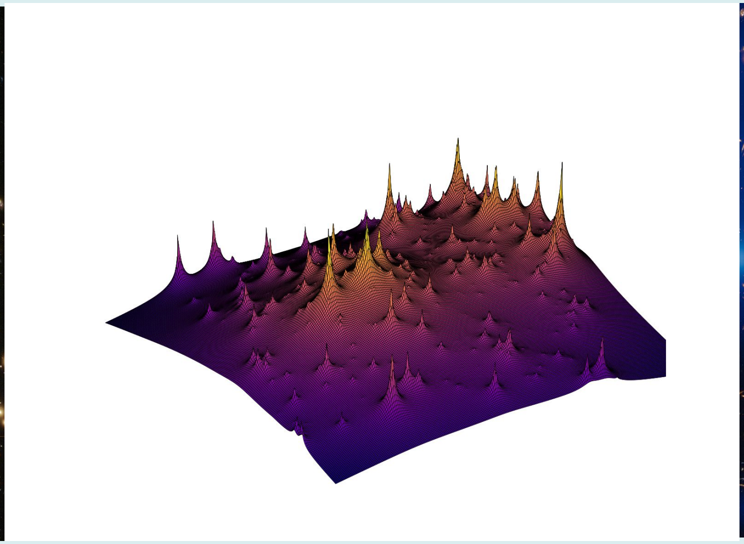
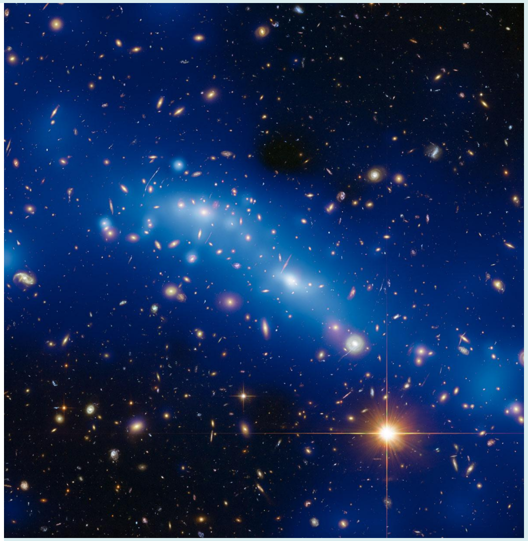
Cluster galaxies as new probes to stress-test the Cold Dark Matter paradigm





Priya Natarajan
Departments of Astronomy & Physics
Yale University

NEW DIRECTIONS IN THEORETICAL PHYSICS 4

Edinburgh, January 2023

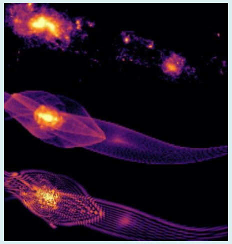
Collaborators

- CATS Jean-Paul Kneib, Johan Richard, Mathilde Jauzac, Hakim Atek, Eric Jullo, Marceau Limousin, Harald Ebeling, Benjamin Clement, Eiichi Egami, Dan Coe, Ana Acerbon,

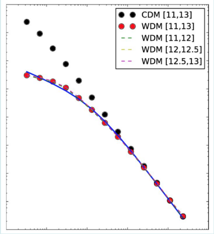
  Anna Niemiec, Giullame Mahler
- ILLUSTRIS Annalisa Pillepich, Volker Springel, Mark Vogelsberger, Lars Hernquist & the Illustris collaboration
- Yarone Takoyer, Urmila Chadayammuri, Anson D'Aloisio & Andrew Davis
- Massimo Meneghetti, Antonio Ragagnin, Guido Davoli, Pietro Bergamini, Piero Rosati, Carlo G Gabriel Caminha, Ben Metcalf, Elena Rasia, Ste Borgani, Francesco Calura, Claudio Grillo, Ama Mercurio, Eros Vanzella

TALK OUTLINE

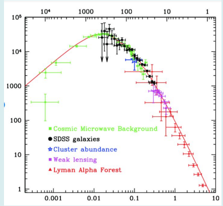
Cluster-lenses as astrophysical laboratories for testing LCDM



Substructure tests of the nature of DM on small-scales in clusters and galaxies



LCDM Predictions & Current Tensions: abundance of subhalos, radial distribution of subhalos, and internal properties of subhalos



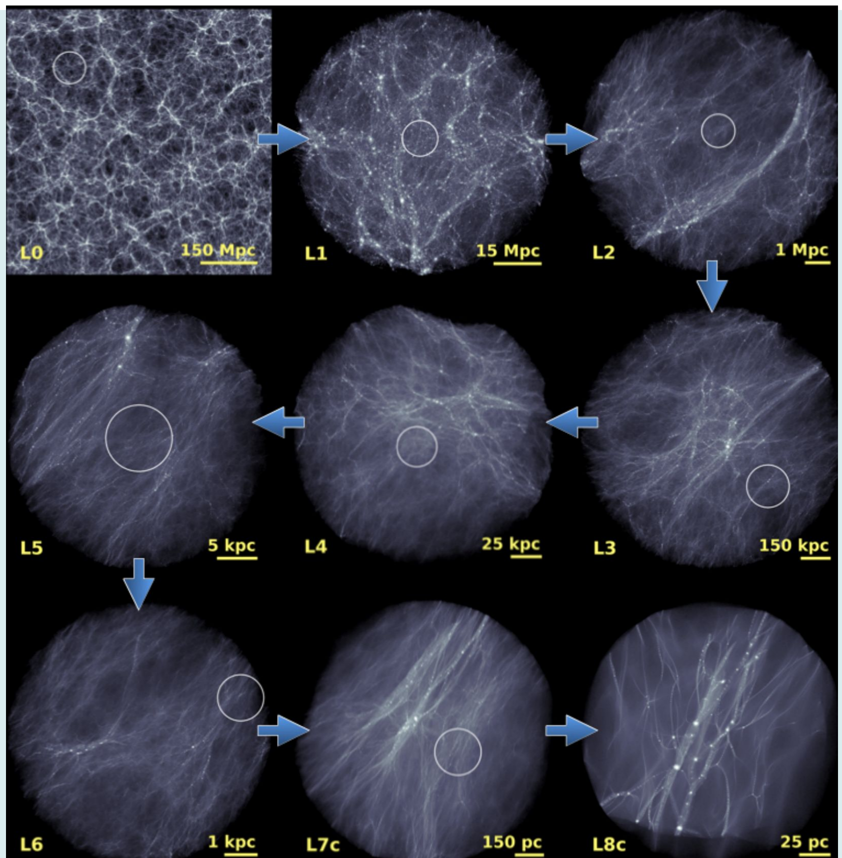
New metrics to probe small-scales: GGSL, Power spectrum analysis

The LCDM paradigm

Particle Physics

Direct detection Experiments

WIMPS
Axions



Astrophysics

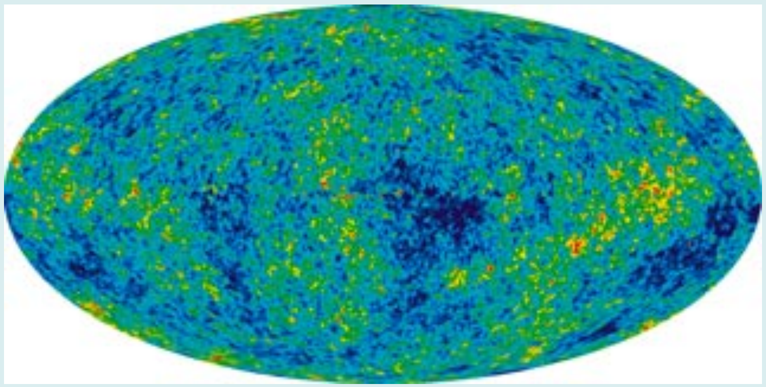
Simulations
as no controlled experiments possible

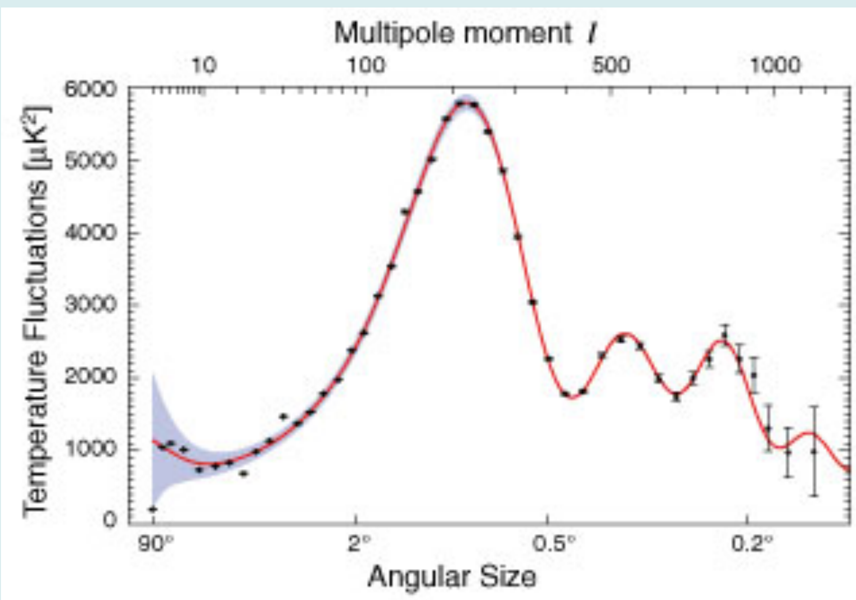
Ample evidence for collision-less (cold) DM

Peebles, Yahil & Ostriker; Blumenthal, Faber, Primack, Rees+; Navarro,

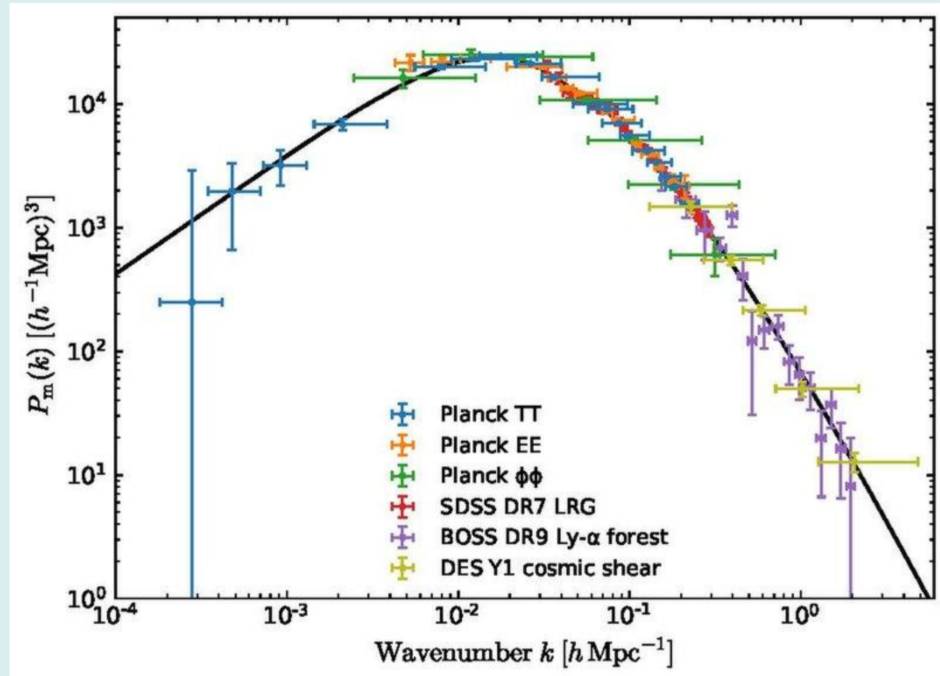
LCDM remarkably successful on large scales > 1 Mpc

CMB, LSS, Galaxy Evolution





WMAP 7-yr data



Linear matter power spectrum
of cold dark matter
multiple independent observational
probes across scales

WAVES OF CRISES IN CDM

MISSING SATELLITE PROBLEM (abundance)

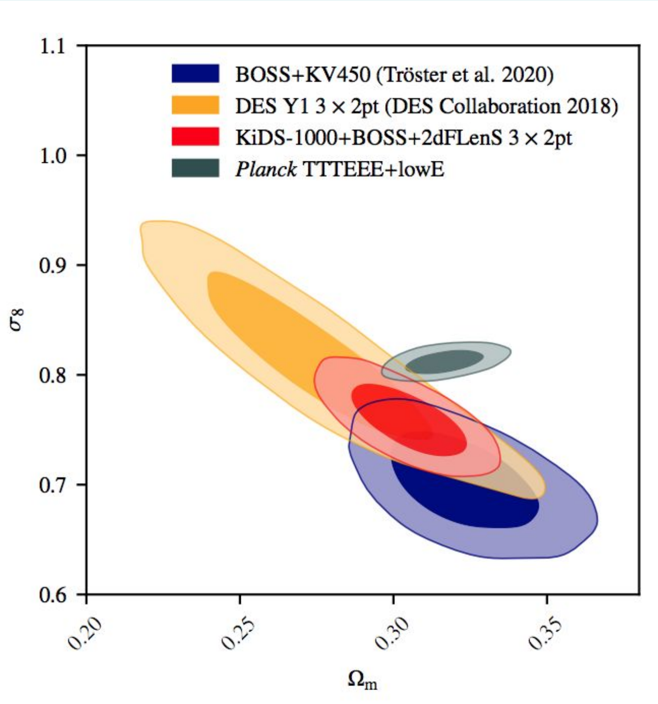
CUSP-CORE PROBLEM (internal structure)

TOO-BIG-TO-FAIL PROBLEM

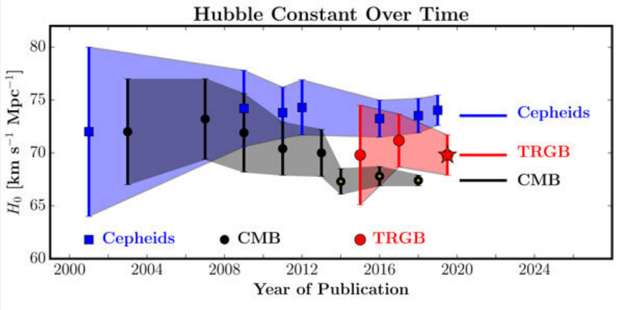
SATELLITE PLANES

CHALLENGE OF BARYONIC TULLY-FISHER

For details see recent reviews:
Bullock & Boylan-Kolchin (2017)
Popolo & Le Delliou (2017)



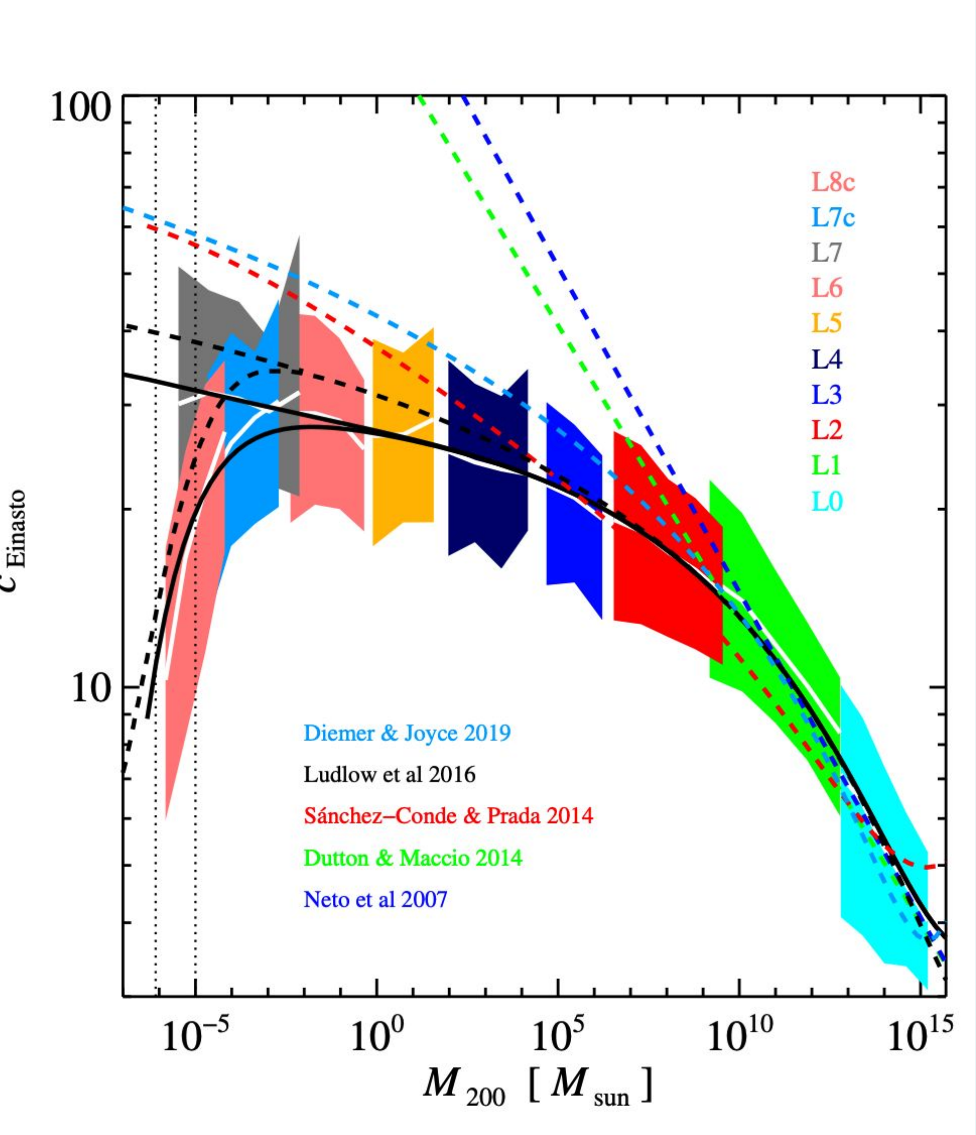
Maybe more fundamental issues, too?

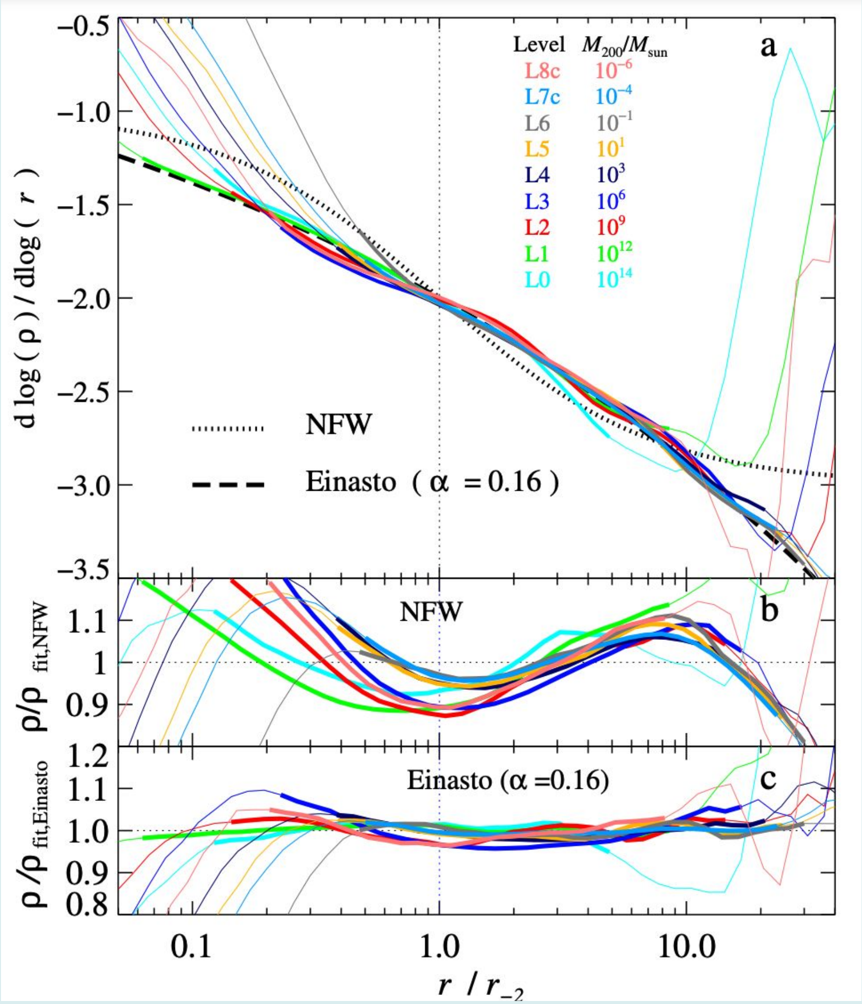


A Crisis in Cosmology – Measurements of Hubble Constant Disagree

Testable CDM predictions

abundance, radial distribution, and internal structure of halos





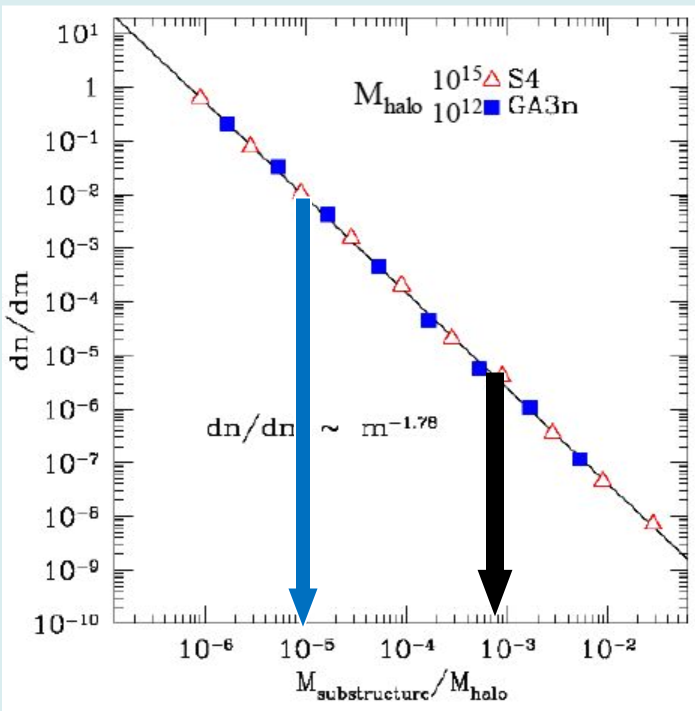
Universal Density Profile
over 20 orders of

Mapping DM substructure on small-scales

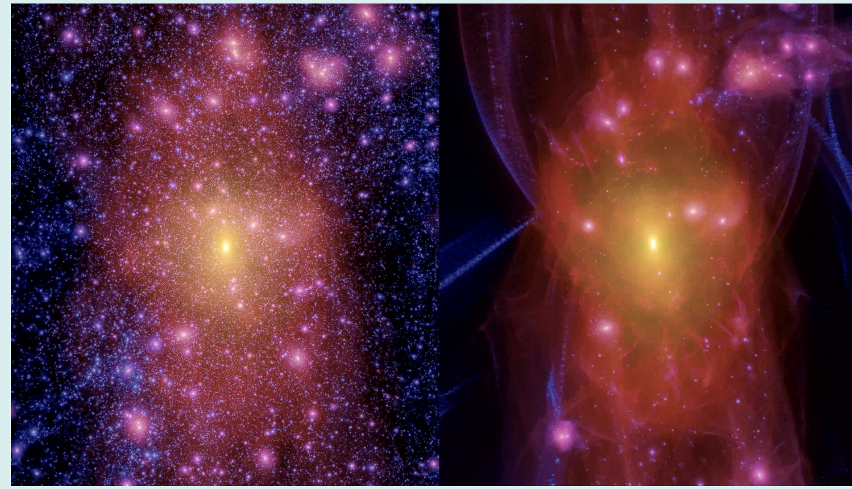
Abundance & Properties

SHMF: concrete LCDM Prediction

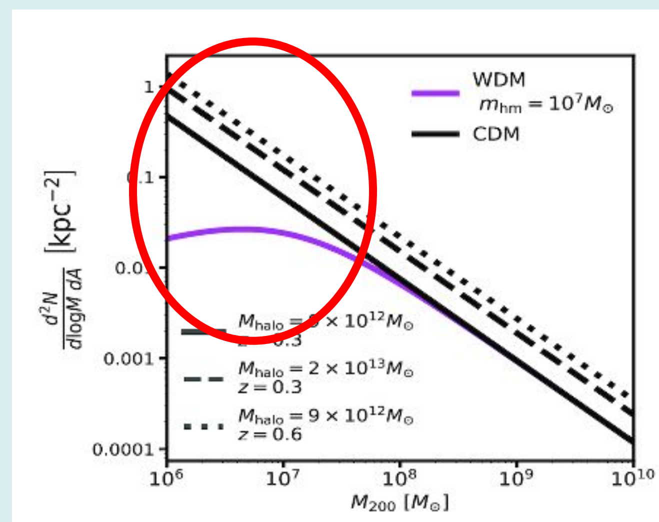
$$\frac{dn}{dm} \propto m^{-1.8}$$



Very weak dependence on halo mass in LCDM

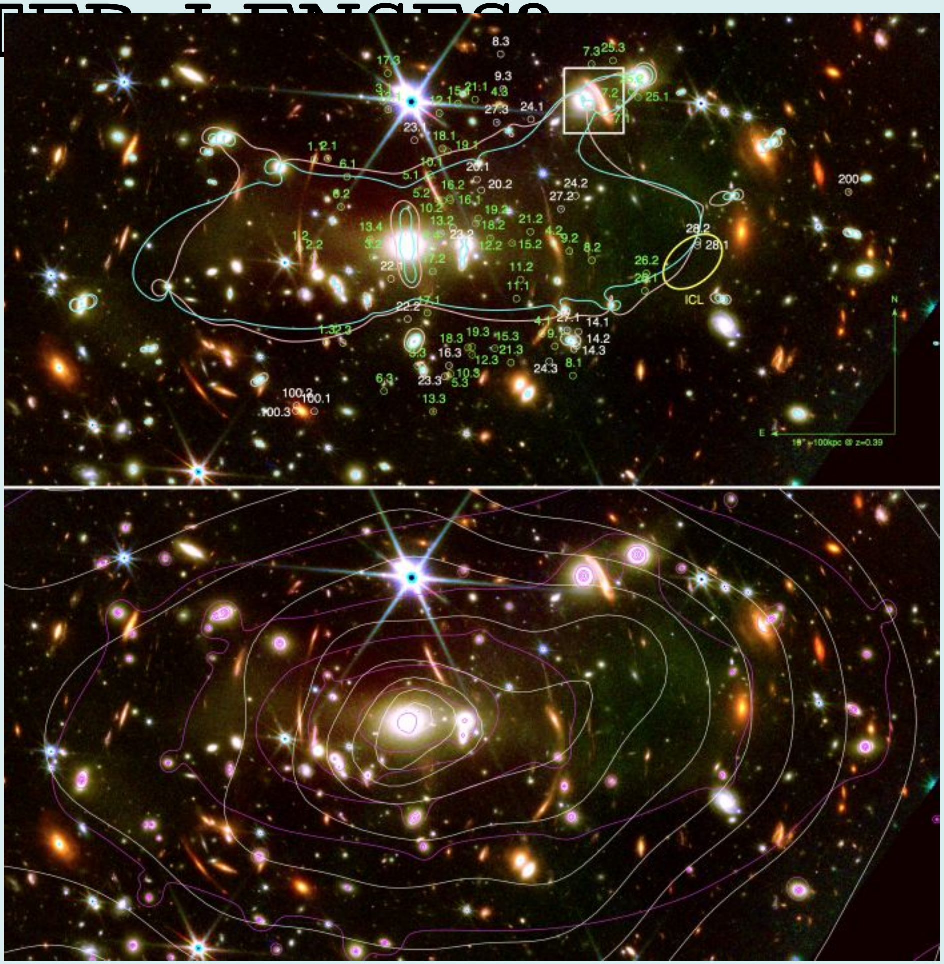


Strong dependence on the nature of DM



PN & Springel 2004; PN, de Lucia & Springel 2007; Gao & Theuns 2007; Gilman+19; Dvorkin+ 19; Des

WHY CLUSTERS? & WHY CLUSTER LENSES?



JWST image of SMACS0723 Model

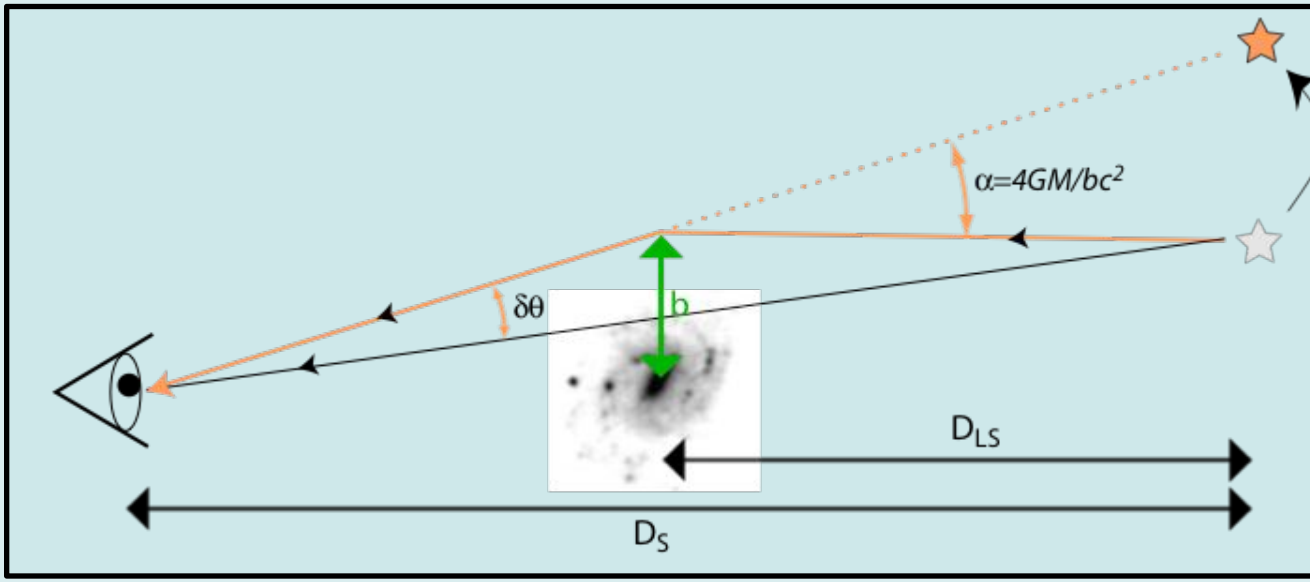
21SL image systems of 17 are new!

Composition

~1 % of mass is in galaxies; ~10 % of mass is hot gas; the rest is DM

Mahler+; Geller+; Ellis+; Rines+; Postman+ CLASH; Treu+; Starikova+; Lotz+ HFF; Newman+; Smail+; Kneib+; Sand+; Bradac+; Williams+; de Lucia+; Hennawi+; Gladders+; Oguri+; Broadhurst+; Jauzac+ BUFFALO; Richard+; Hoekstra+; Coe+ RELICS

Cluster-lenses as astrophysical & cosmological probes



$$\delta\theta = \frac{4GM}{bc^2} \; \frac{D_{LS}}{D_S}$$

We observe this deflection angle (more precisely, gradients of the deflection angle).

Cosmology changes growth rate of mass structures in the Universe.

Cosmology changes the geometric distance factors.

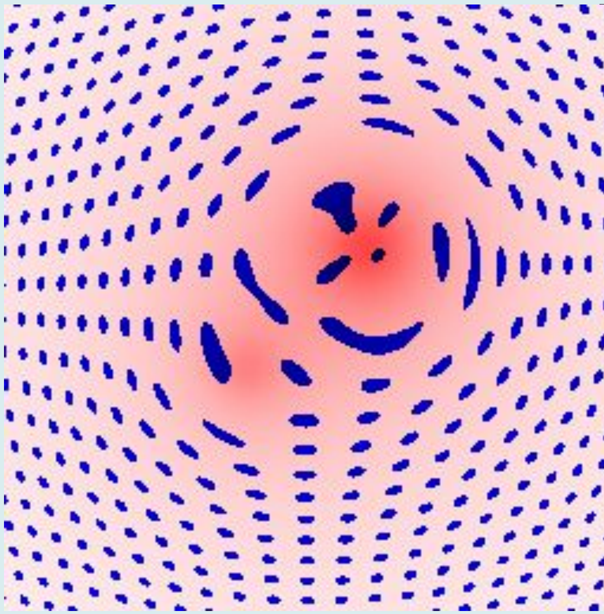
Map DM via properties of the lenses, study lensed high-z sources and constrain DE via cosmography

Blandford & Narayan 92; Schneider Ehlers & Falco 92; Bartelmann & Narayan 97; Kneib &

Strong lensing

number counmultiple images, highly distorted and magnified arcs, depletion of background sources

- Projected surface mass density within the beam $\Sigma(r) > \Sigma_{crit}$
- Mass enclosed within the arc is tightly constrained



Weak lensing

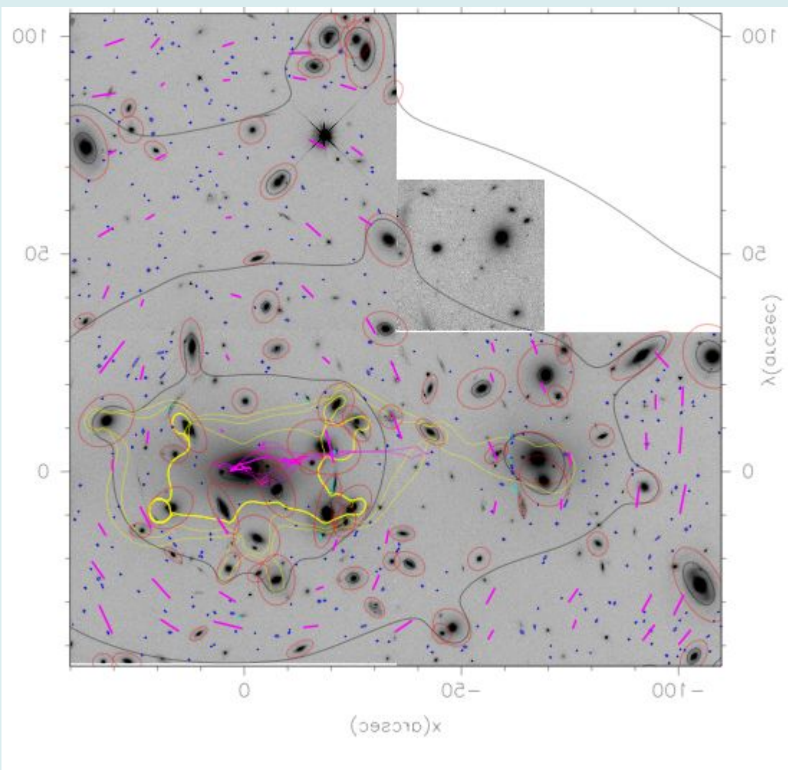
coherent distortion in the shapes of background galaxies

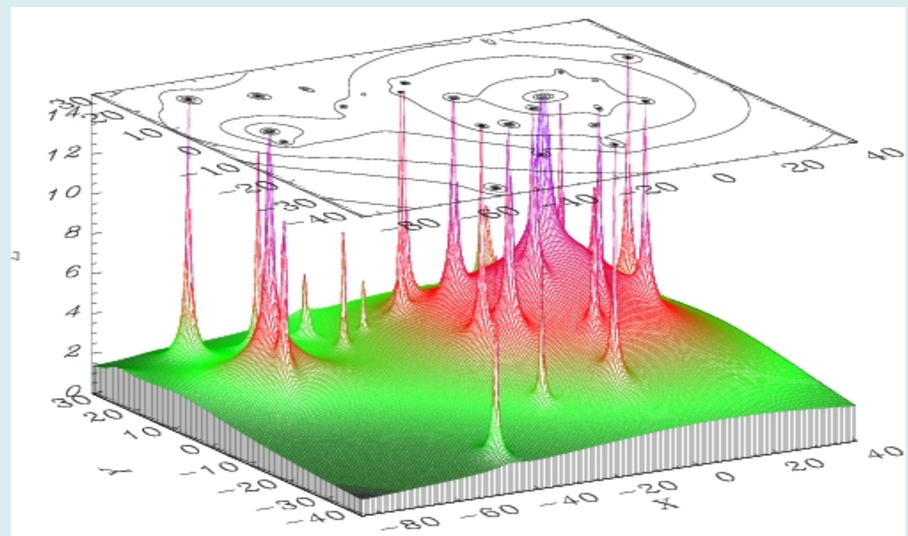
- Shear field used to construct mass map

Kaiser & Squires 93
Smail & Ellis 94, 95,

MAPPING SUBSTRUCTURE IN CLUSTERS

$$\Phi_{cluster} = \sum_i \Phi_{smooth} + \sum_n \Phi_{perturbers}$$





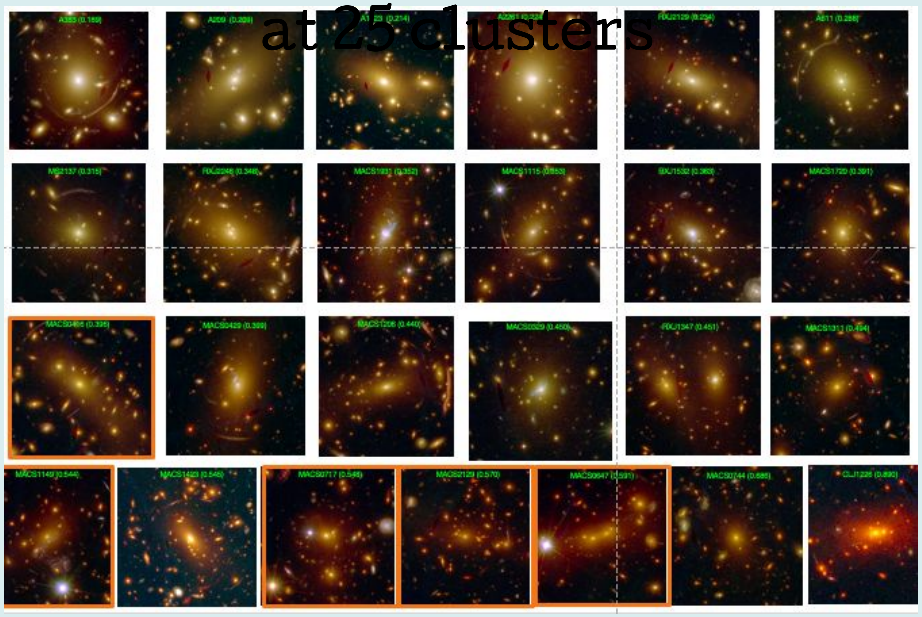
PN & Kneib 1997; PN+ 2005; 2009; 2011

HST Frontier Fields

840 HST orbits deep look at 6 clusters

The CLASH Program

524 HST orbits shallow look at 25 clusters



Ongoing programs:

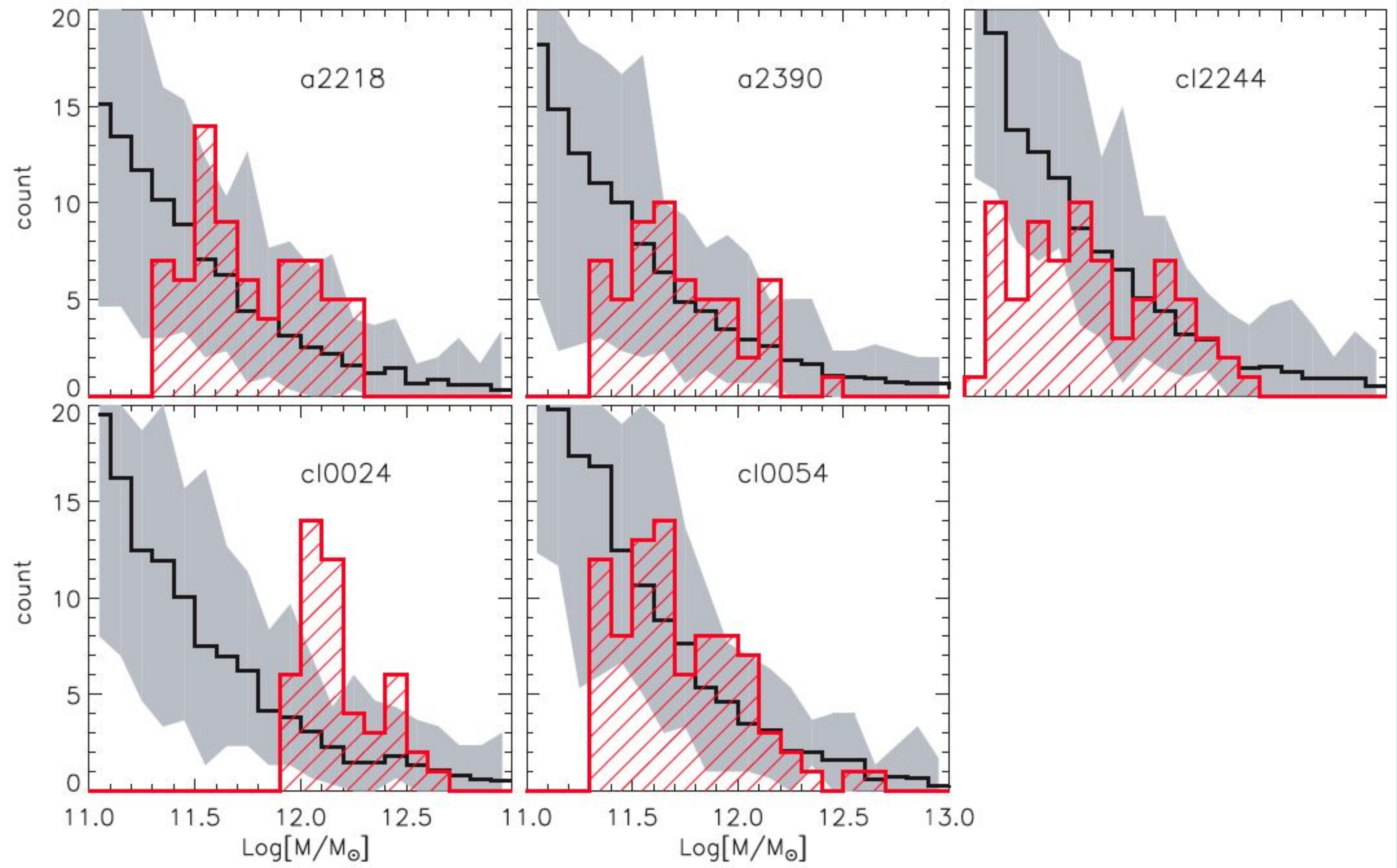
BUFFALO (Jauzac, Steinhardt+)
RELICS (Coe+)

Lotz+

Postman+

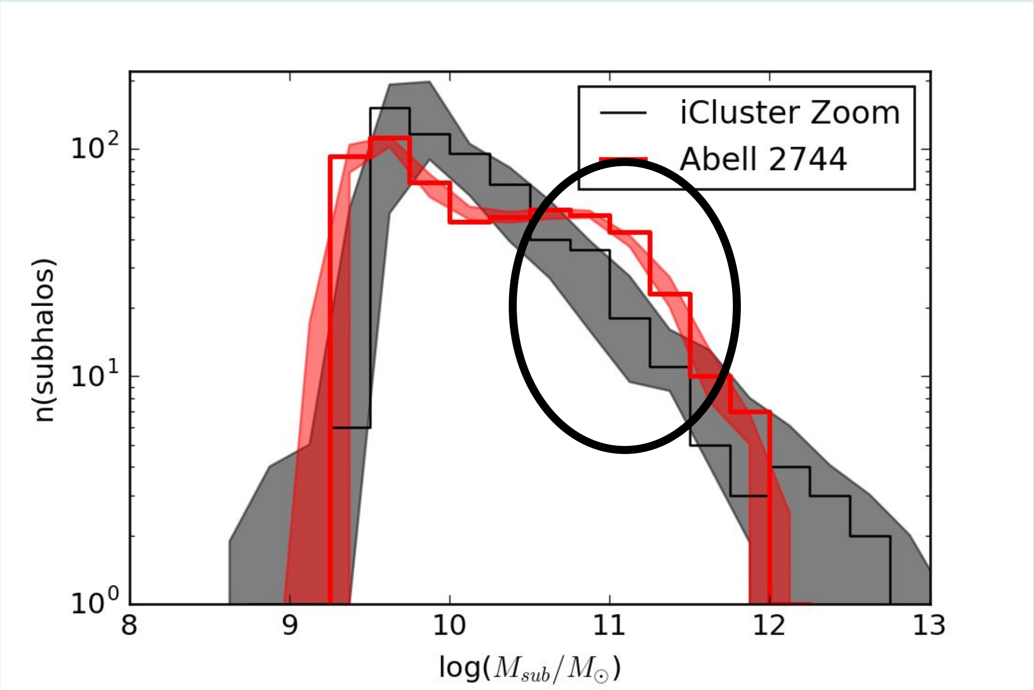
Abundance of substructure: the subhalo mass function

Comparison with LCDM clusters in the Millenium Simulation



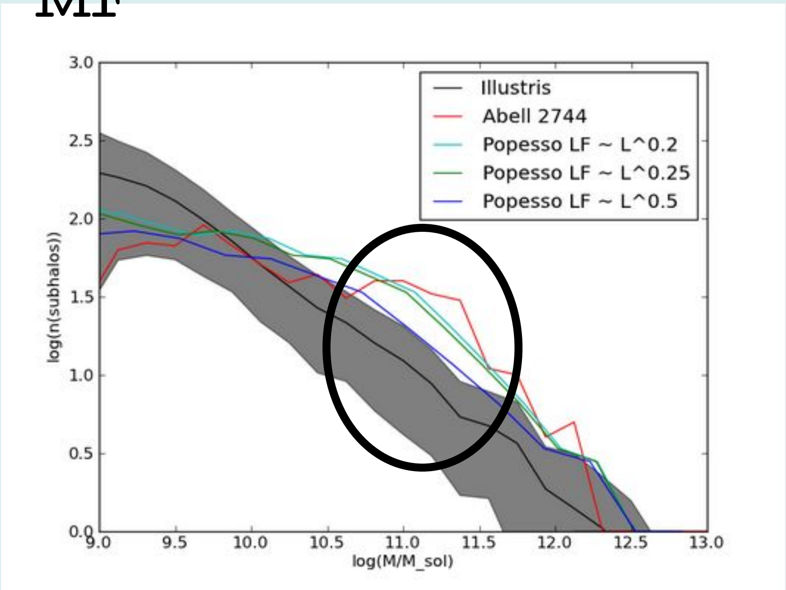
PN & Springel+ 05; PN, De Lucia & Springel 07; PN+ 09, 12, 17

Abdundance of subhalos
Comparison of HFF with Illustris LCDM clusters



(See talk by C. Cerny)

Converting the measured LF MF



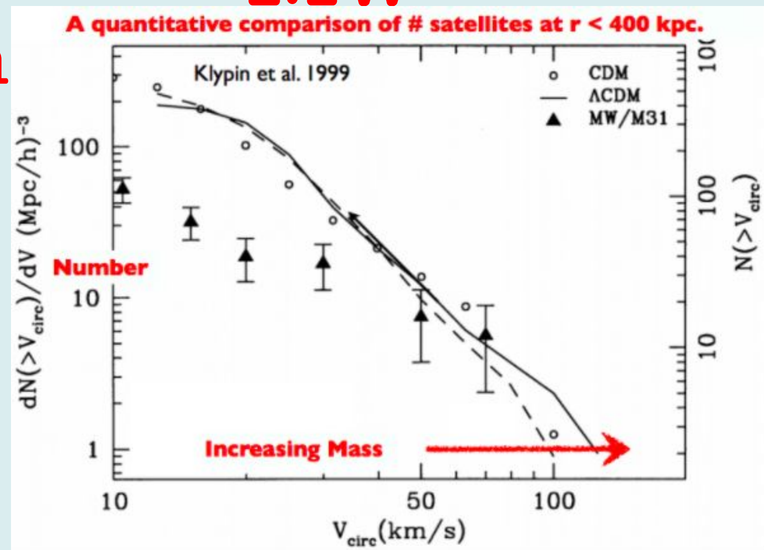
High-precision lens model
ACS+WFC-3 113 lensed images
2 large scale halos+ 563 galaxy-scale halos
M(r=200 kpc) = 2.1 x 10^{14} Msun

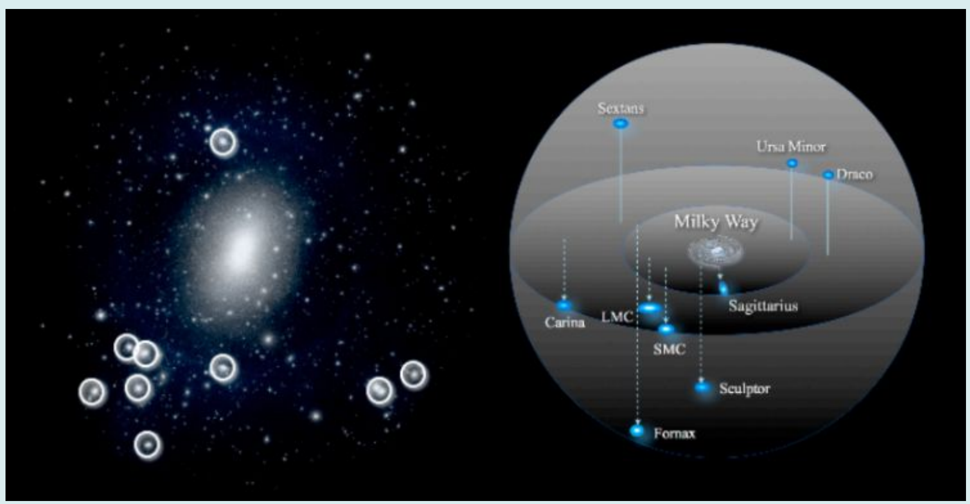
The subhalo mass function

PN+ 17; Jauzac+ 15; 16; Popesso+13; 14

Abundance of sub-halos: MW

the m em



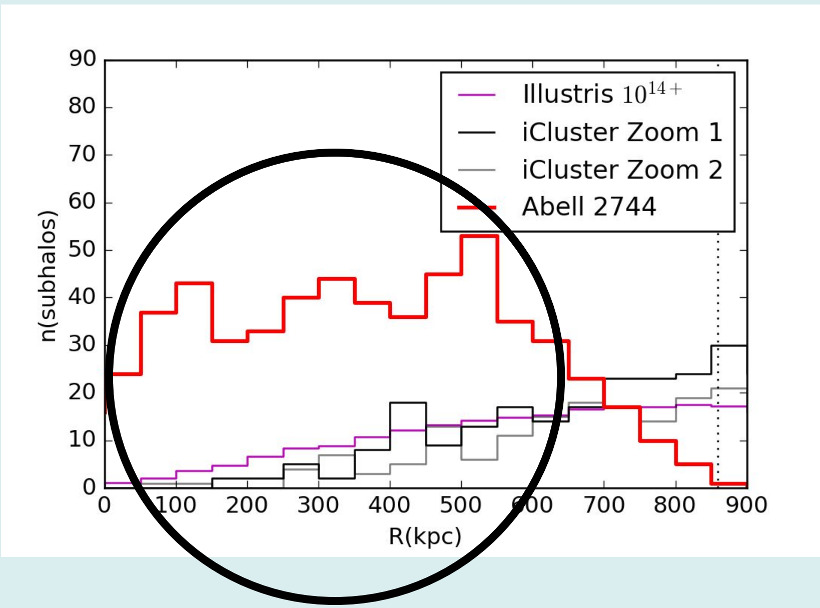


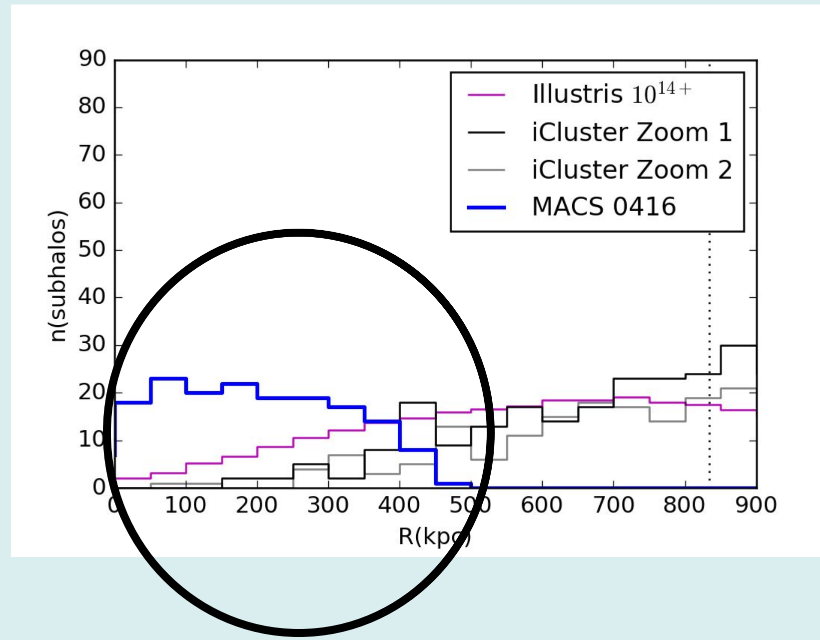
Abundance mis-match resolved when fainter satellites detected,

Moore+; Klypin+;

Radial distribution of sub-halos

Comparison with of HFF cluster lenses with Illustris LCDM clusters



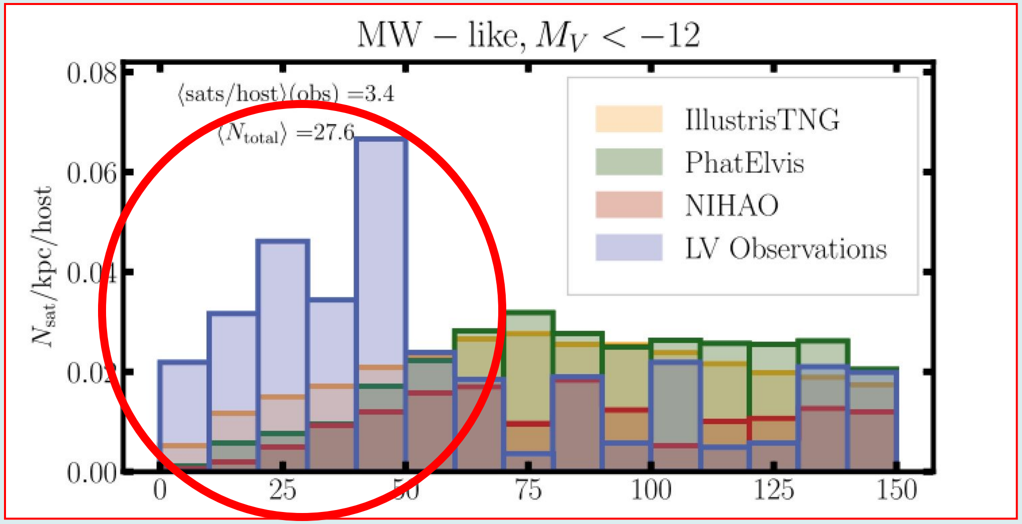


subhalos hosting observed cluster member galaxies
bright, early-type are over-abundant closer to the center
$R < 300$ kpc $[0.15\ R_{vir}]$

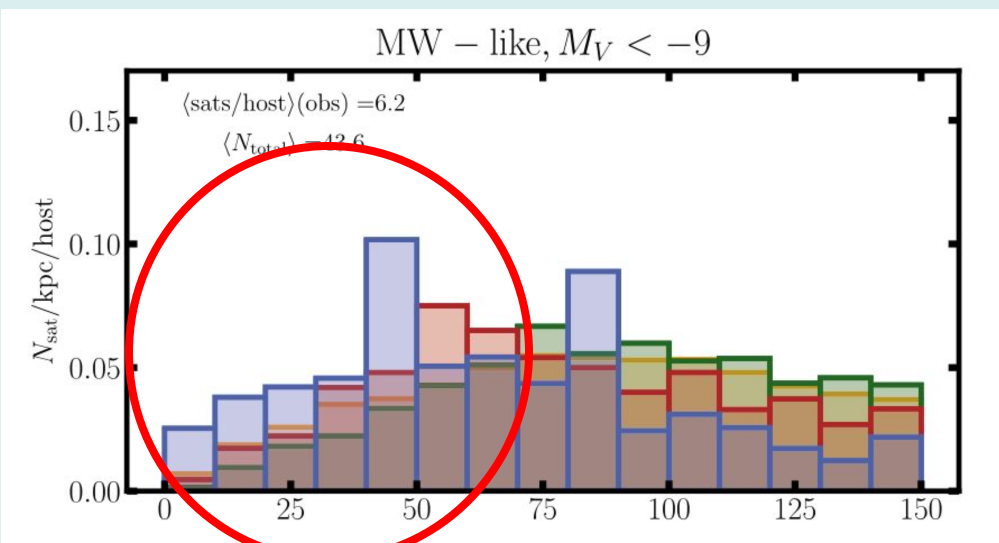
PN+

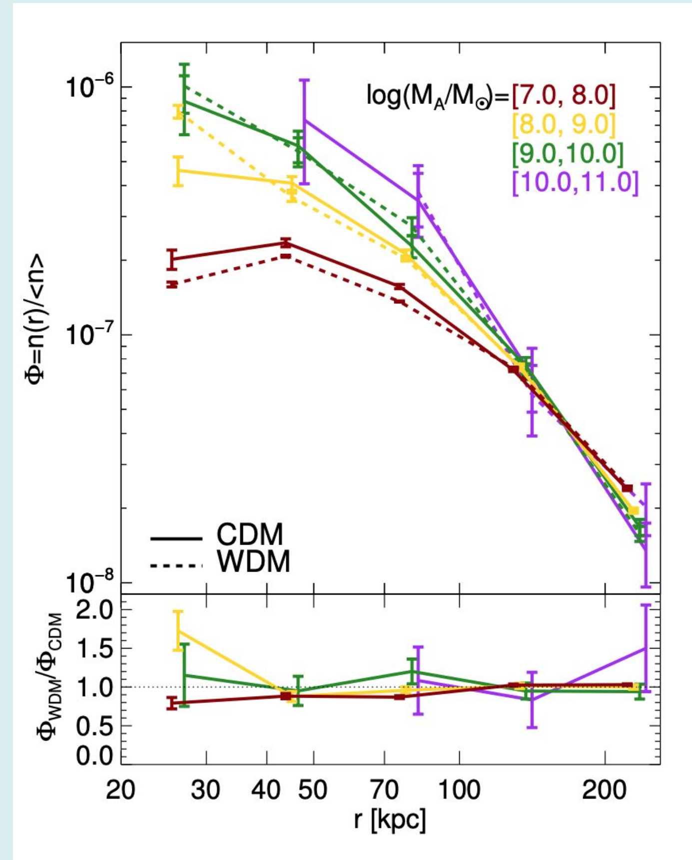
Radial distribution of sub-halos

On galaxy scales



Survey in LV of 12-MW like hosts



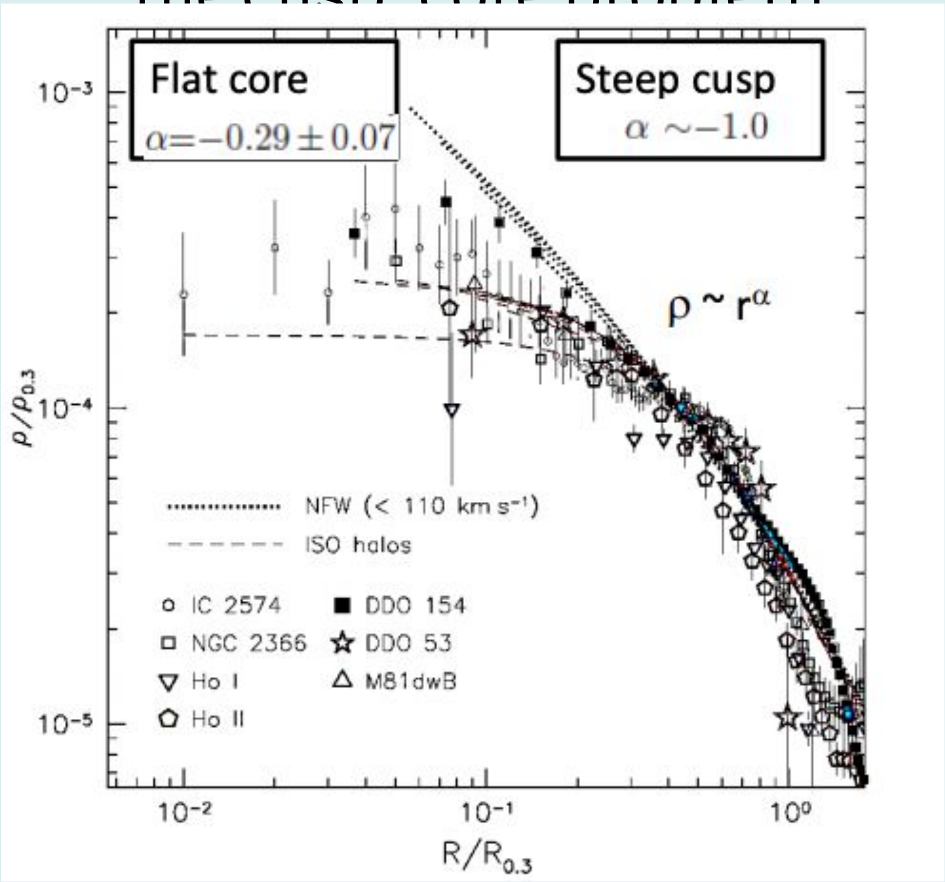


CDM WDM predictions

Carlsten+ 20;

Trouble on small scales in CDM: internal structure halos

the cusp-core problem



GALAXY SCALES
HI measurements
THINGS survey

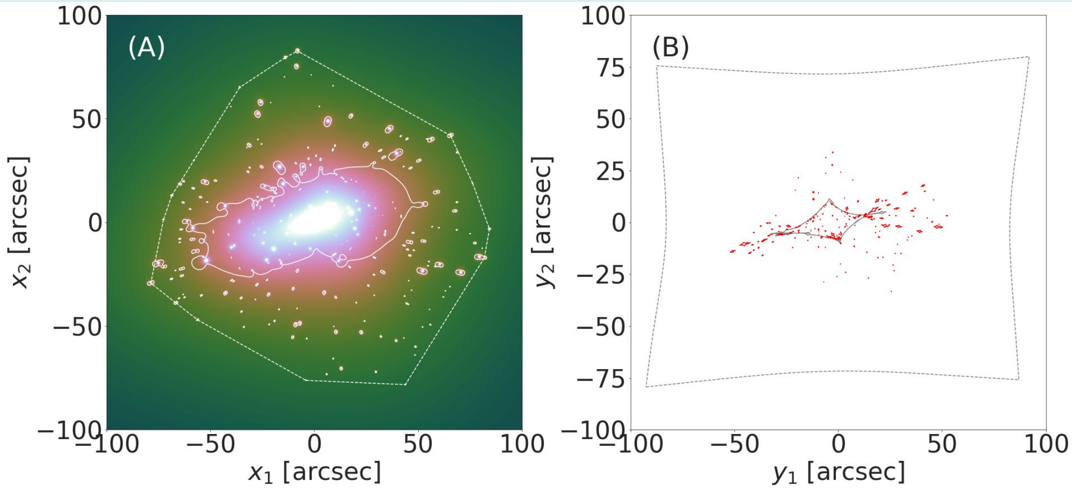
Emerges on sub-kpc scales where resolution of simulations is limited

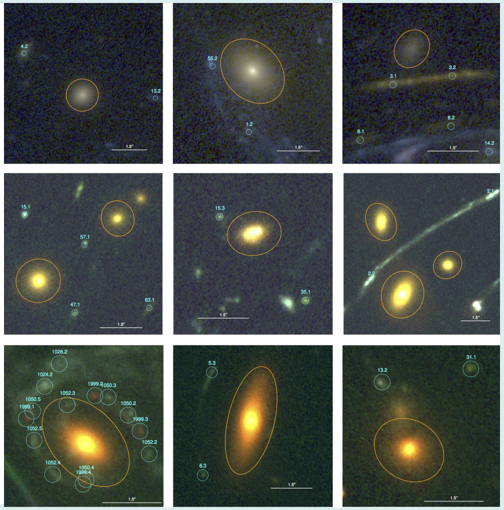
Centers of galaxies complicated by feedback, SF, BH activity

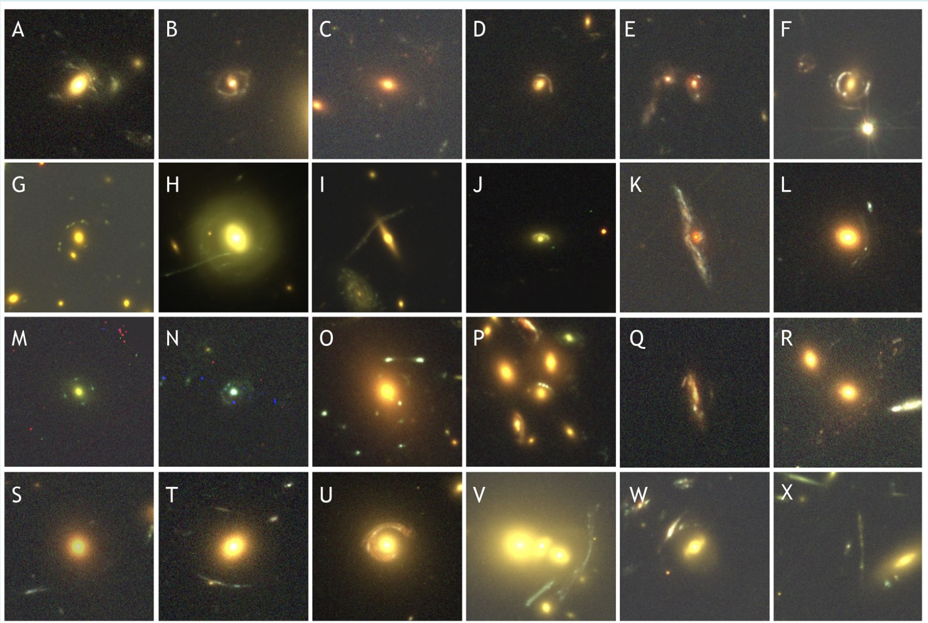
ALTERNATIVE DM MODEL: SIDM proposed

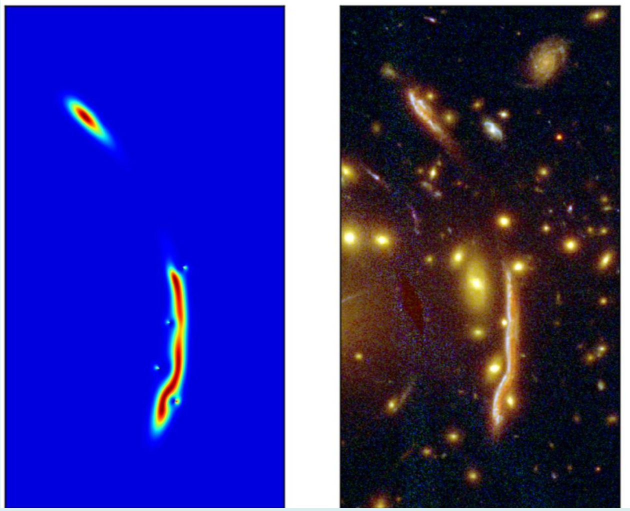
Internal structure of sub-halos

GGSL, concentration









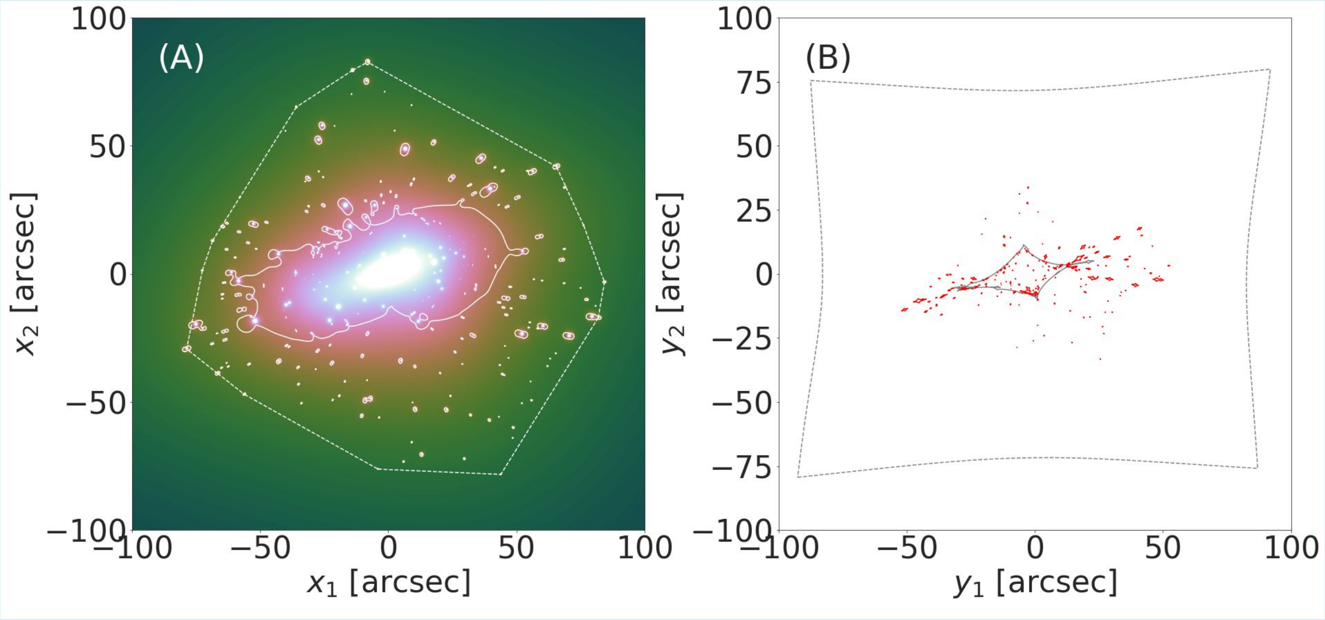
Internal structure of sub-halos

Measuring strong lensing cross-sections and probabilities inside cluster-lenses

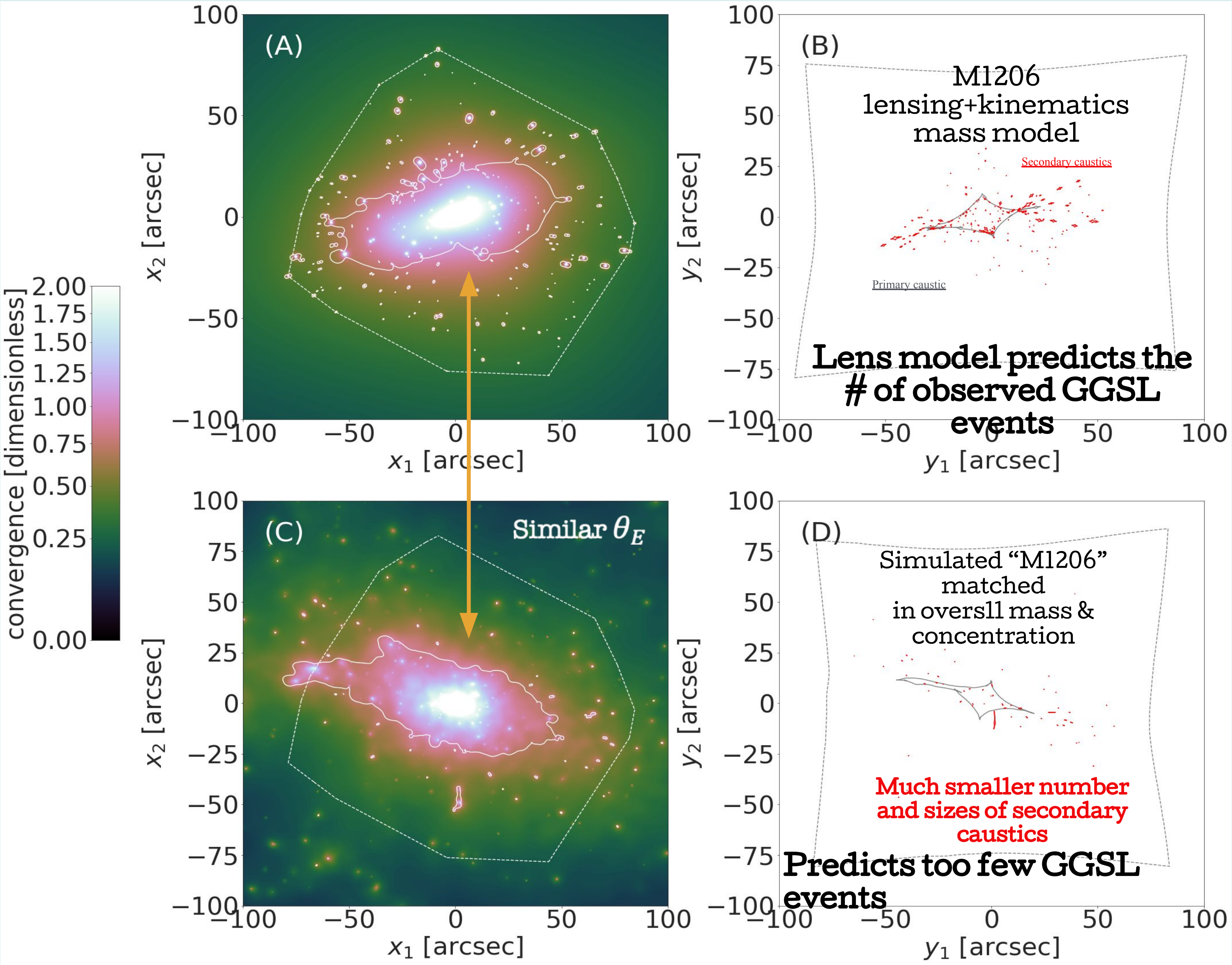
Identify secondary critical lines; Map critical lines into caustics; Measure area enclosed by caustics; Obtain GGSL cross-section by summing up areas

$$P_{\rm GGSL}(z_S) = \frac{\sum_i \sigma_i(z_S)}{A_s(z_S)}$$

$$N_{\rm GGSL} = \int_{S_{lim}}^{\infty} \int_{z_L}^{\infty} n(S, z_S)\sigma_{GGSL}(z_S) dz_S dS$$



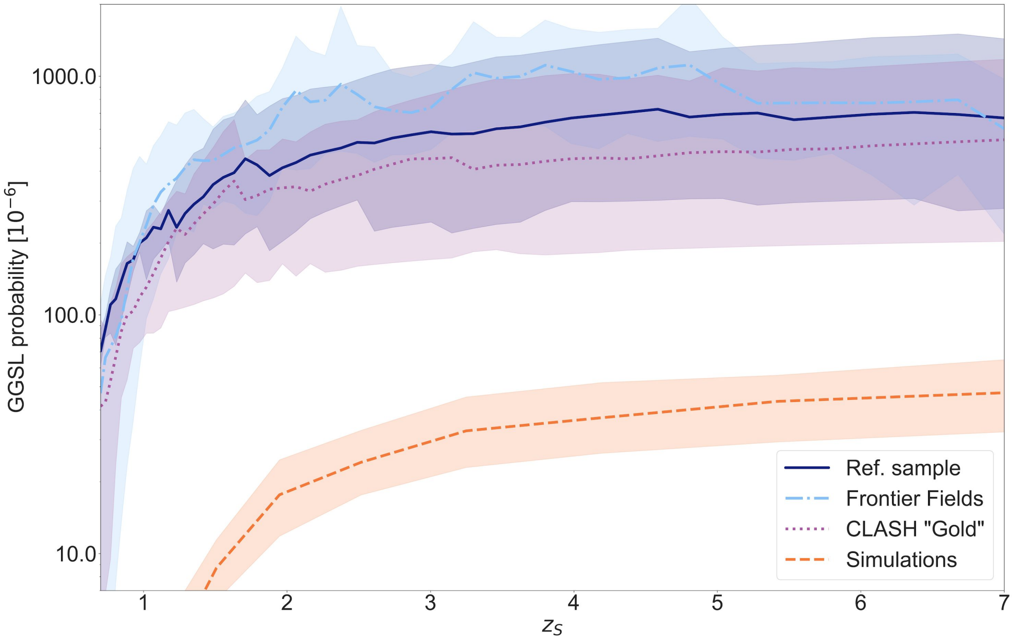
Sources overlapping at the caustics are strongly lensed not only by the cluster, but also by the individual cluster galaxies

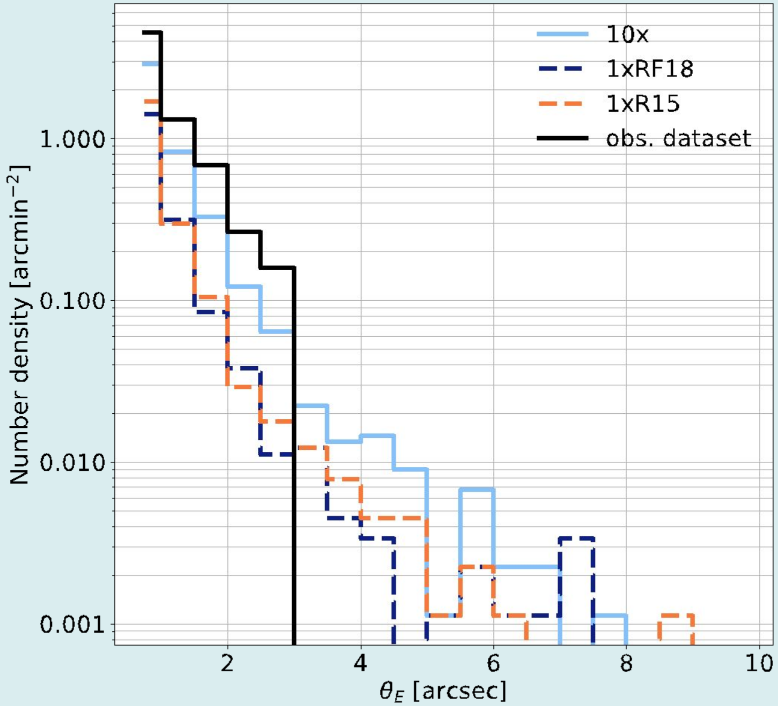


(A)
(B)
M1206
lensing+kinematics
mass model
Secondary caustics
Primary caustic
Lens model predicts the
# of observed GGSL
events
(C)
Similar θ_E
(D)
Simulated "M1206"
matched
in oversll mass &
concentration
Much smaller number
and sizes of secondary
caustics
Predicts too few GGSL
events
convergence [dimensionless]
x_1 [arcsec]
x_2 [arcsec]
y_1 [arcsec]
y_2 [arcsec]

GGSL comparison with simulated clusters

11 Clusters from CLASH + HSTFF



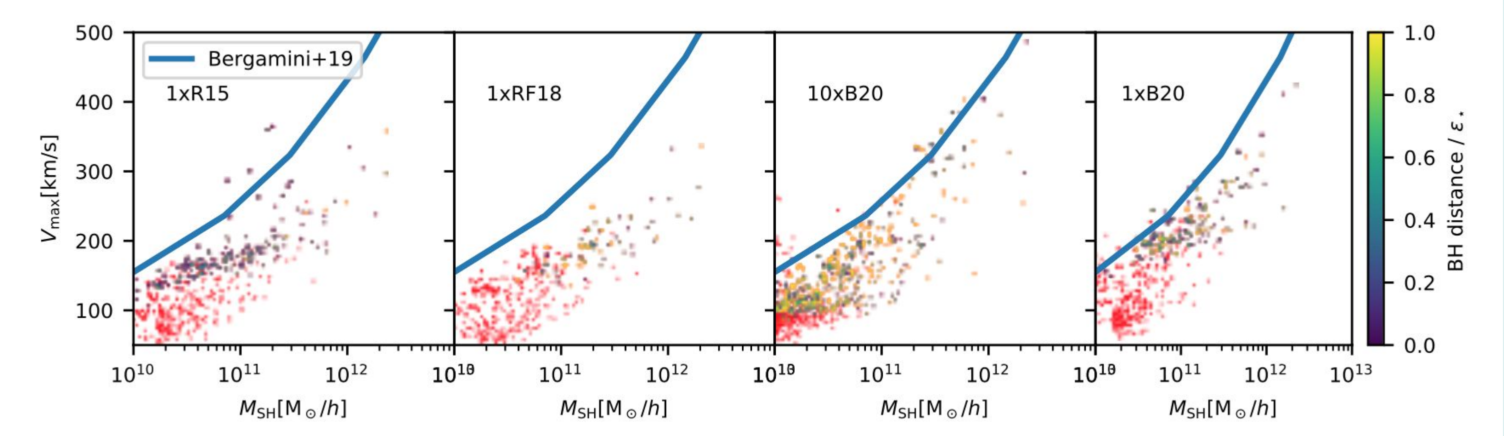


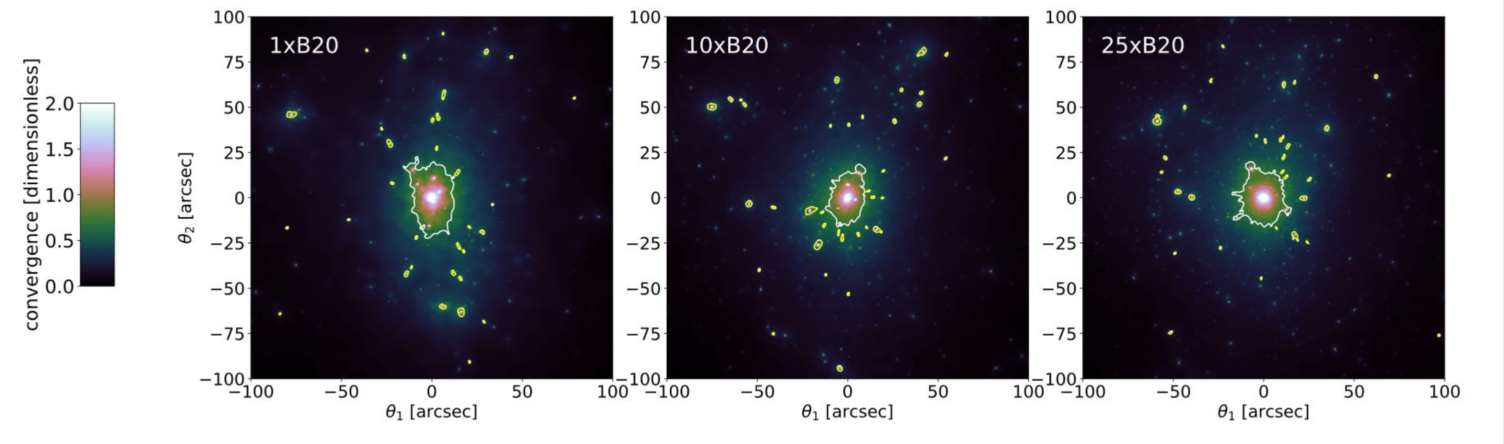
Metric sensitive to mass enclosed within R_E ~ 5- 10 kpc

inner regions of cluster galaxies are more concentrated and are hence more efficient strong lenses than in CDM simulations

Rasia+ 2015; Meneghetti+ 20; 22;

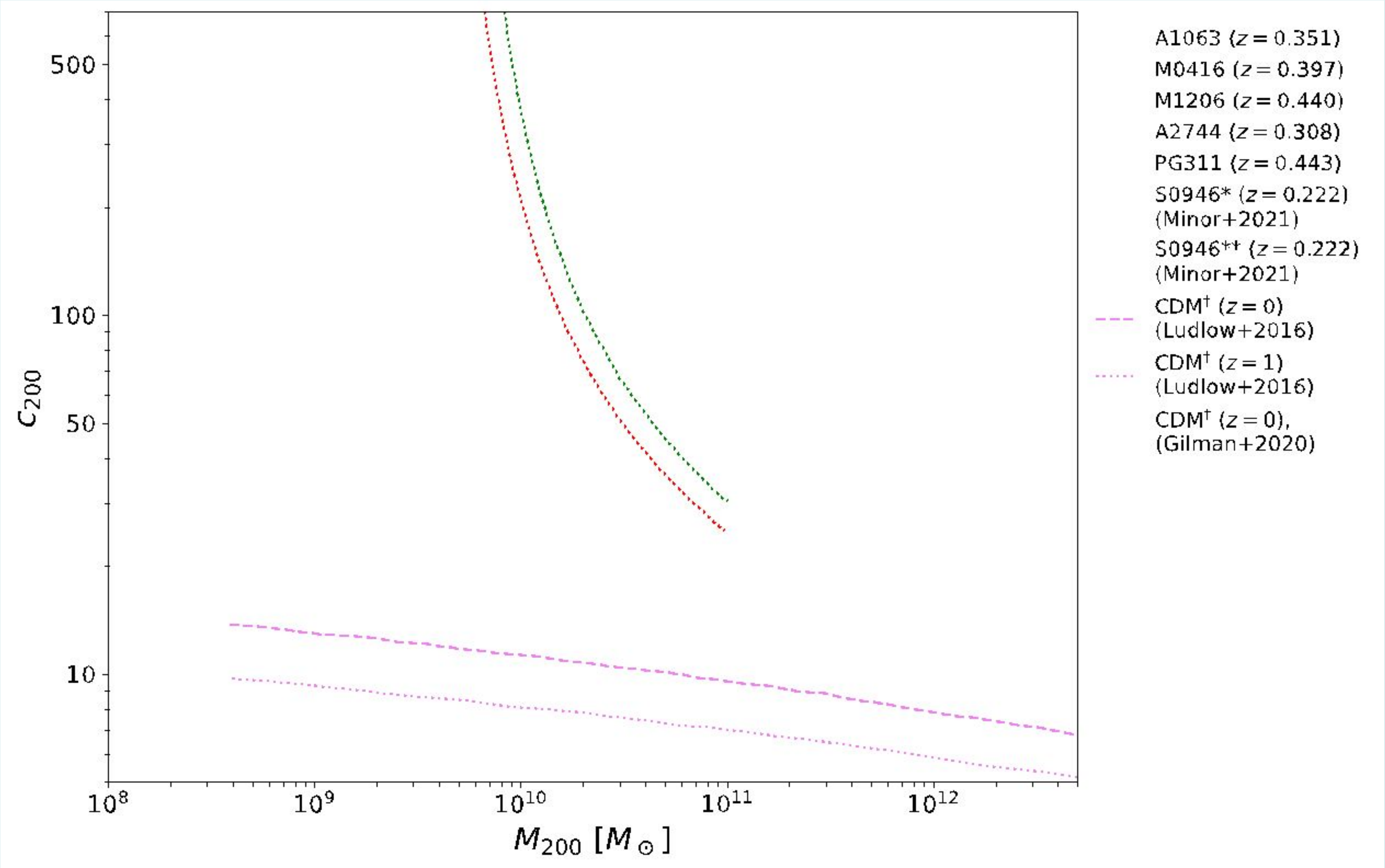
$M_{sub} < 10^{11}$ Msun, the most relevant mass-range for GGSL have maximum circular velocities ~ 30% smaller than those





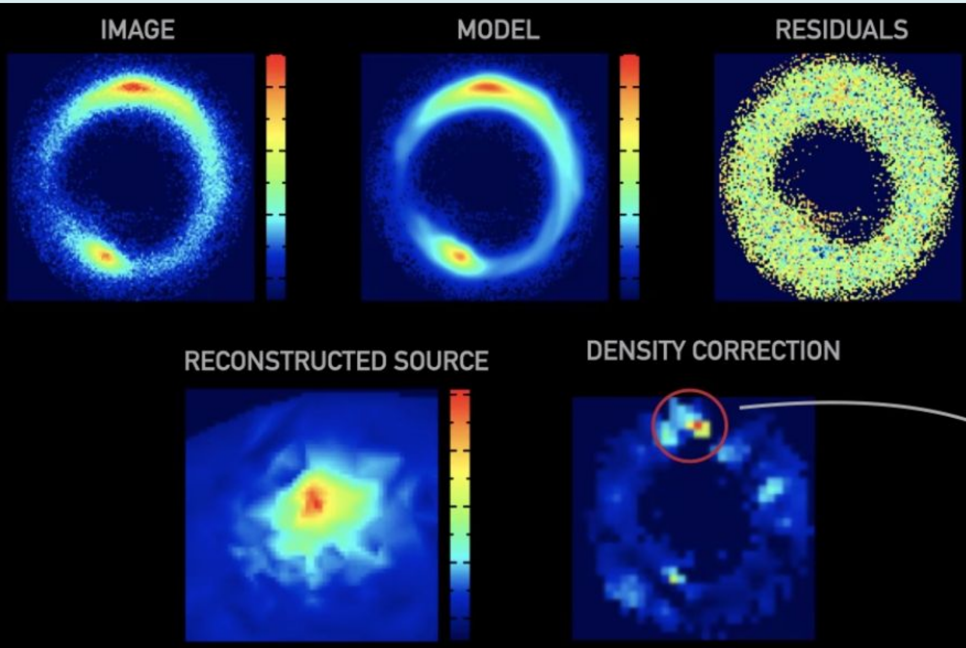
Regardless of the **resolution and galaxy formation model** adopted, simulations are unable to simultaneously reproduce the observed stellar masses and compactness (or maximum circular velocities) of cluster galaxies. The GGSL discrepancy remains!

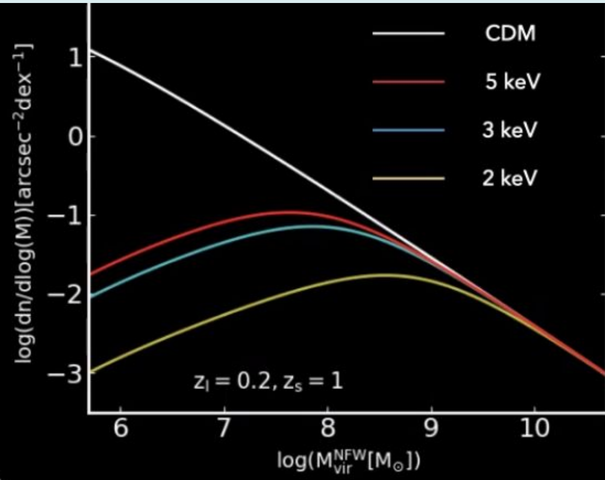
The concentration of subhalos



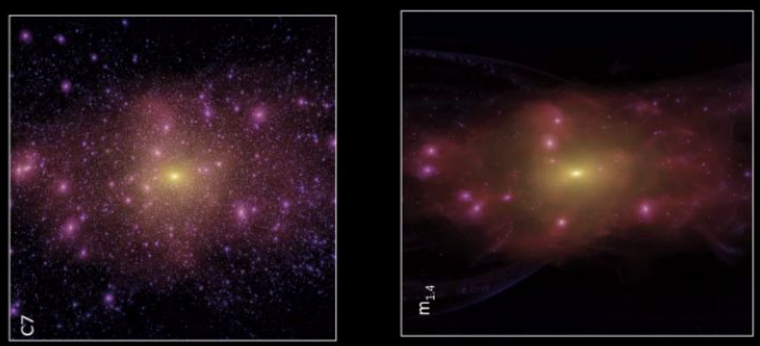
Tokayer, PN+
23

CONSTRAINTS ON DM FROM GALAXY-GALAXY LENSES





constrains on dark matter models



(Lovell et al. 2012)

- Small mass clumps are detected as corrections to an overall smooth potential, based on perturbations in the surface brightness distribution
- if present, more than one can be detected and we can quantify its mass
- in order to claim a detection, we require the smooth lens+clump model to fit the data better than the smooth lens alone at the 10σ level

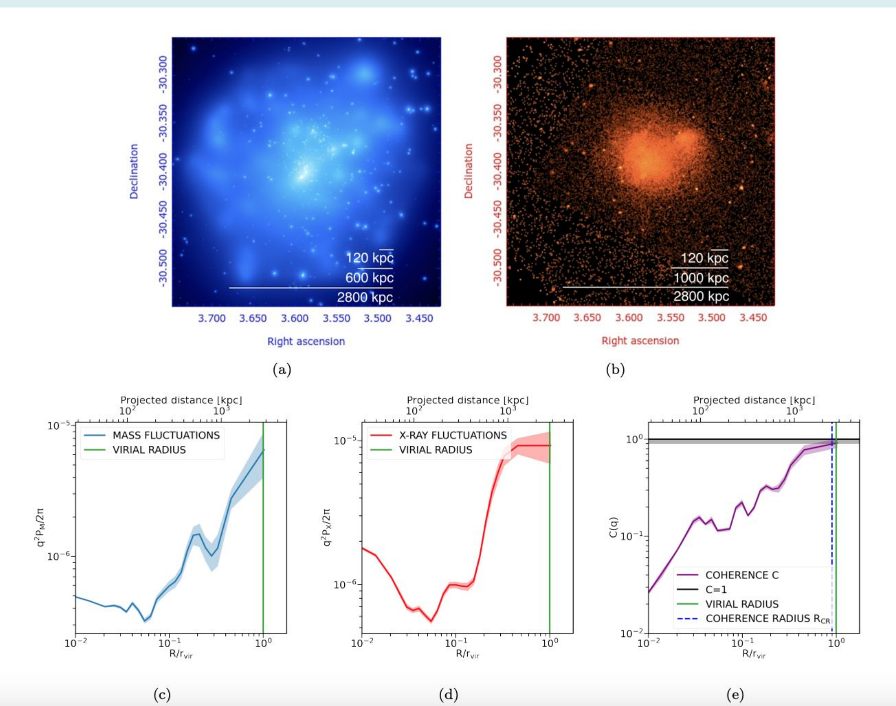
Pushing the subhalo mass function to lower masses

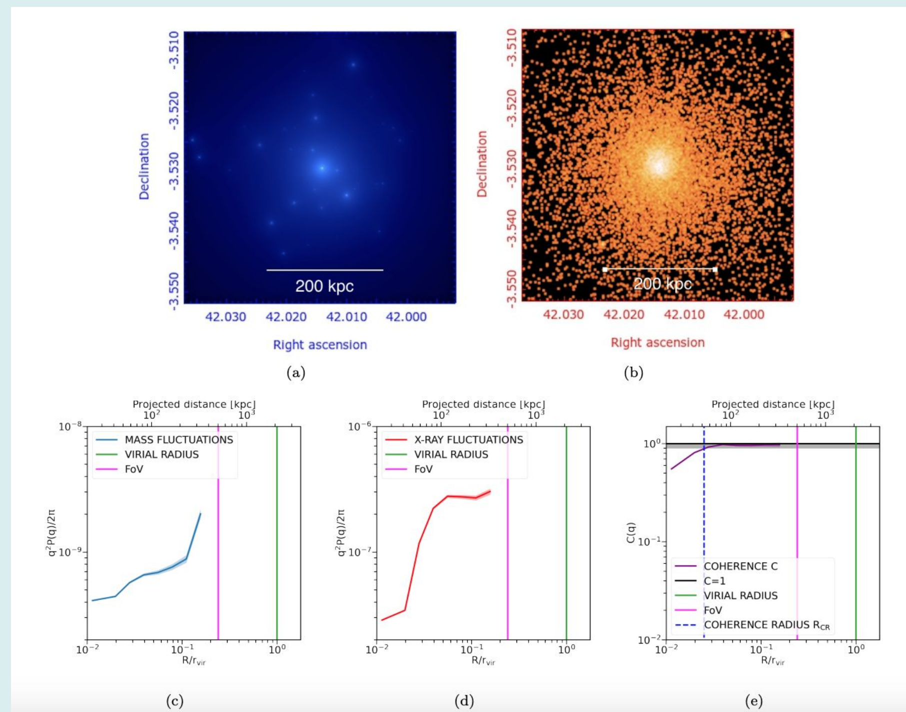
Vegetti+; Despali+; Dorkin+;

New metric to characterize small-scale DM substructure Auto & Cross-Power spectra of mass and gas maps (+light)

Mass Map → $P(q)$
mapping substructure

Mass Map
Xray SB → $P_{\text{mass,X-ray}}(q)$
Gas-Mass Coherence





Cerini+

New metric to characterize small-scale DM substructure Auto & Cross-Power spectra of mass and gas maps (+light)

Mass Map → $P(q)$

mapping substructure

Mass Map

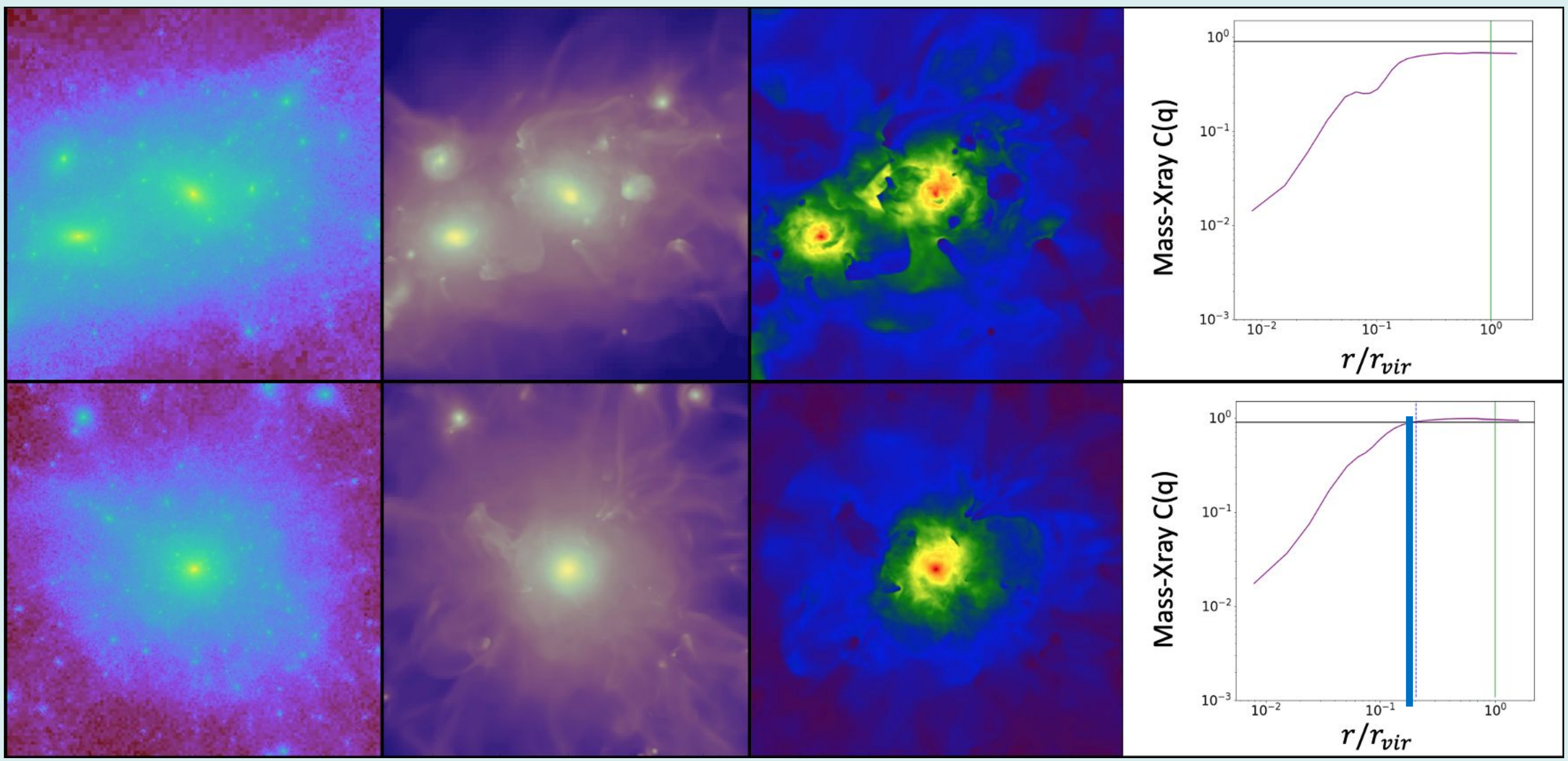
Xray SB

→ $P_{\text{mass,X-ray}}(q)$

Gas-Mass Coherence

Merger

Relaxed



Omega 500 LCDM

Cerini+

OUR CURRENT CONCLUSIONS

ONLY TWO POSSIBILITIES LEFT

Poor understanding of interplay between DM and baryons in the cluster cores

Deeper problems with the CDM paradigm

WHY ARE GAPS IMPORTANT?

Interrogate current paradigm portend refinements & revisions

AND/OR

point the way to radical revisions

DATA FROM UPCOMING SPACE & GROUND OBSERVATORIES & SIMULATIONS

JWST, NANCY ROMAN, EUCLID, LSST RUBIN

ADDITIONAL PRECISION TESTS WITH NEW METRICS

A cosmic book of phenomena

P. J. E. Peebles & Joseph Silk

A comparison of the merits of five general theories for the origin of galaxies and large-scale structure in the Universe with 38 observational constraints from extragalactic astronomy produces no clear winner. Two theories, cold dark matter in an inflationary cosmology and baryonic dark matter in a low-density Universe, emerge slightly ahead of the pack.

Score-card
Peebles & Silk 1990
BEFORE THE DISCOVERY OF DARK ENERGY !
CDM is and was always under scrutiny
Dark Matter?
Dark Energy?

Many challenges!

(WDM, Self-Int DM, Dissipative DM, Plasmon DM, Self-Ann DM, PBHs)


THE FIXION
xkcd.com/1621/
A NEW PARTICLE THAT EXPLAINS EVERYTHING
MAIN COMPONENT OF DARK MATTER
NEUTRALIZES MONOPOLES
SPONTANEOUSLY EMITS DARK ENERGY
INTRODUCES DISPERSION INTO PERYTONS FROM KITCHEN MICROWAVES, EXPLAINING FAST RADIO BURSTS
CAUSES ALPHA EFFECT
INTERCEPTS CERTAIN GRAVITATIONAL WAVES BEFORE THEY'RE OBSERVED
HIGGS-ISH
ACCELERATES CERTAIN SPACECRAFT DURING FLYBYS
MELTS ICE IN "SNOWBALL EARTH" SCENARIO
SUPPRESSES SIGMA IN EXPERIMENTS
CONFINES QUARKS AND GLUONS
SUPPRESSES ANTIMATTER IN EARLY UNIVERSE
MEDIATES PROTON DECAY BUT THEN HIDES IT
BROKEN SYMMETRY CAUSES θ=0, EXPLAINING UNOBSERVED NEUTRON DIPOLE MOMENT
COVERS NAKED SINGULARITIES
CAUSES CORONAL HEATING
SUPERLUMINALLY SMOOTHS ANISOTROPIES IN EARLY UNIVERSE (BUT ADDS FAINT POLARIZATION FOR BICEP3 TO FIND)
TRIGGERS SIBERIAN SINKHOLES
TRANSPORTS NEUTRINOS FASTER THAN LIGHT, BUT ONLY ON CERTAIN DAYS THROUGH ONE AREA OF FRANCE.

GGSL excess

EXTRA SLIDES

Strong lensing
multiple image geometries, magnification for an elliptical lens

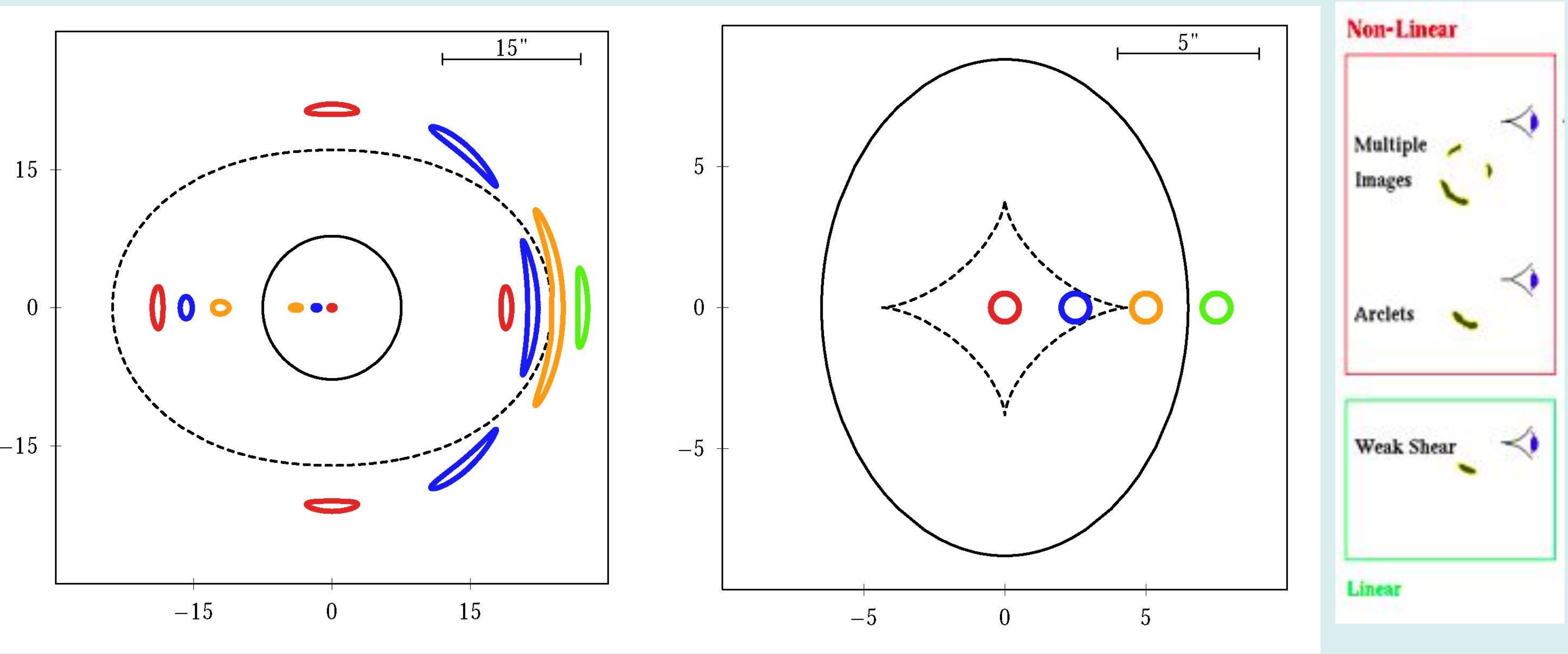
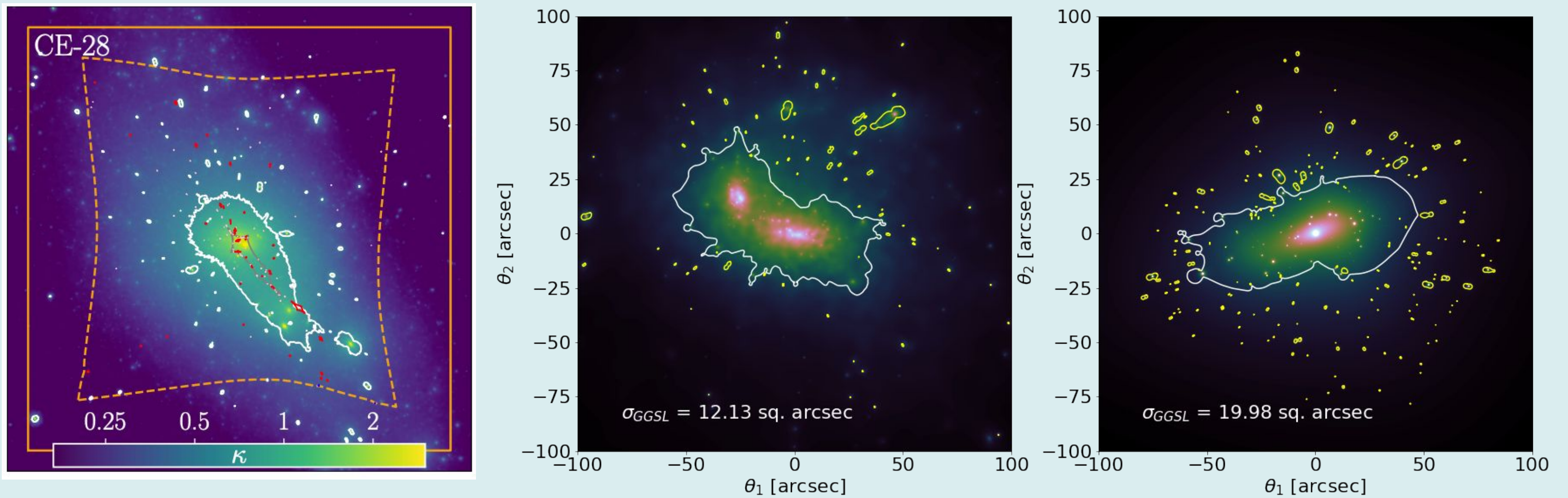


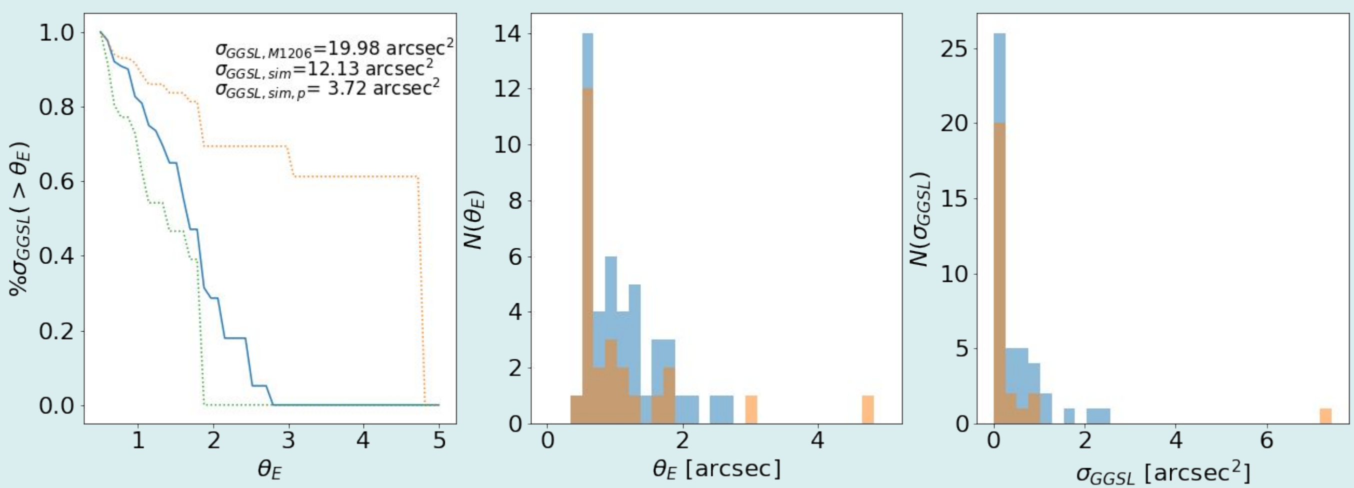
Image plane
critical
curves

Source
plane
caustics

GGSL in MACSJ1206

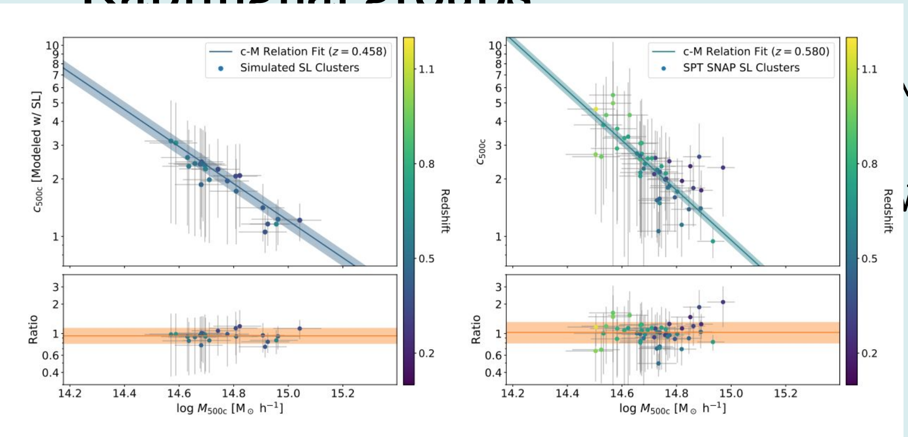
Which substructures contribute mostly to the GGSL cross section in simulated and rea
clusters?





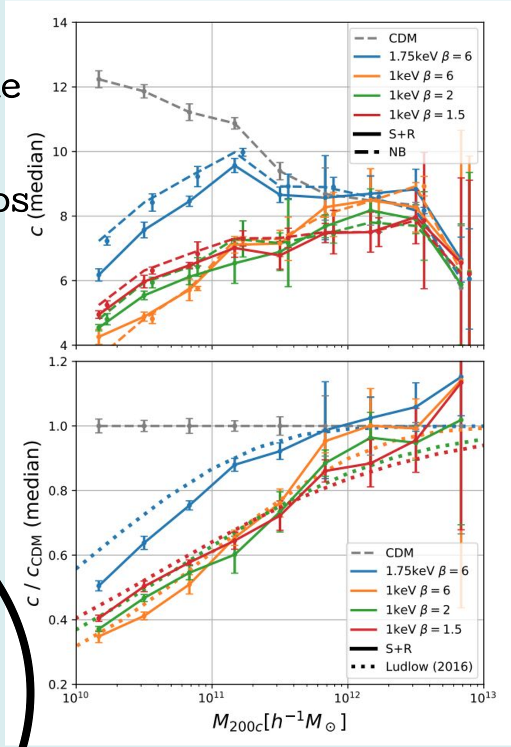
Concentration of subhalos: Subhalos in clusters and galaxies

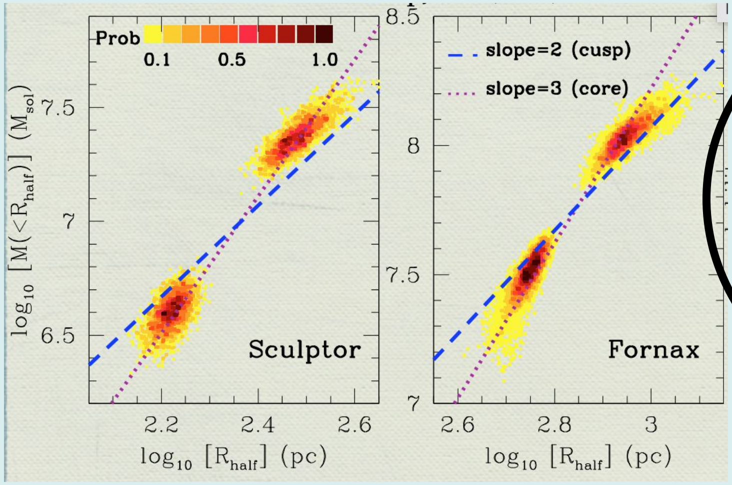
SEE WORK BY: Hezaveh+; Dalal+; Dvorkin+; Despali+; Vegetti+; Kaplinghat groups



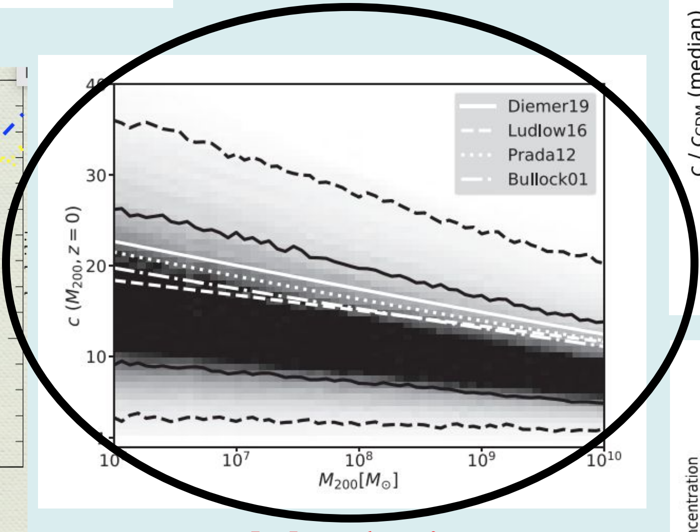
Central DM densities of MW dwarfs are incompatible With LCDM predictions

Work in progress for subhalos in lensing clusters.

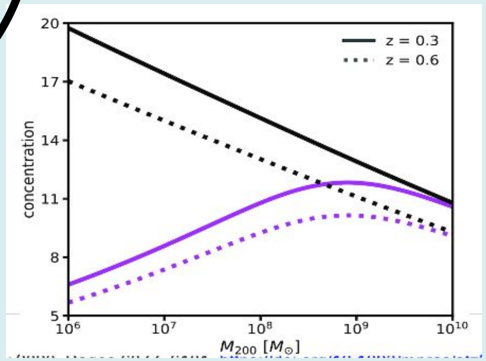




Walker & Pennarubia +12



c-M relation from 11 galaxy lenses (quad images)



Gilman+20; Stucker+