Cluster Cosmology: WFIRST + LSST (+SZ)

Anja von der Linden

Stony Brook University

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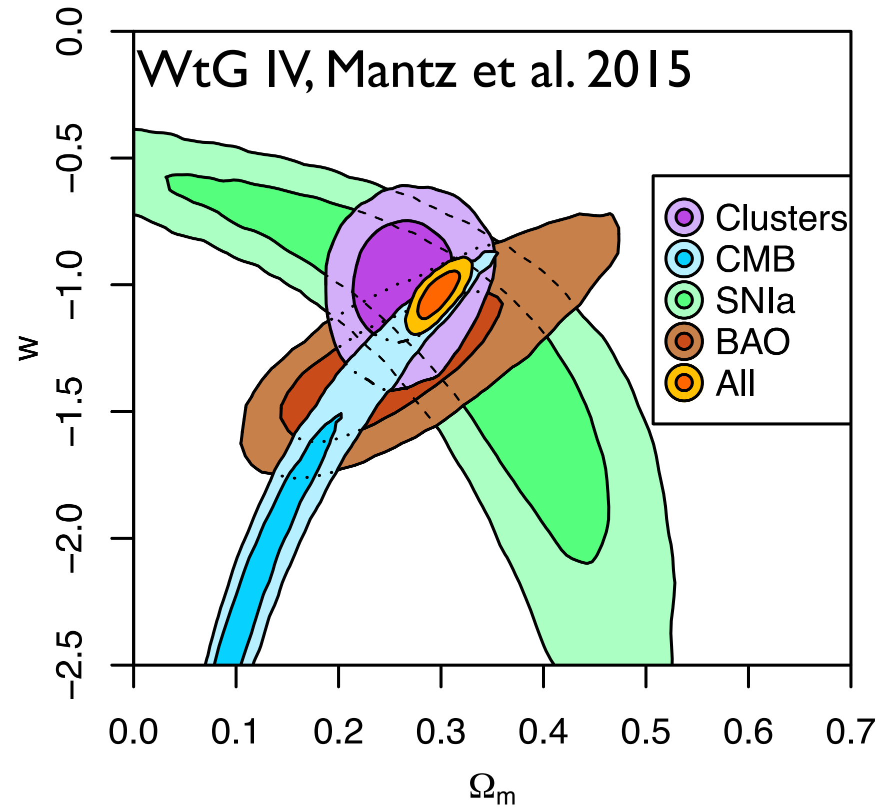
The Big Picture

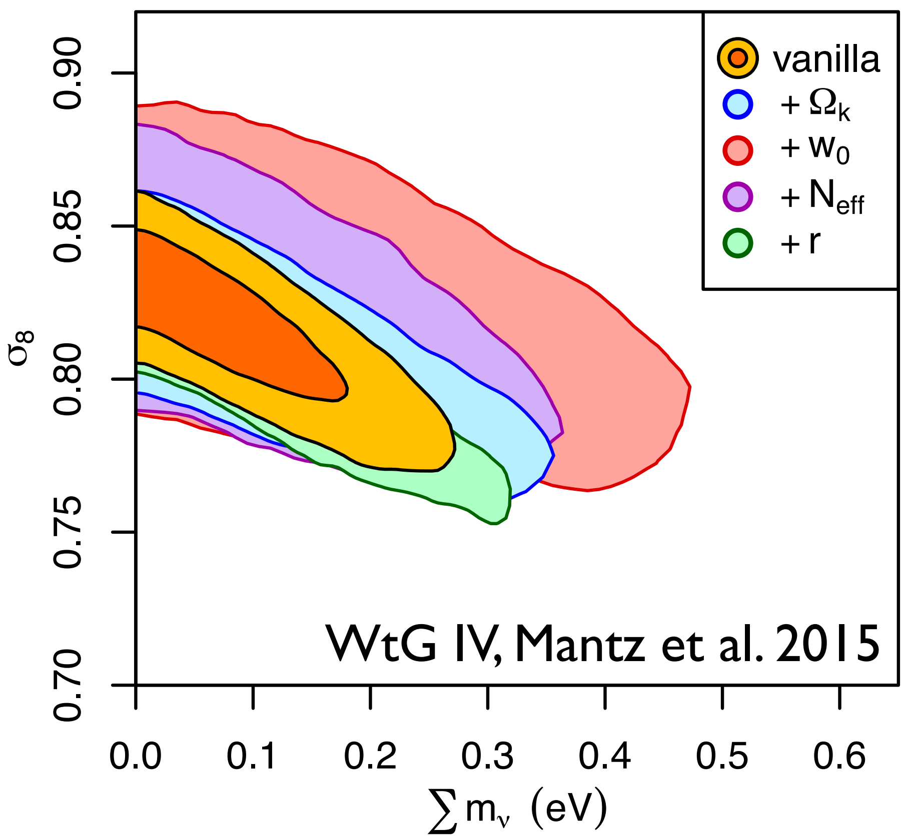
Cosmic Visions Report (2016): "The number of massive galaxy clusters could emerge as the most powerful cosmological probe *if the masses of the clusters can be accurately measured.*"

- Cluster weak-lensing is the most promising observational method to calibrate cluster masses.
- LSST's weak-lensing and photo-z capabilities will yield a precise and accurate cluster mass calibration to at least $z_{cluster} \lesssim 0.8$ (note: DES and HSC already detect cluster lensing signals at higher redshifts)
- WFIRST: better shape + photo-z estimates allow high-quality mass calibration to higher redshifts → esp. important for dark energy

State of the Art

Weighing the Giants IV alone places 15% constraint on *w*; one of the tightest single-probe constraints today





competitive constraints also on neutrino masses - nearly independent of cosmological model

+ modified gravity, evolving w, ...

State of the Art

Weighing the Giants based on

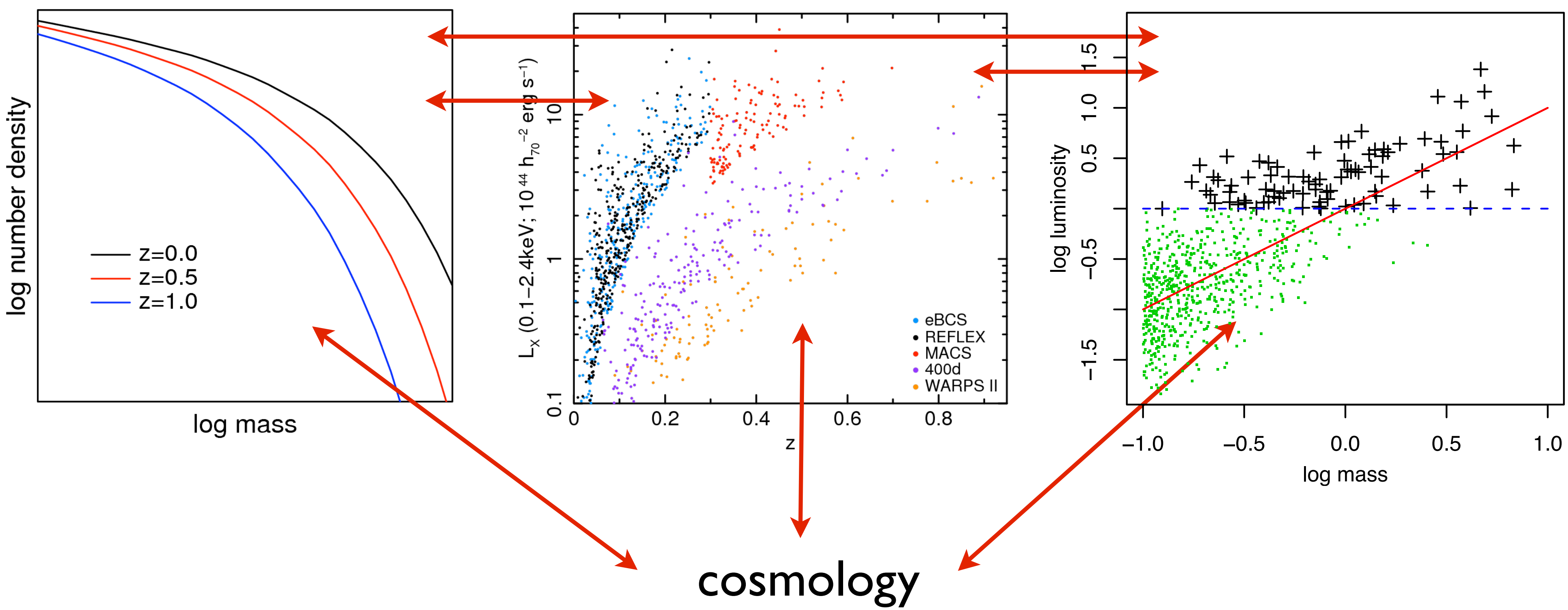
- only(!) ~200 X-ray-selected (ROSAT) clusters at $z<0.5$,
- 50 with weak-lensing masses,
- 90 with *Chandra* imaging
- generous marginalization over systematic uncertainties

competitive constraints also from optical and SZ cluster surveys; DES constraints coming next year

~next decade: 100 000s of clusters, multiple selection methods (optical, SZ, X-ray), to $z\sim2$ → tremendous statistical power

Ingredients for cluster counts cosmology

1. prediction for halo mass function
2. cluster survey (X-rays, SZ, optical) with well understood selection function
3. relation between survey observable and cluster mass
4. self-consistent statistical framework

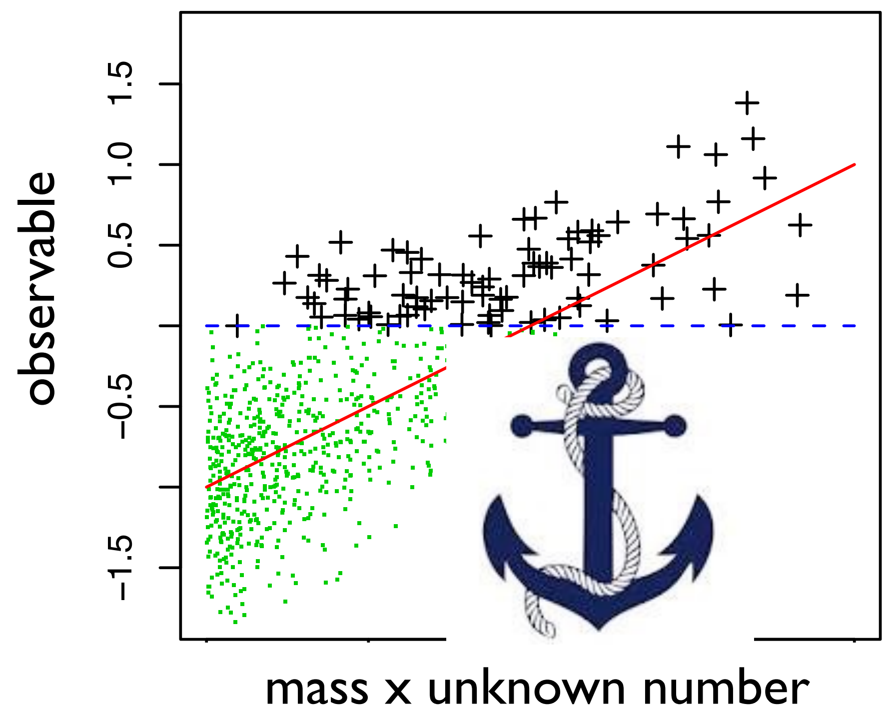


Mass proxies: Precision vs. Accuracy

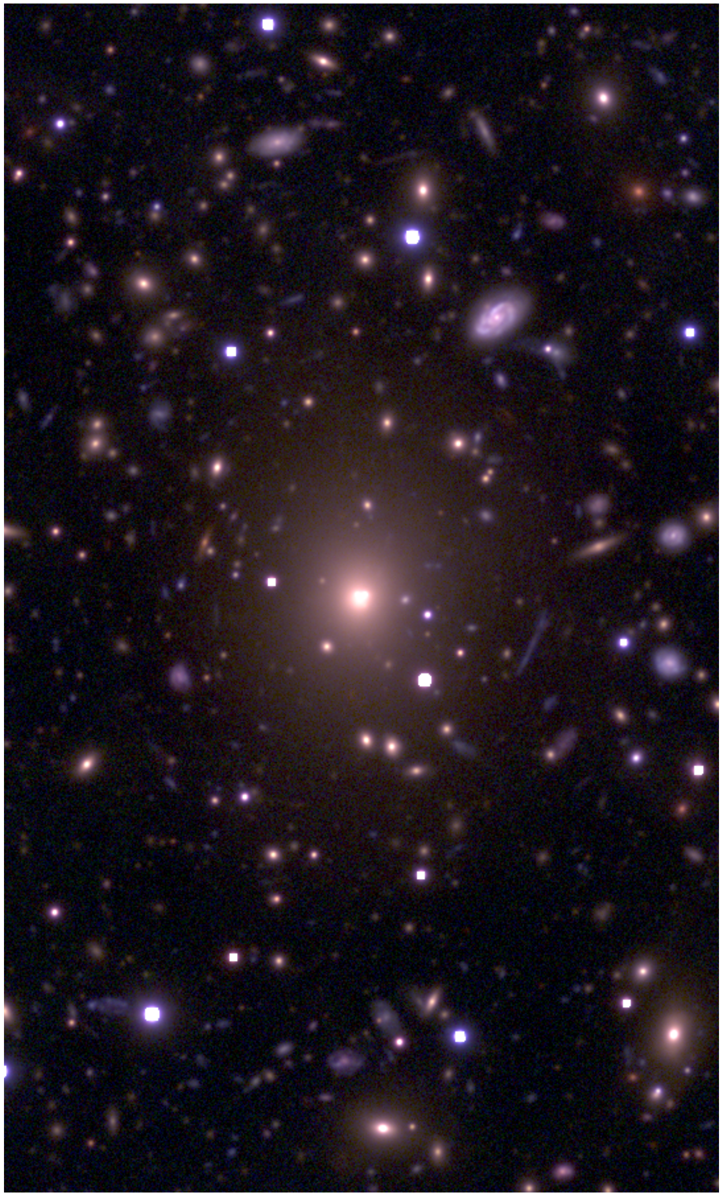
- survey observables (X-ray luminosity, SZ decrement, optical richness) do not measure cluster mass directly
  - correlate with mass, but with considerable scatter, (30-40)%
- follow-up (X-ray) observations can provide a number of *precise* low-scatter (≲10%) mass proxies:
  - ICM temperature T_X; gas mass M_{gas}; $Y_X = M_{gas} \times T_X$
  - *essential for measuring shape and scatter of M-O relation*
  - do *not* provide absolute mass calibration

absolute masses?

- X-ray hydrostatic masses
  ⚡ non-thermal bias, T_X calibration
- galaxy dynamics
  ⚡ large scatter and bias
- weak lensing
  + small bias: accurate
  - scatter ~30%



Calibration by cluster weak lensing



- there are multiple methods of finding clusters (see later)
- cosmological constraining power will depend on precision of weak-lensing mass calibration
- limited by how well we can control systematic uncertainties
- LSST+WFIRST will yield the best cluster WL constraints by a significant margin

Ingredients for cluster mass measurements

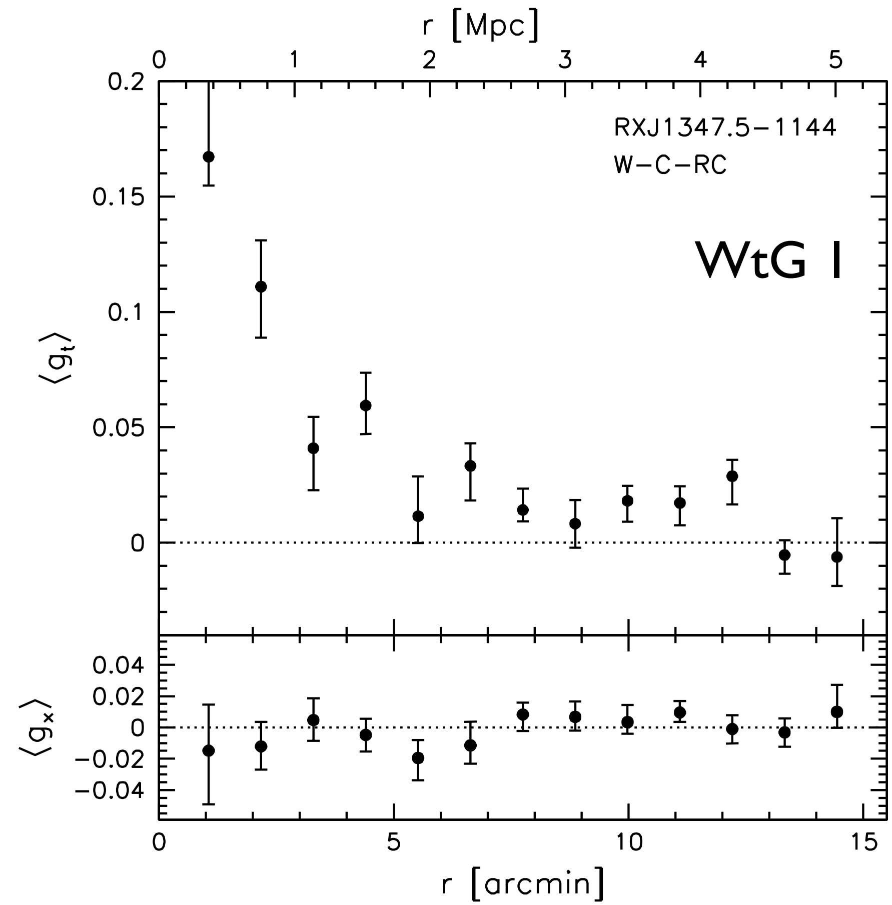
Shear induced on background galaxy depends on:

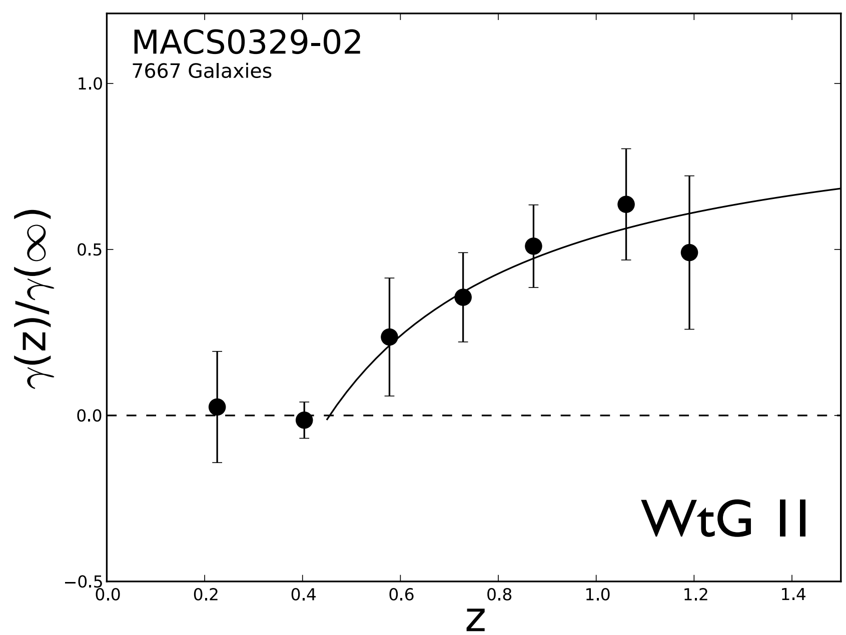
- cluster mass (distribution)
- redshift

To measure cluster mass, need

1. reduced shear measurements
2. (some) assumption on mass distribution
3. redshifts / redshift distribution

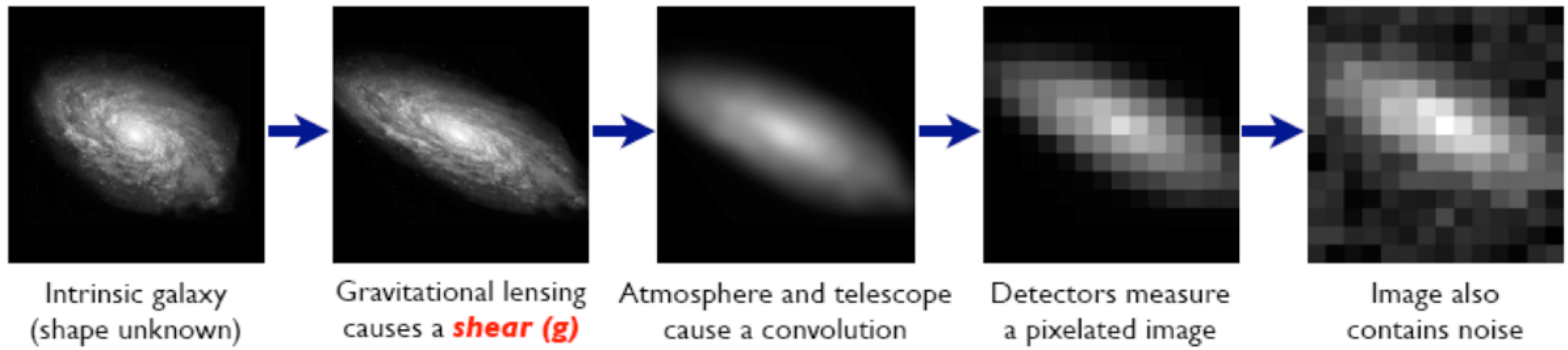
... and need to understand the systematics of each!





(1) Shear measurements

- bias in shear estimates → bias in cluster mass estimate



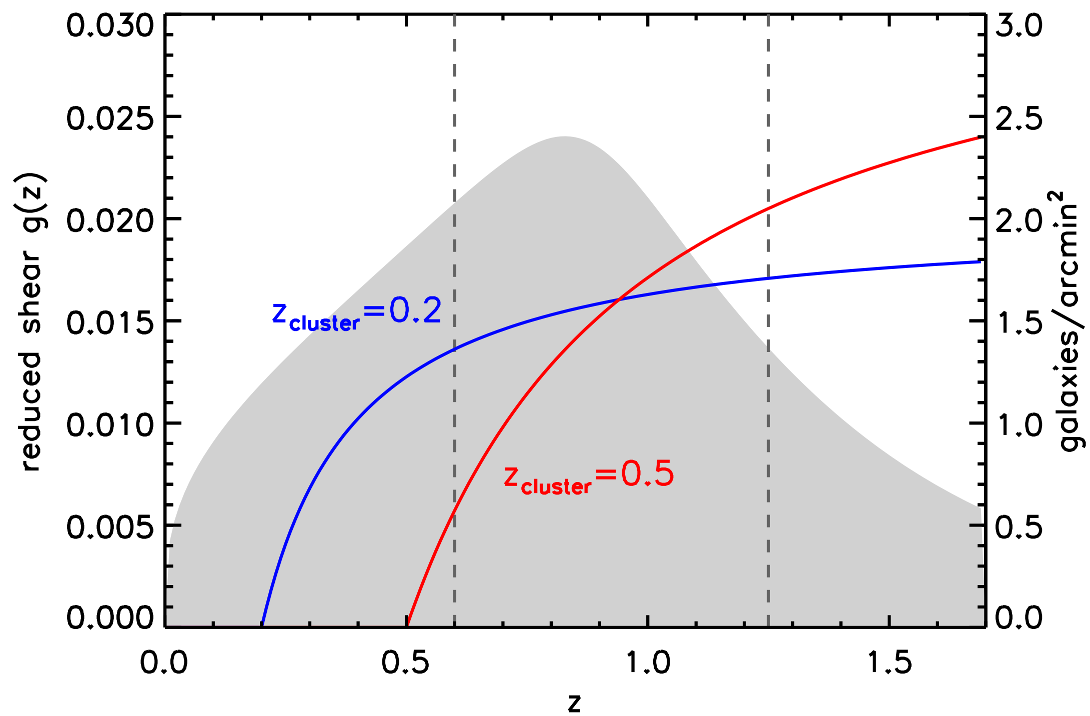
- cluster-specific issues:
  - shear in clusters is larger
  - dense fields: deblending, background subtraction
  + need to calibrate to (only) ~1%, cf. ~10^{-4} for cosmic shear

→ *significant improvements with WFIRST imaging to ~LSST depth*

DESC Clusters Key Project: image simulations (ARCLETS) specifically for cluster fields to quantify shear bias

(2) Shear - redshift scaling

- shear on background galaxy depends on redshift
- shear(z) is a steep function right behind the cluster, then flattens out → error in mass from photo-z's depends on cluster redshift



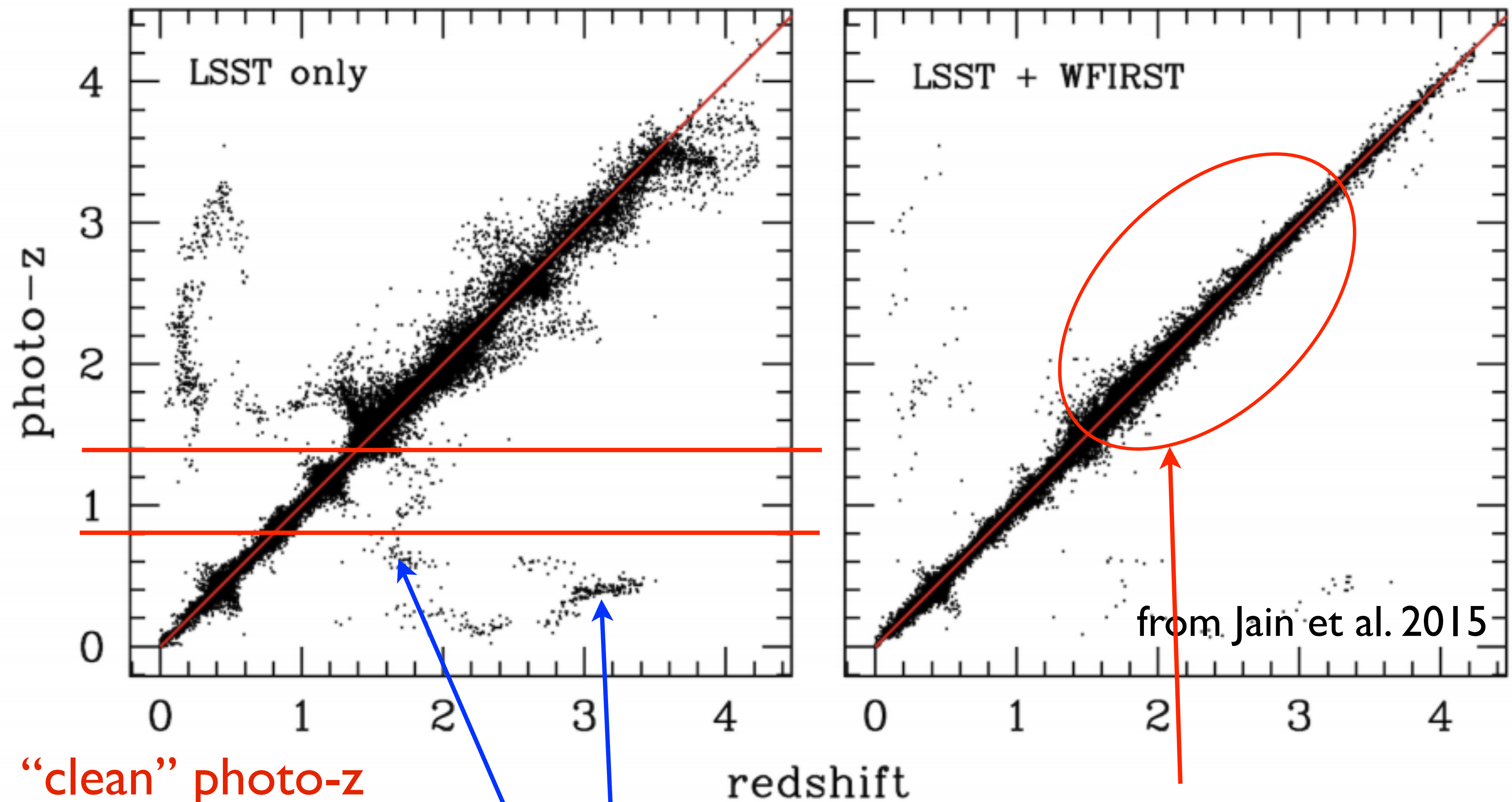
- limitations of ground-based lensing / photo-z's:
- redshift distribution of resolved galaxies peaks at z~0.8 (though deeper data adds high-z tails)
- "good" photo-z's require coverage of 4000Å break; z ≲ 1.4 with LSST's y-band

(2) Photo-z's

- cluster-specific concern: dilution by cluster members
- cluster galaxies not sheared
- (and no empirical evidence for intrinsic alignments, e.g. Sifon et al. 2015)
- any contamination of lensing sample causes mass underestimate

- if cluster galaxies are "simple", then this can be tuned with adjusting photo-z priors (add peak at cluster redshift); probably ok at low-z ($z<0.8$)
- *what are the properties of cluster galaxies at z>1 ?* At WFIRST / LSST depth? In "typical" clusters?
- LSST DESC Clusters WG: efforts to obtain deep multi-object spectroscopy of cluster fields (NOT red-sequence galaxies); would benefit significantly from joint efforts with WFIRST / Euclid
- WFIRST spectroscopy: high-purity lensing galaxy sample

(2) Photo-z's



"clean" photo-z region for LSST for z~0.7 cluster

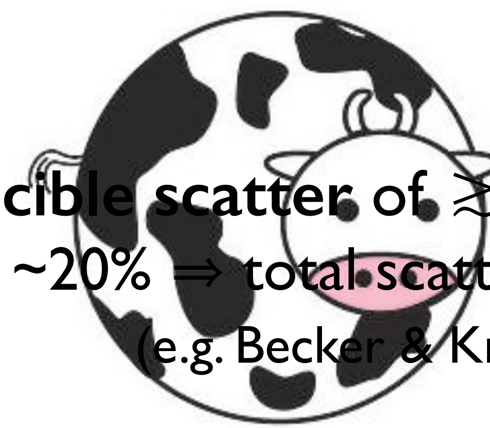
dilution problem?

can gain a lot of high-z background galaxies!

(3) Mass model

- *lensing sensitive to all mass along line-of-sight*
  - measures projected 2D masses
  - for relation to halo mass function, need to infer 3D mass
- galaxies are intrinsically elliptical → weak lensing is noisy
- *can typically measure only one parameter reliably*
- *fit spherically symmetric profile* (also breaks mass-sheet degeneracy)
- inferred (3D) mass depends on cluster triaxiality / orientation / substructure, structure along LOS

e.g. Meneghetti et al. 2010, Hoekstra 2003, 2011

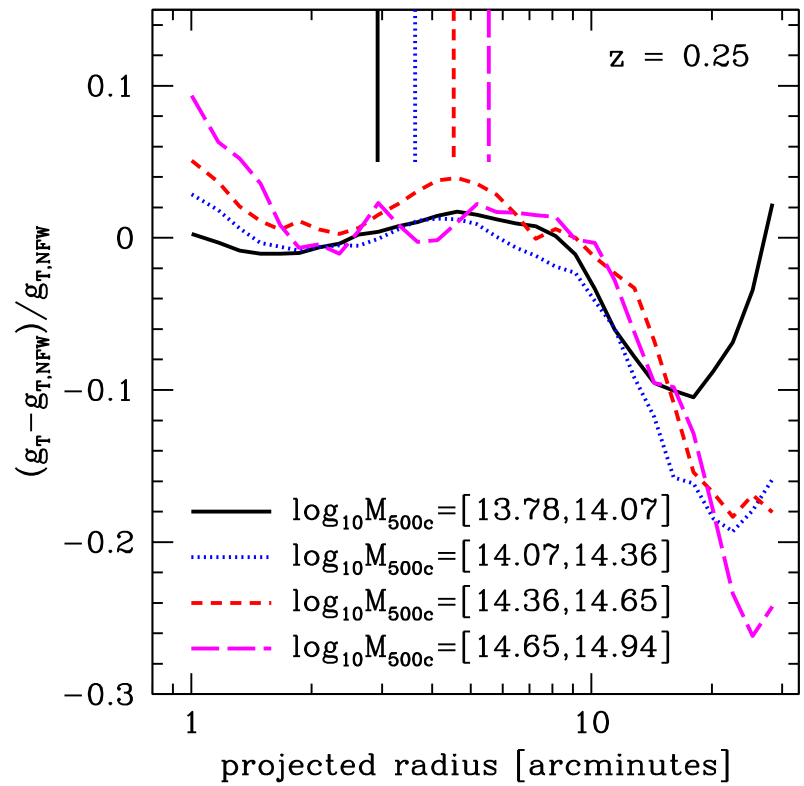


- (3D) lensing masses have **intrinsic/irreducible scatter** of $\gtrsim$ 20% (ground-based: scatter from shape noise also ~20% ⇒ total scatter: ~30%)

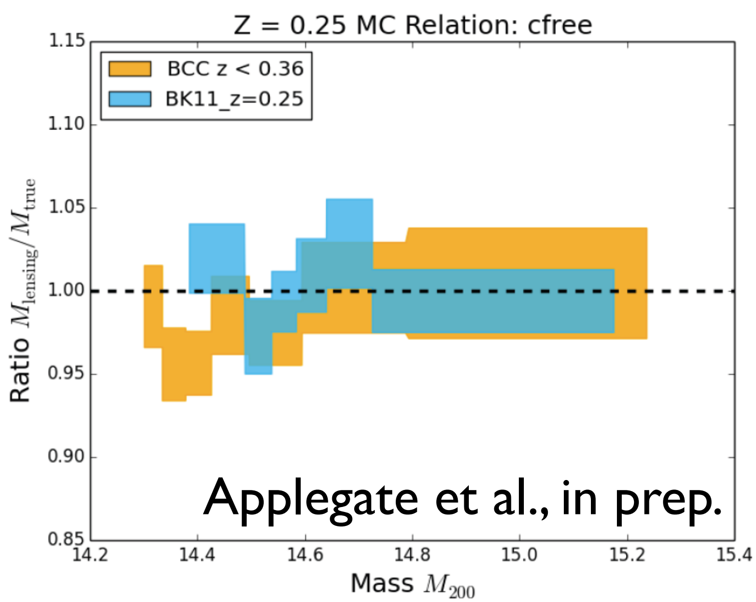
(e.g. Becker & Kravtsov 2011)

Is the *average* lensing mass ~~(un-)biased~~ calibratable?

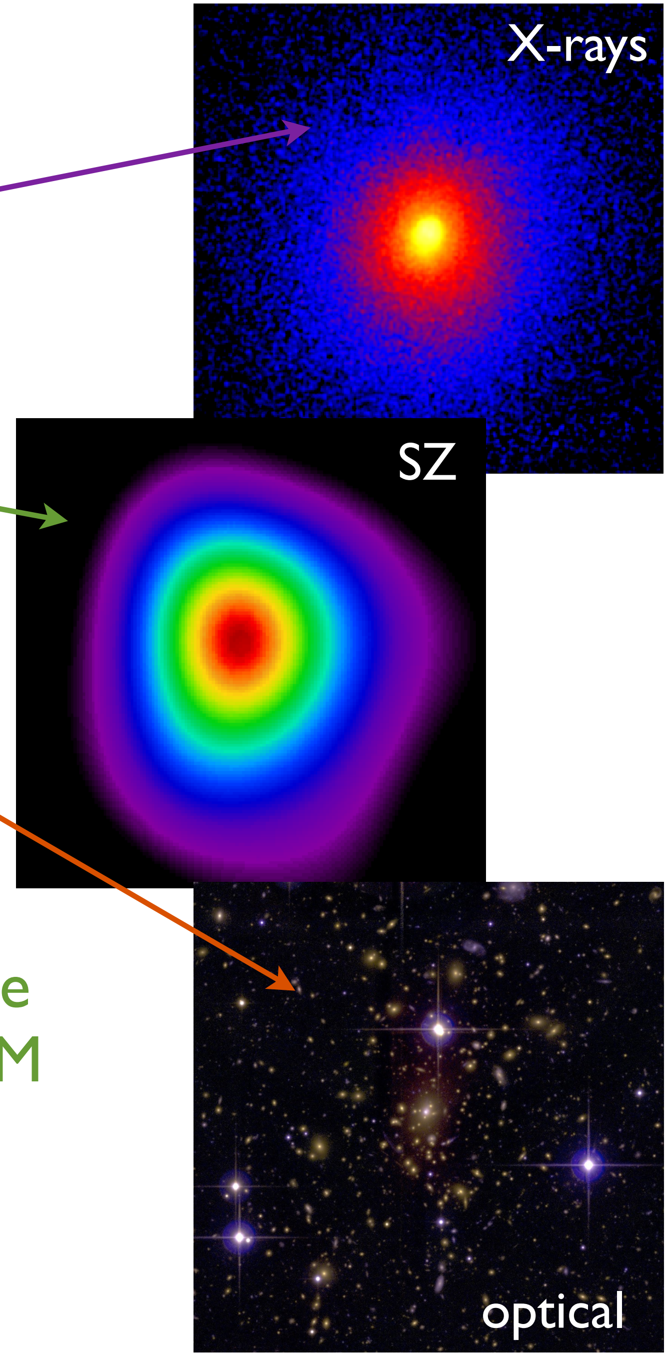
- methodology can be well tested on N-body (+hydro) simulations
- need to quantify mass bias as function of mass, radius, redshift, fitting method, miscentering, cosmology, ...
- significant efforts underway within LSST DESC; machinery will be available to extend to WFIRST



Becker & Kravtsov 2011



(0) Finding clusters



- X-rays: thermal bremsstrahlung from Intra-Cluster Medium (ICM)
- millimeter: Sunyaev-Zeldovich effect - inverse Compton scattering of CMB photons on ICM
- optical: galaxy population - overdensity of (red) galaxies

(0) Finding clusters

optical / NIR

✓ highest completeness, to relatively low masses

- subject to projection effects
- red sequence finding works very well at $z \lesssim 1$, but RS not well populated at higher redshifts

X-rays:

✓ in principle, very high purity and completeness (every extended extragalactic source is a cluster)

- in practice: limited angular resolution leads to impurity / incompleteness due to AGN confusion
- large scatter Lx - mass of ~40%

SZ

✓ nearly redshift-independent mass selection threshold

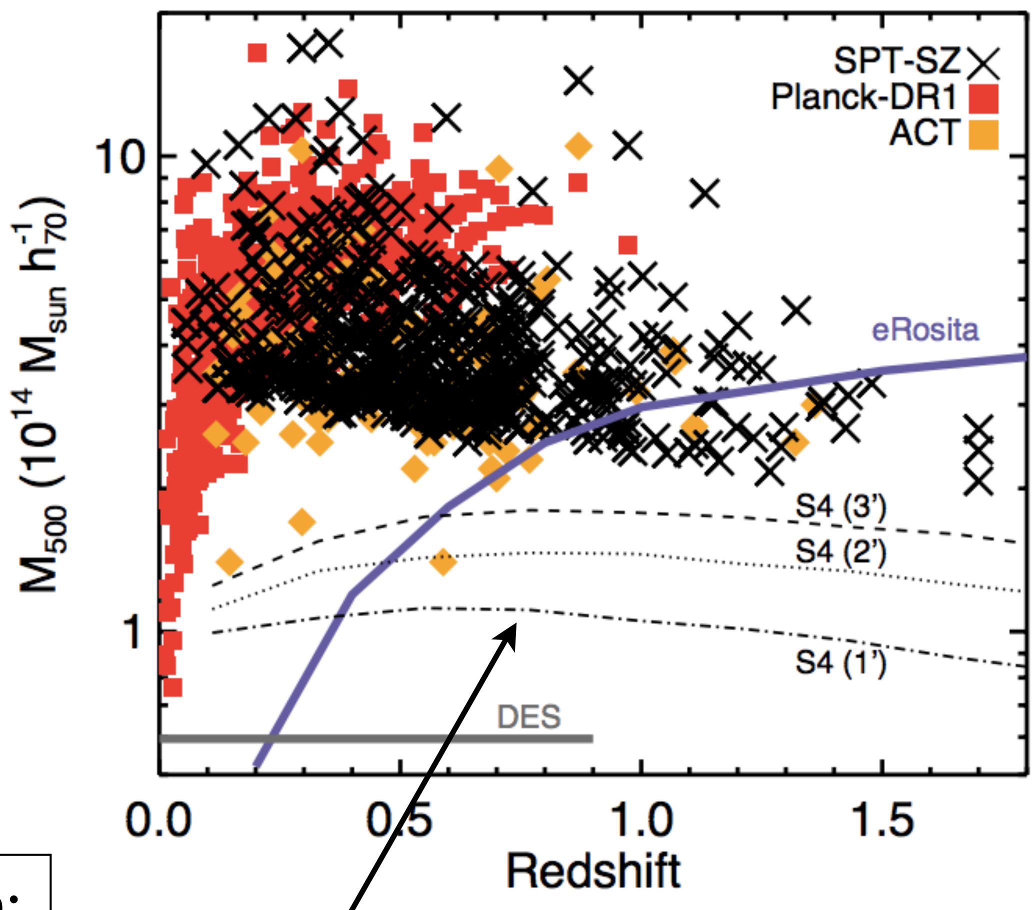
✓ high purity and completeness

✓ relatively small scatter in SZ signal - mass of ~20%

CMB - Stage 4

current proposal by CMB groups

- full-sky (or half-sky)
- low-noise
- main driver: inflation
- could be a fantastic cluster finder (some dependence on resolution)
- 2020-2025



WFIRST goal for cluster detection: $>10^{14} M_\odot$

same as CMB-S4 with 1' resolution, 1 μK-arcmin

thin lines: CMB-S4 mass thresholds (50% completeness) for 3', 2', 1' resolution

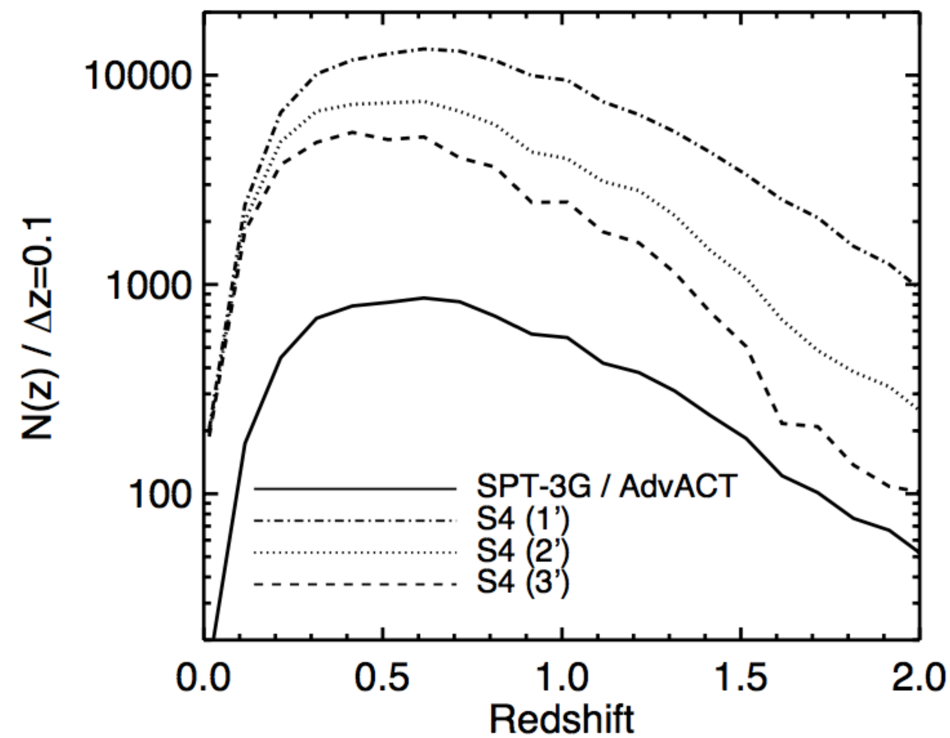
noise: 1 μK-arcmin

Impact of Angular Resolution

SZ mass sensitivity limited by noise + angular resolution

increased angular resolution especially important for:

- cluster finding at z>1
- CMB cluster lensing (mass calibration)



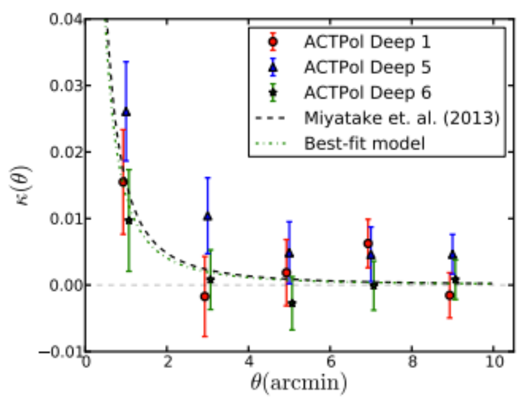
exactly the regime where things become difficult even for WFIRST +LSST:

- cannot rely on red sequence for cluster finding
- have to rely on high-redshift source galaxies for weak lensing

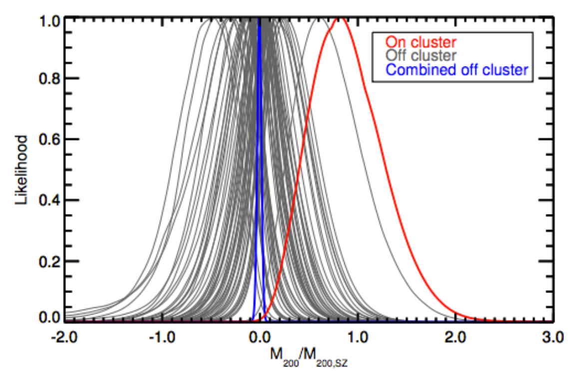
CMB Cluster Lensing Overview

- To date, most cross-correlations between CMB lensing and tracers of the matter density field probe *two-halo regime*
- Recently, CMB lensing in the *one halo* regime has been measured

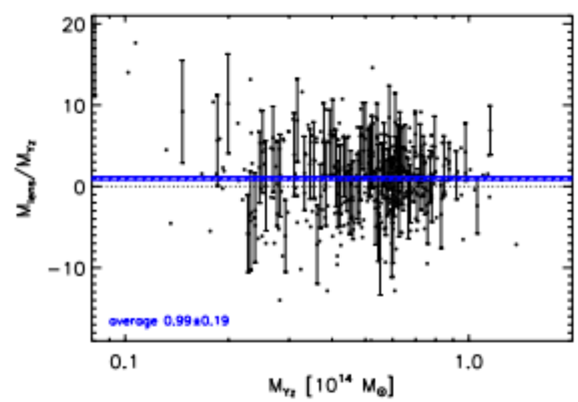
CMASS galaxies (Madhavacheril et al. 2015)



SPT-SZ clusters
(Baxter et al. 2015)



Planck clusters (Planck XXIV 2015)

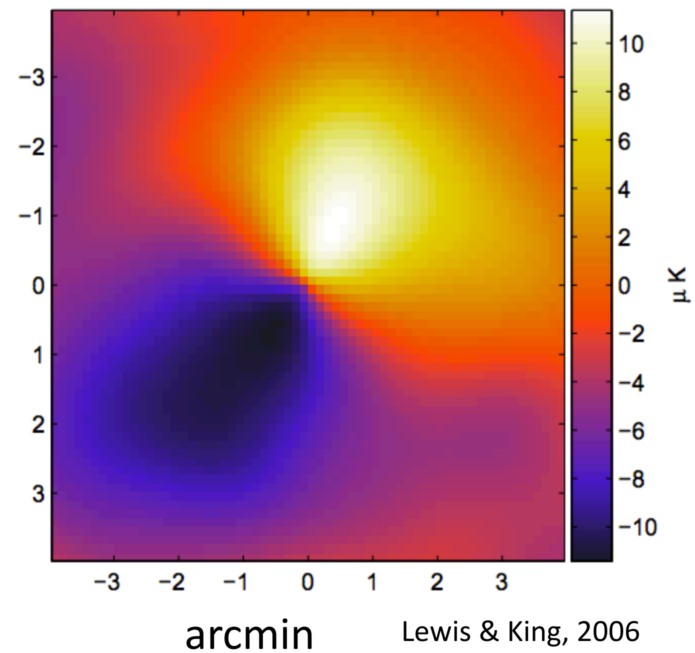


Possibilities & Challenges
with CMB Cluster Lensing

Potentially powerful

- Study cluster masses at high z
  - Galaxy lensing at high-z is difficult because high-z source galaxies are faint and hard to measure
- When combined with galaxy lensing…
  - Test for systematics in other weak lensing measurements
  - Constrain cosmology using distance ratios when combine with galaxy weak lensing (Hu, Holz, Vale 2007)

10^{15} $M_{\odot}$/h cluster at z = 1



Lewis & King, 2006

Challenges

- Small scales ➔ beam is a problem
- Potential biases due to e.g. tSZ and kSZ

Results on Simulations

Mock clusters

NFW profile

M_{200} = 3e14 M_{sun}

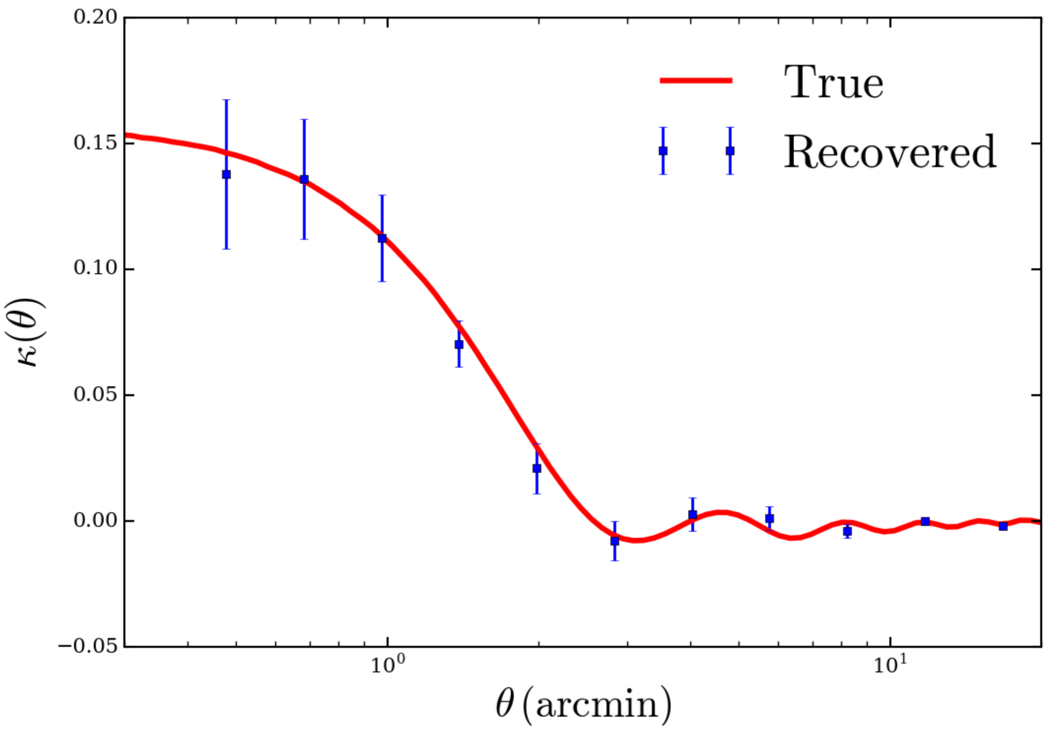
z = 0.7

c = 3

N = 5000

Mock CMB maps

Realistic fields, noise, beam, transfer function, foregrounds



E. Baxter

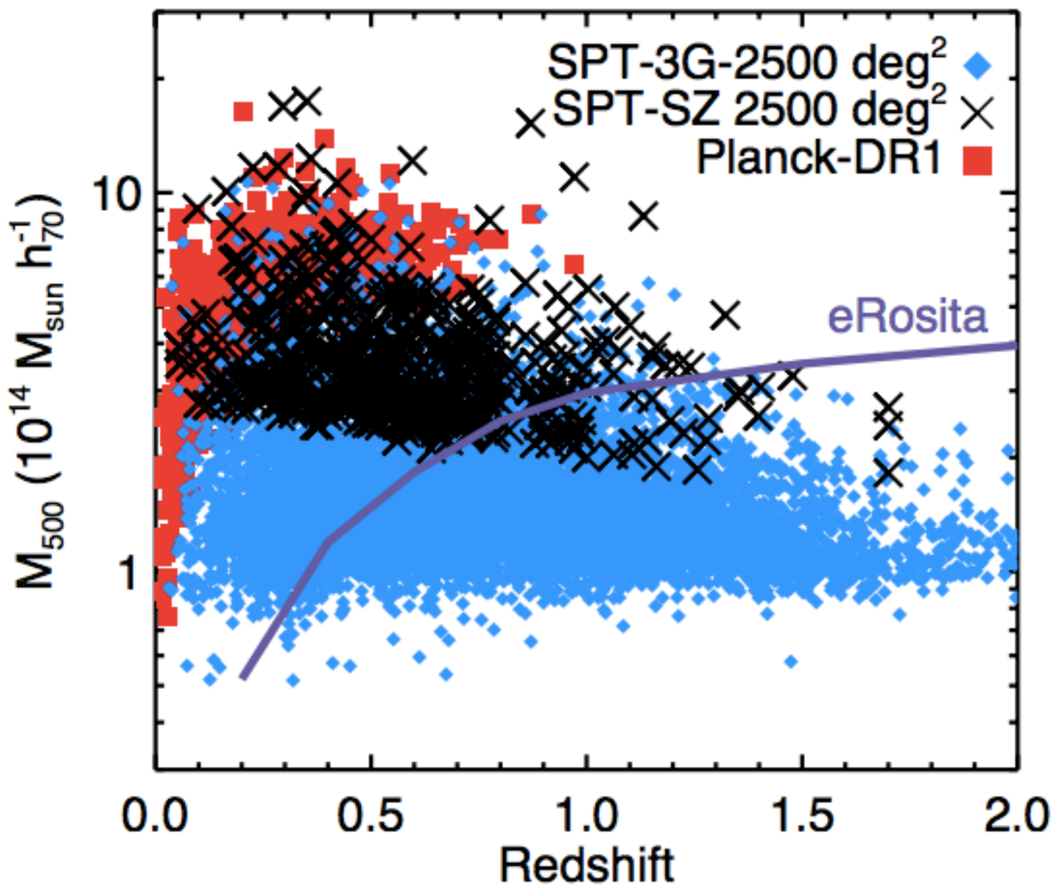
CMB - Stage 4

details still to be decided

possible scenario: incorporate existing telescopes: SPT 10-m, ACT 6-m, Simons Observatory 6-m

existing facilities already provide ~1' resolution

good for clusters!



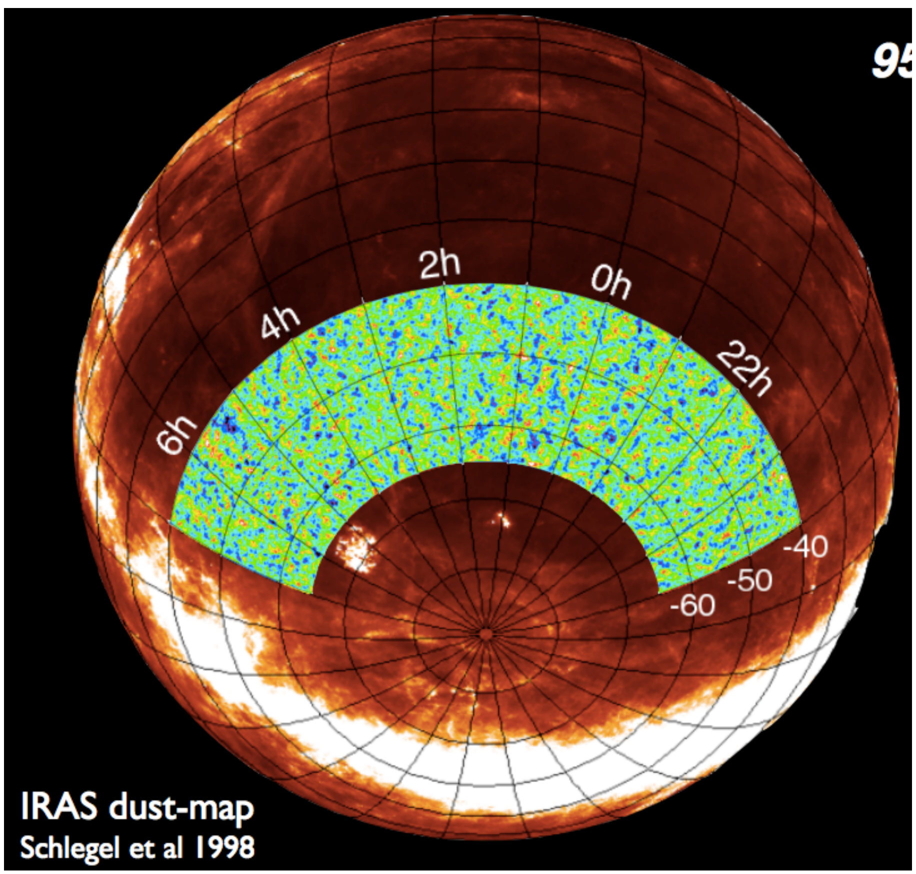
in particular, SPT-3G survey very similar to CMB-S4 goals:

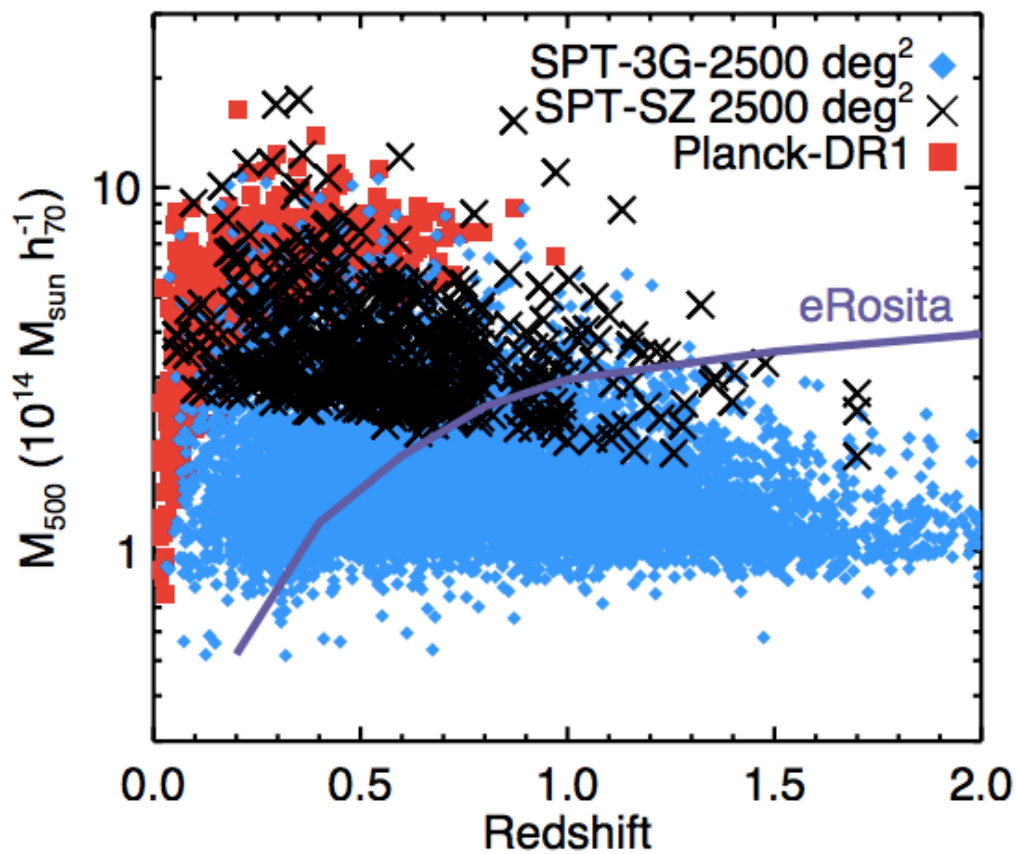
1' resolution; 2 μK-arcmin noise level (cf. 1 μK-arcmin for CMB-S4)

SPT-3G

2500 □° survey, entirely within LSST (and DES) footprint

2016-2019



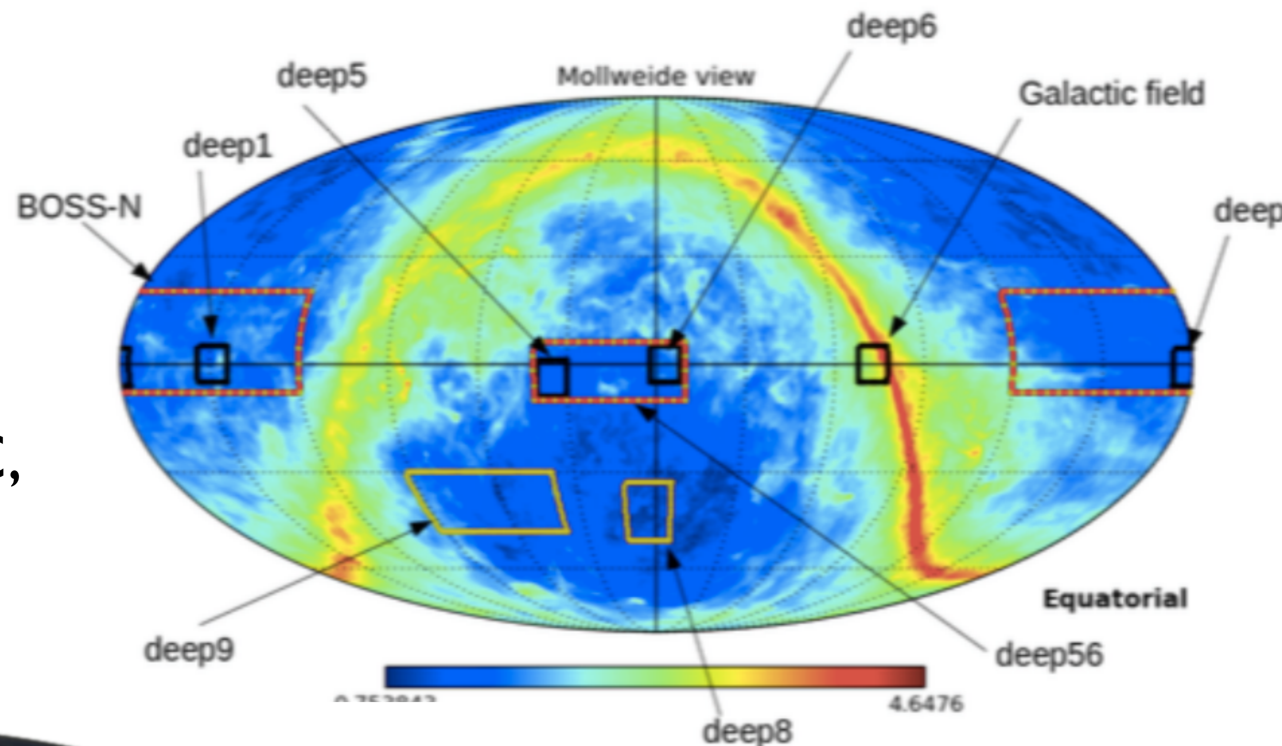


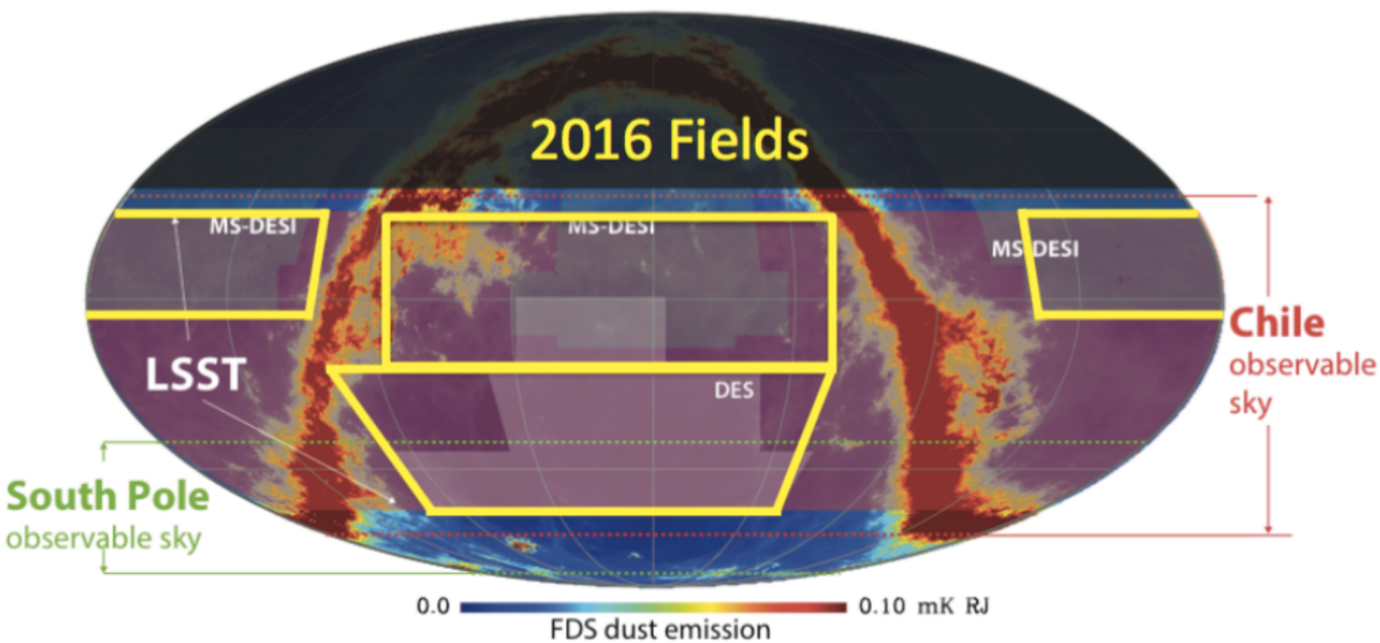
within SPT-3G footprint, we will already know large fraction of clusters with >$10^{14} M_\odot$ by 2020

ACTpol and Advanced ACT

larger-area surveys, ~1.5’ resolution, higher noise level

ACTpol: overlap with HSC, ~15 μK-arcmin (similar to SPT-SZ), completed





AdvACT: ~half-sky, ~10 μK-arcmin, overlap with DESI + DES

Synergy SZ - WFIRST+LSST

1. use SZ as cluster finder (and mass proxy)
2. use WFIRST+LSST for confirmation + redshift determination (and secondary mass proxy)
3. use WFIRST+LSST to identify additional (lower-mass) clusters; verify through SZ stacking
4. two avenues for mass calibration:
   - galaxy-based shear from WFIRST+LSST
   - CMB-cluster lensing (especially useful for high-z; only a stacked measurement)
   - some joint systematics (e.g. miscentering), some independent systematics (photo-z's)
   - systematics for both are difficult to control at required precision → great cross-check
5. inform all-sky surveys (LSST+Euclid+AdvACT)

In practice

CMB-S4 will be "most-sky"; should we just wait for it?

- Not necessarily: the final design might be lower angular resolution than current instruments → significant impact on both cluster finding and CMB cluster lensing

Advantages to considering overlap with current surveys: can utilize follow-up data gathered for SPT and ACT clusters

- X-ray imaging (low-scatter mass proxies! very expensive for high-redshift clusters)
- multi-object spectroscopy
- Spitzer follow-up

Ideal Case for Clusters

complete overlap between SPT-3G and WFIRST HLS footprints (both are ~2500 □°); or at least complete coverage of overlap region between SPT-3G and AdvACT

+ pointed observations of the most massive ACT clusters with LSST or HSC coverage (rare in SPT field)

this would:

- ensure good coverage over wide mass range (from $10^{14}\,M_\odot$ to the rarest, most massive clusters)
- be highly informative for all cluster surveys (including both LSST's and WFIRST's cluster finders), and LSST +Euclid
- yield highly competitive cosmology constraints!

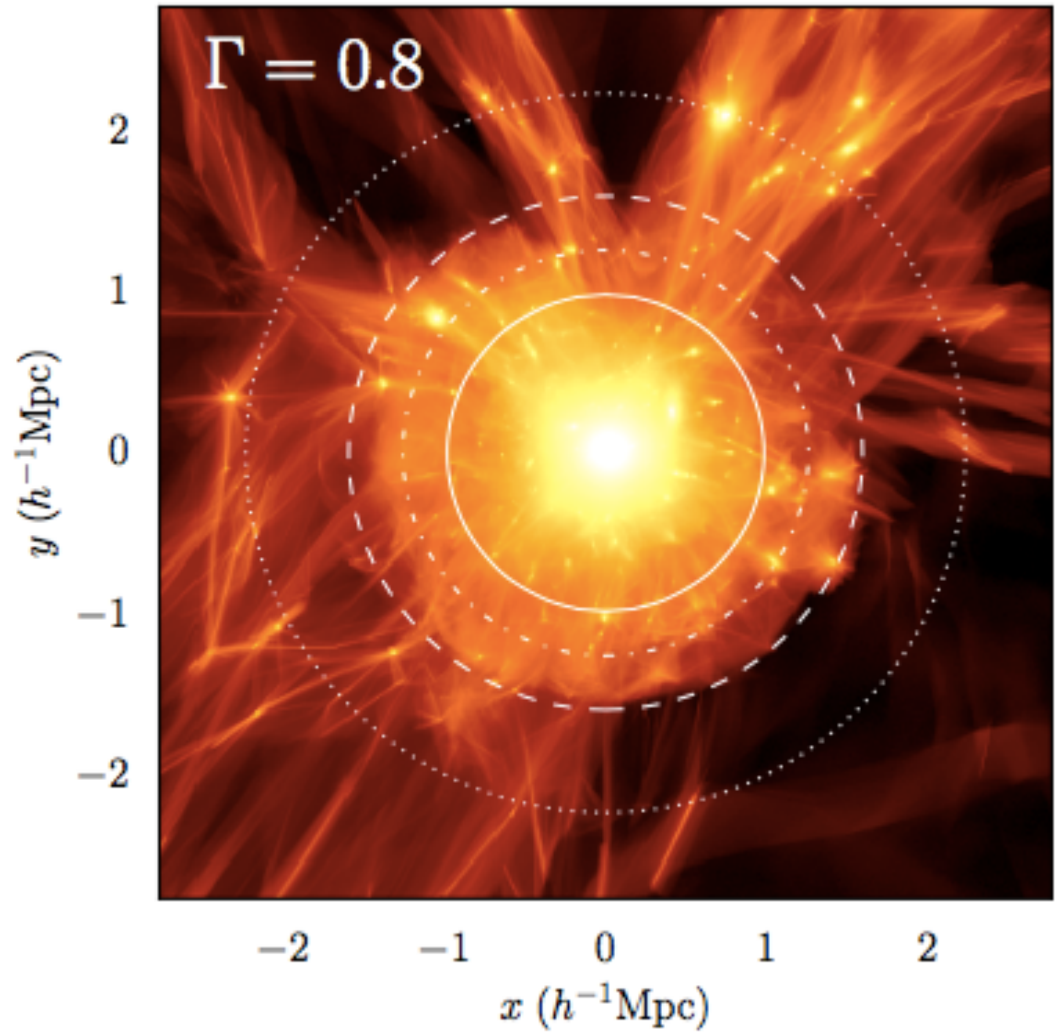
Synergy in Preparation

Can / should / will join efforts on:

1. Calibrating shear measurements
    - good news: less stringent than CS (~1% vs. ~0.01%)
    - complications:
        - shear is large
        - dense fields
        - calibrate on cluster-specific simulations
2. Mass model
    - need to calibrate on simulations
3. Photo-z's
    - sources close behind lenses → good photo-z's are critical !
    - contamination from cluster galaxies
    - need more data, including spectroscopy and NIR imaging

new postdoc (Ying Zu) starting with David Weinberg this fall for WFIRST clusters work, DESC member

Cluster Structure



- Internal structure of an N-body cluster: subhalos and splashback
- Tests of cluster physics and dark matter interactions
- Lensing, galaxy counts and SZ probe this physics
- *Diemer, Kravtsov; More et al; Adhikari et al; DES, in prep*

Discussion topics

- Pixel-level joint processing is essential for deblending, photoz, shear calibration. Challenges for cluster fields?
- Other uncertainties: reduced shear, magnification, projection…How critical is joint processing?
- How much can joint analysis expand redshift range of cluster sample?

Discussion topics: research areas

- Finding the most massive clusters at high-z: with WFIRST and CMB SZ. Can a joint analysis help - validation and evolution?
- Cluster physics, gravity and dark matter interactions: synergies need further study
- Strong lensing, kinetic SZ, other probes?