Astrophysical Probes of Self-Interacting Dark Matter

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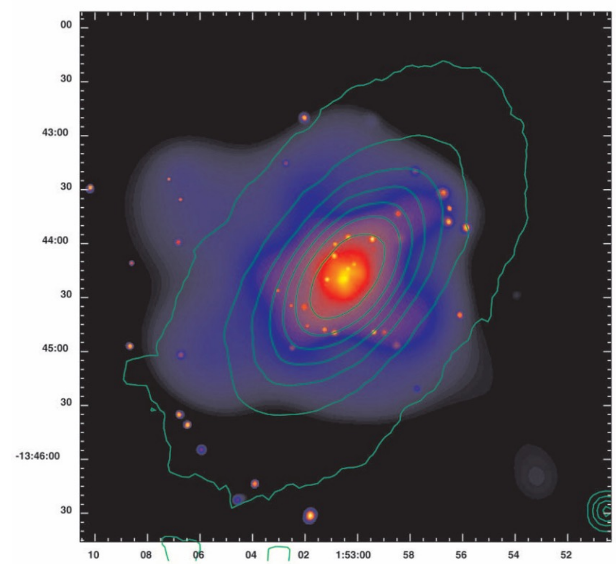
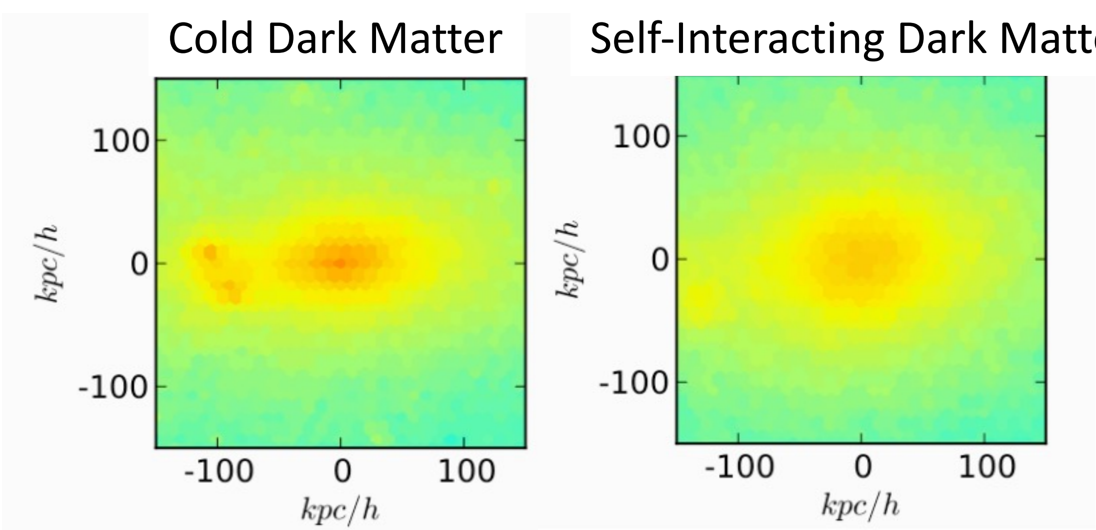


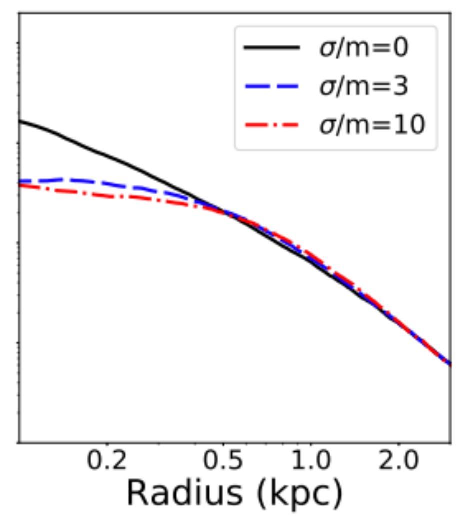
Self-Interacting Dark Matter

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

- Characterize in terms of the cross section over mass

Diversity of galaxy/dwarf rotation curves and densities imply

$\sigma/m > 3 - 10\ cm^2/g$

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)

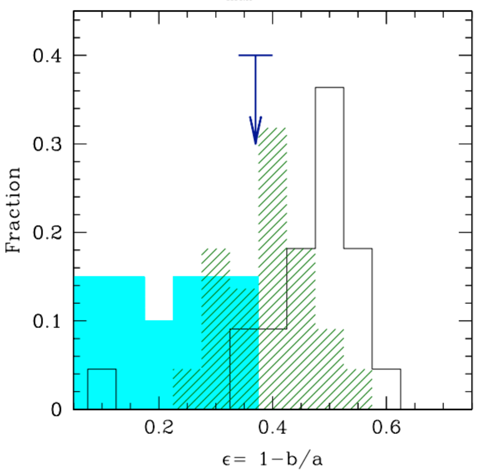
Tulin & Yu 2017, Adhikari+ 2022

Self-Interacting Dark Matter

Limits from a variety of probes imply

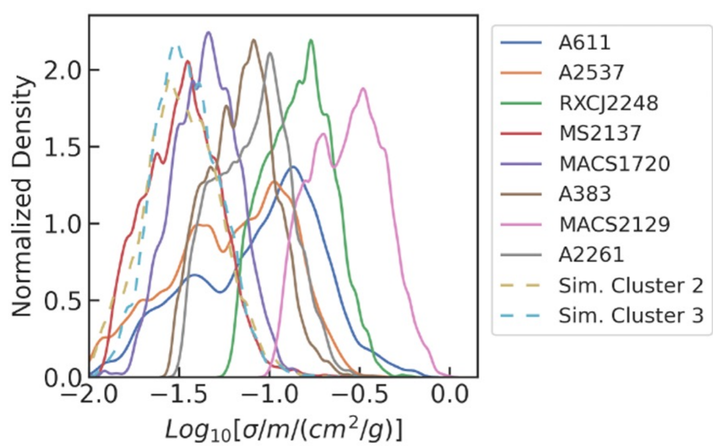
$\sigma/m < 0.1 - 1\ cm^2/g$

Halo ellipticity



Buote, TJ+ 2002,
McDaniel, TJ+ 2021

Cluster central densities

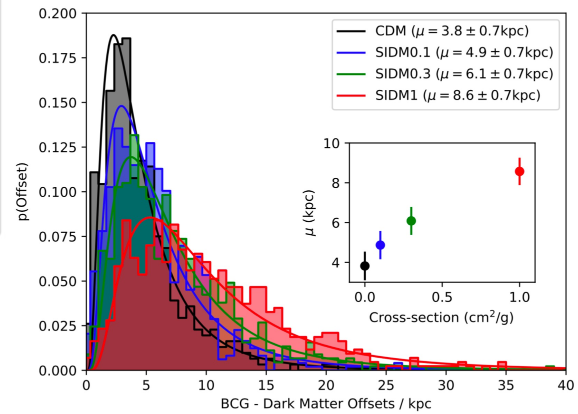


Andrade+ 2022,
Sagunski+2021, Newman+2013

Merging clusters

e.g. Randall+ 2008

BCG oscillations

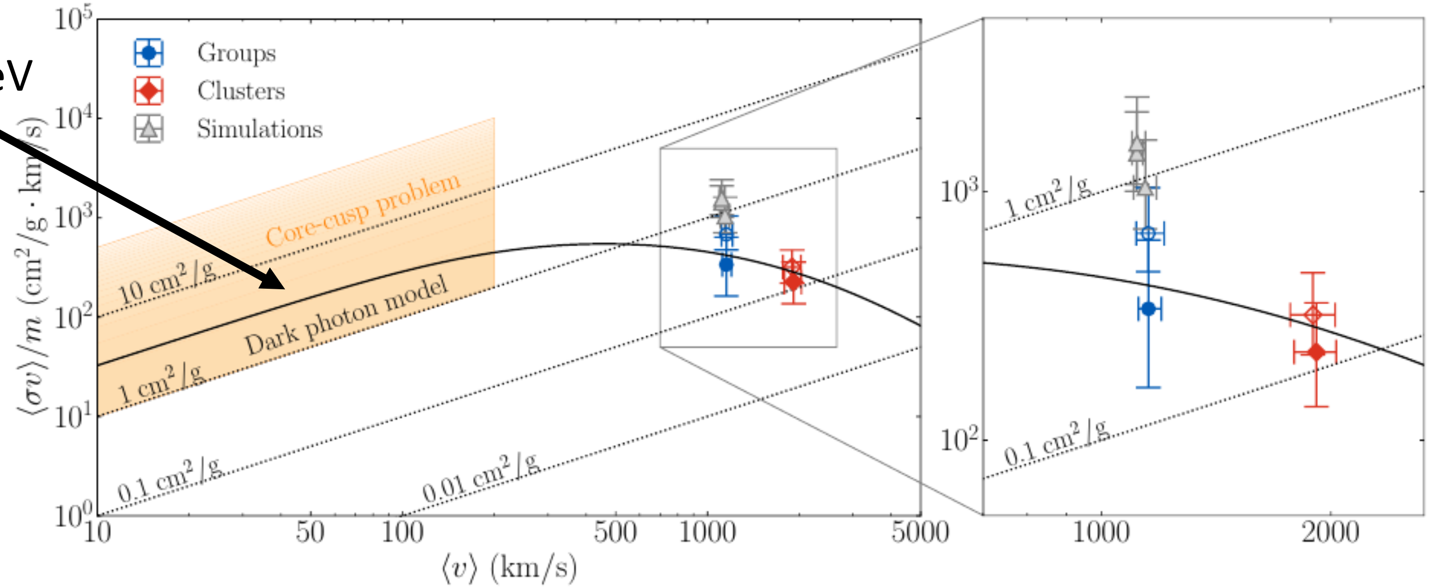


Harvey+ 2019,
Cross, Thoron, TJ+ 2023

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

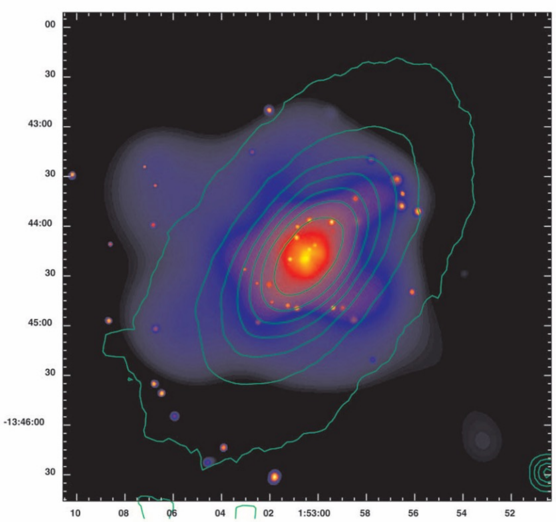


Sagunski+2021

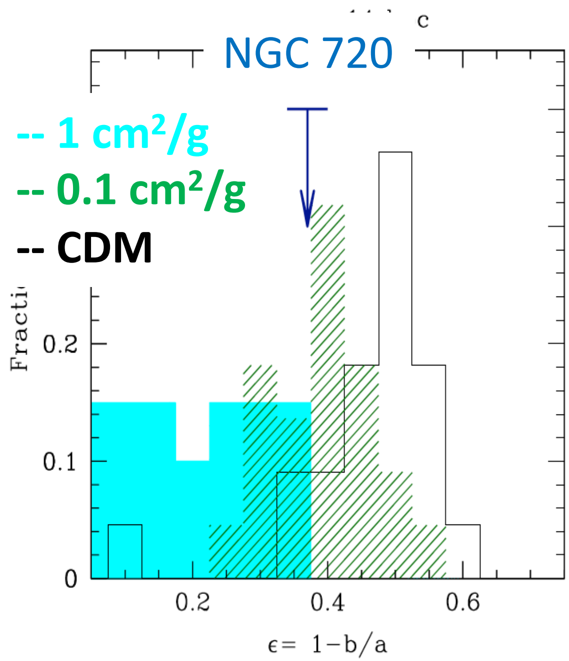
Halo Shapes

- 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 e ~ 0.37 (Buote+2002)

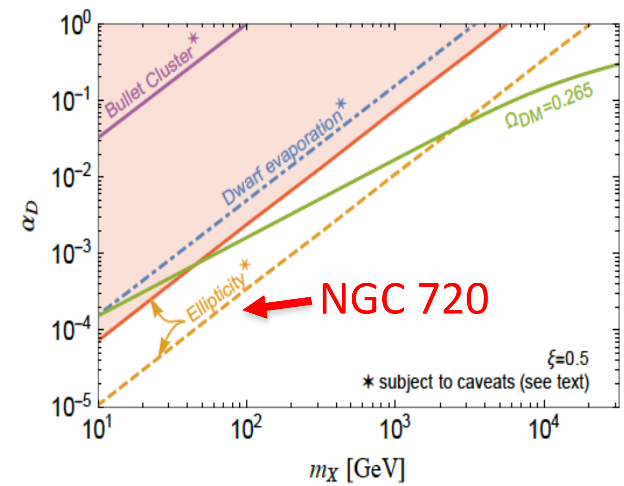
NGC 720



Jeltema+ 2003, Buote+ 2002



Peter et al. 2012



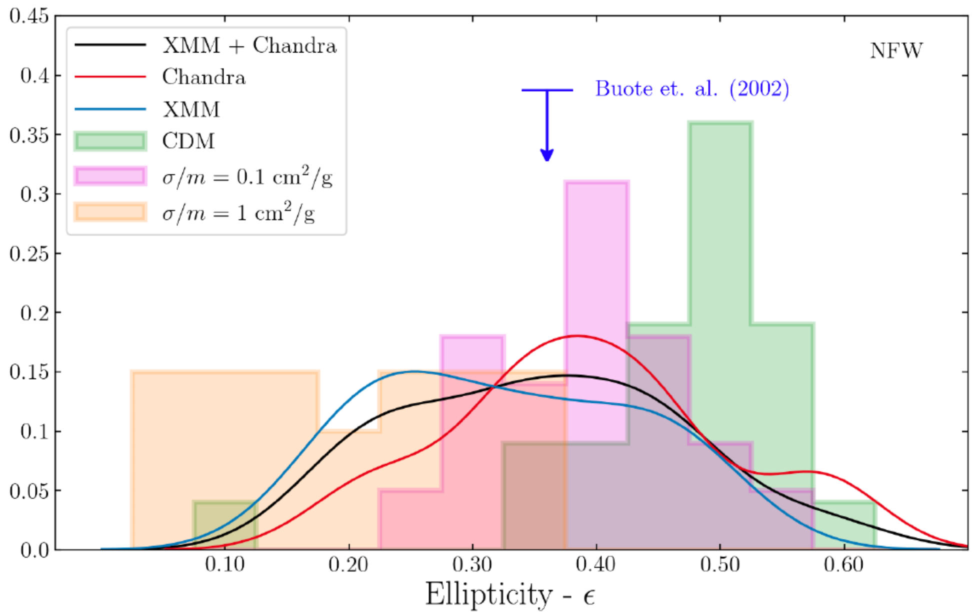
Agrawal et al. 2016

darkly-charged dark matter

Shapes of Isolated Ellipticals

Alex McDaniel

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

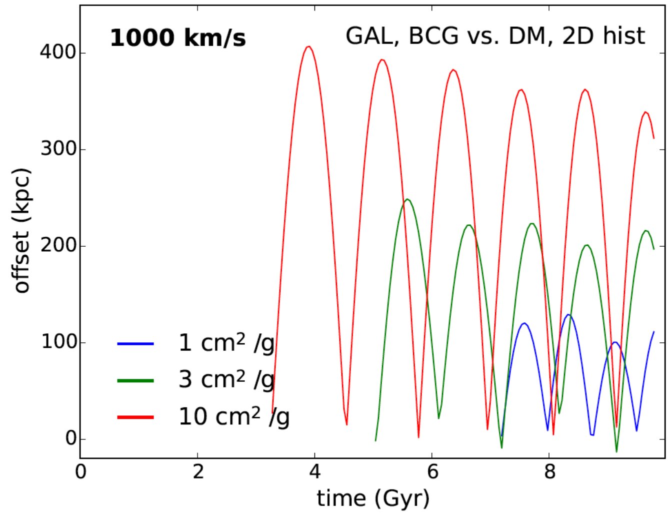


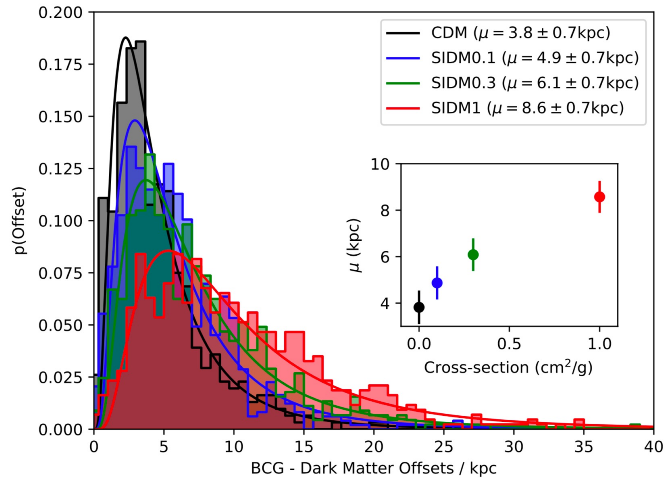
➢ ε = 0.2-0.5 with significant scatter, consistent with mild self-interaction though cannot rule out CDM

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





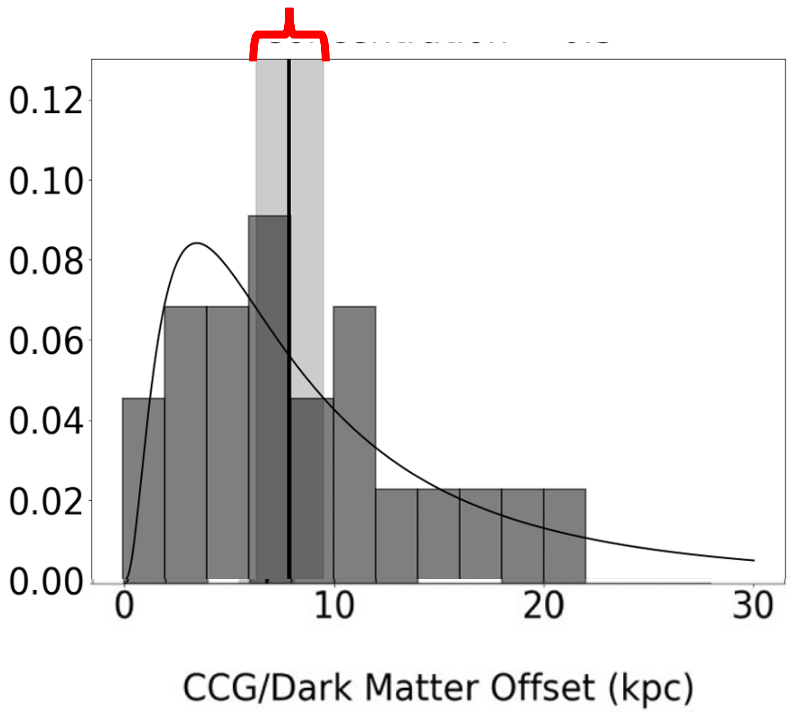
Central Galaxy Offsets

- 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

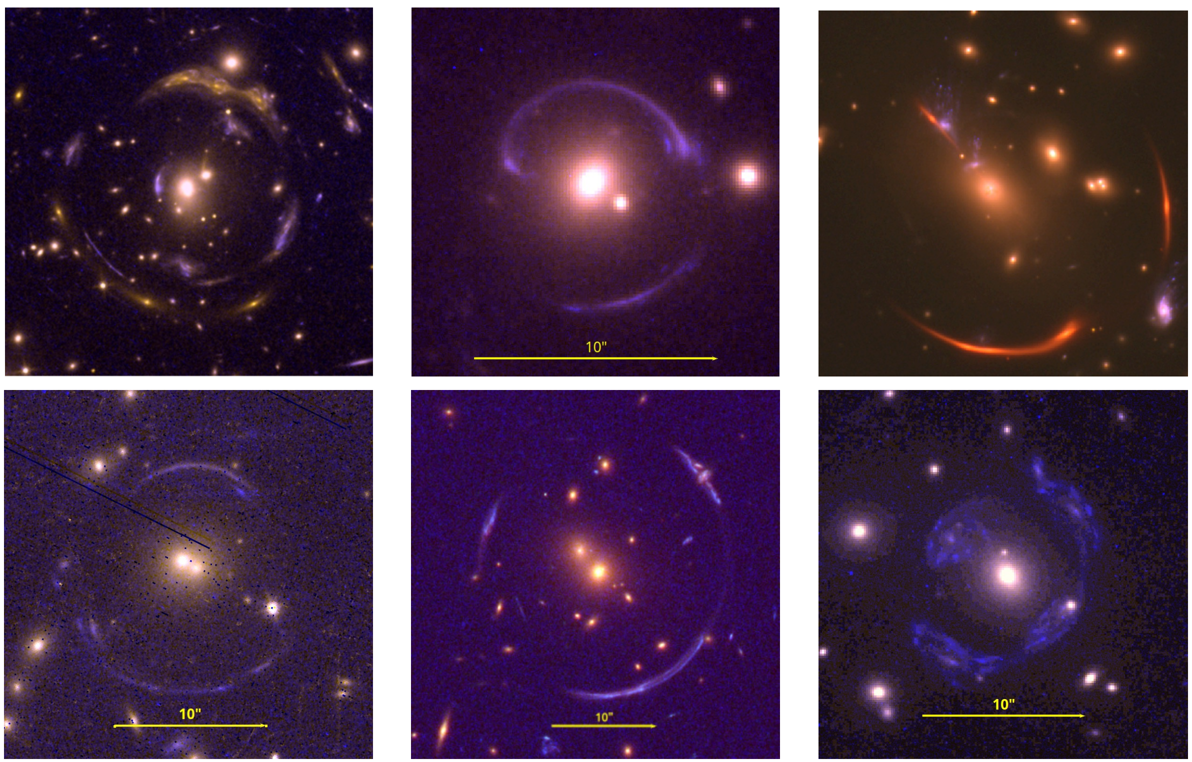
- Consistent with mild self interaction of ~ 1 cm^2/g

Cross, Thoron+ 2023

Cluster Strong Lensing

Jack O'Donnell

- Cluster strong lensing: Cored or cuspy central densities?
- Identified 189 cluster strong lenses in DES Y3 (O'Donnell+ 2022)
- Conducting spectroscopic and X-ray follow up

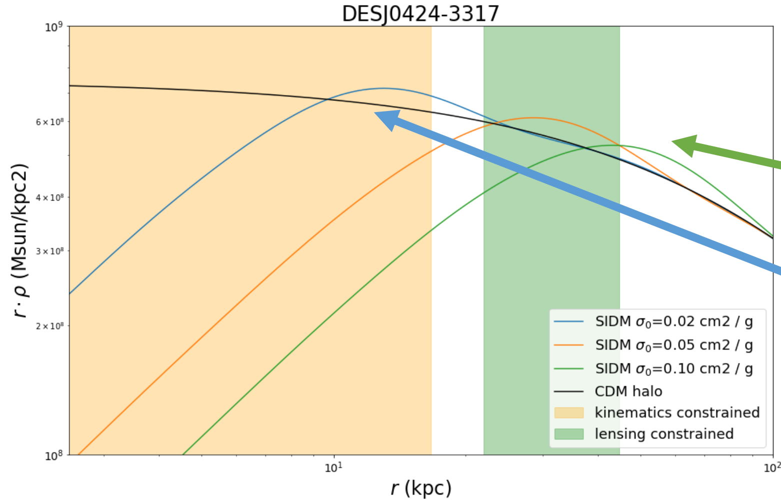


O'Donnell+ 2022

Cluster Inner Density Profile

Jack O'Donnell

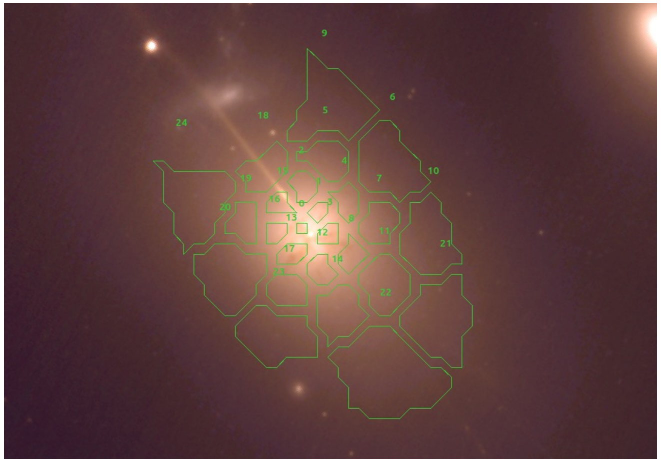
- Measure the inner density profile with resolved kinematics of central galaxy plus strong lensing

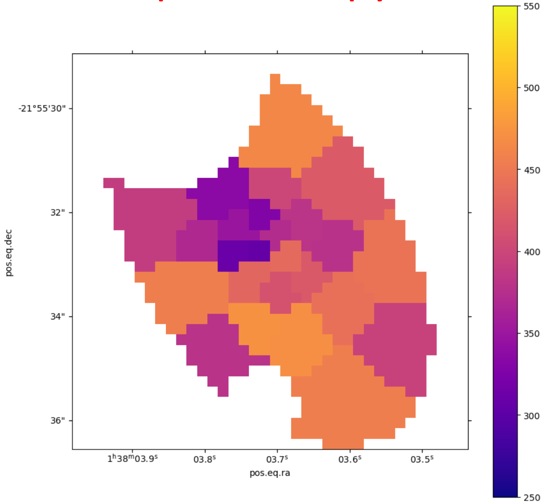


0.1 cm^2/g

0.02 cm^2/g

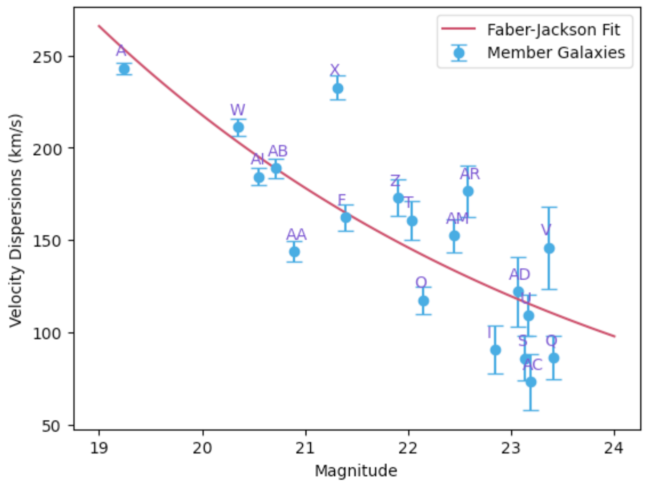
MUSE spatially resolved spectroscopy





- 2D stellar kinematics modeled with Jeans Anisotropic Modelling (JAM) method (Cappellari 2008)

Cluster Inner Density Profile



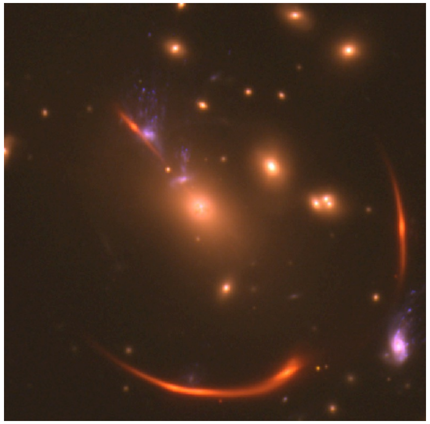
- Including cluster member galaxy masses using MUSE data to measure stellar velocity dispersions and cluster Faber-Jackson relation

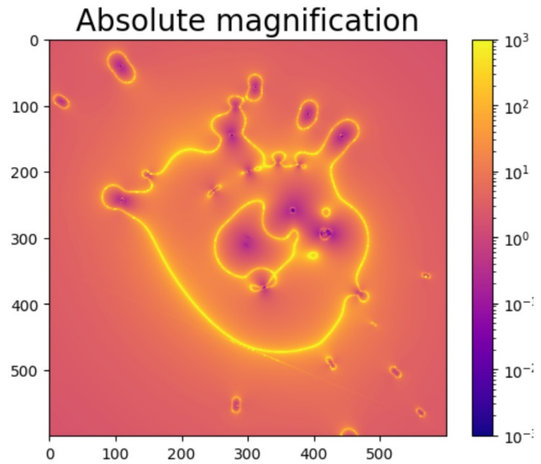
Abigail Flowers

Dhruv Aldas

- Using PyAutoLens (Nightingale+ 2021) edited for cluster strong lens modeling

Example NFW fit:
$M = 10^{15}\ M_{sun}$
$c = 7.3$

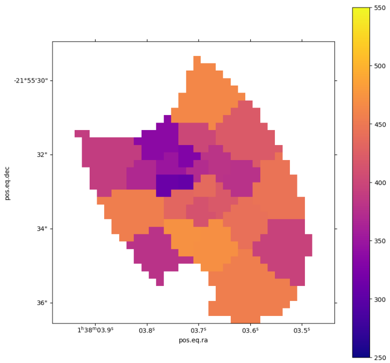




Cluster Inner Density Profile

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

Central and member galaxy dynamics



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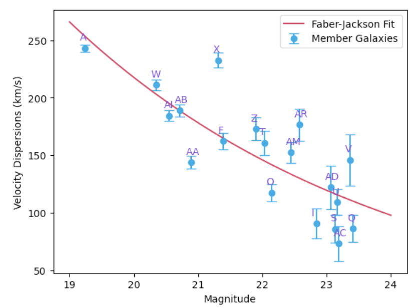

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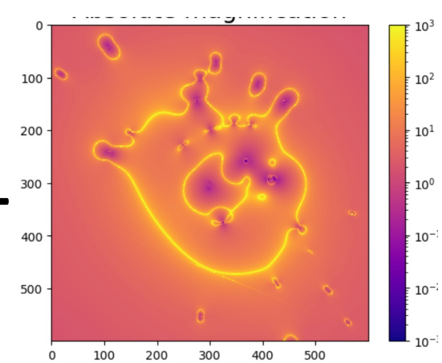
Strong lensing



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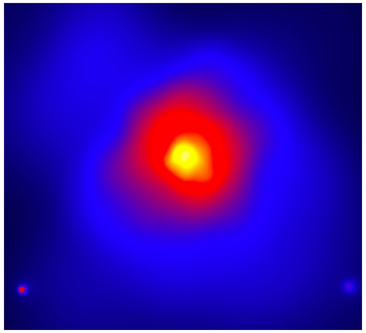
X-ray



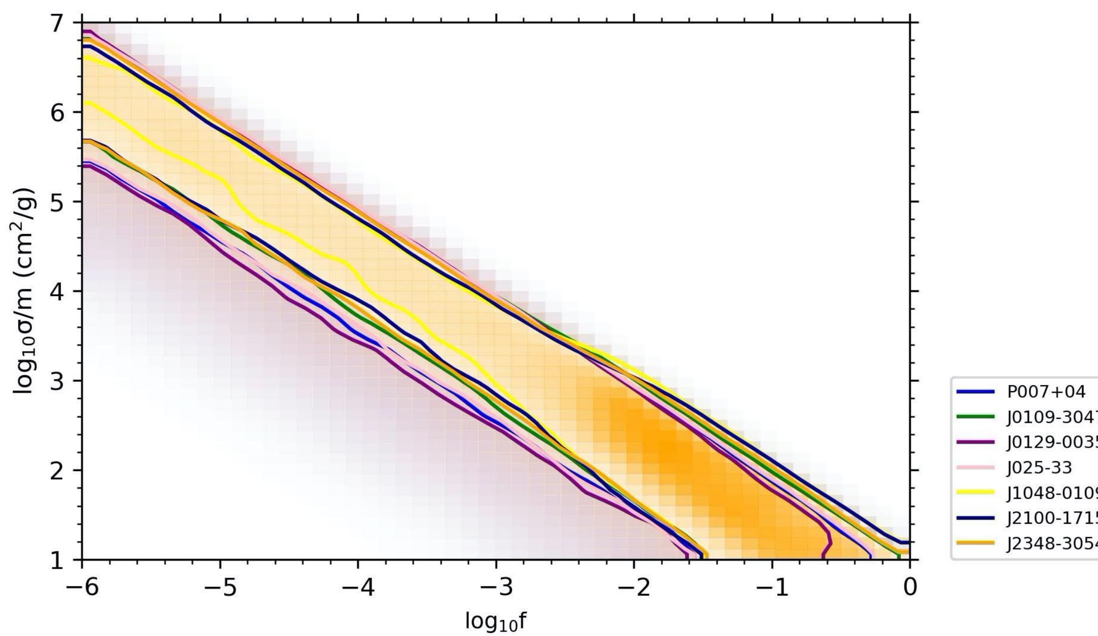
- Will use a fully consistent mass modeling, directly sampling the SIDM parameters and computing the strong lens observables from the predicted density profile plus baryonic components

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



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

- Strong self interaction for a fraction of the dark matter can also help seed supermassive black holes through core collapse


Thank you!