Signal Covariance for Clusters of Galaxies: Theory and Observation

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DE Science and Astrophysics

Astrophysics = DE "nuisance" parameters

– first-principles priors (simulation, theory)

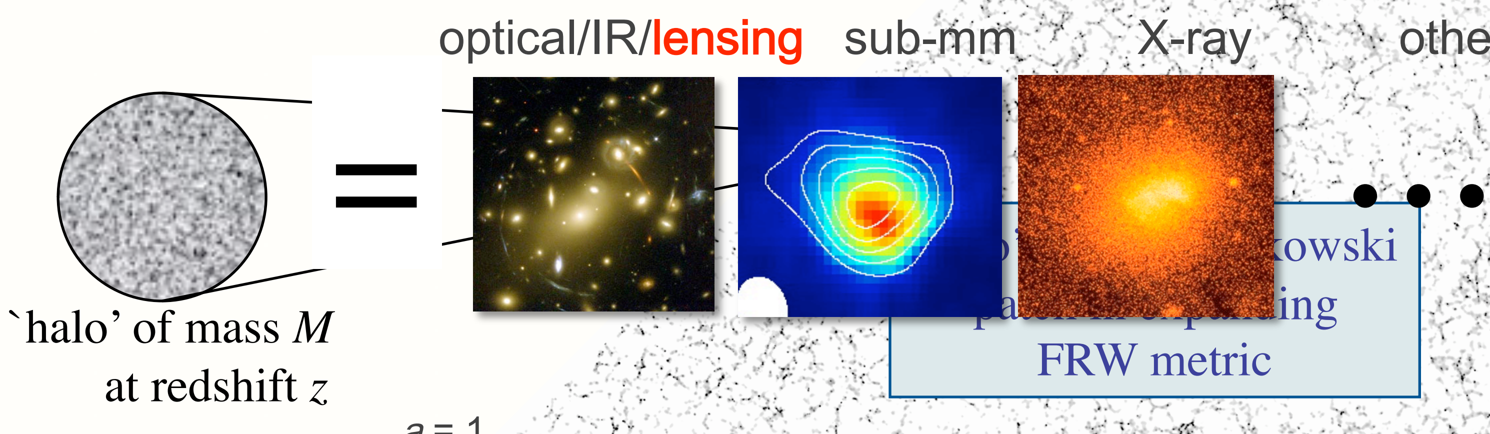
– empirical priors (observation)

LSS tests (WL, GC, BAO) require knowledge of

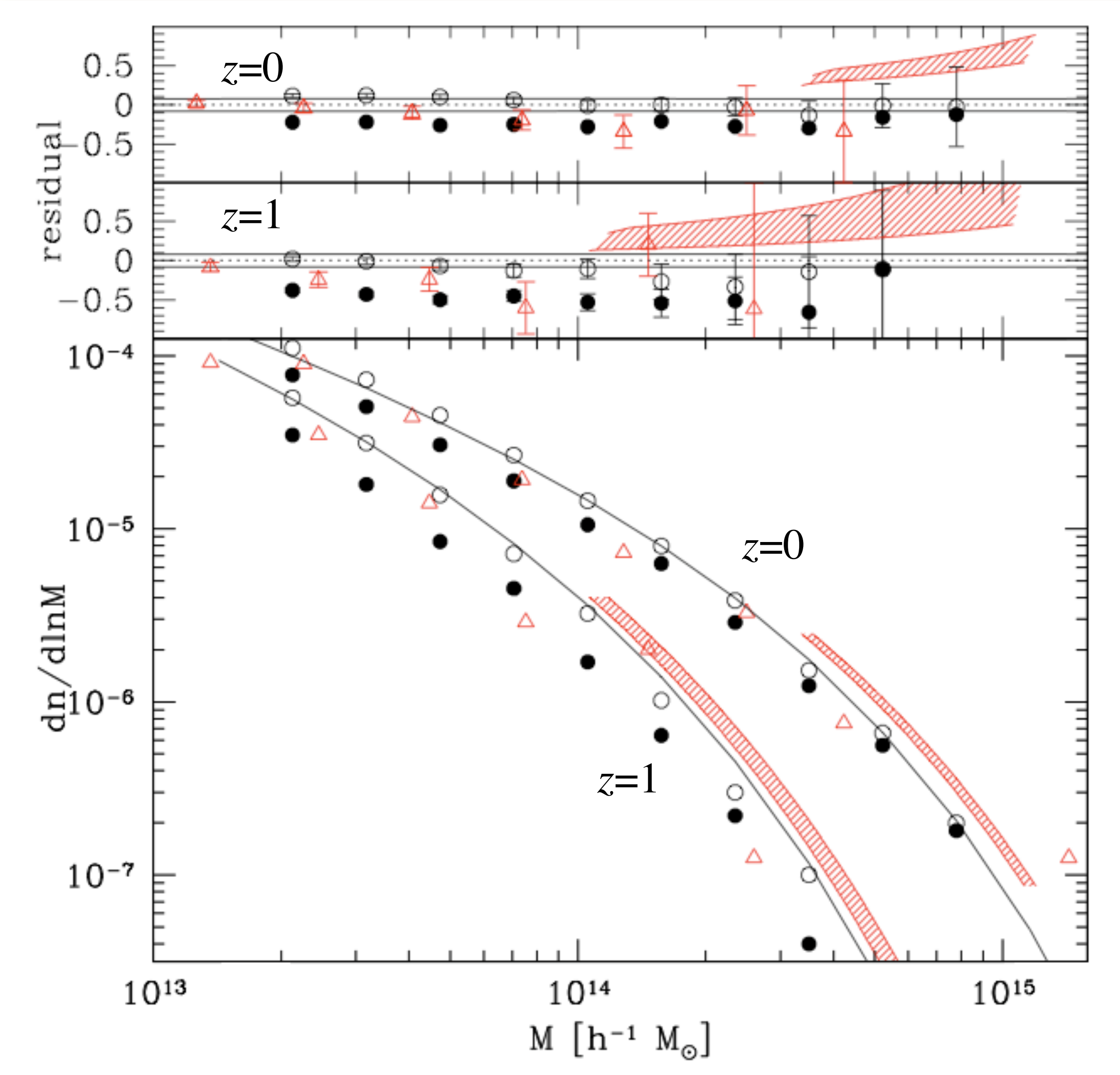
– how DM clusters on small scales,

– how galaxies & gas evolve within DM halos

baryon phenomenology



mass function sensitivity to baryon physics



Stanek et al, 0809.2805

– complex baryon physics shifts halo total mass (M_{500})

– mass function shifts >5% statistical error of Tinker et al (2008)

2 pairs of simulations

o MGS-gravity only

• MGS-preheat

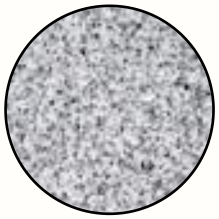
Δ ART-gravity only

ART-cool/star/feedback

(For state-of-the-art sims, see E. Puchwein's poster)

clusters as scaled "standard candles"

optical/IR/lensing sub-mm X-ray other...



halo of mass M
at redshift z

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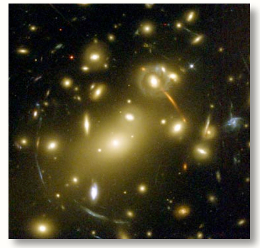

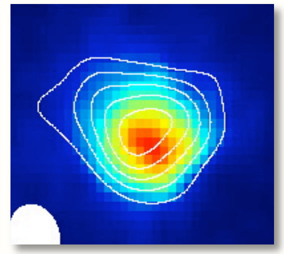

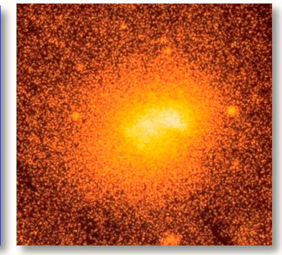

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"Astrophysics for Dummies"

1) To first order, all relations are power-law

e.g., virial theorem $T \sim H(z)^{2/3}\, M^{2/3}$

2) Central limit Th^{m} => deviations are log-normal

bedrock: dark matter virial scaling

Evrard et al 2008

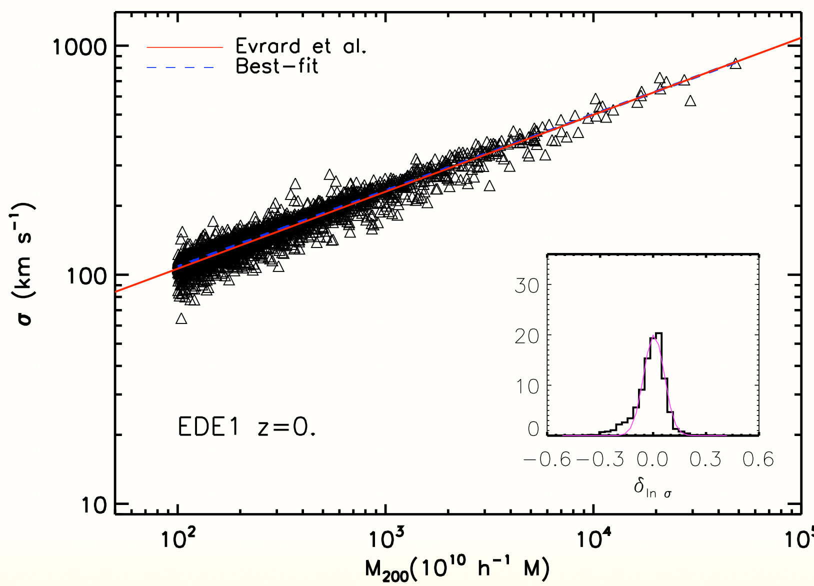
- log-mean specific thermal energy (velocity dispersion) in dark matter

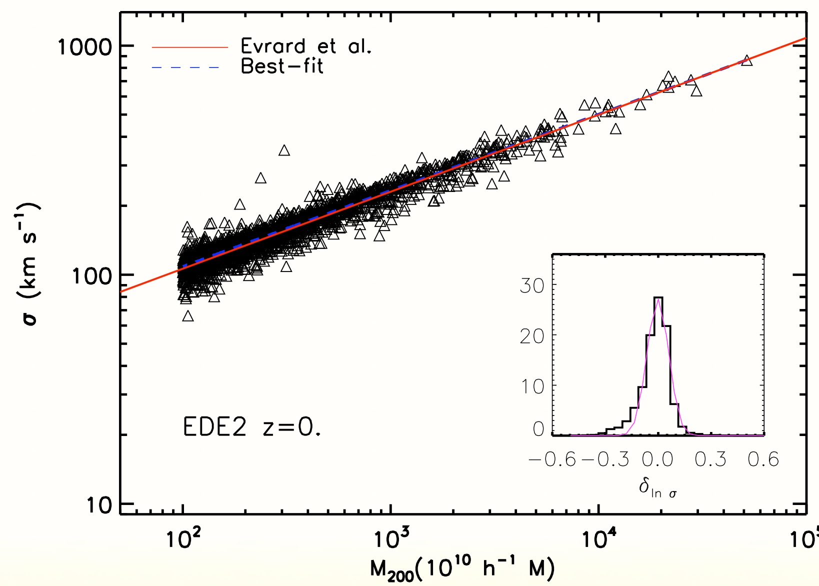
$$\sigma_{\rm DM}(M,z) = (1082.9 \pm 4.0)(E(z)M_{200}/10^{15}\,h^{-1}M_{\rm o})^{0.3361\pm0.0026}\ \ \mathrm{km\ s^{-1}}$$

- deviations approximately log-normal with 4-5% scatter

- confirmed in Early Dark Energy models

Grossi & Springel 2008





power-law + log-normal scatter model for signals

- For i^{th} signal, mean behavior of $s_i = \ln(S_i)$ is linear in $\ln M$ w/ slope m_i. For N such signals

$$\bar{\mathbf{s}}(\mu,z) = \mathbf{m}(z)\mu + \mathbf{b}(z)$$

$$\mu = \ln M$$

- assume a log-normal joint likelihood about the mean

$$p(\mathbf{s} \mid \mu,z) = \frac{1}{(2\pi)^{N/2}|\Psi|^{1/2}} \exp[-\tfrac{1}{2}(\mathbf{s}-\bar{\mathbf{s}})'\Psi^{-1}(\mathbf{s}-\bar{\mathbf{s}})]$$

where Ψ is the ***covariance in signals*** at fixed mass and epoch

$$\Psi_{ij} = \left\langle \left(s_i - \bar{s}_i(\mu,z)\right)\left(s_j - \bar{s}_j(\mu,z)\right)\right\rangle$$

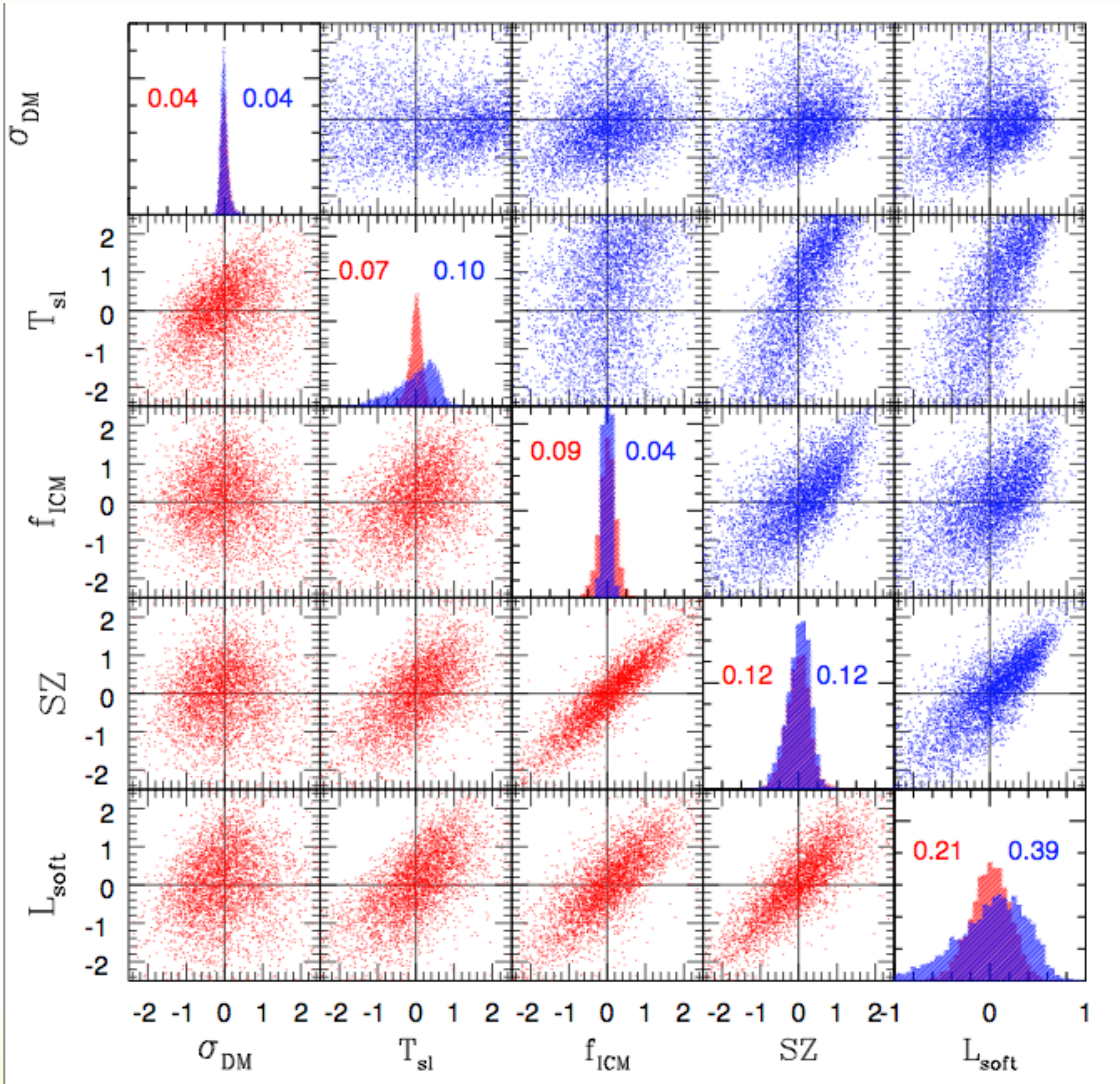
support for power-law + Gaussian covariance

with Lorena Gazzola, F. Pearce (Nottingham)

Millennium Simulation:
Gadget2 with gas under two physical treatments
– preheating
– gravity only

Covariance in ~3000 halos at z=0 with $M_{200} > 3\times10^{13}$ Msun/h

Stanek et al, in prep



local model for signal counts (***signal function***)

- locally power-law mass function $dp = n(\mu)\, dV$

$$n(\mu) = A\exp(-\alpha\mu) \;\; ; \;\; \alpha = \alpha(\mu, z)$$ ⇐ *cosmology*

- convolve with log-normal likelihood for **s** to find the

signal space density

$$n(\mathbf{s}) = \frac{A\Sigma}{(2\pi)^{(N-1)/2}|\Psi|^{1/2}} \exp\left[-\frac{1}{2}\left(\mathbf{s}'\Psi^{-1}\mathbf{s} - \frac{\bar{\mu}^2(\mathbf{s})}{\Sigma^2}\right)\right]$$

where Σ^2 is the mass variance, and $\bar{\mu}$ is the log-mean mass

$$\Sigma^2 = \left(\mathbf{m}'\Psi^{-1}\mathbf{m}\right)^{-1} \qquad \bar{\mu}(\mathbf{s}) = \frac{\mathbf{m}'\Psi^{-1}\mathbf{s}}{\mathbf{m}'\Psi^{-1}\mathbf{m}} - \alpha\Sigma^2$$

Note: **b**(z)=0 assumed.

signal selection effects

- select on s_1, {mass, s_2} likelihood is Gaussian with covariance

$$\tilde{\Psi} = \begin{bmatrix} \sigma_{21}^2 & \tilde{r}\sigma_{21}\sigma_{\mu 1} \\ \tilde{r}\sigma_{21}\sigma_{\mu 1} & \sigma_{\mu 1}^2 \end{bmatrix}$$

$$\sigma_{21}^2 = m_2^2\left(\sigma_{\mu 1}^2 + \sigma_{\mu 2}^2 - 2r\sigma_{\mu 1}\sigma_{\mu 2}\right)$$

$$\sigma_{\mu i} = \sigma_i / m_i \quad \text{mass scatter}$$

$$\tilde{r} = \frac{(\sigma_{\mu 1}/\sigma_{\mu 2} - r)}{\sqrt{1 - r^2 + (\sigma_{\mu 1}/\sigma_{\mu 2} - r)^2}}$$

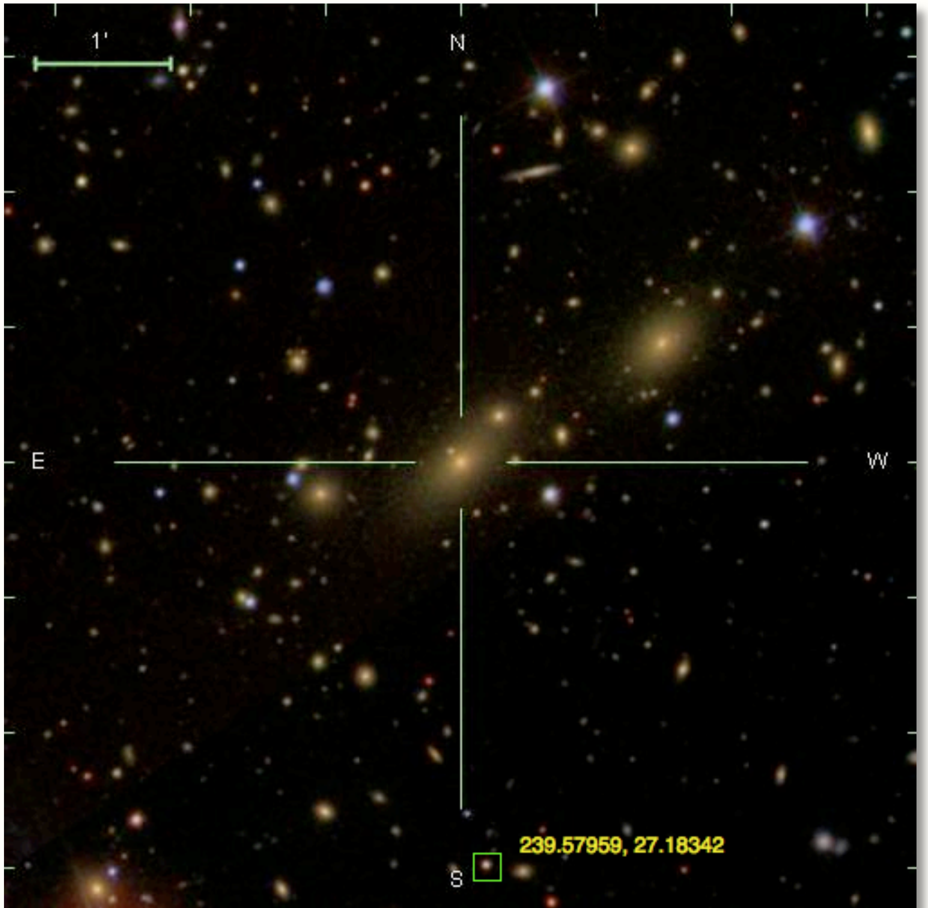
s_2-μ correlation coefficient

- mean s_2 – mass scaling for s_1-binned samples will be biased if $r \neq 0$

$$\bar{s}_2(s_1) = m_2\left(\bar{\mu}(s_1) + \alpha(\bar{\mu},z)r\sigma_{\mu 1}\sigma_{\mu 2}\right)$$

$$d\bar{s}_2 / d\bar{\mu} = m_2\left(1 + (r\sigma_{\mu 1}\sigma_{\mu 2})\partial\alpha(\bar{\mu},z)/\partial\mu\right)$$

SDSS maxBCG cluster sample



based on excess counts of g–r red-sequence galaxies, ~13,000 clusters, richness $N_{200} \geq 10$

Koester et al 2007a,b (T. McKay)

follow-up studies:

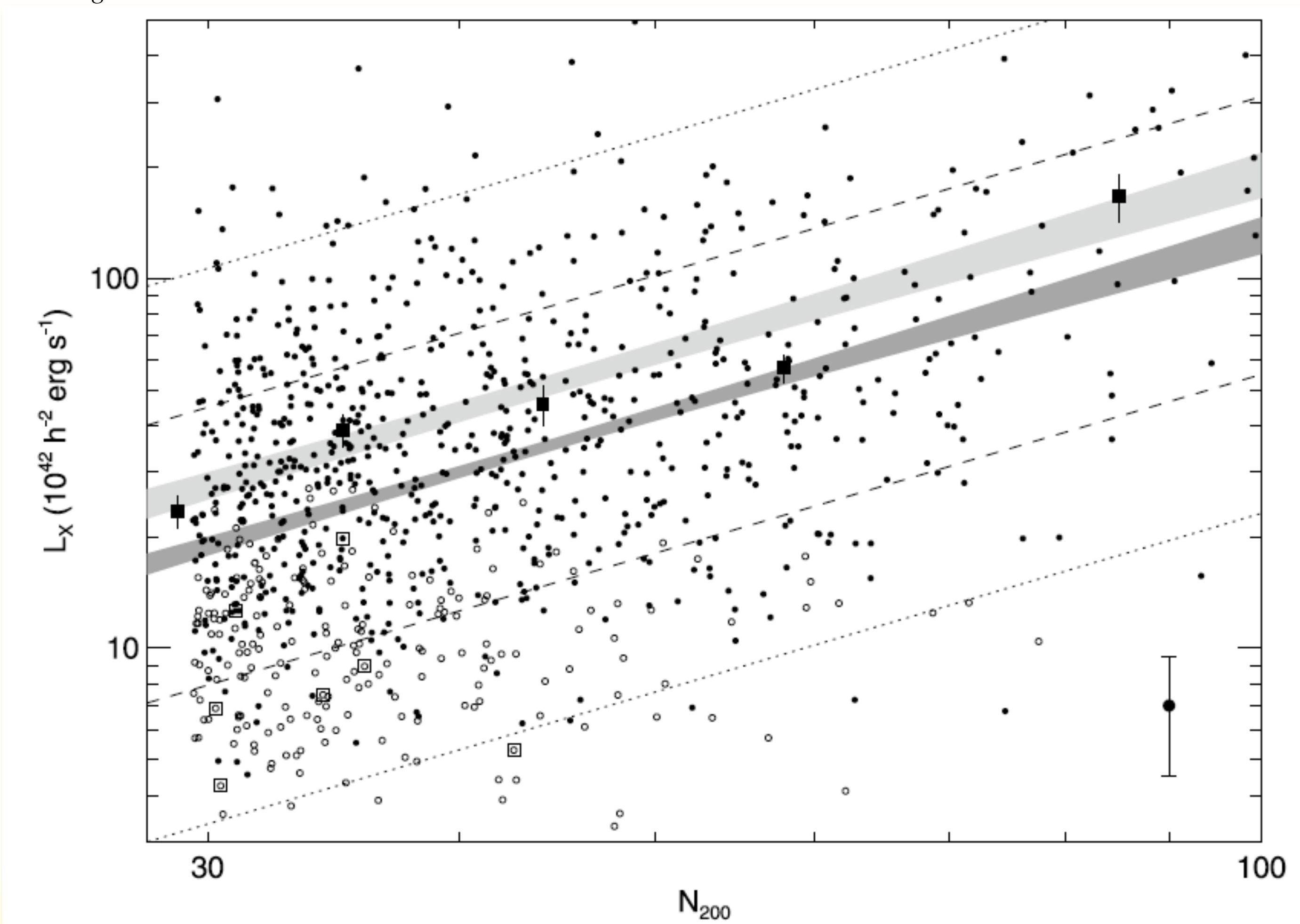
- stacked weak lensing masses
  Sheldon et al 2007; Johnston et al 2007
- velocity dispersion–richness
  Becker et al 2007
- X-ray luminosity–richness
  Rykoff et al 2008a
- X-ray luminosity–lensing mass
  Rykoff et al 2008b
- improved richness estimator
  Rozo et al 2008a
- scatter in mass–richness
  Rozo et al 2008b

L_X–N_{gal} scatter measurement

Rykoff et al 2008a

$$\sigma_{\ln L_X \mid N_{gal}} = 0.83 \pm 0.03$$

~3,000 SDSS maxBCG clusters with RASS detections/upper limits

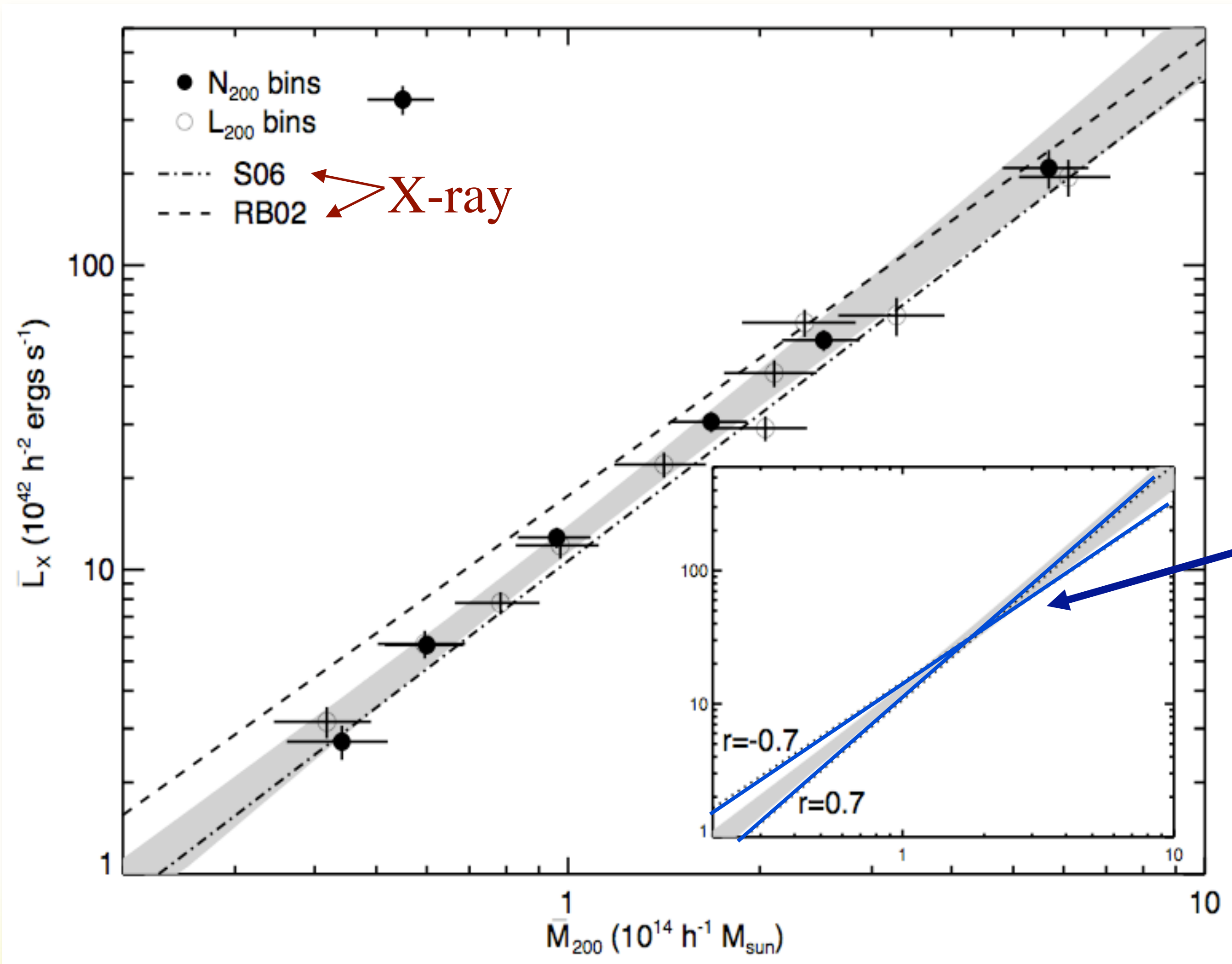


mean L_X–M of N_{gal}–selected sample

17000 clusters, $N_{gal} \geq 9$

Johston et al 2007
Rykoff et al 2008b

M_{200} from weak lensing, L_X from RASS (stacked N_{gal} bins)



Good agreement between X-ray and optically selected samples

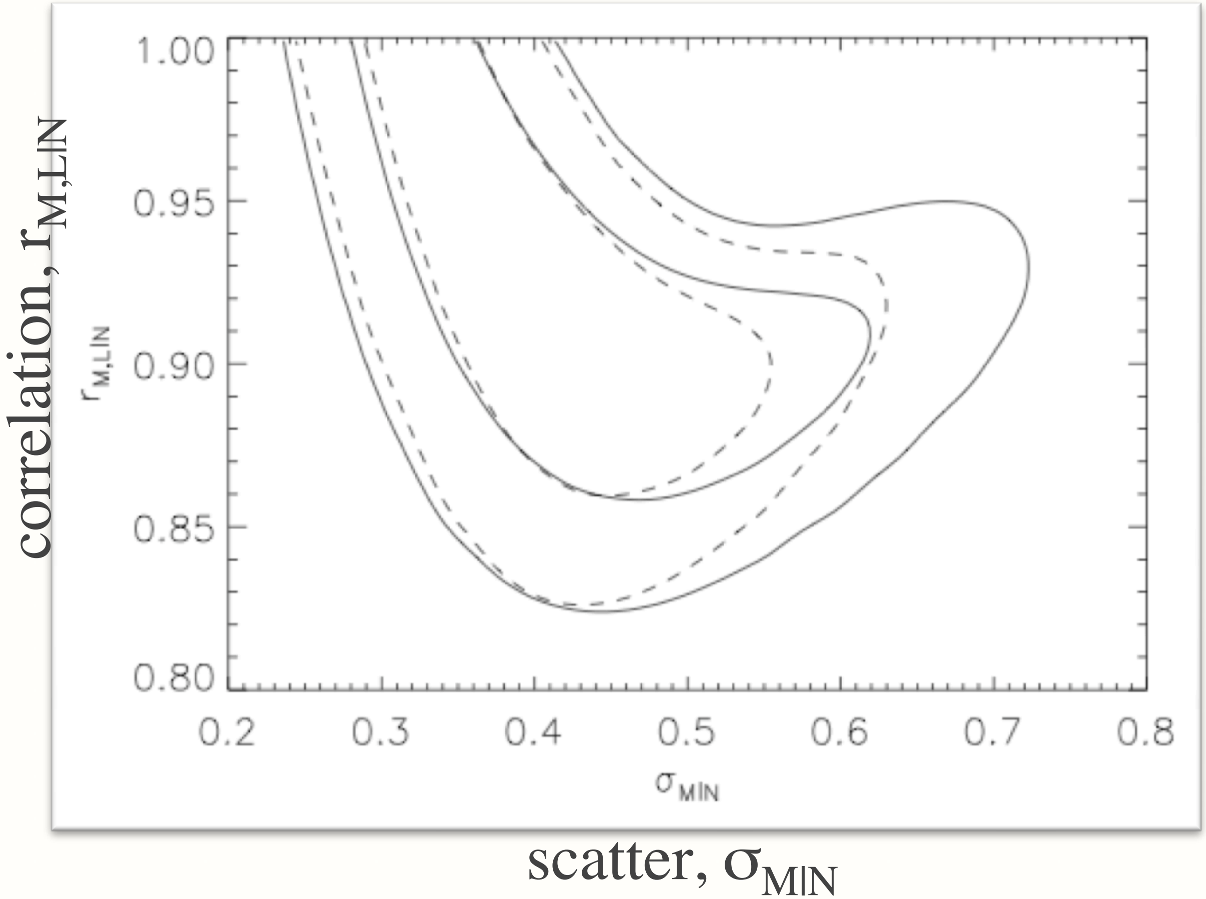
slope = 1.6 ± 0.1

potential ***tilt*** due to optical–X-ray correlation and running of MF slope $\alpha(M)$.

(no formal constraint)

mass–N_{gal} variance and LM covariance

Rozo et al 2008b



solid: current L_X–M_{500} errors (~10%)
dashed: 5% errors on L_X–M_{500}

From SDSS-RASS:

- $dn(N_{200})/dN_{200}$
- L_X–N_{200} scaling
  slope, norm, scatter
- M_{200}–N_{200} scaling
  slope, norm

missing:

M_{200}–N_{200} scatter
M_{200}, L_X | N_{200} correlation

Extra information:

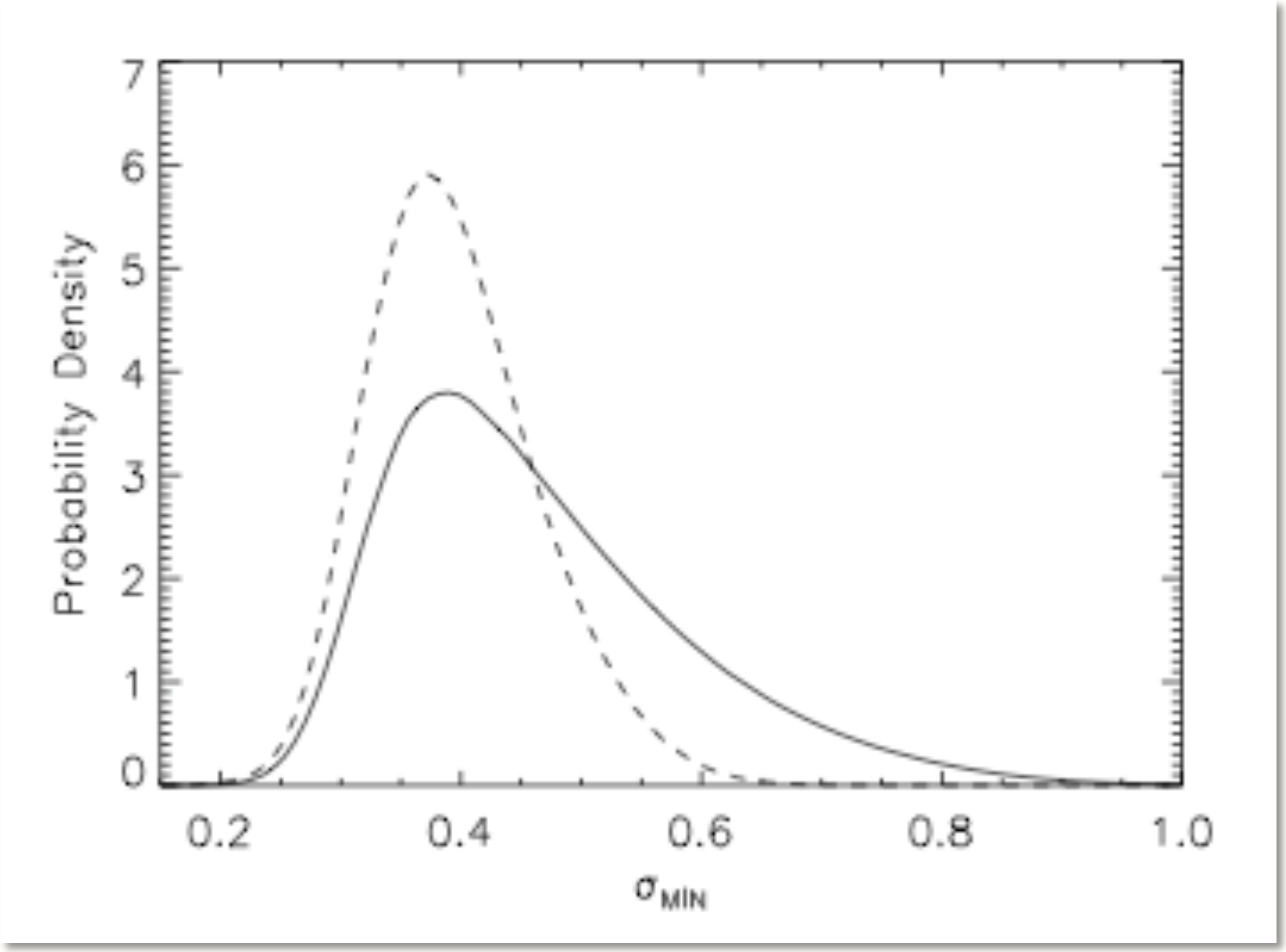
400d survey
L_X–M_{500} scaling
slope, norm, scatter

Vikhlinin et al (2008)

mass–N_{gal} variance constraint

Rozo et al 2008b

$$\sigma_{\ln M \mid N_{200}} = 0.45^{+0.20}_{-0.18} \ (95\% \text{ cl})$$

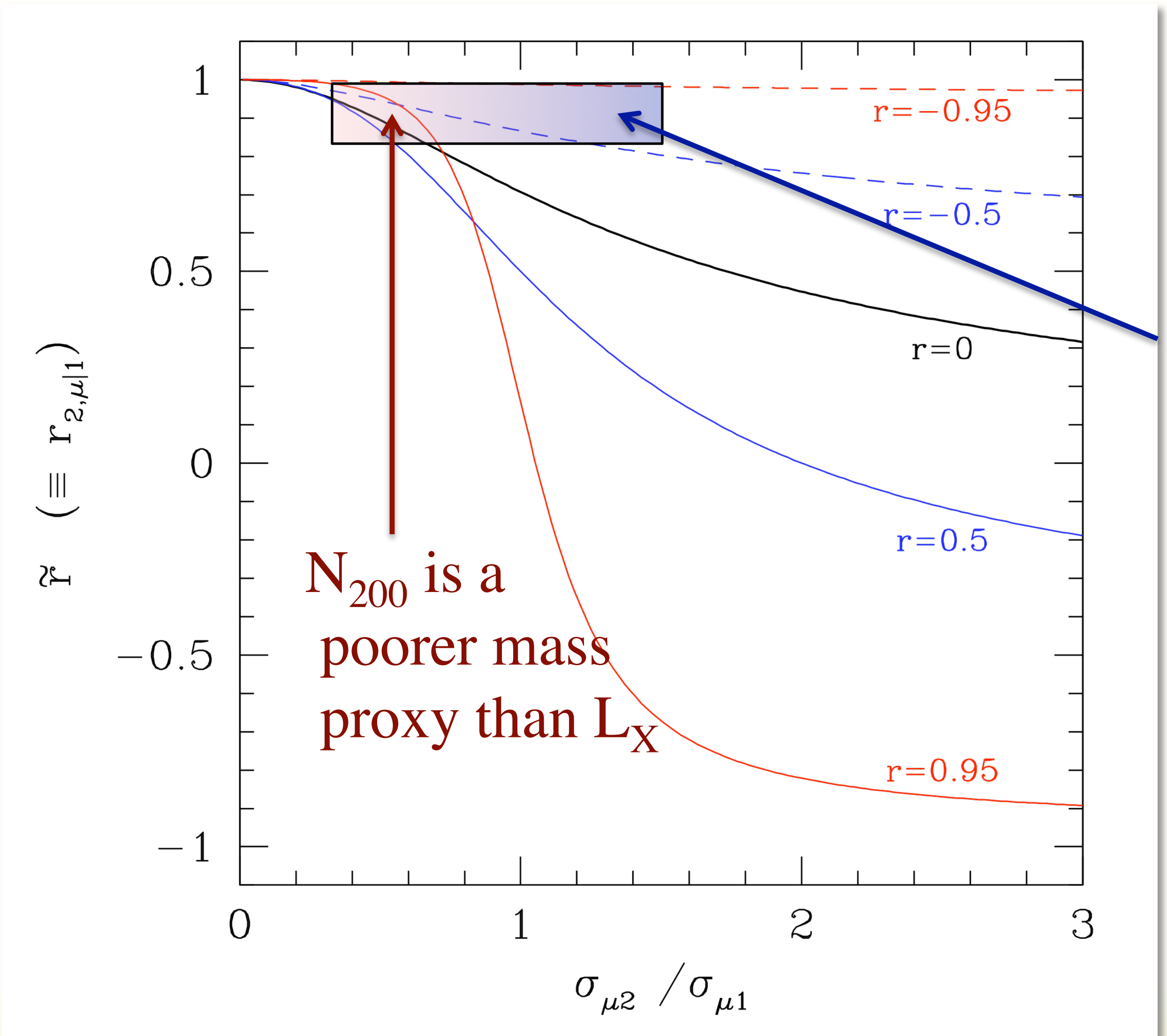


solid: current $L_X - M_{500}$ constraints
dashed: 5% errors on $L_X - M_{500}$

NOTE: scatter is uncorrected for projection and mis-centering

Error in variance is critical for survey self-calibration
Lima and Hu 2005

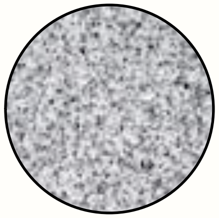
implications for L_X–N_{gal} correlation at fixed M?



N_{200} is a better mass proxy and N_{200} and L_X are anti-correlated at fixed halo mass


Prospects for Cluster Cosmology
Ann Arbor, MI
8-10 June 2009

summary



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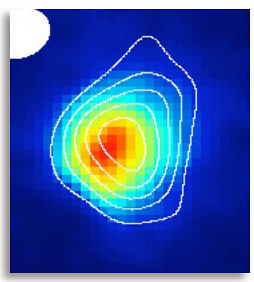

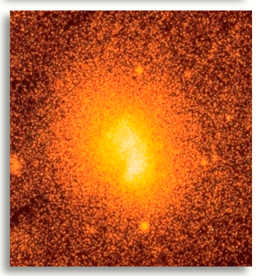

- understanding signal covariance is an important ingredient in precision cosmology with clusters
- large, multi-wavelength cluster surveys invite studies of covariance of multiple halo signals (mass proxies)
- SDSS + RASS + 400d = <u>first measurements</u> of N–M variance and L,M | N correlation
- areas for further study
  - survey selection and projection effects
  - redshift / mass dependences of signal-mass relation
  - hot gas/galaxy covarince from simulations

looking forward to DES + SPT + eRosita! (+ many others)