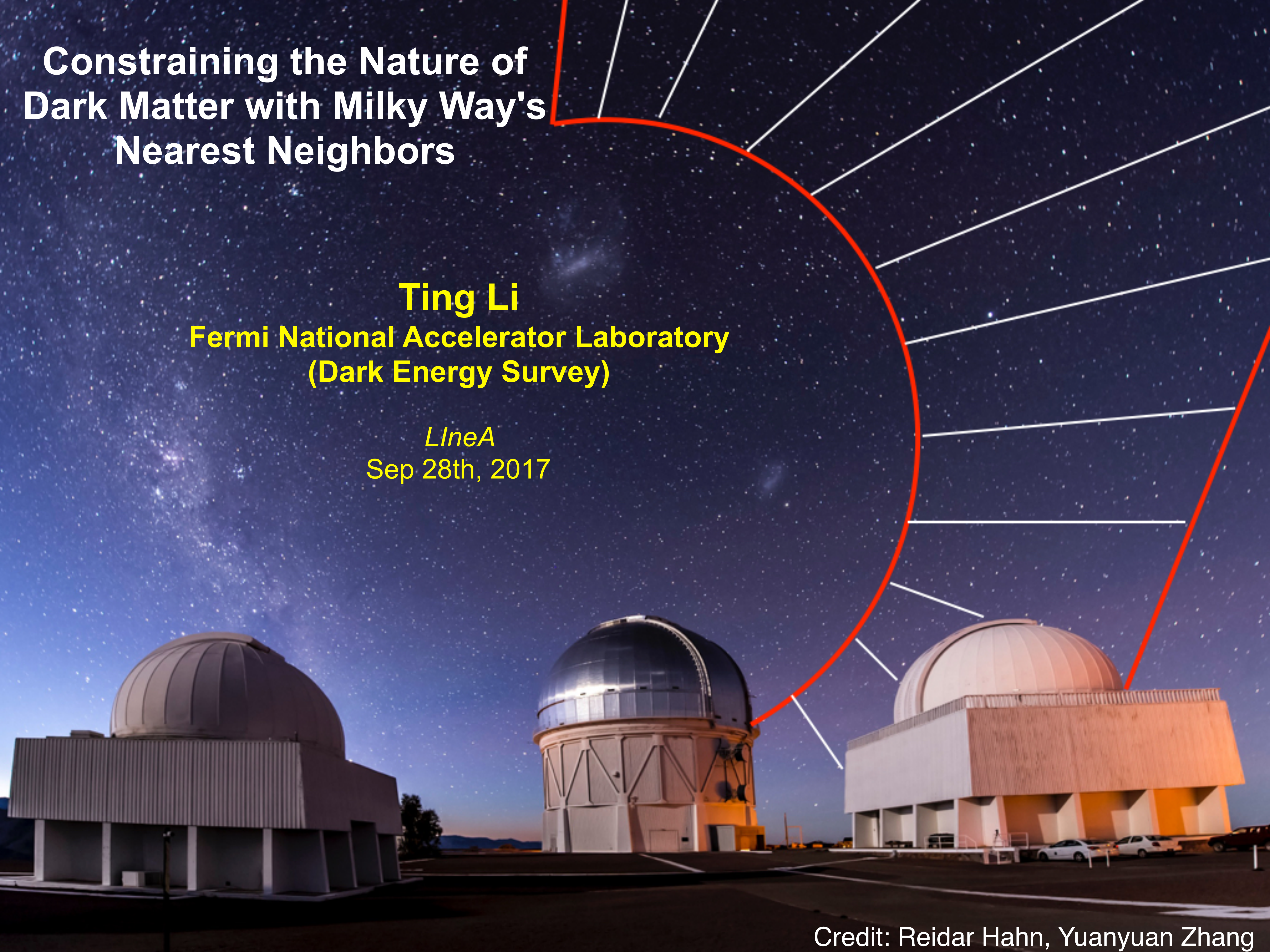
Constraining the Nature of Dark Matter with Milky Way's Nearest Neighbors

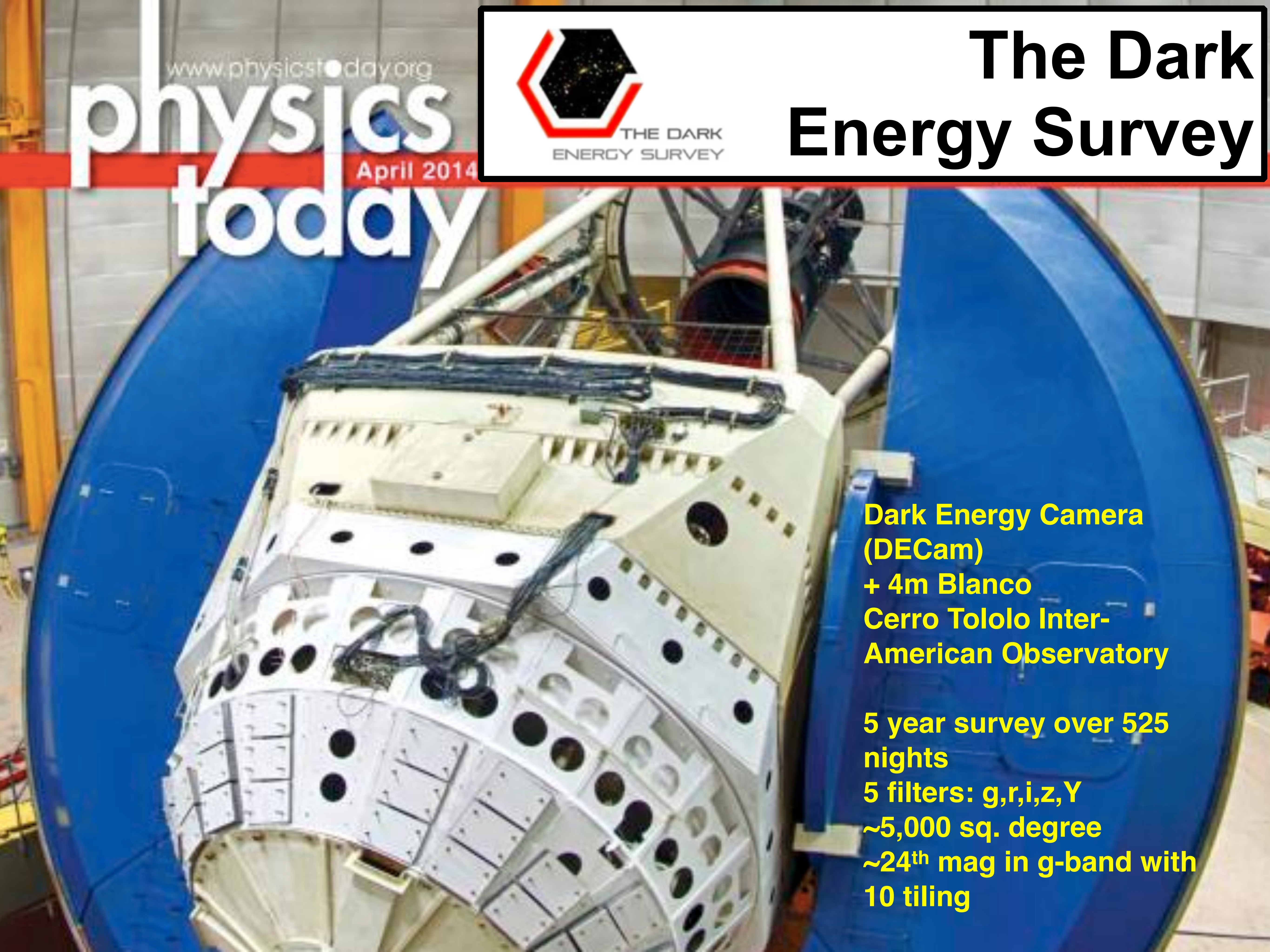
Ting Li
Fermi National Accelerator Laboratory
(Dark Energy Survey)

LIneA
Sep 28th, 2017



Credit: Reidar Hahn, Yuanyuan Zhang

The Dark Energy Survey



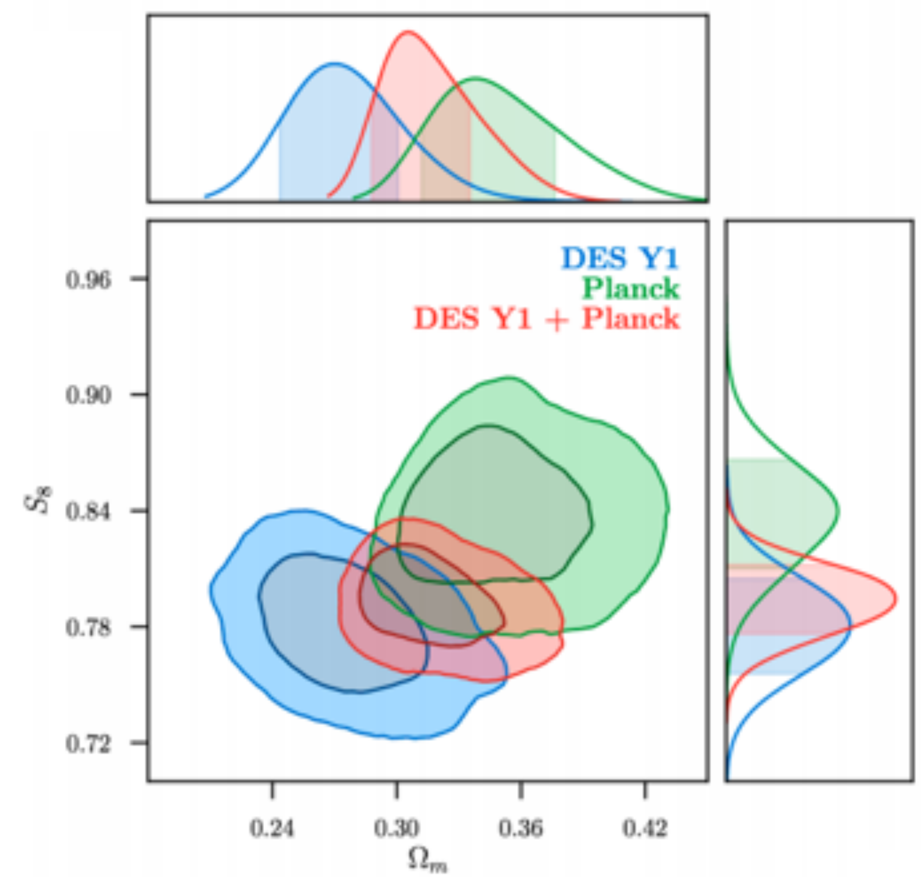
Dark Energy Camera (DECam)
+ 4m Blanco
Cerro Tololo Inter-American Observatory

5 year survey over 525 nights
5 filters: g,r,i,z,Y
~5,000 sq. degree
~24th mag in g-band with 10 tiling

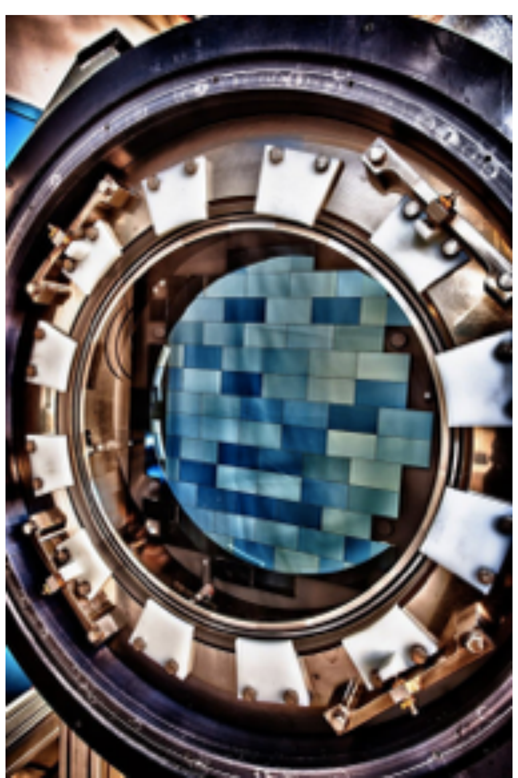
The Dark Energy Survey (DES)

- Constrain the Dark Energy Equation of State with:
  - Supernova
  - Weak Lensing
  - Large Scale Structure
  - Galaxy Clusters

DES Year 1 Cosmology Results from 3x2pt



DES Collaboration 2017



DECam
- 62 2k x 4k CCDs
- 570 megapixel camera
- < 20s readout time
- ~3 deg^2 field-of-view
- Unprecedented sensitivity

Outline

- **Missing Satellites Problem — Dark Matter Models**
  - **CDM vs. WDM vs. SIDM, etc.**

- **Constraints on WIMP Cross Section — Indirect Dark Matter Detection**
  - **WIMP: Weakly Interacting Massive Particles**

- **Constraints on MACHO Abundance**
  - **MACHO: MAssive Compact Halo Object**

Large Scale Structure of the Universe

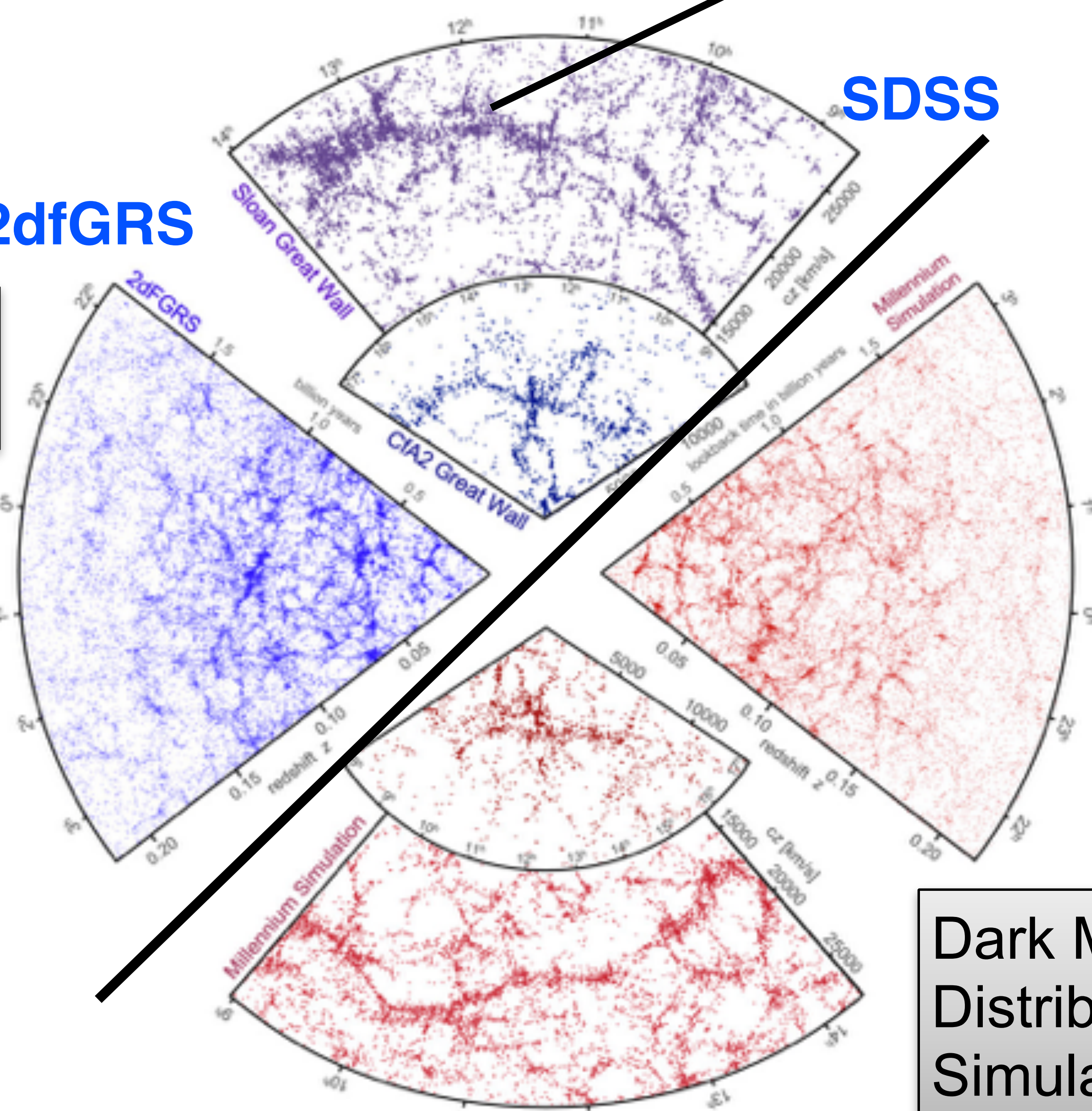
- ΛCDM model is in concordance with astronomical observations

Sloan Great Wall

SDSS

2dfGRS

Galaxy Distributions from Observations

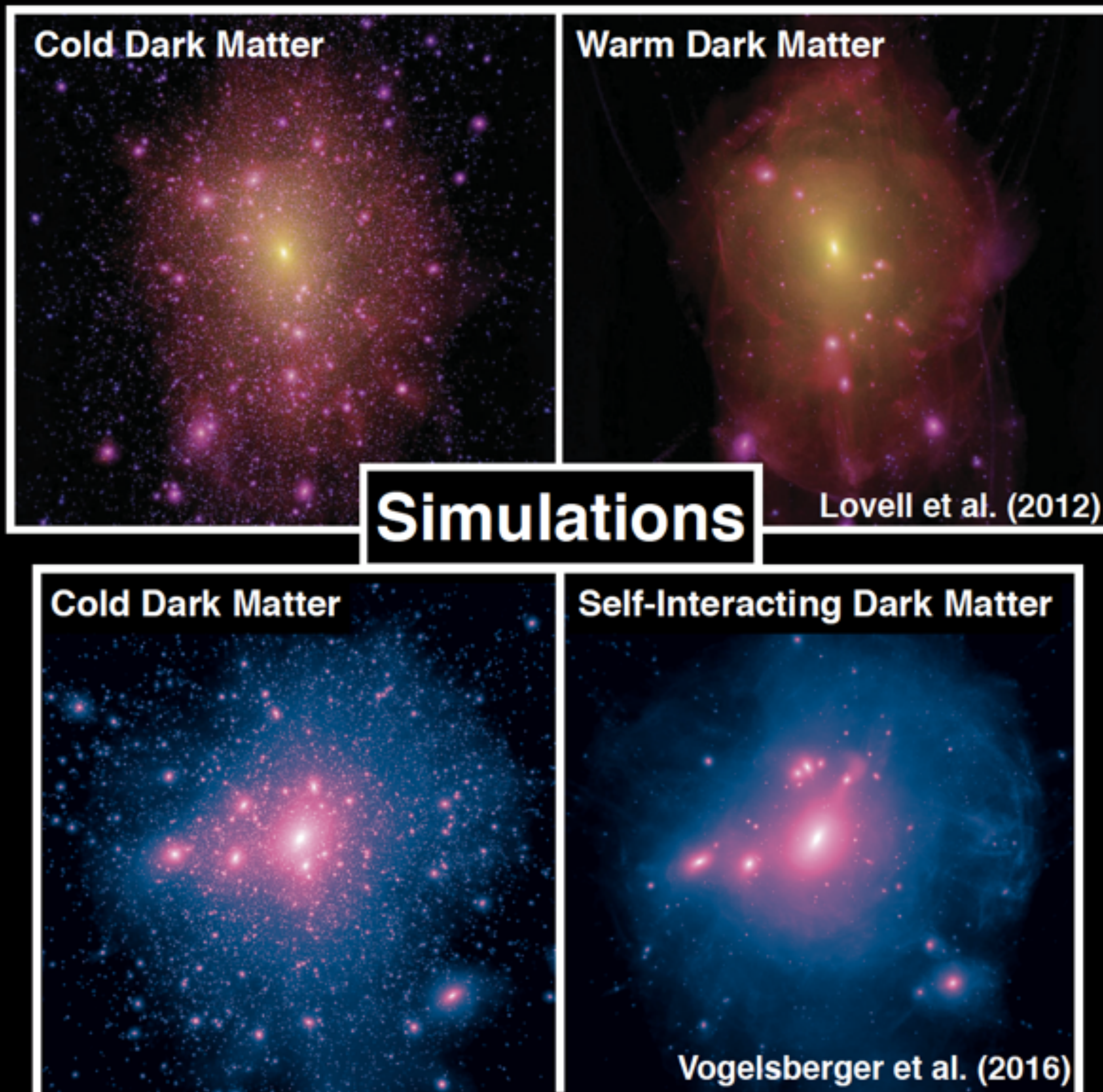


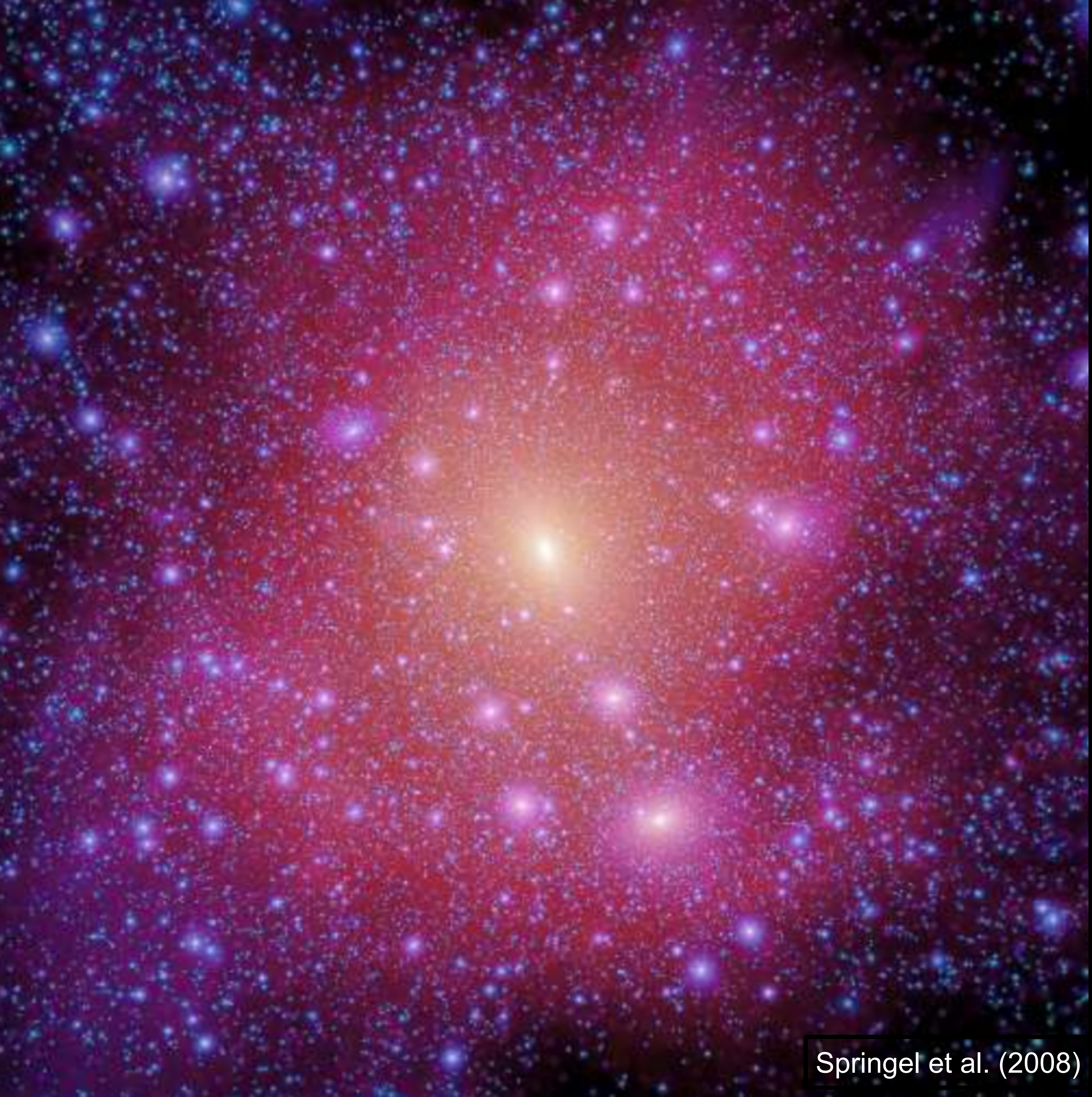
Dark Matter Distribution from Simulations

Springel et al. (2006) *Nature*
The large-scale structure of the Universe

Smallest Structures Probe Fundamental Characteristics of Dark Matter

subhalo
mass
function

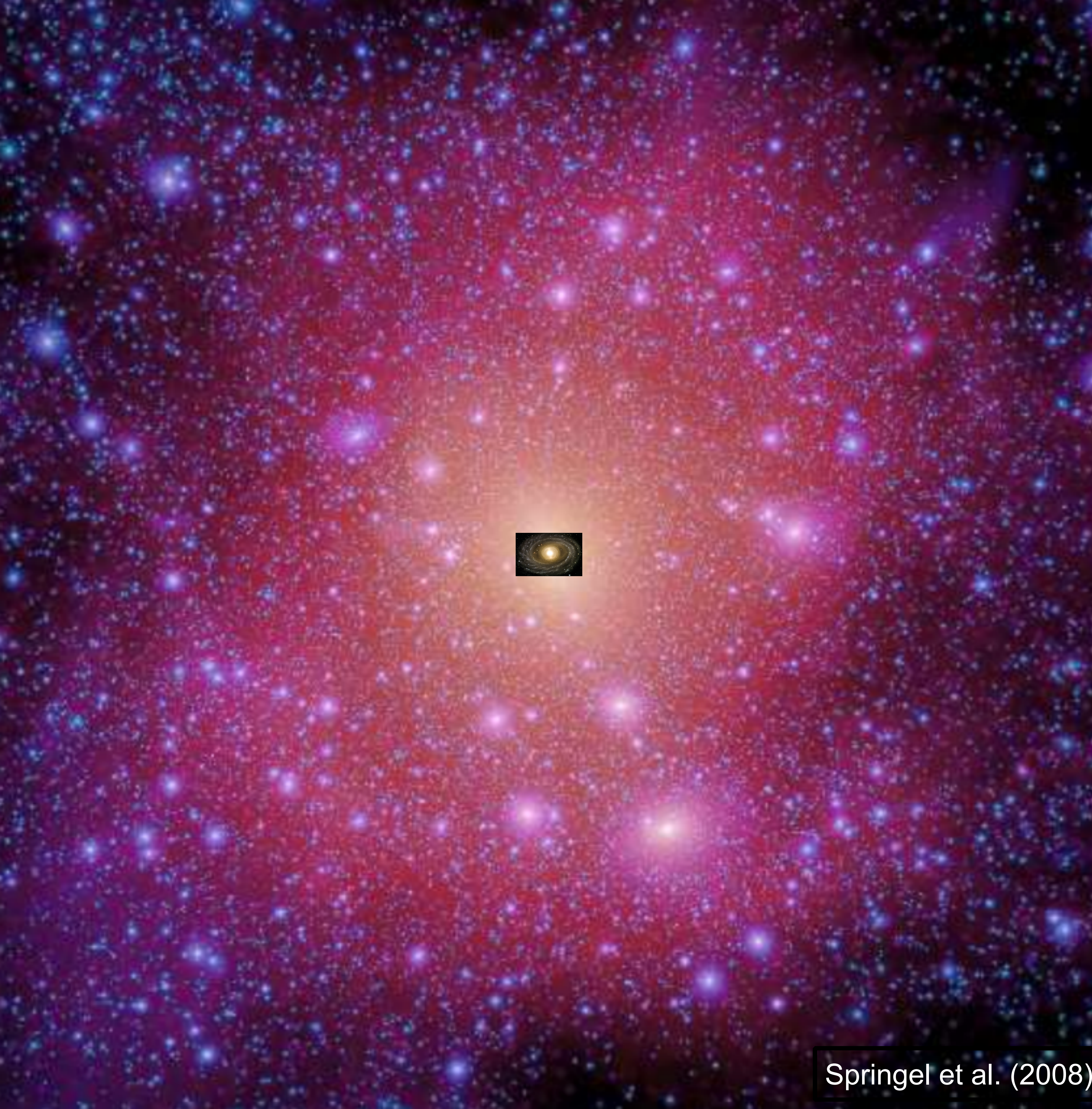




Aquarius Simulation

1 Mpc^3 simulation box

One Milky-Way sized halo



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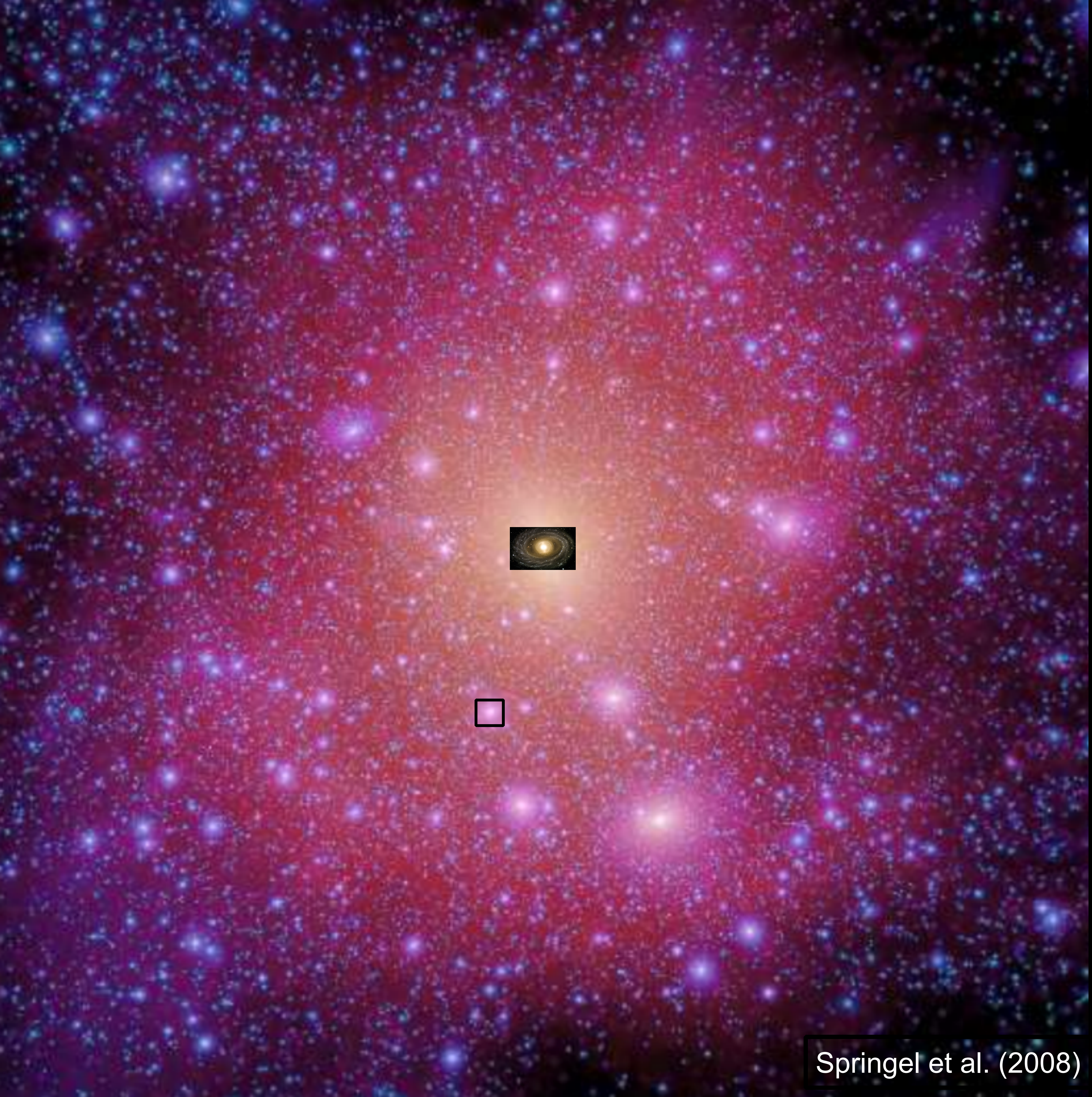

Springel et al. (2008)

Aquarius Simulation

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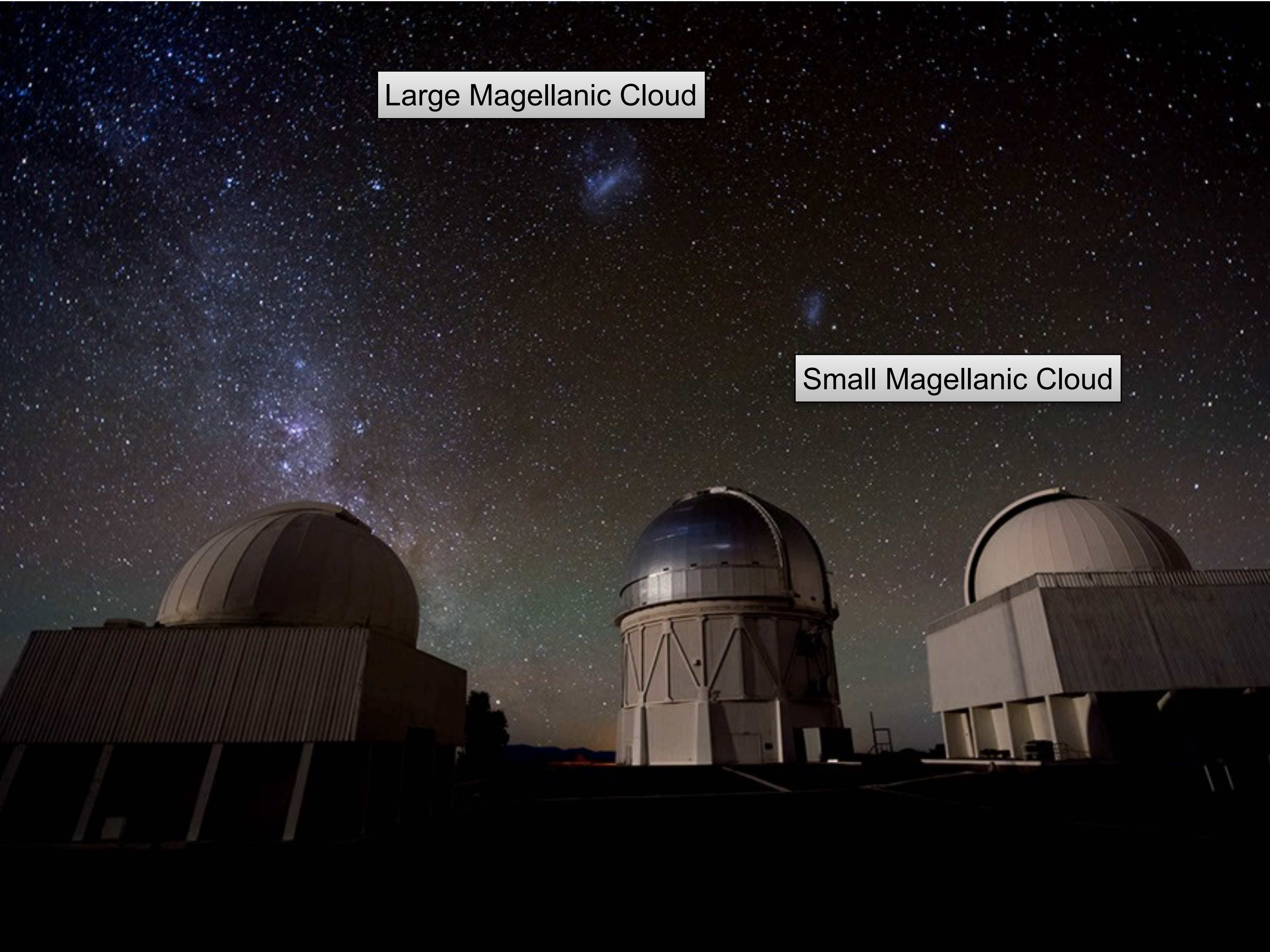
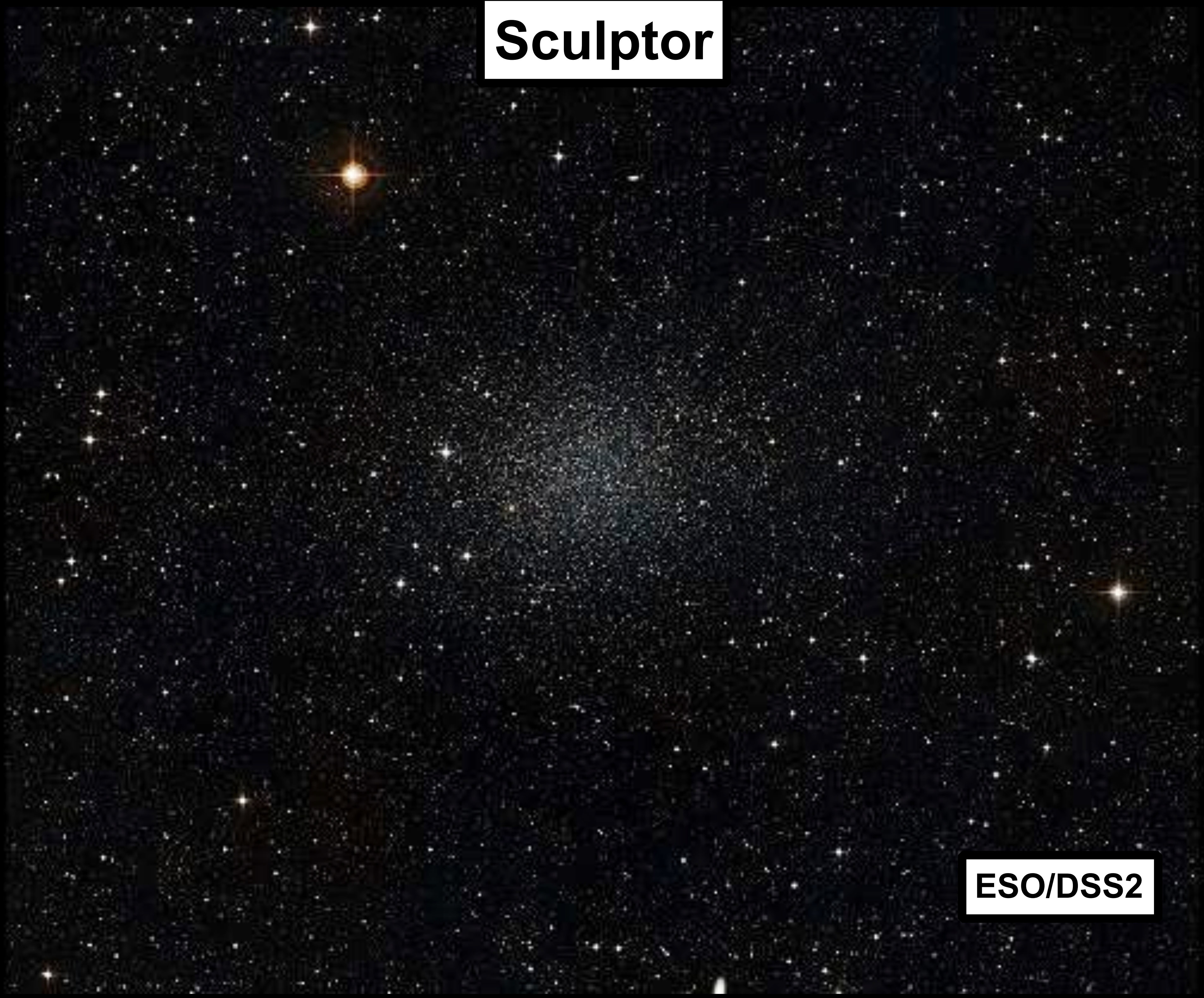
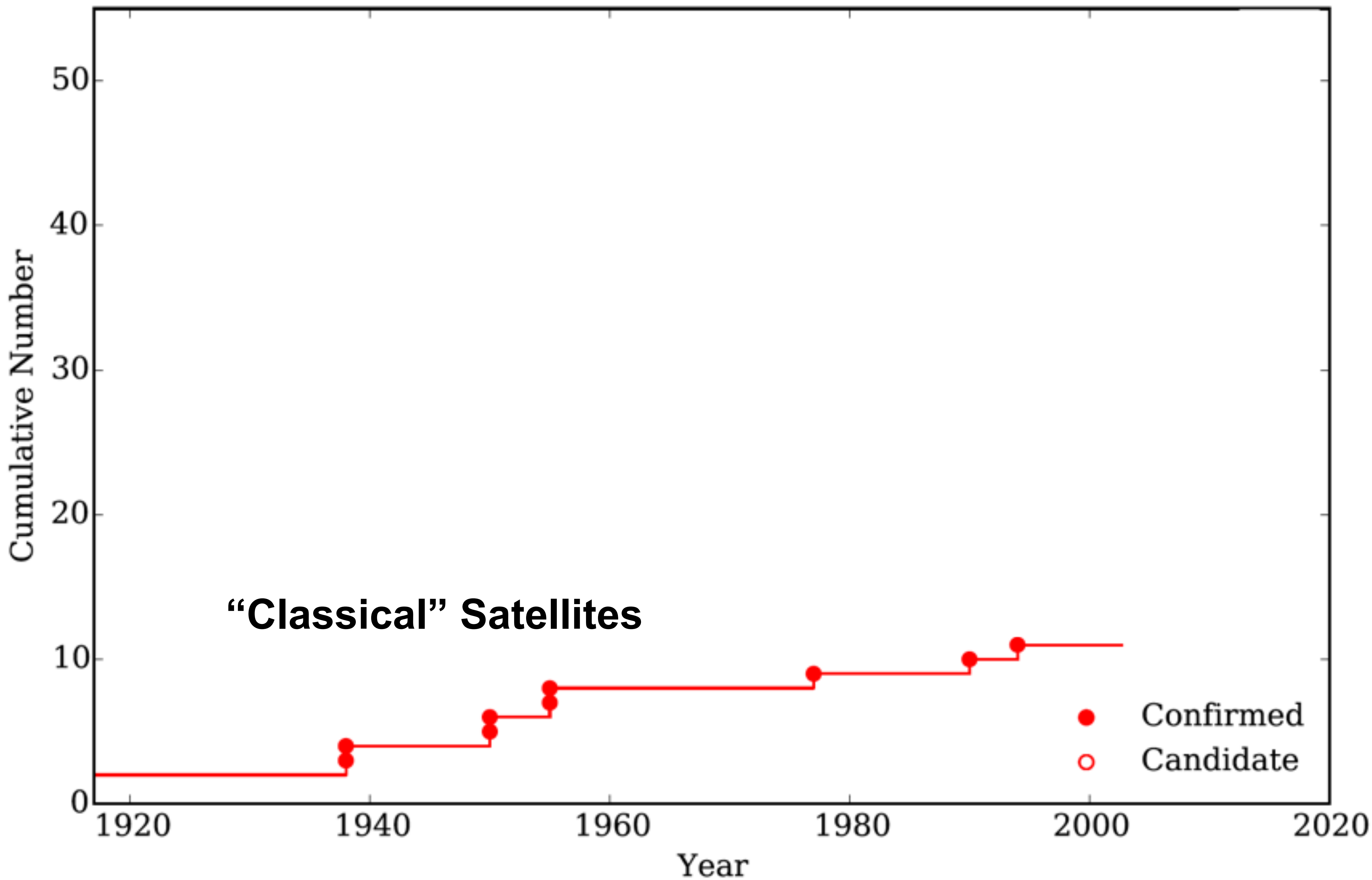
Large Magellanic Cloud


Large Magellanic Cloud
Small Magellanic Cloud

Classical Dwarf Spheroidal Galaxies (dSph)



Dwarf Galaxy Discovery Timeline



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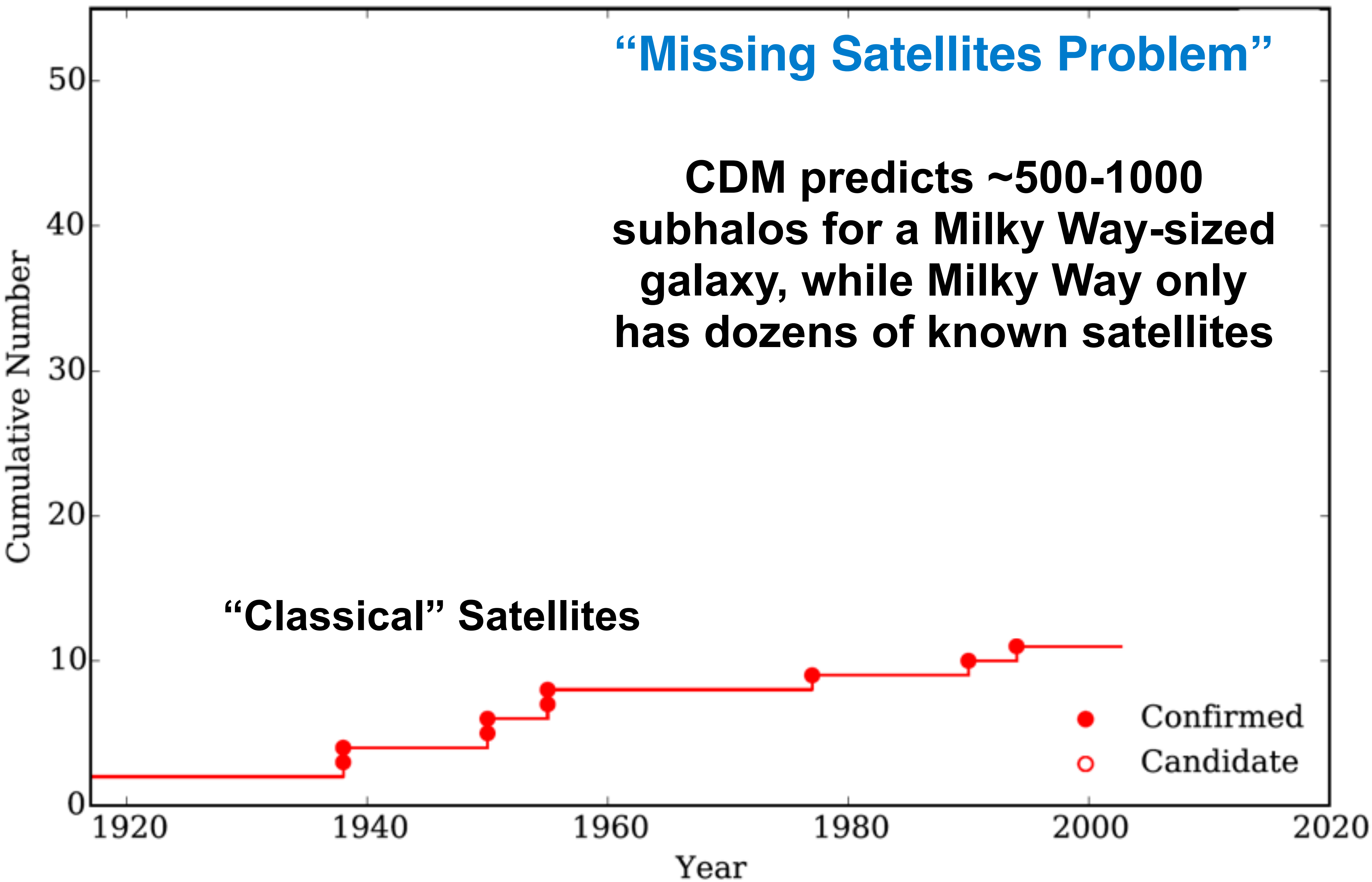
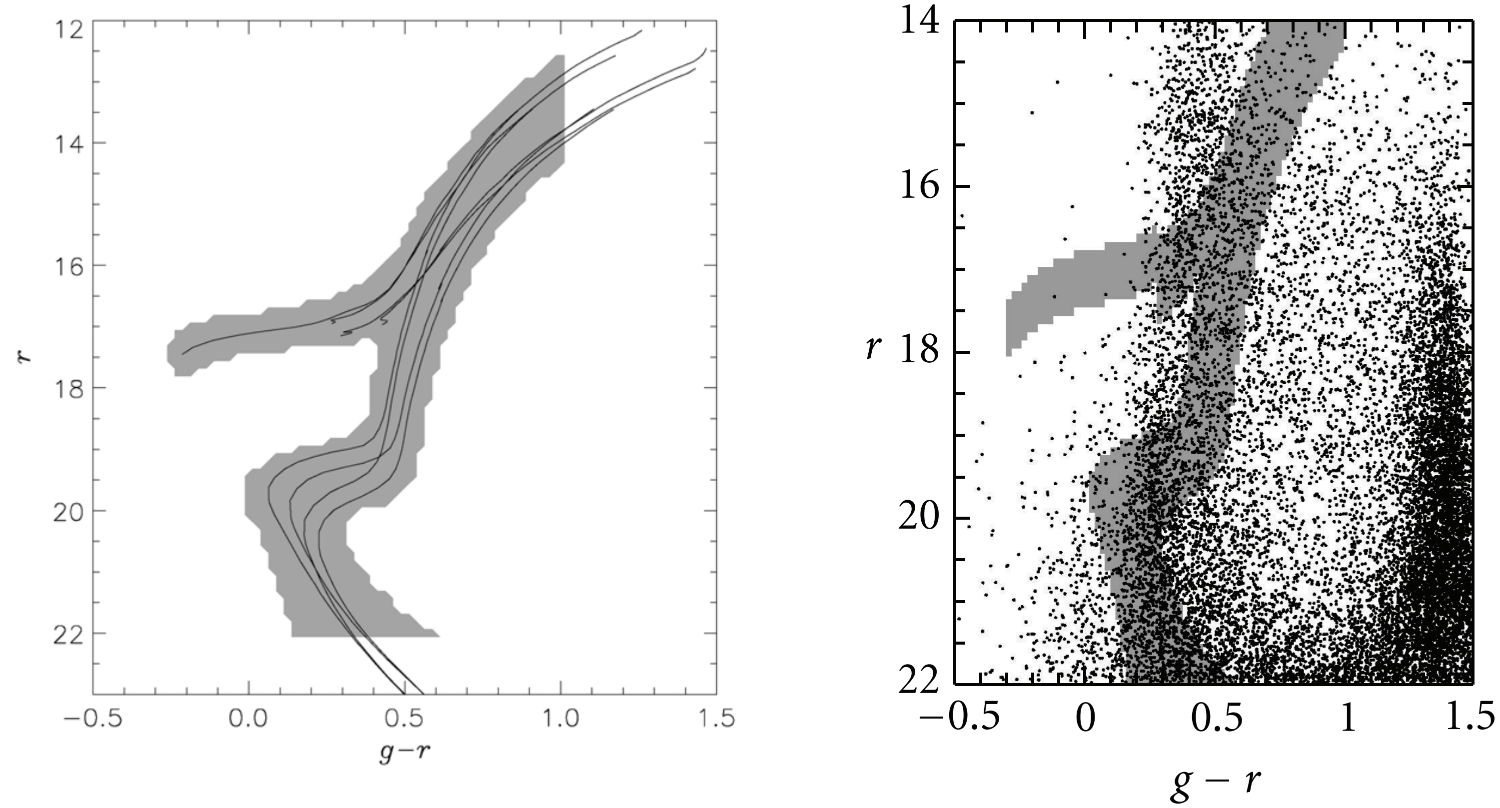


Ultra-Faint Dwarf (UFD) Galaxies

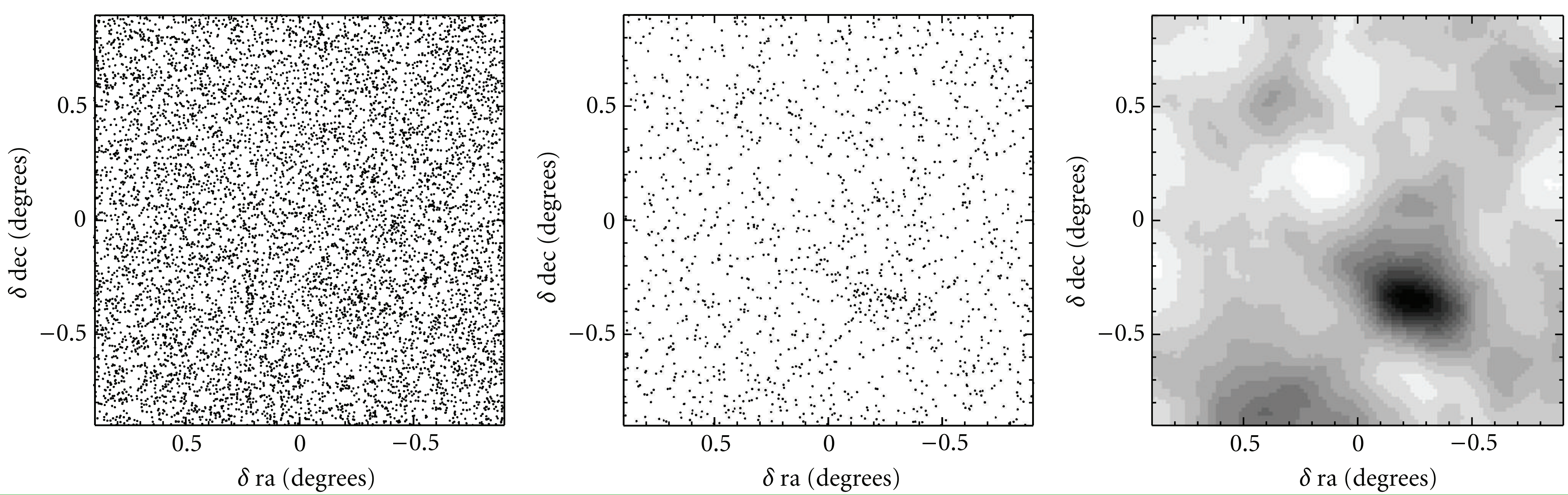
Finding Milky Way Satellite Galaxies

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

Color-Magnitude Domain



Spatial Domain



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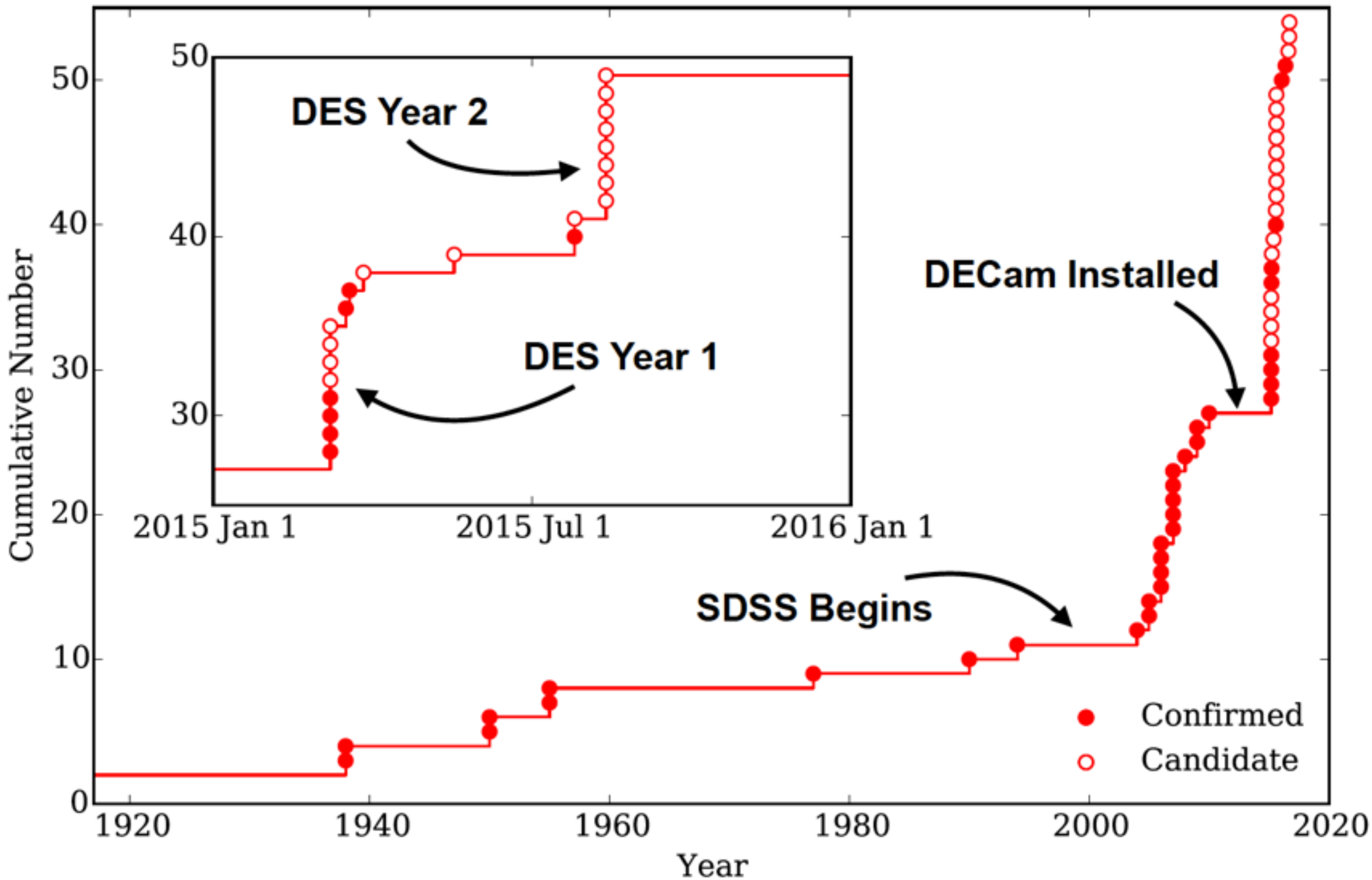
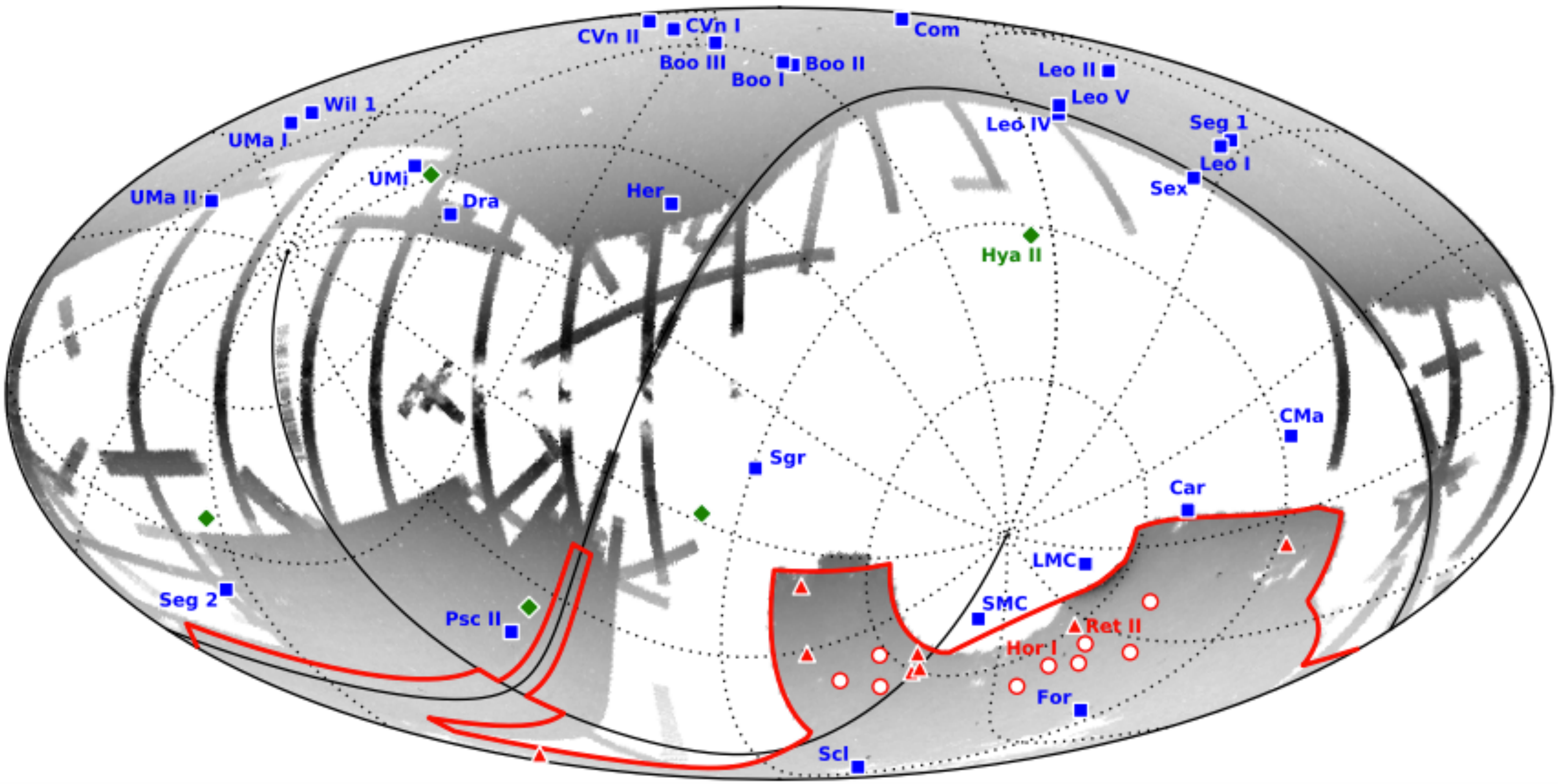


New Dwarf Galaxy Candidates Discovered by DES

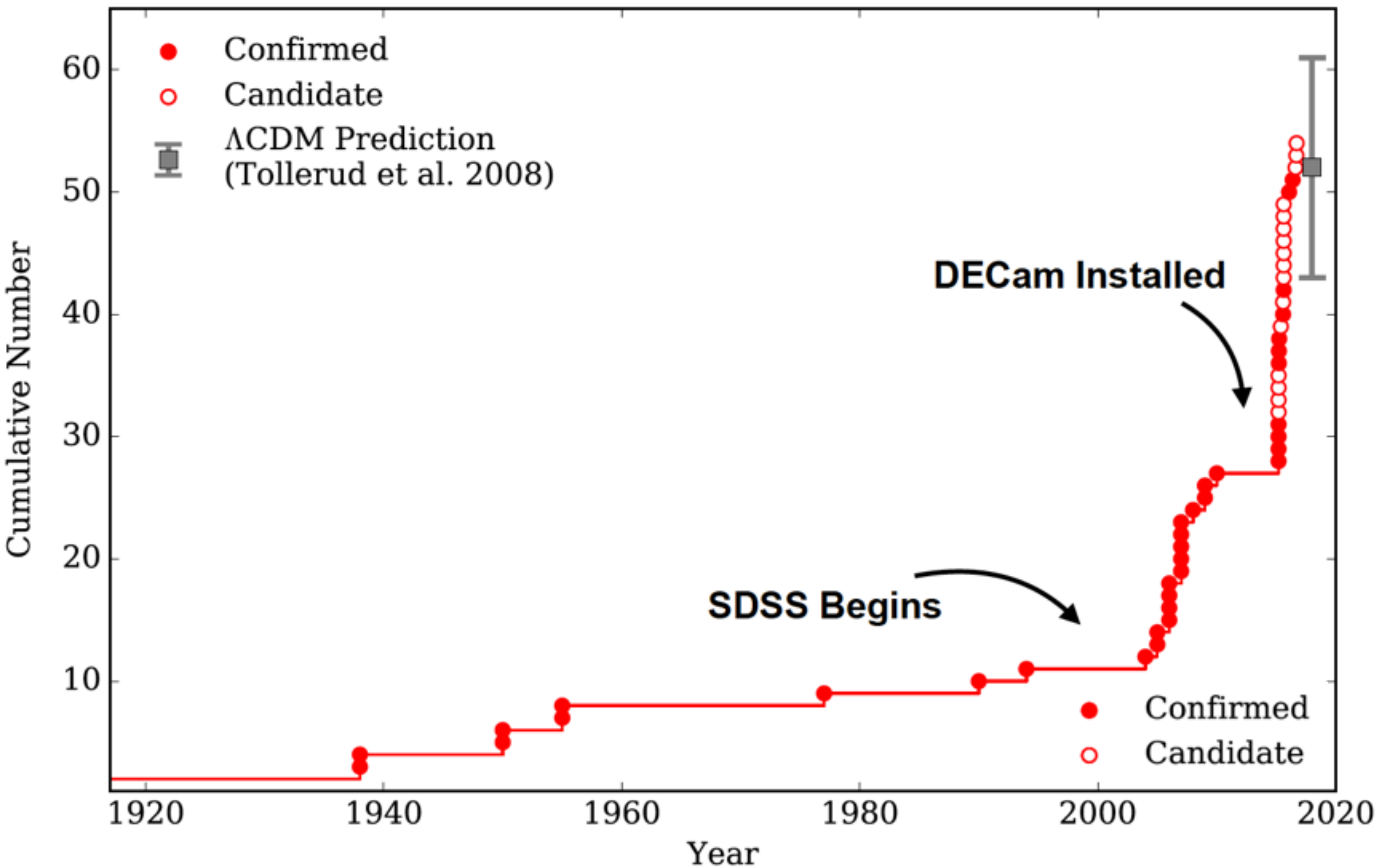
THE DARK ENERGY SURVEY

Year 1 + Year 2 data

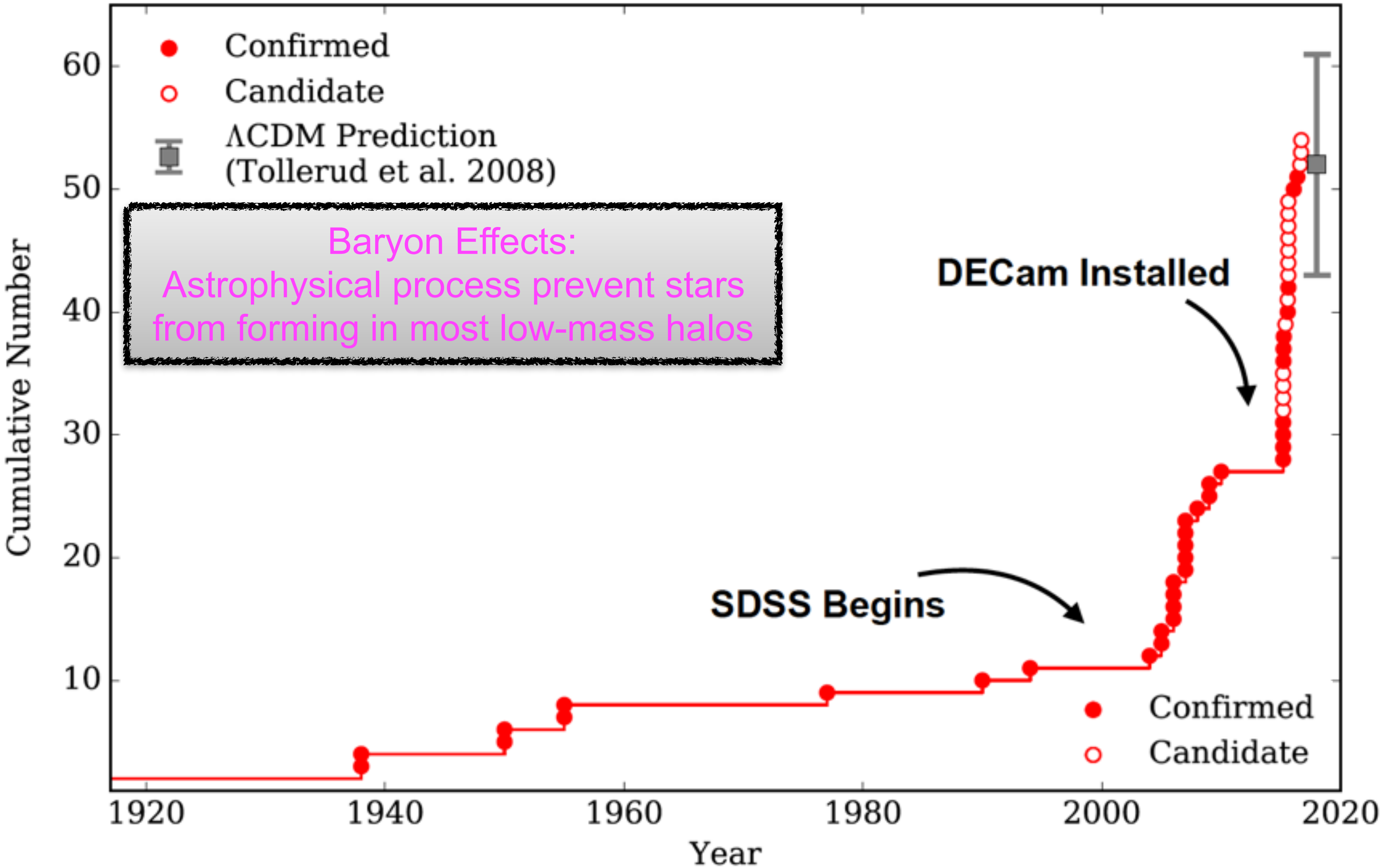


Blue = Known prior to 2015
Red triangles = DES Year 2 candidates
Red circles = DES Year 1 candidates
Green = Other new candidates

Solving the "Missing Satellite Problem"



Solving the "Missing Satellite Problem"



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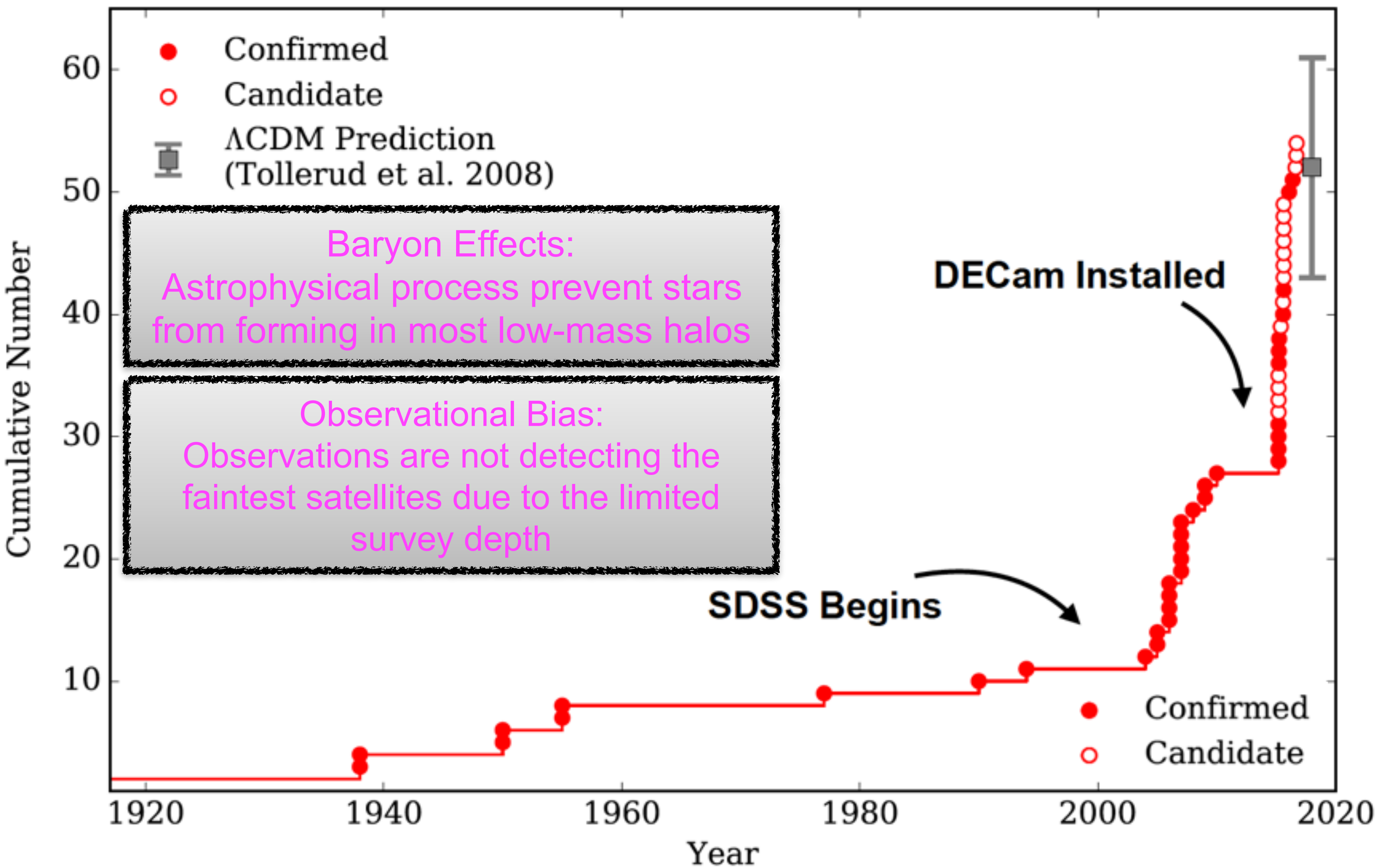
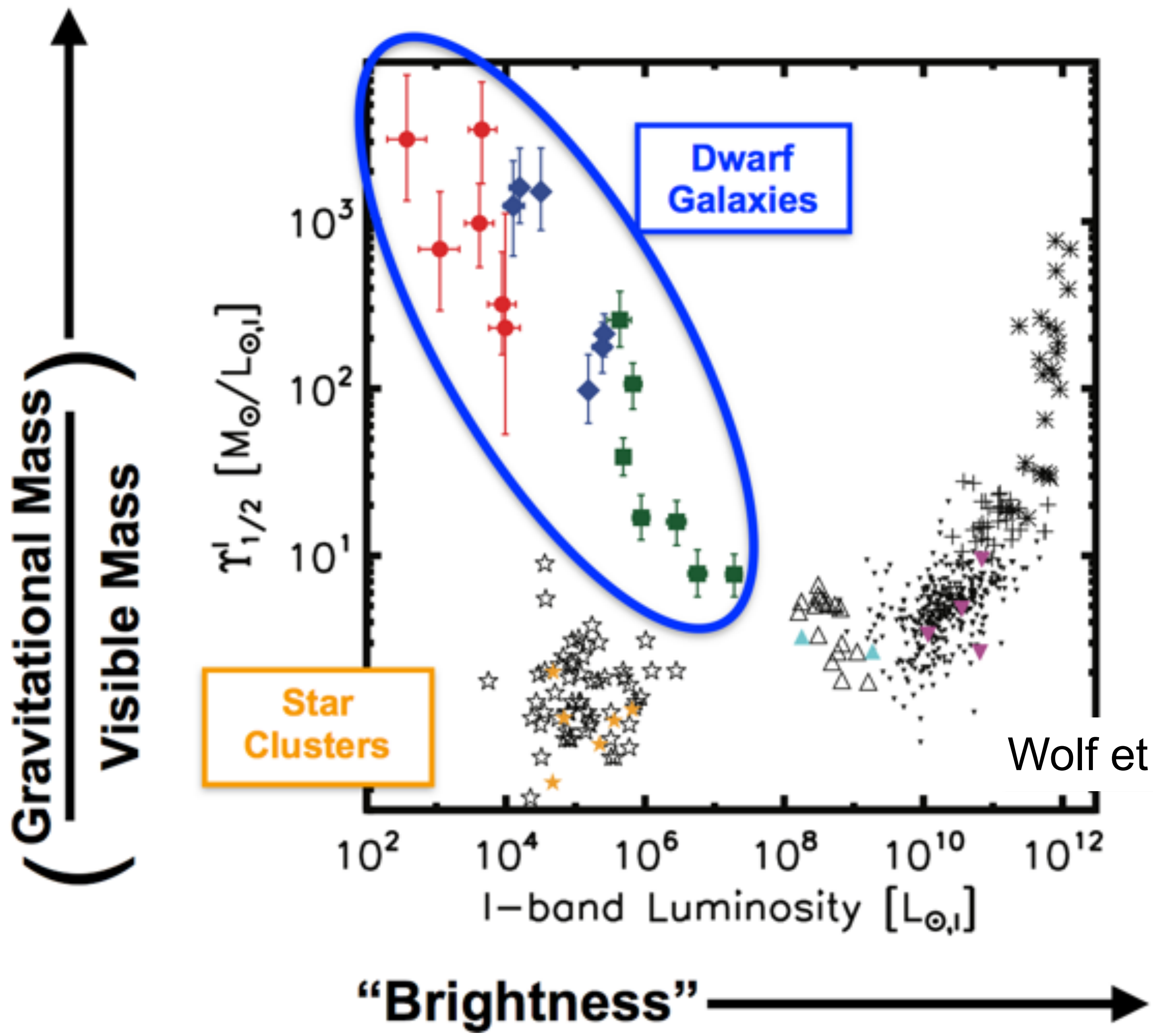


What Are Dwarf Galaxies?

Milky Way Satellites are Most Dark-Matter-Dominated Galaxies.



Wolf et al. 2010

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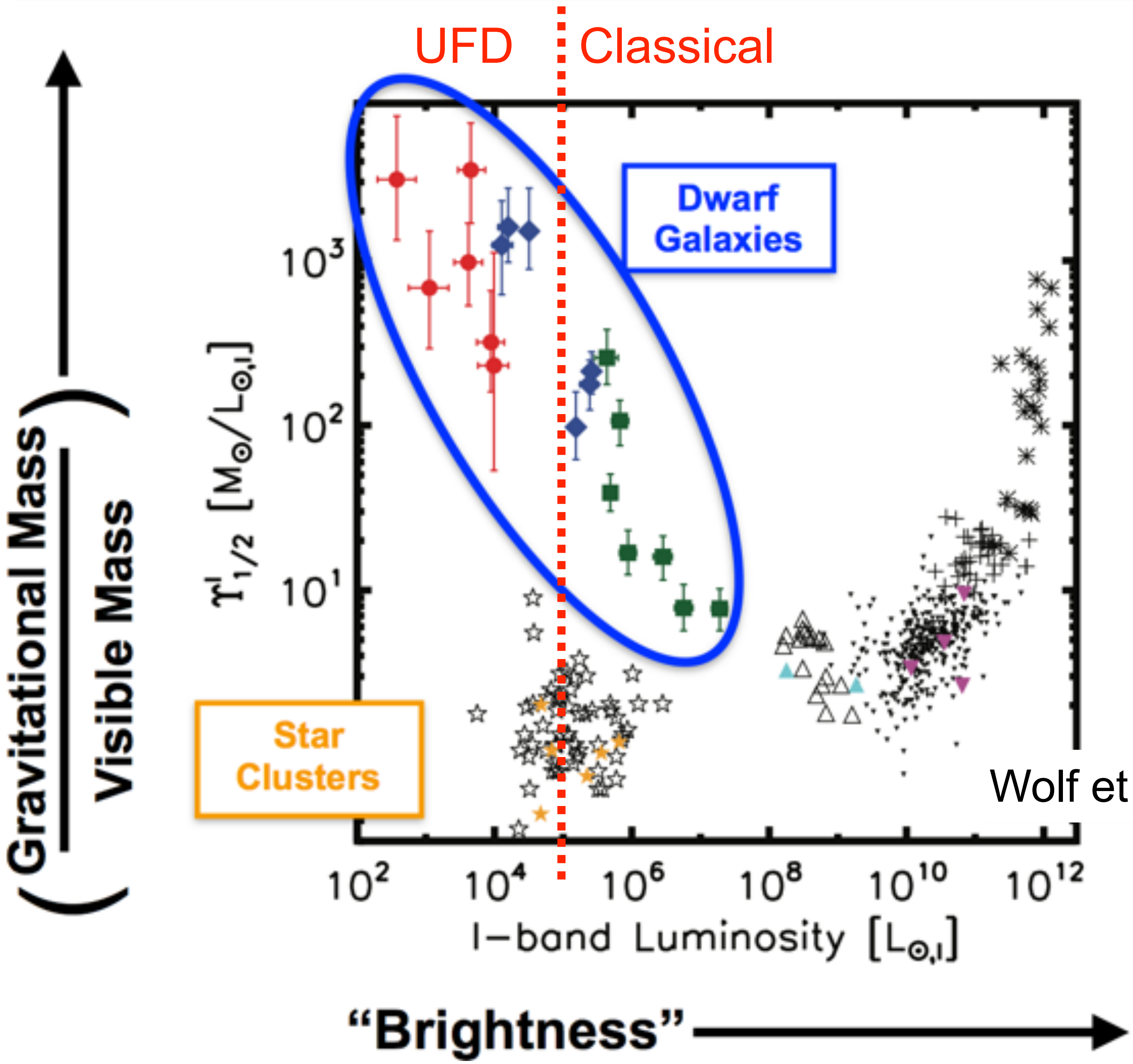
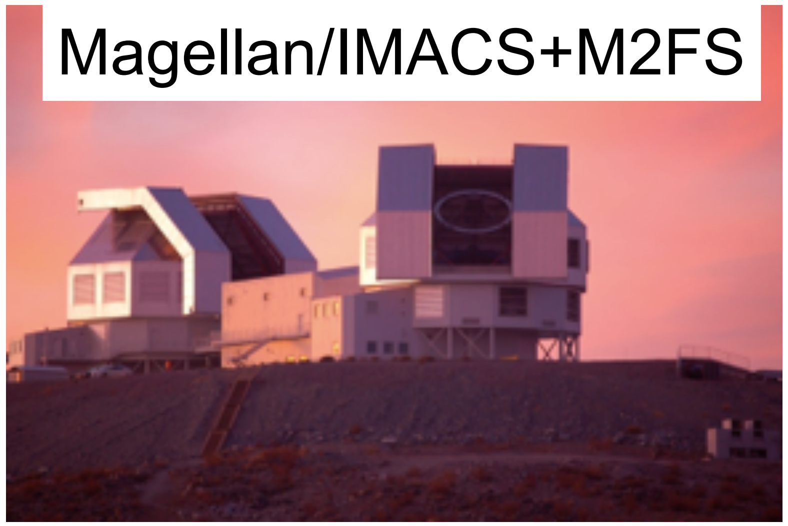
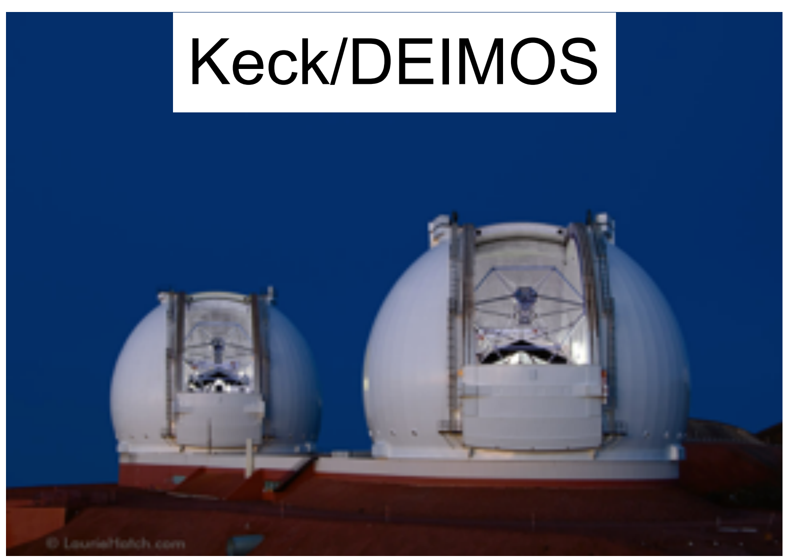
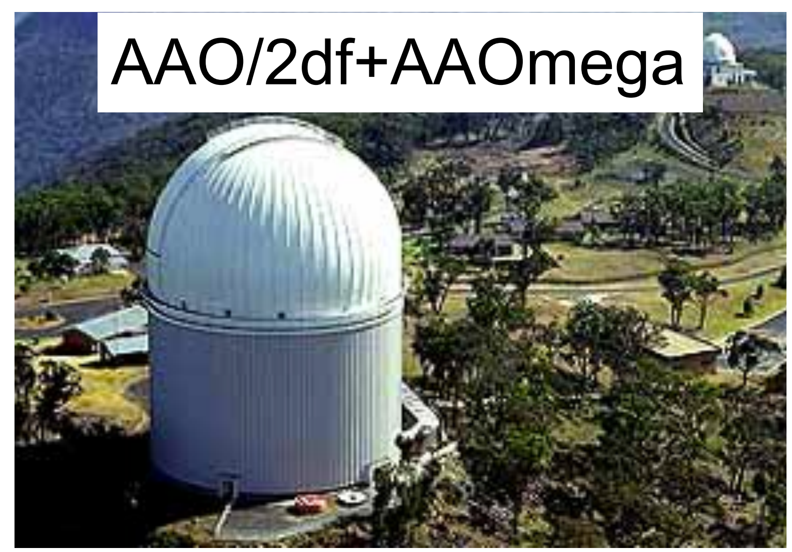


Wolf et al. 2010

Spectroscopic Campaign w/ 4-10 m





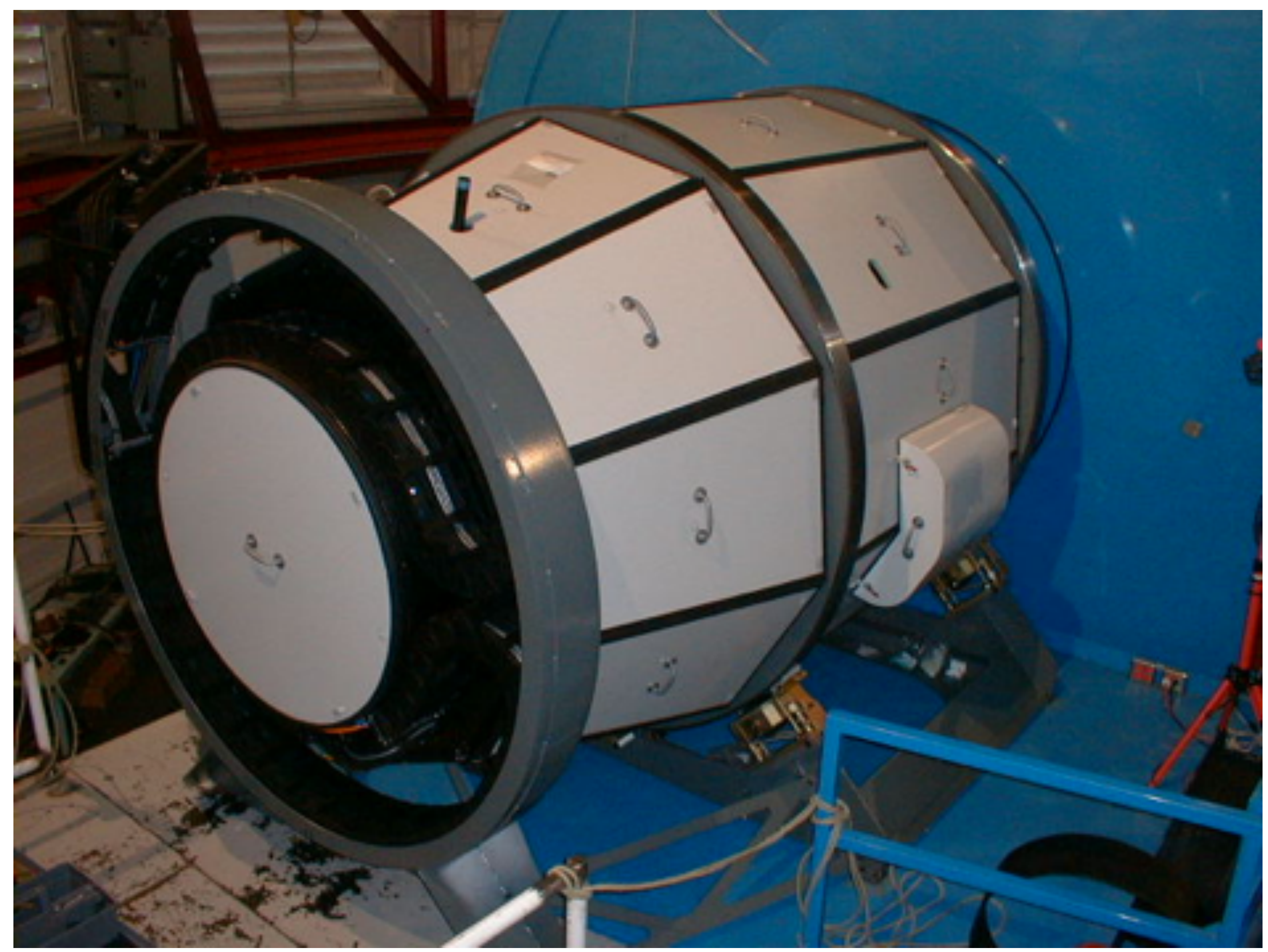


R ~ 5k - 20k
Multiplexing: 50 - 400 stars
FOV: 15 arcmin - 2 deg in diameter
Velocity precision: 0.5 - 2 km/s (at high SNR)

Spectroscopic Followup w/ Magellan/IMACS

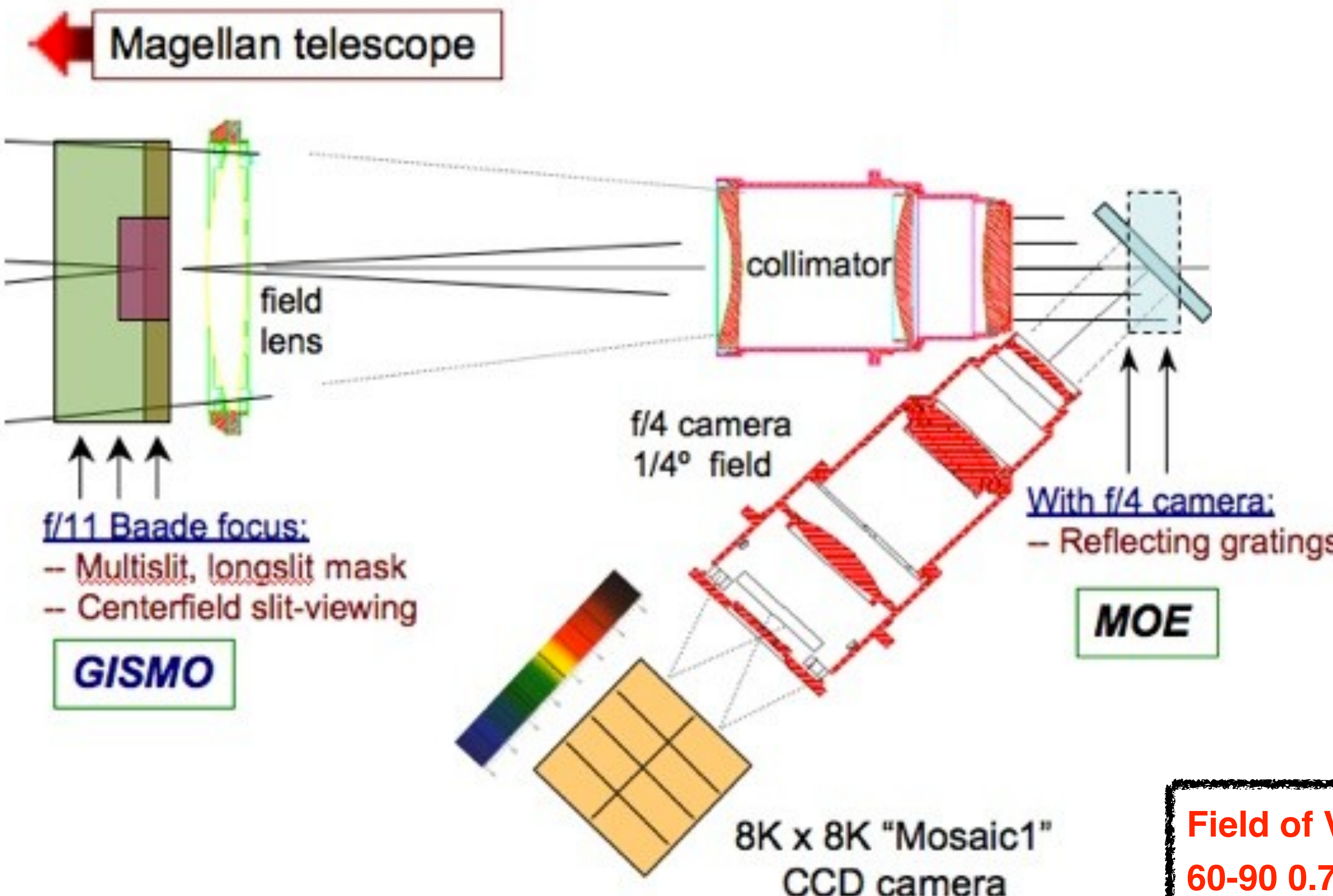
Magellan Telescopes
2 x 6.5m telescopes

Multi-Object Spectrograph

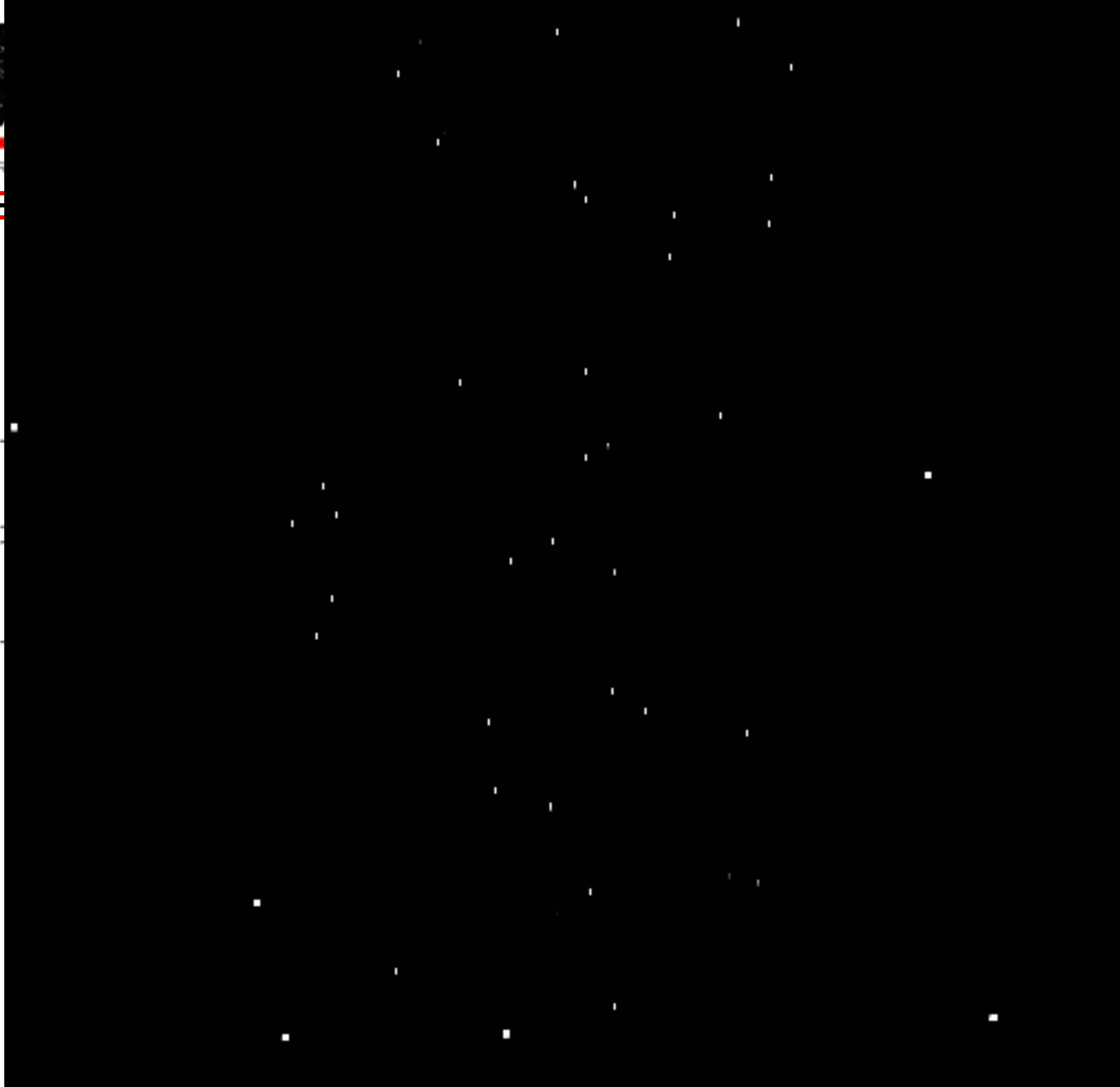


Inamori Magellan Areal Camera and Spectrograph (IMACS)

Magellan/IMACS

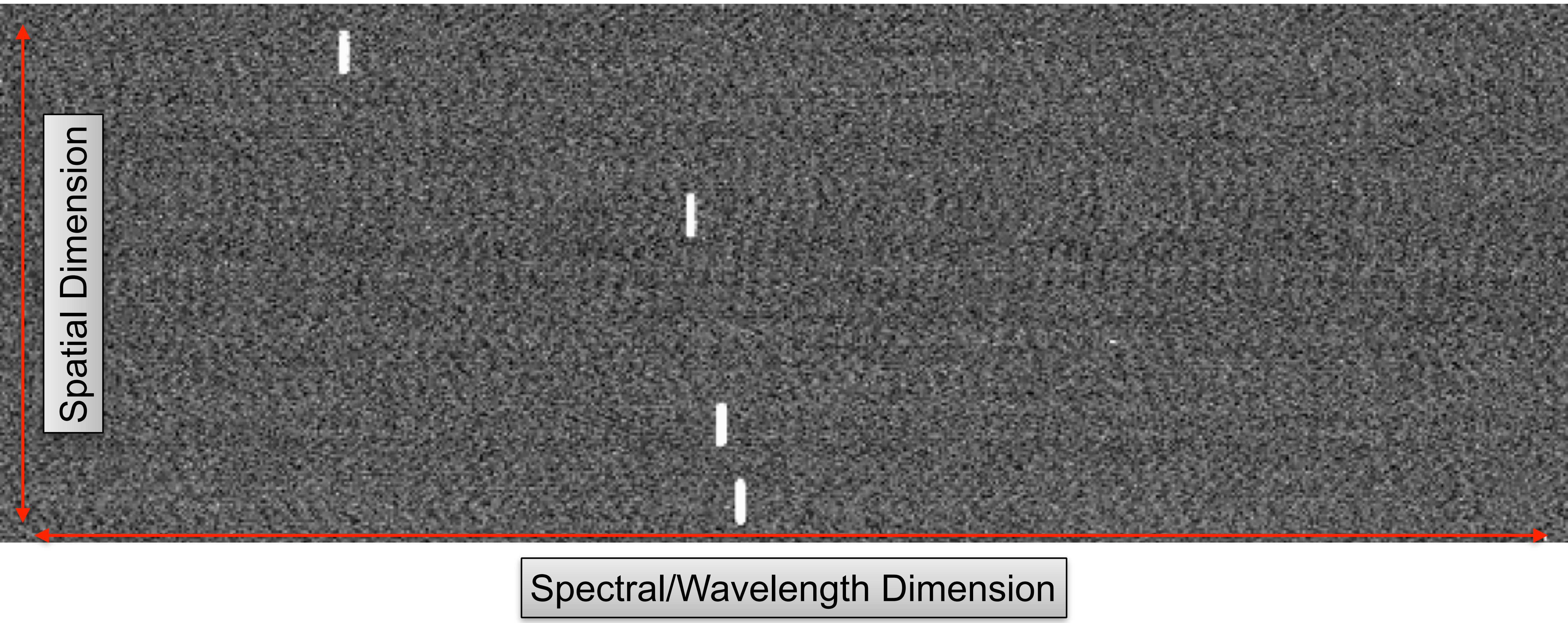


Field of View: 15' x 15'
60-90 0.7"x5.0" slitlets per mask

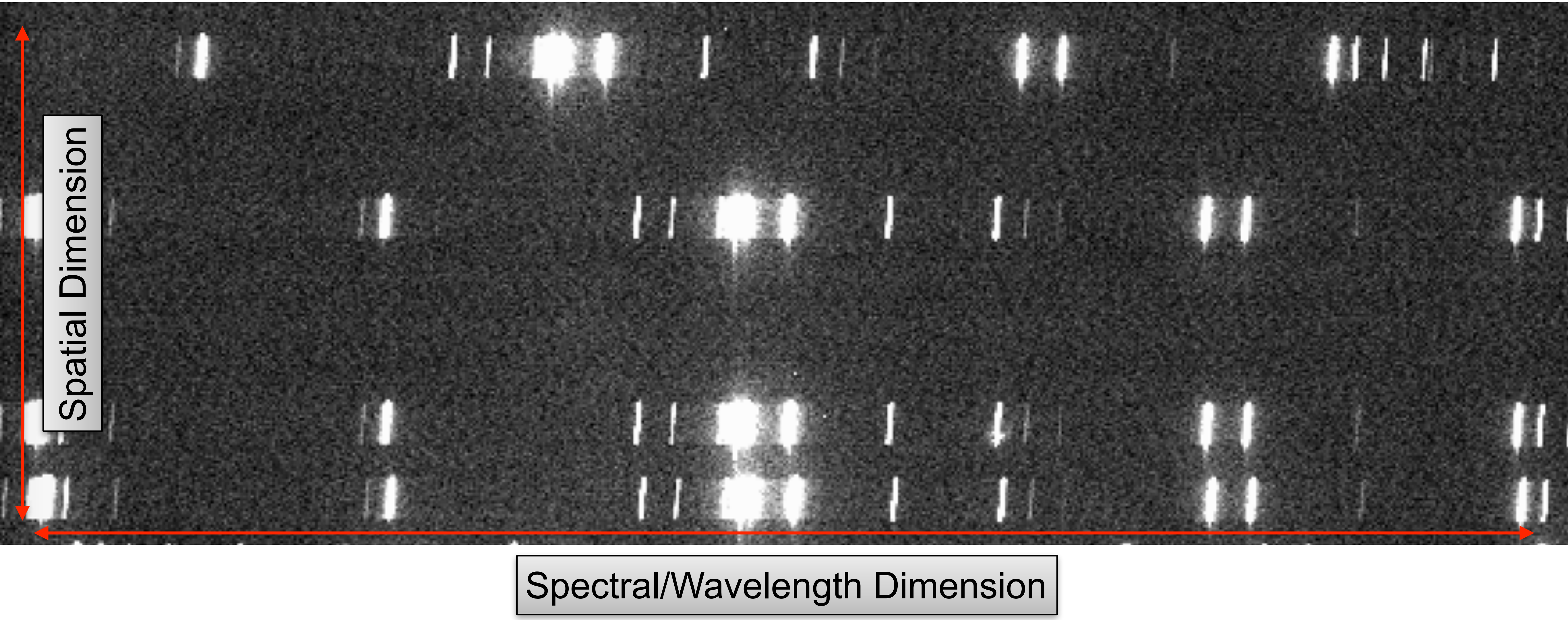


per mask

Slit Mask Image

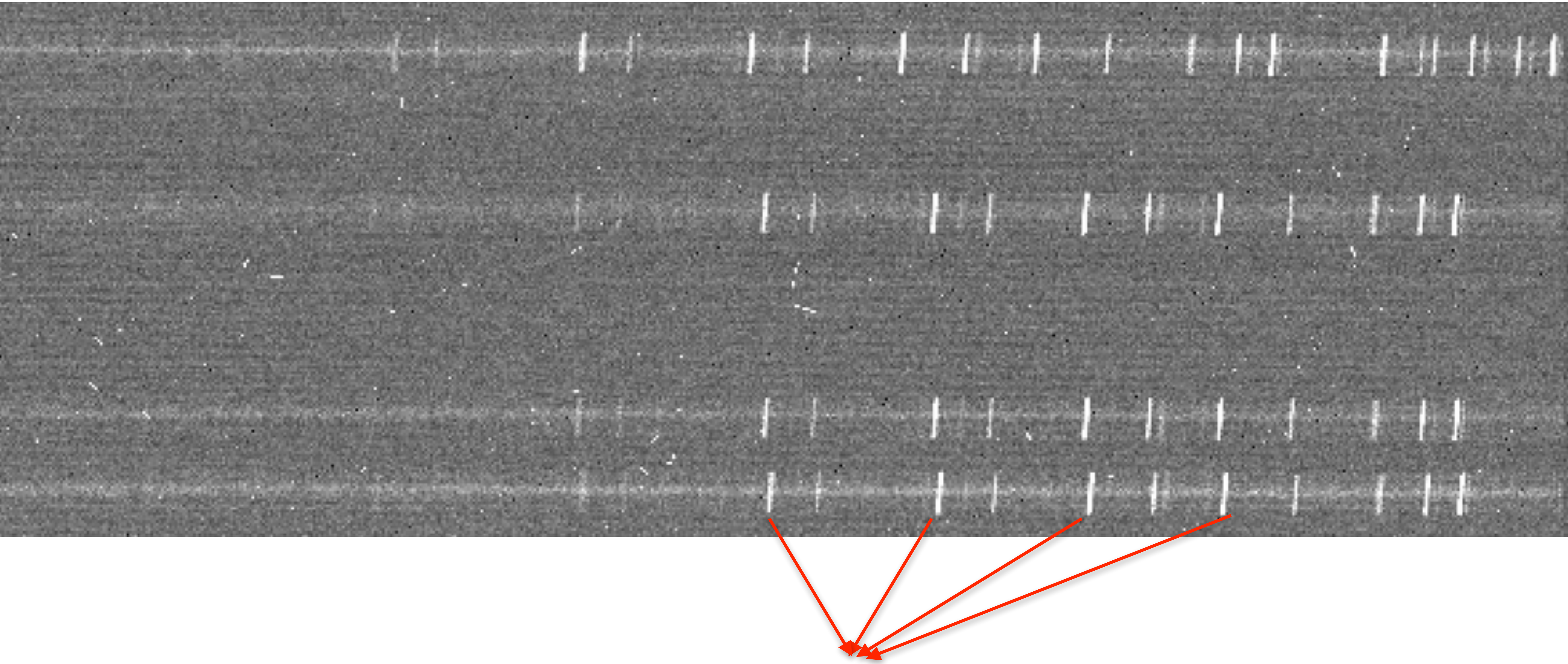


Wavelength Calibration Frame

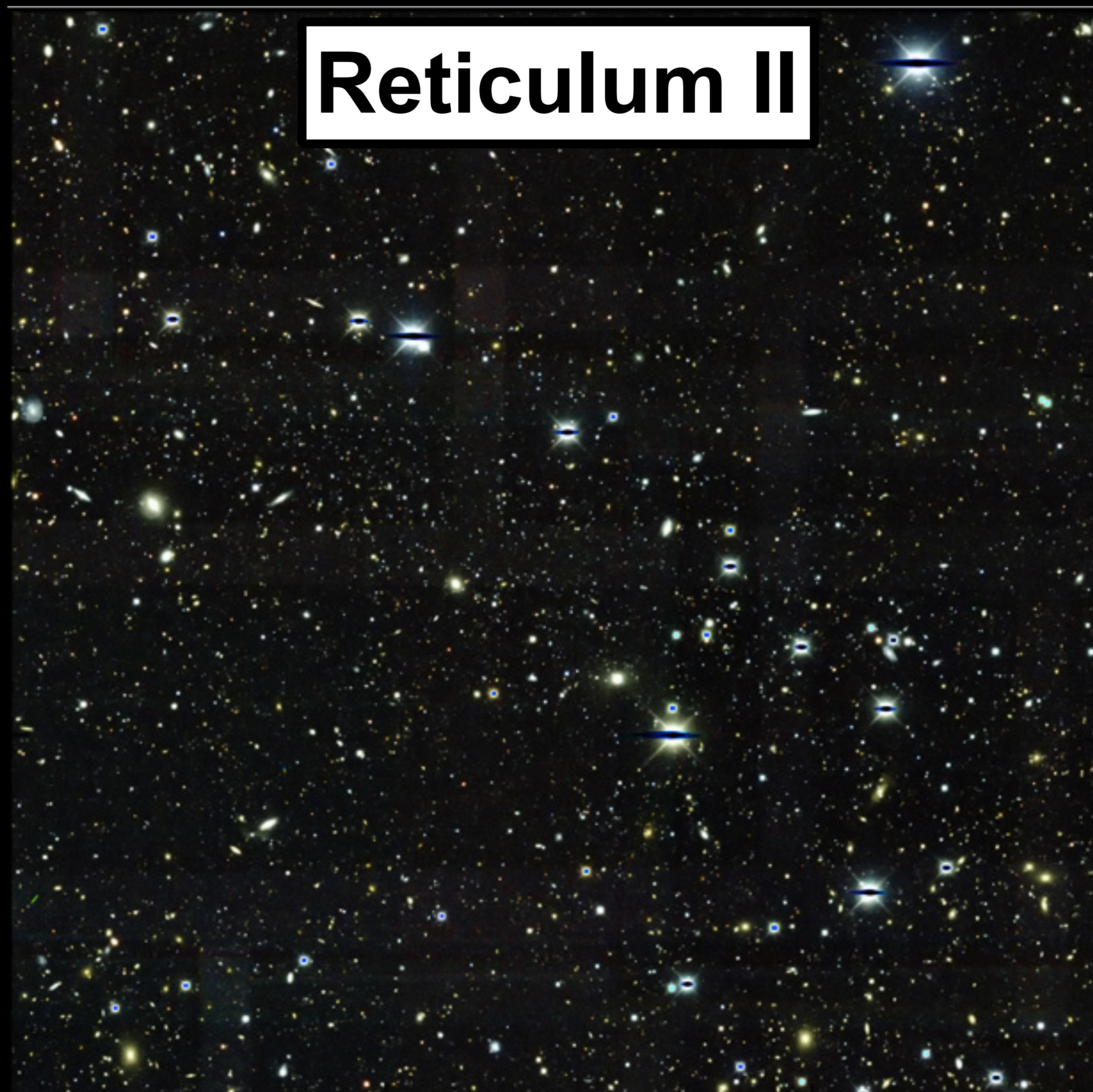


Atomic emission lines from arc lamps

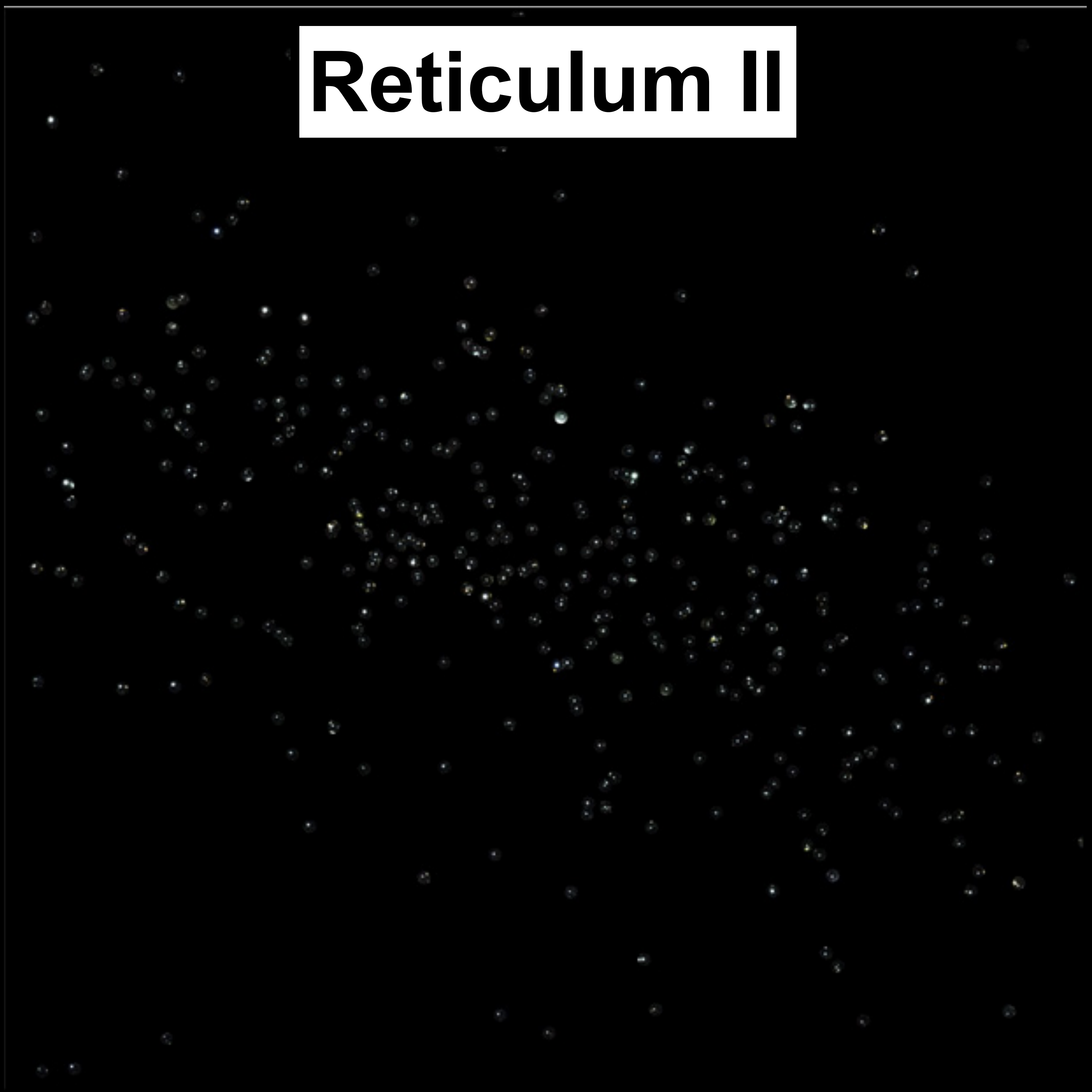
2D Stellar Spectra



Emission lines from sky
Wavelength recalibration

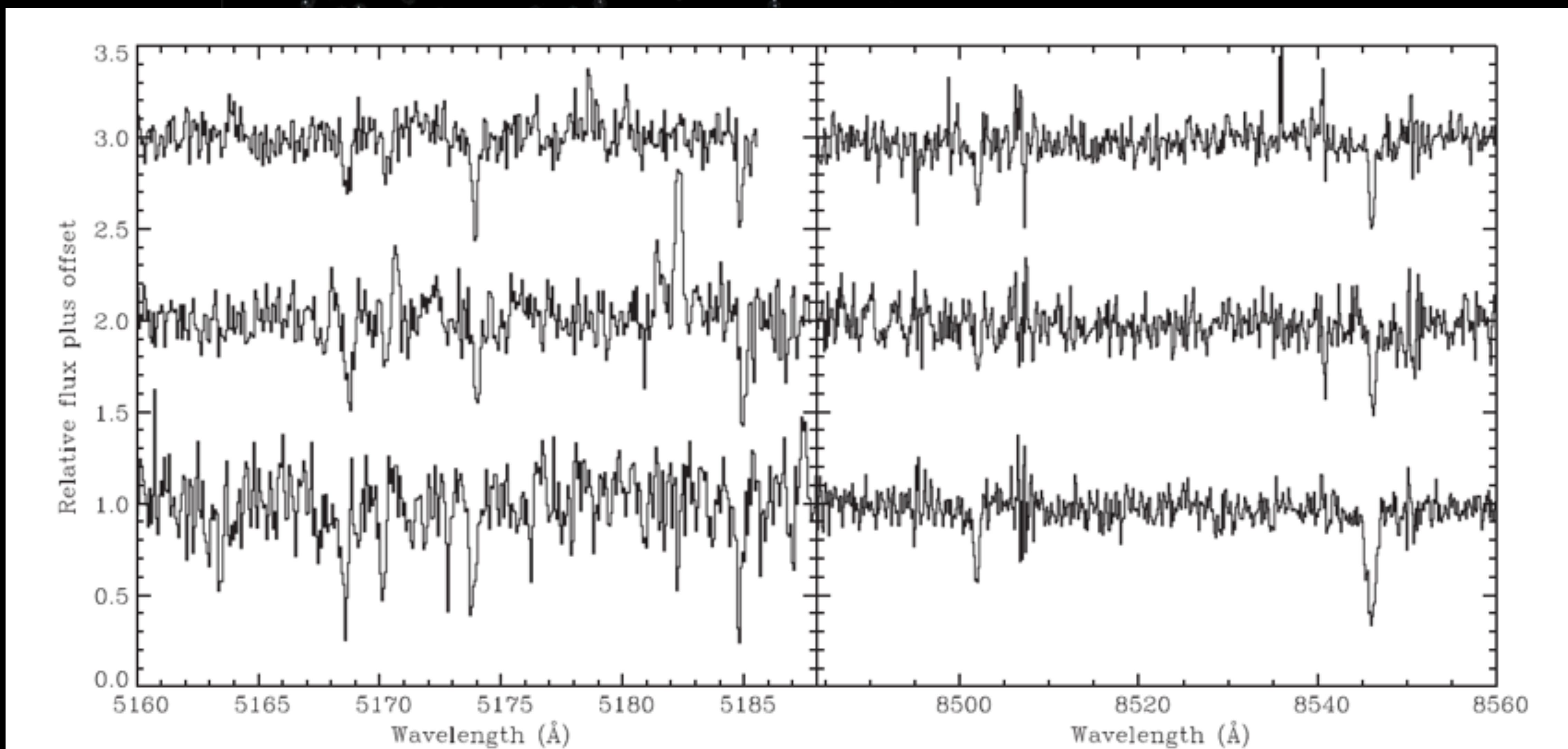


DES Collaboration



DES Collaboration

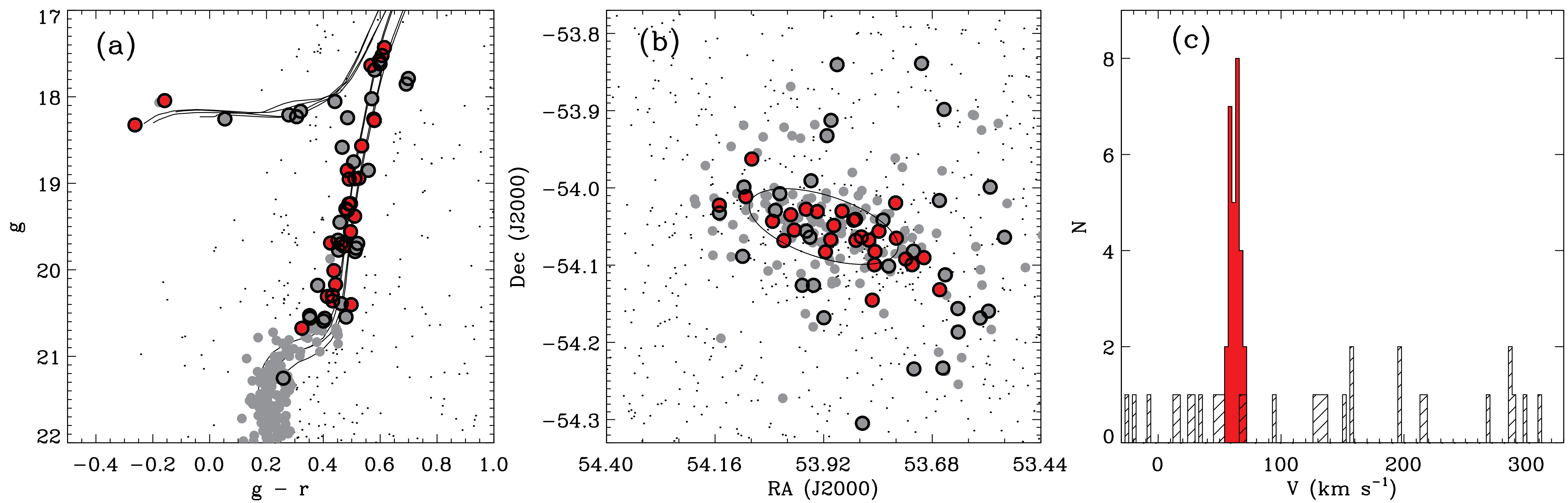
Reticulum II



Stellar Kinematics w/ Resolved Stars

DES Collaboration

Reticulum II:
One of Newest Dwarf Galaxies

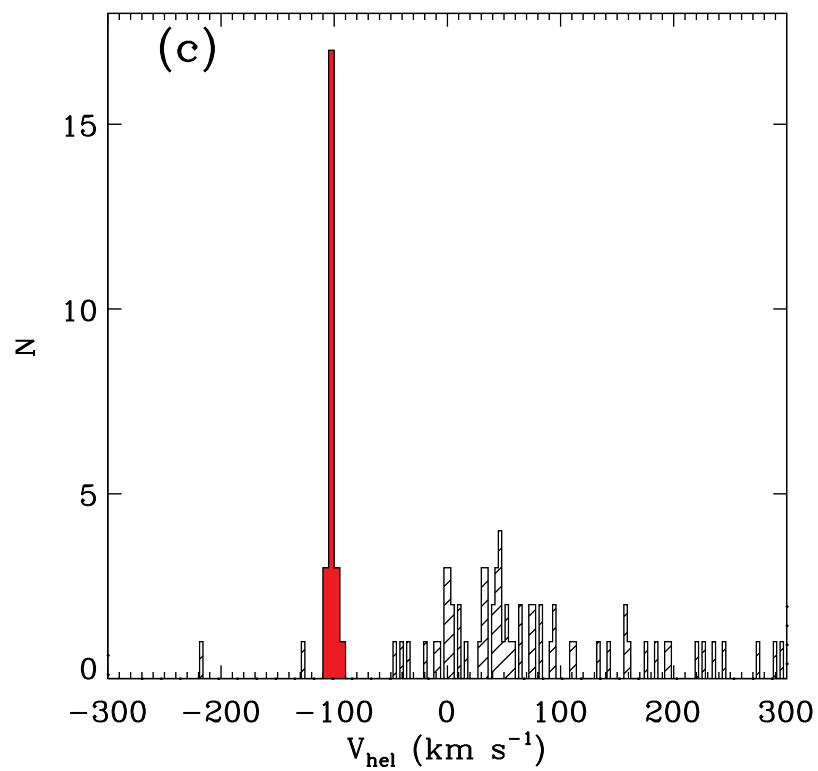


- **~30 members identified in Reticulum II**
- **Velocity peak indicative of a genuine stellar association**
- **Dynamical mass calculated from the width of the velocity dispersion**
- **Every measured characteristic of Reticulum is consistent with the known population of dwarf galaxies**

Quantity	Value
Systemic Velocity	$v = 62.8 \pm 0.5\,\mathrm{km\,s^{-1}}$
Velocity Dispersion	$\sigma_v = 3.3 \pm 0.7\,\mathrm{km\,s^{-1}}$
Metallicity	$[\mathrm{Fe/H}] = -2.65 \pm 0.07$
Metallicity Dispersion	$\sigma_{[\mathrm{Fe/H}]} = 0.28 \pm 0.09$
Dynamical Mass	$M_{1/2} = 5.6 \pm 2.4 \times 10^5\,\mathrm{M_\odot}$
Mass-to-Light Ratio	$M/L = 470 \pm 210\,\mathrm{M_\odot/\,L_\odot}$

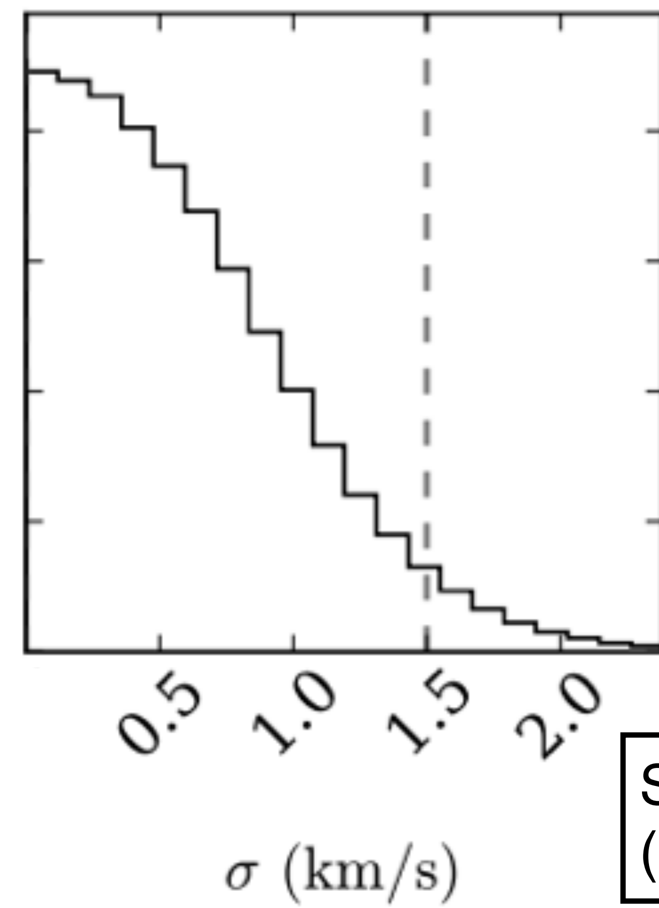
Simon et al. 2015 (DES Collaboration)
(see also Walker et al. 2015, Koposov et al 2015b)

Tucana III: classification unclear



26 members identified

V_{hel} (km s^{-1})	-102.3 ± 0.4
V_{GSR} (km s^{-1})	-195.2 ± 0.4
σ (km s^{-1})[a]	< 1.5
Mass ($M_\odot$)[a]	$< 8 \times 10^4$
M/L_V ($M_\odot/L_\odot$)[a]	< 240

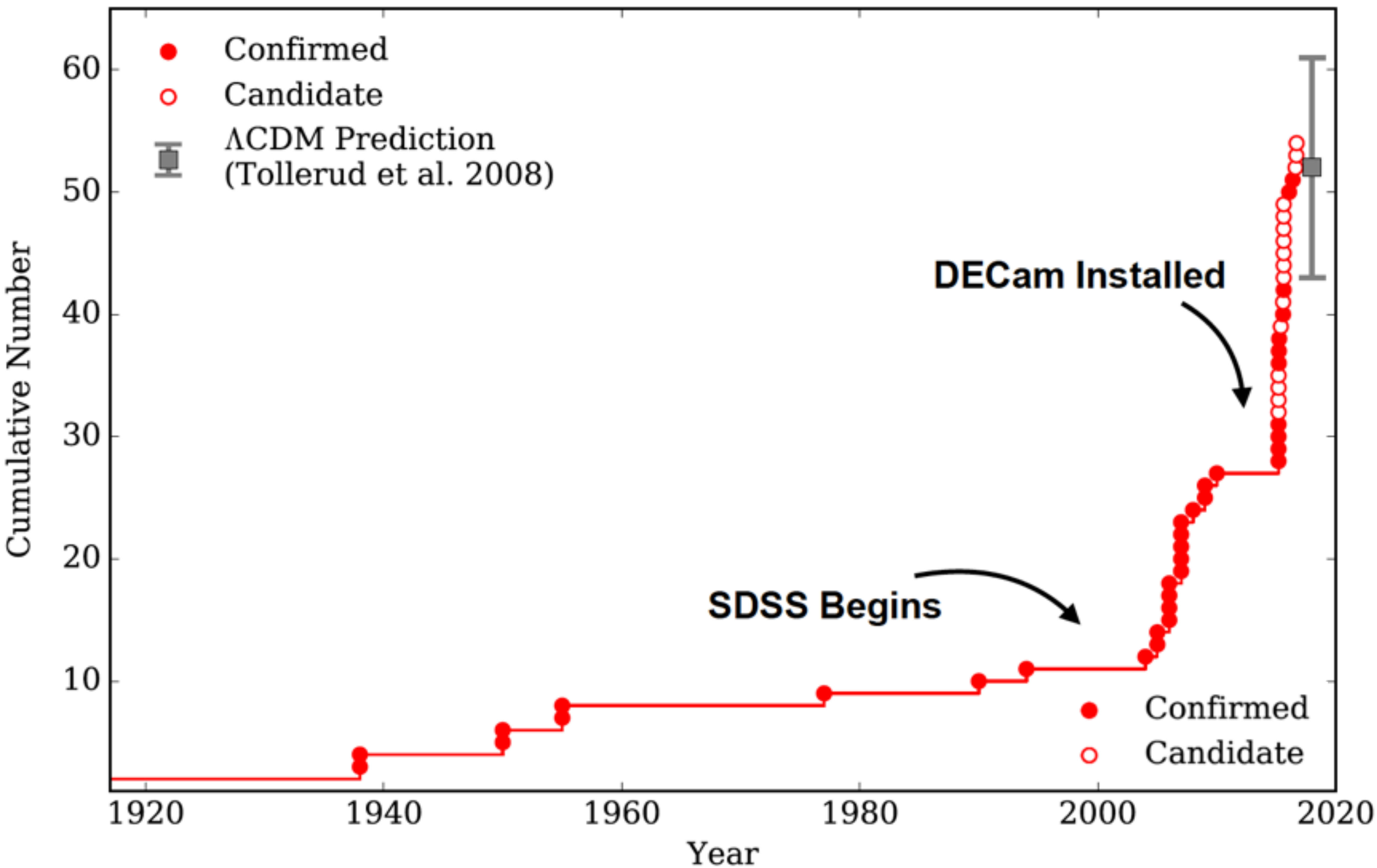


Simon et al. 2017 (DES Collaboration)

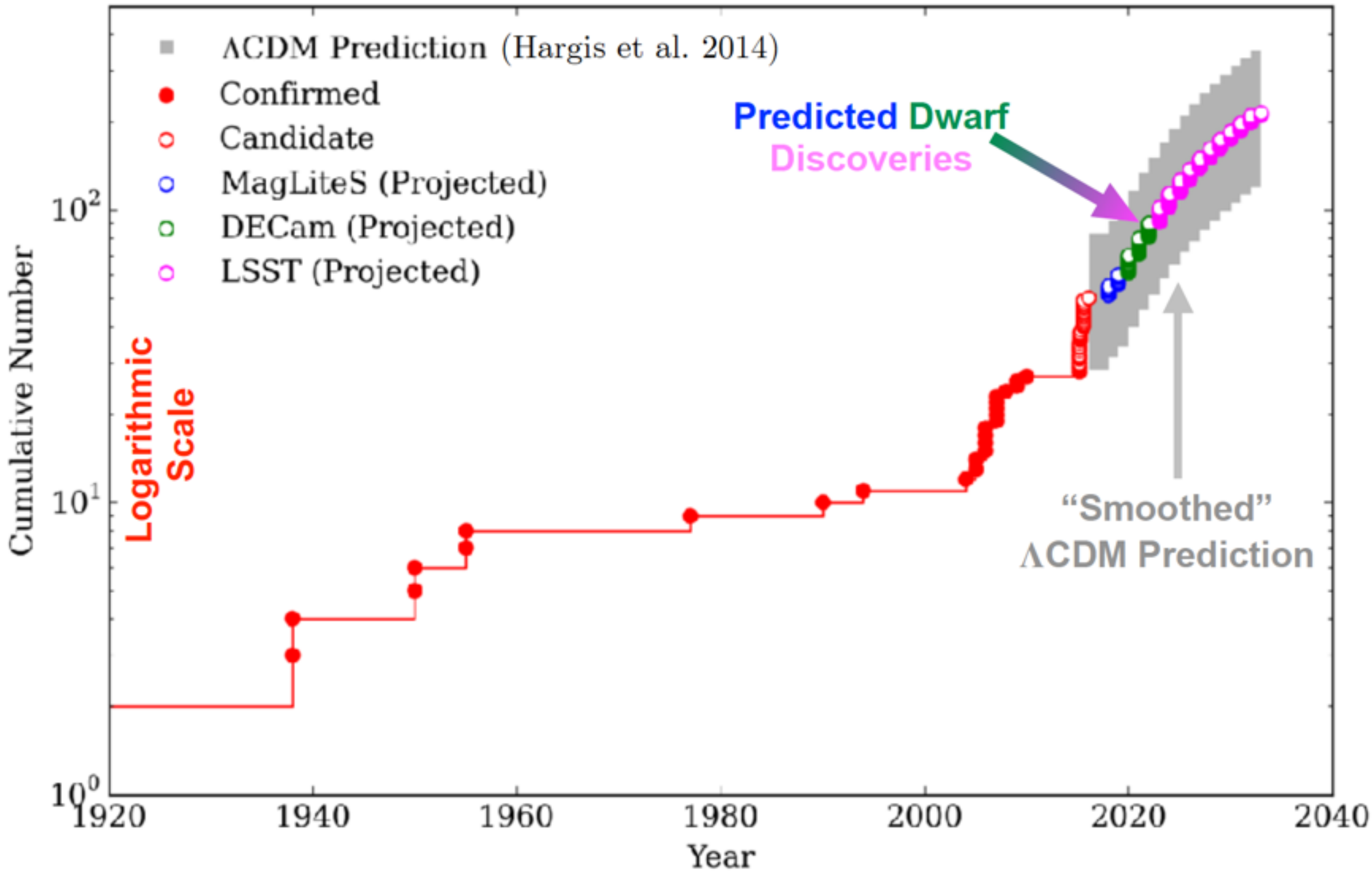
- **Velocity dispersion is NOT resolved**

Need multi-object spectragraph with higher resolution and better stability to achieve higher velocity precision (< 1 km/s)!

Solving the "Missing Satellite Problem"

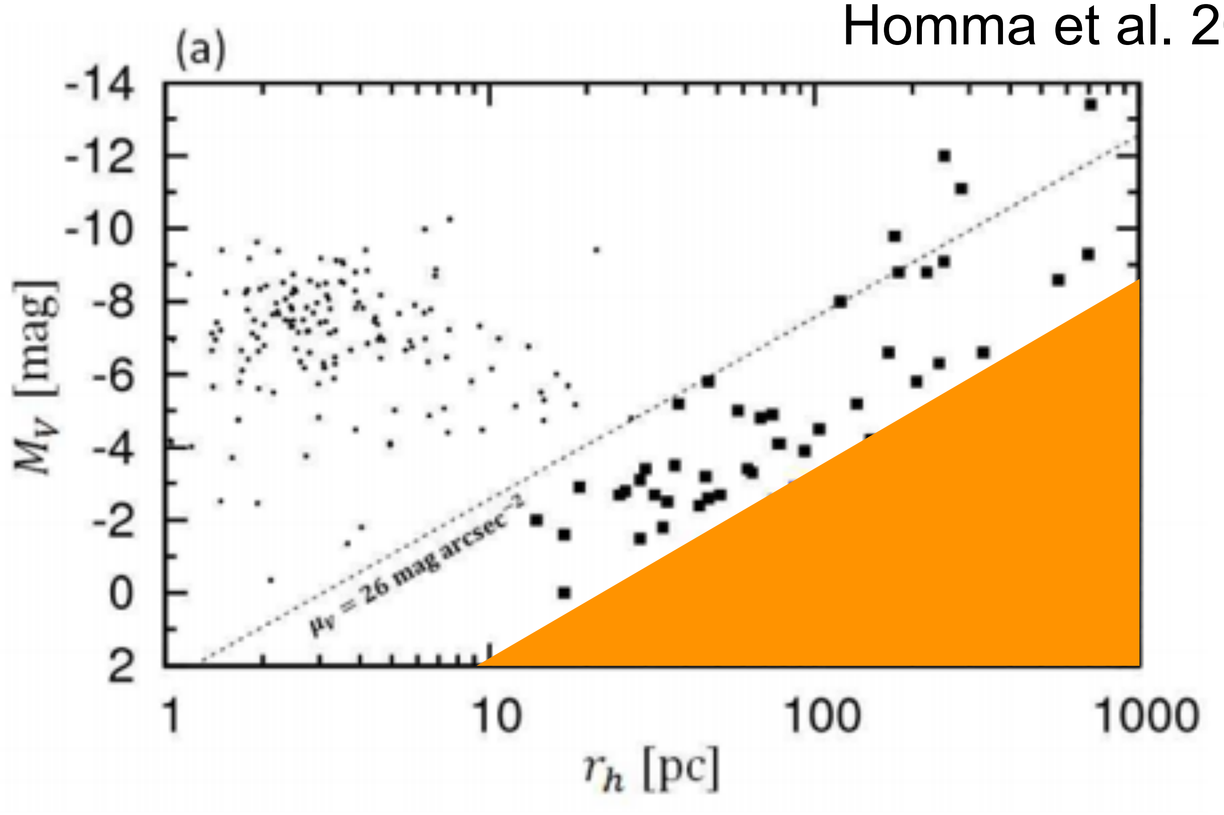


CDM Predictions for Future Dwarf Discoveries



New Dwarf Galaxies in the Era of LSST

Homma et al. 2017

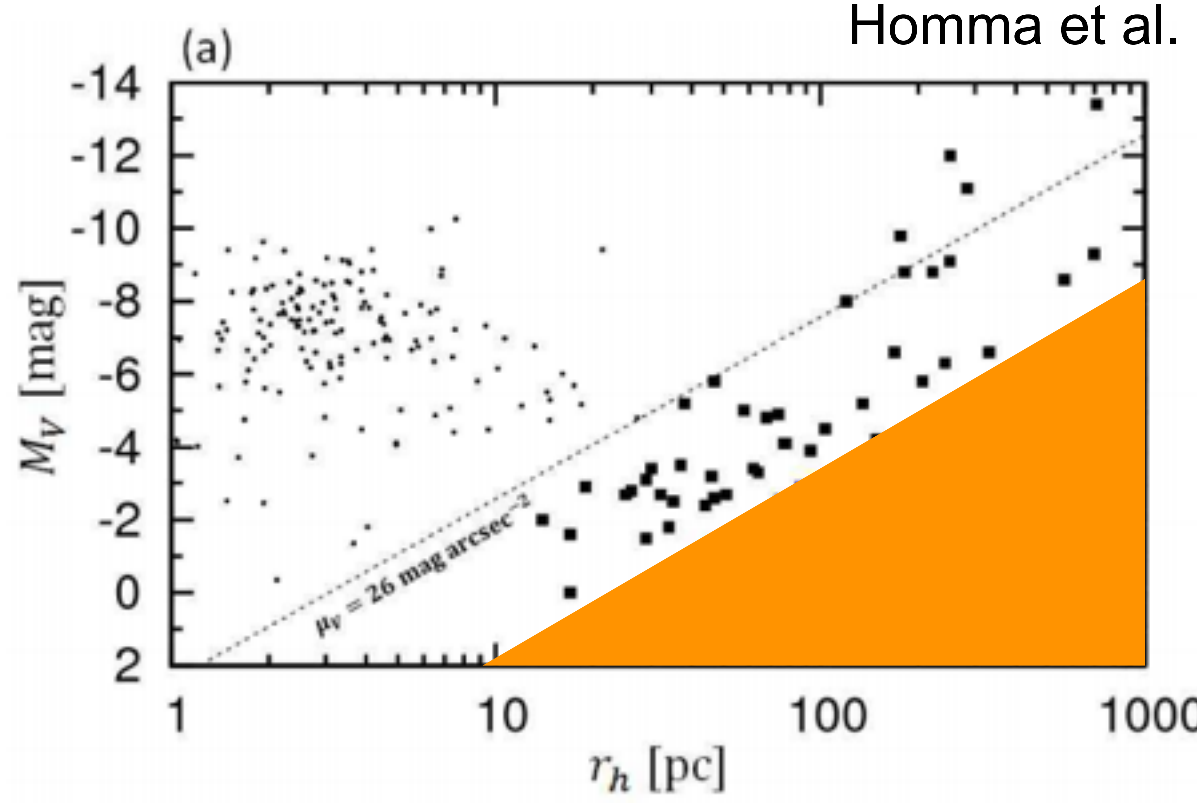


Depth limit w/ DES ~ 30 mag arcsec^{-2}

New Dwarf Galaxies in the Era of LSST

Observational Bias:
Observations are not detecting the faintest satellites due to the limited survey depth

Homma et al. 2017

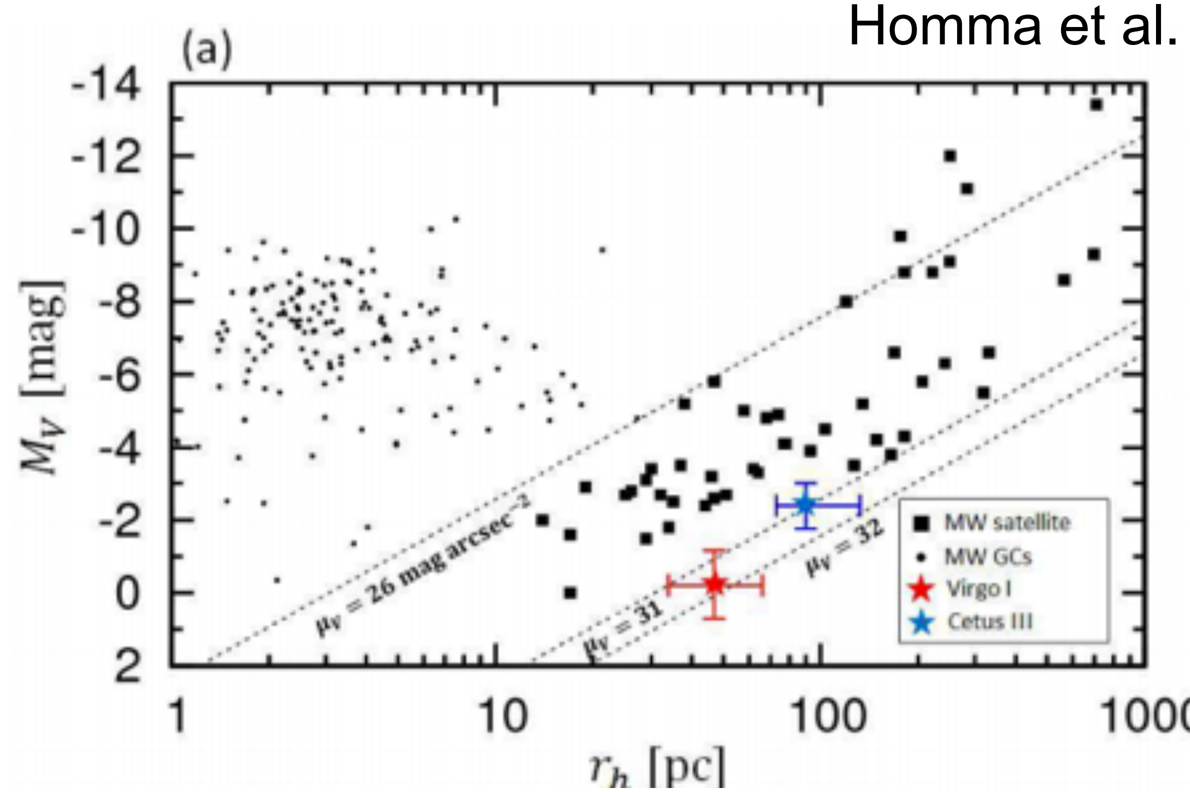


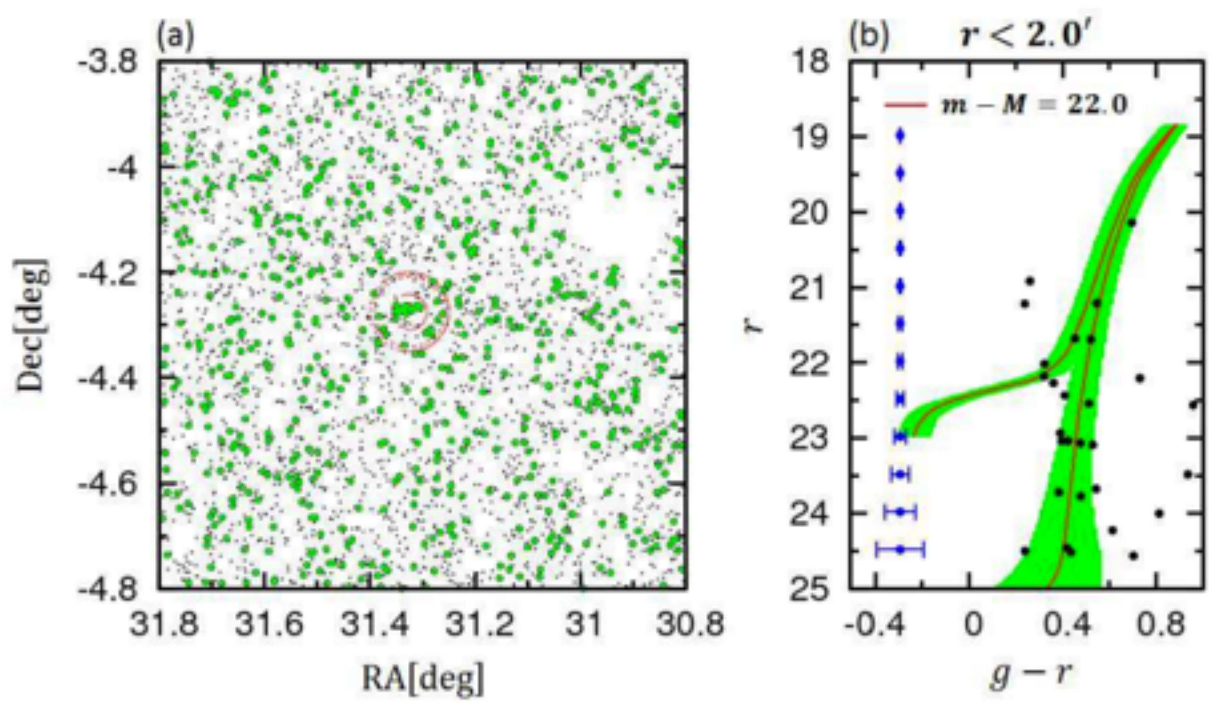
Depth limit w/ DES ~ 30 mag arcsec^{-2}

New Dwarf Galaxies in the Era of LSST

- **Two new ultra-faint galaxy candidates found in first 300 deg^2 of Hyper-Suprime Cam SSP data**
- **They are likely undetectable in any previous survey**
- **< 5 members can be followed spectroscopically with 8-10 m class telescope**

Homma et al. 2017





Need 30 m class telescopes to confirm its dark matter content

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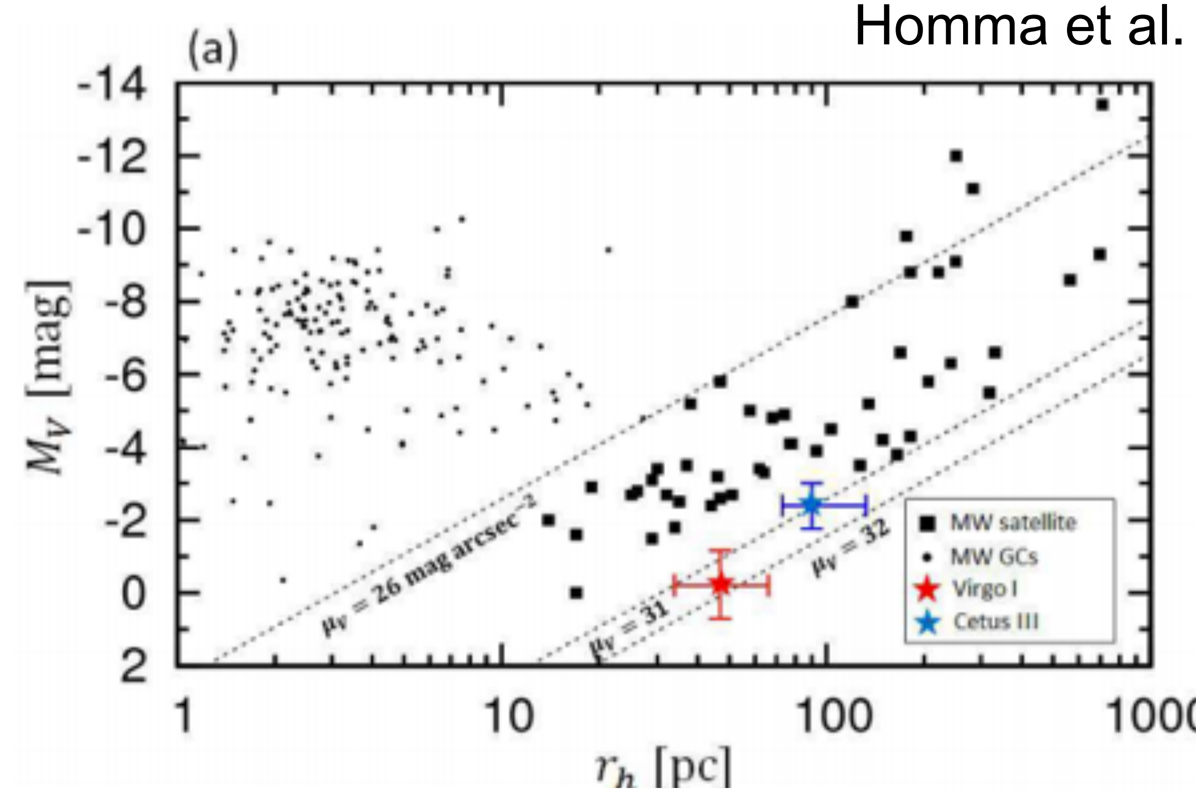
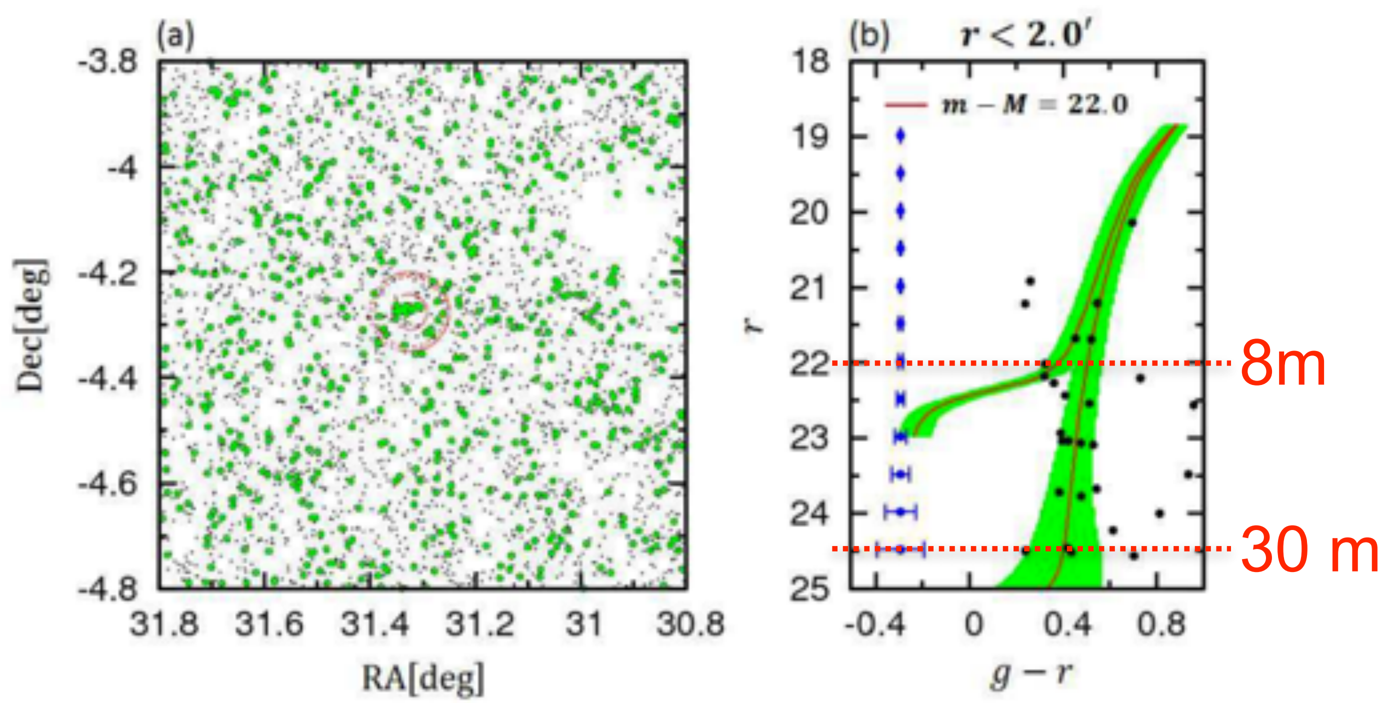




Need 30 m class telescopes to confirm its dark matter content

Why Studying the Milky Way Satellite Galaxies

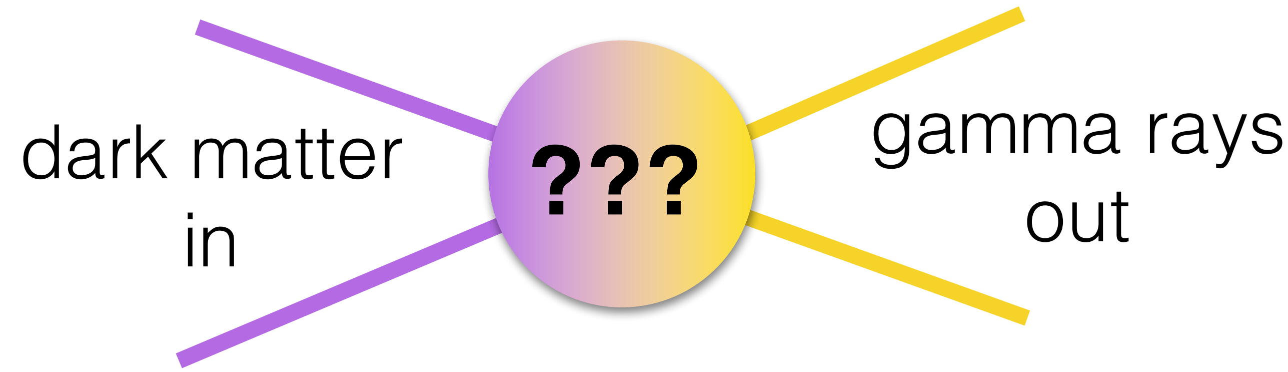
- Missing Satellites Problem — Dark Matter Models
  - CDM vs. WDM vs. SIDM, etc.

- **Constraints on WIMP Cross Section — Indirect Dark Matter Detection**
  - **WIMP: Weakly Interacting Massive Particles**

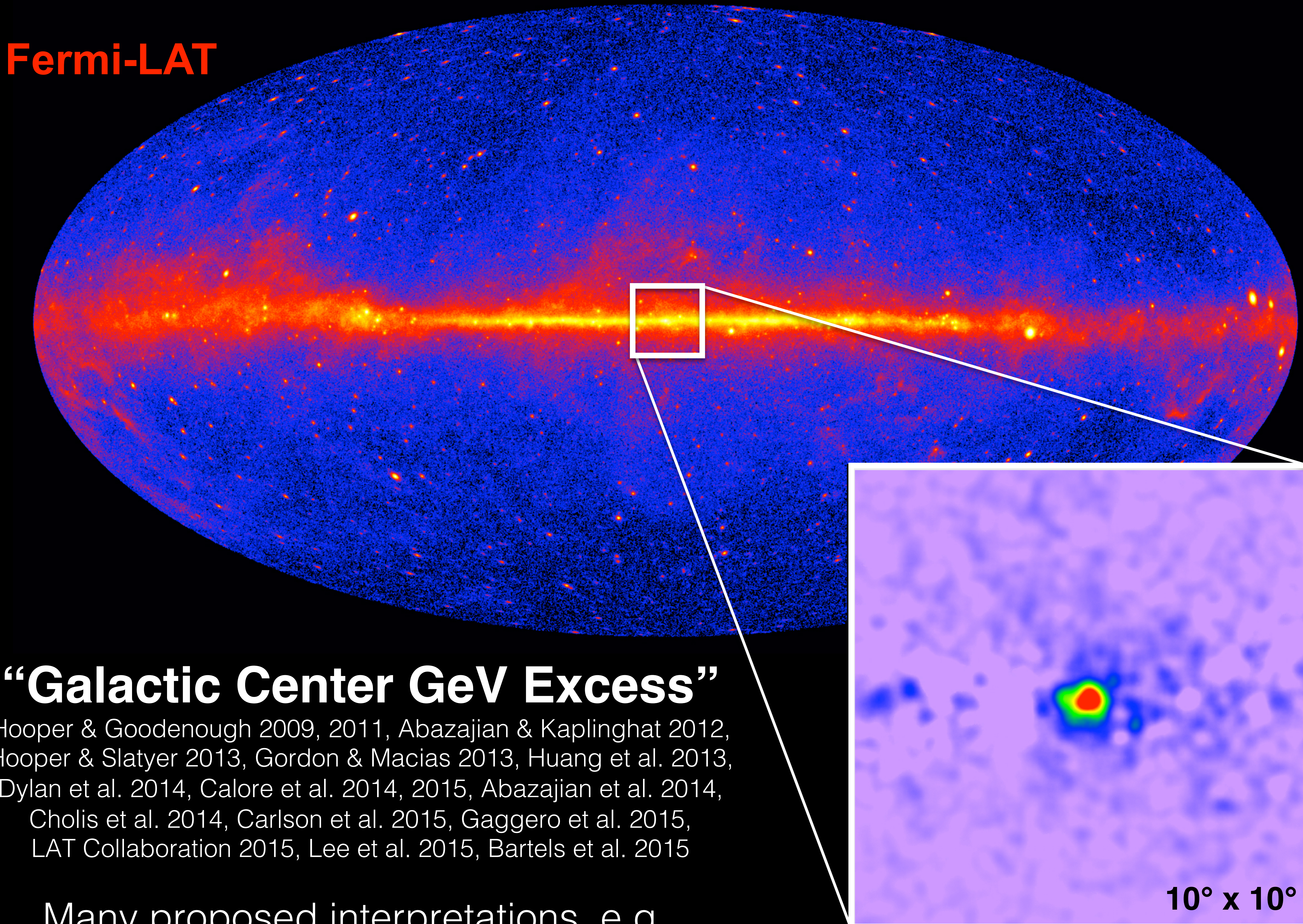
- Constraints on MACHO Abundance
  - MACHO: MAssive Compact Halo Object

Indirect Detection of Dark Matter
WIMP Annihilation

Many dark matter models predict annihilation into energetic Standard Model particles
(e.g., gamma rays, neutrinos, electrons, …)



Annihilation rate scales as density squared



Residual map 1-3 GeV

Image Credit: Tim Linden

"Galactic Center GeV Excess"

Hooper & Goodenough 2009, 2011, Abazajian & Kaplinghat 2012, Hooper & Slatyer 2013, Gordon & Macias 2013, Huang et al. 2013, Dylan et al. 2014, Calore et al. 2014, 2015, Abazajian et al. 2014, Cholis et al. 2014, Carlson et al. 2015, Gaggero et al. 2015, LAT Collaboration 2015, Lee et al. 2015, Bartels et al. 2015

Many proposed interpretations, e.g., millisecond pulsars, outburst of cosmic rays, dark matter annihilation, …

Indirect Detection of Dark Matter
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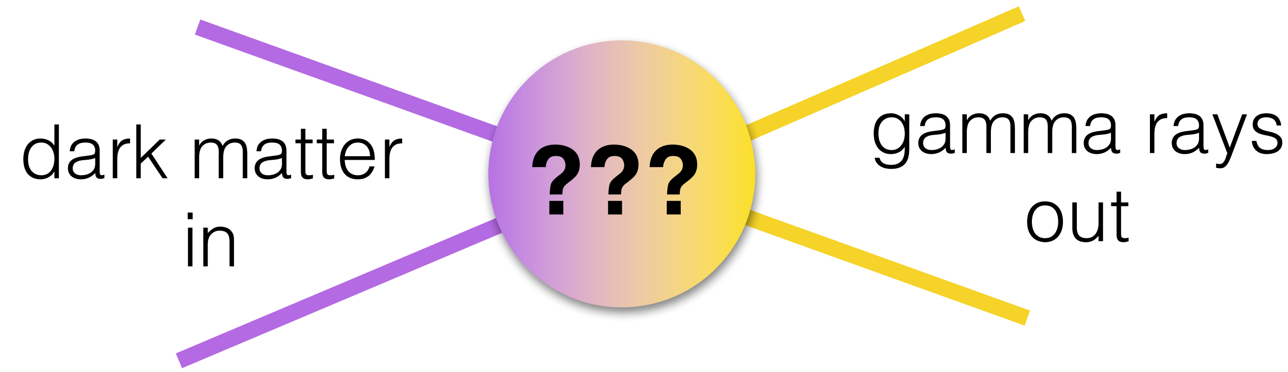


Annihilation rate scales as density squared

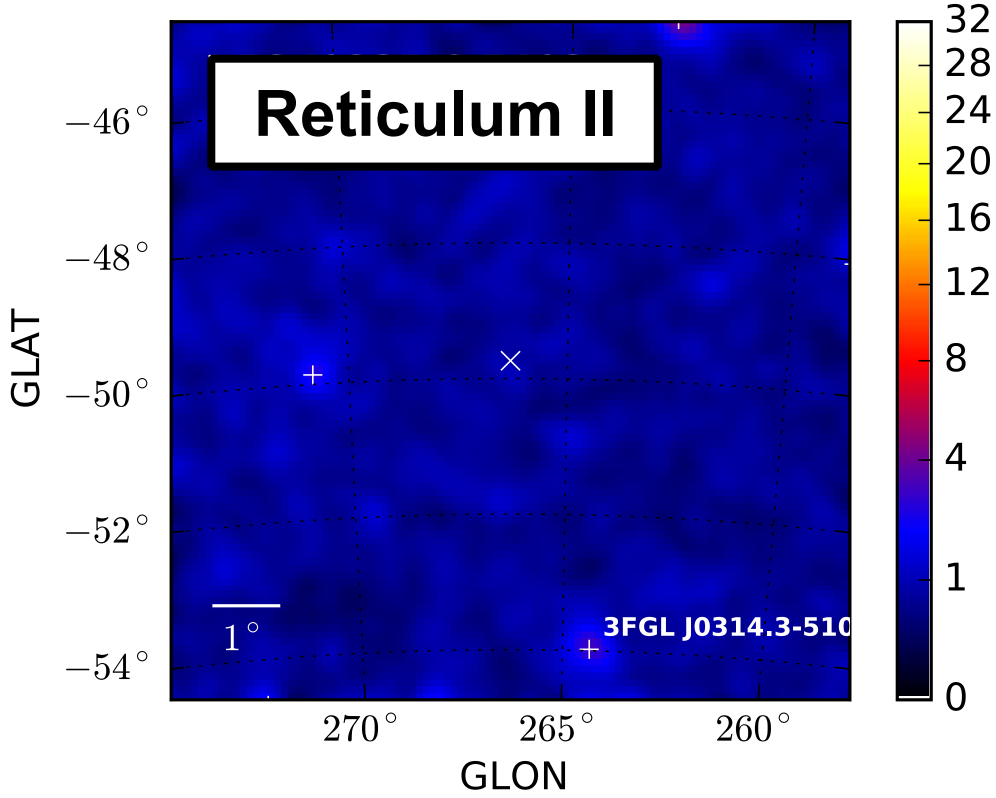
Nearby clumps of dark matter — dwarf galaxies — make ideal targets:

- Clean — no astrophysical source
- Dynamical mass inferred from stellar kinematics
- Cross-section upper limit from non-detection

Dark Matter Searches in Gamma Rays

- **Reticulum II gamma ray excess**
  - **LAT Collaboration, Pass 8: local p-value = 0.06 (1.5σ)**
  - **Geringer-Sameth+2015, Pass 7: local p-value = 0.01 (2.3σ)**

Gamma-ray Counts Map (E > 1 GeV)



Drlica-Wagner et al. (2015) (LAT & DES Collaboration)

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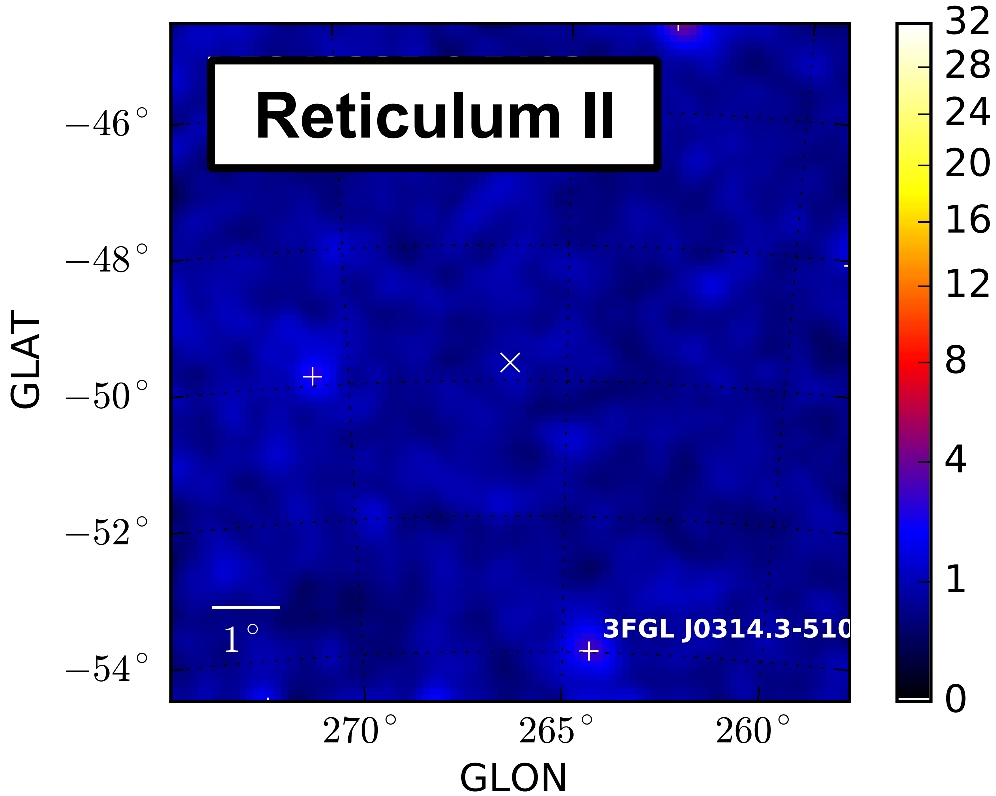

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How strong the signal do we expect to see from Reticulum II?

J-factor — the strength of the annihilation signal, inferred from stellar kinematics

Table 1. Reticulum II

Quantity	Value
J-Factor (0.2°)	$\log_{10} J = 18.8 \pm 0.6\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$
J-Factor (0.5°)	$\log_{10} J = 18.9 \pm 0.6\,\mathrm{GeV}^2\,\mathrm{cm}^{-5}$

Simon et al. 2015 (DES Collaboration)

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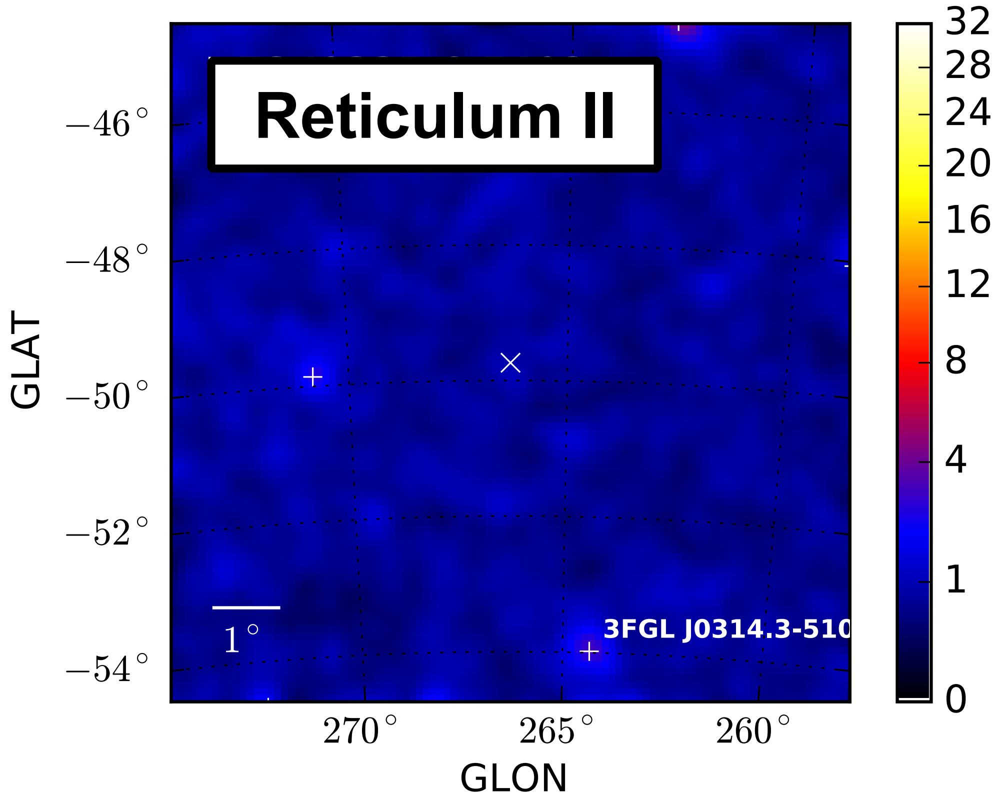

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Simon et al. 2015 (DES Collaboration)

+

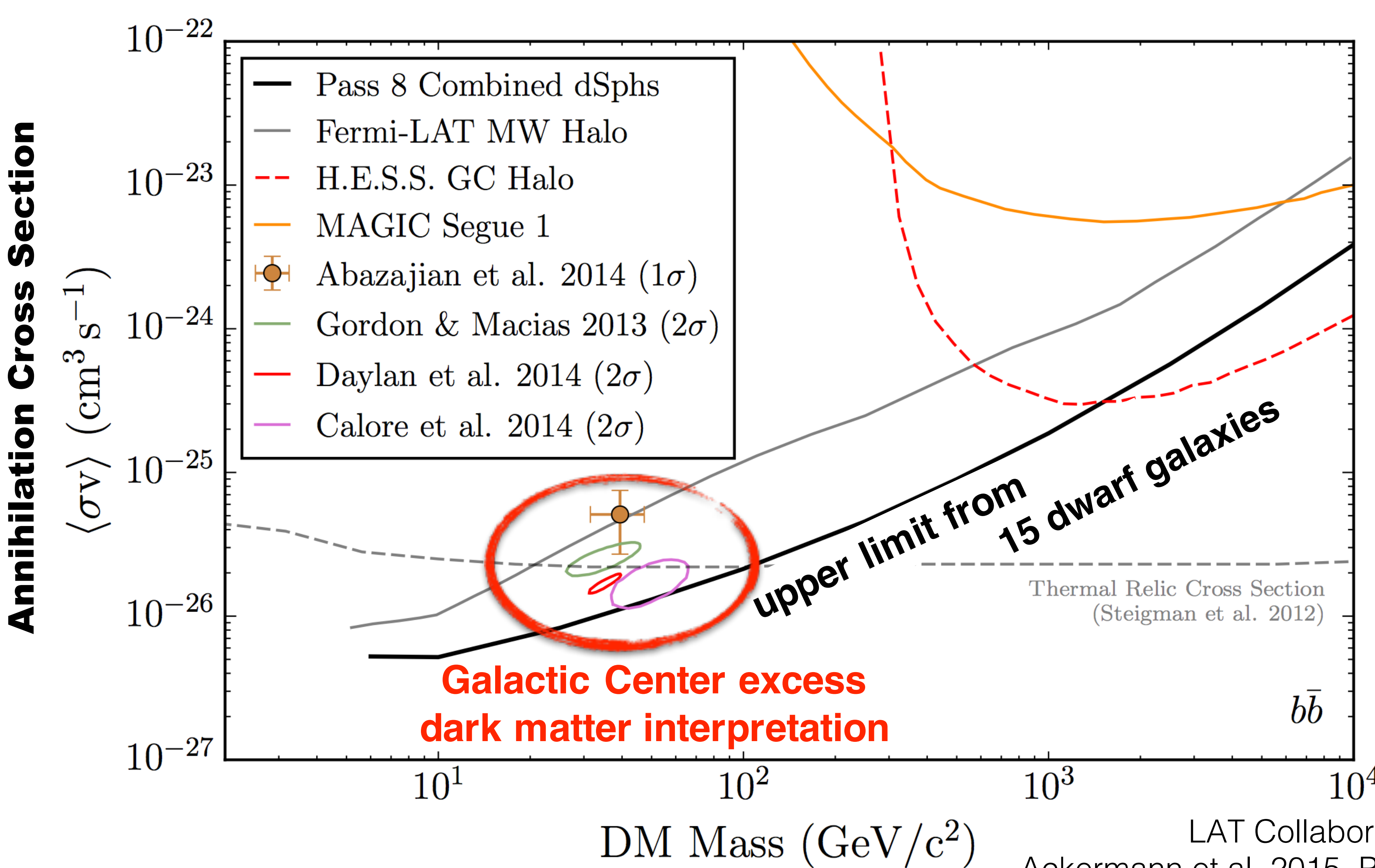
Annihilation Cross Section

Indirect Detection of Dark Matter
WIMP Annihilation

THE DARK ENERGY SURVEY

Fermilab

We will soon be able to either confirm or refute the dark matter interpretation of the Galactic Center excess using Milky Way satellites



Thermal relic cross section

LAT Collaboration
Ackermann et al. 2015, PRL, 115, 231301

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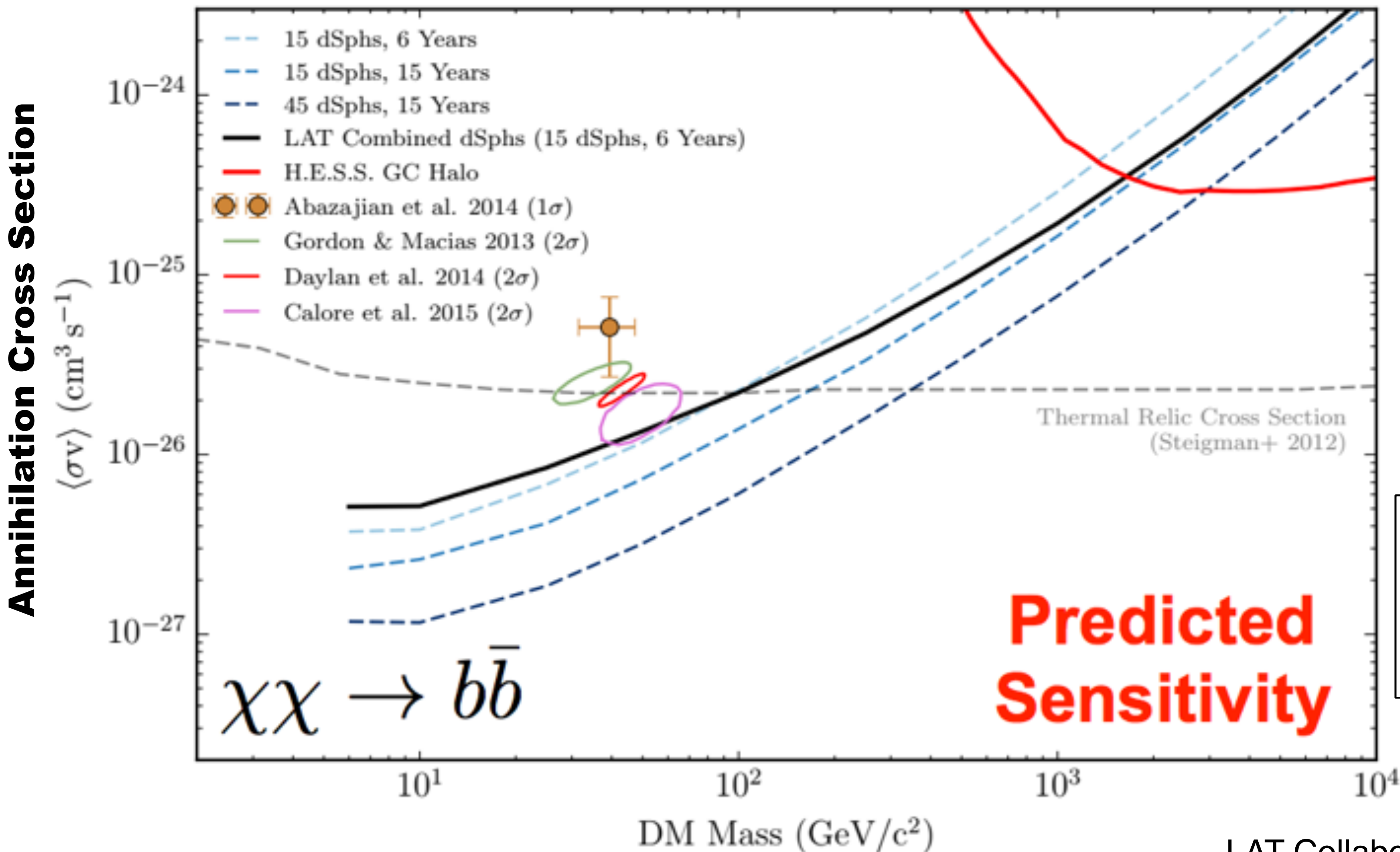
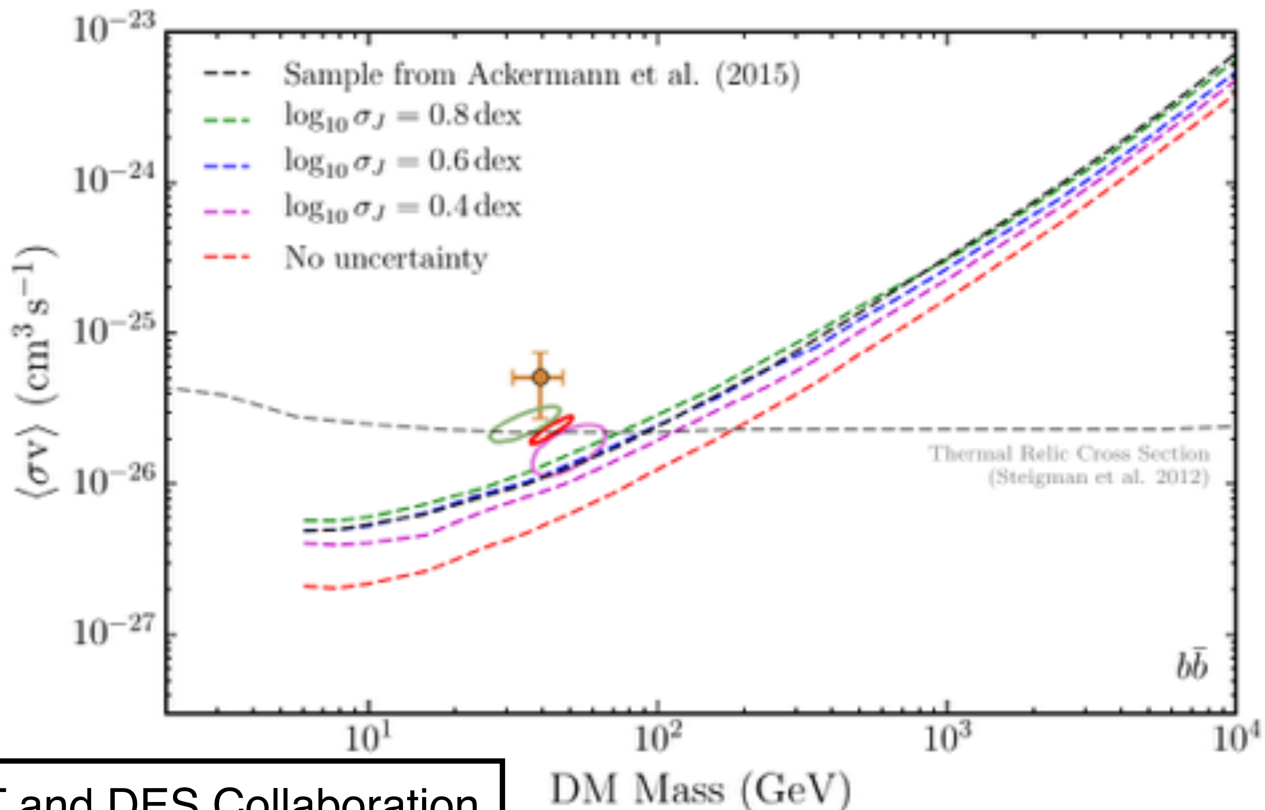


Sensitivity increase:
1. longer LAT monitoring
2. more dSphs
3. higher J-factor precision

LAT Collaboration
Charles et al. 2016 Phys. Rep. 636, 1

Improve J-factor Uncertainty

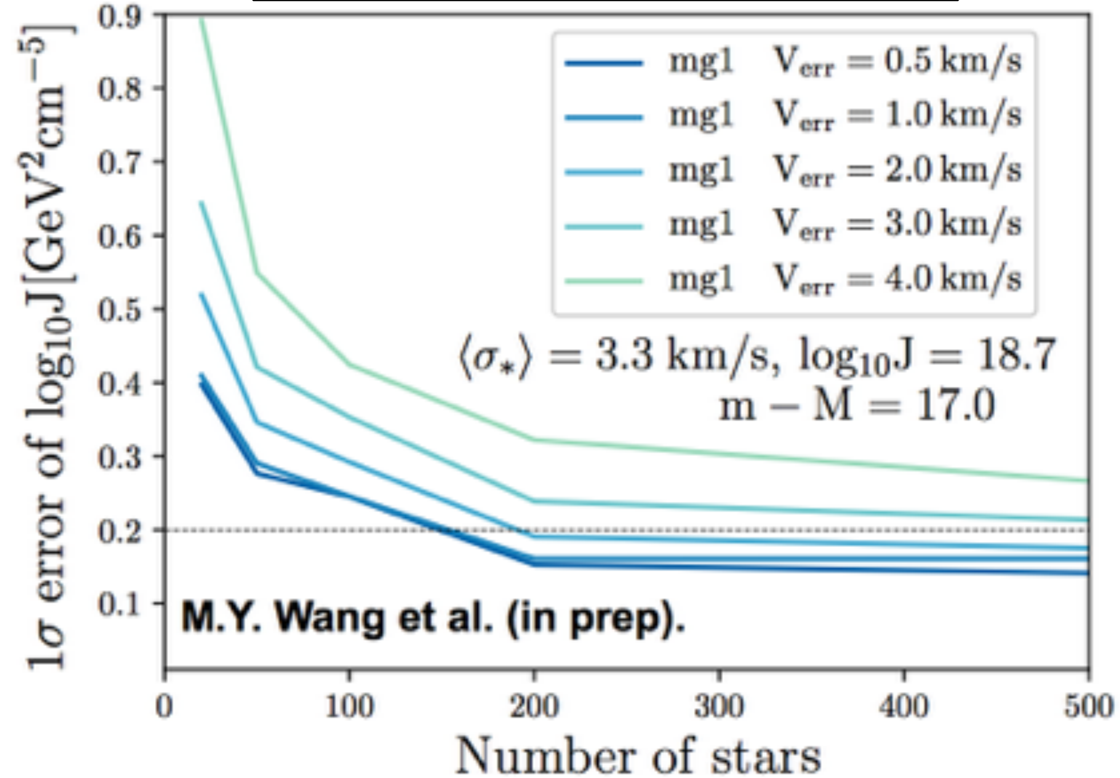


LAT and DES Collaboration
Albert et al. 2016

The cross section analysis depend on J-factor uncertainty.

Decreasing J-factor uncertainty can be a powerful way to improve sensitivity.

Reticulum II like system



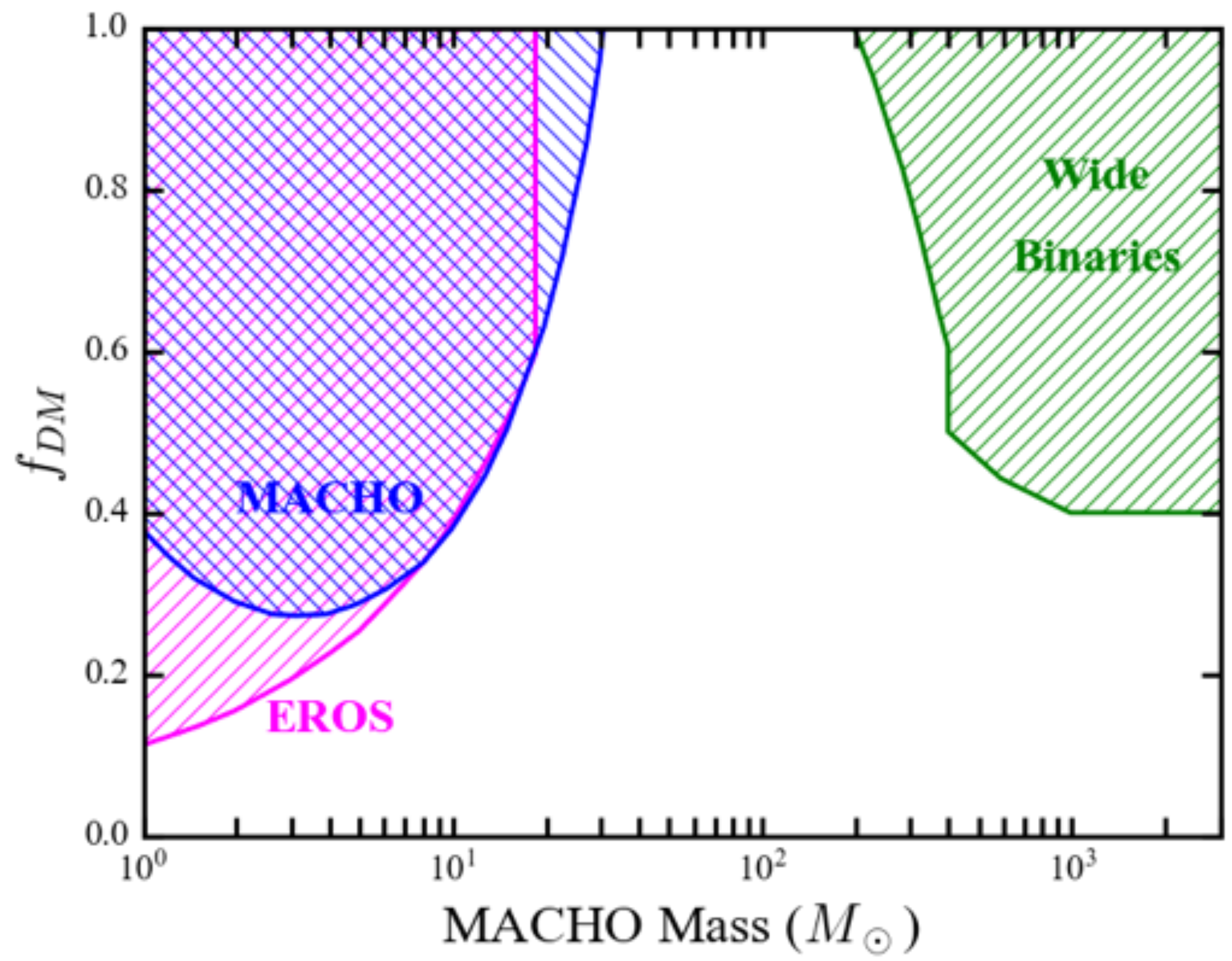
In order to achieve log(J) uncertainty < 0.2 dex:
- **measure >200 stars in each ultra-faint dwarf**
- **w/ high velocity precision < 2 km/s**

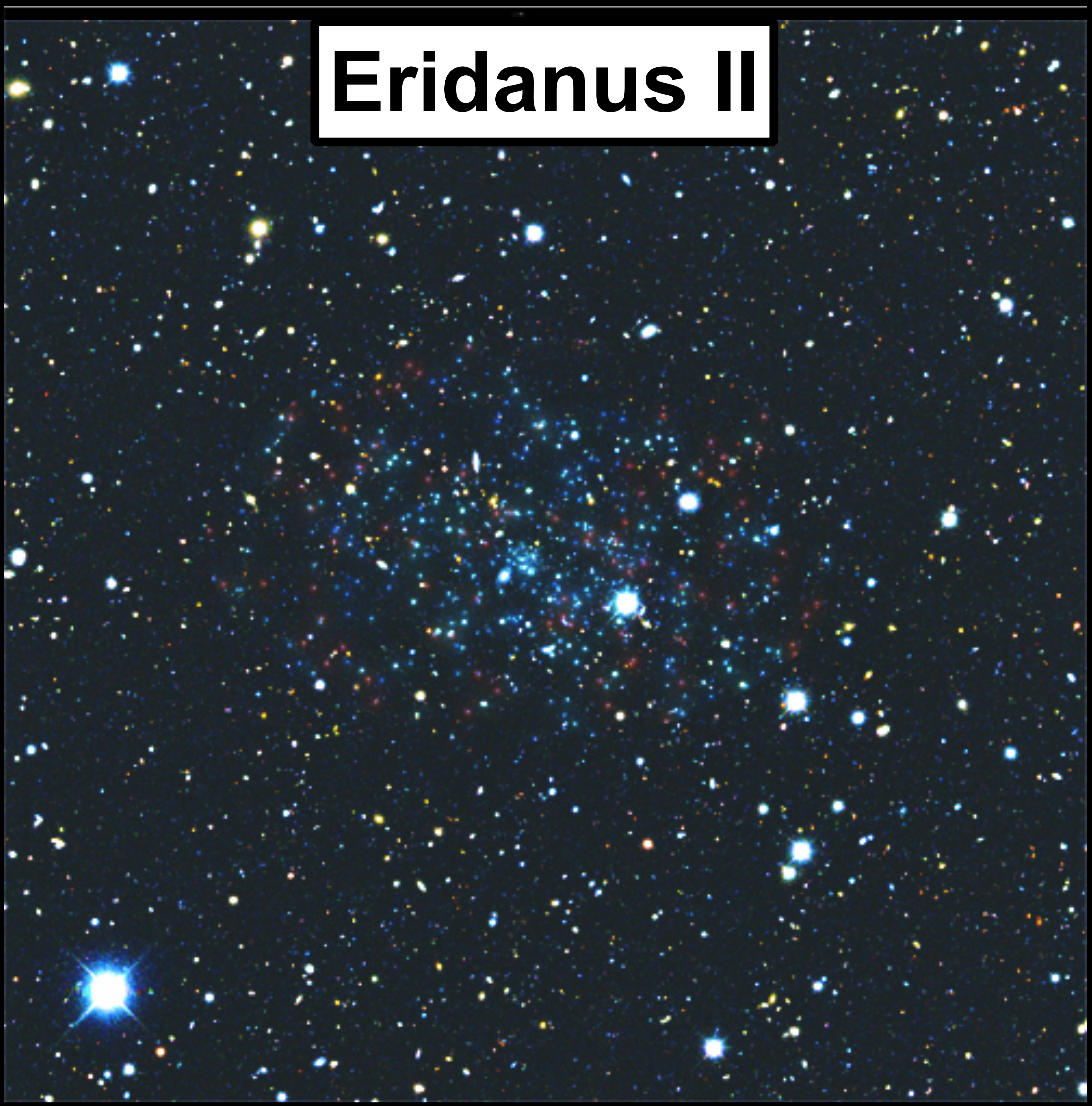
Why Studying the Milky Way Satellite Galaxies

THE DARK ENERGY SURVEY

- Missing Satellites Problem — Dark Matter Models
  - CDM vs. WDM vs. SIDM, etc.
- Constraints on WIMP Cross Section — Indirect Dark Matter Detection
  - WIMP: Weakly Interacting Massive Particles
- **Constraints on MACHO Abundance**
  - **MACHO: MAssive Compact Halo Object**

MACHO Constraints



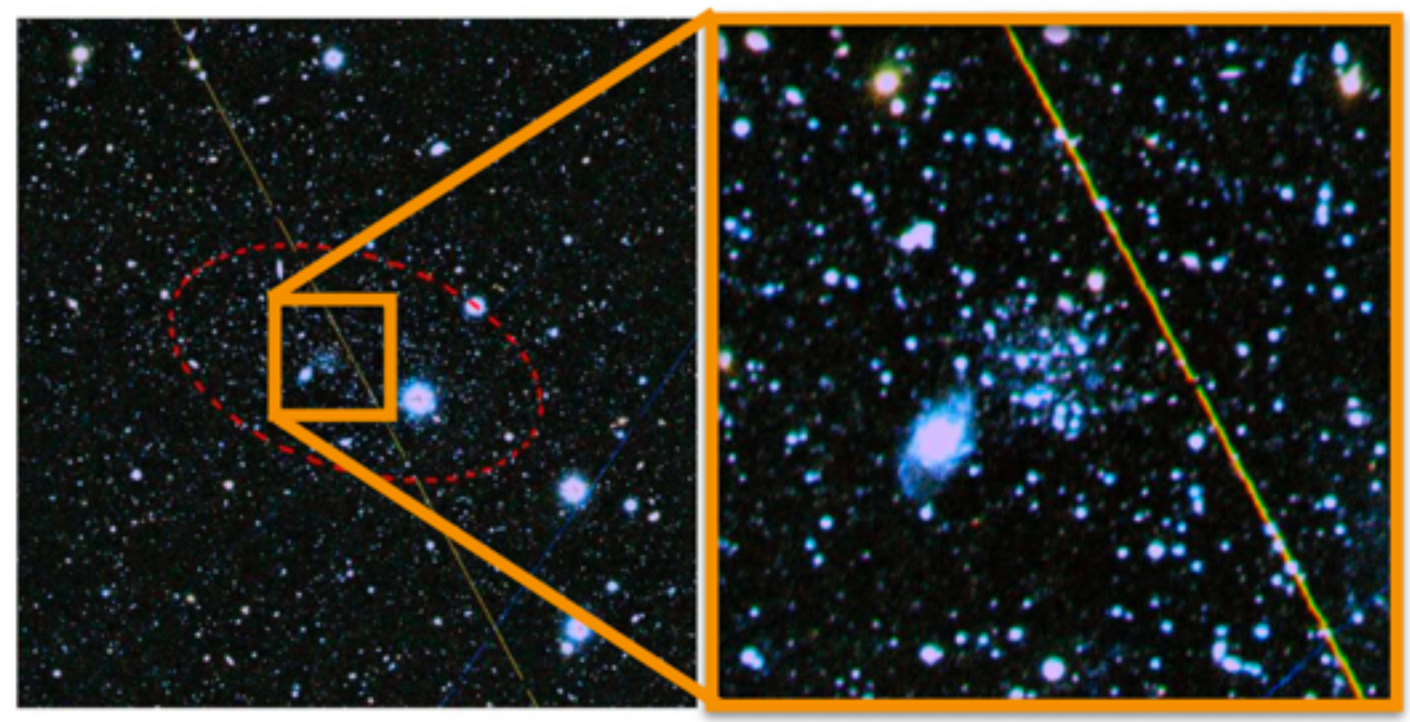


Belokurov & Koposov

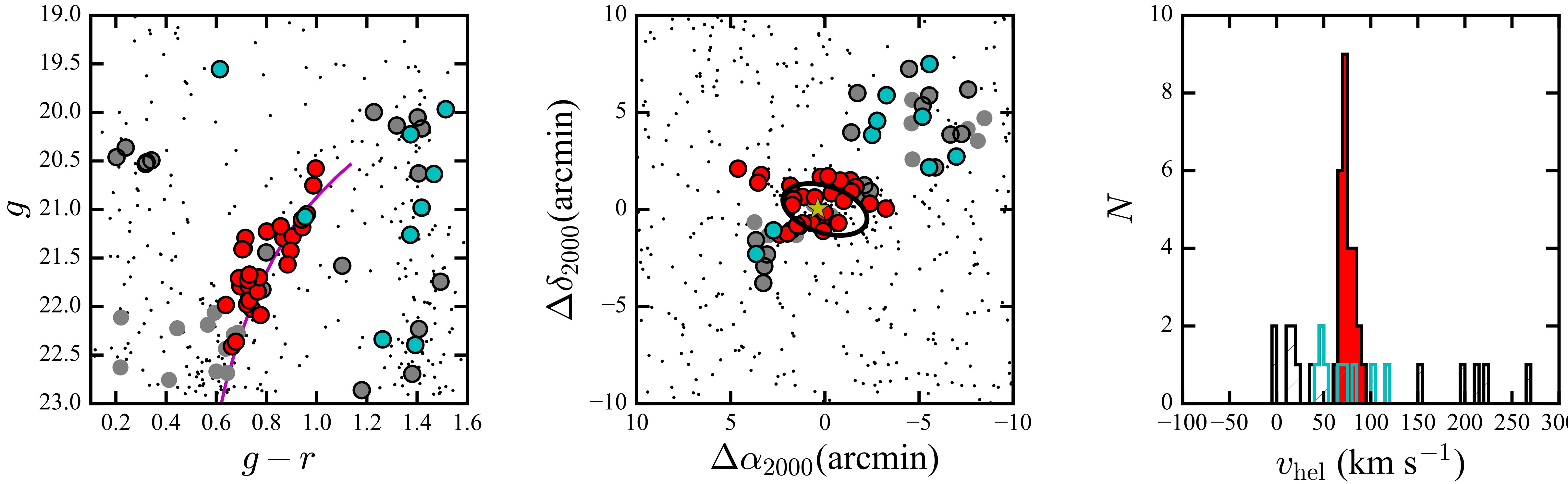
MACHO Dark Matter Constraints w/ Eridanus II

- Dwarf galaxy candidate first discovered in DES
- Distant : ~370 kpc (beyond the virial radius of MW)
- Smallest galaxy that own its star cluster.

Crnojevic et al. 2016



Eridanus II: Dark Matter Content



Li et al. 2017 (DES Collaboration)

28 members identified

$v_{\rm hel}$ (km s^{-1})	$75.6 \pm 1.3 \pm 2.0$
$v_{\rm GSR}$ (km s^{-1})	-66.6
σ_v (km s^{-1})	$6.9^{+1.2}_{-0.9}$
$M_{\rm half}$ (M$_\odot$)	$1.2^{+0.4}_{-0.3} \times 10^7$
M/L_V (M$_\odot$/L$_\odot$)	420^{+210}_{-140}

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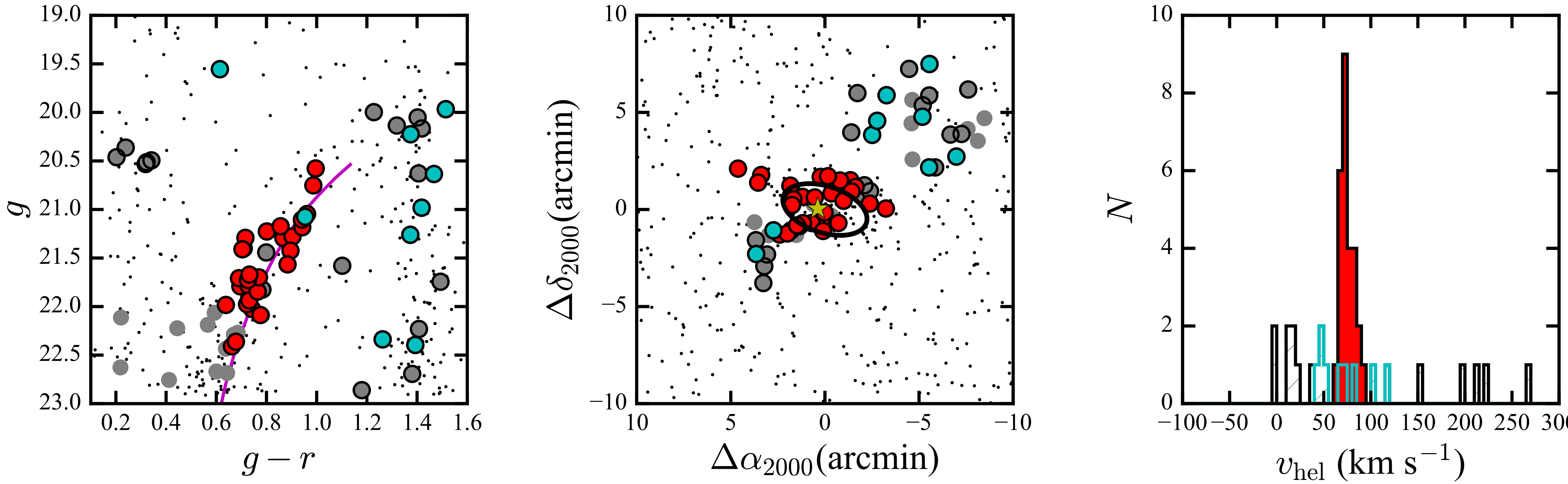

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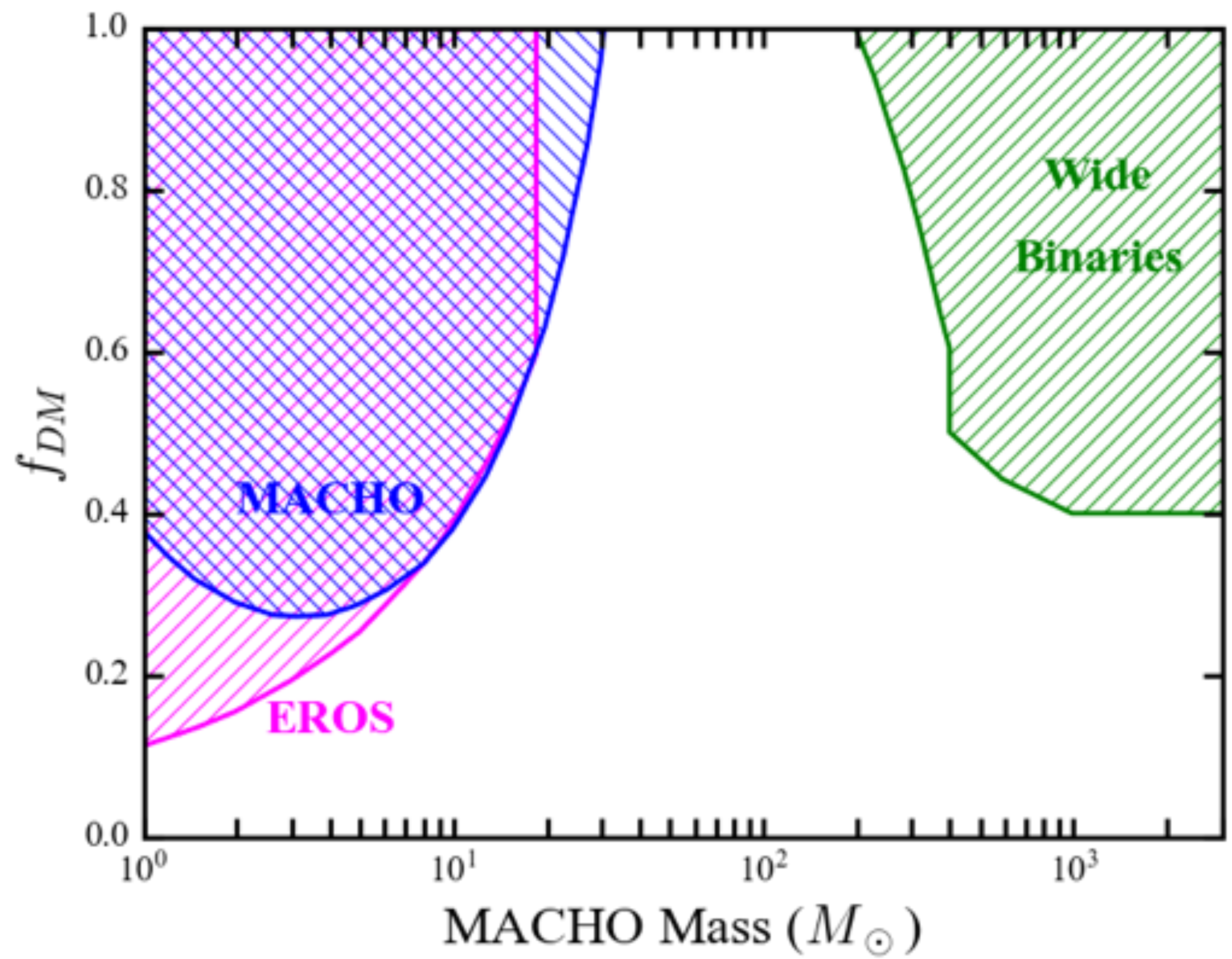
Eridanus II is dark matter dominated dwarf galaxy

MACHO Dark Matter Constraints w/ Eridanus II

- Dwarf galaxy candidate first discovered in DES
- Distant : ~370 kpc (beyond the virial radius of MW)
- Smallest galaxy that own its star cluster.
- **If the cluster is indeed in the center of the dwarf, the survival of this star cluster can place constraints on the MACHO abundance (Brandt 2016)**



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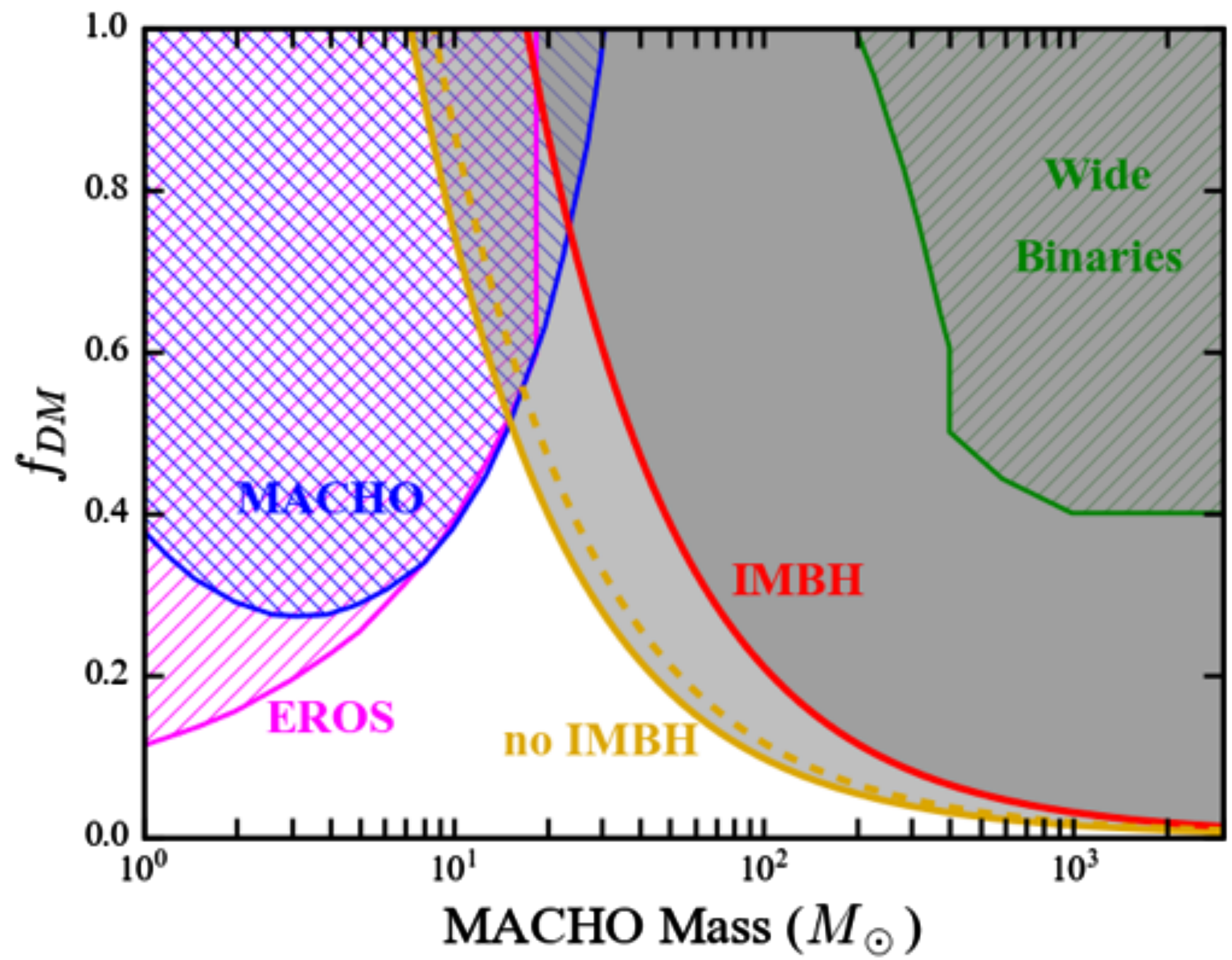

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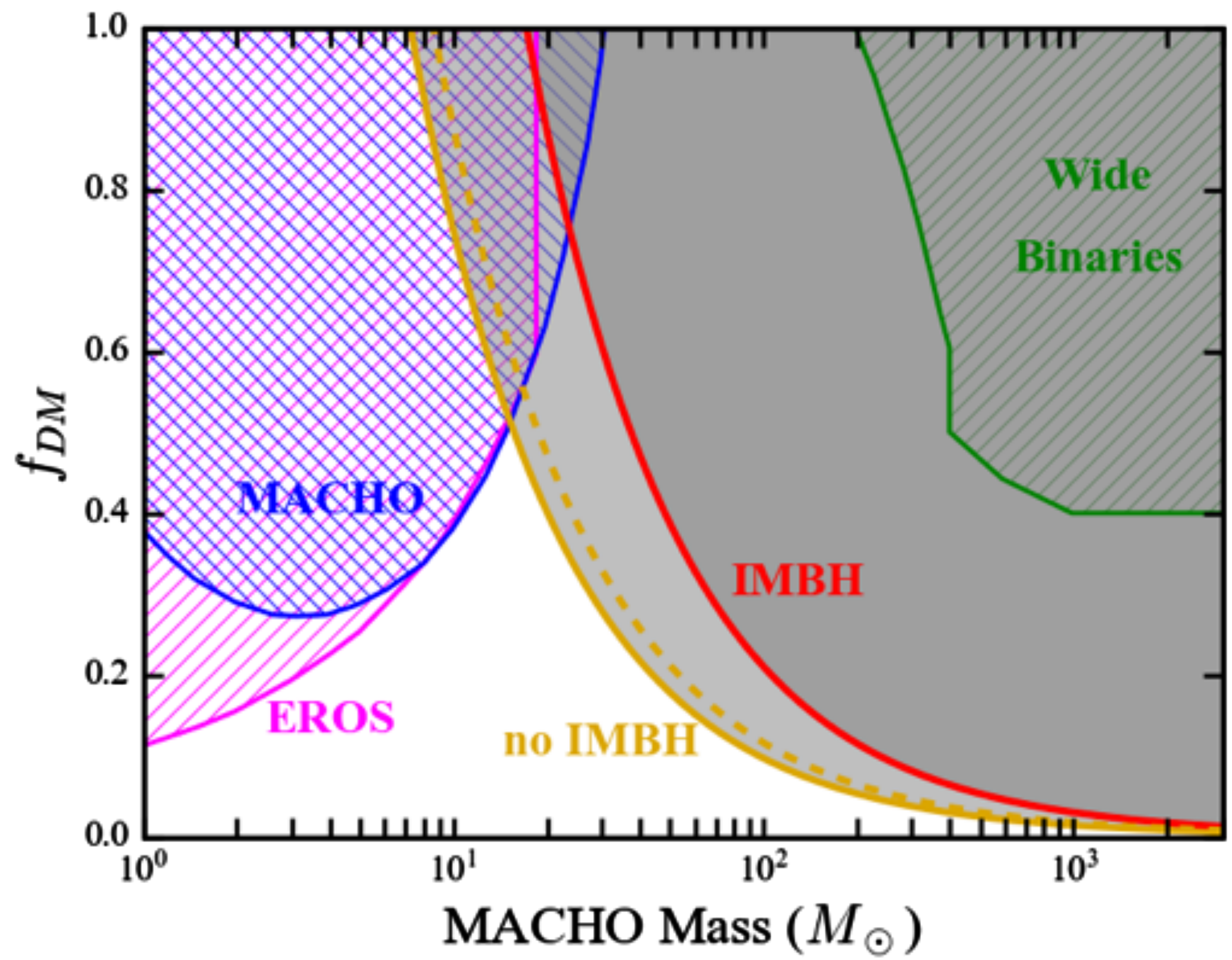

Rule out MACHO as the dominated DM at 10-100 Msun

Li et al. 2017 (DES Collaboration)

Summary

- Milky Way satellites are powerful tools to probe the nature of dark matter.
- Spectroscopic follow-up observations are necessary to confirm the ultra faint dwarf galaxy candidates.
- Ultra faint dwarfs are good site for indirect dark matter search.
- The survival of the central star cluster in the dwarf galaxies can put constraints on the MACHO abundance.
- Ultra faint dwarfs are important to understand the galaxy evolutions on the smallest scale.

backup slides

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  - CDM vs. WDM vs. SIDM, etc.
- Constraints on WIMP Cross Section — Indirect Dark Matter Detection
  - WIMP: Weakly Interacting Massive Particles
- Constraints on MACHO Abundance
  - MACHO: MAssive Compact Halo Object
- **Star Formation in Dwarf Galaxies**

Star Formation in Dwarf Galaxies

Baryon Effects:
Astrophysical process prevent stars from forming in most low-mass halos

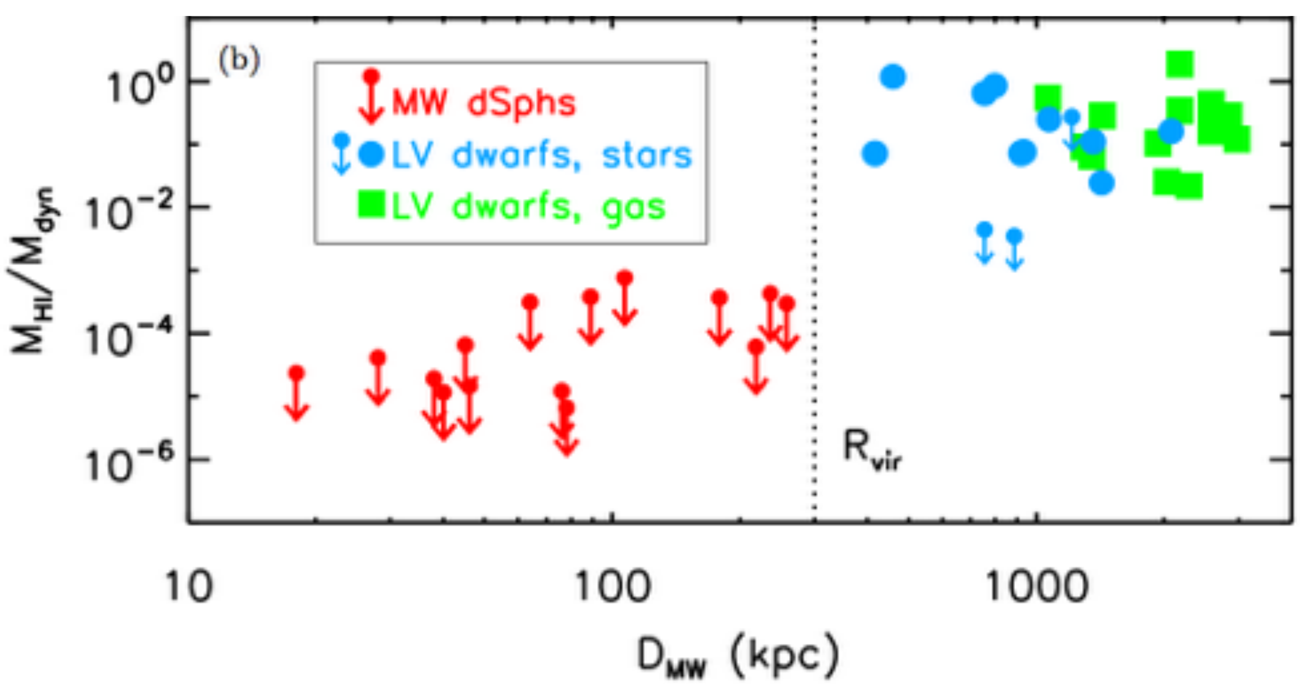
Star Formation in Dwarf Galaxies

THE DARK ENERGY SURVEY

Fermilab

Ram Pressure Stripping?

Quiescent vs Star Forming



HI: Neutron Hydrogen Gas

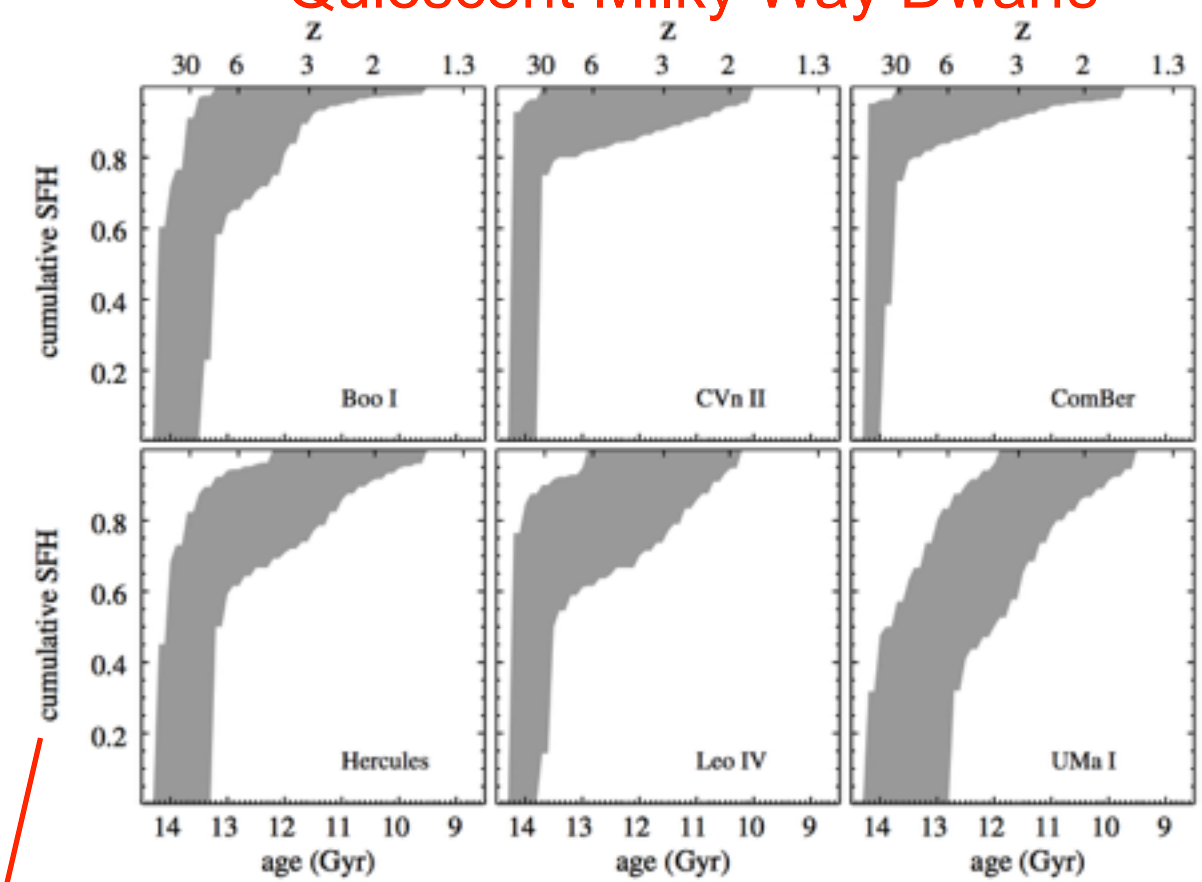
Speakers et al. 2014

Reionization?

80% of the stars formed 13 Gyr ago

100% of the stars formed 12 Gyr ago

Quiescent Milky Way Dwarfs



percentage of stars

age (Gyr)

Brown et al. 2004

Star Formation in Dwarf Galaxies

THE DARK ENERGY SURVEY

Fermilab

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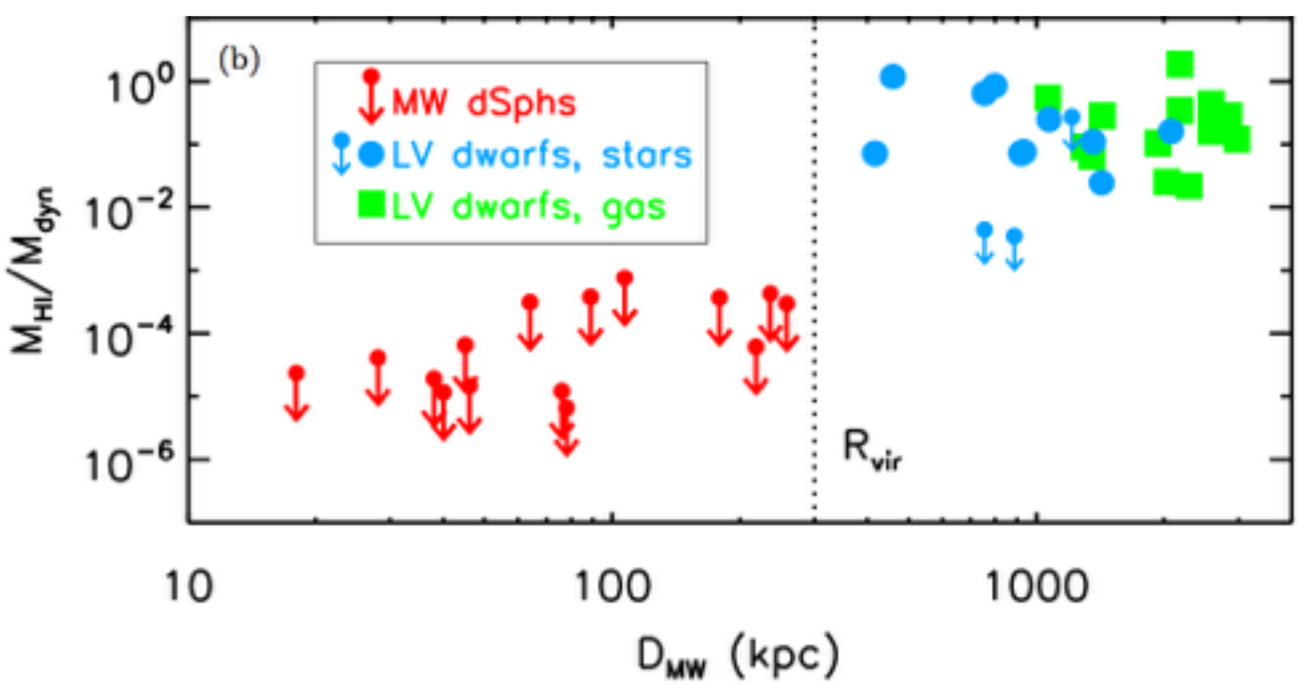

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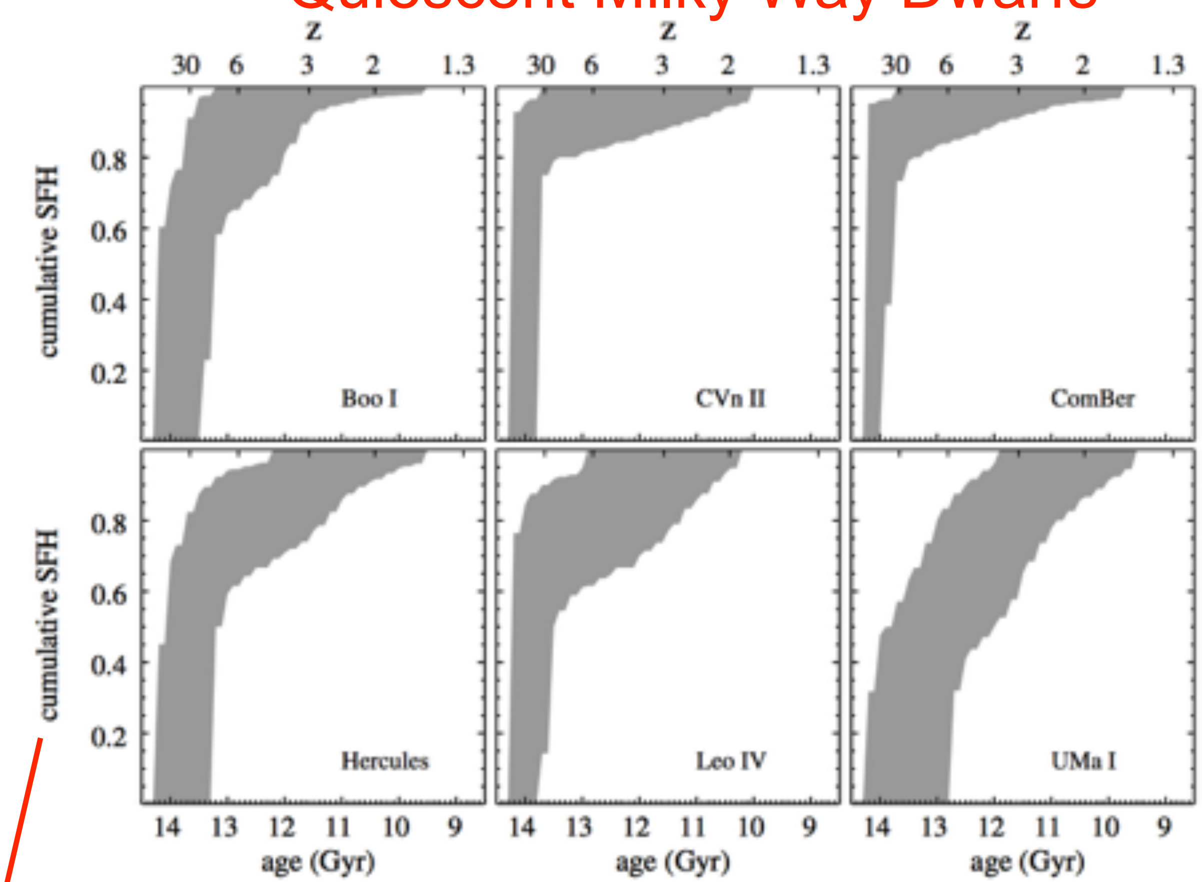

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Brown et al. 2004

What makes these satellites stop forming stars?
Stripping vs. Reionization?

Star Formation in Dwarf Galaxies

THE DARK ENERGY SURVEY

Fermilab

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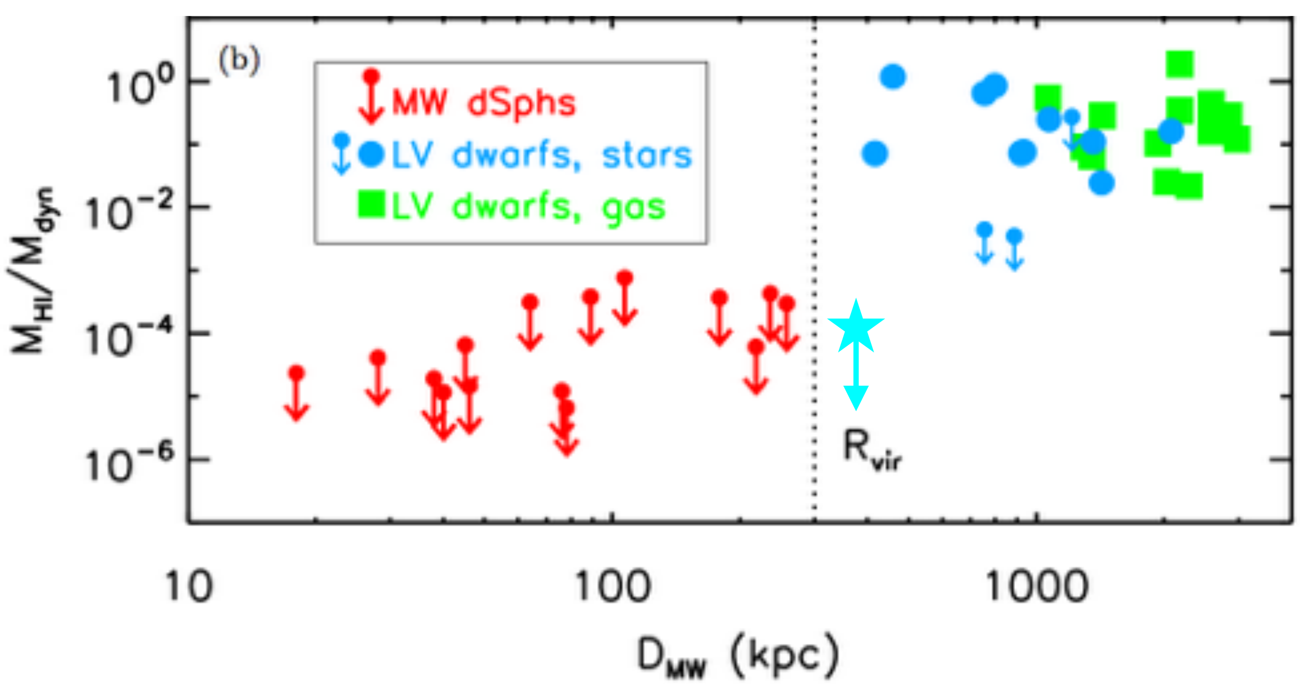

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★ Eridanus II

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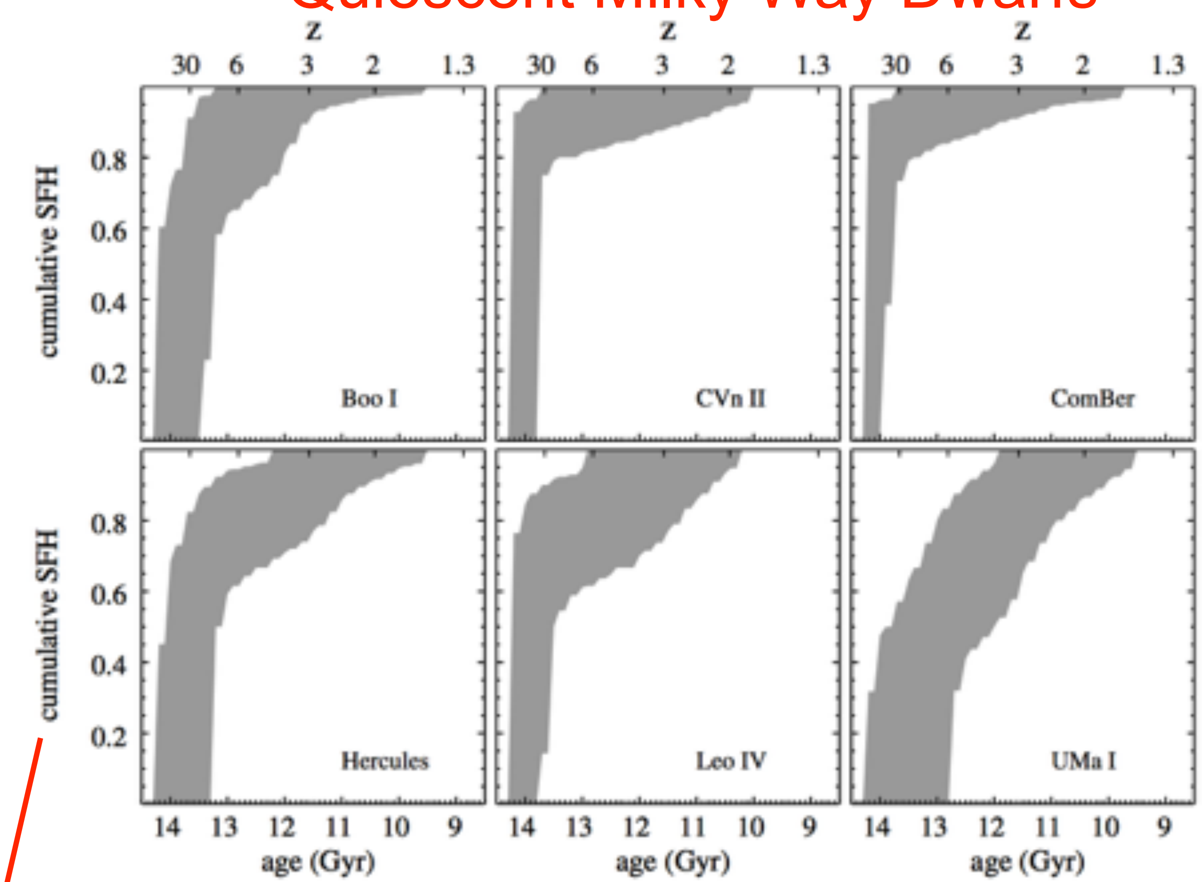

percentage of stars

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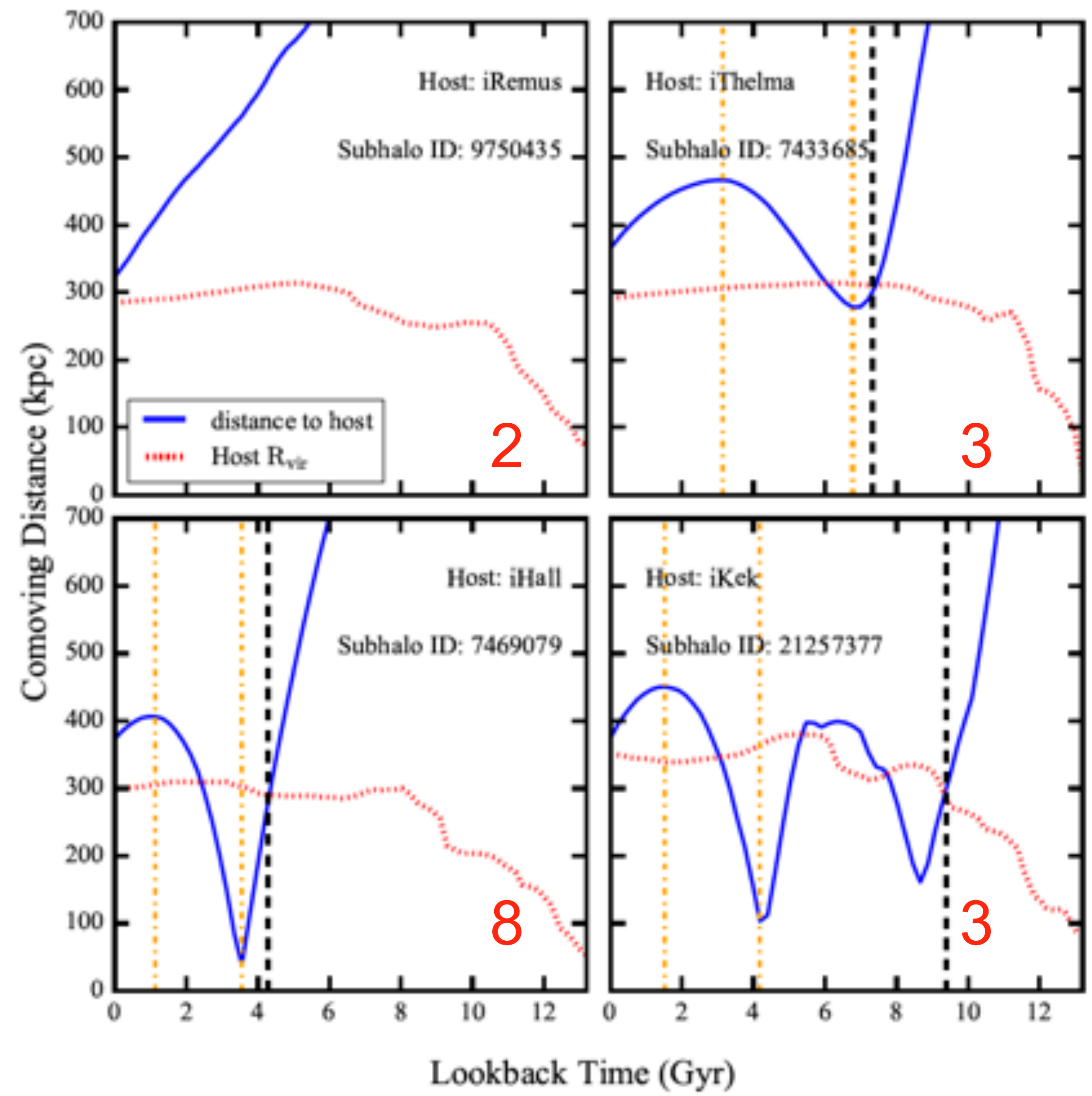
Brown et al. 2004

What makes these satellites stop forming stars?
Stripping vs. Reionization?

Orbit and Infall History

- V_{hel} = 75.1 km/s
- V_{GSR} = -67.0 km/s
- Moving towards Milky Way

- Compared with N-body simulations
- Bound to Milky Way
- Most likely on its second passage
    - orbit w/ high eccentricity



Li et al. 2017 (DES Collaboration)