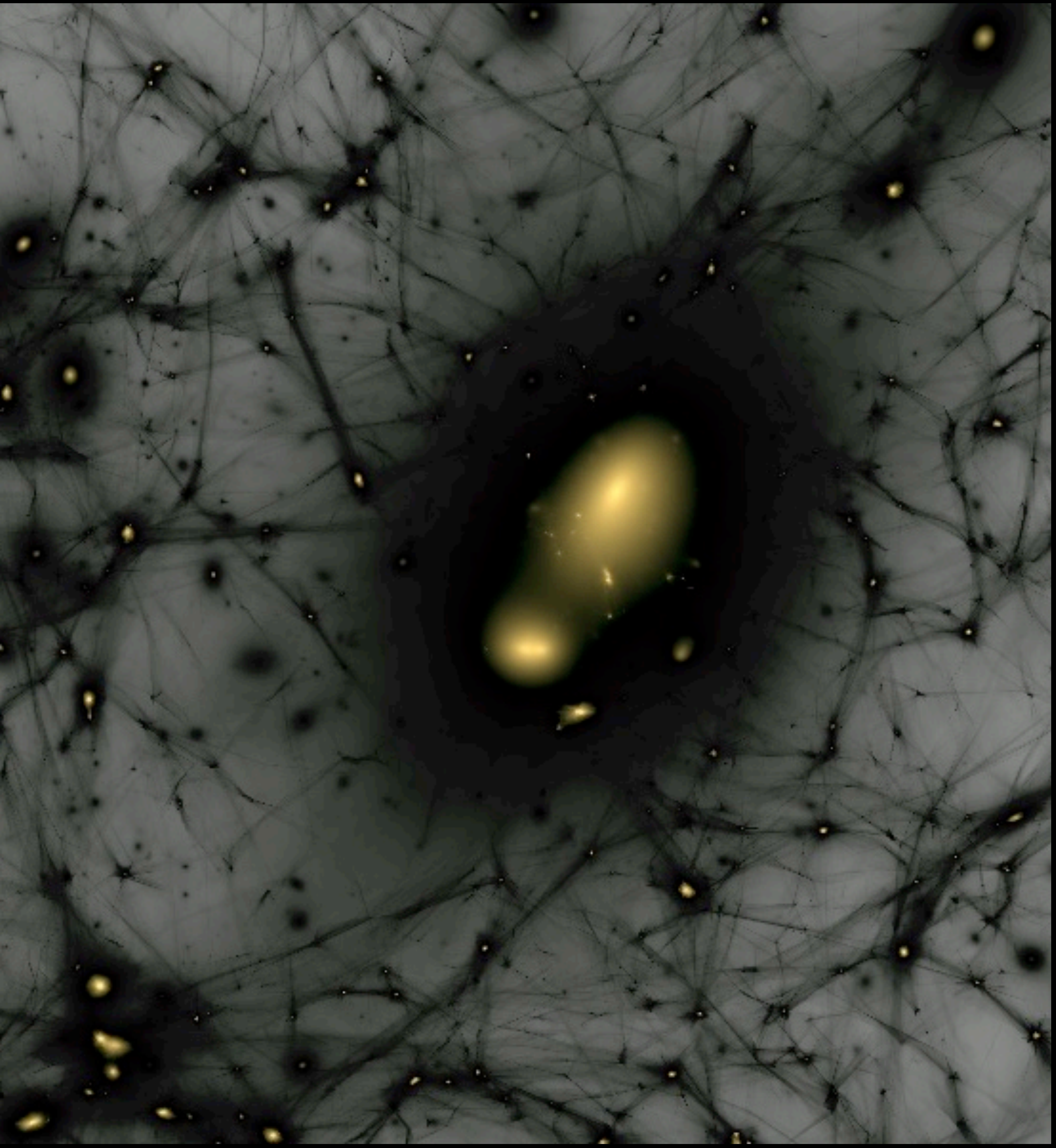
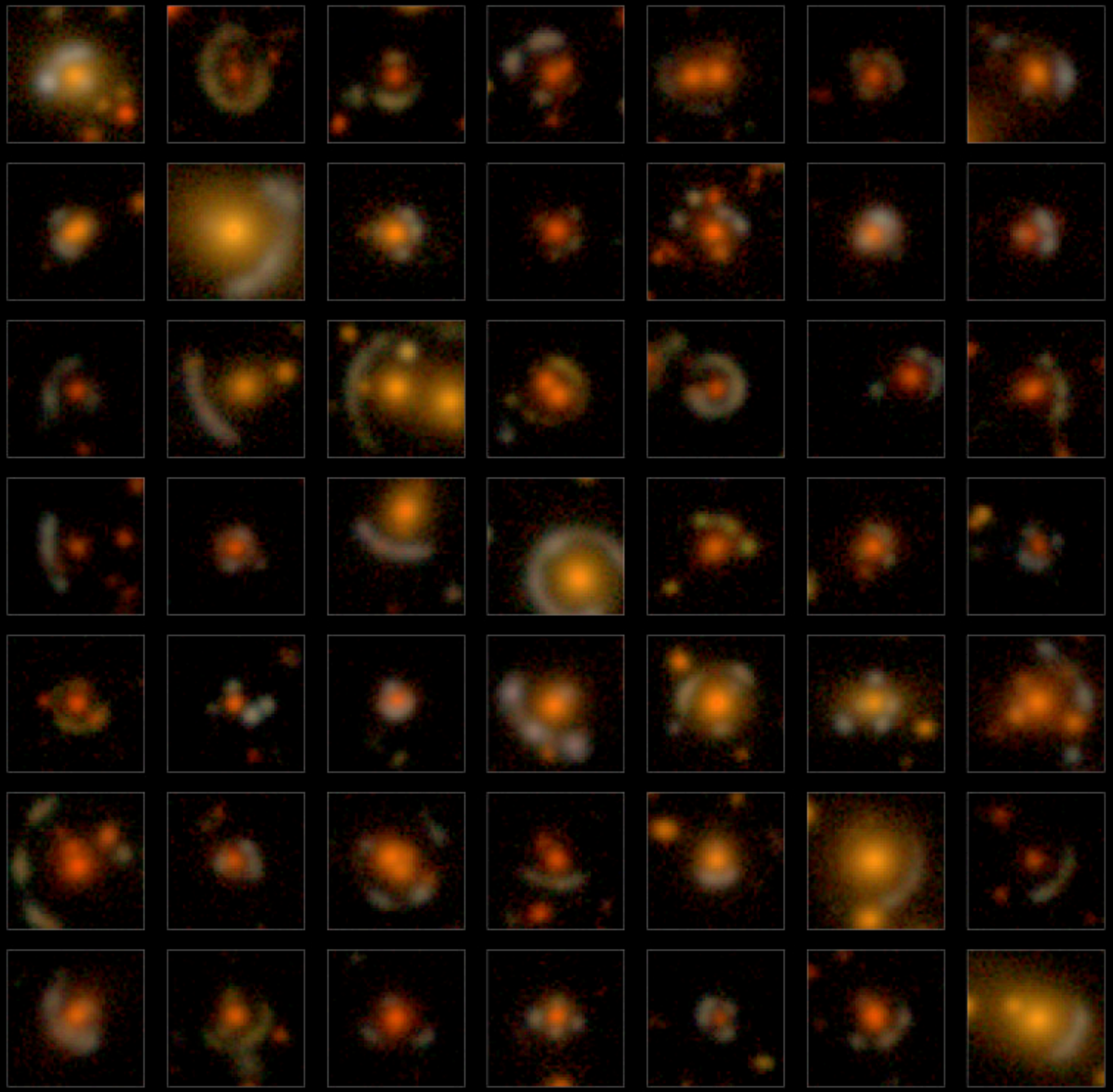
Advancing a search for isolated sub-galactic dark matter halos



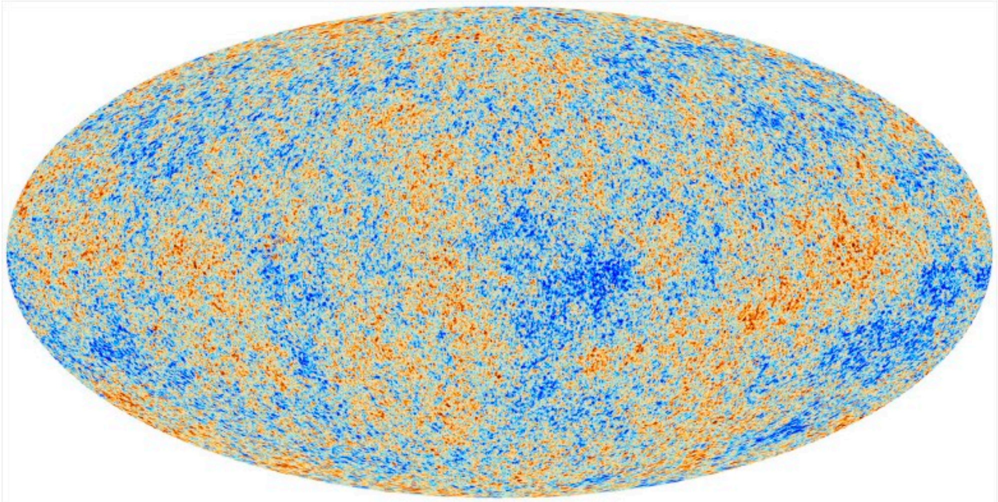


Keith Bechtol

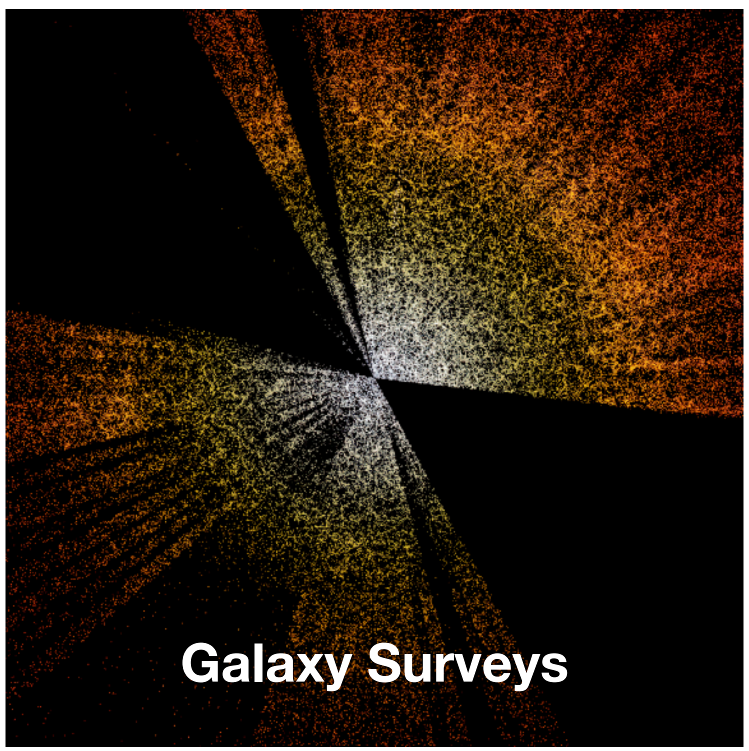
KICP-20: Cosmology past, present, and future

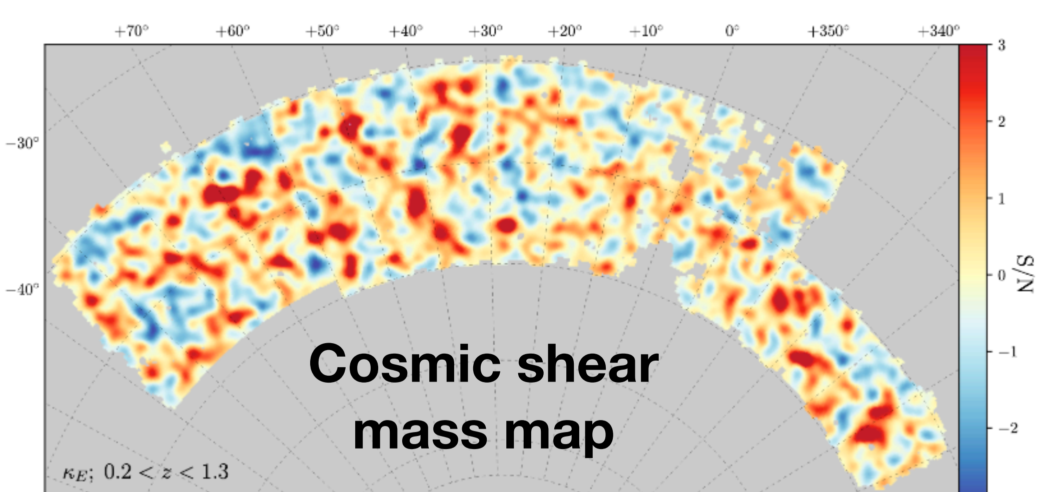
6 June 2024

THE UNIVERSITY of WISCONSIN MADISON

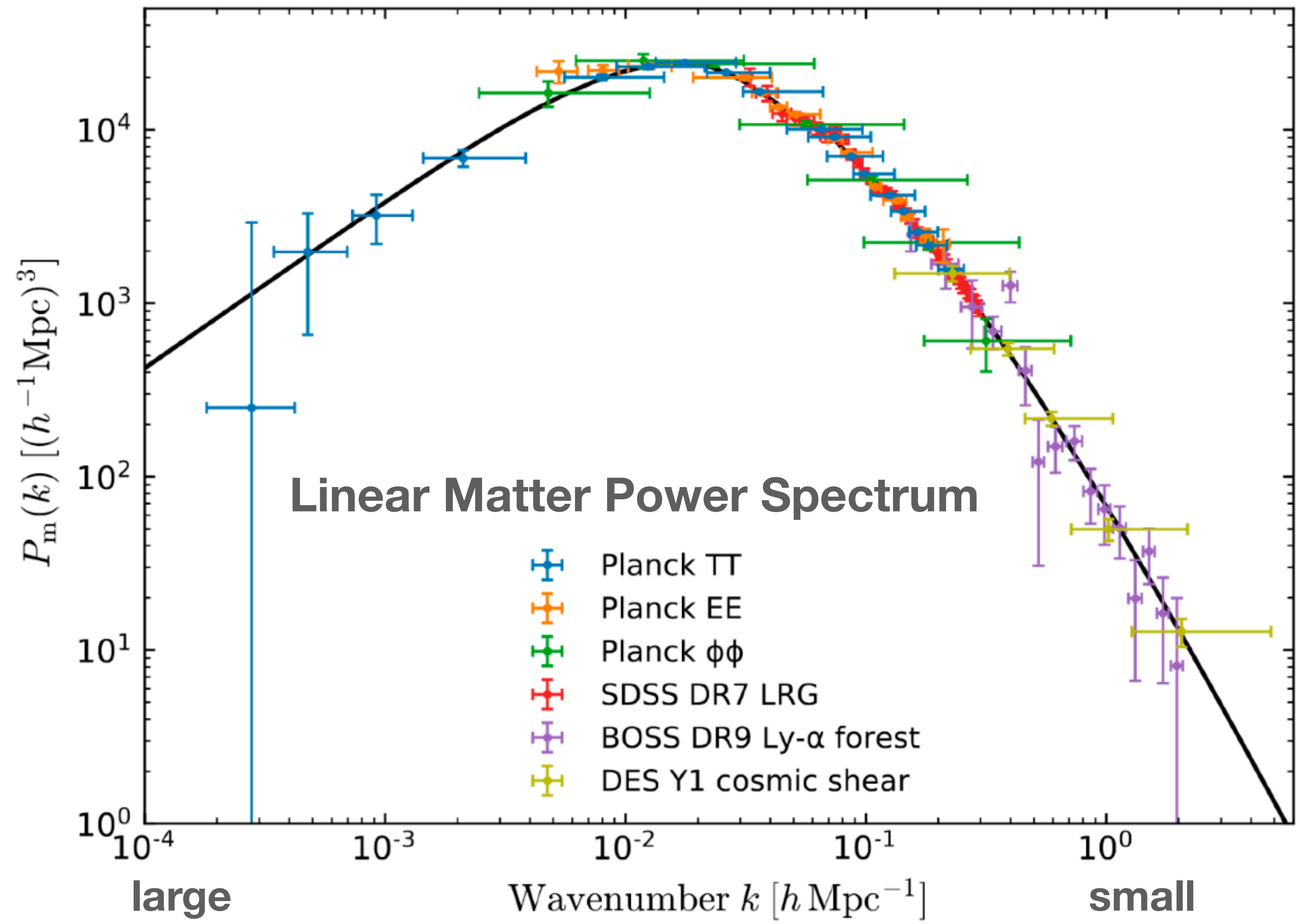


Cosmic Microwave Background





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

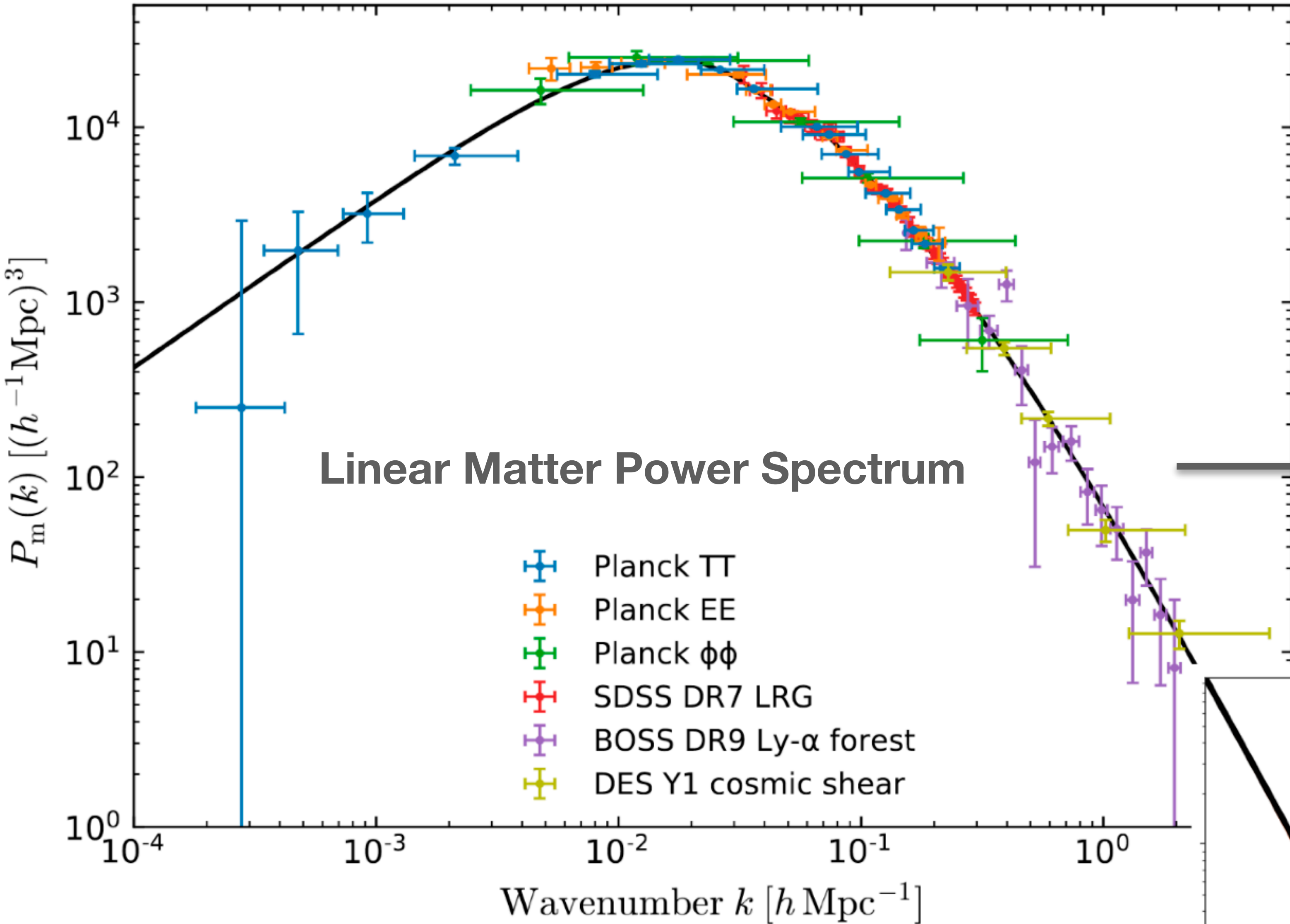


large physical scales

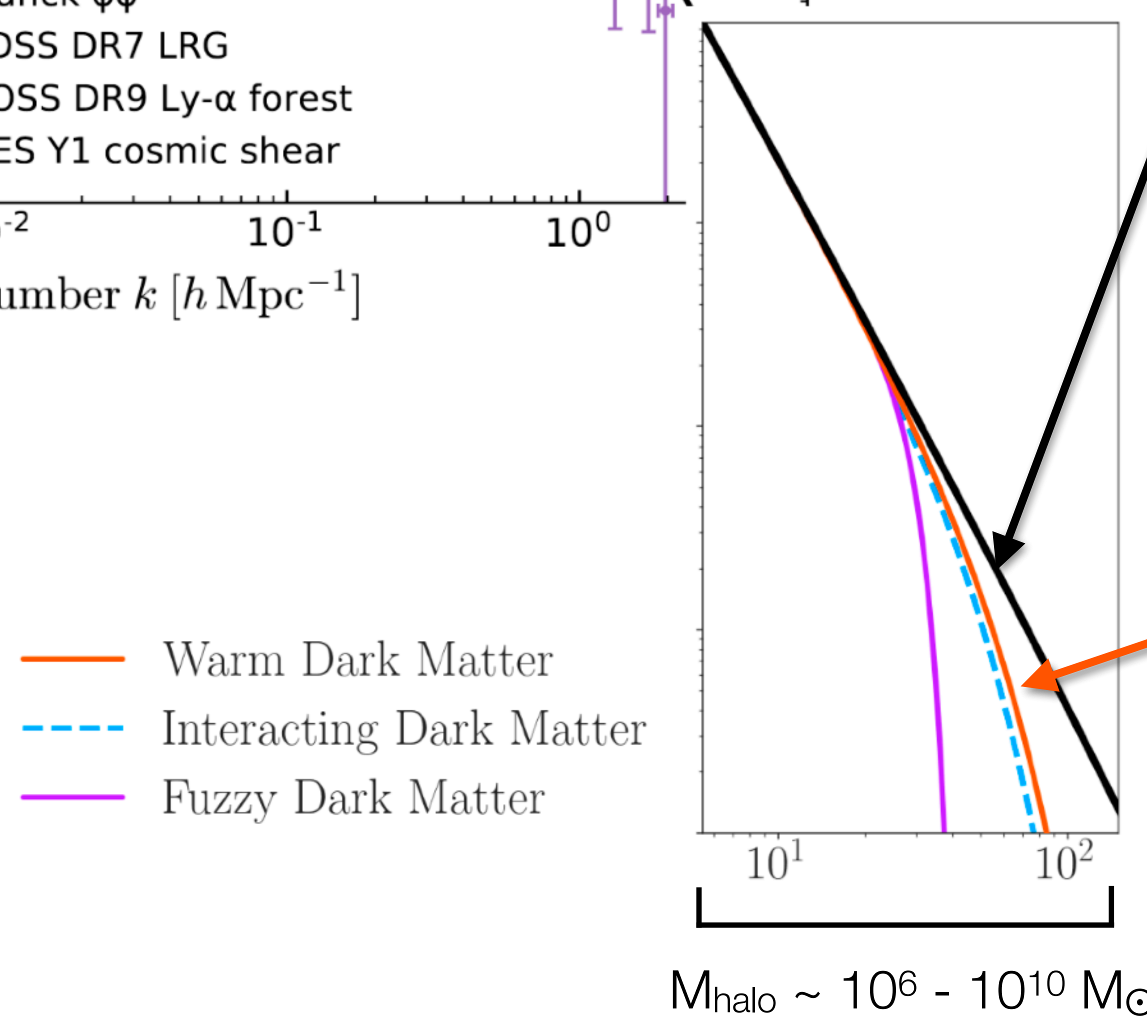
small physical scales

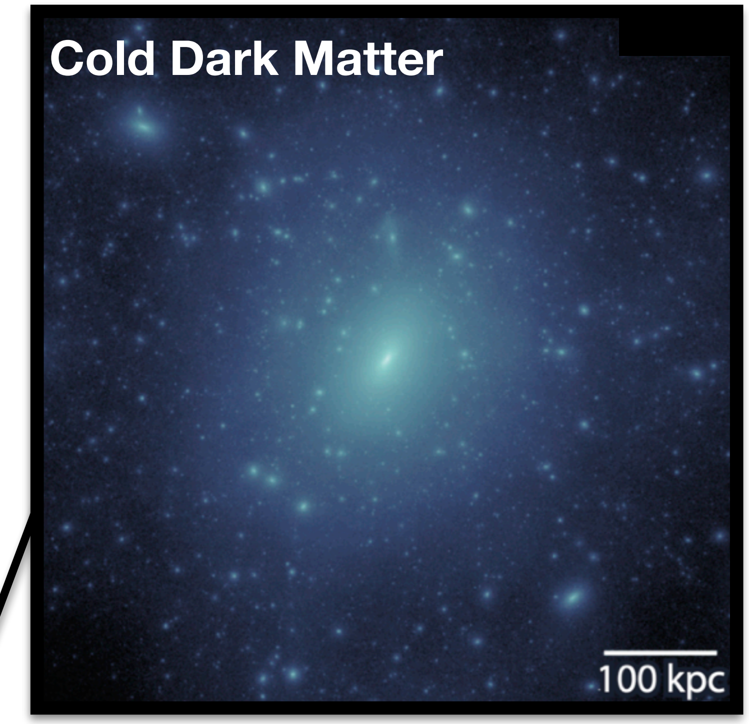
Chabanier 2019
arXiv:1905.08103

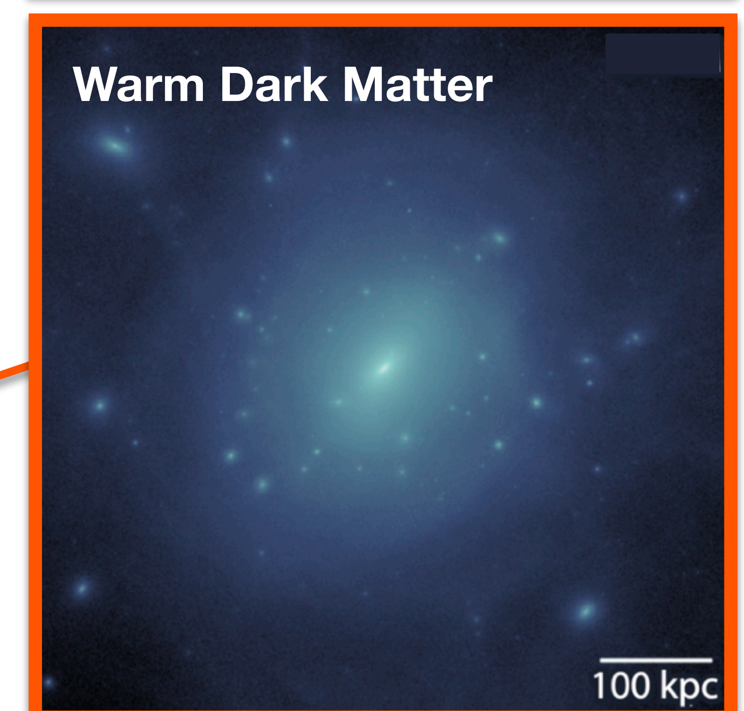
Dark matter microphysics affects structure formation throughout cosmic history



Nonlinear Structure Formation

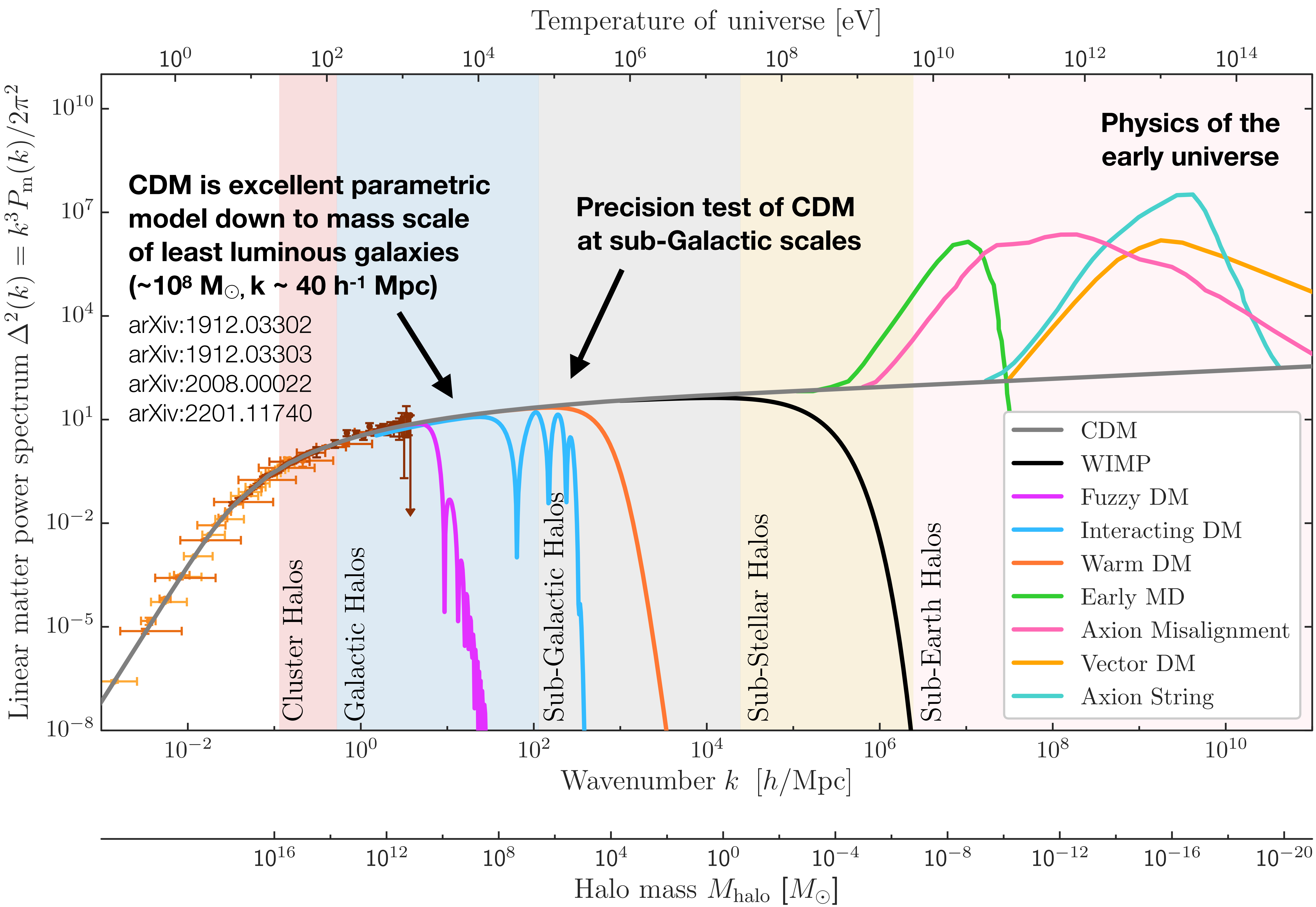




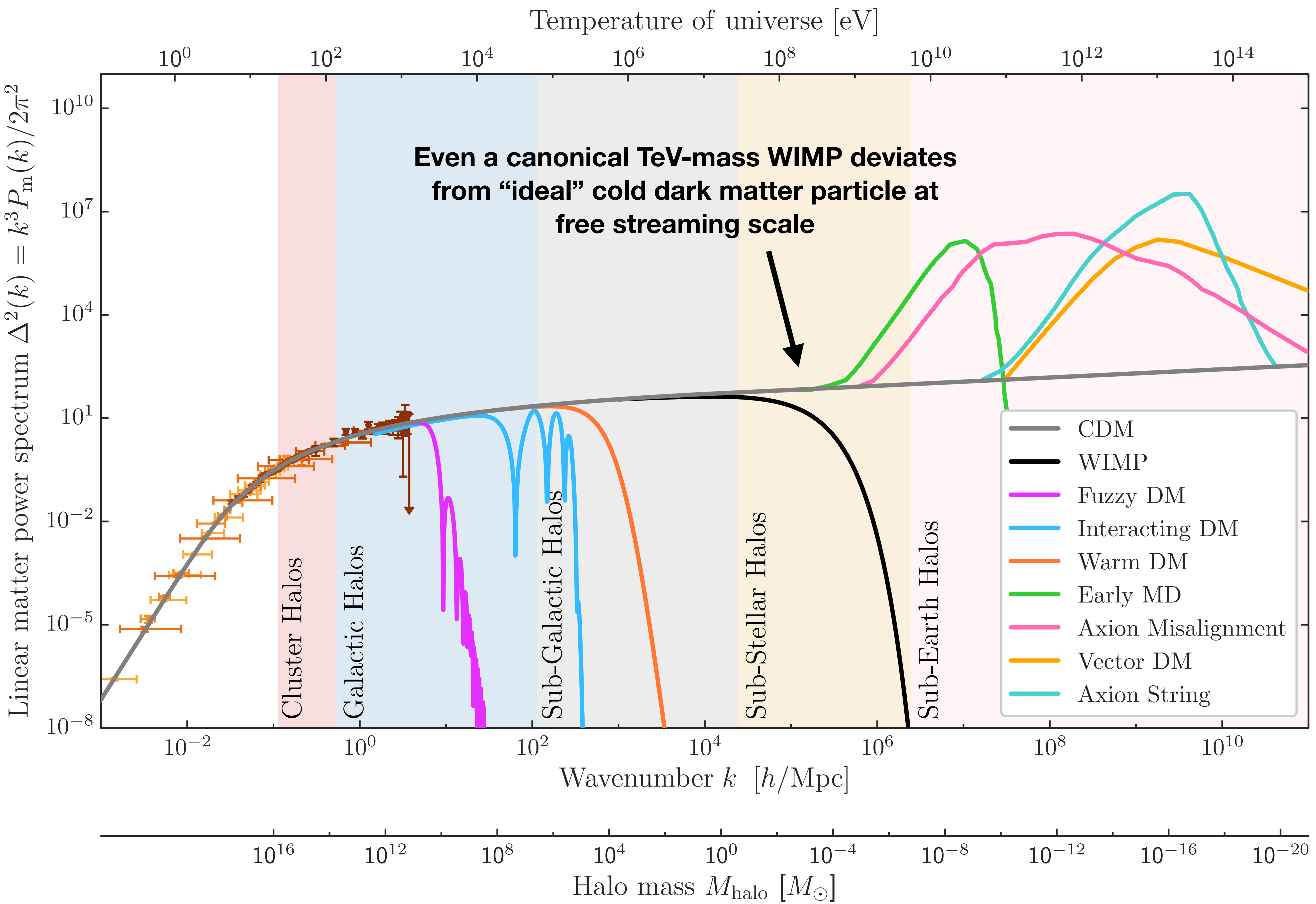


Threshold of galaxy formation??

Slide adapted from Ethan Nadler



Bechtol et al. 2022 arXiv:2203.07354



Bechtol et al. 2022 arXiv:2203.07354

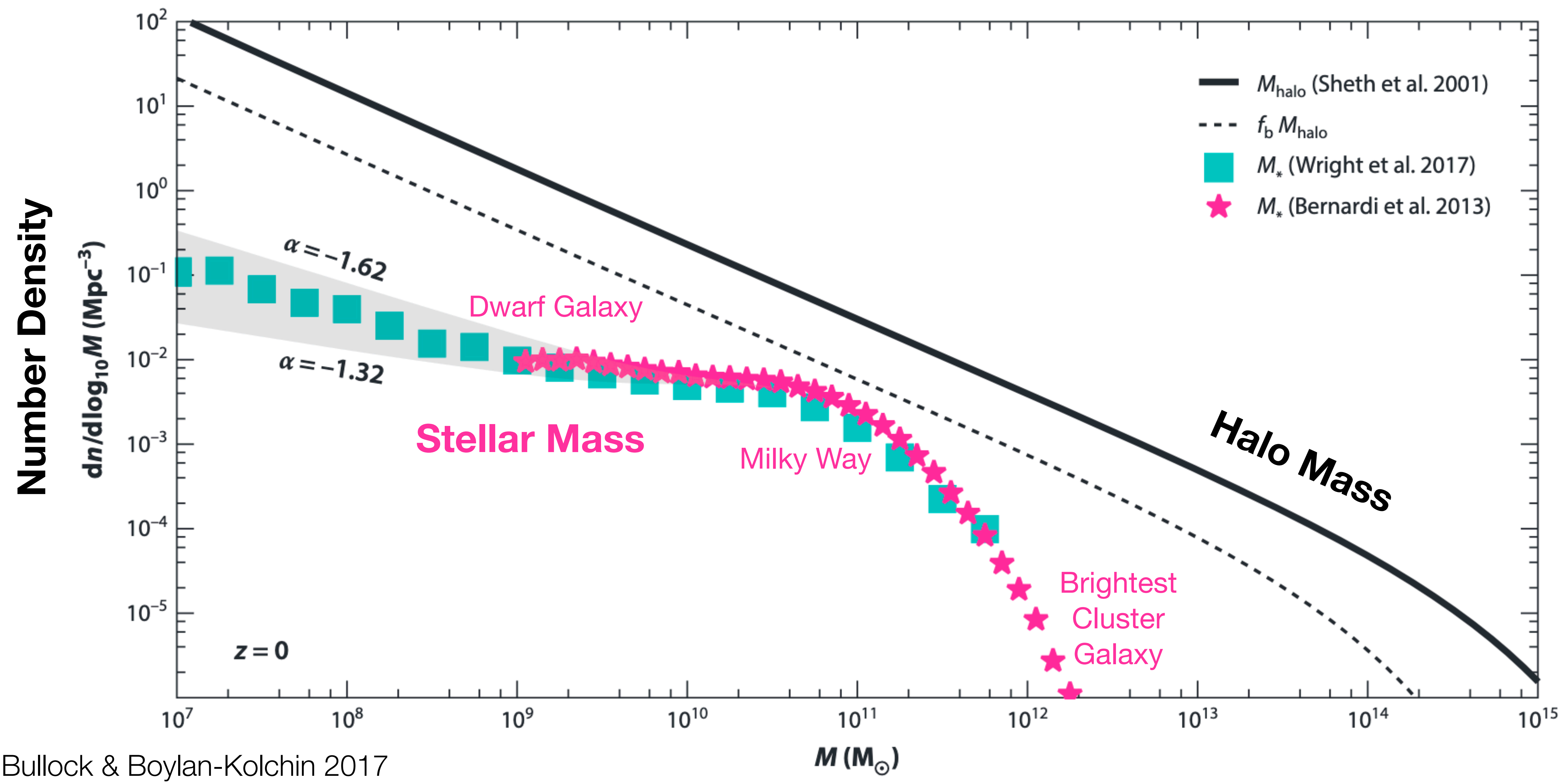
Threshold of Galaxy Formation

What is the minimum halo mass for galaxy formation?

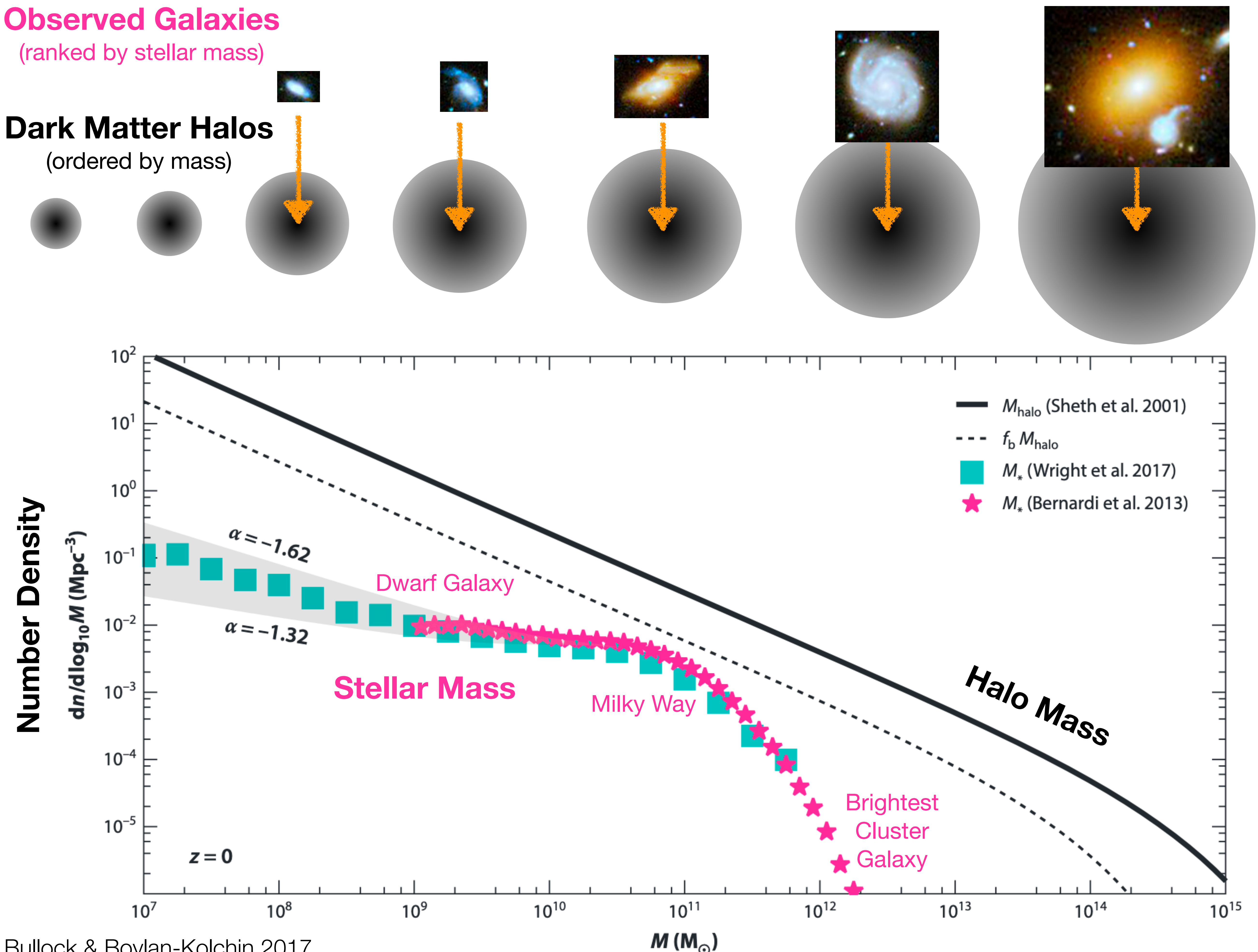
What is the galaxy-halo connection at the extreme faint end of the galaxy luminosity function?

Galaxy-Halo Connection

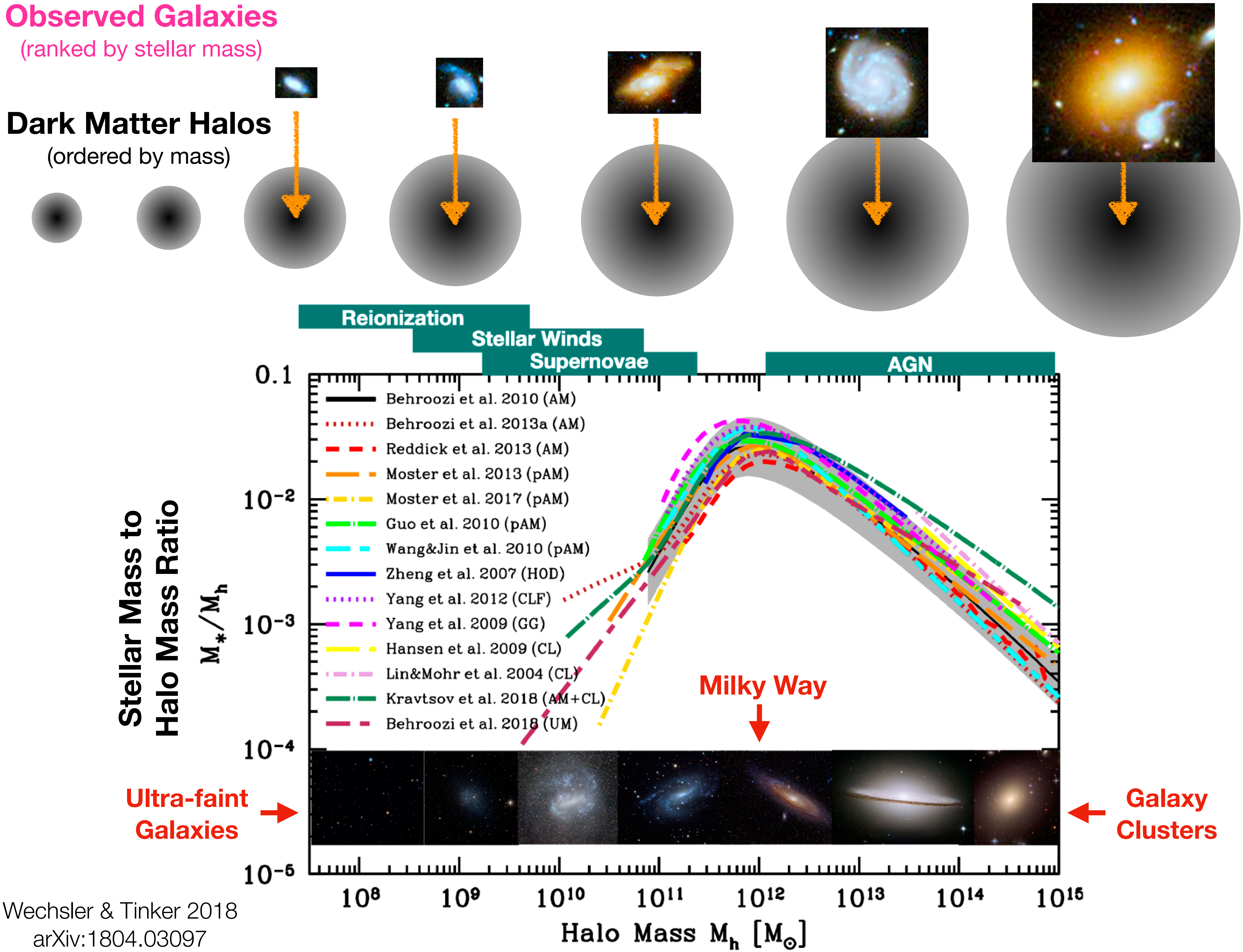
Abundance Matching (simplified):
most massive galaxies by stellar mass tend to occupy the most massive dark matter halos



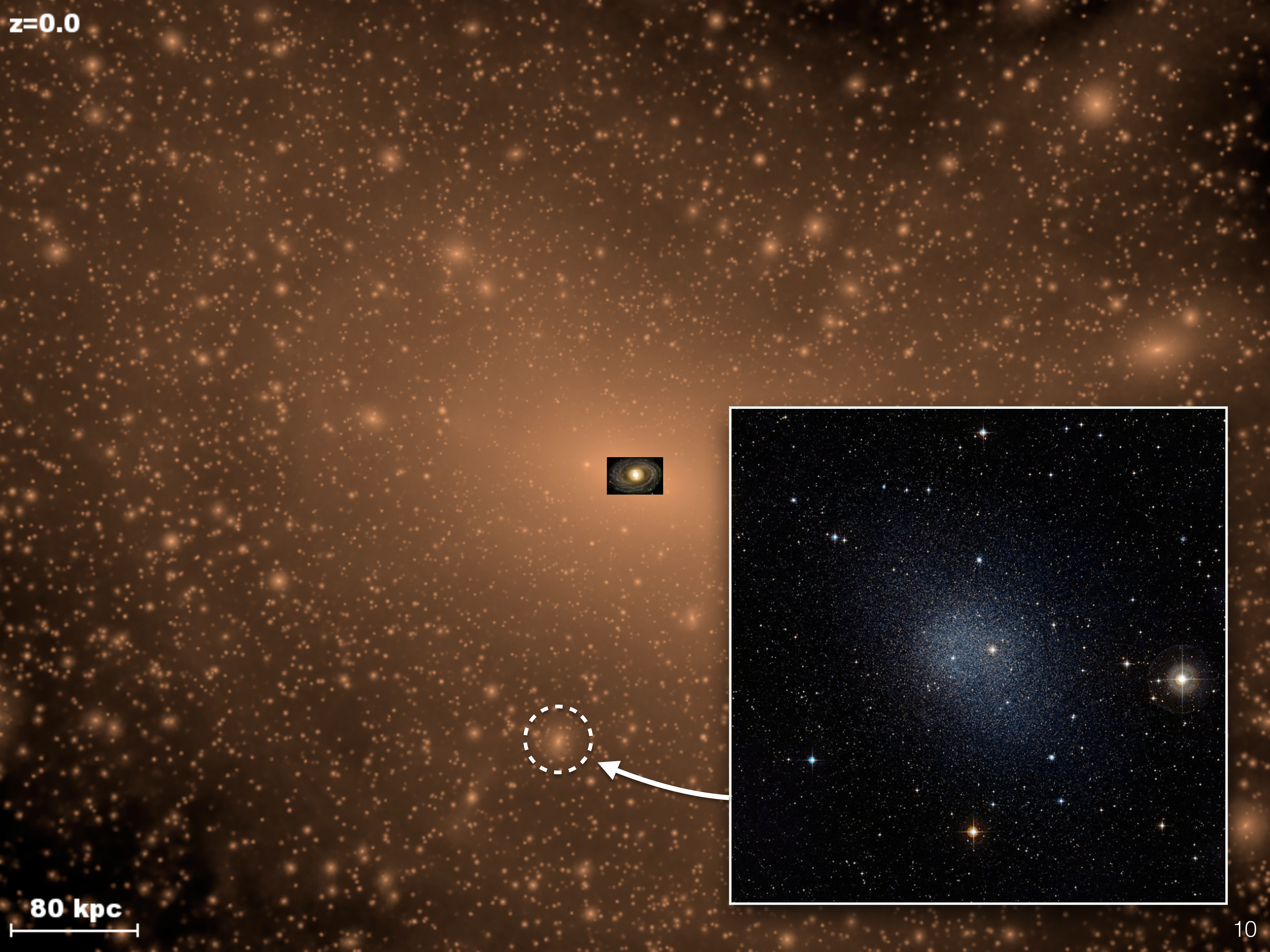
Bullock & Boylan-Kolchin 2017

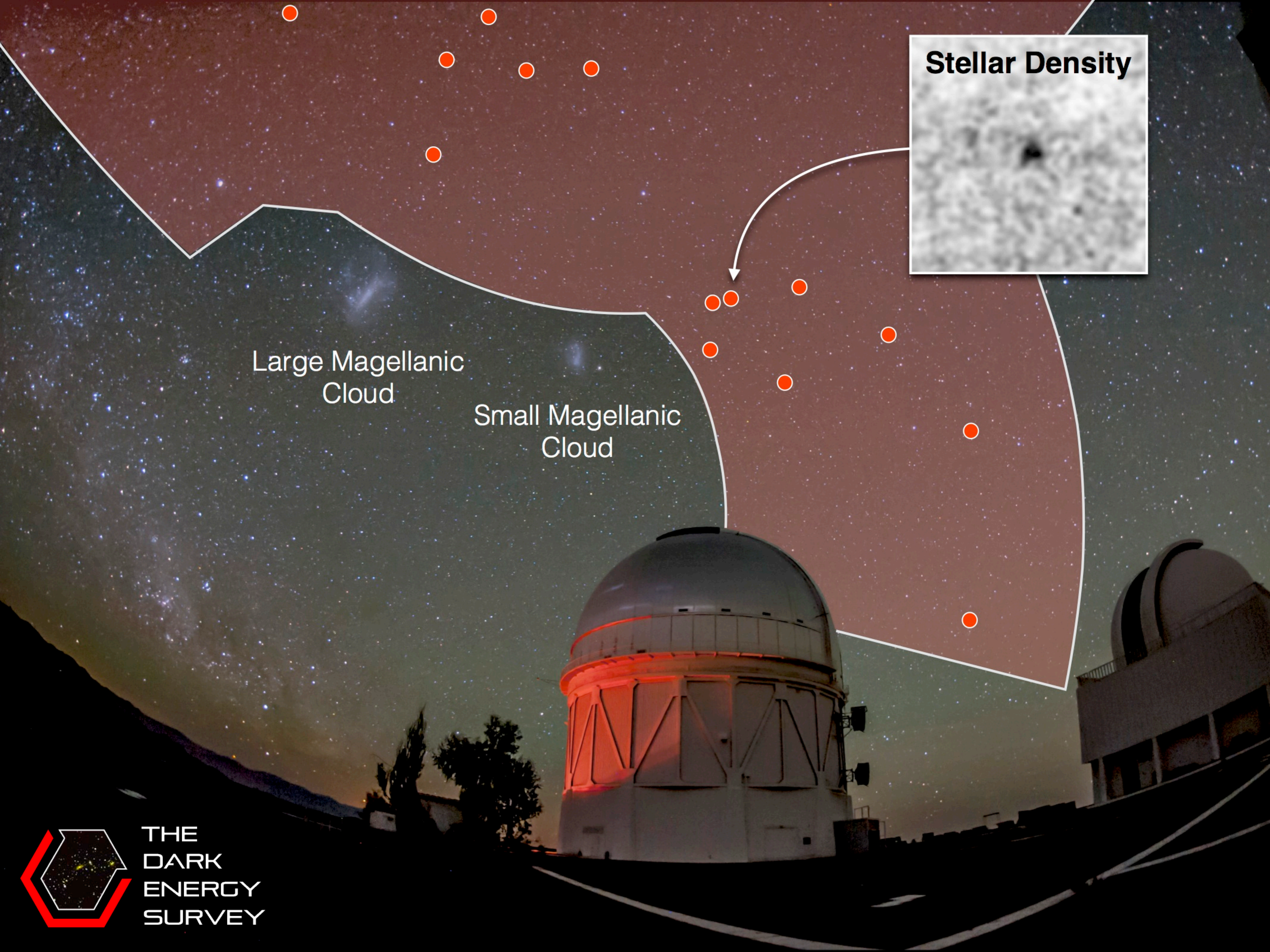


Bullock & Boylan-Kolchin 2017



Wechsler & Tinker 2018
arXiv:1804.03097

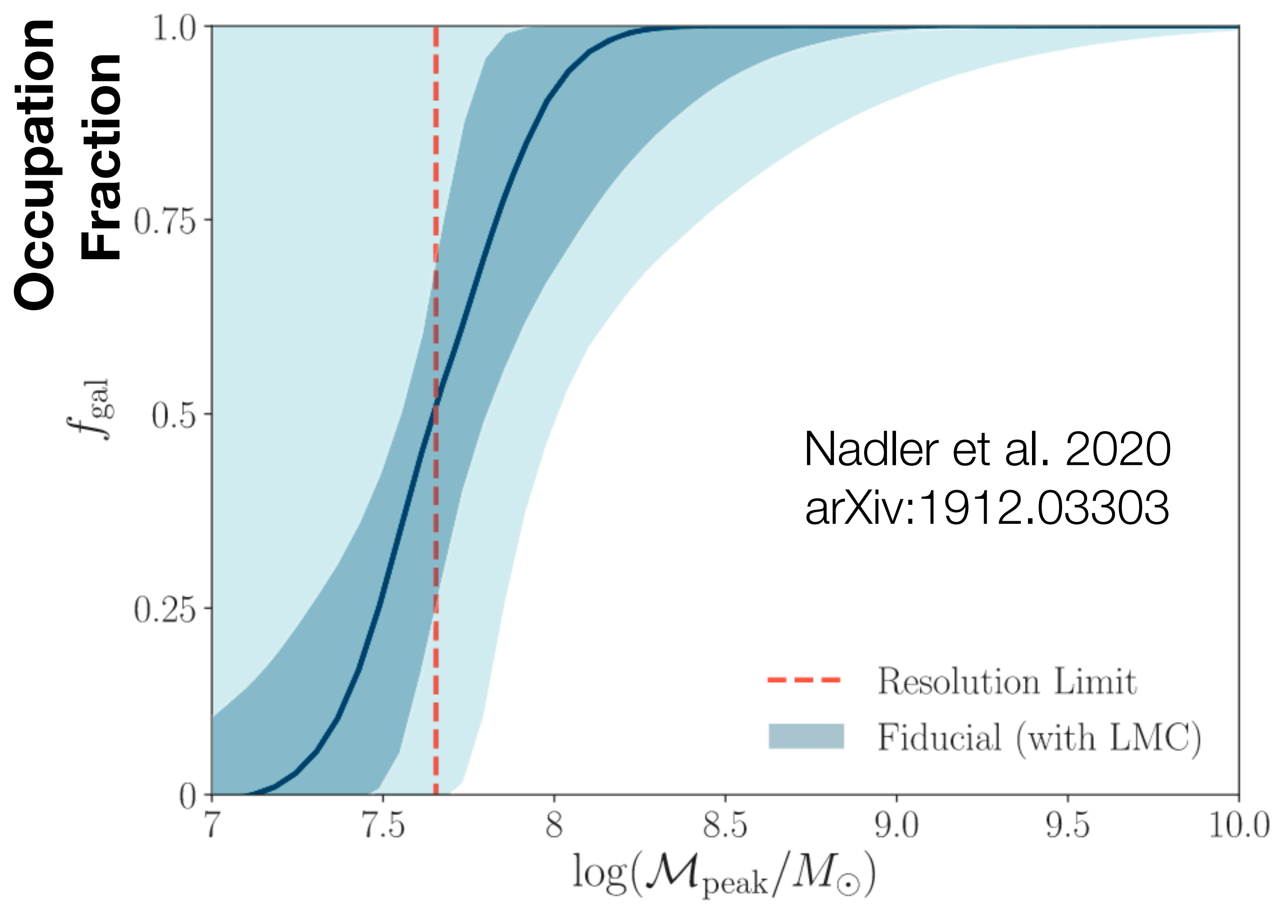

z=0.0
80 kpc


Stellar Density
Large Magellanic Cloud
Small Magellanic Cloud
THE DARK ENERGY SURVEY

Halos hosting the least luminous galaxies

Galaxy Occupation Fraction

(for stellar mass >100 $M_\odot$)

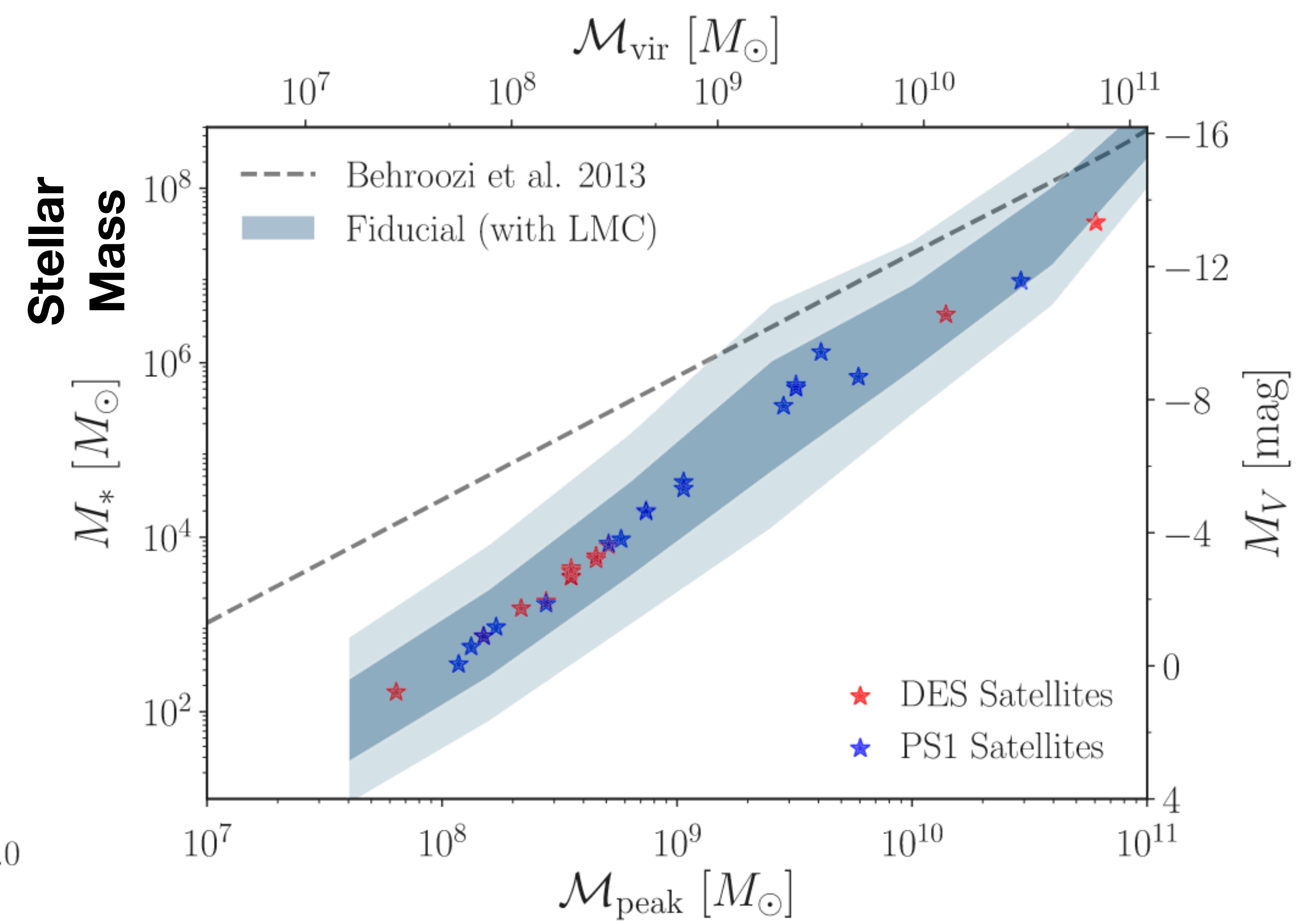


Halo Mass

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

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

Faint-end Luminosity Function



Halo Mass

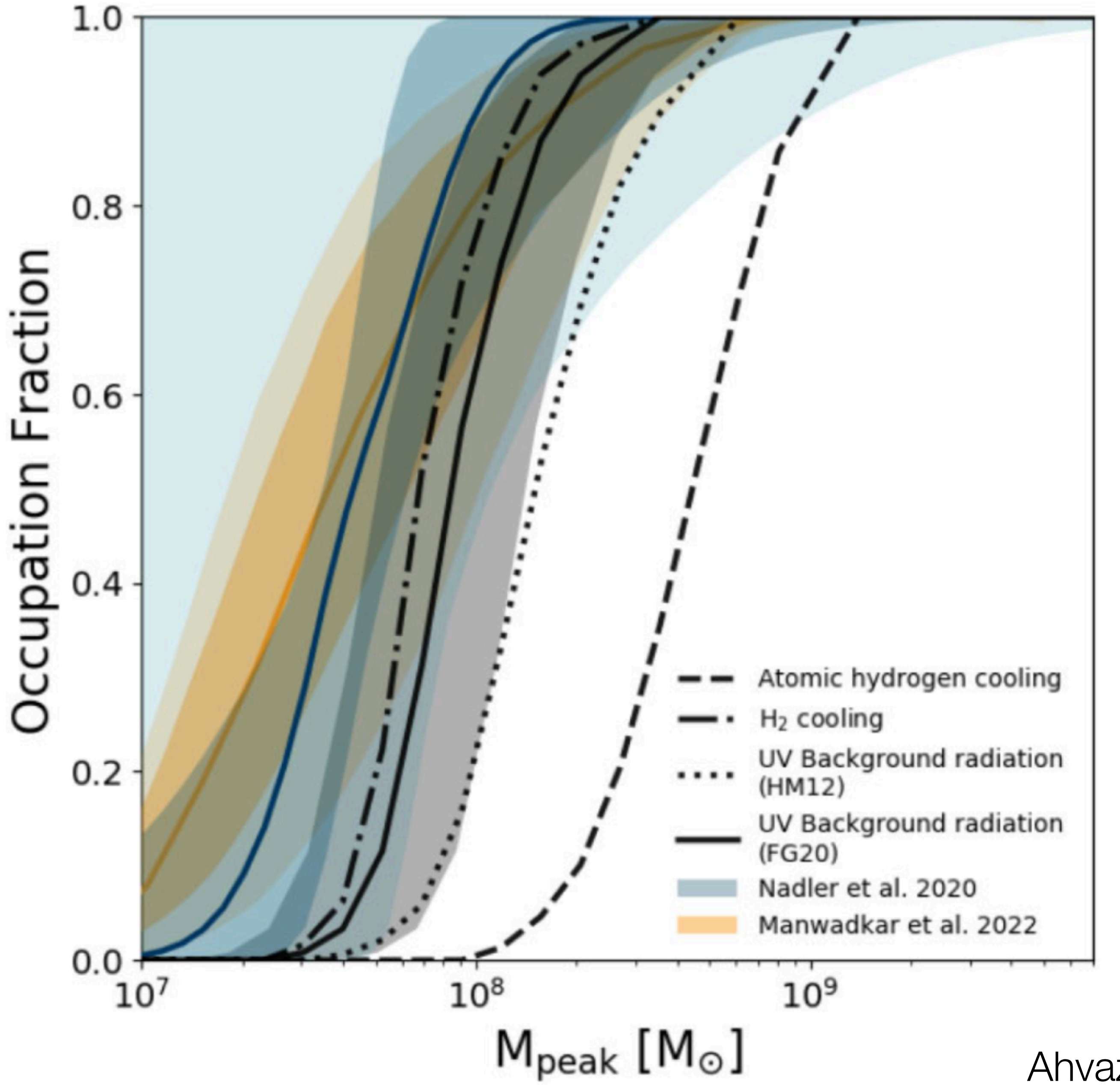
Detected MW satellites likely occupy halos of mass $M_{peak} \sim 10^8\ M_\odot$ (95% CL)

Halos hosting the least luminous galaxies

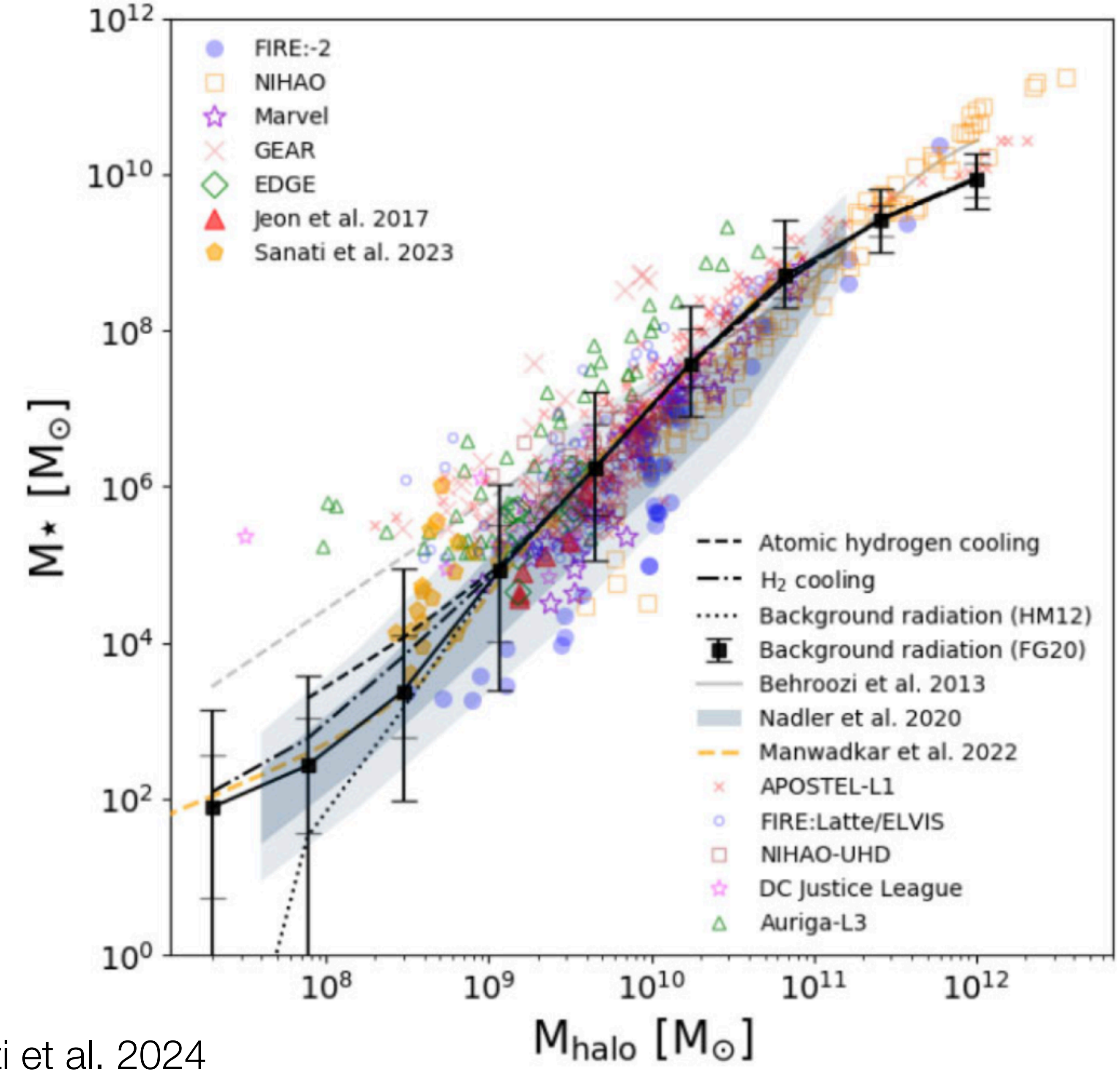
Semi-analytic modeling suggests that molecular hydrogen H_2 cooling and UV background are needed to explain observed properties of Milky Way satellite population

Galaxy Occupation Fraction

(for stellar mass >100 $M_\odot$)



Faint-end Luminosity Function



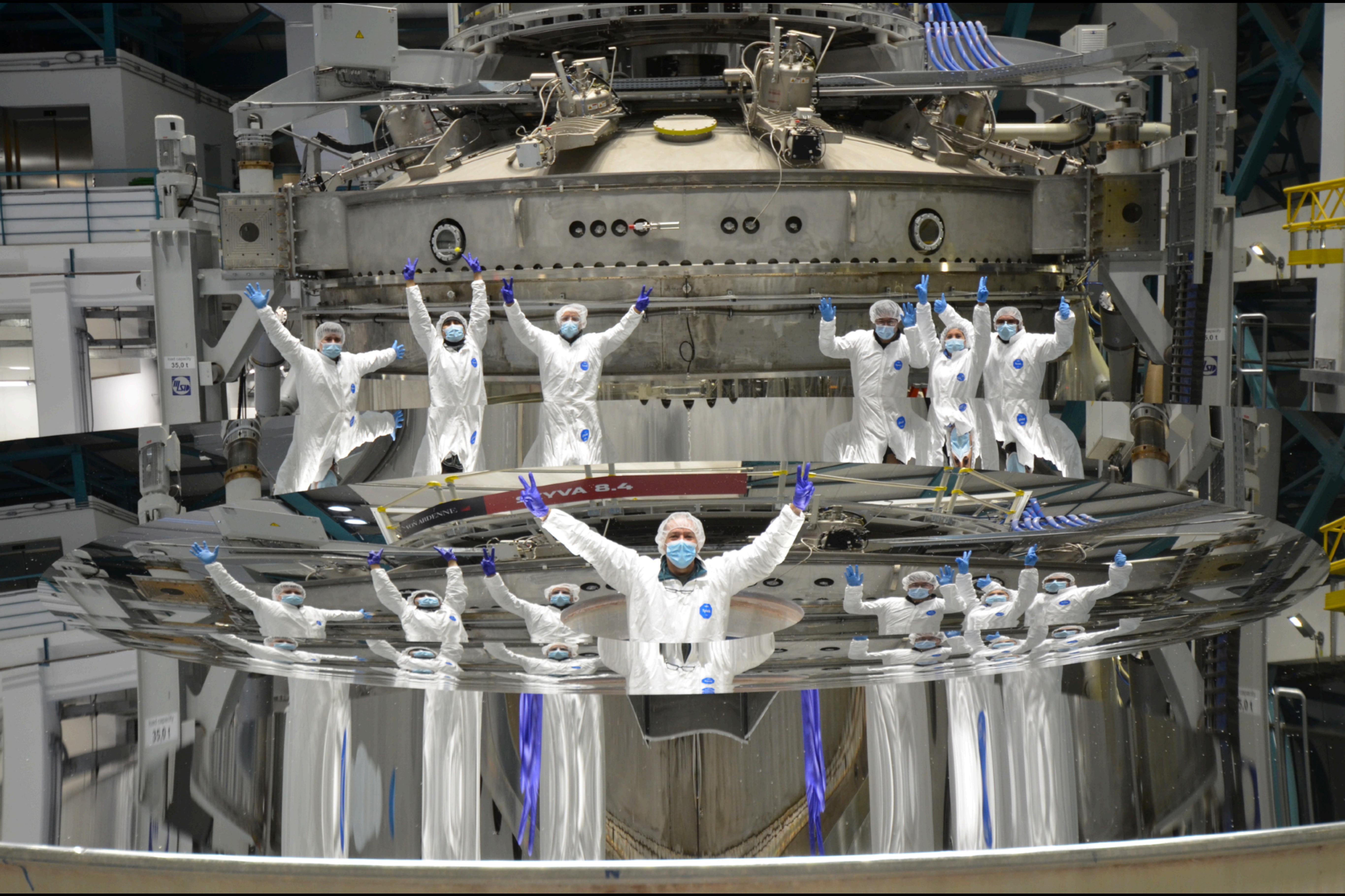
Ahvazi et al. 2024
arXiv:2308.13599

LSST Camera delivered to Cerro Pachón

VERA C. RUBIN
OBSERVATORY


VERA C. RUBIN
OBSERVATORY
SLAC
E
S

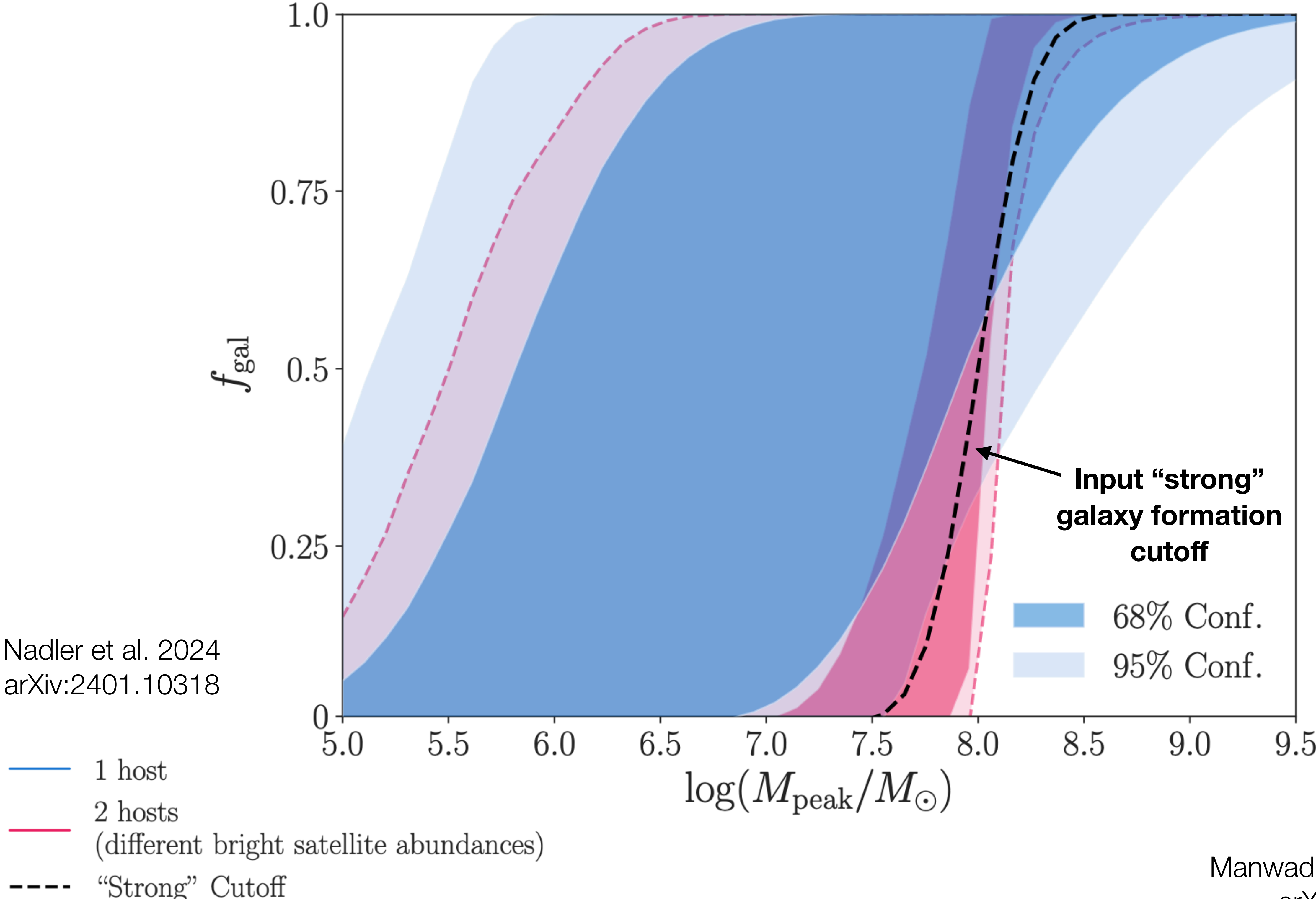
Primary-Tertiary (M1M3) mirror with silver coating at Cerro Pachón



Future comprehensive census of satellite galaxy population around Milky Way-mass host (e.g., Rubin Observatory, Euclid, Roman) could provide evidence at ~1σ level for galaxy formation cutoff at ~10^8 $M_\odot$

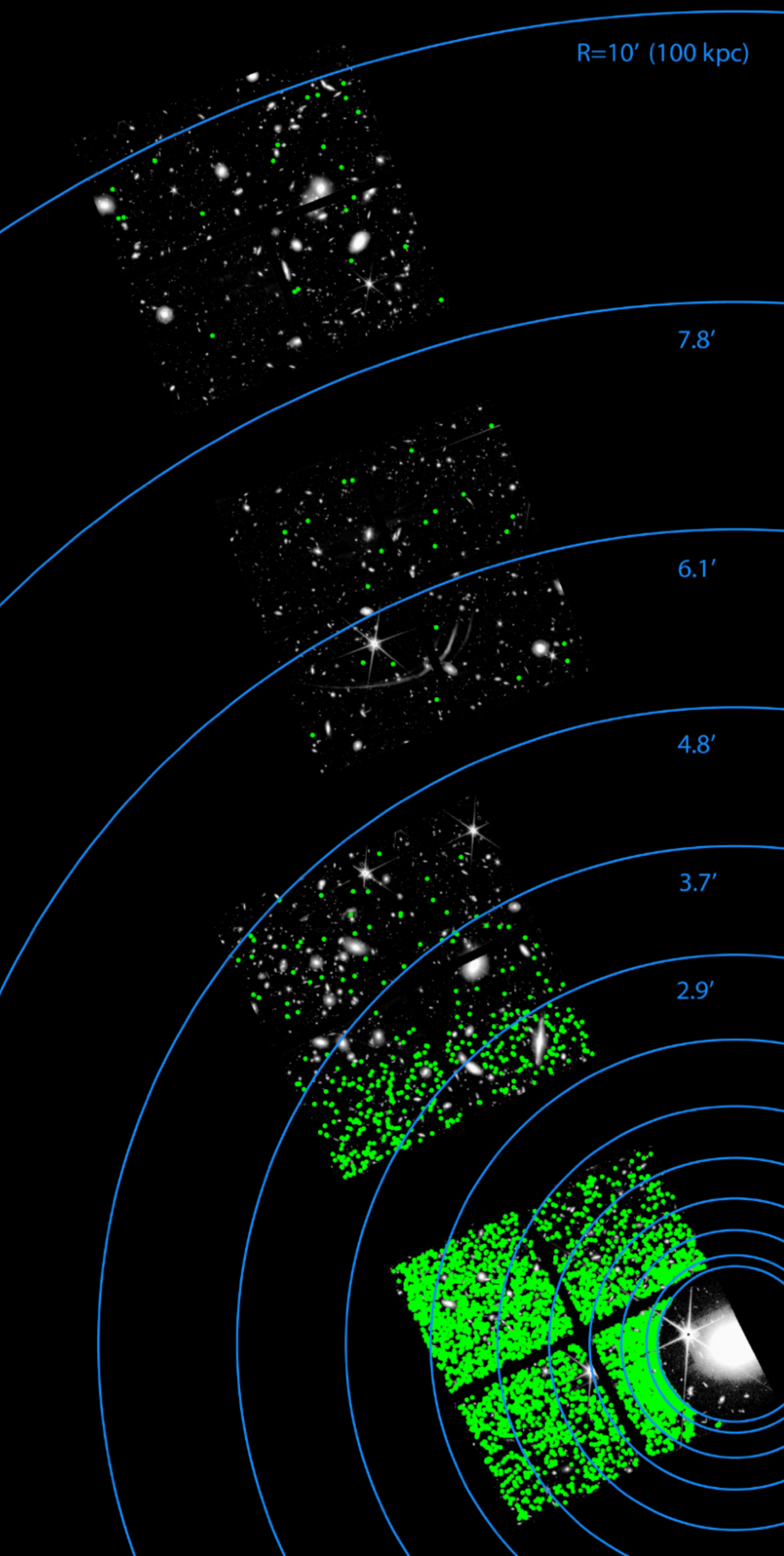
Enhanced sensitivity achieved by probing fainter luminosities and lower surface brightness

Galaxy Occupation Fraction



Nadler et al. 2024
arXiv:2401.10318

see also
Manwadkar & Kravtsov 2022
arXiv:2112.04511

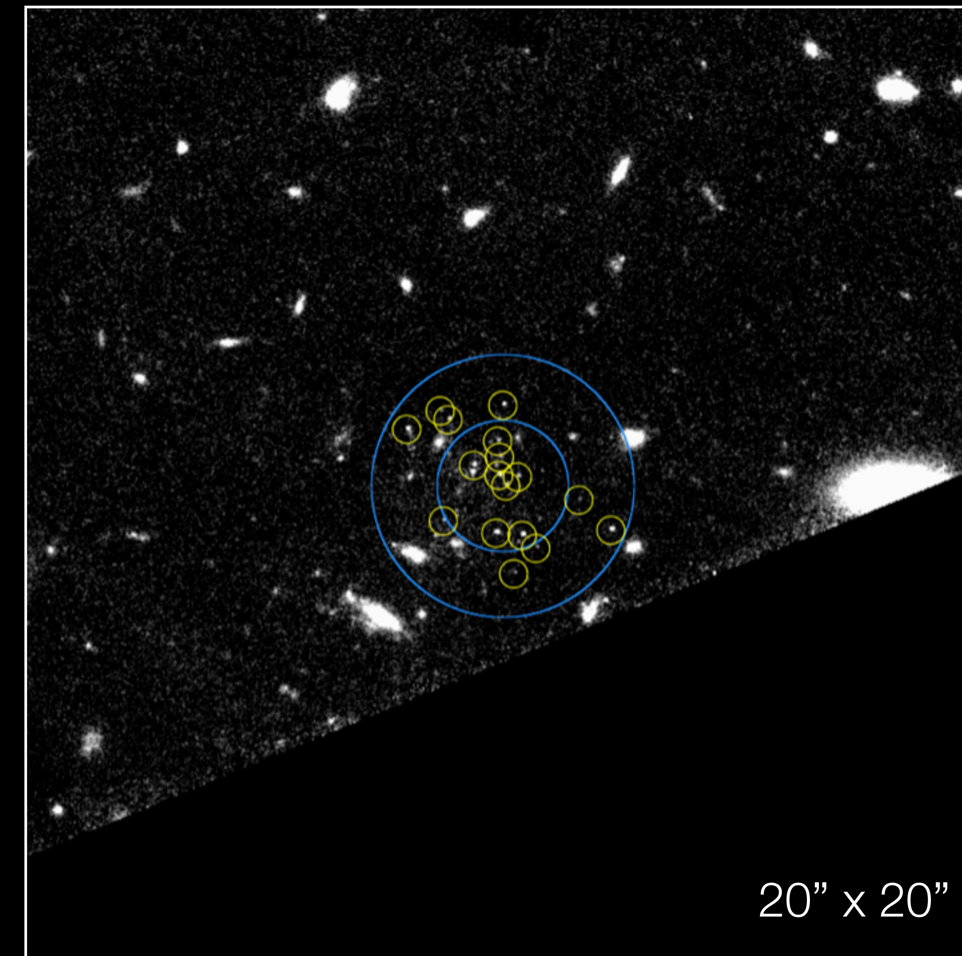


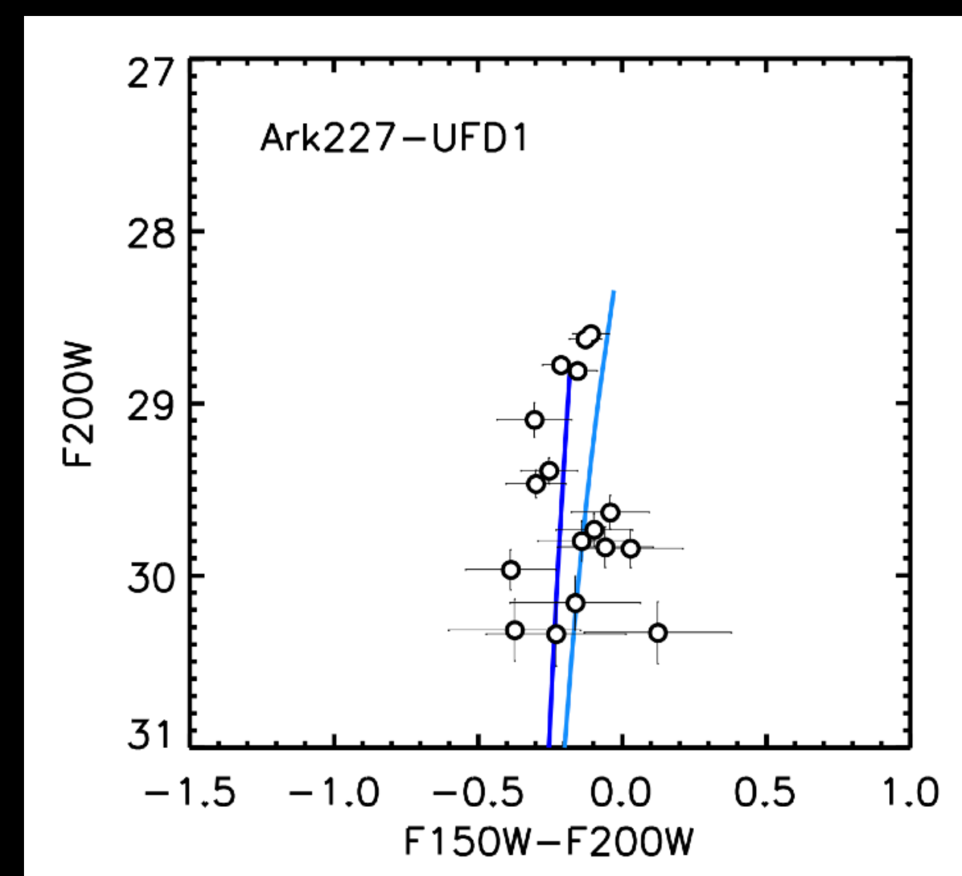
Serendipitous discovery of ultra-faint galaxy at ~35 Mpc in foreground of JWST deep field

Stellar mass ~10^5 $M_\odot$

M_V ~ -7

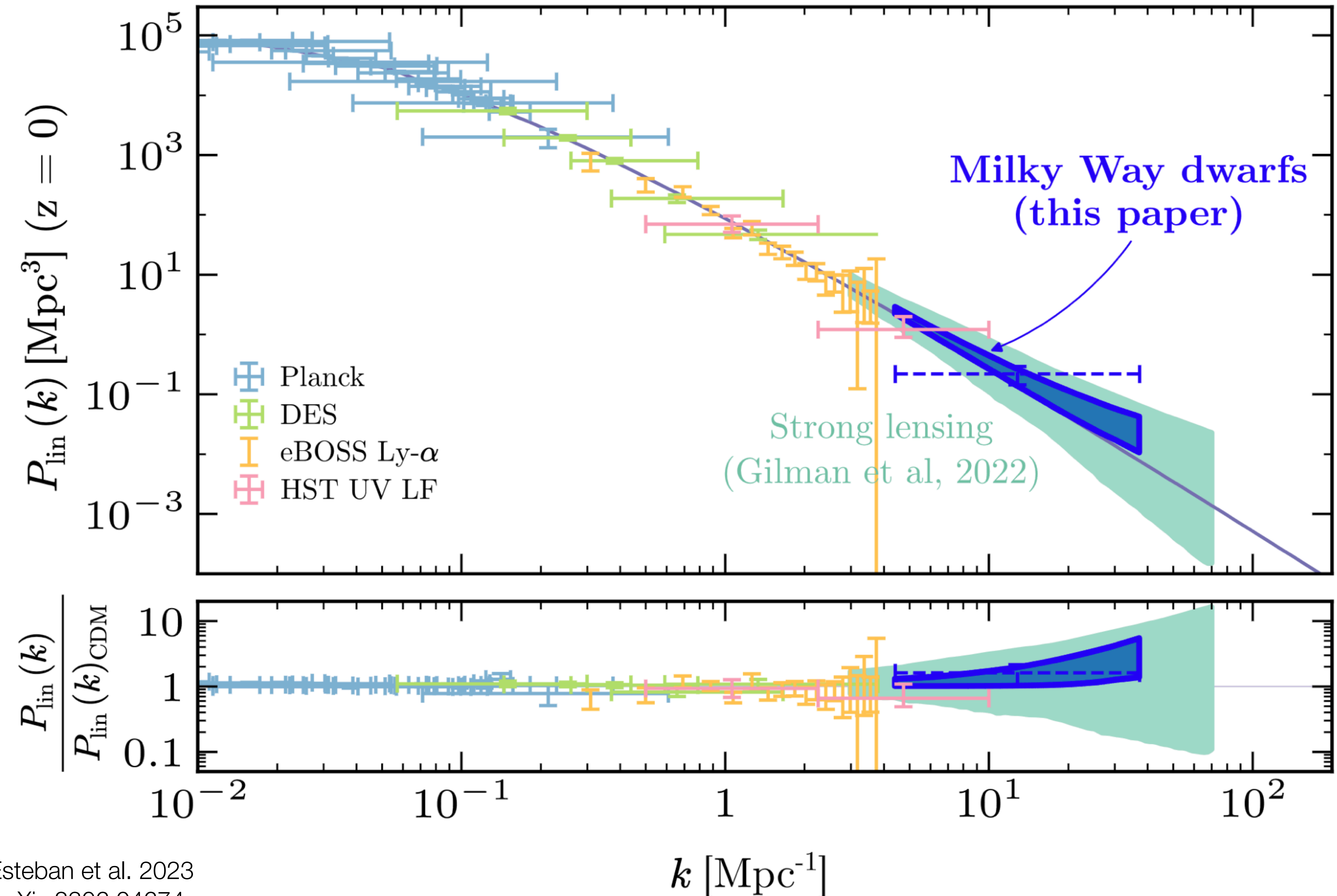
Half-light radius ~230 pc





Conroy et al. 2023
arXiv:2310.13048

Correlation between internal velocities and sizes of dwarf galaxies is a sharp probe of small-scale dark matter properties



Esteban et al. 2023
arXiv:2306.04674

Searching for Isolated Sub-galactic Dark Matter Halos

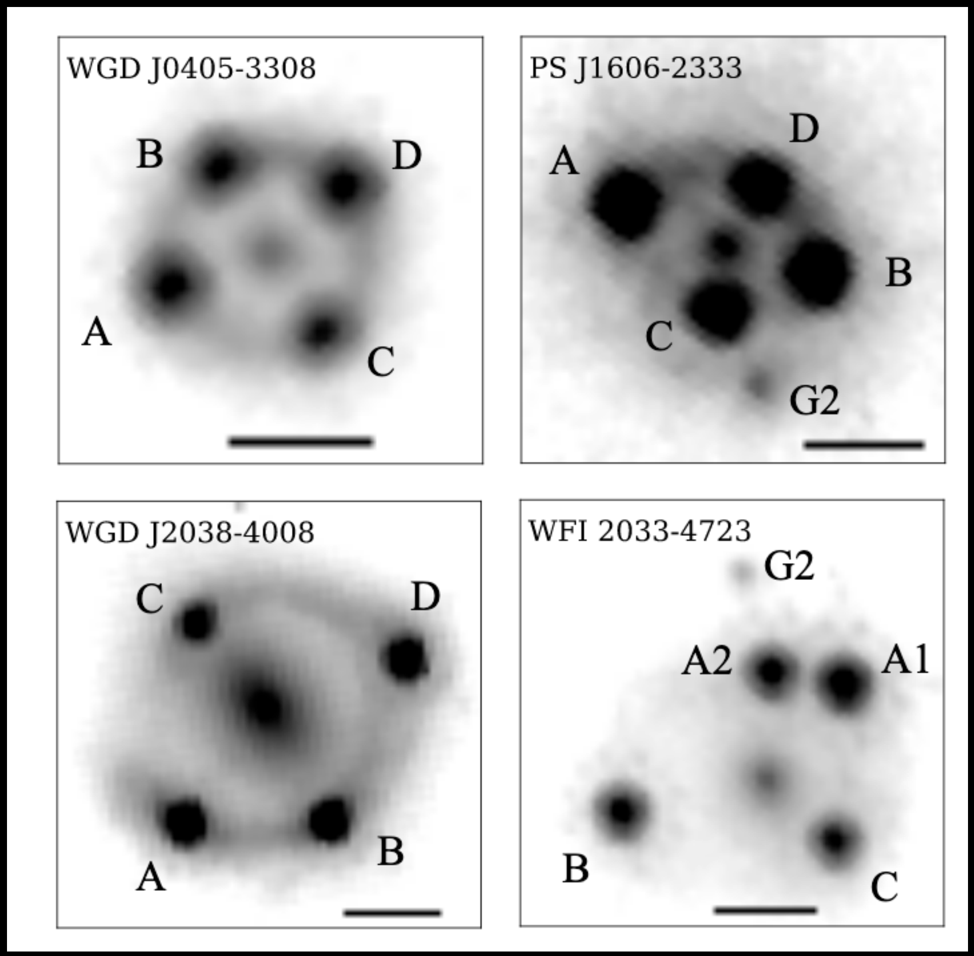
Enhanced sensitivity to dark mark microphysics

Minimizing uncertainties associated with baryonic physics

Complementarity of multiple techniques
(e.g., strong lensing, stellar streams)

Strong lensing methods sensitive to low-mass dark matter halos

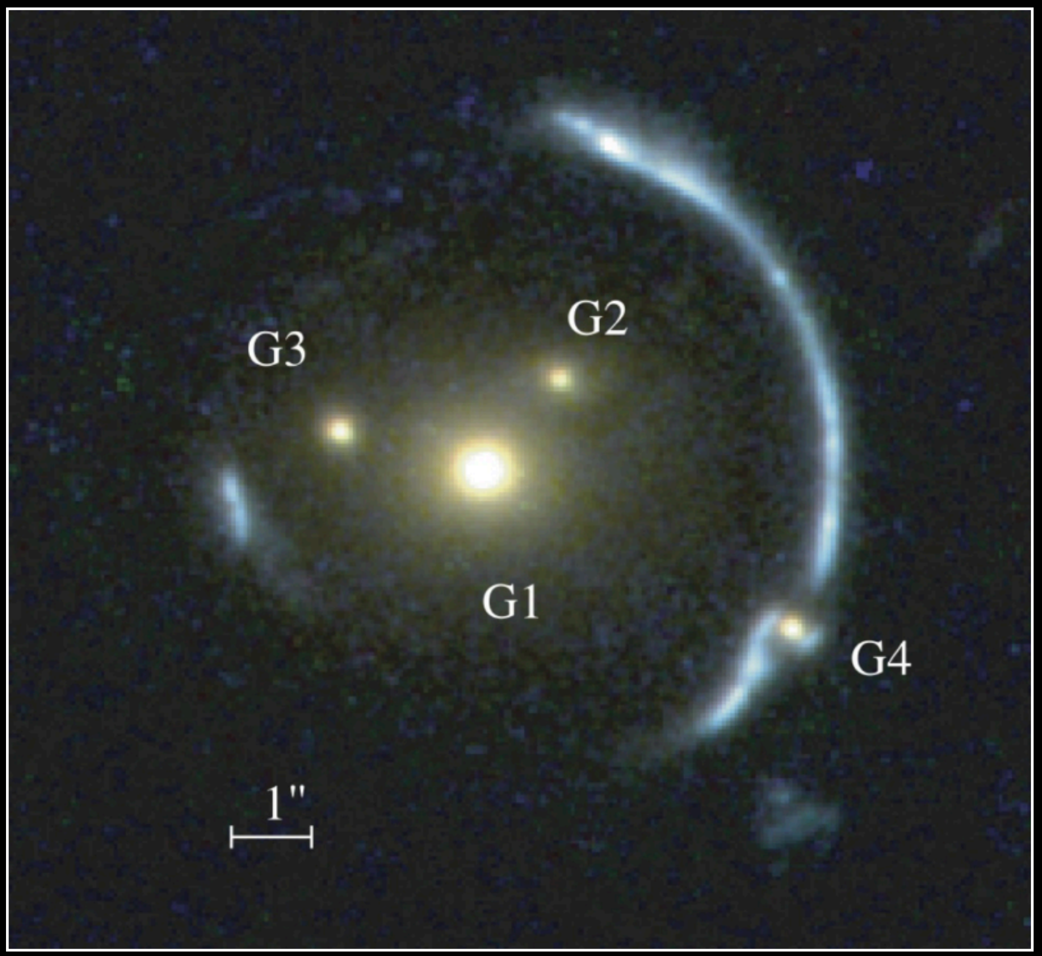
Flux Ratio Anomalies



Nierenberg et al. 2020
arXiv:1908.06344

Image positions and relative magnifications of quad quasars
narrow-line emission on mas scales to avoid microlensing; see also Nierenberg et al. 2024 and Keeley et al. 2024 for JWST

Gravitational Imaging



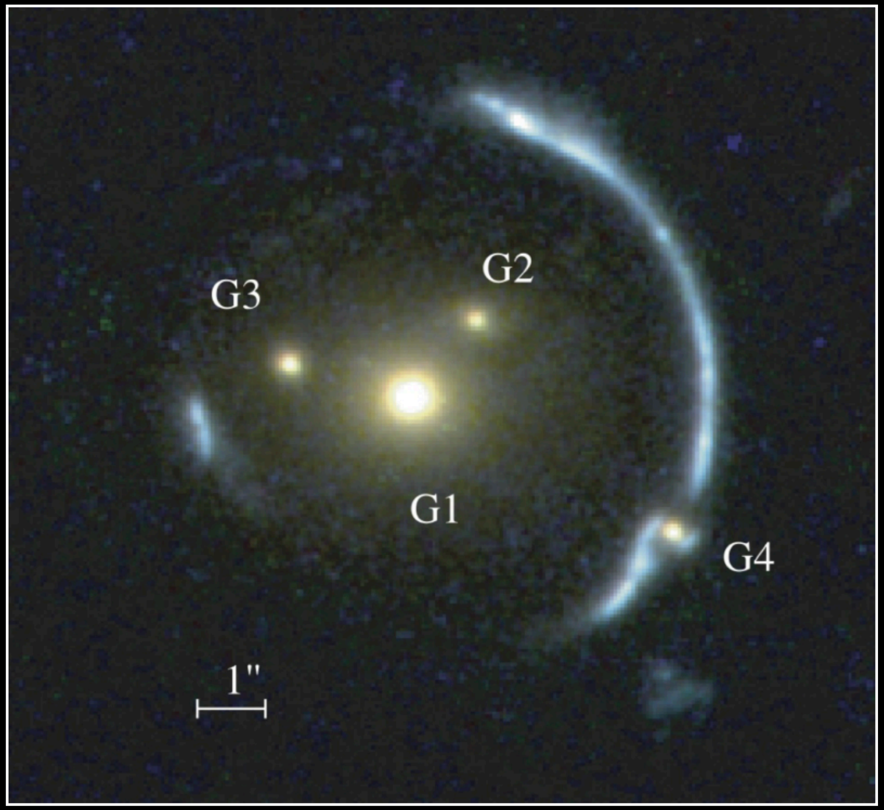
Vegetti et al. 2010
arXiv:1002.4708

Astrometric anomalies of multiply-imaged arcs

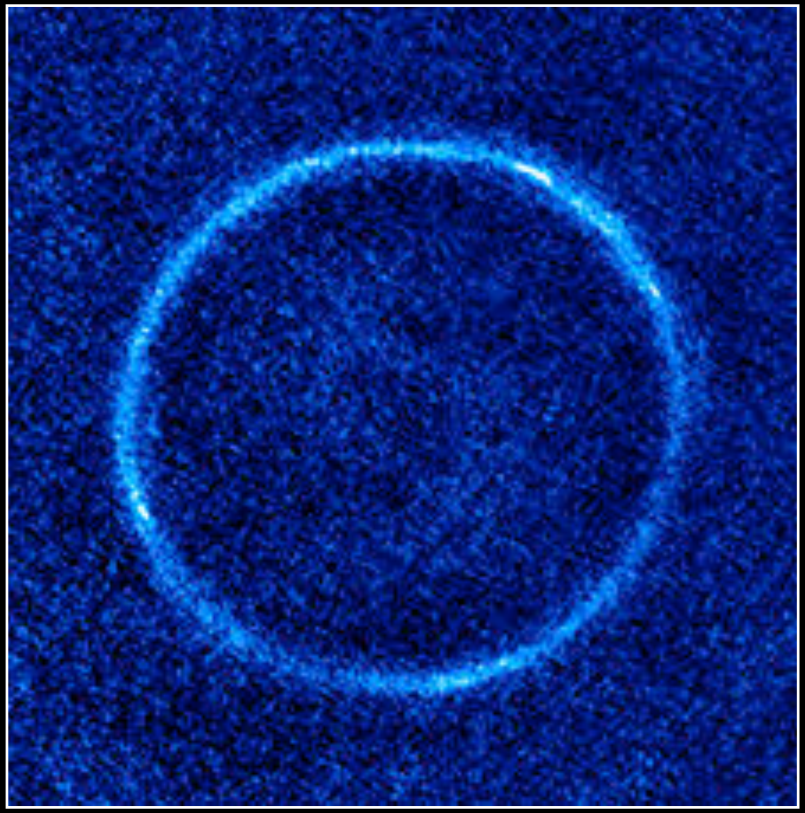
Angular resolution is essential for gravitational imaging technique

e.g., 10^8 solar mass perturber induces **~10 mas** astrometric anomalies for lensed images

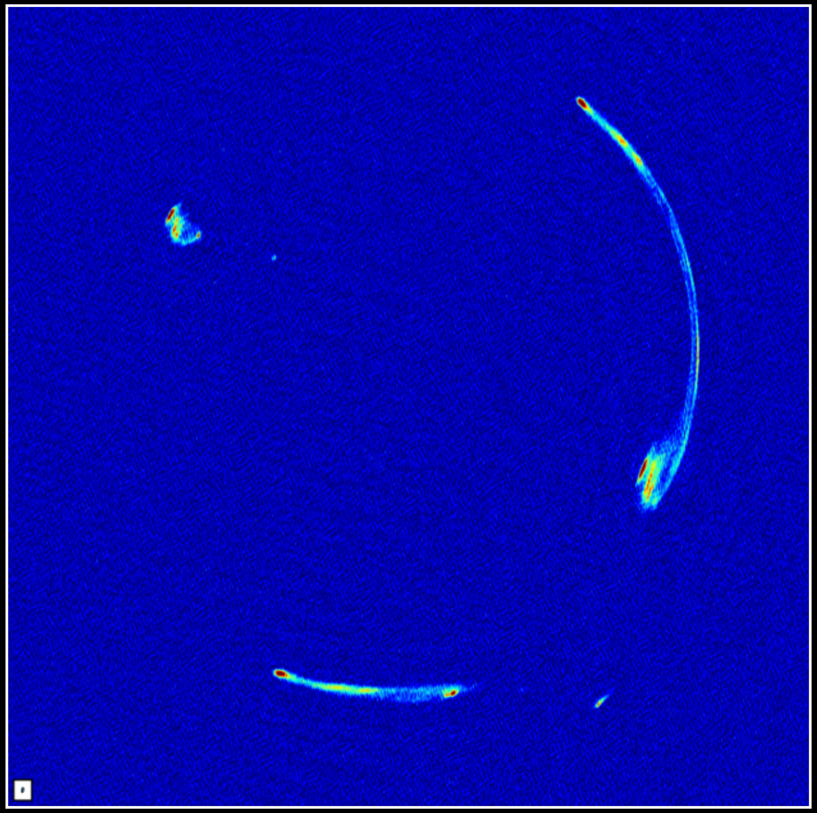
Metcalf & Madau 2001
Chen et al. 2007



HST (optical)
~50 mas



ALMA (sub-mm)
~30 mas

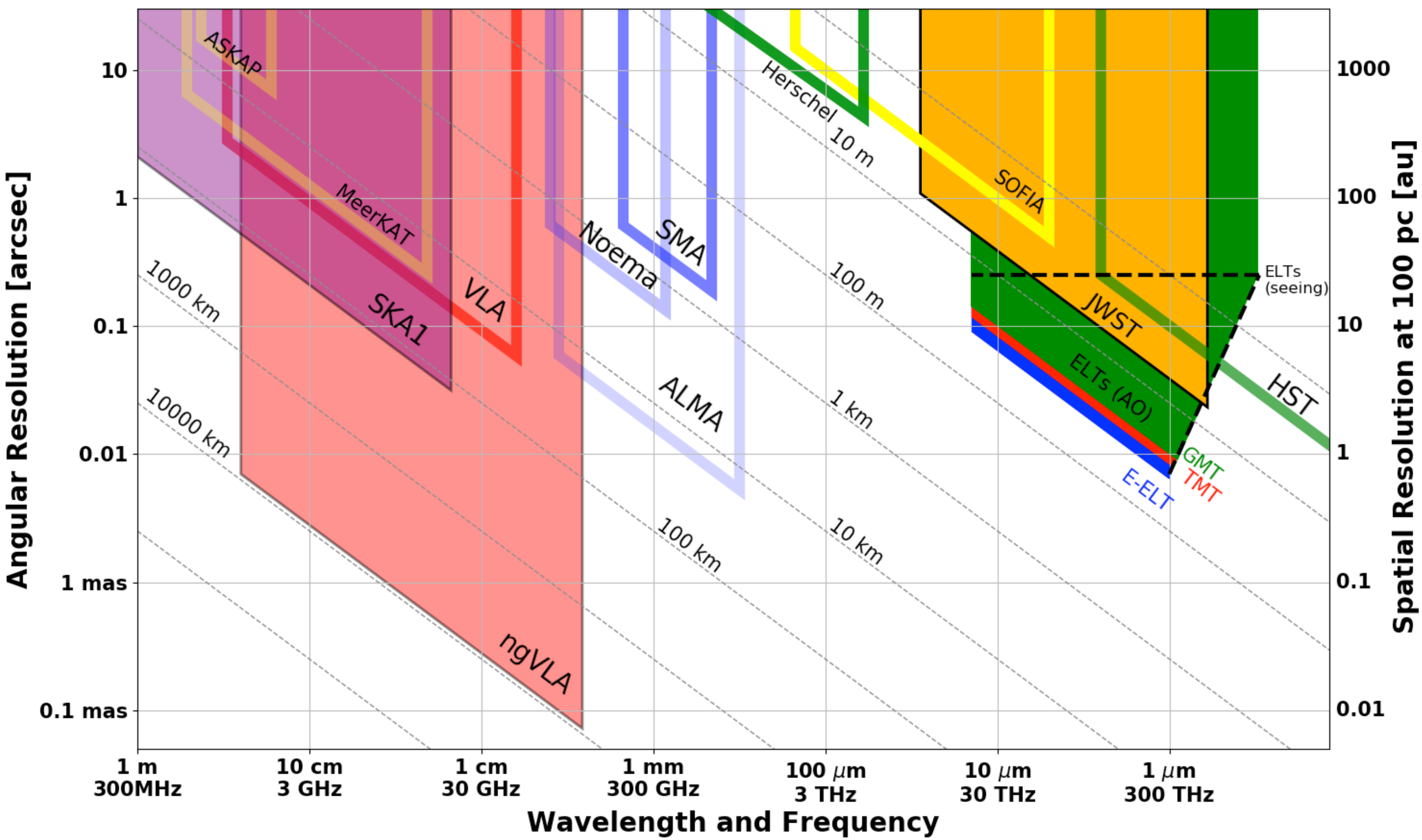


Global VLBI (radio)
~ 5 mas x 2 mas

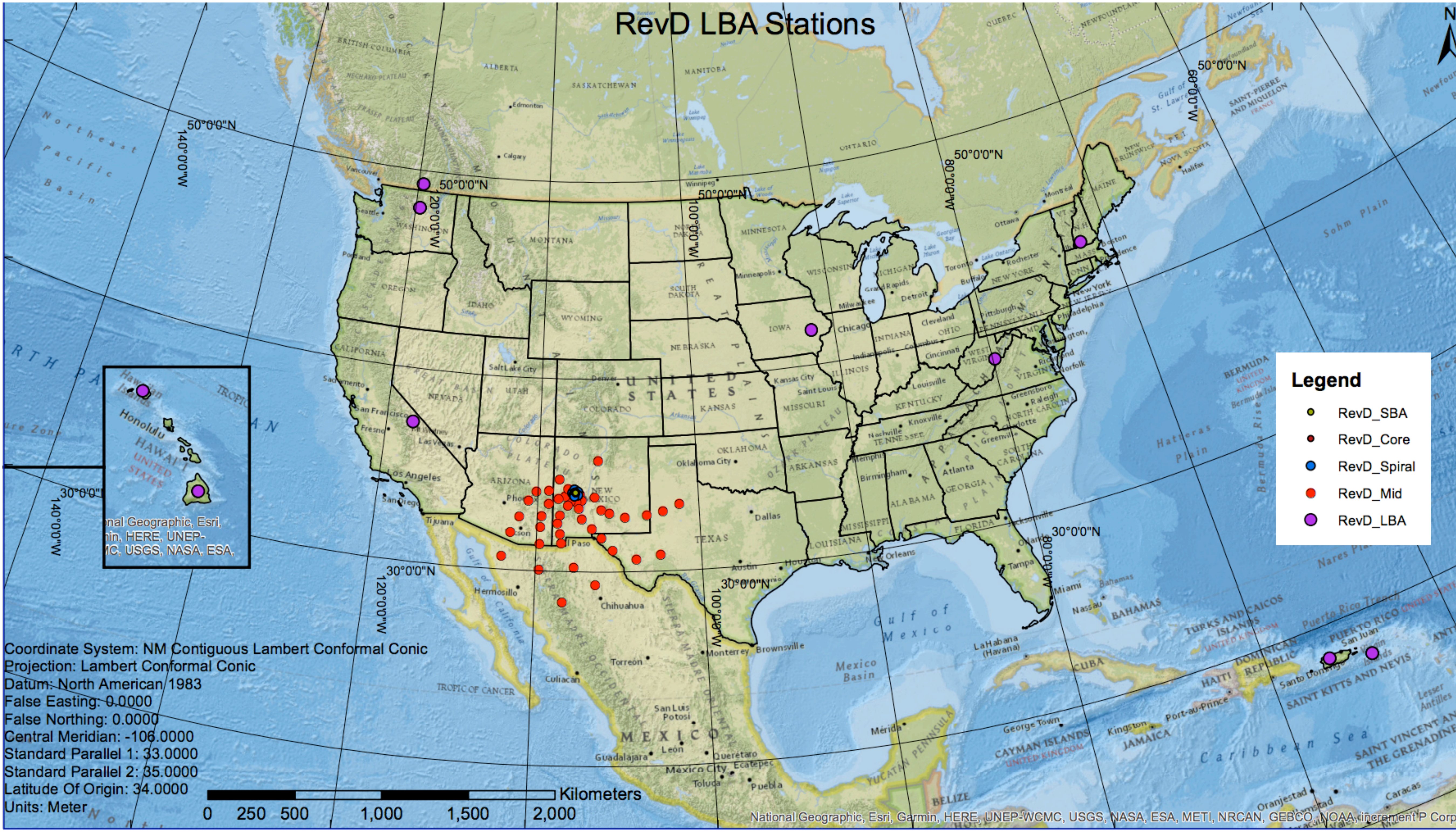
Global VLBI has achieved astrometric precision **0.01-0.05 mas** for lensed images

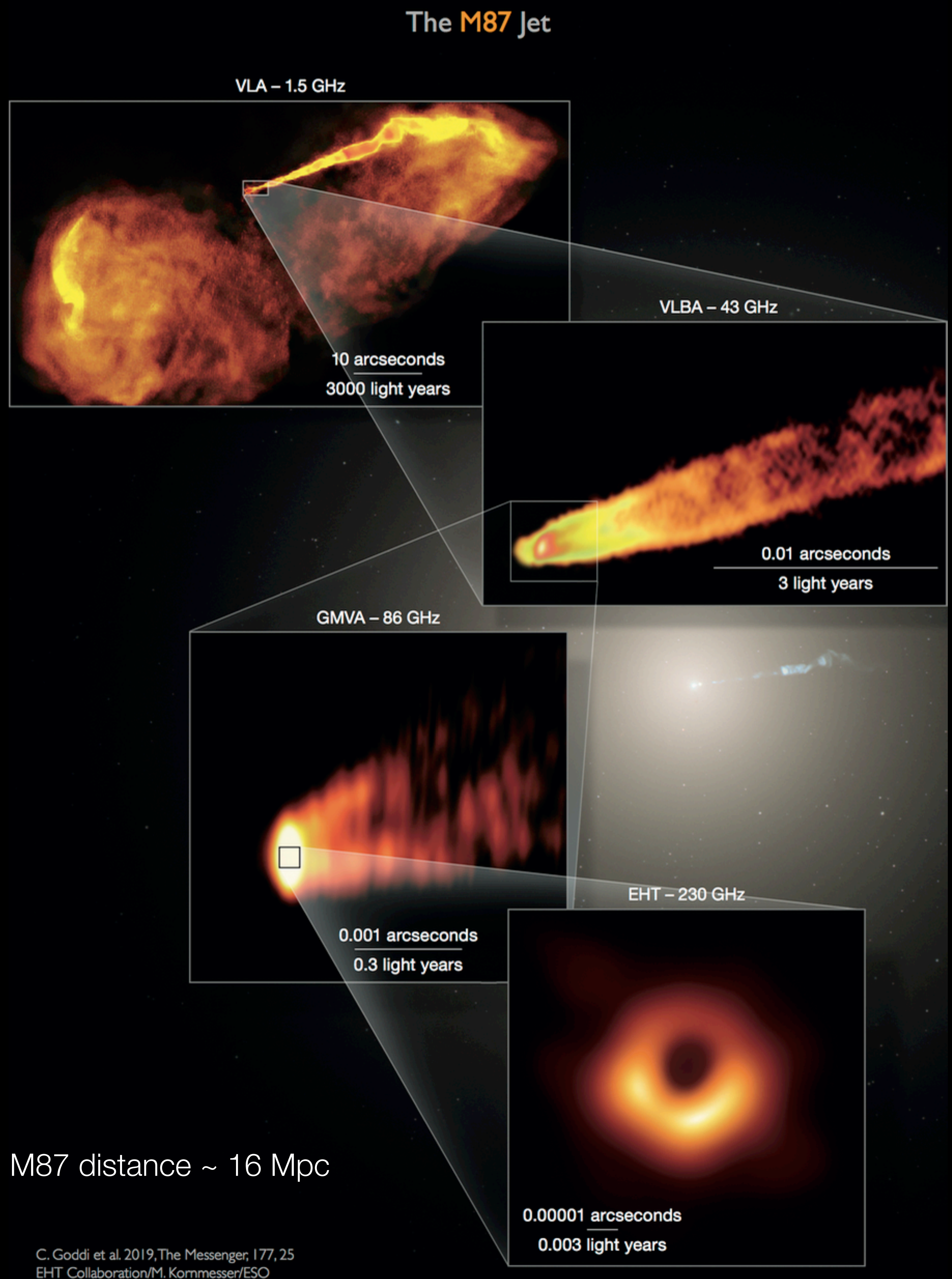
e.g., Spingola & Barnacka 2020

Very long baseline radio interferometry (VLBI) for highest angular resolution imaging



Proposed Next-Generation Very Large Array (ngVLA) Telescope Configuration





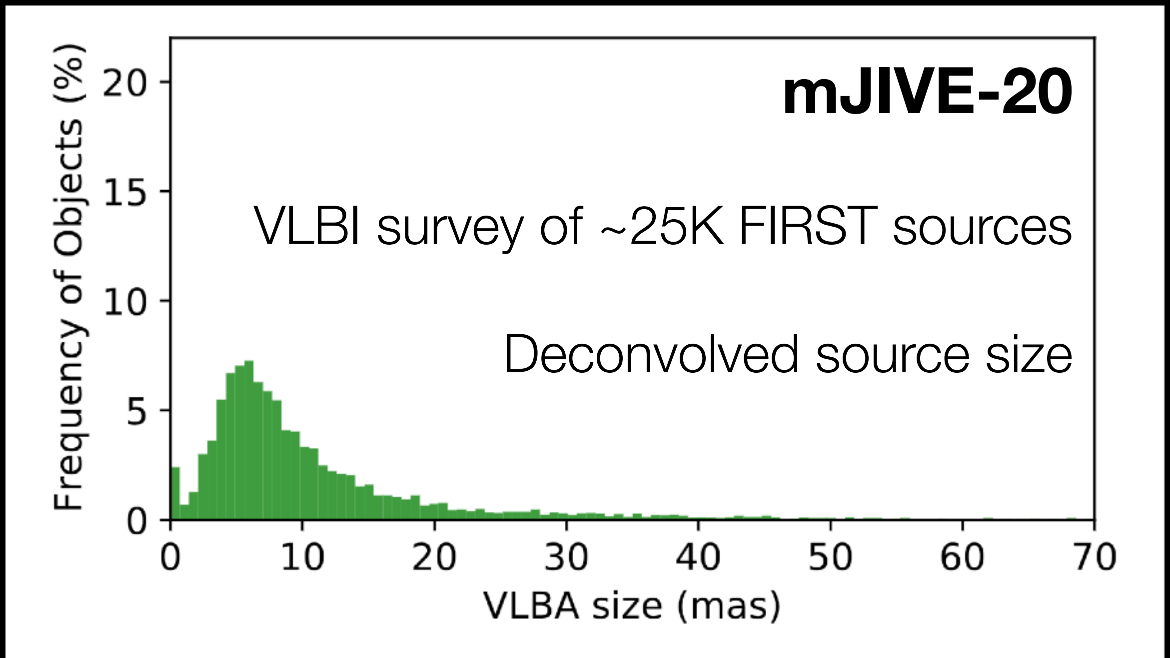
M87 distance ~ 16 Mpc

Most bright radio sources
are **jetted AGN**

Sources at redshifts $1 < z < 3$
have scale of **~8 pc / milliarcsecond**

Almost all VLBI sources have structure on milliarcsecond scales
median ~ 8 mas
20-35% > 16 mas

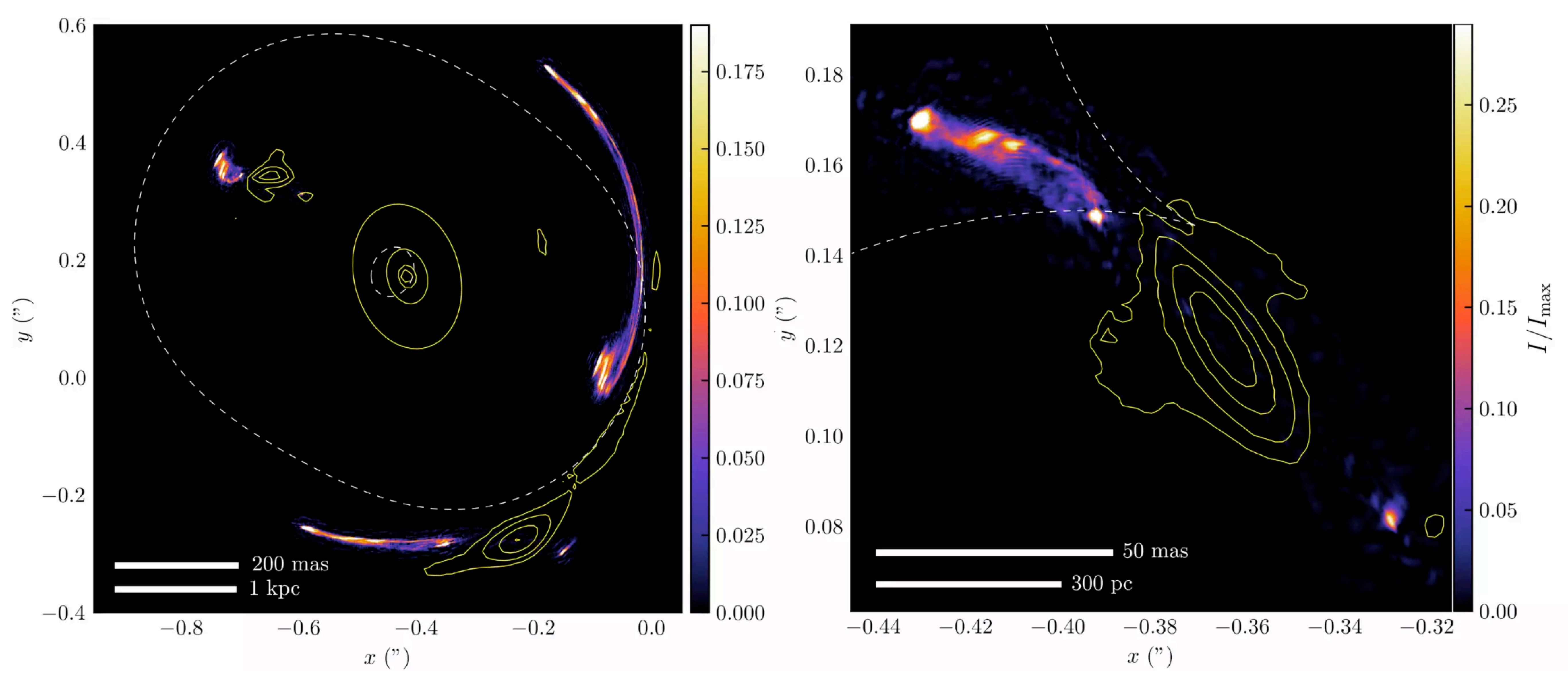
Predict ~10^6 VLBI sources
with $S_{1.4GHz} > 1$ mJy in a 3π survey



Rezaei et al. 2023
arXiv:2308.15859

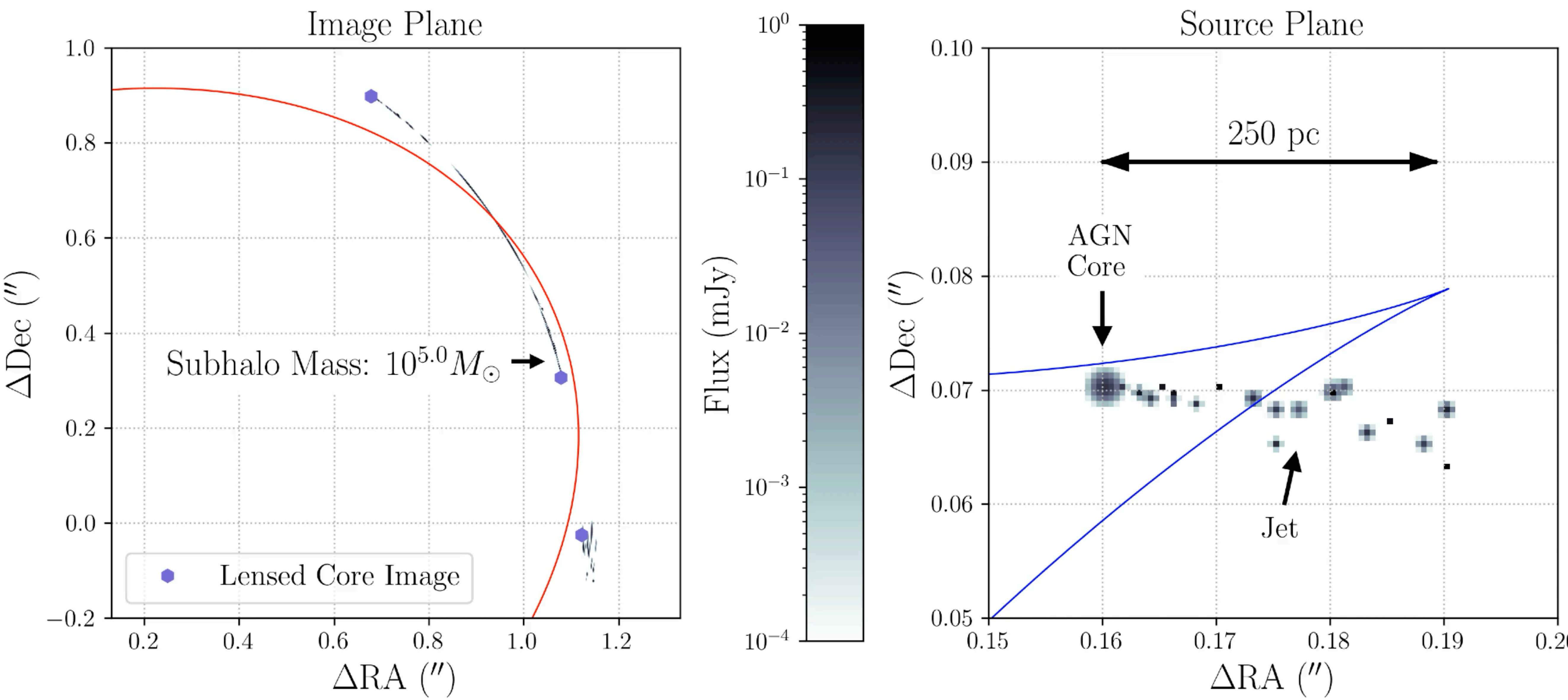
Milliarcsecond-scale resolution for lensed arcs allows detailed characterization of main-deflector (e.g., mass profile, multipole structure) and external potential

Image Plane **Source Plane**

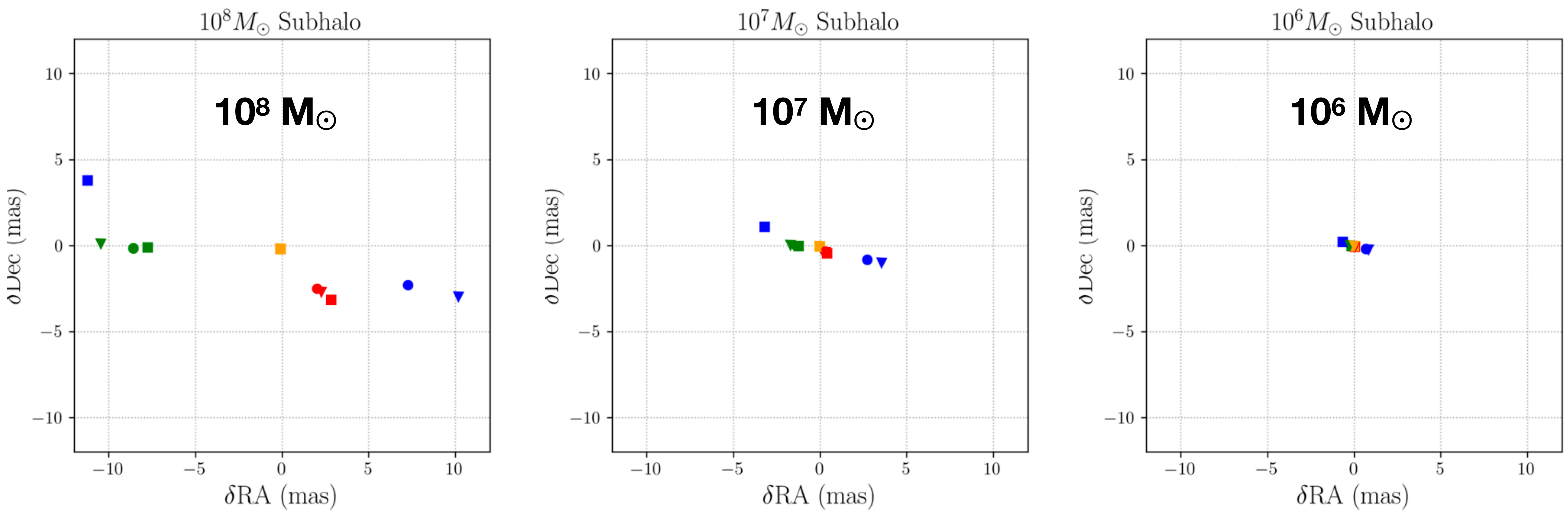


Powell et al. 2022
arXiv:2207.03375

Simulated schematic representation of a lensed AGN jet using macromodel for main deflector + a single line-of-sight low-mass halo perturber



Simulation of astrometric anomalies for hotspots color-coded by “image”



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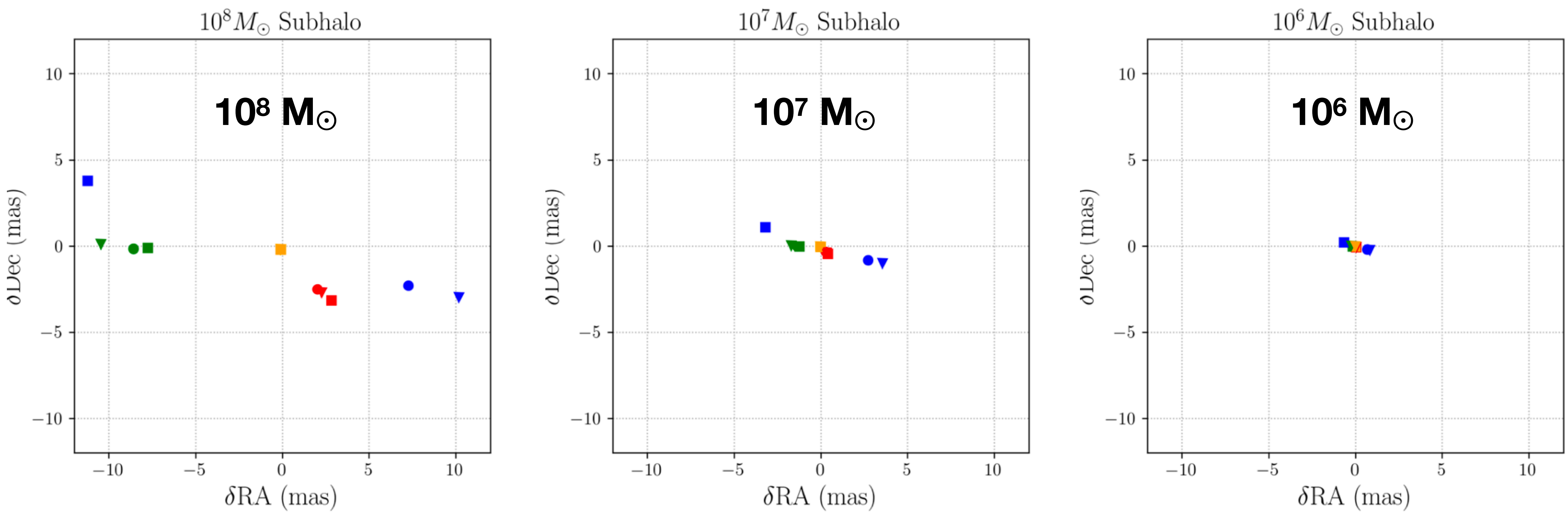
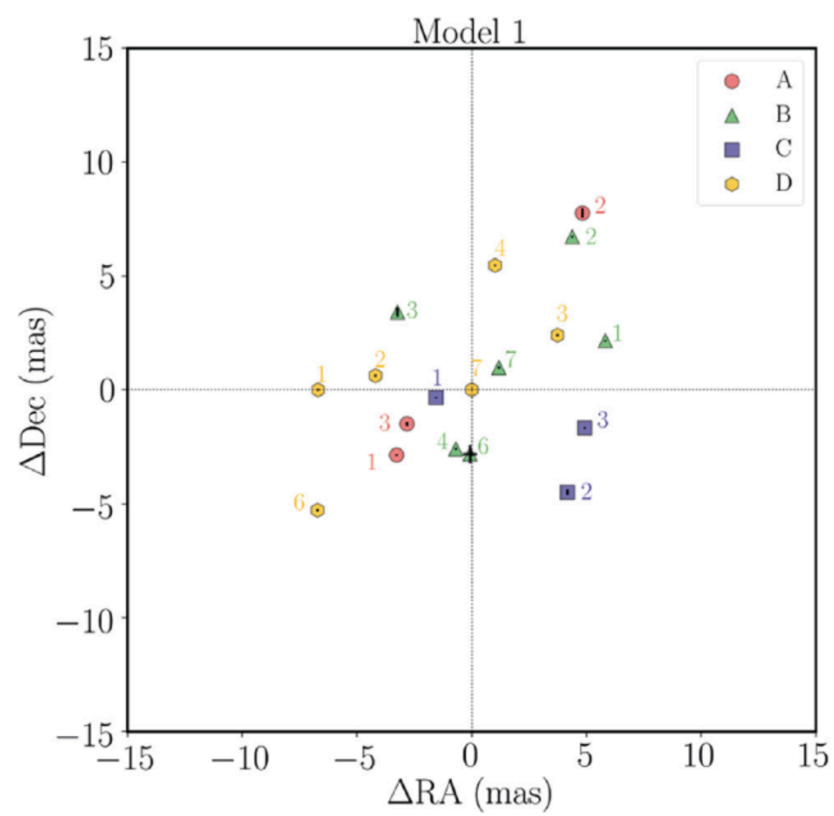




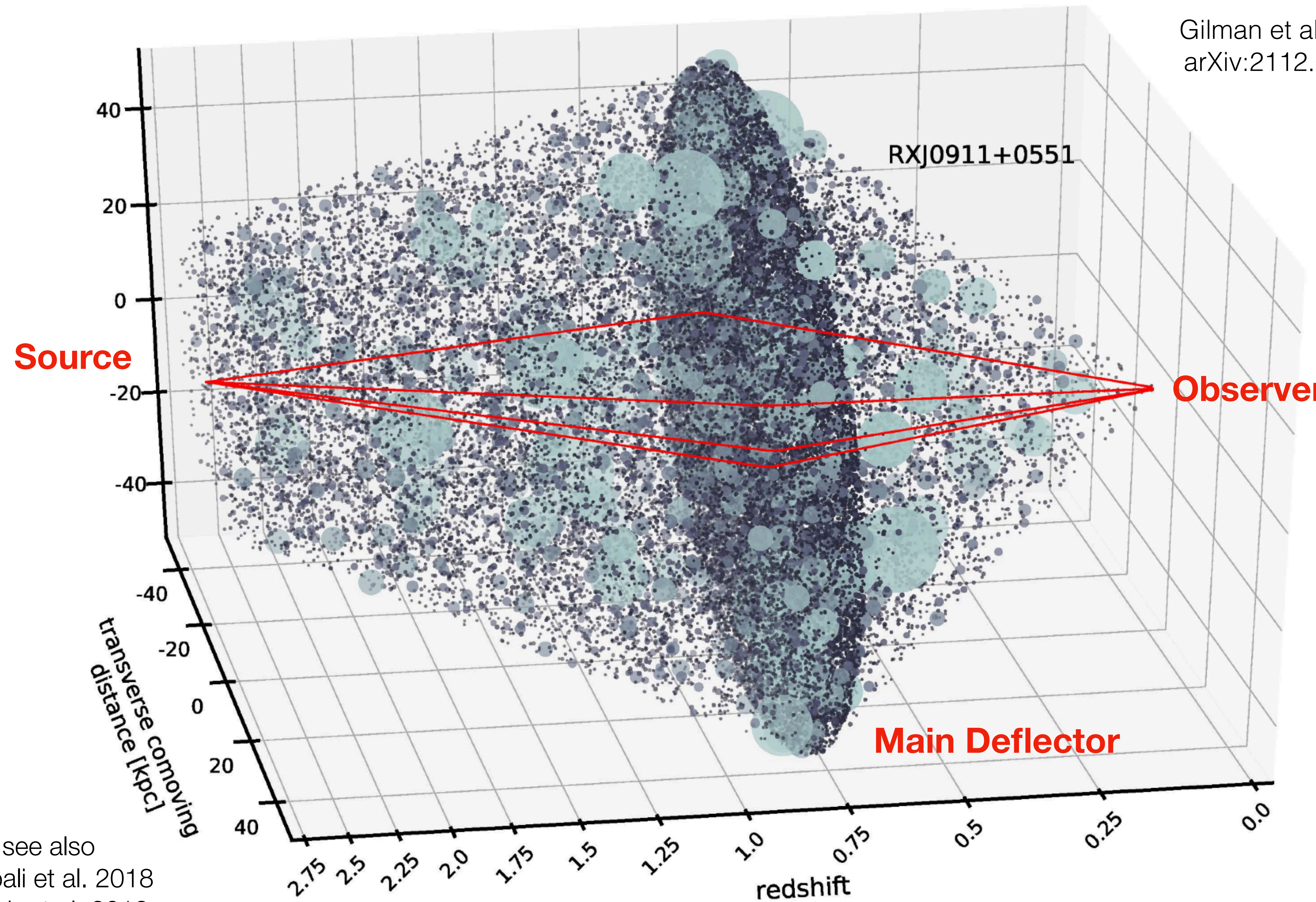
Compare w/ observed image position residuals for MG J0751+271 at level of ~3 mas, much larger than measurement errors ~0.04 mas

Spingola et al. 2018

Additional analysis by Powell et al. 2022 achieves residuals at 1-2 mas level arXiv:2207.03375

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

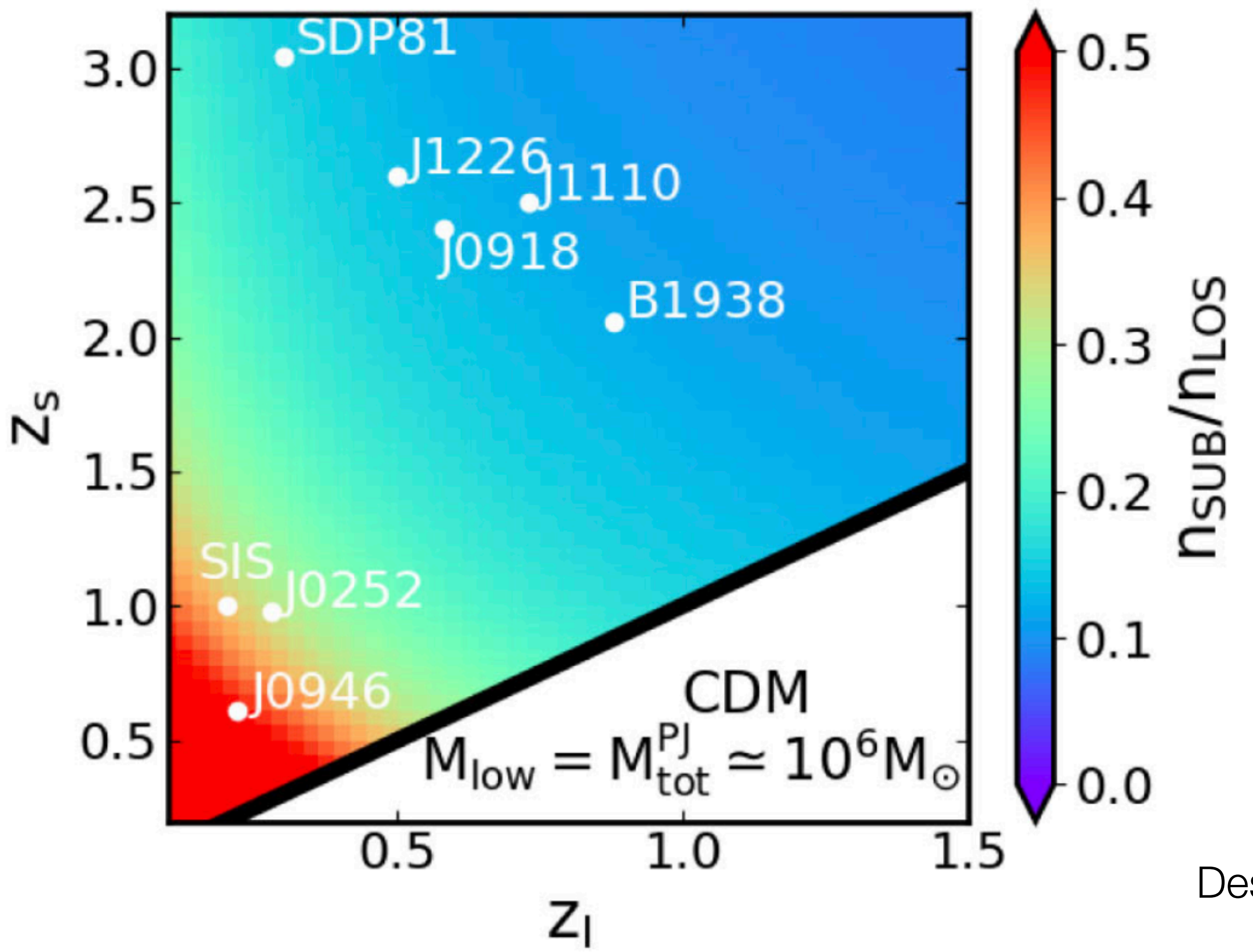
Gilman et al. 2022
arXiv:2112.03293



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

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

Source Redshift



Despali et al. 2018

Main Deflector Redshift

~90% of detectable low-mass perturbers are expected to be line-of-sight halos for many radio lenses

see also
Hsueh et al. 2019

Prior to this year, only ~40 published radio strong lenses

mostly from JVAS and CLASS flux-limited VLBI surveys ~20 years ago (lensing rate of ~1:600)

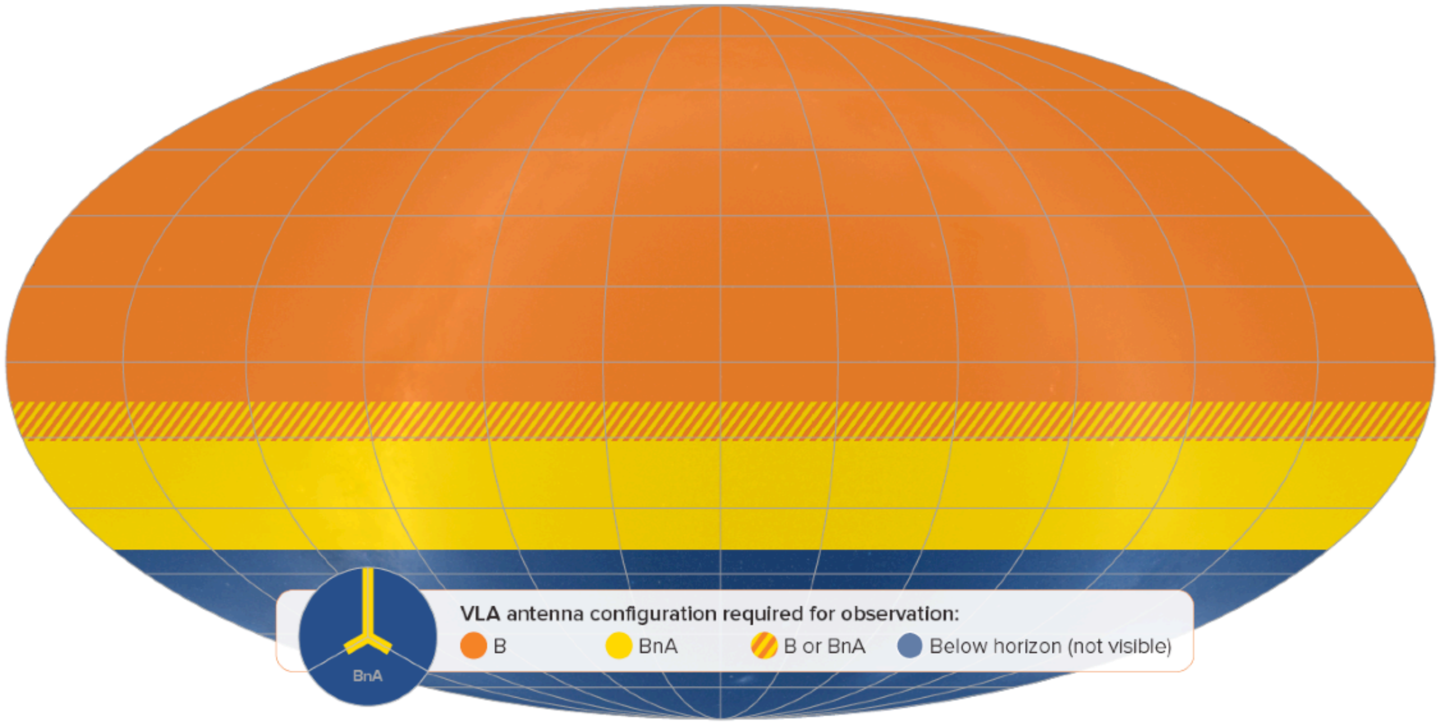
New radio lens search enabled with **VLA Sky Survey (VLASS)** highest angular resolution near-all-sky radio survey to date

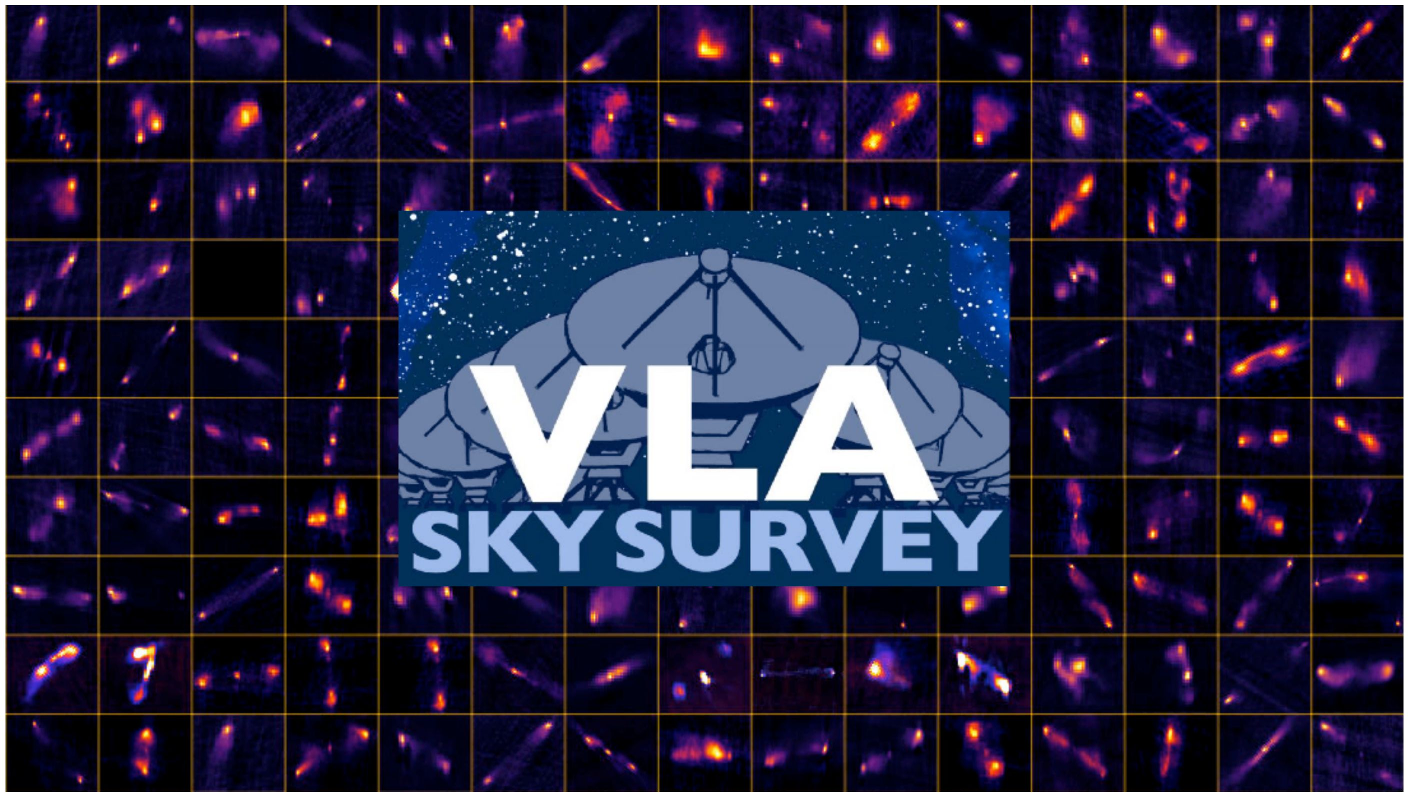
3” FWHM resolution at 2-4 GHz

declination > -40 deg
34,000 deg^2

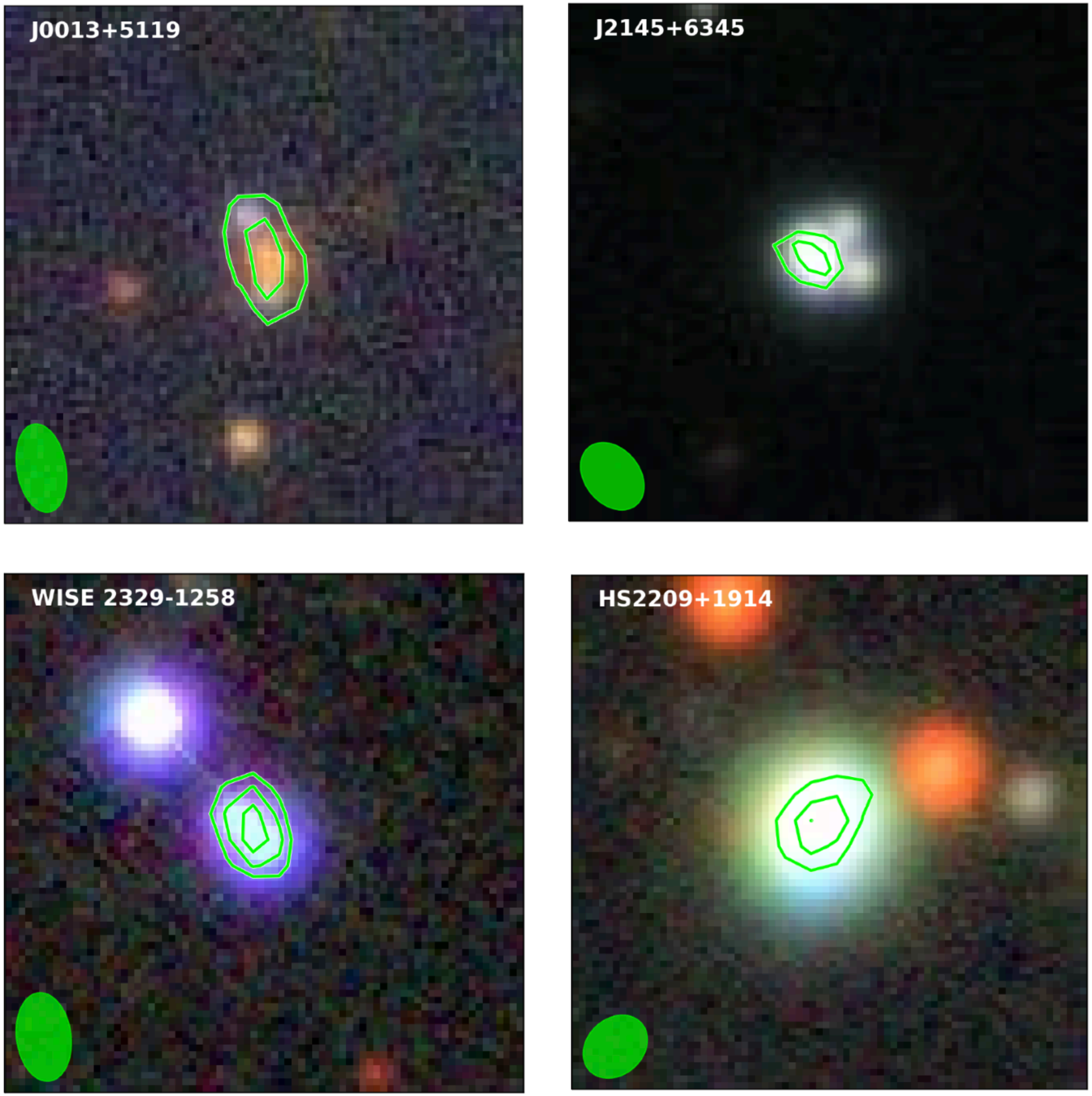
2 million sources in first epoch
Gordon et al. 2021

VLASS angular resolution is not sufficient to resolve the typical Einstein radius of galaxy-scale strong lenses (~1 arcsecond), but is sufficient to provide associations with optical imaging surveys (e.g., DES, DECaLS)





Optical surveys assist radio lens discovery

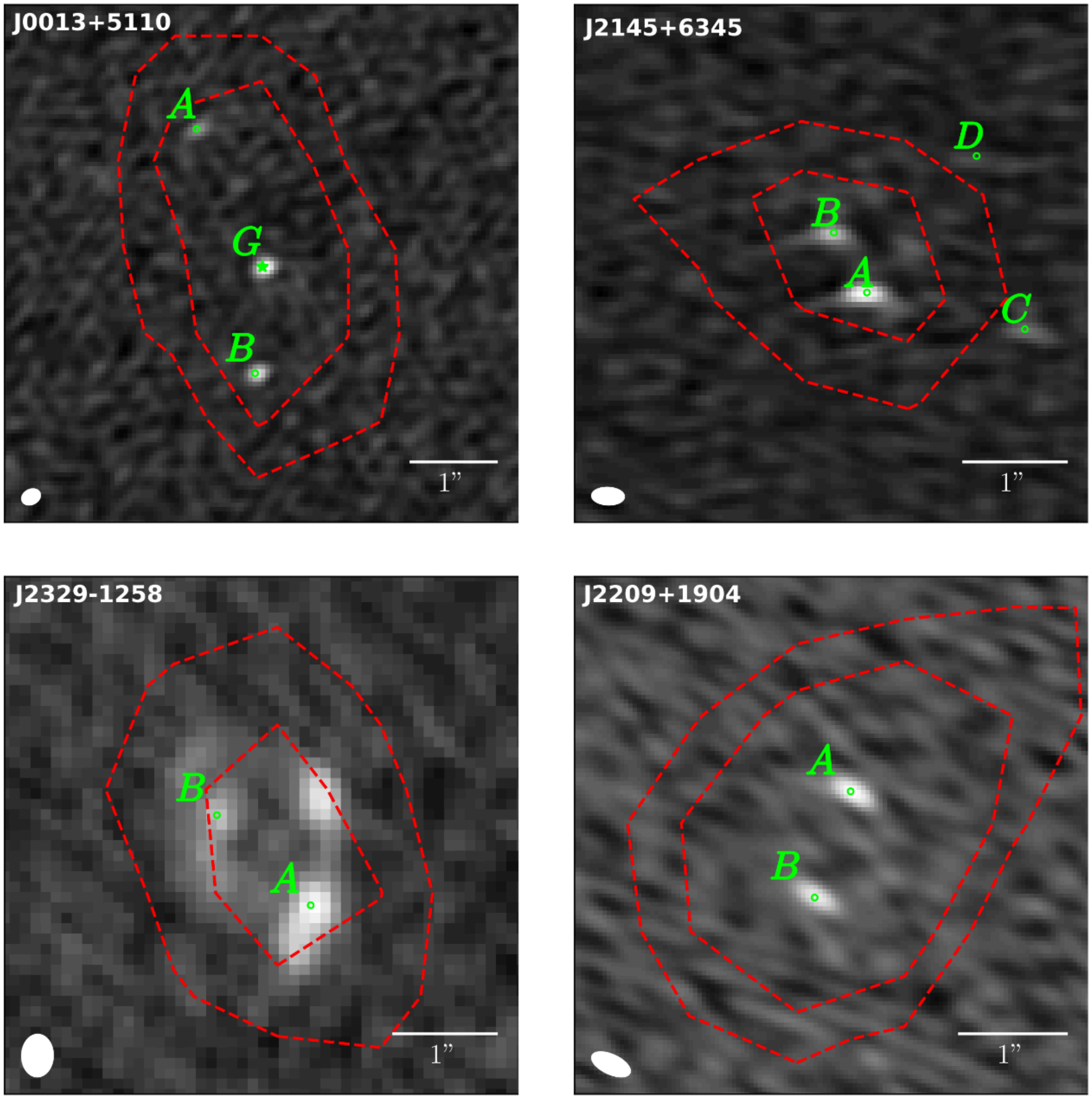


Optical images of lens candidates

VLASS radio contours in green

Martinez et al. 2024
arXiv:2404.09954

Optical surveys assist radio lens discovery



New radio strong lenses found in pilot follow-up campaign w/ VLA A-config w/ 0.2" resolution (~100 sec integration per target)

VLASS contours in red

Gaia quasar positions in green

Efficient method to identify strongly lensed radio sources by combining wide-area optical and radio surveys

Martinez et al. 2024
arXiv:2404.09954

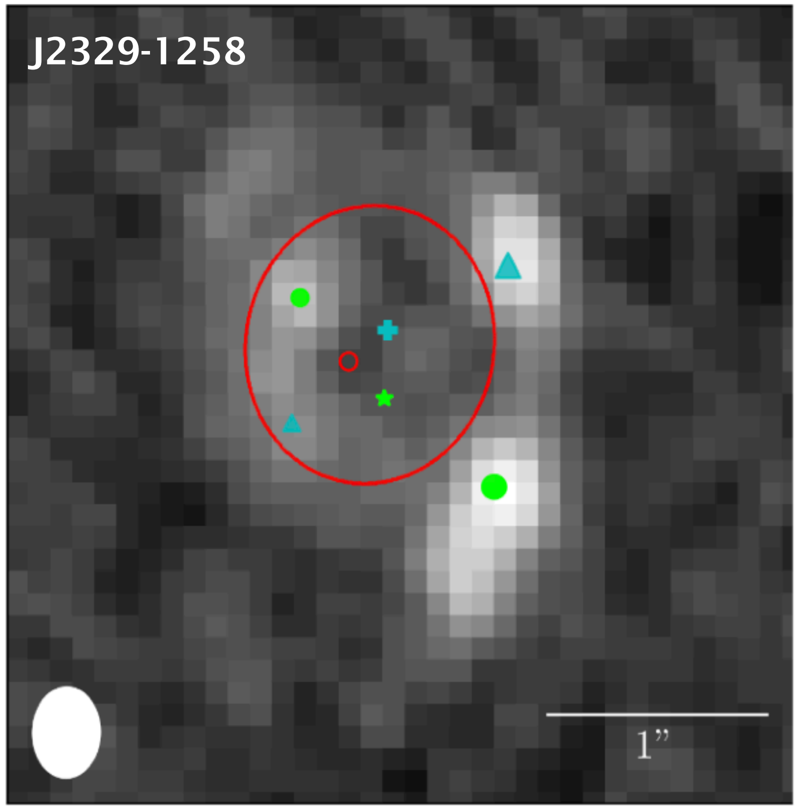
Optical surveys assist radio lens discovery

New radio strong lenses found in pilot follow-up campaign w/ VLA A-config w/ 0.2” resolution (~100 sec integration per target)

VLASS contours in red

Gaia quasar positions in green

Likely at least one additional component besides AGN core is strongly lensed

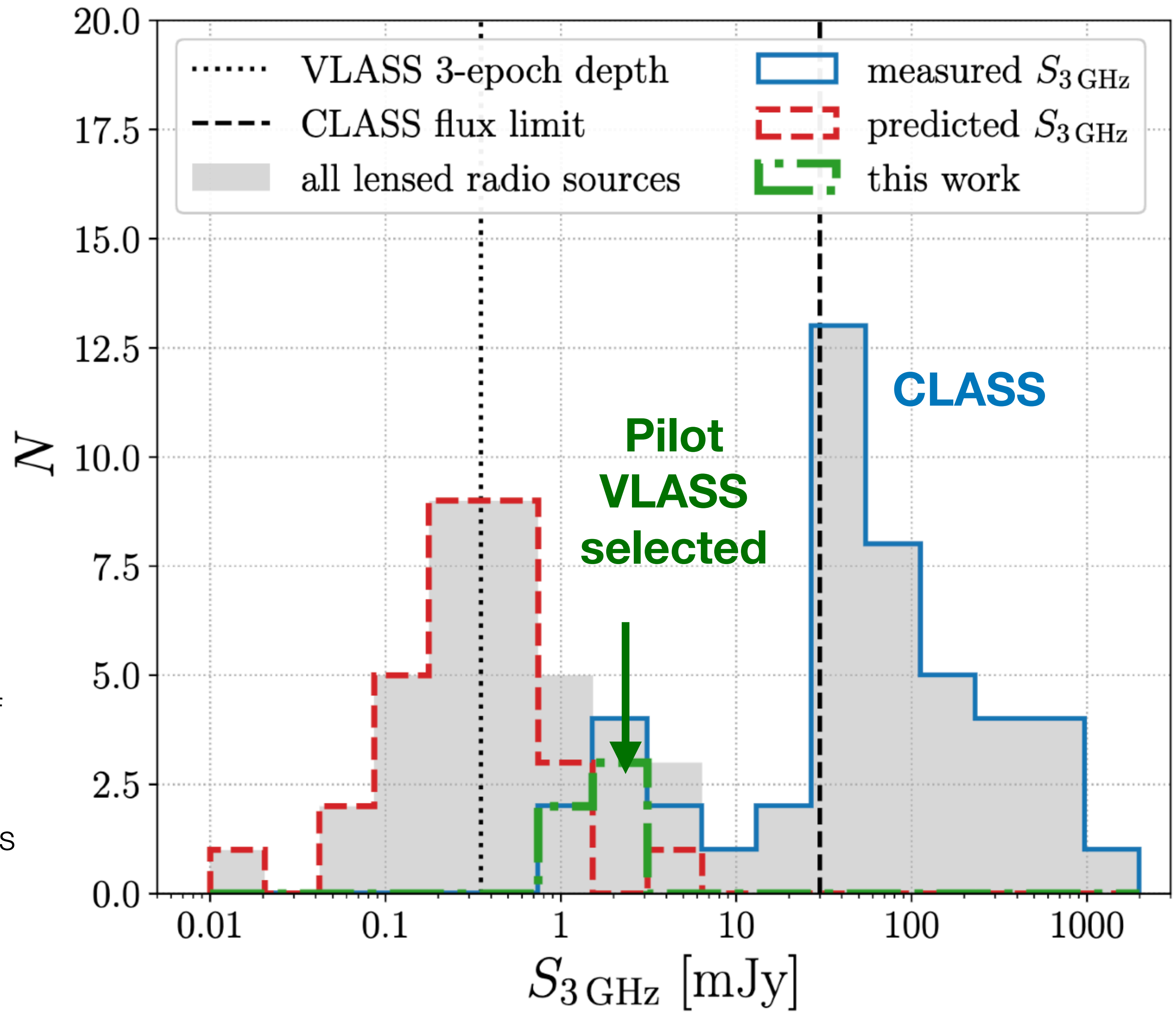


Efficient method to identify strongly lensed radio sources by combining wide-area optical and radio surveys

Martinez et al. 2024
arXiv:2404.09954

Optically selected lensed QSOs w/ VLASS counterparts are bright enough to target for detailed characterization

In next months, expanding radio lens discovery campaign w/ sample of 38 additional targets



Martinez et al. 2024
arXiv:2404.09954

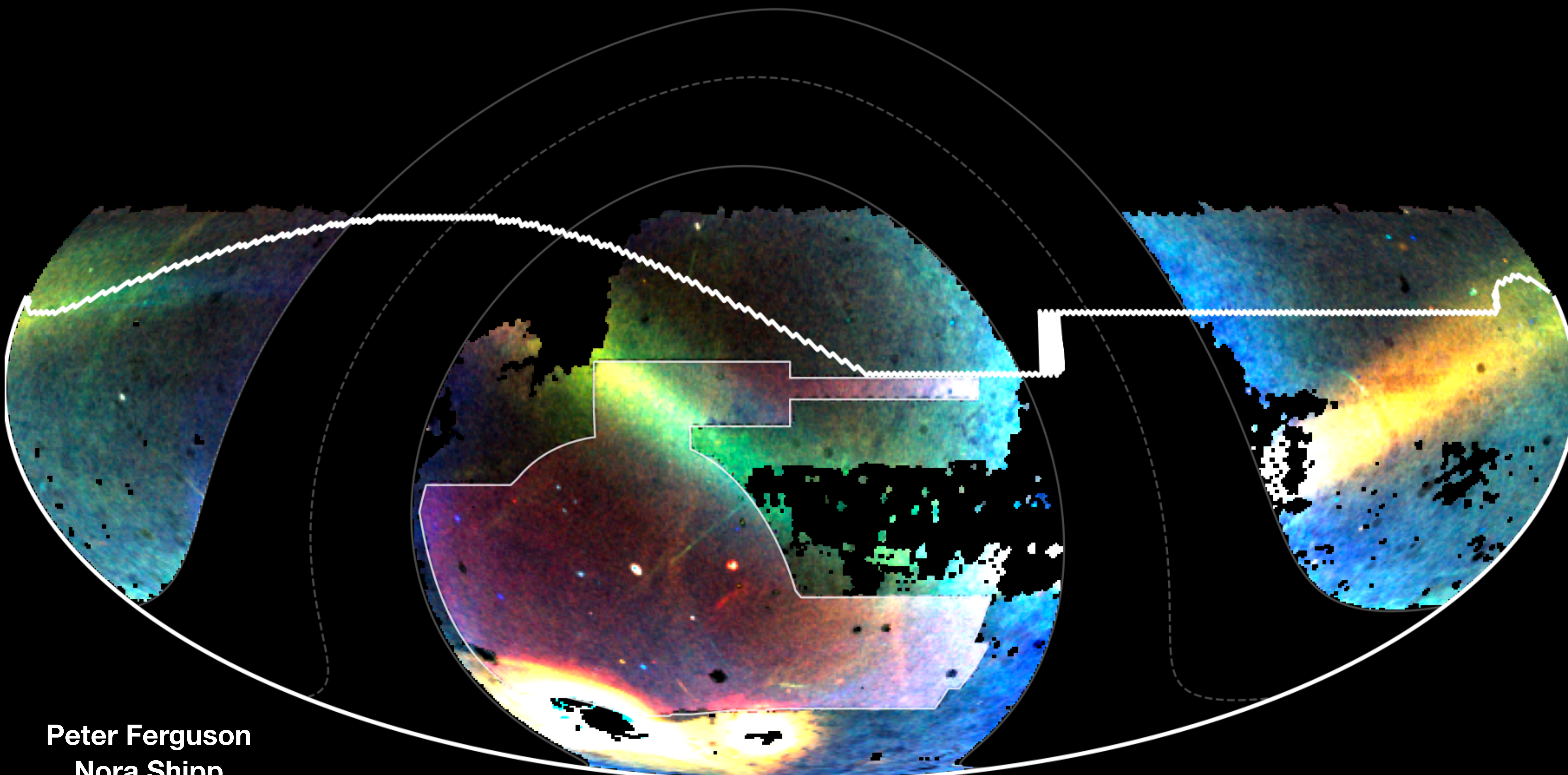
See also identification of radio lenses in deep observations of radio-quiet lensed optical QSOs

Dobie et al. 2024
arXiv:2311.07836

Jackson et al. 2024
arXiv:2403.19357

Stellar streams as dynamical tracers for low-mass dark matter halos

DGSCS 2024: "Dwarf Galaxies, Star Clusters, and Streams in the LSST Era"
workshop @ KICP, 8-11 July 2024



Peter Ferguson
Nora Shipp

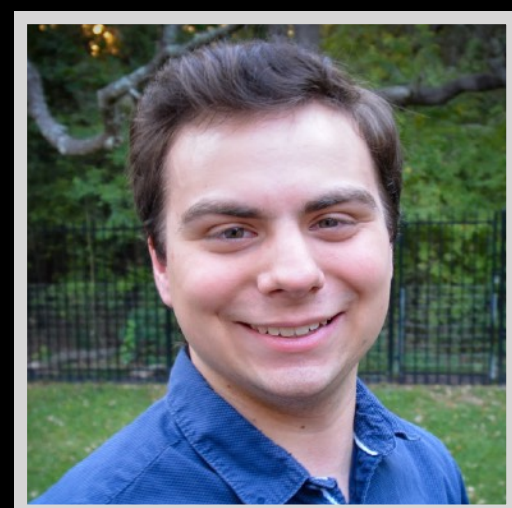

Kyle Boone

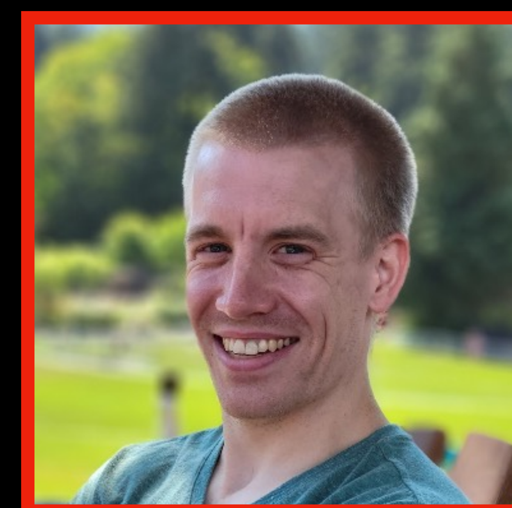

Gillian Cartwright


Julian Beas-Gonzalez


Jimena Gonzalez


Miranda Gorsuch


Michael Martinez


Mitch McNanna


Megan Tabbutt


Peter Ferguson


Yjan Gordon

Near-field Cosmology

THE UNIVERSITY of WISCONSIN MADISON


Kyle Boone


Gillian Cartwright


Julian Beas-Gonzalez


Jimena Gonzalez


Miranda Gorsuch


Michael Martinez


Mitch McNanna


Megan Tabbutt


Peter Ferguson


Yjan Gordon

Strong Lensing

THE UNIVERSITY of WISCONSIN MADISON

Testing the collision-less Cold Dark Matter paradigm brings together **initial conditions, dark matter microphysics, and galaxy formation**

Combination of Rubin Observatory + space-based observations of resolved stellar populations in the Local Volume (and beyond) offer possibility to reveal the **threshold of galaxy formation** in the sense of a stellar population at $z \sim 0$

- Note: numerical simulations predict that the first Population III stars formed in pristine dark matter minihalos with masses of 10^5 - 10^6 $M_\odot$ at $z \sim 20$-30

Emerging capability to use variety of gravity-based probes (e.g., strong lensing) to investigate **sub-galactic halos**

- Access to line-of-sight $\sim 10^6$ $M_\odot$ mass halos via milliarcsecond-scale image resolution and sub-milliarcsecond astrometry of radio VLBI
- Rubin Observatory + space-based imaging surveys + radio surveys (including wide-area VLBI) anticipated to yield thousands of radio strong lenses and candidates for detailed VLBI characterization

KICP

Thank you to my friends at KICP who have been the inspiration for this work — congrats on 20 years!