HUBBLE FRONTIER FIELDS :
AN EXTRAORDINARY VIEW INTO GALAXY CLUSTERS

Cosmic Mergers Workshop
21th September 2017

Durham University

Mathilde Jauzac

Astrophysics & Cosmology Research Unit
ACRU

Dominique Eckert, Matthieu Schaller, Johannes Schwinn, Richard Massey, Carlton Baugh, Priyamvada Natarajan, Eric Jullo, Johan Richard, Marceau Limousin, Jean-Paul Kneib & the CATS team

FROM LENSING TO MULTI-WAVELENGTH : *(SOME OF)* WHAT YOU CAN DO WITH MASSIVE GALAXY CLUSTERS …

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Outlines

1. **Some cosmological context**

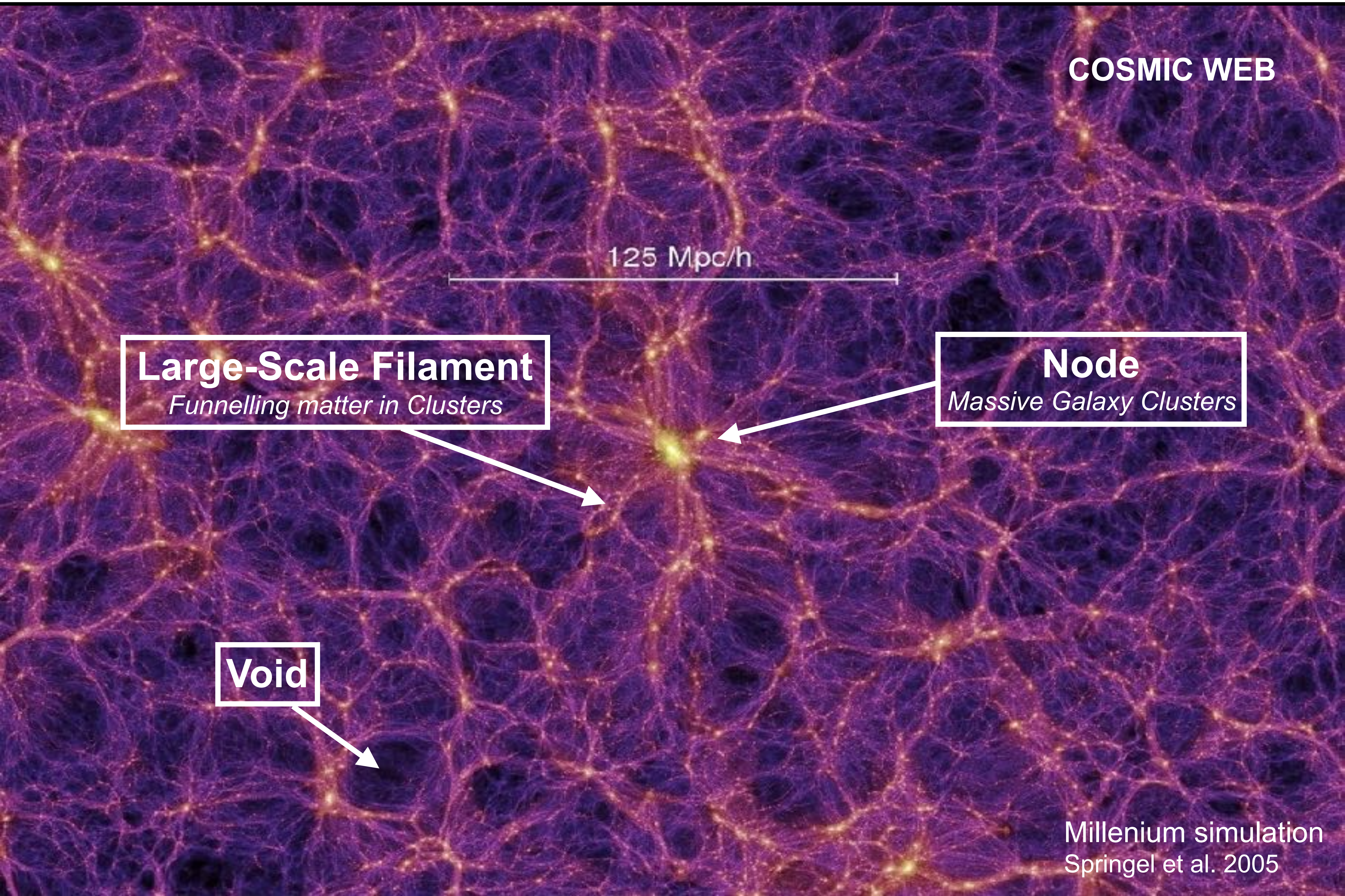
2. Strong Gravitational Lensing

3. Weak Gravitational Lensing

4. Multi-wavelength analysis

5. Conclusion & Perspectives

Cosmological Context



Cosmological Context

3 different scales today :

- Inner Core of Clusters
- 'direct' Outskirts of Clusters
- 'extended' Outskirts of Clusters

Understand how it works ?
Lensing not Enough

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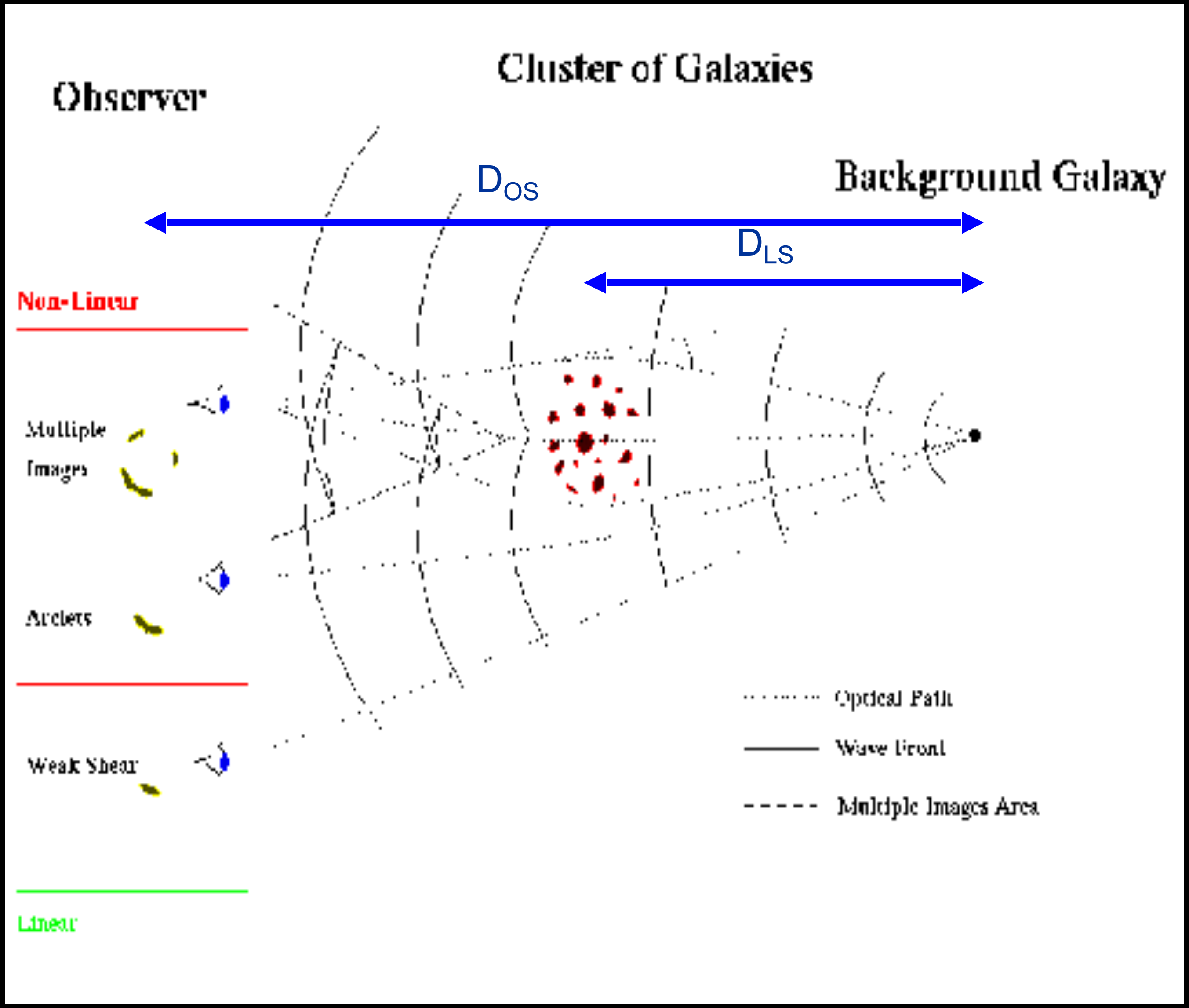
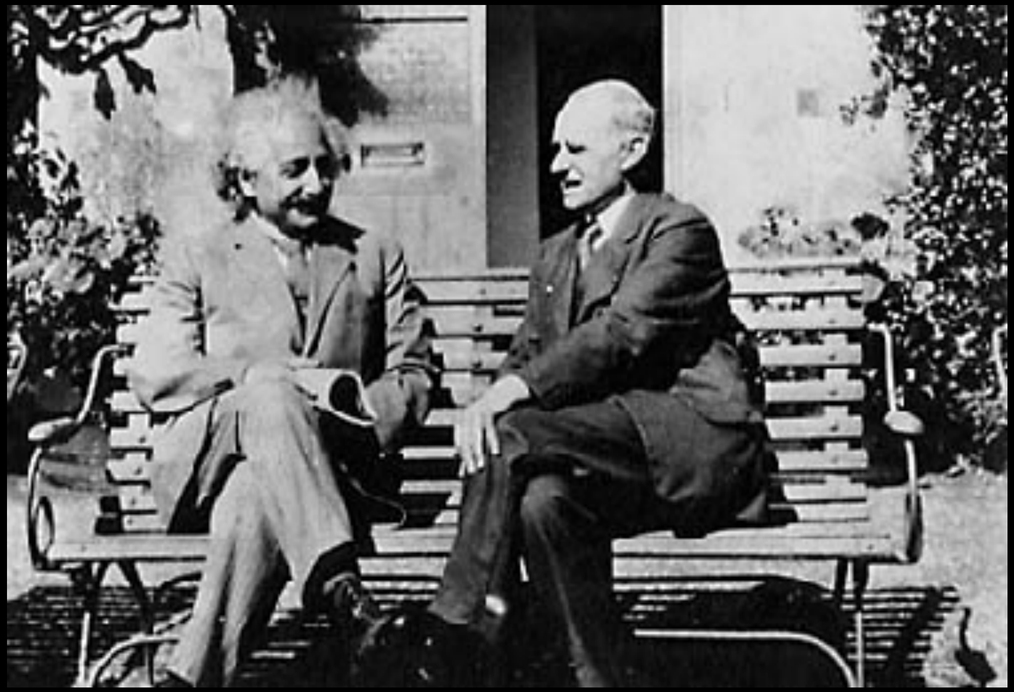
Multi-wavelength !

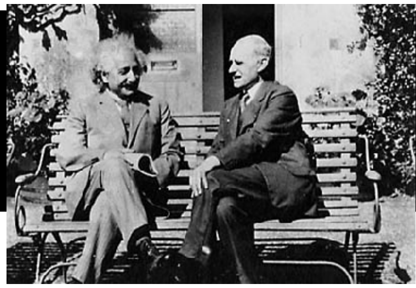
GRAVITATIONAL LENSING

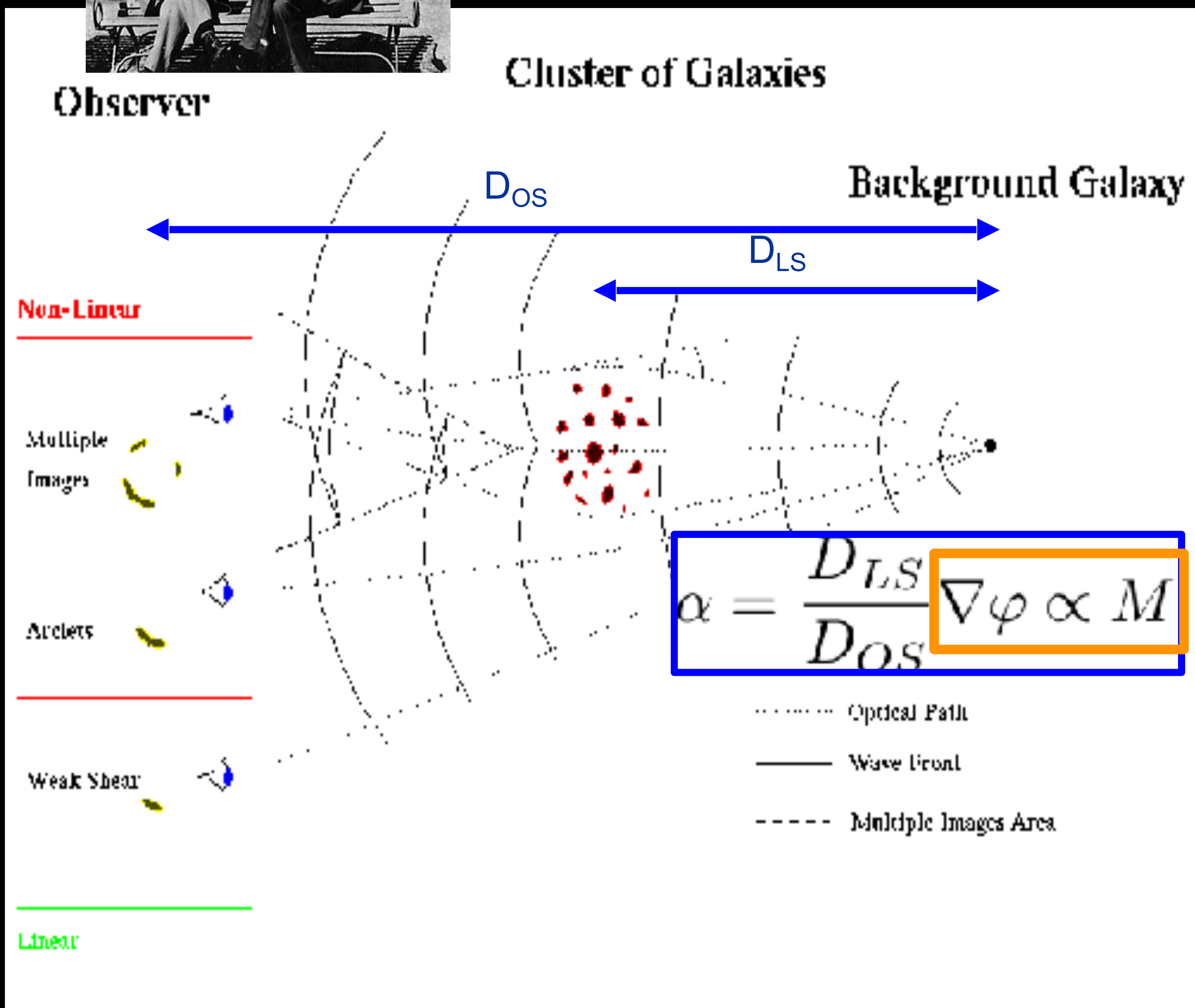


- **Basics of lensing:**
  - Important mass density locally deforms the Space-Time,
  - *A pure geometrical effect, no dependence with photon energy*



GRAVITATIONAL LENSING





- **Basics of lensing:**
  - Important mass density locally deforms the Space-Time,
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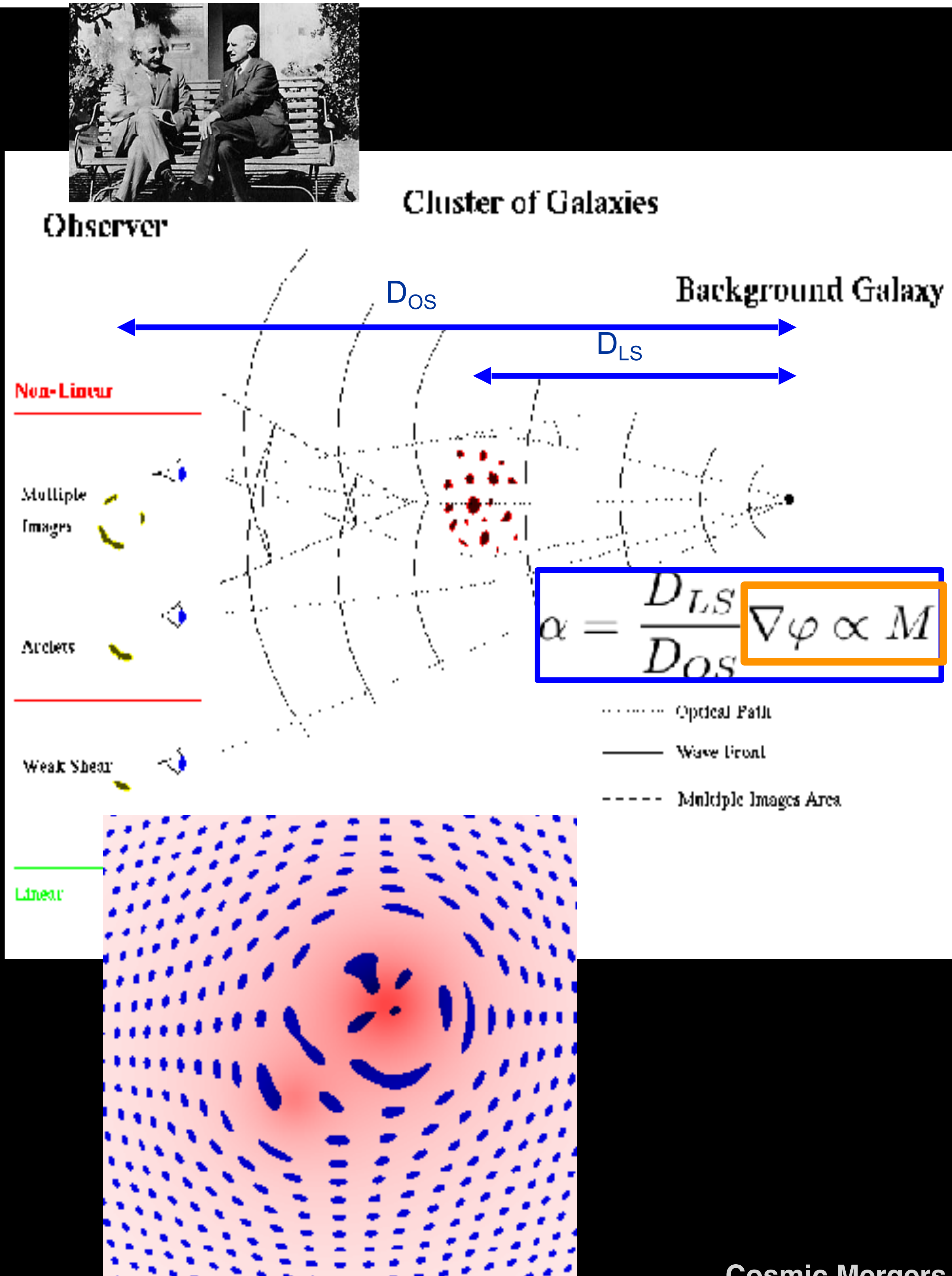
➡ **Gravitational Lensing (GL) is one of the most efficient tool to measure DM distribution in the Universe**

Gravitational Lensing



- **Basics of lensing:**
  - Important mass density locally deforms the Space-Time,
  - *A pure geometrical effect, no dependence with photon energy*

➡ Gravitational Lensing (GL) is one of the most efficient tool to measure DM distribution in the Universe

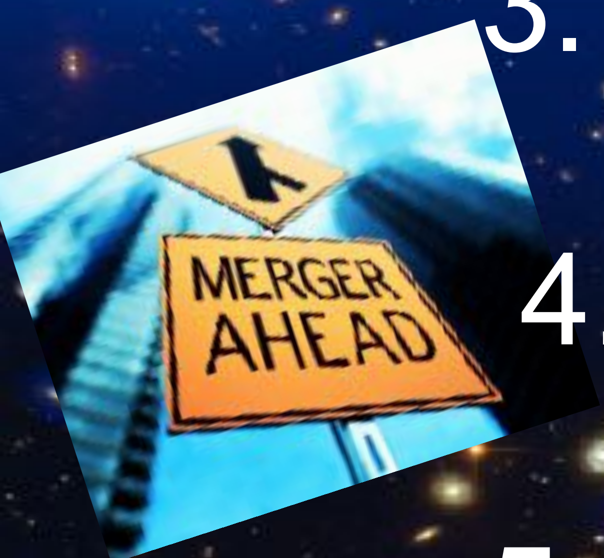
- **Lensing by a (massive) cluster**
  - Strong Lensing (SL) = core of the cluster as arcs & multiple images
  - Weak Lensing (WL) = outskirts of the cluster as statistical deformation of background sources

OUTLINES

1. SOME COSMOLOGICAL CONTEXT

2. STRONG GRAVITATIONAL LENSING

3. WEAK GRAVITATIONAL LENSING

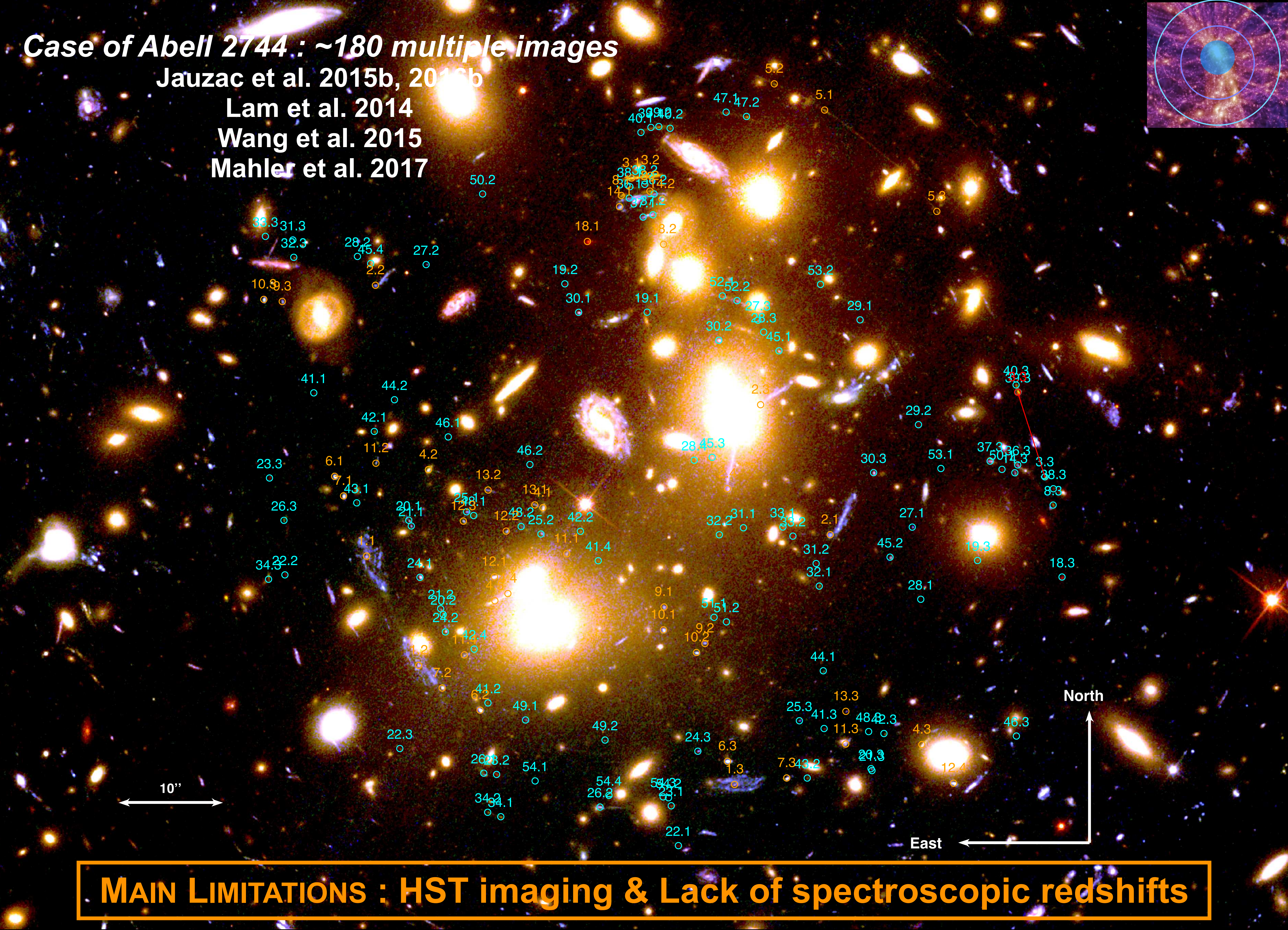


4. MULTI-WAVELENGTH ANALYSIS

5. CONCLUSION & PERSPECTIVES

Case of Abell 2744 : ~180 multiple images

Jauzac et al. 2015b, 2016b
Lam et al. 2014
Wang et al. 2015
Mahler et al. 2017



MAIN LIMITATIONS : HST imaging & Lack of spectroscopic redshifts

1ST STRONG LENSING REVOLUTION : HFF

WHAT ARE THE *HUBBLE FRONTIER FIELDS* ?

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

Lotz et al. 2017

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THE MOST POWERFUL TELESCOPE TO OBSERVE THE DISTANT UNIVERSE

- Highly-constrained Gravitational Lensing mass models
- Highly-precise Magnification estimates

THE DEEPEST DATA EVER OBTAINED FOR LENSING GALAXY CLUSTERS !!!

1. 6 strong lenses & 6 blank fields
2. 140 HST orbits (> 3days of observations) – ACS & WFC3
3. mag ~ 29 in the optical and near-IR

→

1. THE DISTANT UNIVERSE
2. CLUSTER PHYSICS
3. GALAXY EVOLUTION, …

2ND STRONG LENSING REVOLUTION : VLT/MUSE

Courtesy of J. Richard

Abell 2744: 2x2 mosaic
Mahler et al. 2017, sub. to MNRAS

Abell 370: 1 pointing
Lagattuta et al. 2017

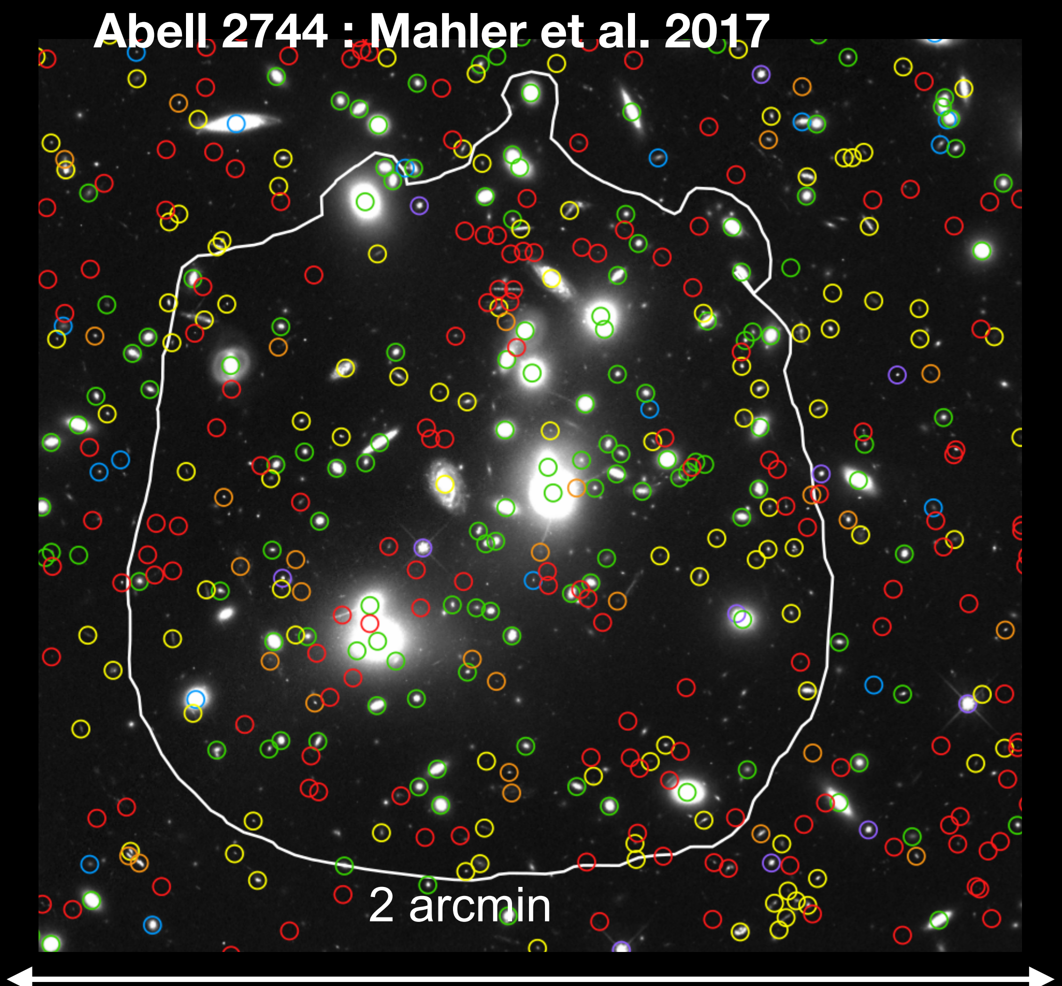
SMACS 2031 : 1 pointing
Richard et al. 2015

MACS0416: 2 pointings
Caminha et al. 2017

MACS1149 : 1 pointing
Jauzac et al. 2016a; Grillo et al. 2016

AS1063 : 2 pointings
Caminha et al. 2016; Karman et al. 2014, 2017

MACS1206 : 1 pointing
Caminha et al. 2017



Cluster Strong Lensing : How to Model the Mass ?

Different algorithms : Parametric & non-Parametric

Parametric

GLAFIC
Oguri10

LTM
Zitrin+09,13

GLEE
Suyu+11

Lenstool
Jullo+07

Non-Parametric

WSLAP+
Diego+07

SaWLens
Merten+09,14

SWUnited
Bradac+05

GRALE
Liesenborgs+06

hybrid-Lenstool
Jullo+09

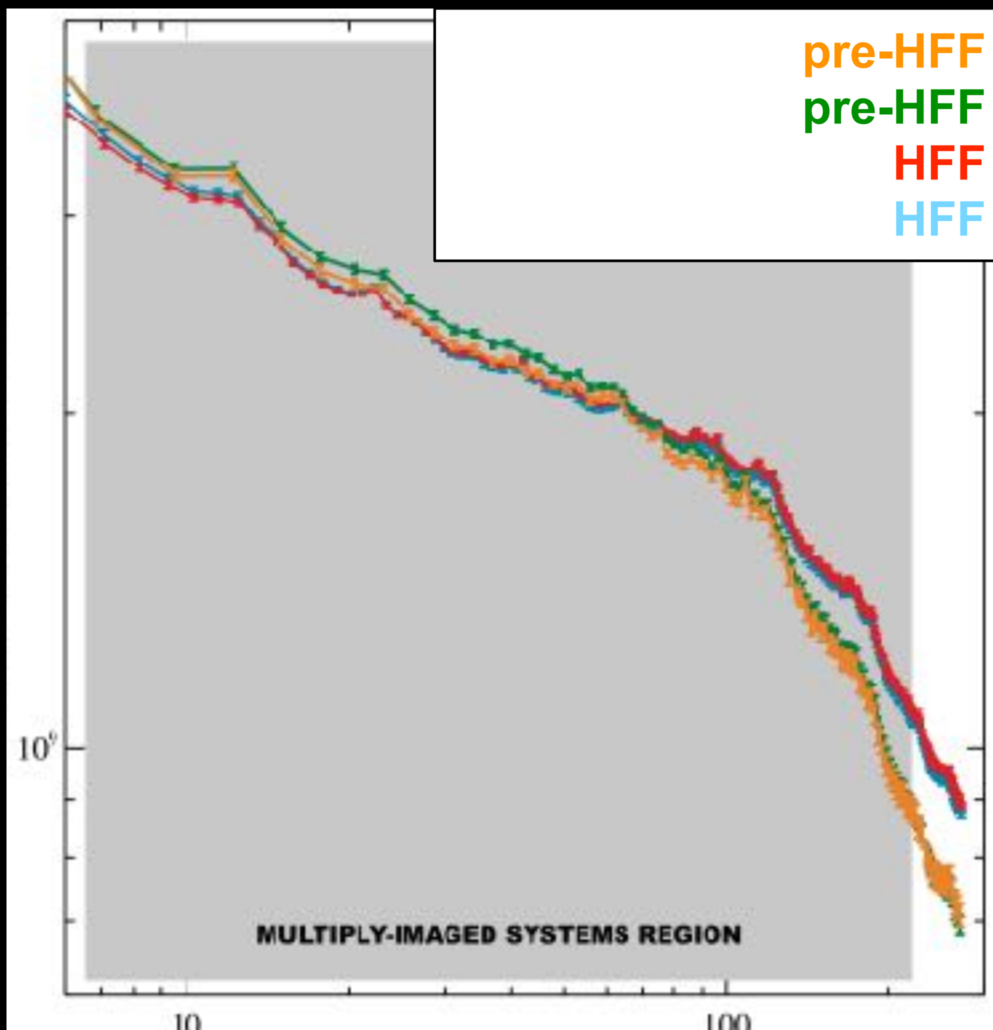
Inputs :

- Cluster-scale halos/Uniform distribution
- Strongly-lensed multiple images
- Cluster galaxies

Outputs :

- Cluster mass maps (convergence, shear, …)
- Magnification maps

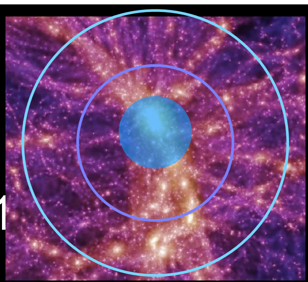
Cluster Strong Lensing : How to Model the Mass ?



Mass estimates:
M(R<250kpc) = 2.765 ± 0.008 (stat) 10^{14} M_{sun}

Magnification estimates :
μ = 5.61 ± 0.10 (stat) ± 0.57 (sys)

SL-only analysis

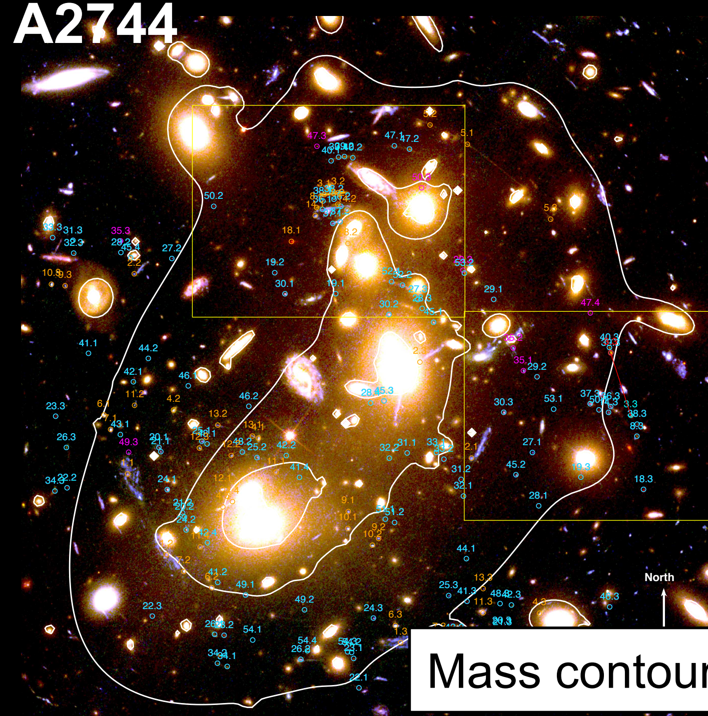


Jauzac et al. 2015b
See also Zitrin et al. 2009, 2011, 2013; Richard et al. 201… 2014; Jullo et al. 2010; Diego et al. 2014, 2015, 2016; Sharon et al. 2015; Limousin et al. 2012, 2016; Lam et al. 2014 …

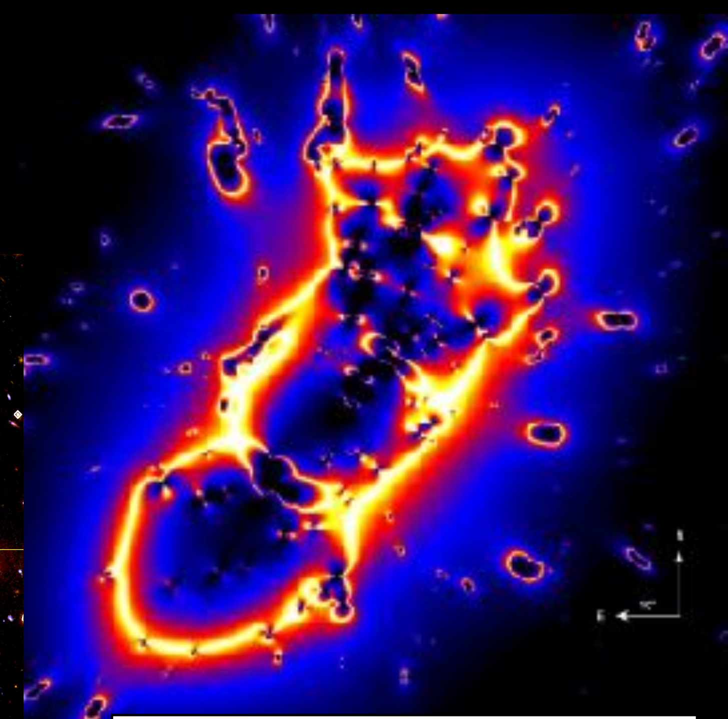
Best-fit parametric mass model - **Lenstool** :

- 154 SL constraints
- 2 DM clumps
- 733 cluster galaxies
- **RMS = 0.79”**

A2744



Mass contours



Magnification map (mags)

Systematics limited : Johnson et al. 2016, Acebron et al. 2017, Chirivi et al. 2017

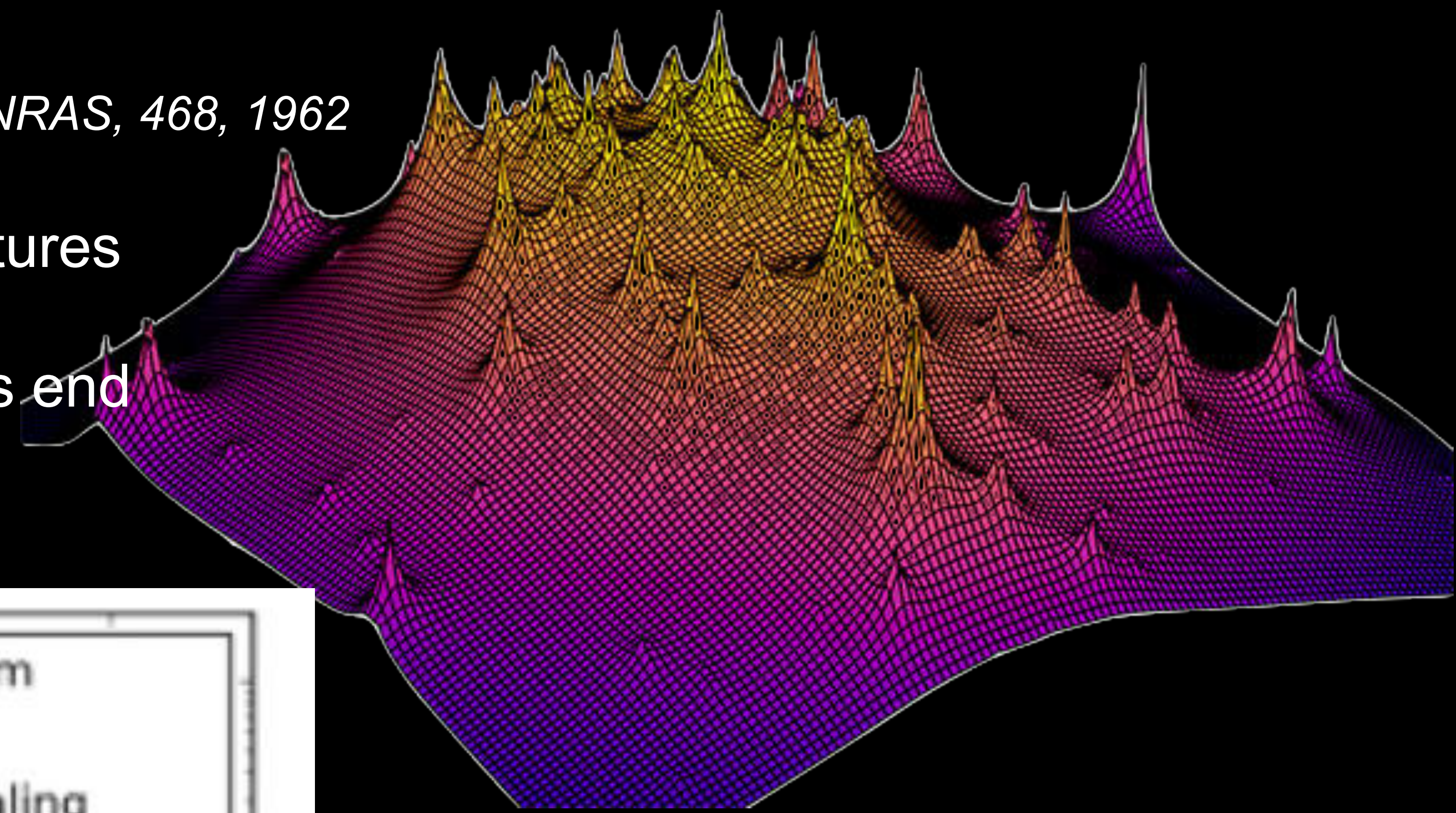
Cluster Strong Lensing : Cosmological Test

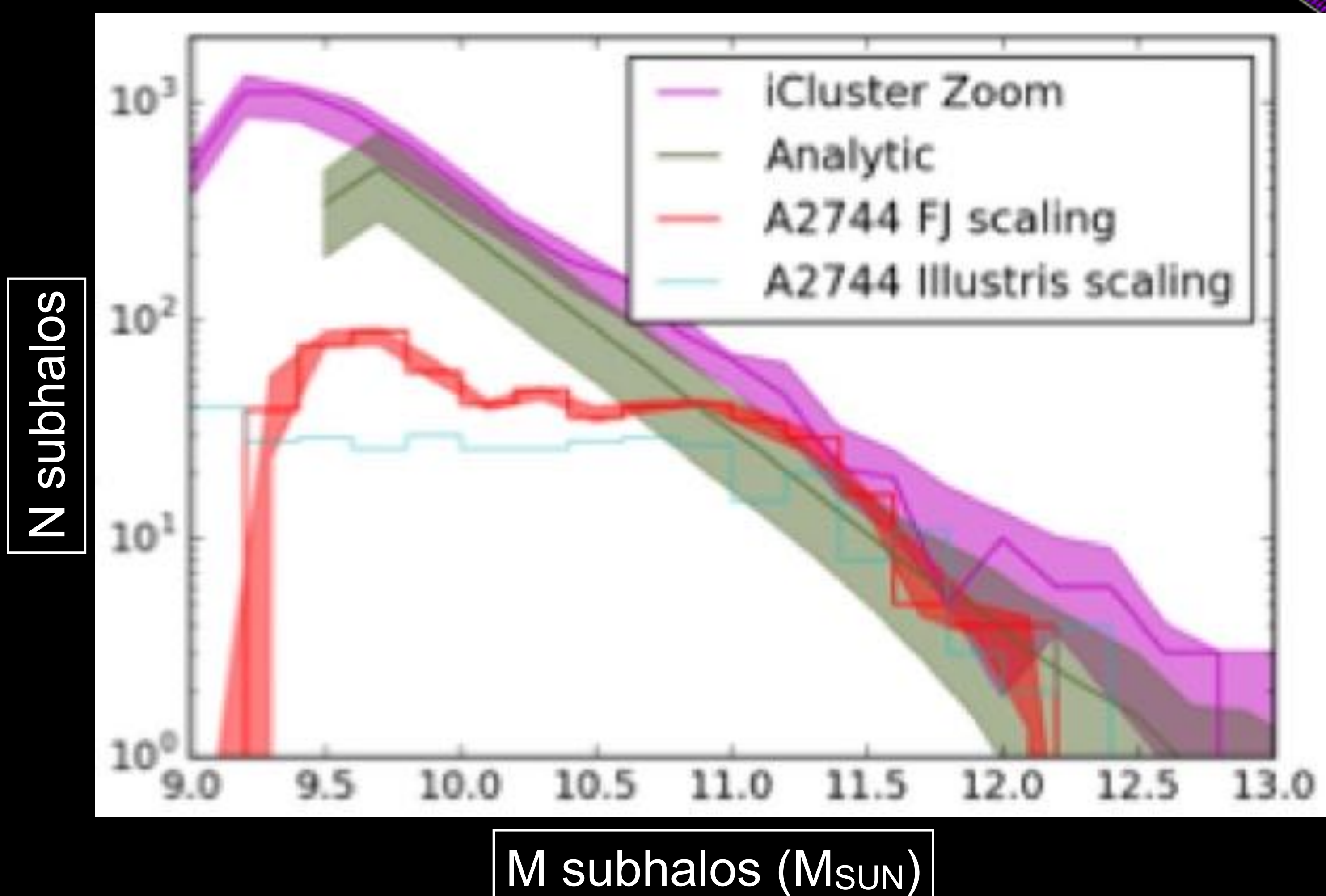
SL-only analysis

Natarajan, Chadayammuri, Jauzac et al. 2017, *MNRAS, 468, 1962*

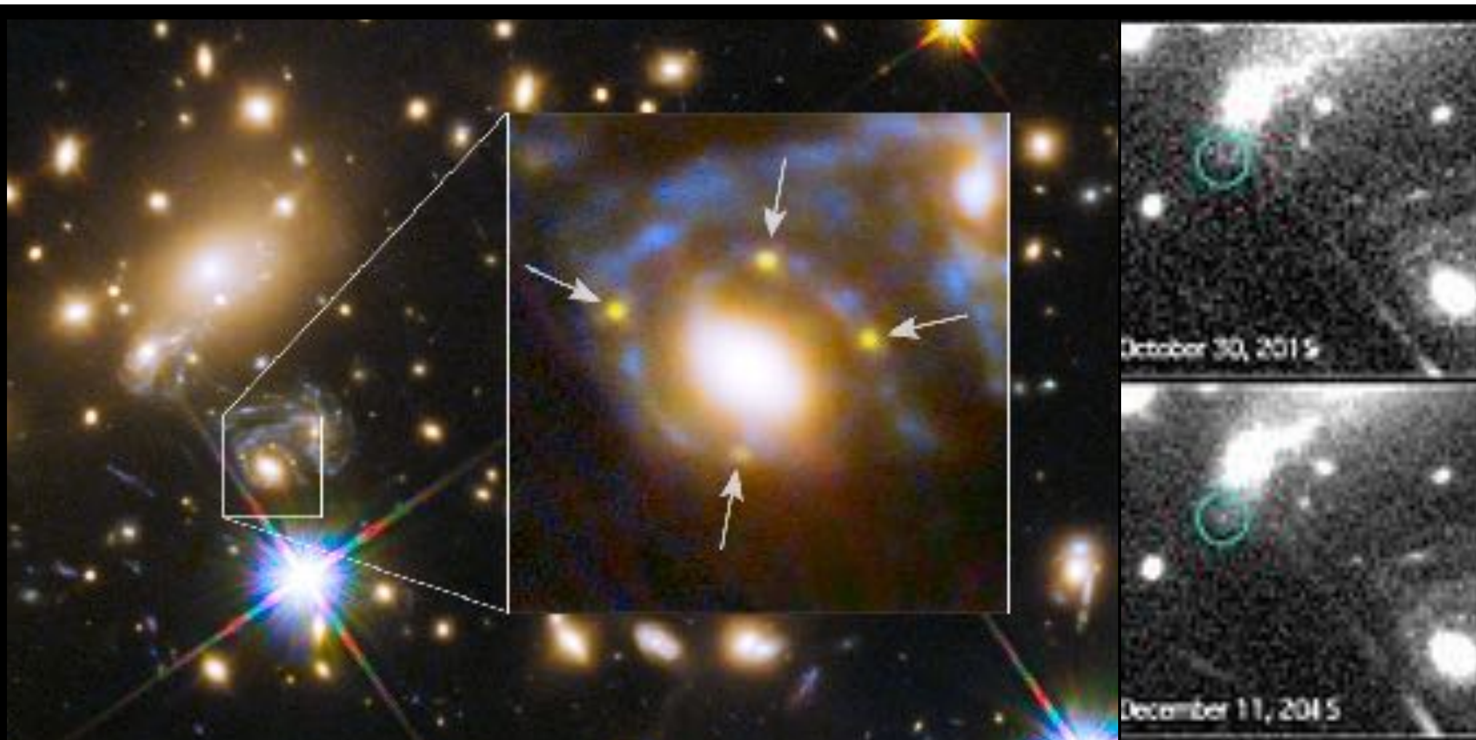
Mass and radial distribution of substructures

- Test of LCDM
- Good agreement at the low-mass end

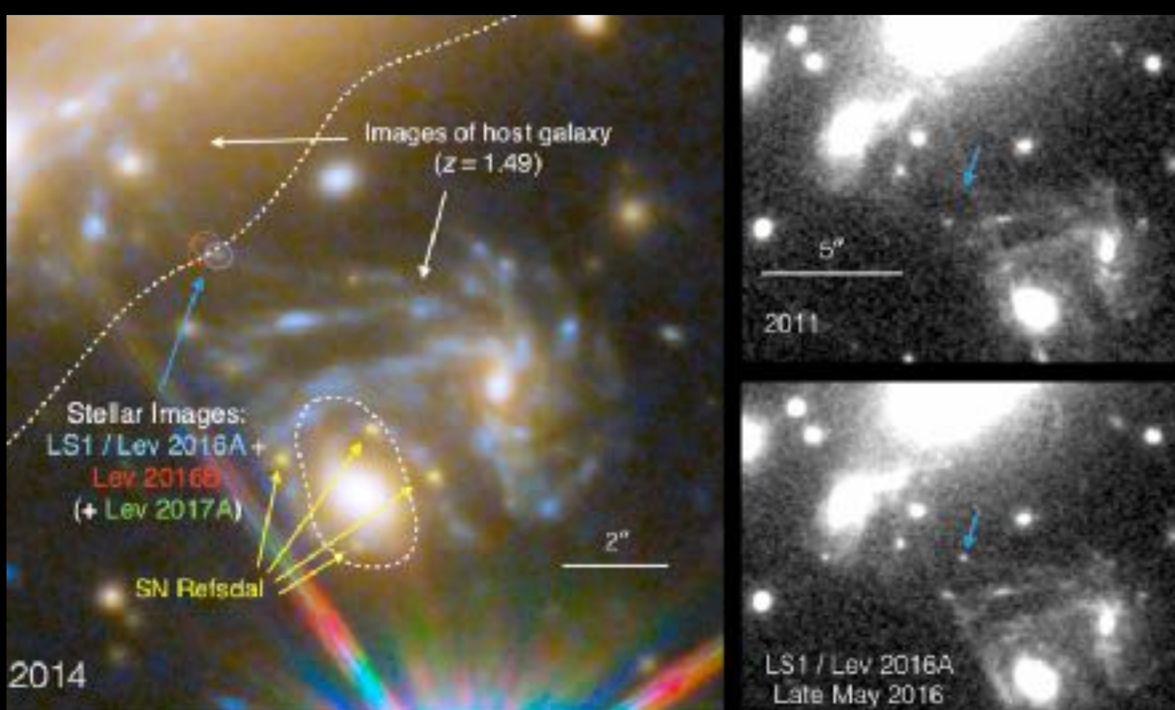




Cluster Strong Lensing : Transient Sources

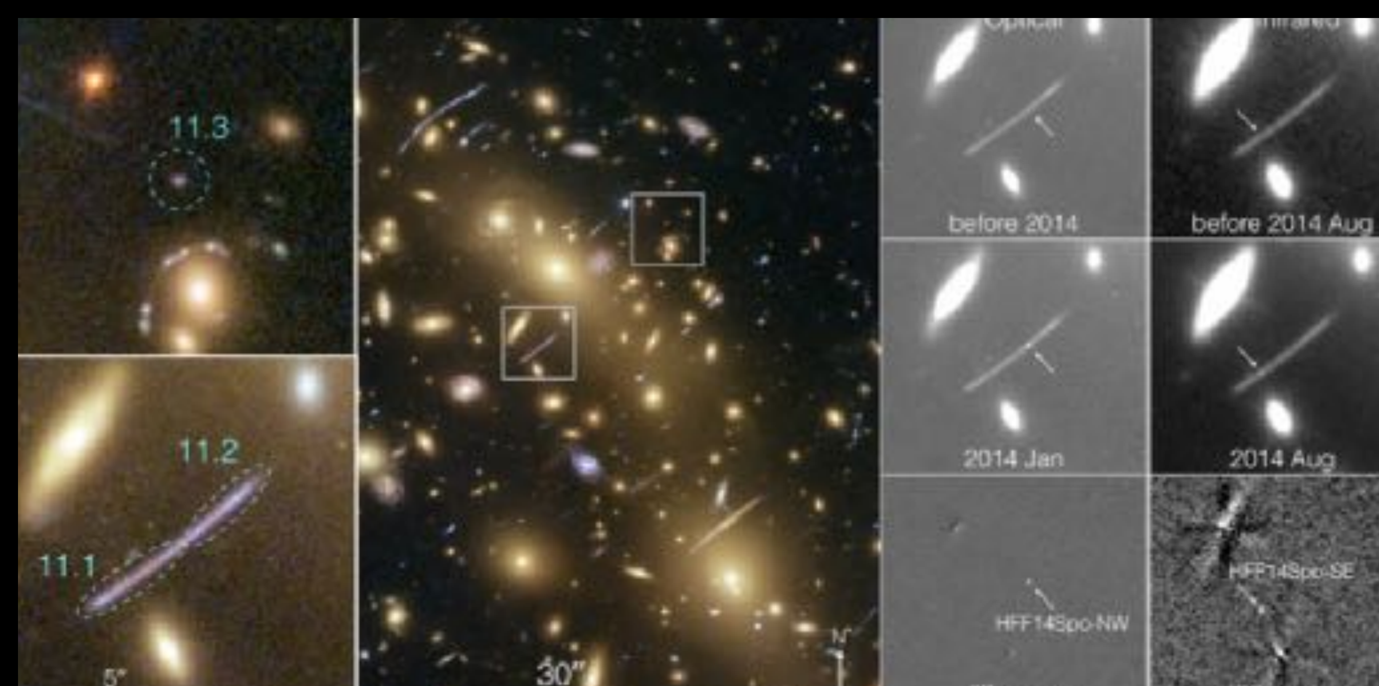


SN Refsdal : 1st multiply-lensed SN
Kelly et al. 2015; Jauzac et al. 2016a; Treu et al. 2016; Grillo et al. 2016



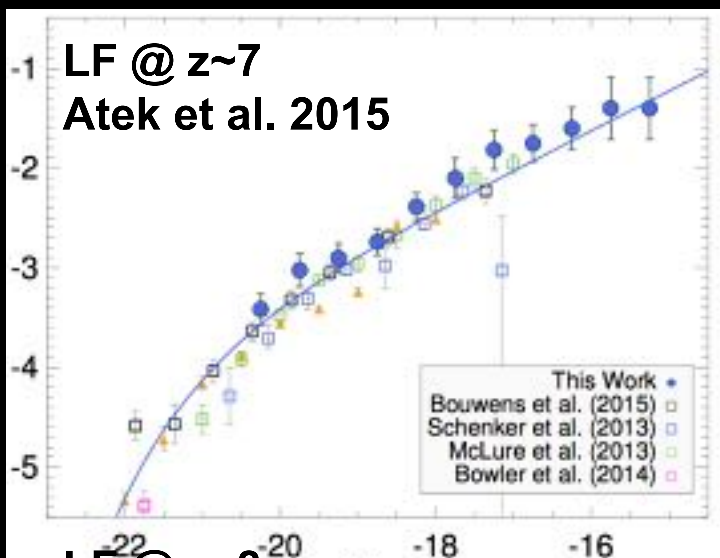
Icarus/Iapyx/Perdrix : 1st lensed star @ z=1.49
Kelly et al. 2017; Diego et al. 2017

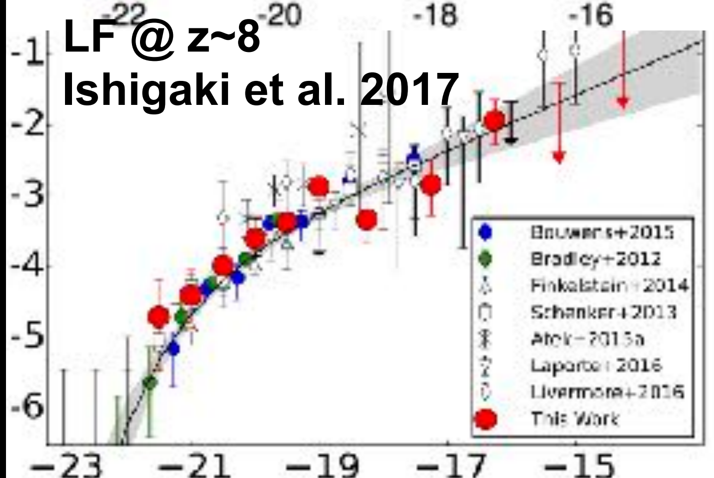
Spock : spatially coincident but not temporally
Rodney et al. 2017

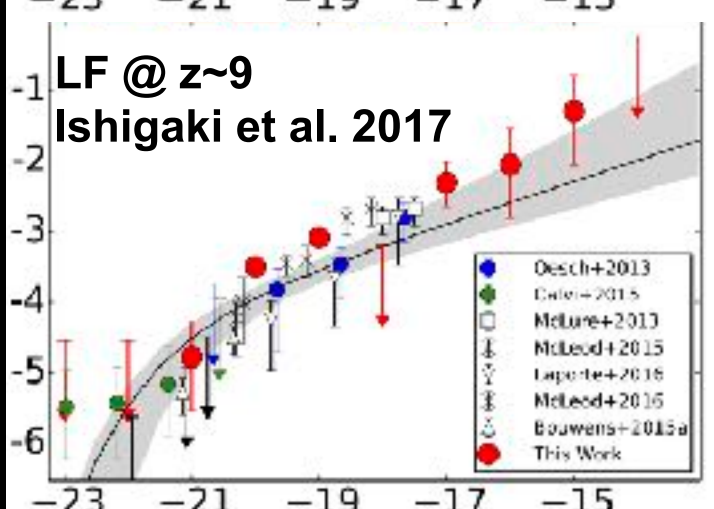


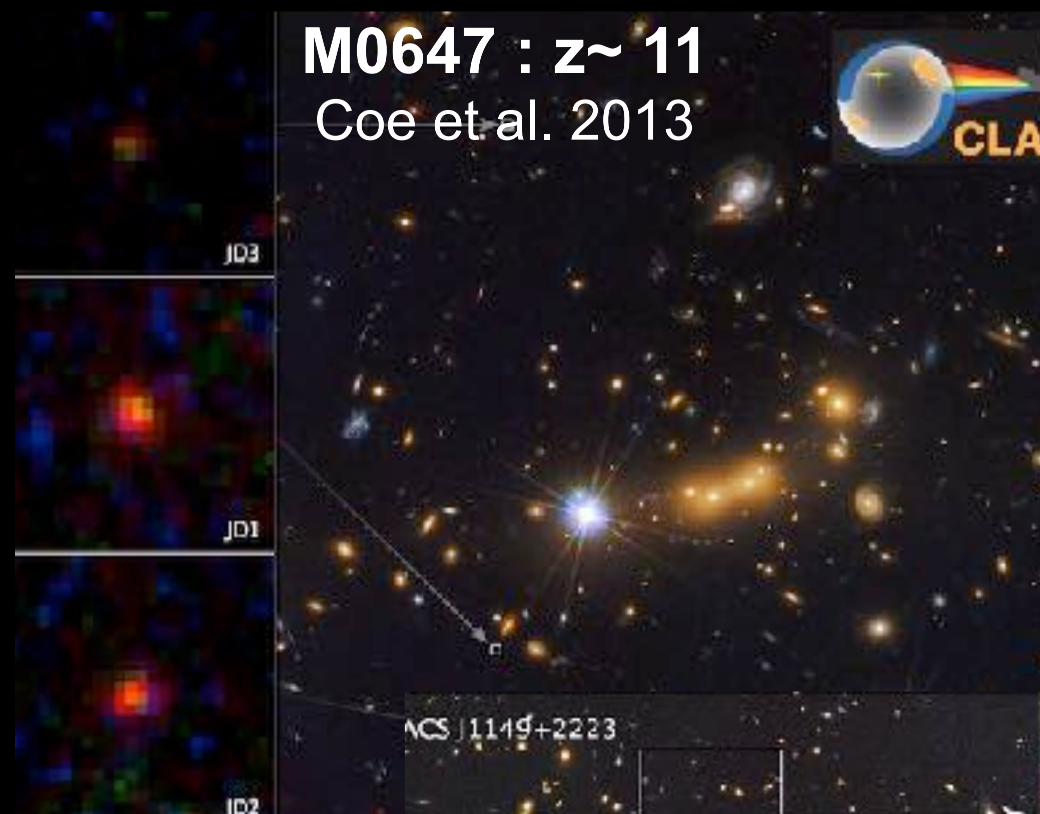
Cluster Strong Lensing : The High-z Universe

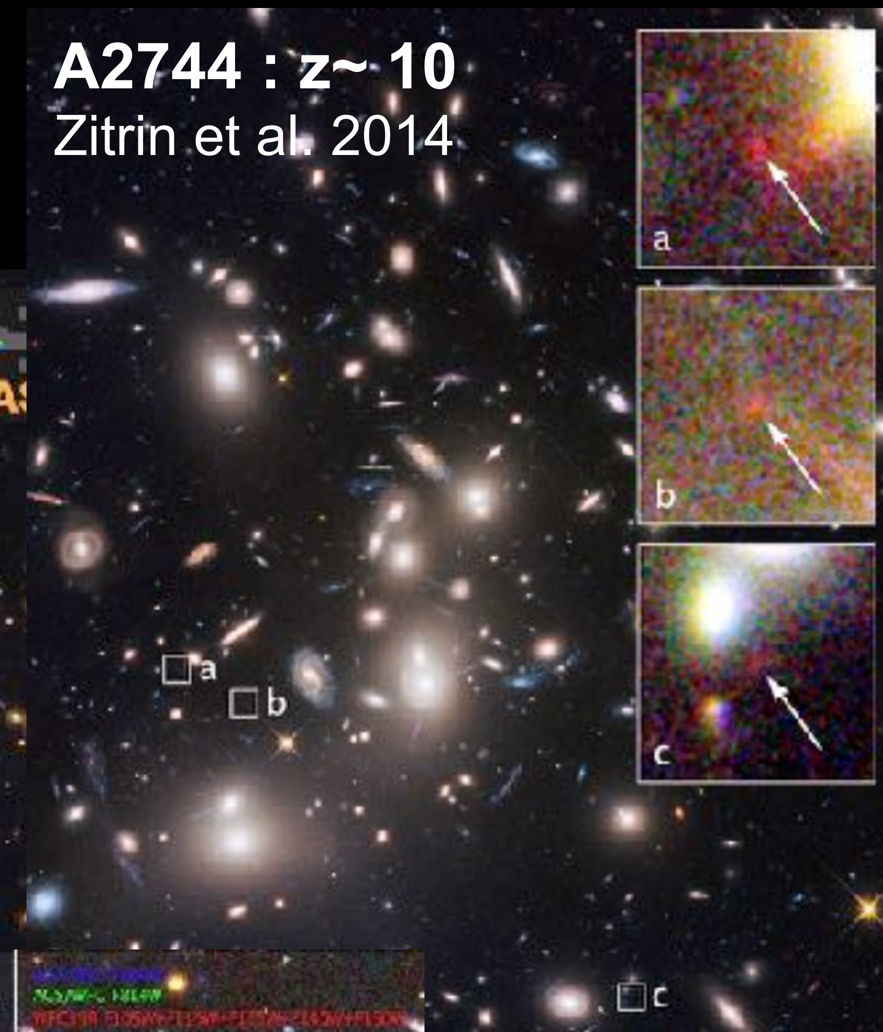
Galaxy Clusters as 'Natural Telescopes' = Take advantage of the lens magnification to probe Reionization

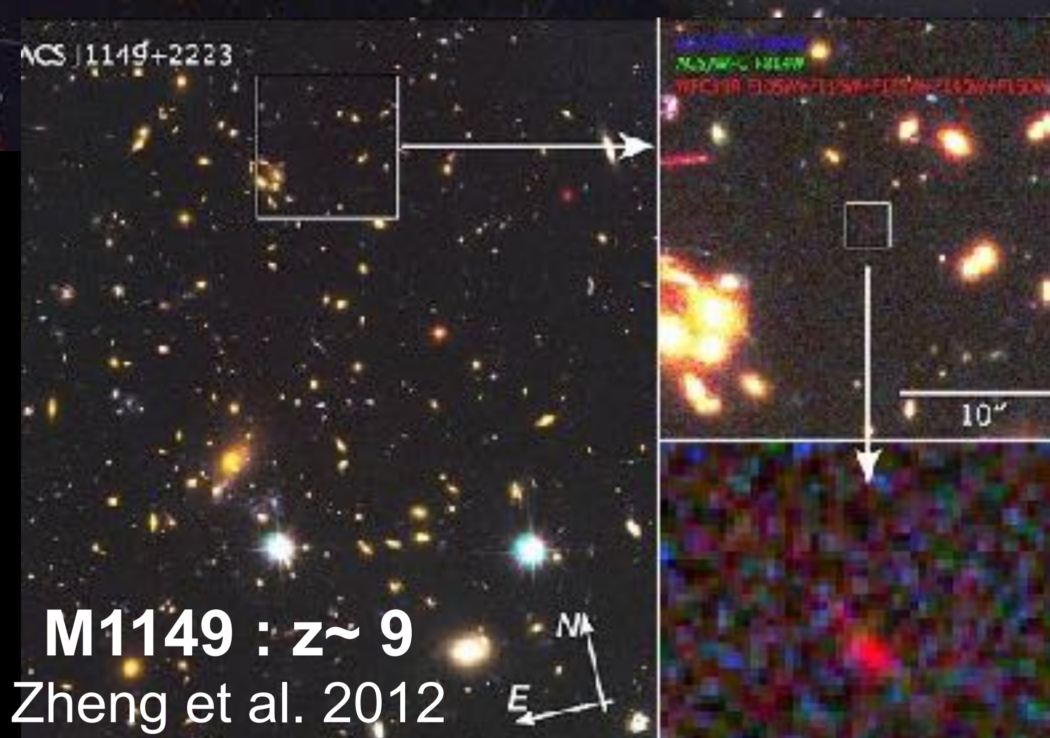












Outlines

1. Some cosmological context

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Cluster Weak Lensing : How to Model the Mass ?

Different algorithms : Parametric & non-Parametric

Parametric

GLAFIC
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LTM
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GLEE
Suyu+11

Lenstool
Jullo+07

Non-Parametric

WSLAP+
Diego+07

SaWLens
Merten+09,14

SWUnited
Bradac+05

GRALE
Liesenborgs+06

hybrid-Lenstool
Jullo+09

Inputs :

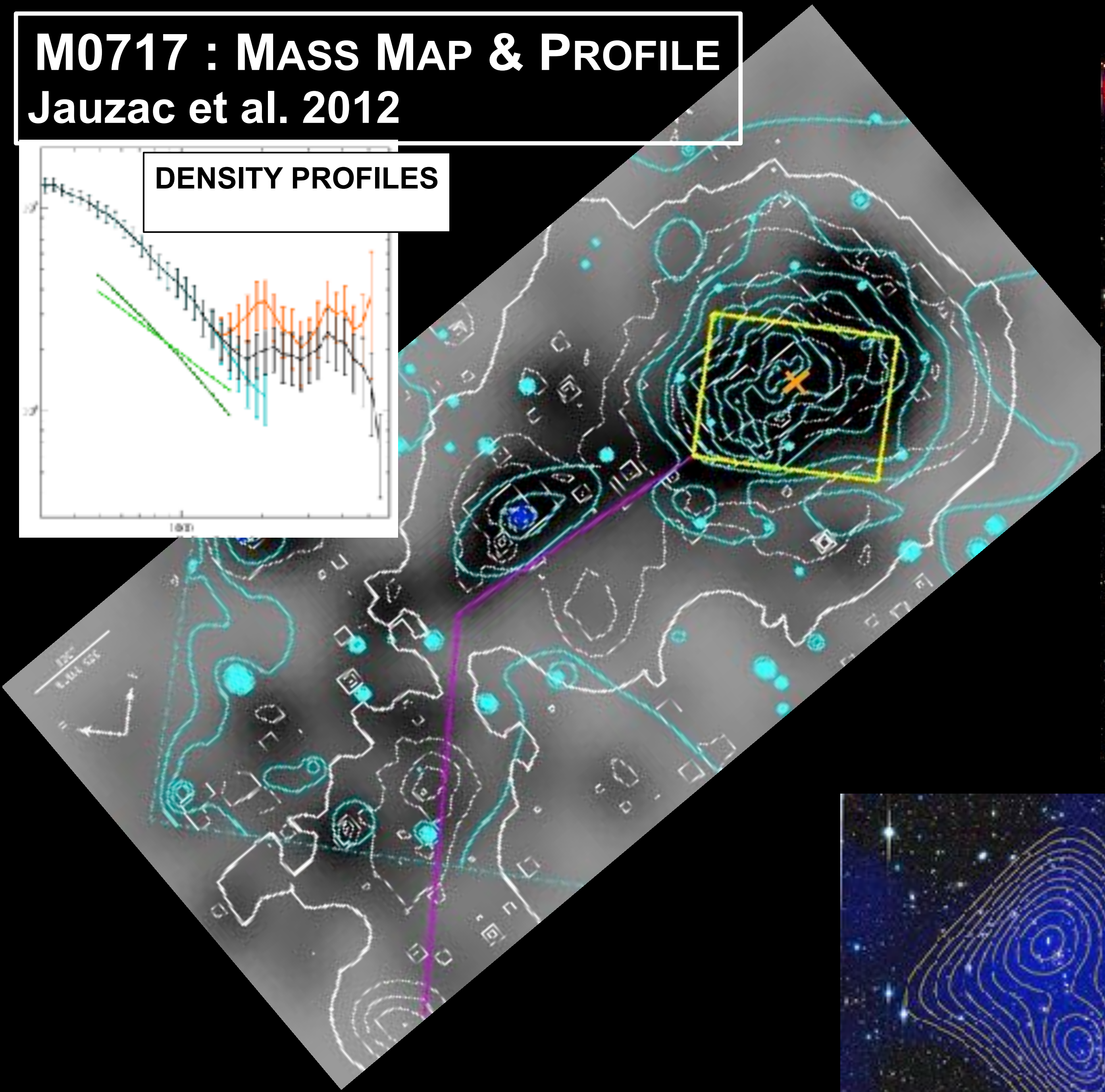
- Multi-scale / Uniform grid of potentials
- Weakly-lensed background galaxies
- Cluster galaxies

Outputs :

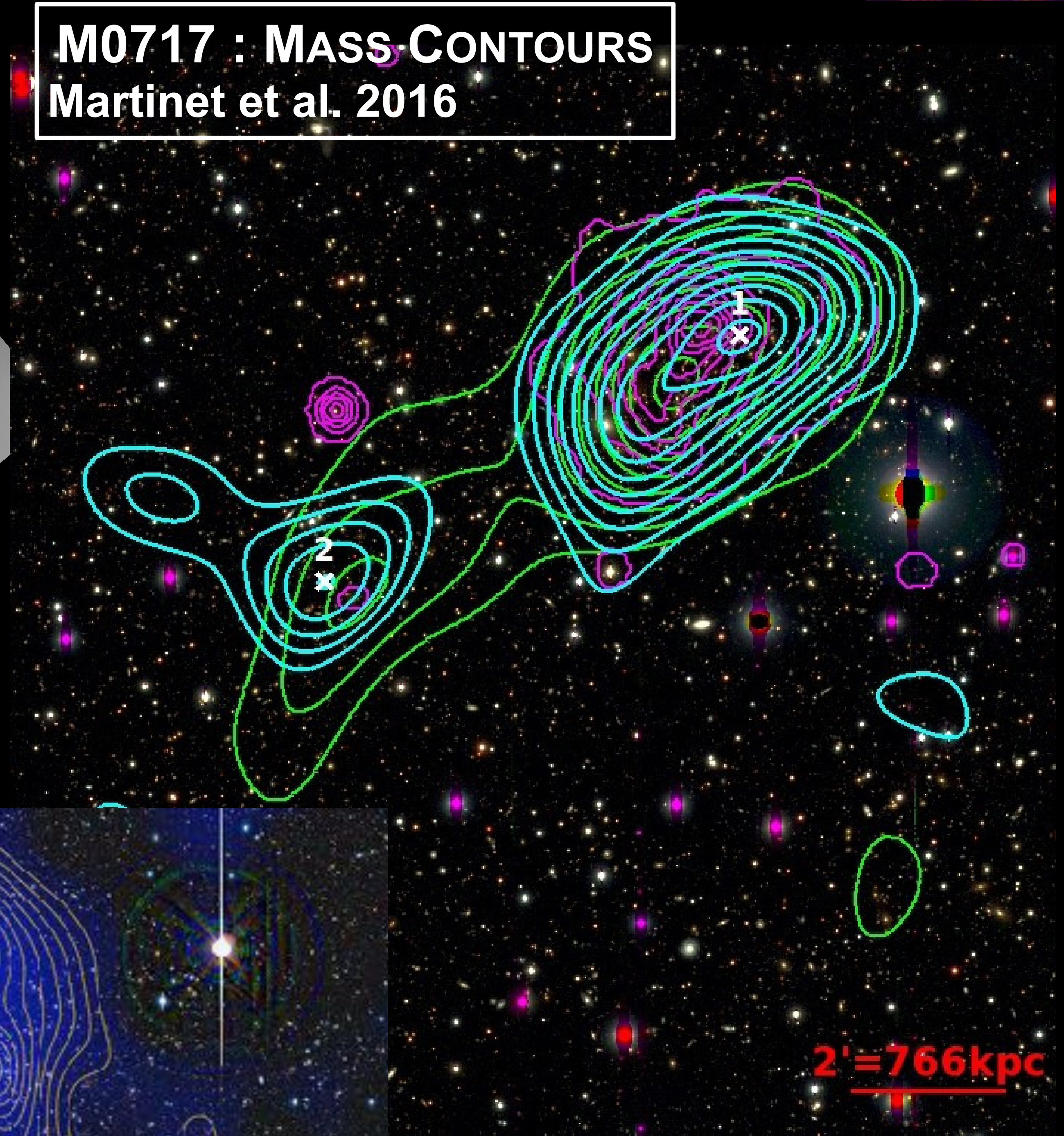
- Cluster mass maps (convergence, shear, …)
- Magnification maps
- Detection of large-scale structures, sub-structures

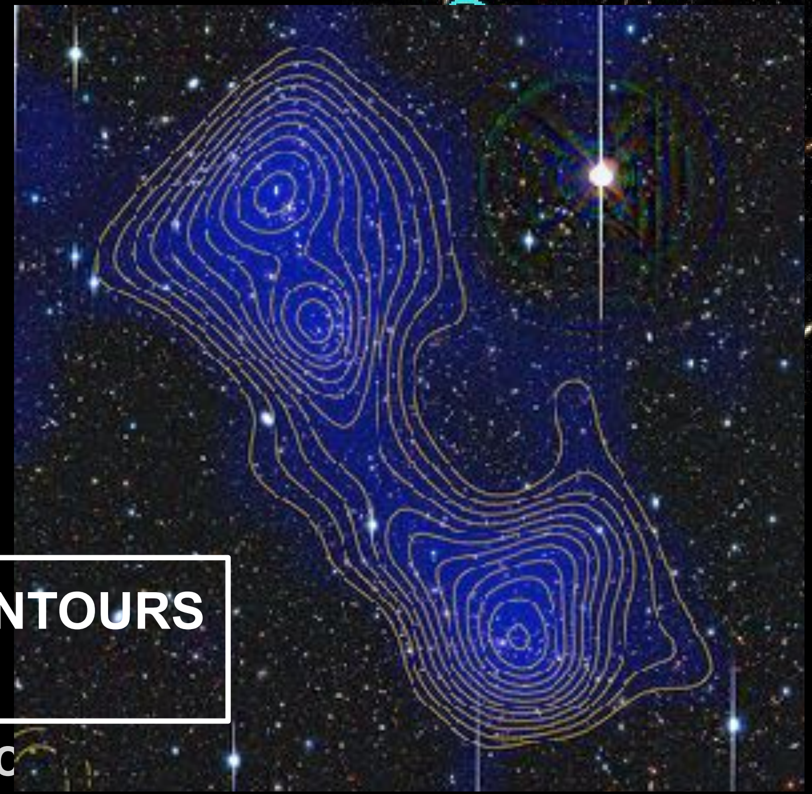
Cluster Weak Lensing : Large-Scale Structures

M0717 : Mass Map & Profile
Jauzac et al. 2012



M0717 : Mass Contours
Martinet et al. 2016





A222/223 : Mass Contours
Dietrich et al. 2012

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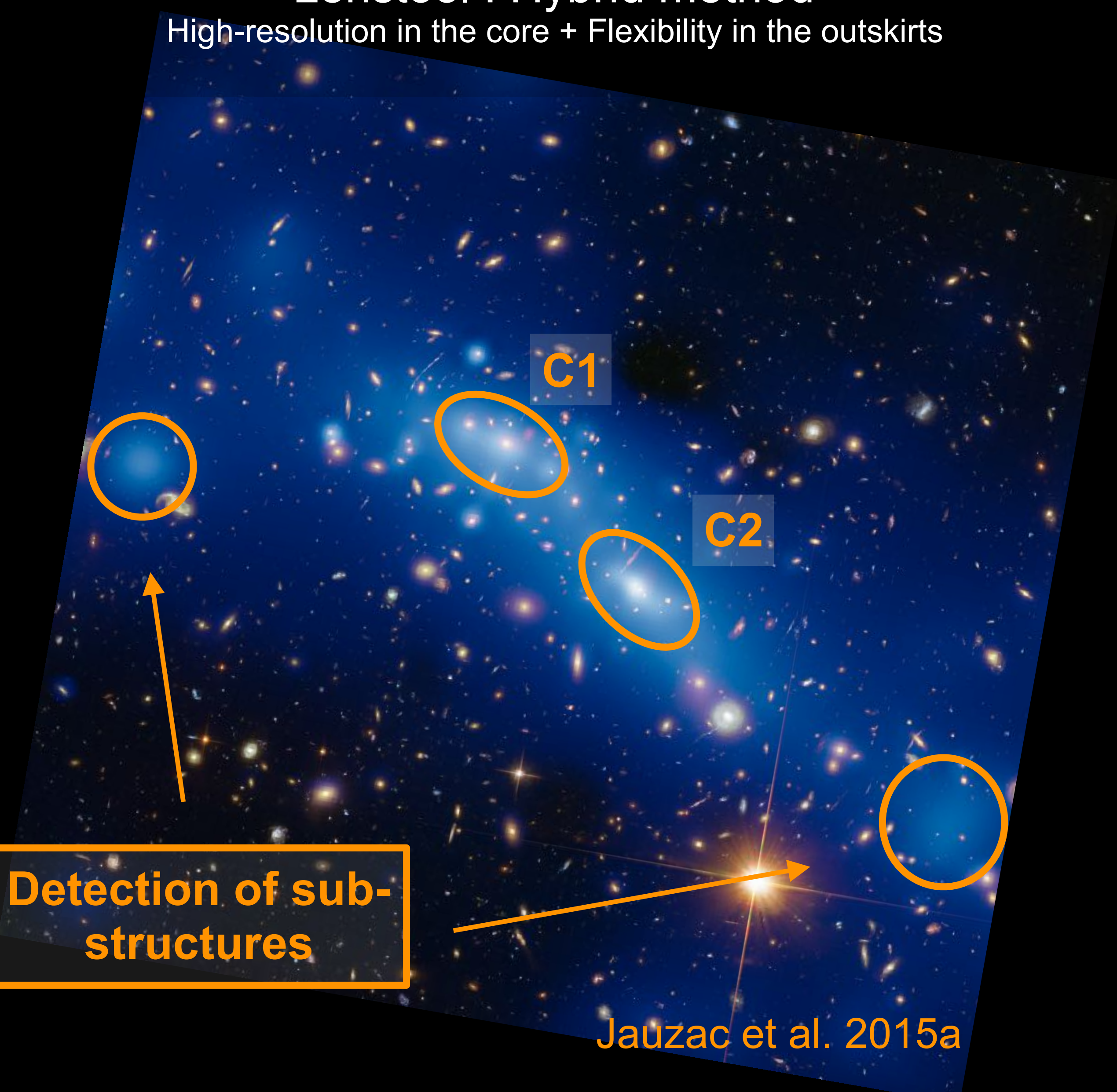
Cluster History : A Multi-Wavelength Approach

Multi-Wavelength Approach

SL + WL : Total Mass

Lenstool : Hybrid method

High-resolution in the core + Flexibility in the outskirts



SL + WL + Xray + zspec : 'Full Picture'

gas/light peaks

alignement/offset between DM-baryons ?

(No) Xray emission for substructures ?

ICL - Montes et al. 2014

Merging Scenario

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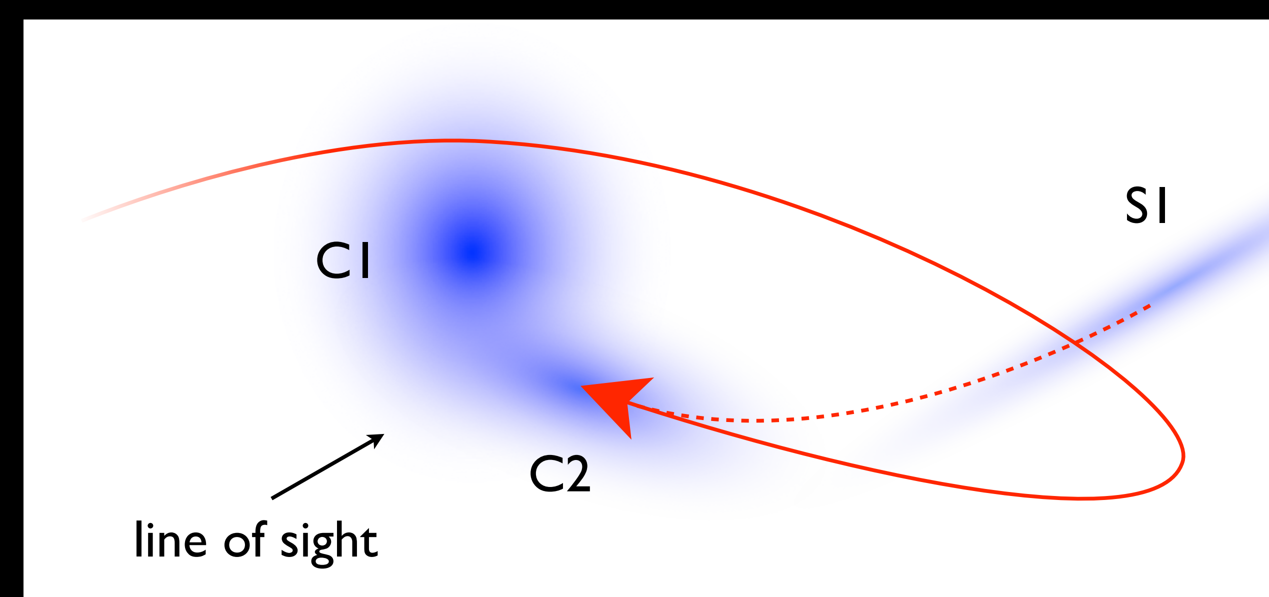
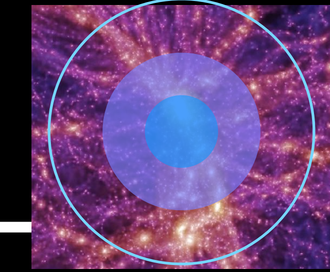
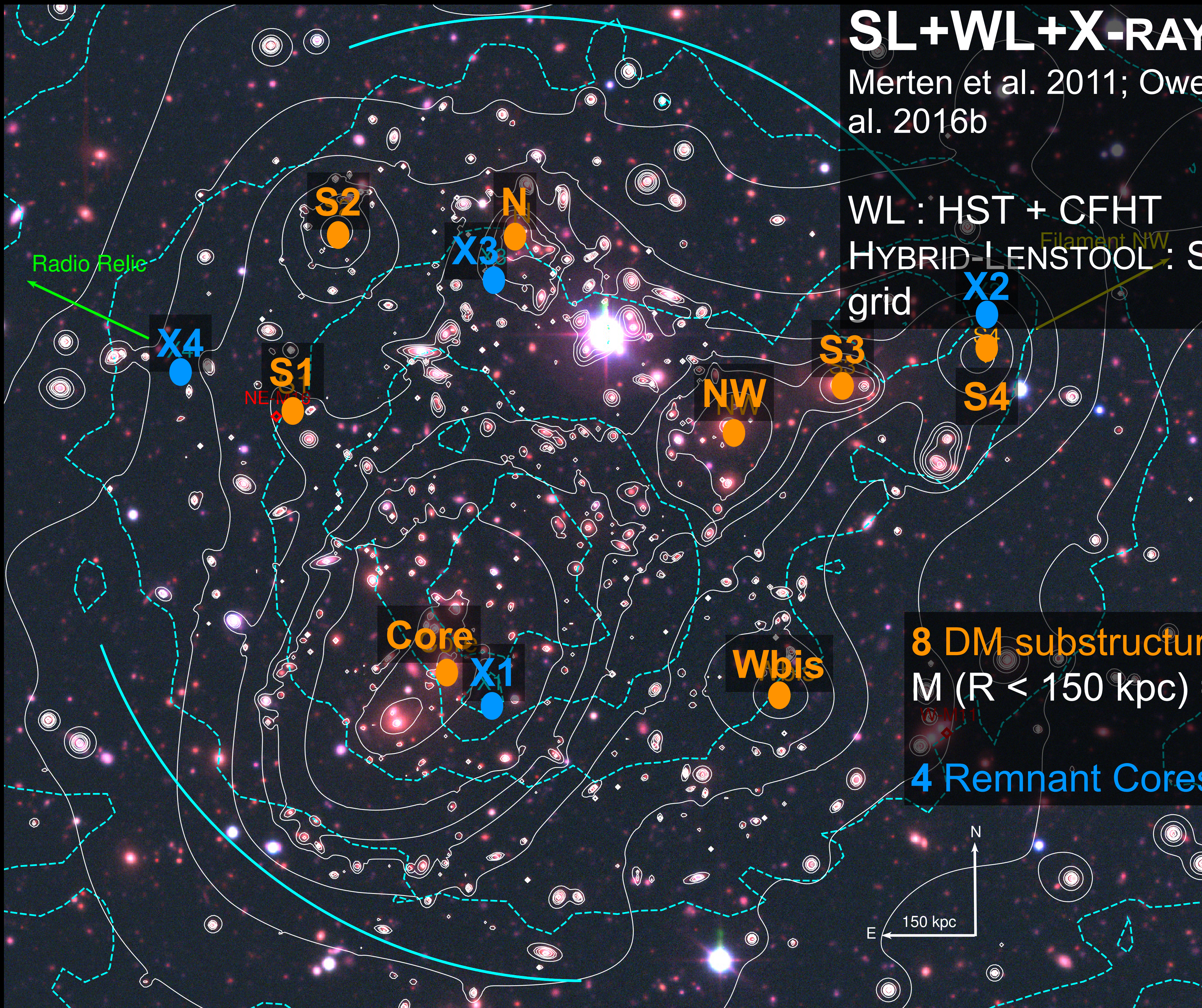
Constraints on Build-up of the Cluster



Cluster History : A Cosmological Test





SL+WL+X-rays Analysis

Merten et al. 2011; Owers et al. 2011; Jauzac et al. 2016b

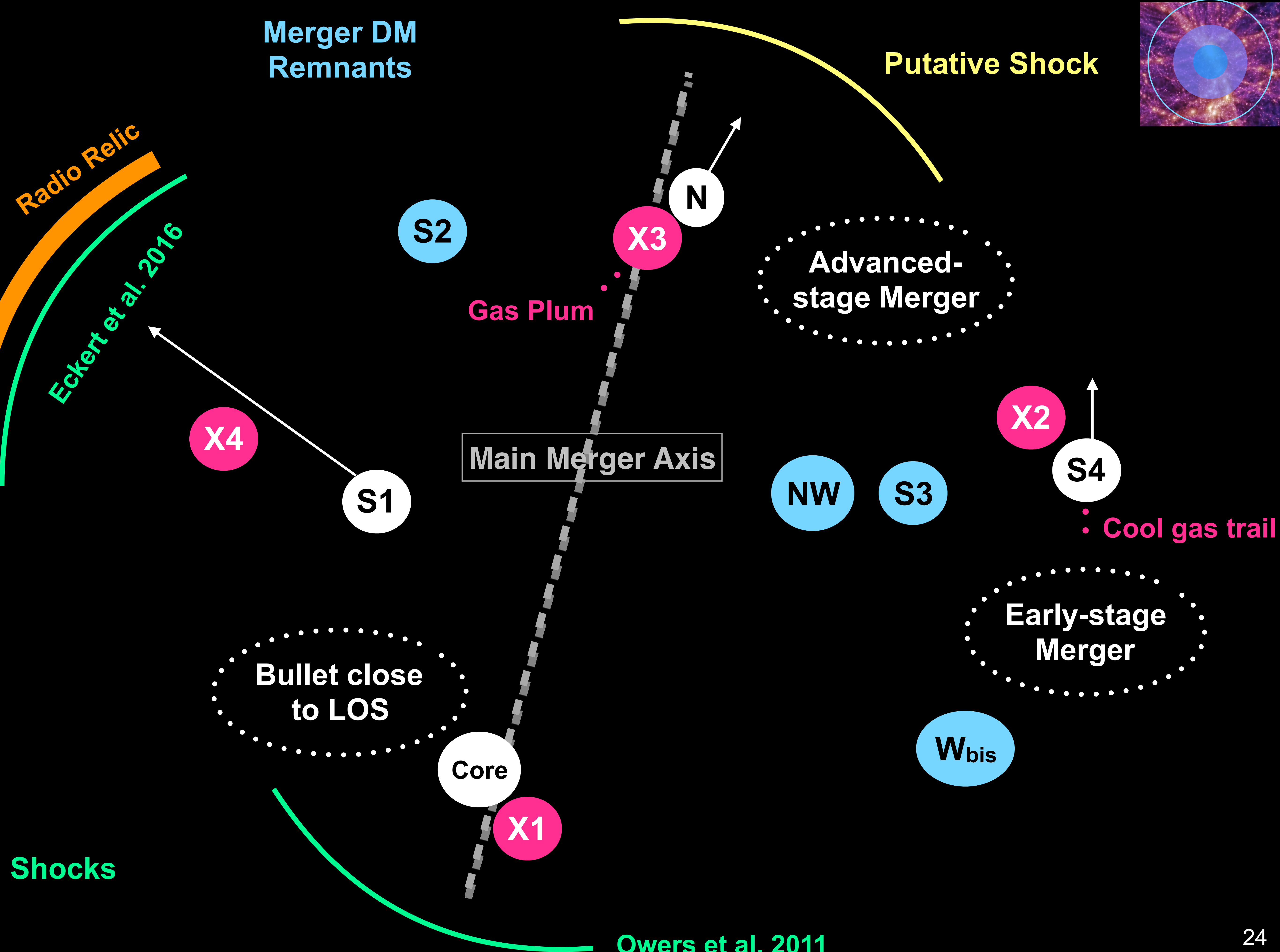
WL : HST + CFHT

Hybrid-Lenstool : SL potentials + Uniform grid

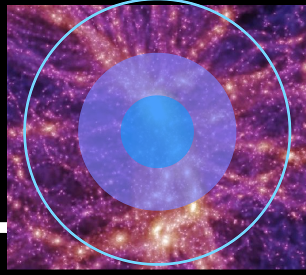
8 DM substructures with SN > 5

M (R < 150 kpc) = 0.5 -1.4 10^{14} M_{sun}

4 Remnant Cores



Merger DM
Remnants
Putative Shock
Radio Relic
Eckert et al. 2016
S2
N
X3
Gas Plum
Advanced-
stage Merger
X2
X4
S4
Main Merger Axis
S1
NW
S3
Cool gas trail
Early-stage
Merger
Bullet close
to LOS
Wbis
Core
X1
Shocks
Owers et al. 2011



COMPARISON WITH MXXL

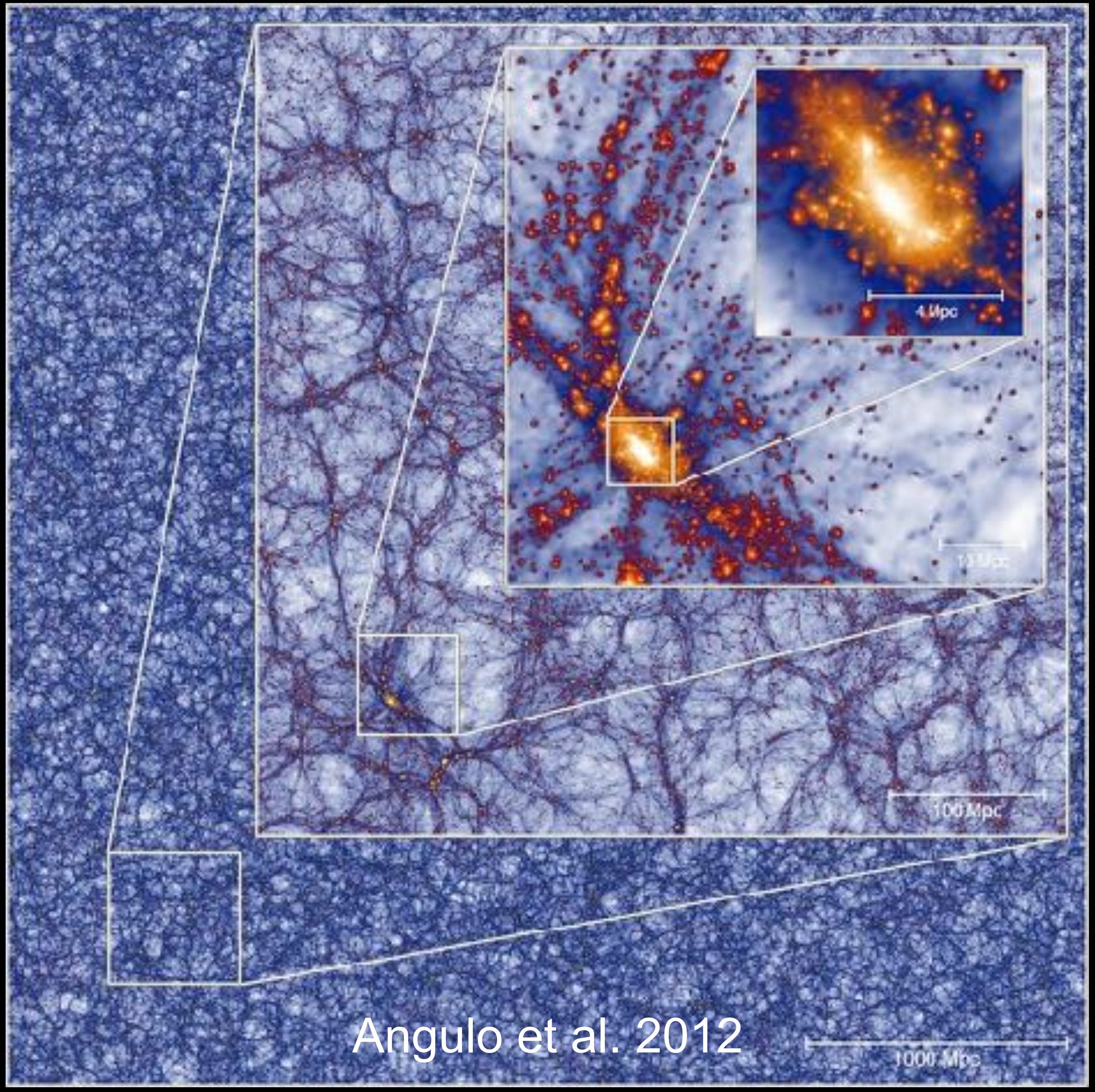
Jauzac et al. 2016b; Schwinn, Jauzac et al. 2017a
Schwinn et al. 2017b, *in prep.*

Total Mass : **~70 clusters** 0.28 < z < 0.32
- ★ **Cluster as massive as A2744 are common**

Number of Substructures : 2 clusters with max of 4 substructures within 1 Mpc
- ★ **A2744 substructure distribution is not observed in MXXL**

NUMERICAL & OBSERVATIONAL CAVEATS

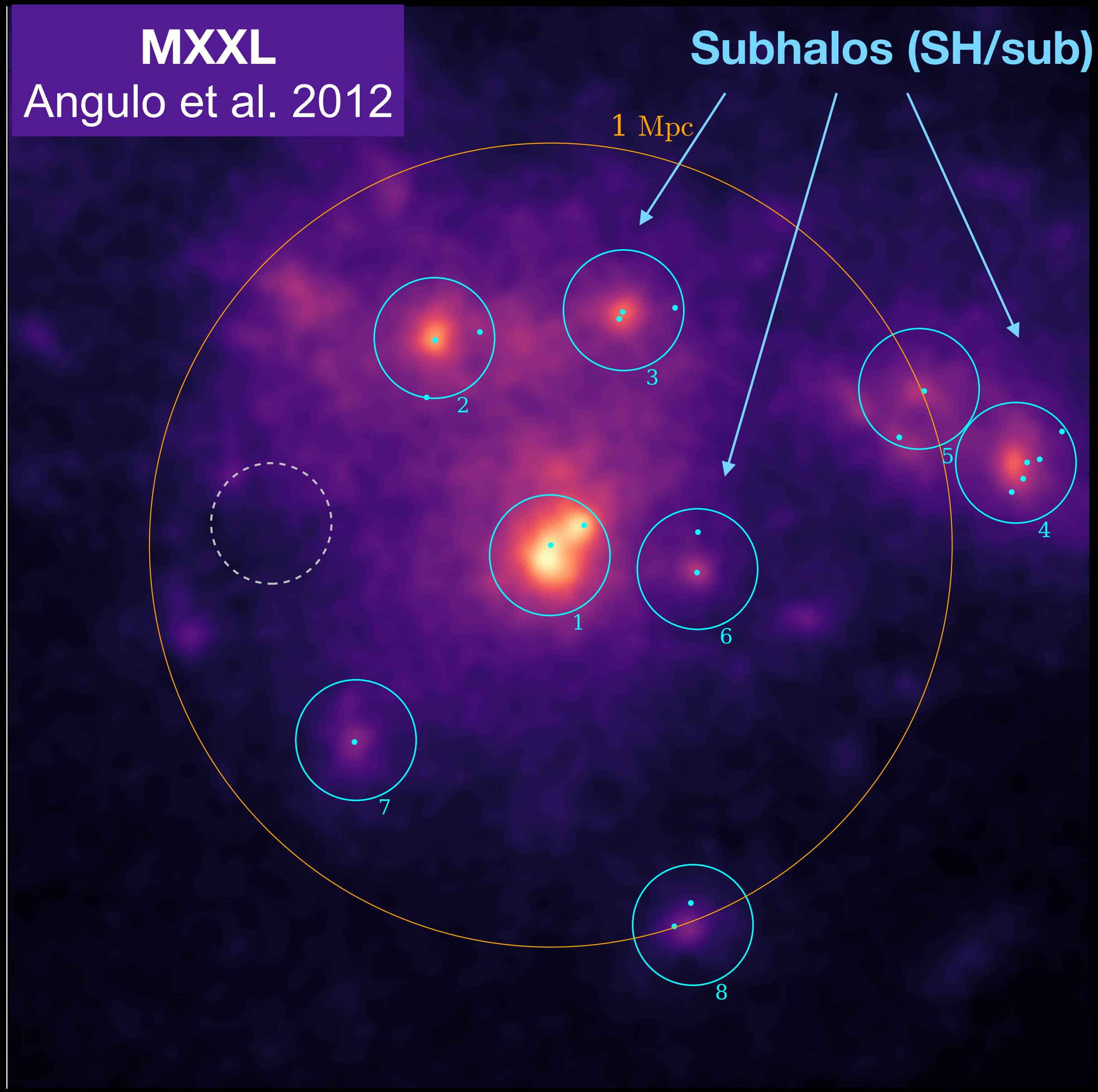
- Lack of resolution for subhalo finder algorithms
- LOS substructures from 2D mass measurements (see Gioccoli+16)



POSSIBLE CONFLICT WITH LCDM ?

Comparison with MXXL particle data

Schwinn, Jauzac et al. 2017, in prep.

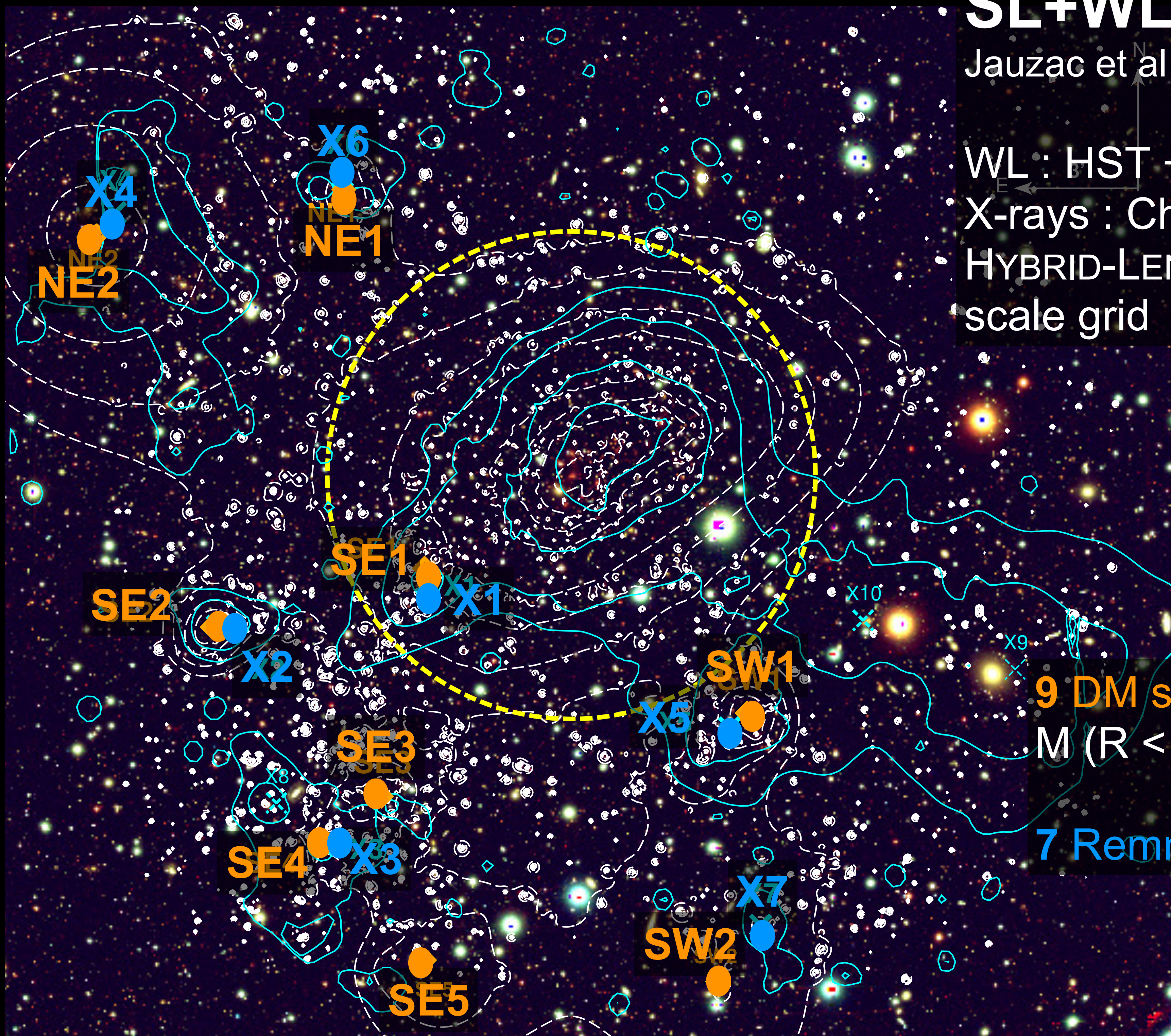


A2744 clusters not that rare …

Main caveat : Mass definition & SH detection algorithms

NO Possible Conflict with LCDM !

Cluster History : A Cosmological Test



SL+WL+X-rays Analysis

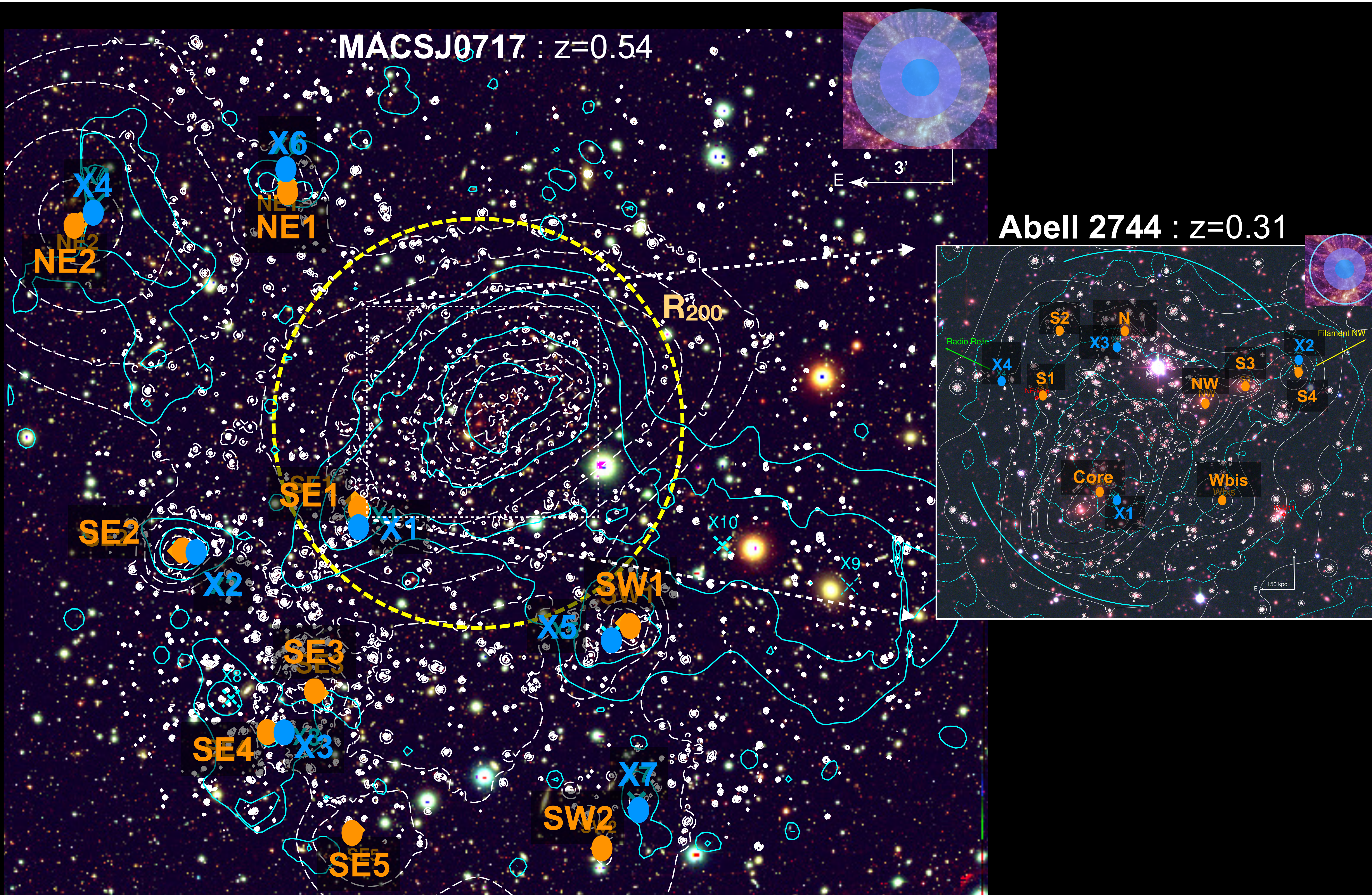
Jauzac et al. 2017, *sub. to MNRAS*

WL : HST + Subaru
X-rays : Chandra & XMM
Hybrid-Lenstool : SL potentials + Multi-scale grid

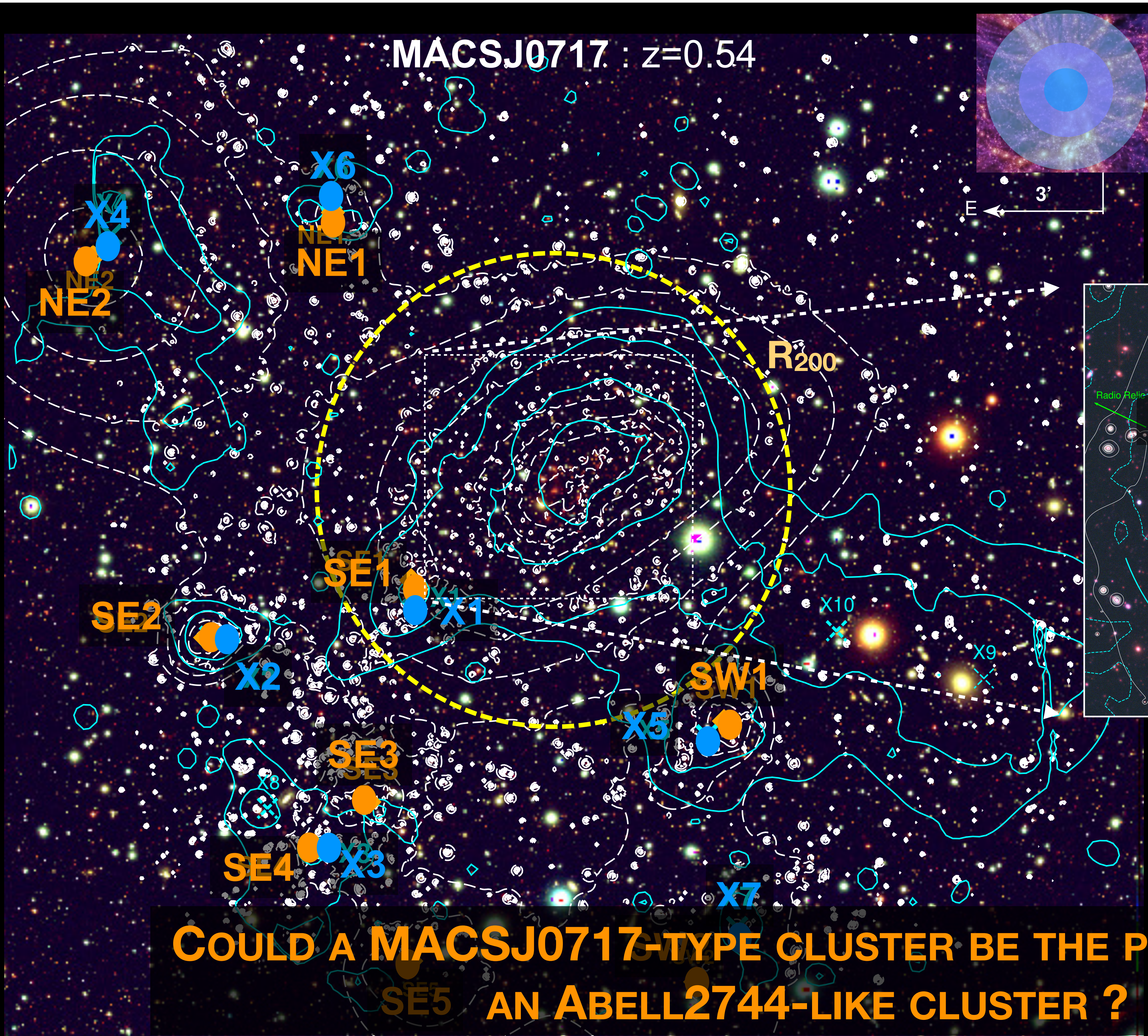
9 DM substructures
M (R < 150 kpc) = 0.1 - 0.3 10^{14} M_{sun}

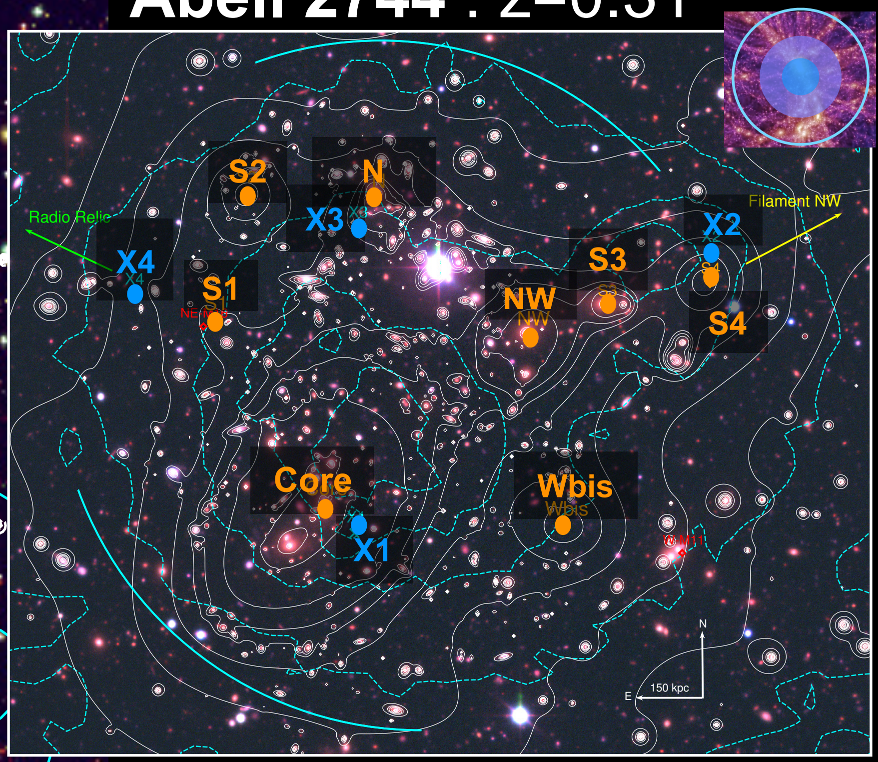
7 Remnant Cores

Cluster History : A Cosmological Test



Cluster History : A Cosmological Test



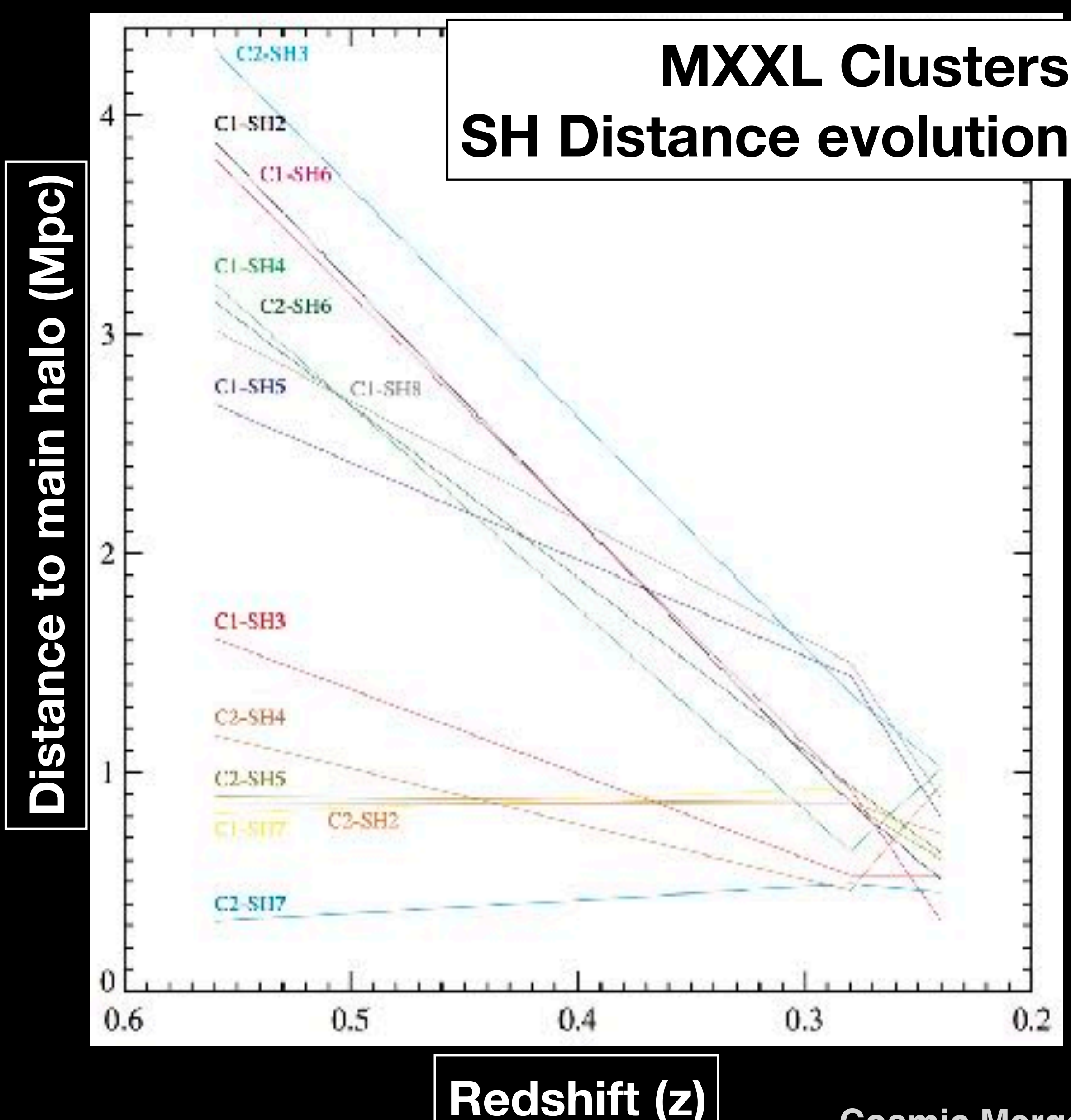


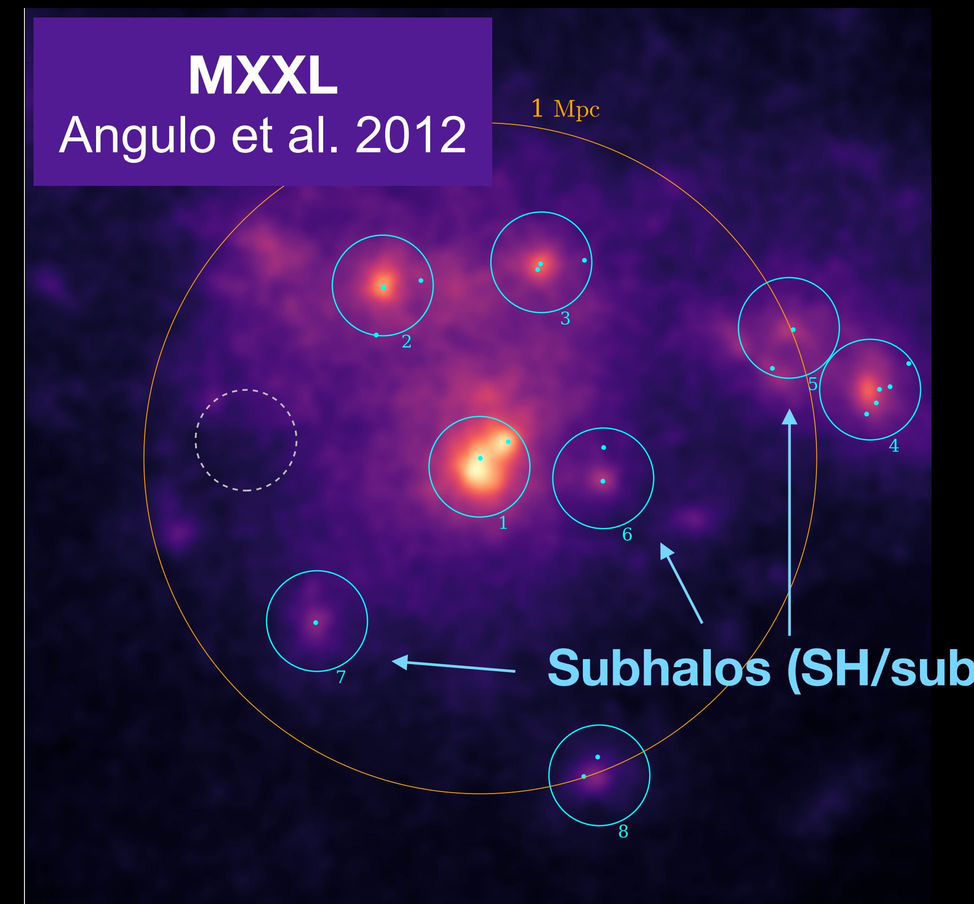
Could a MACSJ0717-type cluster be the progenitor of an Abell2744-like cluster ?

COMPARISON WITH MXXL

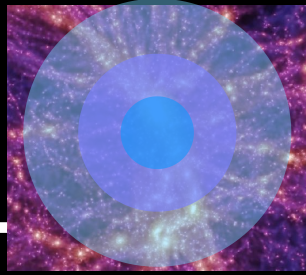
Jauzac et al. 2017, *sub. to MNRAS*

Particle data @ z=0.24 : 2 clusters
Identification of substructures : 8 & 7 substructures
Ray-tracing up to z=0.58





SUBFIND masses : not comparable
Infall distance :
$D_{0.58-0.24}$ ~ 2-3 Mpc



Cluster History : A Cosmological Test

Comparison with C-EAGLE

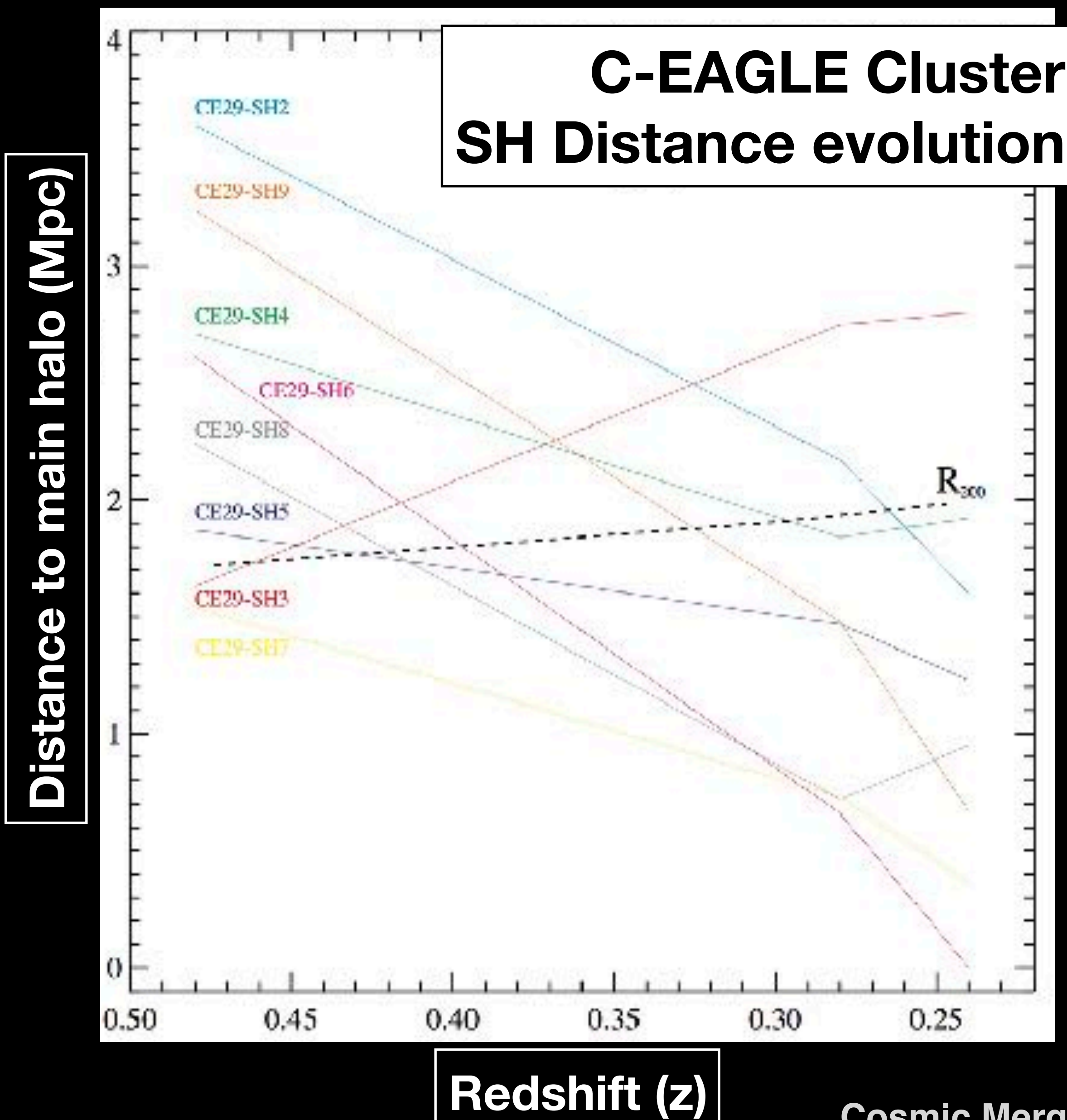
Jauzac et al. 2017, *sub. to MNRAS*

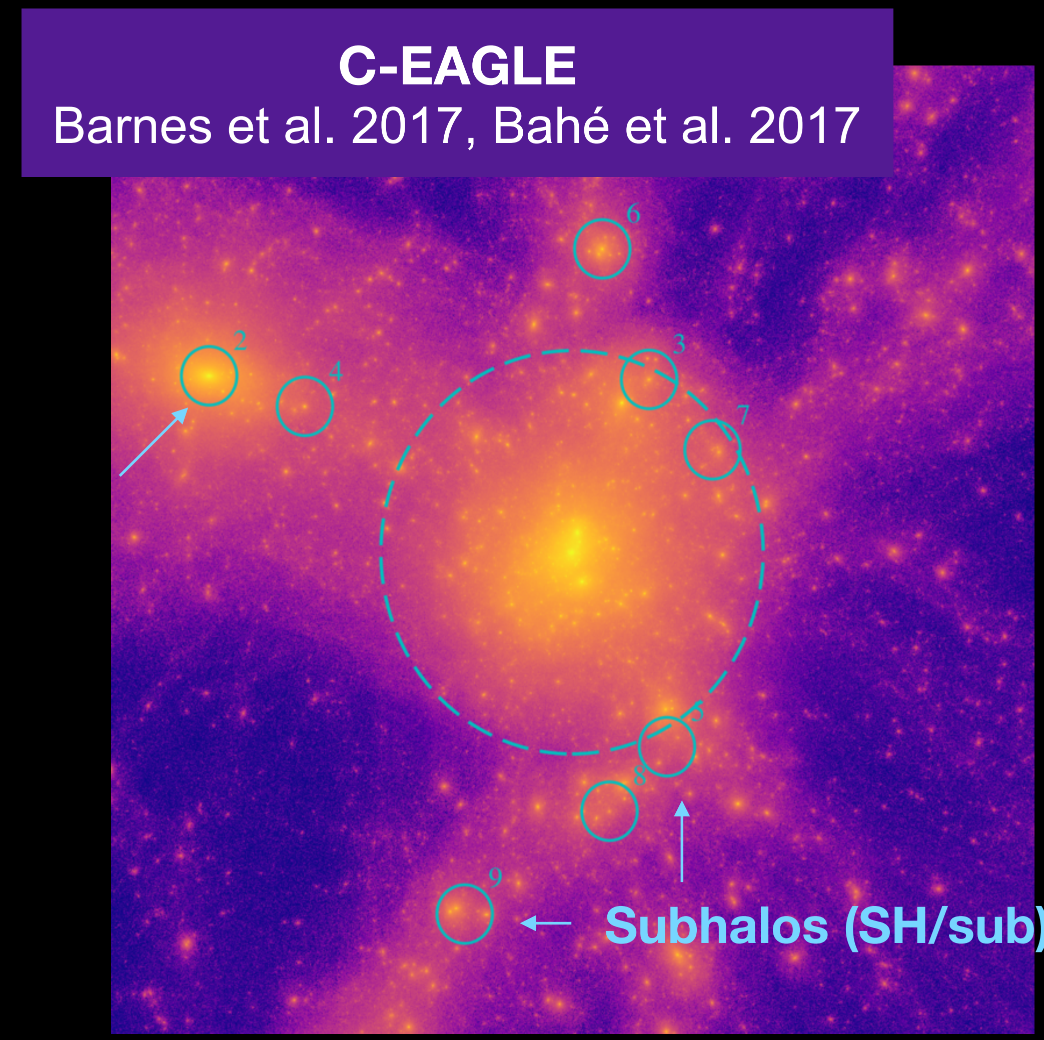
Particle data @ z=0.48, z=0.24, z=0 : 1 cluster

Identification of substructures :

  8 substructures @ $R>R_{200}$

Tracing down to z=0.24





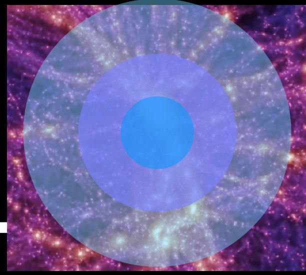
SUBFIND masses : not comparable

Infall distance :

  $D_{0.48-0.24}$ ~ 2 Mpc

Growth rate btw z=0.48 & z=0 = 160%

Cluster History : A Cosmological Test

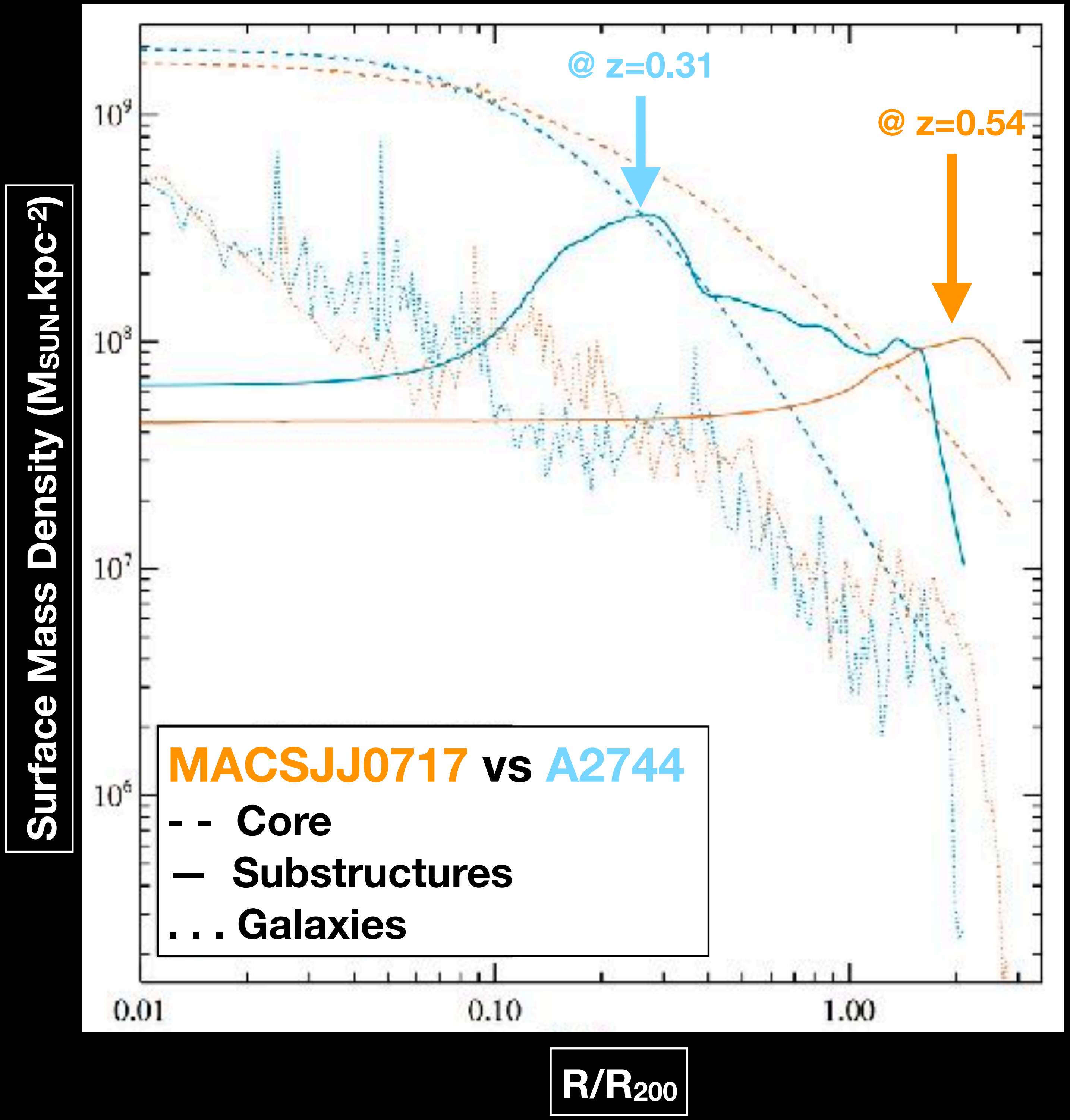


MACSJ0717 vs Abell2744

Jauzac et al. 2017, *sub. to MNRAS*

Different components : core, galaxies and substructures
Change of slope in the core :
  evolution of M-c relation with z
Simple calculation of infall distance :
  ~ 2 Mpc btw z=0.54 and z=0.31
  Agreement with MXXL & C-EAGLE

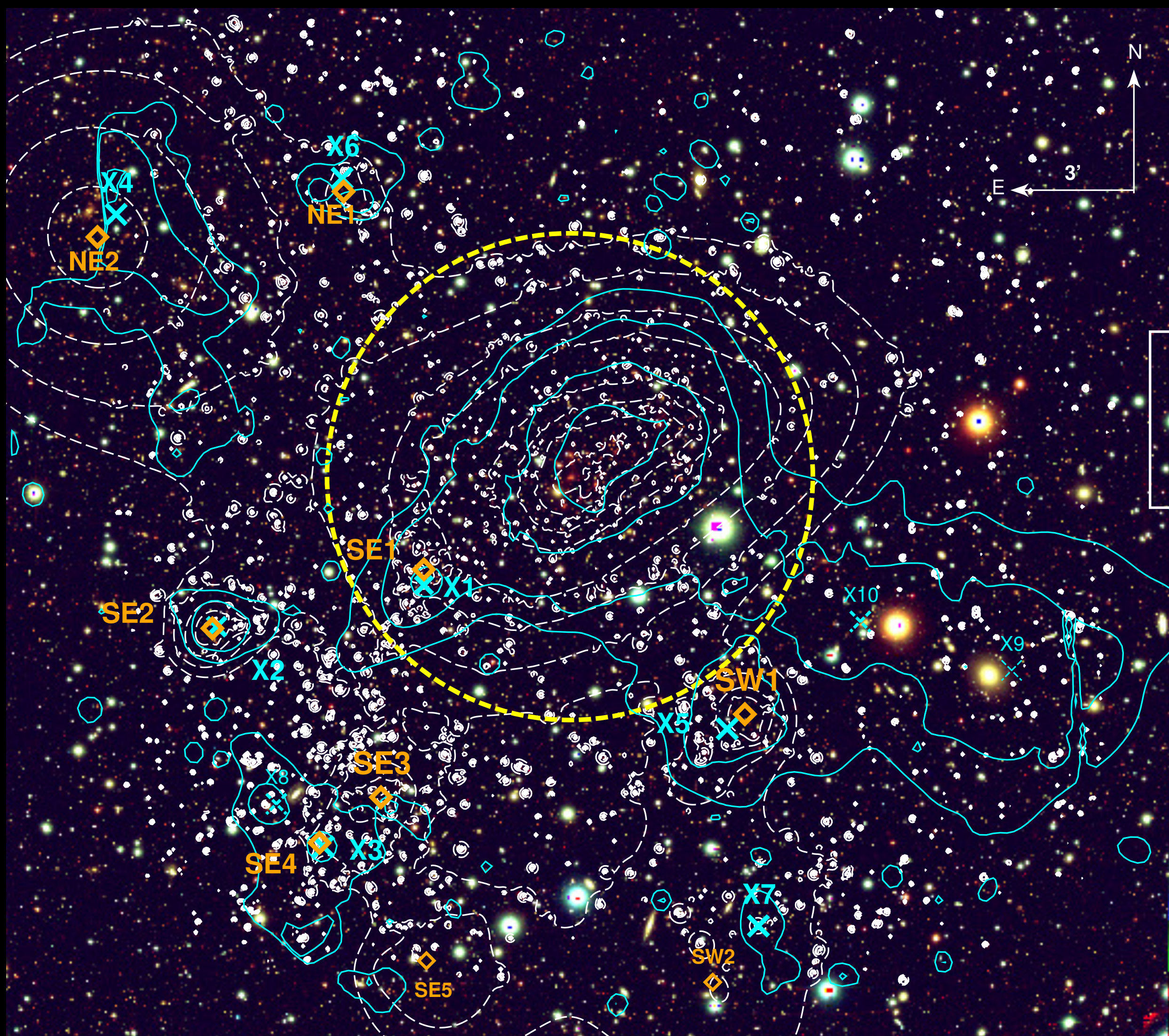
If applied to MACSJ0717 :
  @ z=0.31 : most of the substructures in $R<R_{200}$
  @ z=0 : extremely massive cluster of $M>1x10^{16}M_{SUN}$!



Cluster History : A Cosmological Test

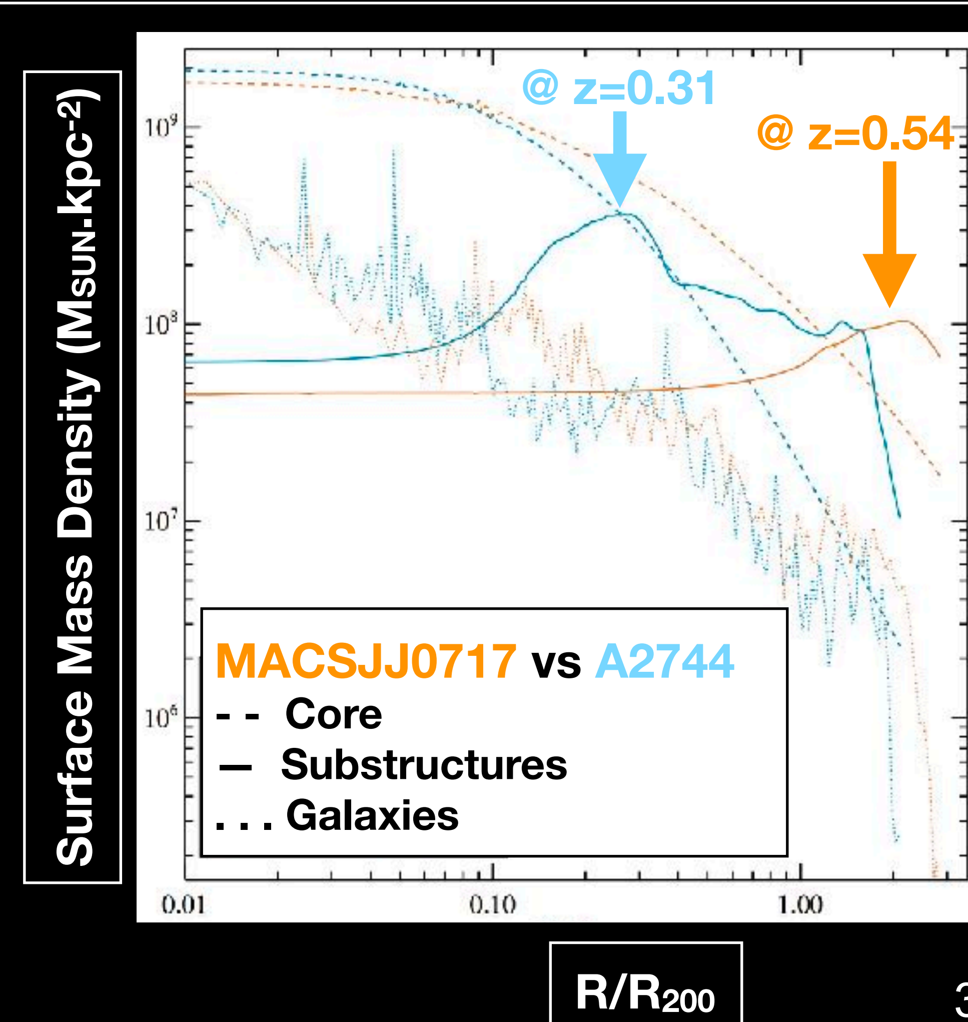
Take-Away Messages :

Jauzac et al. 2017, *sub. to MNRAS*



1. MACSJ0717 :
A super-cluster @ z=0.54

2. MACSJ0717-like clusters most likely progenitors of Abell 2744-like clusters



3. Even if at the limit of LCDM : analogues still exist !

OUTLINES

1. SOME COSMOLOGICAL CONTEXT

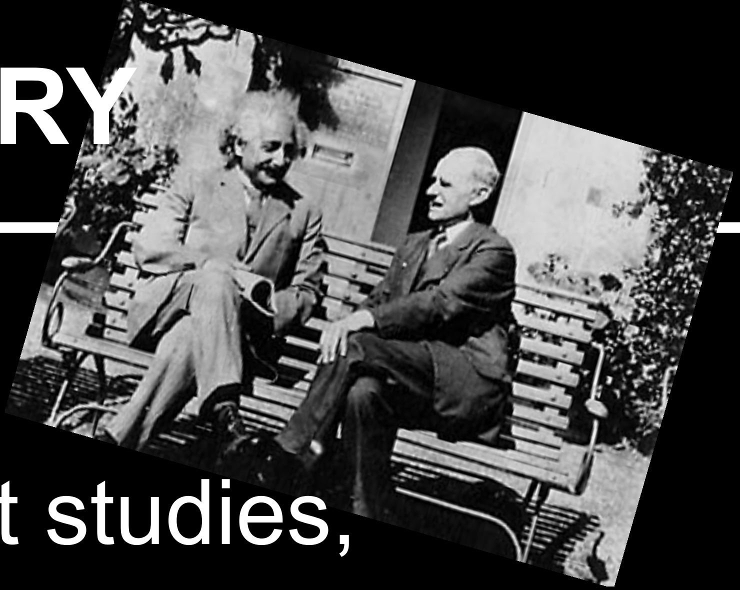
2. STRONG GRAVITATIONAL LENSING

3. WEAK GRAVITATIONAL LENSING

4. MULTI-WAVELENGTH ANALYSIS

5. CONCLUSION & PERSPECTIVES

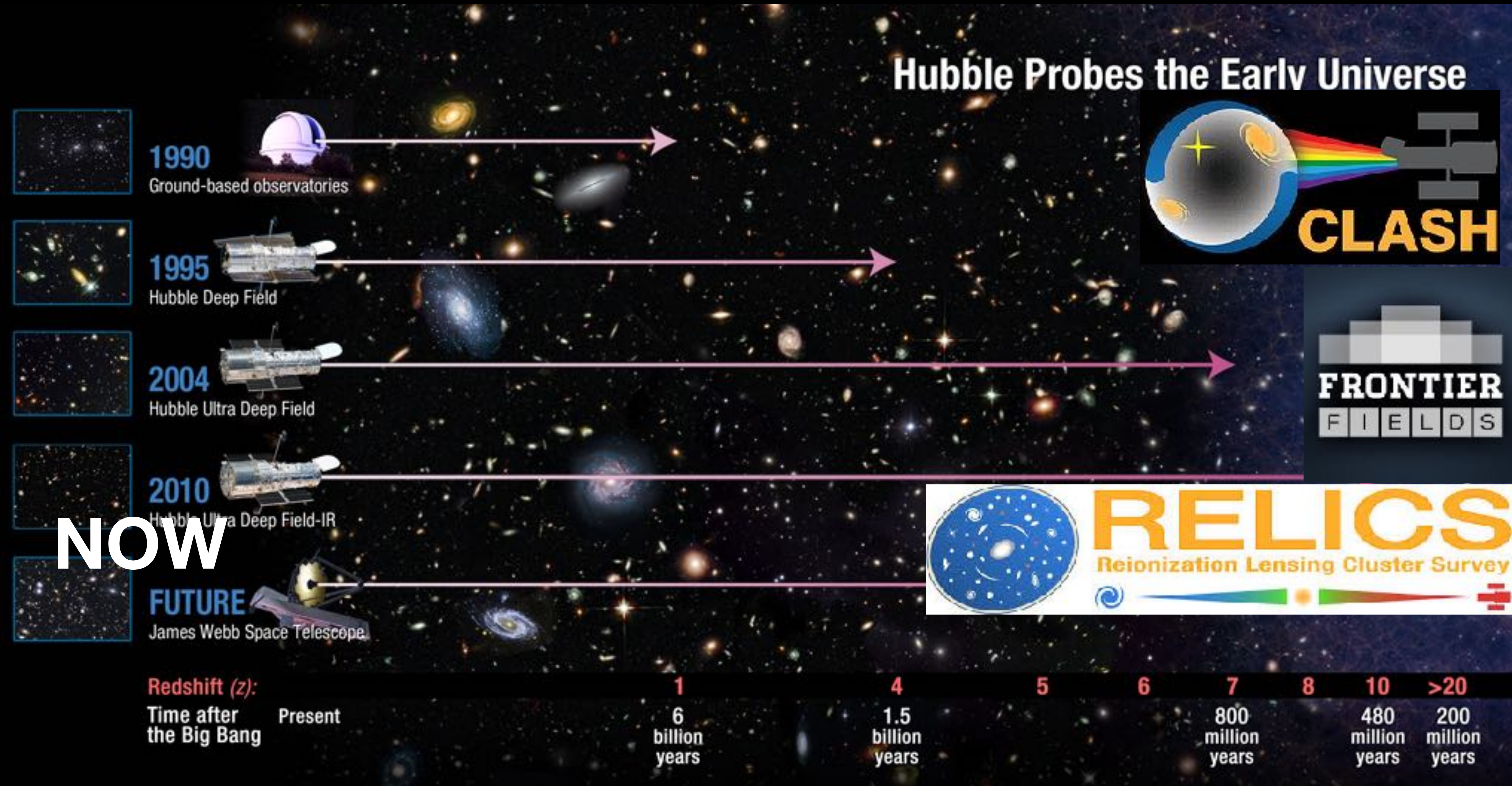
Conclusions/Summary



- **SL only :** useful for high-z Universe, transient studies, reconstruction of lensed sources, …
- **WL only :** useful for detection of ‘low-mass/low-density’ substructures, large-scale structures
- **Multi-wavelength analysis :** THE ONLY WAY TO UNDERSTAND CLUSTER PHYSICS
  - ★ **Constraints on DM nature**
  - ★ **Quantifying content of large-scale filaments**
  - ★ **Powerful constrain the SHMF from high-mass to low-mass end**
  - ★ **Confront theory & observations for the first time**
  - ★ **…**

WHAT'S HAPPENING AT THE MOMENT ?

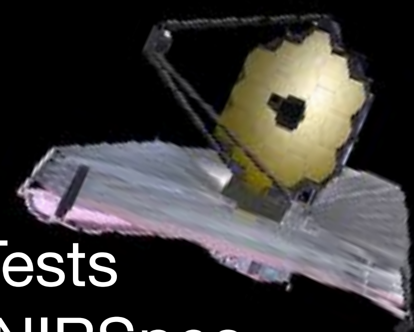
CLUSTER LENSING & REIONIZATION WITH HUBBLE



WHAT'S NEXT ? BUFFALO !

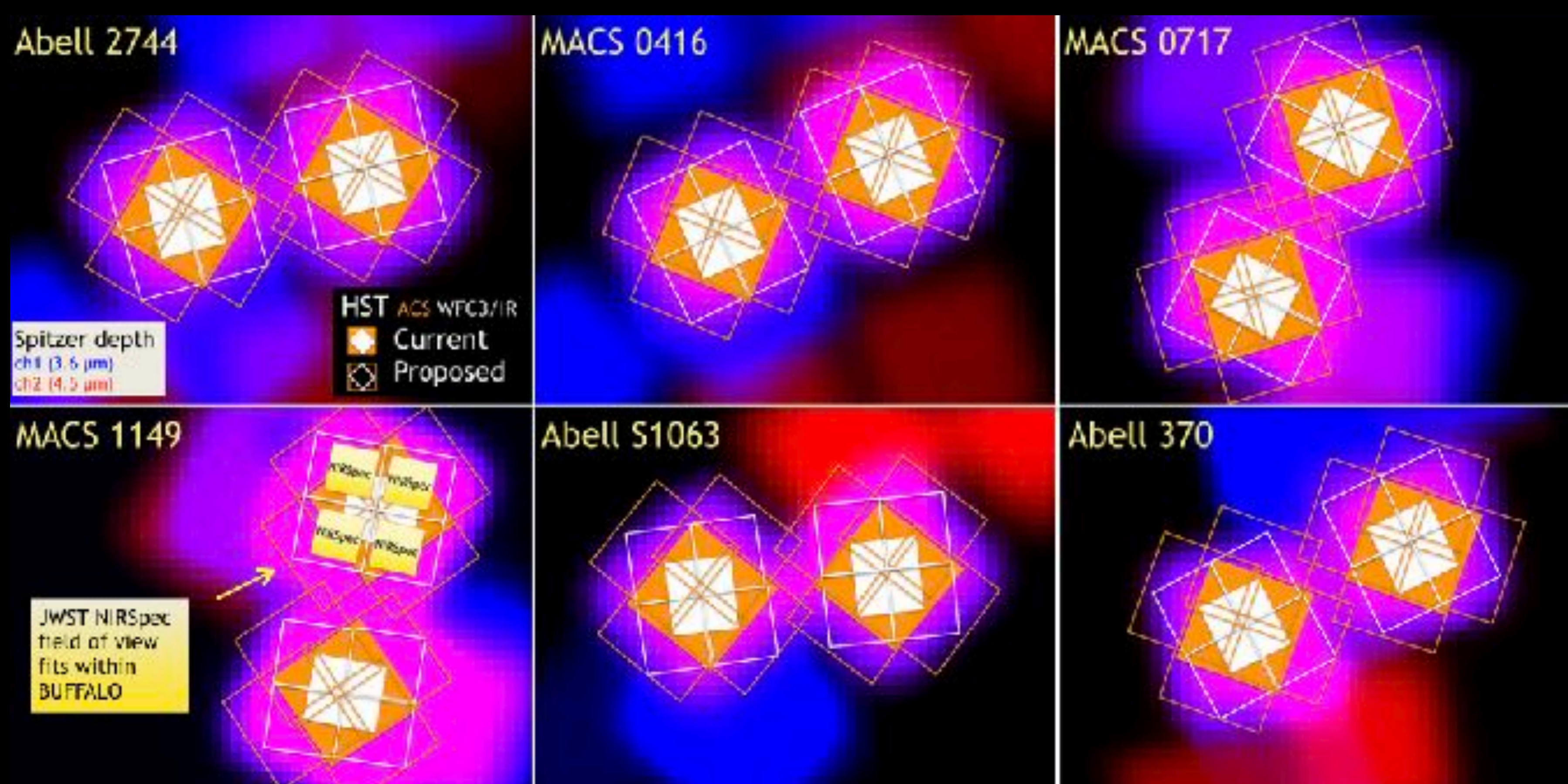
BEYOND ULTRA-DEEP FRONTIER FIELDS AND LEGACY OBSERVATIONS
HST TREASURY PROGRAM

PIs : STEINHART / JAUZAC



EXTENSION OF THE HFF
- High-redshift Universe
- Cluster evolution / Cosmological Tests
- Prepare high-z sources for JWST/NIRSpec

SPECIFICITIES
- 101 HST orbits
- 2 optical filters : F814W & F606W
- 3 NIR filters : F105W, F125W, F160W



THANKS A LOT FOR YOUR ATTENTION

Cluster History : Constraints on DM

‘*bulleticity’ (b)* : mean offset btw DM - gas/light

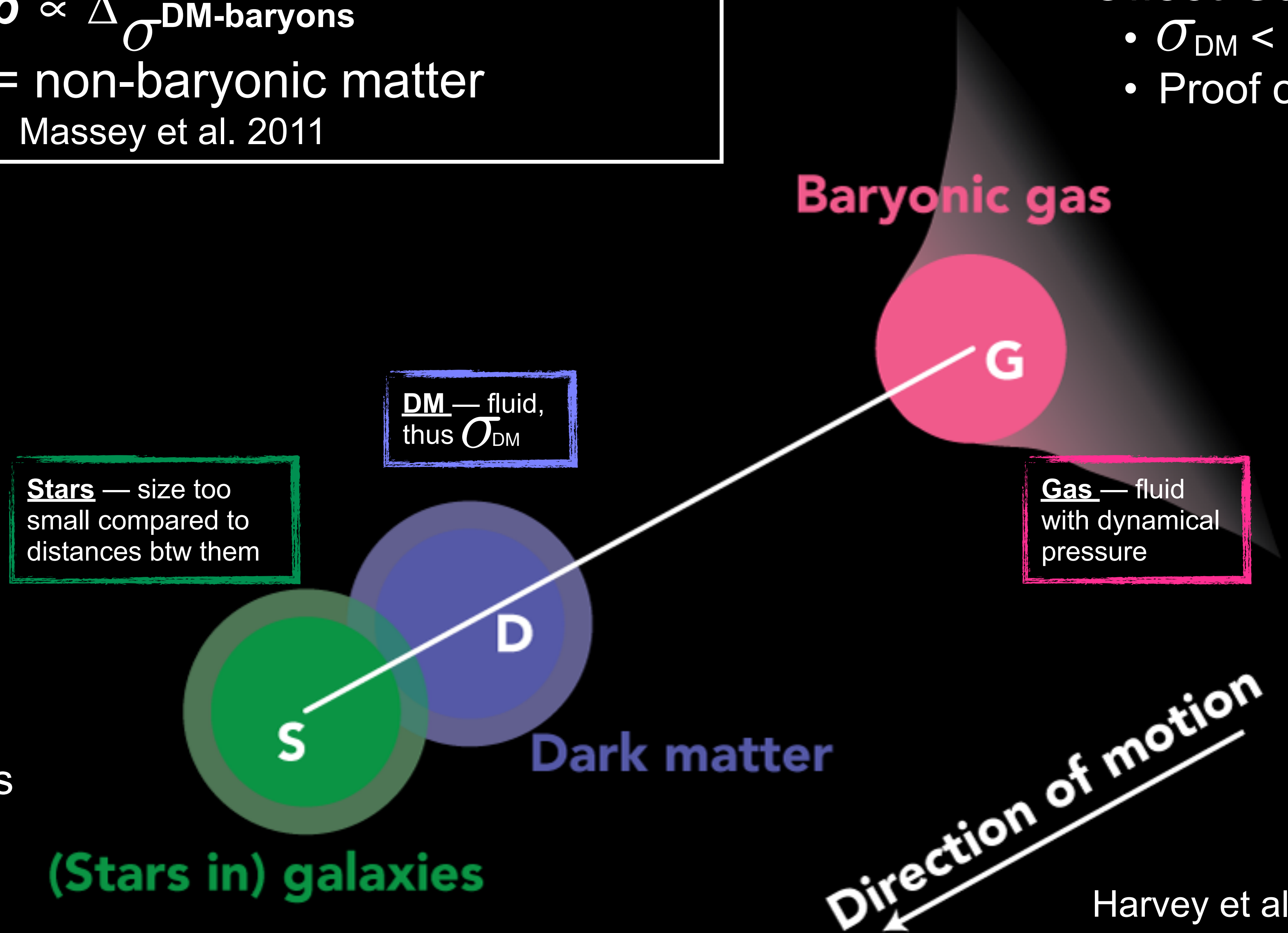
$$b \propto \Delta_{\sigma}\text{DM-baryons}$$

$b \neq 0$ = non-baryonic matter

Massey et al. 2011

Offset **Gaz - DM**

- σ_{DM} < lim
- Proof of DM



Offset **Stars - DM**

- σ_{DM} > lim
- Fluid characteristics
- Projection effects ?

Harvey et al. 2015
Massey et al. 2015

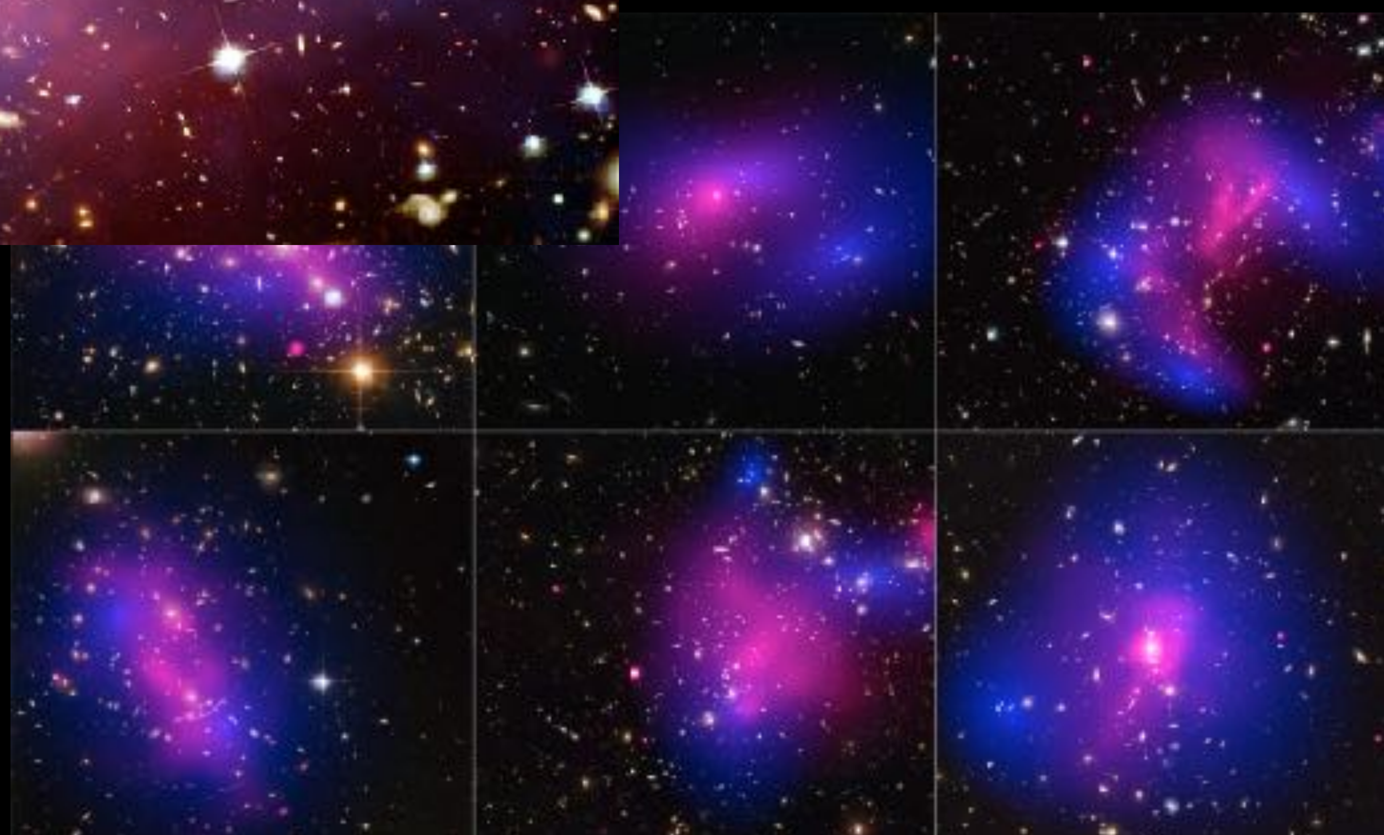
Only Possible with Multi-Wavelength !!!

Cluster History : Constraints on DM

Bullet Cluster

Clowe et al. 2004
Bradac et al. 2008

- Merging cluster
- Evidence for DM
- $\sigma_{DM}/m < 1.25\ cm^2.g^{-1}$



72 clusters HST/ Chandra

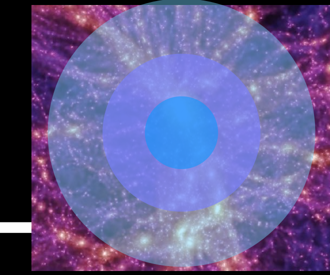
Harvey et al. 2015

- Major & minor mergers
- $\sigma_{DM}/m < 0.47\ cm^2.g^{-1}$

See also Merten et al. 2011, Massey et al. 2015, …

Only Possible with Multi-Wavelength !!!

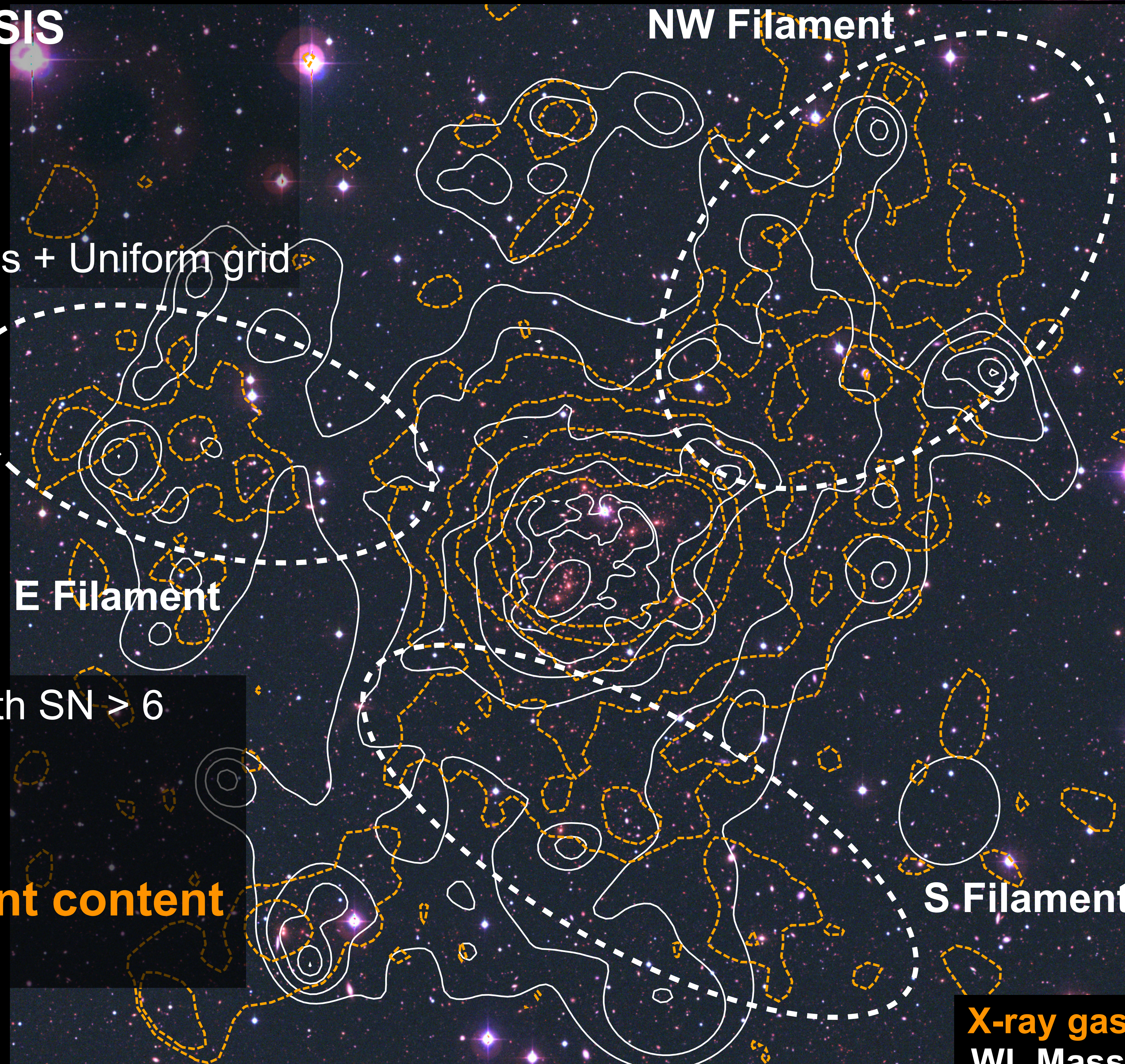
CLUSTER HISTORY : MISSING BARYONS



X-RAY+SL+WL ANALYSIS

Eckert, Jauzac et al. 2015, *Nature*

Deep XMM Observations
WL : HST + CFHT
HYBRID-LENSTOOL : SL potentials + Uniform grid



3 large-scale filaments with SN > 6
T ~ 15-20 10^6 K
DM counterparts for all 3

Gaz ~ 5-10% of filament content