Small Galaxies, Big Science:
The Booming Industry of Milky Way Satellite Galaxies

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David N. Schramm Fellow
Fermilab

Berkeley Cosmology Seminar
January 30, 2018

Outline

- Dark Matter and Dwarf Galaxies
- Search for the Darkest Galaxies
- Search for Dark Matter Annihilation
- Future Prospects

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- Search for the Darkest Galaxies
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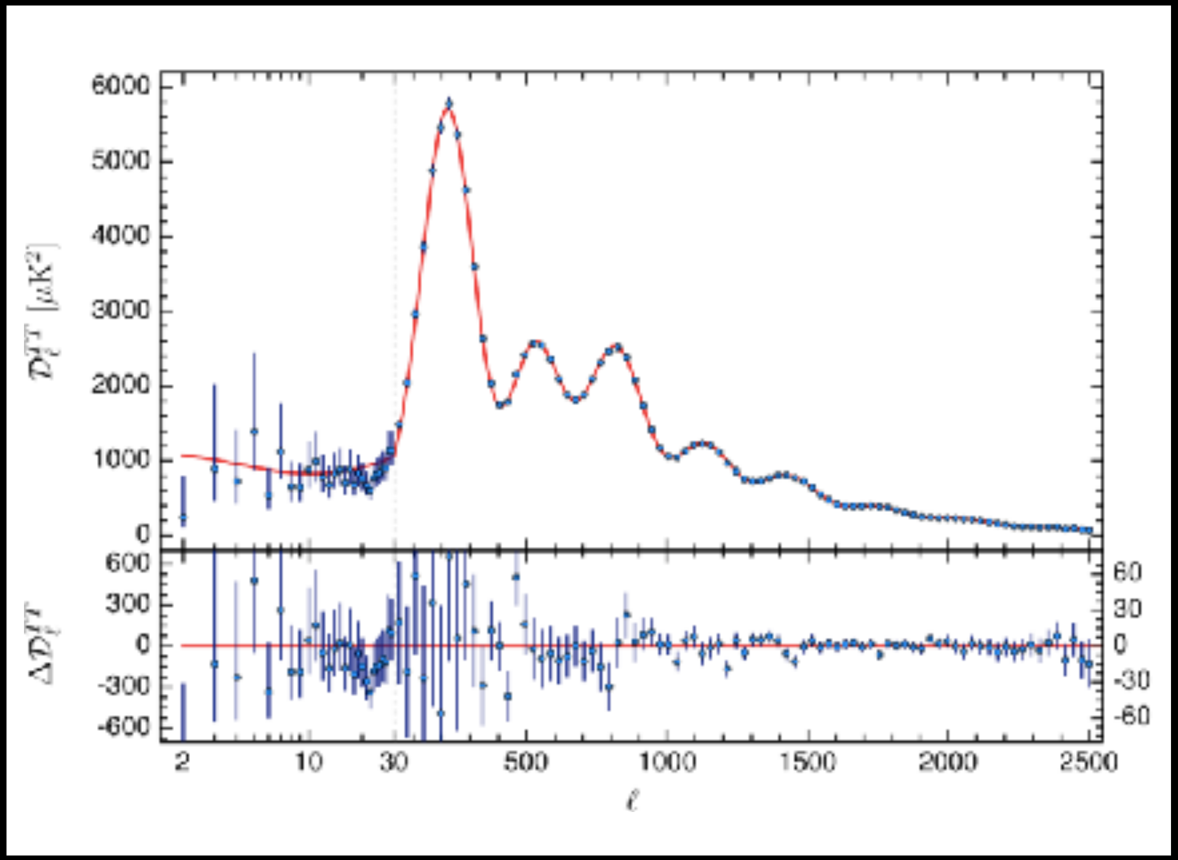
- Future Prospects

The Cosmic Frontier

Fundamental Physics

Dark Matter
Dark Energy
Inflation
Baryon Asymmetry
Neutrino Mass

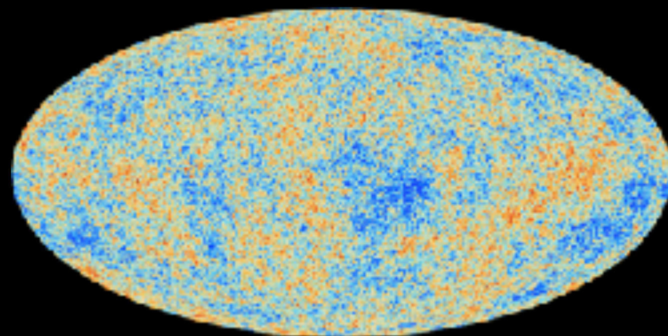
Precision Measurements



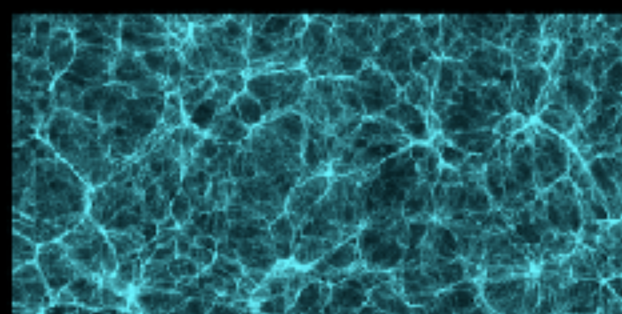
Planck Collaboration (2016)

Composition of the Universe

Observable Universe

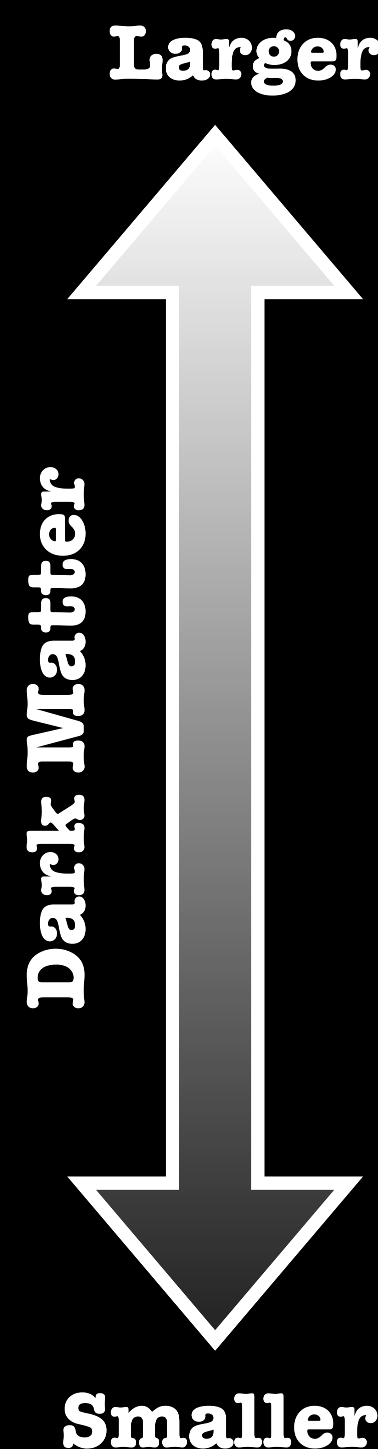


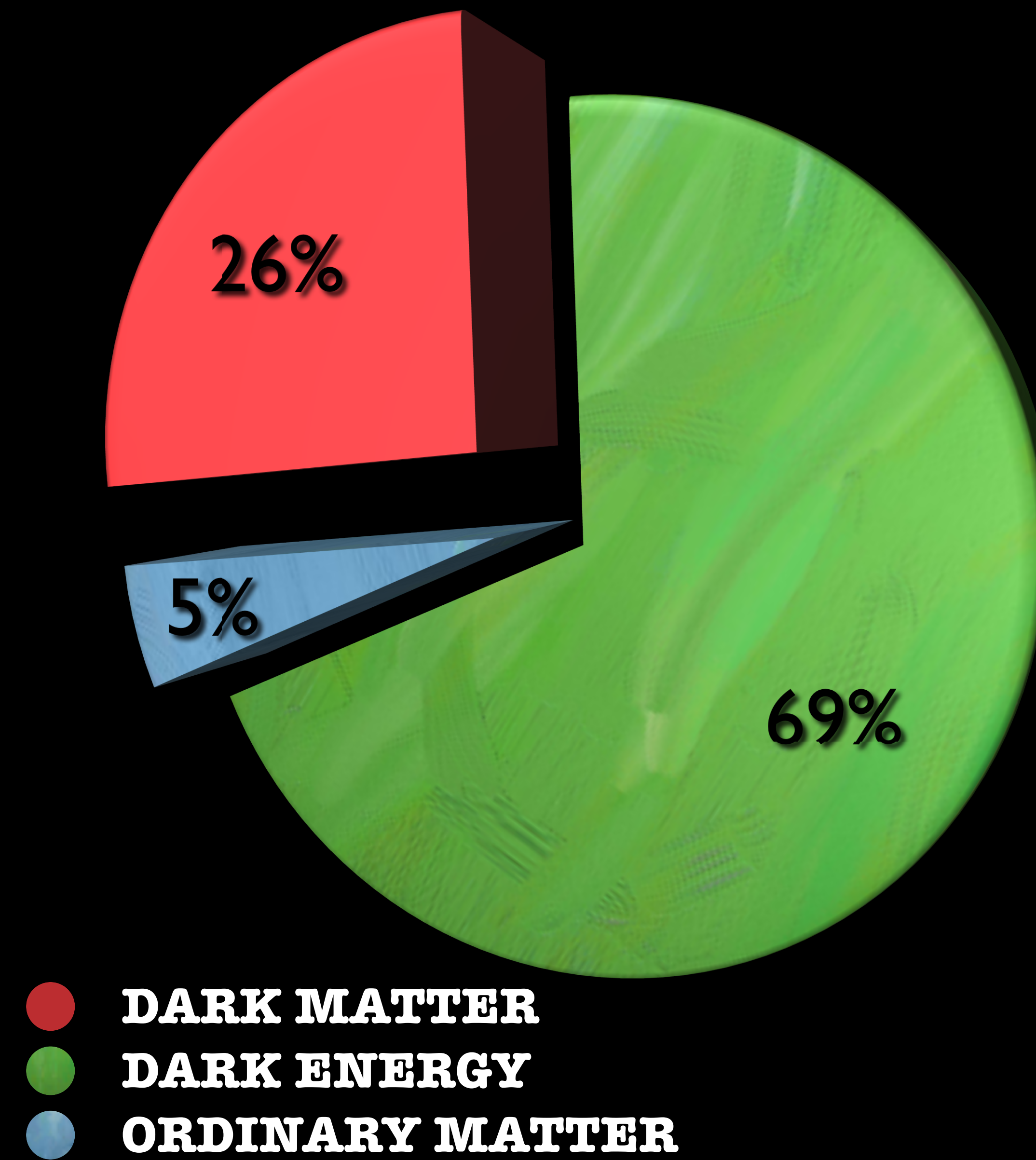
Clusters of Clusters



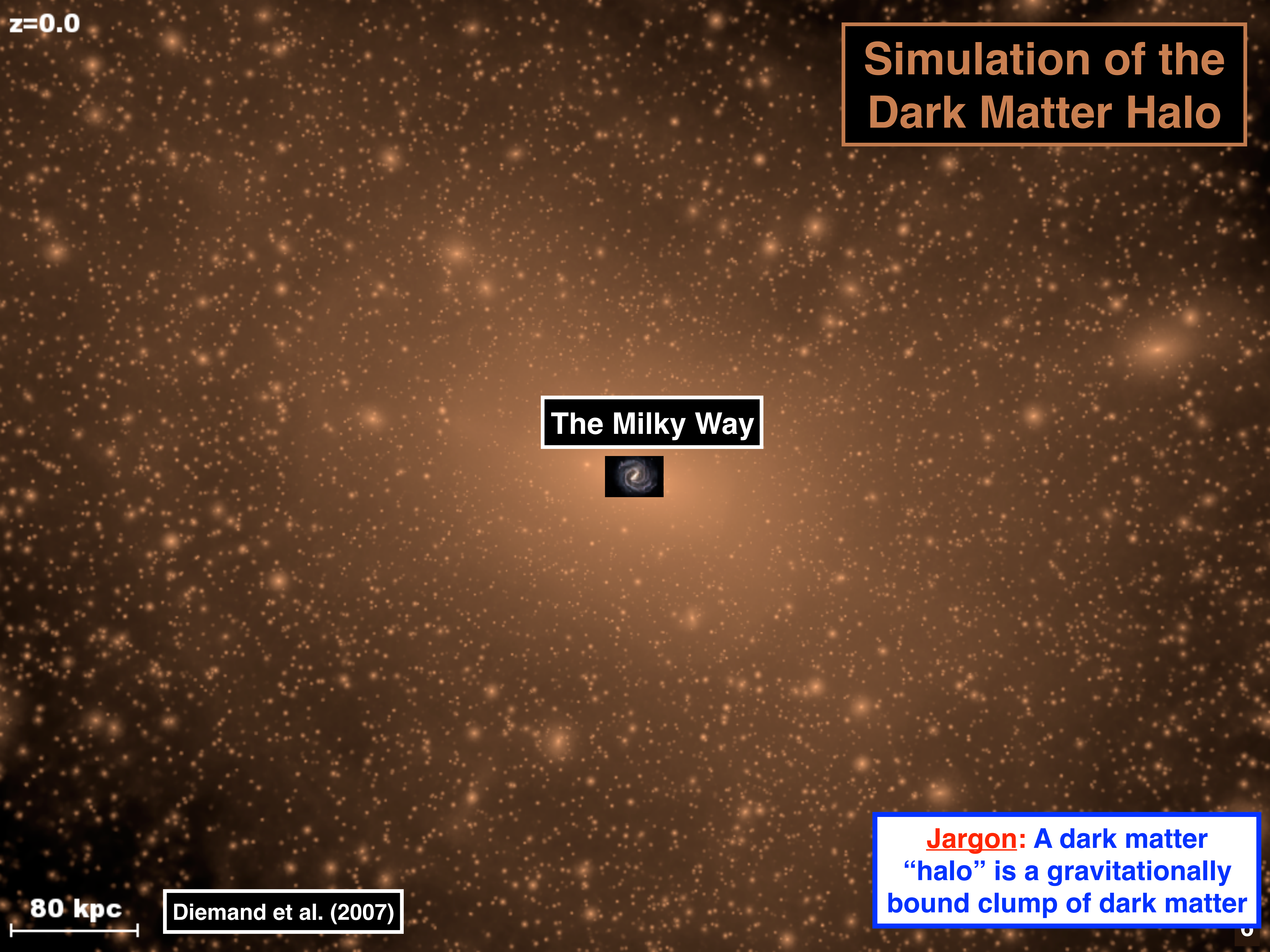
Clusters of Galaxies

Individual Galaxies

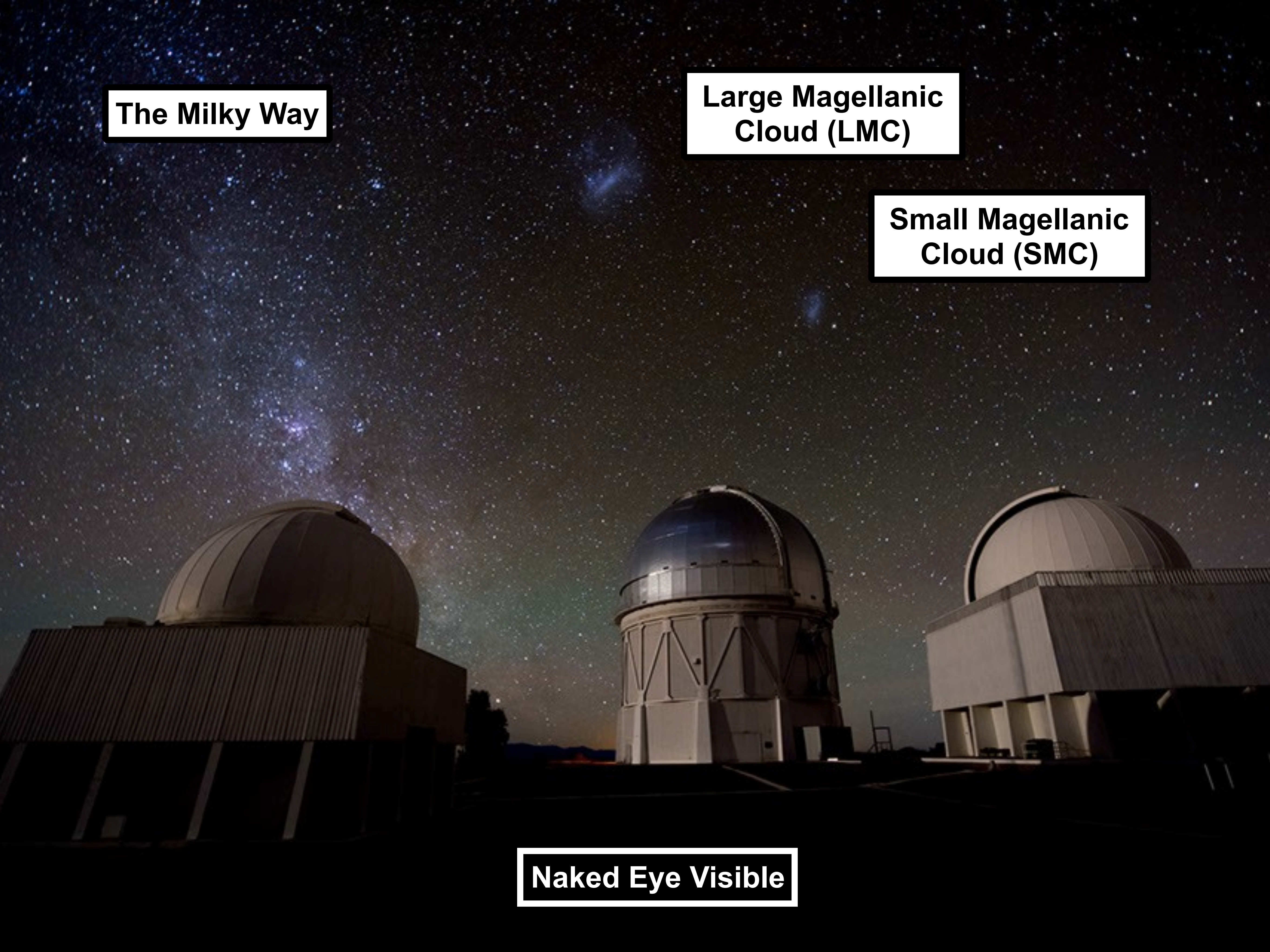




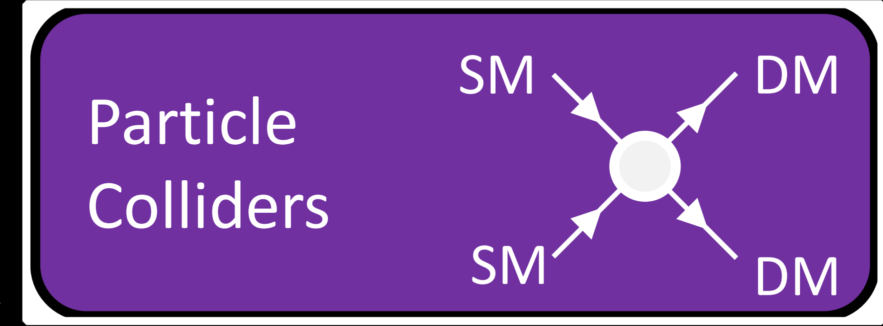
Plank Collaboration (2016)



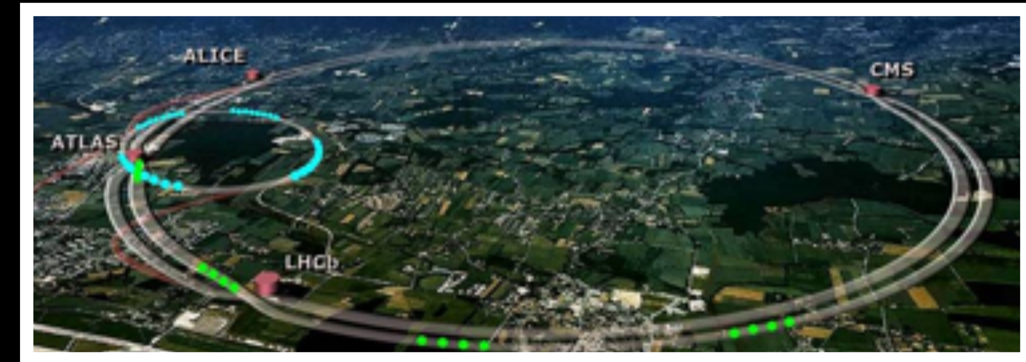
z=0.0
Simulation of the Dark Matter Halo
The Milky Way
80 kpc
Diemand et al. (2007)
Jargon: A dark matter “halo” is a gravitationally bound clump of dark matter

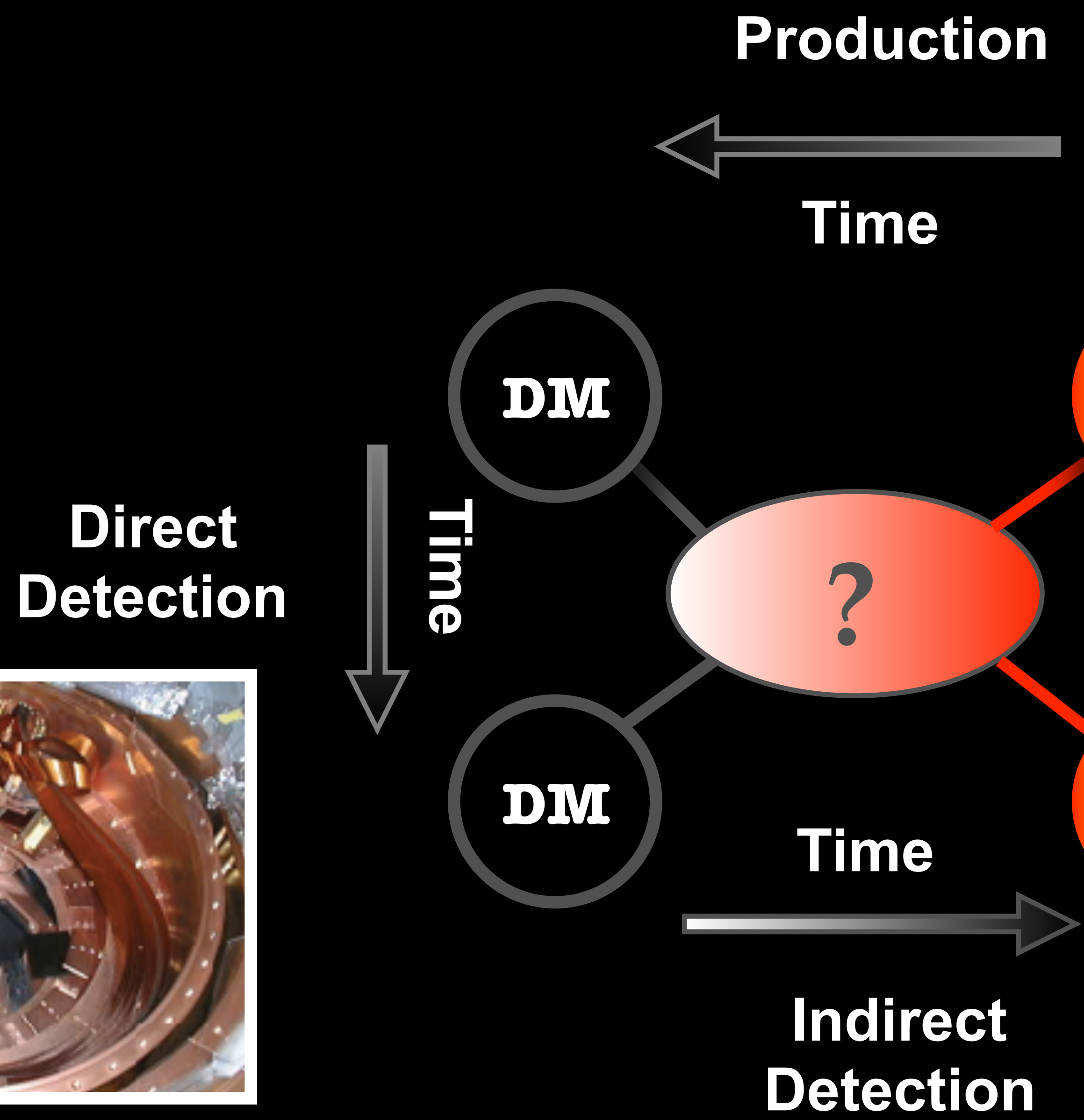

The Milky Way
Large Magellanic Cloud (LMC)
Small Magellanic Cloud (SMC)
Naked Eye Visible

Hunt for Particle Dark Matter

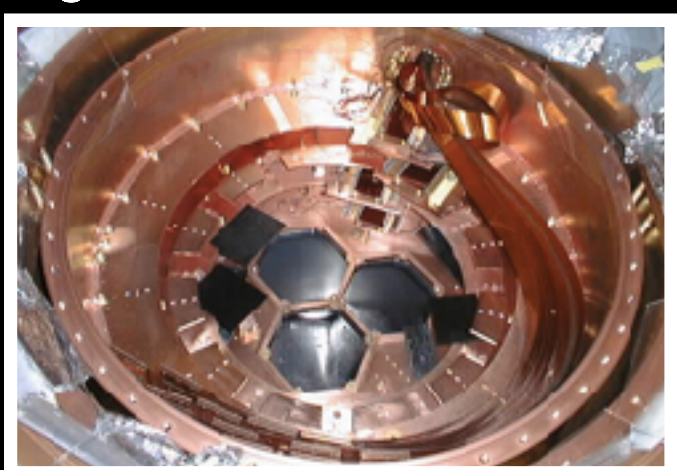


e.g., LHC

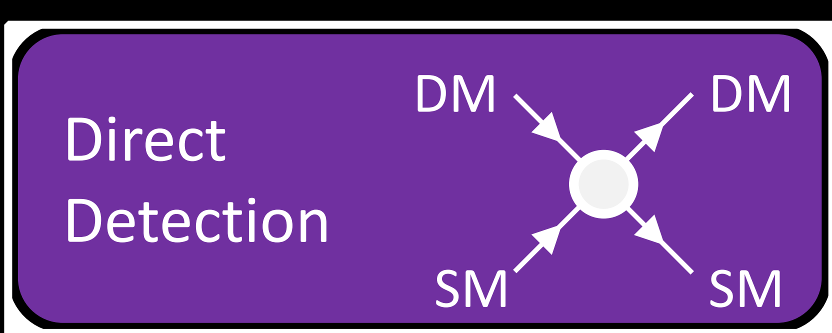


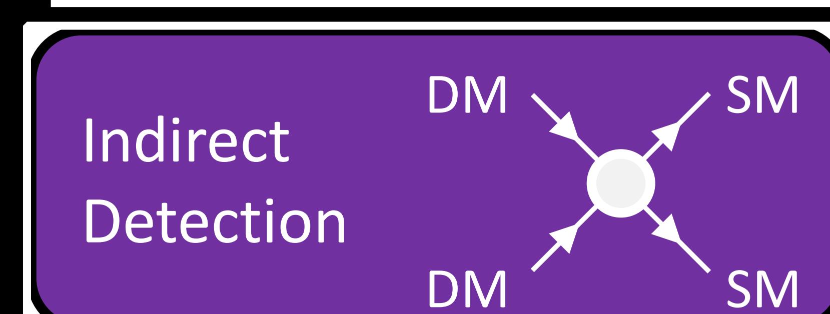


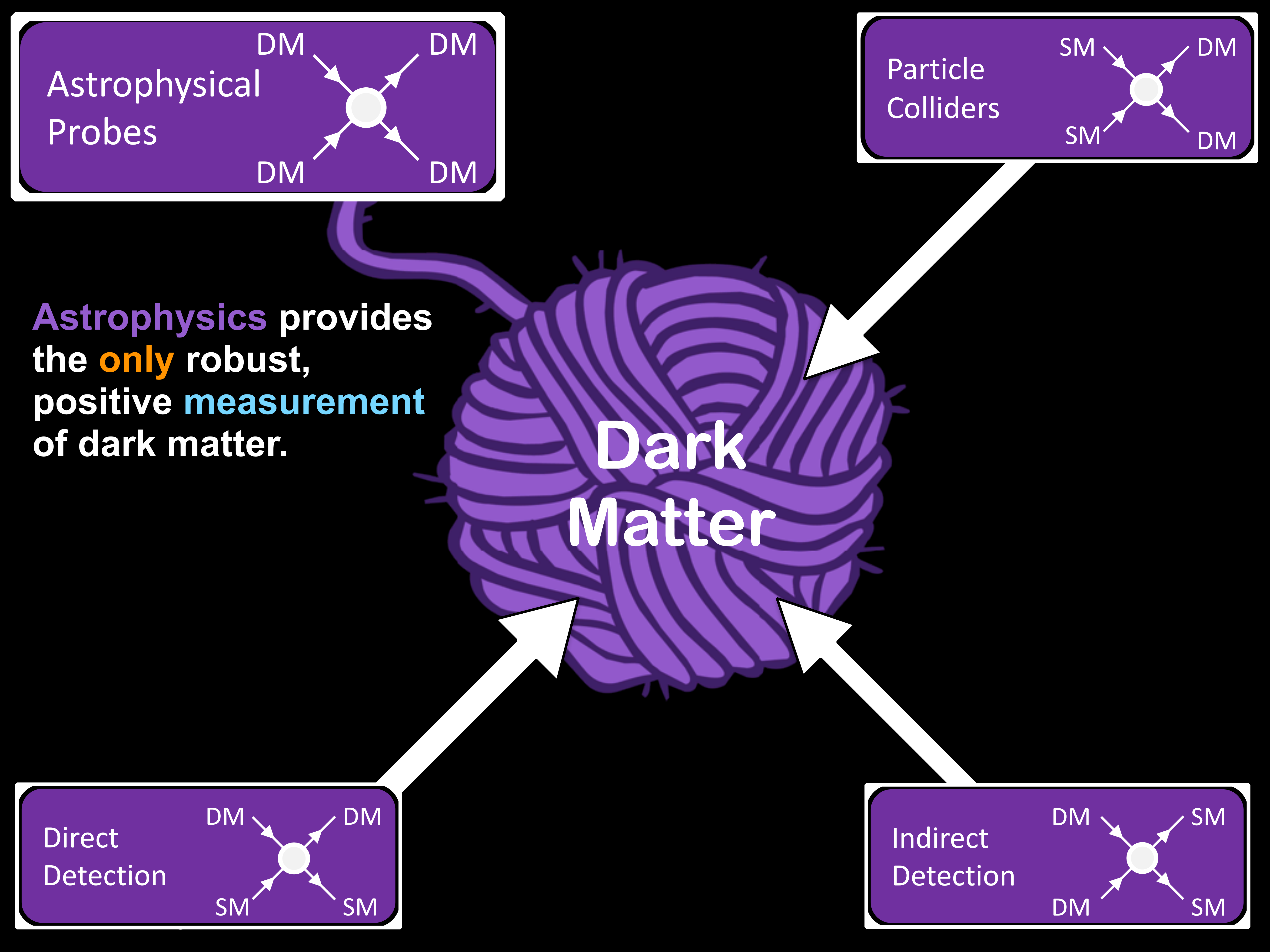
e.g., CDMS

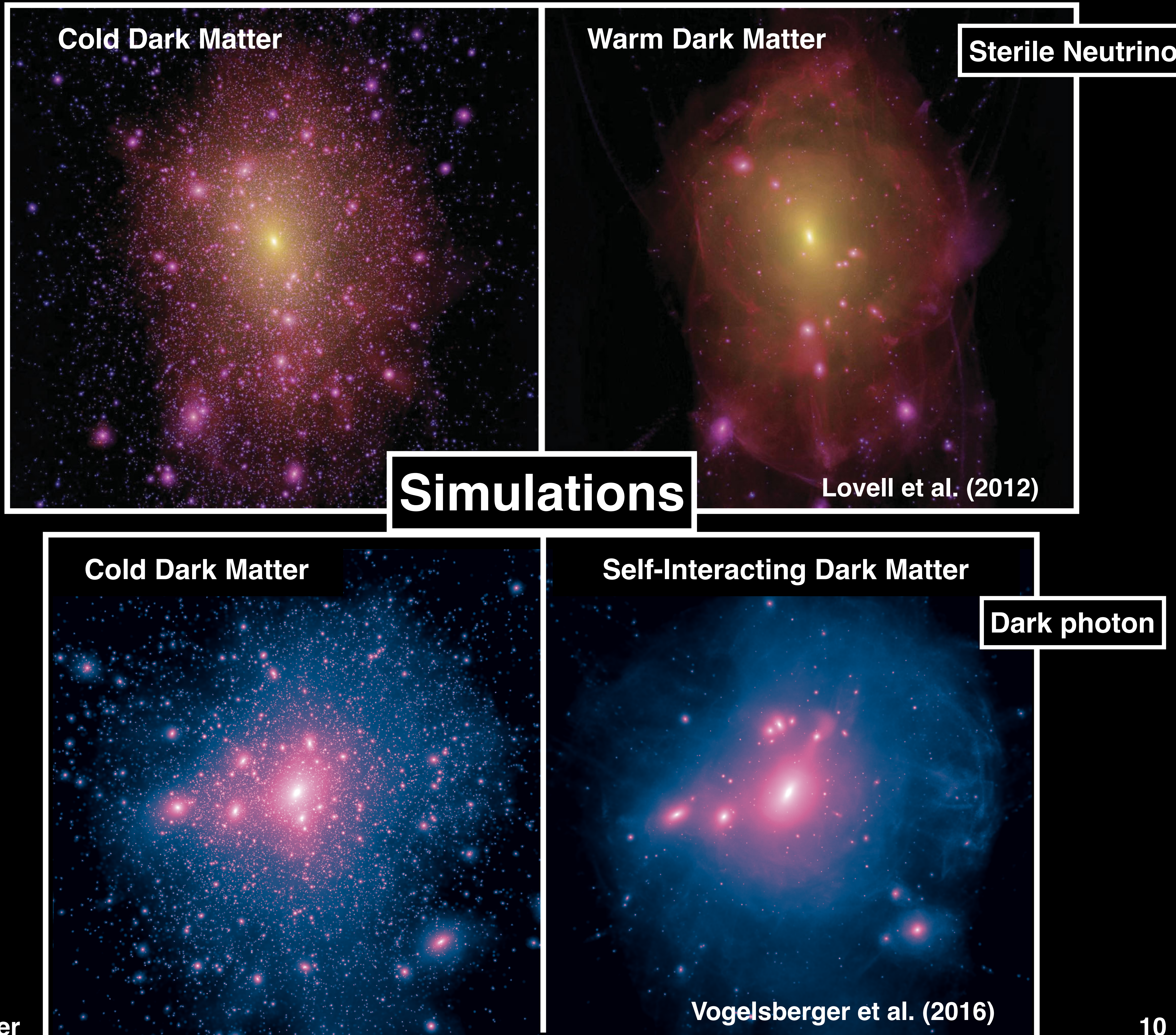


e.g., Fermi-LAT



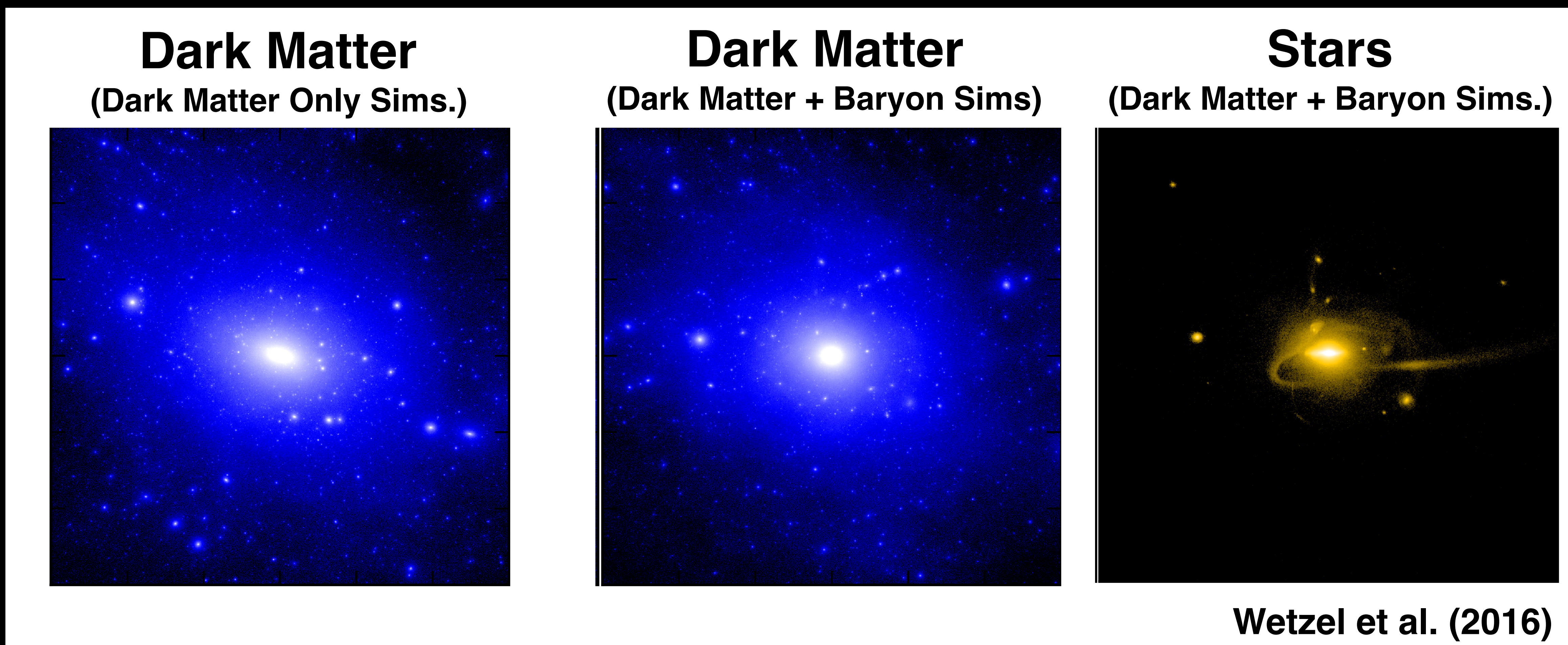



Astrophysical Probes
DM
DM
DM
DM
Particle Colliders
SM
DM
SM
DM
Astrophysics provides the only robust, positive measurement of dark matter.
Dark Matter
Direct Detection
DM
DM
SM
SM
Indirect Detection
DM
SM
DM
SM


Cold Dark Matter
Warm Dark Matter
Sterile Neutrino
Simulations
Lovell et al. (2012)
Cold Dark Matter
Self-Interacting Dark Matter
Dark photon
Vogelsberger et al. (2016)

Beware of Baryons!

Baryons can also disrupt the smallest structures



Jargon: Astrophysicists use "baryons" to refer to all standard model components.

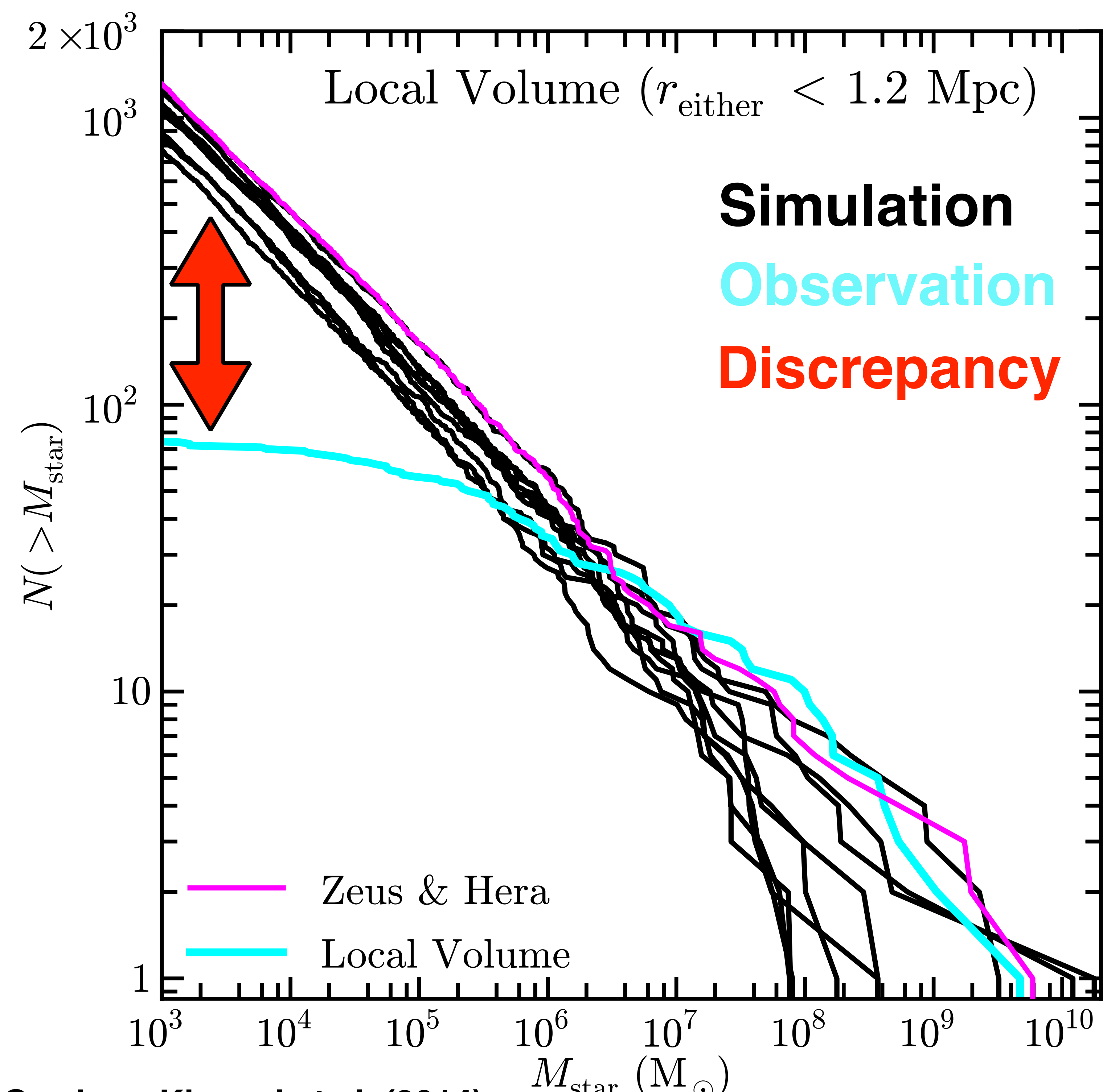
Recent simulations have begun to robustly include baryonic physics (i.e., FIRE, APOSTLE, EAGLE)

The Missing Satellites "Problem"

Simulations predict more dark matter subhalos than the galaxies we see

Where are the smallest galaxies?

Is this dark matter physics or astrophysics?



Garrison-Kimmel et al. (2014)

Alex Drlica-Wagner

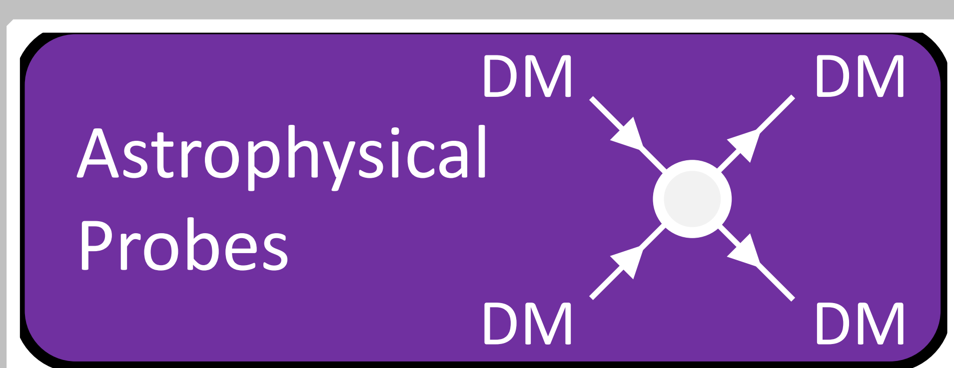
Primary Research Goal

Understand the fundamental nature of dark matter by studying the smallest and most dark-matter-dominated galaxies.

Avenues of Attack

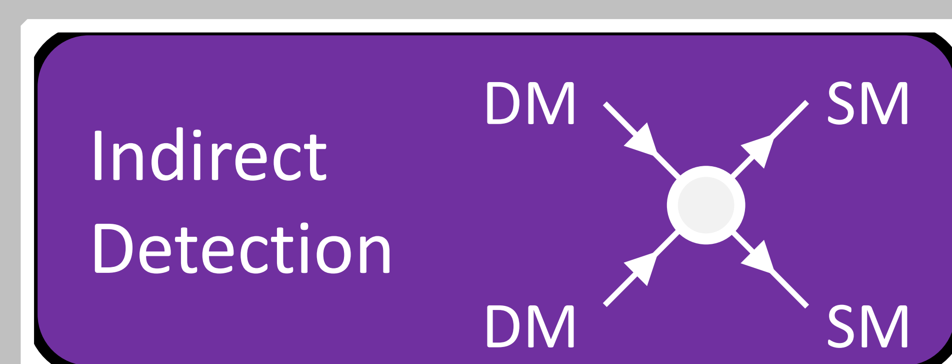
Astrophysical Probes

Test the **cold**, **collisionless** dark matter paradigm directly **using gravity** at the smallest cosmic scales



Indirect Detection

Search for the products of dark matter **annihilation** or **decay** in nearby regions of high dark matter density



Outline

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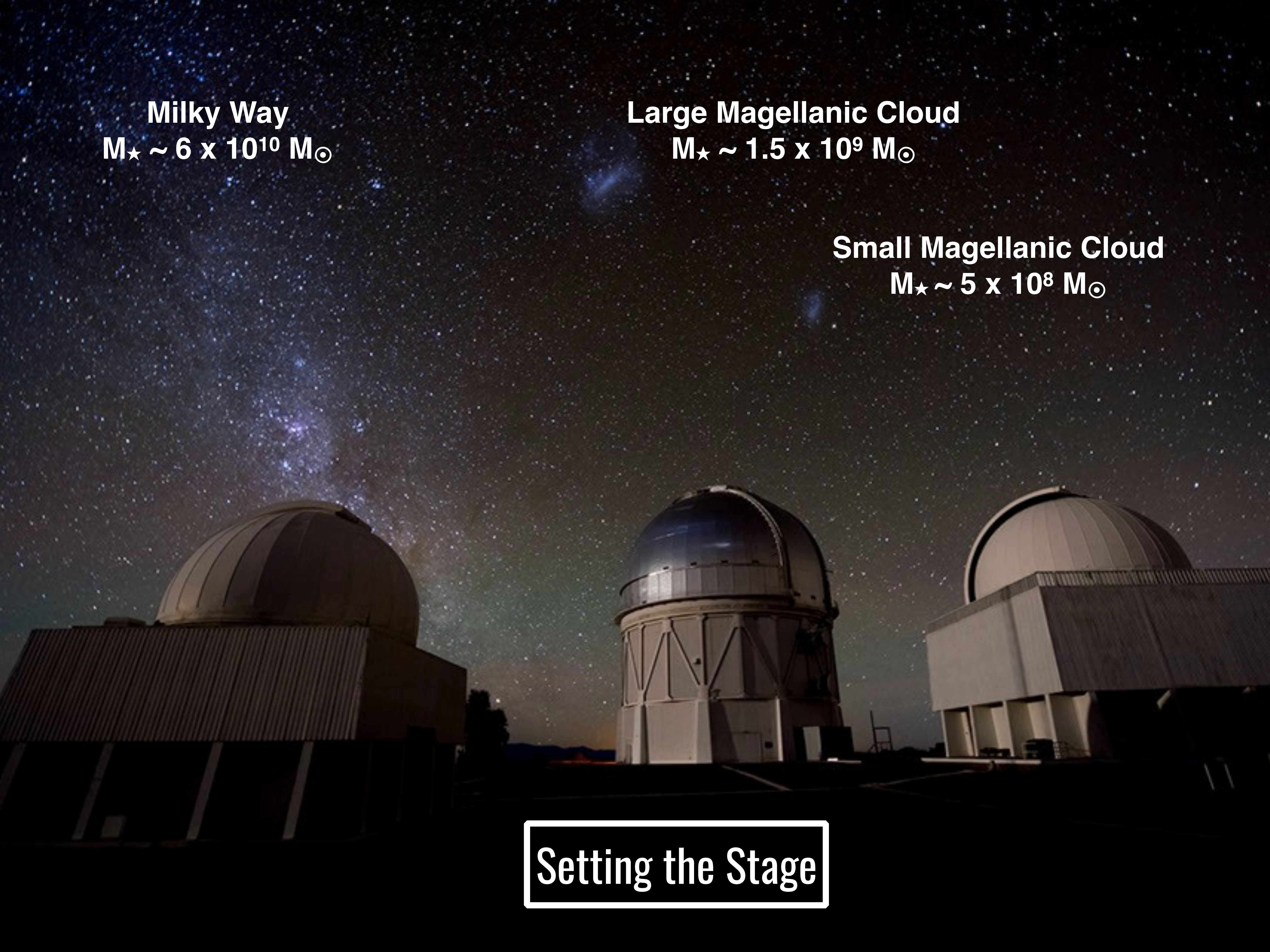
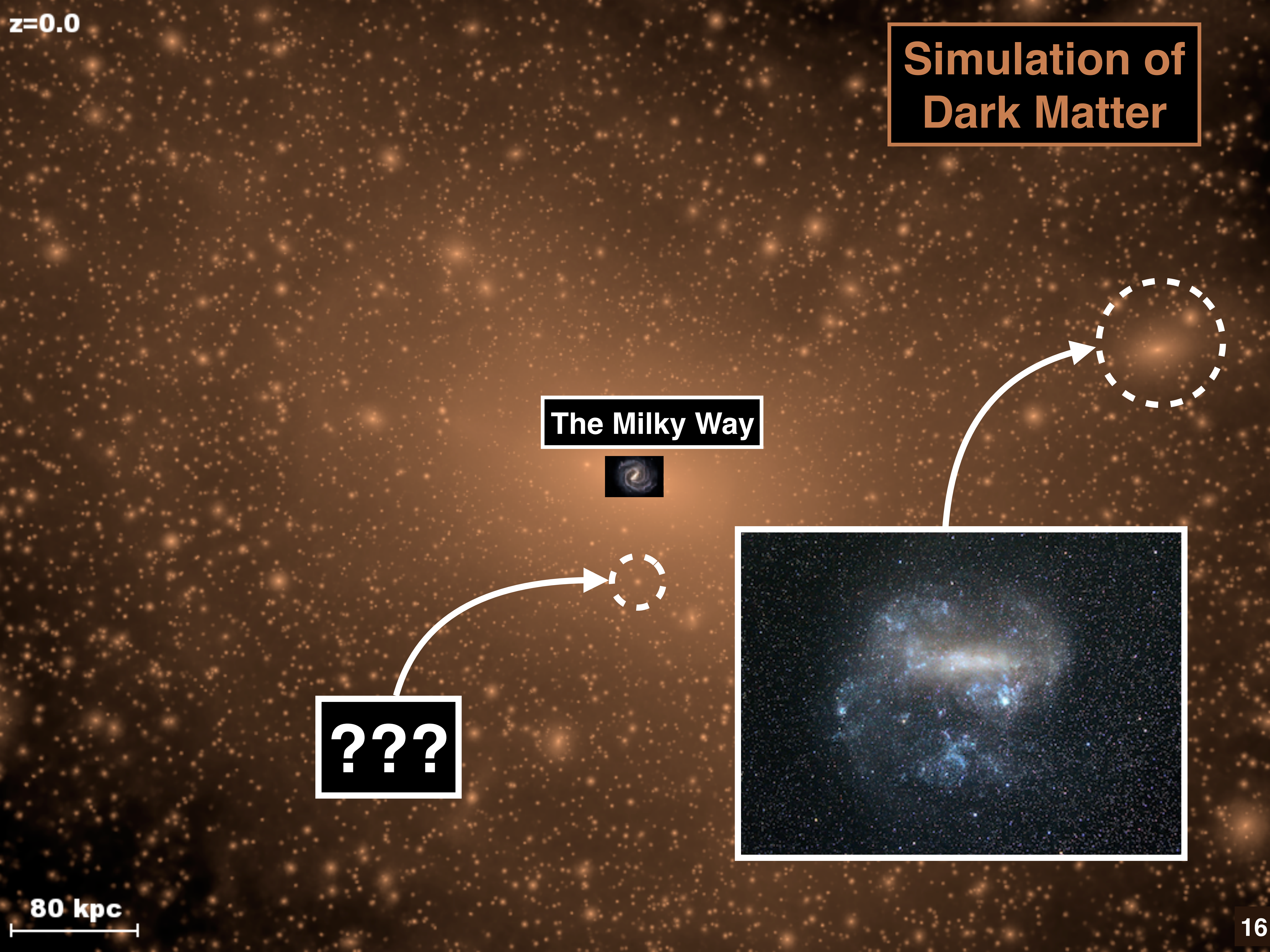
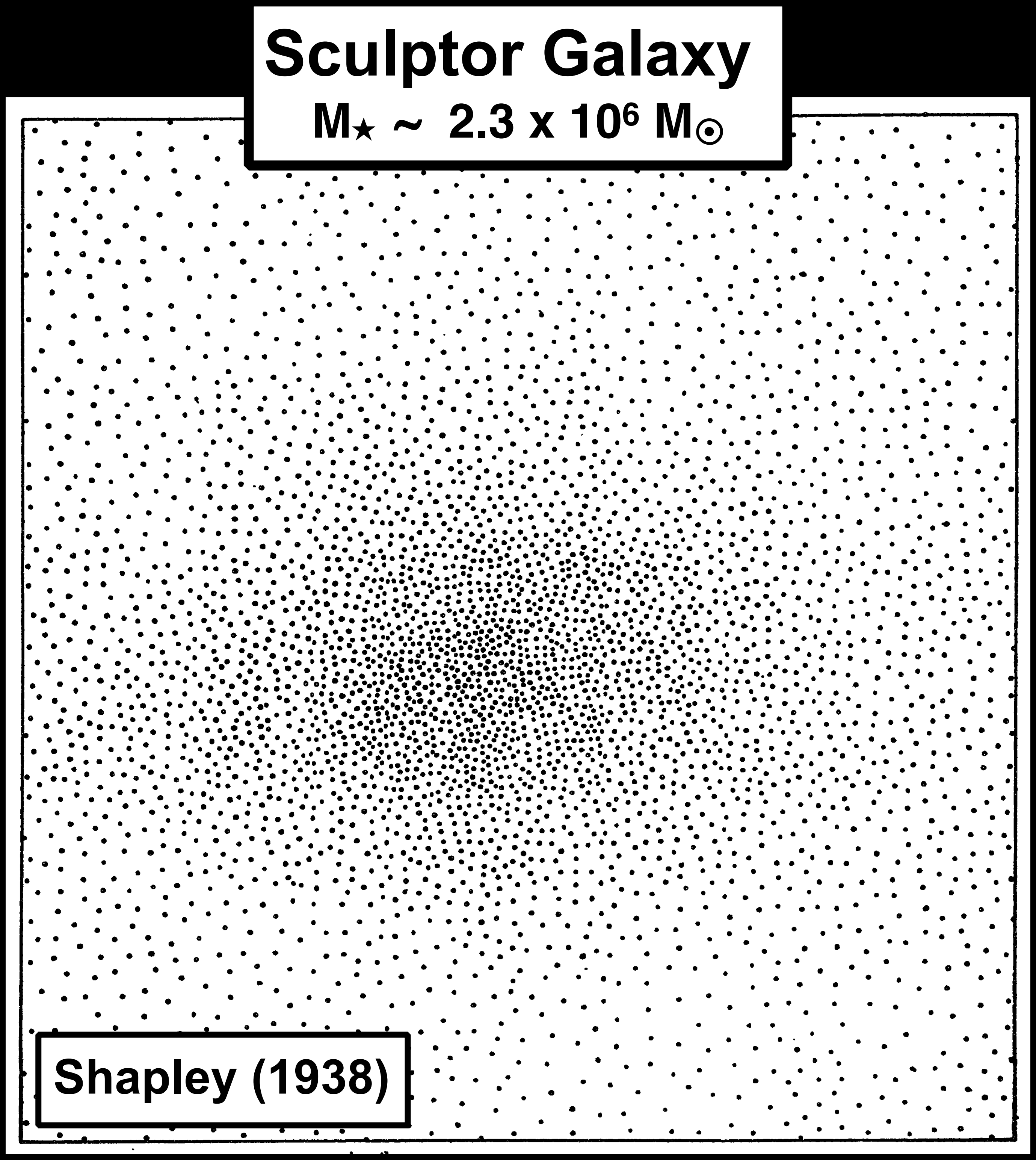
- Search for the Darkest Galaxies
- Search for Dark Matter Annihilation
- Future Prospects

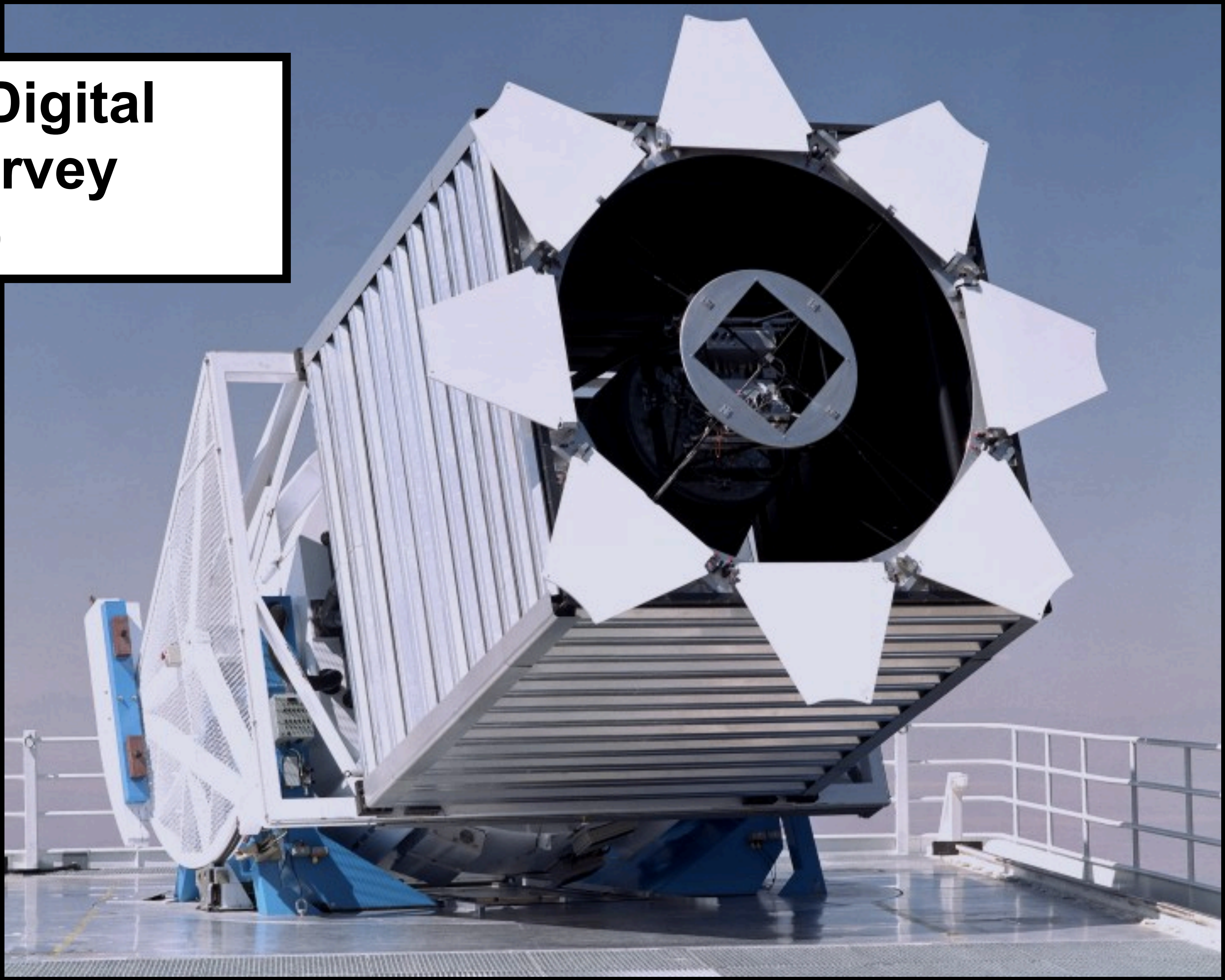

Milky Way
$M_\star \sim 6 \times 10^{10}\ M_\odot$
Large Magellanic Cloud
$M_\star \sim 1.5 \times 10^{9}\ M_\odot$
Small Magellanic Cloud
$M_\star \sim 5 \times 10^{8}\ M_\odot$
Setting the Stage


z=0.0
Simulation of Dark Matter
The Milky Way
???
80 kpc


Sculptor Galaxy
M★ ~ 2.3 x 10⁶ M☉
Shapley (1938)

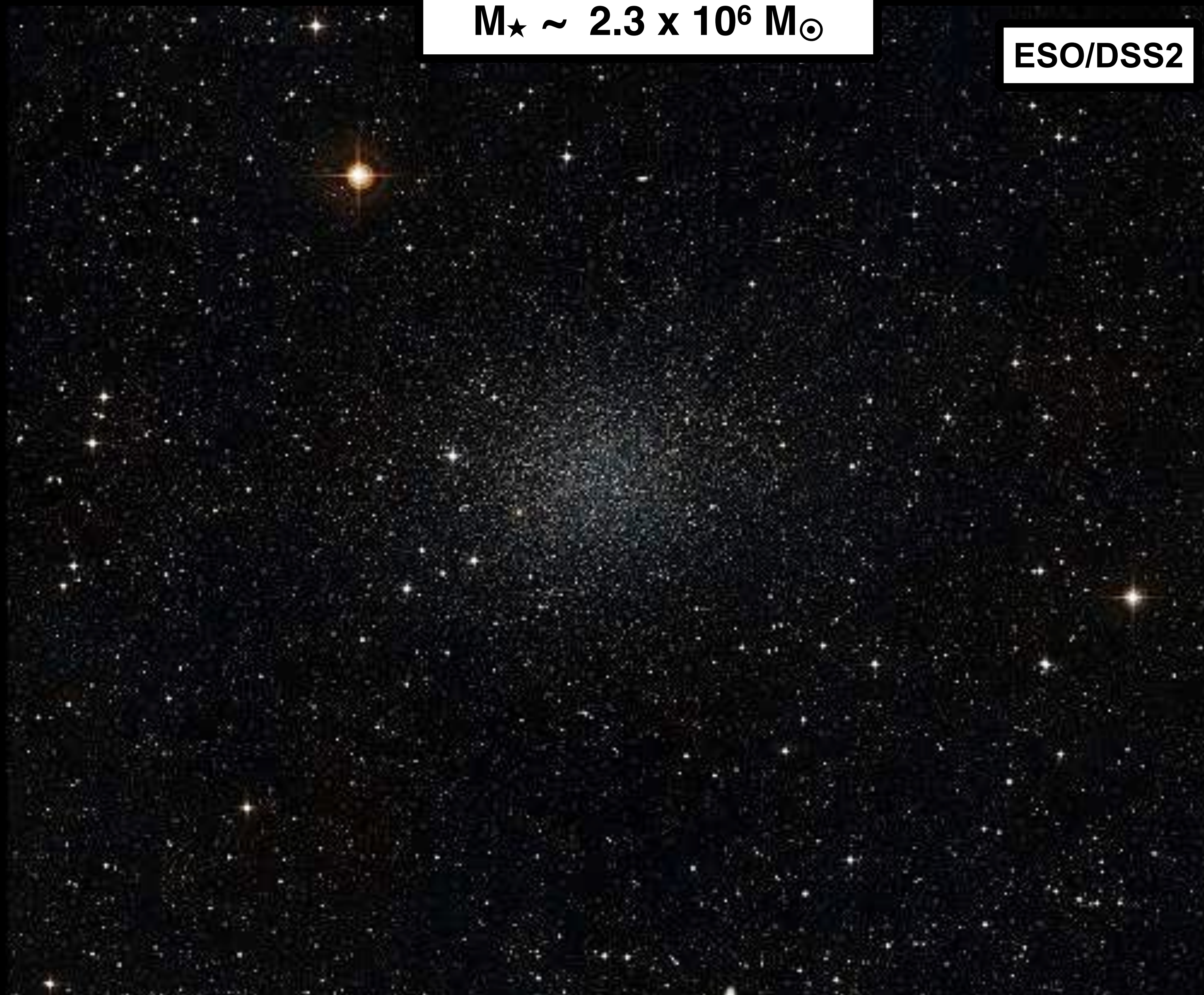
The Era of Precision Observations

Sloan Digital Sky Survey (SDSS)



Sculptor Galaxy

$M_\star \sim 2.3 \times 10^6\ M_\odot$



Stellar Isochrone

Stellar Brightness

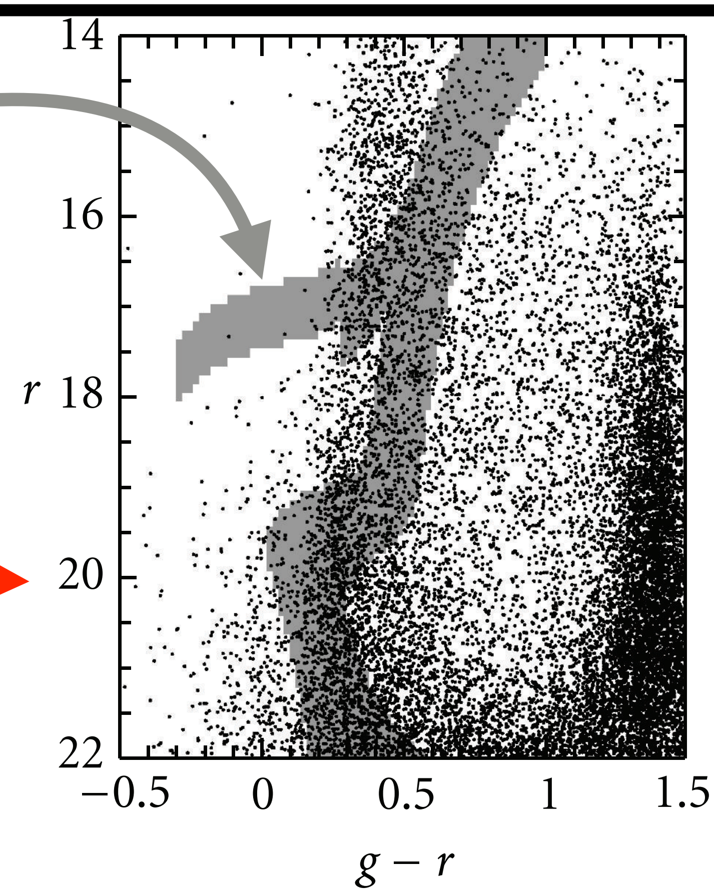
Stellar Color

Credit: NASA, ESA, Anderson & van der Marel (STScI) https://www.spacetelescope.org/videos/heic1017b/

Matched-Filter Searches

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

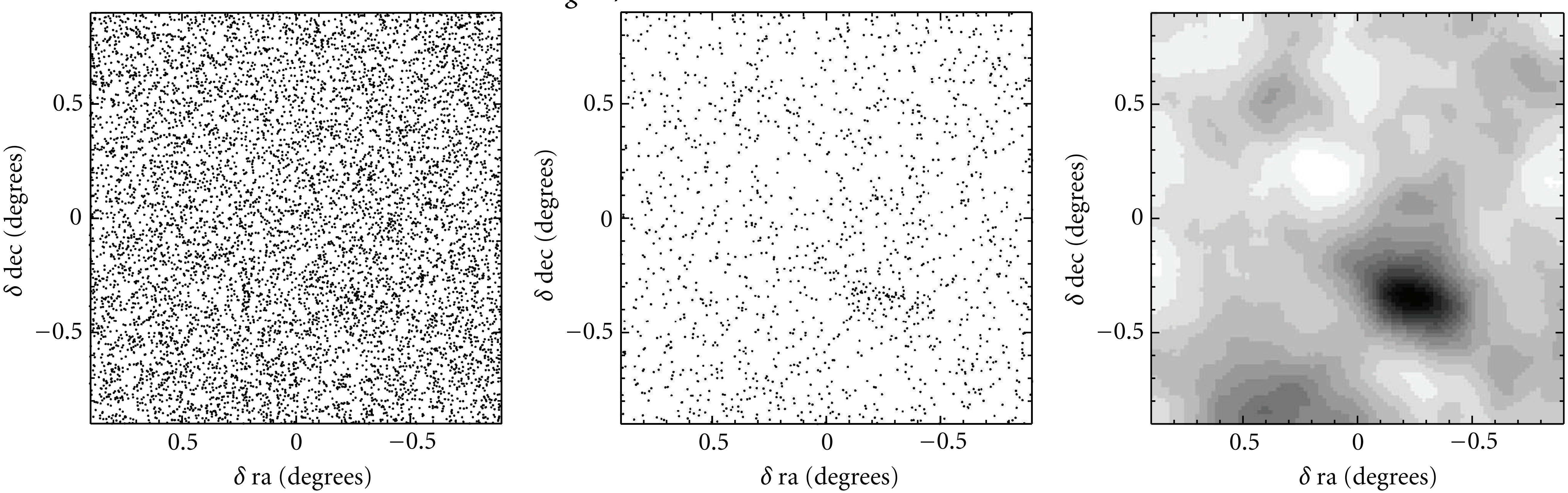
Stellar Isochrone

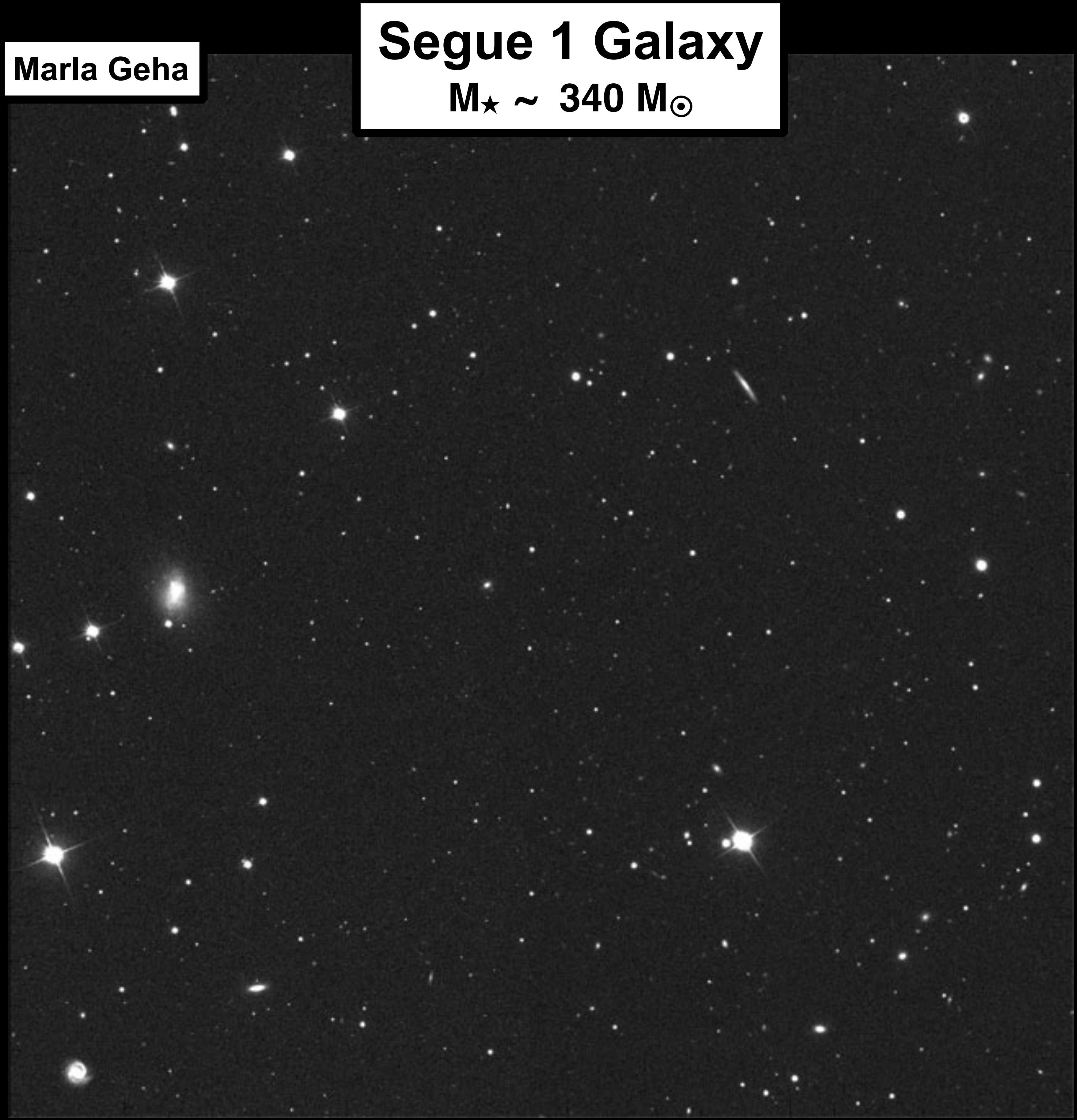


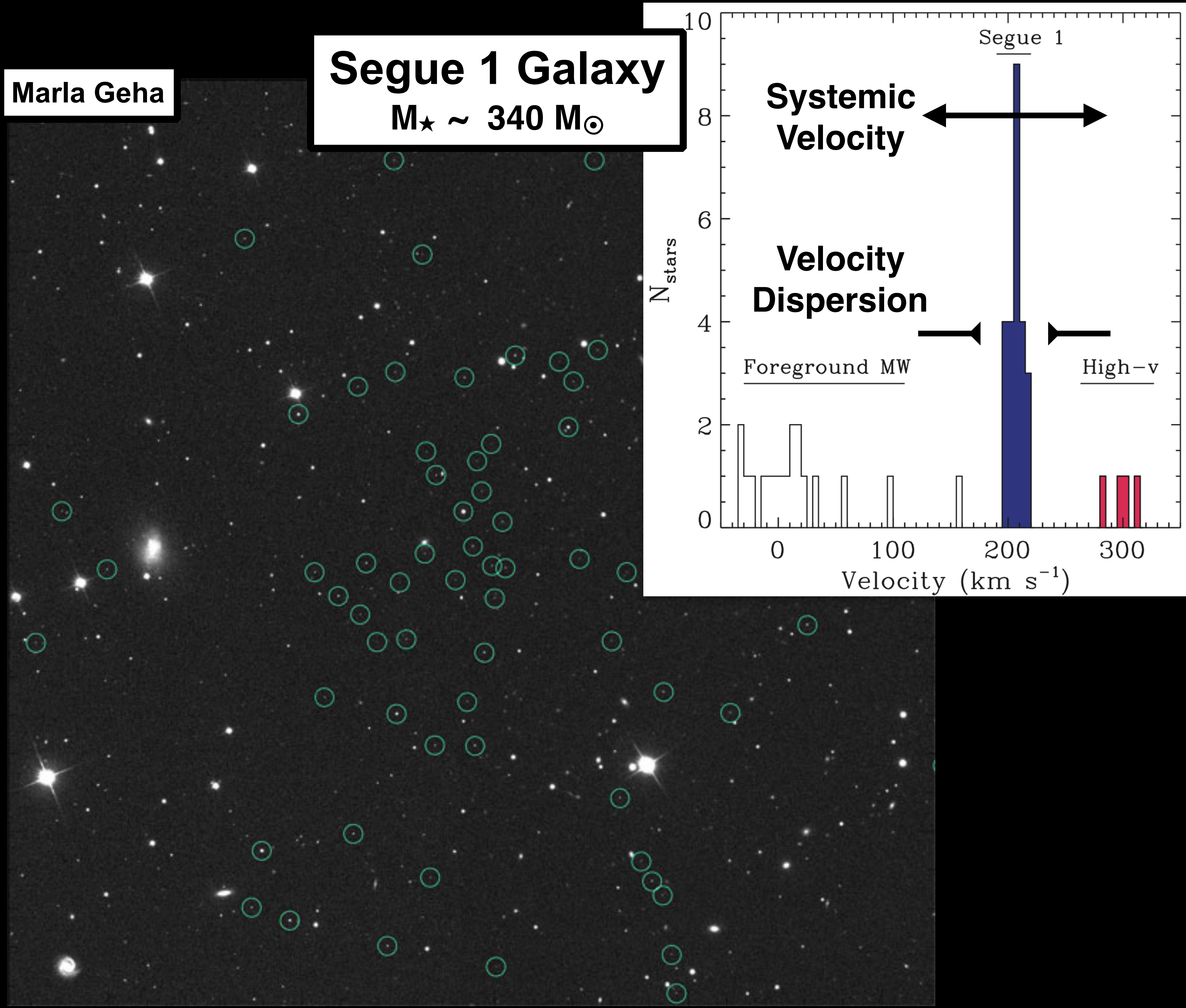
1) Start with a large catalog of stars

2) Apply a selection in color-magnitude space based on a stellar isochrone

3) Convolve with a spatial kernel

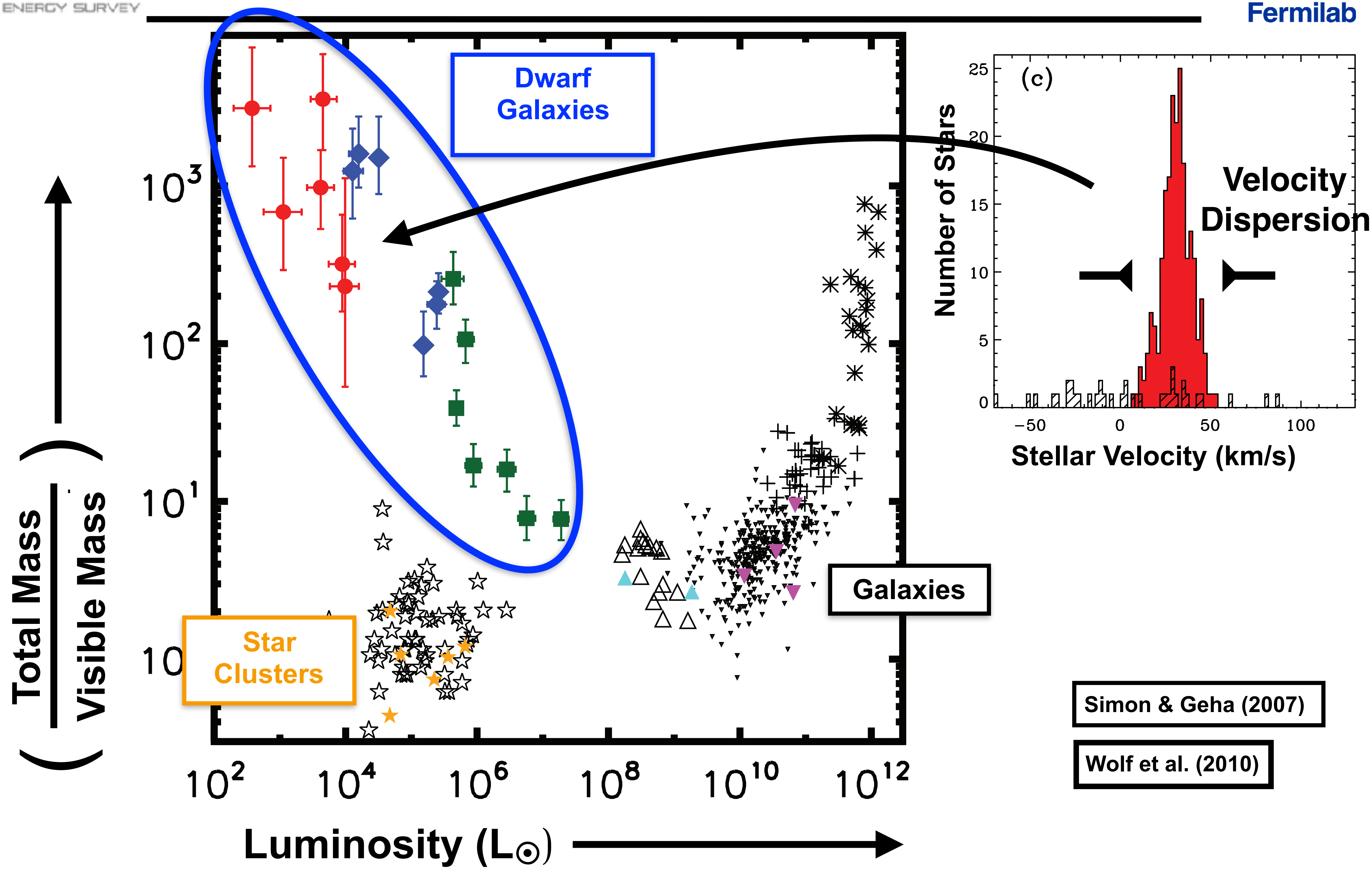



Marla Geha
Segue 1 Galaxy
$M_\star \sim 340\ M_\odot$



Marla Geha
Segue 1 Galaxy
$M_\star \sim 340\ M_\odot$
Segue 1
Systemic Velocity
Velocity Dispersion
Foreground MW
High−v
N_{stars}
Velocity (km s^{-1})
0
2
4
6
8
10
100
200
300

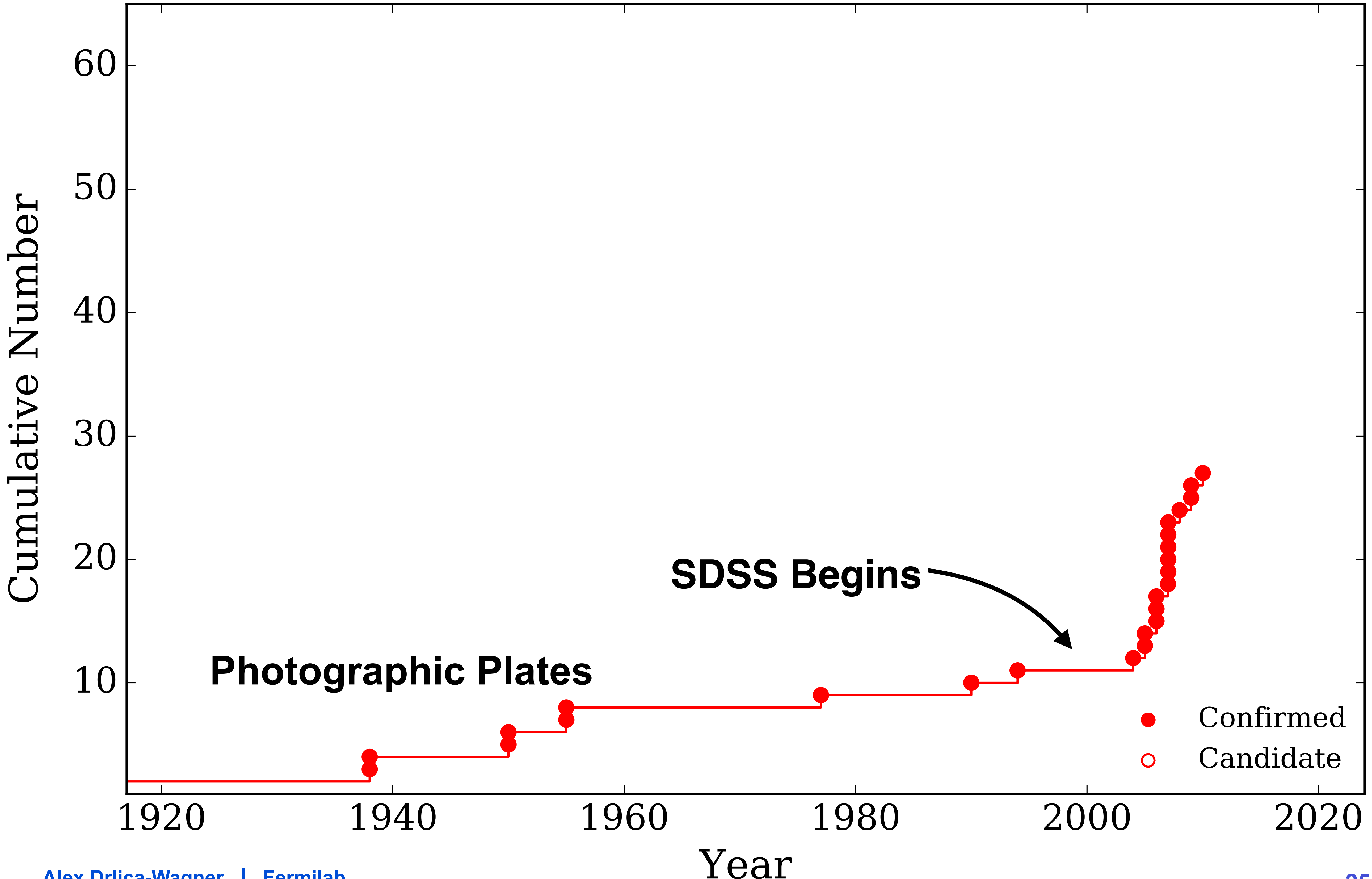
How to Define of a Galaxy?



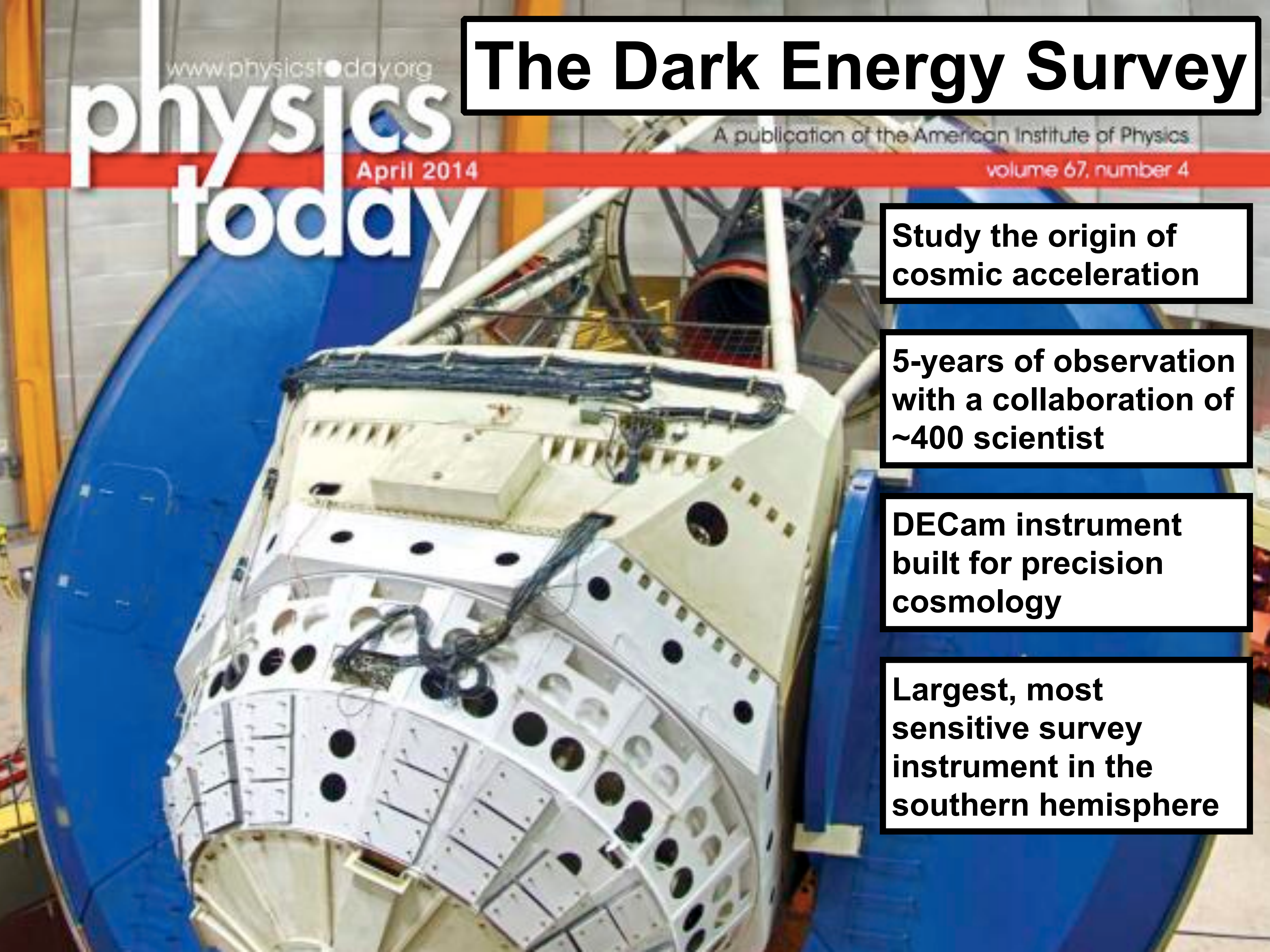
Simon & Geha (2007)

Wolf et al. (2010)

Satellite Galaxy Discovery Timeline



The Dark Energy Survey



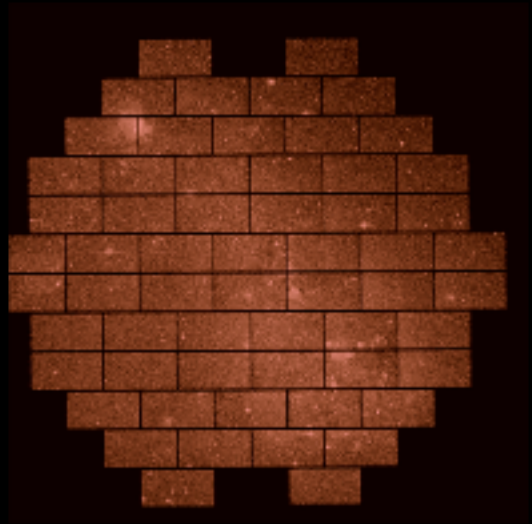
Study the origin of cosmic acceleration

5-years of observation with a collaboration of ~400 scientist

DECam instrument built for precision cosmology

Largest, most sensitive survey instrument in the southern hemisphere

Cartoon



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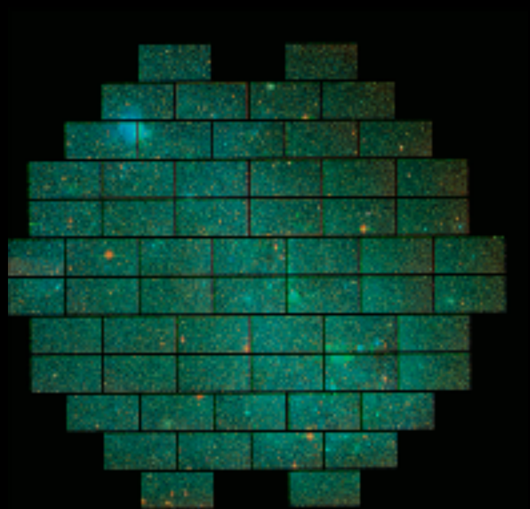

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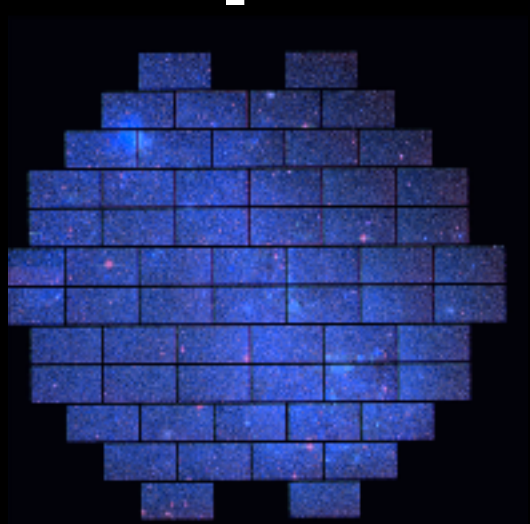

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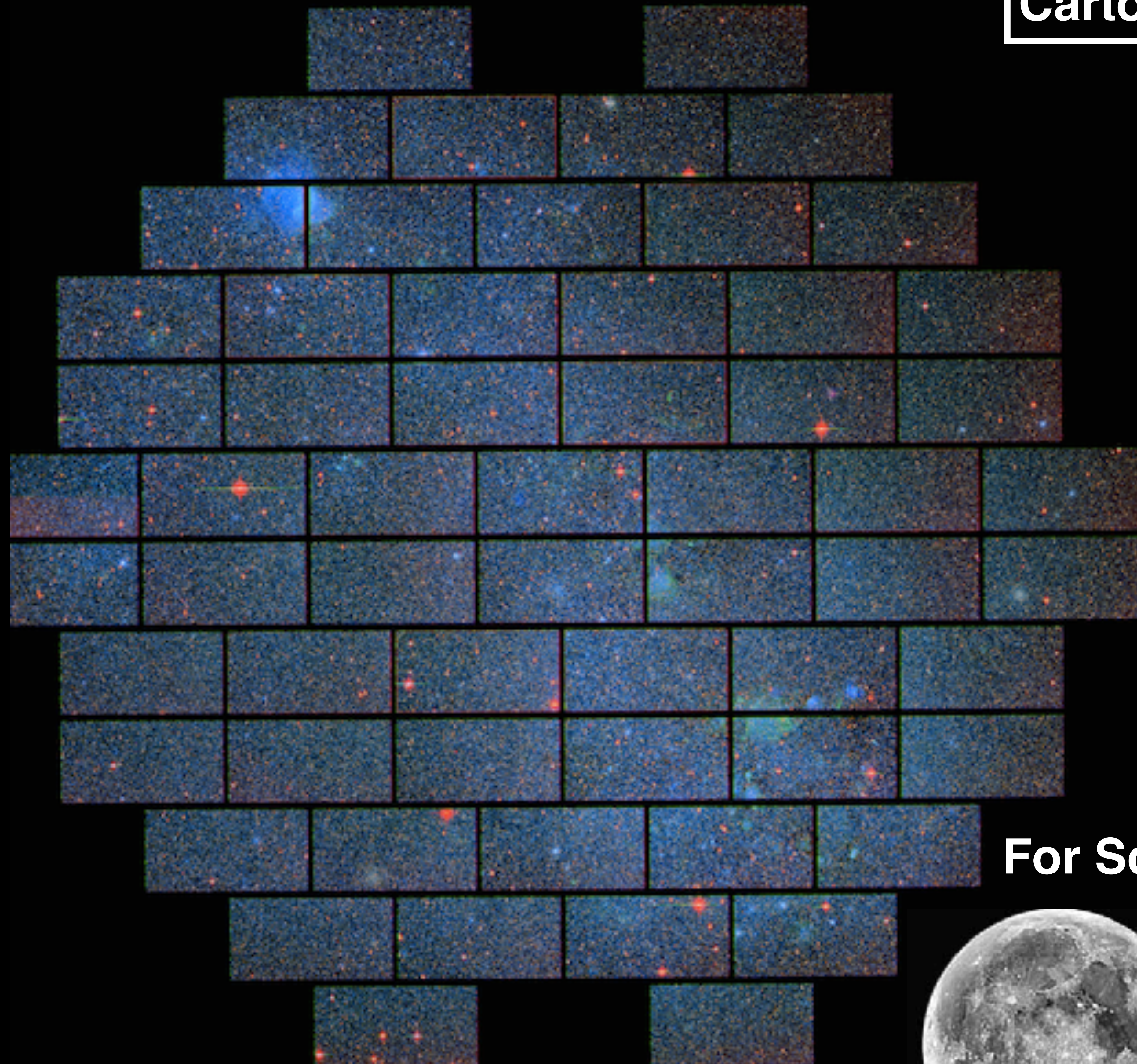
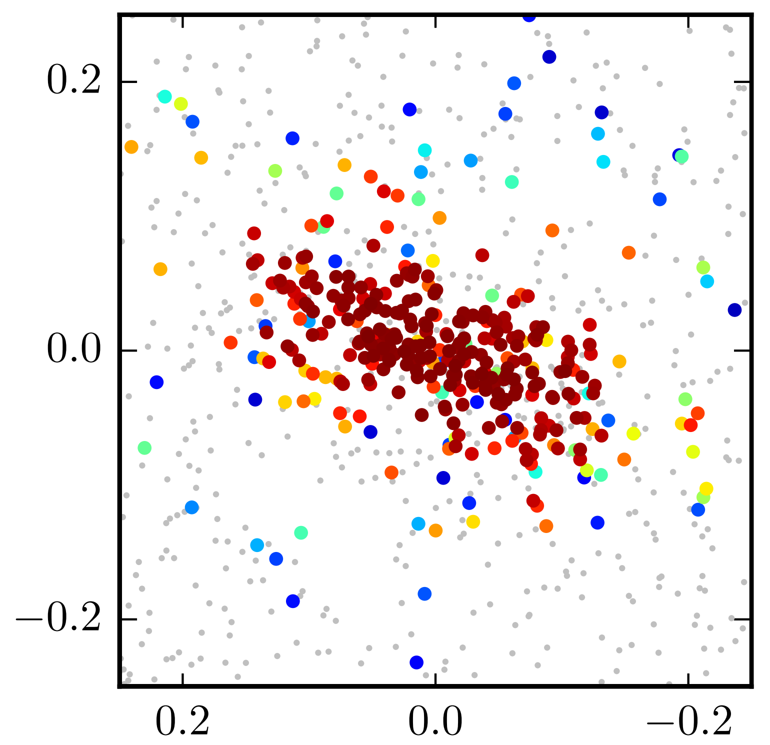


For Scale

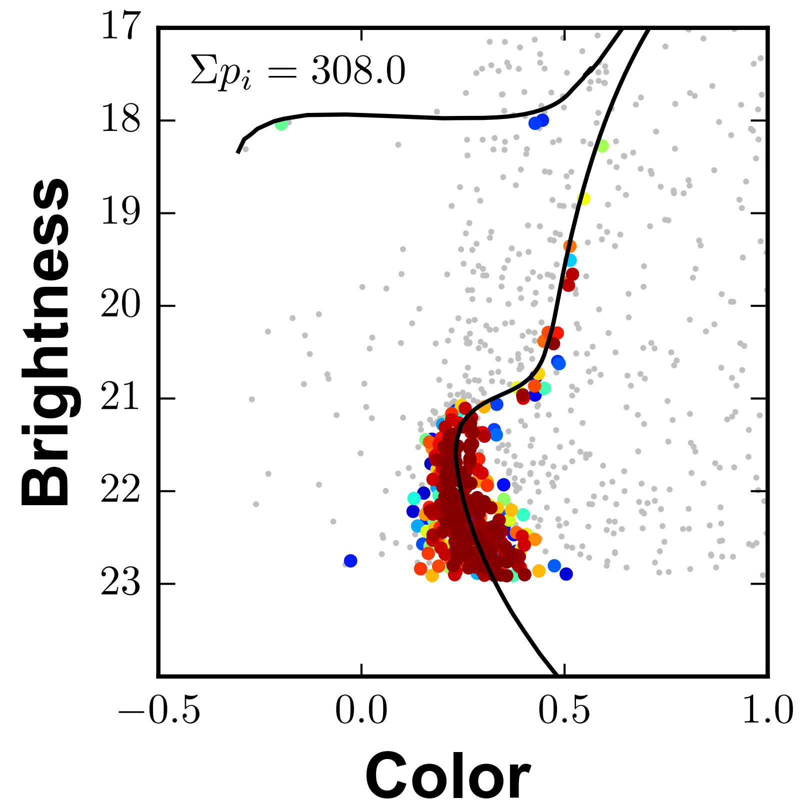
DES Data Release: https://des.ncsa.illinois.edu/releases/dr1

Maximum-Likelihood Searches

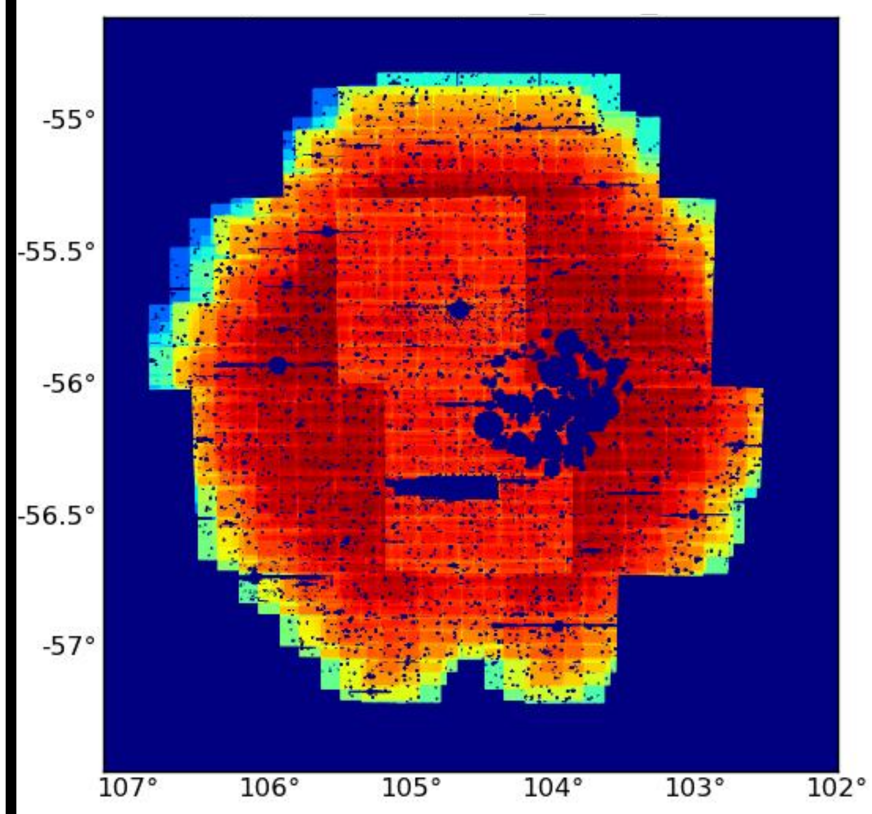
Spatial Model



Spectral Model



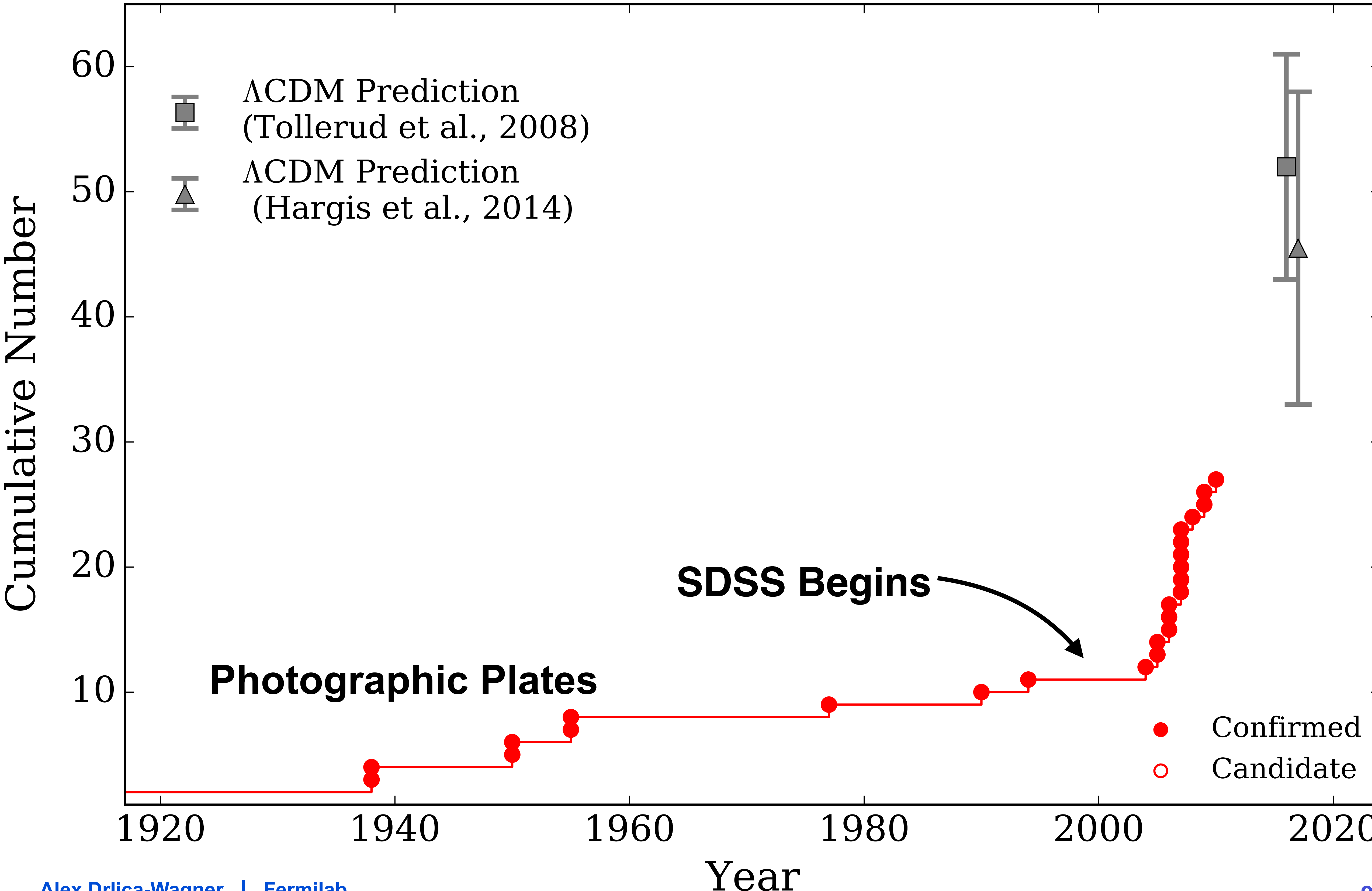
Survey Sensitivity



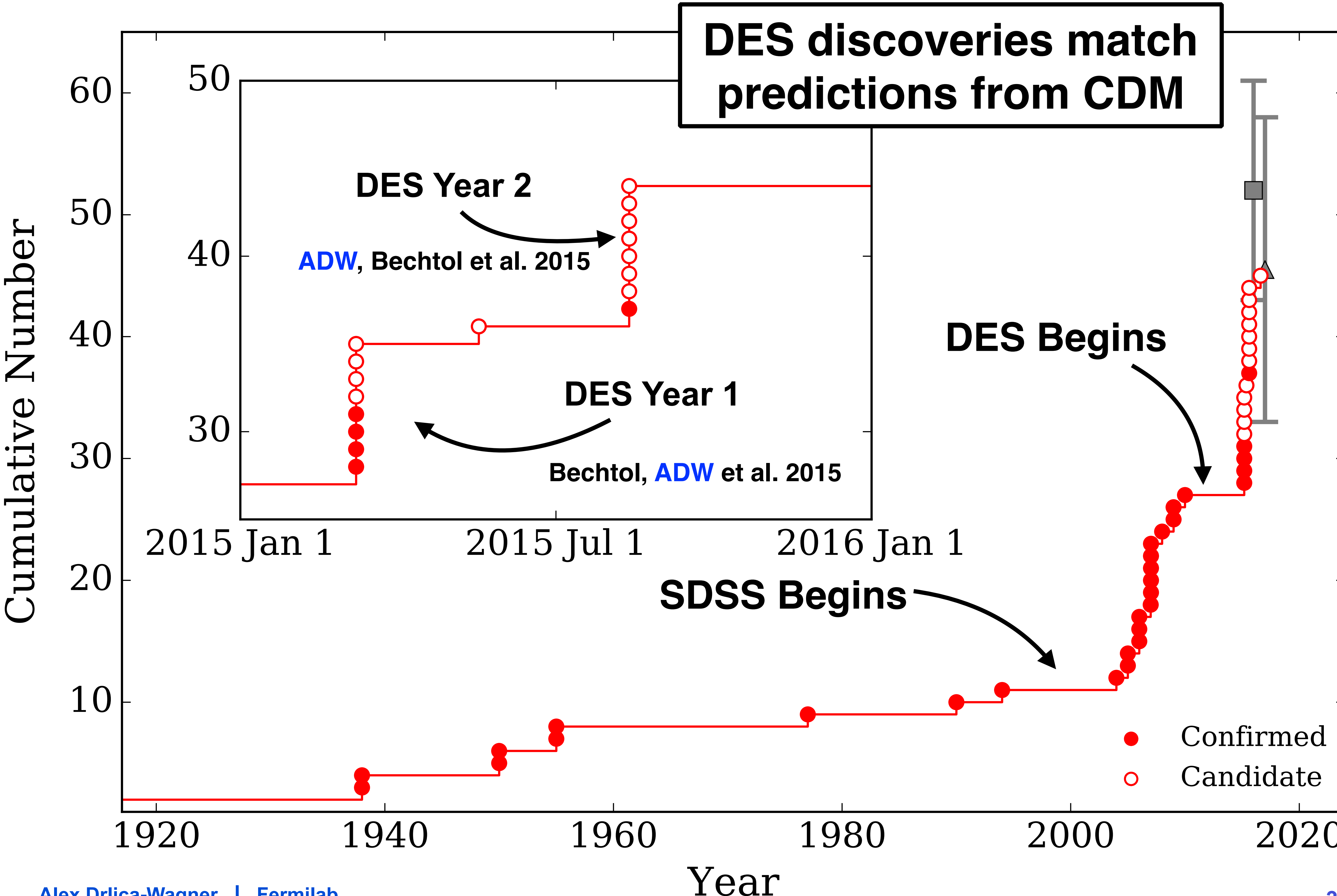
Multi-dimensional likelihood analysis

Scan over ~400 million possible locations

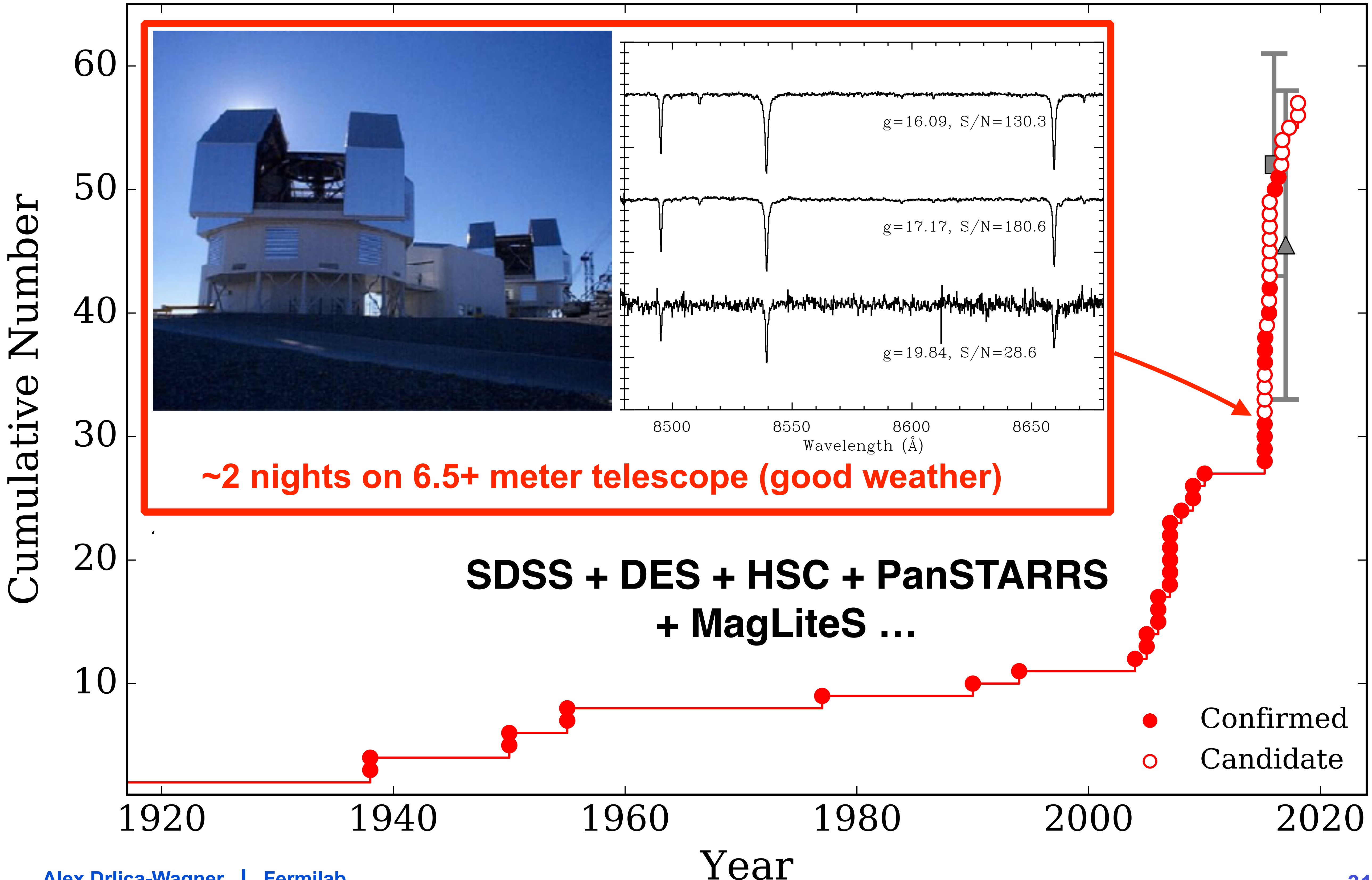
Satellite Galaxy Discovery Timeline



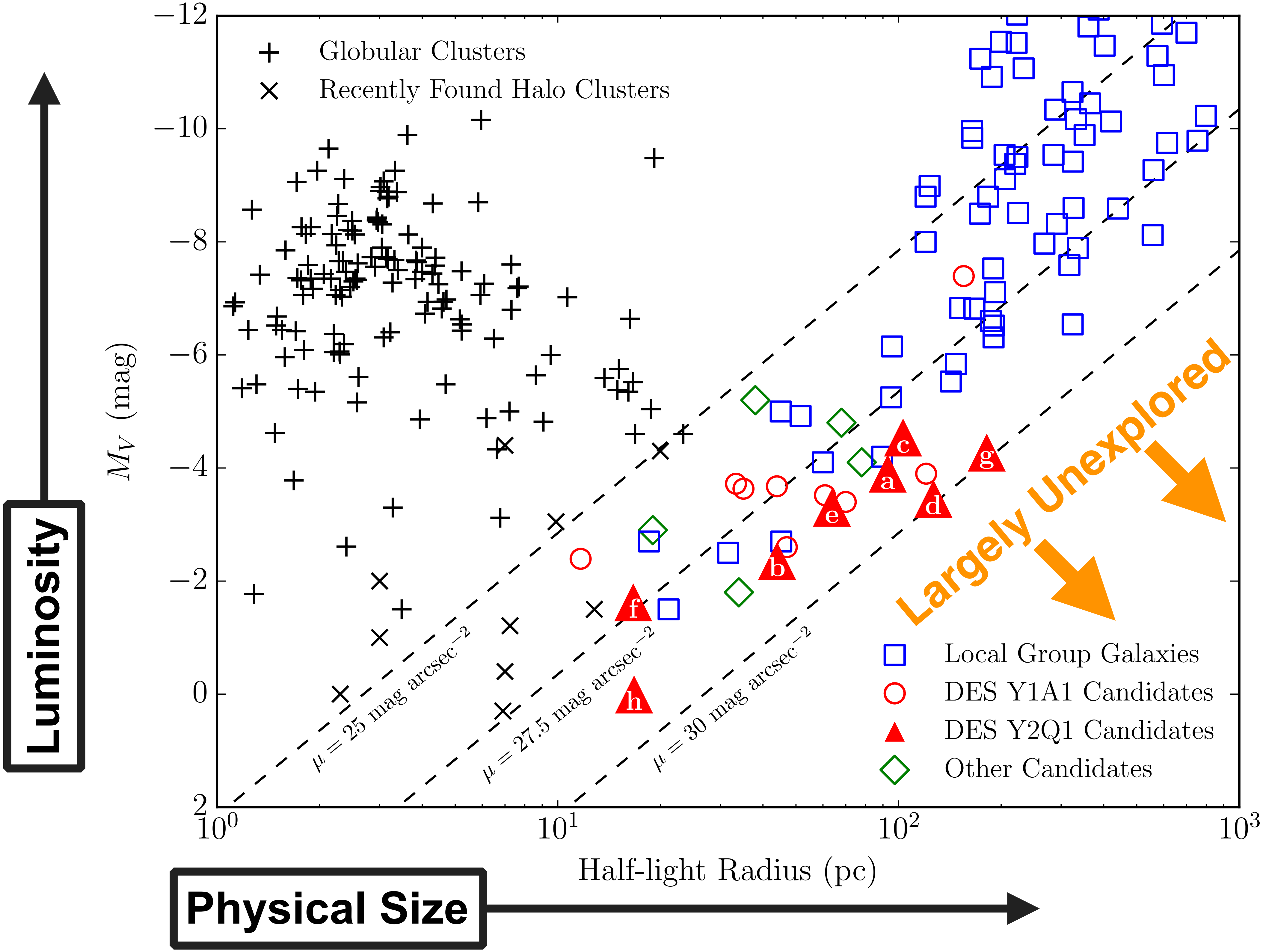
Satellite Galaxy Discovery Timeline



Satellite Galaxy Discovery Timeline



Galaxies or Star Clusters?



ADW, Bechtol, Rykoff et al. (2015)

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- Dark Matter and Dwarf Galaxies
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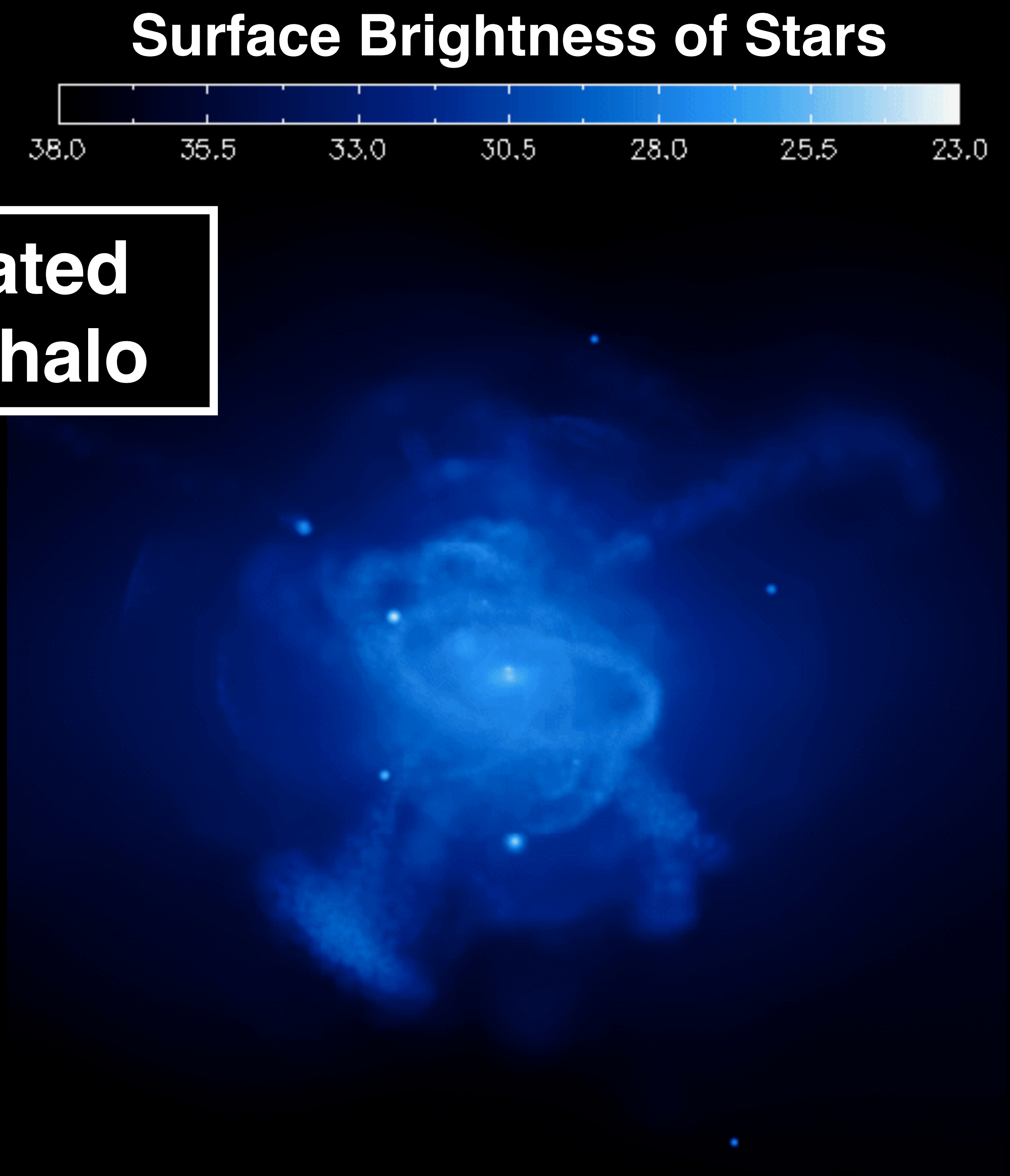
  Aside: The Voracious Milky Way
- Search for Dark Matter Annihilation
- Future Prospects

Milky Way Stellar Halo



Simulated stellar halo

The Milky Way grows by devouring smaller systems

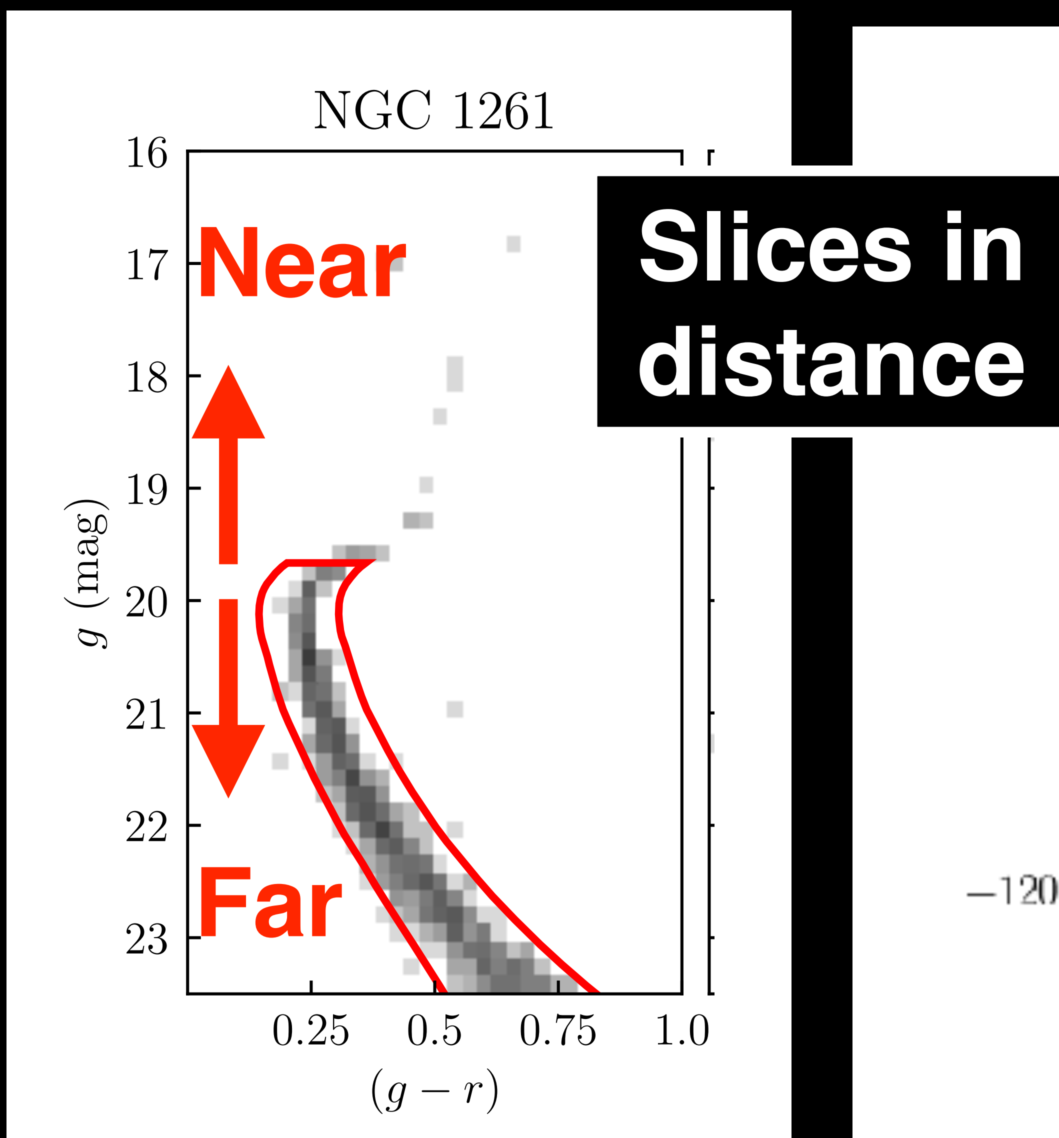
Stellar streams trace the distribution of dark matter around the Milky Way

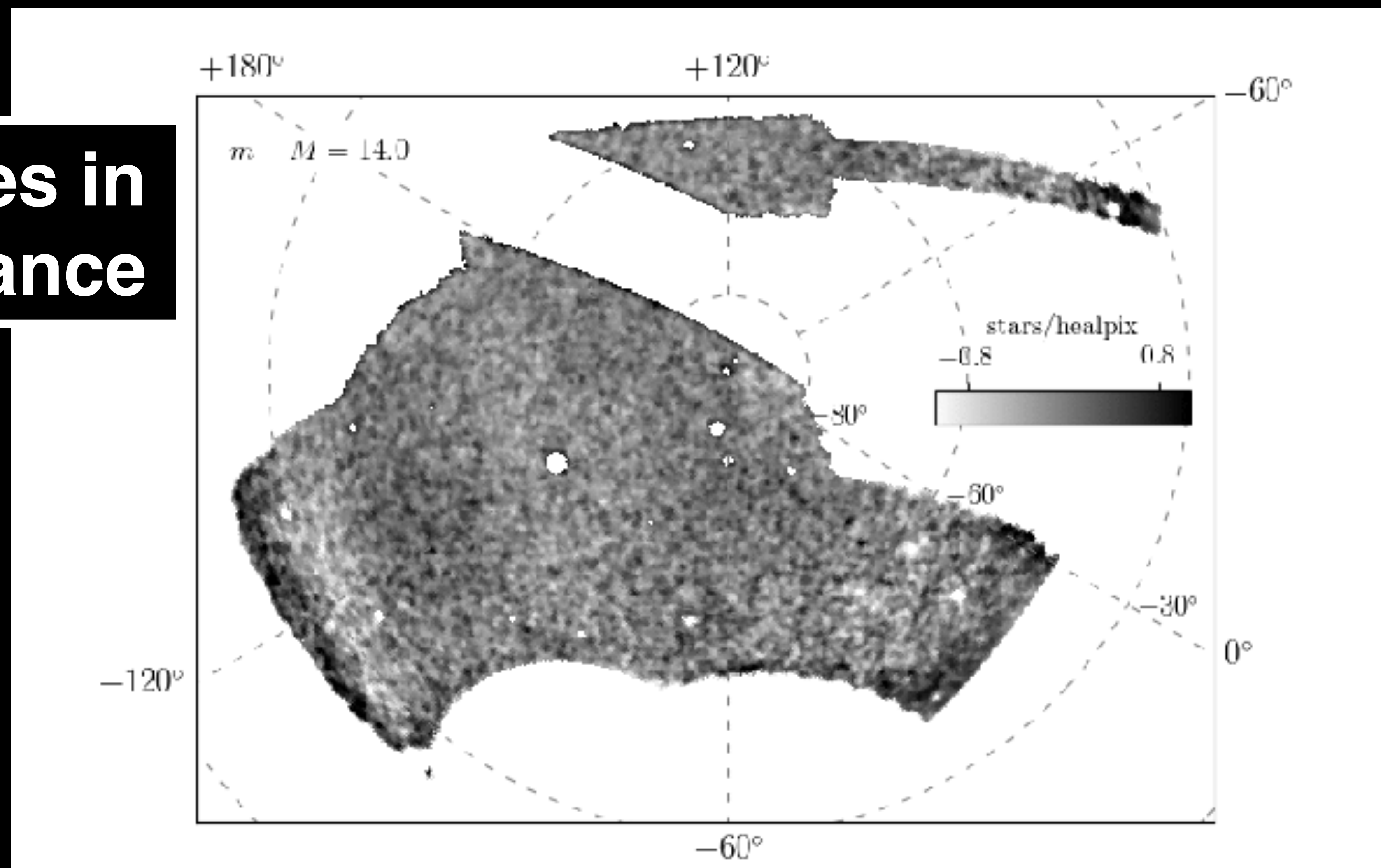
Bullock & Johnston (2005)

New Stellar Streams

11 new stellar streams discovered with DES

Increases the known population by ~ 50%



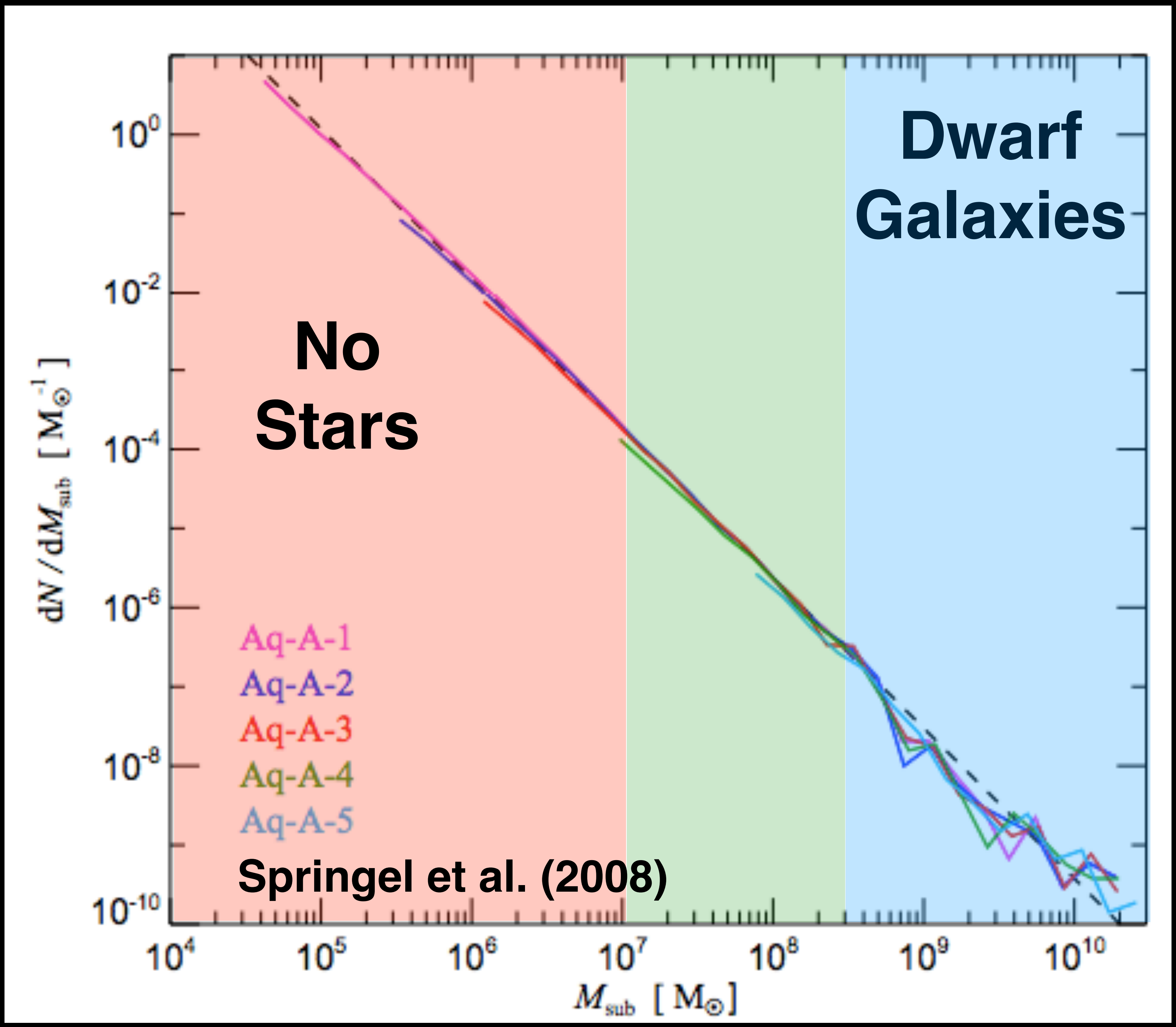


DES Collaboration: Shipp, ADW, et al. (2018)

Alex Drlica-Wagner

Pushing to Lower Mass

Dark Matter Halo Abundance

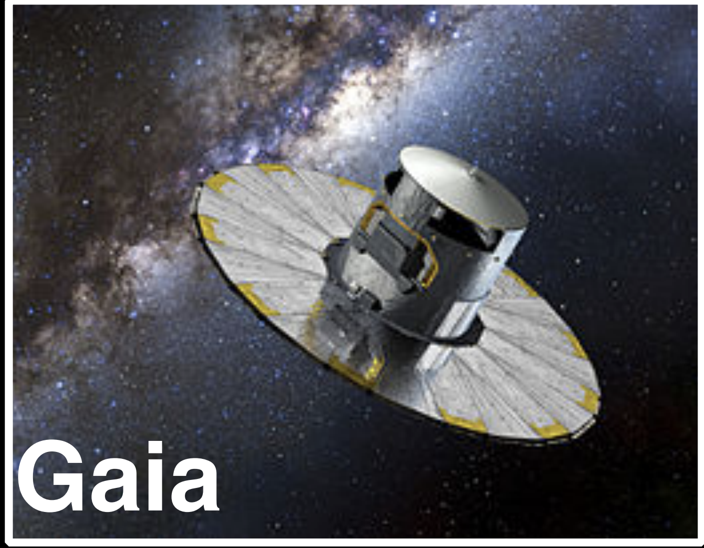


Dark Matter Halo Mass ($M_\odot$)

Strong prediction of cold dark matter

How can we detect dark subhalos?

Gaps in Stellar Streams



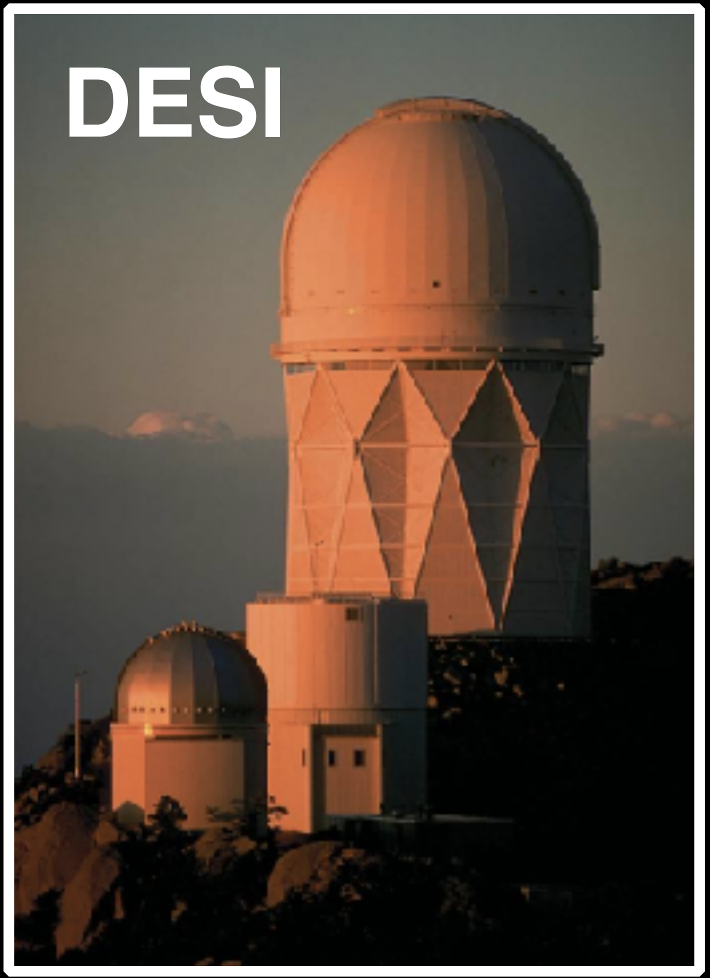
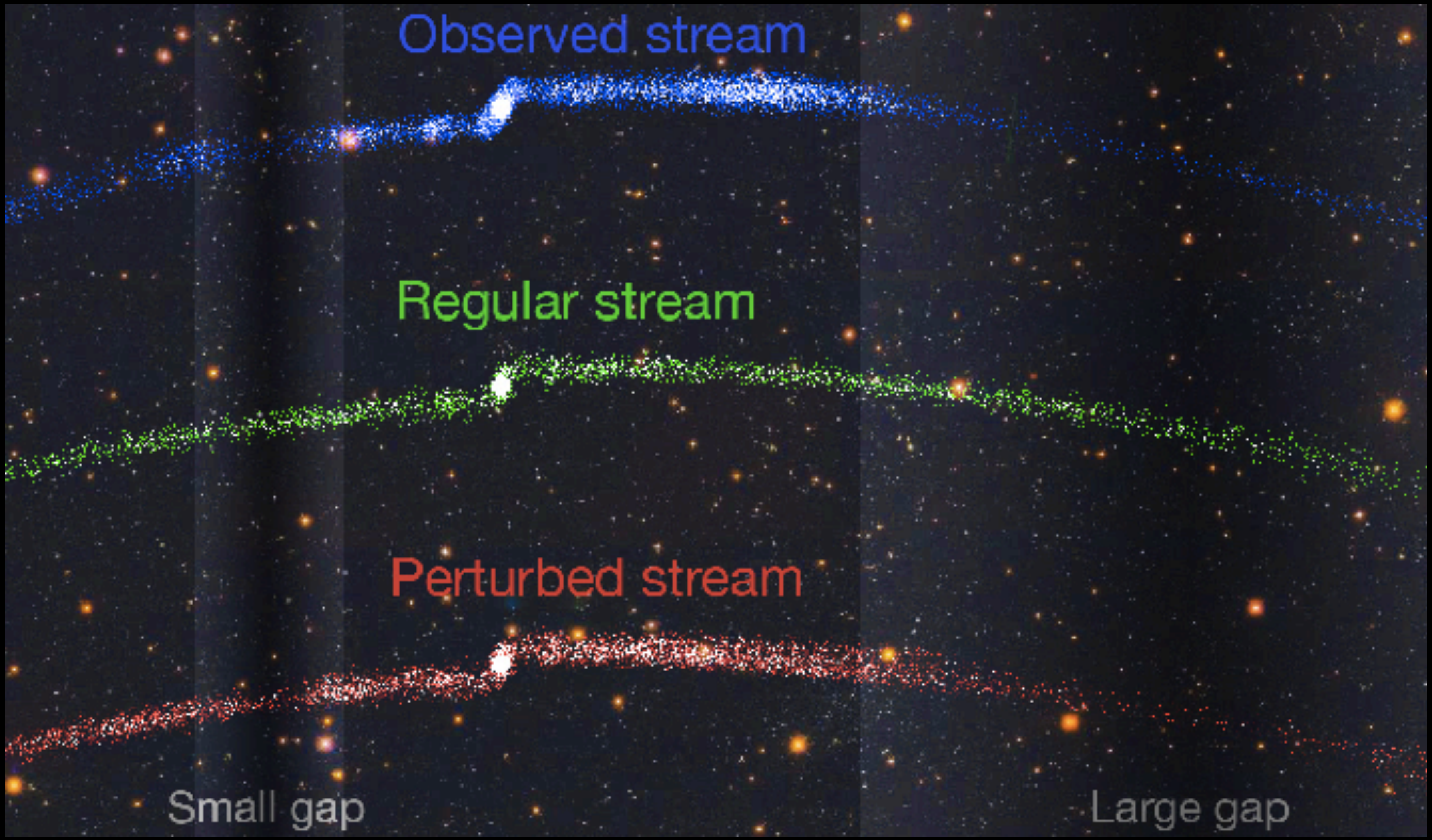


Image: Belokurov+



Erkal et al. (2017); Carlberg et al. (2012); Bovy (2016); etc.

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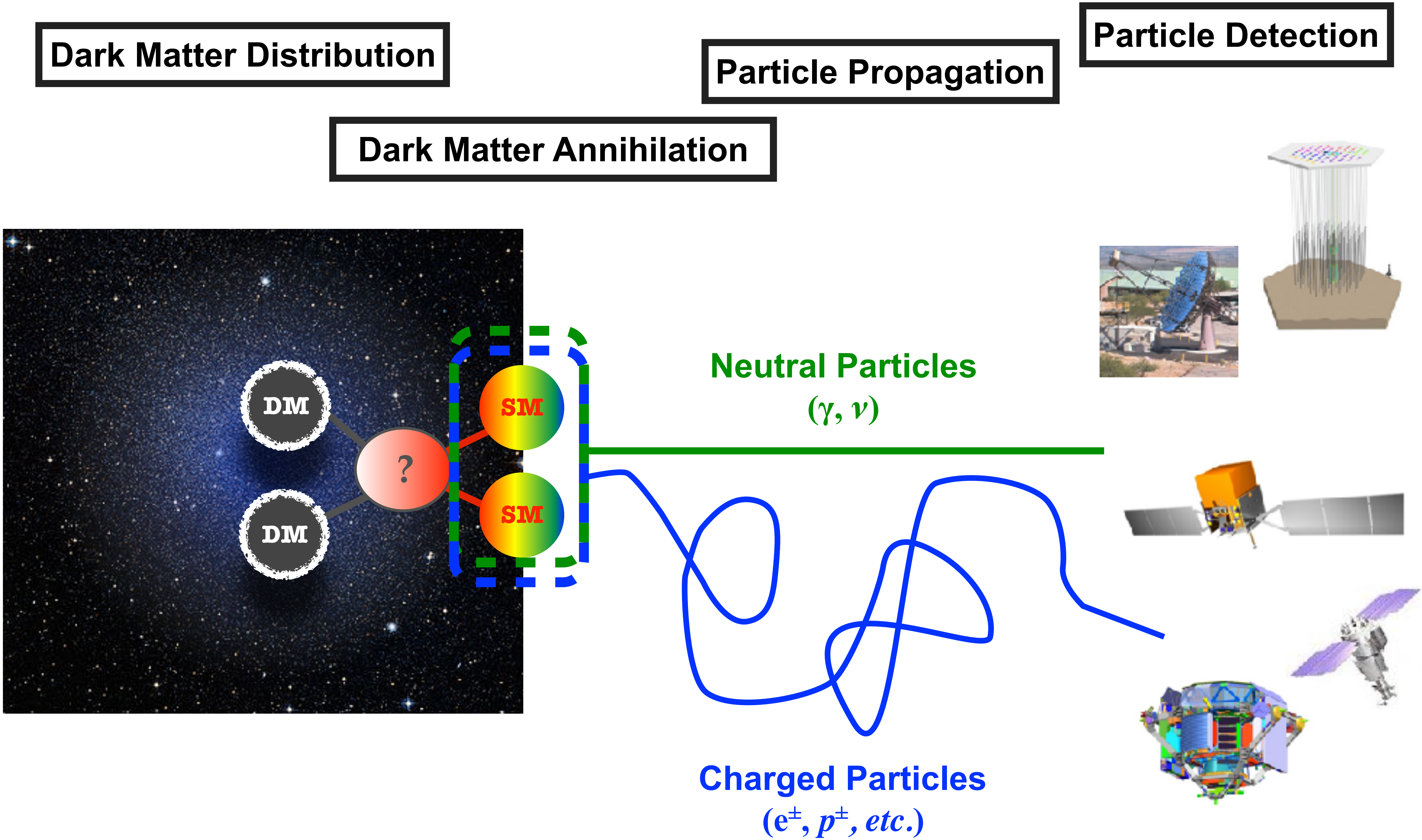
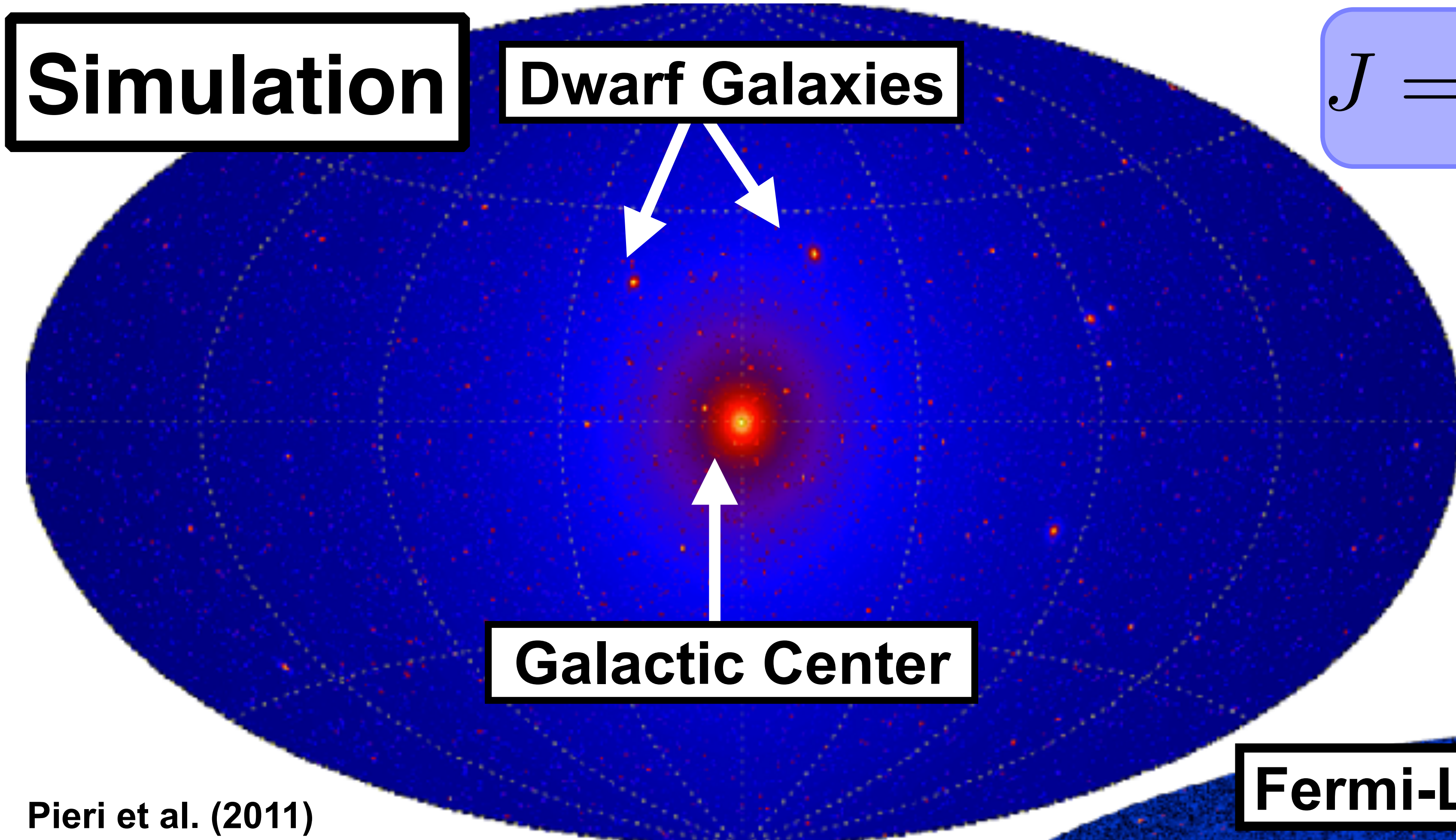
Indirect Detection



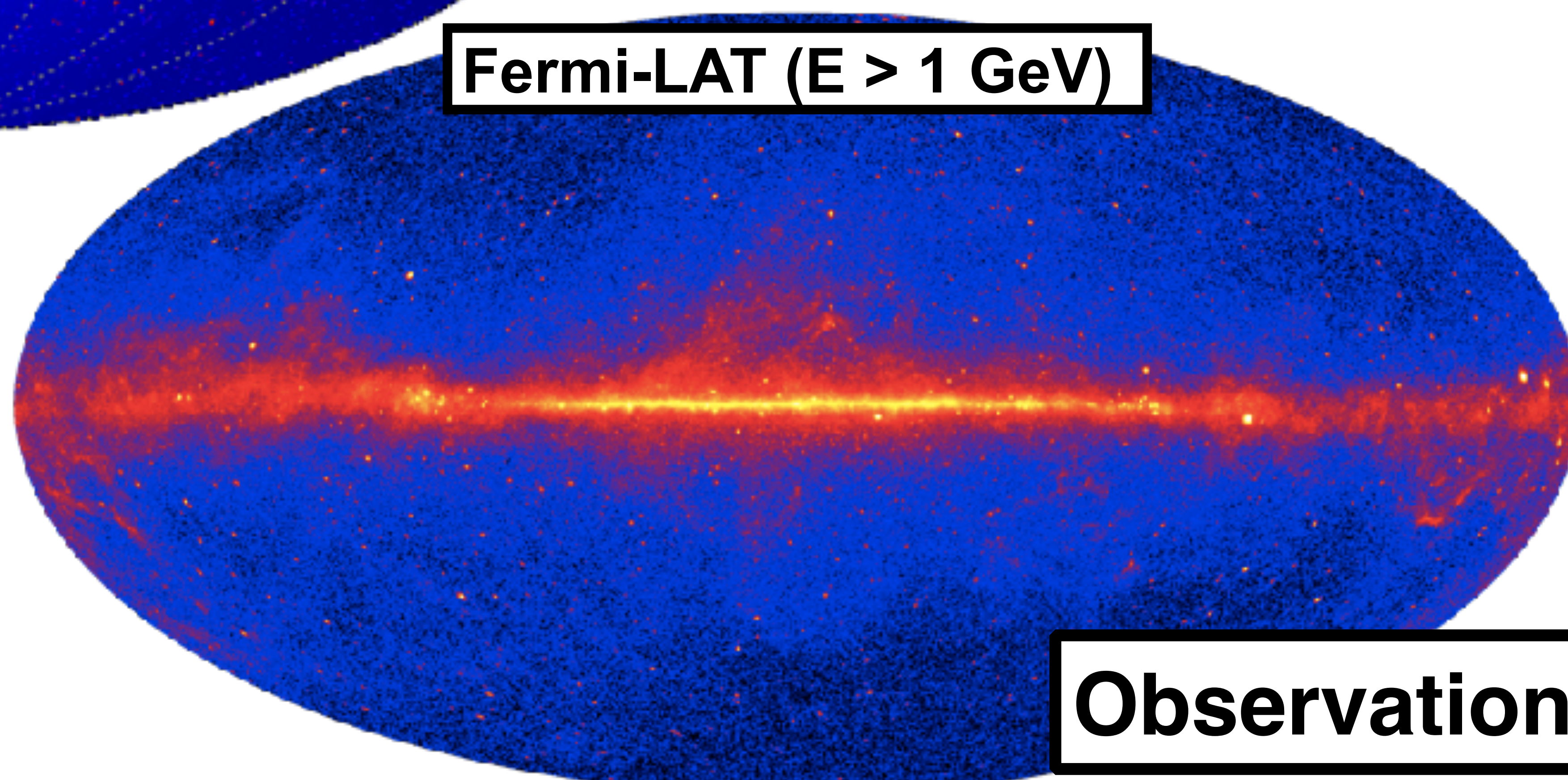
Dark Matter Annihilation

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

Jargon: The "J-factor" is the line of sight integral through the dark matter density squared. It is proportional to the predicted flux from dark matter annihilation.

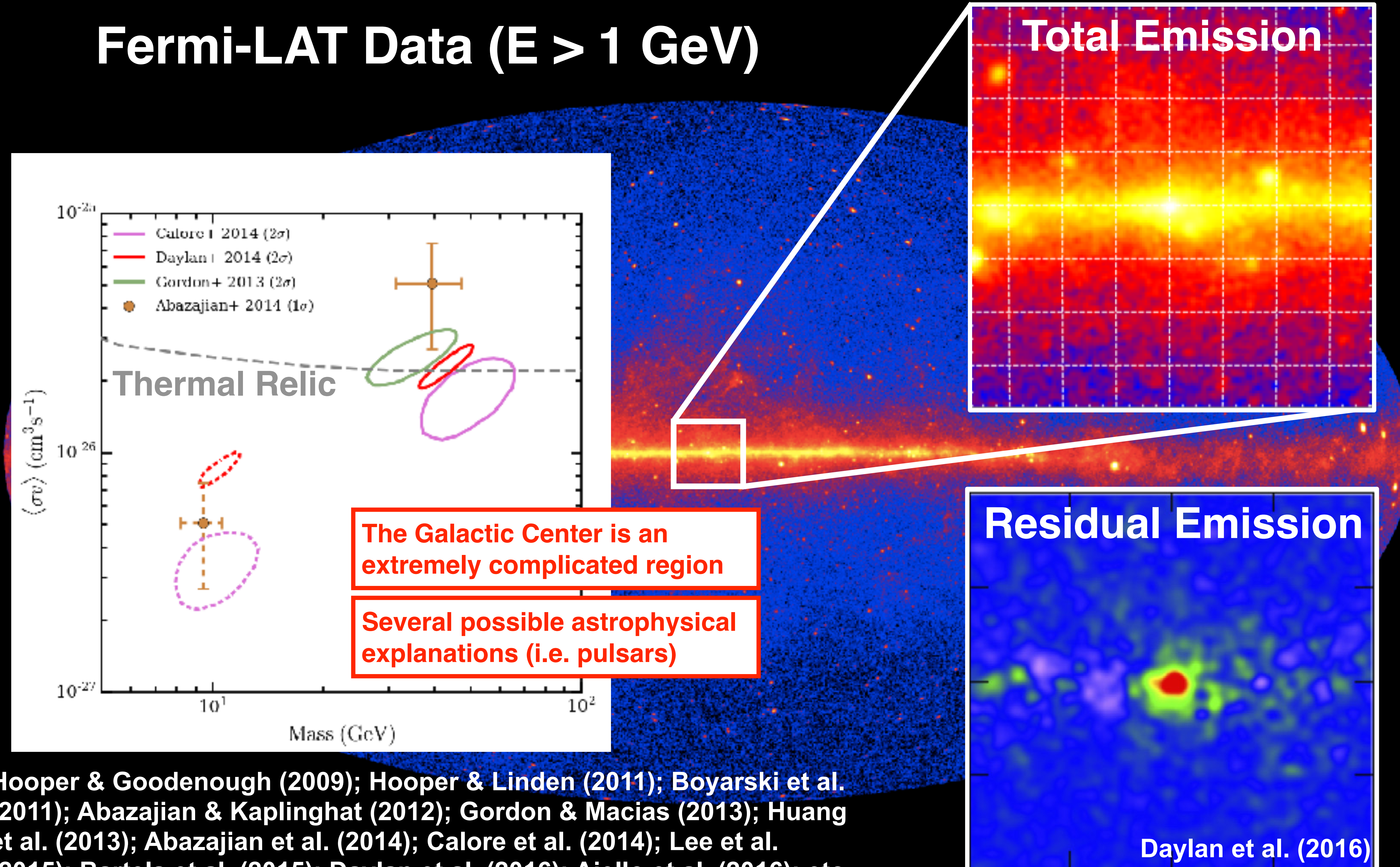


Pieri et al. (2011)



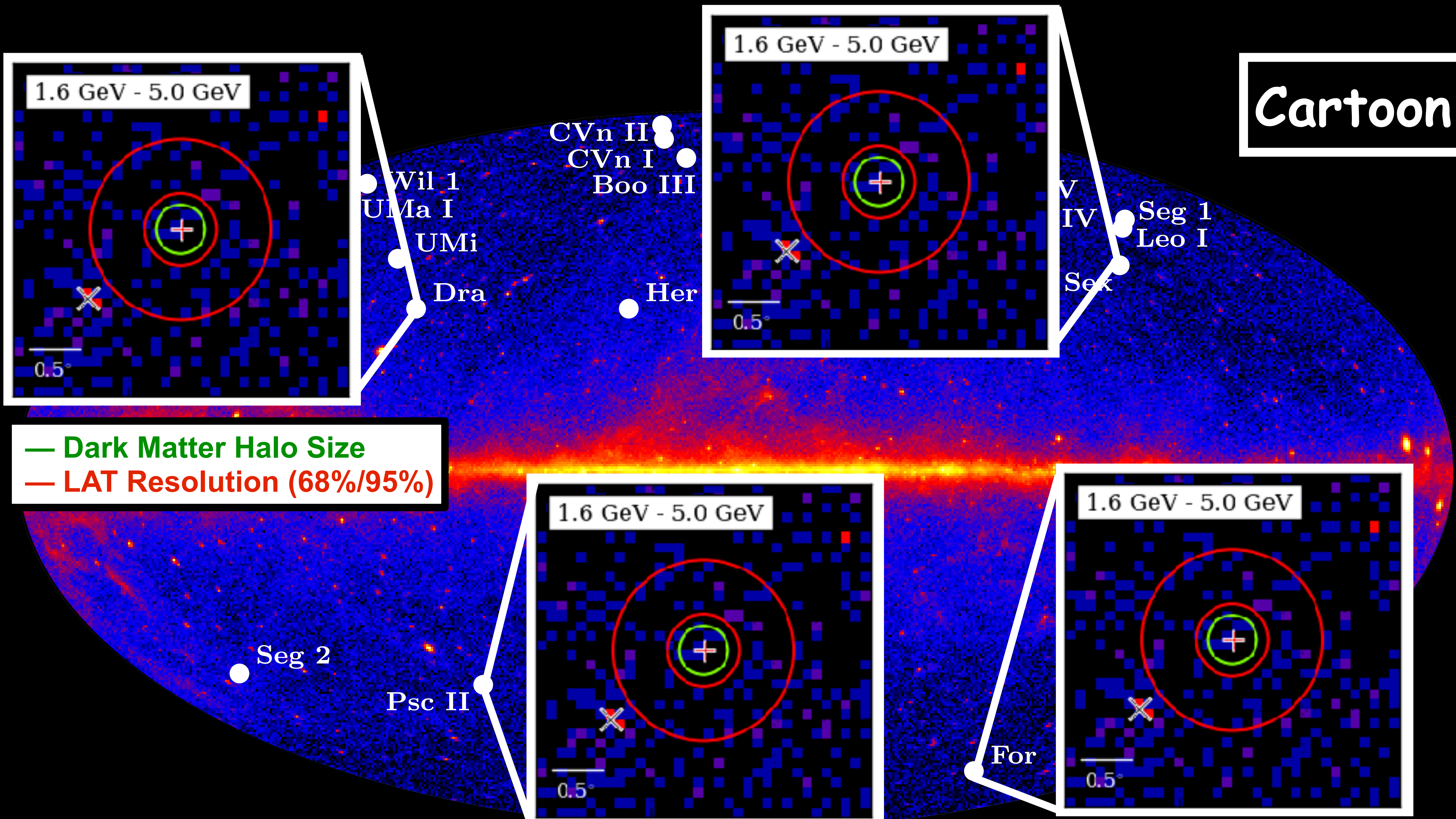
Galactic Center GeV Excess

Fermi-LAT Data (E > 1 GeV)



Hooper & Goodenough (2009); Hooper & Linden (2011); Boyarski et al. (2011); Abazajian & Kaplinghat (2012); Gordon & Macias (2013); Huang et al. (2013); Abazajian et al. (2014); Calore et al. (2014); Lee et al. (2015); Bartels et al. (2015); Daylan et al. (2016); Ajello et al. (2016); etc.

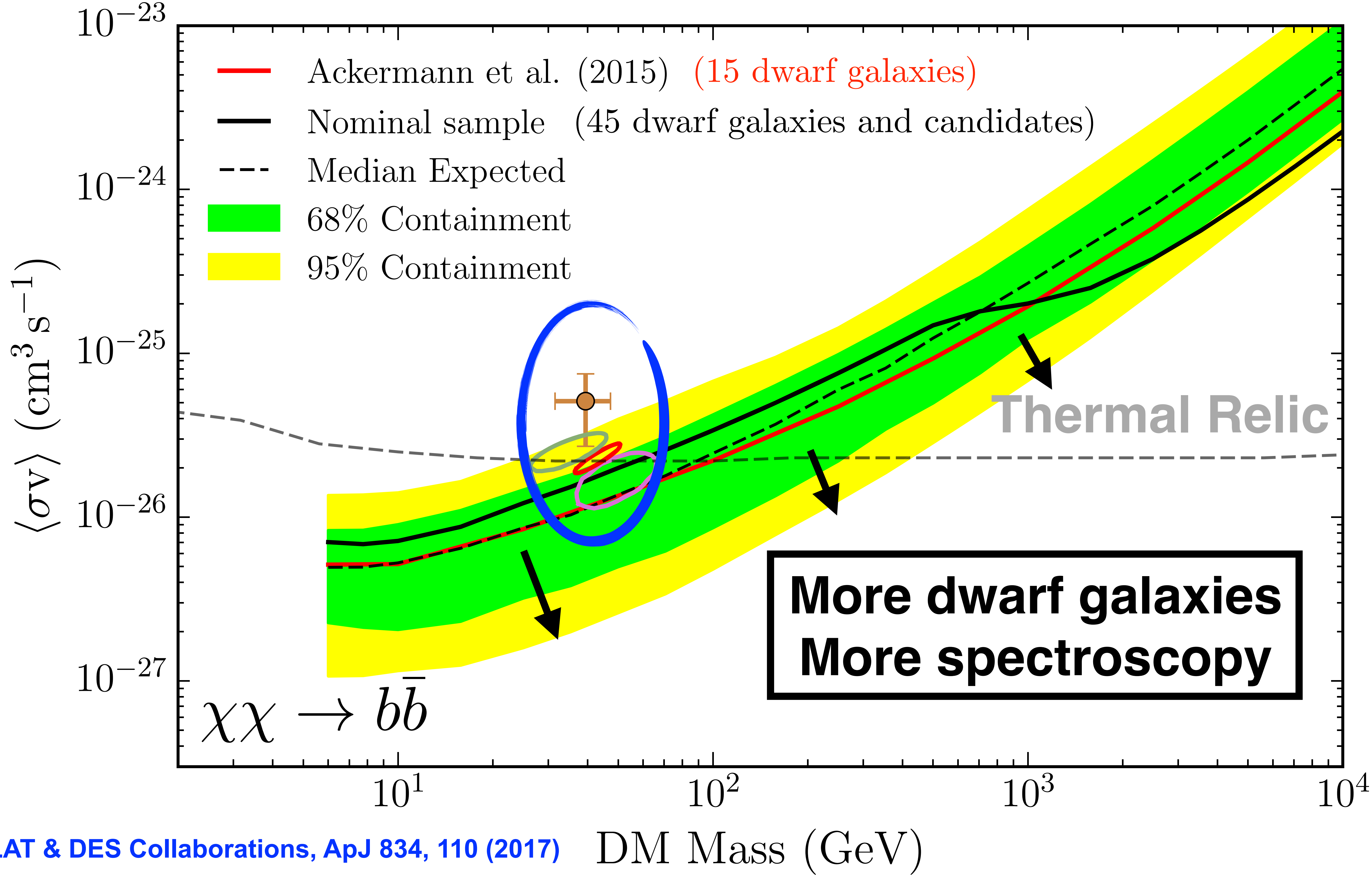
Dwarf Galaxy Observations



LAT Collaboration, PRD 89, 042001 (2013)

Multiple dwarf galaxies can be analyzed together

Dwarf Galaxy Constraints



LAT & DES Collaborations, ApJ 834, 110 (2017)

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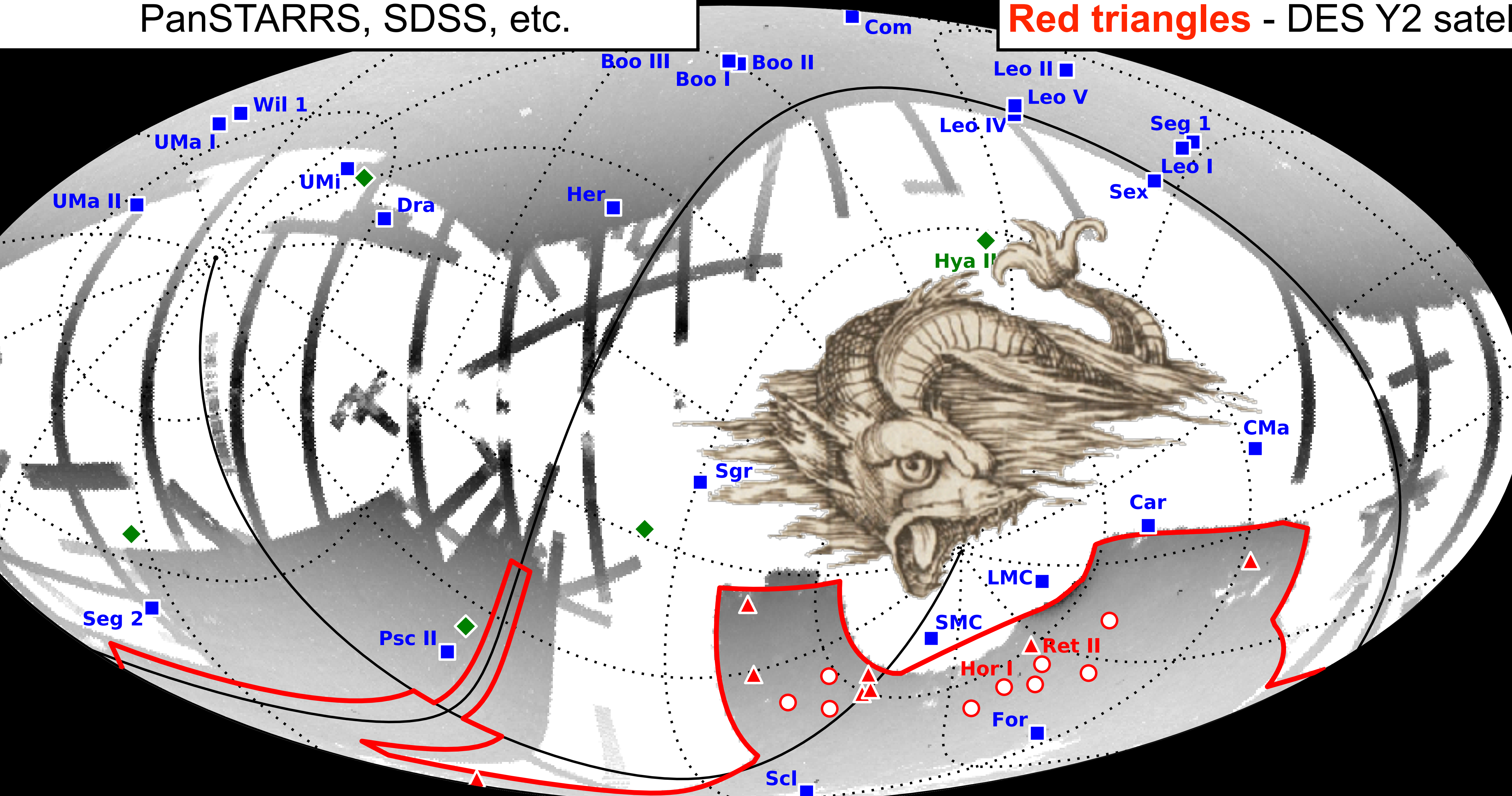
Current Sky Coverage

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



Magellanic Satellites Survey (MagLiteS)

Blanco Imaging of the Southern Sky (BLISS)

NOAO DECam Program
12 nights in 2016-2017
10 nights in 2018-2019
PI: K. Bechtol
Deputy PI: ADW

NOAO DECam Program
12 nights in 2017
Co-PI: ADW
Co-PI: M. Soares-Santos

Search for satellites around the LMC (test of hierarchical structure formation)

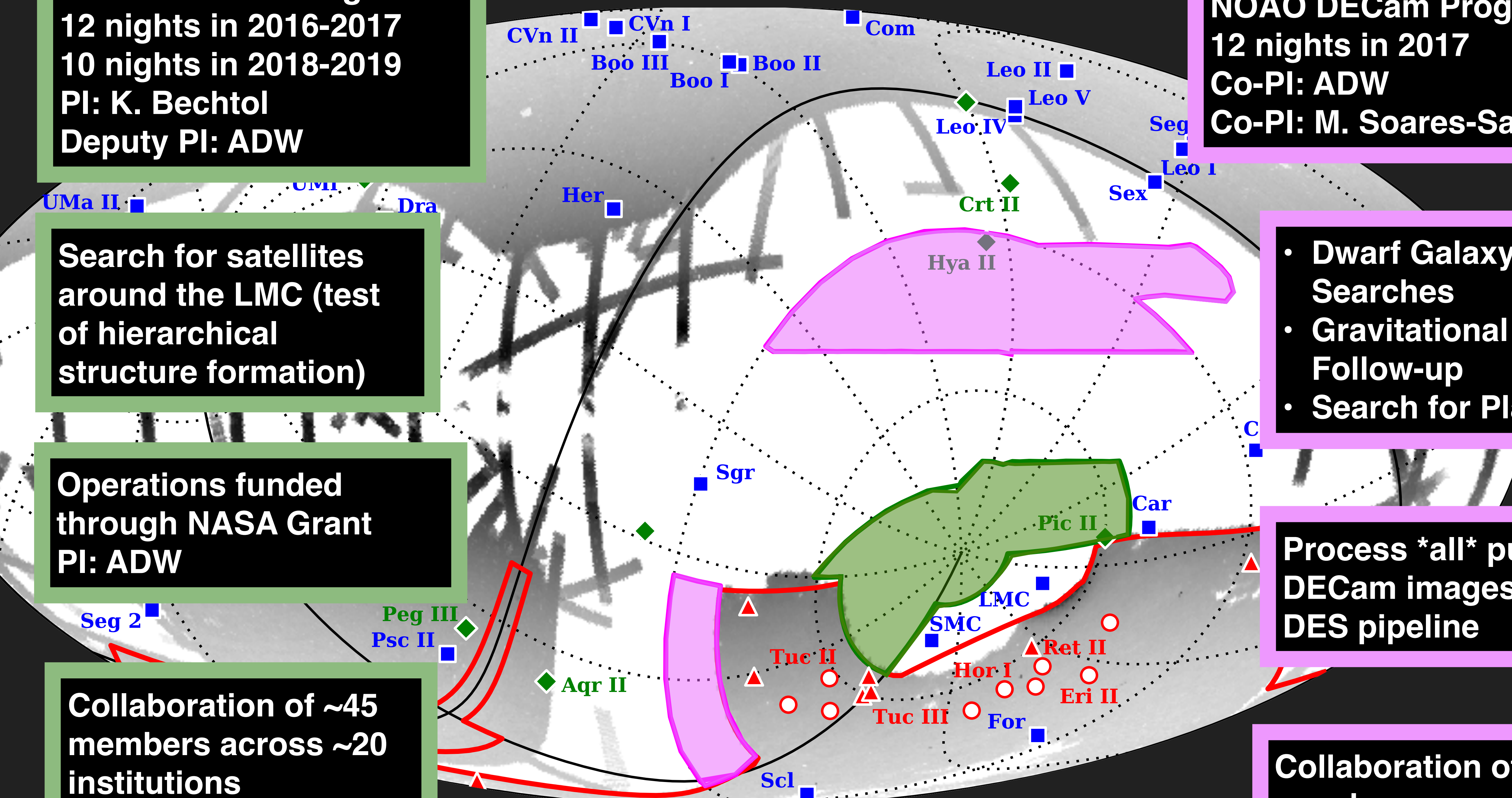
- Dwarf Galaxy Searches
- Gravitational Wave Follow-up
- Search for Planet 9

Operations funded through NASA Grant
PI: ADW

Process *all* public DECam images with DES pipeline

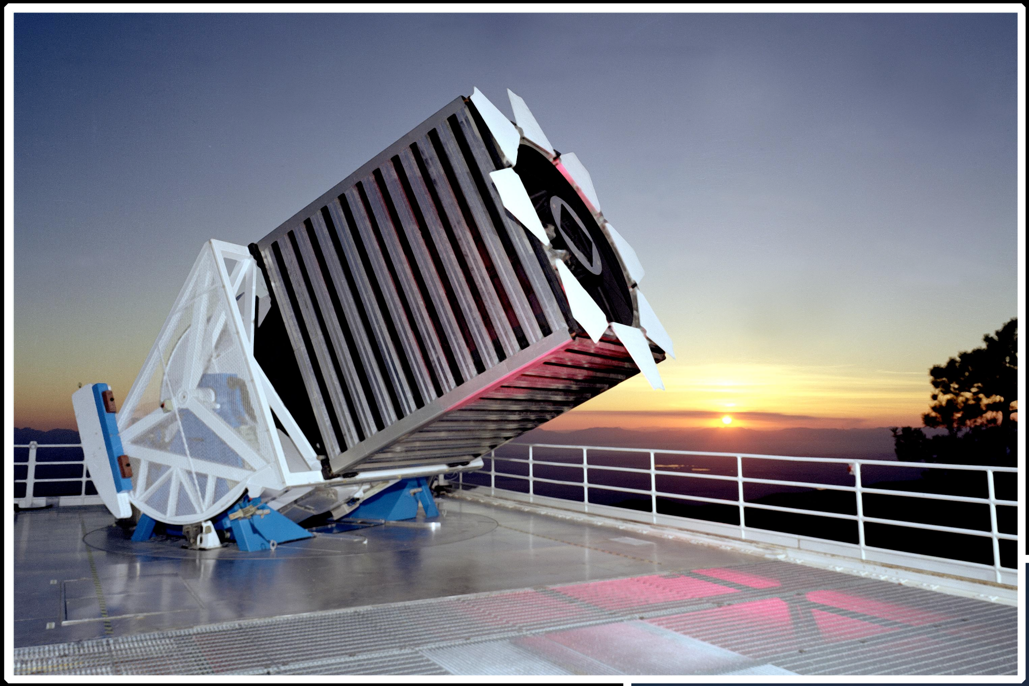
Collaboration of ~45 members across ~20 institutions

Collaboration of ~35 members across ~10 institutions



ADW (MagLiteS & BLISS Collaborations)

Progression of Wide-Field Optical Surveys

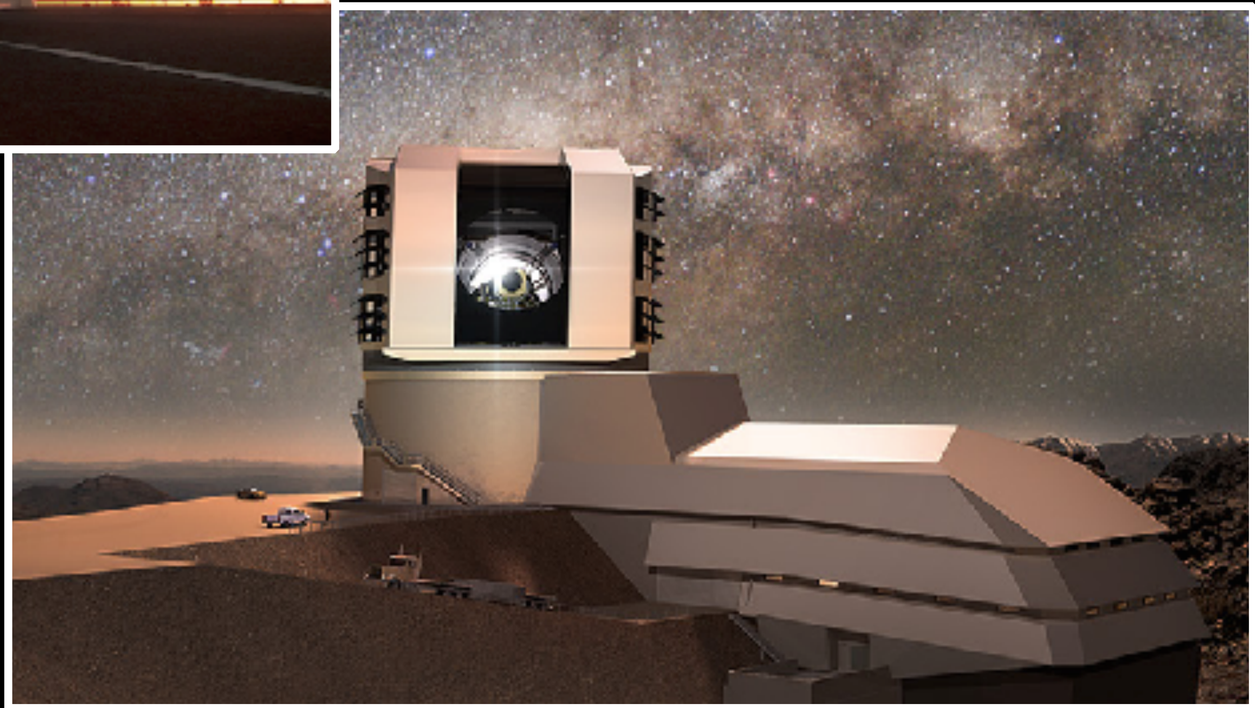


r ~ 22 mag
D ~ 50 kpc

Stage II
e.g. SDSS

r ~ 24 mag
D ~ 125 kpc

Stage III
e.g. DES, PanSTARRS, HSC, Skymapper



r ~ 26 mag
D ~ 315 kpc

Stage IV
e.g. LSST

Large Synoptic Survey Telescope (LSST) is Coming!

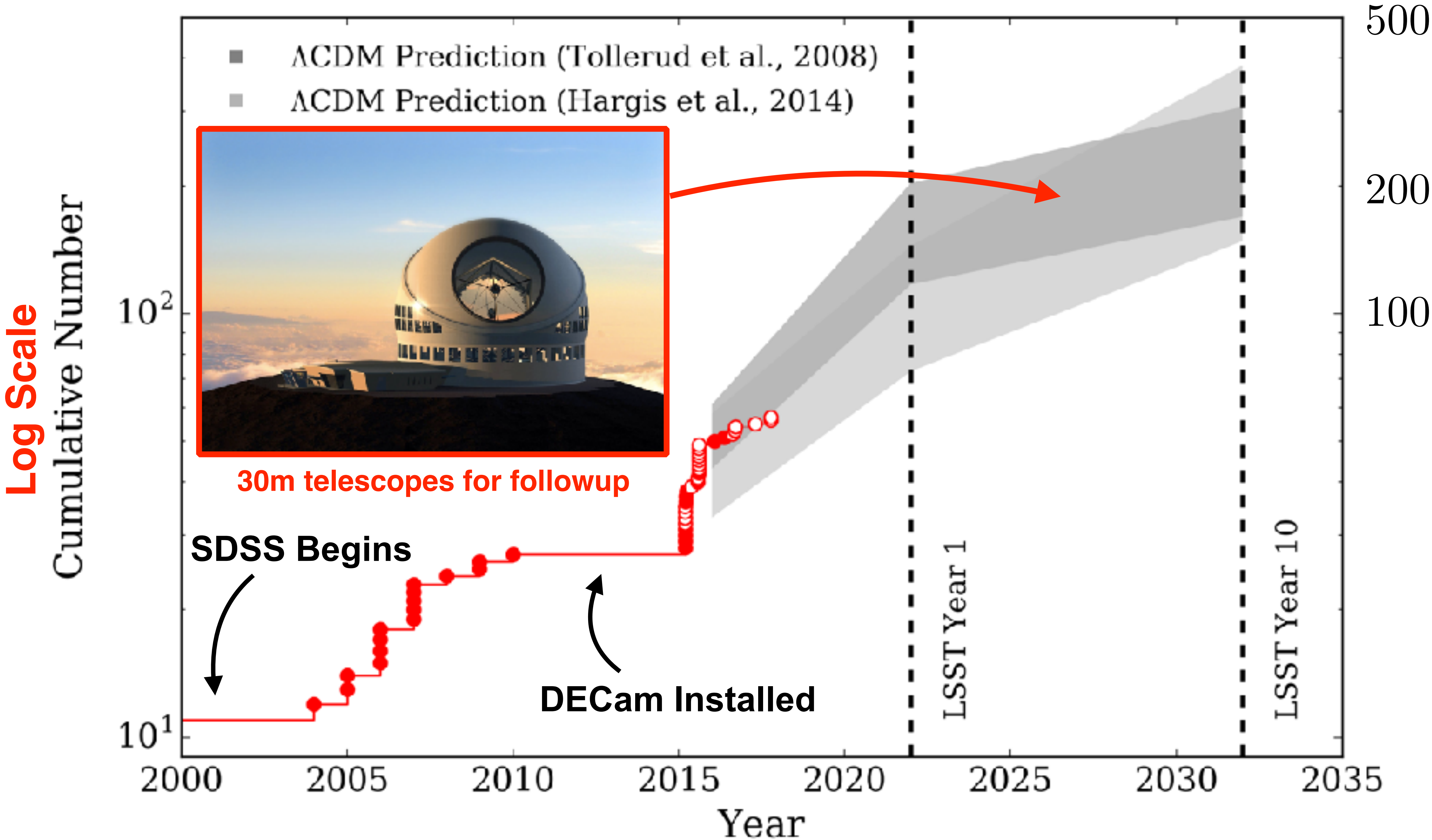
Sensitivity of DES in one 15s exposure!

~$500M construction approved and underway

Commissioning in 2020; survey start in ~2022

Expect ~0.5 EB (exabytes!) of data

Dwarf Galaxy Discovery Timeline



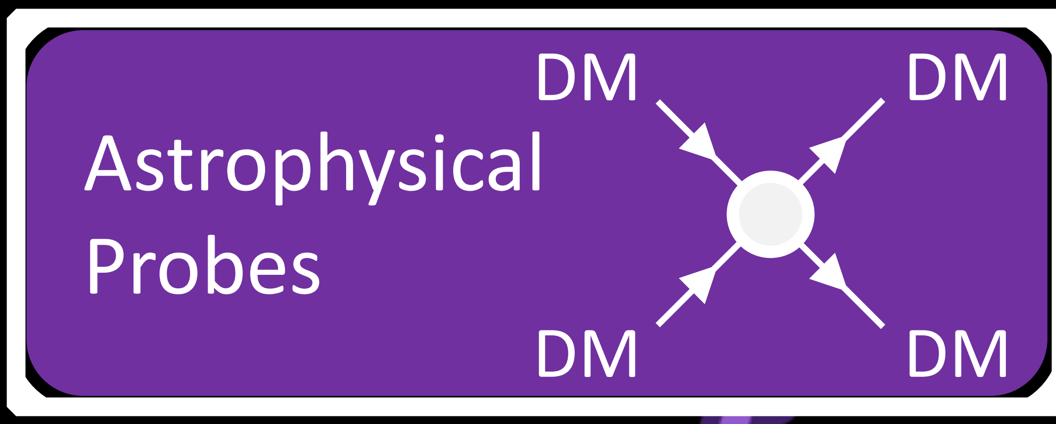
Probing Dark Matter with LSST

https://lsstdarkmatter.github.io/dark-matter-graph/

Self-Interacting DM:
Colliding galaxy clusters;
dwarf galaxies

SUSY:
complementarity with direct and indirect detection

Warm DM:
dwarf galaxies;
stellar streams;
Lyman-α forest

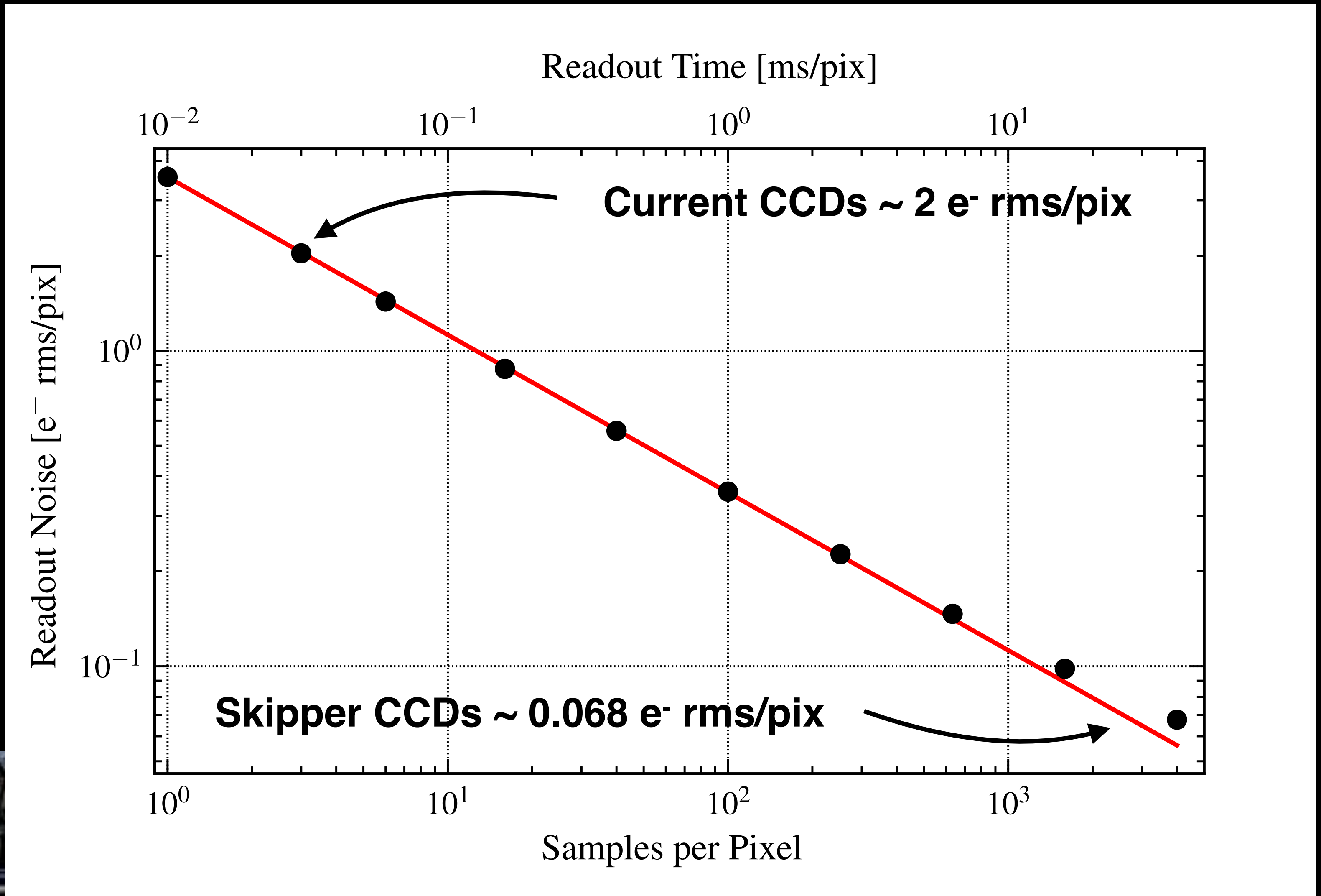


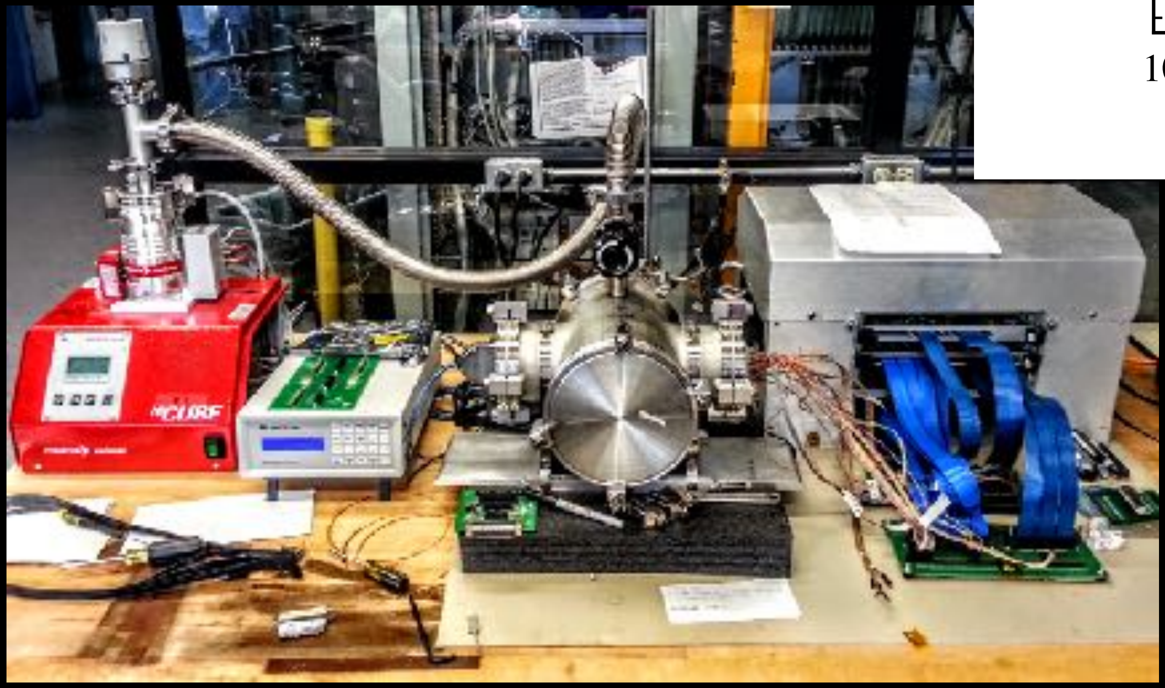
Axions:
anomalous stellar cooling;
white dwarf and RGB population statistics

Primordial Black Holes:
microlensing;
supernova caustics

Alex Drlica-Wagner

New CCDs for New Discoveries





Ultra-low read noise through multiple non-destructive reads of the charge in each pixel

Tiffenberg, Sofo-Haro, ADW, et al. PRL 119, 131802 (2017)

Summary

Dark matter is one of the major open questions in fundamental physics.

Cosmic surveys have entered the era of precision measurement.

Astrophysics provides the only robust, positive measurement of dark matter.

Dwarf galaxy are an important target class for gravitational probes and indirect dark matter searches.

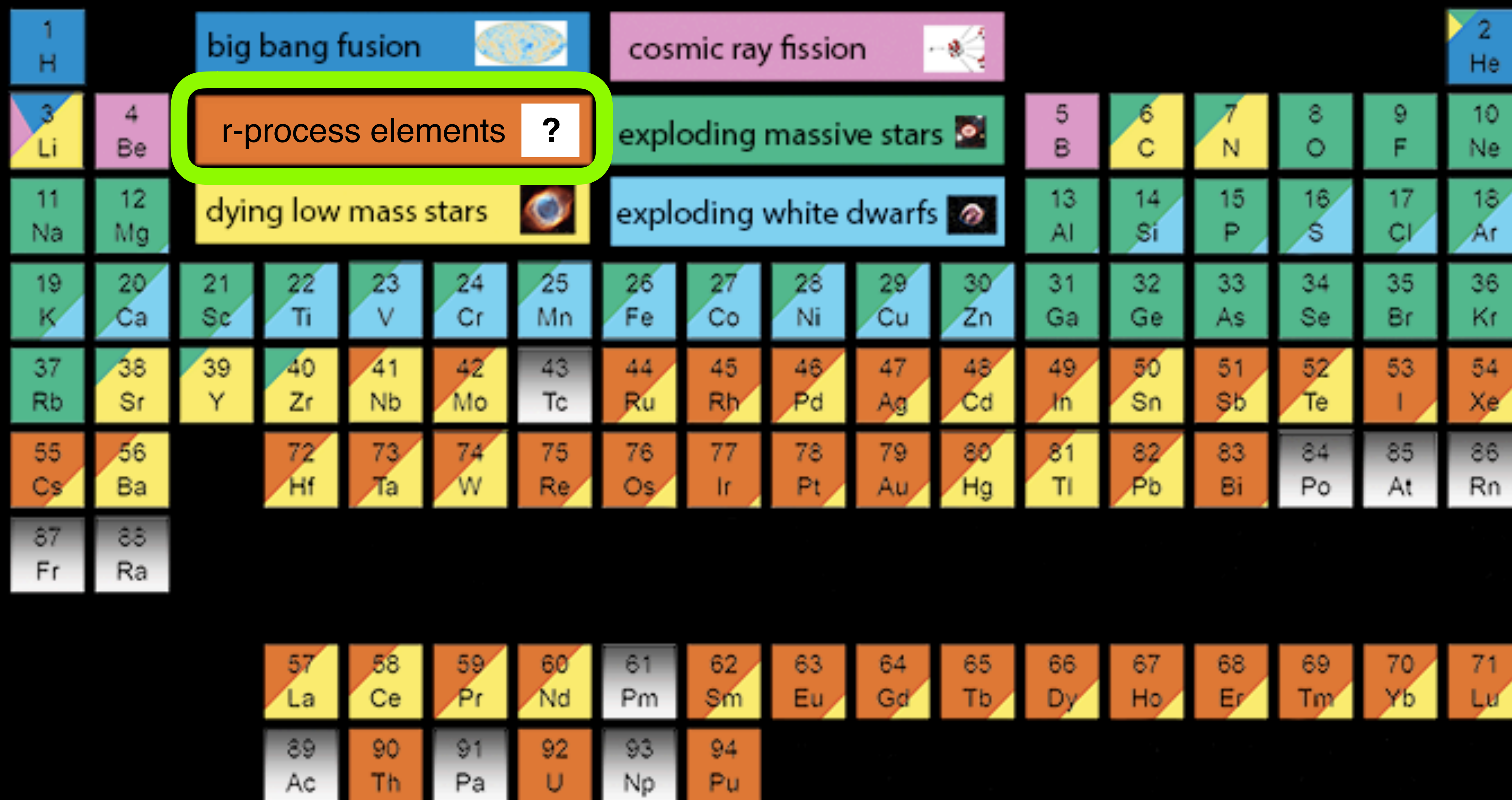
Cosmic surveys will continue to guide particle dark matter searches in the decades to come.

Backup Slides

Outline

- Dark Matter and Dwarf Galaxies
- **Search for the Darkest Galaxies**
  - Aside: Origin of the Heavy Elements
- Search for Dark Matter Annihilation
- Future Prospects

Origin of Heavy Elements



Graphic created by Jennifer Johnson
http://www.astronomy.ohio-state.edu/~jaj/nucleo/

Astronomical Image Credits:
ESA/NASA/AASNova

Origin of Heavy Elements

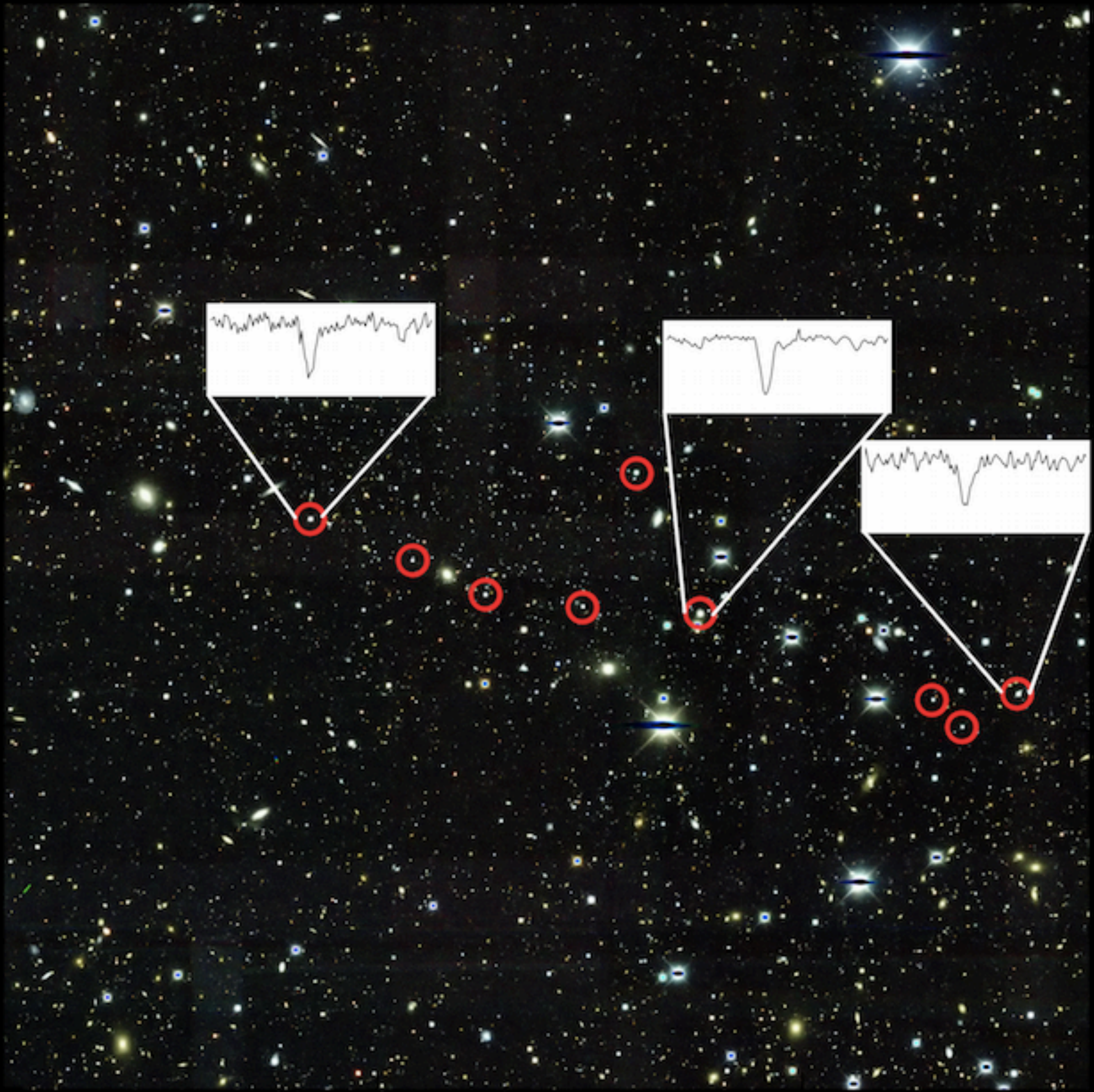
Supernova

High Rate ~ 0.03 per year
Low Yield ~ $10^{-7.5}$ M_{sun} of Eu

Neutron Star Mergers

Low Rate ~ 10^{-3} SN Rate
High Yield ~ $10^{-4.5}$ M_{sun} of Eu

Reticulum II Dwarf Galaxy



Reticulum II Dwarf Galaxy: r-process abundances

High resolution spectroscopy of individual stars

s-process elemental abundances consistent with other dwarf galaxies

r-process elemental abundances enhanced by factor of >100!

Supernova would disrupt the galaxy; suggests rare event (neutron star merger) as the site of r-process

Ji et al. (2016)