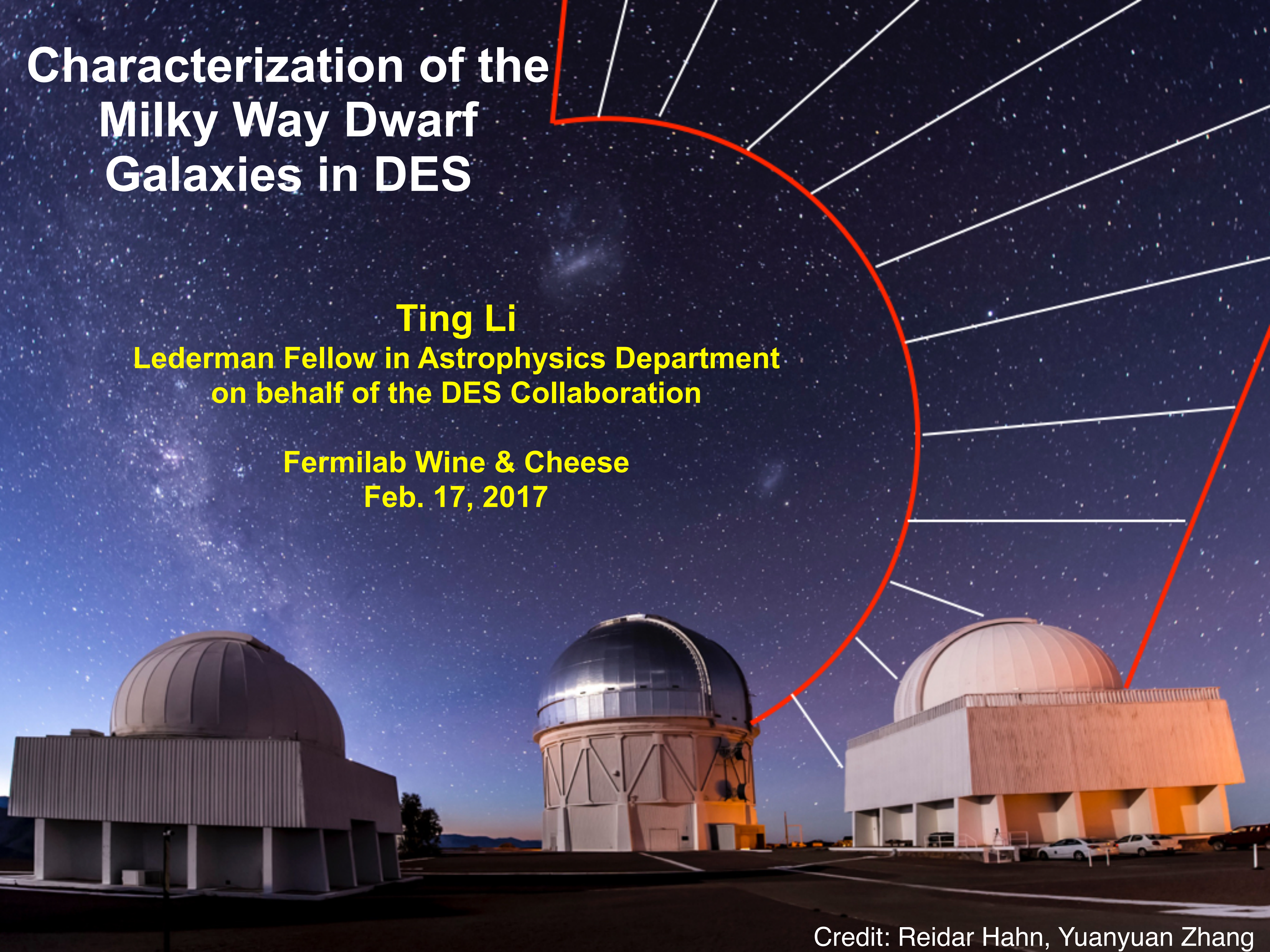
Characterization of the Milky Way Dwarf Galaxies in DES

Ting Li
Lederman Fellow in Astrophysics Department
on behalf of the DES Collaboration

Fermilab Wine & Cheese
Feb. 17, 2017



Credit: Reidar Hahn, Yuanyuan Zhang

Outline

- **Why? — Motivation**
  - Near Field Cosmology
  - Galaxy Formation
  - Indirect Dark Matter Detection
- **How? — Spectroscopy**
  - Precise velocity determination
- **What? — Results**
  - Eridanus II *Li, Simon et al. (2017), arxiv: 1611.05052*
  - Tucana III *Simon, Li et al. (2017), arxiv: 1610.05301*

Why? — Motivation

- Near Field Cosmology
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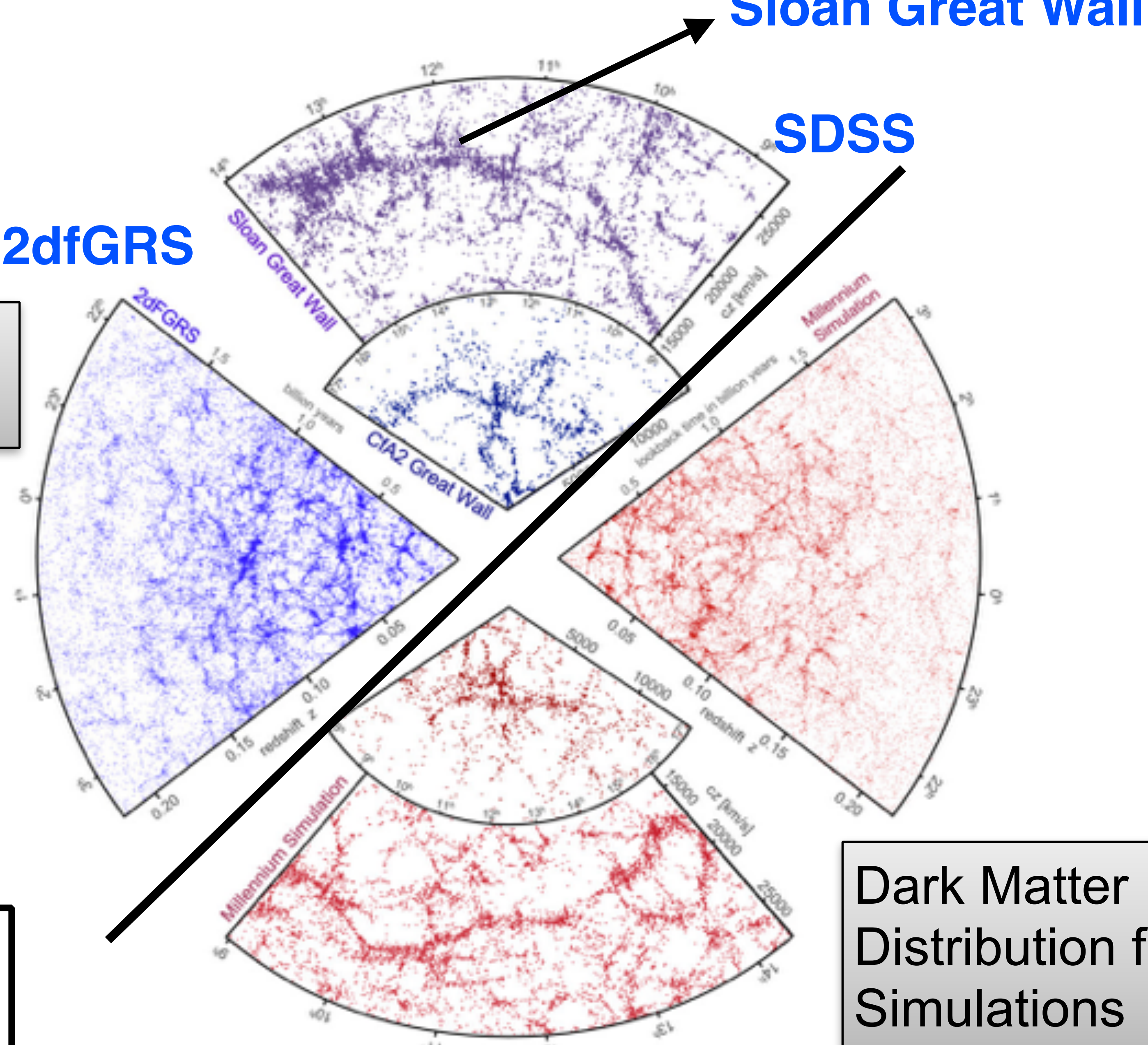
Large Scale Structure of the Universe

- ΛCDM model is in concordance with astronomical observations



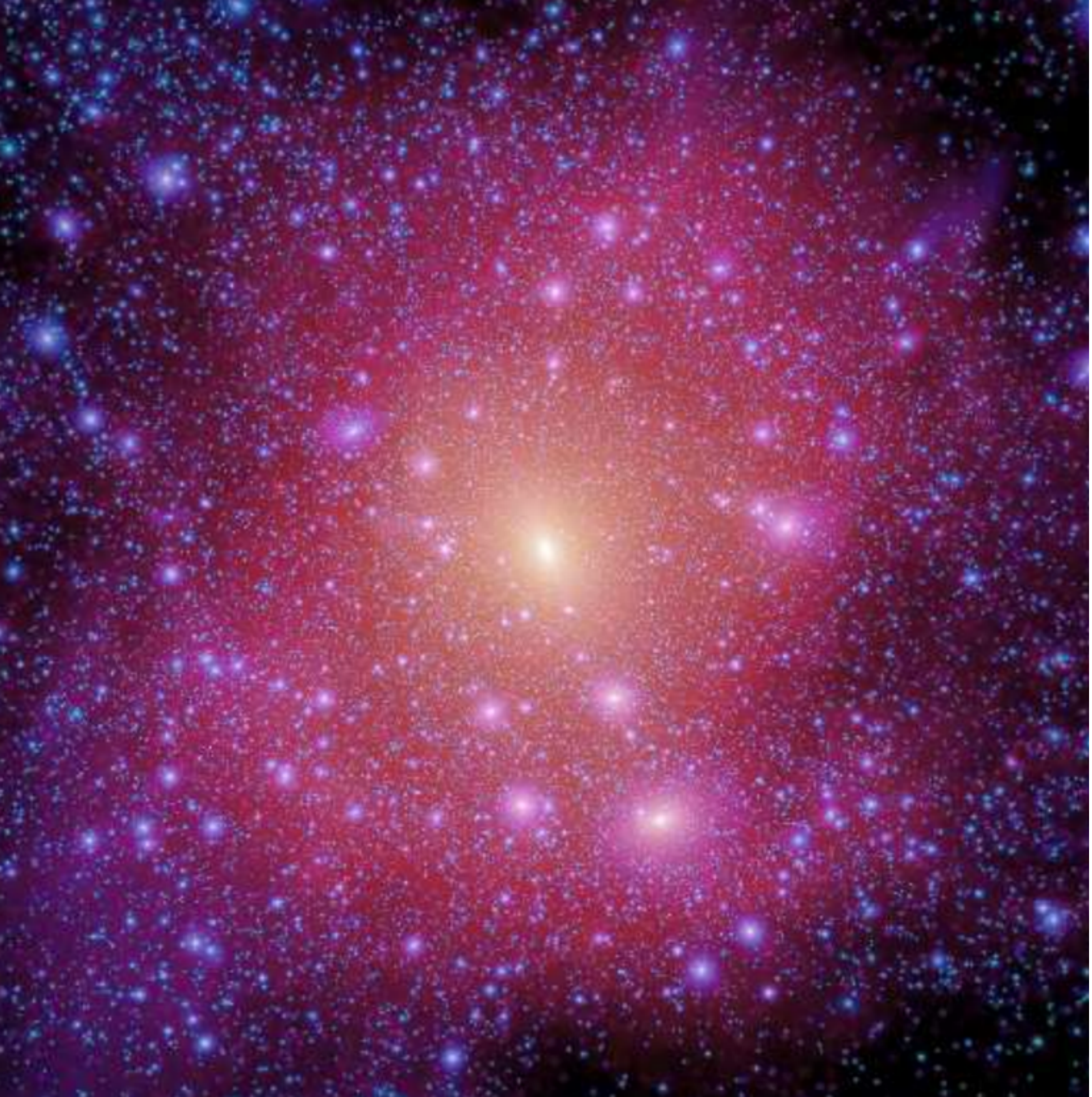
Galaxy Distributions from Observations

redshift 0.1
1.3 Gyr
500 Mpc

redshift 1
8 Gyr
7000 Mpc

Dark Matter Distribution from Simulations

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



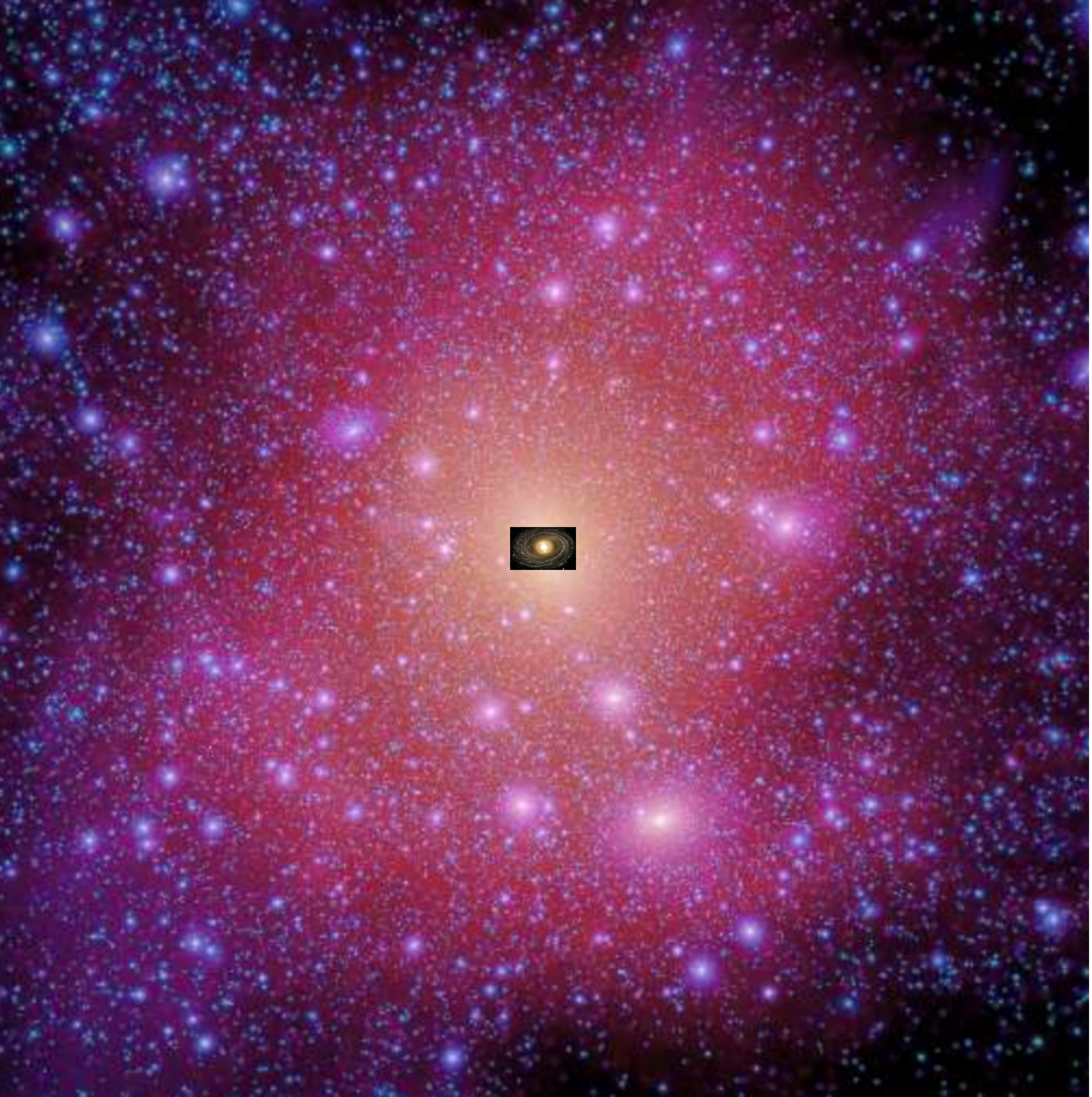
Aquarius Simulation

1 Mpc^3 simulation box

One Milky-Way sized halo

Springel et al. (2008)

1pc = 3 $x10^{16}$ km



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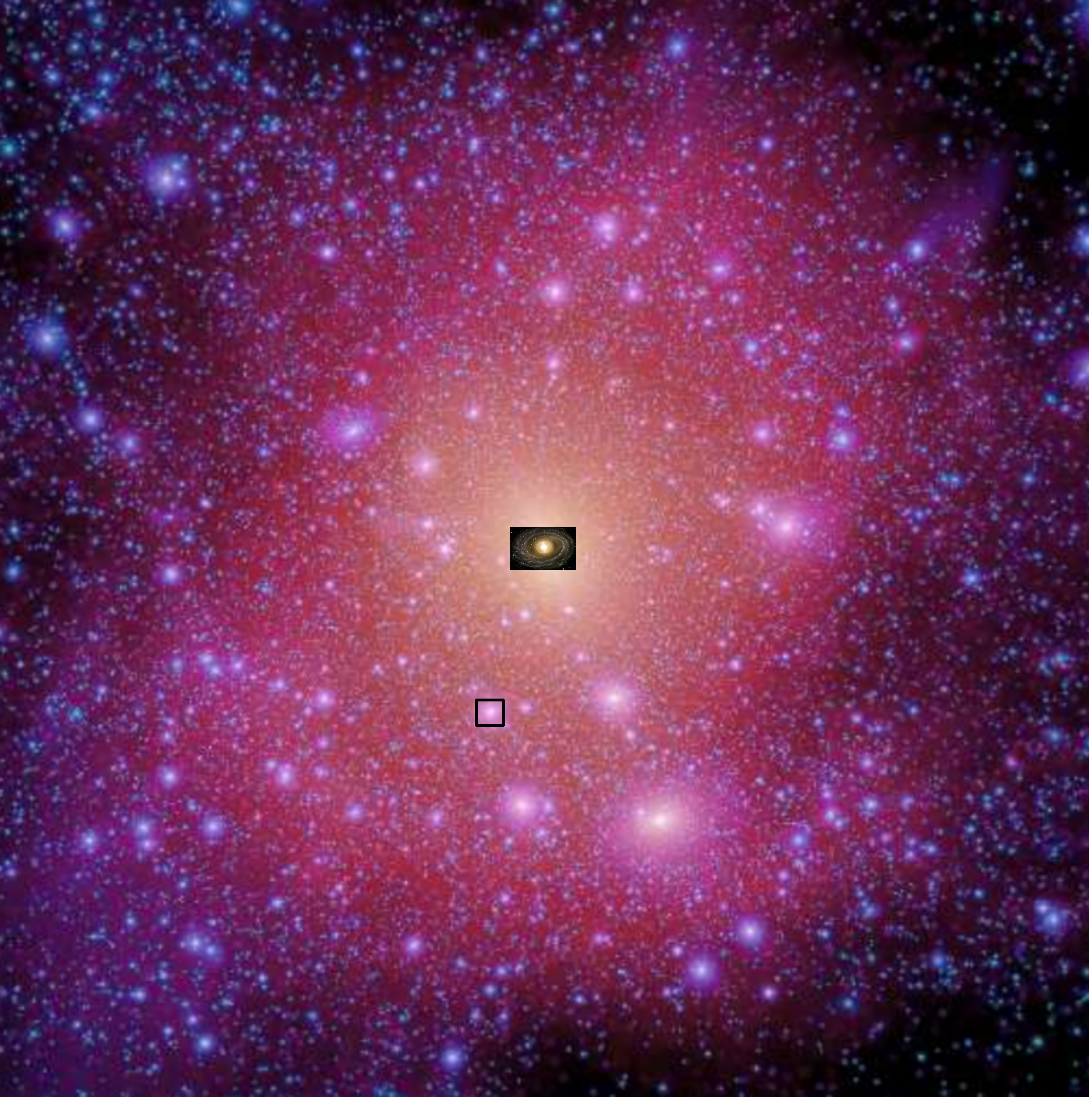

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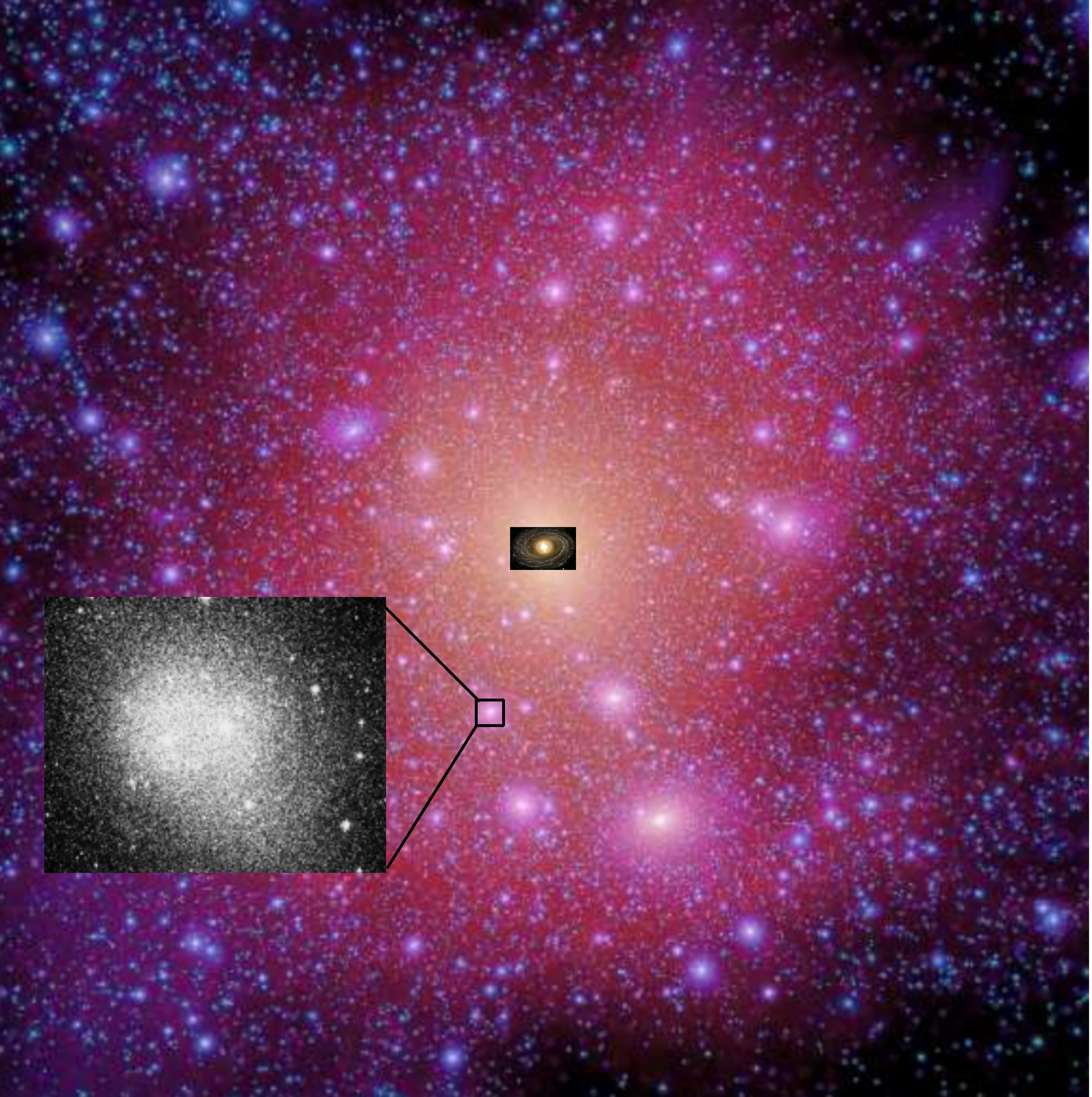

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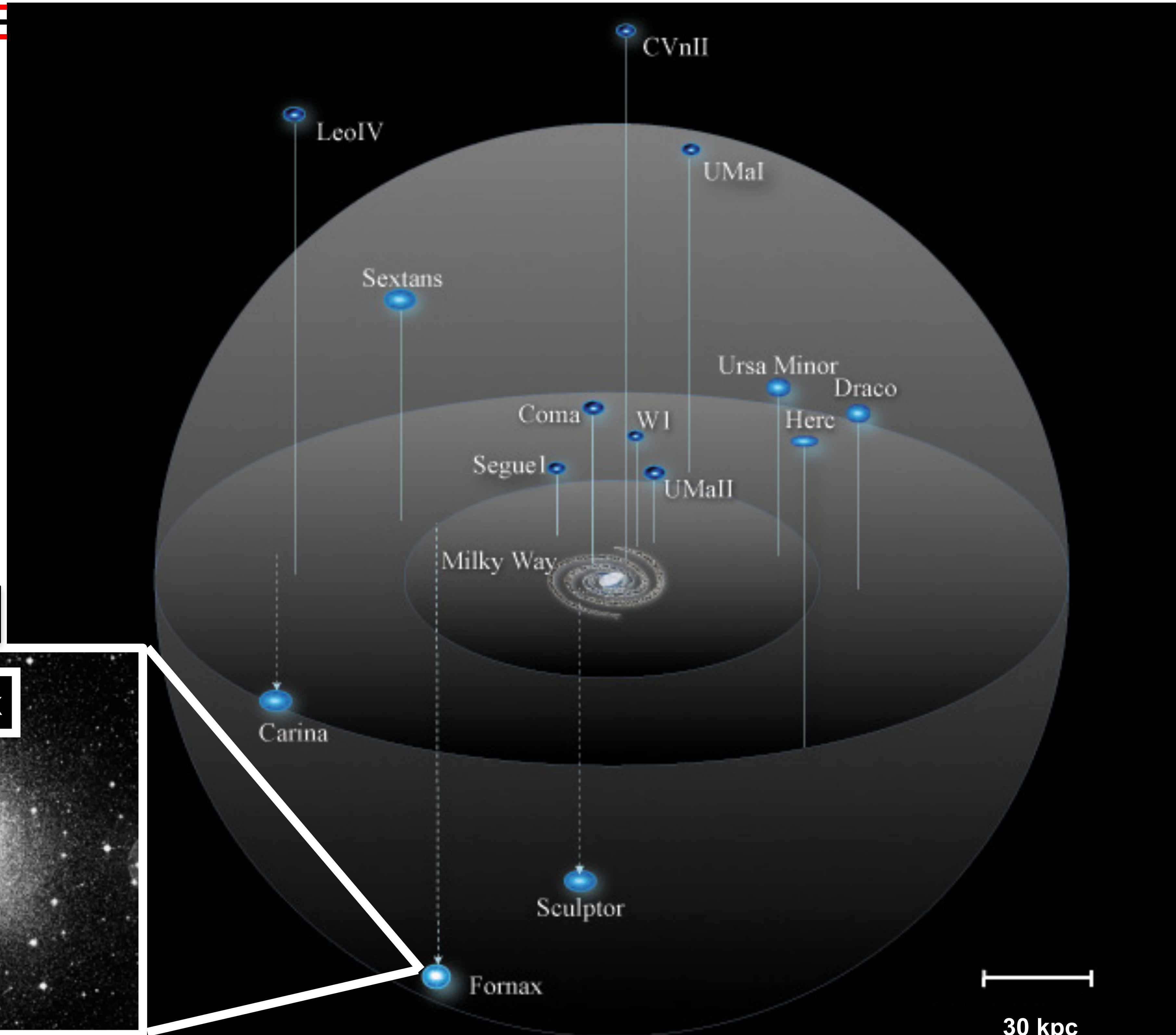
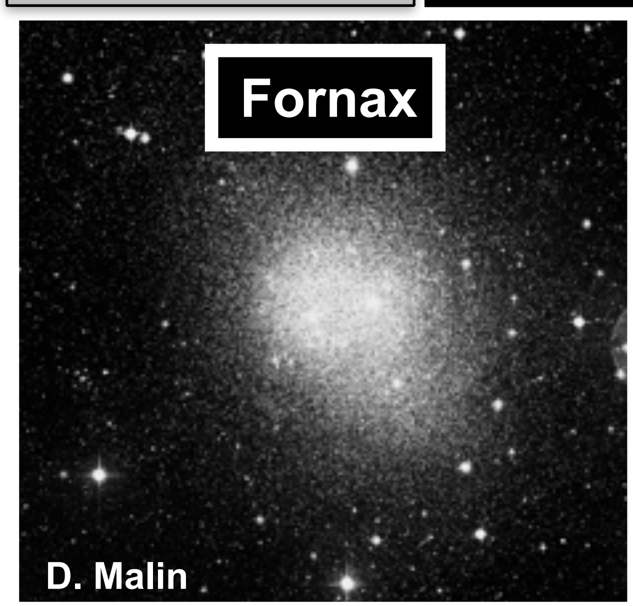
Milky Way Satellite Galaxies

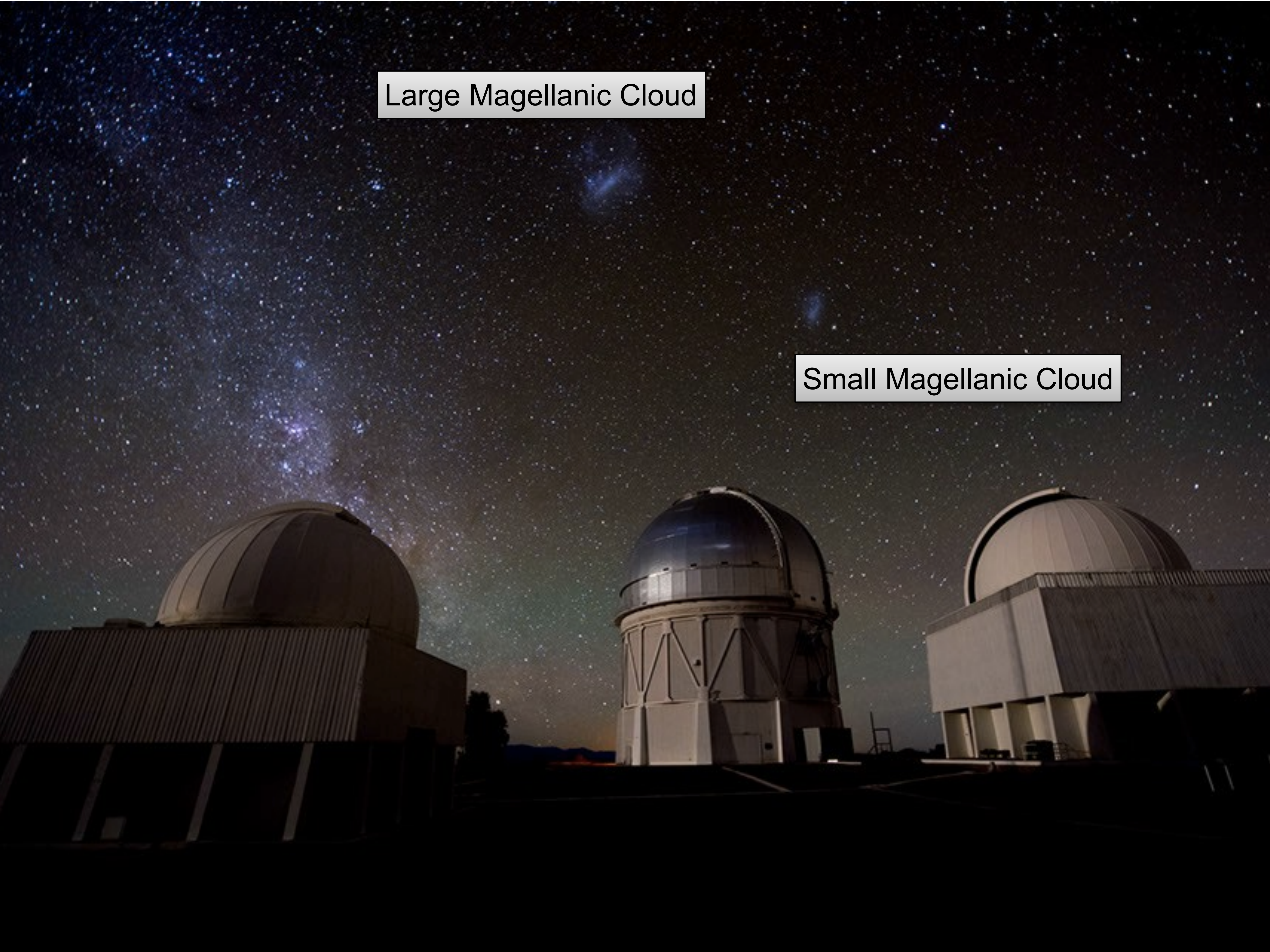


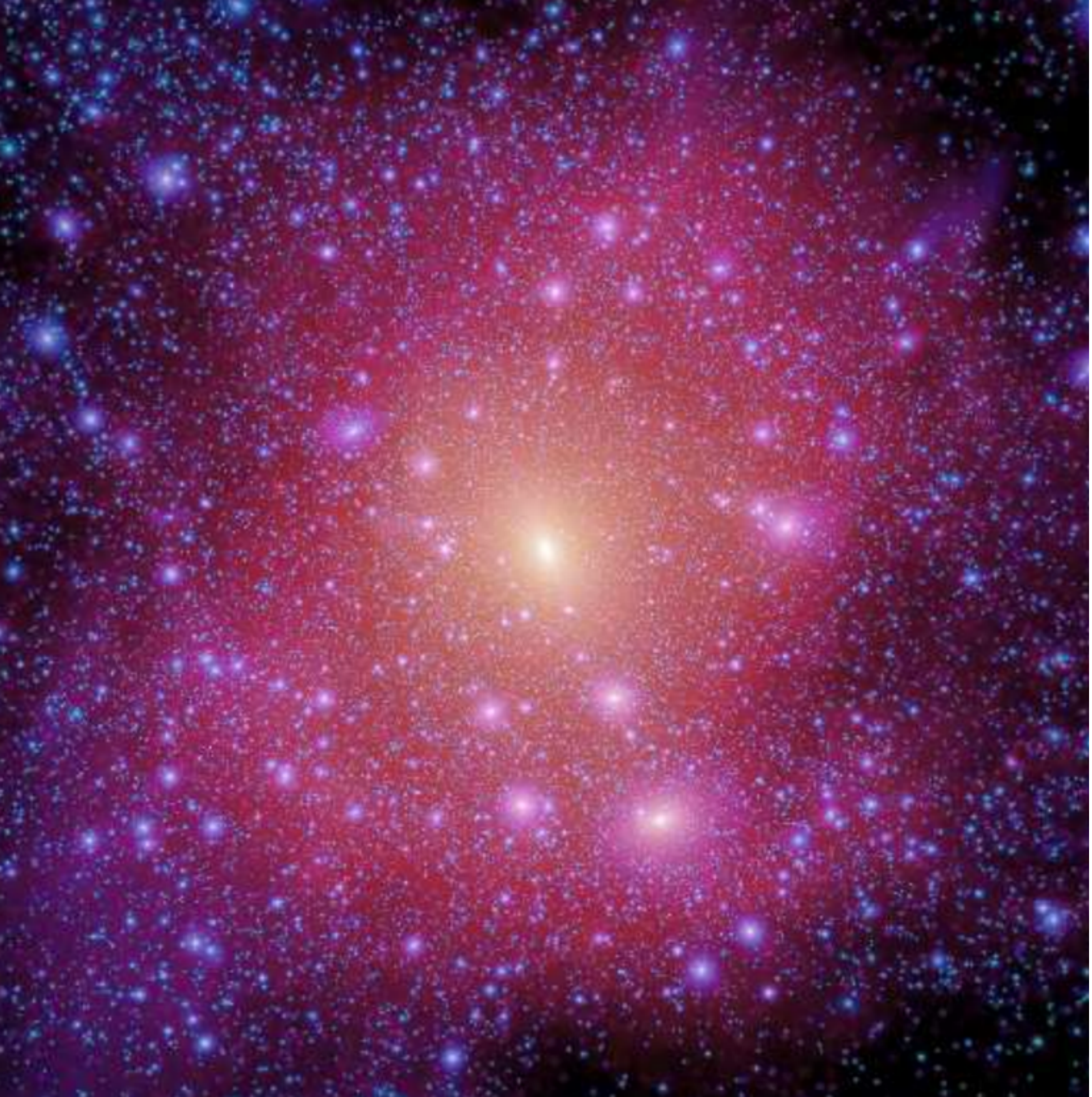
(Bullock, Geha, Powell)

Classical Dwarf




Large Magellanic Cloud


Large Magellanic Cloud
Small Magellanic Cloud



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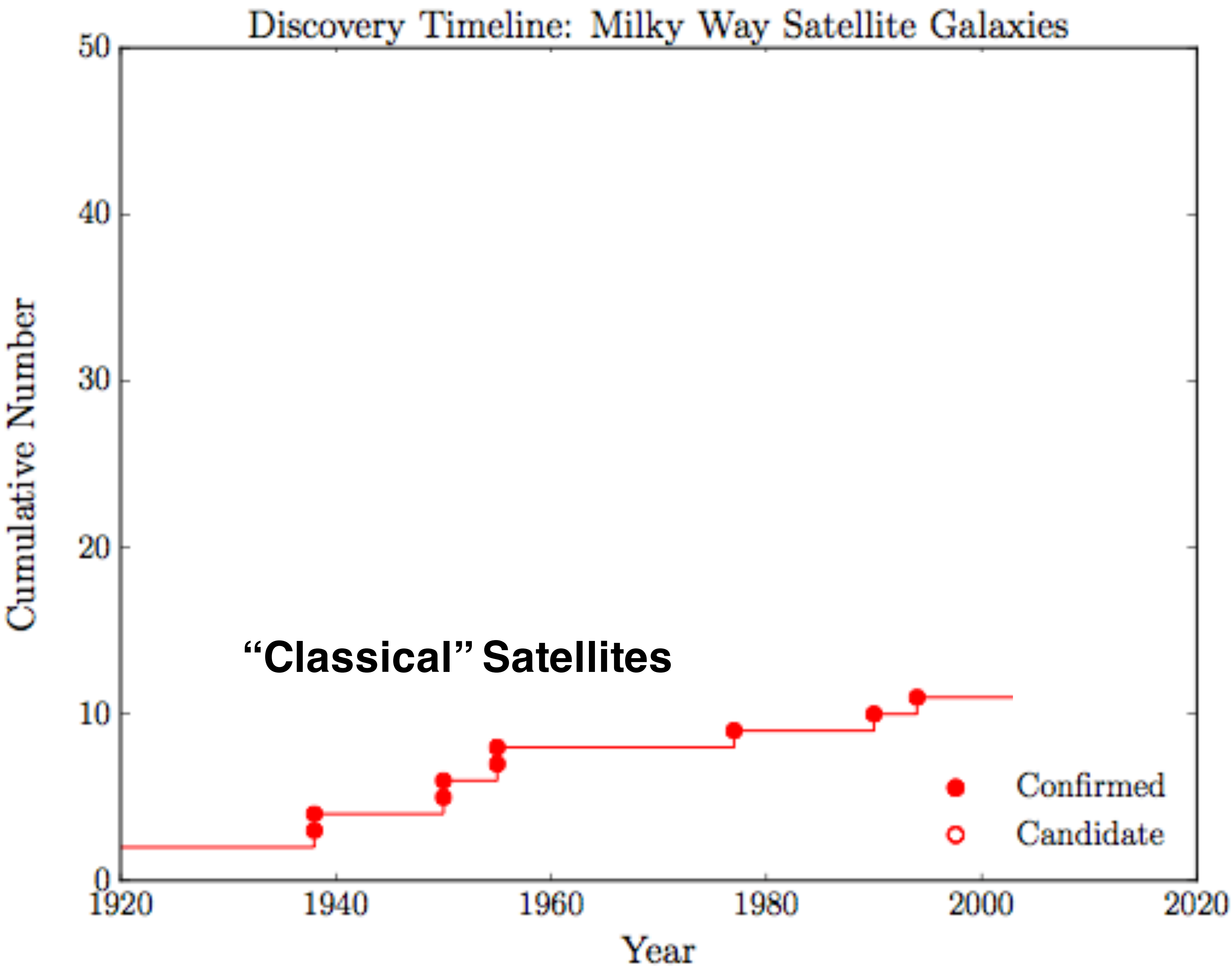
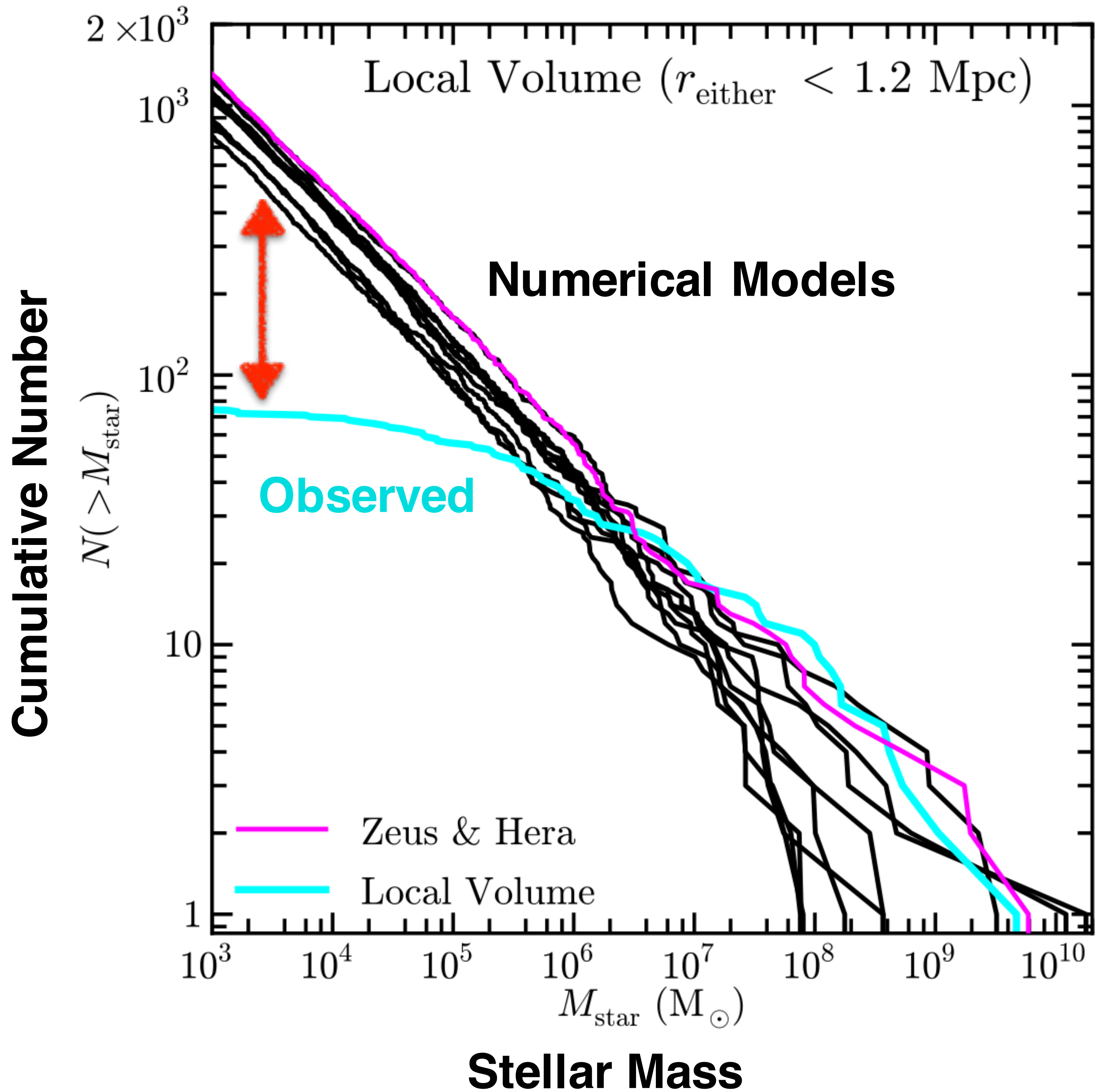
Discovery Timeline



Near Field Cosmology



Garrison-Kimmel et al. (2013)

"Missing Satellites Problem"

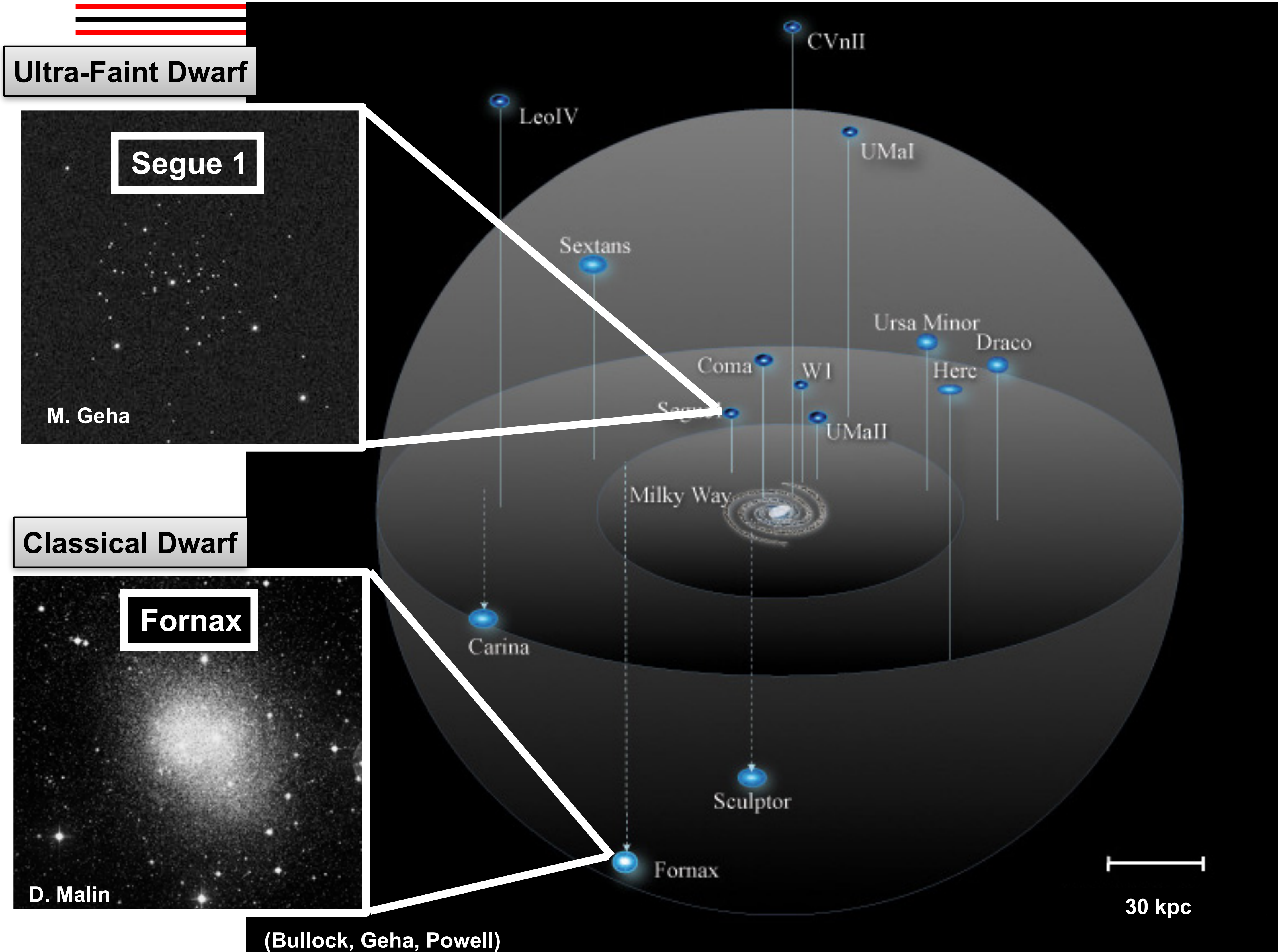
CDM predicts ~500-1000 luminous subhalos for a Milky Way-sized galaxy, while Milky Way only has dozens of known satellites

Are the simulations wrong?

- Cold Dark Matter?
- Warm Dark Matter?
- Self-Interacting Dark Matter?

Do these objects actually exist despite the lack of observational evidence?

Discovery of Ultra-Faint Dwarf Galaxies in SDSS



Discovery of Ultra-Faint Dwarf Galaxies in SDSS

Ultra-Faint Dwarf

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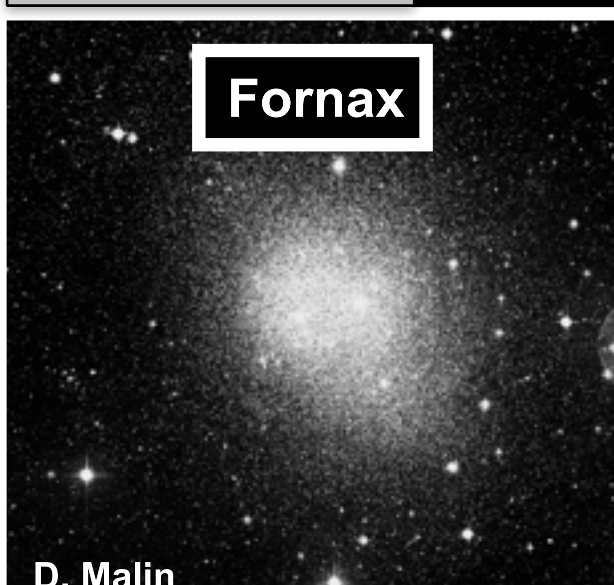
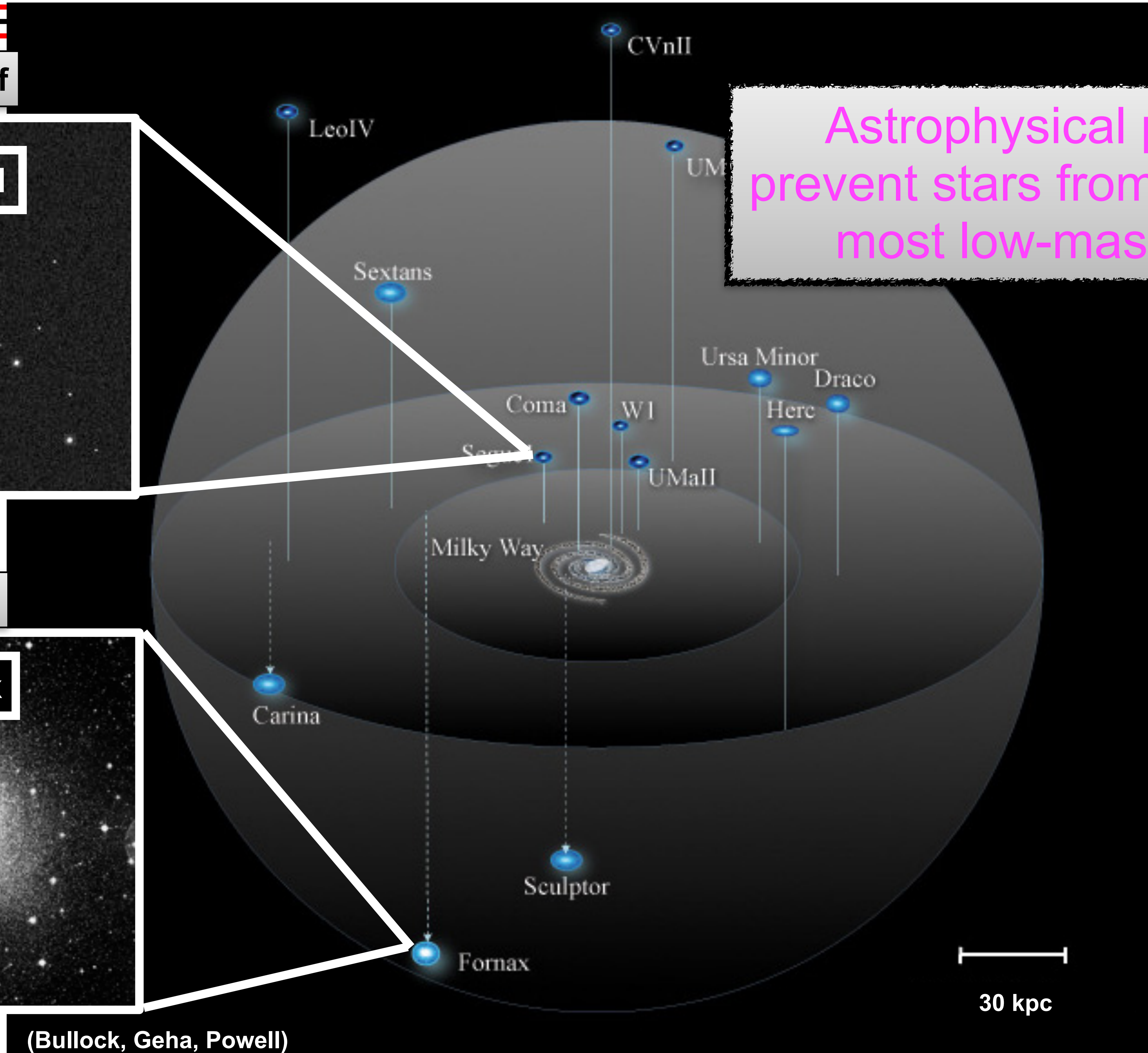
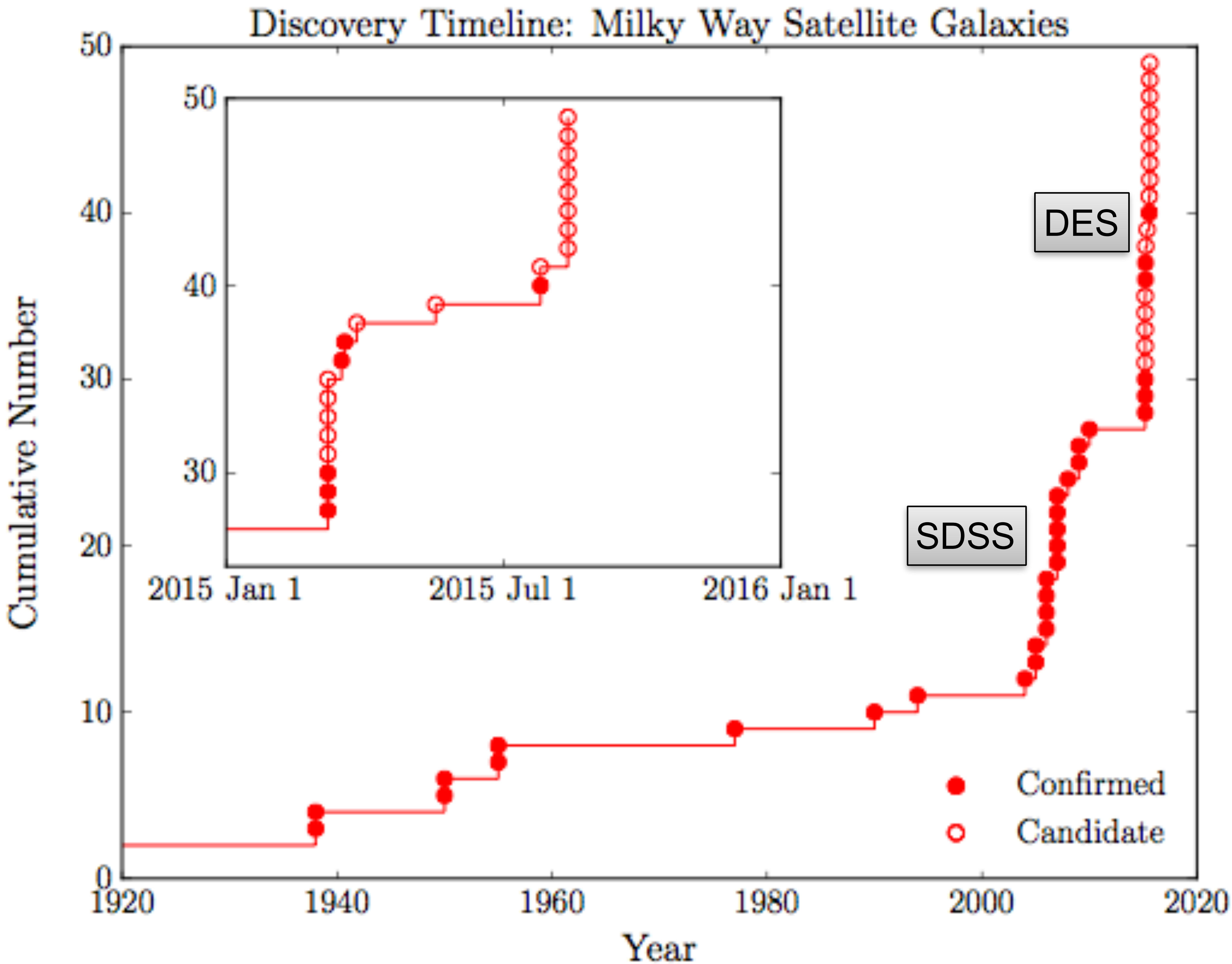




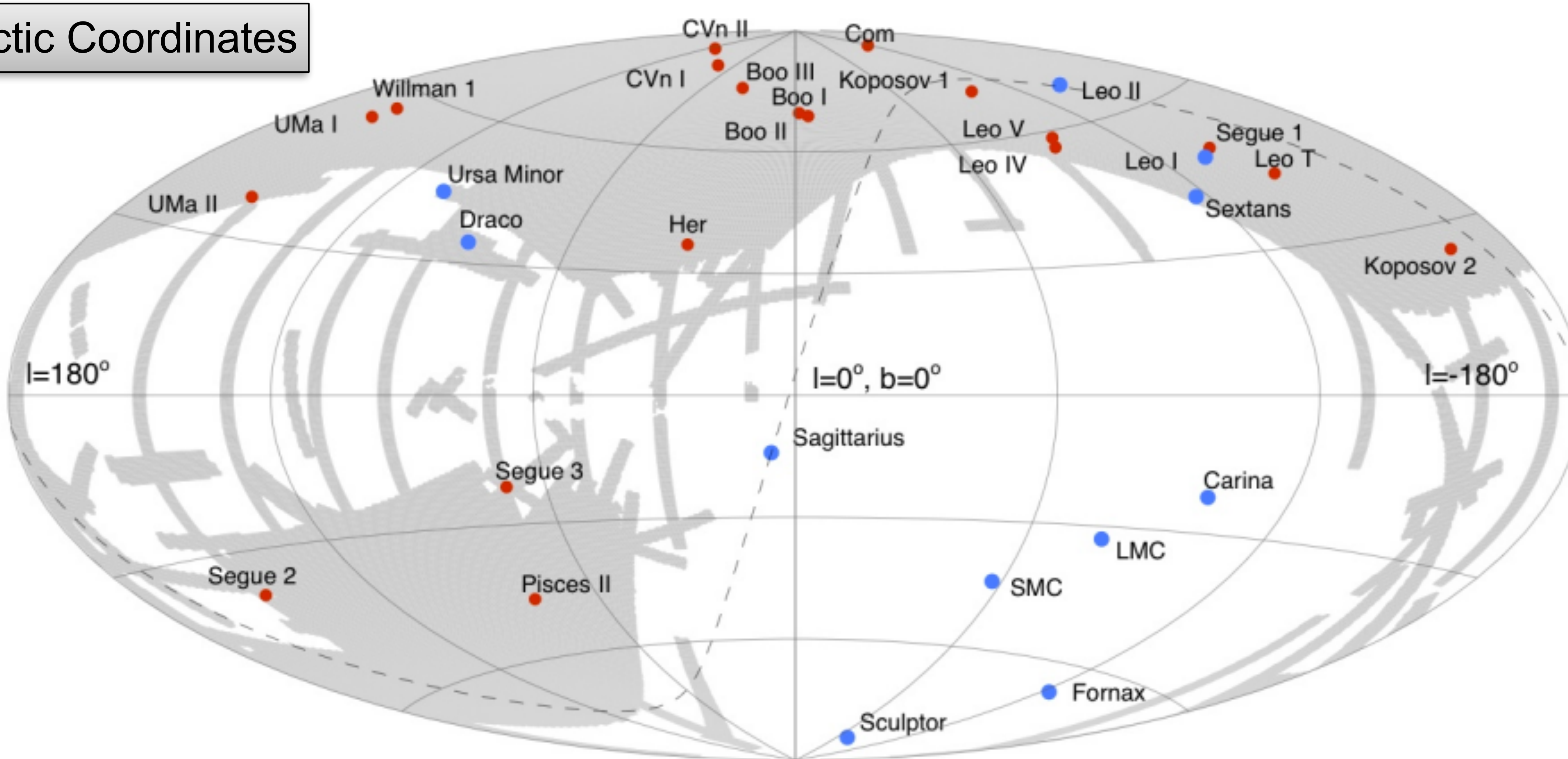
Astrophysical process prevent stars from forming in most low-mass halos

Discovery Timeline



Discovery of Ultra-Faint Dwarf Galaxies by SDSS

Galactic Coordinates

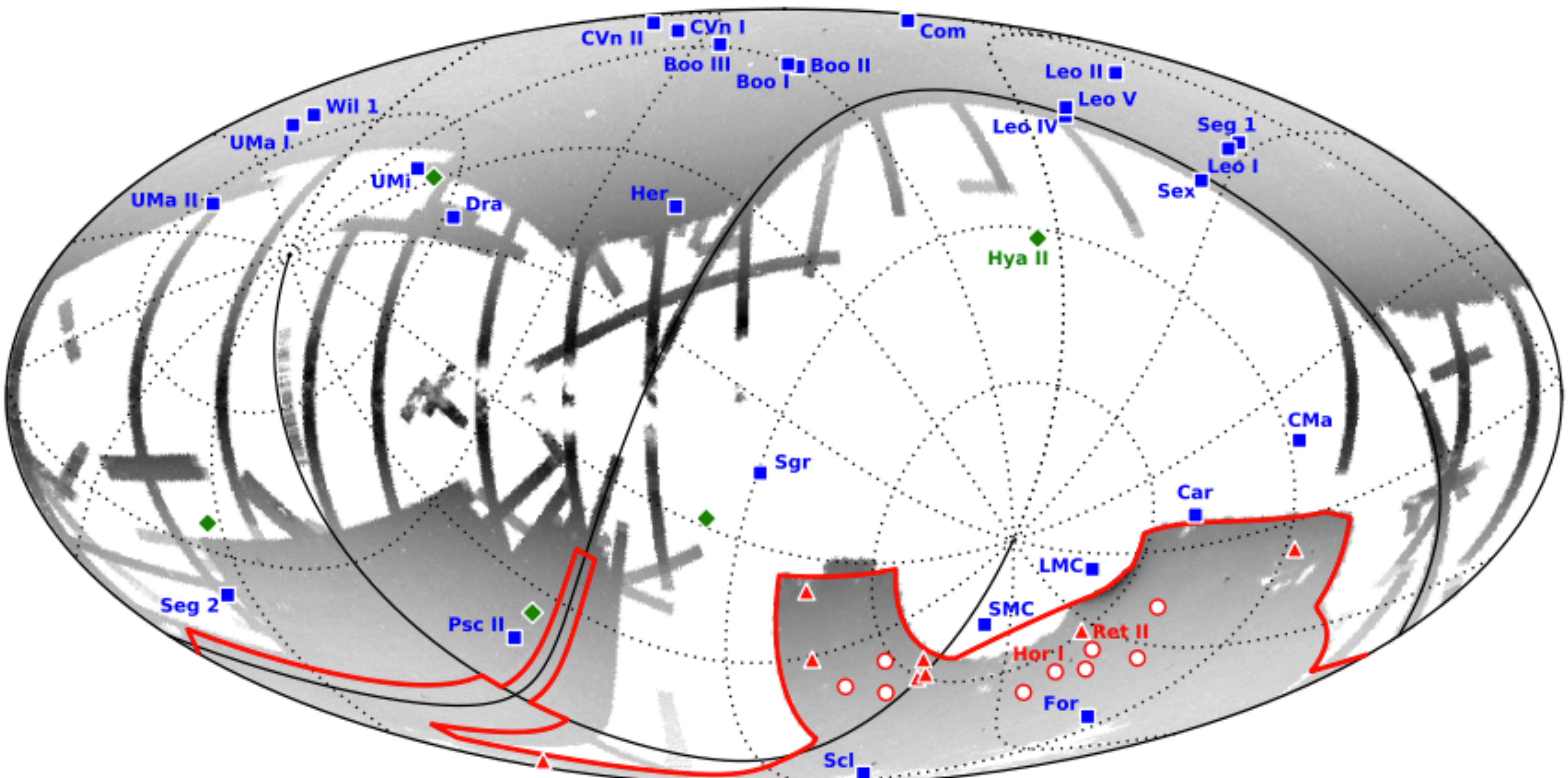


Belokurov et al. (2013)

- Classical dwarf galaxies
- Ultra-faint dwarf galaxies discovered by SDSS

New Dwarf Galaxy Candidates Discovered by DES

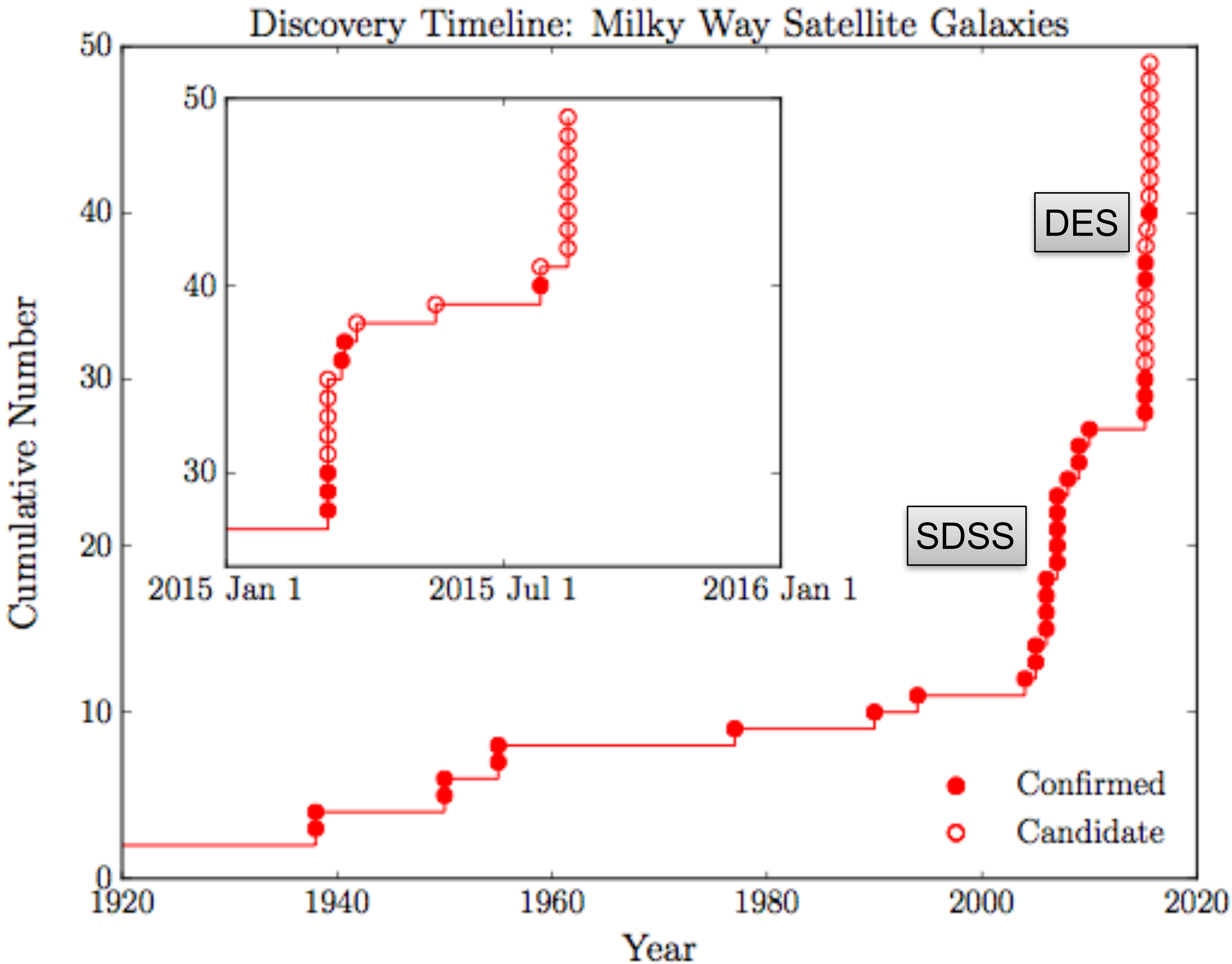
Year 1 + Year 2 data



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

Drlica-Wagner et al. 2015
(DES Collaboration)

Discovery Timeline



Solving the "Missing Satellite Problem"

- **The discovery of ultra-faint galaxies dramatically increases the number of known satellites in the Milky Way.**

- **Meanwhile, the numerical simulations, when including the baryonic feedbacks, predict fewer luminous subhalos in the Milky Way.**

- **The ultra-faint galaxies are results of inefficient star formation in the low-mass subhalos?**

Why? — Motivation

- Near Field Cosmology
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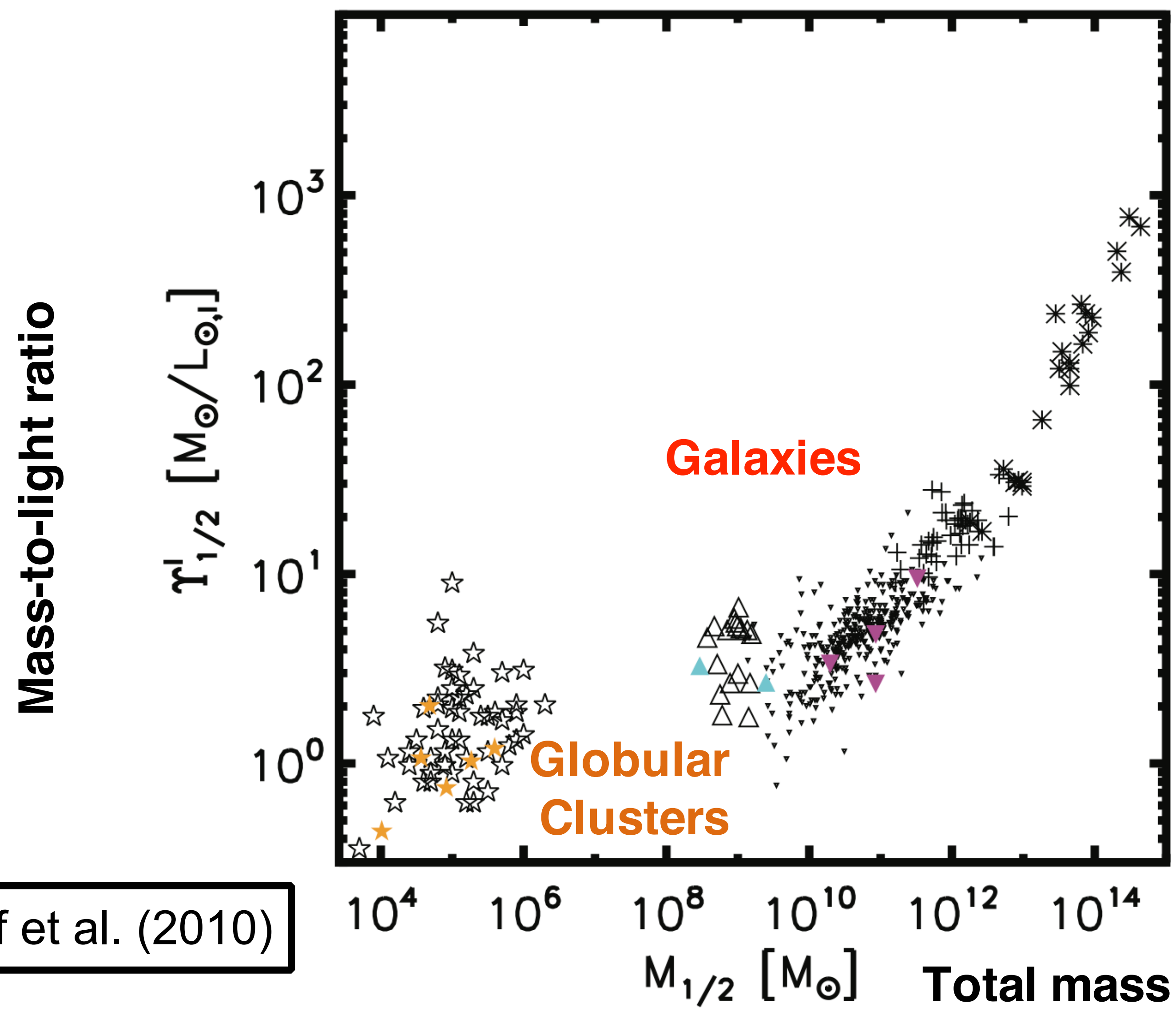
What is "Galaxy"?

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.

Willman & Strader 2012, AJ, 144, 76



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Dwarf Galaxies vs. Globular Clusters

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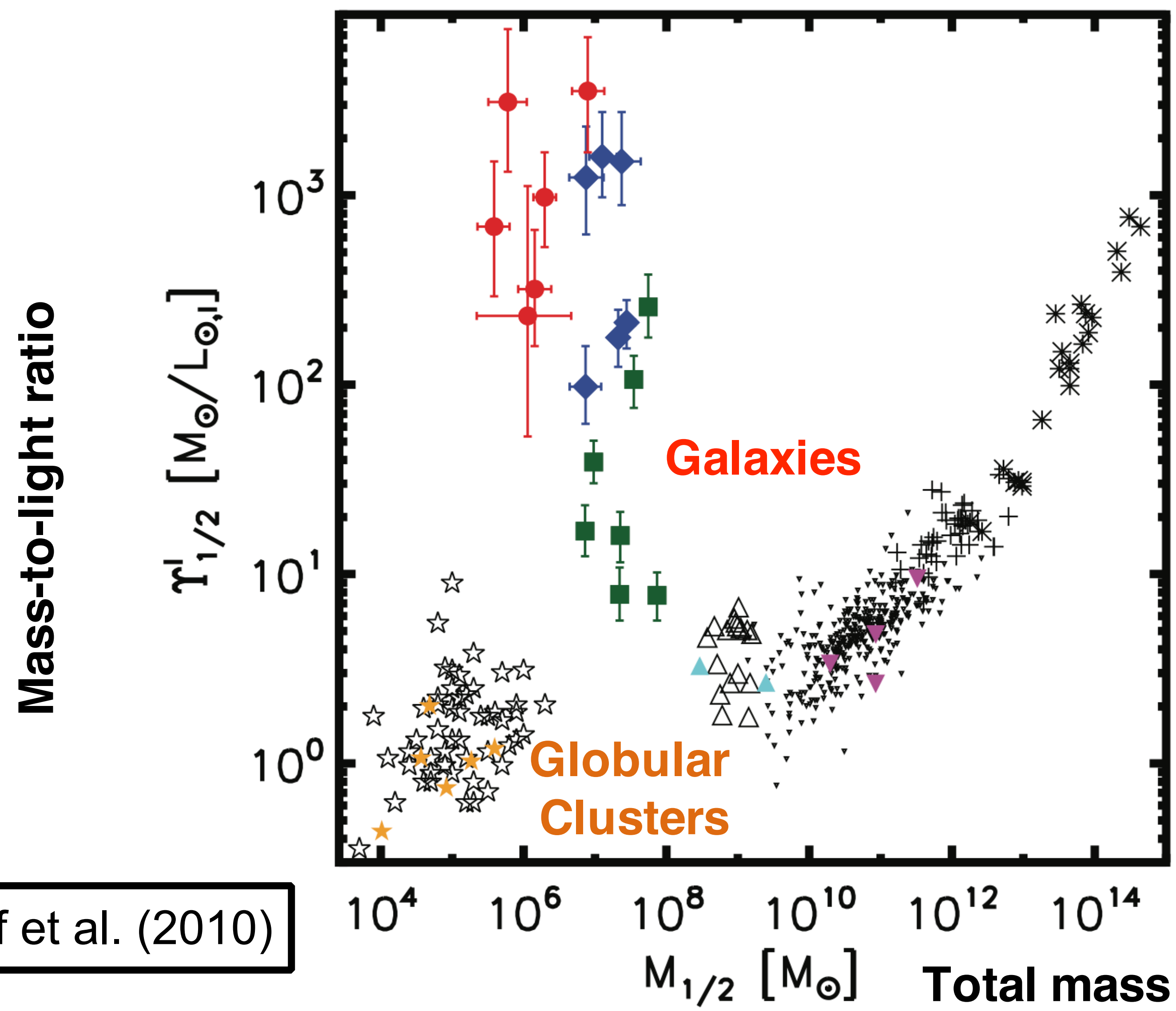

Wolf et al. (2010)

$M/L > 100\ M_\odot/L_\odot$!

- **Dwarf galaxies are dark matter dominated**
- **Globular clusters are baryon dominated**

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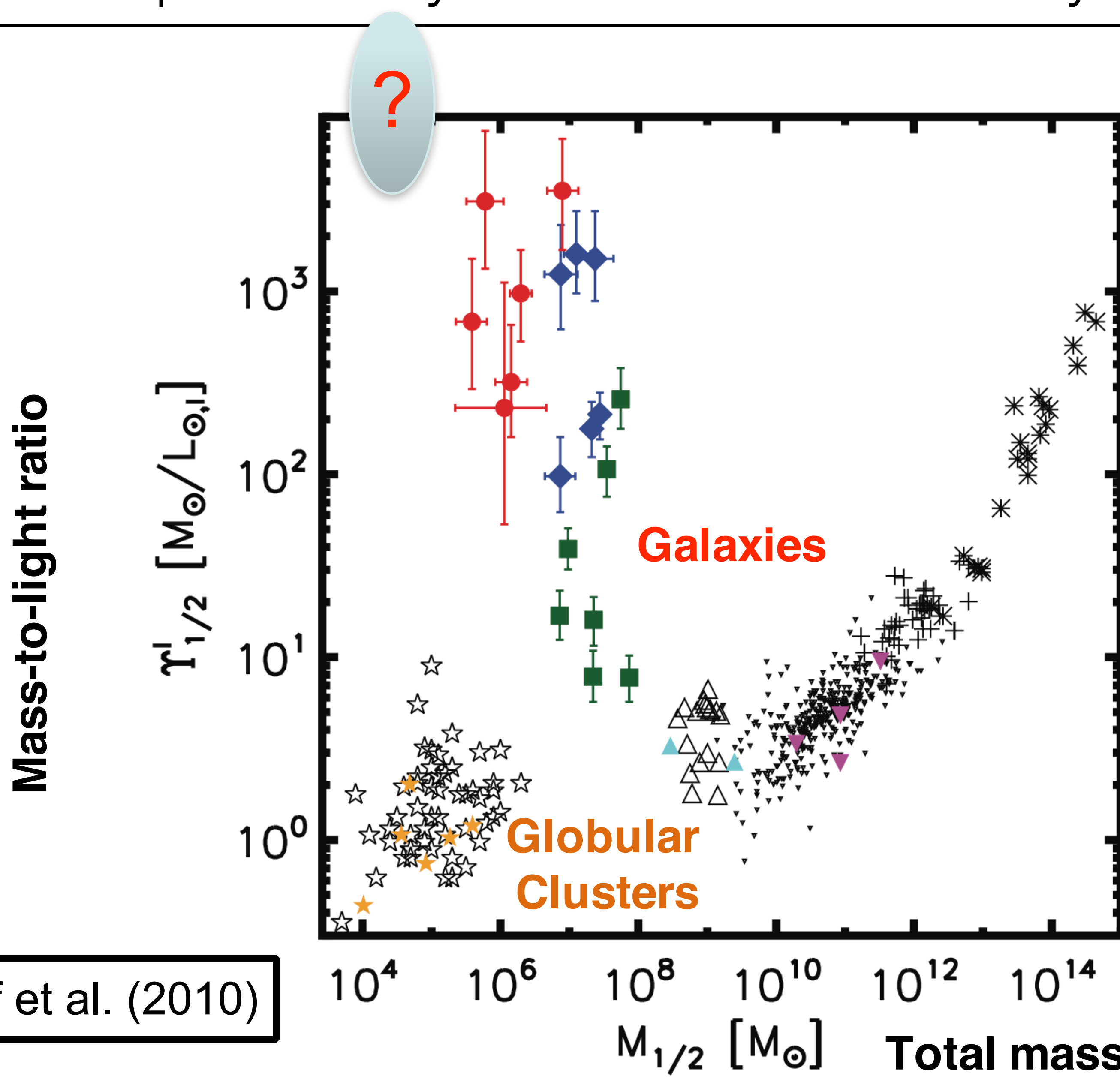

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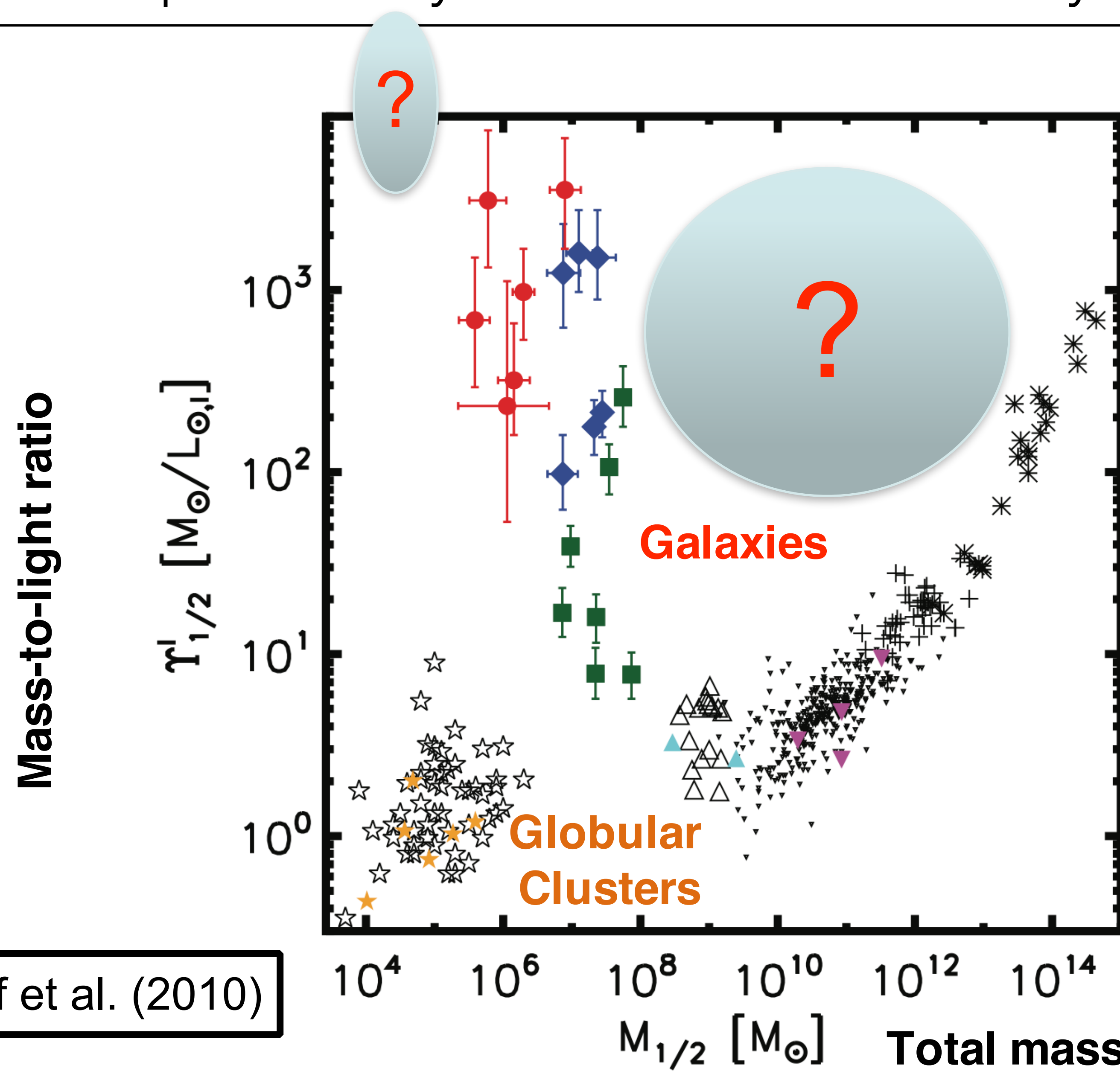

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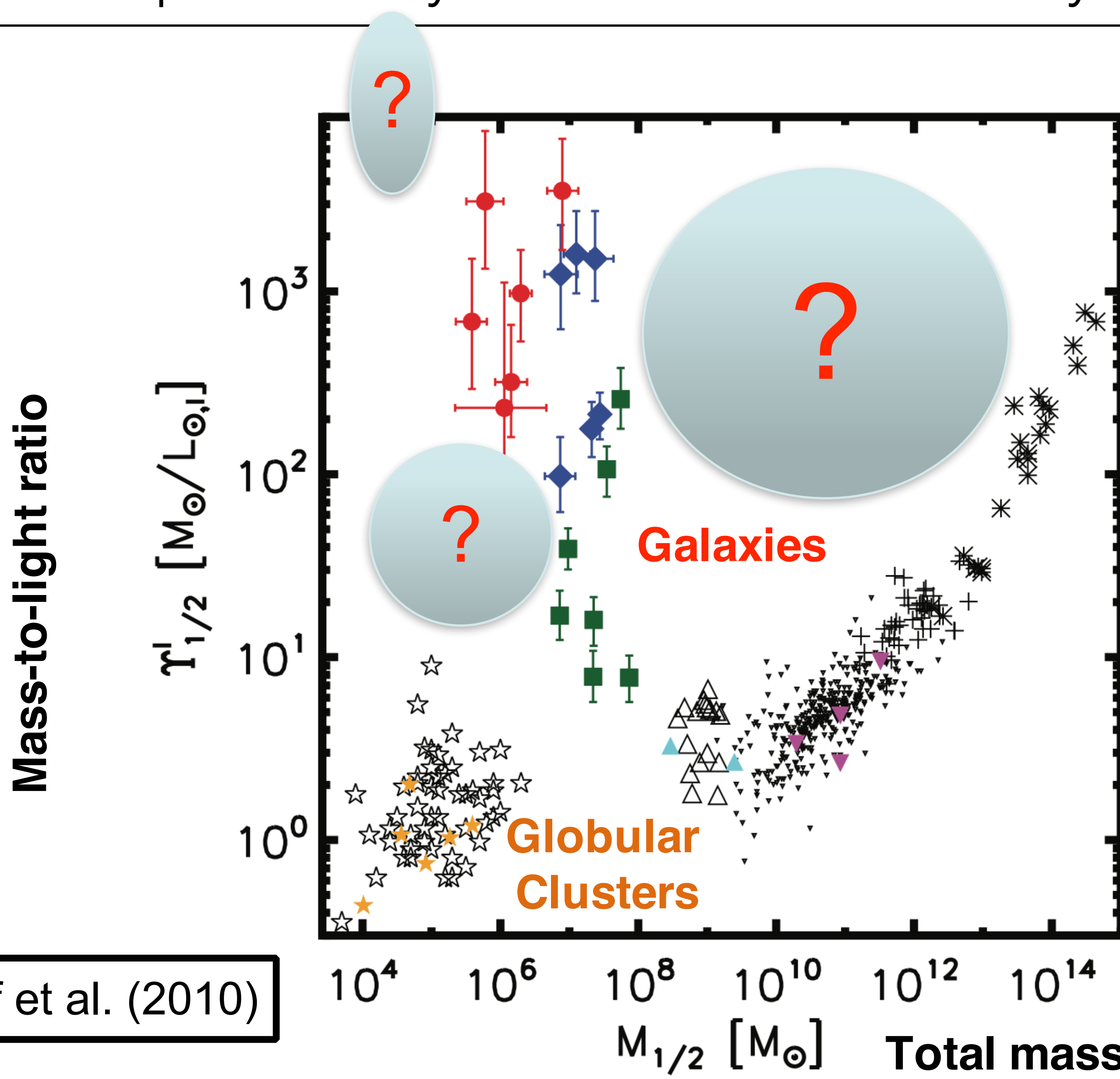

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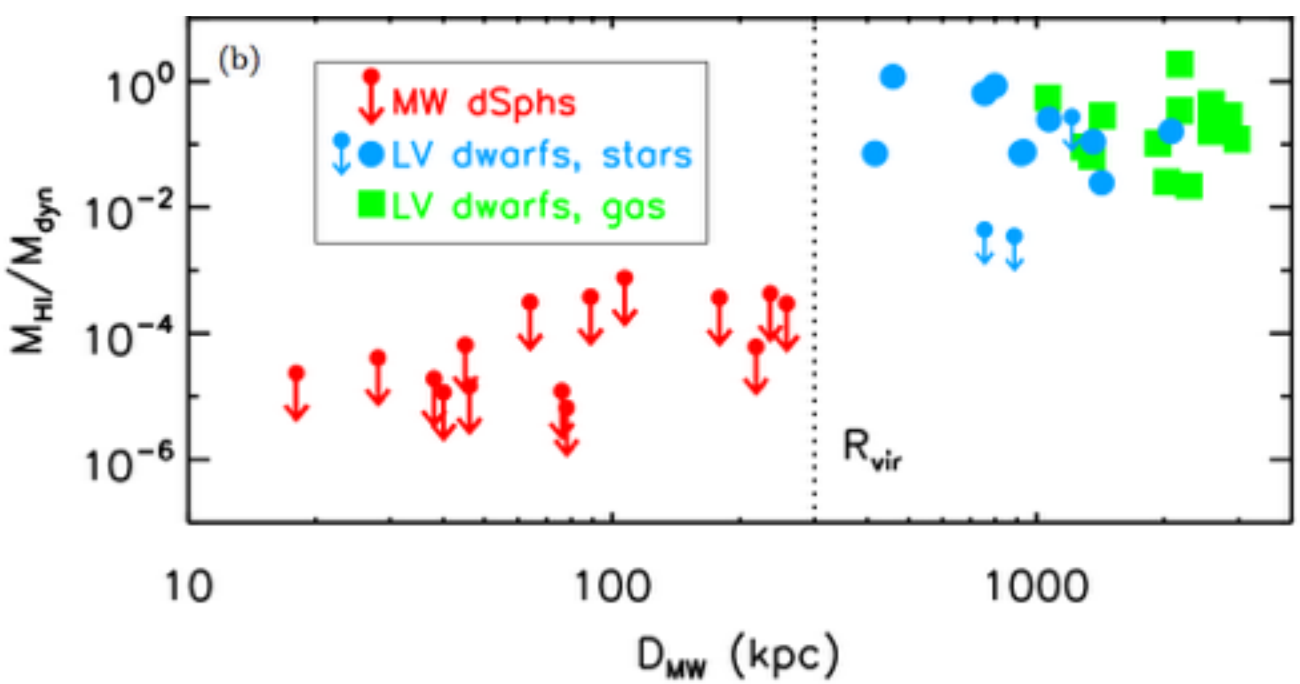
Star Formation in Dwarf Galaxies

Gas Stripping?

Quiescent vs Star Forming



HI: Neutron Hydrogen Gas

Speakers et al. 2014

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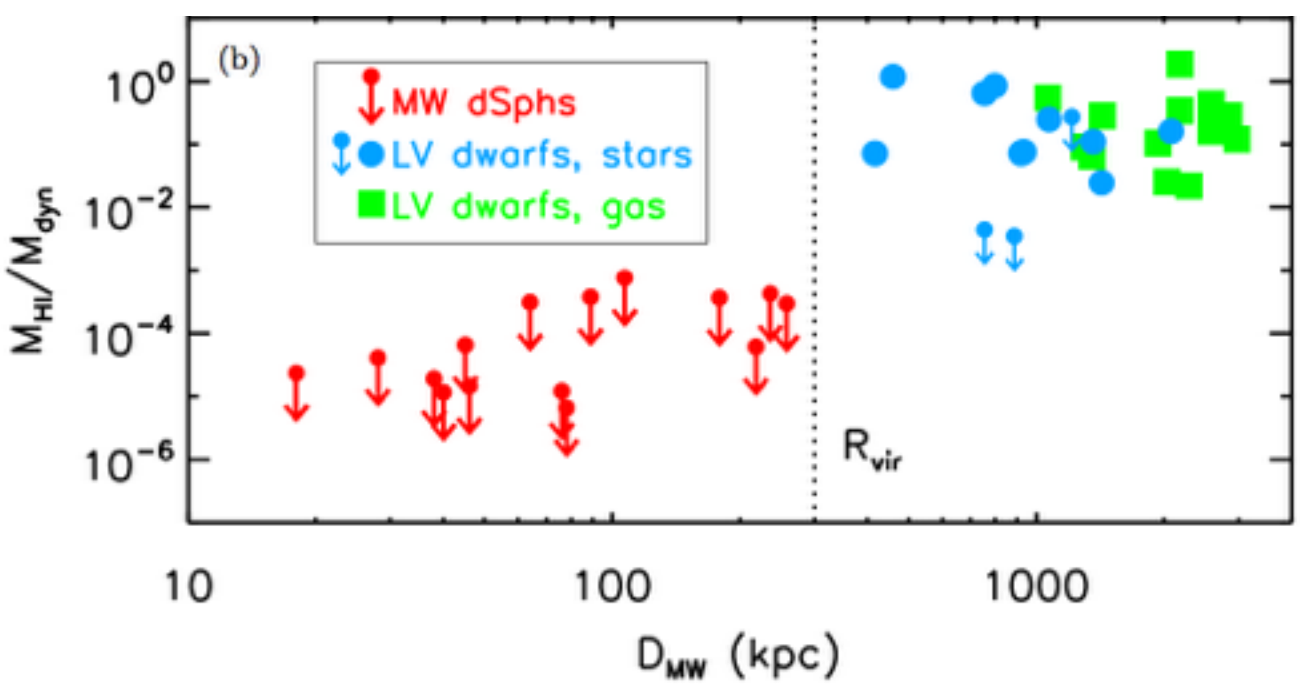

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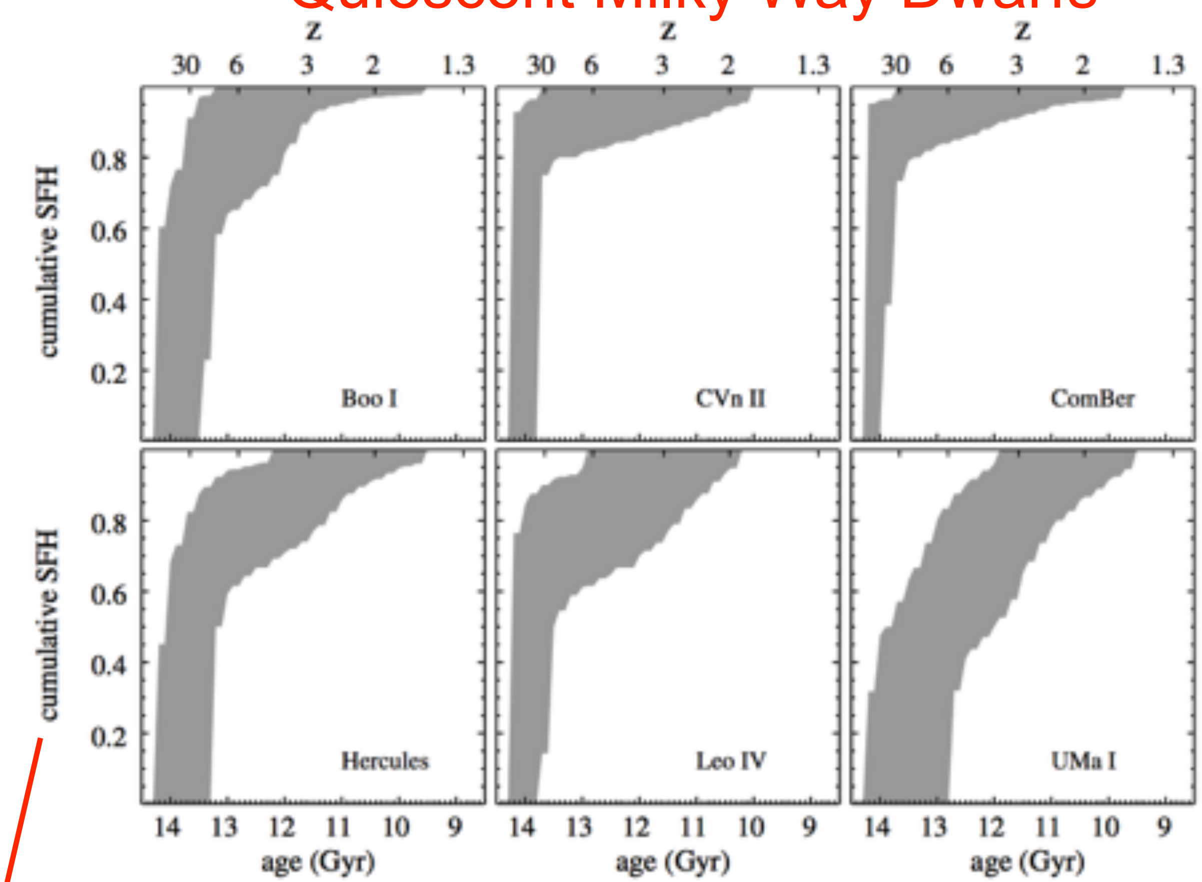
Reionization?

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

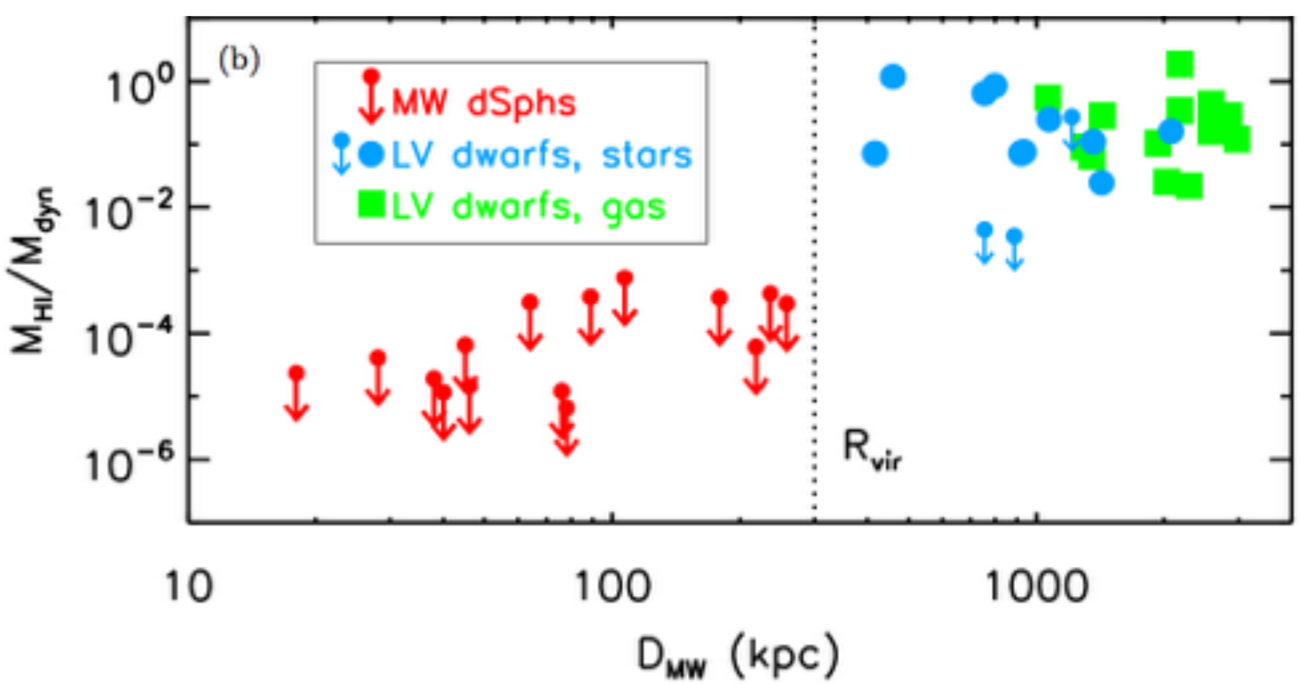
THE DARK ENERGY SURVEY

Star Formation in Dwarf Galaxies

Fermilab

Gas Stripping?

Quiescent vs Star Forming



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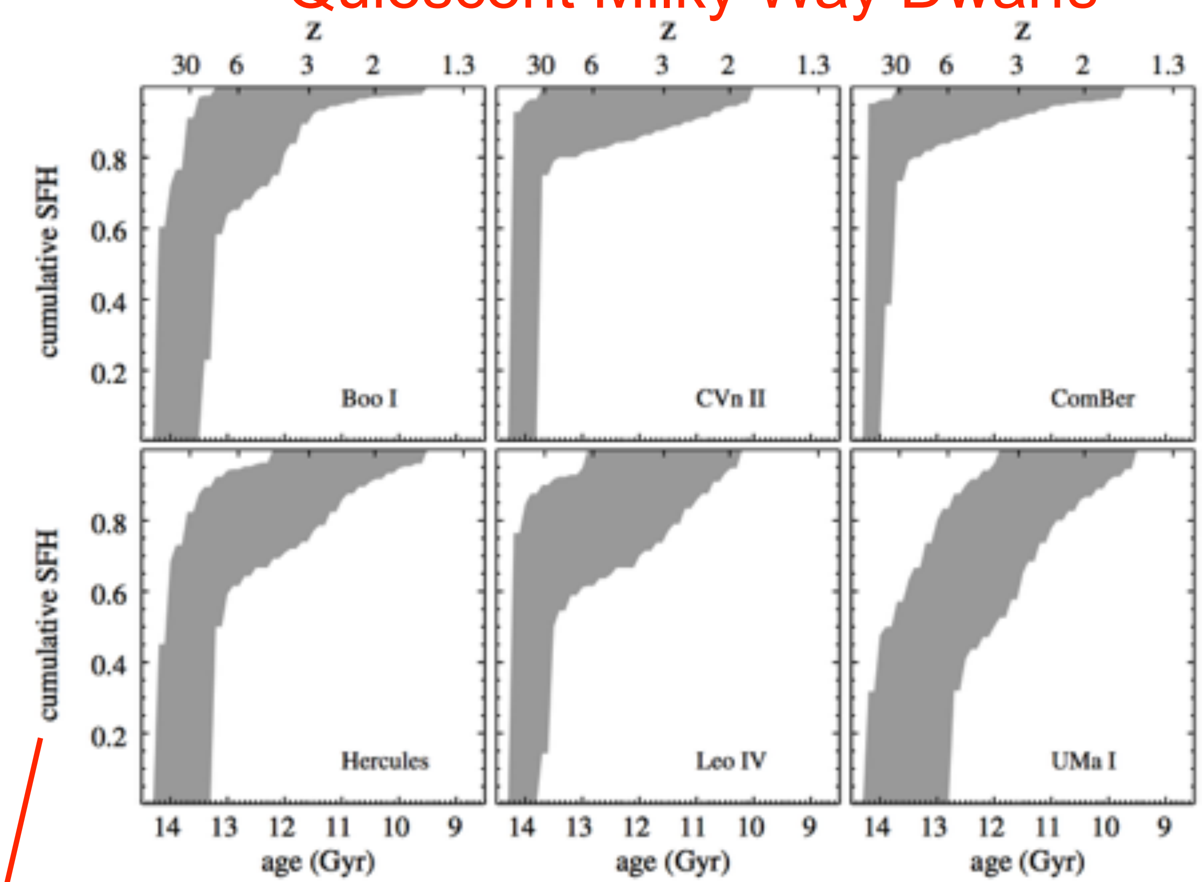


percentage of stars

age (Gyr)

Brown et al. 2004

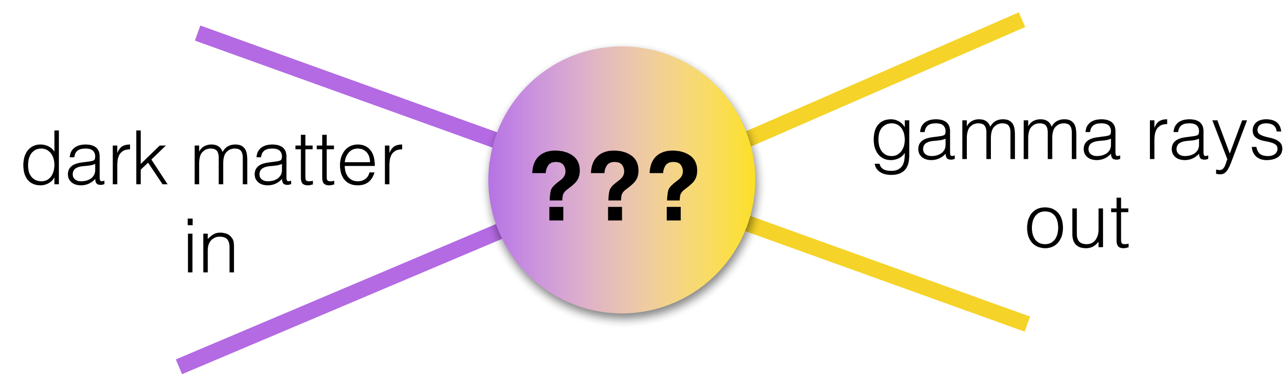
What makes these satellites stop forming stars?
Stripping vs. Reionization?

Why? — Motivation

- Near Field Cosmology
- Galaxy Formation
- Indirect Dark Matter Detection

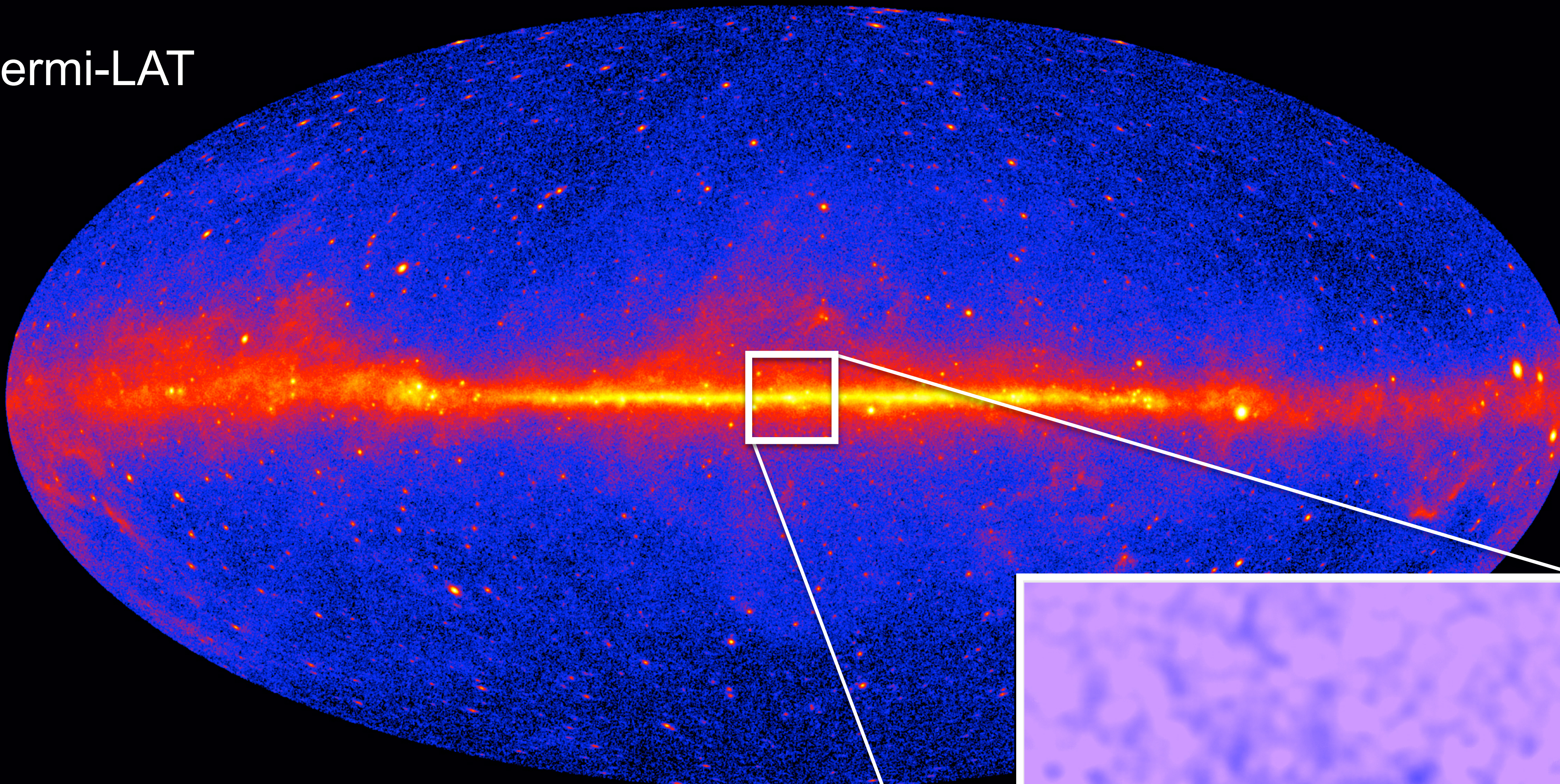
Indirect Detection of Dark Matter
WIMP Annihilation

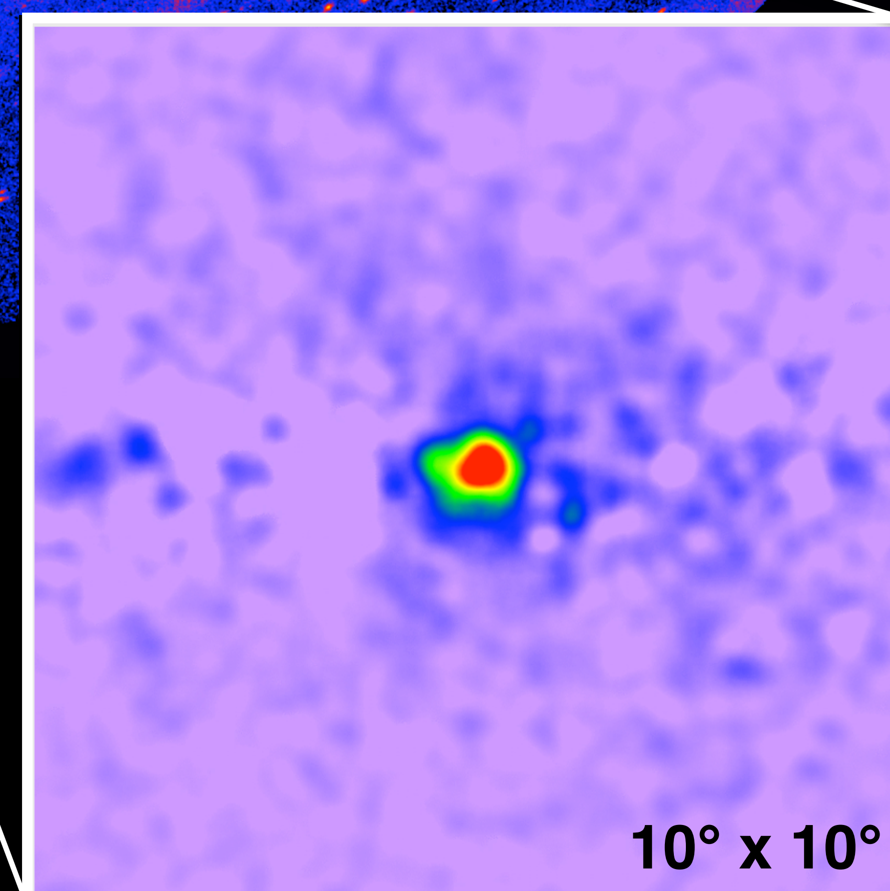
Many dark matter models predict annihilation into energetic Standard Model particles
(e.g., gamma rays, neutrinos, electrons, …)



Annihilation rate scales as density squared

Fermi-LAT





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, …

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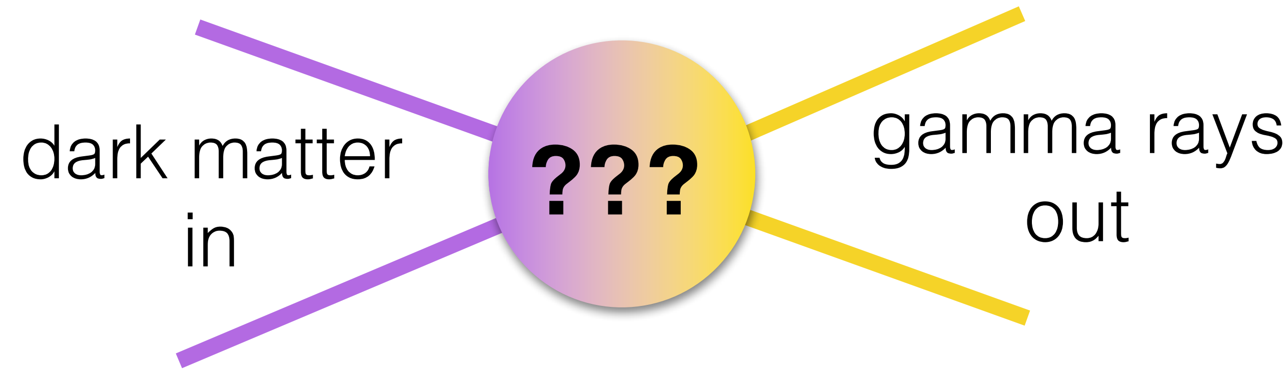

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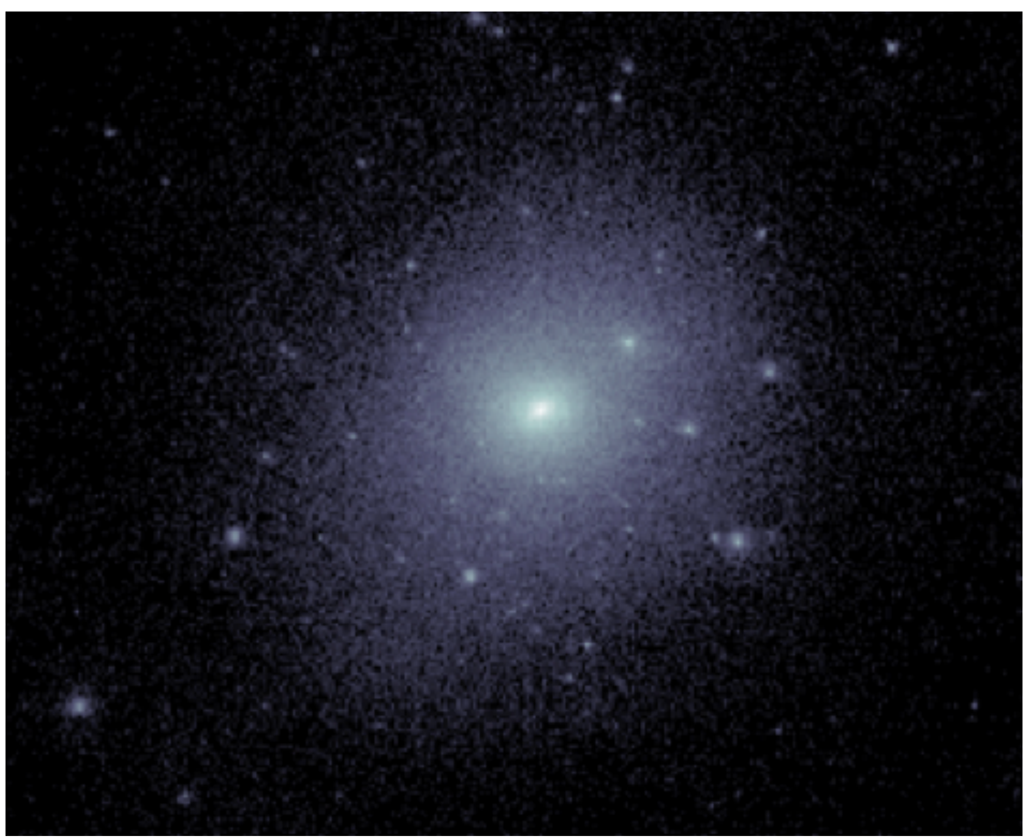
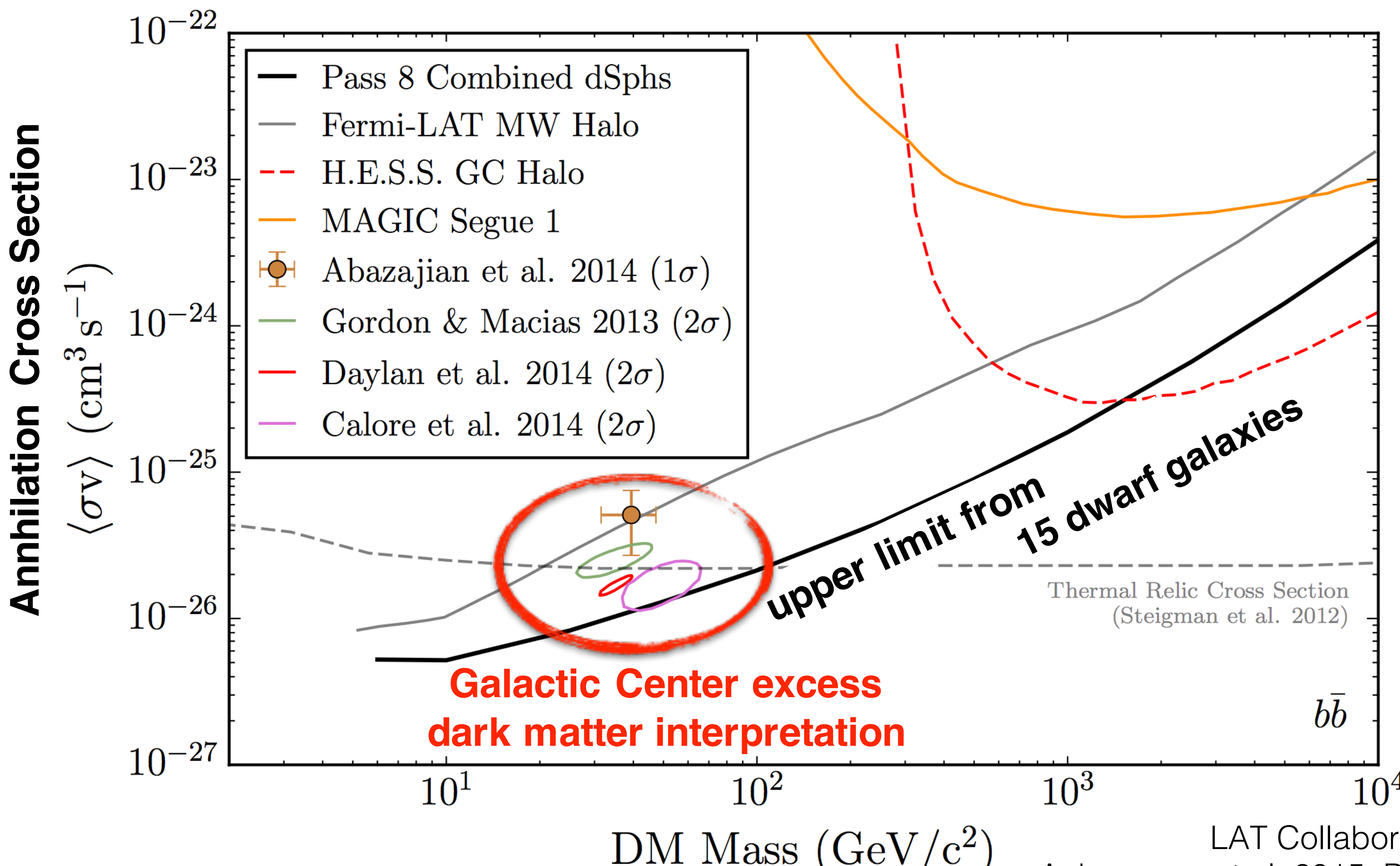


Nearby clumps of dark matter make ideal targets

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

Indirect Detection of Dark Matter WIMP Annihilation

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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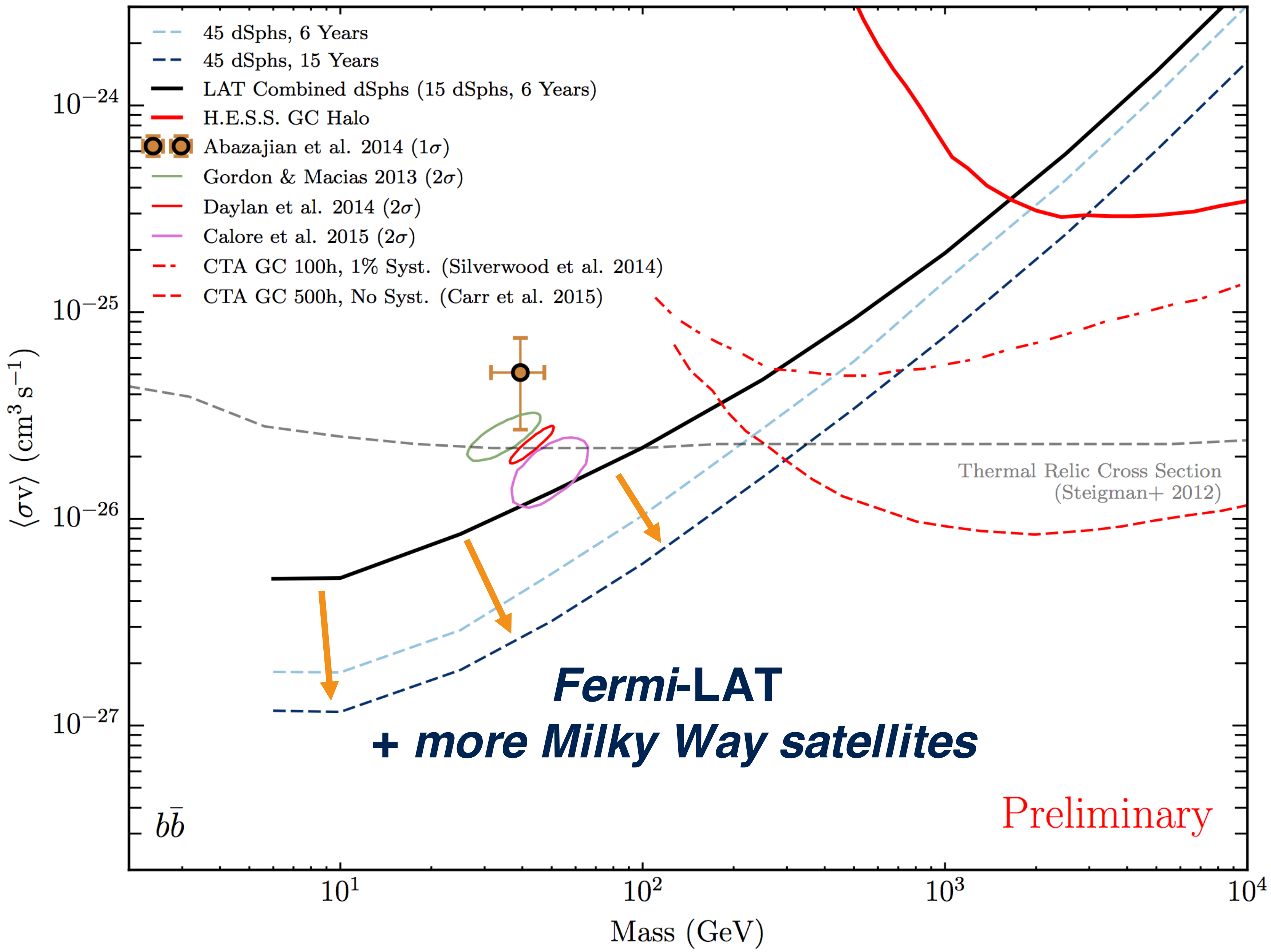

To Summarize

- Milky Way satellites are good testbeds for ΛCDM paradigm
- Milky Way satellites are important to understand galaxy formation
- Milky Way satellites are good site for indirect dark matter search

Discovery → **Characterization**

To Summarize

- **Milky Way satellites are good testbeds for ΛCDM paradigm**

  Are these candidates dark matter dominated dwarf galaxies?
- **Milky Way satellites are important to understand galaxy formation**

  Did they also stop forming stars long time ago?
- **Milky Way satellites are good site for indirect dark matter search**

  Are they ideal targets for detection of annihilation signal?

Discovery → **Characterization**

Outline

How? — Spectroscopy

Measurements on Resolved Stars in Dwarf Galaxies

- **Photometry**
  - brightness
  - color
- **Astrometry**
  - position
- **Spectroscopy**
  - line position
  - line strength

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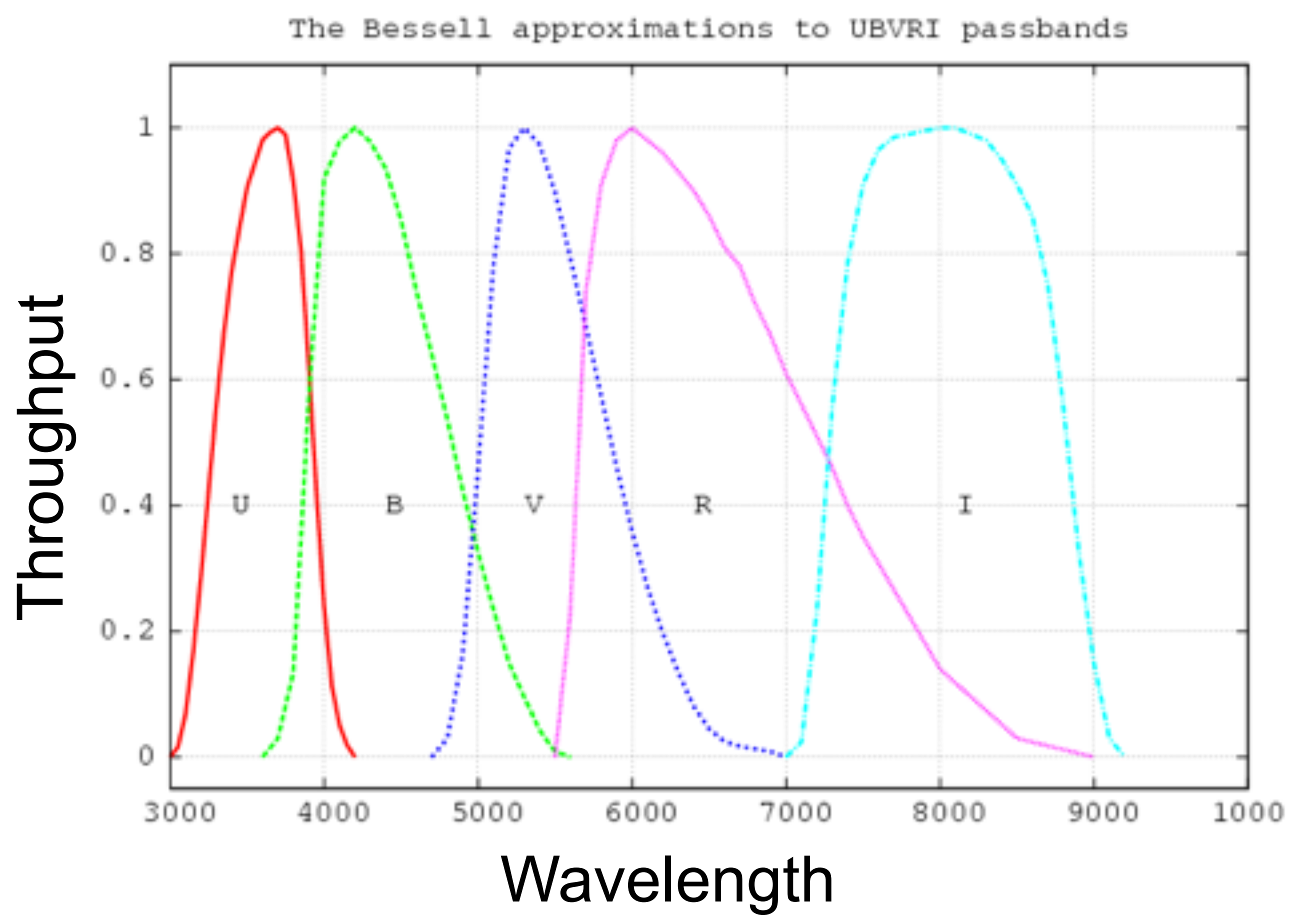
Filter Bandpasses in Imaging Survey



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distance, stellar mass, age(?)…..

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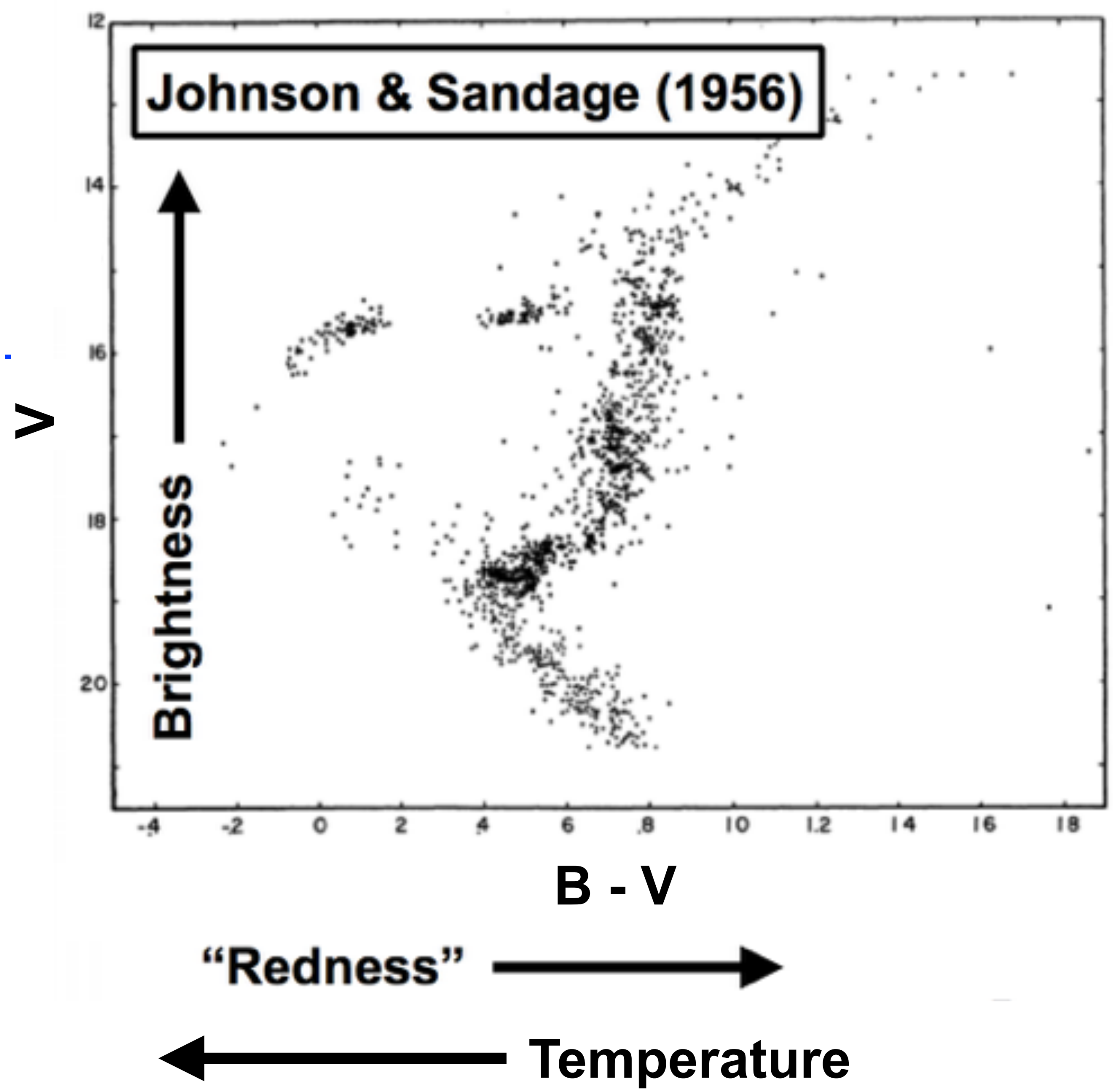

Measurements on Resolved Stars in Dwarf Galaxies

THE DARK ENERGY SURVEY

Fermilab

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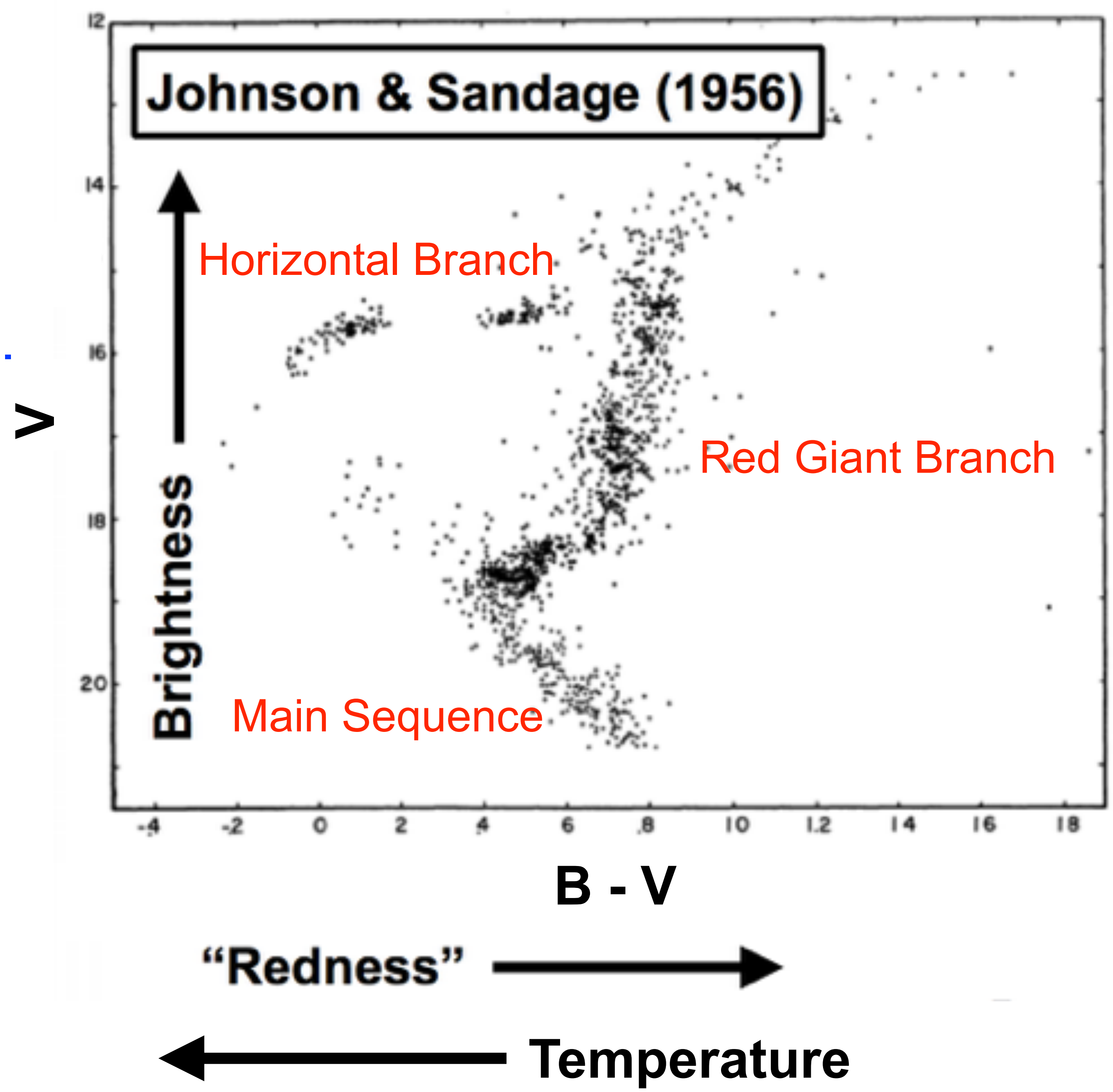

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size, proper motion/transverse velocity

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  - line position
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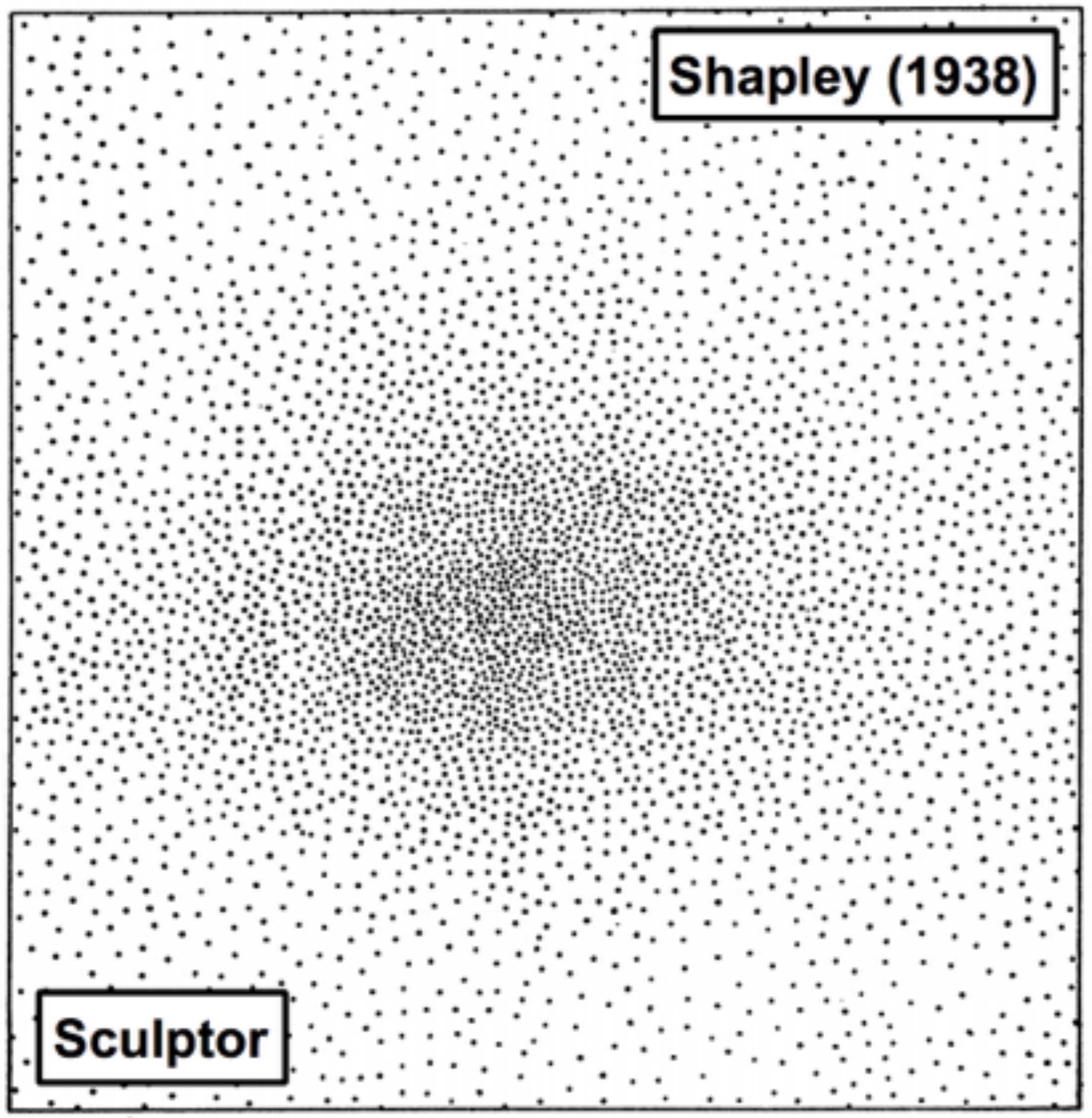

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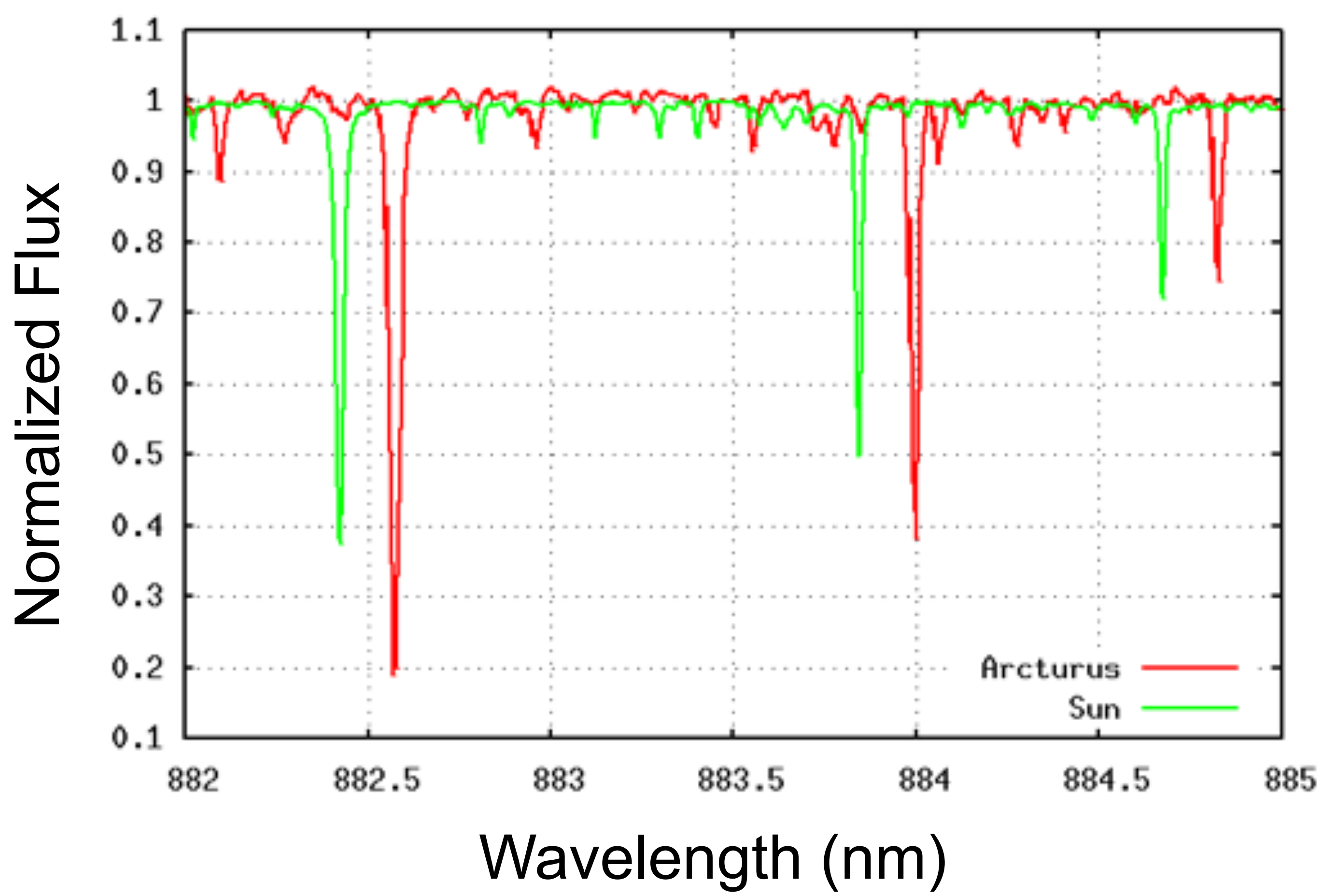

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line-of-sight velocity, chemical abundance or metallicities, dynamical mass

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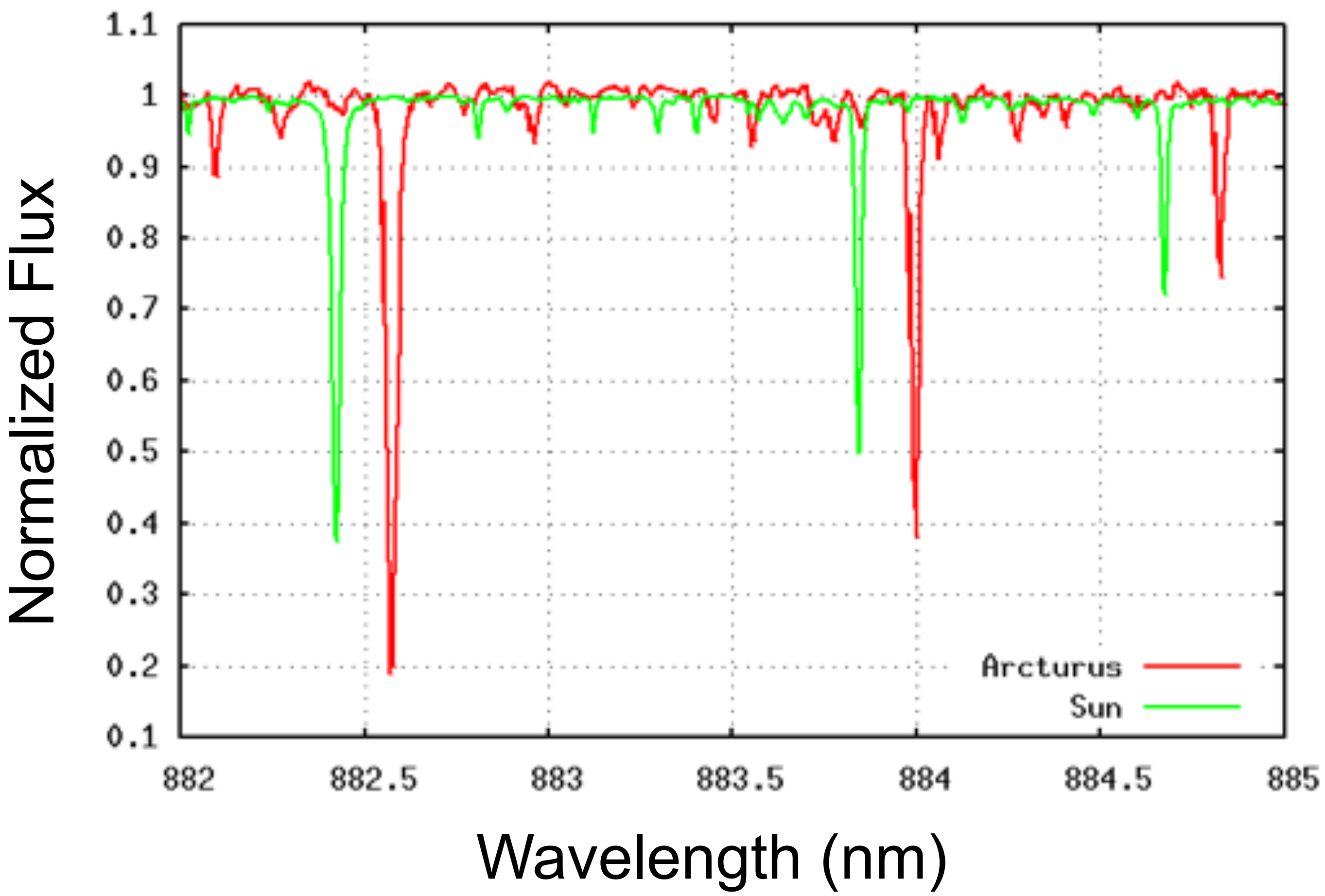

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Measurements on Resolved Stars in Dwarf Galaxies

dynamical mass

- Confirm the dark matter content — dwarf galaxy
- WIMP annihilation rate

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dynamical mass

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- Virial theorem: <T> + <V>/2 = 0
- Dispersion-supported system — velocity dispersion

$$M_{1/2} = 930 \left(\frac{\sigma_v^2}{\mathrm{km}^2\ \mathrm{s}^{-2}}\right)\left(\frac{R_{1/2}}{\mathrm{pc}}\right) \mathrm{M}_\odot.$$

Wolf. et al. (2010)

- Velocity dispersion: ~several km/s — intrinsic scattering
- Velocity accuracy: ***~1 km/s*** —— ~ 0.01 A / ~ 10^{-12} m
- Velocity uncertainty estimation is also important

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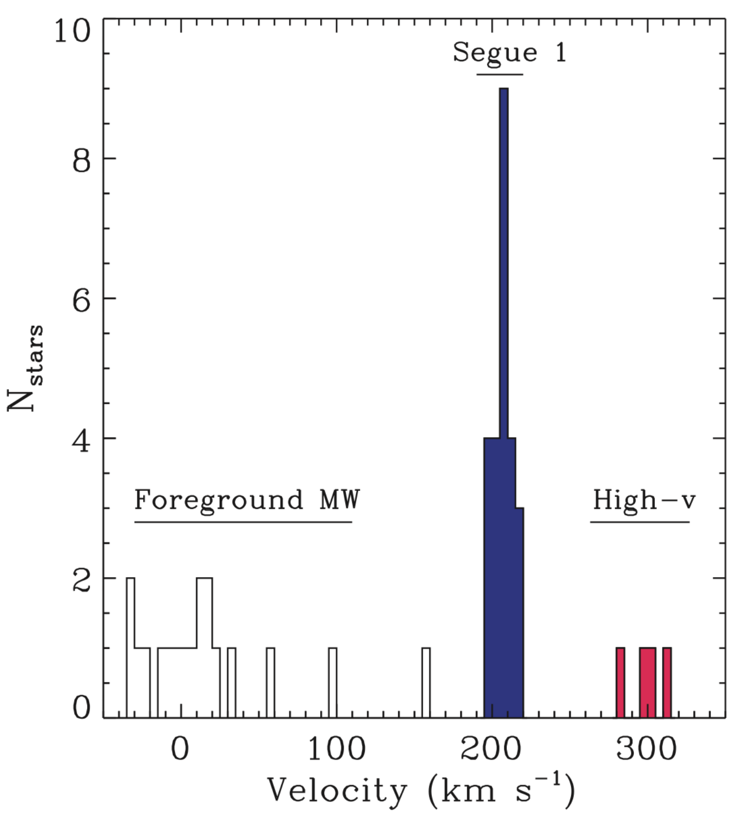

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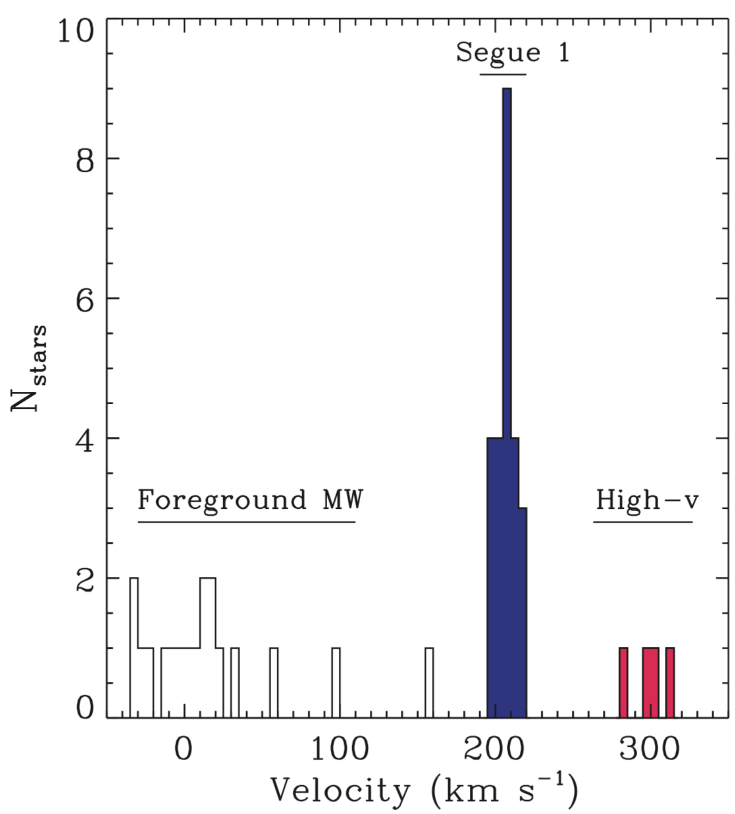

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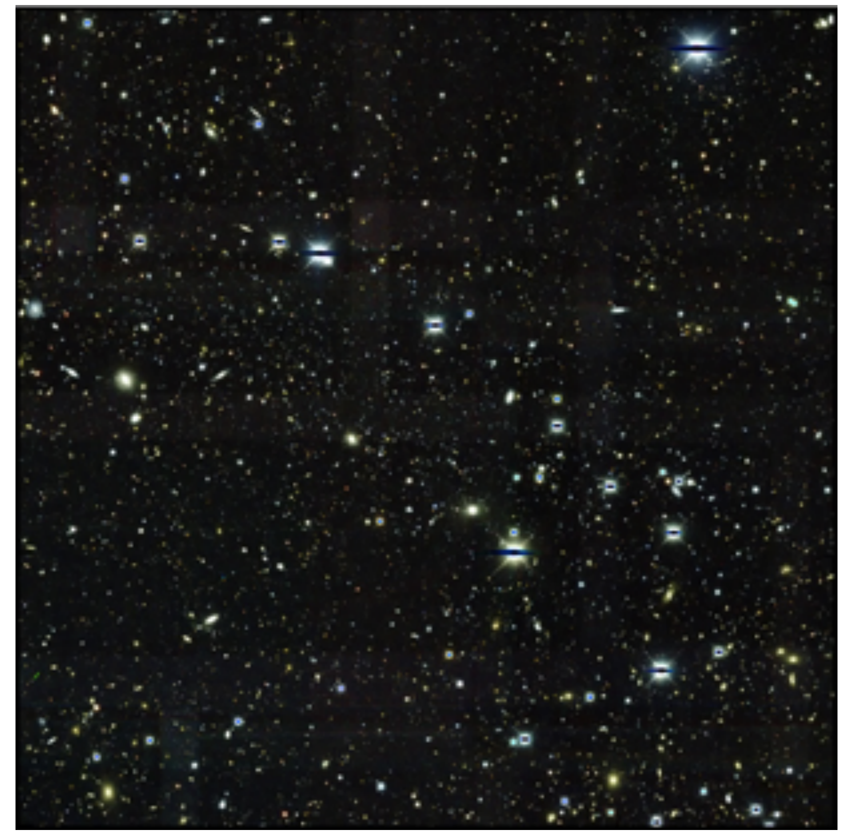
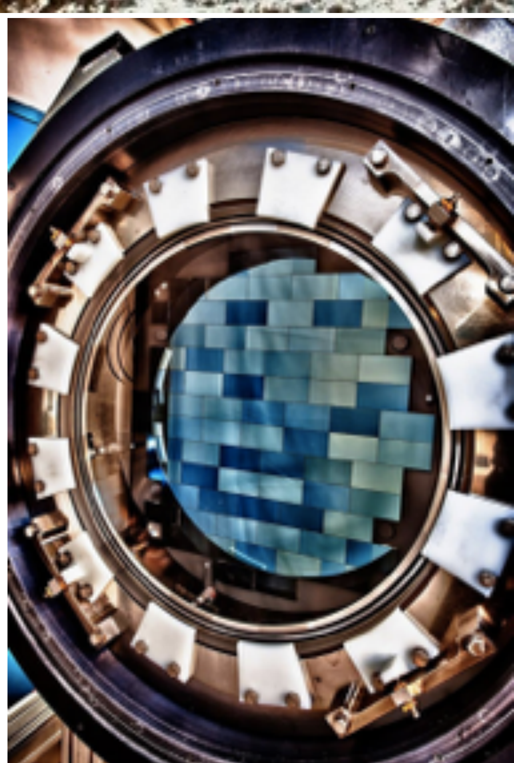
Wolf. et al. (2010)

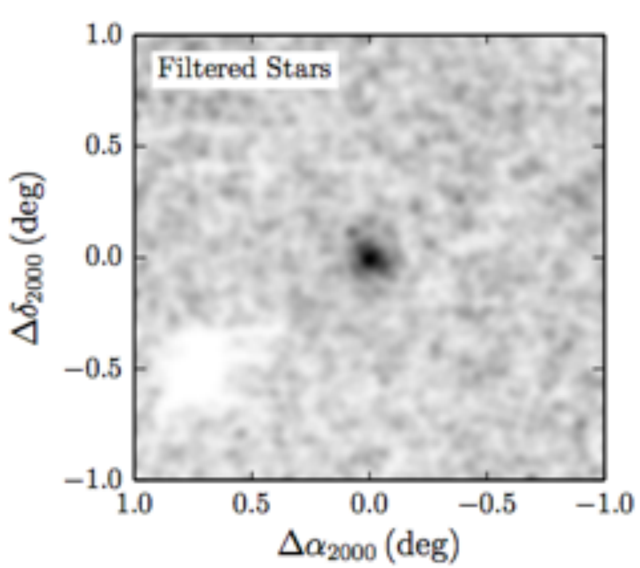
- Velocity dispersion: ~several km/s — intrinsic scattering
- Velocity accuracy: ***~1 km/s*** —— ~ 0.01 A / ~ 10^{-12} m
- Velocity uncertainty estimation is also important

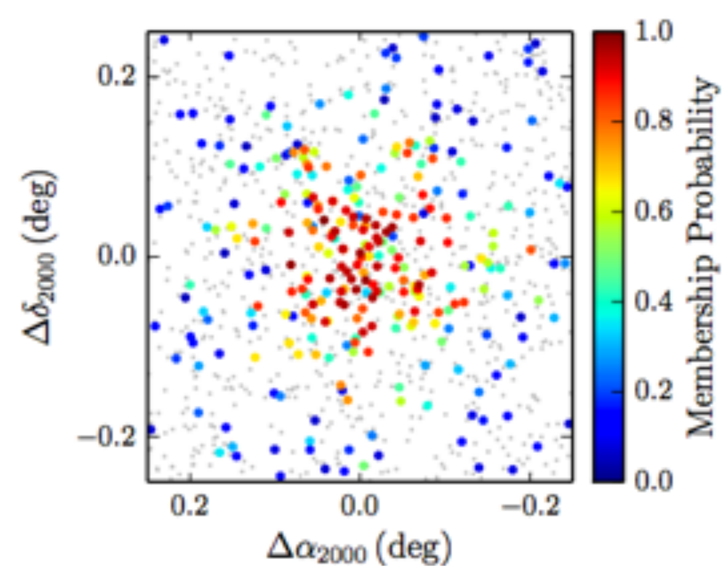
Not only velocity, but also velocity uncertainty need to be accurate

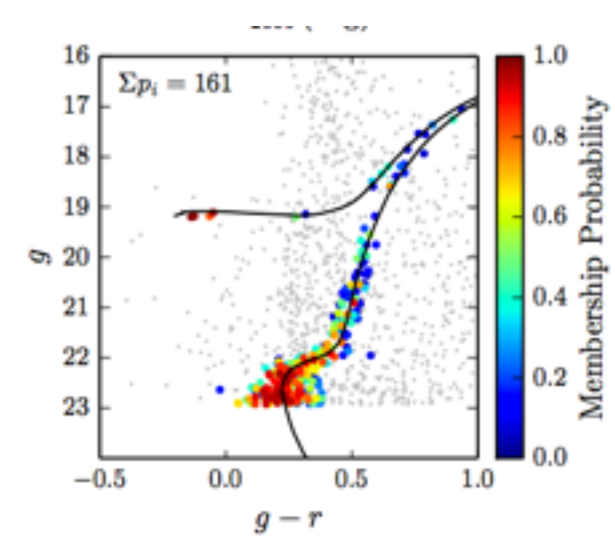
Image Survey — Discovery







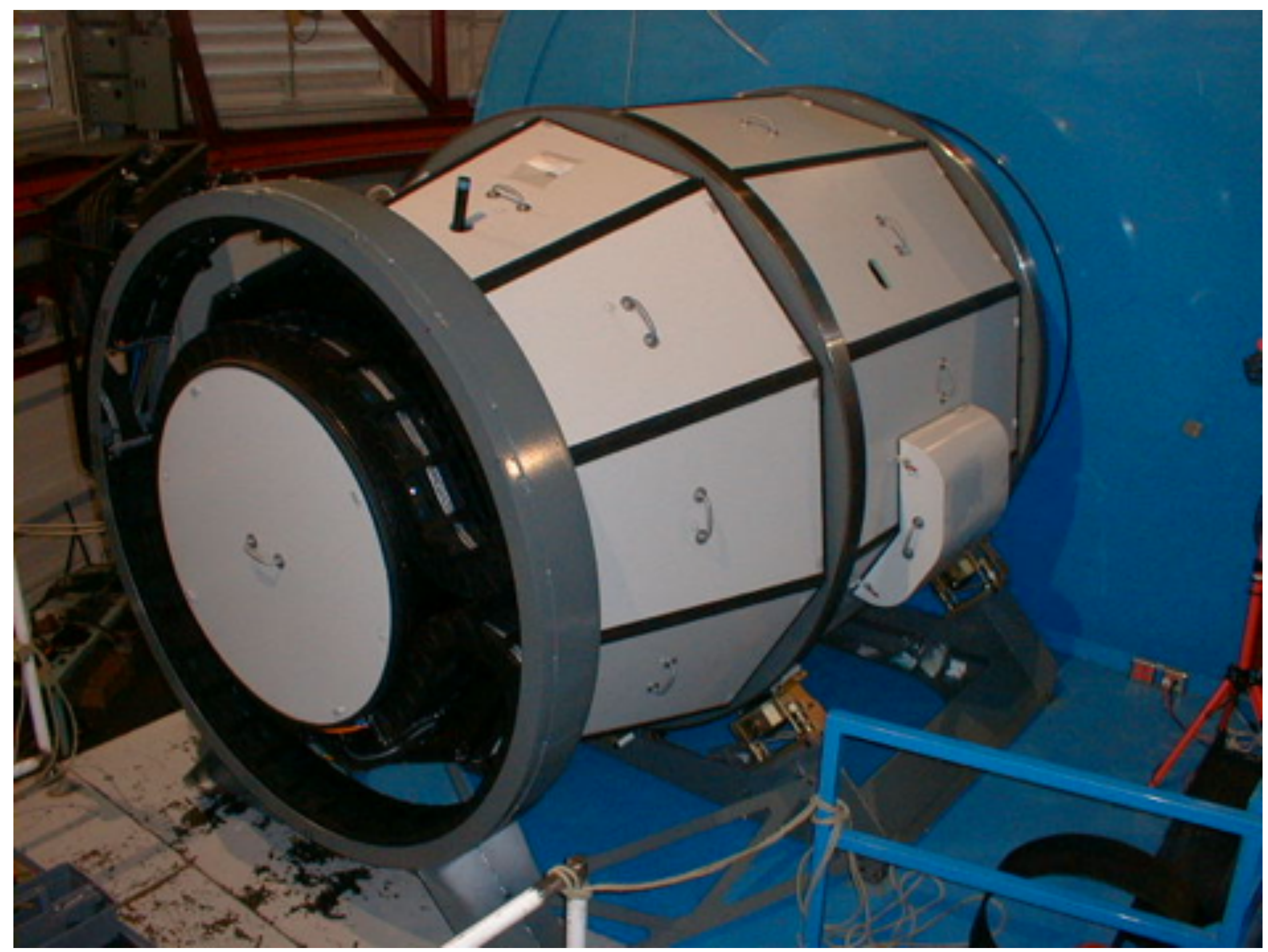




Spectroscopic Followup — Characterization

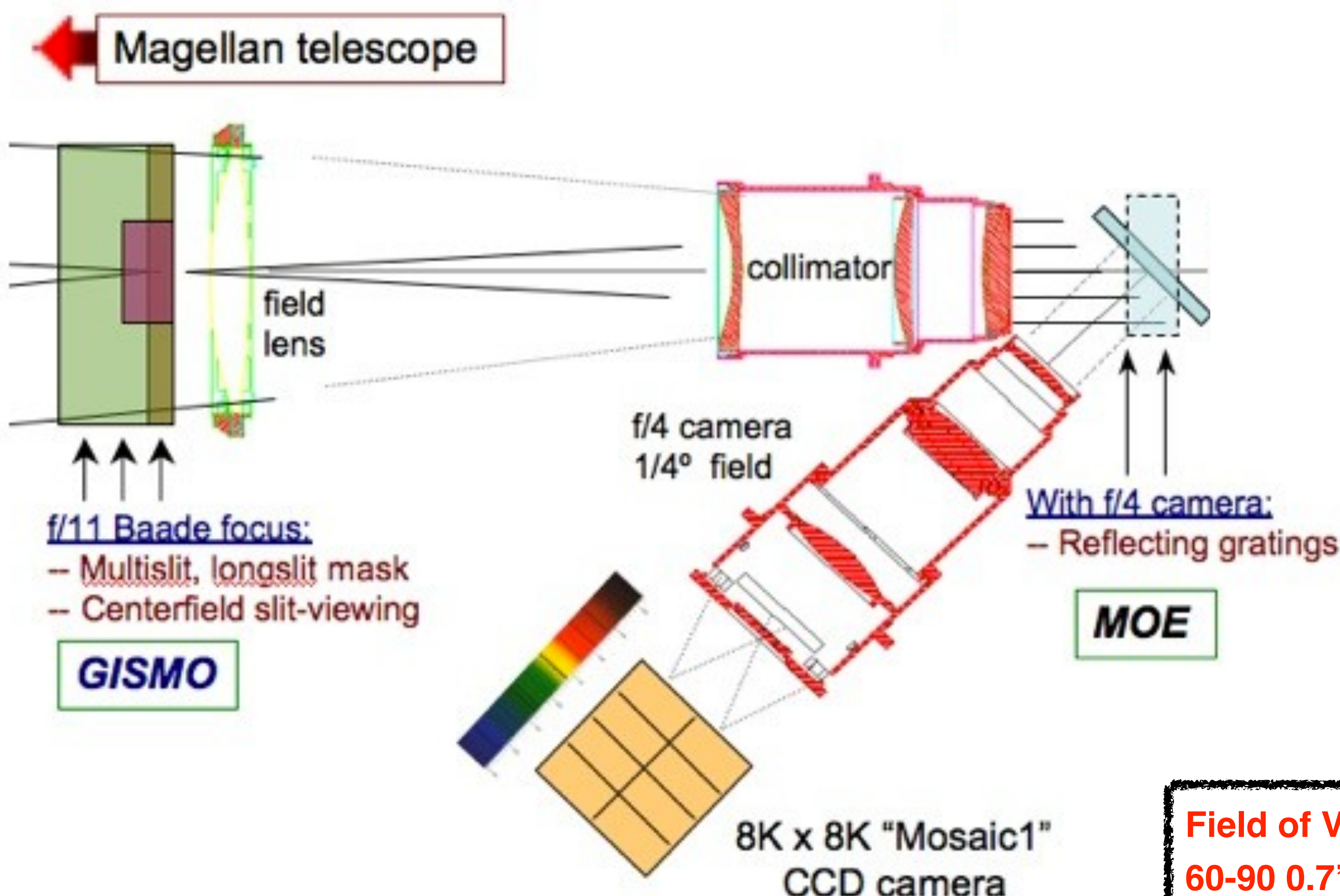
Magellan Telescopes
2 x 6.5m telescopes

Multi-Object Spectrograph



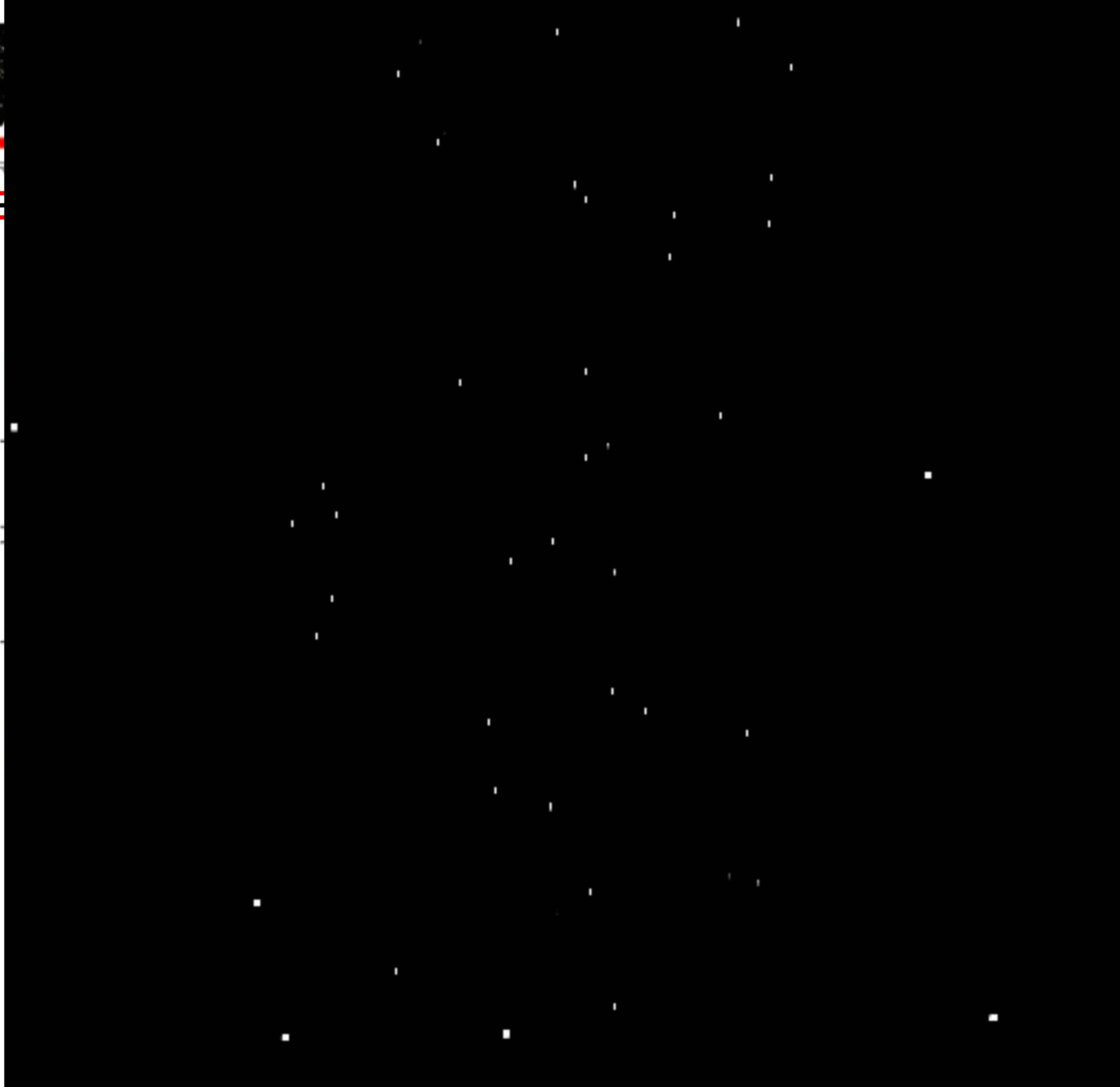
Inamori Magellan Areal Camera and Spectrograph (IMACS)

Magellan/IMACS



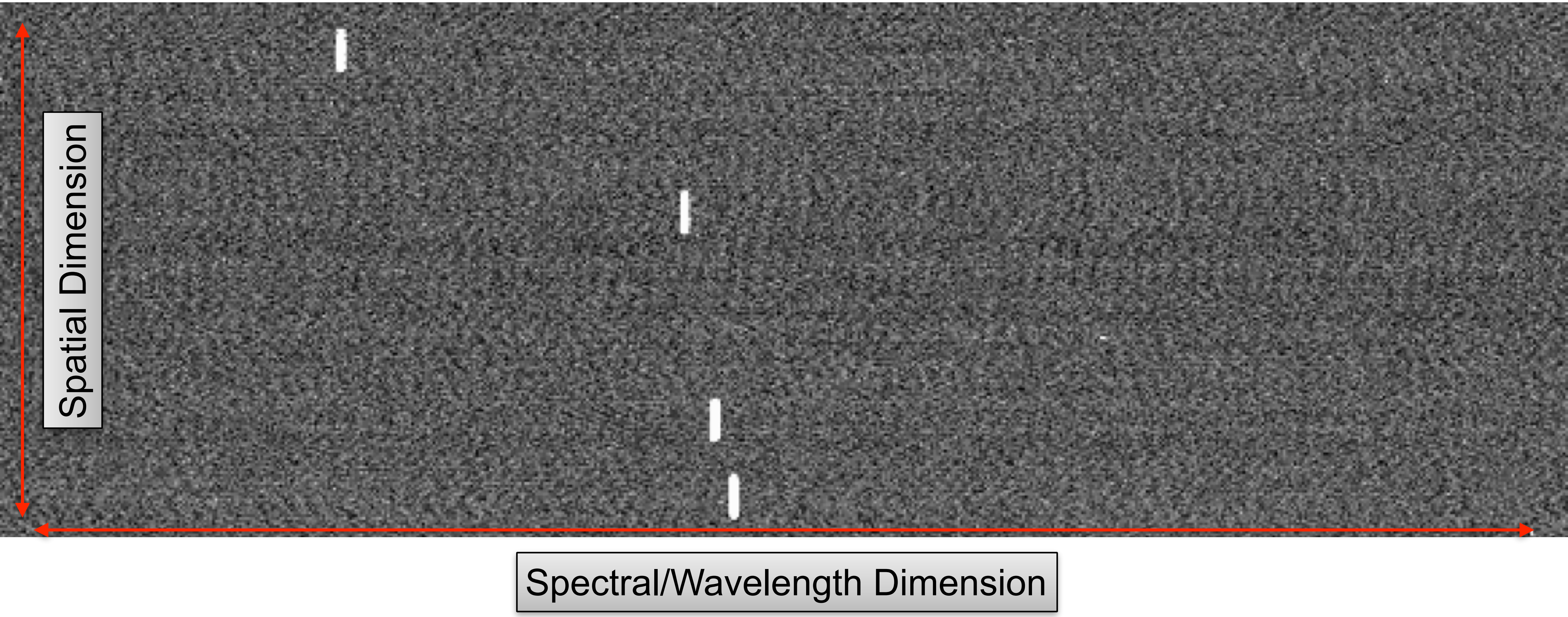
Field of View: 15' x 15'

60-90 0.7"x5.0" slitlets per mask

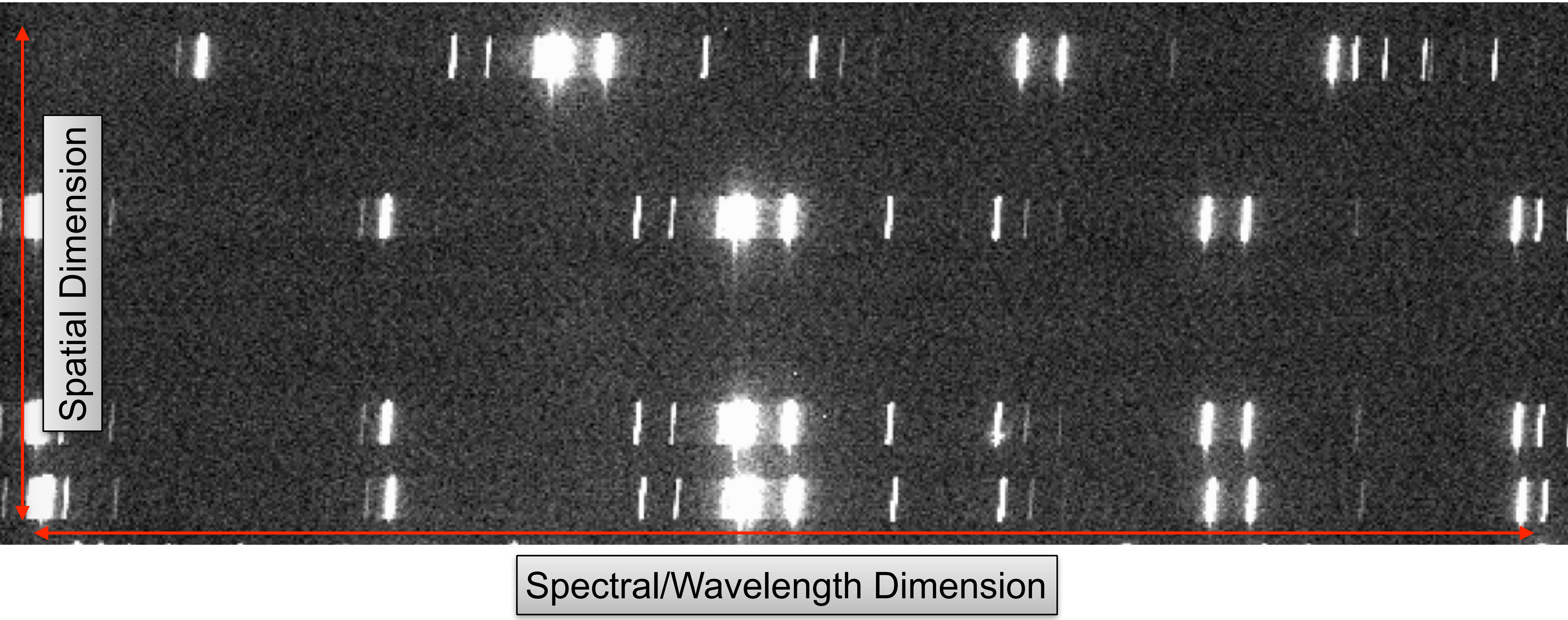


per mask

Slit Mask Image

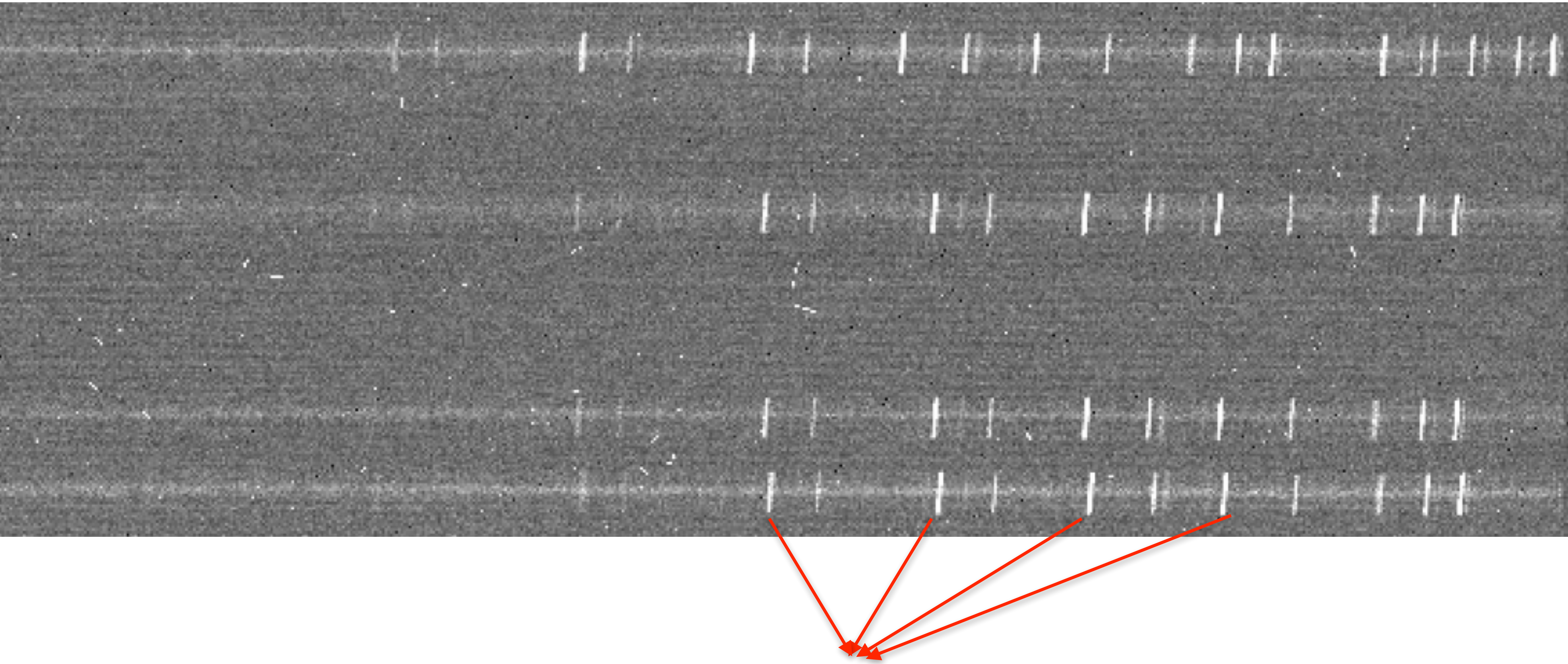


Wavelength Calibration Frame



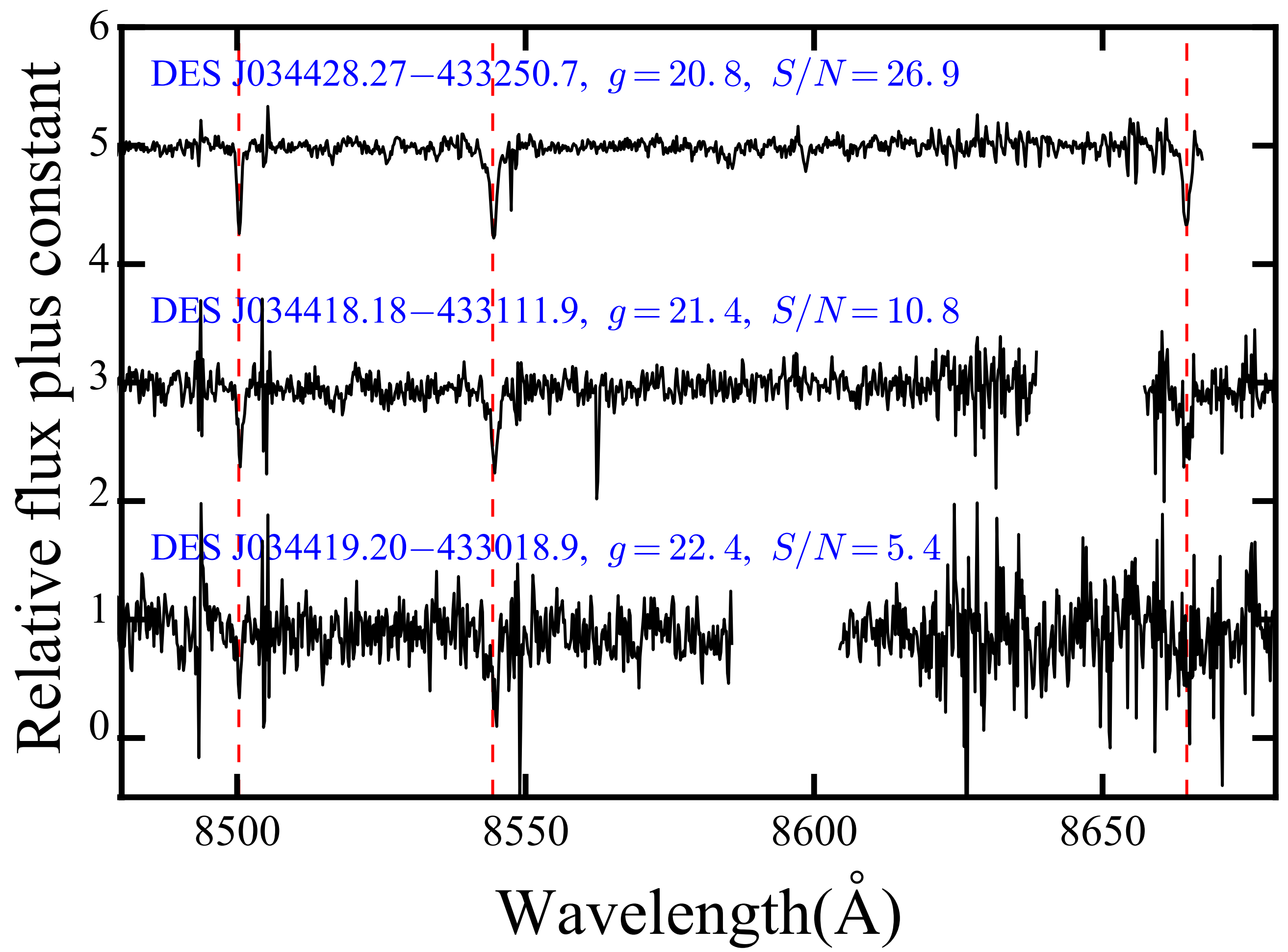
Atomic emission lines from arc lamps

2D Stellar Spectra



Emission lines from sky
Wavelength recalibration

1D Stellar Spectra



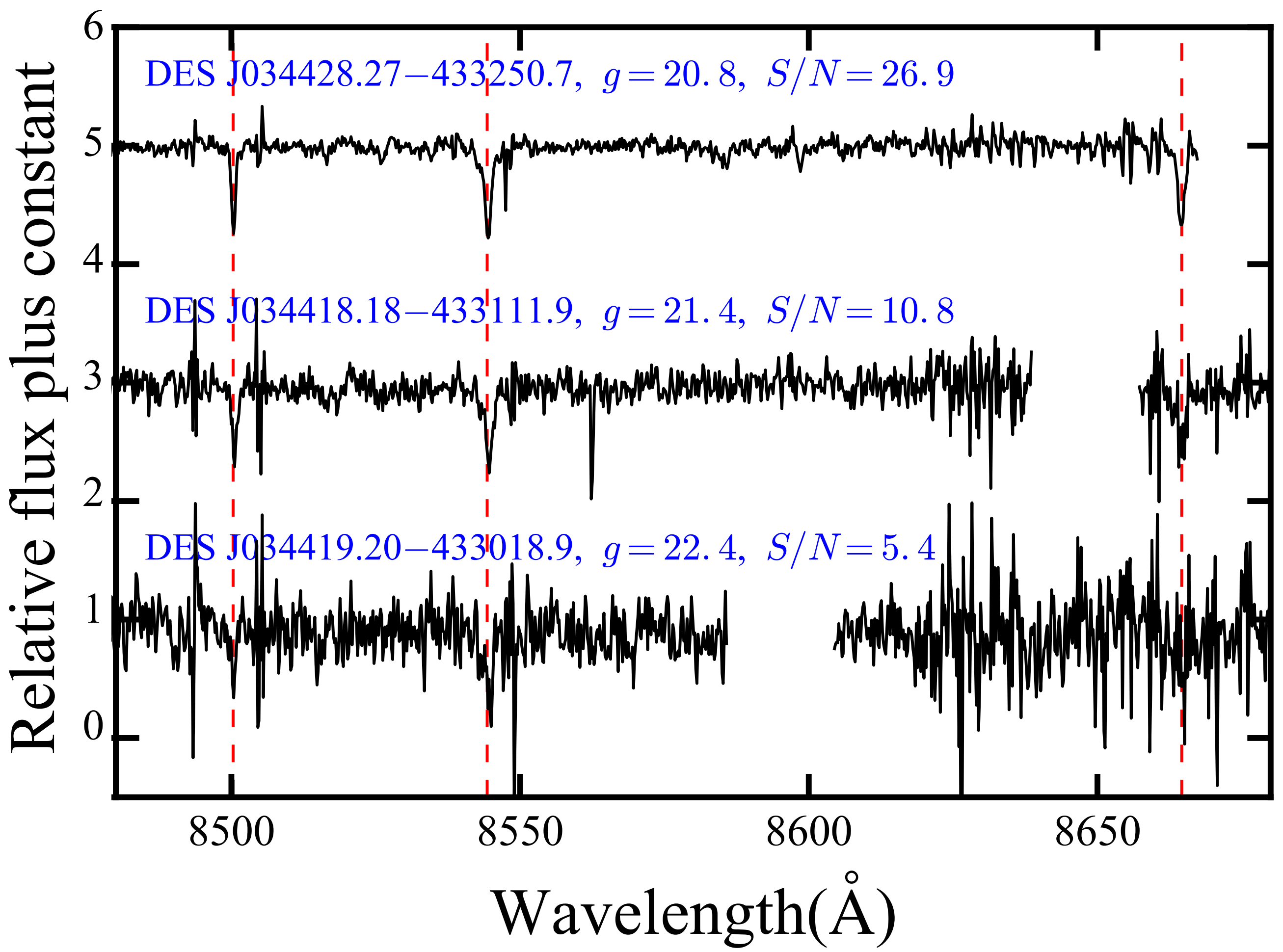
9 hr integration time

Li et al. (2017)

Ca Triplet

1D Stellar Spectra

Resolution: 30 km/s - width of the line
Accuracy: 1 km/s - 1/30 of line width



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Li et al. (2017)

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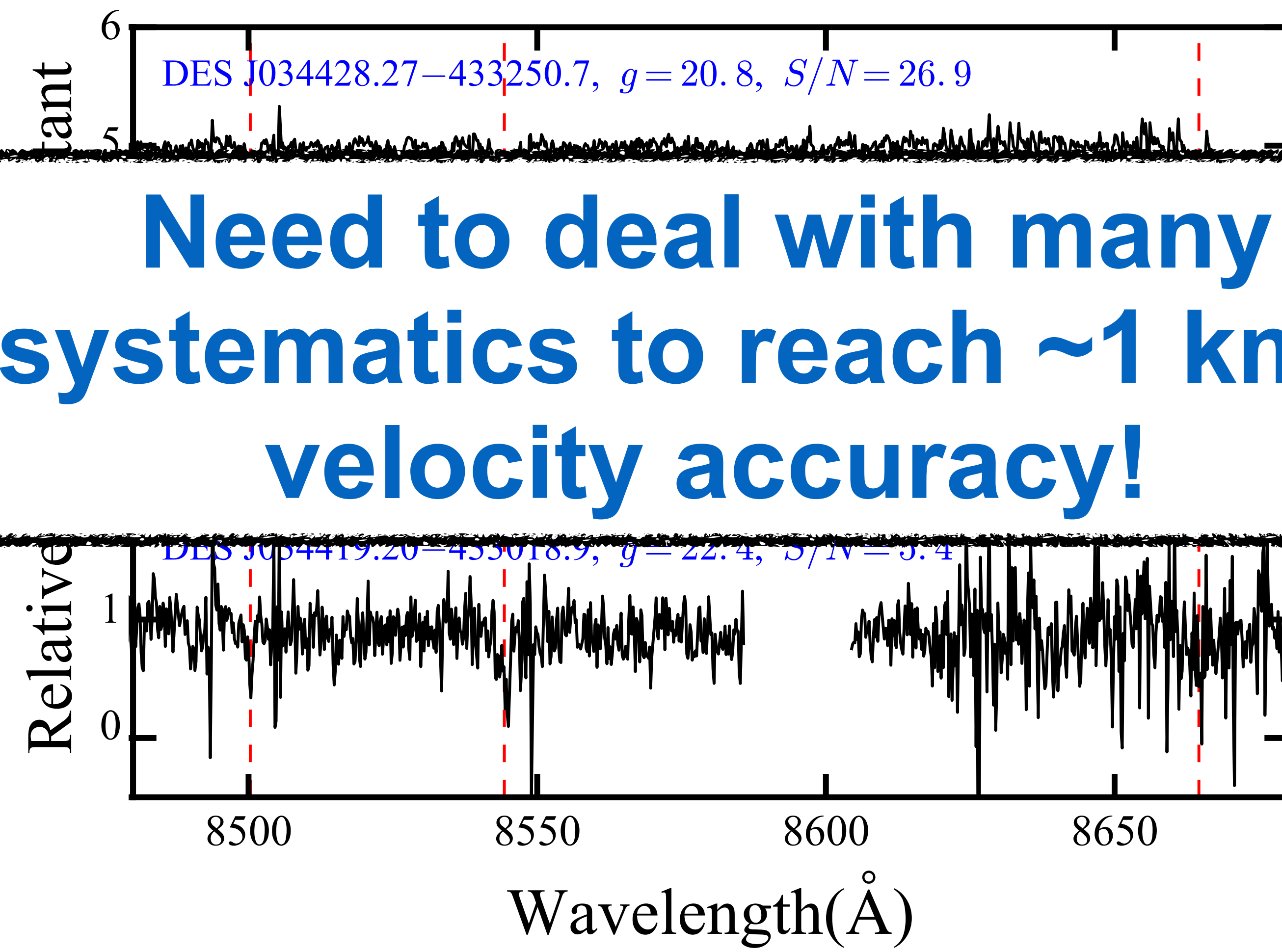


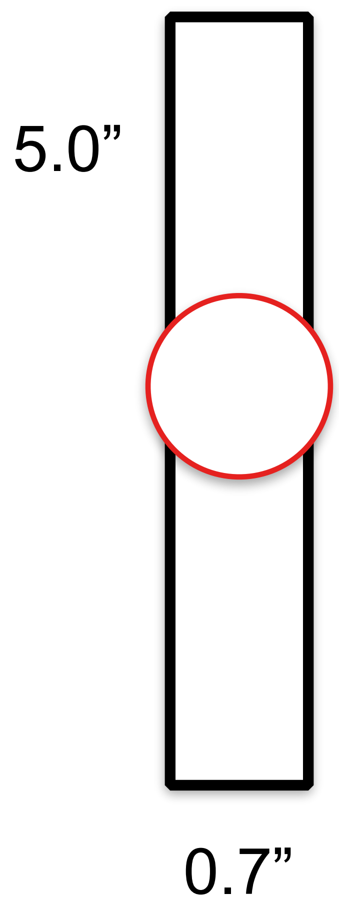
Need to deal with many systematics to reach ~1 km/s velocity accuracy!

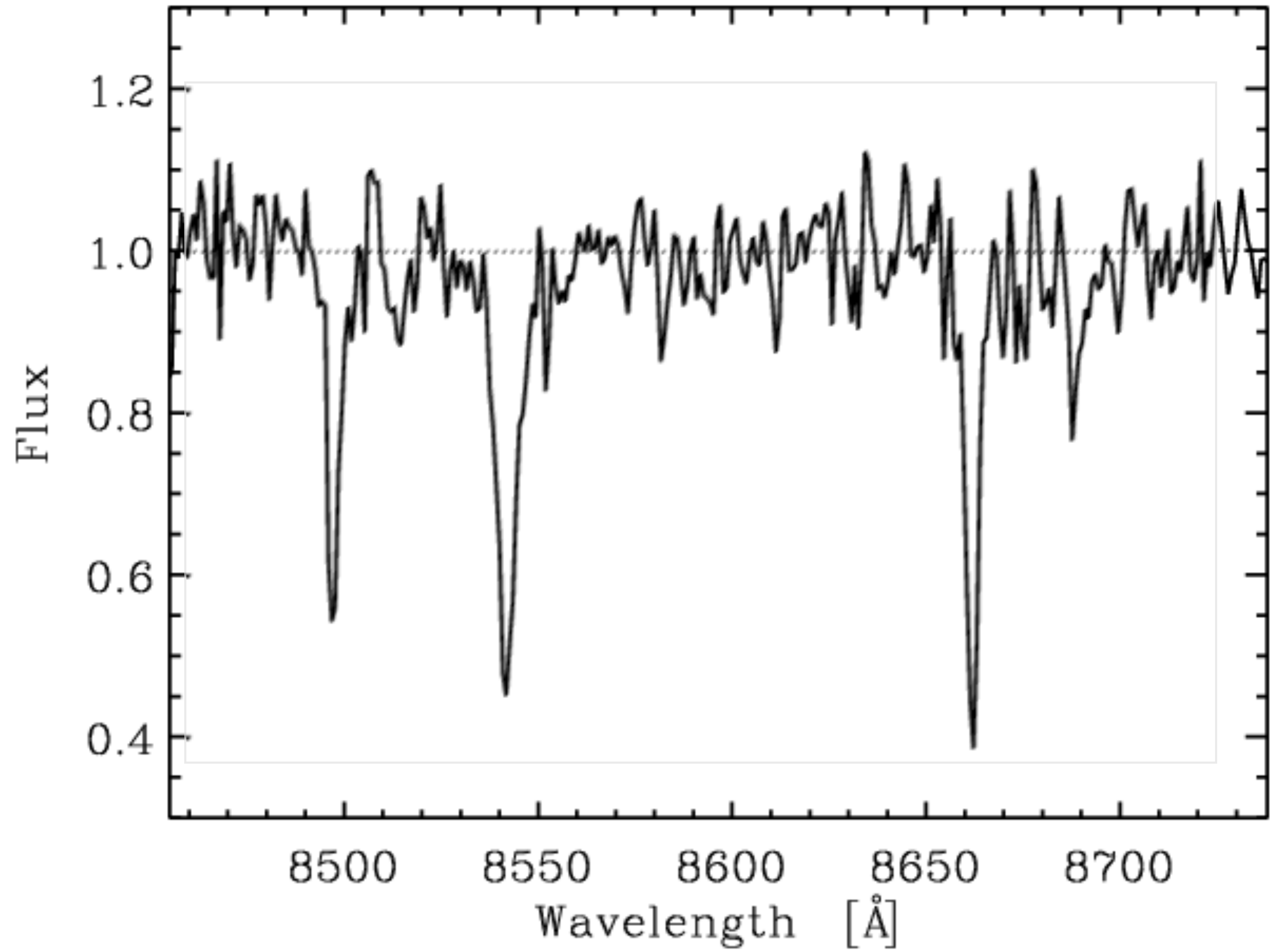
9 hr integration time

Li et al. (2017)

Ca Triplet

One example: slit mis-centering





Li et al. (2017)

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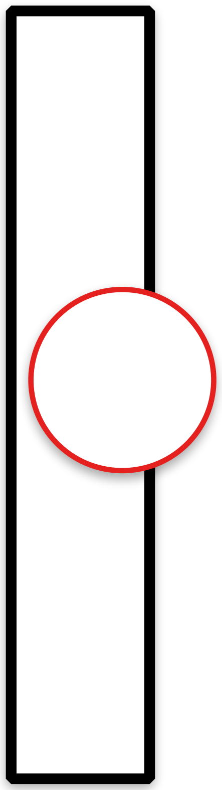

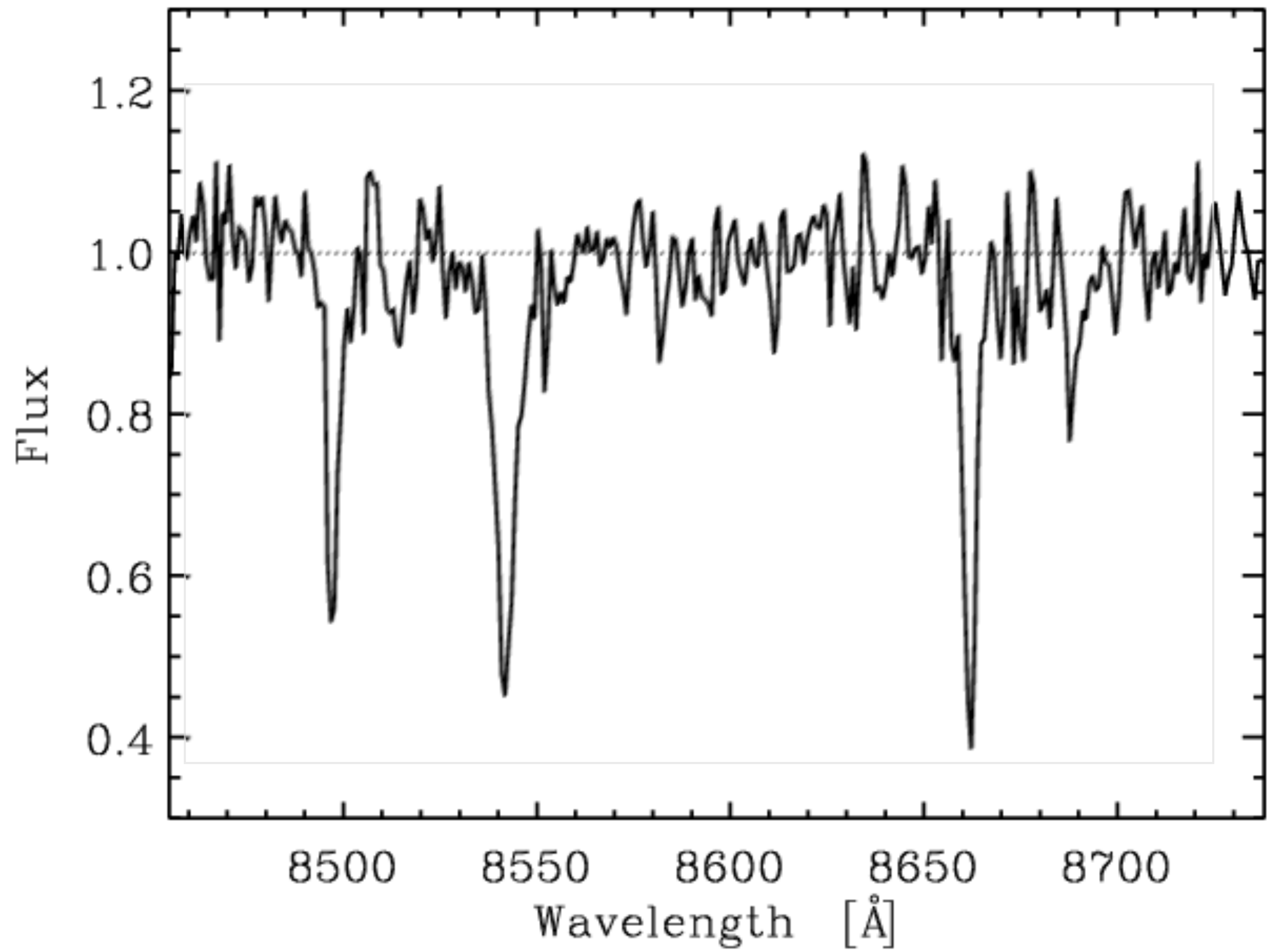

Li et al. (2017)

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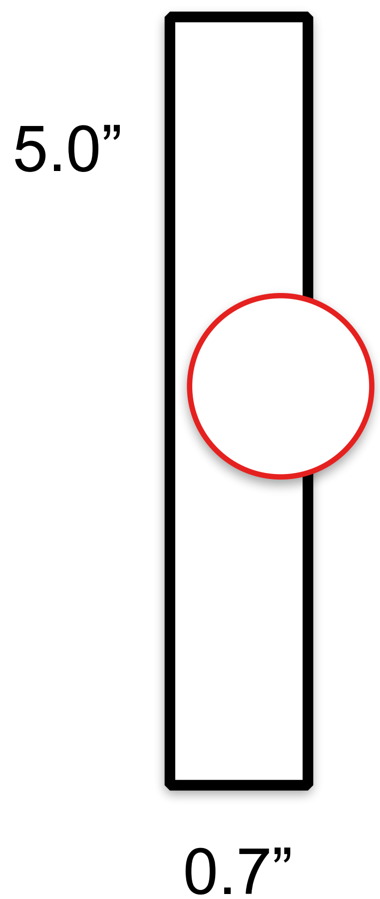

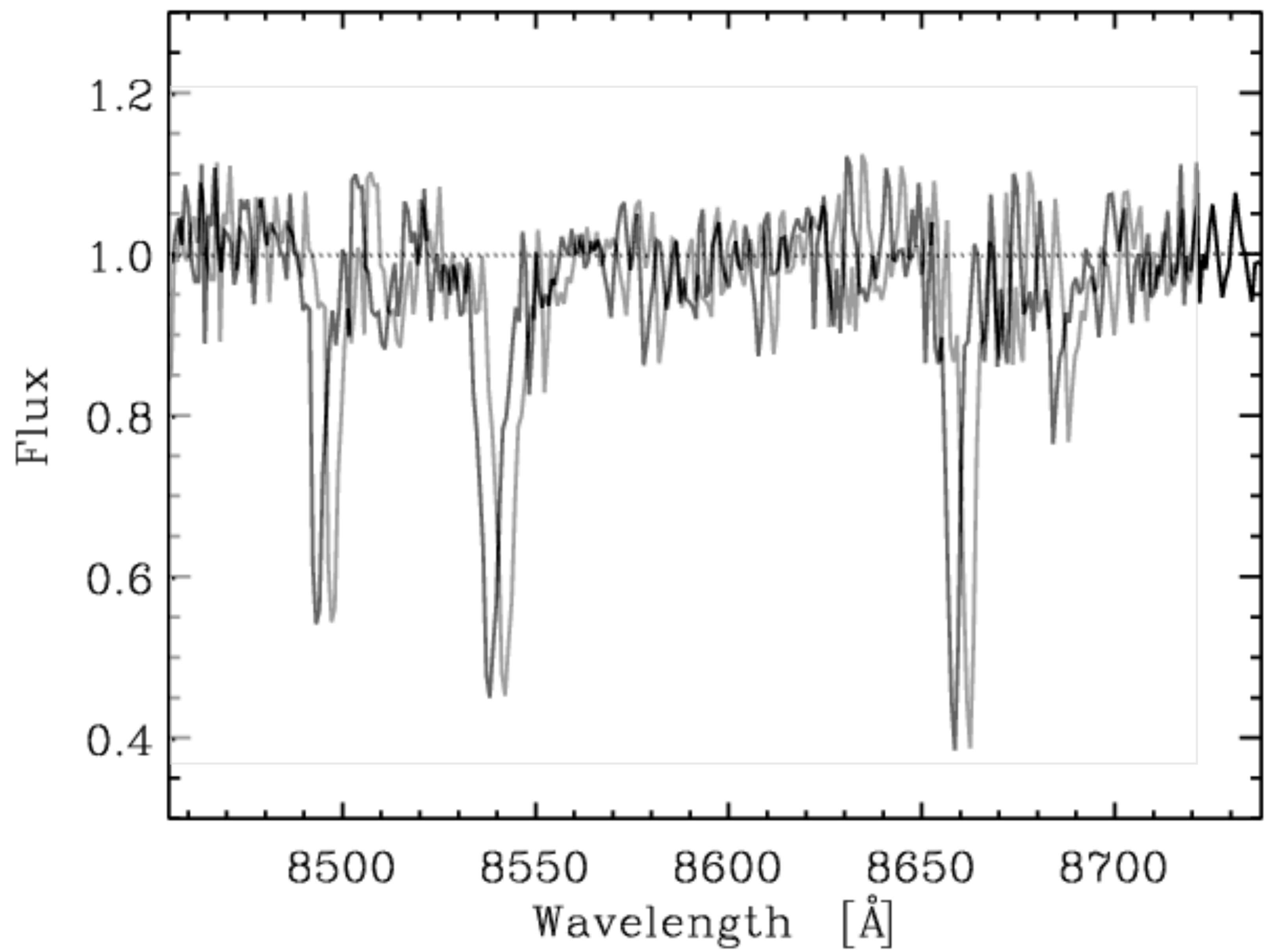

Li et al. (2017)

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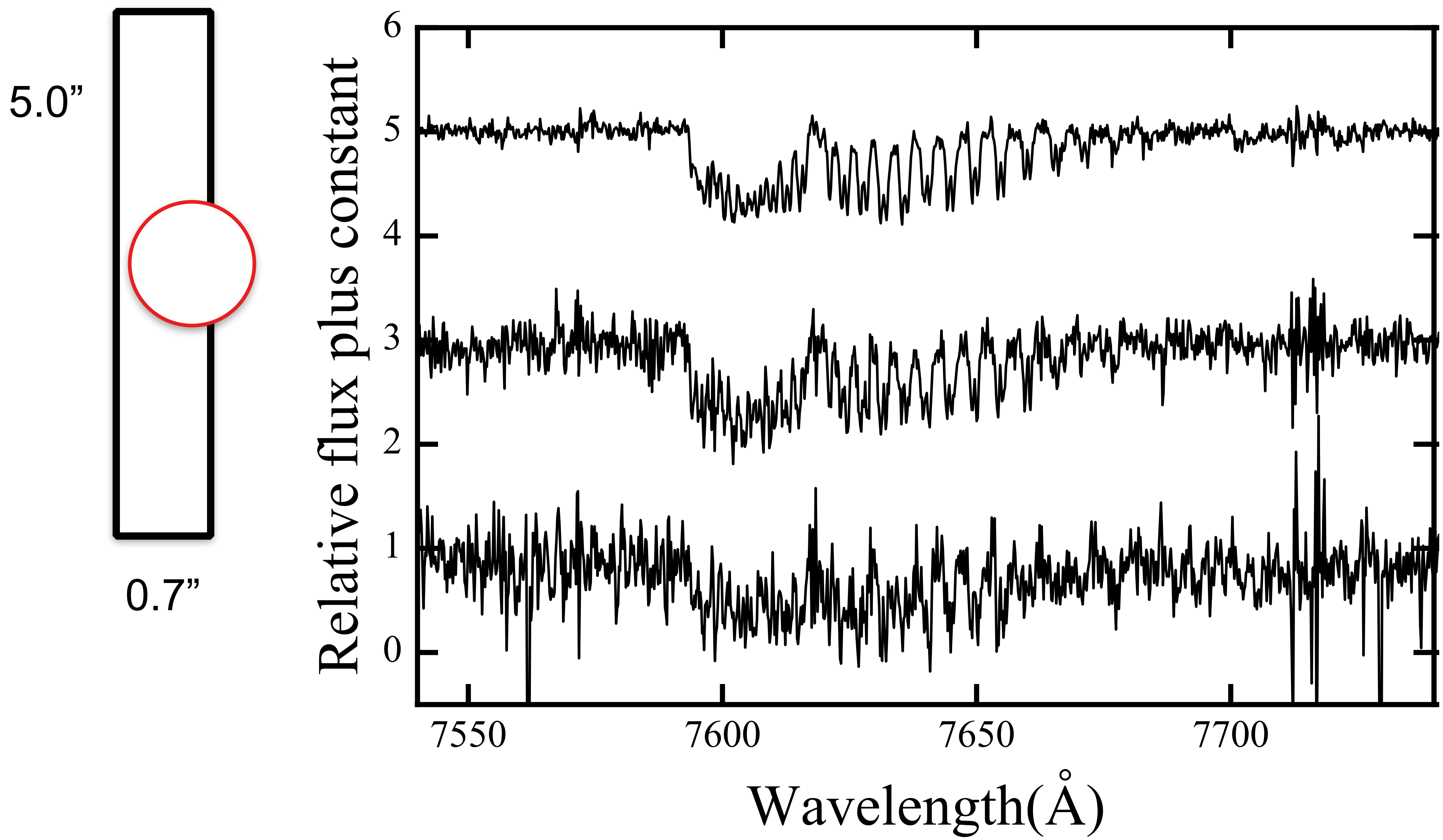

Li et al. (2017)

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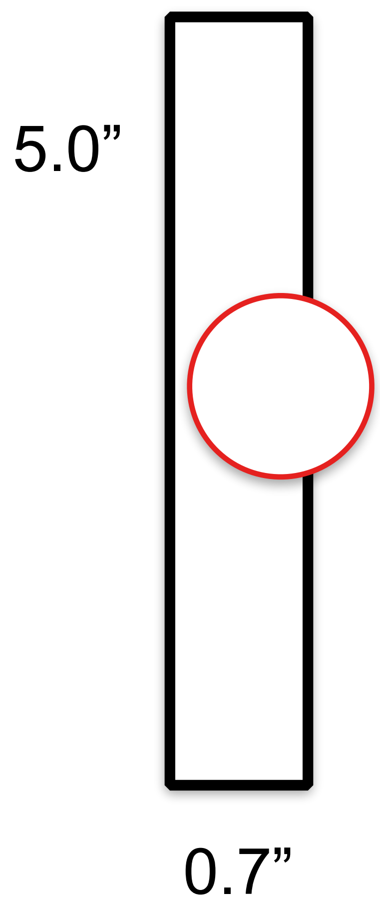
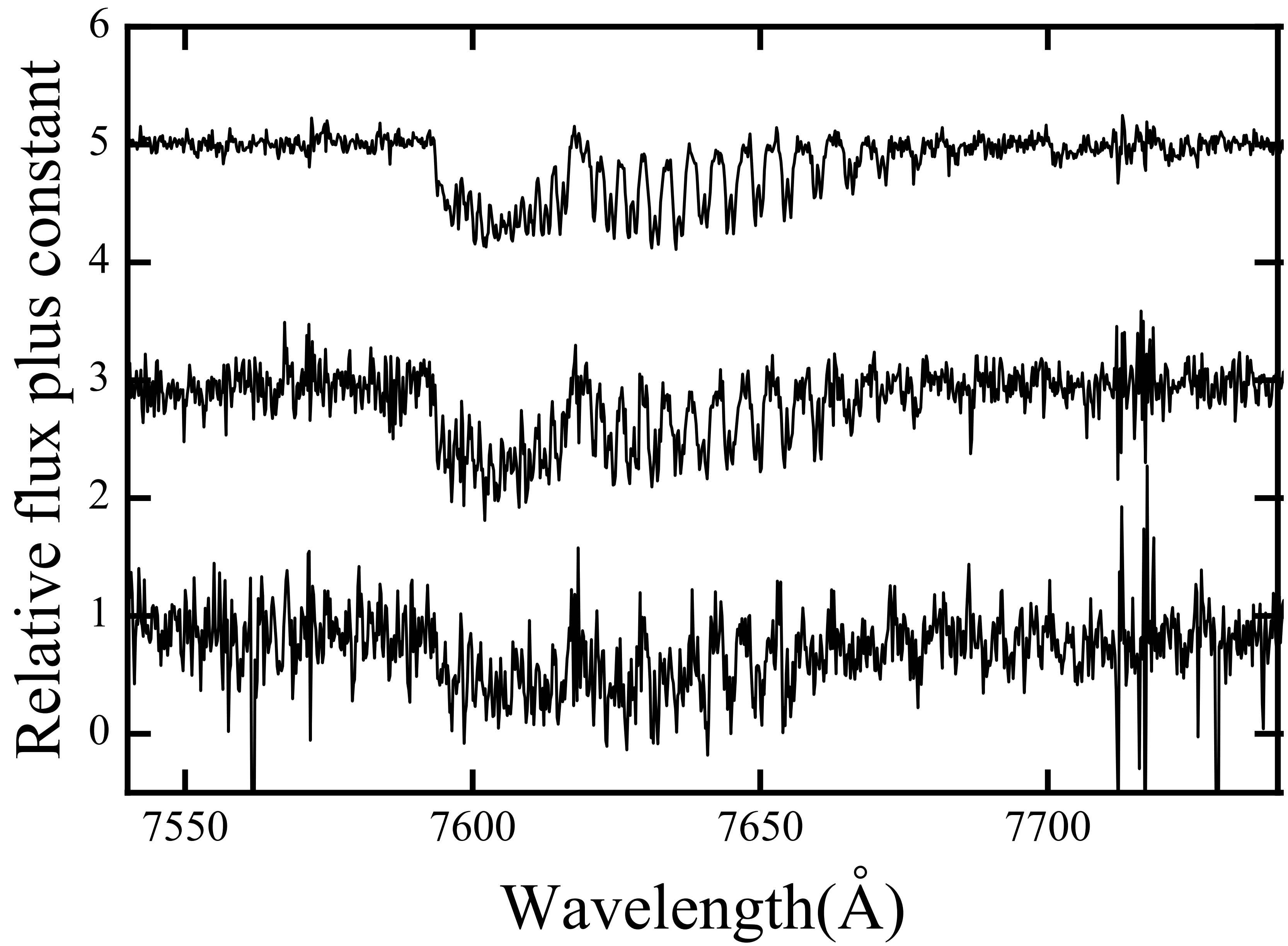
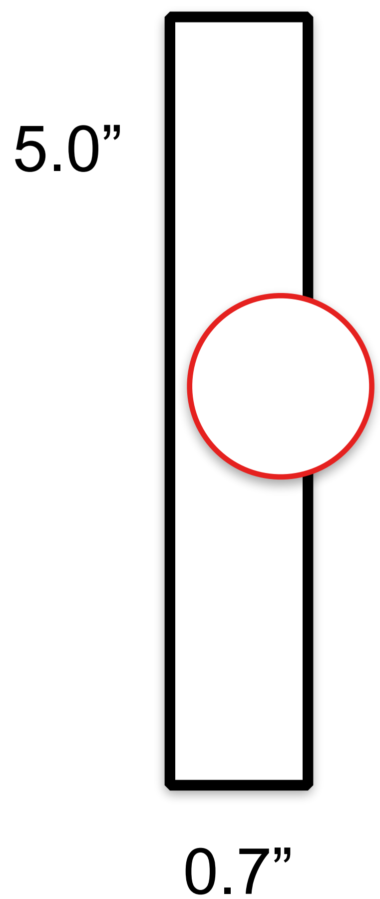


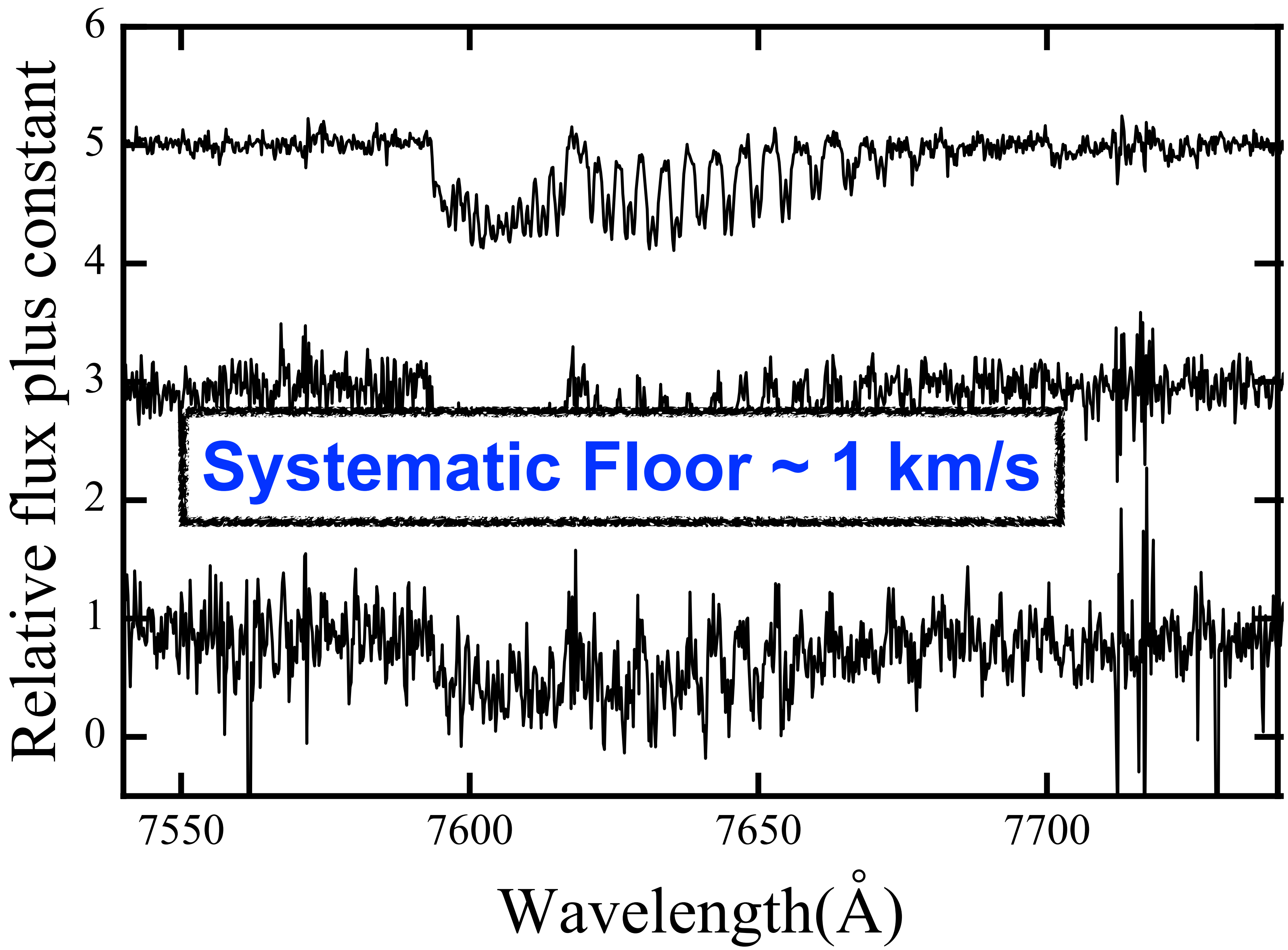


Li et al. (2017)

Fraunhofer A-band
- absorption from O_2 in Earth’s atmosphere

One example: slit mis-centering



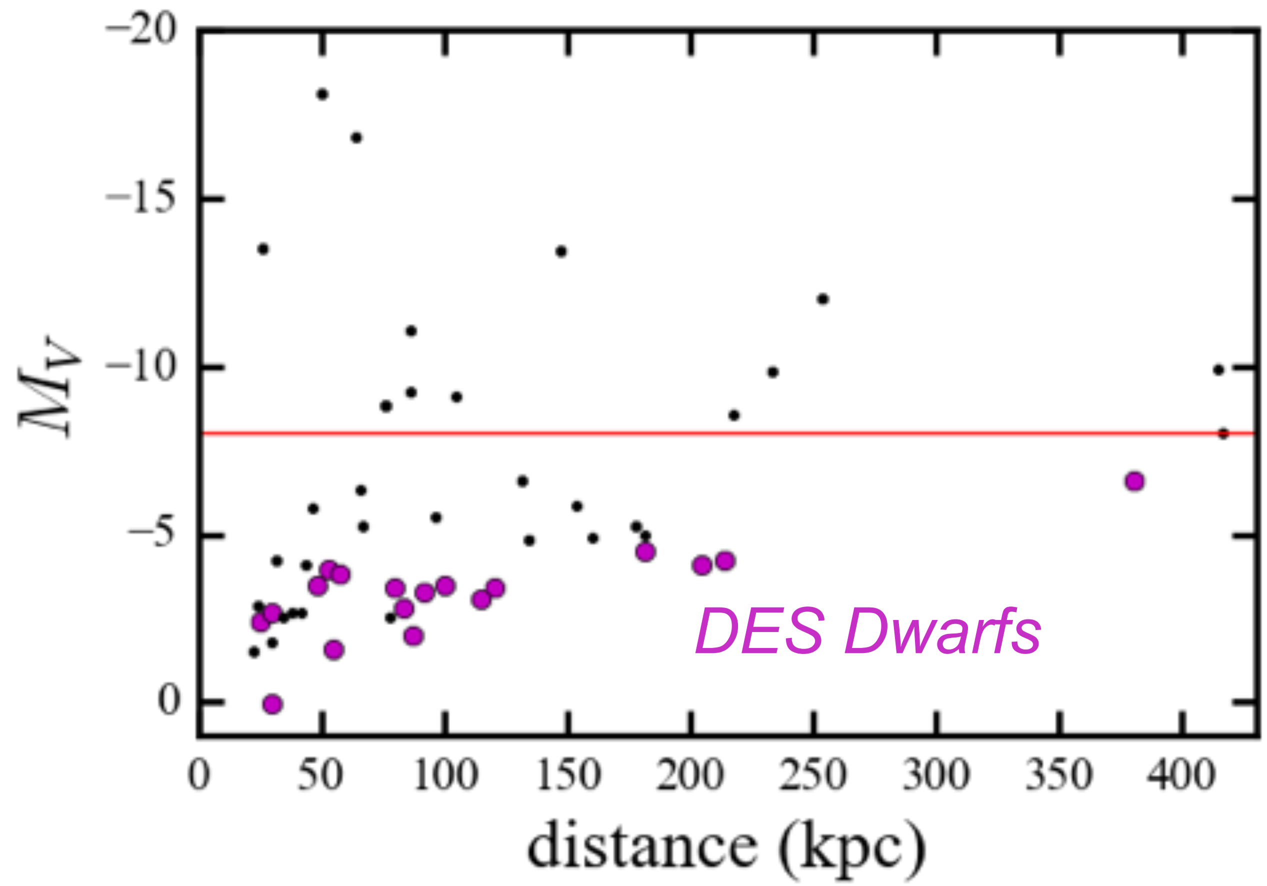


Li et al. (2017)

Fraunhofer A-band
- absorption from O_2 in Earth’s atmosphere

What? — Results

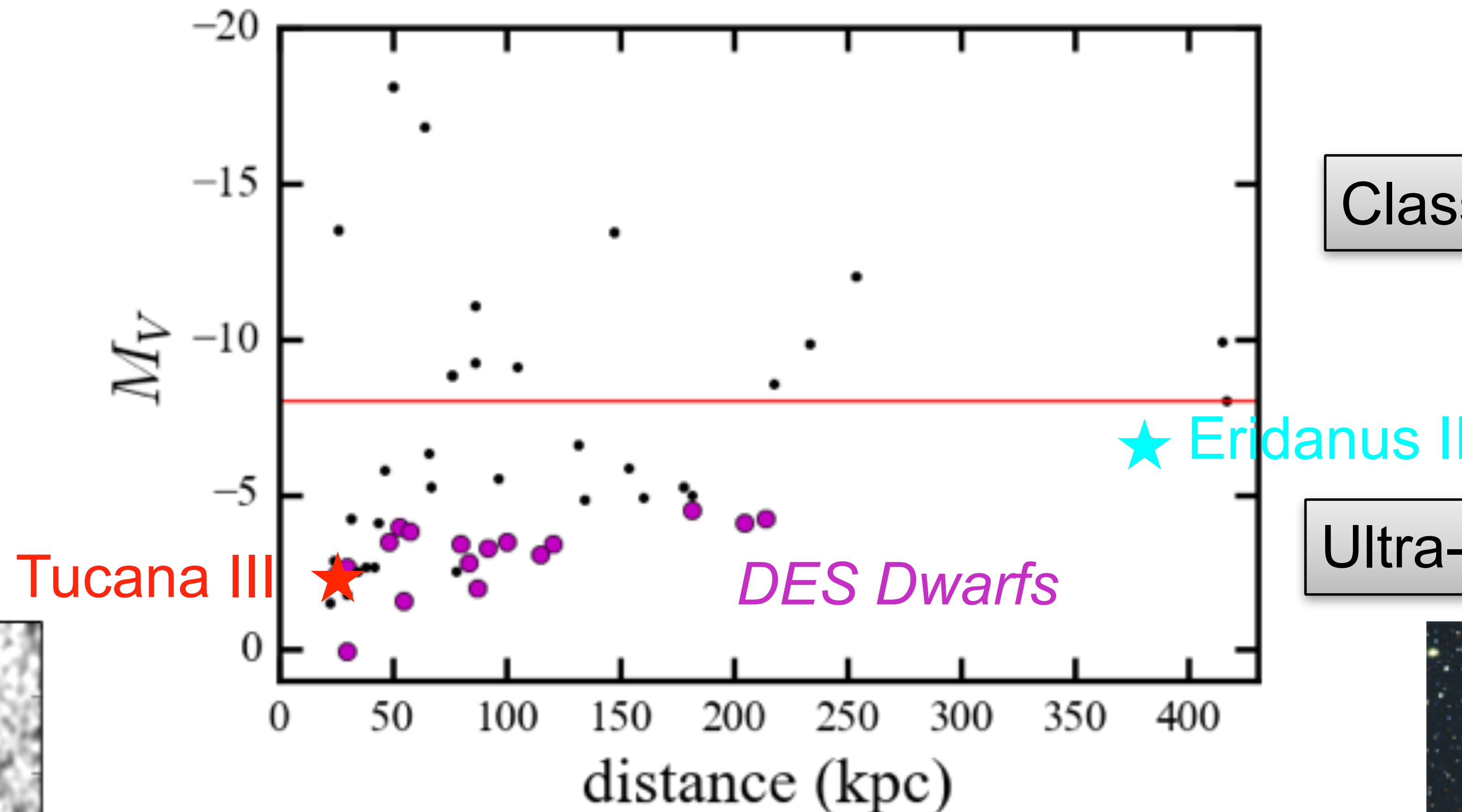
Results



Classical Dwarfs

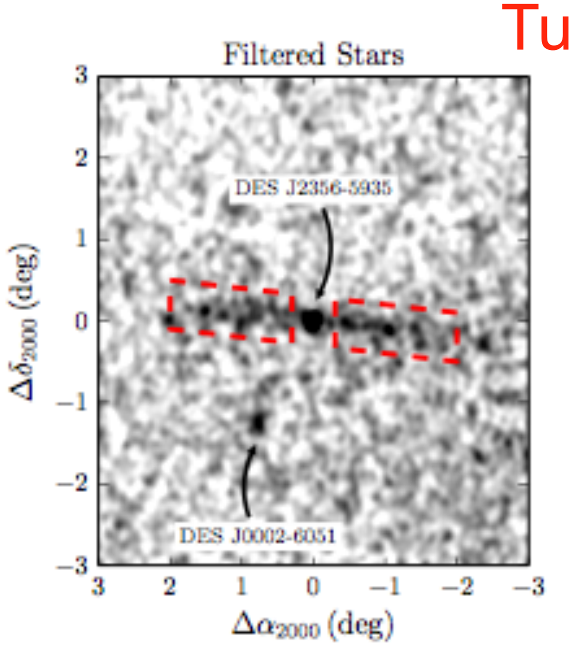
Ultra-Faint Dwarfs

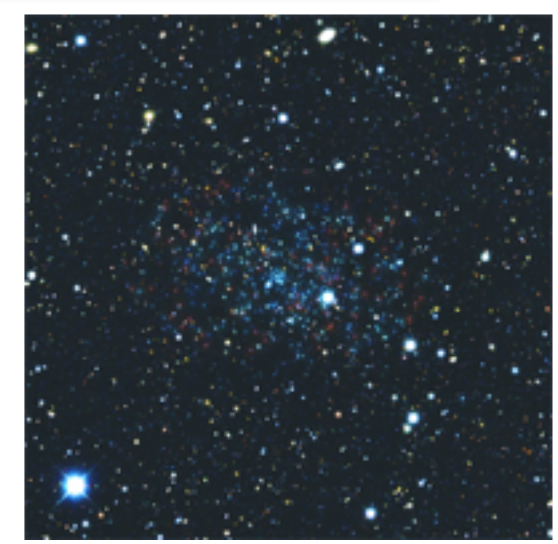
Results



Classical Dwarfs

Ultra-Faint Dwarfs





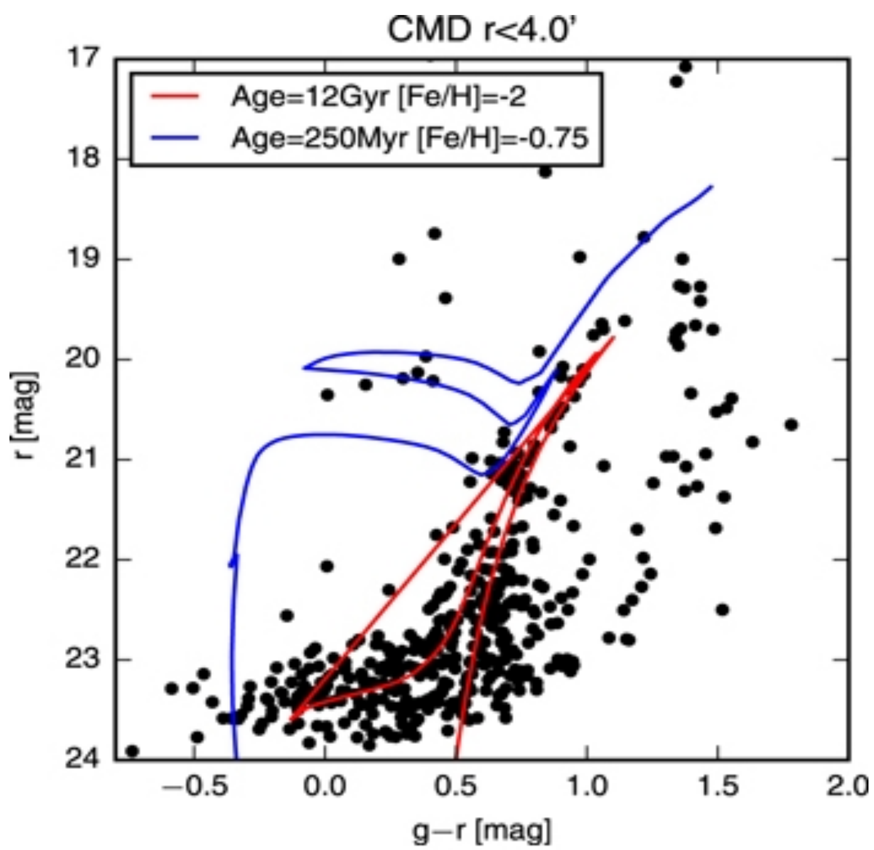
Nearest: Tucana III (25 kpc)
Simon, Li et al. (2017), arxiv: 1610.05301

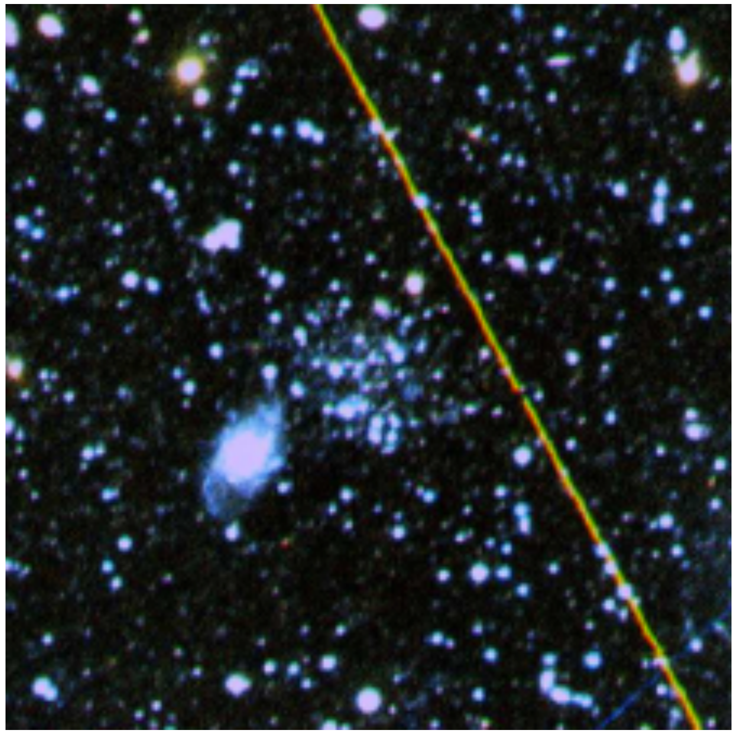
Farthest: Eridanus II (370 kpc)
Li et al. (2017), arxiv: 1611.05052

Eridanus II

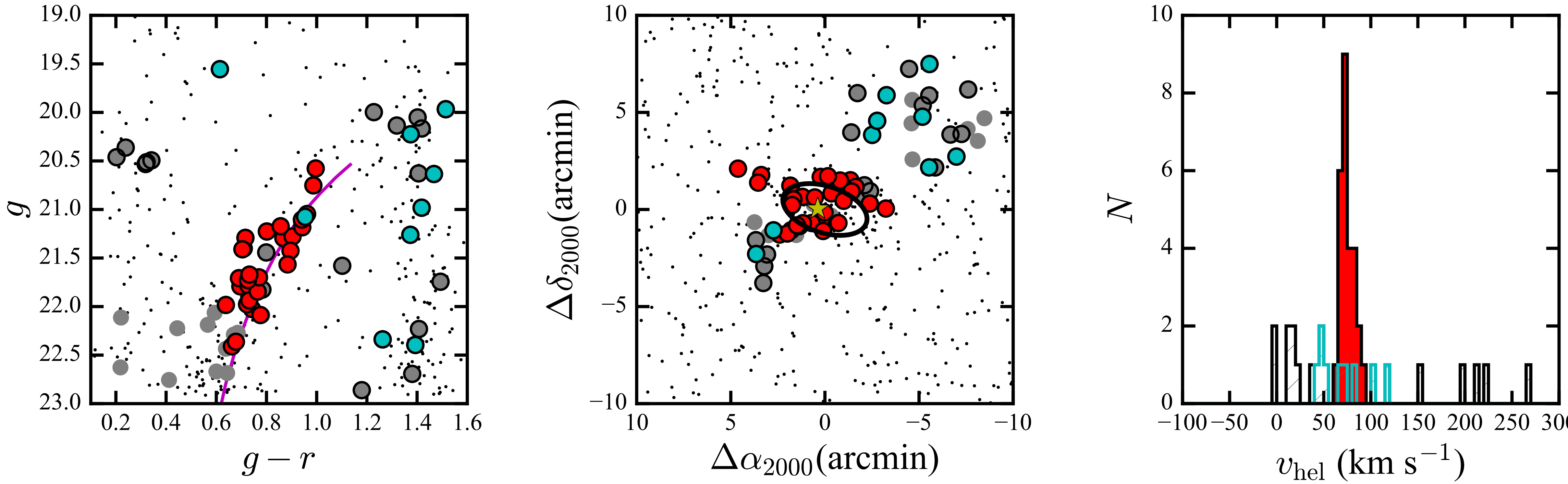
- Dwarf galaxy candidate discovered in DES Year 1 data
- Distant : ~370 kpc (beyond the virial radius of MW)
  - One of the farthest dwarf galaxies in Milky Way
- Smallest star-forming galaxy?
  - Important for understanding the quenching of dwarf galaxies
- Smallest galaxy possessing a central star cluster
  - Provide constraints on MACHO dark matter

Koposov et al. (2015)
Bechtol et al. (2015)
Crnojevic et al. (2016)





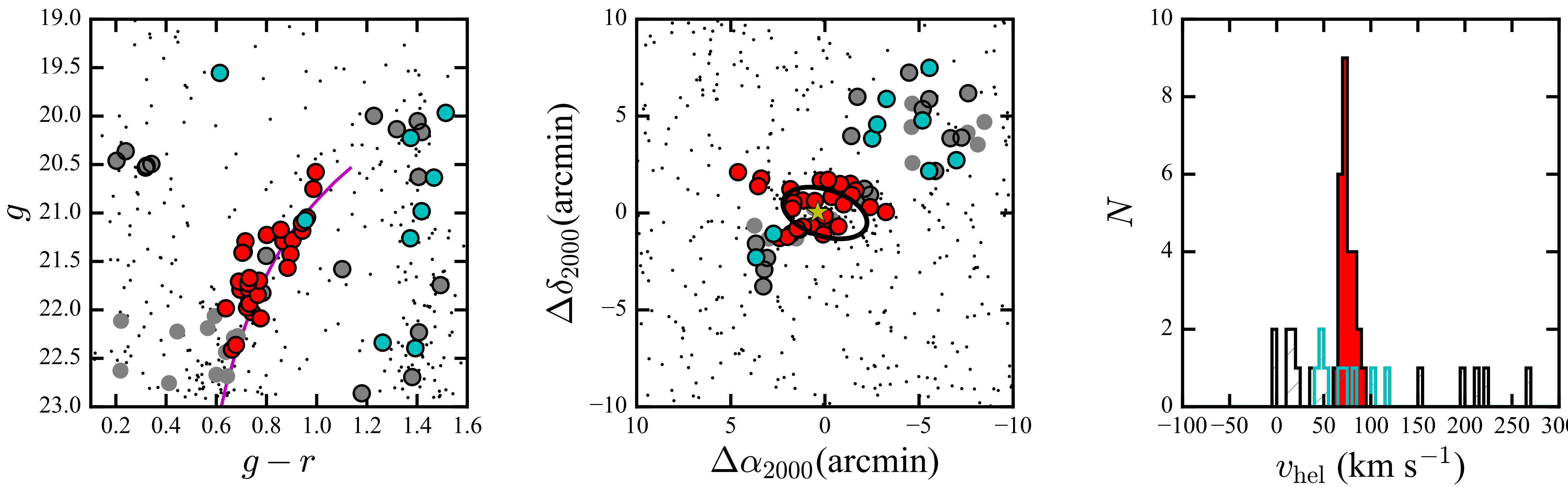
Eridanus II: Membership



Li et al. (2017)

28 members identified

Eridanus II: Dark Matter Content



Li et al. (2017)

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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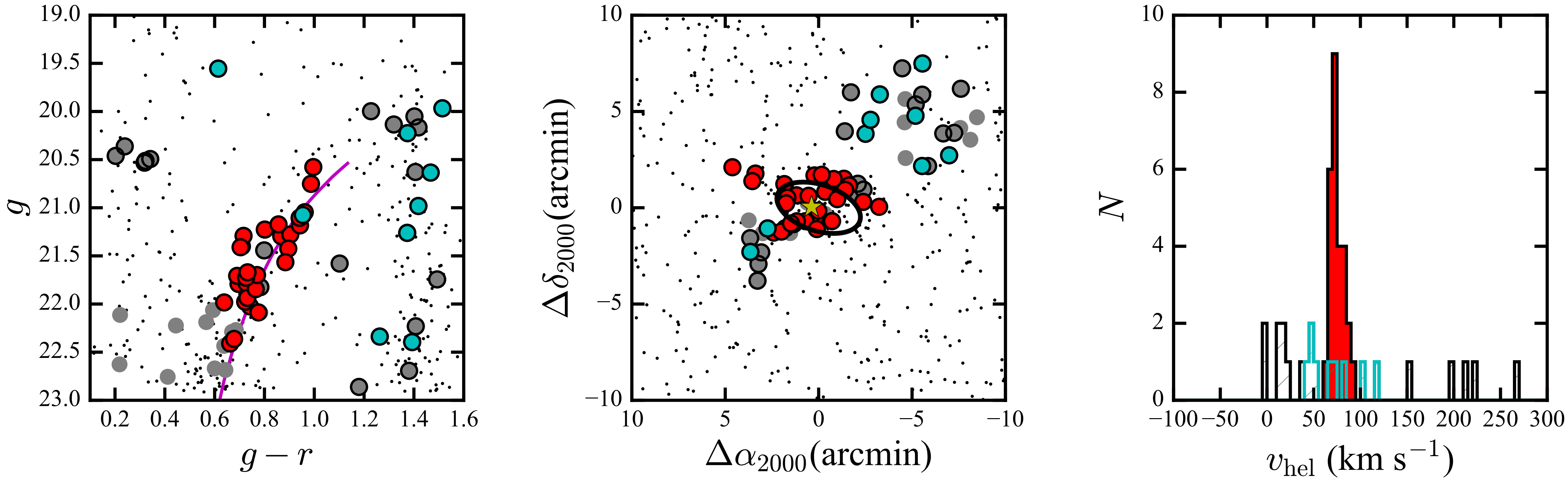

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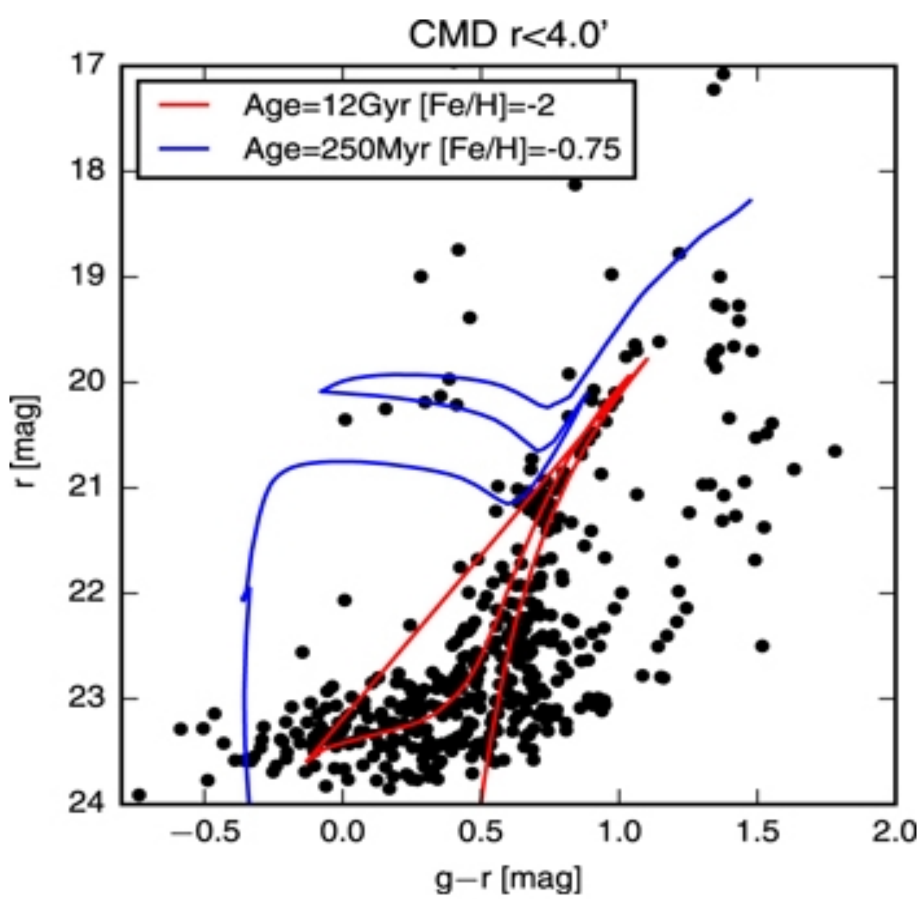
Eridanus II is dark matter dominated dwarf galaxy

Eridanus II: Star Formation

- **Smallest star-forming galaxy?**



Koposov et al. (2015)

Eridanus II: Star Formation

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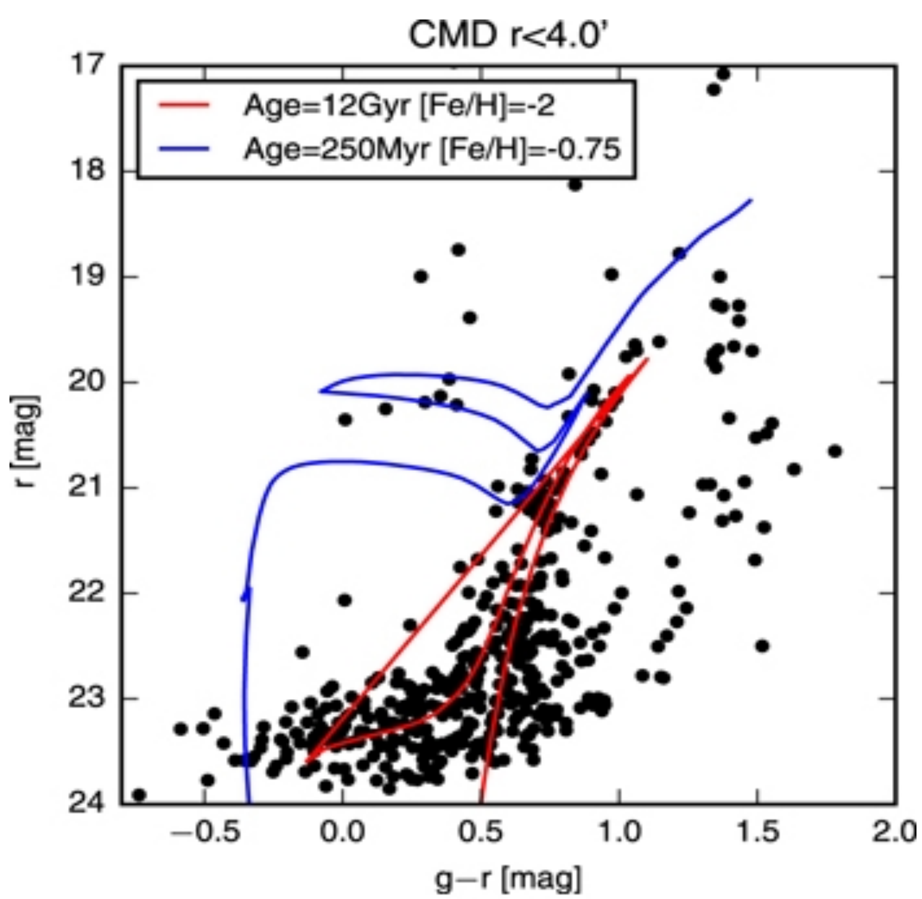
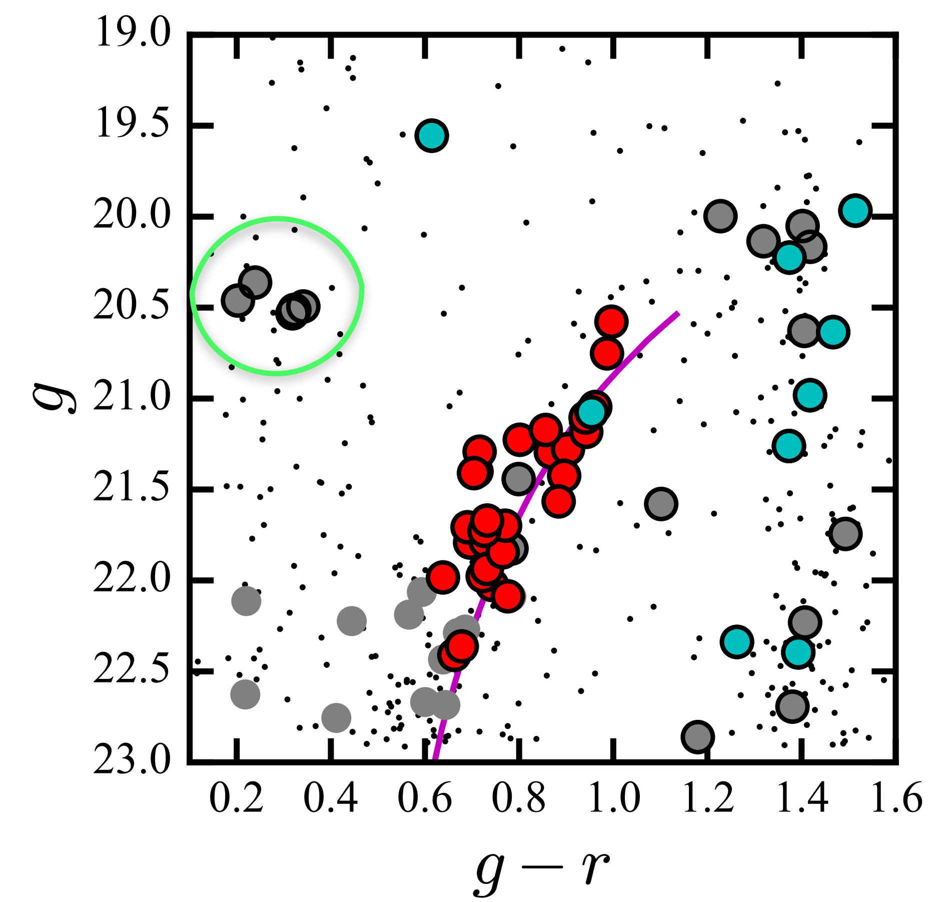


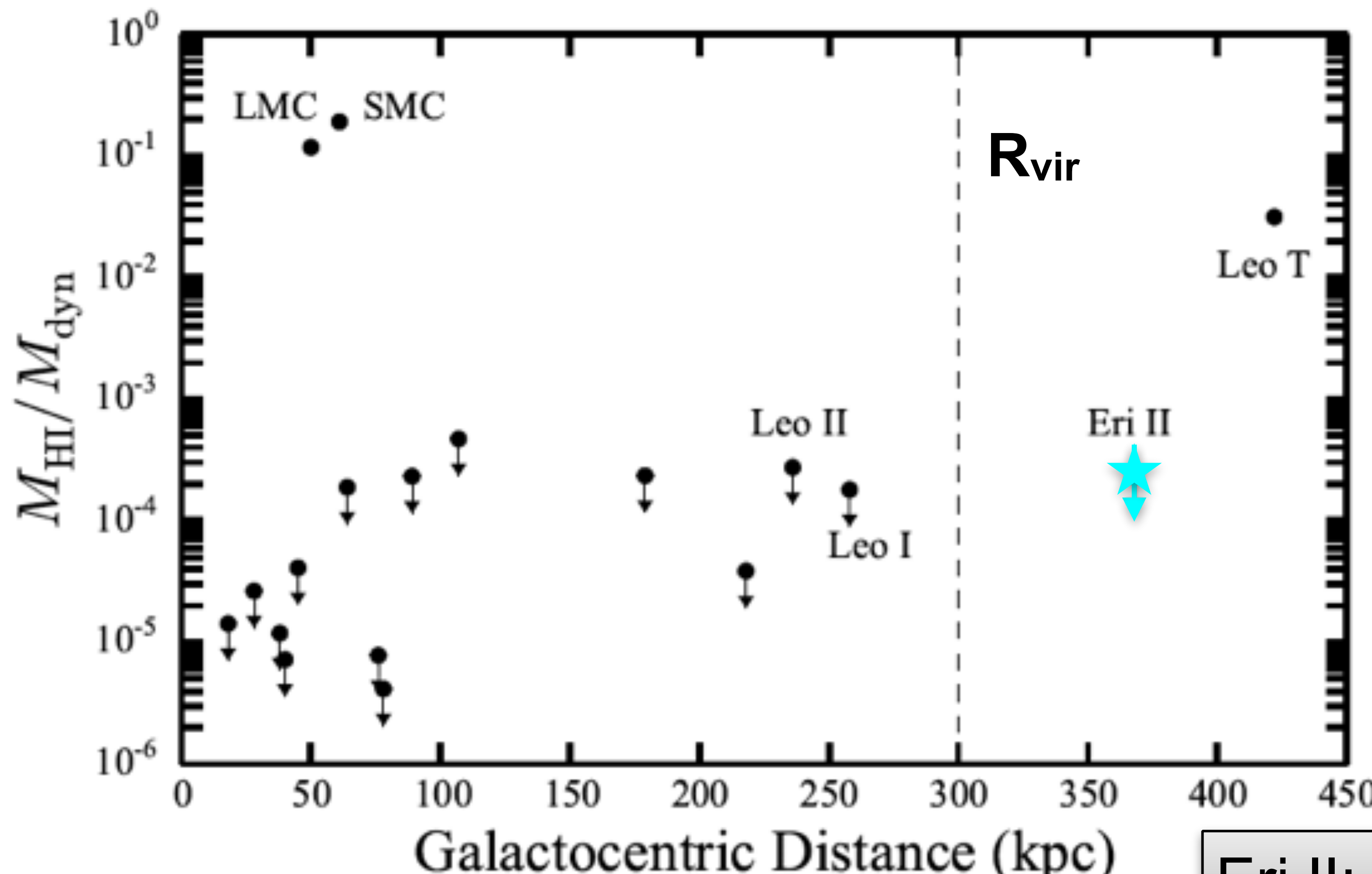
Koposov et al. (2015)

- **No sign of recently forming stars**



Li et al. (2017)

Eridanus II: Star Formation



Eri II: No hydrogen gas detected!

Eri II:
370 kpc
gas-poor
no forming stars
v_{GSR} = -67 km/s

Leo T:
420 kpc
gas-rich
young stars
v_{GSR} = -58 km/s

Li et al. (2017)

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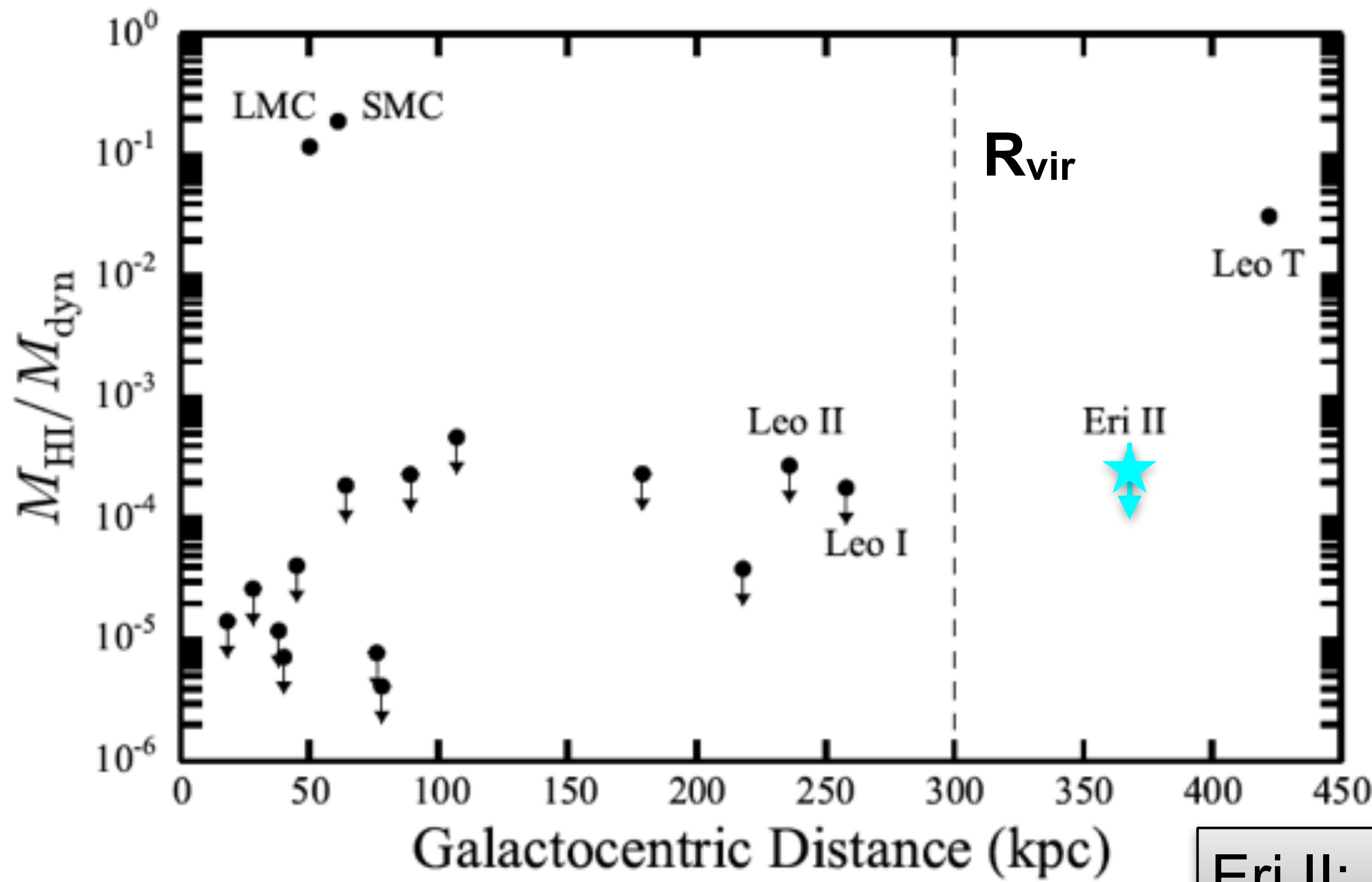

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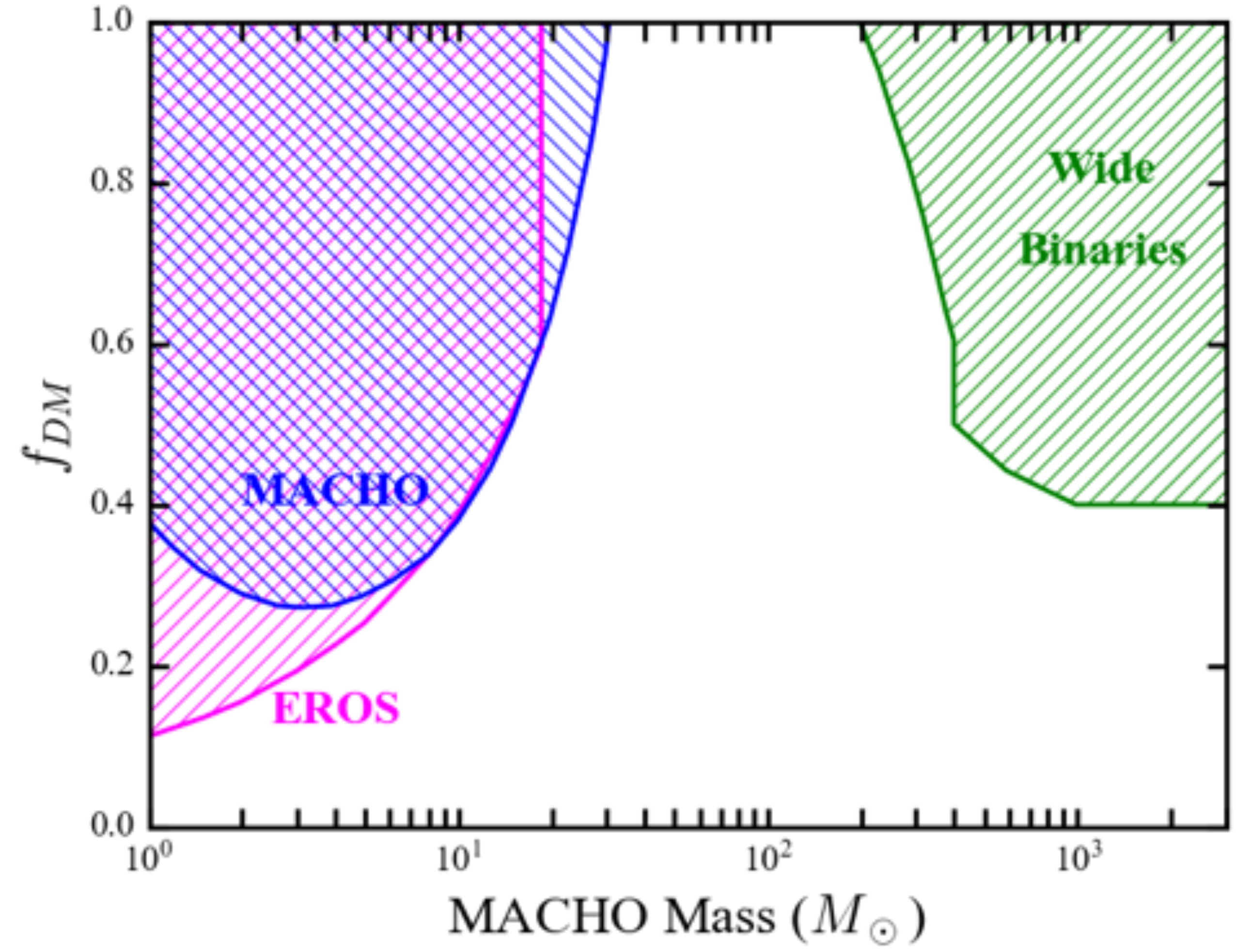
Need proper motion to derive orbit!
Follow-up with Hubble Space Telescope

Li et al. (2017)

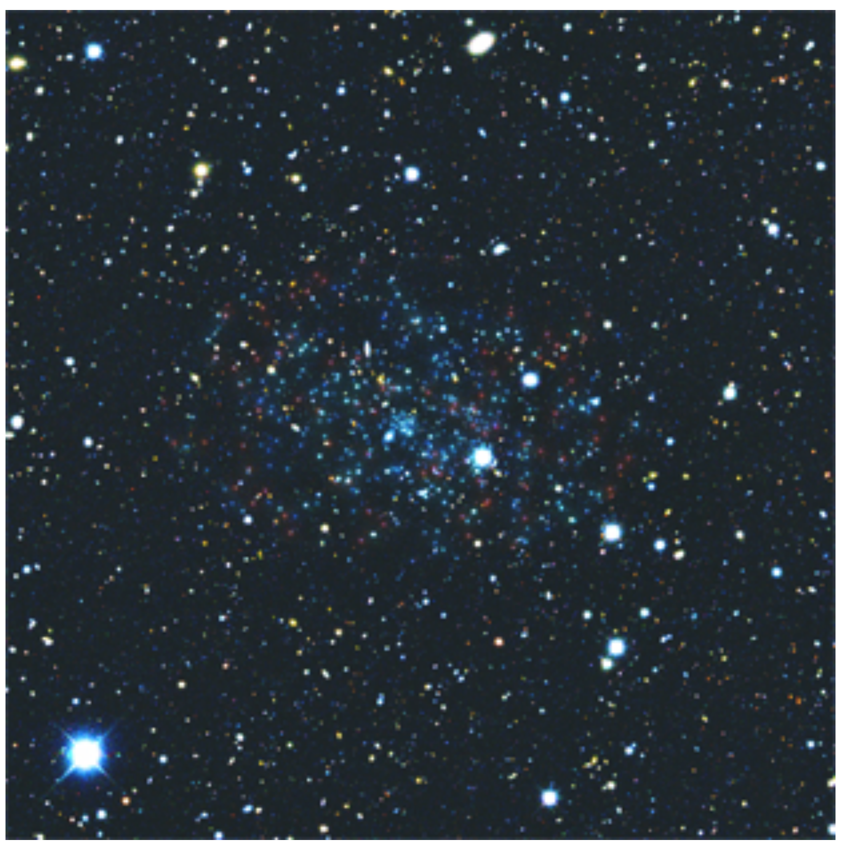
MACHO constraints

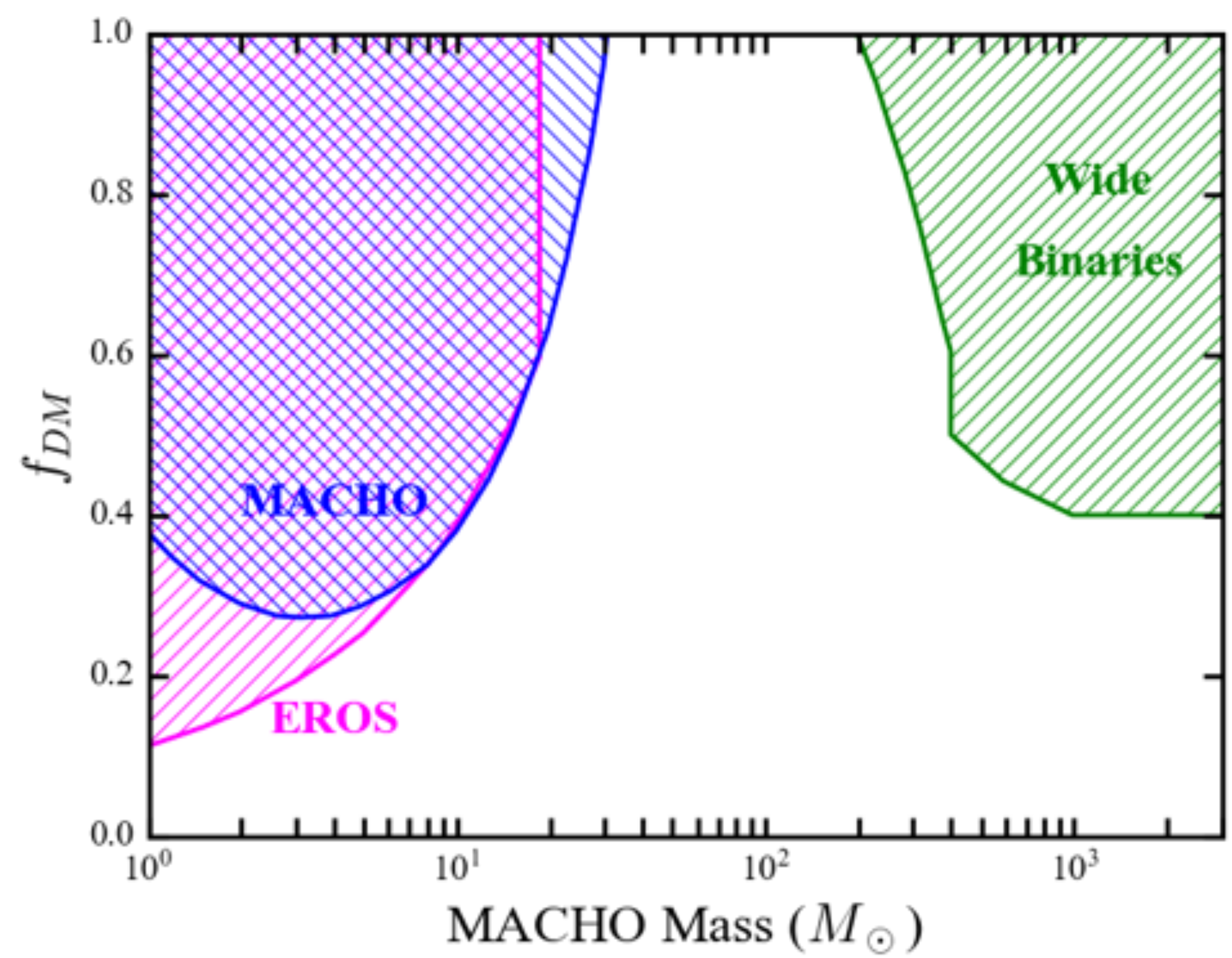


MACHO constraints

- Eri II possesses a central star cluster
- Brandt (2016): MACHO will dynamically heat the cluster until it dissolves
- The survival of the central cluster place strong constrains on MACHO abundance

DECam/DES





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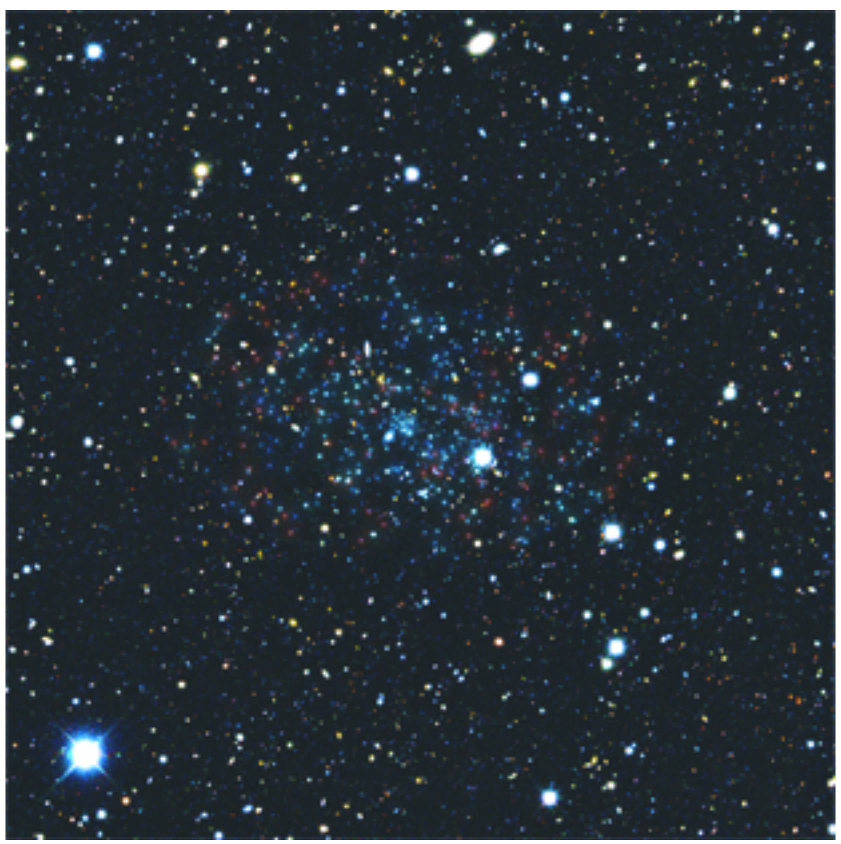
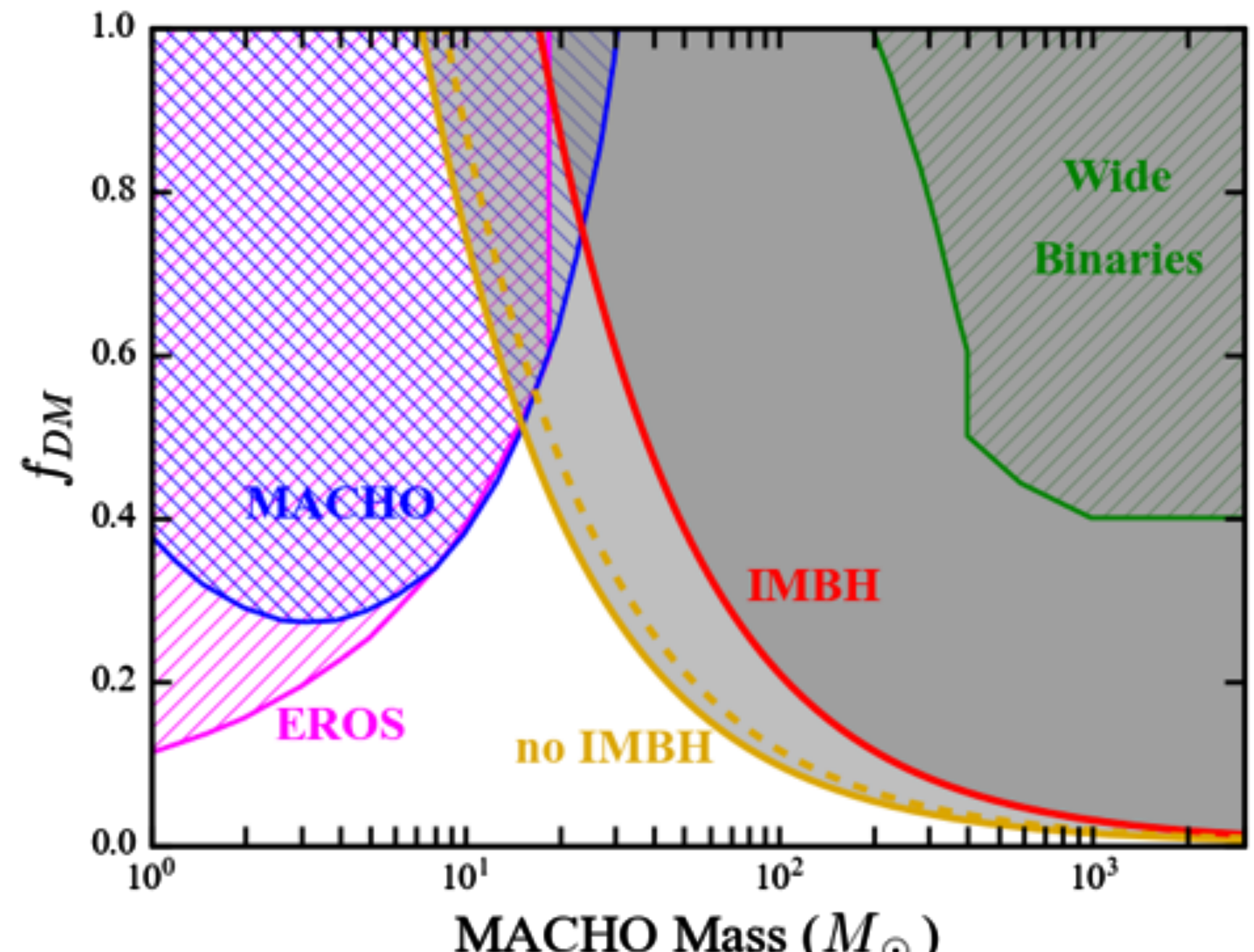
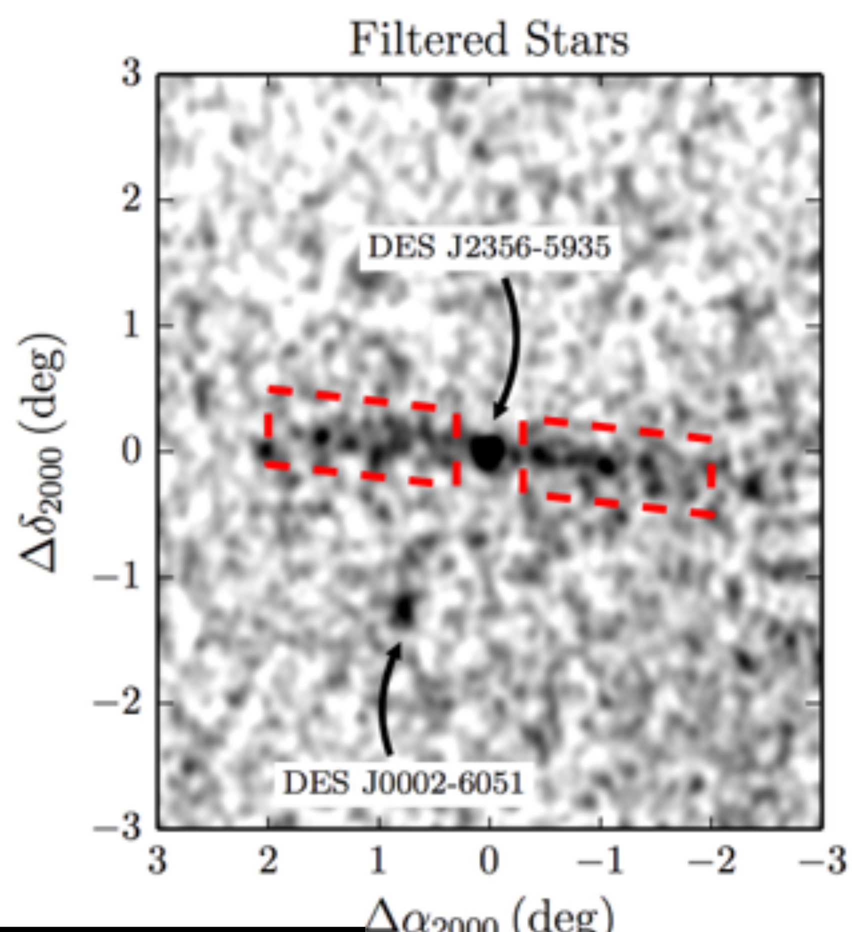


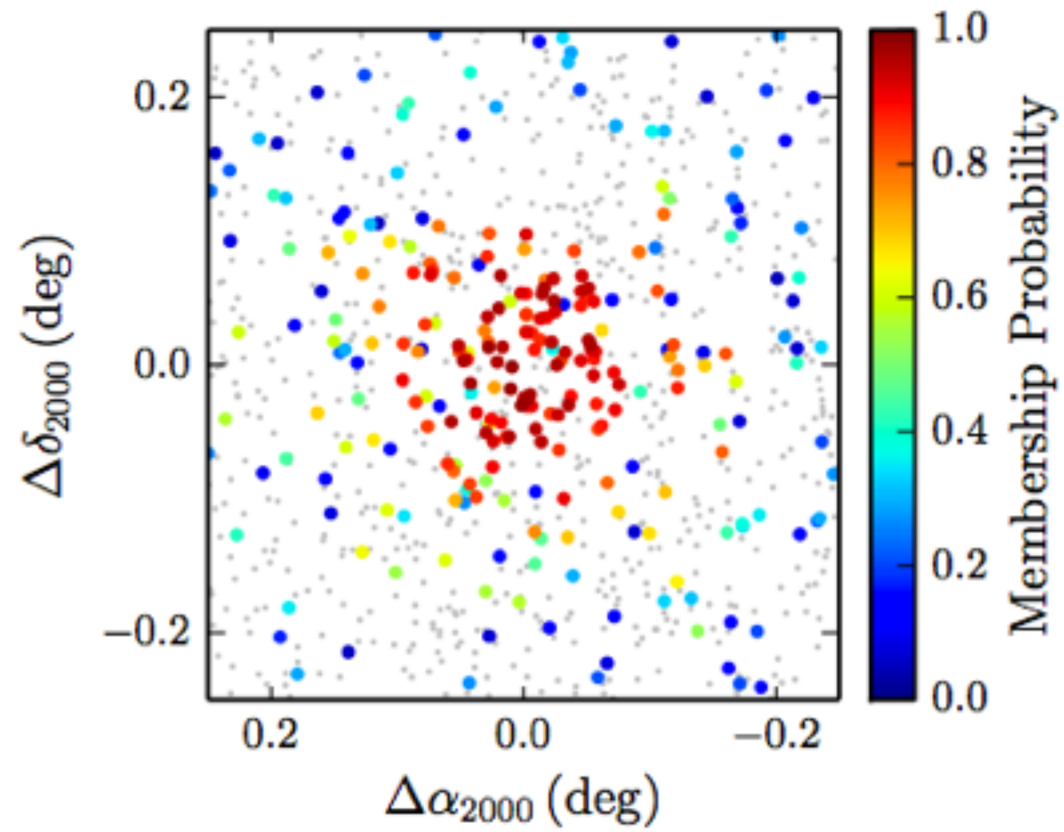


Li et al. (2017)

Tucana III

- Dwarf galaxy candidates discovered in Year 2 data
- Distant to Sun: 25 kpc
  - One of the nearest dwarf galaxy in Milky Way
  - Likely a good candidate for indirect dark matter search
- Linear Structure around Tuc III
  - An ultra-faint dwarf galaxy under tidal disruption?





Drlica-Wagner et al. (2015)

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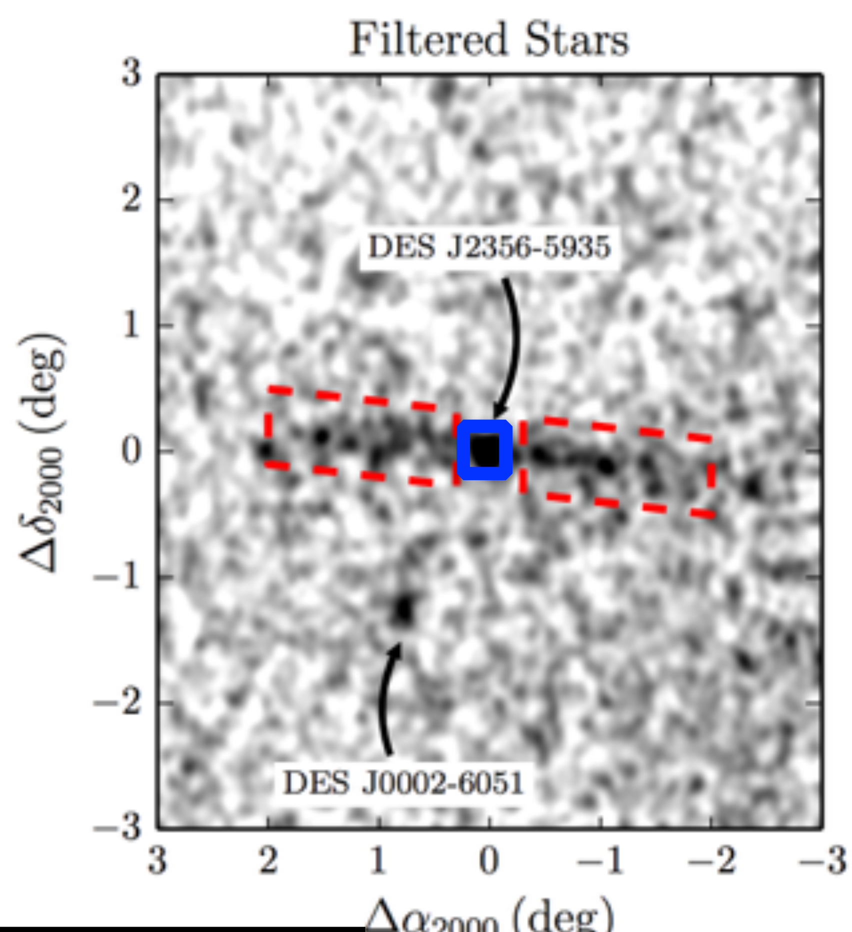
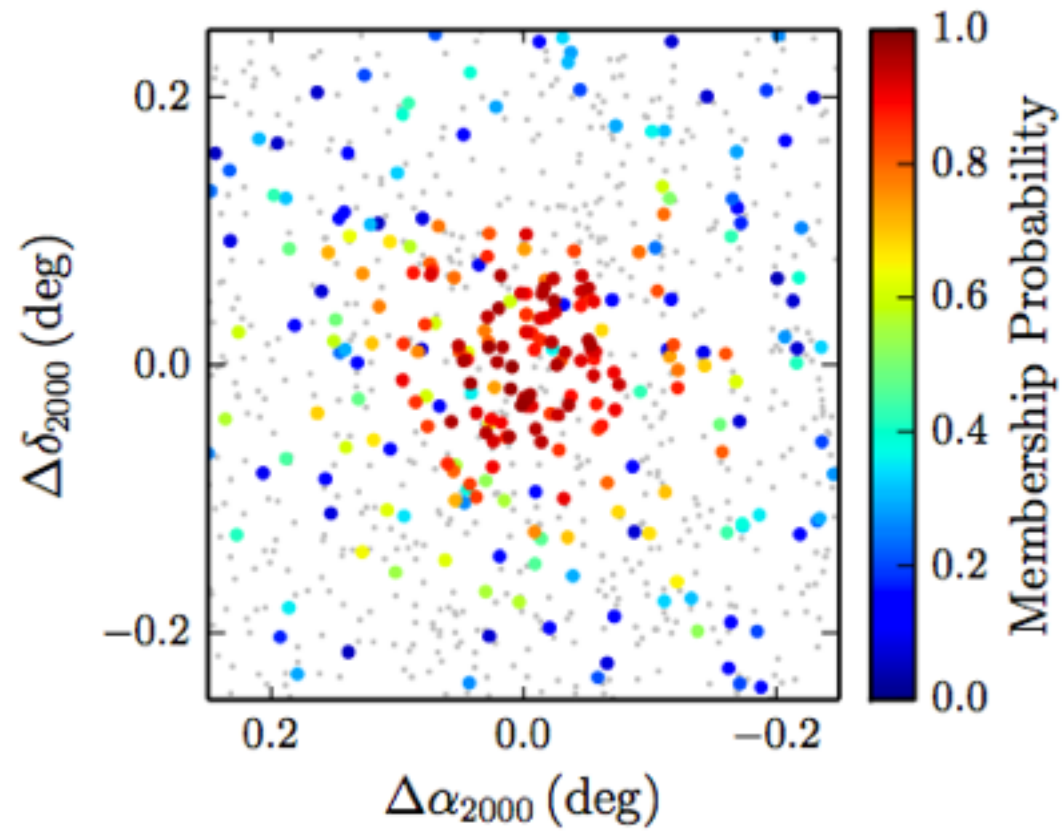
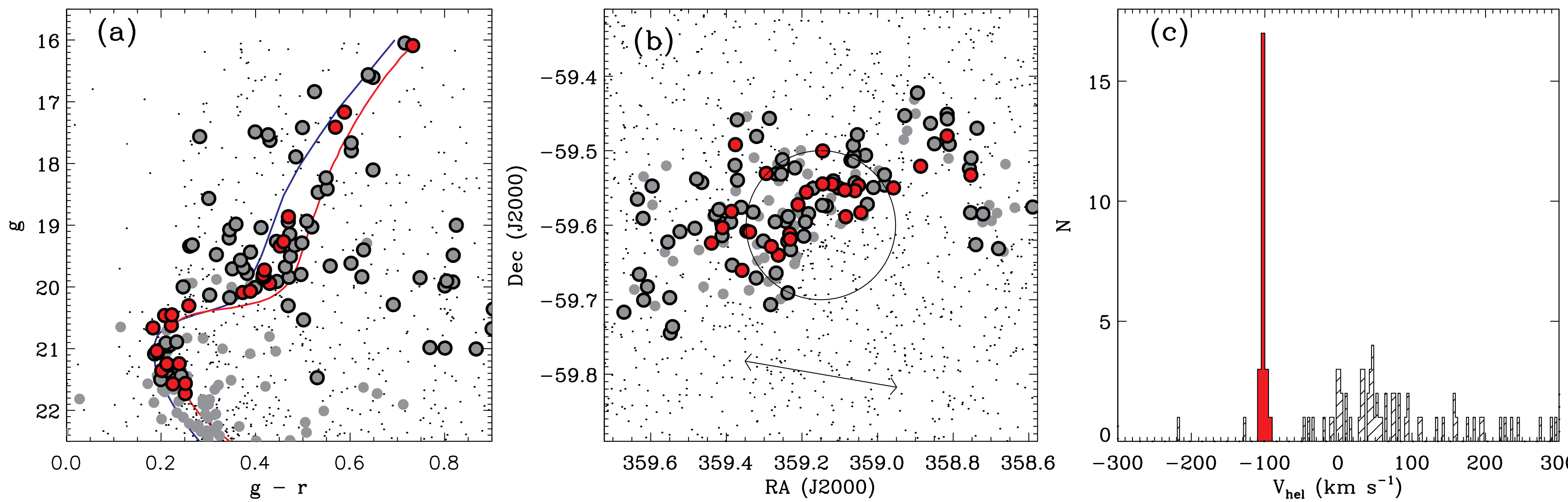


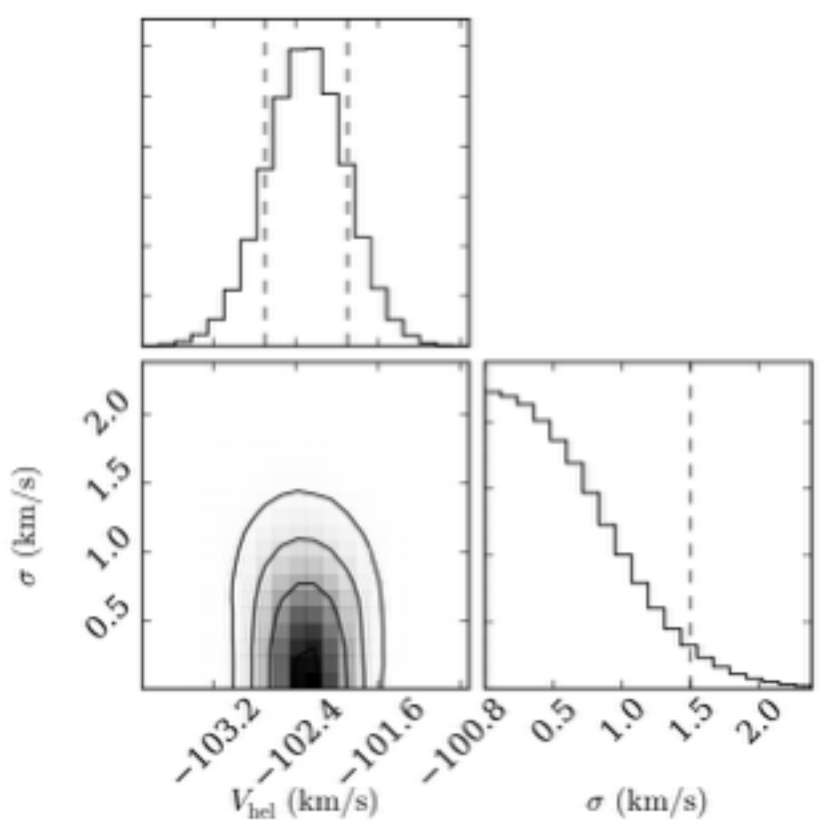


Drlica-Wagner et al. (2015)

Tucana III: Dark Matter Content



26 members identified



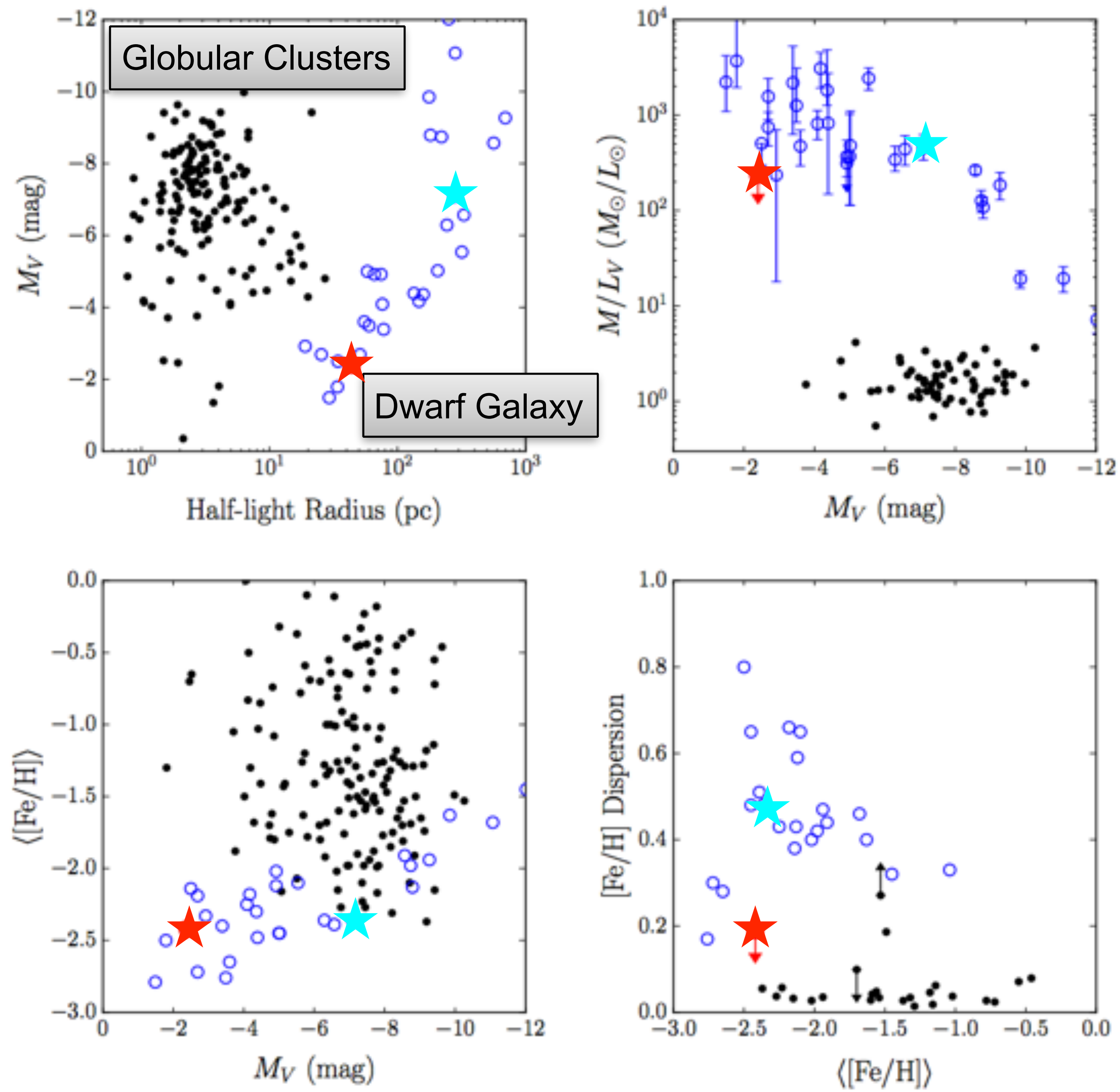
$V_{\rm hel}$ (km s^{-1})	-102.3 ± 0.4
$V_{\rm GSR}$ (km s^{-1})	-195.2 ± 0.4
σ (km s^{-1})[a]	< 1.5
Mass ($M_\odot$)[a]	$< 8 \times 10^4$
M/L_V ($M_\odot/L_\odot$)[a]	< 240

- **Velocity dispersion is NOT resolved**

Simon, Li et al. (2017)

Dwarf Galaxy or Globular Cluster?

- **Globular cluster is possible, but more likely to be a dwarf galaxy**



- **Large radius**
- **Low metallicity**

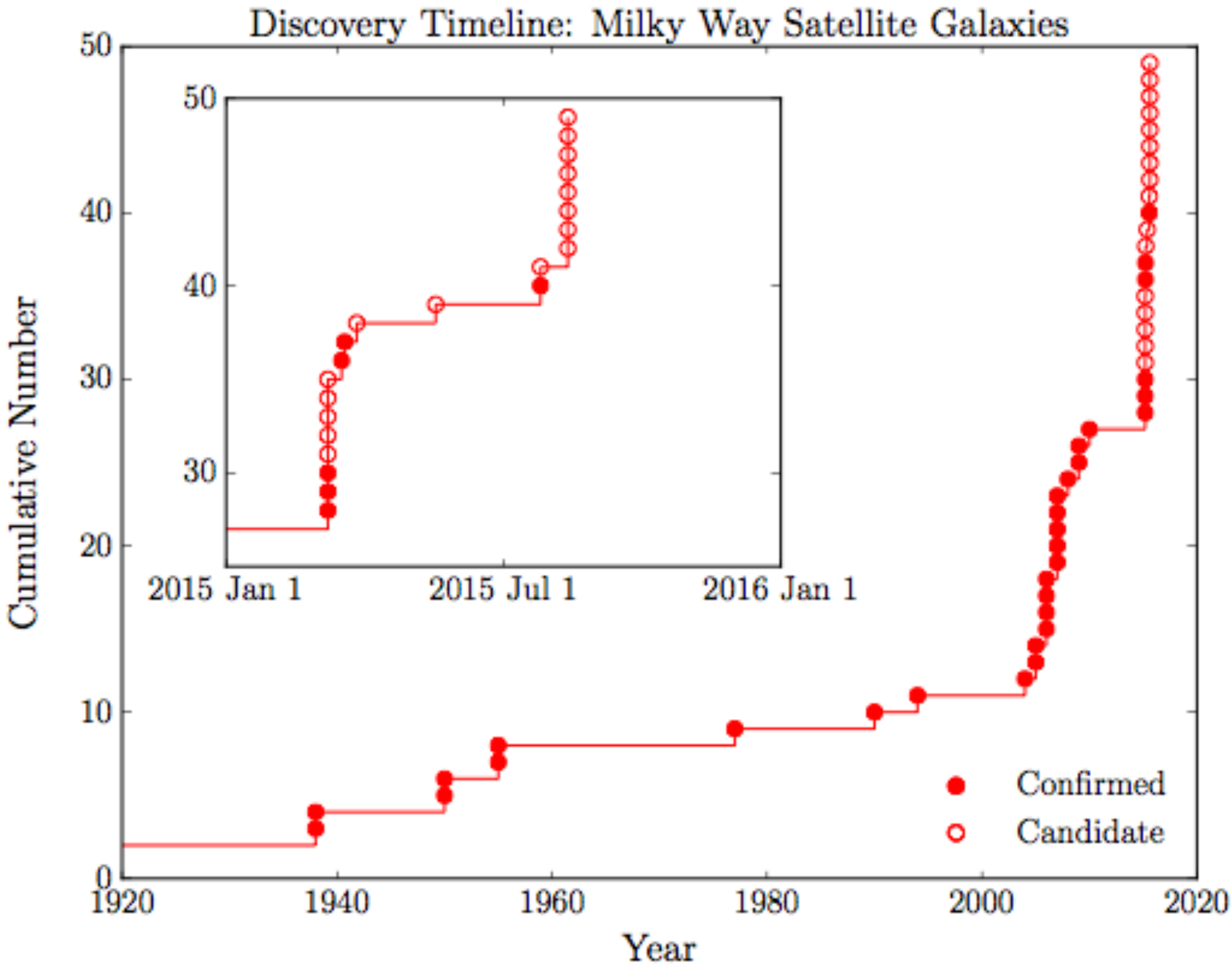
If it is a dwarf galaxy, it will be one of the known dwarf galaxy with lowest mass. Not ideal for indirect dark matter search.

★ Eridanus II

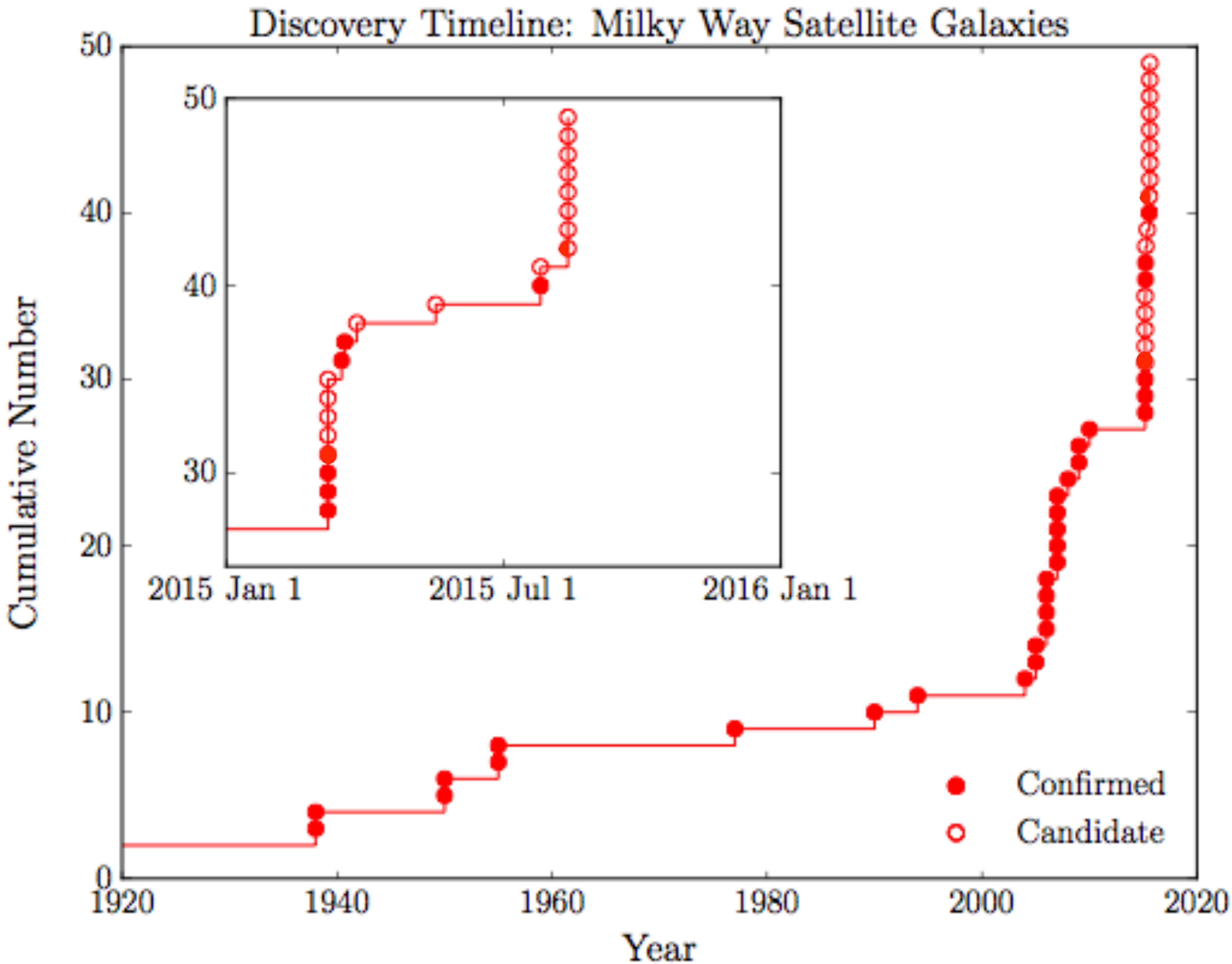
★ Tucana III

Simon, Li et al. (2017)

Discovery Timeline



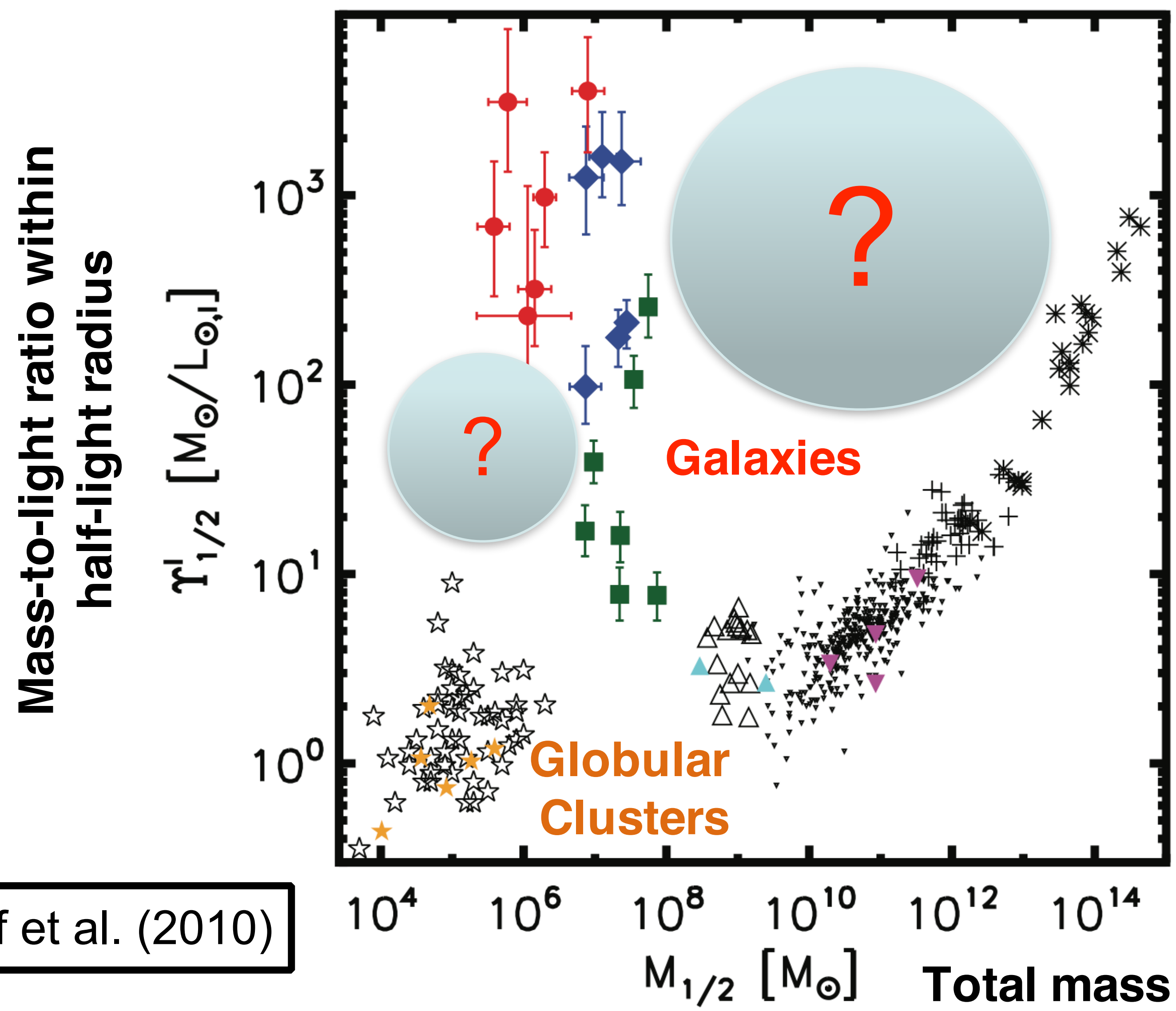
Discovery Timeline



Dwarf Galaxies vs. Globular Clusters

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.

Willman & Strader 2012, AJ, 144, 76



Wolf et al. (2010)

Total mass within half-light radius

M/L > 100 $M_\odot/L_\odot$!

- **Dwarf galaxies are dark matter dominated**
- **Globular clusters are baryon dominated**

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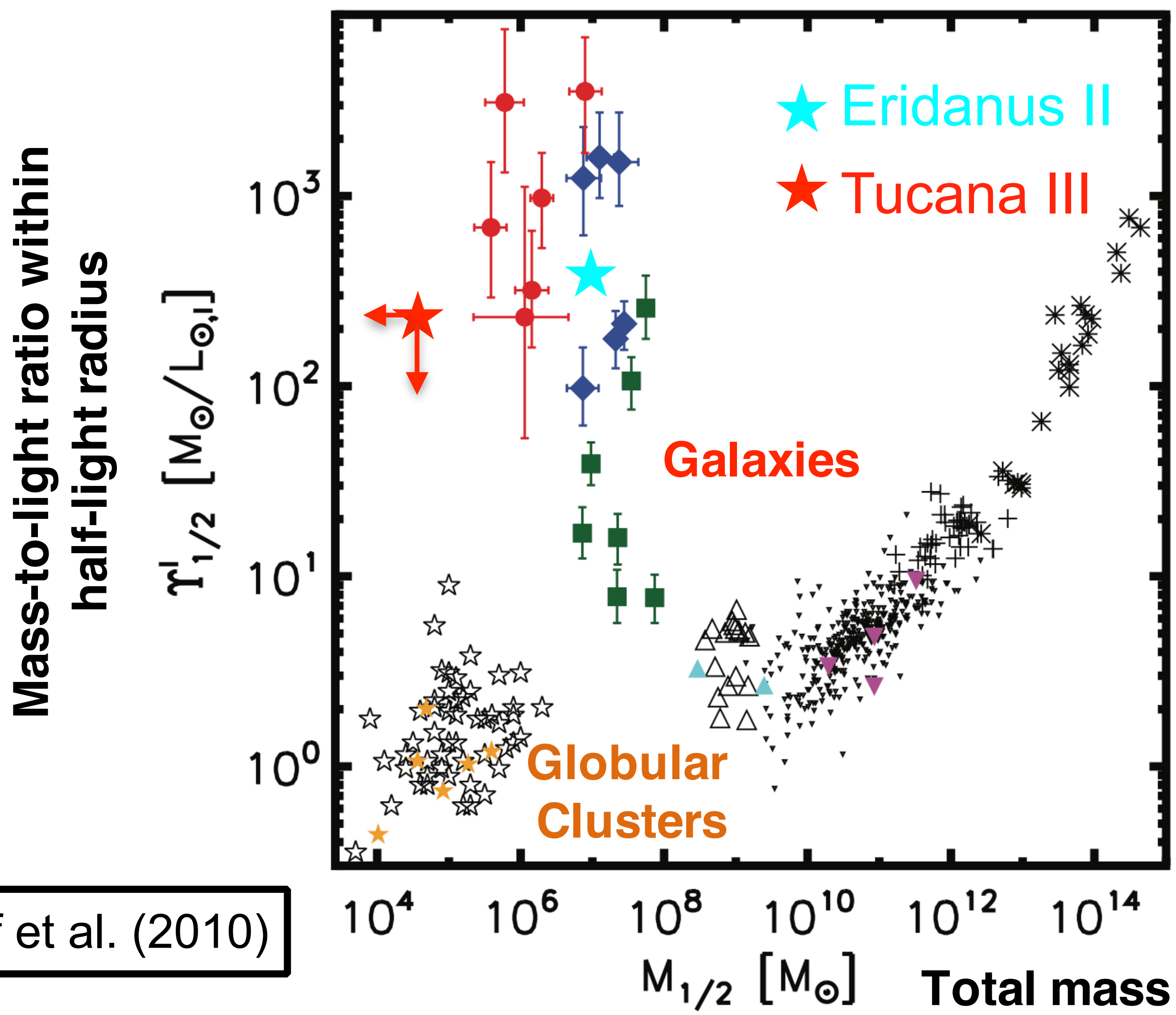

Wolf et al. (2010)

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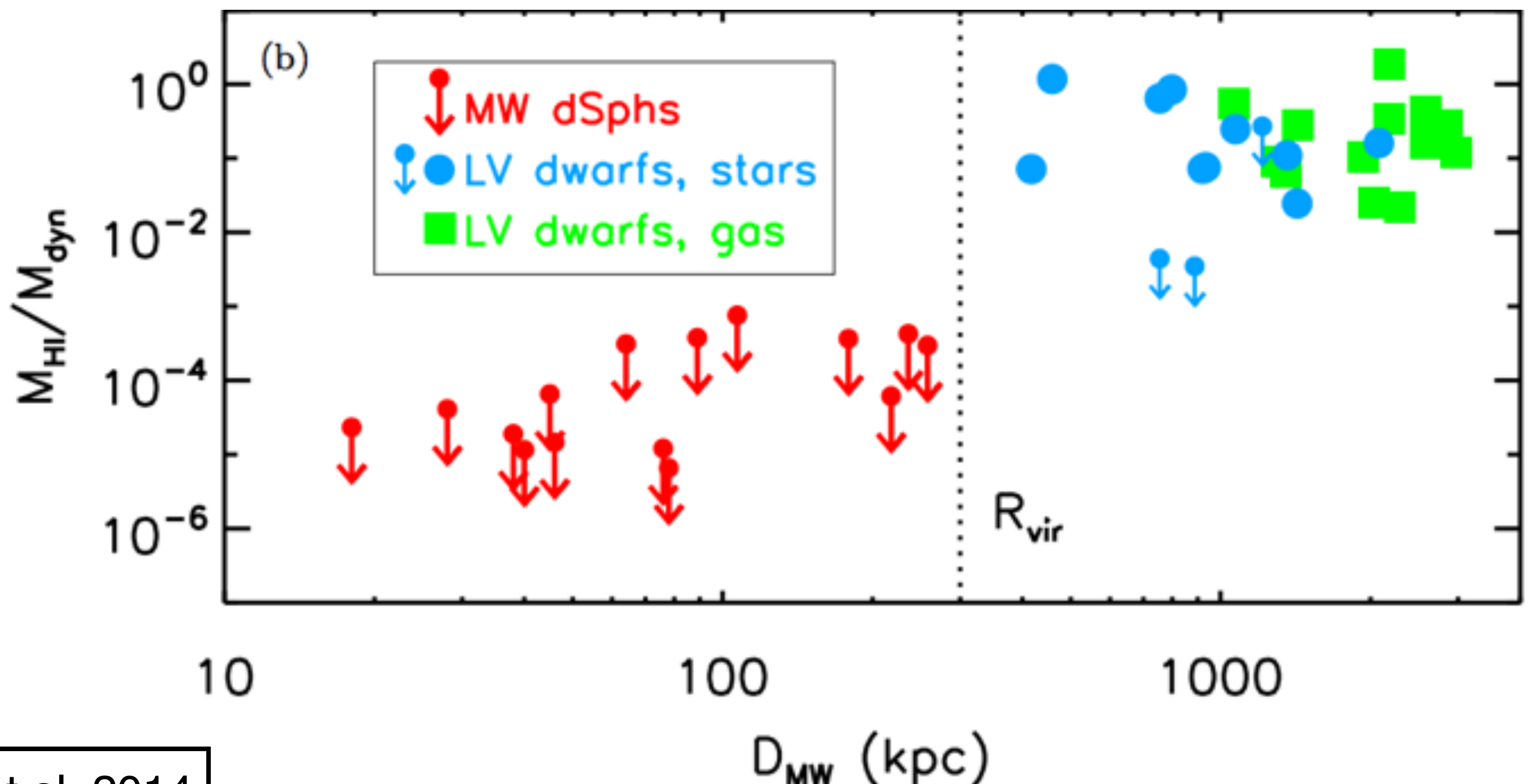
Star Formation in Dwarf Galaxies

Quiescent vs Star Forming

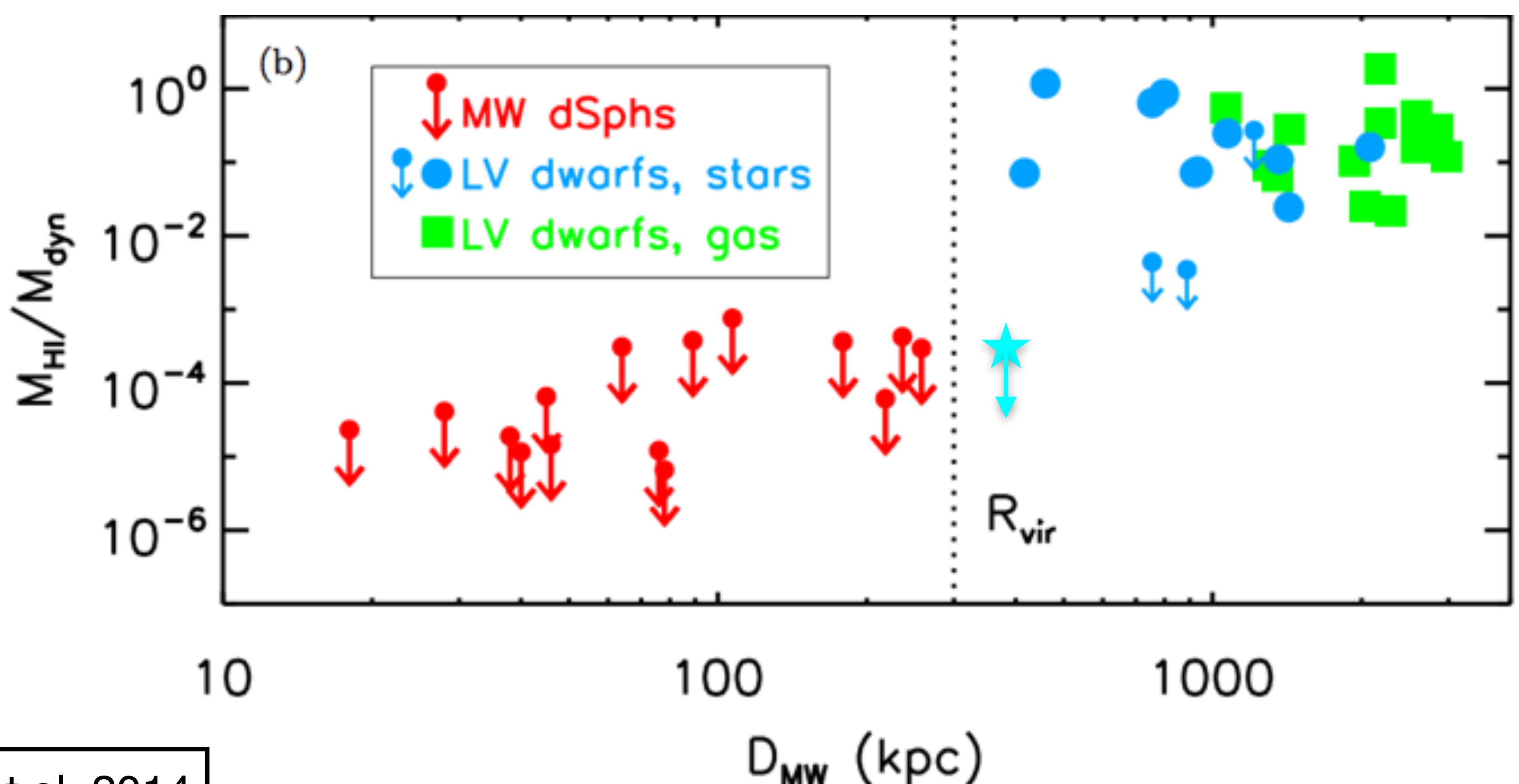


Speakers et al. 2014

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

Star Formation in Dwarf Galaxies

Quiescent vs Star Forming



Speakers et al. 2014

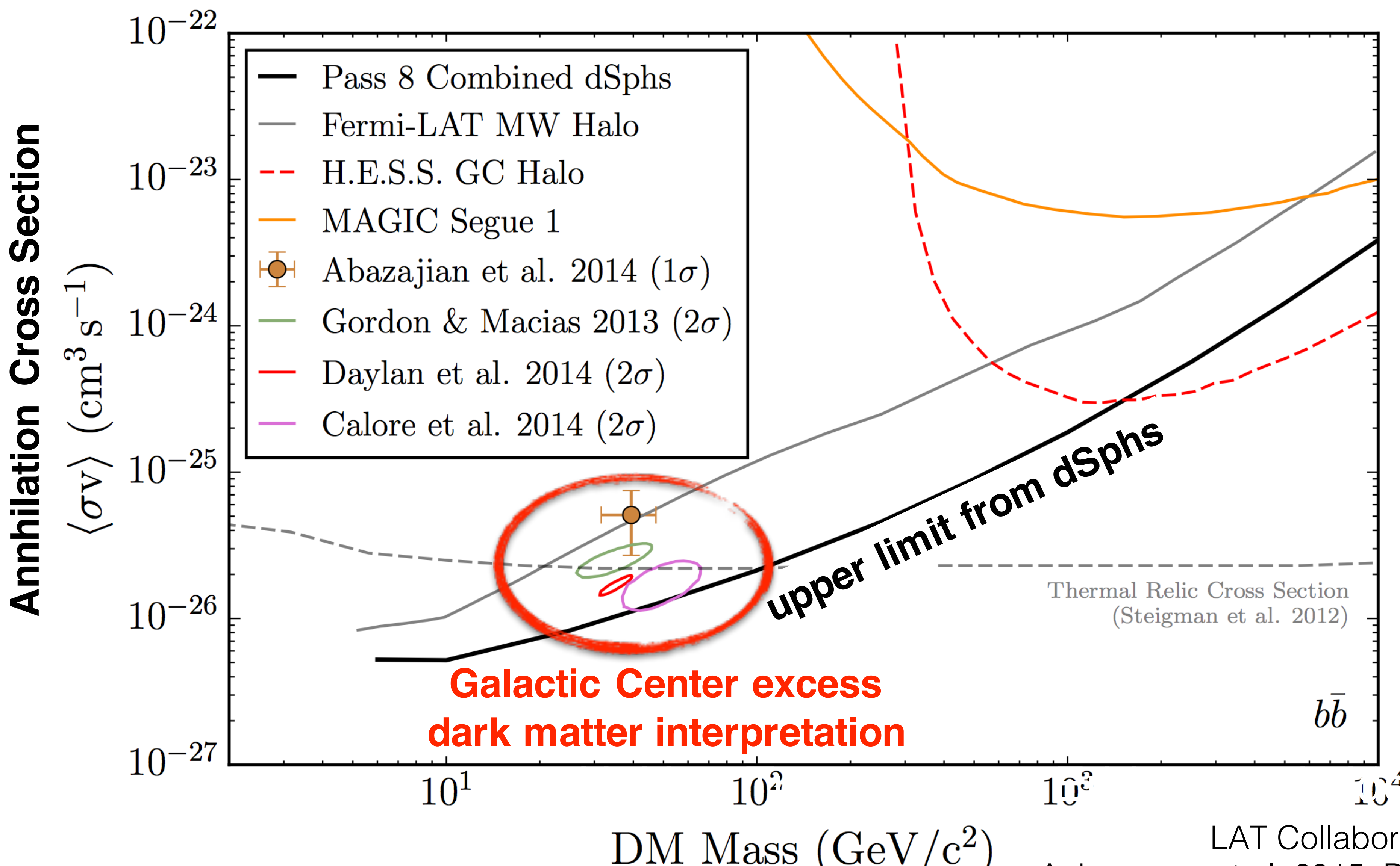
What makes these satellites stop forming stars?
Reionization vs. stripping?

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

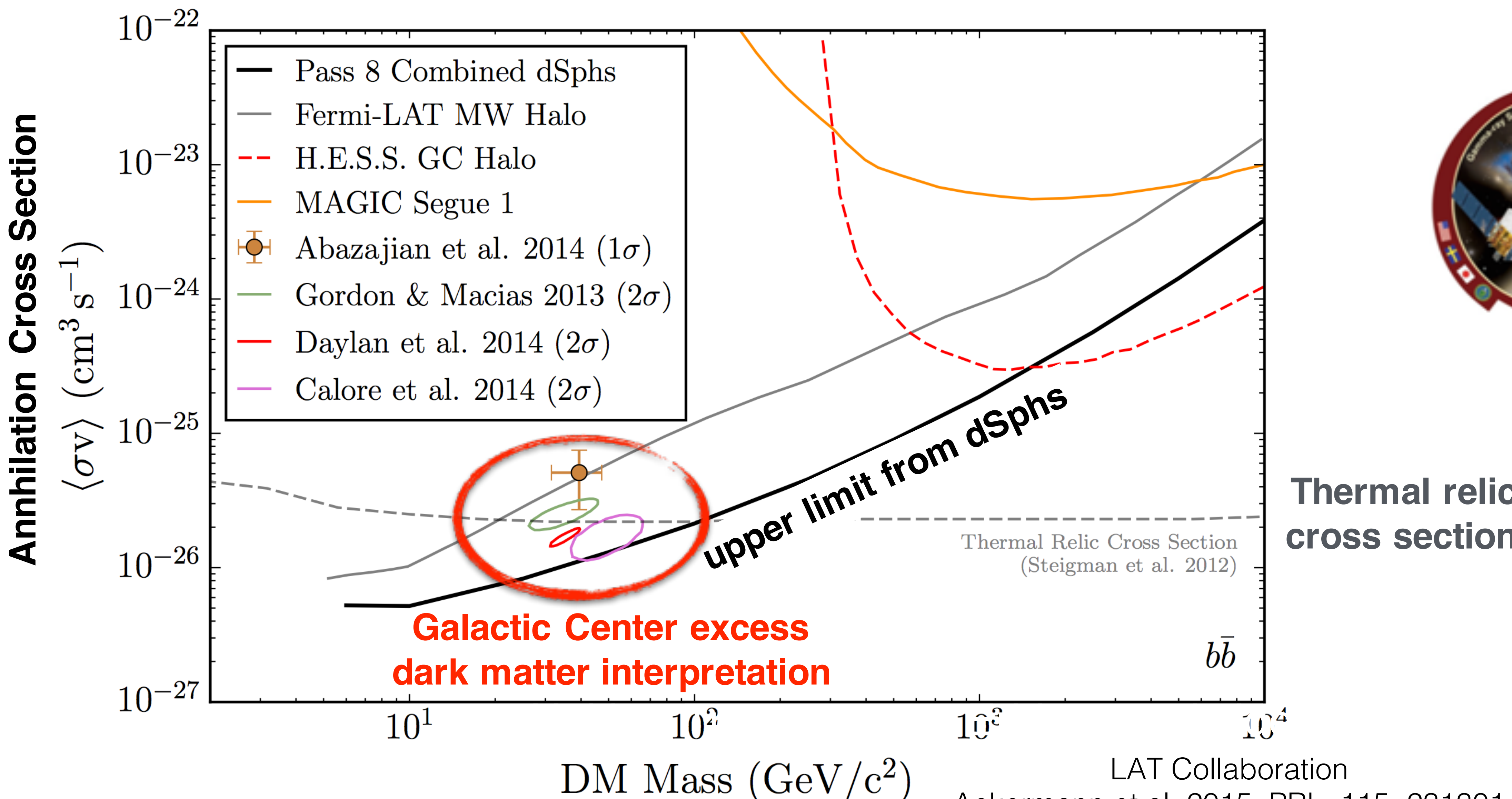
LAT Collaboration
Ackermann et al. 2015, PRL, 115, 231301

Indirect Detection of Dark Matter
WIMP Annihilation

THE DARK ENERGY SURVEY

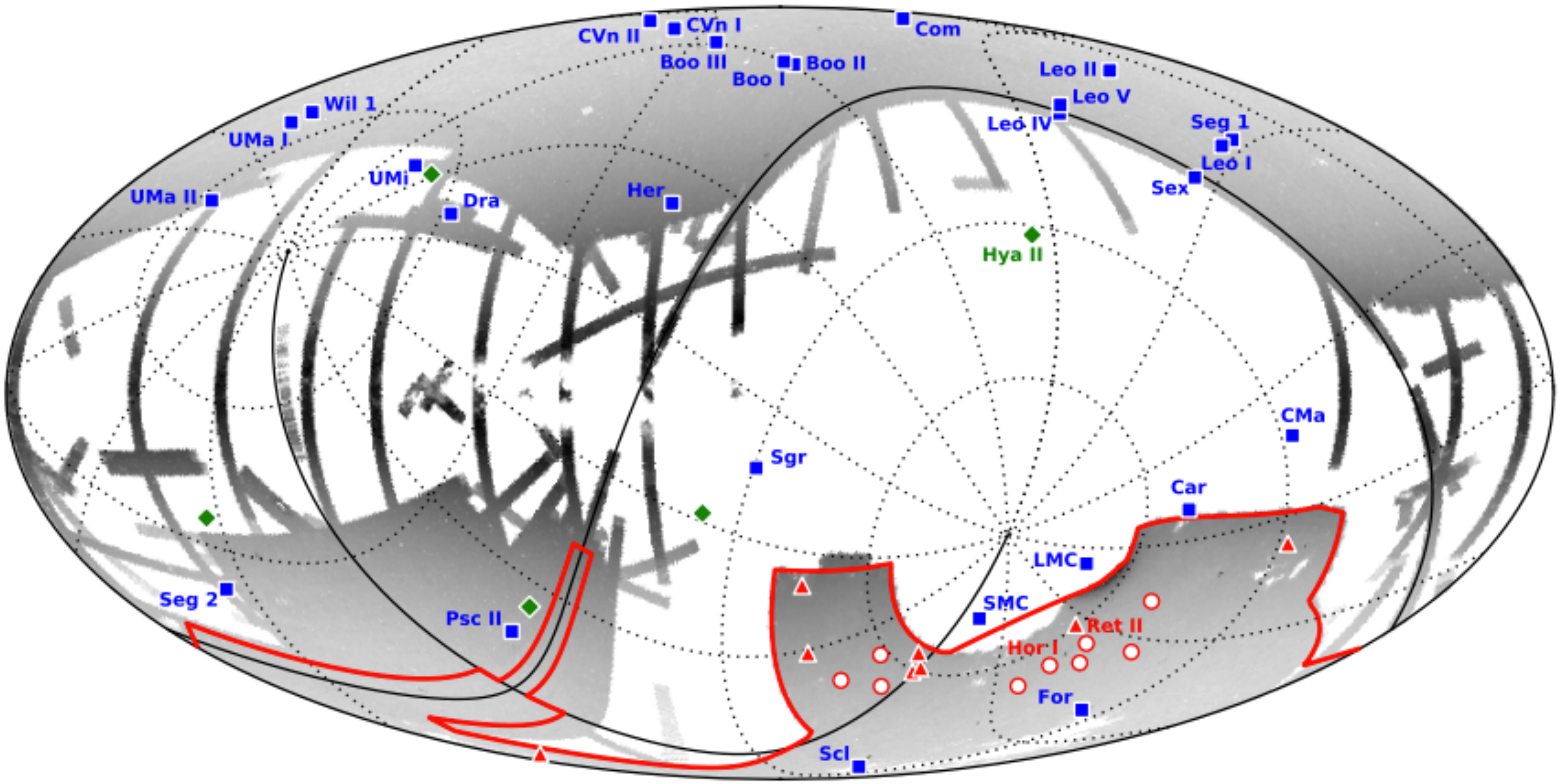
Fermilab

Neither Tucana III nor Eridanus II is ideal candidate for indirect dark matter search



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

More Follow-up Underway

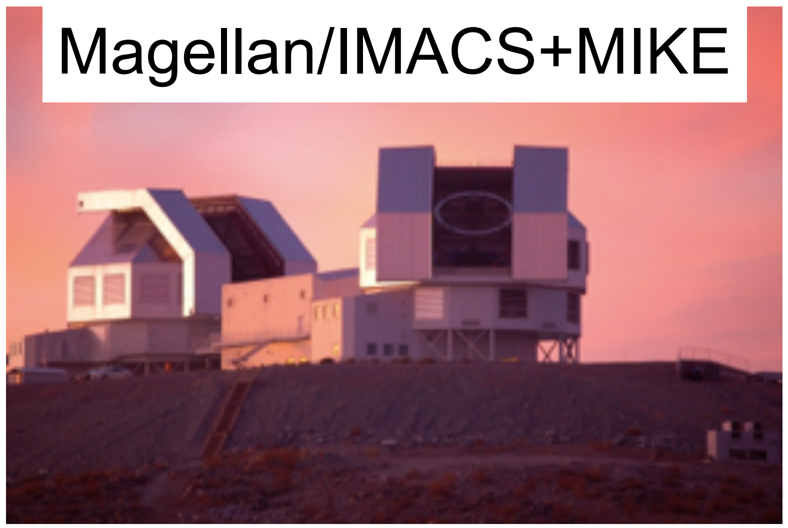


THE DARK ENERGY SURVEY

More Follow-up Underway

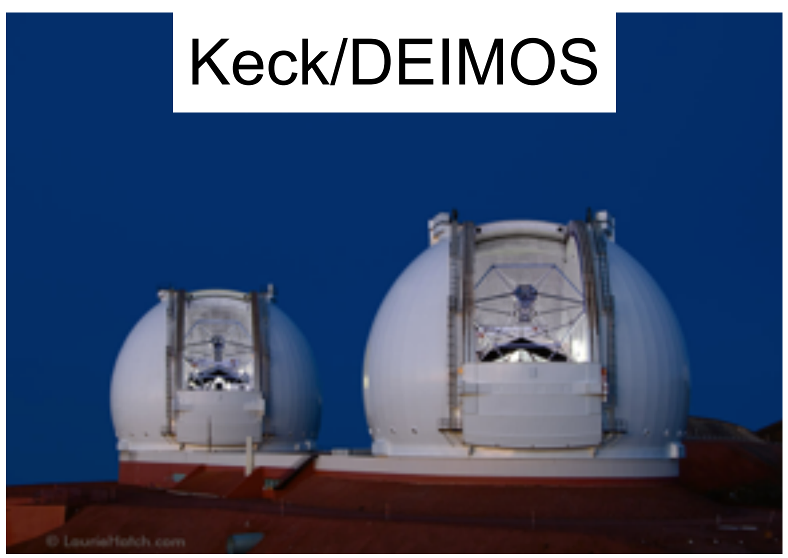
Fermilab

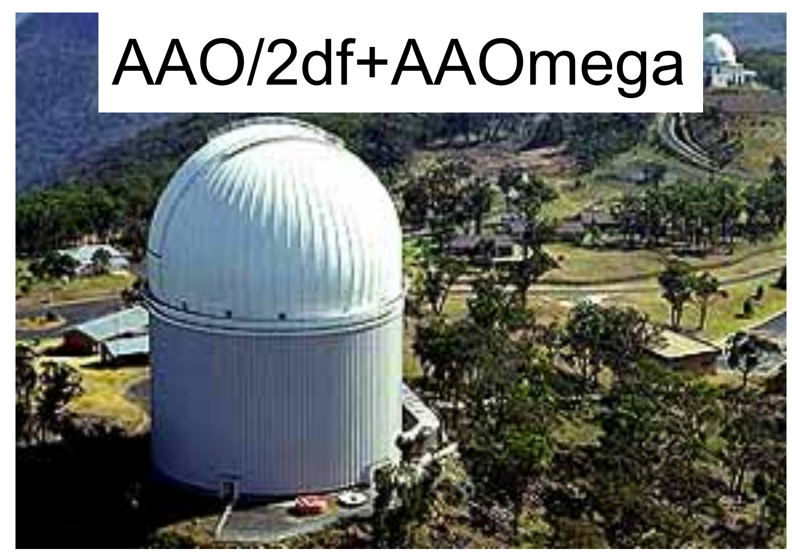
Chile



Chile (Europe)

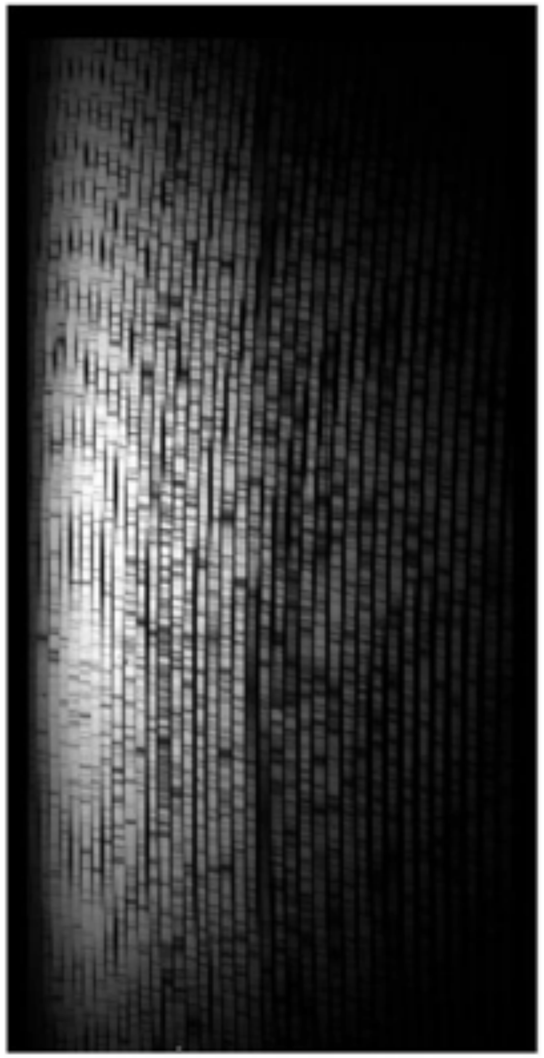
Hawaii, USA

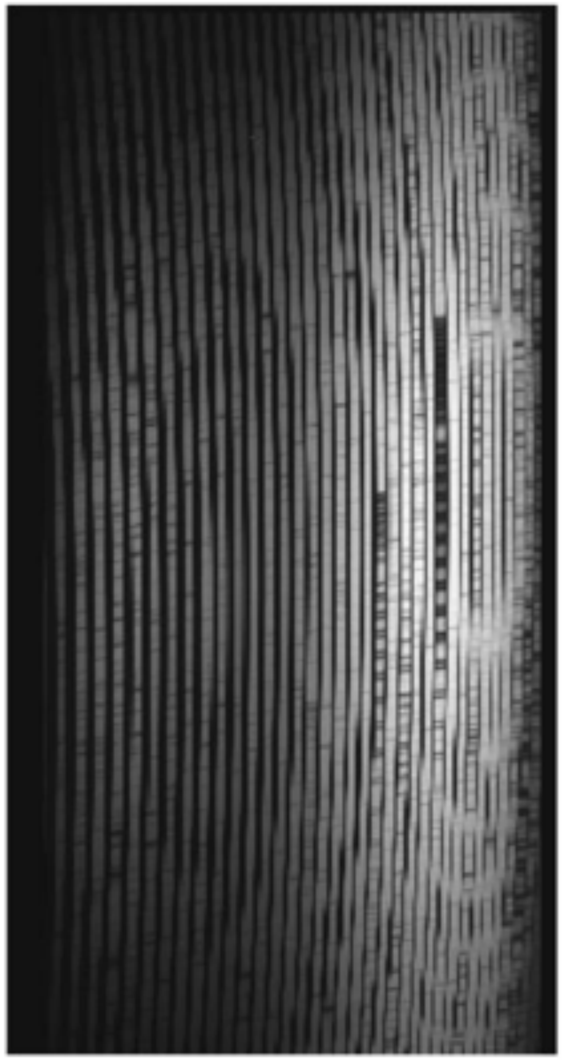


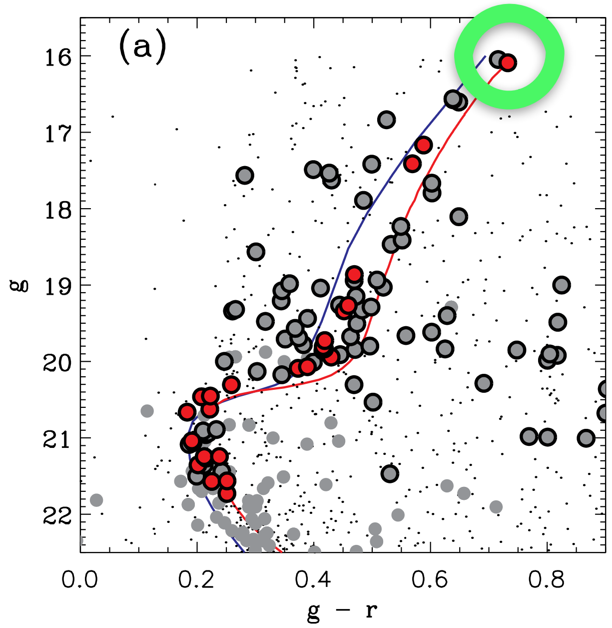


Australia

More Follow-up Underway

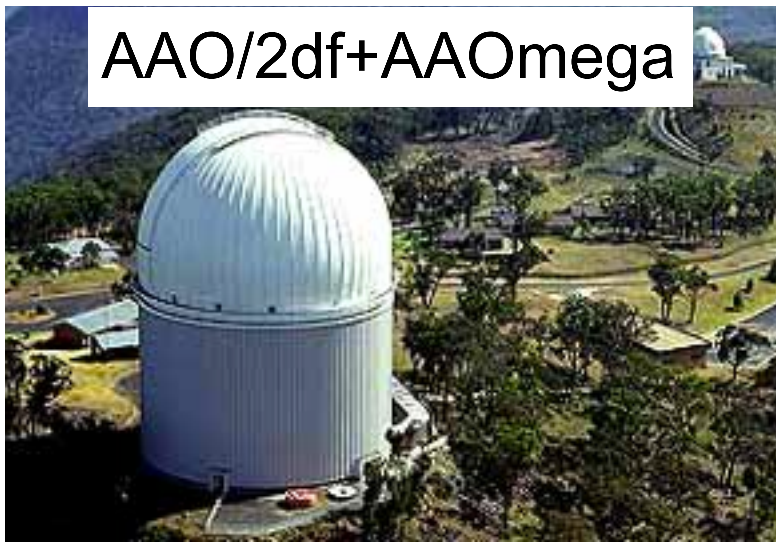




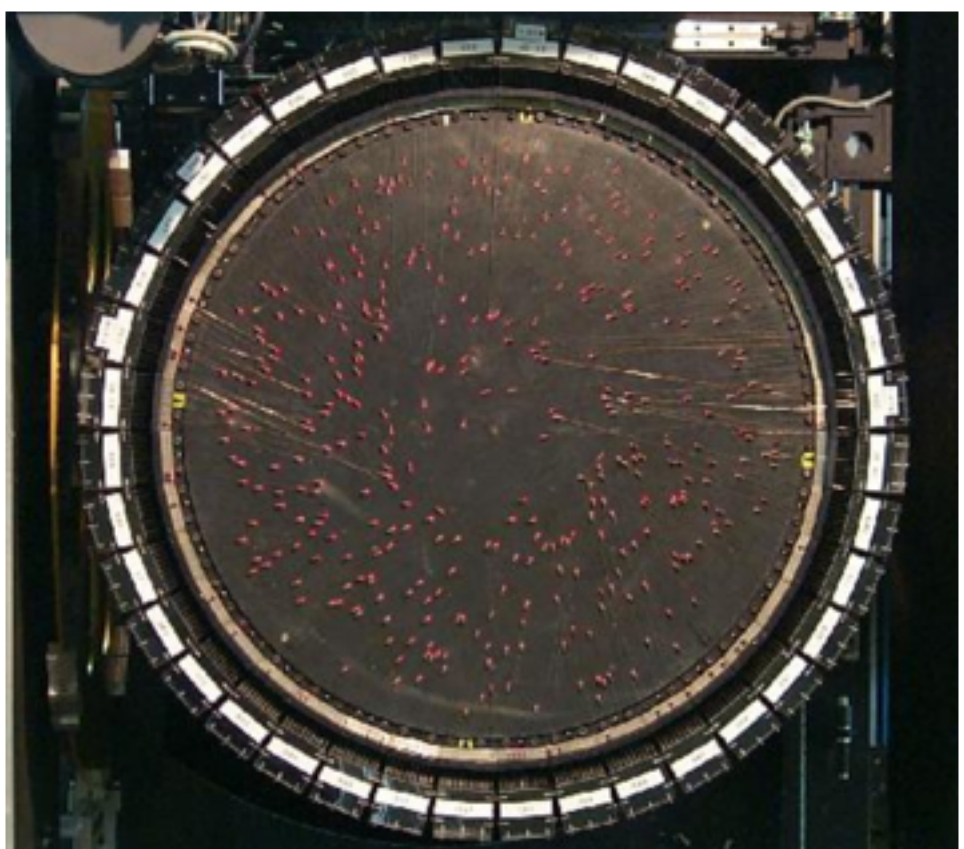


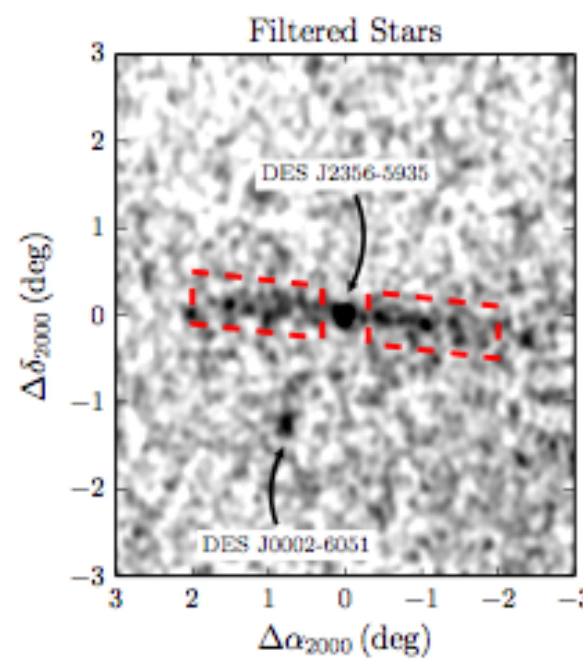
- **V=15.7 in Tucana III**
- **Brightest star in ultra-faint dwarf galaxy**
- **High resolution spectroscopy w/ Magellan/MIKE**
- **Chemical evolution**

Hansen, Simon, Li et al. (2017)



- 4 meter telescope in Australia Angelo Observatory
- Field of view - 2 degrees in diameter (16 x IMACS)
- ~400 fibers/targets per exposure





Tidal tails of Tucana III w/ AAT/2df+AAOmega

Li et al. in prep

`

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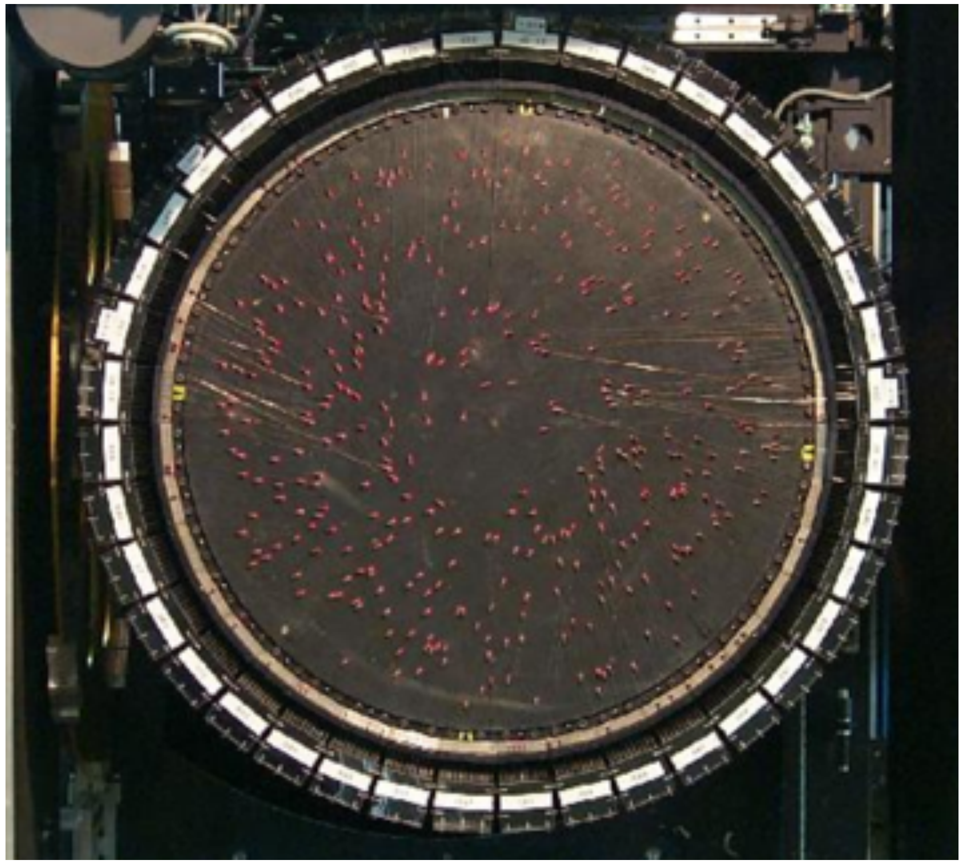

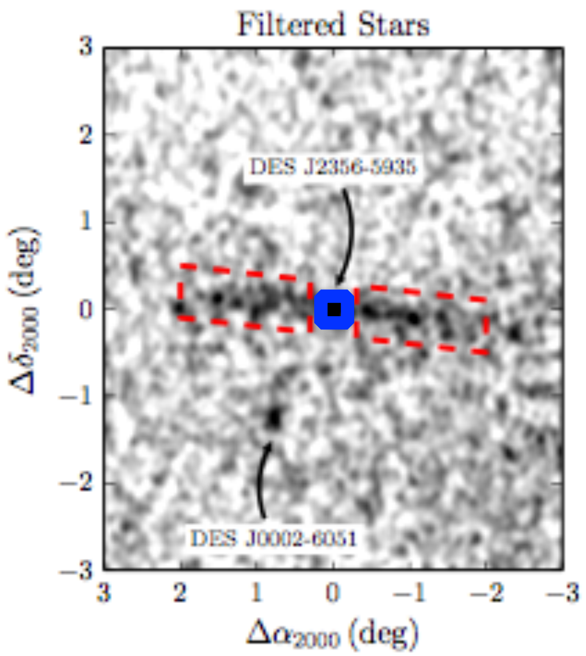

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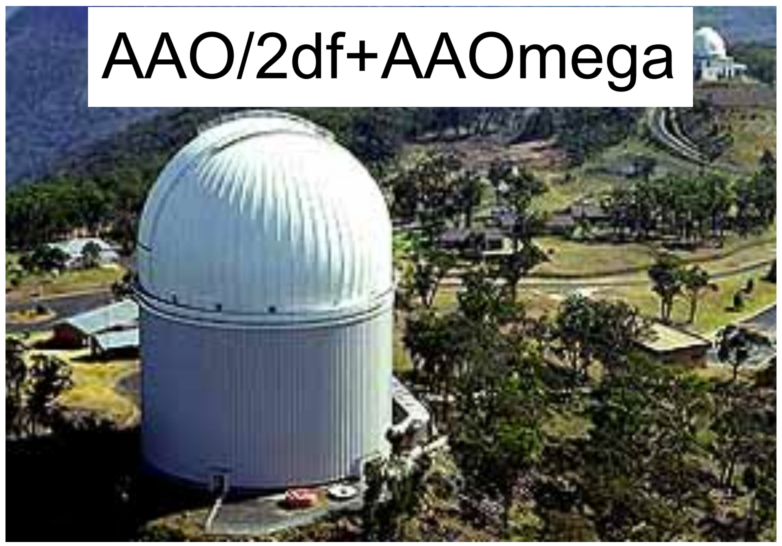
Li et al. in prep



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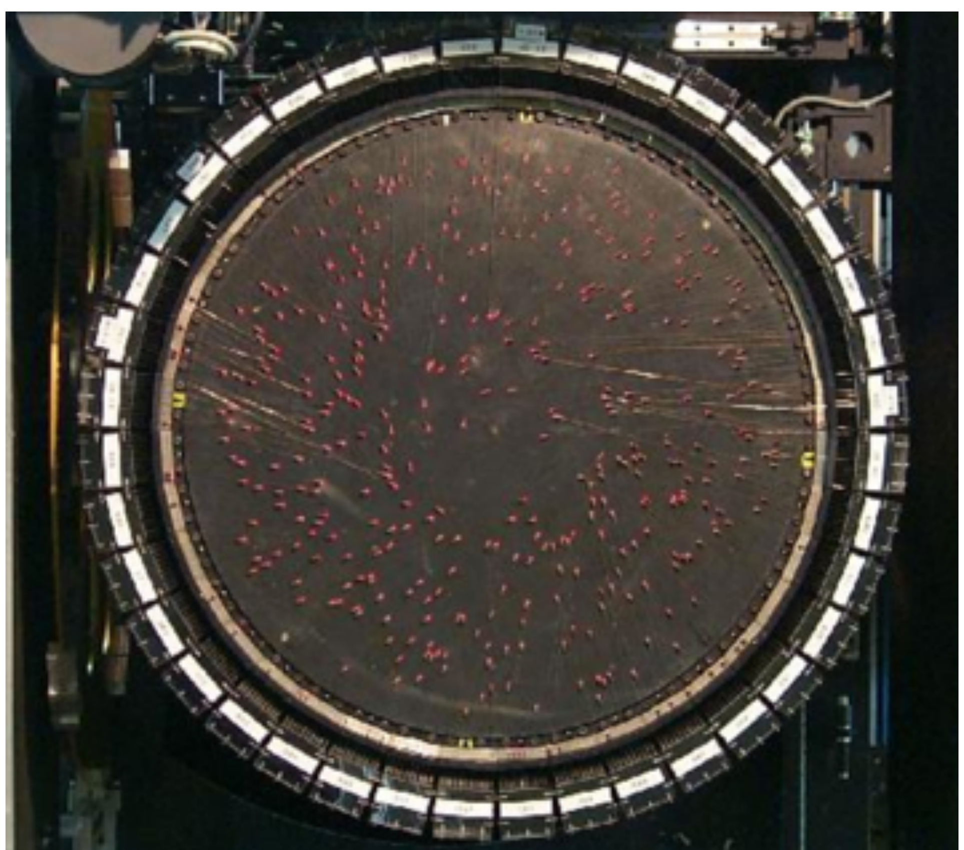
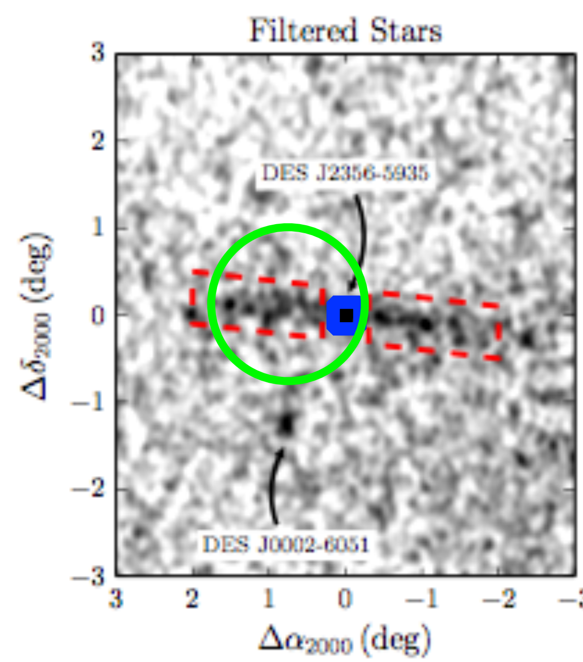




Tidal tails of Tucana III w/ AAT/2df+AAOmega

Li et al. in prep

Take Away Messages

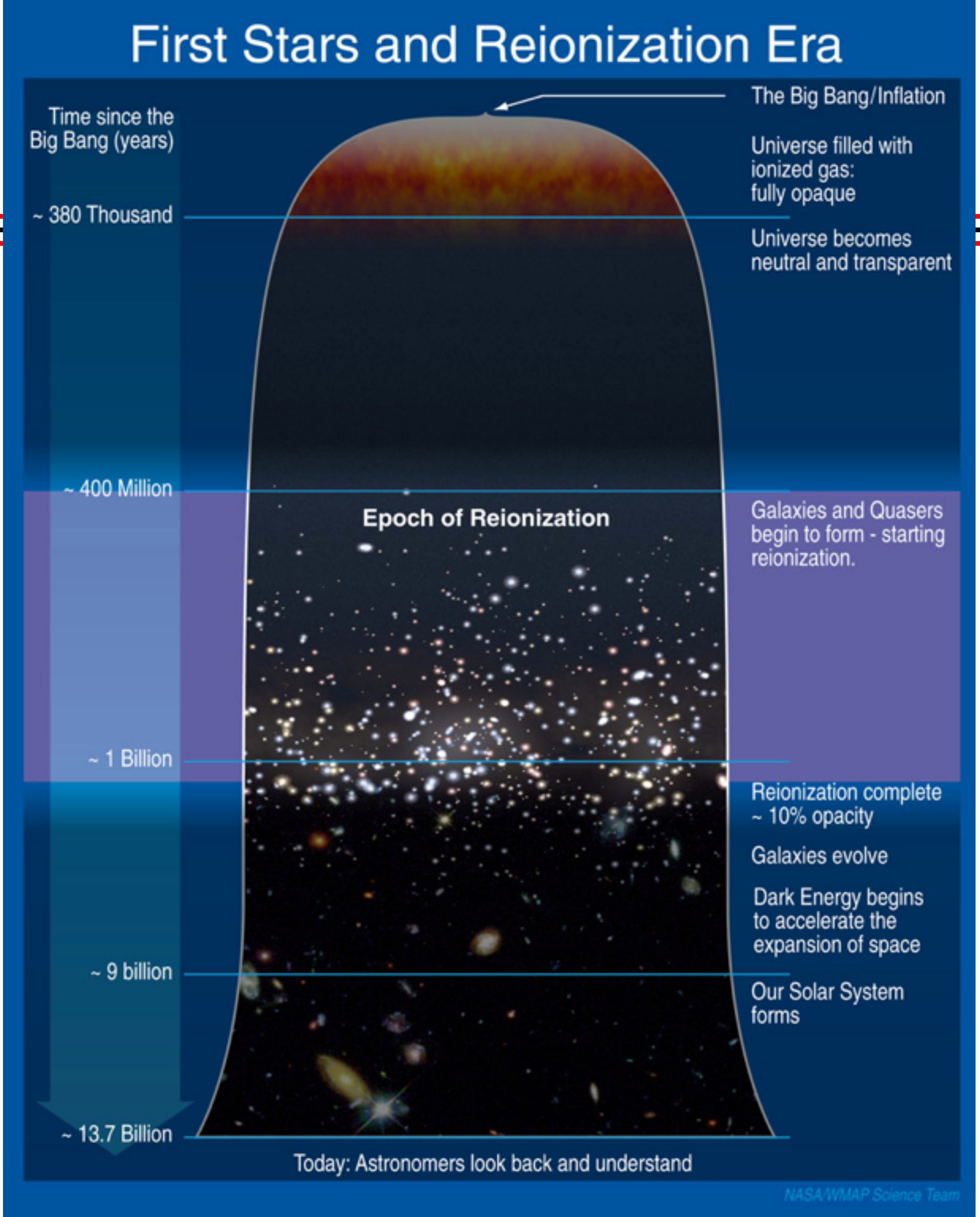
- Milky Way satellites are the ideal targets to
  - test ΛCDM
  - understand galaxy formation
  - search WIMP annihilation signal

- Precise velocity measurements via spectroscopic analysis provide us a unique tool determine the dark matter mass in these systems.

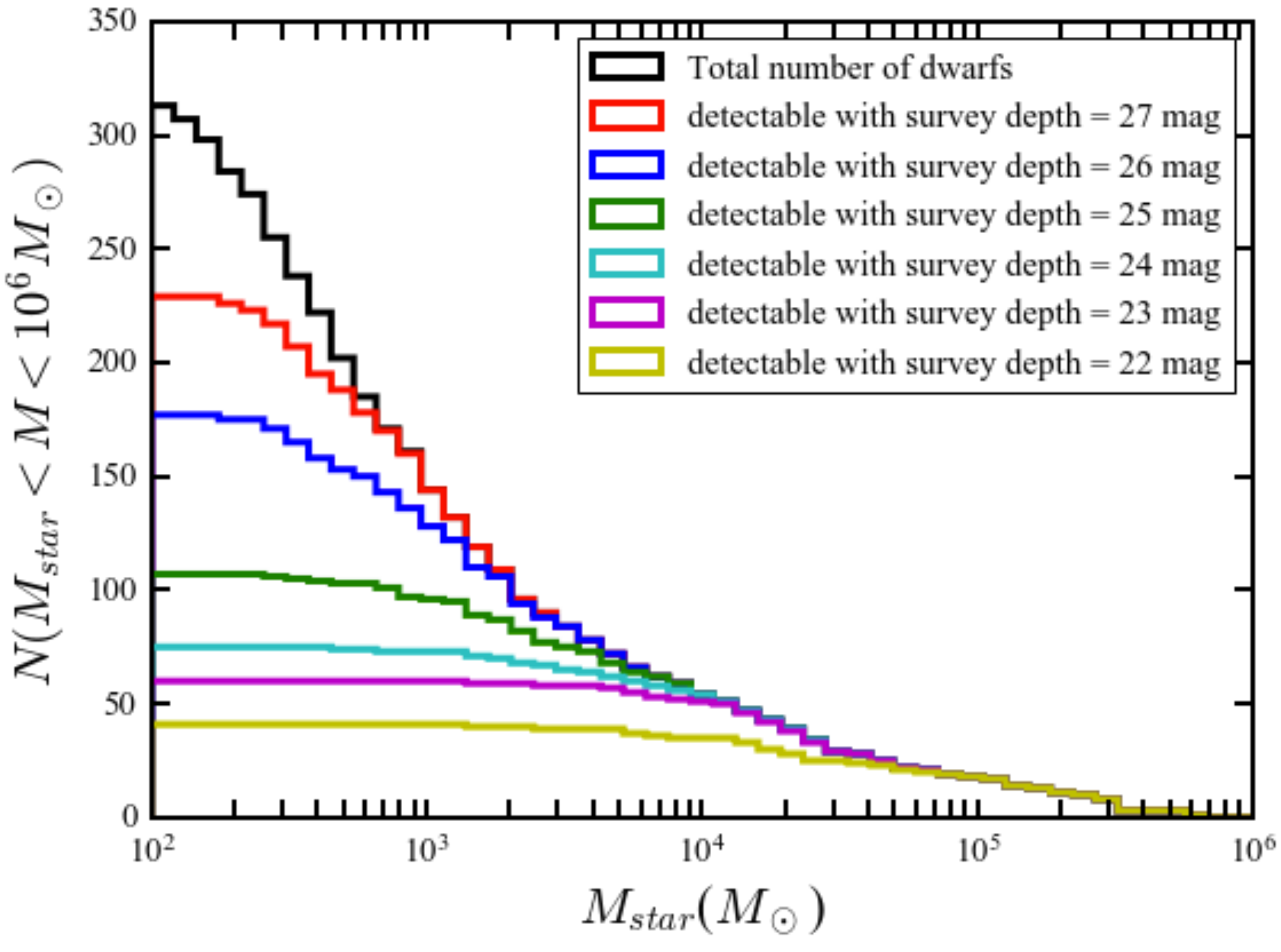
- Eridanus II is a dark matter dominated dwarf galaxy.
  - Beyond Milky Way virial radius but no recent star formation
- Tucana III is likely a dwarf galaxy with very low mass.
  - More precise data is needed for classification

- More follow-ups are underway

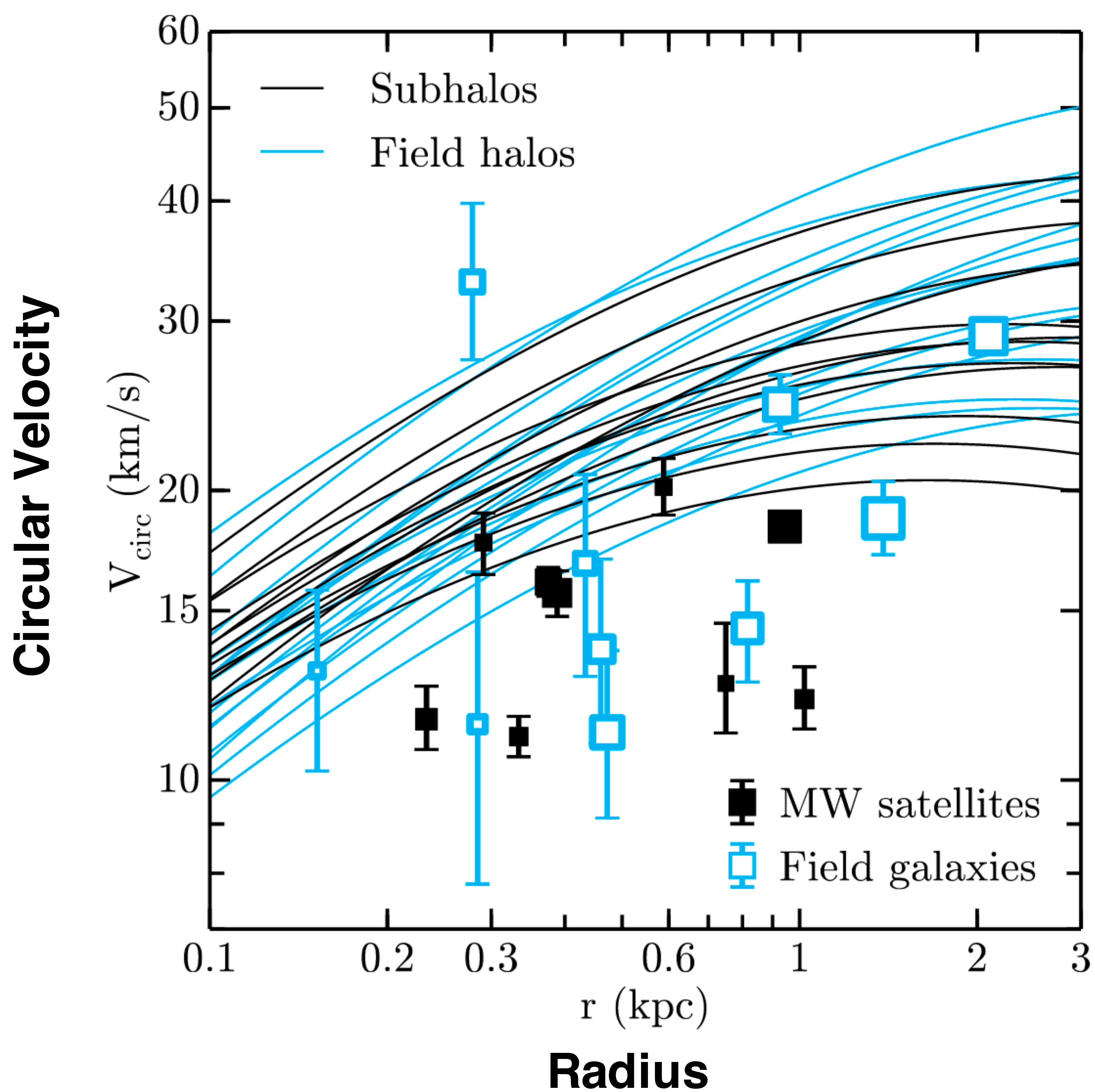
Extra Slides


First Stars and Reionization Era
Time since the Big Bang (years)
~ 380 Thousand
~ 400 Million
~ 1 Billion
~ 9 billion
~ 13.7 Billion
The Big Bang/Inflation
Universe filled with ionized gas: fully opaque
Universe becomes neutral and transparent
Epoch of Reionization
Galaxies and Quasars begin to form - starting reionization.
Reionization complete ~ 10% opacity
Galaxies evolve
Dark Energy begins to accelerate the expansion of space
Our Solar System forms
Today: Astronomers look back and understand
NASA/WMAP Science Team

- **Dark Matter (DM) Subhalo Mass Spectrum on the Smallest Scale**
  - **CDM Simulation vs Observations**

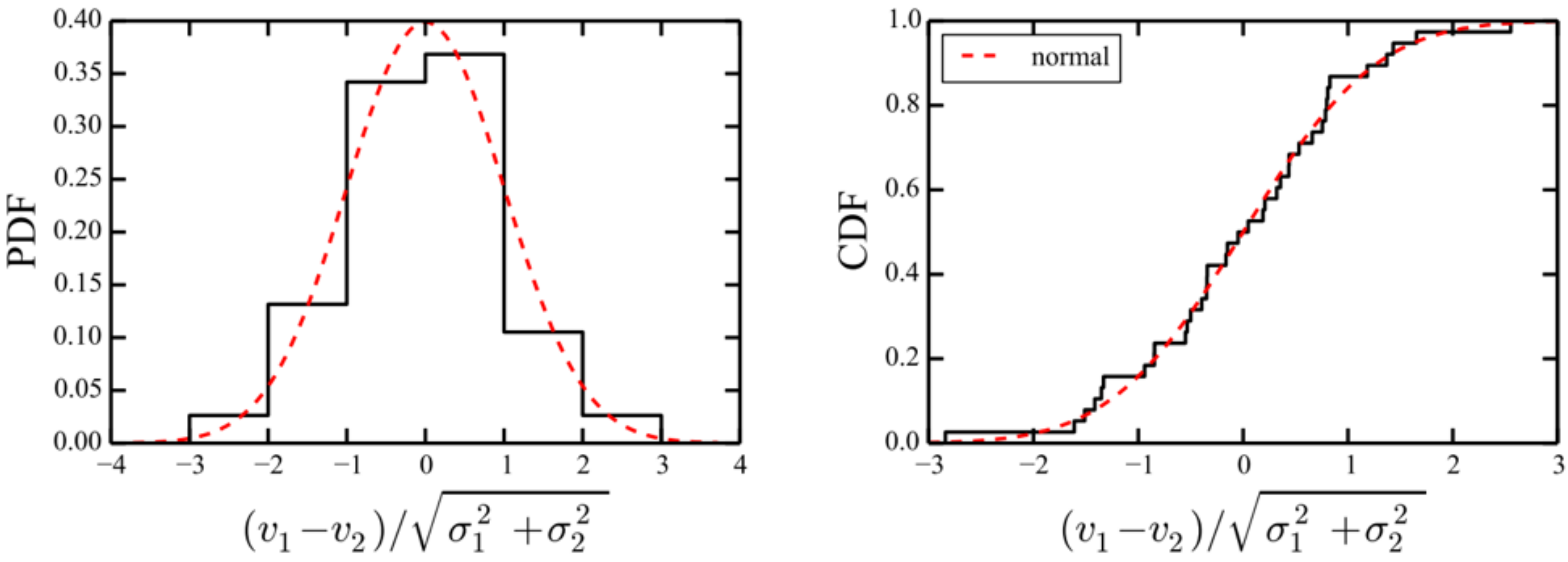


Too big to fail

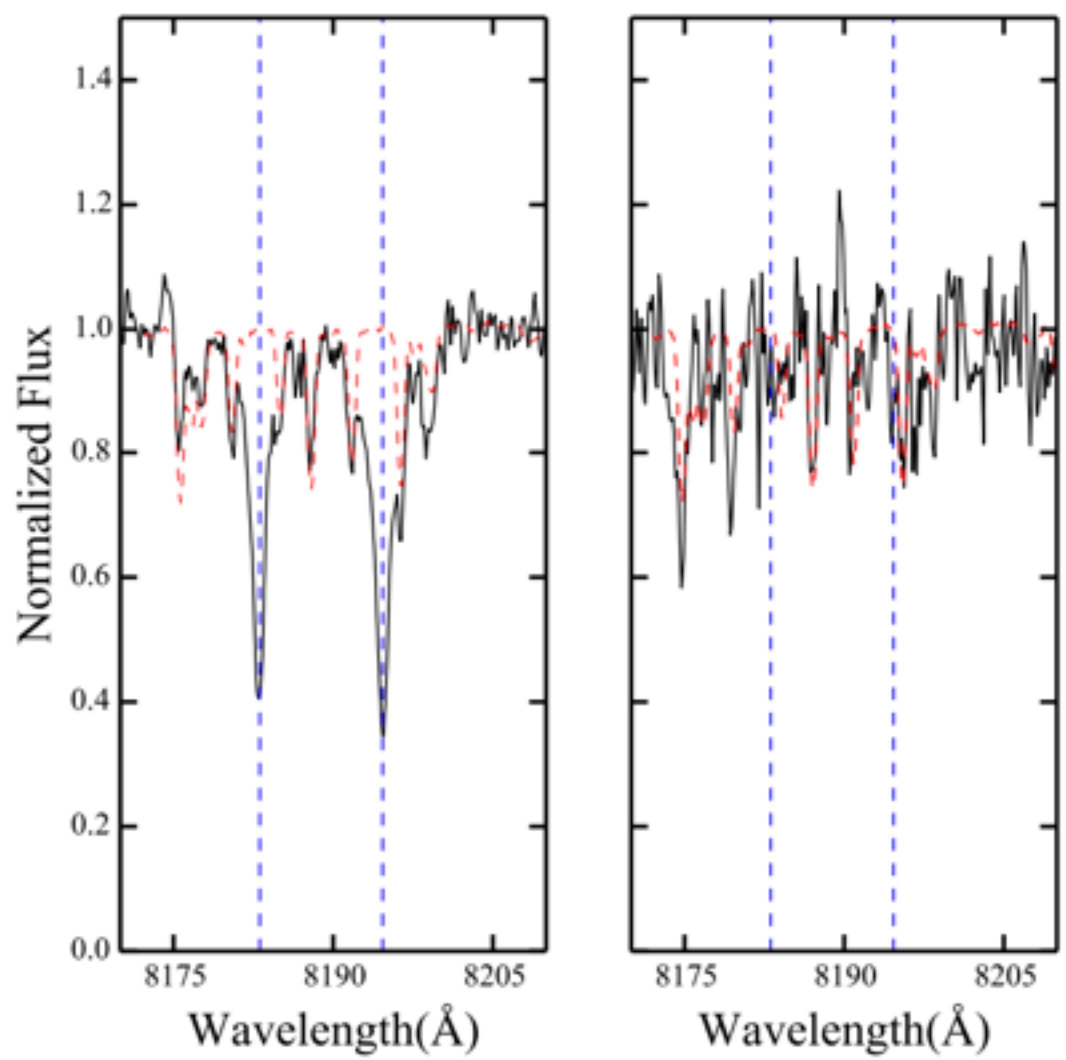


Garrison-Kimmel et al. 2014, MNRAS, 444, 222

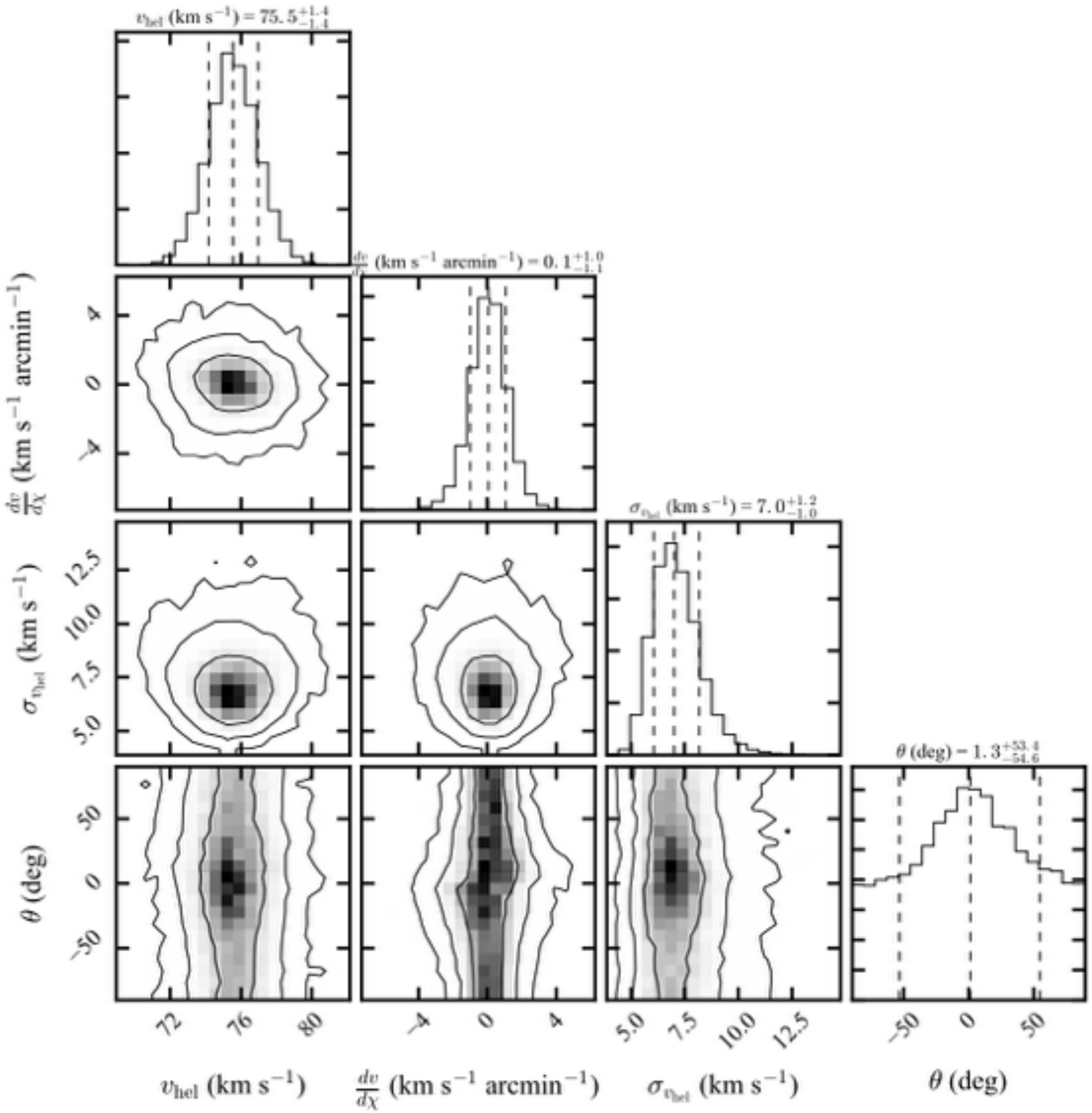
Velocity precision



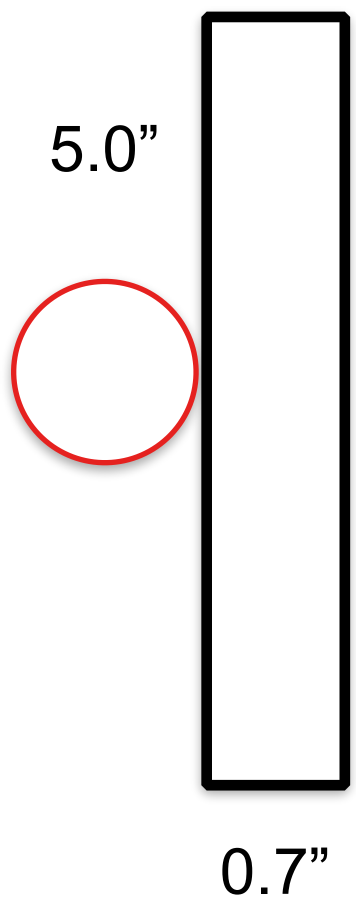
Giant-Dwarf separation



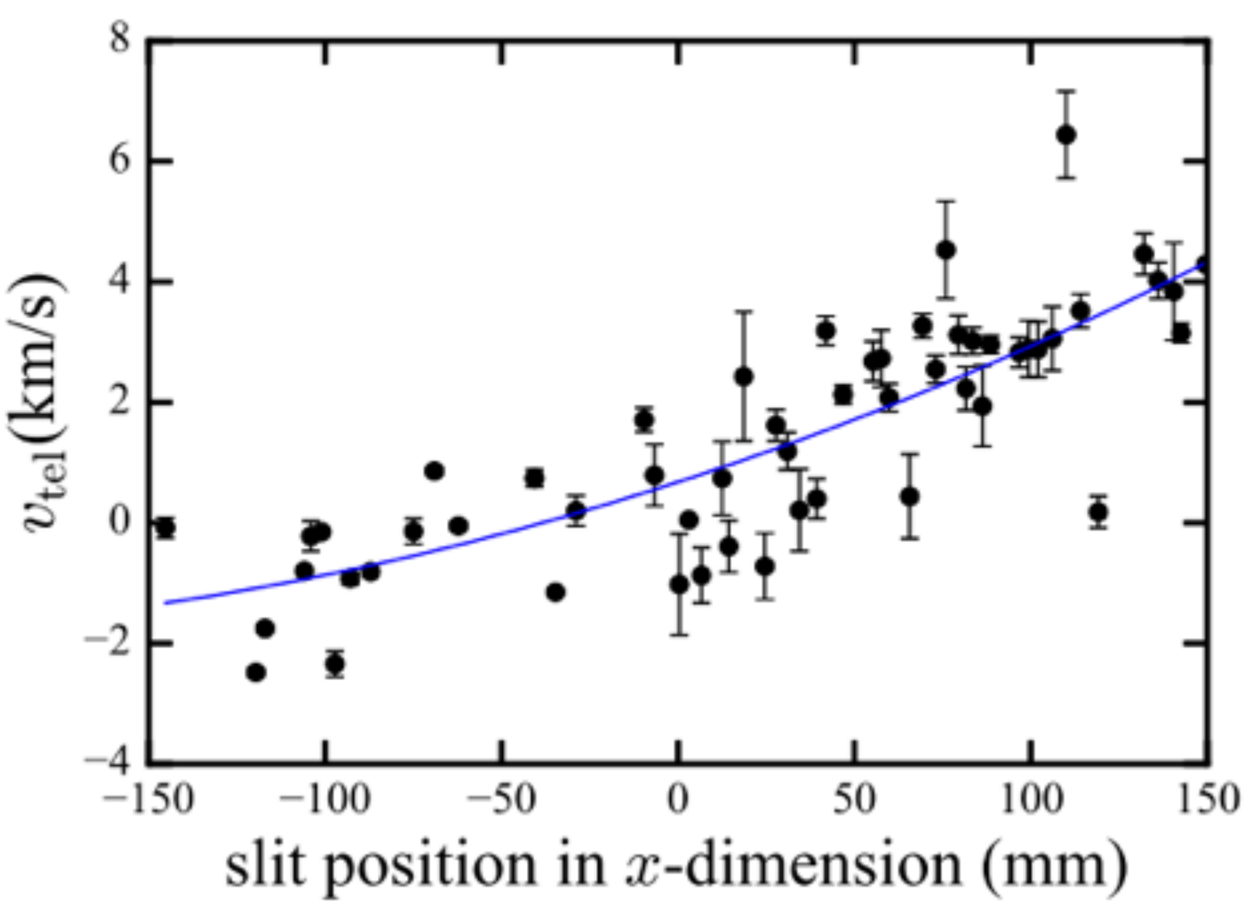
No Velocity Gradient



One example: slit mis-centering



- Drift a bright star across the slit at a constant rate
- Uniformly fill the slit
- Derive a velocity correction for every candidate star on the mask using Fraunhofer A-band



Li et al. (2017)

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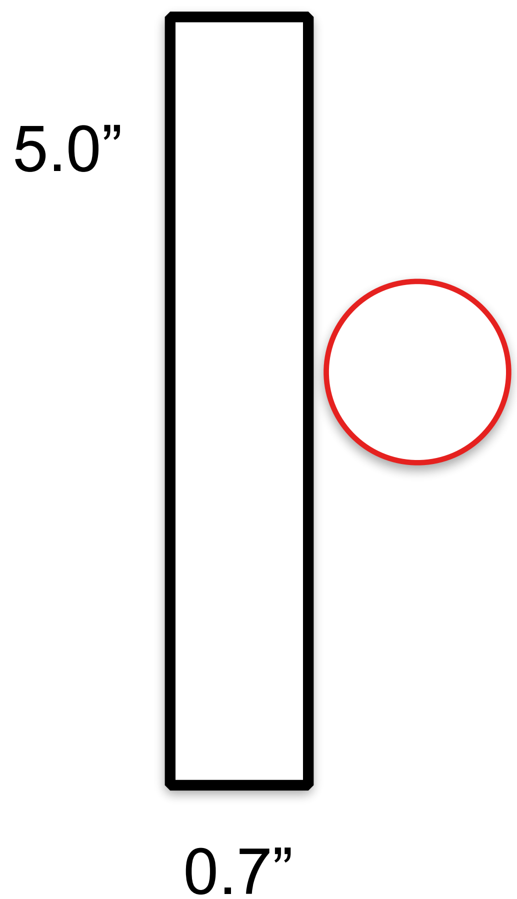

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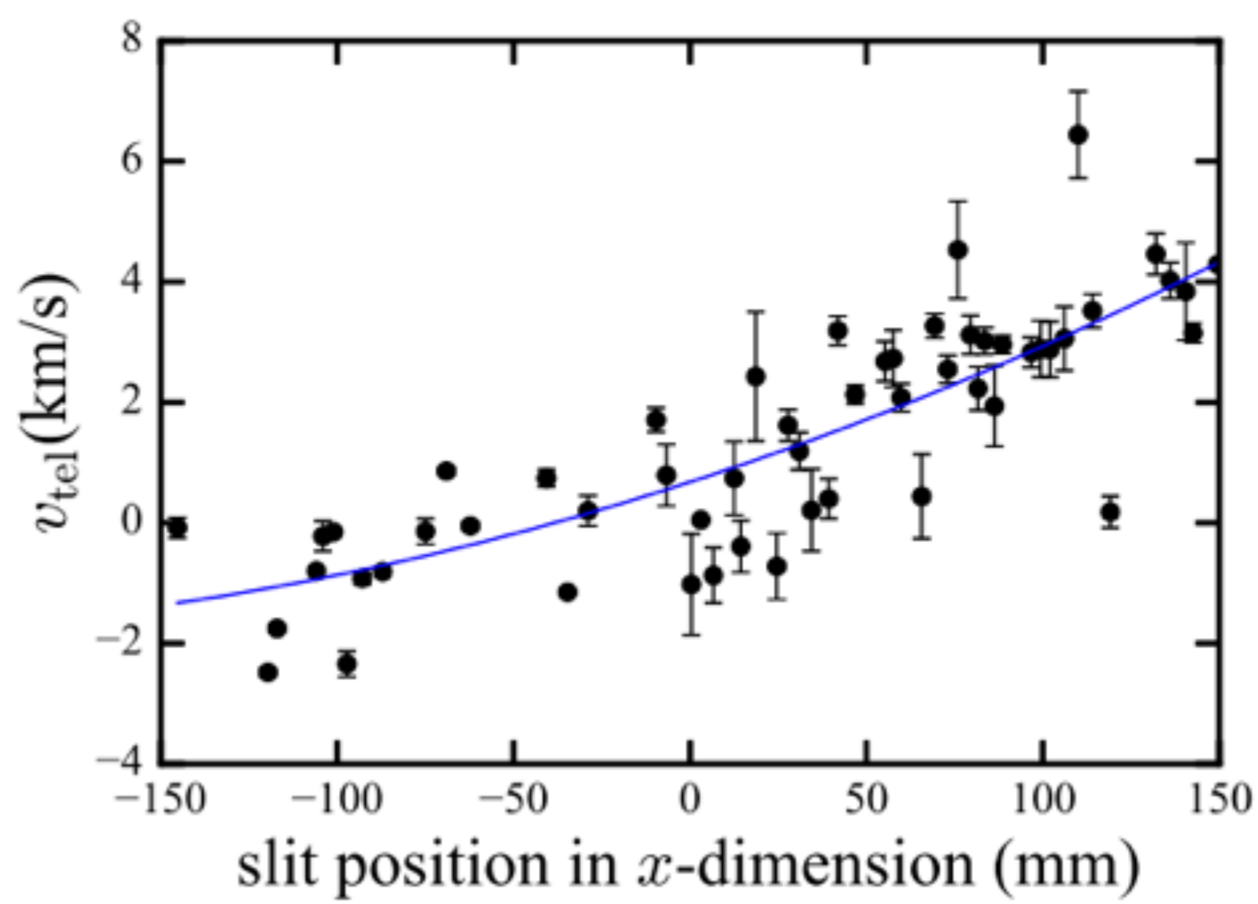
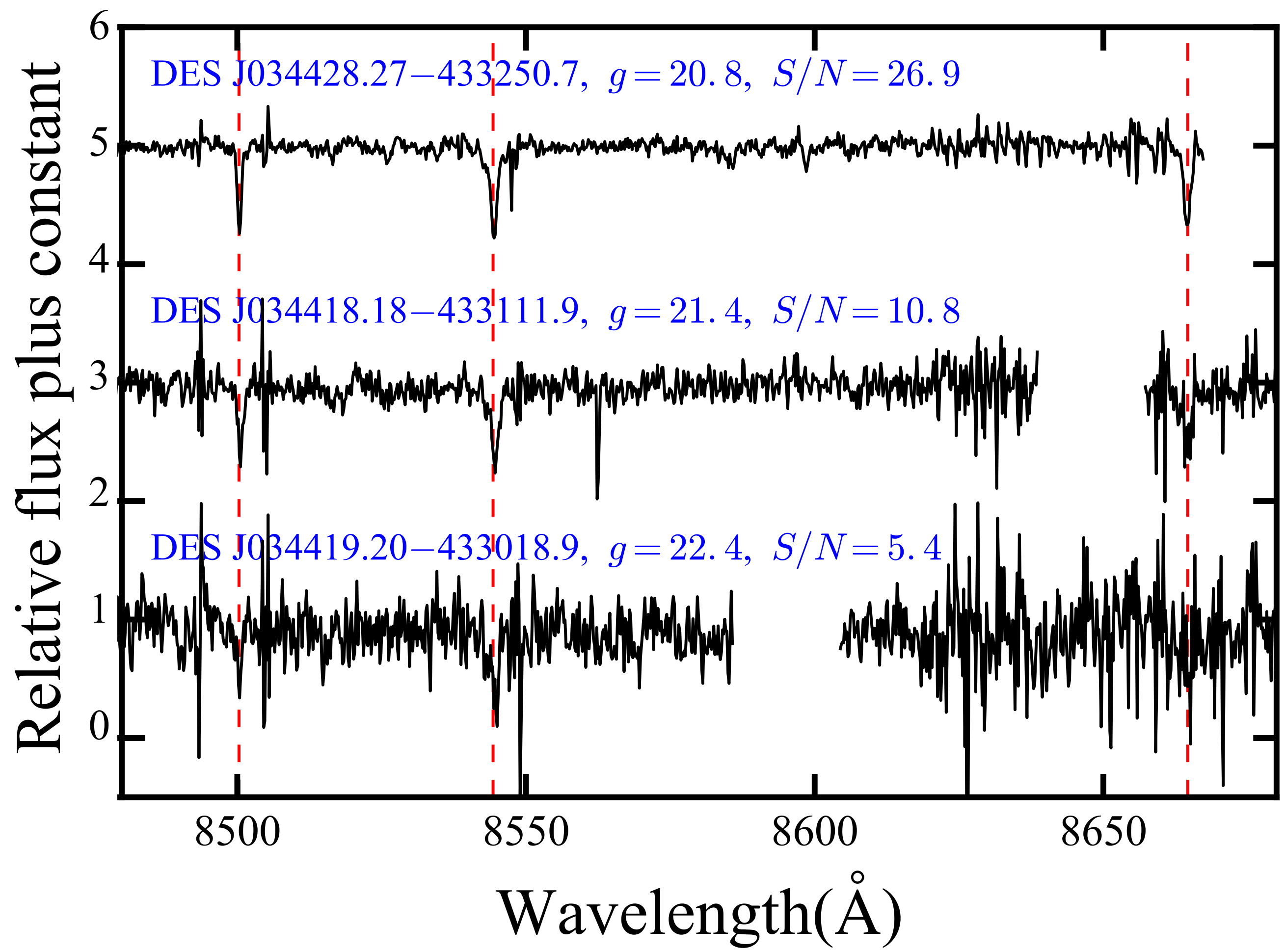


Li et al. (2017)

1D Stellar Spectra

Derive the velocity and its statistical uncertainty using a Markov Chain Monte Carlo (MCMC) sampler and a likelihood function:

$$\log \mathcal{L} = -\frac{1}{2} \sum_{\lambda=\lambda_1}^{\lambda_2} \frac{[f_s(\lambda) - f_{\text{std}}\left(\lambda(1+\frac{v}{c})\right)]^2}{\sigma_s^2(\lambda)}.$$



9 hr integration time

Ca Triplet

Li et al. (2017)

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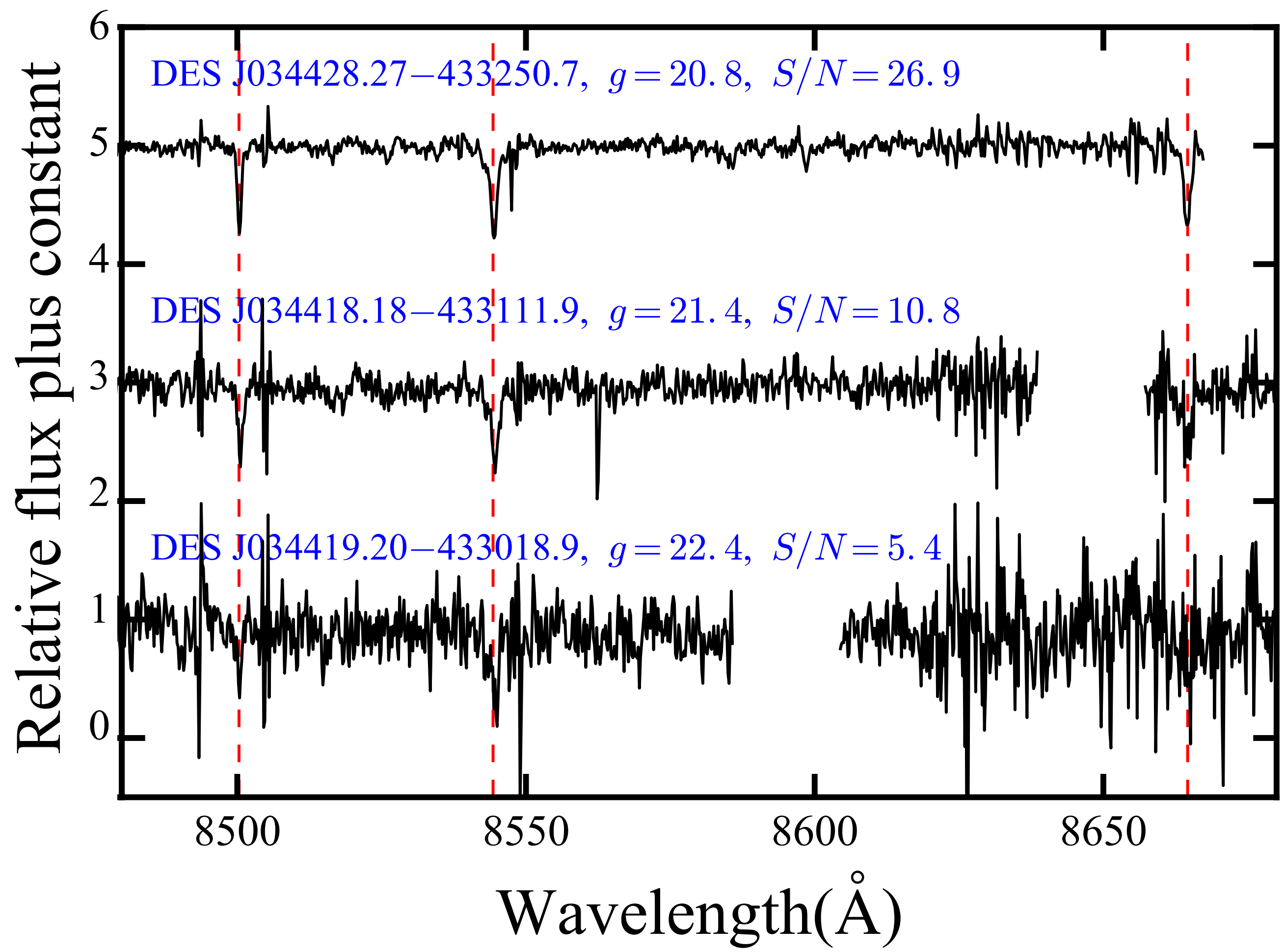

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