Galaxy Clusters from a different point of view

…and some simulation comments more generally

Work with:
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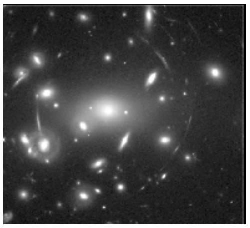
Yookyung Noh (UCB)-finishing next year
1005:3022, 1011:1000, 1105:1397,1204:1577

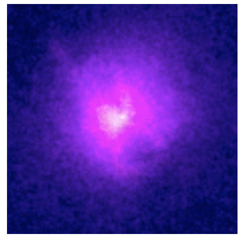
Interest in clusters for many reasons:

E.g.,
Constraining cosmological parameters
Understanding cluster formation/astrophysics
Understanding the transformation and evolution of the galaxies they host

Using several points of view can be fruitful:

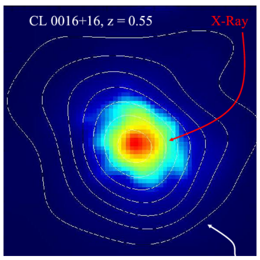


optical: cluster of galaxies



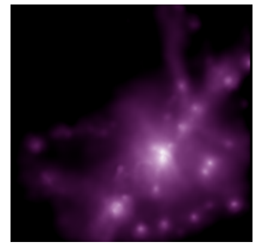
X-ray: deep potential well with hot gas

astroparticle theory: a point particle tracing the universe's matter density and expansion



SZ: 'hole' in the CMB background

Different information depending upon how you view the cluster!



Simulation(~WL optical): dark matter overdensity, perhaps+dynamical requirement,perhaps+hydro

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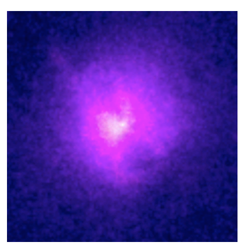

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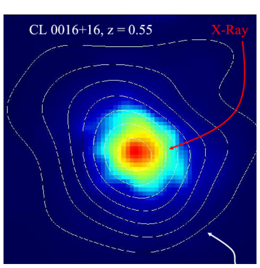
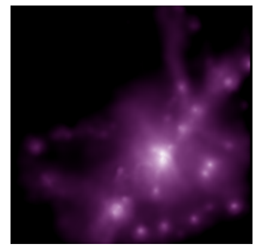


SZ: 'hole' in the CMB background

Not literally "points of view": Observationally, we are only able to see any given cluster from one direction….

Using several points of view can be fruitful:

…but theorists can use a simulation to also look at the same cluster from many different physical directions



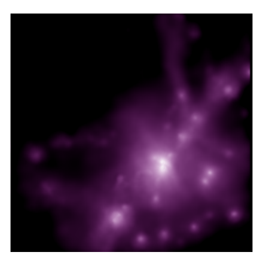
Simulation:
dark matter overdensity,
perhaps+dynamical requirement,perhaps+hydro

Using several points of view can be fruitful:

…but theorists can use a simulation to also look at the same cluster from many different physical directions

--**and** do “mock” mass observations using many different observational methods

Will do both here, together (WCS 10, etc…)



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If clusters were truly spherical cows*, isolated and symmetrical, observing them from many different directions would not provide much insight

Source: wikipedia

*stealing from Gus Evrard

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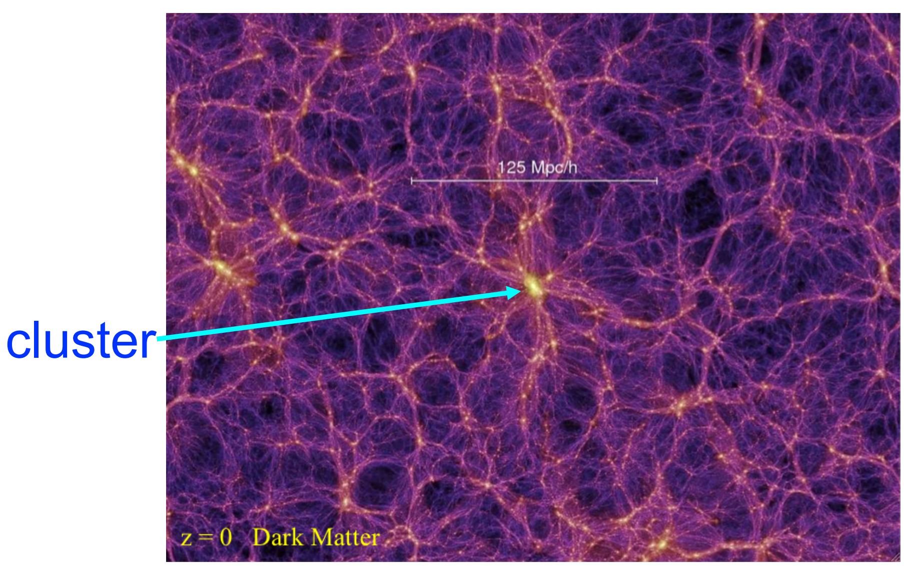
(such approximations
have been useful)

*stealing from Gus Evrard

If clusters were truly spherical cows, isolated and symmetrical, observing them from many different directions would not provide much insight

But clusters are not!

We do know this already 



Millennium dark matter simulation

Springel++
Lemson++

Here we will consider some of the consequences….

Main tool (data set): N-body simulation by M. White

250 Mpc/h box, 2048^3 particles (m_p=1.4e8 M_o/h, ~1/7 MS)
Dark matter (DM), with TreePM (White 2002) code
σ_8= 0.8, Ω_m=0.274, h=0.7, n=0.95, analysis mostly@ z=0.1

high enough resolution to have galaxies as subhalos

- not subsampled DM particles or "orphans"

big enough box to have cosmological environment
Most details are in WCS '10

Cluster population:

243 clusters with $M_{fof(0.168)} \geq 10^{14} h^{-1} M_o$, z=0.1

Galaxy population:

(Galaxies=) Subhalos found using 6dfof (Diemand, Kuhlen, Madau)
Preserves coherence of galaxies that share common origin
go down to 0.2L* when assign luminosities (later slide)

For answers about measurements of observed galaxy clusters
➔Mocks must correctly include measured properties, and their interrelations with each other and derived properties of interest.
(e.g., need to include relevant correlations and not introduce any false ones!)

How good are our mock observations?

trickier than it might sound:

- no ab initio formulations of galaxy or cluster formation.
- for both we have some idea in broad brush, but to go further, the simulations have to constantly be tested and refined against observational data (and against each other).

If you can't model your observation accurately enough, you can't figure out what it is telling you!

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*what exactly is "enough" depends on the measurements and uses of the observation

How good are our mock observations?

start with

- Galaxies, their infall halo masses (DM sims-converged)
- Luminosities (subhalo abundance matching)
- Colors (Skibba and Sheth method tuned on SDSS, fake light cones using FSPS of Conroy, White, Gunn)
- Halo masses and DM particle positions (for SZ)

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tests

- ✓ cluster richness agrees with Yang, Mo, van den Bosch measurements of SDSS cluster catalogue (used same method to find clusters as they did)
- ✓ Galaxy (subhalo) clustering (SDSS)
- ✓ Observed satellite fractions (SDSS)
- ✓ Cluster luminosity function (Hansen++)
- ✓ Cluster galaxy profile (cf. Lin, Mohr, Stanford 04)
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- ✓ Many galaxy and SZ properties captured.

Side comment (tie in to computational theme):

Simulation development, calibration and testing is obviously not just a concern for this project or for clusters!!

- It's an issue for surveys generally and *much harder now* because observational data have gotten much more rich and precise:
- questions care more about "details"
- relying more on simulations to compensate for observational issues ("taking it out in the analysis")

Step back:
Simulations take many different roles

1. understanding/quantifying/discovering consequences of theories
2. generating mock data sets to
   - test/refine data analysis methods
   - estimate selection effects and their and other correlations with quantities of interest
   - estimate error bars
   - confront theory and observation
3. Optimizing observational surveys

Focus on use for interpreting observations here

Because simulations are so crucial, there is a lot of debate & thought about which ones are best

"Best" is science-question and observation data-set specific!

- No simulation captures all gas physics
- No simulation captures all subgrid physics
- No simulation captures everything we know is there from Newton's, Einstein's and Maxwell's equations and beyond (e.g. chemistry, etc.)

Approximations are *built in* and *need to be tested* between methods and ideally with observations

Dark matter simulations:

- Agreement between different codes is very good
  (Katrin, Salman, Martin ++)
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This is what ➔
dark matter alone
predicts*!

*stolen from M. White

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Hydro simulations:

- At code level still a lot of development going on to include more physical effects within simulations themselves
- What to include and how is being explored and tested:
  star formation/feedback, cooling, multiphase medium, non-thermal processes, agn feedback, cosmic rays….and more
- SPH (community standard is Gadget, Arepo is new generation) vs. adaptive mesh (e.g. Enzo)
  - SPH drawbacks getting more under control (Hopkins 12)
- Extensive comparisons of implementations and what to put in/leave out underway (e.g. OWLS)—many huge efforts by many different groups (will hear about Nyx later, e.g.)

Simulations for different observations require mock-up/inclusion of different physics

- *galaxy clustering, motions, galaxies in clusters:* relation of dark matter to galaxy luminosity, color, stellar mass, positions
- *Lyman-alpha:* IGM continuum, UV background, more generally source properties & shielding, radiative transfer, metals and winds
- *Weak lensing:* baryon effects on profiles, source shape correlations
- *X-ray:* cluster gas relations, non-thermal energy injection, etc.
- *SZ:* ditto, for both some coarse graining can help!

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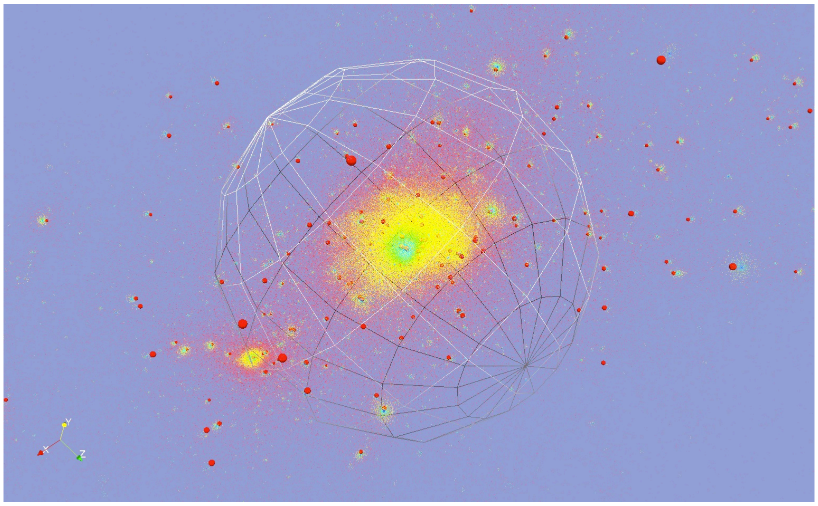
Tune/test proxies w/observational data!

Tune/test proxies w/observational data:

- Be especially wary of correlations
- Appropriate observational data often hard to get
  - example: galaxy mocks in hand work best at z=0.1—availability of SDSS and small sample variance of SDSS has a lot to do with this
- More clever tests to improve mocks using data in hand would be extremely helpful (e.g. cross correlations, marked correlations for galaxies)

….Back to what we found with our simulations, for clusters….



Simulated (N-body) mass measurements (WCS)

Cluster Masses via:

1. Velocity dispersions: dynamics of galaxies in clusters
2. Richness (red gals, MaxBCG, colors via Skibba &Sheth 09)
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4. SZ flux (cylinder, r180b)
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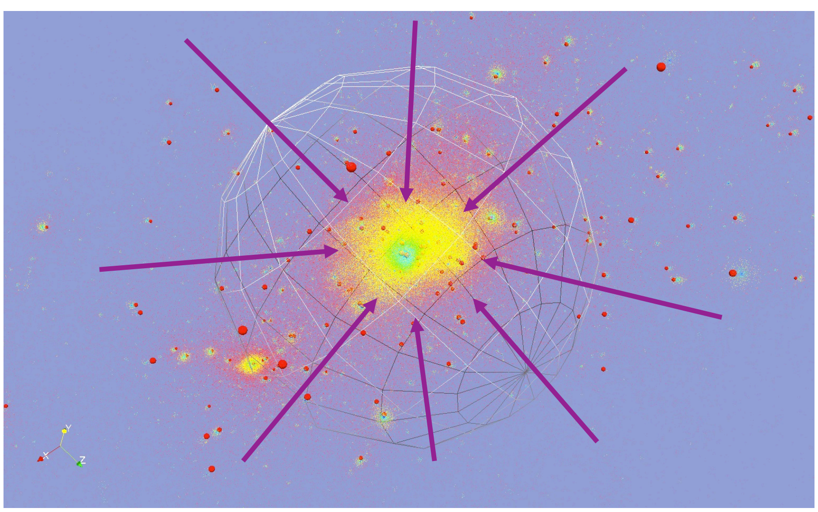

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Mass along **96 lines of sight** for 243 $M>10^{14}\ M_o/h$ clusters at z=0.1 (WCS)

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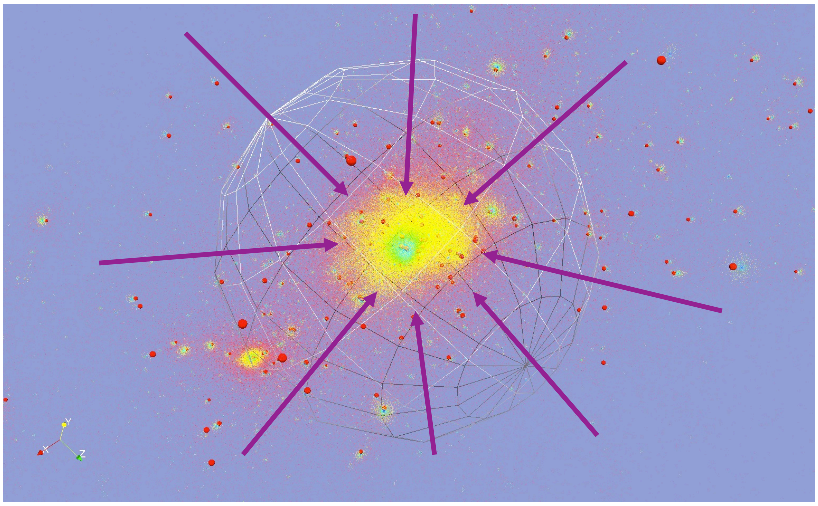

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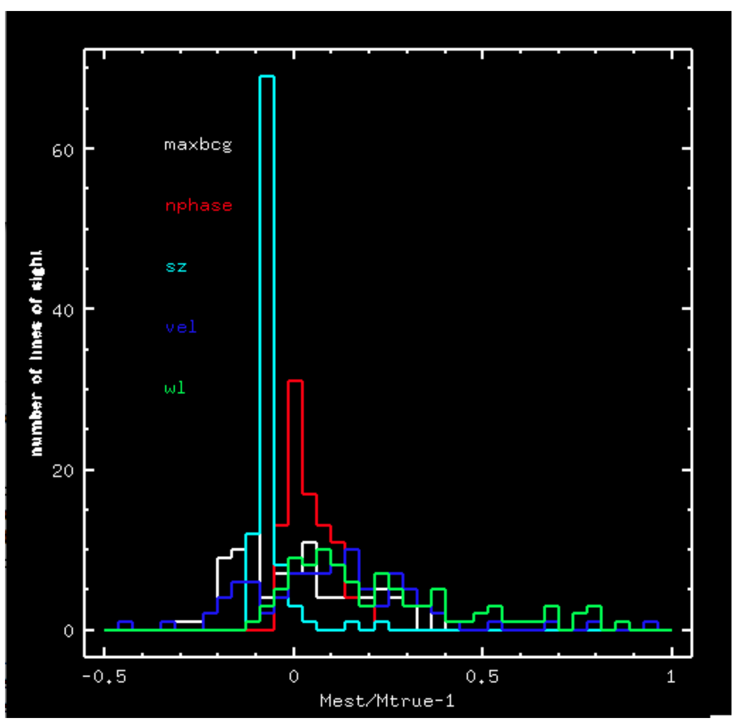
4. SZ flux (cylinder, r180b)-neglect some systematics+small box
5. Weak lensing (r180b) – " "

Scatter due to changing line of sight can be big!

one cluster
$M= 4.8\times10^{14}\ h^{-1}\ M_o$,
mass meas along
~96 lines of sight

--SZ & WL scatter underestimated:

- neglect some known systematics
- box too small



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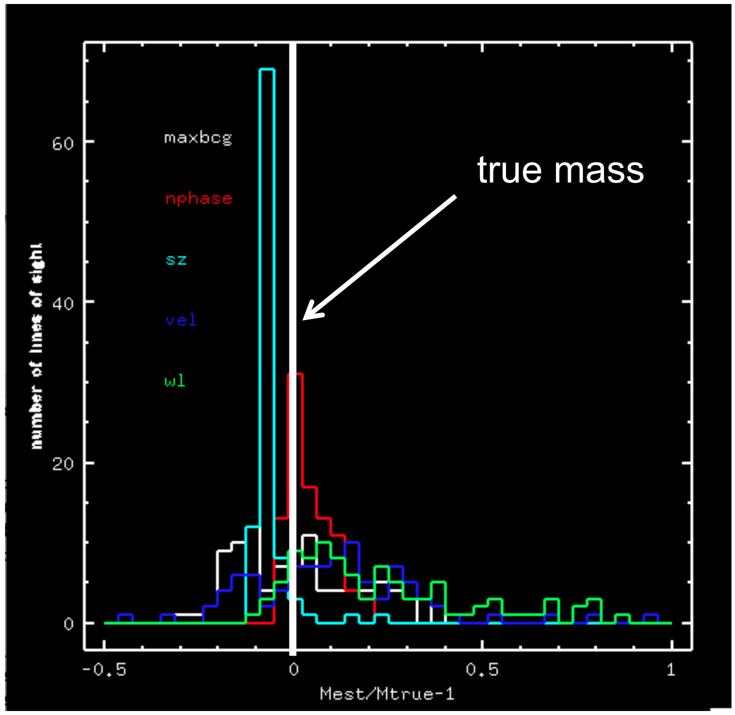

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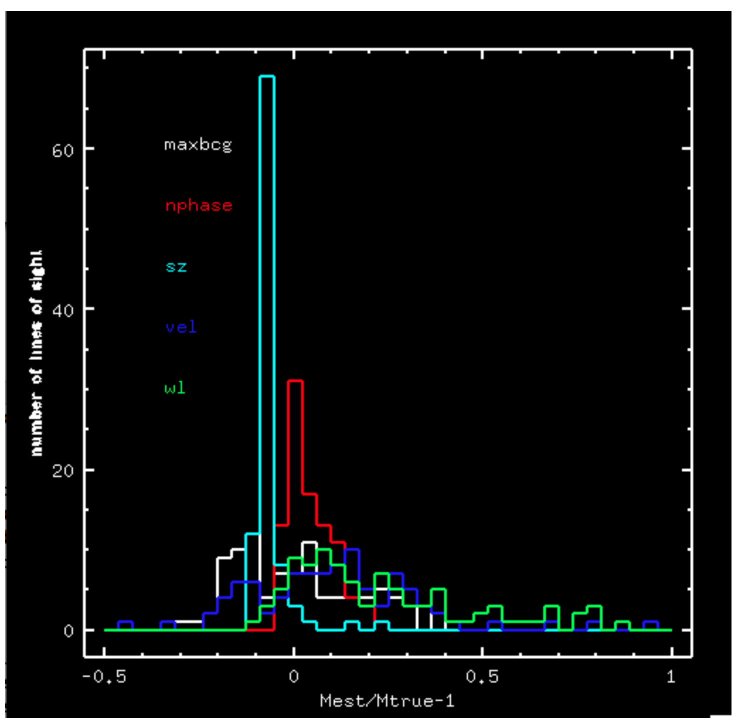
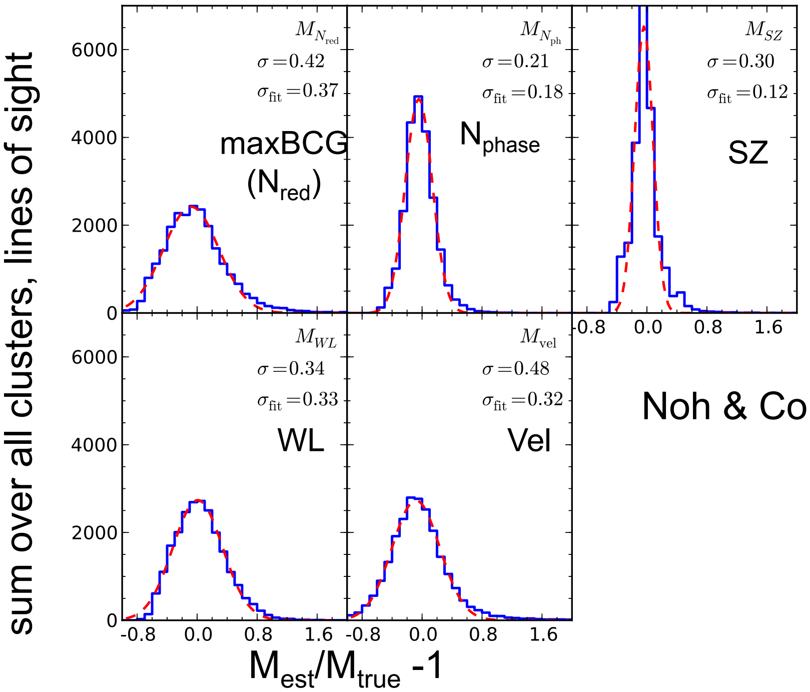


All clusters, together:
methods give ~large measured mass scatters



Noh & Cohn 12

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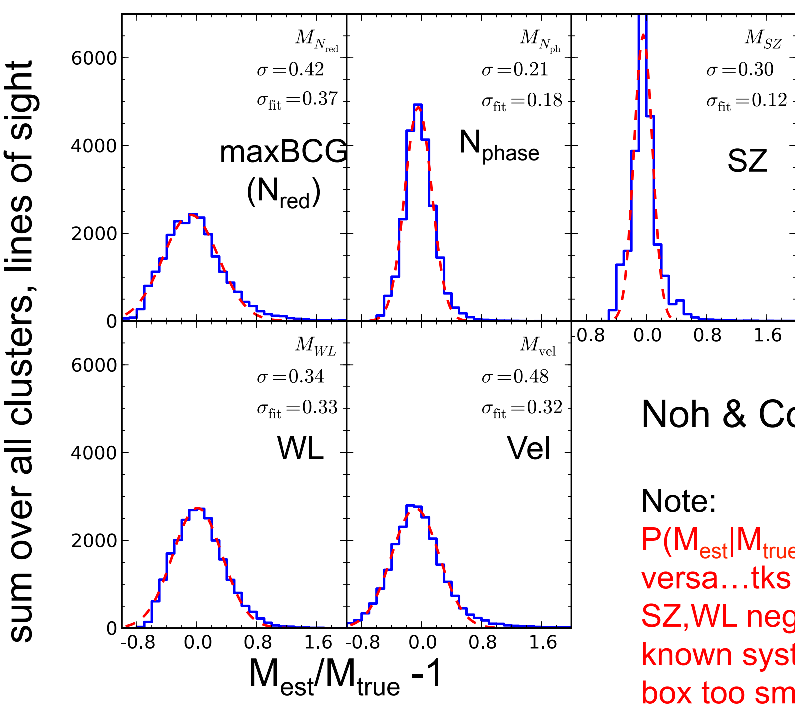
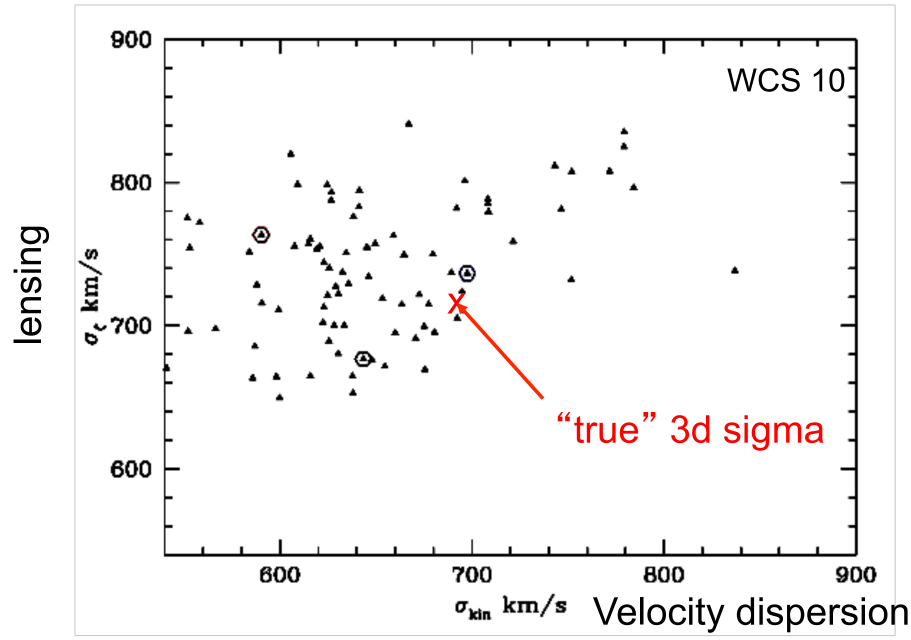


Noh & Cohn 12

Note:
$P(M_{est}|M_{true})$ not vice versa…tks Eduardo!!
SZ,WL neglect some known systematics + box too small

Also, scatters are often correlated…

~96 WL and vel dispersion measurements, along different lines of sight, for **one** cluster

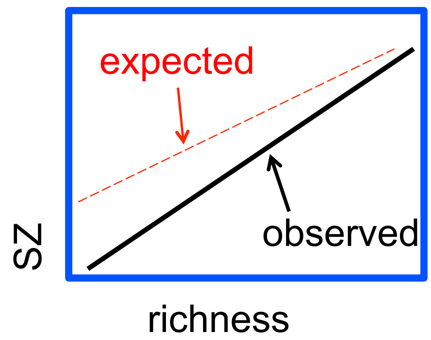


(*Keep in mind—red flag*)

Correlated scatter needs to be taken into account in multiwavelength measurements:

- two measurements can agree and be *wrong*
  - more generally must add errors appropriately
  - relevant in particular for individual clusters
    - e.g. likelihoods for extreme mass objects
- stacking
  - correlations, selection effects can introduce a bias in mass (or other!) relations derived for stack on mass [See Rykoff++08, WCS10, for intrinsic not los Stanek++10, for inclusion Rozo++09]
- one recent place it caused problems:
  Planck clusters-richness, WL, SZ, Xray:
  interpret disagreement in terms of corrlns (Angulo++12),
  Eduardo had X-ray calibration approach

What Planck found….



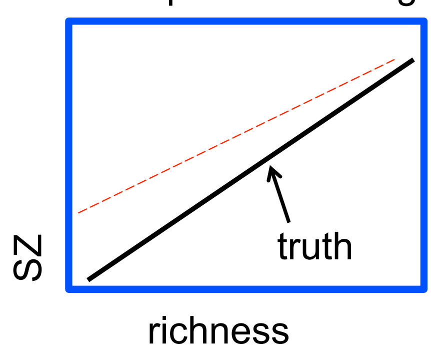
use: richness➔WL mass➔Predicted SZ

Last week:

Eduardo pointed out that WL ➔SZ is actually two steps and relied upon X-ray (Rozo, Bartlett, Evrard, Rykoff '12, 3 papers, different orders for subleading authors).

- The scatter in X-ray measurements was large and changed mass results significantly, cluster by cluster.
- They put together self-consistent mass meas from observations

Interpretation using correlated scatter (Angulo++12)



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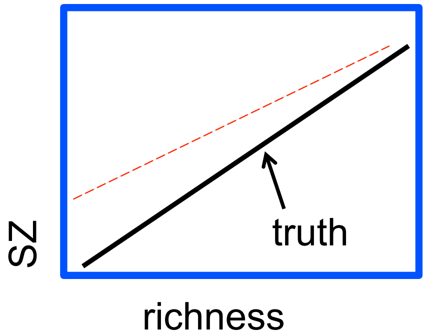

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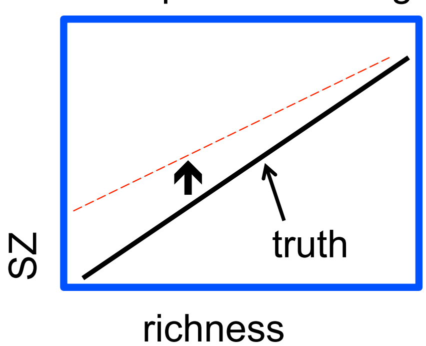

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so “fix”--raise WL mass, use “fixed” WL mass to get SZ
richness → WL mass → WL mass ↑ → Predicted SZ

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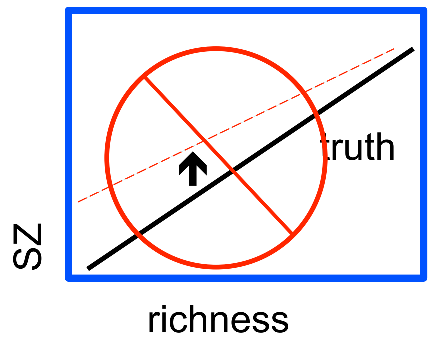

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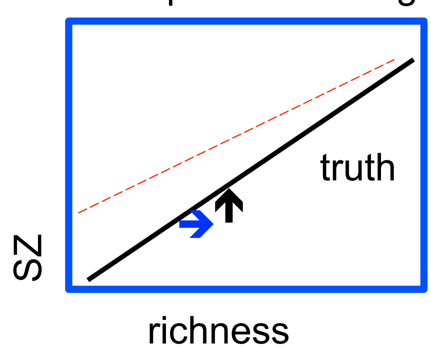
Problem! have neglected richness and WL correlations!!

if raise WL mass and don't take into account that richness also should go up, have fixed richness at one value but raised WL mass, thus broken reln.

Interpretation using correlated scatter (Angulo++12)



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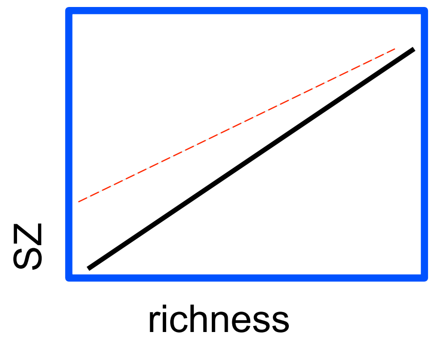
solid black line given at left.
Want a model for SZ(richness).

use: richness➔WL mass➔Predicted SZ

but WL mass↑ than measured because of miscentering,
if raise WL mass, need to first raise richness mass
richness➔WL mass➔Predicted SZ
both WL mass ↑ and richness mass ↑

(they also suggest using X-ray instead of WL and say it works)

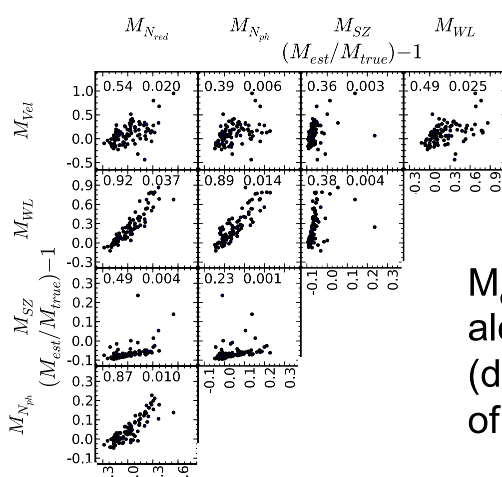
Interpretation using correlated scatter (Angulo++12, cont.)



But: Planck team tested SZ prediction for richness on subsample that had X-ray and got -----result
Why??

Another correlation ☹ (Eduardo mentioned too, see his talk)
X-ray sample takes clusters which have X-ray.
Clusters in sample with X-ray have higher SZ (except for perhaps richest clusters).
X-ray flux limited sample seems to get high SZ clusters and thus bias richness-SZ relation in same way as correction for WL miscentering!

Correlations for our one cluster:
All pairs of mass measurements



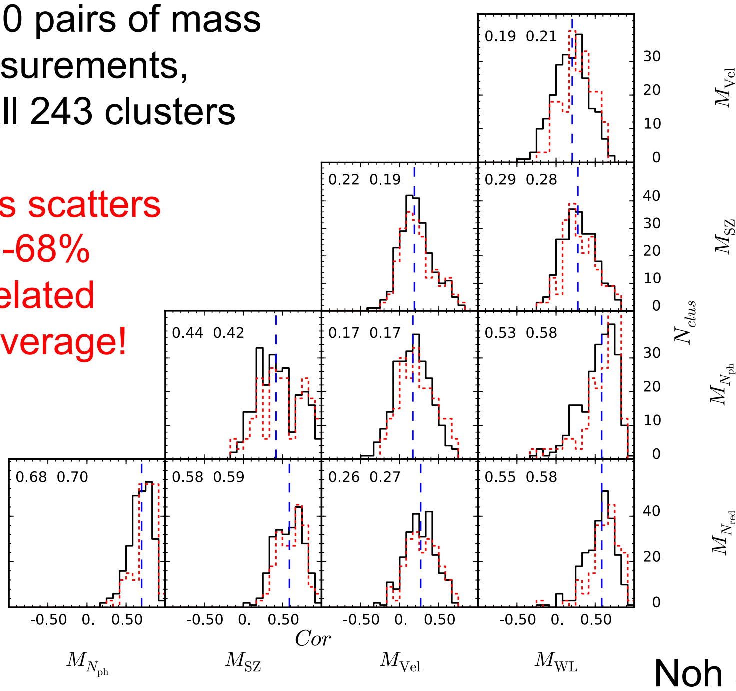
Noh & Cohn 12

M_{est}/M_{true}-1
along both axes
(different types
of mass measurements)

M= 4.8x10^{14} h^{-1} M$_o$, 10 pairs of mass estimates
~96 lines of sight

Correlations of mass measurements
for 10 pairs of mass
measurements,
for all 243 clusters

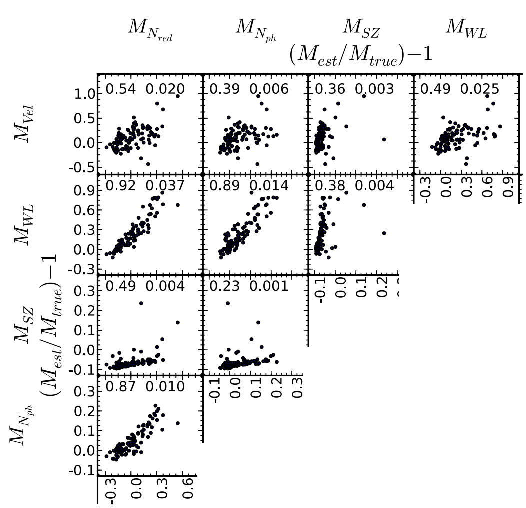
mass scatters
17%-68%
correlated
on average!



dashed
line at
median
value

red:
more
massive

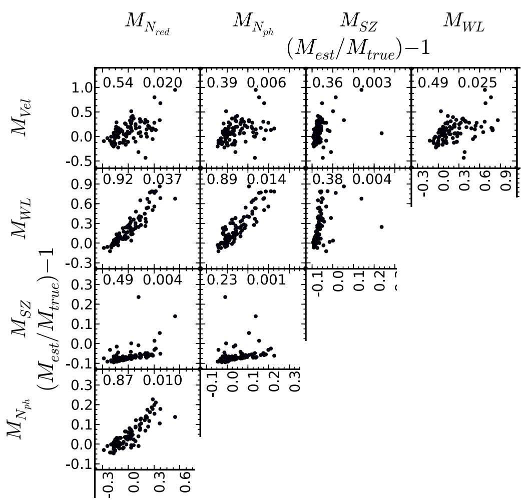
Noh and Cohn,
2012



Back to one cluster:
Each of these plots ~ cross section through a higher dimensional space, with 5 axes, corresponding to the 5 mass estimate methods:
Red, Phase, SZ, Vel, WL

Can try to “rotate” in this space to get directions of uncorrelated measurements

This is what PCA (principal component analysis) does!



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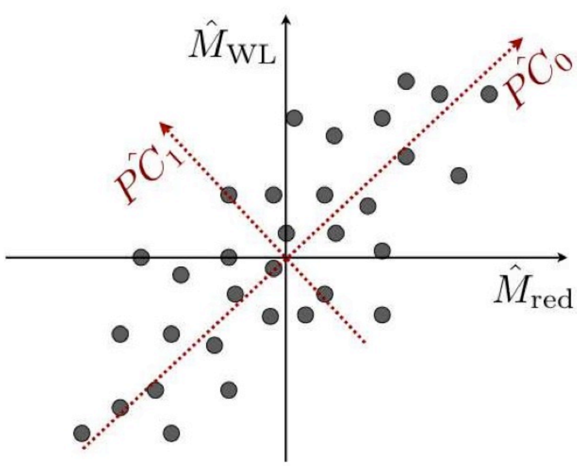
….start with example of 2 mass measurements

PCA for mass est correlations: (Noh & Cohn 12)

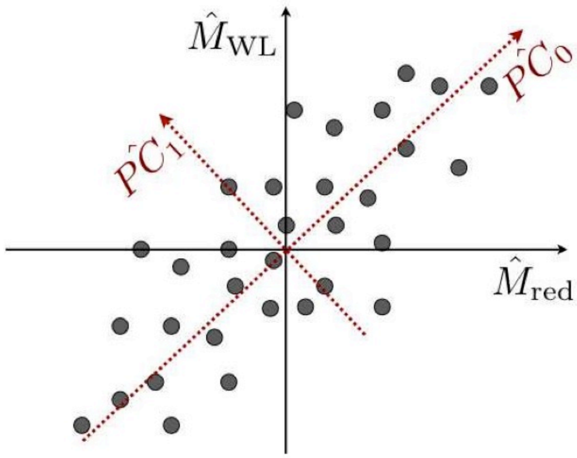


For 2 measurements:

- Diagonalize pair of correlated/covariant mass scatters, M_{WL} & M_{red}
- new basis $P\hat{C}_0$, $P\hat{C}_1$
    - combinations of original measurements with zero covc
- covc matrix eigenvalues indicate "shape" of scatter
- here see M_{WL} & M_{red} tend to be large in size together

We instead have 5 mass measurements, M_{est}/M_{true}
➔new basis $P\hat{C}_0$, $P\hat{C}_1$, $P\hat{C}_2$, $P\hat{C}_3$, $P\hat{C}_4$

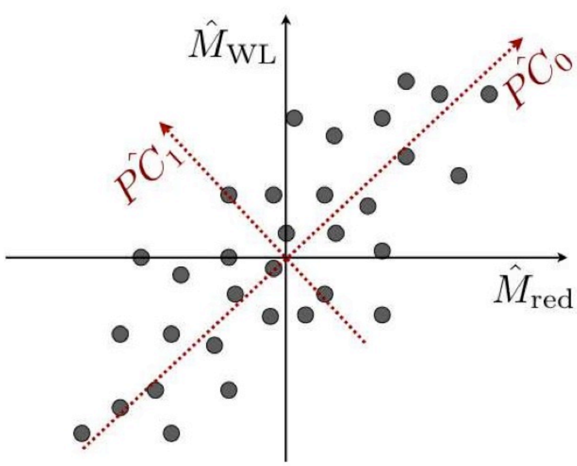
PCA for mass est corrlns: (Noh & Cohn 12)



for clusters,

- on average ~70% of los mass scatter variance from one combination (i.e. $\hat{PC}_0$) of mass measurements
- combination of different measurements often similar cluster to cluster

PCA for mass est corrlns: (Noh & Cohn 12)

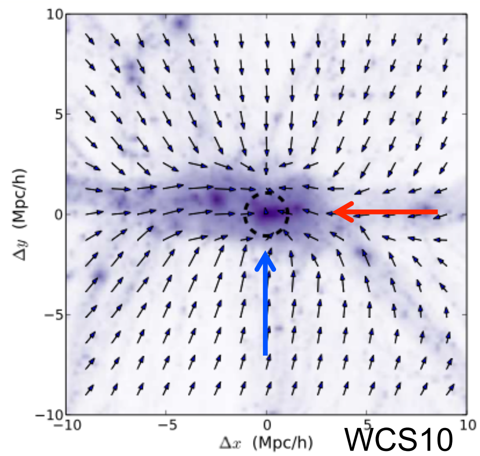


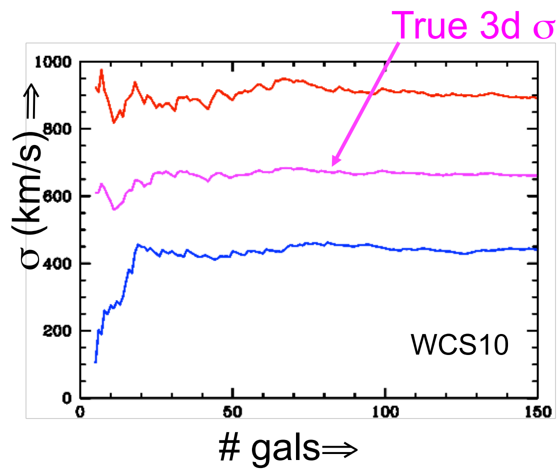
each point in our case is a different physical line of sight.

When scatter is along $\hat{PC}_0$, i.e. direction of biggest scatter, am I looking along a special physical direction in the cluster??

Expect: yes

phys props of/around cluster can have effects on meas mass!



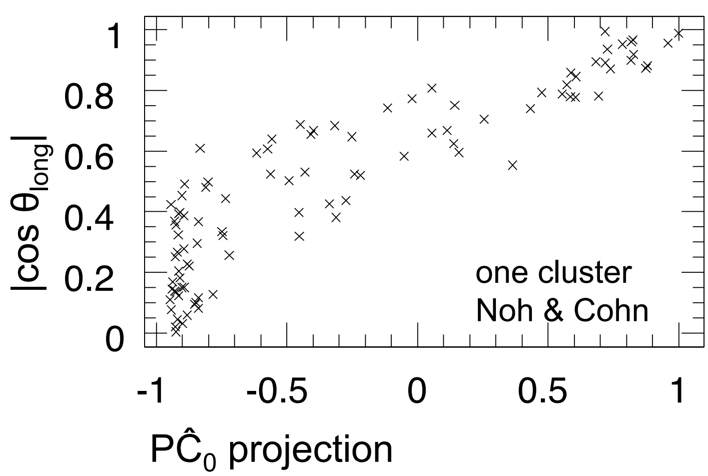


E.g., along cluster long axis one tends to observe higher velocity dispersions, ~same direction as filaments and largest substructures, expect to enhance WL, richness, SZ as well

Cen97,Tormen99,Kasun&Evrard05,WCS10, Noh&Cohn11,12,Cohn12,Saro++12

Find: yes!

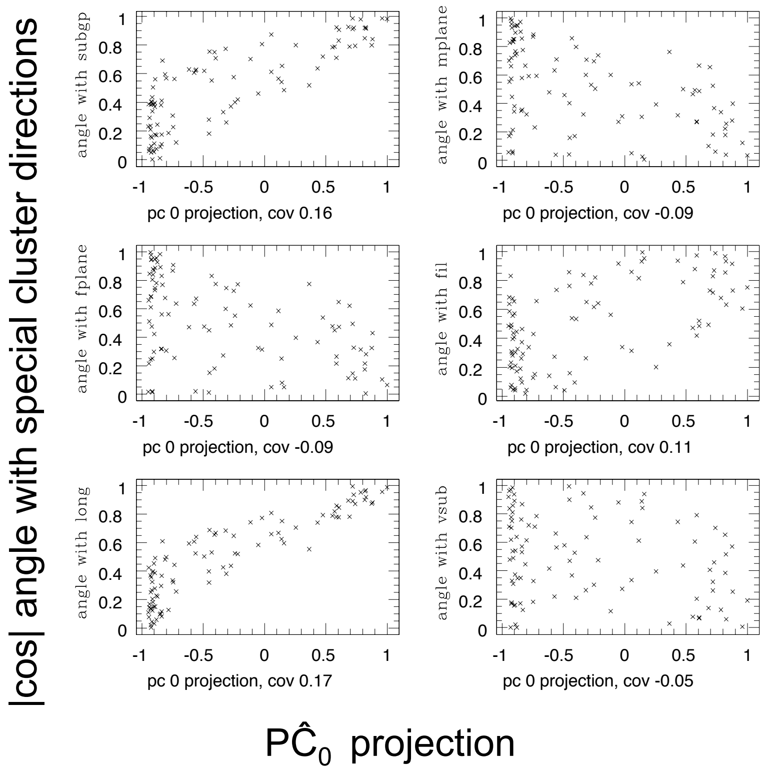
Looking certain physical directions gives points with "more" $P\hat{C}_0$, the dominant scatter combination



looking along long axis of cluster tends to give highest correlations with $P\hat{C}_0$, i.e. combination with largest mass scatter

other related directions:
filament plane around cluster, mass plane around cluster, dir of largest subgroup in cluster, largest filament…

Corrln above=0.17
($P\hat{C}_0 \sim 0.4\, M_{red} + 0.14\, M_{ph} + 0.19\, M_{sz} + 0.83\, M_v + 0.29\, M_{wl}$)
similar direction for $P\hat{C}_0$ for many clusters

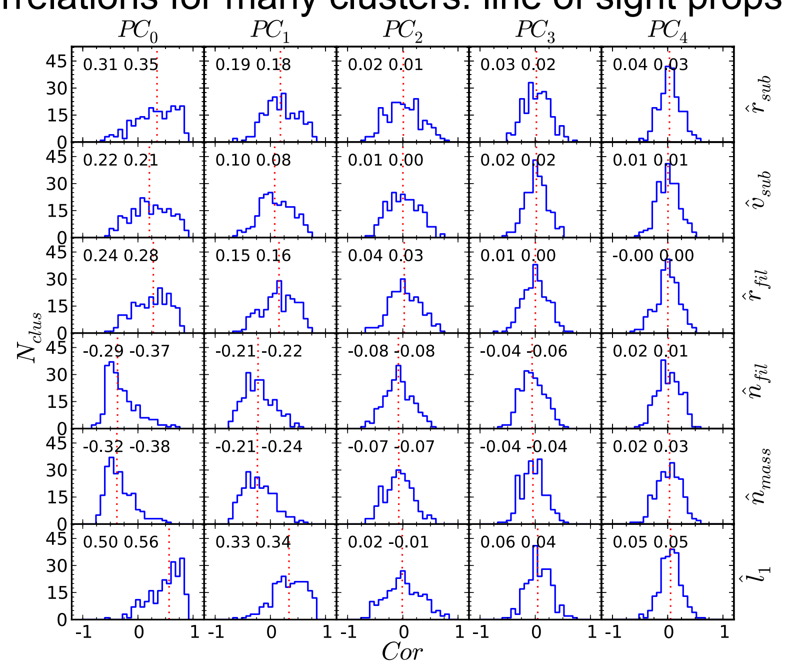


For same cluster, other correlations, for comparison

Noh & Cohn 12 for

There's a range:

Correlations for many clusters: line of sight props and $\hat{PC}_i$



How about cluster to cluster differences?

Mass scatter differences:

- largest scatter often has a large fraction of total (how much?)
- Many clusters have similar direction of largest scatter (how similar?)
- Size of scatter along smallest direction….

Other cluster differences:

- Average (over los) measured mass vs. true mass
- Different environments
  - planarity of mass & filaments nearby
  - nearby large halos (>1.e13 M_0/h)
- substructure size and position, histories, concentration
- triaxiality $(I_1^2 - I_2^2)/(I_1^2 - I_3^2)$, sphericity I_3/I_1, ….

Correlate many properties of different clusters
Get: a big set of correlated variables

➔use PCA to sort out!

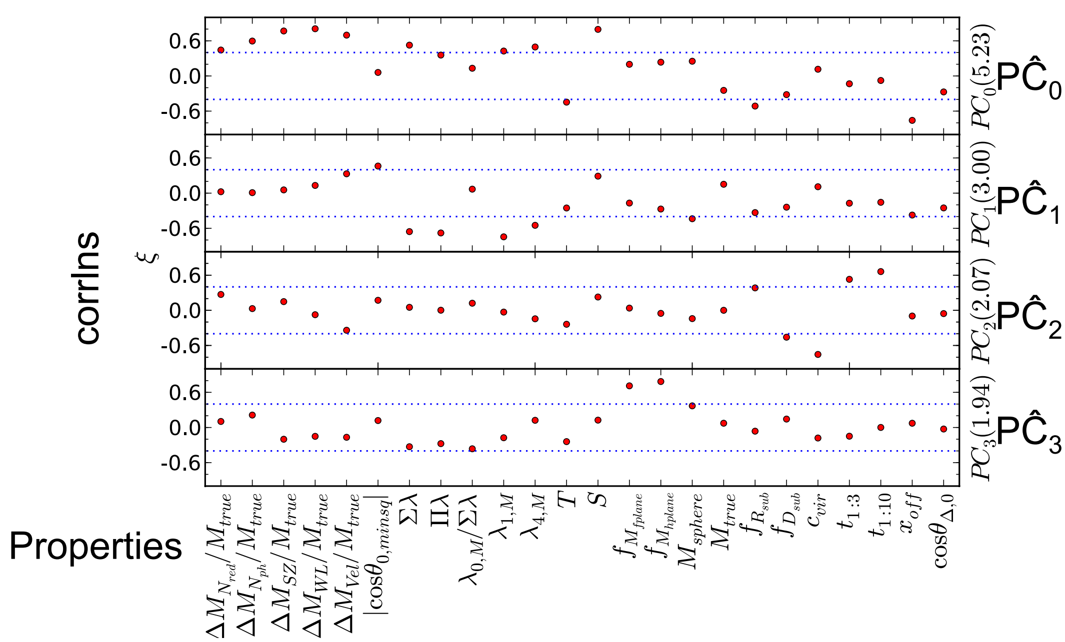
Same idea, different properties, as Jeeson-Daniel++11, Skibba & Maccio 11, Einasto++11 (superclusters)

Find:

- No strongly dominant combinations of changes in cluster properties (largest is 20% of variance not 70%)
- Still, see trends, e.g.
  - ↑ triaxiality
  - ↑ richness in largest subgroup

  when
  - ↓ sphericity
  - ↓ size of and average mass scatter when changing line of sight
  - ↓ planarity of mass & filaments around cluster
  - ….etc. (see Noh & Cohn 12 for plots…)

25 properties, pull out subgroups once see trends



Cluster properties recap:

- 243 clusters in cosmological z=0.1 simulation
  - simulation seems to capture realistic props
  - "observed" clusters from 96 lines of sight, measuring mass 5 ways
    - a lot of line of sight dependent scatter
    - correlated between different measurements
- Use PCA to get uncorrelated combinations of mass measurements
  - largest mass scatter combination
    - tends to be similar cluster to cluster
    - tends to occur when looking along long axis of cluster
- Use PCA on all clusters together, many properties
  - relations between mass scatter, average los mass offset and triaxiality, mass around cluster, substructure, etc.

Other points to note:

Lots of scatter in galaxy cluster mass measurements

- different measured masses often correlated because of shared physical intrinsic/environmental props
- correlations can cause biases, error underestimates, etc. if not taken into account (Stanek++,Rykoff++,WCS,others)

Possible interesting future application

Find $M_{true}(M_{est})$ in simulations and do PCA--use relation of cluster mass measurements to each other

- to get cluster information besides mass,
- to signal issues (problems!) in particular measurements

Simulations were crucial for all this!

- Calibrating the scatters and their correlations requires simulations which faithfully reproduce observables, systematics and selection function (which then can be calibrated and included in analysis) thank you