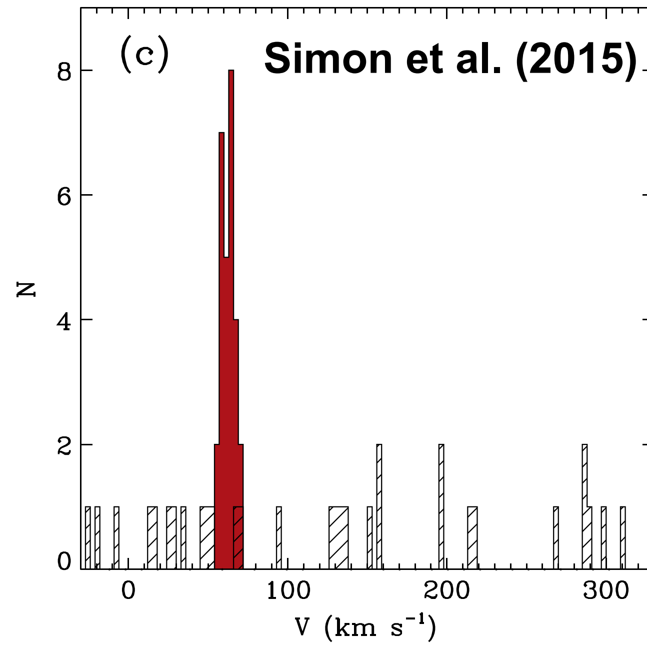
No significant gamma-ray excess from the population of dwarf galaxies.



LAT & DES Collaborations (submitted to ApJ)

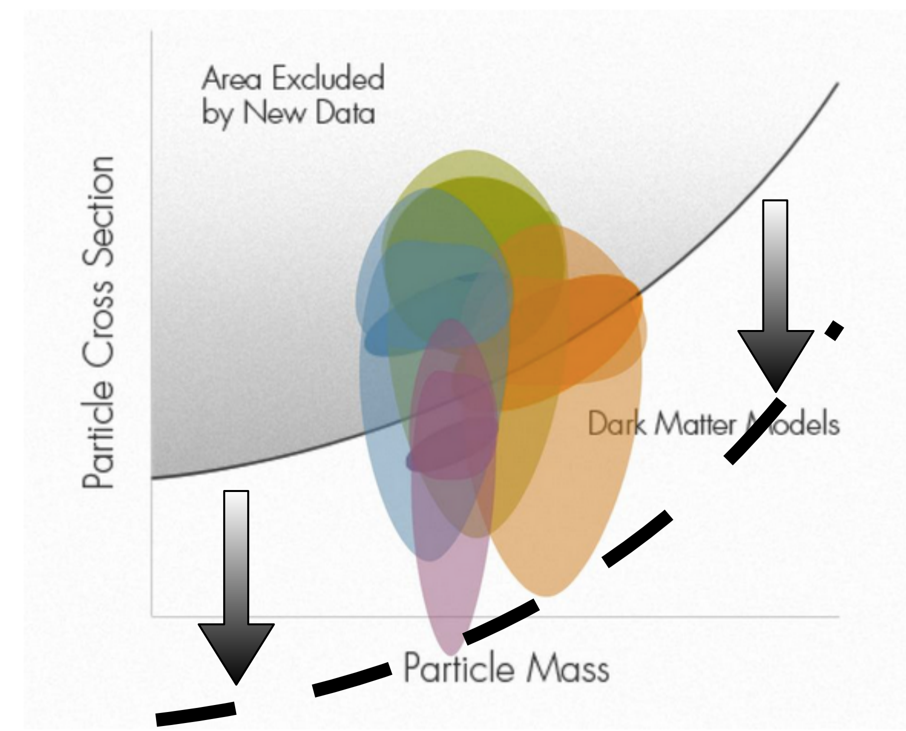
Search for Gamma Rays



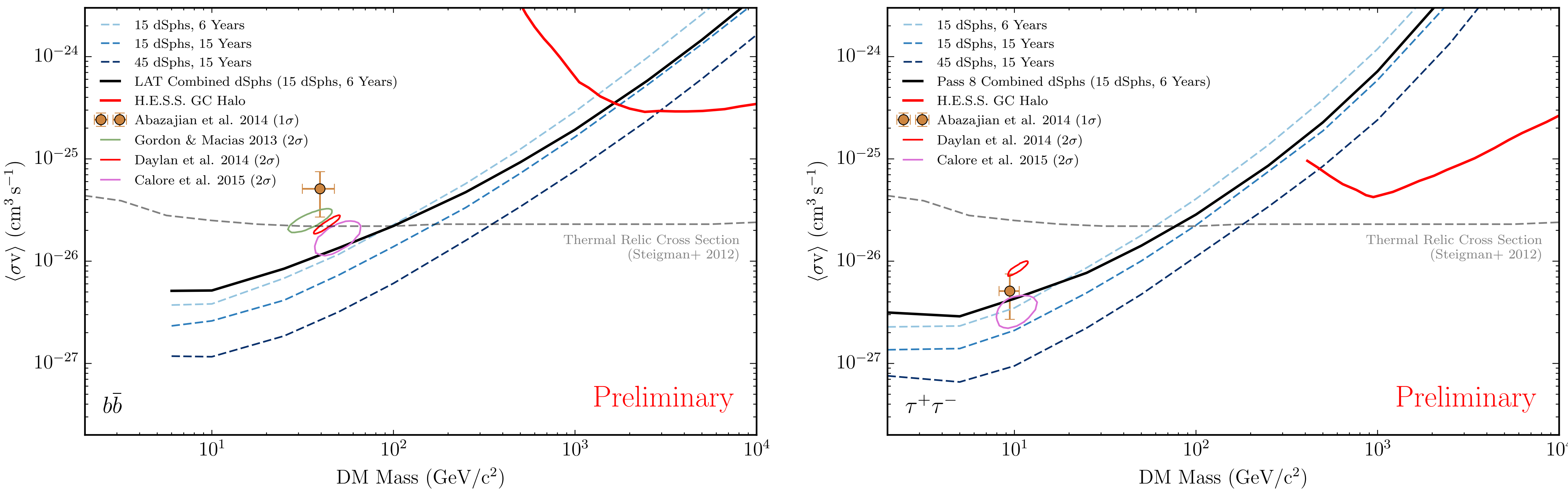


What we need…

DM Content



Looking Forward



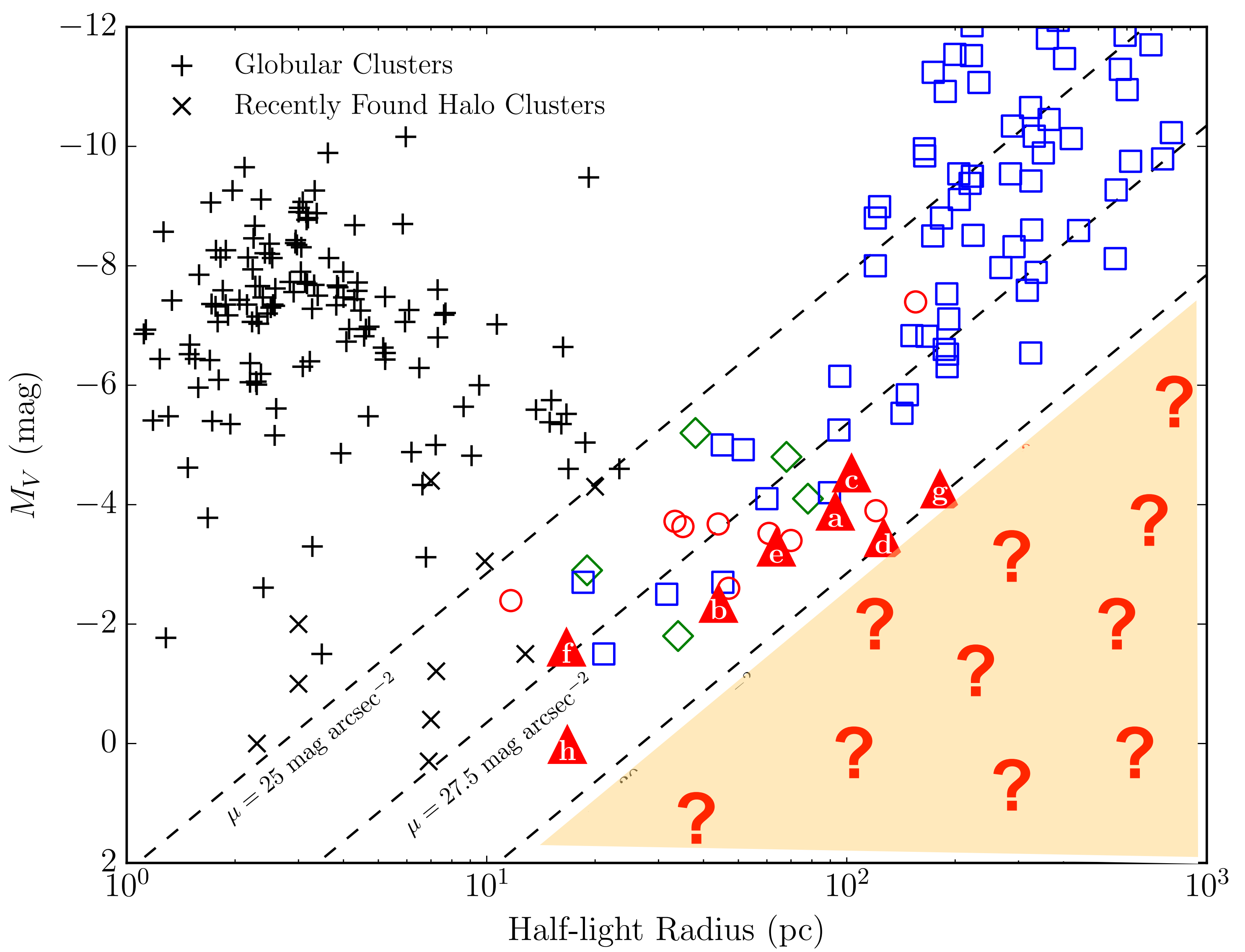
- Introduction to Dwarf Galaxies
- Finding New Dwarf Galaxies
- Our Newest Neighbors
- Dwarf Galaxies and Dark Matter
- **Future Prospects**

The Future with DES

- **DES has started Year 4 (4+ tilings over entire footprint)**

- **A major image-level reprocessing campaign is on-going**
  - **Reduce imaging artifacts**
  - **Increased depth and uniformity**
  - **Better calibration**

- **Sensitivity to fainter dwarf galaxies with large angular sizes**
  - **Do galaxies extend to even lower surface brightness?**
  - **Very nearby hyper-faint dwarf galaxies?**
  - **Diffuse systems inhabiting large dark matter halos?**

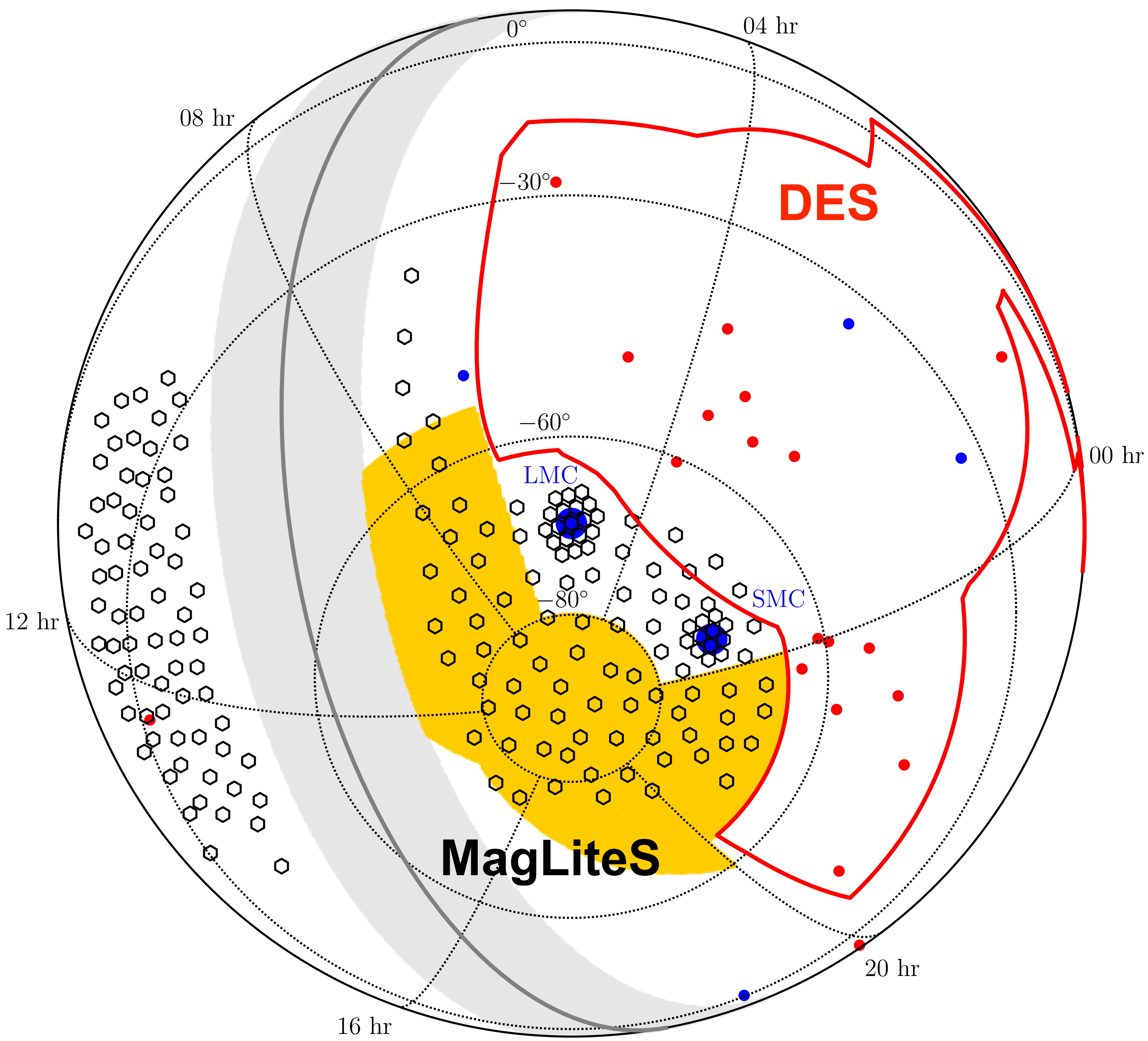


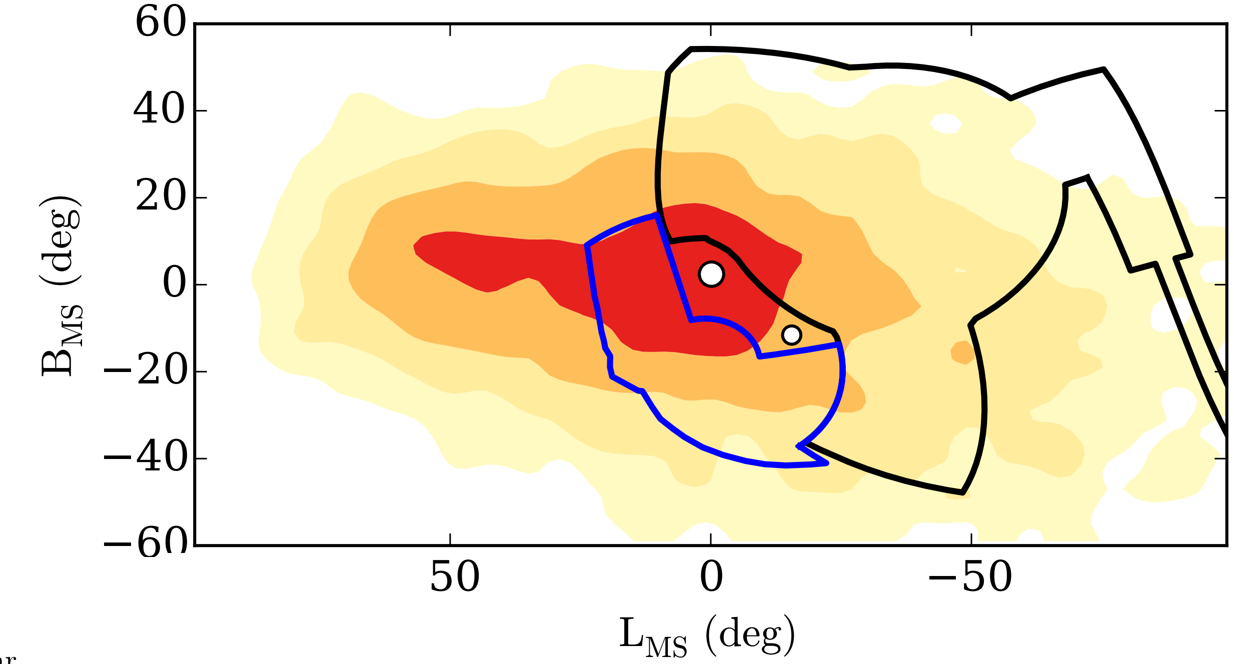
DES Collaboration, ApJ 813, 2 (2015)

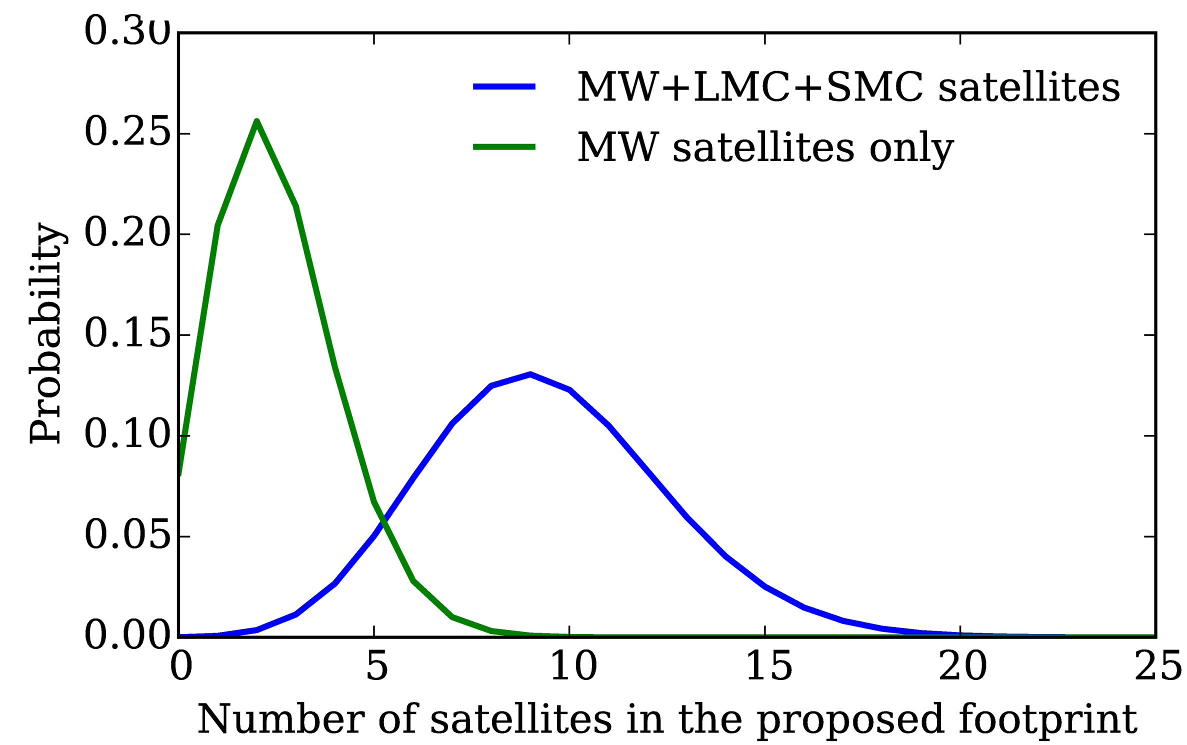
Magellanic Satellites Survey

DES-depth imaging over a ~1200 deg^2 contiguous annulus around the Magellanic Clouds

12 nights between 2016A & 2017A

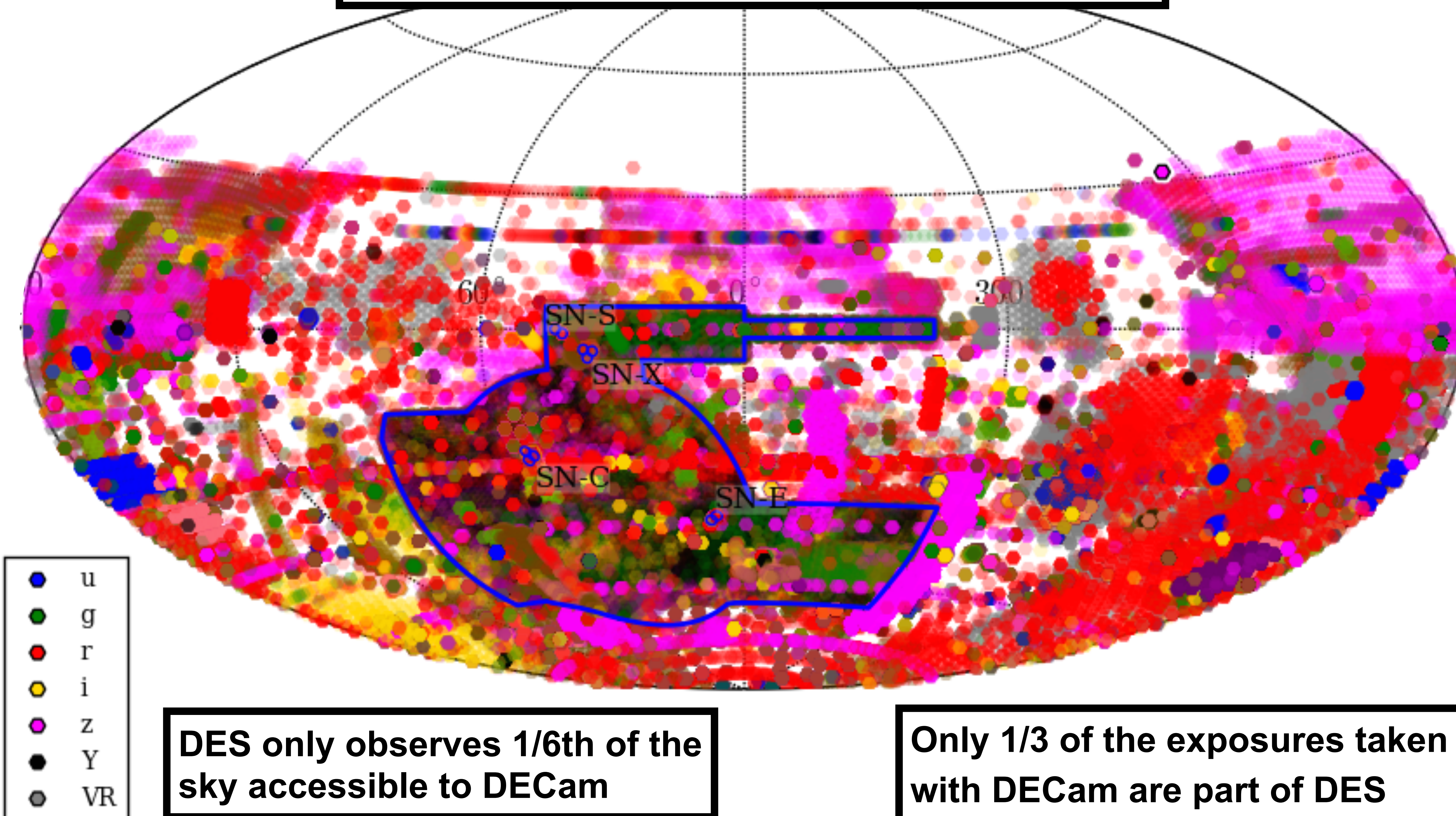






DECam Sky Survey

All-Sky Map of DECam Coverage (Feb 26, 2016)

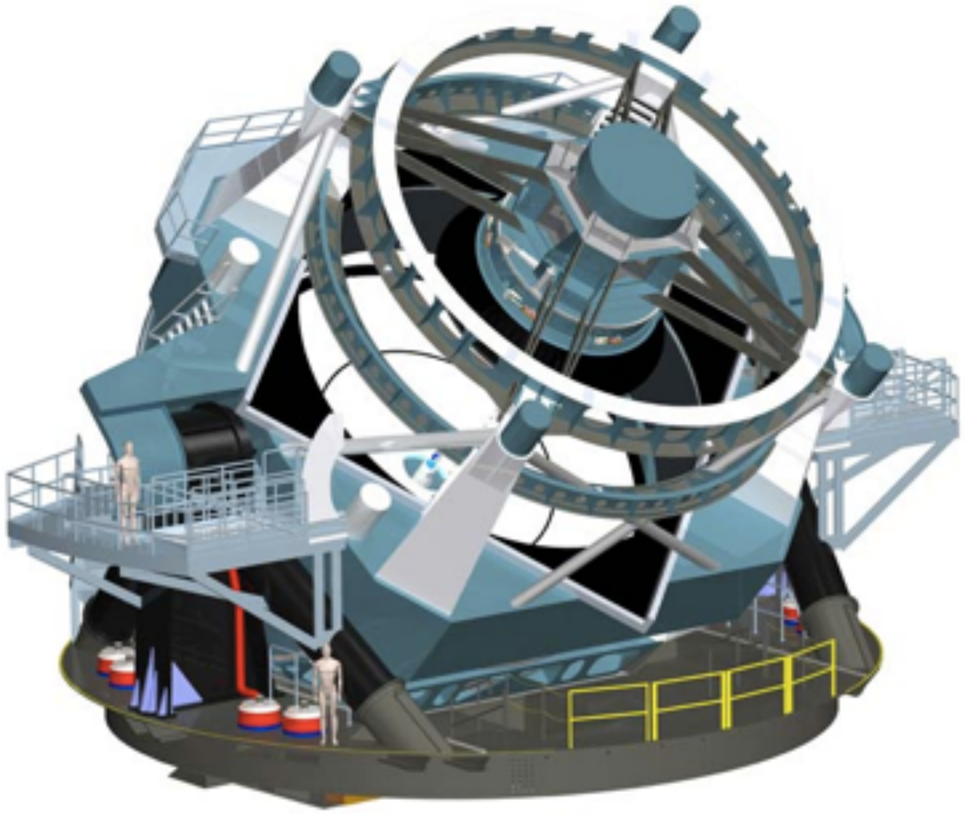


DES only observes 1/6th of the sky accessible to DECam

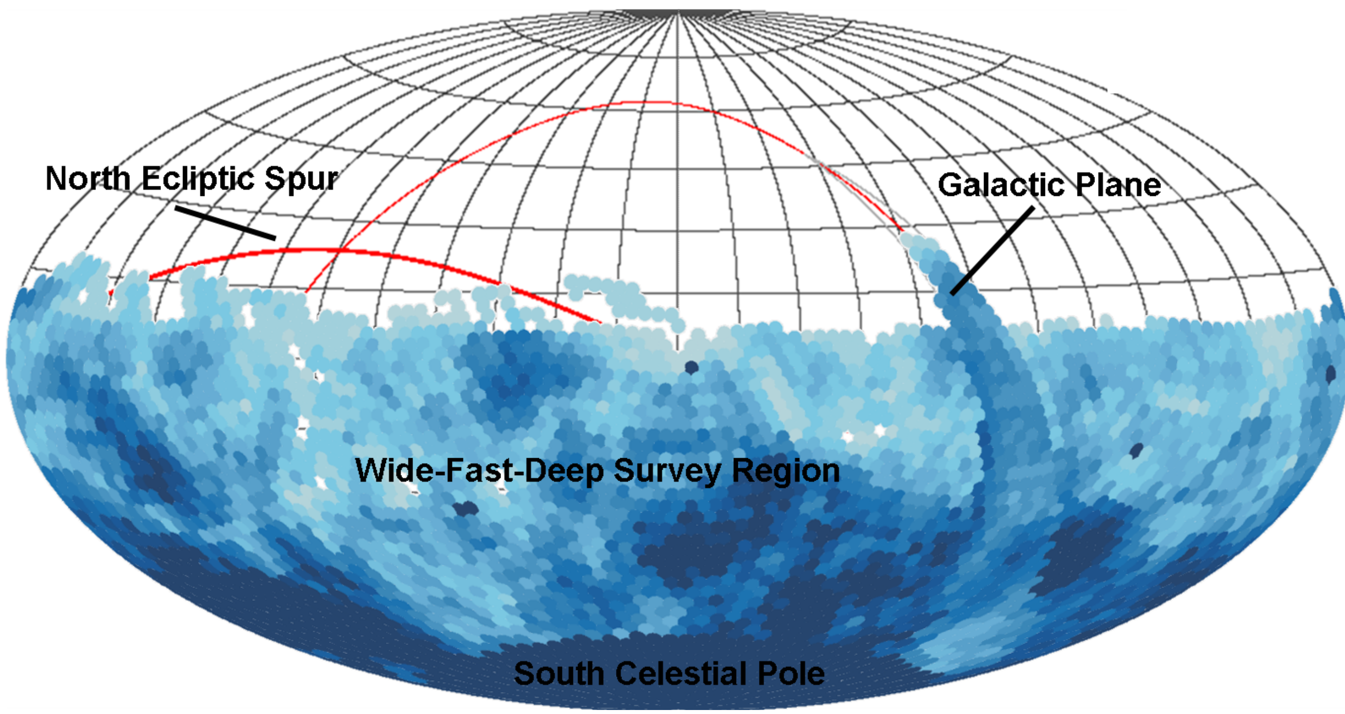
Only 1/3 of the exposures taken with DECam are part of DES

LSST

- **The Large Synoptic Survey Telescope (LSST)**
  - 3.2 gigapixel camera; 8.4-m primary mirror
  - Full DES depth in 2 x 15s exposures
  - 10-year wide, fast, deep survey (~20,000 deg^2) scheduled to start in 2023
  - LSST will deliver: ~17 billion stars, ~20 billion galaxies, ~7 trillion detections, 0.5 exabytes of data

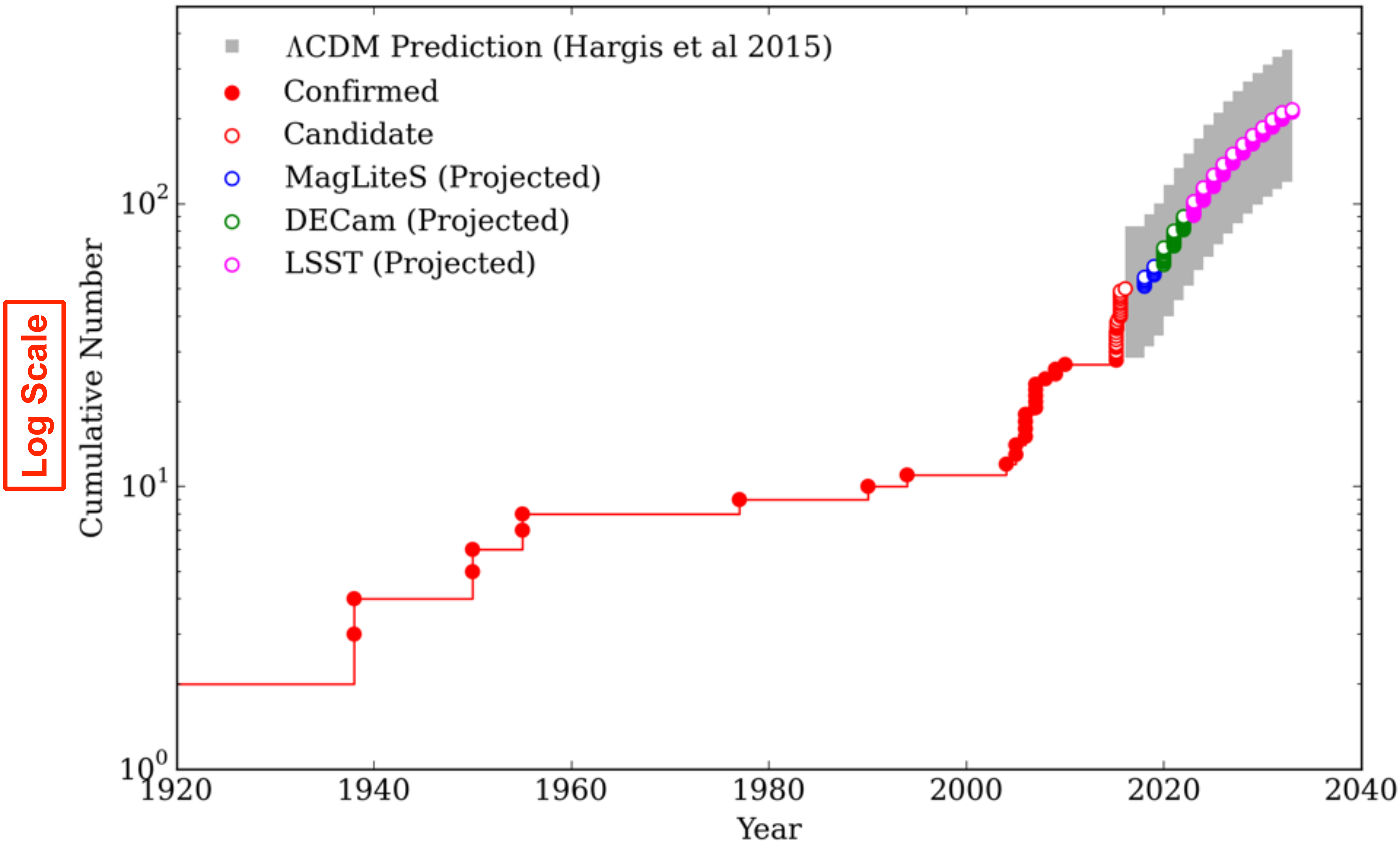


- **LSST should be complete for the faintest known dwarf galaxies out to the virial radius of the Milky Way**
  - Nearby dwarfs with very low surface brightness:
    Dark matter annihilation
  - Ultra-faint dwarfs out to the virial radius:
    Missing satellites problem
  - Massive dark matter halos with low surface brightness galaxies:
    Too big to fail problem



https://confluence.lsstcorp.org/x/dIHYAQ

Projected Timeline



Conclusions

- Ultra-faint galaxies are the most numerous, ancient, chemically pristine, and dark matter dominated galaxies.
- As extreme objects, dwarf galaxies are excellent probes of fundamental physics.
- However, due to their low luminosity, our census of dwarf galaxies is far from complete.
- DES (and other recent surveys) have greatly expanded our understanding of the Milky Way neighborhood
- The next generation of surveys (i.e., LSST) should complete our census of the ultra-faint dwarfs out to the virial radius of the Milky Way.