Using Cosmic Surveys to Understand the Fundamental Nature of Dark Matter

Alex Drlica-Wagner
David N. Schramm Fellow
Fermilab

LBNL RPM
January 30, 2018

Outline

- Dark Matter and Cosmic Surveys
- Search for Dark Matter Annihilation
- Search for the Darkest Galaxies
- Dark Matter with Future Surveys

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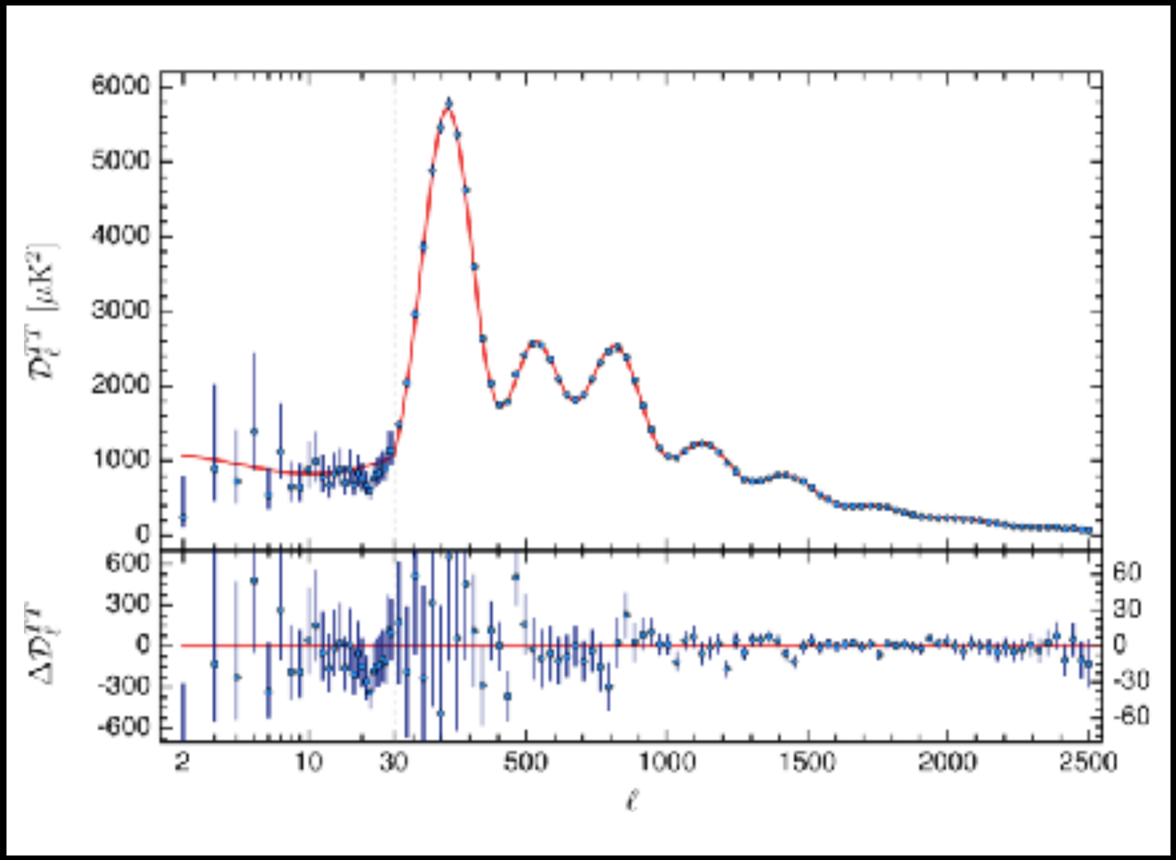
The Cosmic Frontier

Fundamental Physics

Dark Matter
Dark Energy
Inflation
Baryon Asymmetry
Neutrino Mass

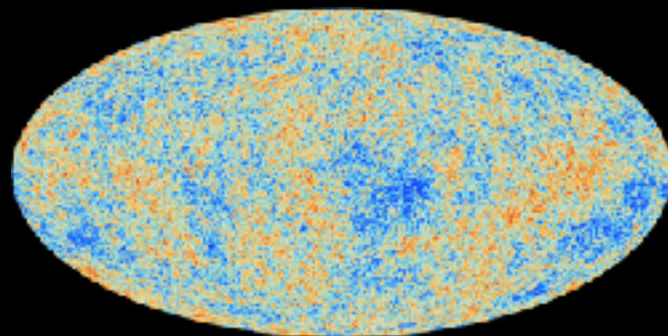
Precision Measurements



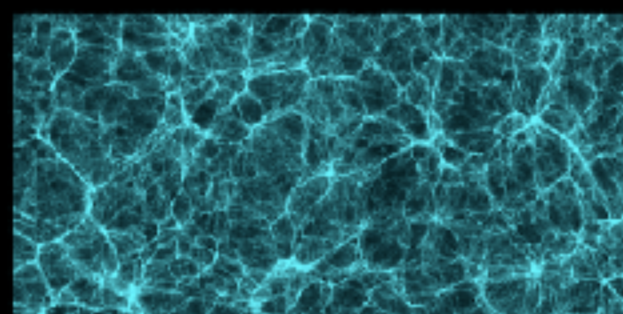
Planck Collaboration (2016)

Composition of the Universe

Observable Universe



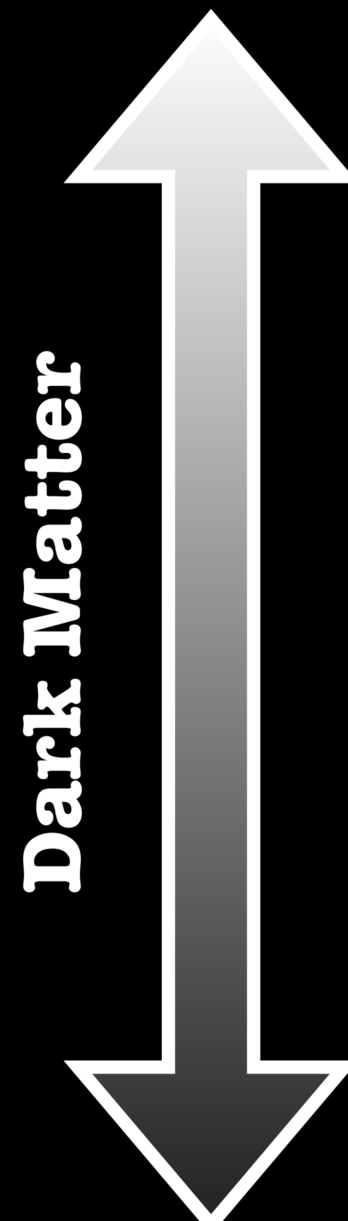
Clusters of Clusters



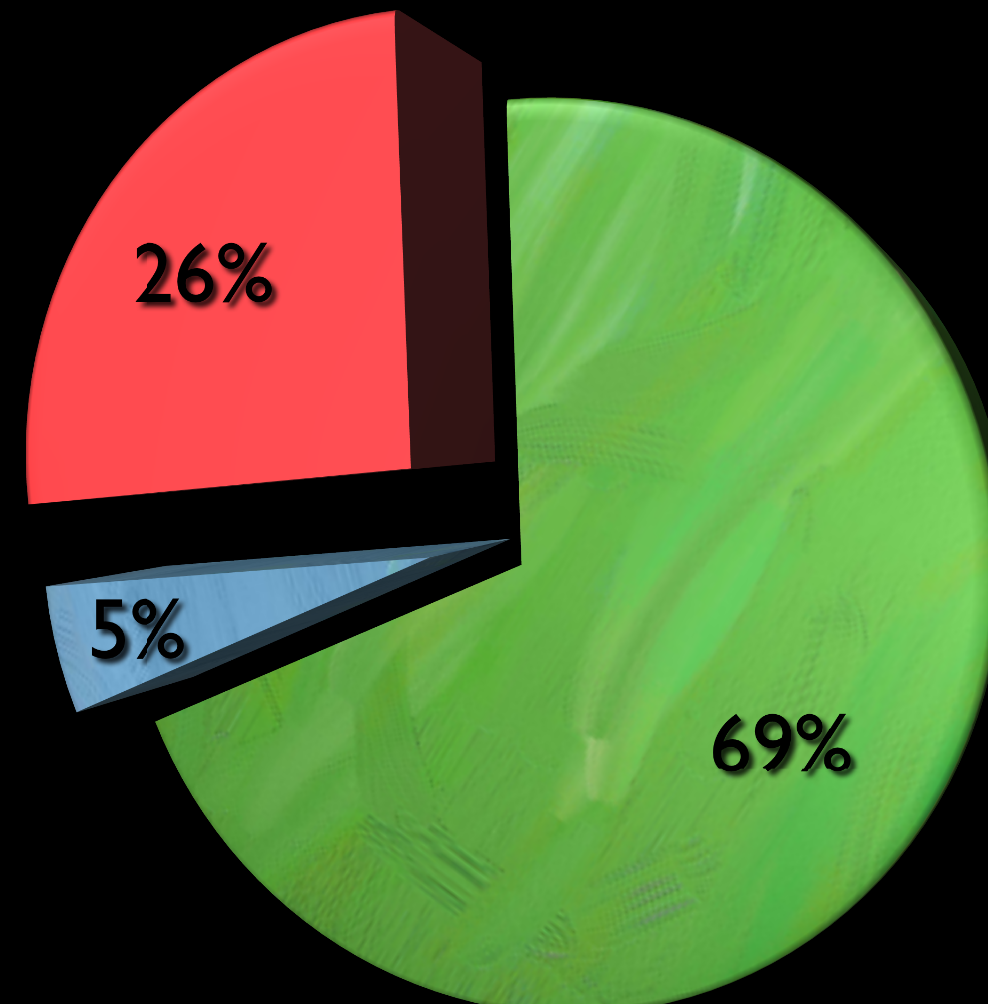
Clusters of Galaxies

Individual Galaxies

Larger

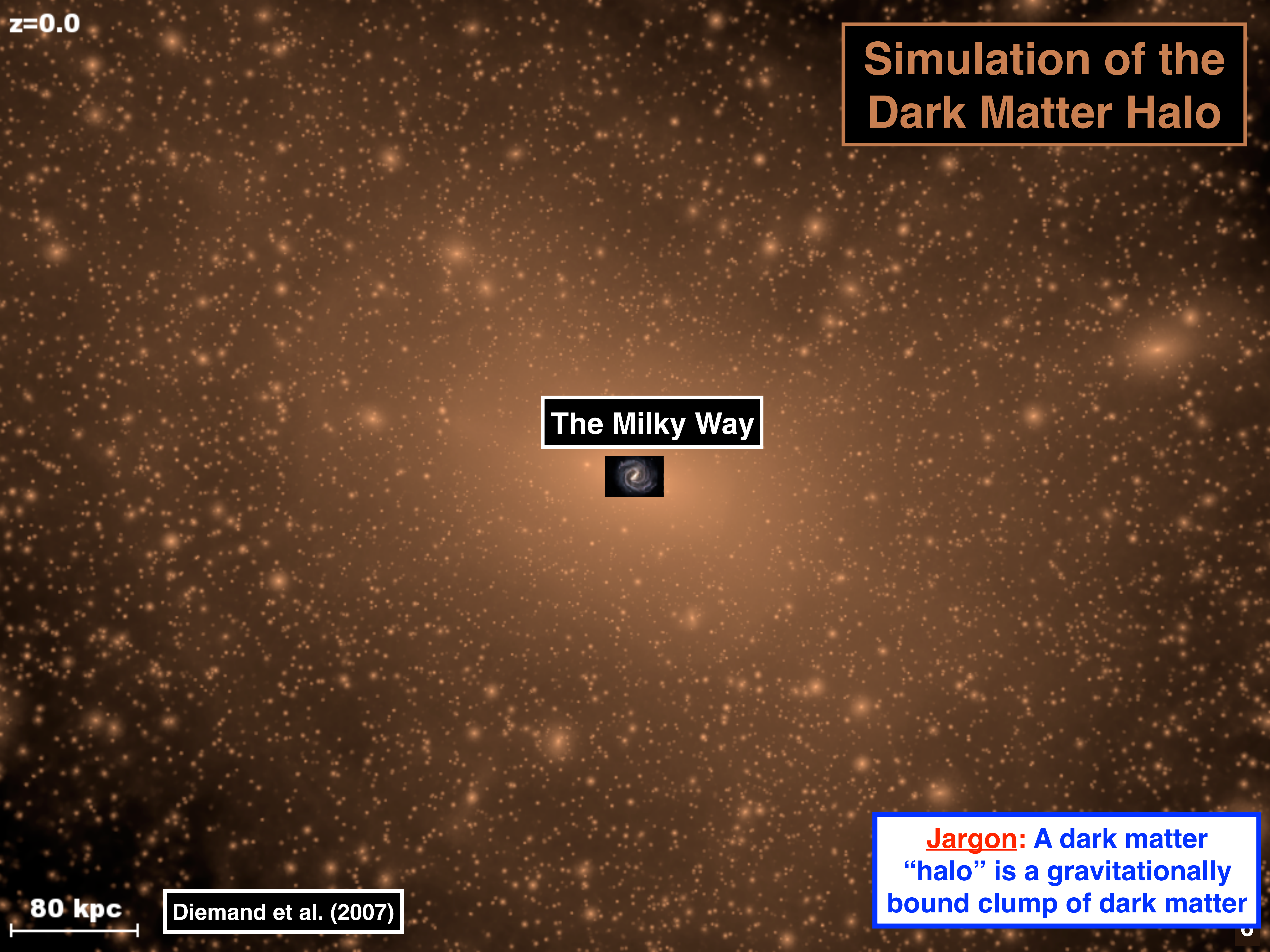


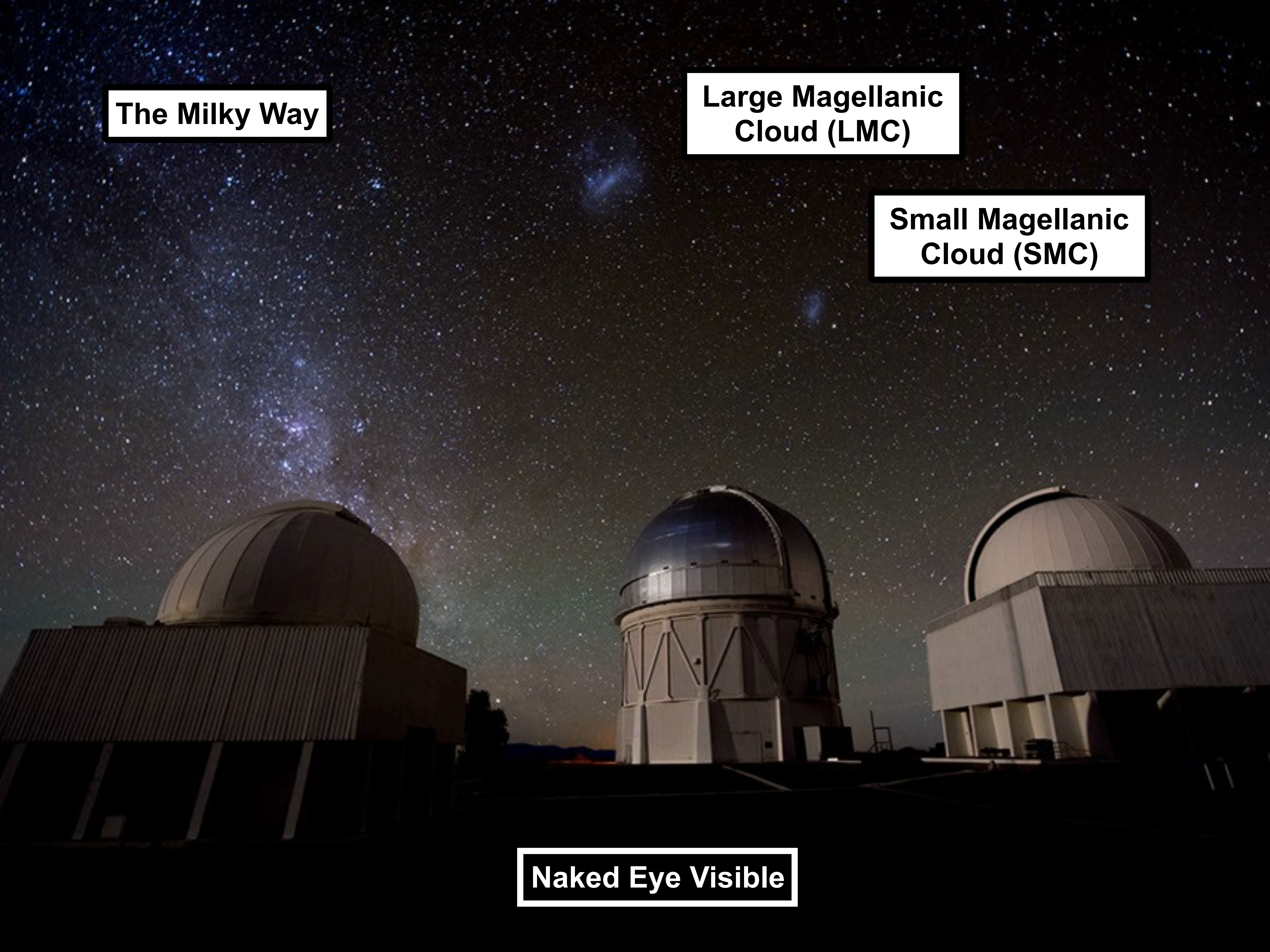
Smaller



- DARK MATTER
- DARK ENERGY
- ORDINARY MATTER

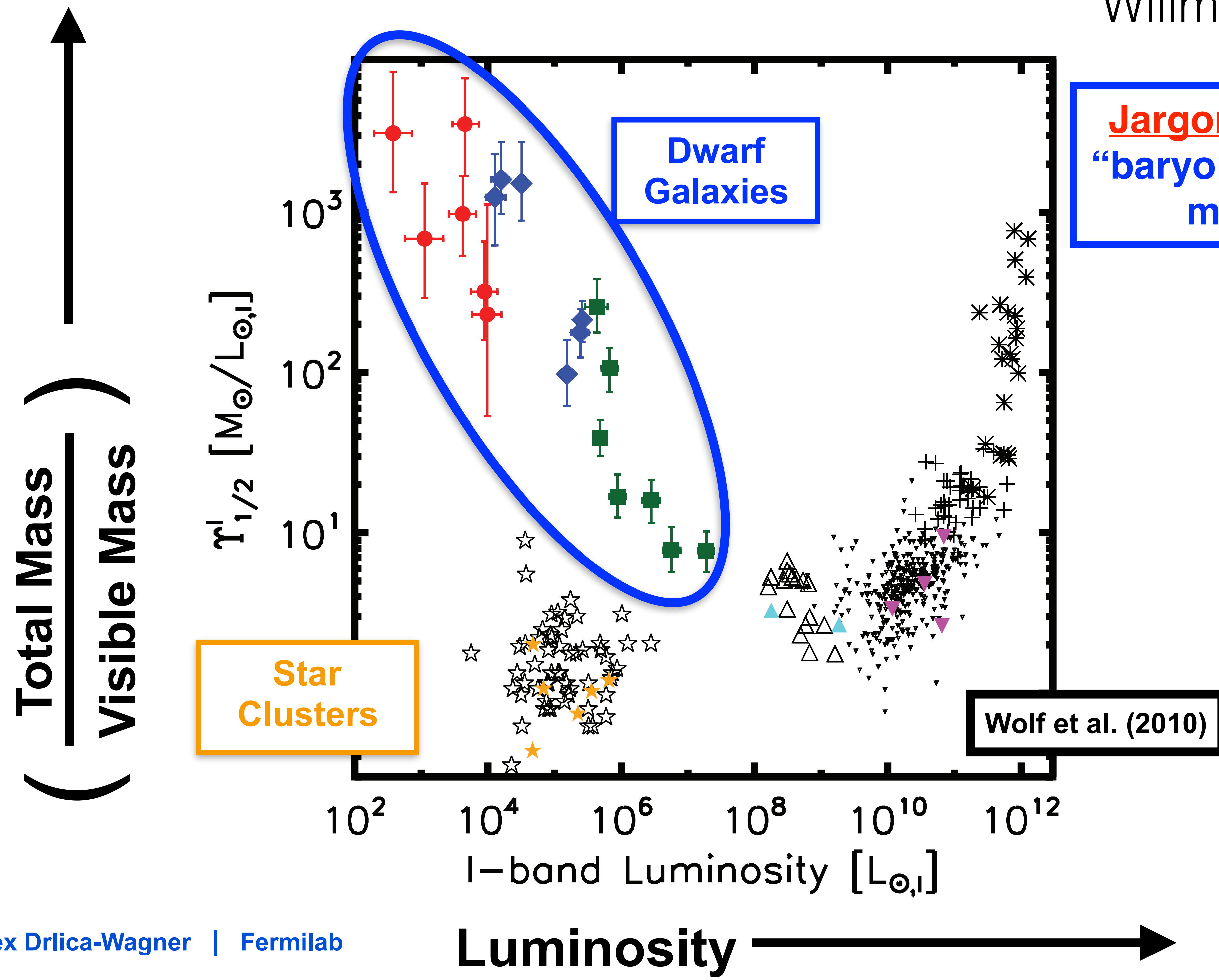
Plank Collaboration (2016)


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

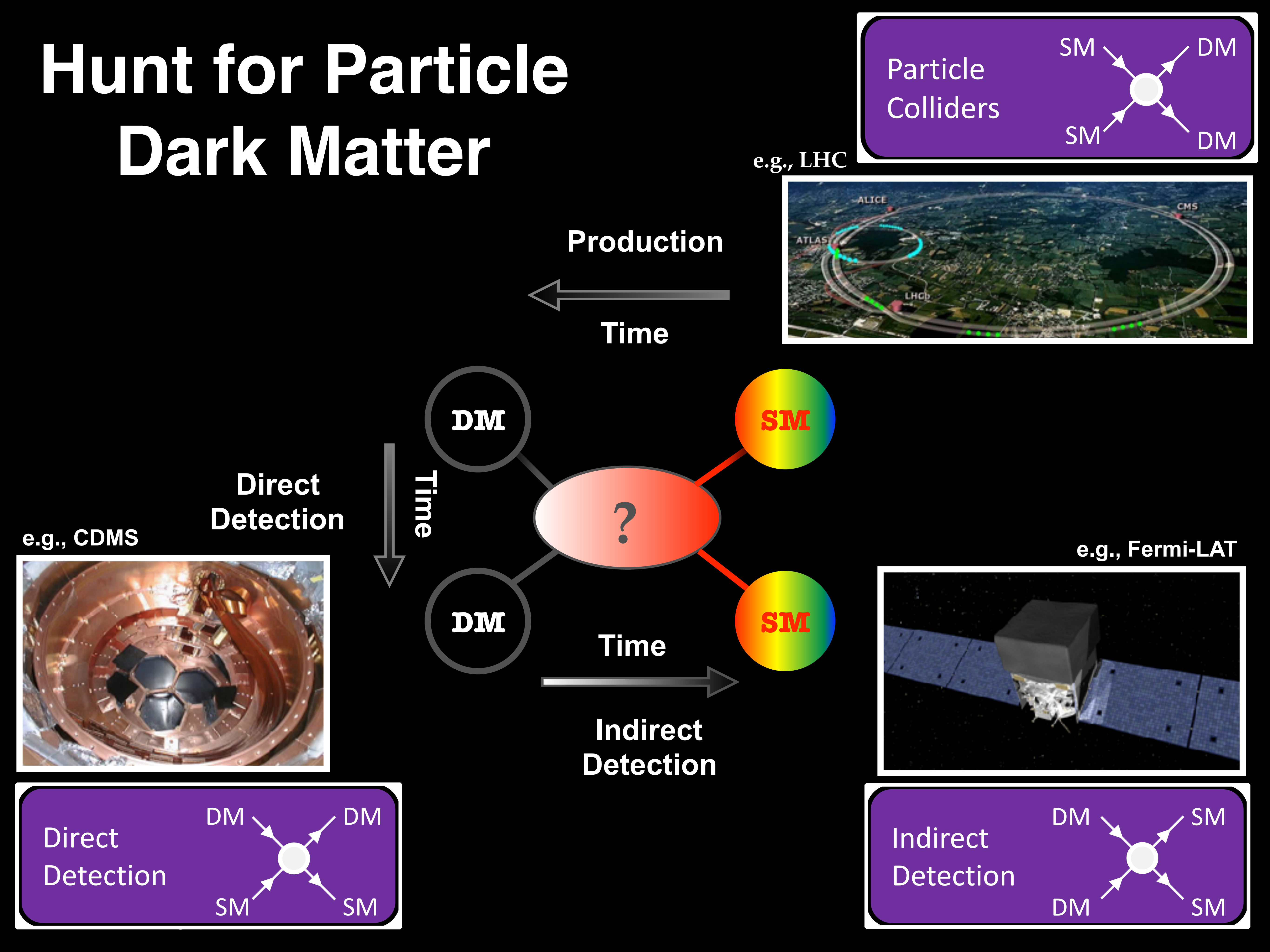

The Milky Way
Large Magellanic Cloud (LMC)
Small Magellanic Cloud (SMC)
Naked Eye Visible

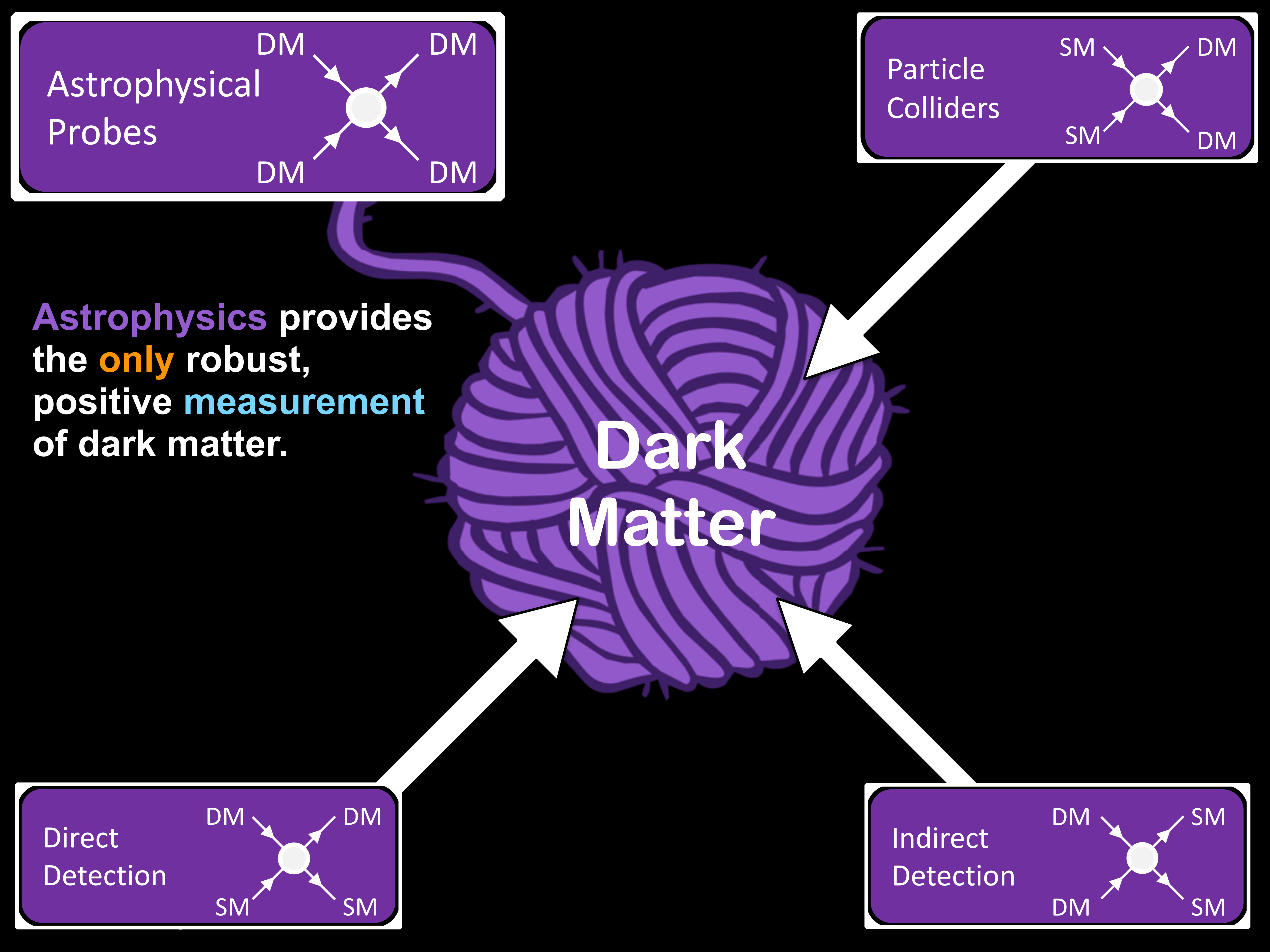
"Galaxy" Defined

"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)

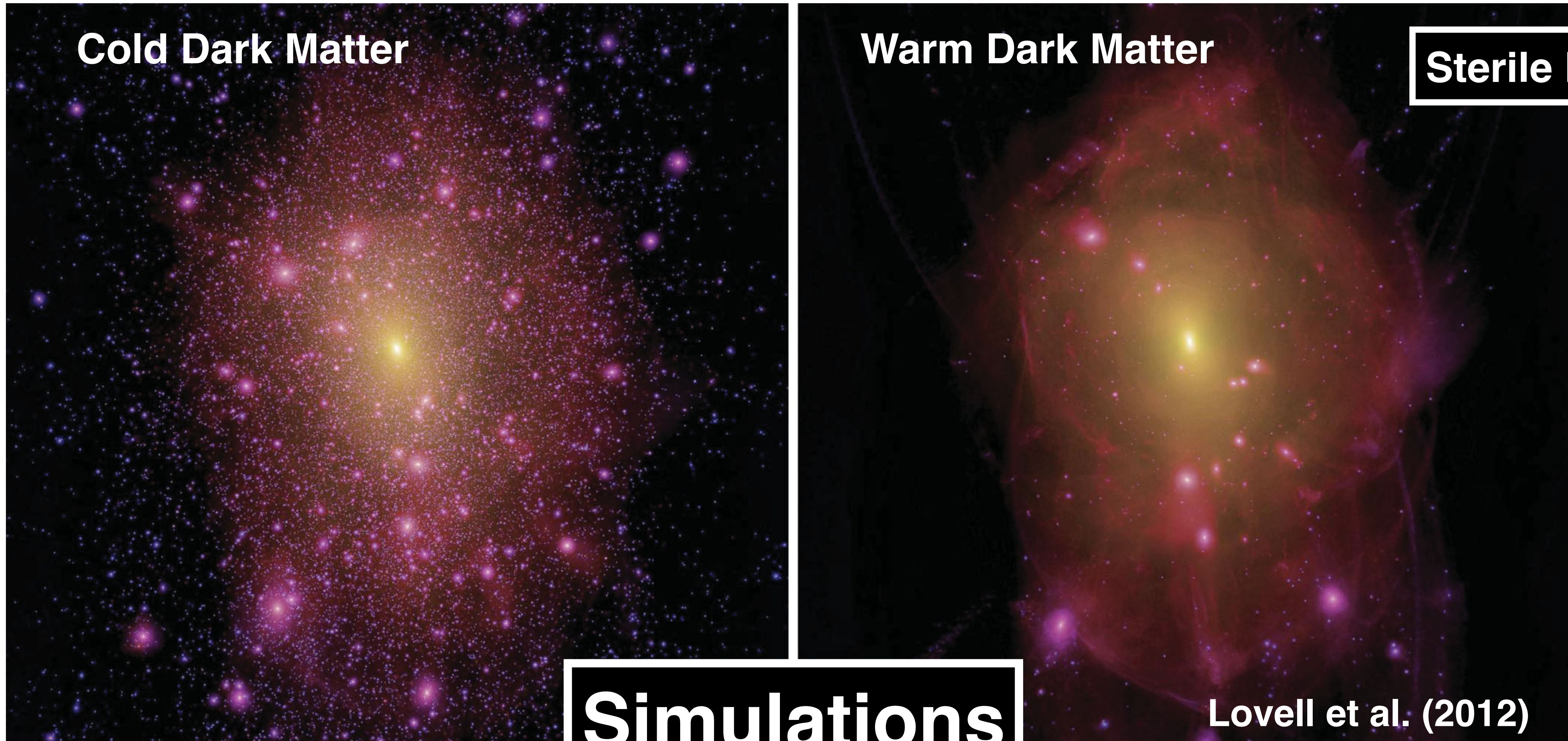


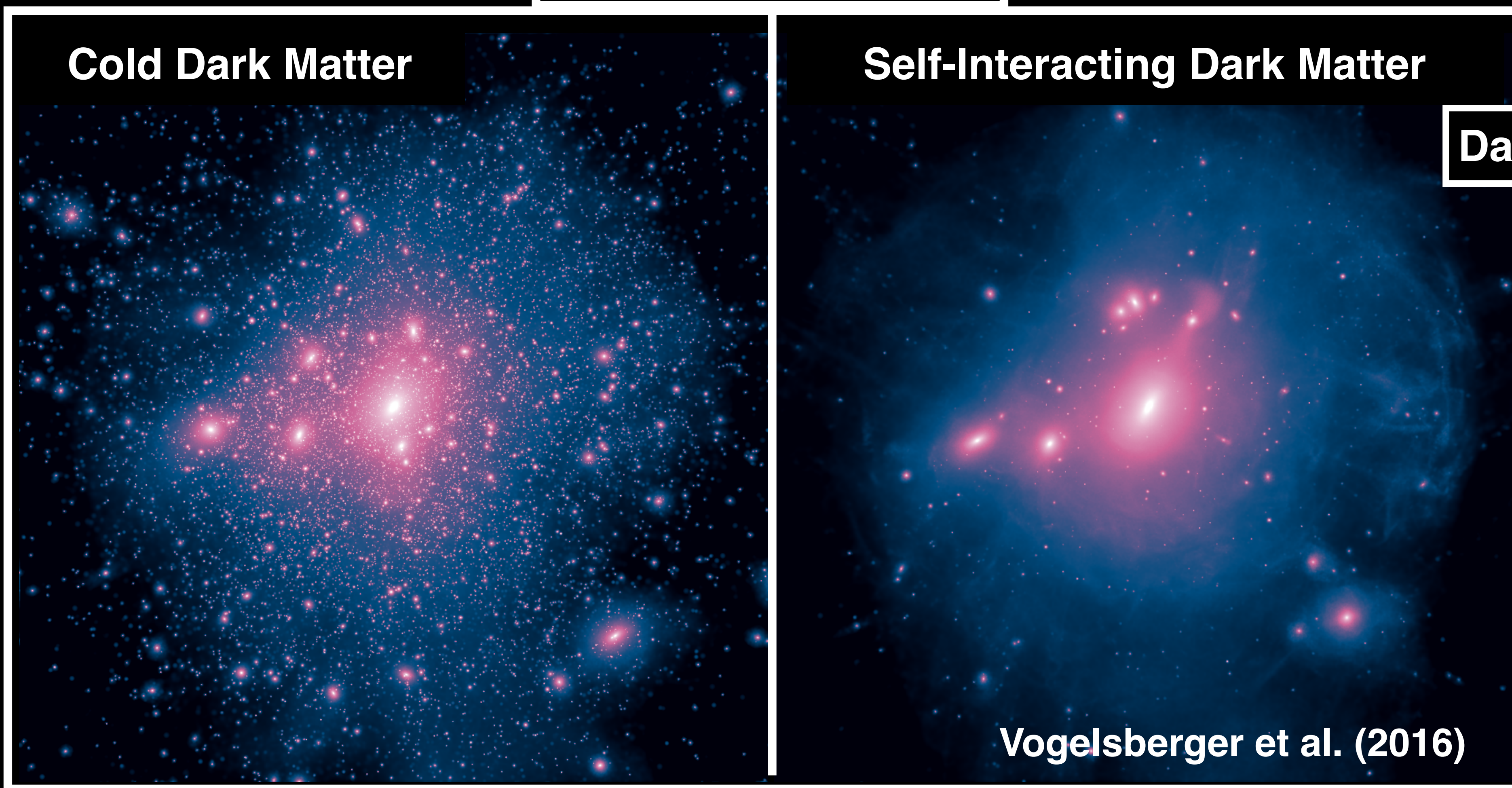
Jargon: Astrophysicists use "baryon" to mean all standard model components.


Hunt for Particle Dark Matter
Particle Colliders
SM
DM
SM
DM
e.g., LHC
ALICE
CMS
ATLAS
LHCb
Production
Time
DM
SM
?
DM
SM
Direct Detection
Time
e.g., CDMS
Time
Indirect Detection
e.g., Fermi-LAT
Direct Detection
DM
DM
SM
SM
Indirect Detection
DM
SM
DM
SM


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

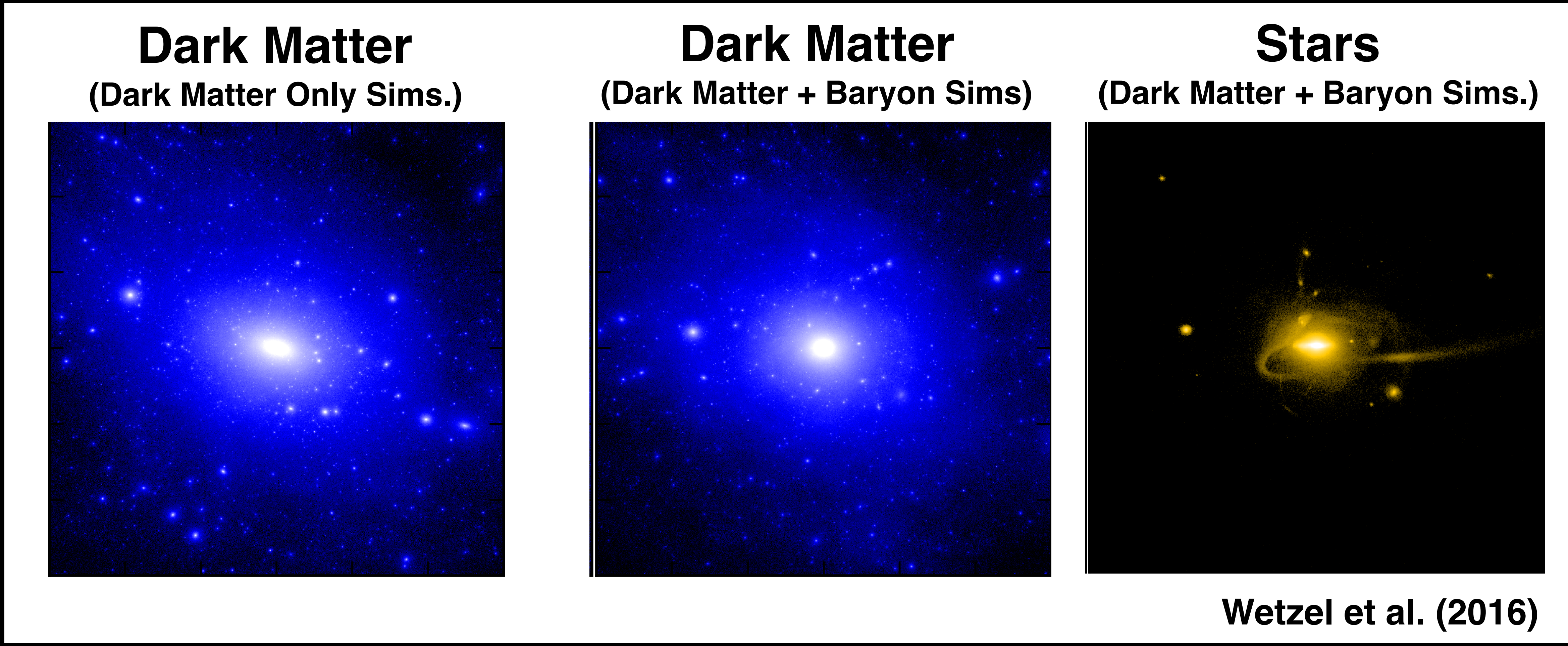
Simulations





Beware of Baryons!

Baryons can also disrupt the smallest structures



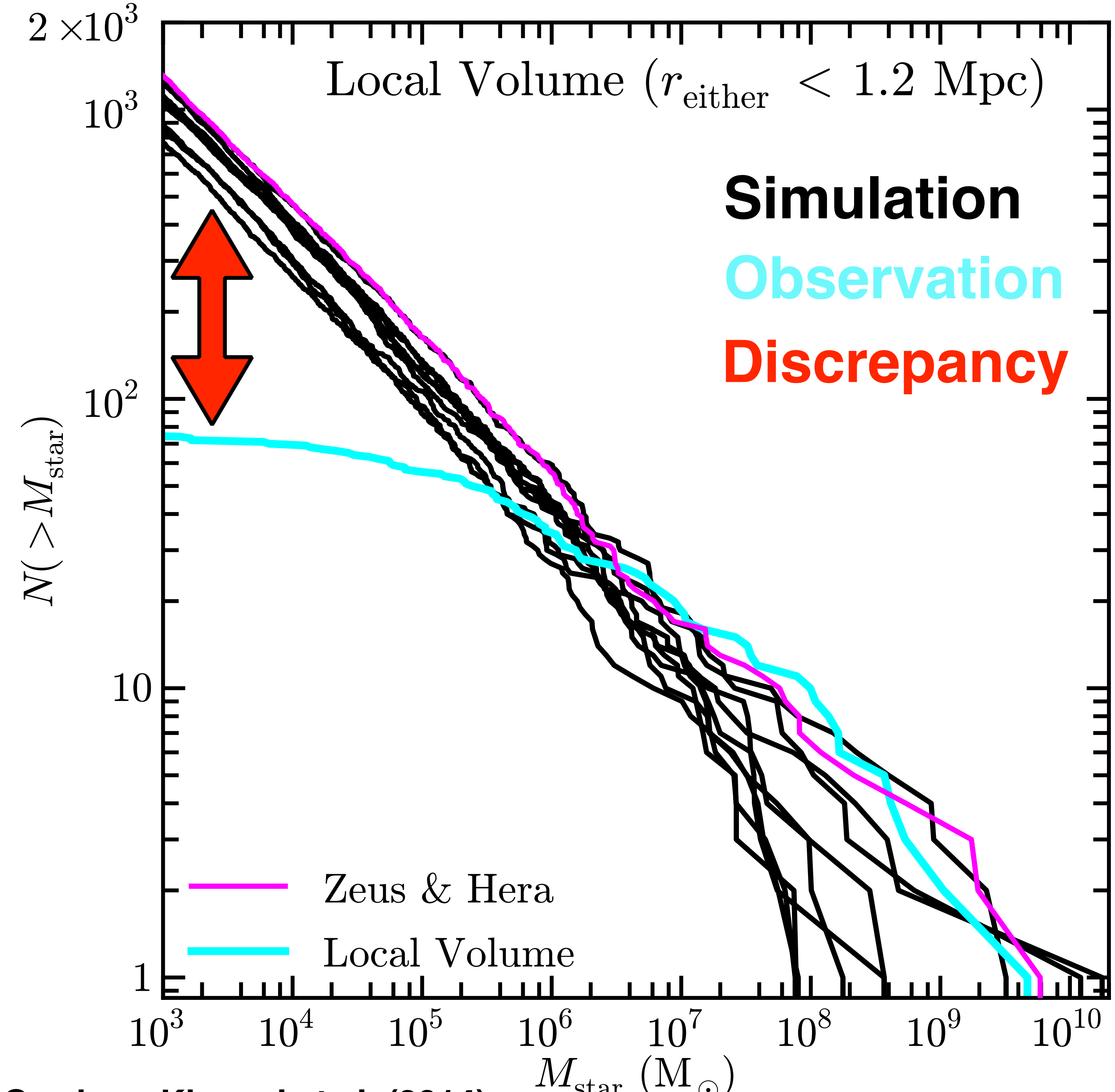
Simulations have begun to robustly include baryonic physics
(i.e., FIRE, APOSTLE, EAGLE)

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

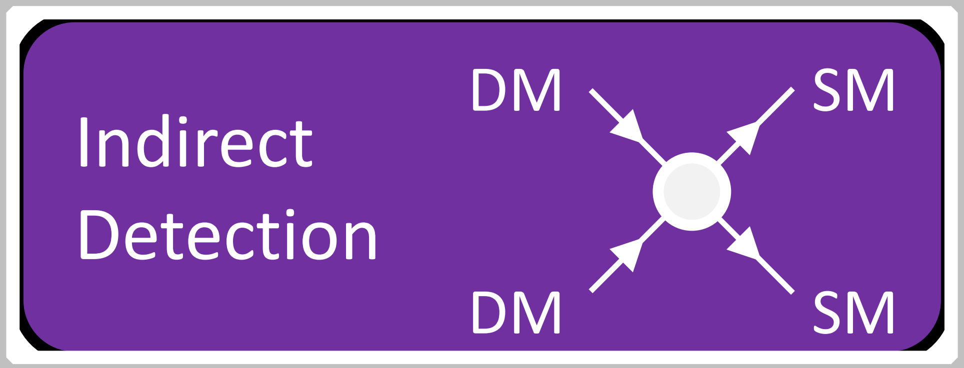
Primary Research Goal

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

Avenues of Attack

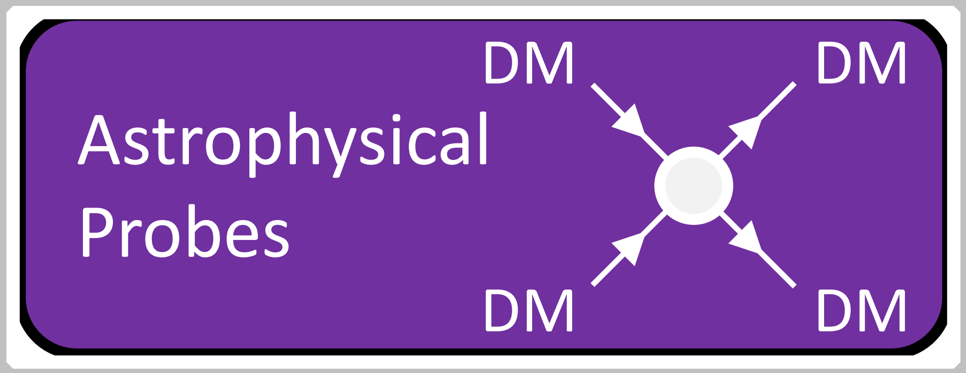
Indirect Detection

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



Astrophysical Probes

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



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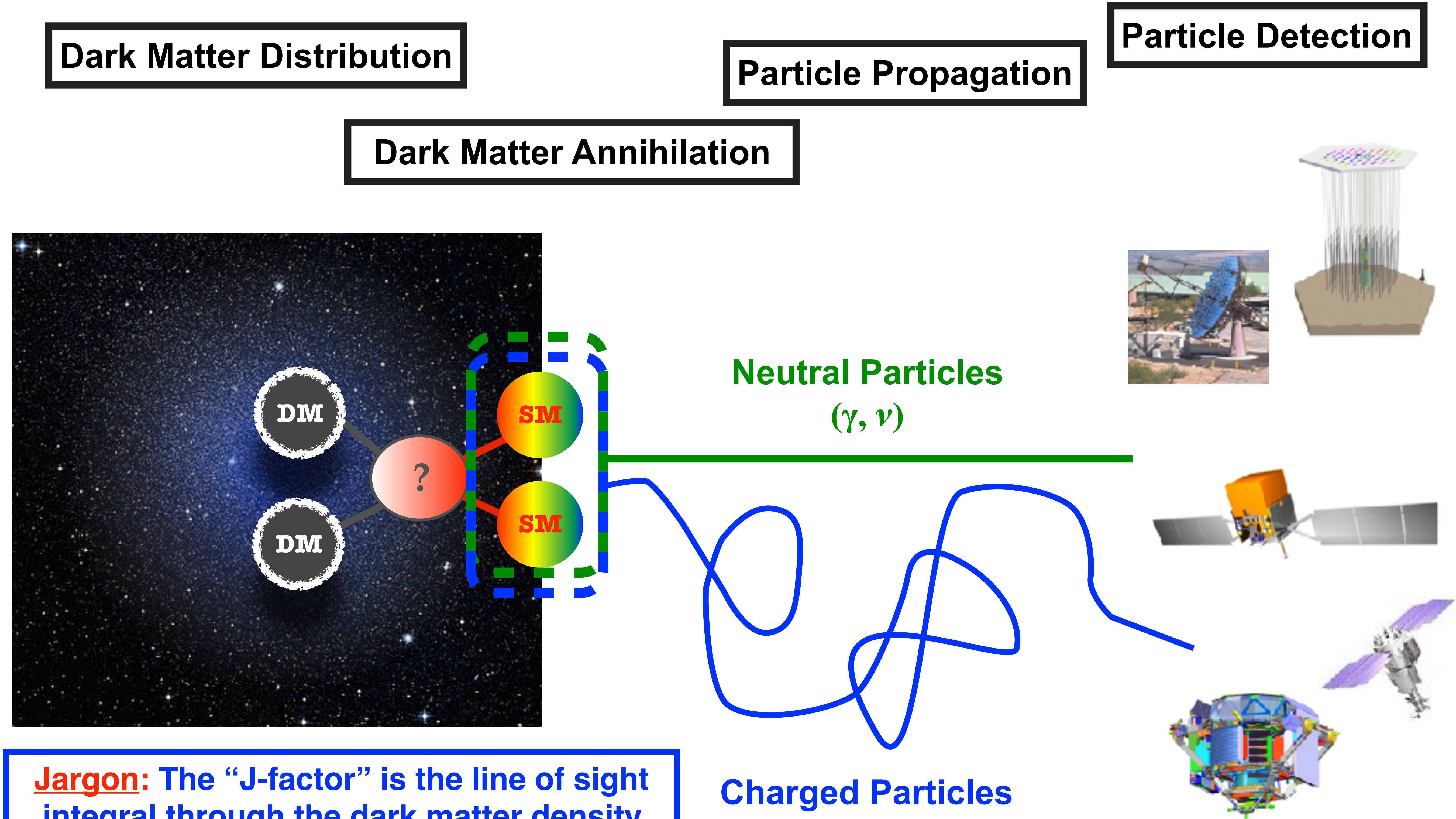
Indirect Detection



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.

Indirect Detection

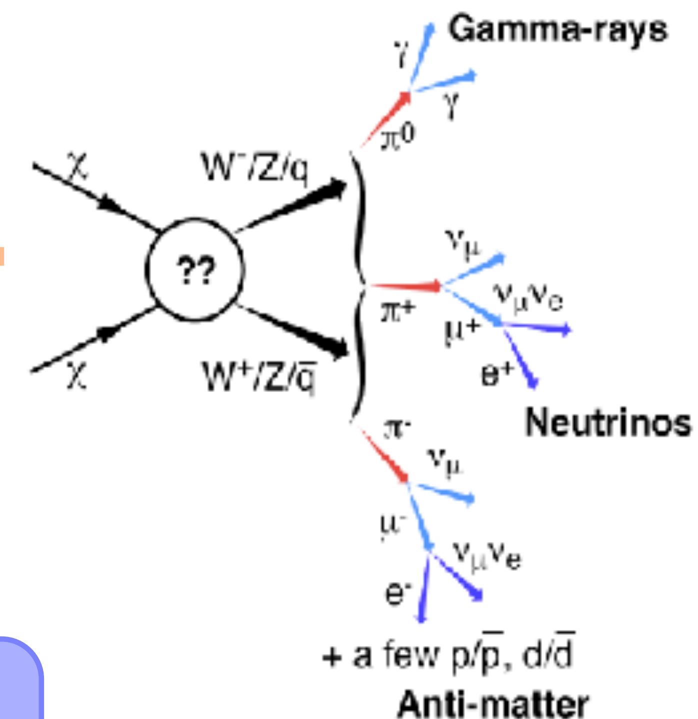
Gamma-ray Flux
(signal in data)

Particle Physics
(photons per annihilation)

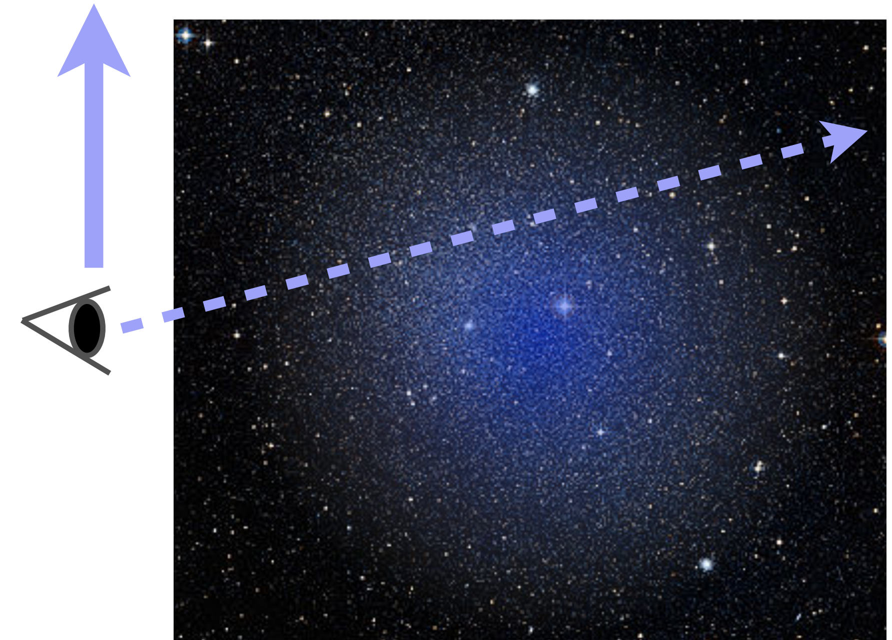
$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times$$

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



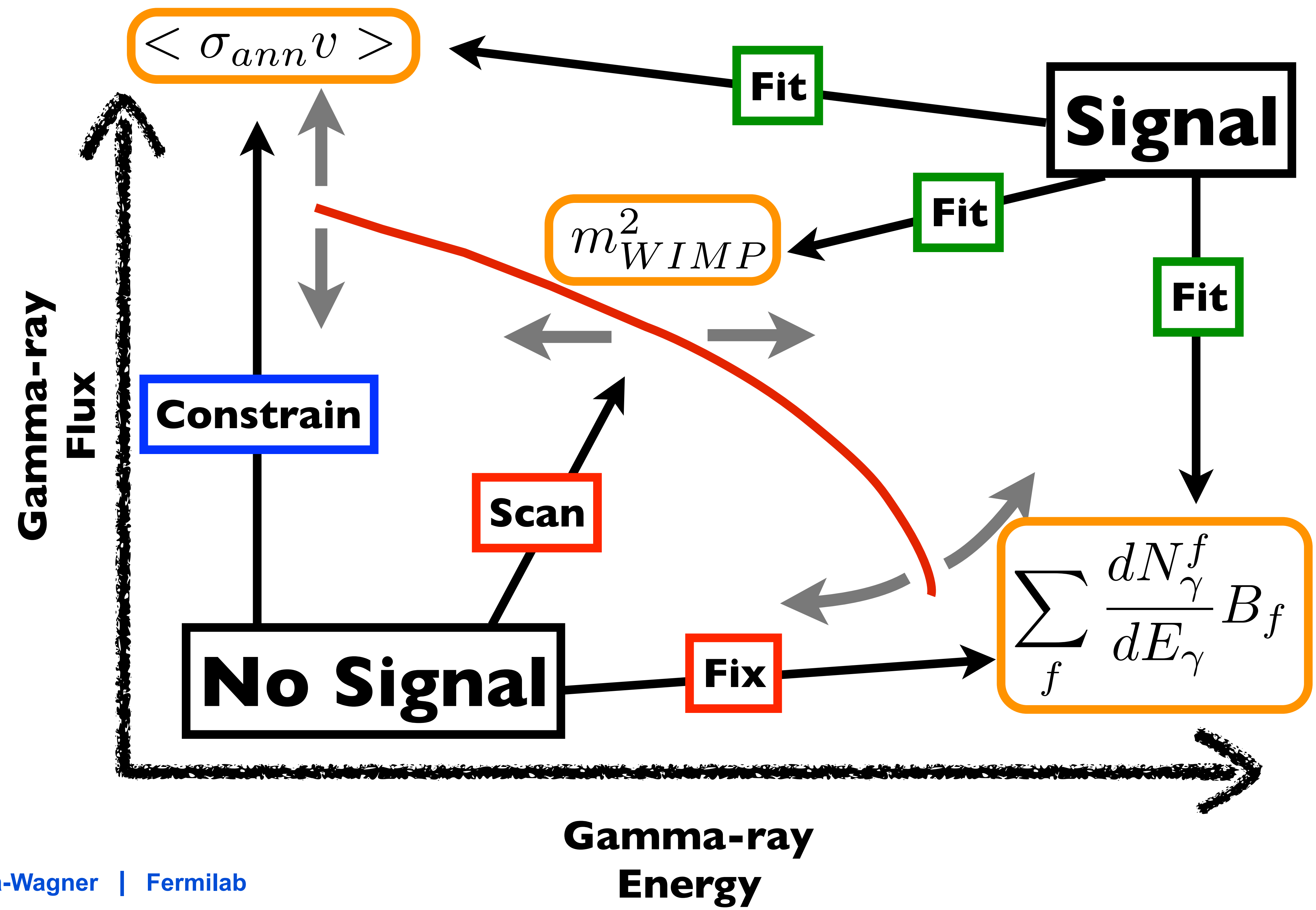
Dark Matter Distribution
(line-of-sight integral)



Gamma-ray Spectrum

$$\frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m_{WIMP}^2}\sum_f \frac{dN^f}{dE}B_f$$

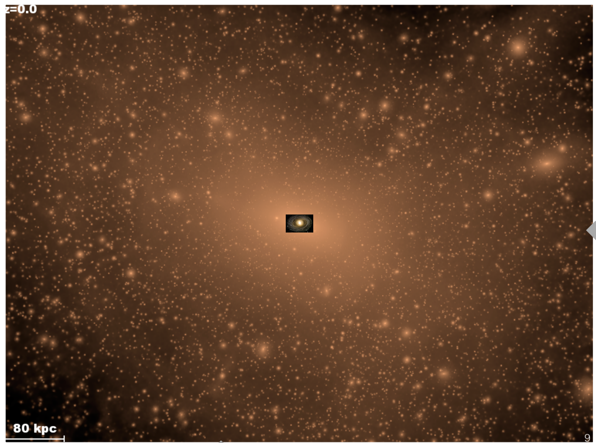
$$\langle \sigma v \rangle \sim 3 \times 10^{-26} \mathrm{cm^3\,s^{-1}}$$

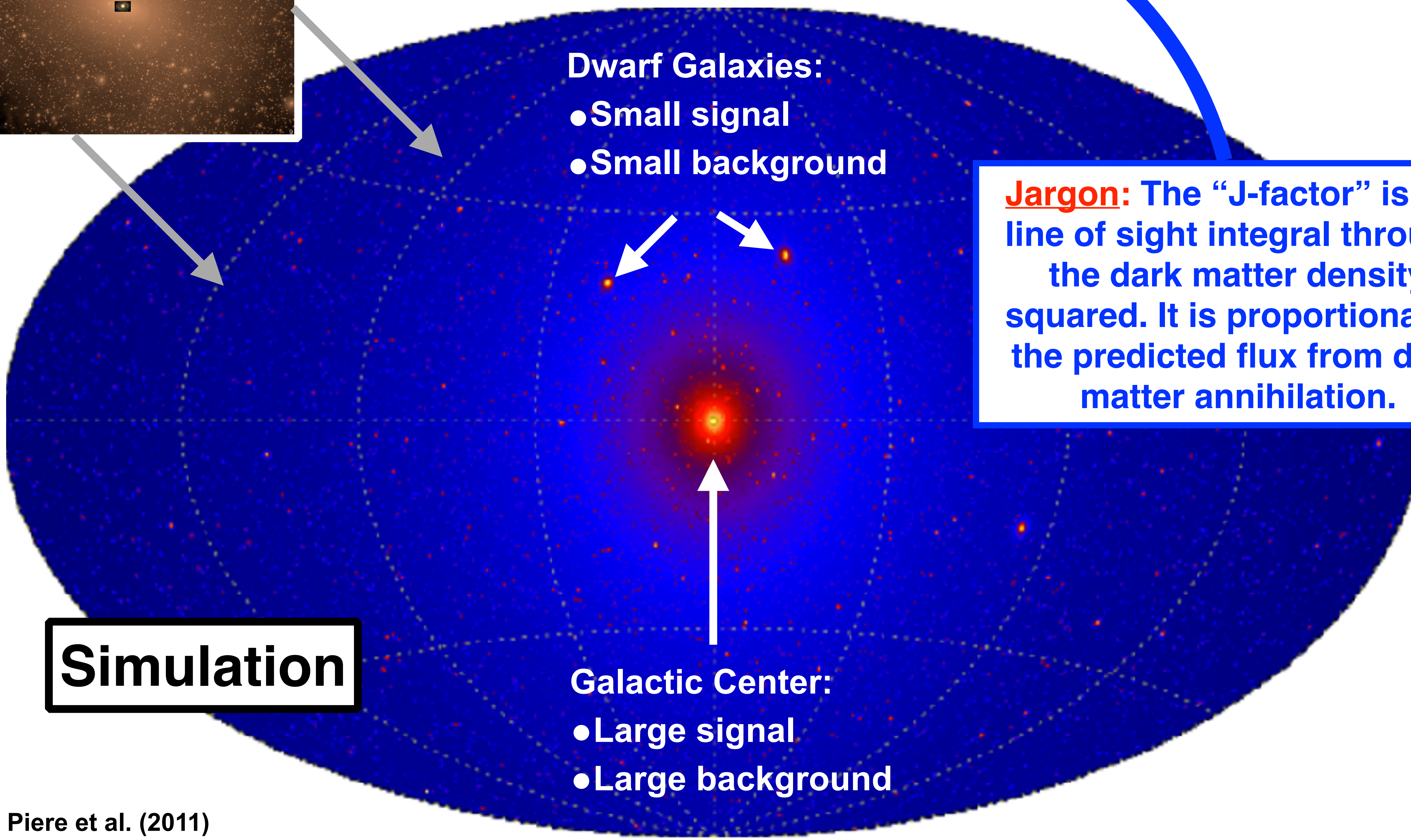


Dark Matter in the Milky Way

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

$$J \sim \frac{1}{\text{Distance}^2}$$





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.

Piere et al. (2011)

The Fermi Large Area Telescope

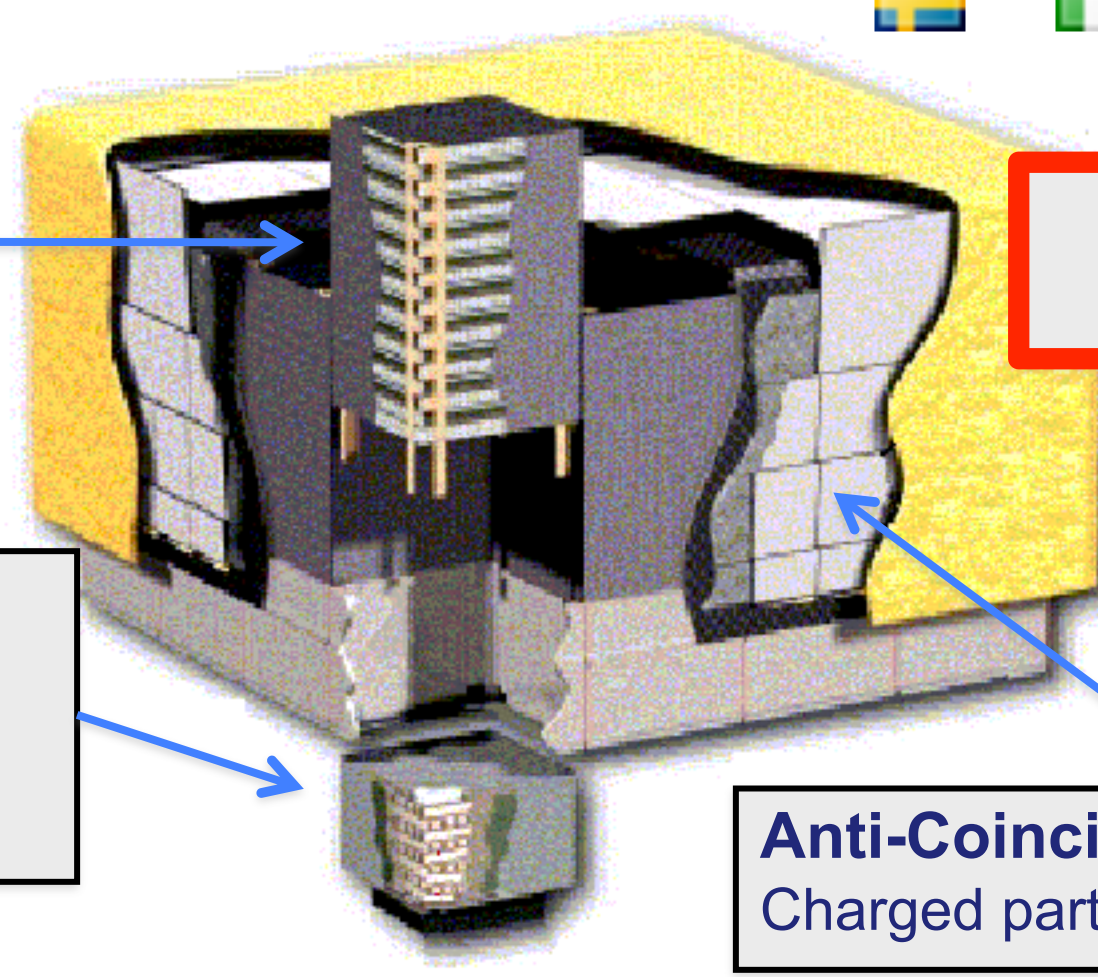
No Magnet

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

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

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

Energy Range:
20 MeV to >1 TeV



Hodoscopic CsI Calorimeter:
measure γ−ray energy
image EM shower
EM vs. hadron separation

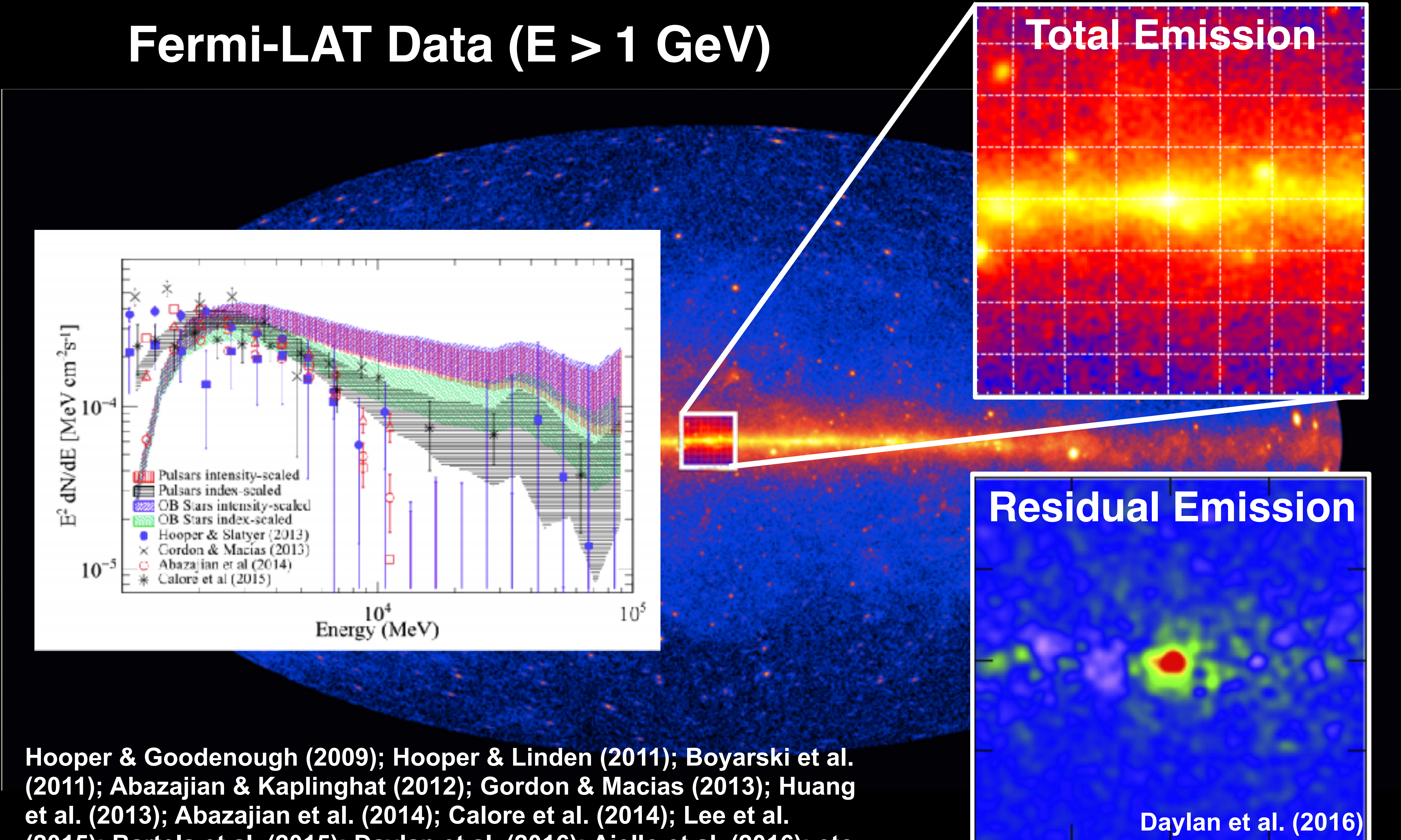
Anti-Coincidence Detector:
Charged particle separation

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

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

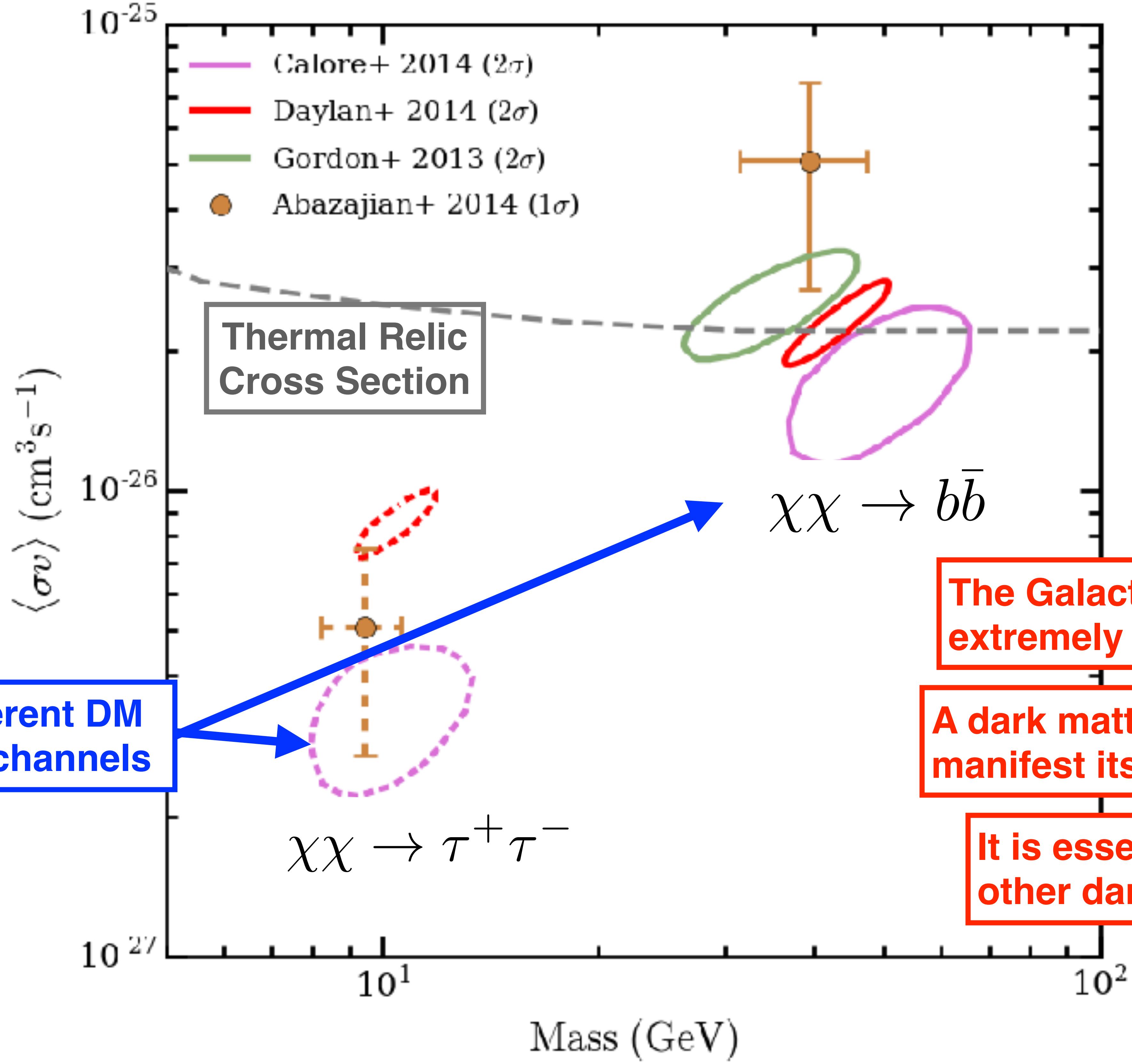
Galactic Center Gamma-Ray Excess

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.

The Galactic Center



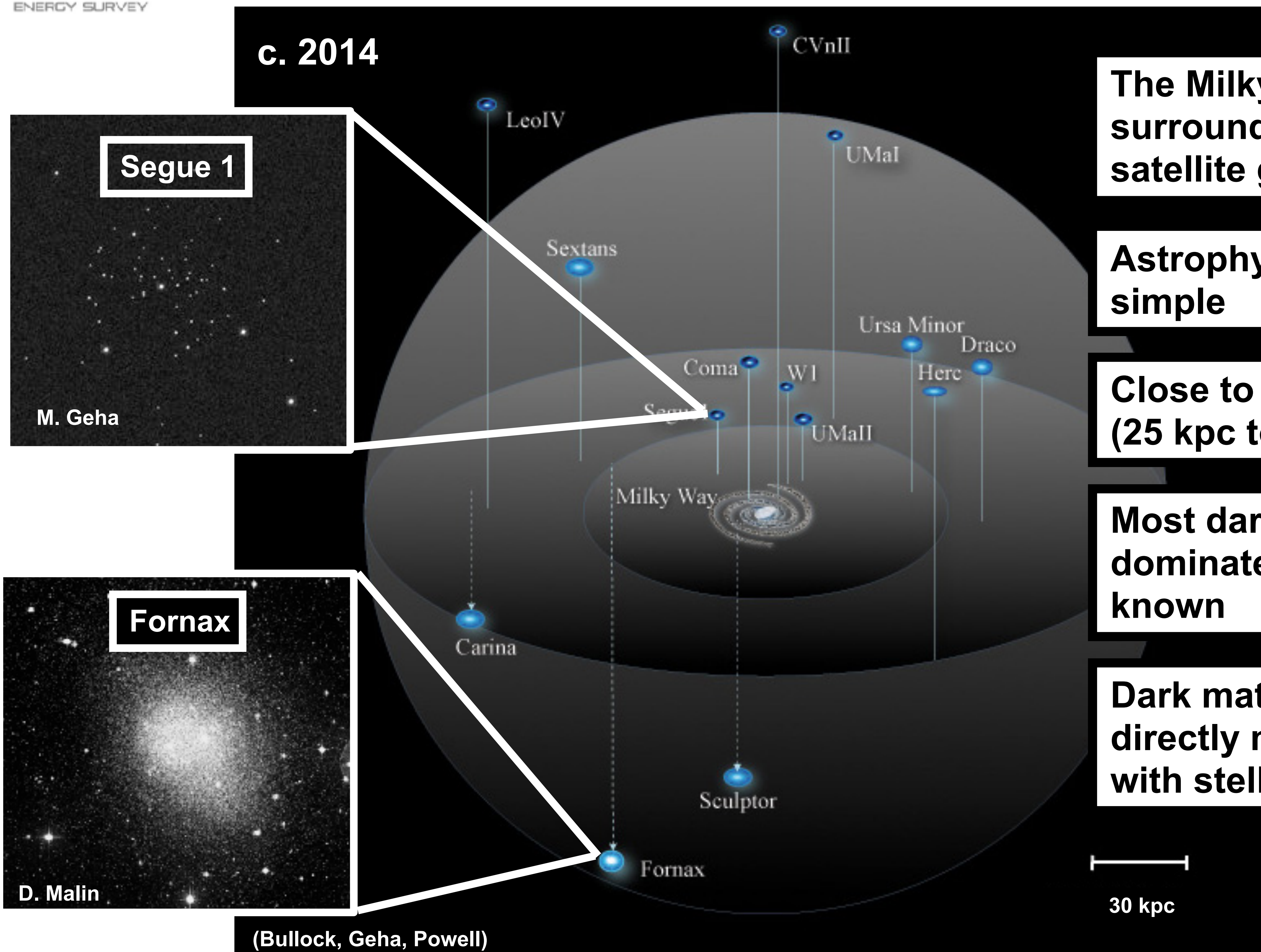
Assume different DM annihilation channels

The Galactic Center is an extremely complicated region

A dark matter signal should manifest itself in other regions

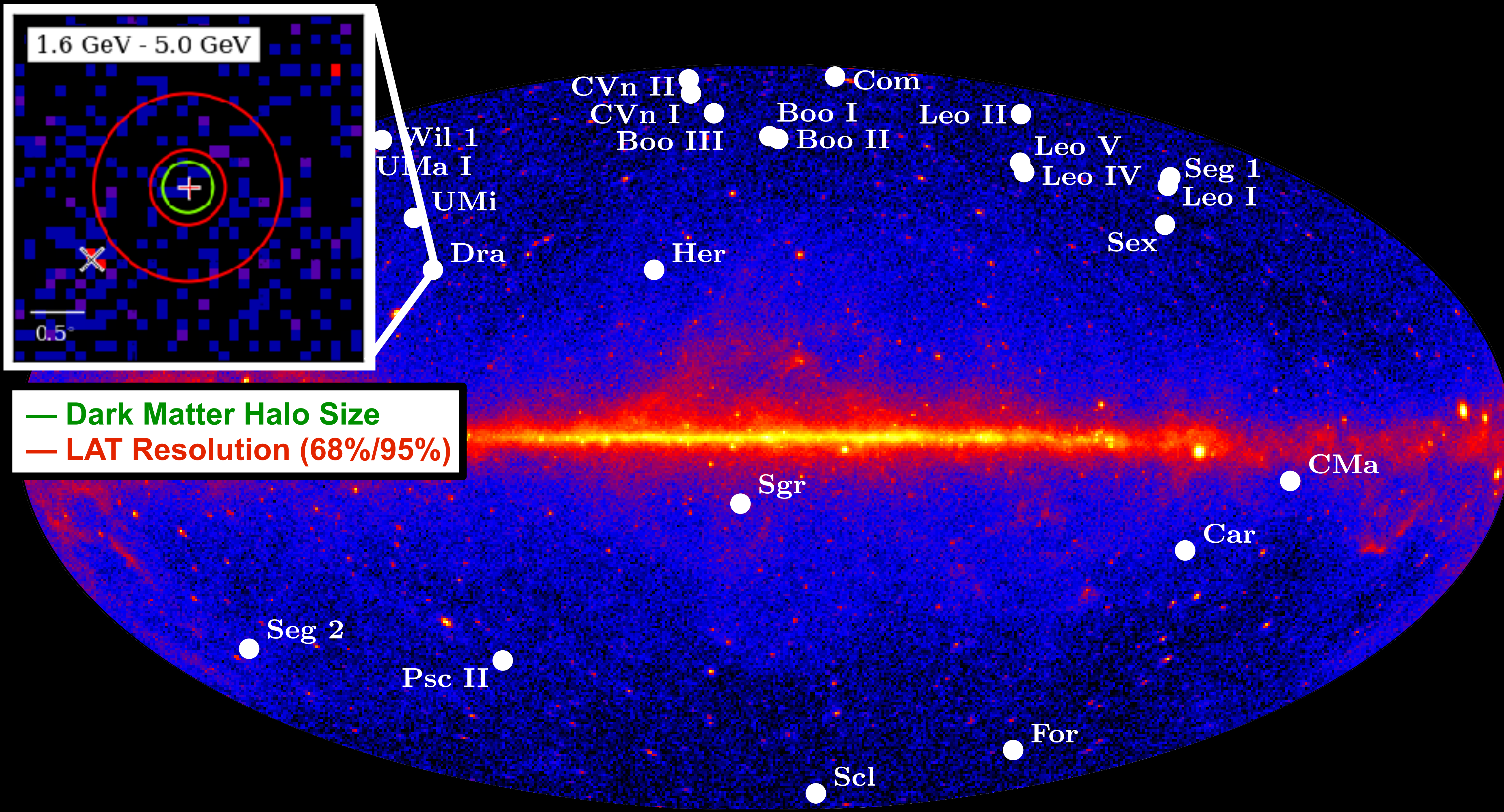
It is essential to investigate other dark matter targets

Milky Way Satellite Galaxies



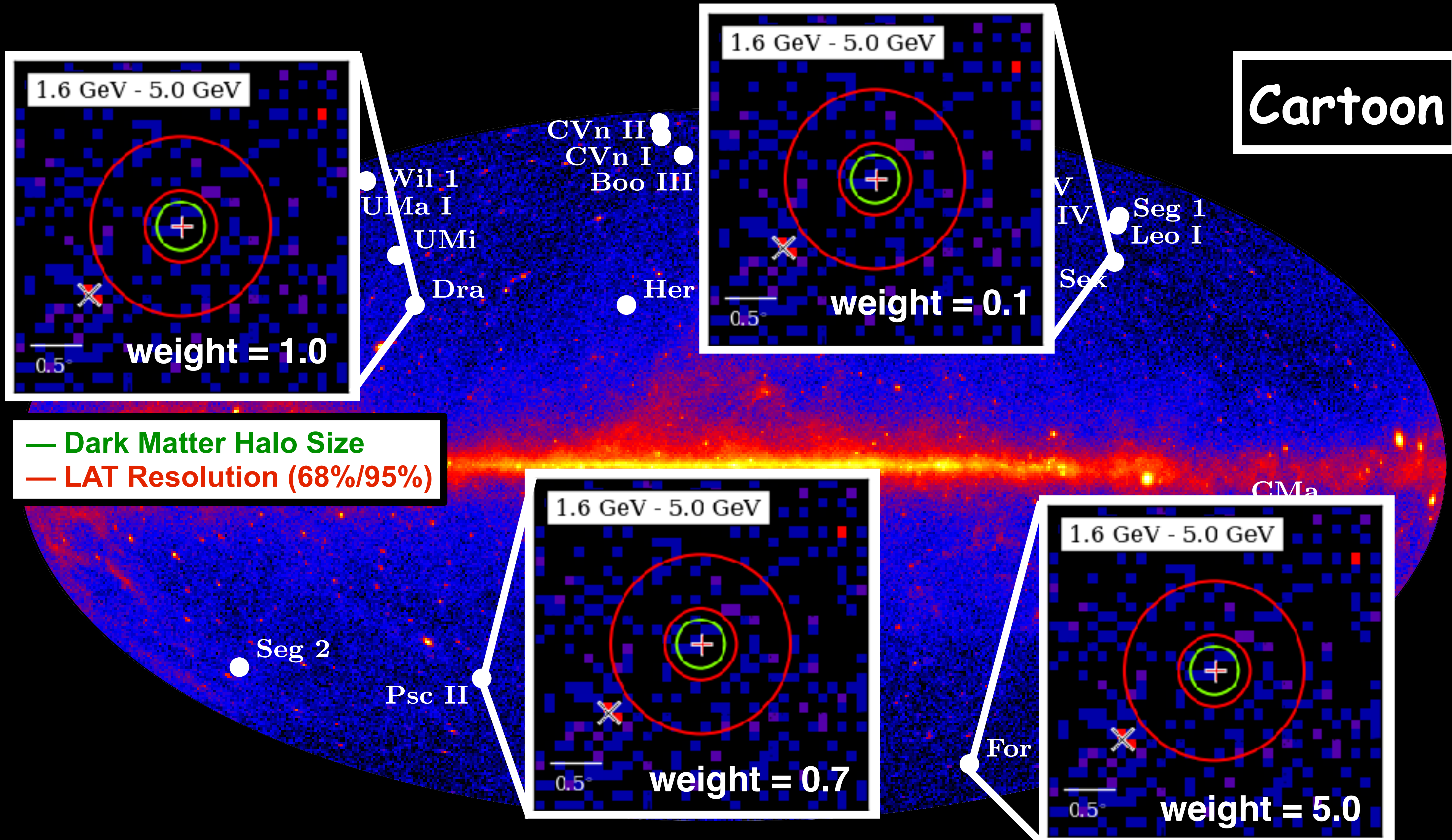
- **The Milky Way is surrounded by small satellite galaxies**
- **Astrophysically simple**
- **Close to Earth (25 kpc to 250 kpc)**
- **Most dark matter dominated objects known**
- **Dark matter content directly measured with stellar velocities**

Annihilation in Dwarf Galaxies



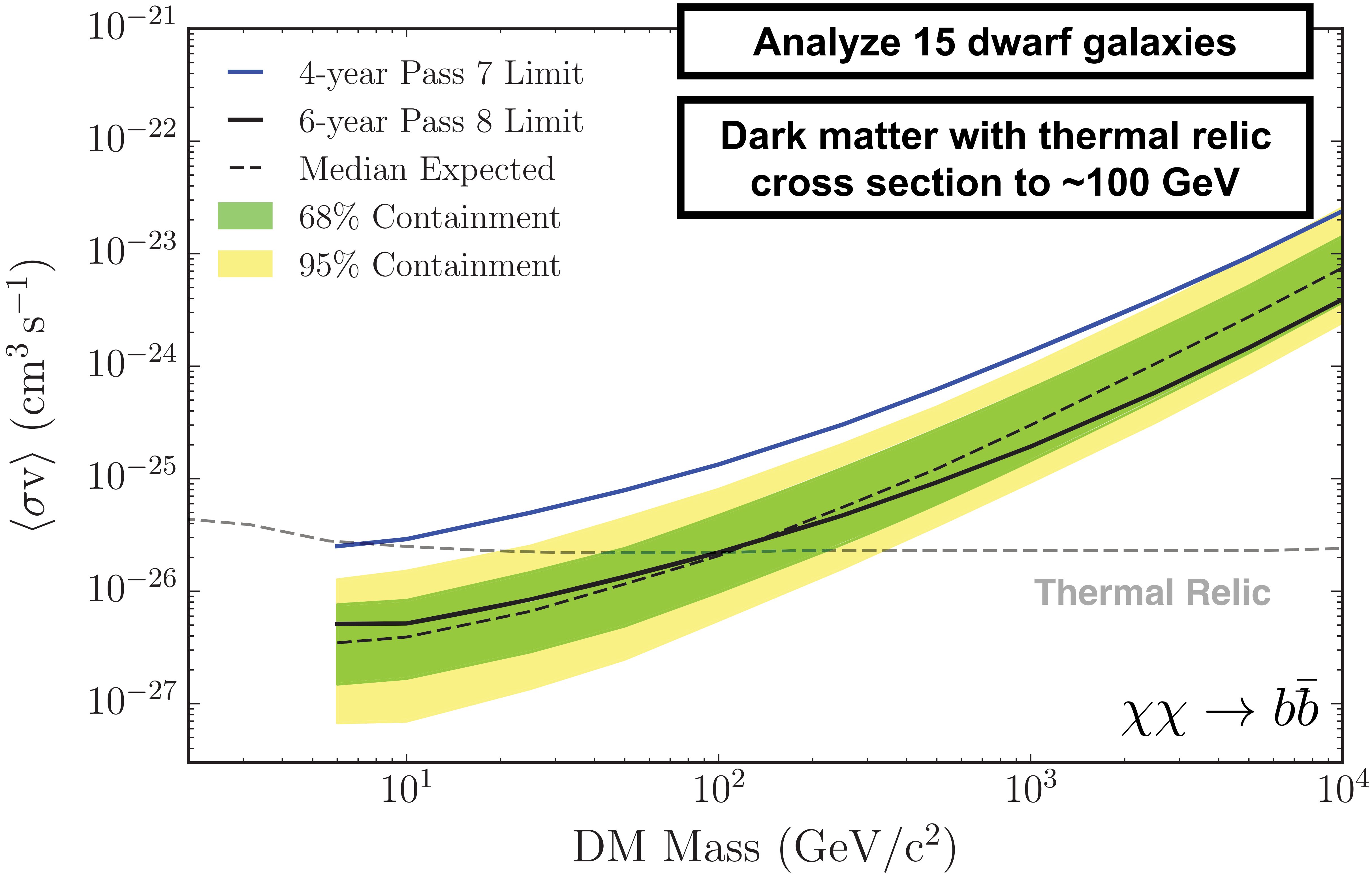
Dwarf galaxies are very clean targets.

Annihilation in Dwarf Galaxies



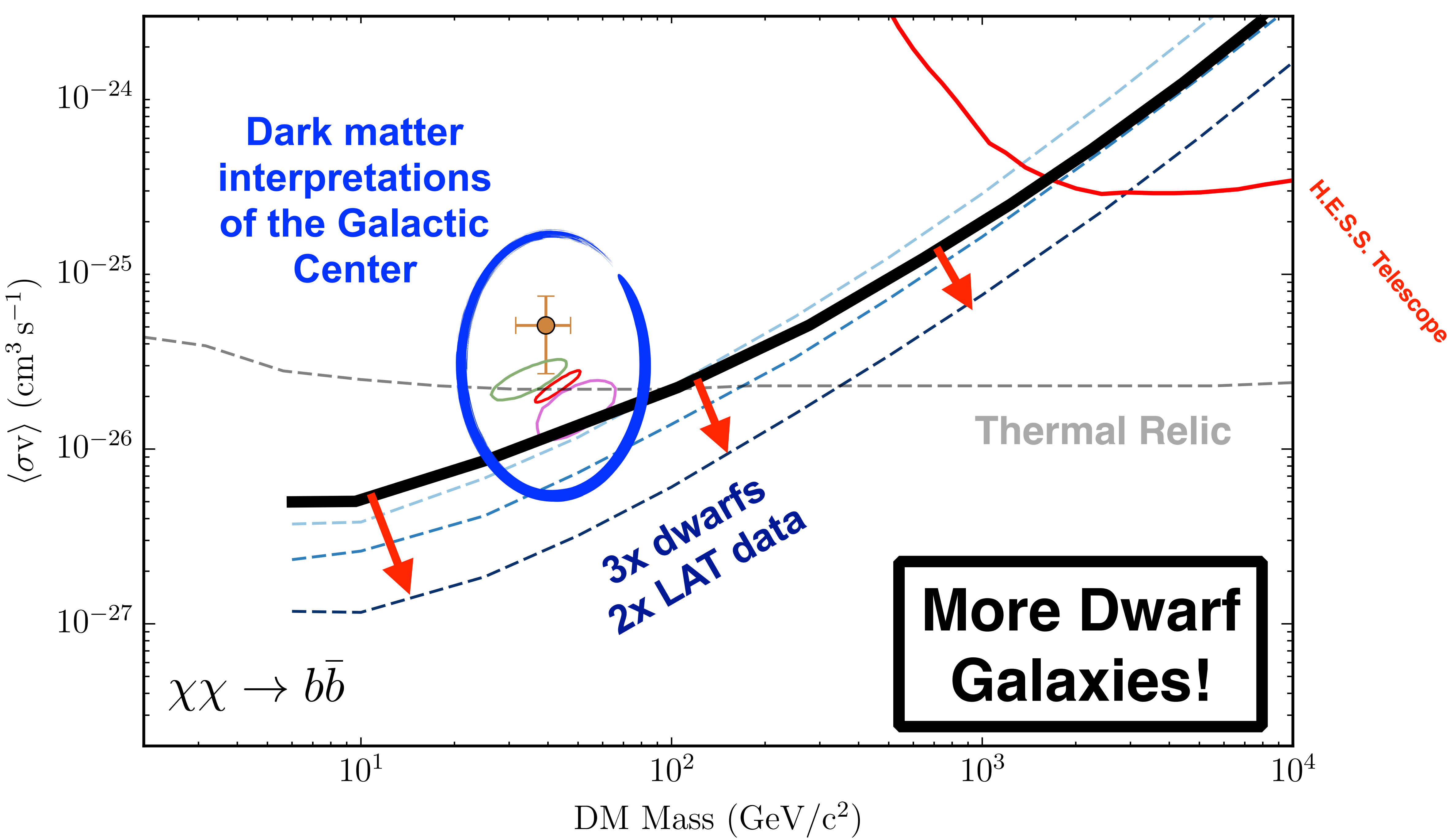
Multiple dwarf galaxies can be analyzed together

Combined Dwarf Galaxy Constraints



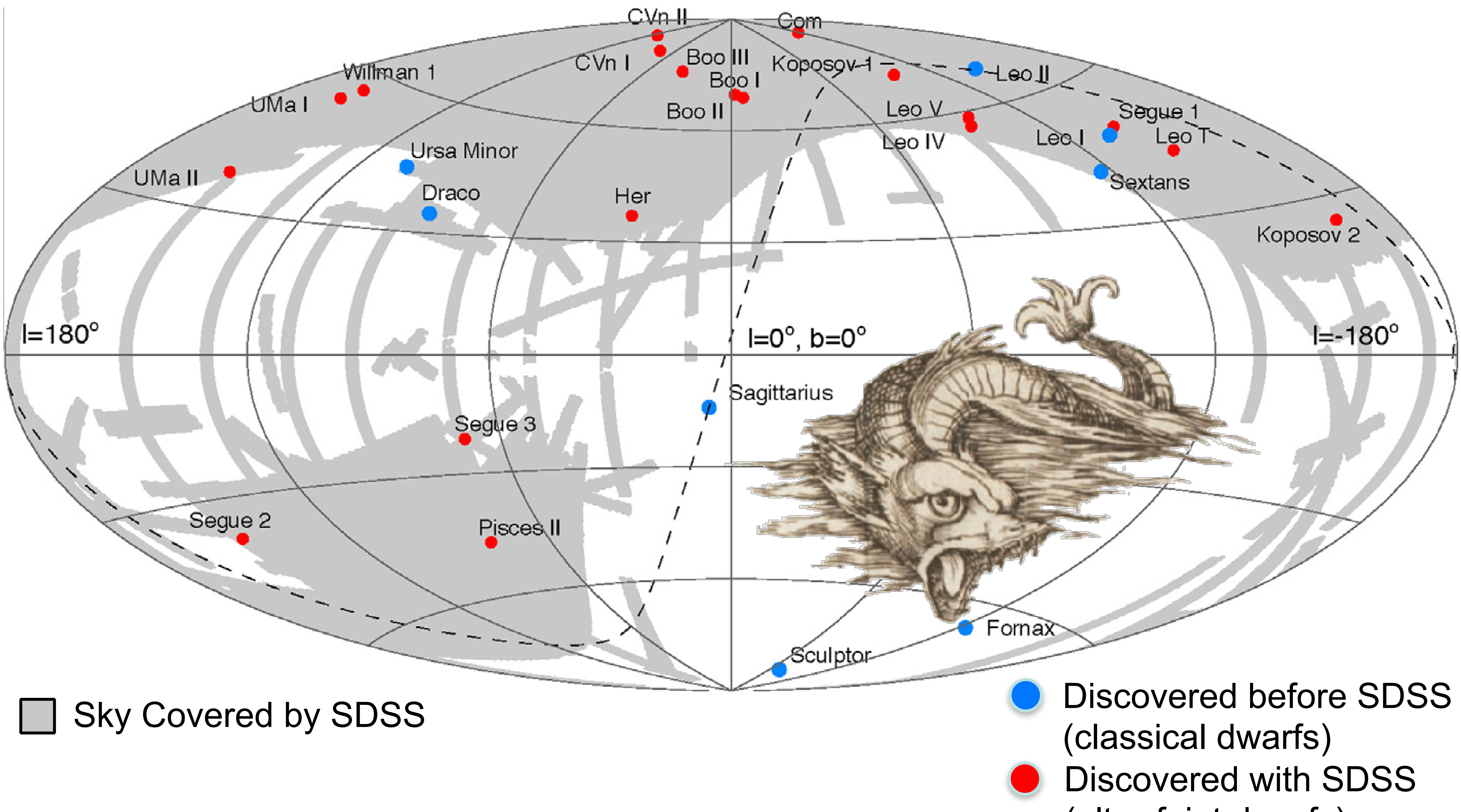
LAT Collaboration, PRL 115, 231301 (2015)

Increased Sensitivity



Galactic Center Contours: Abazajian et al. 2014; Gordon & Macias 2013; Daylan et al. 2014; Calore et al. 2015

Sky Coverage of Dwarf Galaxy Searches



(Belokurov 2013)

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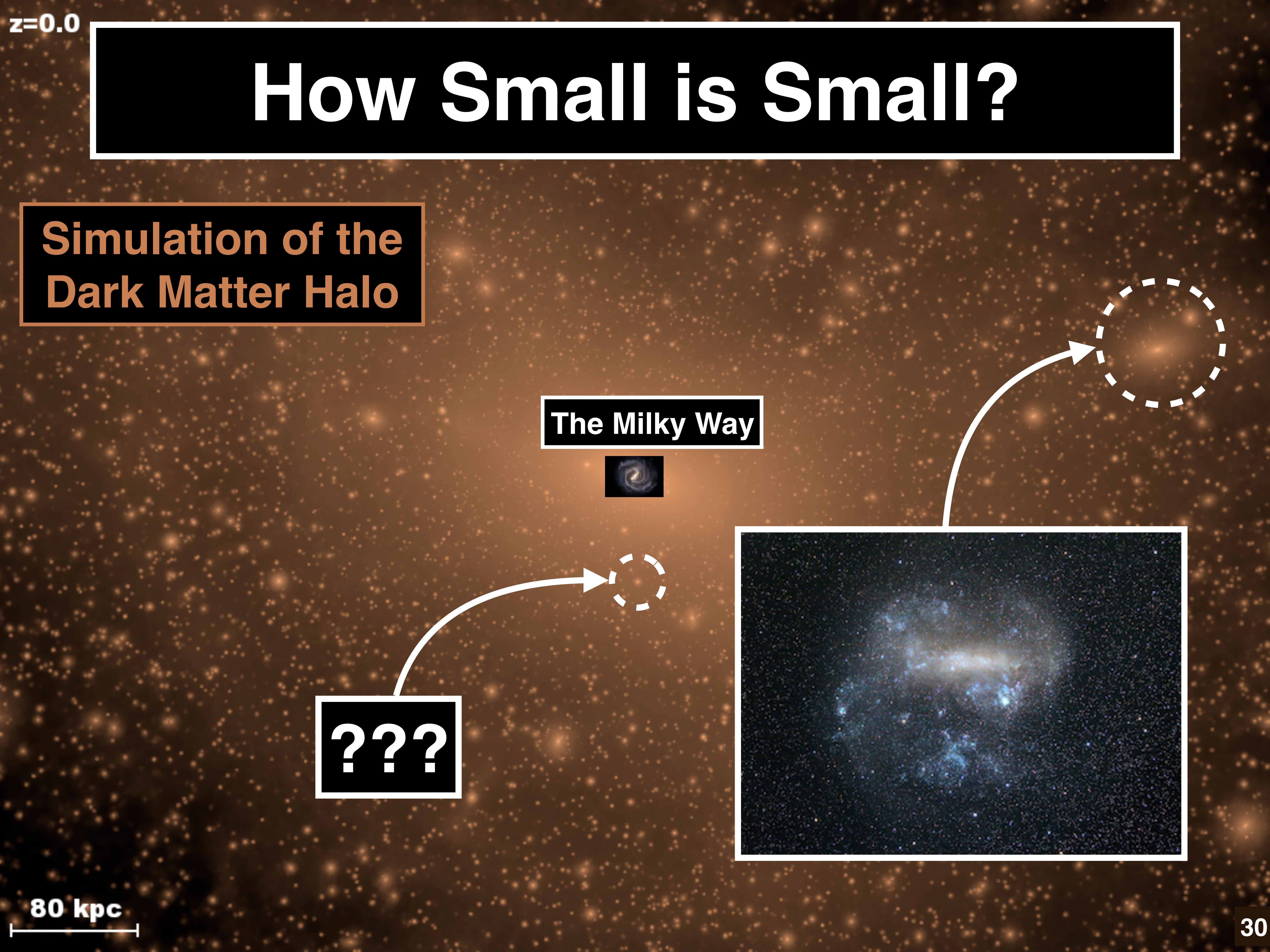
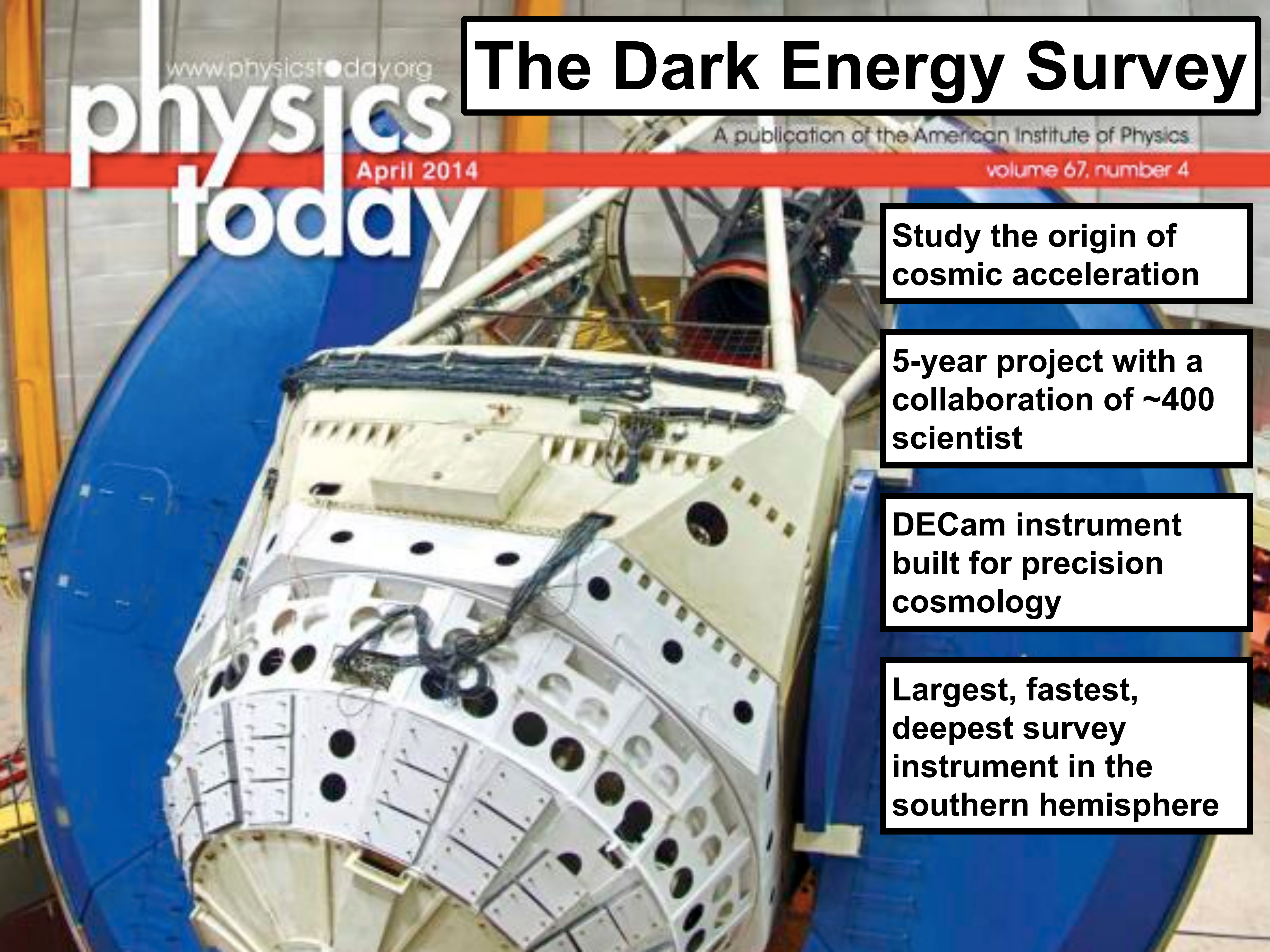

z=0.0
How Small is Small?
Simulation of the Dark Matter Halo
The Milky Way
???
80 kpc

The Dark Energy Survey

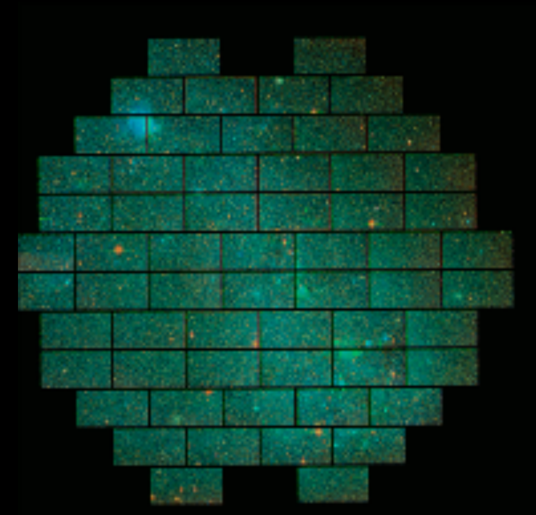


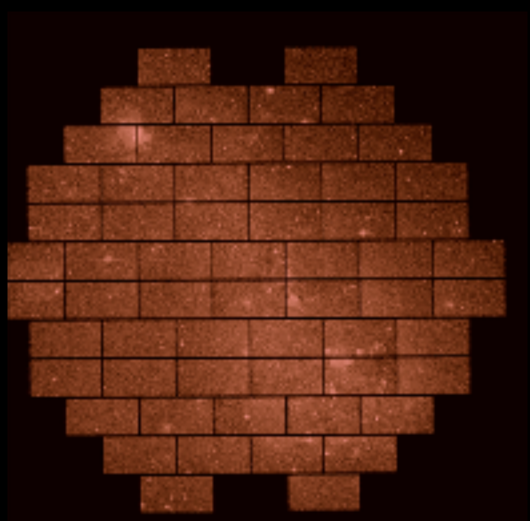
Study the origin of cosmic acceleration

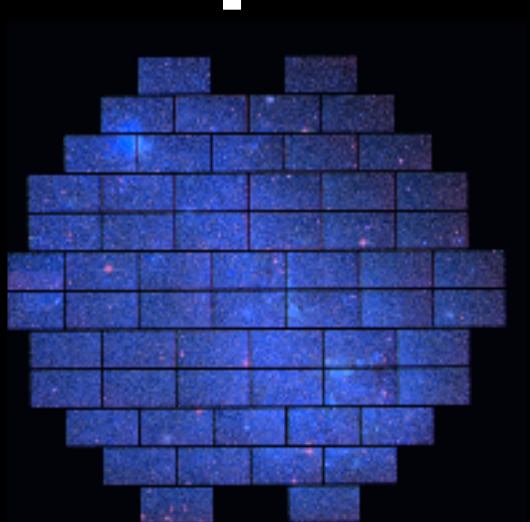
5-year project with a collaboration of ~400 scientist

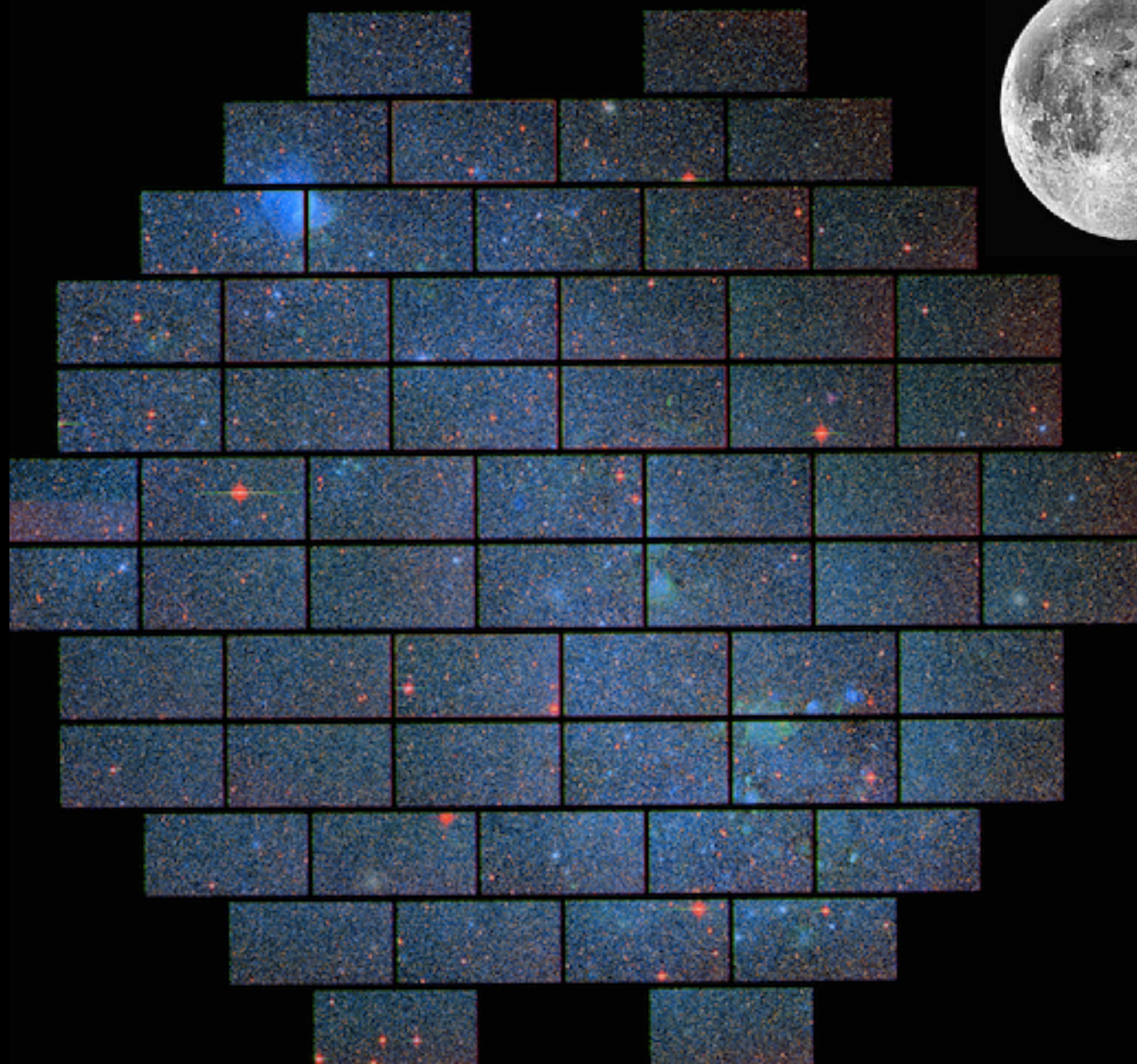
DECam instrument built for precision cosmology

Largest, fastest, deepest survey instrument in the southern hemisphere





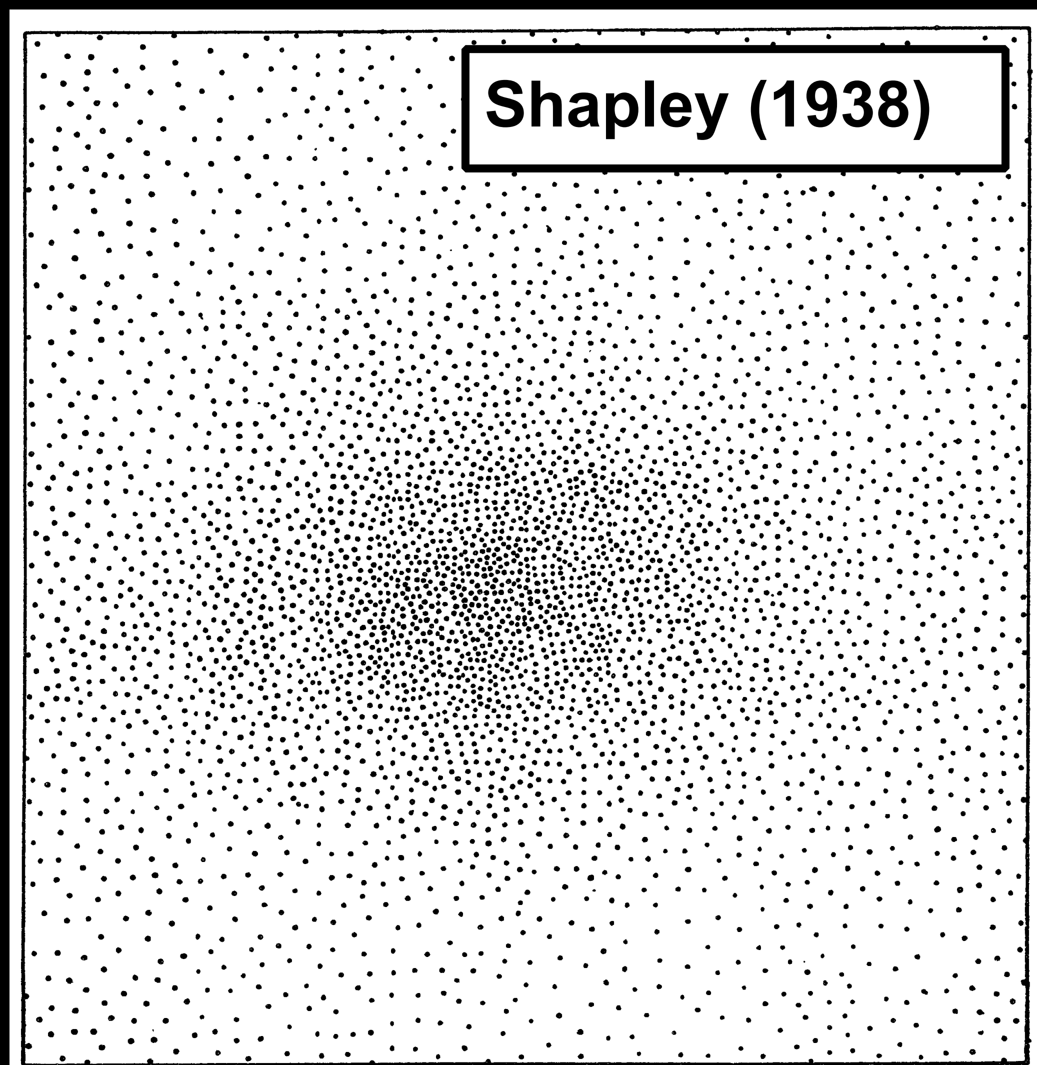




For Scale

Dwarf Galaxies

y (deg)

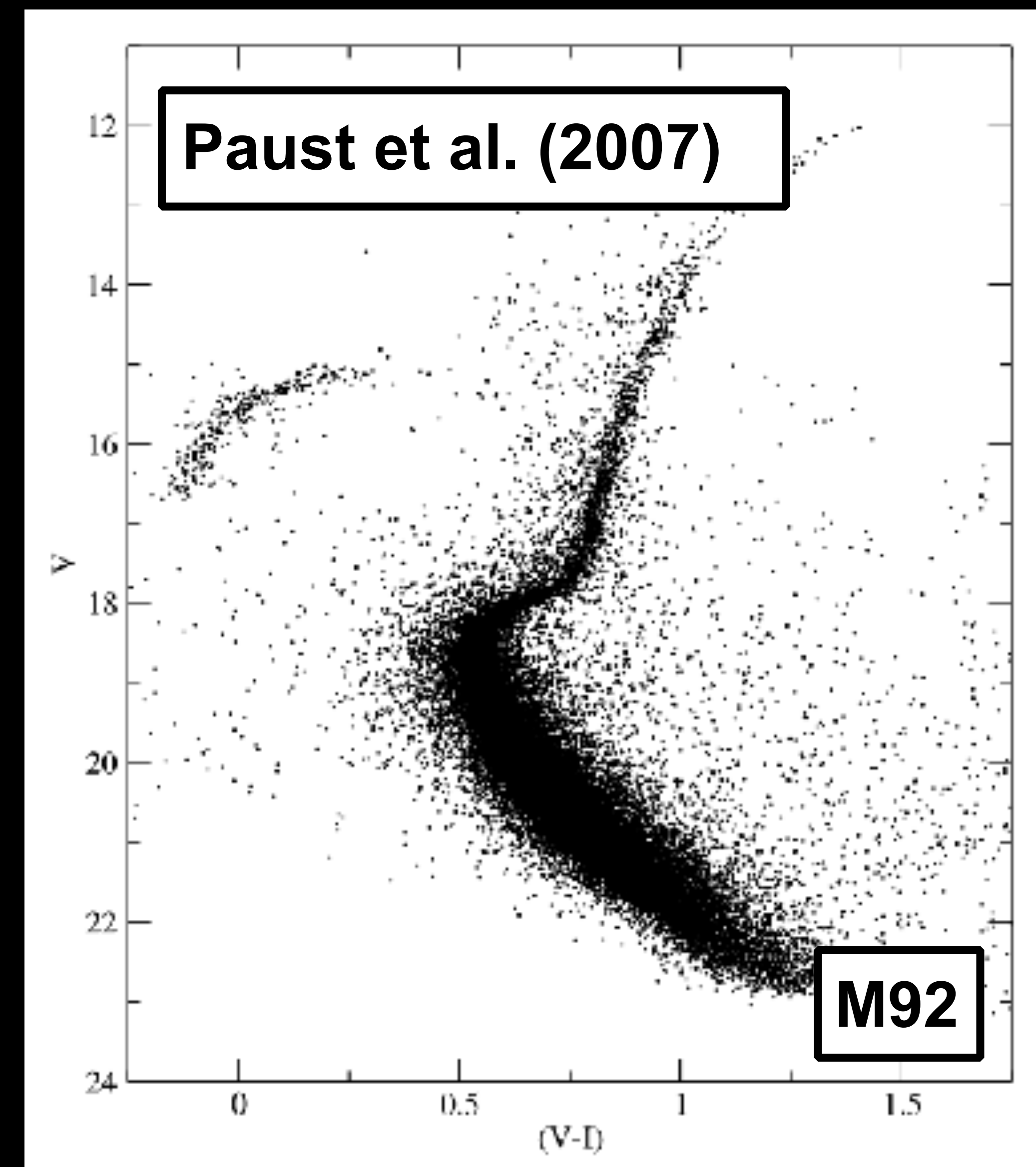


x (deg)

Bright

Magnitude

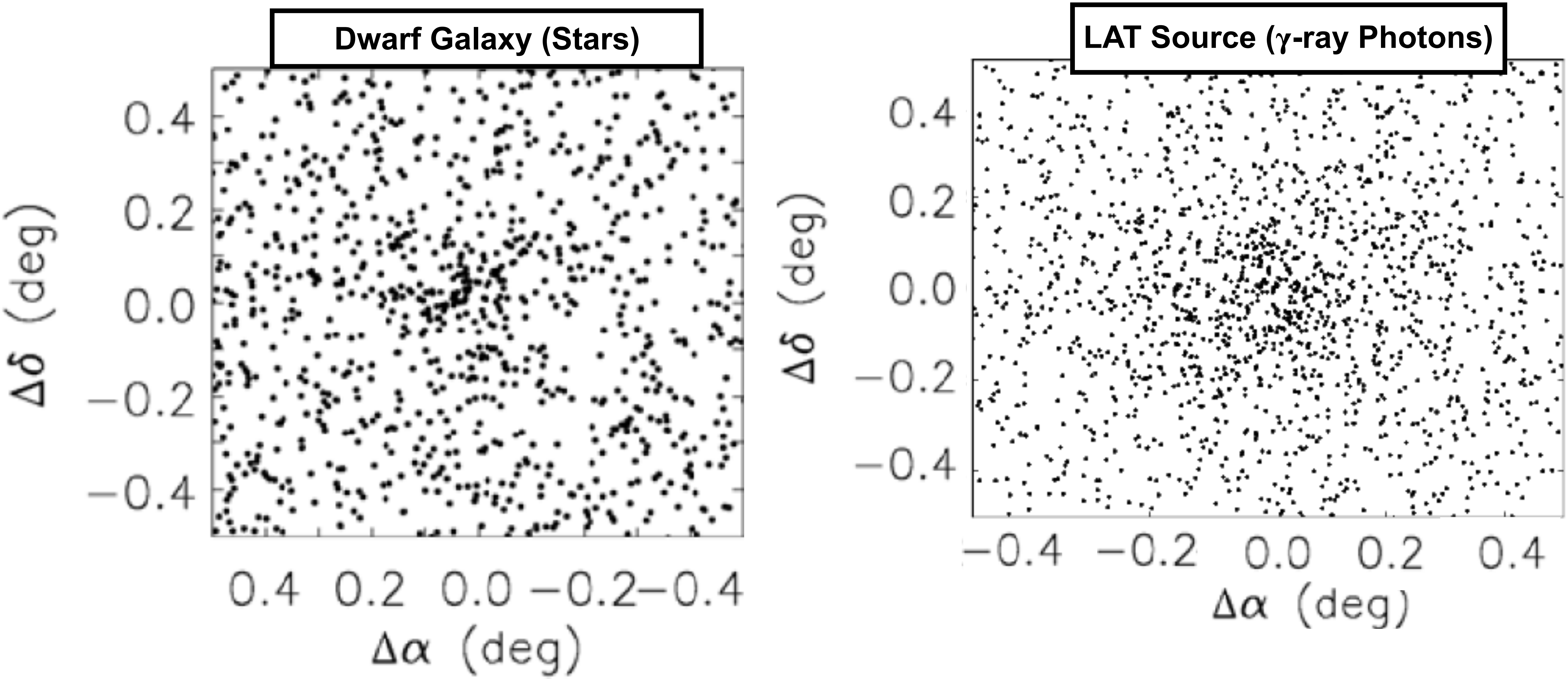
Faint



Color

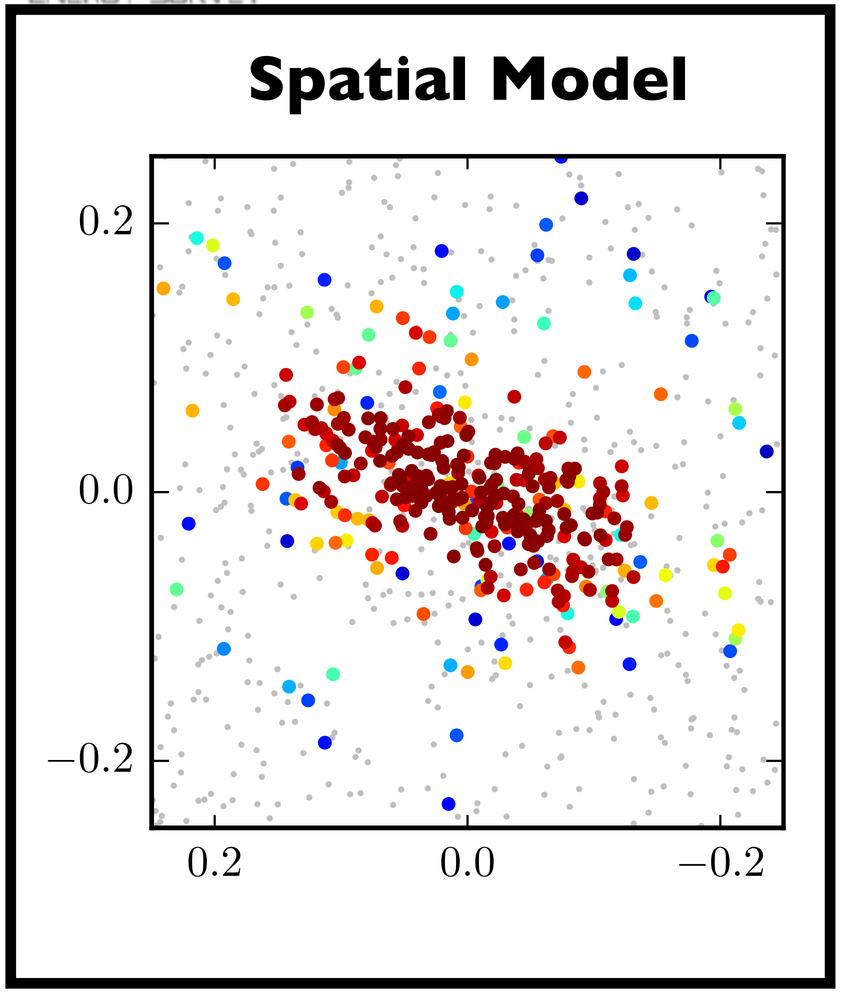
Blue ⟷ Red

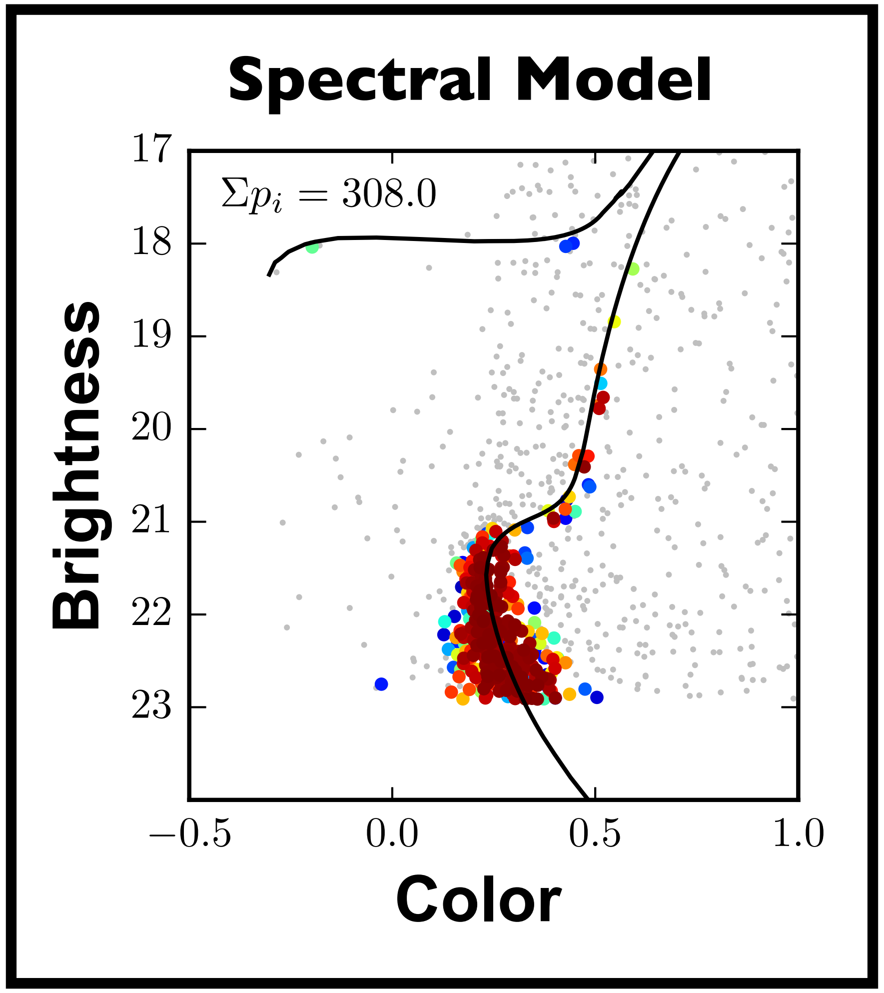
A Familiar Problem

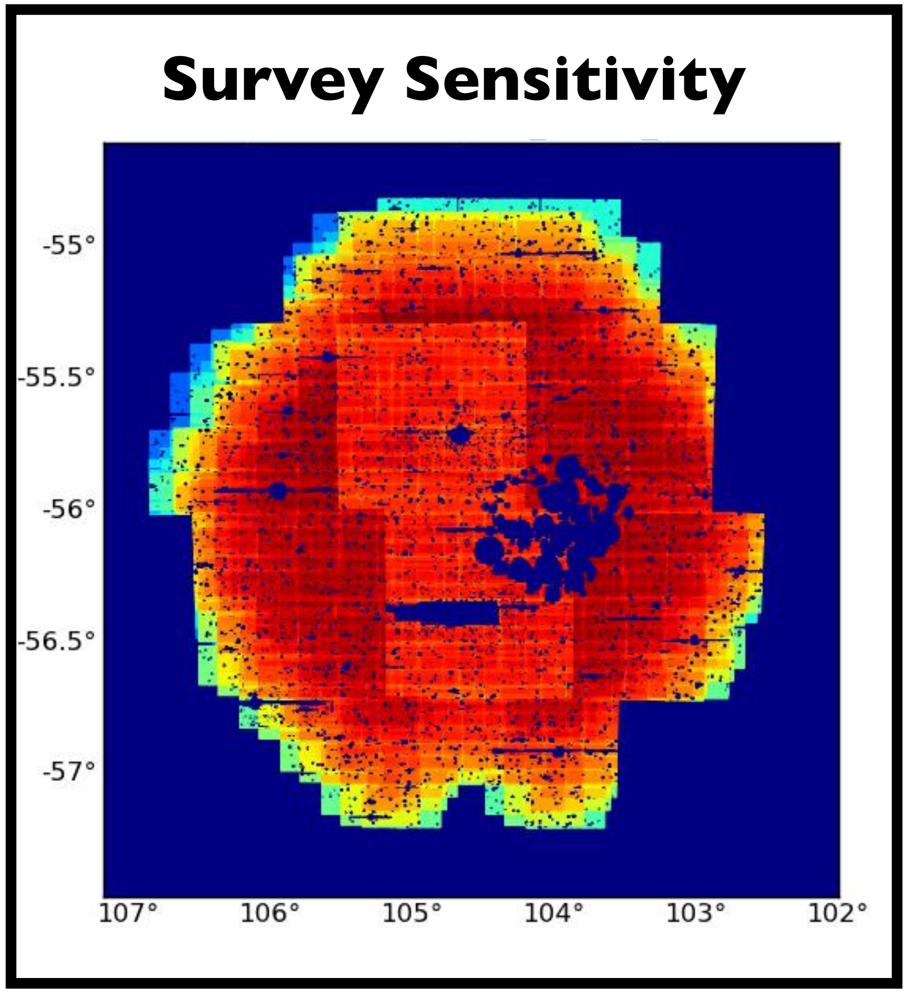


A faint signal in a large, structured background.

Maximum-Likelihood Searches

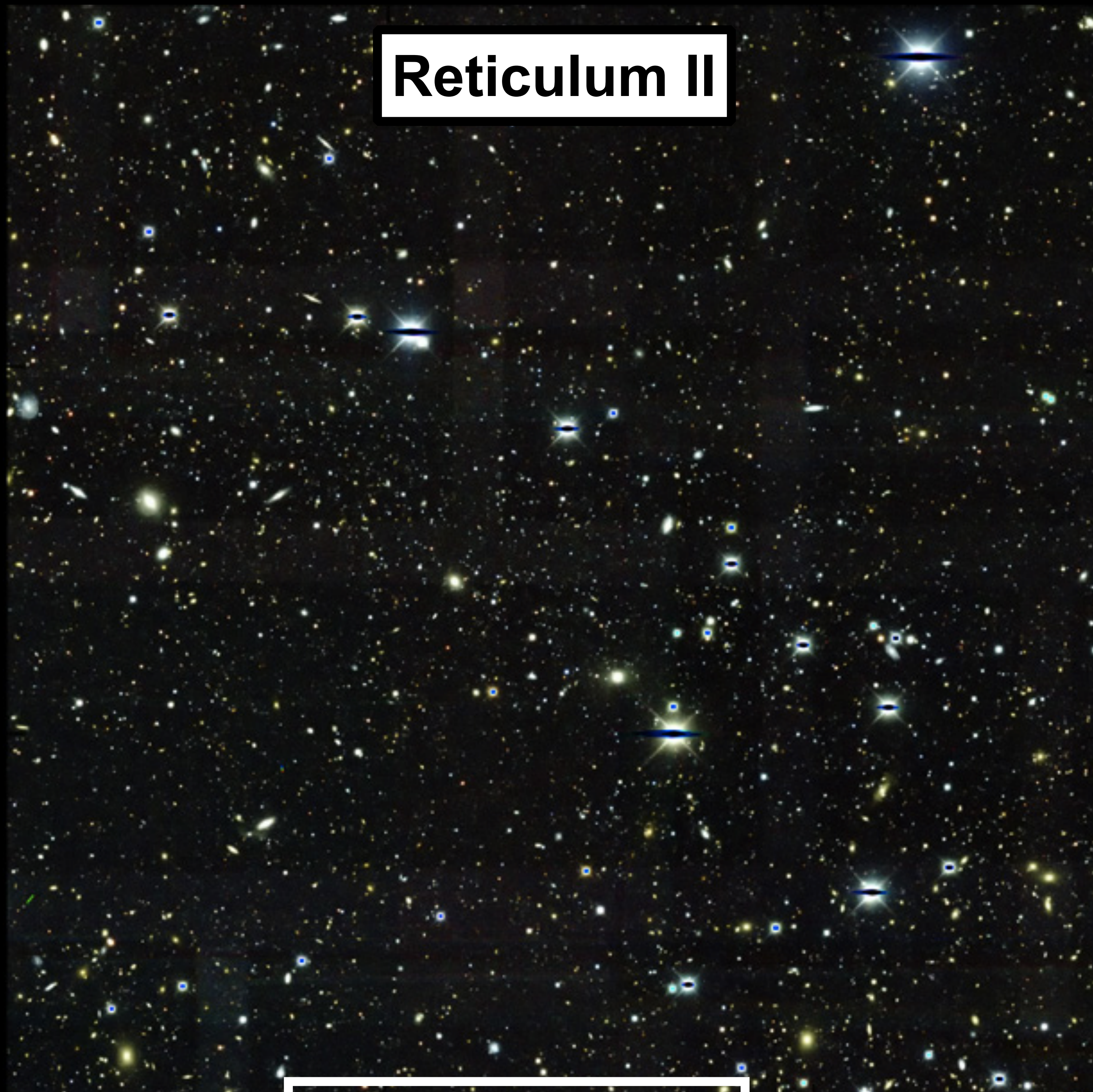






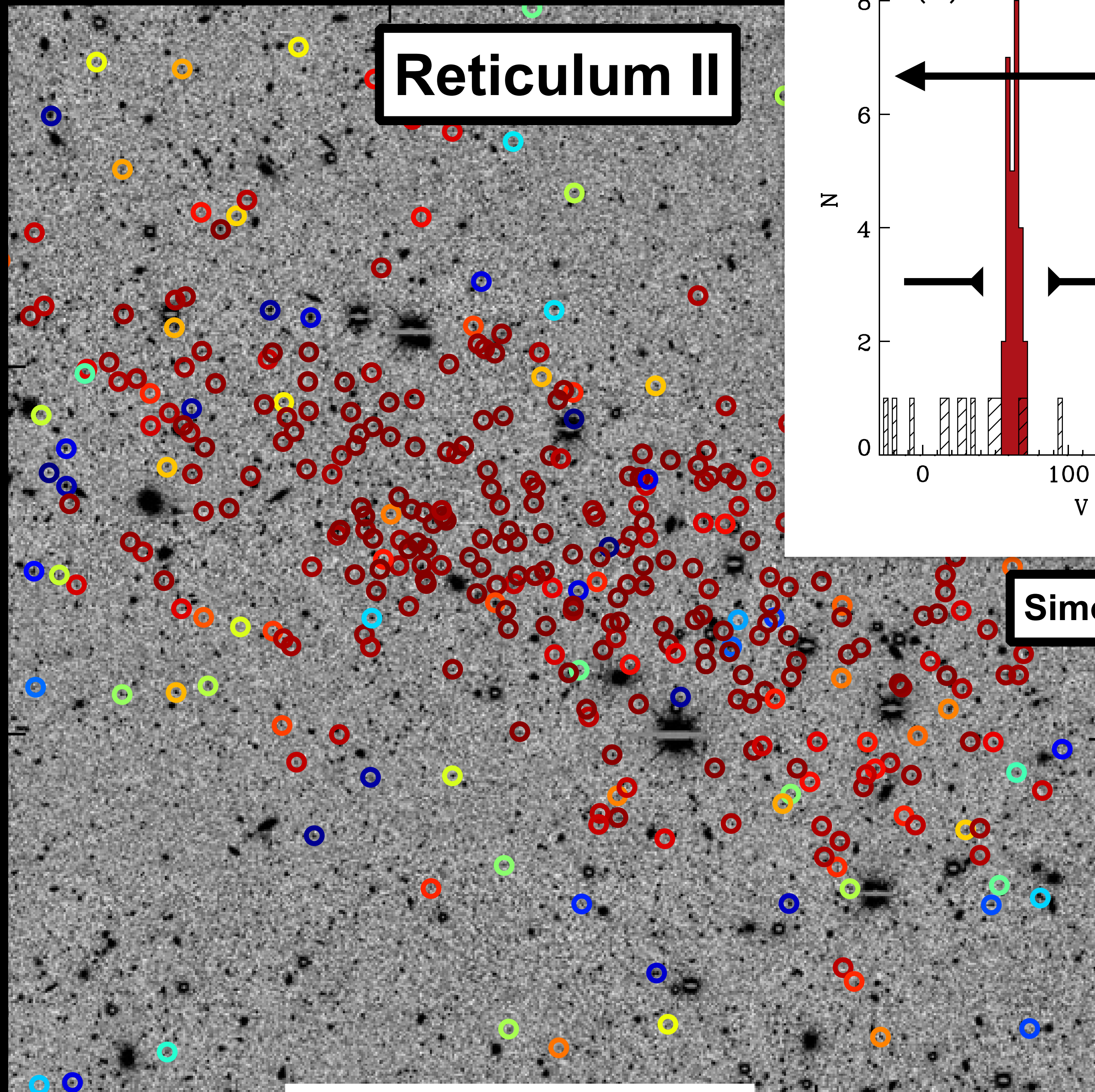
Multi-dimensional likelihood analysis

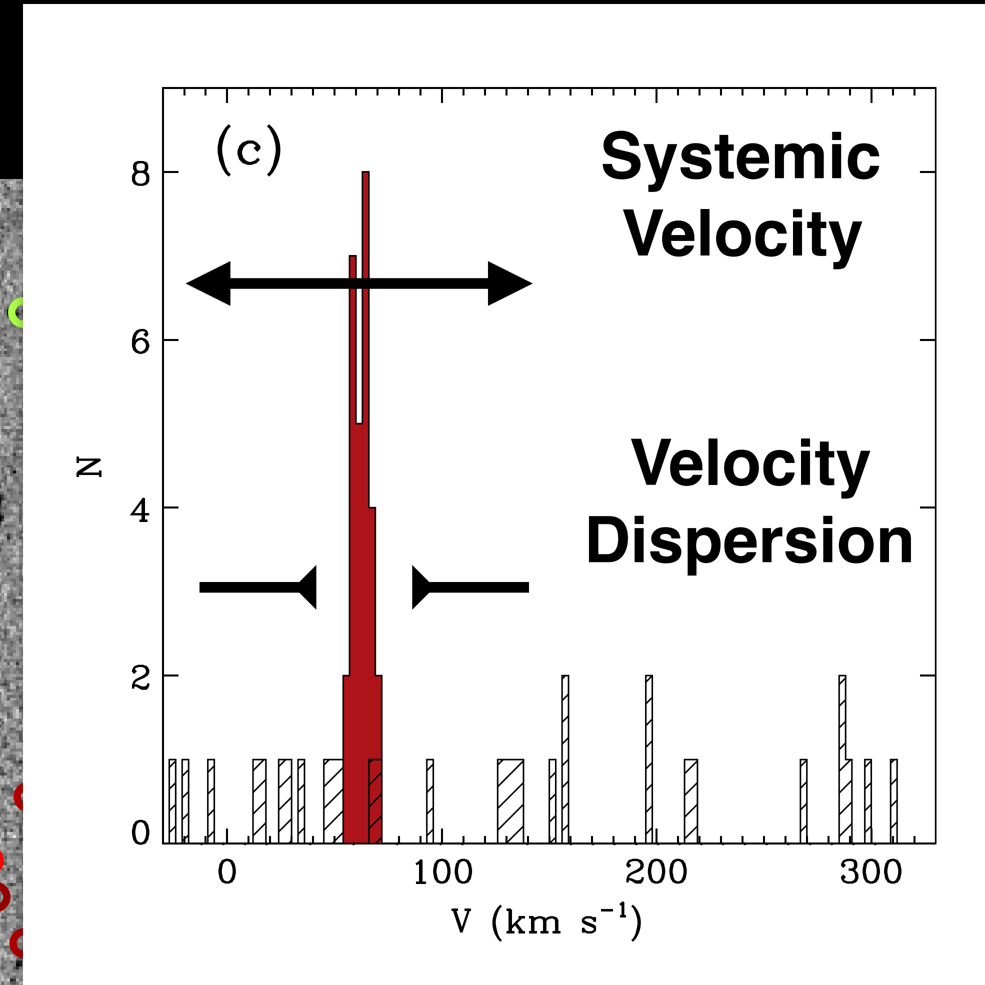
Scan over ~400 million possible locations



4m Telescope
DECam CCD Camera

Bechtol, ADW et al. (2015)





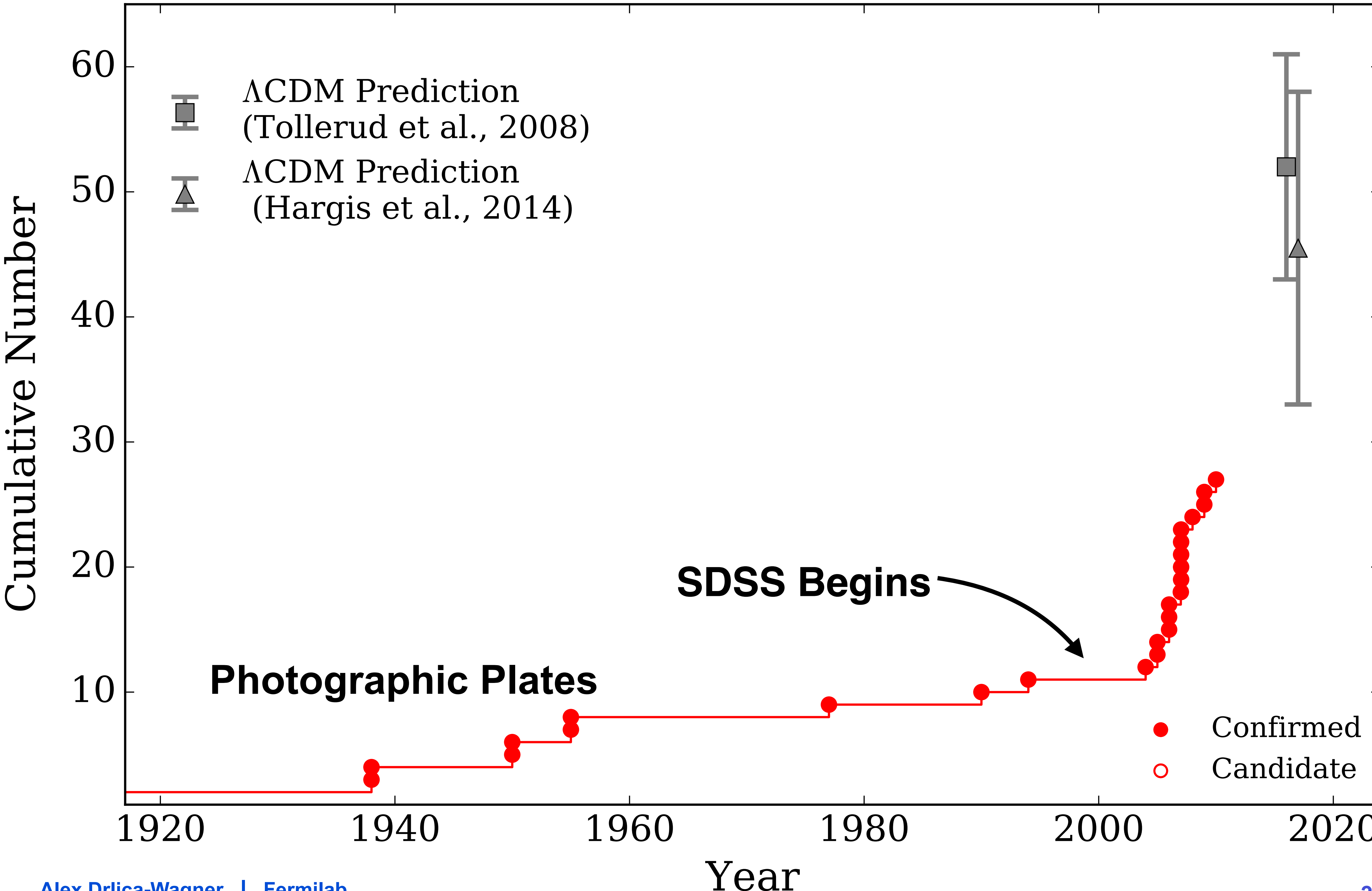
Colors correspond to membership probability assigned to each star by the likelihood analysis

Simon, ADW et al. (2015)

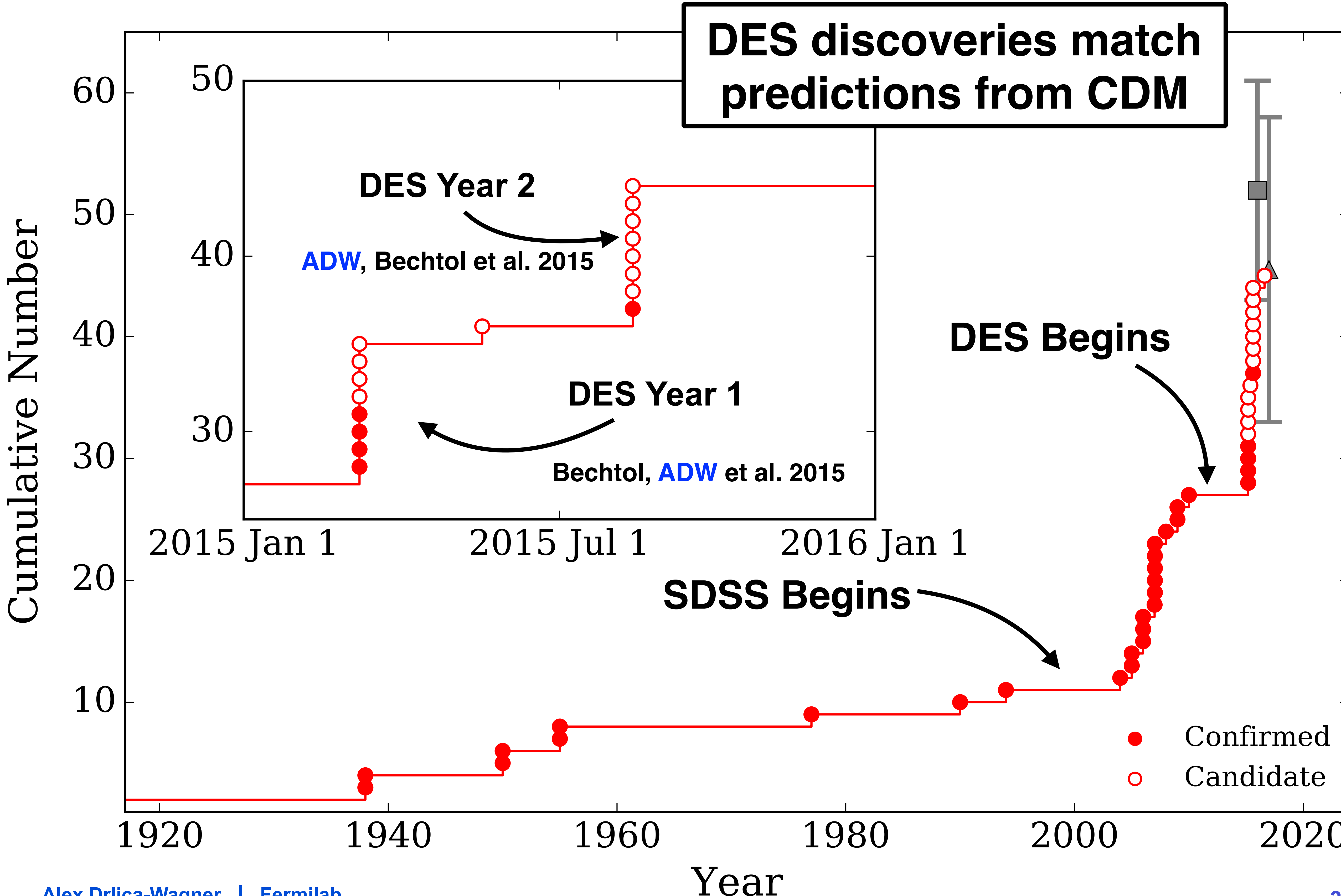
4m Telescope
DECam CCD Camera

Bechtol, ADW et al. (2015)

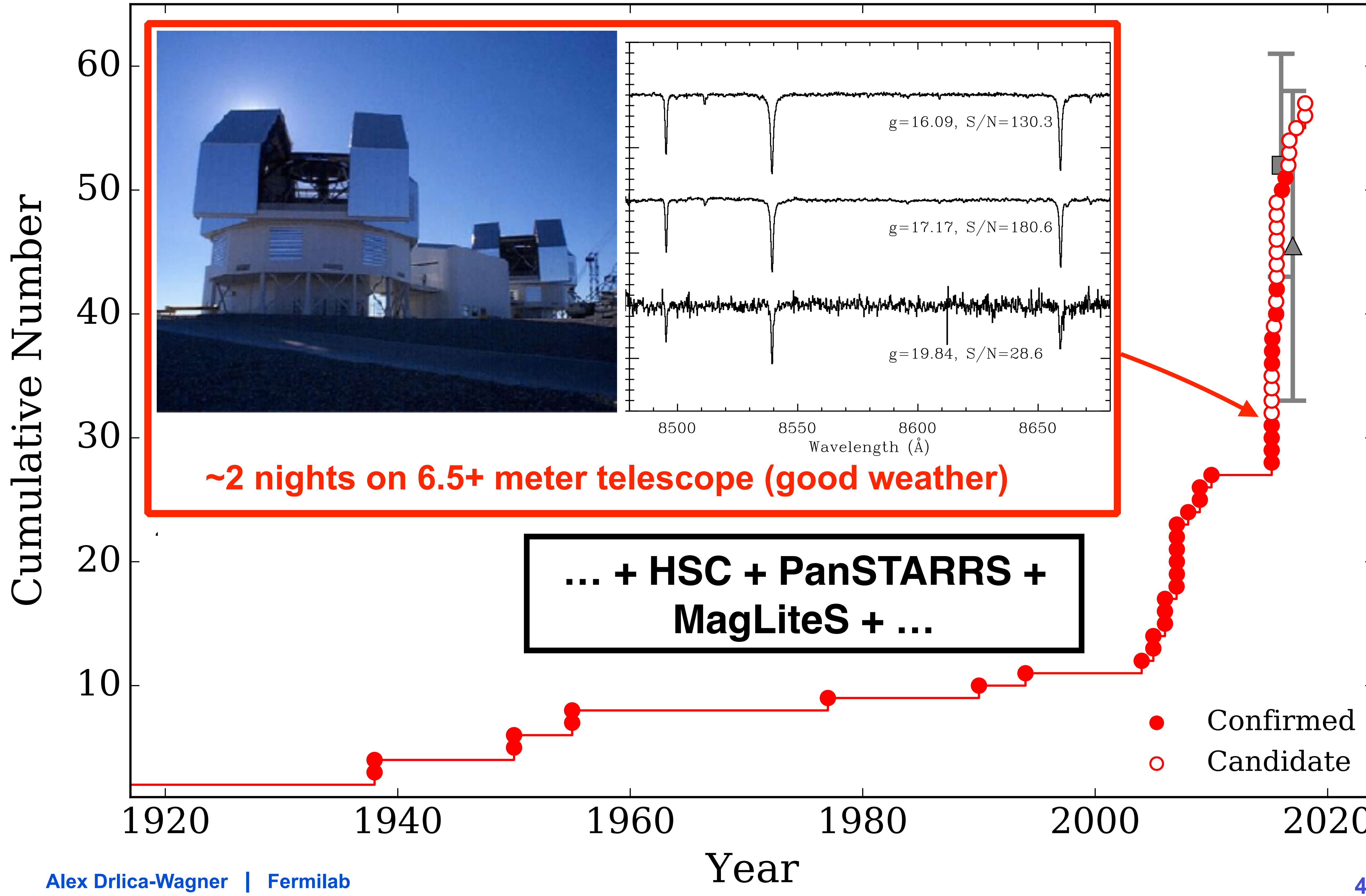
Satellite Galaxy Discovery Timeline



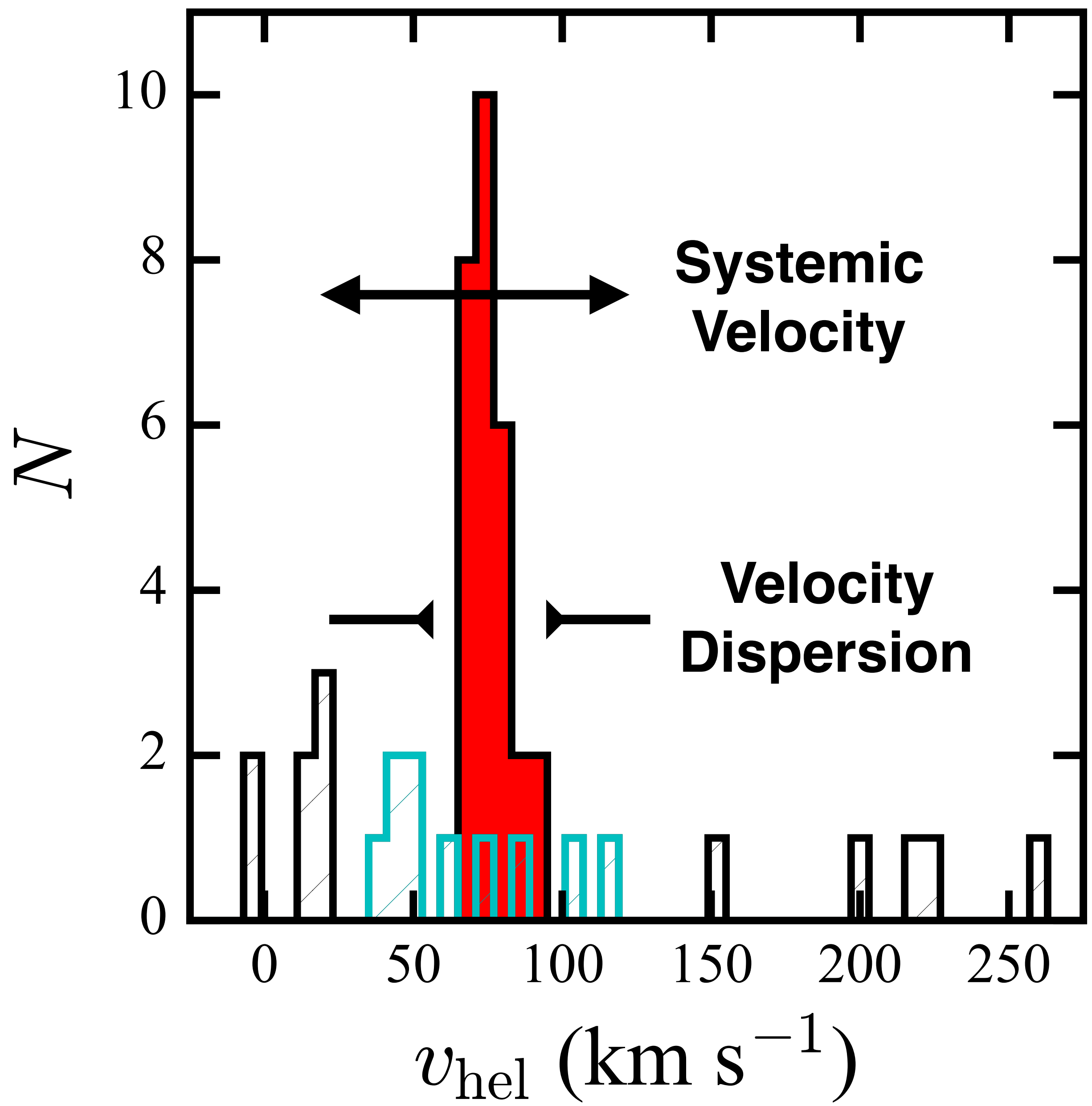
Satellite Galaxy Discovery Timeline



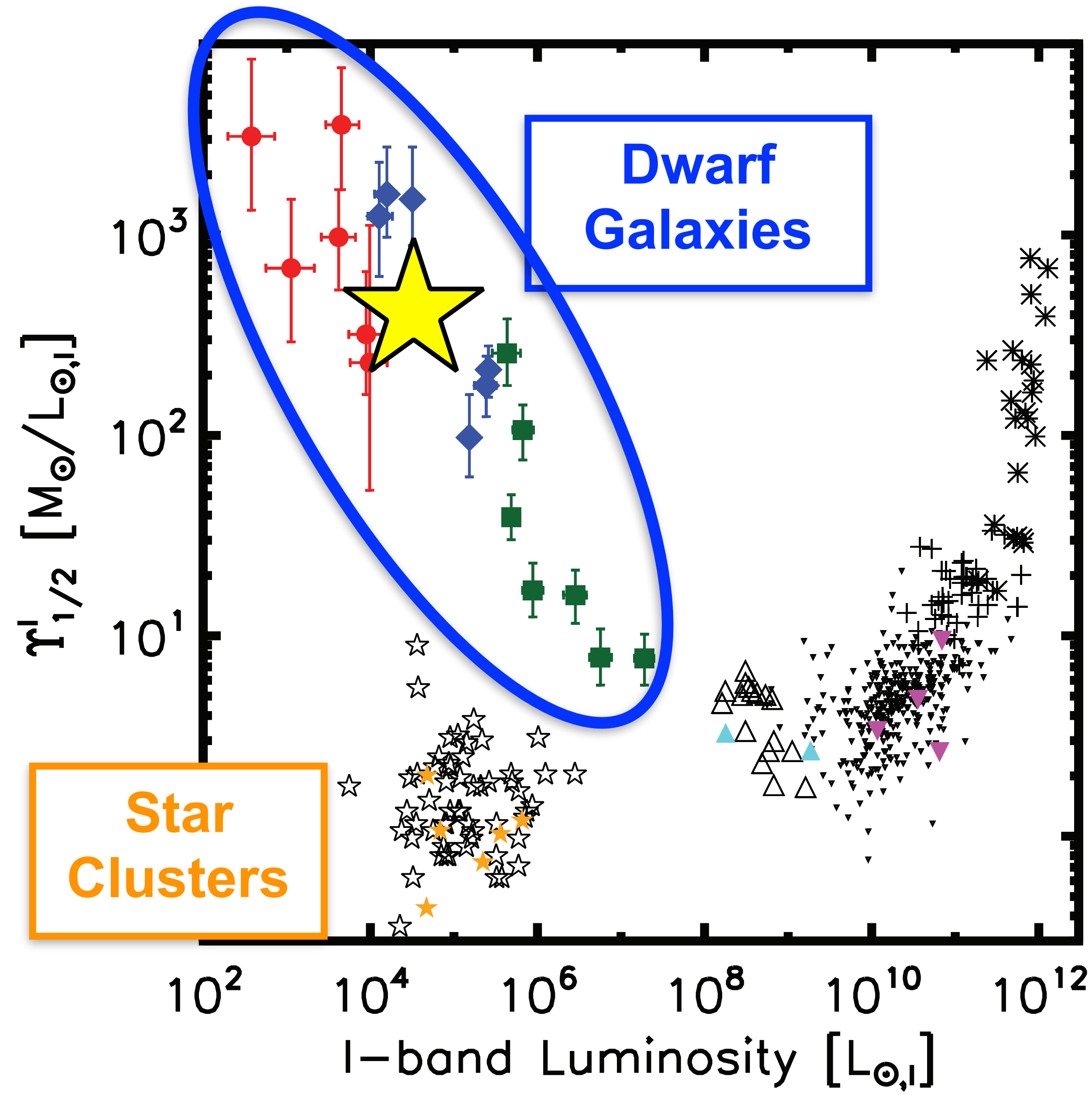
Satellite Galaxy Discovery Timeline



Newly Discovered Dwarf Galaxy: Eridanus II

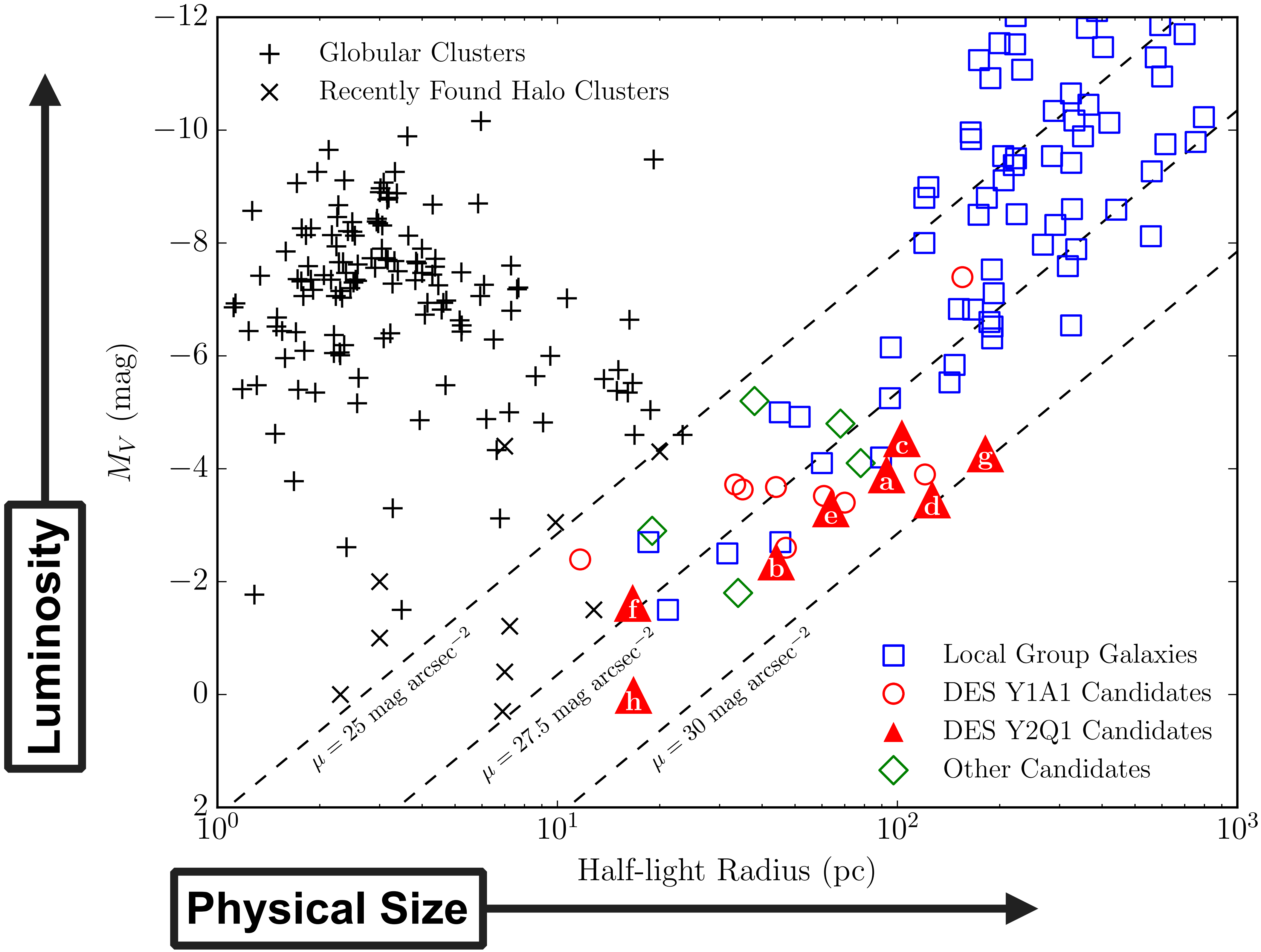


Li, Simon, ADW, et al. (2016)



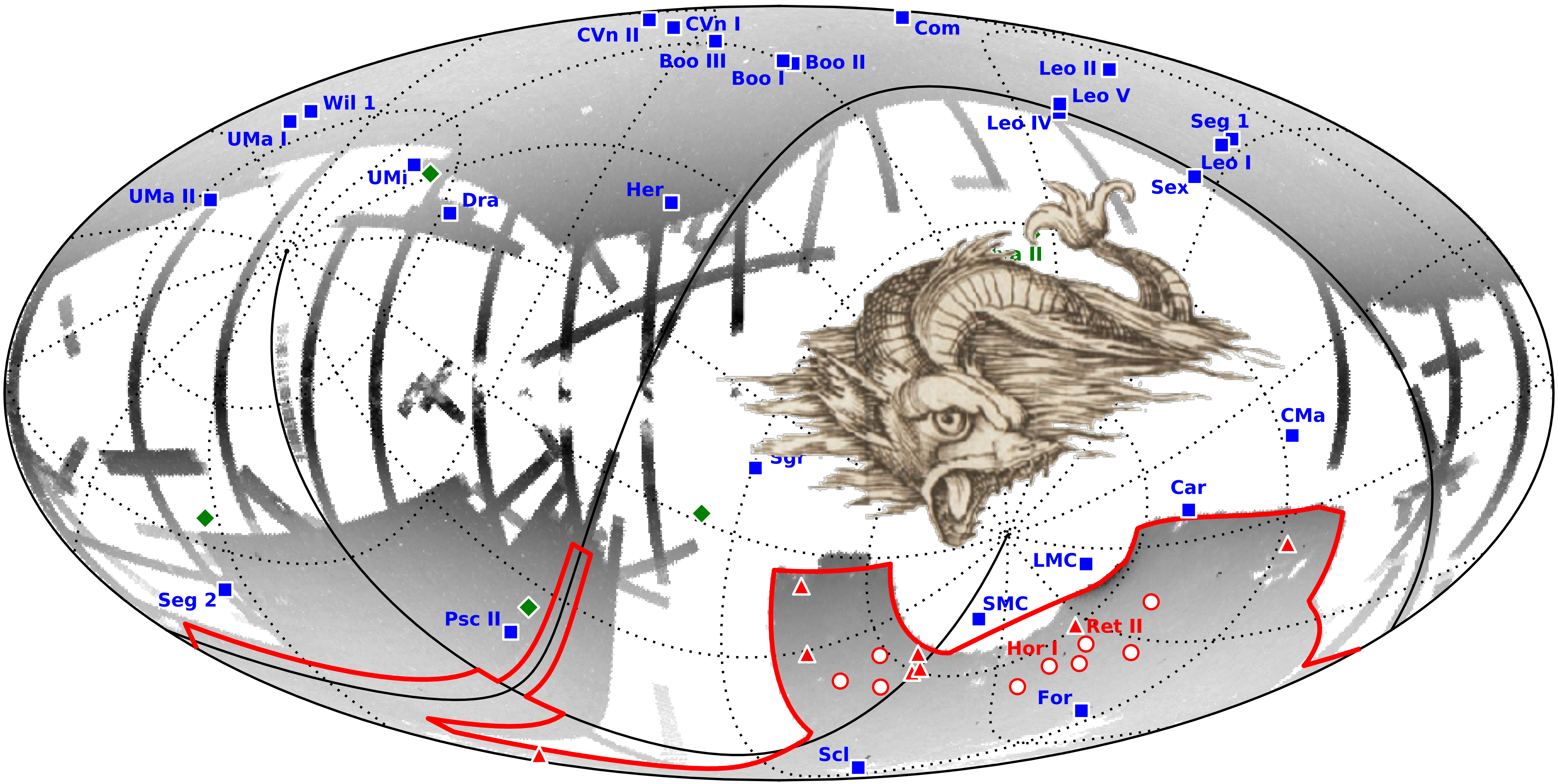
Wolf et al. (2010)

Galaxies or Star Clusters?



ADW, Bechtol, Rykoff et al. (2015)

SDSS + DES Sky Coverage



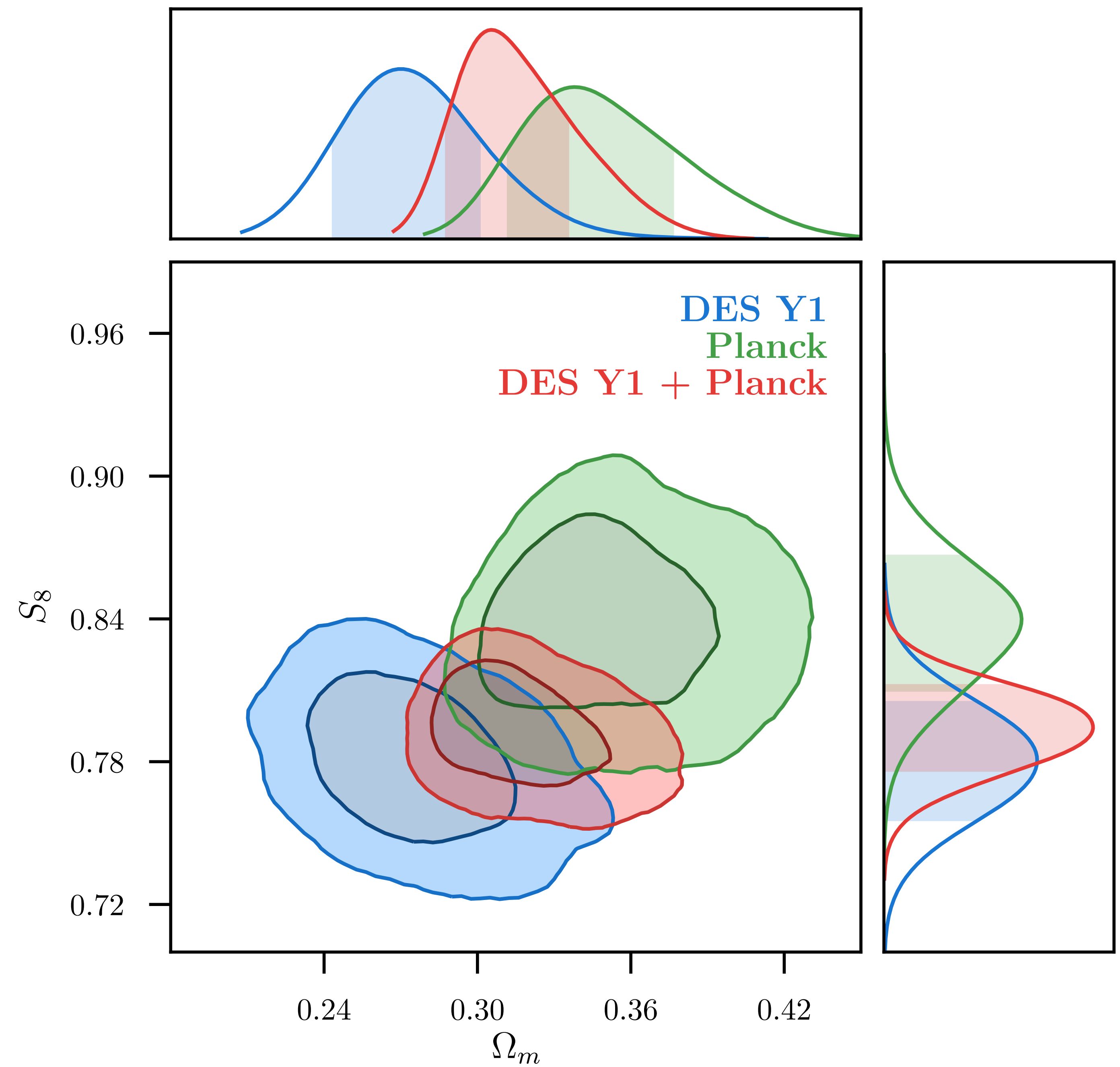
Blue - Previously discovered satellites
Green - Discovered in 2015 with PanSTARRS, SDSS, etc.

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

ADW, Bechtol, Rykoff et al. (DES Collaboration)

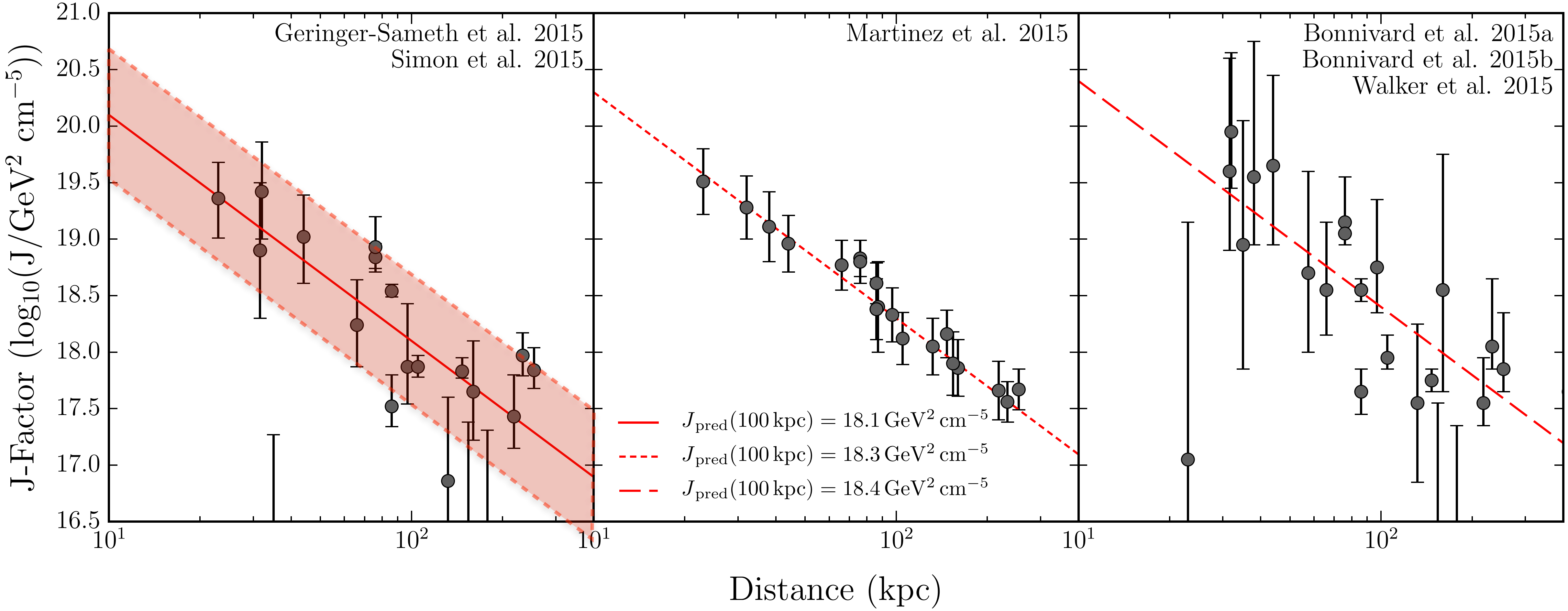
An Aside on DES Cosmology

- **Searches for ultra-faint galaxies are very sensitive to survey systematics.**
- **The data set that we developed for the dwarf galaxy search in 2015 served as the basis for *all* DES cosmology results in 2017.**
- **Dark matter science is an advanced scout for dark energy science.**
- **DES now has world-leading cosmology measurements.**



DES Collaboration (2017)
data set in ADW et al. (2017)

Predicted Dark Matter Content

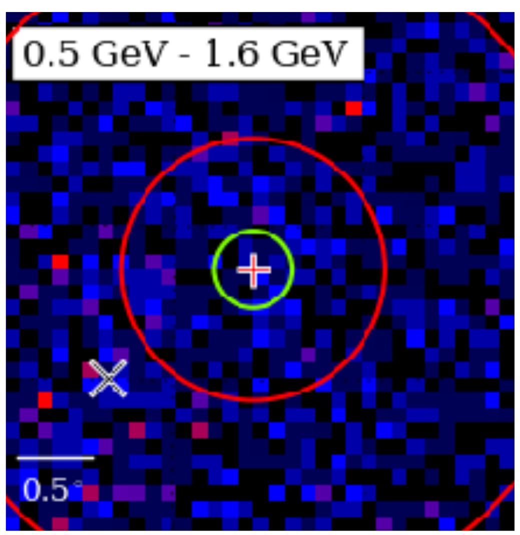


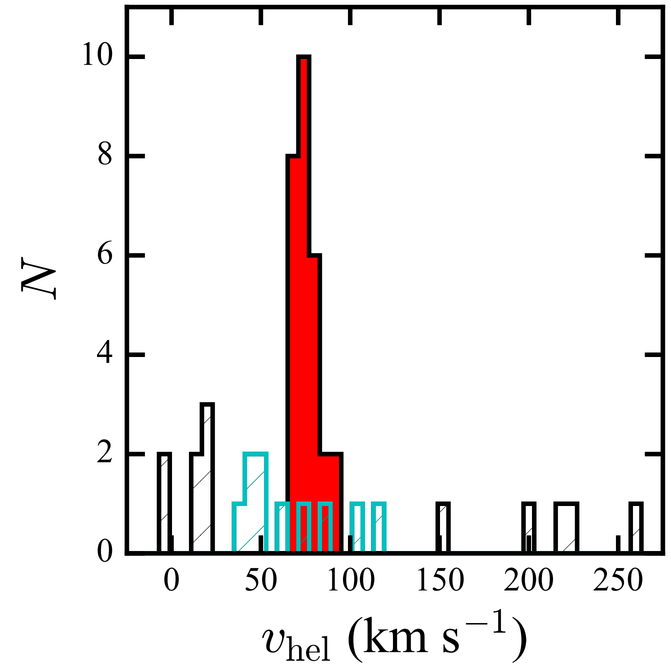
Spectroscopic follow-up on ultra-faint dwarfs is difficult and expensive.

J-factors can be estimated based on distance under the assumption that they are dark matter dominated.

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

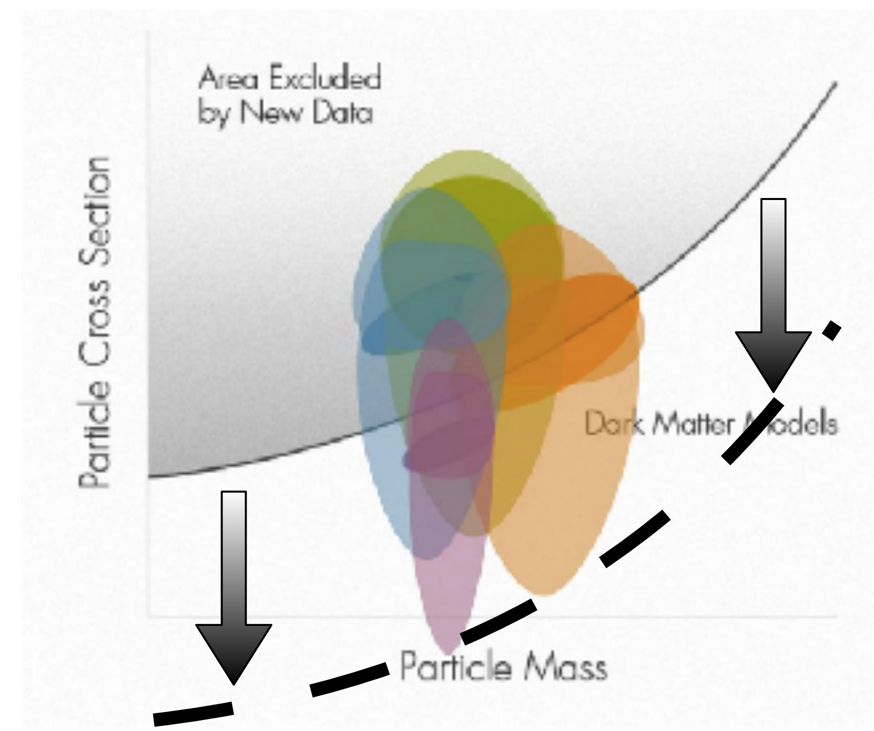
Search for Gamma Rays

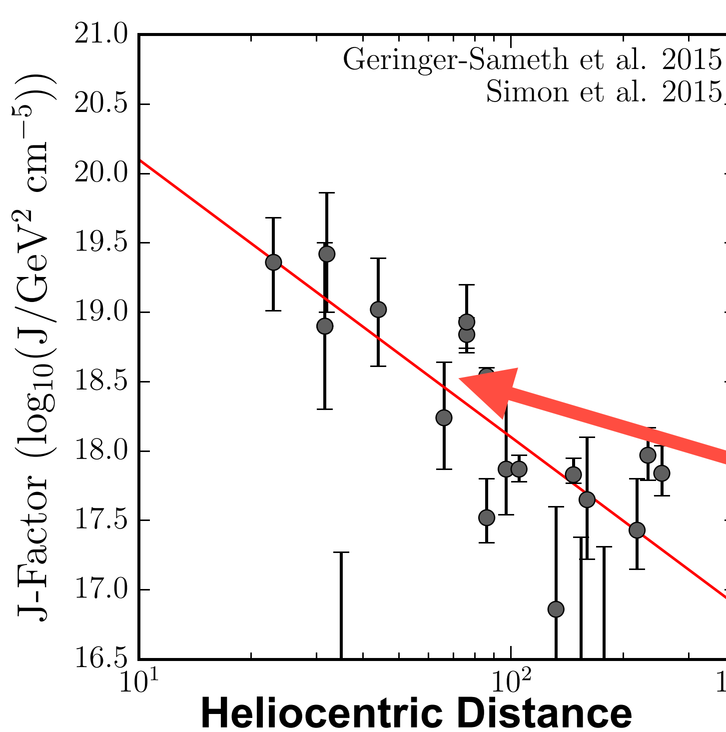




What we want…

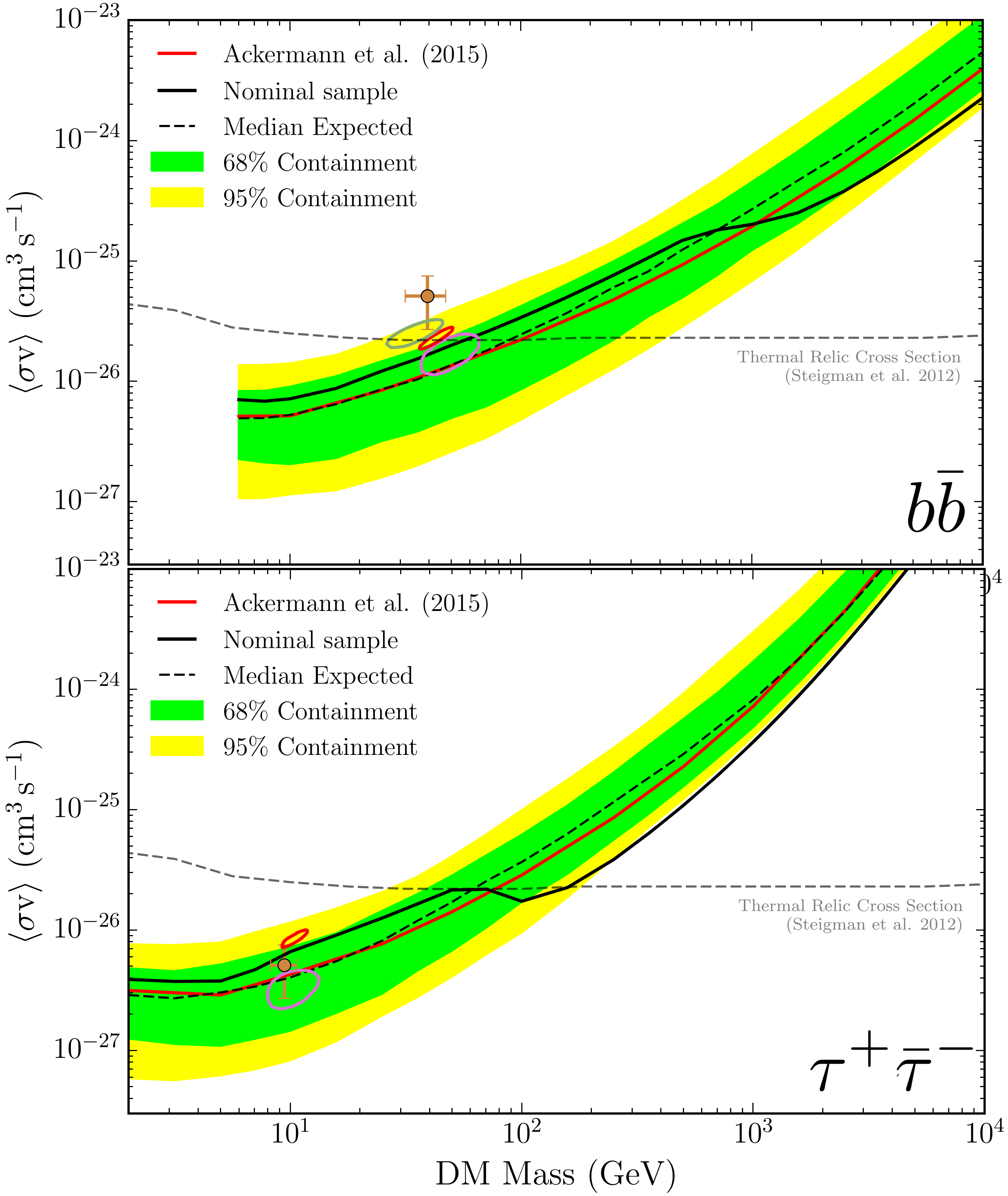
DM Content





What we have…

Gamma-ray Observations



Analyze 45 candidate and confirmed dwarf galaxies

Global significance ~1σ, accounting for trials factors

This result is a "informed estimate" until we have measured J-factors for all targets

More dwarfs and more spectroscopy!

Outline

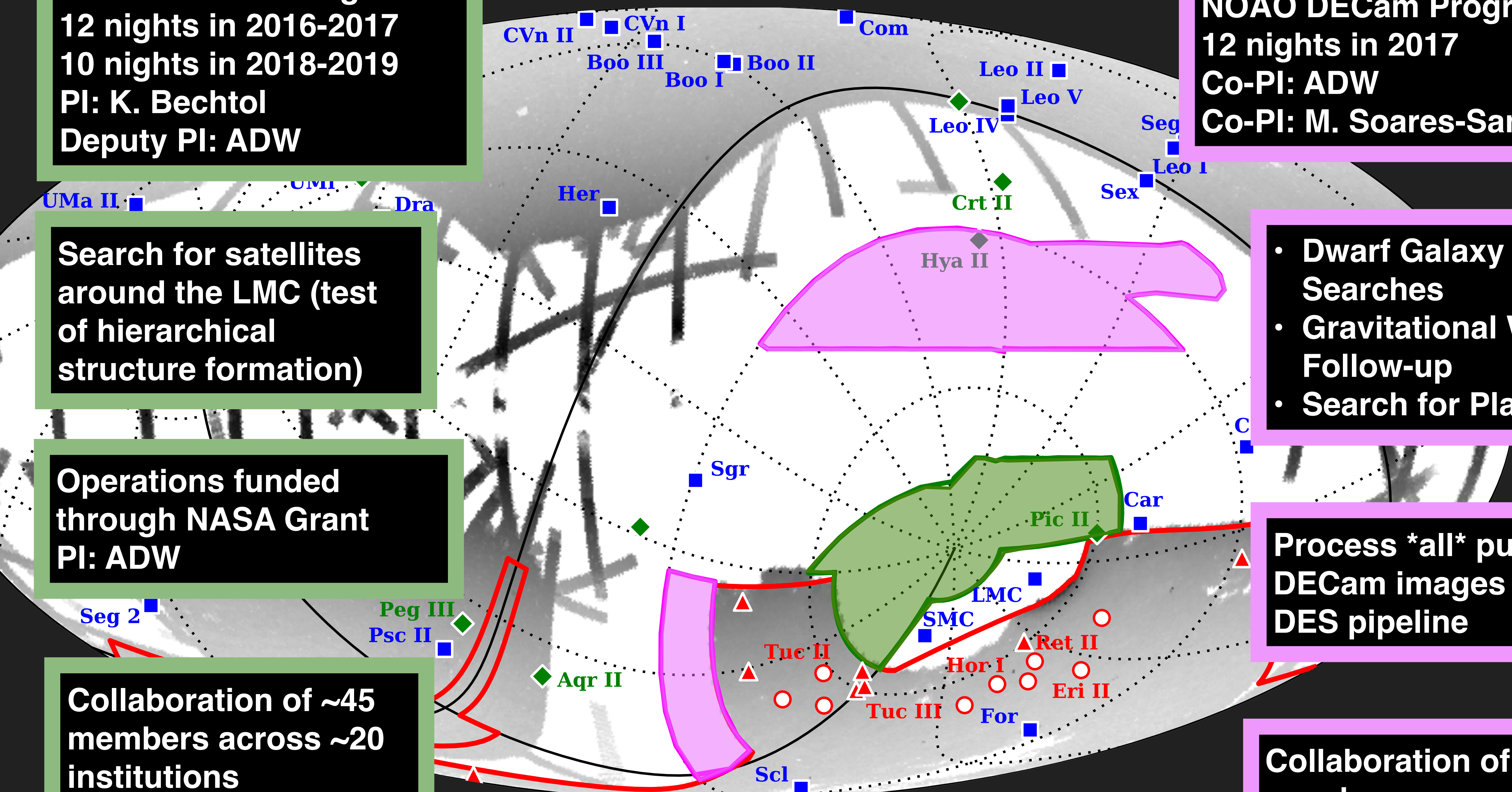
- Dark Matter and Cosmic Surveys
- Search for Dark Matter Annihilation
- Search for the Darkest Galaxies
- Dark Matter with Future Surveys

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

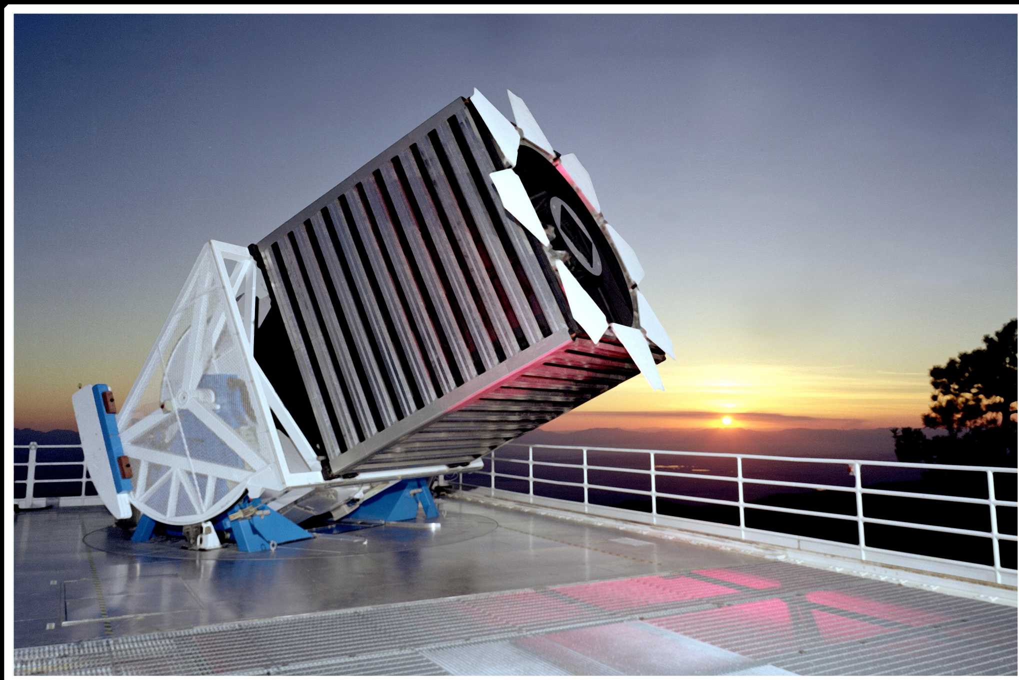
Process *all* public DECam images with DES pipeline

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)

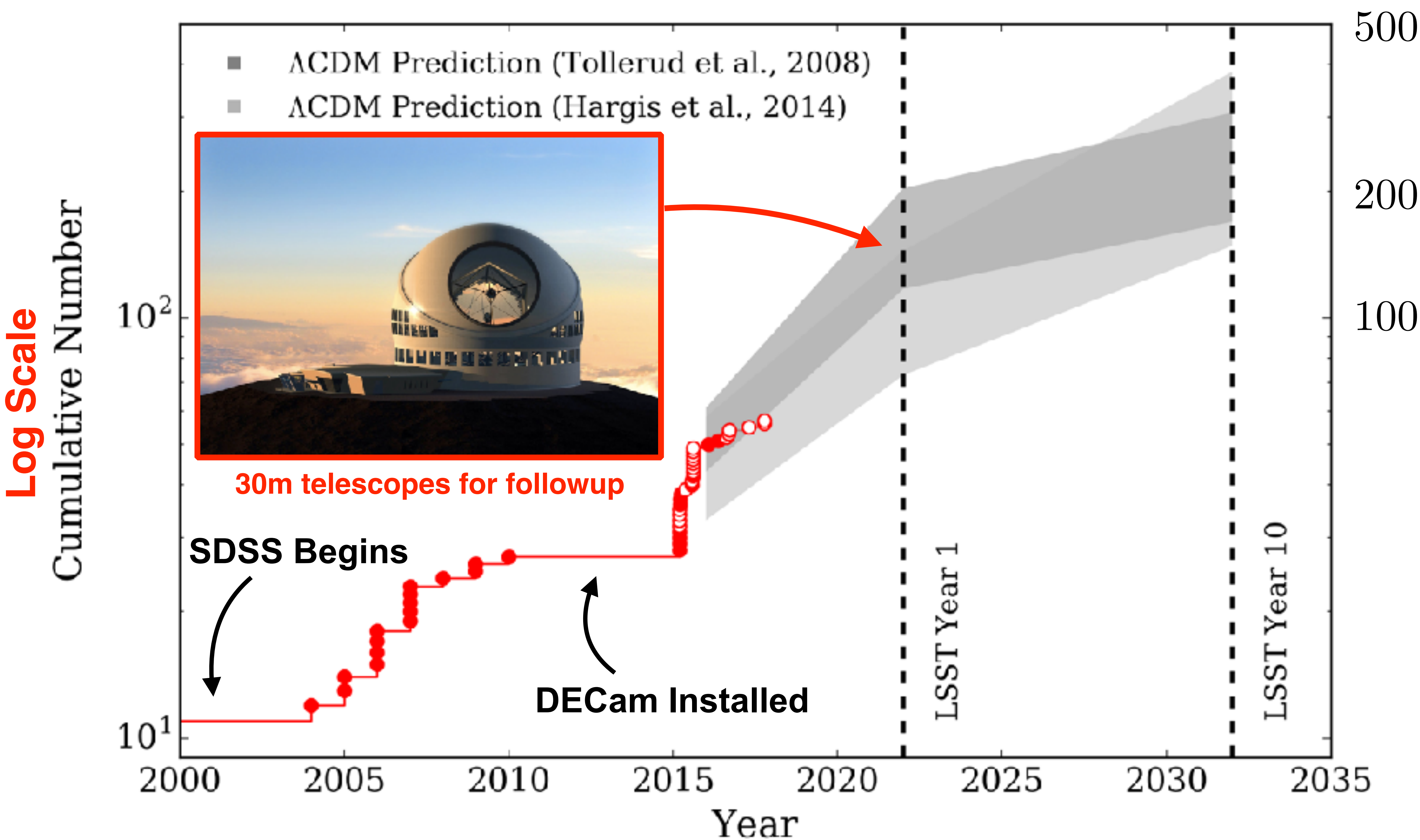
Sensitivity of DES in one 15s exposure!

$500M+ construction approved and underway

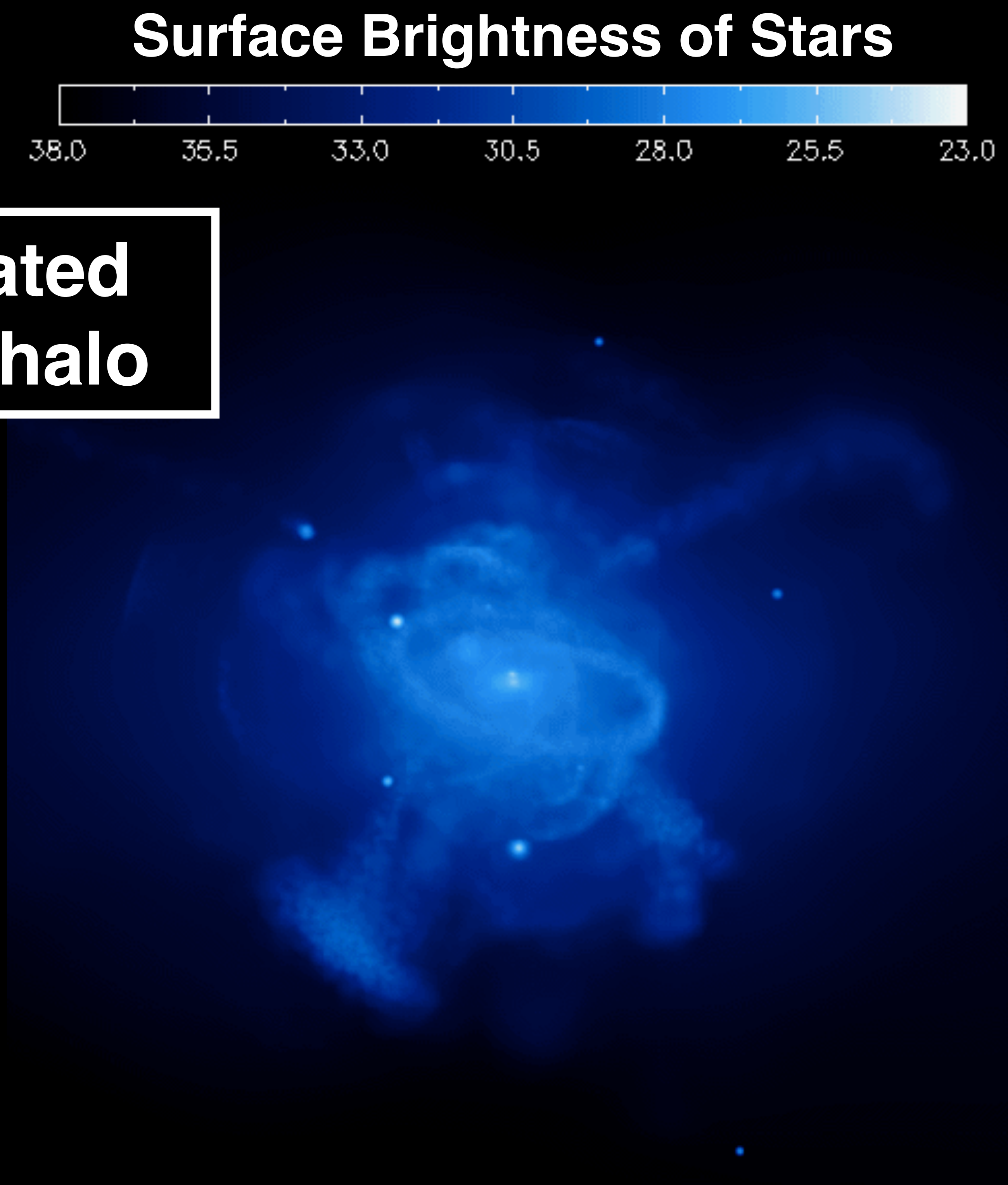
Commissioning in 2020; survey start in ~2022

Expect ~0.5 EB (exabytes) of data

Dwarf Galaxy Discovery Timeline



Milky Way Stellar Halo



Simulated stellar halo

The Milky Way grows by devouring smaller systems

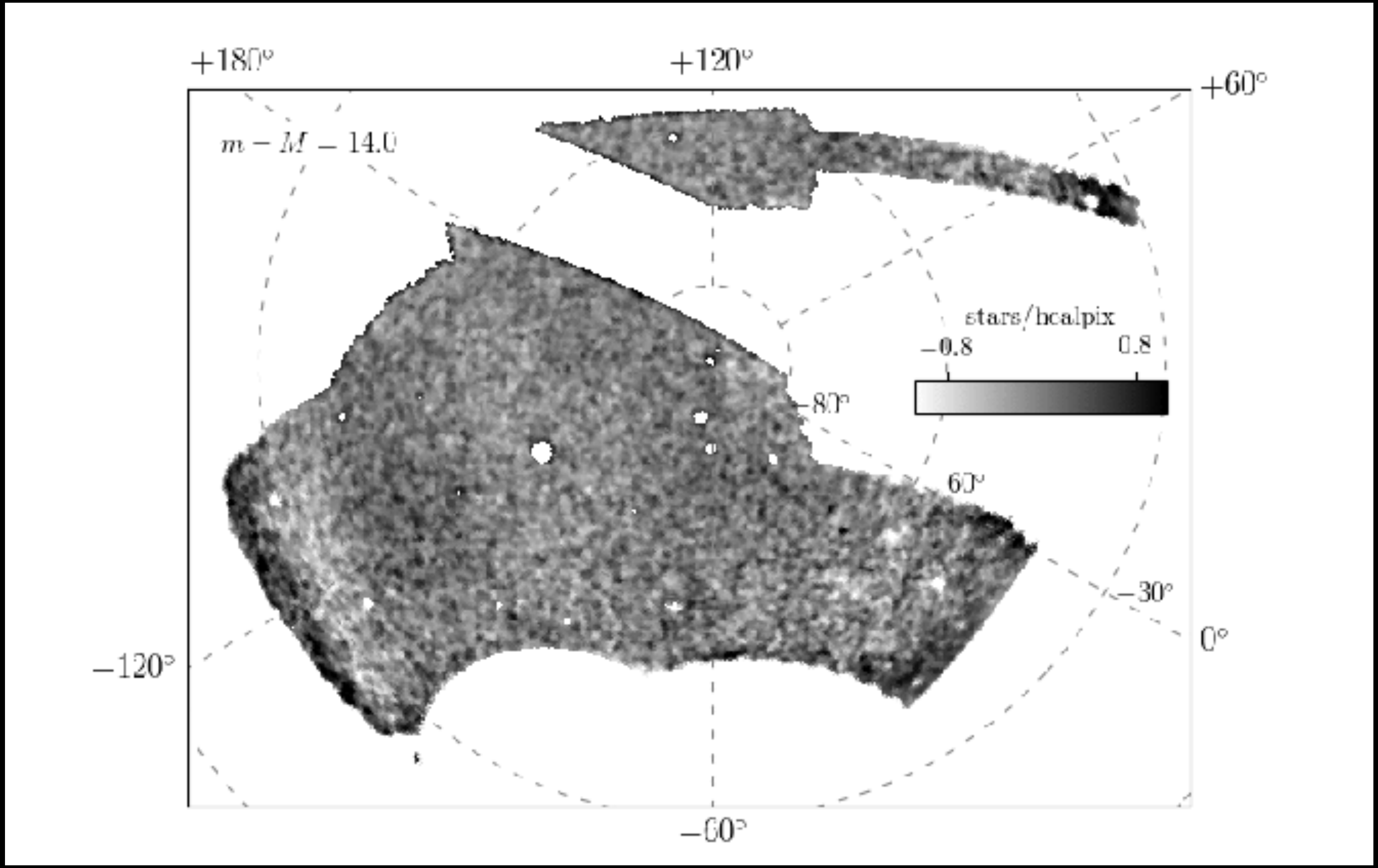
Stellar streams trace the distribution of dark matter around the Milky Way

Bullock & Johnston (2005)

New Stellar Streams

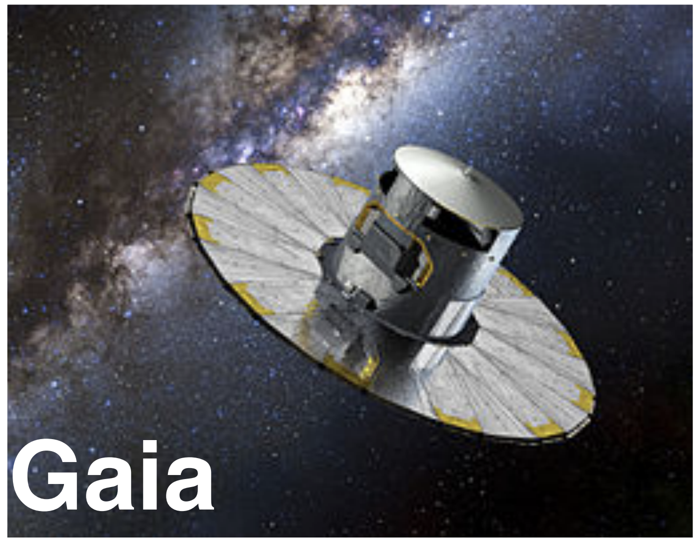
11 new stellar streams discovered with DES

Increases the known stream population by ~ 50%



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

Gaps in Stellar Streams



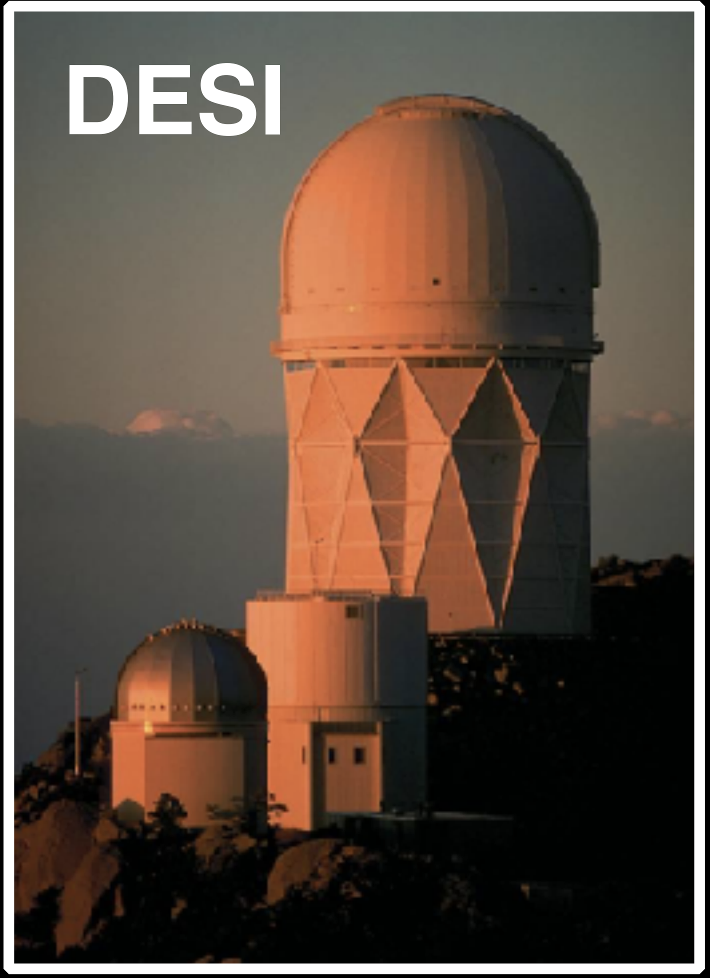
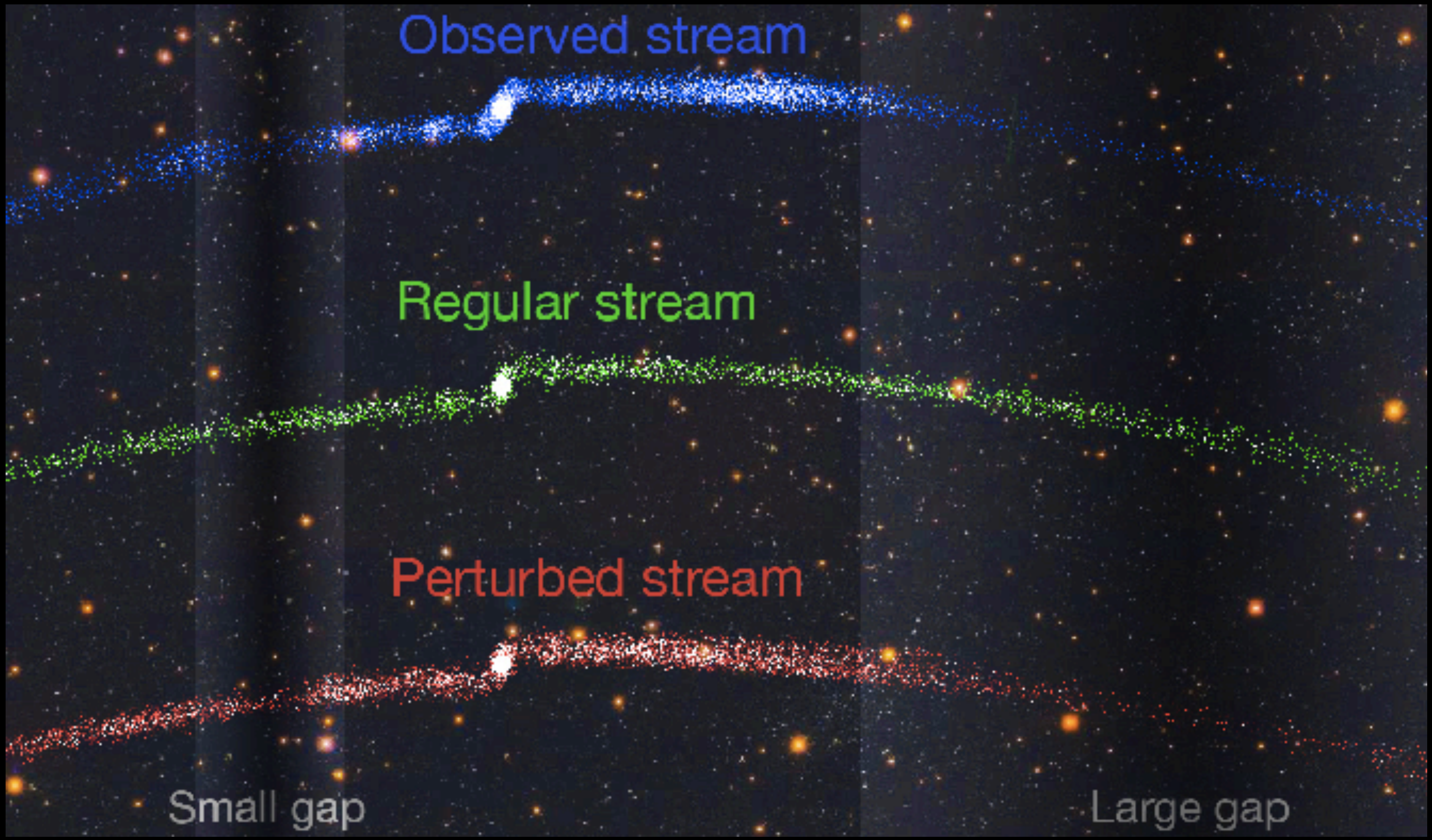


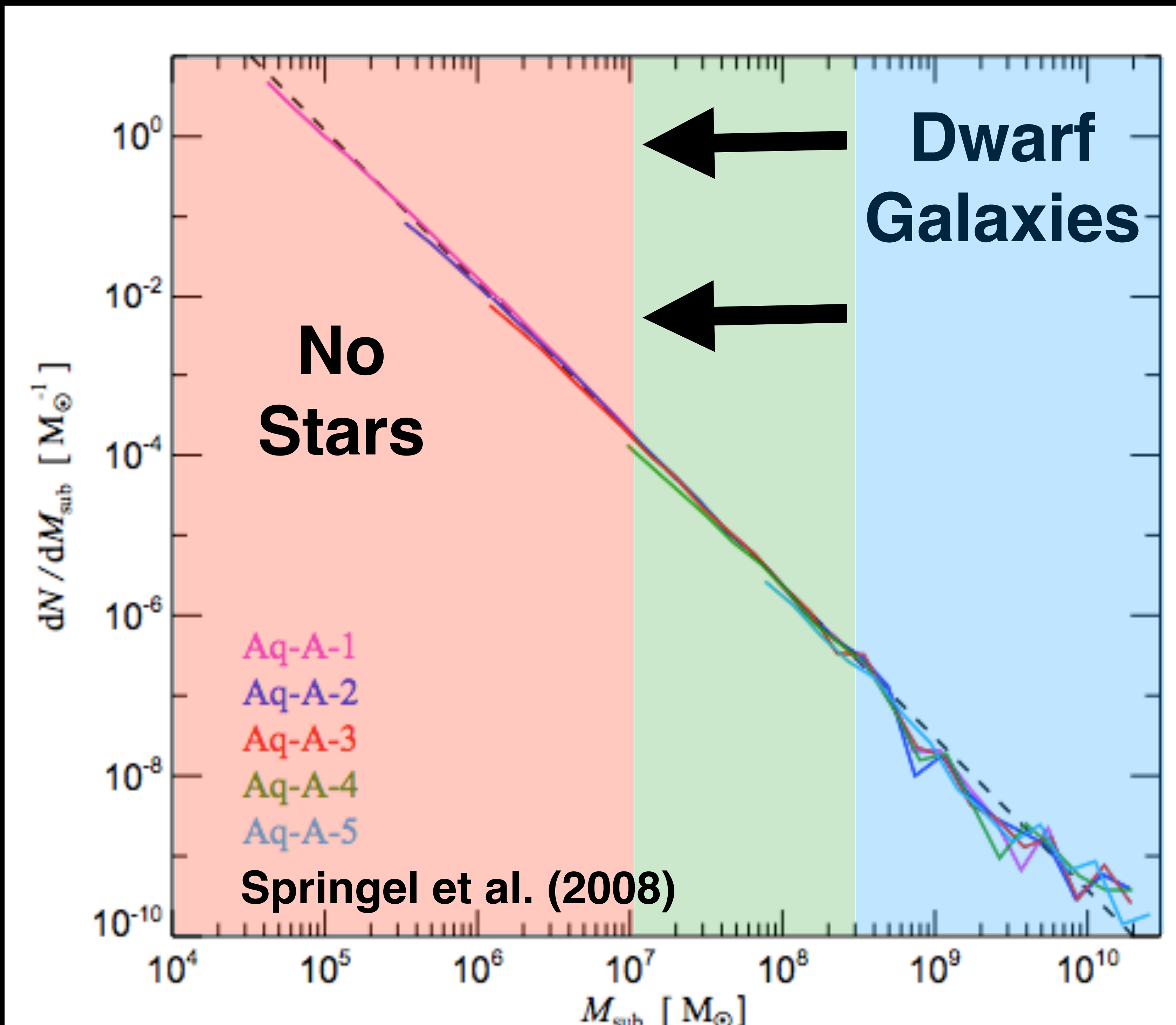
Image: Belokurov+



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

Low Mass Subhalos

Dark Matter Halo Abundance



Dark Matter Halo Mass ($M_\odot$)

Strong prediction of cold dark matter

Stellar Streams

Gravitational Lensing

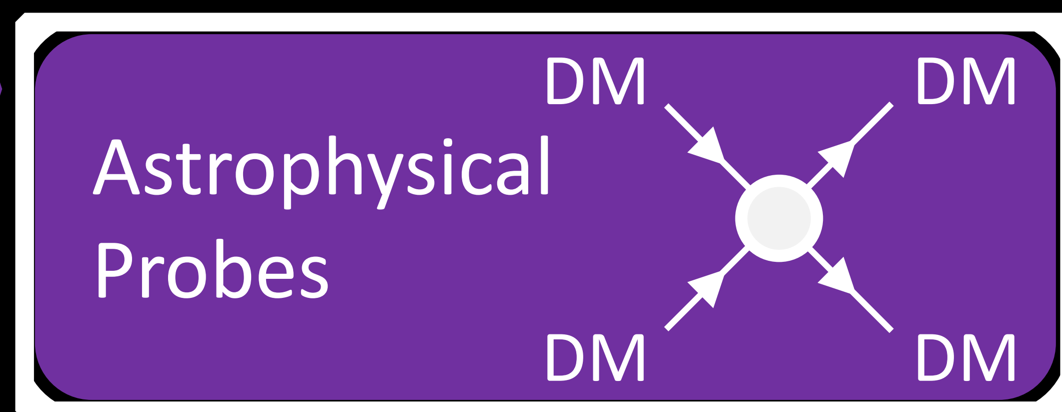
Probing Dark Matter with LSST

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



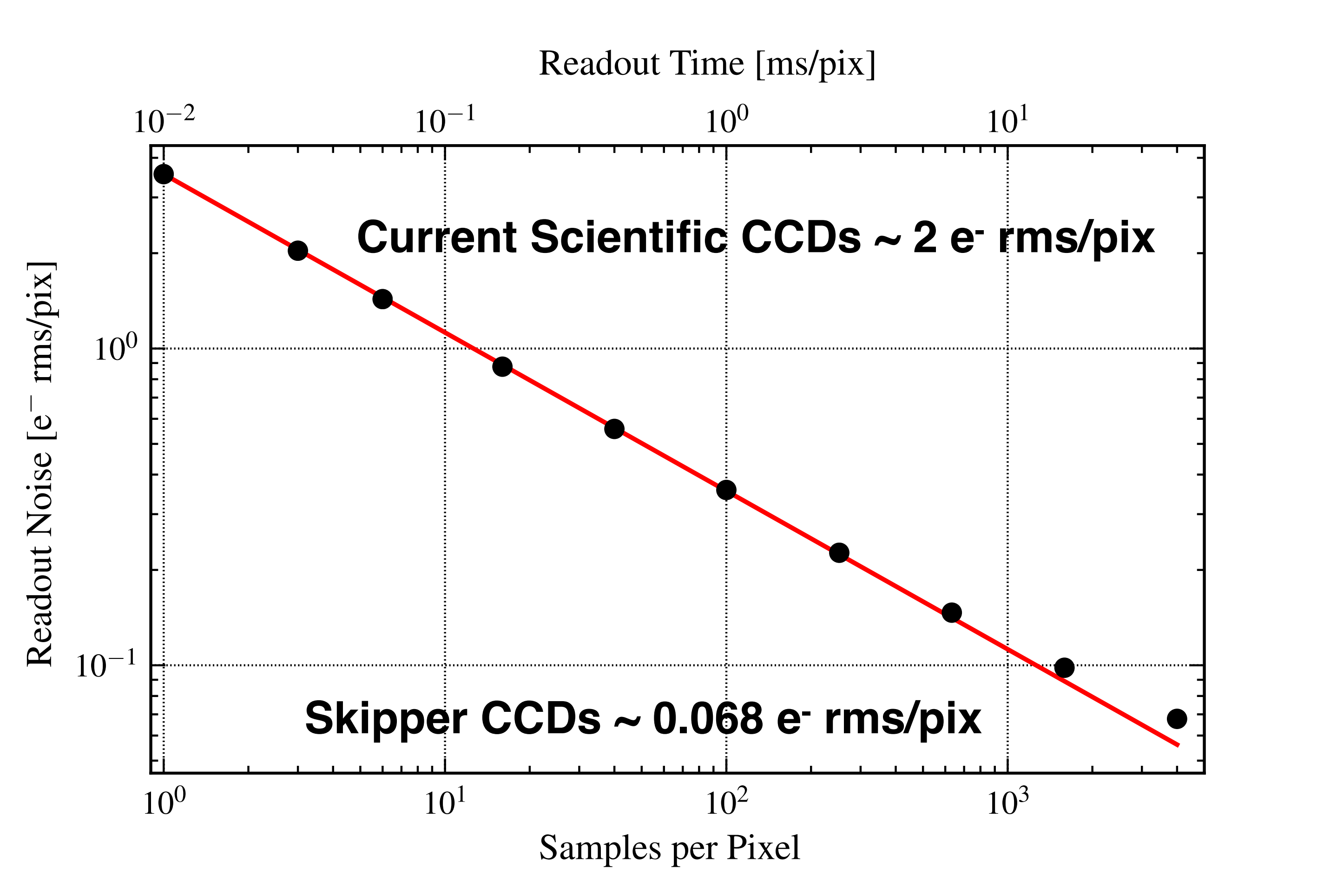
Axions:
anomalous stellar cooling;
white dwarf and RGB population statistics

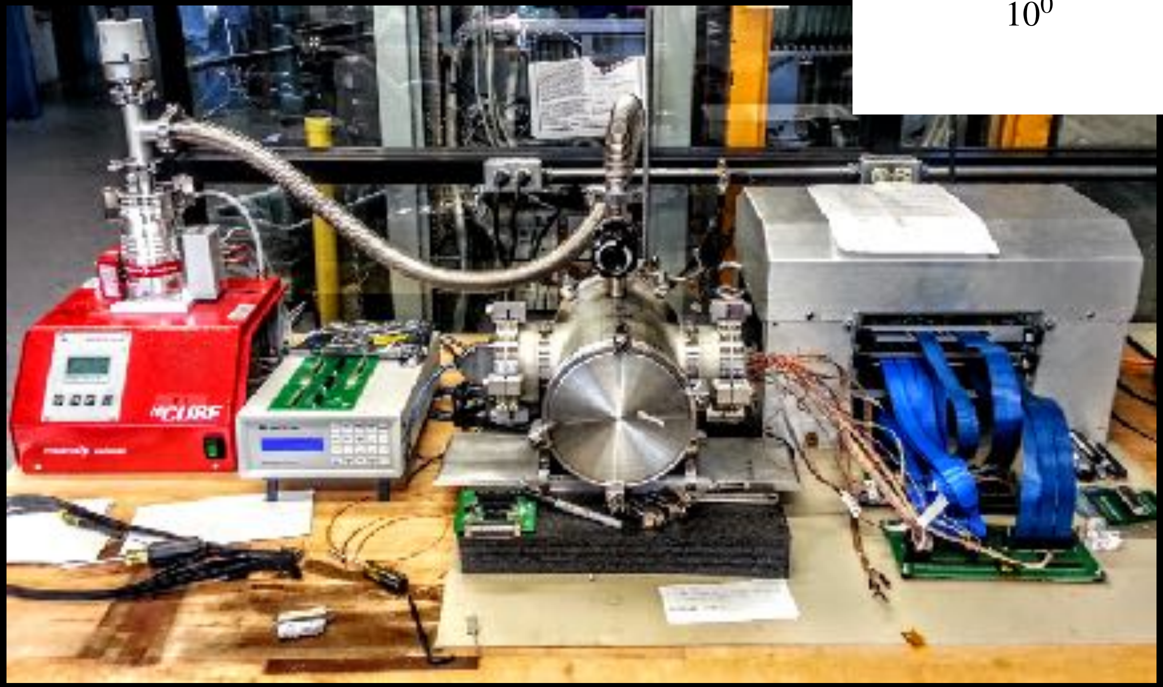
Primordial Black Holes:
microlensing;
supernova caustics

Alex Drlica-Wagner

New CCDs for New Discoveries

Work with FNAL and LBNL

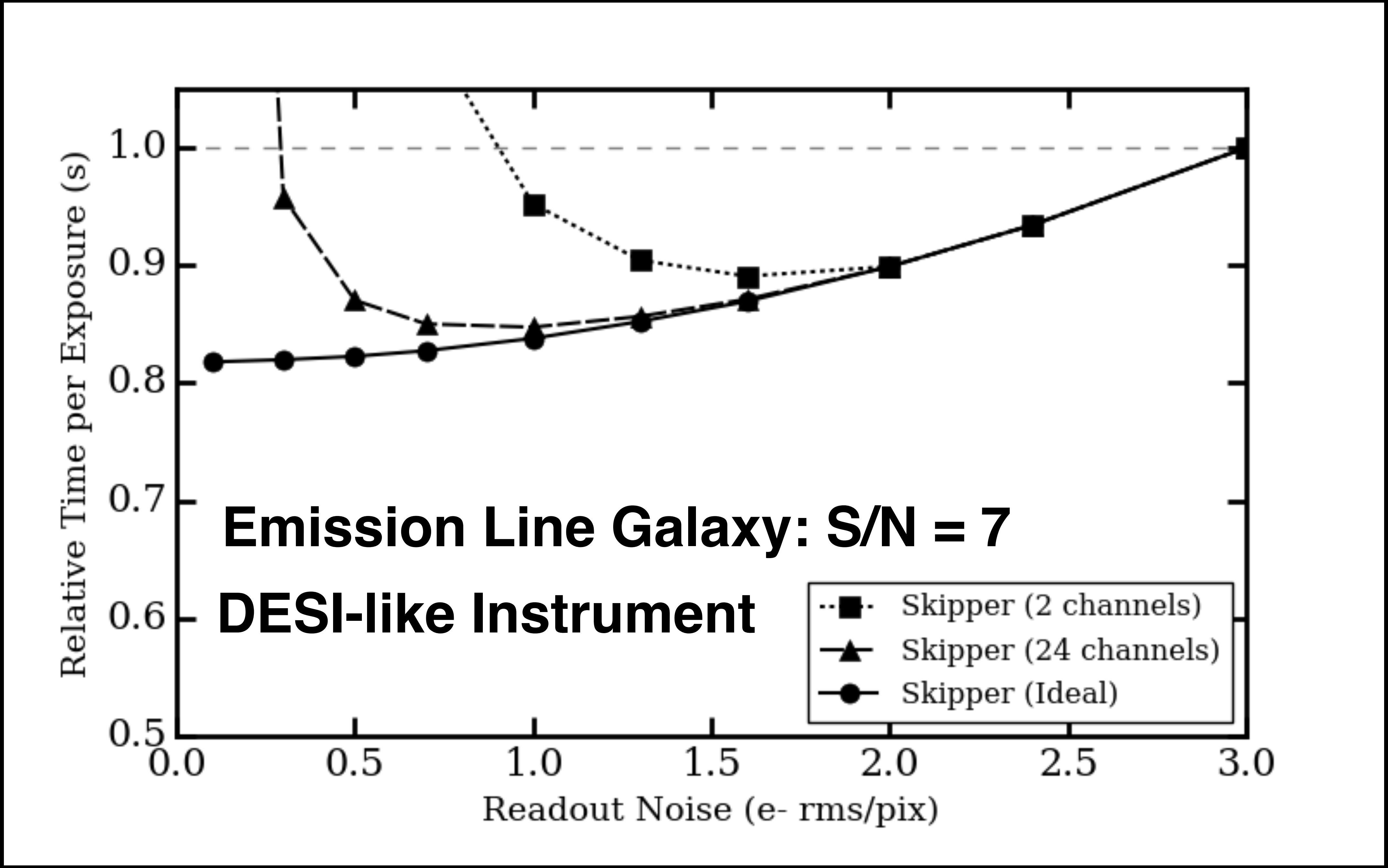




Lower CCD read noise through multiple non-destructive reads of the charge in each pixel

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

Increased Efficiency for Spectroscopic Surveys



Summary

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

Cosmic surveys have entered the era of precision measurement.

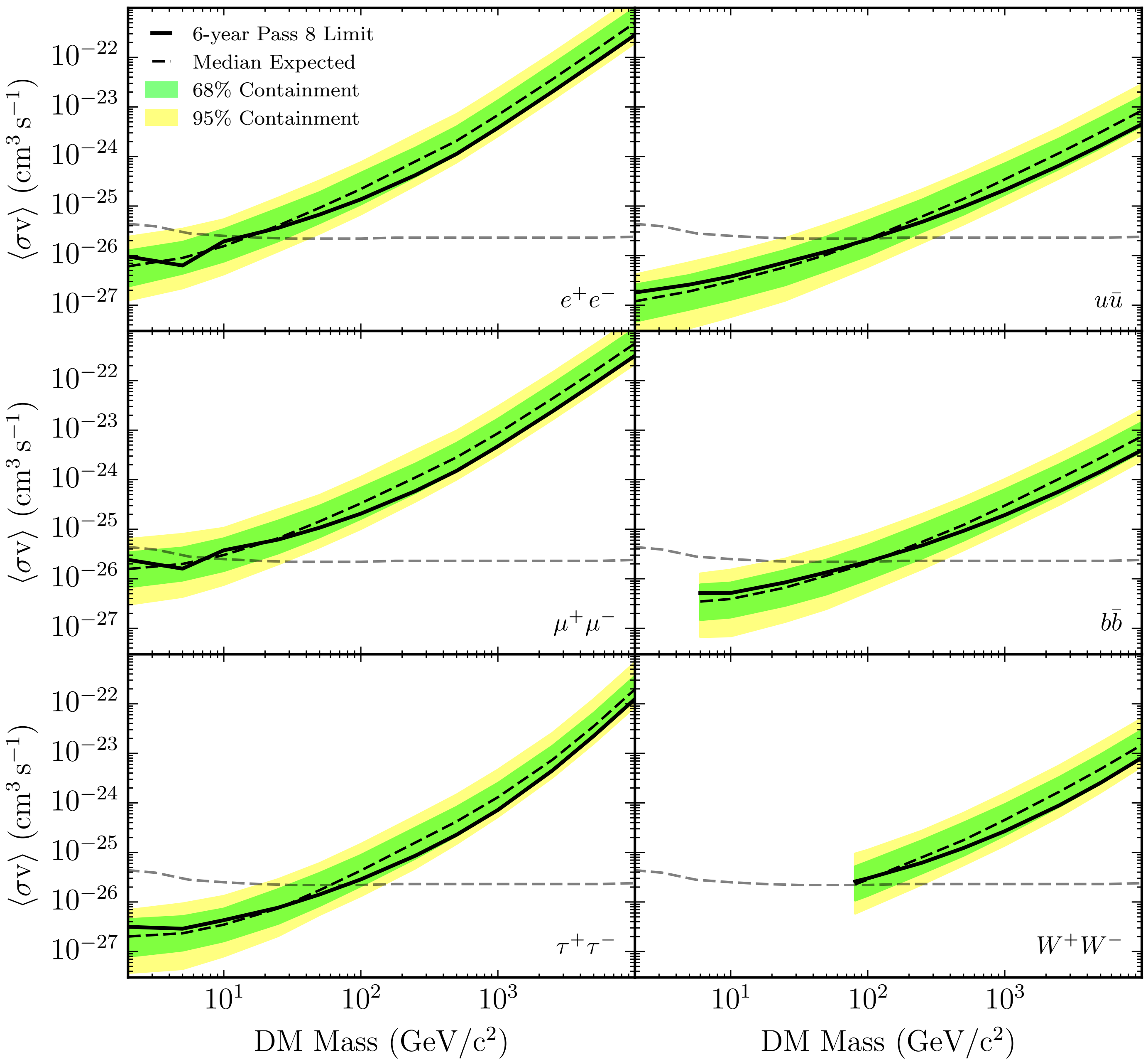
Dwarf galaxy are an important target class for indirect dark matter searches.

Gravitational interactions provide the only robust, positive measurement of dark matter.

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

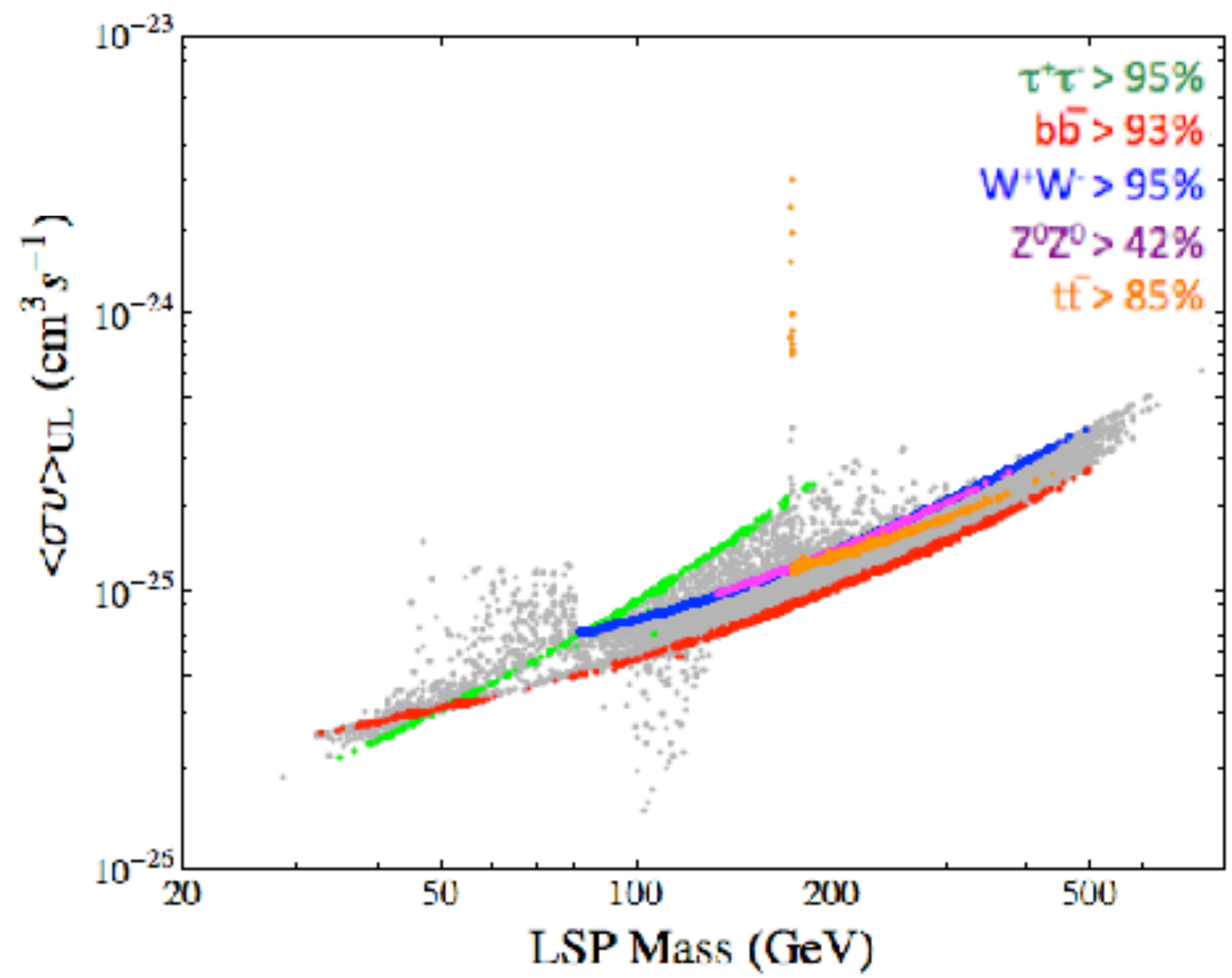
Backup Slides

Other Channels



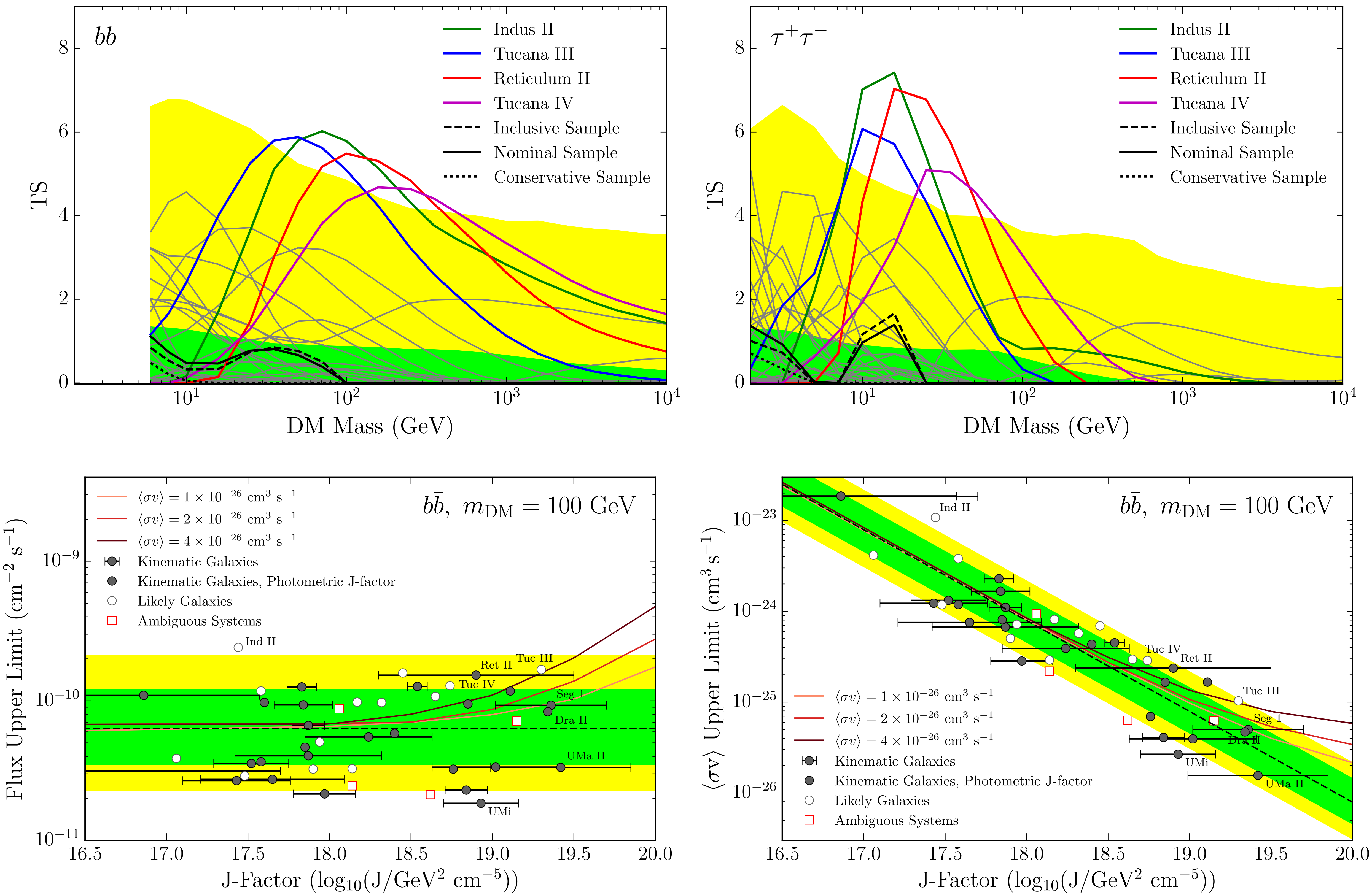
Pure Annihilation Channels

Spectral Dependence

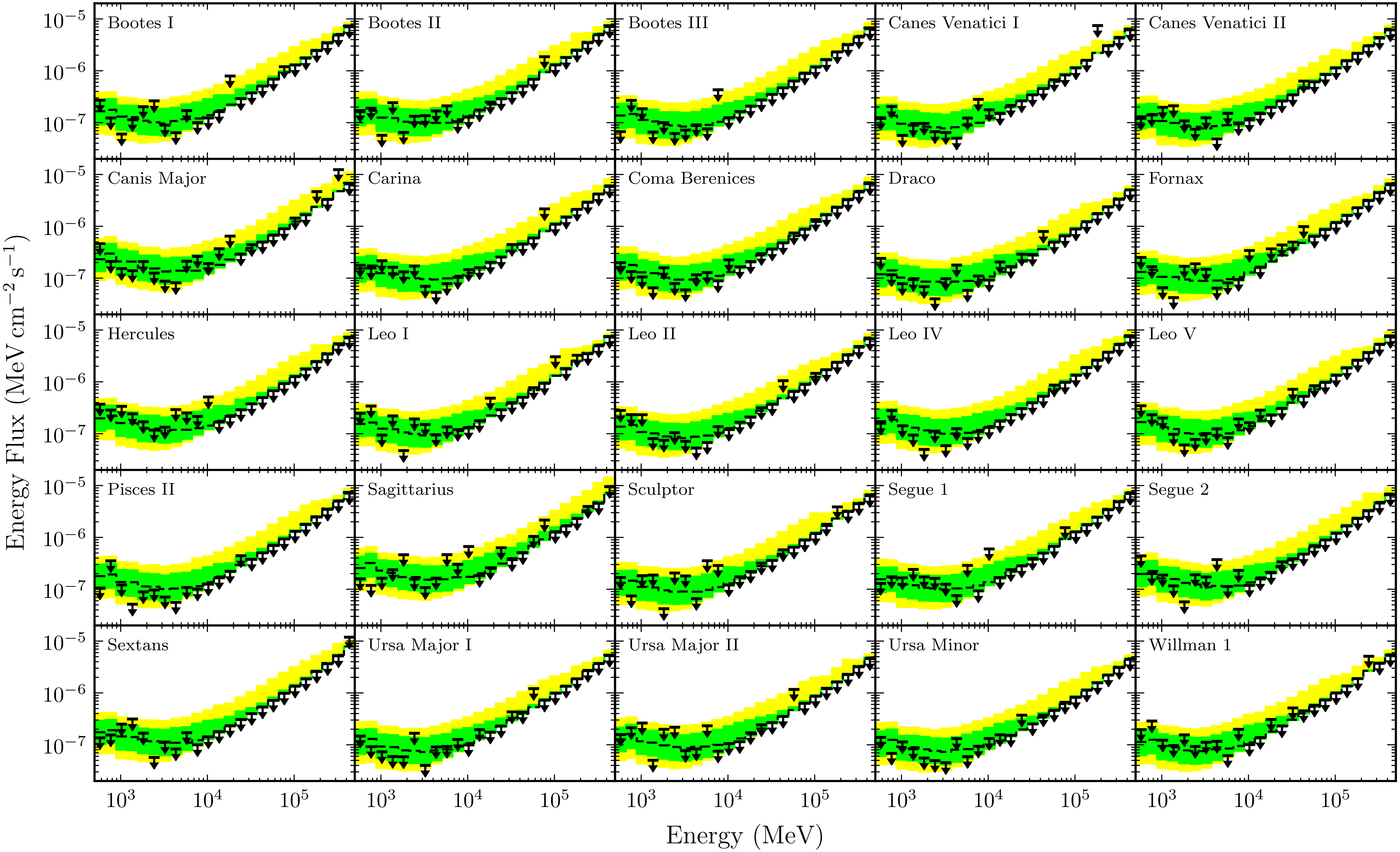


pMSSM Models

Confirmed and Candidate Dwarfs



Bin-by-Bin Sensitivity



LAT Collaboration, PRD 89, 042001 (2014) *