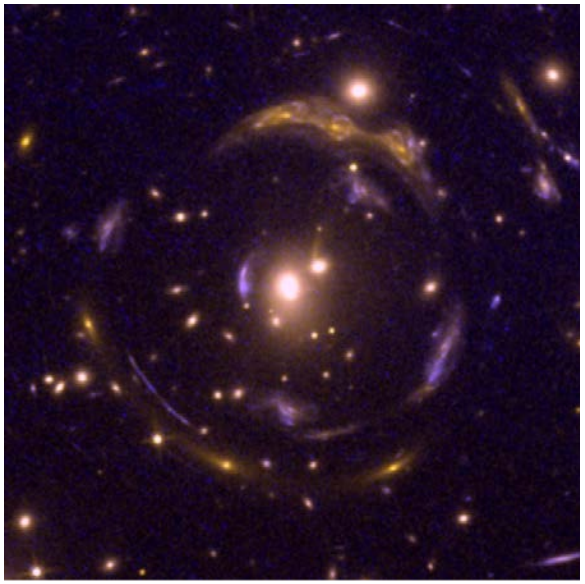
Probes of Self-Interacting Dark Matter and Update on Rubin LSST

Tesla Jeltema

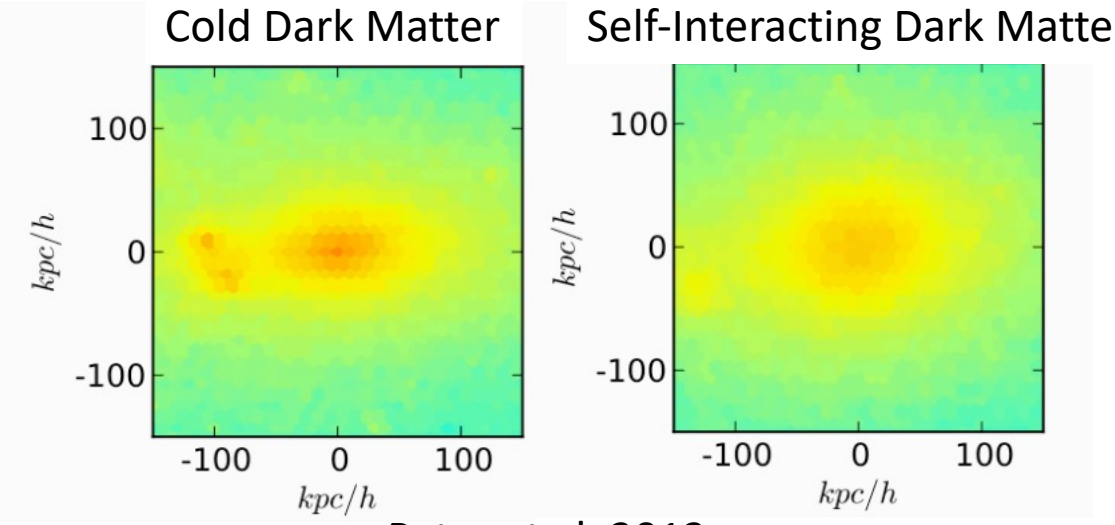
Santa Cruz Institute for Particle Physics
University of California, Santa Cruz



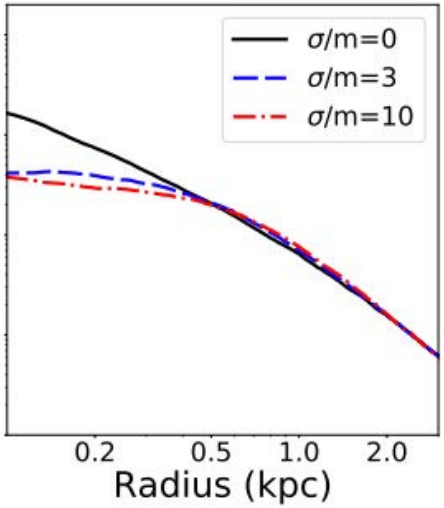
Self-Interacting Dark Matter

Is dark matter actually collisionless?

- Would lead to dark matter halos which are rounder and less dense in the middle.
- Can also lead to gravothermal core-collapse!
- Possible solution to small-scale tension e.g. core-cusp, diversity at dwarf galaxy scales



Peter et al. 2013



Kahlhoefer et al. 2019

Self-Interacting Dark Matter

Diversity of galaxy/dwarf rotation curves and densities imply

$\sigma/m > 3 - 20\ cm^2/g$

with some fraction in core-collapse phase (e.g. Roberts+2024)

- Scattering rate scales with density – SIDM may affect cores but outer structure the same as CDM
- Cross section could be velocity dependent (e.g. smaller for clusters than dwarfs)

Self-Interacting Dark Matter

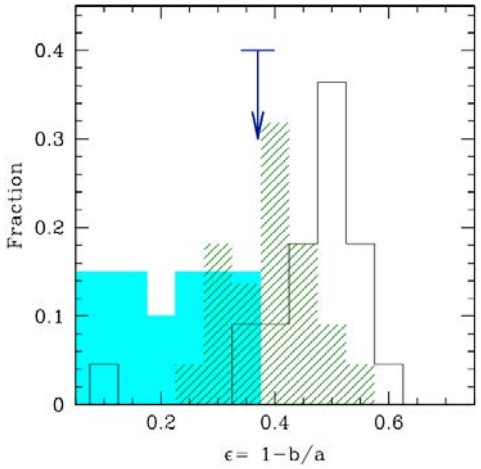
Limits from a variety of probes imply

$\sigma/m < 0.1 - 1\ cm^2/g$

Merging clusters

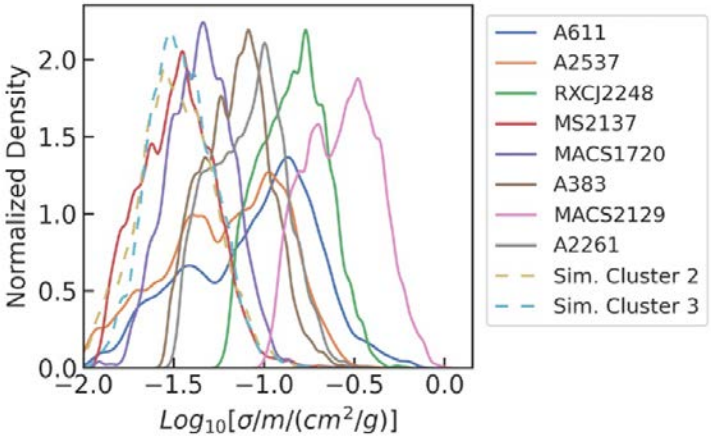
e.g. Randall+ 2008

Halo ellipticity



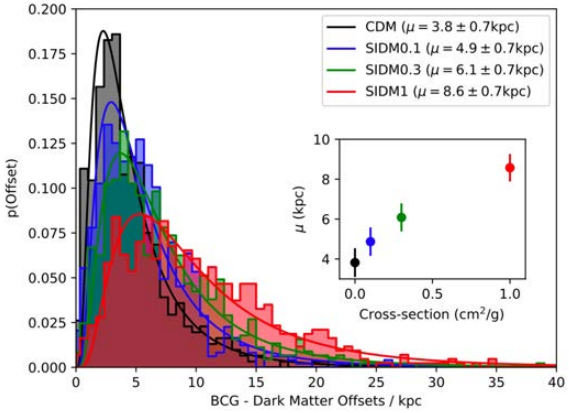
Buote, TJ+ 2002,
McDaniel, TJ+ 2021

Cluster central densities



Andrade+ 2022,
Sagunski+2021, Newman+2013

BCG oscillations

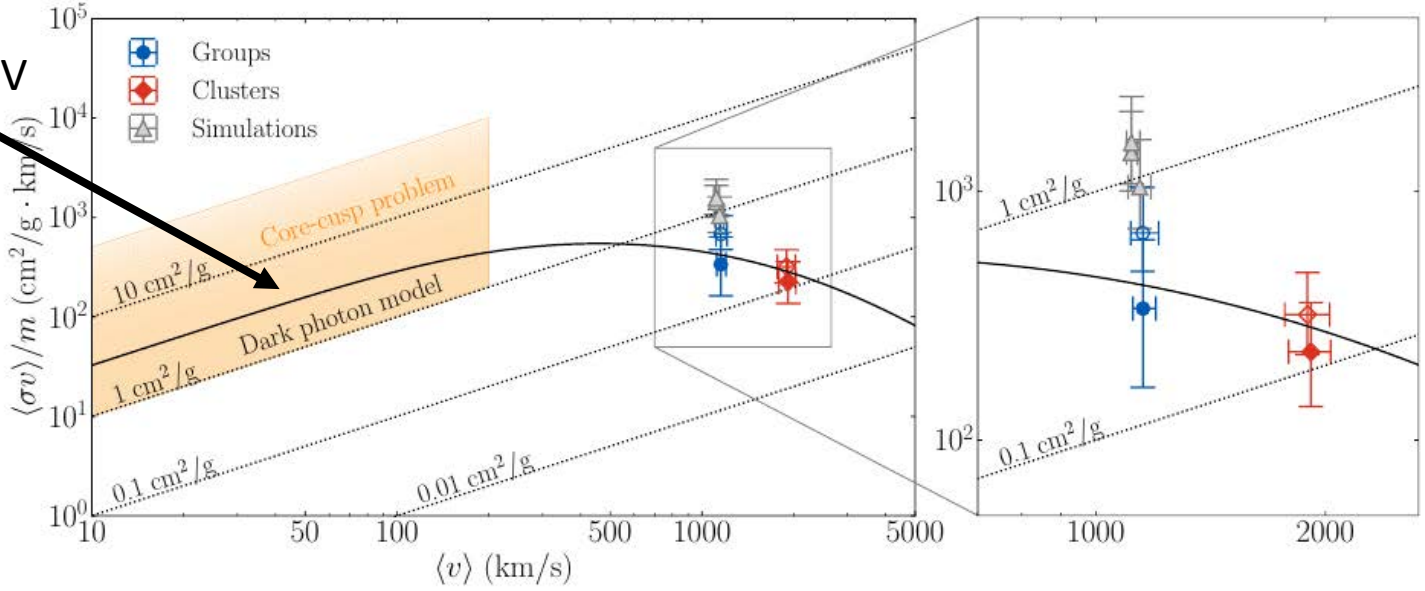


Harvey+ 2019,
Cross, Thoron, TJ+ 2023

Self-Interacting Dark Matter

- Strongest constraints at cluster scales
- Implies a needed velocity-dependent cross-section to explain galaxy and dwarf scale observations
- Natural in many SIDM models, e.g. light mediator

15 GeV DM mediated by 11 MeV dark photon

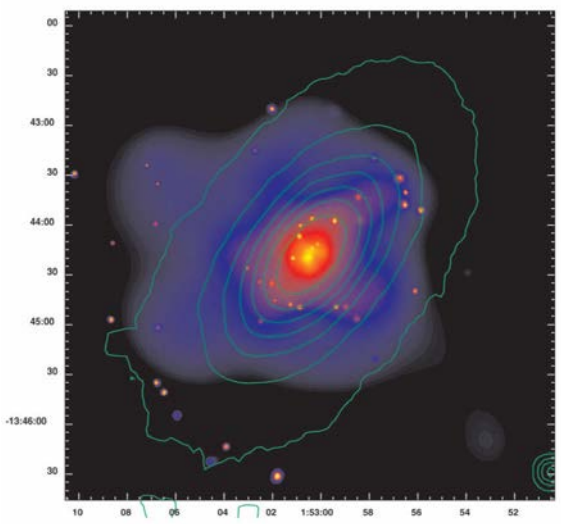


Sagunski+2021

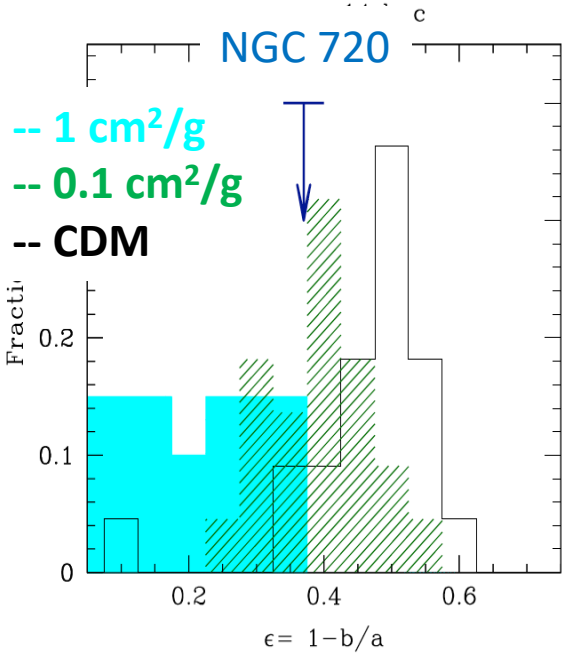
Halo Shapes

- SIDM halos are predicted to be rounder in the inner regions
- X-ray gas in hydrostatic equilibrium constrains shape of DM halo
- NCG 720: isolated elliptical galaxy, measure $\varepsilon \sim 0.37$ (Buote+2002)

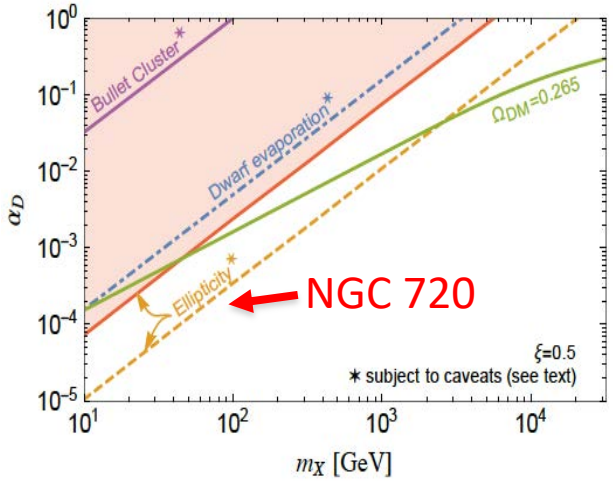
NGC 720



Jeltema+ 2003, Buote+ 2002



Peter et al. 2012



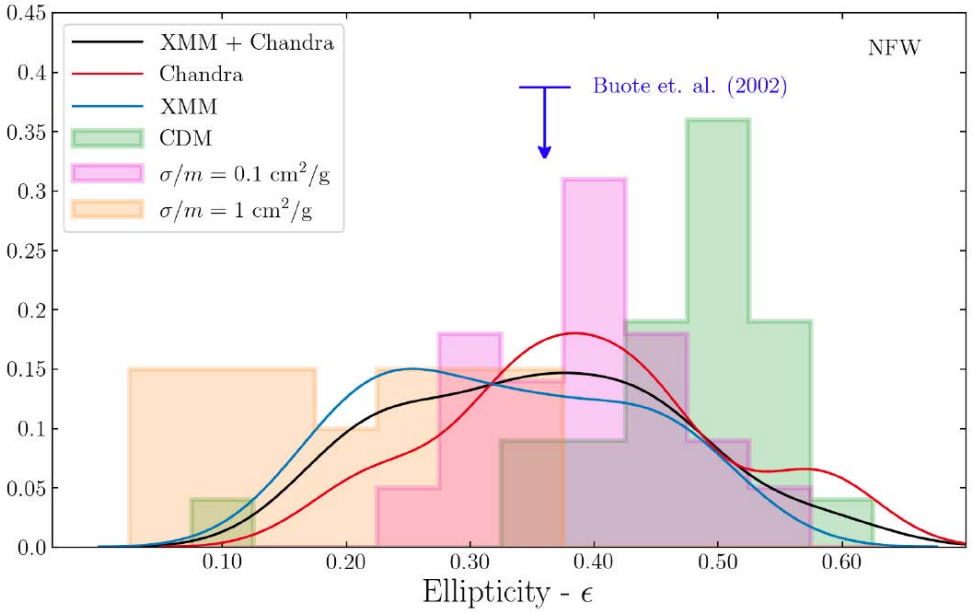
Agrawal et al. 2016

darkly-charged dark matter

Shapes of Isolated Ellipticals

Alex McDaniel

- Measured the shapes of 11 relaxed, isolated ellipticals with XMM (9 also with Chandra)

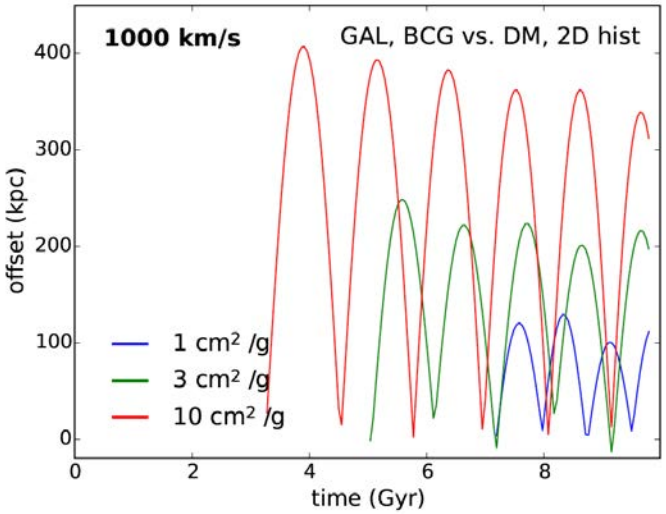


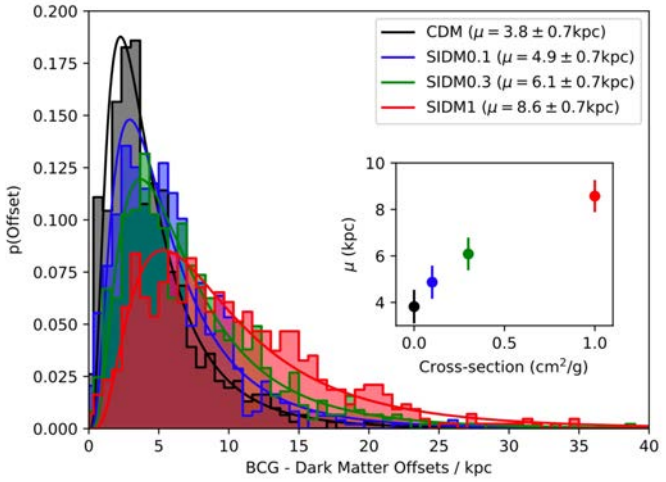
- ε = 0.2-0.5 with significant scatter, consistent with mild self-interaction though cannot rule out CDM

McDaniel et al. 2021

Central Cluster Galaxy Oscillations

- In SIDM, the formation of cores in clusters means the central galaxies orbit over large distances
- Kim et al. 2016 found BCG oscillations on long lived orbits lasting several Gyrs
- Longer lasting signature than merger offsets (e.g. Bullet cluster)
- Including baryons Harvey et al. 2019 found smaller, but measurable offsets of 5-10 kpc even in relaxed clusters





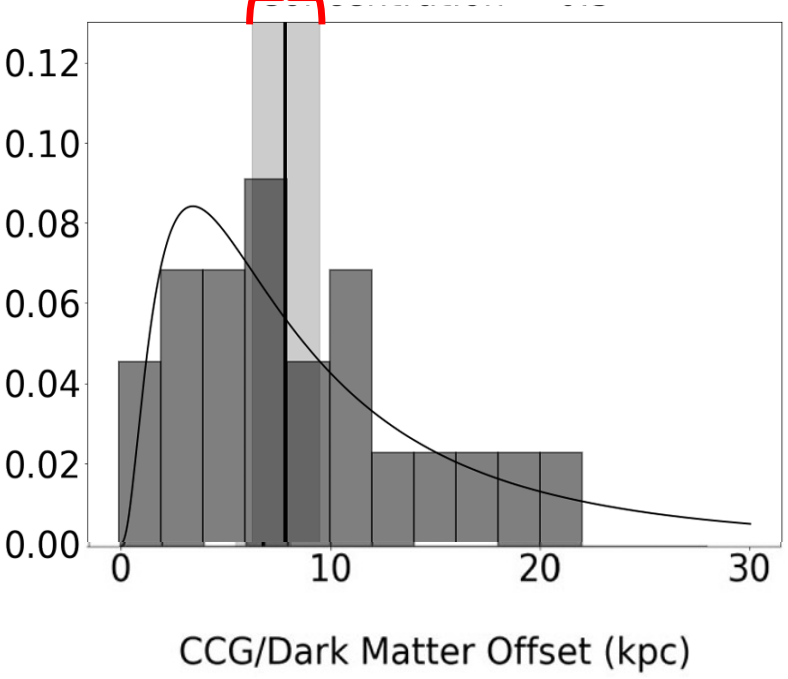
Central Galaxy Offsets

- Measured the offset of the central galaxy from the X-ray center for 23 relaxed, X-ray bright DES and SDSS clusters

Dane Cross

Gray Thoron

$\mu = 6.0$ +/- 1.5 kpc considering positional uncertainties



- Non-zero offsets larger than positional and statistical uncertainties for most of the sample
- Consistent with mild self interaction of ~ 1 cm^2/g

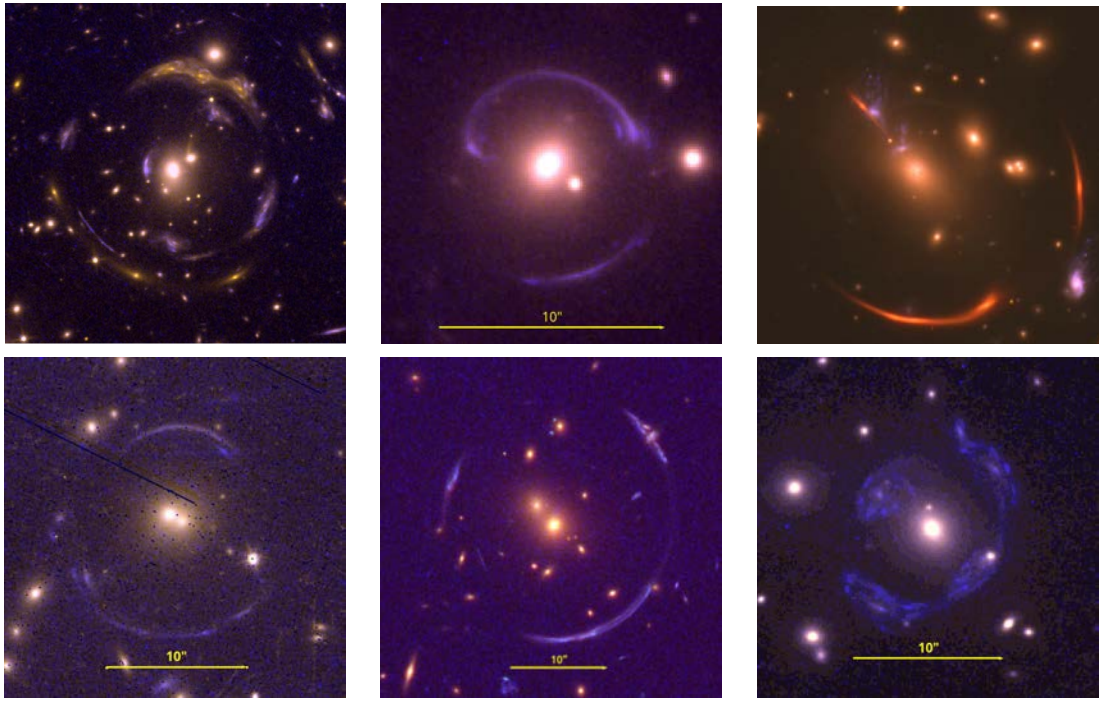
Cross, Thoron+ 2023

Cluster Strong Lensing

Jack O'Donnell

Cluster strong lensing: Cored or cuspy?

- Identified 189 cluster strong lenses in DES Y3 (O'Donnell+ 2022)
- Sample of ~20 relaxed clusters with prominent, symmetric arcs and HST imaging
- Conducting spectroscopic and X-ray follow up, adding systems with HST GAP program

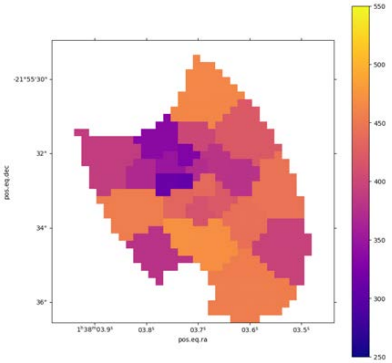


Cluster Inner Density Profile

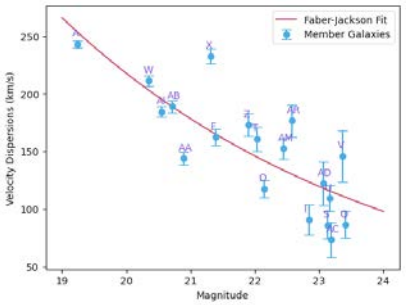
Jack O'Donnell

- Will model density profile from 2 – 500 kpc scales including the contributions from baryons

Central and member galaxy dynamics

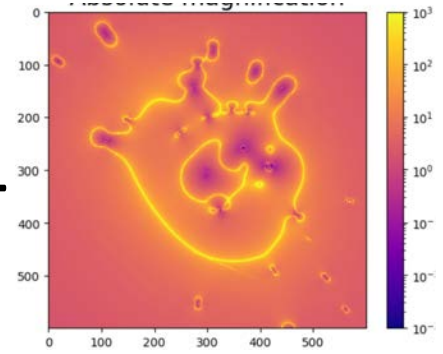


+



Strong lensing

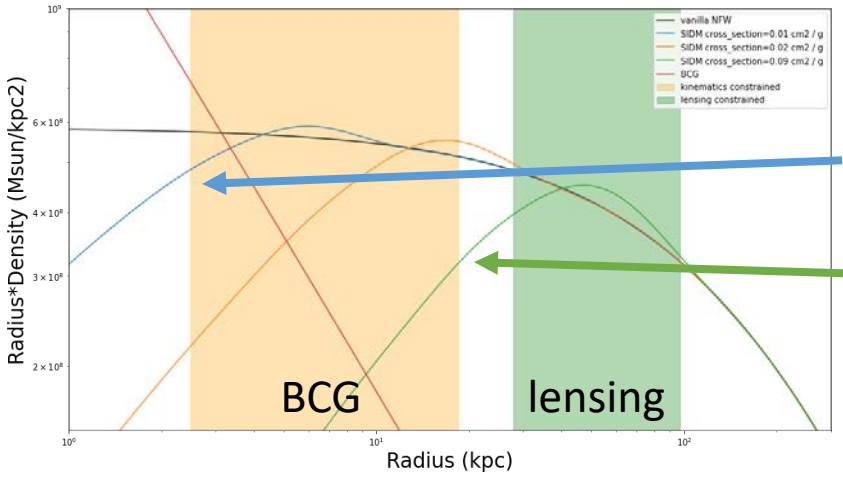
+



X-ray

+

- Use resolved kinematics of central galaxy plus strong lensing



0.02 cm^2/g

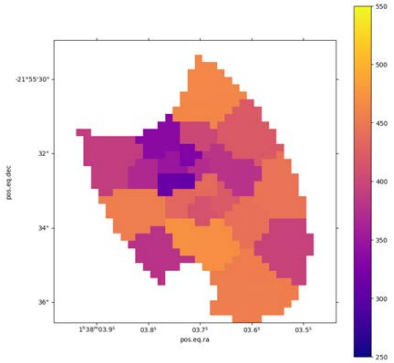
0.1 cm^2/g

Cluster Inner Density Profile

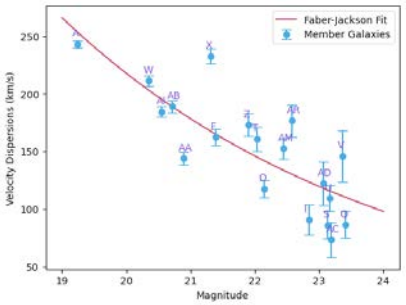
Jack O'Donnell

- Will model density profile from 2 – 500 kpc scales including the contributions from baryons

Central and member galaxy dynamics

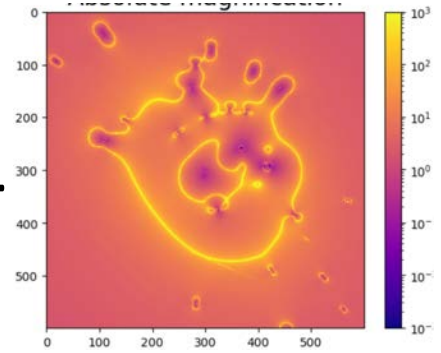


+



Strong lensing

+



+

X-ray

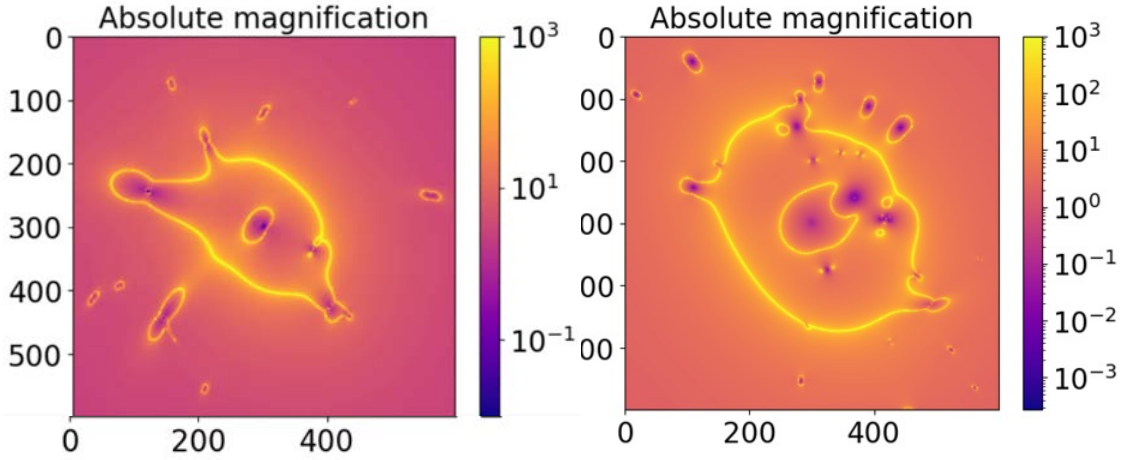
- Use a fully consistent mass modeling, directly sampling the SIDM parameters and computing the strong lens observables from the predicted density profile plus baryonic components

Strong Lensing

- Using PyAutoLens (Nightingale+ 2021) edited for cluster strong lens modeling
- Mass model:
  - Isothermal Jeans model – isothermal within core + NFW outer halo (decomposed as sum of CSEs)
  - BCG stellar mass
  - Cluster member galaxies scaled by Faber-Jackson relation

Dhruv Aldas

Emma Strickland

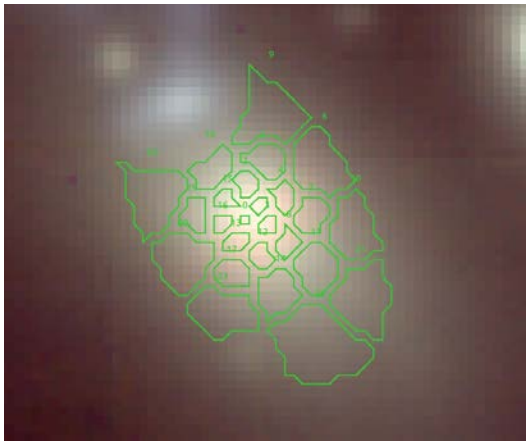


BCG Kinematics

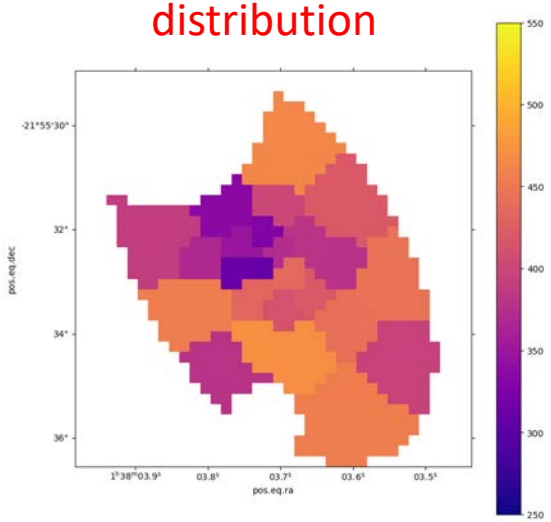
Jack O'Donnell

- IFU data used to model 2D stellar velocity dispersion
- Stellar kinematics modeled with Jeans Anisotropic Modelling (JAM) method (Cappellari 2008)
- HST 2D light profile constrains stellar mass

MUSE spatially resolved spectroscopy



Stellar dispersion distribution



Systematics tests

108 set ups varying:

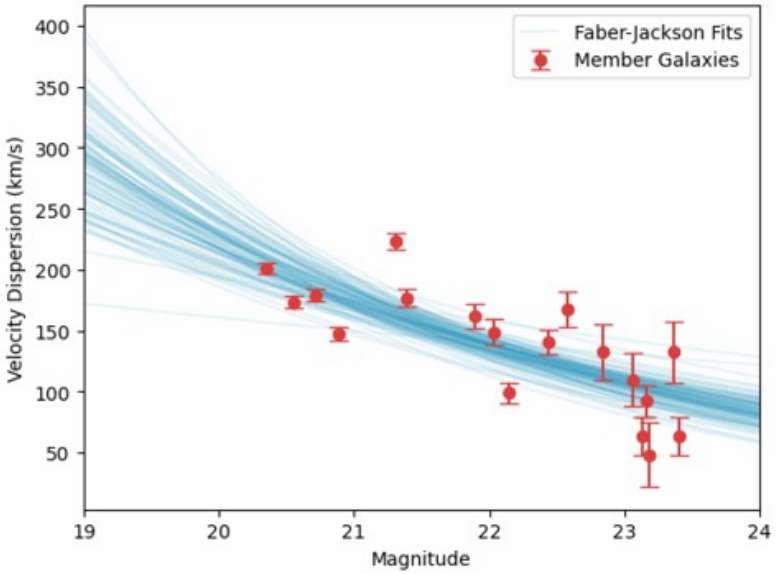
- Wavelength range
- Background model
- Template library
- Dust model

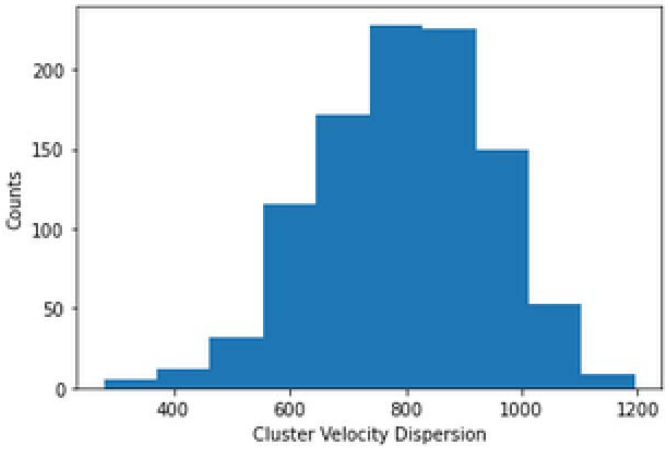
→ Systematics subdominant to statistical uncertainties

Cluster Substructure

Abigail Flowers

- Cluster member galaxy masses using cluster Faber-Jackson relation
- MUSE data used to measure member galaxy stellar velocity dispersions



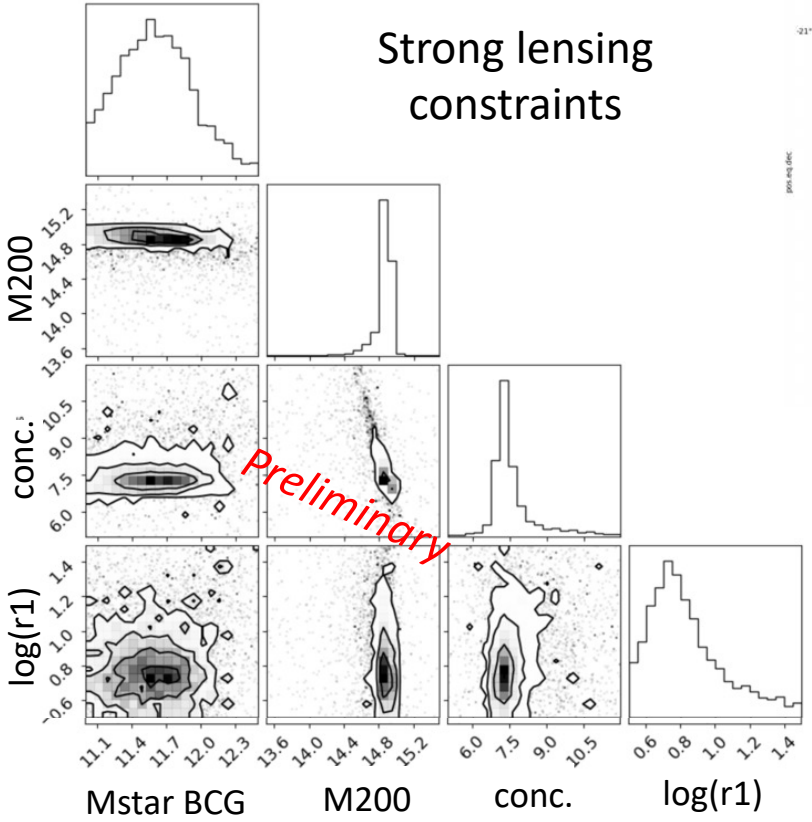


- Also get velocity dispersion of galaxies within the cluster

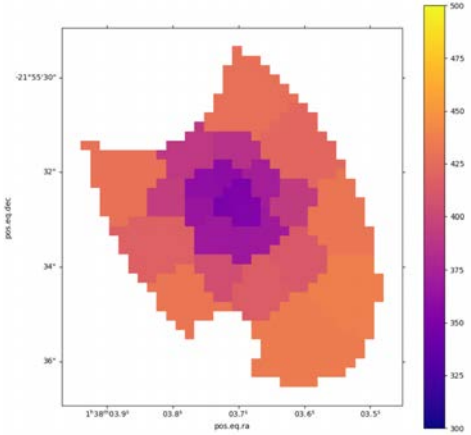
Example Constraints

Jack O'Donnell

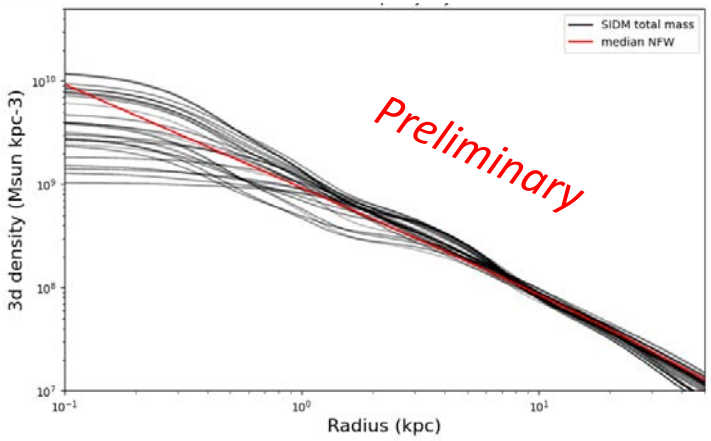
Strong lensing constraints



BCG dynamical model



Kinematic-constrained mass model



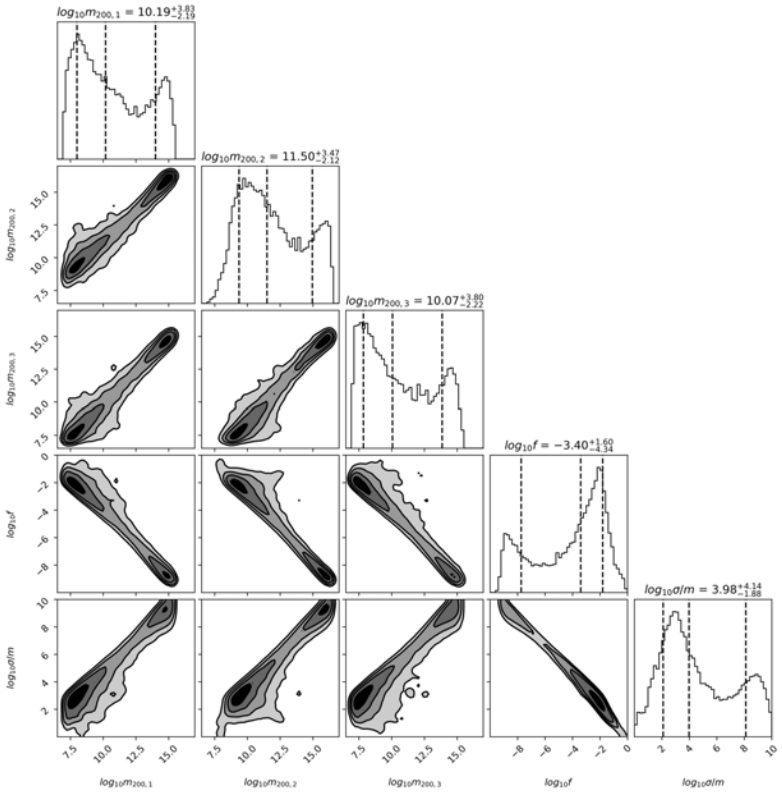
- Very small/negligible interaction cross section for this cluster

Seeding Black Holes – Core Collapse

Grant Roberts

- We find populations of high-z (z>6) supermassive black holes (M_{BH}>10^9) whose formation so early is difficult to explain.
- If a fraction of the dark matter is ultra-strongly interacting, these black holes can be seeded by core collapse (e.g. Pollack+2014)

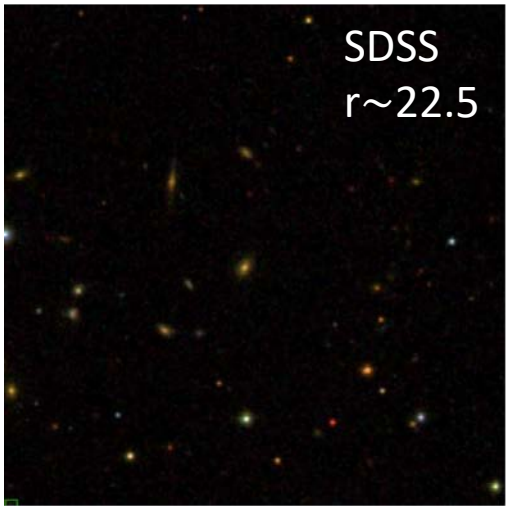
- We find constraints on the DM fraction versus interaction cross section for a sample of z = 6-10 quasars

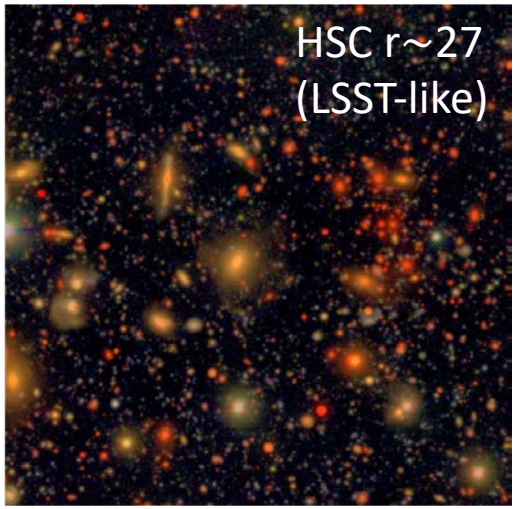


Rubin Observatory Legacy Survey of Space and Time

- The 10-year Rubin Observatory Legacy Survey of Space and Time (LSST) will observe half of the sky and will:
  - Record 37 billion stars and galaxies
  - 10 million alerts
  - 20 TB of data, every night!

Rubin LSST

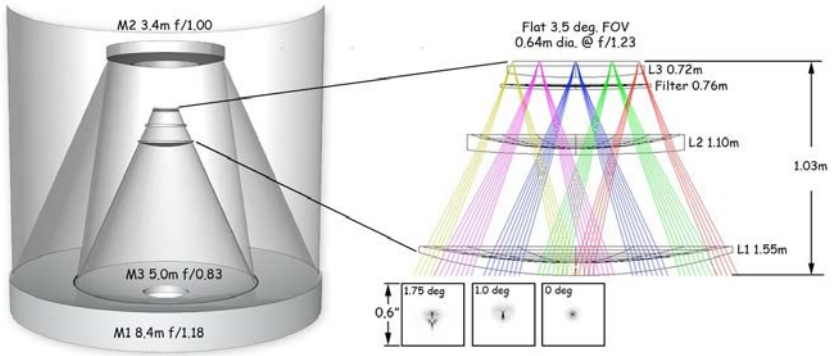




LSST Camera

- 3.5 deg diam FOV
- 3.2 gigapixels
- 189 4k X 4k CCDs, ugrizy

Simonyi Survey Telescope



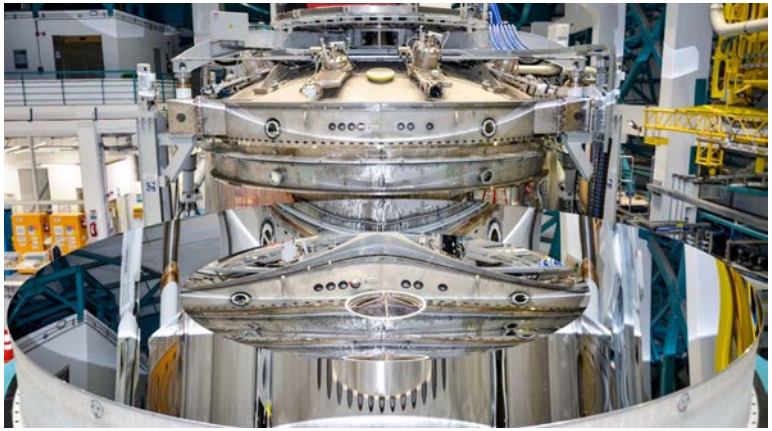
- 8.4-m primary mirror
- Three mirror design → good imaging over wide FOV

Recent Milestones

LSST Camera arrived at Cerro Pachón on May 16, 2024

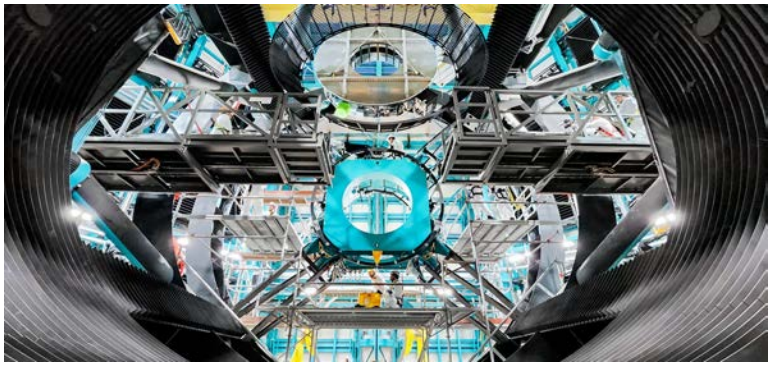
Olivier Bonin/SLAC

8.4-meter primary/tertiary mirror was coated with silver April 27, 2024



RubinObs/NSF/AURA/T. Vučina

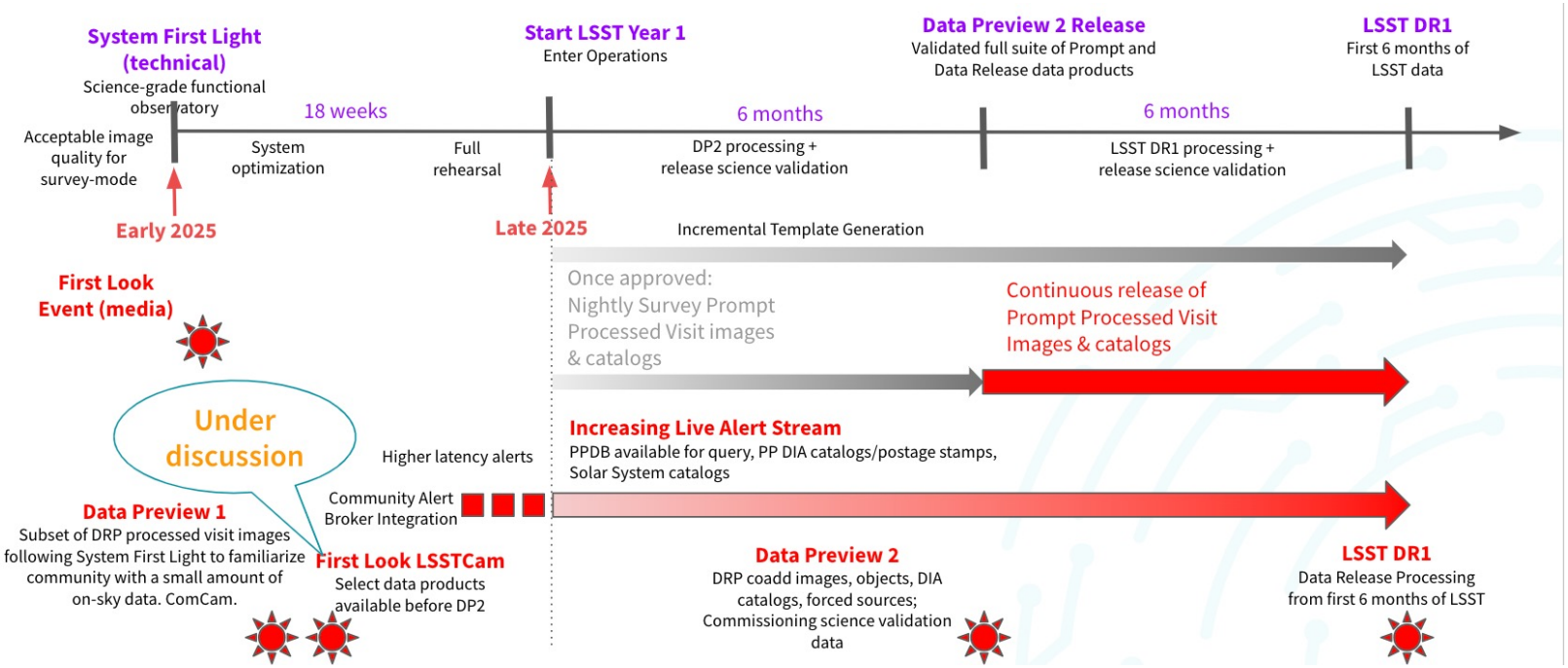
Secondary mirror installed July 24, 2024



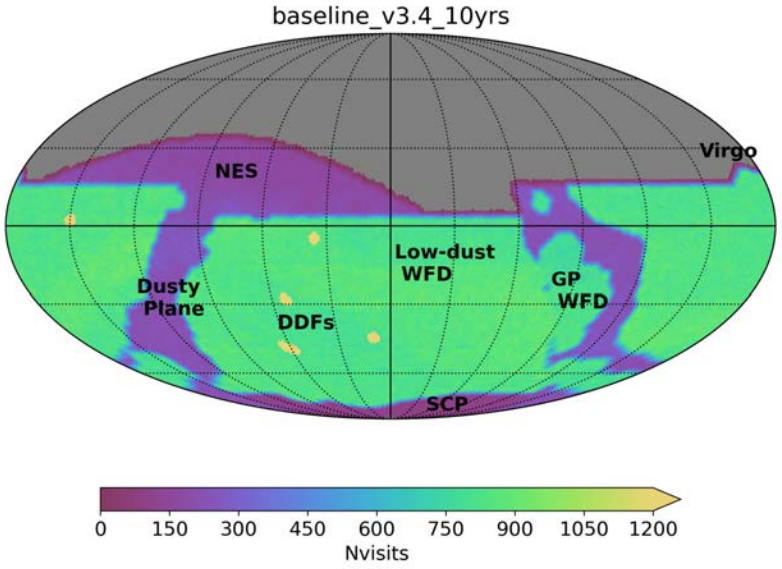
Rubin Observatory/NSF/AURA/F. Munoz Arancibia

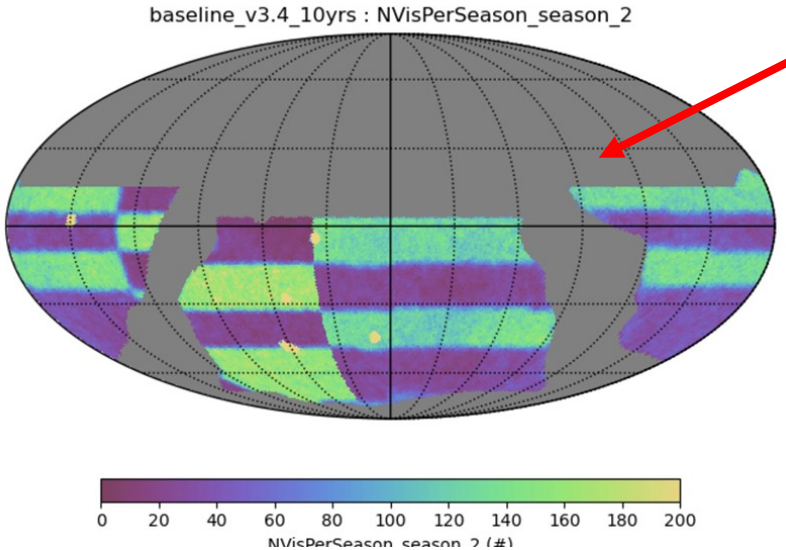
Survey Start Next Year!!

- Commissioning with ComCam (9 CCDs) this Fall
- LSST Cam on telescope ~ December/January
- Rubin first light and science verification ~ Spring - Summer 2025



Survey Strategy





Baseline Survey Strategy designed to achieve the core science goals over 10 years

Wide-Fast-Deep survey:

- approximately 18000 deg^2
- median 800 visits per field in 10 years
  ~ 3 day cadence (time between visits)
- same-night same-field re-visit "pairs"
- Rolling cadence reduces time between visits with same filter

Deep Drilling Fields: 5 fields, single pointings with ~20k visits, 40k for COSMOS and several sequences of visits within 1 night

Mini-Surveys + ToO's

See survey-strategy.lsst.io

Rubin LSST Science Collaborations

Transients and Variable Stars			Stars, Milky Way, and Local Volume
Dark Energy			Solar System
Galaxies			Active Galactic Nuclei
Strong Lensing			Informatics and Statistics

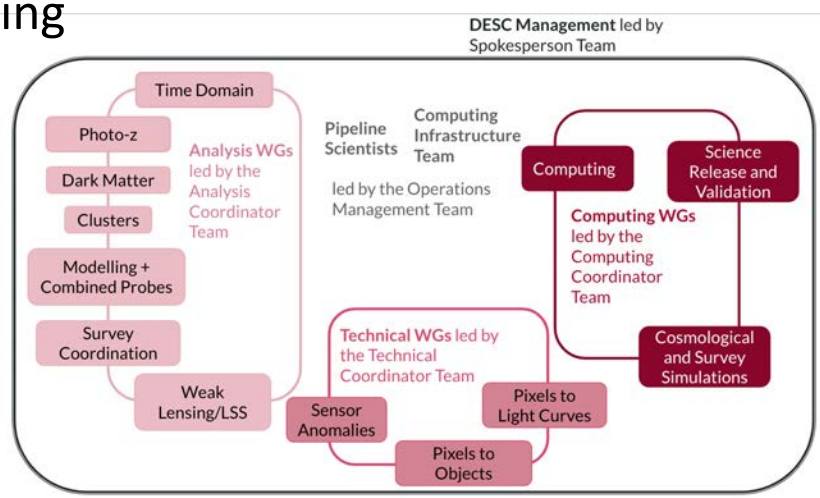
https://lsstdiscoveryalliance.org/lsst-science-collaborations/

Dark Energy Science Collaboration

- Scientific aim: Explore the physics of the dark universe including dark energy, dark matter, neutrinos and inflation
- Our approach: Combine cosmological probes: clusters of galaxies, large-scale structure, supernovae, weak lensing and strong lensing (Science Overview Document)

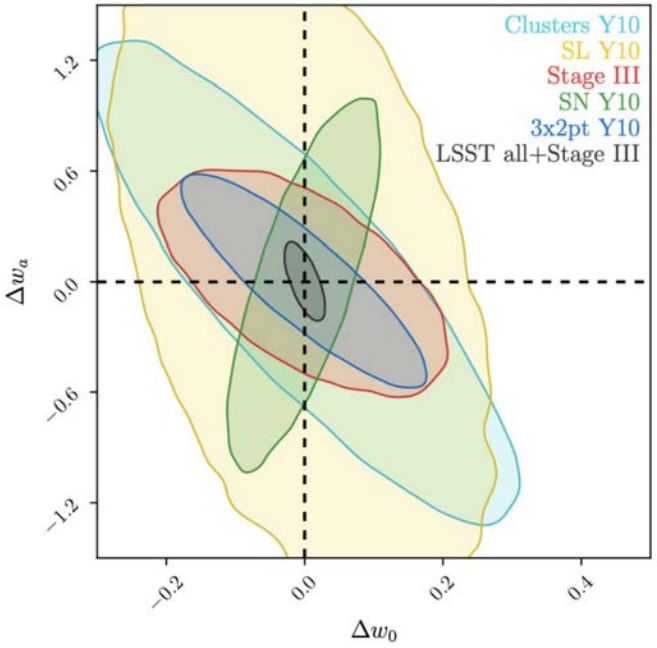
Spokesperson team:
Renée Hložek (U. Toronto)
Tesla Jeltema (UC Santa Cruz)

1,250+ members, 250+ full members (with voting rights on policies, etc.)
For DESC membership apply here



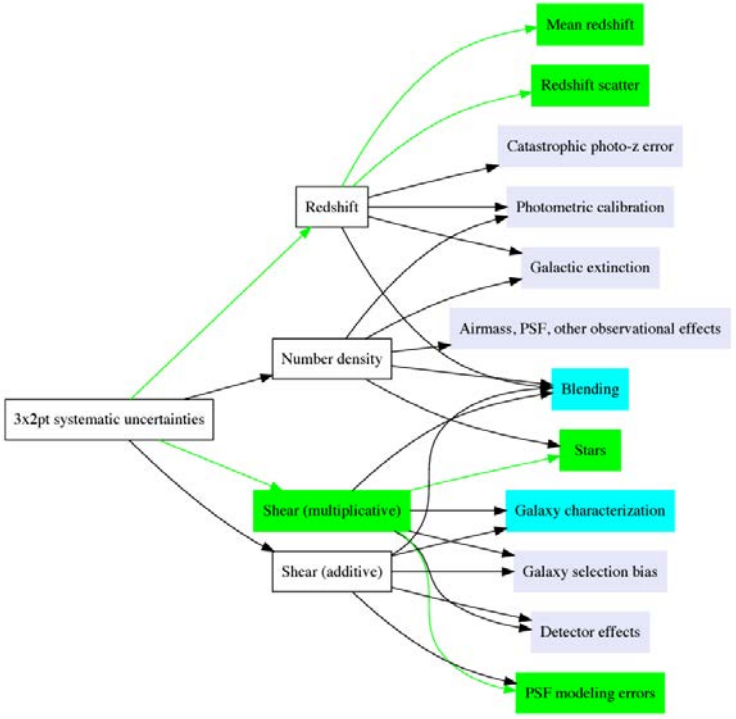
Working groups and topical teams to build pipelines and perform analysis

Dark Energy with LSST



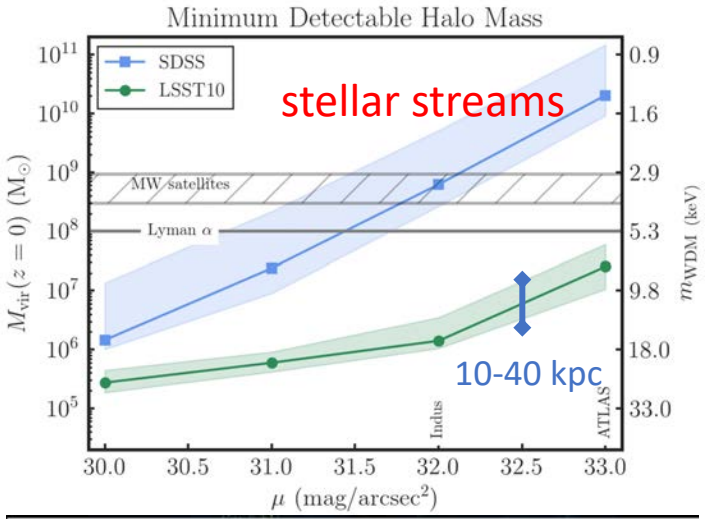
- Dark energy constraints with 10-year LSST (an enormous amount of work to get to this plot)

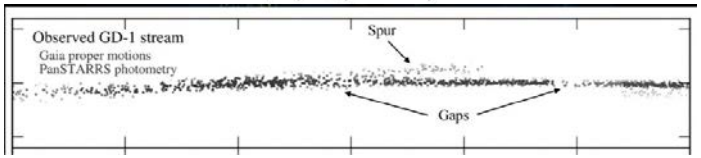
- Example of anticipated systematics in 3x2pt analysis

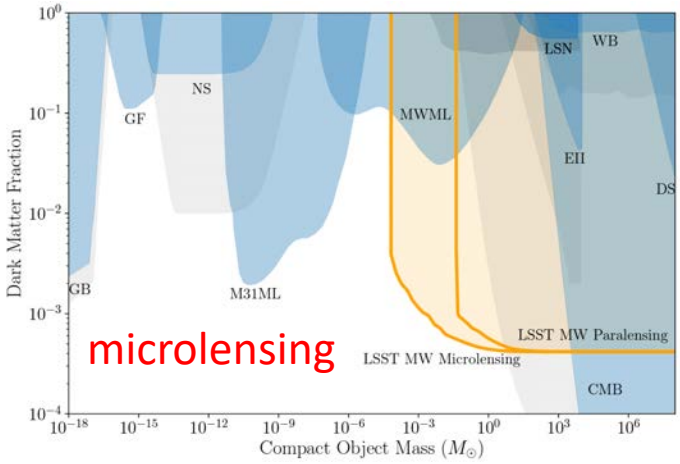


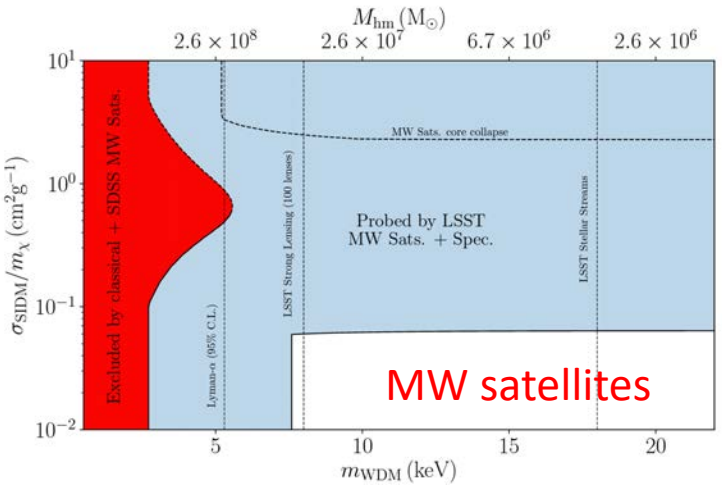
DESC Science Requirements, 2018

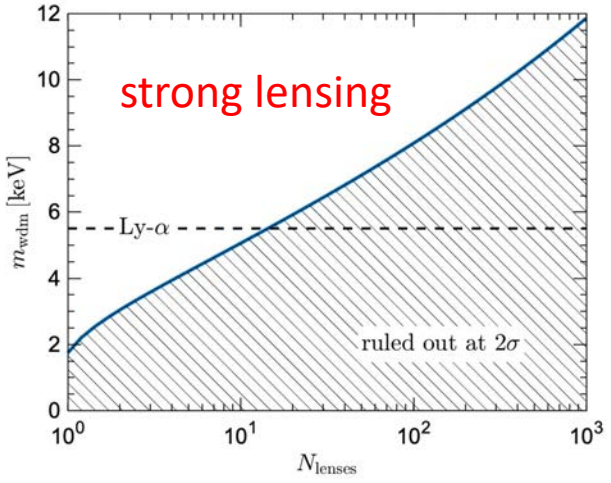
Dark Matter with LSST











LSST Dark Matter Group 2019, arXiv:1902.01055

Summary

- Galaxy shapes and central galaxy offsets consistent with mild dark matter self interaction of $\sigma \lesssim 1$ cm^2/g
- Strong constraints coming from cluster strong lensing plus galaxy stellar dynamics
- LSST is almost here!!


Thank you!