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

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

Observer

Lens

Source

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

Non-Linear

Multiple Images

Arclets

Weak Shear

Linear

--- Multiples Images Area
**Strong lensing**

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

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

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**Weak lensing**

cohrent distortion in the shapes of background galaxies

- Shear field used to construct mass map
MAPPING SUBSTRUCTURE IN CLUSTERS

\[ \Phi_{\text{cluster}} = \sum_i \Phi_{\text{smooth}} + \sum_n \Phi_{\text{perturbers}} \]

PN & Kneib 97; 14; PN+ 05; 09; 11
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?
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 $z_{S1}$ & $z_{S2}$

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

$$\frac{R_{E1}}{R_{E2}} = \left[ \frac{D_{LS1}}{D_{OS1}} \right] \left[ \frac{D_{OS2}}{D_{LS2}} \right]$$

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

\[ \theta = \beta + \alpha(\theta, \xi; M) \]

\[ \xi = \frac{D(0, z_{1})D(z_{1}, z_{s})}{D(0, z_{s})} = \frac{D_{1s}}{D_{zs}} \]

For multiple images of the same source

\[ \beta_f = \theta_{f,i} - \nabla \varphi_{M}(\theta_{f,i}, \xi) \]

notation denotes the position of the \( i \)th image of family \( f \)

Taking the ratio of 2 distinct families of multiple images

\[ \left\{ \frac{D_{ls_1}}{D_{os_1}} \frac{D_{os_2}}{D_{ls_2}} \right\} \frac{\sum_{i=1}^{m} \nabla \varphi_{M}(\theta_{1,i})}{\sum_{j=1}^{n} \nabla \varphi_{M}(\theta_{2,j})} = \frac{-m \beta_1 + \sum_{i=1}^{m} \theta_{1,i}}{-n \beta_2 + \sum_{j=1}^{n} \theta_{2,j}}. \]

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

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:**

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

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

Abell 1689

\( z = 0.18 \)

Positional error = 0.25"

Positional error = 1.0"
Probing dark energy models

Model B EoS:

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

EOS remains linear at low z

Abell 1689
\[ z = 0.18 \]

positional error = 1.0”  Magana+ 18; Acebron+ 18
Probing dark energy models

Model C EoS:

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

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

Abell 1689
\( z = 0.18 \)

Positional error = 1.0”  Magana+ 18; Acebron+ 18
Probing dark energy models

Model D EoS:

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

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

Abell 1689
\( z = 0.18 \)

positional error = 1.0
**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

Testing theories: why look for gaps?

Deviations 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.

Deviations in the orbit of Mercury from Newton’s prediction:
Urbane Le Verrier predicted presence of another planet, Vulcan was not found, doesn’t exist.
Upended Newton’s view of gravity explained by Einstein’s GR.

"L’essentiel est invisible pour les yeux"