Yes!

We Can Realize the Cosmological Potential of Galaxy Cluster Surveys with Multi-wavelength Surveys

Next-generation analysis methods for modern surveys

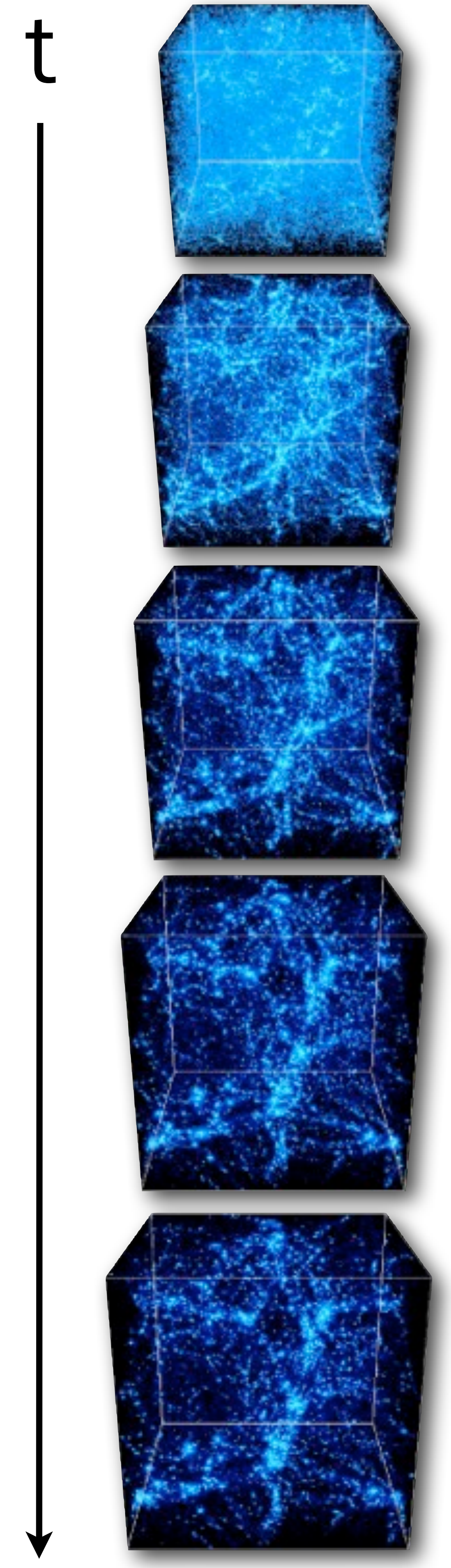
Brian Nord

with
T. Mckay, J. McMahon, C. Miller
T. Biesiadzinski, B. Moreland, E. Rykoff

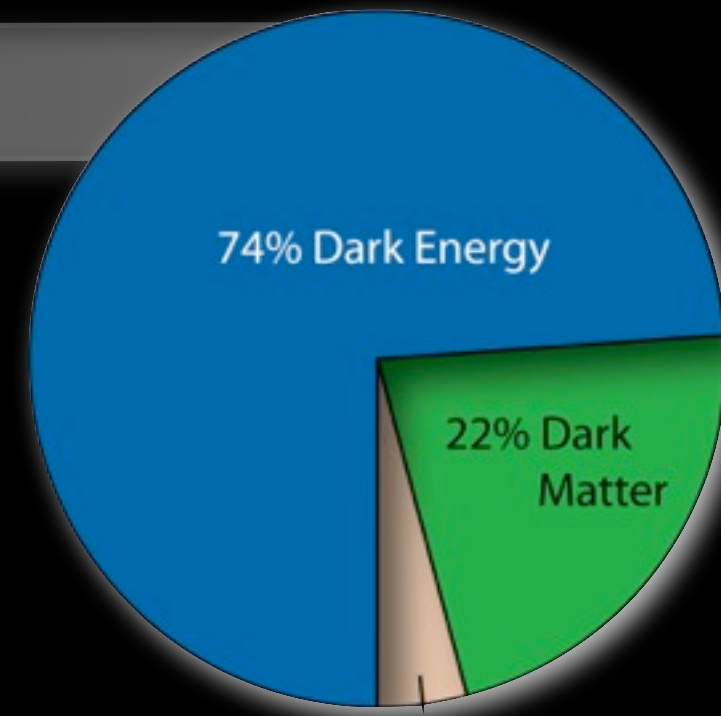
FCPA @ FNAL, Jan. 5, 2012

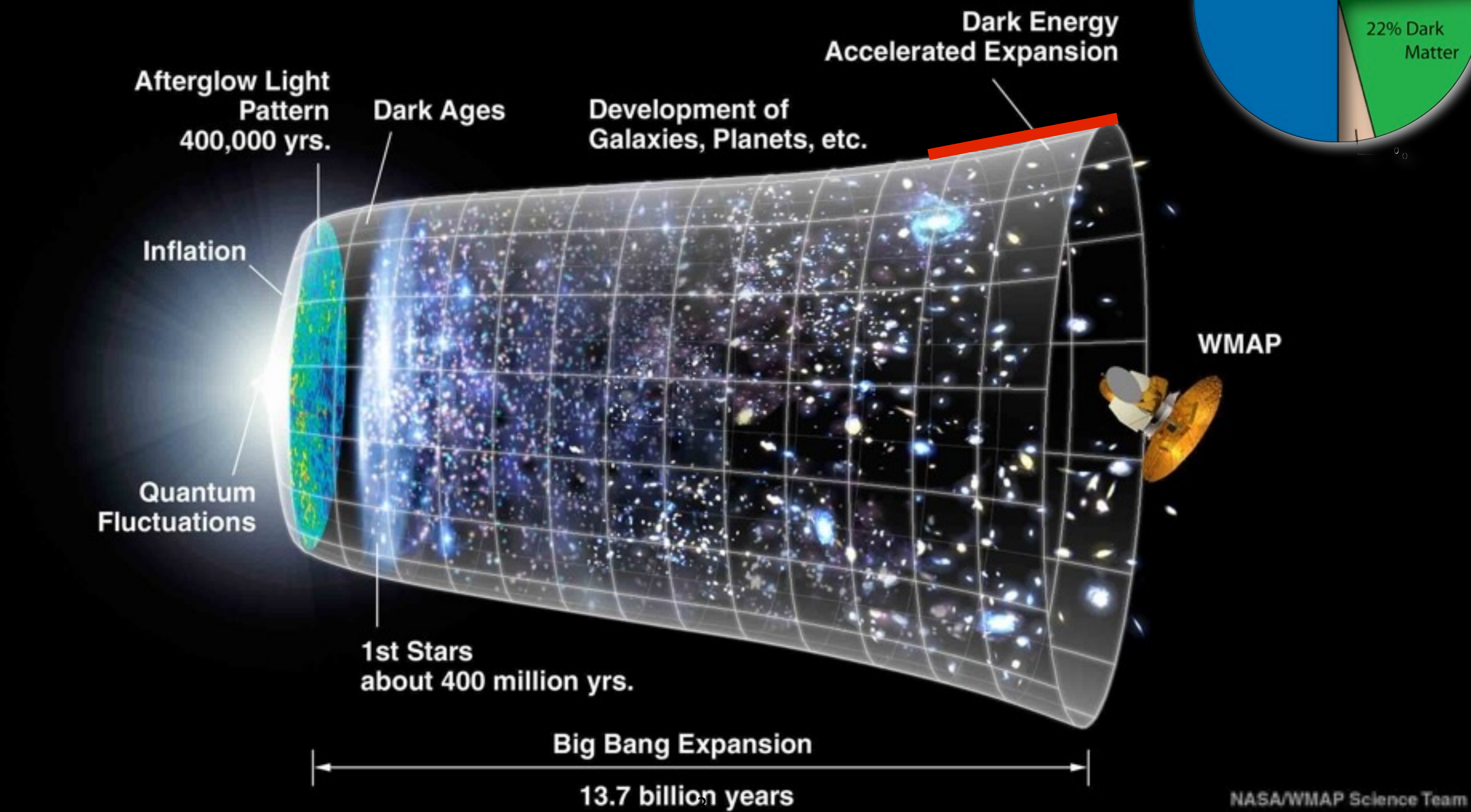
Overview: Probing dark energy with galaxy clusters

- Brief Review of Modern Cosmology
  - Dark energy: cosmological effects and physical composition
  - Probing the expansion rate with large-scale structure
- Clusters of Galaxies and DM Halo Counterparts
  - how do they teach us about expansion?
  - Connecting observables and mass
- Maximizing Output of Multi-wavelength Surveys
  - Multi-wavelength Mass calibration
  - Detecting cluster centers and substructures
  - *Joint-wavelength* cluster analysis



Cosmology today





The nature of dark energy: evidence for the modern paradigm

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Supernovae

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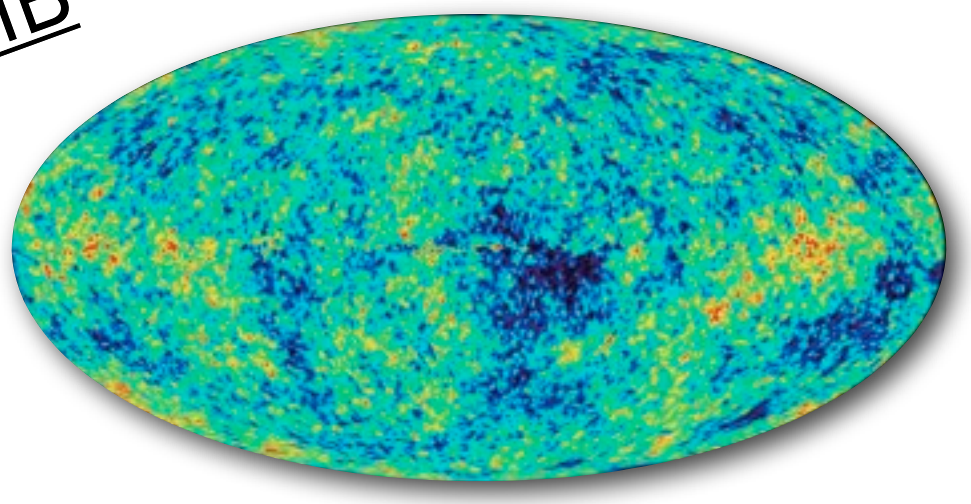

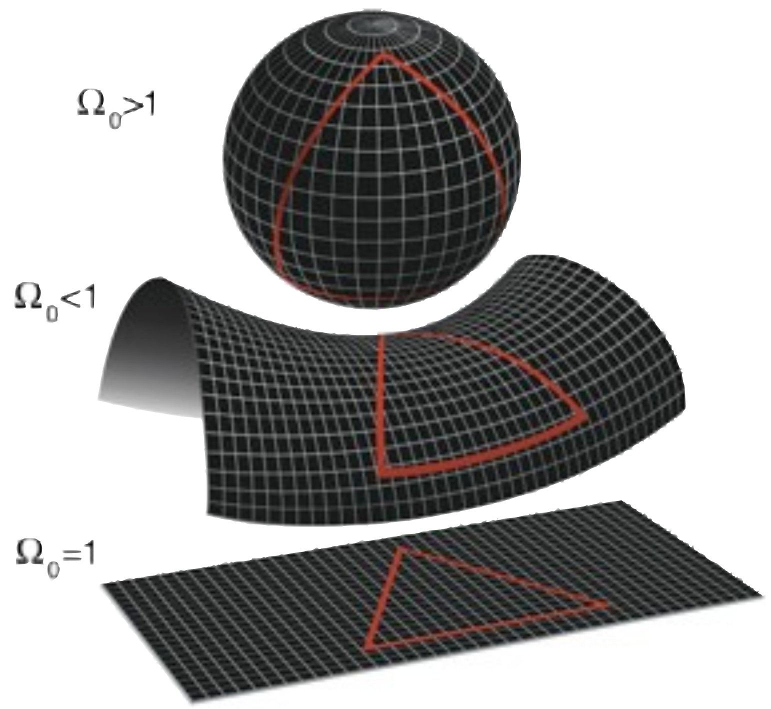

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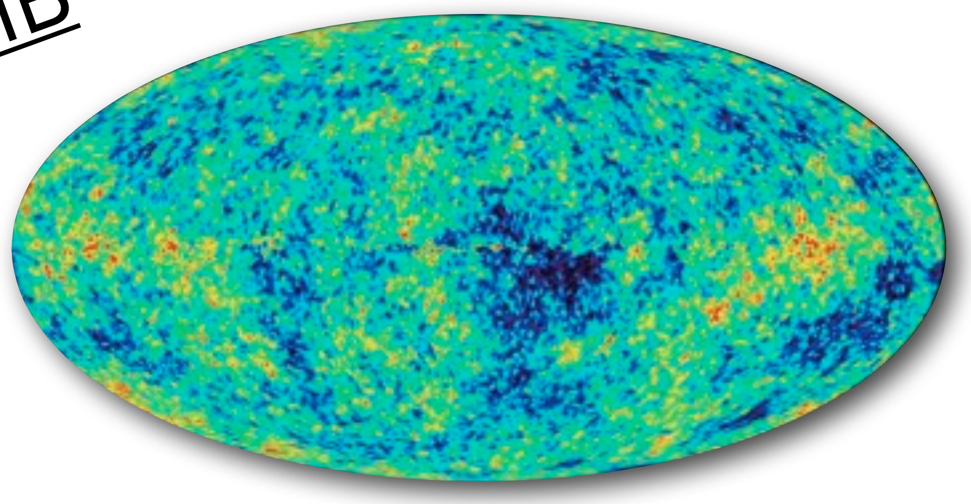

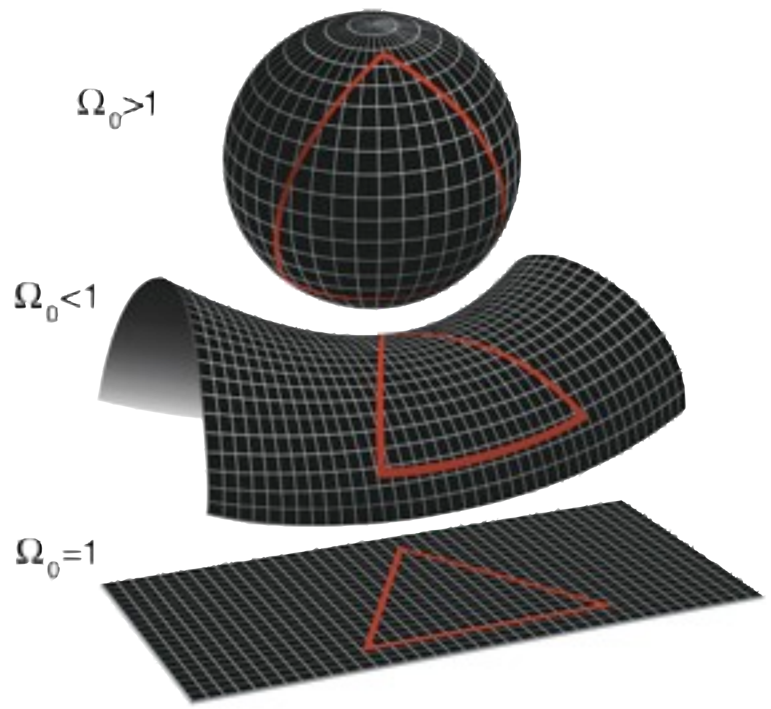

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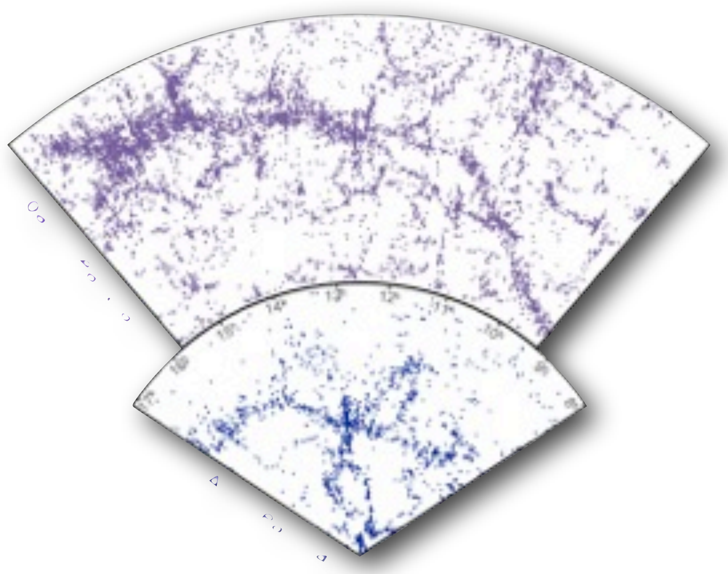

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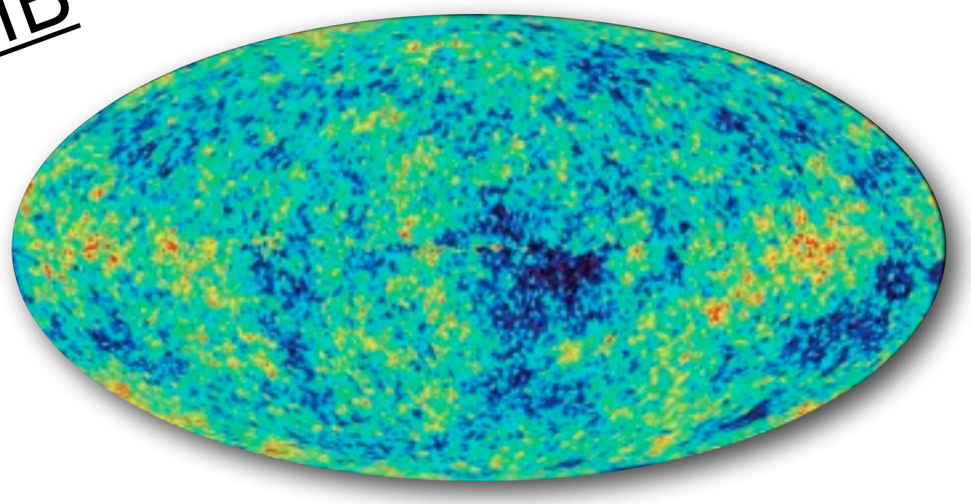

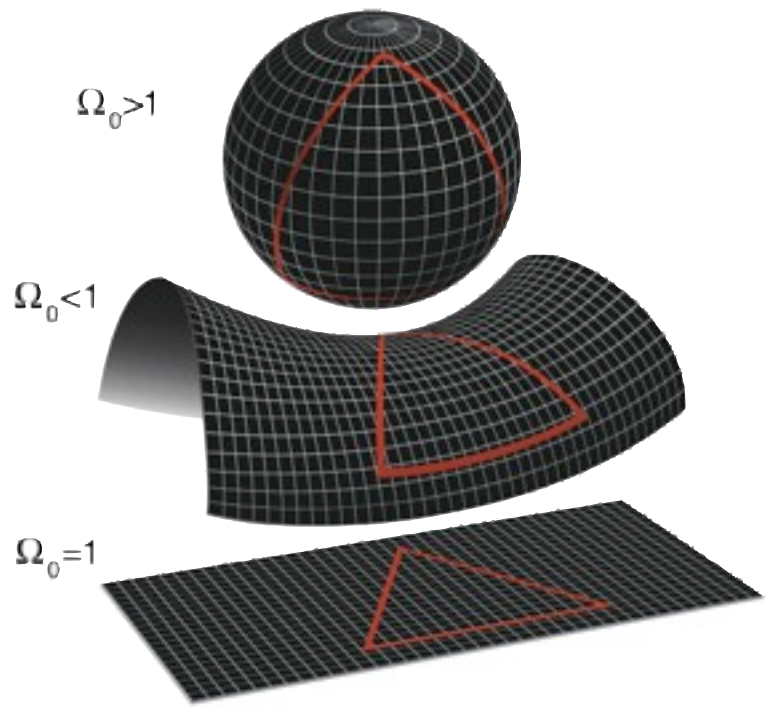

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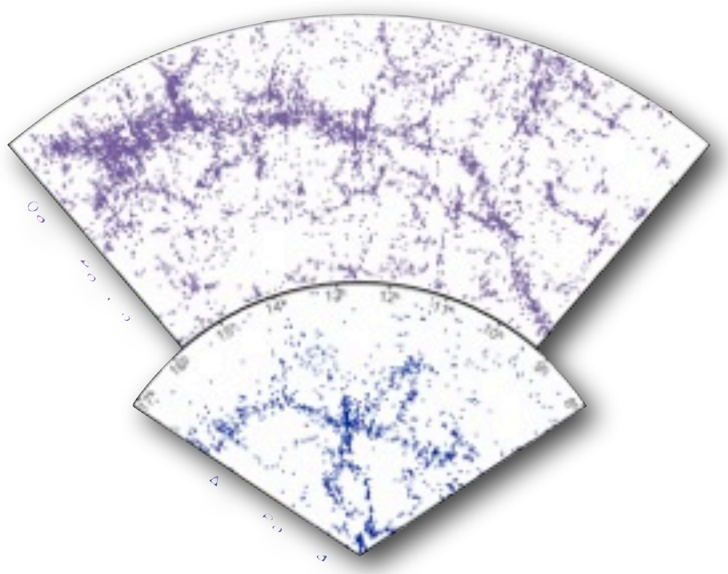
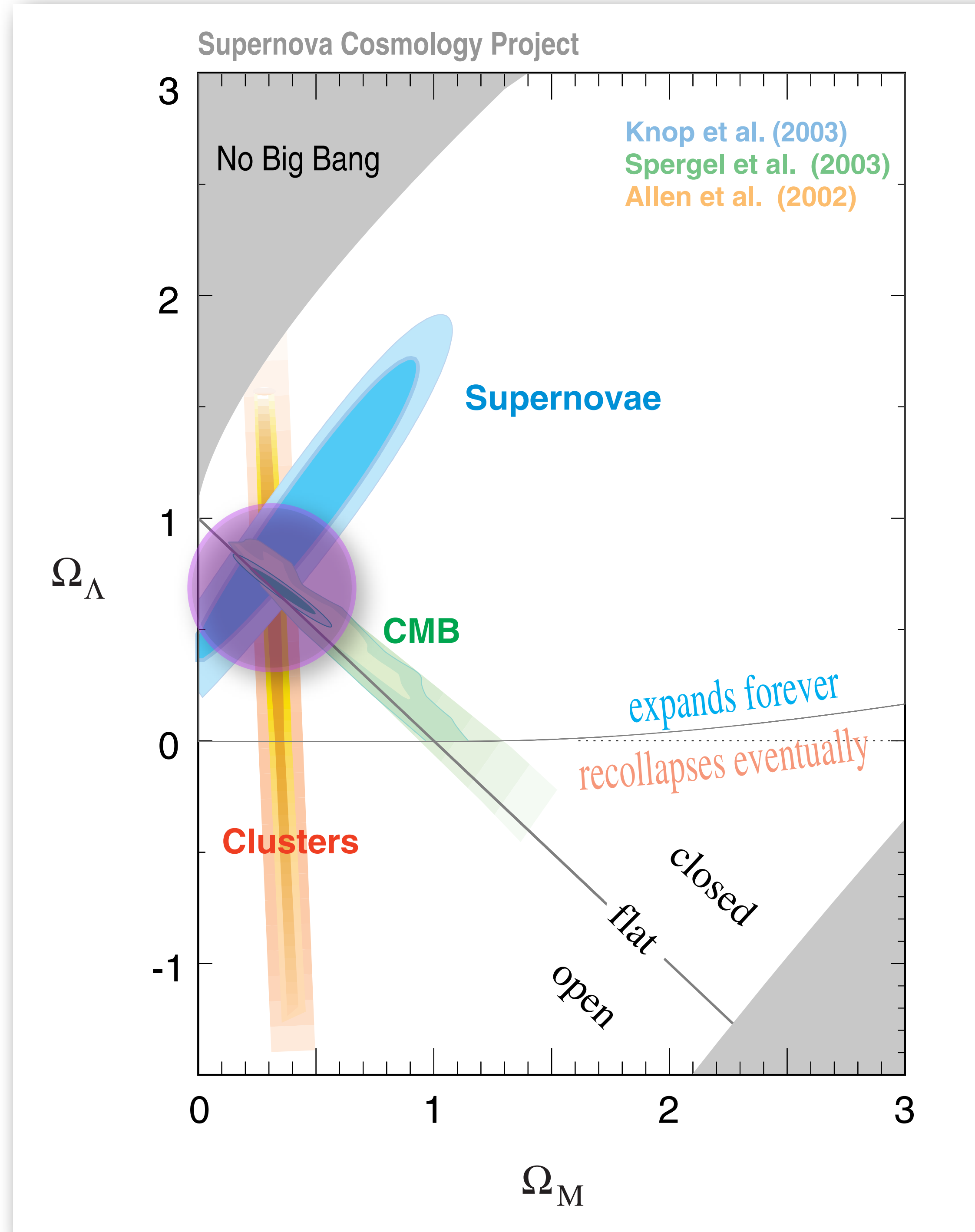
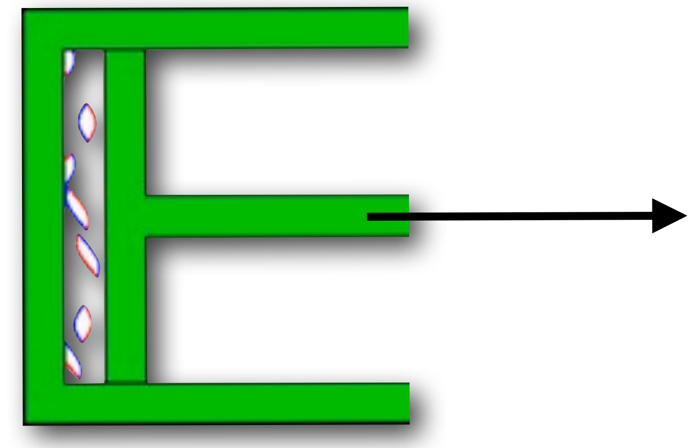




The nature of dark energy: composition and evolution



Basic Properties

Fluid with negative pressure -- **piston pulled from outside**

Isotropic, homogeneous distribution

Two Canonical Options

Constant Vacuum energy:

the cost of having space

Evolving Scalar field ("quintessence")

parametrize equation of state parameter via a constant and a slope

e.g., $w(a) = w_0 + w_a(1-a)$

$$R_{\mu\nu} - \frac{1}{2}g_{\mu\nu}R + g_{\mu\nu}\Lambda = \frac{8\pi G}{c^4}T_{\mu\nu}$$ (Einstein Field Eqn)

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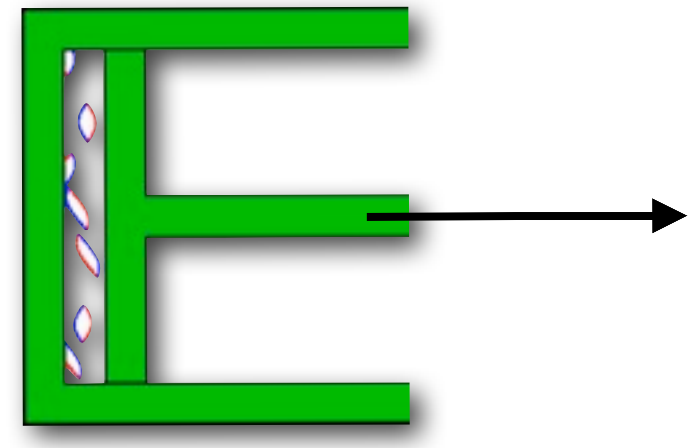

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Or Einstein's work is not finished!

Dark energy modifies the formation of structure.

Two Universes, both just like ours, except for the dark energy parameter.

<u>Parameters</u>

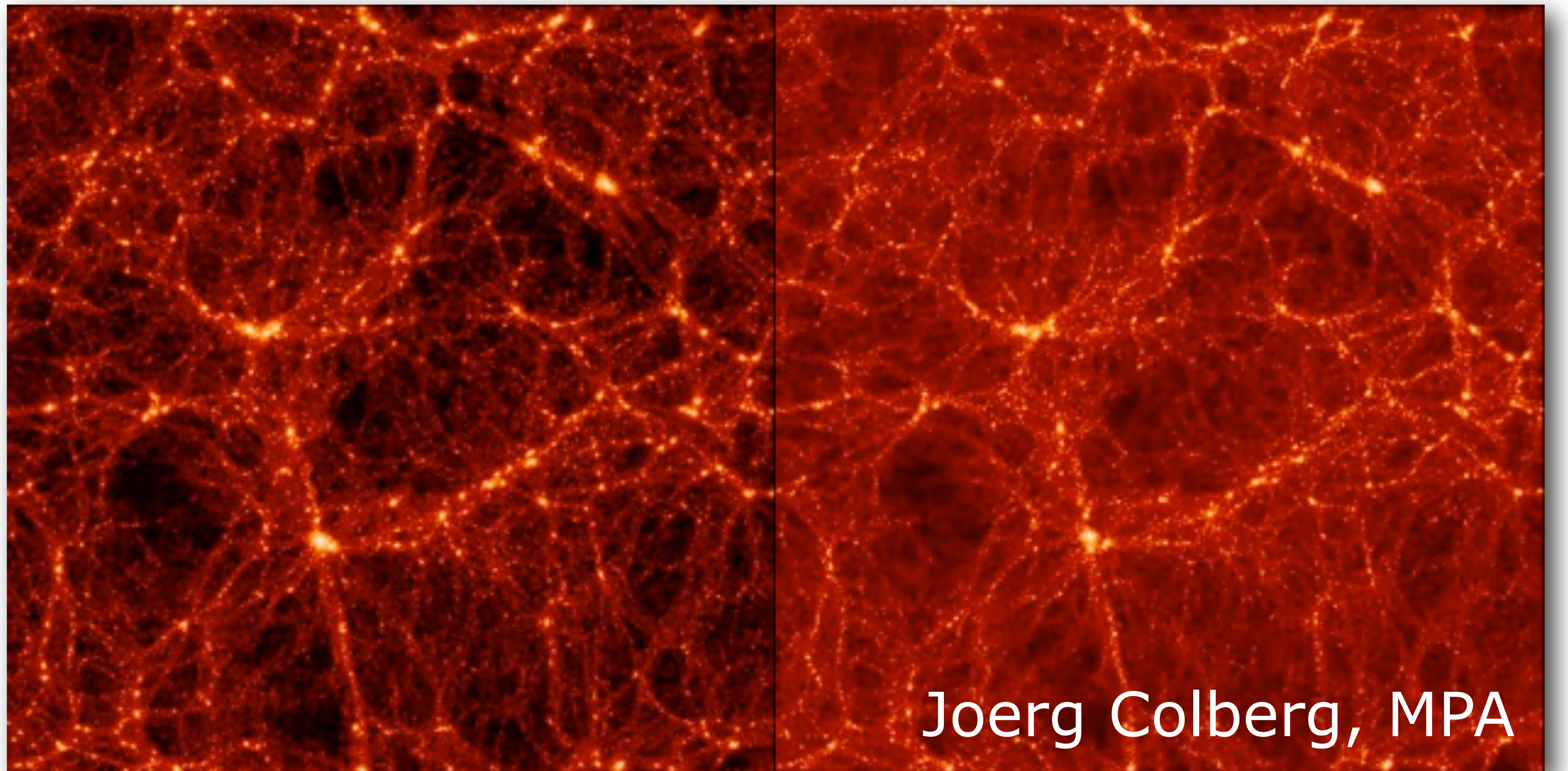
Ω_m=0.30

σ_8 = 0.85

H_0 = 70.0 [km/s/Mpc]

Ω_Λ = ?

Can you tell the difference?



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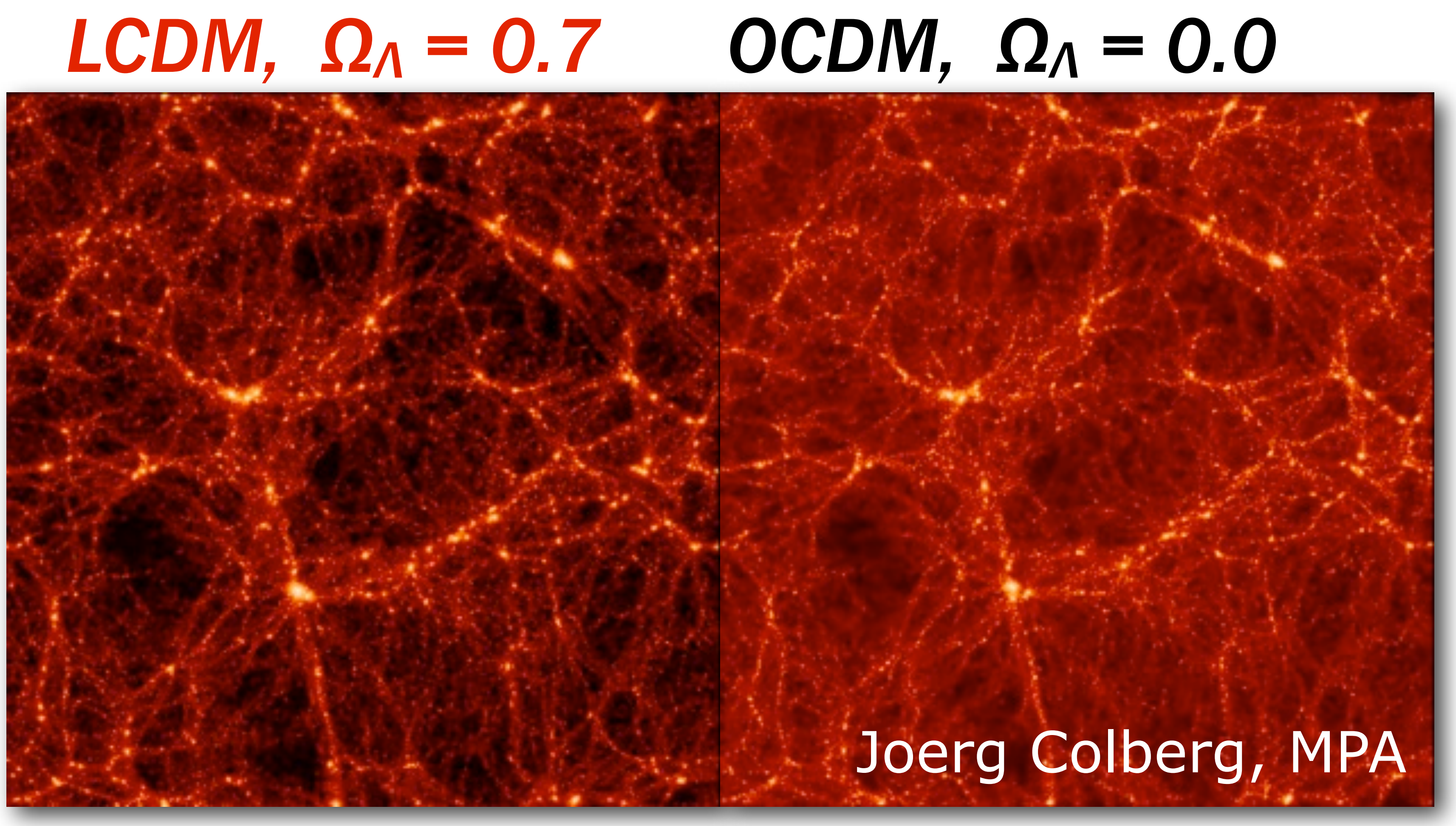

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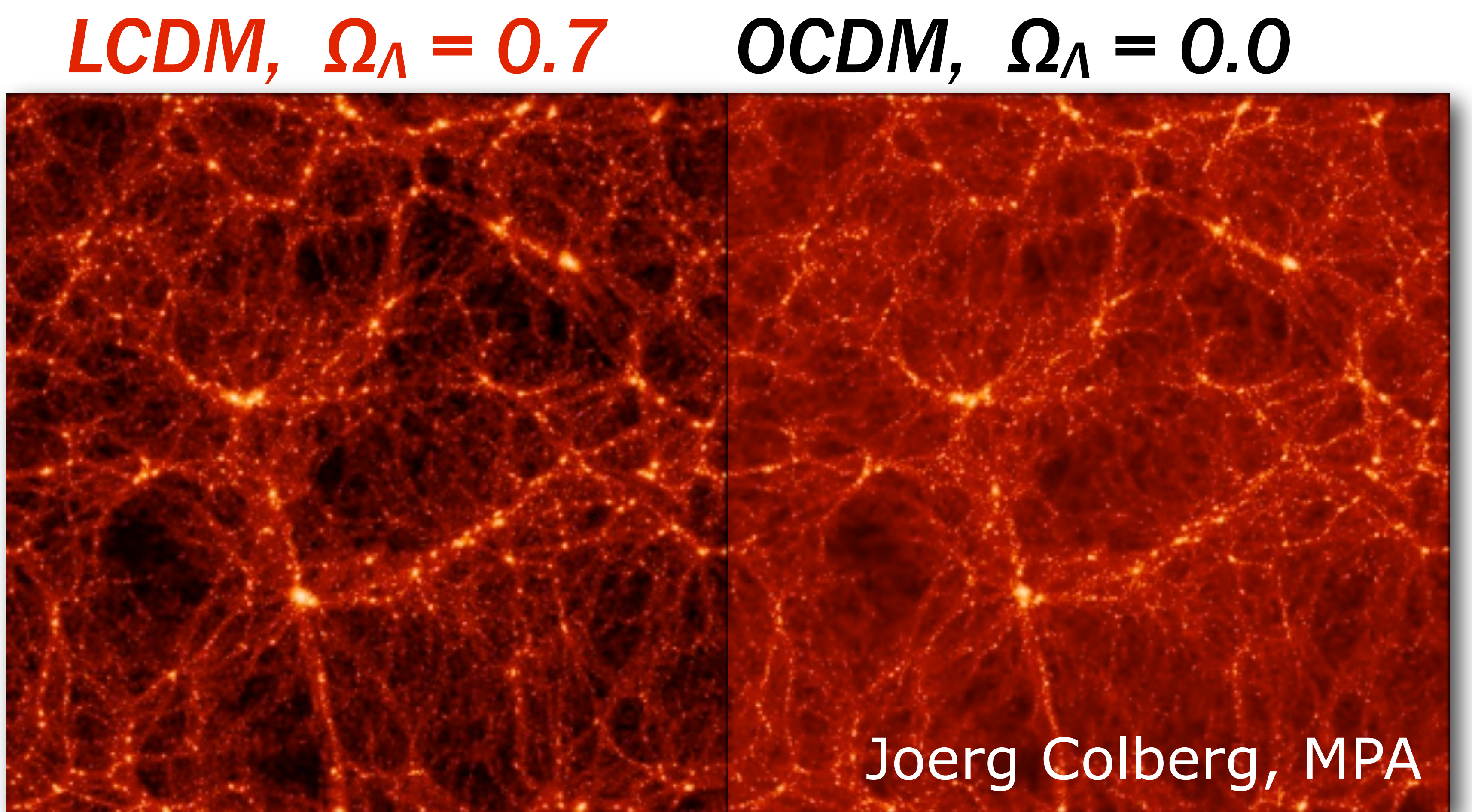

Gravitational Instability
+
linear growth

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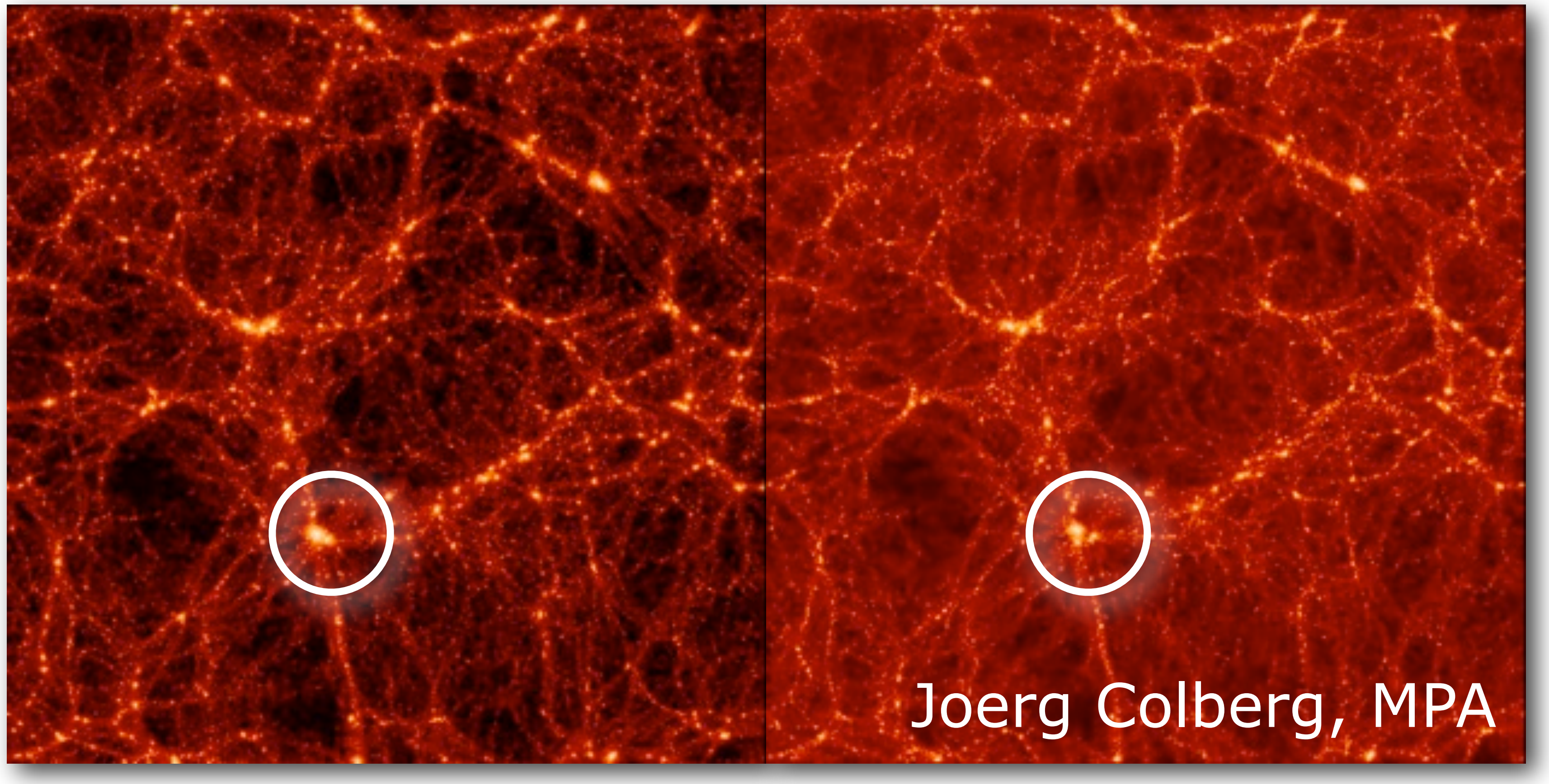

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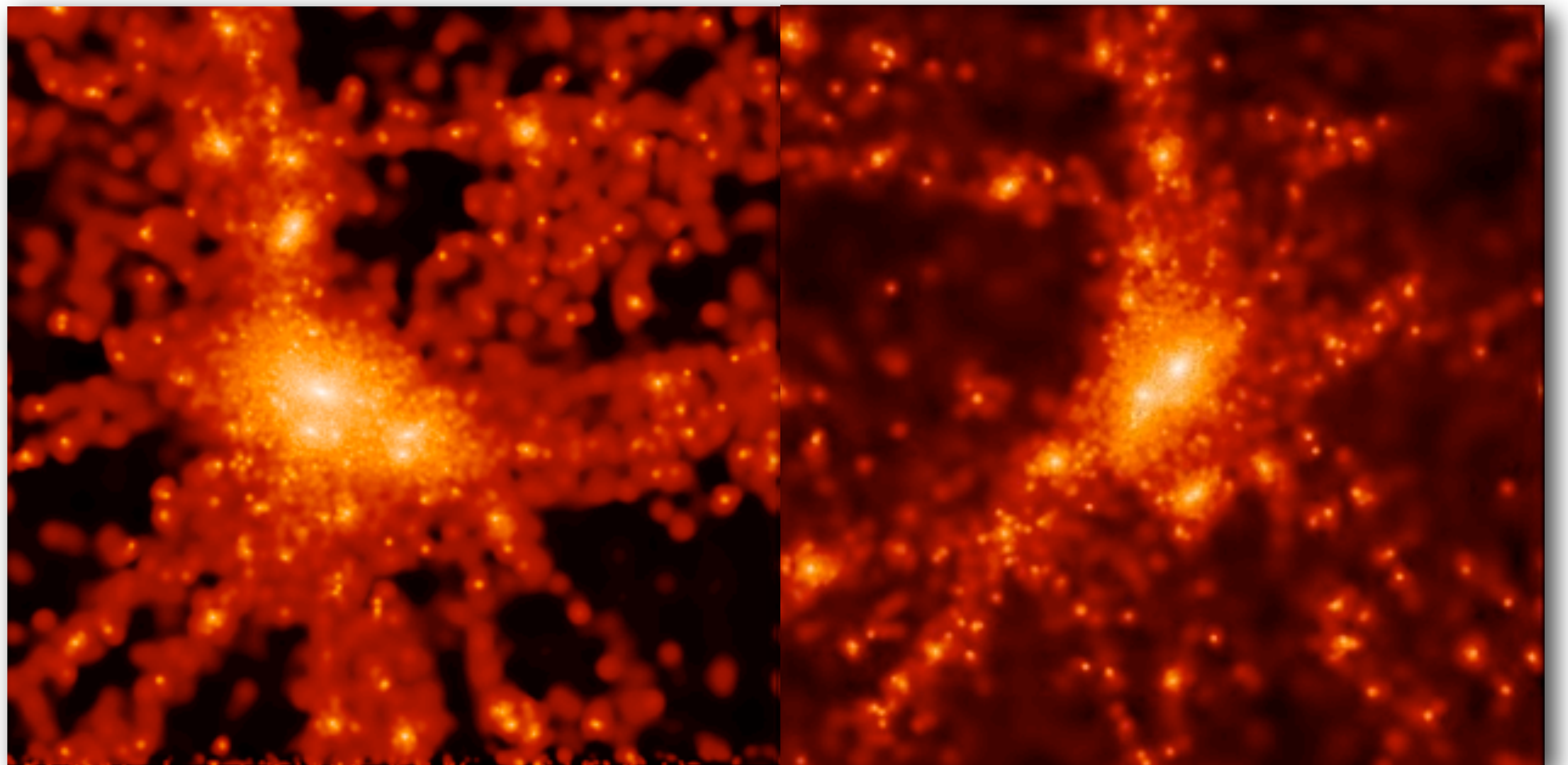

Dark Matter halos are actually more concentrated in LCDM cosmologies! (Dolag et al., 2003)

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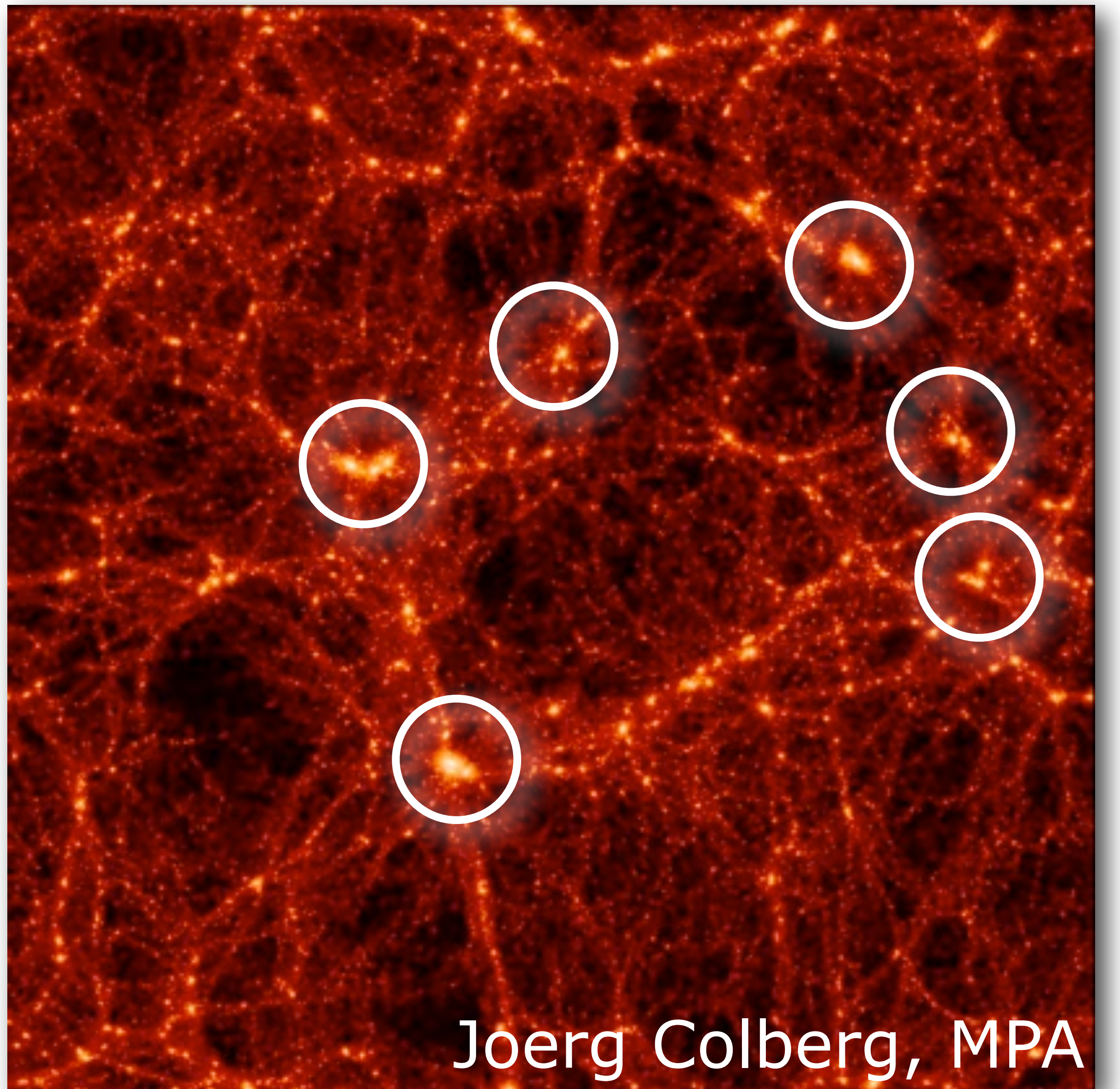
The halo mass function houses principle parameters.

Acquiring large halo populations is the key to using clusters as cosmological probes.



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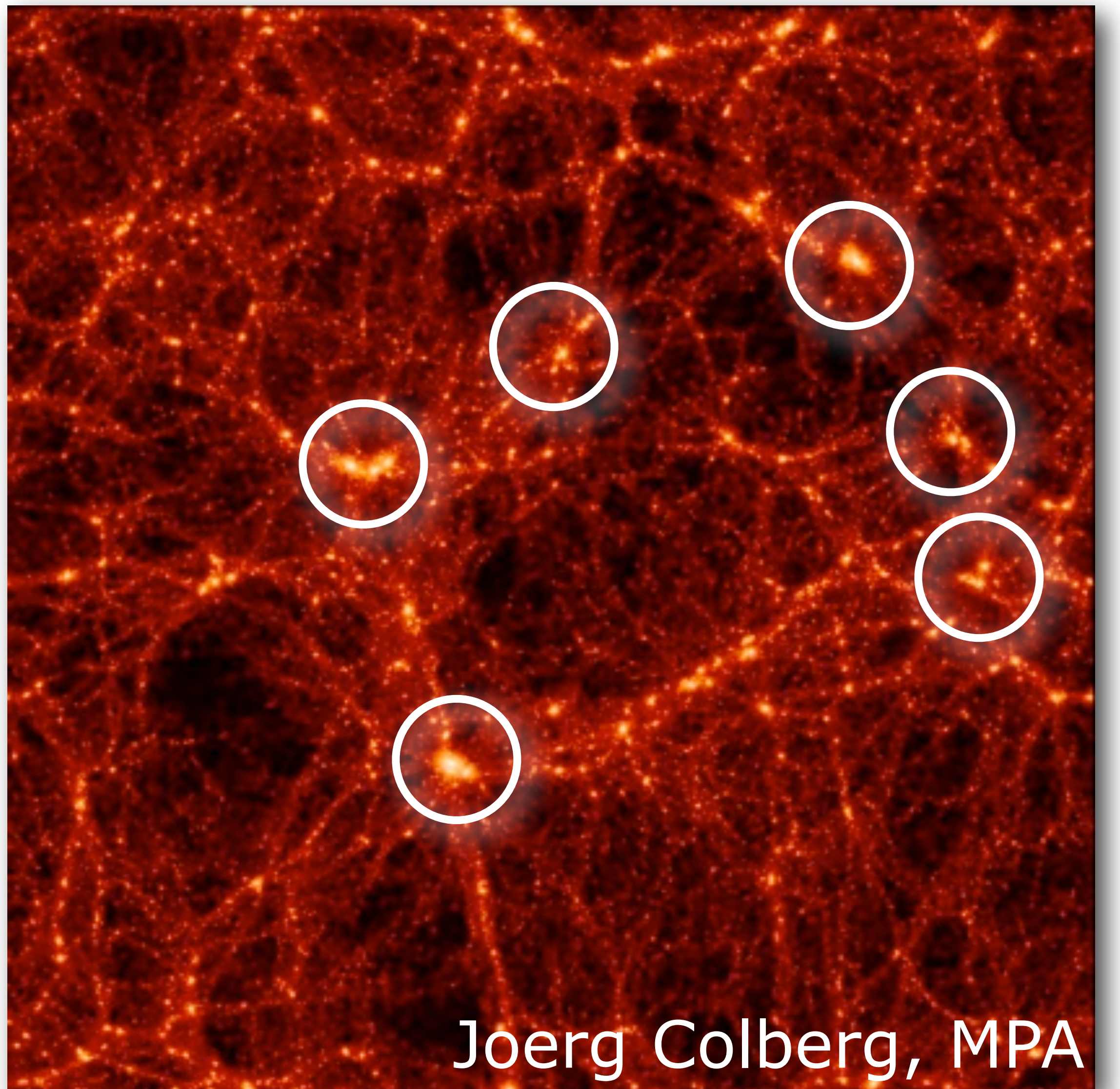

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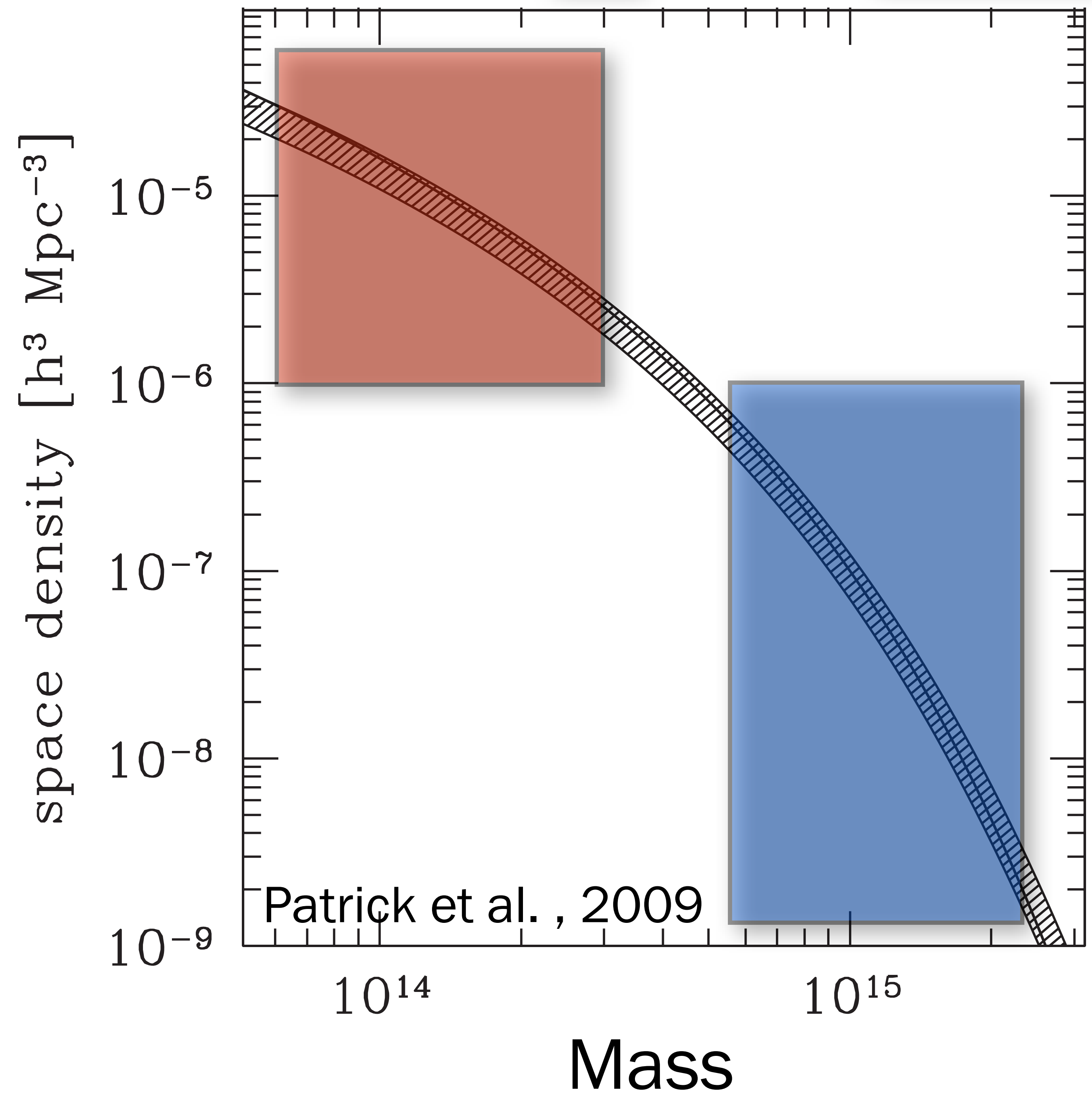
$$\frac{\mathrm{d}n}{\mathrm{d}M} \propto \left(\sigma^{-a}+1\right)\frac{\bar{\rho}}{M}\frac{\mathrm{d}\ln\sigma^{-1}}{\mathrm{d}M}\mathrm{e}^{-c/\sigma^2}$$



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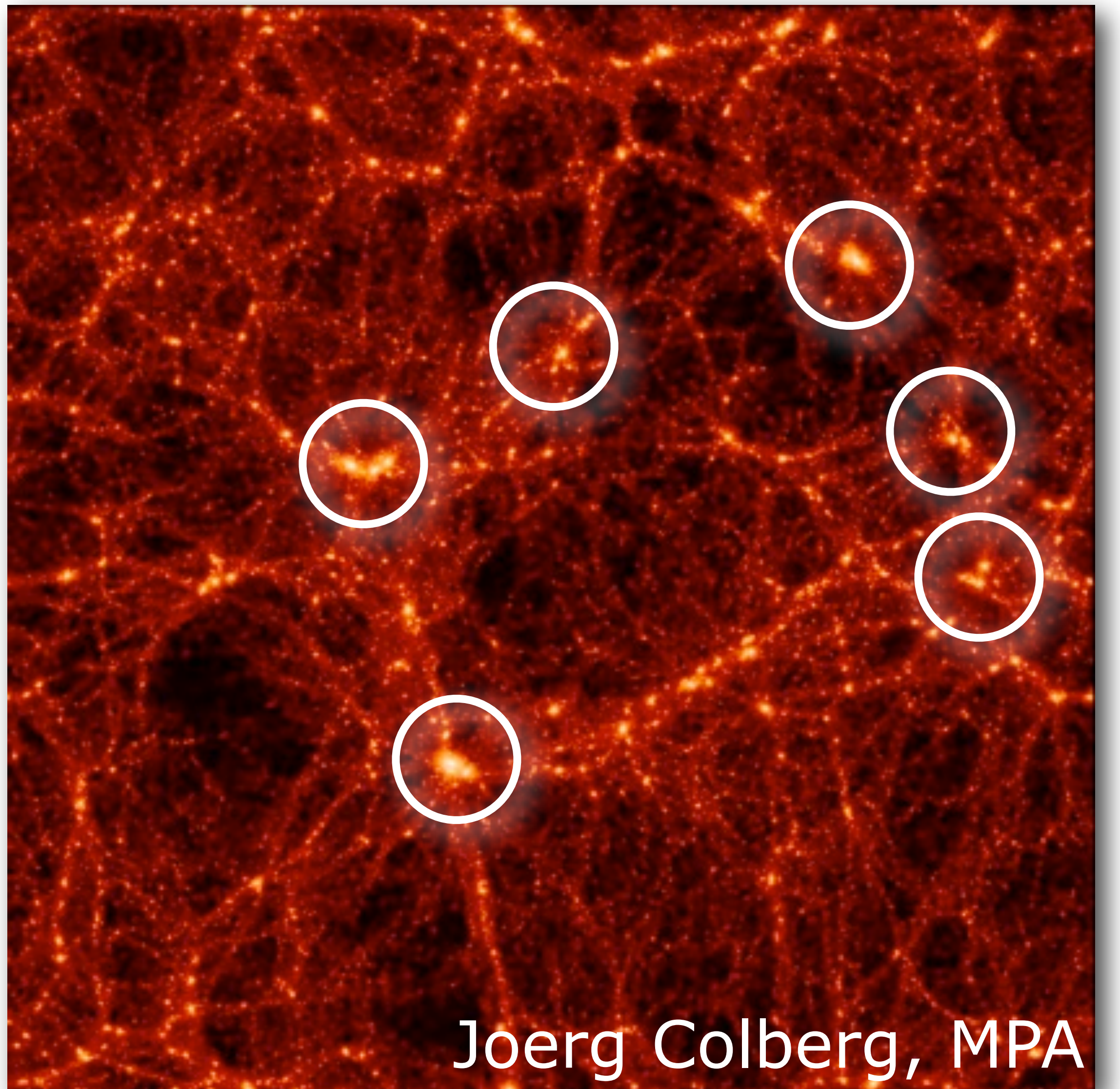

E.g., σ_8 is the variance in halo masses on a given size scale.

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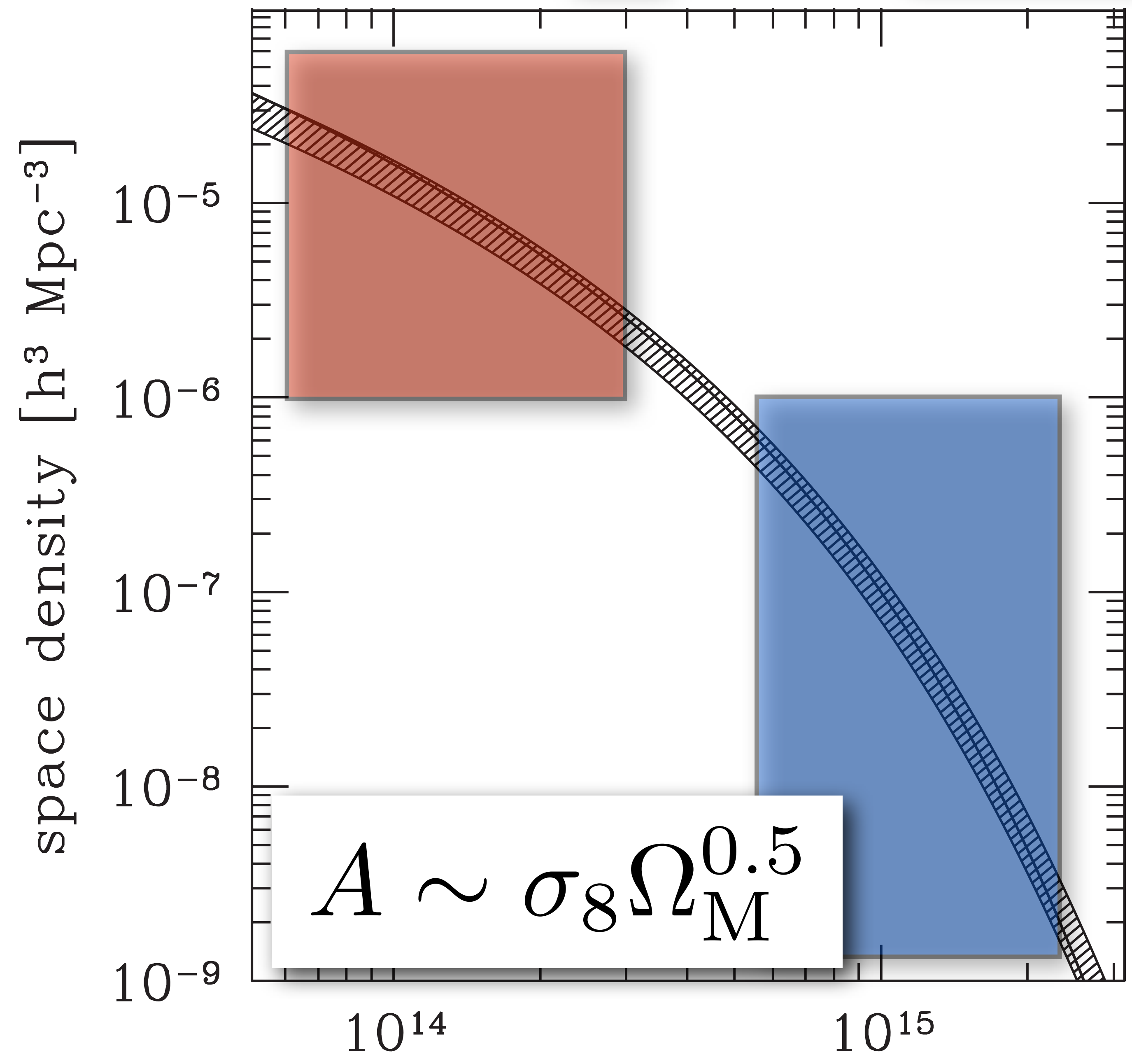

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Optical Richness [N_{gals}]......P(N_{gals} | M,z)

$\sigma_{N_{gals}|M}$ ~ 35-50%

+ Catalogues are volume-limited to low masses.
− High scatter in mass-richness (e.g., substructure, selection).

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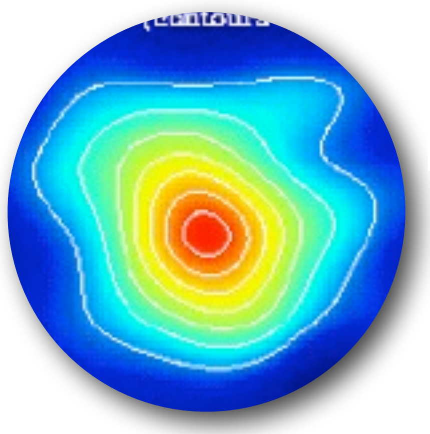

Sub-mm [Y_{SZ}]......................$y_{SZ} \propto \int p d\ell$ $\sigma_{Y|M}$ ~ 15-25%

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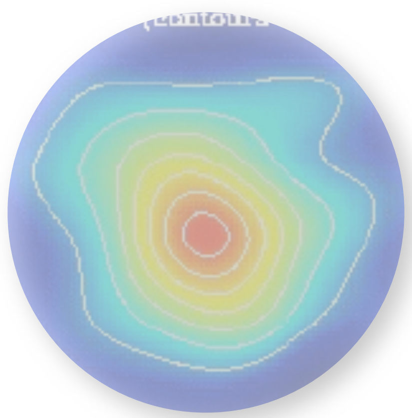

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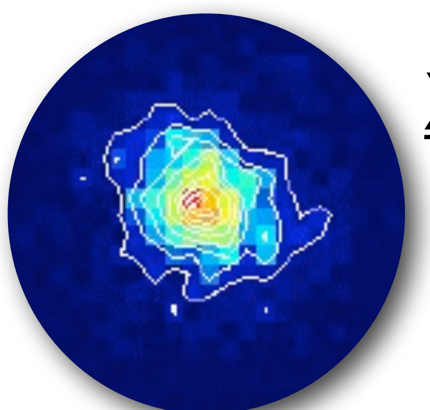


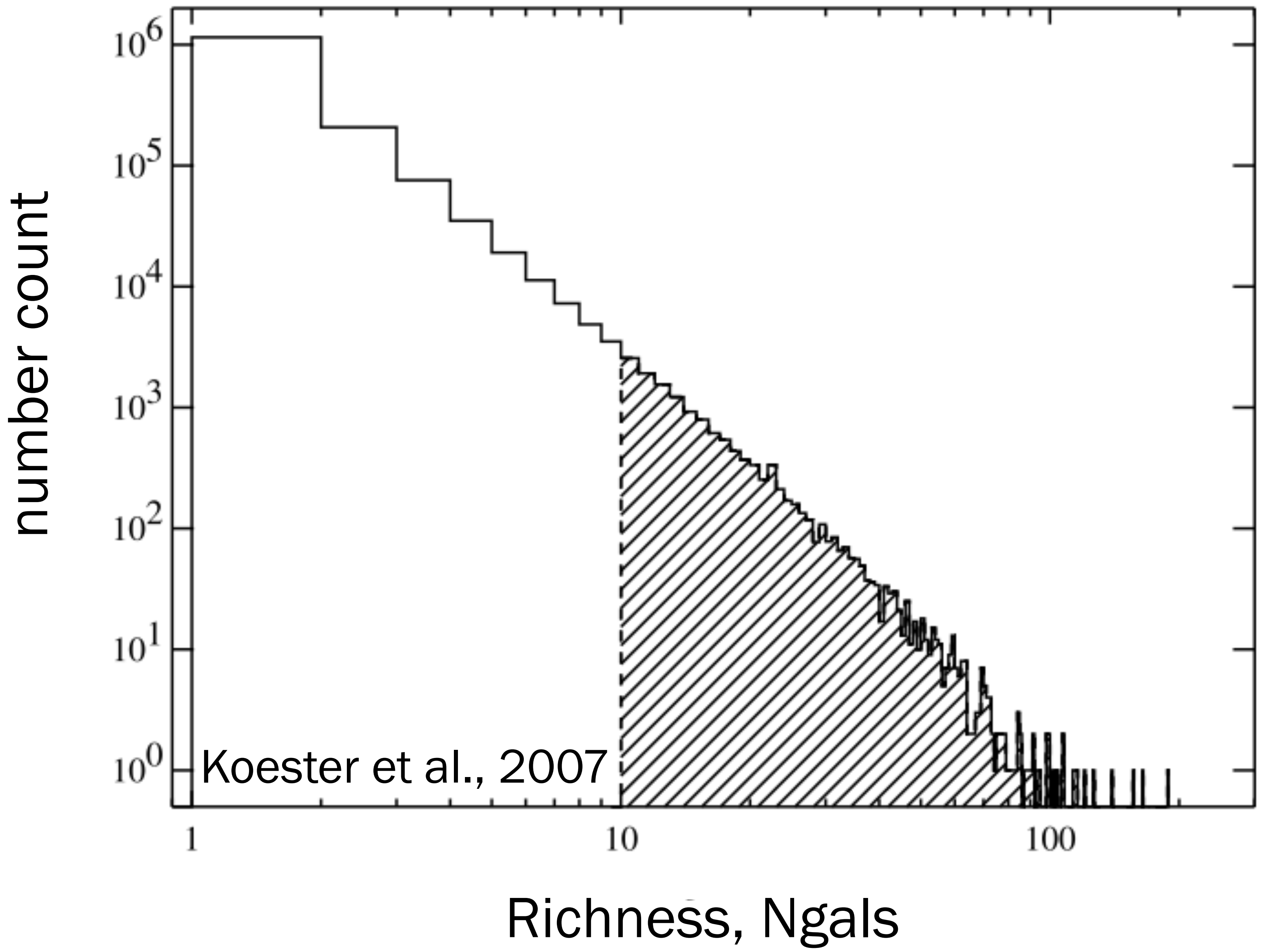
X-ray [T_X]..............................$\epsilon_X \propto T^{1/2} n_e n_i$

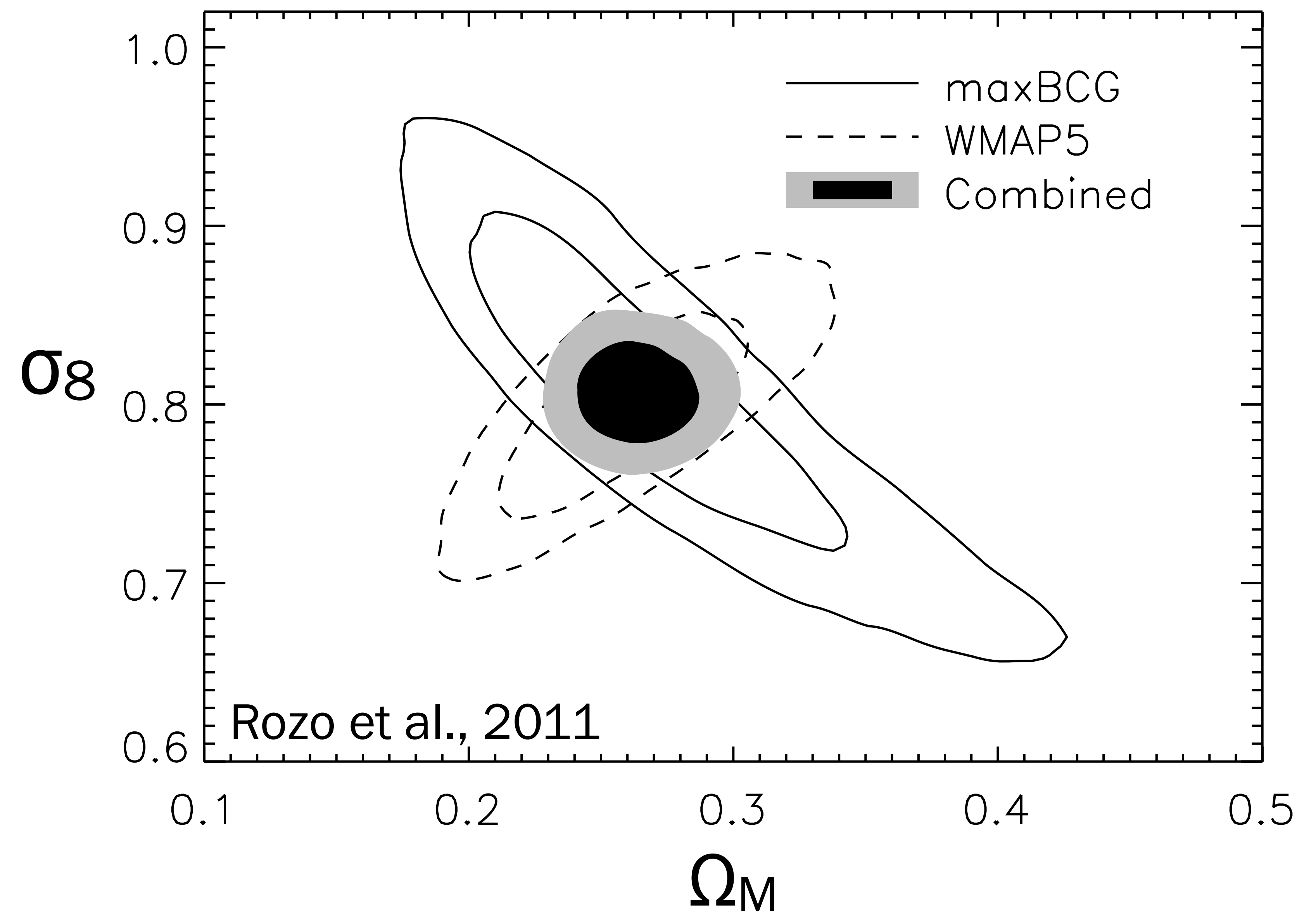
$\sigma_{T_X|M}$ ~ 10-20%

+ Clear identification at high mass and low redshift. Small scatter.
− High mass-limit, small numbers; defining selection function.

Cluster abundances probe dark energy and large-scale structure

SDSS maxBCG optical catalogue





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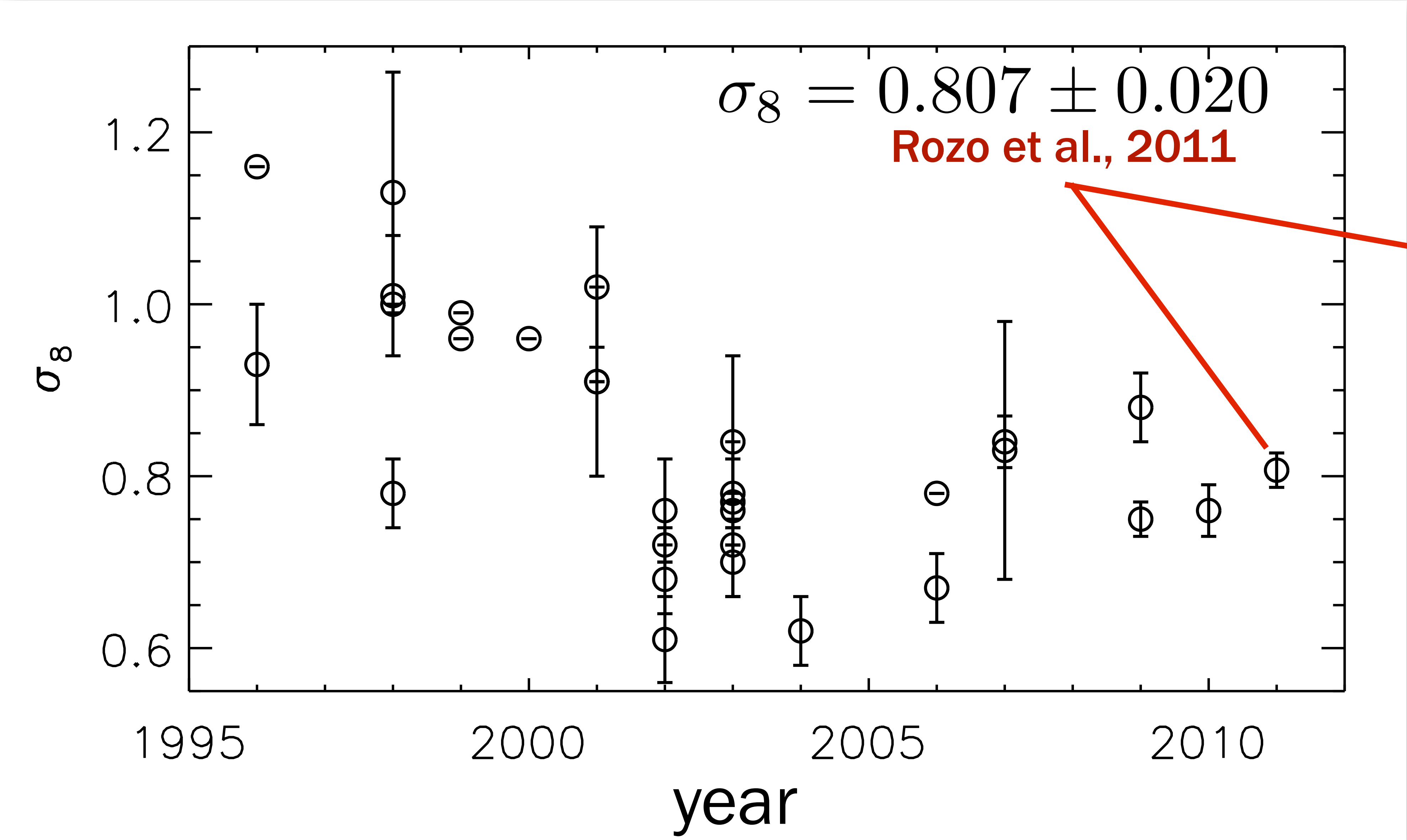
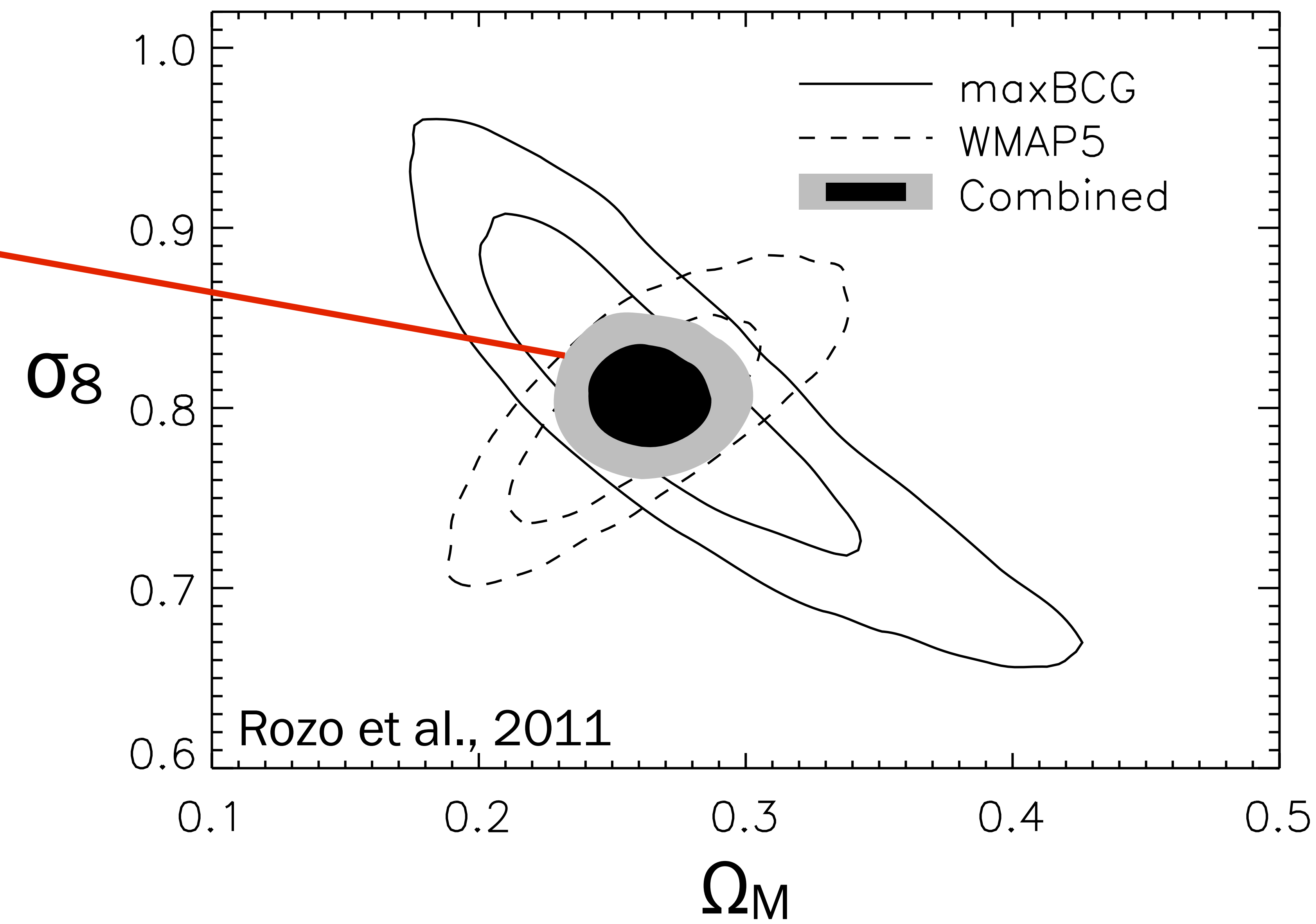
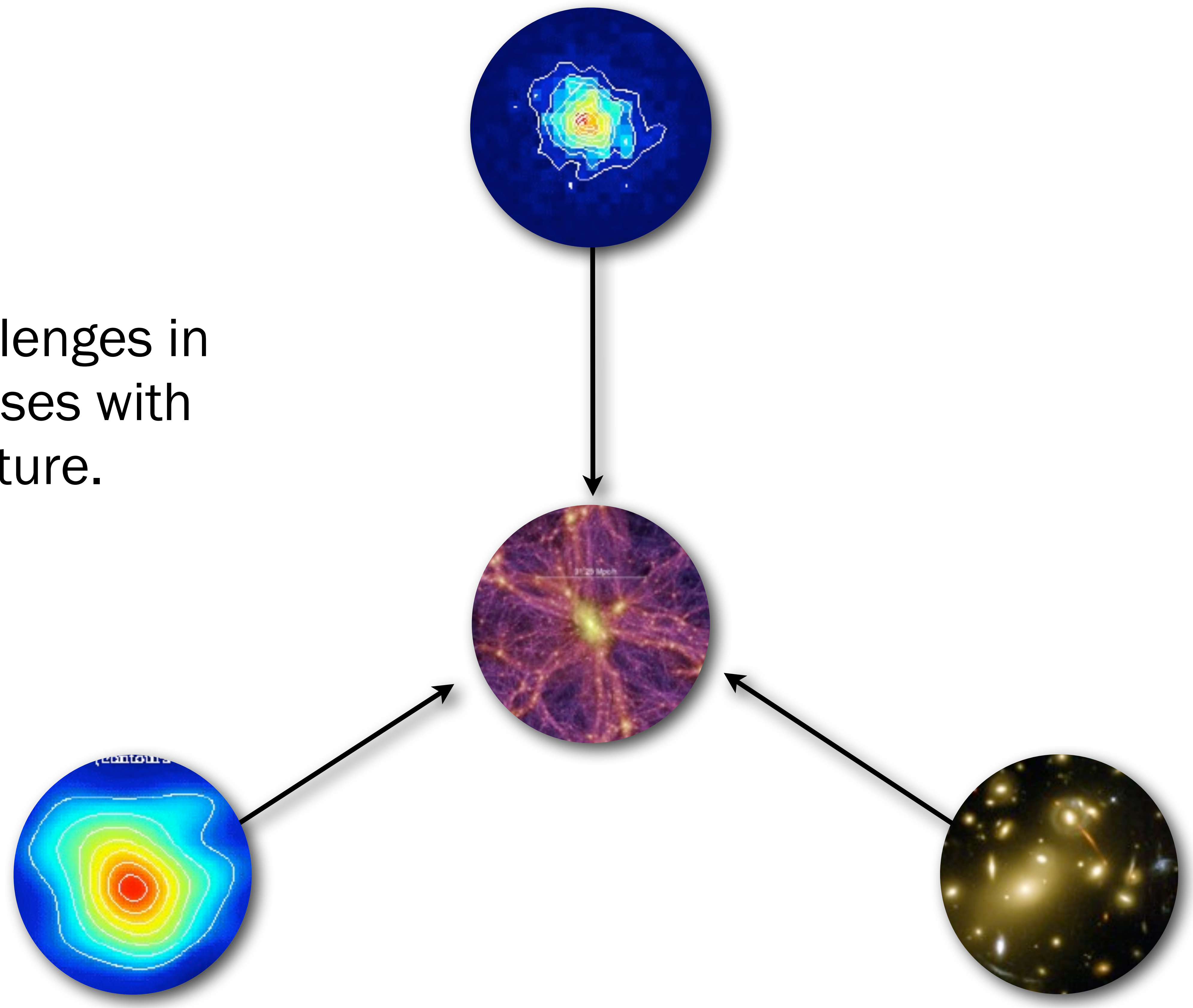




From cluster abundances, we can measure key cosmological features with cluster abundances.

Cluster mass calibration challenge: the trifecta

We face a suite of challenges in calibrating cluster masses with each observable signature.



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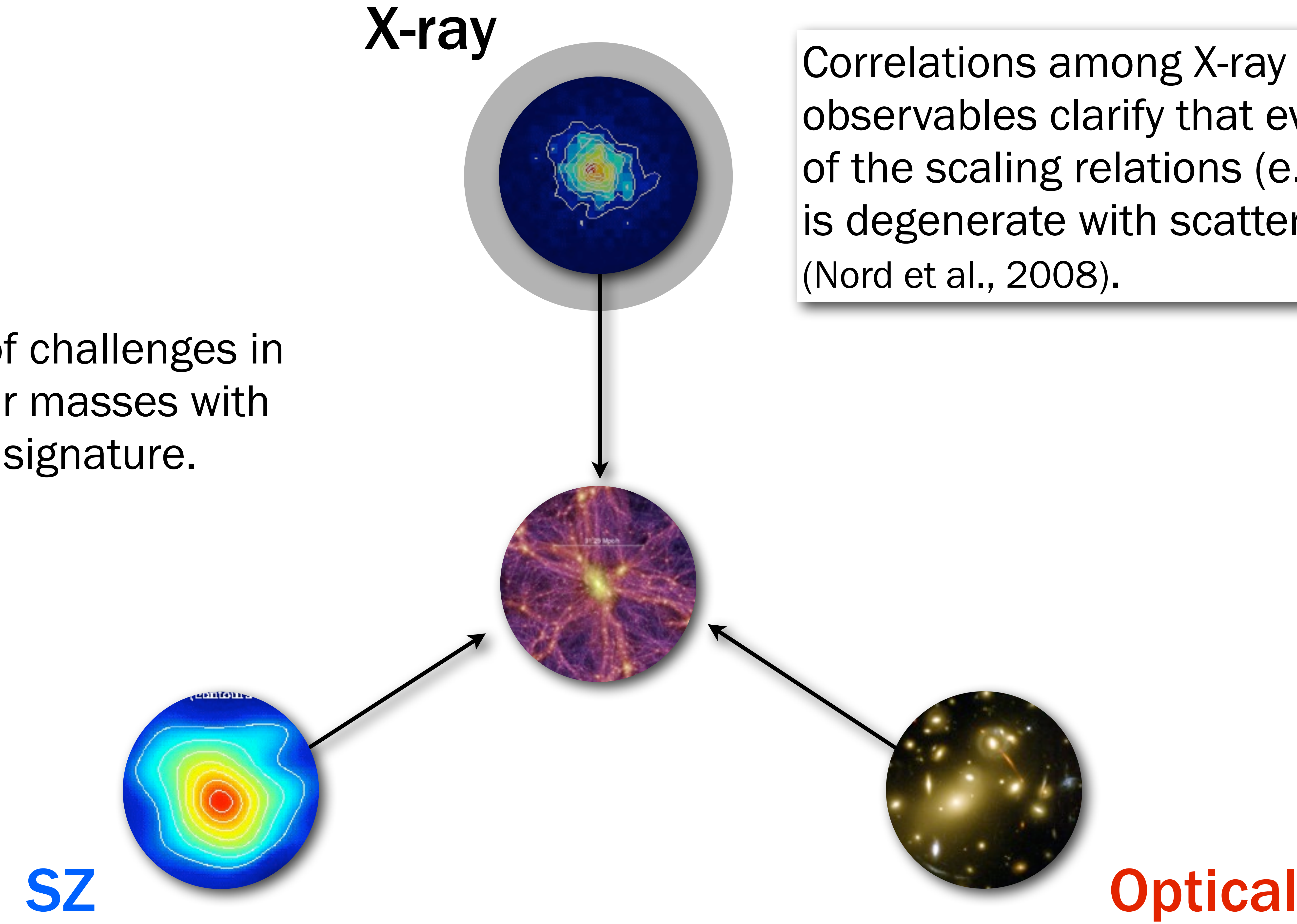

Correlations among X-ray observables clarify that evolution of the scaling relations (e.g., L_X-T_X) is degenerate with scatter (Nord et al., 2008).

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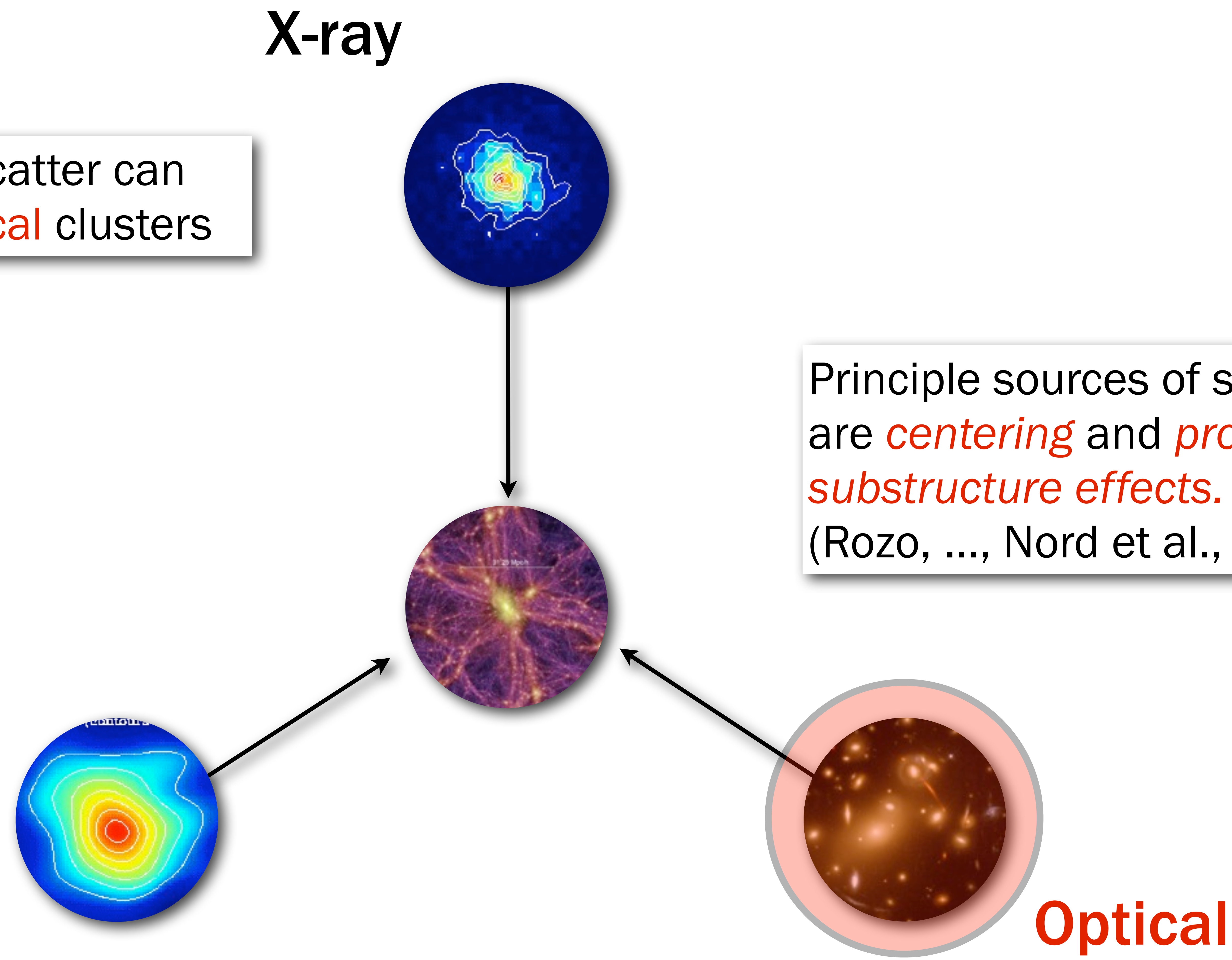

Multiple sources of scatter can be calibrated for optical clusters

Principle sources of scatter are *centering* and *projection/ substructure effects.* (Rozo, ..., Nord et al., 2011)

Observed substructure of clusters obfuscates cluster cosmology

Rozo, ..., Nord et al., 2011

Nearby projected mass affects ~15% of all haloes---the cluster-to-cluster background.

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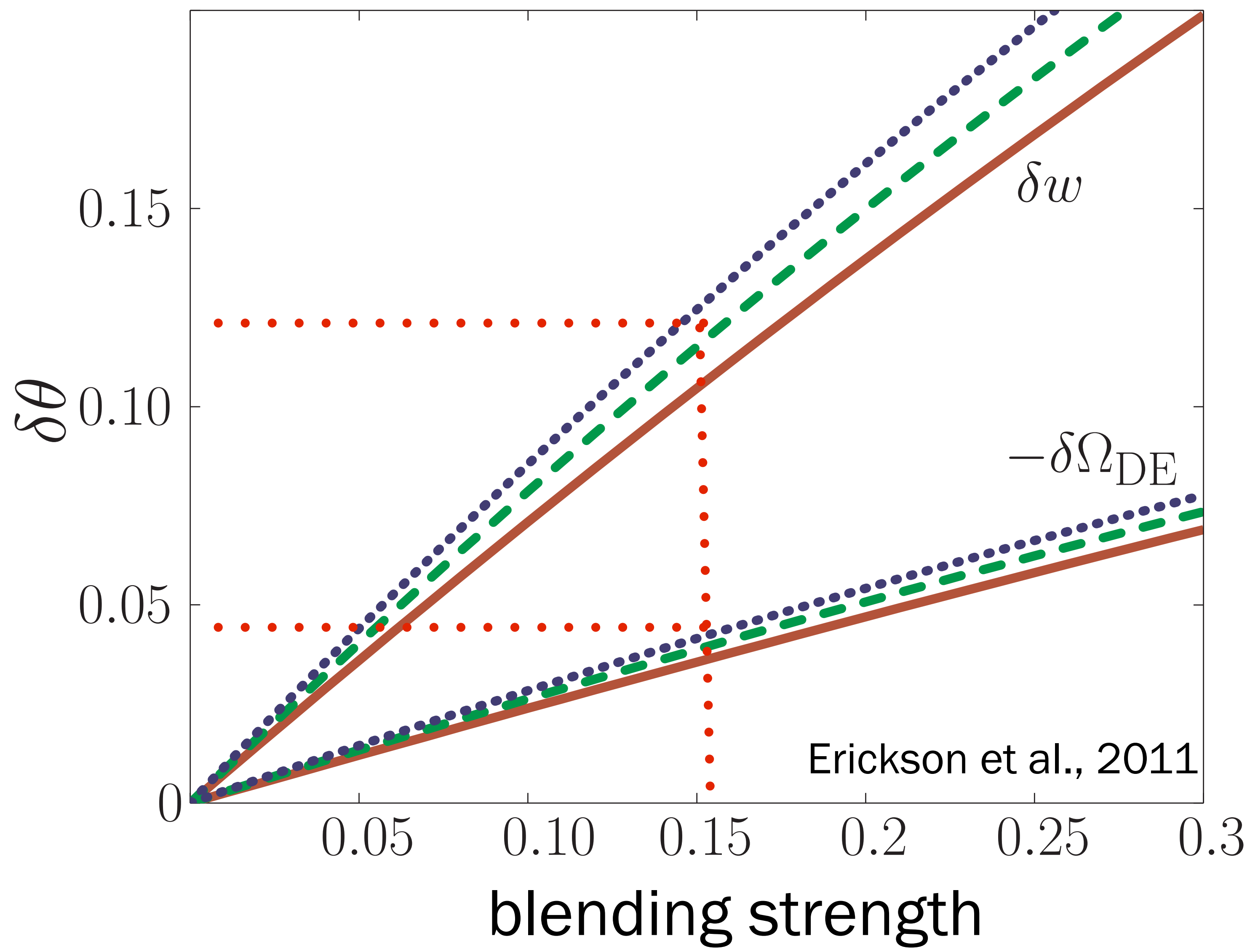
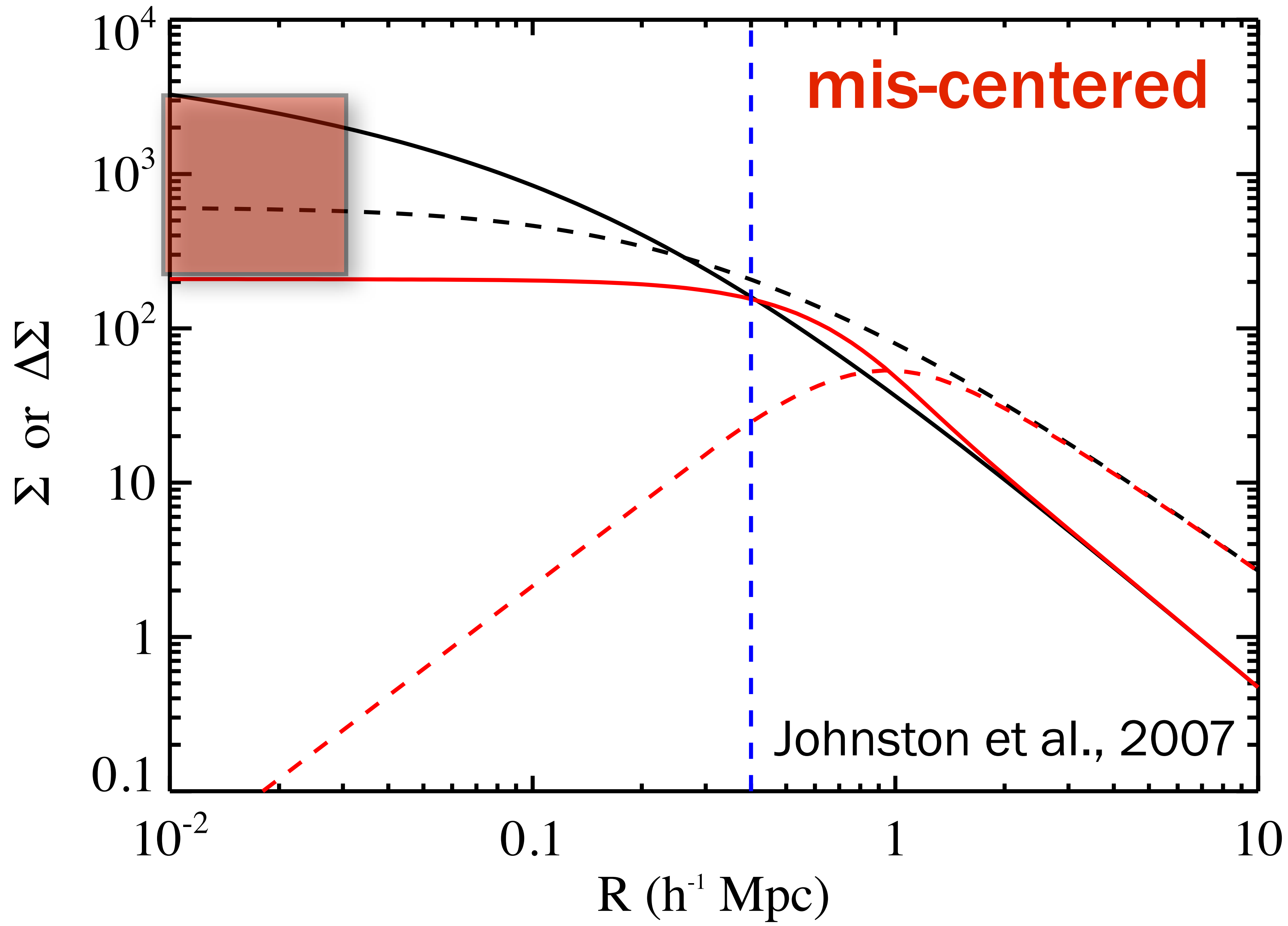
Fisher Matrix predictions



Projection via blending degrades dark energy constraints: even moderate blends increase uncertainties of both **Ω_Λ (5%)** and **w (12%)**.

Cluster mis-centering is a major optical systematic



The weak lensing contrasts profiles are dramatically *reduced* and flattened.

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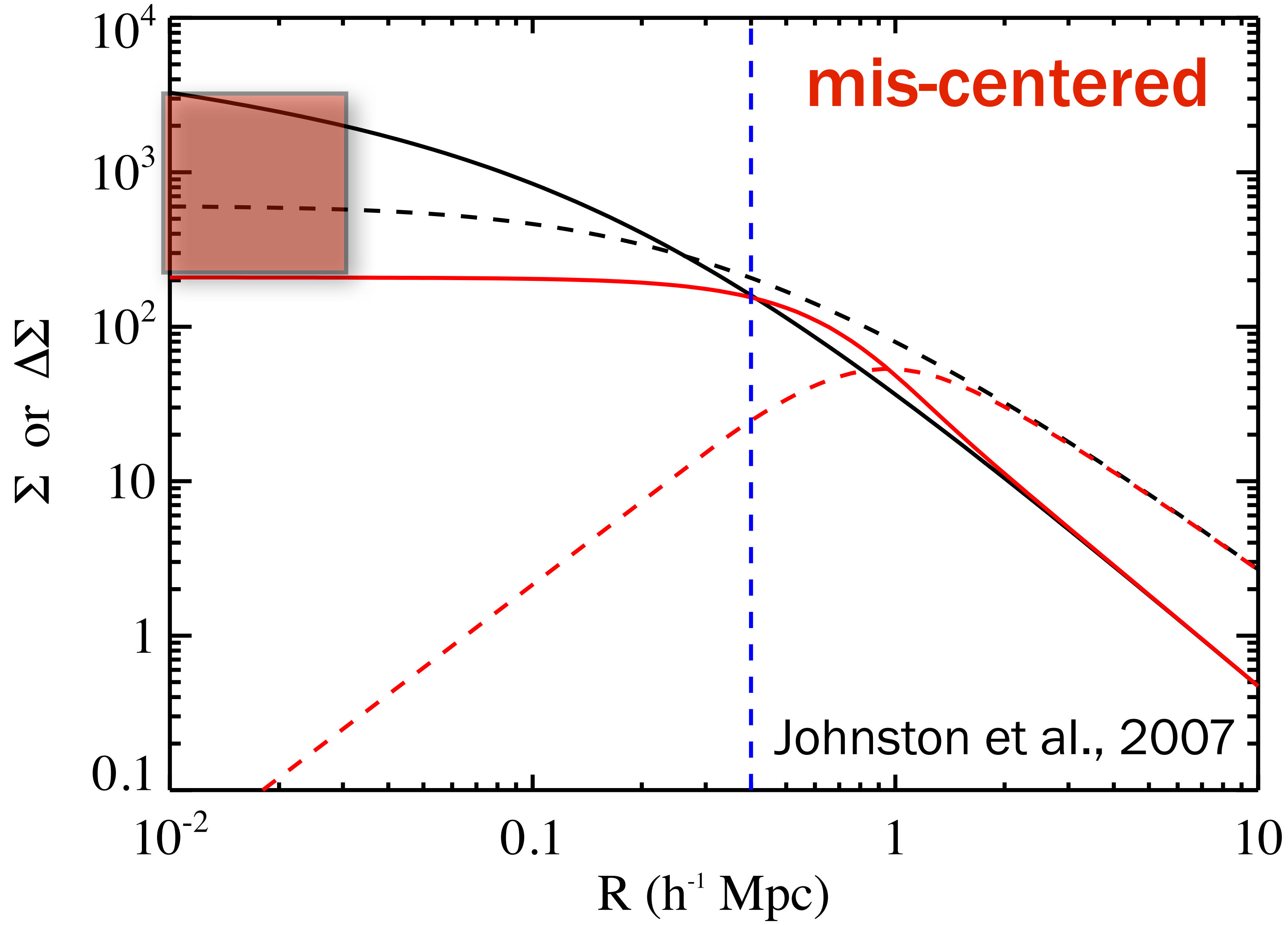

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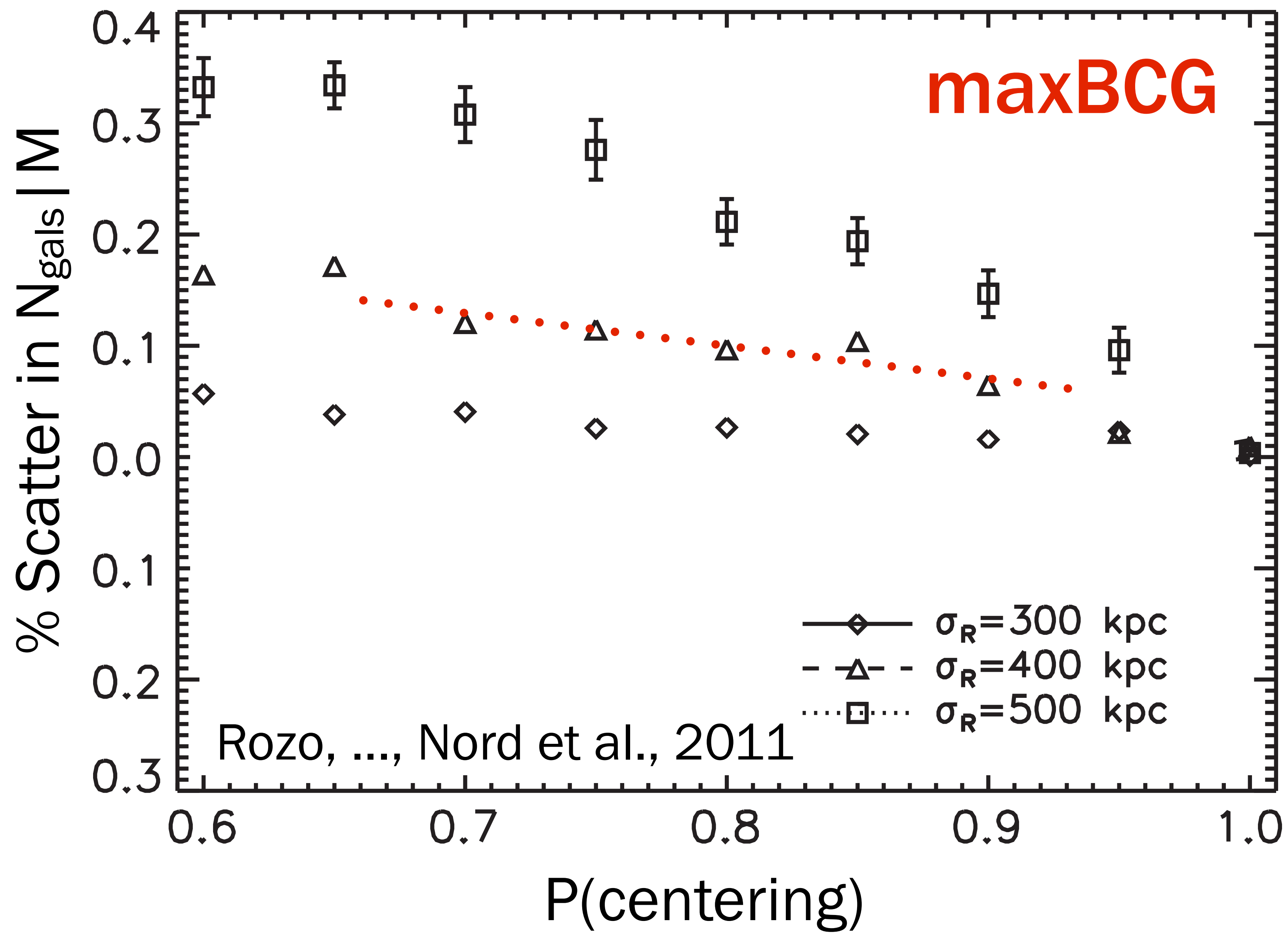
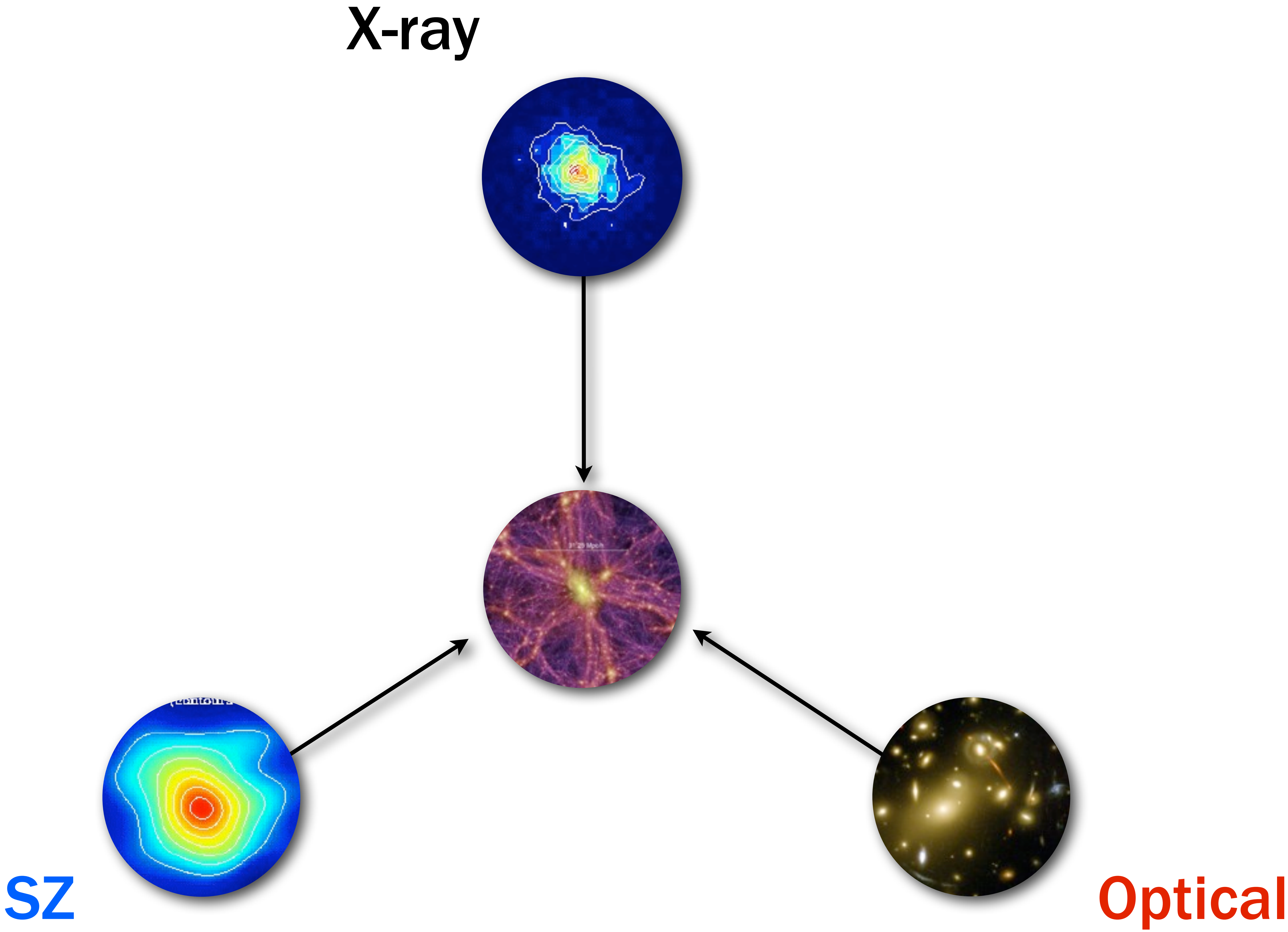


The mass-richness relation receives much of its *extrinsic* scatter from mis-centering.

Cluster mass calibration: cross the streams!



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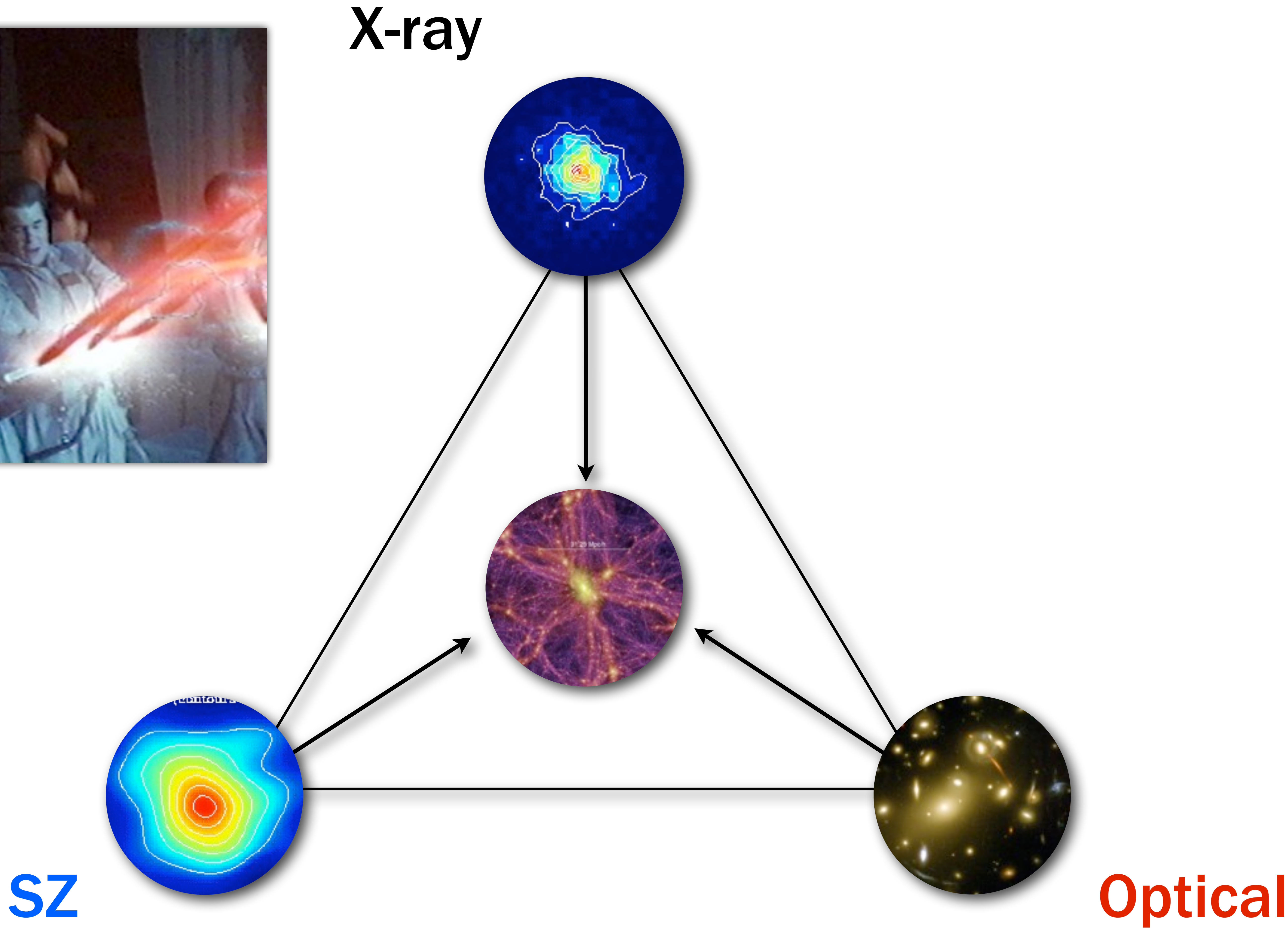

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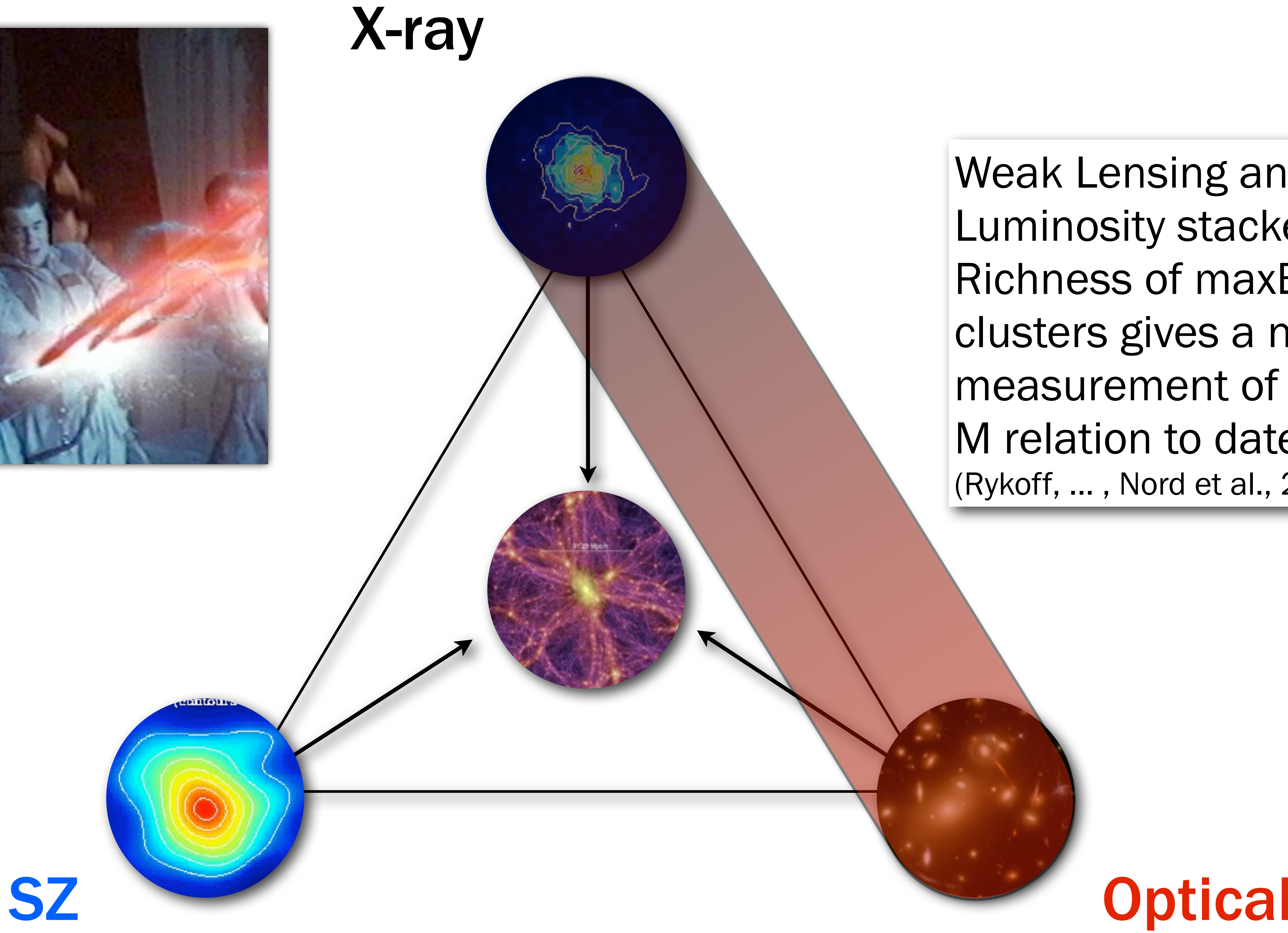
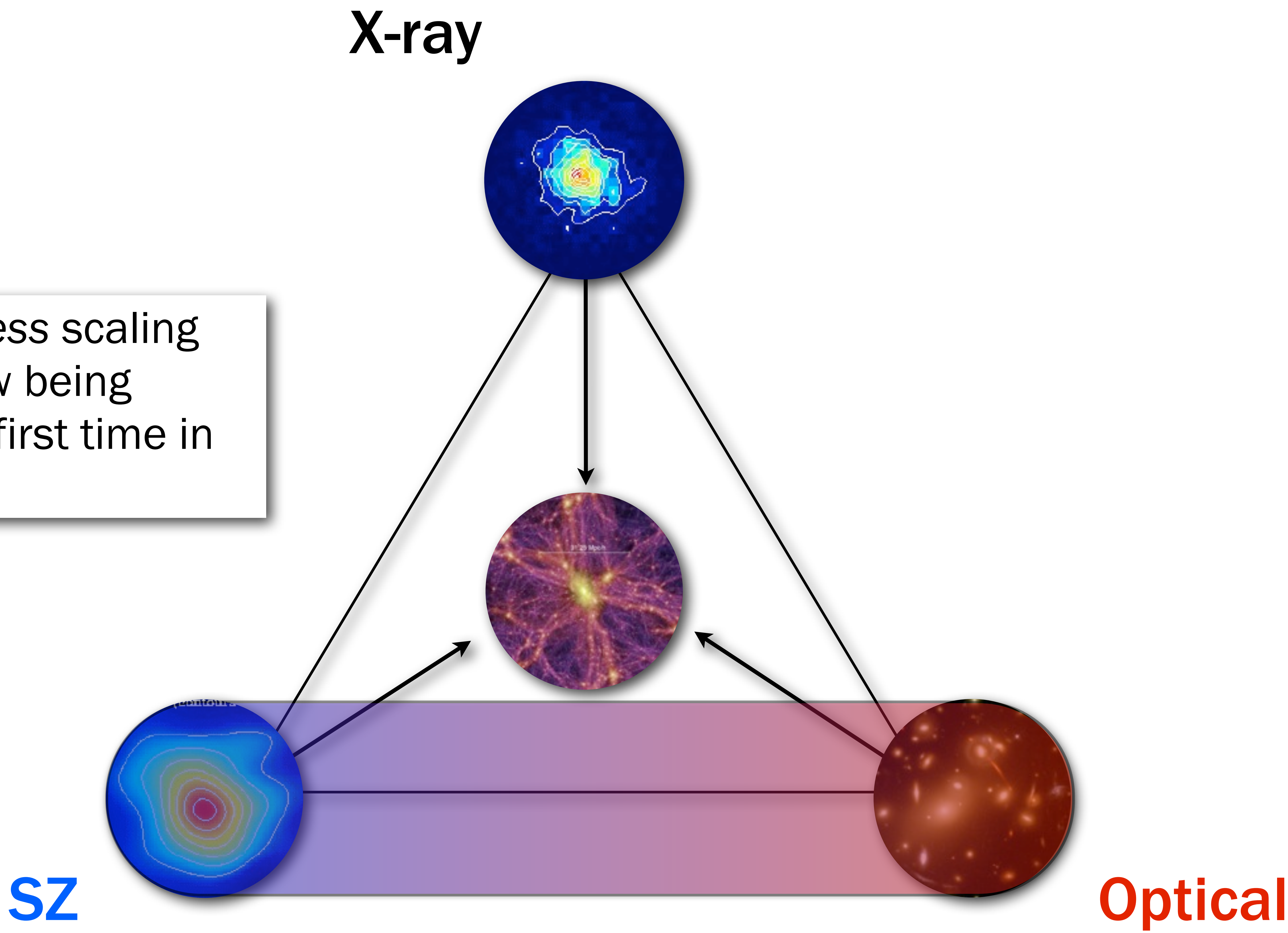


Weak Lensing and X-ray Luminosity stacked on Richness of maxBCG clusters gives a new measurement of the L_X-M relation to date.
(Rykoff, ... , Nord et al., 2008)

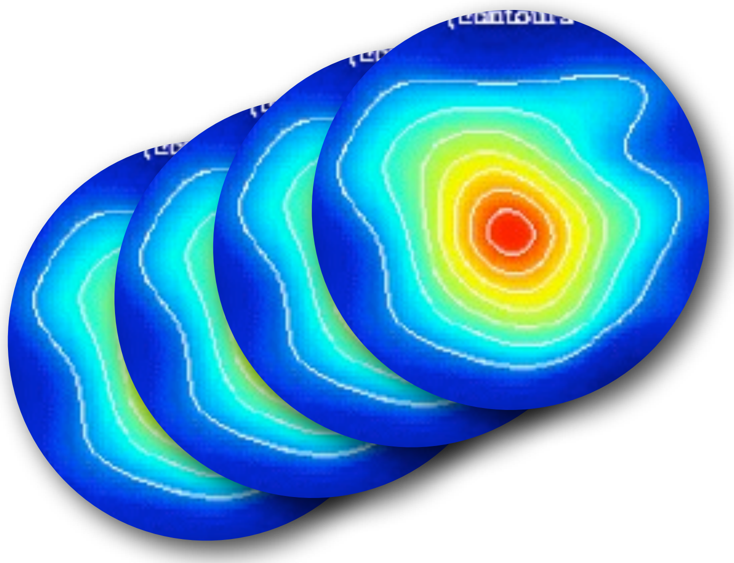
Cluster mass calibration: the trifecta

SZ-Optical *richness* scaling relations are now being explored for the first time in data.



Do optical, SZ and X-ray mass proxies agree?

Stacking the SZ decrement: collecting the SZ signal within an optical richness bin...



[---------N_{gals} bin--------]

... and taking the average within that bin.

Recent history of stacking:

- weak lensing mass of optical clusters (Sheldon/Johnston et al., 2006/7)
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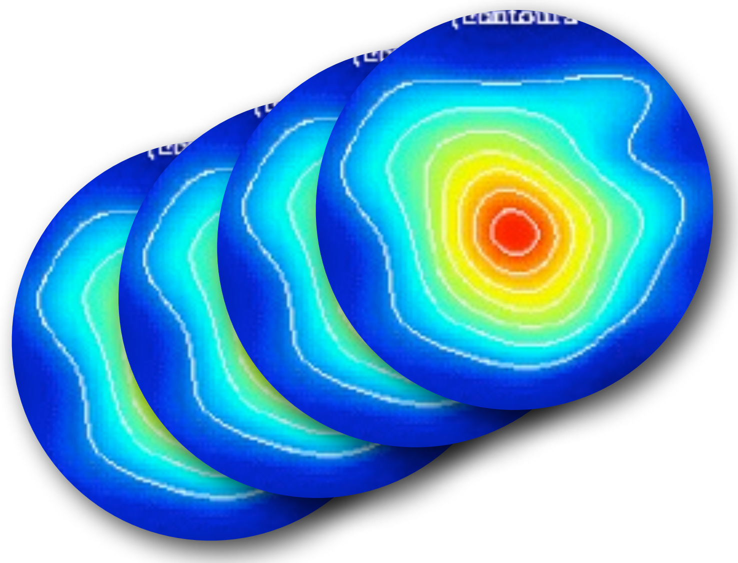

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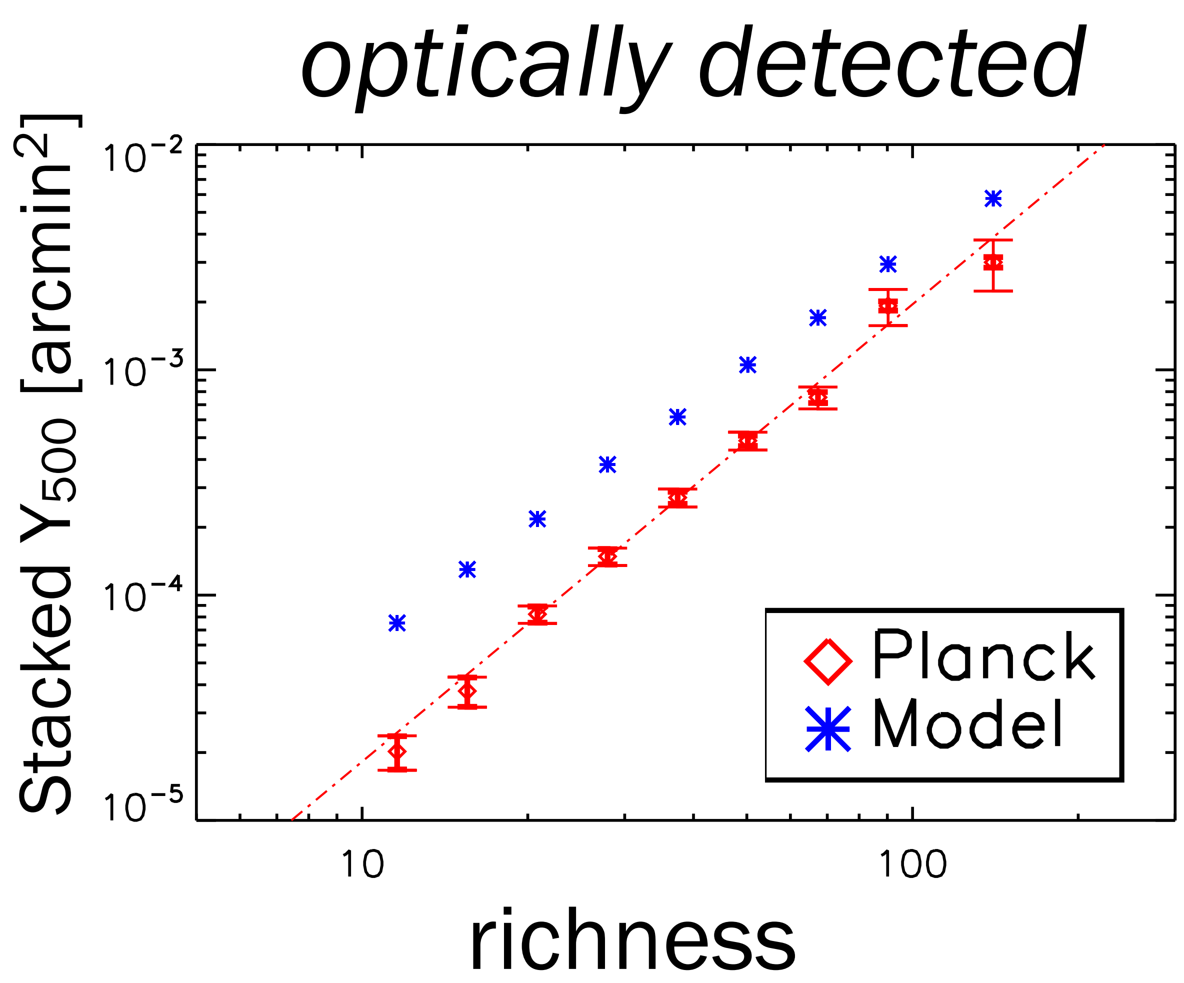

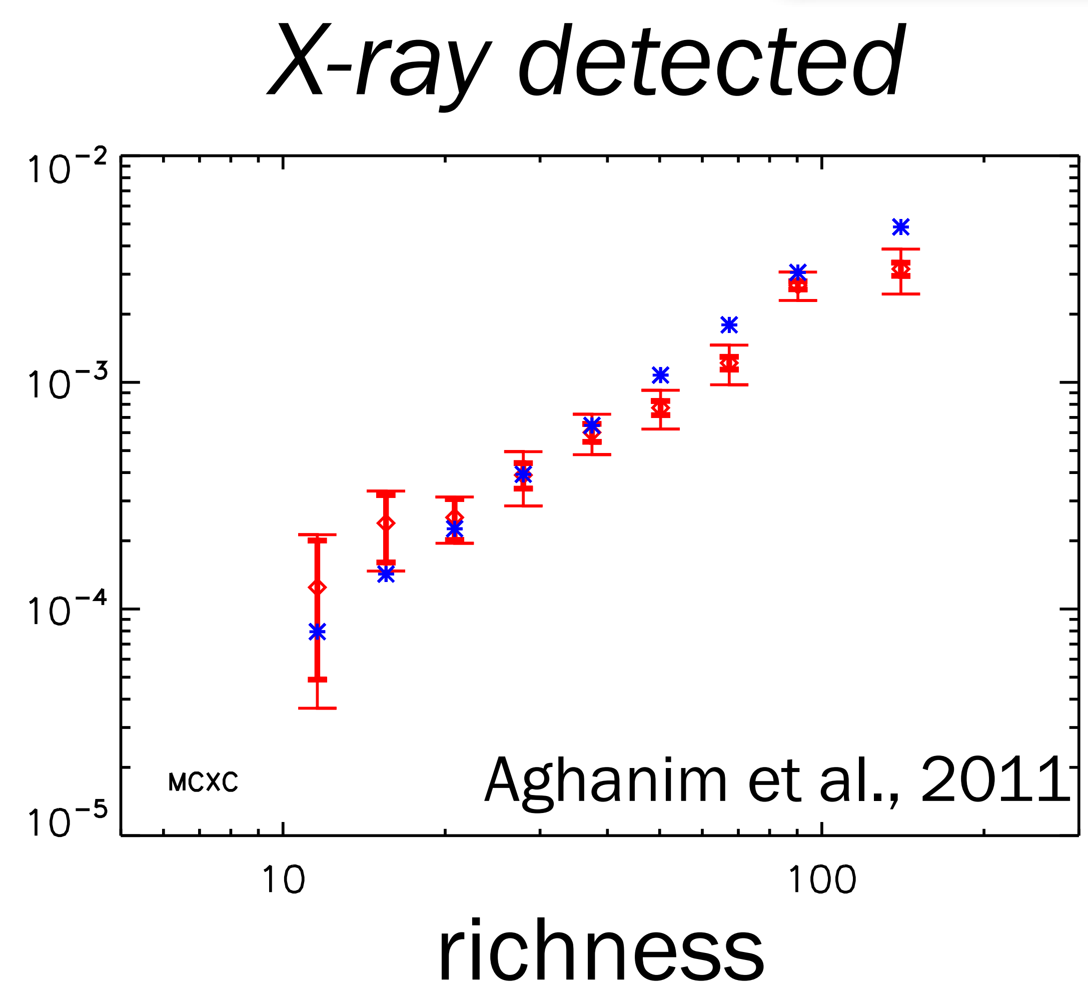

There exists an *apparent discrepancy* in the mass estimate among the three signatures.

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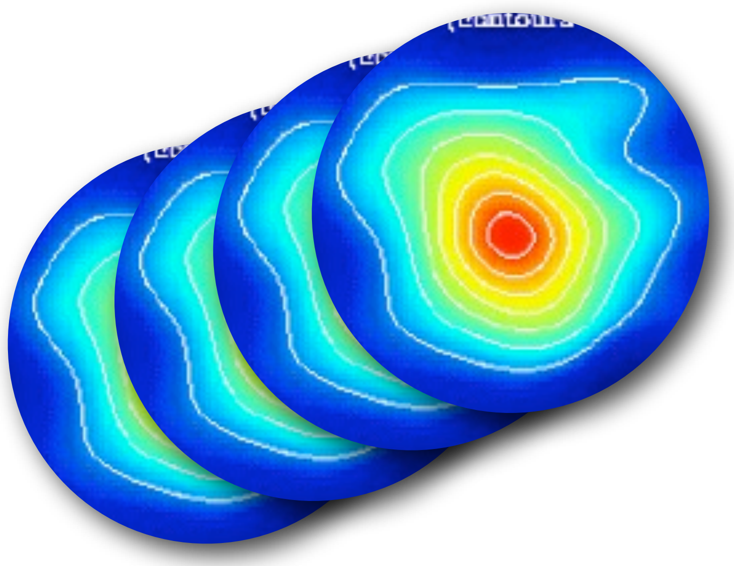
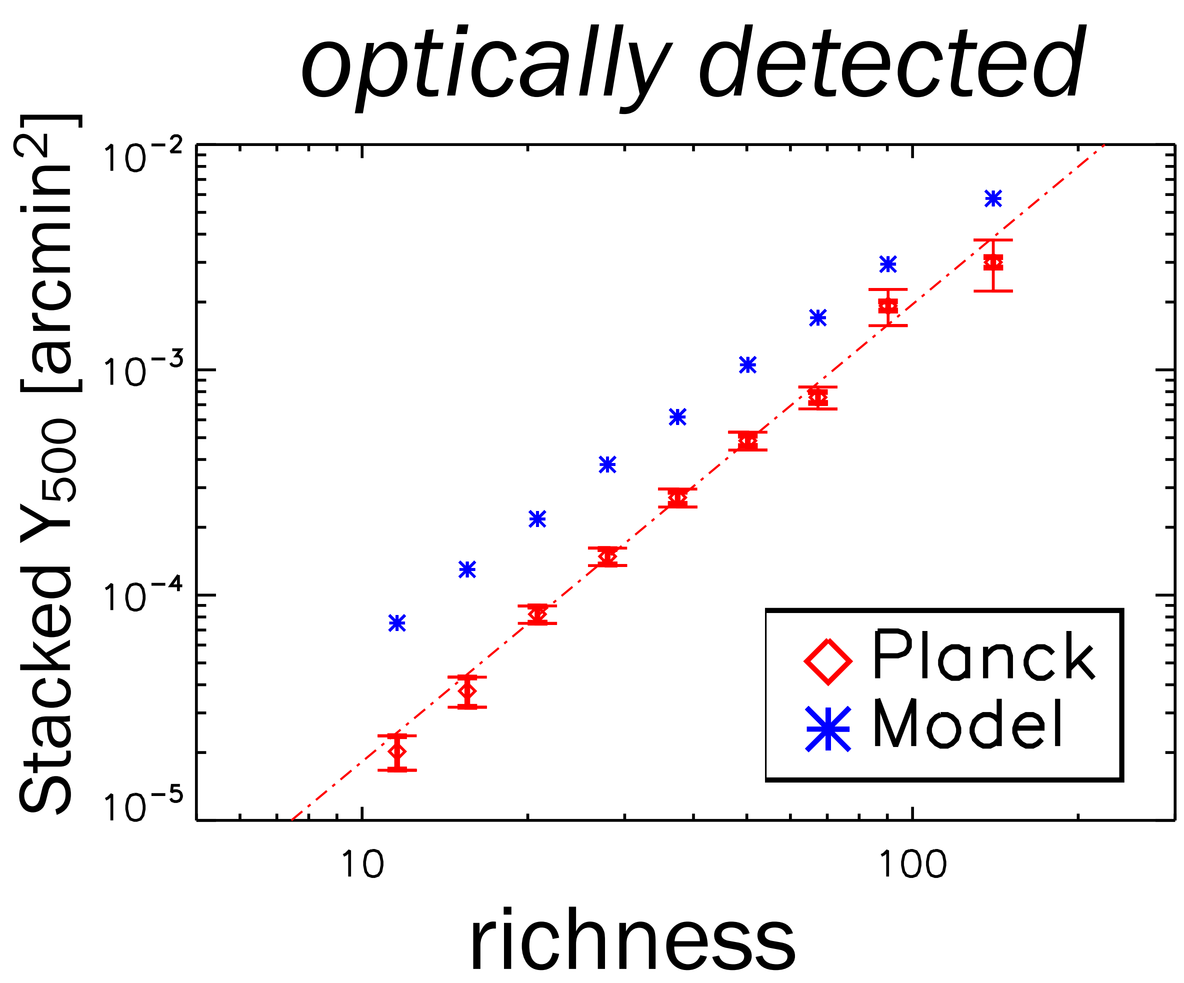
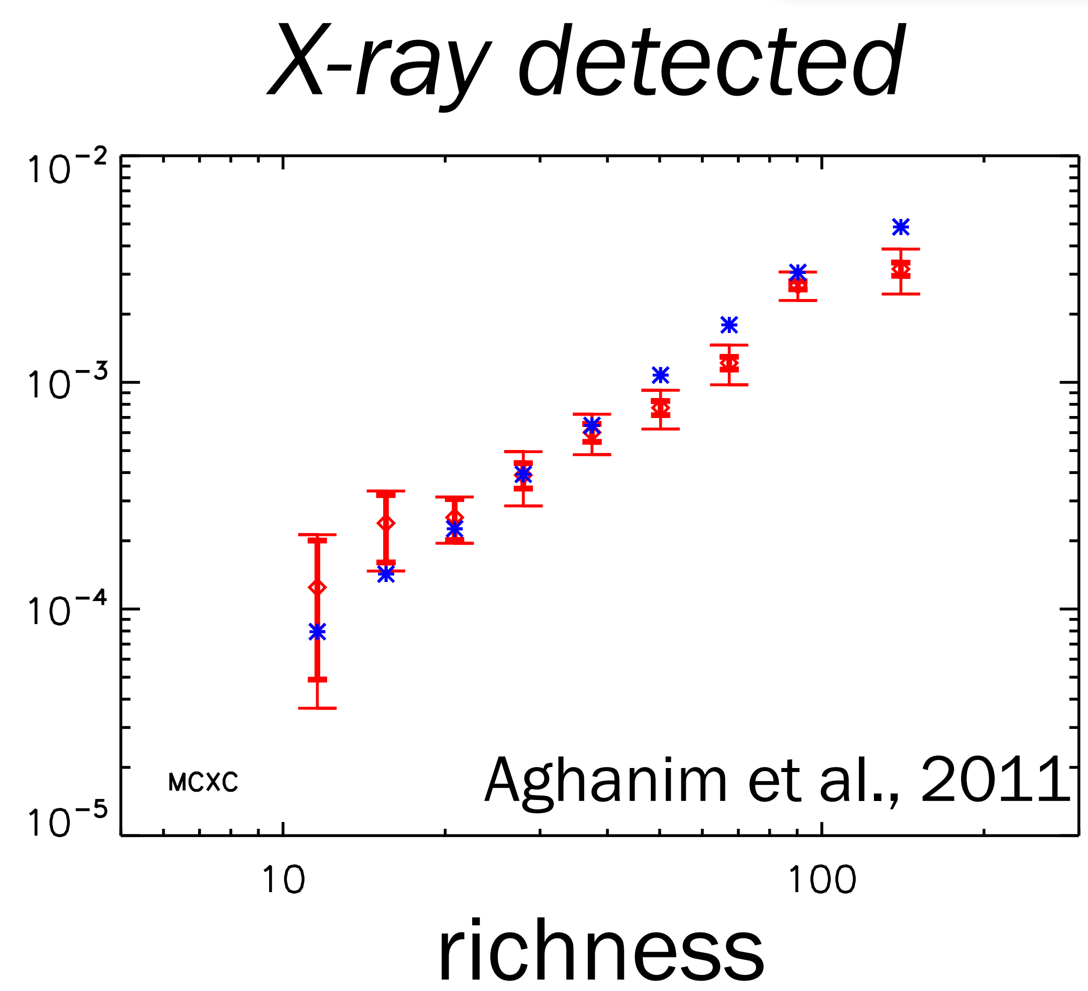
Stacking the SZ decrement: collecting the SZ signal within an optical richness bin...



[---------N_{gals} bin--------]

... and taking the average within that bin.





There exists an *apparent discrepancy* in the mass estimate among the three signatures.

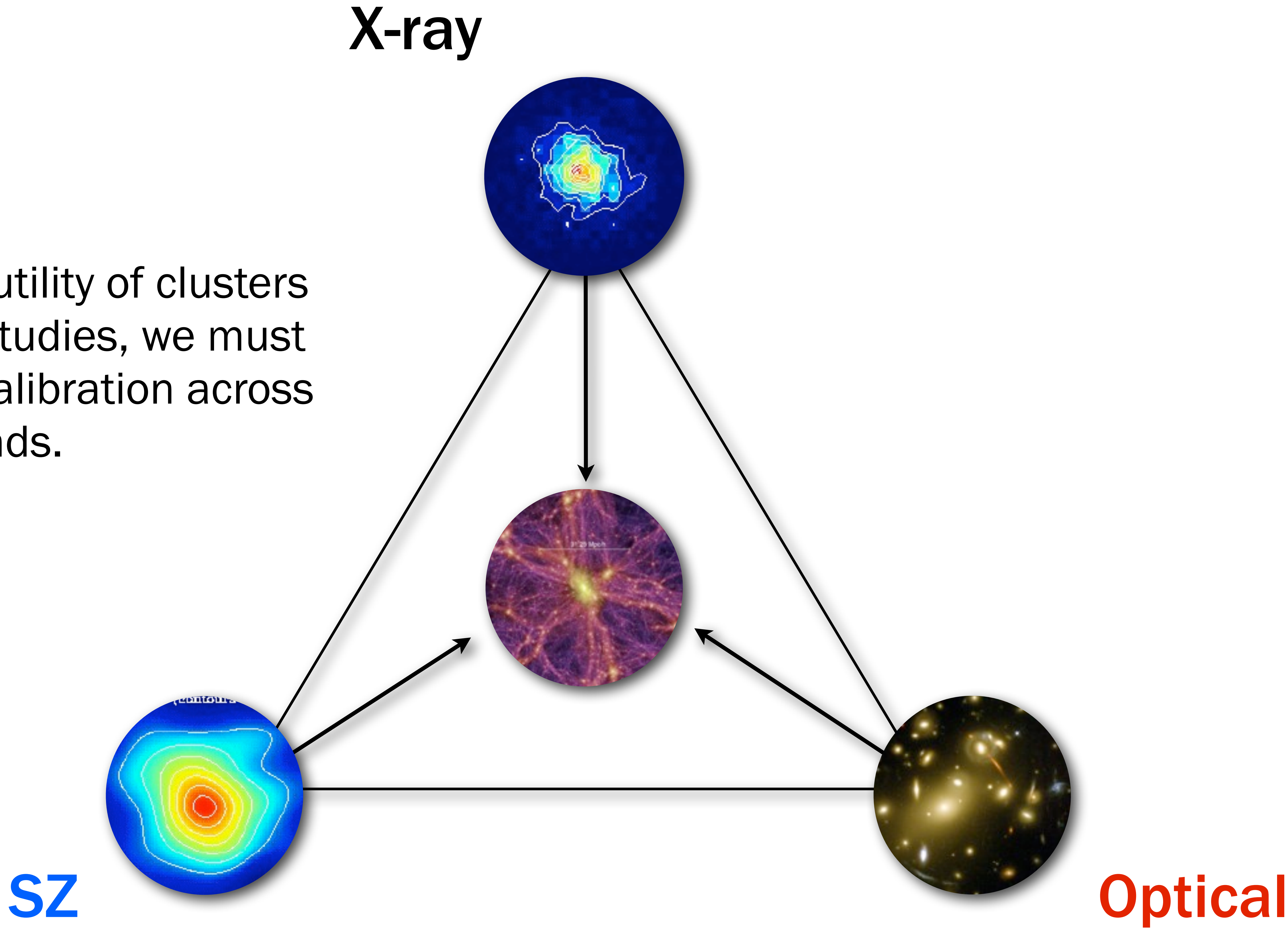
Corroborated by WMAP-based work by Draper et al., 2011!

<u>Recent history of stacking</u>:

- weak lensing mass of optical clusters (Sheldon/Johnston et al., 2006/7)
- theoretical SZ-optical cross-correlation (Fang et al. 2011, Li et al., 2011)

Cluster mass calibration: the trifecta

To maximize the utility of clusters in cosmological studies, we must reconcile mass calibration across multiple wavebands.



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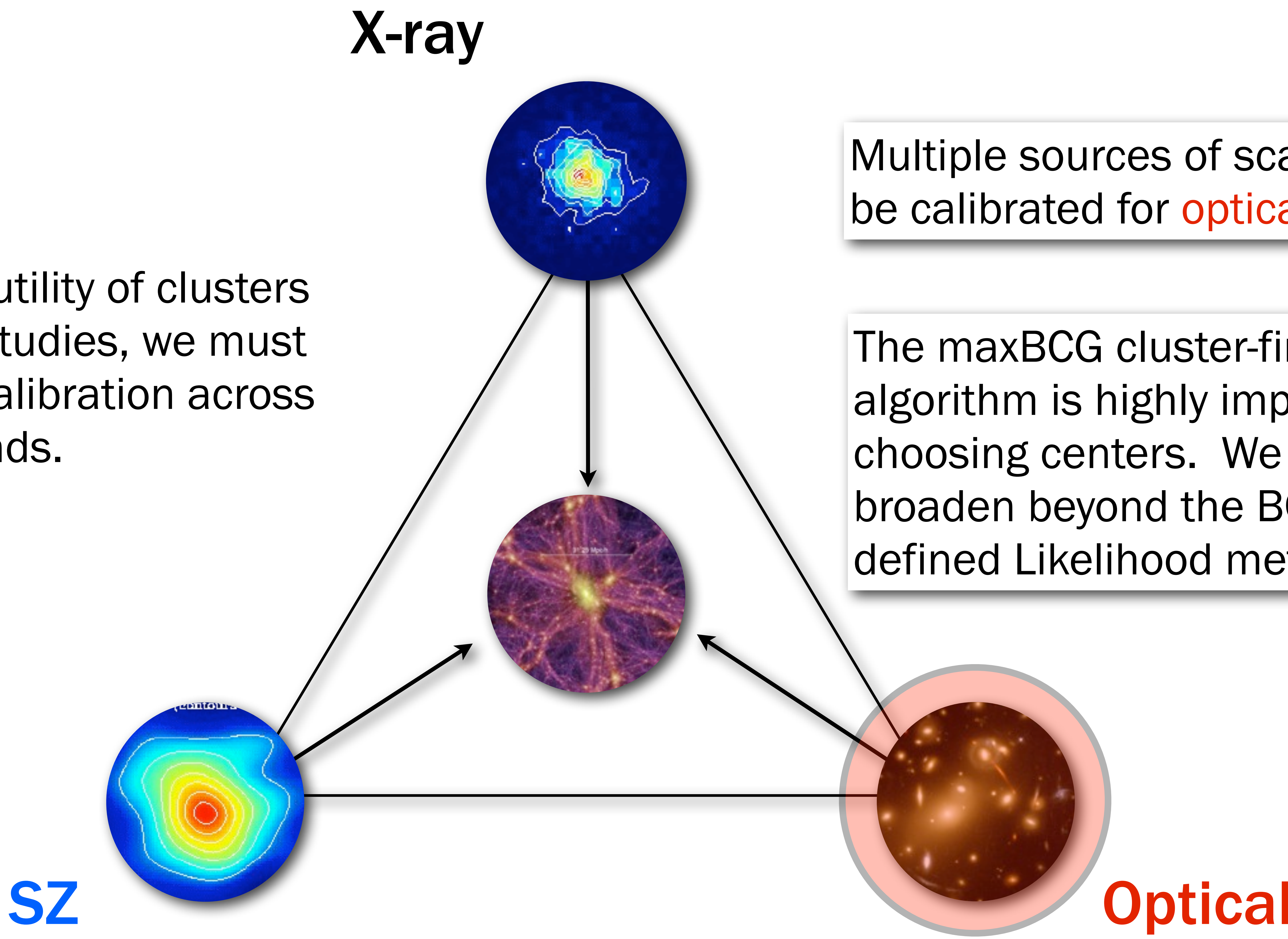
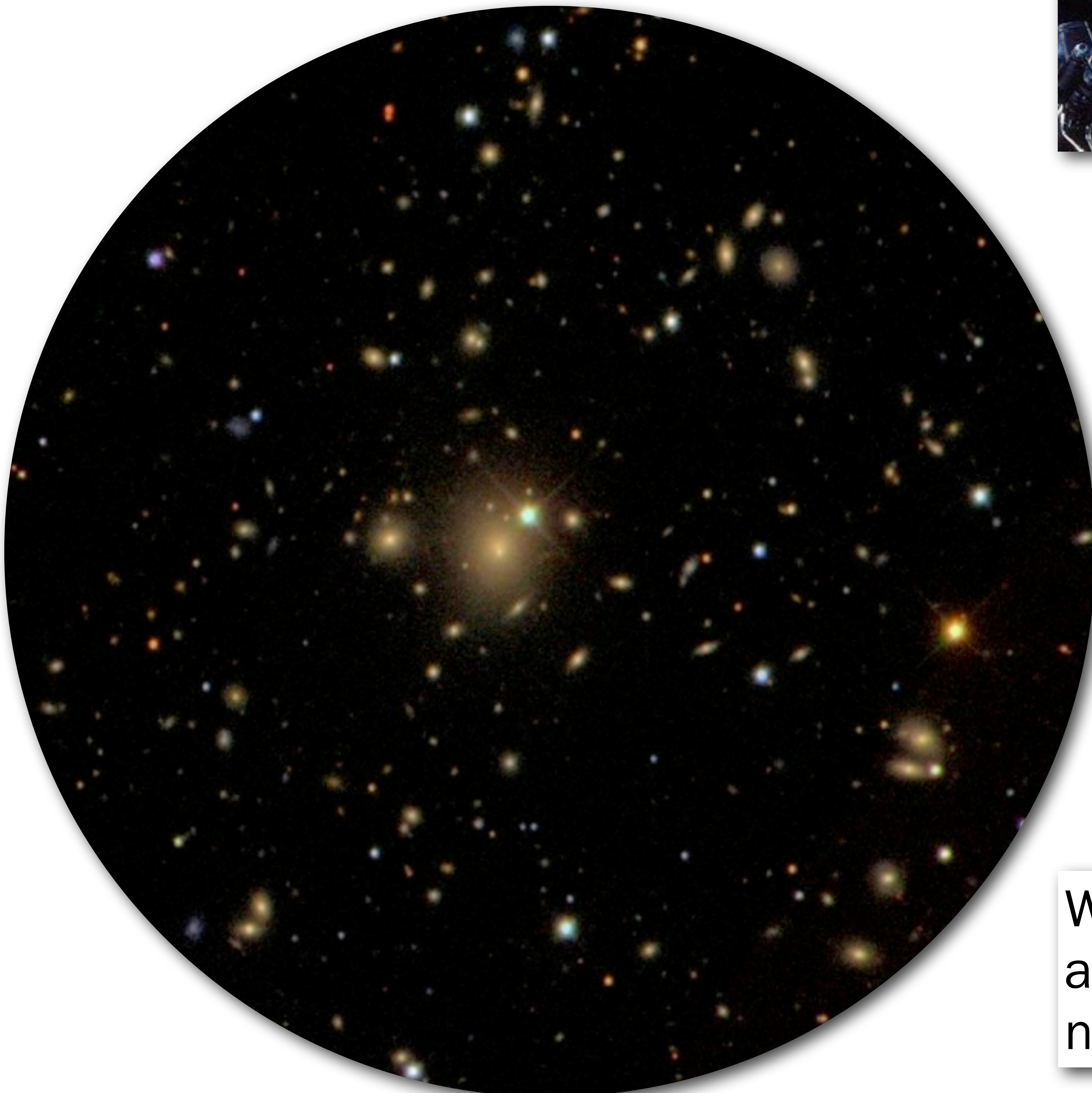


Multiple sources of scatter can be calibrated for optical clusters.

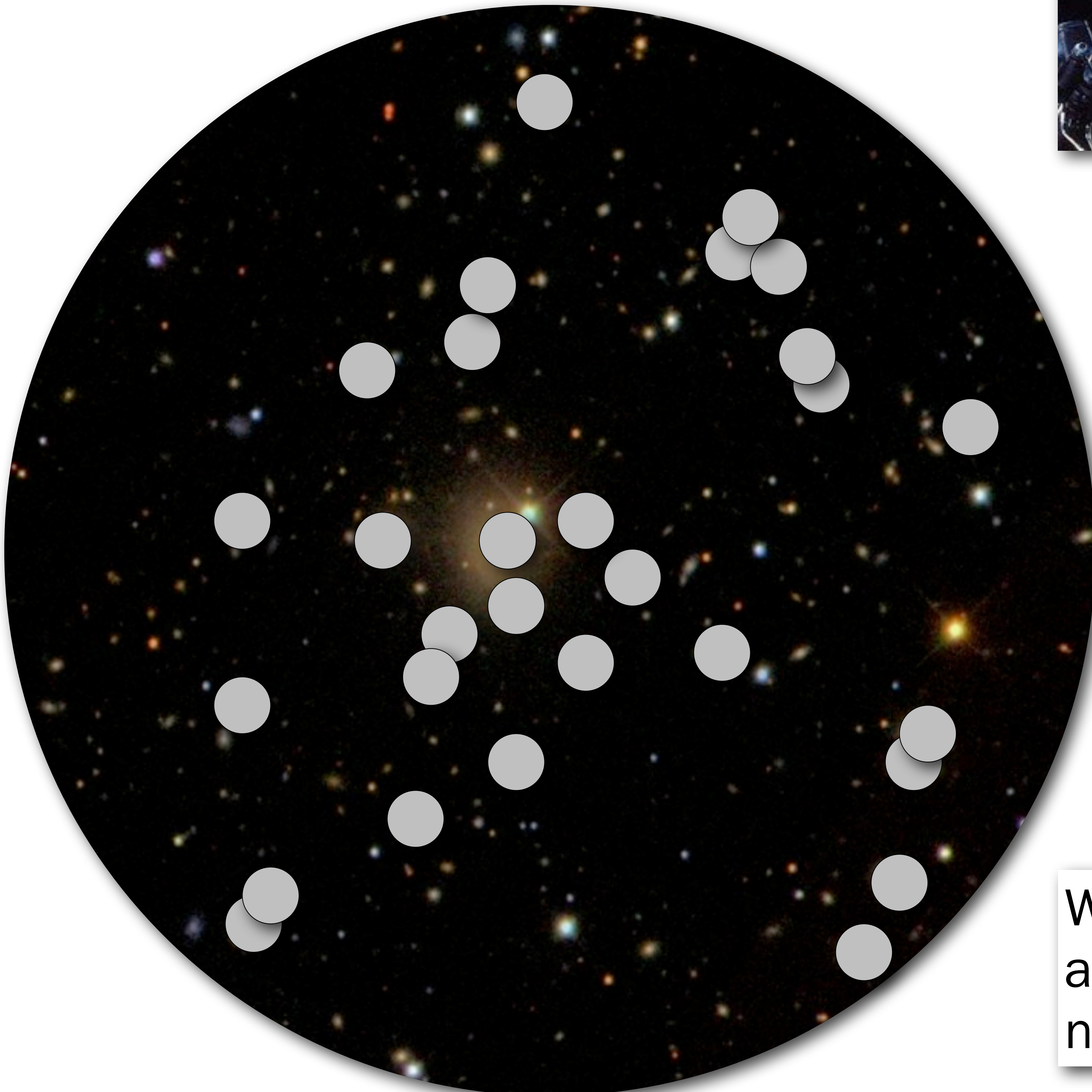
The maxBCG cluster-finding algorithm is highly imperfect at choosing centers. We need to broaden beyond the BCG-defined Likelihood method.

Consider a new approach to measuring substructure.



We look at the cluster as a network of galaxies with nodes and edges.

Consider a new approach to measuring substructure.



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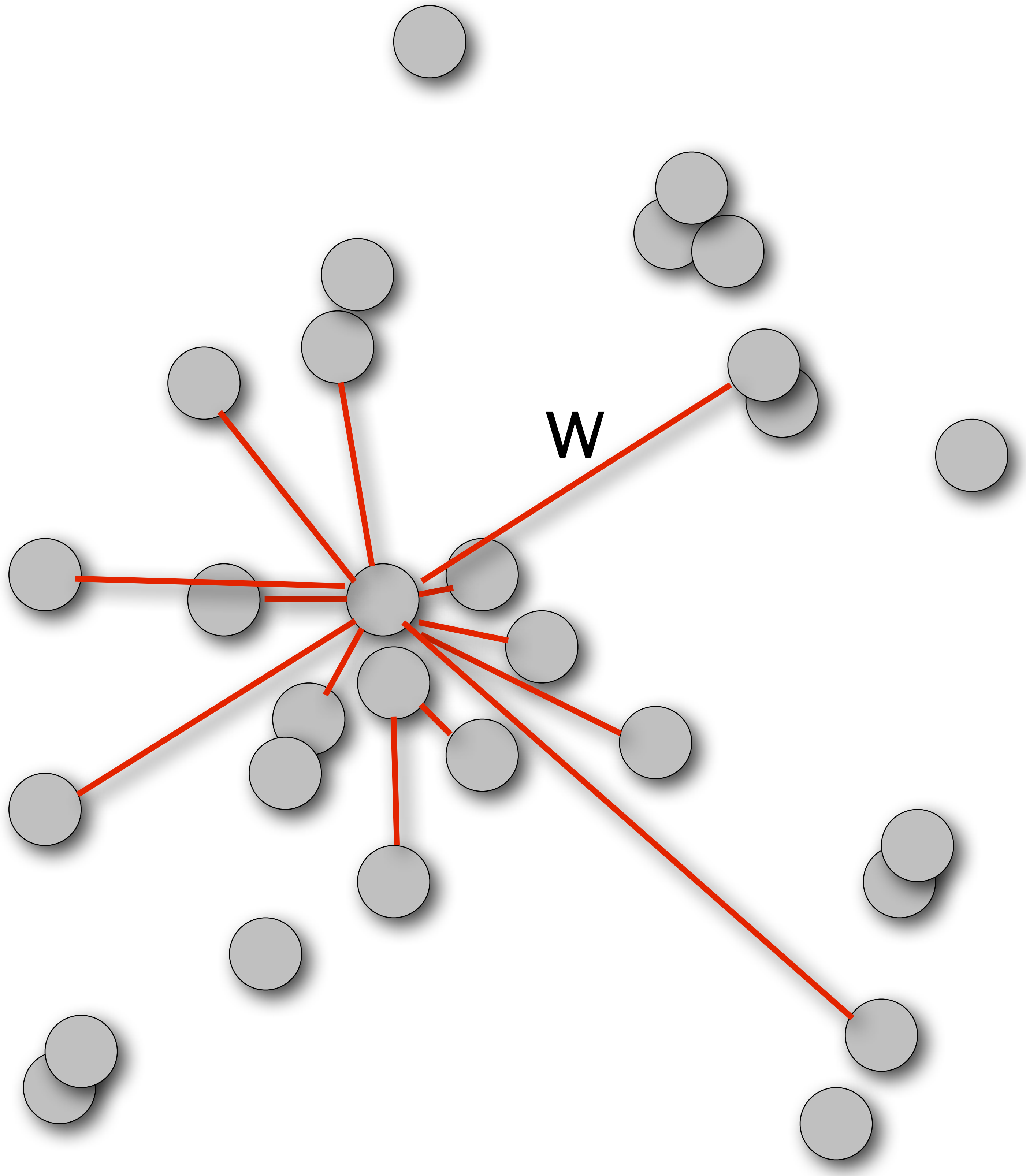
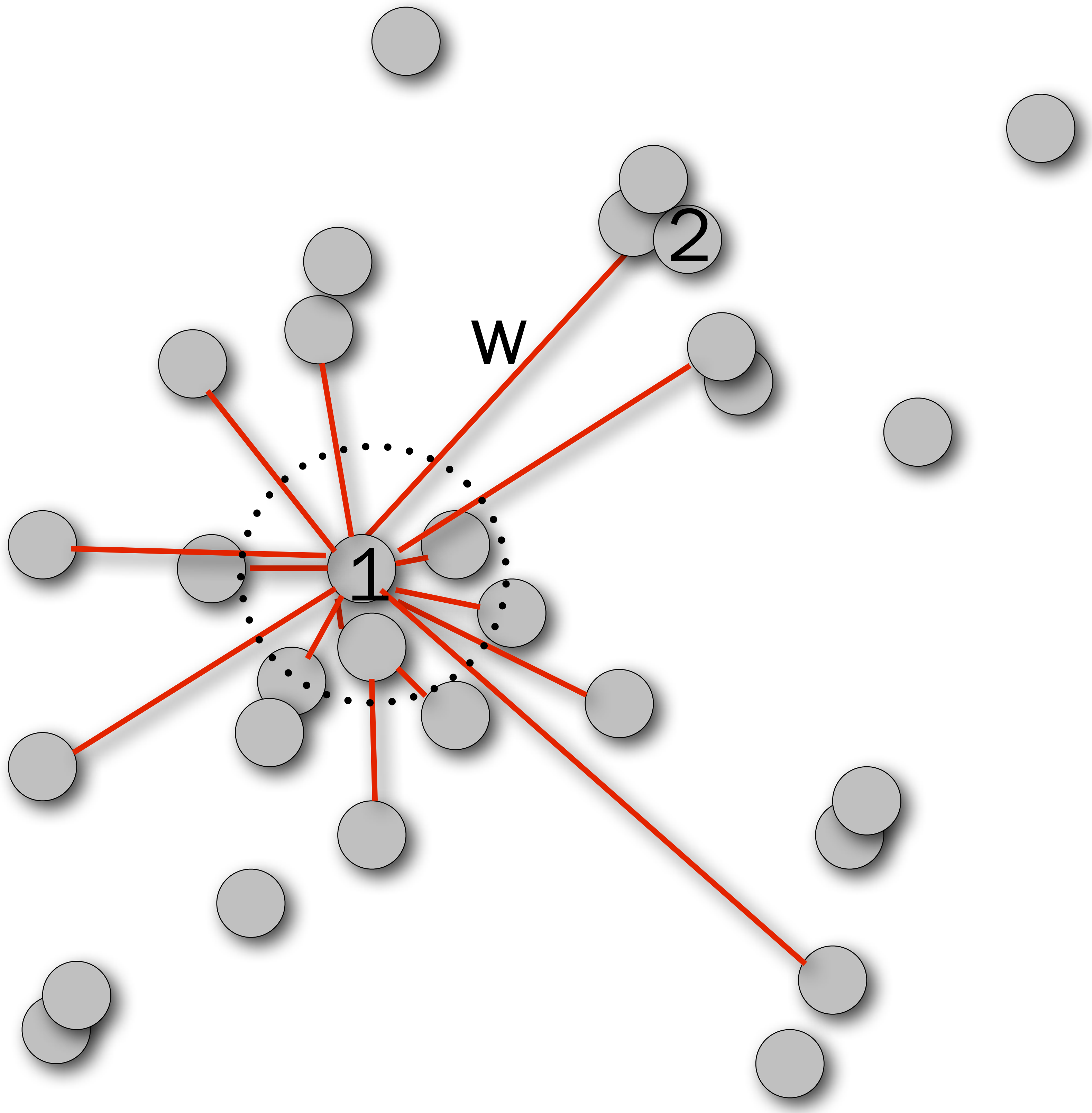


We look at the cluster as a network of galaxies with nodes and edges.

Consider a network of linked by mutual gravitational attraction

The weight of links between galaxies is a proxy for *gravitational attraction*:

$$w_{ij} \sim \tilde{\Phi} \sim \frac{\sqrt{L_i L_j}}{r_{ij}}$$



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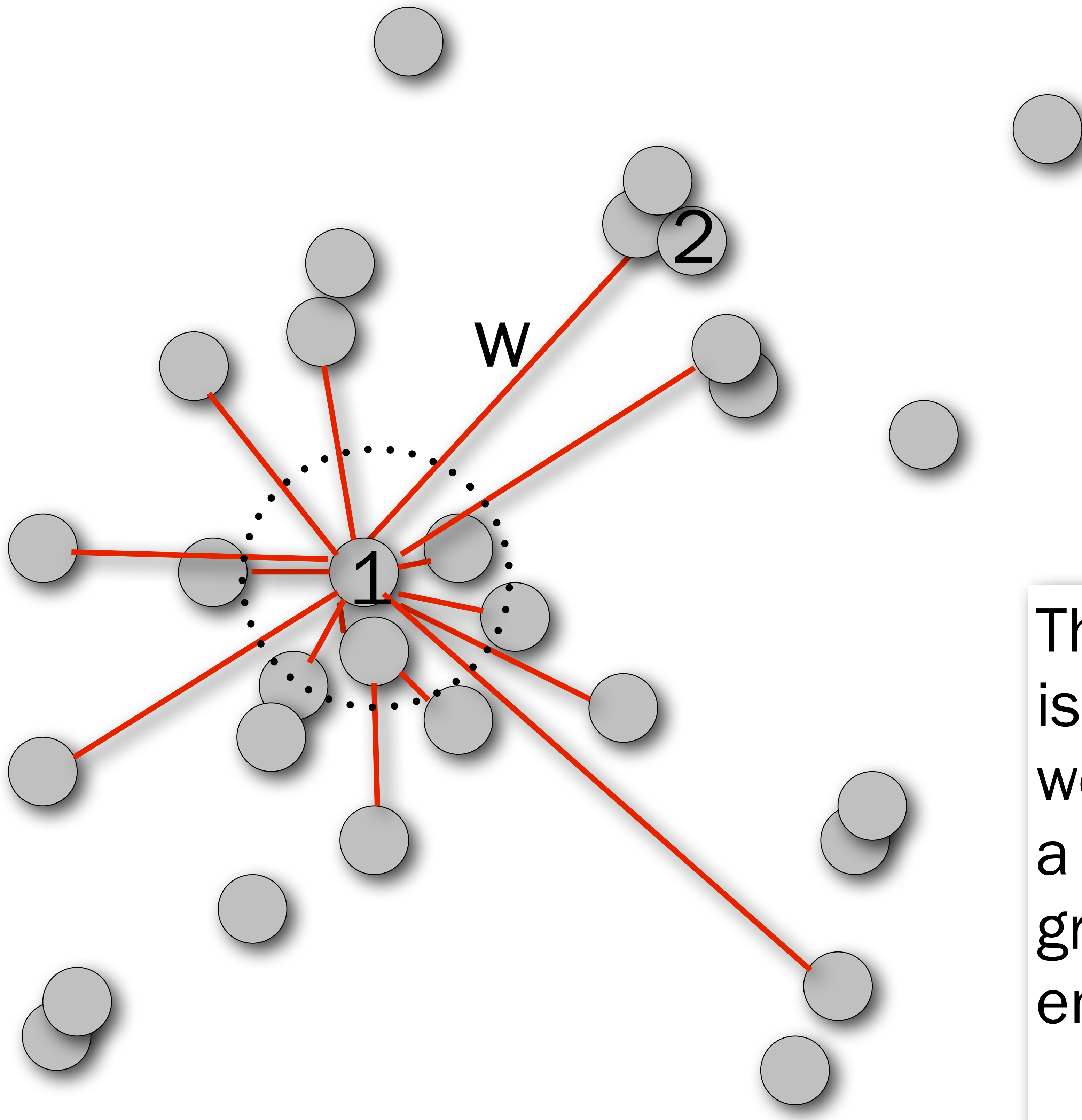


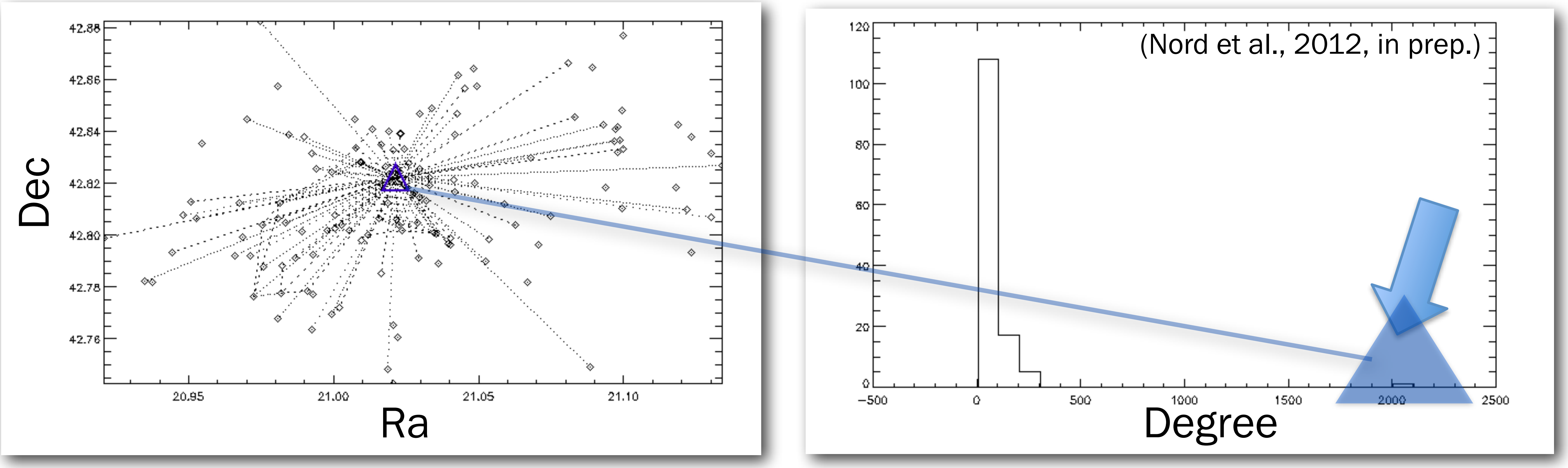
The <u>degree</u> of one galaxy is the sum total of the weights in all its links and a proxy for the total gravitational potential energy:

$$d_1 = \sum w_{1j}$$

SkyNet centering: tests with single clusters and weak lensing

Cluster FOV

Degree Distribution



The halo center is chosen by Skynet as the most connected galaxy, and thus the center.

SkyNet centering: tests with single clusters and weak lensing

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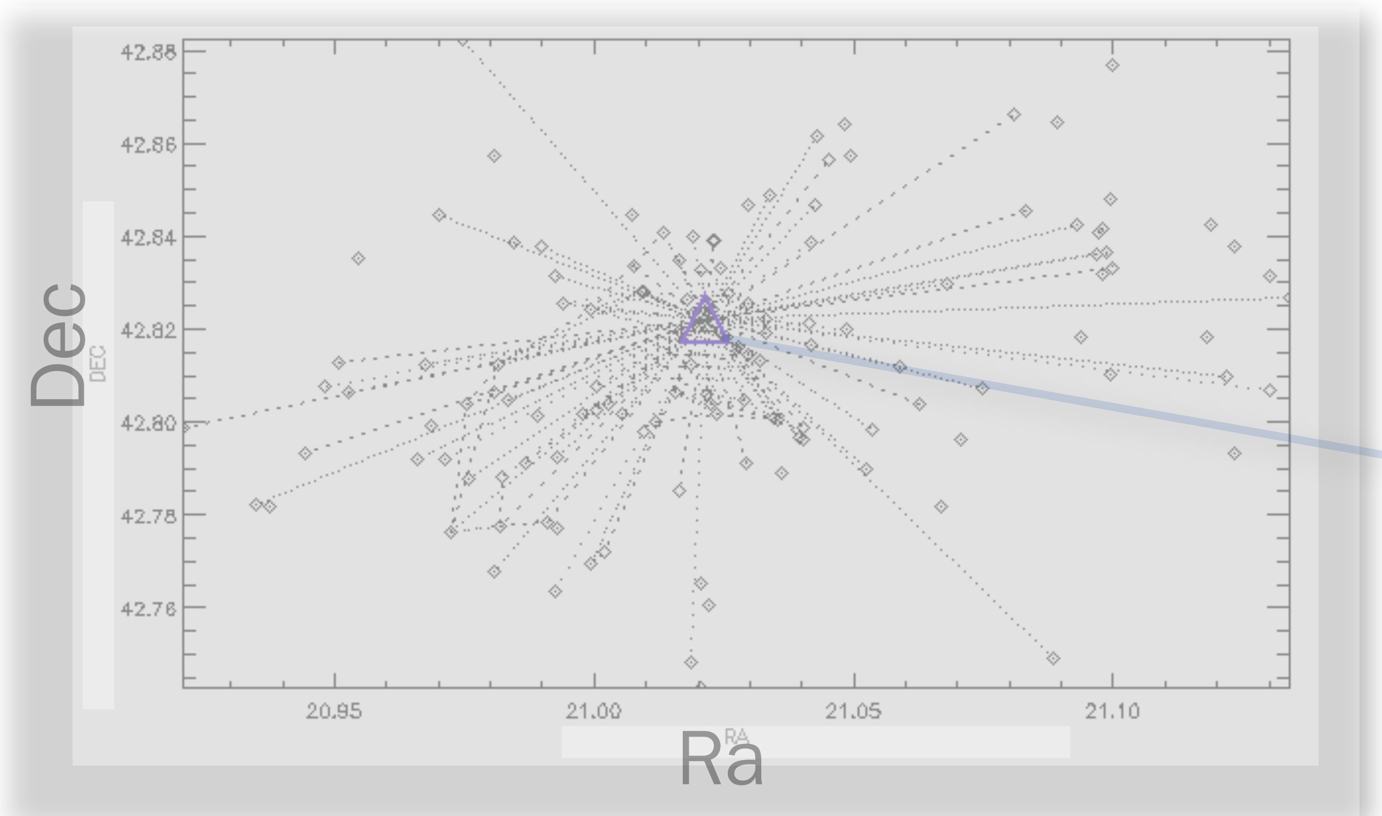

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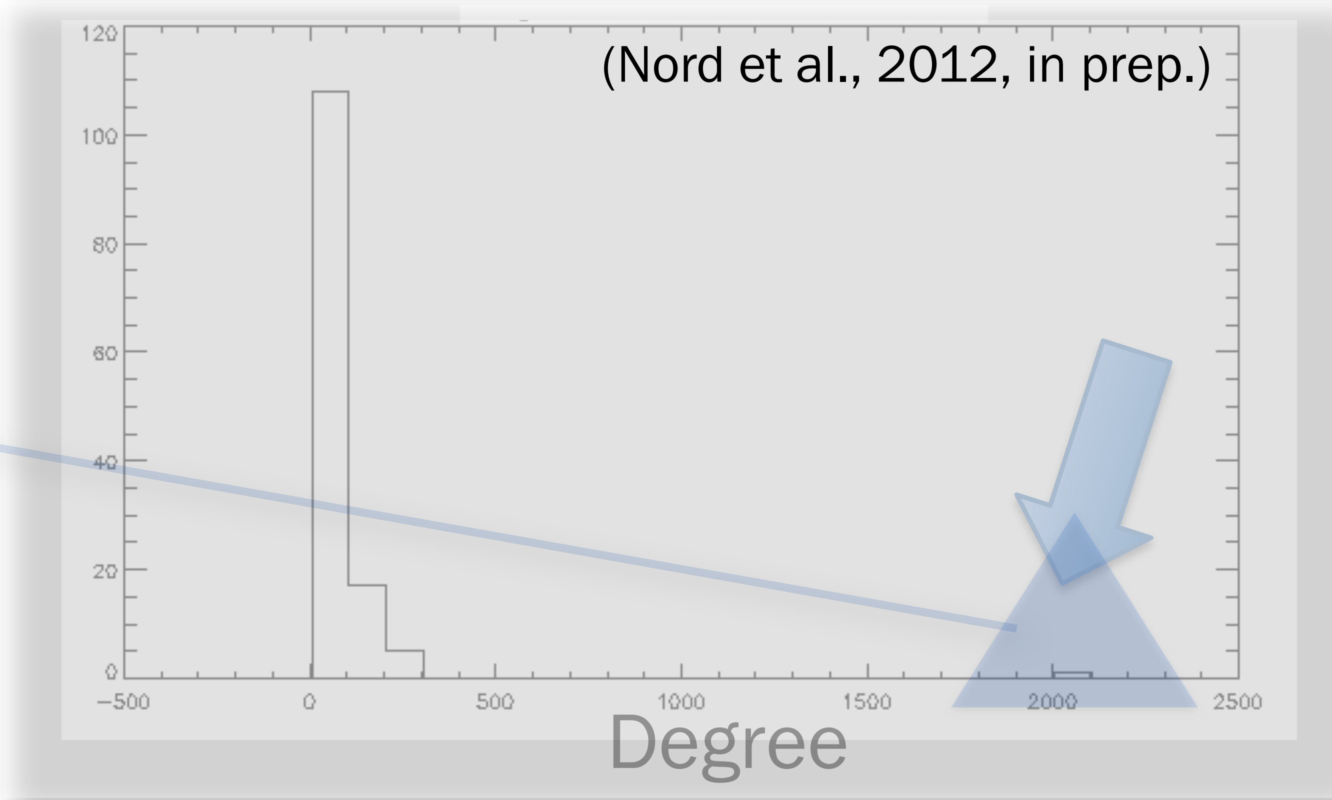

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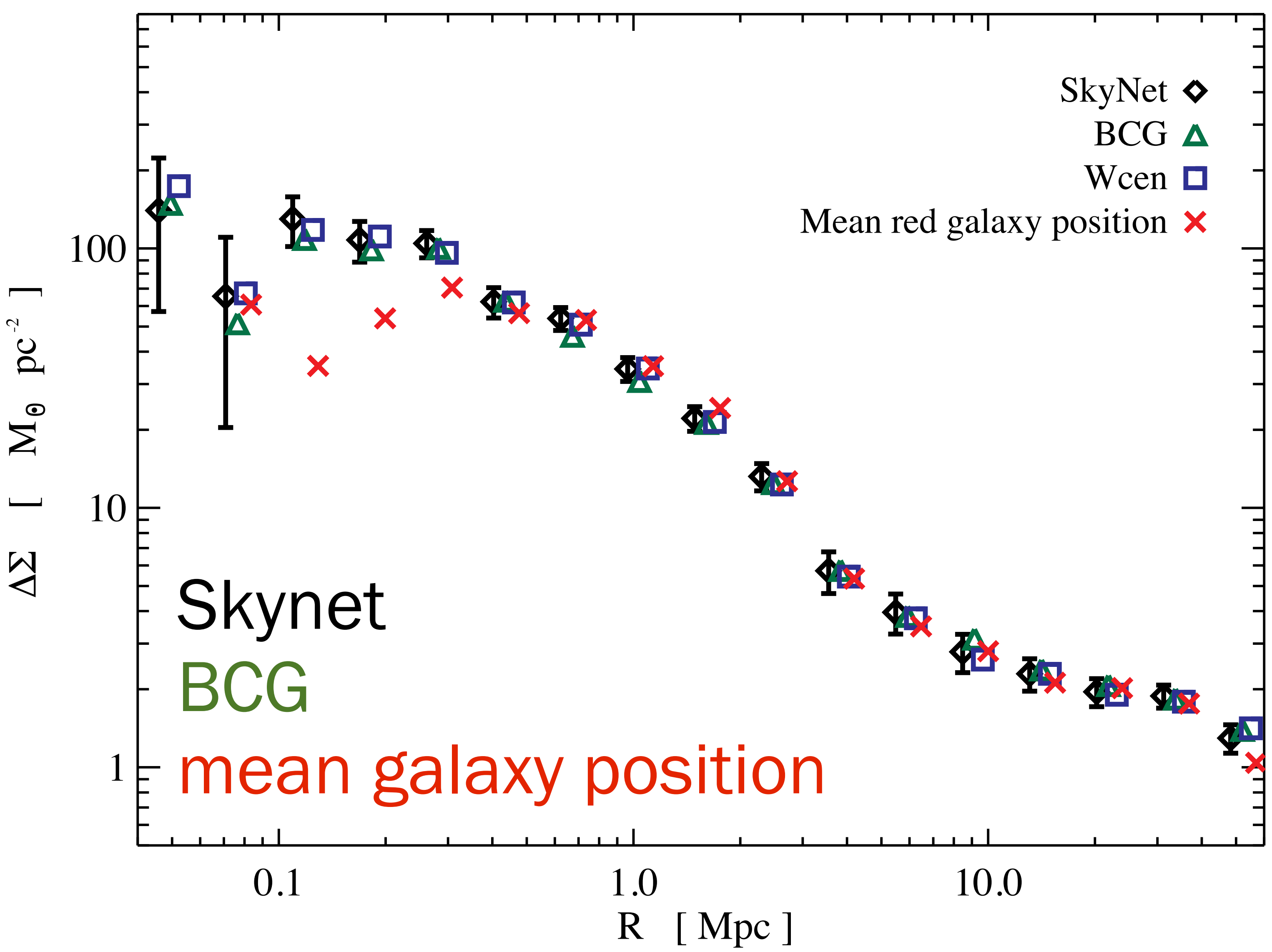
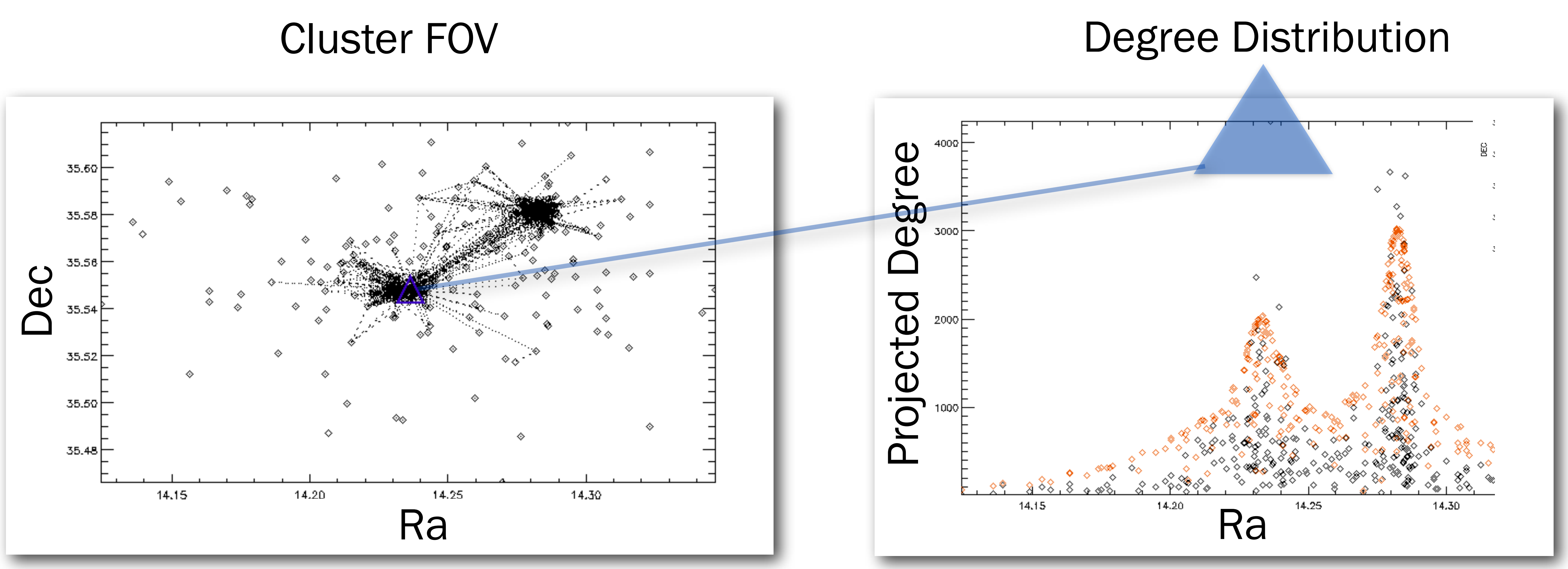


Weak lensing profiles

- Stacking ~450 clusters in SDSS Stripe 82 at z~0.4
  (by Rykoff, Lethaud, Kneib, Makler, van Waerbeke)
- Skynet finds centers at least as good as the ‘BCG’ algorithm.

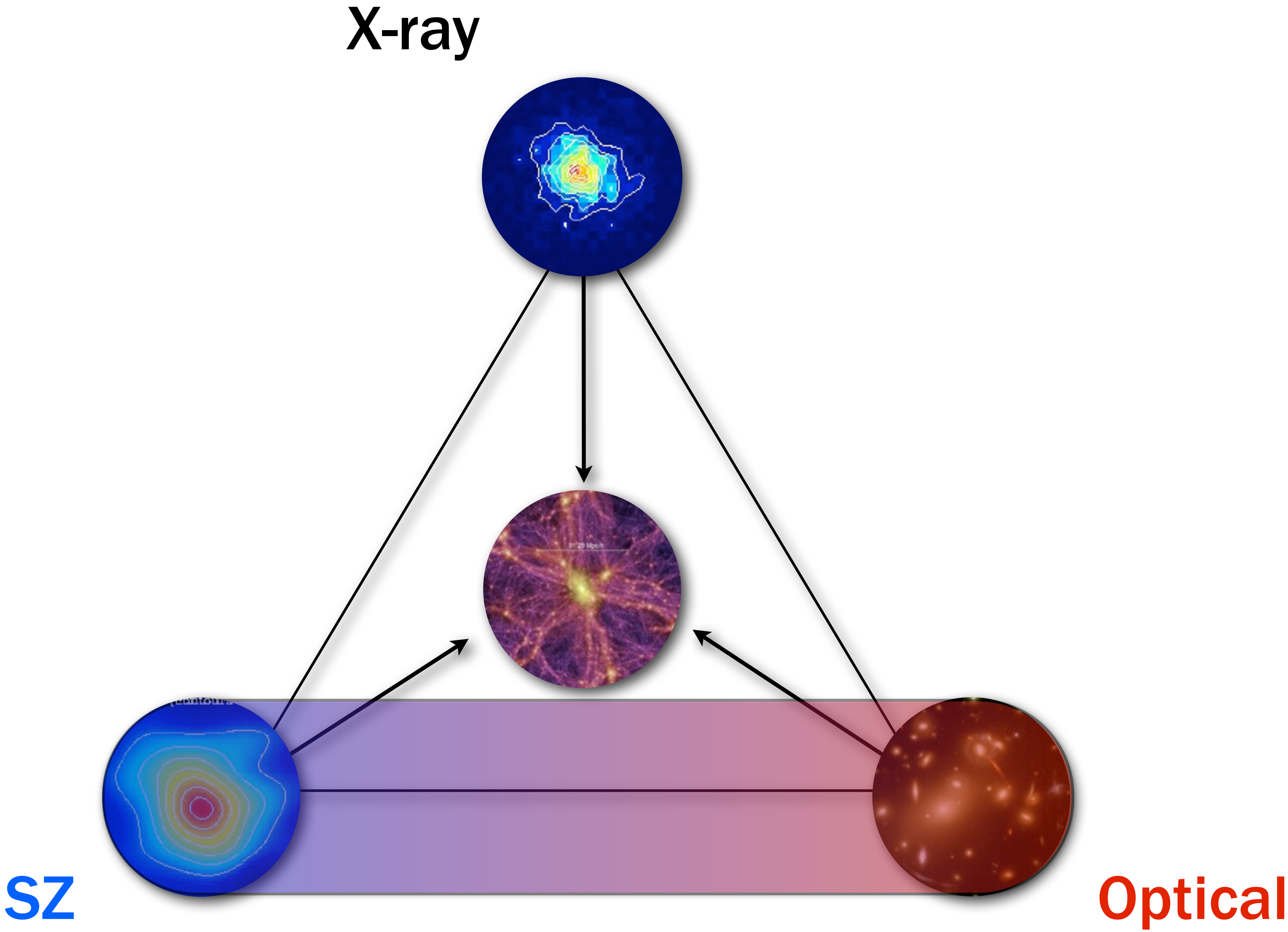
Skynet reveals optical cluster substructure



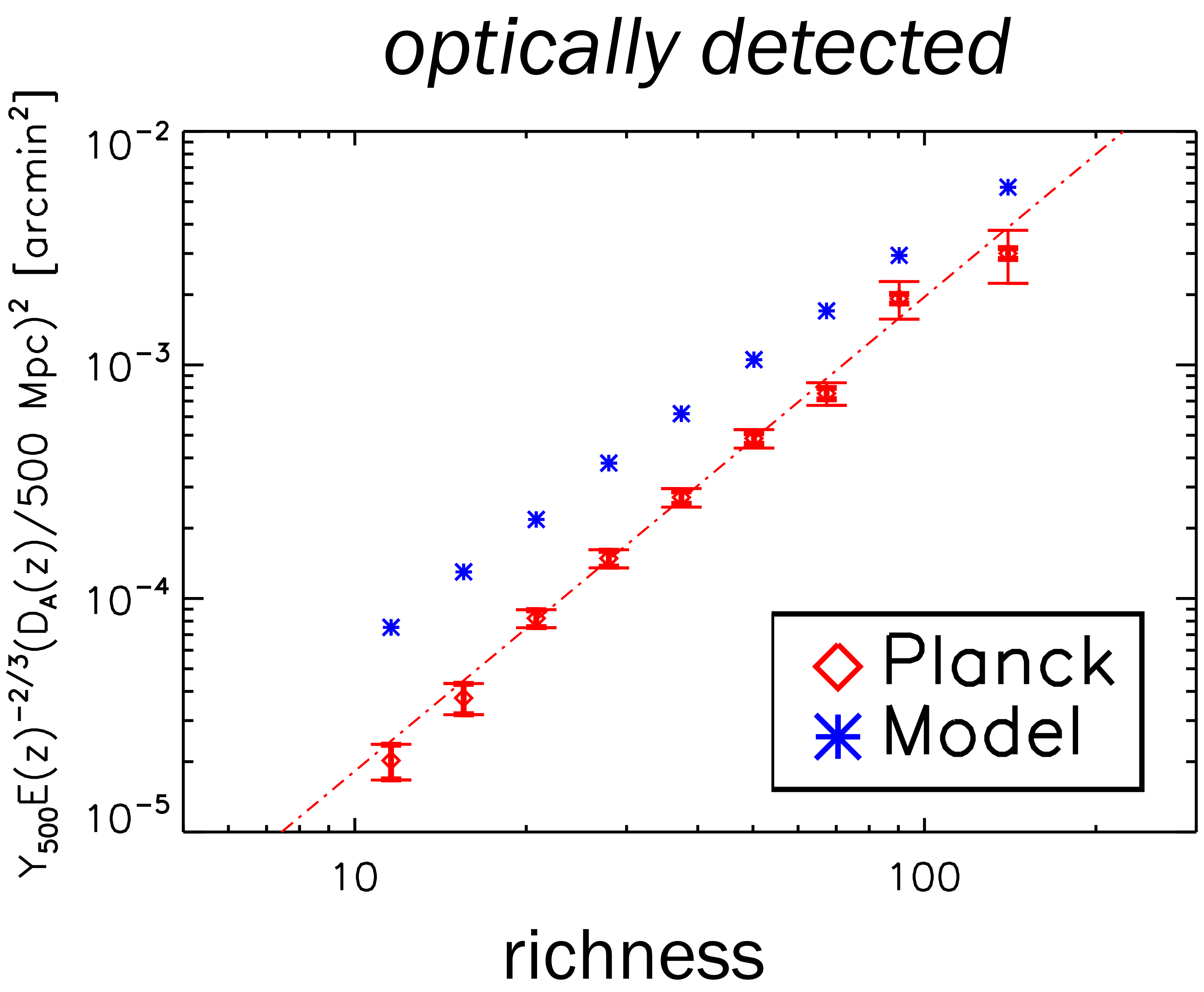
Some centers are inherently ambiguous:

this leads us to notions of substructure
-- both dynamical and projection-related.

Cluster mass calibration: the trifecta



The Impact of systematics on the SZ-Optical scaling relation



The Impact of systematics on the SZ-Optical scaling relation

We apply a Monte Carlo simulation of all systematic effects known in the maxBCG cluster catalogue to a halo catalogue to assess the impact on stacked SZ measurements

Family of systematics:

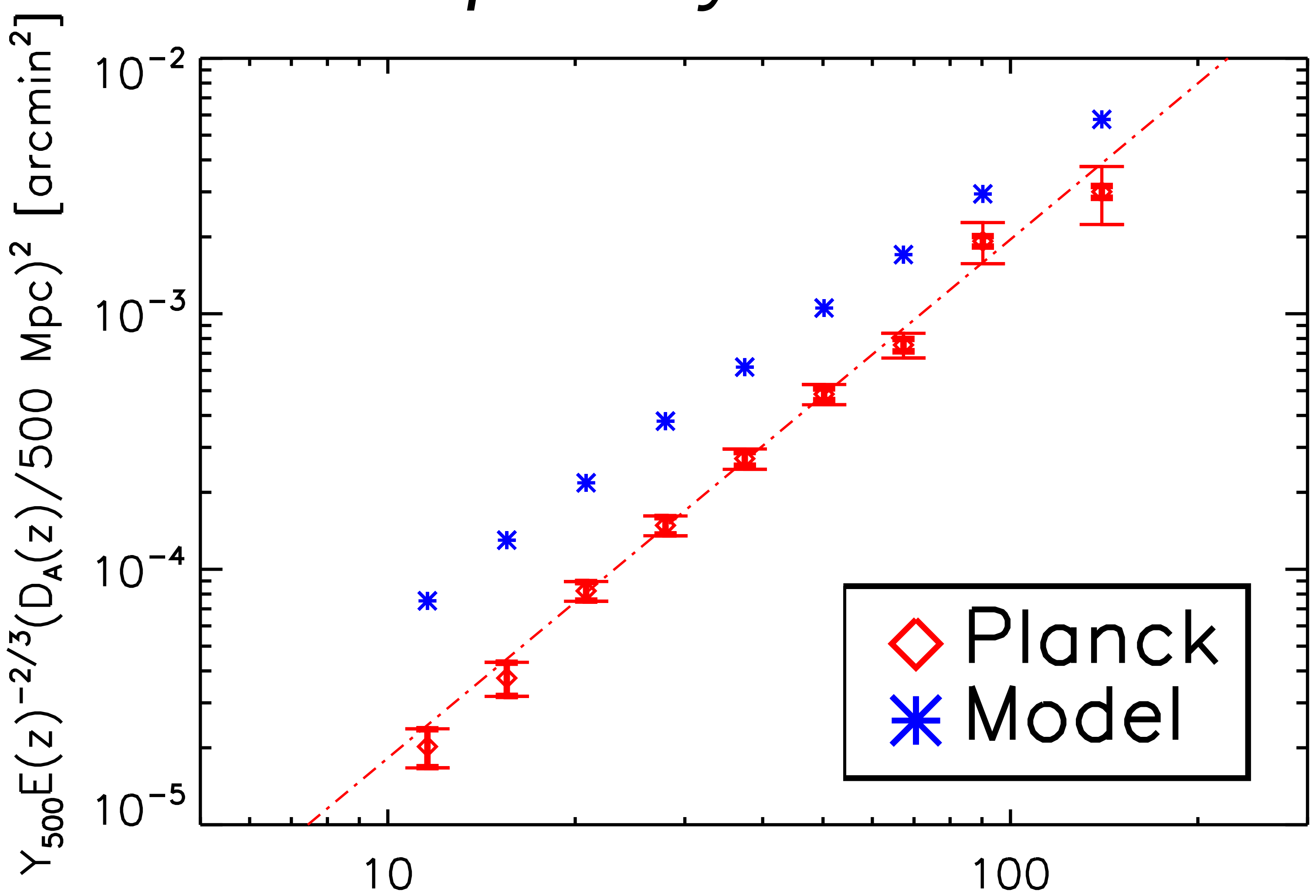
mass-richness calibration

- Rozo et al., 2009; Johnston et al., 2007

catalogue systematics

- catalogue completeness/purity
- photometric redshift
- mass scatter
- mis-centering

optically detected



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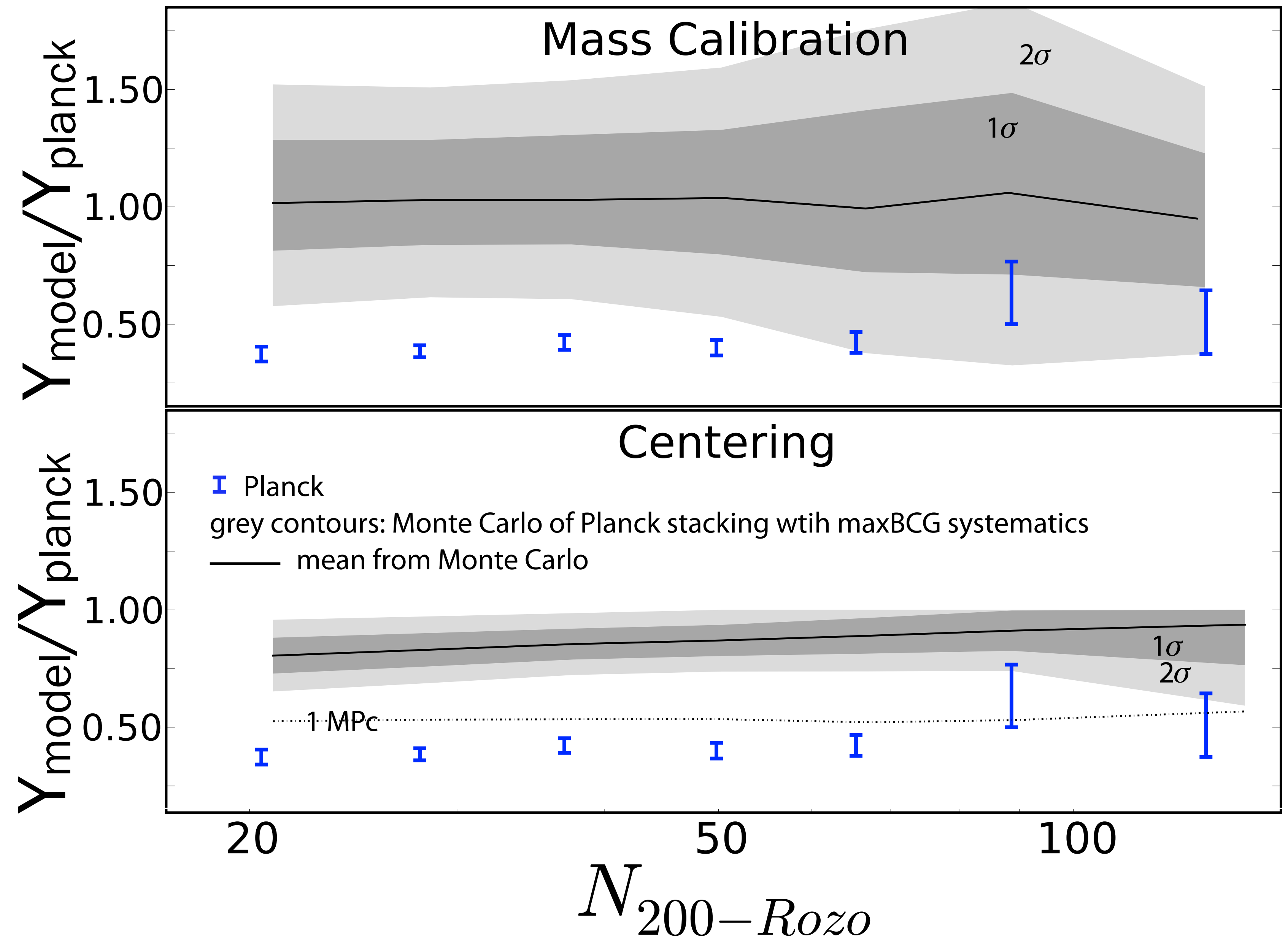

Biesiadzinski, ..., Nord et al. 2012

Baseline Rozo model with Planck error bars

Our Model with Monte Carlo of systematics

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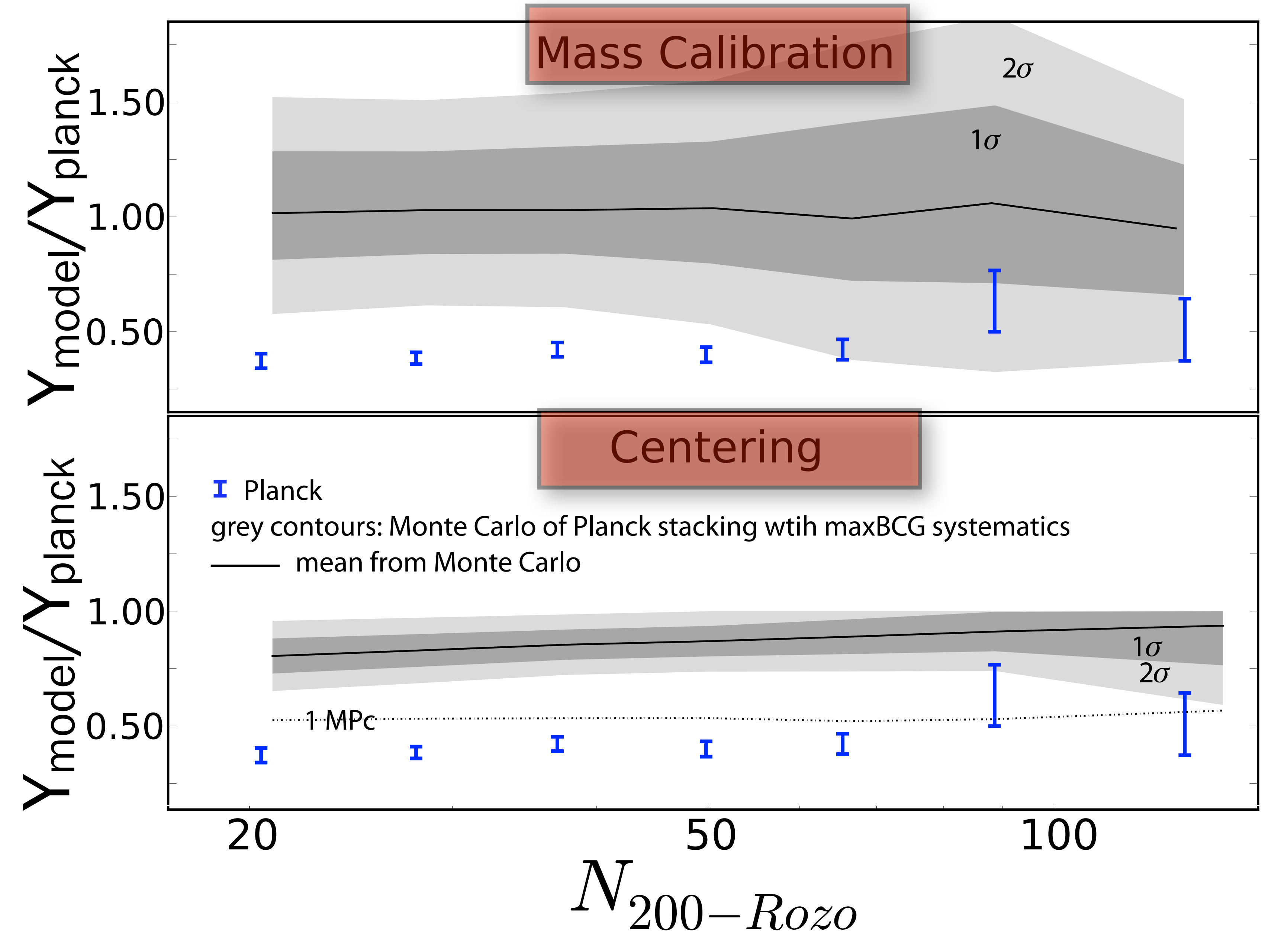

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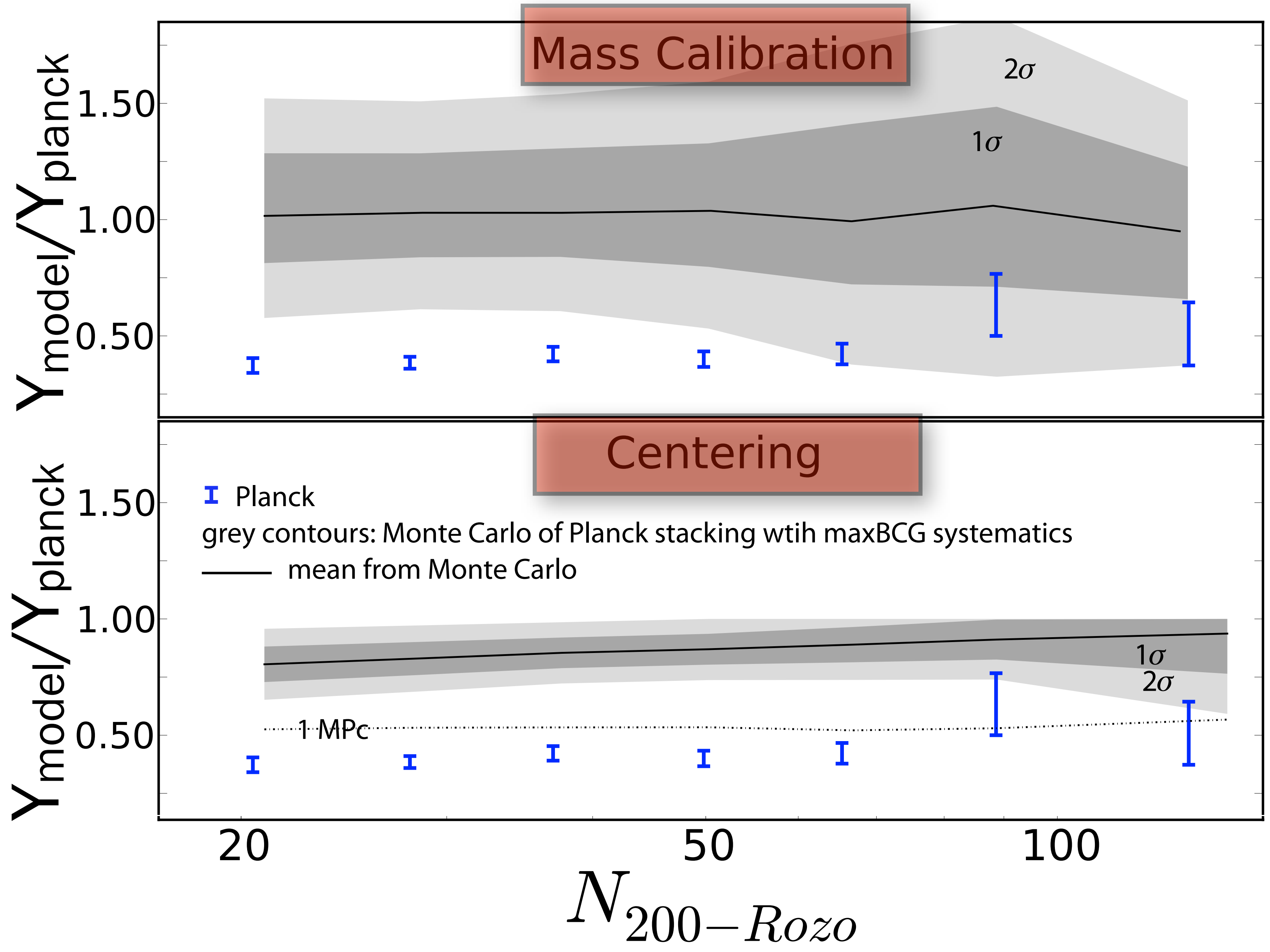

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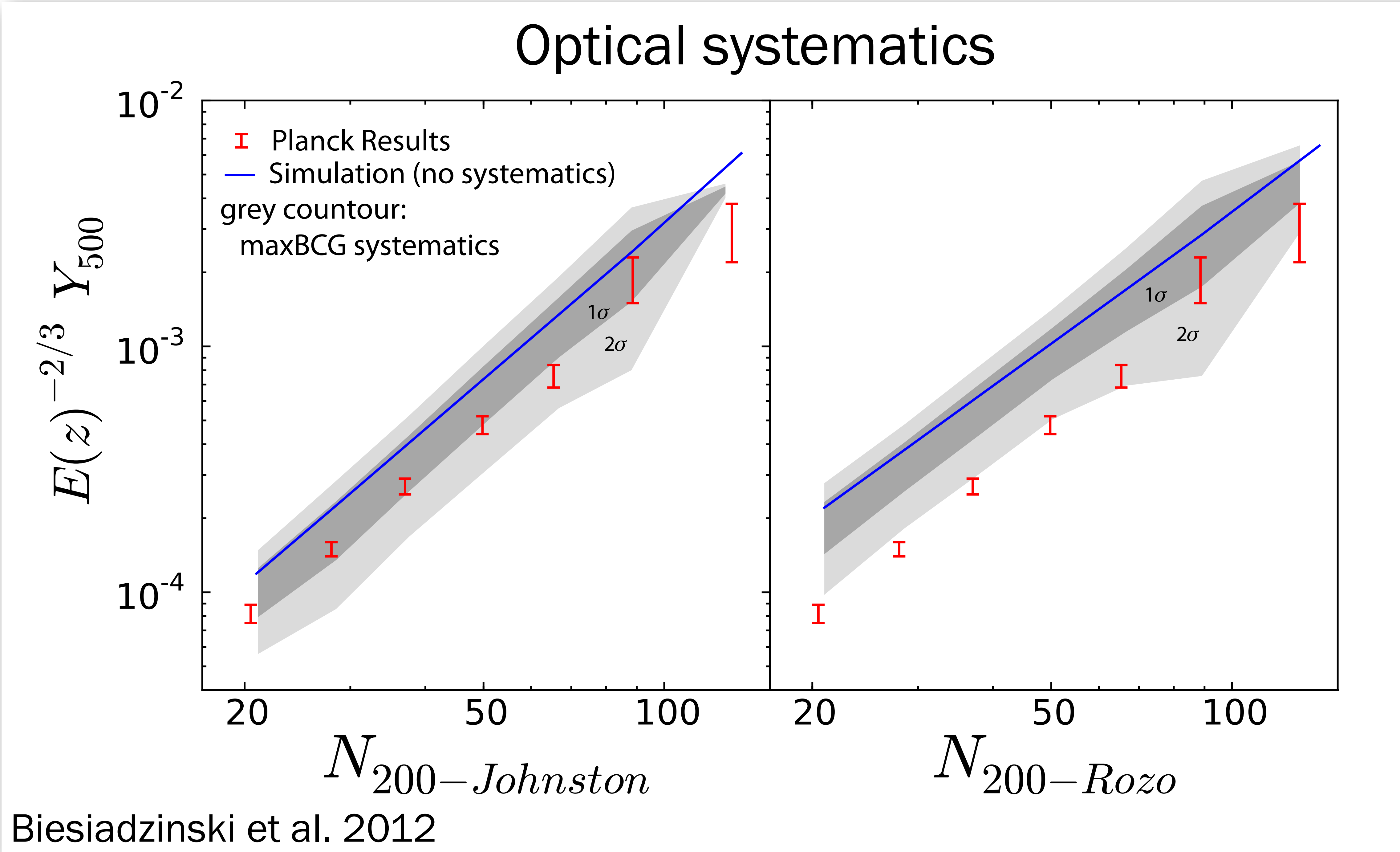
Baseline Rozo model with Planck error bars

Our Model with Monte Carlo of systematics

Results:
- Systematics in the *mass-richness calibration* cause a large range in the model behavior: **25-50% (1σ-2σ)**
- Mean from Monte Carlo of systematic mis-centering is **biased low by 20%** with **12-25% range in scatter**
- **Both of these MC models are less biased than the Rozo model**

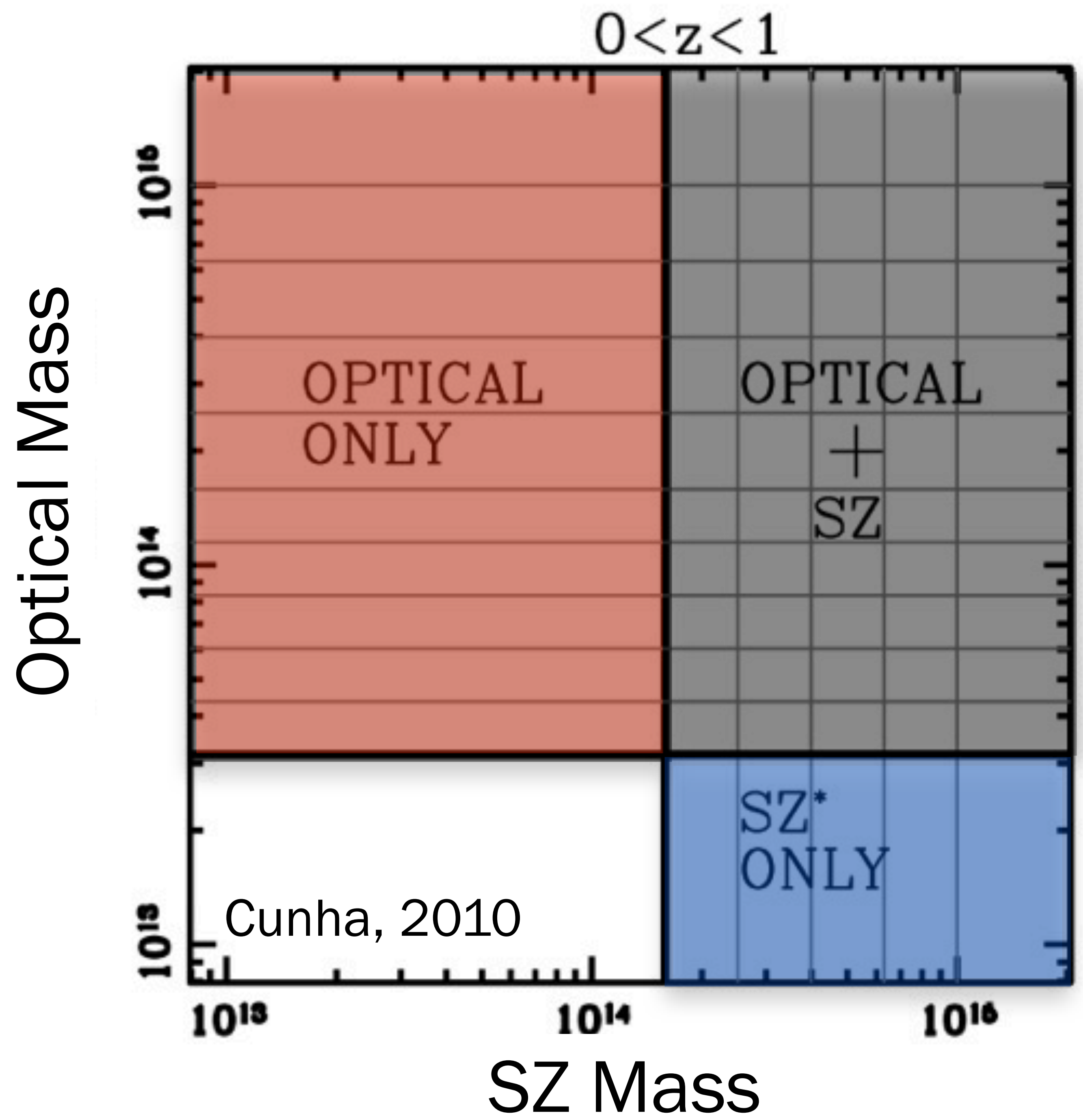
Including systematics brings *near*-agreement.

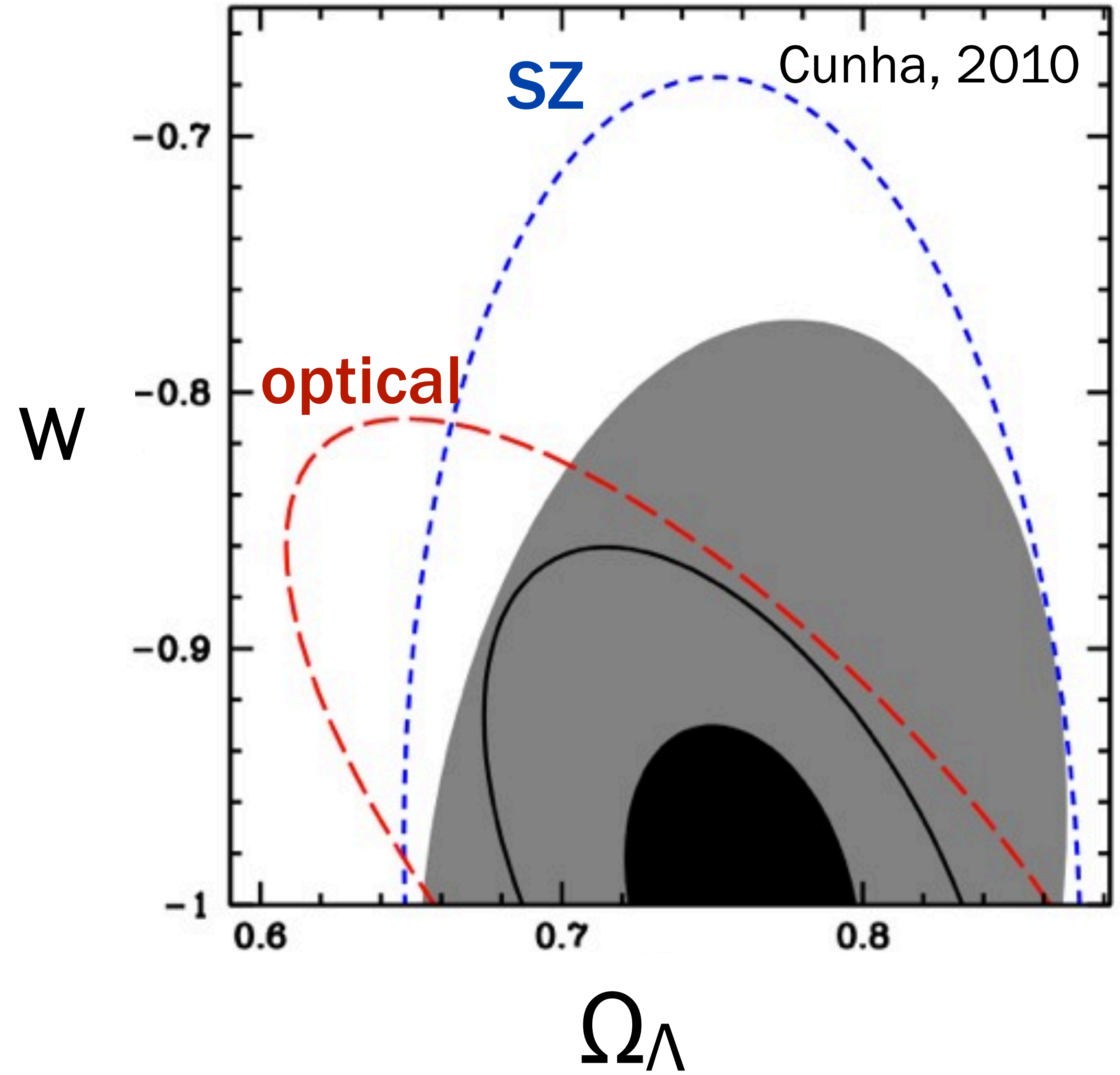


Simulations without systematics are significantly offset from the Planck data.

Simply accounting for systematics brings the model and data close to agreement.

Joint cluster abundance analysis





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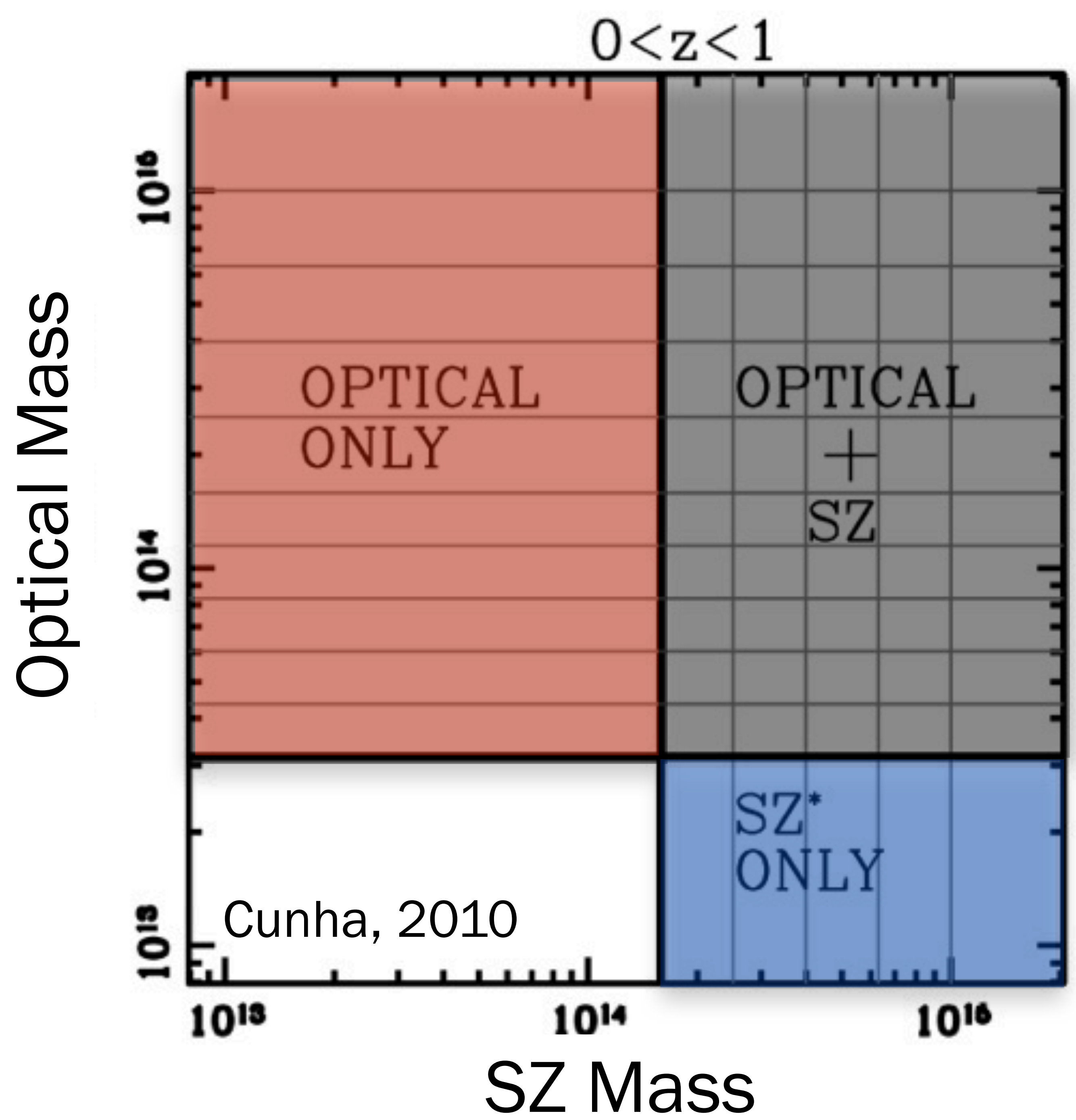
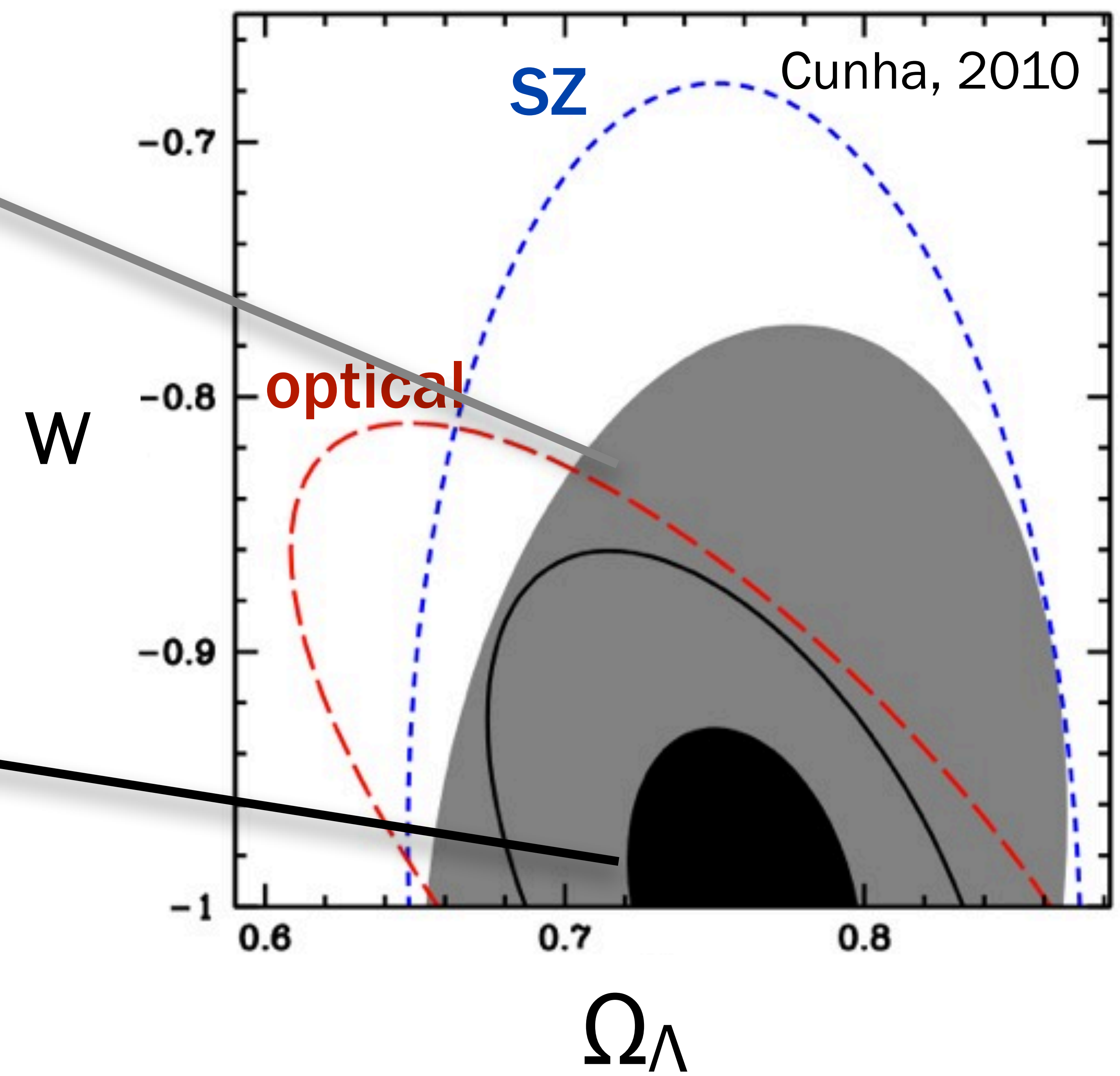


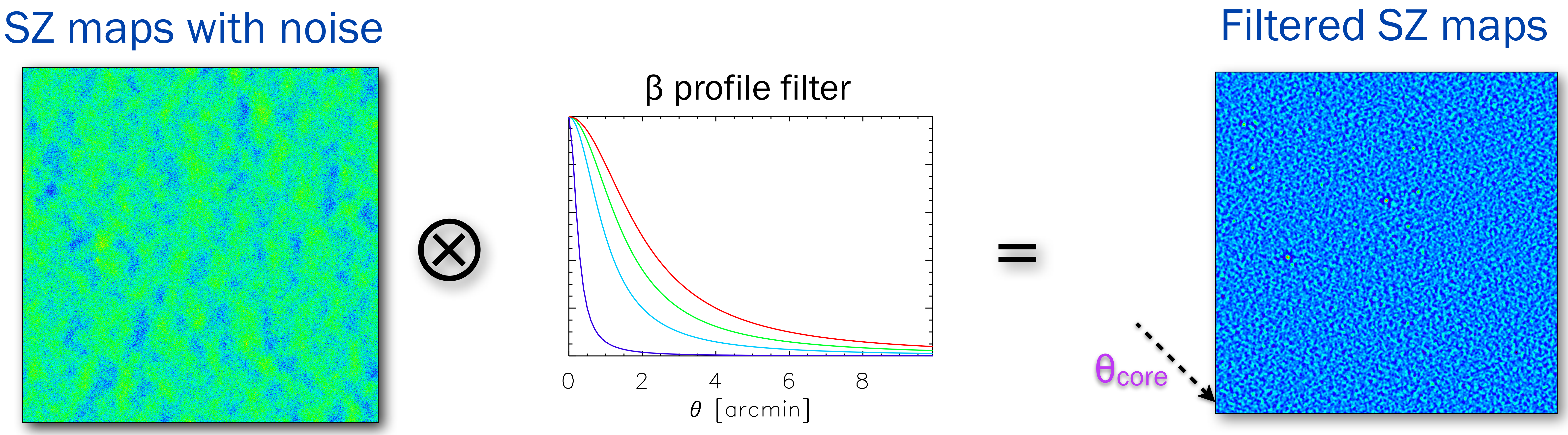
basic cat combination

fully joint analysis!



While basic combining can bring more clusters, fully ***joint*** analysis can improve dark energy constraints by factors 2-3.

Conjoin optical and SZ maps through signal-to-noise measurements.



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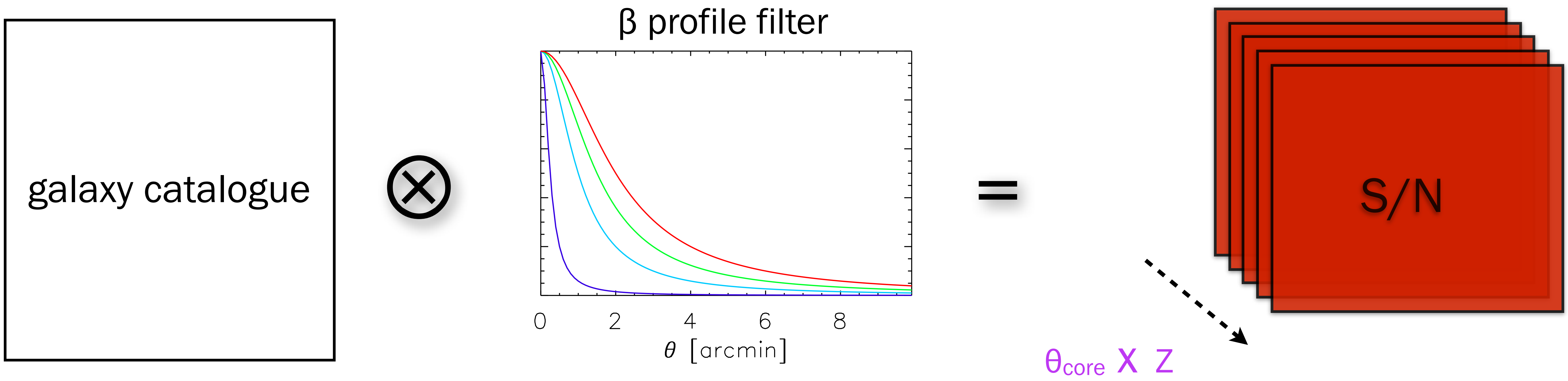

Statistical Question:

What's the probability that a cluster lives at any given location in the map?

Approach:

Fit beta profiles to optical density to make s/n maps

... the same as the process for SZ match-filter detection.

Optical S/N for each pixel (proof of concept)

Cluster Model: Beta Profile

$$\psi(\theta|A, \theta_c, \beta) = A\left[1 - \left(\frac{\theta}{\theta_c}\right)^2\right]^{\frac{1-3\beta}{2}}$$

β = 1, fixed

A

core radius

Optical S/N for each pixel (proof of concept)

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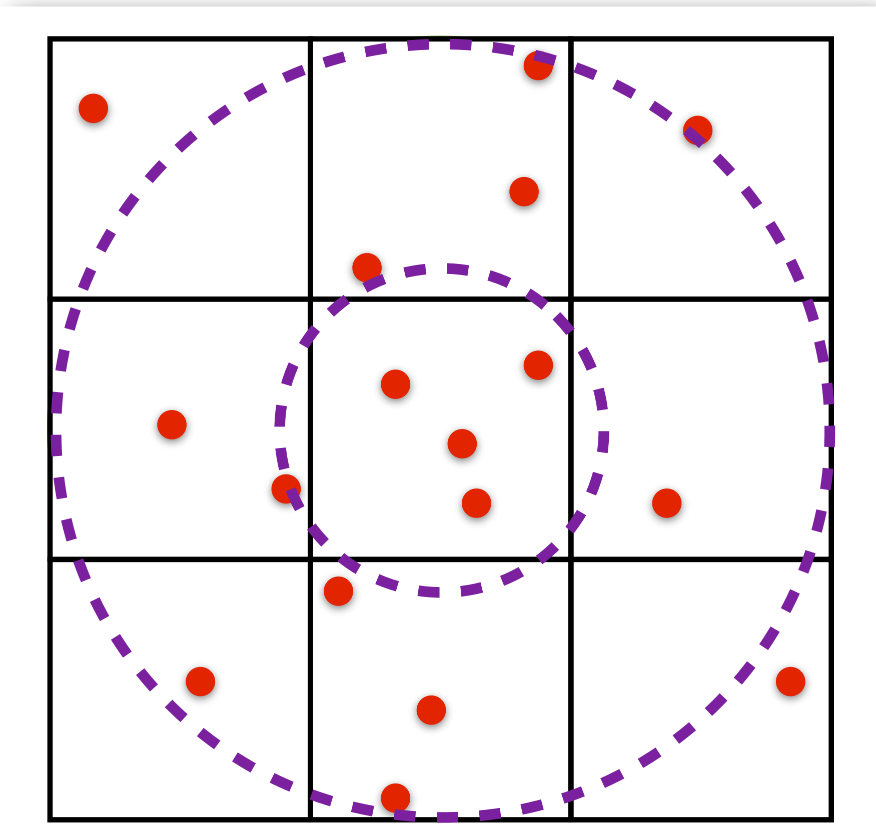
Schematic of
Galaxies in Cluster



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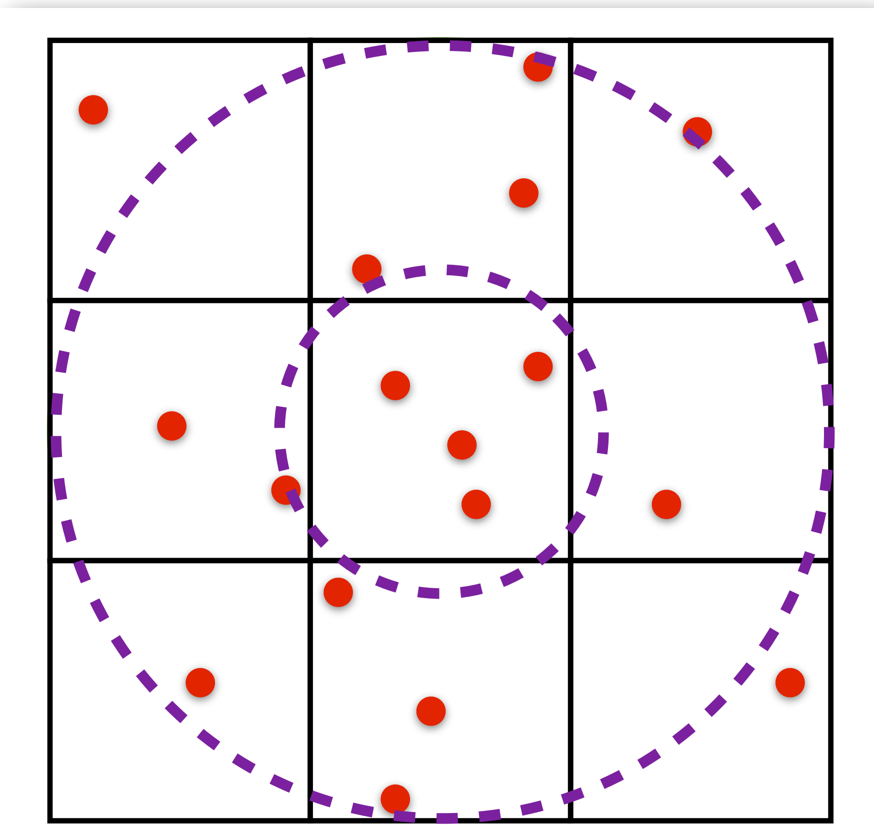


S/N Measurement Process

1. Measure the poisson noise in each radial bin
2. Fit for <A>
3. Error in fit is σA

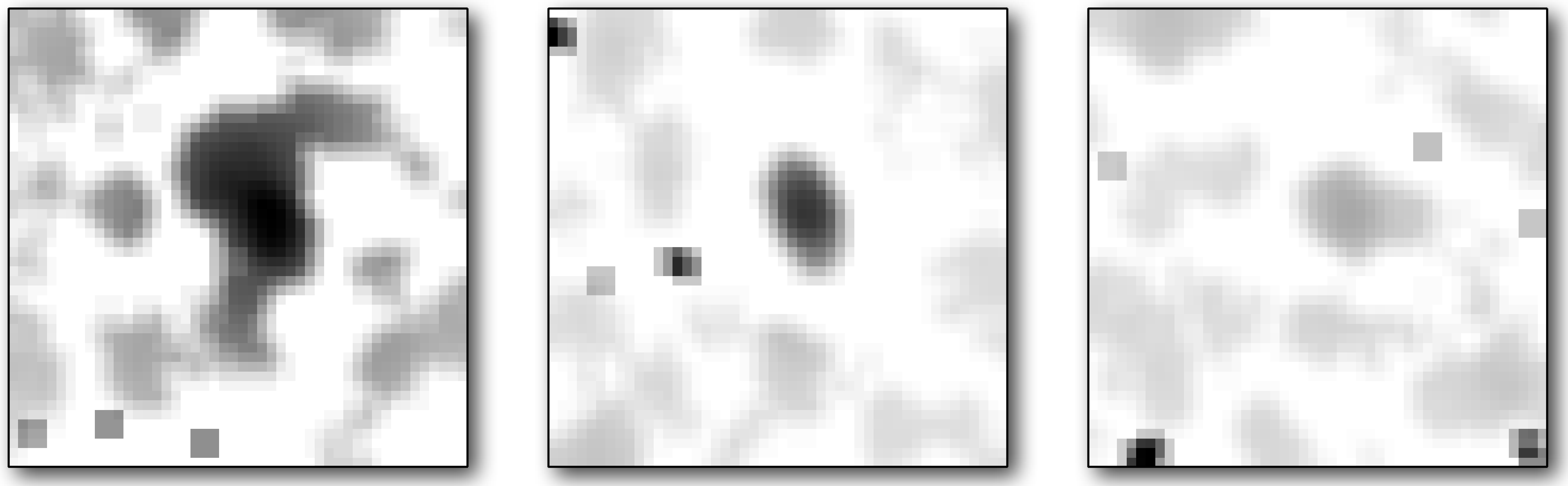
$$S/N = \frac{\langle A \rangle}{\sigma_A}$$

Optical S/N calculations and maps (proof of concept)

using DES mocks

Mass [Msol]	7.00E+14	2.00E+14	6.00E+13
z	0.25	0.75	0.65
N_{gal}	814	478	78
S/N	4.5	1.7	1.0

6'x 6' Optical S/N Maps



Clusters found by the c4 cluster-finding algorithm

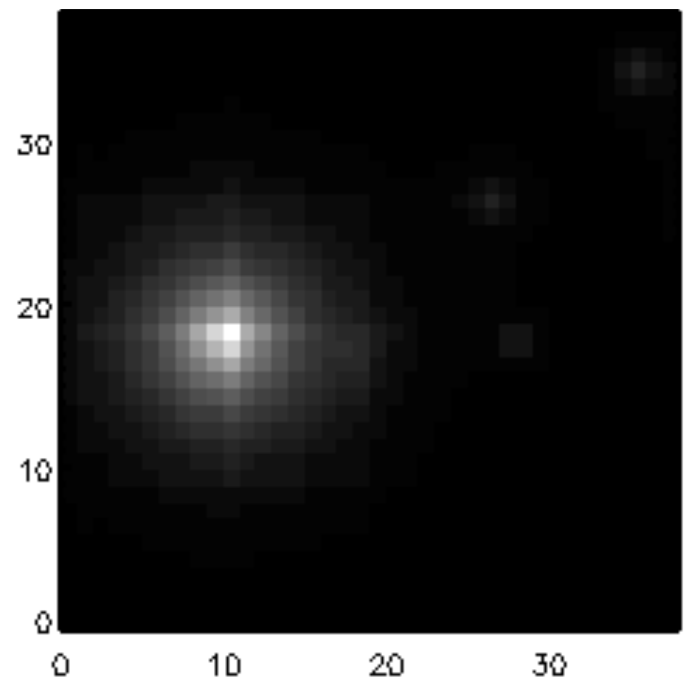
We can measure the S/N in optical maps to prepare for comparison and combination with SZ S/N maps.

Joint SZ-Optical maps of halos

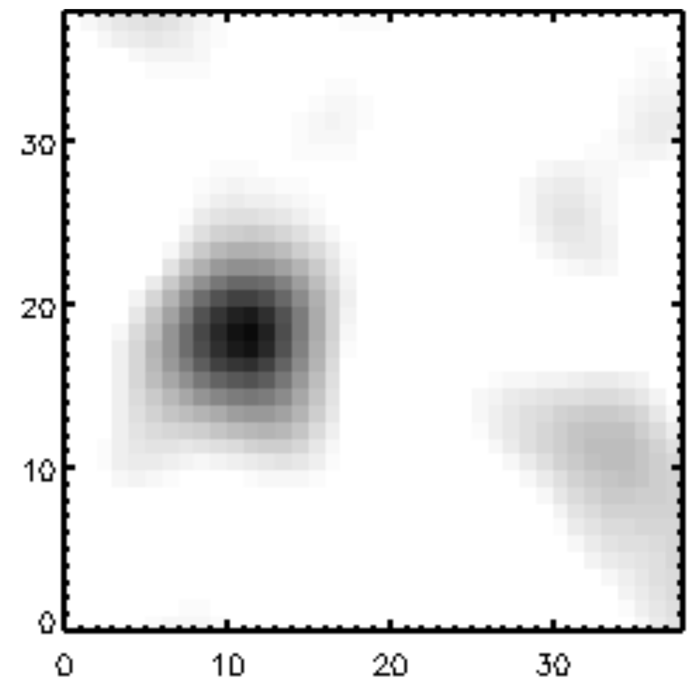
Halo SZ

Joint SZ-Optical maps of halos

Halo SZ



Cluster SZ



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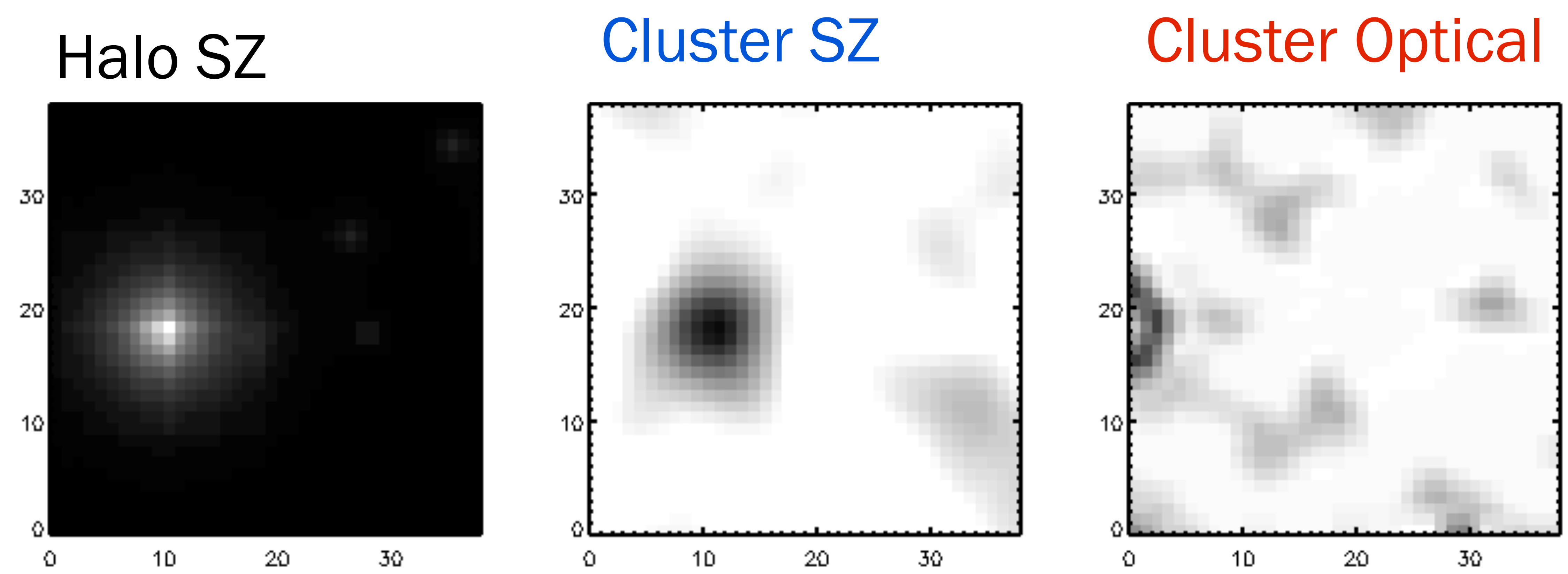

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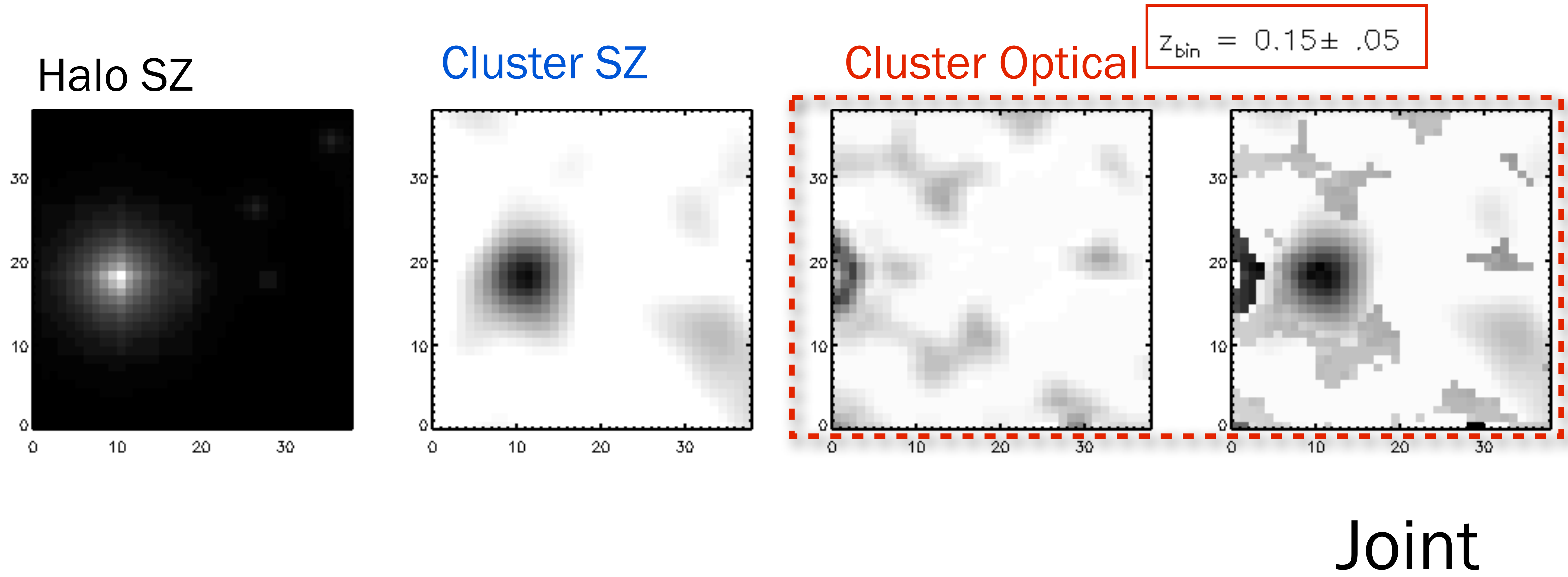

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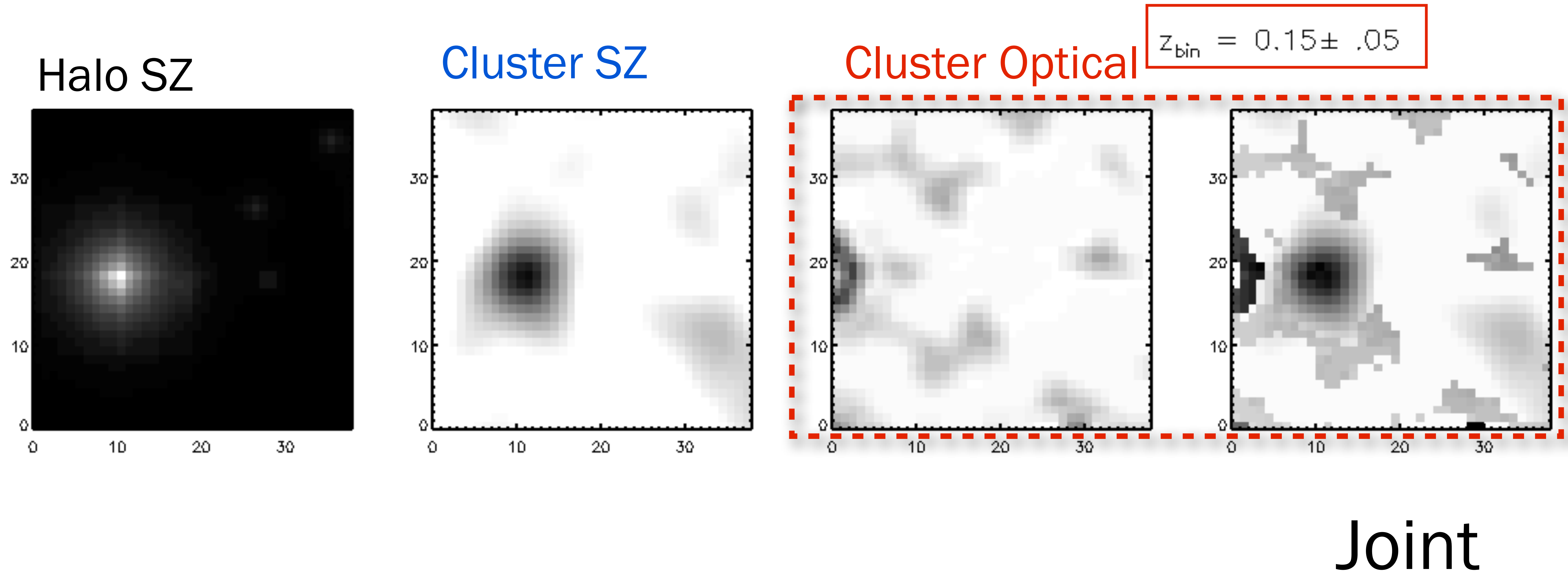

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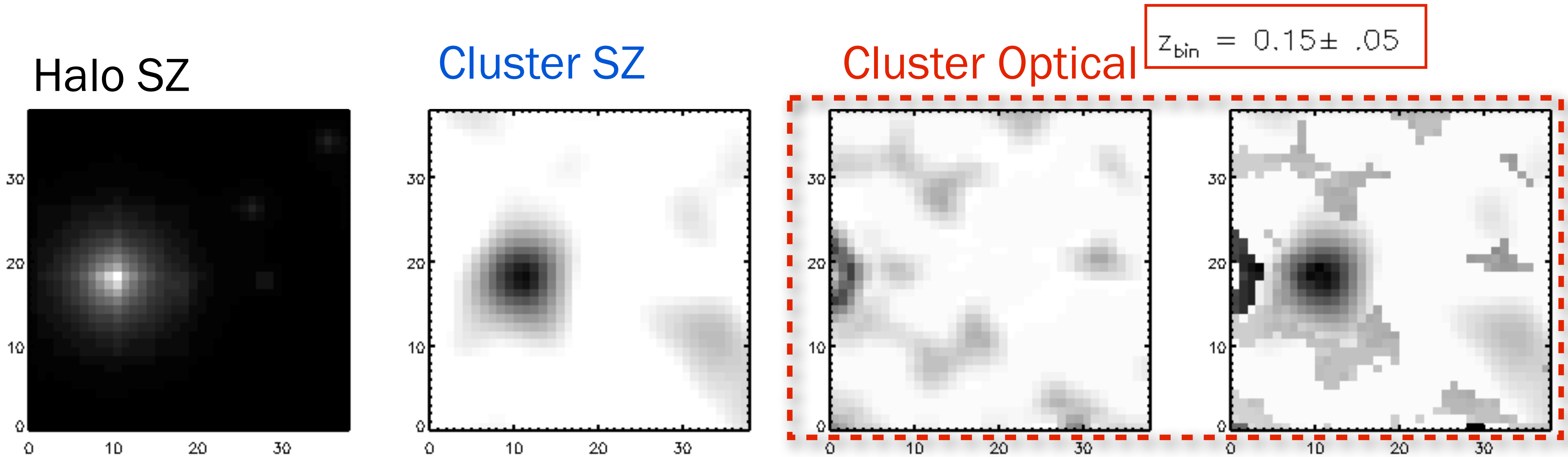
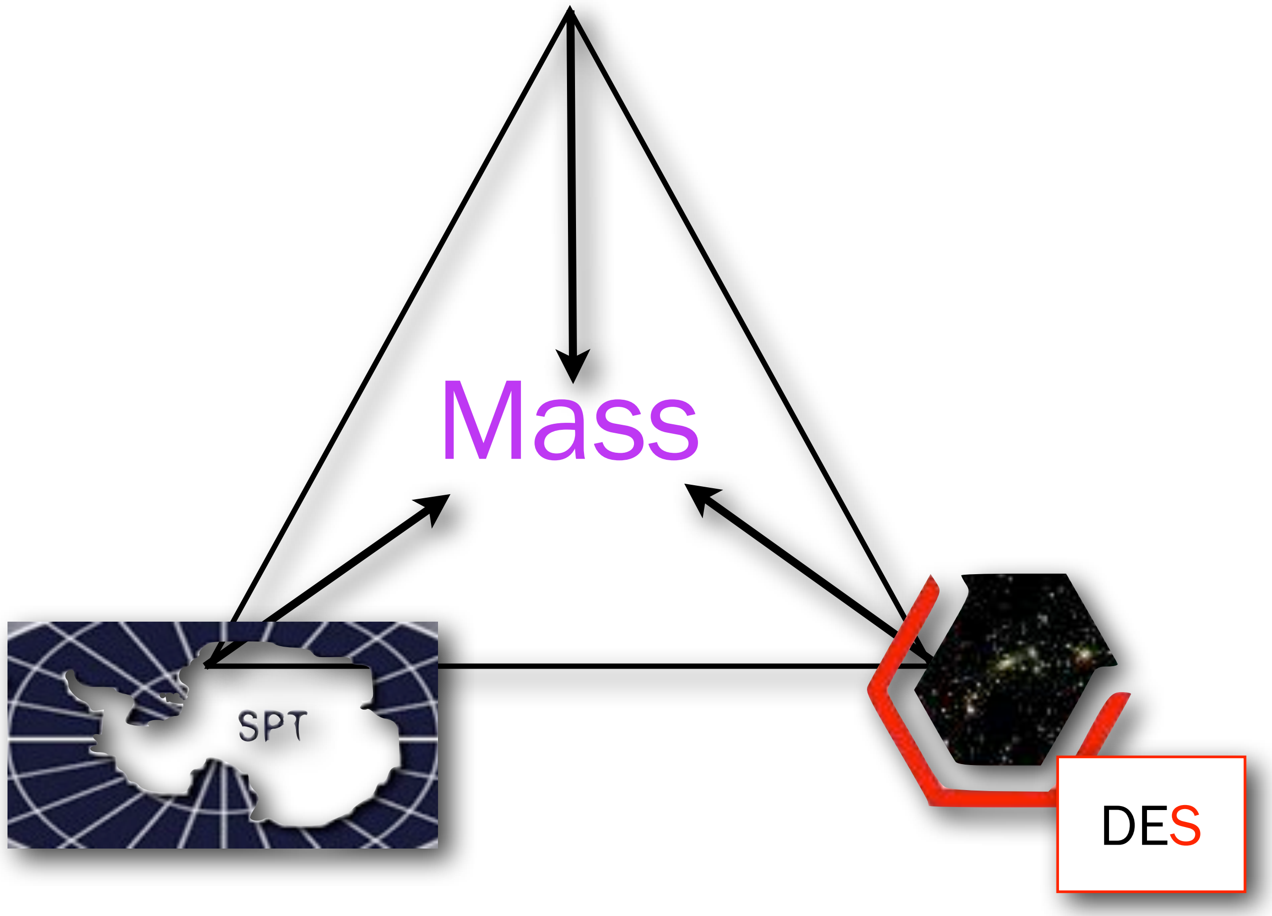


Joint

$(S/N)_{optical} = 7.5$

We can find a cluster and select the right halo with this joint-signal analysis.

Concluding remarks and Looking forward



Cluster populations ...

... have the power to deliver constraints on Ω_Λ, Ω_M and σ_8 via the mass function.

... have large scatter in mass measurement.

How do we realize the potential of clusters?

Calibrate Masses:

... Seek out systematic effects and re-calibrate

... Cross-calibrate clusters across multiple wavebands.

Jointly detect clusters for larger numbers

... Prepare with the large simulations of DES

... Perform the full test of measuring cosmology with the joint catalogues and calibrations.