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



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### **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



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

#### LCDM remarkably successful on large scales > 1 Mpc CMB, LSS, Galaxy Evolution





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



**Chive tails seen com Braviews**NIC Toutlock & Deng Kolchin (2017) Popolo & Le Delliou (2017)

Maybe more fundamental issues, too?

1.1



A Crisis in Cosmology – Measurements of Hubble Constant Disagree

#### Testable CDM predictions abundance, radial distribution, and internal structure of halos



#### Mapping DM substructure on small-scales Abundance & Properties

SHMF: concrete LCDM Prediction<sub>dn</sub>  $\propto m^{-1.8}$ 





Strong dependence on the nature of DM



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

#### WHY CLUSTERS? & WHY CLUSTERS - WHY



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 Mahler+; Geller+; Ellis+; Rines+; Bastman+ 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



#### 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 bean  $\Sigma(r) > \Sigma_{crit}$
- Mass enclosed within the arc is tightly constrained



#### Weak lensing

•generation in the shapes of background •generation in the shapes of background •generation in the shapes of background

Kaiser & Squires 93 Smail & Ellis 94, 95,

#### MAPPING SUBSTRUCTURE IN CLUSTERS



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

#### HST Frontier Fields 840 HST orbits deep look at 6 clusters



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

Lotz+



# 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



12.14



Abundance mis-match resolved when fainter satellites detected, Moore+; Klypin+;

#### Radial distribution of

## Comparison **Stable balos** F cluster lenses with Illustris LCDM clusters



#### Radial distribution of sub-halos On galaxy scales





CDM WDM predictions

Carlsten+20;

## Trouble on small scales in CDM: internal structure halos



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



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



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



#### GGSL comparison with simulated clusters 11 Clusters from CLASH + HSTFF

![](_page_22_Figure_1.jpeg)

## Metric sensitive to mass enclosed within $R_{\rm E}\,^{\sim}$ 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

![](_page_23_Figure_1.jpeg)

![](_page_23_Figure_2.jpeg)

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

![](_page_24_Figure_1.jpeg)

Tokayer, PN+ 23

#### CONSTRAINTS ON DM FROM GALAXY-GALAXY LENSES

![](_page_25_Figure_1.jpeg)

(Lovell et al. 2012)

#### Pushing the subhalo mass function to lower masses Vegetti+; Despali+; Dorkin+;

to fit the data better than the smooth lens alone at the  $10\sigma$  level

![](_page_26_Figure_0.jpeg)

Cerini+

![](_page_27_Figure_0.jpeg)

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.

#### A cosmic book of phenomena

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THERE is a tendency at scientific meetings, when a particularly important but tentative result is presented, to demand of one's agnes what odds they would give for eventual confirmation lings-scale situature of the Universe. This one is devoted to the observable phenomena that therois scatomarily linvake (or ignore) in developing models for the formation of the galaxies. Which observations are reliable? Which observations can be used to discriminate between alternative theories? As issues in extragalatical startonny rarely are settled by any one measure-ment, an array of assessments, such as that in Table 1, may be what finally loads us to a true standard model for the origin of

galaxies and the large-scale structure of the Universe. We remind punters that the redshift z of an object is defined We remain practices that the redshift  $z \neq a$  an object is defined to the start  $s \neq s$  in the start  $s \neq s$  in the start  $s \neq s$  and  $s \neq s$  and scosmological tests, but at the crude level of our table it is only a scaling factor.

#### Theories

Of critical importance in the table of odds is the cosmological density parameter  $\Omega_{i}$  defined as the ratio of the mean mass density in the Universe to the value in the scale-invariant Einstein-de Sitter universe,  $\Omega = 3H^2/8 - \Omega_{i}$  where O is the gravitational constant. Luminous matter (both stars and gas) con-tributes  $\Omega \simeq 0.007$ . Mass estimates based on the dynamics of where 01-0007. Mas estimates based on the dynamics of systems of paintics smally indicate (10-01 (ref. 2). Thereiss almost all agree that (1) is probably close to usity. Free, inflation marks the against constrained fait o which (10%, which implies indicates the system) of the system of the system of the neuroinar gramework for the indicates of the system functional system of the system of the system of the neuroinar gramework for first marks (1) is proportional to the indicate faith of the system of the system of the system to which of the system of the system of the system of the neuroinar gramework for the system of the system of the neuroinar gramework (1) is the system of the system of the neuroinar system. There is will also be with a consolingial constant, then system of the in officiant (1) is the system of the system of the system is officiant (1) of the system of the in officiant (1) of the system of the system of the system of the in officiant (1) of the system of the system of the system of the system of the in officiant (1) of the system of the system

NATURE - VOL 346 - 19 JULY 1990

so much material could be hidden from observation, and a high baryon density would make it difficult to reconcile the calculation of abundances of the light elements produced in the hot Big Bang with observed abundances<sup>3</sup>. On the other hand, there is rough with observed abundances". On the other hand, there is rough agreement between the haryas density needed to account for light-element nucleosynthesis with the mass density required to account for the dynamics of galaxies. The two popular interpre-tations are that the mass of the Universe is dominated by some sort of exotic non-baryonic weakly interaction gamatter, or that  $\Omega = 0.1$ , throatical arguments netwithstanding, and the mass density network.

REVIEW ARTICLE

density predominantly baryonic. In the cold dark matter (CDM) theory<sup>8,1</sup>, an Einstein-de Sitter In the cold dark matter (CDM) theory<sup>64</sup>, as Einstein-d-Silver intervers is dominated by weakly interacting matter with single-networks and the second structure of the second structure prover by gravitational instability out of a scale-invariant spe-rum of primary allohibid: density factuations (where the primary ainties of local member densities of plotters, haryon through second structure) and the structure of the scale through second structure of the structure of the scale through sequences of the scale structure of the scale through sequences of the scale structure of the scale structure plant from in studies of the dynamics of systems of per galaxy found in studies of the dynamics of systems of plantics can be consistent with the high net mass per galaxy implied by the 1-1. The degree of binning resulted depends to we assume that the ran, interastion dot N/N is the galaxy count in a randomly placed sphere of radius equal to the galaxy cluster, ing length,  $n_{\pm}^{\pm} < 24.1$  k/M with a site system. A nettation dawy in the mass floated in the sphere. In the hot data matter (JUM) model', the particles of dark

In the hot dark matter (1DM) model", the particles of dark matter have have a princised velocity characteristic of a randino matter density of excitons left over from the hot Hig Barg, the mass density in neutrinos rankes l=1. Structure grows by gavity out of adubticity fluctuations in the mass density out of adubticity fluctuations in the mass density matter and the structure mass and the present of the structure structure. The structure form the bott Hig Barg, the structure is made to the structure form the bott Hig Barg, the structure of the structure prove by gavity out of adubticity fluctures and the structure formation of the structure formation of the dark matter produces a mass otherware length of  $\sim 50^\circ$  Migc at the present epoch.

There are two classes of models in which strengths formation is seeded by princeal numbers presentations. In the aring a seeded by princeal numbers presentations of the aring attional effect of a network of coemic string that untangles as the Universe expansion, such at any expect 106 Universe which the Barbook length c contains a few long strings and closed hourse present collisions have low even the Universe from accretion on isolated loops to impremention of the wake of long atting, makes the string-seeded galaxy formation, not string the universe the universe string strengths and the strength strength strengths and the strength strength strength strength strengths and strength strengths atting strength strength strength strength strength strengthstre

more attractive. In the explosion (XPL) picture<sup>8</sup> locally inserted energy, per-haps from early supernovae, piles baryons into ridges which collapse to produce new star closetters. We know that non-gravita-tional ansertances such as explosions and coding baryon an essential ses such as explosions and cooling have an e role in the behaviour of the interstellar medium and in star

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

		Cold dark.		Hot clark.		String		Explosion		Daryonic		
	Weight	P	itter r	p	r in the second	persur	bations /	pertu	rbation /	dark p	nate	
Cosmology												
a 0~0.1	0.7	0.05	0.18	0.05	0.18	0.3	0.96	0.5	-0.50	0.95	0.	
0.0 tom=0.1.0 tom	1.0	01	0.10	0.1	0.10	01	0.20	0.7	0.70	0.95	0.	
Coartic backatound radiation												
a isotropy: \$7/7 <1 ×10"4 at <10 arcsec	1.0	0.95	0.95	0.5	0.50	0.3	0.30	0.1	0.10	0.2	0.	
b, lastropy \$7/7 < 2×50 <sup>-8</sup> at ~30 arcmin	1.0	0.95	0.95	0.05	0.05	0.7	0.70	0.7	0.70	0.7	0.	
<. Spectrum Compton y < 0.001.	1.0	0.95	0.95	0.5	0.50	0.4	0.40	0.1	0.10	0.95	0	
Hab sectshift obscorpera												
a There are quasars at z~5	1.0	0.5	0.10	0.05	0.05	0.95	0.95	0.95	0.95	0.95	. 0	
<li>b) intergalactic H i clouds are weakly clustered at 1 a 2 5.</li>	1.0	0.96	0.95	0.05	0.05	0.5	0.90	0.5	0.50	0.05	0	
4. The quesar abundance peaks at 2 ~ 2.5	1.0	0.5	0.50	0.1	0.10	0.1	0.10	0.1	0.10	0.05	. 0	
d The metagalactic ionizing-radiation field is	1.0	0.5	0.90	0.05	0.05	0.95	0.95	0.95	0.95	0.95	đ	
a. There are young (~0.3 Ger) galaxies at z=3	0.6	0.95	0.77	0.5	0.68	0.5	0.50	0.2	0.37	0.05		
f. There are clusters of galaxies as massive as Gorsa at $z \sim 1$	0.6	0.05	0.14	0.4	0.42	0.95	0.85	0.95	0.85	0.95	đ	
The largest structures												
a. The galaxy distribution tends to be sheet-like	1.0	0.6	0.60	0.95	0.95	0.8	0.80	0.95	0.95	0.05	0	
A. There are coherent structures in the galaxy dis- tribution >50 k <sup>-1</sup> Mpc across	1.0	0.1	0.10	0.2	0.20	0.95	0.95	0.05	0.05	0.1	0	
c. Vold diameters can exceed 25 h <sup>-1</sup> Mpc	1.0	0.95	0.86	0.95	0.95	0.05	0.05	91	0.10	0.9	0	
d Mean separation of rich clusters is	1.0	0.95	0.95	0.9	0.90	0.5	0.50	0.1	0.10	0.8	0	
#, Cluster clustering length is 22(A4) h <sup>-1</sup> Mpc	0.7	0.05	0.18	0.0	0.71	0.5	0.50	0.4	0.43	0.9	0	
> 10 <sup>45</sup> b <sup>-1</sup> M <sub>0</sub> , central M/L ~ SOD A	0.9	0.1	614	0.95	0.90	0.5	0.50	0.5	0.50	0.8	0	
g. The r.m.s. peculiar velocity smoothed over c=30 F <sup>-1</sup> Mar is 2-500 are s <sup>-1</sup>	07	0.05	018	07	0.64	0.6	nar	0.05	018	0.65	0	
Small-scale clustering												
a the r.m.s. relative velocity of galaxies at	~ ~											
b Calary rivelating length is a with a 1 Mar	1.0	0.95	0.95	0.2	0.05	0.2	0.05	0.05	0.10	0.95		
C At / 5 to the painty distribution approximates a	~~										. 7	
tractal with D=1.23	1.D	0.95	0.95	0.1	0.50	0.5	0.50	0.8	0.80	0.8	0	
d The power law East breaks at r~2r,	1.0	0.1	0.10	0.5	0.50	0.1	0.50	0.5	0.50	0.05	. 0	
e. Early type galaxies prefer dense regions	1.0	0.8	0.60	0.5	0.50	0.5	0.50	0.5	0.50	0.5	. 0	
c Spiral goldwers formed outside protoclusters g Dwarfs avoid the voids defined by giants	0.8	0.95	0.95	0.05	0.05	0.9	0.50	0.3	0.30	0.95	0	
Evolution of galaxies at z < 1												
<ol> <li>The comoving number aevisity of bright galaxies</li> </ol>	9.8	0.99	0.86	0.96	0.86	0.2	0.26	0.1	0.18	0.05	0	
is unchanged (±50%) since z = 0.7	0.9	0.05	0.10	0.05	0.50	0.5	0.50	0.5	0.50	0.95	0	
<ol> <li>Spinal disks are not accreting, massive objects of The are difference between disk and enhanced</li> </ol>	0:9	1.0	0.14	0.2	0.23	0.5	0.50	0.7	0.68	0.8	0	
populations in a spinal galaxy in 3 Gyr	0.7	0.9	0.78	0.5	0.50	0.9	0.71	0.5	0.50	0.9	0	
denomination of an inclusion of the second sec												
<ul> <li>Default or generates</li> <li>The framework distribution of the simular adjustic</li> </ul>												
ic, has a hard upper cutoff	1.0	0.2	0.20	0.2	0.20	0.2	0.20	0.5	0.50	0.5		
In At hr = 1 to 30 kpc, v, is approximately flat	1.0	0.9	0.90	0.1	0.10	0.1	0.10	0.2	0.20	0.7	0	
2, 9, correlates well with lunenceity	1.0	0.9	0.90	0.6	0.60	0.5	0.50	0.6	0.50	0.5	.0	
al The dark matter in haloes is beryonic	0.5	0.05	0.28	0.05	0.28	0.3	0.40	0.5	0.50	0.95	ಿ	
e tres augment correlates poorly with	10	0.5	0.50	61	0.02	05	0.50	0.1	0.55	05	-	
f. Eliptical alignment correlates with environment	10	07	0.70	0.9	0.90	0.6	0.60	0.9	0.90	0.3	ě	
# Eligiticals have radial colour stadients	1.0	0.95	0.95	0.9	0.90	0.5	0.50	0.9	0.90	0.05	6	
h, Metal-poor stars are rare in dieka.	0.8	0.5	0.50	01	0.18	0.05	0.54	0.2	0.25	0.8		
a consume counters counter around galaxies.	1.0	-1	47	-2	0.50		0.50	-	0.50	-1		
P, (cmt)			174		0.00		0.56		0.37		-14.8	
F. 8 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1 - 1		CARGE.						- 9.67		- 204		

(WDM, Self-Int Map Dissibatiges M, Plasmon DM, Self-Ann DM, PBHs)

![](_page_30_Figure_0.jpeg)

### **EXTRA SLIDES**

#### **Strong lensing** multiple image geometries, magnification for an elliptical lens

![](_page_32_Figure_1.jpeg)

Image plane critical curves

Source plane caustics

### GGSL in MACSJ1206

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

![](_page_33_Figure_2.jpeg)

# **Concentration of subhalos:** Subhalos in clusters and SEE WORK BY: Hezaveh+; Dalar, Dvirkin+; Despali+; Vegetti+; Kaplinghat groups

![](_page_34_Figure_1.jpeg)

Gilman+20; Stucker+