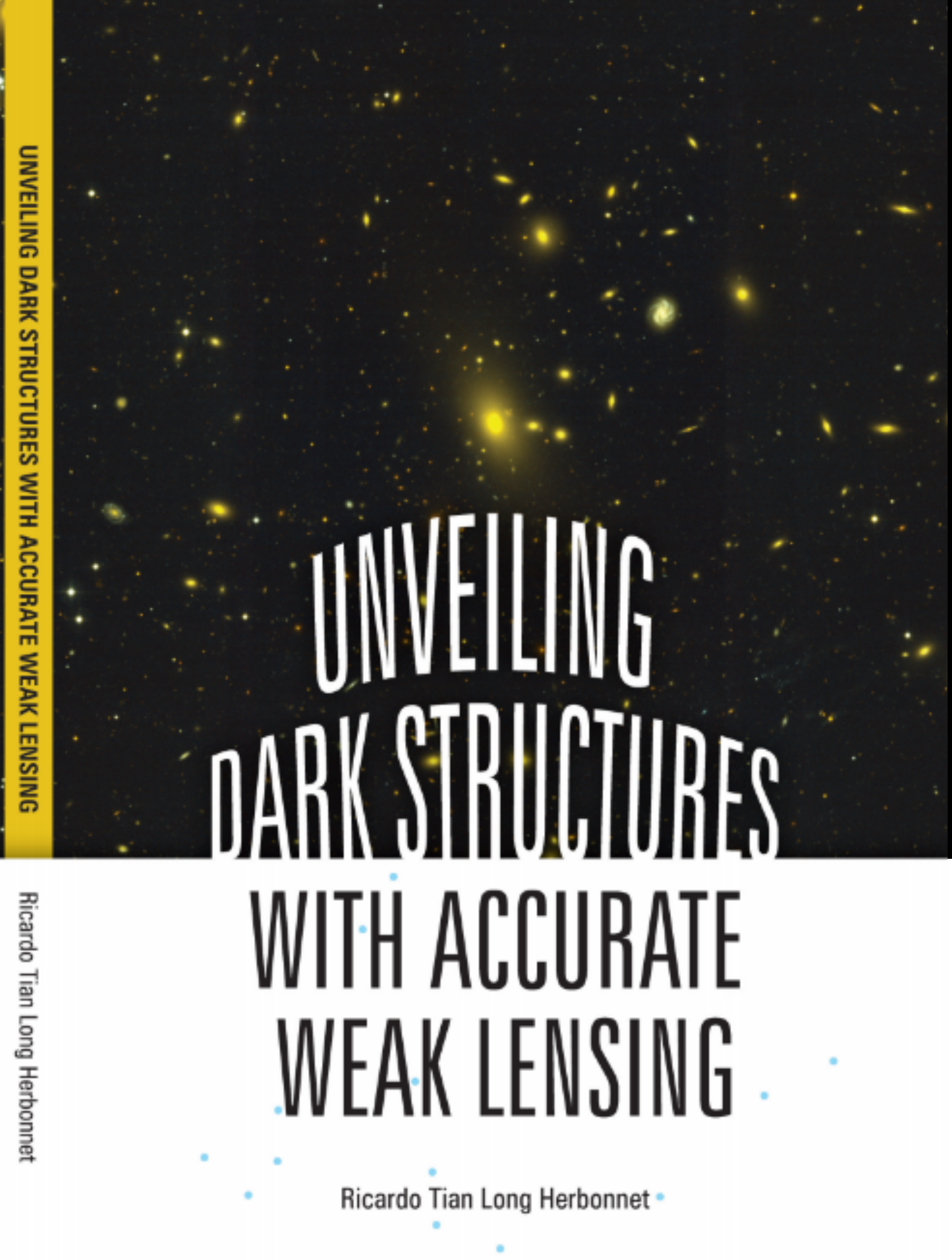
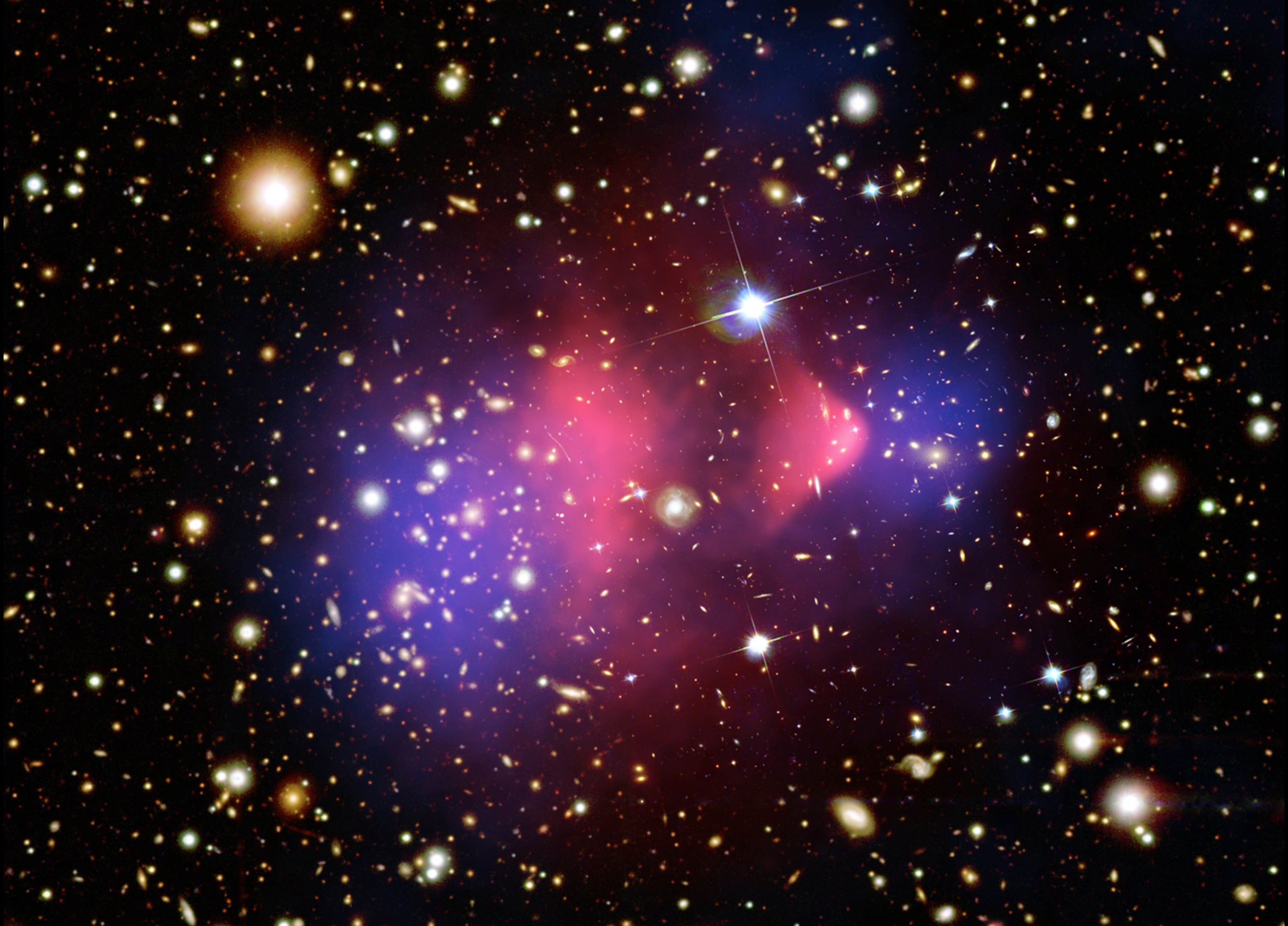


Weak lensing masses and scaling relations for 100 clusters

Kavli IPMU

May 13 2019



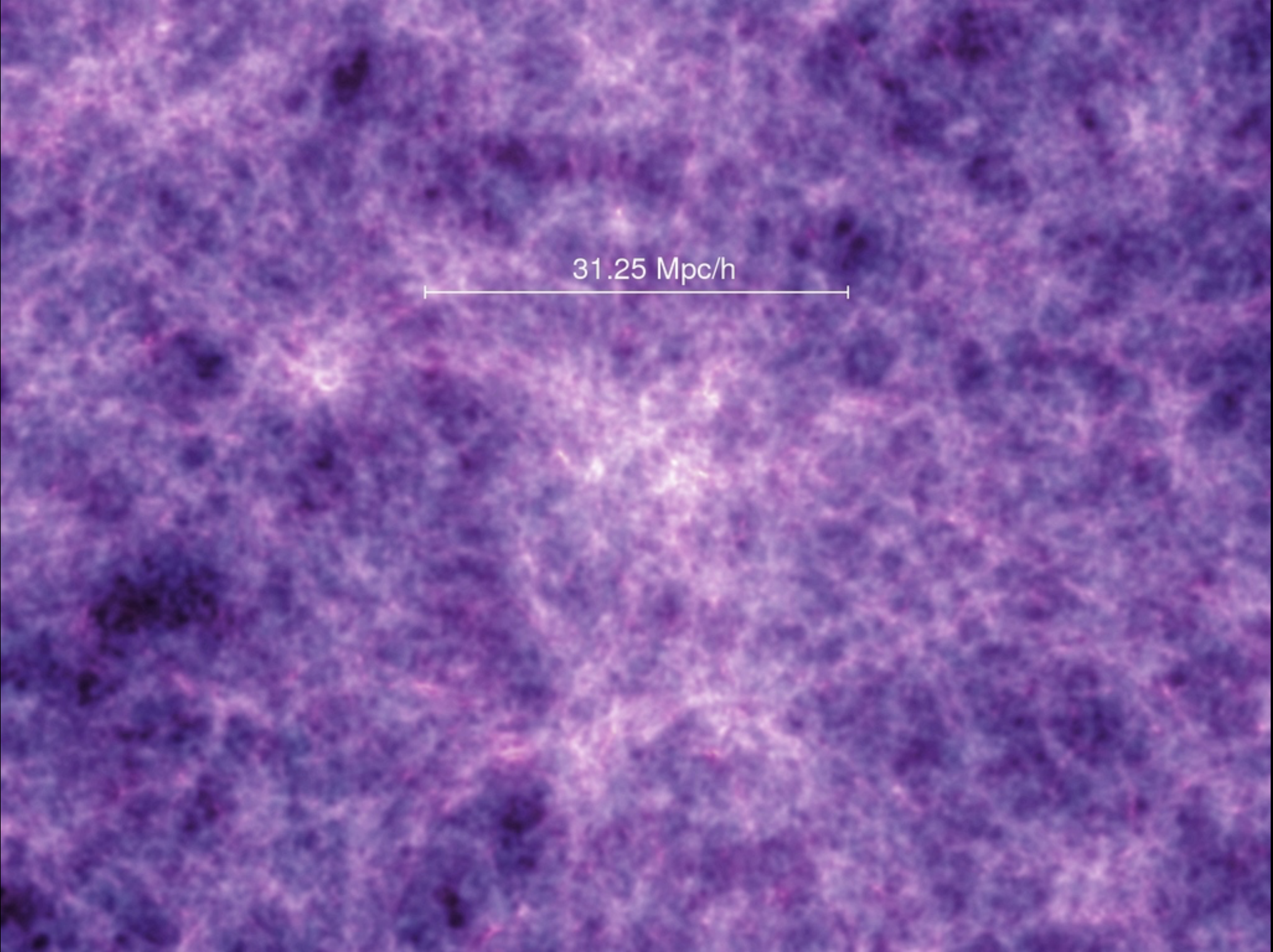
Bullet cluster

~18%
Hot X-ray emitting intracluster gas

~2%
Mostly red and dead galaxies

~80%
Dark matter
Weak gravitational lensing

Bullet cluster
NASA/CXC/M. Weiss

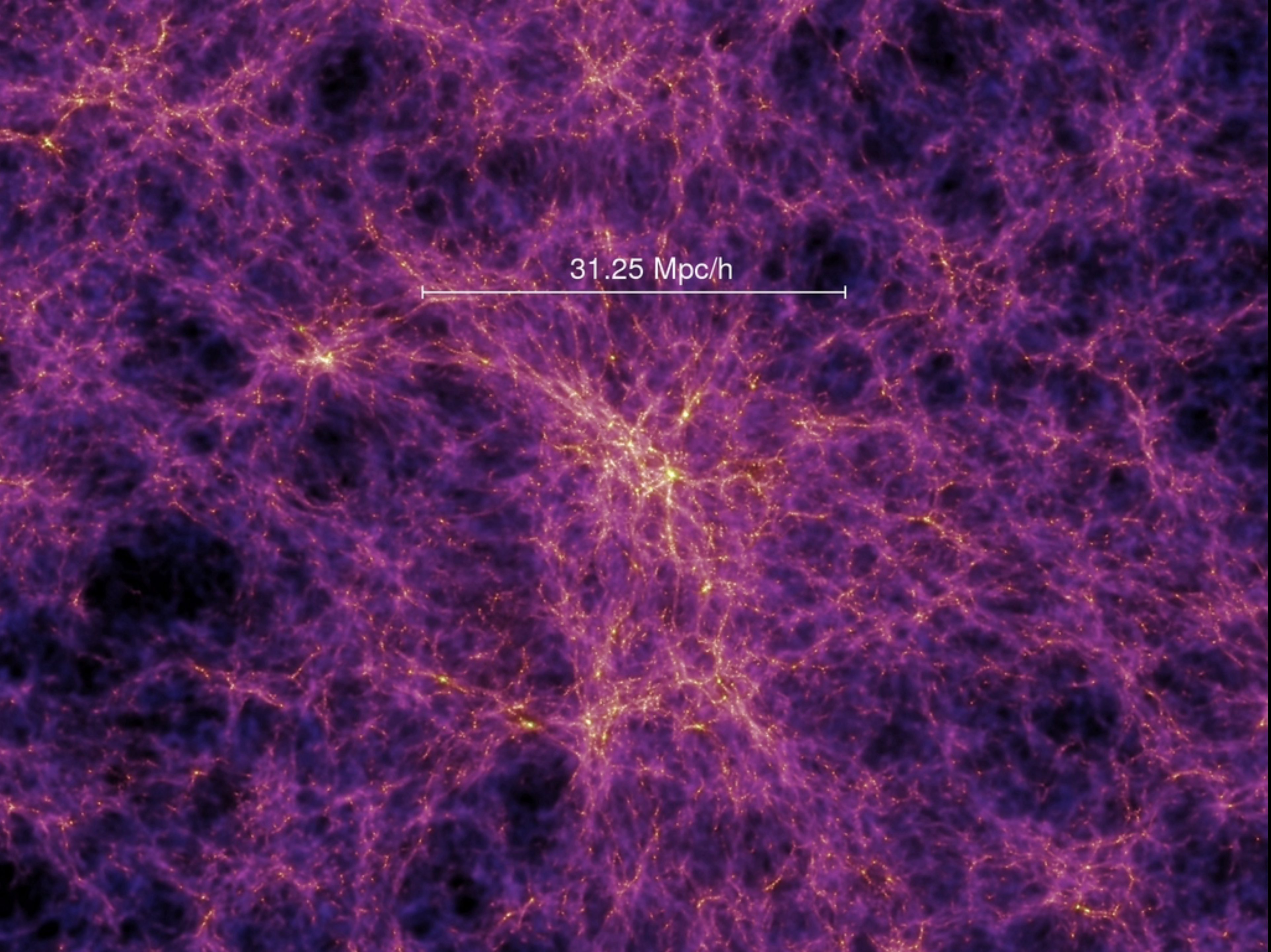


How do galaxy clusters form?

Millennium Simulation

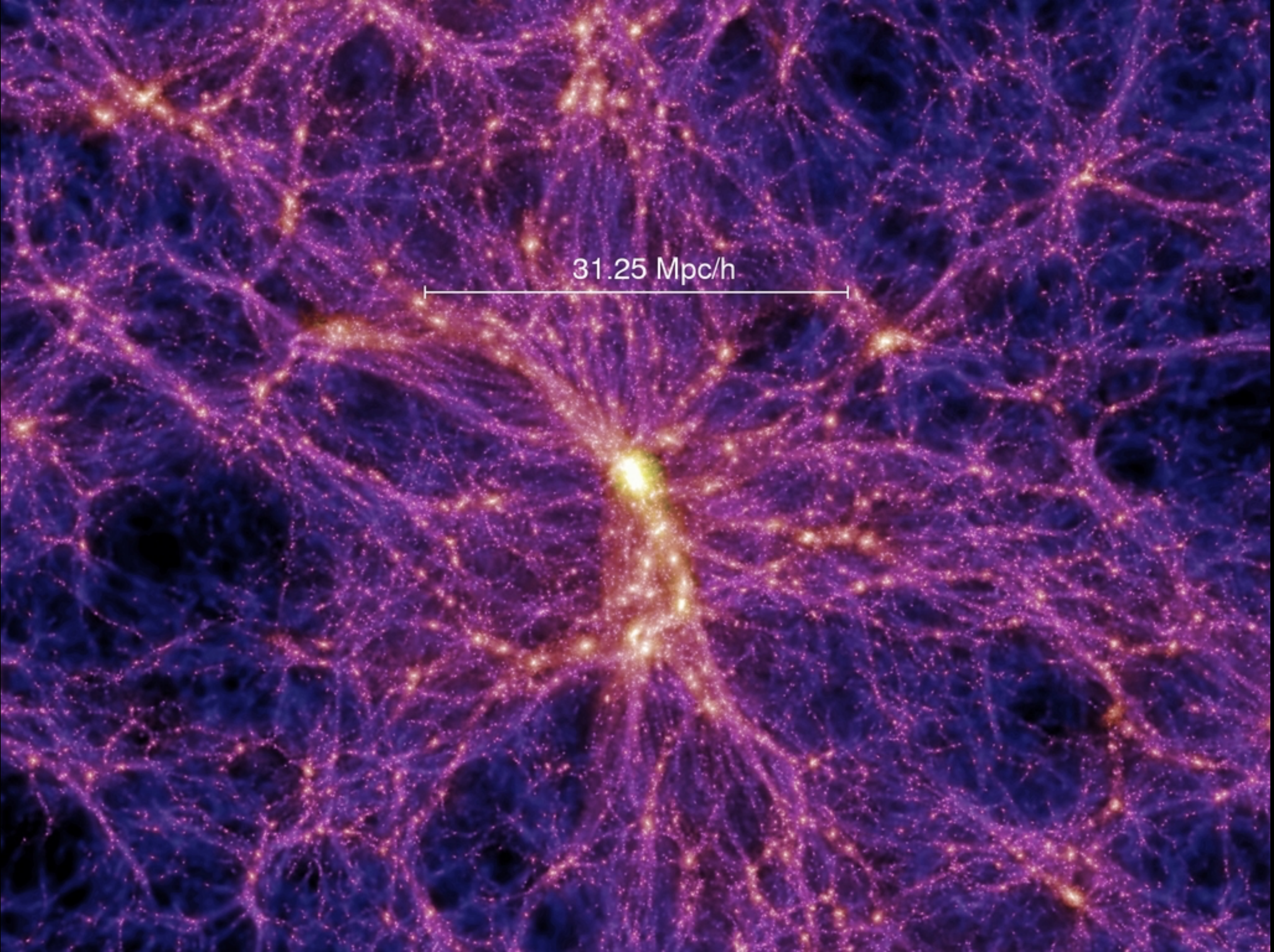
(Dark) matter is distributed isotropic and homogenous in the early Universe with random fluctuations

Springel et al. (2005)



As time progresses matter coalesces under the influence of gravity

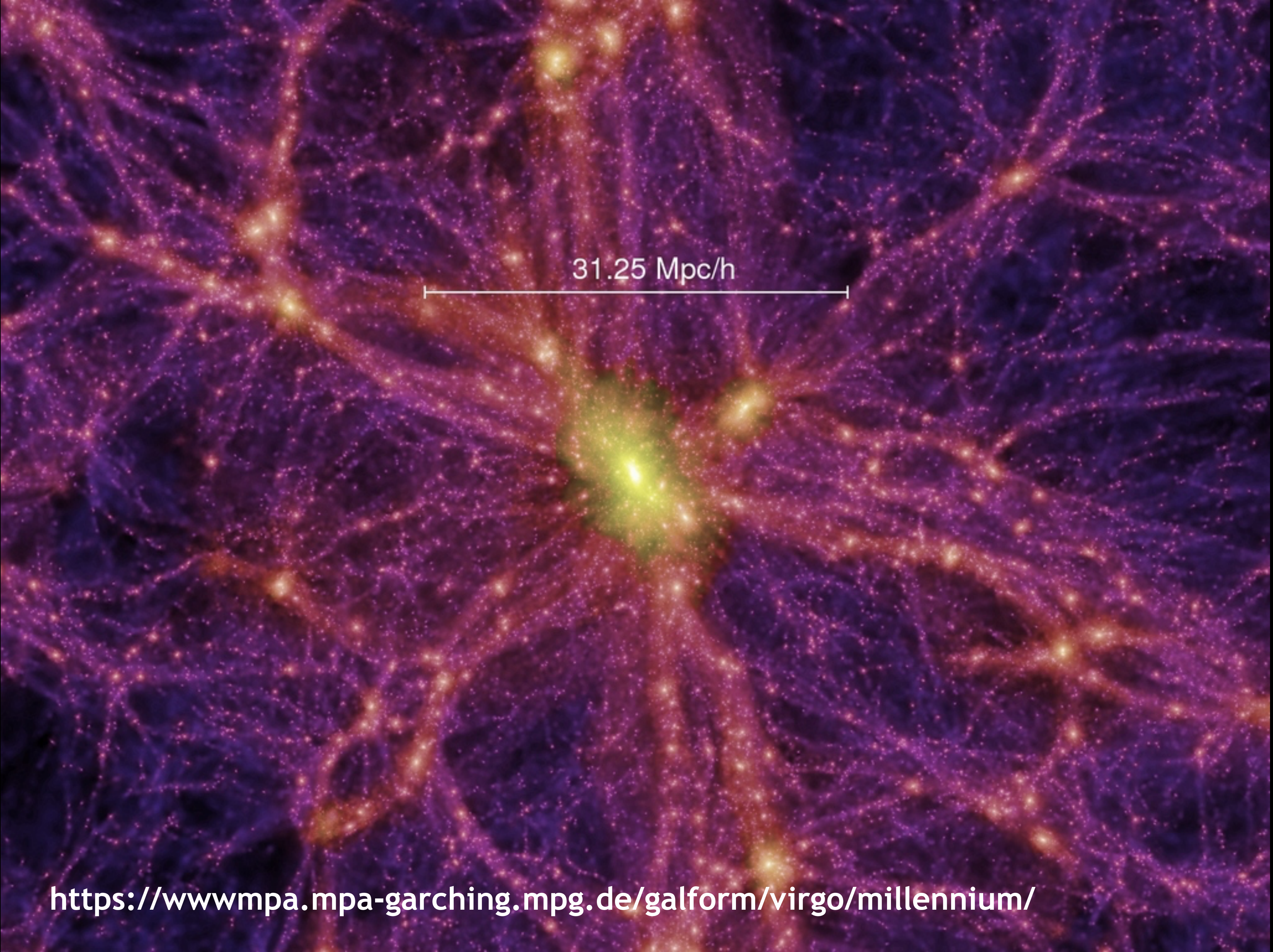
Springel et al. (2005)



Haloes of dark matter form connected by long filaments of matter

Meanwhile, dark energy pulls the entire Universe apart, impeding the growth of haloes

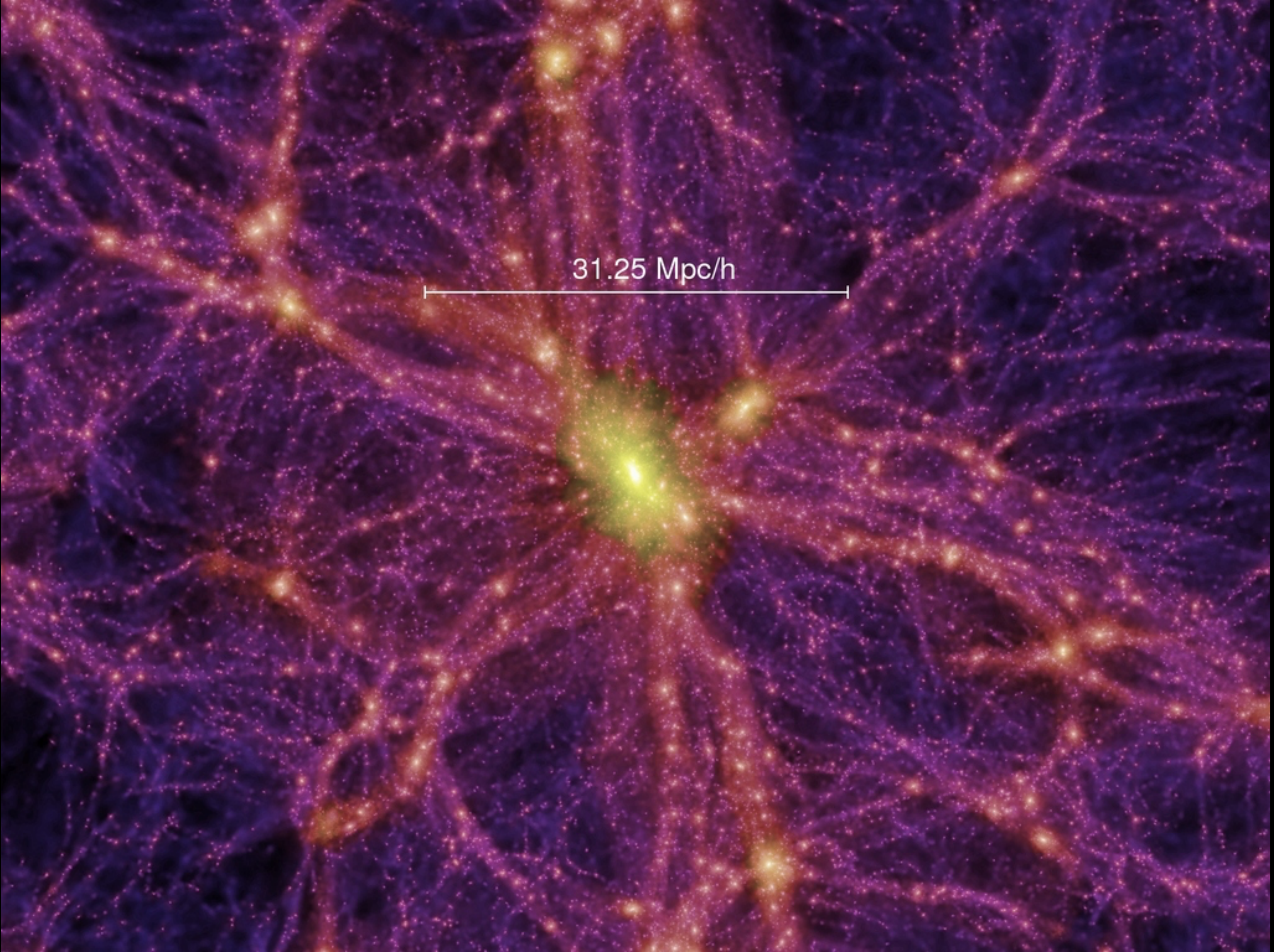
Springel et al. (2005)



Light emitting matter, attracted by the gravitational pull of dark matter haloes, follow the distribution set by the dark matter filaments

In the center a galaxy cluster is formed

Springel et al. (2005)

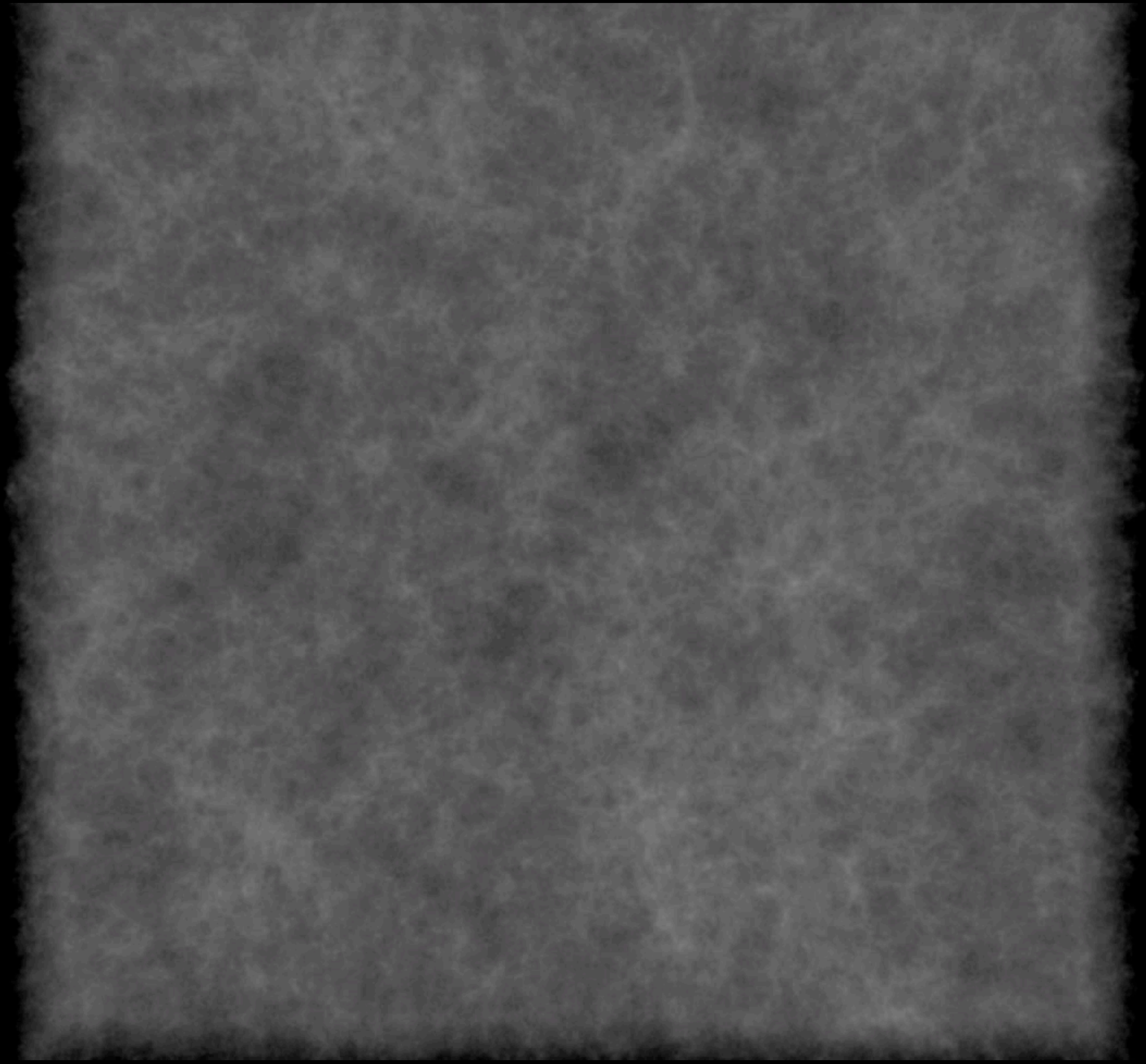


Given the large region which collapses to form a galaxy cluster, clusters are thought to have a similar composition to the entire Universe.

Measuring the dark matter mass and the mass in standard model particles in clusters determines the total dark matter content of the Universe.

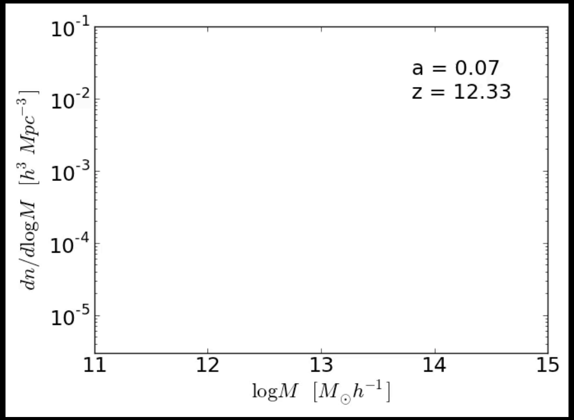
$$\left(\frac{M^{\mathrm{SM}}}{M^{\mathrm{DM}}}\right)_{\mathrm{cluster}} = \left(\frac{M^{\mathrm{SM}}}{M^{\mathrm{DM}}}\right)_{\mathrm{Universe}}$$

Counting Halos



Matt Becker, Ralf Kaehler, Yao-Yuan Mao, Rachel Reddick, Anja von der Linden, Risa Wechsler (Stanford/SLAC)

halo mass function



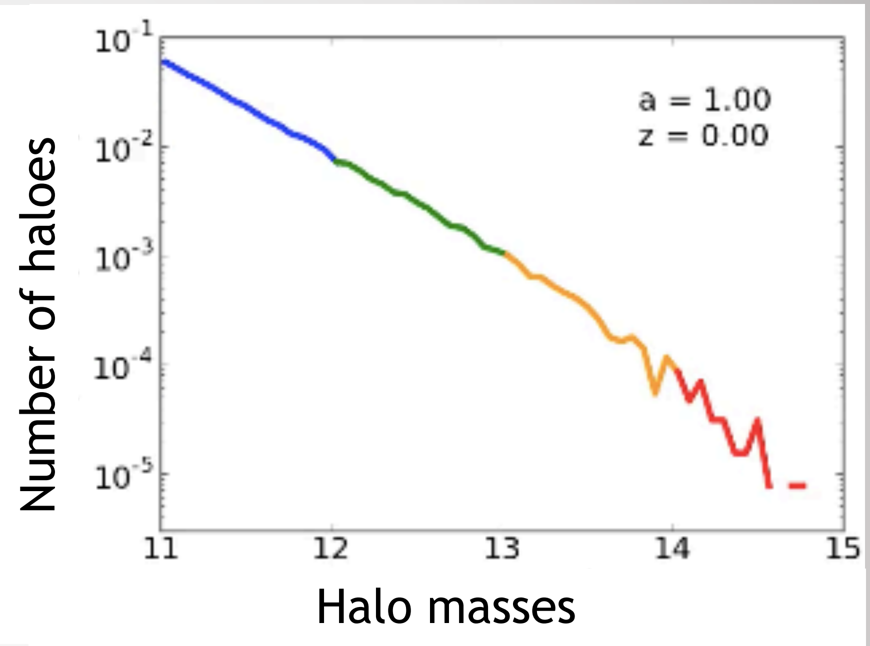
- number of gravitationally bound halos sensitive to cosmological model
- both *geometry* (volume) and *growth of structure* (evolution of mass function)

Cluster number counts

Observationally constraining the halo mass function

Galaxy clusters are rare and powerful probes

- Detect galaxy clusters
    - Sunyaev-Zeldovich effect in Planck, ACT, SPT
    - Extended X-ray sources in ROSAT, Chandra, XMM
    - Optical overdensities of (red) galaxies: redmapper, CAMIRA, …
- Scaling relation between observable and halo mass
    - Detection based on baryonic matter not easily linked to halo mass
    - Empirical relation between baryonic observable and halo mass
    - Measuring halo masses —> Weak gravitational lensing



Weak lensing cluster sample

MENeaCS

Multi Epoch Nearby Cluster Survey

Most X-ray luminous clusters in the local Universe

~50 galaxy clusters
$0.05 < z < 0.15$ $M_{200} > 10^{14}\ M_\odot$

deep *r* band CFHT observations
seeing < 0.8" $20 < m_r < 24.5$

CCCP

Canadian Cluster Comparison Project

Hoekstra et al. 2012
Hoekstra, Herbonnet et al. 2015

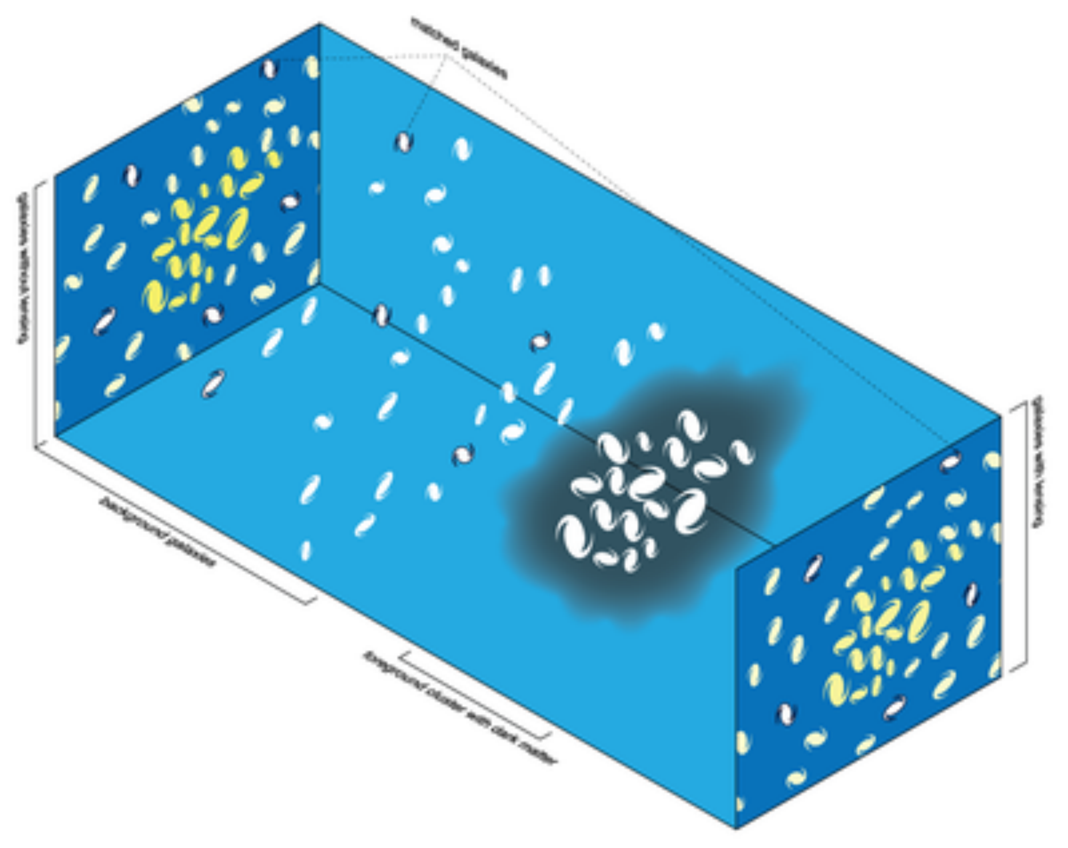
~50 galaxy clusters
$0.15 < z < 0.55$ $M_{200} > 3\times10^{14}\ M_\odot$

deep *r* band CFHT observations
seeing < 0.9" $22 < m_r < 25$

Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

Unfortunately each step of the process introduces uncertainty and error

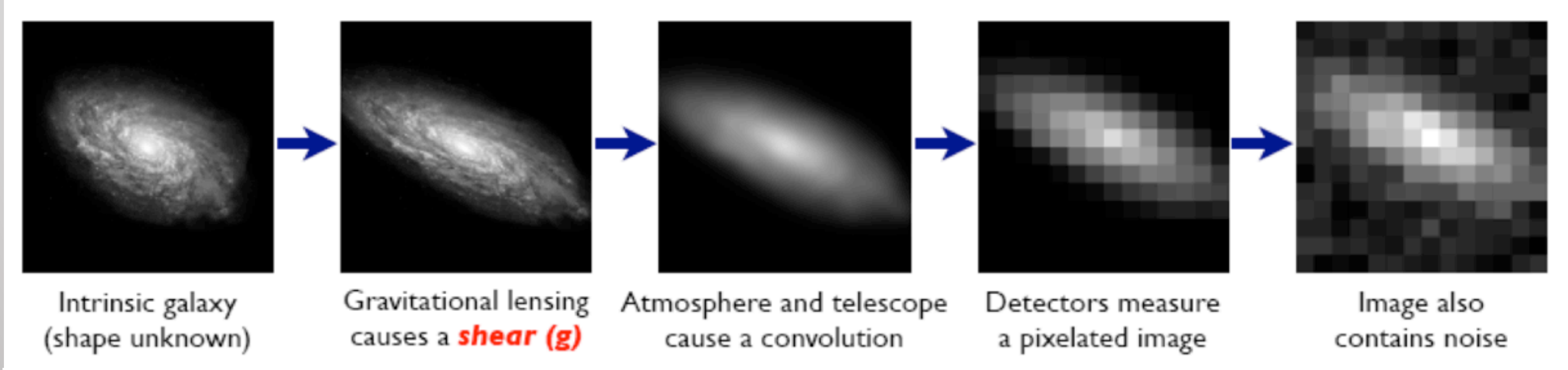


Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

~0.3 ~0.01

$$g^{est} \approx \Sigma_{gal}(\epsilon^{int} + g^{true})/N_{gal}$$



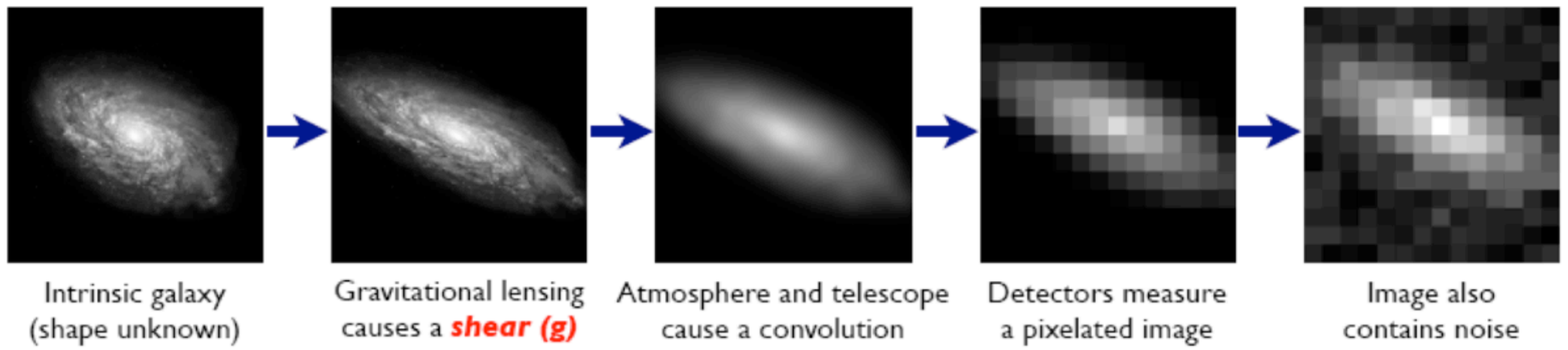
Bridle et al. 2008

Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

Calibrate shear measurement algorithm with extensive image simulations
Hoekstra, Herbonnet et al. 2015

Corrected for the effect of cluster galaxies
Sifon, Herbonnet et al. 2017

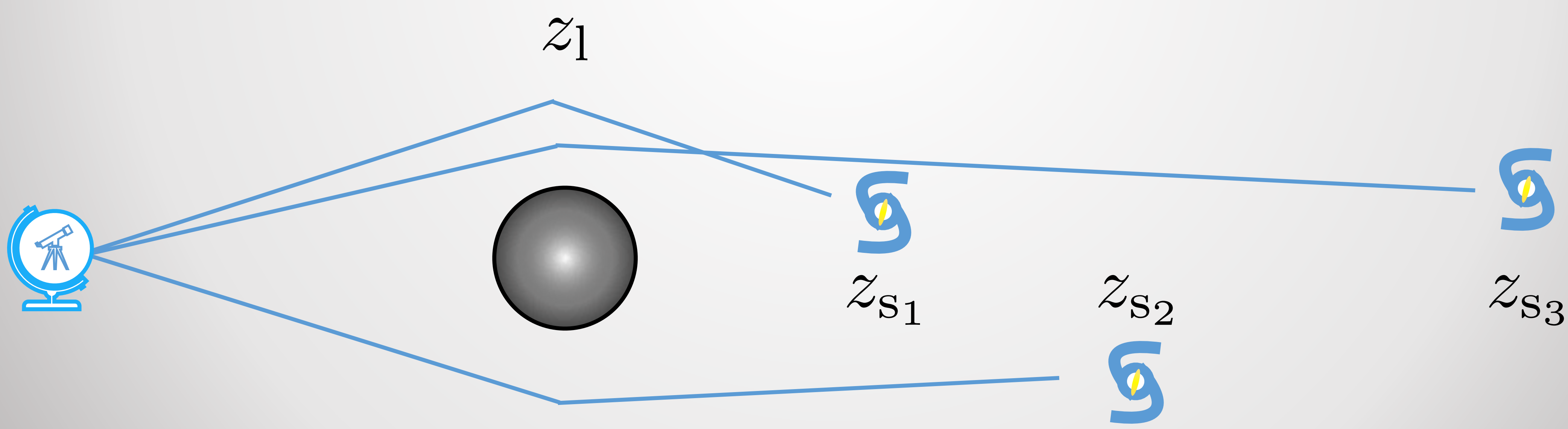


Bridle et al. 2008

Steps in cluster weak lensing

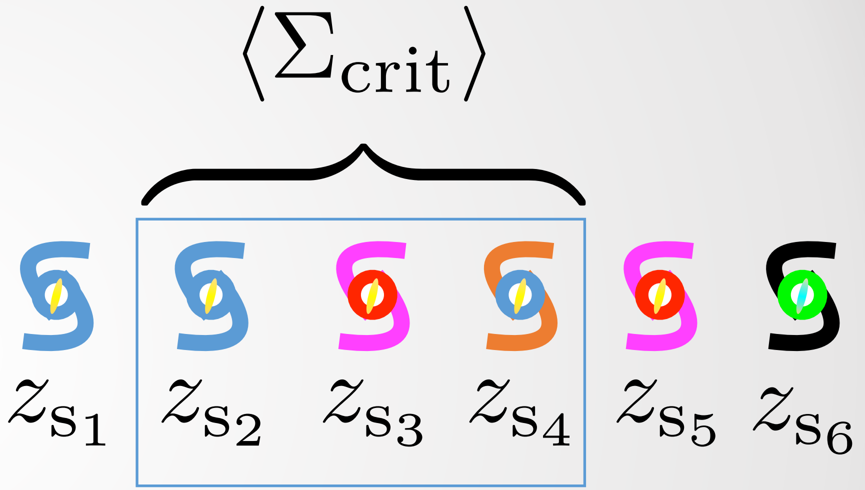
- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

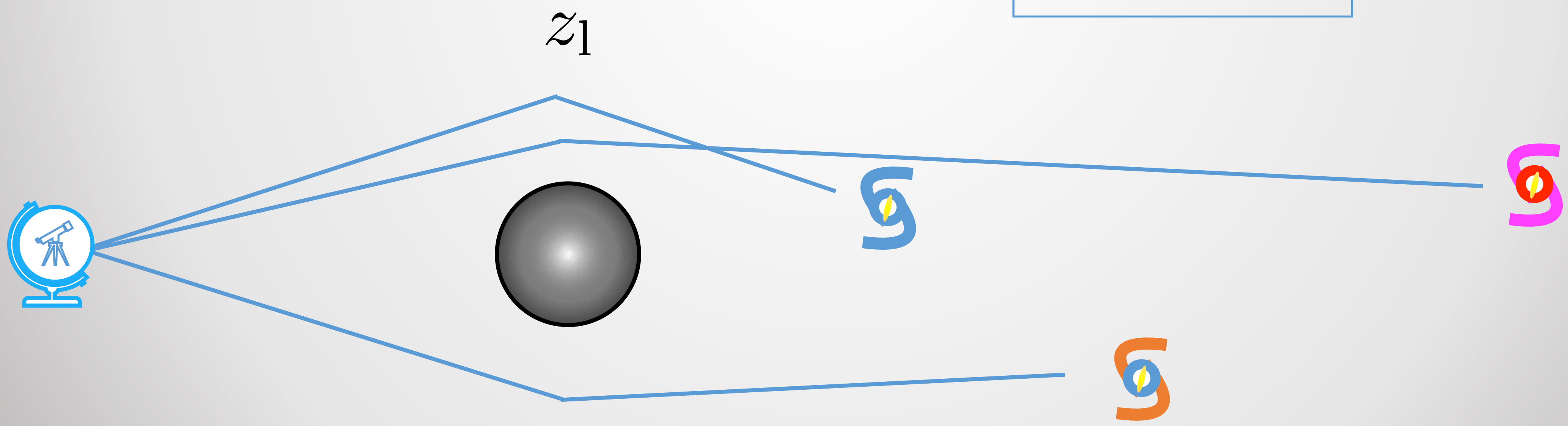
$$\Sigma_{\mathrm{crit}} = \frac{c^2}{4\pi G} \frac{D(0, z_{\mathrm{s}})}{D(z_{\mathrm{l}}, z_{\mathrm{s}}) D(0, z_{\mathrm{l}})}$$



Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination





Photometric redshift distribution

COSMOS2015 Laigle et al. 2016
2 sq. deg. 30+ filter photometry

1 sq. deg. lensing measurements
Matched COSMOS catalogue to lensing catalogue to mimic each cluster observation

1 sq. deg. for $\langle \Sigma_{\rm crit} \rangle$ measurement

1 sq. deg. for Poisson errors <3%

CFHT Deep fields Ilbert et al. 2006
~4 sq. deg. 5 filter photometry

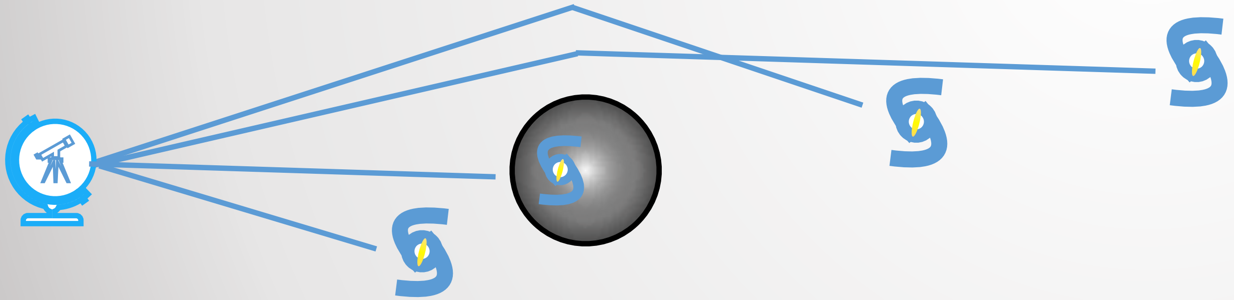
Cosmic variance <3%

UltraVista DR3 Muzzin in prep.
~0.73 sq. deg. 50+ filter photometry

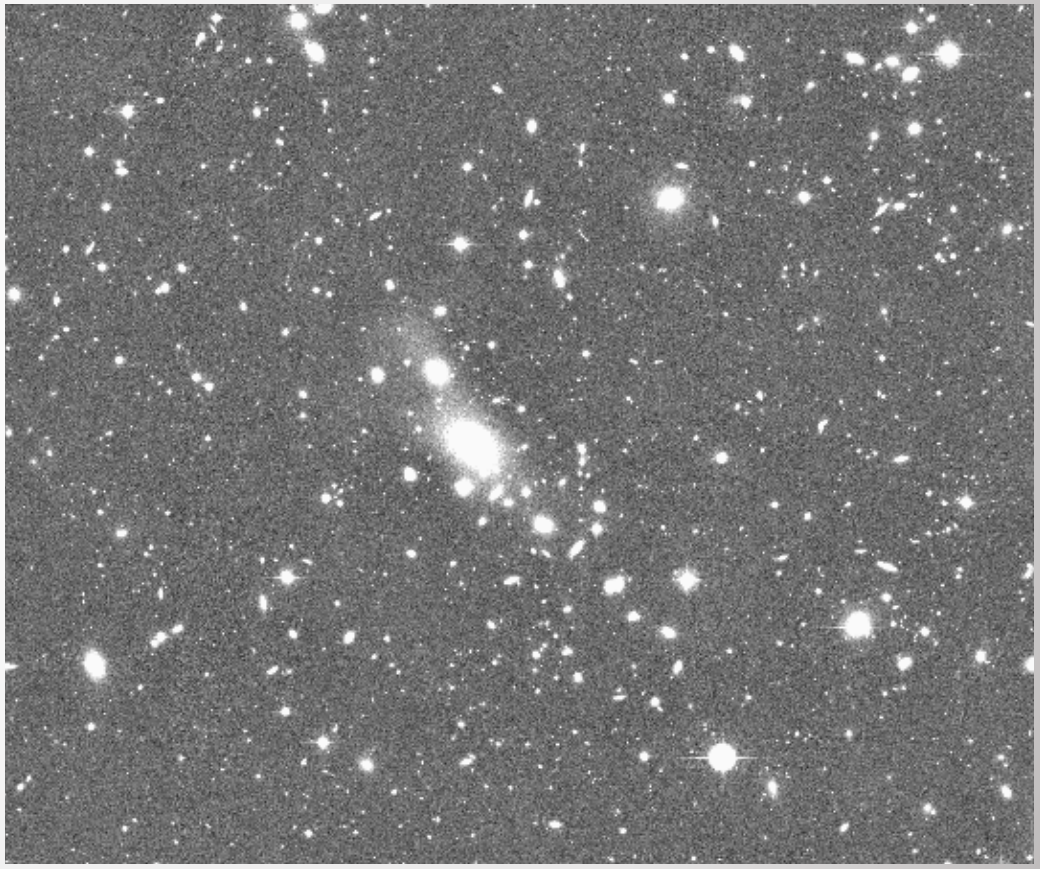
Comparison of different photo-z codes <1%

Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination



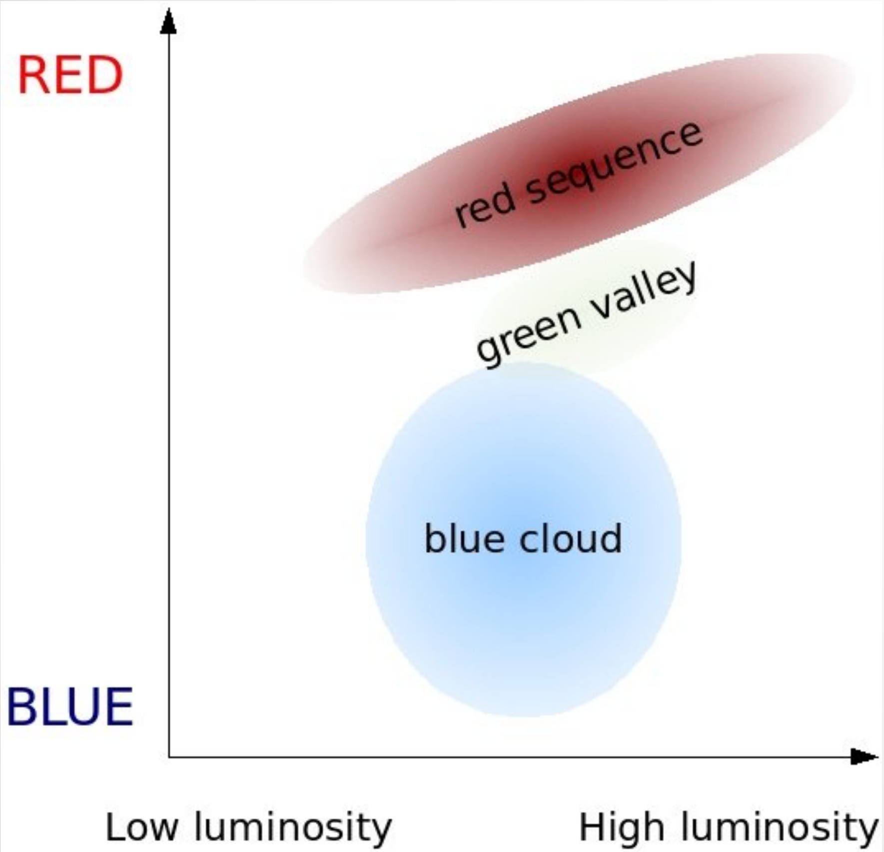
Only galaxies behind the cluster carry lensing signal
Adding other galaxies dilutes the lensing signal



Which galaxies are behind the cluster?

Colour-based selection of cluster members

Remove red sequence in cluster fields

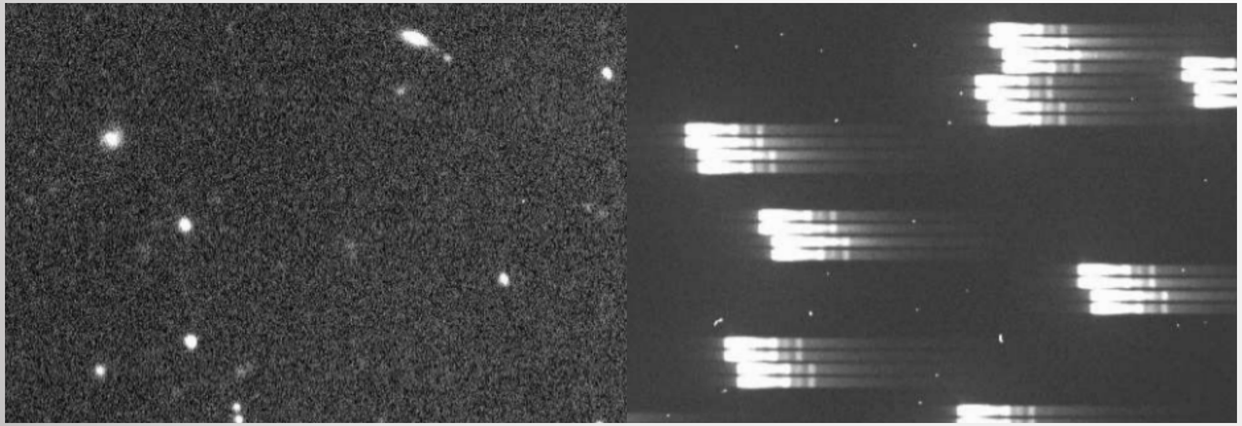


Accurate redshifts for cluster lensing

Lensing requires large numbers of (faint) galaxies

With low resolution spectra (R~20-60)
many objects can be imaged simultaneously

Combination of short spectra and photometry can increase the accuracy of redshift estimates

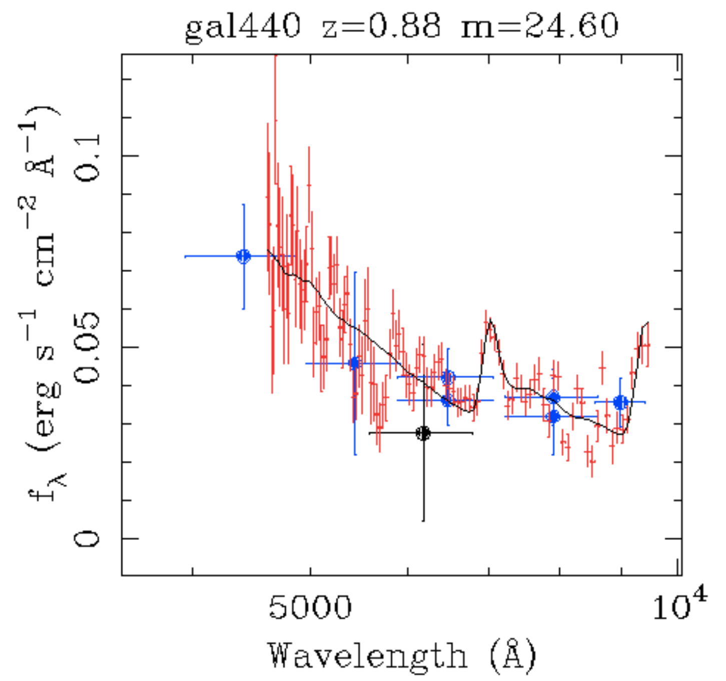


PRIMUS Coil et al. 2012

Pilot study with IMACS at Magellan

Clusters MACS0454 and RXJ2248

Galaxies down to 25th magnitude



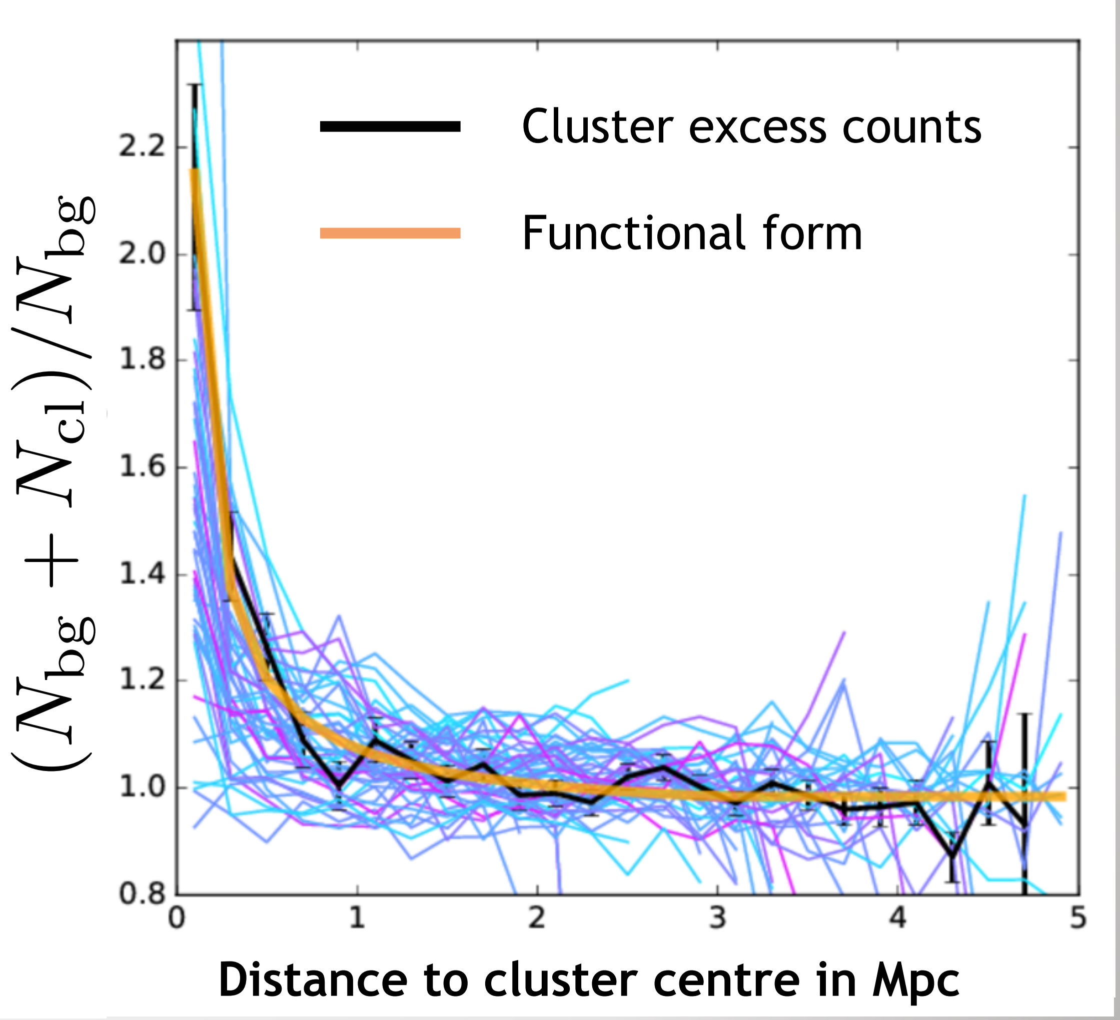
Preliminary result

Contamination by cluster members

Contamination of the source sample lowers the shear signal proportional to the number of cluster galaxies

Measure the fraction of cluster galaxies to correct for contamination

Fit a functional form to individual clusters with which to boost their shear signal

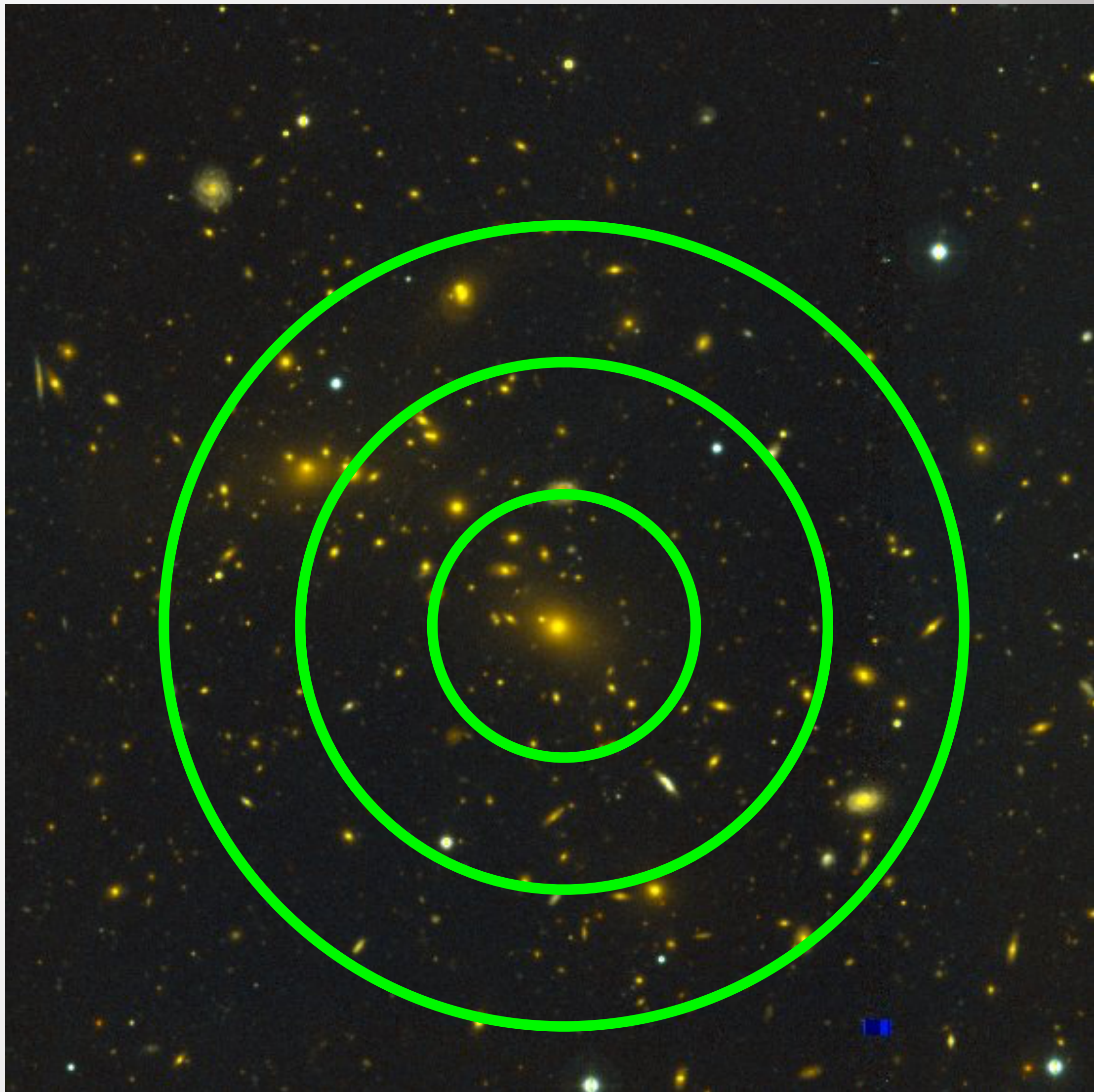


Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

Cluster centre:
brightest cluster galaxy
centre of the X-ray profile

Agree on centre for our sample



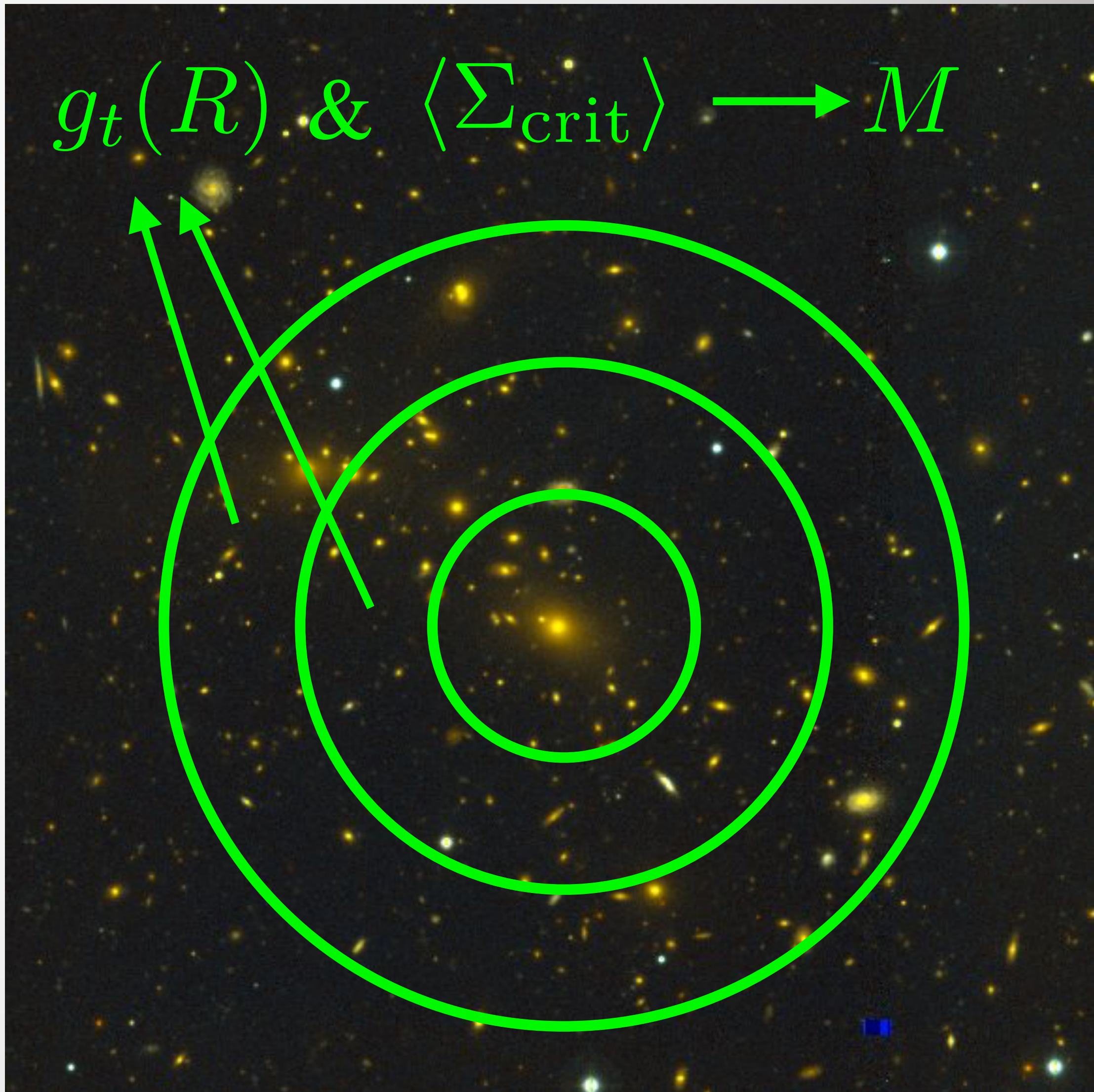
Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

Mass modelling:
Fit a spherical NFW density profile

Mass distribution of dark matter haloes determined from numerical simulations

Fits well to the data on average for certain regions of the haloes



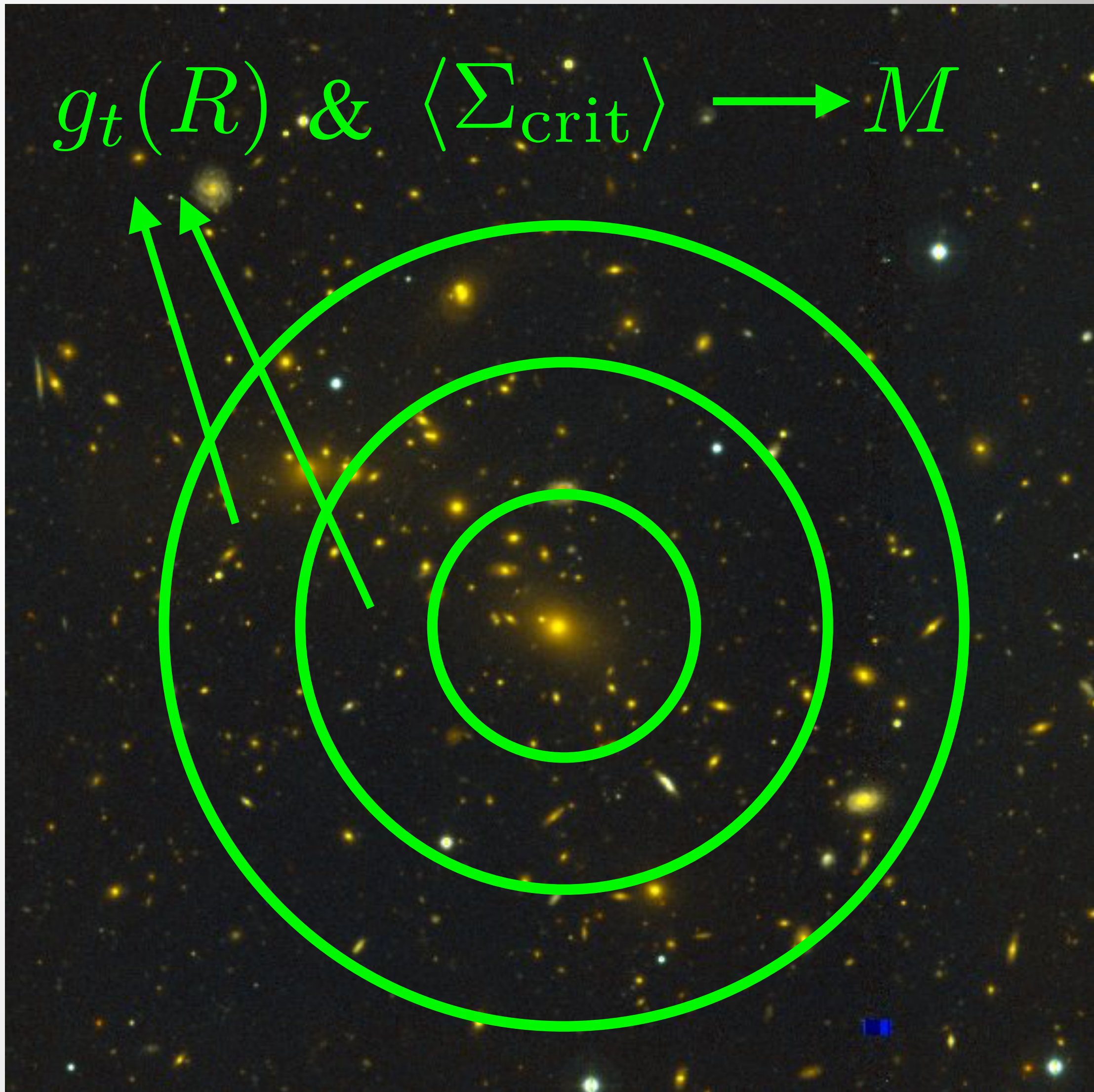
Steps in cluster weak lensing

- Shear measurement
- Photometric redshift distribution
- Source galaxy selection
- Mass determination

Mass modelling:
Deprojected aperture masses

Compute 2D mass in an aperture based on assumption on convergence profile

Compute 3D mass by assuming an NFW mass distribution along the line of sight



Mass determination

Aperture mass

Projected average surface density

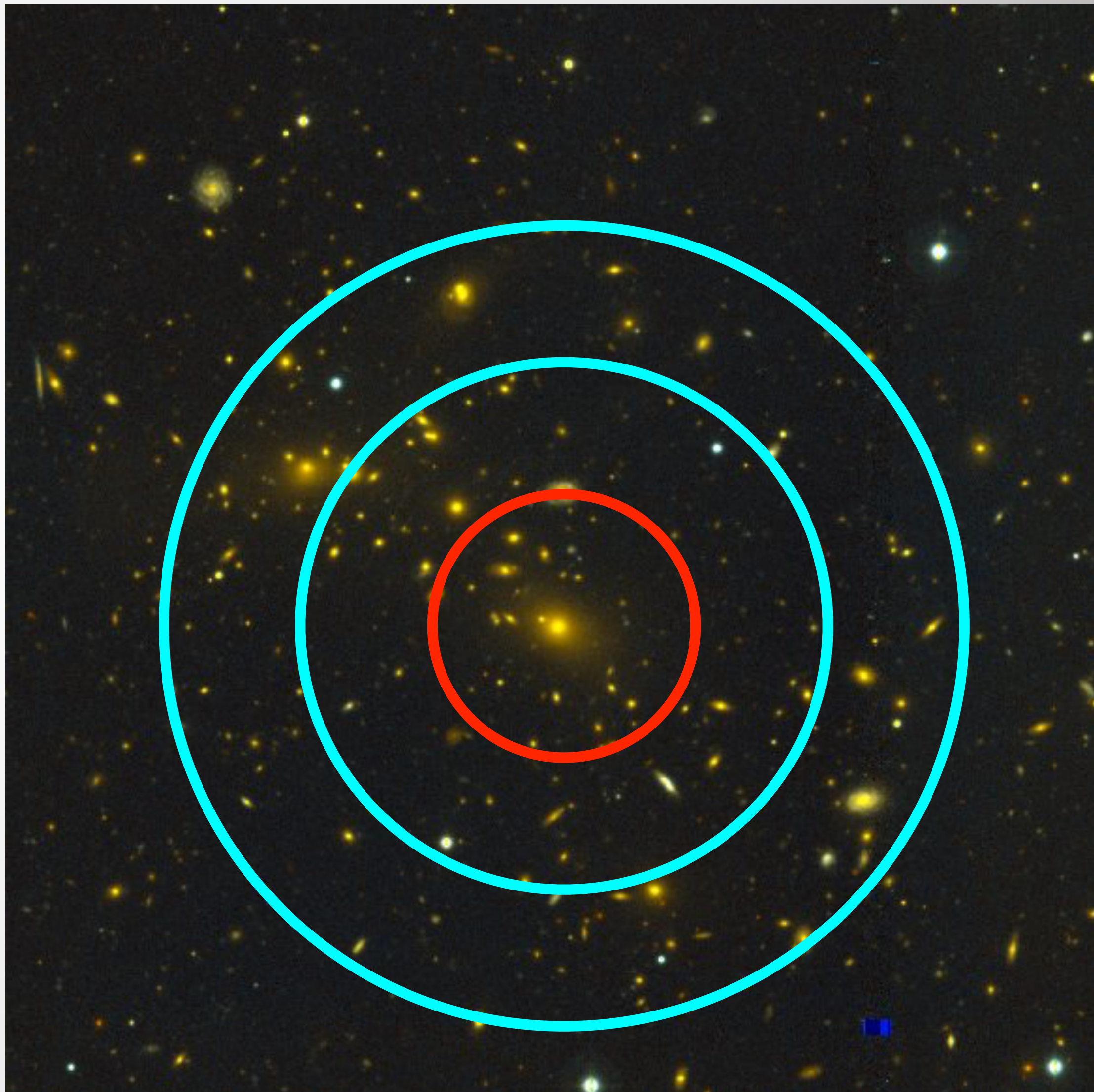
Projected average density in annulus

$$\boxed{\overline{\kappa}(r \le r_1)} - \boxed{\overline{\kappa}(r_2 < r \le r_{\max})} =$$

$$\boxed{\begin{array}{l} 2\int_{r_1}^{r_2} \langle \gamma_t \rangle d\ln r + \\ 2(1 - r_2^2/r_{\max}^2)^{-1} \int_{r_2}^{r_{\max}} \langle \gamma_t \rangle d\ln r \end{array}}$$

Compute from shear measurements

Deproject assuming NFW along the line of sight



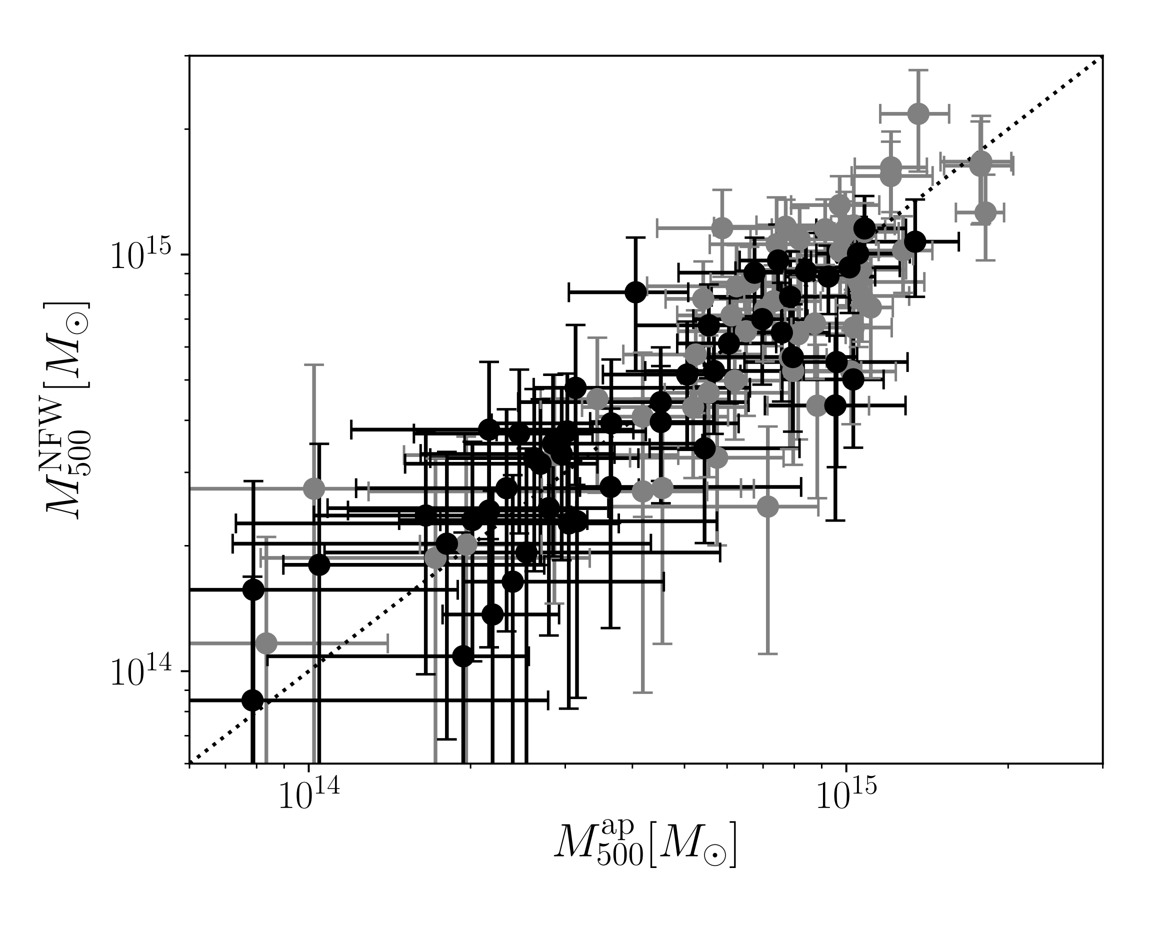
Mass determination

Comparison between mass estimators

Good agreement between deprojected aperture masses and NFW masses at M_{500}

Fit ranges:
NFW determined between 0.5 — ~2 Mpc
Aperture masses determined from >~1 Mpc

Confidence that mass estimates are reliable



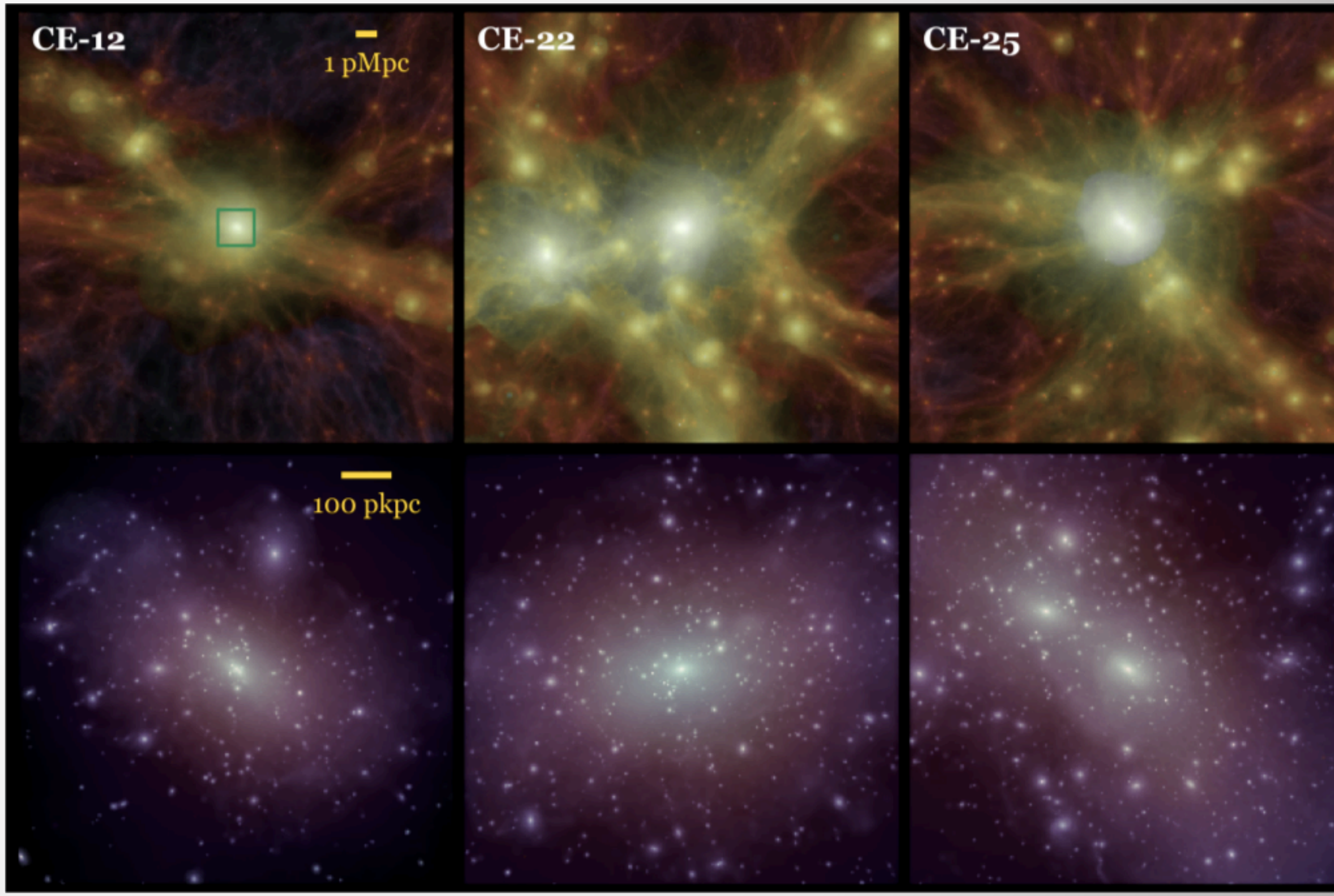
Mass determination

Assess on realistic simulations of clusters

HYDRANGEA (Bahé et al. 2017) are high resolution hydrodynamical simulations of clusters with baryonic and dark matter

Checked mass estimation pipeline on HYDRANGEA cluster simulations

Quantitatively we find
~5 +/- 3% bias for NFW masses
~3+/-2% bias for aperture masses



Cluster cosmology

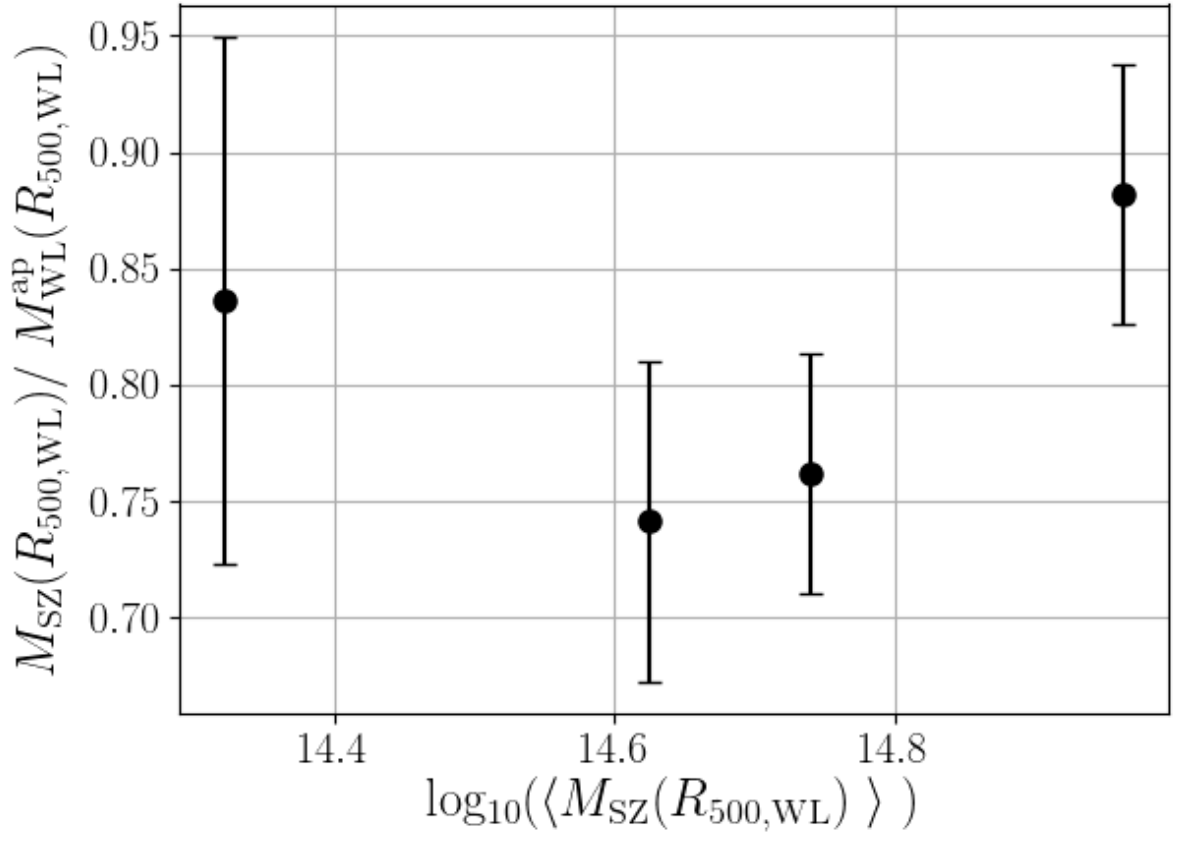
Planck has measured SZ masses for hundreds of clusters

- SZ masses are biased estimates of true cluster mass
- WL masses are imprecise estimates of true cluster mass
- Use WL to calibrate SZ masses

Consistent with 0.8, used for the 2015 *Planck* cosmological analysis

Higher than 0.71+/-0.10 of the reanalysis by Zubeldia & Challinor (2019)

No significant trend with mass



Preliminary result

Cluster cosmology

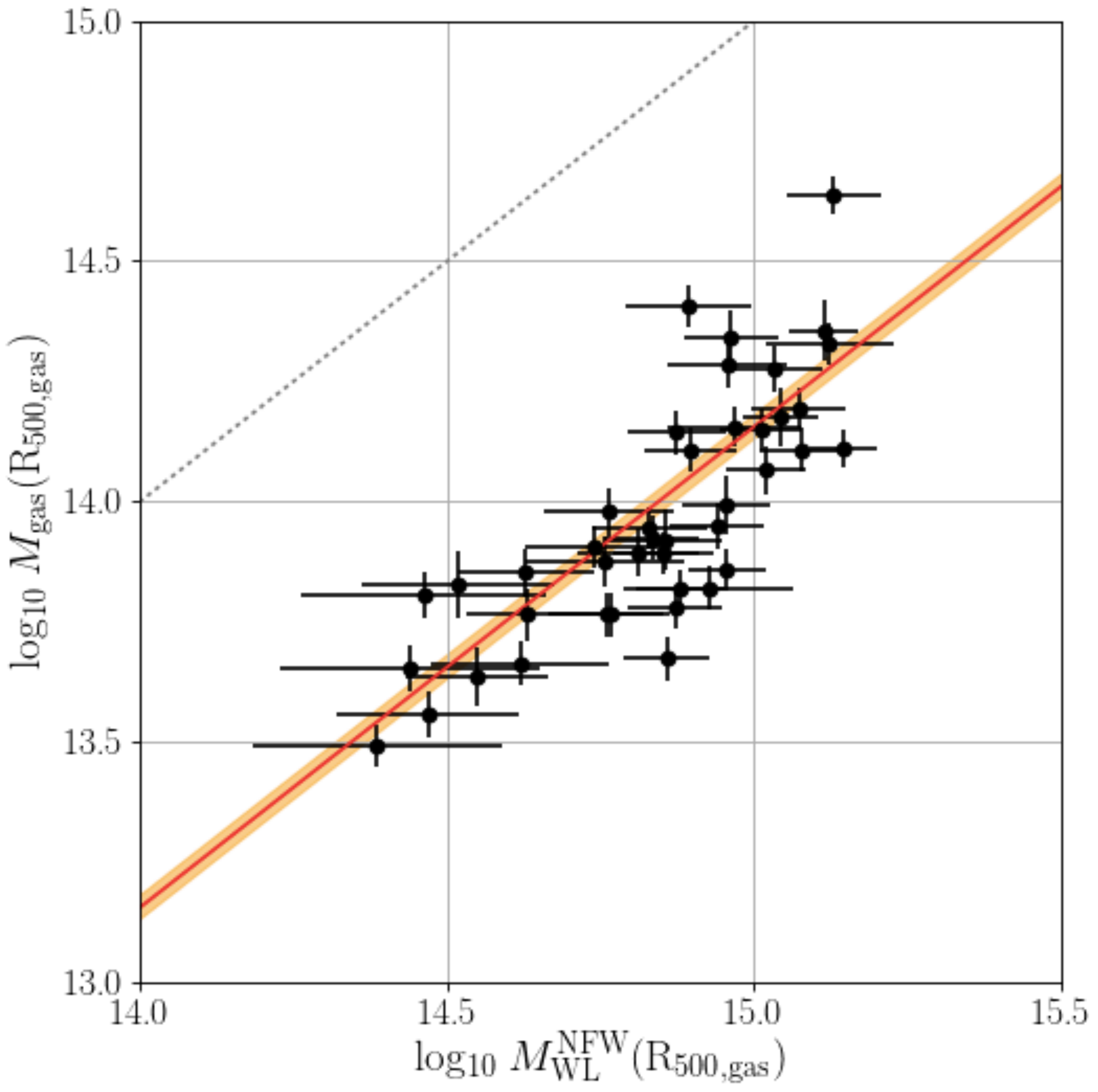
Mantz et al. have measured the mass of the gas content in clusters

44 are in our weak lensing sample

Slope = 0.143 +/- 0.008

12 out of 44 are relaxed clusters

Gas fraction in relaxed clusters can be related to total amount of mass in the Universe Ω_m



Preliminary result

Weak gravitational lensing of galaxy clusters

Challenges

- Shear measurement
  ~2% uncertainty
- Redshift distribution
  ~4% uncertainty
- Contamination
  ~2% uncertainty
- Mass determination
  ~2% uncertainty

MENeaCS + CCCP

Great sample to constrain scaling relations with other mass proxies

- Range in masses and redshifts

Cluster lensing with single filter observations are possible

- Good news for Euclid

Look forward to cluster physics and cosmology