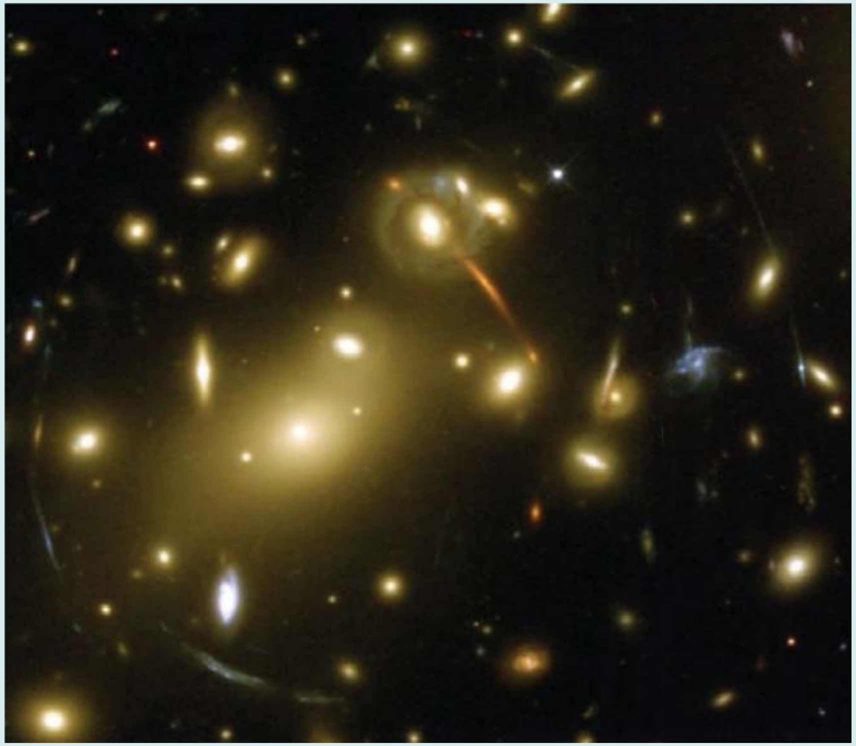
Diagnosing emerging tensions in the cold dark matter model? & more….



Priyamvada Natarajan
Departments of Astronomy & Physics
Yale University

The Hubble Constant Controversy: Status, Implications and Solutions, November 10, 2018
WE-Heraeus Symposium, Berlin

Talk Outline

I. Cluster-lenses as cosmic laboratories to probe the underlying cosmological model – current status in terms of potential tensions with LCDM

II. Cosmography with cluster strong lensing (CSL) to probe dark energy models. While CSL is not sensitive to H_0 it is also a geometric method that has degeneracy similar to SNe but orthogonal to other cluster diagnostics

III. Current results and future prospects for constraining w(z) with cluster-lenses using CSL – analysis in progress for the HSTFF sample

IV. Closing philosophical considerations on what is special about the LCDM that makes it hard to falsify (history of how it was developed and honed)

Collaborators

- **CATS** Jean-Paul Kneib, Johan Richard, Mathilde Jauzac, Hakim Atek, Eric Jullo, Marceau Limousin, Harald Ebeling, Benjamin Clement, Eiichi Egami, Ana Acebron
- **ILLUSTRIS** Lars Hernquist, Mark Vogelsberger, Volker Springel and the Illustris collaboration
- Urmila Chadayammuri
- Anson D'Aloisio
- Massimo Meneghetti
- **History & Philosophy of Science**

  David Kaiser, Barry Loewer, Tim Maudlin

Cluster-lenses are powerful cosmic laboratories

- Uniquely offer constraints on dark matter and dark energy simultaneously
- Originally the objects that provided evidence for the existence of dark matter
- Test-bed for two independent regimes – dynamically (classical Newtonian view) and gravitational lensing (GR)

Composition

~1 % mass is in galaxies; ~ 10% mass is in hot gas; the rest is dark matter

Characterizing clusters

how much mass? Newtonian estimate, Lensing estimate

does light trace mass? How biased are the tracers – gas & stars

how is the dark matter distributed? Test of the world model

how granular is the dark matter? Test of the nature of dark matter

Cluster-lenses

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)

Lensing constraints on dark enery

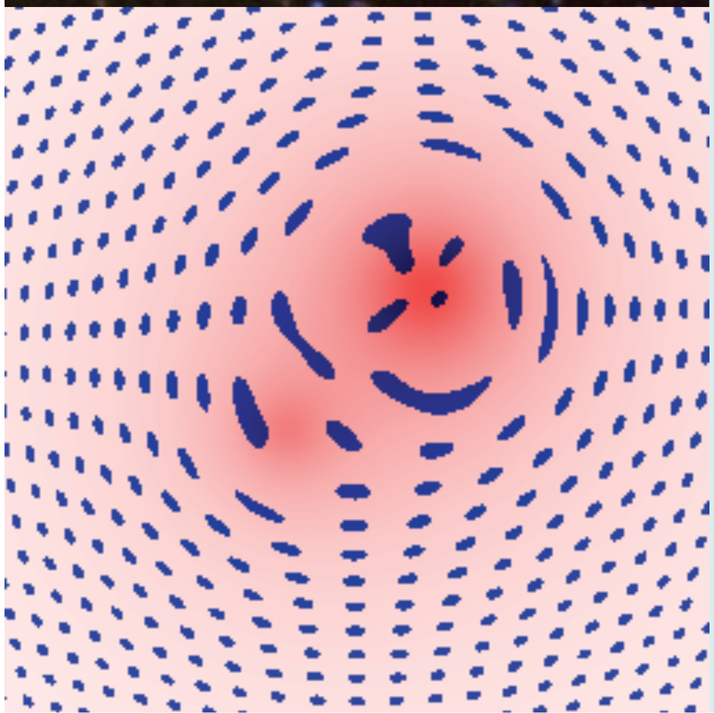
Cosmography with strong lensing (CSL)

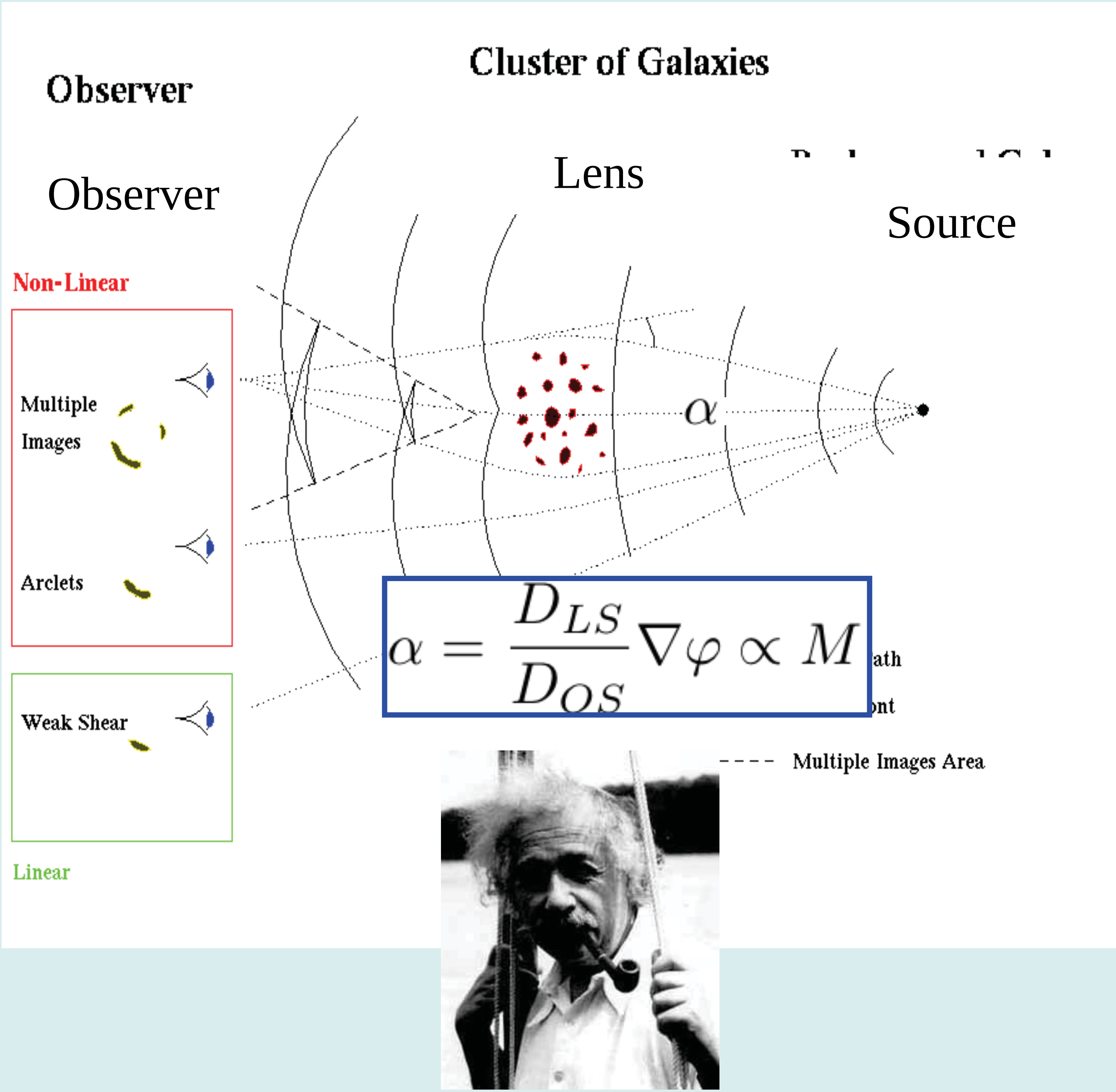
Triplet statistics

Lensing tests of the standard world model

Primordial Non-Gaussianity (Arc-statistics)

Growth of Structure and Structure Formation



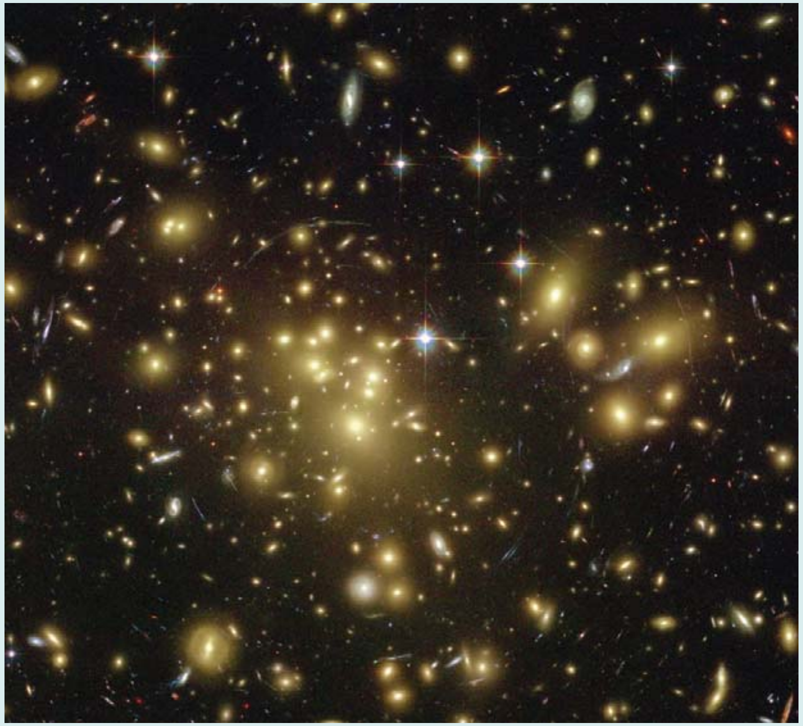


$$\alpha = \frac{D_{LS}}{D_{OS}} \nabla \varphi \propto M$$

Strong lensing

multiple images, highly distorted and magnified arcs, depletion of background number counts

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



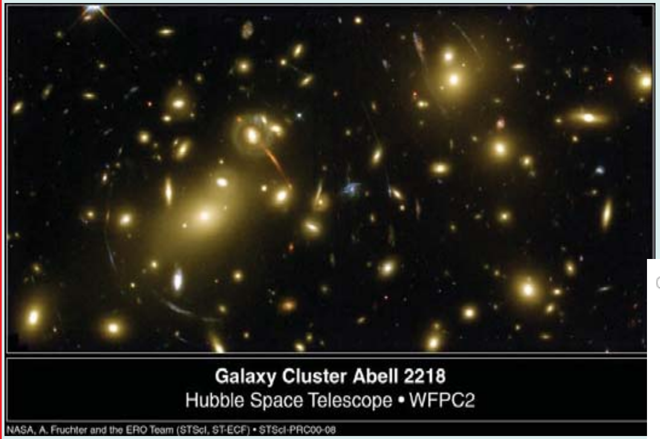
Weak lensing

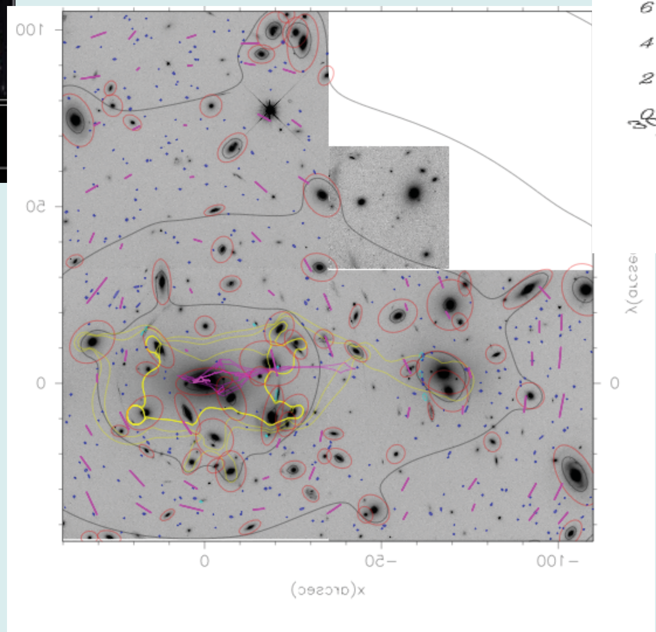
coherent distortion in the shapes of background galaxies

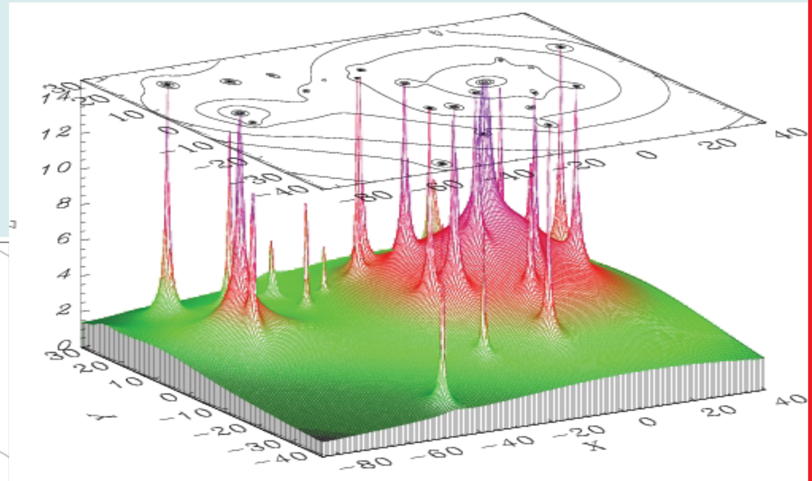
- Shear field used to construct mass map

MAPPING SUBSTRUCTURE IN CLUSTERS

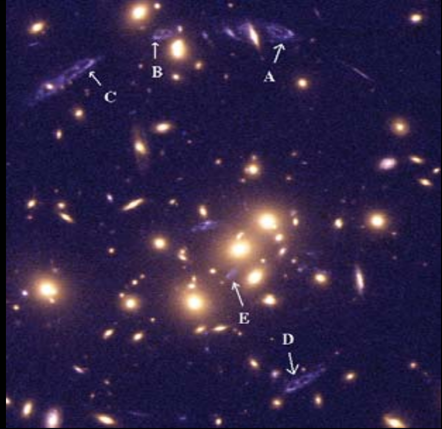
$$\Phi_{cluster} = \sum_i \Phi_{smooth} + \sum_n \Phi_{perturbers}$$

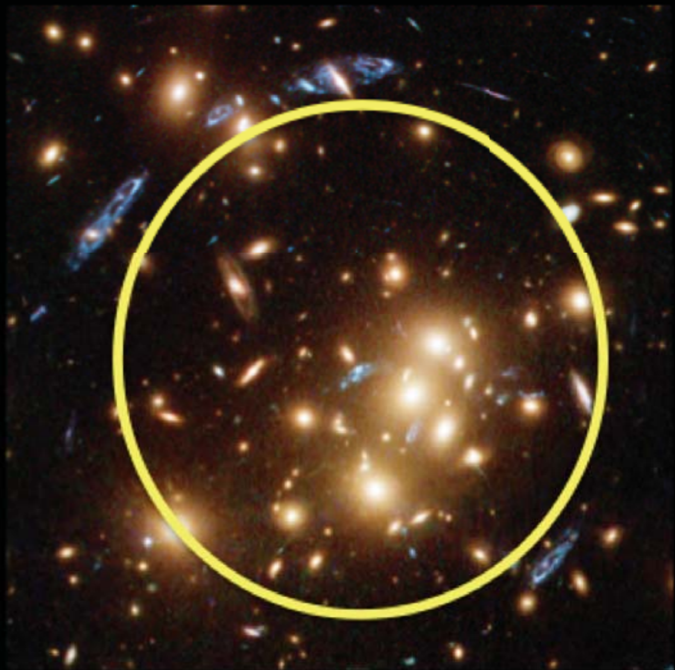


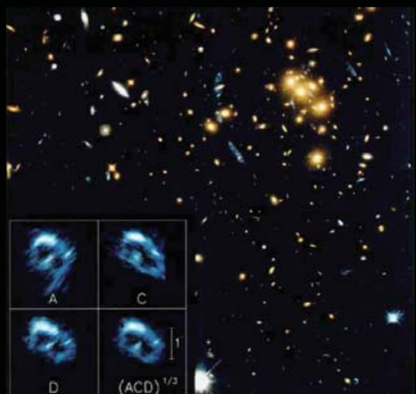


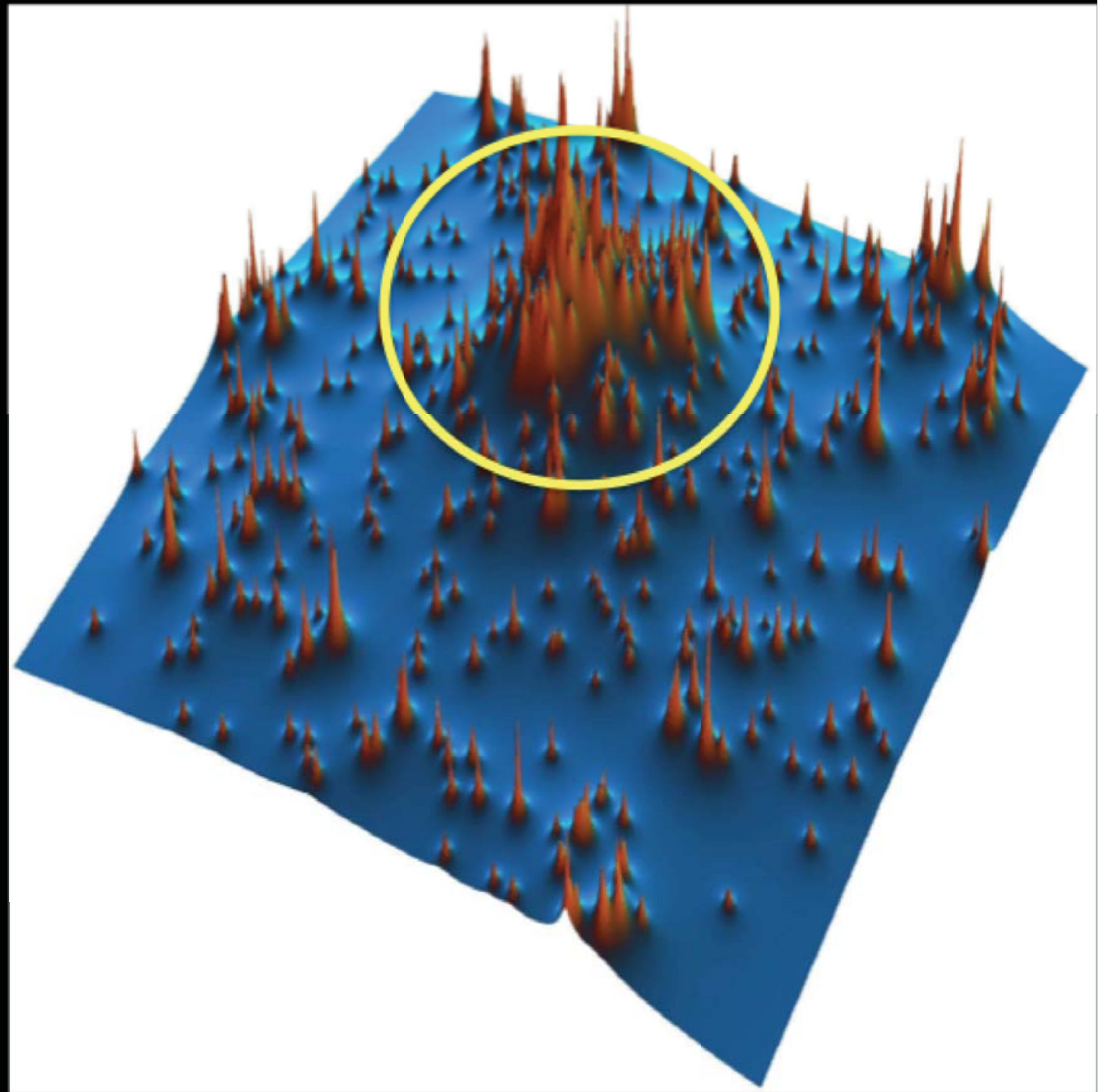


PN & Kneib 97;14; PN+ 05; 09; 11

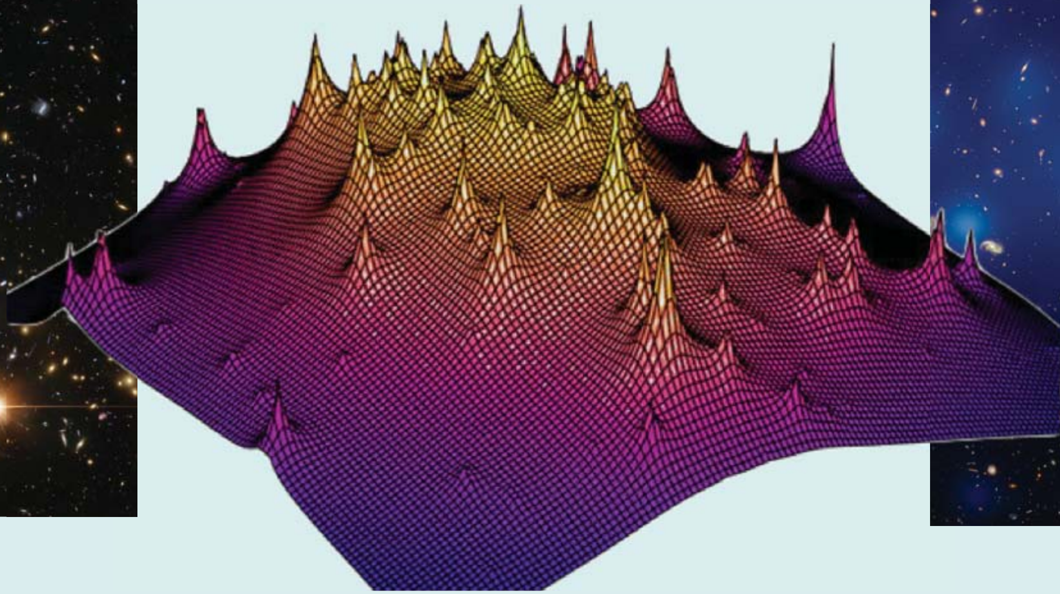

B
A
C
E
D




A
C
D
(ACD)^1/3
1

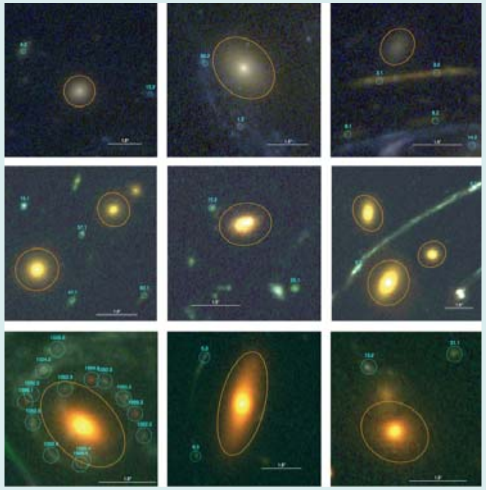


HUBBLE FRONTIER FIELDS

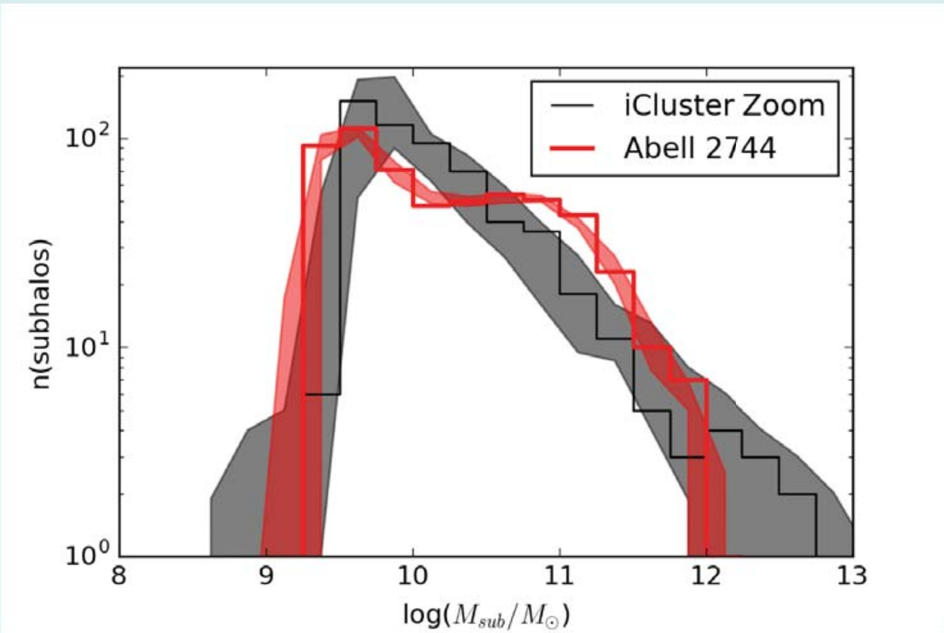


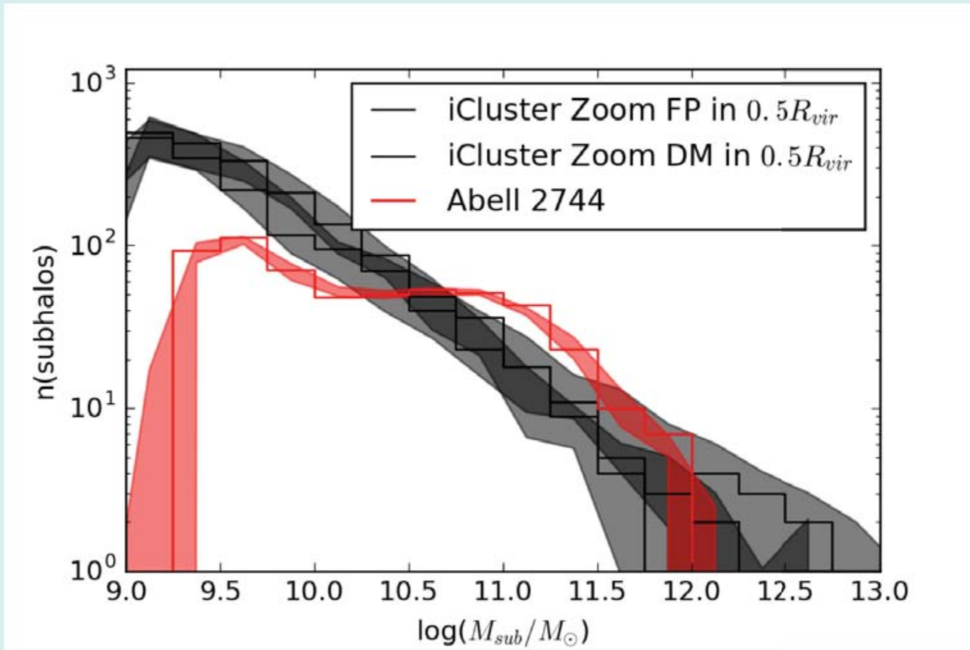
Comparison with Illustris LCDM clusters

NO SUBSTRUCTURE CRISIS !



SUBHALO MASS FUNCTION Agrees with LCDM

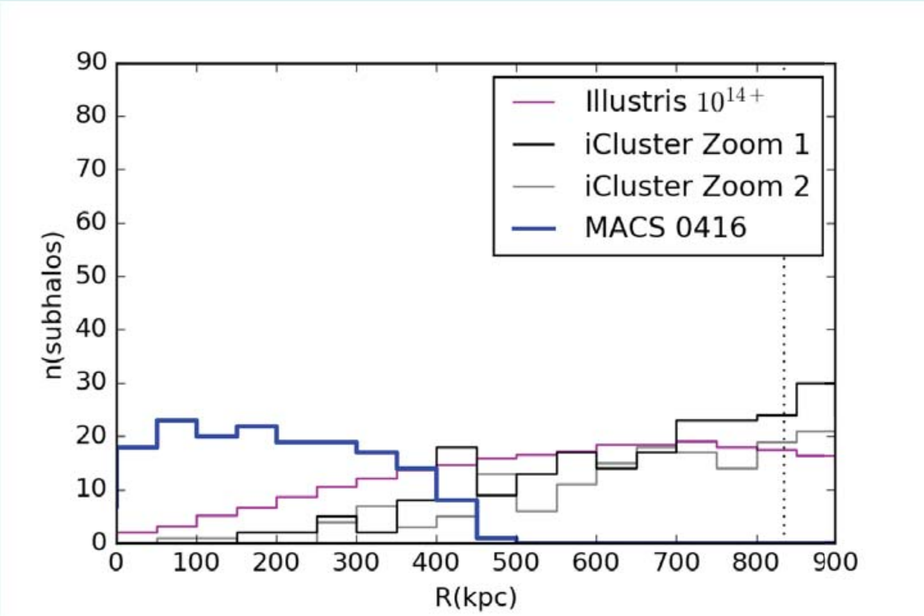


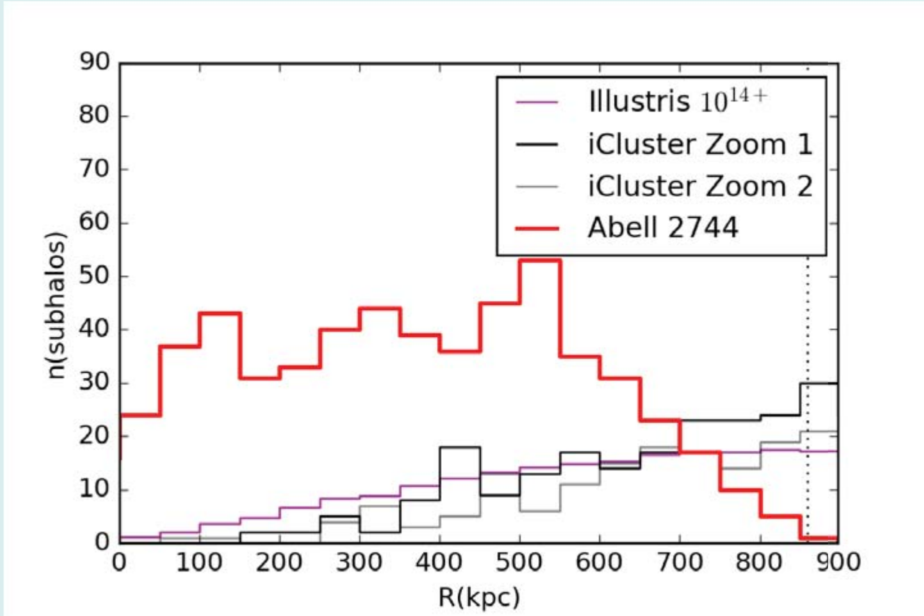


PN & Springel 04; PN, De Lucia & Springel 07; PN, Chadayammuri+ 17

Comparison with Illustris LCDM clusters

Radial distribution of subhalos





POTENTIAL TENSION WITH LCDM

Properties of simulated subhalos associated with cluster galaxies have

Systematic issues in simulations

(over-efficient tidal stripping) van den Bosch+

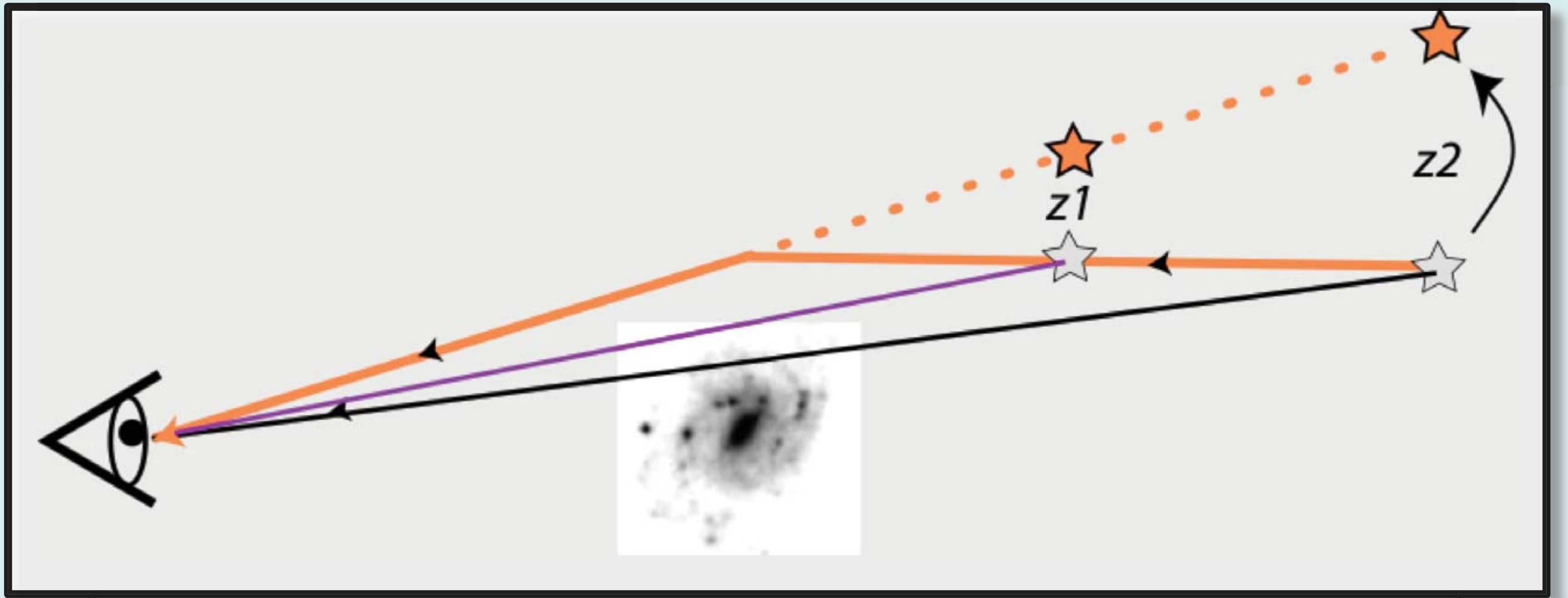
Halo finder systematics? Over-efficient tidal stripping?

Cluster-lenses "special" Transient states? Missing physics?

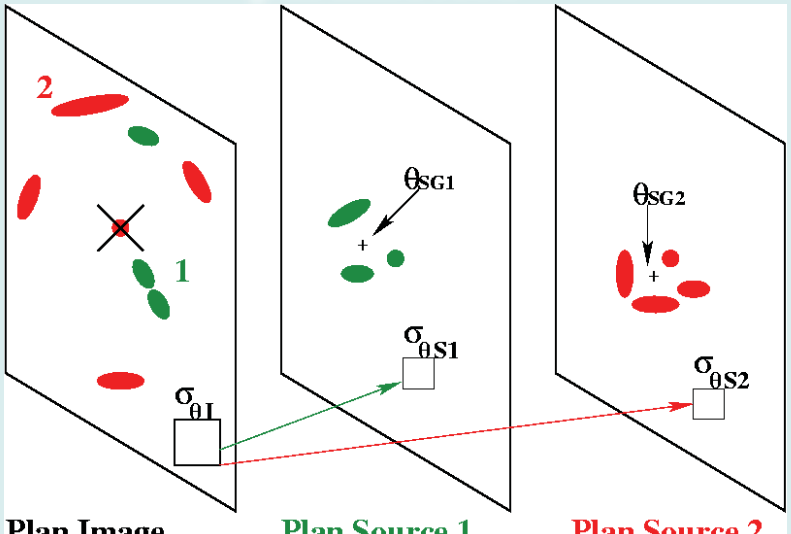
Are simulations missing/poorly modeling physics?

Hint of problem with LCDM? Do baryons & DM couple?

COSMOGRAPHY WITH CLUSTER STRONG LENSING
Einstein radii at multiple source redshifts

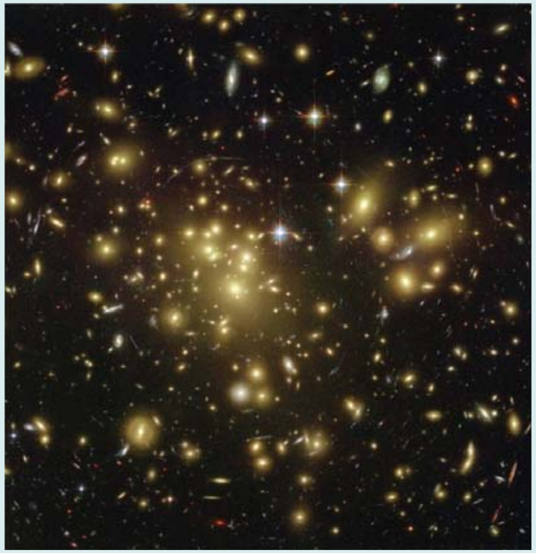


Ratio of the position of multiple images,depends on mass distribution and cosmological parameters



How does this work?

ISOTHERMAL SPHERE LENS lens at $z = z_L$; sources at z_{S_1} & z_{S_2}



$$D_{ij} \equiv f(z_i, z_j, \Omega_M, \Omega_x, w_x)$$

$$\frac{R_{E_1}}{R_{E_2}} = [\frac{D_{LS_1}}{D_{OS_1}}][\frac{D_{OS_2}}{D_{LS_2}}]$$

Obtained from data

Solve for cosmological parameters

- EXTENDING TO MORE COMPLICATED MASS PROFILES AND MORE MULTIPLY IMAGED SOURCES

Hubble constant drops out

Multiple image families and sensitivity to dark energy

$$\boldsymbol{\theta} = \boldsymbol{\beta} + \boldsymbol{\alpha}(\boldsymbol{\theta}, \xi; M)$$

$$\xi = \frac{D(0, z_l)D(z_l, z_s)}{D(0, z_s)} \equiv \frac{D_{ol}\, D_{ls}}{D_{os}}$$

For multiple images of the same source

$$\boldsymbol{\beta}_f = \boldsymbol{\theta}_{f,i} - \boldsymbol{\nabla}\varphi_M(\boldsymbol{\theta}_{f,i}, \xi).$$

notation denotes the position of the i^{th} image of family f

Taking the ratio of 2 distinct families of multiple images

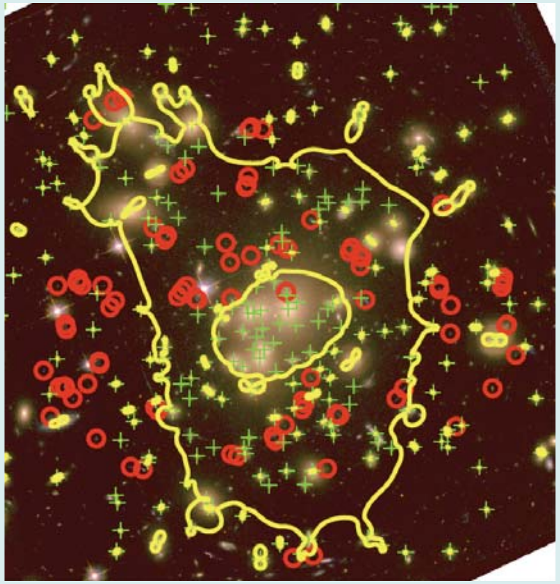
$$\left\{\frac{D_{ls1}}{D_{os1}}\frac{D_{os2}}{D_{ls2}}\right\}\frac{\sum_{i=1}^{m}\boldsymbol{\nabla}\phi_M(\boldsymbol{\theta}_{1,i})}{\sum_{j=1}^{n}\boldsymbol{\nabla}\phi_M(\boldsymbol{\theta}_{2,j})} = \frac{-m\boldsymbol{\beta}_1 + \sum_{i=1}^{m}\boldsymbol{\theta}_{1,i}}{-n\boldsymbol{\beta}_2 + \sum_{j=1}^{n}\boldsymbol{\theta}_{2,j}}.$$

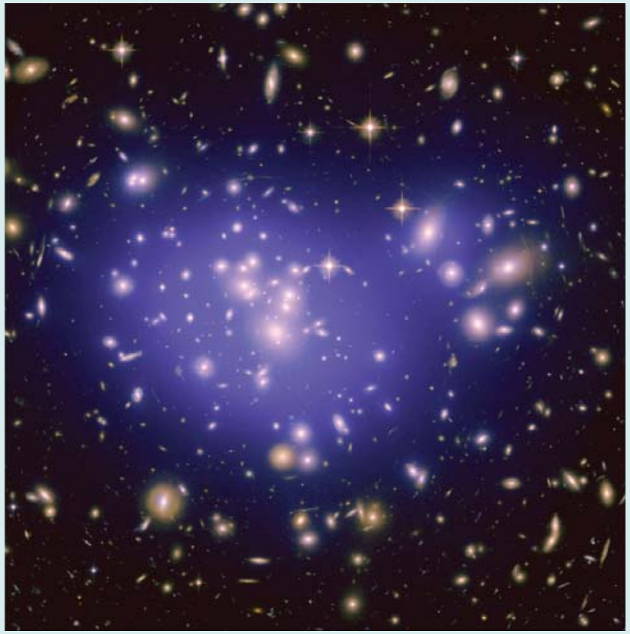
Dependence on the mass distribution

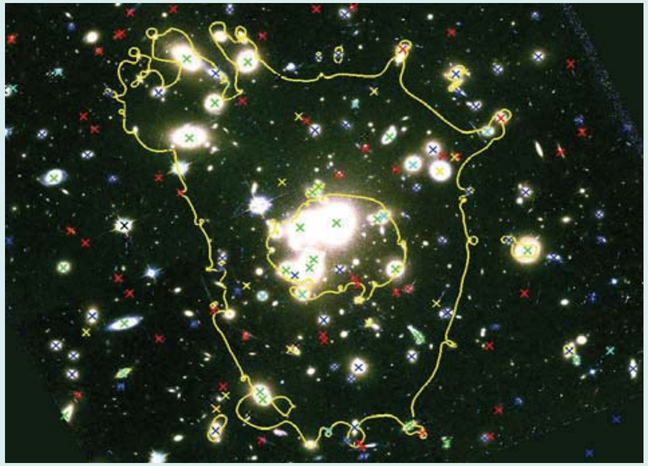
$$\Xi(z_1, z_{s1}, z_{s2}; \Omega_M, \Omega_X, w_X) = \frac{D(z_1, z_{s1})}{D(0, z_{s1})}\frac{D(0, z_{s2})}{D(z_1, z_{s2})}$$

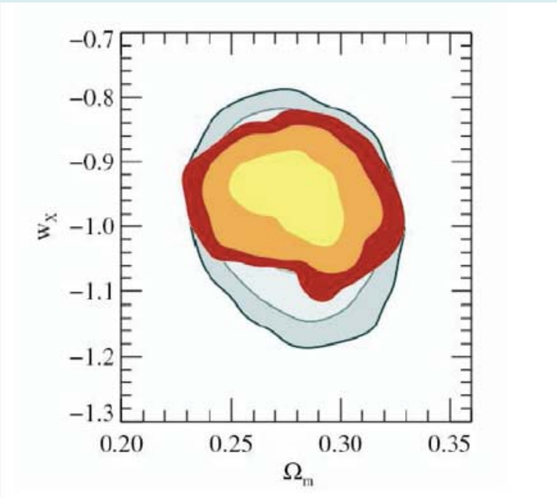
Gilmore & PN 09; D'Aloisio & PN 10; PN 10; Jullo, PN + 10

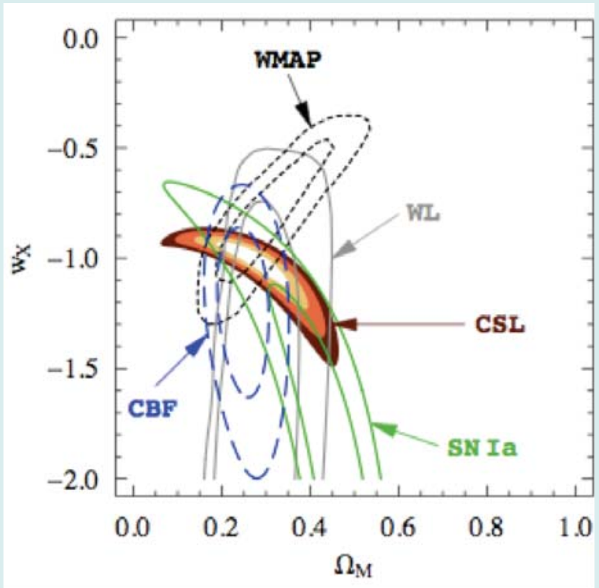
CSL results for A1689

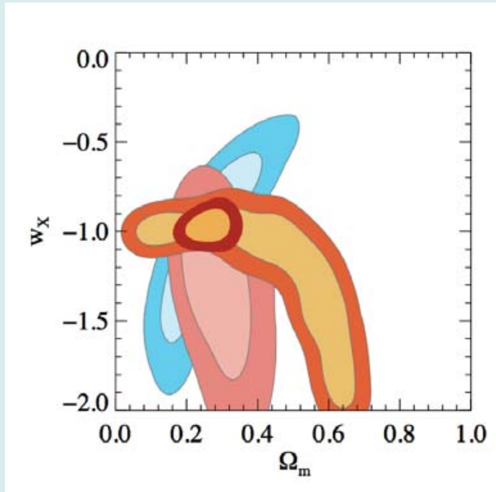












Contribution of structure behind the lens plane

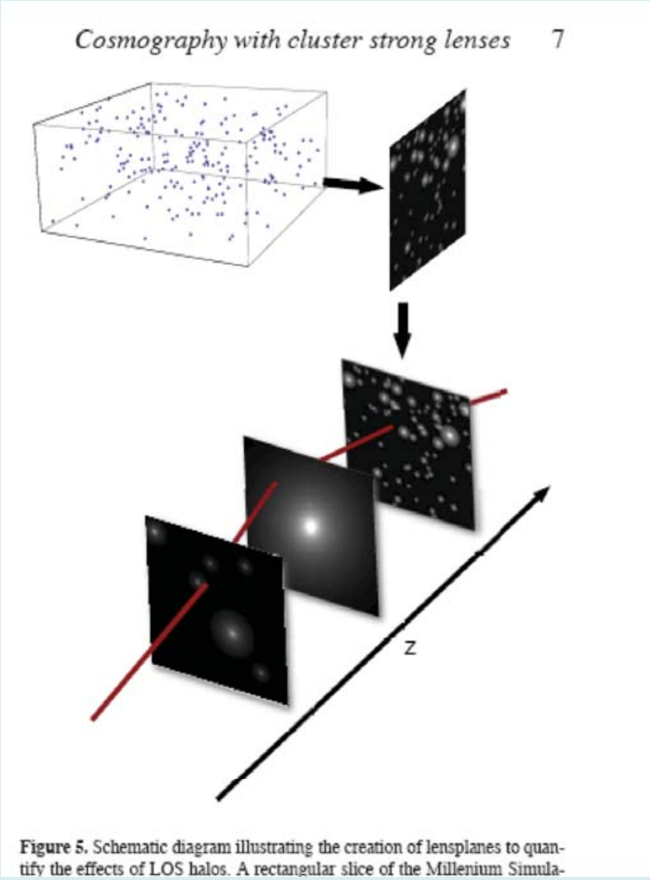
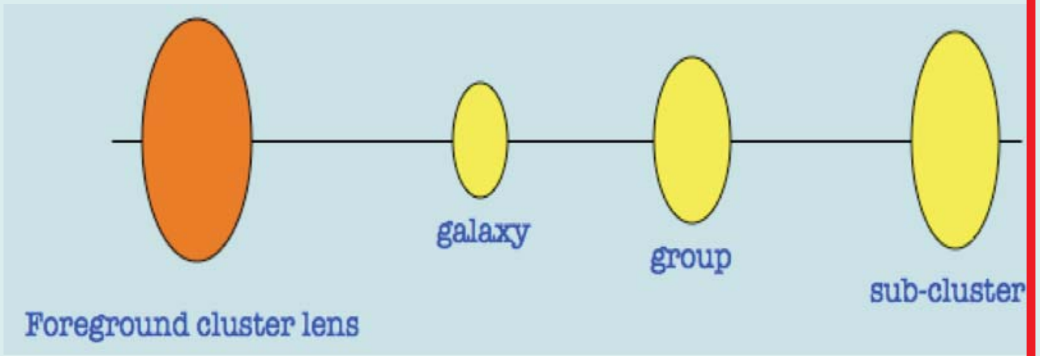
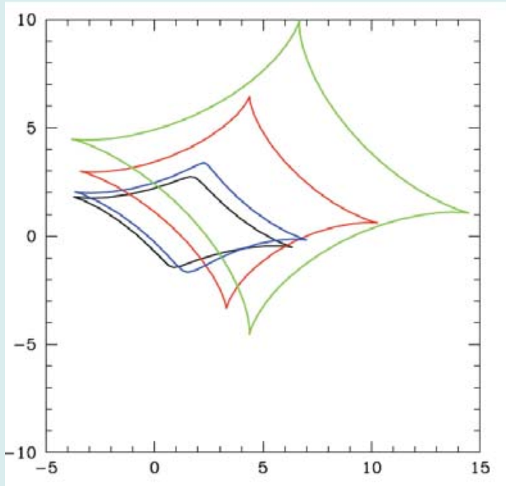

Cosmography with cluster strong lenses 7

Figure 5. Schematic diagram illustrating the creation of lensplanes to quantify the effects of LOS halos. A rectangular slice of the Millenium Simula-





KEY SYSTEMATICS

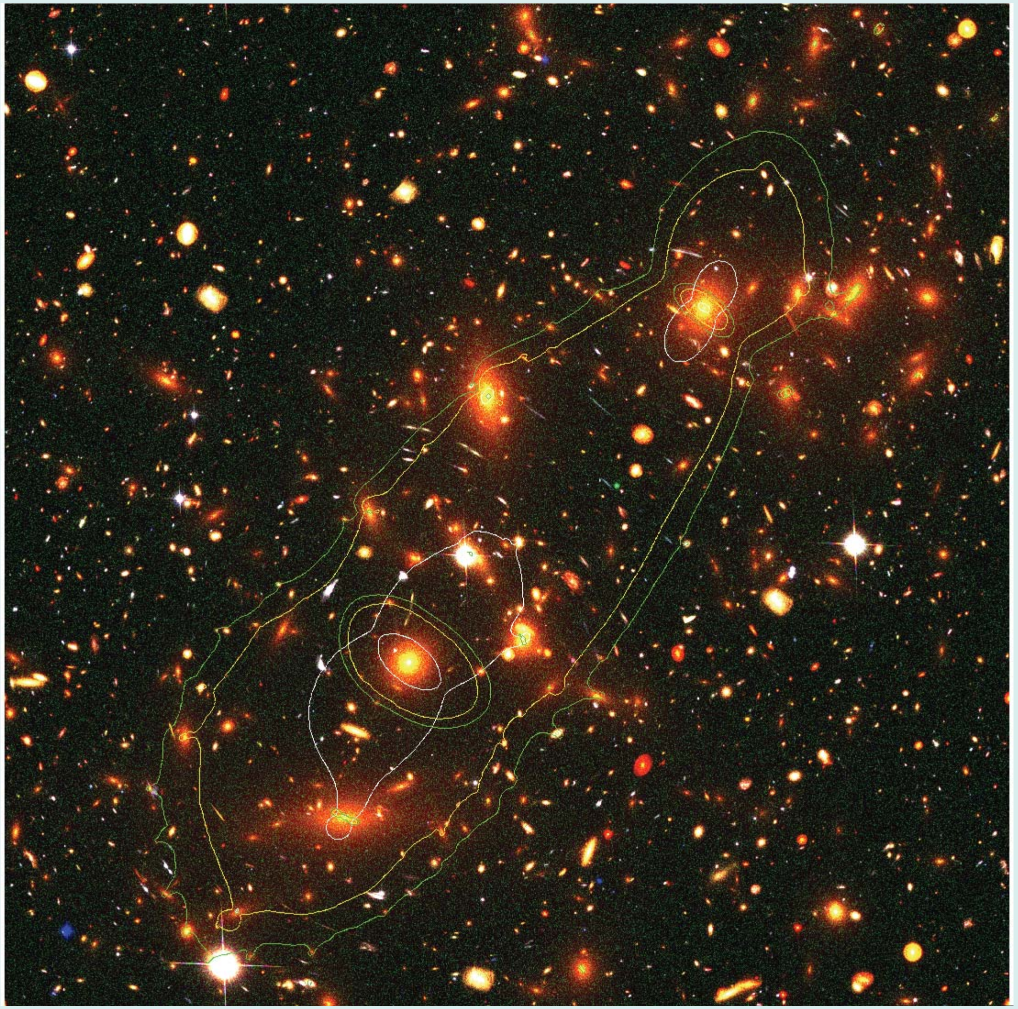
Modeling Errors (relation between mass & light)

Correlated LOS (infalling subclusters, filaments)

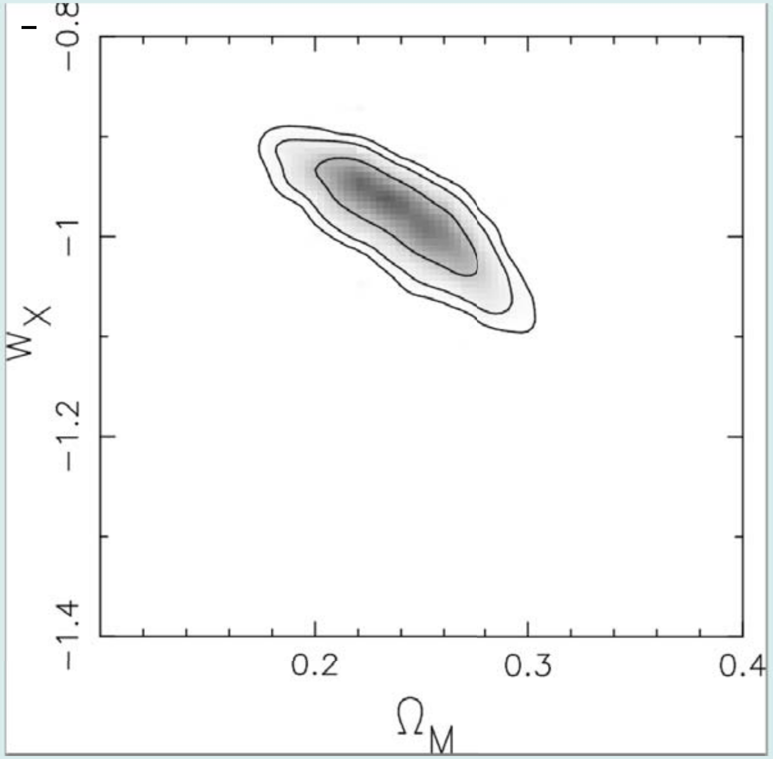
Uncorrelated LOS (primary contribution to the errors)

D'Aloisio & PN 10; Zabludoff+ Hwang+ 12, 13 UBER-LENSES

Cosmography with 100 multiple images simulated cluster Ares HSTFF analog



Optimized in the image plane with 242 image constraints from 85 sources (122 multiply imaged families)



$$\Omega_M = 0.2395 \pm 0.0230 \quad w_X = 0.9691 \pm 0.0348$$

Jullo, PN+ 10; Acebron, Jullo+ 15, 17; Meneghetti , PN & Coe 17

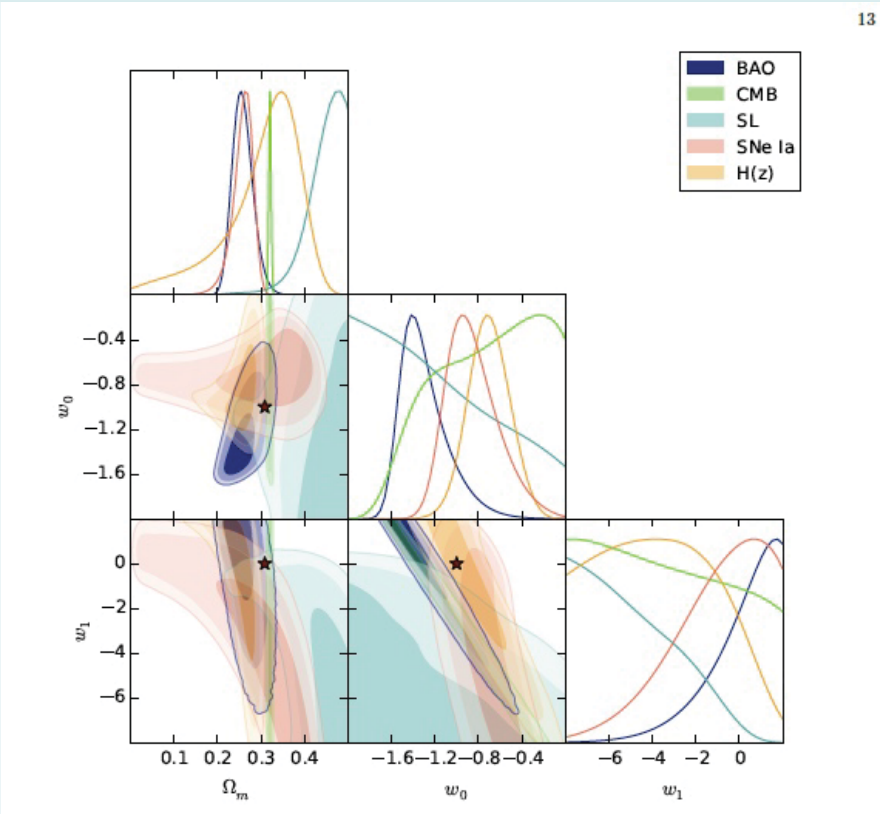
Probing dark energy models

Model A EoS:

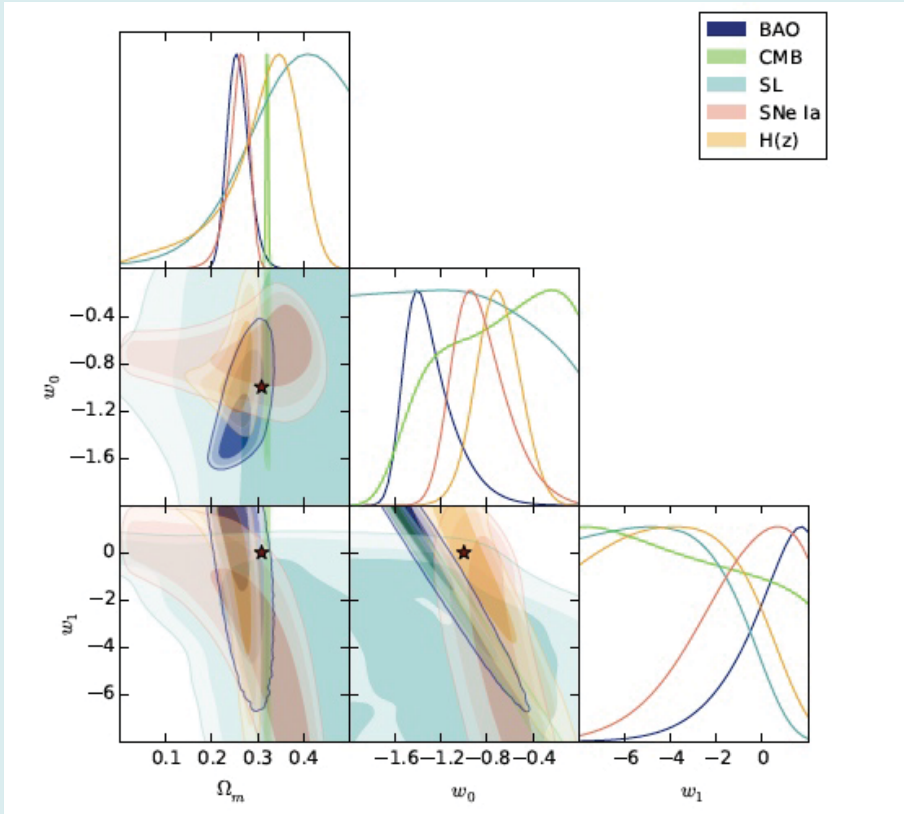
$$w(z) = w_0 + w_1 \frac{z}{(1+z)^2},$$

Abell 1689
z = 0.18

Model permits rapid variation at low z; the EoS is consistent at high and low z $w \sim w_0$



positional error = 0.25”



positional error = 1.0”

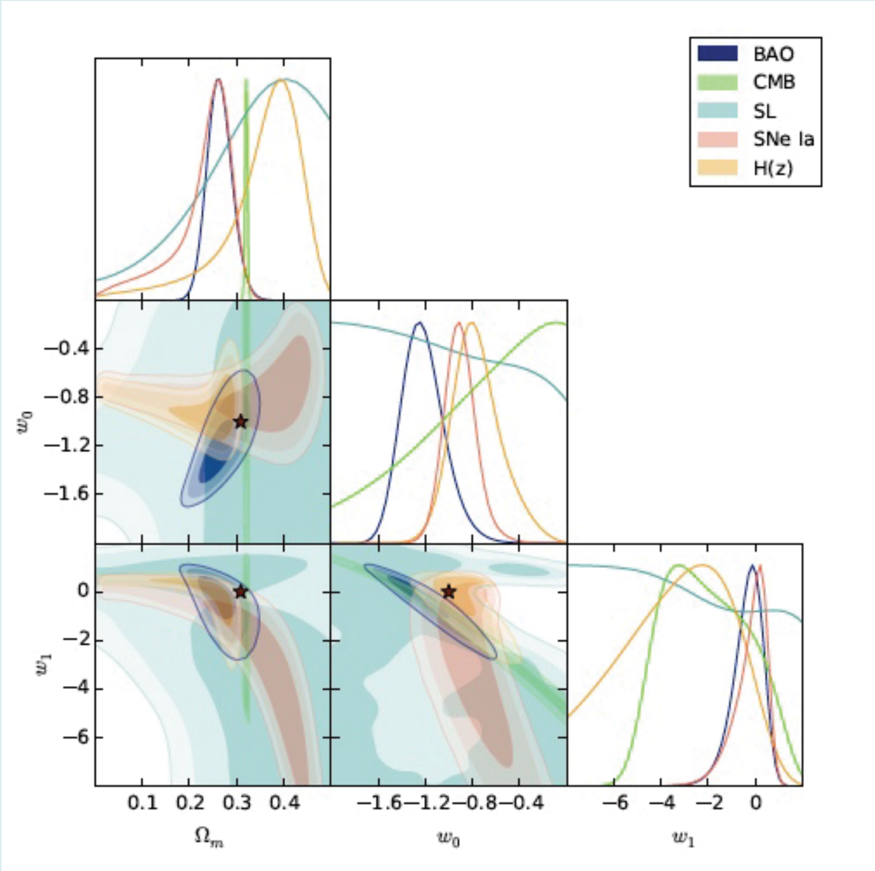
Probing dark energy models

Model B EoS:

$$w(z) = w_0 + w_1 \frac{z(1+z)}{1+z^2}.$$

Abell 1689
z = 0.18

EOS remains linear at low z



positional error = 1.0” Magana+ 18; Acebron+ 18

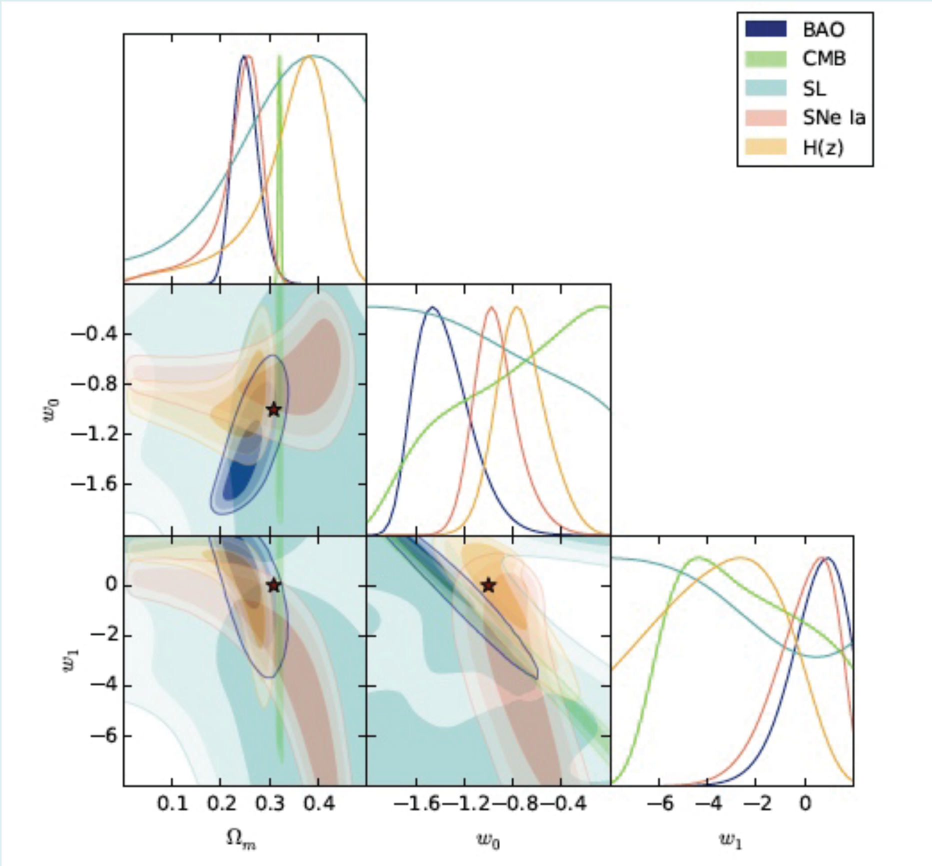
Probing dark energy models

Model C EoS:

$$w(z) = w_0 + w_1 \frac{z}{1+z^2},$$

Abell 1689
z = 0.18

w(z) linear at low z, EOS form convergent at all epochs



positional error = 1.0”

Magana+ 18; Acebron+ 18

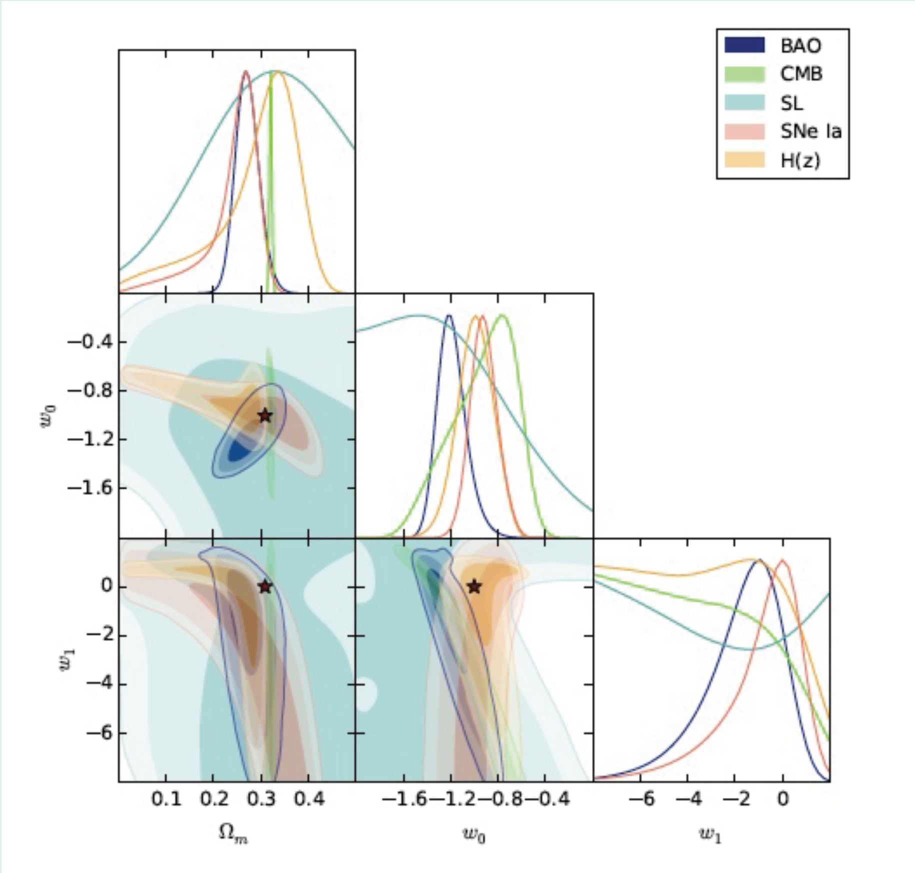
Probing dark energy models

Model D EoS:

$$w(z) = w_0 + w_1 \frac{z^2}{1+z^2}$$

Abell 1689
z = 0.18

w(z) is quadratic at low z, EOS converges for all z



positional error = 1.0"

HFF COSMOGRAPHY

INPUTS

Spectroscopic redshifts for as many multiple images
Central velocity dispersions for cluster galaxies
High fidelity mass models

KEY SYSTEMATICS

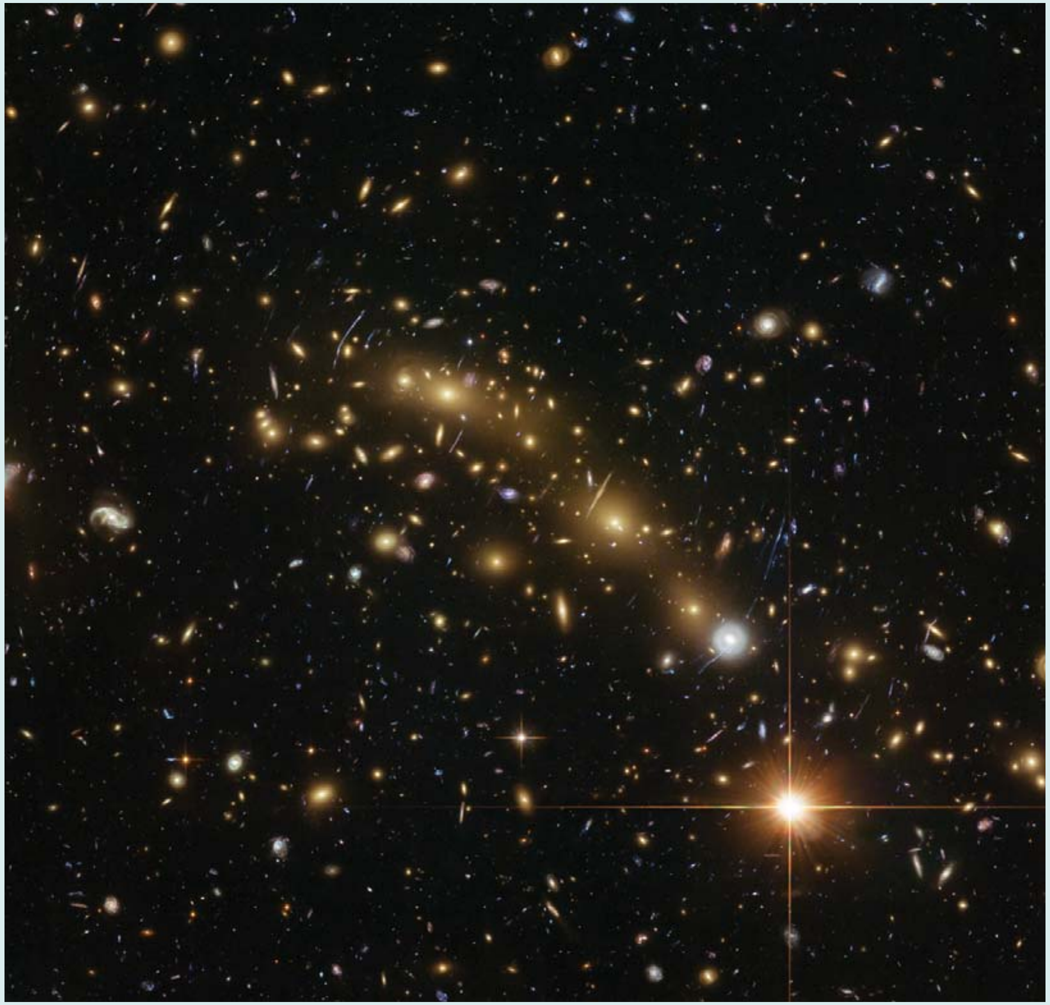
LOS SUBSTRUCTURE
Correlated LOS (infalling subclusters, filaments)
Uncorrelated LOS (primary contribution to the errors)

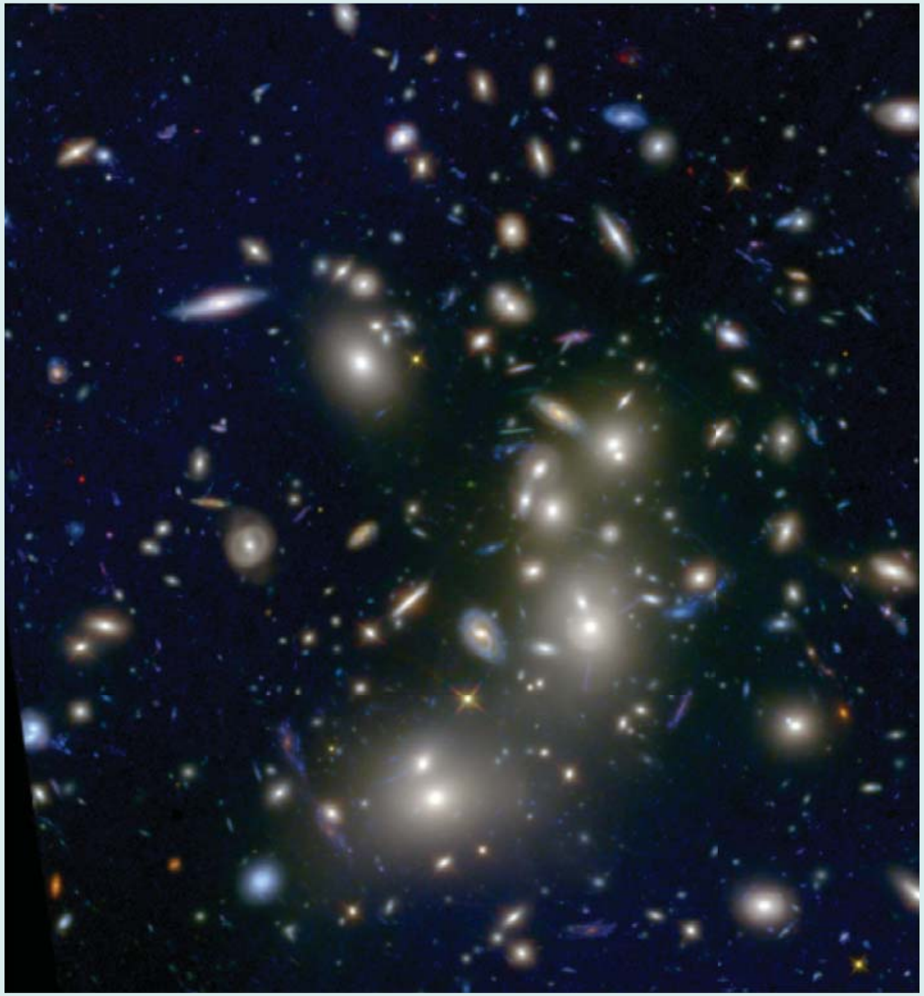
RELATING MASS TO LIGHT
Scatter in Scaling Relations

D'Aloisio & PN 10, 11, D'Aloisio, PN & Shapiro 14; Acebron+ 16, 17

MUSE Richard+ CATS, HST Grism GLASS

FF CLUSTERS MACS0416 & Abell2744





Jauzac+ 2014a,b CATS

Key philosophical problems with cosmology

What sets cosmology apart as a science? (methodological & epistemic issues)

Inability to perform any kind of controlled experiments; the Universe itself cannot be subjected to physical experimentation; cannot be observationally compared to other Universes; the concept of any laws of physics that apply to only one object are problematic; the concept of probability is problematic in the context of the existence of one object; limits on testing theories - cosmic variance; the interpretation and comparison of observations with requires a model (further assumptions)

Role of models and simulations

provide a temporal realization of a complex process; enable comparison with observed reality; relationship between models/simulations and reality – descriptive? representational? inferential?

FALSIFIABILITY OF THE LCDM MODEL

Status: It's complicated!

By virtue of the history of how the model was developed and refined with every new piece of observational data, the model accommodated, degrees of freedom

Schweber & Wachter 2000; Keller 2000; Ruphy 2010; Yanoff & Weinrich 2010; Natarajan 2016

Testing theories: why look for gaps?

Deviation in the orbit of Uranus from Newton's prediction
Urbane Le Verrier predicted in 1845 presence of another planet
and Neptune was discovered in 1846

Deviation in the orbit of Mercury from Newton's prediction
Urbane Le Verrier predicted presence of another planet
Vulcan was not found, doesnt exist
Upended Newton's view of gravity explained by Einstein's GR