The Abdus Salam
International Centre for Theoretical Physics

United Nations
Educational, Scientific and
Cultural Organization

IAEA
International Atomic Energy Agency

2419-2

Workshop on Large Scale Structure

30 July - 2 August, 2012

Galaxy Clusters and the Cosmic Web

J. Cohn
University of California at Berkeley

Galaxy Clusters and the Cosmic Web

Work with:
Martin White (UCB)
Renske Smit (UCB, now Leiden)
Yookyung Noh (UCB)-finishing upcoming year
1005:3022 (WCS), 1011:1000,
1105:1397,1204:1577

note related work by Angulo et al presented today as well

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

Many large multiwavelength surveys underway and huge simulation/theory efforts
already heard some discussion, will hear more later: Benson, Bohringer, Huterer, Majumdar, Sehgal

Spherical Cows*:

A lot of progress has been made with simplified cluster models

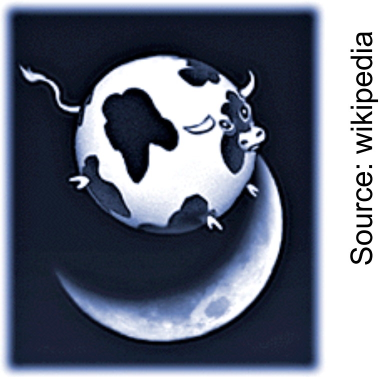
Source: wikipedia

*stealing from Gus Evrard

Modeling simplifications include treating clusters as

- Isolated (spherical infall model)
- Spherical
- Smooth

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



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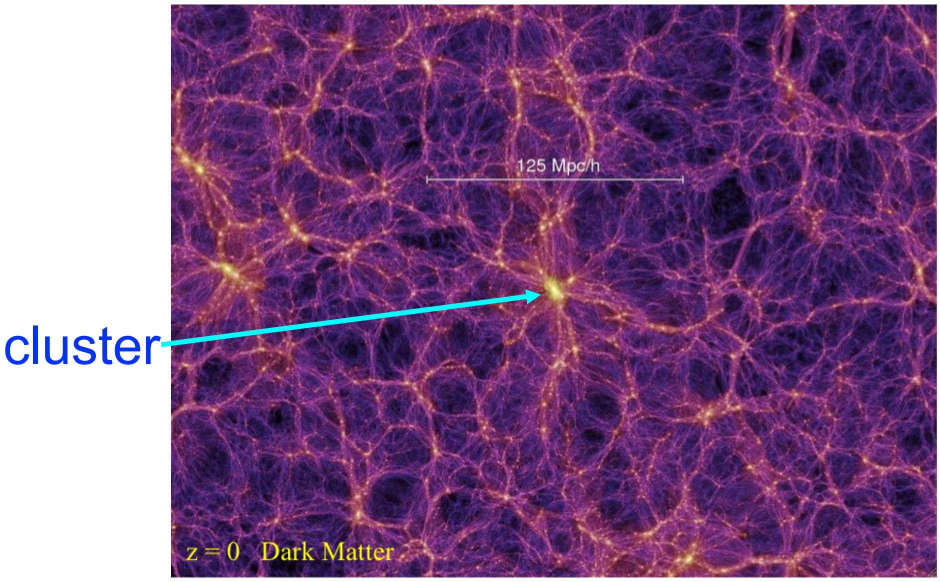
But clusters are not!

We do know this already ☺



picture from Millennium dark matter simulation

Springel++
Lemson++

Cluster modeling simplifications don't hold:

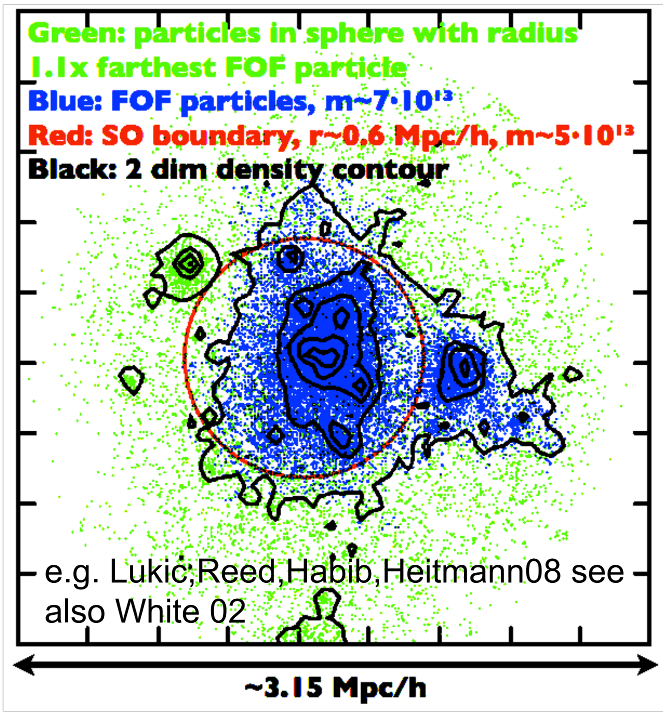
- ~~Isolated (spherical infall model)~~
  - ➢Cosmic Web
- ~~Spherical~~
  - ➢Triaxial or more complicated shapes
- ~~Smooth~~
  - ➢Substructure in dark matter, galaxies and gas

(triaxiality and the cosmic web are related….)

(triaxiality: not clear where cluster ends and web begins…)

FoF (b=0.2,shaded)
SO(Δ) (Δ~200ρ_c) inside circle

Blue region outside red circle would be filament in one defn, cluster in other



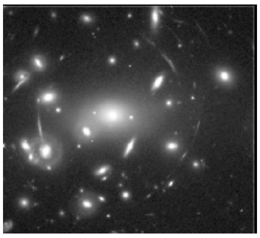
e.g. Lukic,Reed,Habib,Heitmann08 see also White 02

Approach here:
Use many different directions to observe a given cluster in an N-body simulation

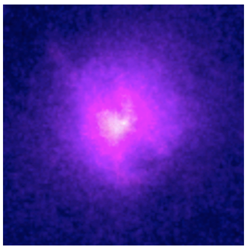
Use several (5) mass measurement methods

- intercompare mass estimates *and their scatters*
- relate mass scatters to cosmic web/ cluster anisotropy

Several ways to observe clusters



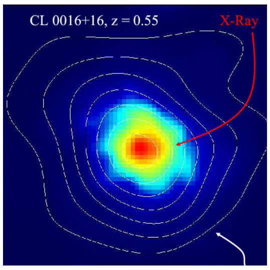
optical: cluster of galaxies



X-ray: deep potential well with hot gas

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

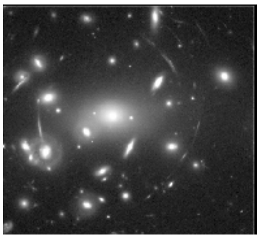
Simulation(~WL optical): dark matter overdensity, perhaps+dynamical requirement,perhaps+hydro



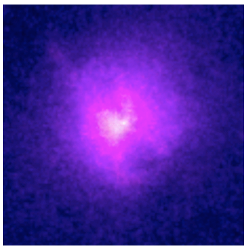
SZ: 'hole' in the CMB background

Often use many together to get complementary information

Here use three (really five) techniques:



optical: cluster of **galaxies**



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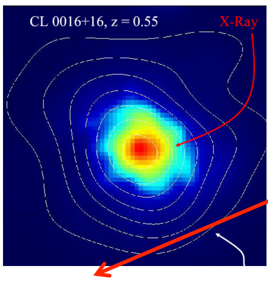

SZ: 'hole' in the CMB background

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
Detailed description 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

Dark matter simulations:

- Agreement between different N-body codes is very good (Heitmann++ 2008)
- Rest of physics is included via post-processing

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This is what ➔
dark matter alone
predicts*!

*stolen from M. White

How good are our mock observations?

start with

- Galaxies, their infall halo masses (DM sims-converged)
- Luminosities (subhalo abundance matching) to 0.2L*
- 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, by Wetzel&White 10)
- ✓ Observed satellite fractions (SDSS)
- ✓ Cluster luminosity function (Hansen++)
- ✓ Cluster galaxy profile (cf. Lin, Mohr, Stanford 04)
- ✓ For SZ gas estimates, on scales required for comparison with SPT/ACT/APEX, agrees with hydro simulations with heating, etc. of White, Hernquist, Springel 2002

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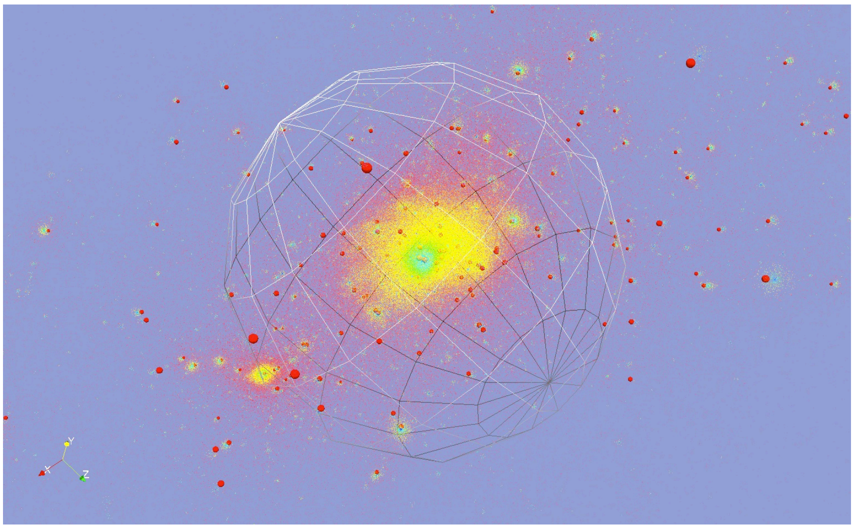
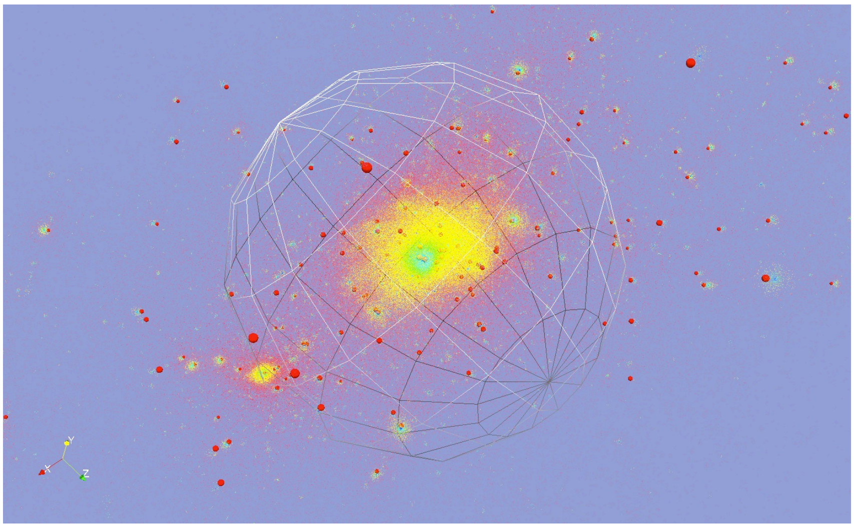
- ✓ For SZ gas estimates, on scales required for comparison with SPT/ACT/APEX, agrees with hydro simulations with heating, etc. of White, Hernquist, Springel 2002
- ✓ Many galaxy and SZ properties captured.



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)
3. Richness (all gals, cluster membership using Yang, Mo, van den Bosch07, phase space)
4. SZ flux (cylinder, r180b)
5. Weak lensing (r180b)



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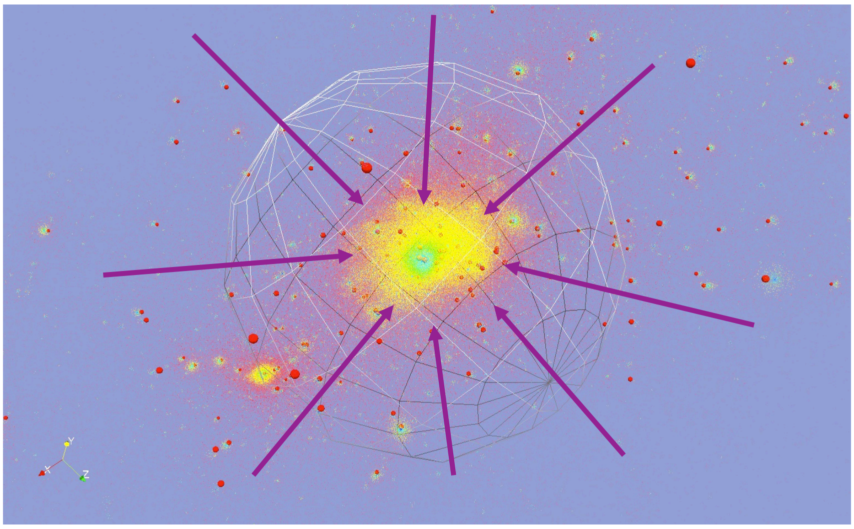
4. SZ flux (cylinder, r180b)-neglect some systematics+small box
5. Weak lensing (r180b) – “ “ cf Sehgal’s talk



Simulated (N-body) mass measurements

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

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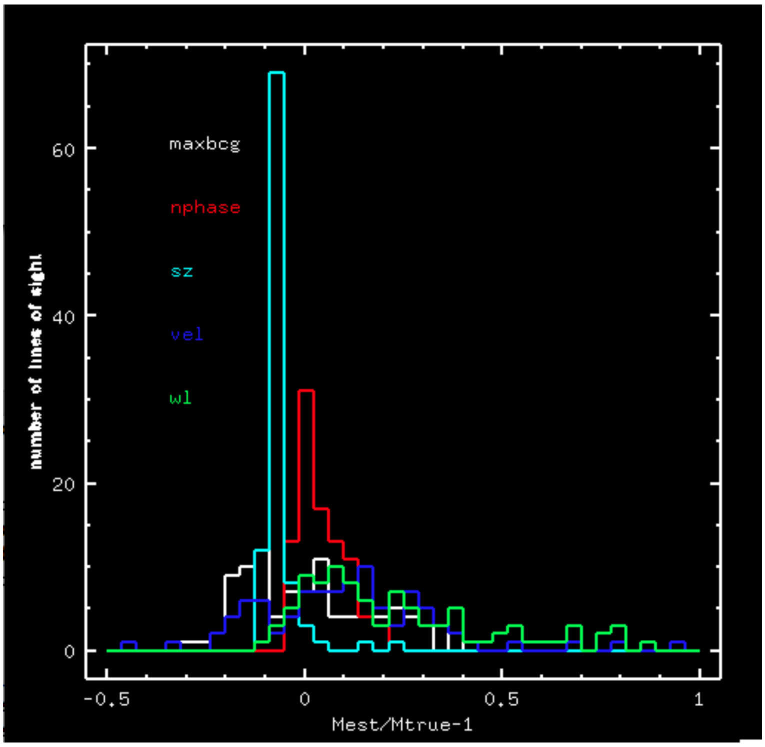
Scatter due to changing line of sight can be big!

one cluster
$M= 4.8\mathrm{x}10^{14}\,h^{-1}\,M_o$,
mass meas along ~96 lines of sight

--SZ & WL scatter underestimated:

- neglect some known systematics
- box too small



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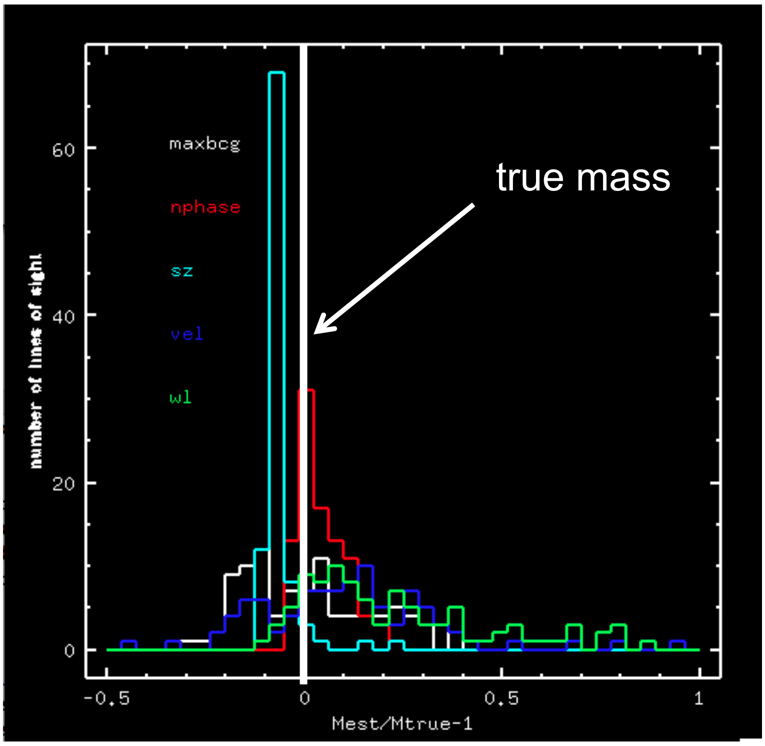

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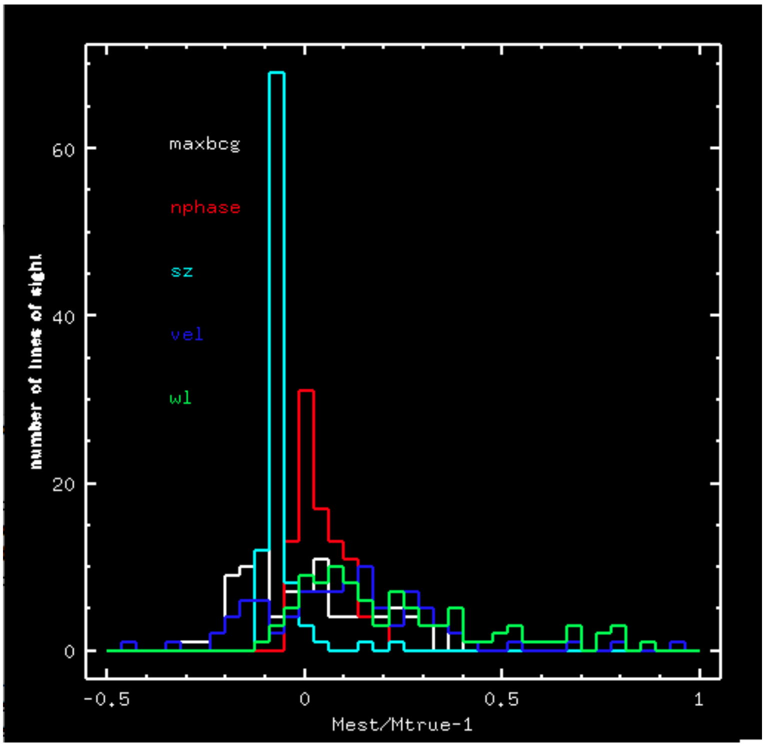
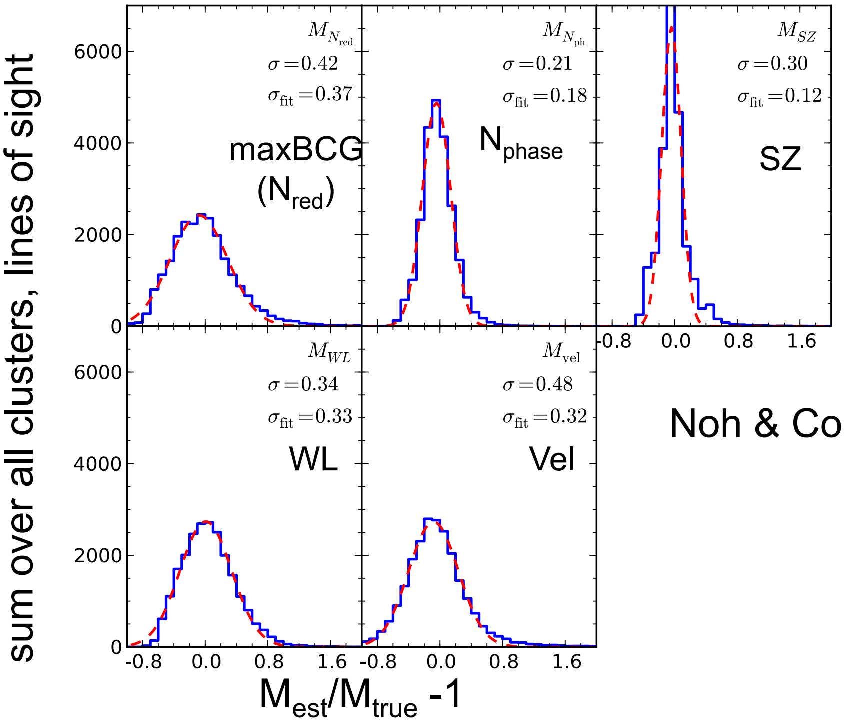


All 243 clusters, together: methods give ~large measured mass scatters



Noh & Cohn 12

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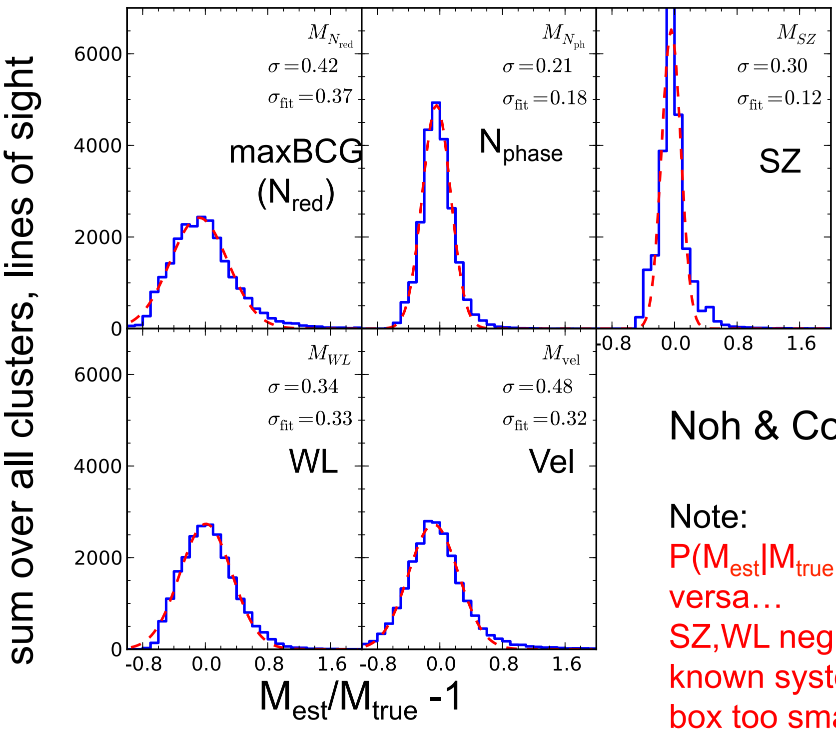
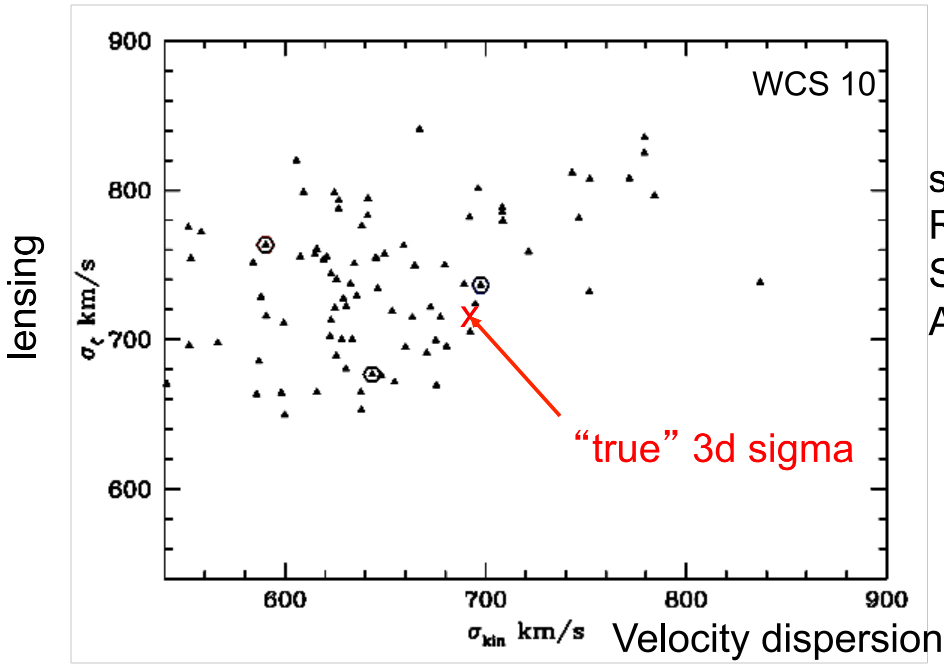


Noh & Cohn 12

Note:
$P(M_{est}|M_{true})$ not vice versa…
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



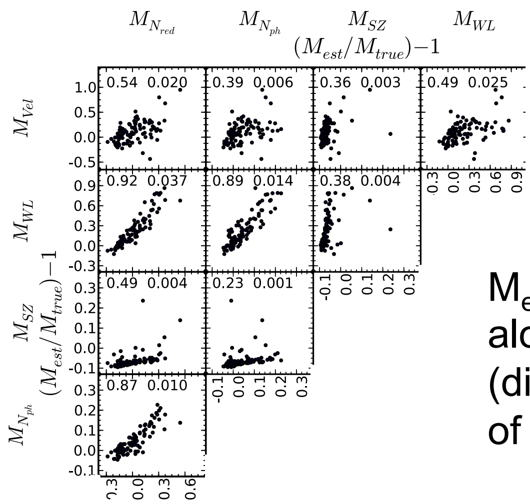
see also
Rykoff++08
Stanek++10
Angulo++12

(*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 [Rykoff++08, WCS10, Angulo++12, for intrinsic not los see Stanek++10, see Rozo++09 for inclusion]
- one recent place it caused problems:
  Planck clusters-richness, WL, SZ, Xray:
  interpret disagreement in terms of corrlns (Angulo++12)

Correlations for our one cluster:
All pairs of mass measurements



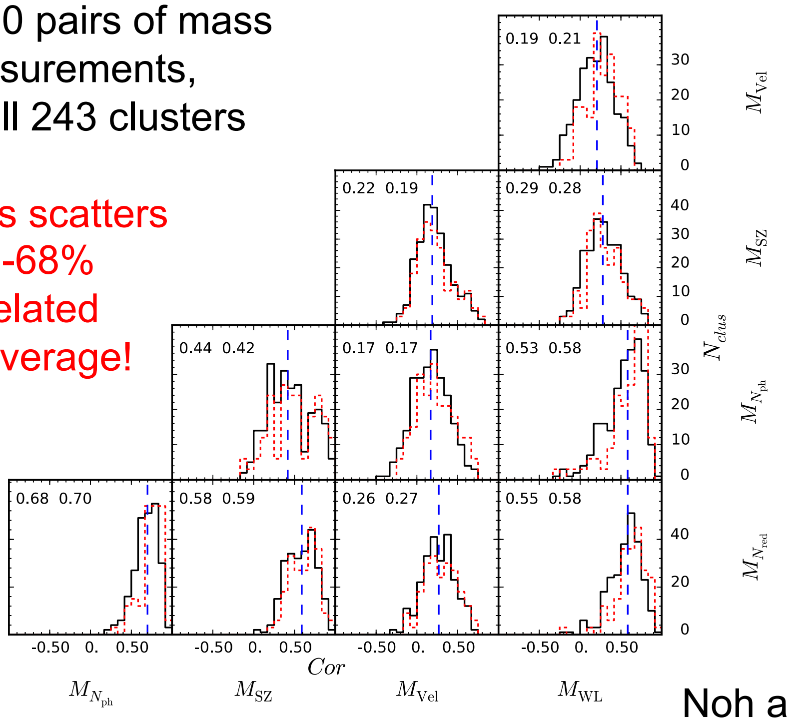
Noh & Cohn 12

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

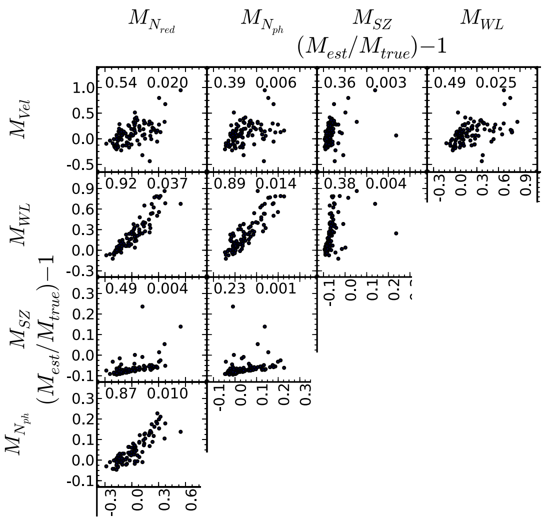
mass scatters
17%-68%
correlated
on average!



dashed
line at
median
value

red:
more
massive

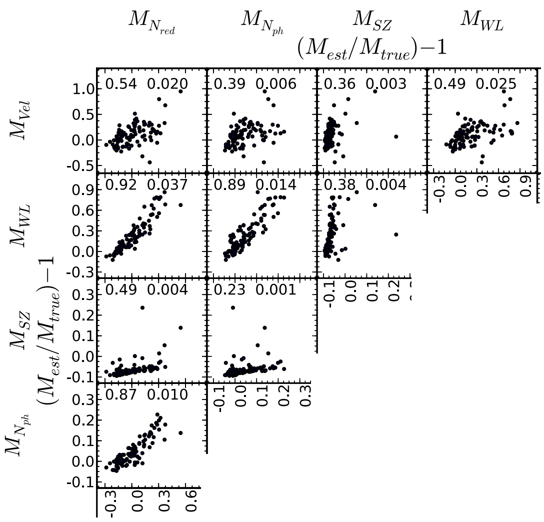
Noh and Cohn,
2012



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 combinations of measurements

This is what PCA (principal component analysis) does



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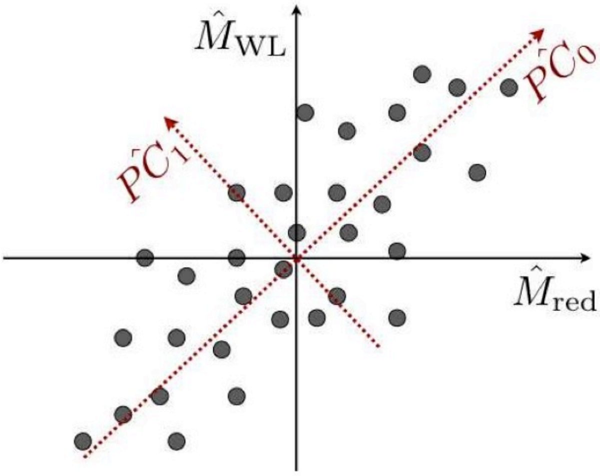
….start with example of 2 mass measurements

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



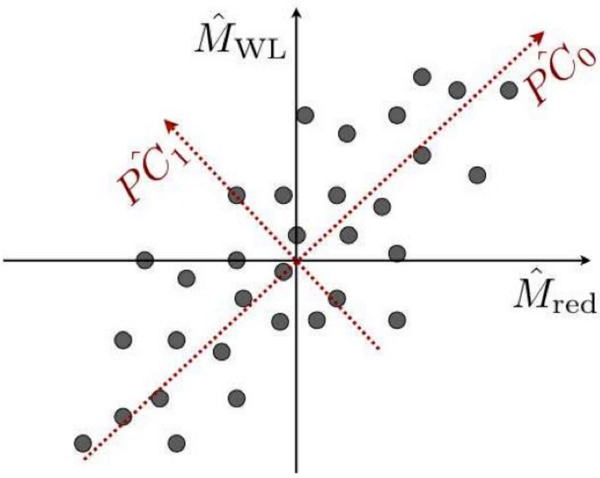
For 2 measurements:

- find new basis $P\hat{C}_0$, $P\hat{C}_1$ combinations of original measurements with zero covc
- characterize “shape” of scatter
- characterize trends, e.g. here 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,

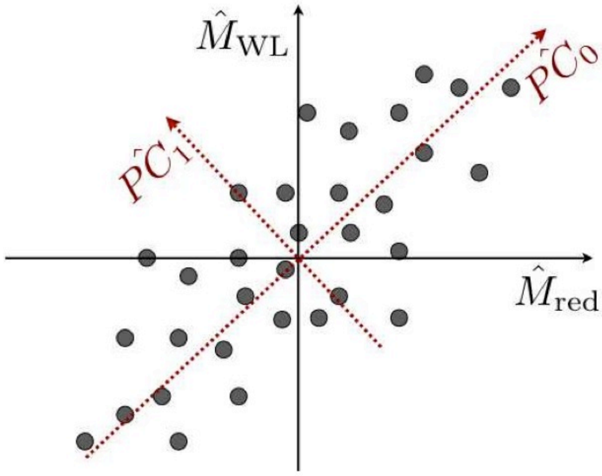
one comb of mass measurements has on average ~70% of los mass scatter variance

similar combination of mass scatters for many clusters

$P\hat{C}_{0,minsq}$ ~0.42 M_{red} + 0.14 M_{ph}+0.19 M_{SZ}+0.83 M_{vel}+0.29M_{wl}

(Mvel has largest variance on its own, as well)

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



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

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

Expect: yes
phys props of/around cluster can have effects on measured mass

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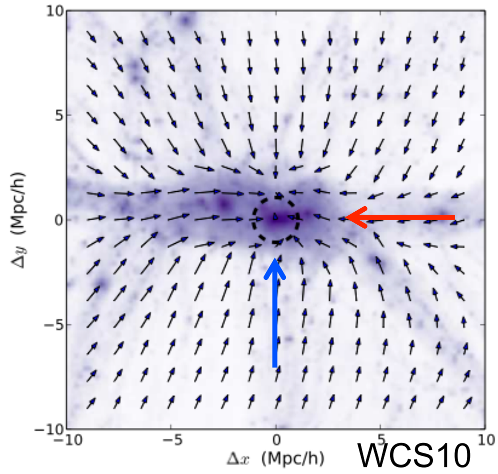
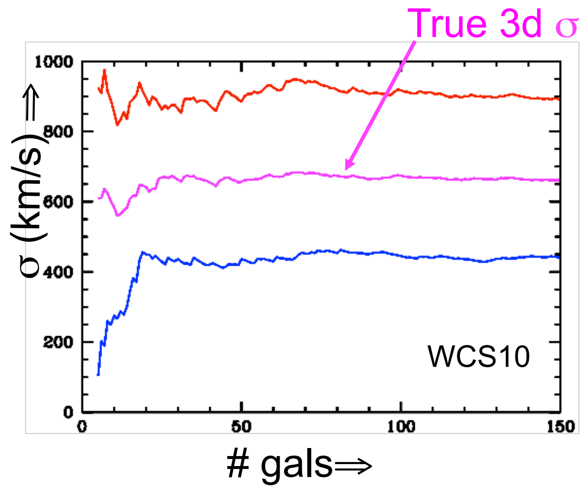


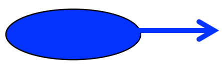


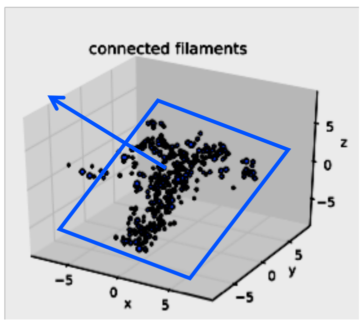
E.g., along cluster long axis one tends to observe higher velocity dispersions, ~same direction as filaments and largest substructures, expect to enhance WL, richness, SZ as well

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

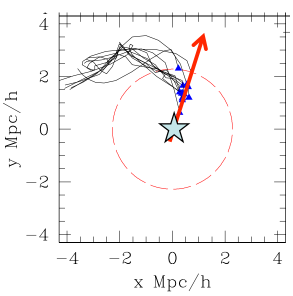
Cluster related directions

long axis of cluster





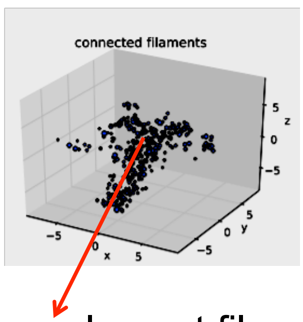
filament or mass plane around cluster



largest galaxy subgroup

(for this sim, studied Cohn 11)

(all of these are of course correlated too….)

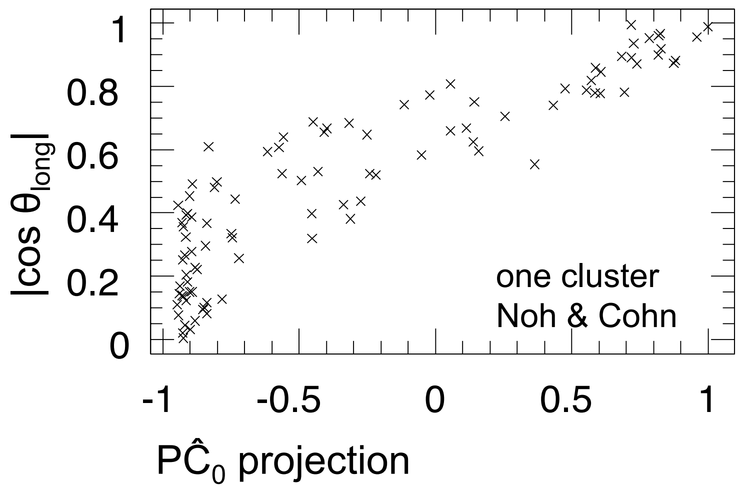


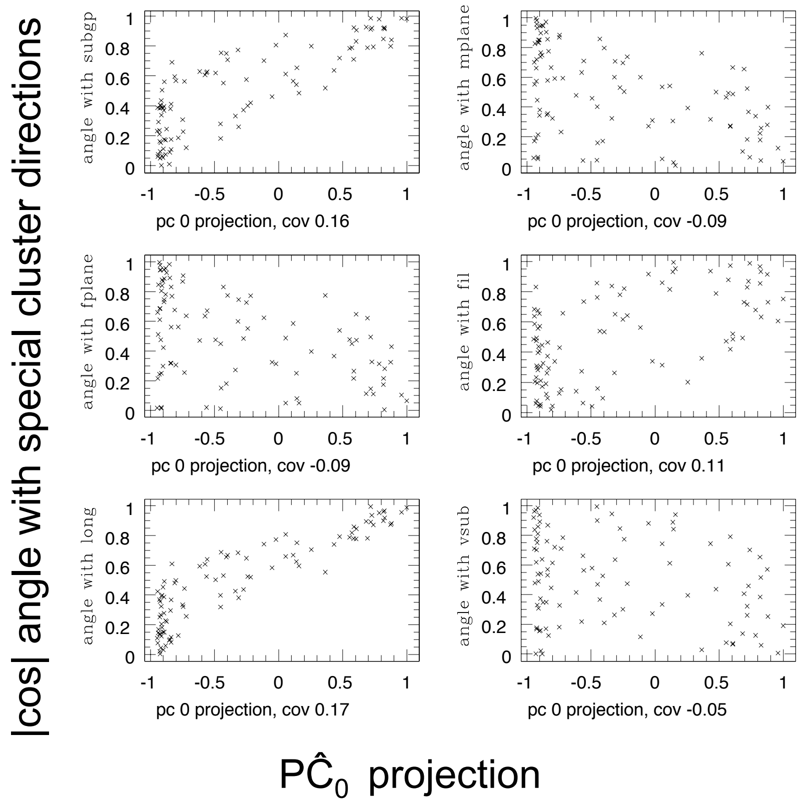
(for this sim, studied Noh & Cohn 11)

largest filament

Find:

Looking along long axis of cluster tends to gives points with "most" $P\hat{C}_0$, the dominant scatter combination





For same cluster, other correlations, for comparison

Noh & Cohn 12

Cluster to cluster correlated properties?

(PCA following Jeeson-Daniel++, Skibba & Maccio, Einasto++)

- Largest mass scatter often is (how?) large fraction of total
- Similar (how?) direction of largest PCA mass scatter
- Size of mass scatter along smallest direction?
- 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 $(l_1^2-l_2^2)/(l_1^2-l_3^2)$, sphericity l_3/l_1, ...

Do PCA on all of these!

But…no combinations strongly dominate full sample.

still--some trends:

↑ triaxiality, richness in largest subgroup

↓ sphericity, size of & average mass scatter when changing los, planarity of mass & filaments around cluster

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 cluster properties but no one dominant combination.

Other take-away points:

- Calibrating the scatters and their correlations requires simulations which faithfully reproduce observables, systematics and selection function
  - an issue for surveys generally and *much harder now* because data have gotten much more rich and precise: questions care more about "details"
- 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 ("into account"==model, simulate)

Possible interesting future application:

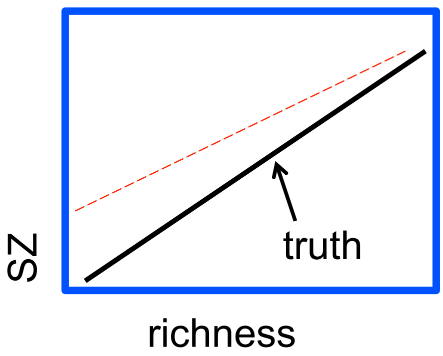
Get $M_{true}(M_{est})$ and do PCA--use relation of cluster mass measurements to each other to get cluster information besides mass, and to signal issues in particular measurements

?"reverse engineer" relation of mass measurements to each other

grazie

extra slides

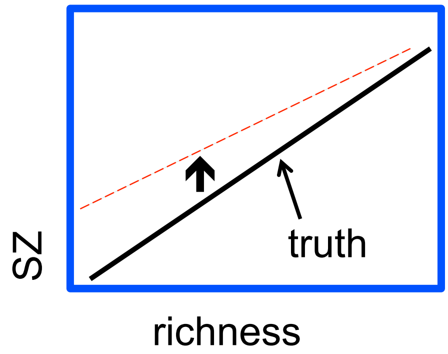
Want to compare SZ and richness masses (Angulo++12)



Say the true relation is
solid black line given at left.
Want a model for SZ(richness).

use: richness→WL mass→SZ

Want to compare SZ and richness masses (Angulo++12)



Say the true relation is
solid black line given at left.
Want a model for SZ(richness).

use: richness→WL mass→SZ

but WL mass↑ than measured because of miscentering,
so "fix"--raise WL mass, use "fixed" WL mass to get SZ
richness→WL mass→WL mass ↑→SZ

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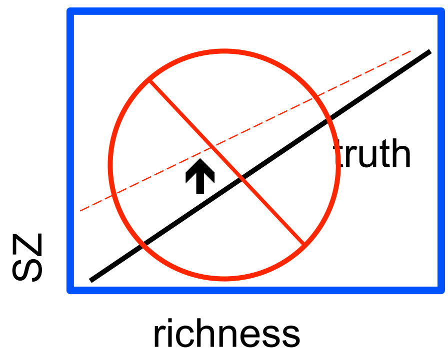

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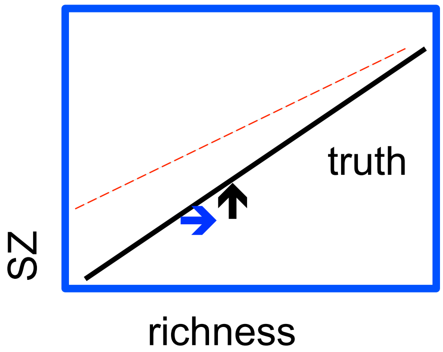
Problem! have neglected richness and WL correlations!!

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.

Want to compare SZ and richness masses (Angulo++12)



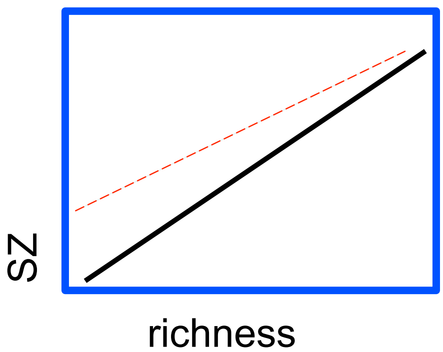
Say the true relation is solid black line given at left. Want a model for SZ(richness).

use: richness → WL mass → SZ

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

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

Want to compare SZ and richness masses (Angulo++12, cont.)



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

Another correlation ☹
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 limit to high SZ clusters and thus bias richness-SZ relation in same way as correction for WL miscentering!
see also work by Rozo, Evrard,Bartlett, Rykoff (3 papers) getting consistent scaling relations for multiwavelength sample; many other issues (e.g. X-ray measurements)