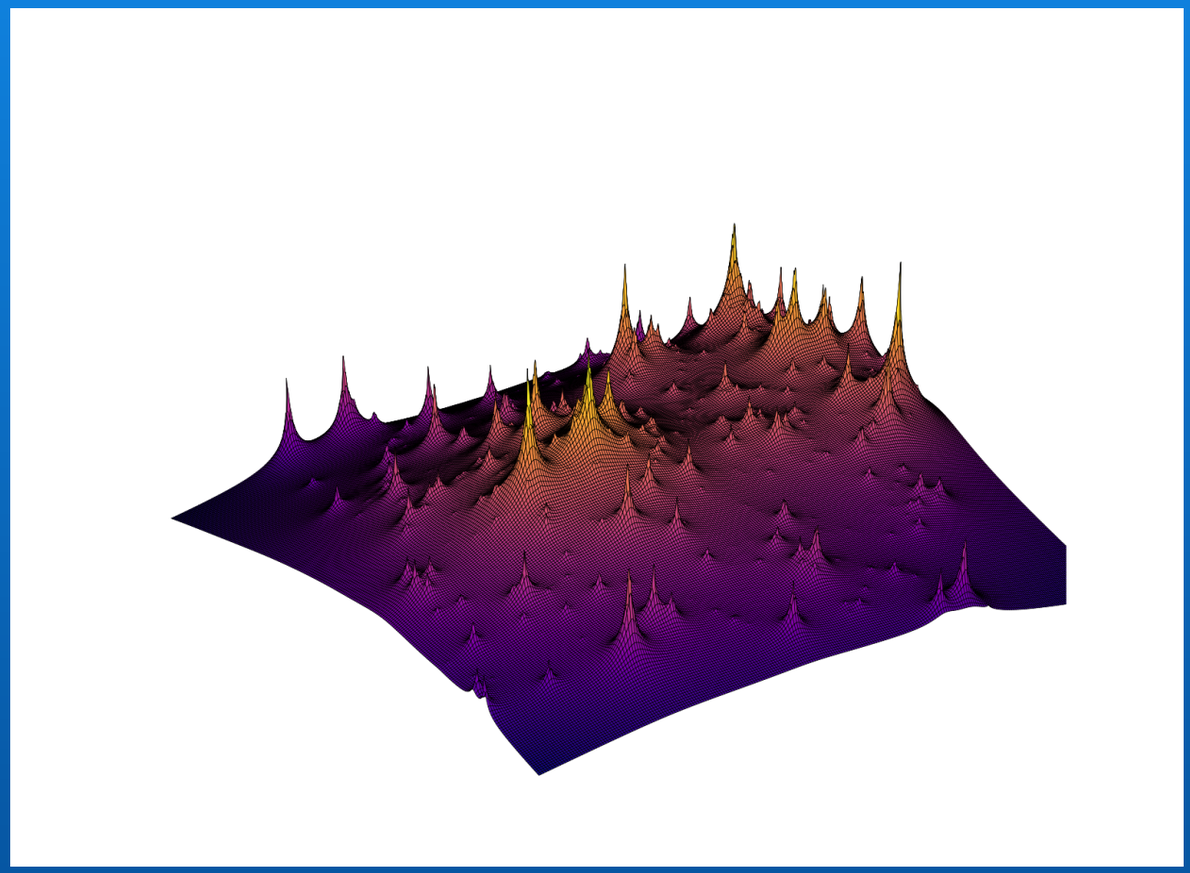
Light and Mass: new insights from cluster lensing



KITP Galaxy-Halo Connection
May 15, 2017

Priyamvada Natarajan
Yale University

COLLABORATORS

CATS collaboration

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

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Lars Hernquist, Annalisa Pillepich, Mark Vogelsberger, Volker Springel and the Illustris collaboration

Urmila Chadayammuri
Massimo Meneghetti

Jennifer Lotz, Dan Coe and the HSTFF team at STScI
All participant teams in the HSTFF model comparison project

TALK OUTLINE

- BRIEF OVERVIEW OF CLUSTER LENSING
- CALIBRATING CLUSTER LENS MODELING: ARES & HERA
  comparison of methods
  fidelity of light tracing mass
- NEW RESULTS FROM LENS MODELING OF HSTFF DATA
  Abell 2744
- NEW INSIGHTS FROM COMPARING HSTFF DATA WITH ILLUSTRIS SIMULATIONS
  iCluster Zooms

http://www.stsci.edu/hst/campaigns/frontier-fields/

List of all HSTFF publications to date available
Jauzac+; Meneghetti, PN, Coe+ 16; PN 17

Cluster lenses as astrophysical laboratories

Lensing tests of dark matter

Mass profiles of clusters: concentration
Substructure: abundance, profiles, spatial distribution
Density profiles - inner and outer slopes
Shapes of dark matter halos
Higher order statistics: flexion, correlation function of substructure – pencil beam surveys, P(k)
Science by stacking

Lensing constraints on dark energy

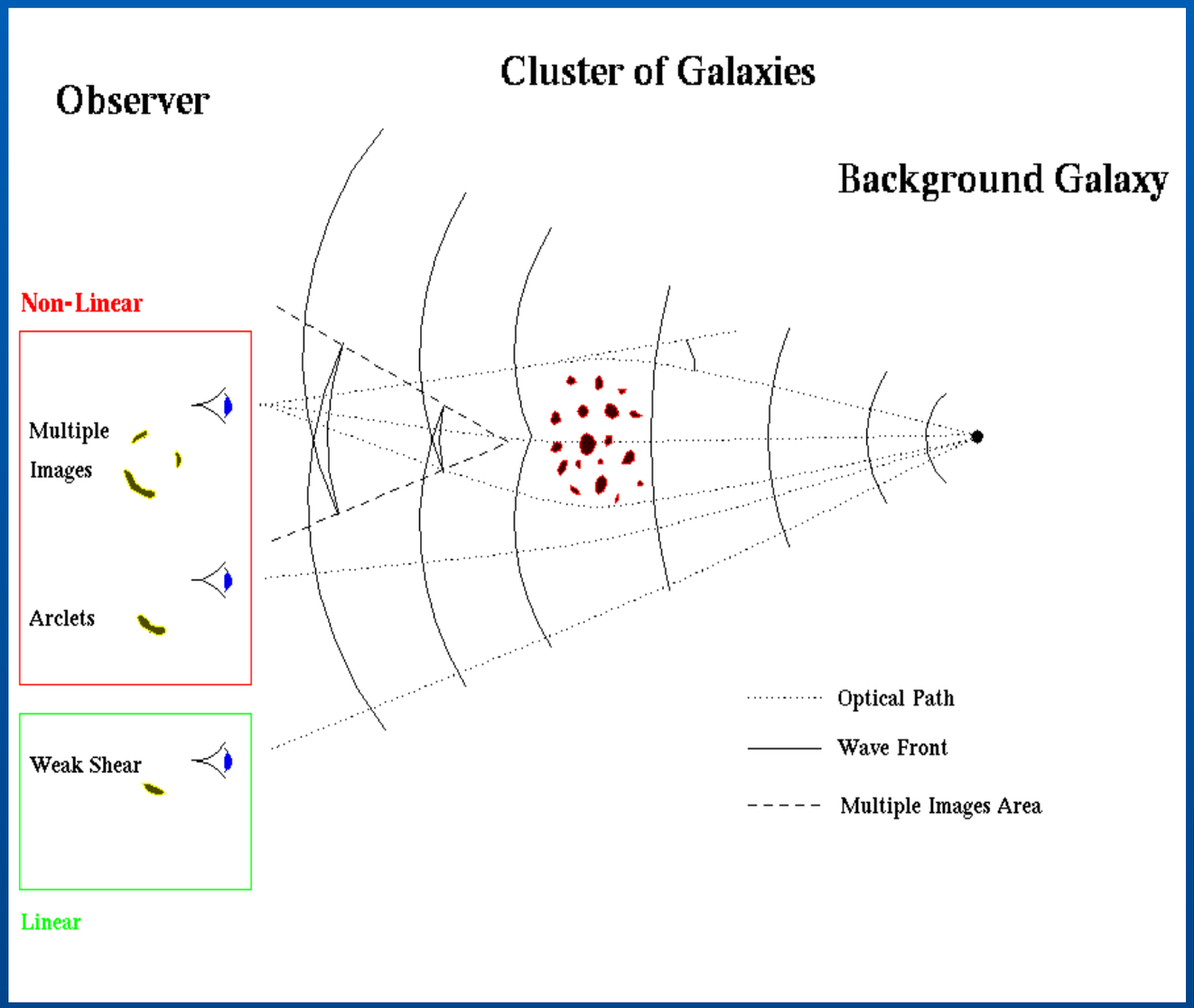
Cosmography with strong lensing (CSL)
Triplet statistics

Lensing tests of the standard world model

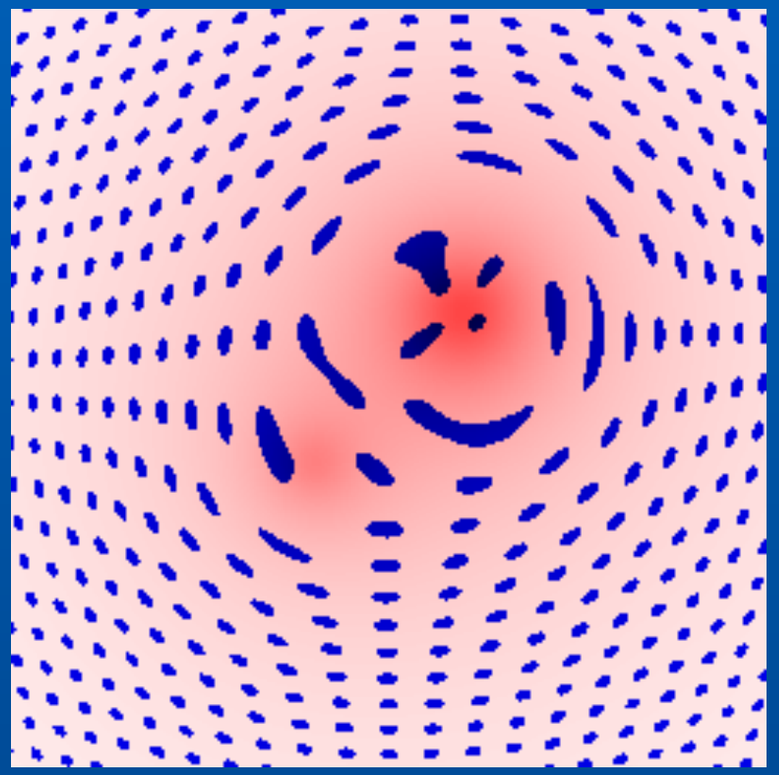
Primordial Non-Gaussianity (Arc-statistics)
Growth of Structure and Structure Formation

see Review by Kneib & PN 11

STRONG LENSING REGIME
Non-linear mapping between source and image plane



multiple images, highly distorted and magnified arcs depletion of background number counts
Projected surface mass density within the beam
Mass enclosed within the arc is tightly constrained



RANGE OF MULTIPLE IMAGE CONFIGURATIONS

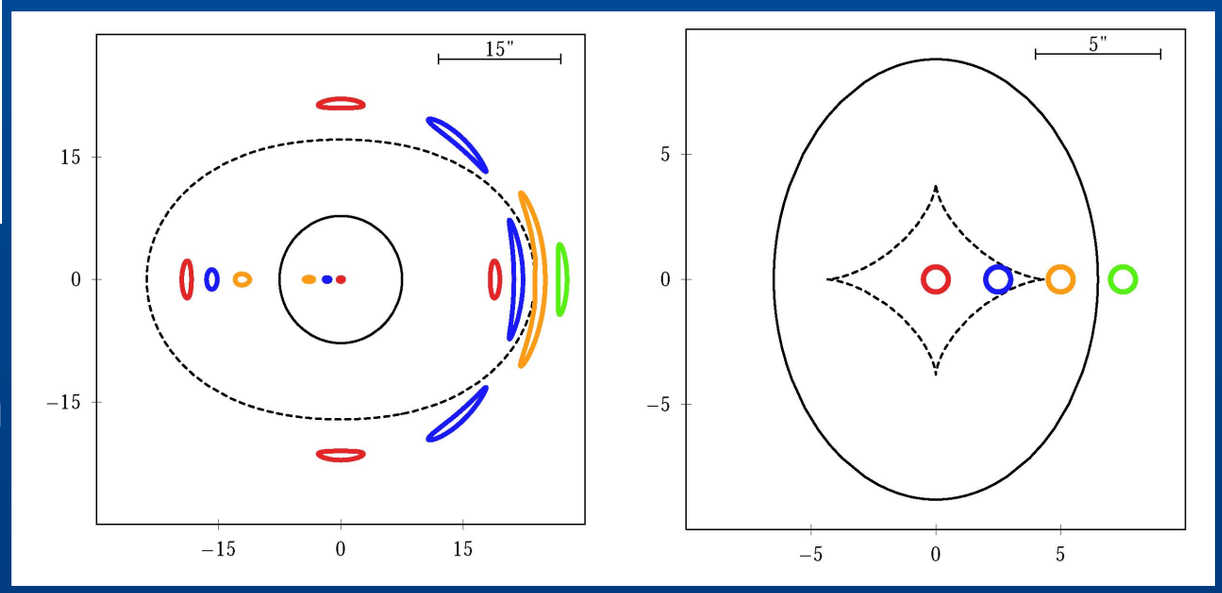
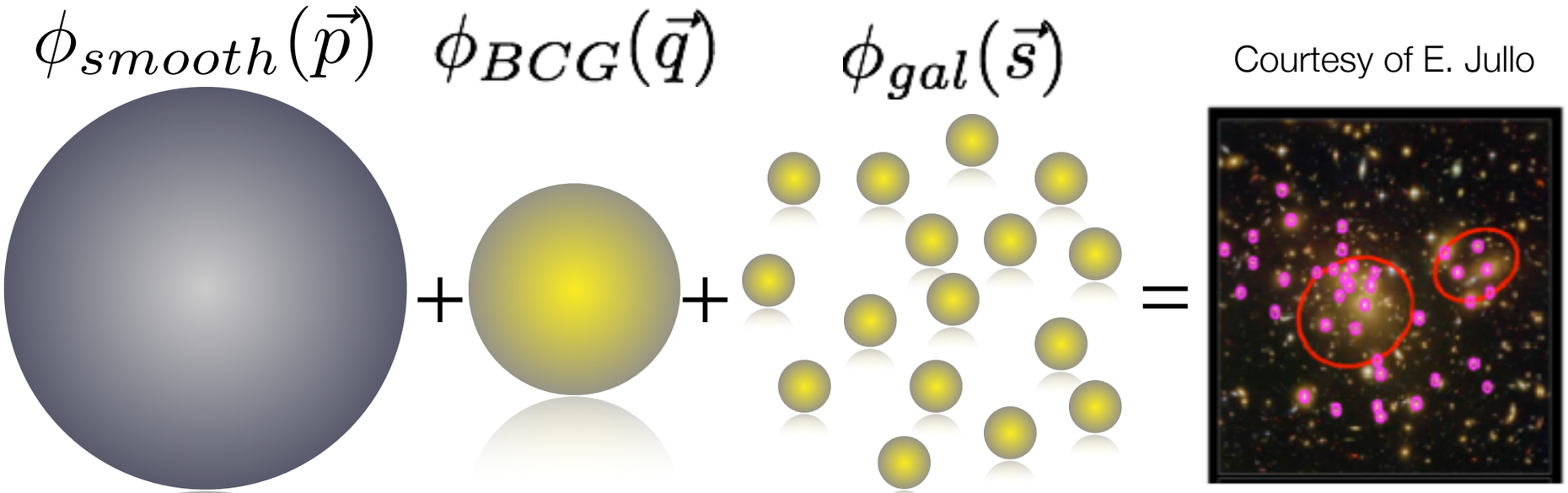


IMAGE PLANE SOURCE PLANE

PARAMETRIC VS FREE FORM METHODS

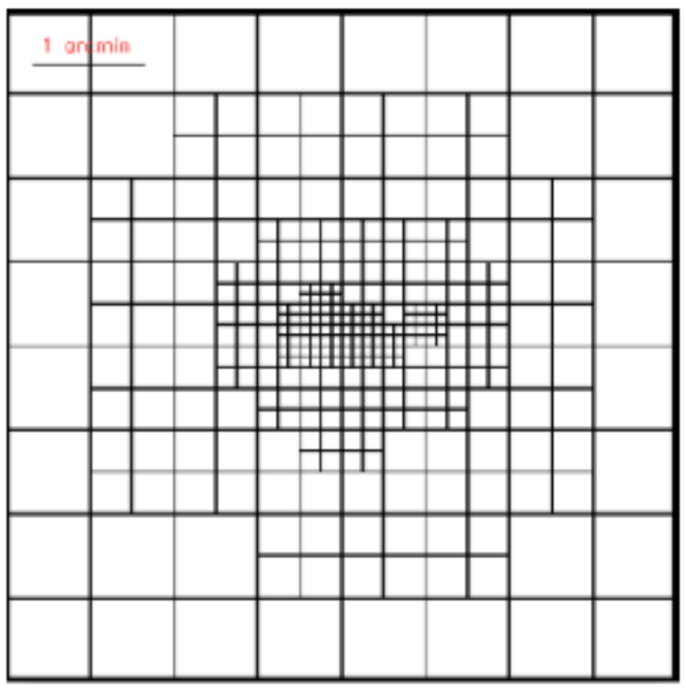
parametric



Courtesy of E. Jullo

Light traces mass

free-form
(non-parametric)

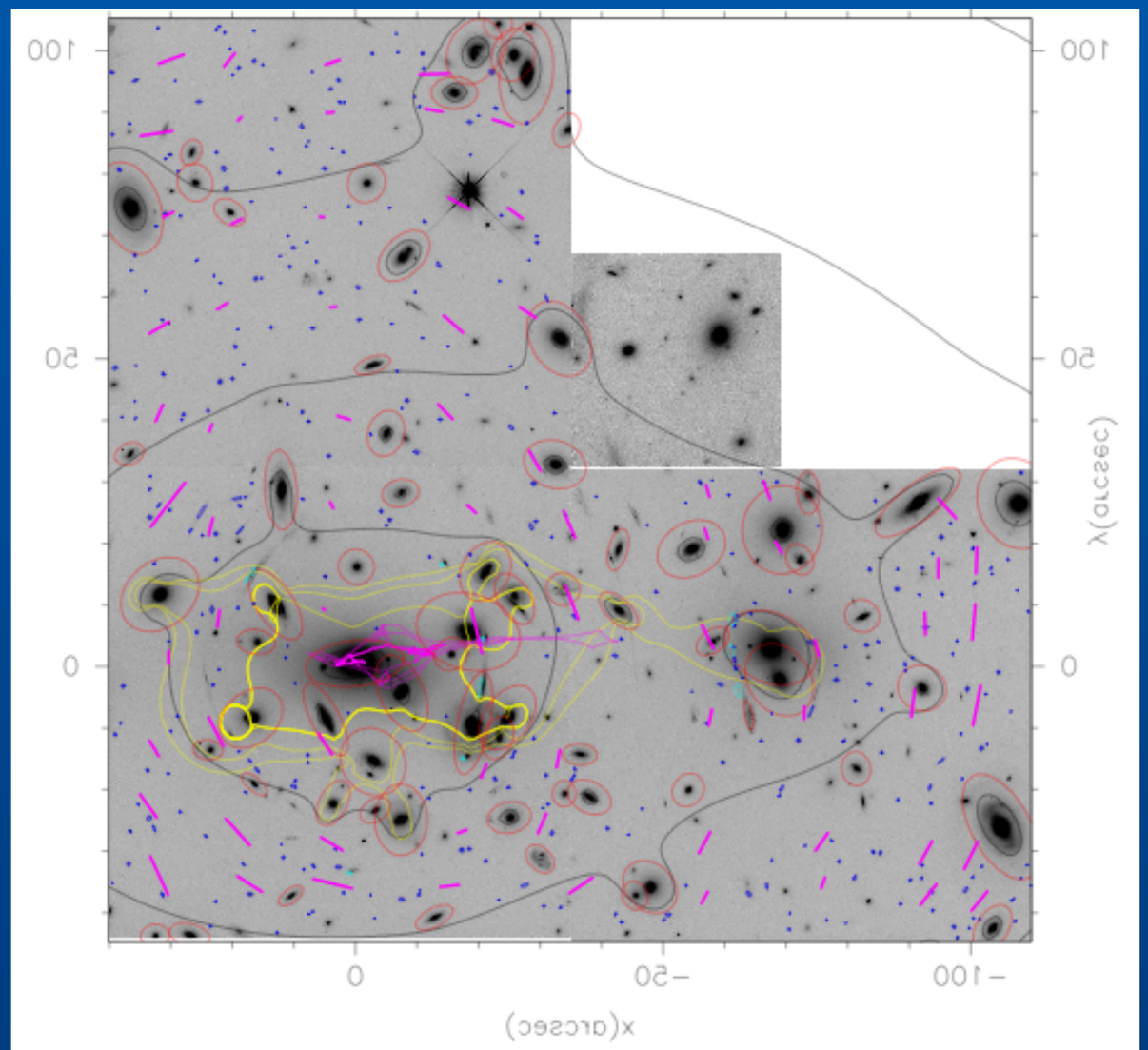


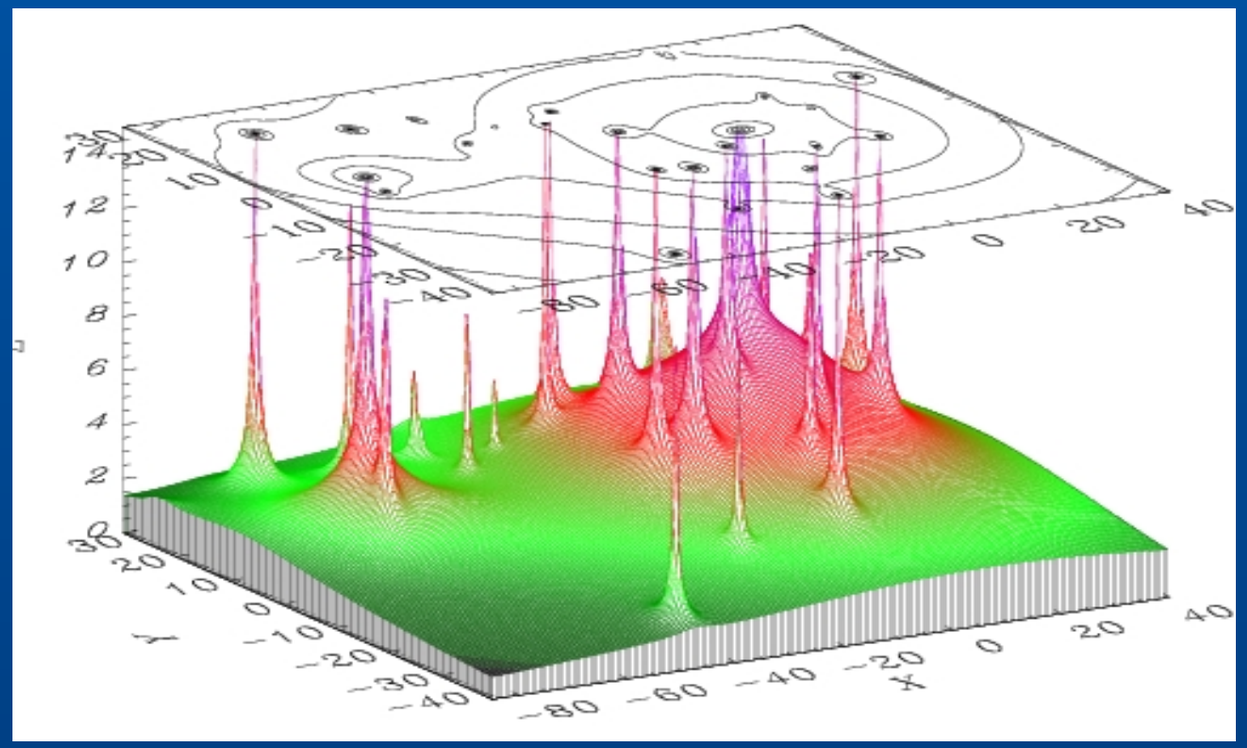
Courtesy of E. Jullo

No assumption that light traces mass or on the shape of the density profiles
Decomposition into pixels or RBFs
Work better with many constraints

RELATING MASS AND LIGHT IN LENS MODELING

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



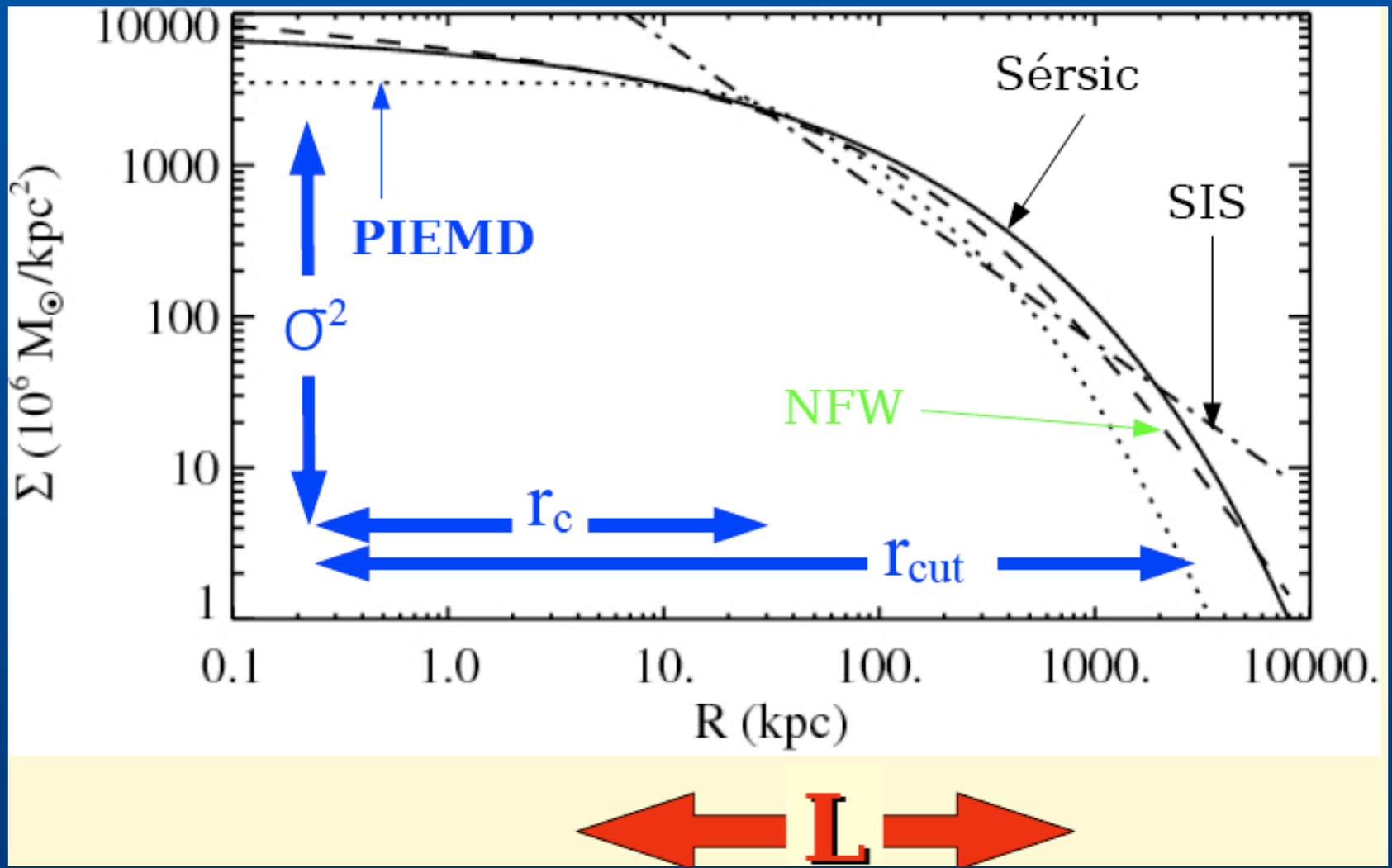


PN & Kneib 1997; PN+ 2005; 2009; 2011
Implemented in Lenstool

RELATING MASS AND LIGHT IN LENS MODELING
scaling relations for cluster galaxies & their host subhalos

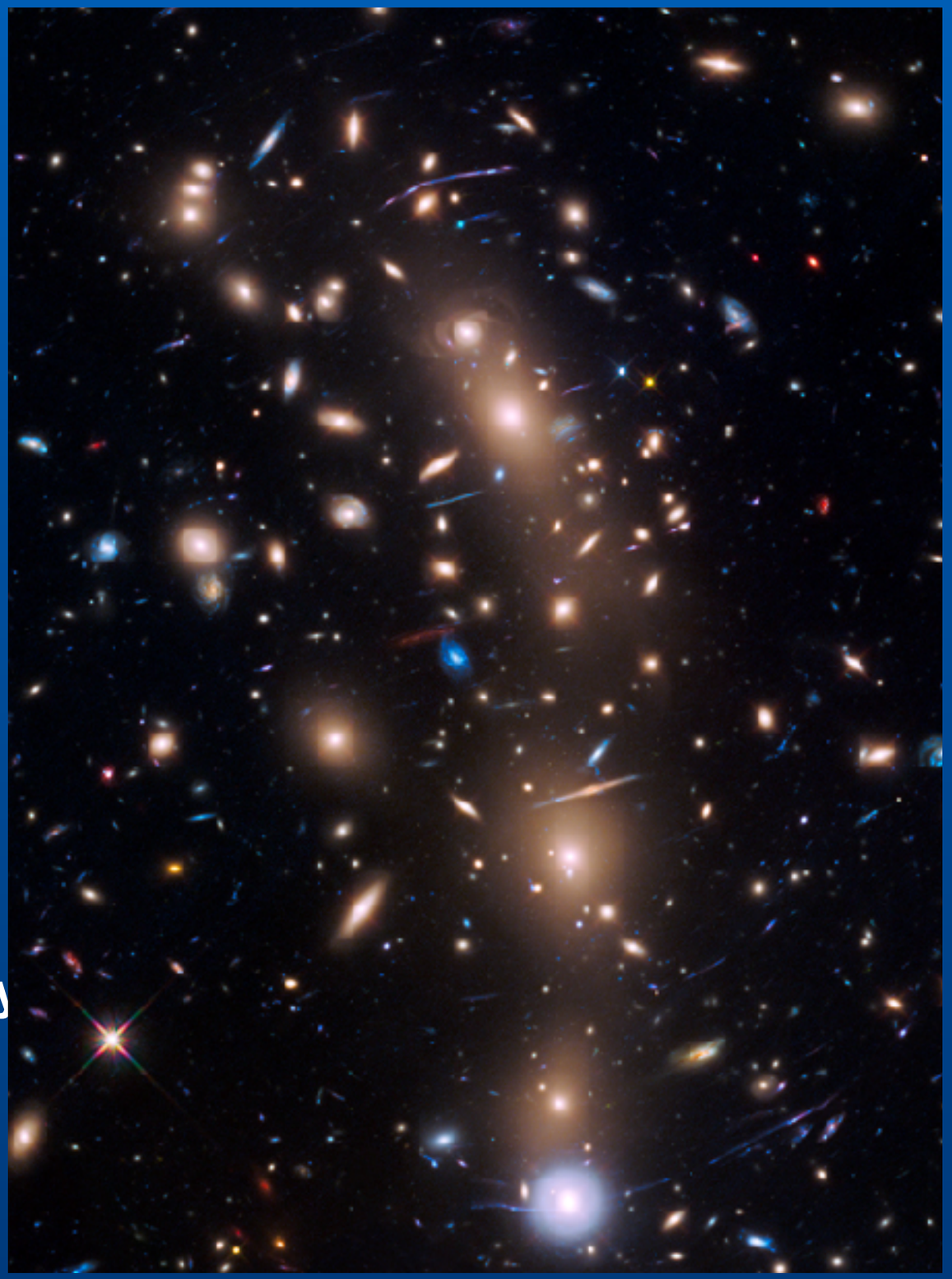
Mhalo -> velocity dispersion -> galaxy luminosity

$$r_{core} = r^*_{core}\left(\frac{L}{L^*}\right)^{\frac{1}{2}} \quad r_{cut} = r^*_{cut}\left(\frac{L}{L^*}\right)^{\alpha} \quad \sigma = \sigma^*\left(\frac{L}{L^*}\right)^{\frac{1}{4}}$$



HST FRONTIER FIELDS INITIATIVE
deep imaging of 6 cluster lenses

- ~40 -80 families of multiple images, ~100 images with spectroscopic redshifts (GLASS, CLASH-VLT, MUSE…)
- multi-wavelength coverage
- new insights into cluster-lenses and lensed galaxies
- what is the nature of dark matter?
- **Cluster density profiles, shapes of the cores**
  substructures
- what are the properties of the faint, high-redshift lensed galaxies?
- **Role in re-ionizing the universe, luminosity functions, magnification**
- what is the nature of dark energy?
- **Strong Lensing cosmography**



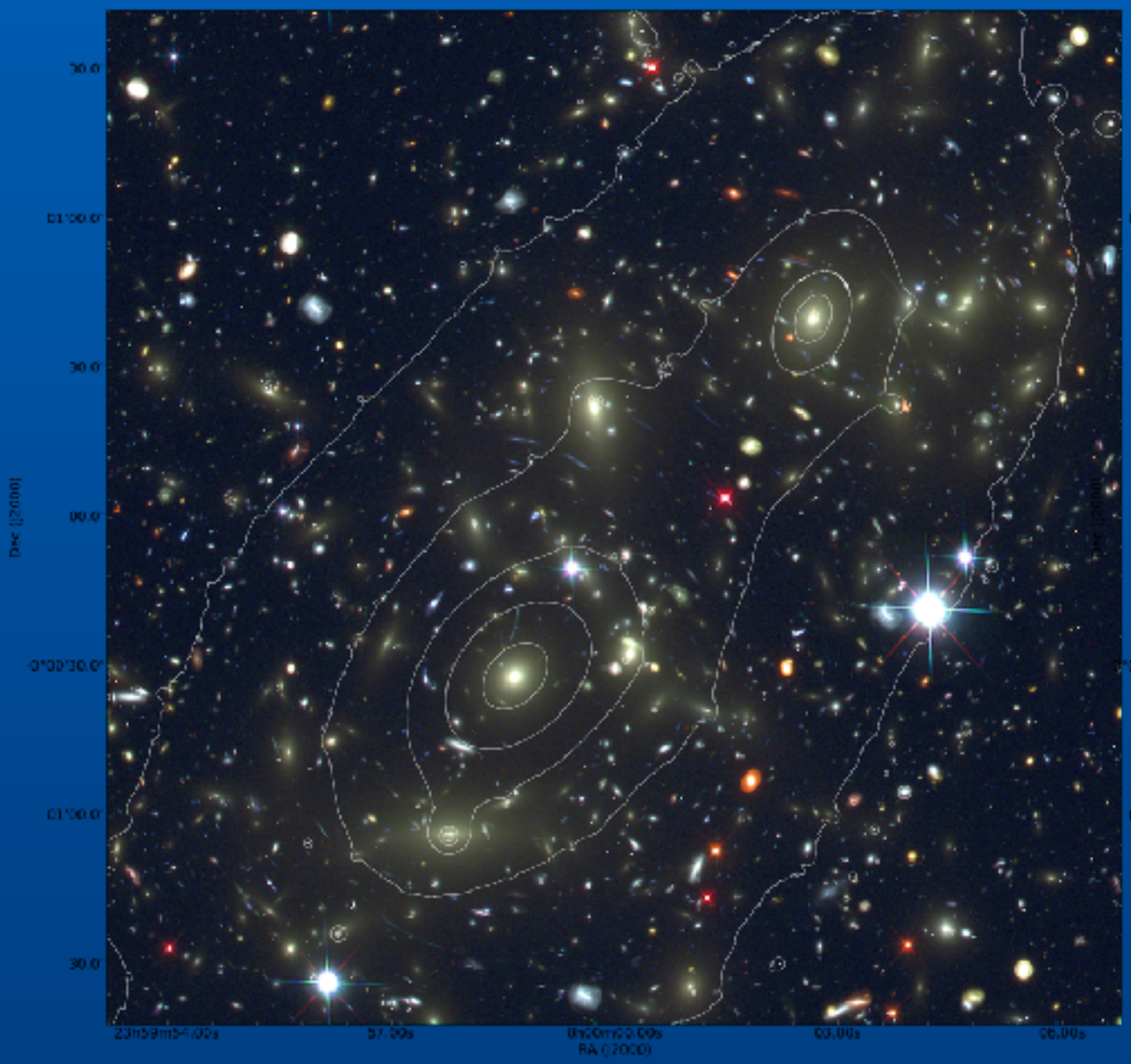
HSTFF MODEL COMPARISON PROJECT

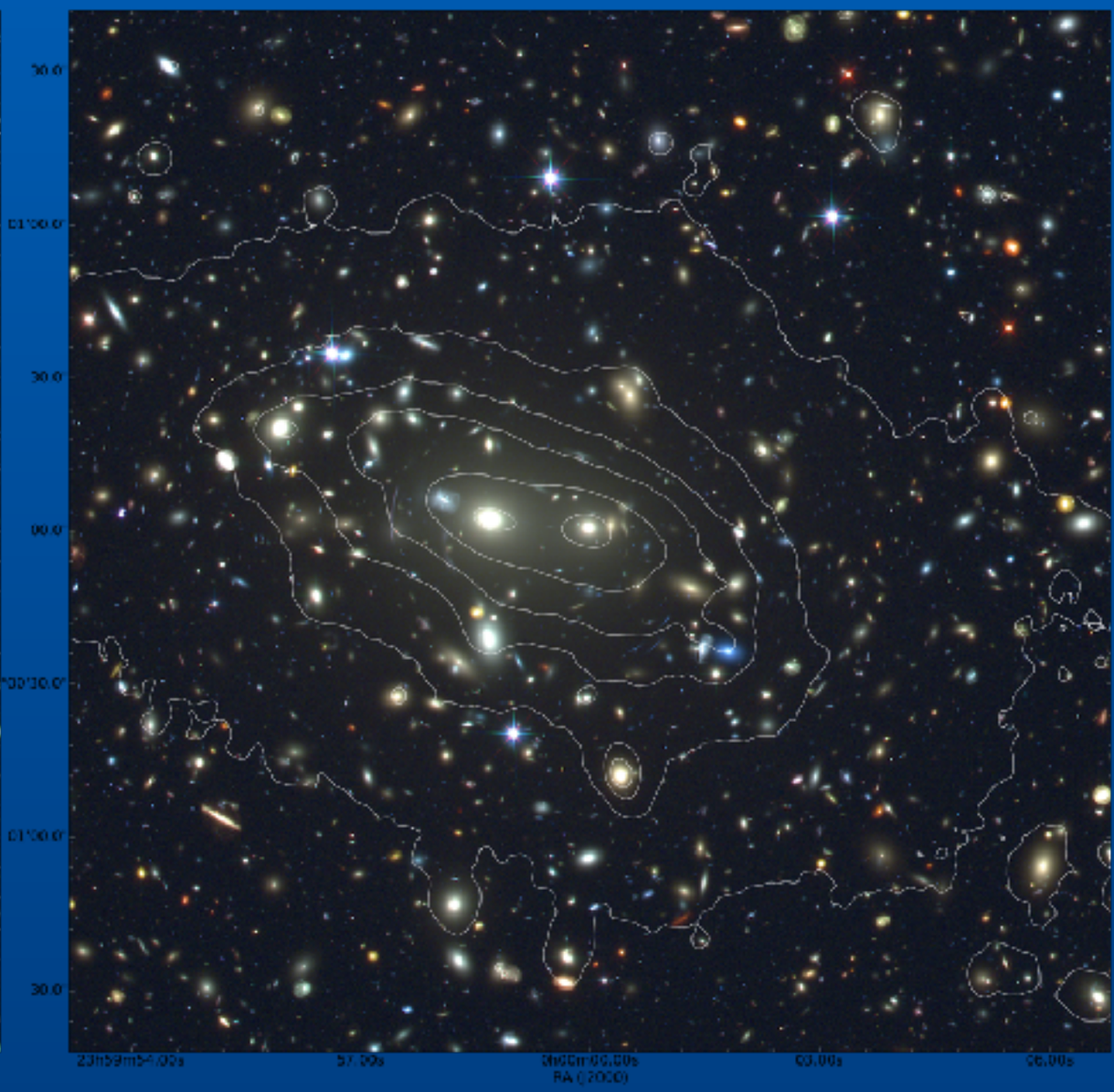
- Teams are using various reconstruction algorithms, independently developed - parametric free-form & hybrid
- Assessing how these algorithms perform and how they compare
- Provided 2 simulated clusters where true data known for blind reconstruction, given the same inputs to all teams
- How robust are these models? strengths & limitations, improvements

Group/Author	Method	Model	Cluster	Approach	Blind
M. Bradac & A. Hoag	SWUnited	Bradac-Hoag	*Ares*+*Hera*	free-form	yes
J. Diego	WSLAP+	Diego-multires	*Hera*	hybrid	yes
J. Diego	WSLAP+	Diego-overfit	*Hera*	hybrid	yes
J. Diego	WSLAP+	Diego-reggrid	*Ares*+*Hera*	hybrid	yes
D. Lam	WSLAP+	Lam	*Hera*	hybrid	no
J. Liesenborgs, K. Sebesta & L. Williams	`Grale`	GRALE	*Ares*+*Hera*	free-form	yes
D. Coe	LensPerfect	Coe	*Ares*	free-form	yes
CATS	`Lenstool`	CATS	*Ares*+*Hera*	parametric	yes
T. Johnson & K. Sharon	`Lenstool`	Johnson-Sharon	*Ares*+*Hera*	parametric	yes
T. Ishigaki, R. Kawamata & M. Oguri	GLAFIC	GLAFIC	*Ares*+*Hera*	parametric	yes
A. Zitrin	LTM	Zitrin-LTM-gauss	*Ares*+*Hera*	parametric	no
A. Zitrin	PIEMDeNFW	Zitrin-NFW	*Ares*+*Hera*	parametric	no

Meneghetti, Natarajan & Coe+ 16

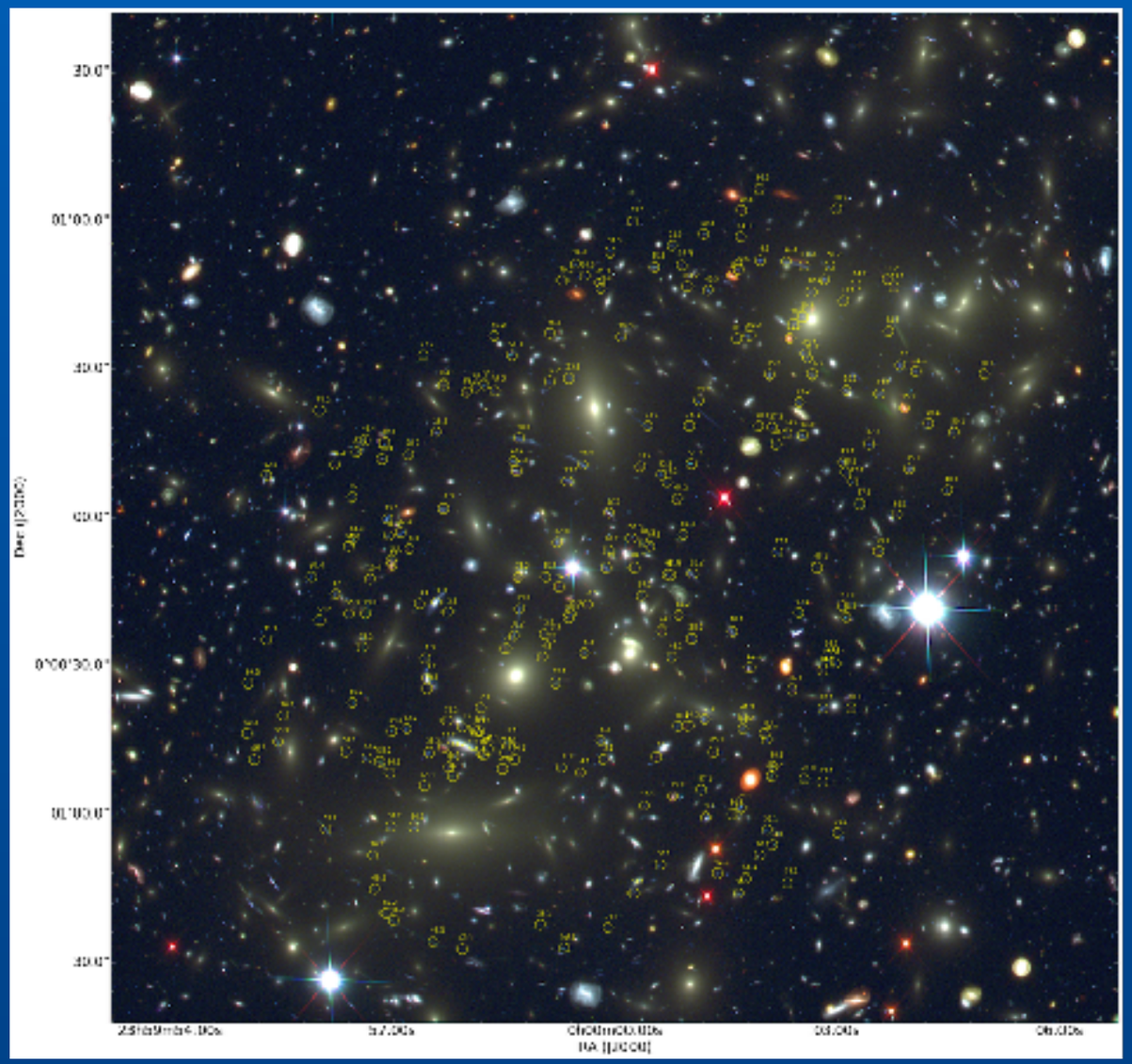
ARES & HERA CONSTRUCTED USING SKYLENS





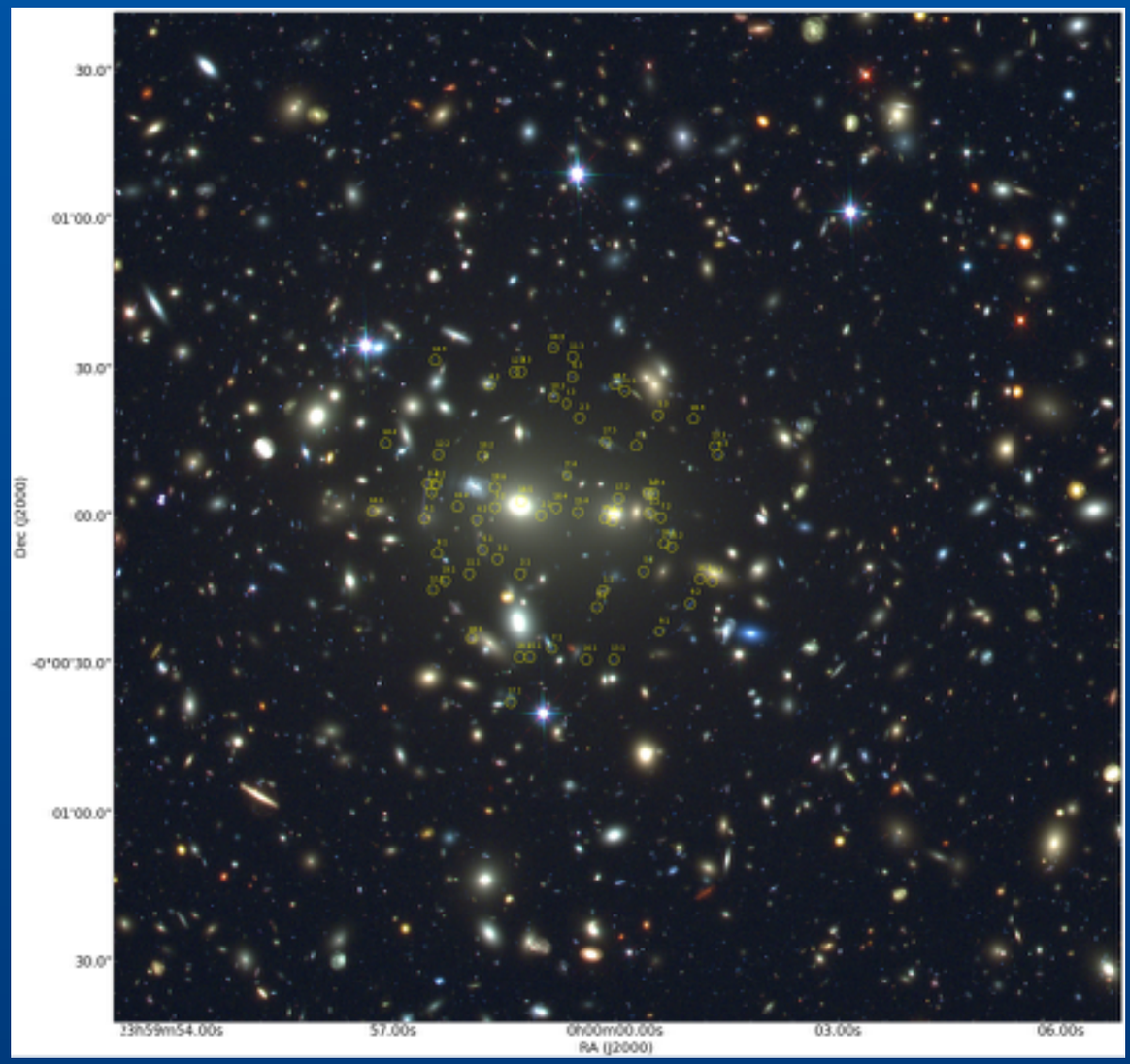
Meneghetti+ 08 10

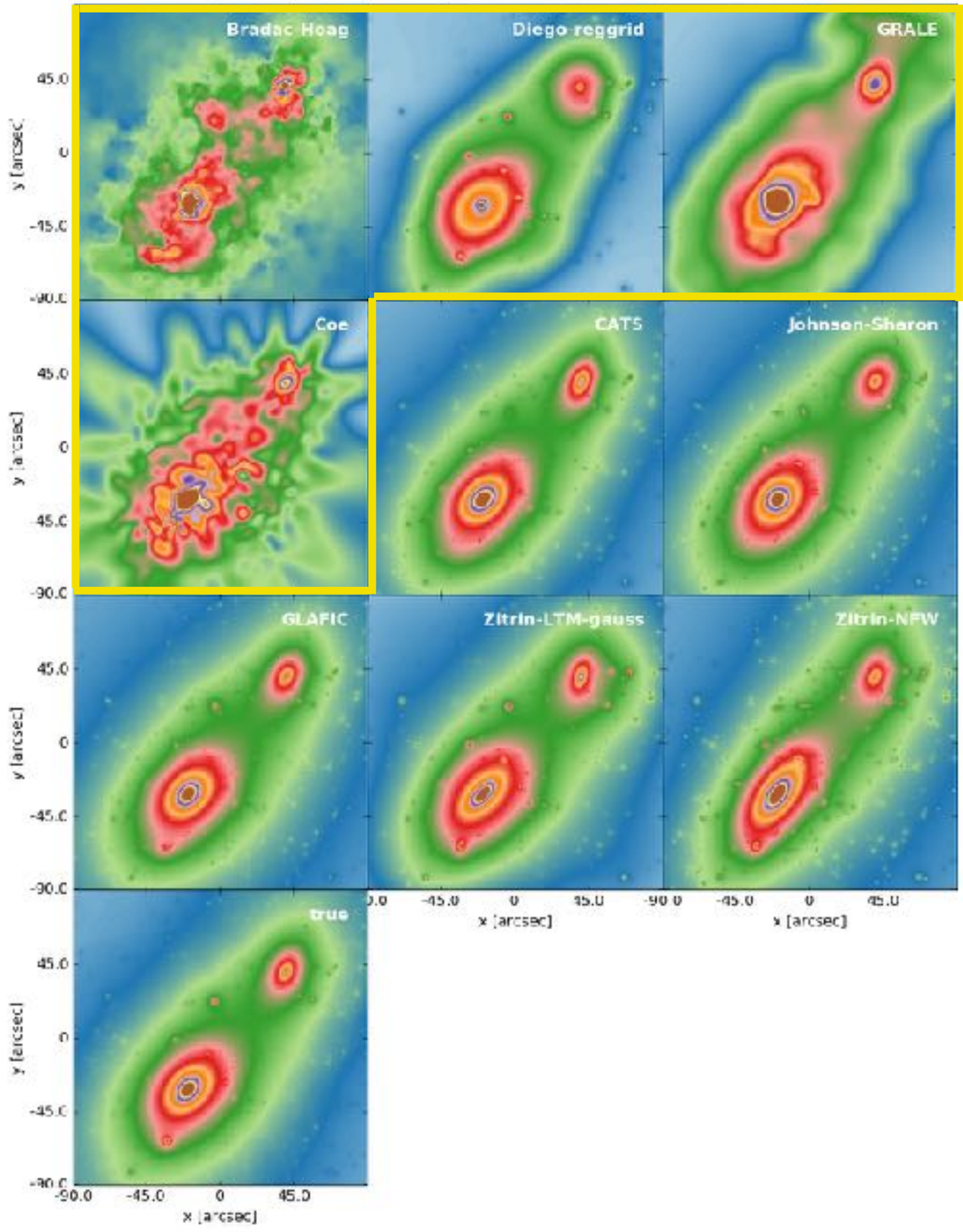
TWO SIMULATED CLUSTER LENSES
ARES & HERA



242 IMAGES OF 82 BACKGROUND SOURCES

65 IMAGES OF 19 BACKGROUND SOURCES




Bradac Hoag
Diego-reggrid
GRALE
Coe
CATS
Johnson-Sharon
GLAFIC
Zitrin-LTM-gauss
Zitrin-NFW
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x [arcsec]
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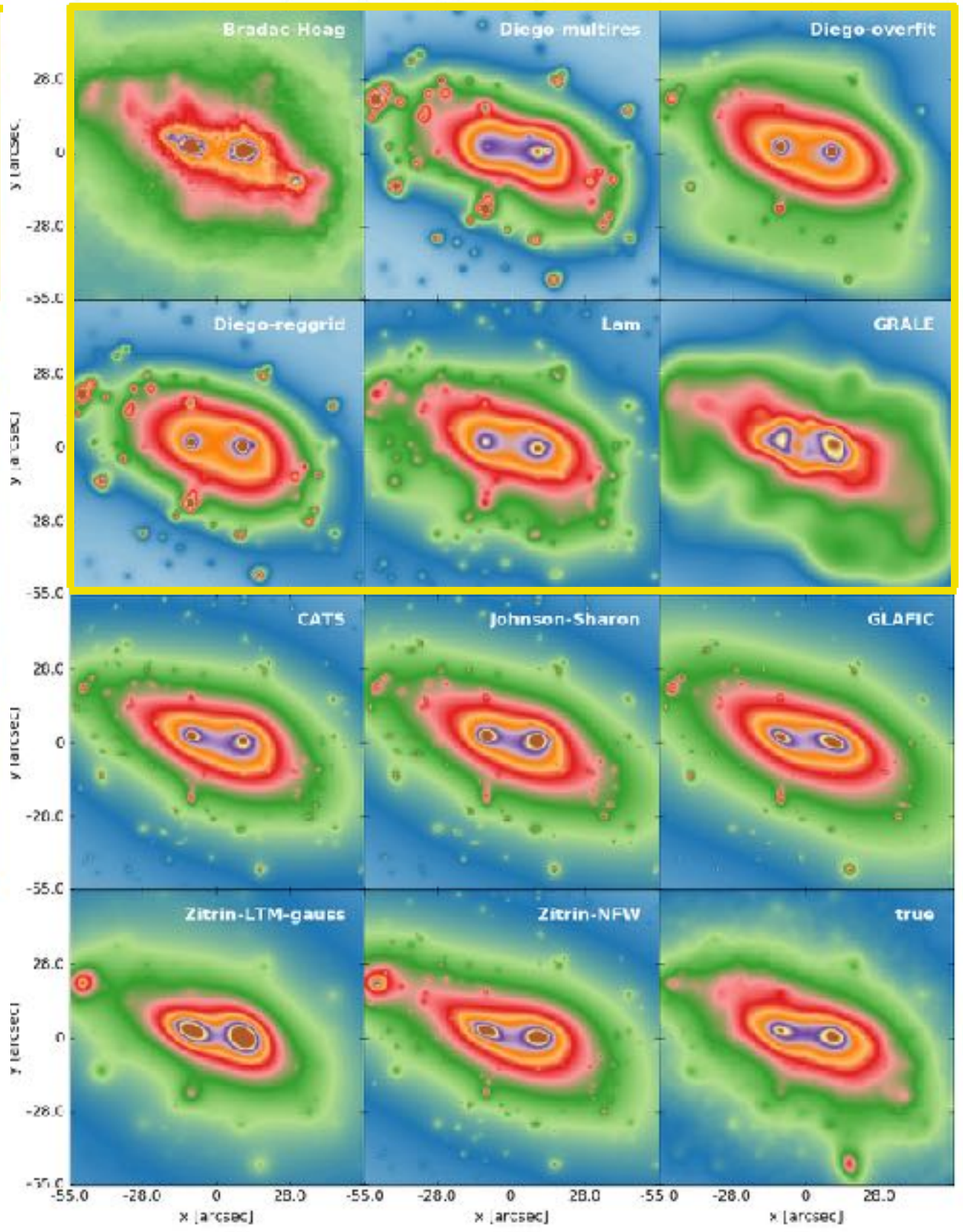
-90.0


Bradac Hoag
Diego-multires
Diego-overfit
Diego-reggrid
Lam
GRALE
CATS
Johnson-Sharon
GLAFIC
Zitrin-LTM-gauss
Zitrin-NFW
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x [arcsec]
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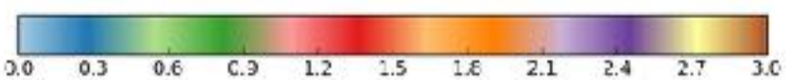
-55.0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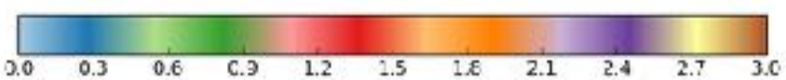
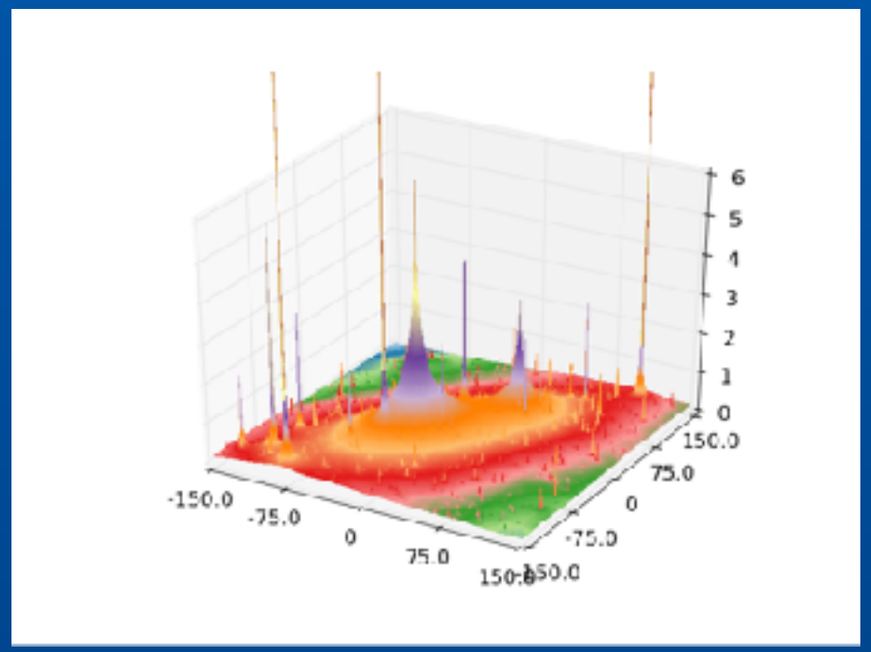
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0

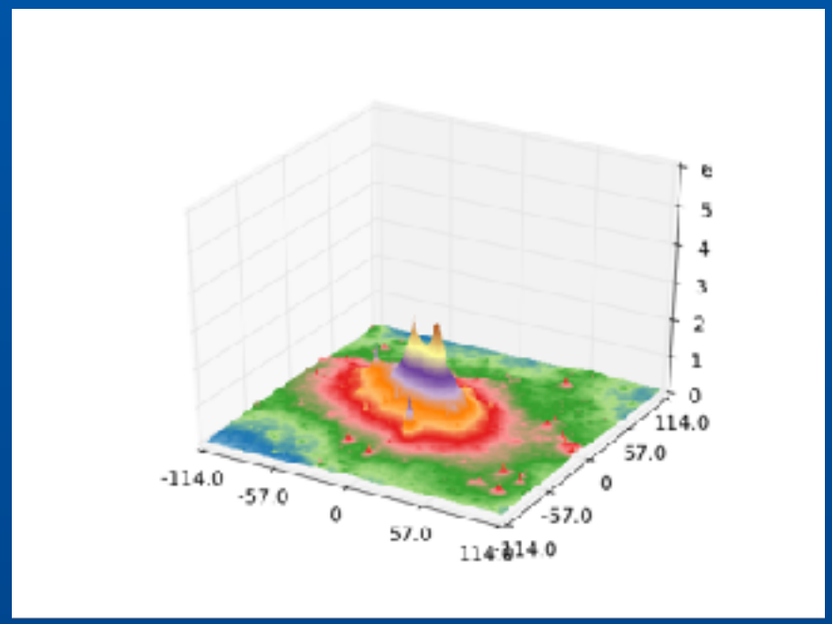

0.0
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0

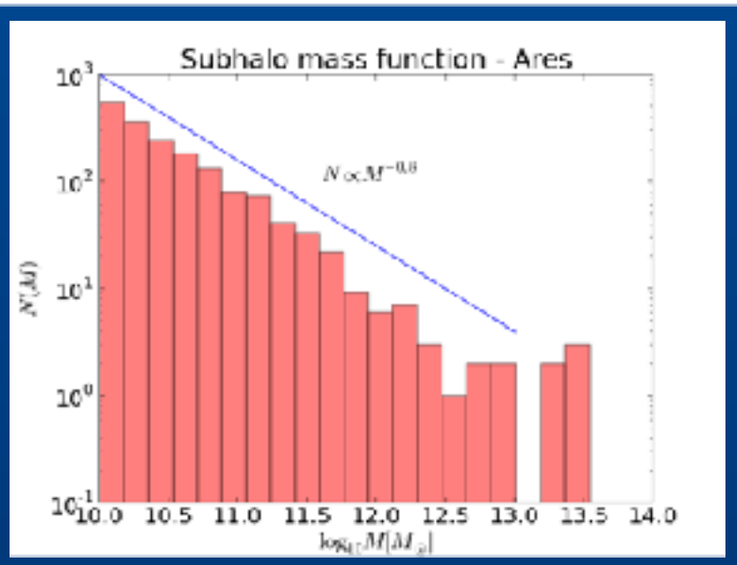
COMPARING RECOVERY OF SUBSTRUCTURE

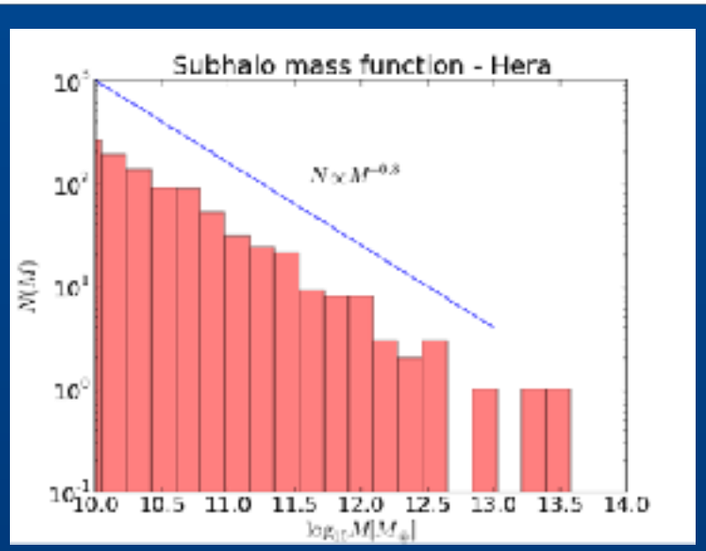
"Coring" to test how precise are models at the expected substructure locations

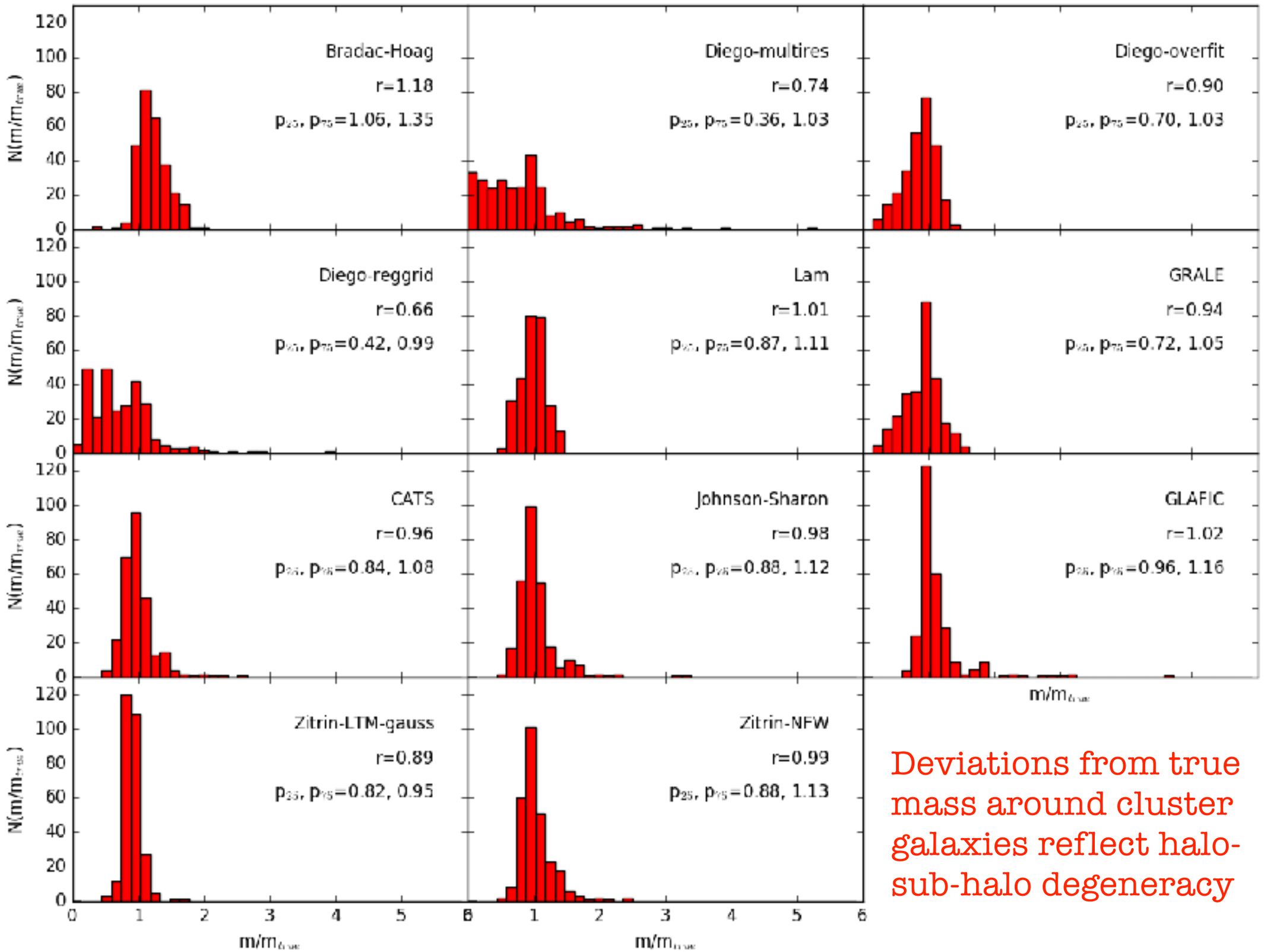
center at the galaxy positions, define apertures with radius equal to a few times the half-light radius, measure projected mass in aperture, repeat same procedure on true and reconstructed mass maps





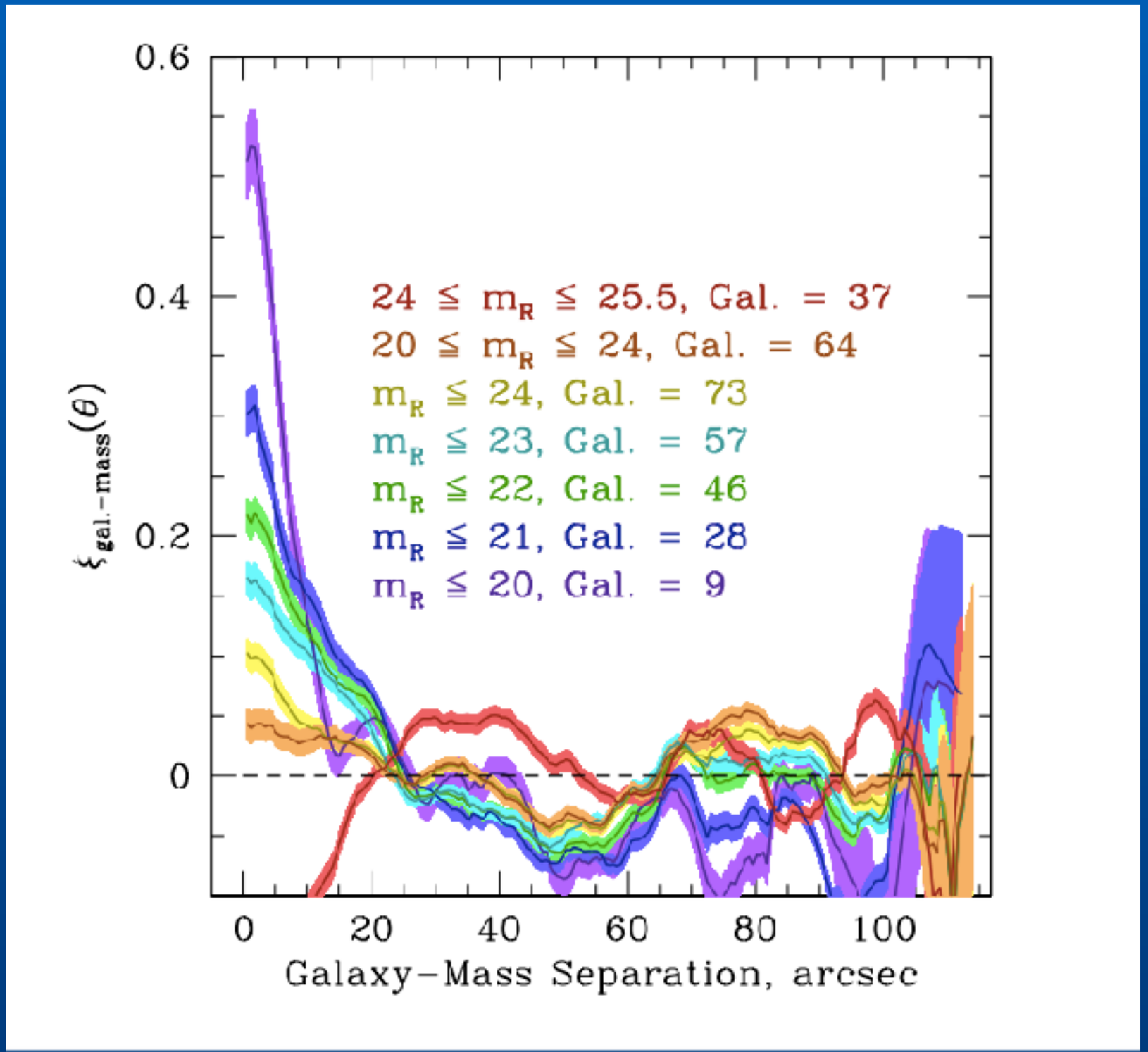






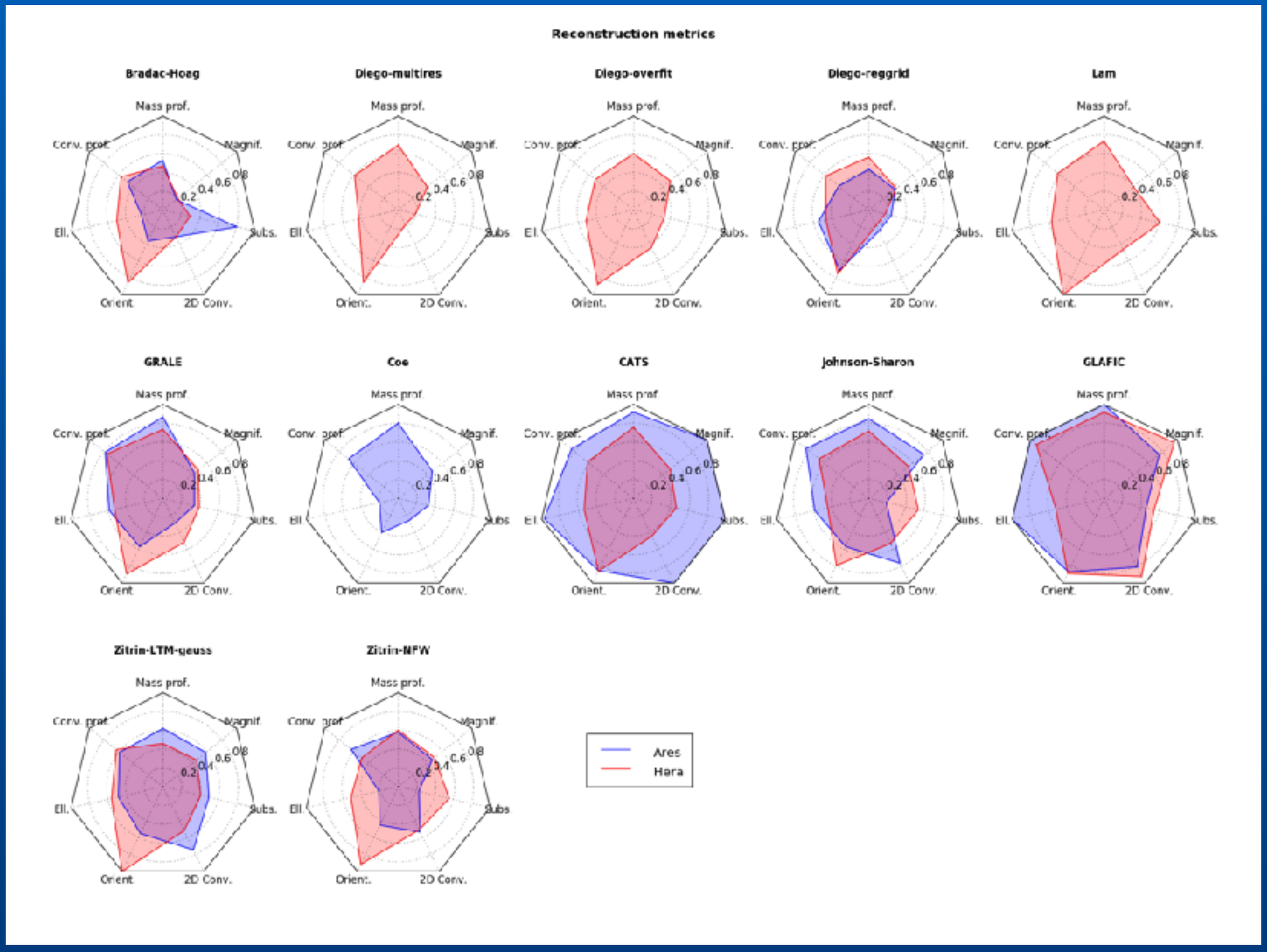
Deviations from true mass around cluster galaxies reflect halo-sub-halo degeneracy

HOW WELL DO LIGHT & MASS TRACE EACH OTHER?
Galaxy-Mass correlation function

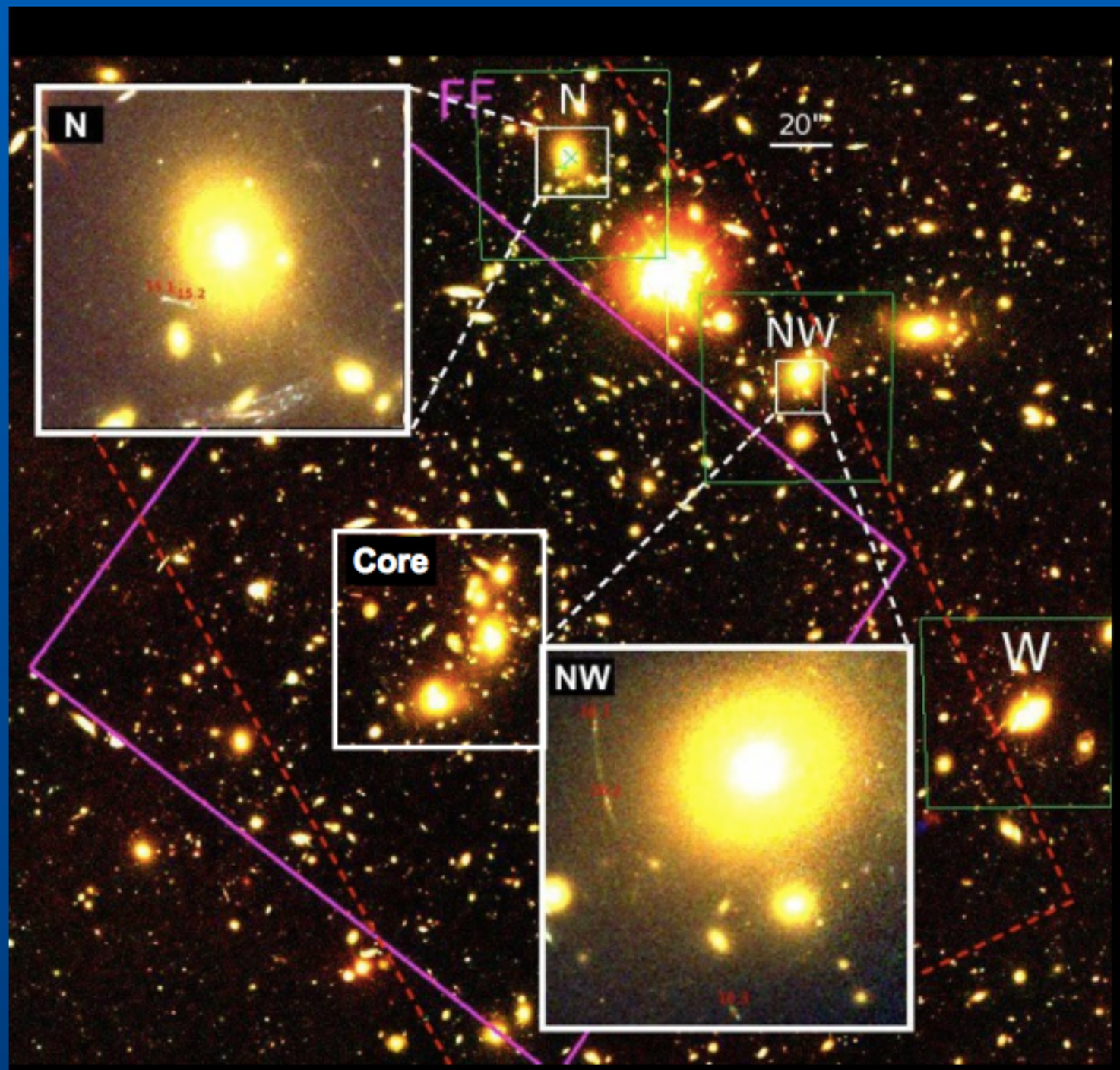


Sebesta+ 16

COMPARISON OF METHODS
combined metric for several recovered properties



LENS MODELING CONSTRAINTS BEFORE THE HSTFF



Previous GL analysis :

Smail et al. 1997, *APJ, 479, 70*
Allen 1998, *MNRAS, 296, 392*
Merten et al. 2011, *MNRAS, 417, 333*

- Lensing + X-ray
- SL constraints :

34 images of 11 galaxies

- Active merger with 4 cluster-mass components

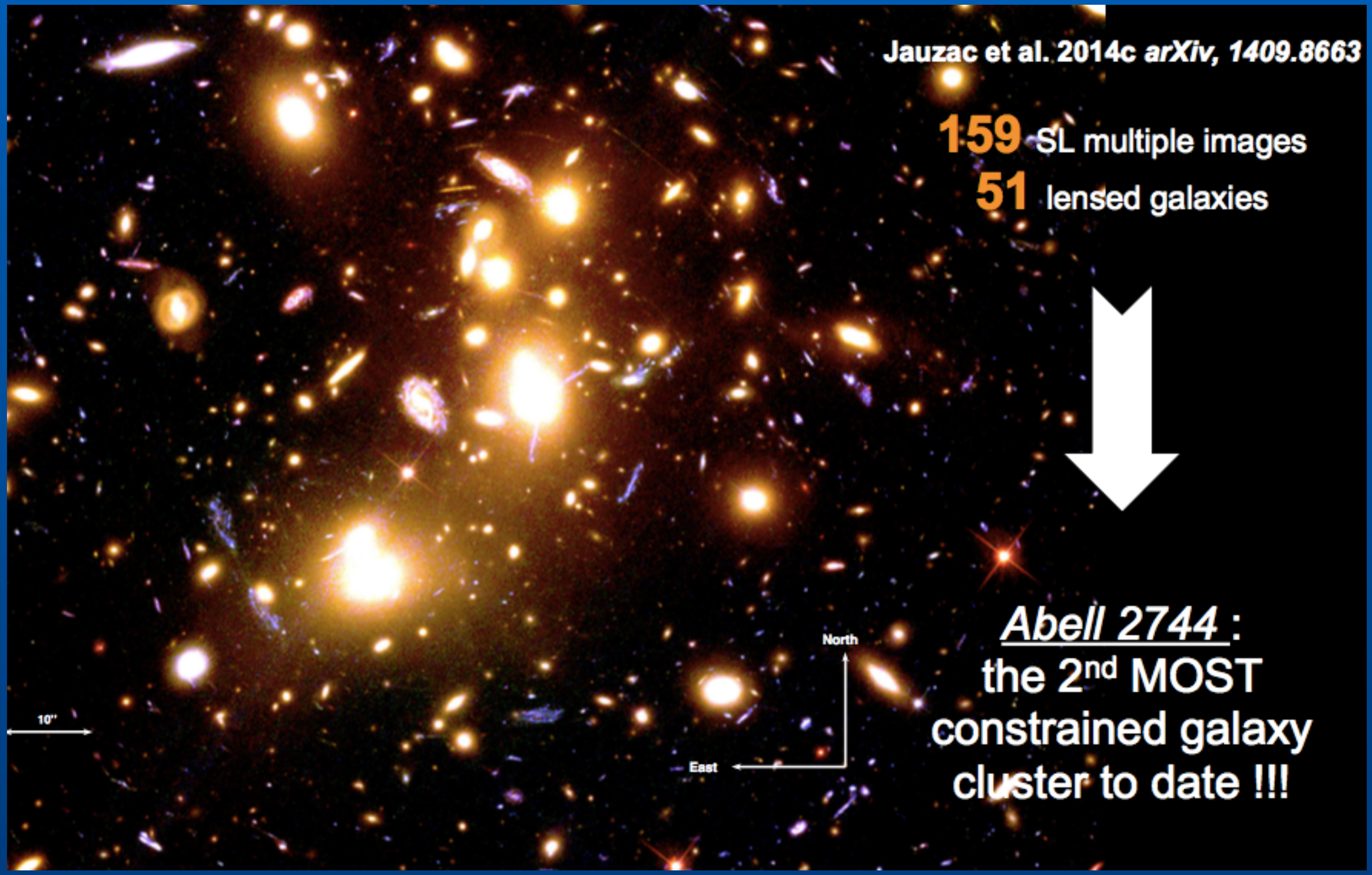
PreHFF GL analysis :

Richard, Jauzac et al. 2014, *MNRAS, 444, 268*
Johnson et al. 2014, *arXiv 1405.0222*
Coe et al. 2014, *arXiv 1405.0011*

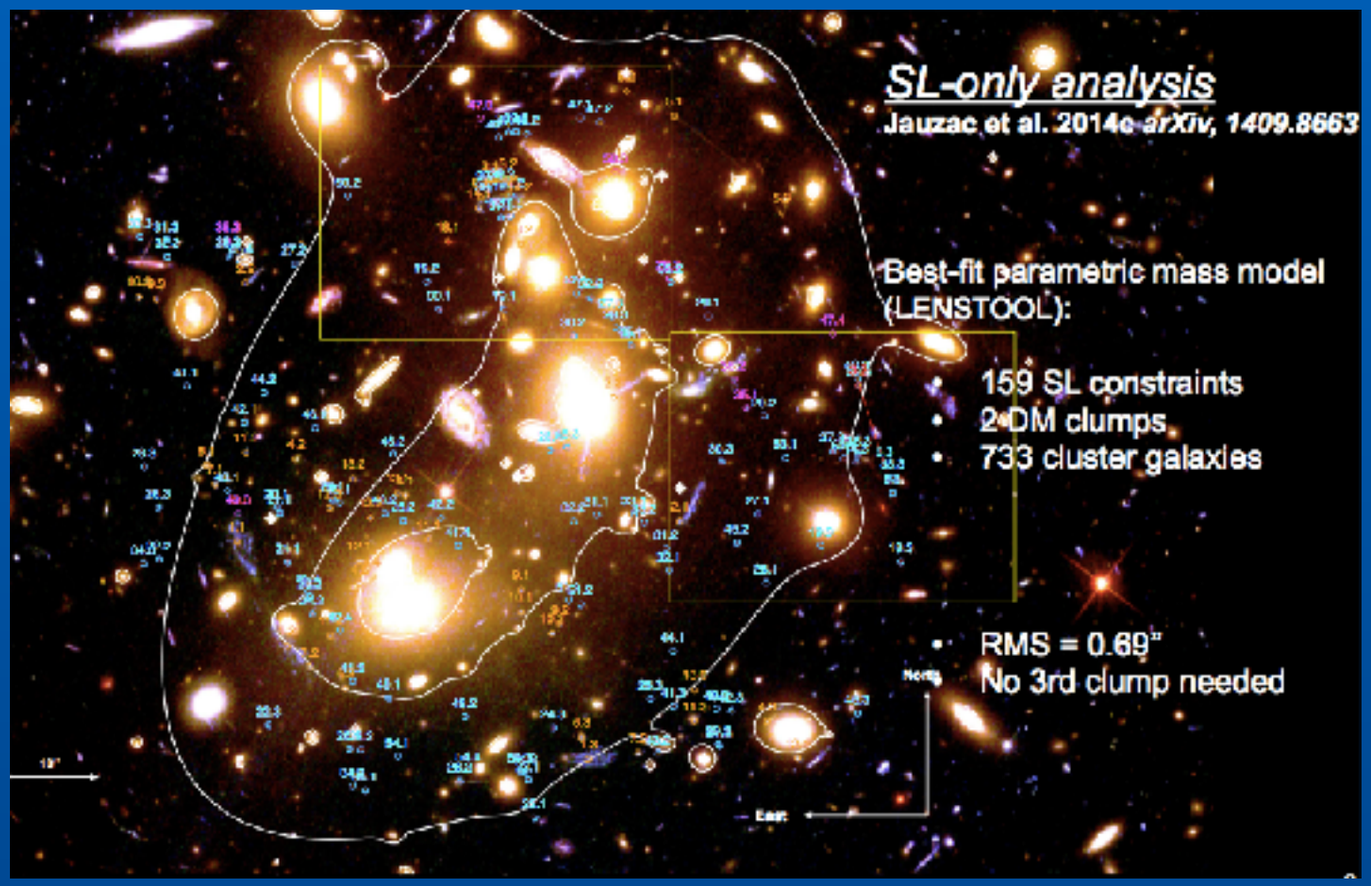
- SL constraints :

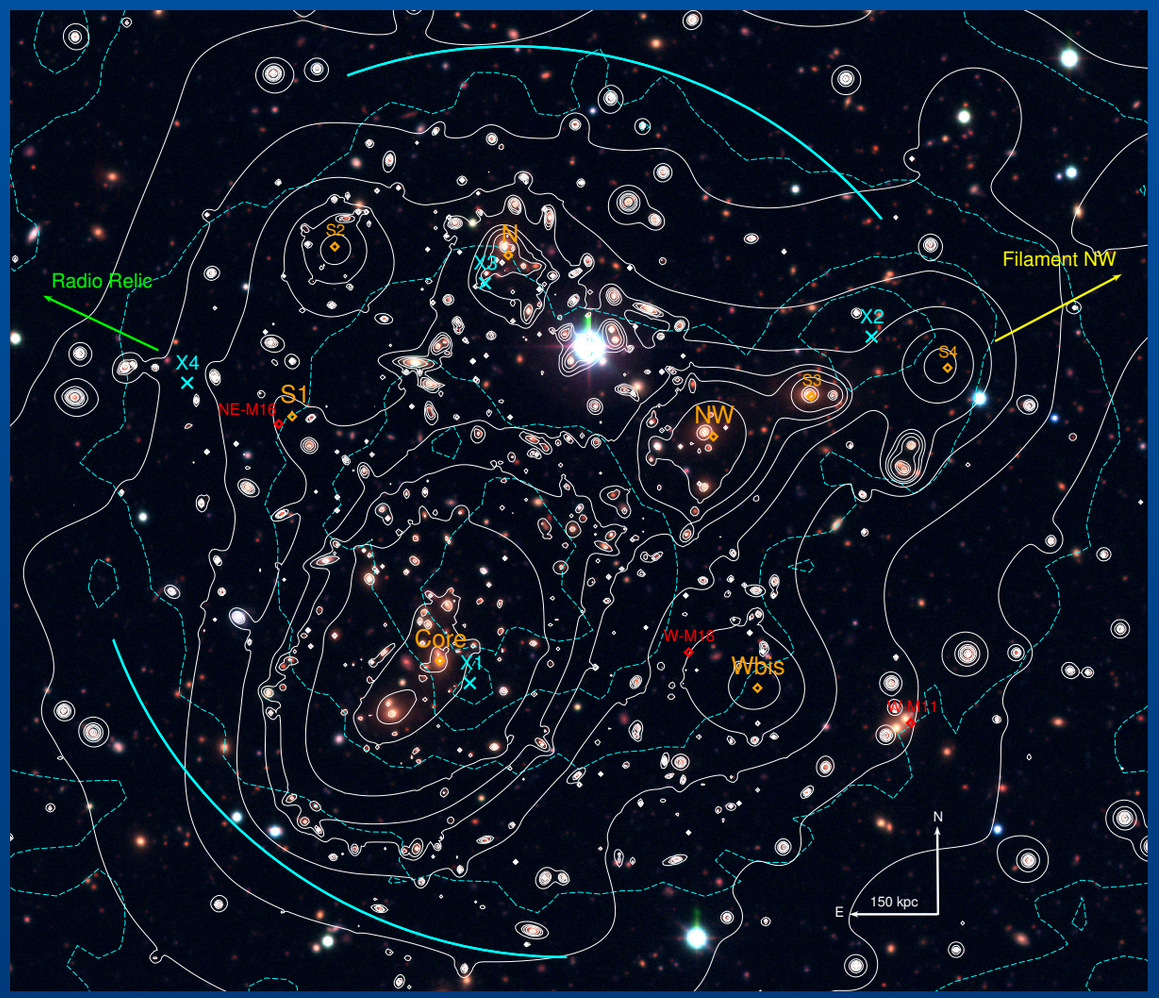
55 images of 18 galaxies
- 5 cluster-mass components

LENS MODELLING POST HFF

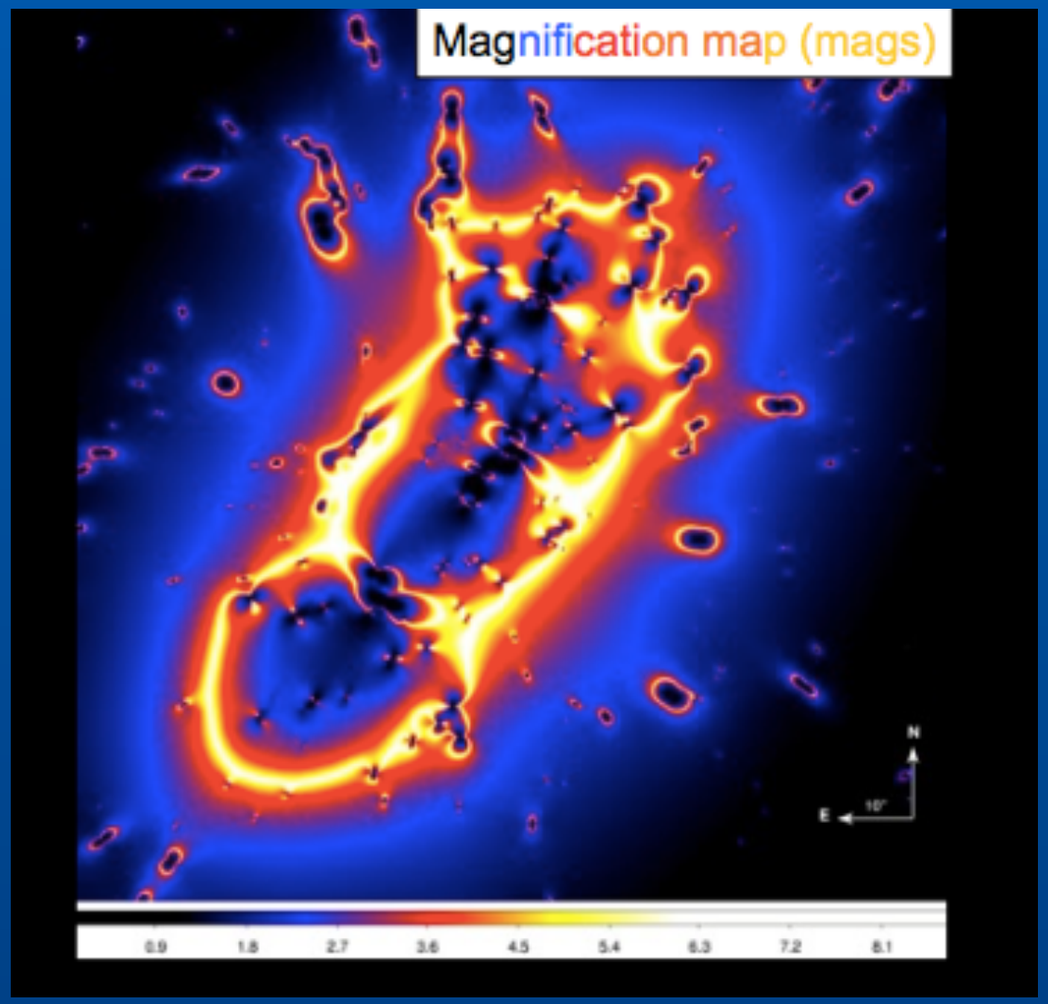


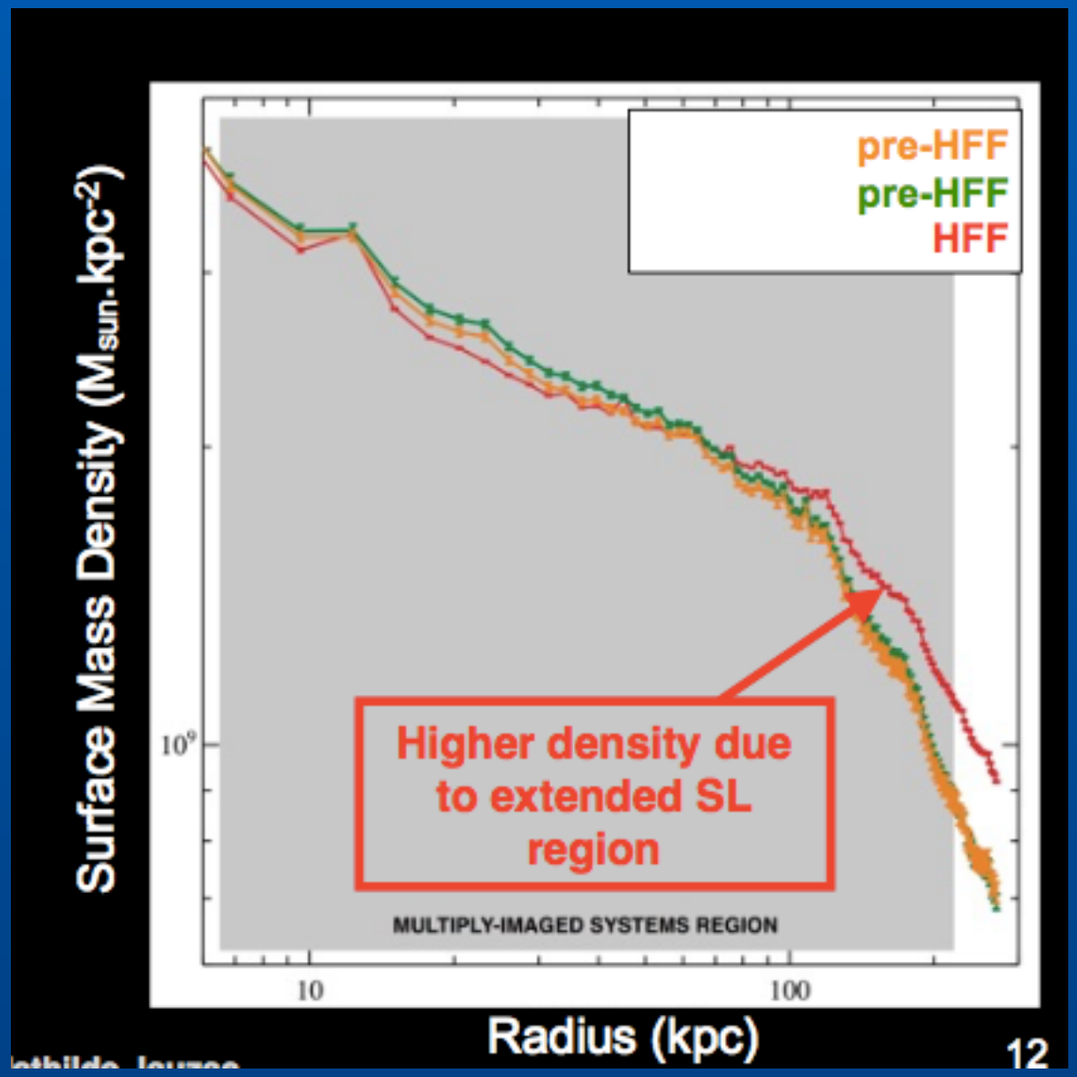
BEST-FIT MASS MODEL FOR Abell 2744



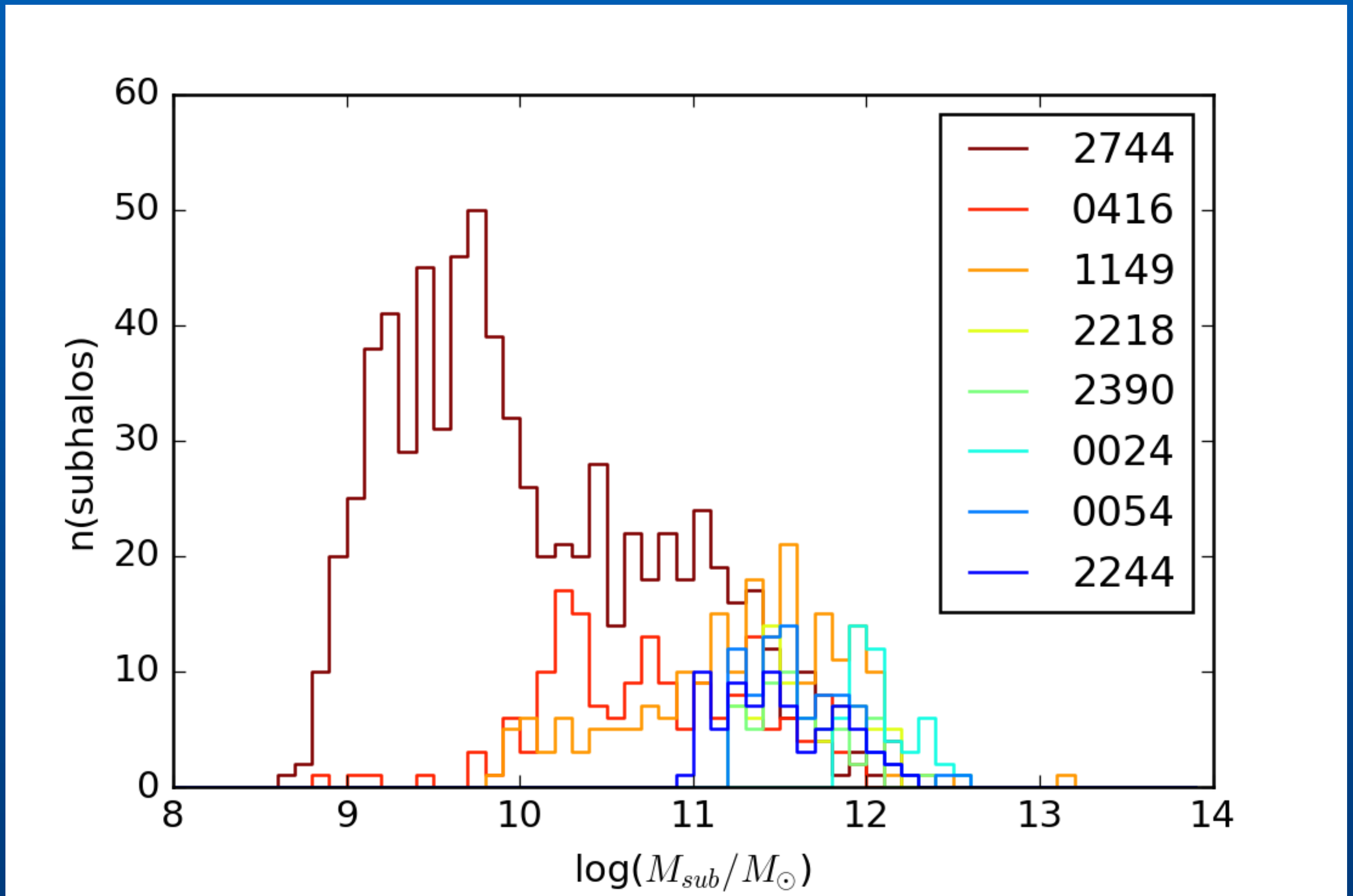


BEST-FIT MASS MODEL FOR Abell 2744

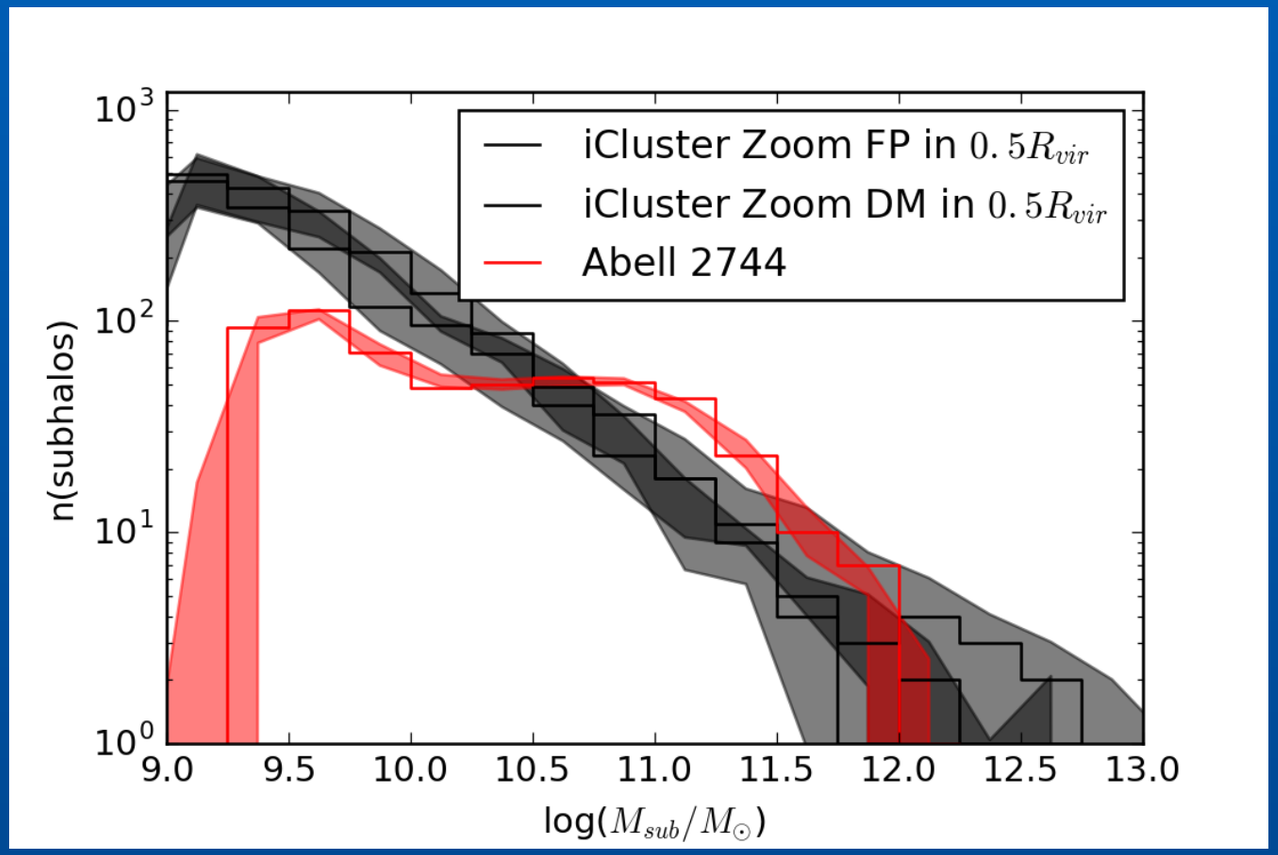


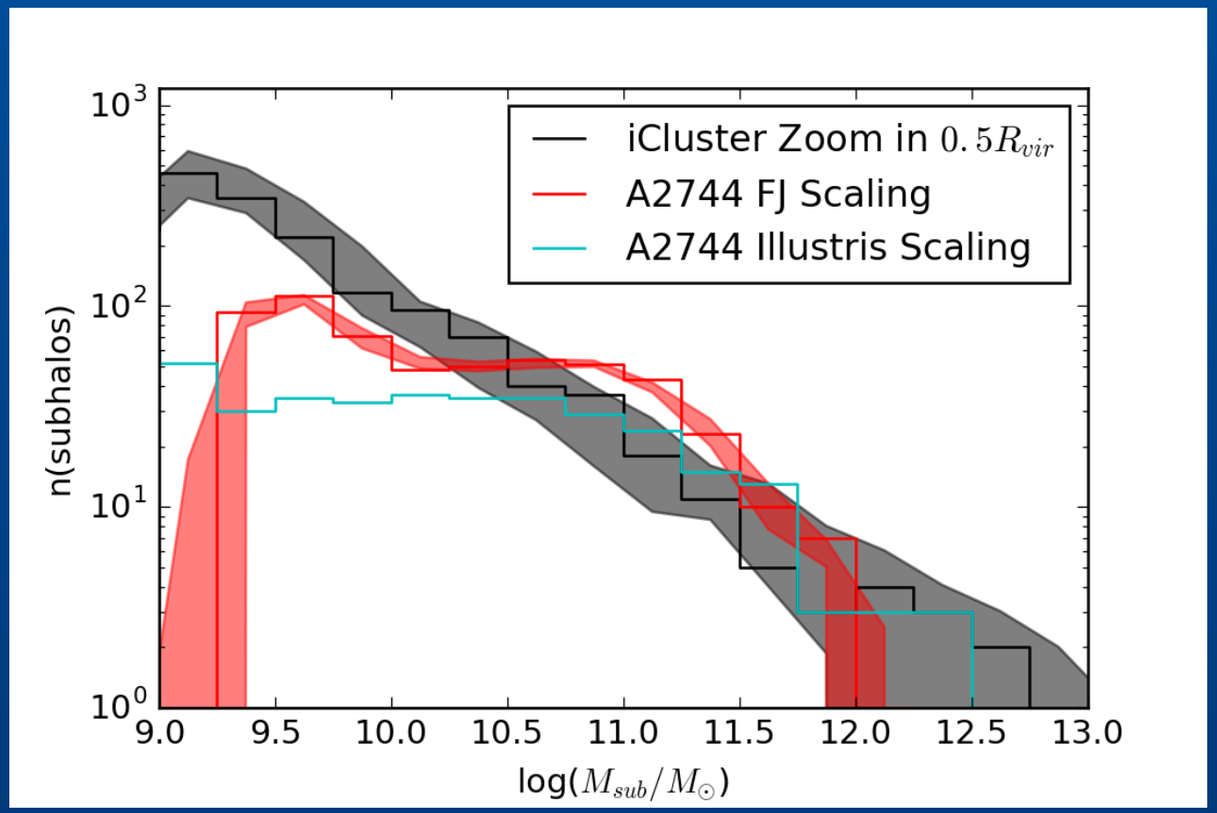


LENSING DERIVED SUBHALO MASS FUNCTION



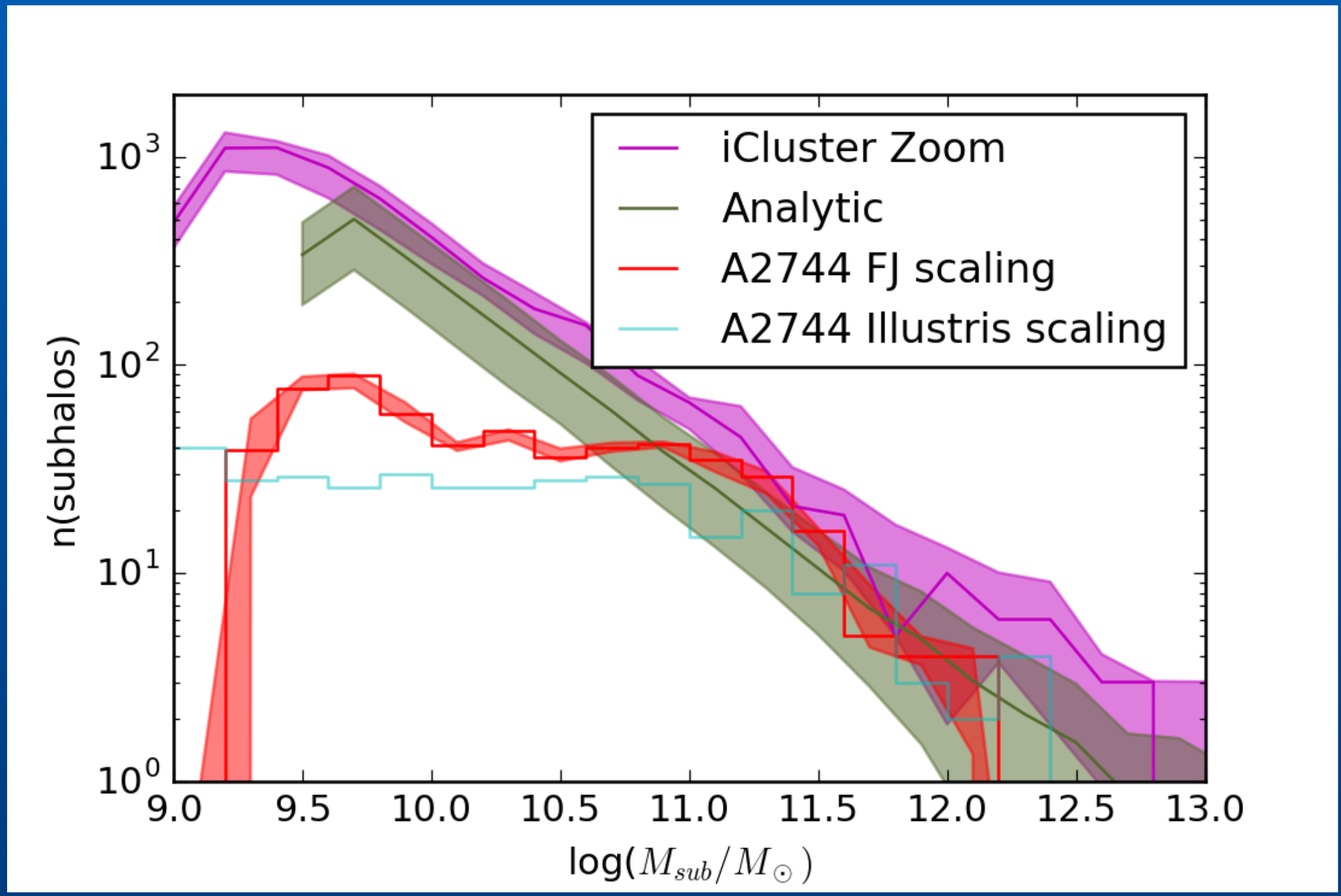
COMPARISON OF HSTFF SUBSTRUCTURE WITH LCDM PREDICTIONS



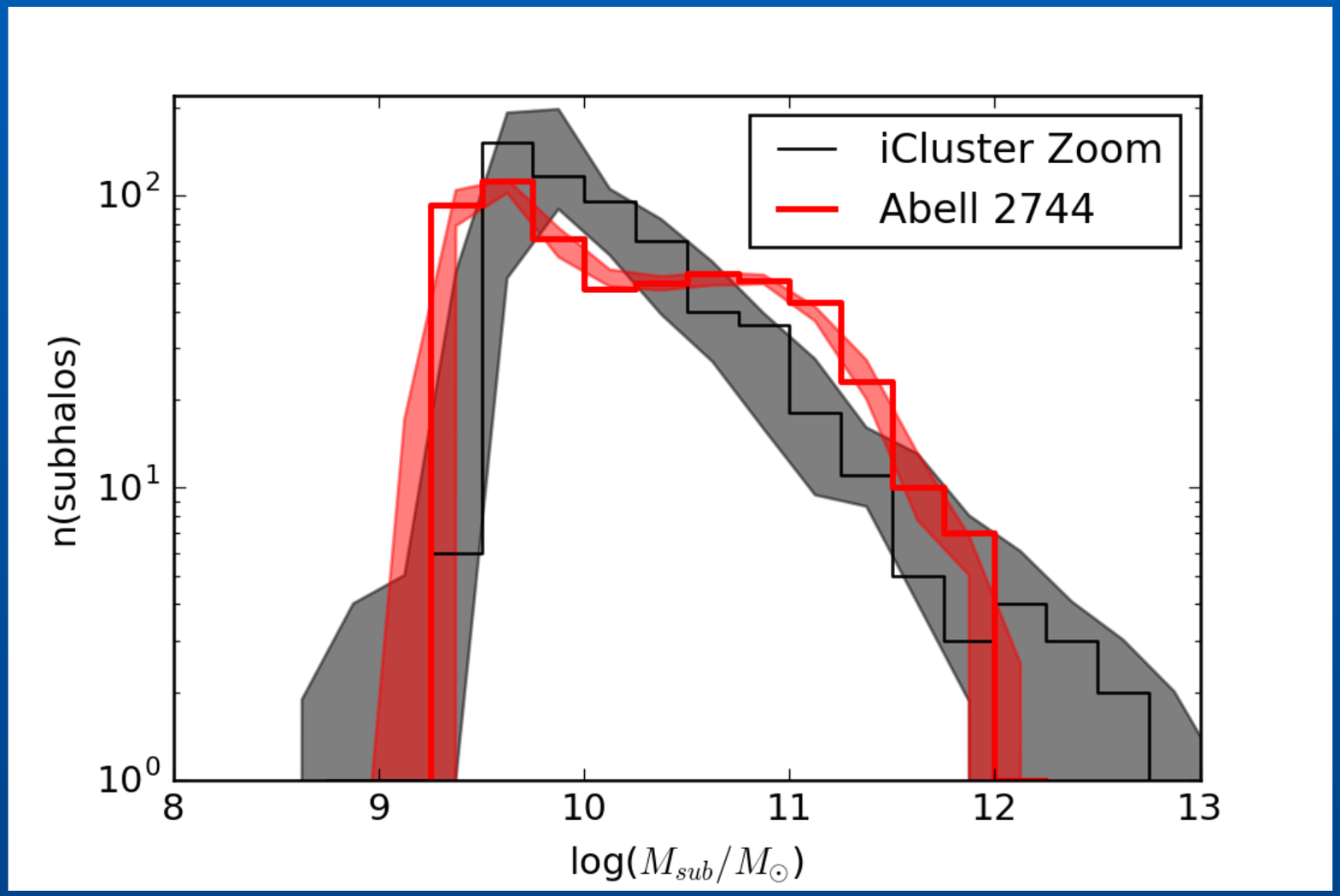


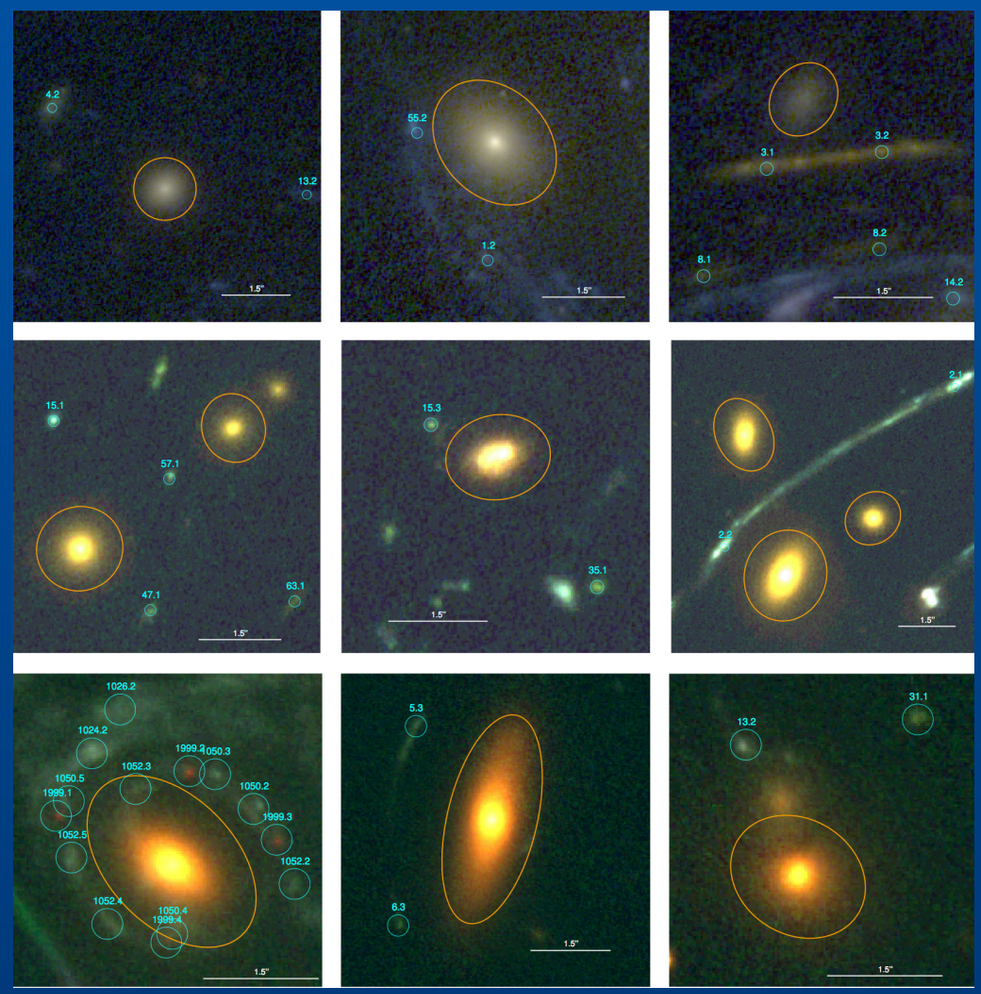
PN+ 17

COMPARISON OF HSTFF SUBSTRUCTURE WITH LCDM PREDICTIONS



COMPARISON OF HSTFF SUBSTRUCTURE WITH LCDM PREDICTIONS





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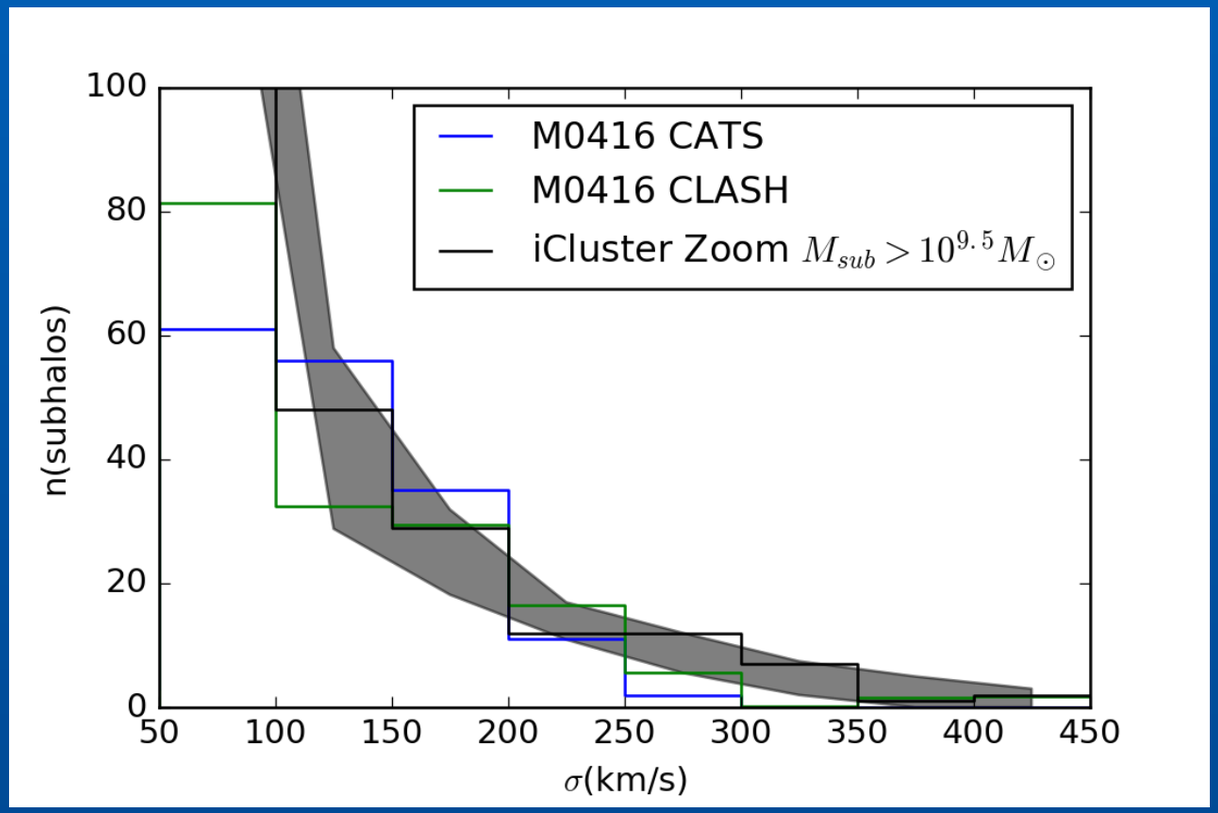

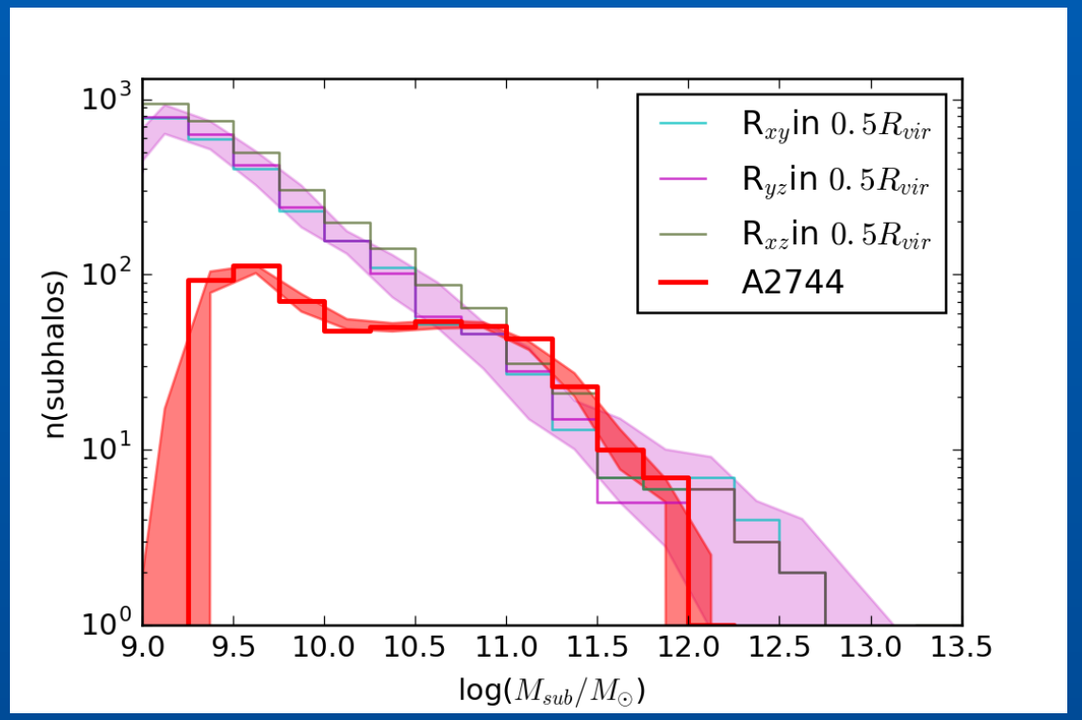

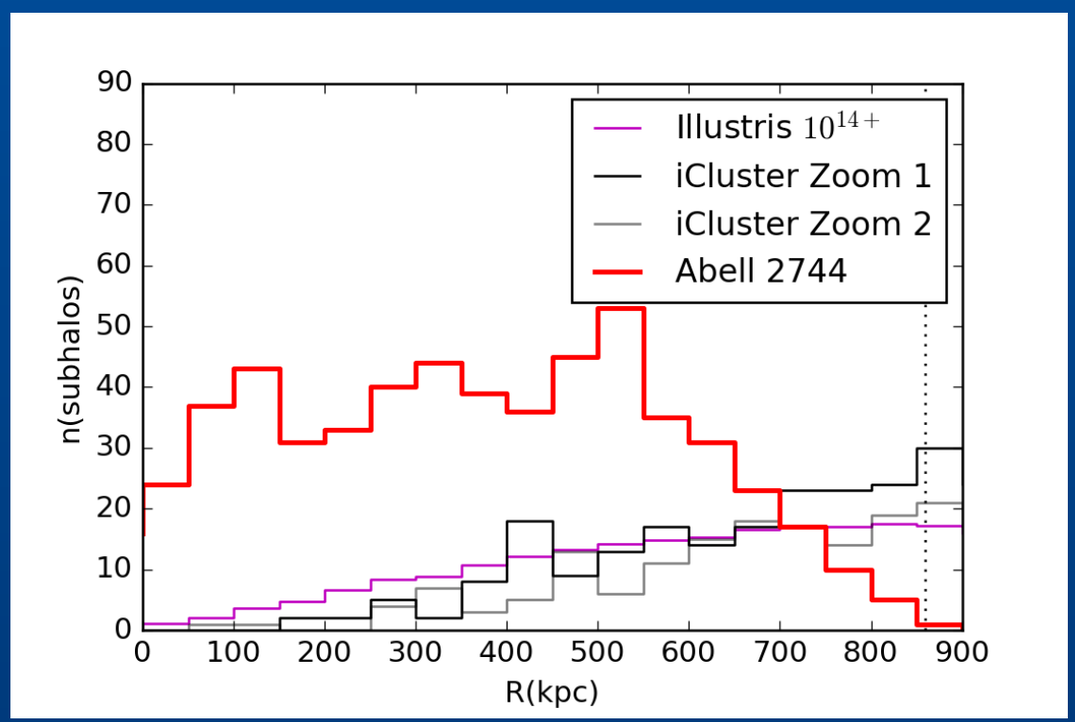

see also Schwinn+ 17 analysis of Eagle simulations

CURRENT STATUS OF RELATION BETWEEN MASS & LIGHT FROM CLUSTER-LENSES

- Light appears to trace mass with high fidelity within clusters as inferred from parametric and non-parametric lens reconstructions methods
- All lens modeling techniques have limitations even with HSTFF quality data at the present time
- Given the accuracy of the reconstruction techniques available caution advised in assessing any claims about dark clumps, displacement between light and mass in the inner regions
- The SHMF derived in the inner regions of cluster-lenses is in good agreement with theoretical LCDM expectations for parametric reconstruction methods
- The SHMF in the inner regions of cluster lenses is in very good agreement with mass matched Illustris clusters
- However the spatial distribution of sub halos in LCDM simulations is markedly different from the radial distribution inferred from lensing
- Need new formalism to address the relationship between mass and light in transient, assembling structures like massive cluster lenses