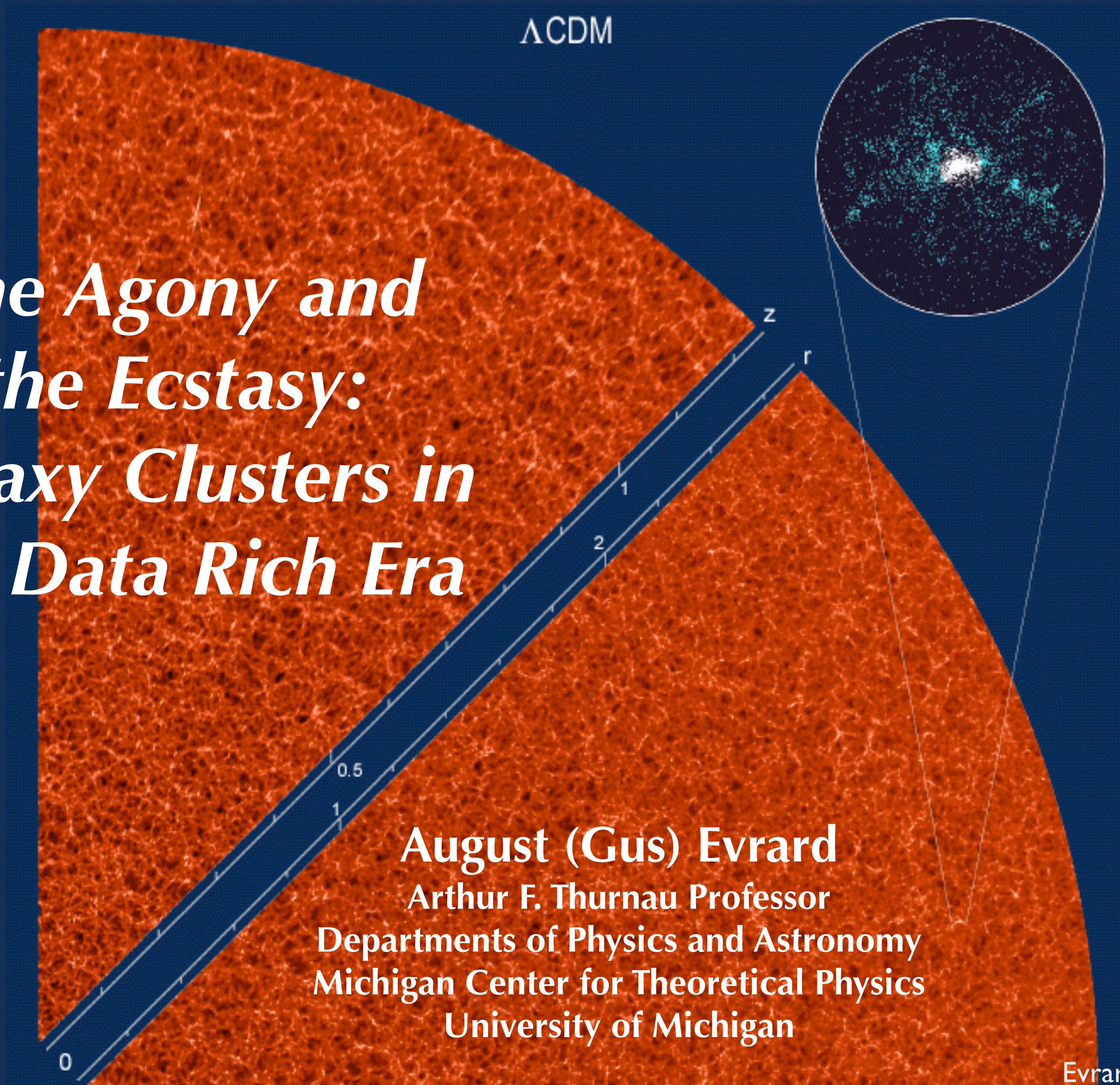
The Agony and the Ecstasy: Galaxy Clusters in the Data Rich Era



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Departments of Physics and Astronomy
Michigan Center for Theoretical Physics
University of Michigan

Evrard et al 2002


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Director: Carol Reed
Writers: Irving Stone (novel)
Philip Dunne (screen story and screenplay)
Contact: View company contact information for The Agony and the Ecstasy on IMDbPro.
Release Date: 7 October 1965 (USA) more
Genre: Drama | History more
Tagline: From the age of magnificence comes a new magnificence in motion pictures more
Plot: The biographical story of Michelangelo's troubles while painting the Sistine Chapel at the urging of Pope Julius II.
full summary | add synopsis
Plot Keywords: Spoiler alert! Rollover or vote to view plot keyword: more
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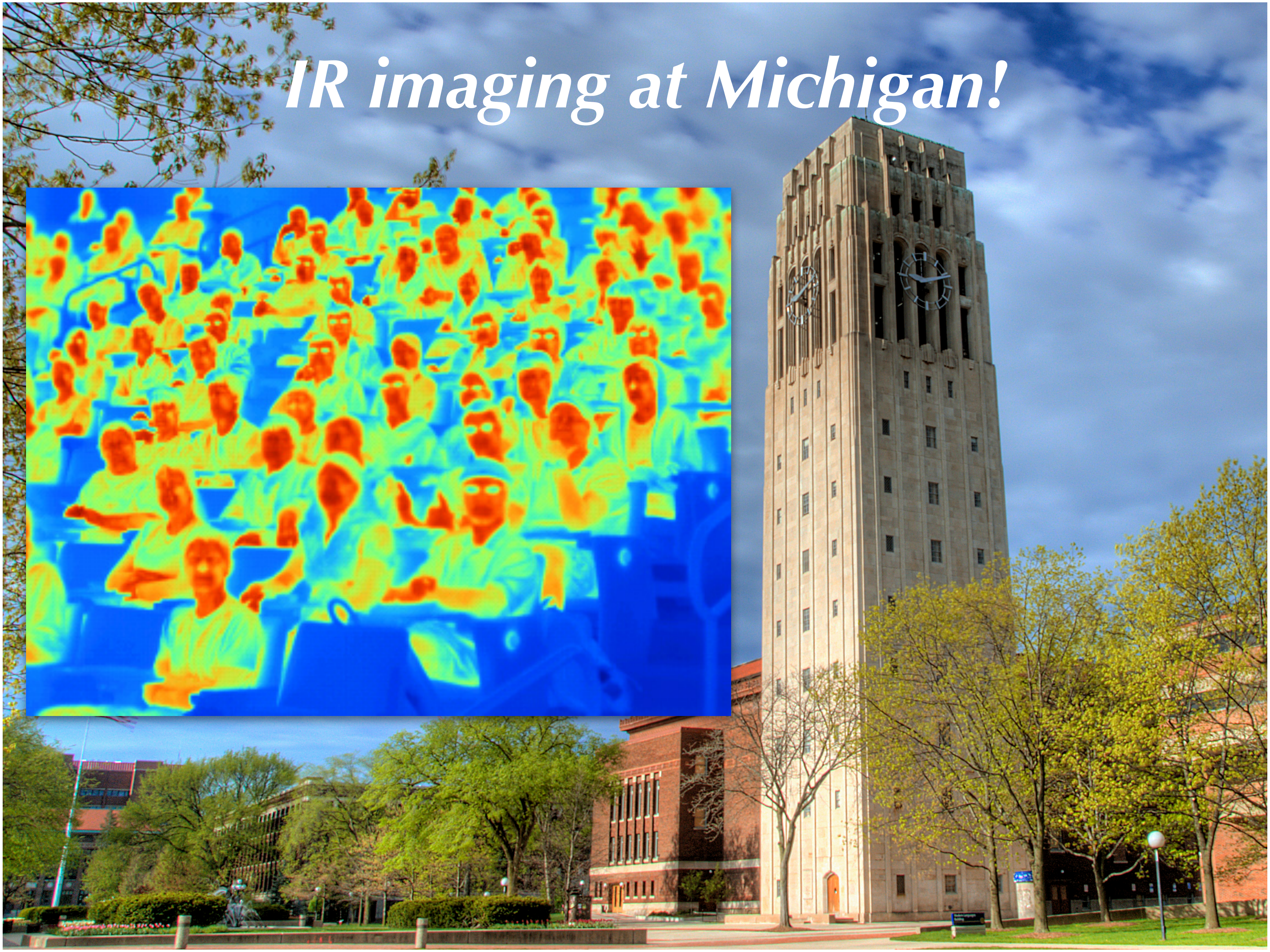
I will be finished
when I am done!

Michaelangelo,
when will you be
finished ?!

IR imaging at Michigan!



The ecstasy:
new physics!

Use cluster signatures (and other probes) to convincingly demonstrate a non-trivial dark energy equation of state, $w \neq -1$.

The agony: <u>systematics</u>!

1. 3D halo mass is not observable
   need accurate ***form*** of observable-mass scaling relations, $p(M_{obs}, z_{obs} \mid M, z)$

2. We observe on the sky, not in real-space
   must model cluster-halo selection function including projection effects along Gpc sight-lines

3. Require theory to map counts to cosmological parameters
   N-body simulation calibrations need to include baryons

4. Cluster redshifts (≥10k of them!) are needed
   require mapping from photometric to spectroscopic z's

Some definitions

1. **Halo -**

   a self-bound, quasi-equilibrium cosmic structure comprised of multiple interacting fluids (dark matter, multi-phase baryons, and radiation)

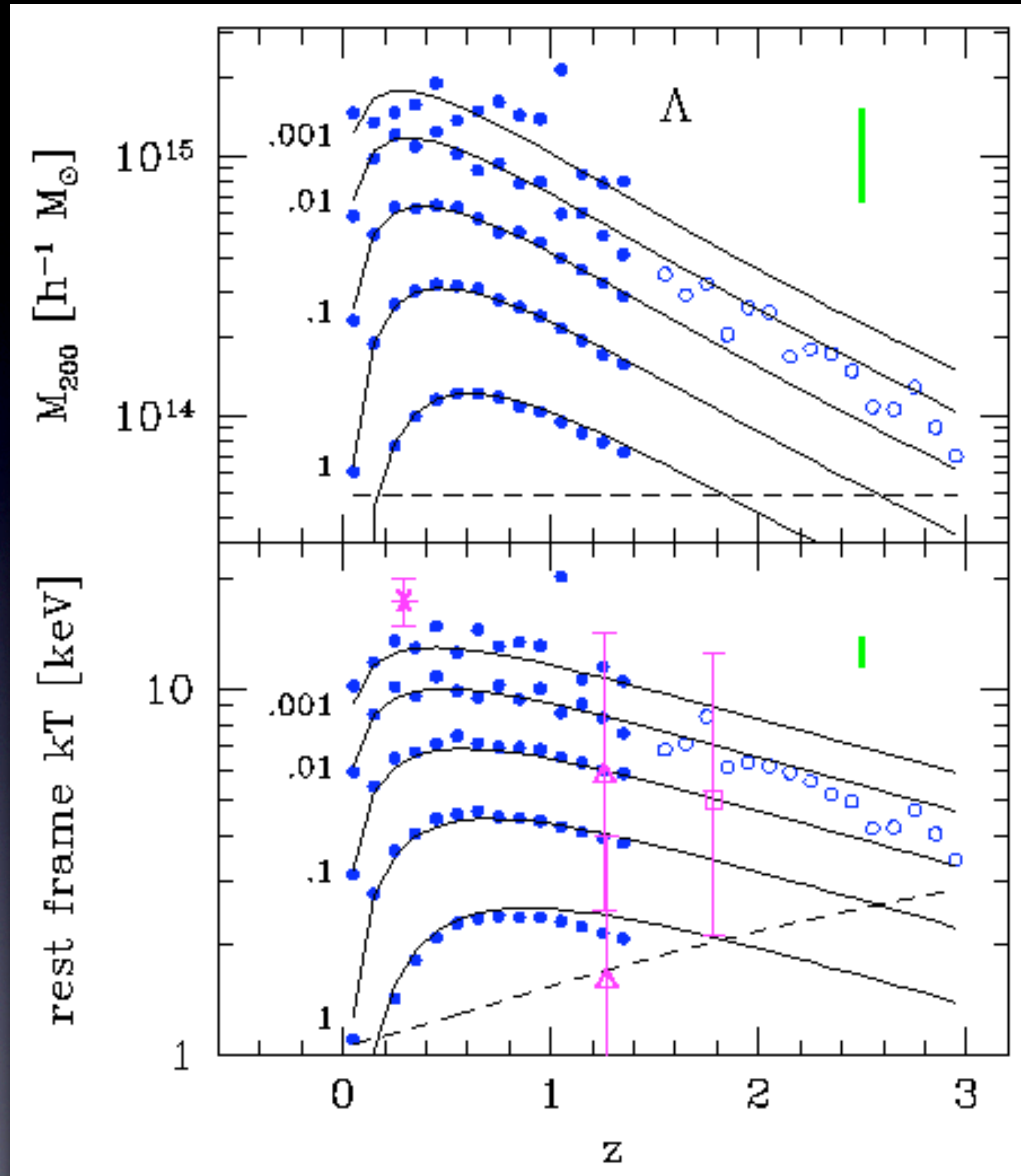
2. **Cluster -**

   an observable manifestation of a massive halo containing multiple, bright galaxies

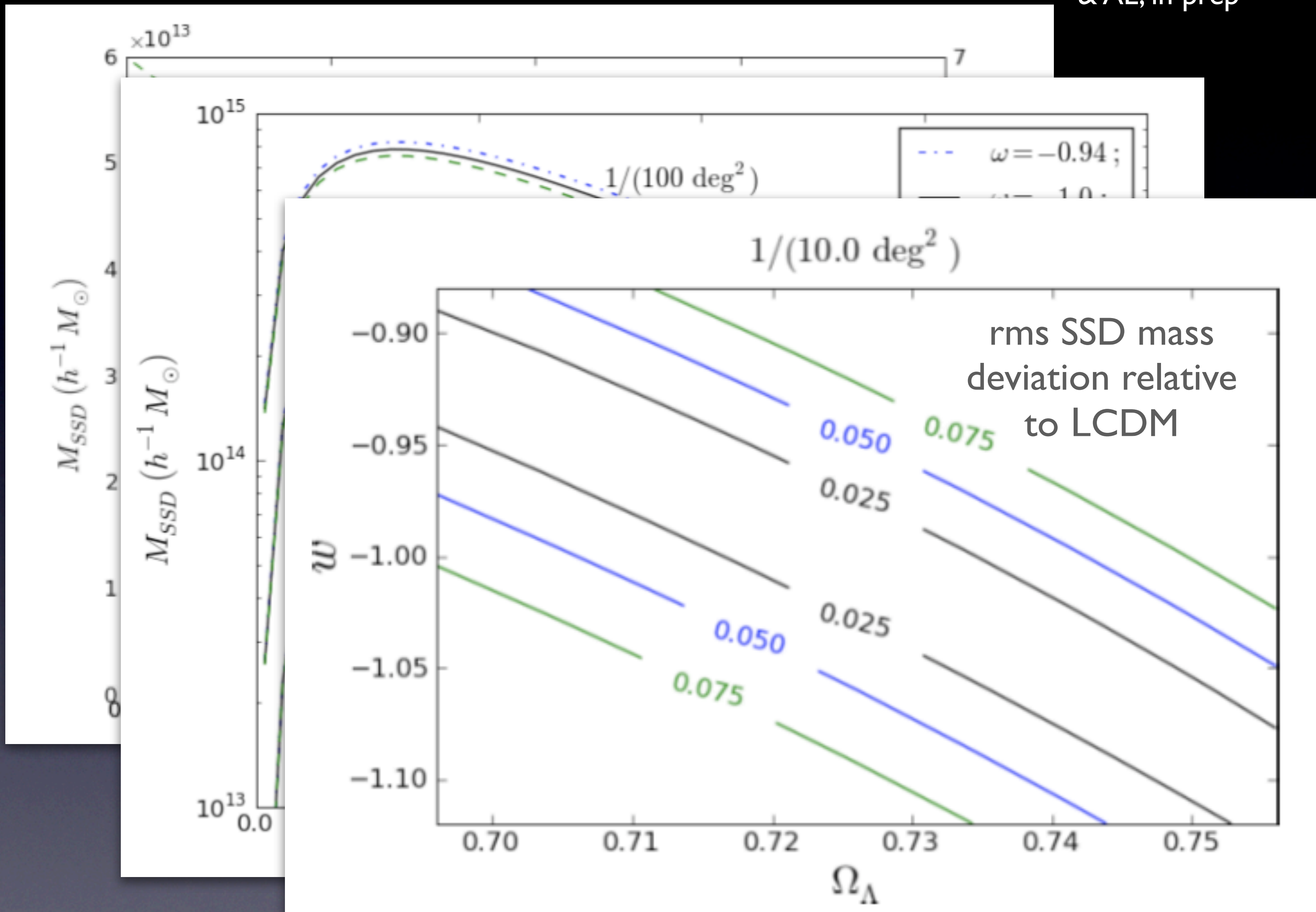
sky surface density
characteristic mass
and temperature

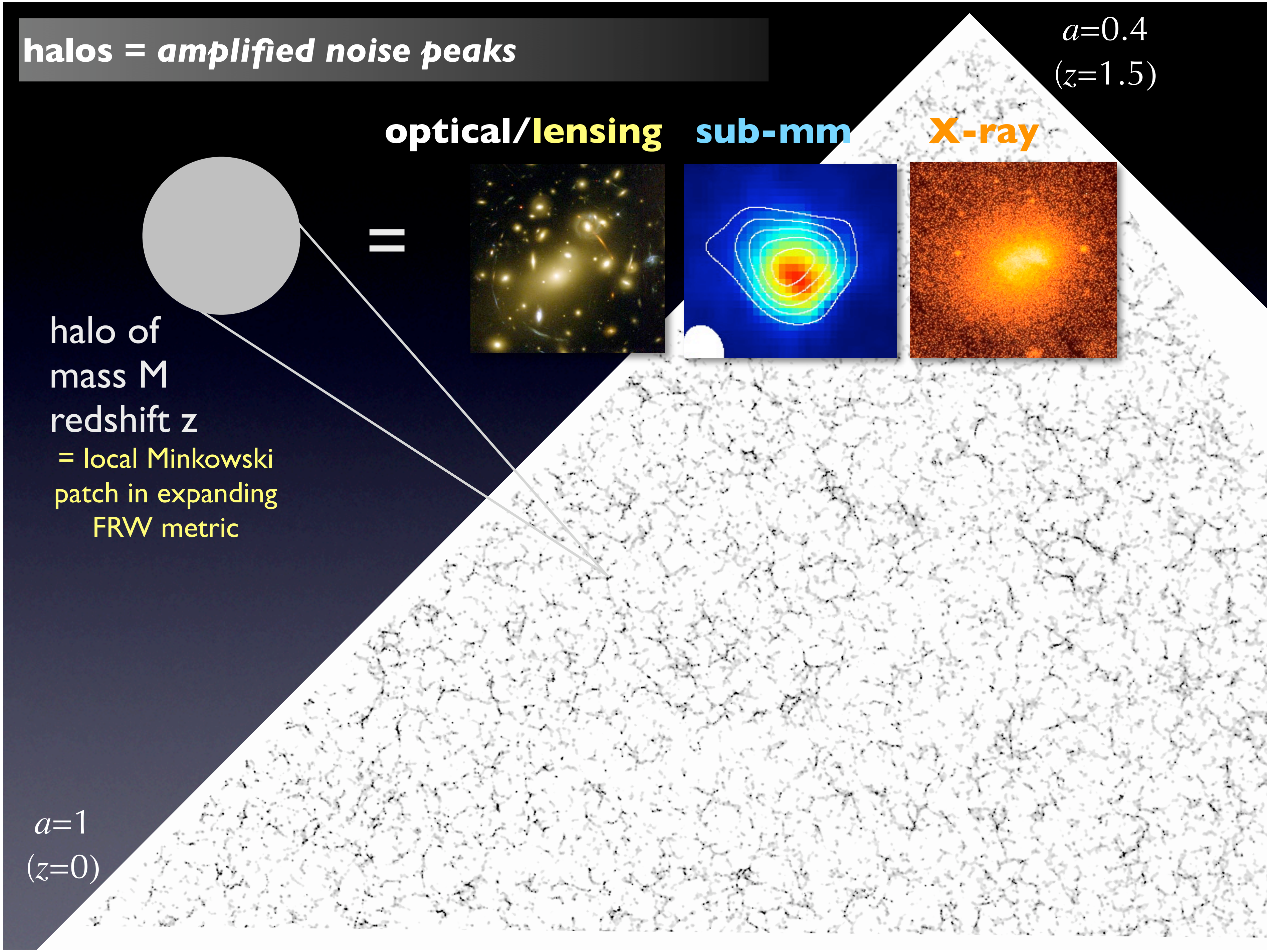
values obtained by ranking halos in thin redshift shells, identifying scales reached at fixed dN/dz
(# / sq deg / unit z)

Evrard et al 2002



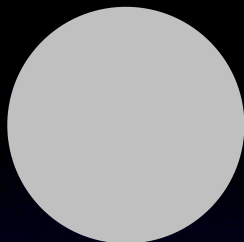
UMich undergrad Greg Green & AE, in prep




halos = amplified noise peaks
a=0.4
(z=1.5)
optical/lensing
sub-mm
X-ray
=
halo of
mass M
redshift z
= local Minkowski
patch in expanding
FRW metric
a=1
(z=0)

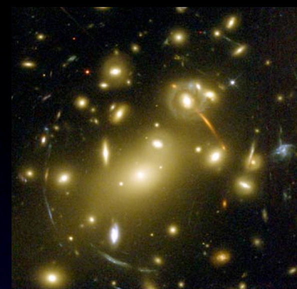
massive halo phenomenology: observable signal likelihoods

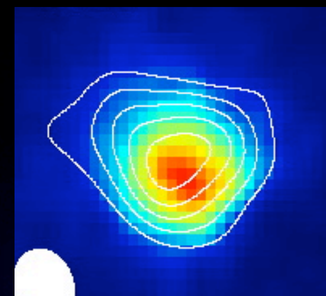
optical/lensing sub-mm X-ray

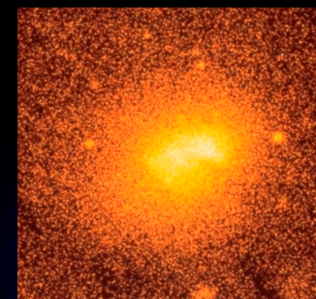


halo of
mass M
redshift z

=







"Astrophysics for Dummies"

1. Dimensional analysis => mean relations are power-laws

2. Central Limit Theorem => deviations are log-normal

power-law mean + log-normal covariance model for signals

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

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

$$\mu = \ln M$$

and the halo signal likelihood is

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

with covariance

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

local approach to the signal space density

Take a (locally) power-law mass function

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

and convolve it with the signal–mass relation to find the

signal space density

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

with mean mass

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

and mass variance

$$\Sigma^2 = \left(\mathbf{m}'\Psi^{-1}\mathbf{m}\right)^{-1}$$

signal selection effects

Select a halo sample based on some signal, s_1.

Then the {mass, s_2} likelihood is Gaussian with covariance

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

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

$\sigma_{\mu i} = \sigma_i / m_i$ ass scatter

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

and the s_2–mass scaling for s_1-binned samples may be biased

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

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

collaborators and topics

+ Heidi Wu's talk

Fisher forecasts

Huterer
Cunha
Smith

simulations

Rasia
Stanek
Nord
Chen
Rudd (IAS)
Pearce (Nottingham)

clusters as massive halos

optical surveys
SDSS maxbcg
=> DES

McKay
Wechsler (Stanford)
Hao (Fermilab)
Koester (Chicago)
Rozo (Chicago)
Rykoff (UCSB)
Sheldon (BNL)
Johnston (JPL)
Becker (Chicago)

Fall 2009: Jeff McMahon (SPT) joins Physics
Winter 2010: Chris Miller (SDSS C4) joins Astronomy

SDSS maxbcg analysis

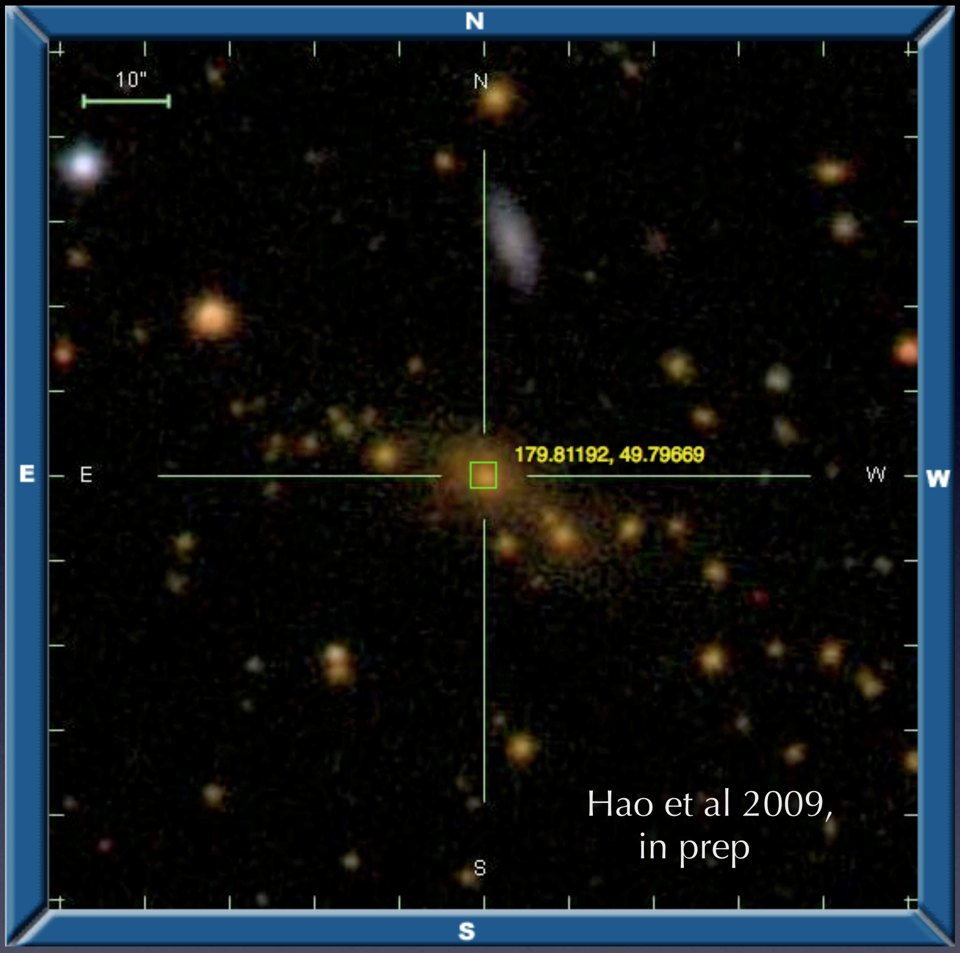
SDSS maxbcg cluster sample studies

~13,000 clusters, ≥10 galaxies

$0.1<z<0.3$

based on excess counts of *g–r* red sequence galaxies

Koester et al 2007a,b



Hao et al 2009, in prep

extension to r–i pushes to higher z

$N_{gals}=79$, $z=0.35$

follow-up studies:

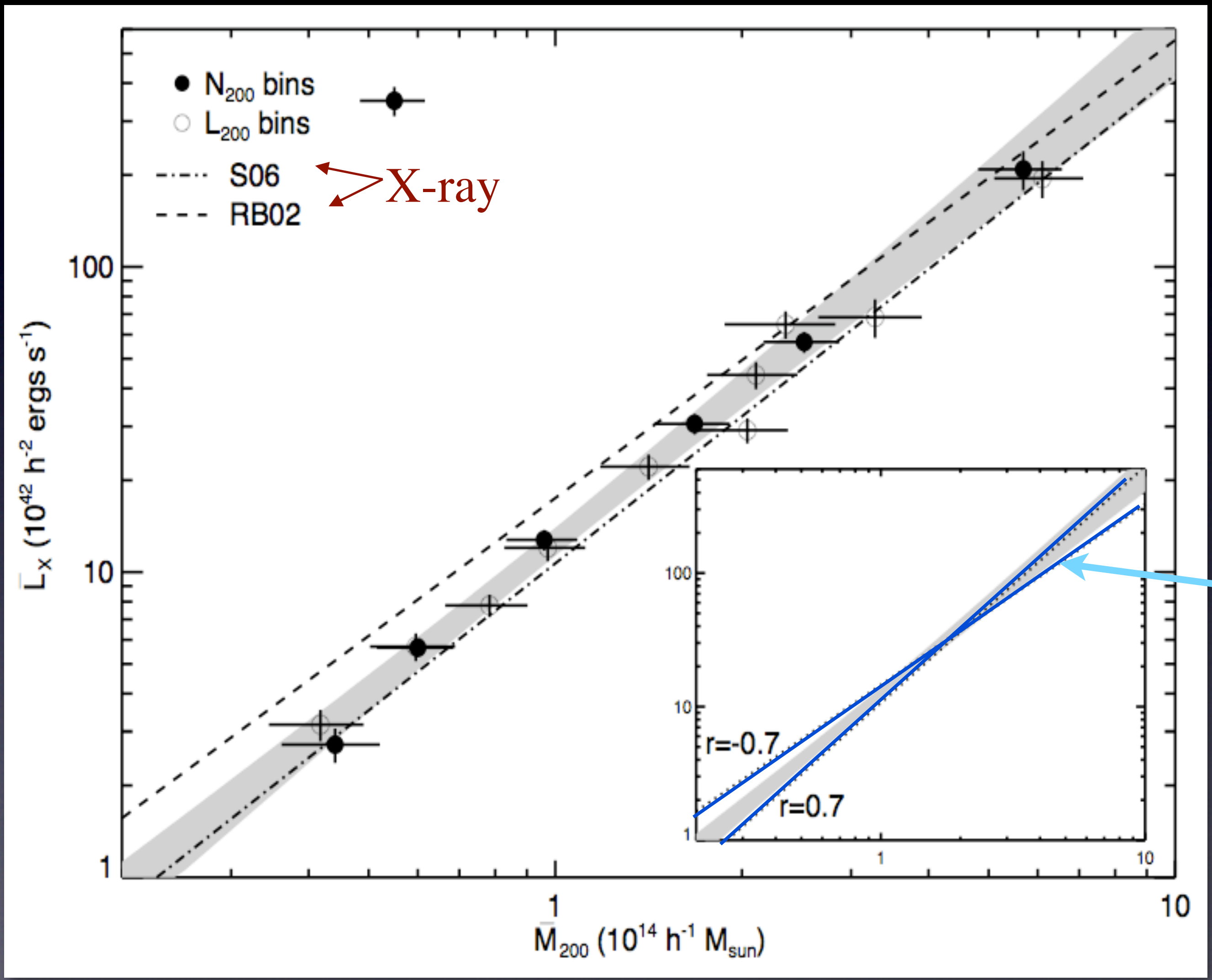
- ★ stacked weak lensing masses
  Johnston etal 2007; Sheldon etal 2007
- ★ velocity dispersion–richness
  Becker et al 2007
- ★ X-ray luminosity–richness
  Rykoff et al 2008a
- ★ X-ray luminosity–lensing mass
  Rykoff et al 2008a
- ★ improved richness estimator
  Rozo et al 2008a
- ★ scatter in mass–richness
  Rozo et al 2008b
- ★ cosmological constraints
  Rozo et al 2009

mean Lx-Mass scaling

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

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

Johston et al 2007
Rykoff et al 2008b



Good agreement between X-ray and optically selected samples

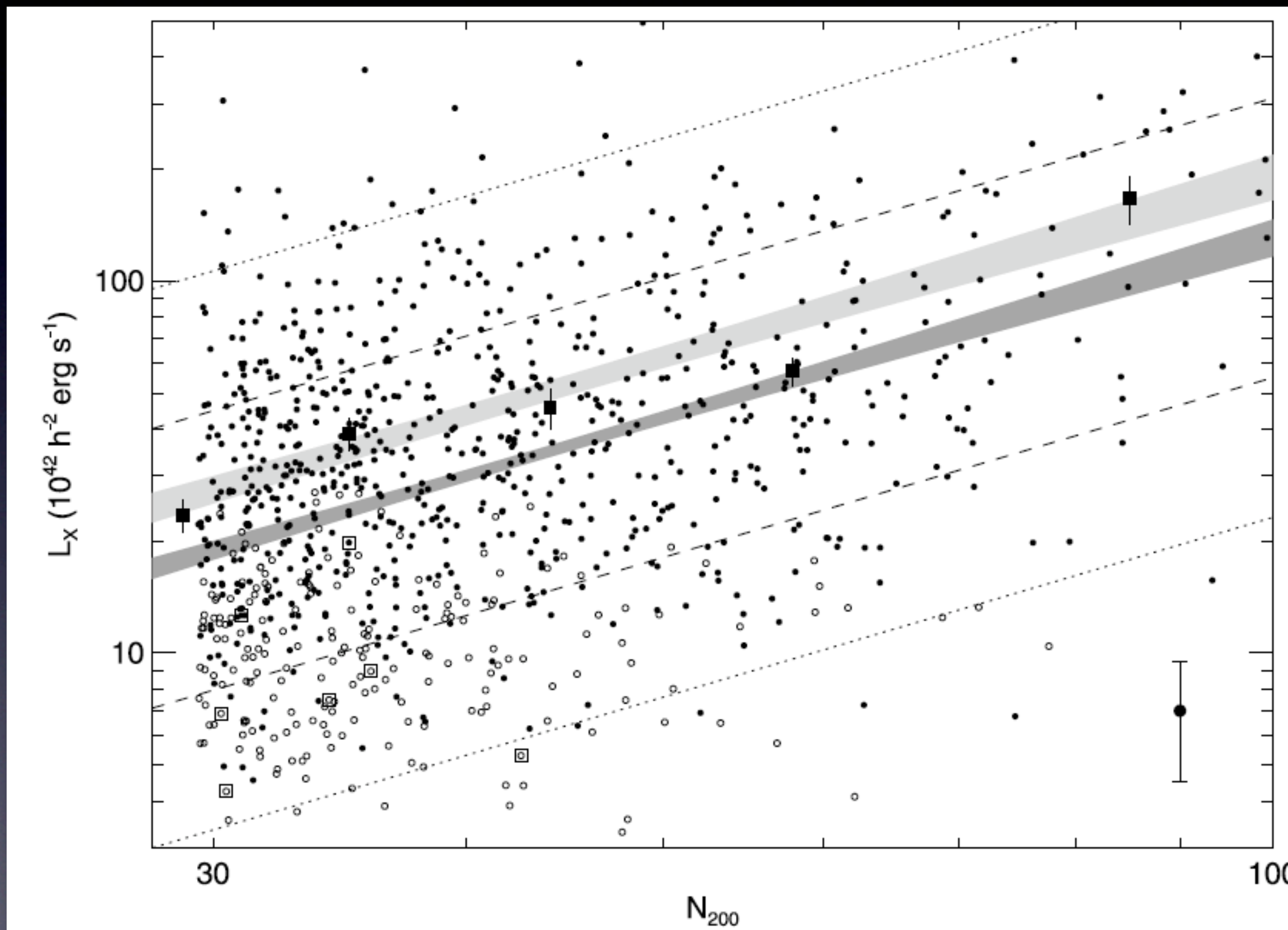
slope = 1.6 ± 0.1

potential ***tilt*** due to optical–X-ray correlation and running of MF slope

Lx variance at fixed optical richness

Rykoff et al 2008a

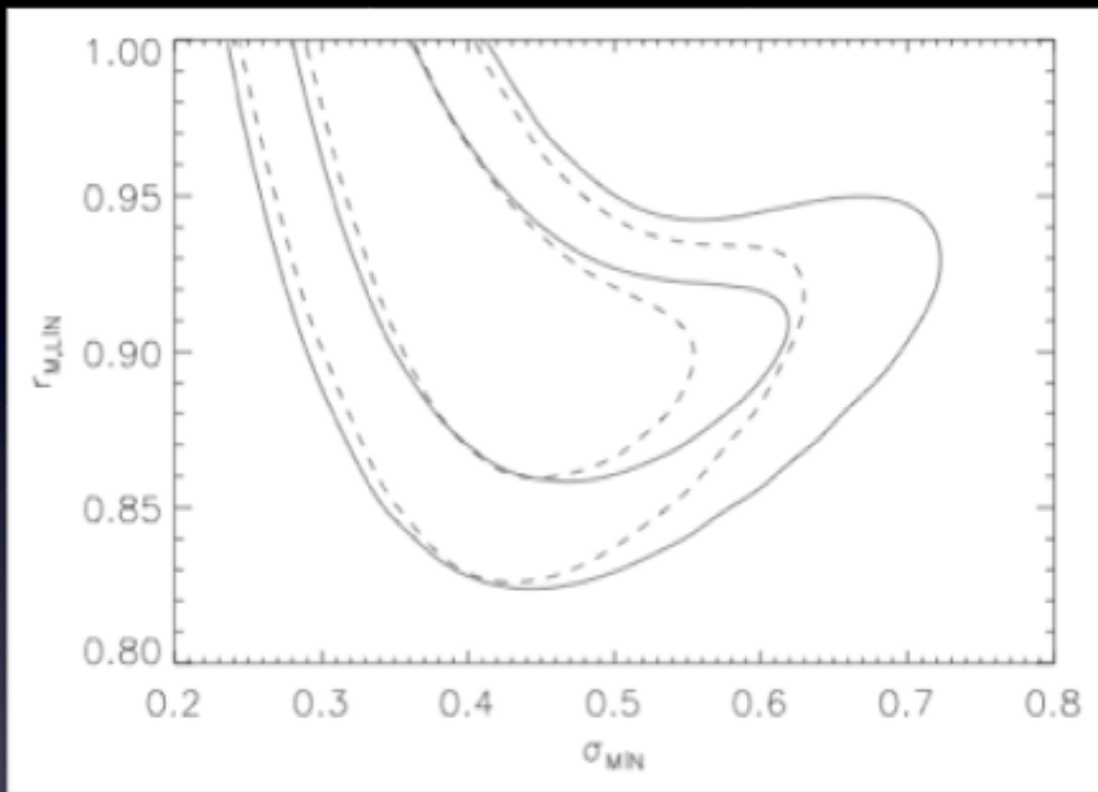
variance in Lx at fixed Ngal $\sigma_{\ln L_X | N_{gal}} = 0.83 \pm 0.03$



first measurement **of property covariance for clusters**

Rozo et al 2008b

correlation, $r_{M,L|N}$



scatter in ln(mass) at fixed Ngal

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

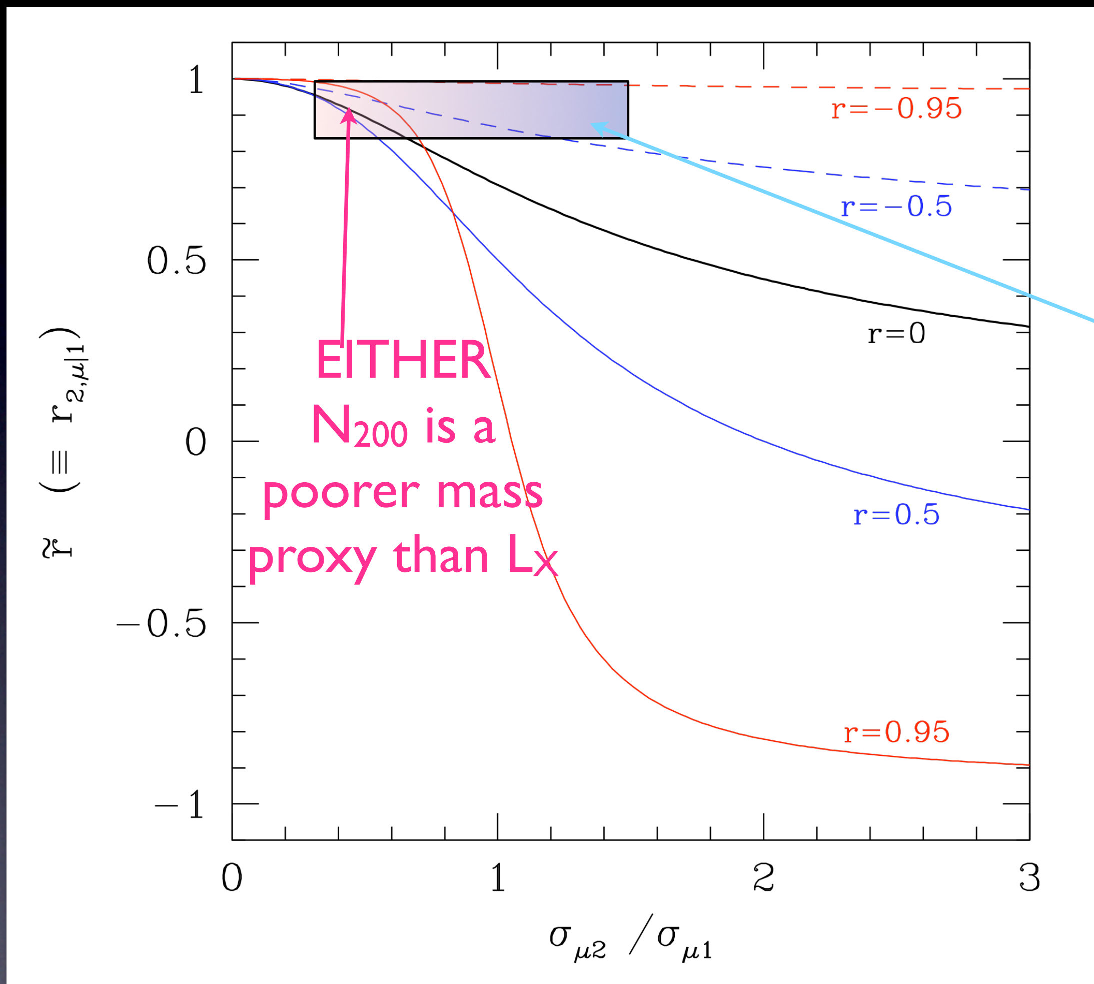
L_X –M_{500} scaling

slope, norm, scatter

Vikhlinin et al 2008

what does a large covariance in mass and Lx mean?

correlation, $r_{M,L|N}$



OR
N_{200} is a better mass proxy <u>and</u> N_{200} and L_X are anti-correlated at fixed halo mass

ratio of rms mass variance (Lx / Ngal)

cosmological constraints from maxbcg counts and lensing

Rozo et al 2009

COSMOLOGICAL CONSTRAINTS FROM THE SDSS MAXBCG CLUSTER CATALOG

Eduardo Rozo[1], Risa H. Wechsler[2], Eli S. Rykoff[3], James T. Annis[4], Matthew R. Becker[5,6], August E. Evrard[7,8,9], Joshua A. Frieman[4,6,10] Sarah M. Hansen[11], Jiangang Hao[7], David E. Johnston[12], Benjamin P. Koester[6,10], Timothy A. McKay[7,8,9], Erin S. Sheldon[13], David H. Weinberg[1,14]

Draft version February 21, 2009

ABSTRACT

We use the abundance and weak lensing mass measurements of the SDSS maxBCG cluster catalog to simultaneously constrain cosmology and the richness–mass relation of the clusters. Assuming a flat ΛCDM cosmology, we find $\sigma_8(\Omega_m/0.25)^{0.41} = 0.832 \pm 0.033$ after marginalization over all systematics. In common with previous studies, our error budget is dominated by systematic uncertainties, the primary two being the absolute mass scale of the weak lensing masses of the maxBCG clusters, and uncertainty in the scatter of the richness–mass relation. Our constraints are fully consistent with the WMAP five-year data, and in a joint analysis we find $\sigma_8 = 0.807 \pm 0.020$ and $\Omega_m = 0.265 \pm 0.016$, an improvement of nearly a factor of two relative to WMAP5 alone. Our results are also in excellent agreement with and comparable in precision to the latest cosmological constraints from X-ray cluster abundances. The remarkable consistency among these results demonstrates that cluster abundance constraints are not only tight but also robust, and highlight the power of optically-selected cluster samples to produce precision constraints on cosmological parameters.

cosmological constraints from maxbcg counts and lensing

Rozo et al 2009

TABLE 3

Parameter[a]	Prior[b]	Importance[c]
σ_8	[0.4,1.2]	unrestrictive
Ω_m	[0.05,0.95]	unrestrictive
$\langle \ln N_{200} \| M_1 \rangle$	flat	unrestrictive
$\langle \ln N_{200} \| M_2 \rangle$	flat	unrestrictive
$\sigma_{N_{200}\|M}$	[0.1,1.5]	unrestrictive
β	1.00 ± 0.06; [0.5, 1.5]	restrictive

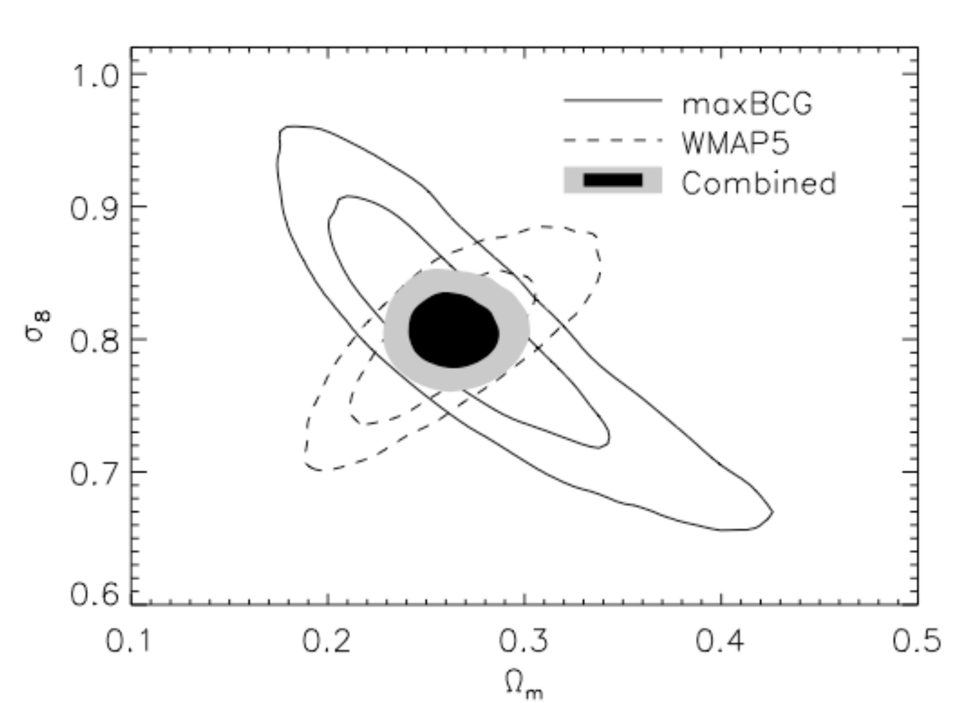


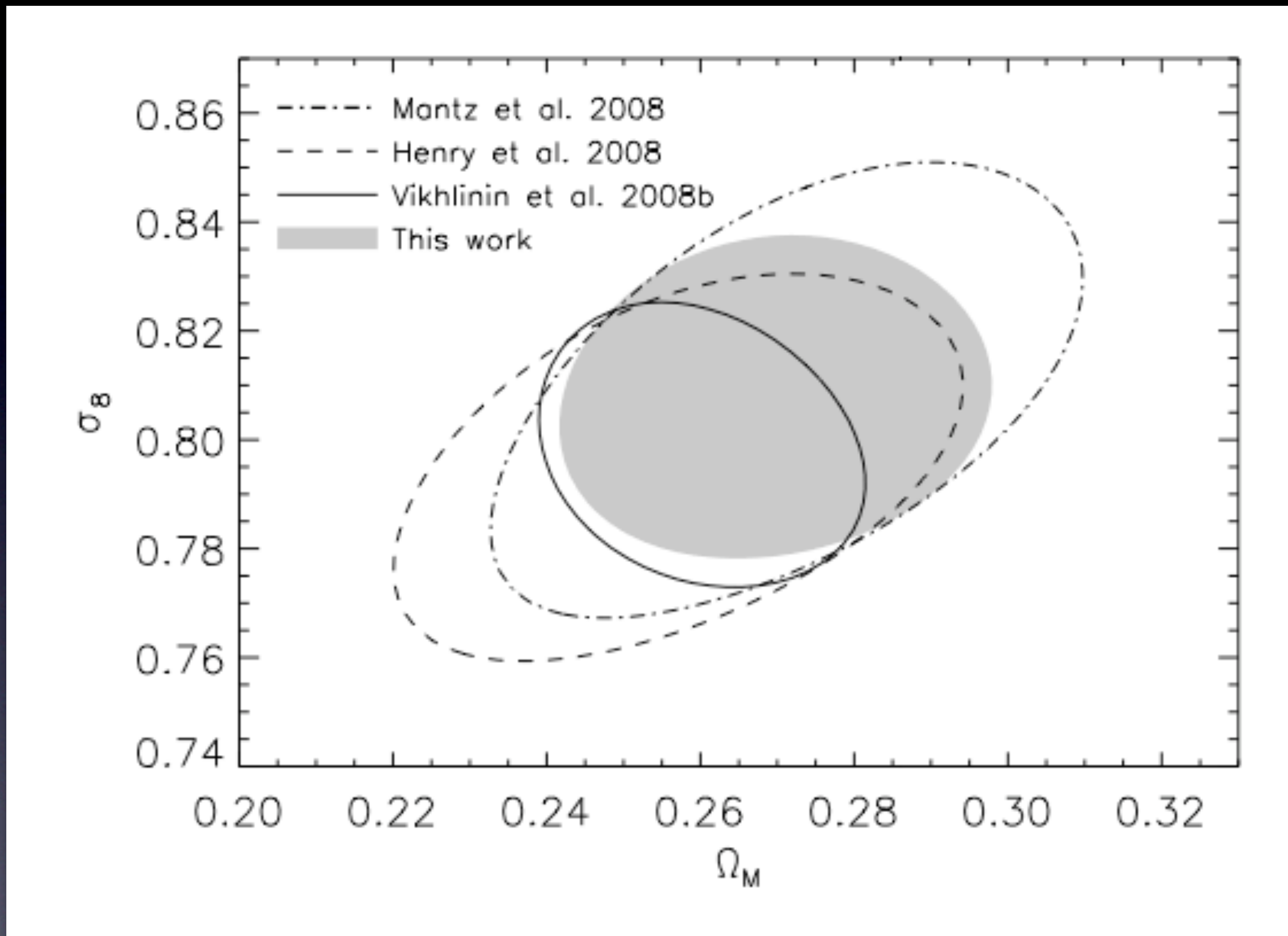
TABLE 4
BEST FIT MODEL

Parameter[a]	maxBCG	maxBCG+WMAP5[b]
σ_8	0.804 ± 0.073	0.807 ± 0.020
Ω_m	0.281 ± 0.066	0.269 ± 0.018
$\langle \ln N_{200} \| M_1 \rangle$	2.47 ± 0.10	2.48 ± 0.10
$\langle \ln N_{200} \| M_2 \rangle$	4.21 ± 0.19	4.21 ± 0.13
$\sigma_{N_{200}\|M}$	0.357 ± 0.073	0.348 ± 0.071
β	1.016 ± 0.060	1.013 ± 0.059

[a]The masses M_1 and M_2 are set to $1.3 \times 10^{14}\ M_\odot$ and $1.3 \times 10^{15}\ M_\odot$ respectively.
[b]These values are obtained by including the WAMP5 prior $\sigma_8(\Omega_m/0.25)^{-0.312} = 0.790 \pm 0.024$. See Section 4.3 for details.

comparison with X-ray constraints

Rozo et al 2009



SDSS analysis summary

- ★ red sequence finders identify ~same population as X-rays
- ★ stacked lensing masses + X-ray => Lx ~ M^(1.6 ±0.1)
- ★ scatter in mass-richness ~0.45 ± 0.09
- ★ beginning to explore covariance in Lx-Ngal

- ★ cosmological constraints

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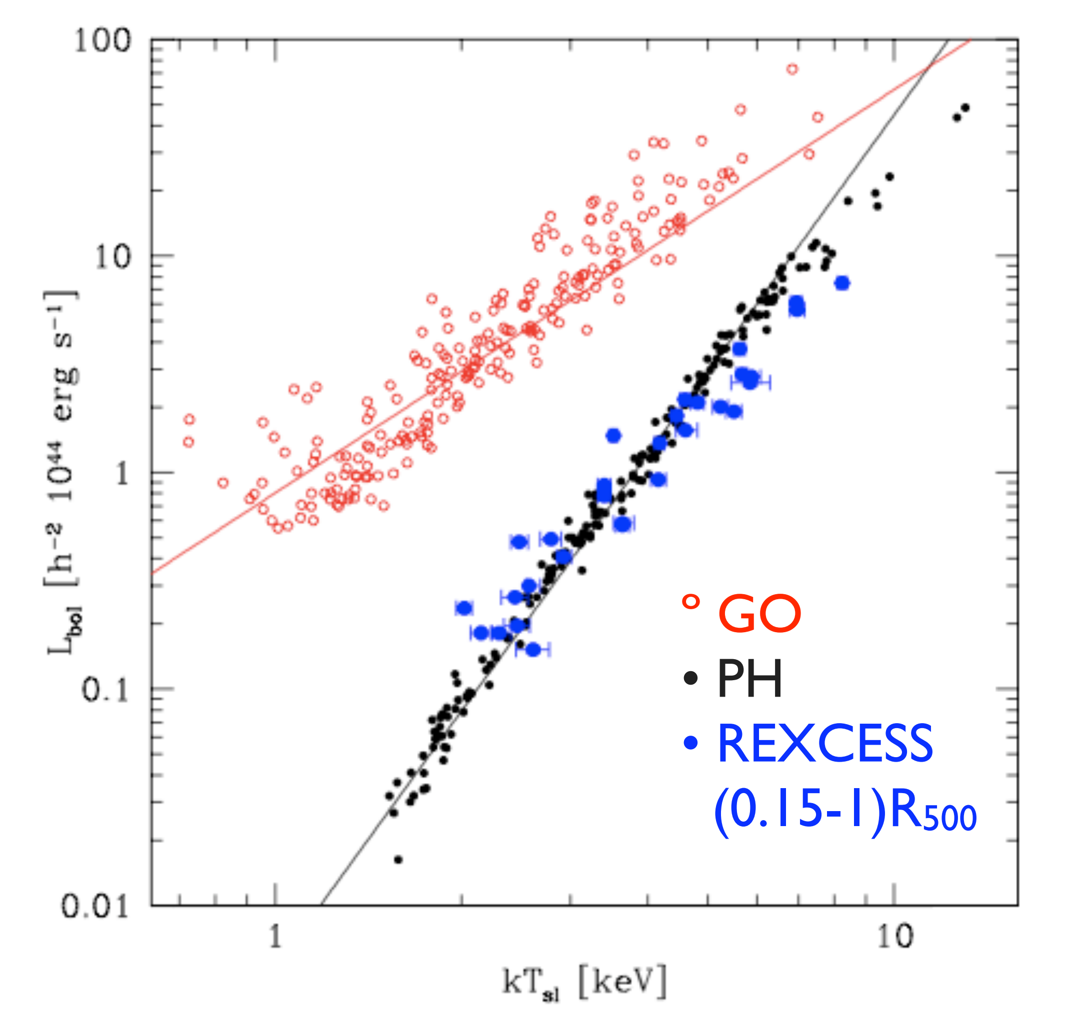
Millennium Gas Simulations (MGS)

Millennium Gas Simulations



GADGET-2 resimulations of Millennium Sim volume

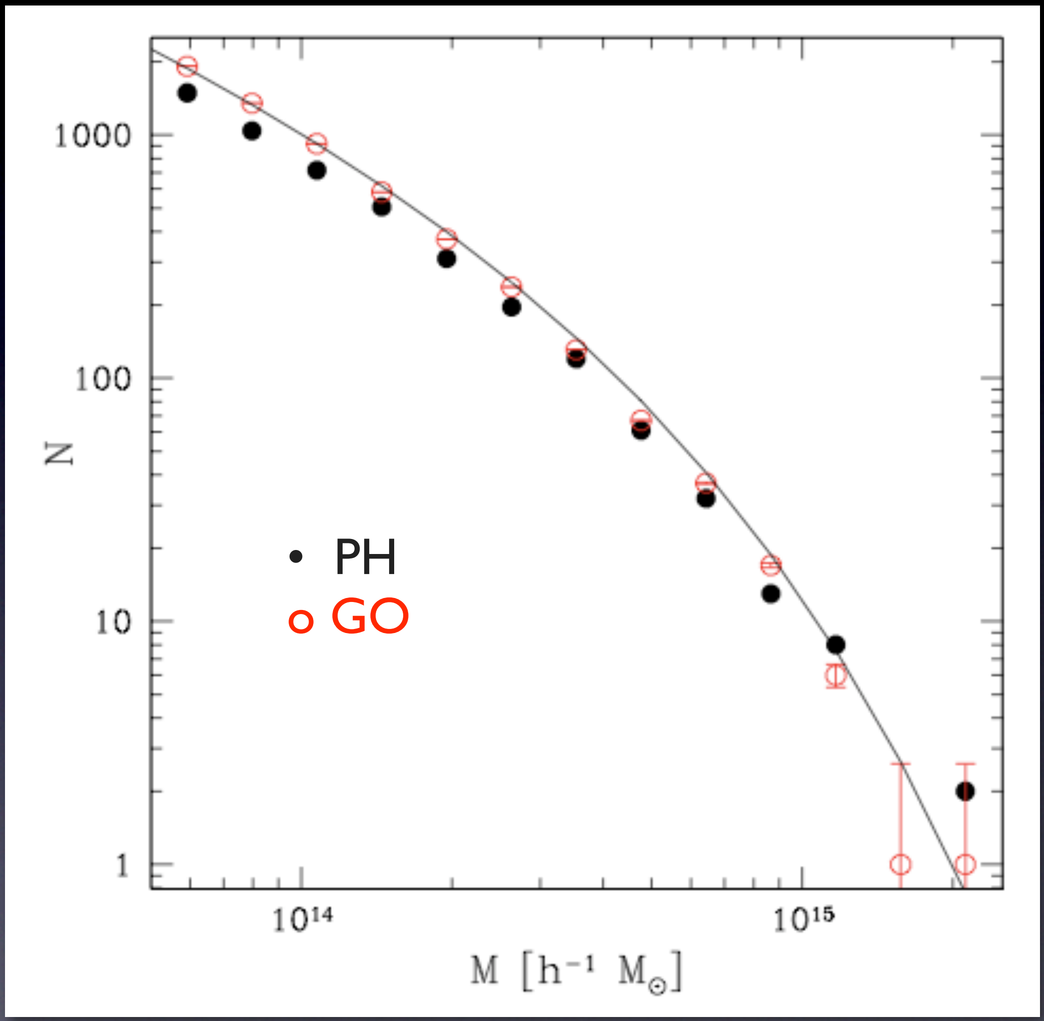
- 500 Mpc/h
- 1e9 gas+DM particles
- m_p(DM) ~ 1.4e10 Msun
- 25 kpc/h softening
- same cosmology as MS

<u>physical treatments:</u>

GO: gravity only

PH: preheated gas 200 keV-cm2 @z=4

MGS massive halo yield

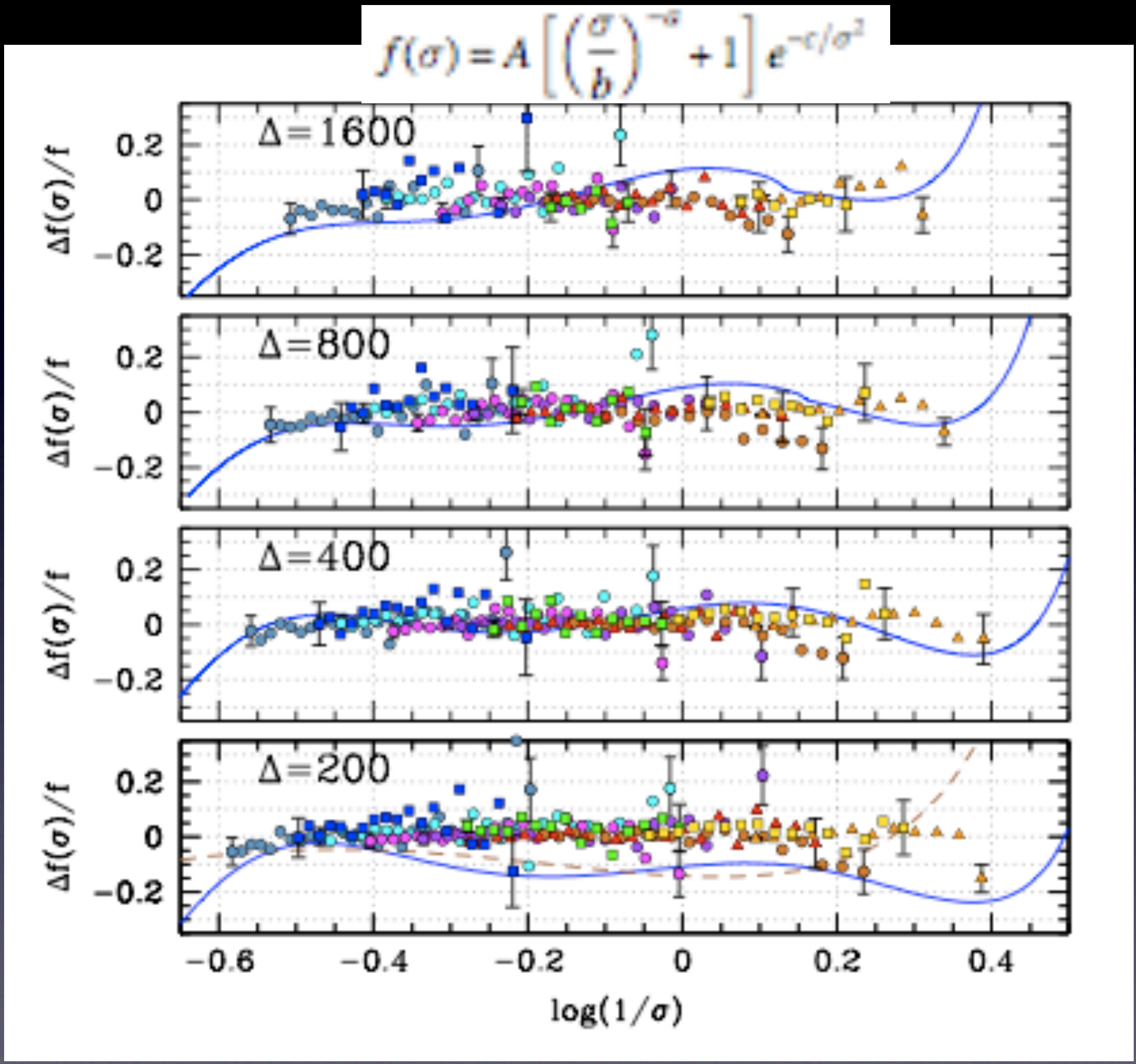


halos at z=0 with
$M_{200} \geq$ 5e13 Msun/h:

4474 (PH)
5612 (GO)

halo space density from large N-body simulations

Tinker et al (2008)



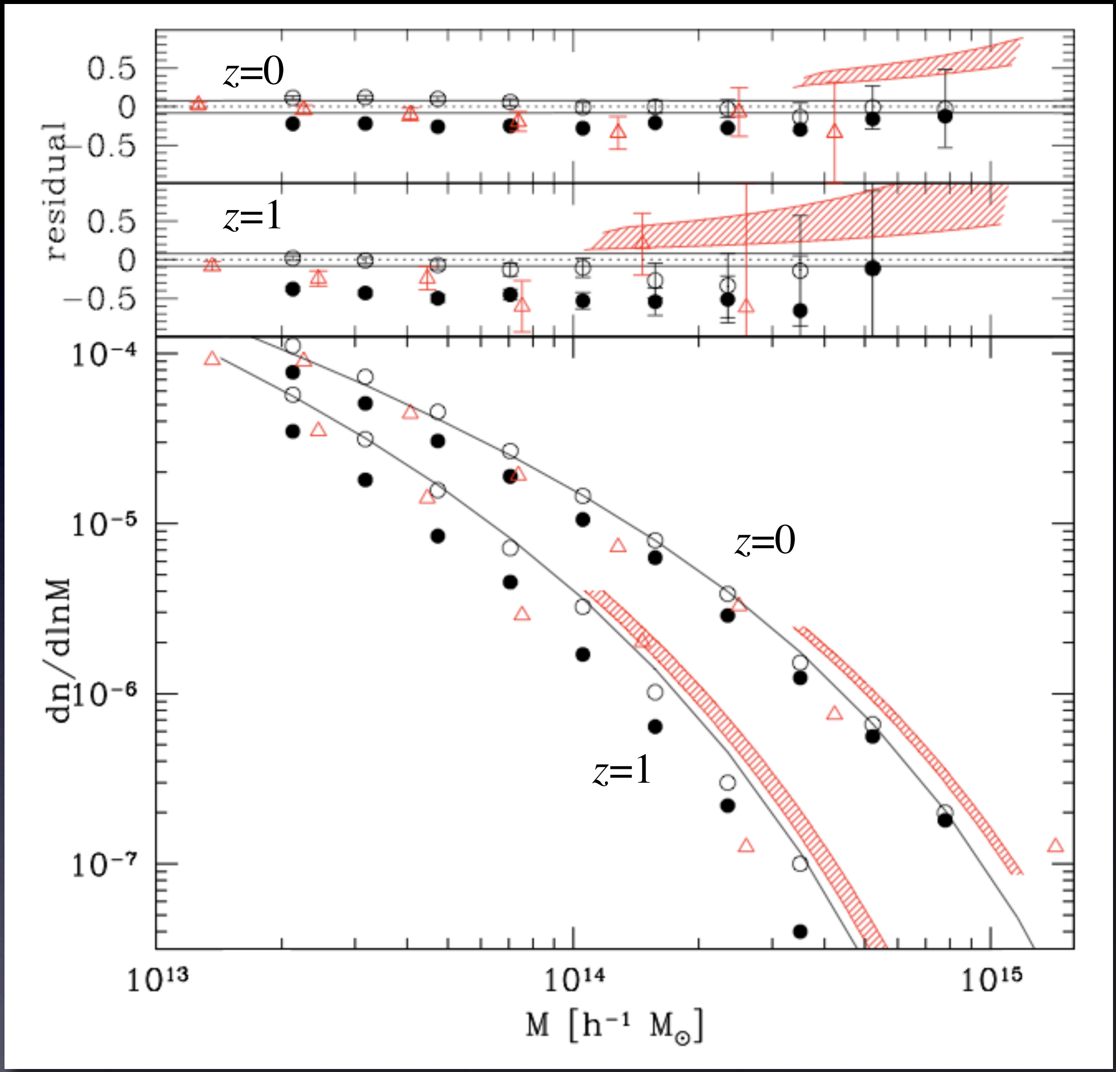
22 N-body simulations with N ≥ 512^3

– 5% statistical accuracy in counts

– similarity not exact in time (need *z*-factors)

see also:
Sheth & Tormen 1999
Reed et al 2000
Jenkins et al 2001
Evrard et al 2002
Hu & Kravtsov 2003
Warren et al 2006

sensitivity of halo space density to baryon physics



Stanek et al 2009

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

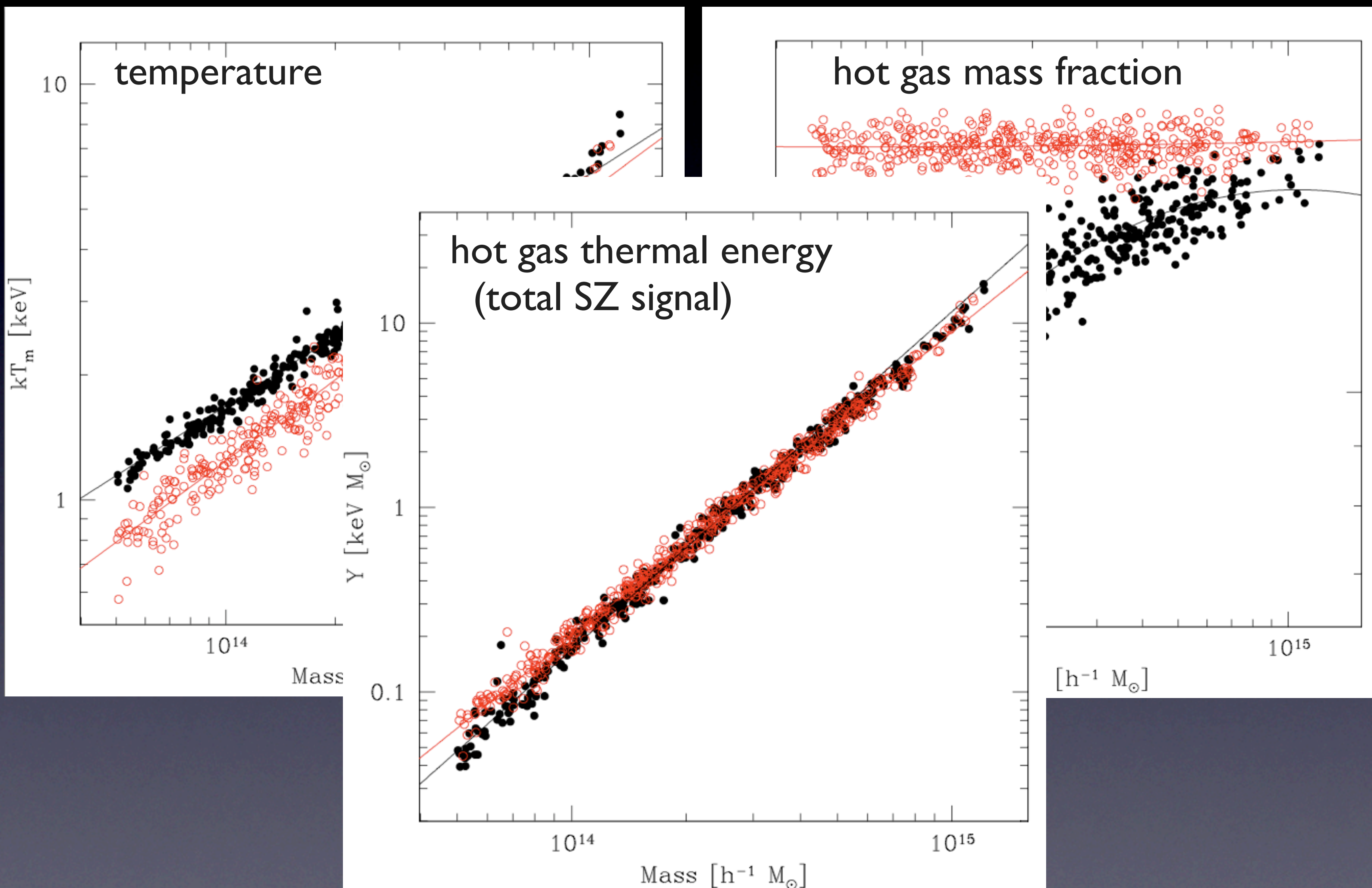
– **maximal** effects are >5% statistical error of Tinker et al (2008)

2 pairs of simulations

- o MGS-gravity only
- • MGS-preheat
- Δ ART-gravity only
- ART-cool/star/feedback

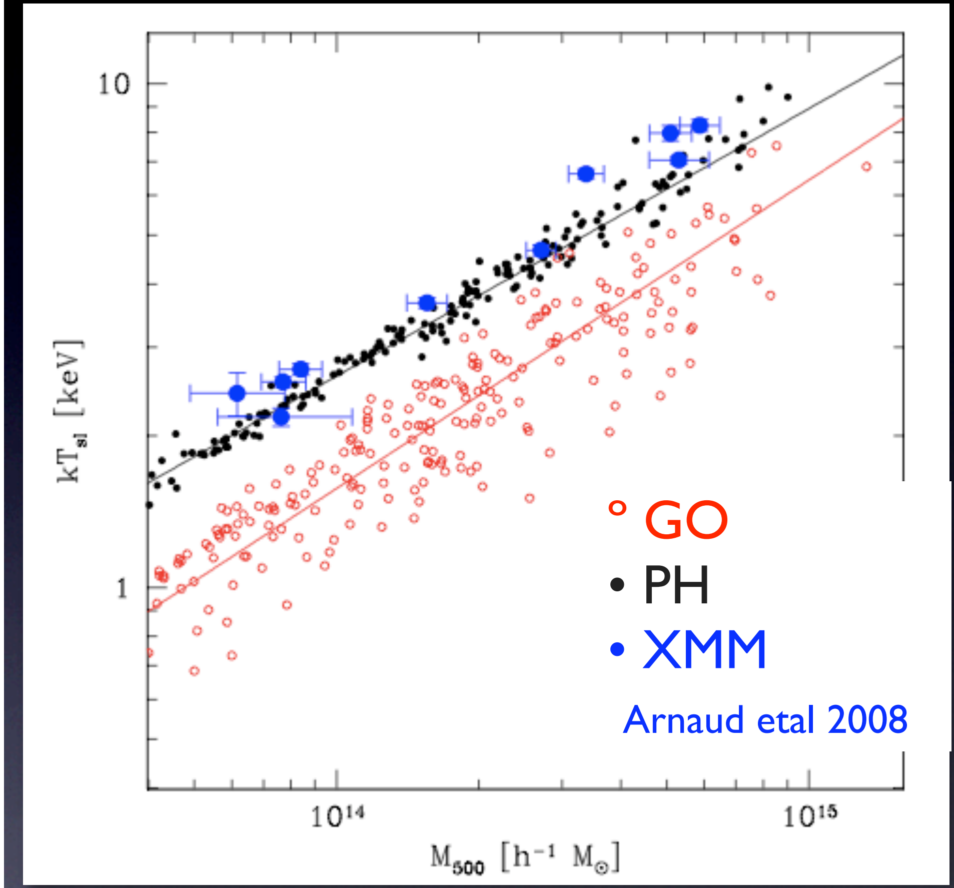
MGS: z=0 scaling relations w/ different physical treatments

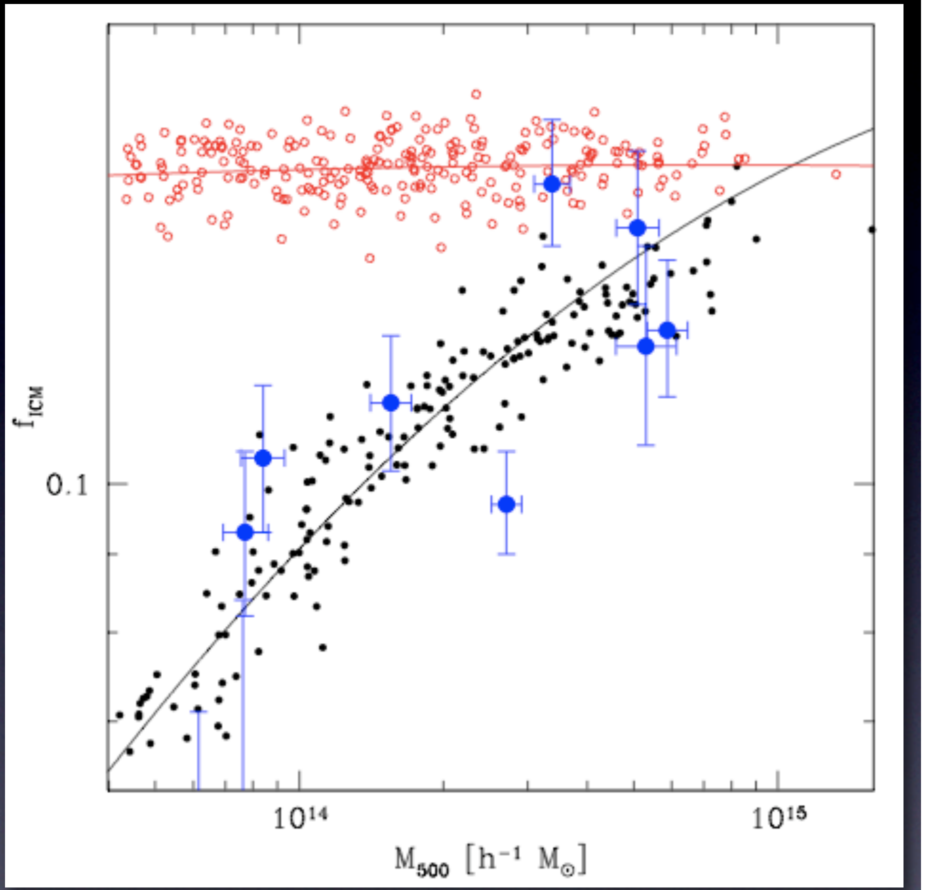
Stanek et al, 0910.1599



MGS: comparison to observations

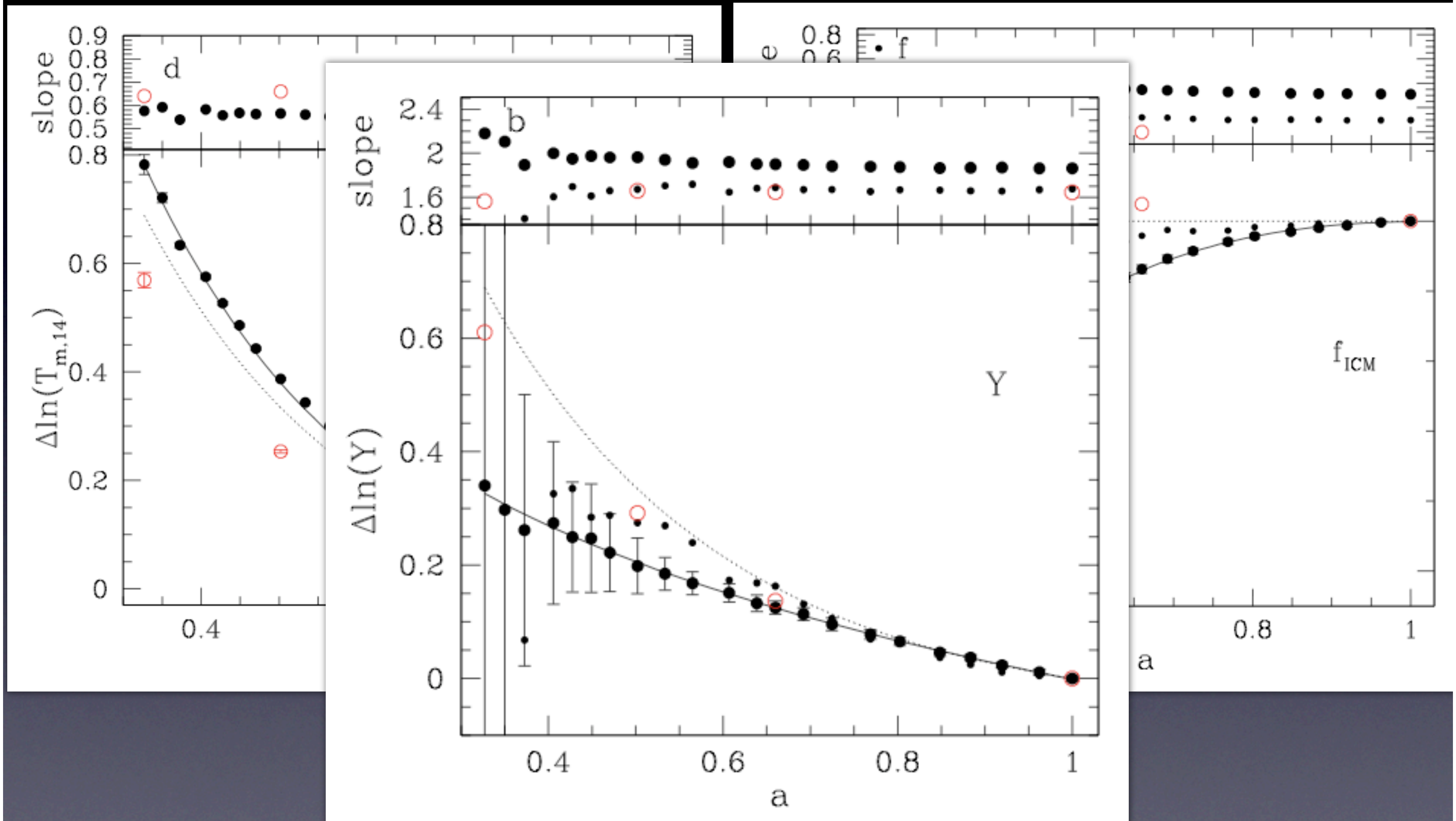
Stanek et al, 0910.1599





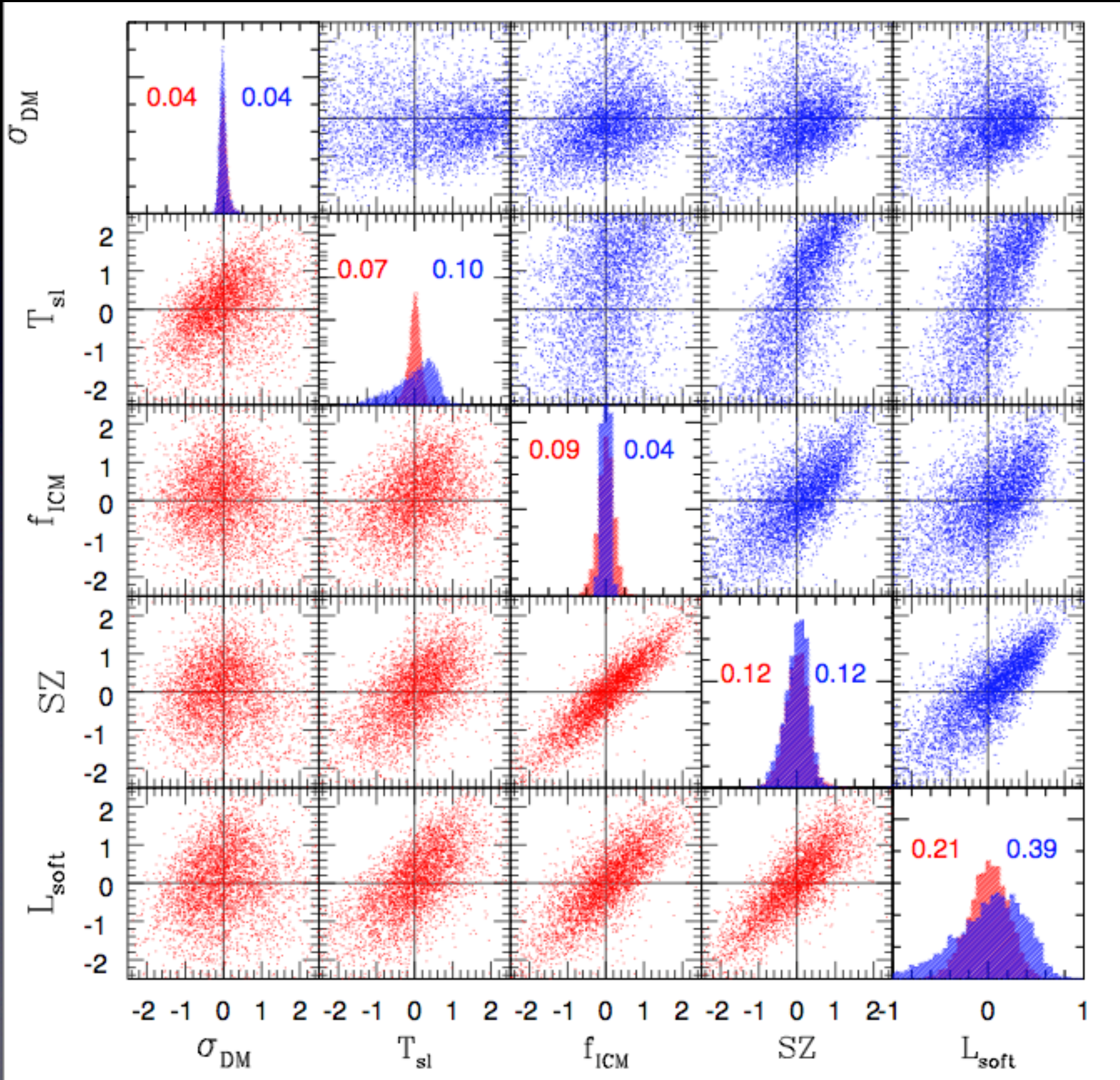
MGS: evolution of scaling relation slope and intercept

Stanek et al, 0910.1599



MGS: covariance of multiple signals at fixed halo mass

Stanek et al, 0910.1599



preheating
gravity only

effective mass scatter using pairs of signals

$$\Sigma^{-2} = (1 - r^2)^{-1}(\sigma_{\mu 1}^{-2} + \sigma_{\mu 2}^{-2} - 2r\sigma_{\mu 1}^{-1}\sigma_{\mu 2}^{-1}).$$

TABLE 6
MASS SCATTER AT REDSHIFT ZERO [a]

Cluster Property	σ_{DM}	T_{sl}	f_{ICM}	Y	L	PH	GO
σ_{DM}	–	0.12	0.12	0.075	0.12	0.12	0.12
T_{sl}	0.10	–	0.35	0.050	0.26	0.12	0.38
f_{ICM}	0.11	0.12	–	0.054	0.21	0.28	0.12
Y	0.062	0.069	0.041	–	0.056	0.069	0.075
L	0.090	0.10	0.093	0.066	–	0.11	0.26

[a] The redshift zero mass scatter for each pair of signals, with the results from the PH simulation in the lower, left-hand half, and the results from the GO simulation in the upper, right-hand half, as in Figure 11 The mass scatter for the individual signal is listed on the right-hand side of the table.

Stanek et al, 0910.1599

MGS summary

★ preheating offers good match to observed core-excised X-ray emission properties

★ halo mass is affected by baryon physics at ~10% level => number density at fixed mass shifts by ~20-30% ; need more large volume simulations with gas physics!

★ preheating causes scale-dependent deviations from self-similar evolution in Y, Lx, T and ficm (few % at 10^{14.5} Msun/h)

★ covariance in signal pairs generally positive and stable in z

★ pairing of ficm and Y may offer sensitive mass selection (4%)

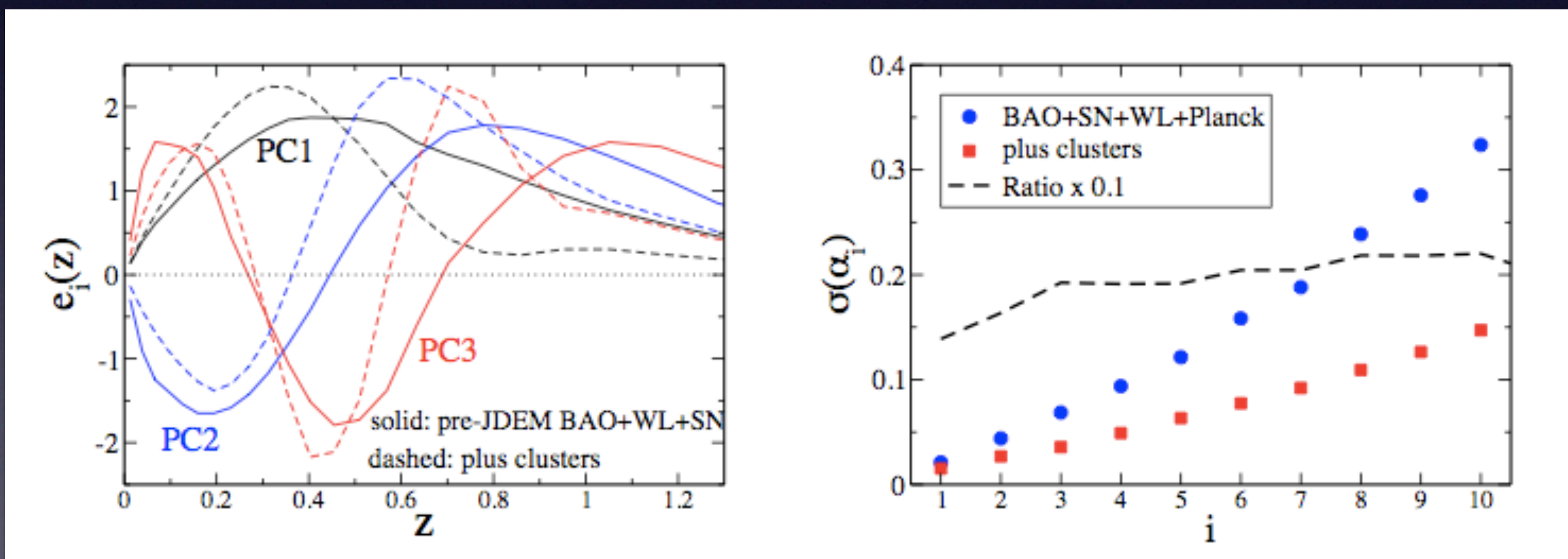
Fisher forecasts

Fisher analysis of value of cluster counts and clustering

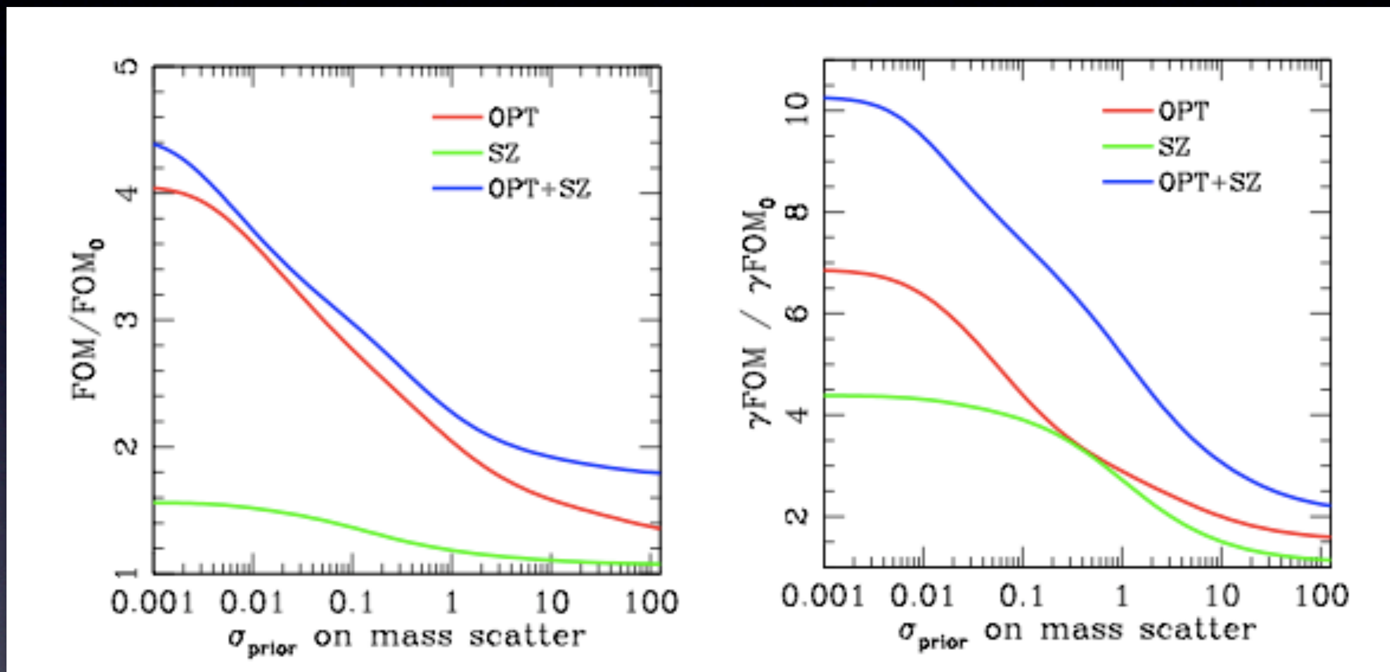
Cunha, Huterer
Frieman, 0904.1589

$$\ln M^{\rm bias}(M_{\rm obs},z) = \ln M_0^{\rm bias} + a_1 \ln(1+z) + a_2(\ln M_{\rm obs} - \ln M_{\rm pivot}) \quad (3)$$

$$\sigma^2_{\ln M}(M_{\rm obs},z) = \sigma_0^2 + \sum_{i=1}^{3} b_i z^i + \sum_{i=1}^{3} c_i(\ln M_{\rm obs} - \ln M_{\rm pivot})^i \quad (4)$$



additional improvements from prior in Mobs proxy



further exploration into Mobs and Mass Function/Bias

Cunha et al (2009)

$$p(M_{\rm obs}|M) = \frac{1}{\sqrt{2\pi\sigma^2_{\ln M}}} \exp\left[-x^2(M_{\rm obs})\right], \quad (11)$$

where

$$x(M_{\rm obs}) \equiv \frac{\ln M_{\rm obs} - \ln M - \ln M_{\rm bias}(M,z)}{\sqrt{2\sigma_{\ln M}(M,z)^2}}. \quad (12)$$

We model systematic error in the mass proxy by introducing a redshift-dependent bias and variance

$$\ln M_{\rm bias}(z) = B_0 + B_1(1+z), \quad (13)$$

$$\sigma^2_{\ln M}(z) = \sigma_0^2 + \sum_{i=1}^{3} s_i z^i, \quad (14)$$

We write the space density of halos as

$$\frac{dn}{dM} = f(\sigma)\frac{\bar\rho_m}{M}\frac{d\ln\sigma^{-1}}{dM} \quad (15)$$

and adopt the Tinker parameterization of $f(\sigma)$ [?]

$$f(\sigma) = A\left[\left(\frac{\sigma}{b}\right)^{-a} + 1\right] e^{-c/\sigma^2}. \quad (16)$$

Following [?], we allow the first three parameters of $f(\sigma)$ to vary with redshift, so that

$$A(z) = A_0(1+z)^{A_z} \quad (17)$$

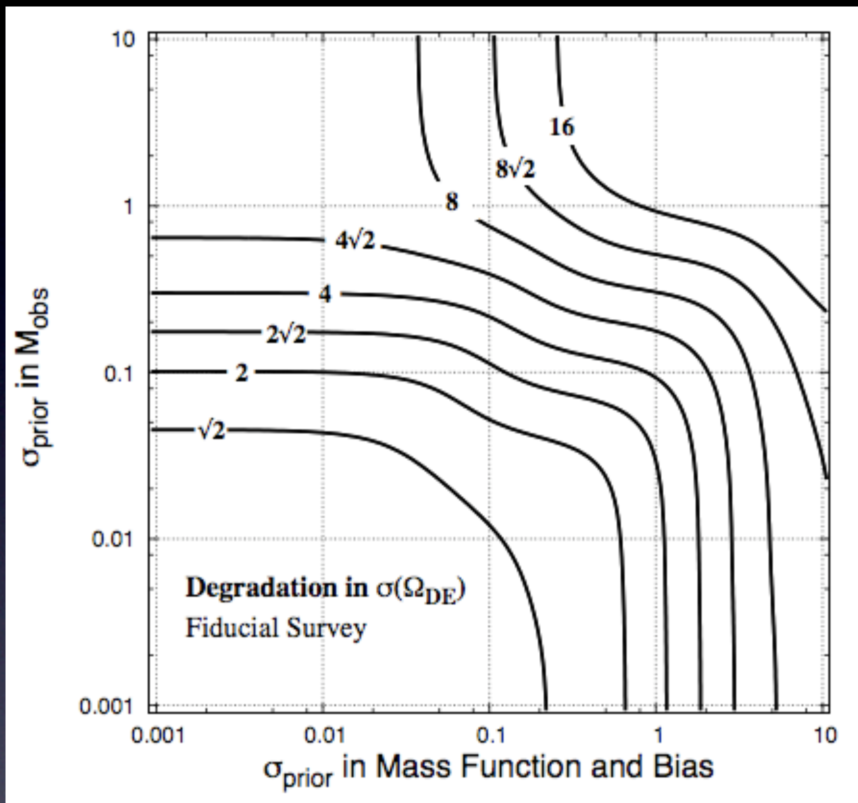
$$a(z) = a_0(1+z)^{a_z} \quad (18)$$

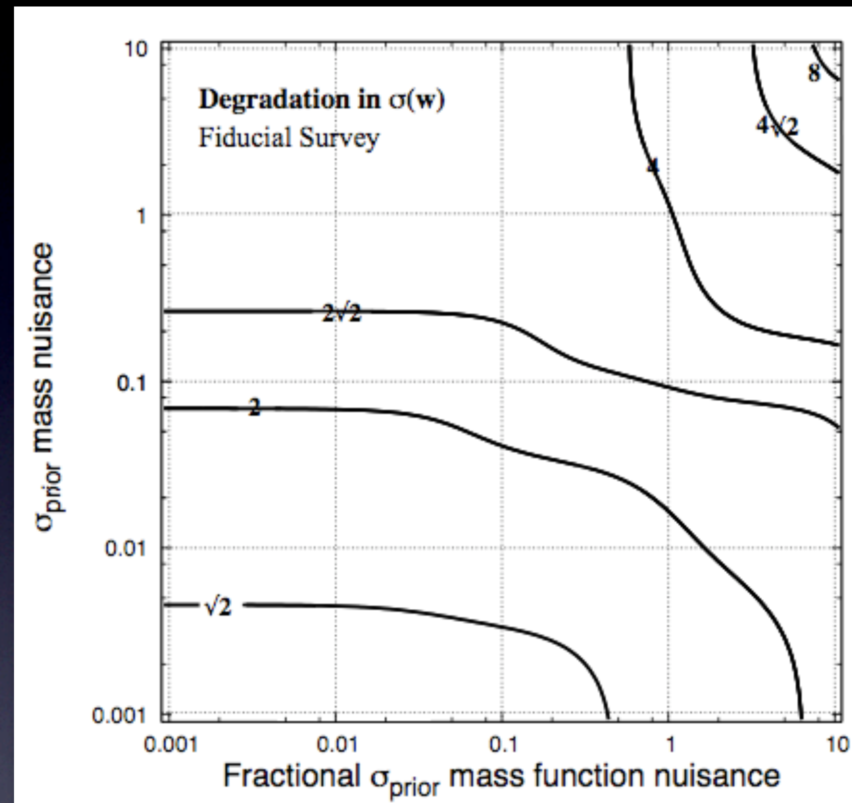
$$b(z) = b_0(1+z)^{-\alpha} \quad (19)$$

TABLE I: Fiducial constraints on cosmological parameters for perfectly known nuisance parameters

				Sharp priors		No priors	
Survey	$M_{\rm th}[h^{-1}M_\odot]$	$N_{\rm tot}$	σ_0	$\sigma(\Omega_{\rm DE})$	$\sigma(w)$	$\sigma(\Omega_{\rm DE})$	$\sigma(w)$
Fid.	$10^{14.2}$	8,400	0.2	0.010	0.050	0.91	2.19
1	$10^{14.2}$	16,400	0.5	0.0083	0.039	0.82	1.81
2	$10^{13.5}$	229,200	0.2	0.0025	0.011	0.098	0.23
3	$10^{13.5}$	287,200	0.5	0.0023	0.0097	0.22	0.35

sensitivity to Mobs and Mass Function/Bias priors





the (near) future...

Dark Energy Survey is approaching

An NSF/DOE-funded study of dark energy using four techniques

1) Galaxy cluster surveys (with SPT)
2) Galaxy angular power spectrum
3) Weak lensing/cosmic shear
4) SN Ia distances

Two linked, multiband optical surveys

5000 deg^2 *g r i z* colors to ~24^{th} mag

Repeated observations of 40 deg^2

Development and schedule

Construction: 2007-2011

- New 3 deg^2 camera on Blanco 4m, Cerro Tololo
- Data management system at NCSA

Survey Operations: 2011-2016

- 510 nights of telescope time over 5 years

John Peoples, Director

Fermilab, U Illinois, U Chicago, LBNL, U Michigan
CTIO/NOAO, Barcelona, UCL, Cambridge, Edinburgh


KITP Workshop
Galaxy Clusters: The Crossroads
of Astrophysics and Cosmology
January 31 – April 22, 2011
Organizers:
Andrey Kravtsov
Dan Marrone
Peng Oh
Advisors:
Dick Bond
John Carlstrom
Megan Donahue
Gus Evrard
Maxim Markevitch
Mark Voit