High-redshift galaxy clusters and their galaxy population

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Galaxy clusters

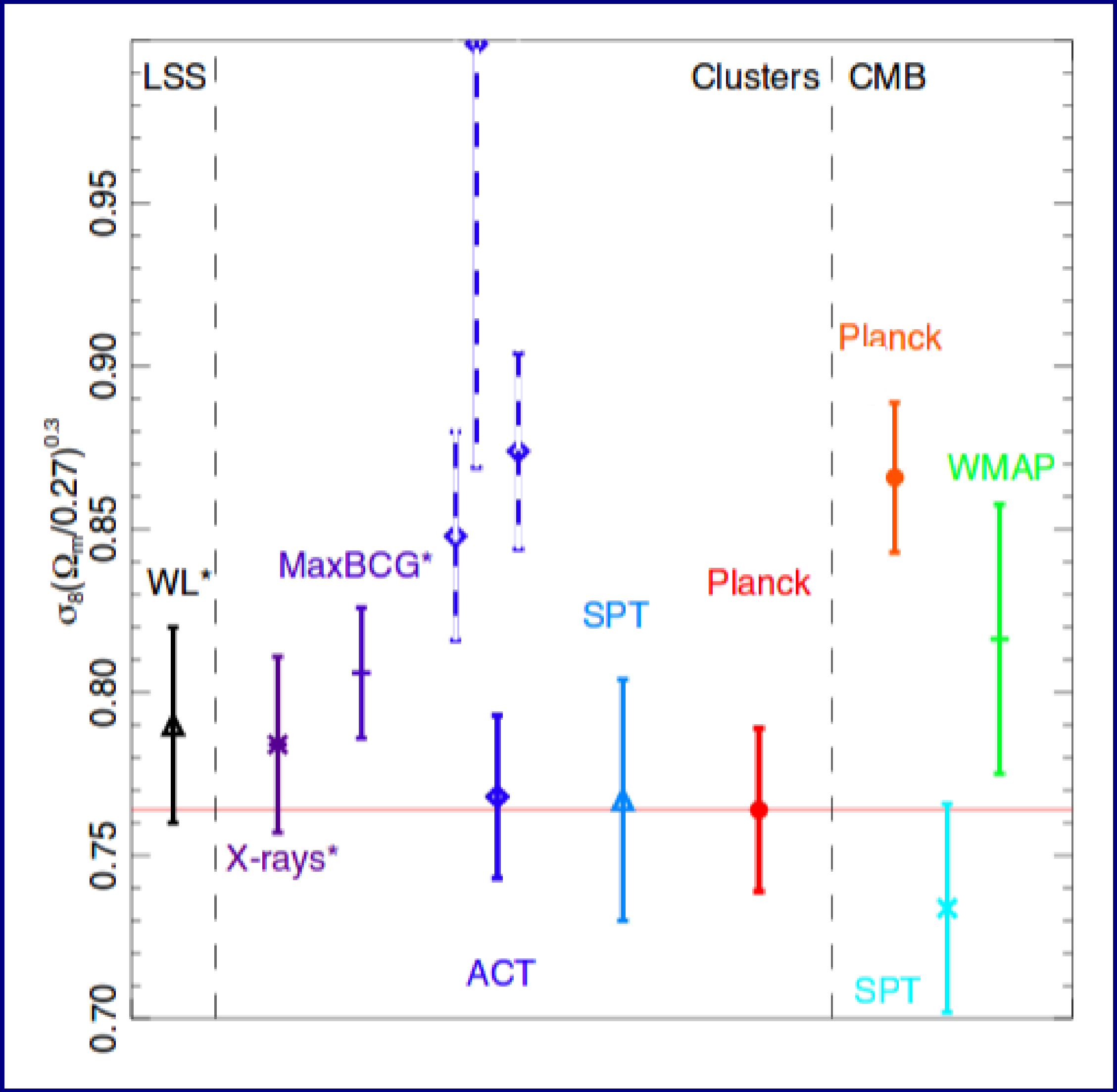
NASA, N. Benitez (JHU), T. Broadhurst (Hebrew Univ.), H. Ford (JHU), M. Clampin(STScI), G. Hartig (STScI), G. Illingworth (UCO/Lick Observatory), the ACS Science Team and ESA
STScI-PRC03-01a

- **Gravitationally bound systems** originated from primordial perturbations in the gravitational density field (Peebles 1993, Peacock 1999)

- Masses ~$10^{14\text{-}15}$ solar masses
- Sizes ~1-10 Mpc
- N ~ 50-1000 galaxies

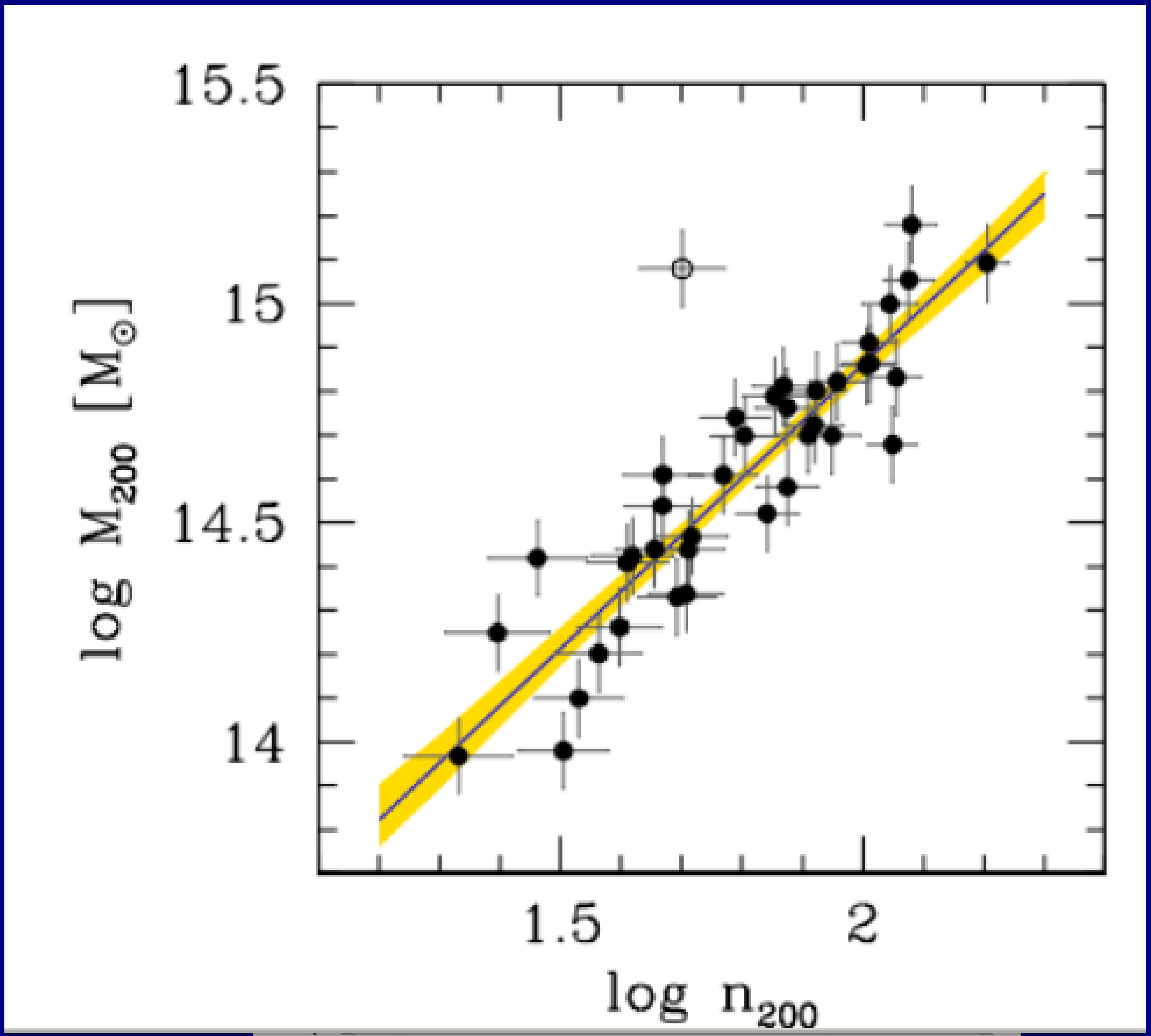
- ~90% of z<1 galaxy clusters host Low Luminosity Radio Galaxies (LLRGs) – Branchesi+06, Ledlow & Owen '95, '96

Galaxy Clusters and cosmology



Planck collaboration XX (2013)

Mass – Richness relation



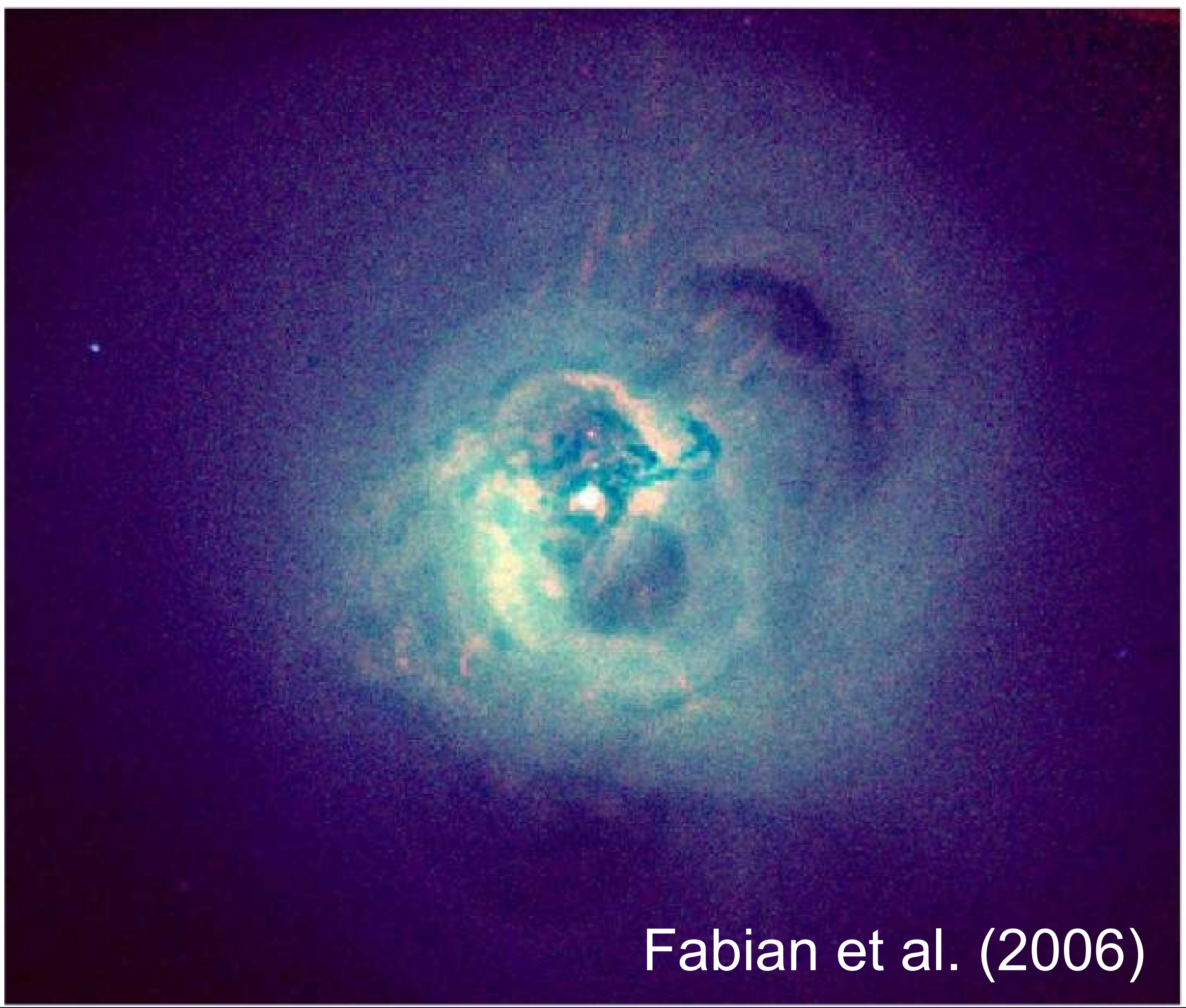
Andreon et al. (2015)

Red Sequence galaxies within r_{200}

$0.1 < z < 0.22$

0.16 dex scatter if compared to Caustic Mass

AGN *feedback* in clusters

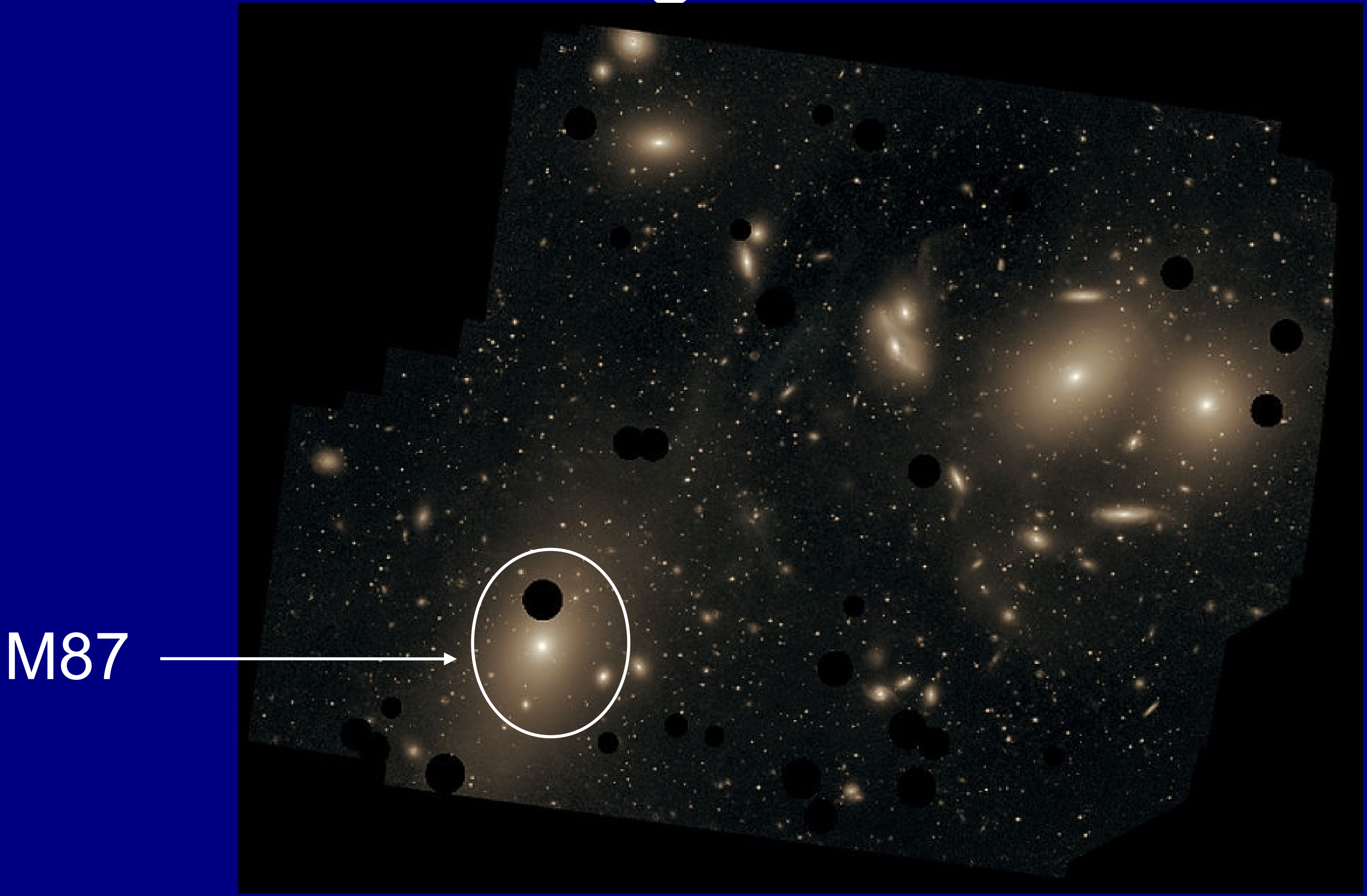


Perseus Cluster

X-rays Chandra

LLRG Perseus A

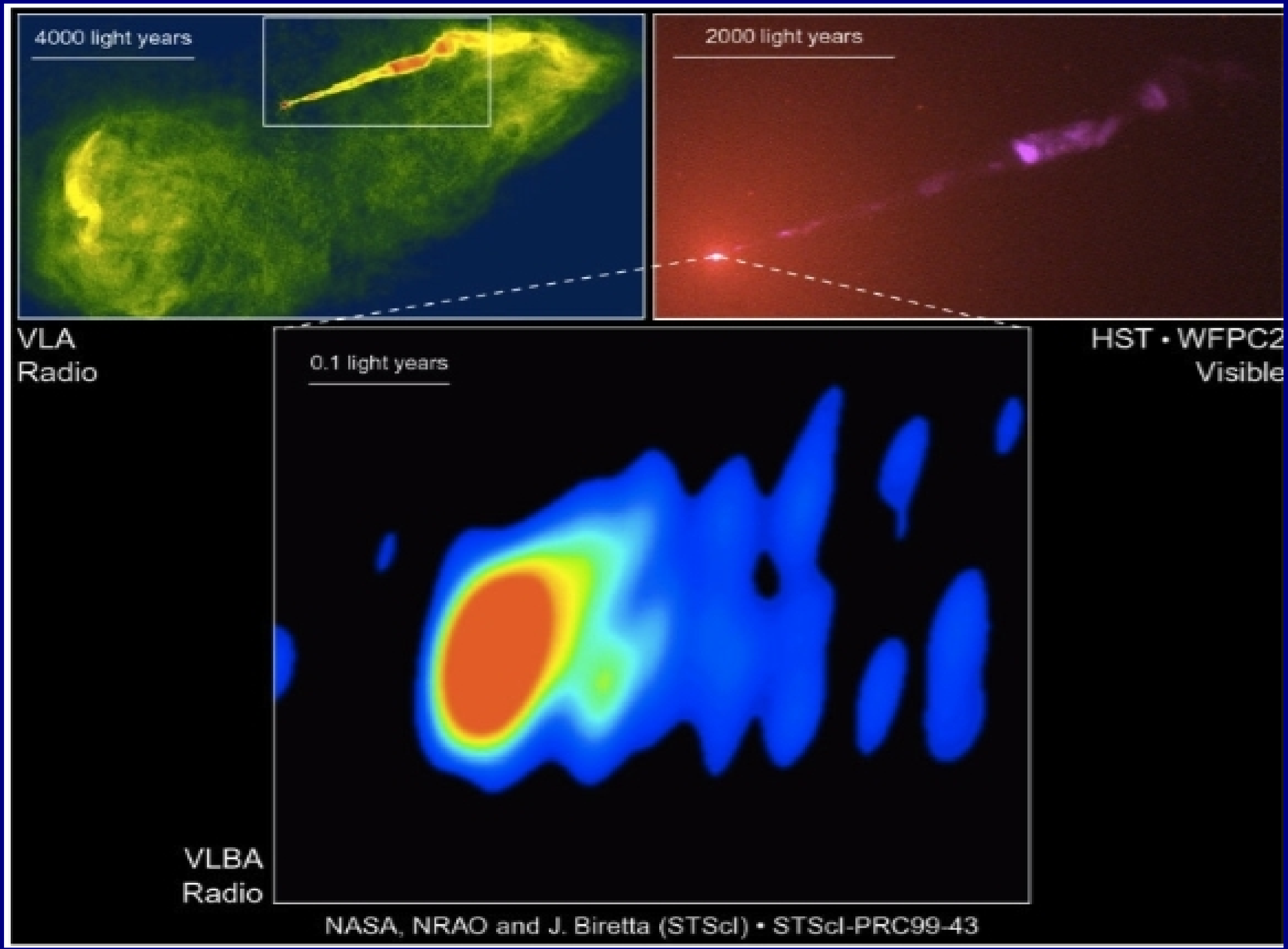
Virgo cluster



Credit:

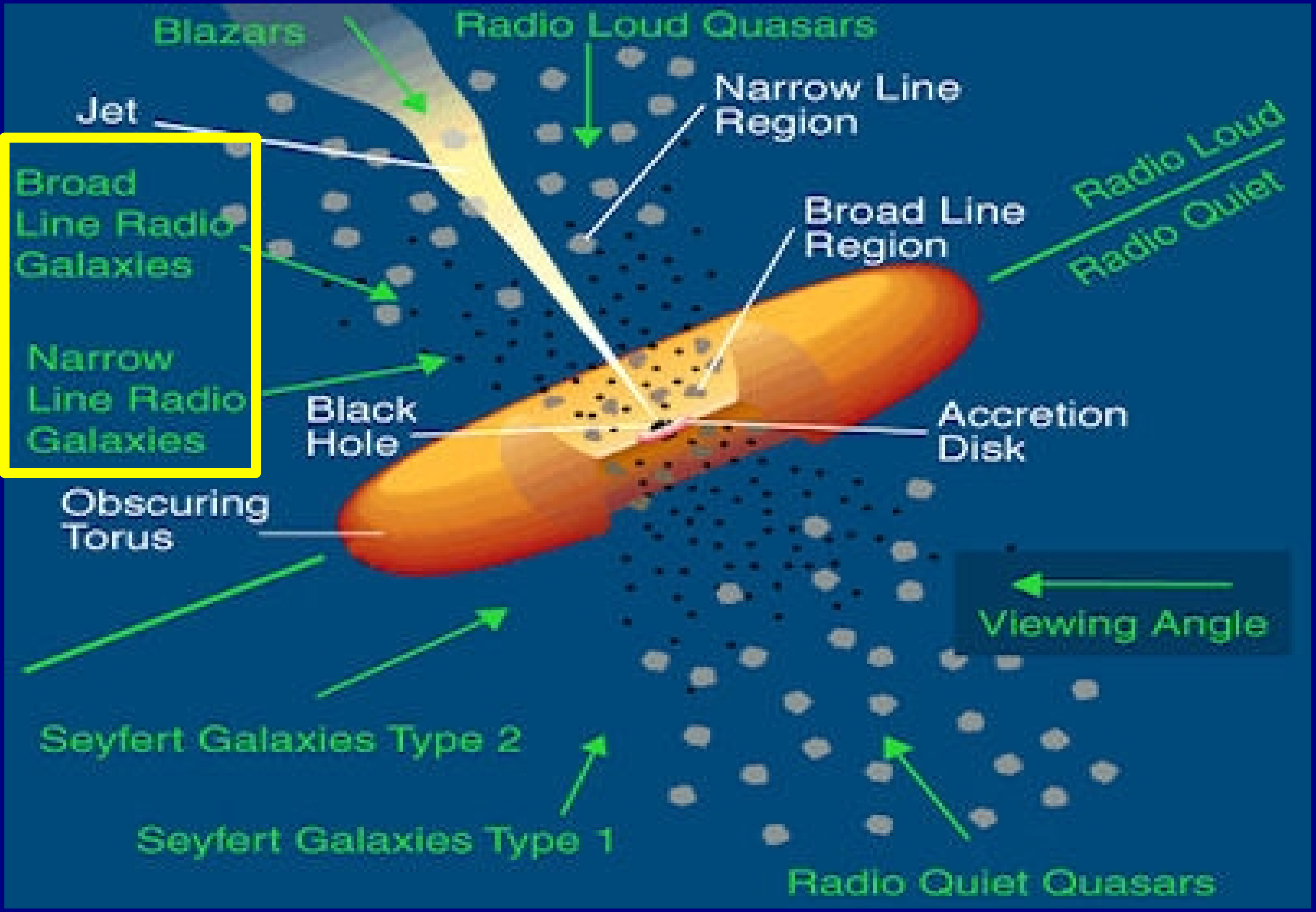
Chris Mihos (Case Western Reserve University)/ESO – Schmidt telescope

M87



Credits: National Radio Astronomy Observatory/National Science Foundation,NASA and John Biretta (STScI/JHU), National Radio Astronomy Observatory/Associated Universities, Inc.

AGN Unification Scheme

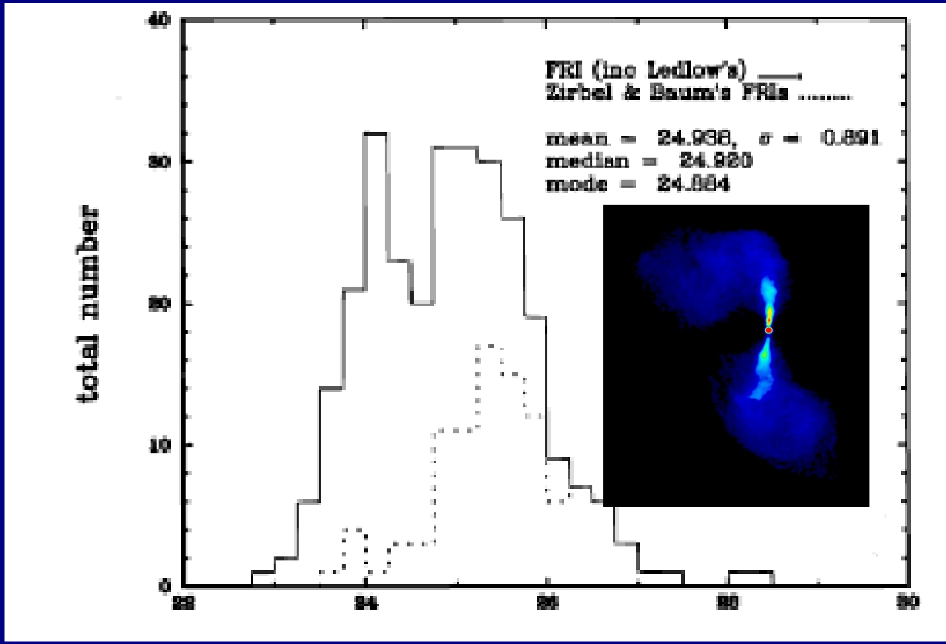


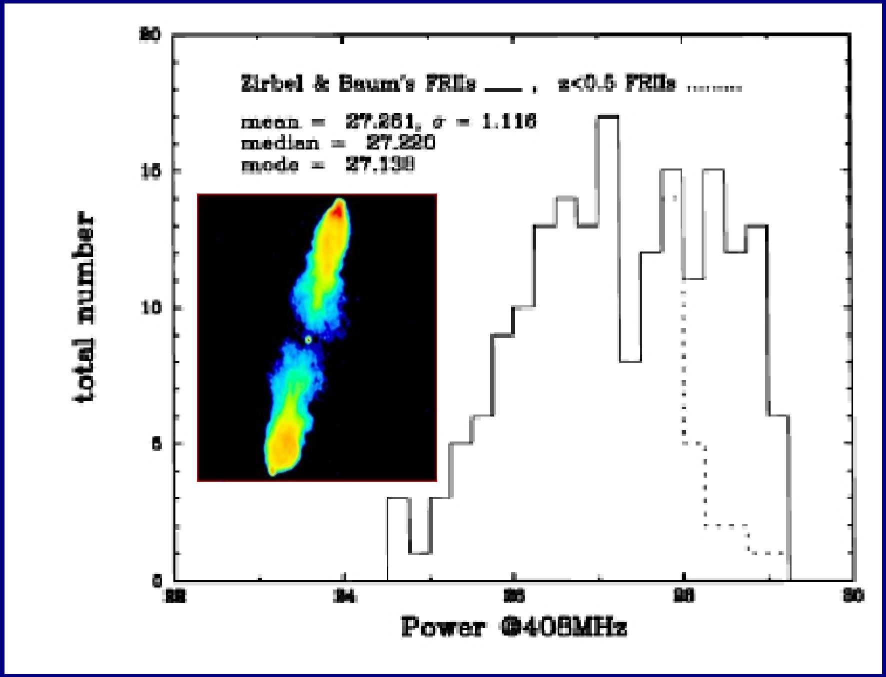
Urry & Padovani (1995)

Radio morphologies.
Fanaroff & Riley (1974) classification

FRIs

FRIIs





Zirbel (1996)

- FRI: Jet decelerates to v << c at ~1kpc
- FRII: Relativistic jet on scales ~100 kpc up to ~1Mpc
- FRI / FRII divide: $L_{178\ MHz} < 10^{26}$ W Hz^{-1}

Local FRIs

- **"starved quasar"**: faint optical nuclear emission (Chiaberge et al. 1999, Leiptzki et al. 2009, Baldi et al. 2010)
- Host galaxy: mainly **giant elliptical (cD)** with the most massive BHs (Donzelli et al. 2007, Zirbel & Baum 1997)
- **~70% of them in rich clusters**, at variance with FRIIs (Hill & Lilly 1991; Zirbel 1997; Wing & Blanton 2011)

High-z FRIs

- **Two FRIs at z~1** (Snellen & Best 2001)
- **~30 FRI candidates at z~1-2** (Chiaberge et al. '09)

FRIs at z~1-2.   Why?

Clusters

- **Beacons for HIGH REDSHIFT CLUSTERS**
- **Link between z>~2 protoclusters and clusters**
- Formation and evolution of the **red sequence**

AGN

- Hints for strong **cosmological evolution** up to z~1.0 (Sadler et al., 2007, Smolcic et al. 2009, McAlpine et al. 2013)
- Formation and evolution of the **most massive galaxies and BHs**
- **Feedback**: BH accretion - environment

The sample

- **FRIs** candidates at **z~1-2** (Chiaberge et al. 2009, C09)
- **COSMOS** (2sq degrees)
- Mainly based on **radio (FIRST) and optical selection**, NOT on redshifts

Redshifts

- **Accurate redshifts** (Baldi et al. 2013) are required to **redefined the sample in radio power**
- **Few spectroscopic-z:** zCOSMOS bright (Lilly et al. 2007), Magellan (Trump et al. 2007)
- **Photo-z**: SED modeling includes stellar and dust emission

Clusters around LLRGs?

Cluster candidates around Low Luminosity Radio Galaxies? (FRIs)

The C09 sample redefined in radio power

- **21 LLRGs**
- **11** High Luminosity Radio Galaxies (HLRGs)

Two cluster candidates

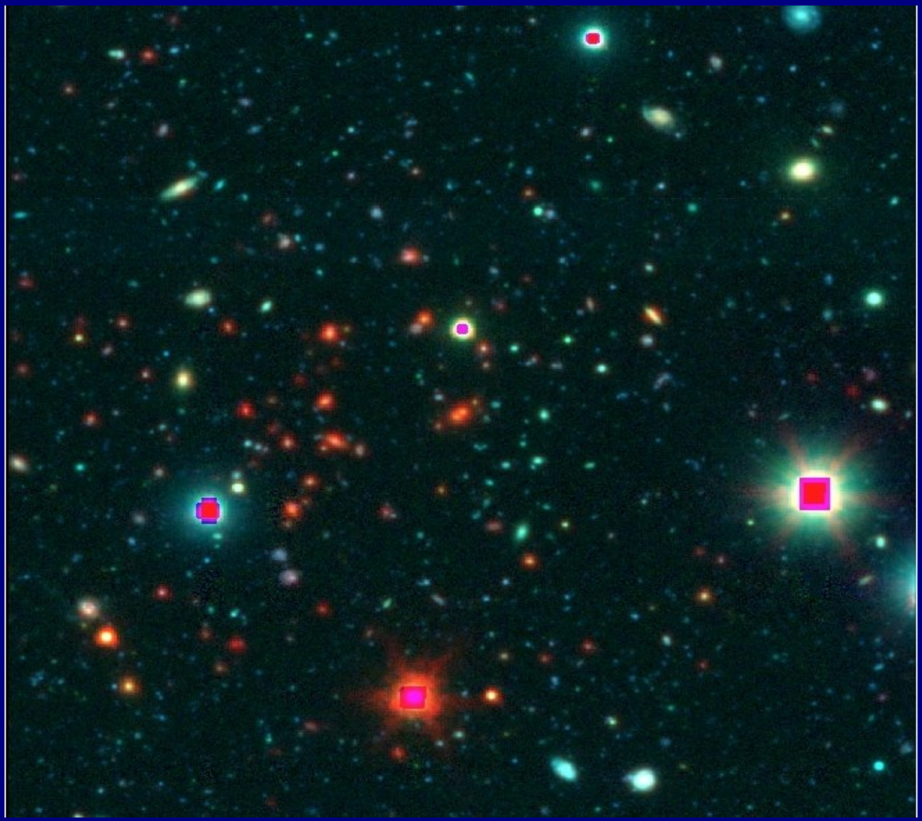


Figure: Field of COSMOS-FRI 01, cluster from visual inspection

RGB images. Red: Spitzer 3.6μm. Green: optical i-band. Blue: optical V-band

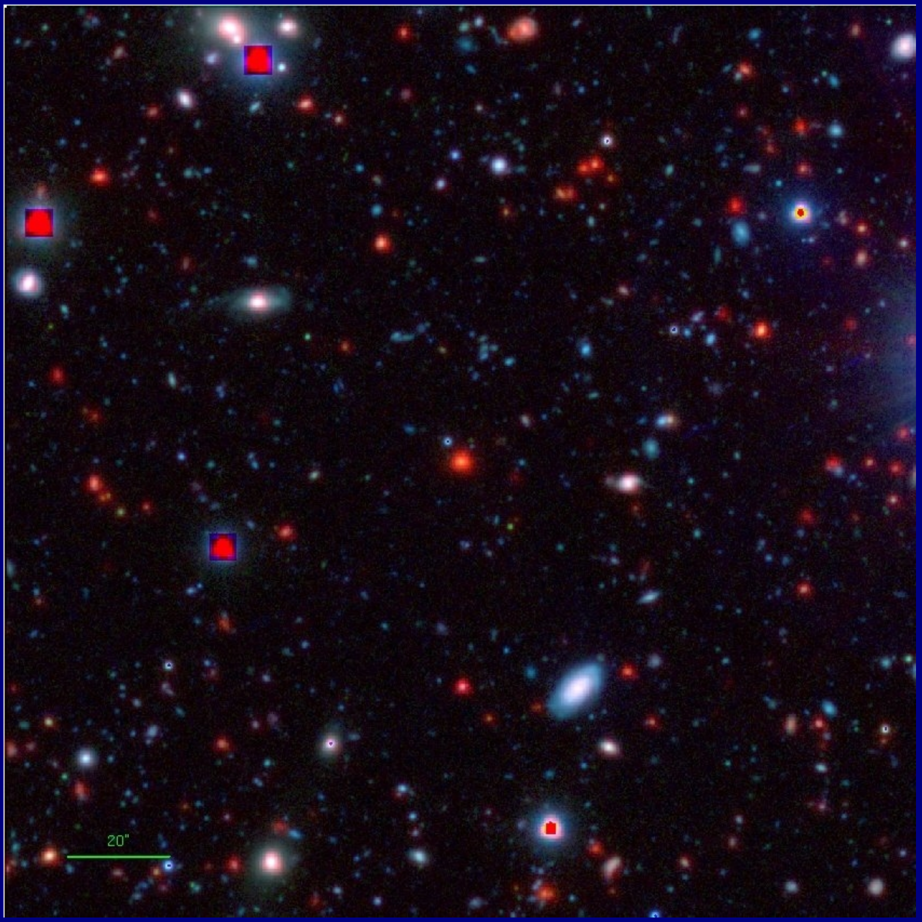


Figure: Field of COSMOS-FRI 026, cluster?

Cluster search techniques

- **SZ effect,** only a few at z>1 (e.g. Planck coll. XXIX 2013; Hasselfield et al. 2013, Reichardt et al. 2013)
- **X-ray** (Rosati et al. 2002) ; $I_0 = I_e(1+z)^{-4}$
- **Photo-z and number counts** (Eisenhardt et al. 2008; Knobel 2009, 2012; Bellagamba et al. 2011)
- **Planck – Herschel** (Clements et al., 2013)
- **Color selection** (e.g. Gladders & Yee 2005; Papovich 2008). **Red-sequence** is just forming between z~1-2 (Hilton et al. 2010; Fassbender et al. 2011; Santos et al. 2011)
- **Search around radio galaxies** (Miley & De Breuck 2008, Galametz et al. 2012, Wylezalek et al. 2013);

only FRIIs are adopted

Motivations for a new method

- **Existing methods seem to be less effective at z>~1.5**

(only ~15 spectroscopically confirmed z>~1.5 clusters, see Tozzi et al. 2013 and refs. Therein, e.g. Papovich+2010, Cooke et al. 2016, ...)

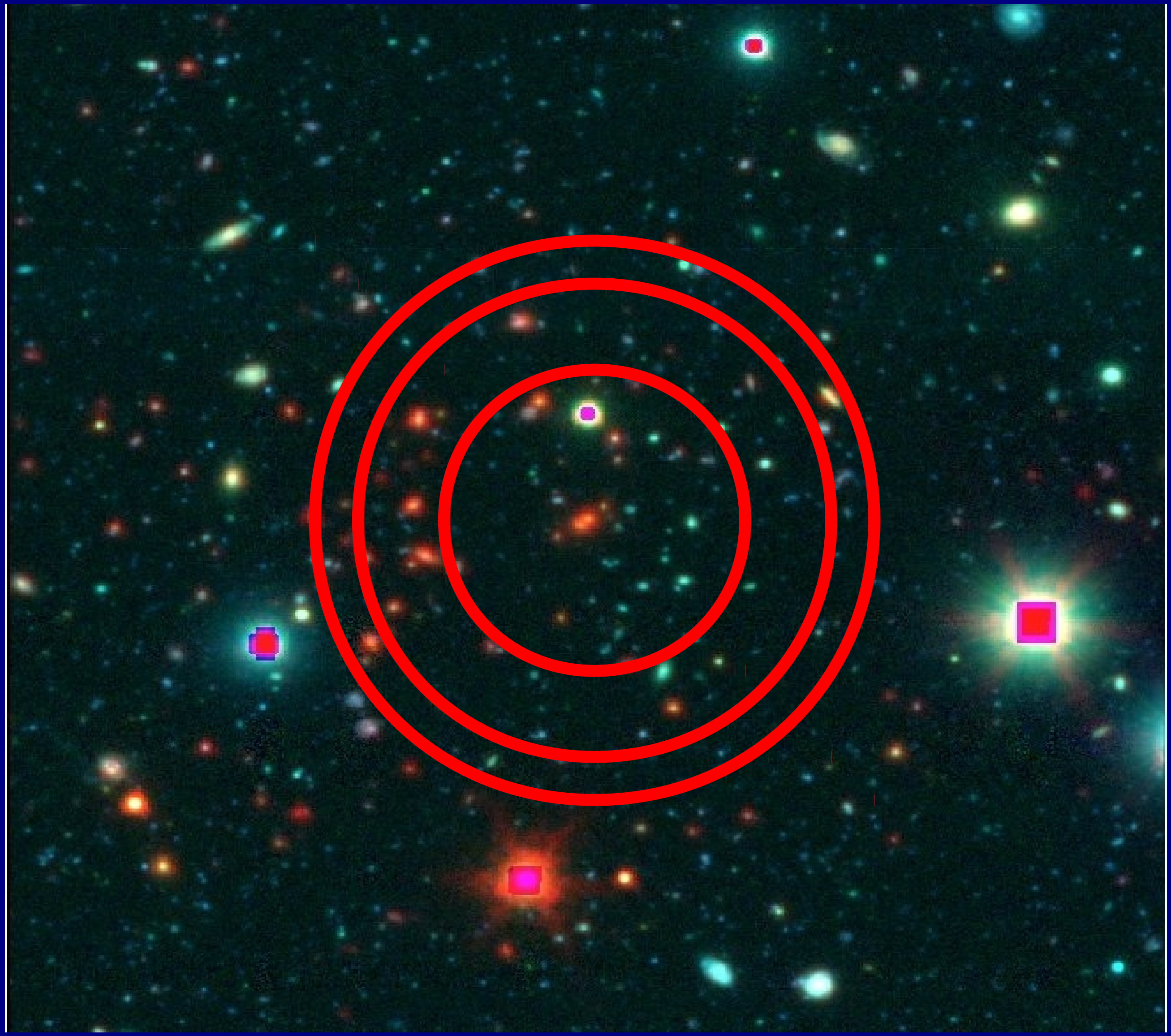
- **Methods based on photo-z and number counts** (Scoville+2013 and ref. therein) **affected by:**

1) low number counts

2) increasing photo-z uncertainties

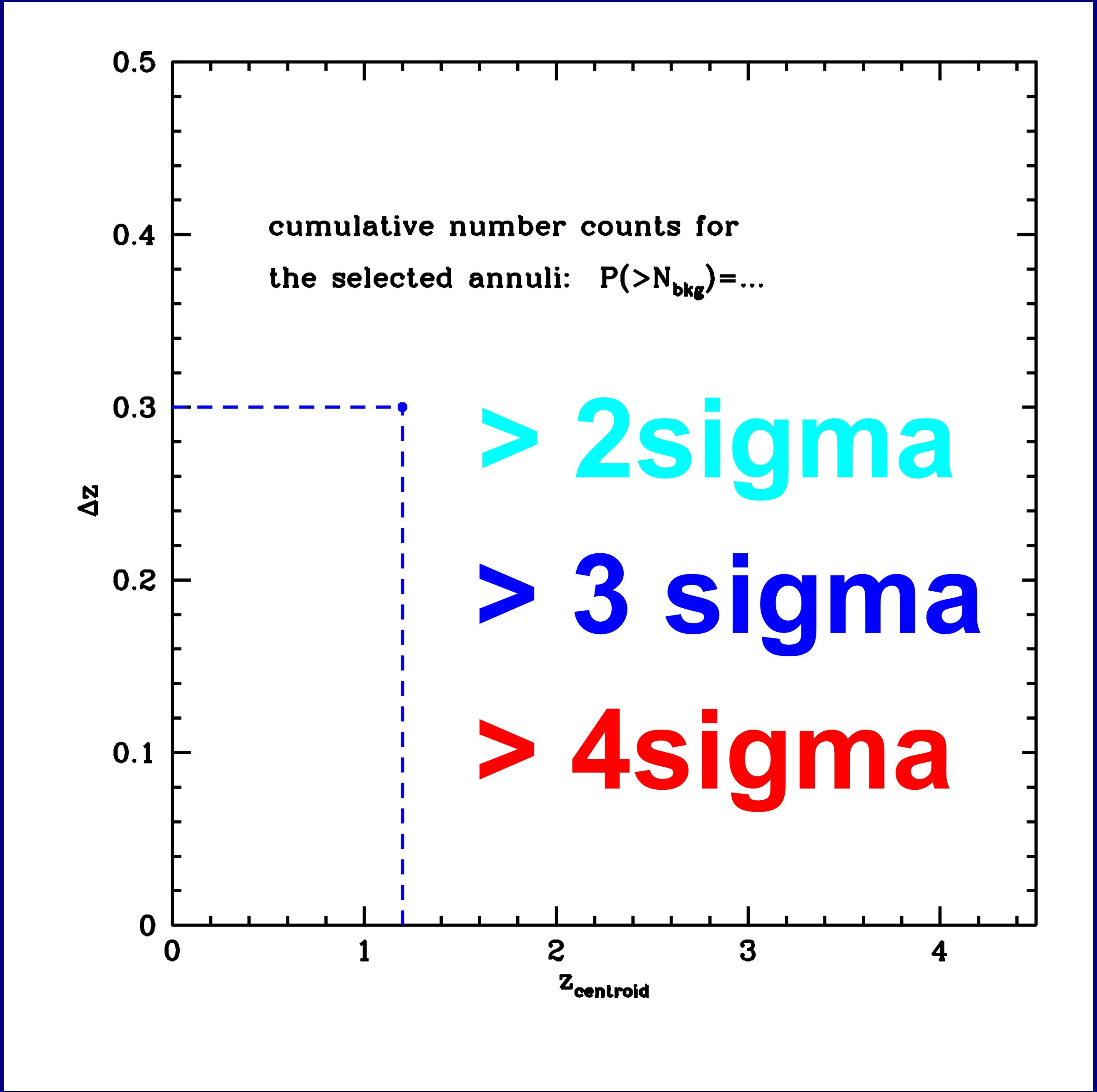
3) photo-z catastrophic failure at z>~1.5 (redshift desert)

Poisson Probability Method (PPM). How does it work?

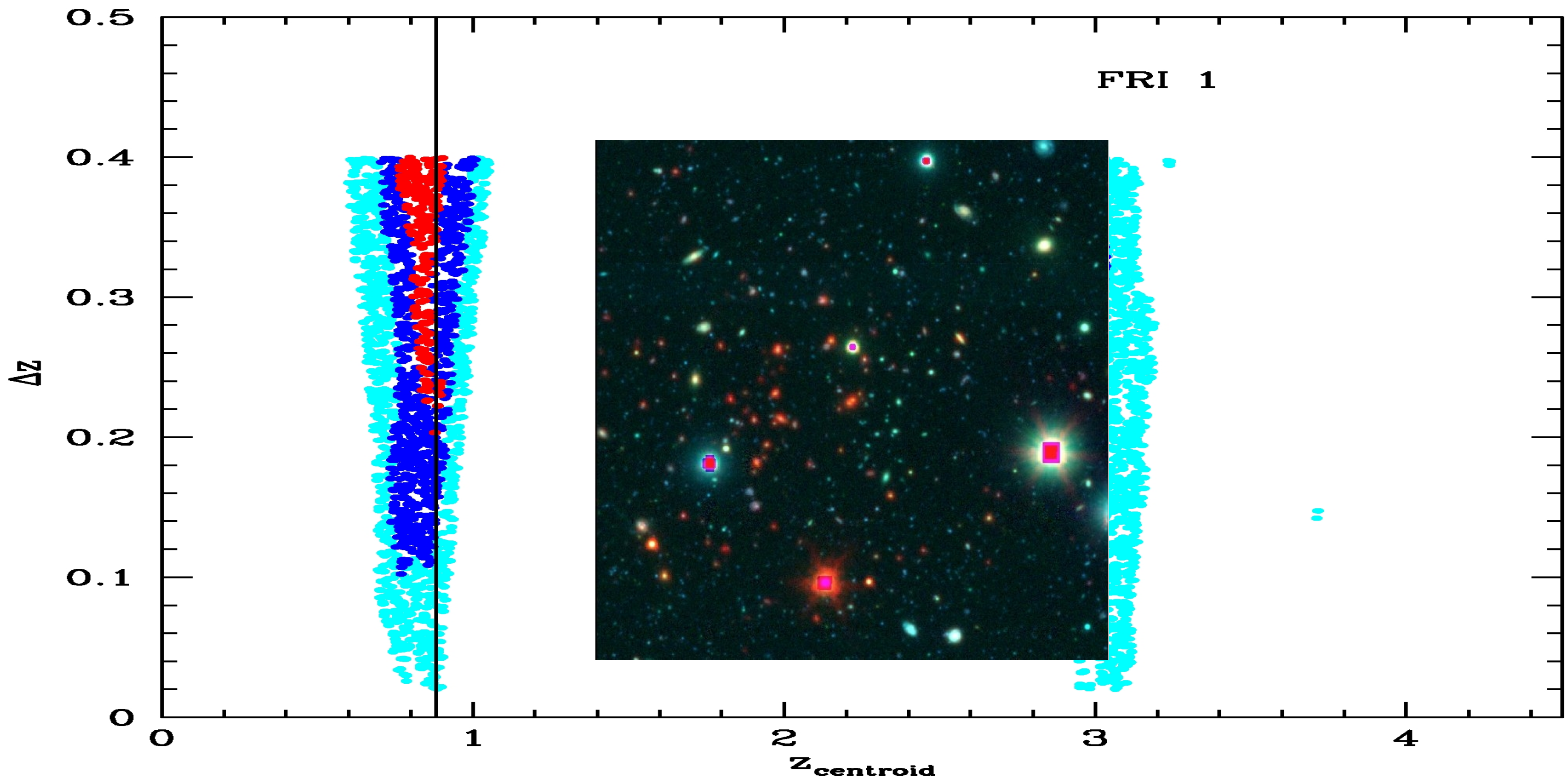


Castignani et al. (2014a, ApJ, 792, 113)

PPM, how does it work?

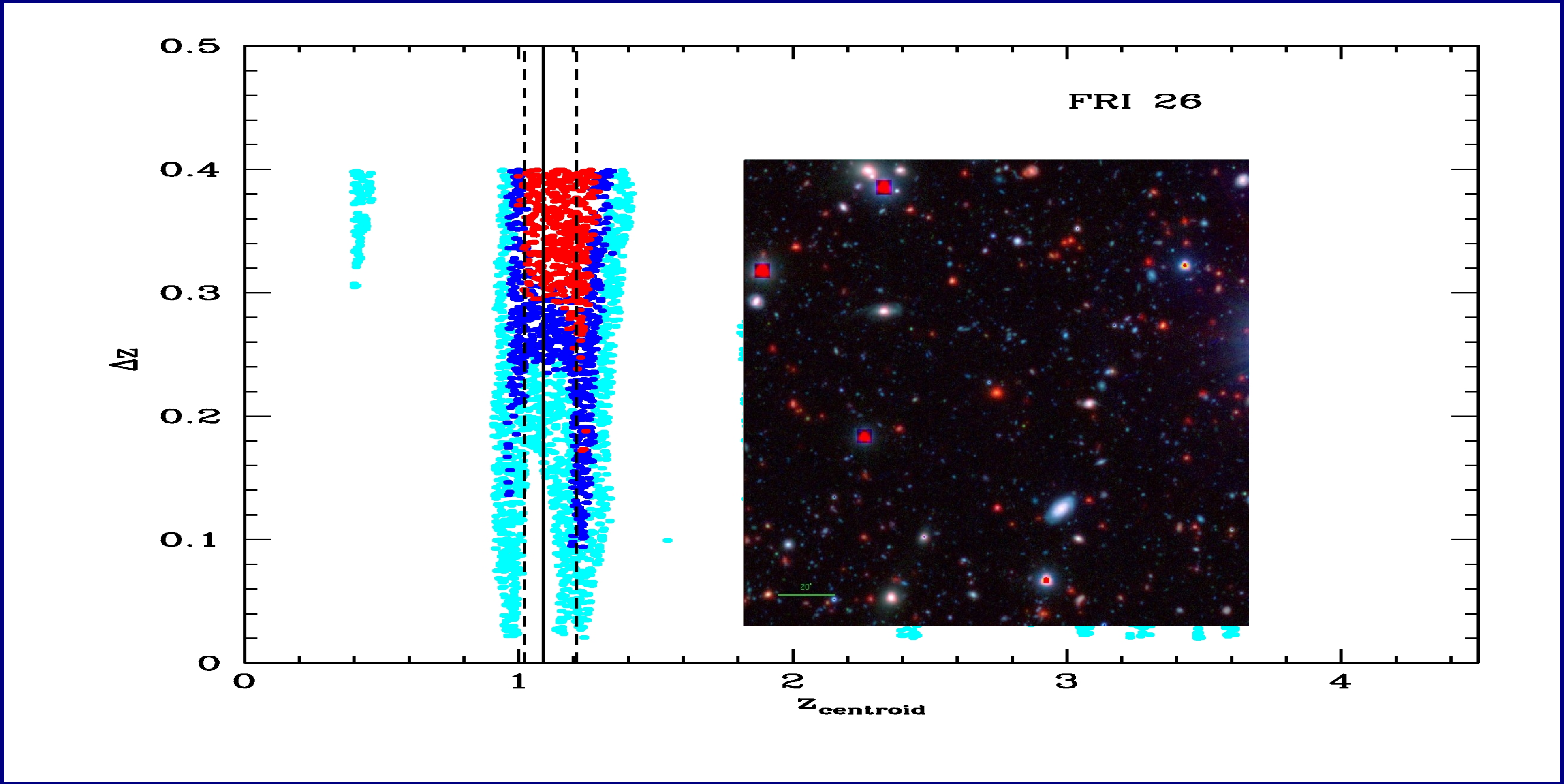


PPM plots



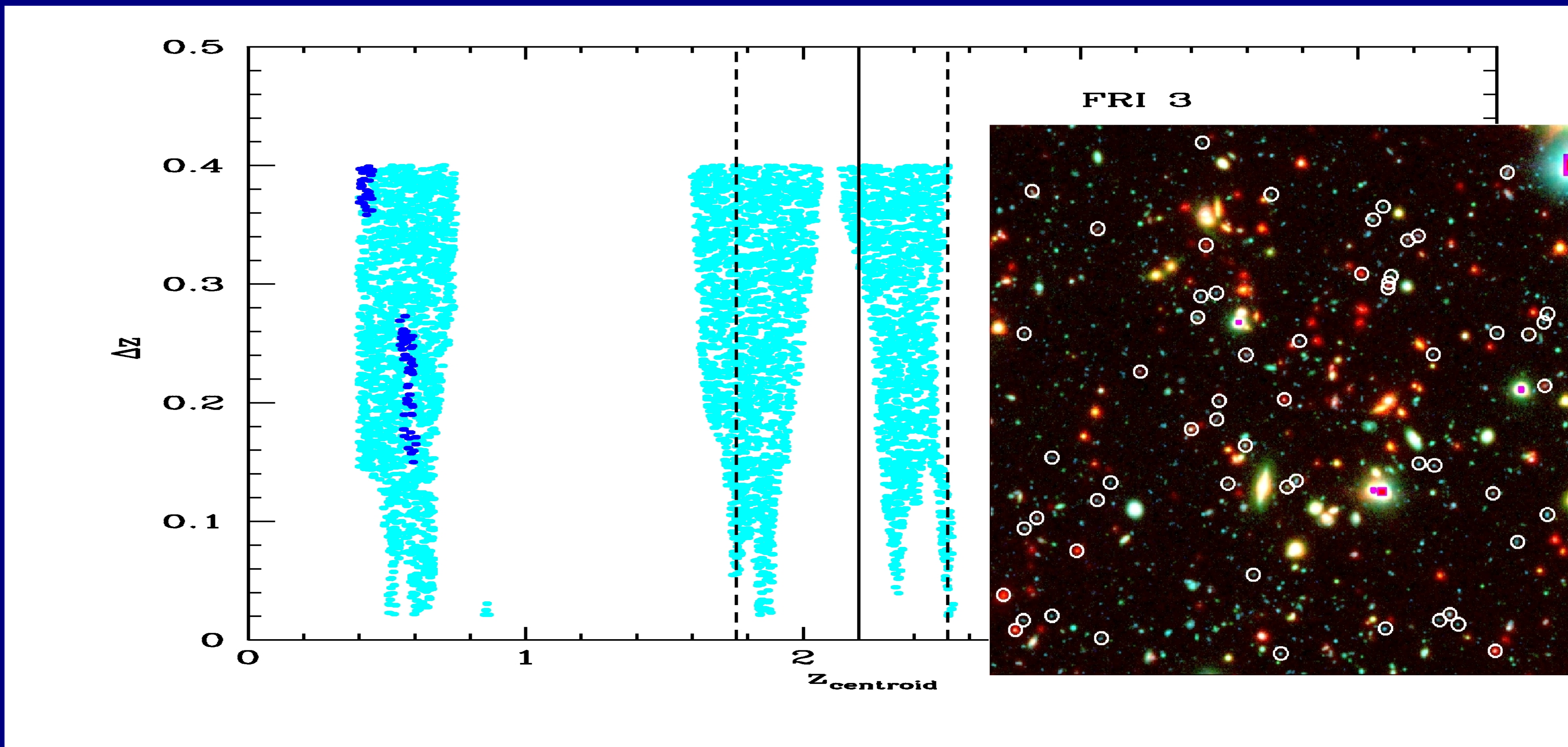
3.5σ detection

PPM plots



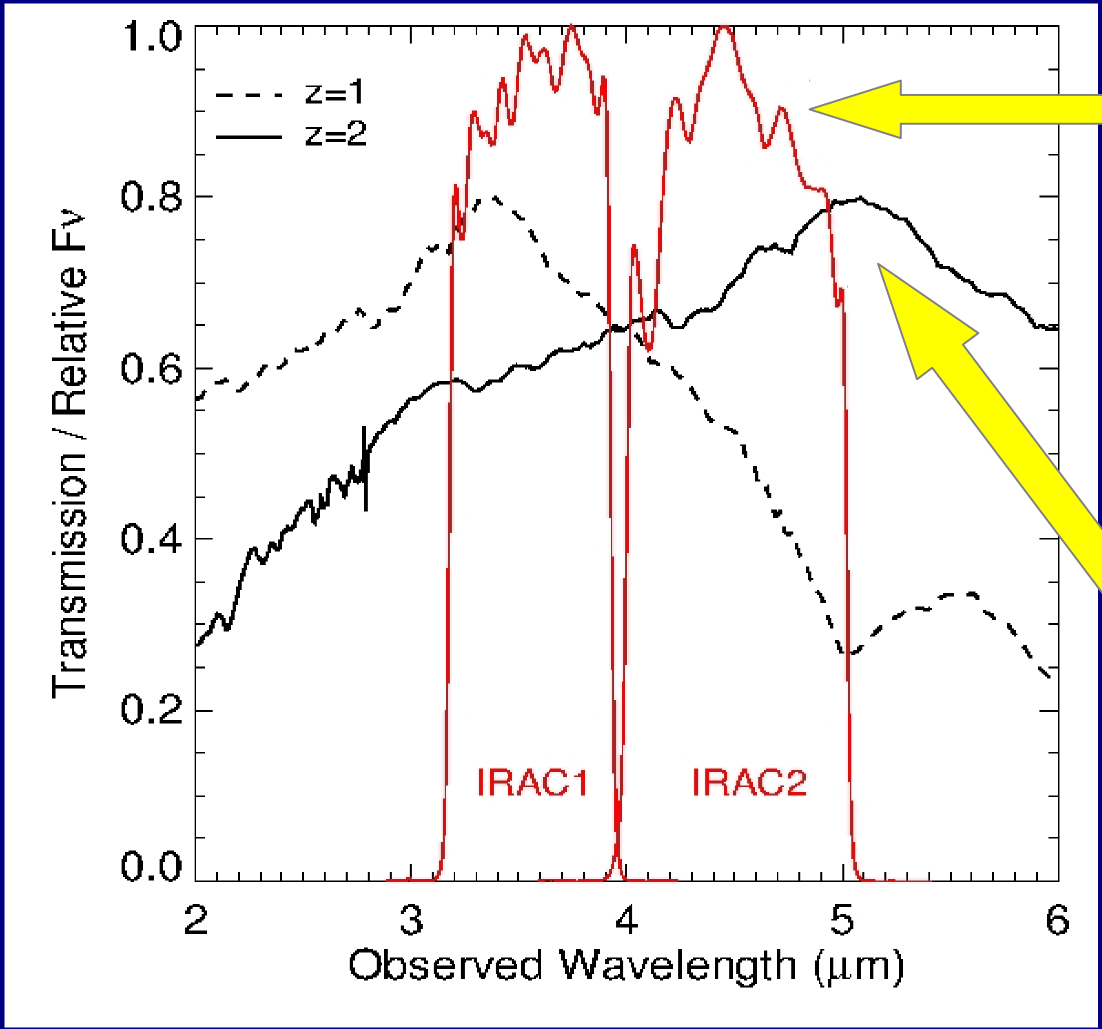
3.9σ detection

PPM plots



2.5σ detection

Papovich (2008) method



Galametz et al. (2012)

Spitzer-IRAC channels at 3.6 and 4.5 **μm**

1.6 μm bump in the SED of red galaxies (opacity of the H^- ion in atmospheres of cool stars, John 1988)

Papovich (2008) method

- **Overdensities of red galaxies** are searched for.
- The method is effective at z>1.3
- **Six >2σ orverdensities** are detected
- **All of them are also found with the PPM**
- The Papovich (2008) test does not find seven of our z>1.3 clusters
- ...and some of our z≈2 candidates (e.g. 05, 226, also suggested in Chiaberge et al. (2010).

Overdensity detections

Castignani et al. (2014b, ApJ, 792, 114)

- *The overdensities found within the FRI redshifts uncertainties are associated with the radio galaxy.*

- LLRGs: 14/21
- HLRGs: 8/11

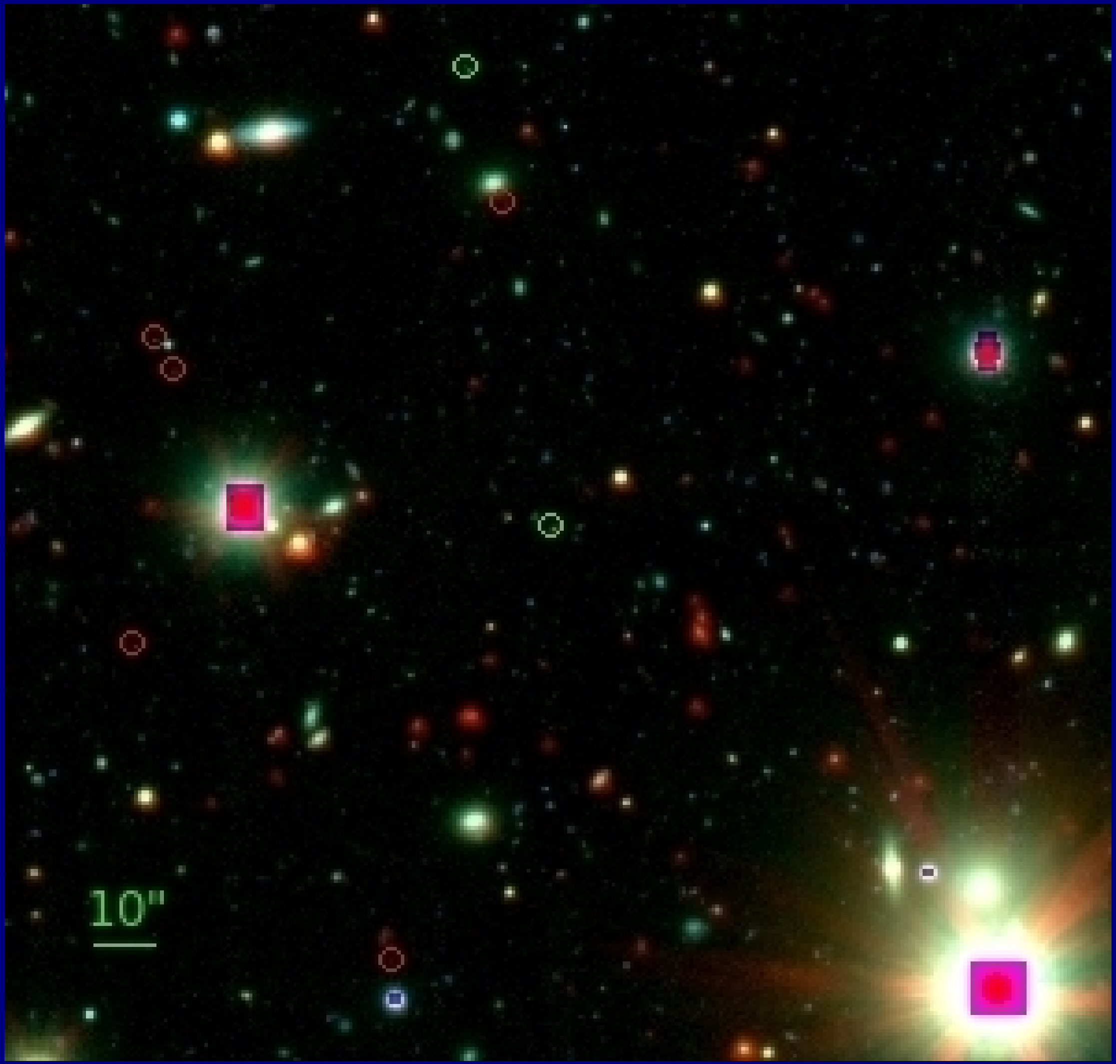
$\Bigg\}$ **69%**

...in agreement with what found locally (Zirbel 1997)

…higher than what found for FRIIs at similar redshifts (Galametz et al. 2012, Wylezalek et al. 2013)

A proto-cluster candidate at z=2.63

Castignani et al. in prep.



10” =~81kpc
@ z=2.6

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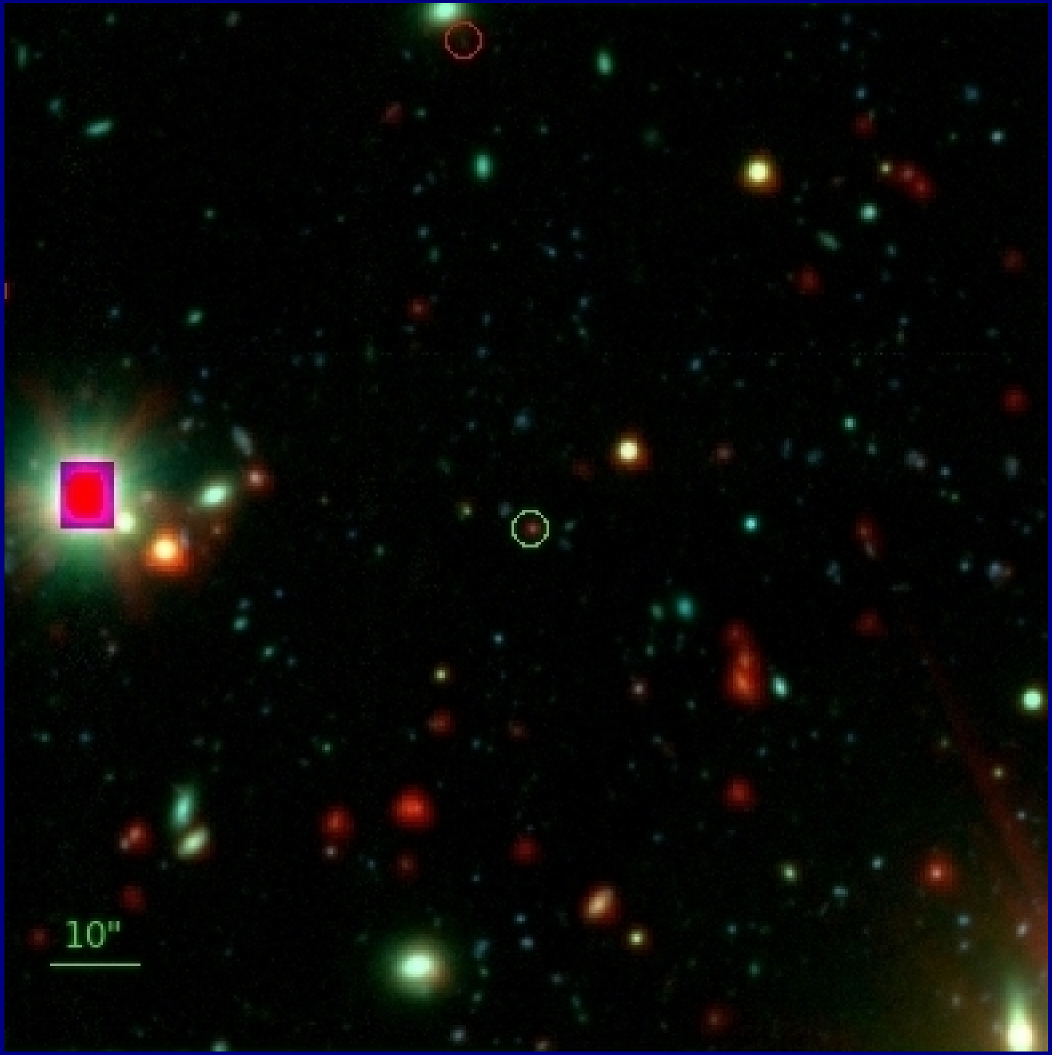

10” =~81kpc
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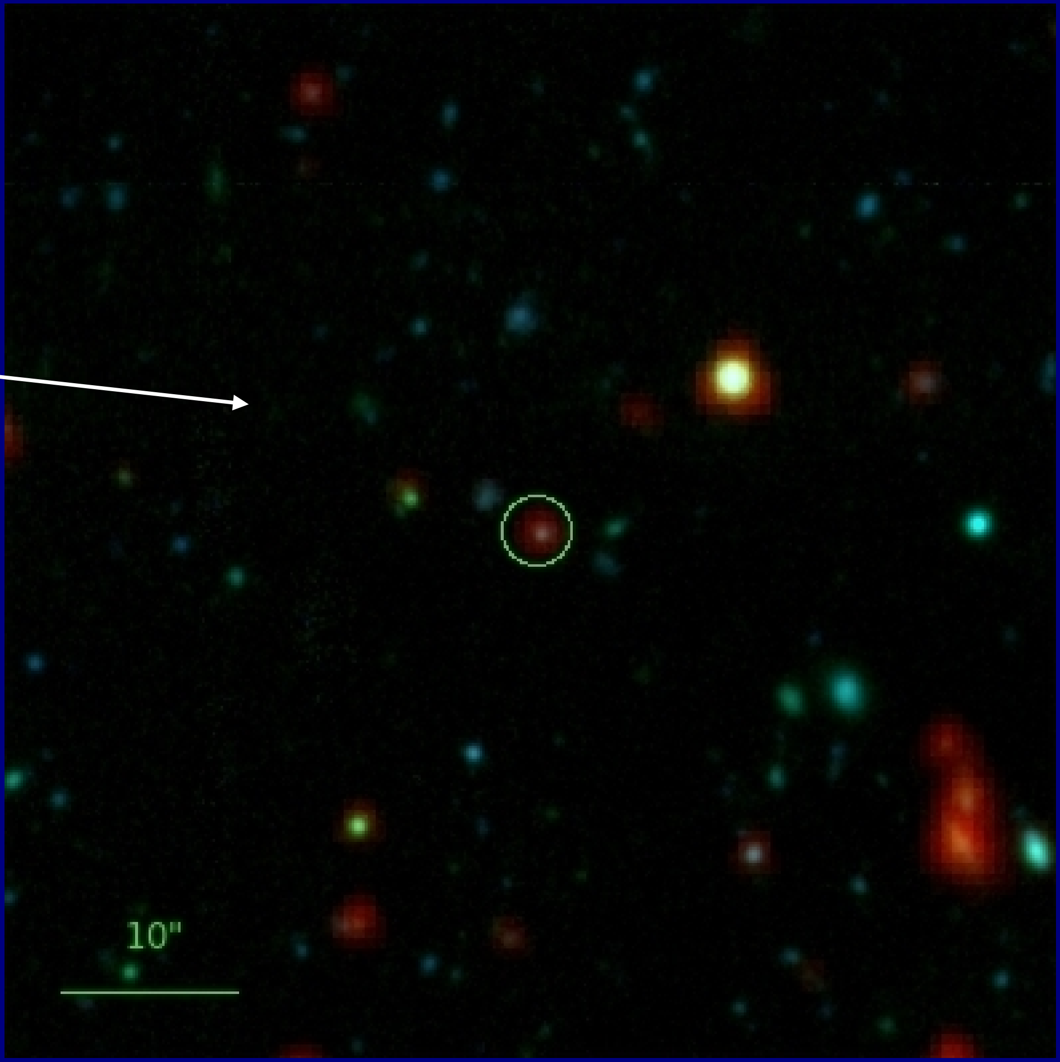
Castignani et al. in prep.

Blue cluster?

Not detected with P08 method



10” =~81kpc @ z=2.6

Gravitational arc in the field of COSMOS-FRI 01!!

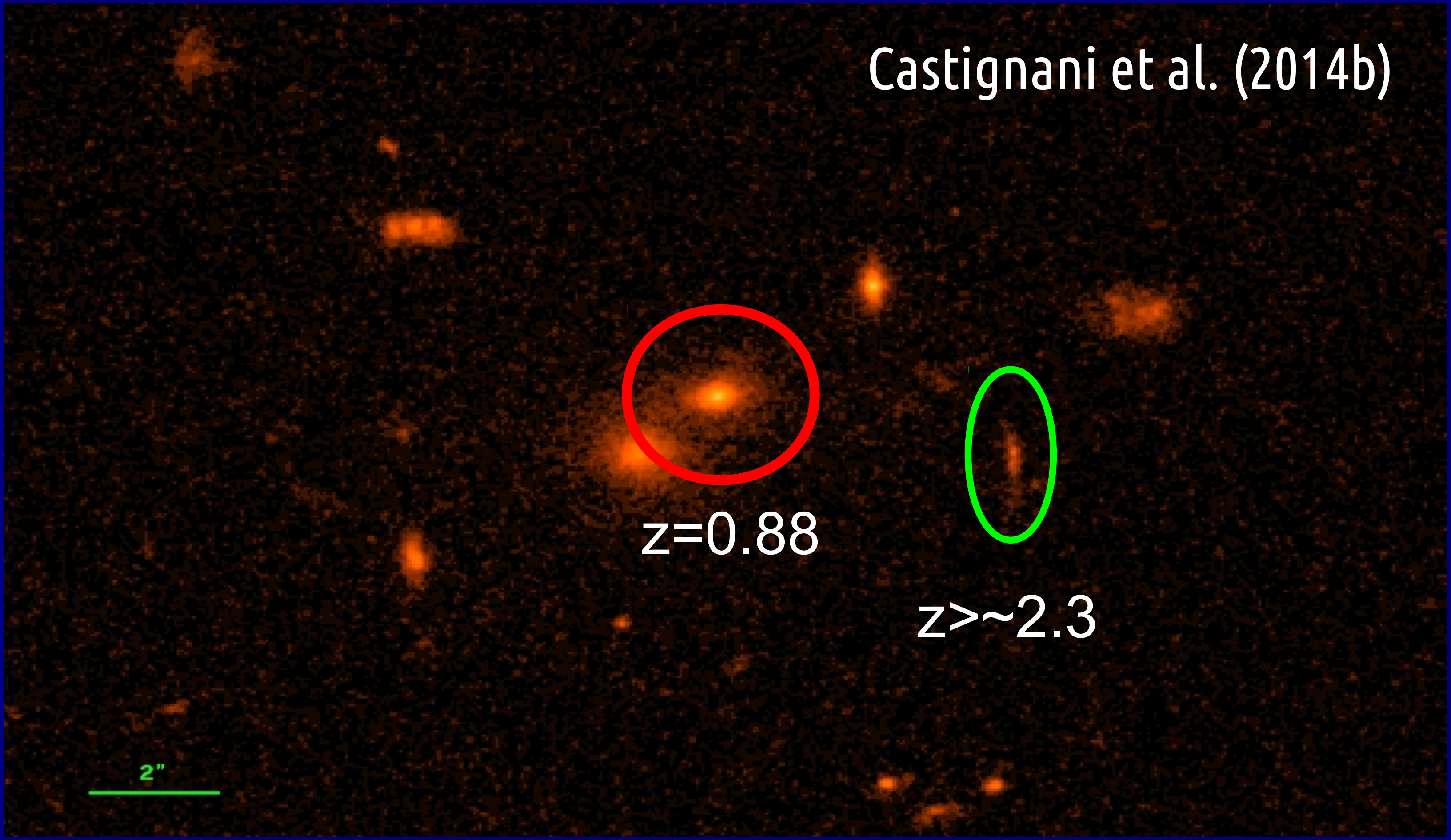
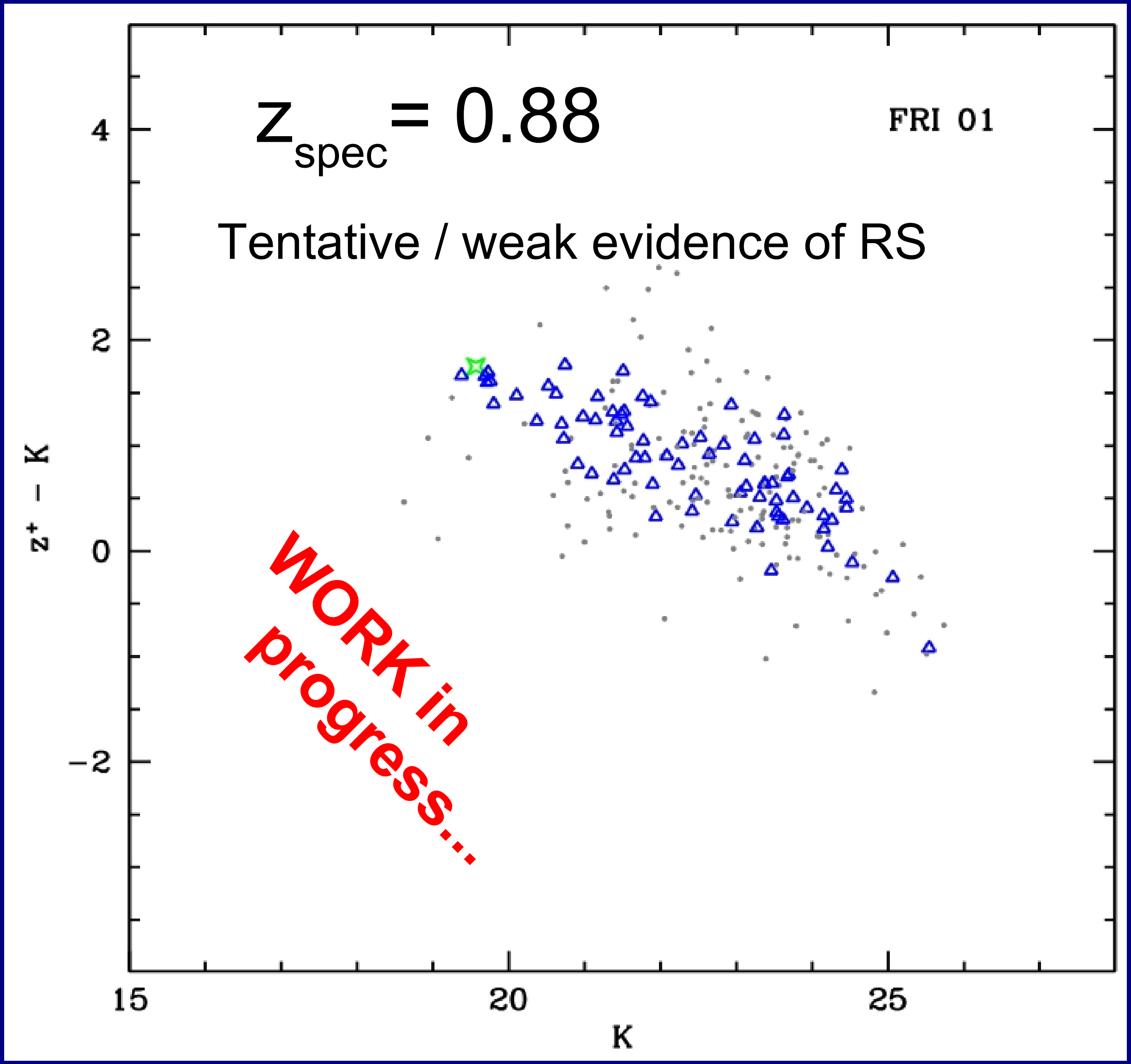


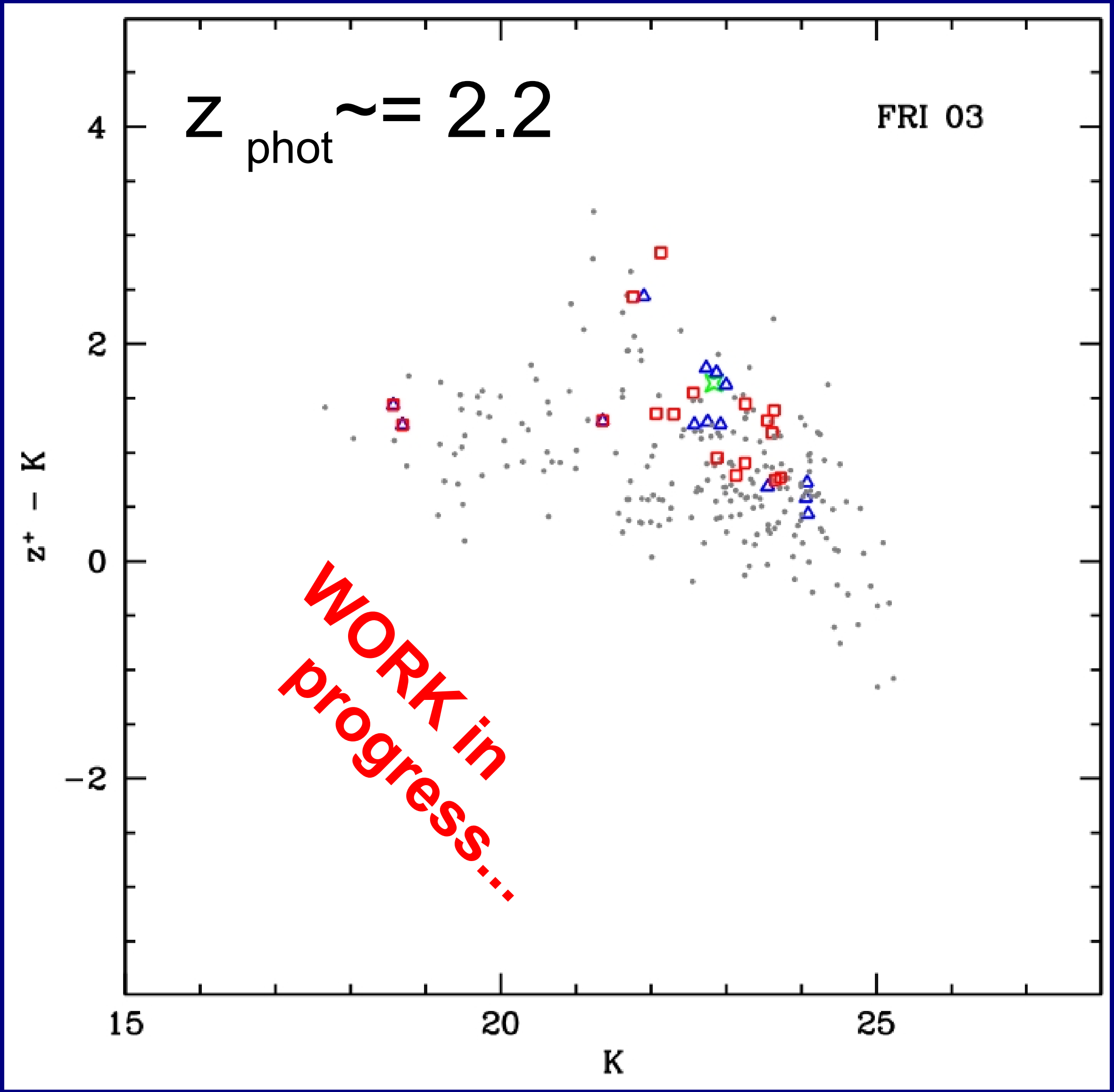
Figure: HST ACS image of the field of COSMOS-FRI 01

Color – Magnitude plots



galaxies within FRI photo-z uncertainties and 70 arcsec angular separation

Color – Magnitude plots



Robust membership assignments with careful consideration of photo-z information are needed!

The importance of robust membership assignments

Cluster galaxy population

- cluster members study (segregation within the core, morphology, colors, type, Strazzullo et al. 2013, 2015 Rykoff et al. 2014)
- Presence and evolution of the **red sequence** (Papovich et al. 2010)
- **Feedback** in galaxy clusters (e.g. star-formation quenching and AGNs, e.g. Brodwin et al. 2013)

Galaxy clusters

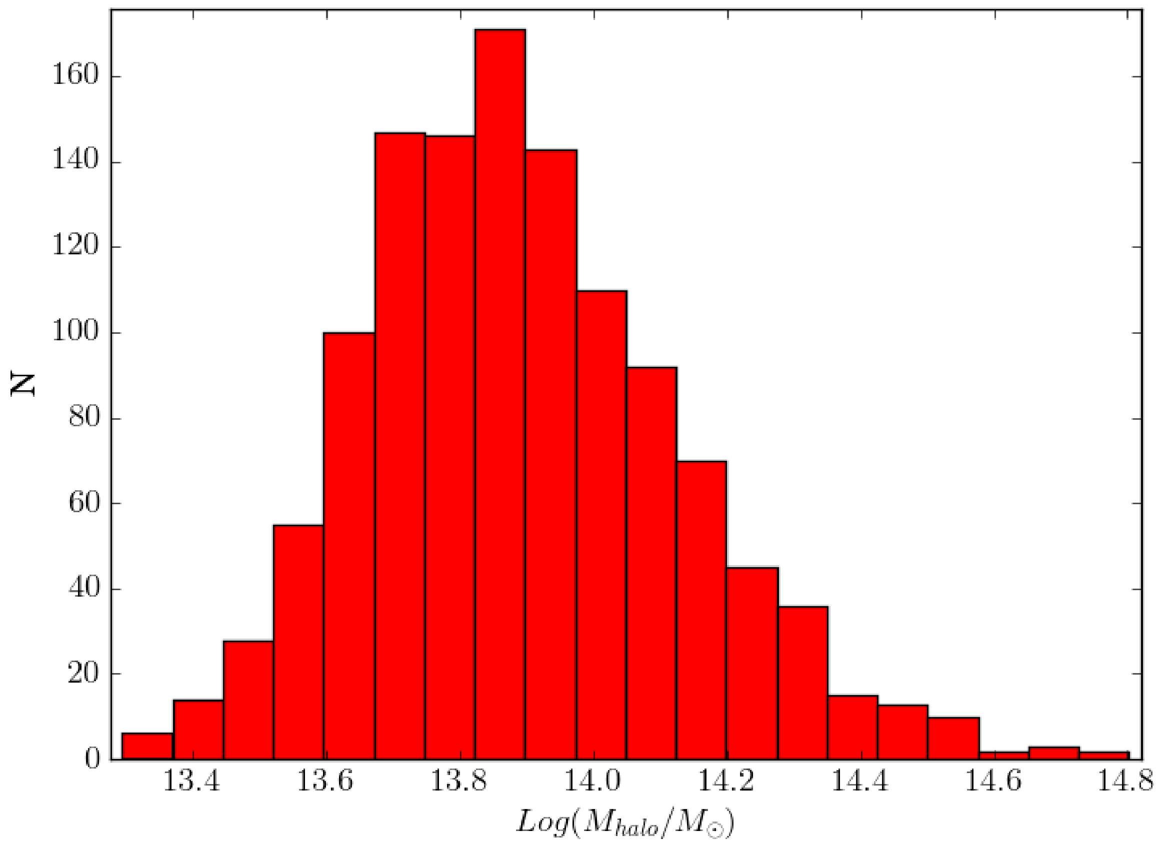
- **Completeness** and **purity** of the cluster catalogs through **membership matching** between the detected clusters and the simulated halos (Gerke et al. 2005, Knobel et al. 2009, 2012)
- **Richness estimator:** $\lambda \sim \sum p_{members}$ (Rykoff et al. 2014)
- **Cosmological studies** (e.g. halo mass function, DES collaboration, in prep.)

Probabilistic galaxy cluster memberships

The Sample

Halos

- 1,208 halos; ~20 sq. degree JHK Euclid deep H<26 mock catalog (Merson et al. in prep.)
- N_{mem} > 10 within r_{200}
- z~0-2.55
- $M_{vir} \sim 10^{13\text{-}15}\, M_{\odot}$



Galaxies

- ~10 milion galaxies
- simulated photo-zs

$\sigma(z) = \sigma_0(1+z)$; $\sigma_0 = 0.03$

Probabilistic galaxy cluster memberships

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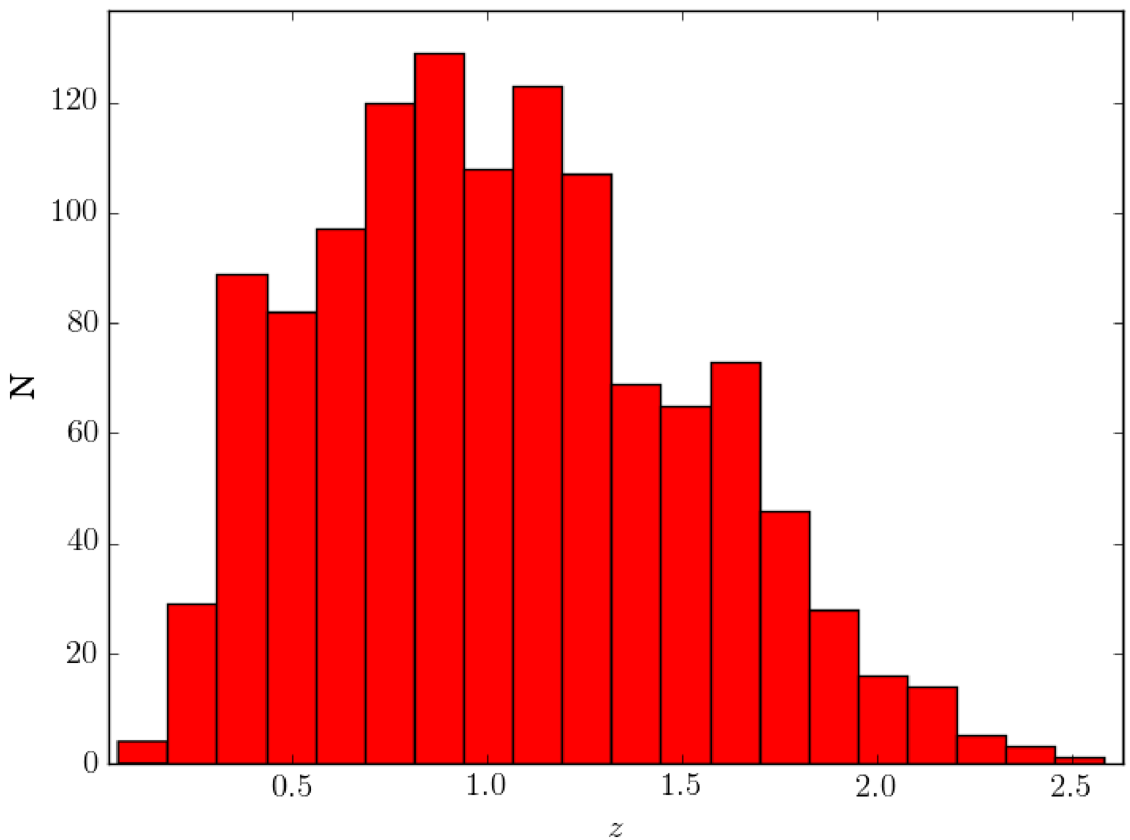

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The formalism
(G.C. & Benoist, submitted to AA)

Priors:

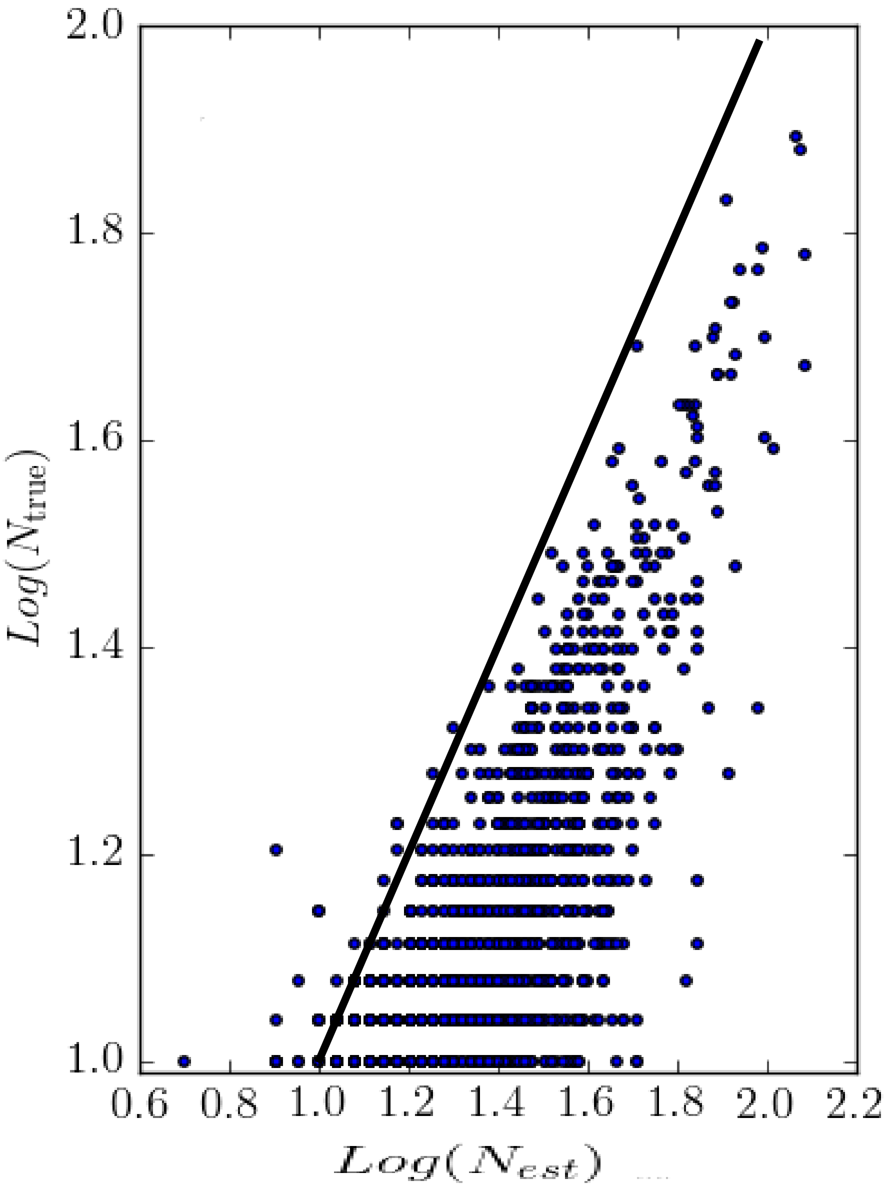
$$\Pi = \{r_{c,g}\,;\, P_g(z)\,;\, P'_g(m)\,;\, \mathrm{ra}_c\,;\, \mathrm{dec}_c\,;\, P_c(z)\,;\;\; N_{tot,c}(m,z,r_{c,g}), N^{loc}_{bkg,c}(m,z)\}$$

Membership probabilities

$$\mathcal{P}(g \in c|\Pi) = \left[1 - \frac{\langle N^{loc}_{bkg,c}(m_g, z_c)\rangle}{\langle N_{tot,c}(m_g, z_c, r_{c,g})\rangle}\right] \int P_g(z) P_c(z)\, dz \,.$$

True vs. Estimated Richness

(G.C. & Benoist, submitted to AA)



Accurate richness estimates:

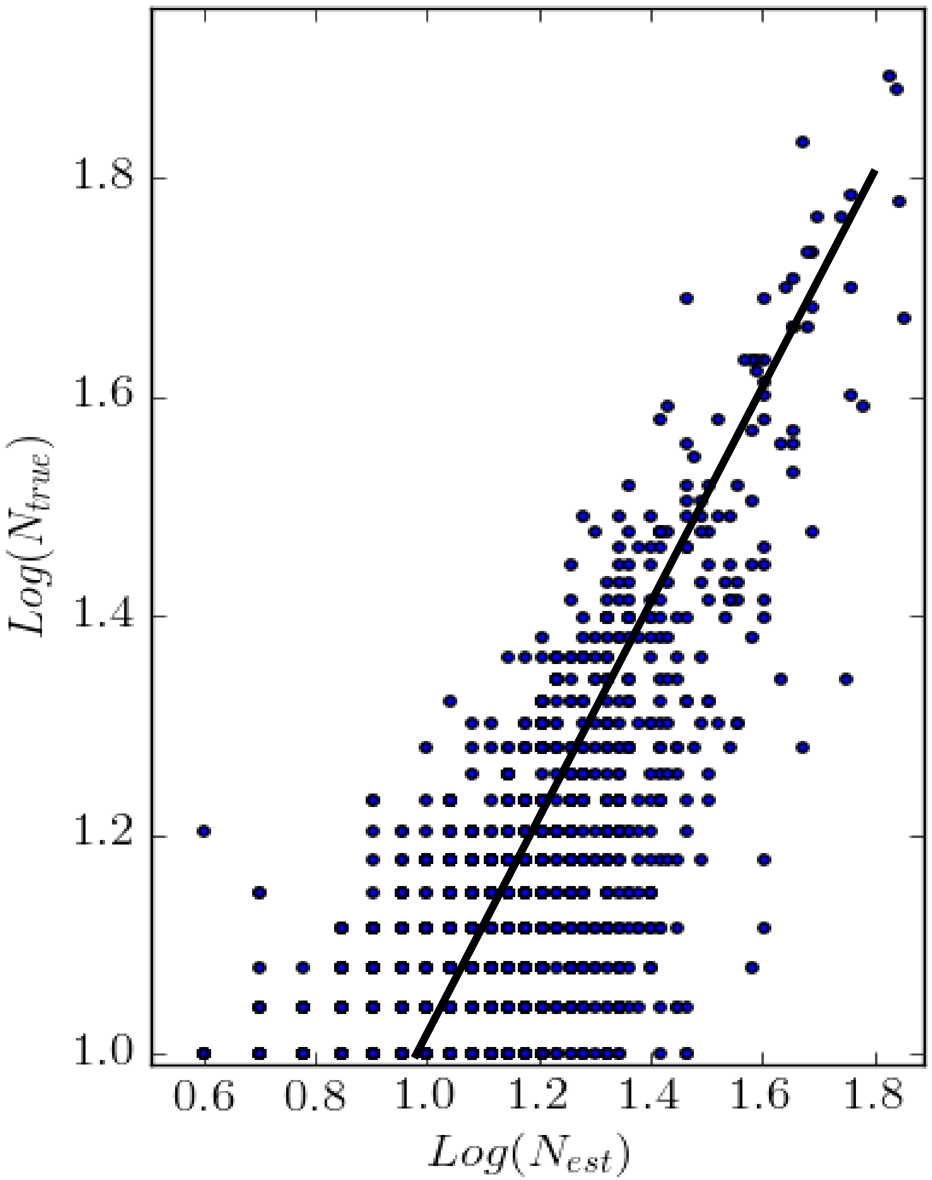
<Log(Ntrue/Nest)> = 0.25±0.14

Crucial for cosmology (e.g. Rozo et al. 2009, Saro et al. 2015)

The offset is fairly independent of both cluster redshift and richness within ~few%

True vs. Estimated Richness

(G.C. & Benoist, submitted to AA)



Richness correction

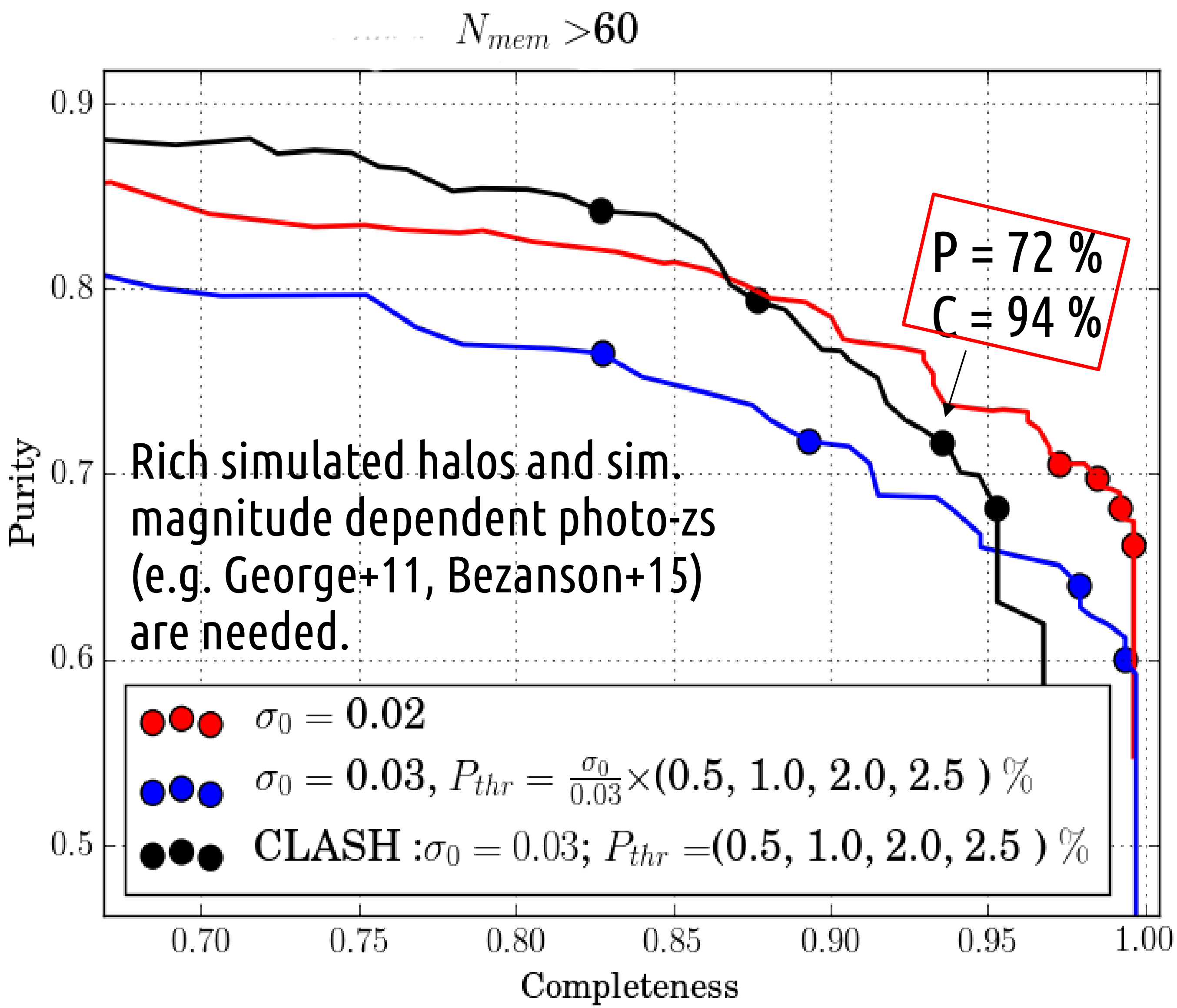
$\text{Log } P_{mean}/C_{\mathbf{mean}} = -0.23$

$\langle \text{Log}(\text{Ntrue}/\text{Nest}) \rangle = 0.02 \pm 0.14$

The calibration can be also performed with targeted observations of clusters with independent mass estimates (WL, SZ, X-ray,...)

CLASH MACS J1206.2-0847

- 1.4×10^{15} $M_\odot$ cluster at z=0.44. (Biviano+2013)
- CLASH-VLT. PI : Rosati
- Subaru photometry (Mercurio+in prep.)
- VIMOS VLT + Magellan spectro-zs (Rosati+in prep.)



Conclusions

- New general method to assign cluster membership using photometric redshift information
- Tests on simulations: Purity ≈ 70% , completeness ≈ 95% at $r_{200}/2$
- The method is general and can be applied to any list of galaxy cluster positions

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Future work

- Inclusion of more realistic mag. dependent PDFs(z)
- Application to real data such as SDSS (MSc thesis: N. Longeard)
- Cluster matching based on membership using simulated halos and clusters detected from the simulations (Adam et al., in prep.)

Main results and conclusions
(high-z galaxy clusters and RGs)

- **~70% FRIs are in clusters or rich groups, as found locally**

- **PPM → valuable alternative to existing methods to search for $z\sim1$-2 galaxy clusters**

Future work on high-z galaxy clusters

Spectroscopic confirmation of our best candidates (at $z>1.5$) with VLT (FORS spectrograph)...

...but also ALMA, and JWST in the near future

blue clusters, red sequence?

PPM applied to ongoing and forthcoming surveys:

- DES deep fields: clusters up to $z\sim2$ are expected (Cast+in prep.)
- *Euclid + SKA (and precursors):* ~ 10^7 clusters at $z\sim1$-2