The cosmic variance of the cluster weak lensing signal

Daniel Gruen

with Stella Seitz, Matt Becker and others

work in progress, comments/suggestions very welcome

OPINAS group seminar
November 24, 2014

Contents

- Introduction
- Cosmic variance of cluster weak lensing
  - Why, how and how well do we model it?
  - Effects on mass measurement
  - Effects on mass-observable relation calibration
- Summary

Introduction

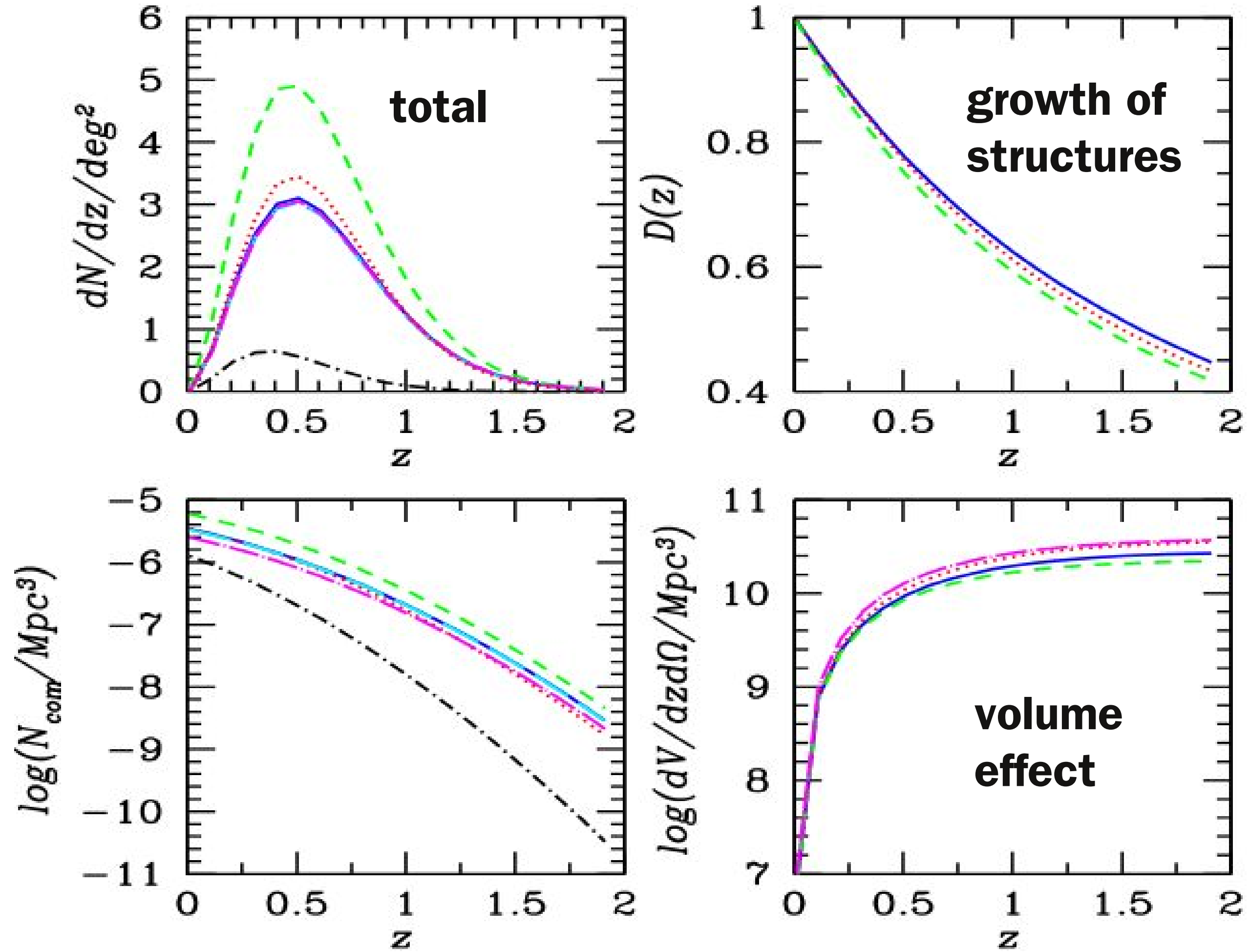
Cluster cosmology

- Cosmology from cluster counts

  Ingredients:

  - Cluster catalog
  - Cluster mass function
  - Mass-observable relation

- exponential sensitivity at high mass / redshift



Source: Battye & Weller 2008

Cluster cosmology: MOR

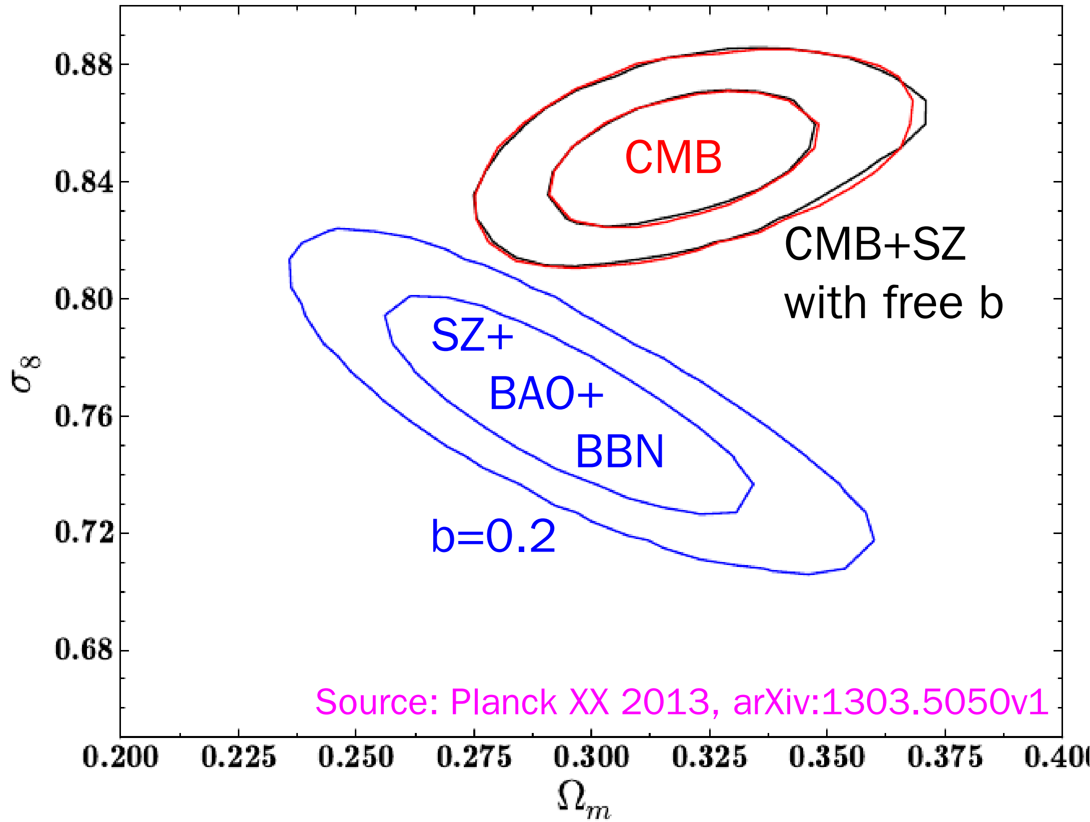
requirement: mass observable relation (MOR)

$$E(z)^{-2/3} \times \left(\frac{D_A^2 \times Y_{500c}}{\mathrm{Mpc}^2}\right) = 10^A \times \left(\frac{M_{500c} \times (1-b)}{6 \times 10^{14} h_{70}^{-1} M_\odot}\right)^B + \mathrm{Err}(\sigma_{\mathrm{int}})$$

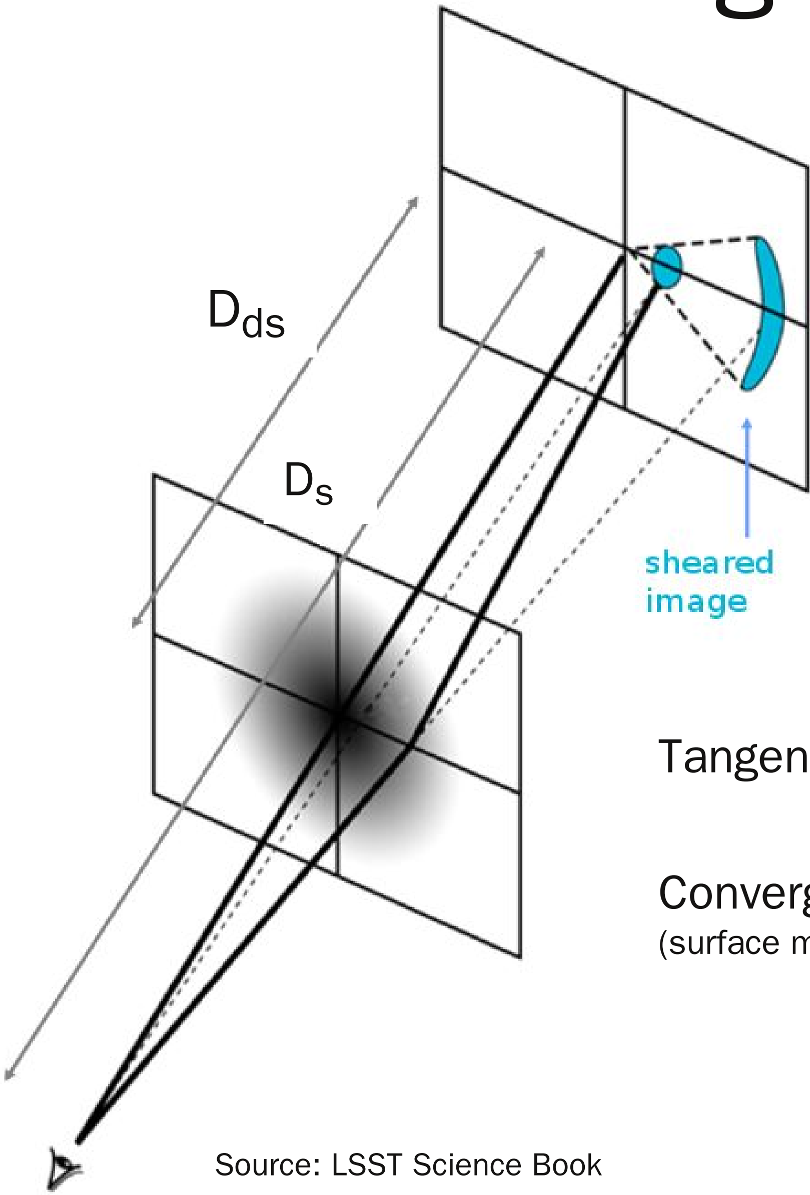
- complications:
  - mass scale, hydrostatic bias

    $$M_{500}^{\mathrm{HE}} = (1-b)\, M_{500}$$

  - self-similarity, B=5/3?
  - intrinsic scatter
  - self- vs. external calibration
- MOR uncertainty dominates statistical errors



Weak Lensing



Source: LSST Science Book

- Matter (also dark) bends space-time (and therefore light rays)
- Weak effect: % distortion
- Tangential distortion ~ overdensity

Tangential shear $\gamma_t(\theta) \quad = \quad \langle \kappa(\theta') \rangle_{\theta' < \theta} - \kappa(\theta)$

Convergence
(surface mass density) $\kappa \quad = \quad \Sigma / \left[\frac{c^2}{4\pi G} \frac{D_\mathrm{s}}{D_\mathrm{d} D_\mathrm{ds}} \right]$

- Mass measurement w/o 'dirty' astrophysics!

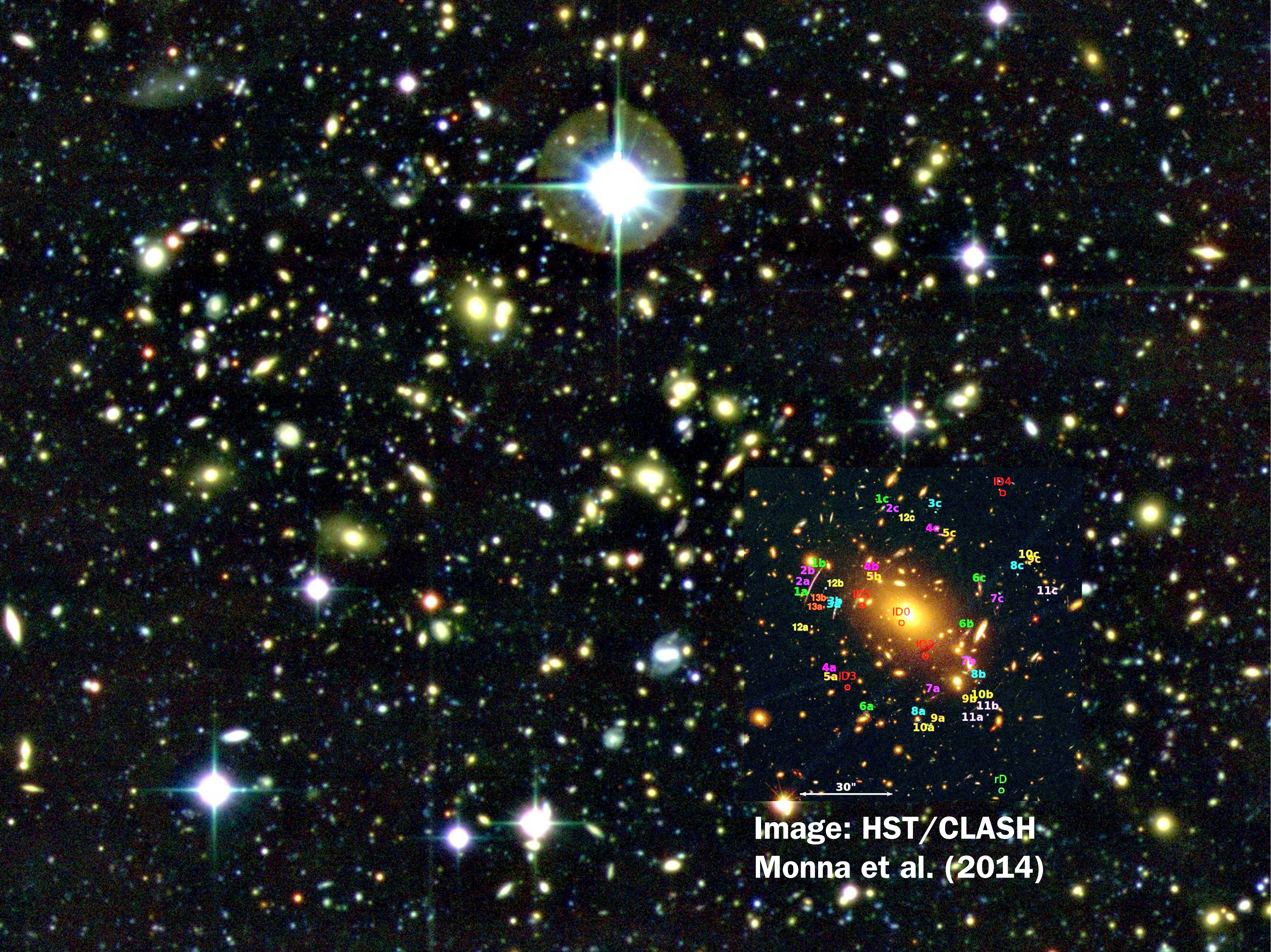
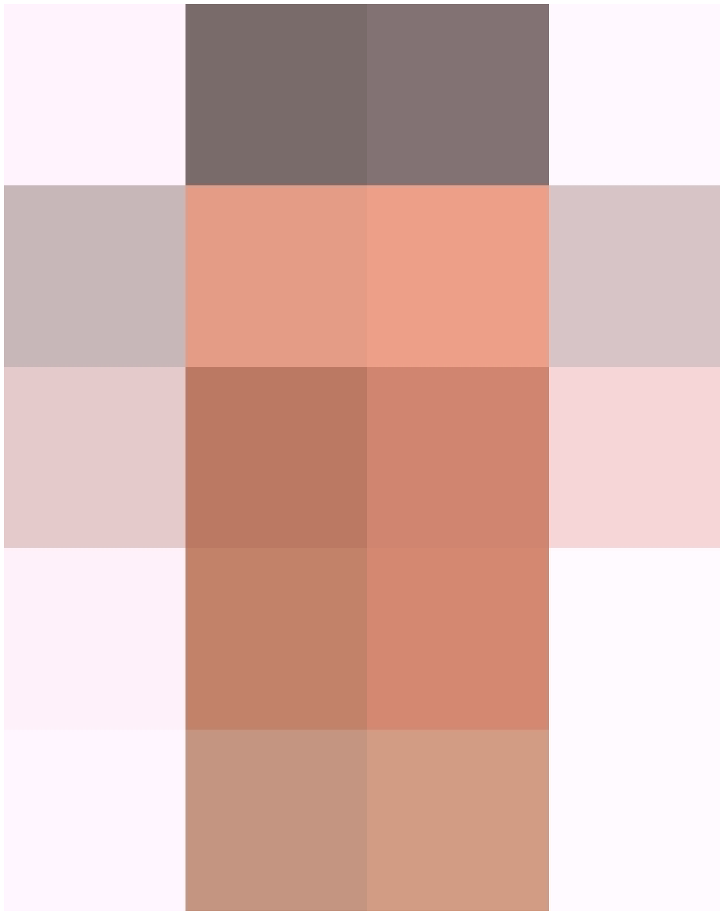
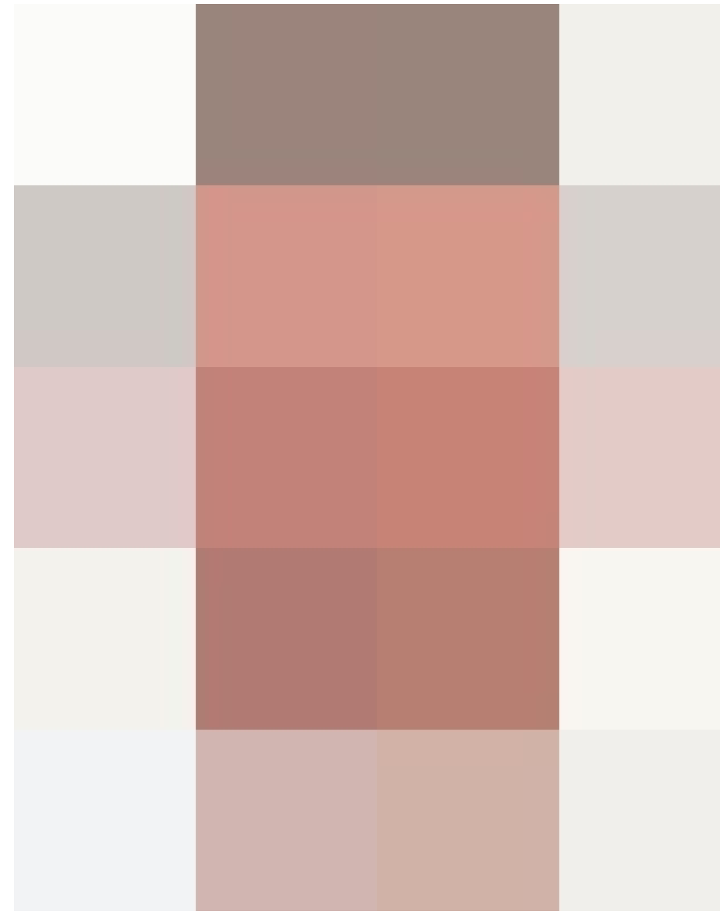
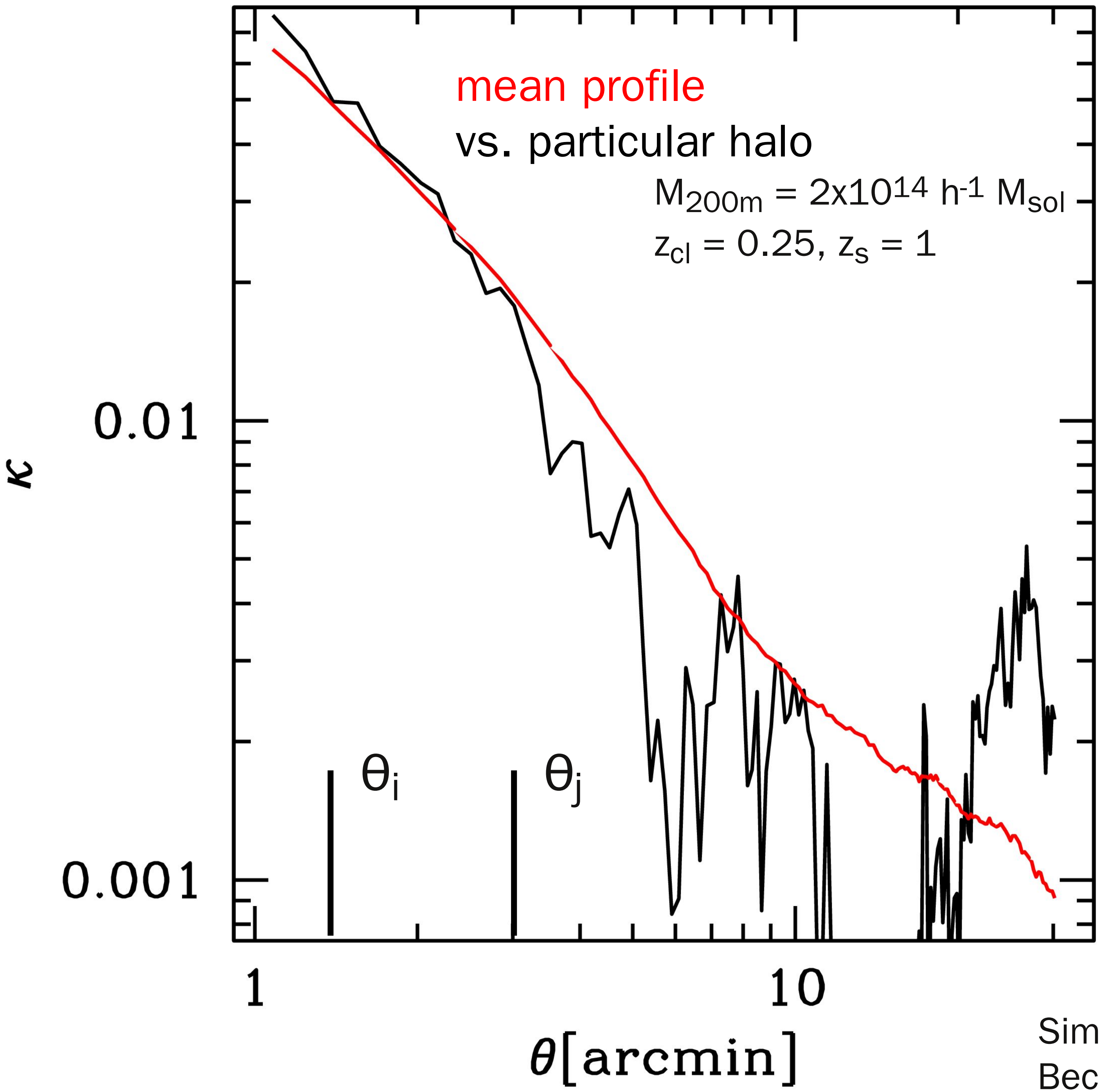


Image: HST/CLASH
Monna et al. (2014)






Source: M. Gruendl, Institute for Psychology, Regensburg University



Goal:
model the covariance of $(\kappa\text{-}K)_i$, $(\kappa\text{-}K)_j$

Method:
tune and test against 15,000 simulated clusters

Simulated cluster profiles:
Becker & Kravtsov 2011

Why bother?

$\kappa \xrightarrow{\mathrm{Cov}(\kappa_i,\kappa_j;M)} \mathbb{L}(M) \longrightarrow \mathbb{L}(A,B,\sigma_{int})$

$$E(z)^{-2/3} \times \left(\frac{D_A^2 \times Y_{500c}}{\mathrm{Mpc}^2}\right) = 10^A \times \left(\frac{M_{500c} \times (1-b)}{6 \times 10^{14} h_{70}^{-1} M_\odot}\right)^B$$

$+ \mathbb{E}\mathrm{rr}(\sigma_{int})$

Covariance model for κ(r)

The **κ** data vectors for two clusters of same mass could differ due to

- observational uncertainty $\mathbf{C}^{\mathbf{obs}}$
- uncorrelated structure $\mathbf{C}^{\mathbf{LSS}}$
  (e.g. Hoekstra 2001, 2003; Dodelson 2004; Schirmer+2007)

common

- Intrinsic variations of cluster profiles
  - Concentration scatter $\mathbf{C}^{\mathbf{conc}}$
  - Halo ellipticity and orientation $\mathbf{C}^{\mathbf{ell}}$
  - Projected correlated haloes $\mathbf{C}^{\mathbf{corr}}$

new

Component 1: Uncorrelated structures

- Uncorrelated line-of-sight structure adds noise to lensing signal independent of cluster mass (e.g. Hoekstra 2003)
- Limiting factor for single group-scale lenses (e.g. Spinelli+2012)
- here: uncorrelated structures in the 400 h^{-1} Mpc cut-out box

$$C_{ij}^{\mathrm{LSS}} = \int \frac{l\mathrm{d}l}{2\pi} P_\kappa(l) \hat{J}_0(l\theta_i) \hat{J}_0(l\theta_j)$$

$$P_\kappa(l) = \frac{9H_0^2\Omega_m^2}{4c^2} \int_{\chi_1}^{\chi_2} \mathrm{d}\chi \left(\frac{\chi_s - \chi}{\chi_s a(\chi)}\right)^2 P_{\mathrm{nl}}(l/\chi, \chi)$$

Component 2: Scatter in concentration

- Dark matter haloes are described well (on average) by Navarro, Frenk & White (NFW) profiles with two parameters: mass and concentration $c_{200m} = r_{200m}/r_{\rm s}$
- At fixed mass, concentration is log-norm around mean (e.g. Bullock+2001, Duffy+2008)

$$
\begin{aligned}
C_{ij}^{\rm conc} &= \int {\rm d}P(c)\kappa_i\kappa_j \\
&- \left[\int {\rm d}P(c)\kappa_i\right] \times \left[\int {\rm d}P(c)\kappa_j\right]
\end{aligned}
$$

Component 3: Correlated haloes

- Clusters live in dense environments with excess density of neighbouring haloes → excess shot noise in **K**

$$C_{ij}^{\mathrm{corr}} \times \Sigma_{\mathrm{crit}}^2 = \int \mathrm{d}P_c(\boldsymbol{h}|\boldsymbol{h}_{\mathrm{cl}})\Sigma^i(\boldsymbol{h})\Sigma^j(\boldsymbol{h})$$

$\mathrm{d}P_c(\boldsymbol{h}|\boldsymbol{h}_{\mathrm{cl}}) =$ probability of finding correlated halo $\boldsymbol{h} = (M, \theta)$

$$= b(M_{\mathrm{cl}})b(M)\frac{\mathrm{d}N(M, z_{\mathrm{cl}})}{\mathrm{d}M\mathrm{d}V}W(\theta, z_{\mathrm{cl}})2\pi\theta\mathrm{d}\theta\mathrm{d}M$$

- Ingredients:
  - halo mass function (Tinker+2008)
  - halo bias (Tinker+2010)
  - linear angular correlation
  - assumption of Poissonian process for halo placement

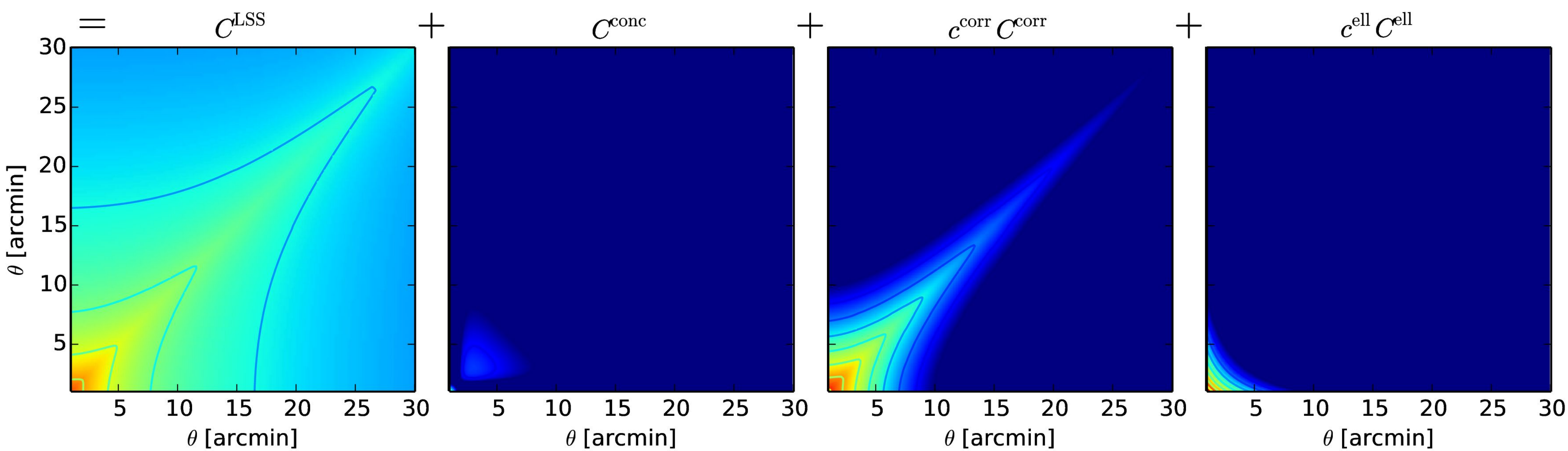
Component 4: Halo asphericity and orientation

- Cluster haloes are triaxial with preference for prolateness (e.g. Bett+2007)
- Known bias in lensing mass depending on orientation w.r.t. LOS (Corless+2007)
- Complete degeneracy with mass / concentration (Dietrich+2014)
- We assume prolate halo, log-normal axis ratio q, isotropic orientation

$$
\begin{aligned}
C_{ij}^{\mathrm{ell}} &= \int \mathrm{d}P(q, \cos\alpha)\kappa_i\kappa_j \\
&- \left[\int \mathrm{d}P(q, \cos\alpha)\kappa_i\right] \times \left[\int \mathrm{d}P(q, \cos\alpha)\kappa_j\right]
\end{aligned}
$$

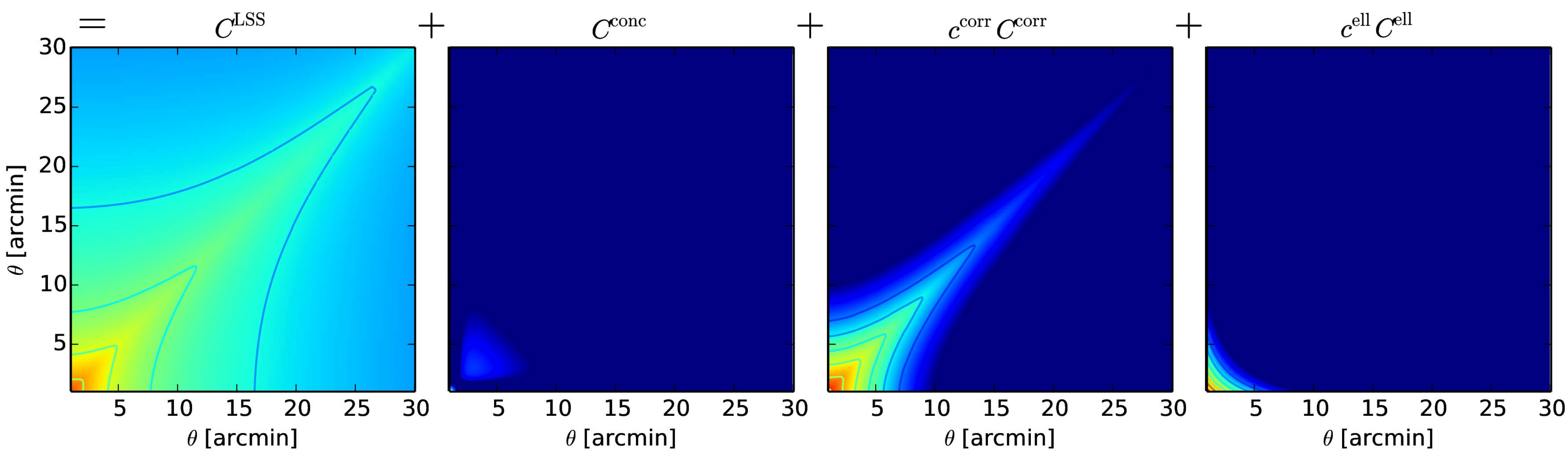
Putting it all together: Covariance model C(M) for κ

$$C(M) = C^{\rm obs} + C^{\rm LSS} + C^{\rm conc}(M) + c^{\rm corr}(\nu)C^{\rm corr}(M) + c^{\rm ell}(\nu)C^{\rm ell}(M)$$



Putting it all together: Covariance model C(M) for κ

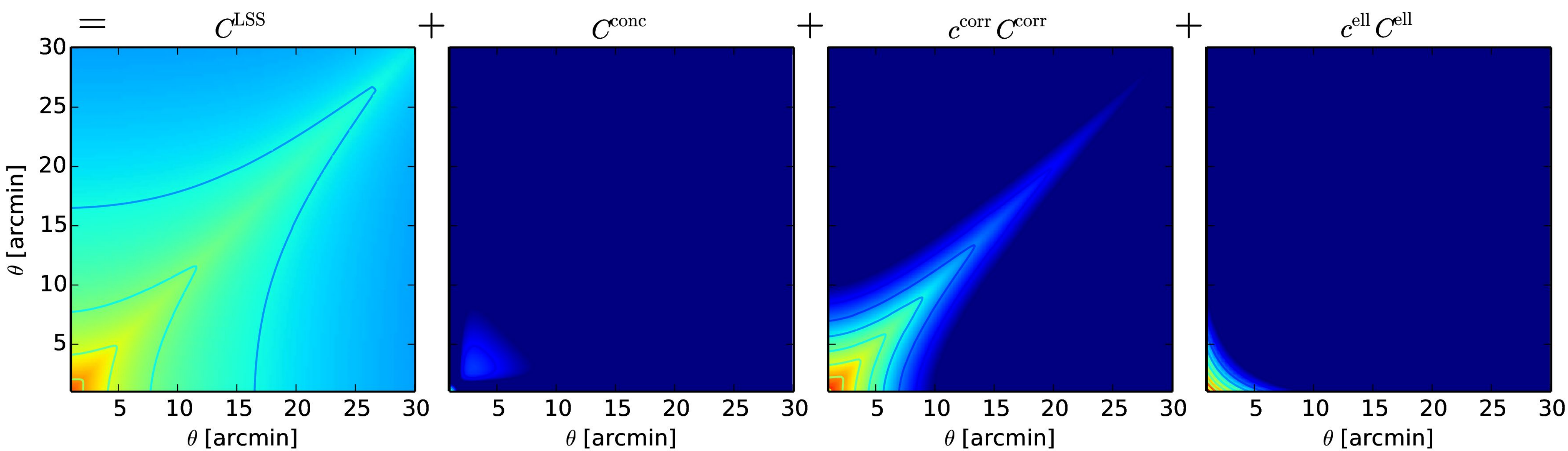
$$C(M) = C^{\rm obs} + C^{\rm LSS} + C^{\rm conc}(M) + c^{\rm corr}(\nu)C^{\rm corr}(M) + c^{\rm ell}(\nu)C^{\rm ell}(M)$$



$$c^{\rm corr}(\nu) = c_0^{\rm corr} + (\nu - \nu_0^{\rm corr})c_1^{\rm corr}$$
$$c^{\rm ell}(\nu) = c_0^{\rm ell} + (\nu - \nu_0^{\rm ell})c_1^{\rm ell}\ ,$$

Putting it all together: Covariance model C(M) for κ

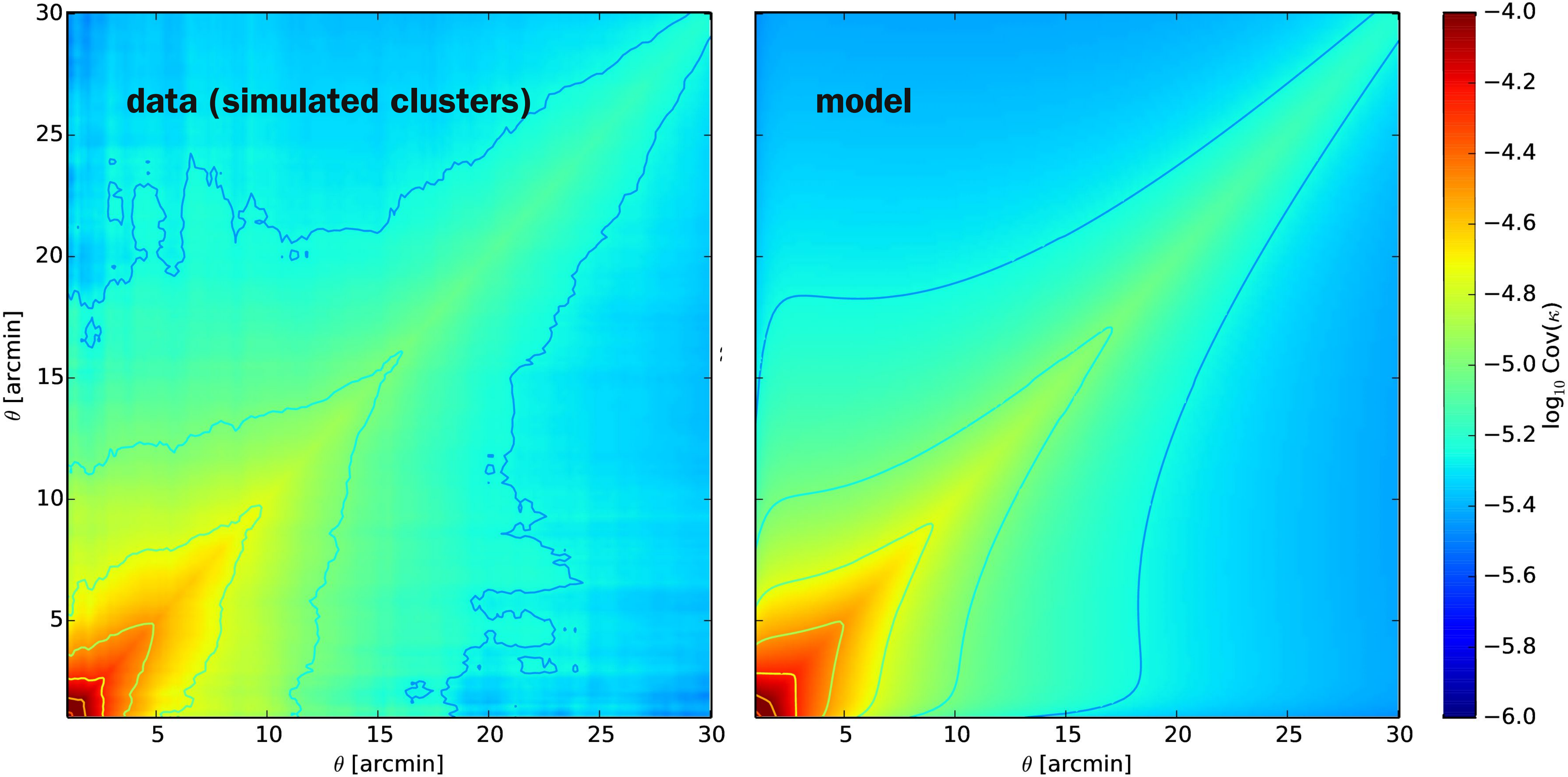
$$C(M) \quad = \quad C^{\rm obs} + C^{\rm LSS} + C^{\rm conc}(M) + \quad c^{\rm corr}(\nu) C^{\rm corr}(M) + c^{\rm ell}(\nu) C^{\rm ell}(M)$$



$$c^{\rm corr}(\nu) \quad = \quad c_0^{\rm corr} + (\nu - \nu_0^{\rm corr}) c_1^{\rm corr} \quad = \ 5.0 \pm 0.3$$

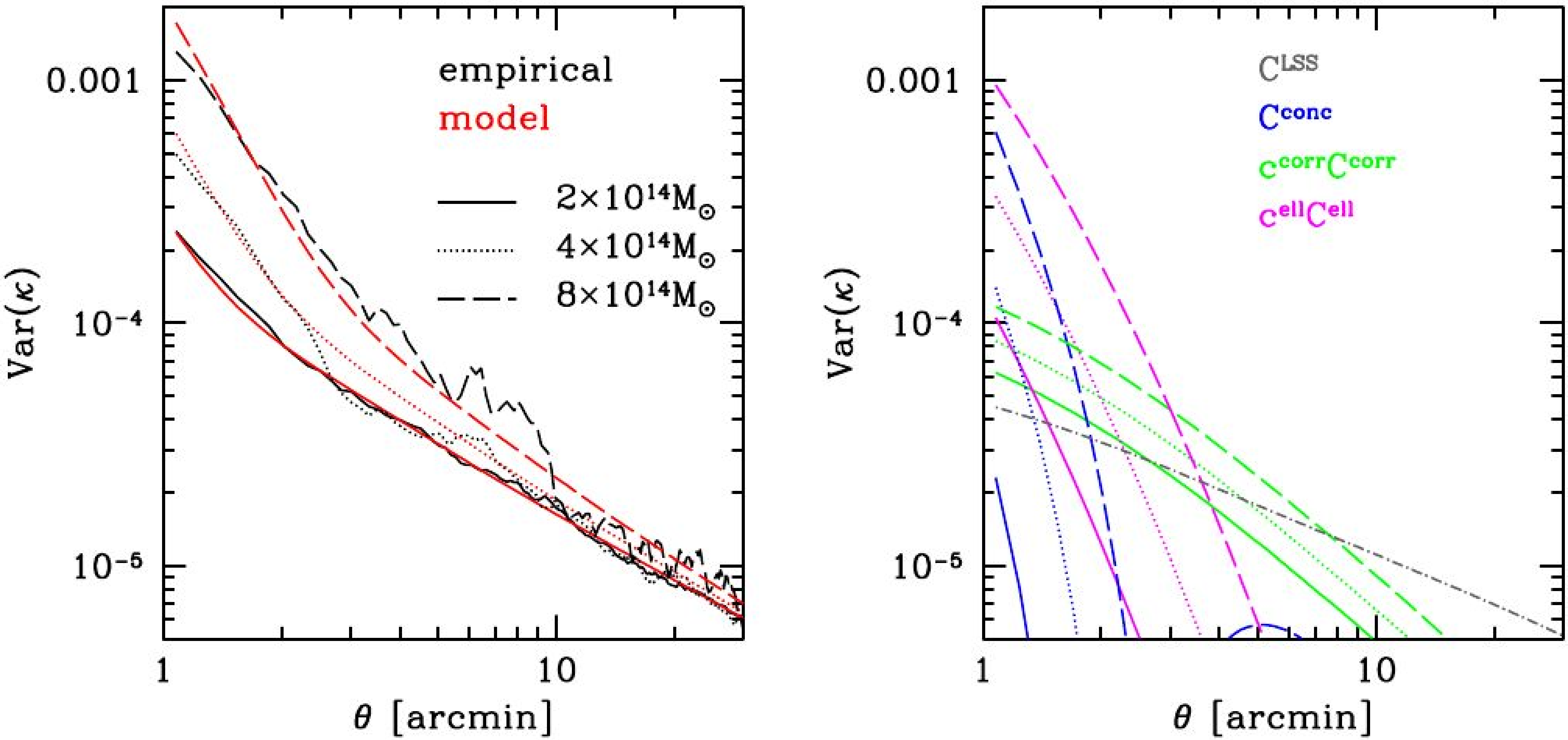
$$c^{\rm ell}(\nu) \quad = \quad c_0^{\rm ell} + (\nu - \nu_0^{\rm ell}) c_1^{\rm ell}\,, \quad = \ 3.7 \pm 0.3$$

Covariance model C(M) for **κ**



z_l=0.25, z_S=1, M_{200m}=2x10^{14} h^{-1} M_{sol}

Covariance model C(M) for κ

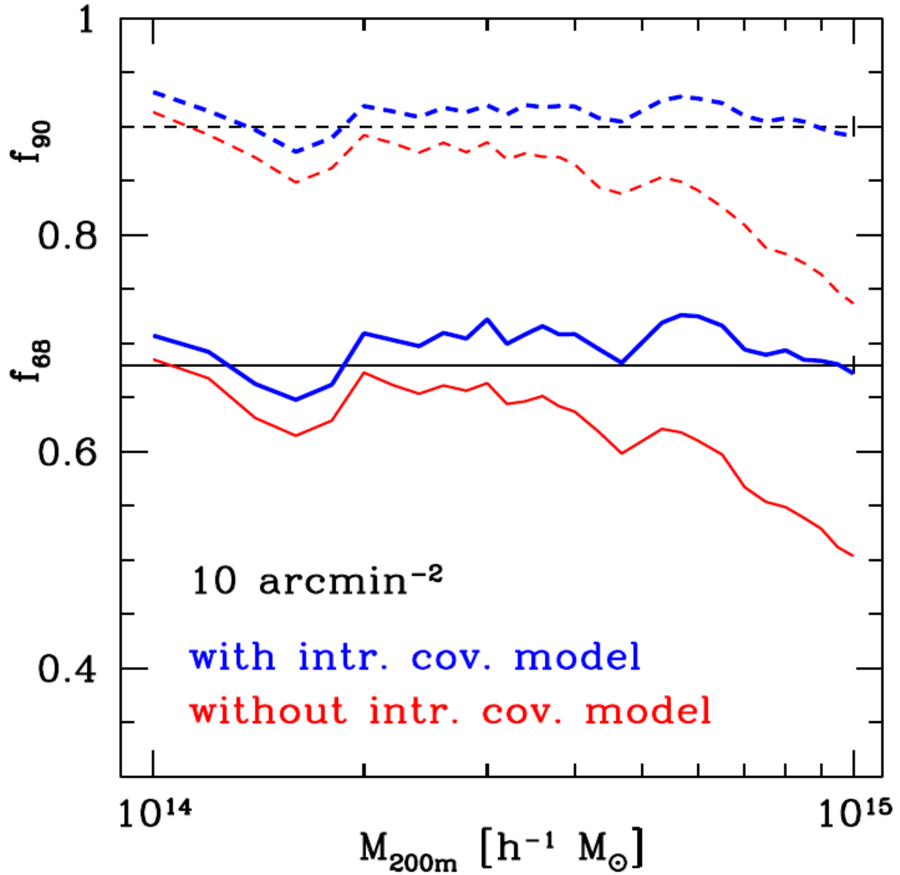


Effect on mass measurement

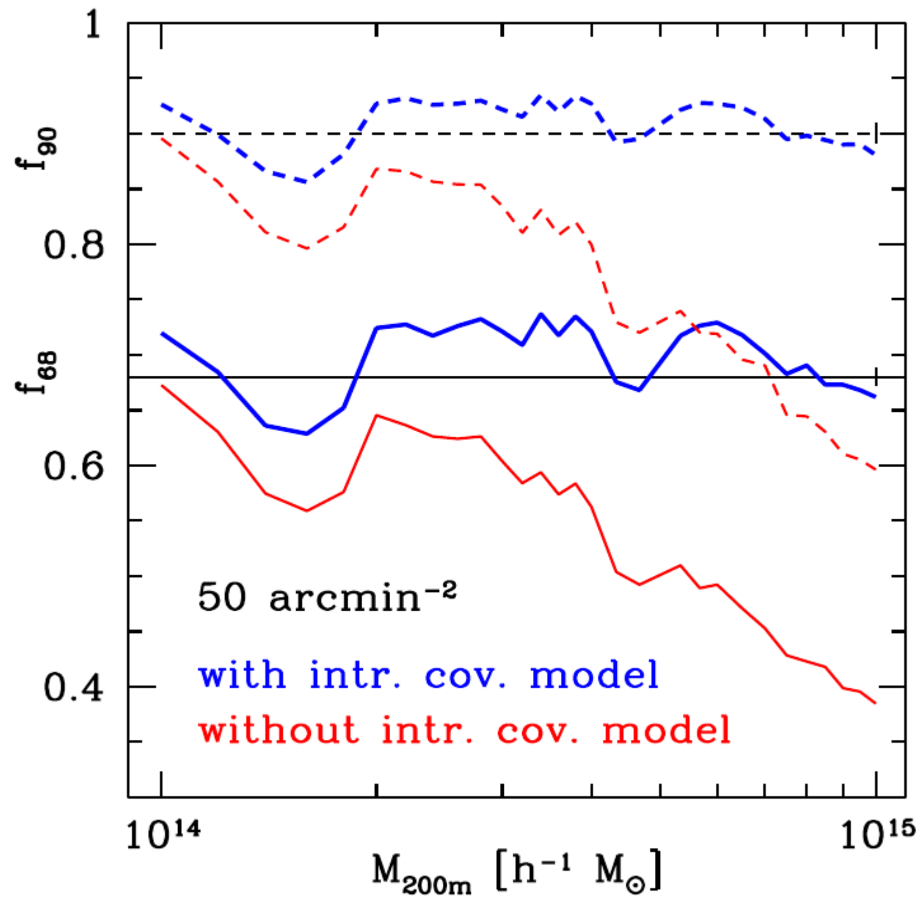
$$\begin{aligned} -2\ln\mathcal{L} &= \ln\det C(M) \\ &+ (\boldsymbol{\kappa}(M)-\boldsymbol{K})^{\mathrm{T}} C^{-1}(M)(\boldsymbol{\kappa}(M)-\boldsymbol{K}) \\ &+ \text{const}\ . \end{aligned}$$

- Likelihood of observed convergence **K** in mass
- C(M) can include only C^{obs} + C^{LSS} or also our C^{int}
- Q: how does C^{int} influence mass measurement?

Mass uncertainty: Confidence intervals



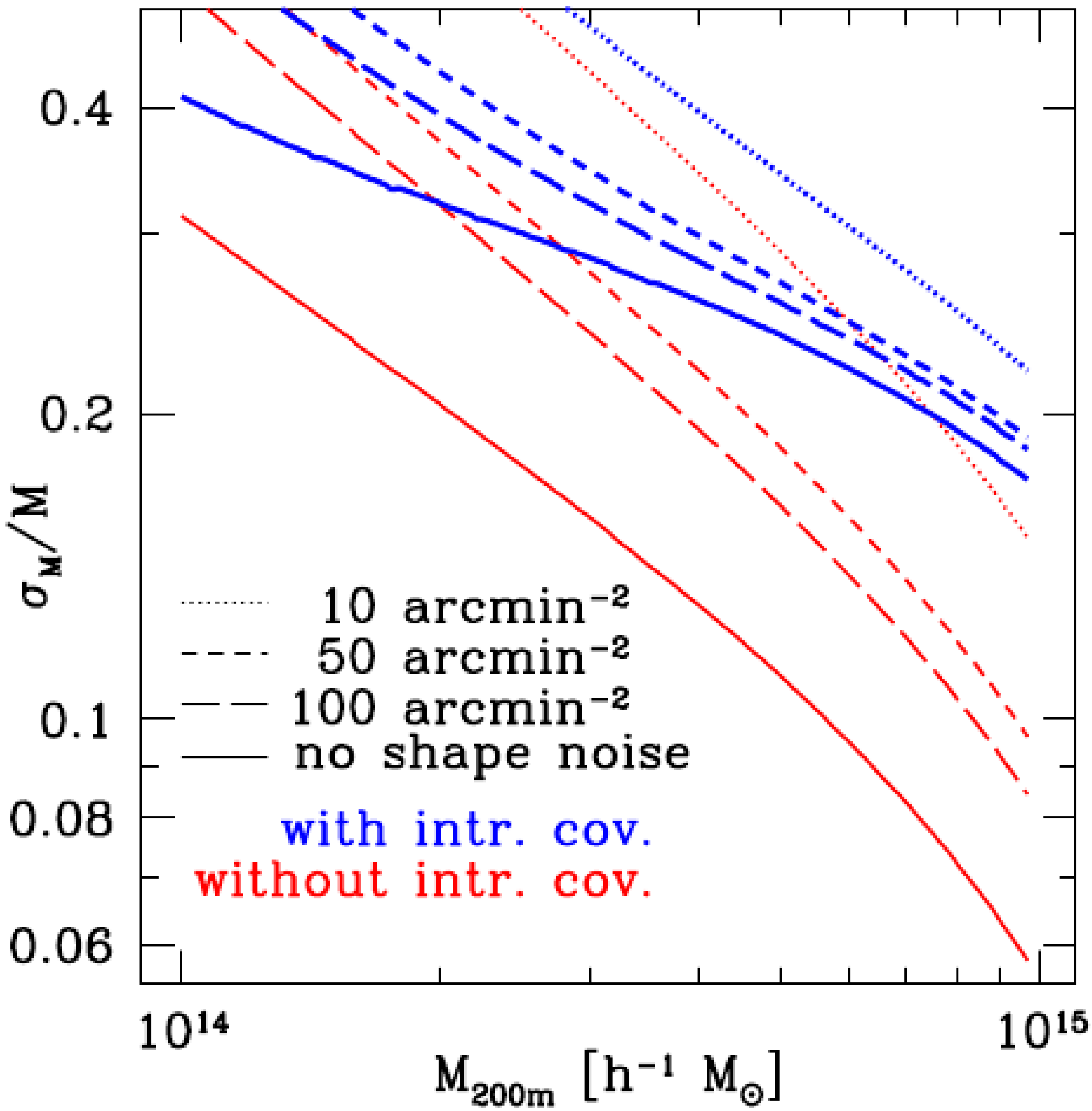
(typical ground based)

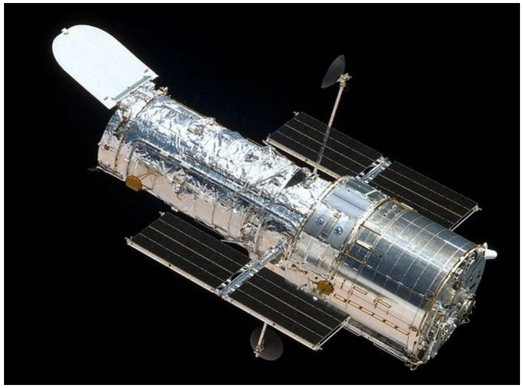


(best ground based / space based)

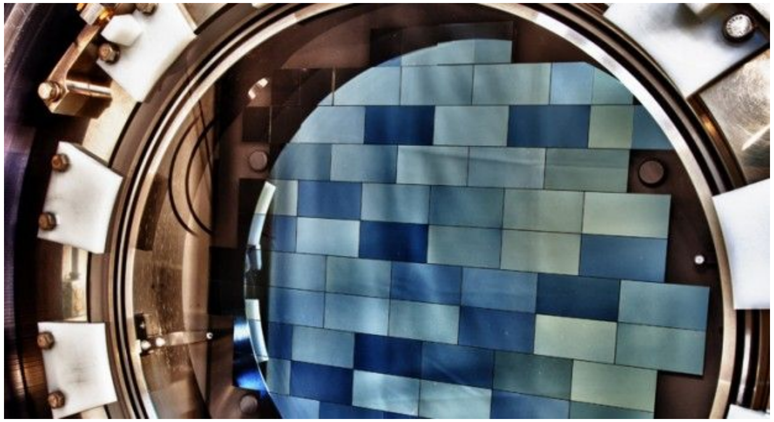
Empirical coverage of 68% and 90% confidence intervals (without C^{int} and including C^{int}) for simulated clusters

Mass uncertainty: Fisher prediction





vs.



- Increase in depth of only moderate help for massive clusters
- Increase in mass of only moderate help for given depth

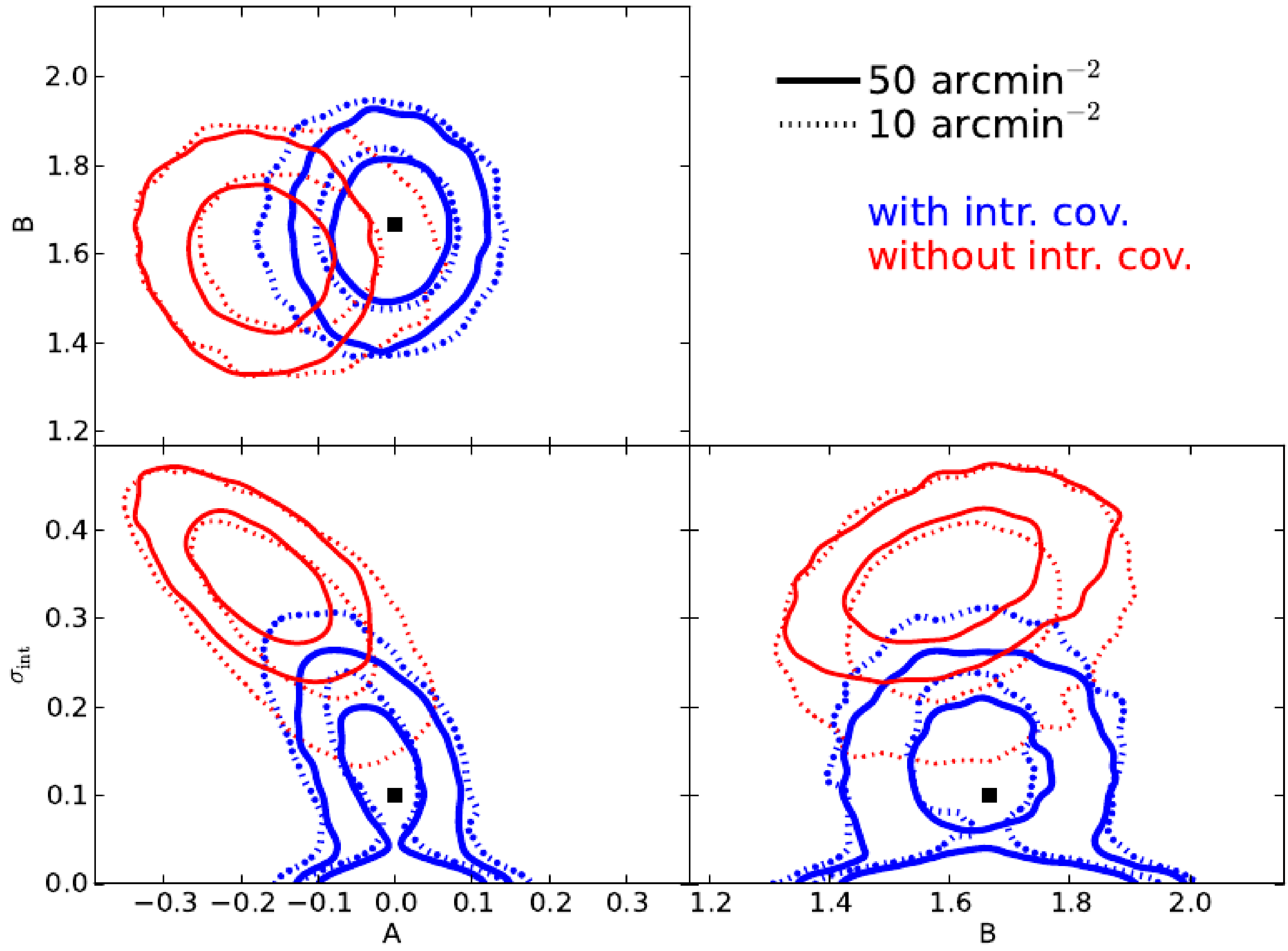
Mass observable relation estimation

- Consider lensing survey of sample of 100 observable-limited clusters
- Use mass likelihood from lensing to constrain power-law MOR

$$\ln Y_0(M)/\hat{Y} = A + B \ln M/\hat{M} + \mathcal{N}(\mu = 0, \sigma) \qquad \sigma = \sqrt{\sigma_{\rm int}^2 + \sigma_{\rm obs}^2}$$

- Simulate cluster profiles including $C^{\rm int}$ model
- Effect of cluster profile covariance?

Mass observable relation estimation



To do

- Redshift dependence
  - all results so far at z=0.25
  - using second snapshot, extend to z=0.5
- Effect of baryons
  - outside scope, but interesting
- Higher redshift, higher resolution
  - outside scope, but interesting

Summary

- Simple model for variation in projected cluster profiles at fixed mass
  - analytic templates
  - re-scaled to match simulations
- Potential uses
  - correct mass confidence intervals
  - Fisher analyses for cluster WL surveys
  - unbiased estimation of intrinsic scatter and other parameters of mass-observable relation