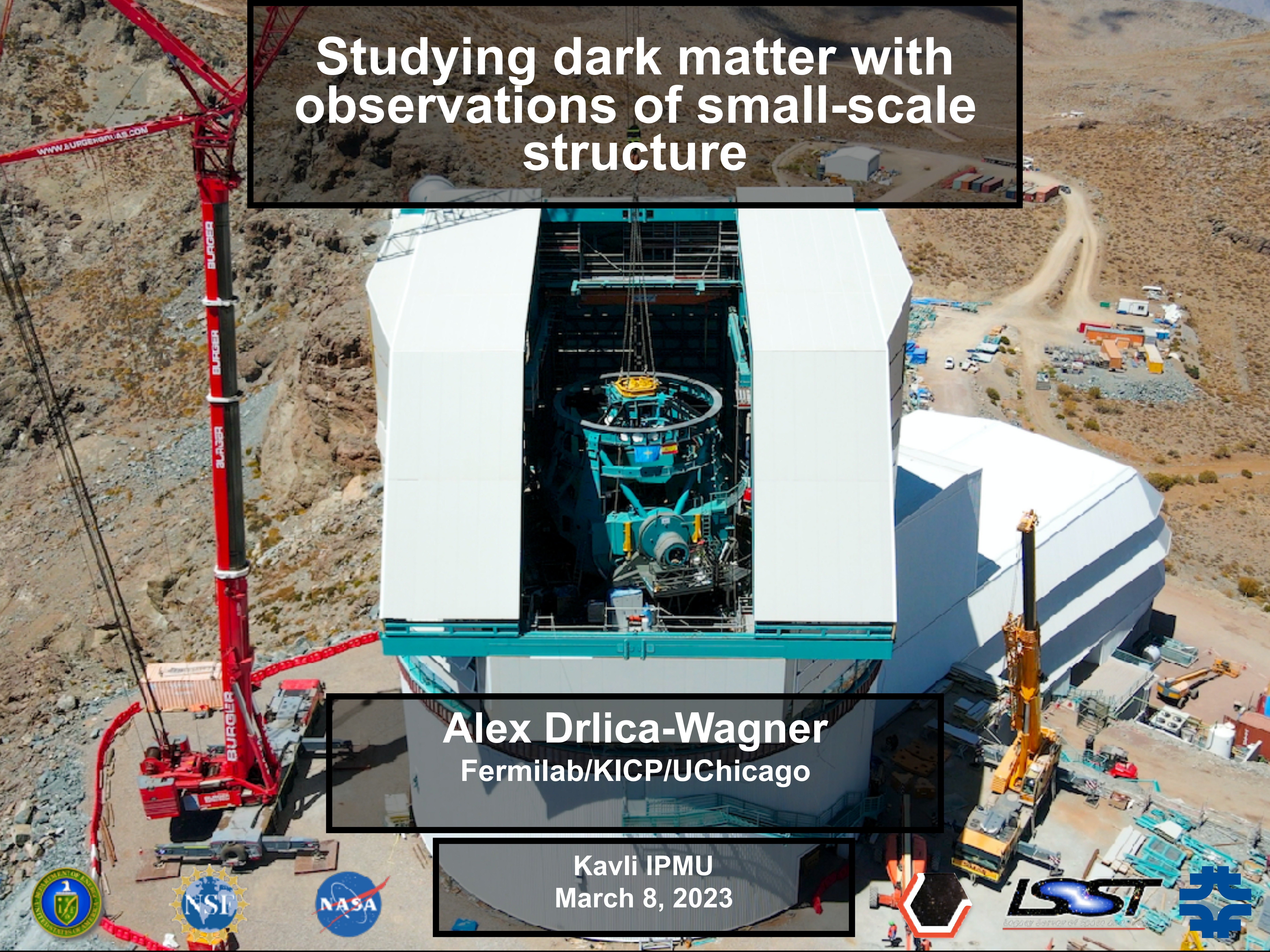


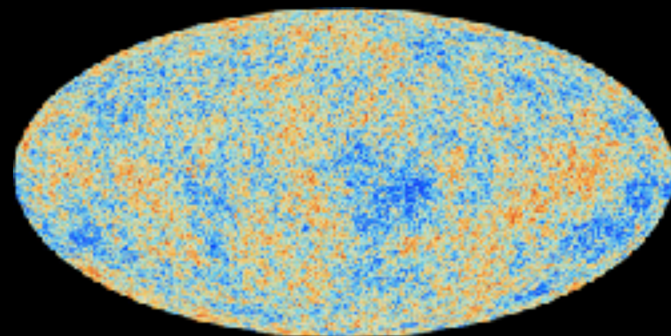
Studying dark matter with observations of small-scale structure

Alex Drlica-Wagner
Fermilab/KICP/UChicago

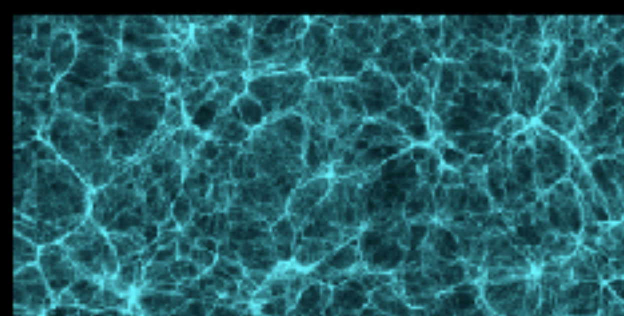
Kavli IPMU
March 8, 2023

Composition of the Universe

Observable Universe



Large Scale Structure



Clusters of Galaxies

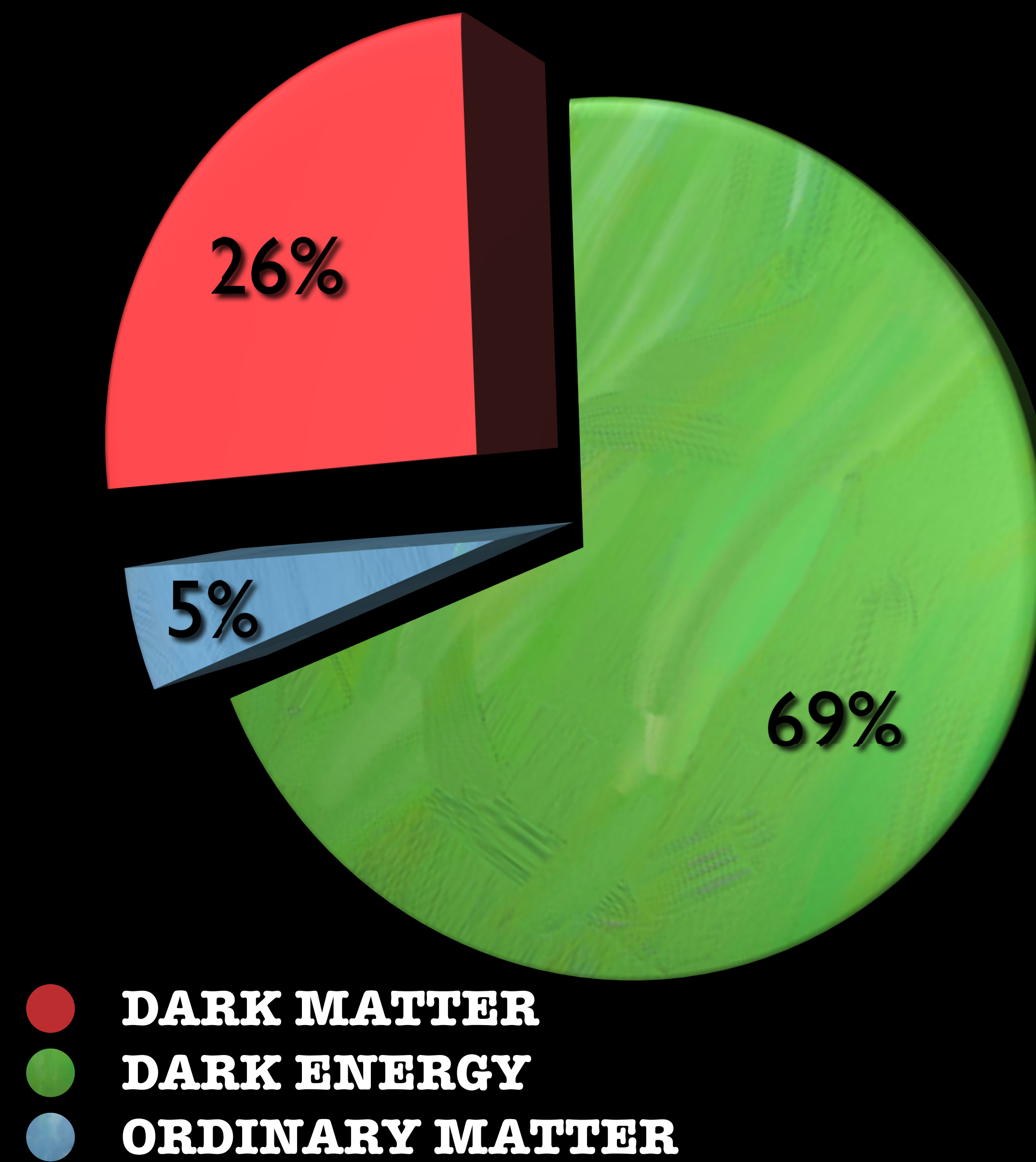
Individual Galaxies

Larger

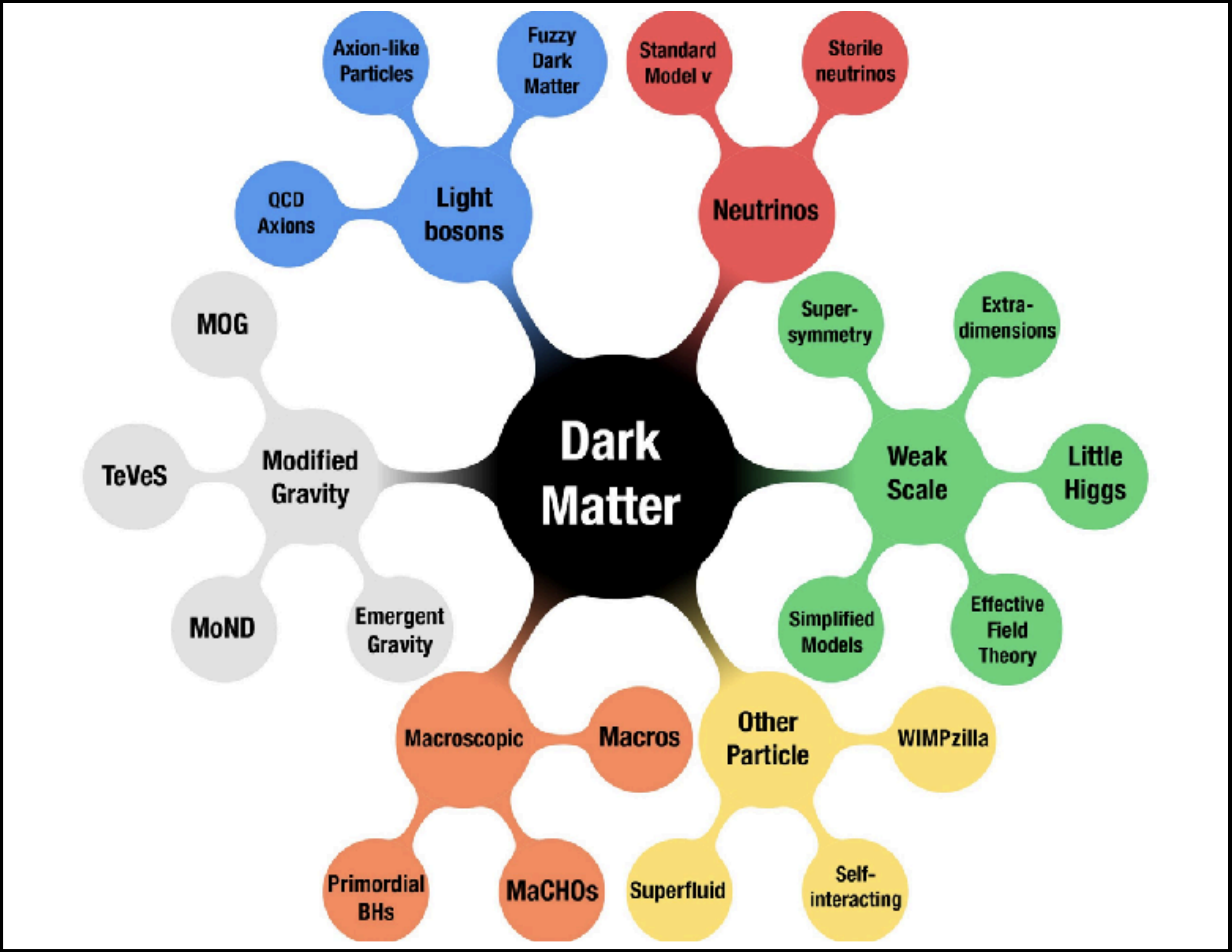
Dark Matter

Smaller

Plank Collaboration (2018)



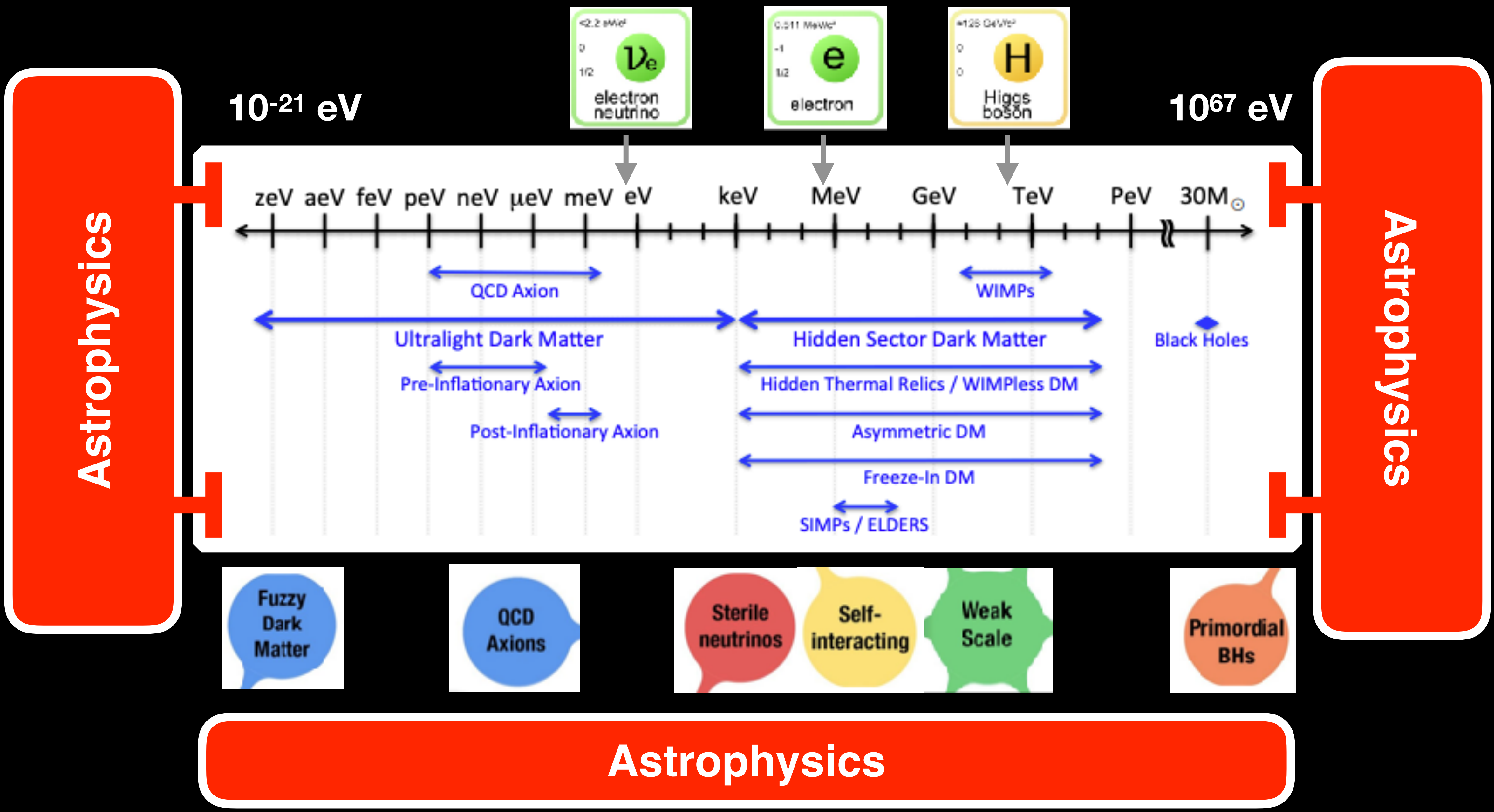
Dark Matter Candidates



Bertone & Tait, Nature 562, 51 (2018)

Dark Matter Candidates

https://arxiv.org/abs/1707.04591



Astrophysical observations provides the only robust, positive measurement of dark matter and bounds the mass range of dark matter candidates

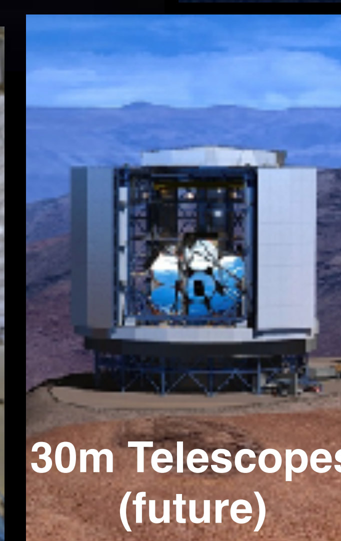
Use the

to learn about the

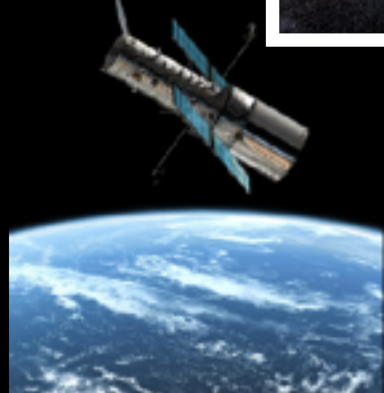
Current and Near-Future Experiments

Wide-Area Imaging

Spectroscopic Measurements

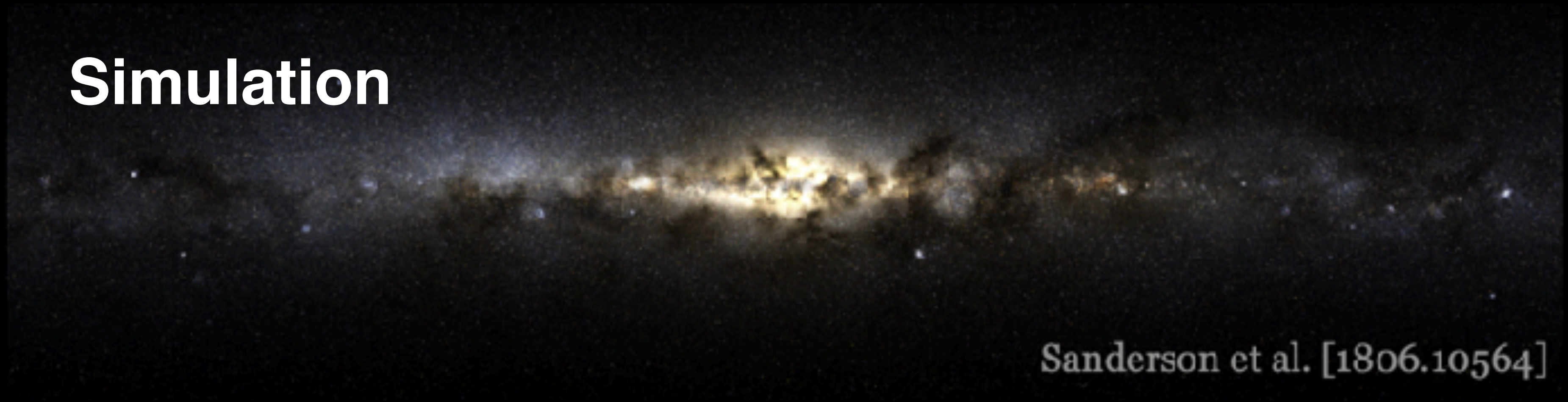


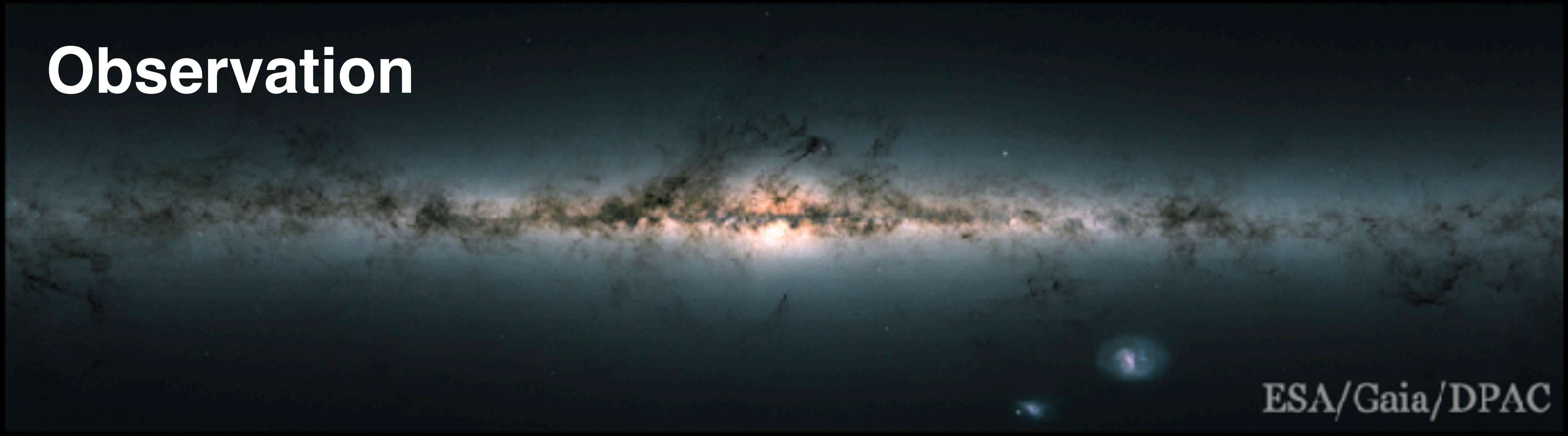
High Resolution Imaging



Advances in Simulations

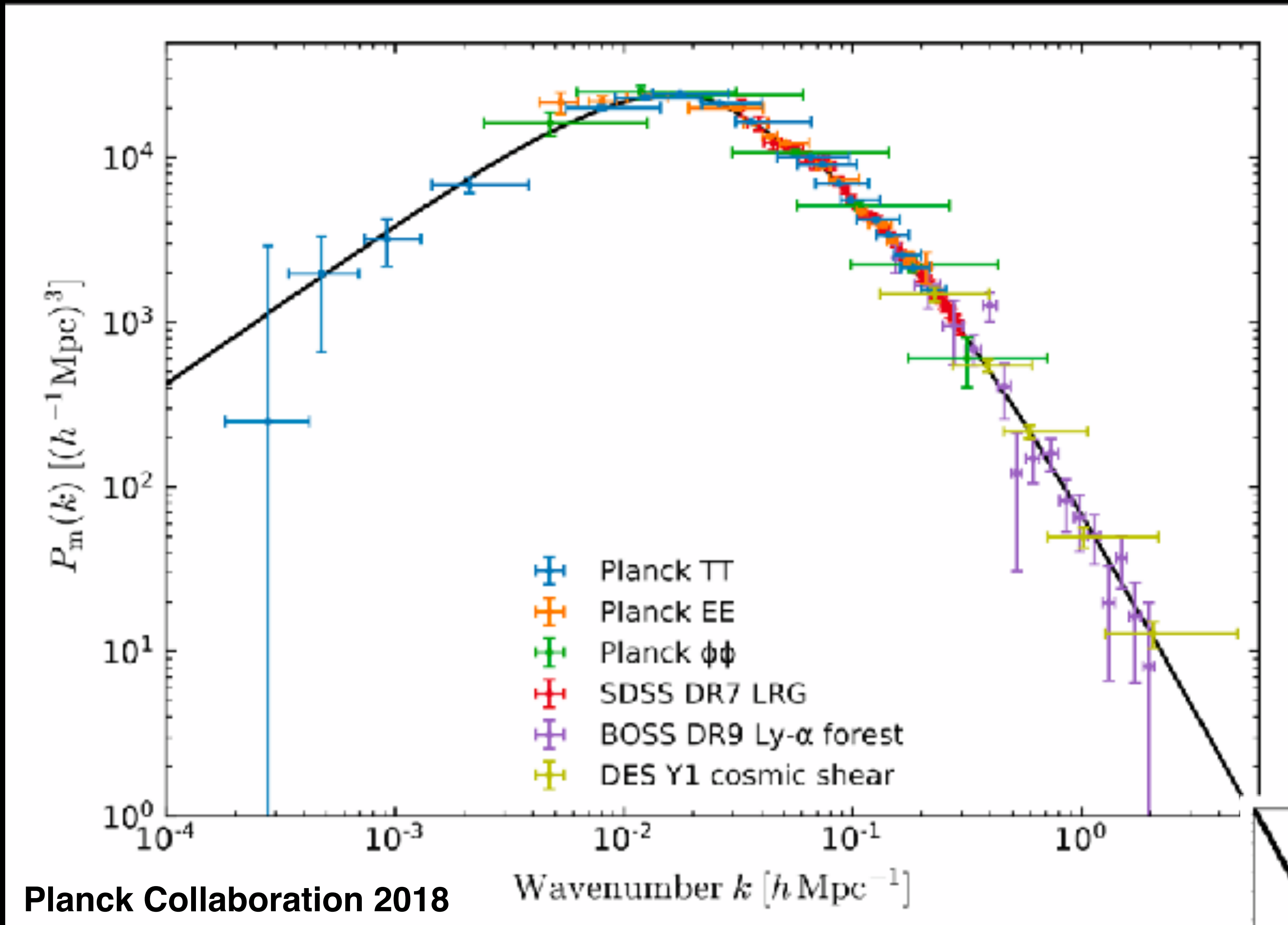
High-resolution cosmological simulations are now able to robustly include core elements of baryonic physics at dwarf galaxy scales (e.g., FIRE/Latte, EAGLE/APOSTLE, etc.)



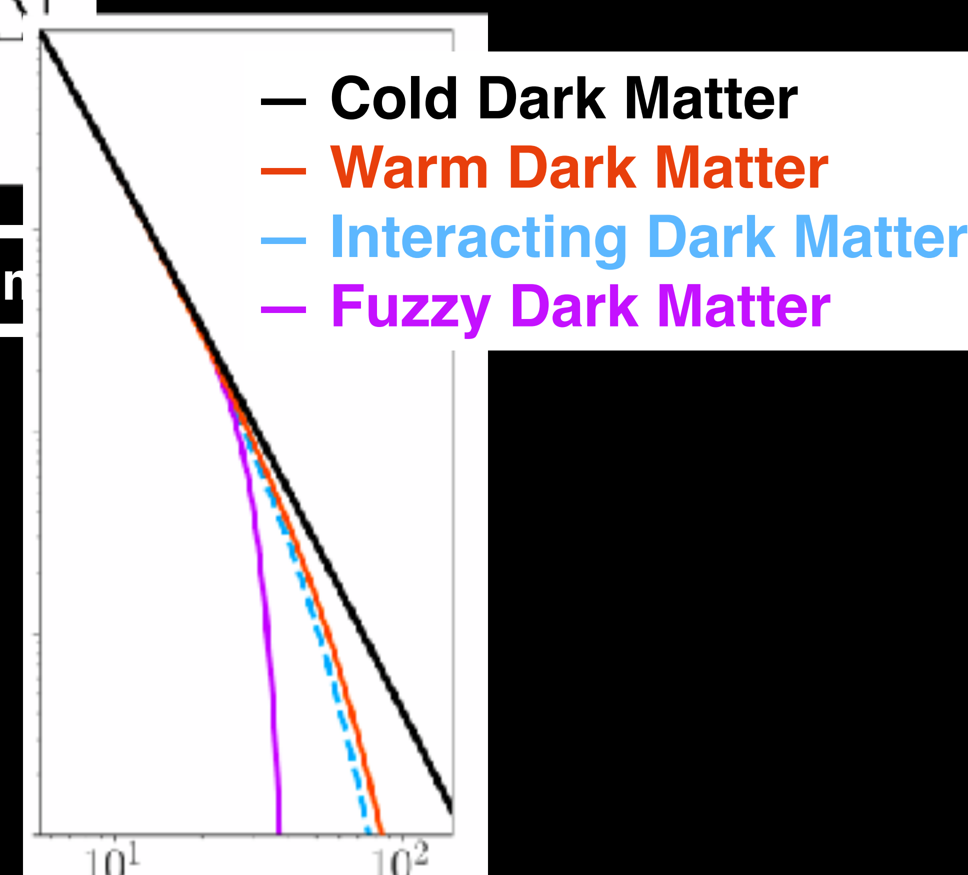


The Small-Scale Structure of Dark Matter

Amount of Clustering



Distribution of Dark Matter



Large ← Length Scale of Clustering →

Composition of Dark Matter

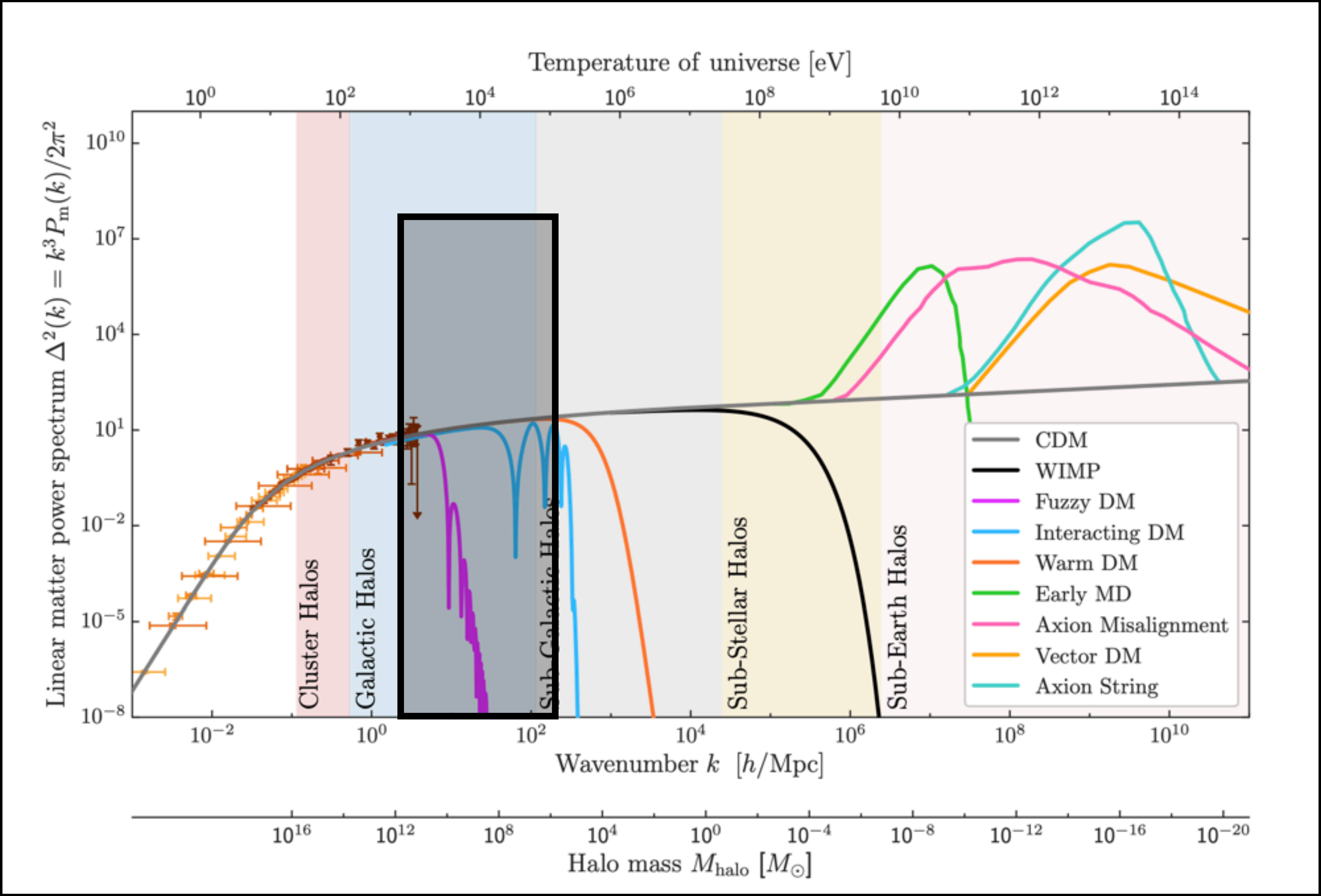
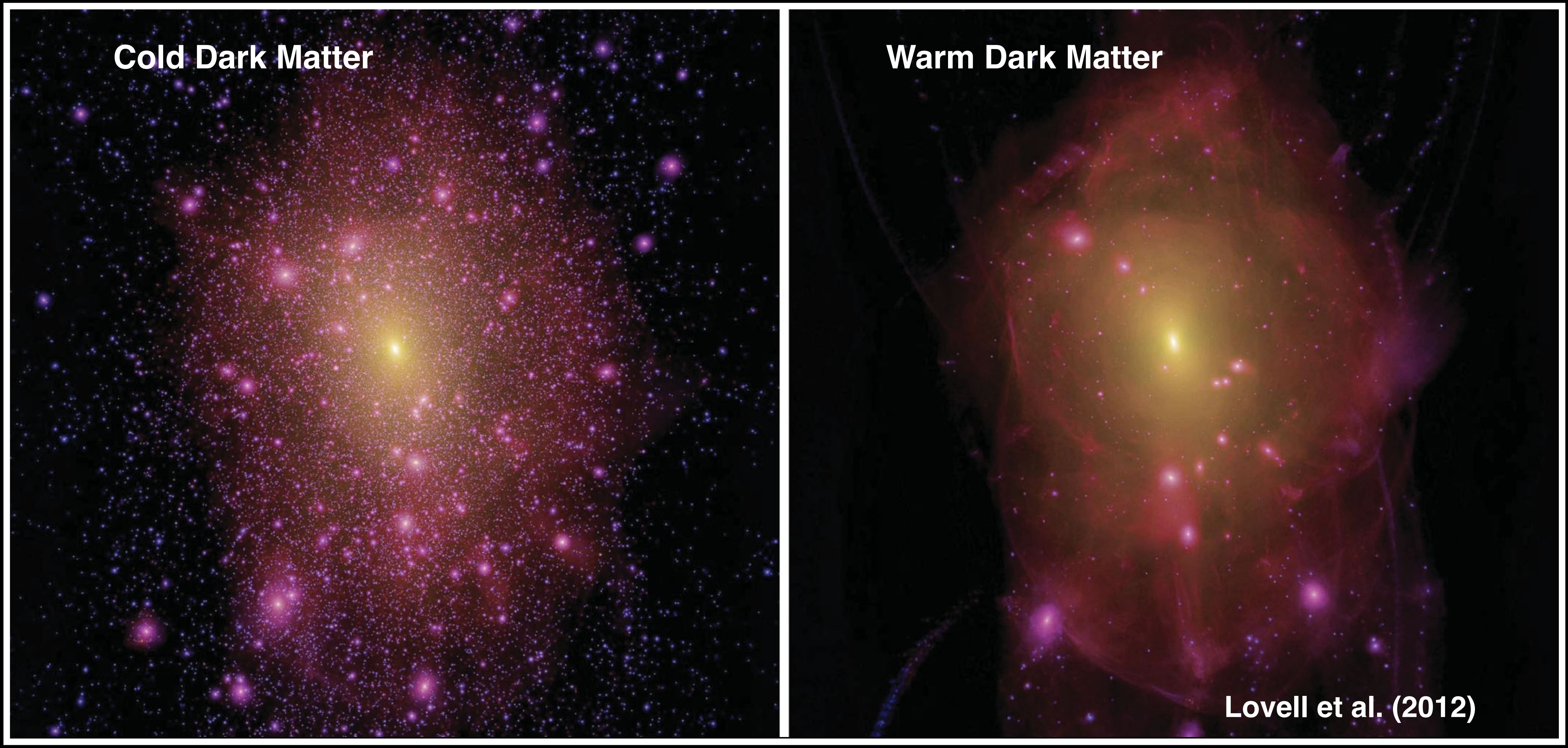


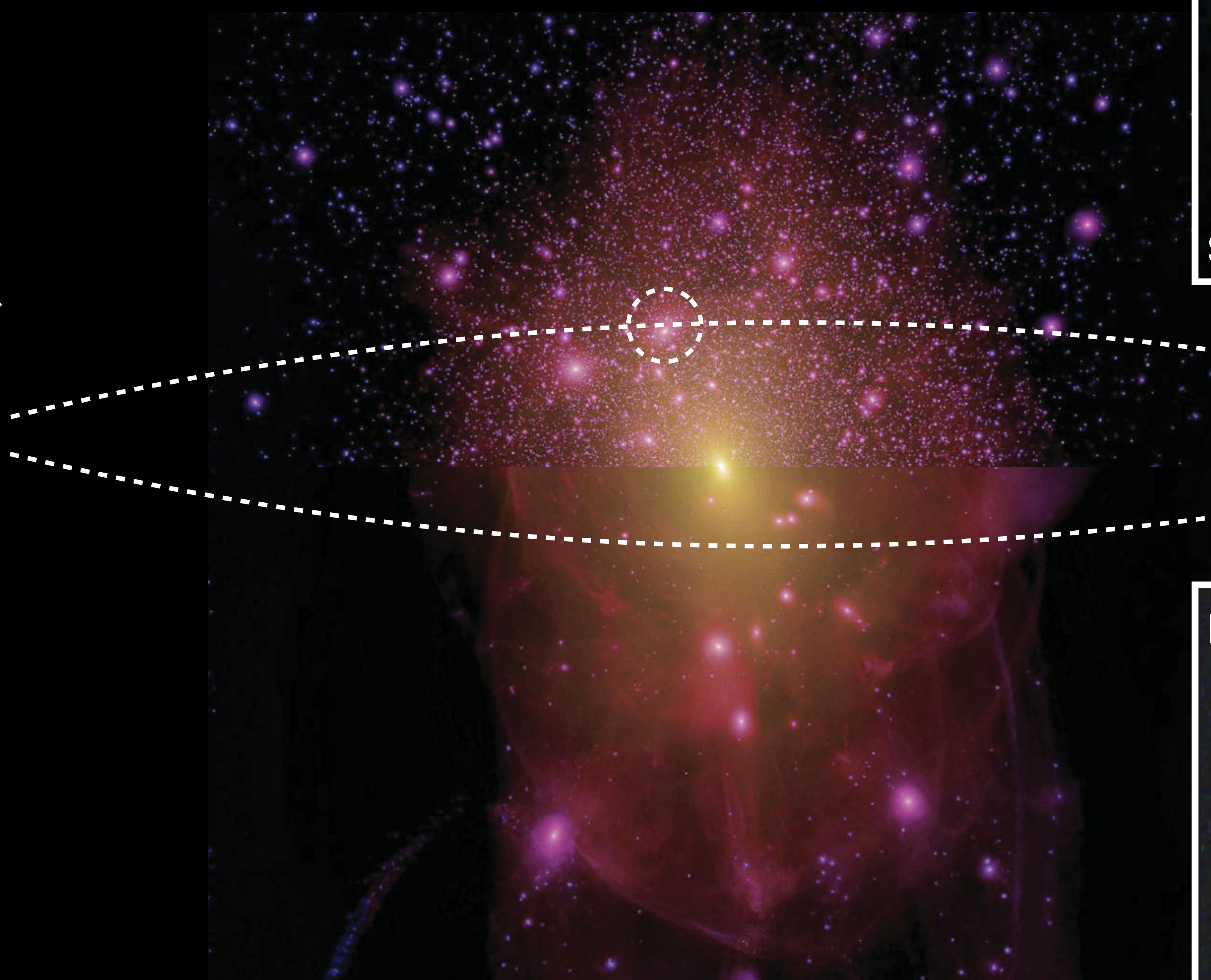
Figure: Nadler, Schutz, ADW (2203.07354)

Simulations

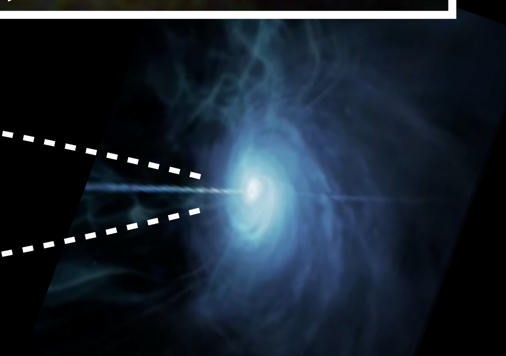


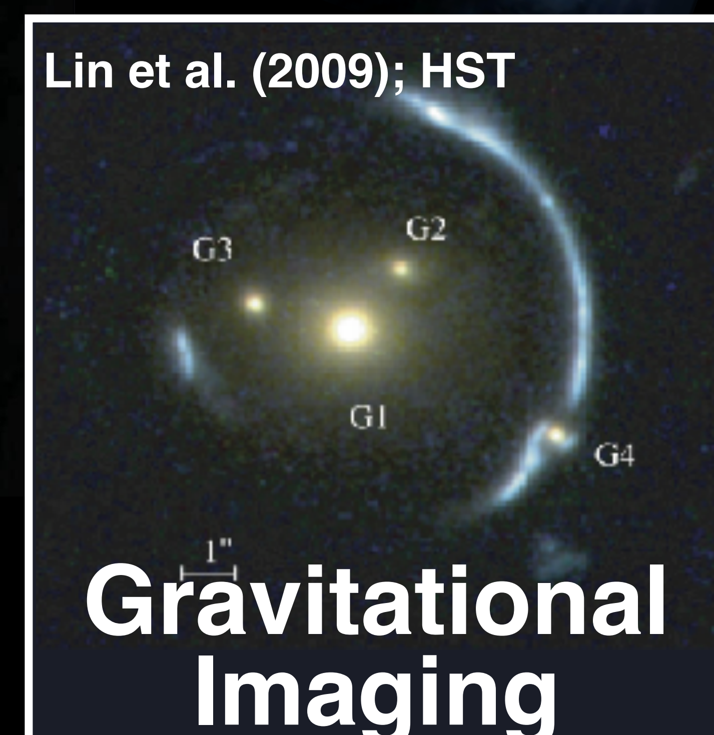
e.g., Sterile Neutrino

Strong Gravitational Lensing



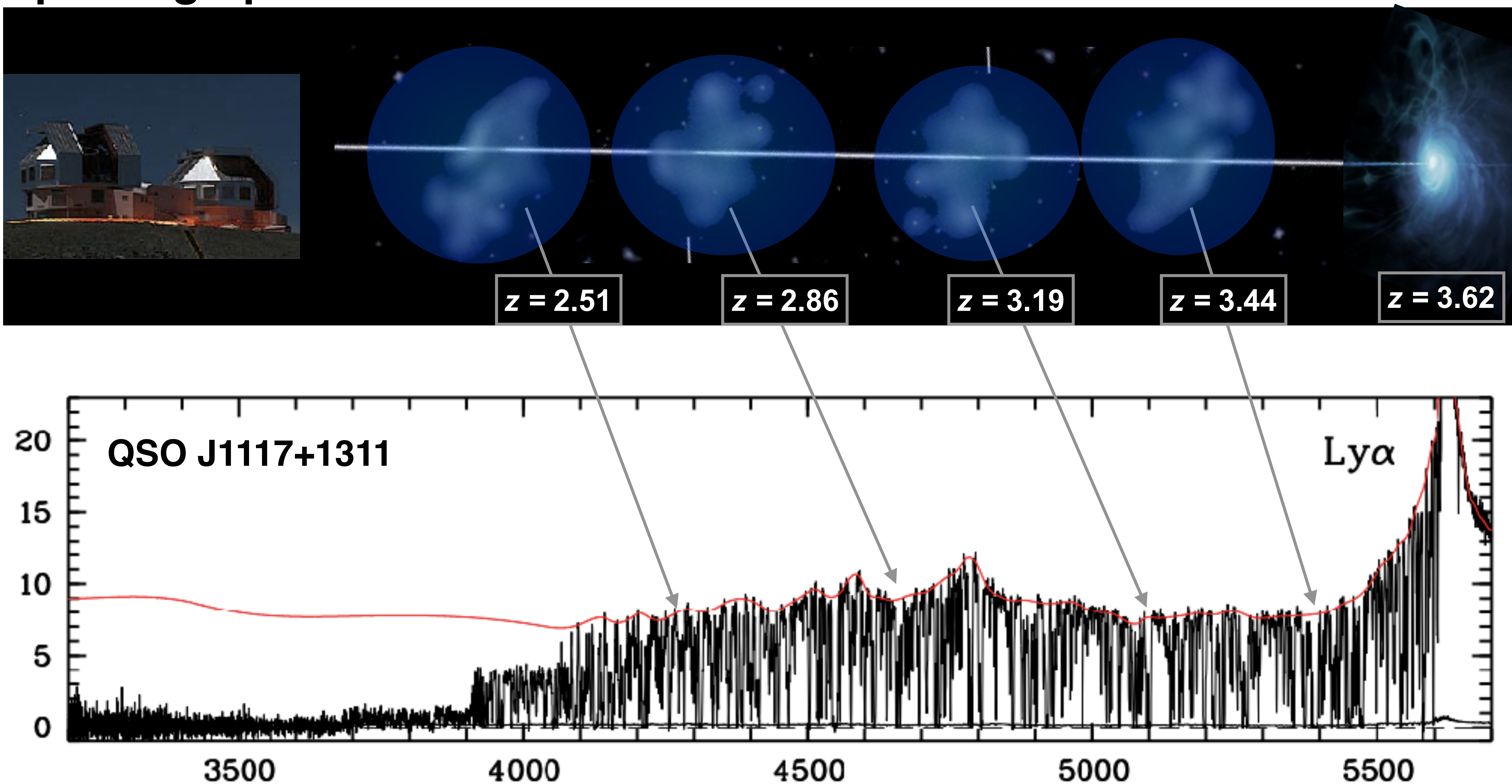
Lovell et al. (2012)





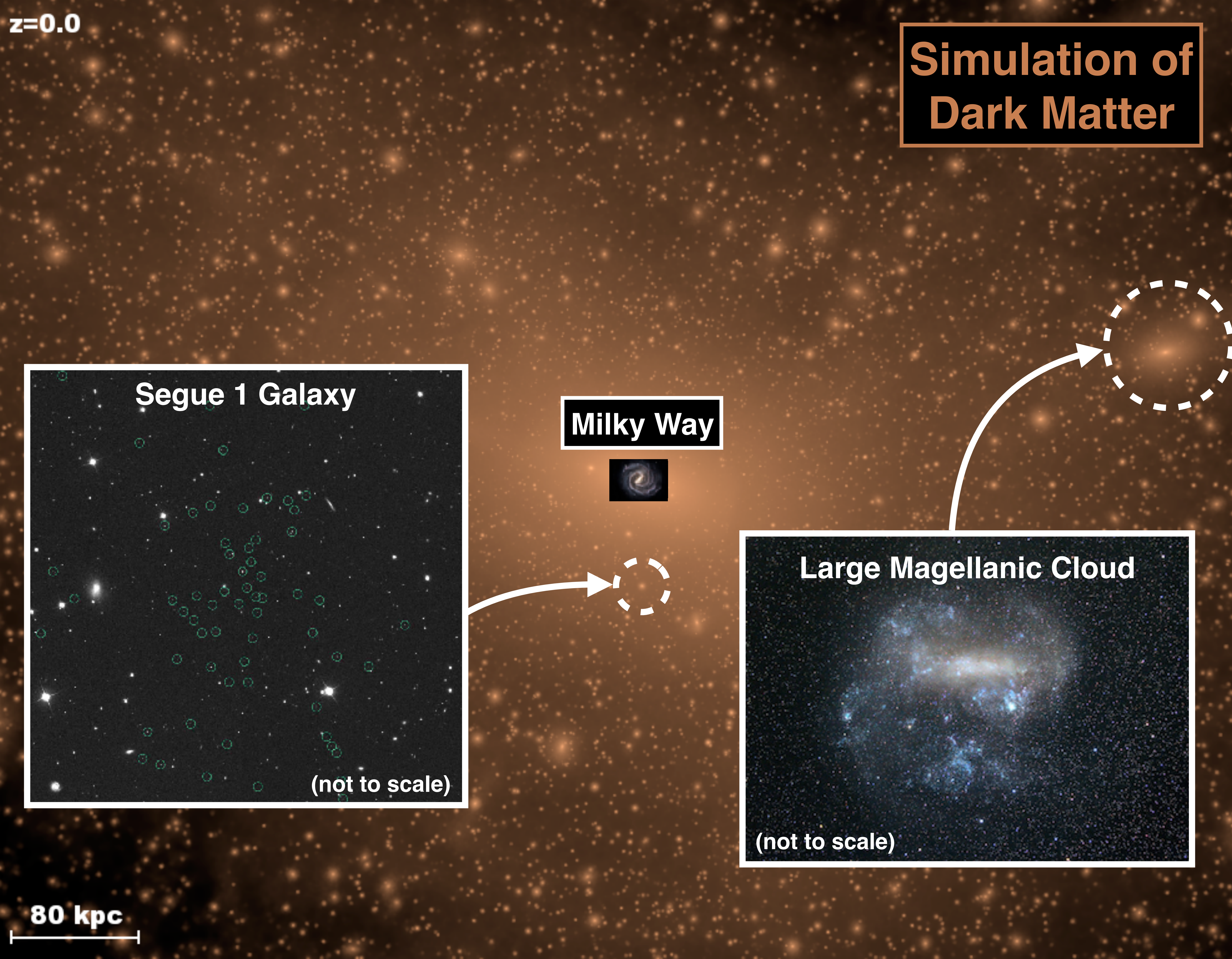
Lyman-alpha Forest Measurements

Spectrograph | **Hydrogen Absorption in Dark Matter Halos** | **Distant Quasar**



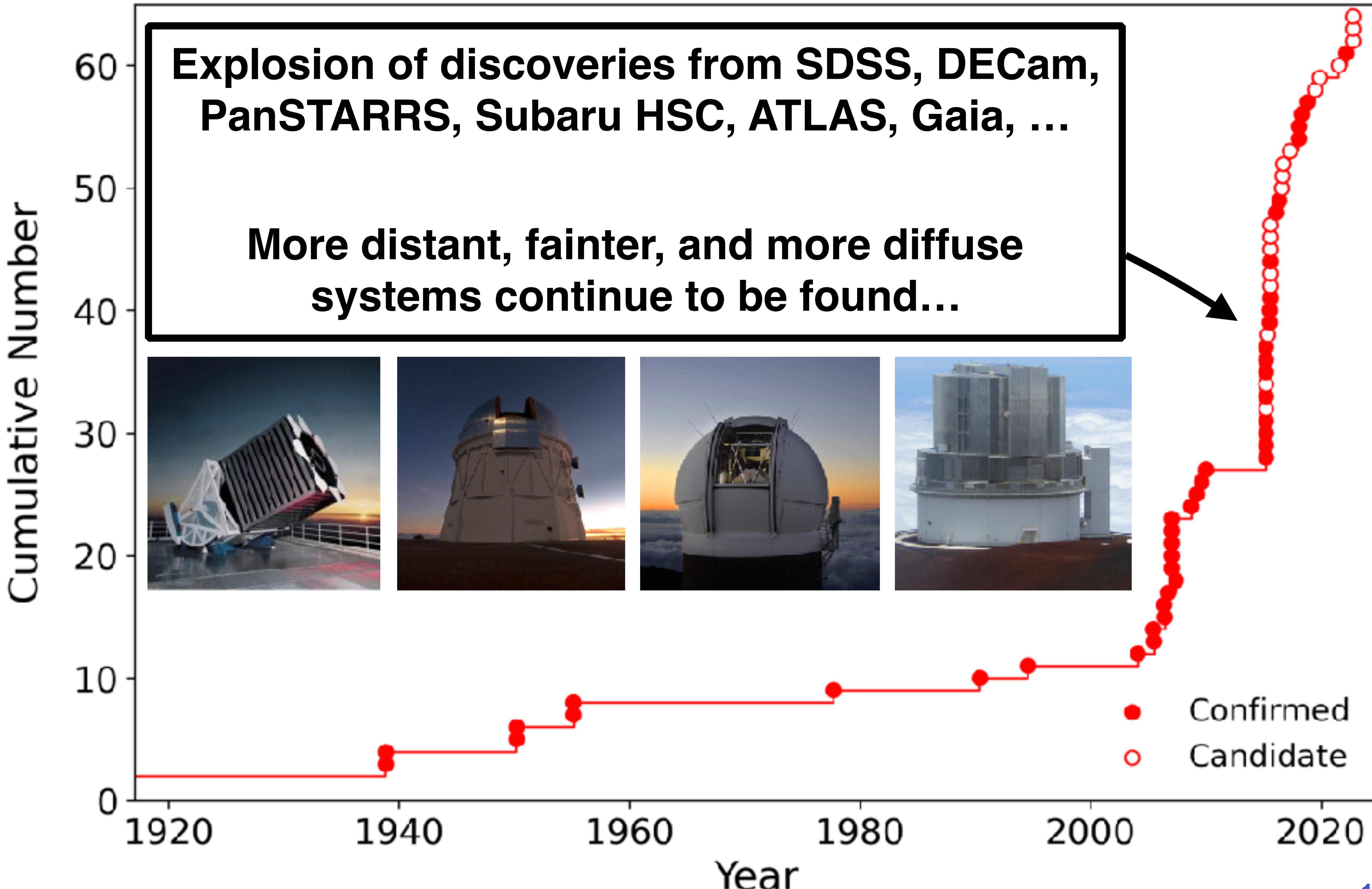
Wavelength (Å)

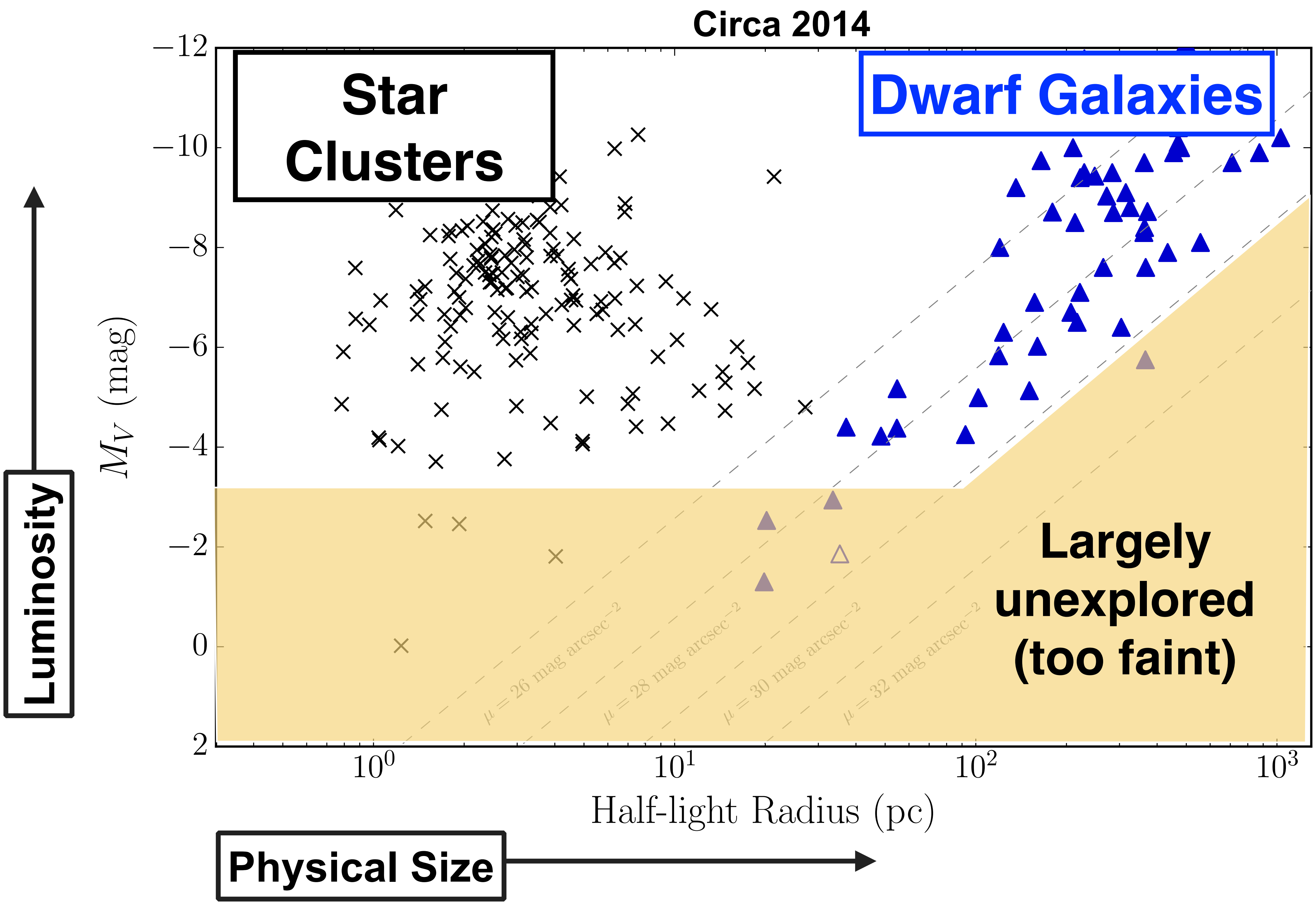
López et al. (2016)



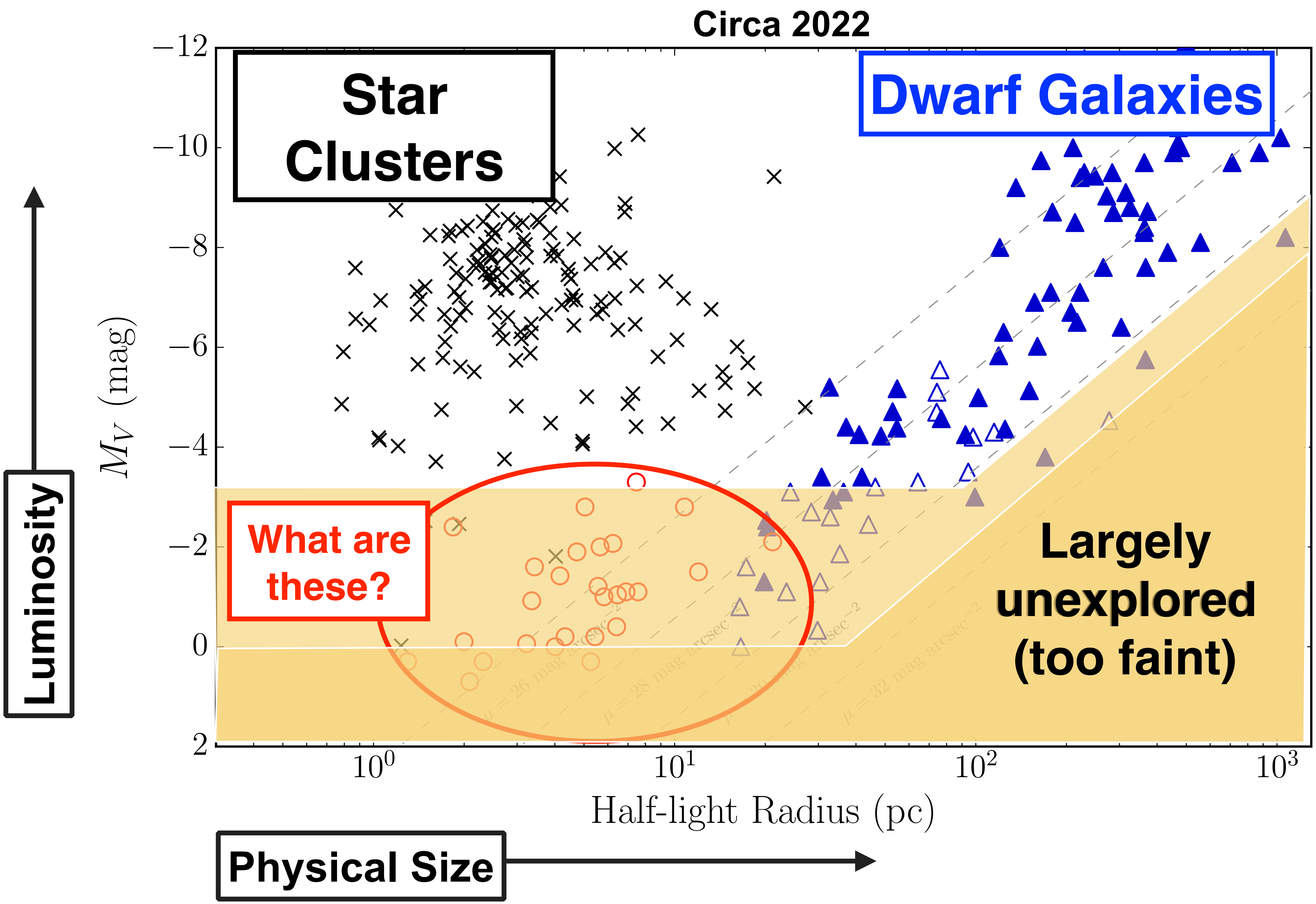
z=0.0
Simulation of Dark Matter
Segue 1 Galaxy
(not to scale)
Milky Way
Large Magellanic Cloud
(not to scale)
80 kpc

Milky Way Satellite Galaxy Discovery Timeline



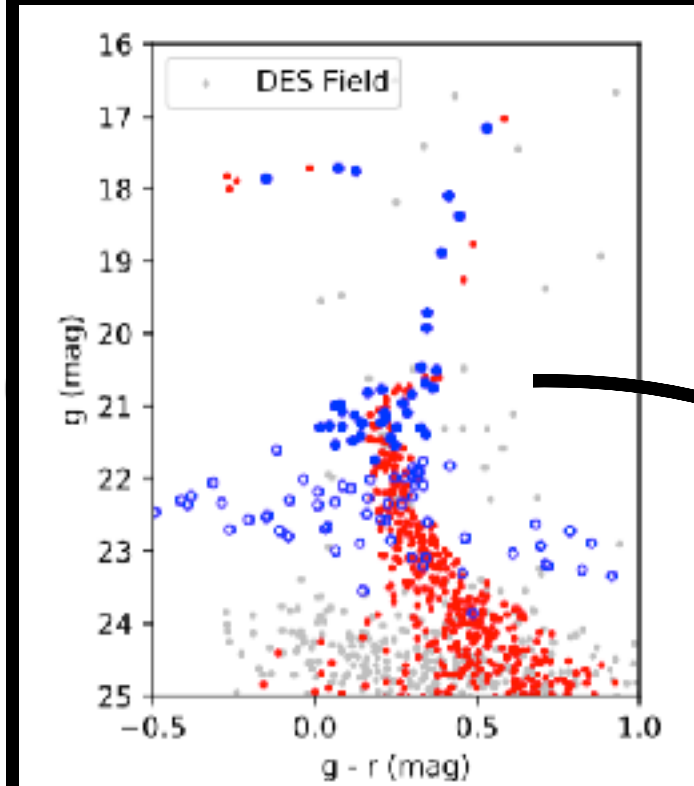


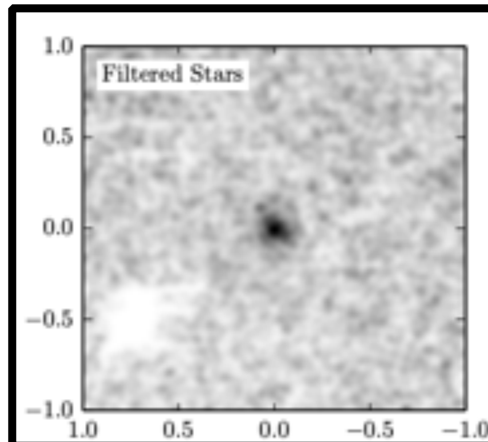
Circa 2014
Star Clusters
Dwarf Galaxies
Largely unexplored (too faint)
Luminosity
Physical Size
M_V (mag)
Half-light Radius (pc)
−12
−10
−8
−6
−4
−2
0
2
10^0
10^1
10^2
10^3

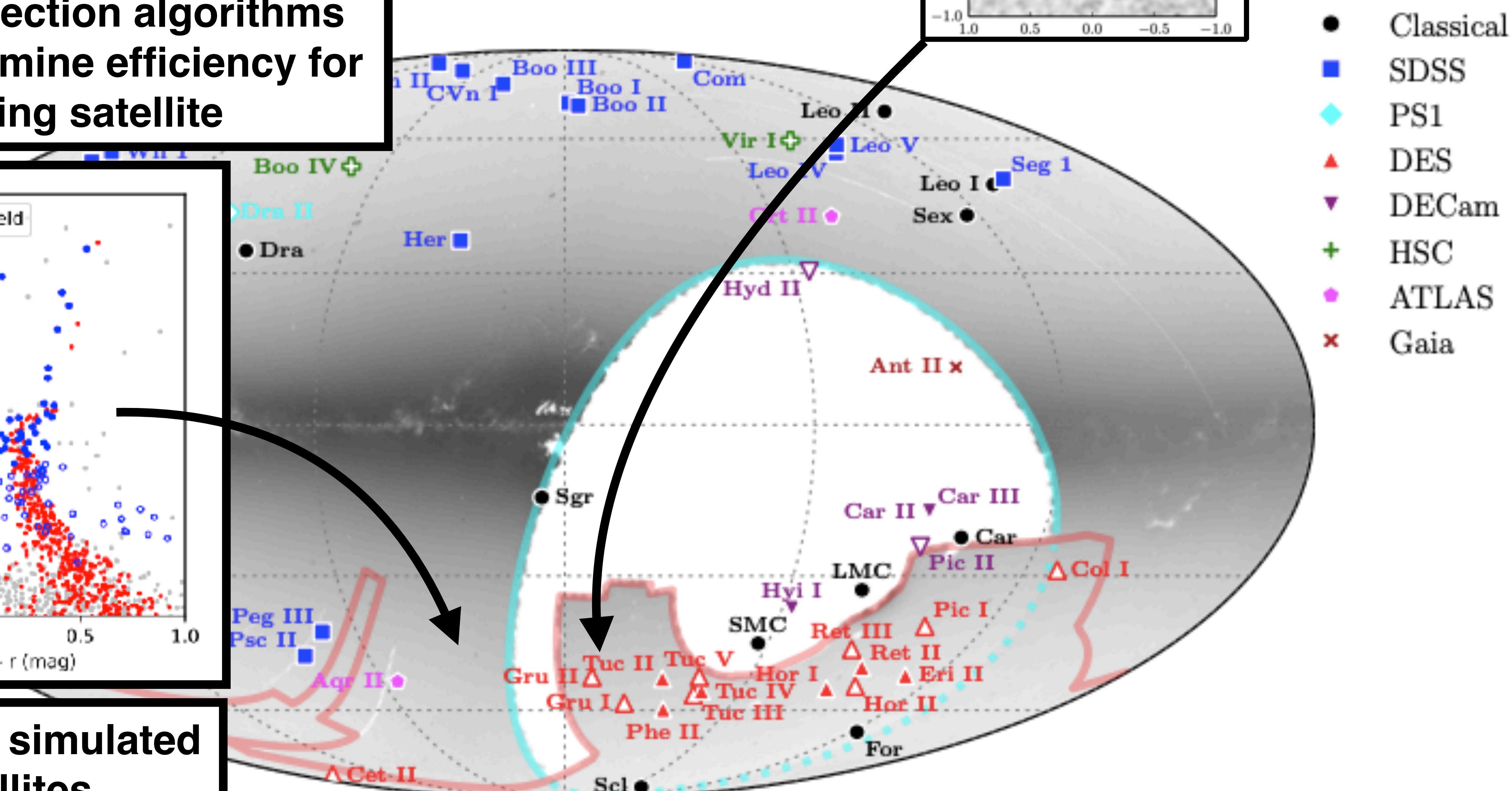

Circa 2022
Star Clusters
Dwarf Galaxies
What are these?
Largely unexplored (too faint)
Luminosity
Physical Size
M_V (mag)
Half-light Radius (pc)
−12
−10
−8
−6
−4
−2
0
2
10^0
10^1
10^2
10^3

An Accurate Census of Milky Way Satellite Galaxies

1. Simulate satellites including detailed sensitivity of each survey
2. Embed satellites into the survey data
3. Run detection algorithms to determine efficiency for recovering satellite



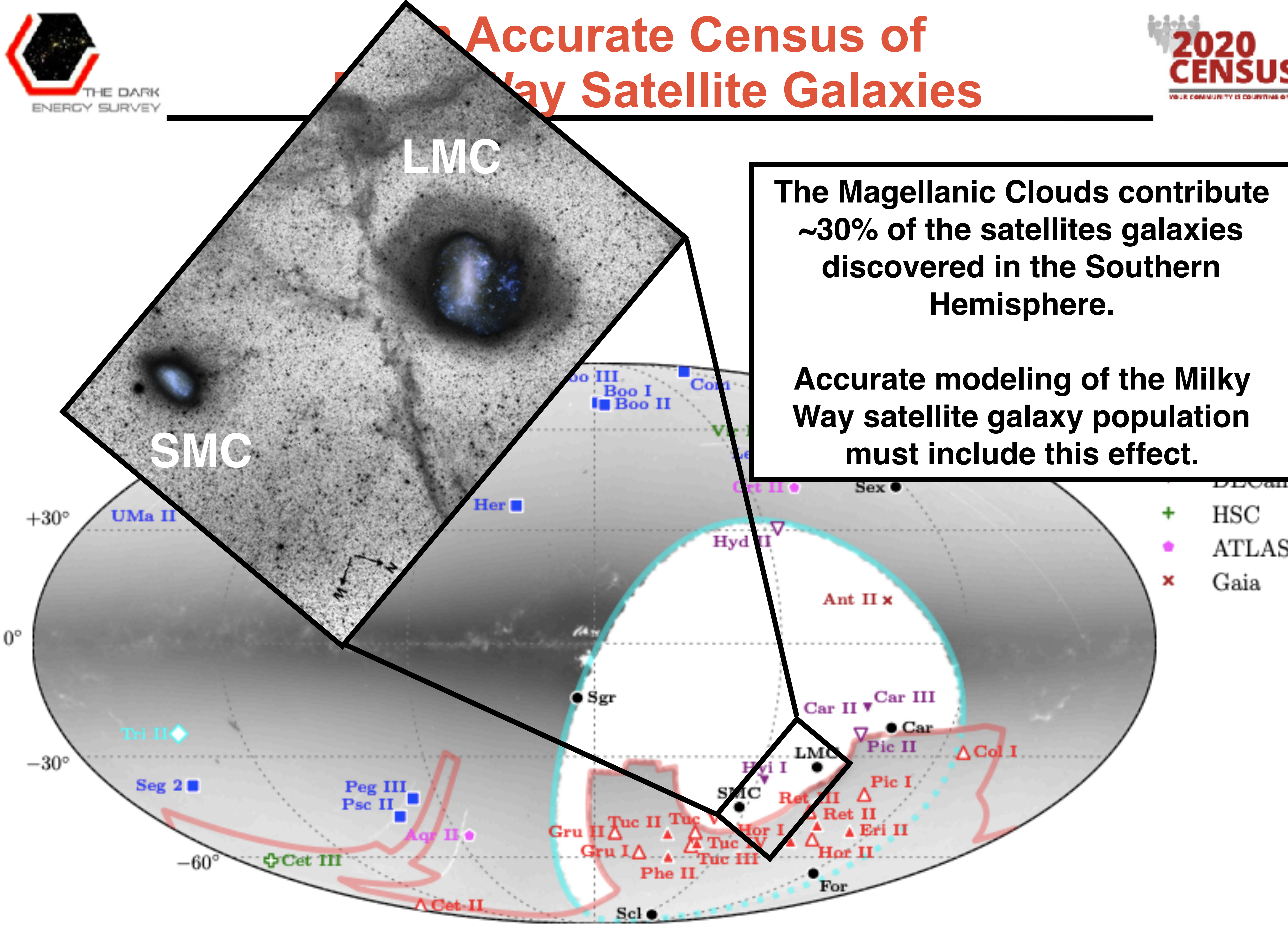




>1 million simulated satellites

ADW, Bechtol, et al. (2020)

Accurate Census of ... Way Satellite Galaxies



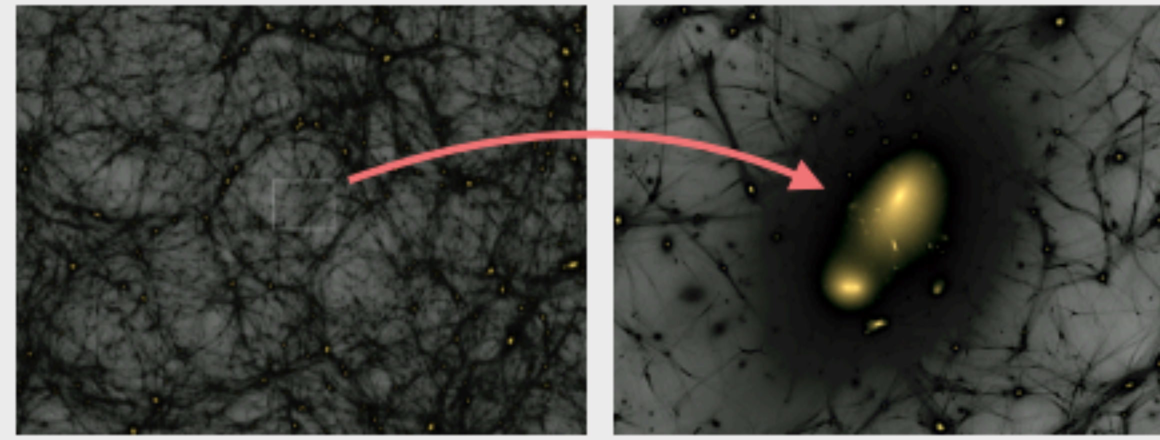
The Magellanic Clouds contribute ~30% of the satellites galaxies discovered in the Southern Hemisphere.

Accurate modeling of the Milky Way satellite galaxy population must include this effect.

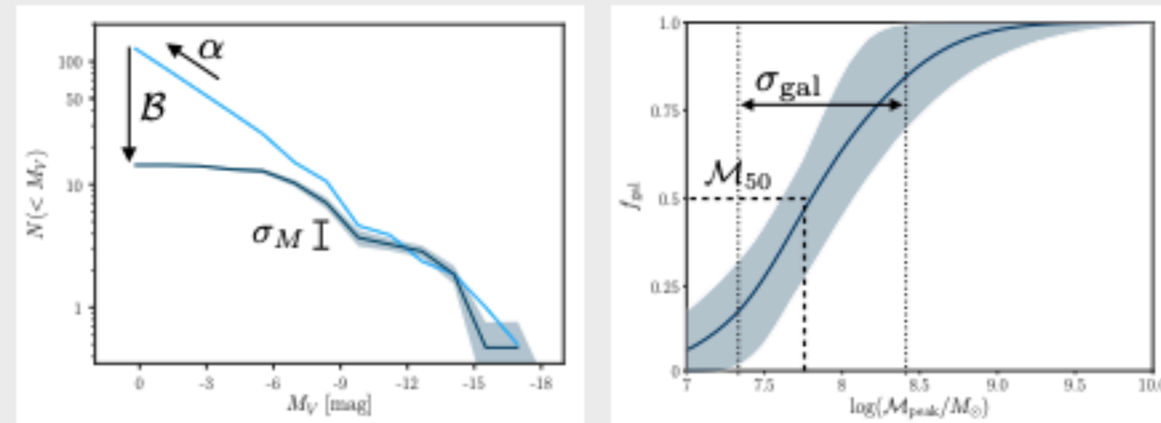
ADW, Bechtol, et al. (2020)

Markov Chain Monte Carlo

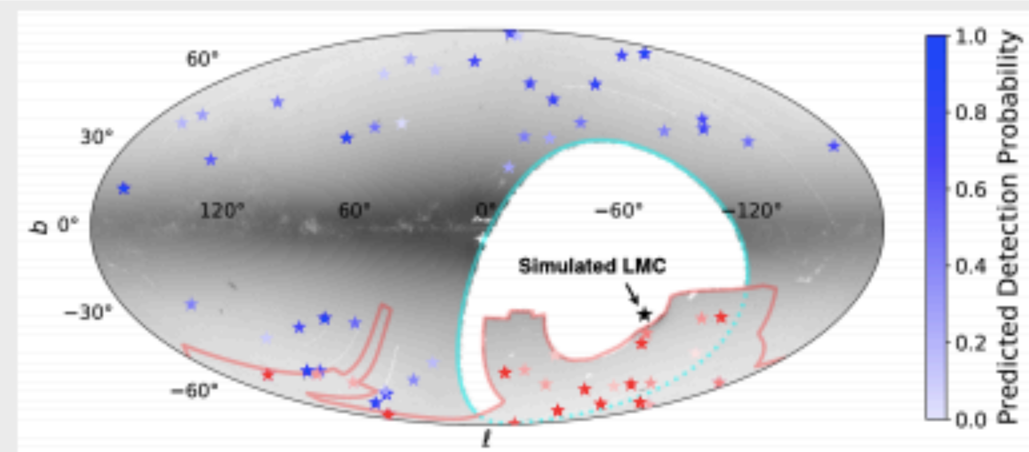
1. **Resimulate Milky Way-like halos from large cosmological volume.**



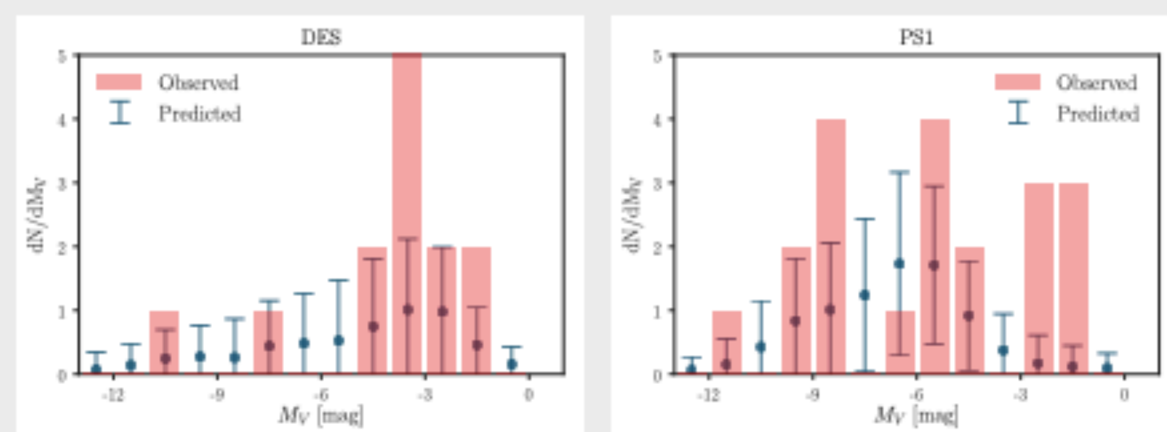
2. **Paint satellite galaxies onto subhalos using galaxy—halo model.**



3. **Apply observational selection functions based on imaging data.**

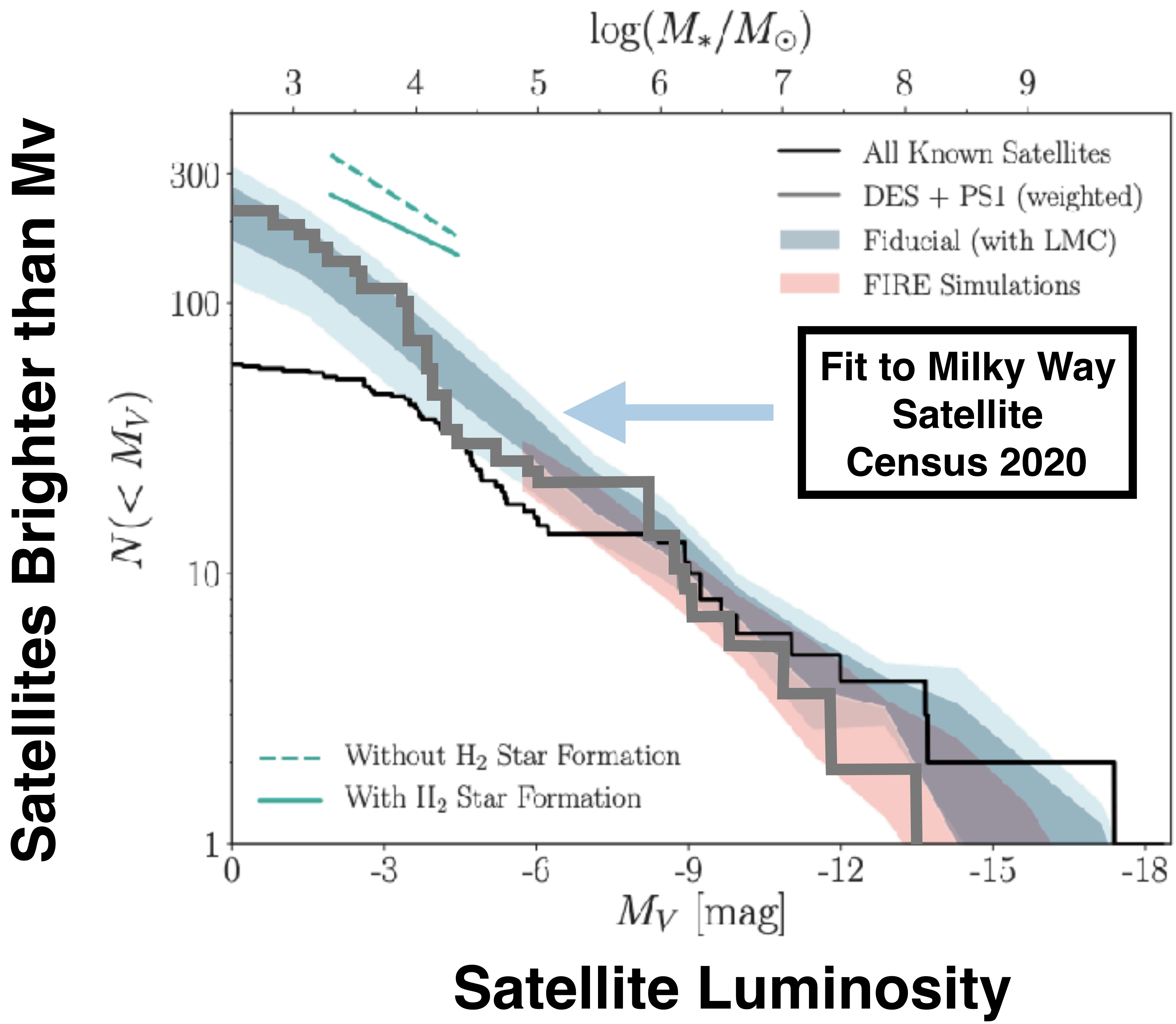


4. **Calculate likelihood of observed satellites given galaxy—halo connection parameters.**



Nadler, et al. (2020)

Milky Way Satellite Luminosity Function



Observed satellites are consistent with CDM + galaxy formation.

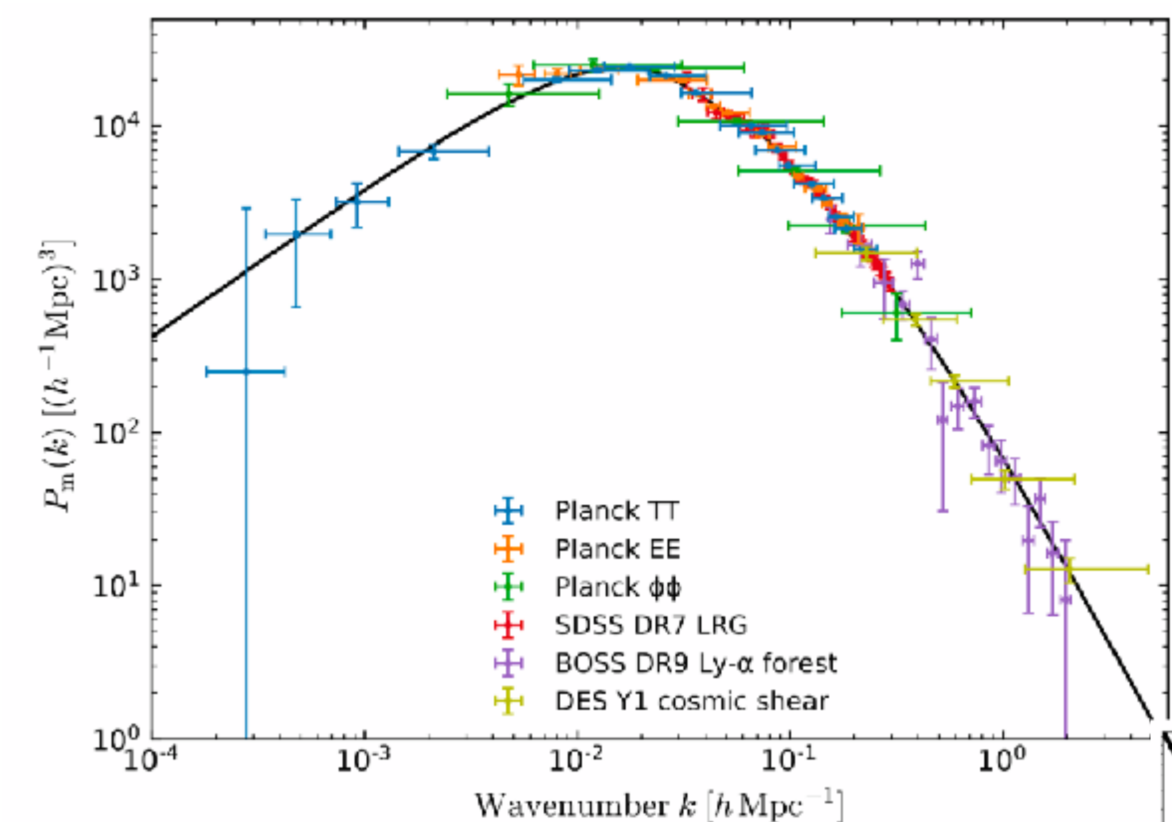
There is no missing satellites problem!

See also: Jethwa et al. 2018, Newton et al. 2018, Kim et al. 2018, Applebaum et al. 2020

Nadler et al. ApJ 893, 48 (2020)

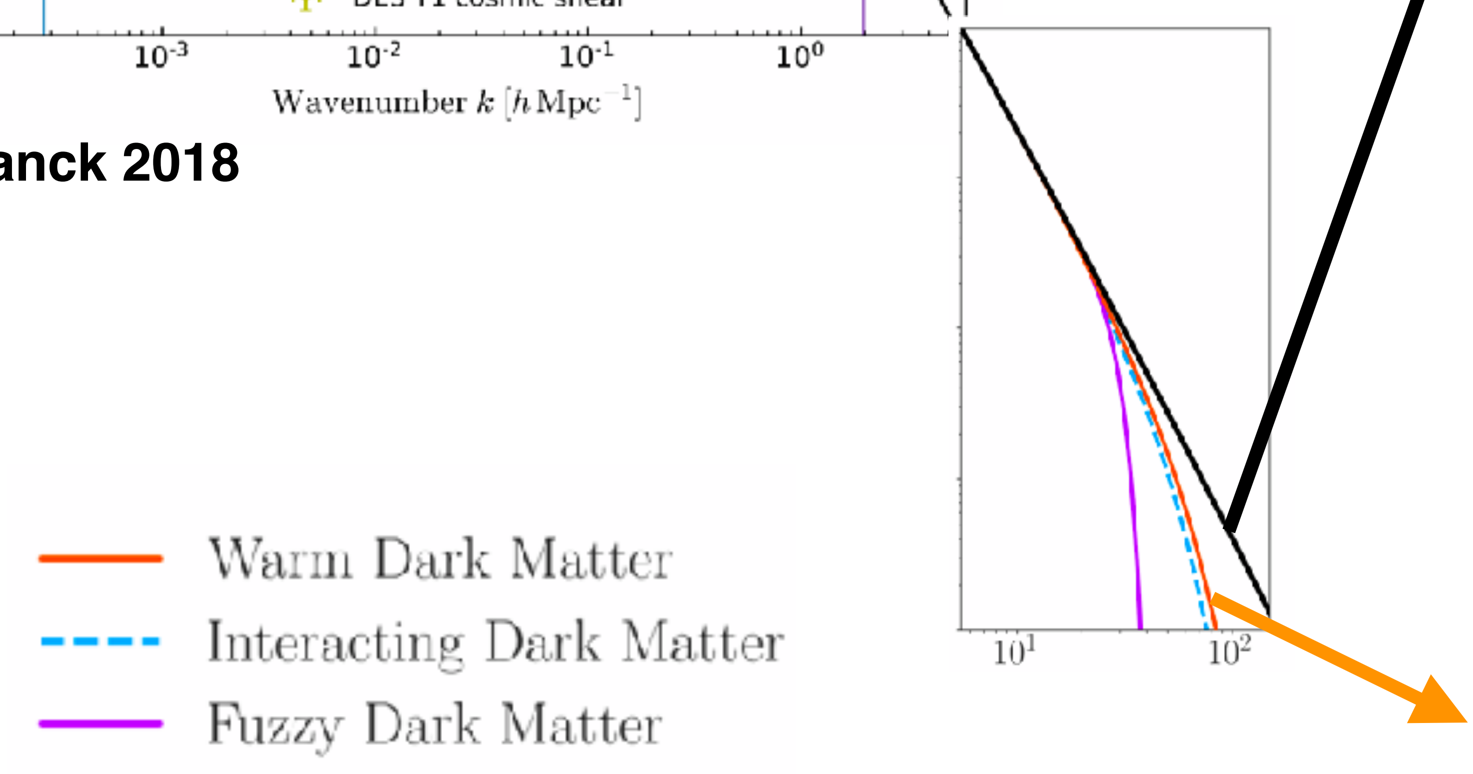
Dark Matter Physics

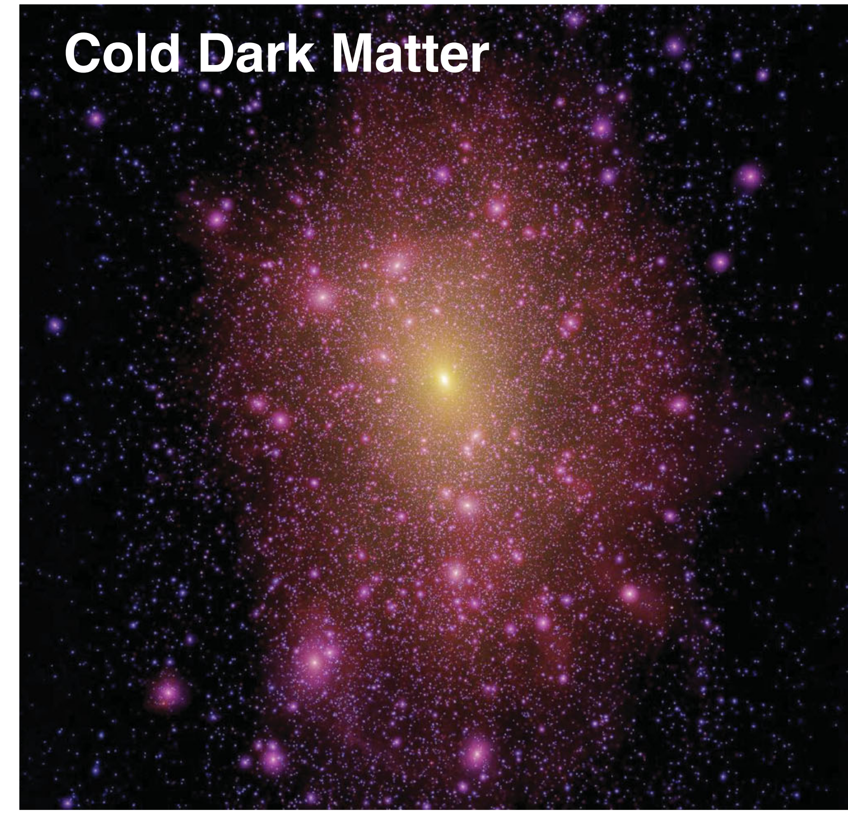
Power Spectrum

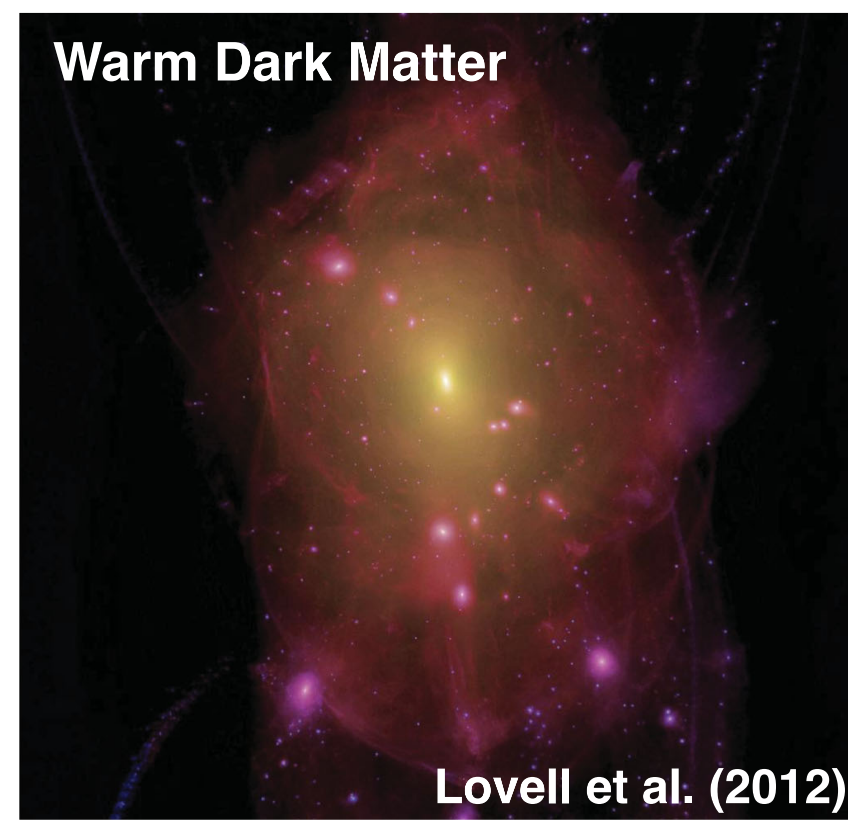


Planck 2018

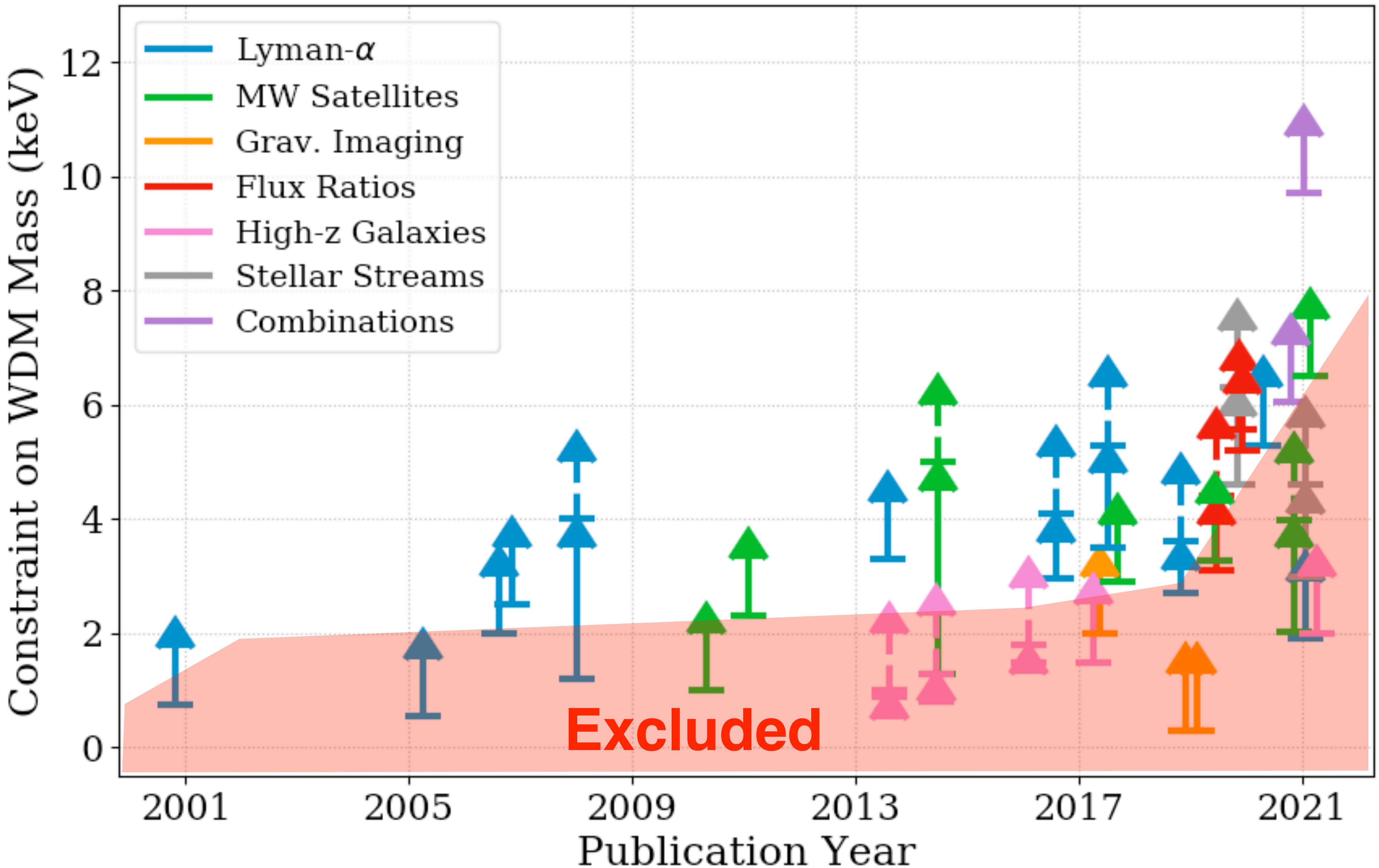
Non-Linear Physics







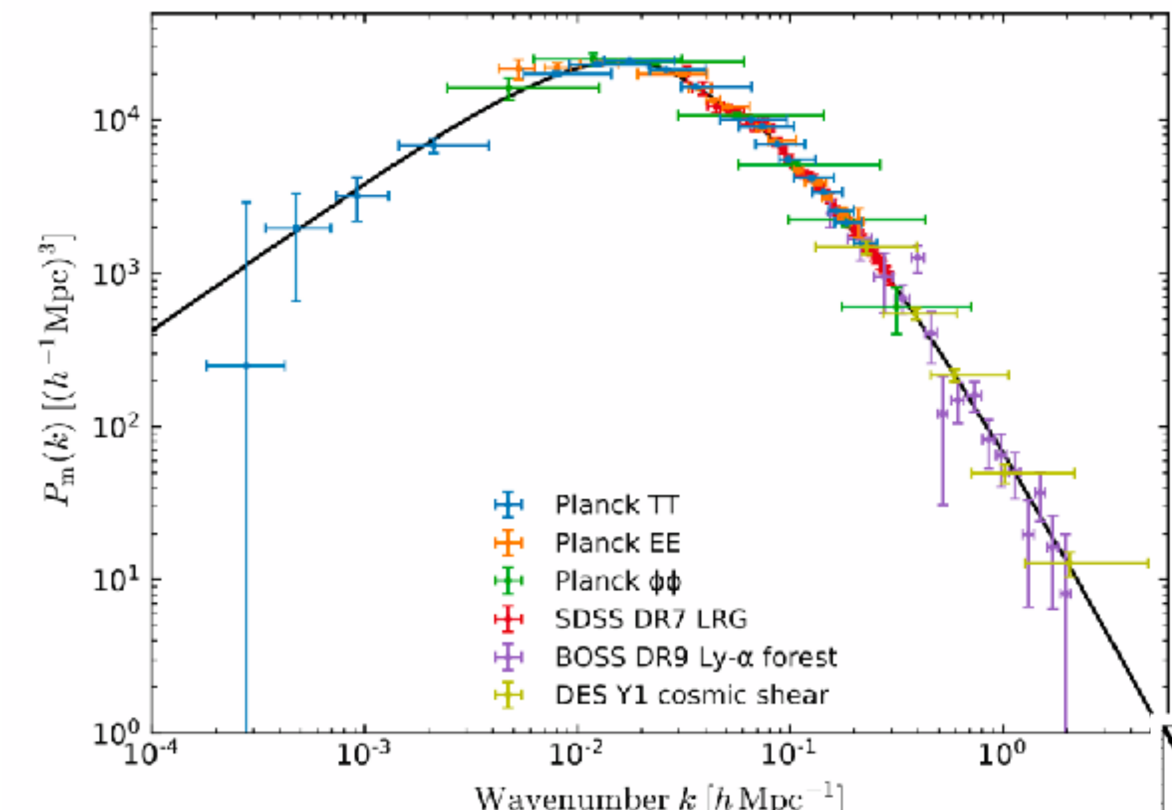
Warm Dark Matter Constraints



Constraints from: Viel et al. 2005, Viel et al. 2006, Seljak et al. 2006, Polisensky et al. 2011, Kennedy et al. 2014, Birrer et al. 2017, Irsic et al. 2017, Jethwa et al. 2017, Murgia et al. 2018, Vegetti et al. 2018, Ritondale et al. 2019, Gilman et al. 2019a,b, Hseuh et al. 2019, Palanque-Delabrouille et al. 2020, Enzi et al. 2020, Rudakovskyi et al. 2021, Banik et al. 2019,2021, Nadler et al. 2019,2021a,b, etc.

Dark Matter Physics

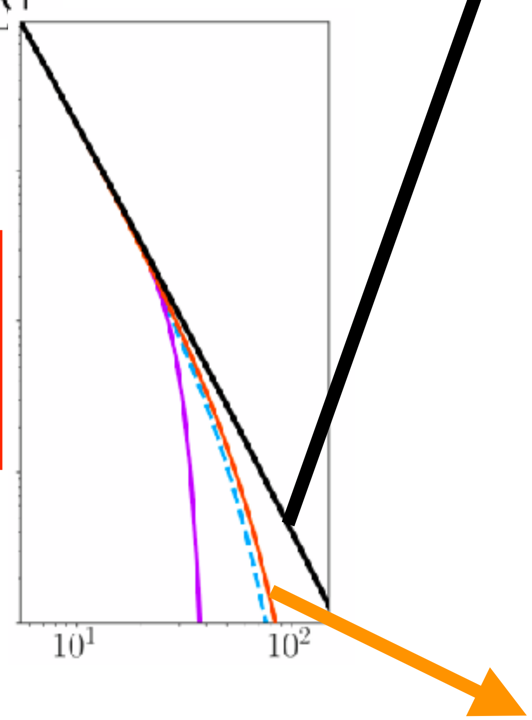
Power Spectrum

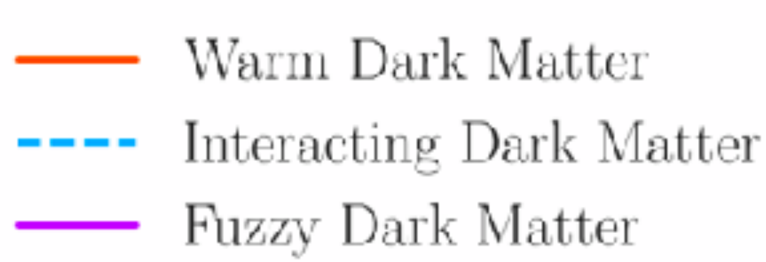


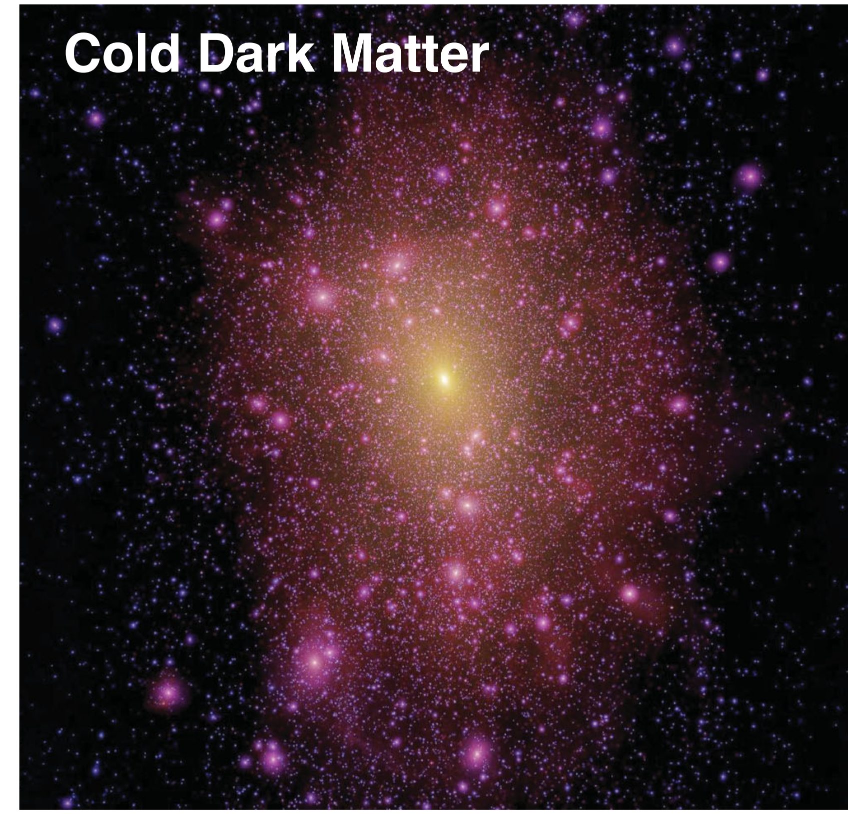
Planck 2018

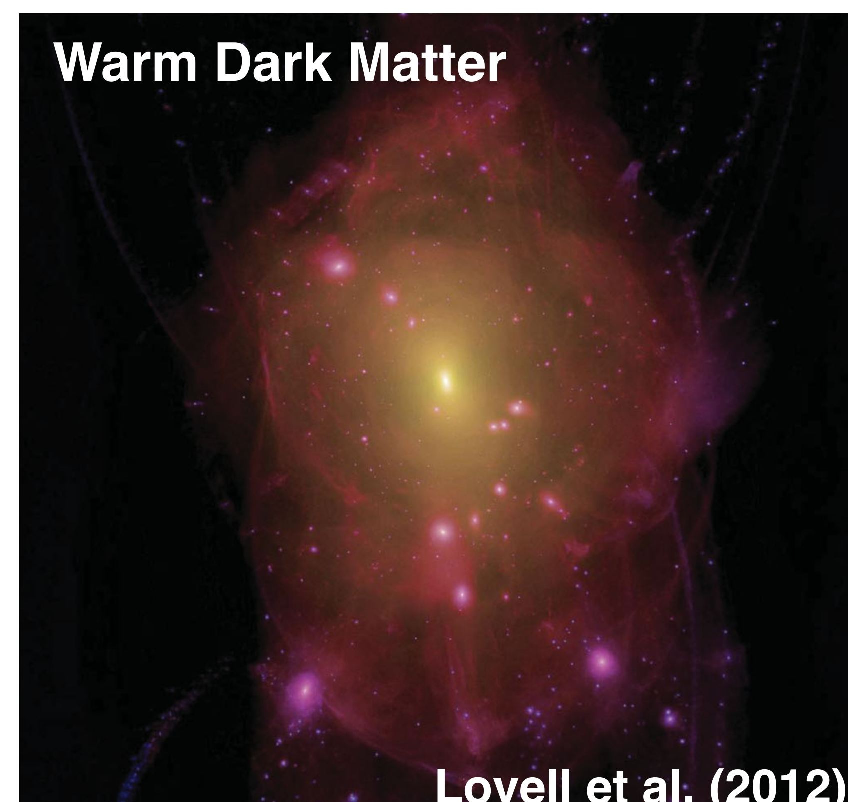
Non-Linear Physics

Several dark matter models suppress structure similarly

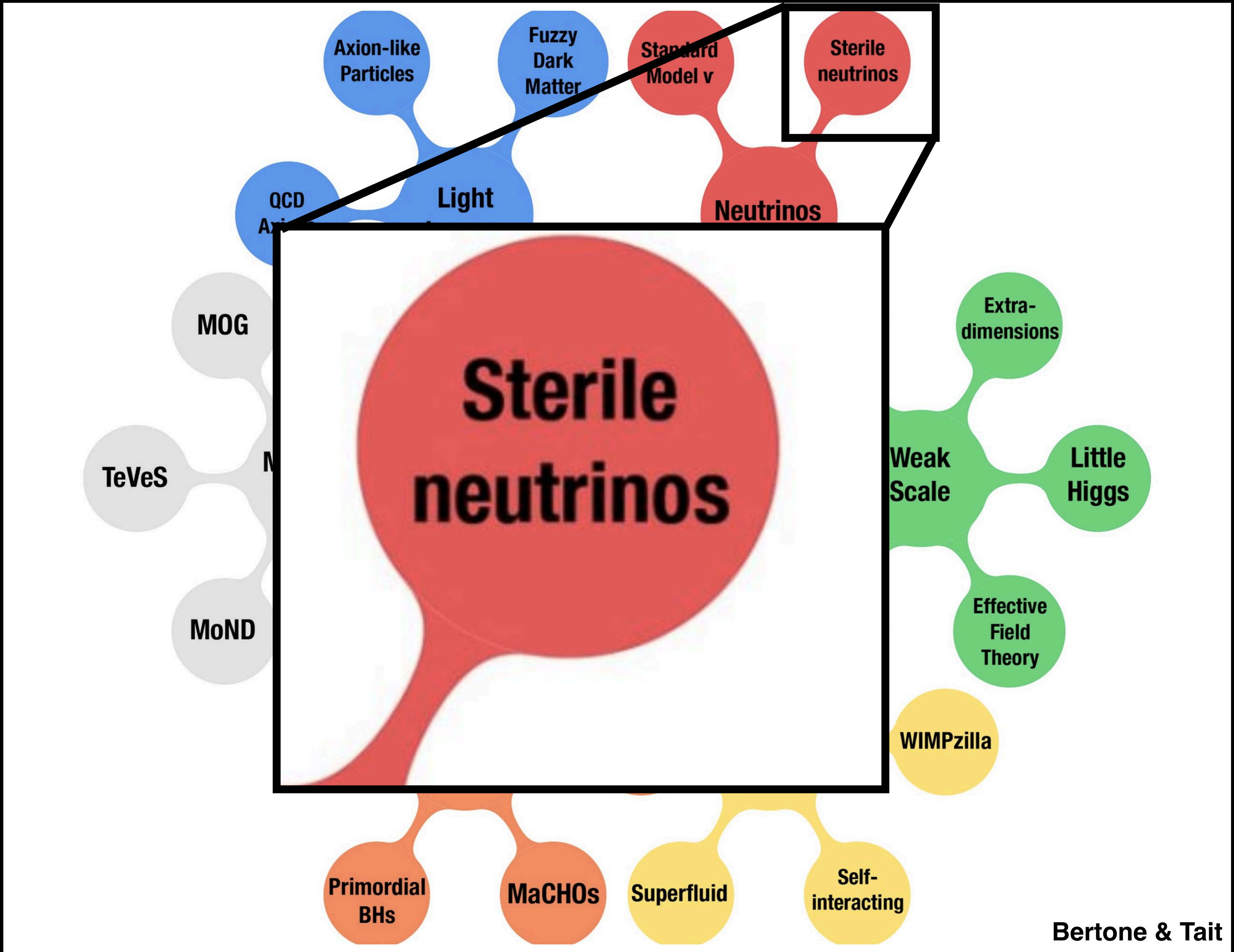








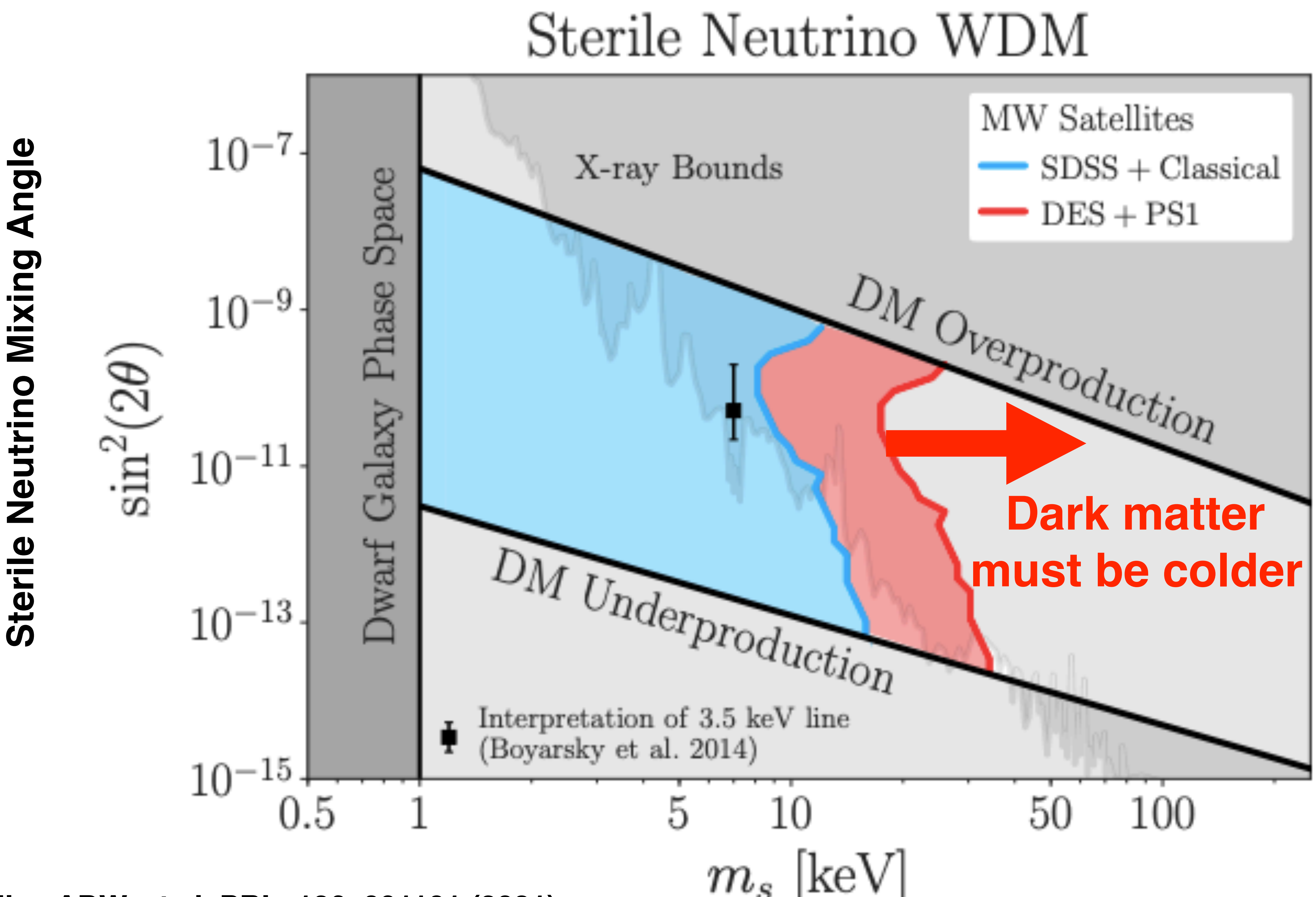
Dark Matter Candidates



Bertone & Tait

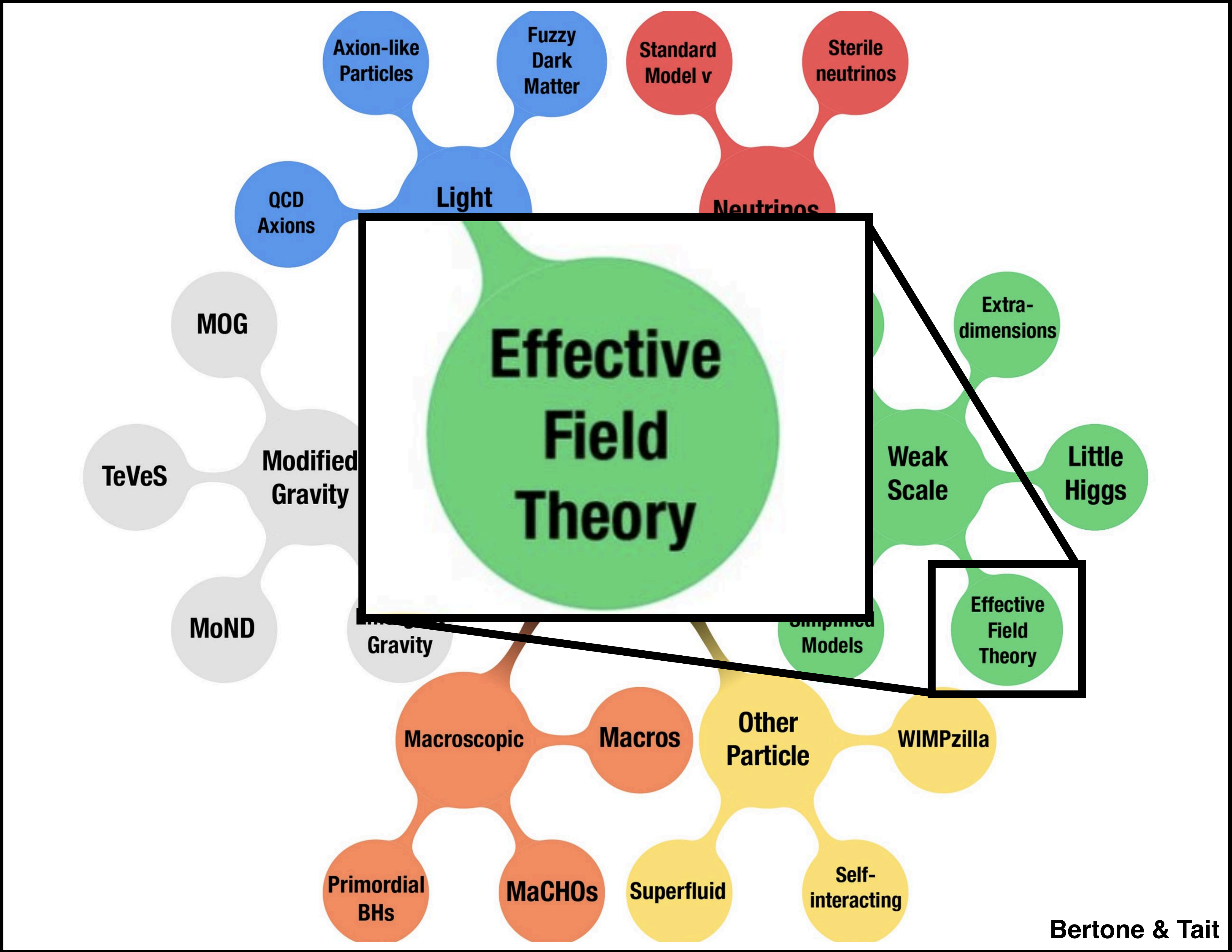
Sterile Neutrino Warm Dark Matter

Warm dark matter has large primordial velocity dispersion; free-streaming suppresses formation of low-mass halos



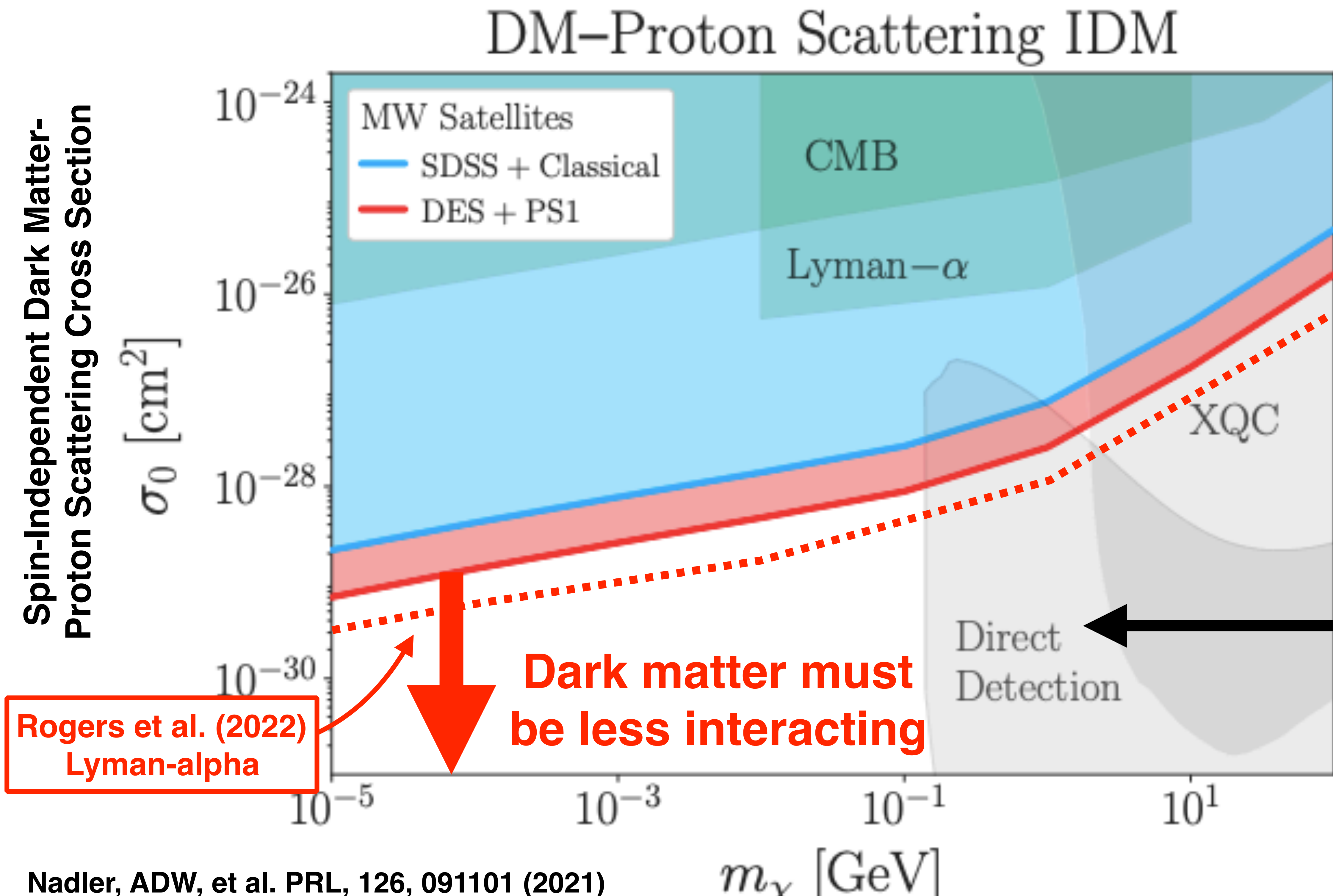
Nadler, ADW, et al. PRL, 126, 091101 (2021)
See also: Schneider (2016), Cherry & Horiuchi (2017), Dekker et al. (2022), An et al. (2023)

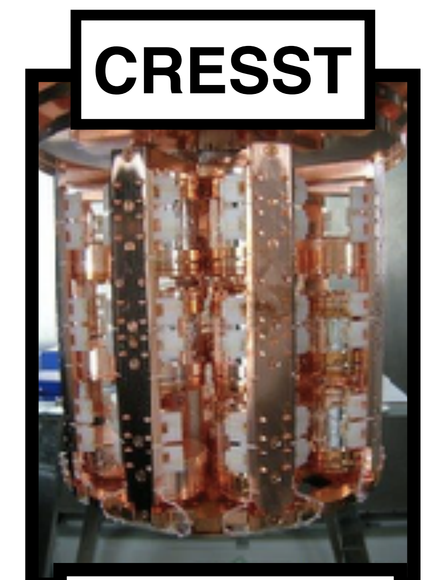
Dark Matter Candidates

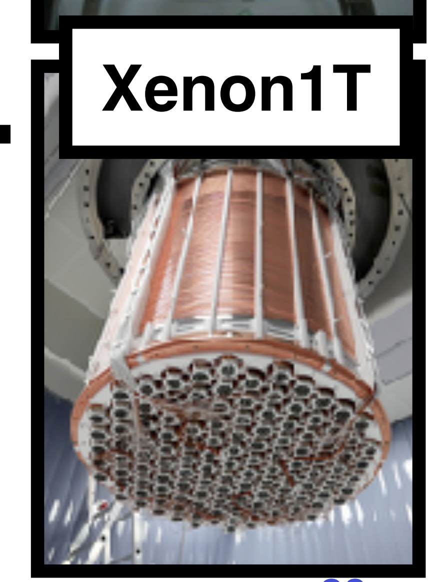


Interacting Dark Matter

Collisional damping due to DM–baryon scattering in the early Universe suppresses power on small scales

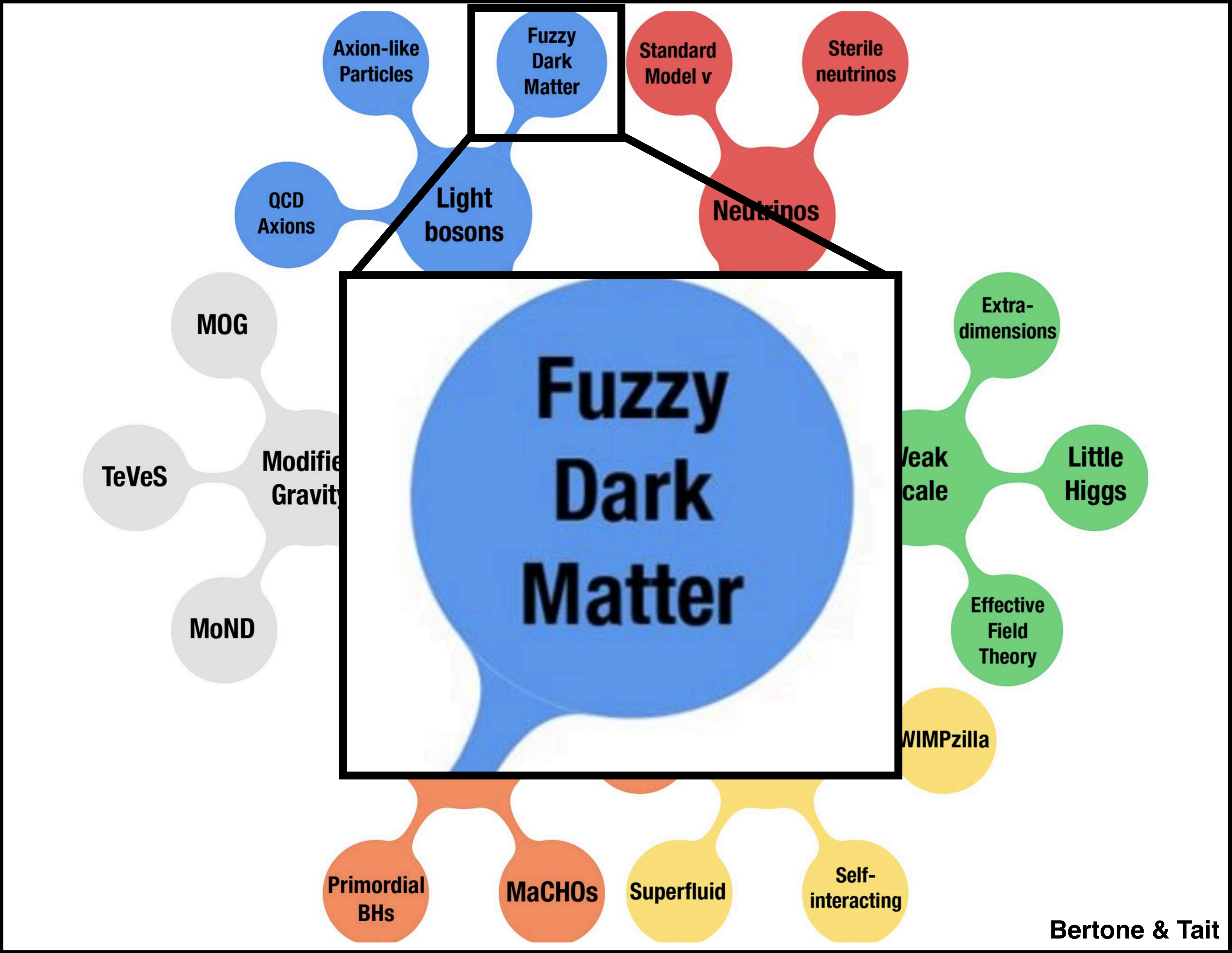






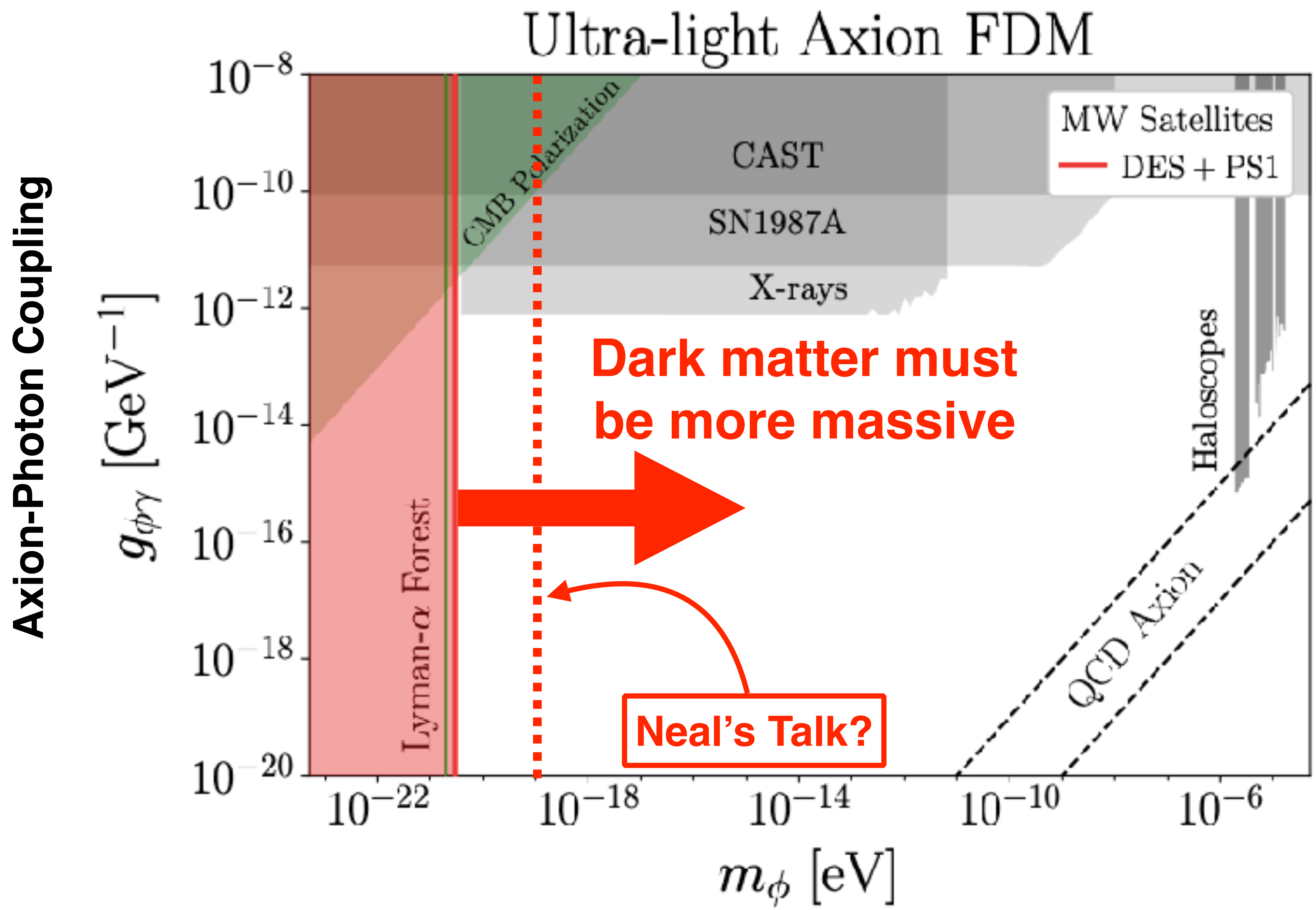
Nadler, ADW, et al. PRL, 126, 091101 (2021)
See also: Nadler et al. (2019), Rogers et al. (2022)

Dark Matter Candidates



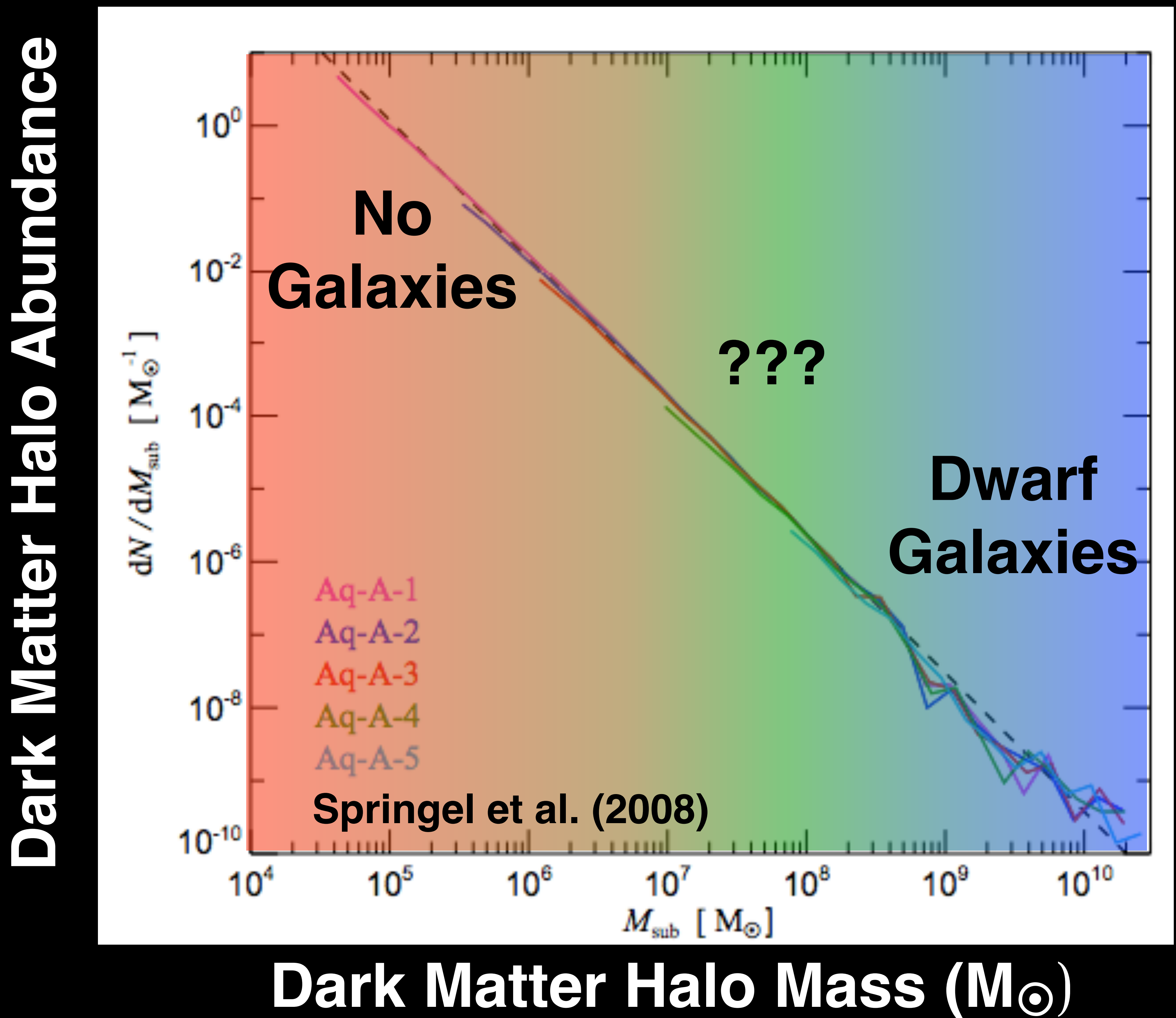
Fuzzy Dark Matter

The de Broglie wavelength of dark matter must be smaller than the halos hosting ultra-faint dwarf galaxies (~1 kpc)



Nadler, ADW, et al. PRL, 126, 091101 (2021)
See also: Irsic et al. (2017), Rogers et al. (2021), Dalal & Kravtsov (2023)

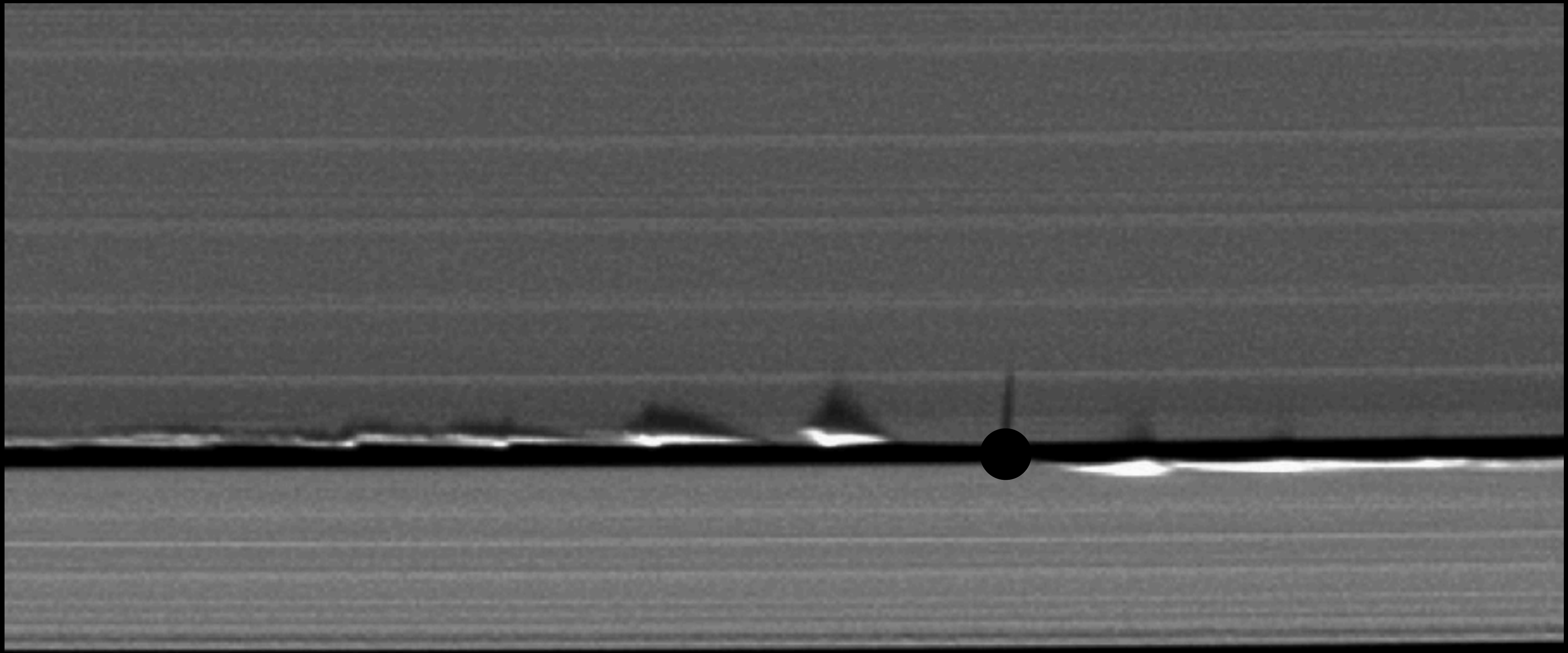
Pushing to Lower Mass



Standard CDM predicts the existence of small subhalos.

How do we detect completely dark subhalos?

Analogy: Saturn's Shepard Moons



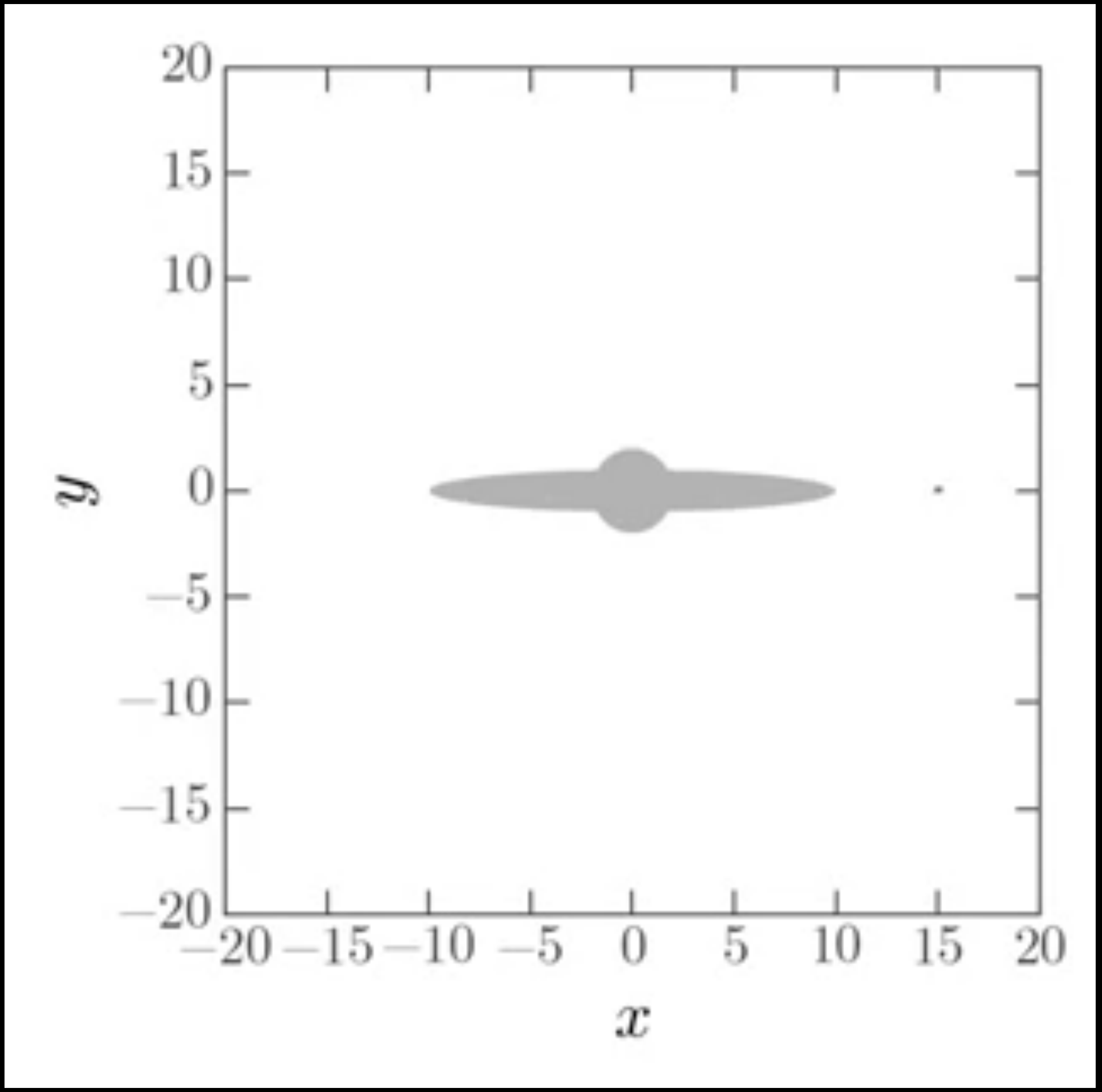
Shepard moons are detectable indirectly through their gravitational wake

Stellar Streams

Tidal remains of dwarf galaxies and star clusters

Stars spread out along original orbit; fragile dynamical systems

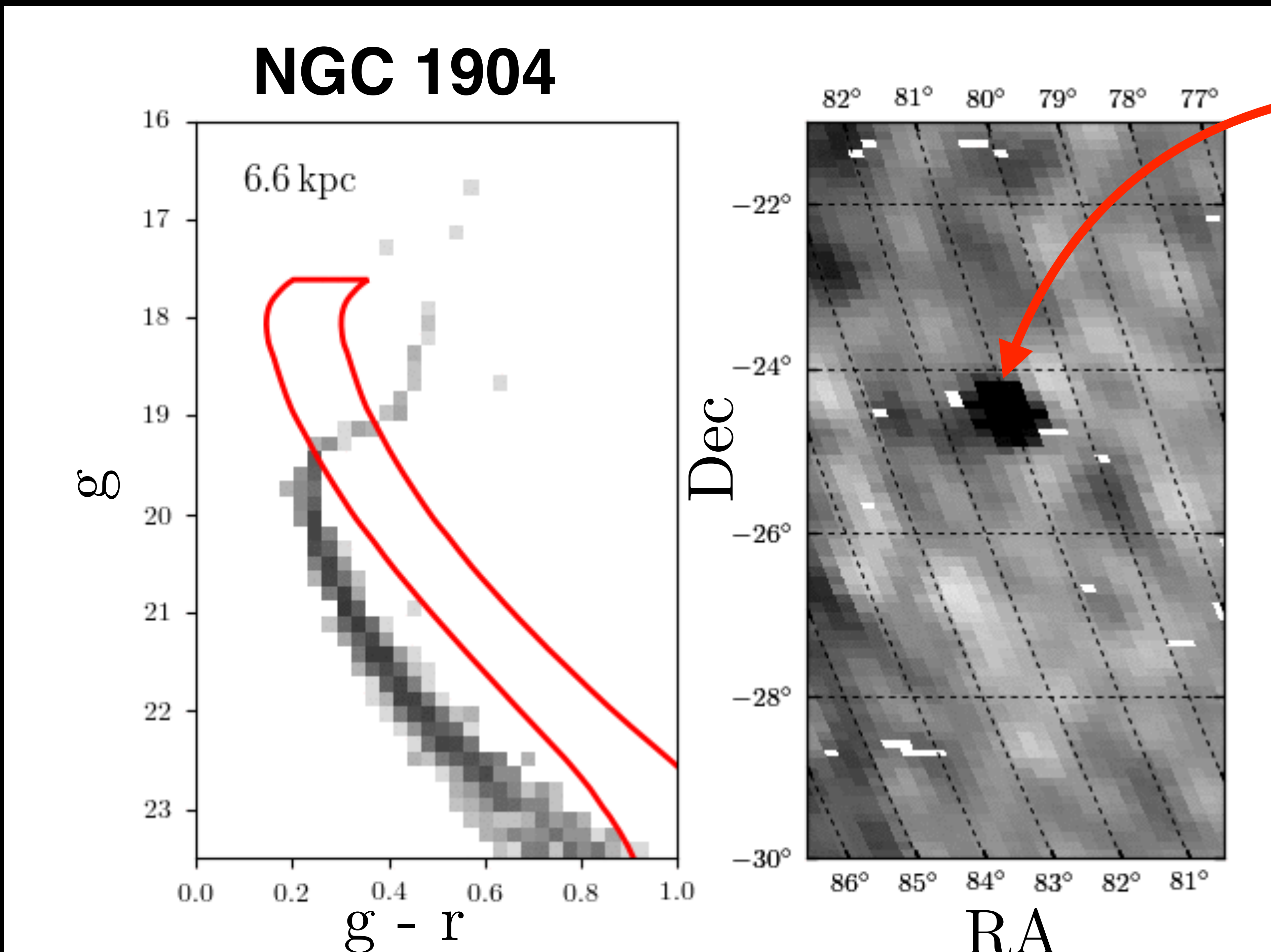
Sensitive to both the smooth and clumpy distribution of matter

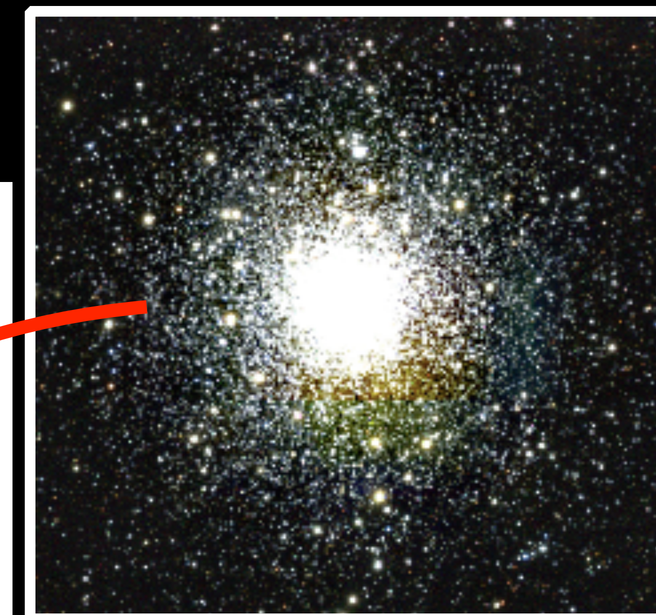


A. Price-Whelan

Isochrone Selection

w/ Nora Shipp





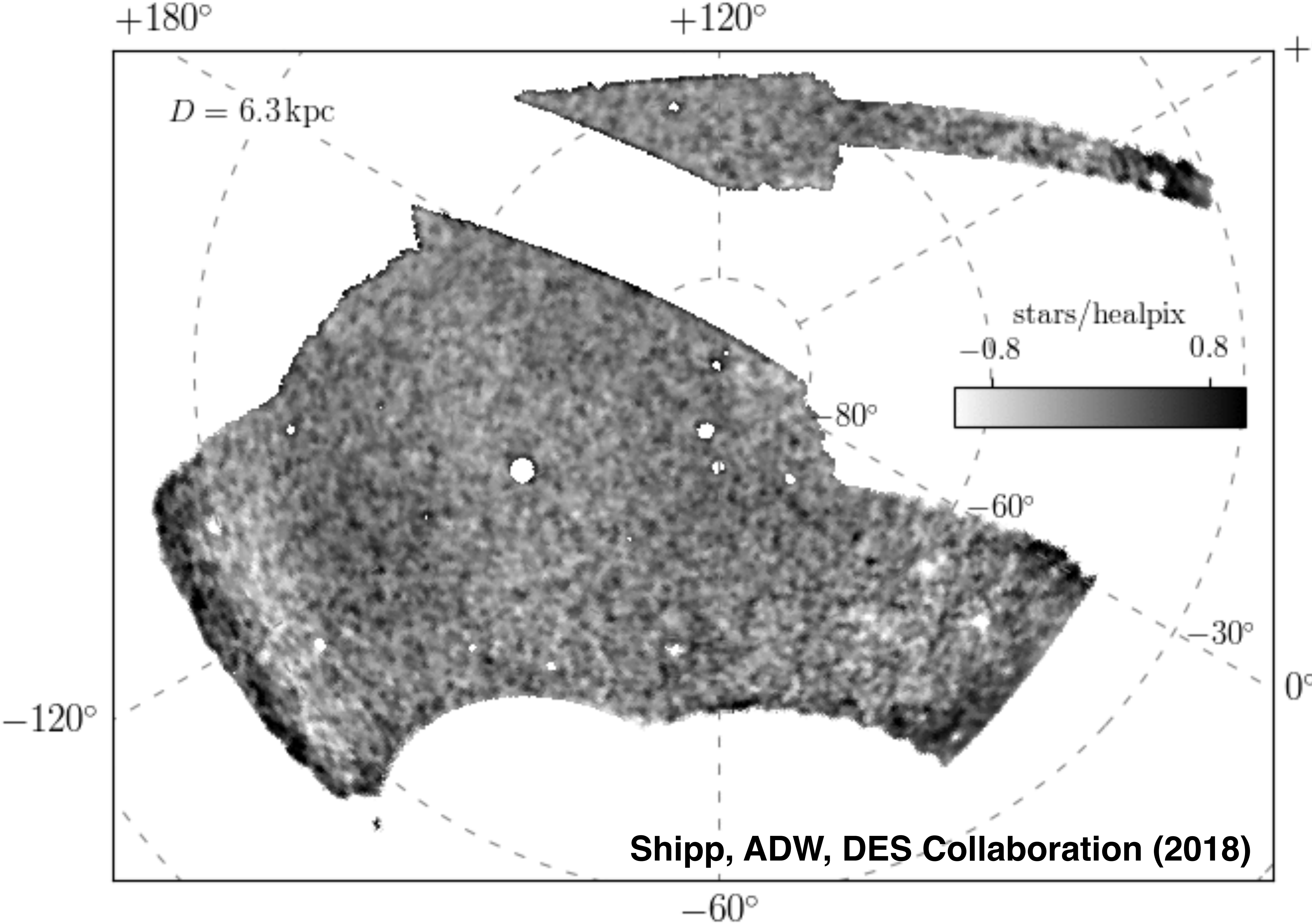
NGC 1904

Select old, metal poor stars in bins of distance

Shipp, ADW, DES Collaboration (2018)

Tour Through the Milky Way Halo

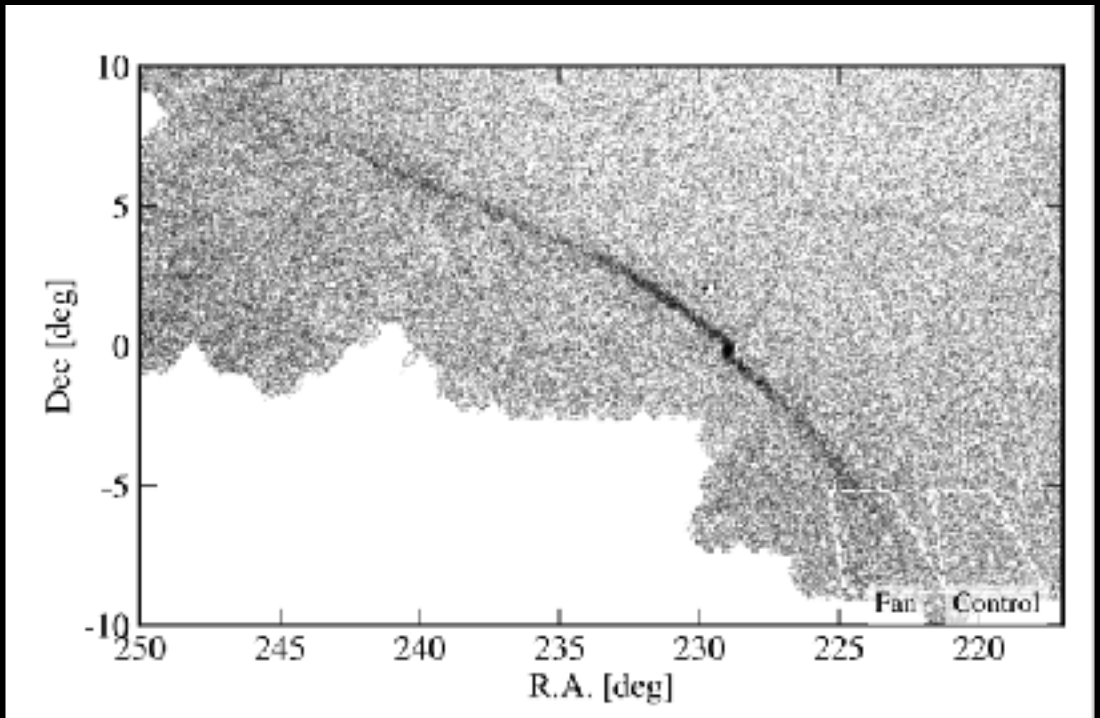
w/ Nora Shipp



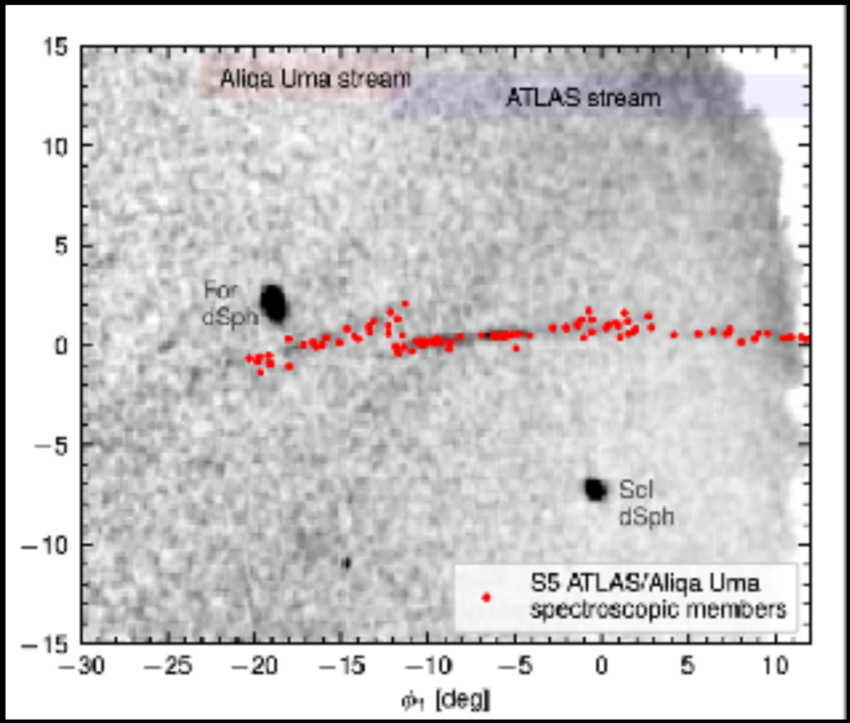
Shipp, ADW, DES Collaboration (2018)

Density Variations in Stellar Streams

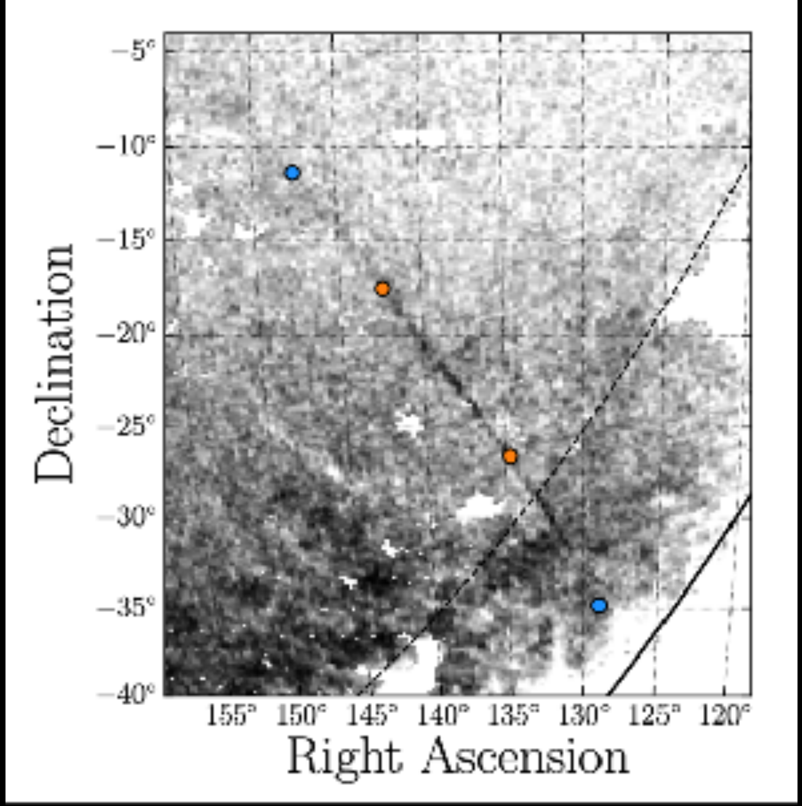
Palomar 5 (Bonaca et al. 2019)



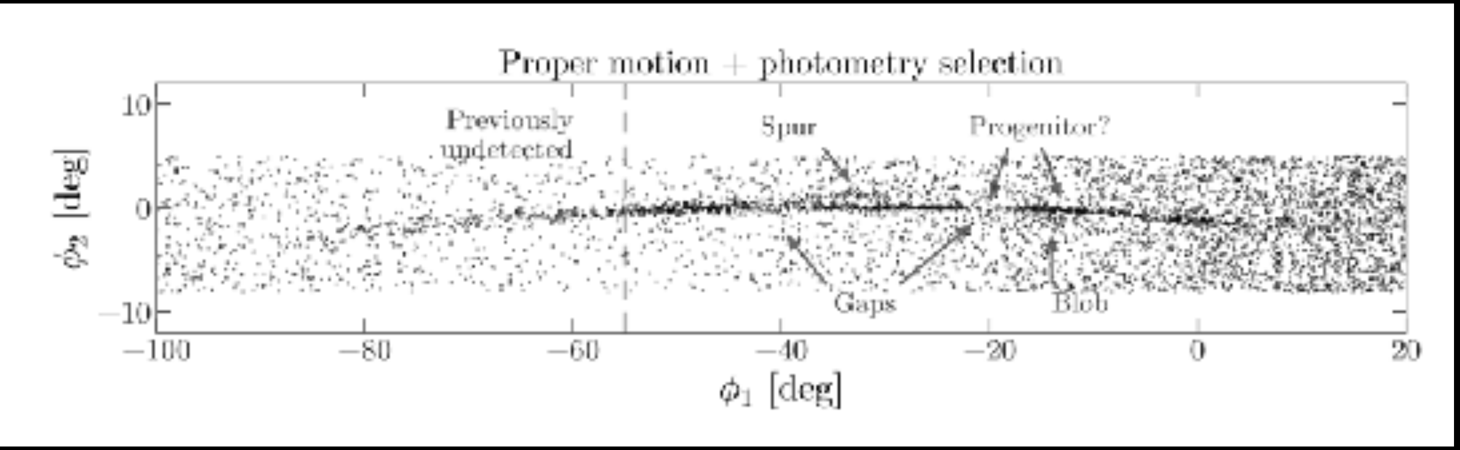
ATLAS-Aliqa Uma (Li et al. 2020)



Jet (Ferguson et al. 2021)

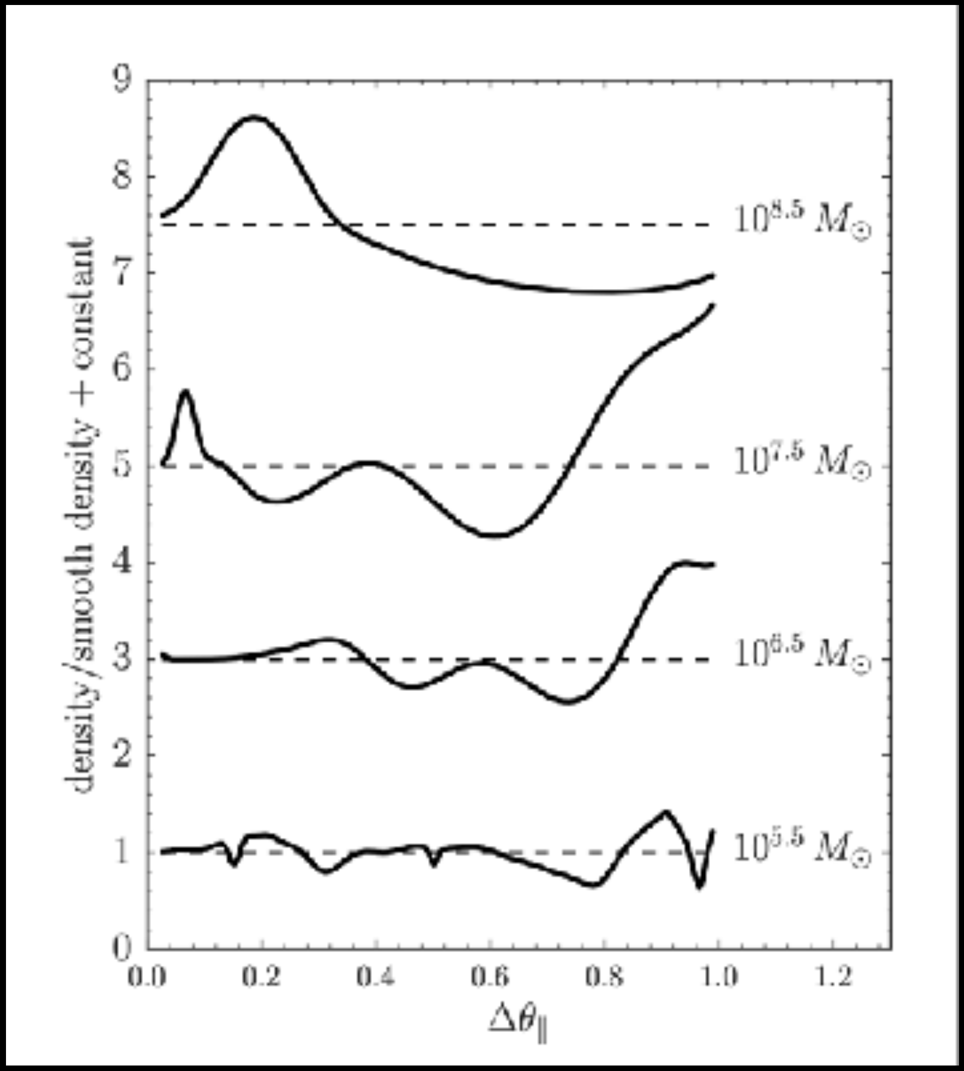


GD-1 (Price-Whelan et al. 2018)



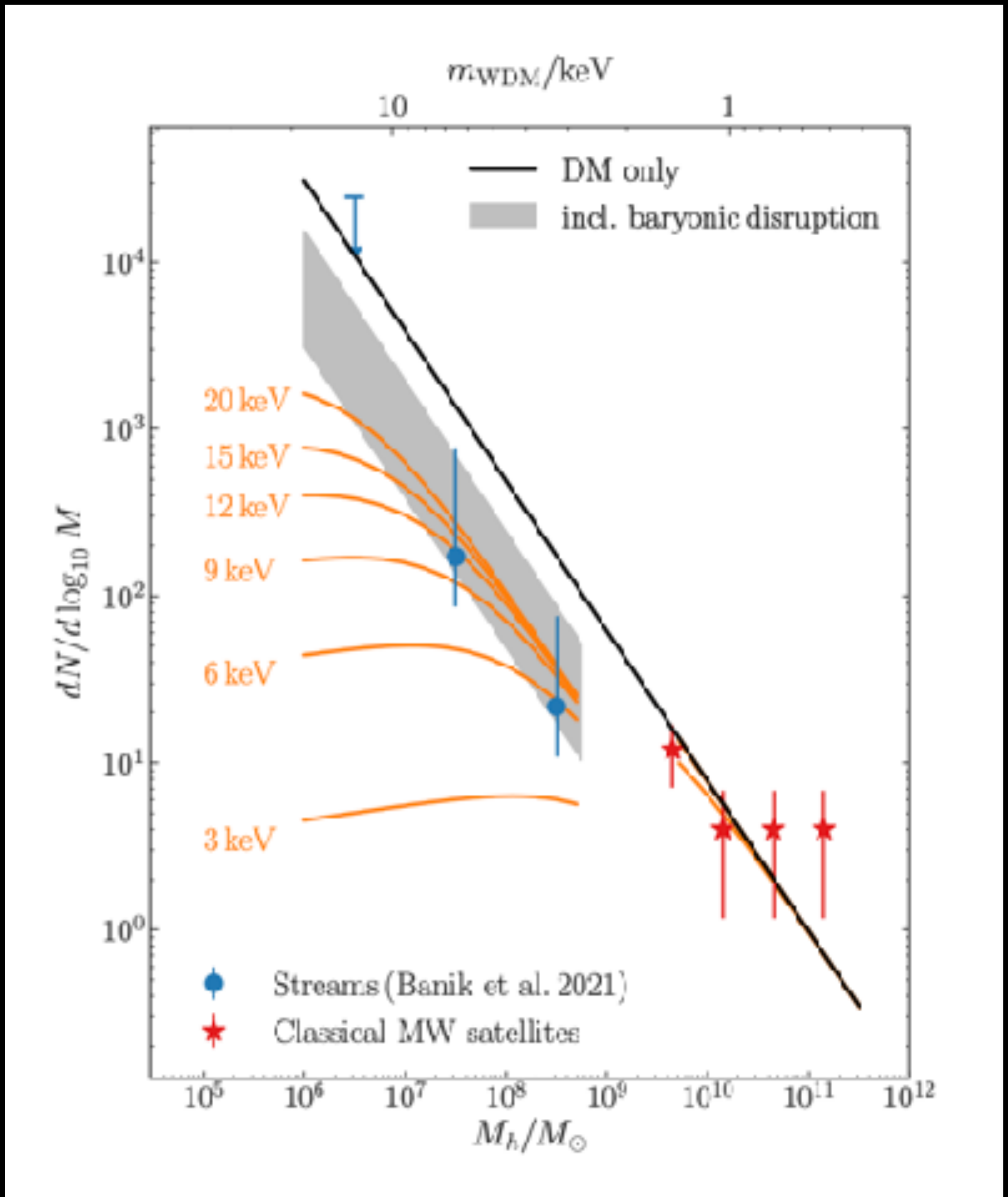
Dark Matter Constraints from Stellar Streams

Bovy et al. 2017



Subhalos of different mass perturb stream density on different scales.

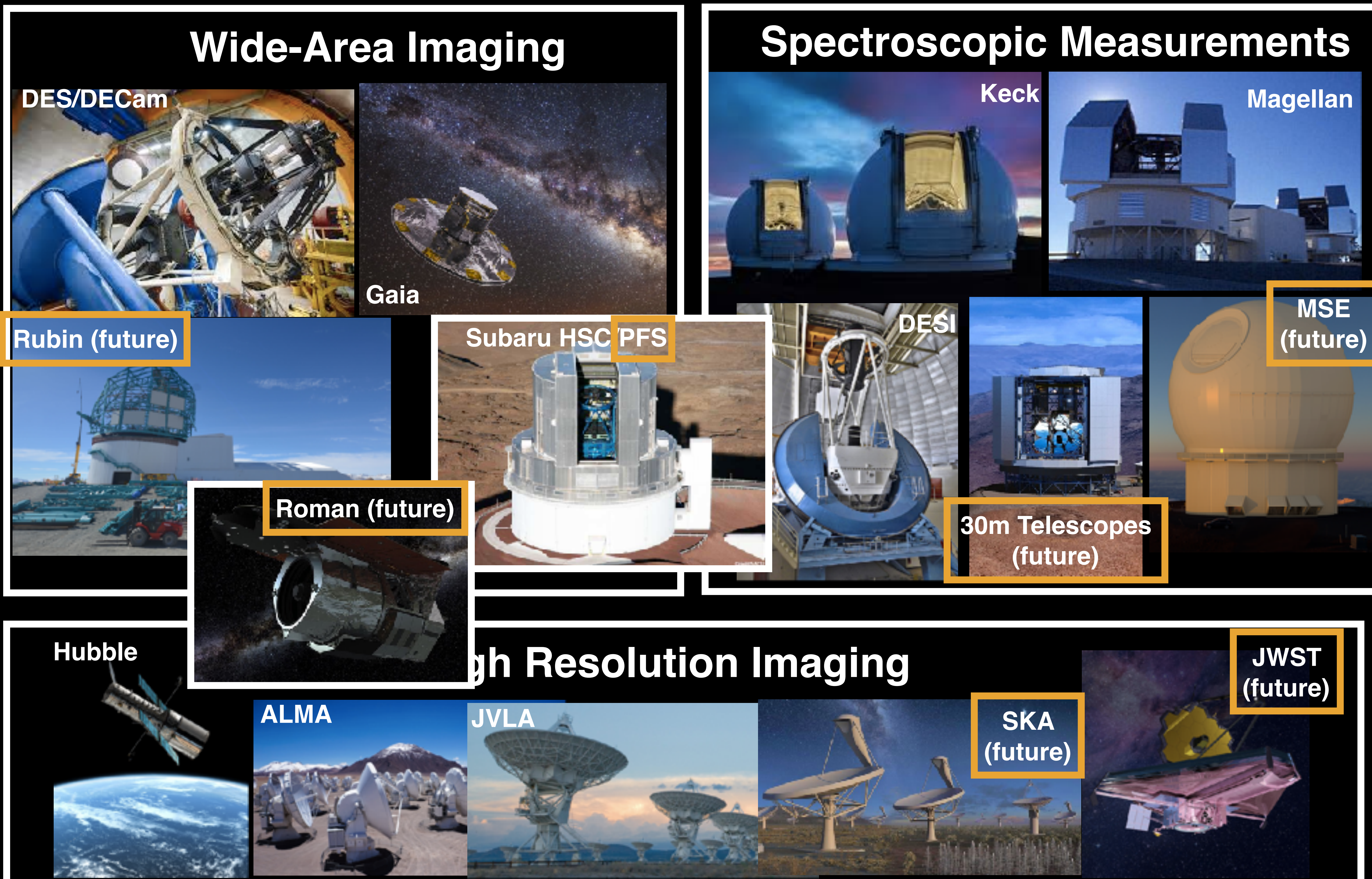
1D power spectrum stream stellar density contains information about impact history



Banik et al. 2021

Maybe Neal will talk more about streams and fuzzy dark matter

Current and Near-Future Experiments



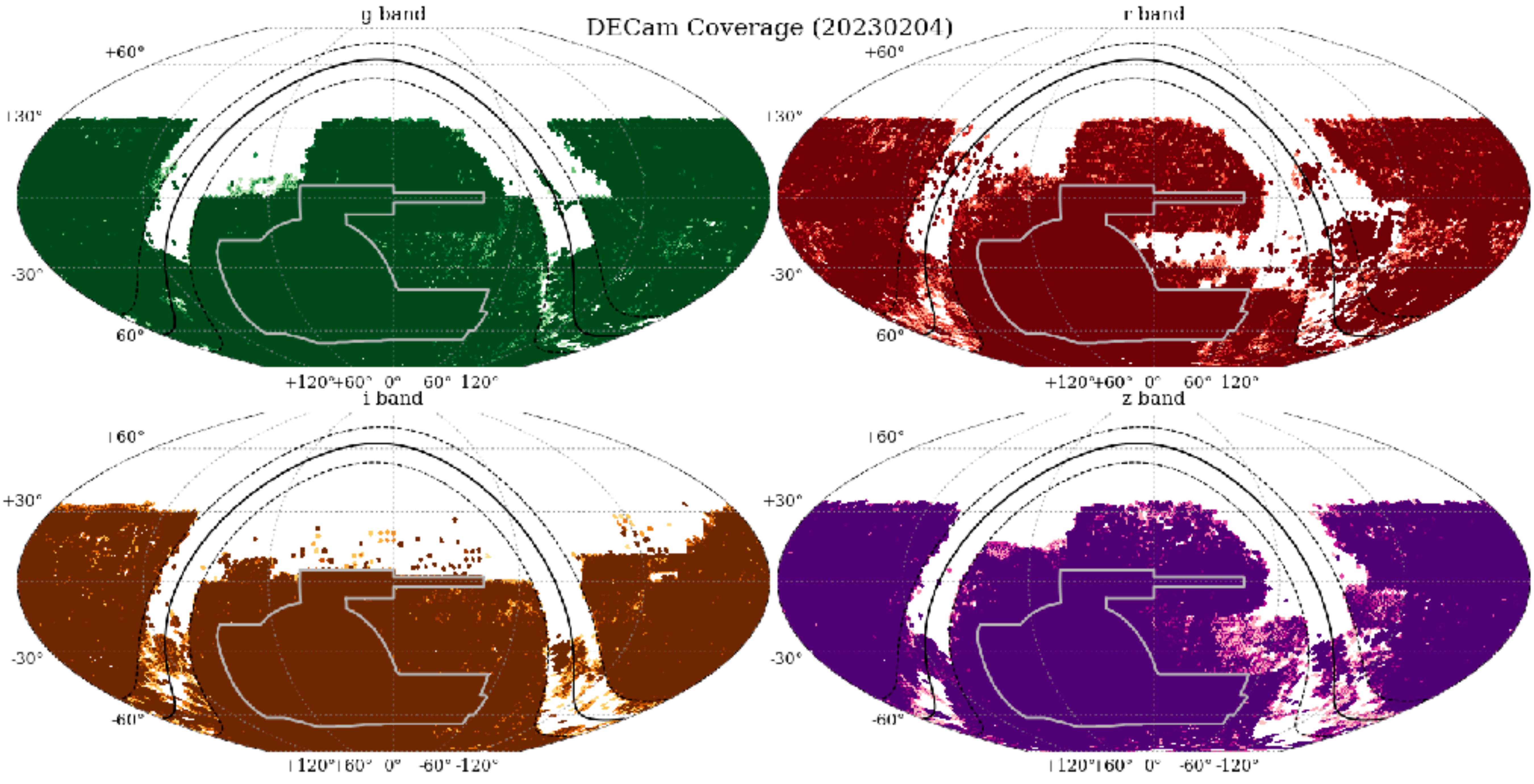
DECam Local Volume Exploration Survey

126+ nights to complete high-galactic latitude DECam sky coverage.

Depth comparable to first 2 years of DES.

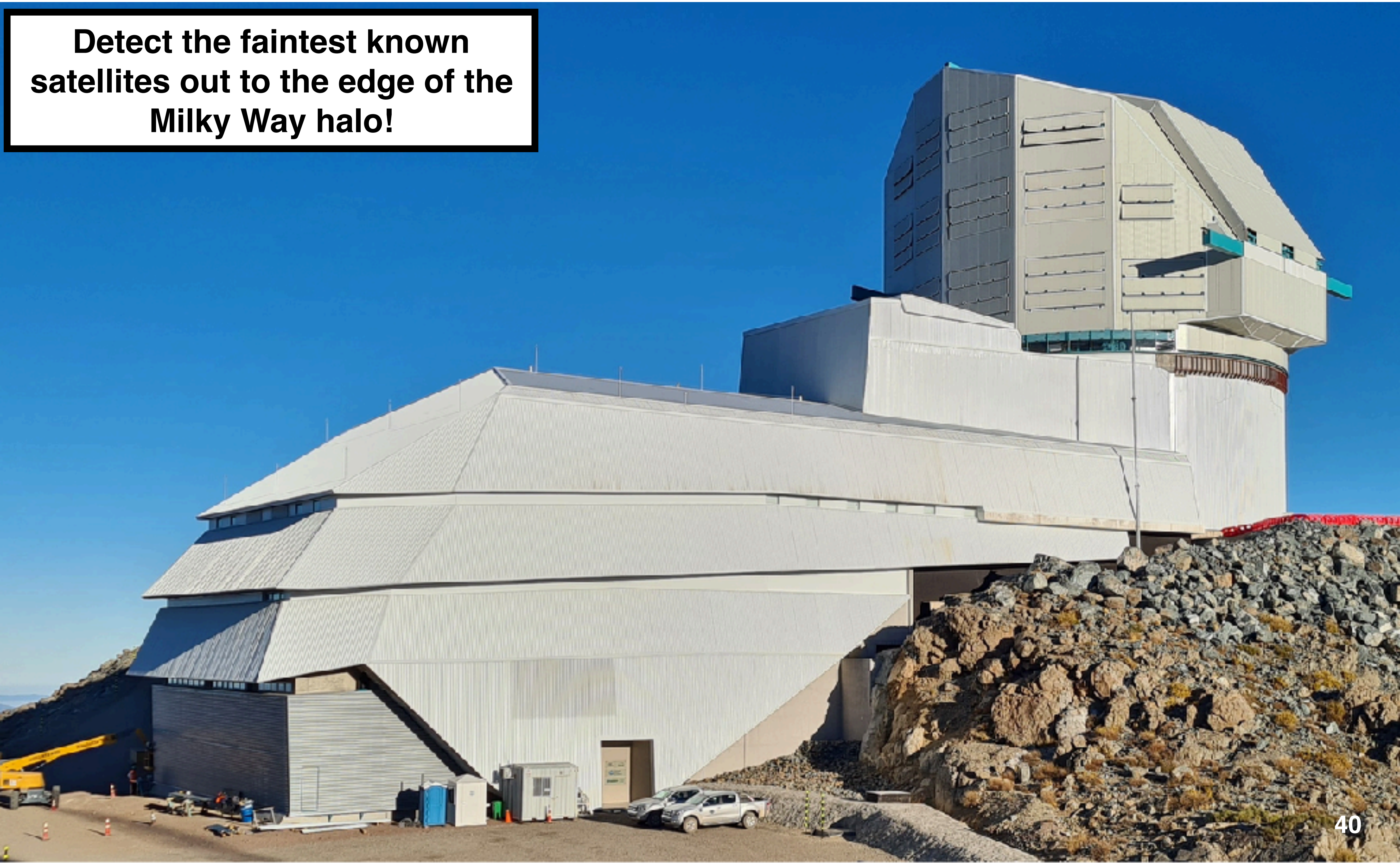
All data public immediately!

https://delve-survey.github.io/



The Vera C. Rubin Observatory is Coming!

Detect the faintest known satellites out to the edge of the Milky Way halo!



Summary

- Astrophysics and cosmology probe fundamental particle physics of dark matter via gravity.
- Observations and simulations continue to improve our ability to disentangle dark matter physics from baryonic effects.
- Exciting new experiments are under construction!