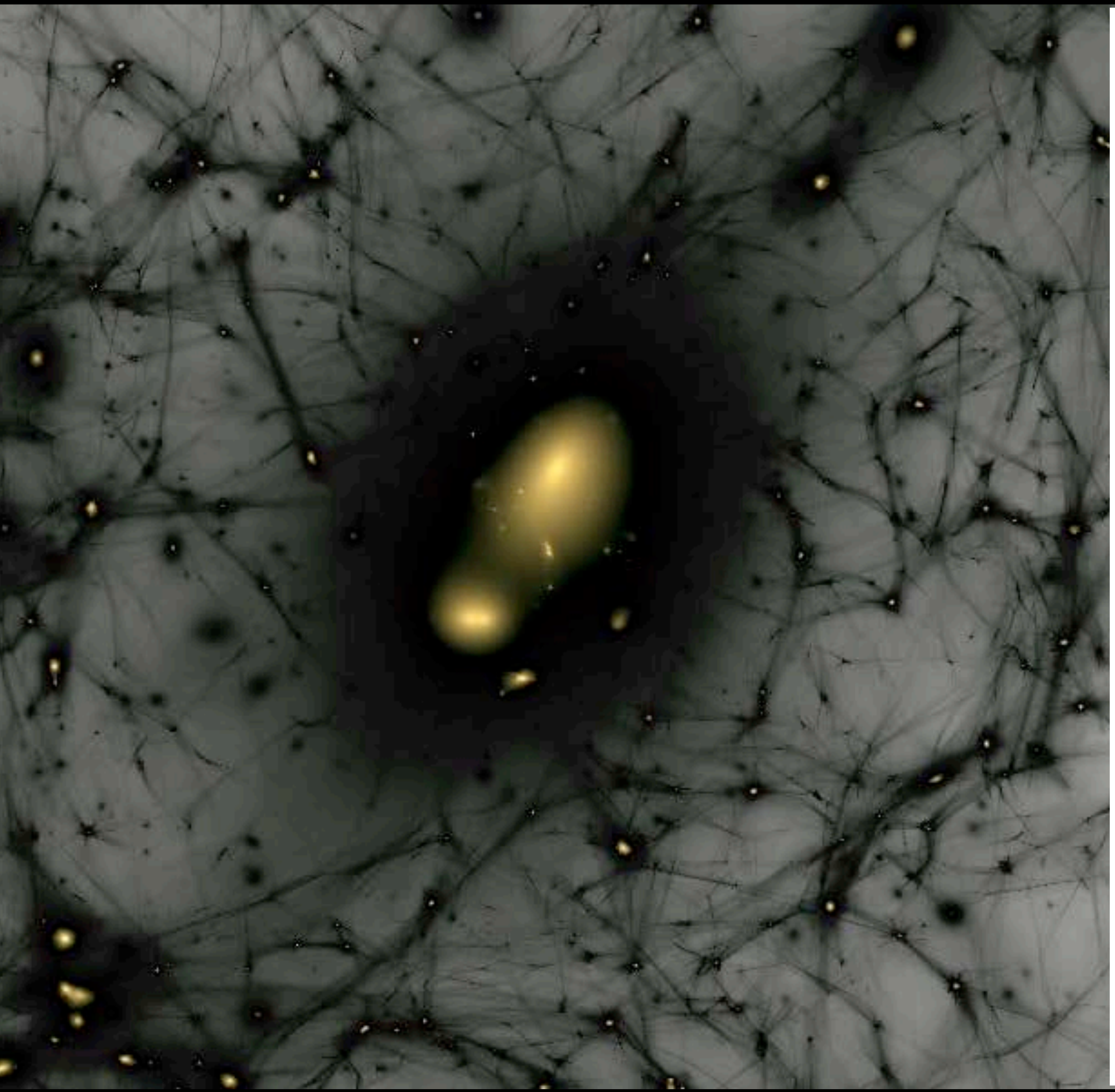
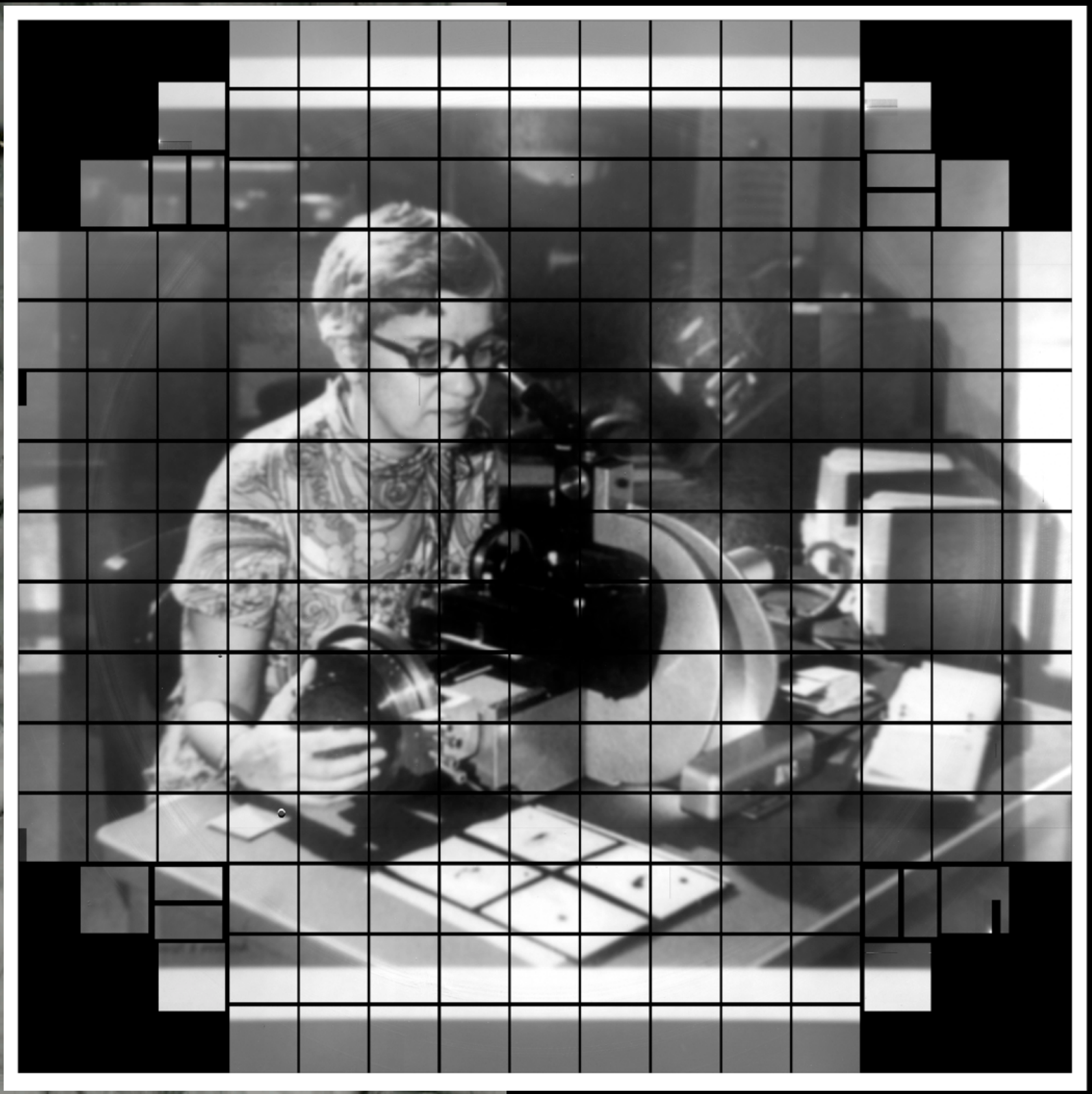
Cosmic Probes of Dark Matter with the Vera C. Rubin Observatory





Keith Bechtol
Steve Kahn Symposium
3 March 2023

LSST DESC
Dark Energy Science Collaboration

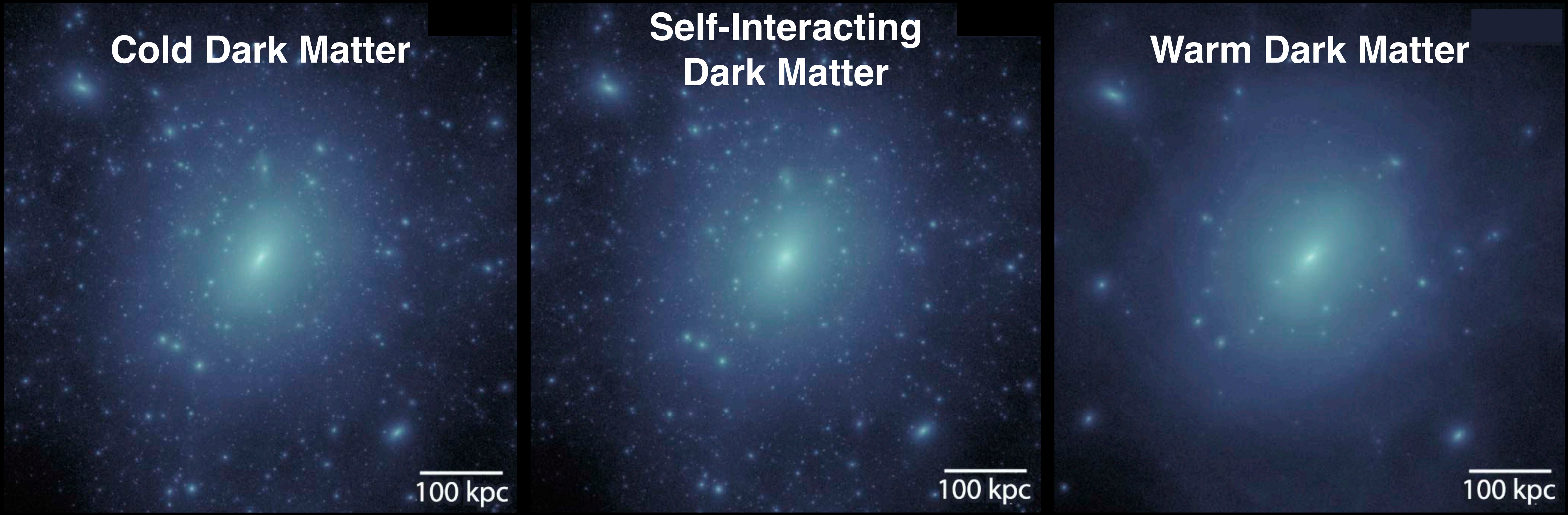
VERA C. RUBIN
OBSERVATORY

THE UNIVERSITY of WISCONSIN
MADISON

LSST will map the small-scale distribution of dark matter…

(e.g., halo abundance, mass profiles, spatial distribution)

Reviewed by Bullock & Boylan-Kolchin 2017



Cored Density Profiles

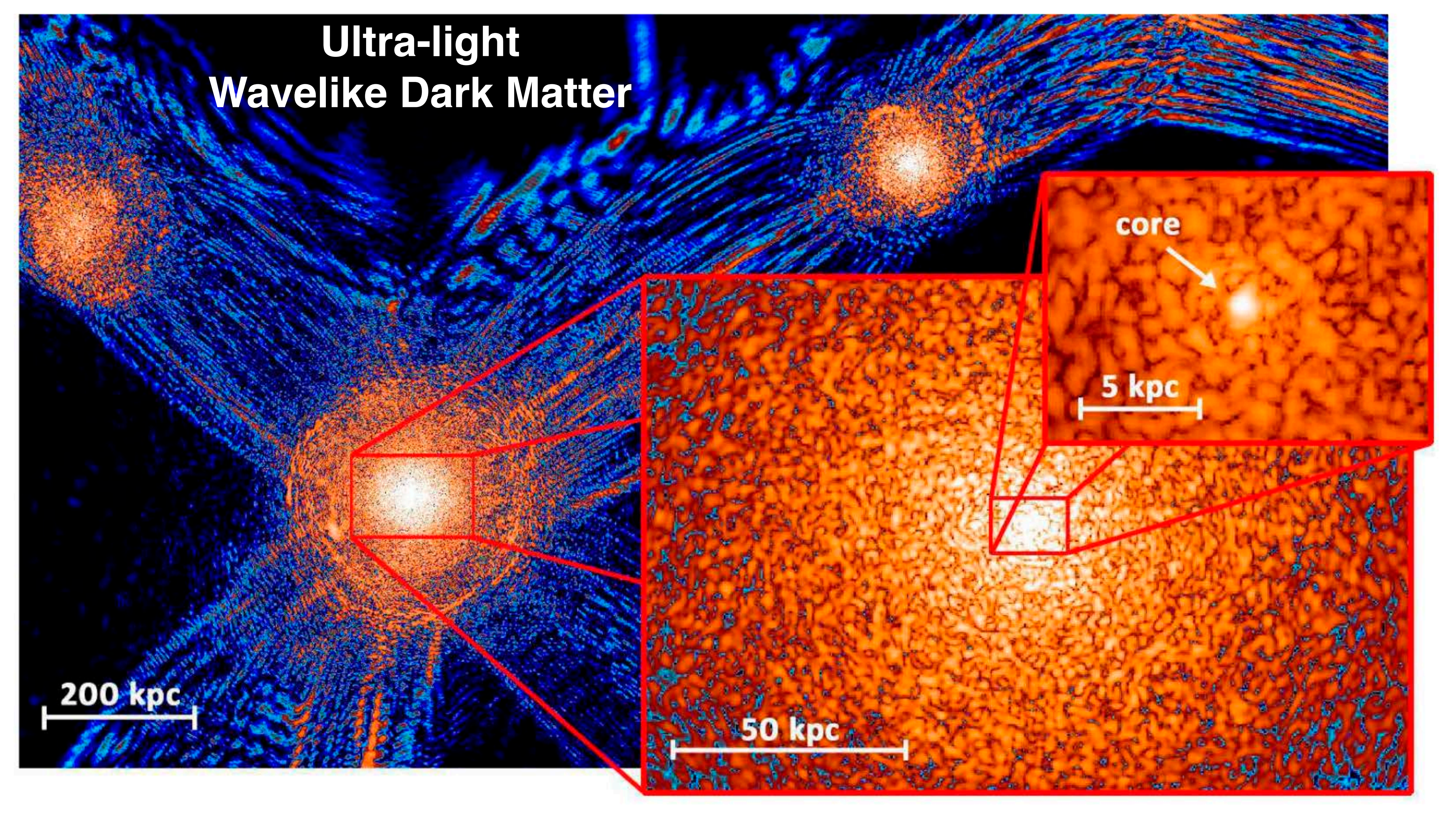
Fewer Substructures

…to measure the microphysics of dark matter

(e.g., mass, interaction cross section, boson/fermion, lifetime, production mechanism)

LSST will map the small-scale distribution of dark matter…

(e.g., halo abundance, mass profiles, spatial distribution)



Schive et al. 2014

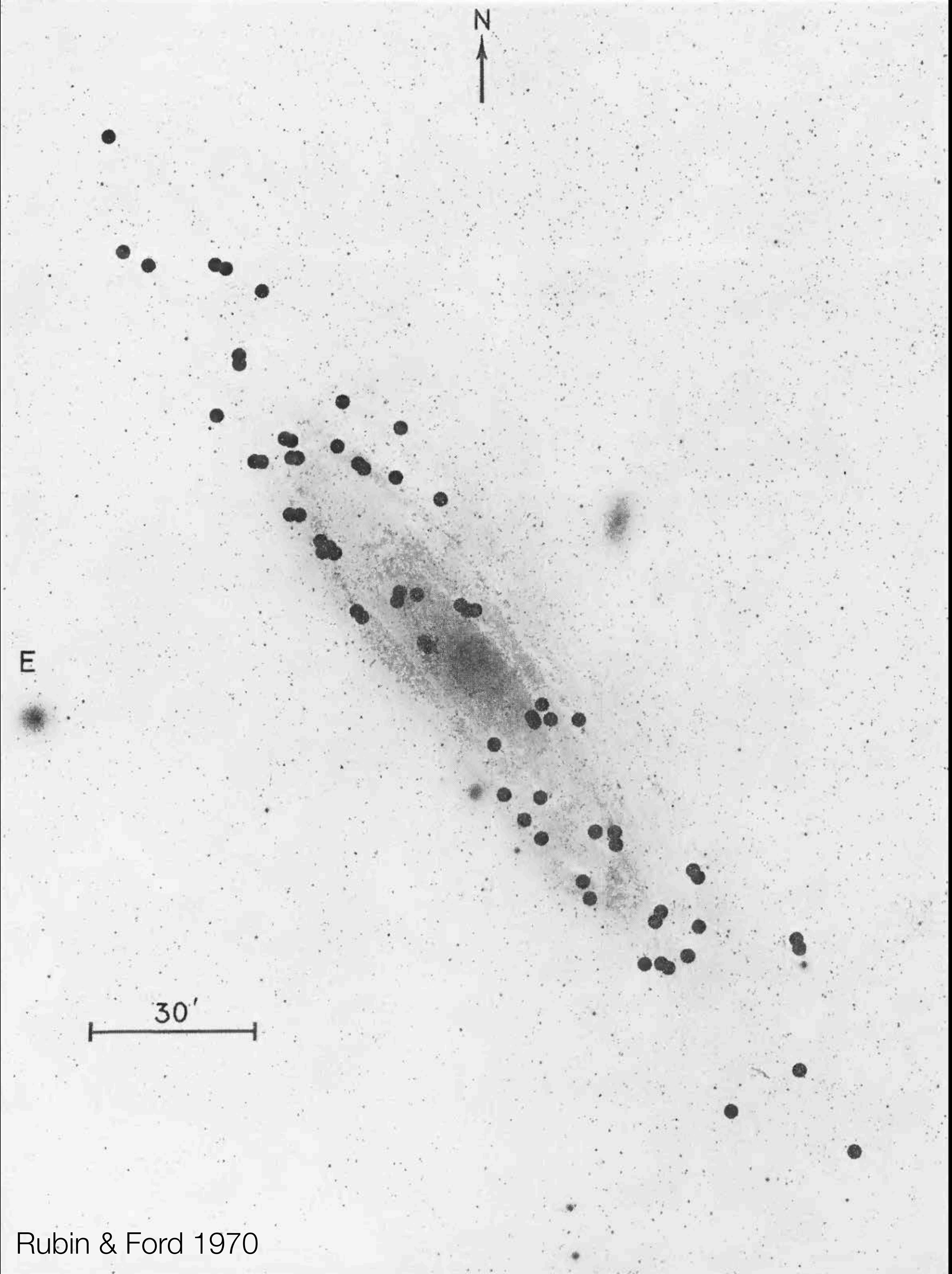
…to measure the microphysics of dark matter

(e.g., mass, interaction cross section, boson/fermion, lifetime, production mechanism)

Motivation for a "Dark Matter Telescope"

Development of the collision-less Cold Dark Matter paradigm

Physics beyond the Standard Model



Rubin & Ford 1970

Vera Rubin designed an observing program that collected spectra of 67 H II regions from 3 to 24 kpc from the nucleus of M31, yielding the first rotation measurements at such large distances from a galaxy center

Rubin works with the cascaded image tube spectrograph developed by Kent Ford that improved the quantum efficiency of photographic plates by factor 10

Galaxy rotation curves show that galaxies are embedded within **extended "halos" of invisible mass**

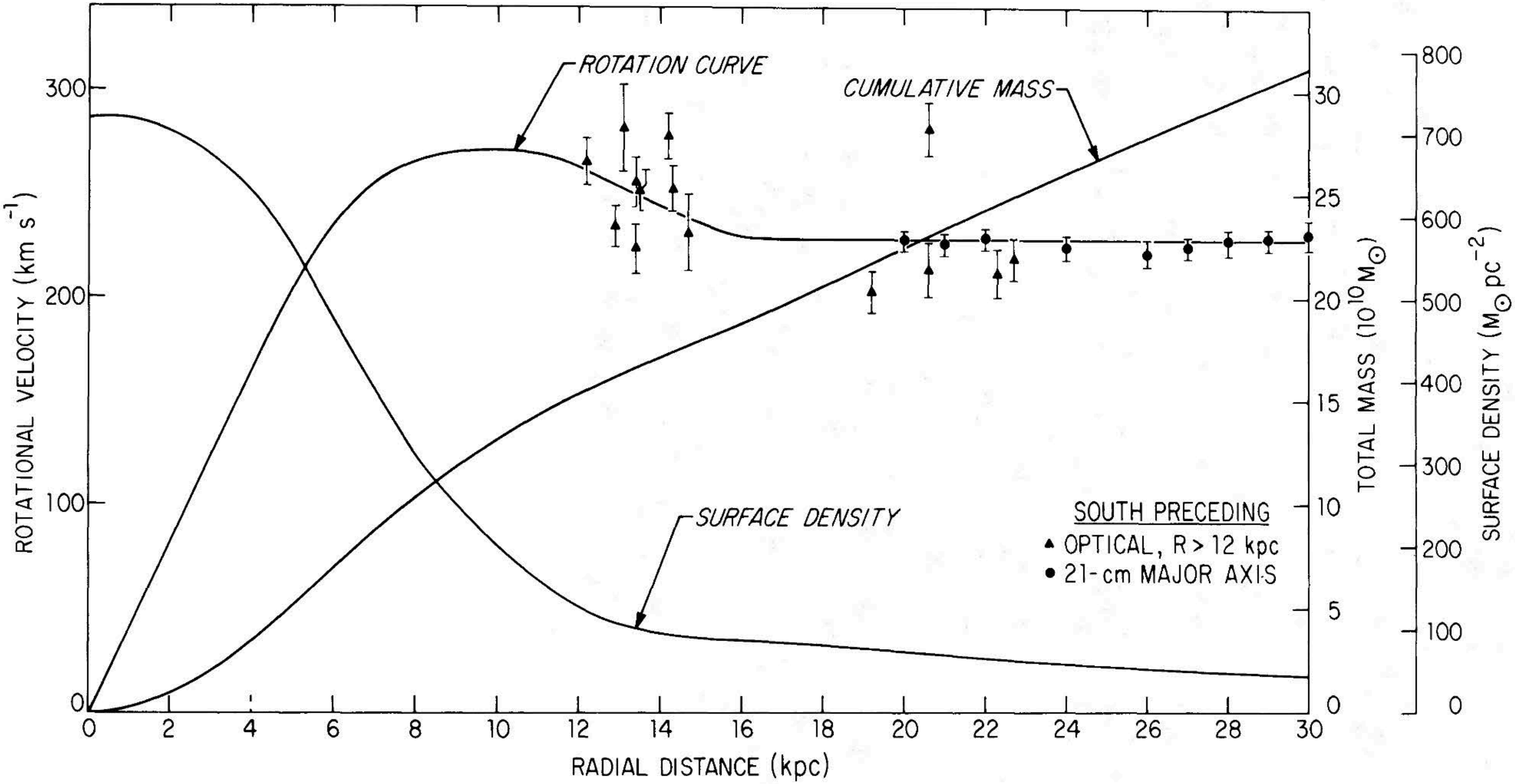


FIG. 16.—The adopted rotation curve, a composite of optical (Rubin and Ford 1970) data and 21-cm major axis measurements. The surface density and cumulative mass curves are for a highly flattened model.

Roberts & Whitehurst 1975

VERA C. RUBIN OBSERVATORY

"Science progresses best when observations force us to alter our preconceptions"

- Vera Rubin

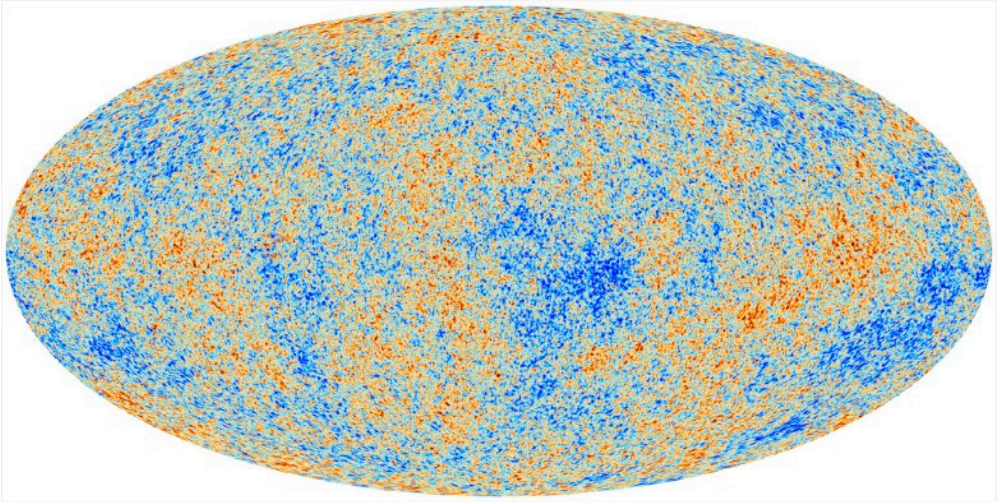
https://rubinobs.org/explore/why-vera-rubin

Vera Rubin challenged preconceptions

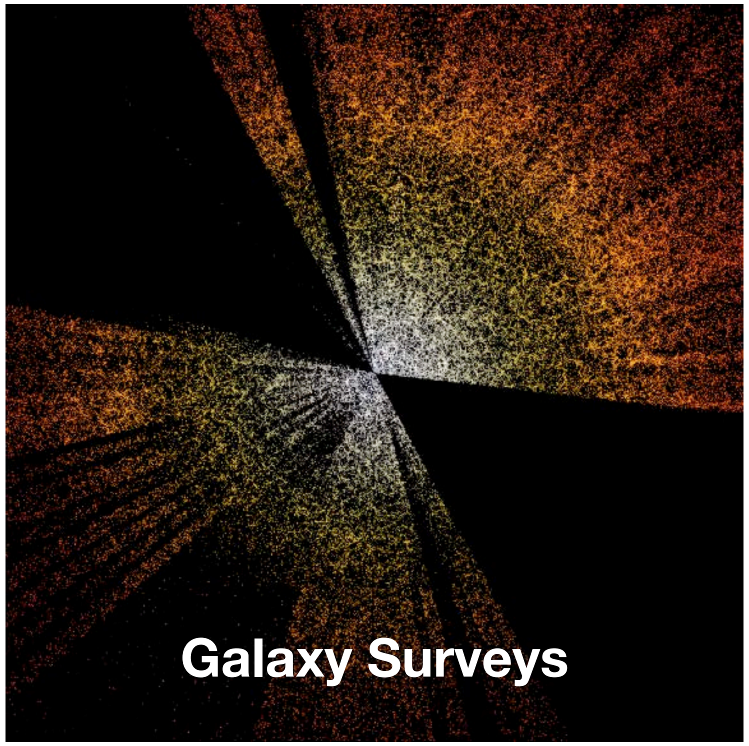
in galaxy formation, cosmology, and particle physics …

of who could be a scientist …

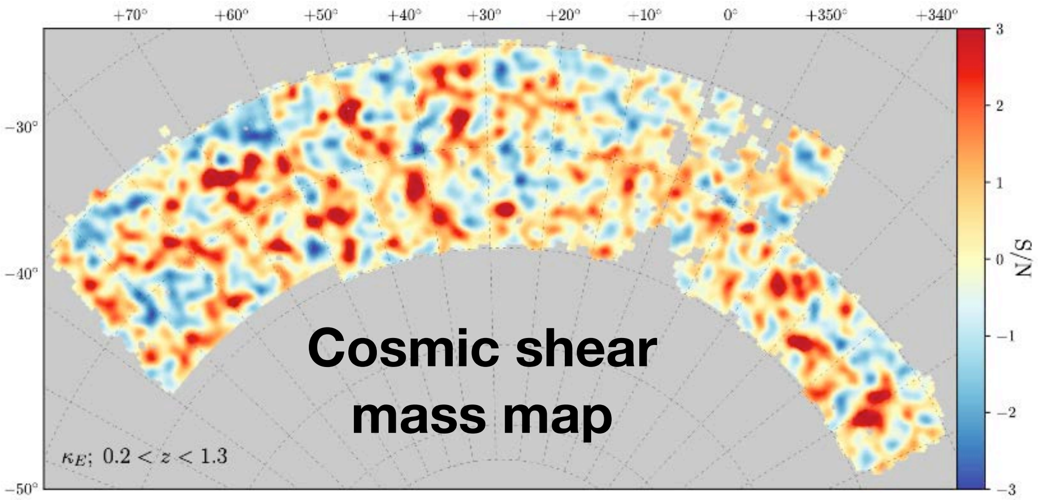
https://rubinobs.org/explore/why-vera-rubin



Cosmic Microwave Background

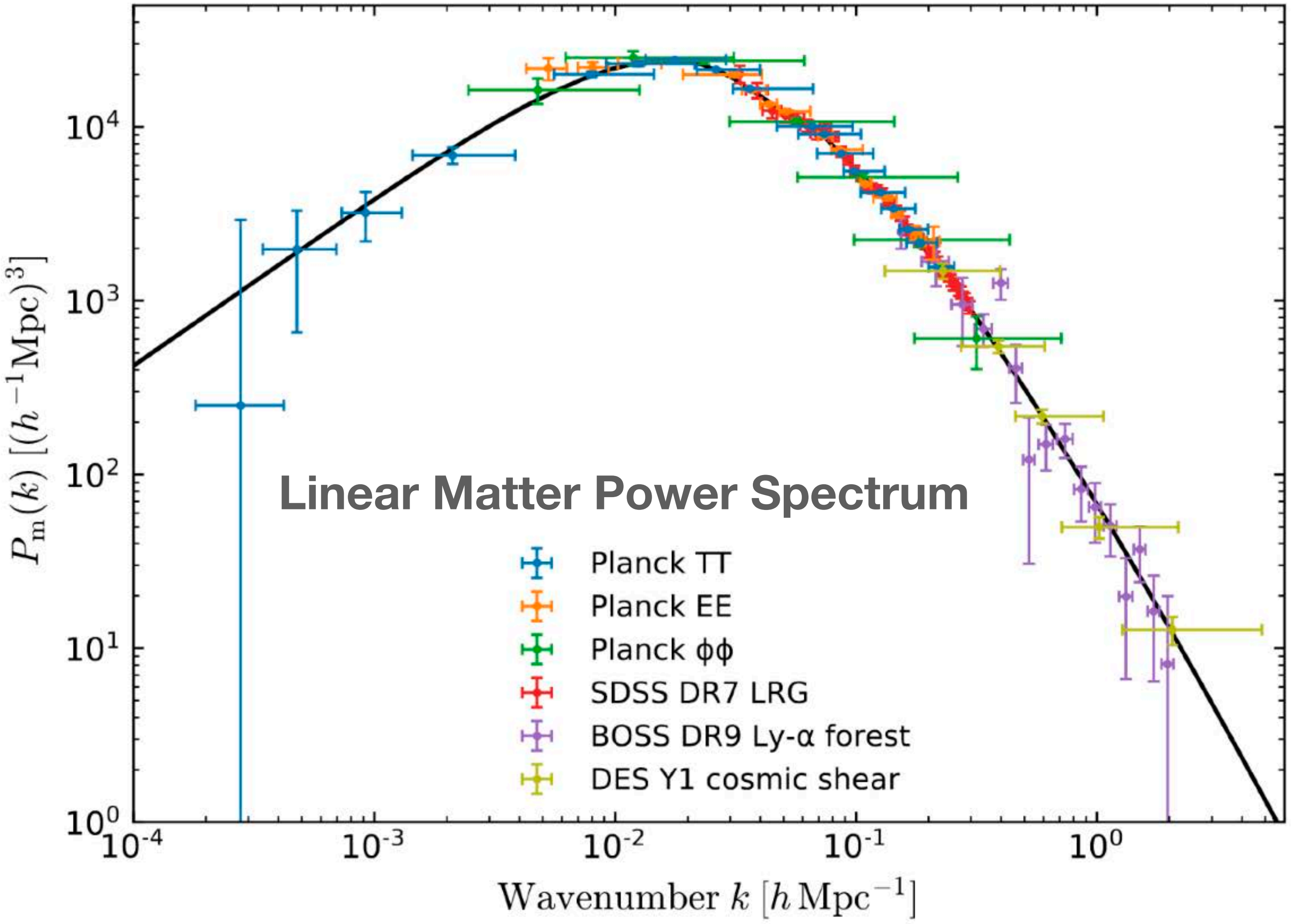


Galaxy Surveys



Cosmic shear mass map

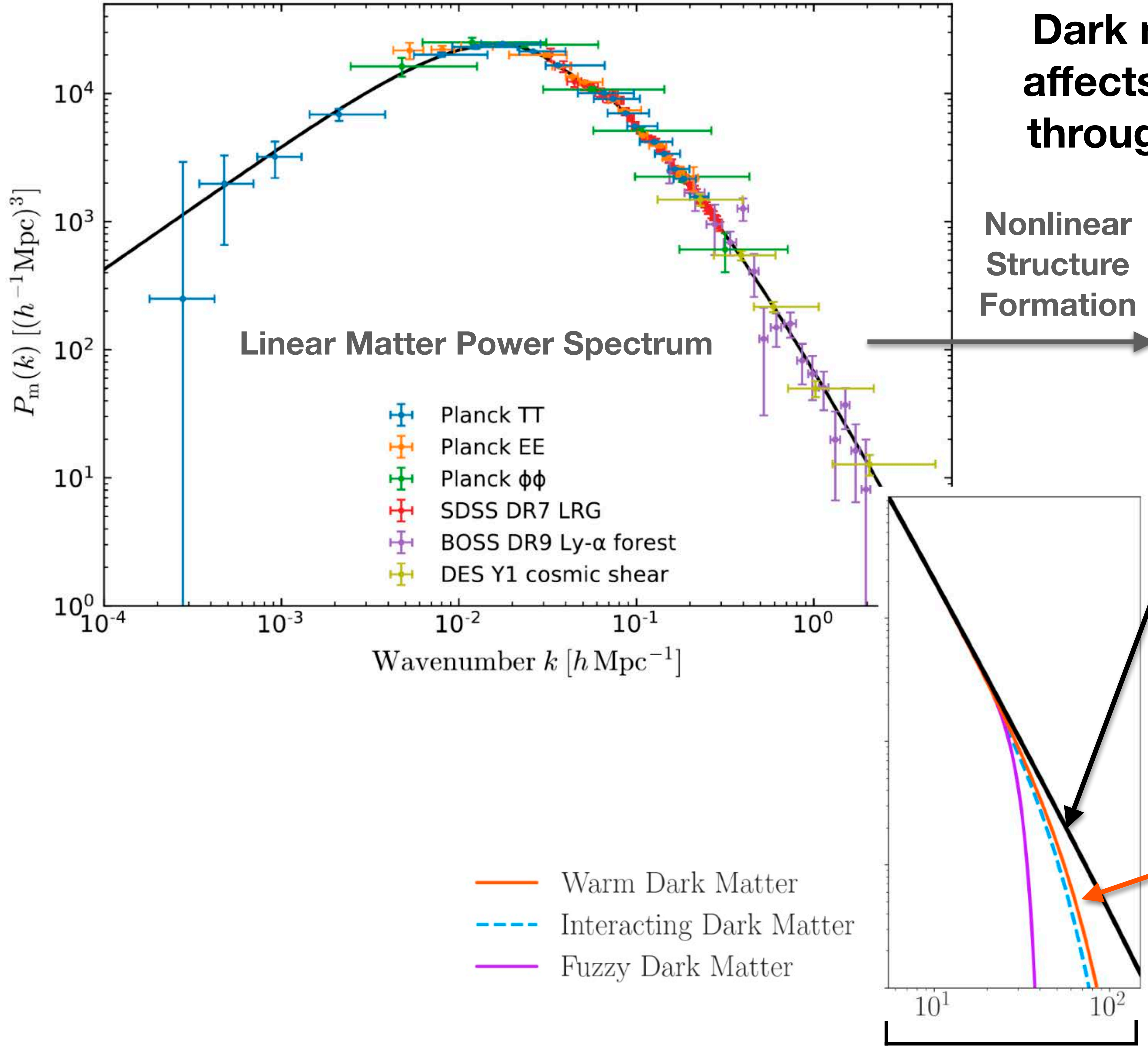
Detailed mapping between luminous galaxies and their invisible dark matter halos across 13 billions years of cosmic history and 7 orders of magnitude in dark matter halo mass



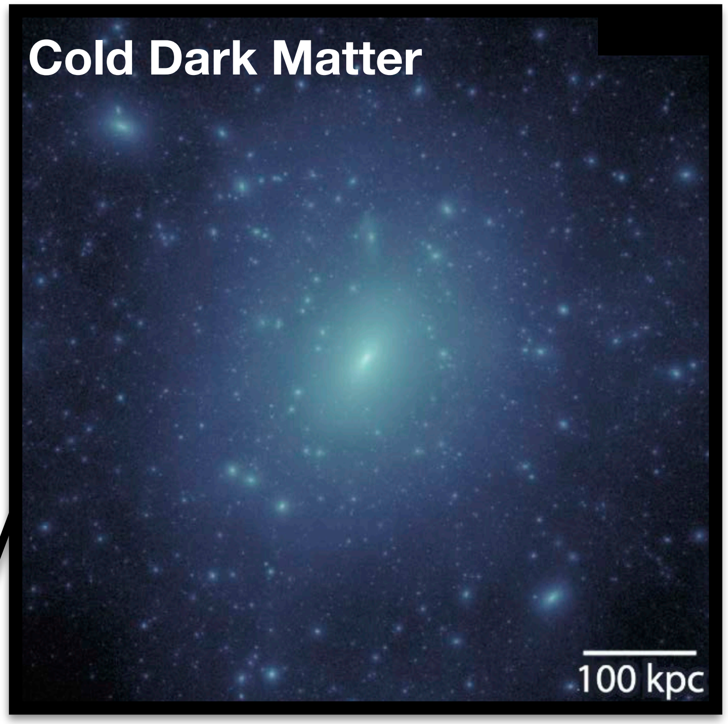
Linear Matter Power Spectrum

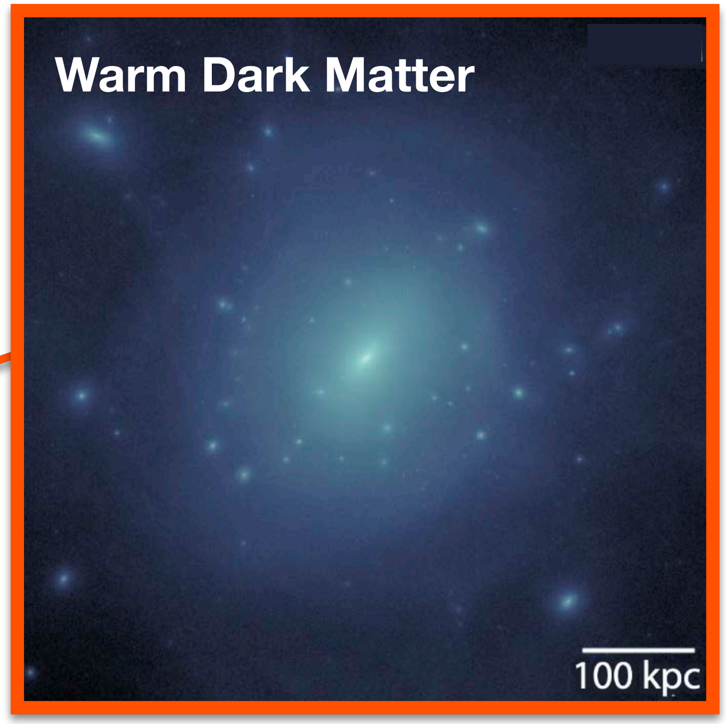
Chabanier 2019
arXiv:1905.08103

Dark matter microphysics affects structure formation throughout cosmic history



Nonlinear Structure Formation

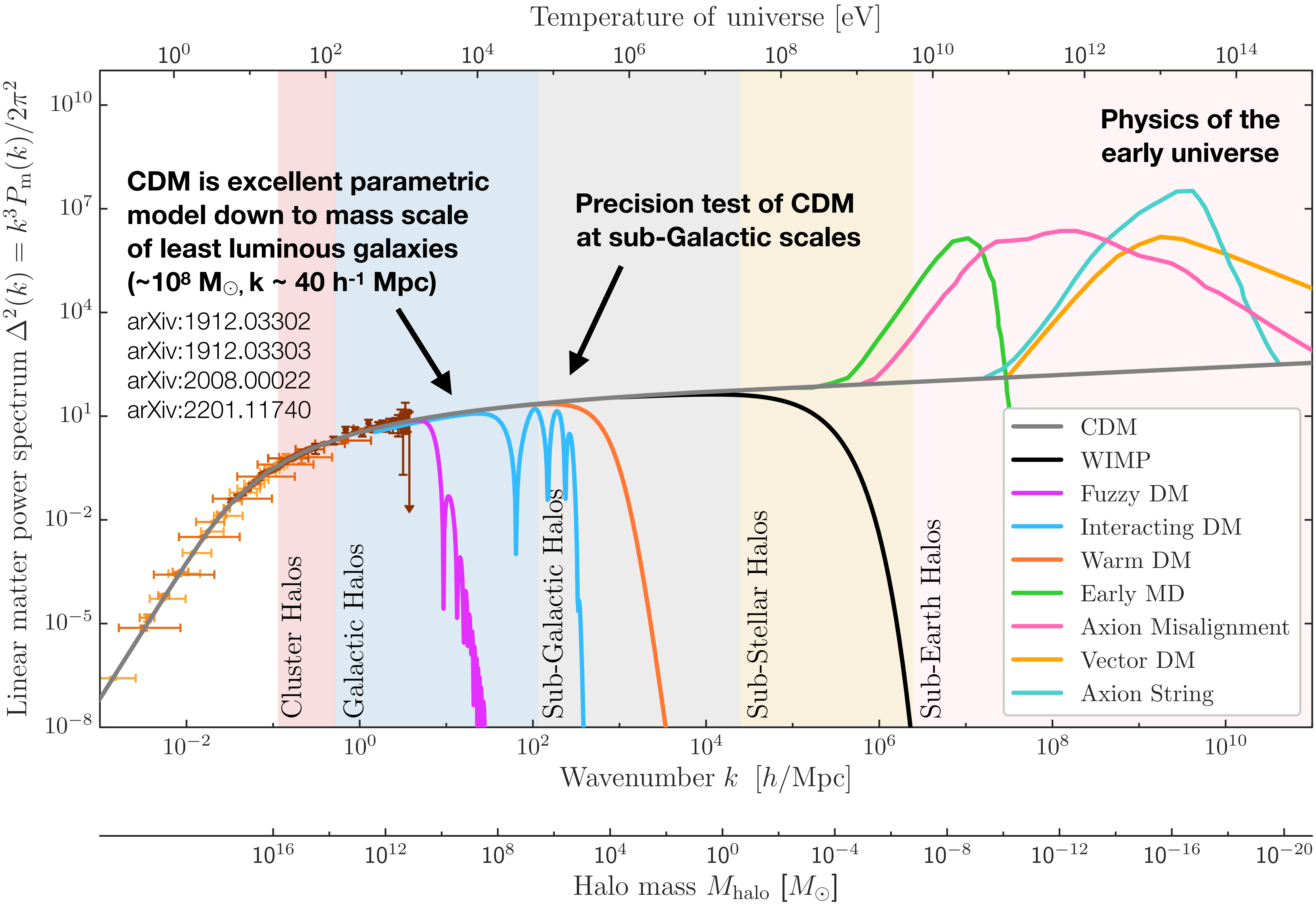




$M_{\mathrm{halo}} \sim 10^6 - 10^{10}\ M_\odot$

Scales measured w/ LSST

Slide adapted from Ethan Nadler



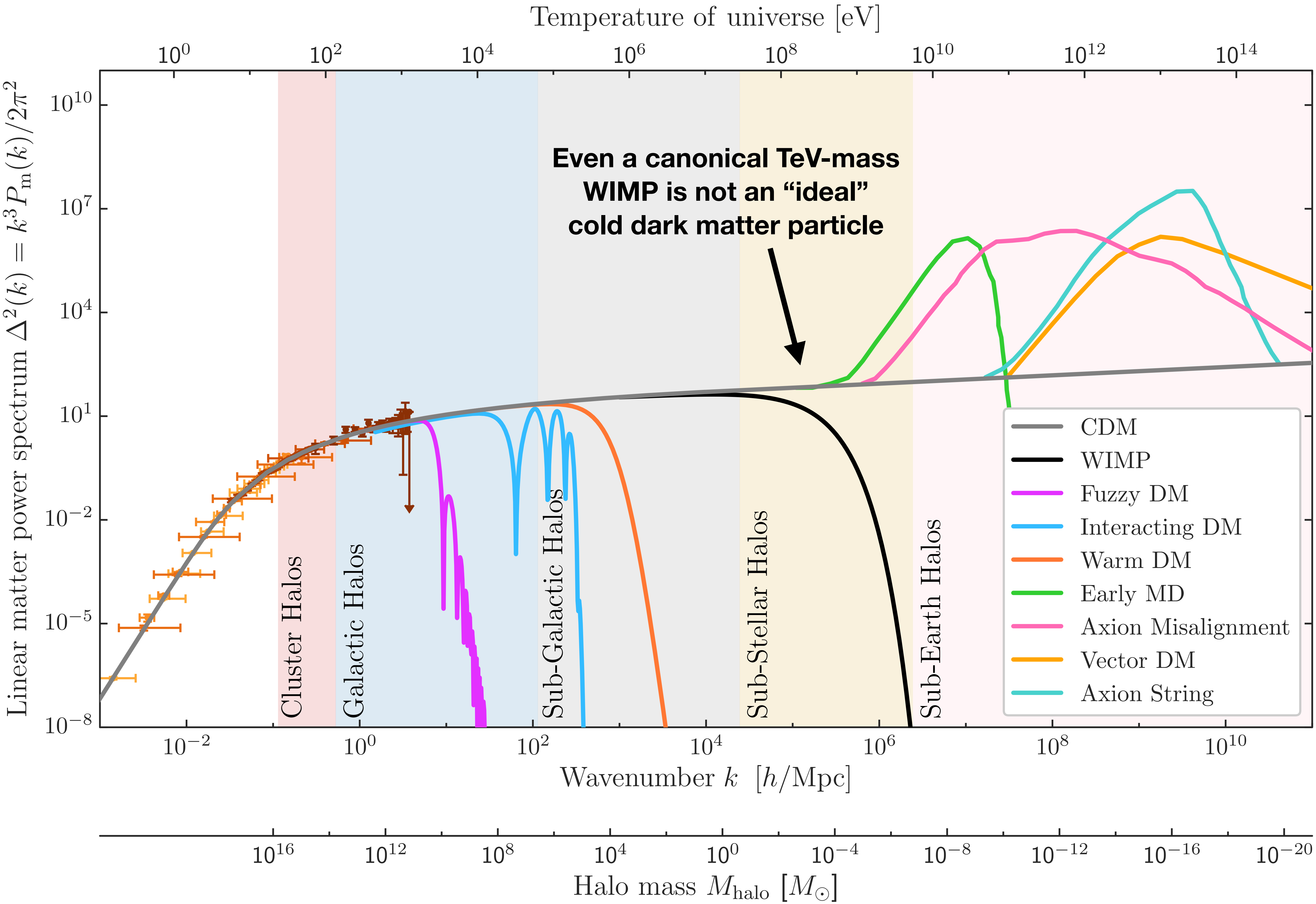
CDM is excellent parametric model down to mass scale of least luminous galaxies (~10^8 $M_\odot$, k ~ 40 h^{-1} Mpc)

arXiv:1912.03302
arXiv:1912.03303
arXiv:2008.00022
arXiv:2201.11740

Precision test of CDM at sub-Galactic scales

Physics of the early universe

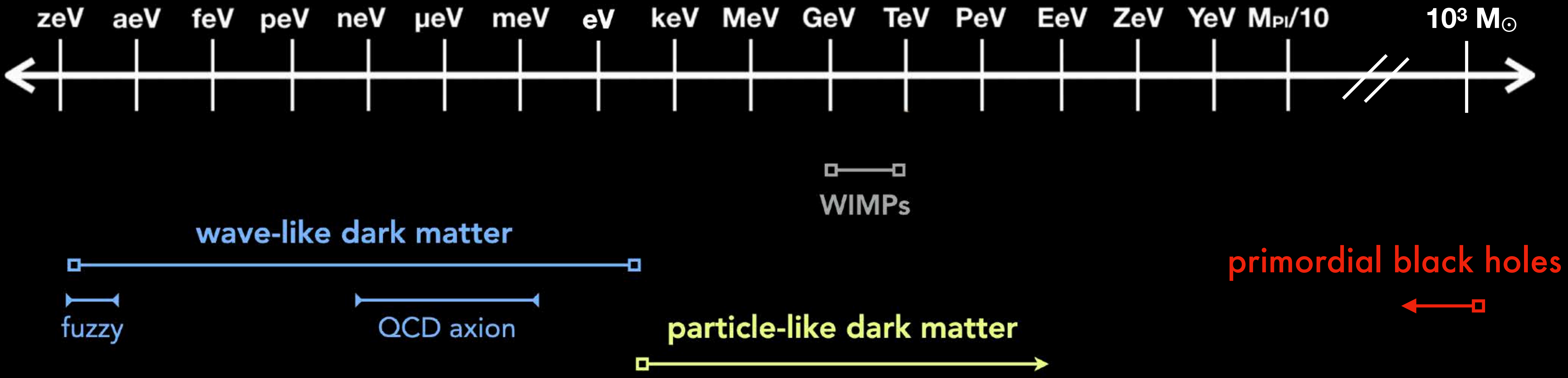
Bechtol et al. 2022 arXiv:2203.07354



Even a canonical TeV-mass WIMP is not an “ideal” cold dark matter particle

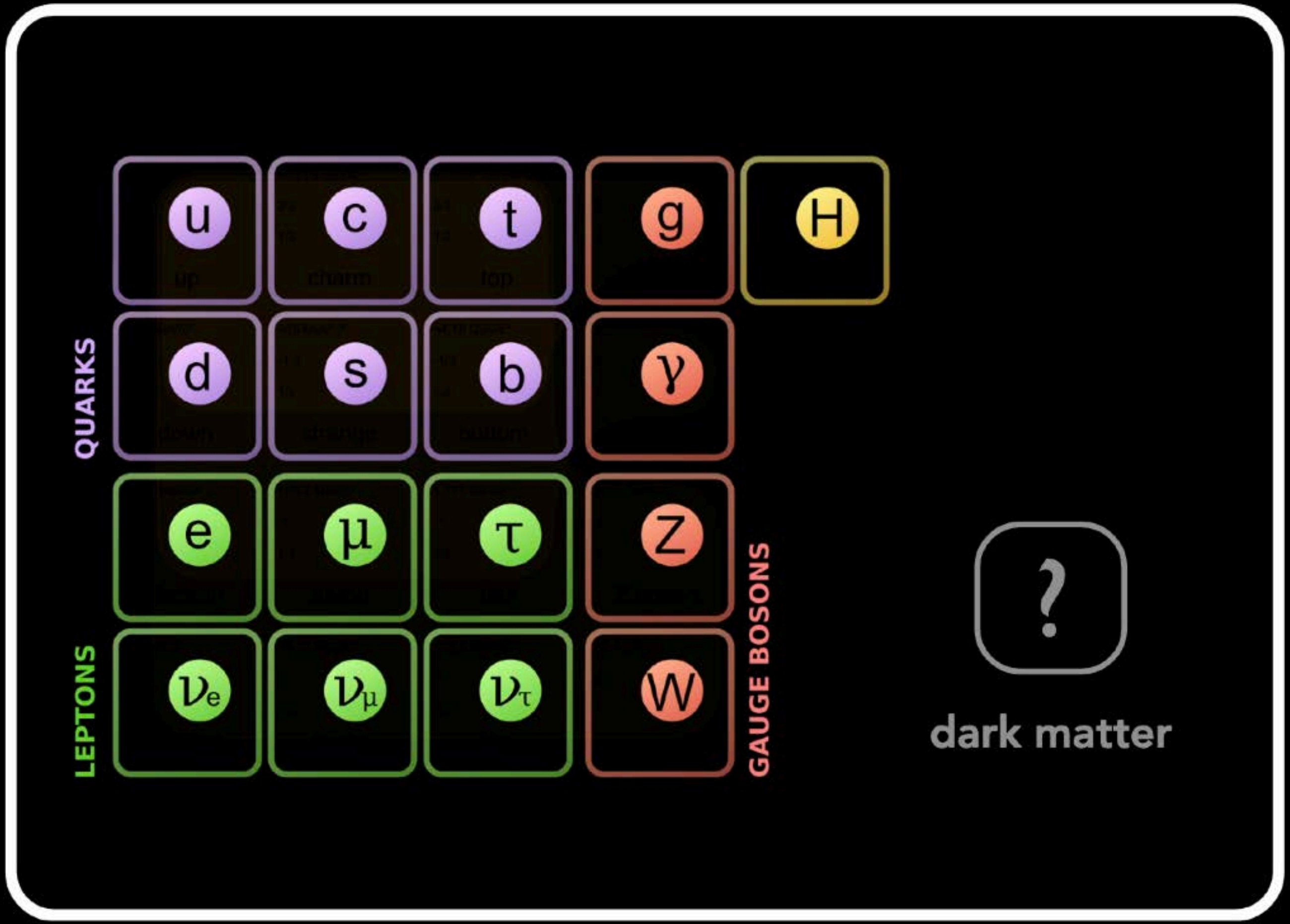
Bechtol et al. 2022 arXiv:2203.07354

- ✓ Interacts through **gravity**; rarely, if at all, via strong, weak, or electromagnetic forces
- ✓ Nearly collision-less
- ✓ Spin unknown — fermion or boson ??
- ✓ Multiple particles / additional states in same sector ??
- ✓ Stable on timescales comparable to age of the Universe
- ✓ Mostly non-relativistic, i.e., “cold”
- ✓ Average cosmic density ~5 times larger than density of baryons
- ✓ Initially distributed with nearly scale-free density perturbation spectrum
- ✓ 10^{-21} eV (de Broglie wavelength) < mass < 10^3 $M_\odot$ (CMB, BBN, LSS)

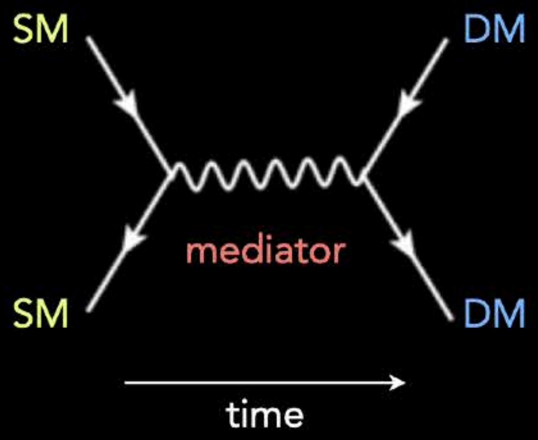


Adapted from Mariangela Lisanti

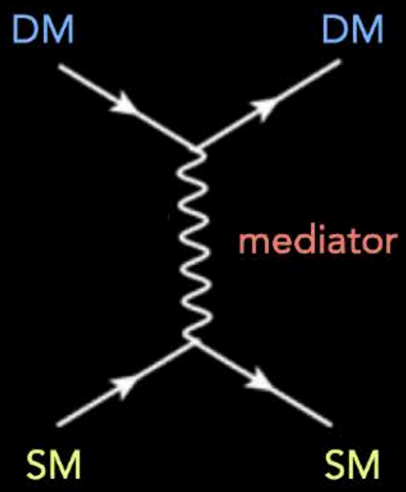
Weakly Interacting Massive Particle (WIMP)



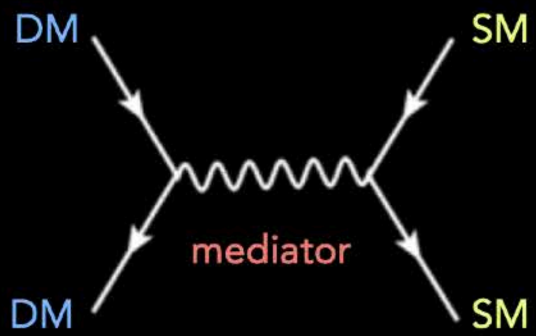
Adapted from
Mariangela Lisanti



DM Production in Colliders

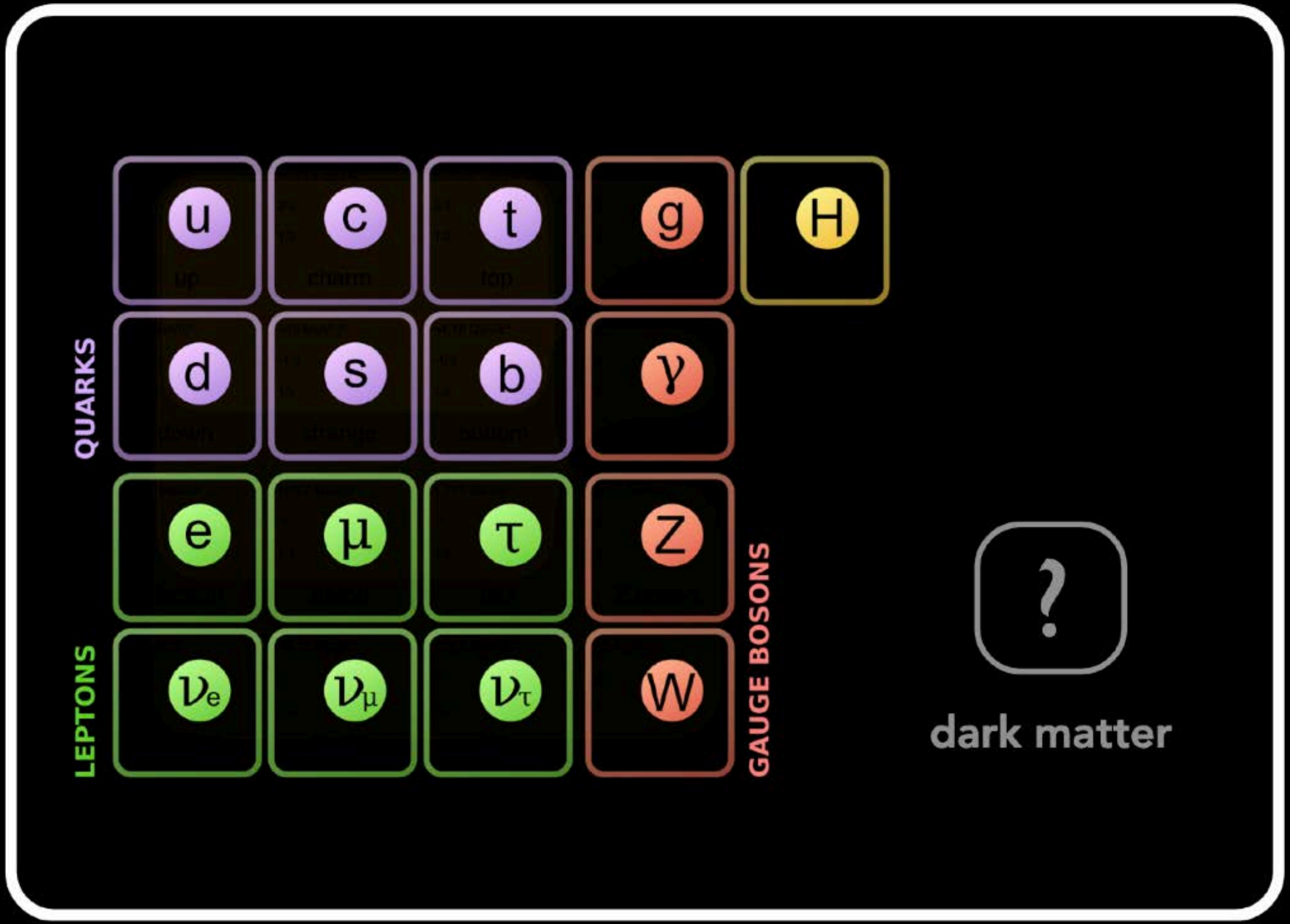


DM Scattering in Laboratory

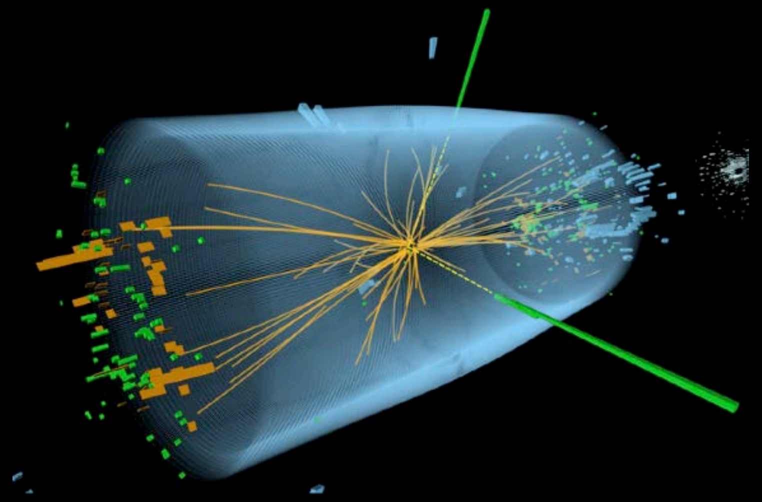


DM Annihilation

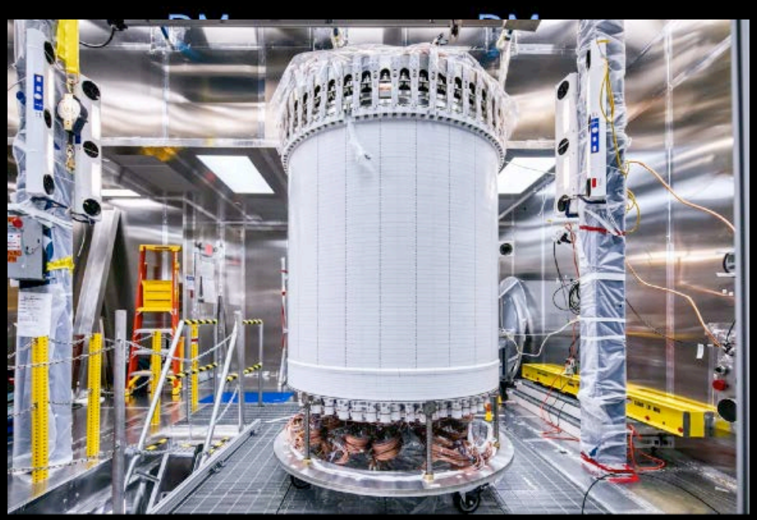
Weakly Interacting Massive Particle (WIMP)



Adapted from
Mariangela Lisanti



DM Production in Colliders



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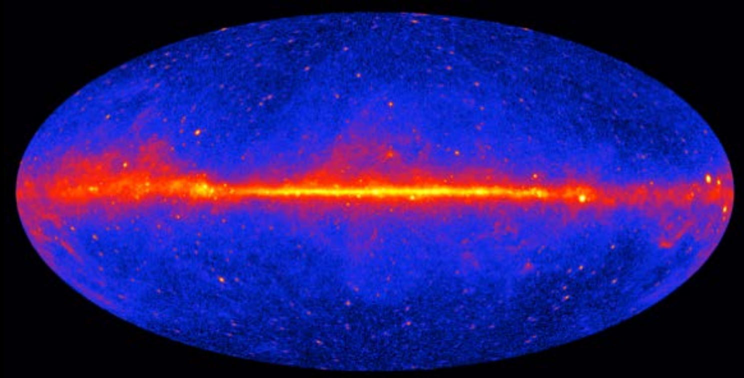
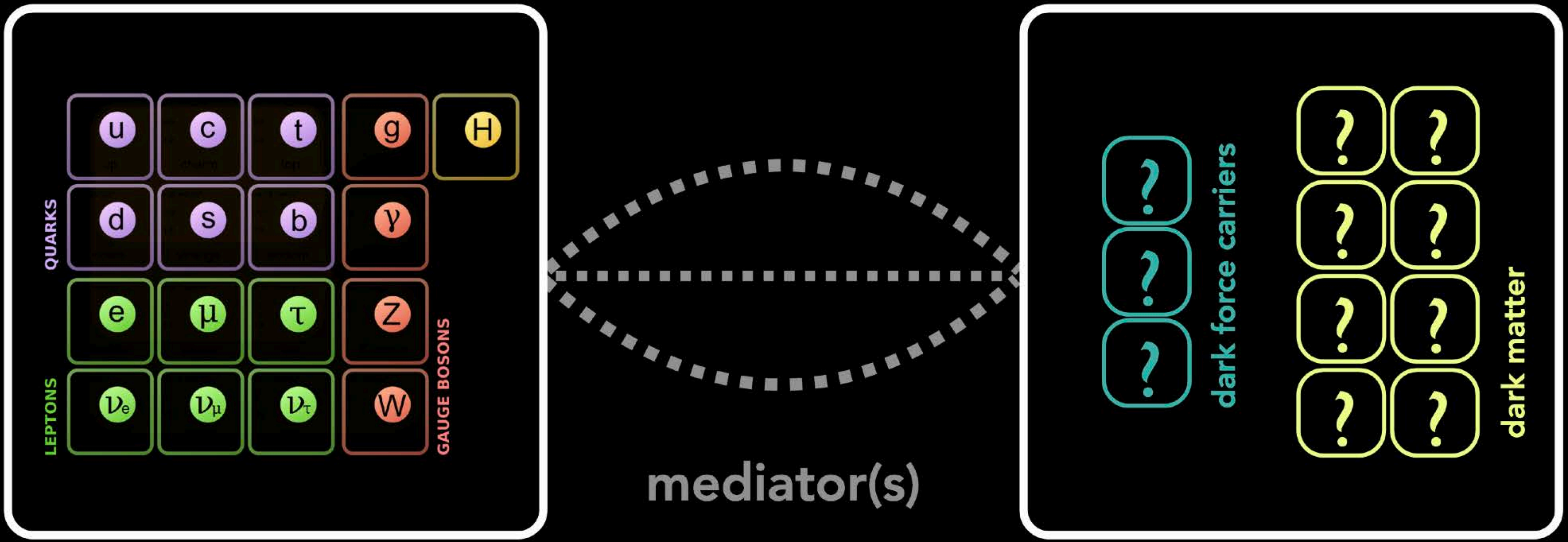
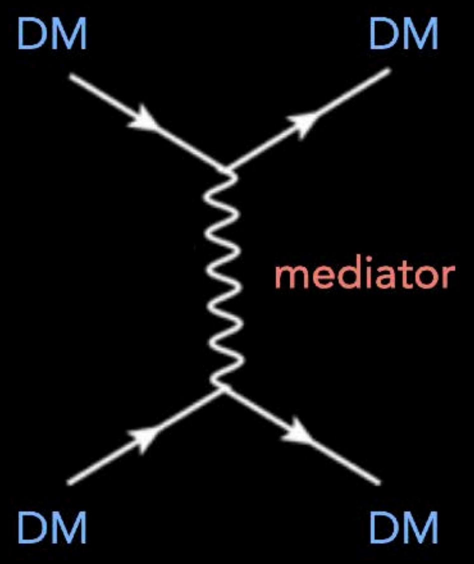


DM Annihilation

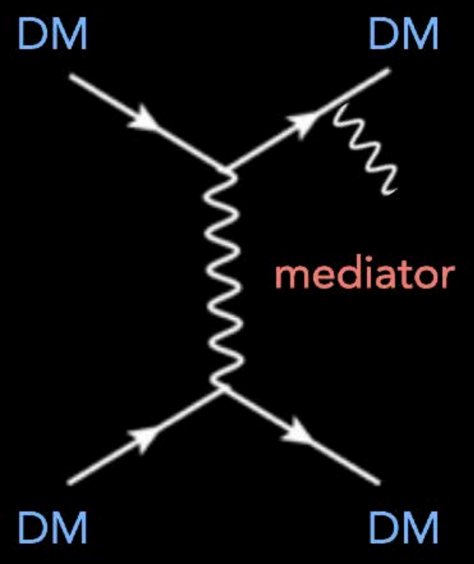
Dark Sectors



Adapted from
Mariangela Lisanti

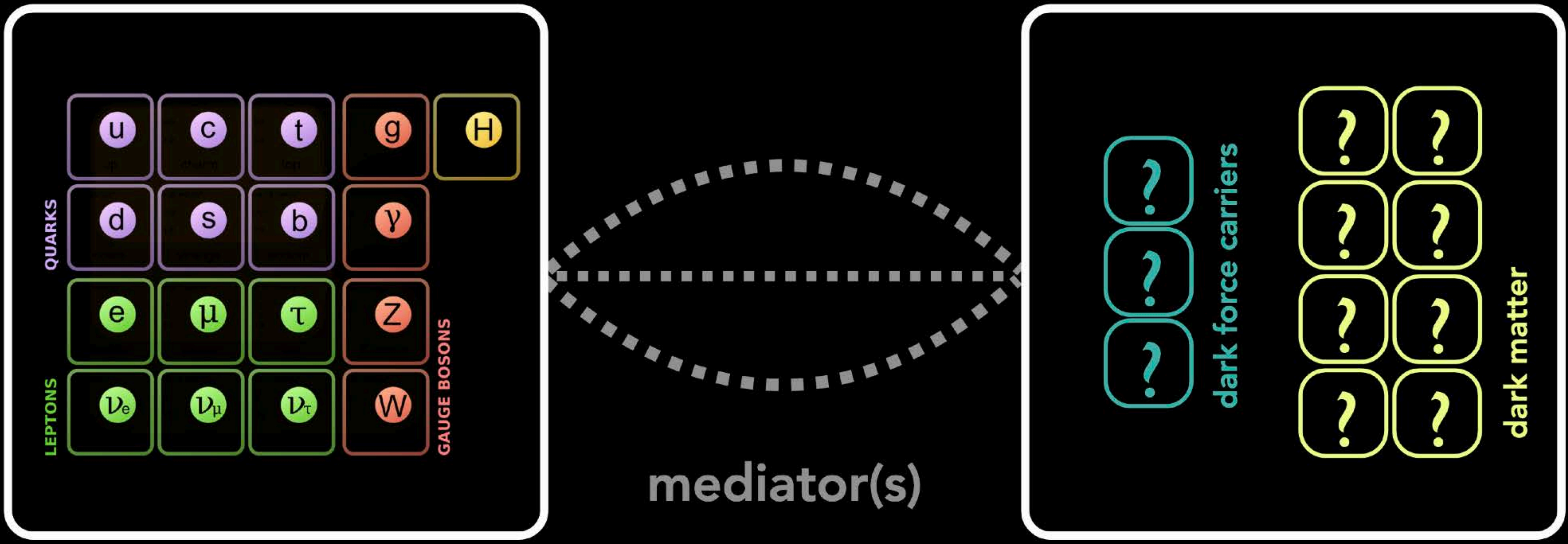


Self-Interacting DM



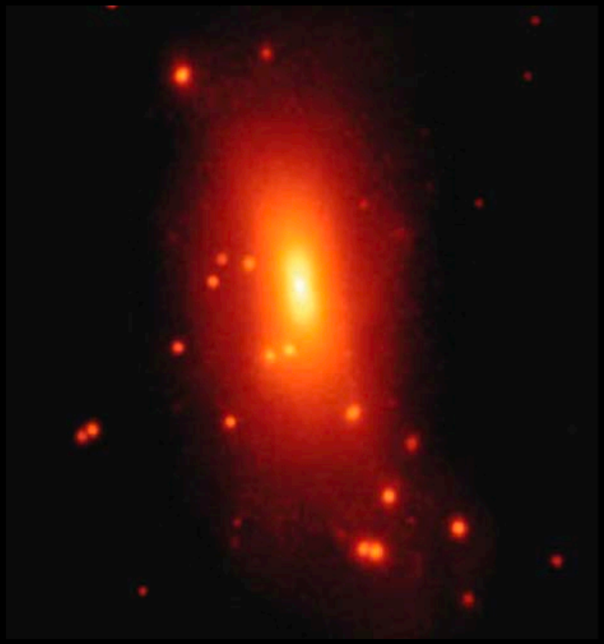
Dissipative DM

Dark Sectors



Adapted from
Mariangela Lisanti

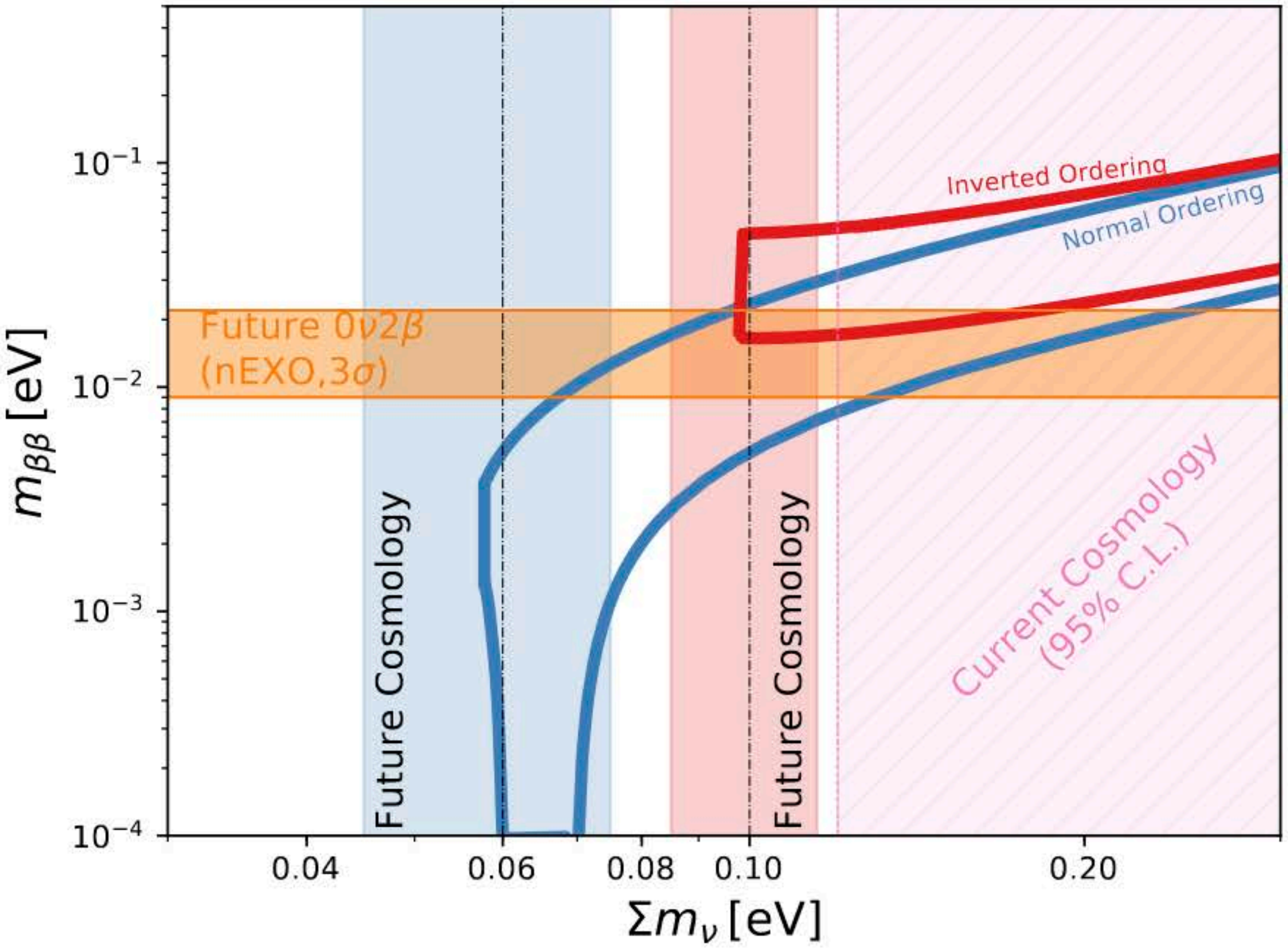
Self-Interacting DM



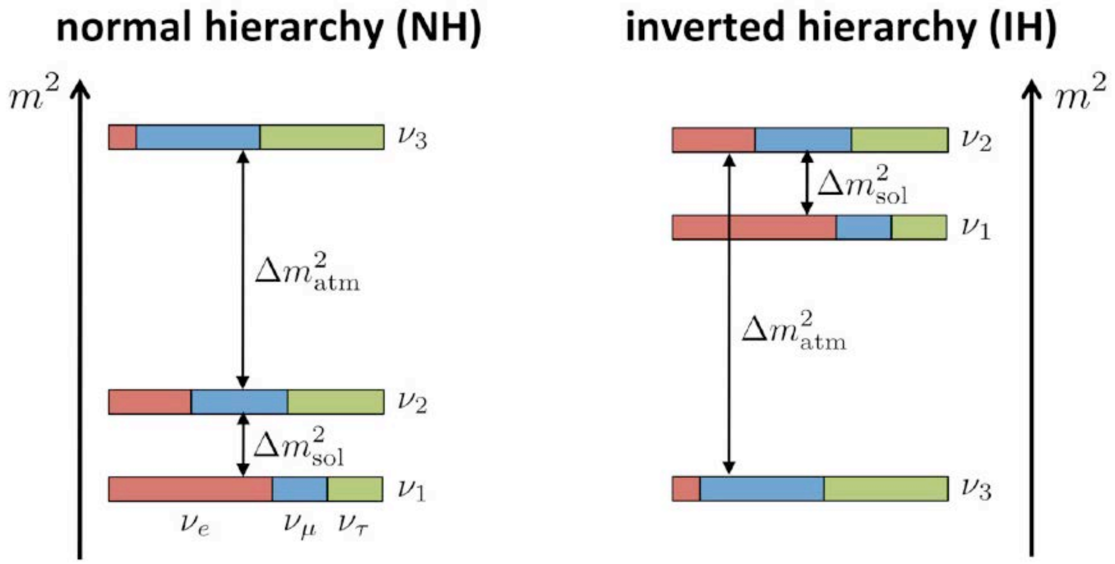
Dissipative DM

Neutrino absolute mass scale: a case study of using galaxy surveys to do particle physics

Mass Associated with Rate of Neutrino-less Double Beta Decay



Sum of Neutrino Masses



CMB-S4 arXiv:1907.04473

Minimum mass threshold implied by oscillation data: $\Sigma m_\nu > 58\ \text{meV}$

$\sigma\left(\Sigma m_\nu\right) = 20\ \text{meV}$ **(LSST + CMB-S4)**

Mishra-Sharma et al.
arXiv:1803.07561

Possible to disfavor inverted hierarchy, and can help distinguish between Dirac / Majorana nature in combination with neutrino-less double beta-decay experiments

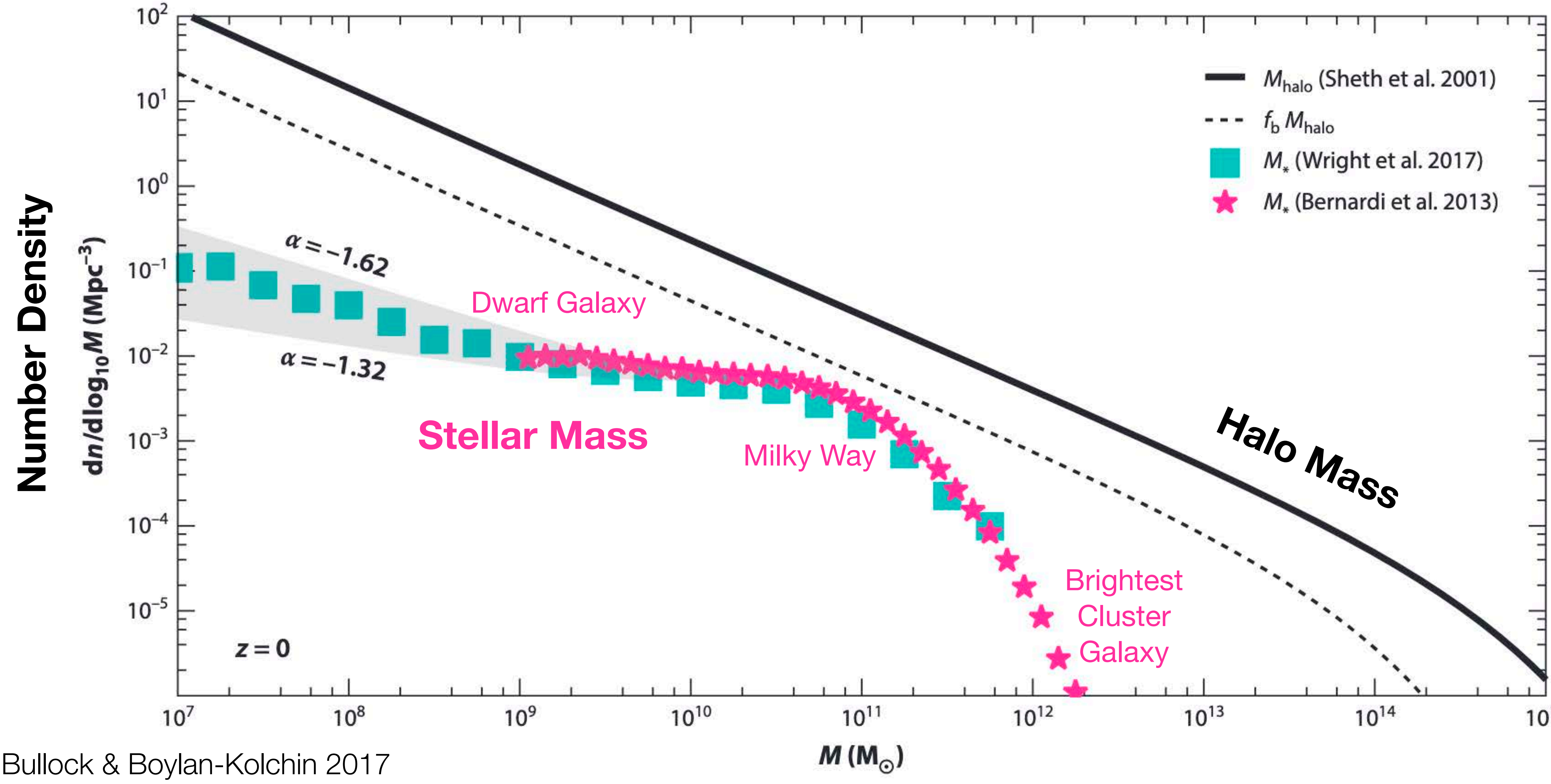
Threshold of Galaxy Formation

What is the minimum halo mass for galaxy formation?

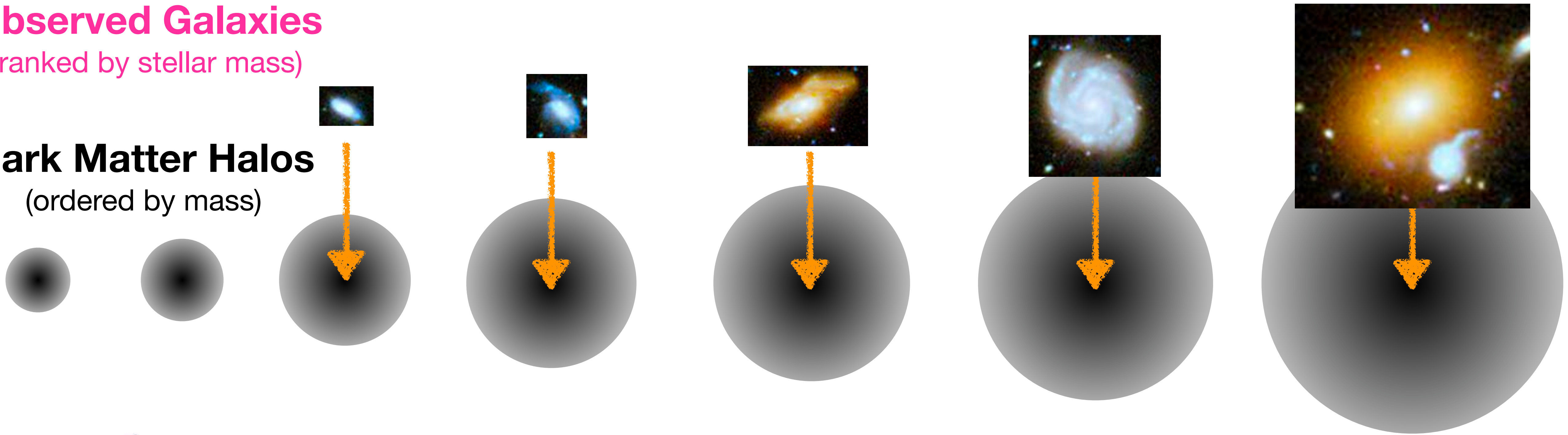
What is the galaxy-halo connection at the extreme faint end of the galaxy luminosity function?

Galaxy-Halo Connection

Abundance Matching (simplified):
most massive galaxies by stellar mass tend to
occupy the most massive dark matter halos



Bullock & Boylan-Kolchin 2017

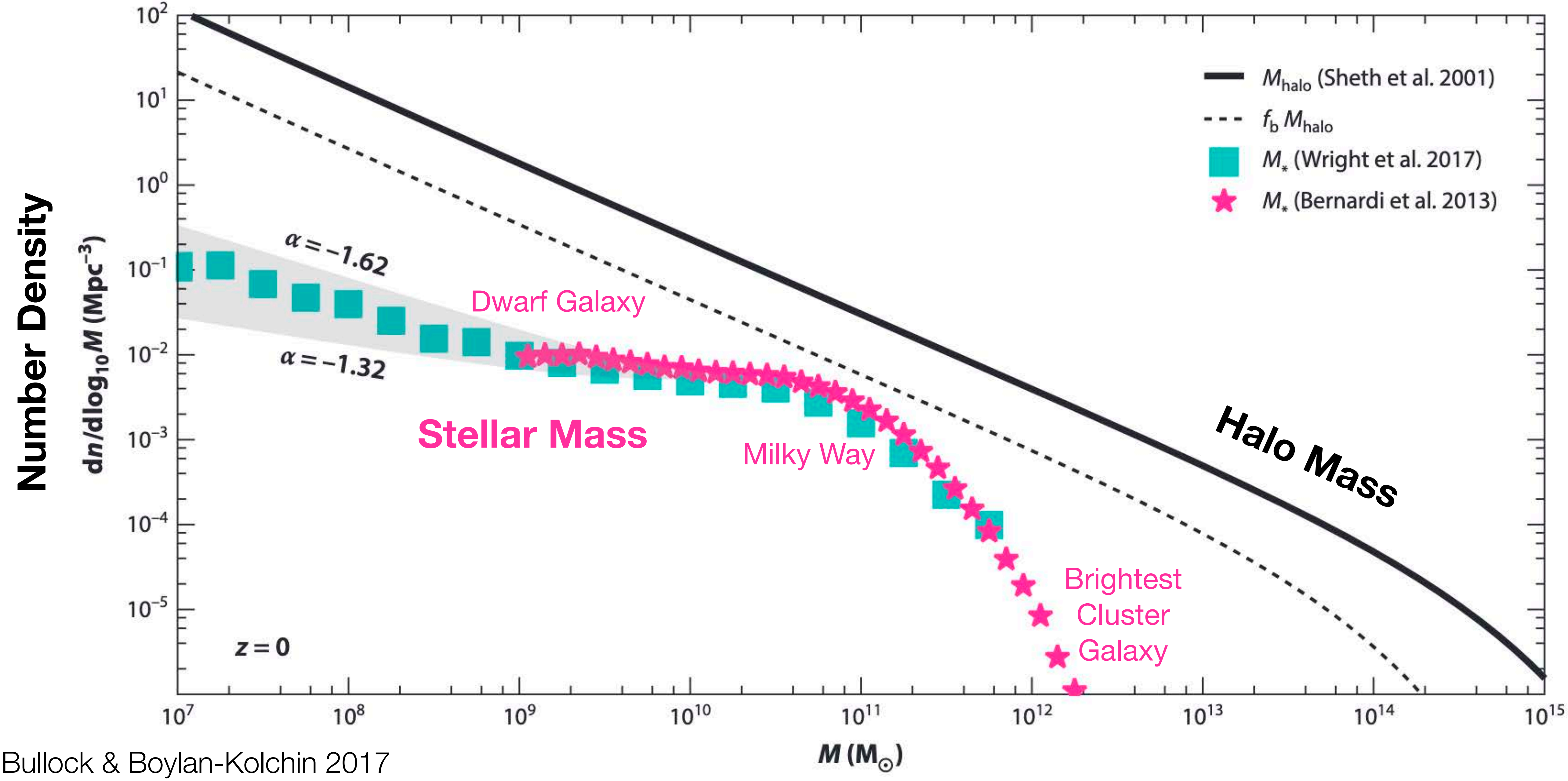


Observed Galaxies

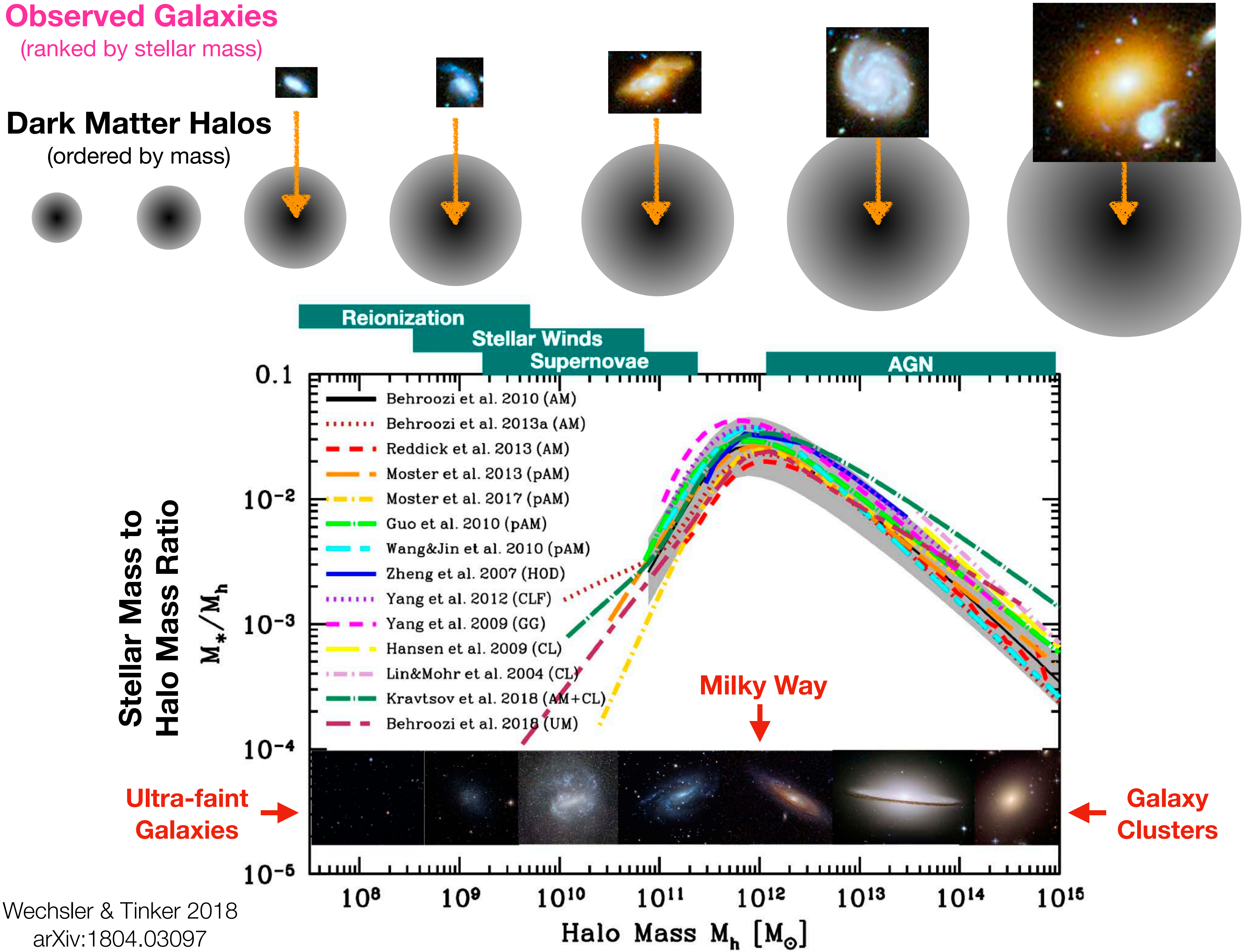
(ranked by stellar mass)

Dark Matter Halos

(ordered by mass)



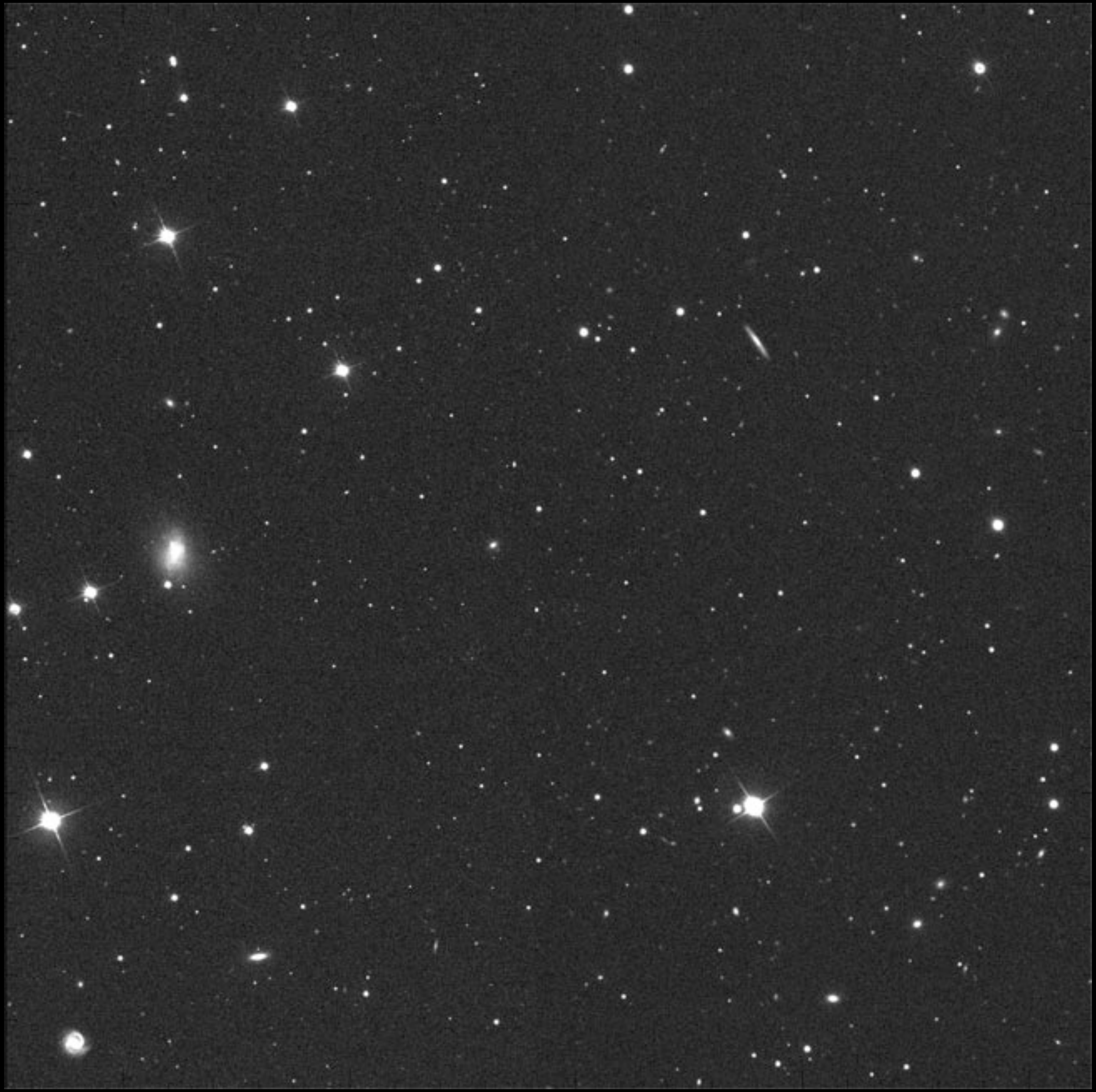
Bullock & Boylan-Kolchin 2017



Observed Galaxies
(ranked by stellar mass)

Dark Matter Halos
(ordered by mass)

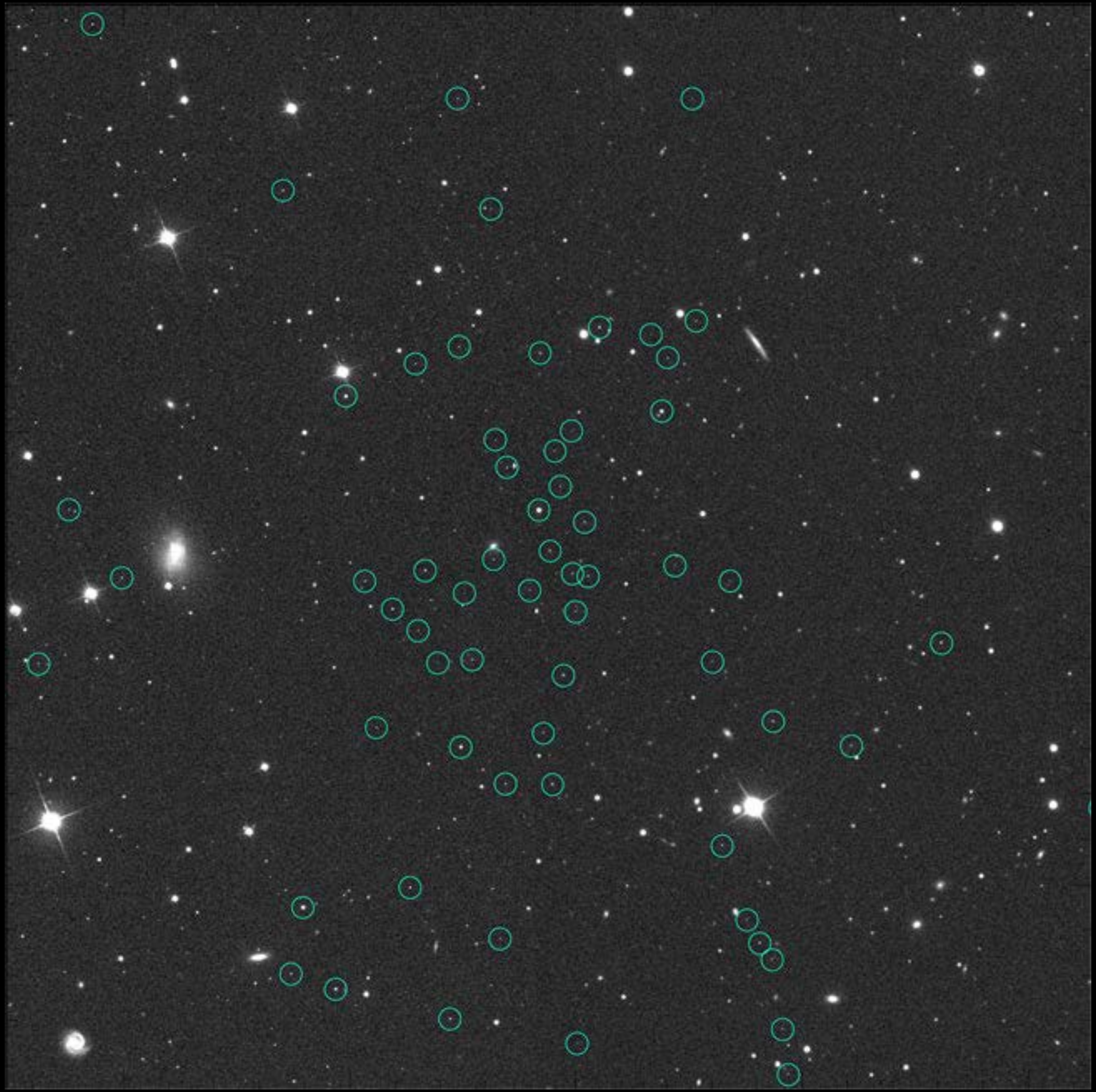
Wechsler & Tinker 2018
arXiv:1804.03097



Segue 1

$M_{☆}$ = ~300 $M_{☉}$

Credit: Marla Geha



Segue 1

$M_{\star} = \sim 300\ M_{\odot}$

Credit: Marla Geha

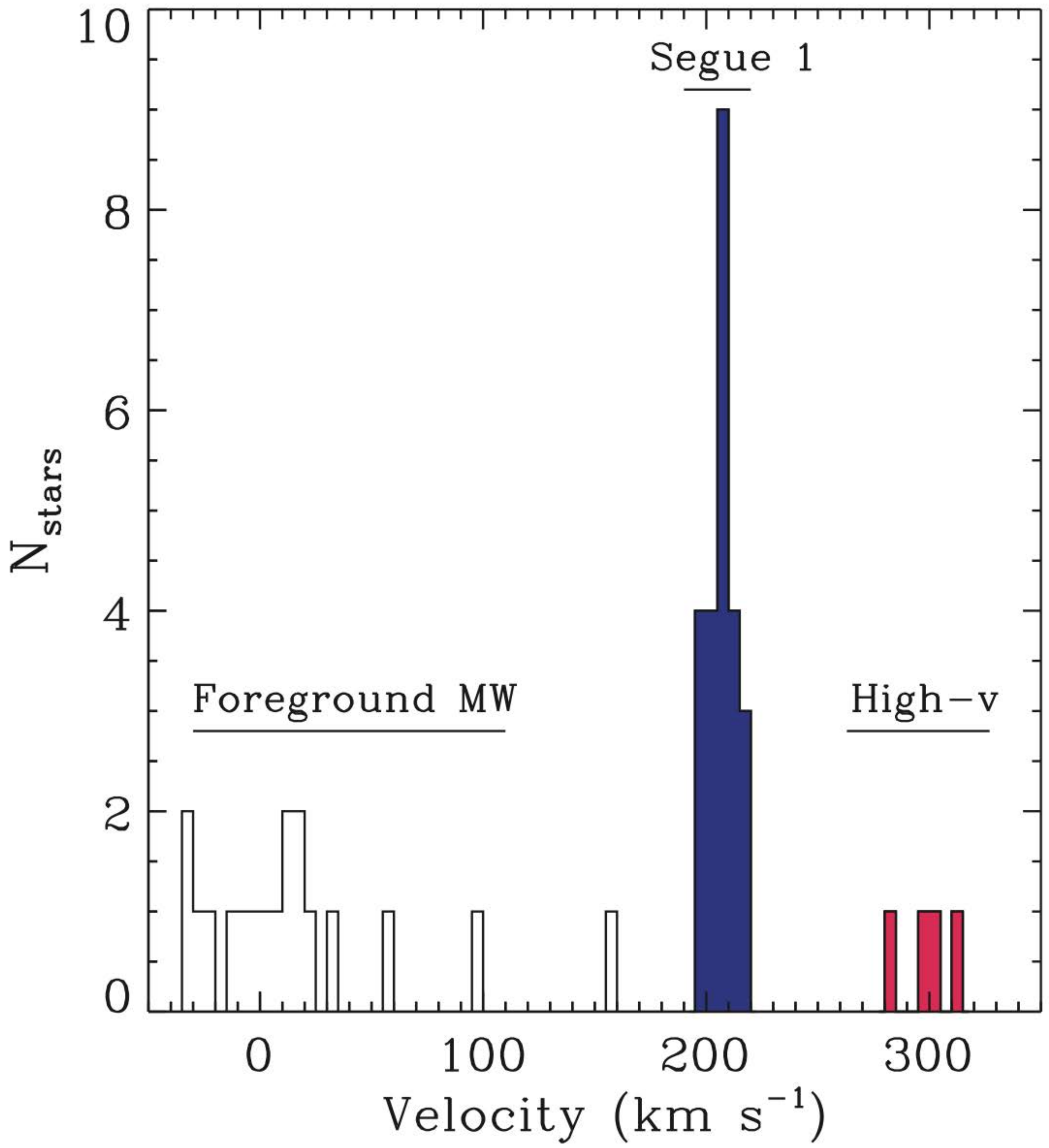
Ultra-faint galaxies are discovered as arcminute-scale statistical over-densities of individually resolved stars

Segue 1

$M_{\star} = \sim 300\ M_{\odot}$

Credit: Marla Geha

Ultra-faint galaxies are the most numerous, ancient, chemically pristine, and **dark-matter dominated galaxies**



Measure Doppler shifts of individual stars

Satellite member stars are distinguished by their **distinct locus in velocity-space**

The **velocity dispersion** is too large to be explained by the stellar mass alone

Segue 1 has mass-to-light ratio of >1000 within the half-light radius!

Geha et al. 2009, ApJ, 692, 1464

“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.*

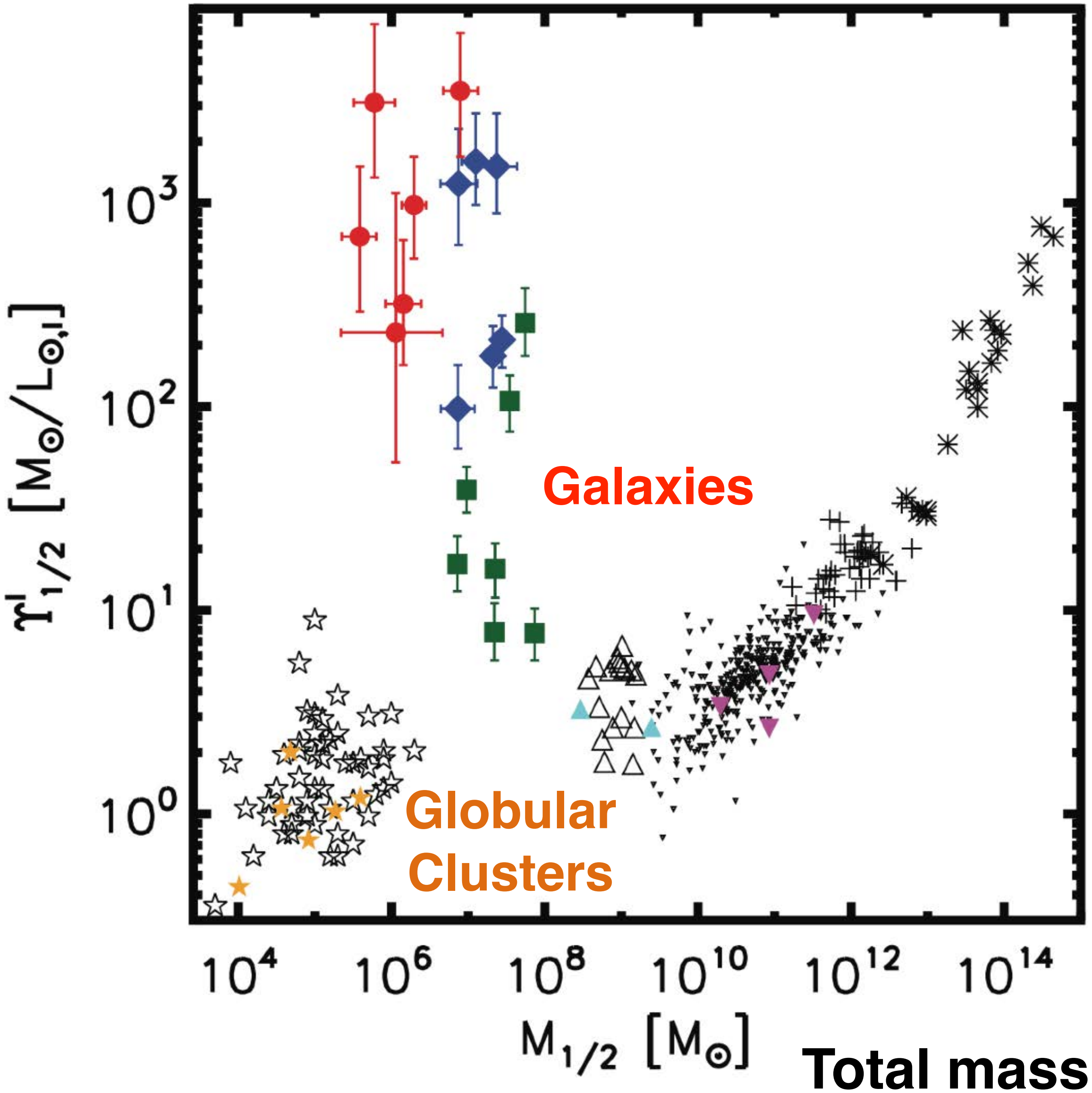
Willman & Strader 2012

“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.*

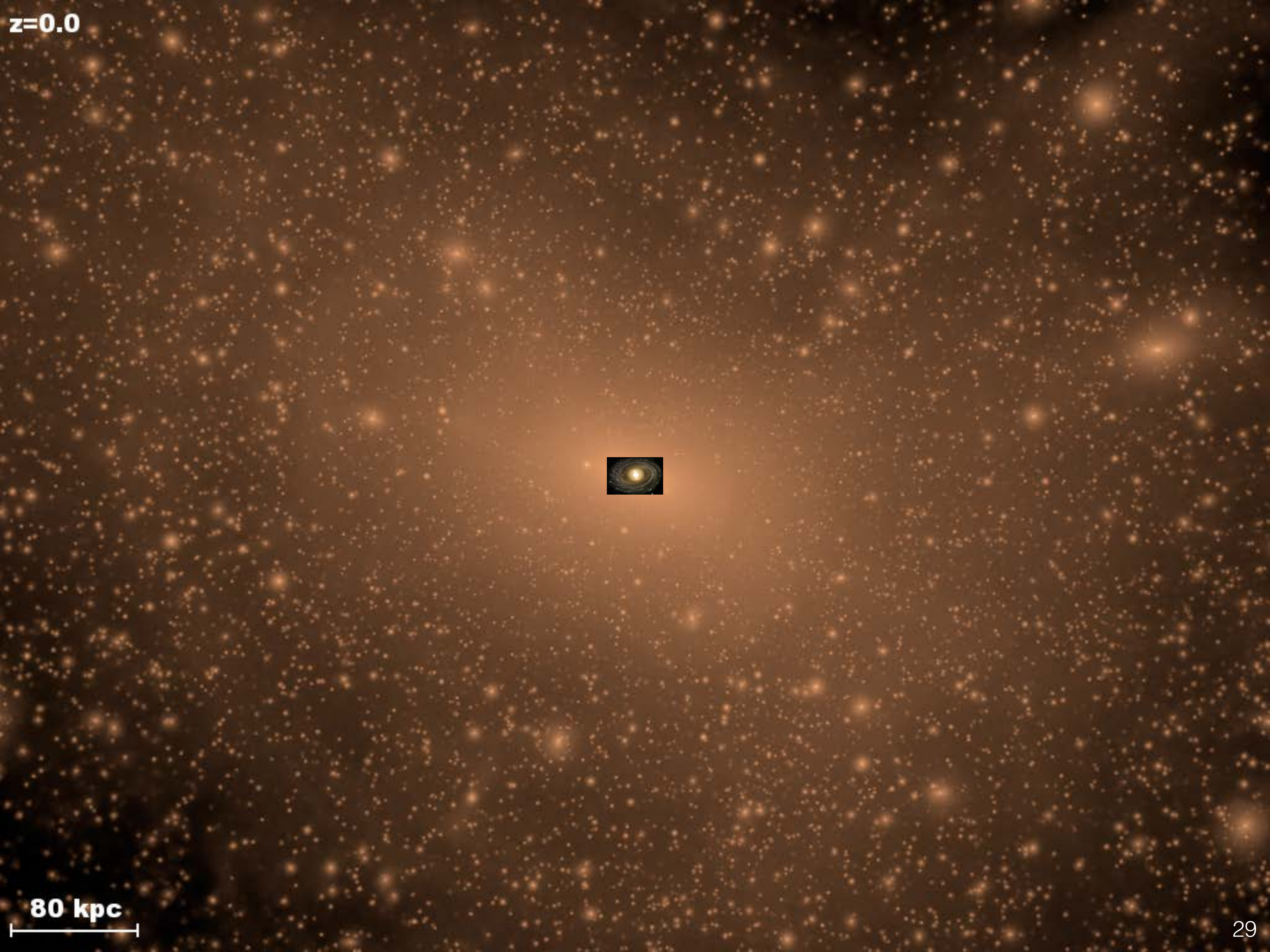
Willman & Strader 2012

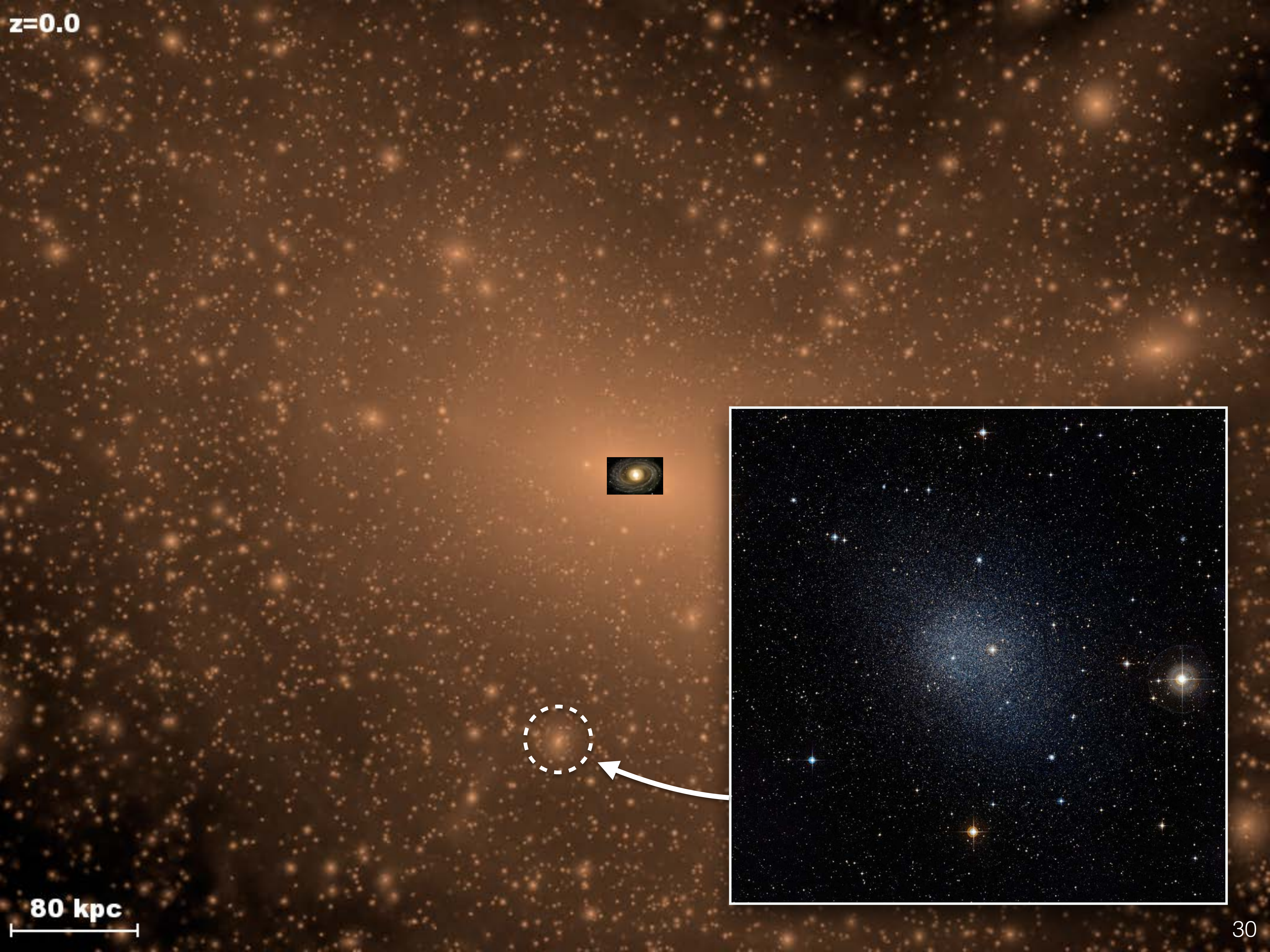
Mass-to-light ratio within half-light radius



Wolf et al. 2010

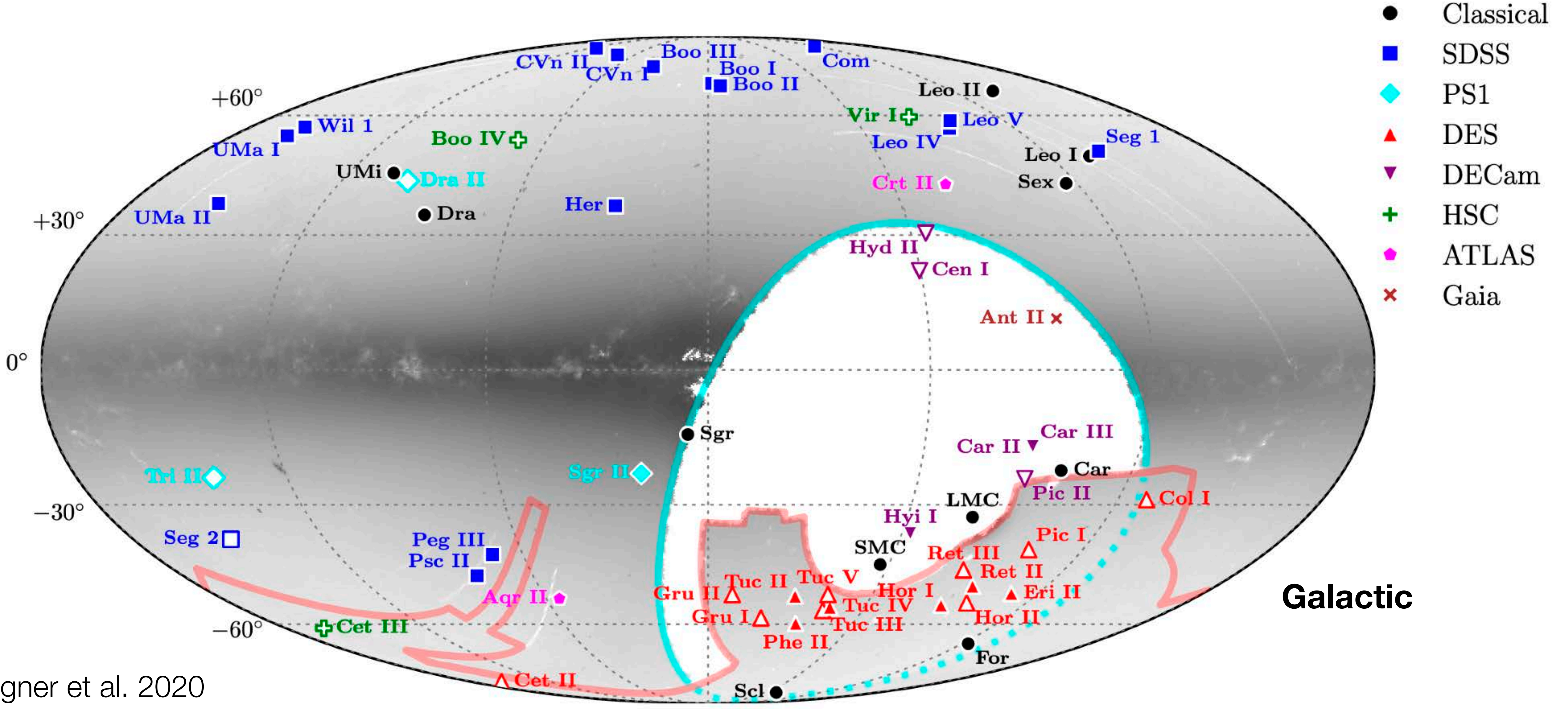
Total mass within half-light radius


z=0.0
80 kpc


z=0.0
80 kpc

Satellite Search of 3/4 of the Sky using DES Y3 + Pan-STARRS PS1

Deep optical imaging over nearly the entire high-Galactic-latitude sky



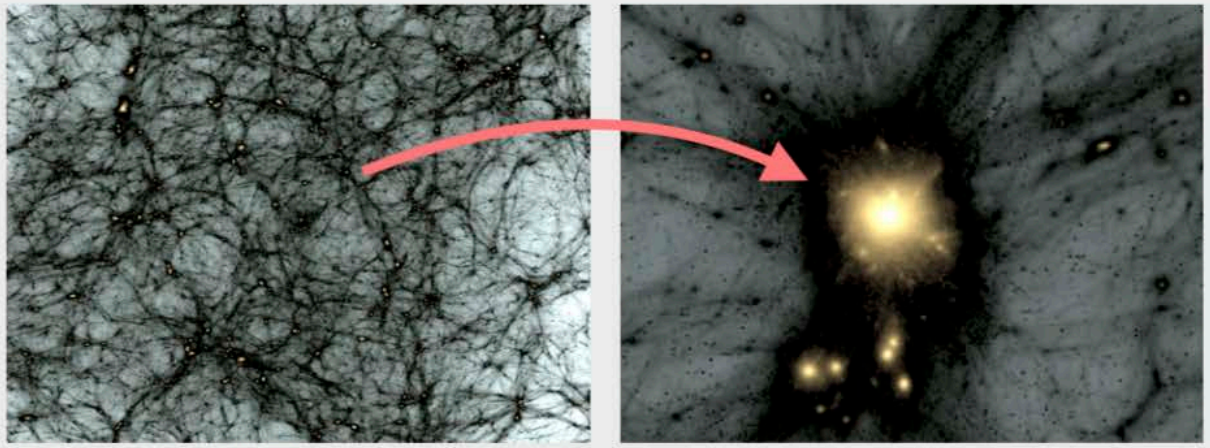
Drlica-Wagner et al. 2020
arXiv:1912.03302

Total coverage ~32,500 deg^2
including over 75% of non-dusty sky (~24,300 deg^2 after masking)

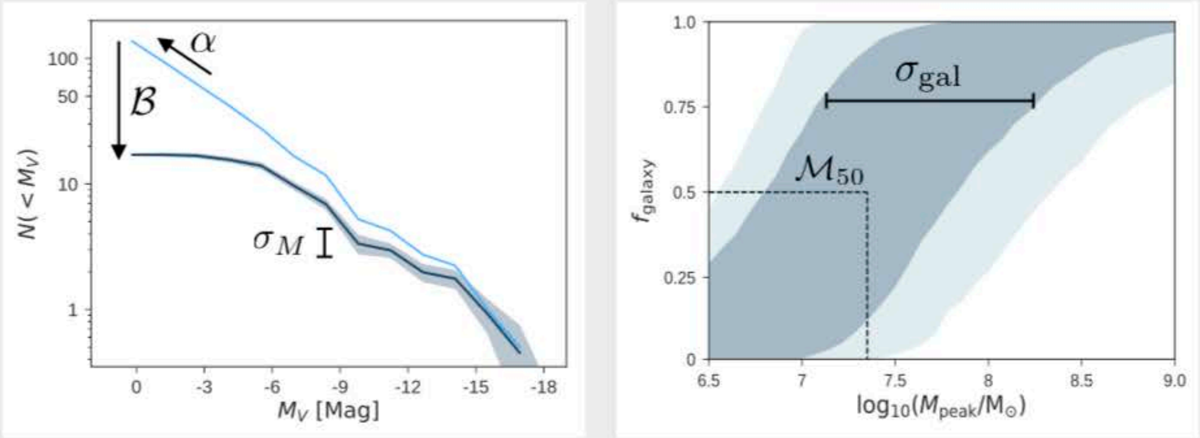
Nadler et al. 2020
arXiv:1912.03303

Markov Chain Monte Carlo

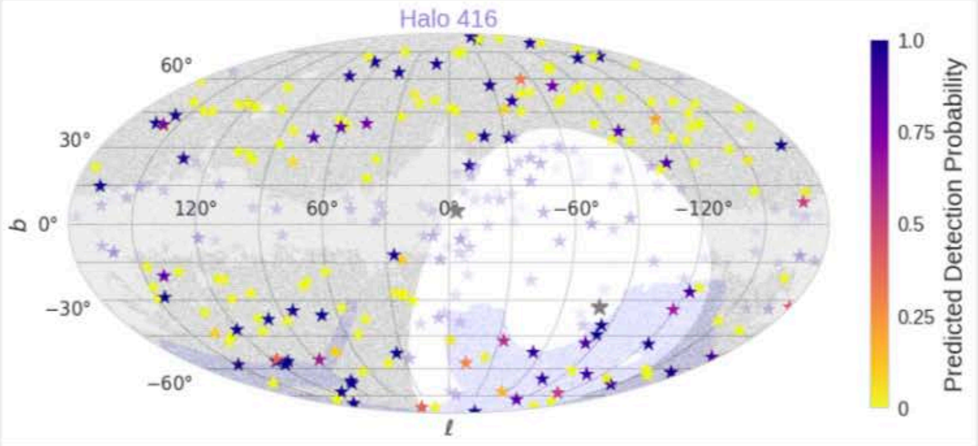
1. Resimulate Milky Way-like halos from large cosmological volume.



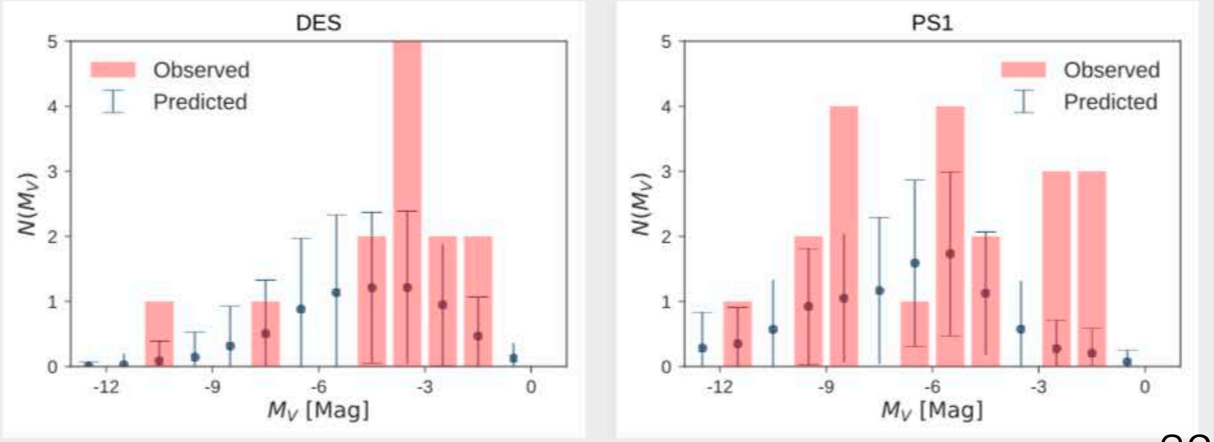
2. Paint satellite galaxies onto subhalos using galaxy—halo model.



3. Apply observational selection effects based on imaging data.



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

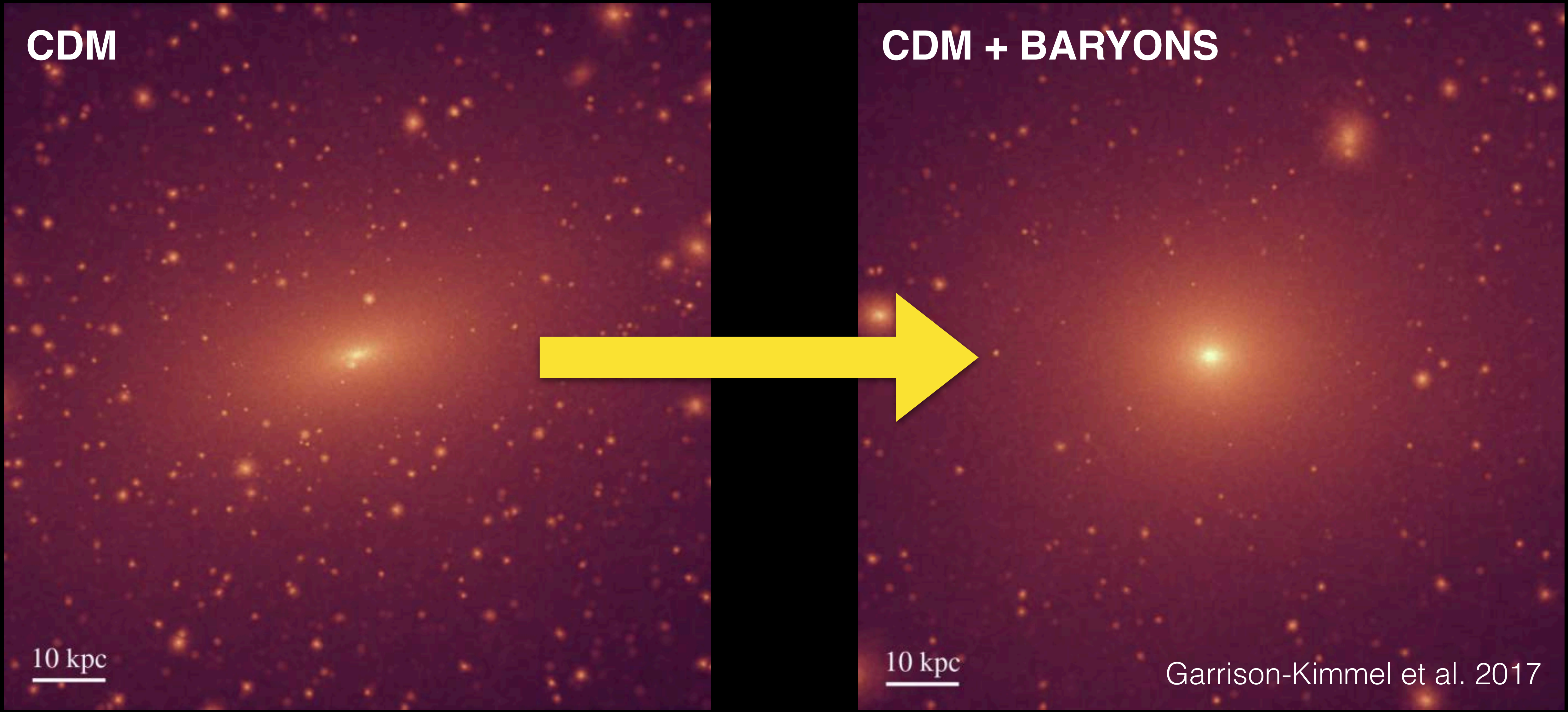


See also
Kim et al. 2018
Jethwa et al. 2018
Newton et al. 2018
Manwadkar & Kravsov 2022

Baryons are Essential Model Component

Suite of zoom-in N-body simulations for sufficient statistics on low-mass halos. Train on hydrodynamical simulations (FIRE) to account for baryonic effects, including halo disruption by Milky Way disk.

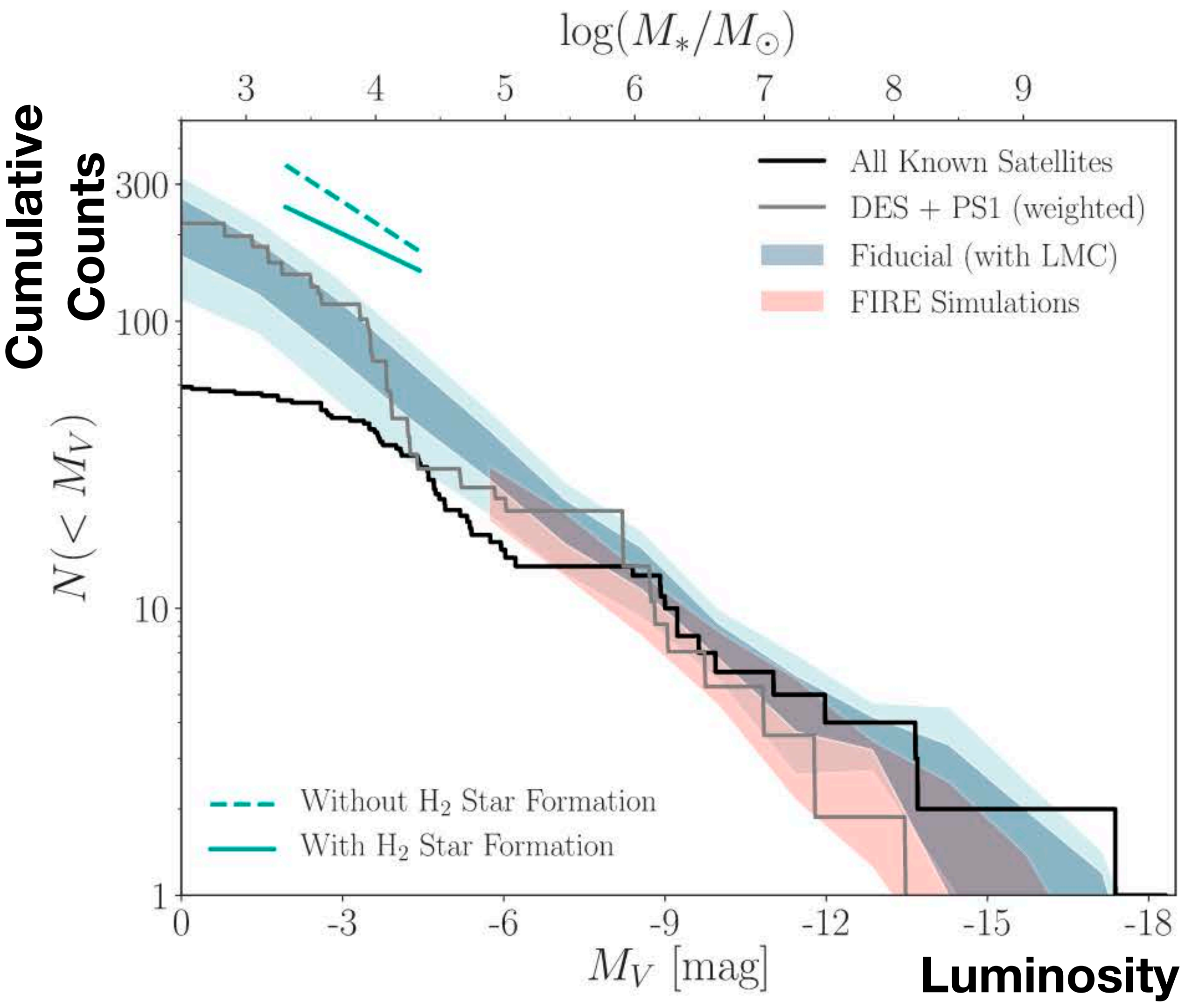
See Nadler et al. 2019 (arXiv:1809.05542) for details

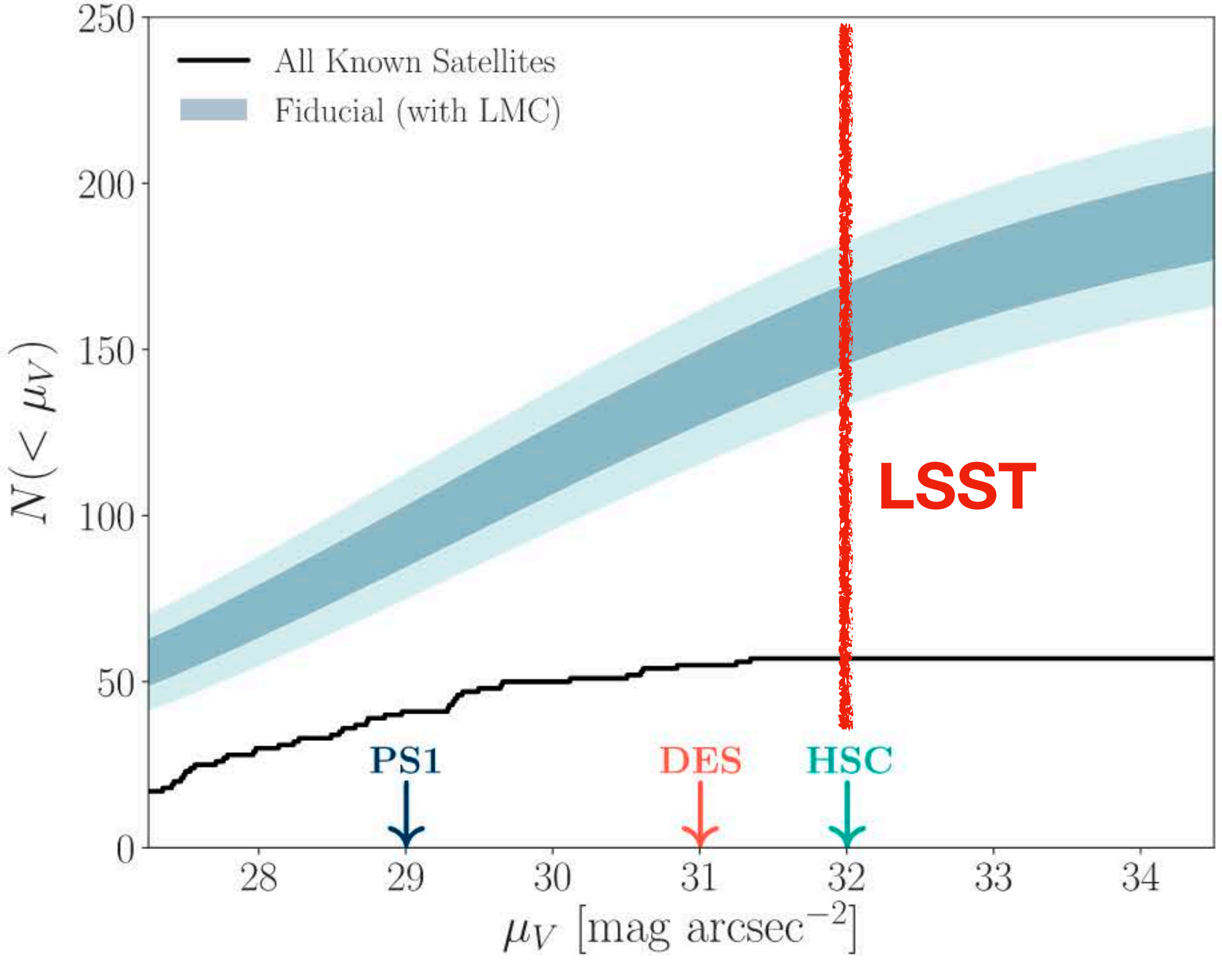


Garrison-Kimmel et al. 2017

Consistency with CDM considering observational and baryonic effects

Even with the doubling of known Milky Way satellites since 2015, the majority of Milky Way satellites remain hidden because they either contain **too few bright stars** or are **too low surface brightness**



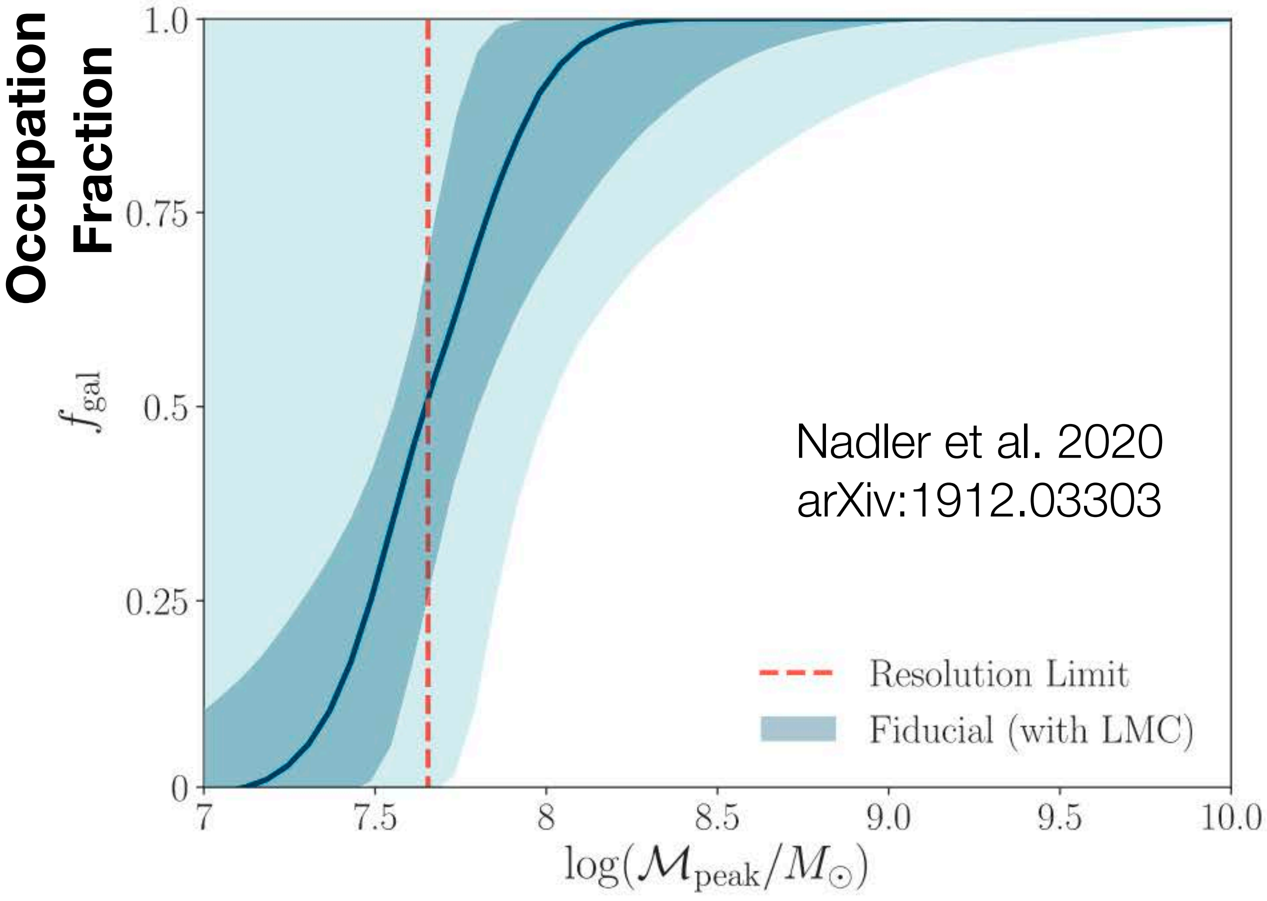


Nadler et al. 2020
arXiv:1912.03303

220 ± 50 total within MW viral radius; ~150 undiscovered;
41 ± 7 satellites within LMC viral radius at time of infall on MW

Halos hosting the least luminous galaxies

Galaxy Occupation Fraction



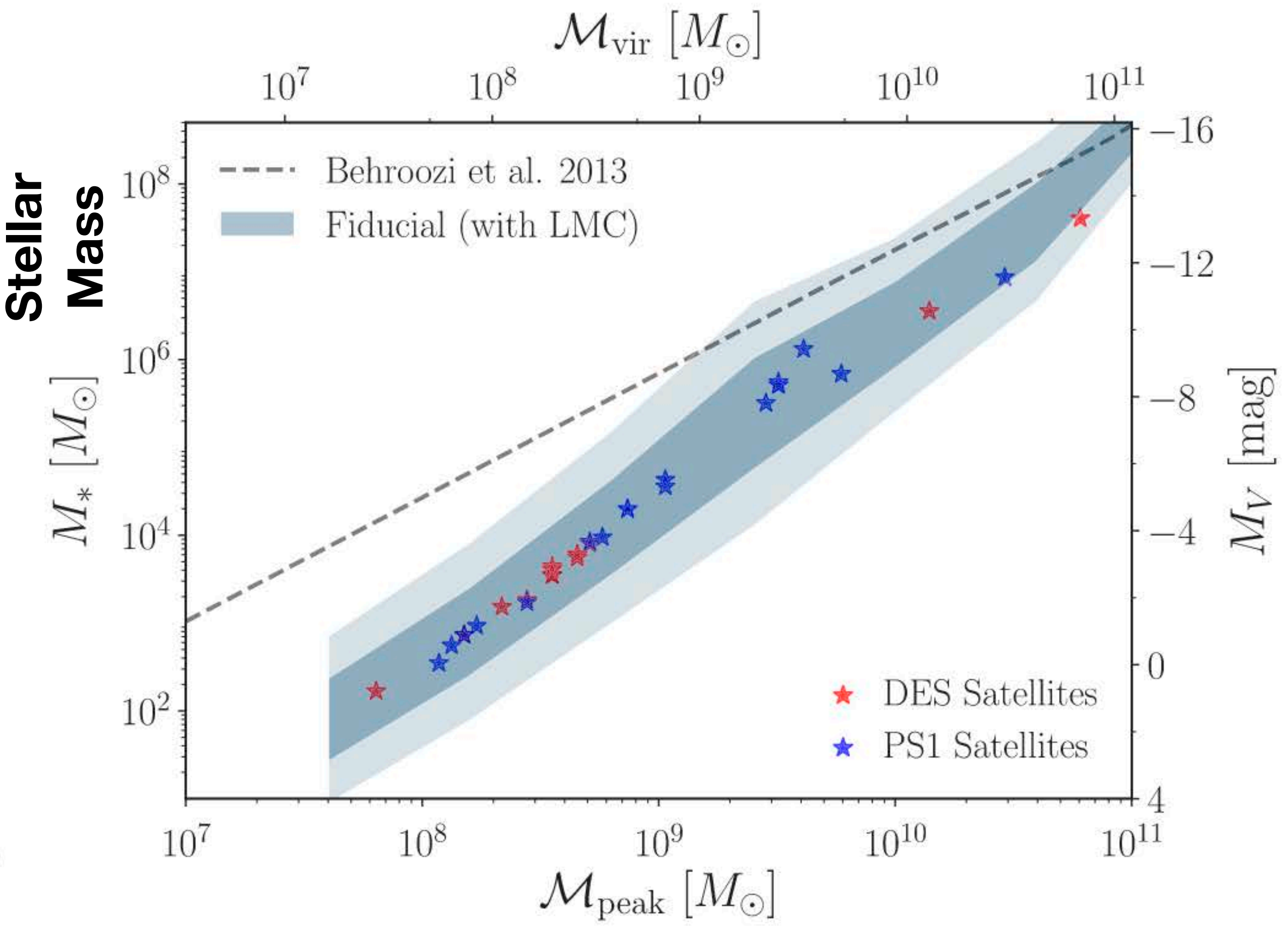
Nadler et al. 2020
arXiv:1912.03303

Halo Mass

$M_{min} < 3.2 \times 10^8\ M_\odot$ (95% CL)

$v_{peak} < 21$ km s^{-1} (95% CL)

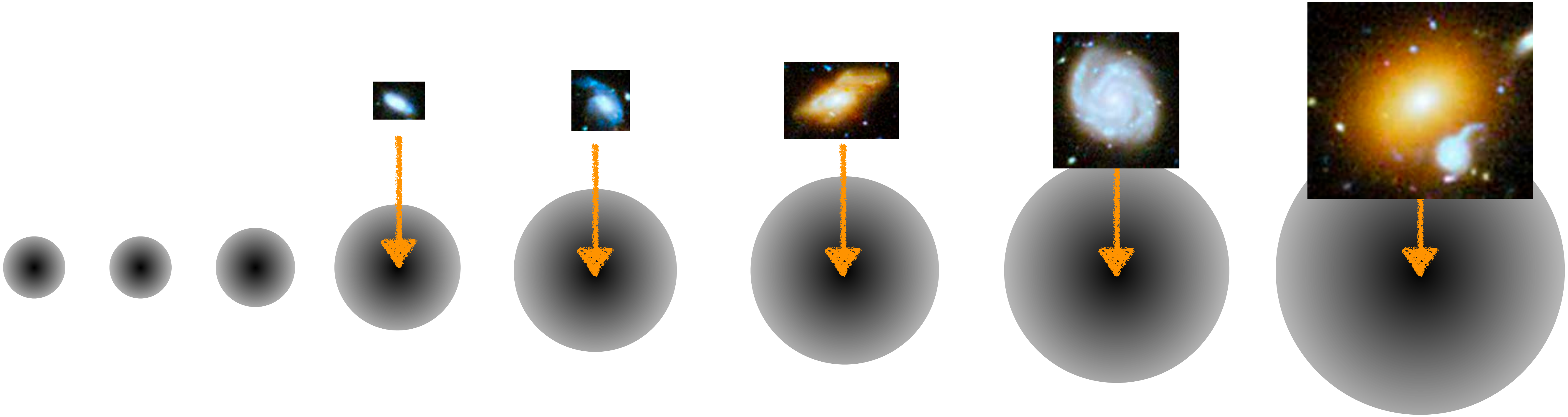
Faint-end Luminosity Function



Halo Mass

Detected MW satellites likely occupy halos of mass $M_{peak} \sim 10^8\ M_\odot$ (95% CL)

Most conservative (unrealistic, observationally disfavored) scenario assumes confirmed satellites strictly occupy most massive MW subhalos



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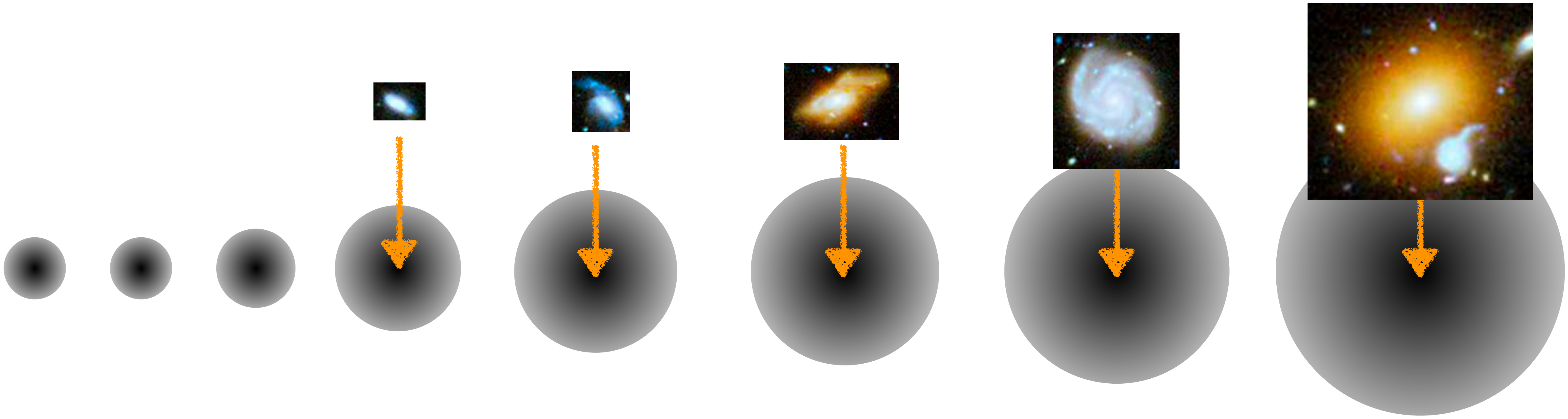
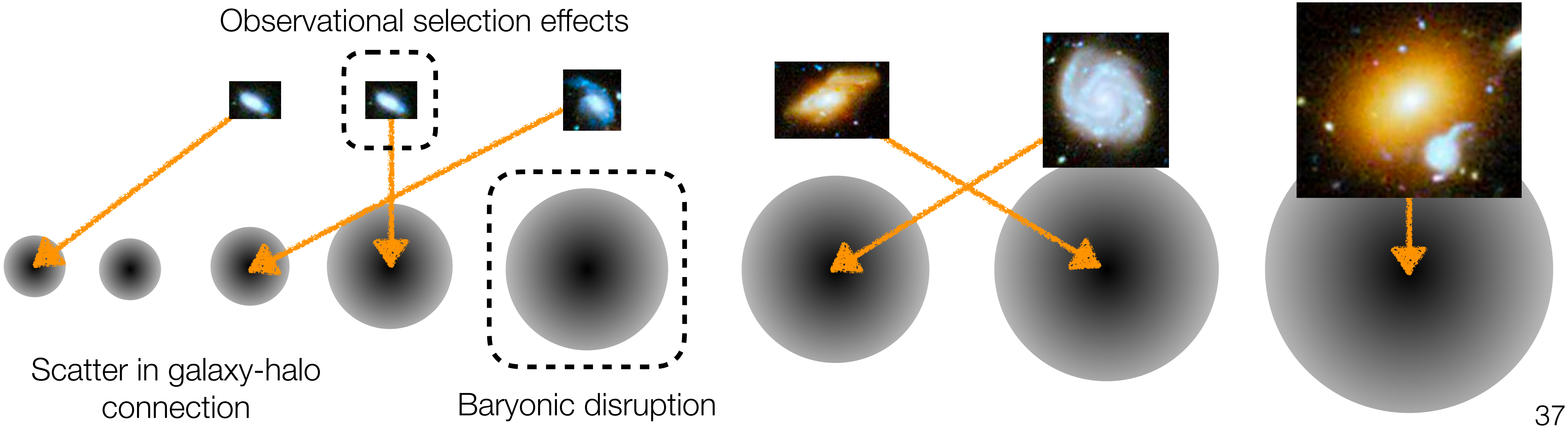


More realistic modeling of baryonic disruption, scatter in stellar mass - halo mass relation, and observational selection effects implies that observed ultra-faint galaxies reside in lower mass dark matter halos



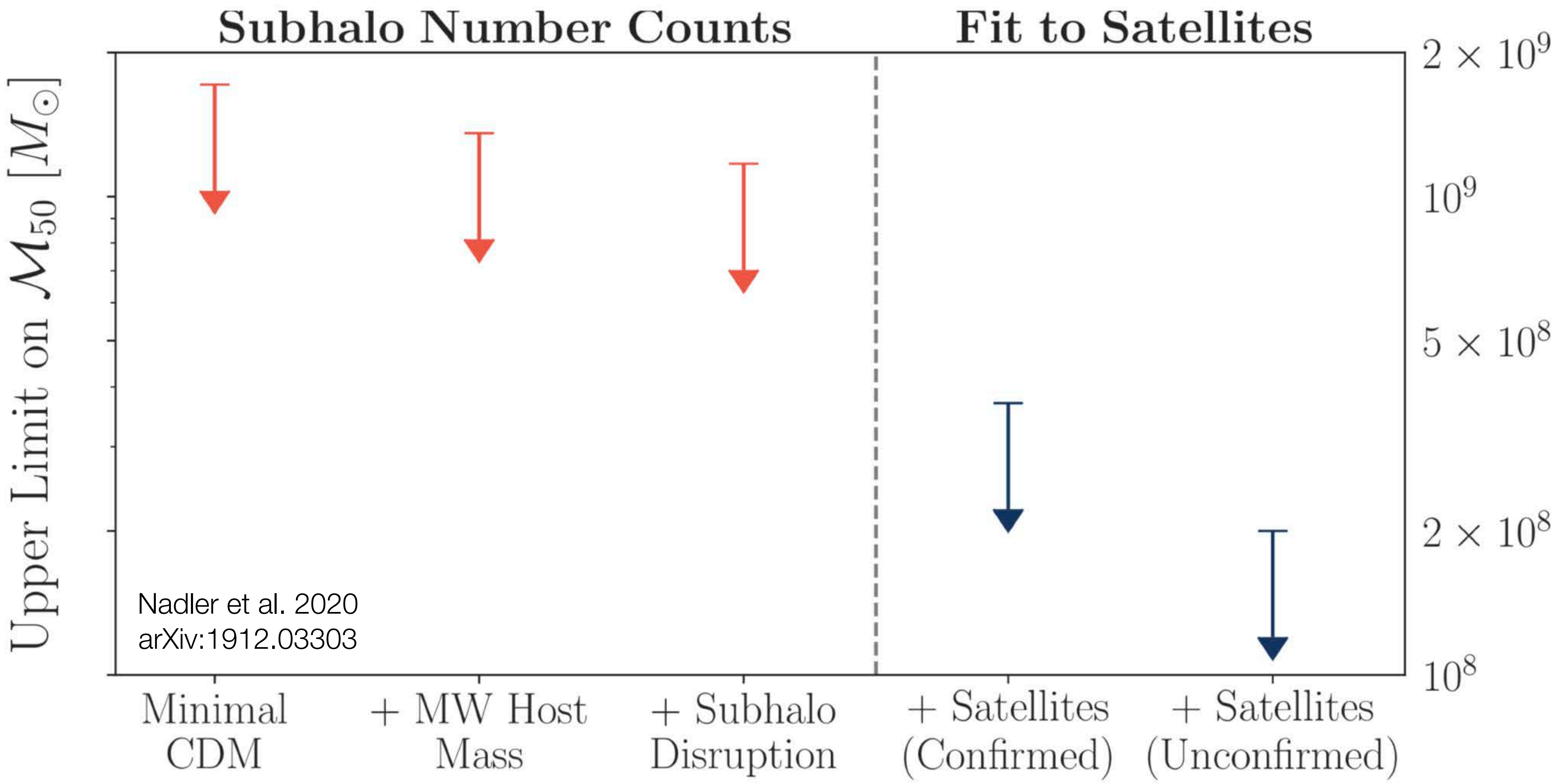
Observational selection effects

Scatter in galaxy-halo connection

Baryonic disruption

Quantifying Modeling Uncertainties

Scenario with no-scatter abundance matching and no baryonic tidal disruption gives *conservative* upper bound on minimum halo mass (but poor quality fit to data)



Nadler et al. 2020
arXiv:1912.03303

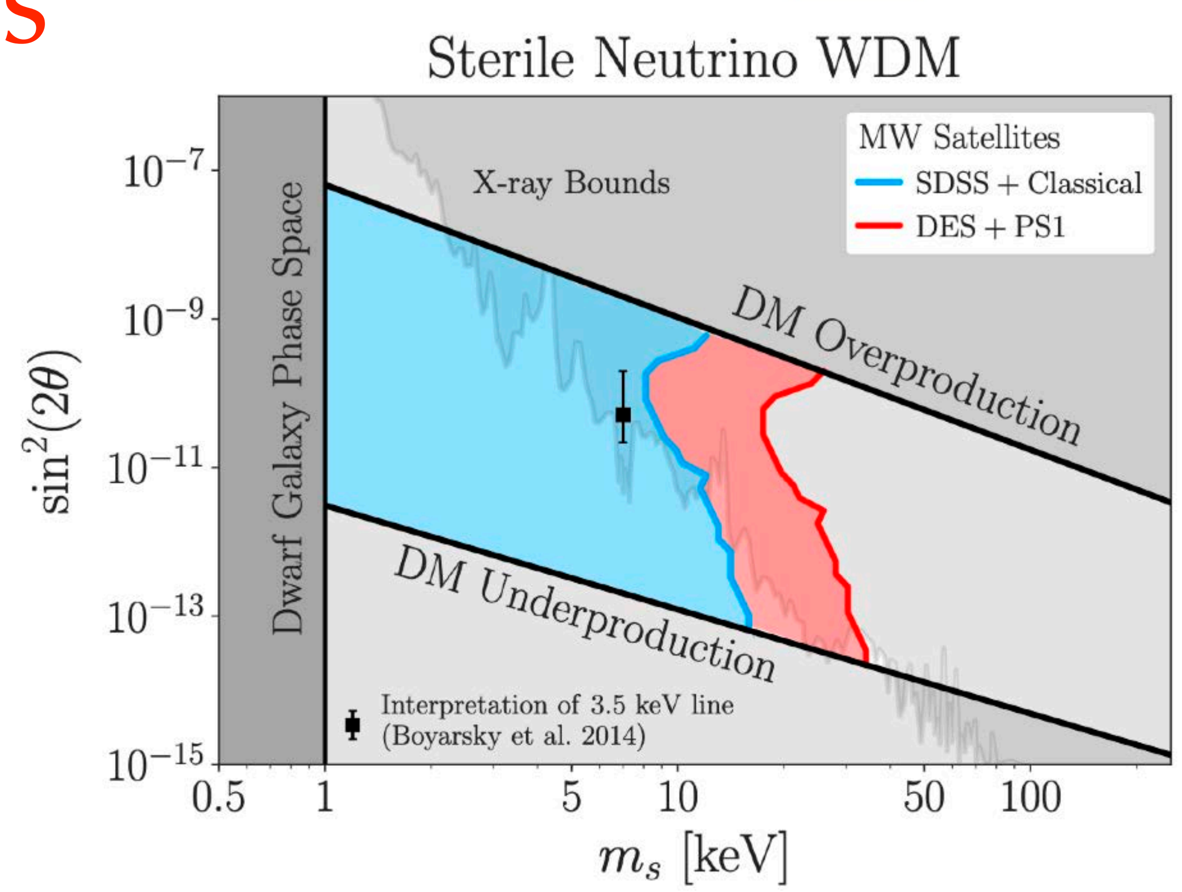
Gains in sensitivity to minimum halo mass largely from modeling of the observational selection function and galaxy-halo connection

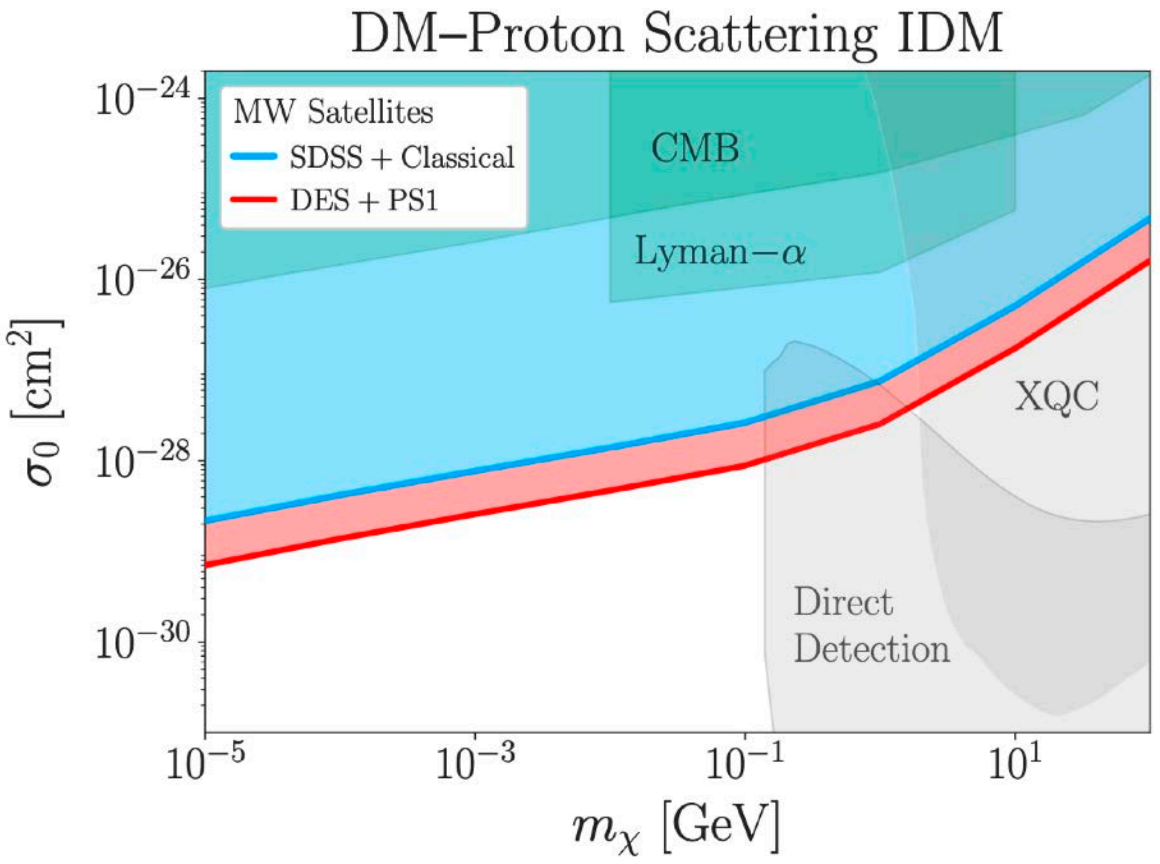
Beyond CDM:
Dark Matter Microphysics

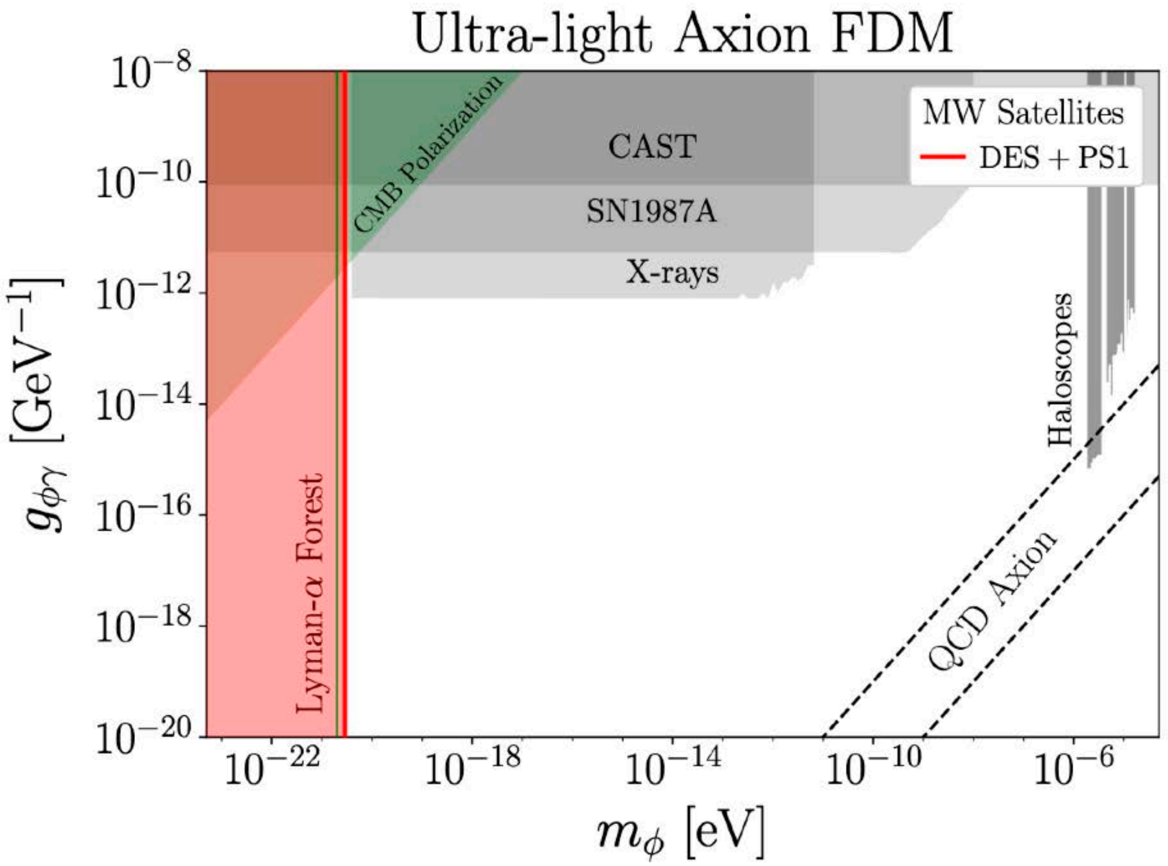
THE
DARK
ENERGY
SURVEY

Application of Milky Way satellite population constraints to example dark matter models

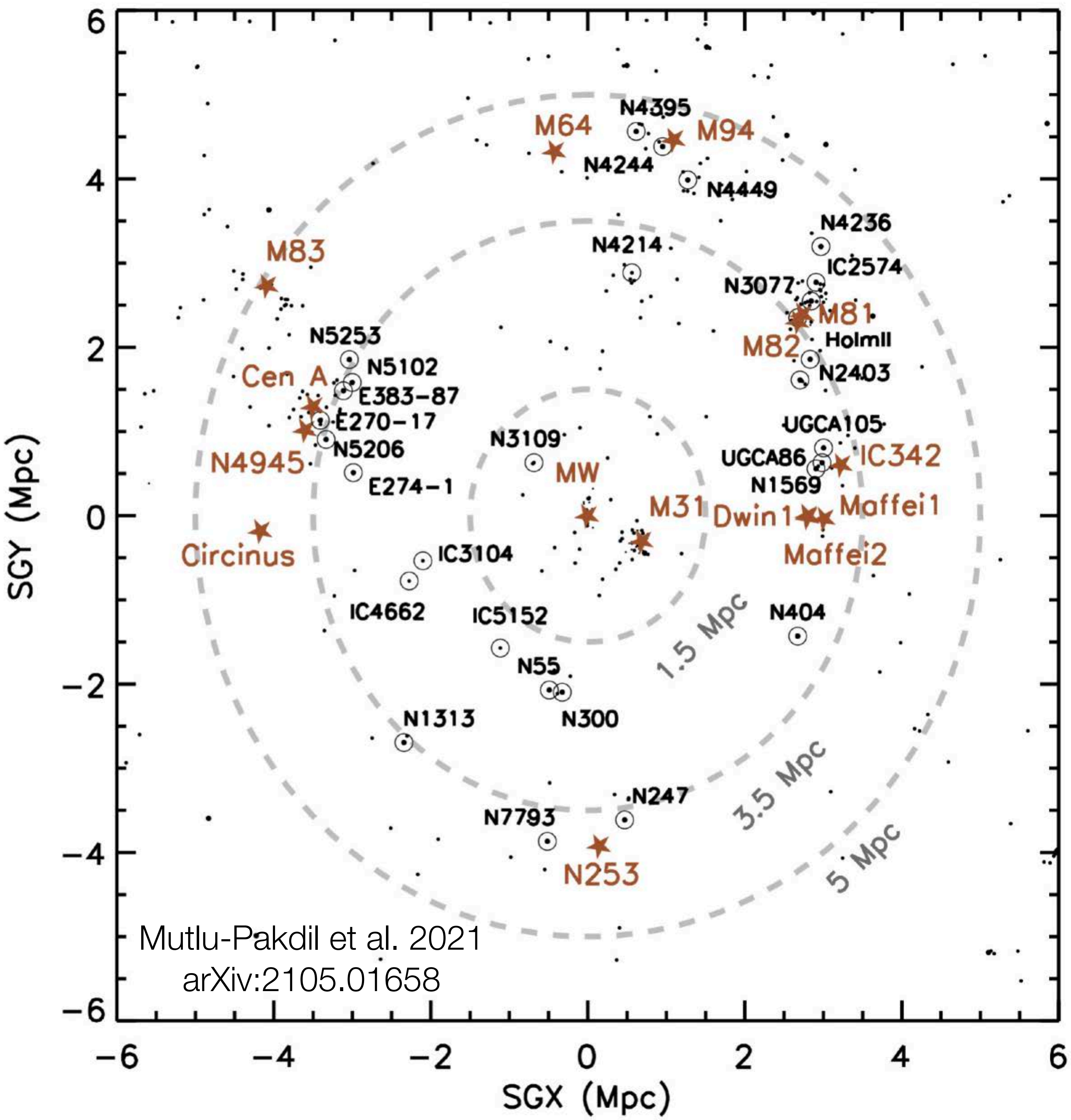
Nadler et al. 2020
arXiv:2008.00022



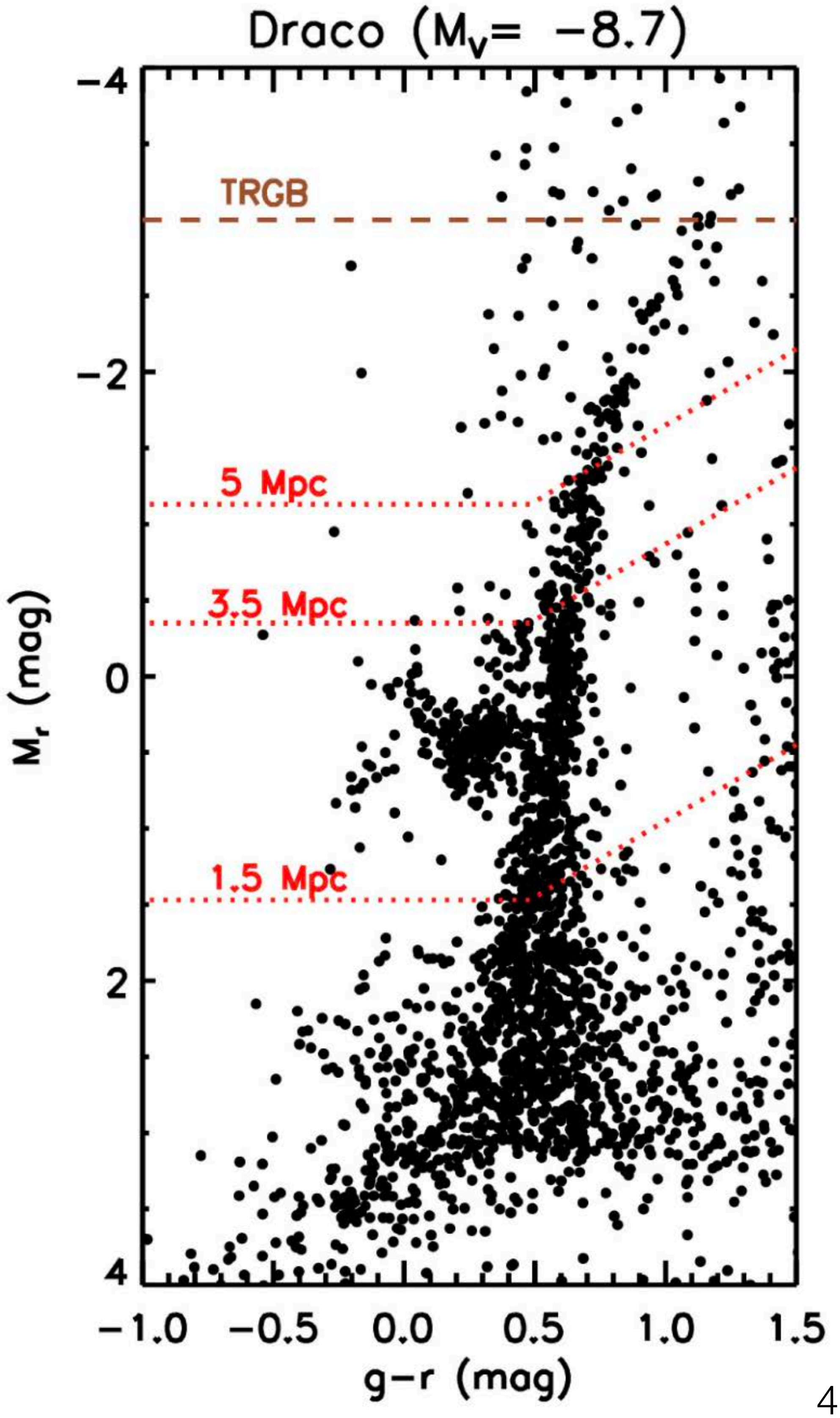


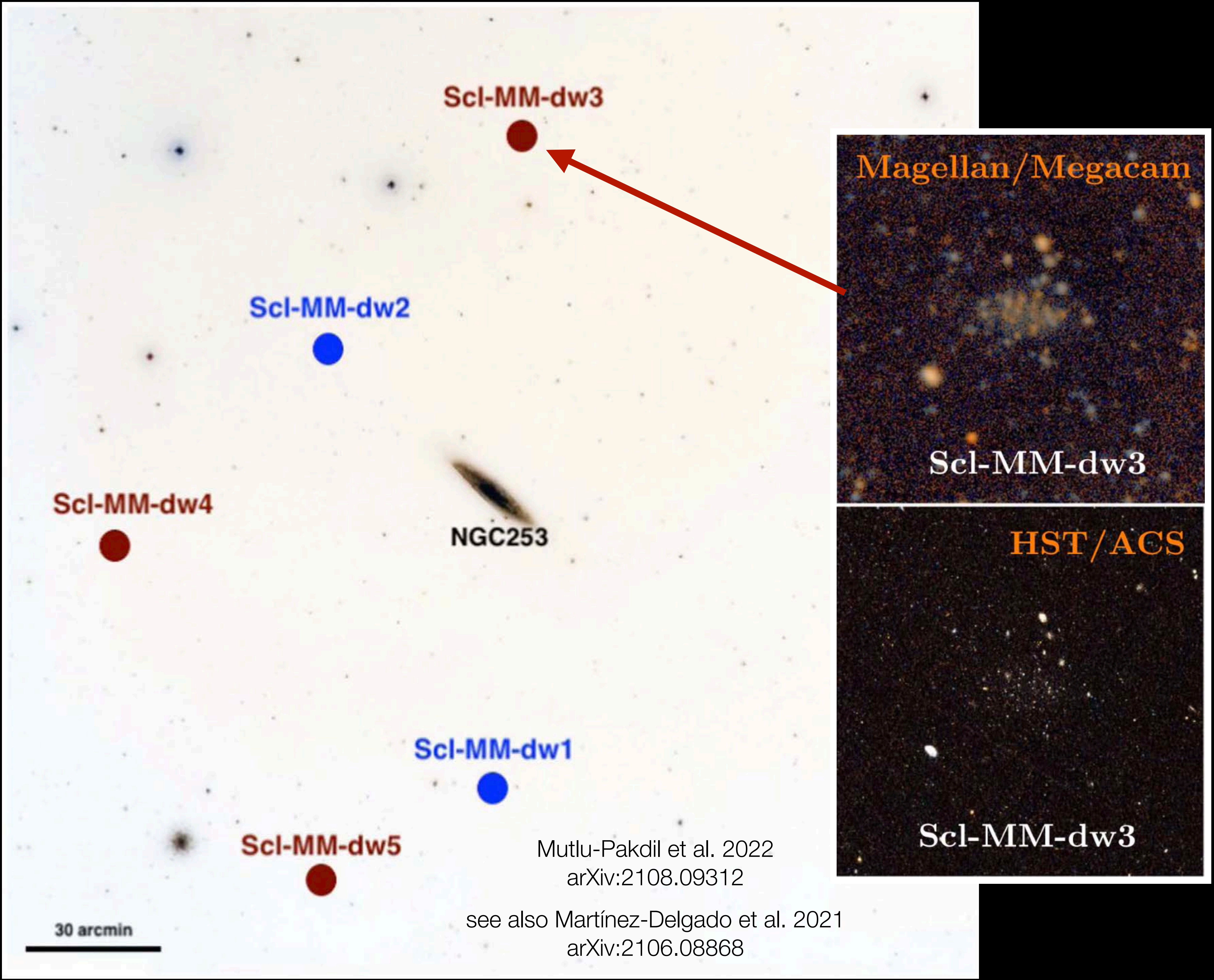


LSST will extend the census of ultra-faint galaxies throughout the Local Volume



Mutlu-Pakdil et al. 2021
arXiv:2105.01658

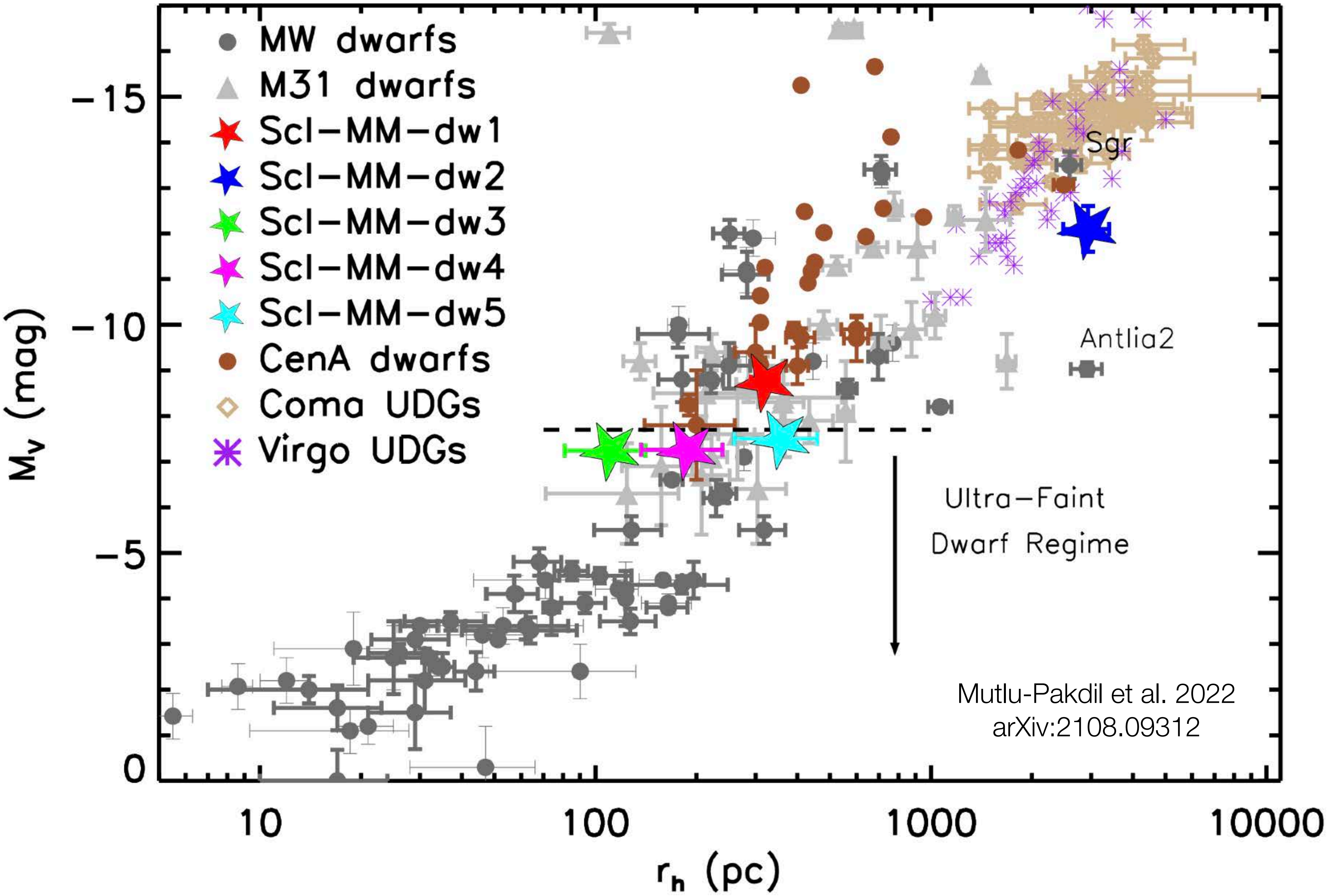




Mutlu-Pakdil et al. 2022
arXiv:2108.09312

see also Martínez-Delgado et al. 2021
arXiv:2106.08868

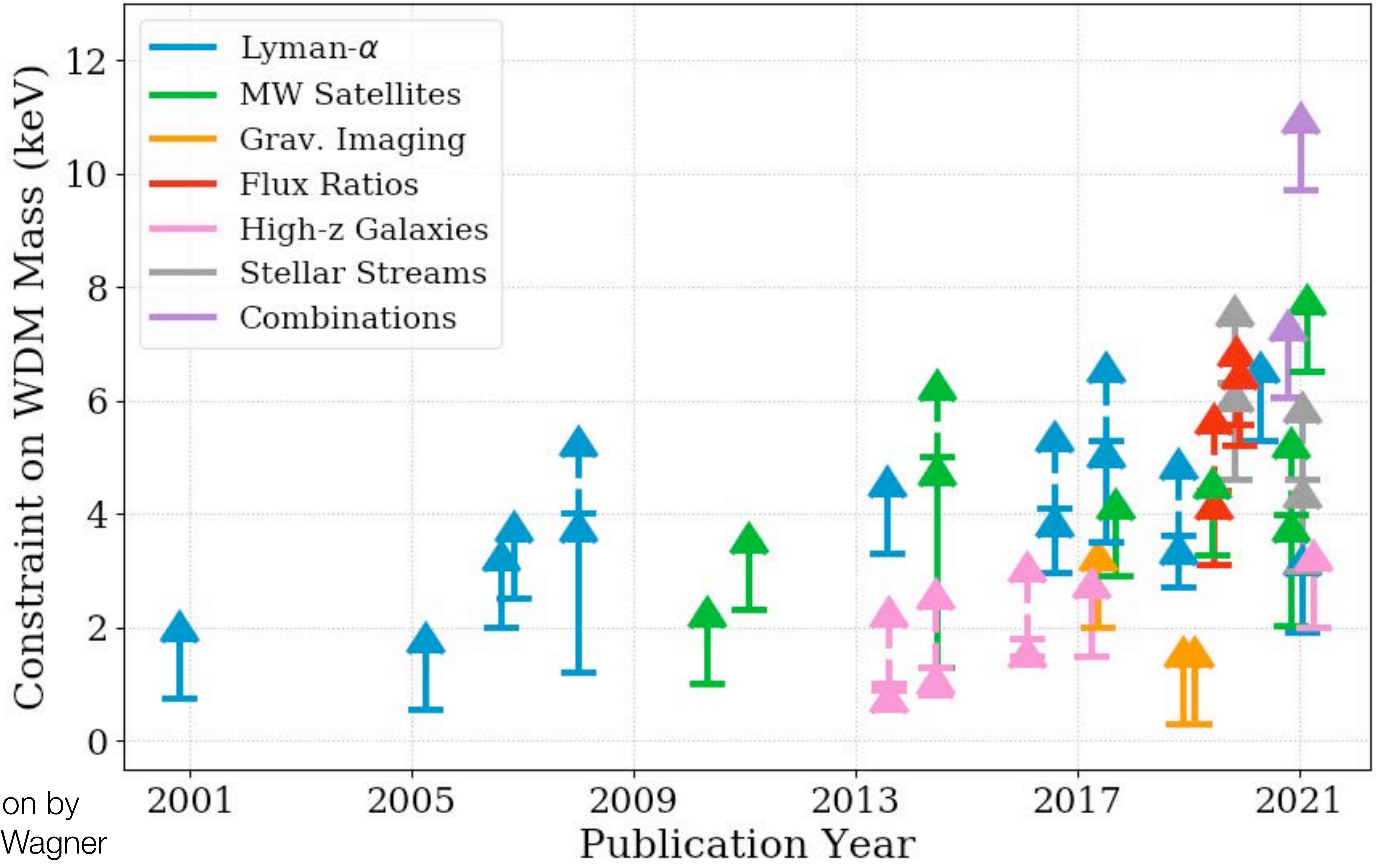
LSST will extend the census of ultra-faint galaxies throughout the Local Volume



Mutlu-Pakdil et al. 2022
arXiv:2108.09312

Consistency with CDM to nearly the threshold of galaxy formation

Multiple methods achieving sensitivity to ~10^8 $M_\odot$ halos



MW satellites
+
strong lensing
flux ratios

Compilation by
Alex Drlica-Wagner

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, Nadler et al. 2019,2021a,b

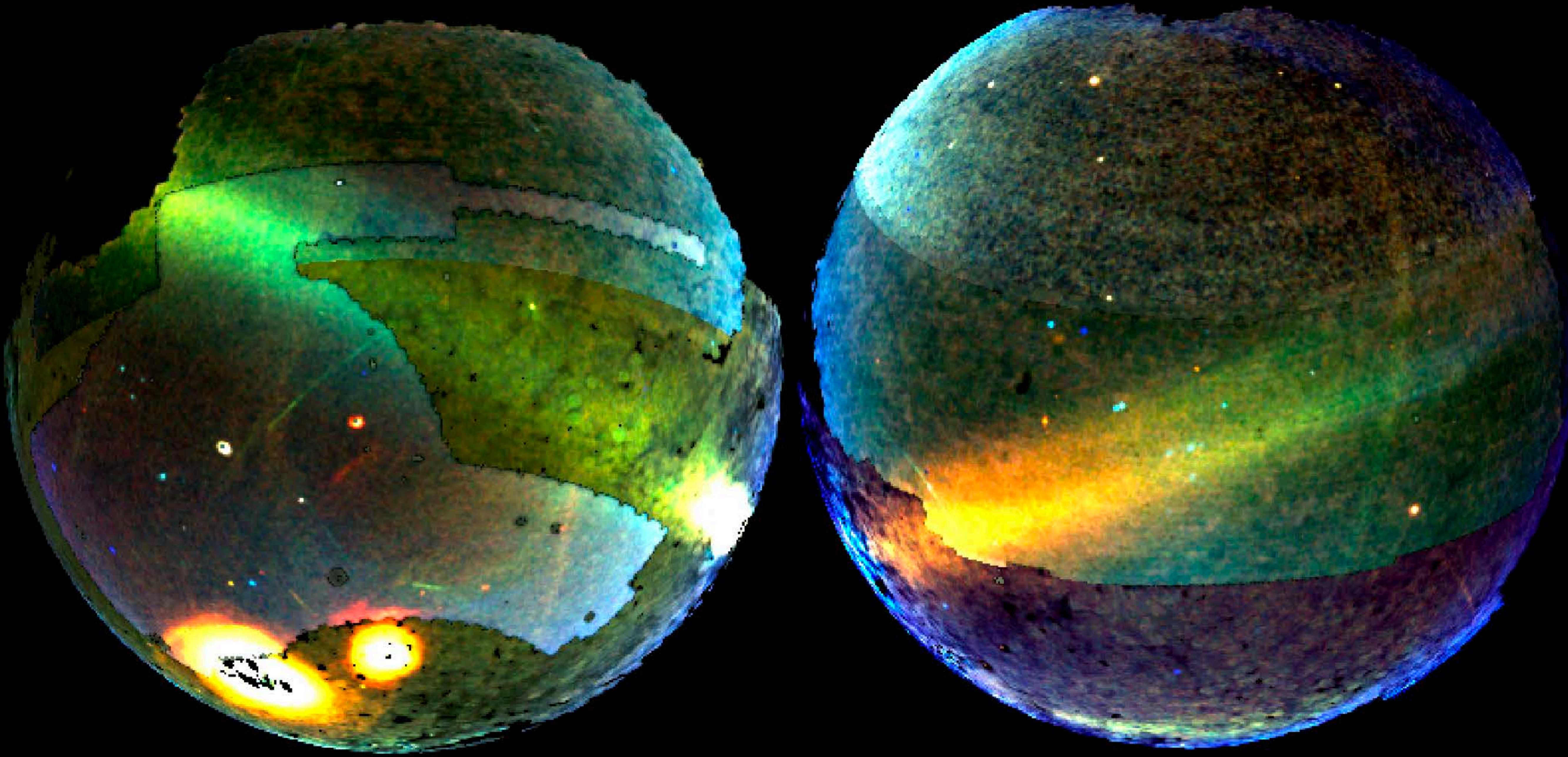
Searching for Completely Dark Halos

Increased sensitivity to dark mark microphysics

Minimizing uncertainties associated with baryonic physics

Complementarity of multiple techniques

Stellar Streams are dynamical tracers of the mass distribution around the Milky Way



Peter Ferguson and Nora Shipp

Stellar Streams are dynamical tracers of the mass distribution around the Milky Way

Malhan et al. 2022
arXiv:2202.07660

Atlas of 41 stellar streams

Low-mass dark matter subhalos perturb passing stellar streams, producing enhanced density variations along stream length and proper motion / radial velocity anomalies

Simulations

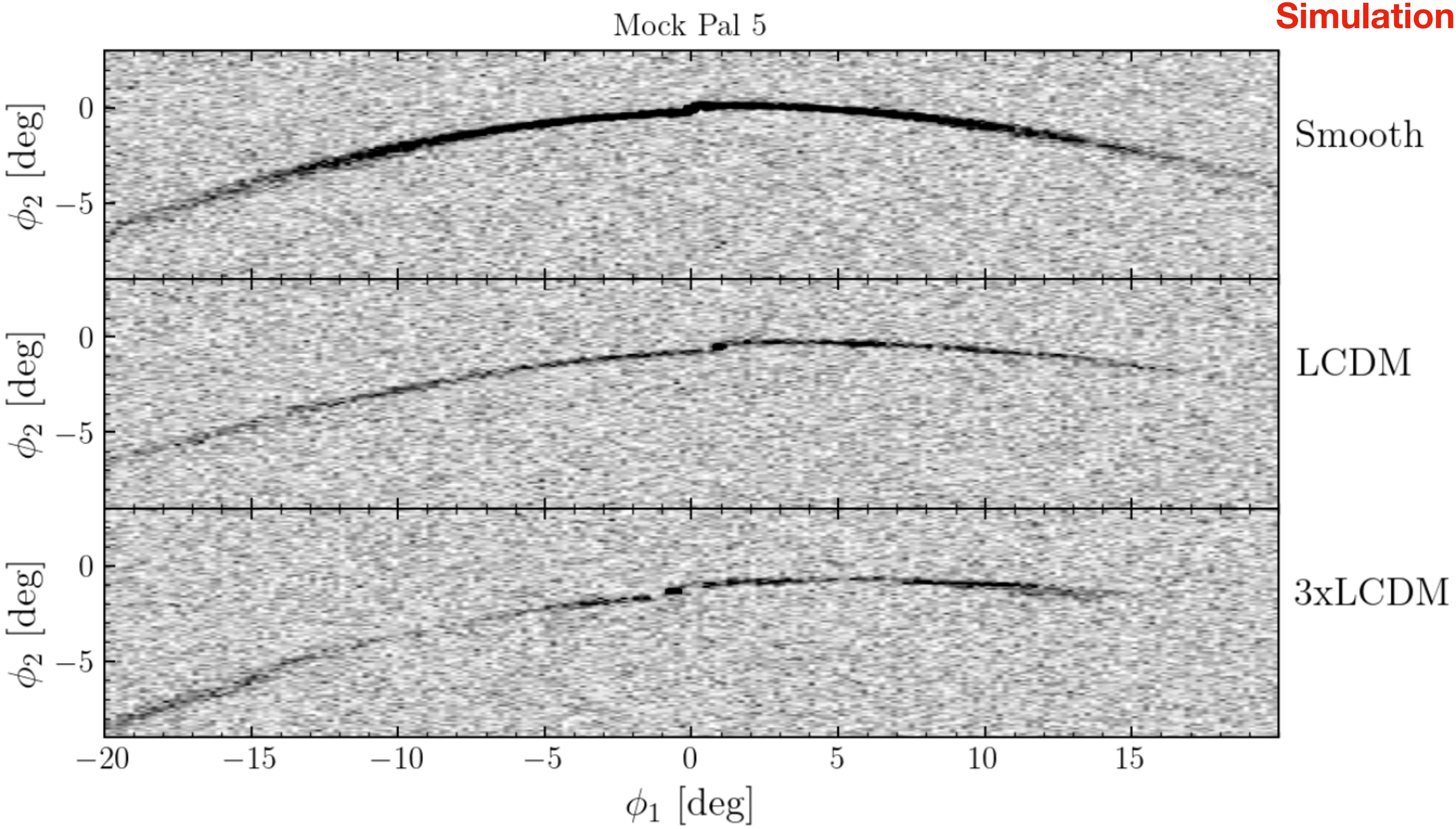
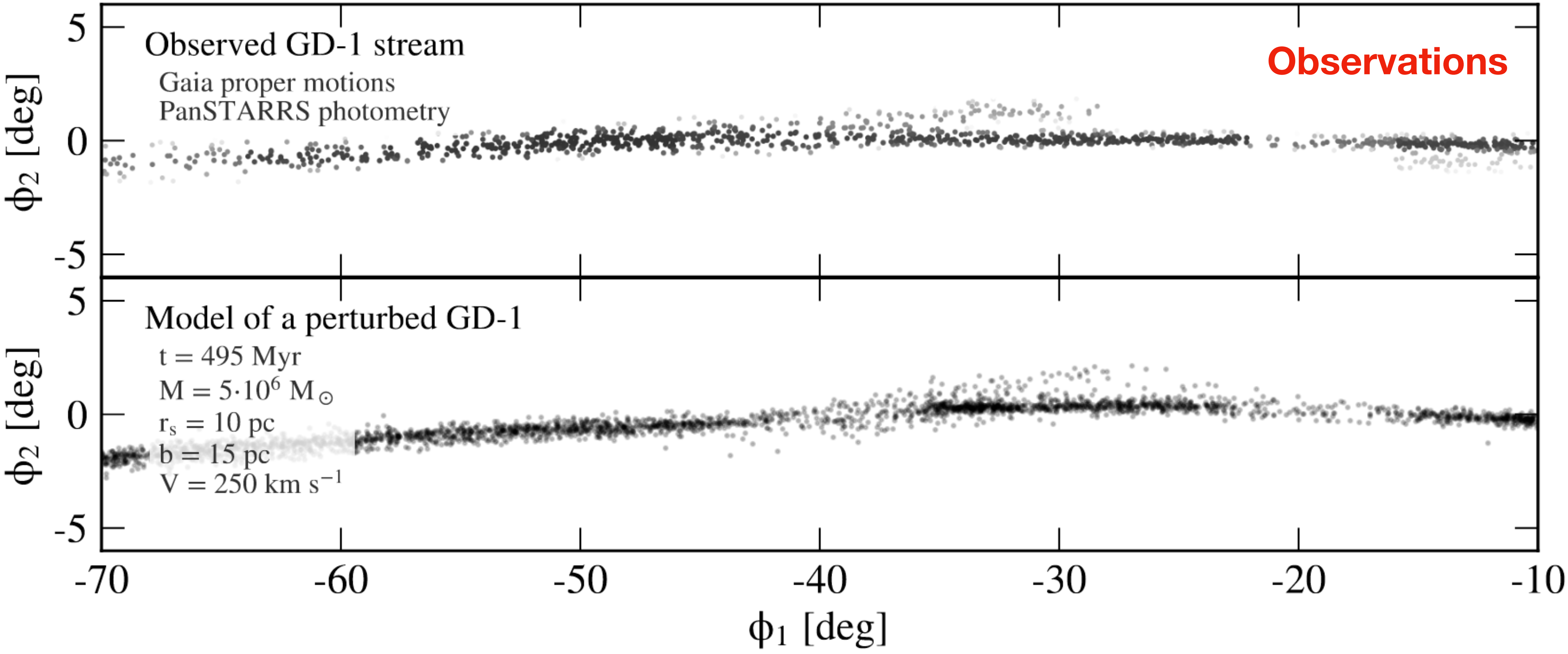


Figure: Peter Ferguson
Simulations: Denis Erkal

Low-mass dark matter subhalos perturb passing stellar streams, producing enhanced density variations along stream length and proper motion / radial velocity anomalies

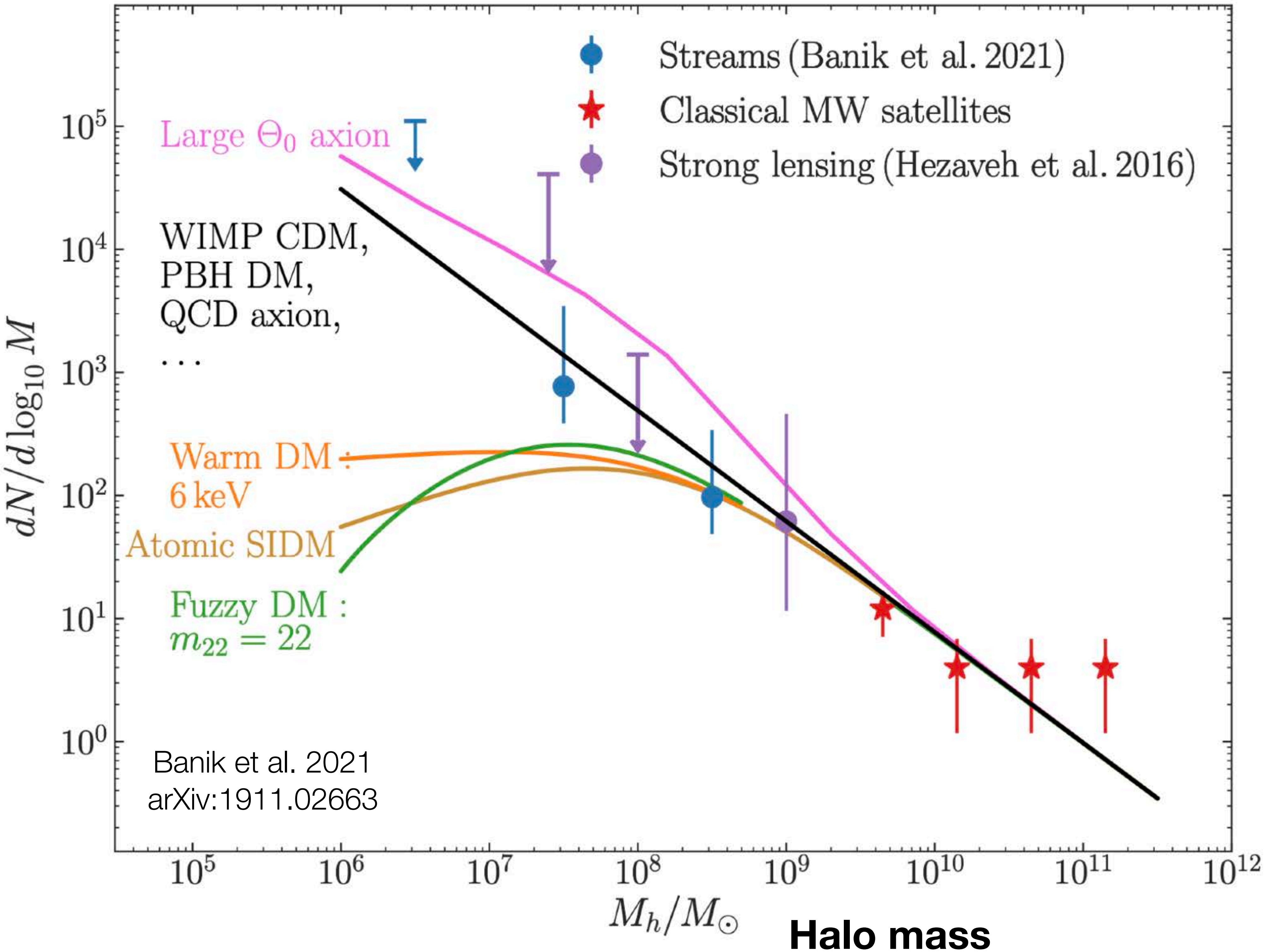


Bonaca et al. 2018
arXiv:1811.03631

LSST will discover more distant streams and allow detailed characterization of known streams

Current sensitivity ~10^8 $M_\odot$ halos; LSST anticipated to reach 10^7 to 10^6 $M_\odot$ halos

Halo abundance

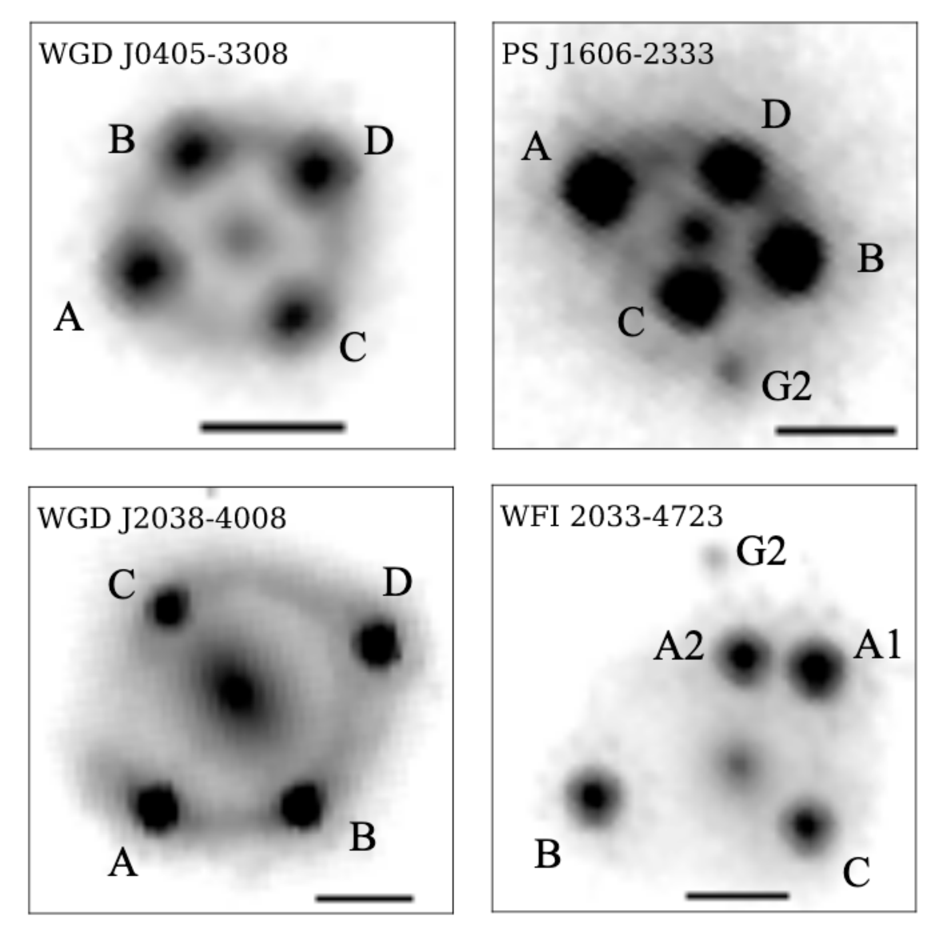


Banik et al. 2021
arXiv:1911.02663

Halo mass

LSST will advance two strong lensing methods sensitive to low-mass dark matter halos

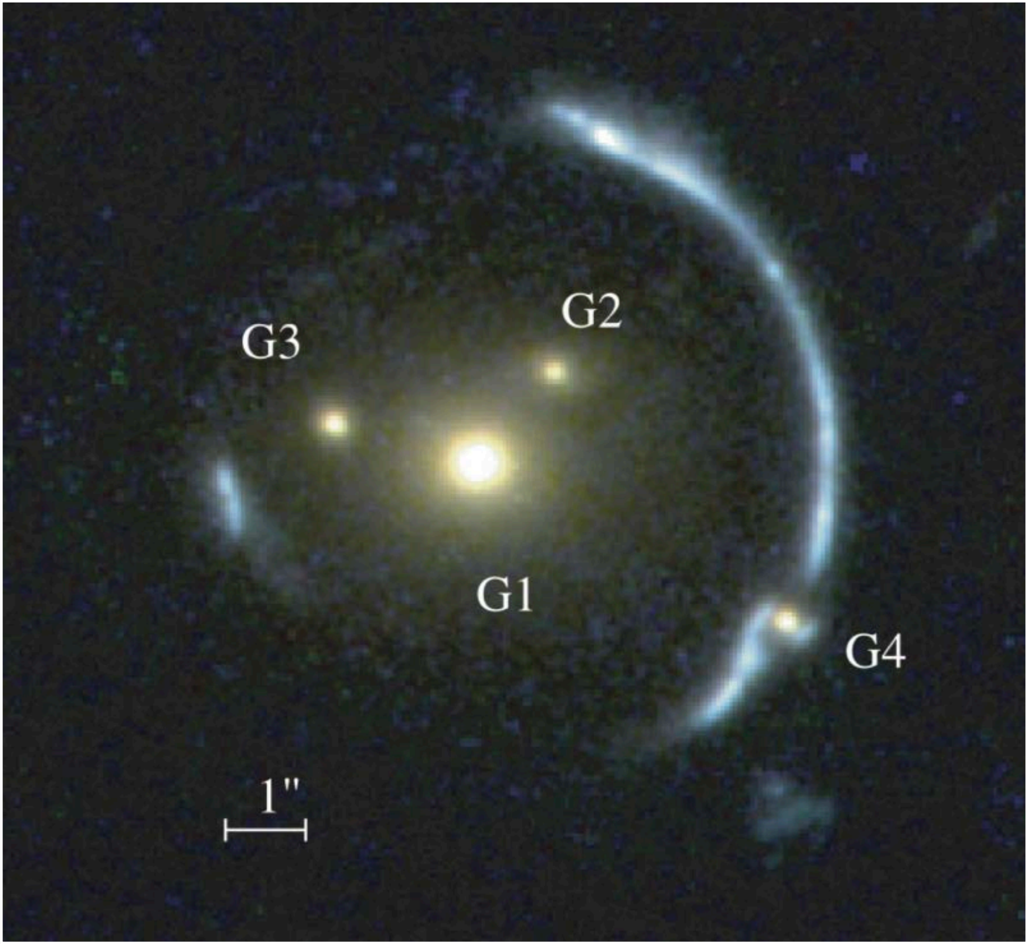
Flux Ratio Anomalies



Nierenberg et al. 2020
arXiv:1908.06344

Image positions and relative magnifications of quad quasars
narrow-line emission to avoid microlensing

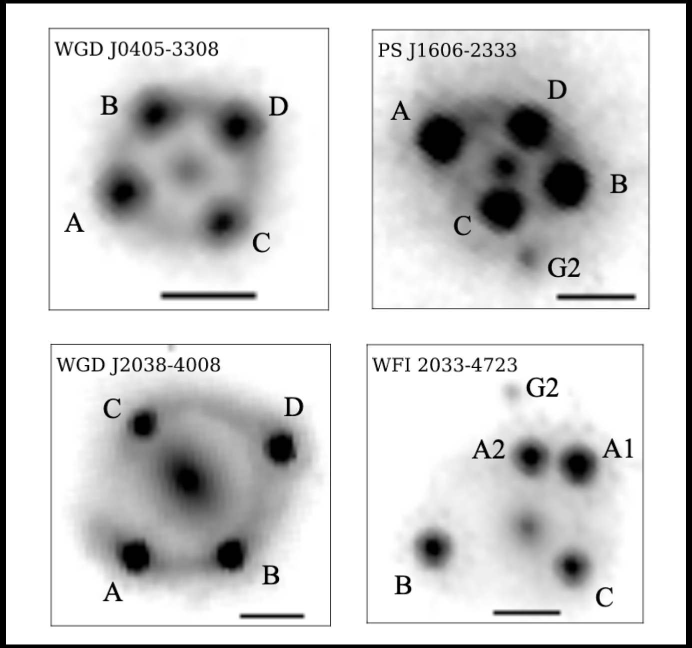
Gravitational Imaging



Vegetti et al. 2010
arXiv:1002.4708

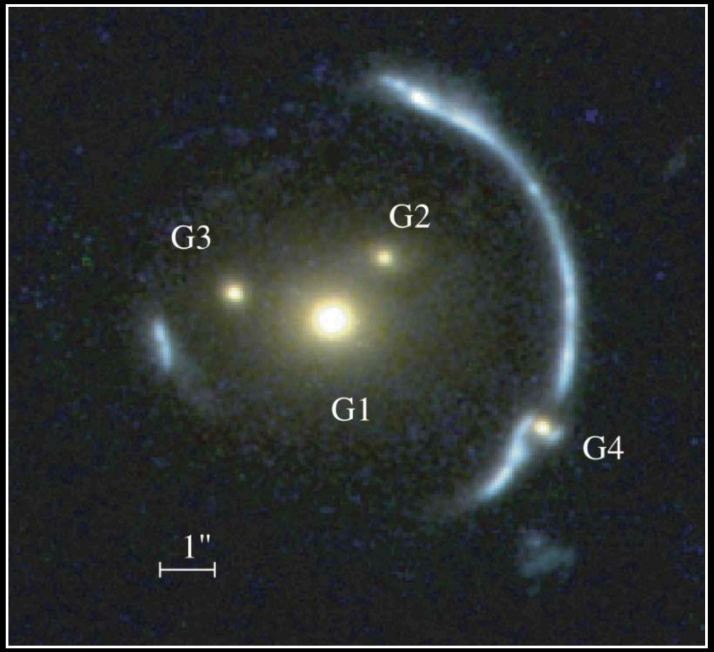
Astrometric anomalies of multiply-imaged arcs

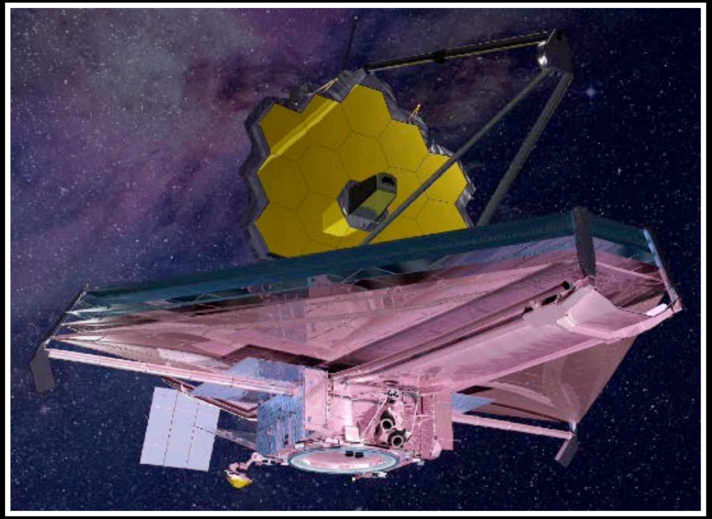
LSST will help build requisite samples of ~100 suitable lenses for high-resolution follow-up observations to constrain mass of main deflector and characterize source images → statistical studies of dark halos

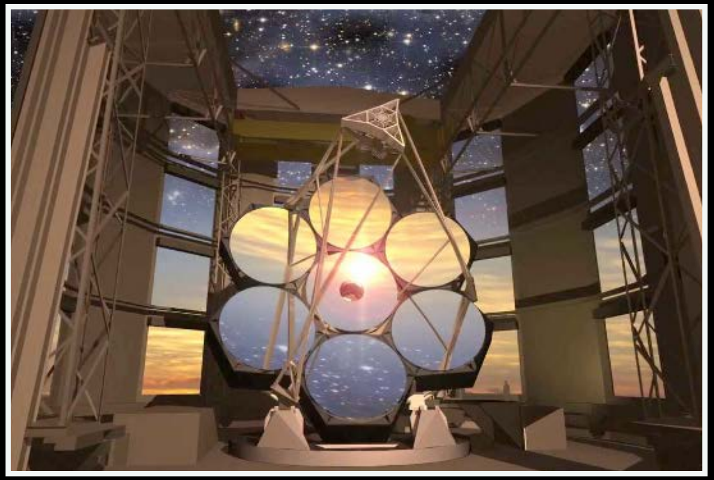


Target
lens systems

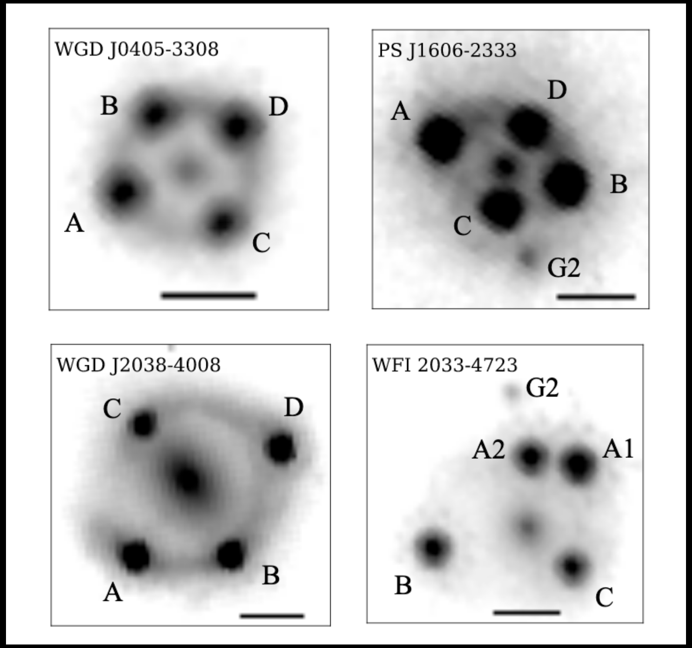
* HST images for
illustration purposes







LSST will help identify requisite samples of ~100 suitable lenses for high-resolution follow-up to constrain mass of main deflector and characterize source images, allowing statistical studies of dark halos



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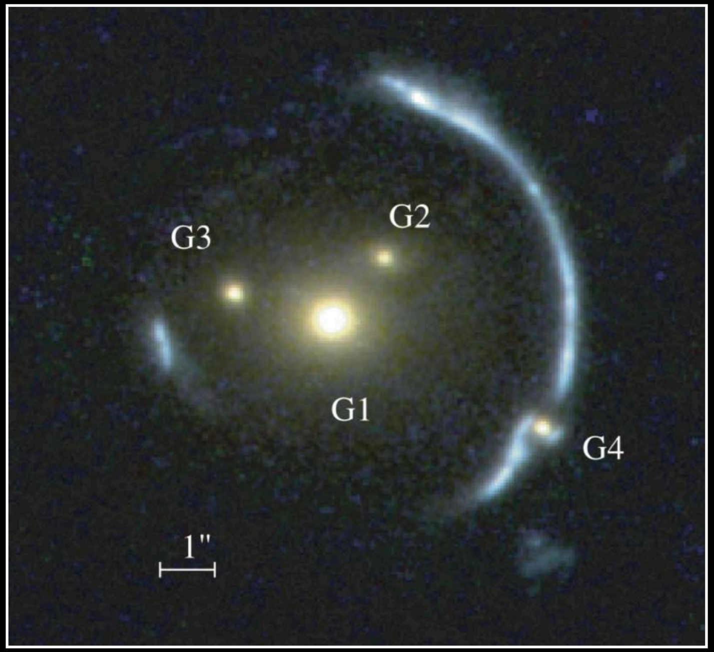
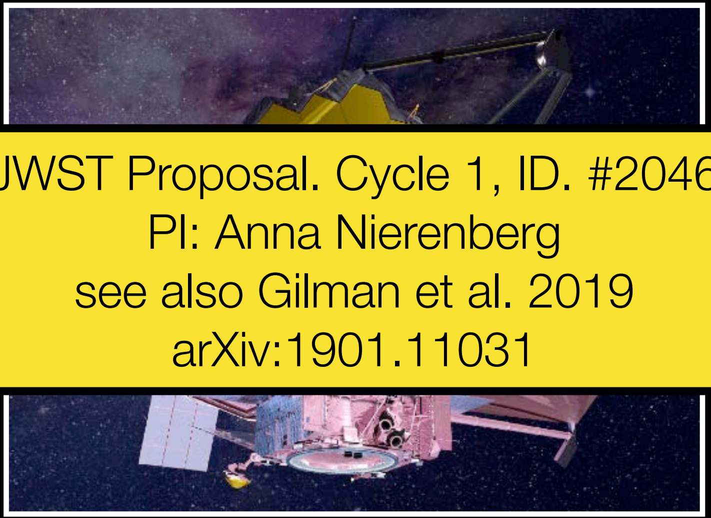
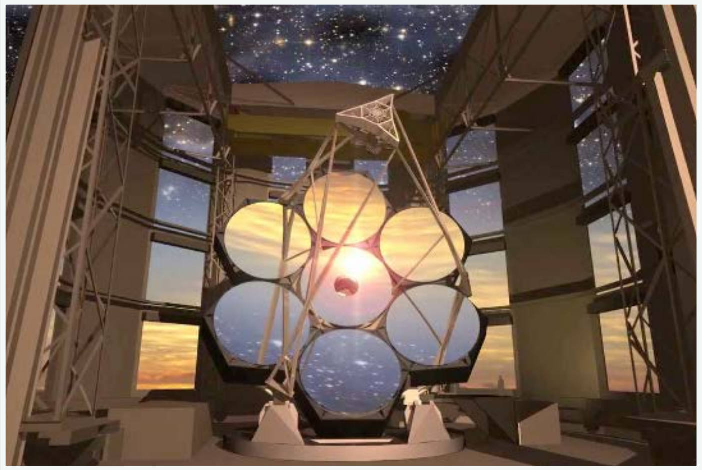


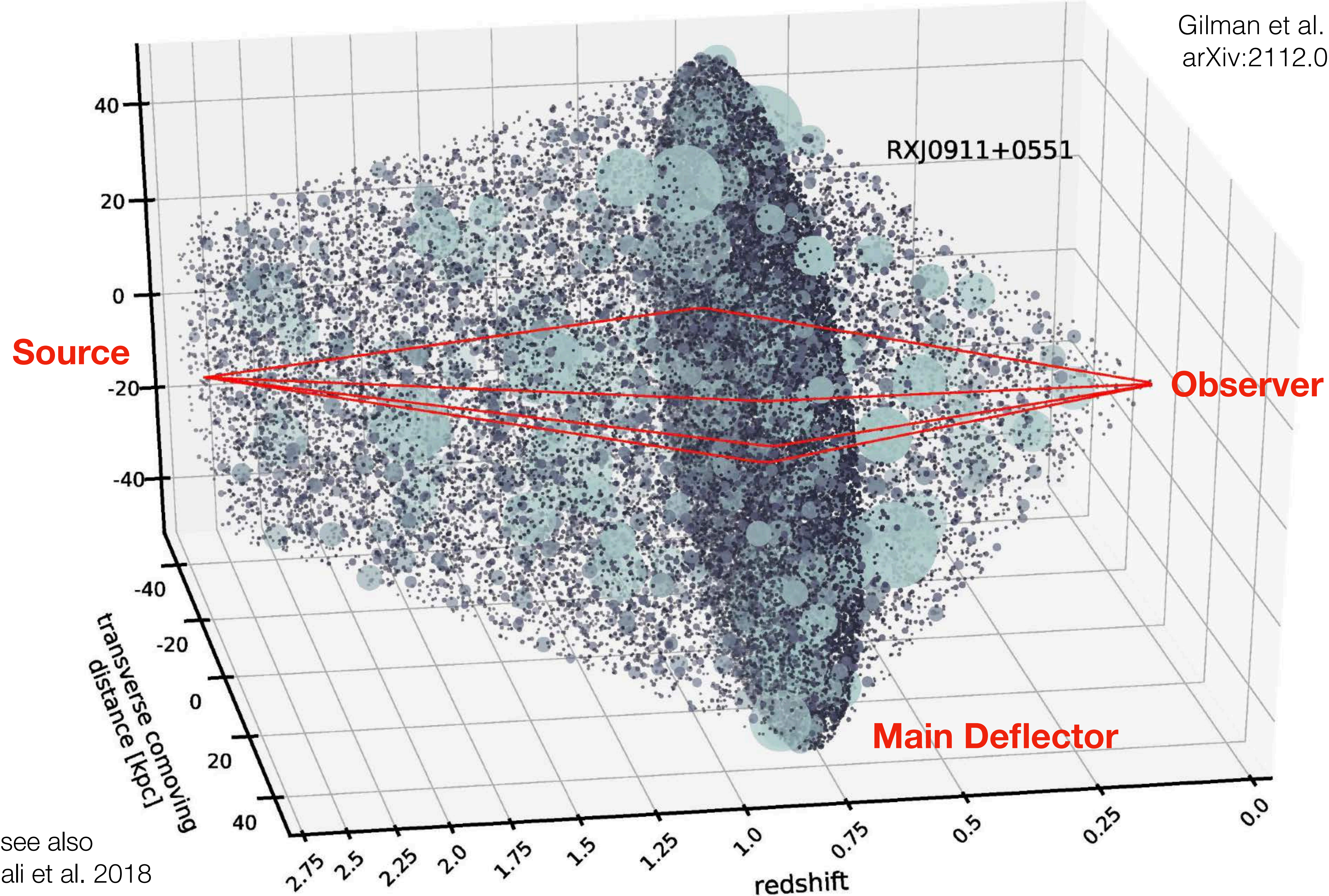


JWST Proposal. Cycle 1, ID. #2046
PI: Anna Nierenberg
see also Gilman et al. 2019
arXiv:1901.11031



High redshift sources offer sensitivity to isolated line-of-sight dark matter halos

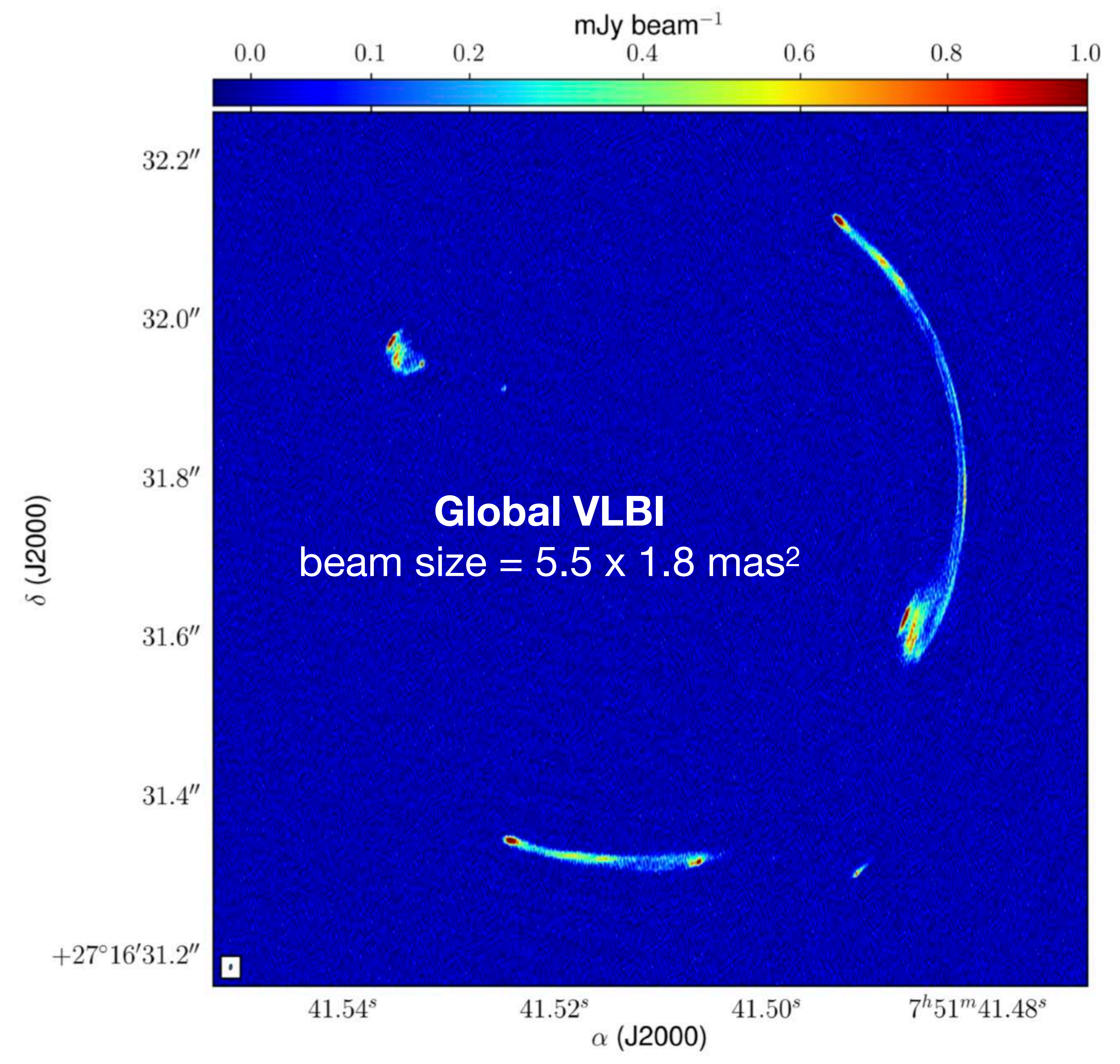
Gilman et al. 2022
arXiv:2112.03293



see also
Despali et al. 2018
Hsueh et al. 2019

Current leading angular resolution comes from global VLBI

Ongoing work to combine optical and radio surveys (e.g. LSST + VLASS) to enlarge current sample of ~40 known radio-load lenses

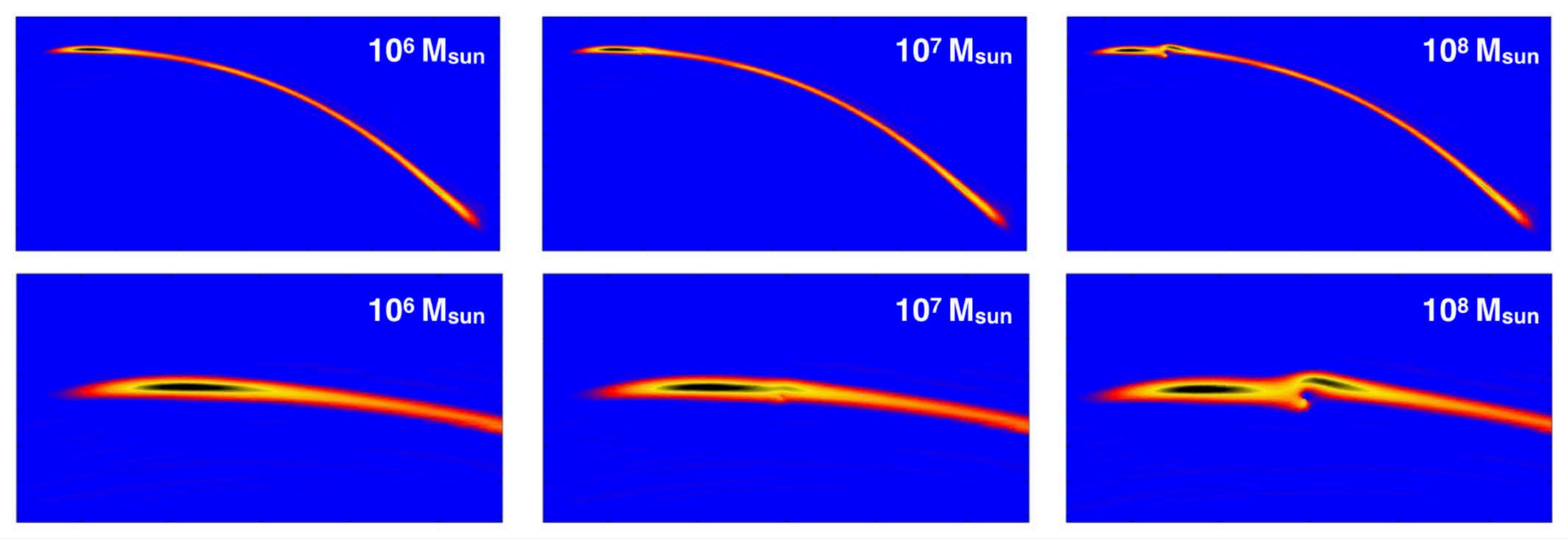


Global VLBI

beam size = 5.5 x 1.8 mas^2

Spingola et al. 2018
arXiv:1807.05566

Gravitational imaging with milli-arcsecond resolution could be sensitive to isolated line-of-sight dark halos



McKean et al. 2015 arXiv:1502.03362

ELTs aim for comparable angular resolution and sensitivity

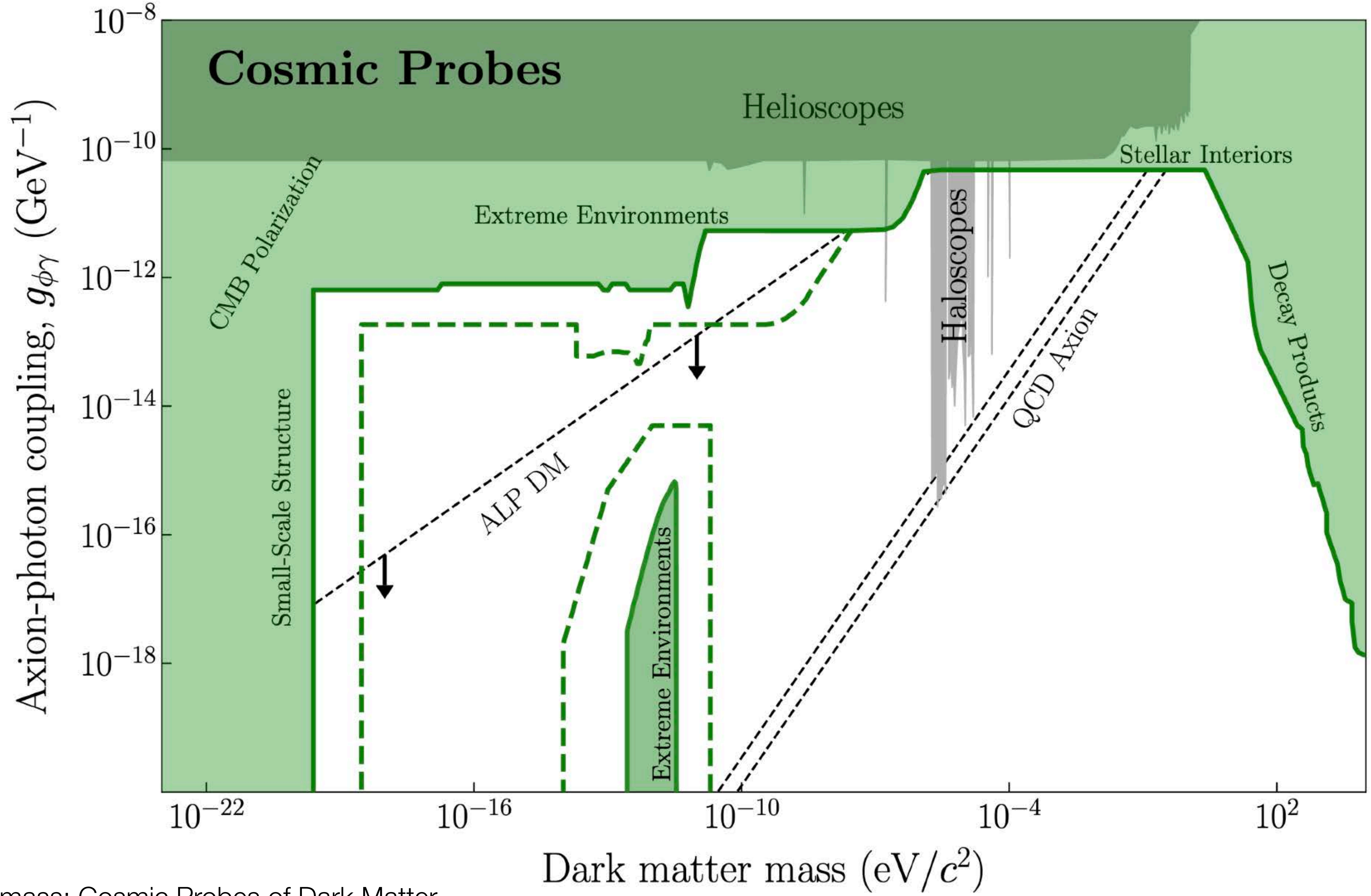
Impact of Rubin Observatory

Physics beyond the Standard Model

Near-term benchmarks and longer-term goals

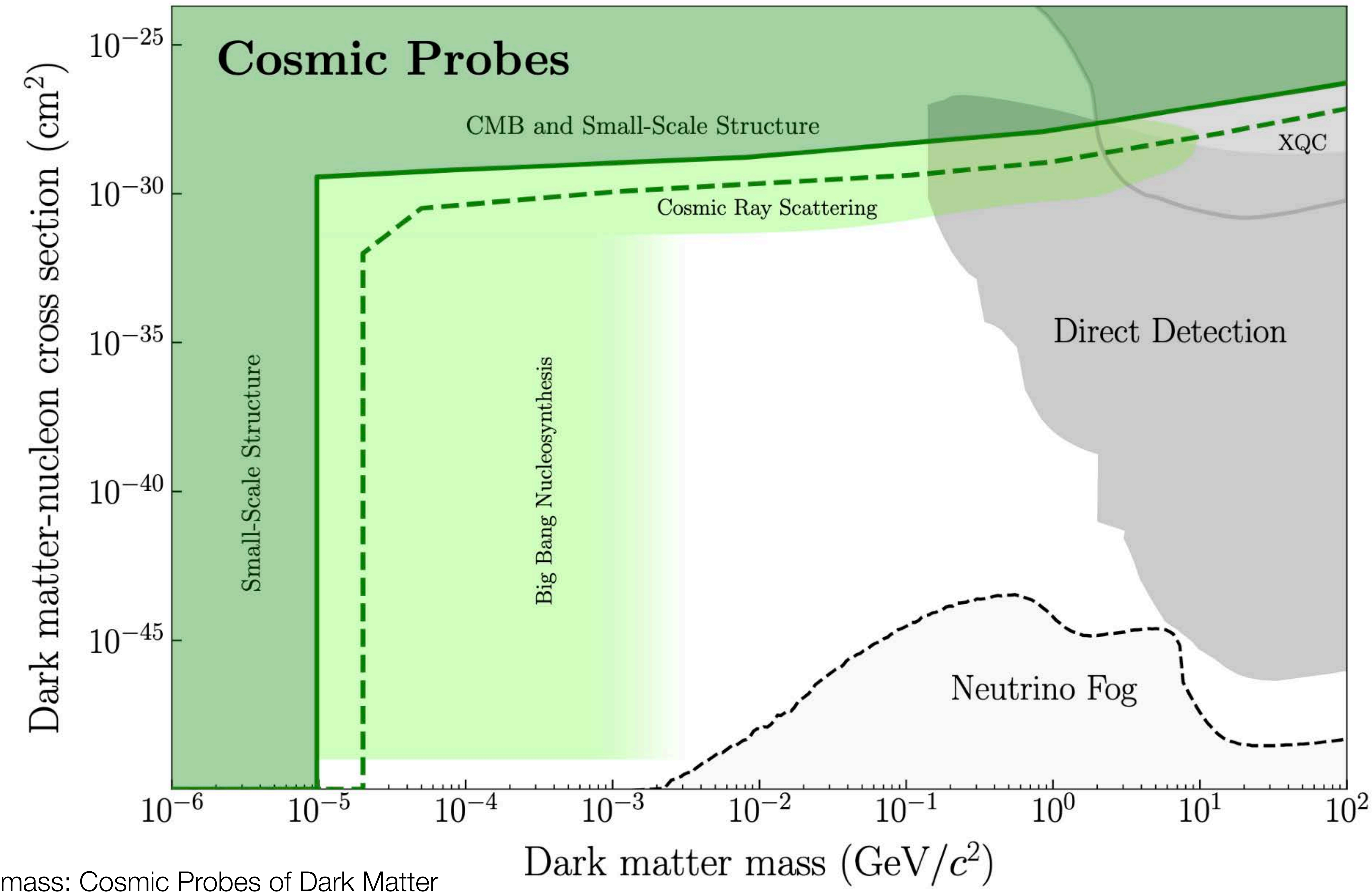
Building an open and interdisciplinary community

Wave-like Dark Matter: Example Sensitivity



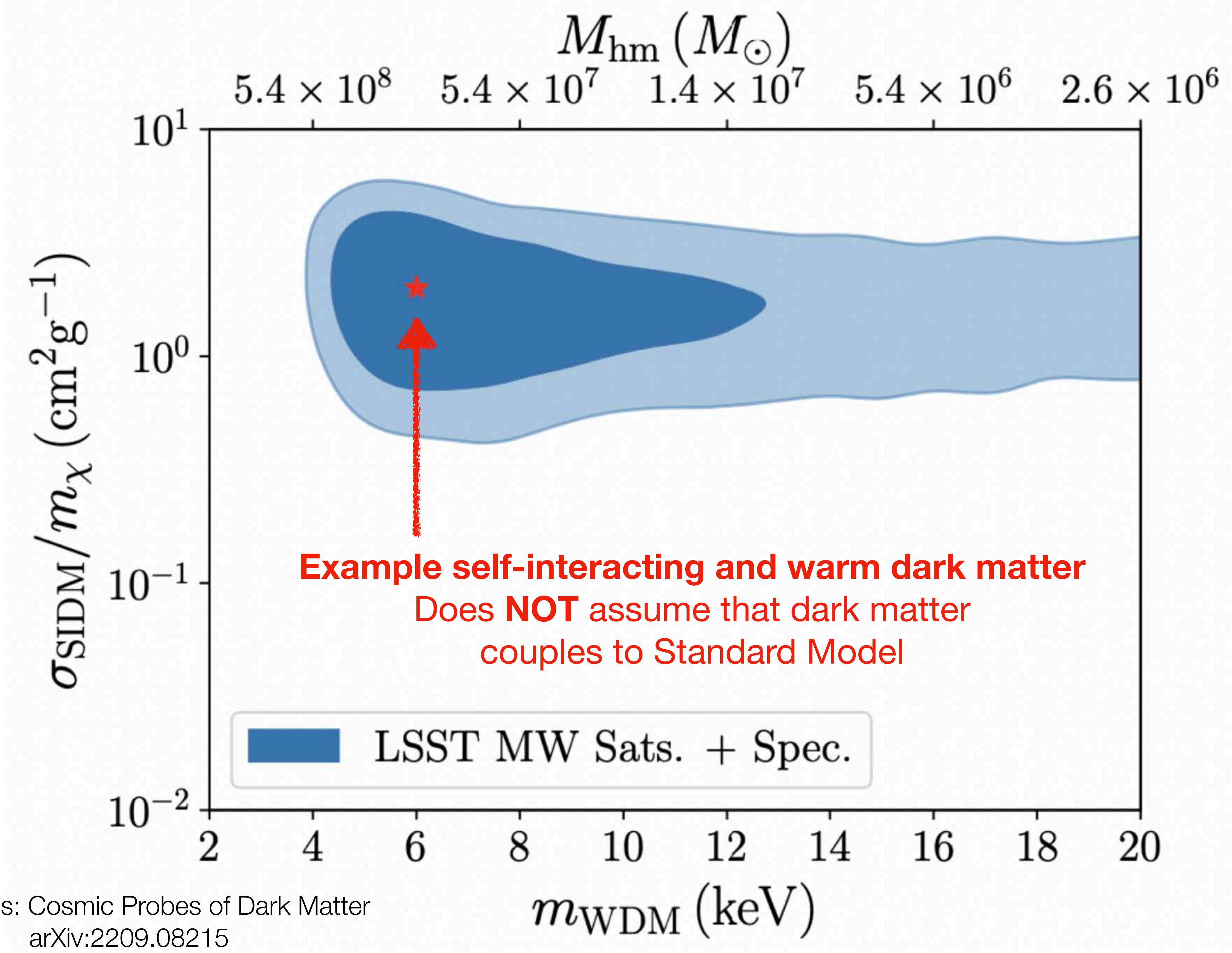
Snowmass: Cosmic Probes of Dark Matter
arXiv:2209.08215

Particle Dark Matter: Example Sensitivity



Snowmass: Cosmic Probes of Dark Matter
arXiv:2209.08215

Particle Dark Matter: Example Discovery

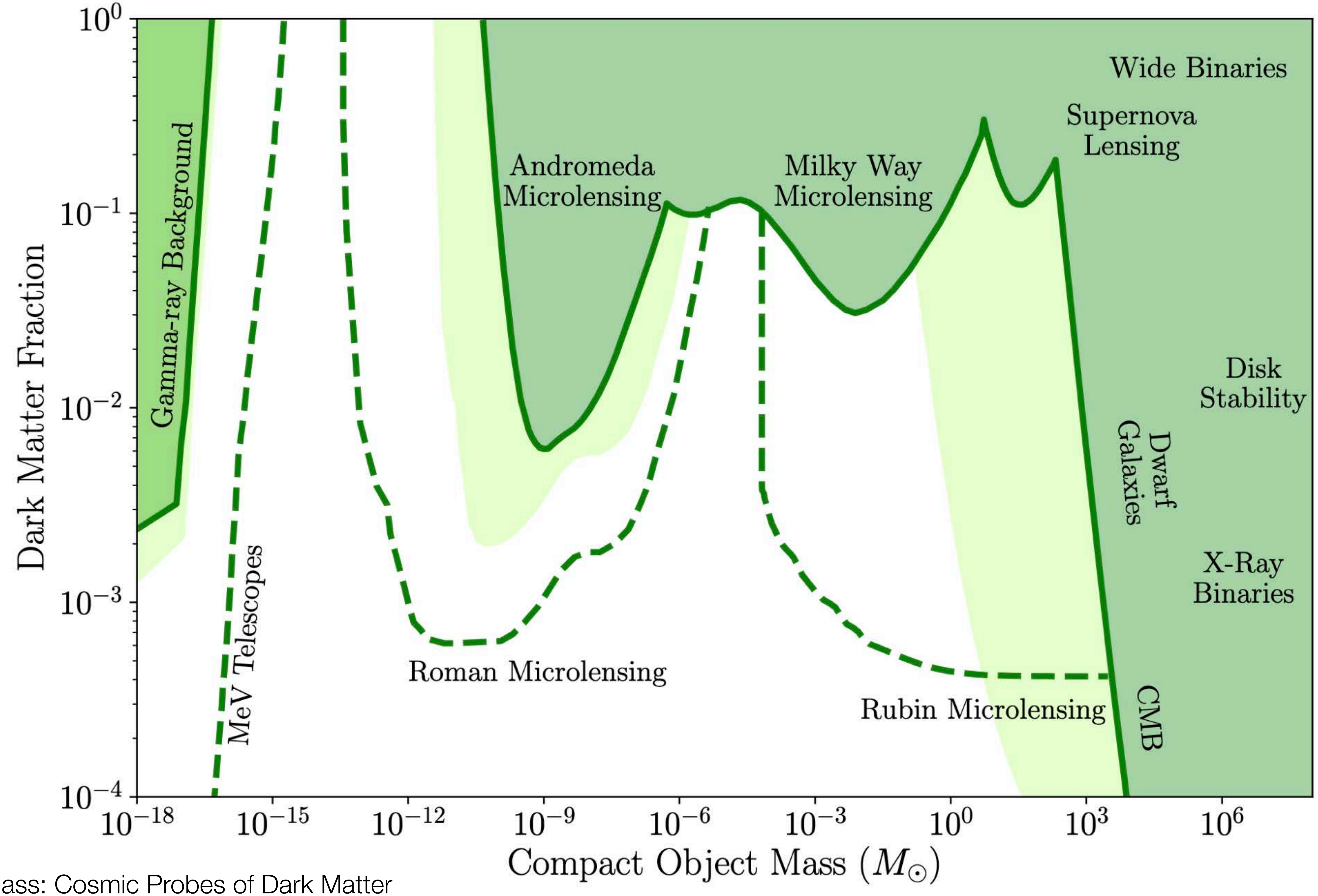


Example self-interacting and warm dark matter

Does **NOT** assume that dark matter couples to Standard Model

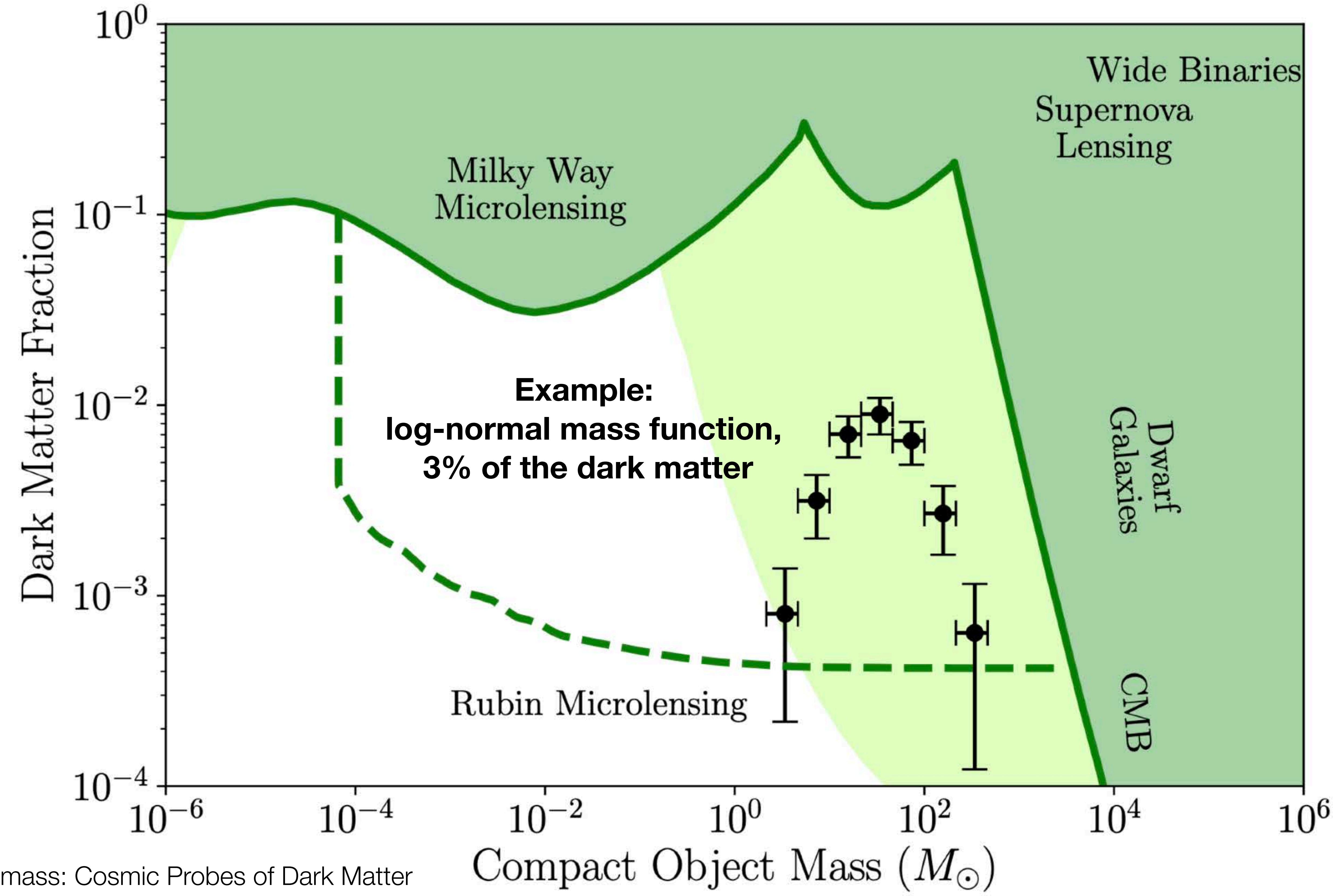
Snowmass: Cosmic Probes of Dark Matter
arXiv:2209.08215

Primordial Black Holes: Sensitivity



Snowmass: Cosmic Probes of Dark Matter
arXiv:2209.08215

Primordial Black Holes: Example Discovery



Example:
log-normal mass function,
3% of the dark matter

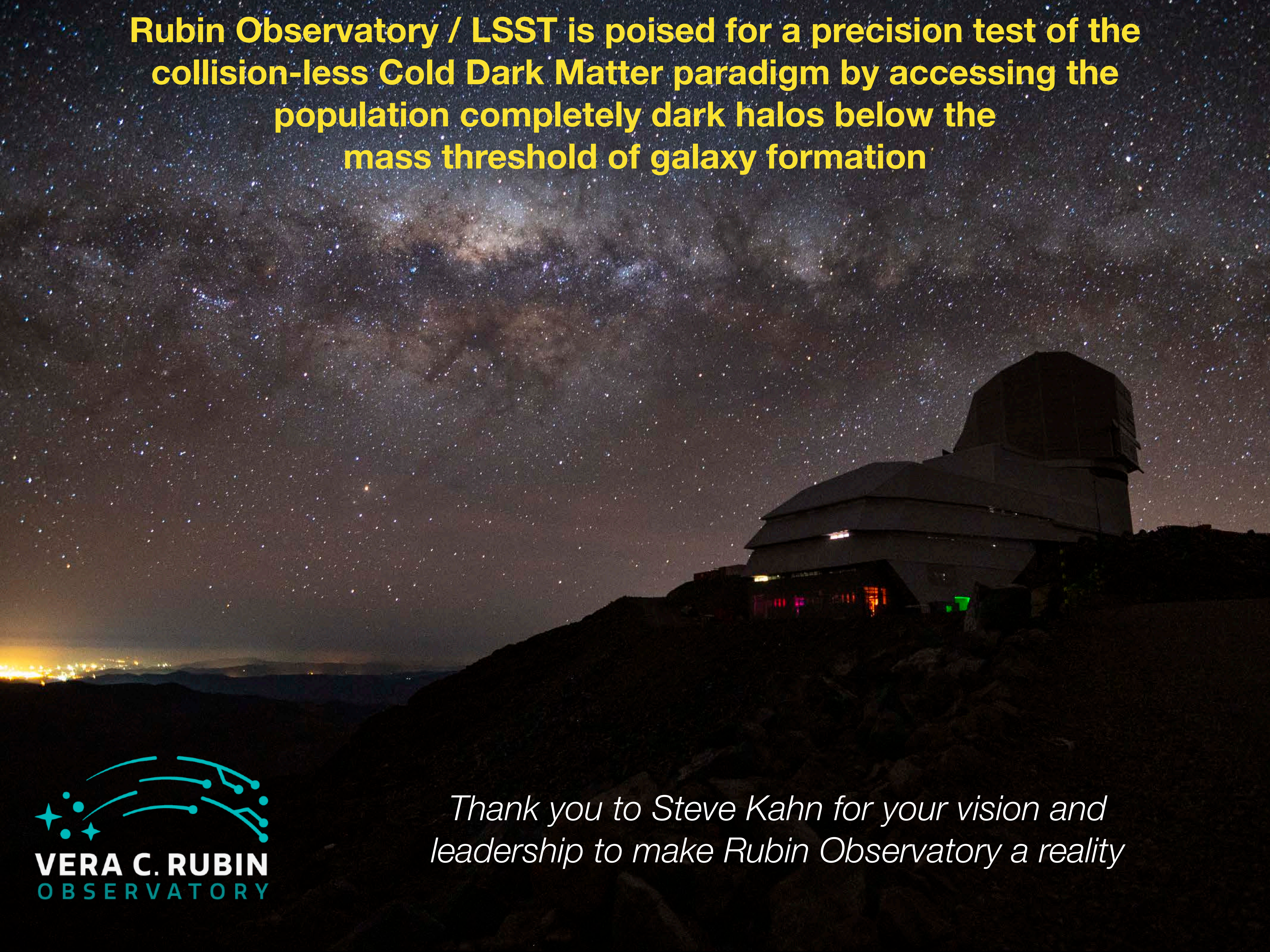
Snowmass: Cosmic Probes of Dark Matter
arXiv:2209.08215

Interdisciplinary approach is essential to making the most of Rubin Observatory as a dark matter experiment

- Support theory to develop **rich phenomenology of the dark sector**
  - Particle theory + numerical simulations + galaxy-halo connection
  - Broad range of physical scales and environments, including baryonic effects
  - Tight collaboration between theory modeling and observation

- Build the **community** (e.g., LSST DESC)
  - Open data, open software
  - Range of collaboration participation/membership levels

- **Joint analysis** with other datasets
  - High angular resolution and sensitivity
  - Complementarity w/ Euclid and Roman



Rubin Observatory / LSST is poised for a precision test of the collision-less Cold Dark Matter paradigm by accessing the population completely dark halos below the mass threshold of galaxy formation

Thank you to Steve Kahn for your vision and leadership to make Rubin Observatory a reality

VERA C. RUBIN
OBSERVATORY

Extras