Using massive clusters to test the cosmological paradigm and unveil the first light in the Universe

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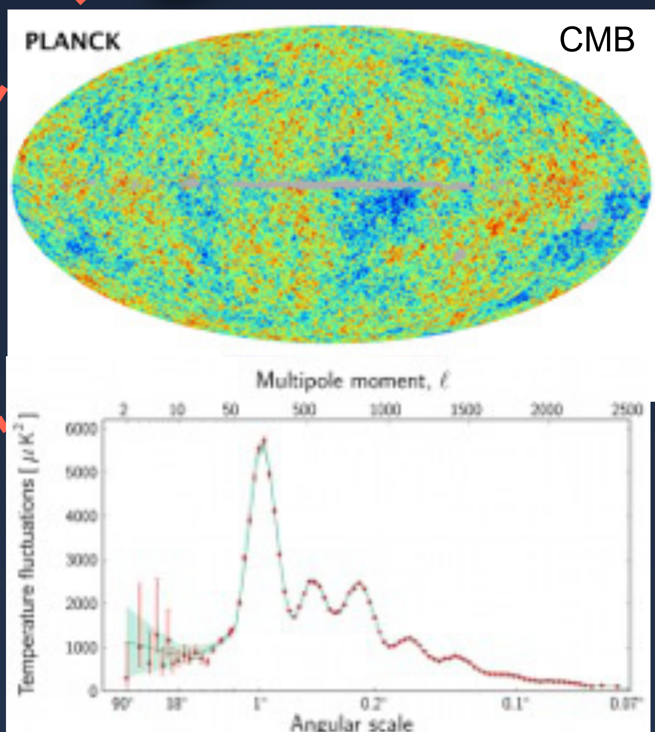
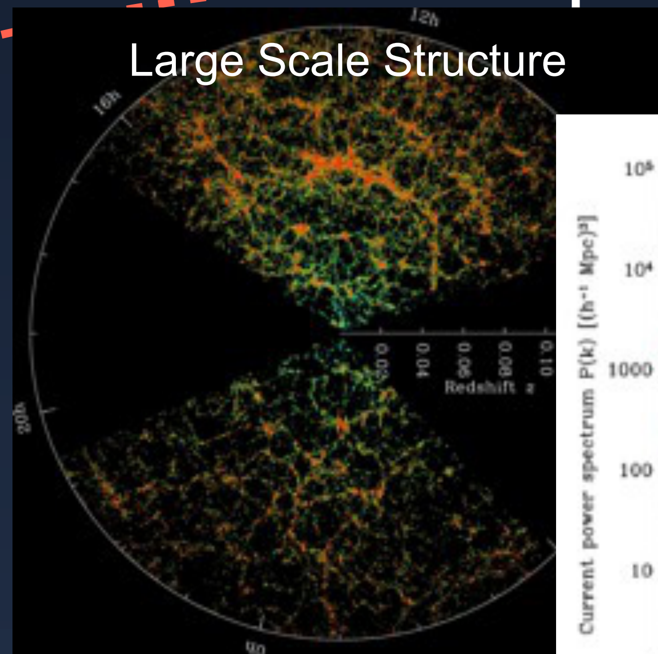
Niccolo' Cabeo School
IUSS, Ferrara, May 23, 2014

“Standard” ΛCDM Cosmological Model

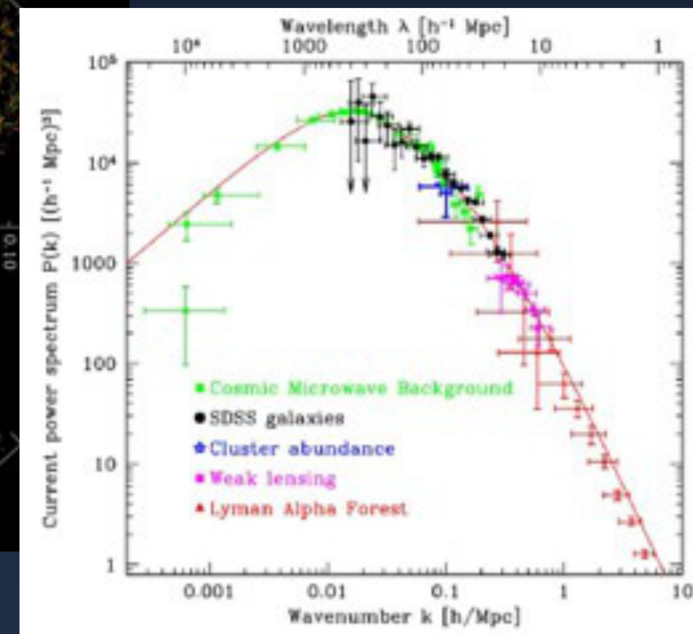
Successes



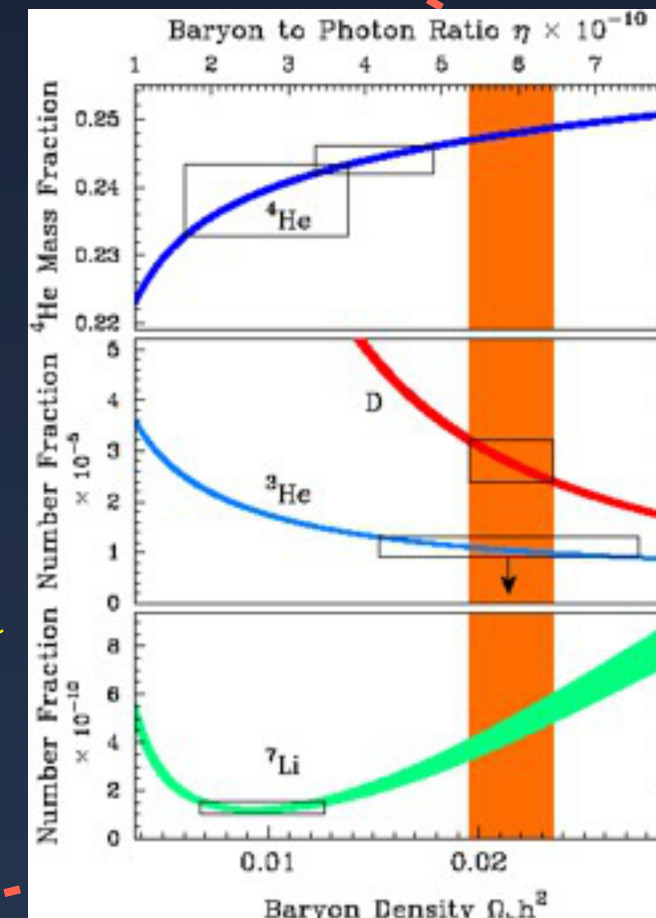
Large Scale Structure



Power spectrum of density fluctuations



Big Bang Nucleosynthesis

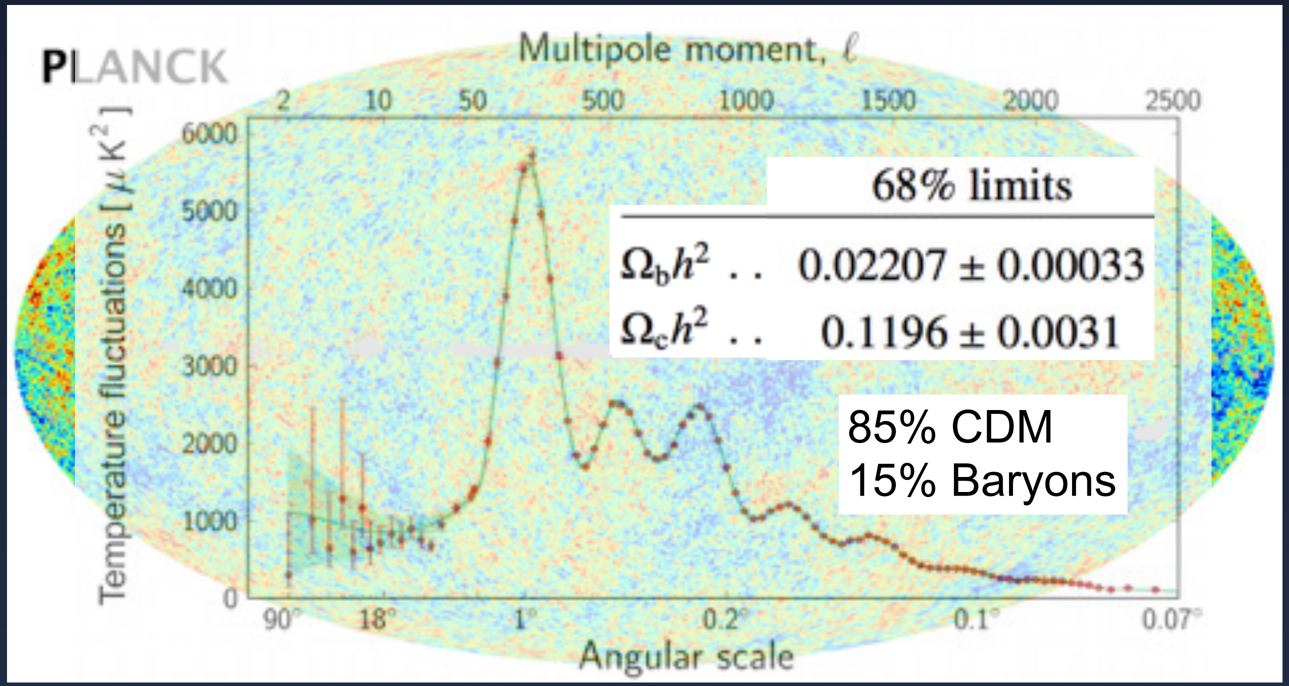


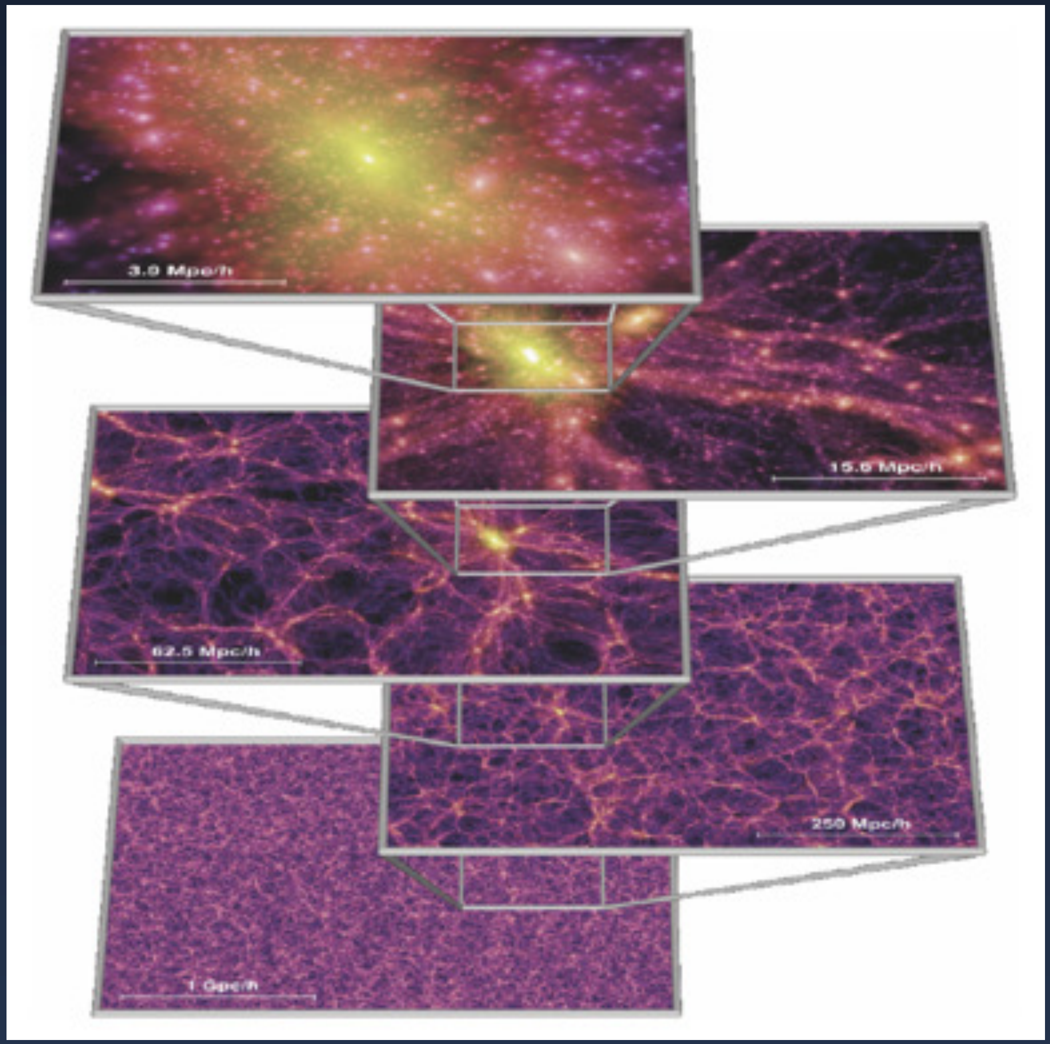
- GR + isotropy and homogeneity
- Inflation (initial perturbation spectrum)
- Non-baryonic Cold Dark Matter (WIMPS?)
- Dark energy (Cosmological constant)

Challenges

- Cluster mass profiles: inner slope ? concentrations too high ?
- Too many satellites in the outskirts of the Milky Way ?
- Large scales: too few superclusters in simulations ? Planck low ℓ anomalies ?
- DM? DE ??? Is GR the ultimate gravity theory ?
- Baryogenesis ? matter/anti-matter asymmetry ?

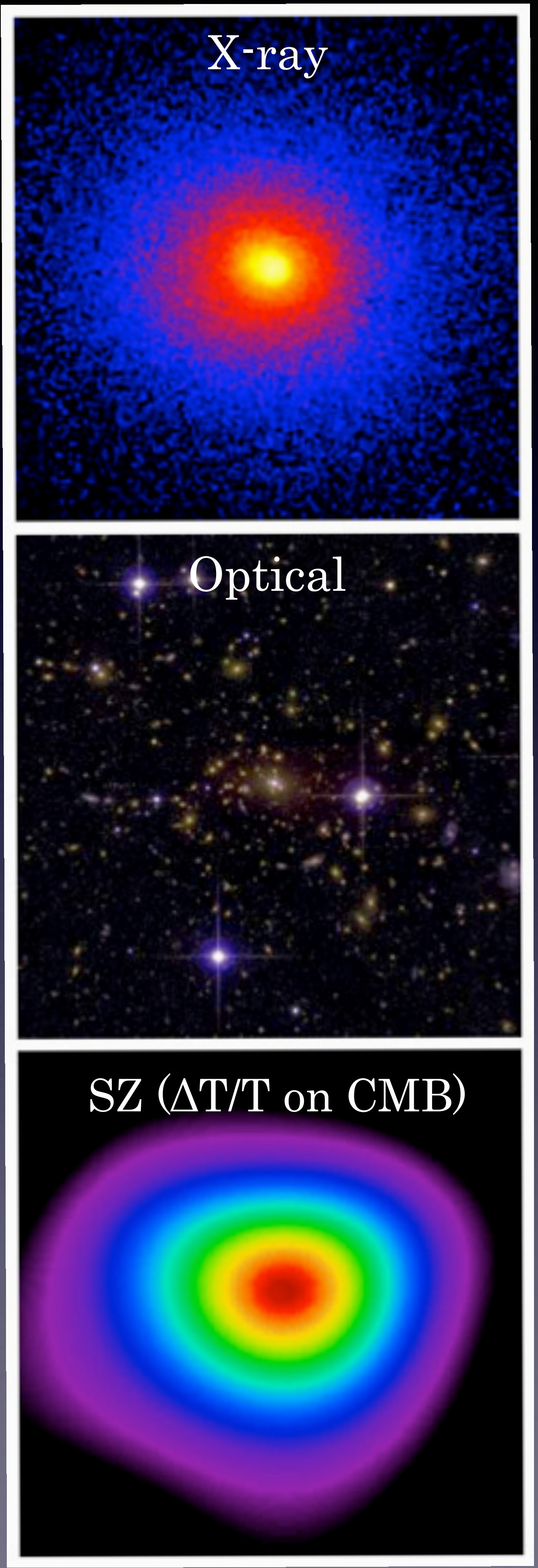
Structure formation in ΛCDM





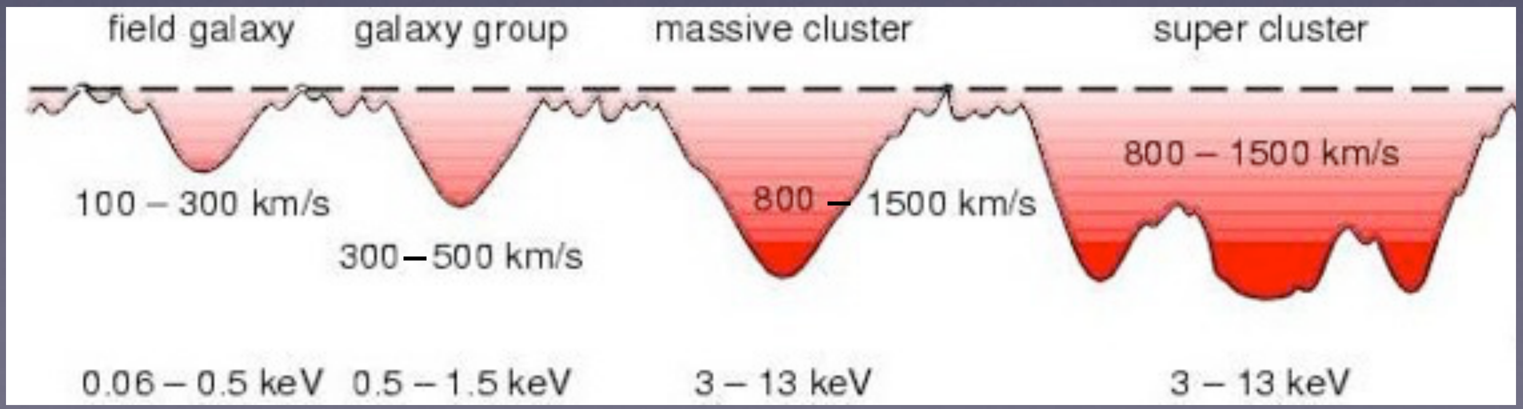
- Initial conditions are now very well known
- We know what the Universe is made of
- We know the structure at all relevant scales

- N-body codes (only gravitational physics) can predict the (non linear) evolution of the abundance, internal structure and clustering of DM halos with high precision
- Galaxies form from the cooling and condensation of the gas in the potential wells of the evolving population of DM halos (radiative cooling, heating, feedback, metal enrichment)
- We predict well what we cannot see and don't understand its nature (DM)
- Complexity of baryonic physics (hot/cold phase transitions, star/galaxy-formation, etc.) is hard to model (hydro-simulations, semi-analytical models)



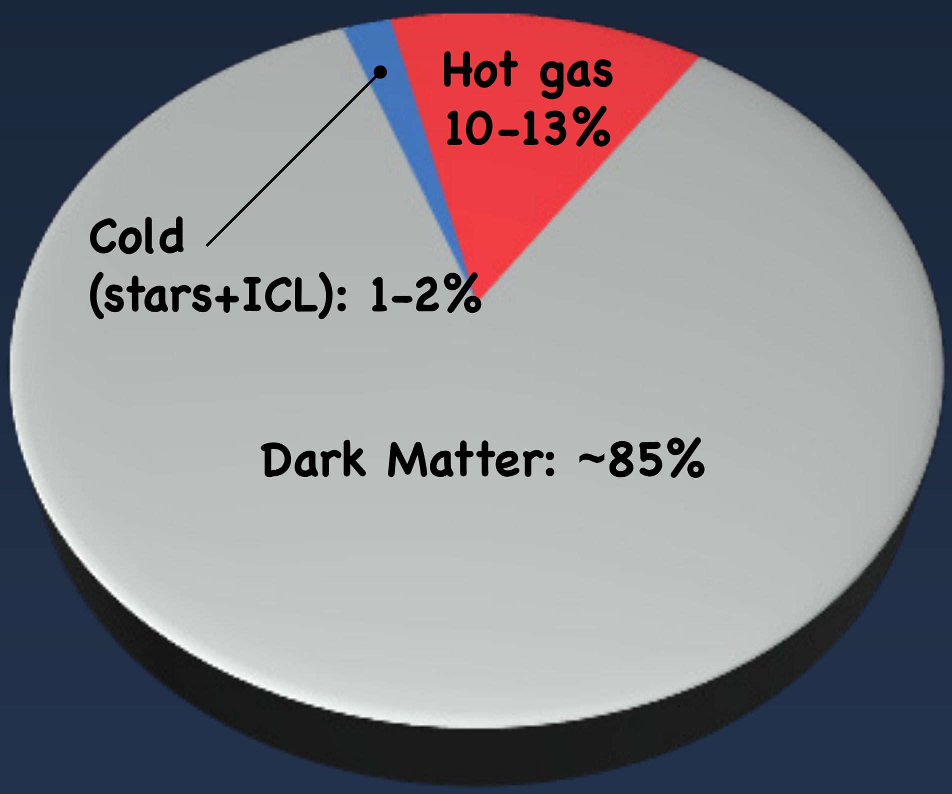
Clusters of galaxies

- The largest gravitationally bound structures in the Universe
- Concentration of 100–1000 galaxies within $\sim R_{vir} \sim 1$–2 Mpc
- Velocity dispersion (observed): $\sigma_v \sim 1000$ km s^{-1} $\sim$ 1 Mpc/Gyr
- Virial masses $\Rightarrow M = 10^{14}$–$10^{15}\ M_\odot$
- Fully ionized, metal rich intra-cluster gas thermalized in cluster potential weel at temperatures $\Rightarrow T_X \approx 3$–10 keV
- Bremmstrahulung emission with high X-ray luminosities $\Rightarrow L_X \sim 10^{43}$–$10^{45}$ erg s^{-1}
- Mass components: $f_{baryons} \approx 10$–15% ($f_{gas} \approx 10\%$, $f_{gal} \approx 2$–5 %), $f_{DM} \approx 80$–90%
- Historically provided the first evidence of DM (Zwicky 37)



Clusters are powerful probes of structure formation and cosmological models

1) Sensitive probes of the **dark sector** of the Universe (DM+DE)



Cluster mass budget

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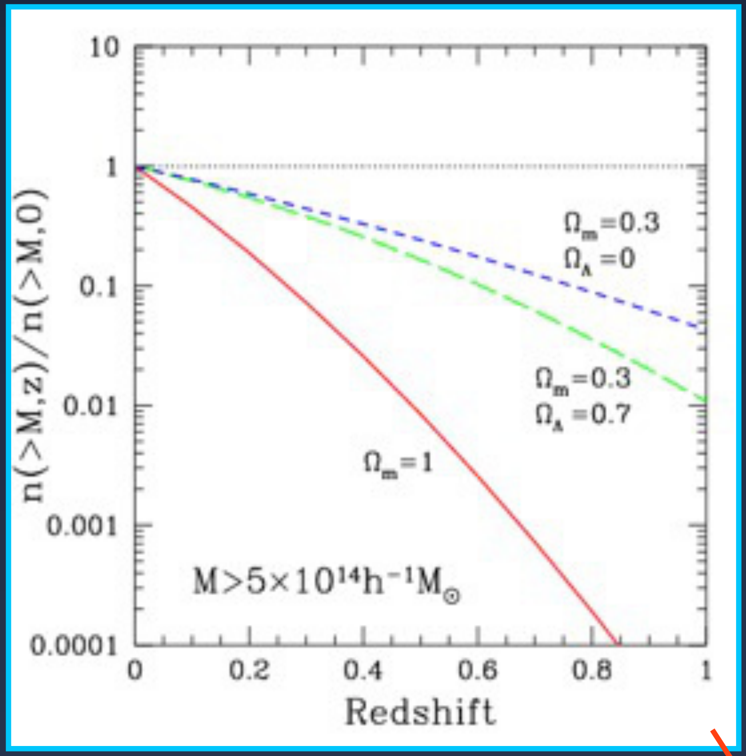
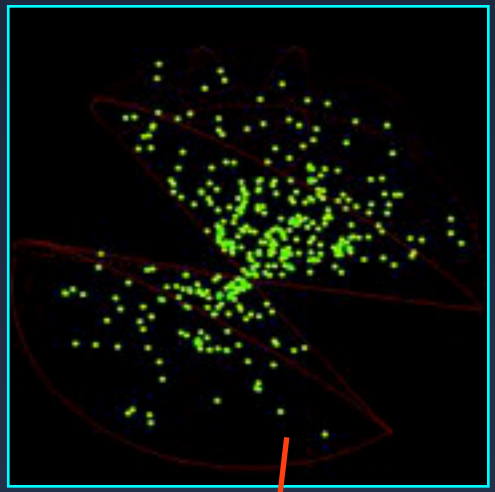
Mass function and distribution of DM halos (~ Gpc scale)

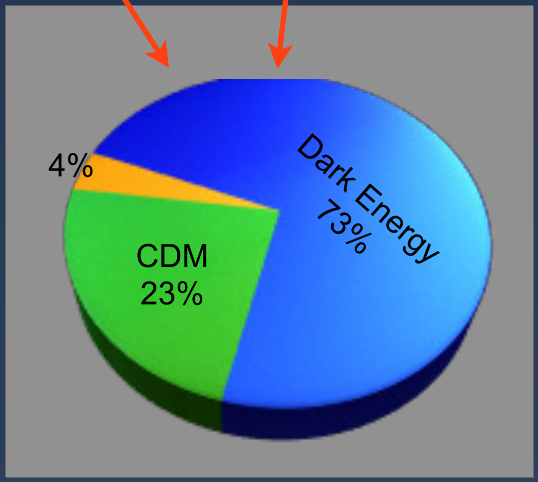




3D distribution

.. depends on
Geometry and Growth:

1. background Cosmology
2. gravity law



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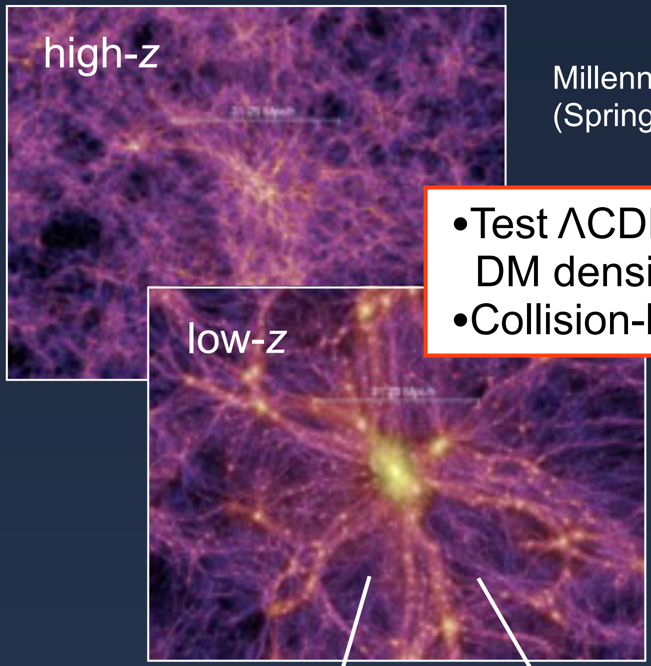
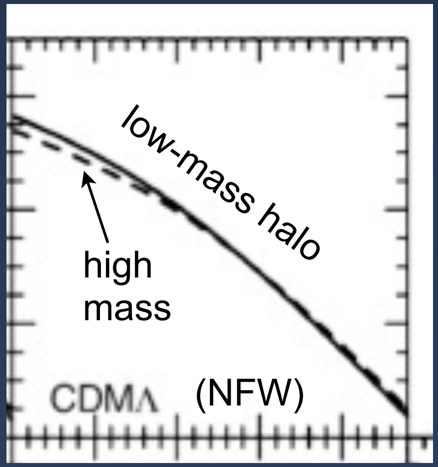
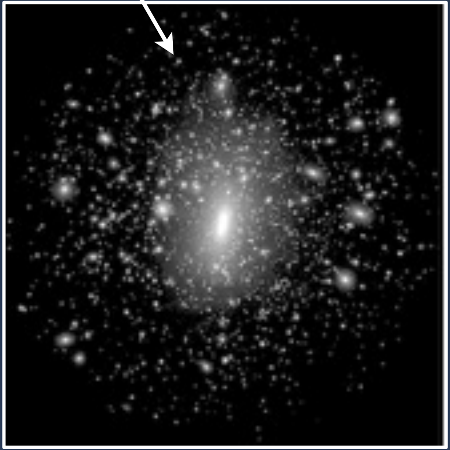
Structure of DM halos
(≲1 Mpc scale)



Millennium simulations
(Springel et al. 2005)

- Test ΛCDM predictions on DM density profiles
- Collision-less nature of DM?





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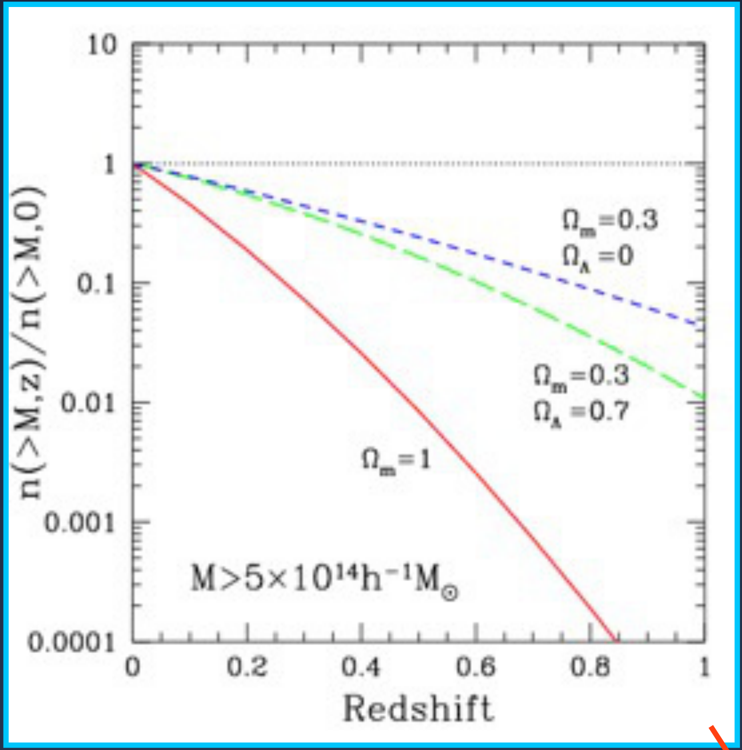

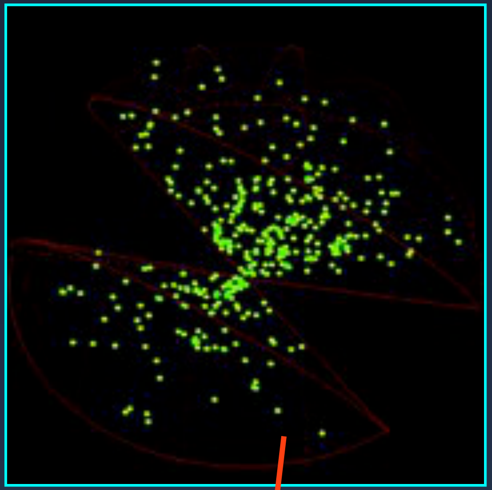

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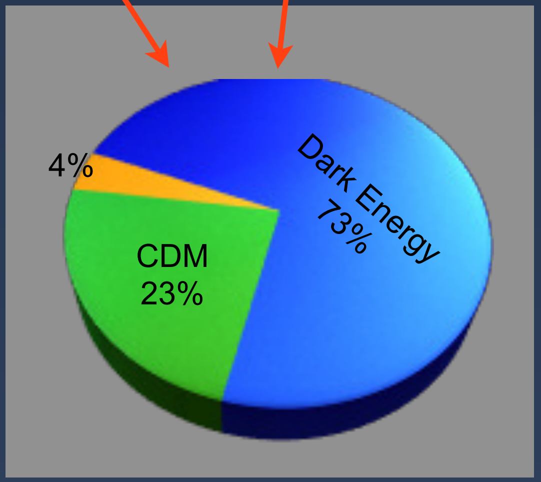
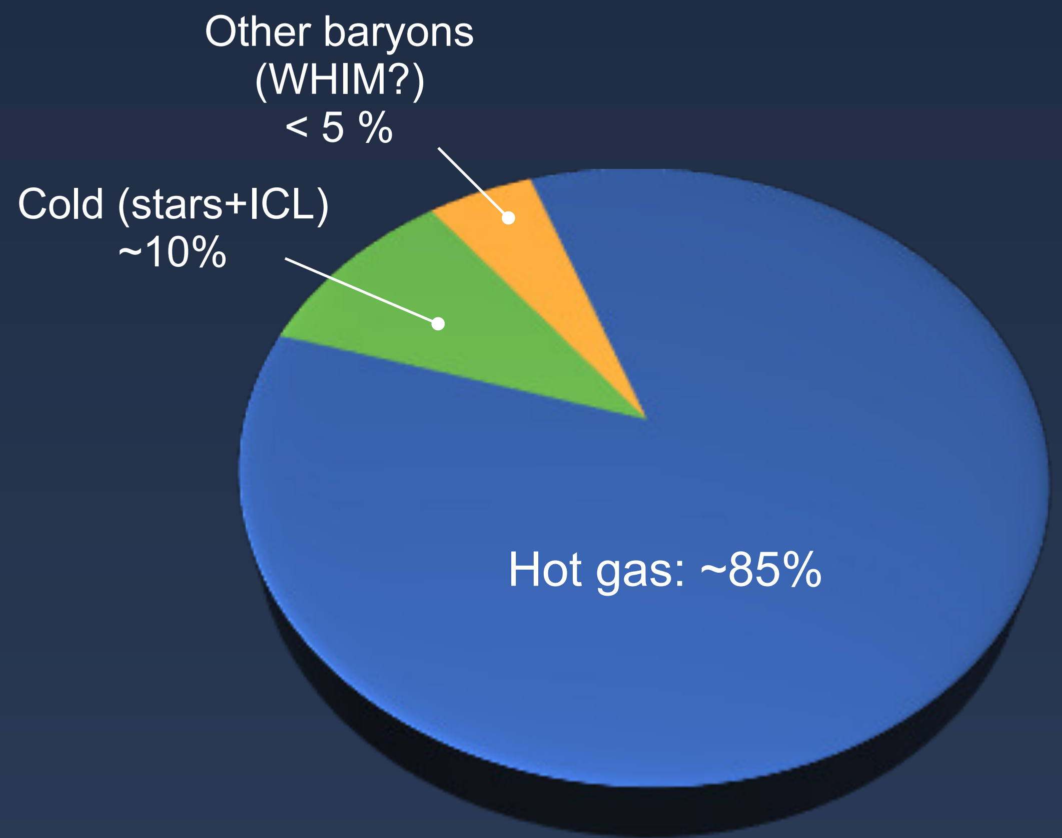


Clusters are powerful probes of structure formation and cosmological models

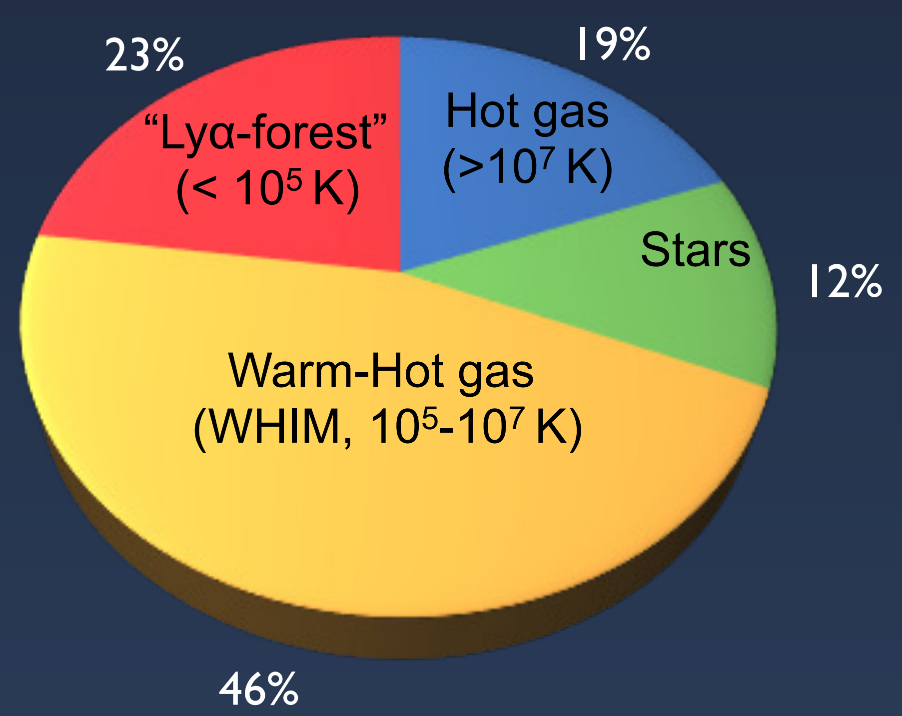
1) Sensitive probes of the **dark sector** of the Universe (DM+DE)

2) Excellent places to trace the cosmic cycle of **baryons** and study the effect of galaxy formation and BH accretion on the ICM (energy feedback, Z enrichment)

- Most of the baryons in clusters are detectable ! (X-ray gas + galaxies)



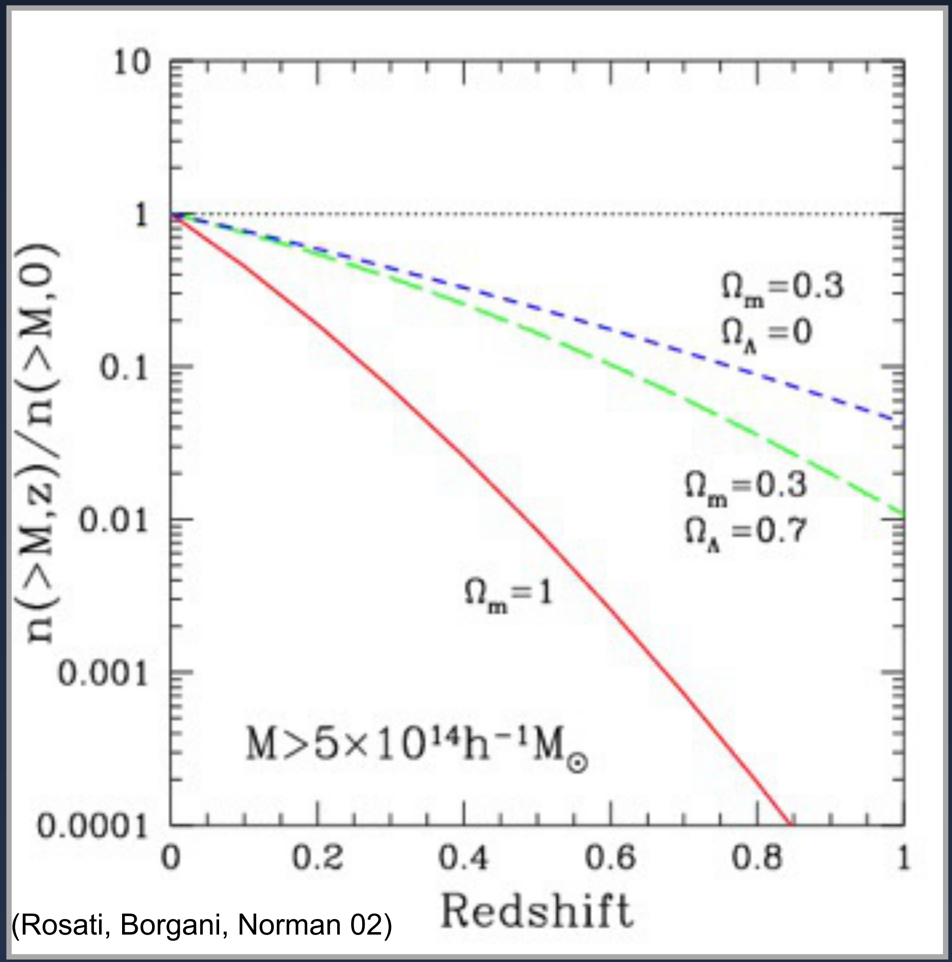
Cluster baryon budget at low z



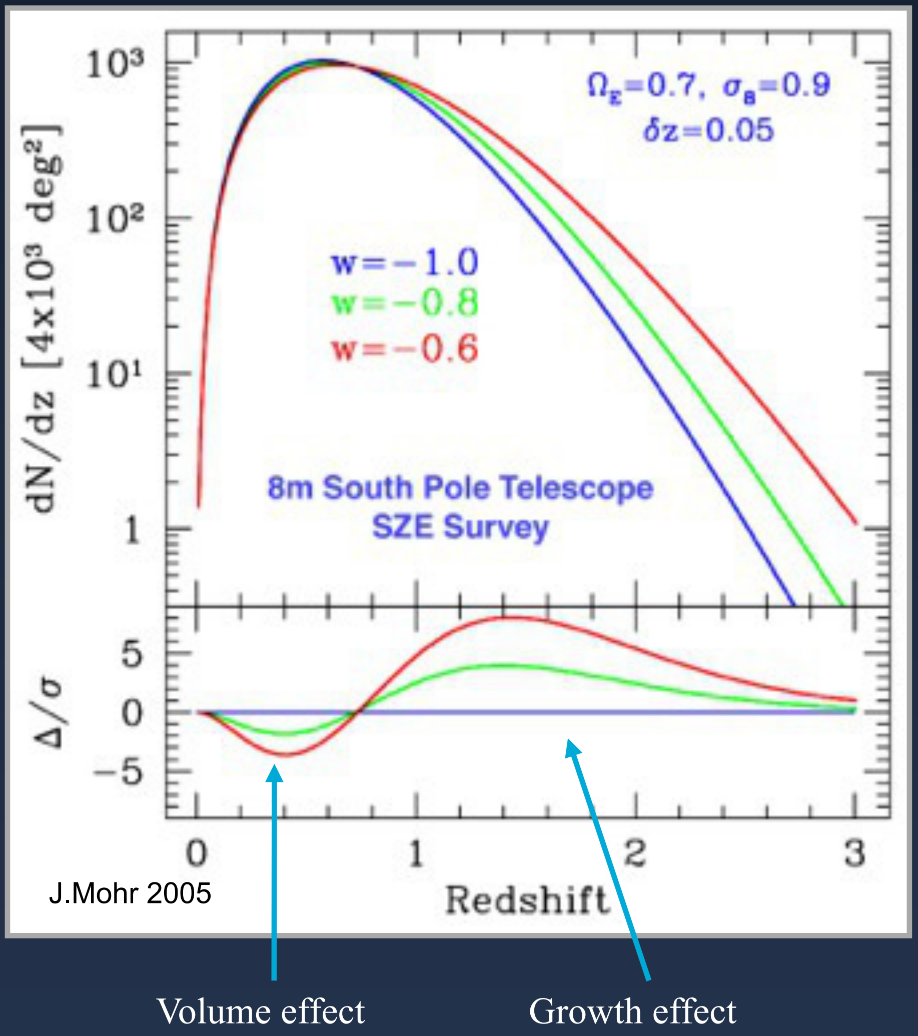
Cosmic baryon budget at z~0

(Cen & Ostriker 1999)

Precision Cosmology from cluster abundance ?



Methodology



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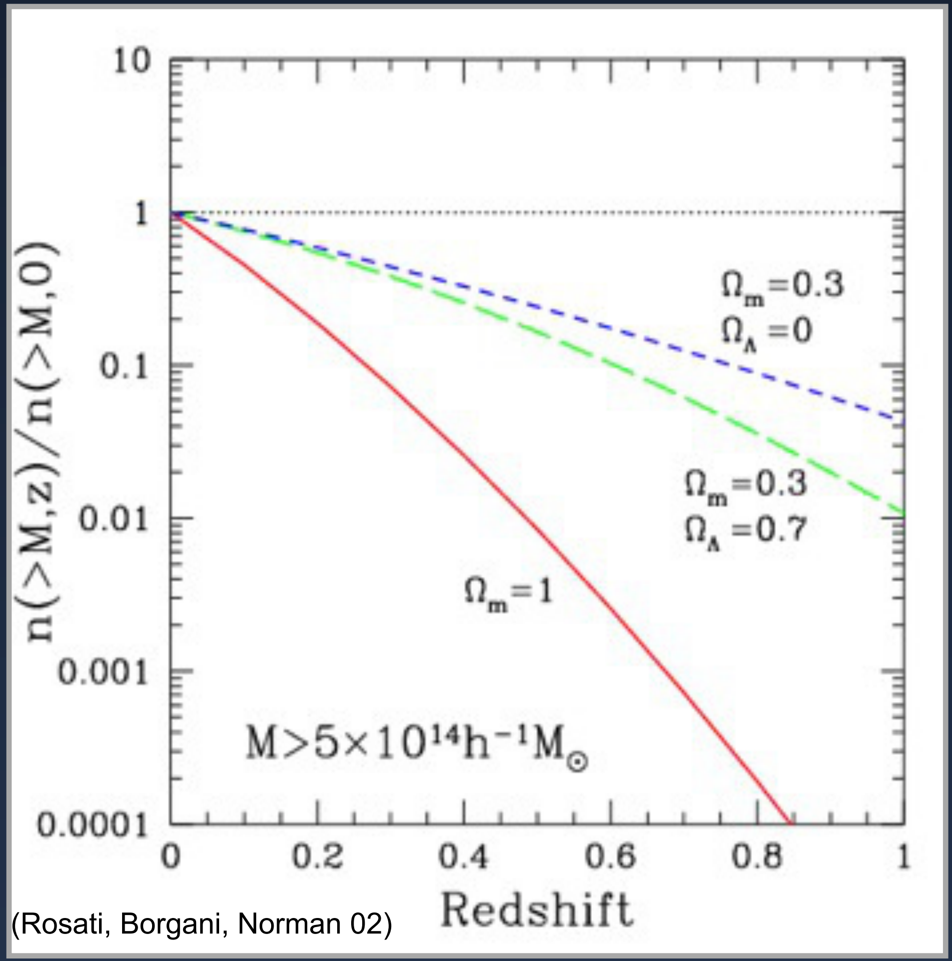

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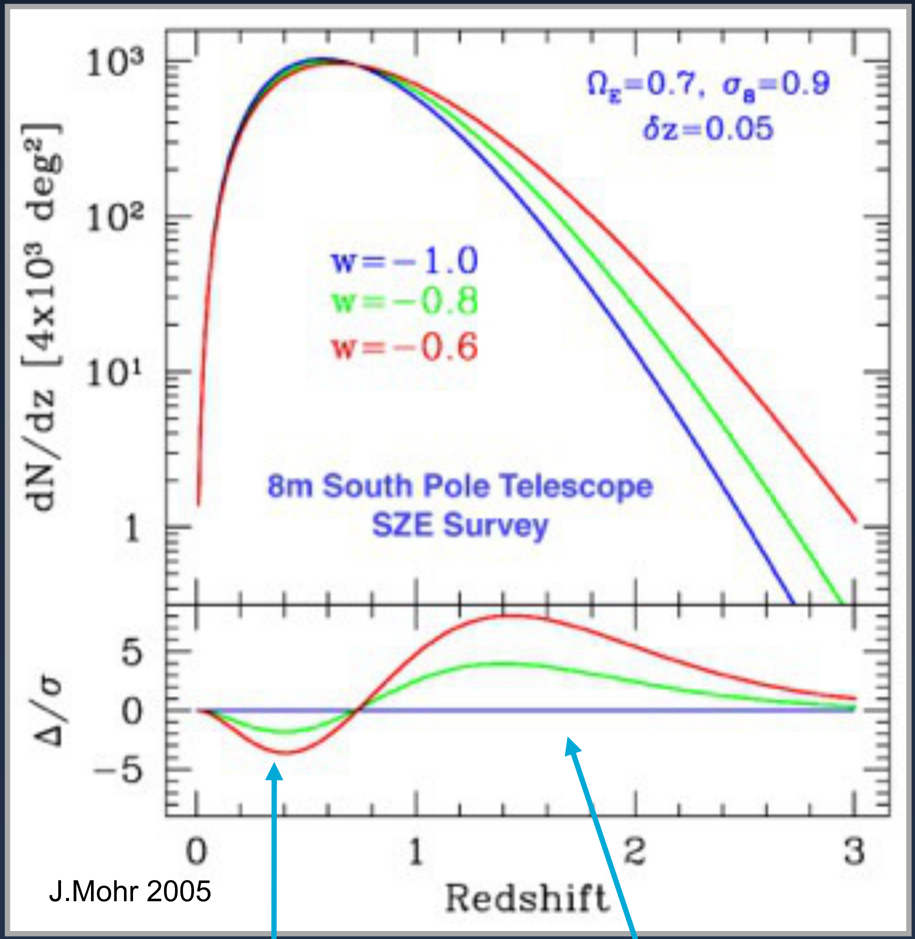


Volume effect

Growth effect

Geometry

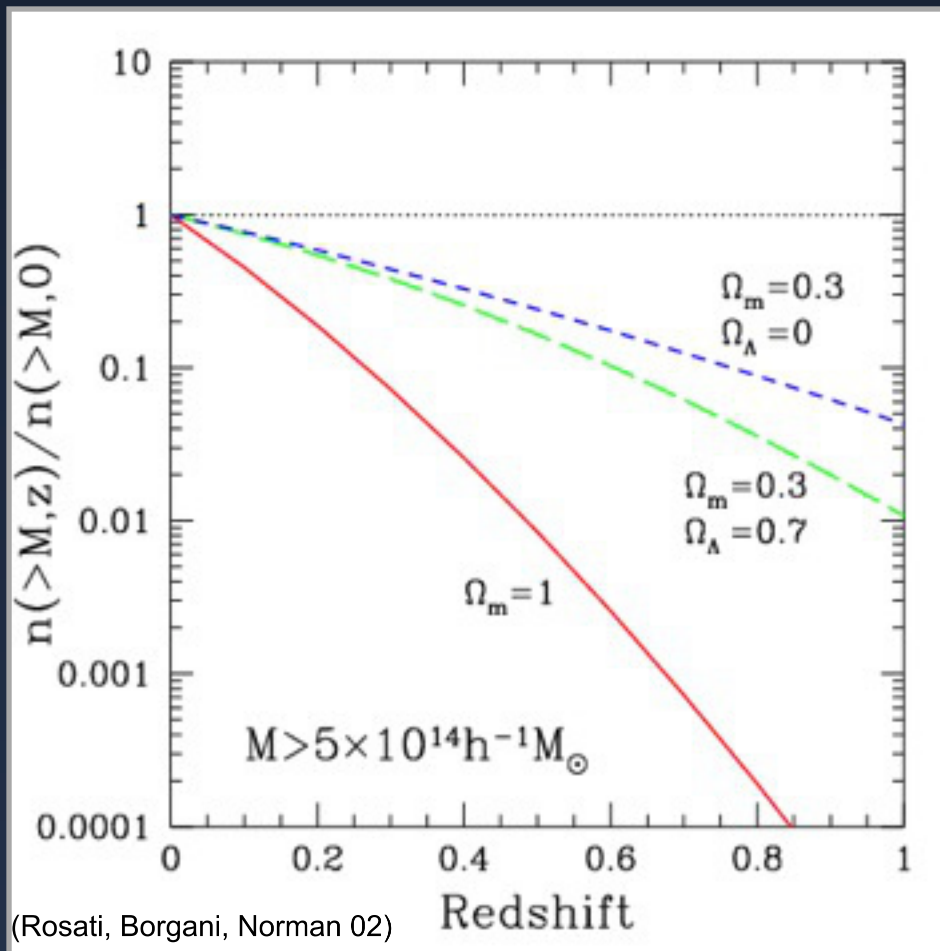
$$\frac{d^3N}{dM\,d\Omega\,dz}(M,z) = \frac{dn_M}{dM}(M,z) \cdot \frac{d^2V_{\rm com}}{dz\,d\Omega}(z)$$

MF evolution:
robust prediction from
large N-body simulations

$$\frac{dn_M}{dM}(M,z) = \frac{dn_X}{dX}(M,z) \cdot \frac{dX}{dM}(M,z)$$

Observed
(robust for X-ray selection)

Precision Cosmology from cluster abundance ?



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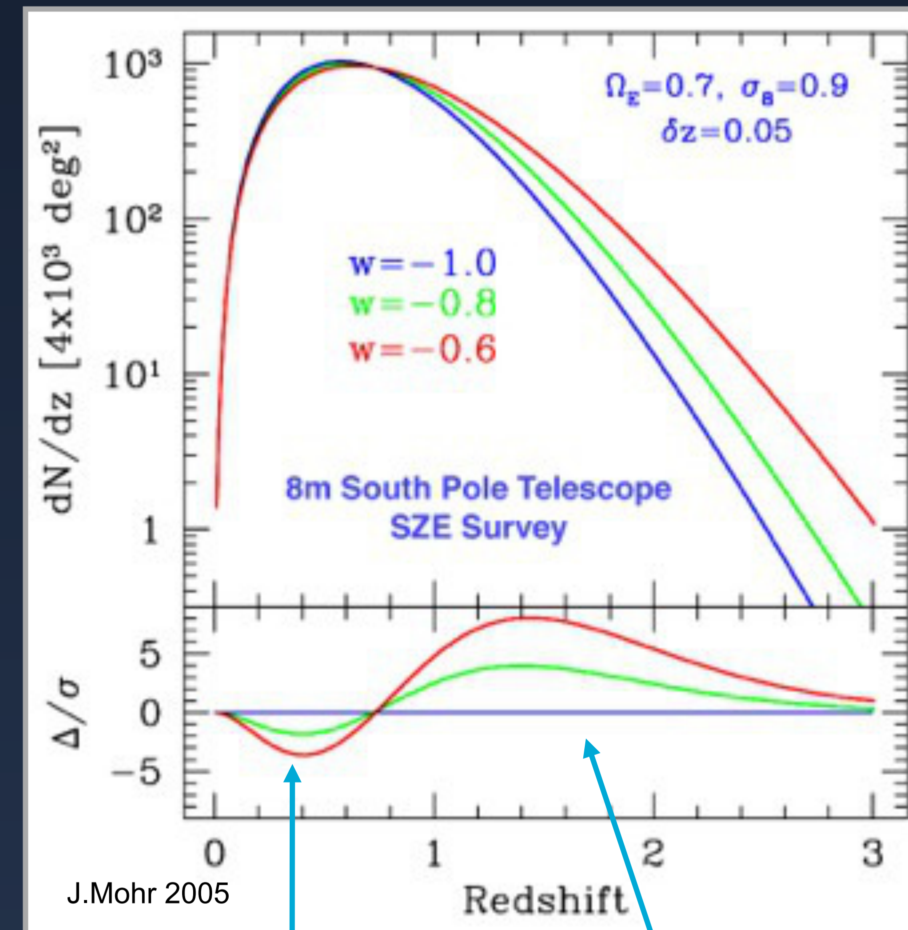

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MF evolution:
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$$\frac{dn_M}{dM}(M,z) = \frac{dn_X}{dX}(M,z)\cdot\frac{dX}{dM}(M,z)$$

X: observable proxy of the total mass
(L_x, T, Y_{SZ}, Y_x, M_{gas}, M_{opt}, σ_V..)

☛ Need $\langle X\rangle(M,z)$ and $\sigma_X(M,z)$

Observed
(robust for X-ray selection)

Empirical (scaling relations), Hydro-simulations
(uncertainties due to complex cluster physics)

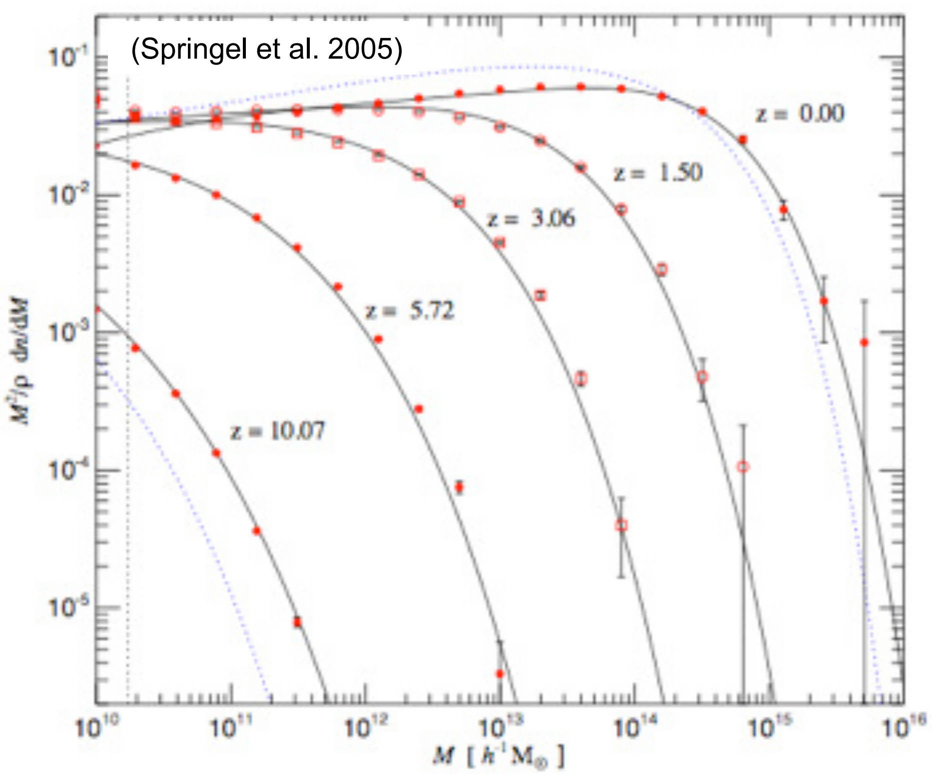
Methodology: matching predicted with observed quantities, marginalizing over a set of cosmological parameters {σ_8, Ω_M, Ω_Λ, (Ω_{DE},w), w',...} and astrophysical ("nuisance") parameters {α_1, α_2, ...)

How to compute the cluster mass function

$$\frac{d^3N}{dM\,d\Omega\,dz}(M,z) = \frac{dn_M}{dM}(M,z) \cdot \frac{d^2V_{\rm com}}{dz d\Omega}(z)$$

Growth of perturbations: robust prediction from large N-body simulations

Geometry



$$\frac{dV}{d\Omega dz} = \frac{c}{H(z)} D_A^2(z)(1+z)^2$$

from FRW metric

$$\mathrm{H}^2(z) = H_0^2[\Omega_M(1+z)^3 + \Omega_\Lambda(1+z)^{3(1+w)} + (1-\Omega_0)(1+z)]$$

$$E^2(z) = [\Omega_M(1+z)^3 + (1-\Omega_M-\Omega_\Lambda)(1+z)^2 + \Omega_\Lambda]$$

Several analytic approximations exists for the mass function (Press-Schecter; Sheth-Tormen; Jenkins)

How to compute the cluster mass function

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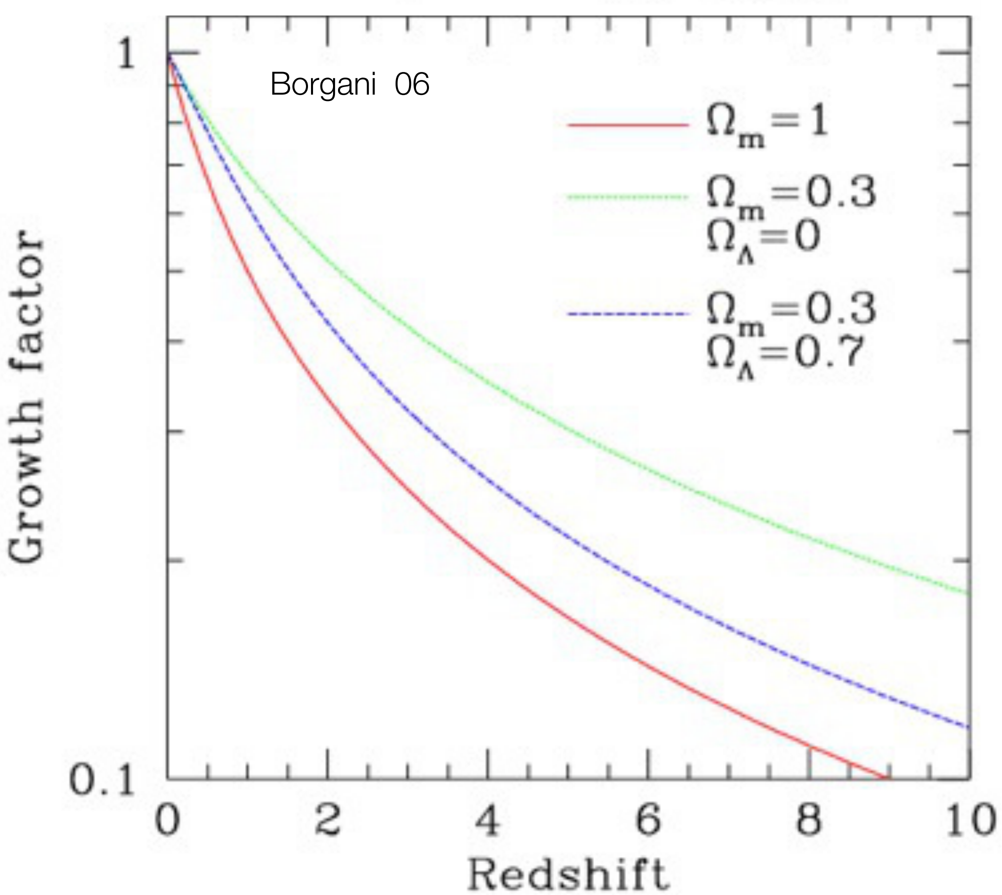
Growth of perturbations: robust prediction from large N-body simulations

Geometry

$$D_+(z) = \frac{5}{2}\,\Omega_m E(z)\int_z^\infty \frac{1+z'}{E(z')^3}\,dz'$$



$$\frac{\partial^2\delta}{\partial t^2} + 2H(t)\frac{\partial\delta}{\partial t} - 4\pi G\bar{\rho}\delta = 0\,.$$

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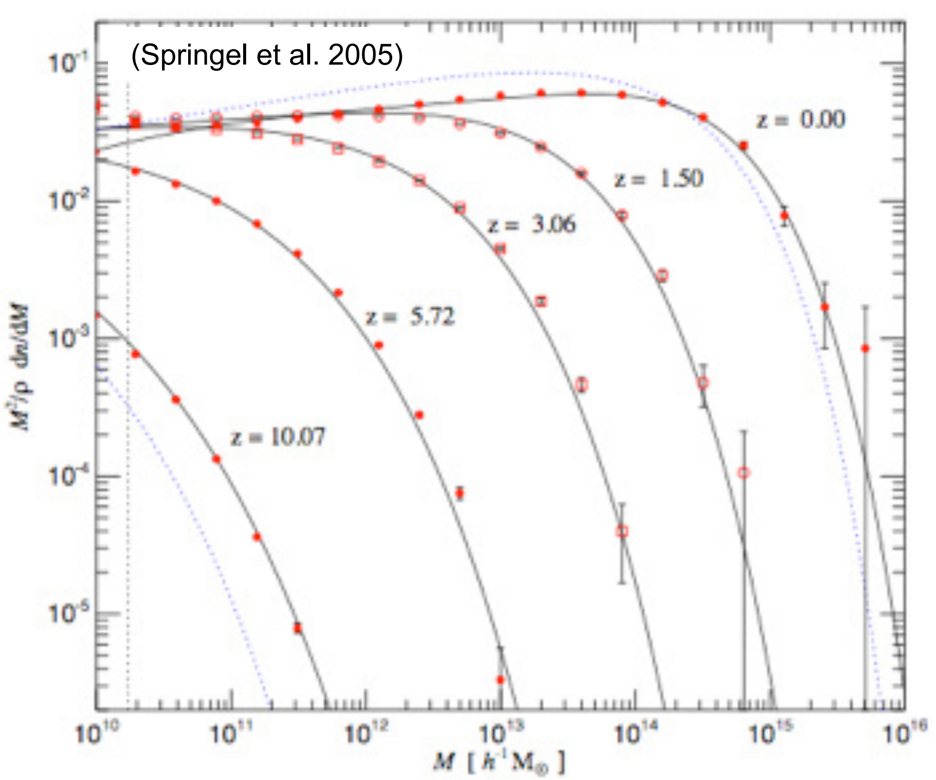

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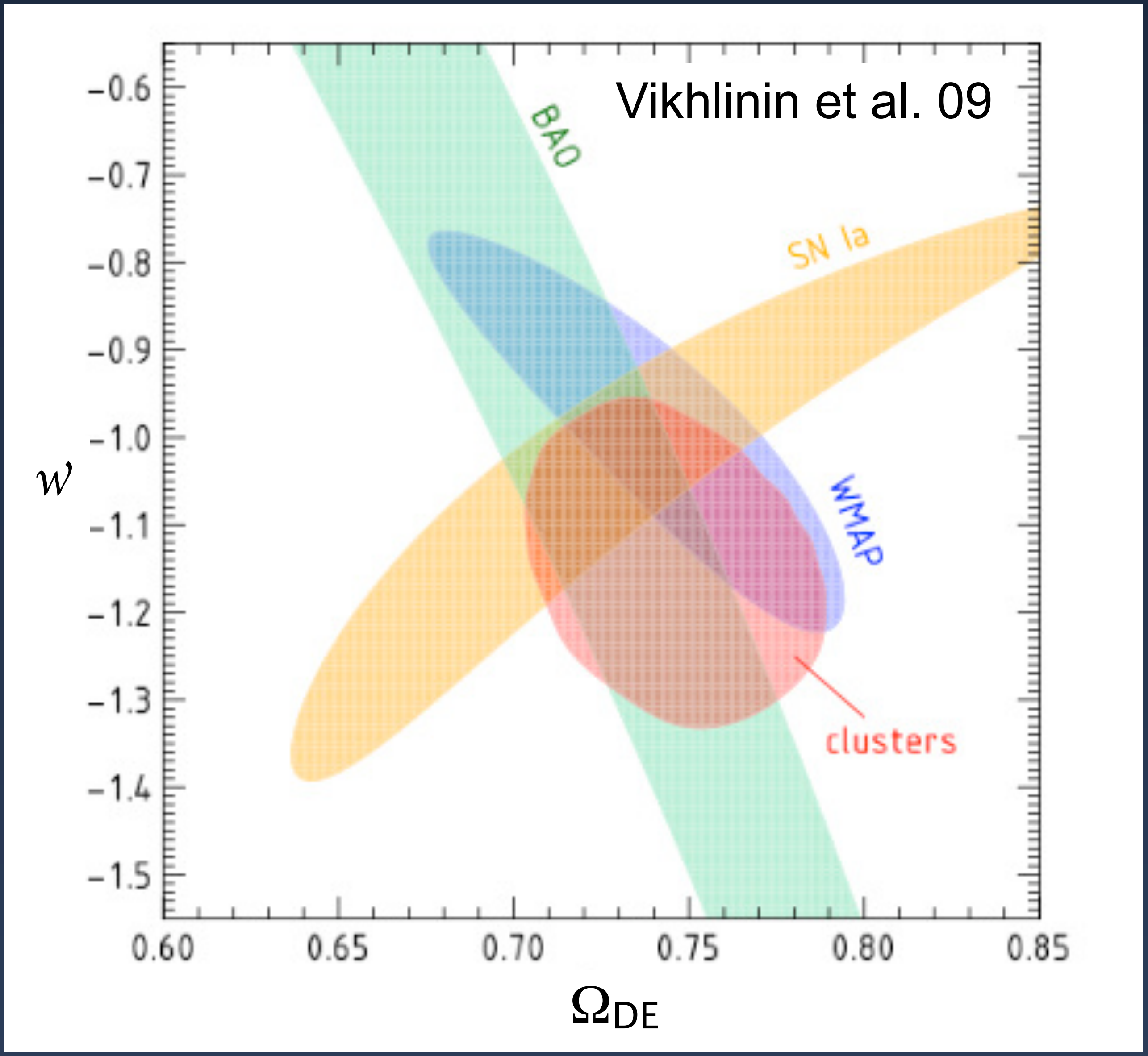
The redshift distribution of clusters per unit solid angle is obtained by integrating the MF weighted by the survey selection function *f(M,z)*

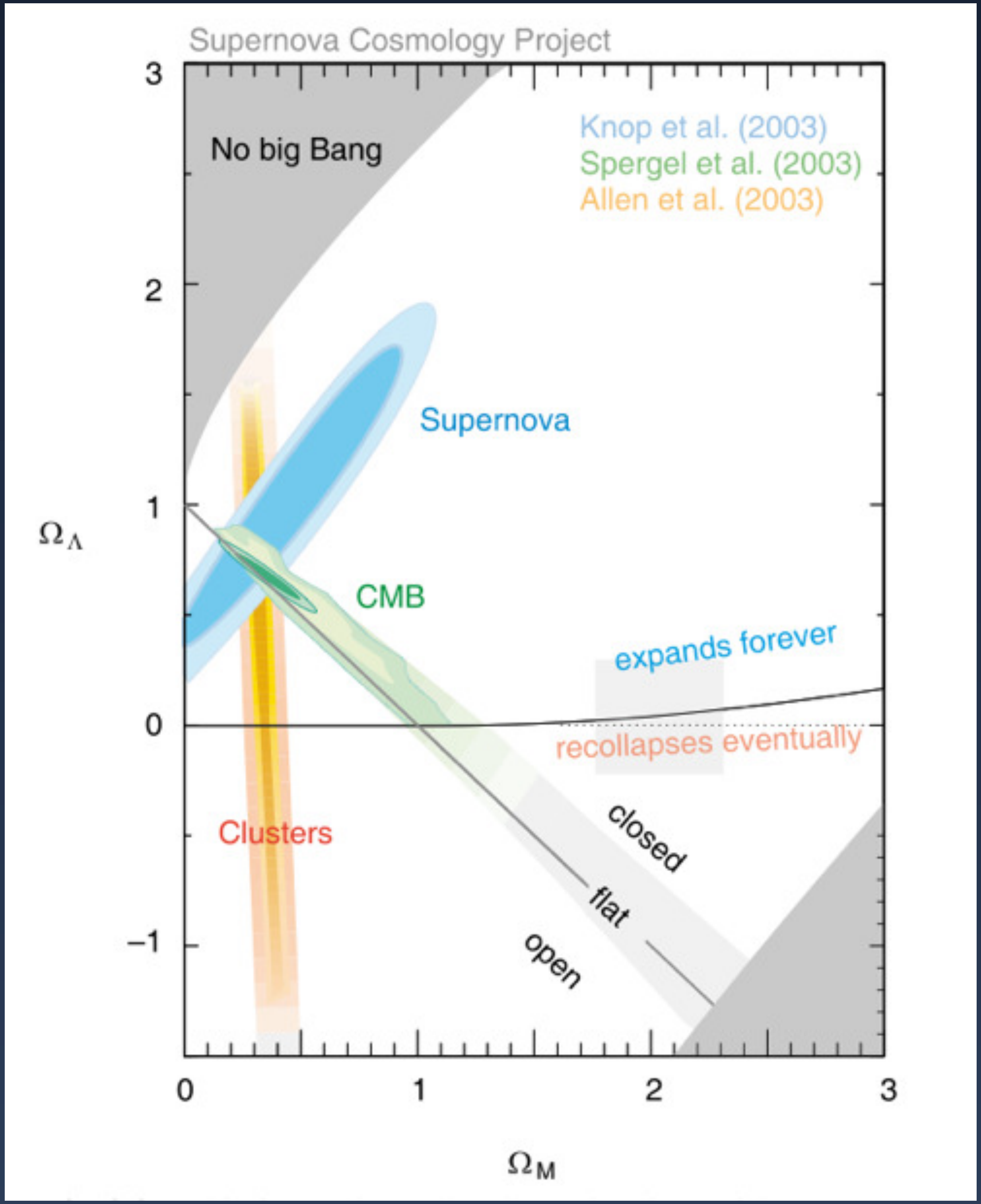
Geometry — Selection fnct — Growth

$$\frac{d^2N}{dz\,d\Omega}(z) = \frac{d^2V}{dz\,d\Omega}(z)\,N_{com}(z) = \frac{c}{H(z)}D_A^2(1+z)^2\int_0^\infty dM\,f(M,z)\,\frac{dn}{dM}(M,z)$$

Cosmological constraints from cluster abundance ?

Still waiting for era of precision cosmolgy with clusters (a few % accuracy on comological parameters)



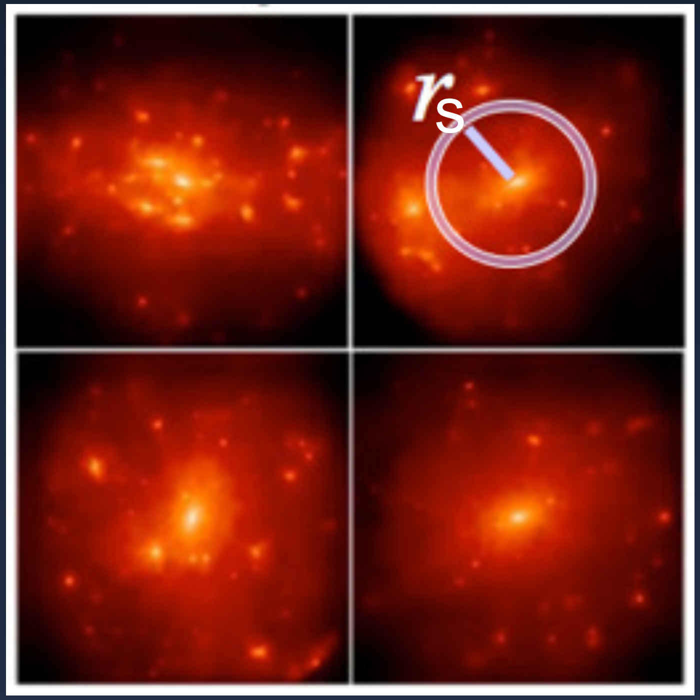


Annual Reviews: Rosati et al. 2002, Allen et al. 2011

ΛCDM Predictions for DM Mass Profiles

Hierarchical assembly of CDM halos predicts:

1. mass profiles with a (quasi) universal shape (gals→CL)
2. prominent triaxial shapes
3. "cuspy" inner mass slopes (β ≈ 1)
4. a large degree of substructure
5. halo radial structure result of mass assembly history



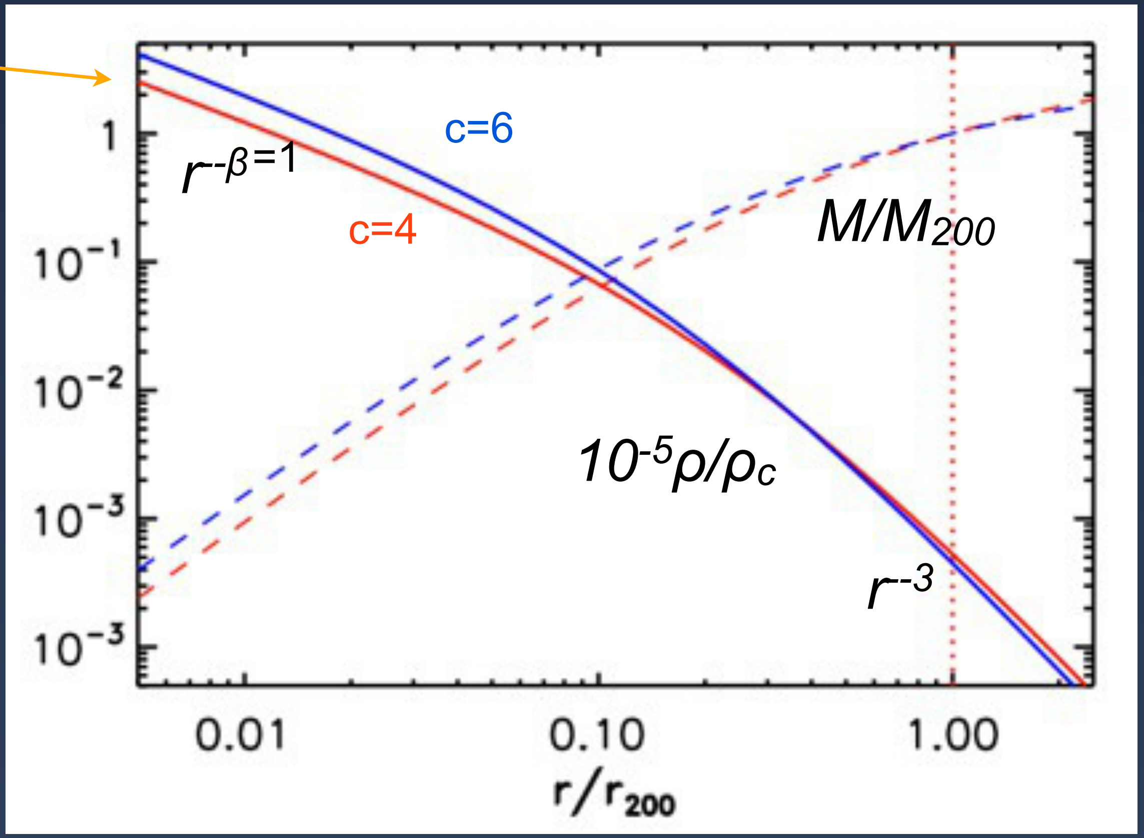
$$\rho(r) = \frac{\rho_S}{(r/r_S)^{\beta}(1+r/r_S)^{(3-\beta)}}$$

gNFW

$$\rho_S = \delta_c \rho_{crit}(z)$$

$$c \equiv \frac{r_{200}}{r_S}$$

concentration parameter



c depends (mildly) on mass&redshift via the **formation epoch of DM halos**, which depends on the structure formation scenario ➔ **testable prediction of ΛCDM**

(e.g. Navarro+ 97, Duffy+ 08, Gao+ 2008, Bullock+ 11, Klypin+ 2011, Giocoli+ 2012, Bhattacharya+ 2011)

ΛCDM Predictions for DM Mass Profiles

Highly debated issues

- Concentration-Mass relation: *c(M,z)*
- DM & baryons distribution in the inner core: inner slope of ϱ(r)
  - DM physics or dynamical effects of baryons ?

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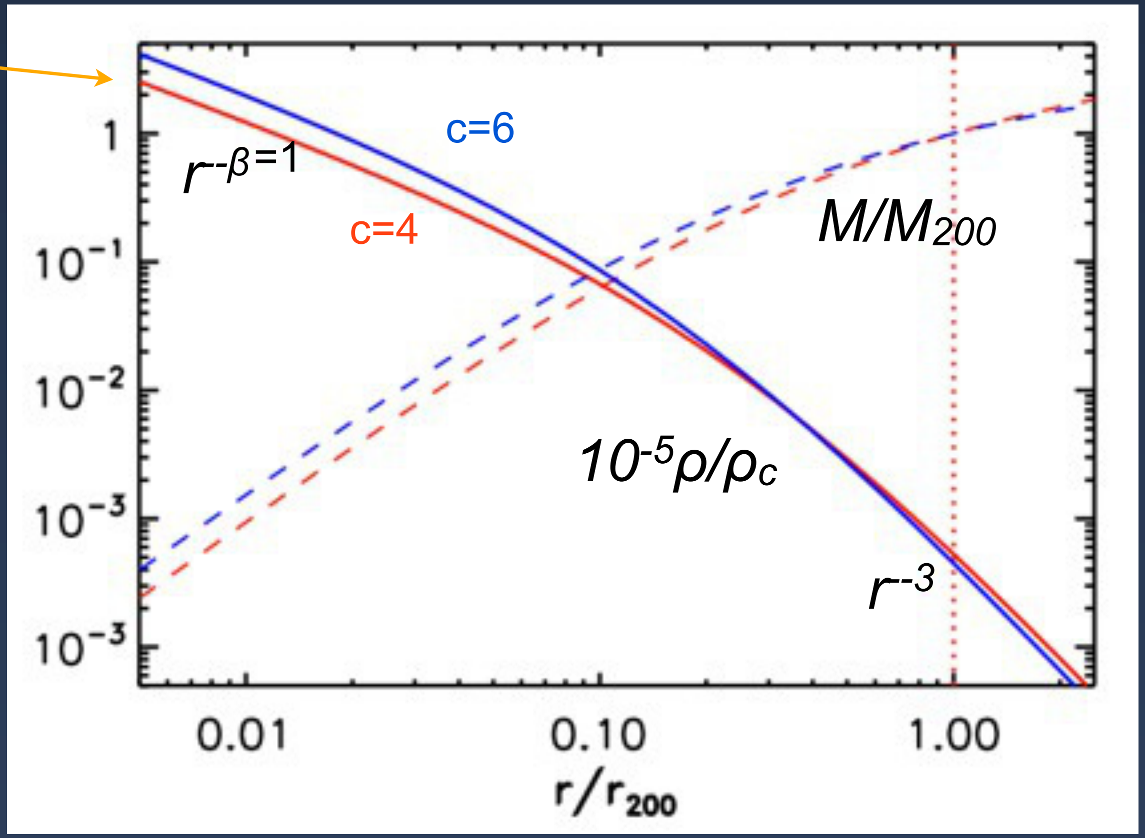
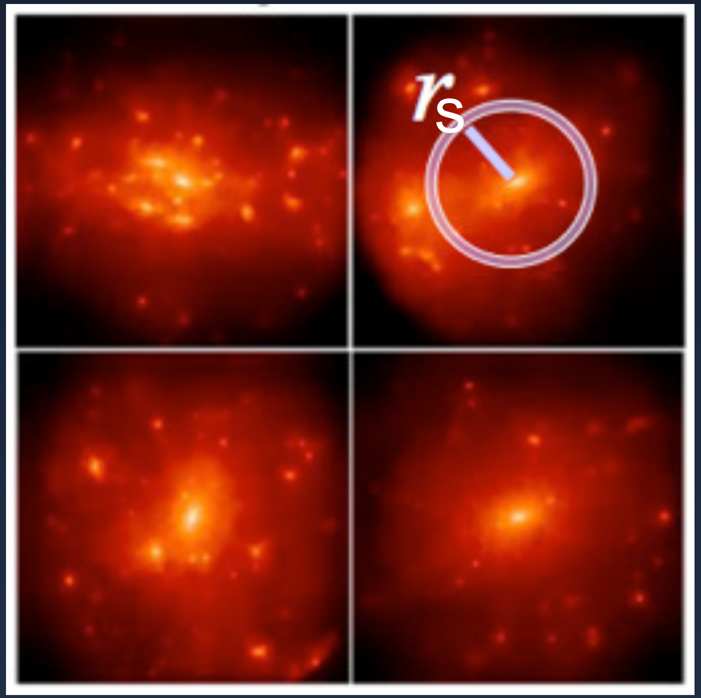


ΛCDM Predictions for DM Mass Profiles

N-body simulations have shown (Navarro, Frenk, White 96, **NFW**) that CDM halos have self-similar profiles, differing only by simple rescaling of size and density over 4 decades in mass (gal→CL)



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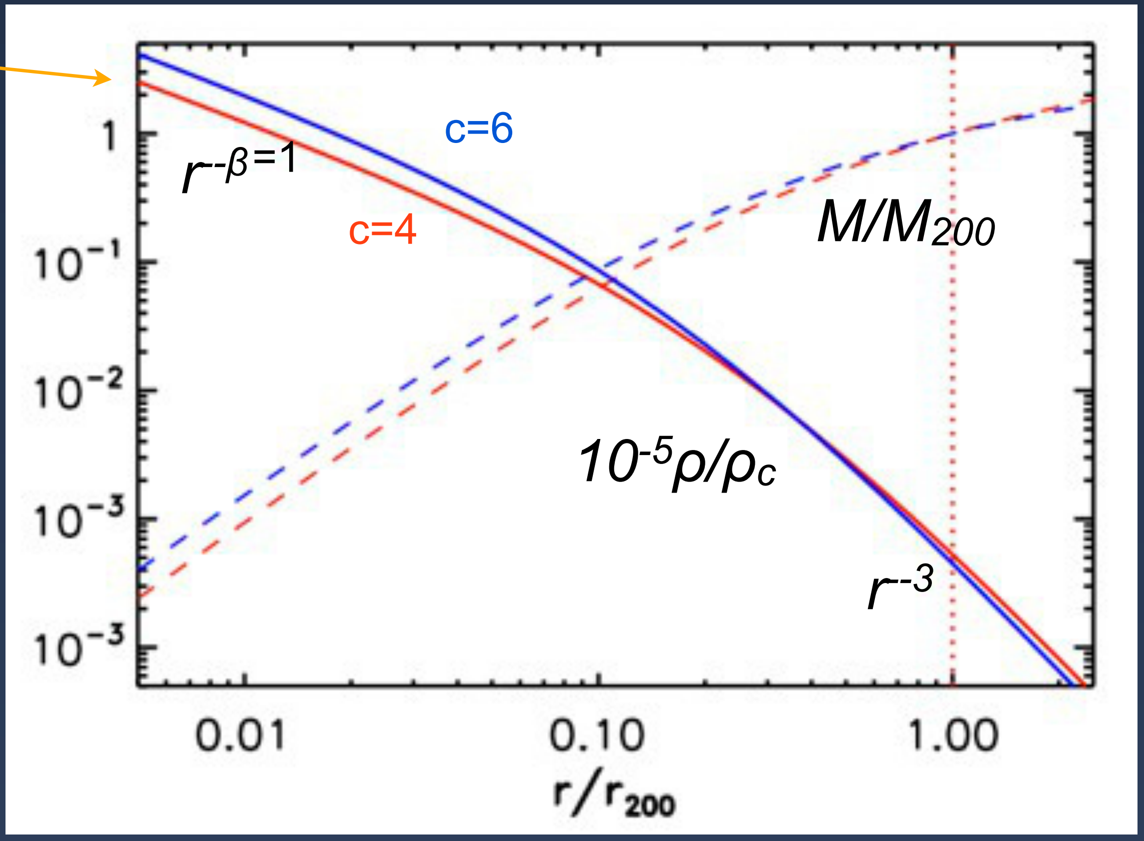

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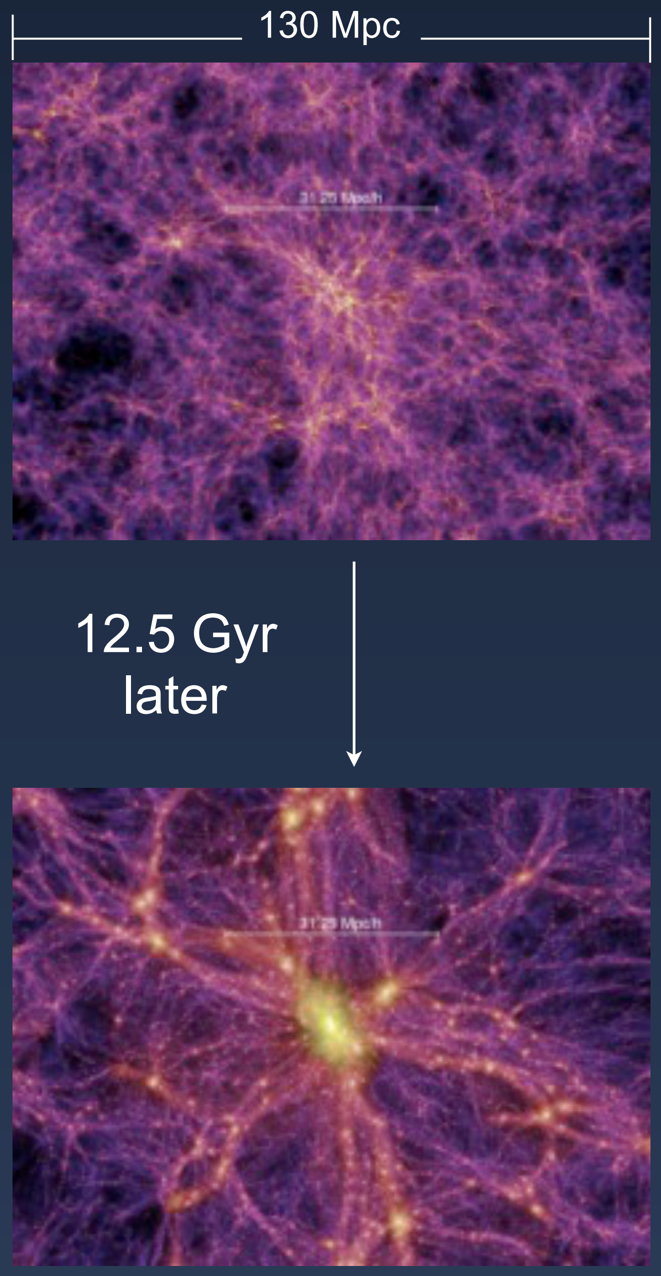
Fundamental Questions that remain Unanswered or Unverified

- How is dark matter distributed in cluster & galaxy halos?
  - How centrally concentrated is the DM? Implications for epoch of formation.
  - What degree of substructure exists? and on what scales?
  - How does the DM distribution evolve with time and varies with mass?
  - How the distribution of baryonic matter affects (dynamically) the DM?
  - Is the DM mass profile universal?
  - Can we constrain the nature of the DM? (e.g. self-interaction cross-section)

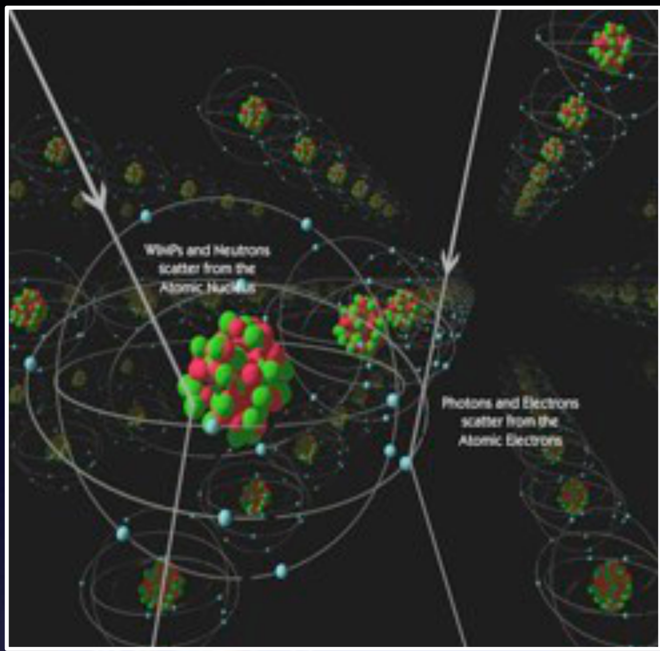
- How to measure cluster masses and compared them with simulations ?



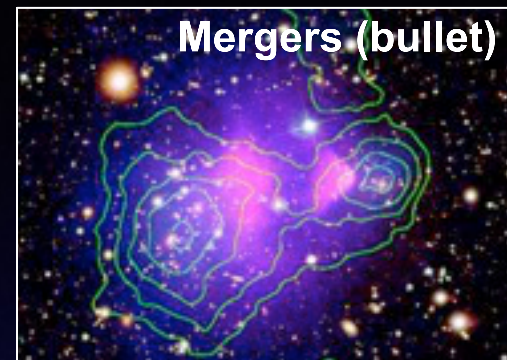
“Millennium” simulation of DM (Springel et al. 2005)

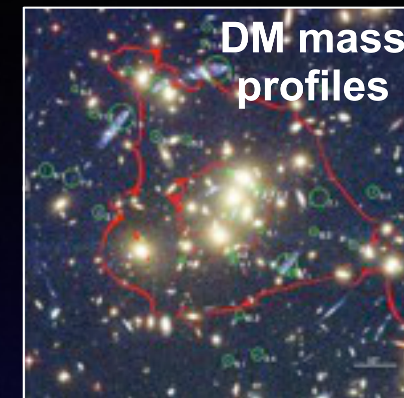
Understanding the nature of Dark Matter

Direct detection of DM
(underground experiments)



Indirect clues on DM properties from Clusters





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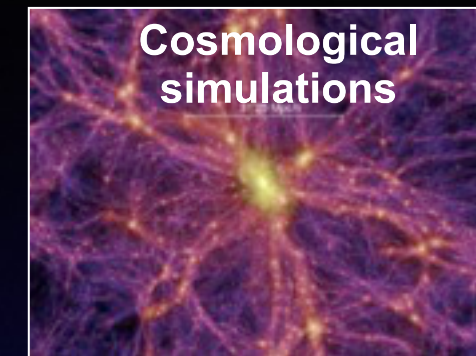
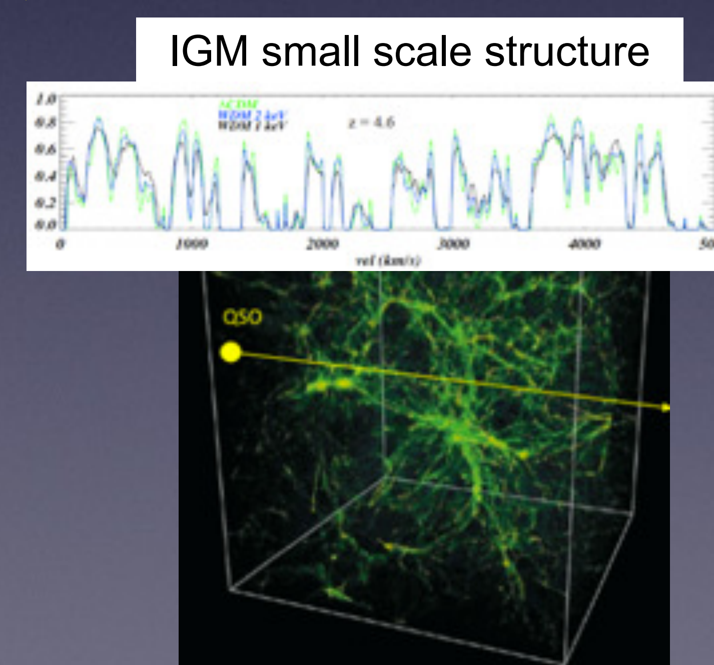


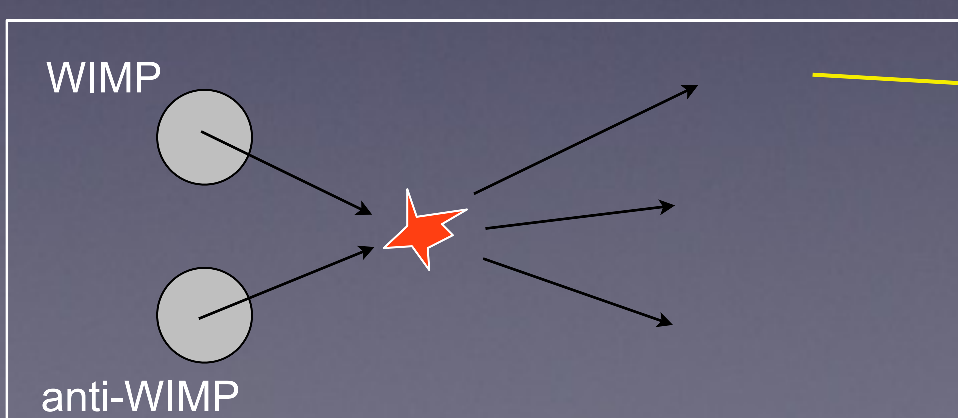
Constraints on self-interacting DM

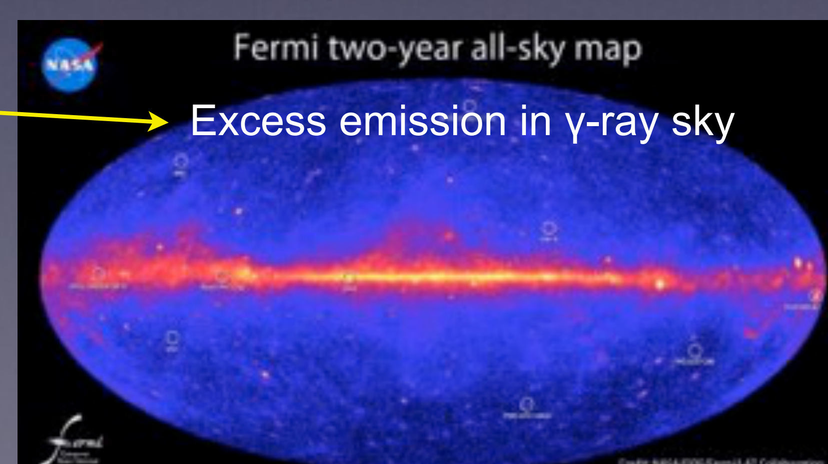
Dark Matter particle properties: $M_X, \sigma_X, \sigma_{X\bar{X}}$
+
Beyond Standard Model

Cold vs Warm DM



Indirect detection of DM (if WIMPs..)





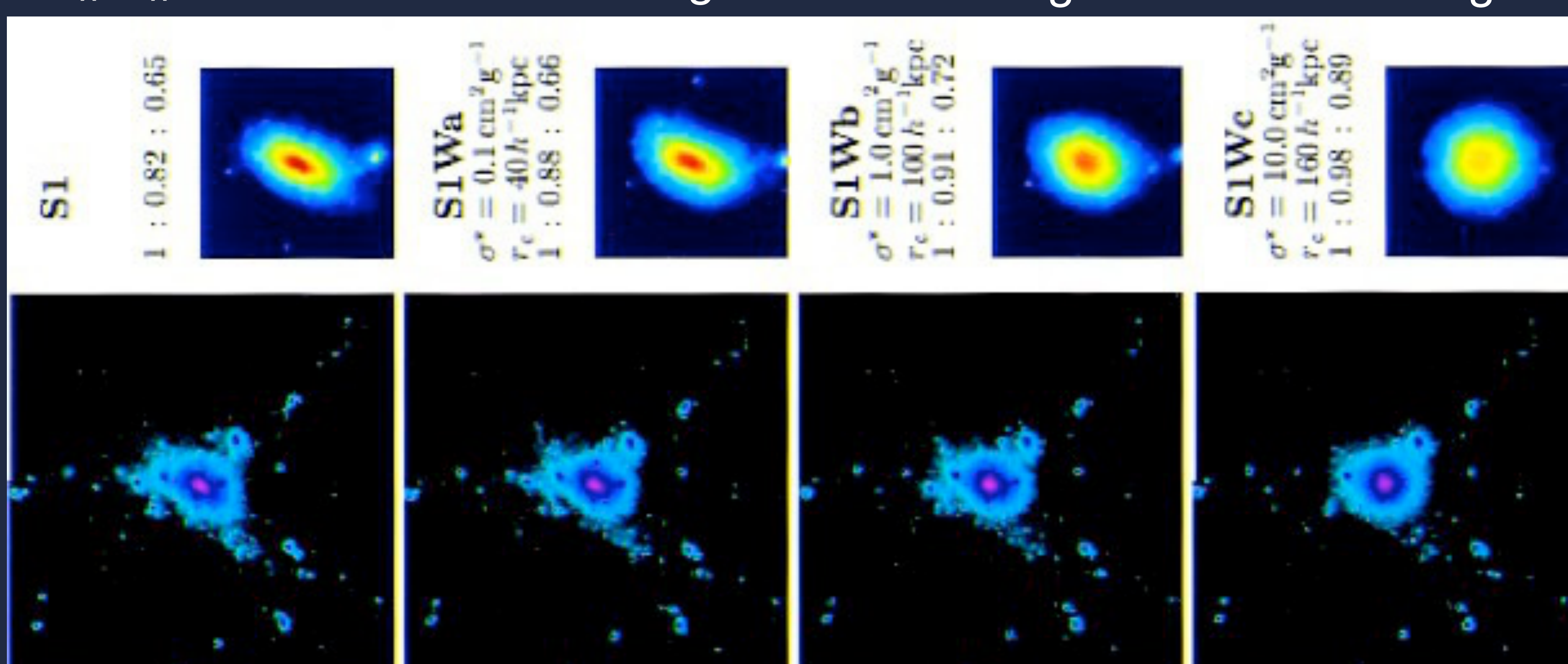
The effect of a collisional DM on cluster density profiles

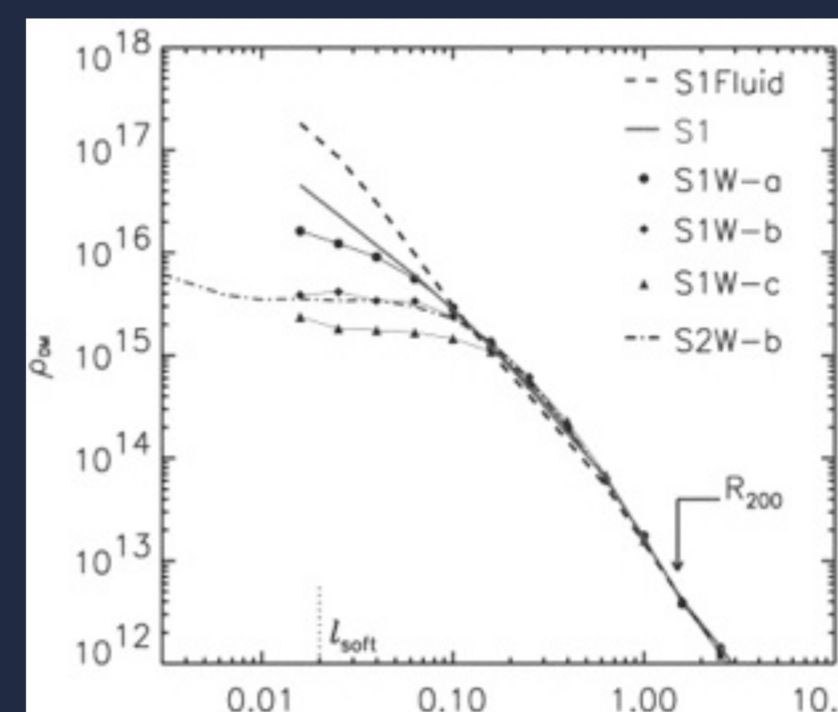
- The presence of a non-negligible self-scattering DM cross section leads to the formation of less cuspy and more spherical cores (Spergel&Steinhardt 2000)
  - $\sigma_x/m_x \lesssim 0.02\ cm^2/g$ (Miralda-Escude 2000) from lack of spherical core in cluster MS2137 (note that the Bullet cluster implies only $\sigma_x/m_x \lesssim 1\ cm^2/g$)
  - $\sigma_x/m_x \lesssim 0.1\ cm^2/g$ from the presence of cores with $r_c \lesssim 40h^{-1}$ kpc (Yoshida et al. 2000)
  - $\sigma_x/m_x \lesssim 0.01\text{-}0.6\ cm^2/g$ (Firmani et al. 2000)

$$\frac{\sigma}{m_x} \lesssim 0.2\ \mathrm{cm^2/g} \left(\frac{0.02 M_\odot \mathrm{pc}^3}{\rho}\right)\left(\frac{100\ \mathrm{km/s}}{v_0}\right)$$
$$(\tau_{\rm coll} \sim 1/n\sigma v = H_0^{-1})$$

- A systematic study (cluster selection, multi mass probes of the inner core) on a sample of relaxed clusters has never been carried out

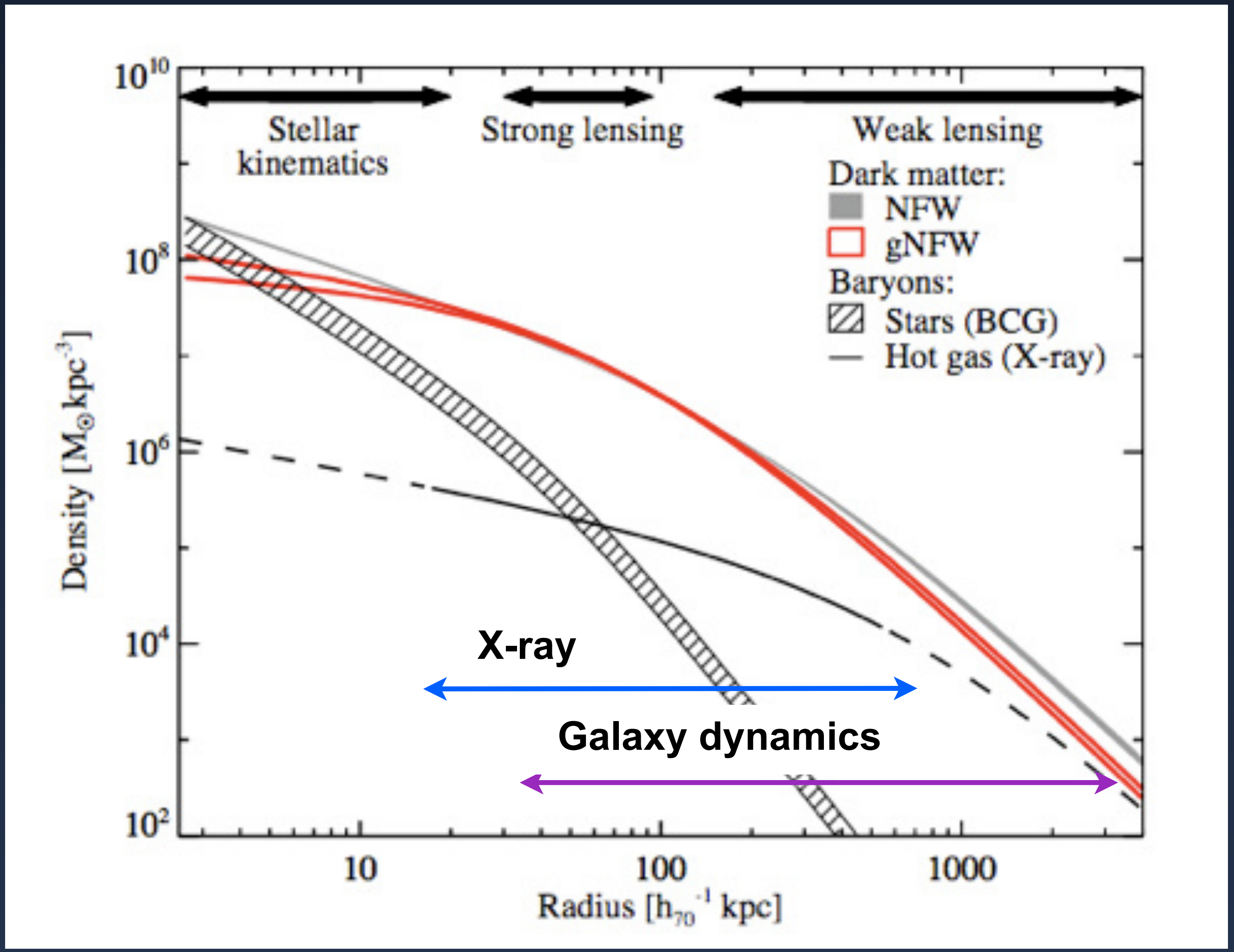
$\sigma_x/m_x \rightarrow 0$ $0.1\ cm^2/g$ $1\ cm^2/g$ $10\ cm^2/g$





Yoshida et al. 2000 (velocity independent cross-section)

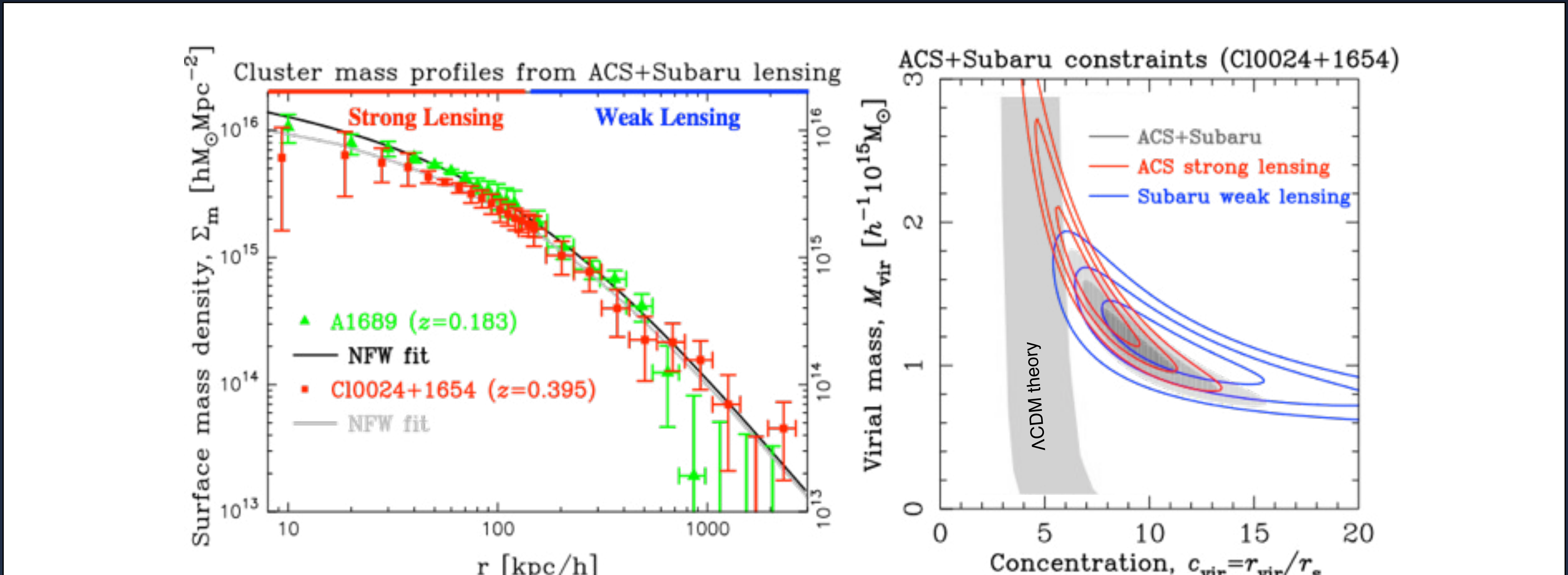
Measuring DM and Baryon mass density profiles in clusters



Newman et al. 09

- **Key**: use a variety of complementary probes
  - to cover 2-3 decades in scale in a complementary fashion
  - to mitigate systematics (different for each method)
    - Lensing: LSS projections, triaxiality
    - X-ray: deviation from hydrostatic equilibrium, non thermal support
    - Dynamics: deviation from equilibrium, substructures, projections

DM and Baryon mass density profiles in clusters



Umetsu&Broadhurst 2008

- Early and recent results point to a *possible* tension with ΛCDM: shallow inner slopes, large mass concentrations, large Einstein radii:
  - Do we understand how baryonic physics shapes the inner DM potential ? (dynamical back-reaction effects induced by cooling, feedback, AGN, etc.)
  - Does ΛCDM have problems on small scales despite the success on large scales ?
  - Is DM really collision-less? (e.g. Spergel&Steinhardt 2000, Rocha+ 2012)
- *But this is based on a handful of clusters.. often with heterogeneous data quality* small (biased) samples ? cl-cl variance ?

Cluster Lensing And Supernova survey with Hubble

HST multi-cycle Treasury Program (530 orbits) - PI: M.Postman

An HST Multi-Cycle Treasury Program (530 orbits, PI: M.Postman) designed to place new constraints on the fundamental components of the cosmos: dark matter, dark energy, and baryons in the early Universe

How ?

Use panchromatic HST imaging of 25 massive lensing clusters at <z>≈0.4 to probe dark matter and to magnify distant galaxies + multi-wavelength observations

SNe-Ia search at 1<z<2 from parallel fields/multi epoch, combined with CANDELS

MAIN GOALS

- Accurate mass density profiles using high-quality, homogeneous strong+weak lensing, dynamics, X-ray methods over 10-3000 kpc radial range. Mapping DM in clusters with high resolution and fidelity
- Magnified galaxies out to z~12 ➡ early galaxy growth, reionization epoch
- Improving constraints on time evolution DE equation of state parameter w

Cluster Lensing And Supernova survey with Hubble

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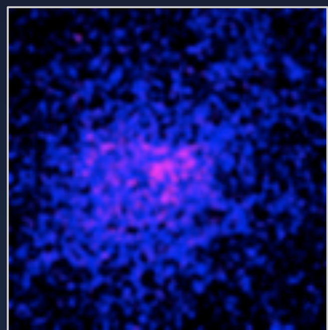
CLASH-VLT

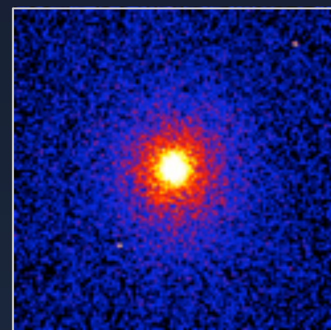
VIMOS Large Programme (230 hr over 4 years) - PI: P.Rosati

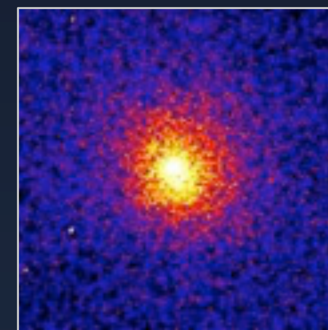
“Dark Matter Mass Distributions of Hubble Treasury Clusters and the Foundations of ΛCDM Structure Formation Models”

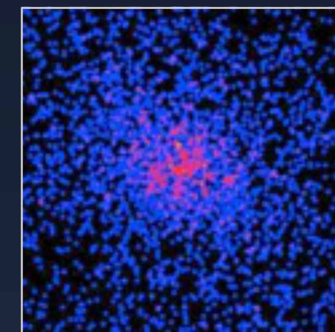
- Panoramic spectroscopic survey of 14 southern CLASH clusters at z=0.3-0.6
- Dynamical analysis out to R_{vir} and beyond with ~500 members per cluster
- Highly magnified galaxies out to z~7
- Galaxy structure and stellar pop properties from high to low density environments

X-ray images of the 25 CLASH clusters


Abell 209


Abell 383


Abell 611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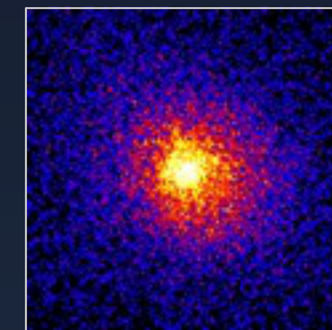
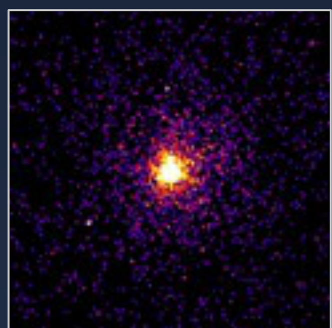
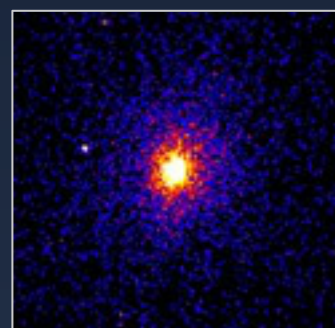

Abell 2261


MACS 0329-0211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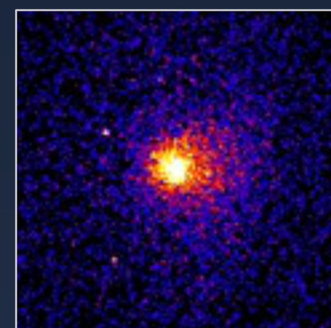
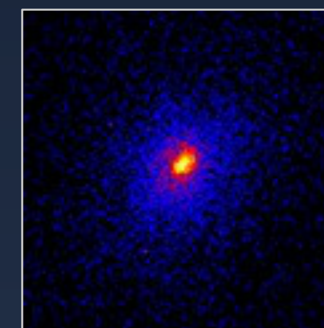

MACS 0744+3927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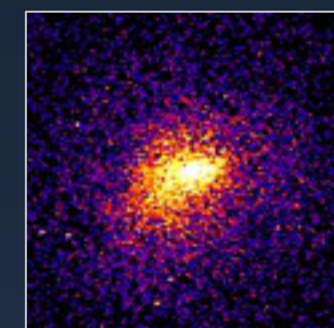
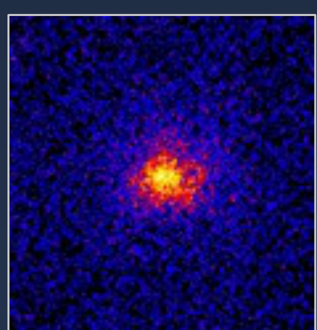
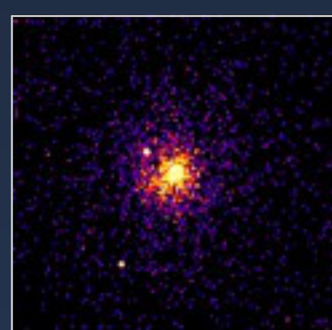
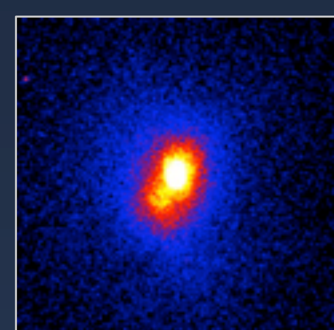
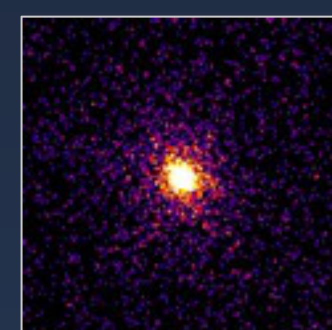
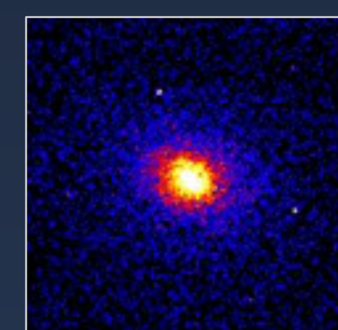

MACS 1206-0847

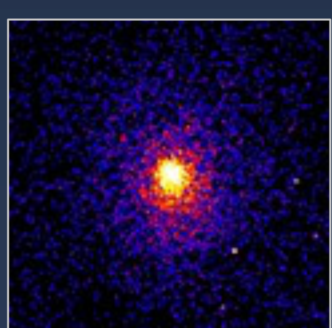

CLJ1226+3332

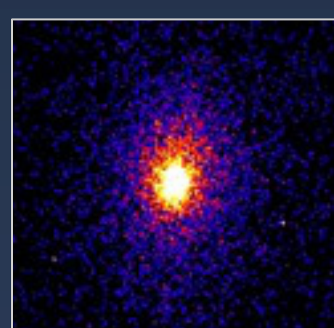

MACS 1311-0310


RXJ 1347-1145


MACS 1423+2404


RXJ 1532+3020


RXJ 1720+3536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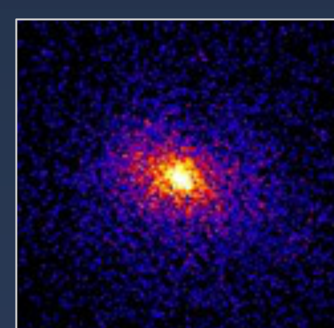
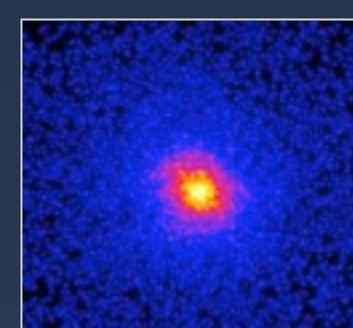
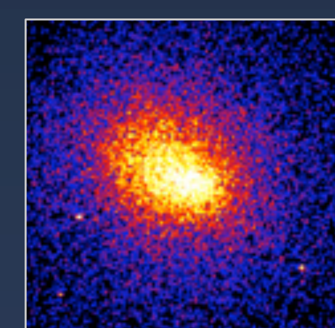

RXJ 2129+0005


MS-2137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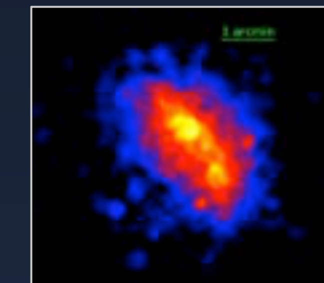
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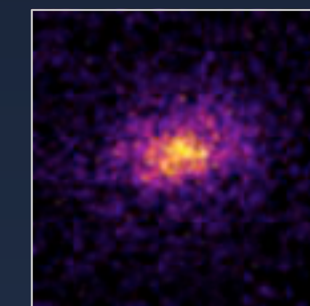
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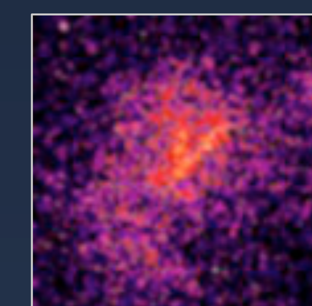
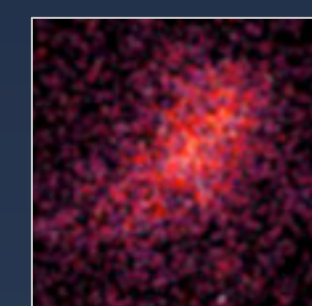
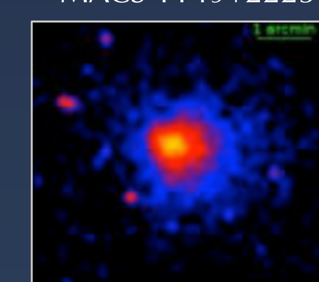
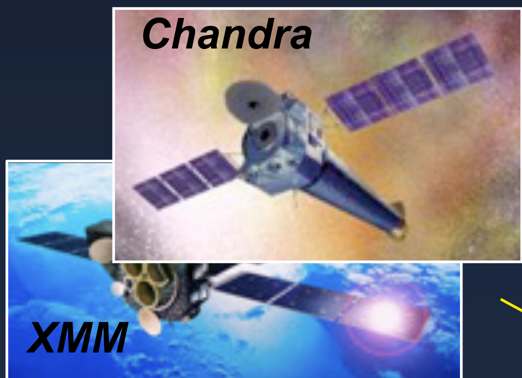

MACS 0717+3745


MACS 1149+2223


MACS 2129-0741

20 are selected to be "relaxed" clusters (based on their X-ray morphology)
5 (last column) are selected specifically because they are big lenses $\theta_E > 35''$
All have $T_X > 5$ keV

CLASH multiple facilities: DM & Baryonic Mass Distribution from independent probes over the 10 kpc ~ 3 Mpc range



PI: M. Donahue

Baryon mass distribution
X-ray masses
ICM physics & metallicity

PI: S.Ettori

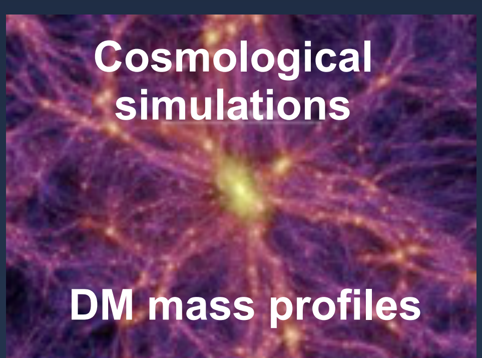
VLT

VIMOS Large Prog (230 hr)
~500 members per cluster
+ arcs redshifts

PI: P. Rosati

High-z gals
Dynamical analysis
Stellar masses

DM and Baryons in Clusters

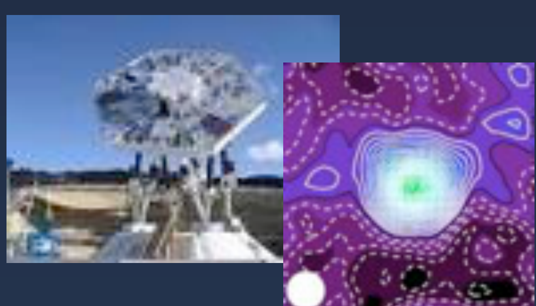


LBT

High-z gals

PI: M. Nonino

Bolocam, Mustang



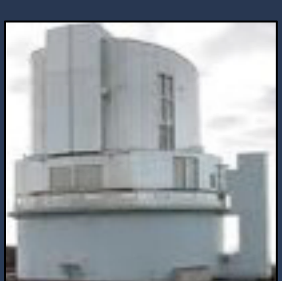
ICM physics
DM&Baryon
masses

SZ observations

PI: K. Umetsu

WL masses profile
Stellar masses

Subaru (+ ESO-WFI)



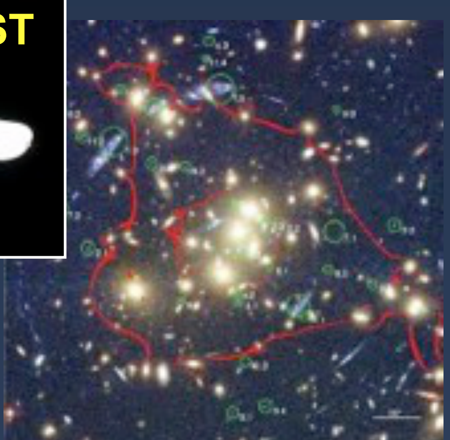
PI: K. Umetsu
M. Nonino

Spitzer

High-z galaxies

PI: W. Zheng R. Bowuens

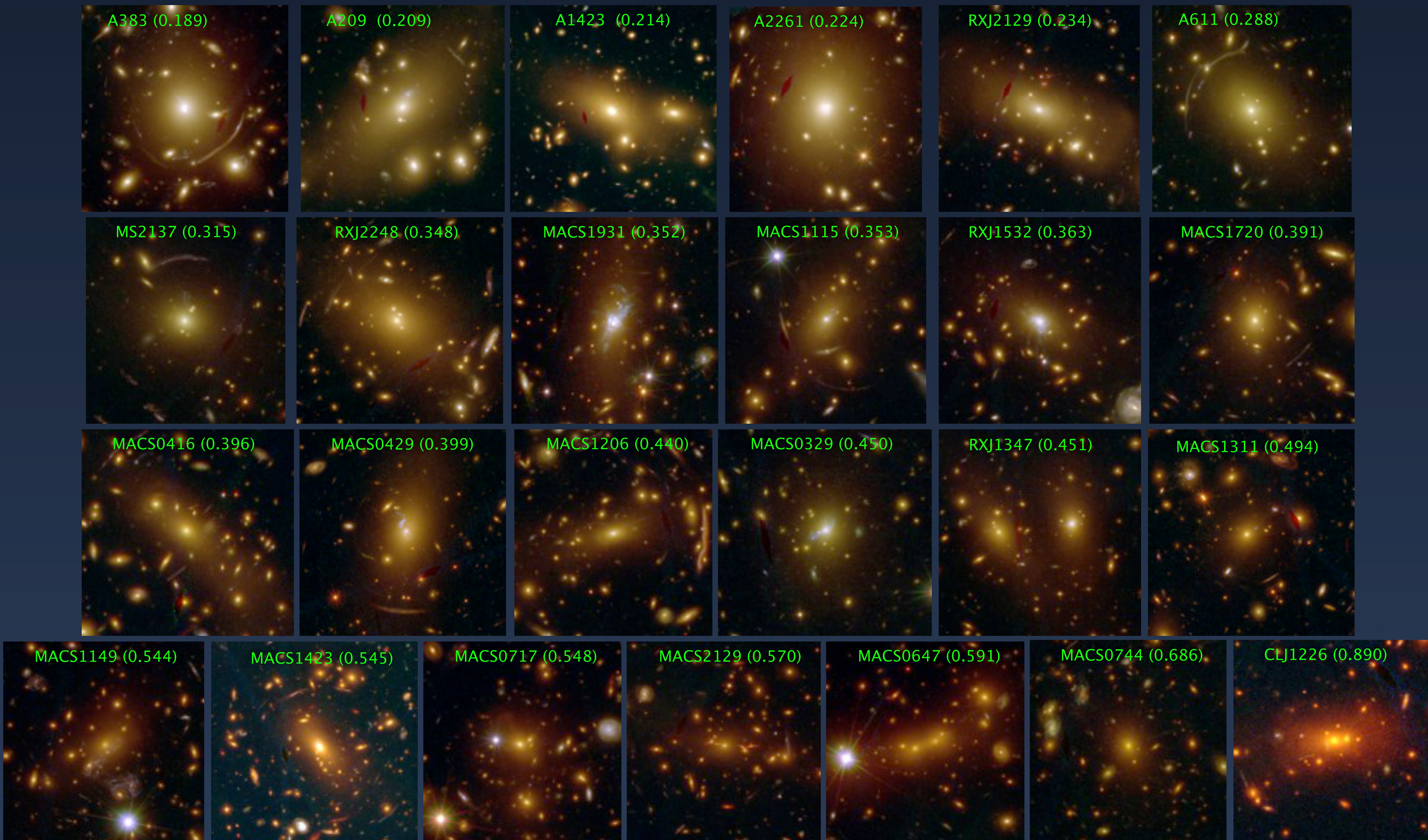
Strong Lensing
Mass profile in the core



Treasury Program
(530 orbits)

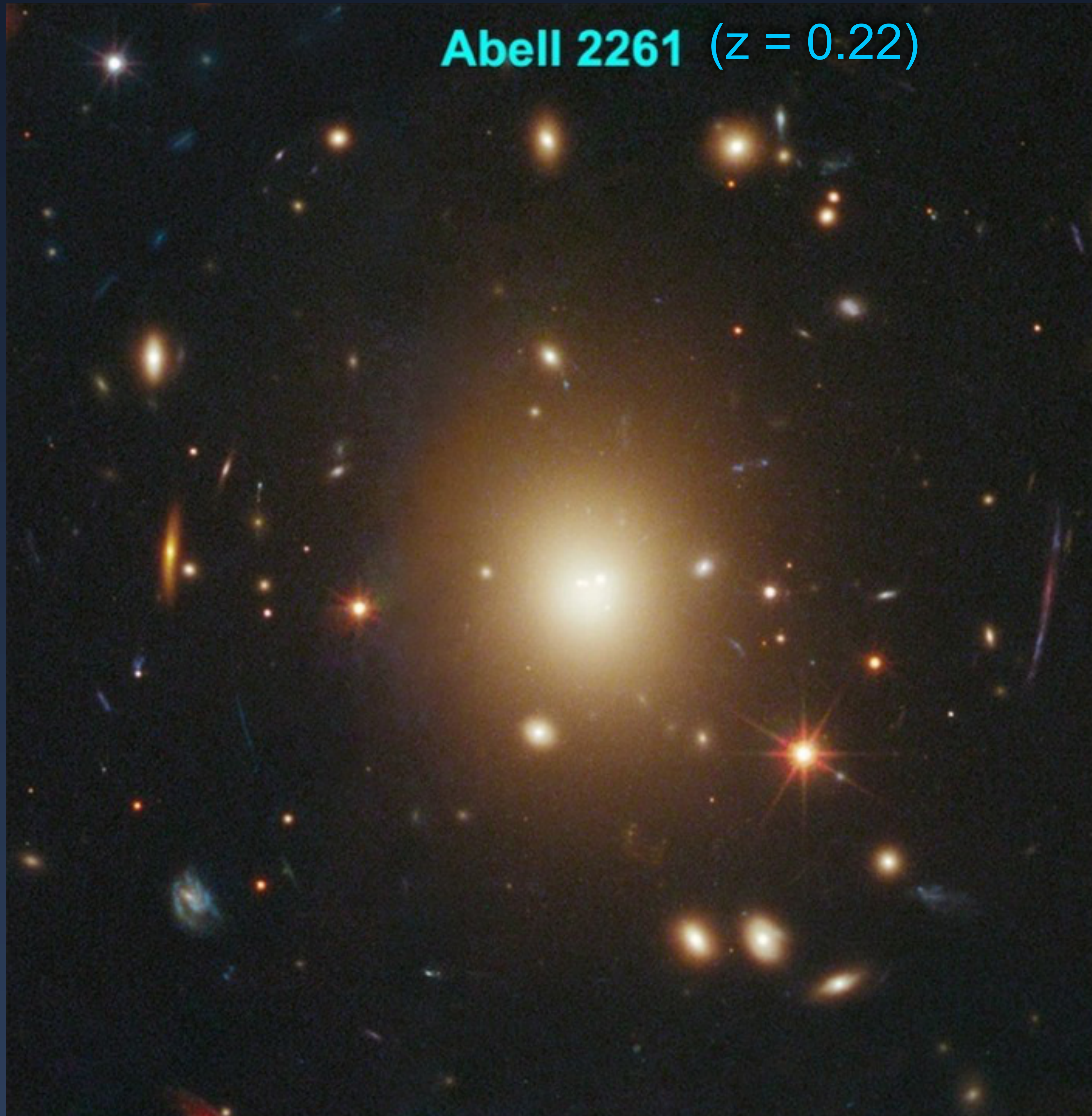
PI: M. Postman

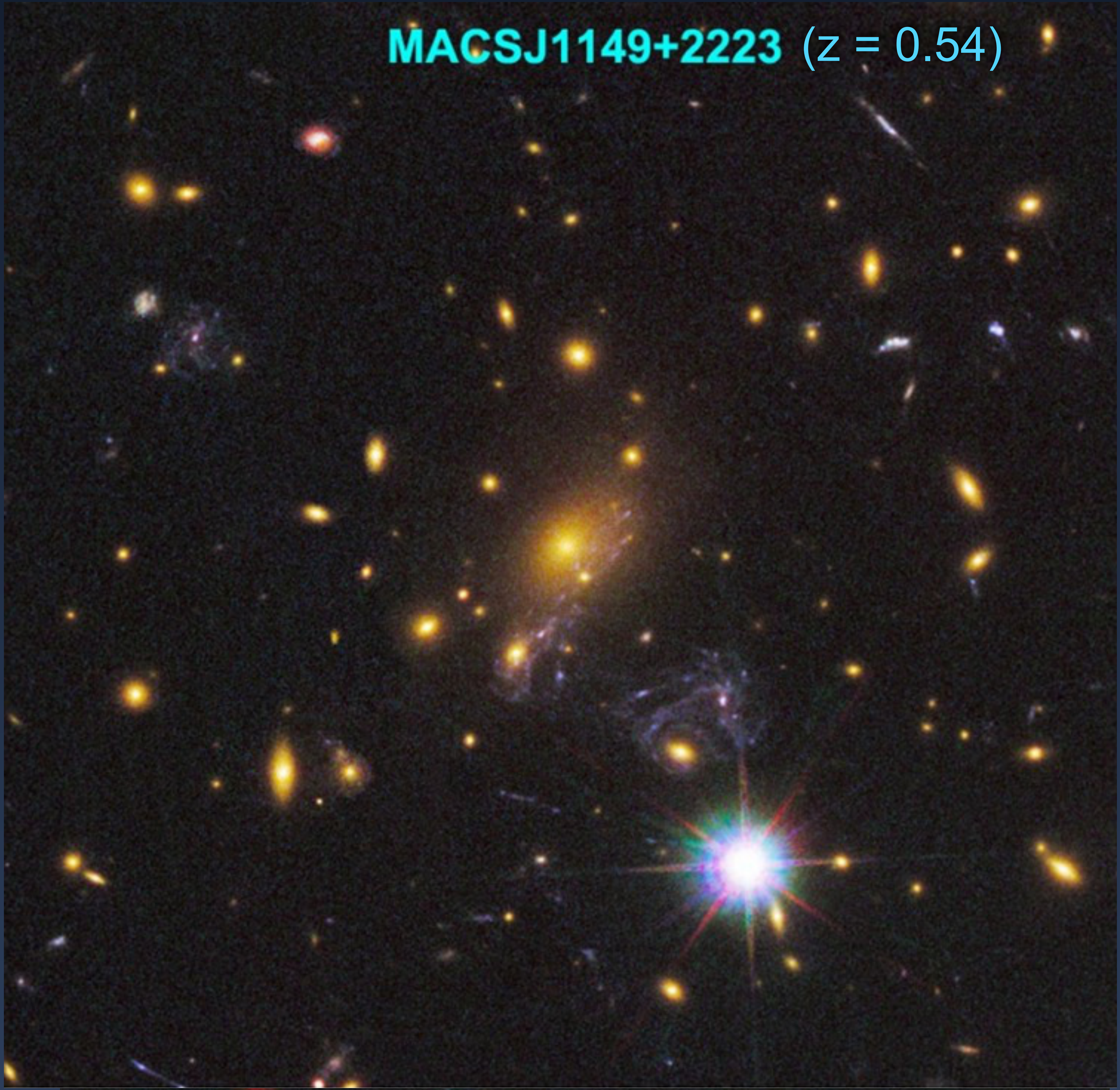
CLASH Gallery: All 25 Clusters

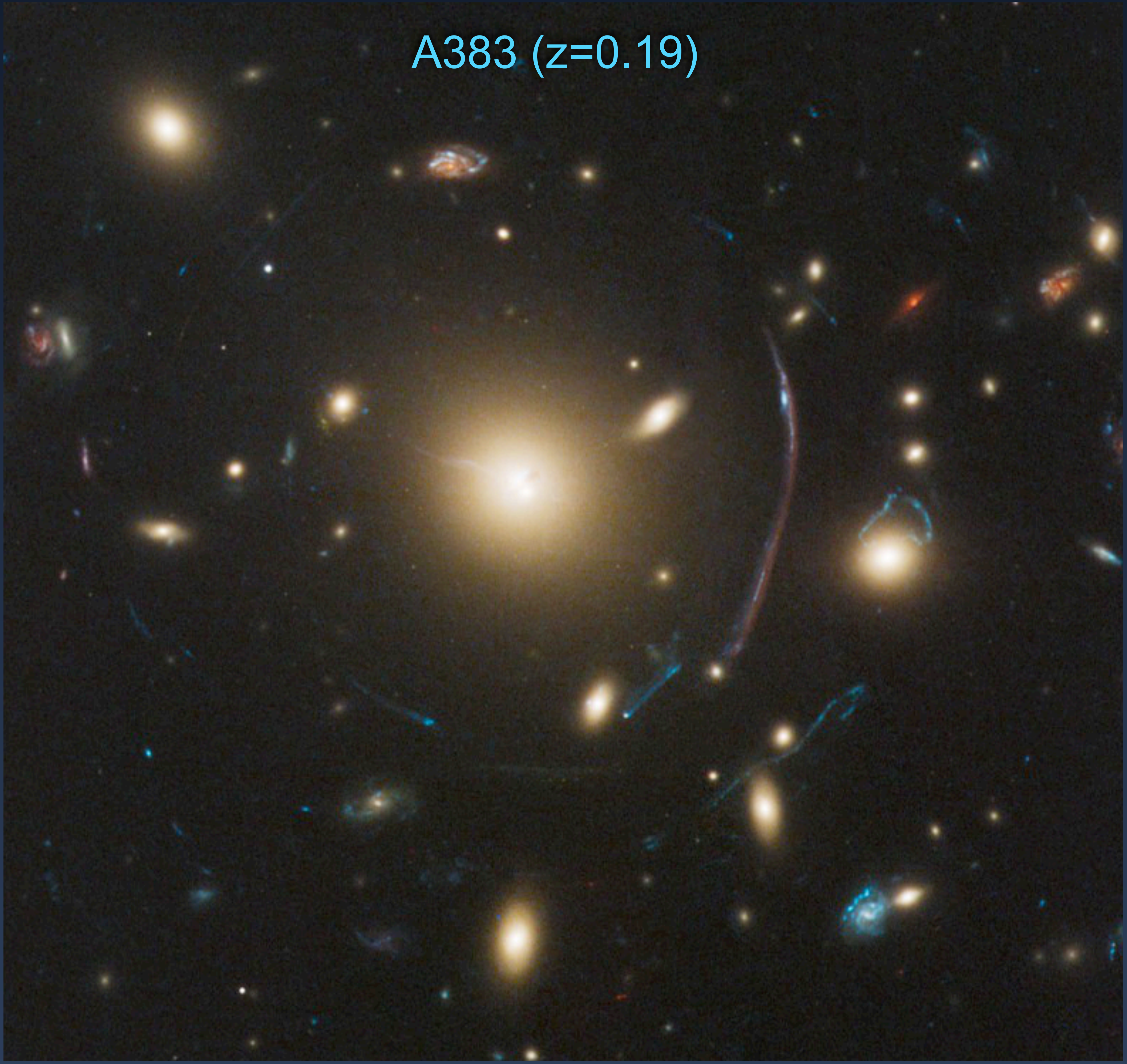


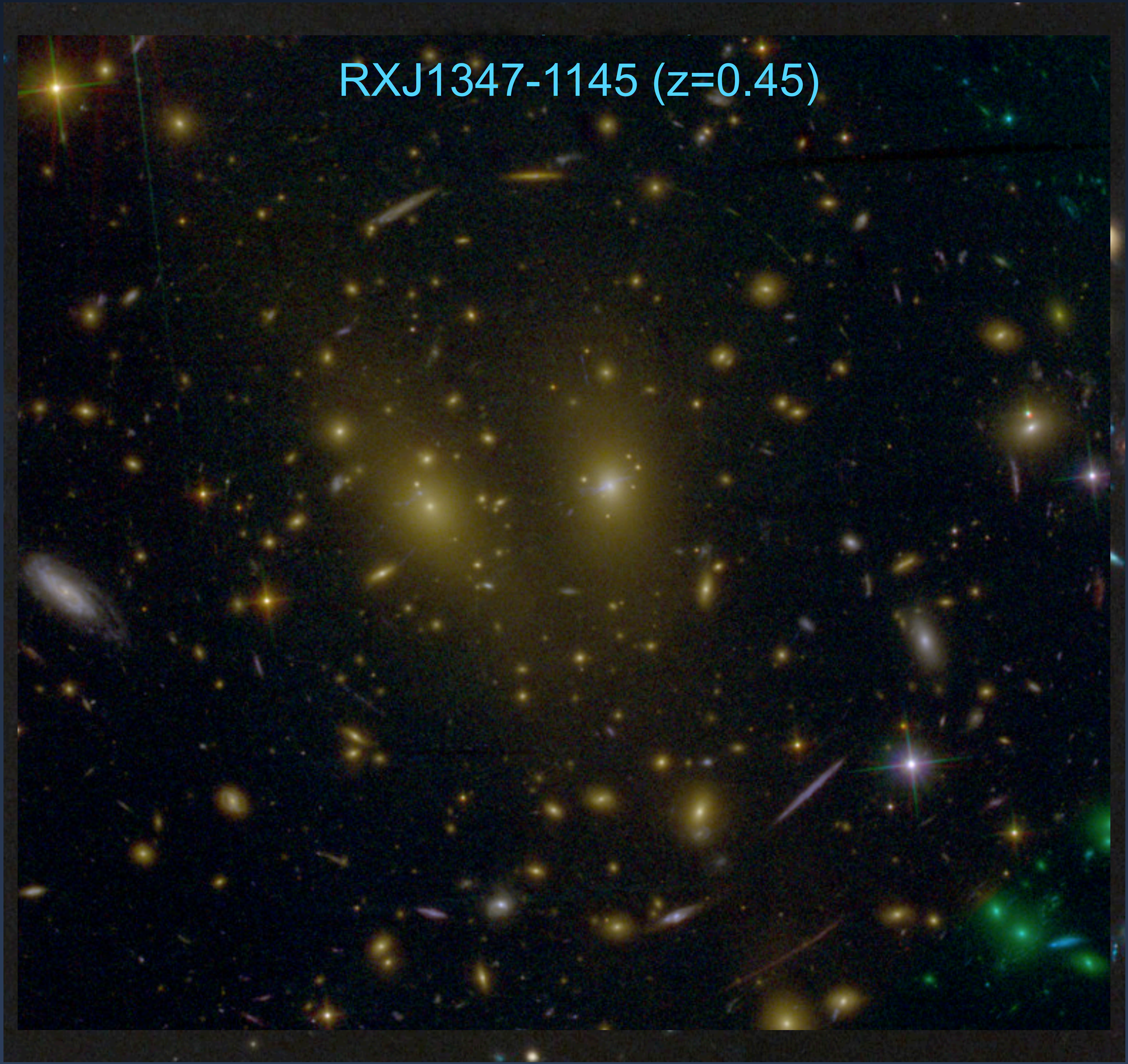
All HST observations completed in July 2013. Data products in the STScI Archive.

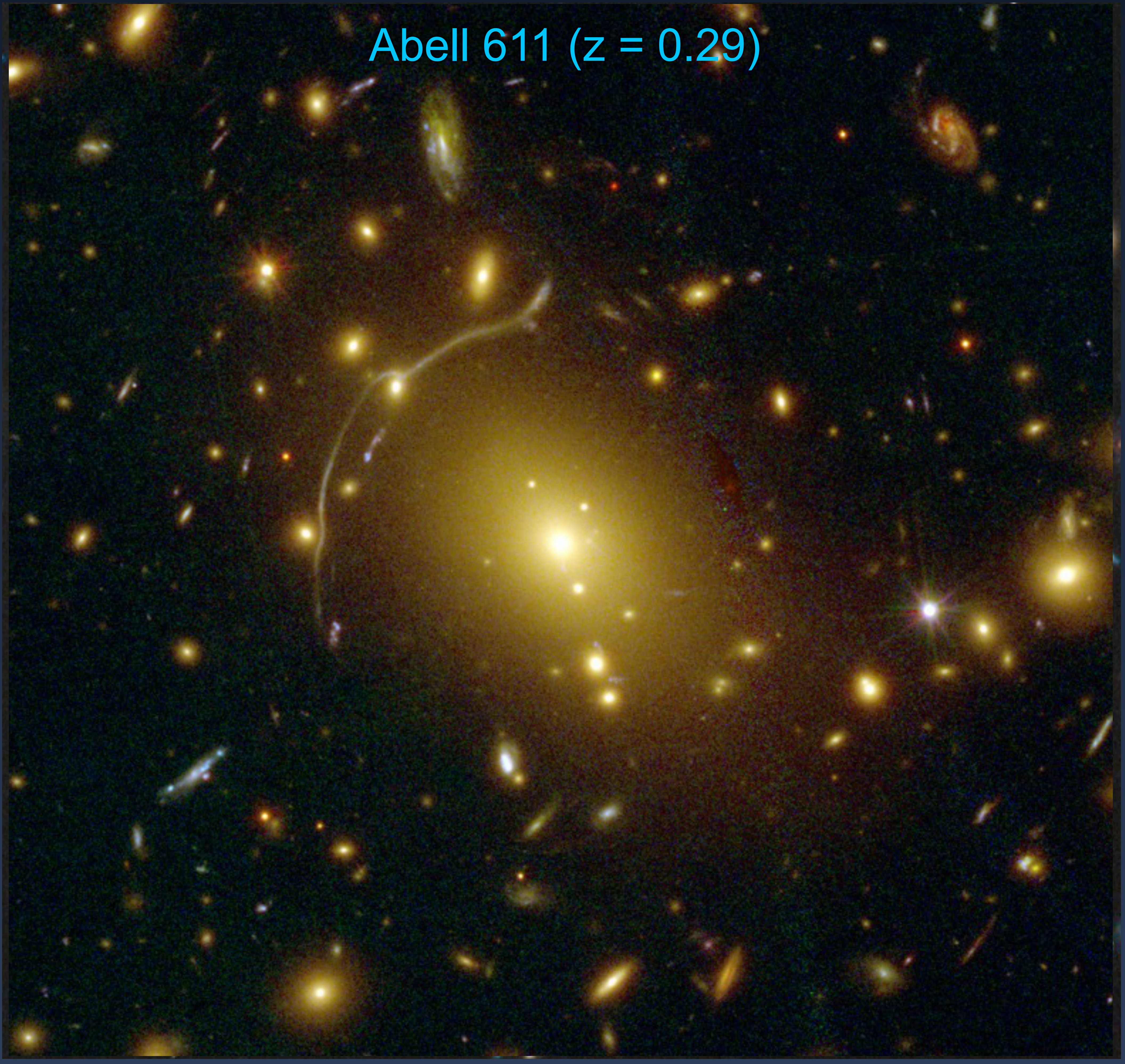
A quick CLASH slide show...

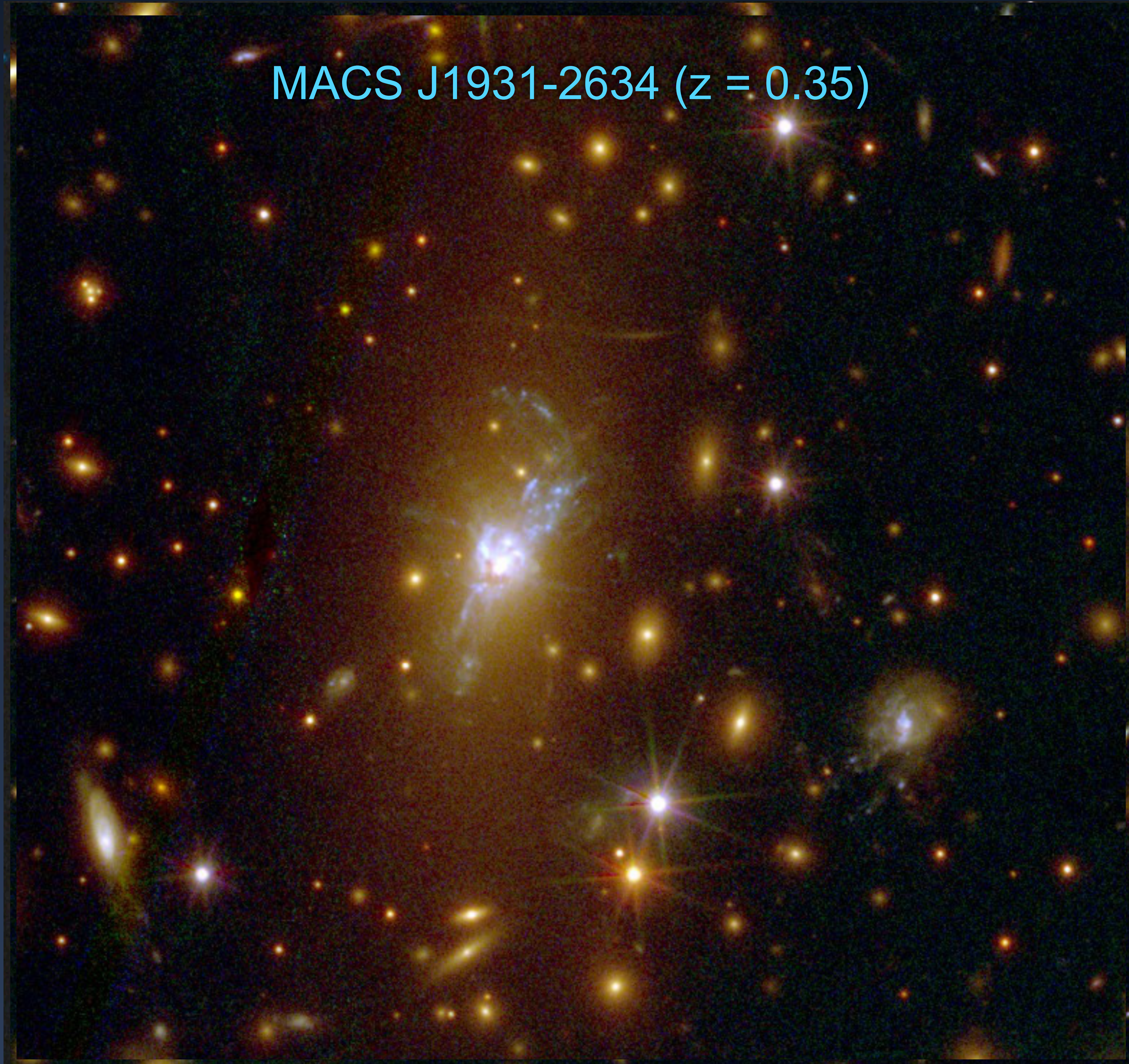

Abell 2261 (z = 0.22)


MACSJ1149+2223 (z = 0.54)

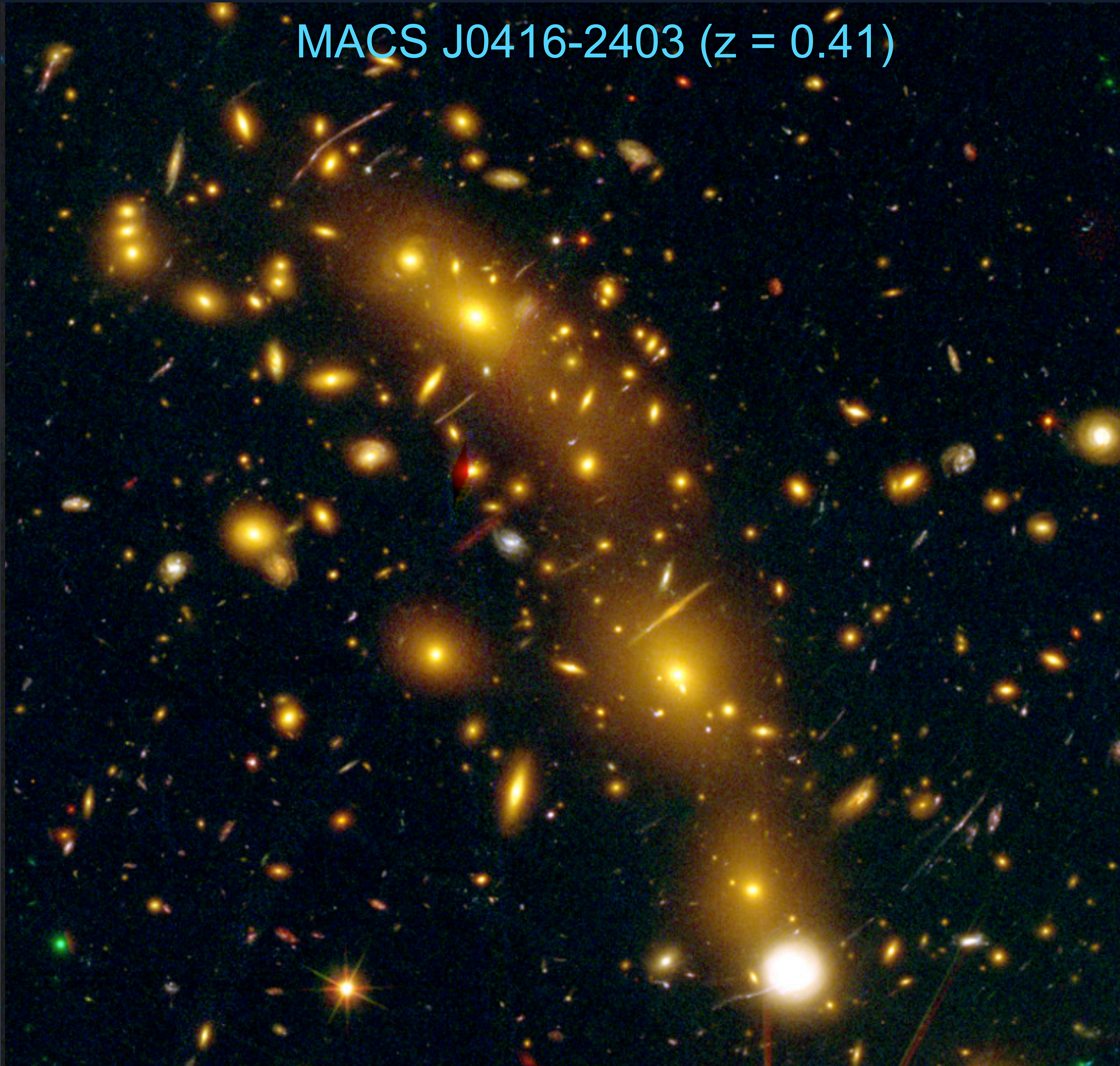

A383 (z=0.19)


RXJ1347-1145 (z=0.45)

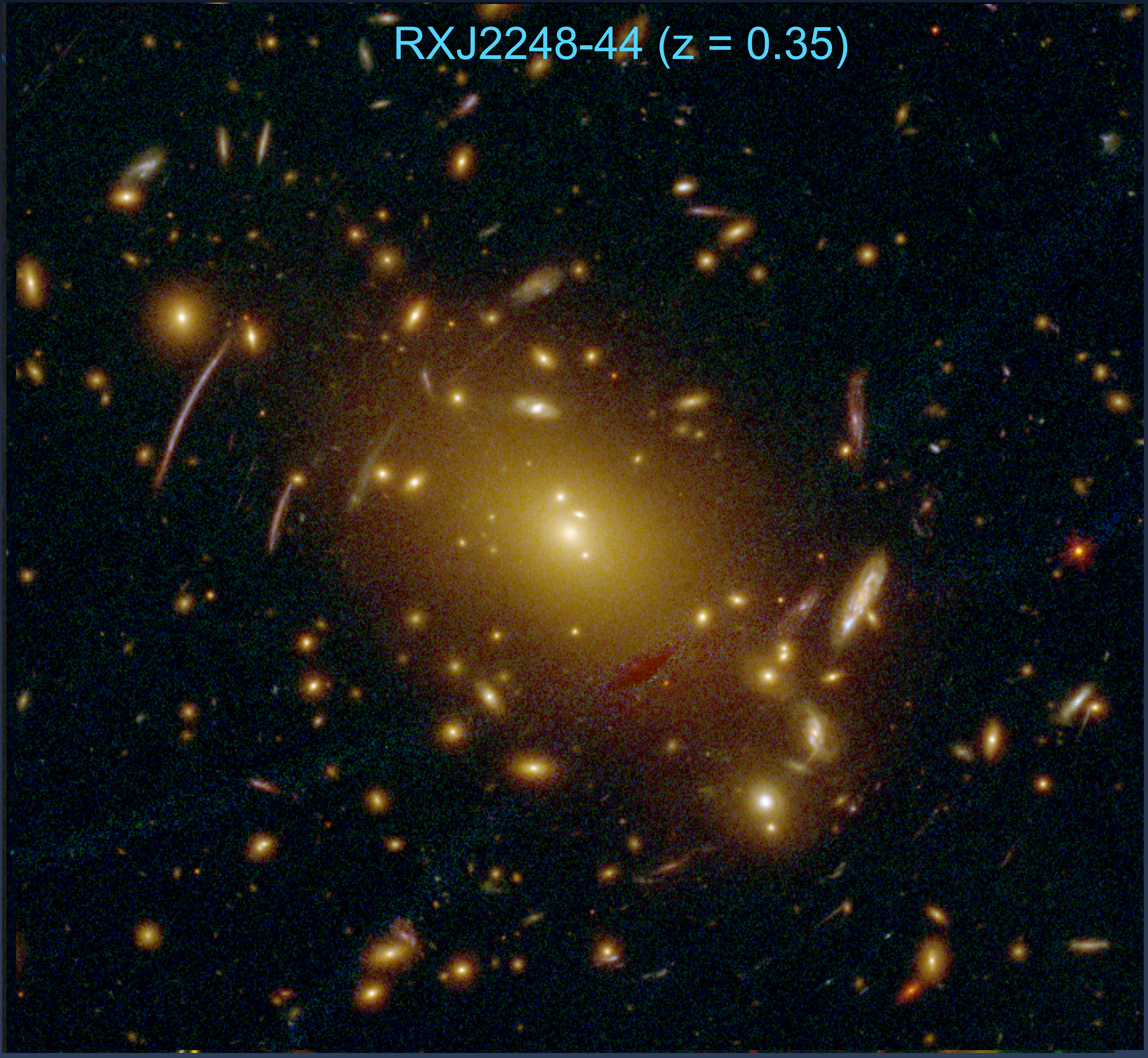

Abell 611 (z = 0.29)


MACS J1931-2634 (z = 0.35)

MACS J0416-2403 (z = 0.41)



RXJ2248-44 (z = 0.35)

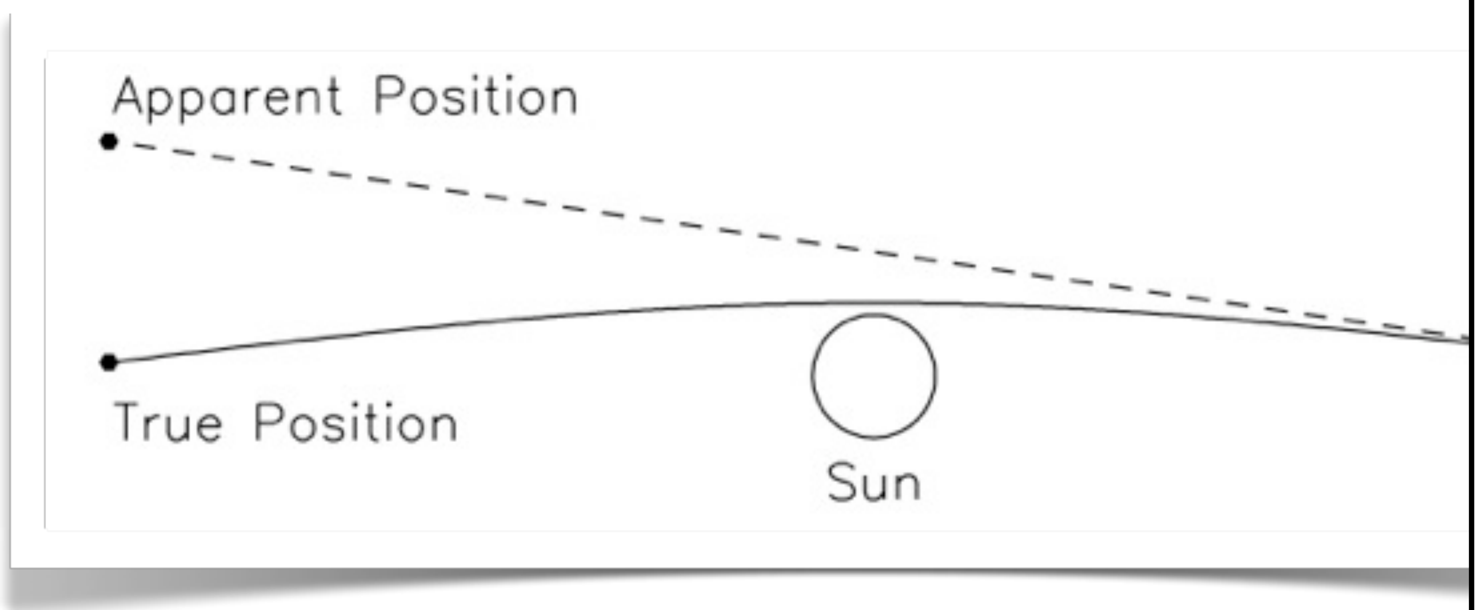


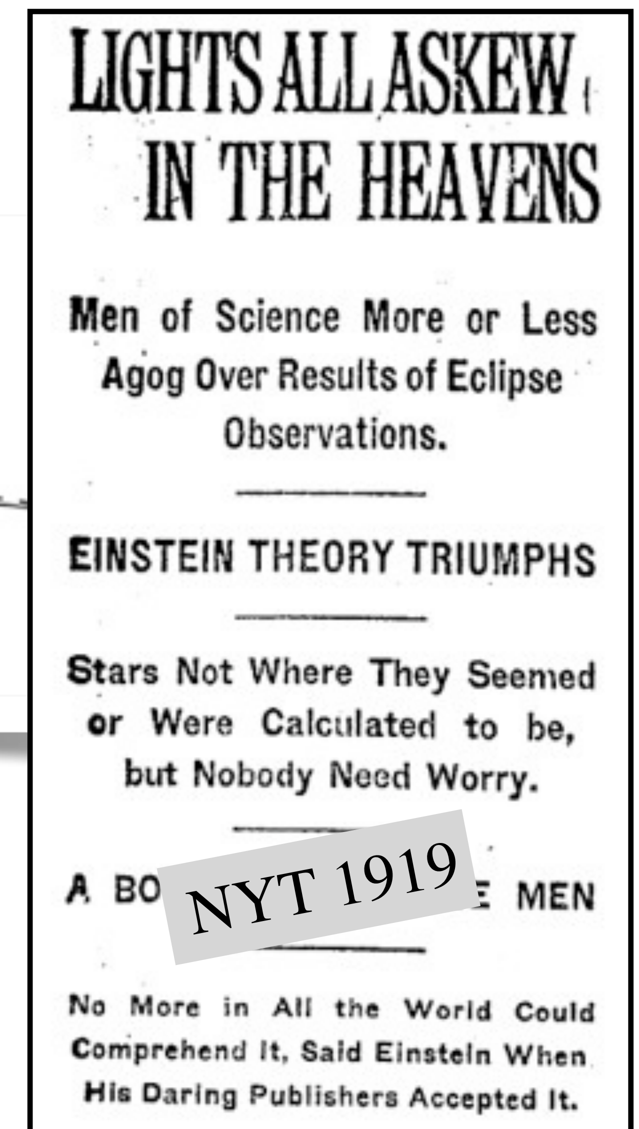
Brief historical perspective

- Hypothesis of light deflection by Newtonian gravity goes back to Newton and Laplace, Soldner (1804) derives the classical deflection formula

$$\alpha = \frac{2GM}{c^2}\frac{1}{r}$$

- Einstein (1915) using GR equations finds a deflection angle with a factor of 2 higher than the classical formula (1.74” for the Sun)
- Eddington (1919) confirms the deflection prediction of stars near the solar limb




LIGHTS ALL ASKEW IN THE HEAVENS

Men of Science More or Less Agog Over Results of Eclipse Observations.

EINSTEIN THEORY TRIUMPHS

Stars Not Where They Seemed or Were Calculated to be, but Nobody Need Worry.

A BO[...]E MEN

No More in All the World Could Comprehend It, Said Einstein When His Daring Publishers Accepted It.

NYT 1919

Brief historical perspective

- Hypothesis of light deflection by Newtonian gravity goes back to Newton and Laplace, Soldner (1804) derives the classical deflection formula

$$\alpha = \frac{2GM}{c^2}\frac{1}{r}$$

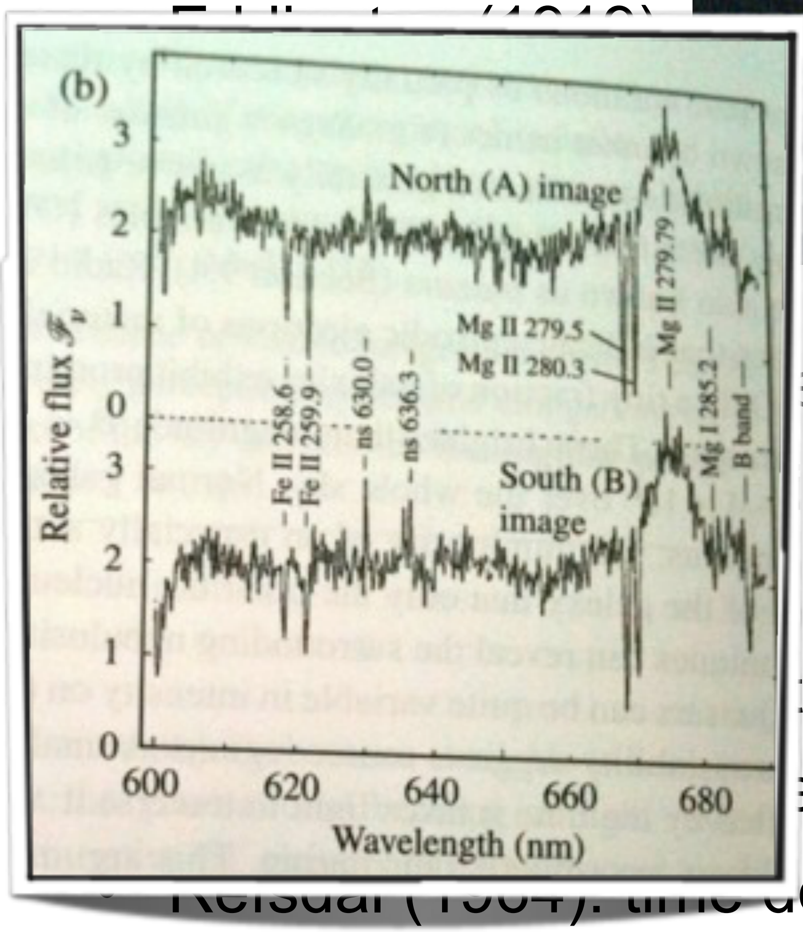
- Einstein (1915) using GR equations finds a deflection angle with a factor of 2 higher than the classical formula (1.74” for the Sun)
- Eddington (1919) confirms the deflection prediction of stars near the solar limb
- Chwolson (1926) conceives the possibility of multiple images (“fictitious stars”) of stars by a lensing stars, and even rings in symmetric geometry
- Einstein (1936) considers the same possibility (also rings) and concludes there is little chance to observe the effect for stellar-mass lenses..

Brief historical perspective

- Hypothesis of light … to Newton and Laplace, Soldner (… la

$$\alpha = \frac{2GM}{c^2}\frac{1}{r}$$

- Einstein (1915) usi … ith a factor of 2 higher … n)
- … ear the solar limb
- … (“fictitious stars”) of … y
- … ers the same possibility (also rings) and concludes there is … e the effect for stellar-mass lenses..
- … s new galaxy mass estimates (~4×11 M☉) concluded:
  - … can split images to large observable angles
  - … to estimate galaxy masses
  - … ead to access distant faint galaxies!
- … (1964): time delay from variability of multiple sources can be used to measure H_0 (if an accurate mass model is available..)
- Walsh et al. (1979) discover lensed QSO0957+561 (6” apart)



Brief historical perspective

- Hypo … d
  Lapl…
- Eins…
  a fac…
- Eddi… nb
- Chw… s") of
  stars
- Eins… ere is
  little

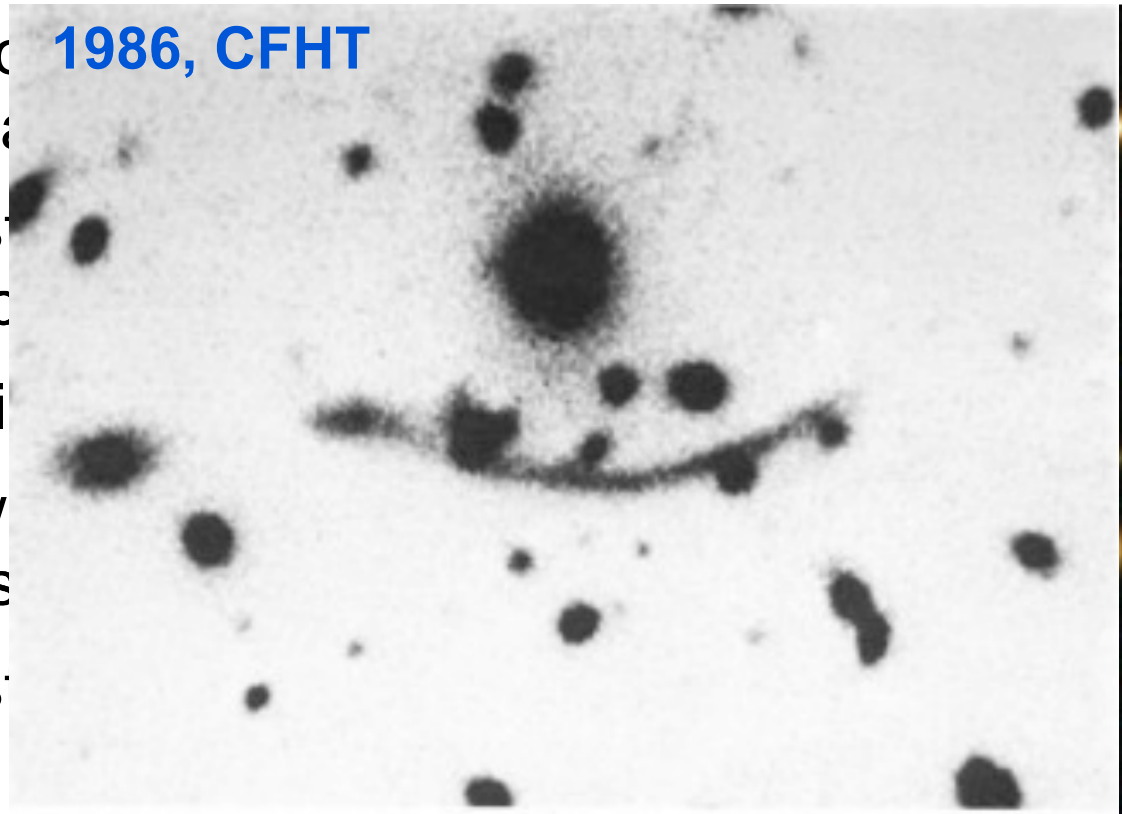
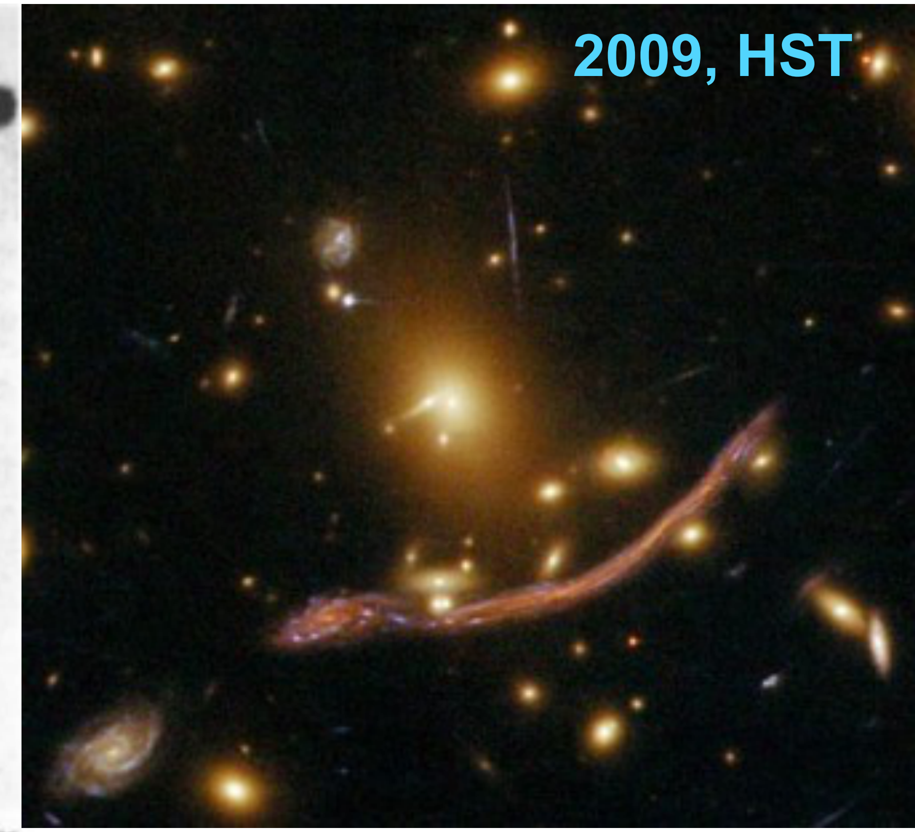


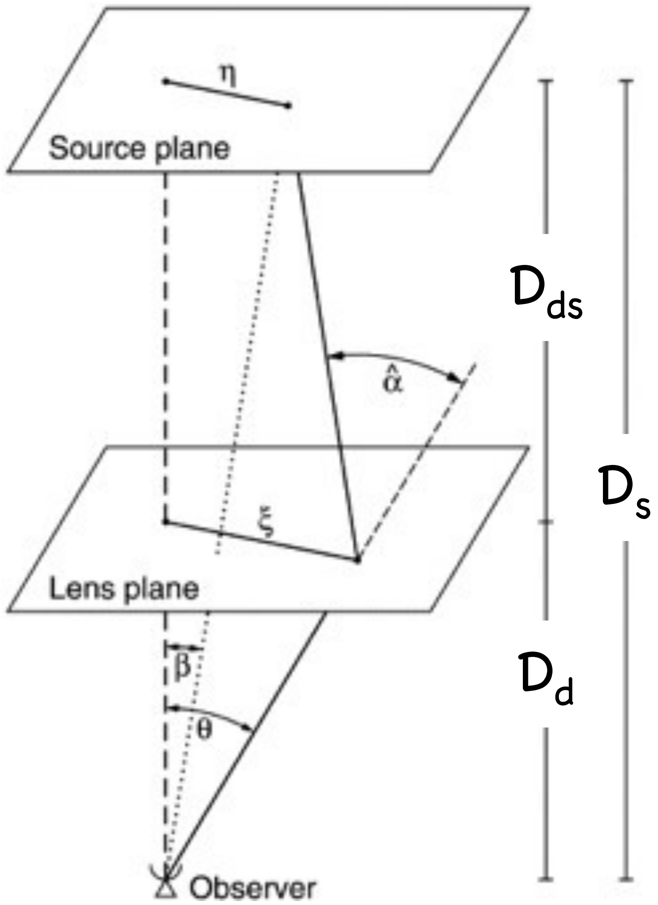
Figure 2: The giant luminous arc in Abell 370. CFHT, 0.″2/pixel, 10 min., seeing 0.″7, November 25, 1986.



$$\alpha = \frac{2GM}{c^2}\frac{1}{r}$$

- Zwic… stimates (~4×11 $M_\odot$) concluded:
  - lensing by galaxies can split images to large observable angles
  - this could be used to estimate galaxy masses
  - magnification can lead to access distant faint galaxies!
- Refsdal (1964): time delay from variability of multiple sources can be used to measure H_0 (if an accurate mass model is available..)
- Walsh et al. (1979) discover lensed QSO0957+561 (6" apart)
- First giant arcs discovered (Soucail et al. 87). Paczynski (87): right interpretation

Lensing basics



- A lens is fully characterized by its surface mass density Σ(θ), or K(θ)= Σ(θ)/Σ_{cr} (*convergence*), $$\Sigma_{cr} = \frac{c^2 D_s}{4\pi G D_d D_{ds}}$$

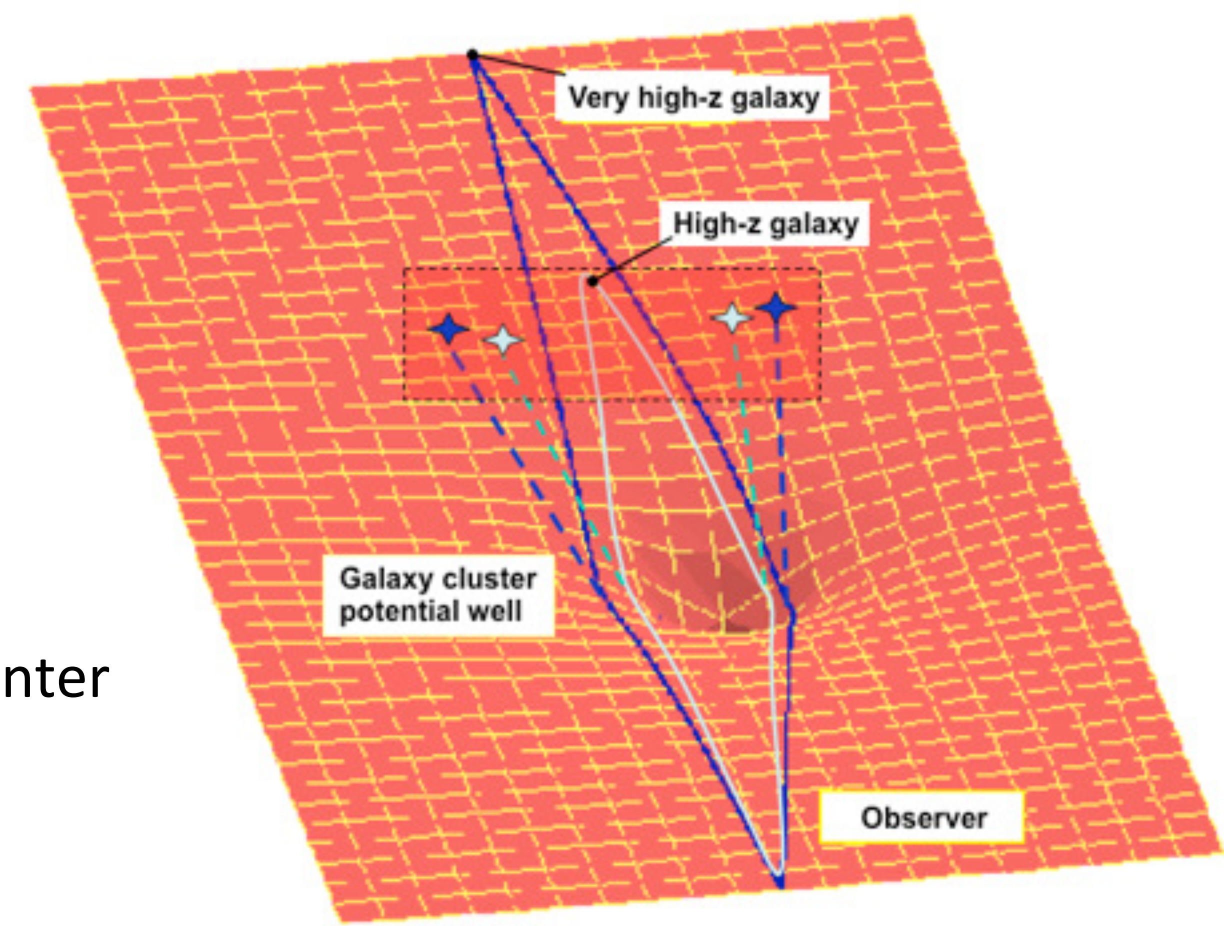
Lensing equation

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}\psi = \frac{1}{\pi}\int \kappa(\vec{\theta}')\frac{\vec{\theta}-\vec{\theta}'}{|\vec{\theta}-\vec{\theta}'|^2}d^2\theta'$$ deflection field

Einstein radius ➔ scale of lensing/multiple images

- For circularly symmetric (supercritical) lens with a mass profile M(θ), an on-axis (β=0) source is imaged as ring with radius θ_E

$$\theta_E = \left[\frac{4GM(\theta_E)}{c^2}\frac{D_{ds}}{D_d D_s}\right]^{1/2}$$

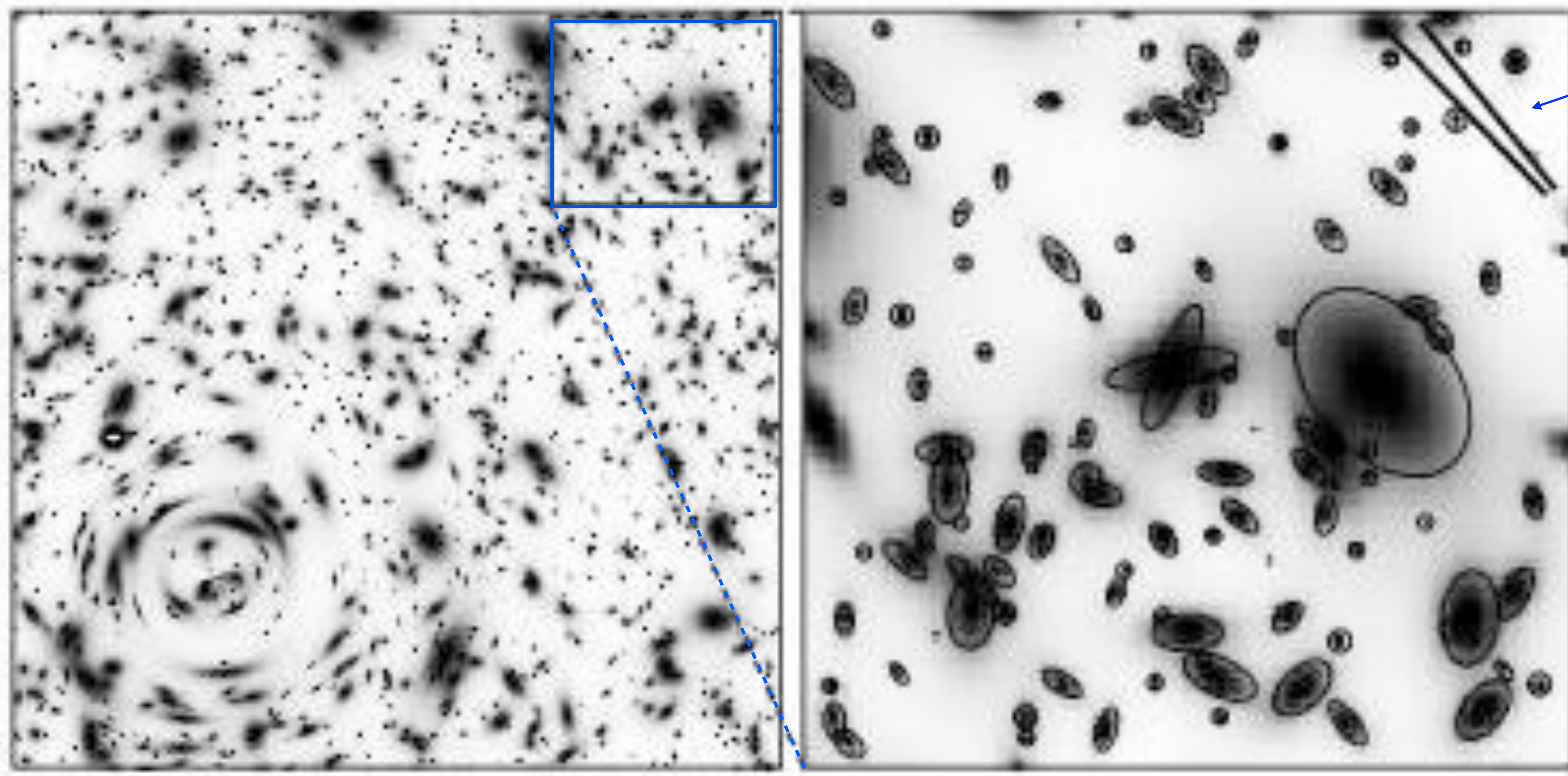


Lensing mapping involves:

- Universal geometry (Ω_M, Ω_Λ)
- Lens geometry (z_L, z_S)
- Cluster mass distribution

- More distant galaxy is imaged further from cluster center
- Geometric lensing deflections can further constraint source redshift

Strong and Weak lensing from a cluster with projected surface mass density K(θ)



Mellier 2001

Avg orientation of gals yields the "shear"

$$K(\theta) = \Sigma(\theta)/\Sigma_{cr}$$

$$\Sigma_{cr} = \frac{c^2 D_s}{4\pi G D_d D_{ds}}$$

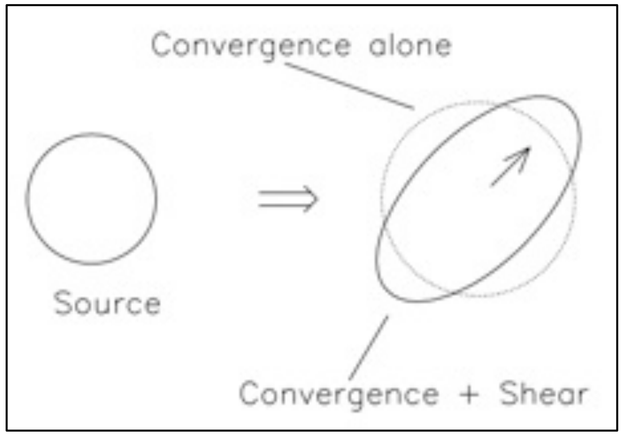
Strong lensing regime: $K(\theta) \gtrsim 1$

Giant arcs, multiple images.
Parametric and non-parametric techniques to invert the lensing equation, i.e. determine the deflection field.
Resolution of resulting $\Sigma(\theta)$:

Weak lensing regime: $K(\theta) << 1$

From the statistical distortion of background galaxy shapes (averaged ellipticities) ➔ PSF corrected reduced shear ➔ $K(\theta)$
➔ if the redshift distribution of the background galaxies is know the mass distribution $\Sigma(\theta)$ can be inverted up to a constant

Convergence and Shear



convergence magnifies the image isotropically, the *shear* deforms it to an ellipse (anisotropic part of the lens mapping)

Jacobian matrix $\mathcal{A}$ of the lens mapping $\vec{\beta} = \vec{\theta} - \vec{\alpha}(\vec{\theta})$

$$\mathcal{A} \equiv \frac{\partial \vec{\beta}}{\partial \vec{\theta}} = \left(\delta_{ij} - \frac{\partial \alpha_i(\vec{\theta})}{\partial \theta_j}\right) = \left(\delta_{ij} - \frac{\partial^2 \psi(\vec{\theta})}{\partial \theta_i \partial \theta_j}\right)$$

$$\gamma = (\gamma_1^2 + \gamma_2^2)^{1/2}$$ magnitude of the shear

$$\kappa = \frac{1}{2}(\psi_{11} + \psi_{22})$$ *convergence* isotropic term

Under the transformation **β**=$\mathcal{A}$ **ϑ**, a circular object gains an ellipticity *(a-b)/(a+b)* of:

$g = \gamma/(1-\kappa)$ (*reduced shear*), with *magnification*:

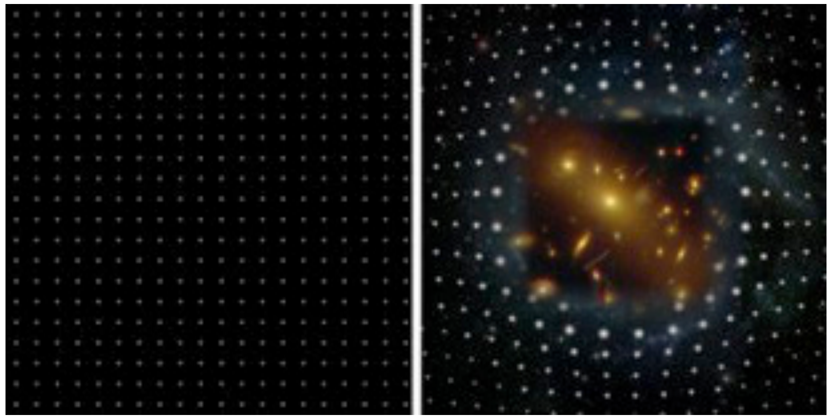
surface brightness is conserved, both galaxy fluxes and sizes are amplified

det $\mathcal{A}$(**ϑ**) = 0 ➔ *critical curves*

Mass-sheet degeneracy:

Any reconstruction method is insensitive to isotropic expansions of images
➔ the measured ellipticities are invariant under $\mathcal{A}$ ➔ $\lambda \mathcal{A}$

which leaves the reduced shear *g* invariant under the transformation: $(\kappa \rightarrow 1 - \lambda + \lambda\kappa)$

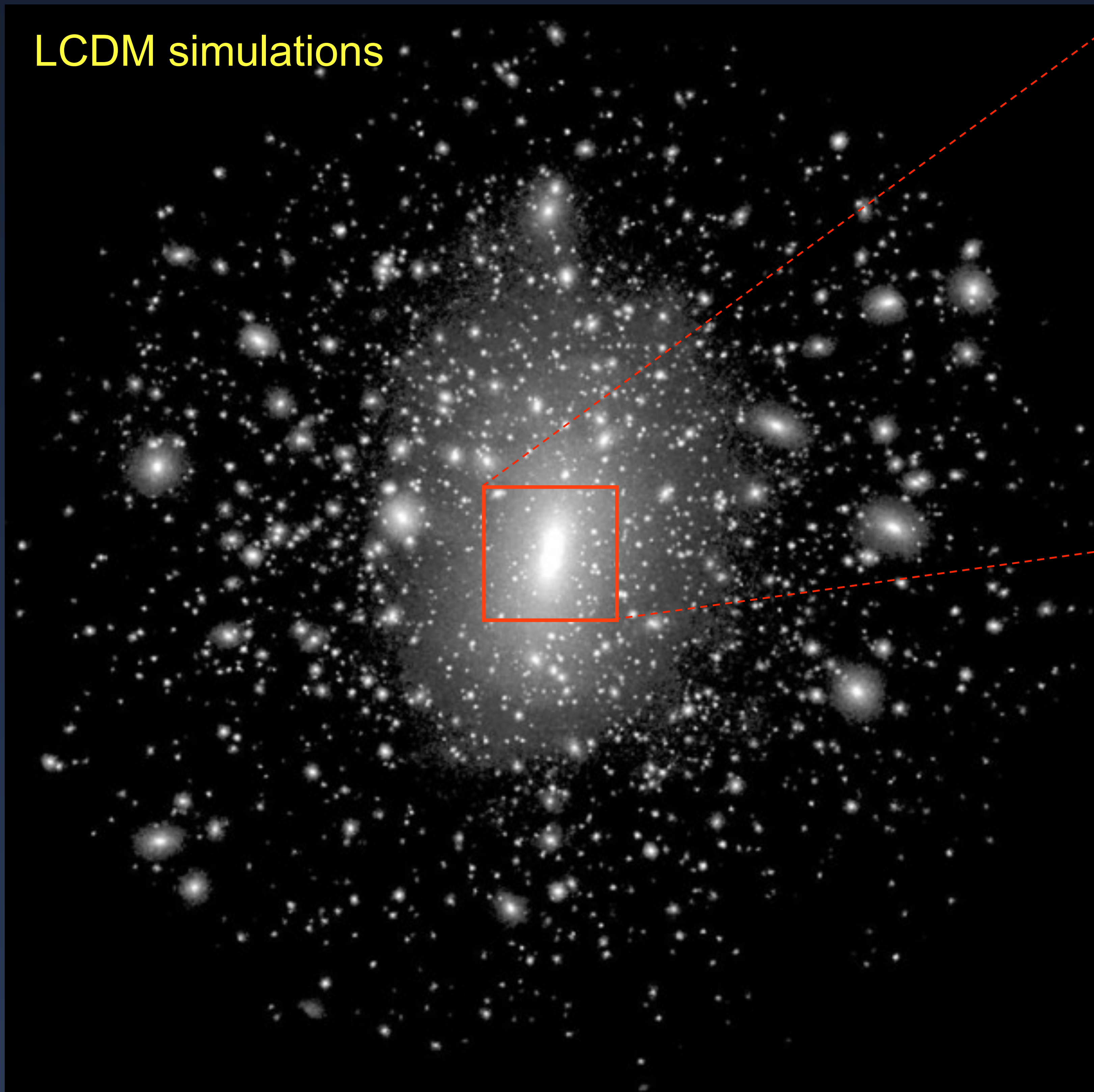


- can be removed by measuring independently the magnification, since "*magnification bias*", or *number counts depletion* : $\mu \propto \lambda^{-2}$

$$N'(m) = N_0(m)\, \mu^{2.5\,s-1} \qquad s = \frac{d\log N(m)}{dm}$$

(Broadhurst et al. 95)

Strong lensing can resolve dark matter halos !

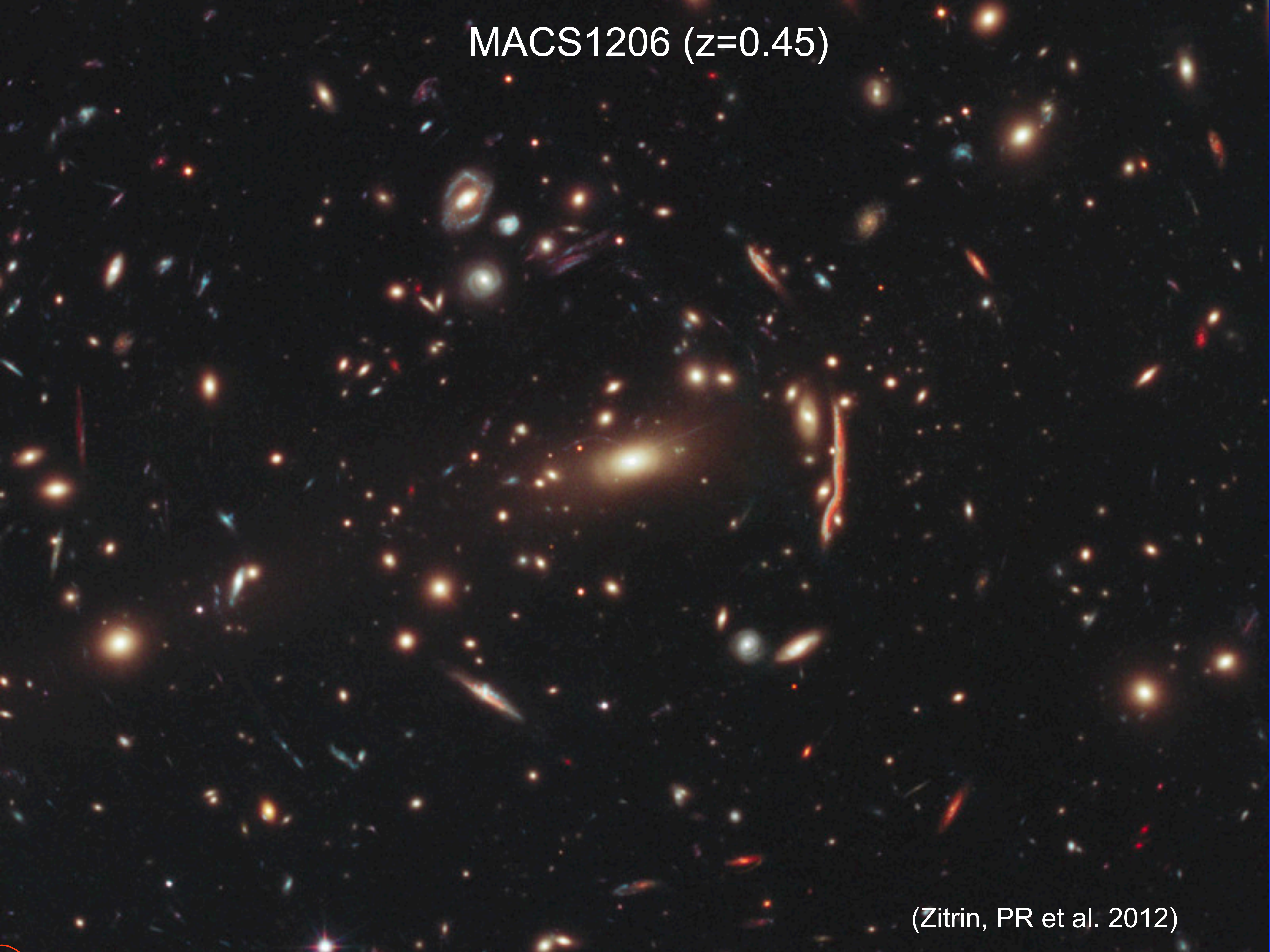


Dark matter density distribution from a high resolution simulation of a massive cluster to the virial radius (Diemand et al. 2005)

Deep HST image of massive cluster

Reconstructed total mass with resolution $R \propto \frac{\theta_{\mathrm{Einstein}}}{\sqrt{N_{\mathrm{Arcs}}}}$

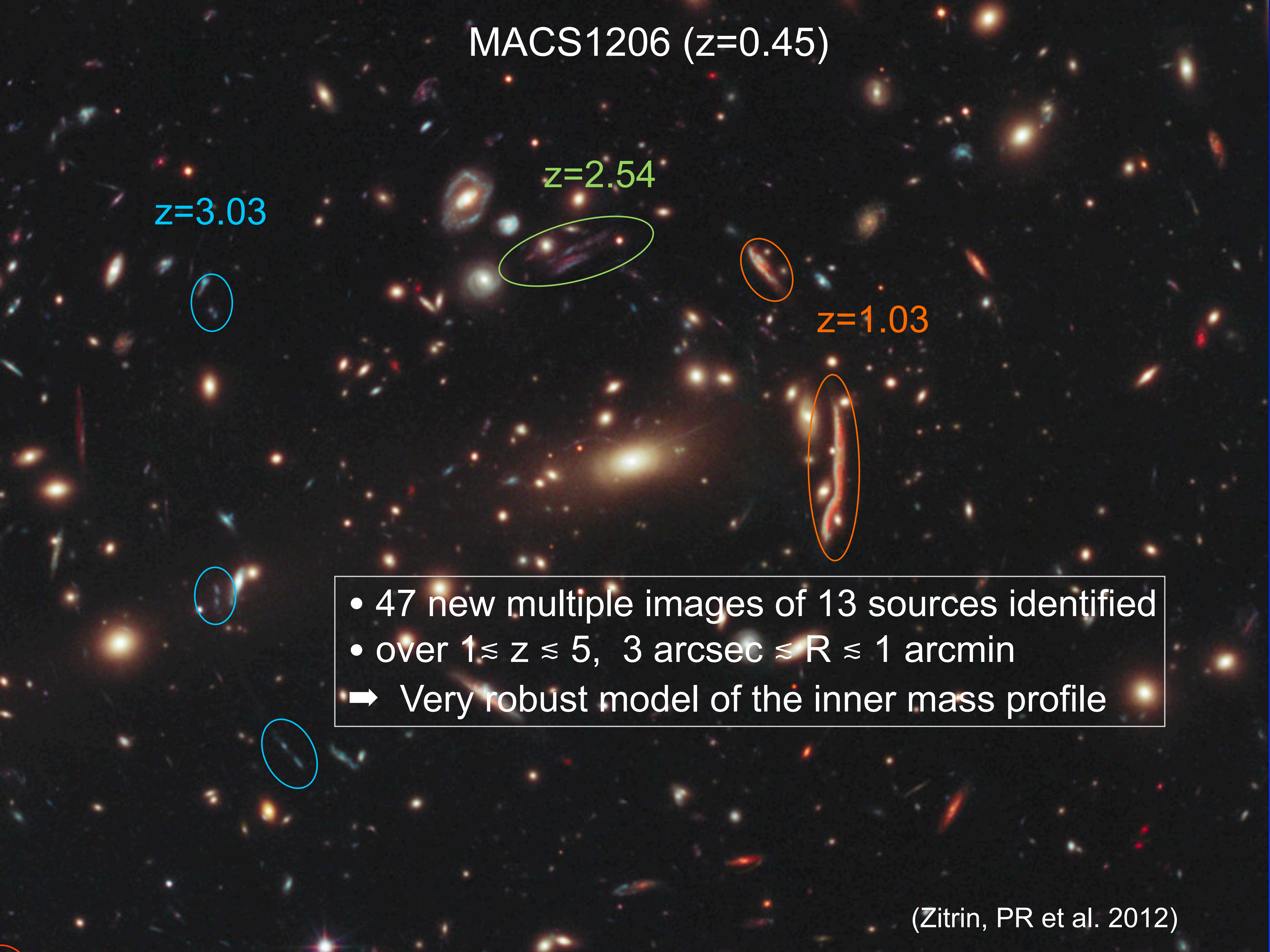
MACS1206 (z=0.45)



(Zitrin, PR et al. 2012)

(Zitrin, PR et al. 2012)

MACS1206 (z=0.45)

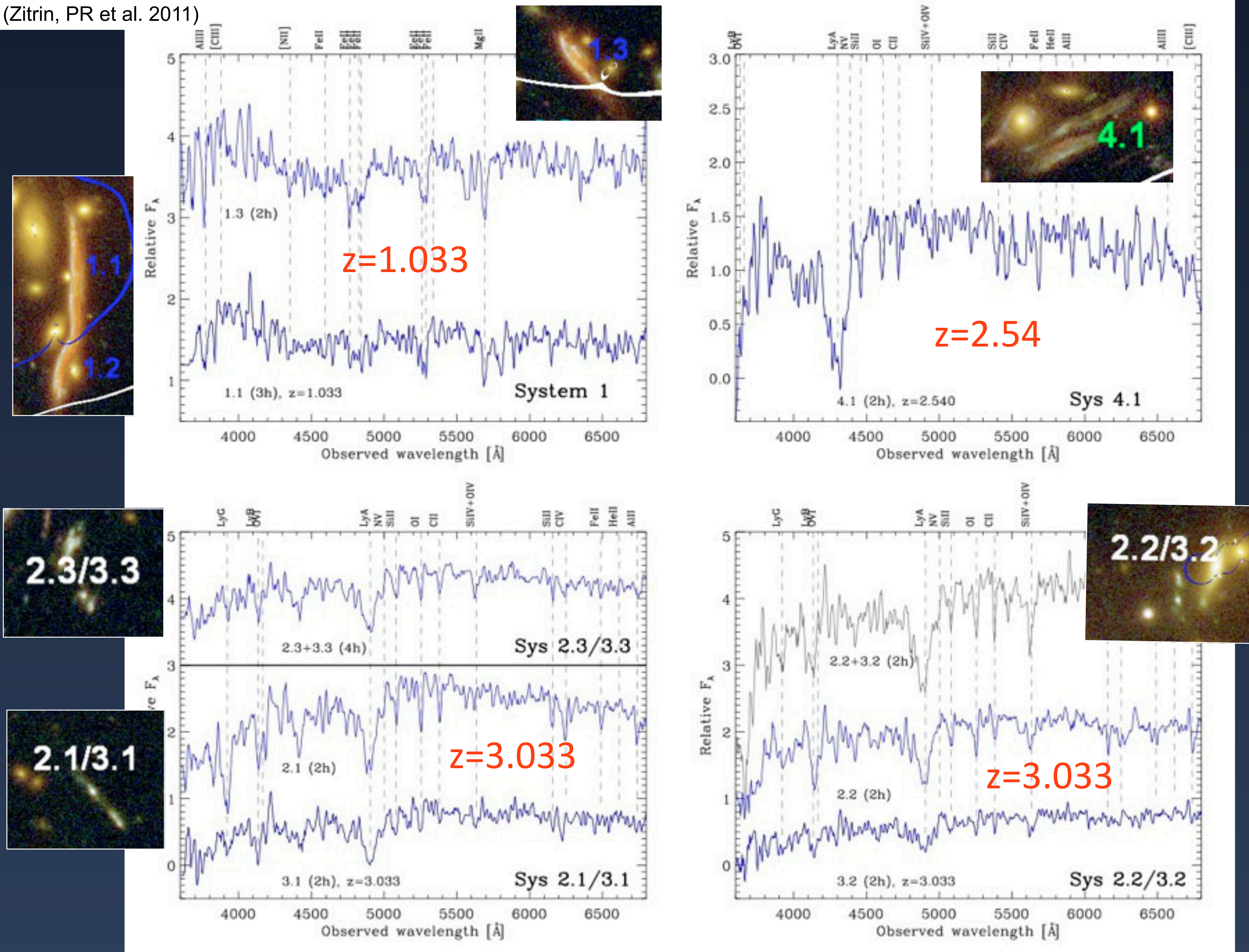


- 47 new multiple images of 13 sources identified
- over 1≲ z ≲ 5, 3 arcsec ≲ R ≲ 1 arcmin

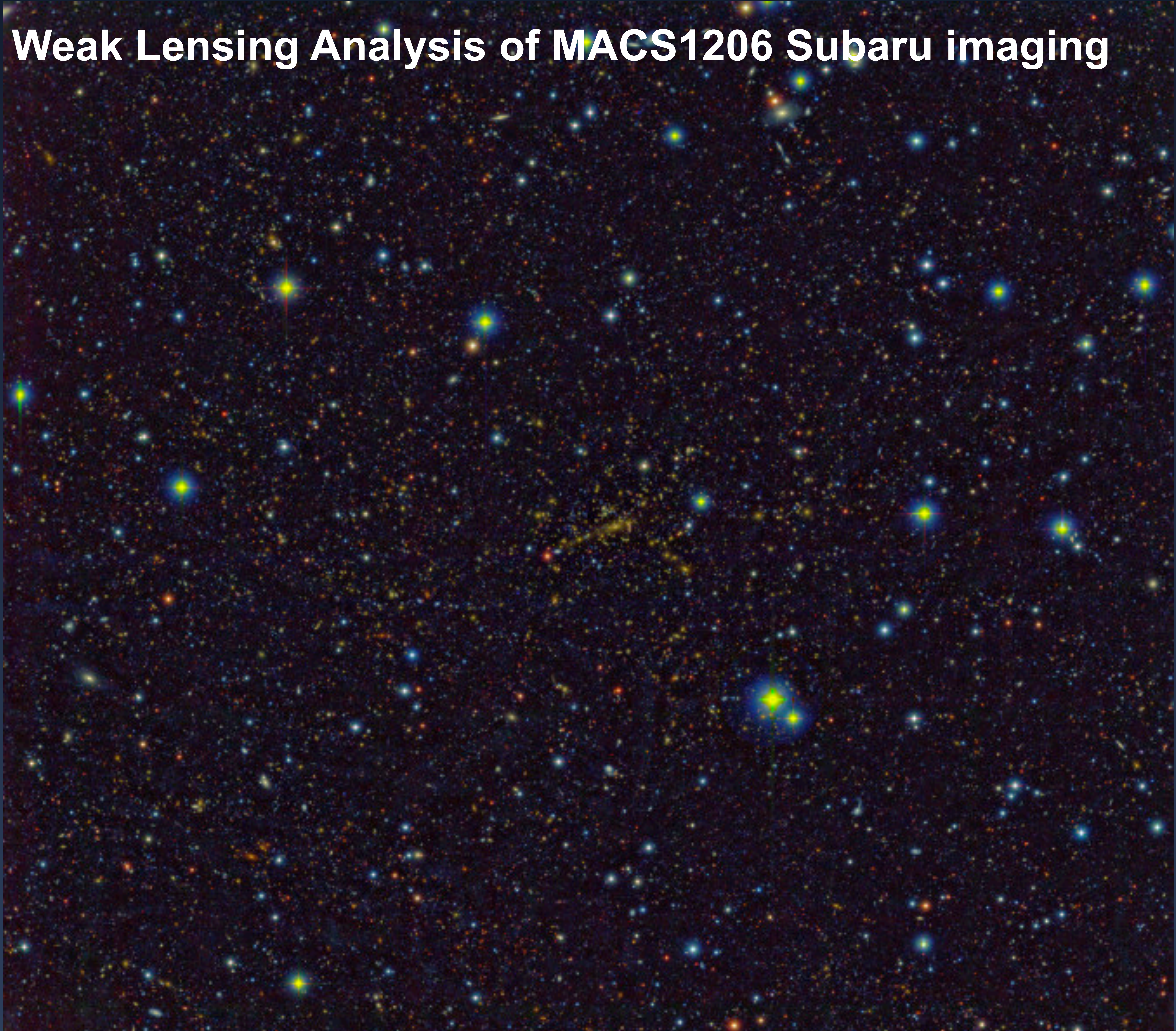
➡ Very robust model of the inner mass profile

(Zitrin, PR et al. 2012)

(Zitrin, PR et al. 2011)

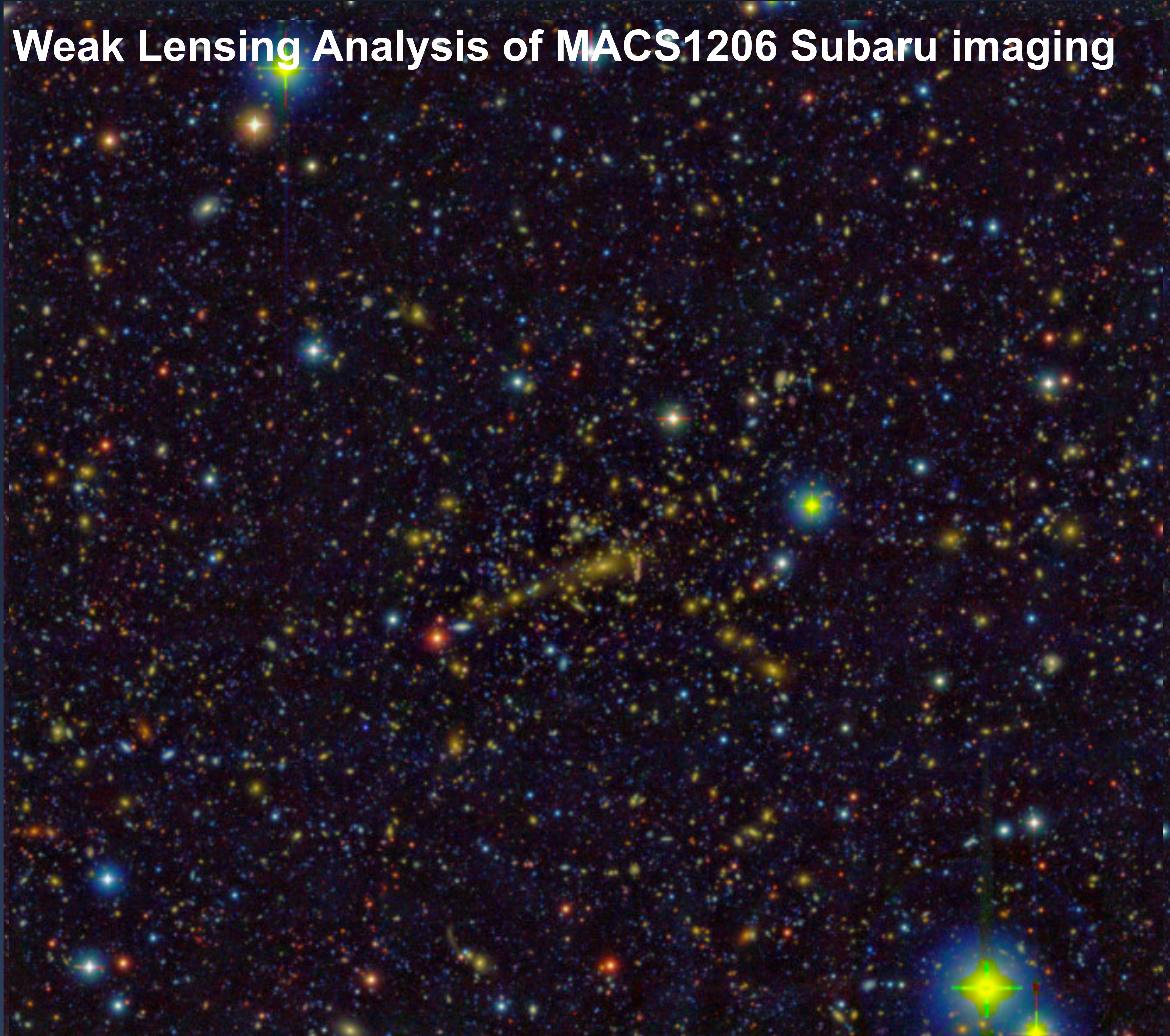


Weak Lensing Analysis of MACS1206 Subaru imaging



BVRIZ

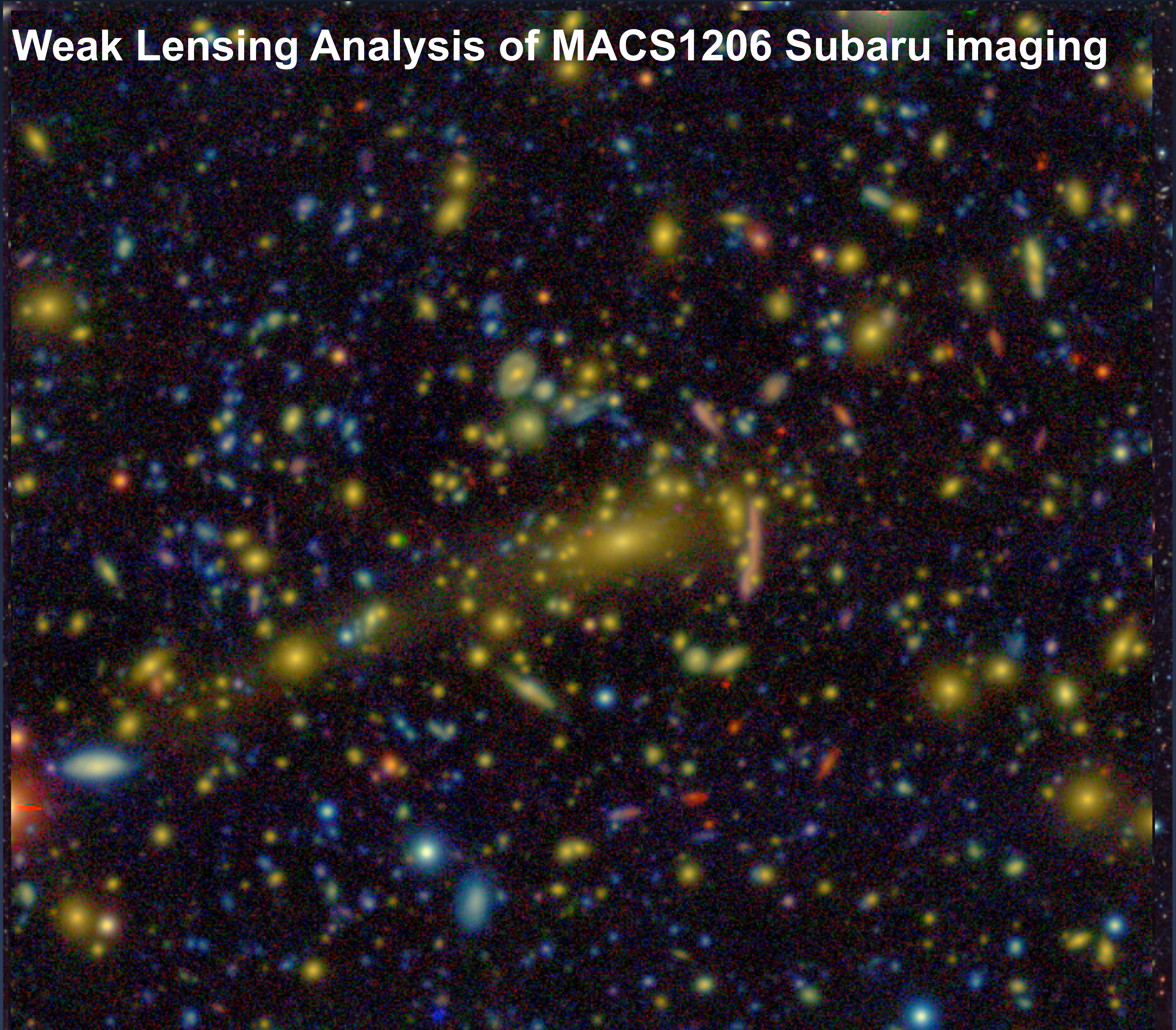
Weak Lensing Analysis of MACS1206 Subaru imaging



BVRIZ

Weak Lensing Analysis of MACS1206 Subaru imaging

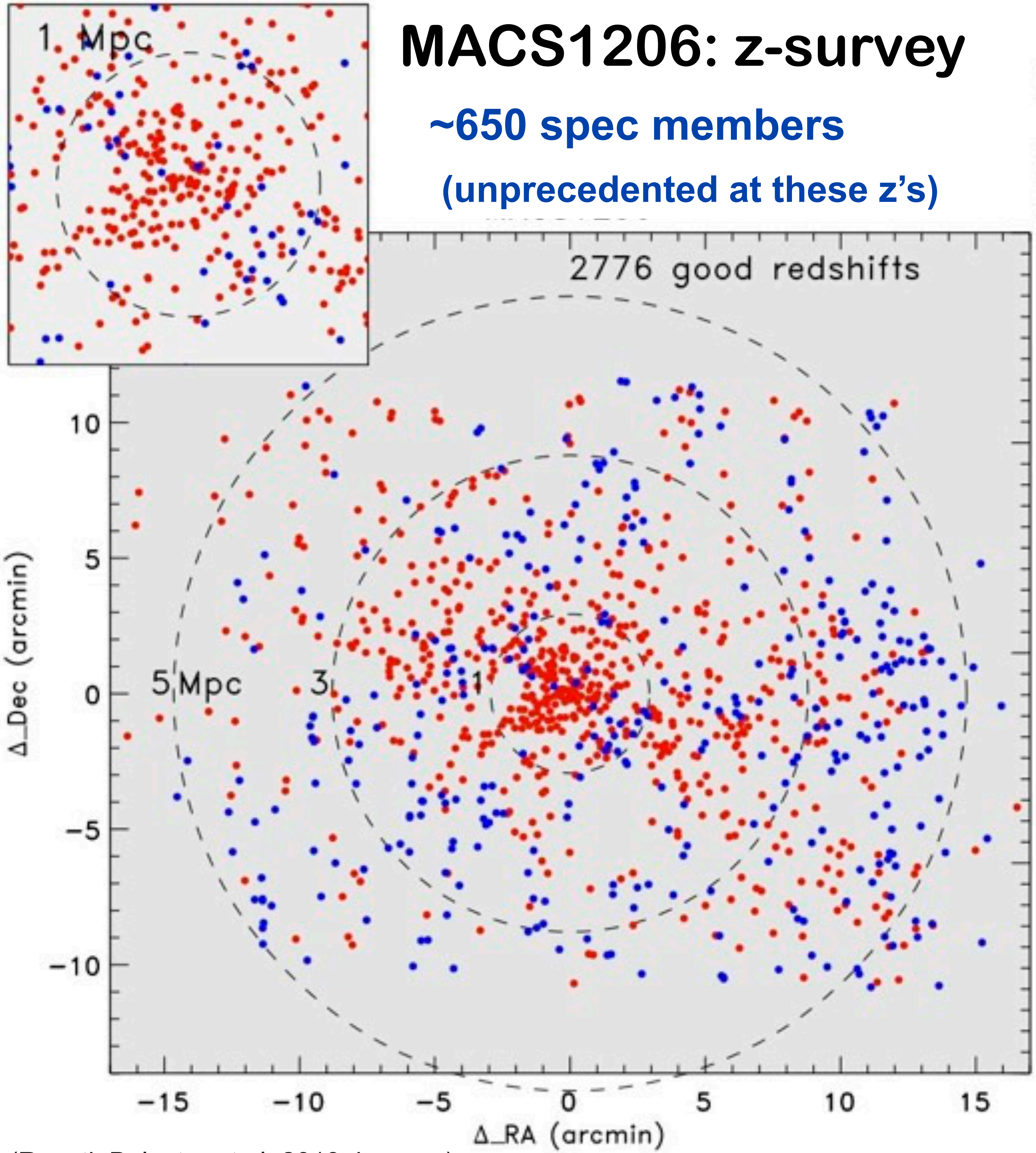
BVRIZ



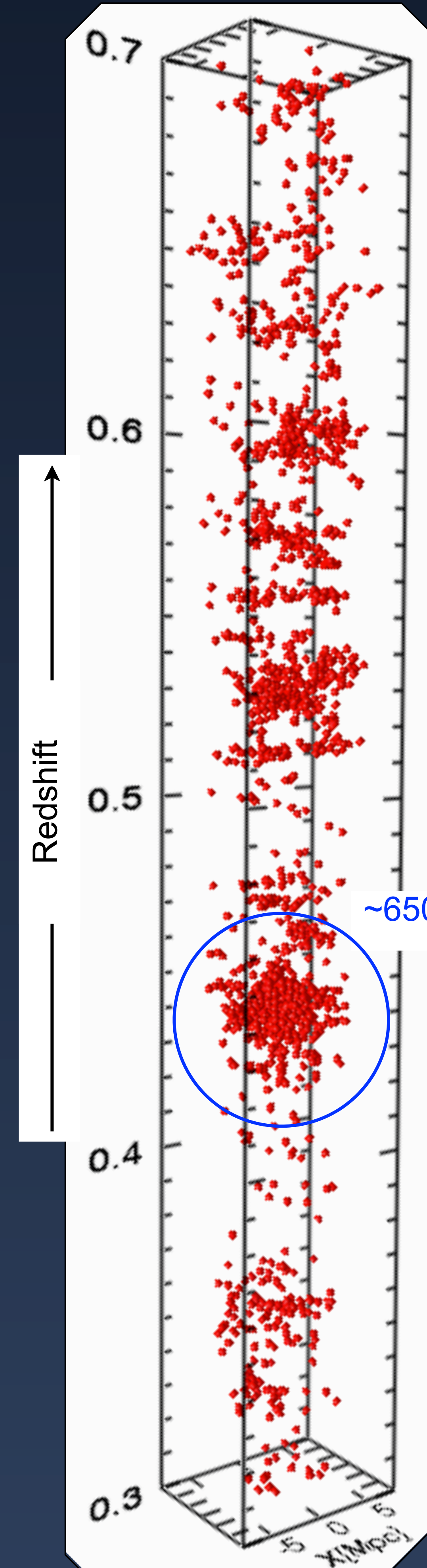
MACS1206: z-survey

~650 spec members

(unprecedented at these z's)



(Rosati, Balestra et al. 2013, in prep.)



Mass profile from dynamical and X-ray analyses

Jeans equation

density profile   radial vel.dispersion profile   anisotropy profile

$$M_J(<r) = -\frac{r\sigma_r^2}{G}\left[\frac{d\ln\nu(r)}{d\ln r} + \frac{d\ln\sigma_r(r)^2}{d\ln r} + 2\beta(r)\right]$$

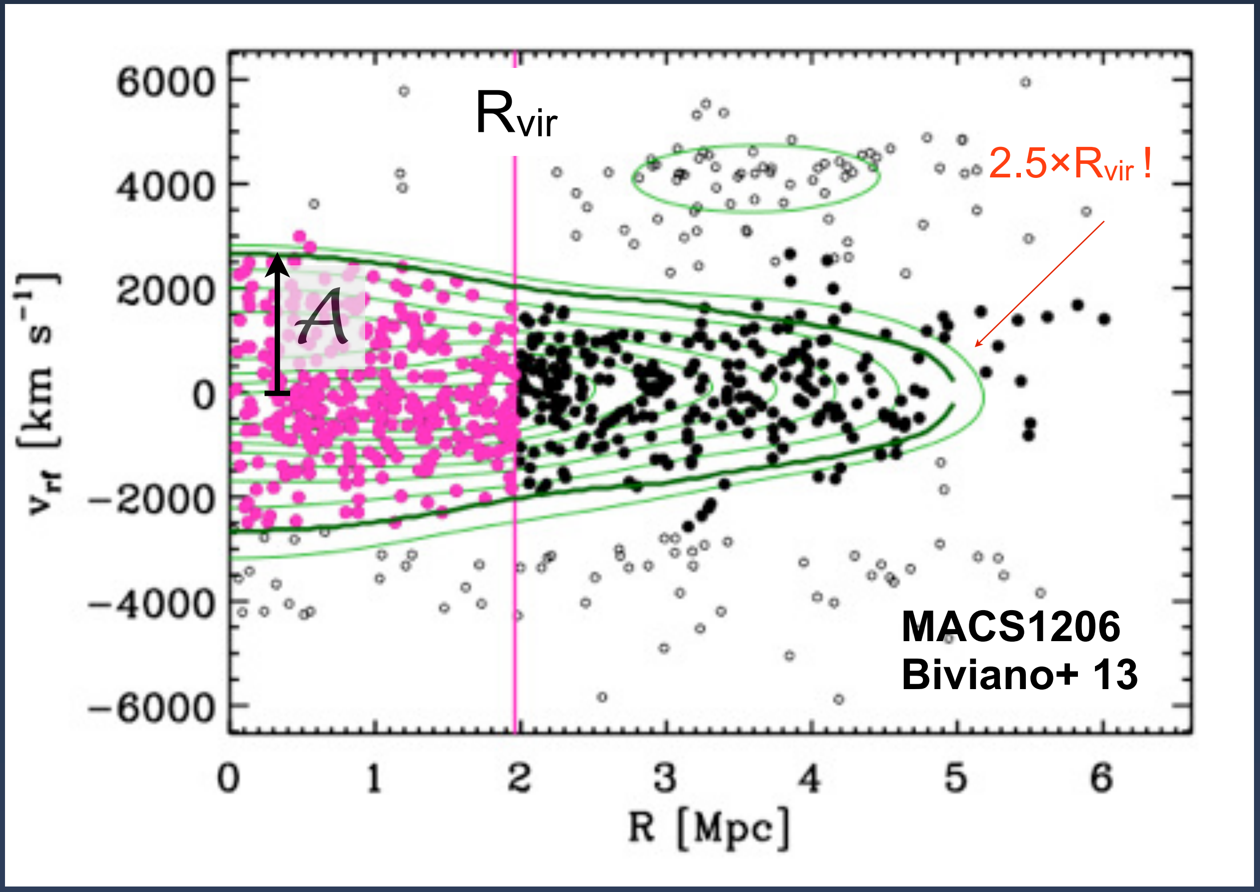
$$\beta = 1 - \frac{\sigma_t^2}{2\sigma_r^2}$$

The observed quantities: N(R) projected density profile and $\sigma_{los}(r)$ l.o.s. vel.dispersion profile need to be deprojected to obtain $\nu(r)$ and $\sigma_r(r)$, with an ansatz on $\beta(r)$.

Hydrostatic equilibrium X-ray gas

Caustic technique

(Diaferio & Geller 2009)



Amplitude of the caustics $\mathcal{A}(R)$ reflects escape velocity
➔ avg component along the l.o.s. of the v_{esc} at r=R

vel. anisotropy param.

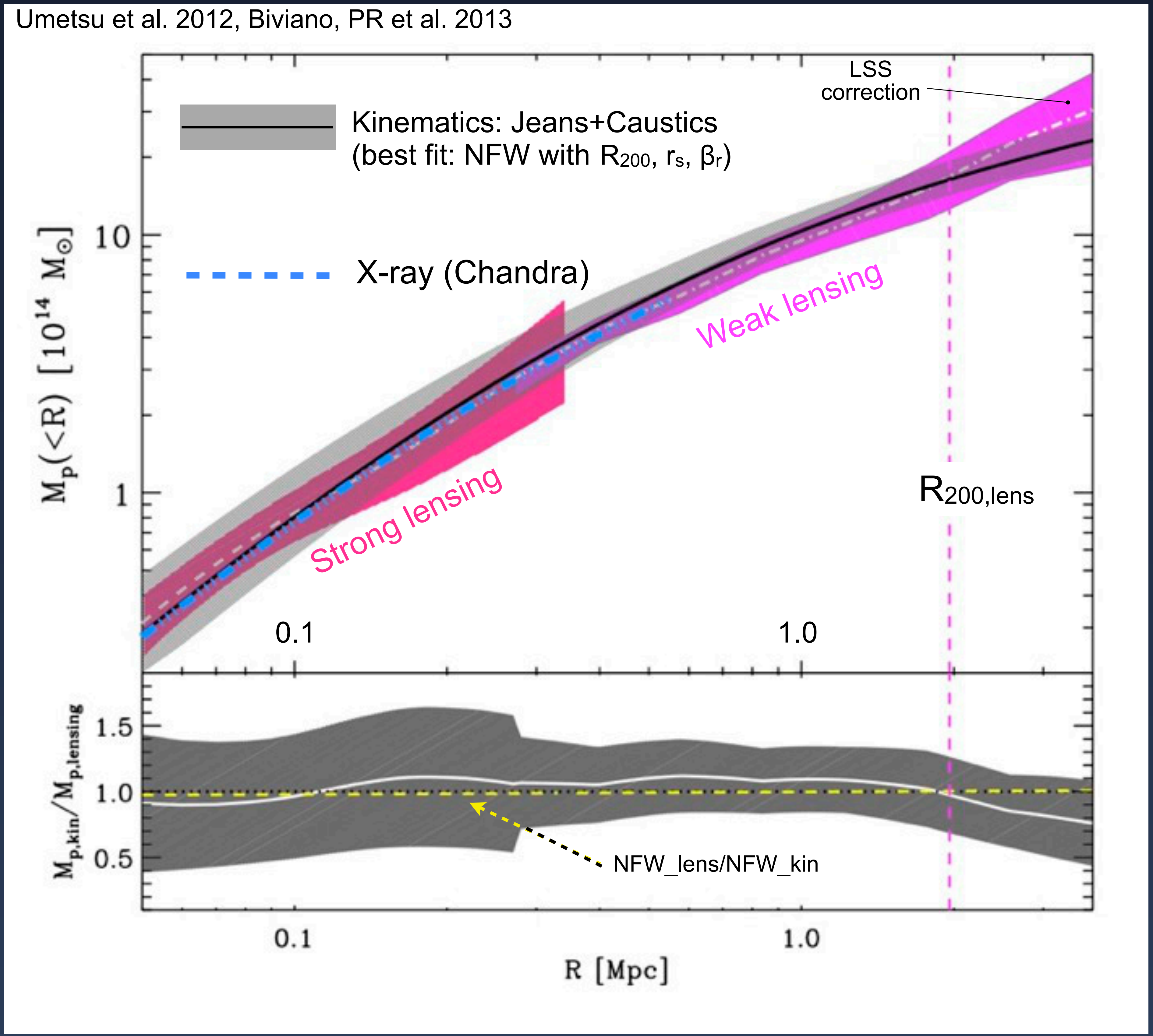
$$v_{esc}^2(r) = -2\phi(r)$$

$$\mathcal{A}^2(r) = \langle v_{esc,los}^2 \rangle \Rightarrow \quad -2\phi(r) = \mathcal{A}^2(r) g(\beta)$$

$$GM(<r) = \int_0^r \mathcal{A}^2(r)\mathcal{F}_\beta(r)\mathrm{d}r \simeq \mathcal{F}_\beta \int_0^r \mathcal{A}^2(r)\mathrm{d}r$$

- Does not require assumption of dynamical equilibrium
- All galaxies even beyond R_{vir} can be used
- M(<R) can be determined at R>R_{vir} in a model indep. way, but systematics due to approximation on $\mathcal{F}_\beta(r)$

Mass profile from Lensing and Dynamics

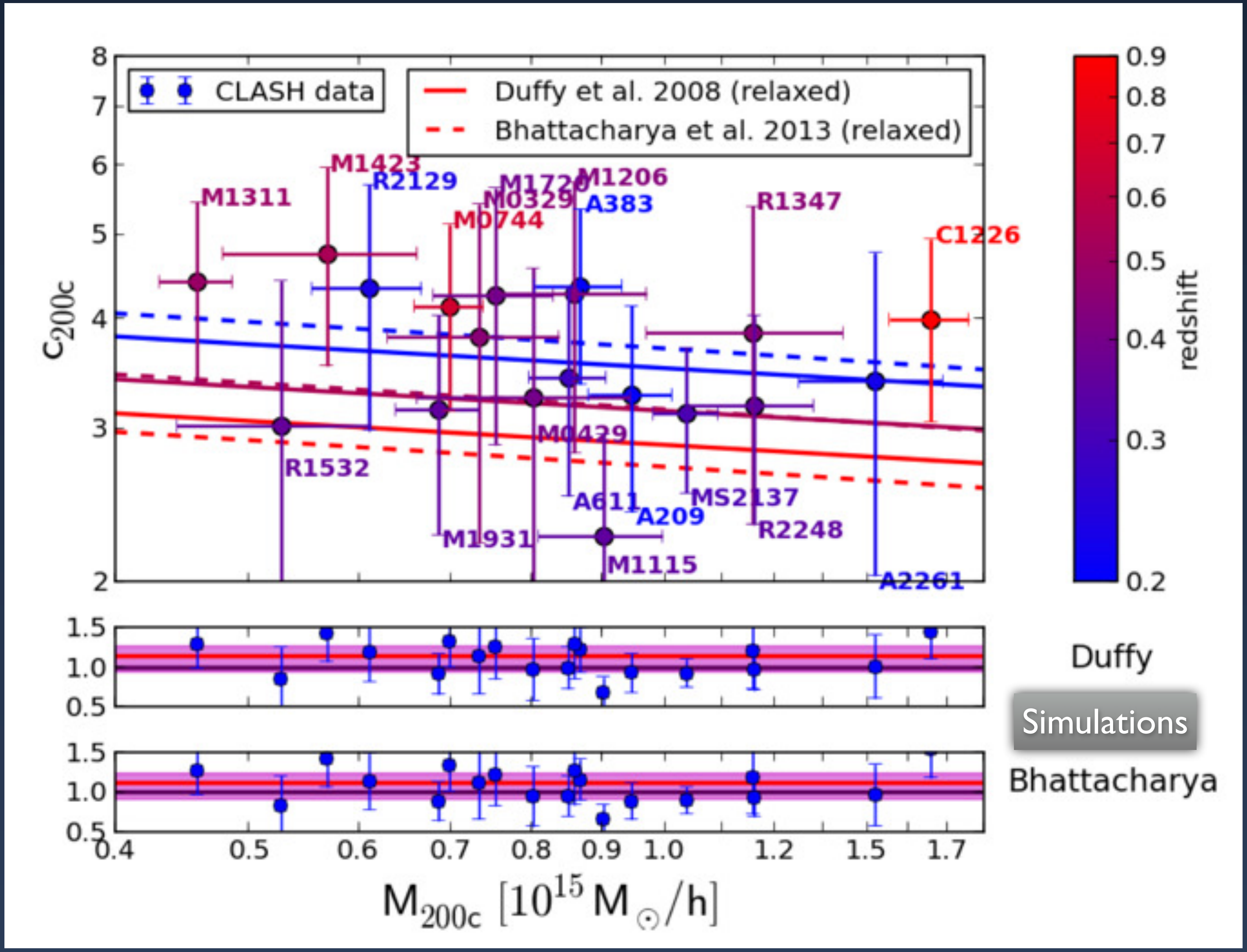


Remarkable agreement among different, independent probes over 2 decades

CLASH Concentration – Total Mass Relationship

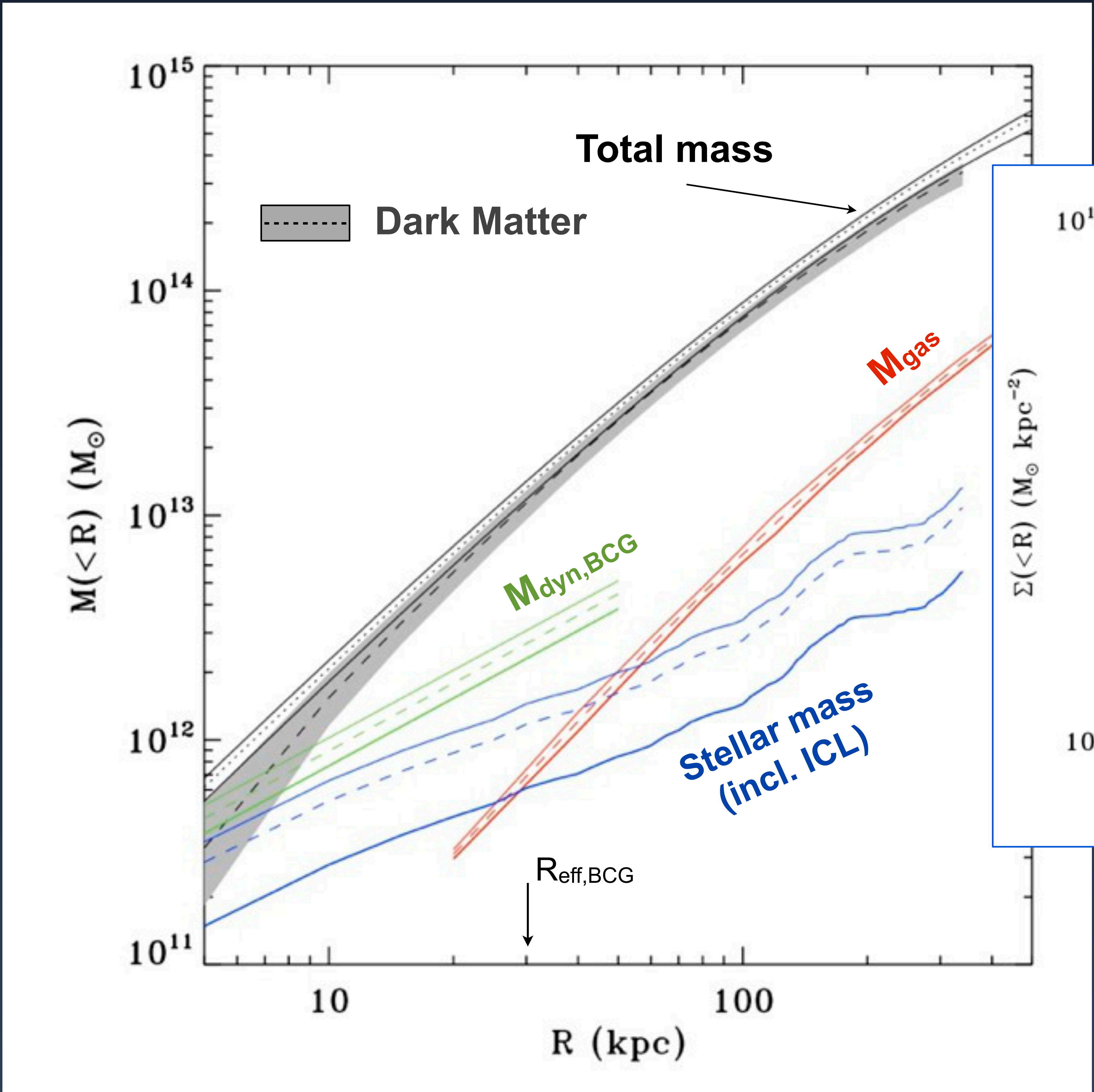
(J.Merten & CLASH team 2014, submitted)

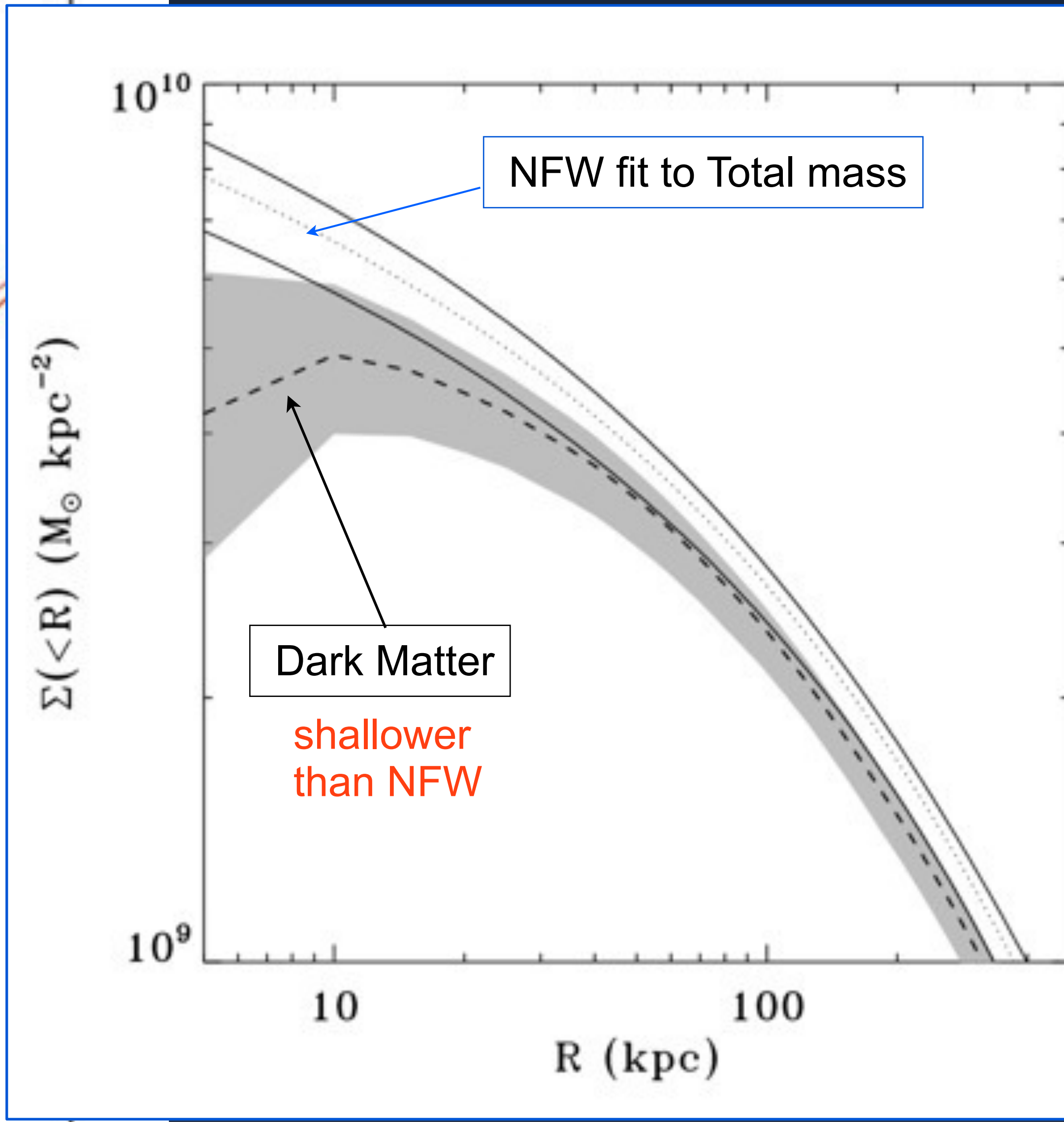
NFW fits of weak & strong lensing profiles from 19 CLASH X-ray selected clusters



➔ No significant tension with predicted c-M relation in ΛCDM

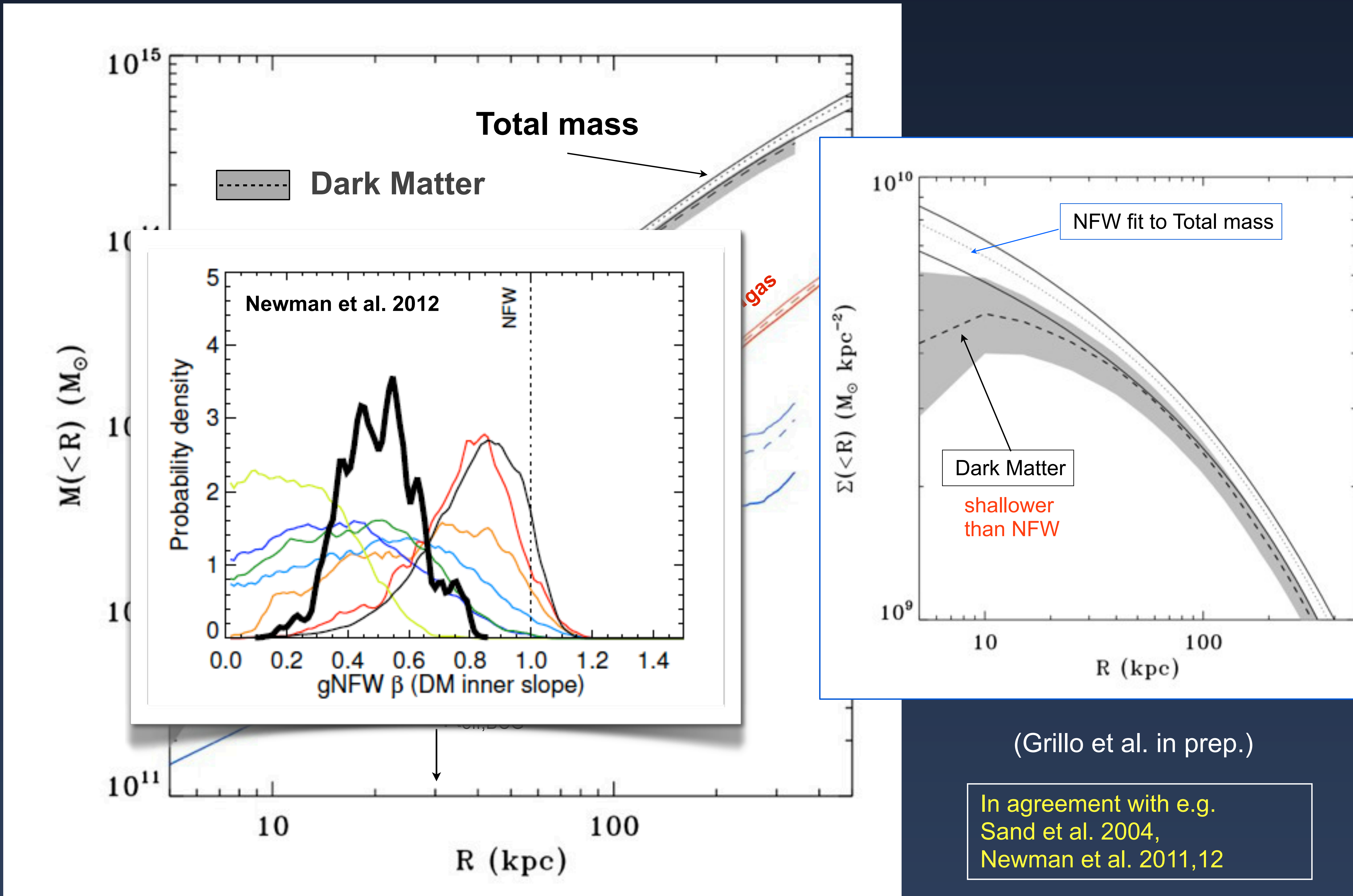
Decomposing baryons and DM in the inner core of MACS1206





(Grillo et al. in prep.)

Decomposing baryons and DM in the inner core of MACS1206



(Grillo et al. in prep.)

In agreement with e.g.
Sand et al. 2004,
Newman et al. 2011,12

Constraining the DM Equation of State

(Sartoris et al., ApJL, 2014)

Testing whether DM is pressureless p=0 (method proposed by Faber&Visser 2006)

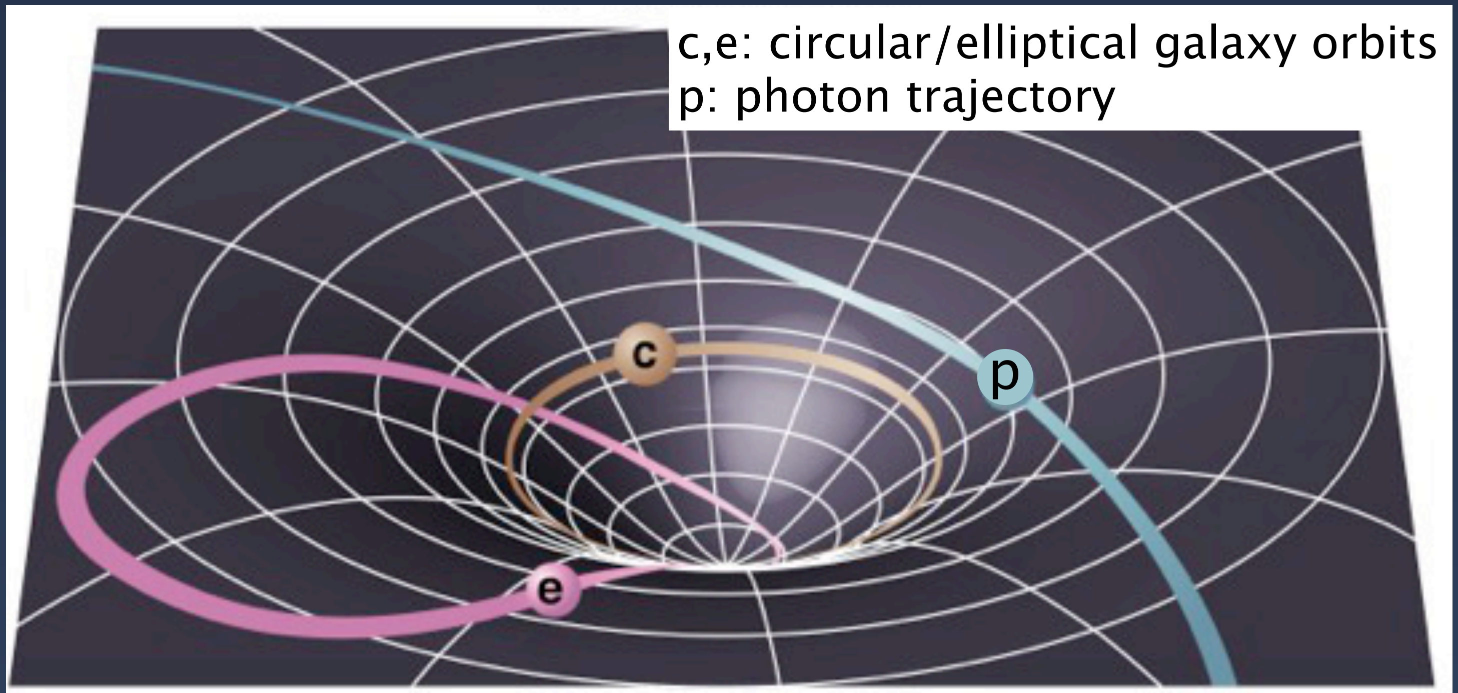
Made possible by our high-quality lensing and kinematic mass profiles for MACS1206, a "well relaxed cluster" with negligible systematics

- In GR, the cluster potential well Φ is shaped by the whole mass-energy content of the clusters: density and pressure separately

$$ds^2 = -e^{2\Phi(r)/c^2}\, c^2 dt^2 + \left(1 - \frac{2Gm(r)}{c^2 r}\right)^{-1} dr^2 + r^2 d\Omega^2$$

Metric of space-time inside a static, spherically symmetric system

- Galaxies are non relativistic, their velocity distribution depends only on Φ(r)
- Light trajectories respond to both Φ(r) and a relativistic term depending on m(r)



Constraining the DM Equation of State

(Sartoris et al., ApJLett, in press)

- EoS *parameter:*

$$w(r) = \frac{p_r(r) + 2\,p_t(r)}{3\,c^2 \rho(r)}$$

- $p_r(r)$, $p_t(r)$: radial and tangential pressure profiles fnct of m(r), Φ(r) and their derivatives
- ρ(r) is the density profile which depends on m(r): *ρ(r)* = (1/4π) *m'(r)/r²*
- m(r), Φ(r) can be determined from independent determinations of $m_{kin}(r)$ and $m_{lens}(r)$

$$\nabla^2 \Phi = \frac{4\pi G}{c^2}\left(c^2 \rho + p_r + 2 p_t\right)$$

$$m_k(r) = \frac{r^2}{G} \nabla \Phi(r)\,.$$

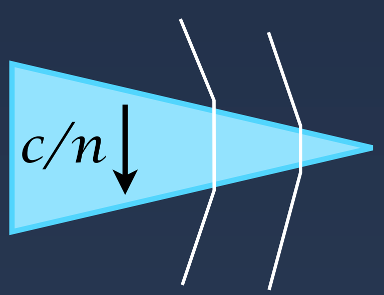
in weak field approx

$$(2\Phi \ll c^2 \text{ and } 2mG/r \ll c^2)$$

Effective refraction index for lensing

with:

$$2\Phi_l(r) = \Phi(r) + G \int \frac{m(r)}{r^2} dr\,.$$



→

$$m_l(r) = \frac{r^2}{G}\Phi_l'(r) = \frac{r^2}{2G}\Phi'(r) + \frac{m(r)}{2} = \frac{m_k(r)}{2} + \frac{m(r)}{2}$$

Constraining the DM Equation of State

(Sartoris et al., ApJLett, in press)

- EoS *parameter:*

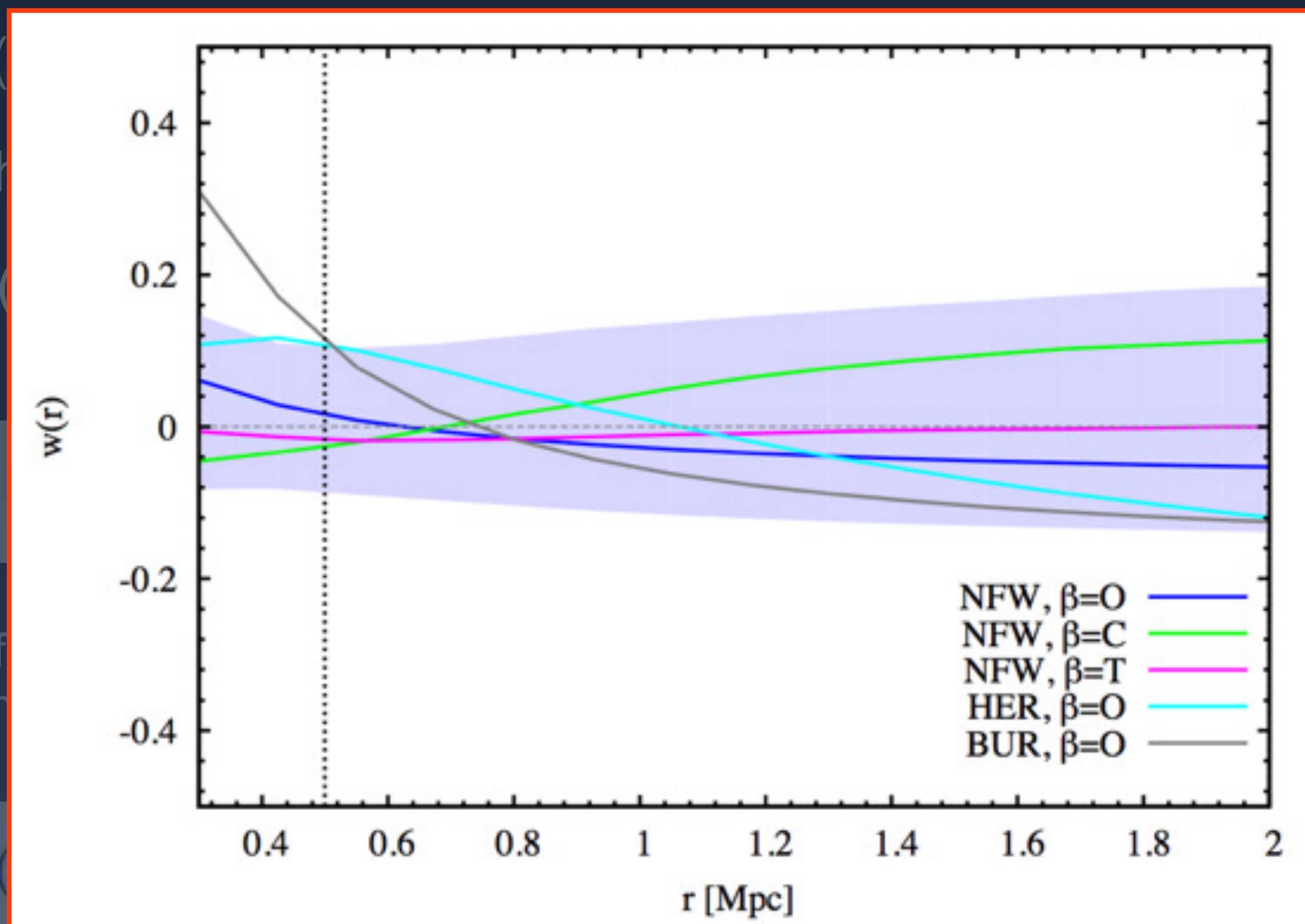
$$w(r) = \frac{p_r(r) + 2\,p_t(r)}{3\,c^2\rho(r)}$$

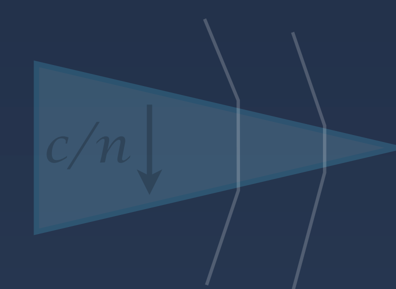
- $p_r(r)$, $p_t($ … , $\Phi(r)$ and their derivatives
- $\rho(r)$ is th …) *$m'(r)/r^2$*
- $m(r)$, $\Phi($ … ions of $m_{kin}(r)$ and $m_{lens}(r)$

$\nabla^2\Phi =$ … in weak field approx $(2\Phi \ll c^2$ and $2mG/r \ll c^2)$

Effective ref … index for len …

→ $m_l($ …



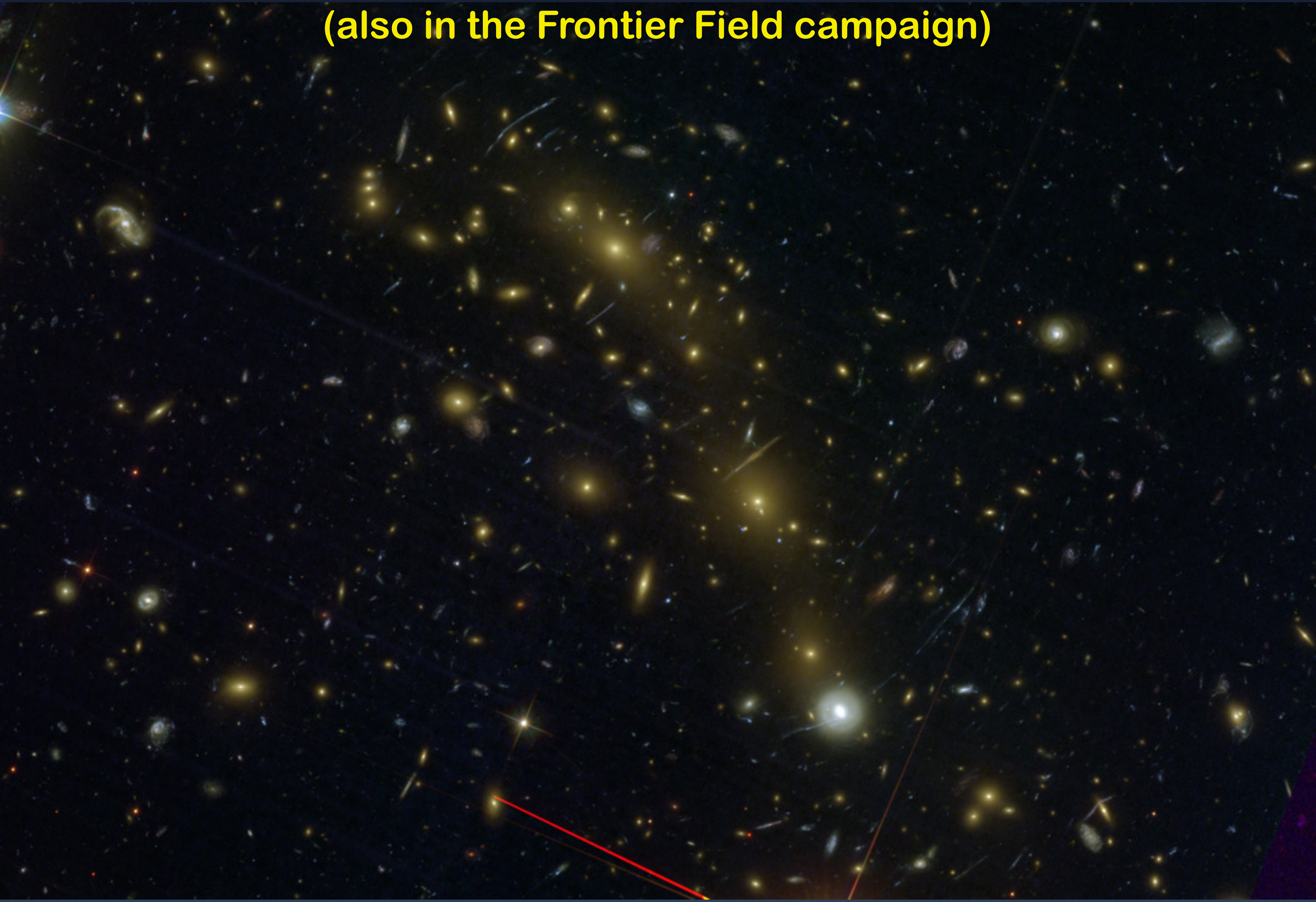


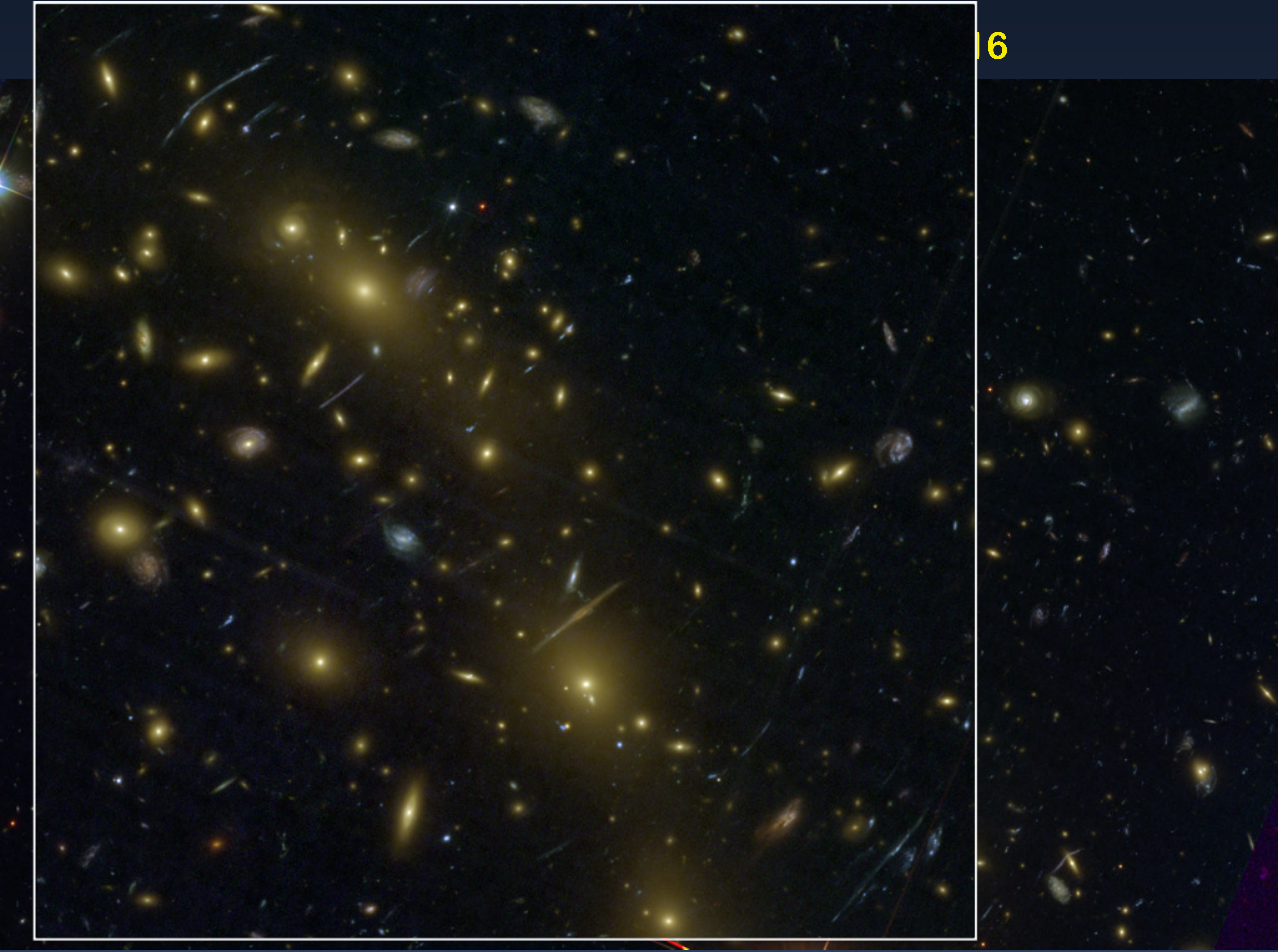
➔ For the cluster fluid, essentially DM (averaging over 0.5 Mpc−R_{vir} ≃ 2 Mpc), we find:

- Systematics will be better understood (and reduced?) when extended to 12 CLASH-VLT clusters

Detailed DM halo structure of MACS0416

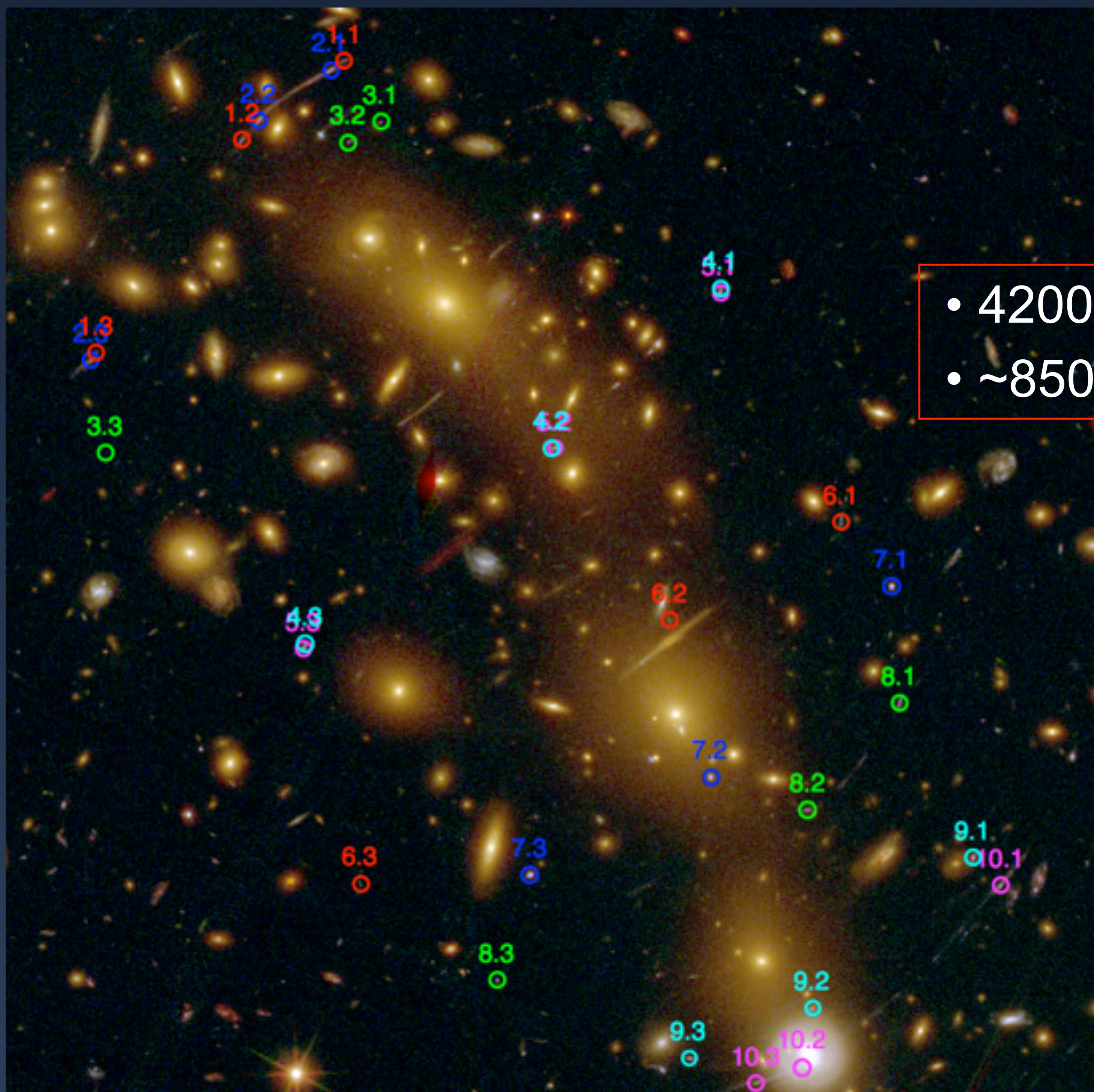
(also in the Frontier Field campaign)



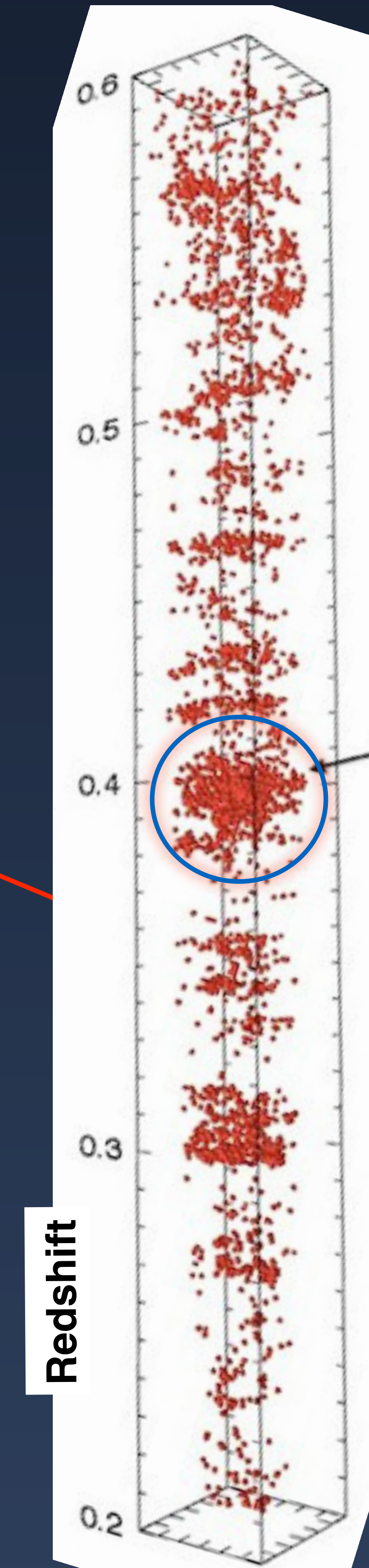


CLASH-VLT spectroscopic campaign of MACS0416

- gives 3D distribution in the cluster field
- secures the redshifts and identifies 13 multiple systems (39 multiple images with 1.6<z<3.2)

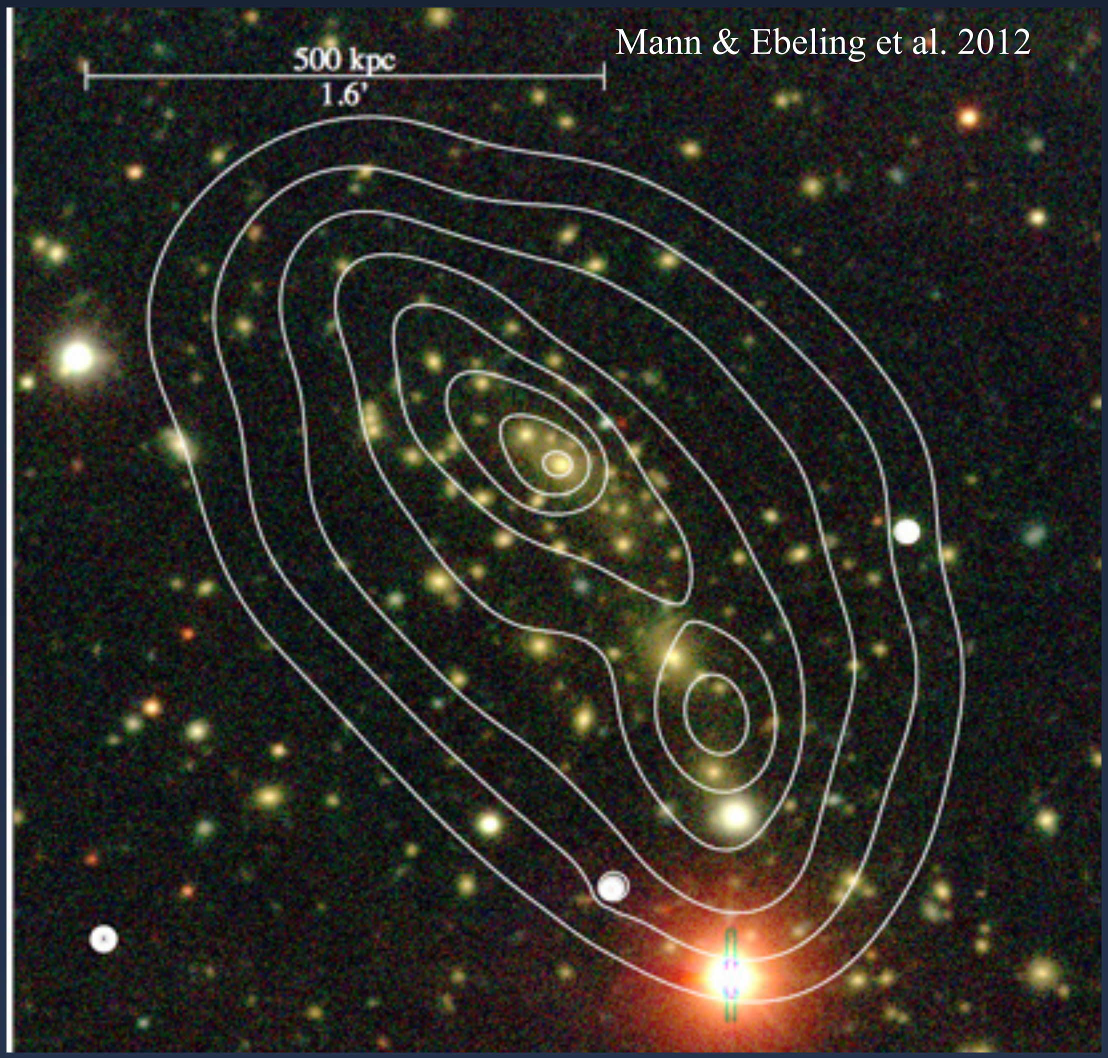


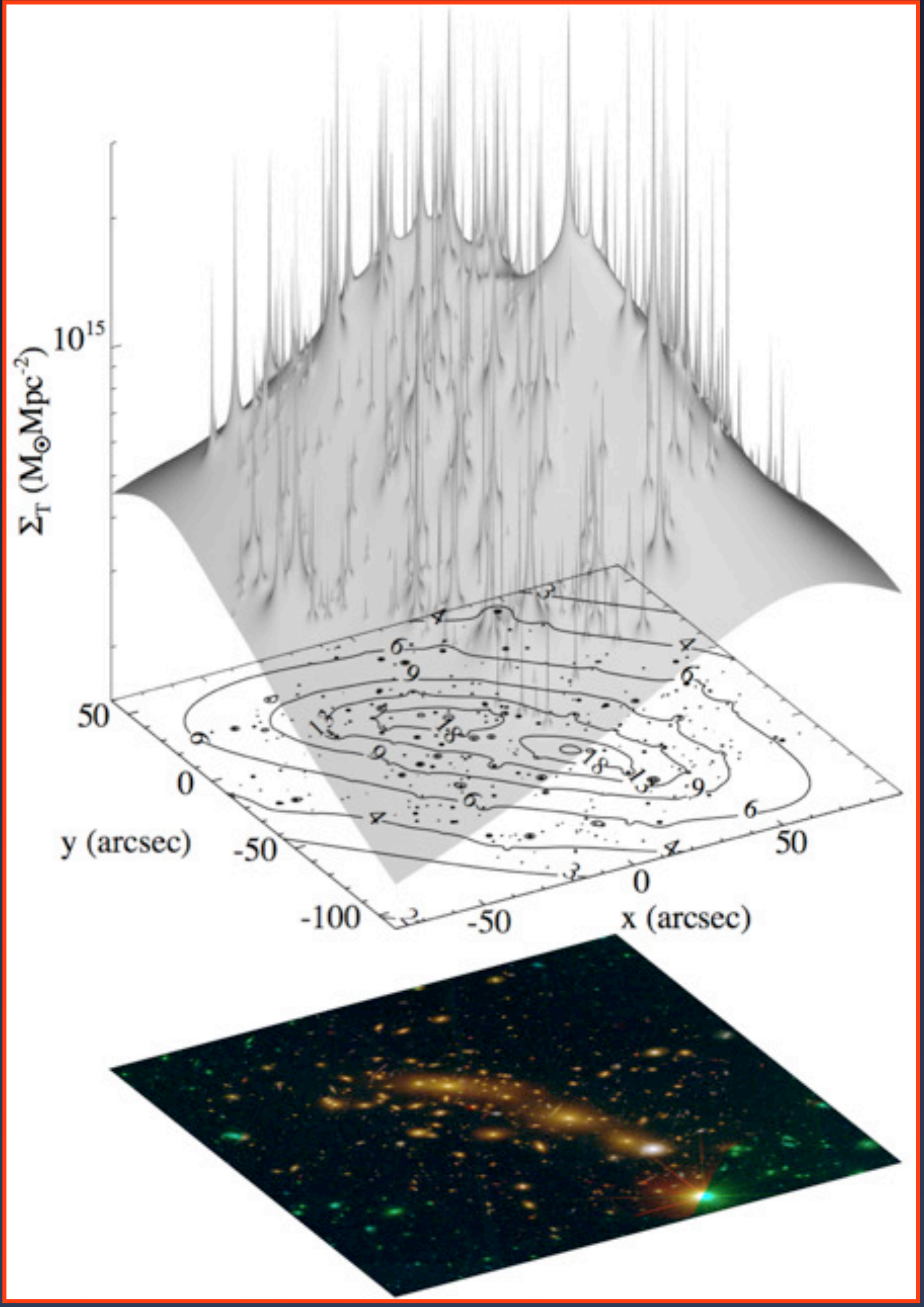
- 4200 redshifts in the field
- ~850 members !



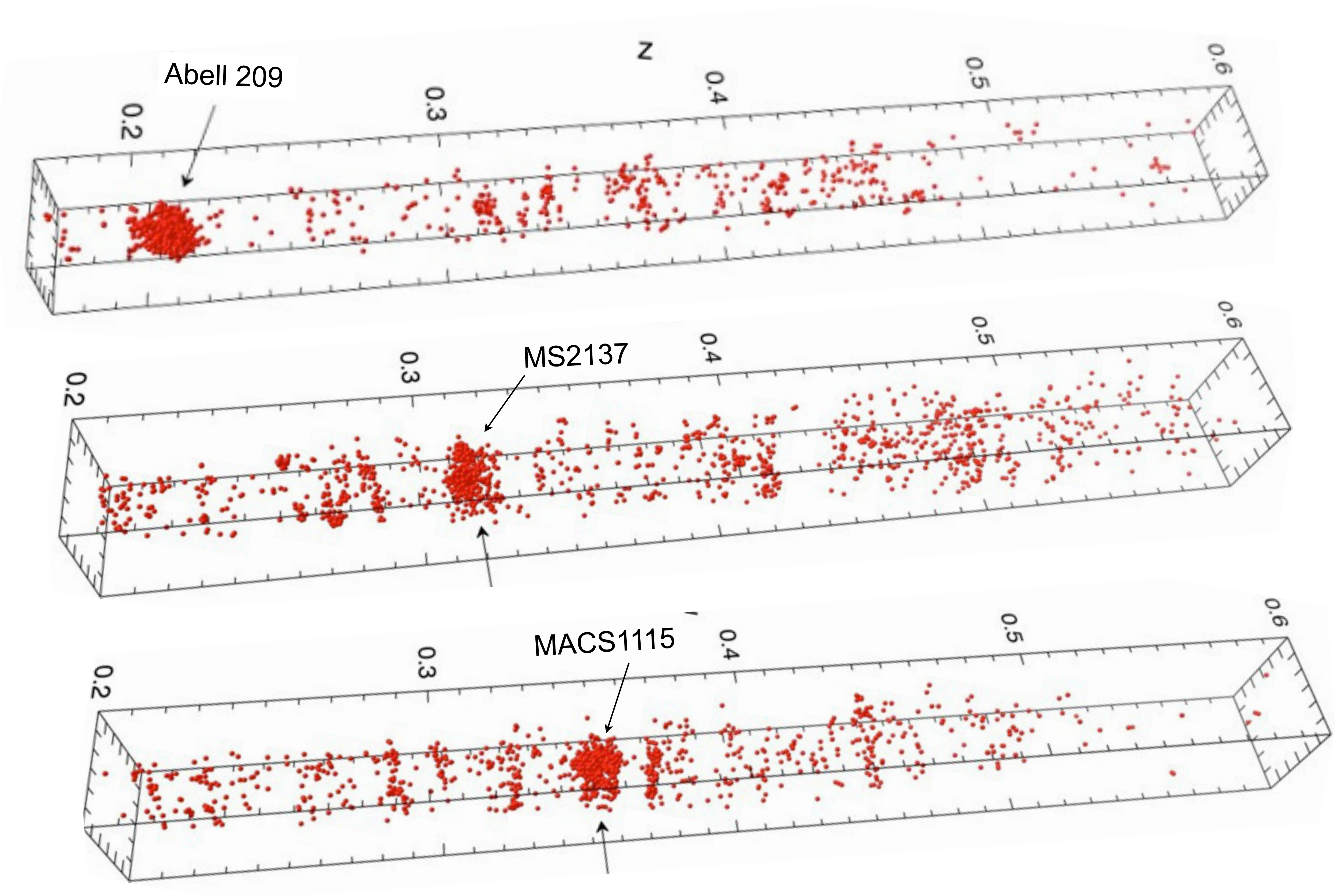
Detailed DM halo structure of MACS0416

Chandra X-ray overlay





CLASH-VLT will deliver ~30000 redshifts (~7000 of which cluster members, ~300 lensed galaxies to z~7)

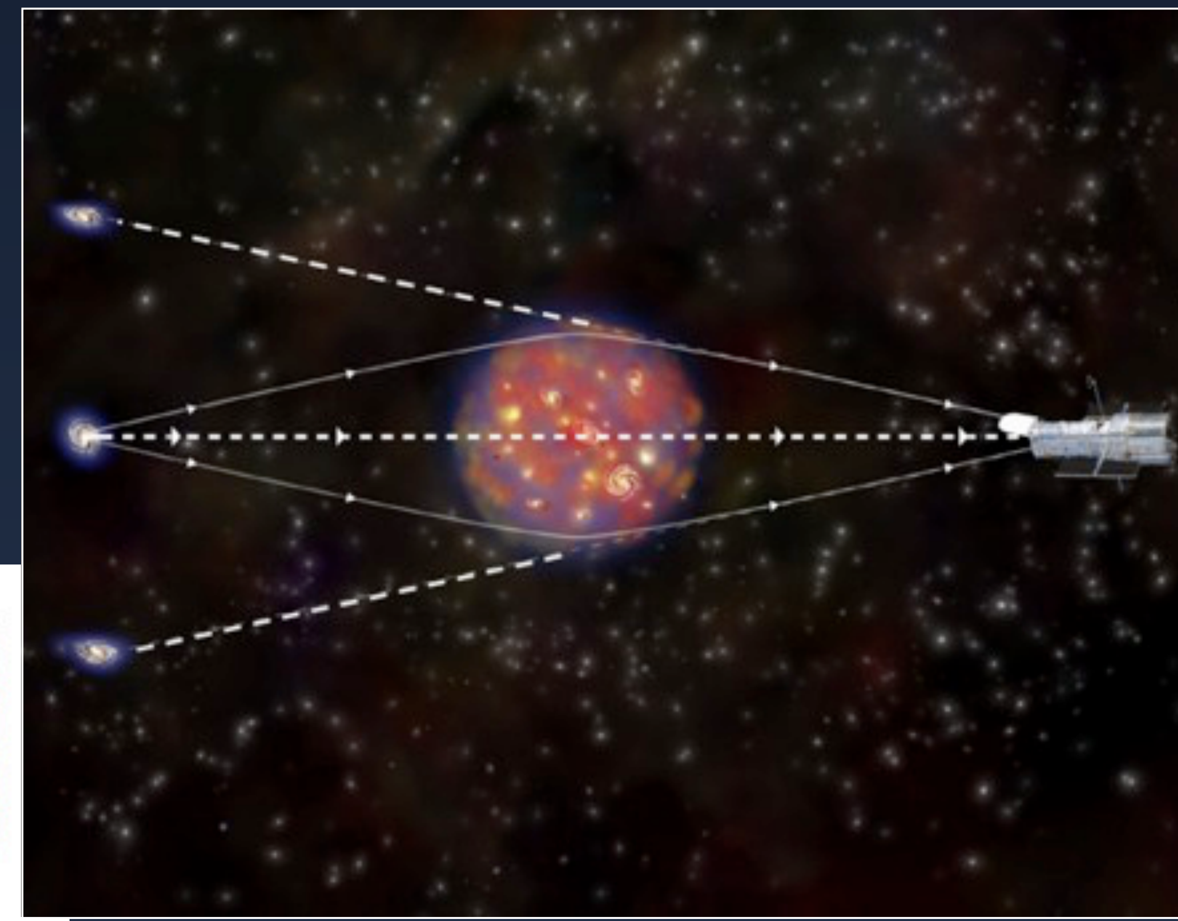


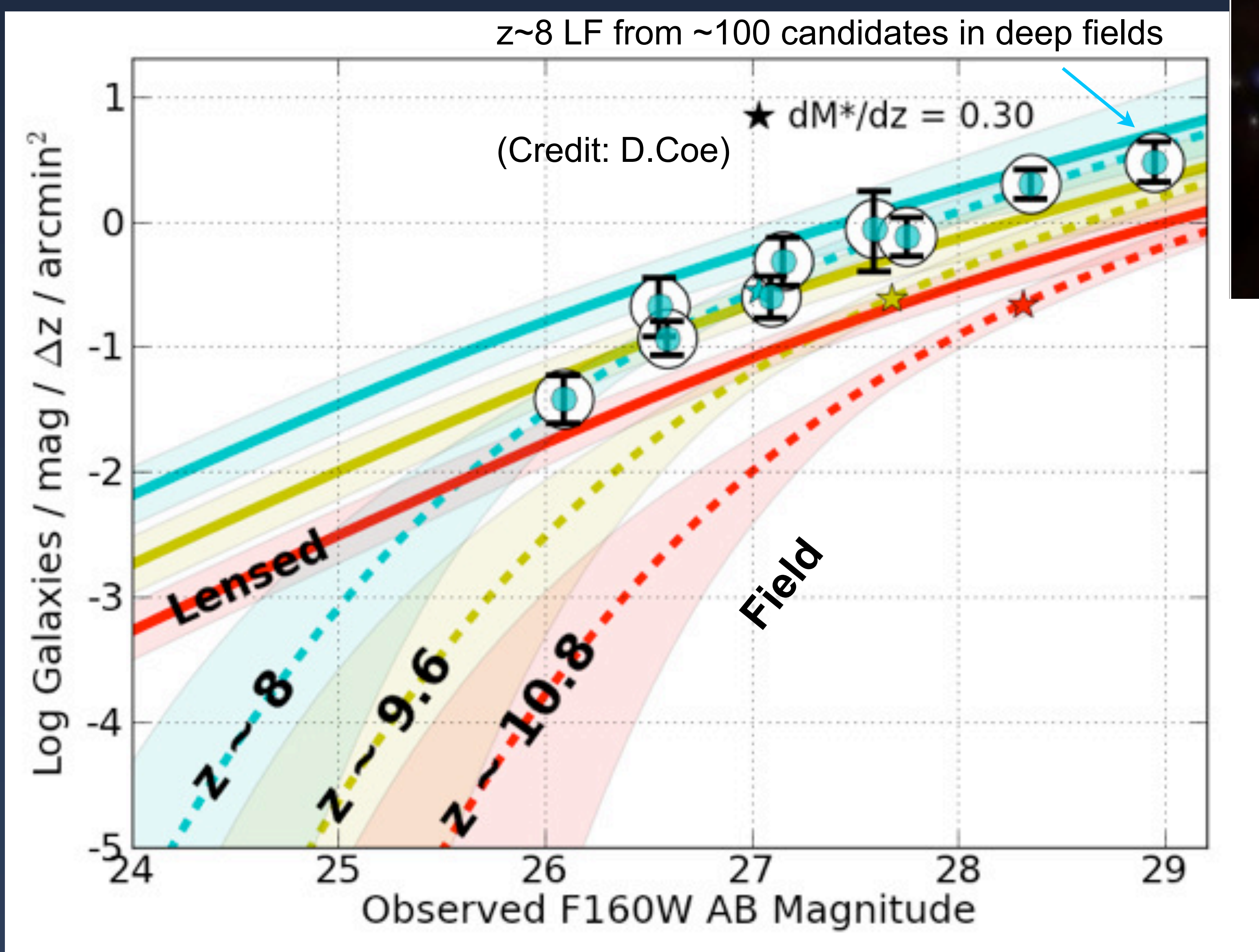
Recap from recent studies of clusters

- Upcoming new cluster samples will probe cosmological background via geometry and structure growth thus testing GR on large scales
- We now can measure DM halo profiles and their structure with great accuracy. Excellent consistency between different probes (WL, SL, galaxy dynamics, X-ray gas).
- The overall shape of DM halos and c-M relation fairly consistent with LCDM predictions (DM-only simulations)
- ...However, DM decomposition in cluster cores ($5<R<100$ kpc) (incl. $M_{stellar}$ ICL, M_{gas}, $\sigma_{V,BCG}$) shows a inner slope shallower than NFW!
- Theoretical uncertainties on magnitude and sign of baryonic effects in cluster cores make the interpretation still difficult
- High accuracy of $M_{kin}(r)$ and $M_{lens}(r)$ allows constraining DM EoS

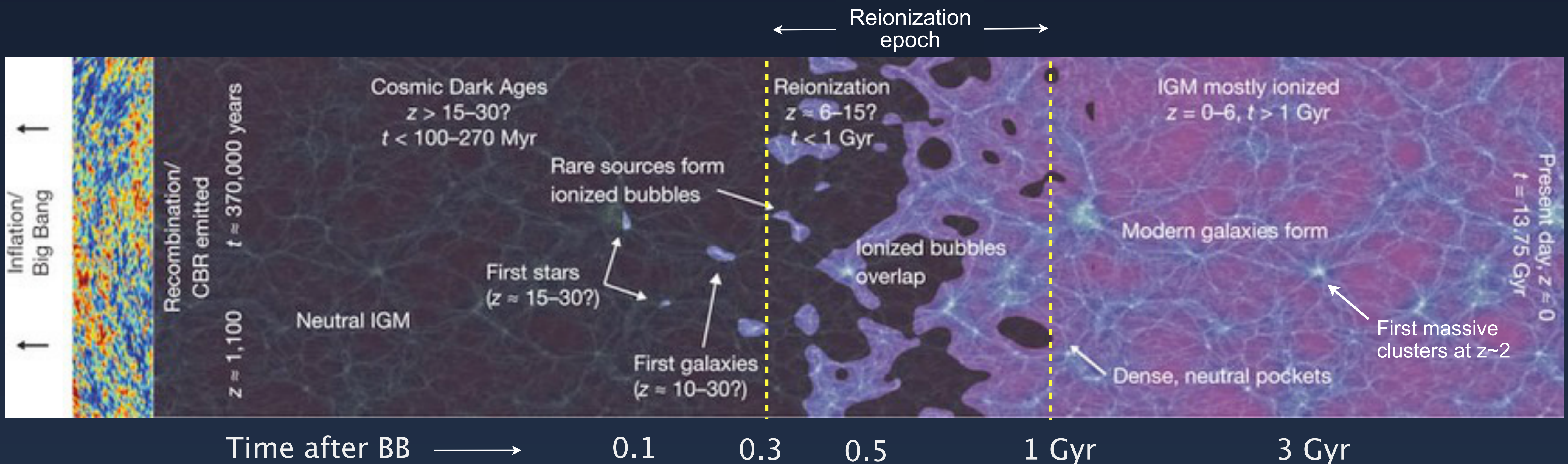
Galaxy Clusters as Cosmic Telescopes

- Phenomenal progress over last 10 years driven by HST (ACS...WFC3/IR)
- Magnification (μ~3–100) significantly increases discovery efficiency for galaxies at fainter mags or/and higher redshifts, but also the volume shrinks by $A_S \sim 1/\mu$





Approaching the first light (stars, SMBHs)



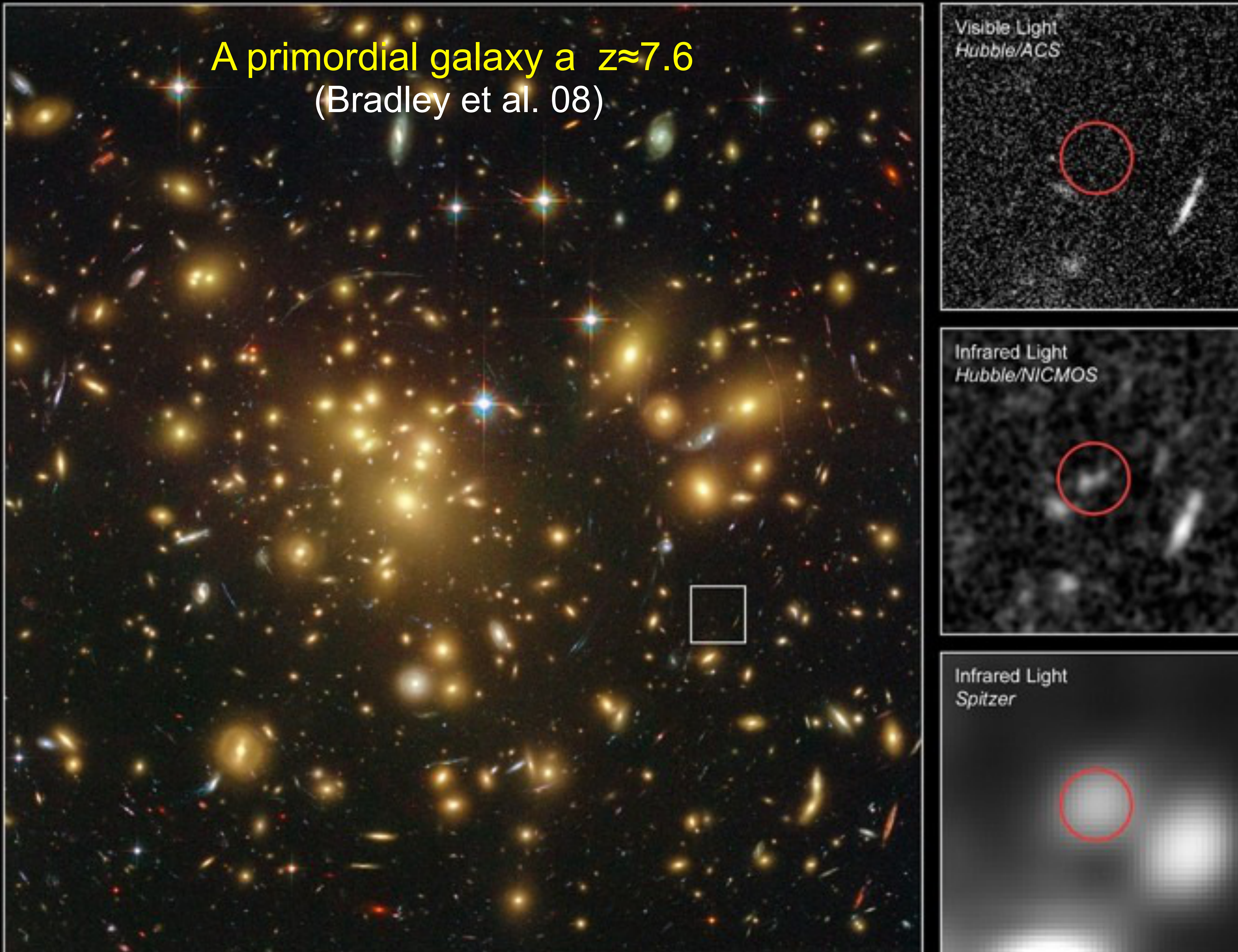
- Probing the first billion years of cosmic history (z>6) is critical to understand the reionization: major phase transition in the Universe at the end of the dark ages when the intergalactic space became transparent to UV photons

- First star formation challenging: no metals, collapse in massive minihalos > simulations show that macrophysics of early SF is linked to microphysics of DM particles (CDM vs WDM)

- Need identify sources of reionization (first stars, first SMBH ?) and physical processes which led to first galaxies and AGN

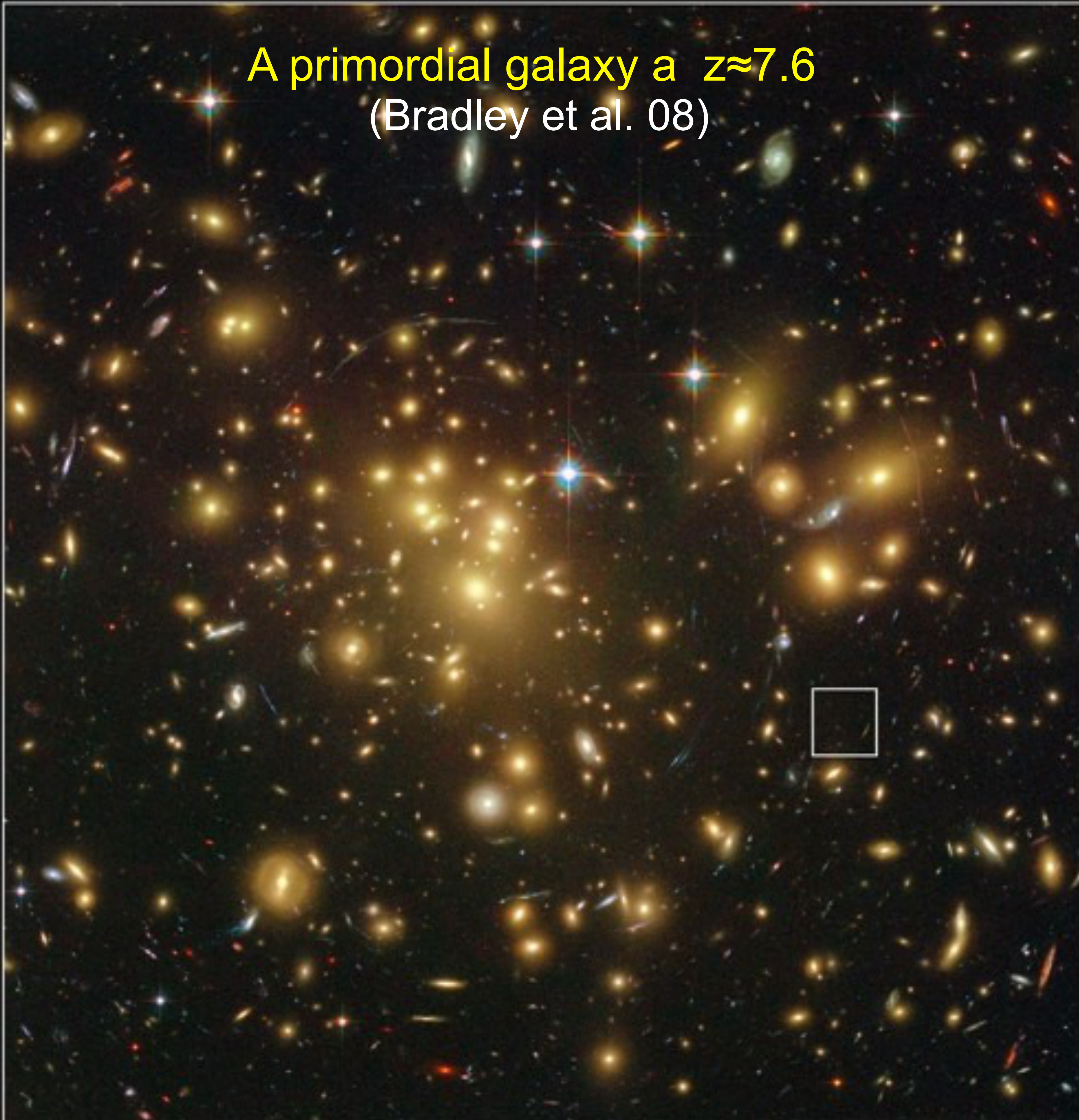
- QSOs spectra at z~6-8 suggest that reionization is not fully completed by z~7

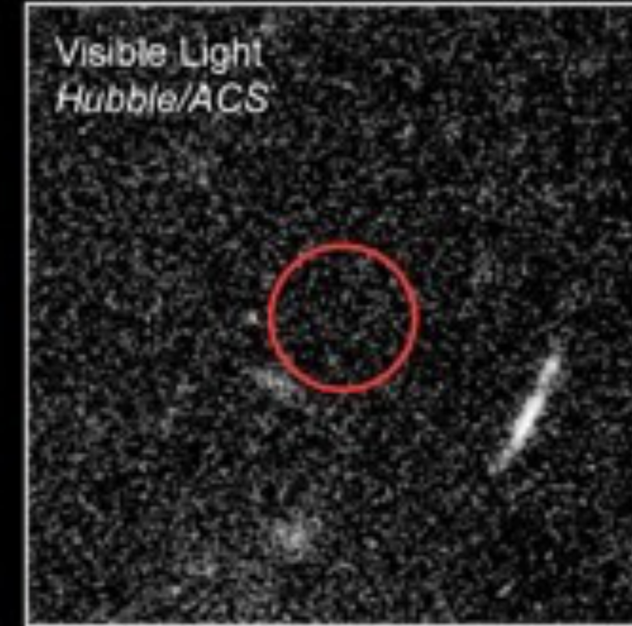
A primordial galaxy a z≈7.6
(Bradley et al. 08)

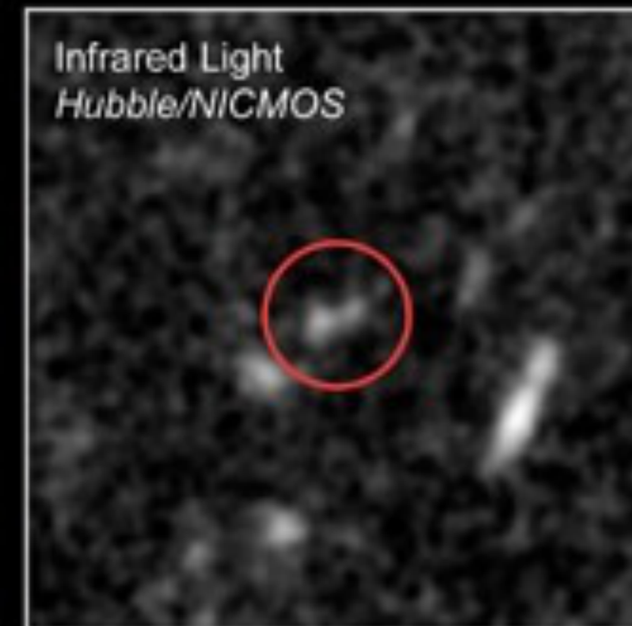


A primordial galaxy a z≈7.6

(Bradley et al. 08)







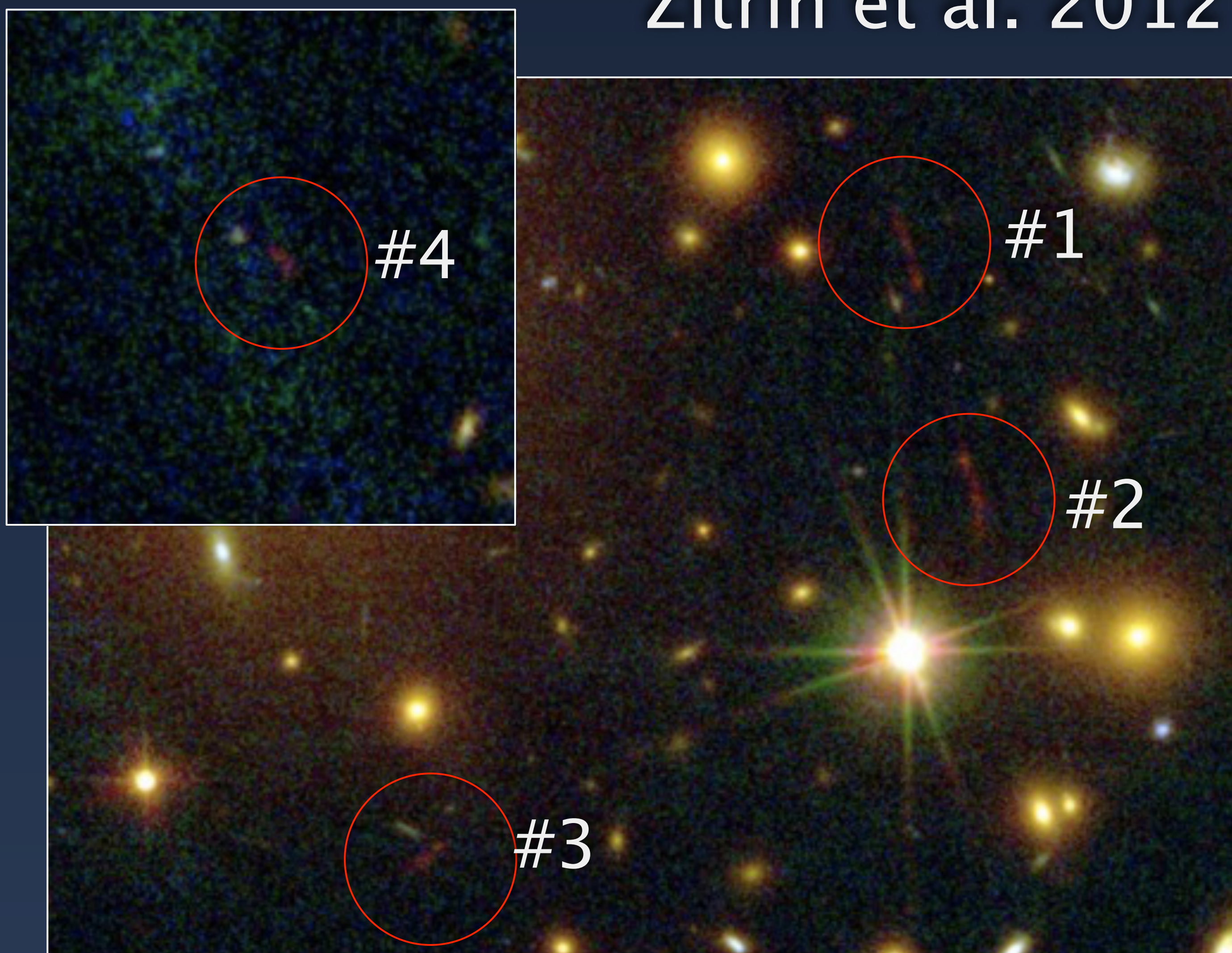
H_{160}=24.7AB (observed)
=27.1AB when
corrected for μ=9.3

$M_S=(1\text{-}4)\times10^9\ M_\odot$
Age=(40-300) Myr
z_F~8-10

Lensing also magnifies galaxy sizes !

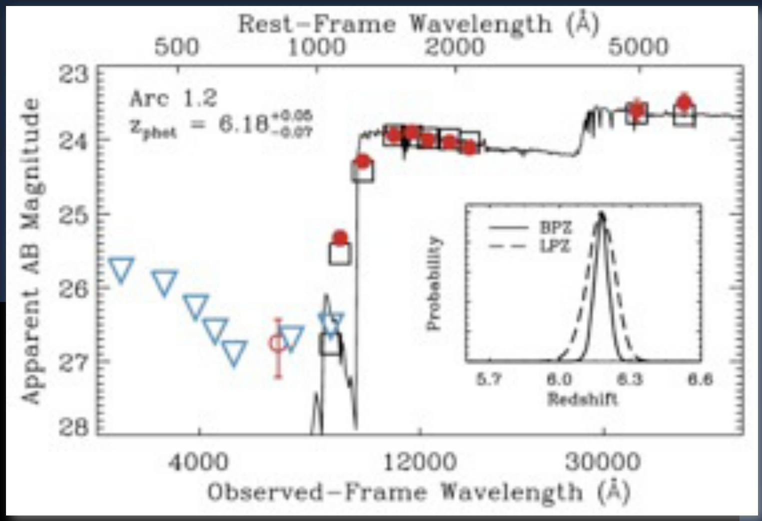
MACS J0329-02:
Quadruply-lensed Galaxy at $z_{ph} = 6.1$

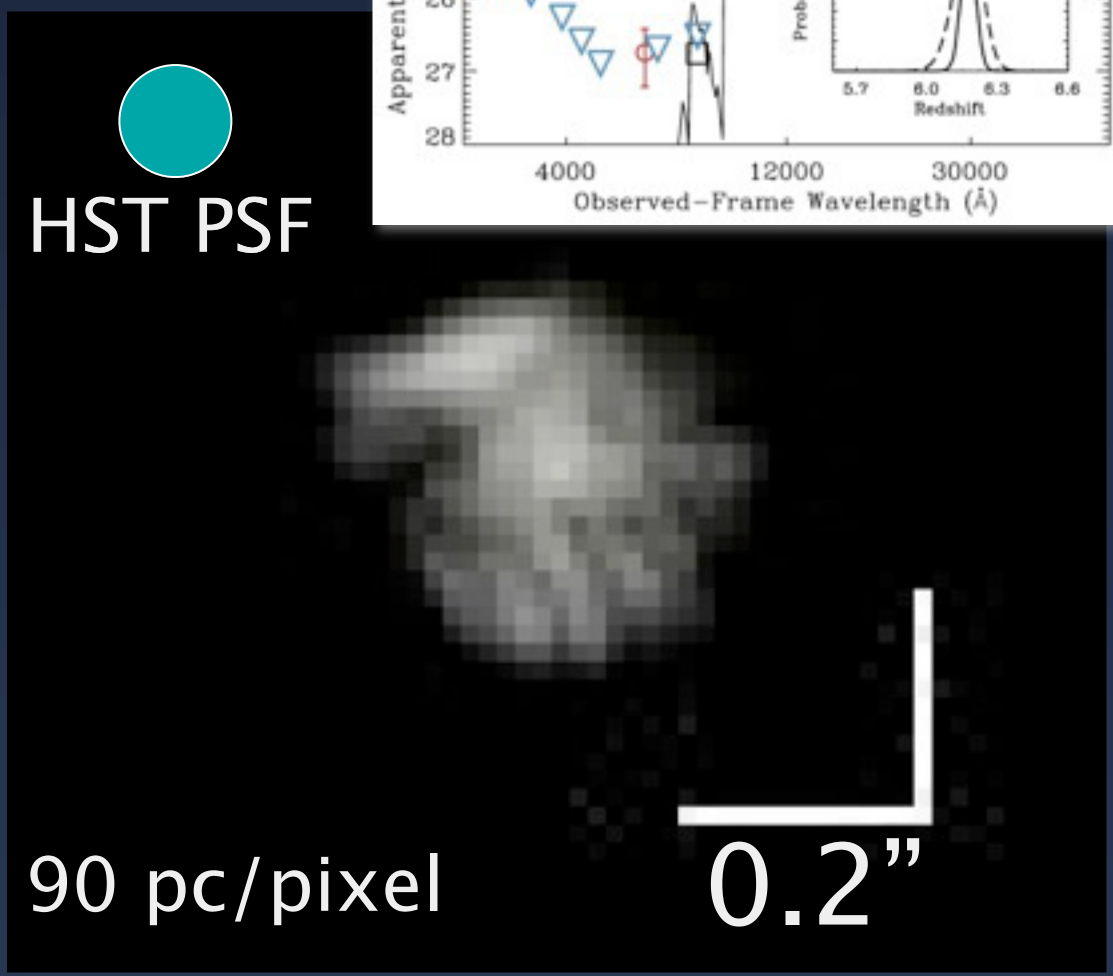
Zitrin et al. 2012



Magnifications: #1 = 11.6, #2 = 17.6,
#3 = 3.9, #4 = 3.7

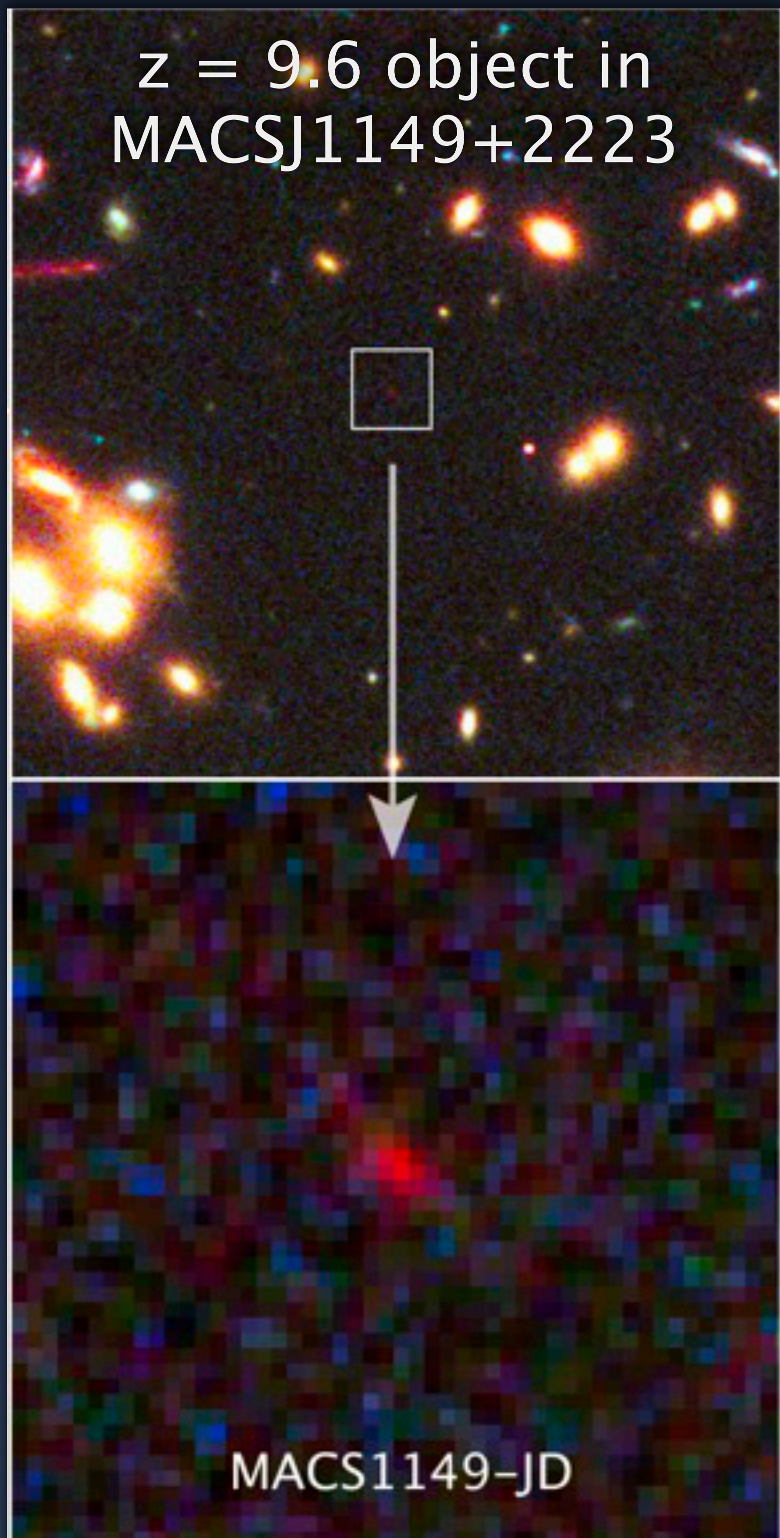
Age <400 Myr



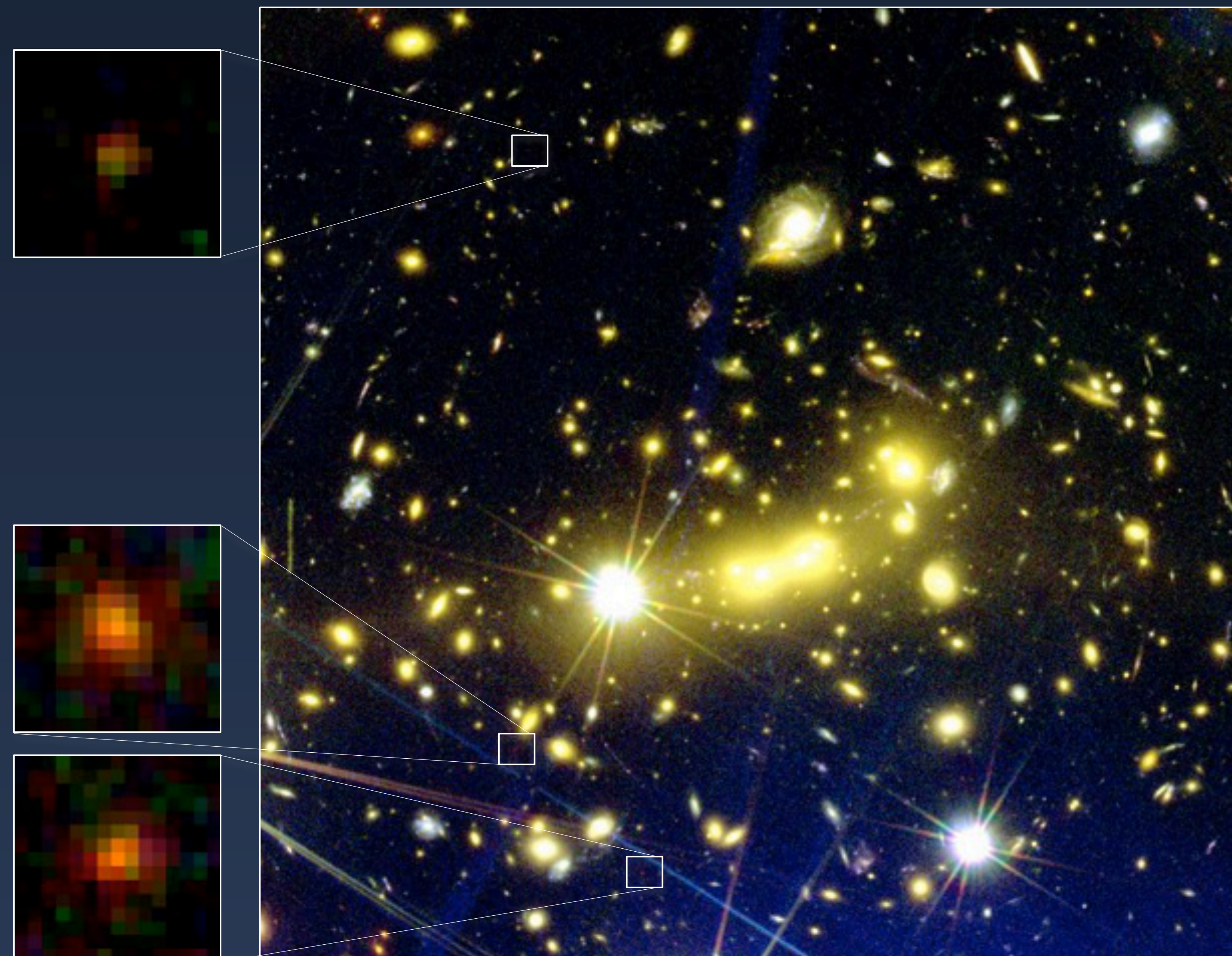


Delensed view
(source plane)

Two z > 9 Lensed Galaxies



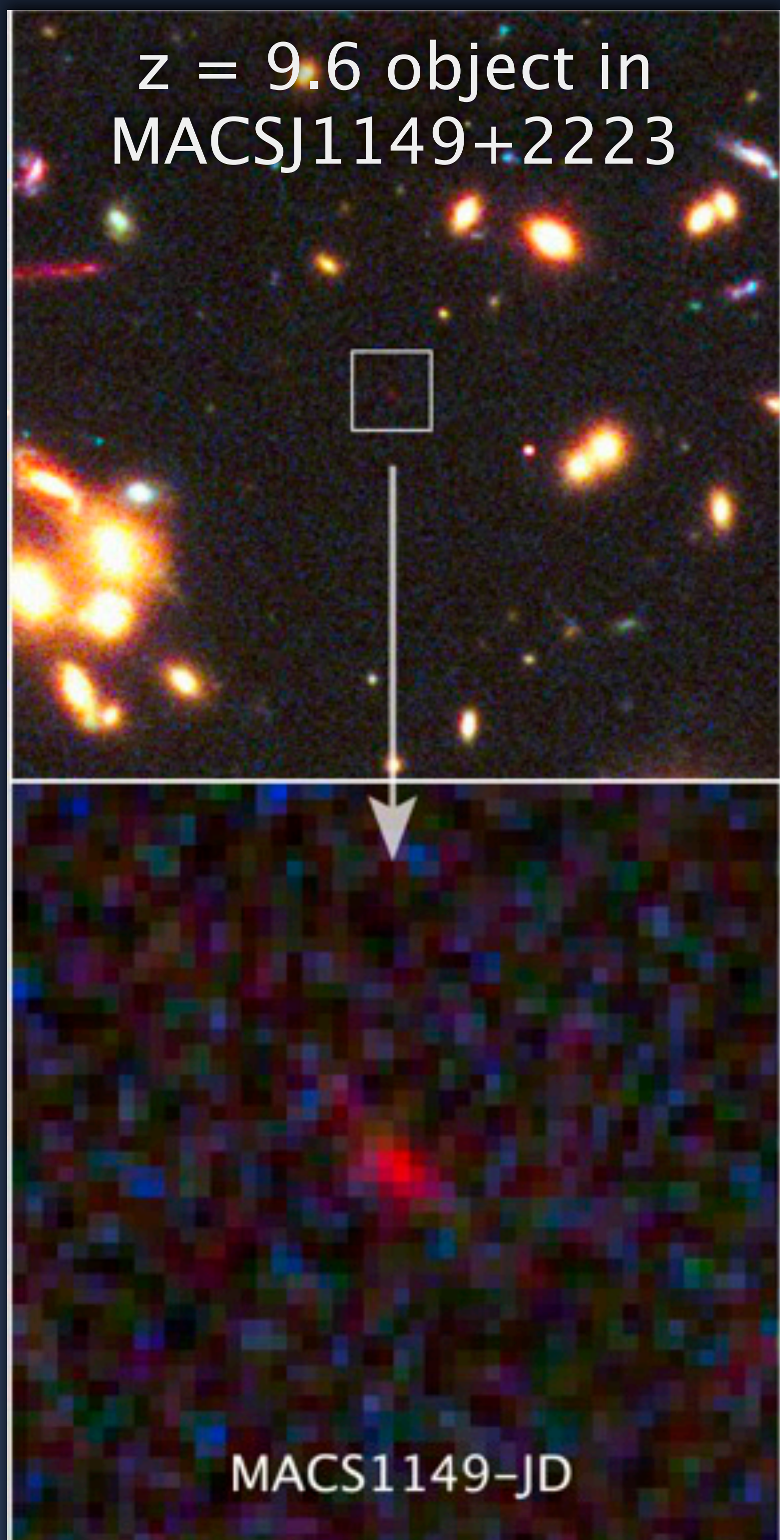
z = 10.8±0.3 object in MACSJ0647+7015



Coe et al. 2013, ApJ, 762, 32

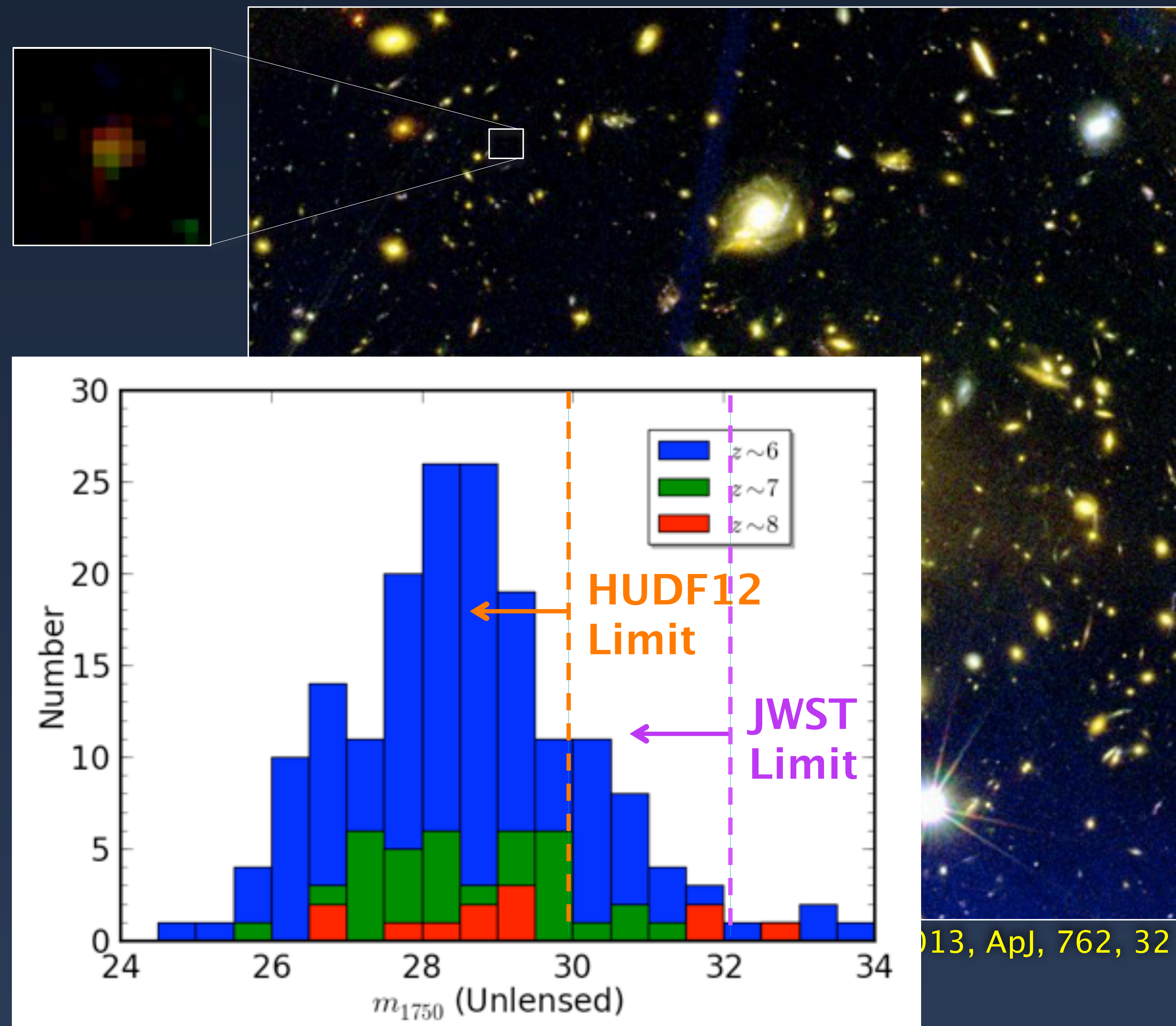
Zheng et al. 2012, Nature, 489, 406

Two z > 9 Lensed Galaxies



Zheng et al. 2012, Nature, 489, 406

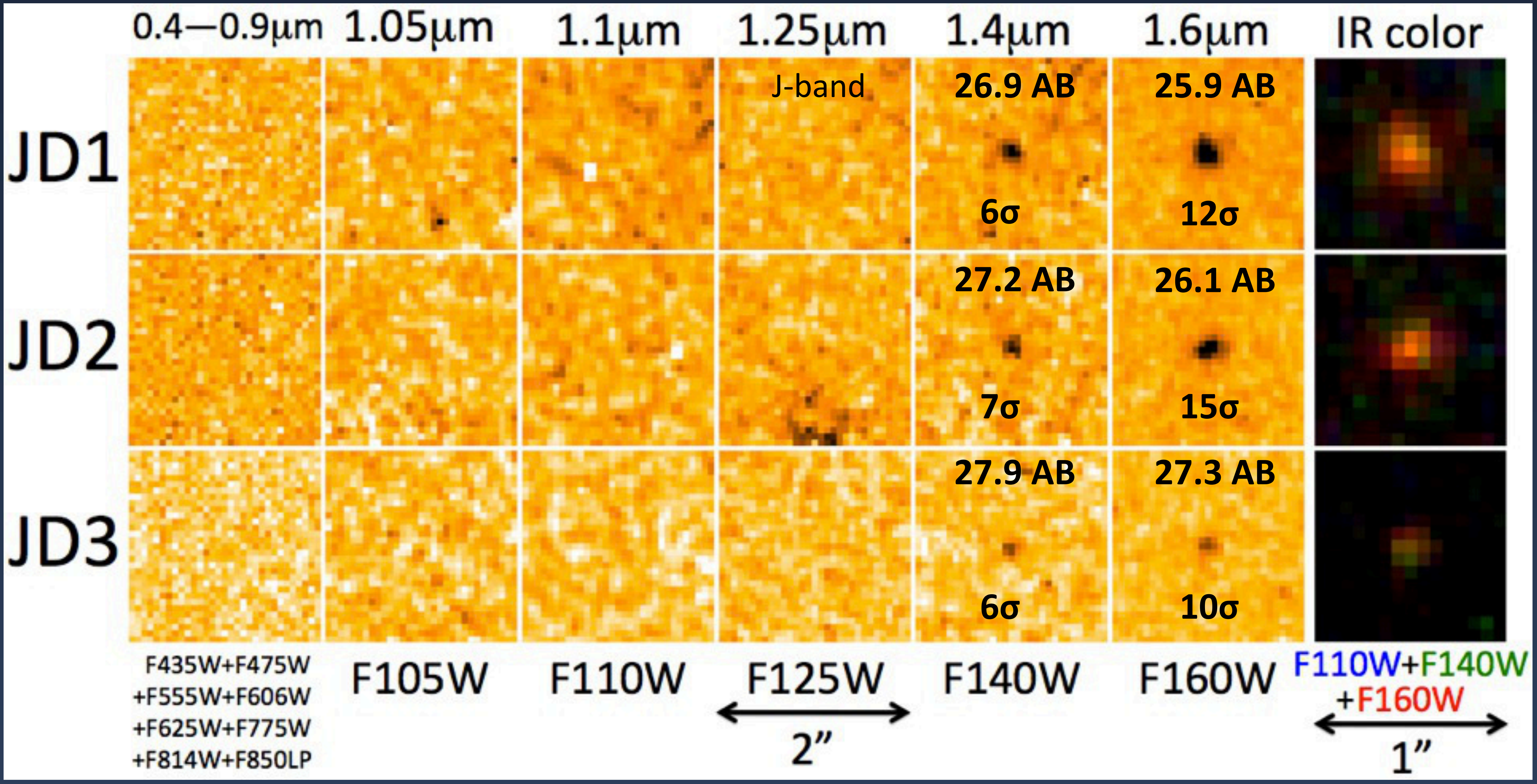
z = 10.8±0.3 object in MACSJ0647+7015



013, ApJ, 762, 32

MACS0407-JD (Coe et al. 2013)

- Each lensed images (with μ≈8, 7, 2) is observed only in the two reddest WFC3 filters + upper limits with IRAC 3.6μ and 4.5μ (JD1 ~3 mag brighter than HDF12 z~9 candidates)



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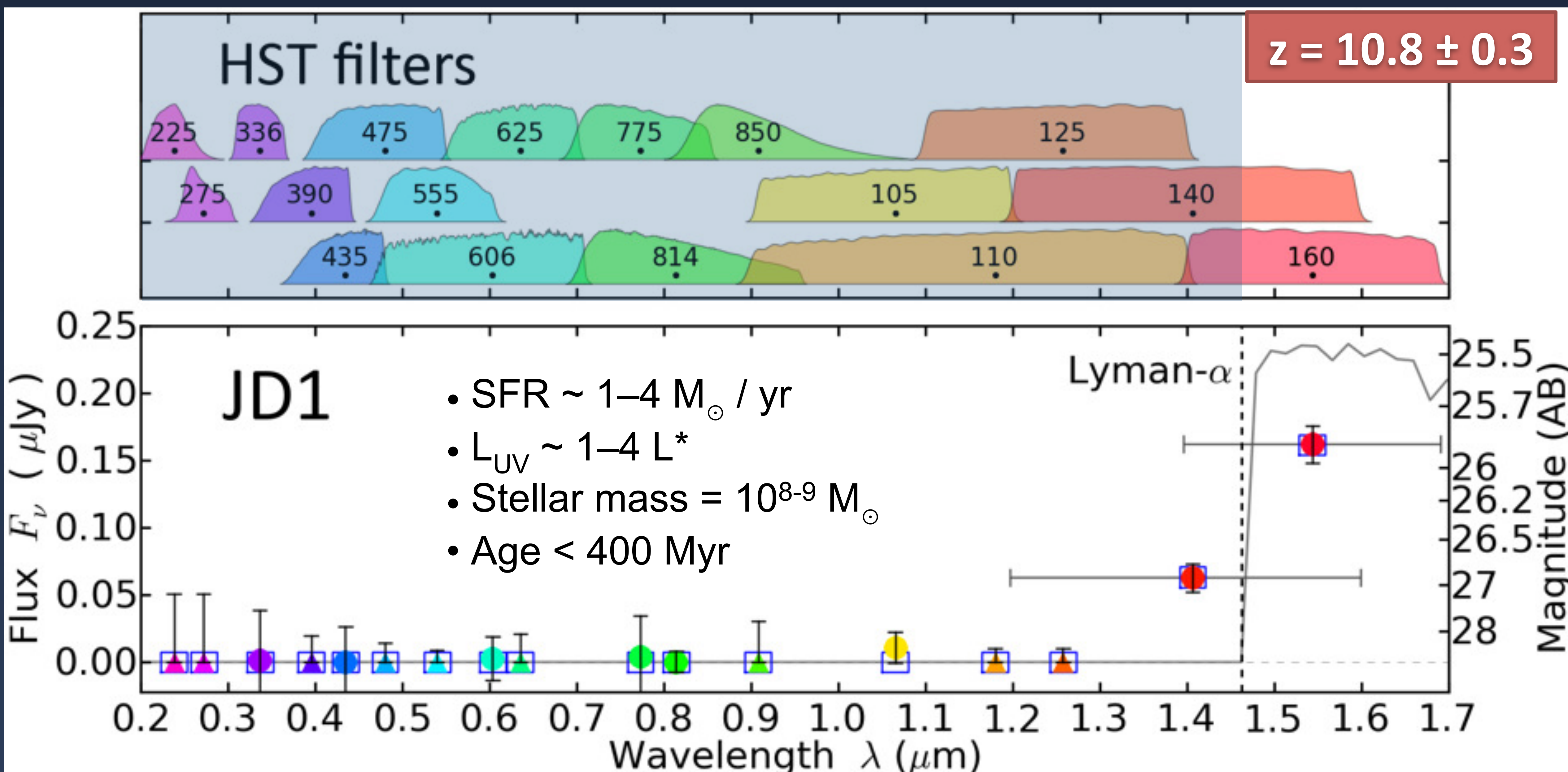

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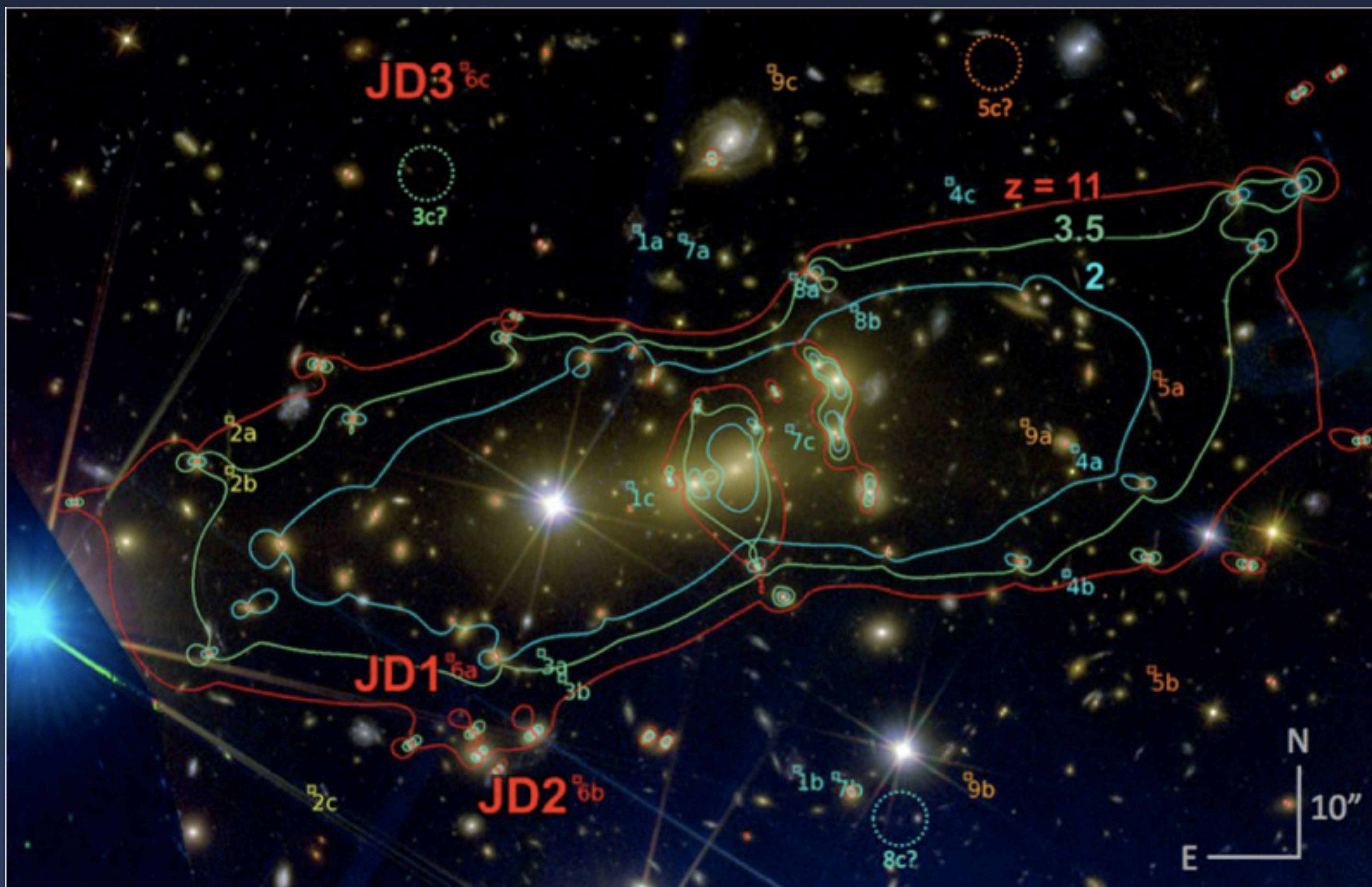
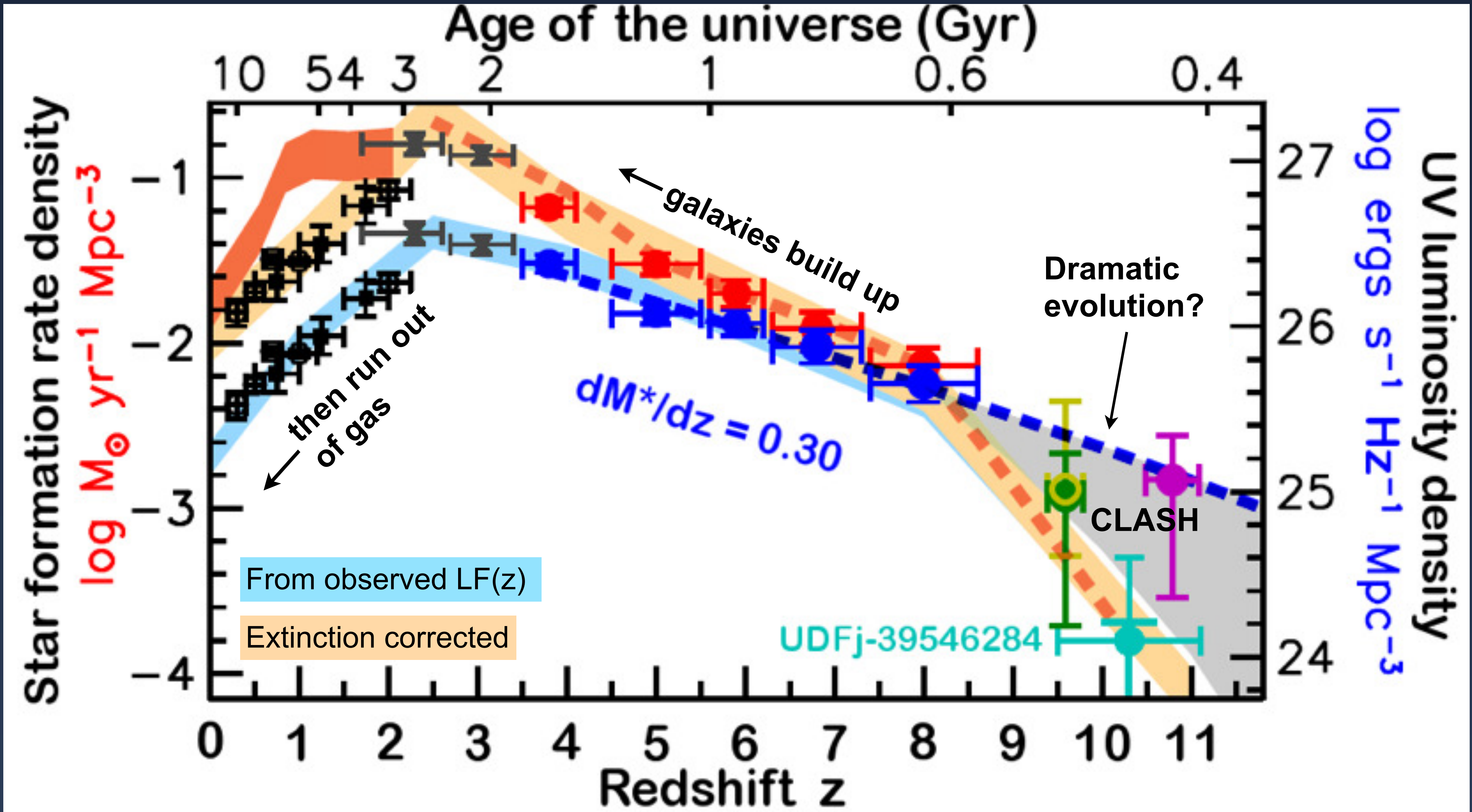
- HST photometry is best fit by a starburst galaxy spectrum at z ~ 11, "all" other solutions extremely unlikely (z<9.5 interlopers ruled out at 7.2σ)
- Observed positions and fluxes are consistent with the lens models, based on 20 strongly lensed images of 8 other galaxies



CLASH+Hubble Deep fields provide

- the first census of galaxies ~500 Myr after the big bang
- first constraints on galaxy evolution at z > 8
- ...but more observations are required to confirm/rule out a rapid growth with important implications for reionization

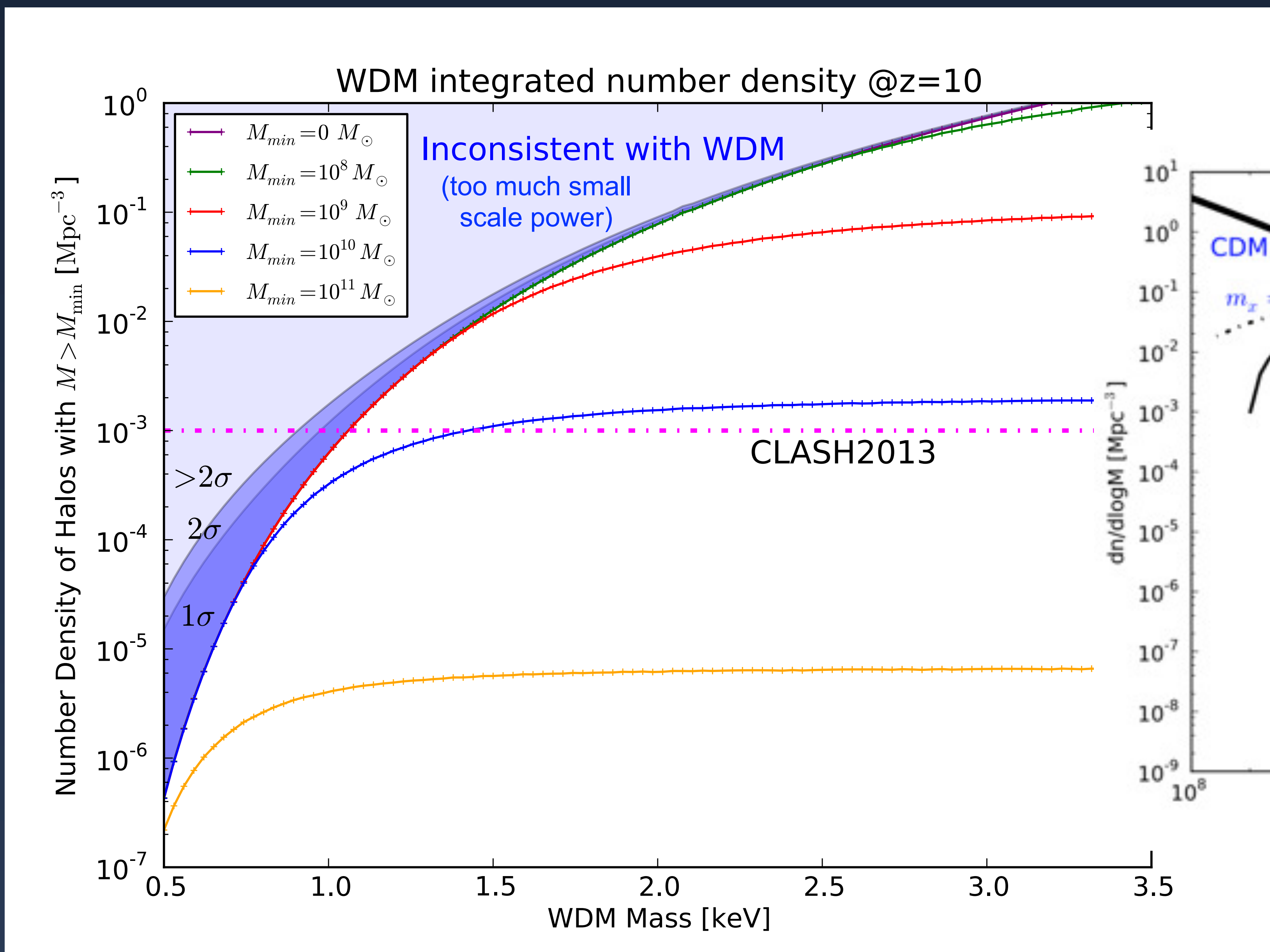


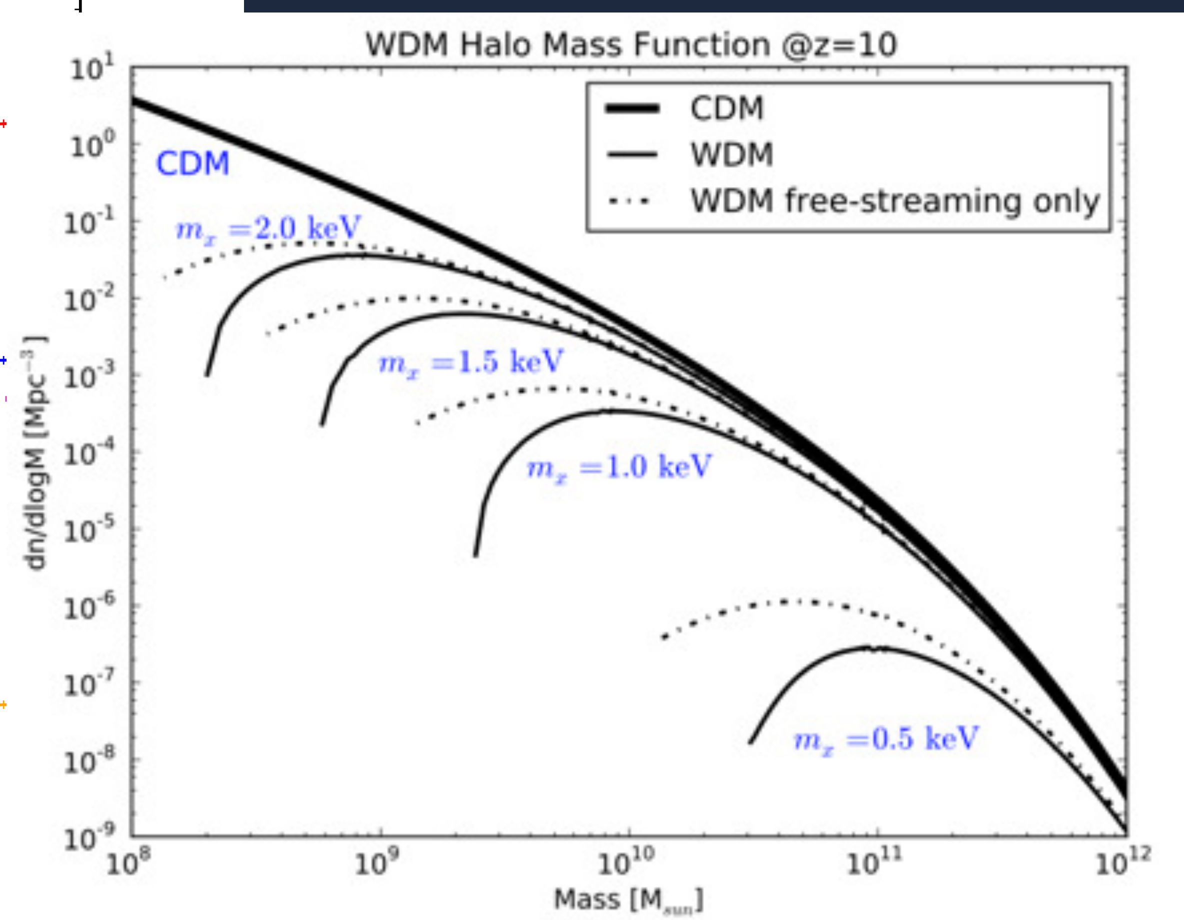
(Schiminovich+2005, Reddy&Steidel 2009, Oesch+ 2010, Bouwens+ 2007,11,12, Coe+2013)

Independent constraints on the nature of DM from the number density of primordial galaxies

- Existence of galaxies at very high z implies significant primordial power on small scales (lower limit to the number density of collapsed DM halos)

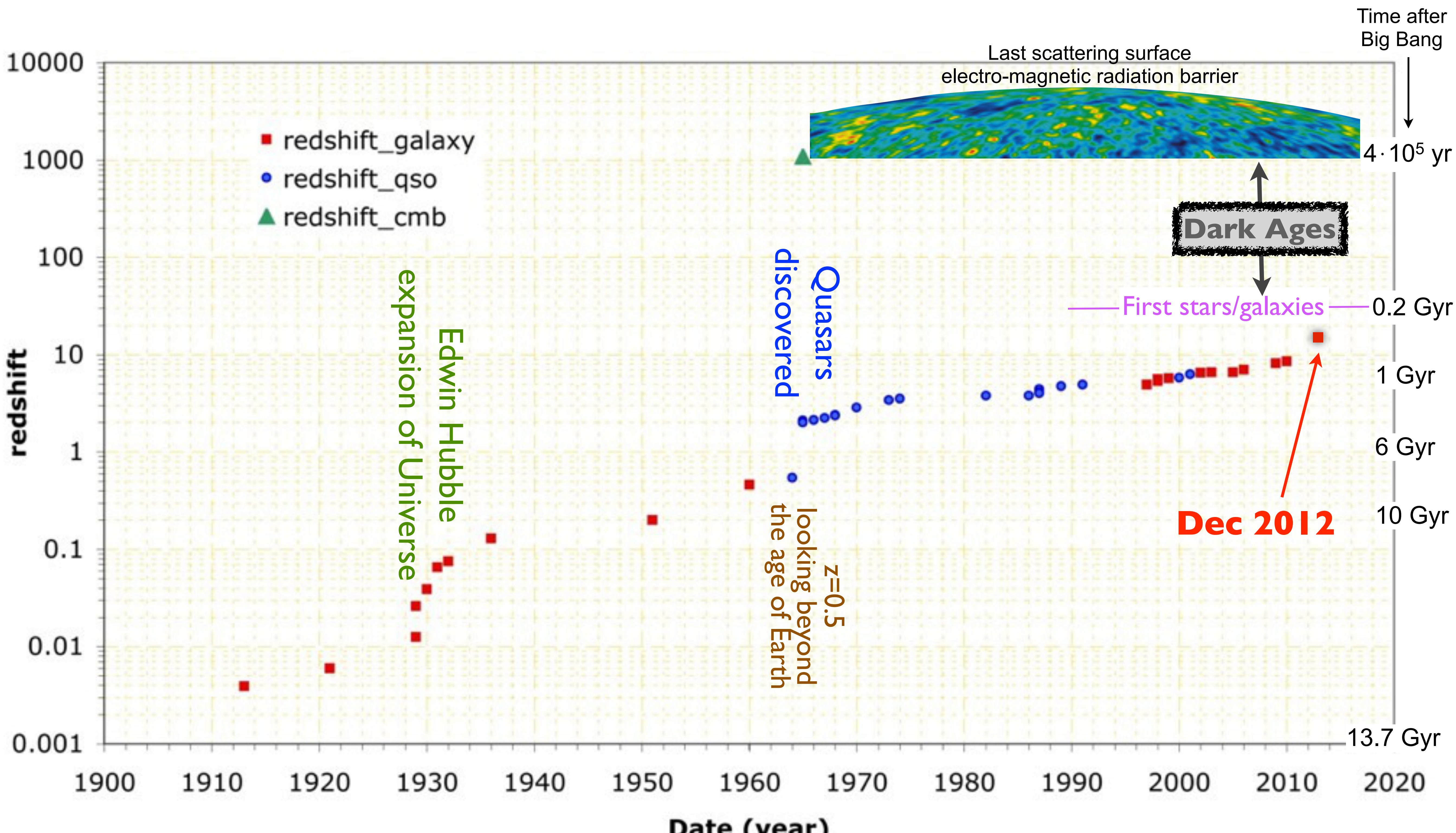
Pacucci et al. (2013)





- Even only two galaxies at z~10 allow one to exclude WDM particles with m_X<1 keV
- Limit depends only on WDM halo mass function, not on astrophysical modeling

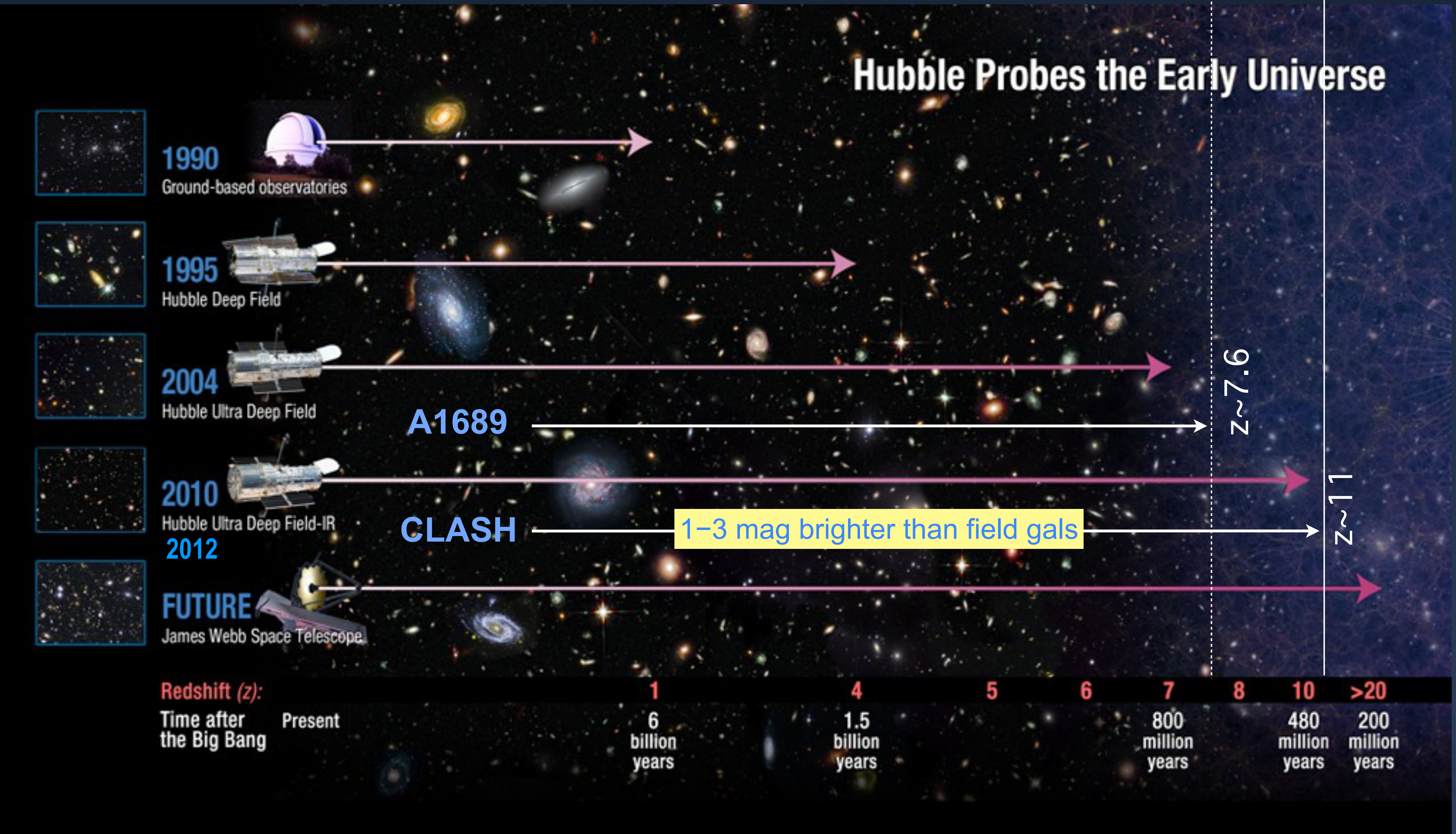
Redshift record with time



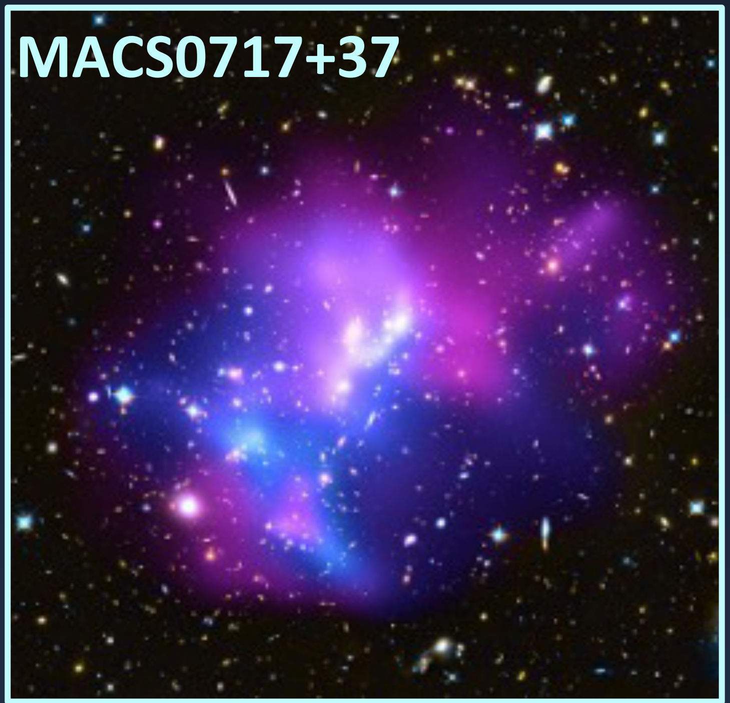
(Courtesy of B.Fosbury)

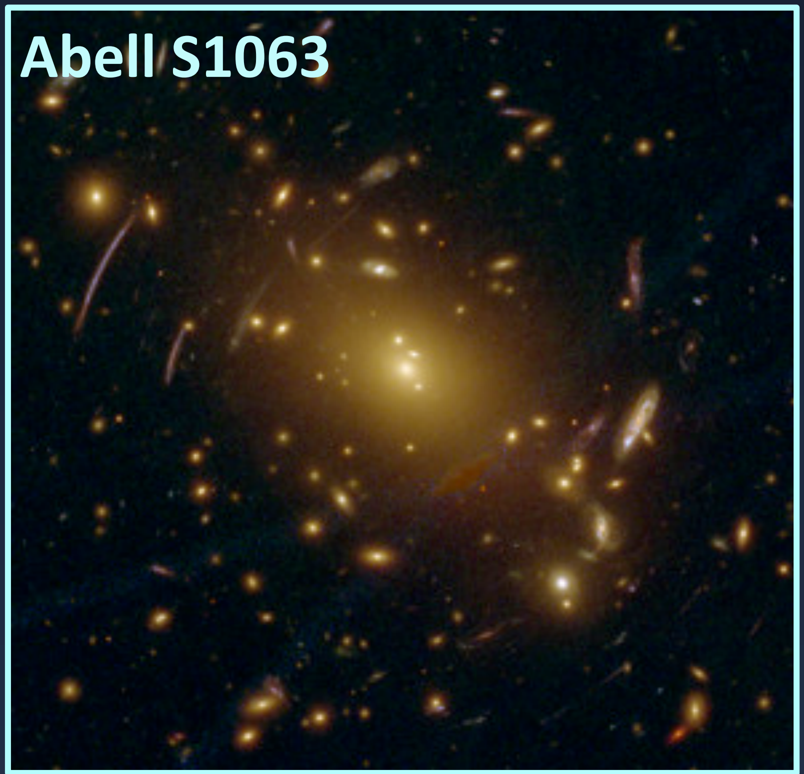
Pushing into the reionization epoch with lensing clusters

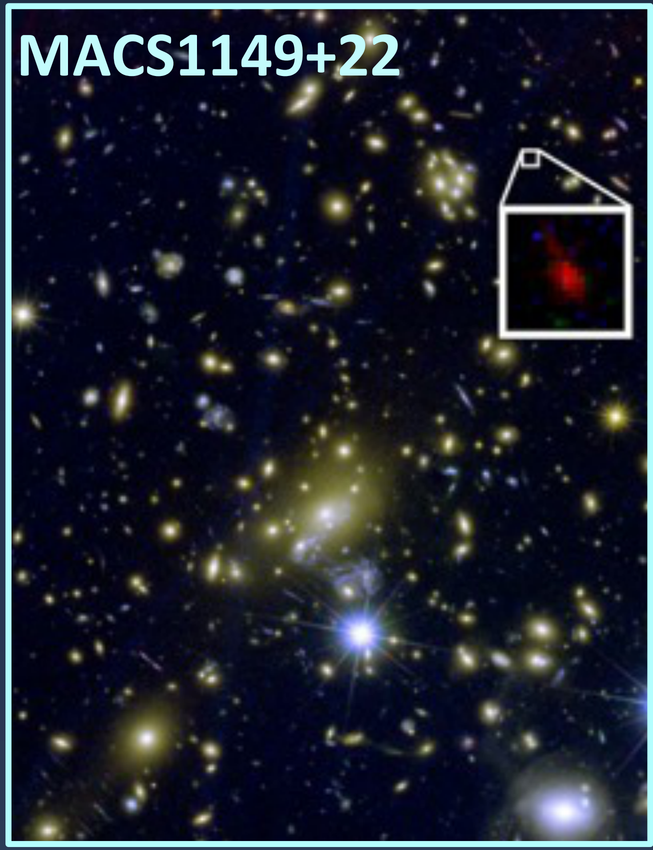
Cluster lensing enables to probe back to 4-500 Myrs after Big Bang



Next: The Frontier Fields







- → 70 orbits ACS + 70 orbits WFC3/IR, 1.2 mag deeper than CLASH (Fall 2013 – Fall 2016)
- → Chandra large program for deep X-ray observations

Outlook

- Clusters have a critical role in testing the LCDM paradigm
- It remains critical to use methods which probe both geometry and growth of perturbations to distinguish “DE” from non-standard gravity
- Accurate DM and baryon mass distributions on Kpc−Mpc scales allow us to constrain DM nature (both relaxed systems and bullet-like clusters)
- A combined approach is missing in analyzing dynamical and lensing observations: solving for both microphysics of DM particles (EoS) and large scale mass distribution
- Varying EoS parameter w(z) to be constrained by a number of experiments (incl. Euclid!) at a few % level, but not many clues from theory.. so is it worth the effort ?
- What if DM particles are not weakly interacting, WIMP miracle is perhaps a fluke ?
- Measuring the abundance of primordial galaxies and observing formation of first stars can probe the nature of DM particles (first glimpse with lensing, will JWST say the last word ?)