The Mystery of Missing Mass

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Fermilab

Laser Safety Officer Workshop
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CRIME SUMMARY

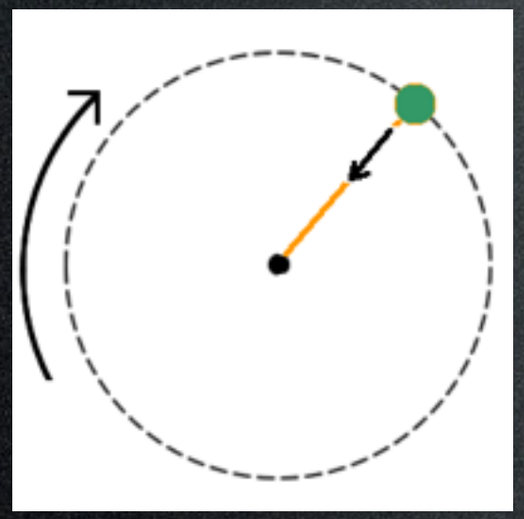
- How can we measure mass?
- Where do we find dark matter?
- How can we explain dark matter?
- How can we test these explanations?
- What have we found so far?

FORENSICS

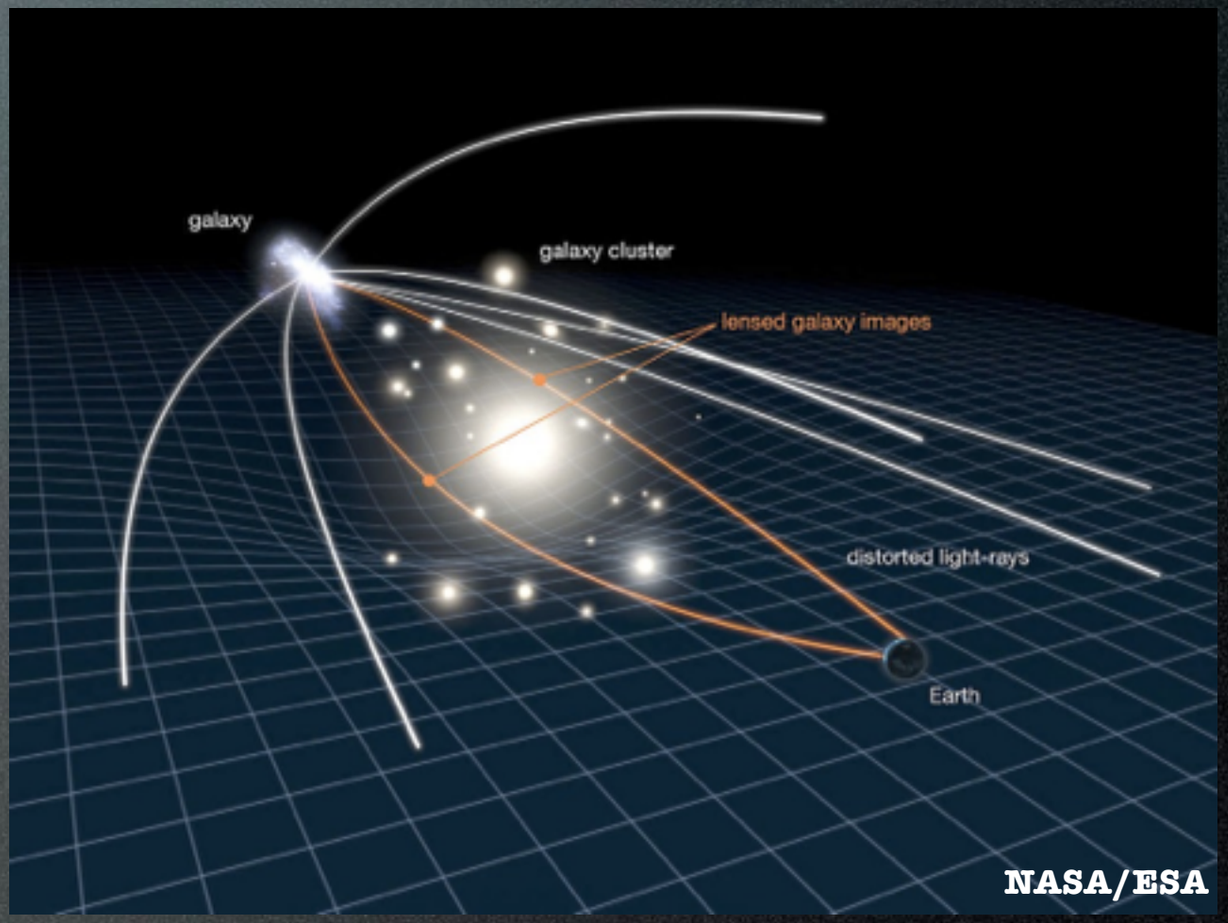
How do we measure mass?

Tools for Measuring Mass

Light to Mass



Orbital Velocity

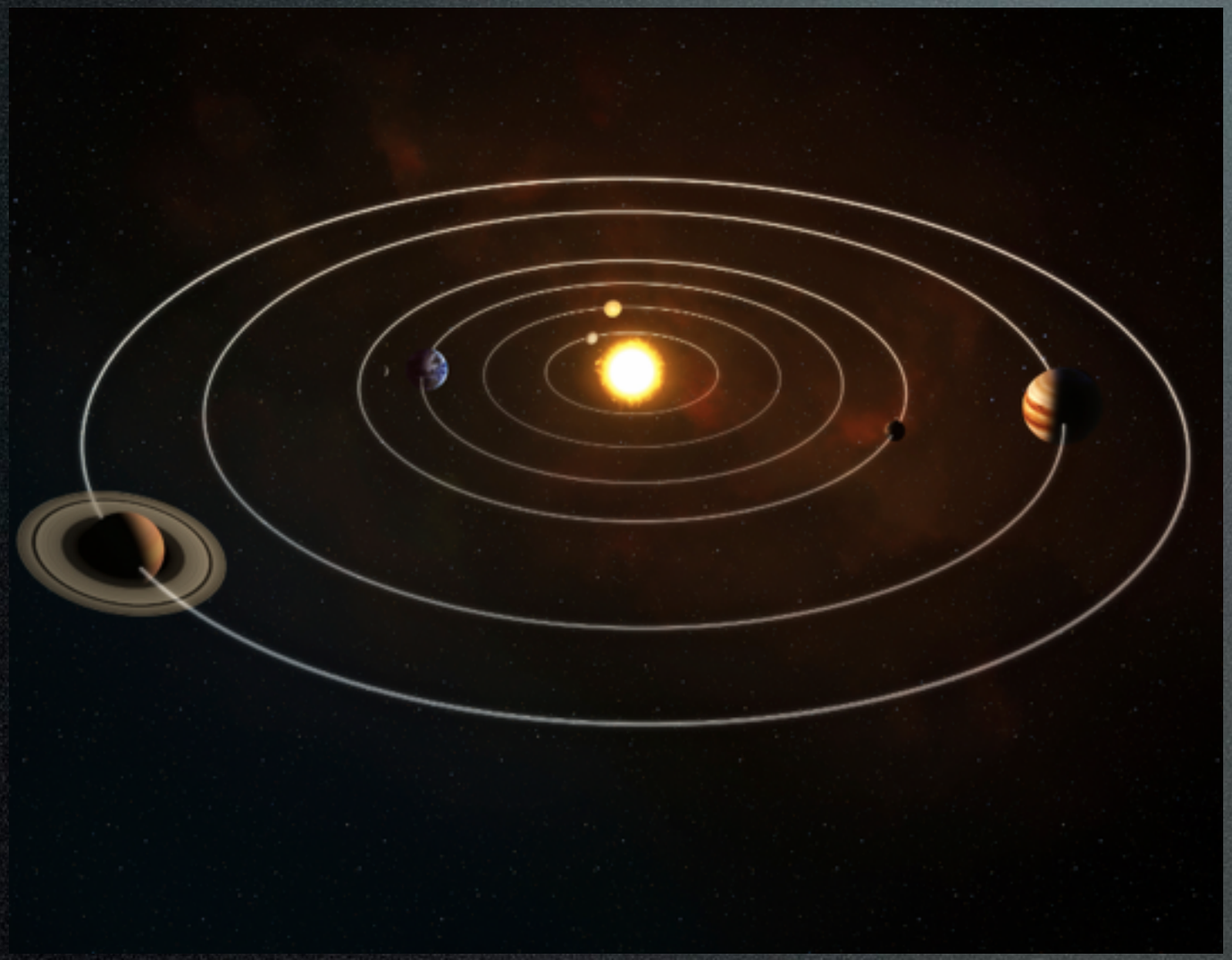


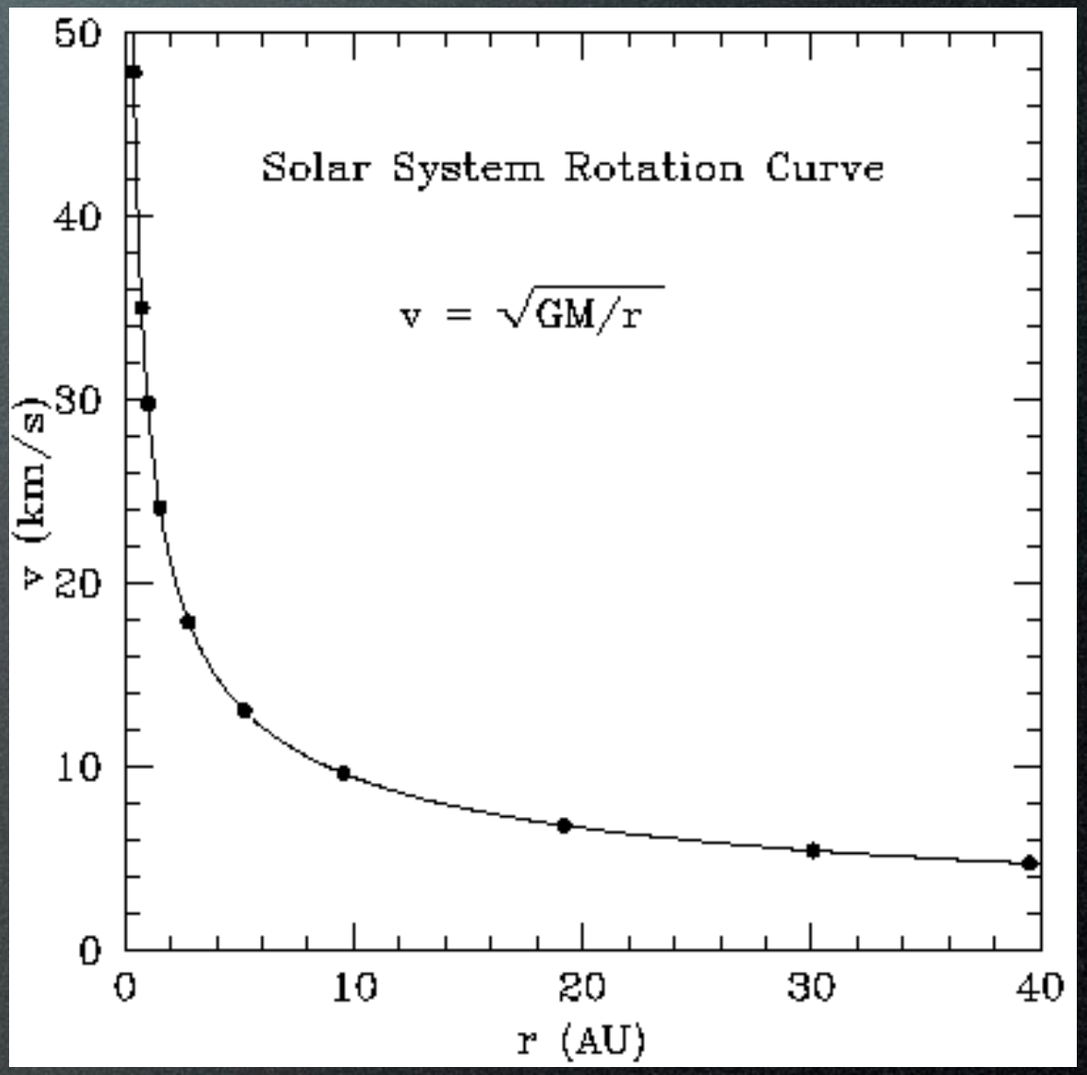
Gravitational Lensing

CRIME SCENE

What objects are missing mass?

Our Solar System?

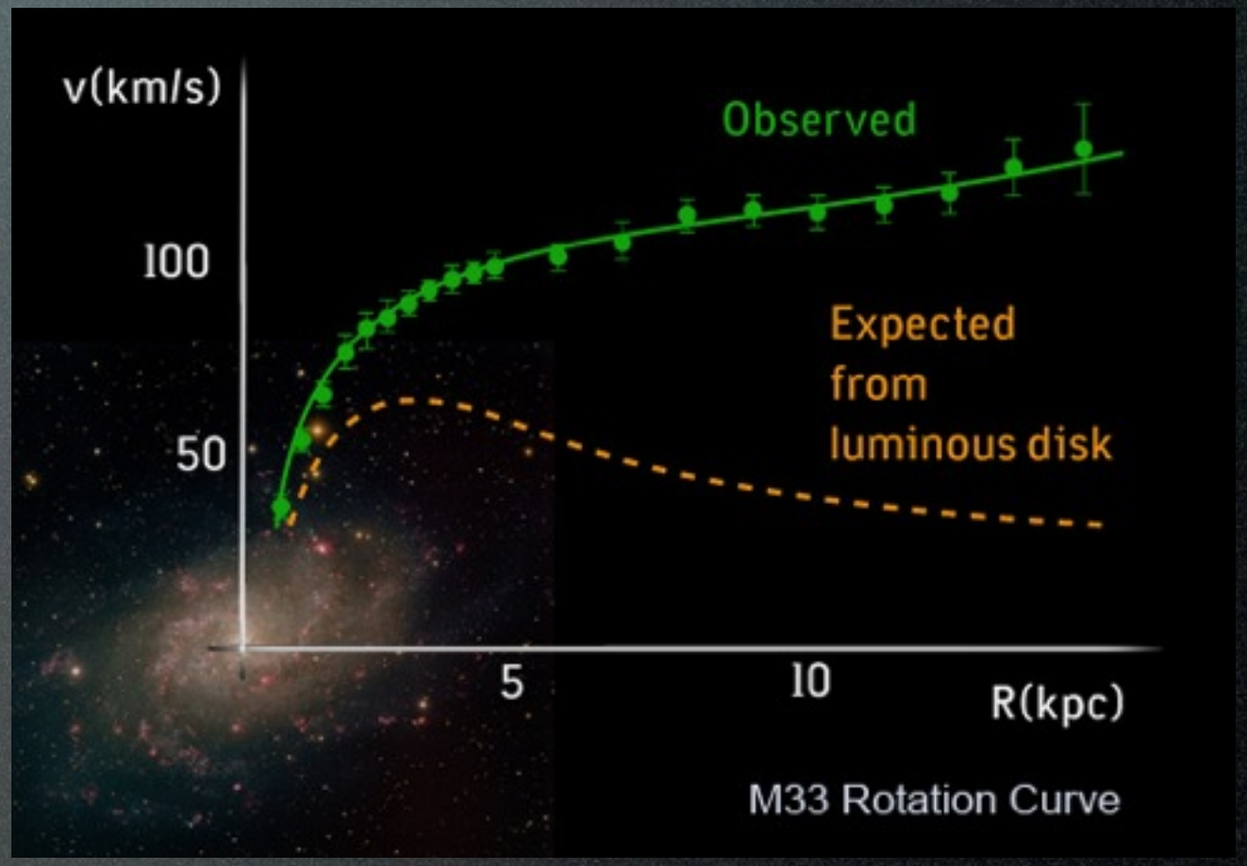




Solar Sytem Rotation Curve (Bustard, 2007)

Individual Galaxies

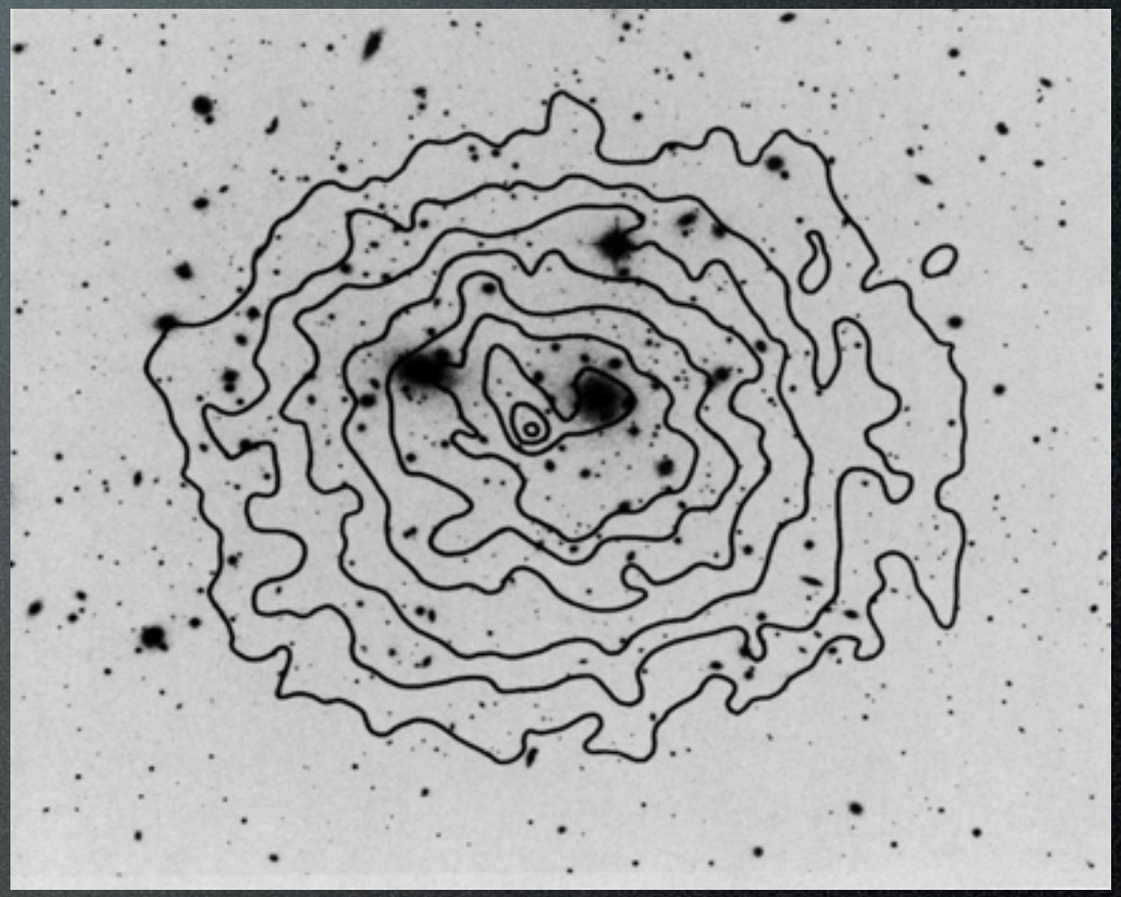
NGC 3198 Optical Image (Vickery & Matthes)



Galaxy Rotation Curve (NOAO, AURA, NSF, T.A. Rector)

Clusters of Galaxies

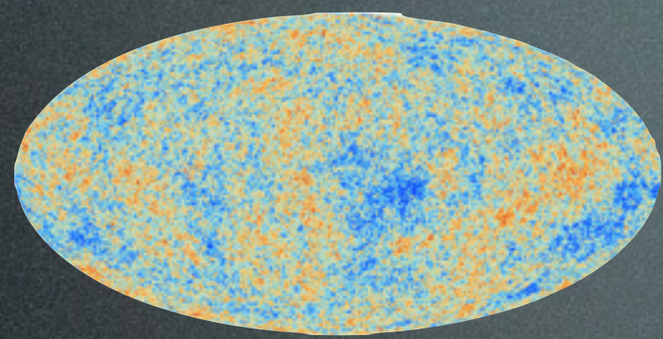
Coma Cluster in Visible Light (SDSS, 2005)



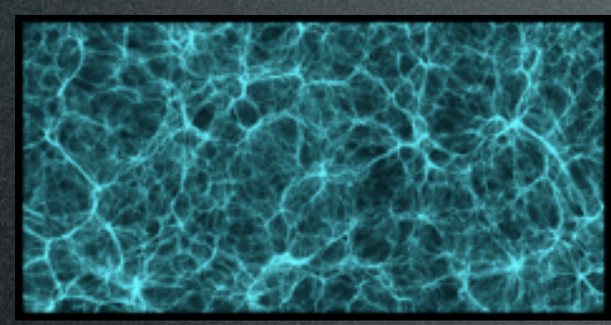
Coma Cluster in X-rays (Jones & Forman)

Crime Scene

Observable Universe



Clusters of Clusters



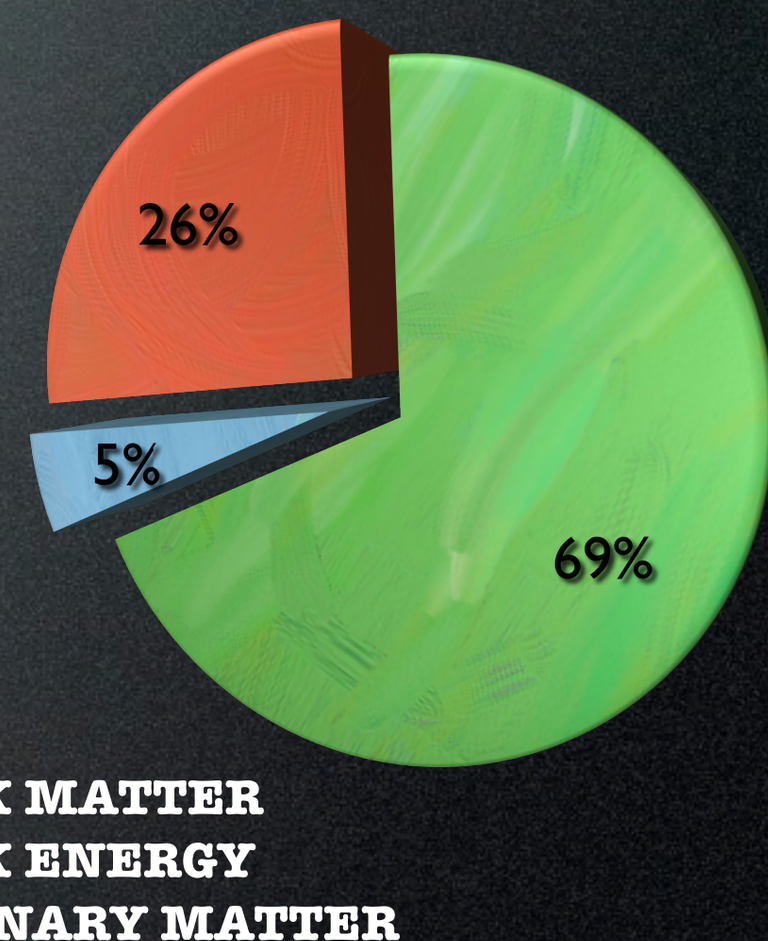
Clusters of Galaxies

Individual Galaxies

Larger

Smaller

Composition of the Universe

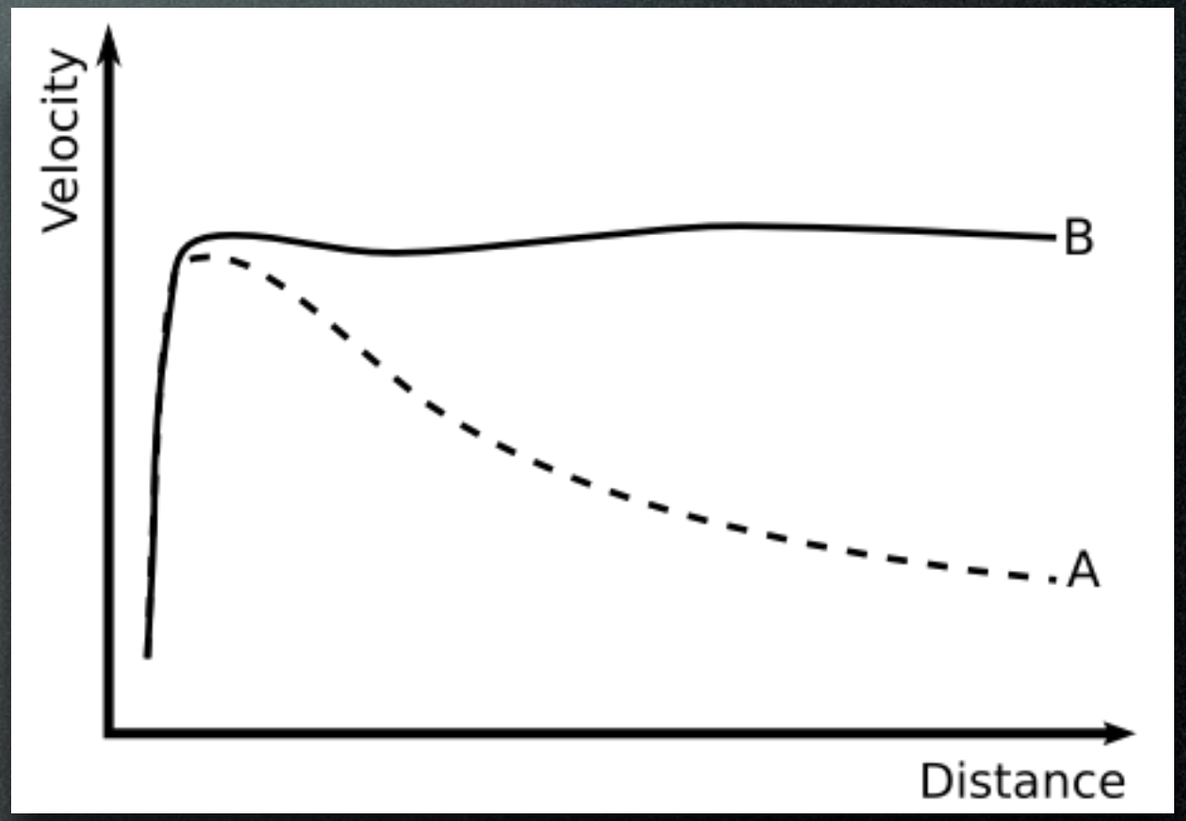


SUSPECTS

What is the missing mass?

Modified Newtonian Dynamics (MOND)

- Modify the equations of gravity at large distances
- This would mean there is no missing mass!
- All alterations to gravity should be tied to the mass that we can see (normal matter is still the source)...



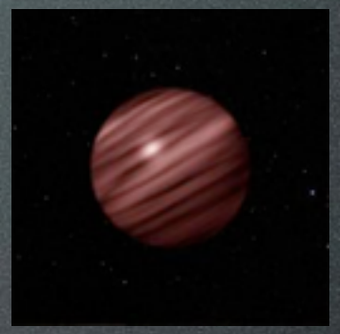
A Hard Question for MOND...

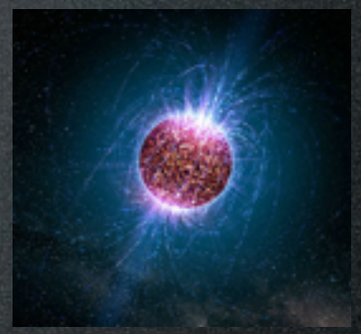
Bullet Cluster (Markevitch & Clowe, 2006)

MACS J0025.4-1222 (Allen & Bradac, 2008)

Massive Compact Halo Objects (MACHOs)

Black Holes

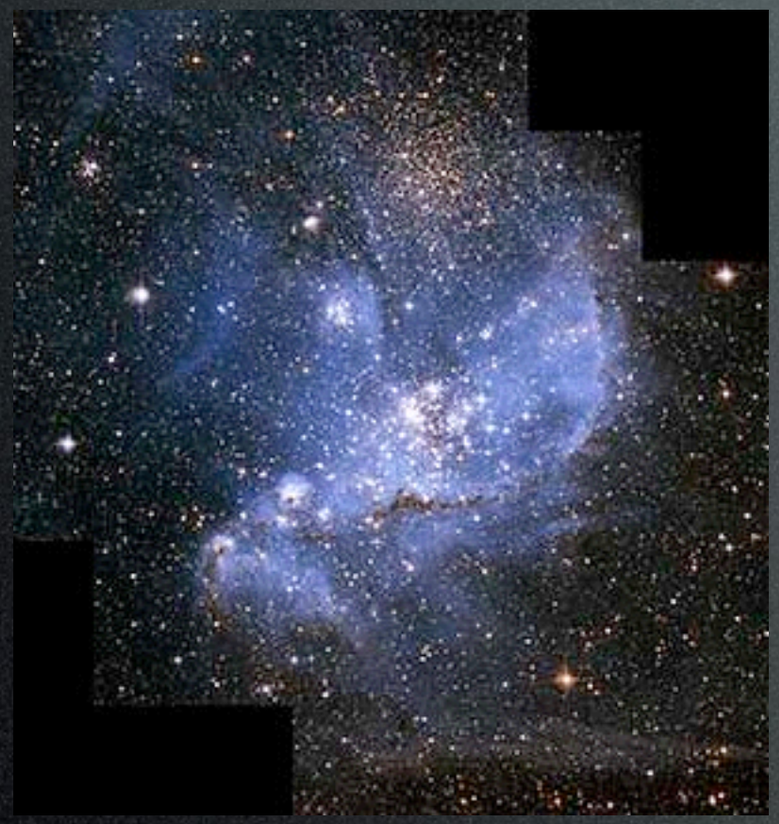




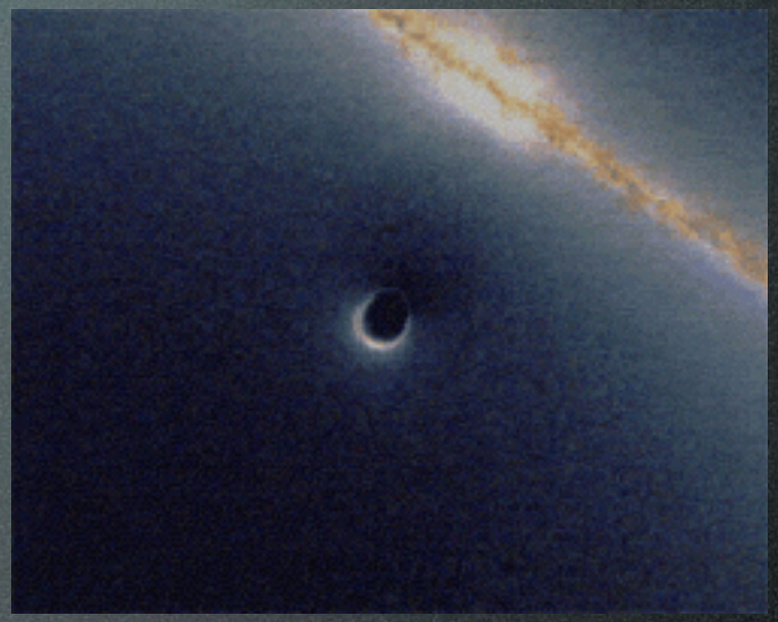
Dwarf Stars

Asteroids

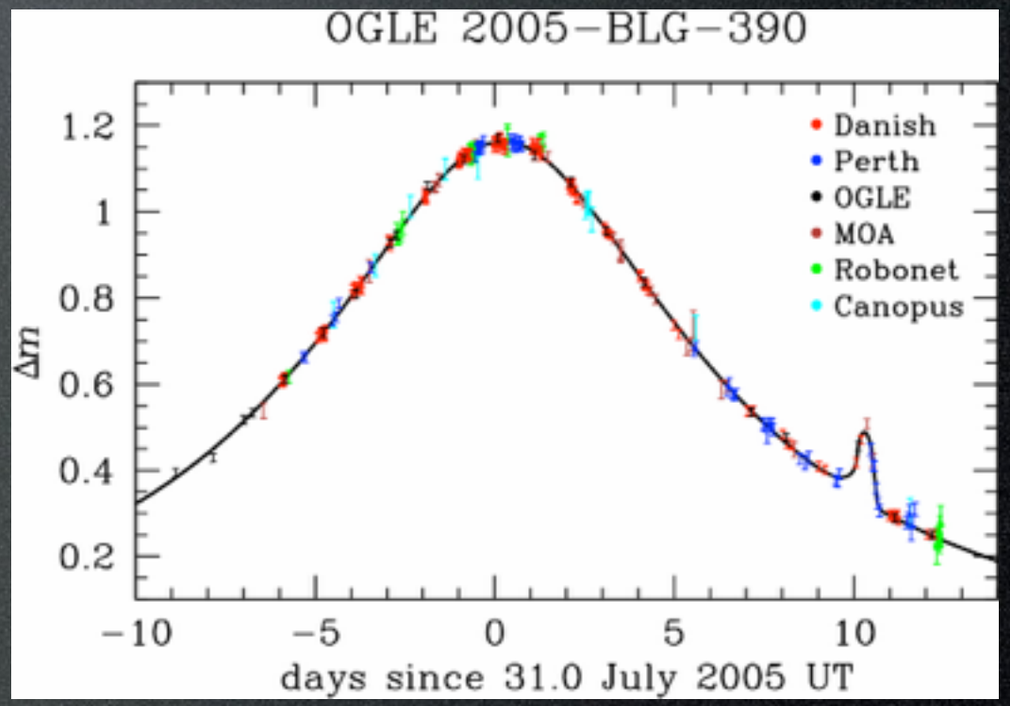
MACHOs (II)



Small Magellanic Cloud (HST)



Gravitational Lensing



Microlensing Event (OGLE 2006)

Weakly Interacting Massive Particles (WIMPs)

- **Independently invented to solves other problems in particle physics**
- **Interact little with ordinary matter (like neutrinos)**
- **Roughly the mass of 100 protons**
- **Are difficult (but not impossible) to detect experimentally**

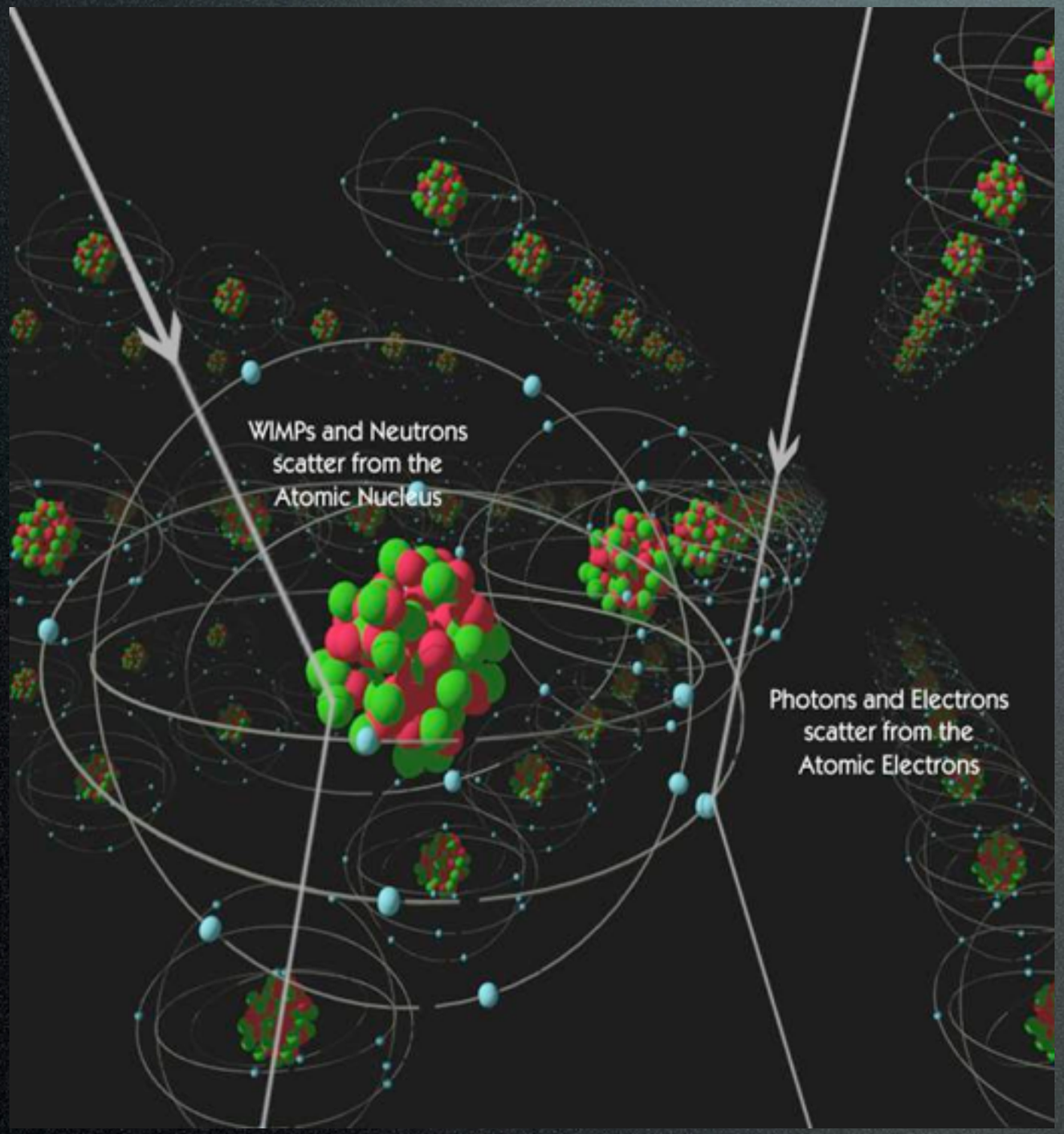
- This room contains ~10^8 dark matter particles
- They each have roughly the mass of a silver atom
- They pass through the walls, ceiling, floor, and us at ~500,000 mph
- Their gravity holds the galaxy together
- We don't have any direct evidence for their existence except for gravity

- This isn't as strange as it sounds… think about neutrinos!
- Roughly 10^8 neutrinos pass through the tip of your finger every second!

THE MANHUNT

Can we catch the WIMP?

Direct Detection



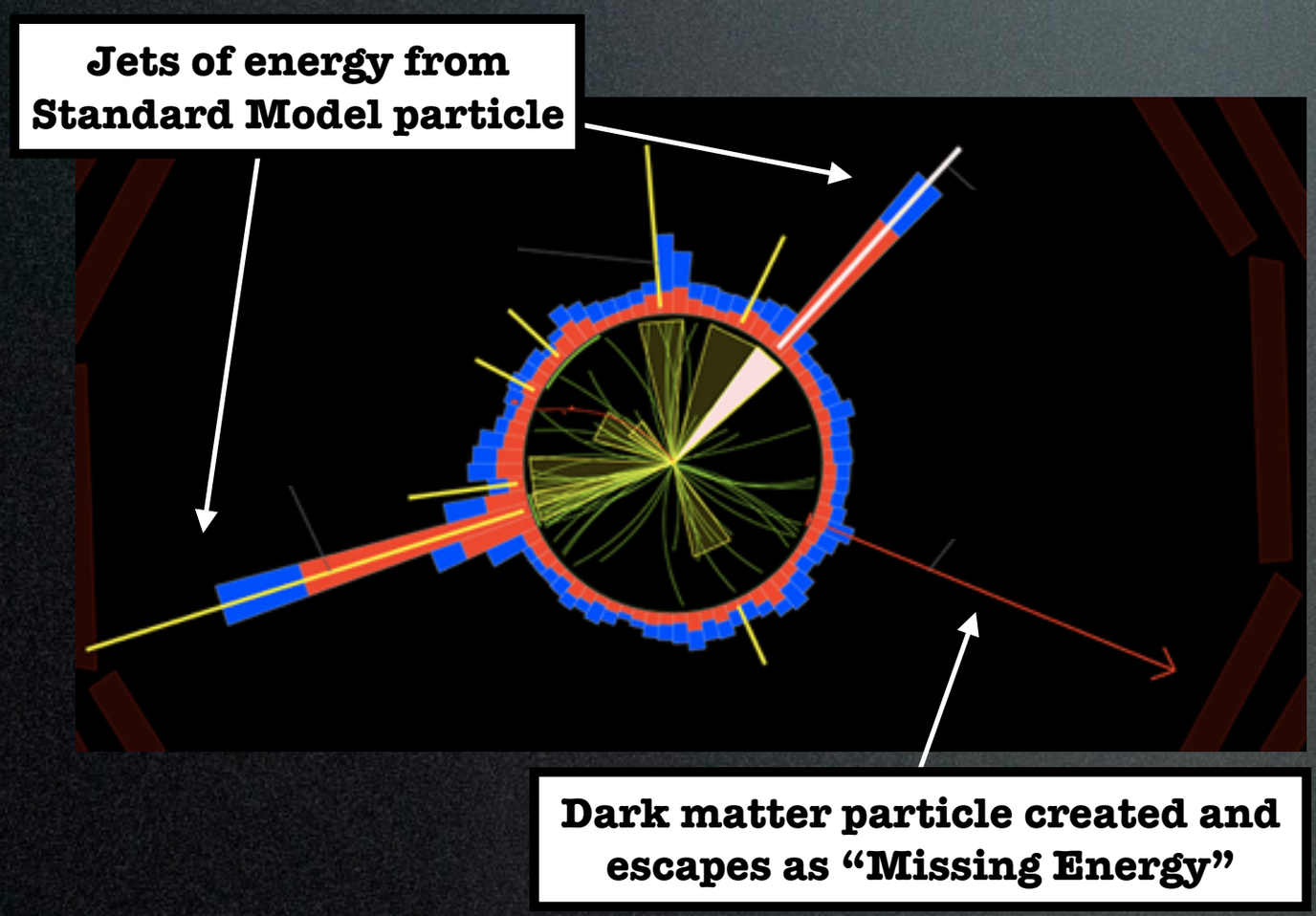
Elastic Scattering of Dark Matter (Cooley, 2009)

CDMS Solid-State Germanium Detector

LUX Liquid Xenon Detector

Collider Creation

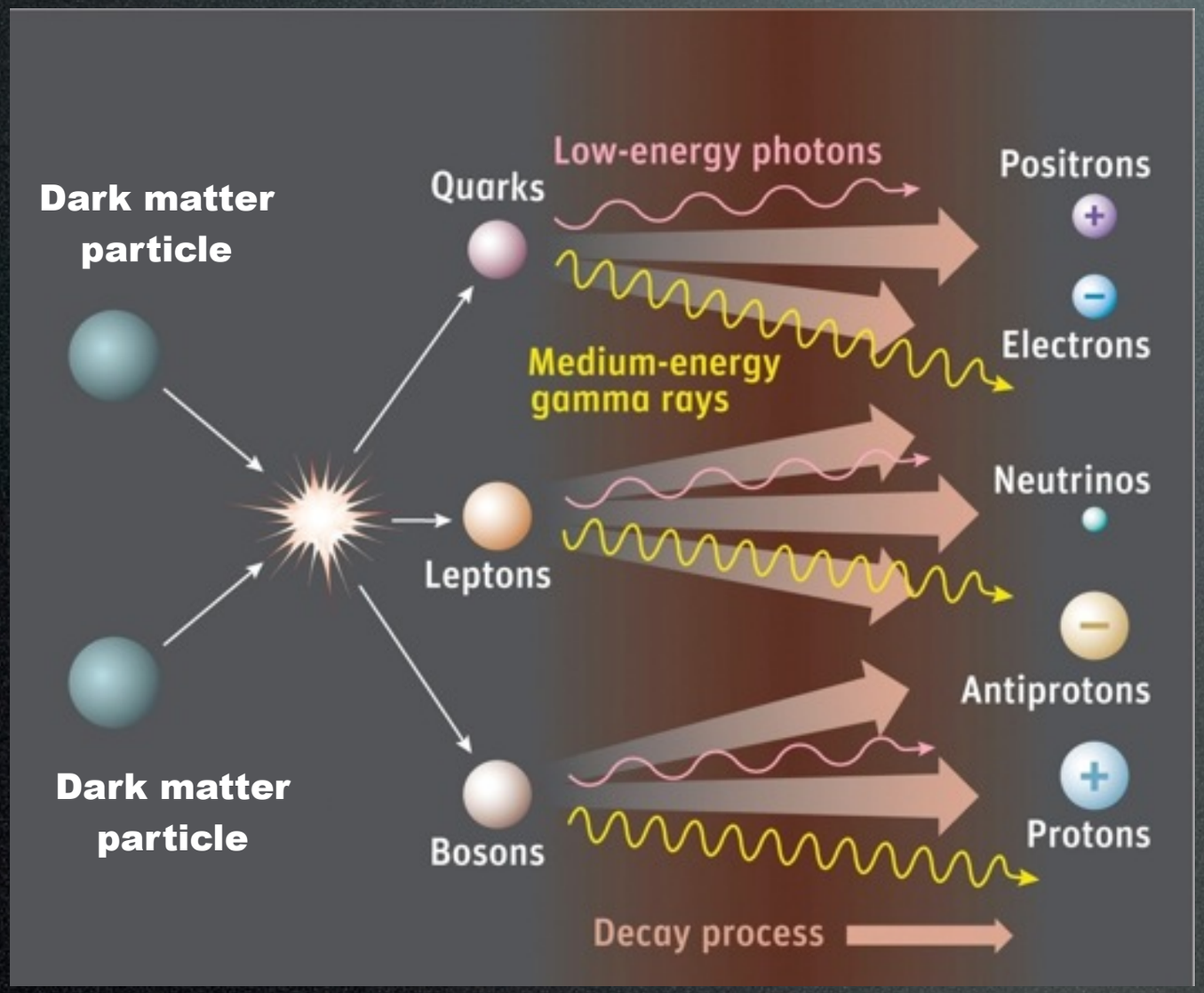
Slam two protons together...



Tevatron at Fermilab (Batavia, IL)

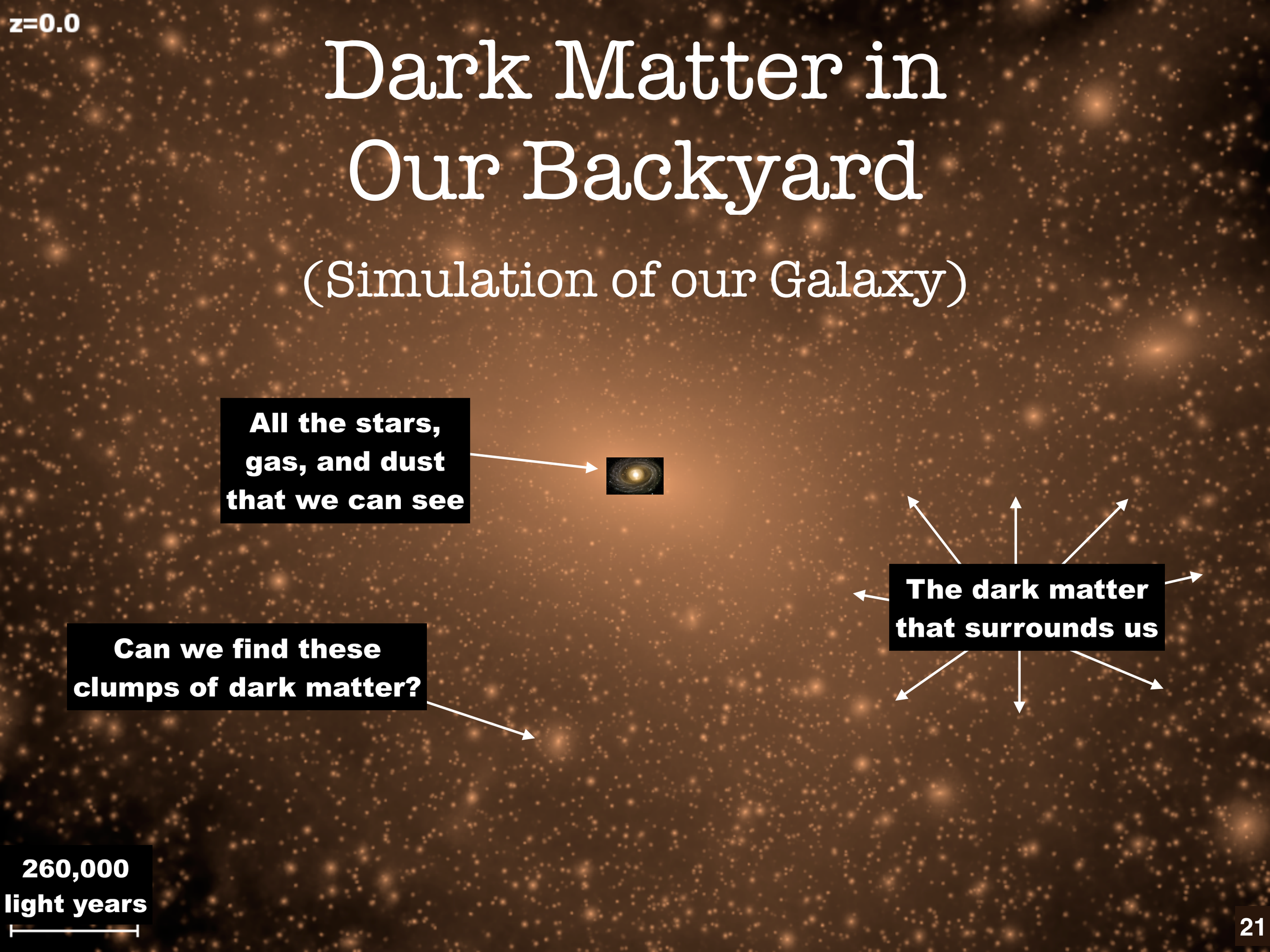
LHC at CERN (French-Swiss Border)

Indirect Detection



WIMP Annihilation (Dinderman, 2007)

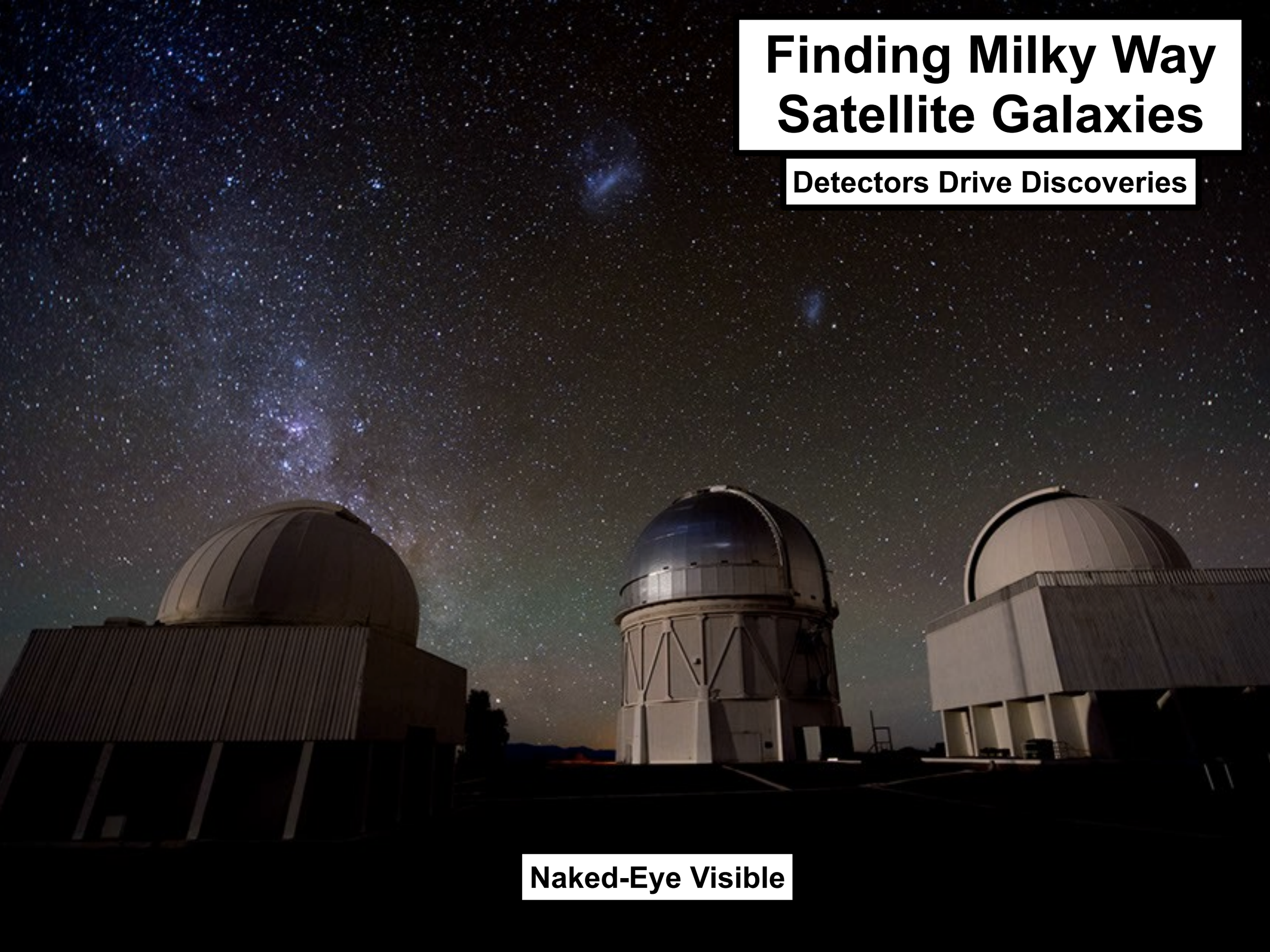
Fermi Gamma-ray Space Telescope


z=0.0
Dark Matter in Our Backyard
(Simulation of our Galaxy)
All the stars, gas, and dust that we can see
The dark matter that surrounds us
Can we find these clumps of dark matter?
260,000 light years

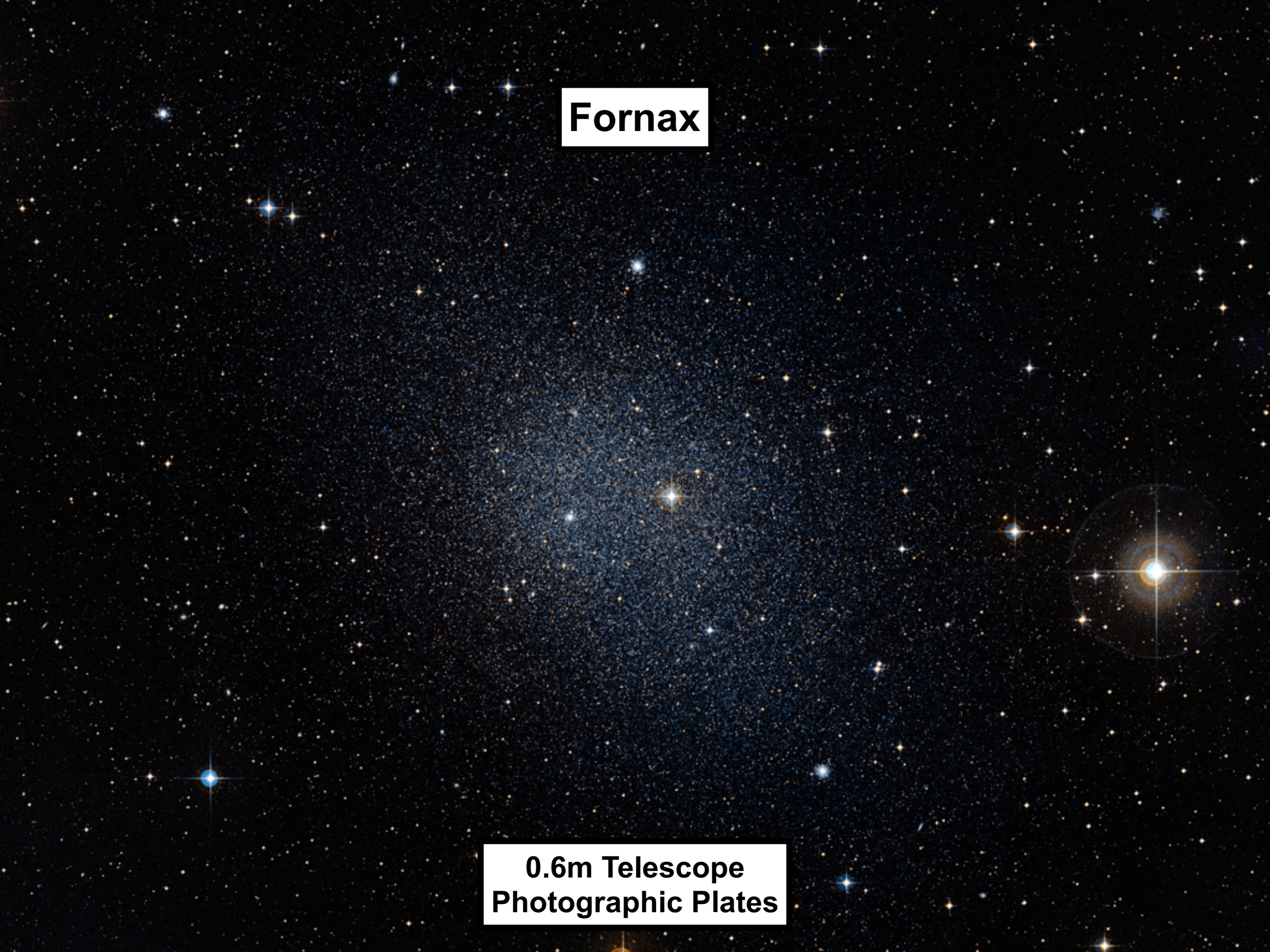
z=0.0
Dark Matter in Our Backyard
Can we find these clumps of dark matter?
YES!
The Fornax Dwarf Galaxy
80 kpc

Finding Milky Way Satellite Galaxies

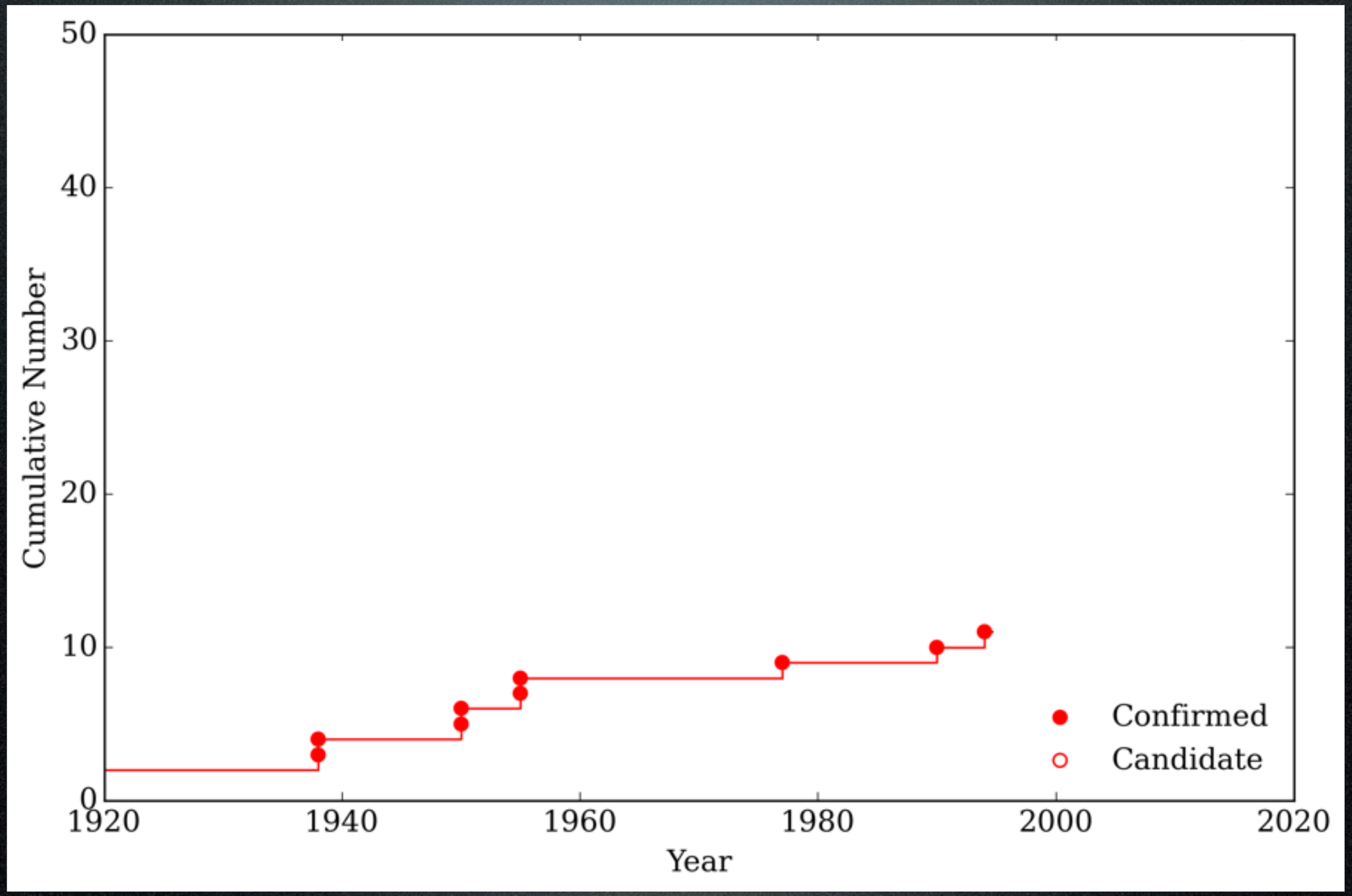
Detectors Drive Discoveries

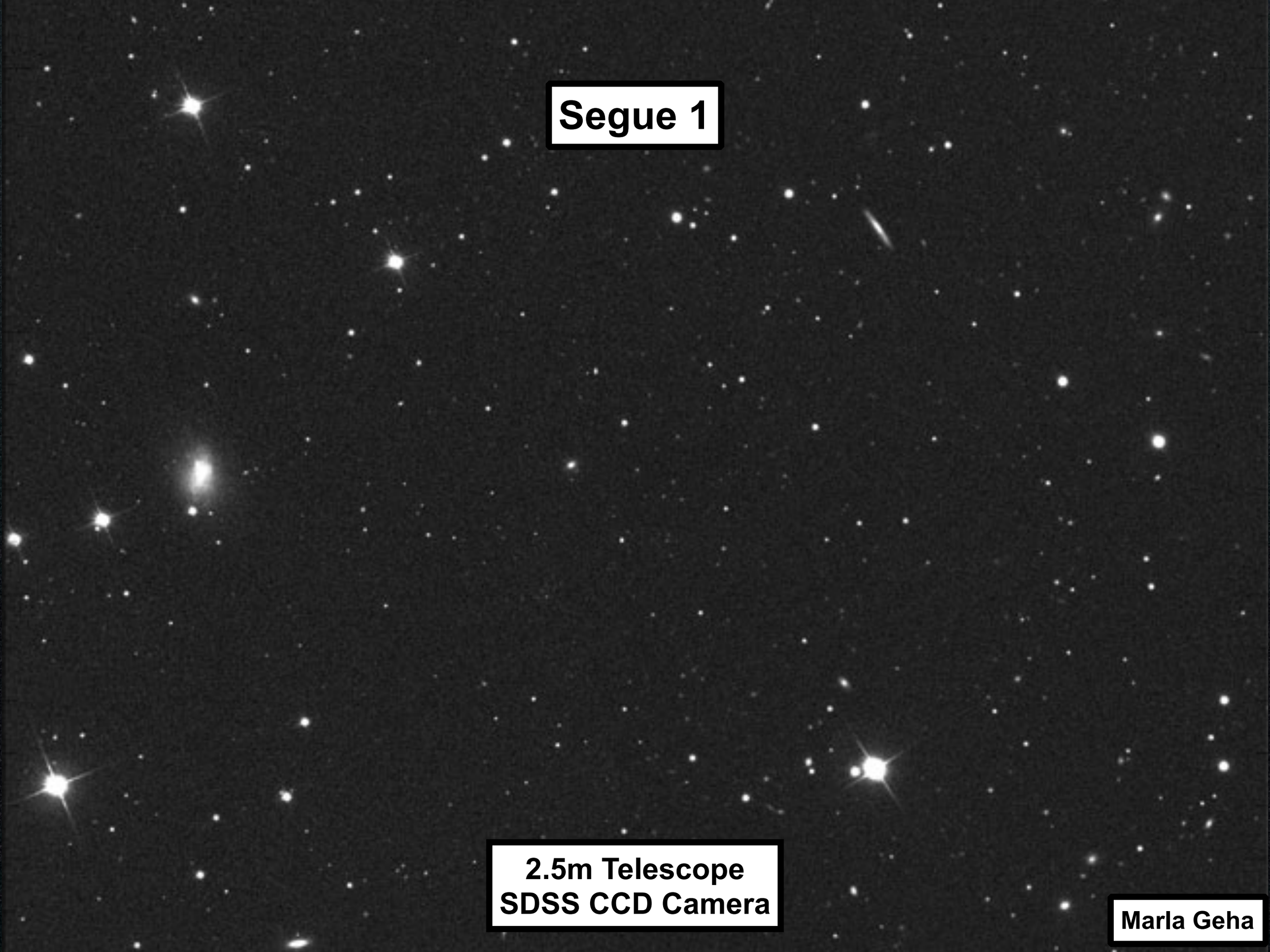


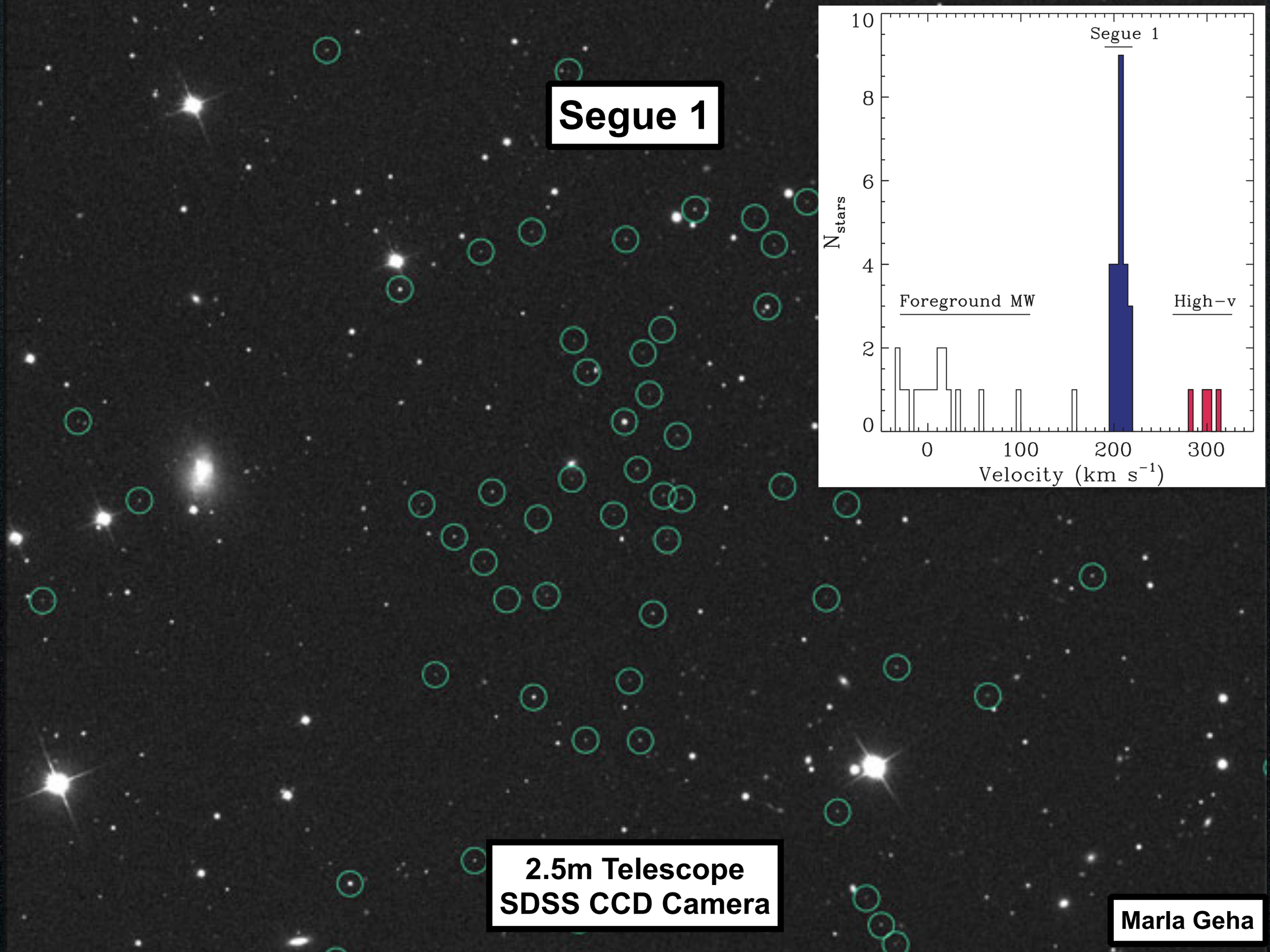
Naked-Eye Visible


Fornax
0.6m Telescope
Photographic Plates

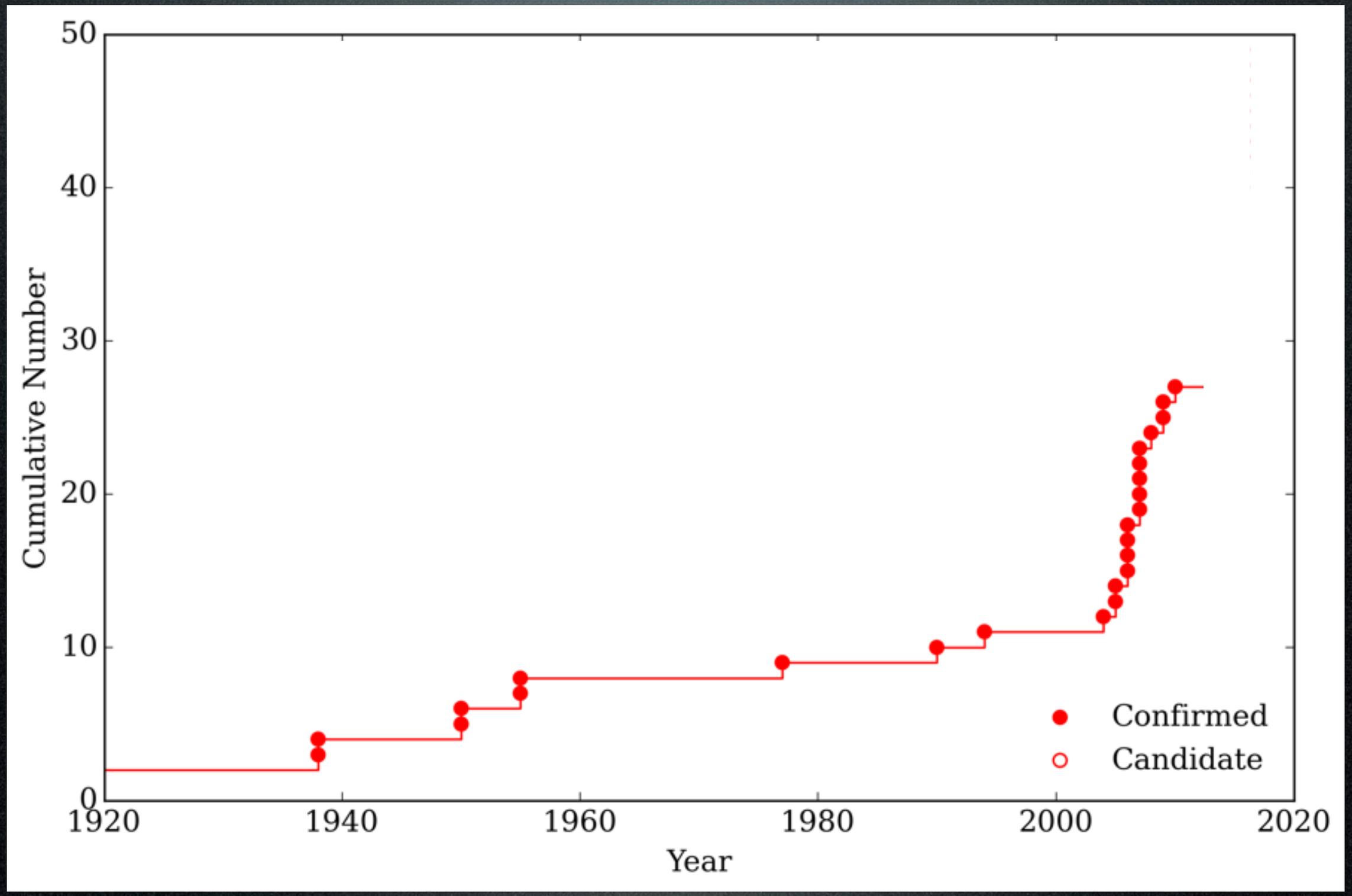
Dwarf Galaxy Discovery Timeline



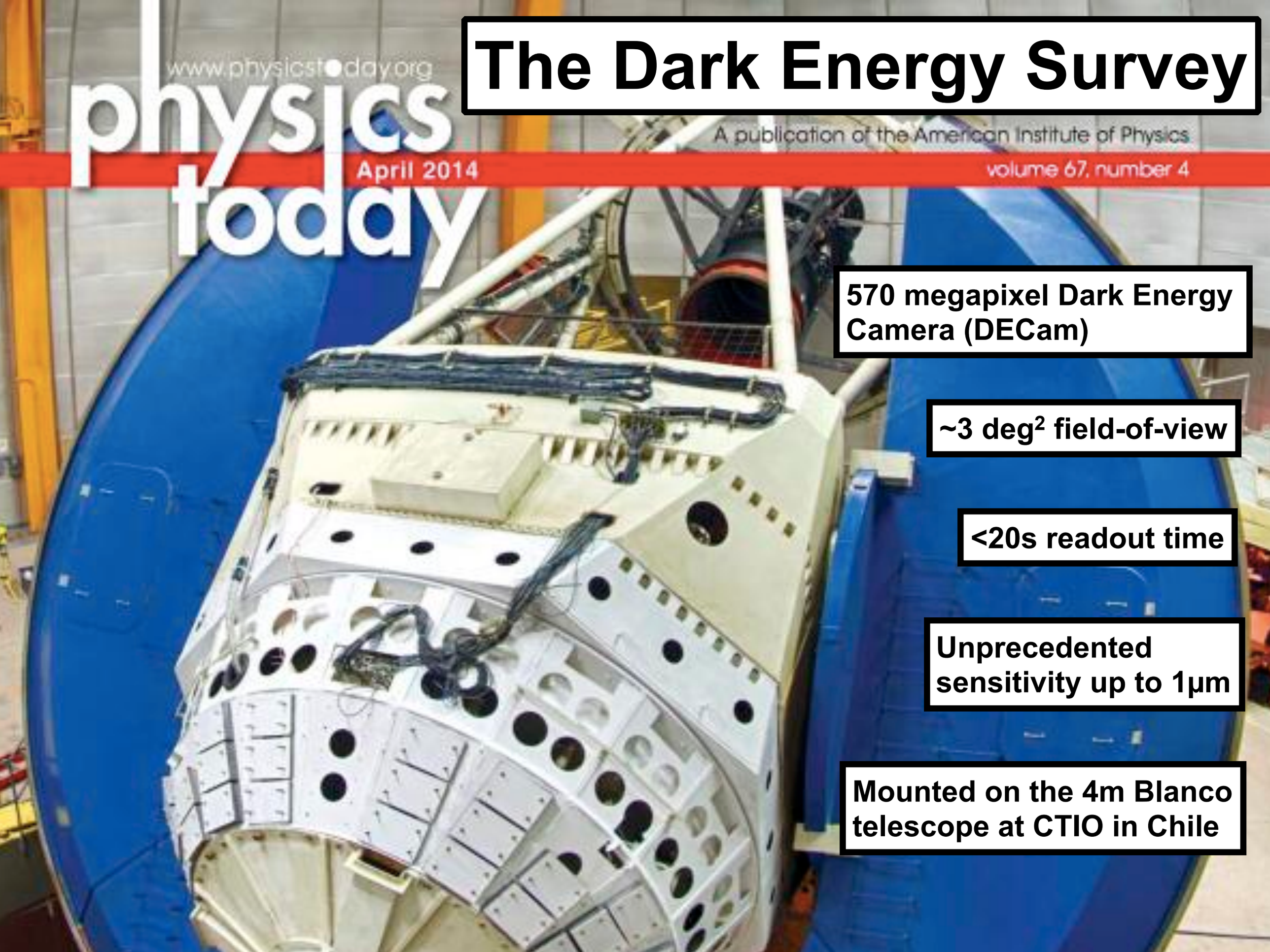

Segue 1
2.5m Telescope
SDSS CCD Camera
Marla Geha


Segue 1
Segue 1
Foreground MW
High−v
N_{stars}
Velocity (km s^{-1})
0
100
200
300
0
2
4
6
8
10
2.5m Telescope
SDSS CCD Camera
Marla Geha

Dwarf Galaxy Discovery Timeline



The Dark Energy Survey



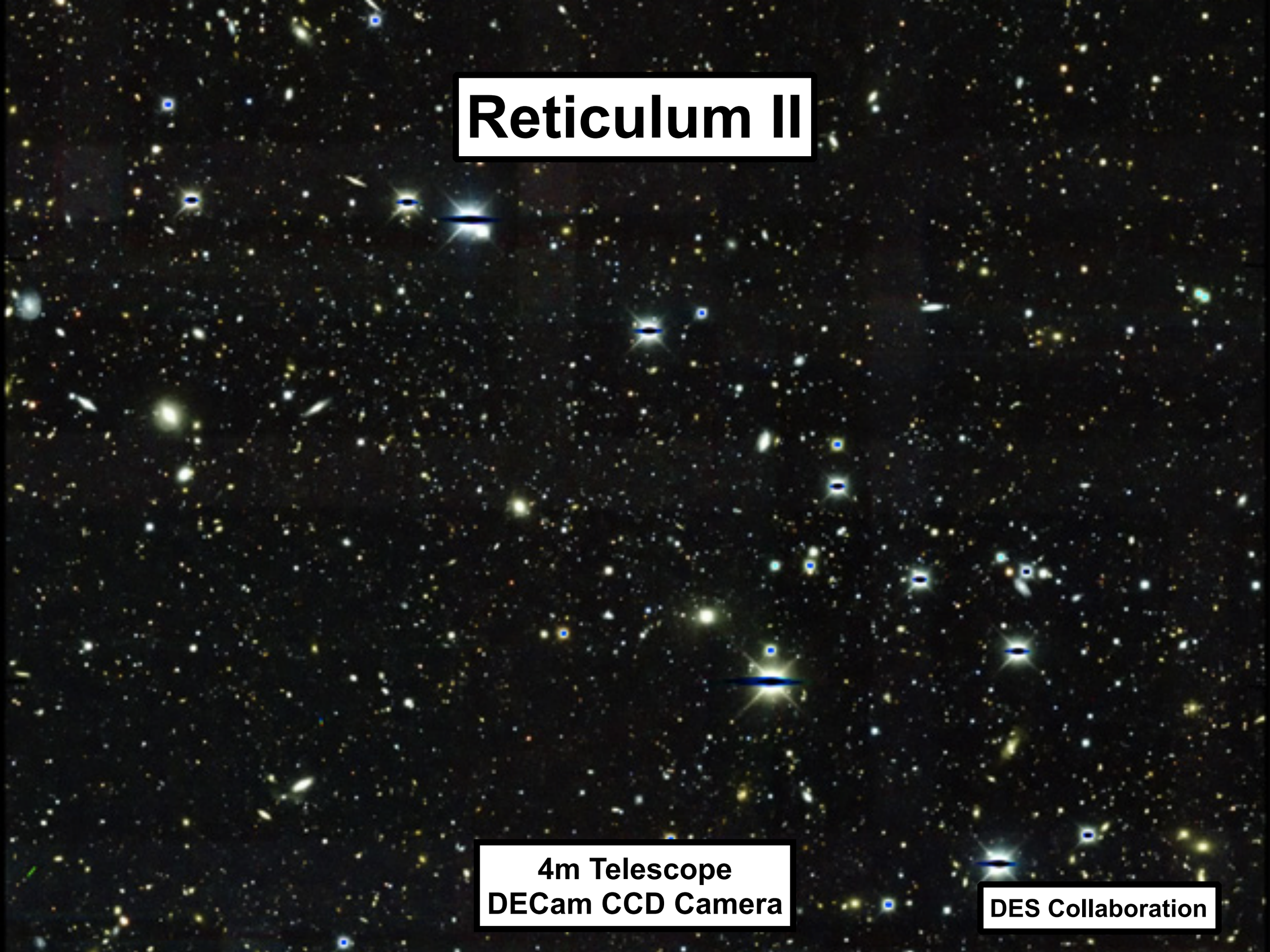
570 megapixel Dark Energy Camera (DECam)

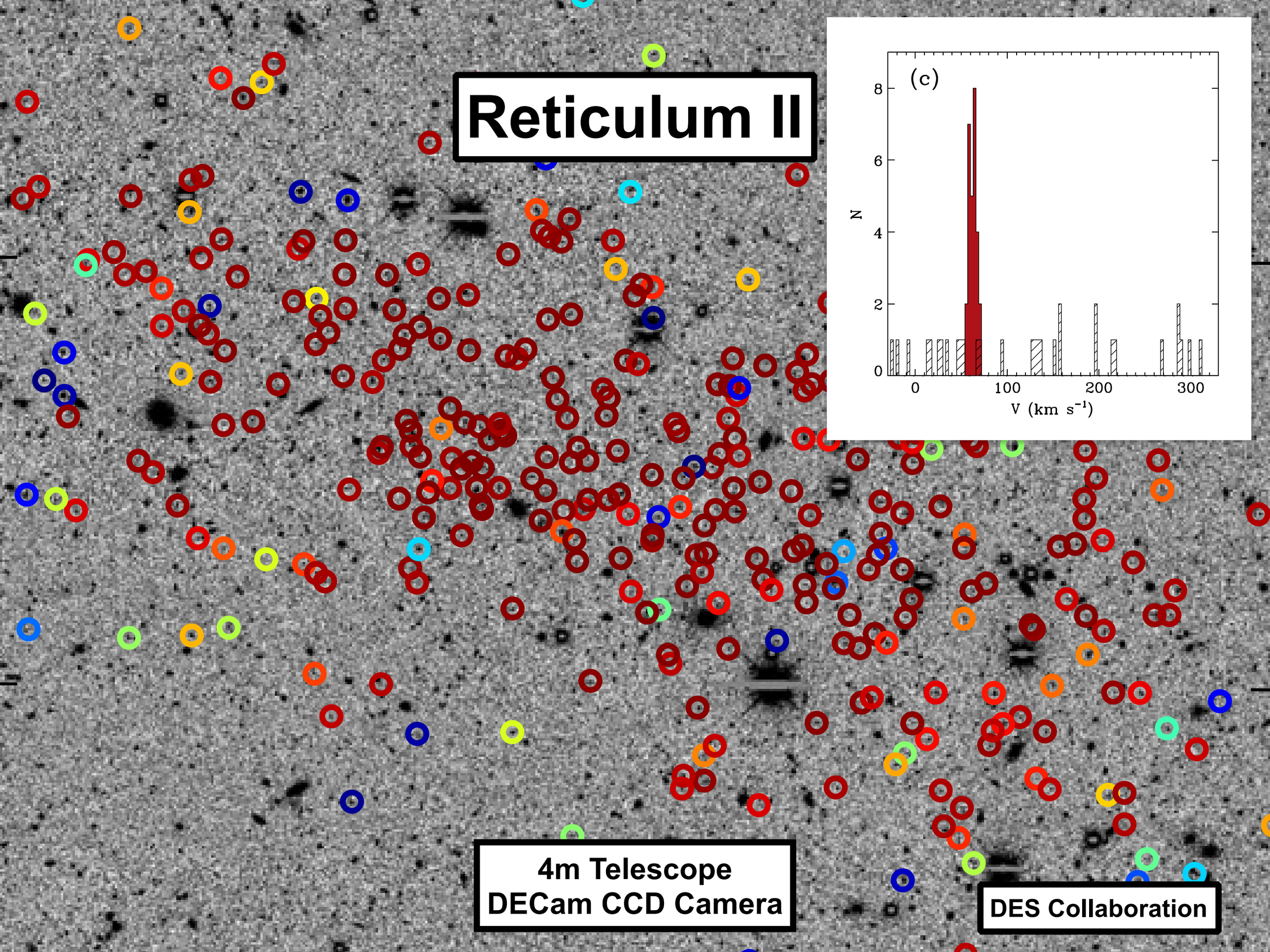
~3 deg^2 field-of-view

<20s readout time

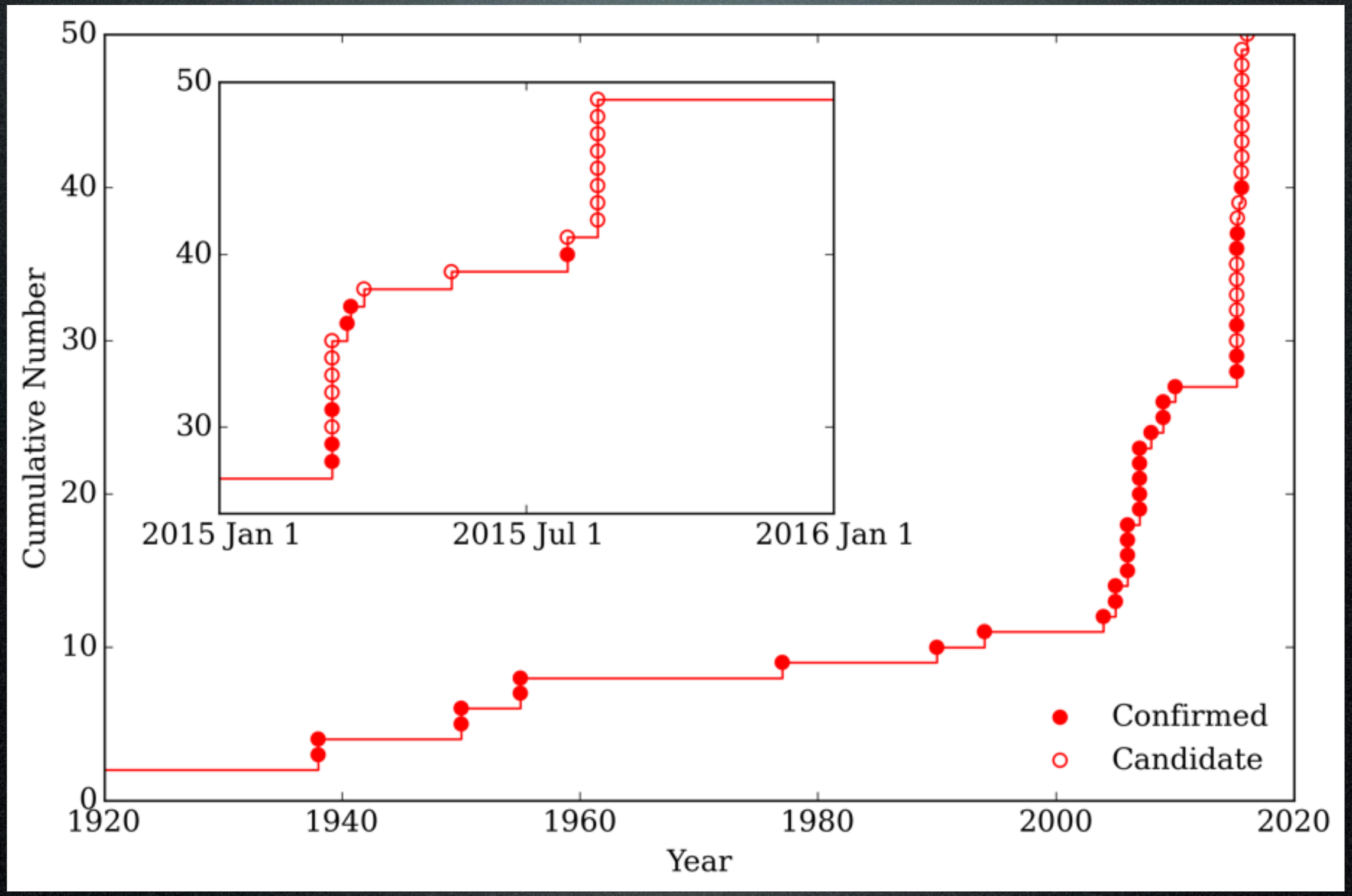
Unprecedented sensitivity up to 1μm

Mounted on the 4m Blanco telescope at CTIO in Chile


Reticulum II
4m Telescope
DECam CCD Camera
DES Collaboration


Reticulum II
(c)
N
V (km s^{-1})
0
2
4
6
8
0
100
200
300
4m Telescope
DECam CCD Camera
DES Collaboration

Dwarf Galaxy Discovery Timeline



THE PAPERWORK

- **THE MYSTERY**: Nearly 85% of the mass of the Universe is unaccounted for.
- **THE CRIME SCENE**: This missing mass seems to be present in all large gravitationally bound systems.
- **THE SUSPECTS**: The PRIME SUSPECT is a Weakly Interacting Massive Particle (WIMP) that is fundamentally different from particles we are familiar with.
- **THE STAKEOUT**: There are a wide variety of experiments attempting to detect a candidate dark matter particles.
- **THE EVIDENCE**: There are no definitive detections of WIMPs, but the sensitivity of experiments is rapidly increasing and the next 10 years will be very exciting.