Title: Recent Progress on Clusters at Michigan

Date: Apr 29, 2009 11:00 AM

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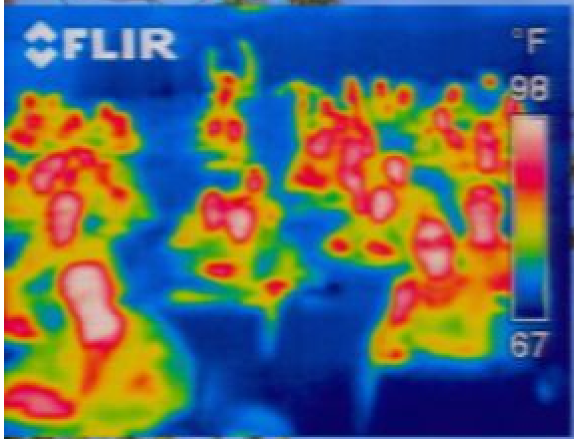
Abstract: The coming era of large, multi-wavelength surveys motivates and, ultimately, will inform a multivariate statistical framework describing cluster properties in relation to underlying halo mass and redshift. In this talk, I will present work at Michigan that focuses on a multivariate Gaussian likelihood approach to this problem, and includes empirical studies using optical and X-ray observations of the SDSS maxbcg sample as well as a computational program using Gadget resimulations of the Millennium Simulation with preheated gas dynamics. I will show evidence from the models that a combination of fgas measurements from X-rays along with Ytot from thermal SZ can constrain mass at the rms level of 4%.

Progress on Clusters at Michigan



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University of Michigan

collaborators and issues

clusters as massive halos

Fisher forecasts

- Huterer
- Cunha
- Smith

simulations

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

optical surveys
SDSS maxbcg
=> DES

- McKay
- Wechsler (Stanford)
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- Rozo (OSU)
- Rykoff (UCSB)
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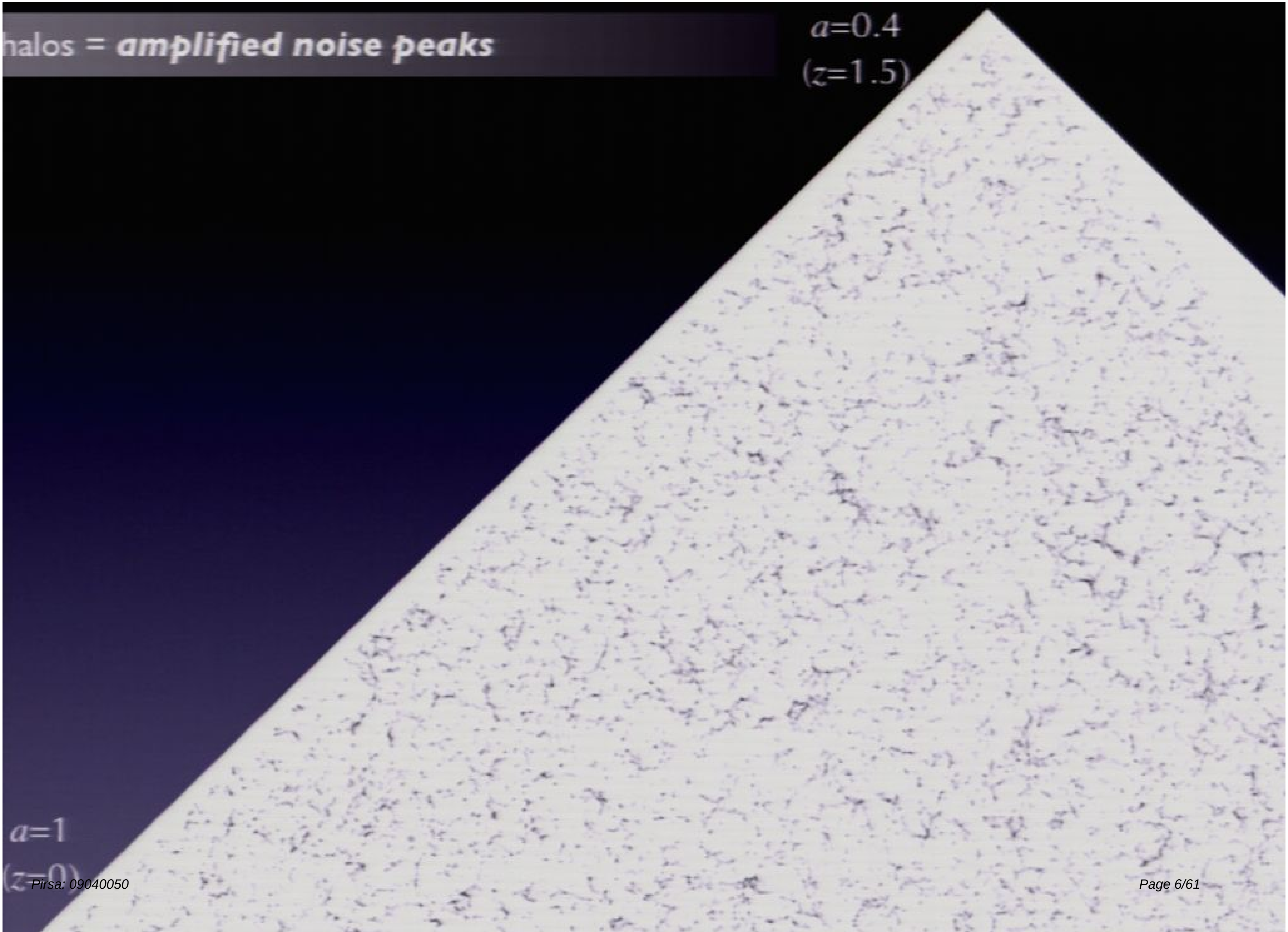
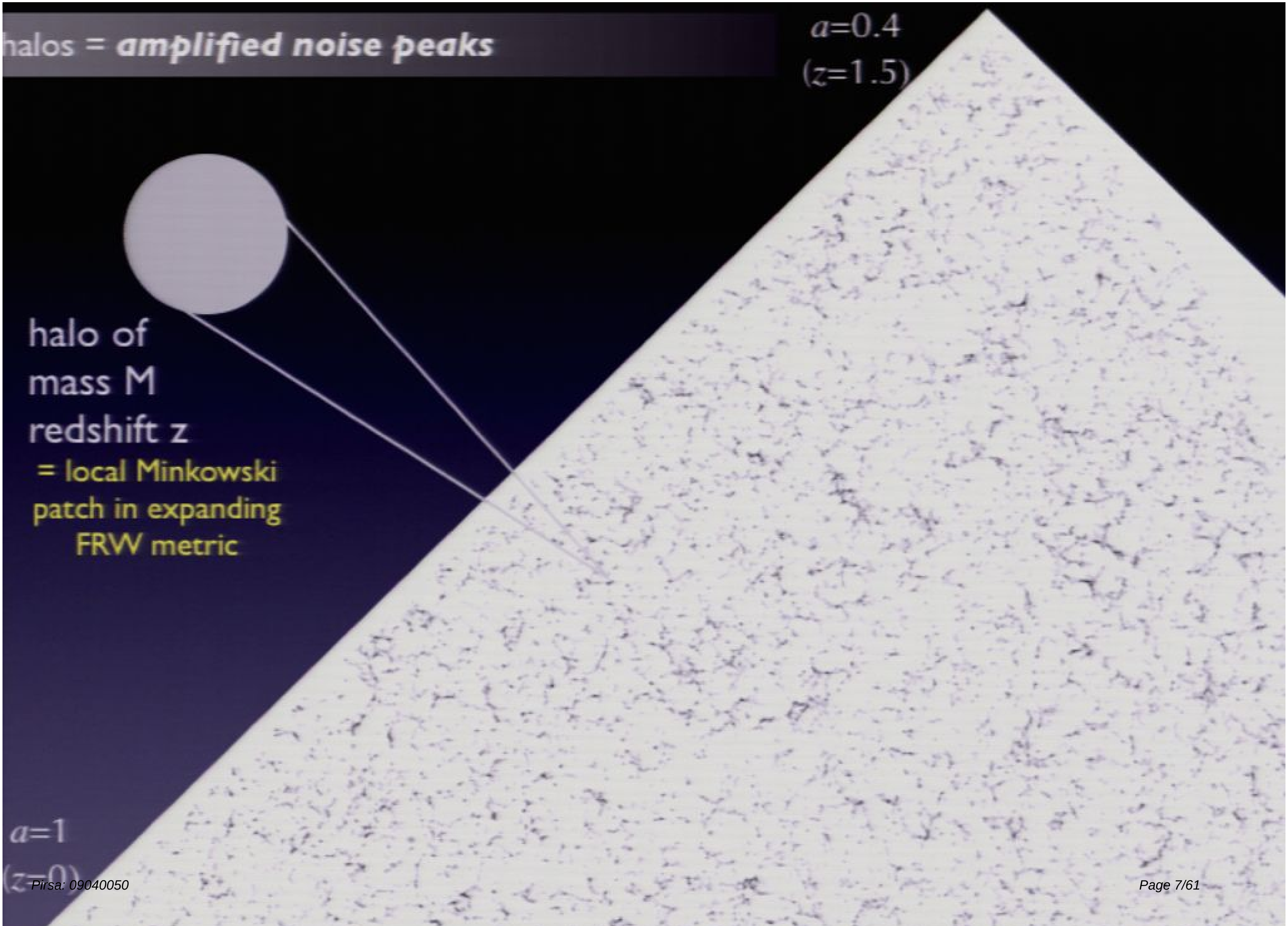
Fall 2009: Jeff McMahon (SPT) to Physics
Chris Miller (SDSS C4) to Astronomy

the crew


halos = amplified noise peaks
a=0.4
(z=1.5)
a=1
(z=0)


halos = amplified noise peaks
a=0.4
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halo of
mass M
redshift z
= local Minkowski
patch in expanding
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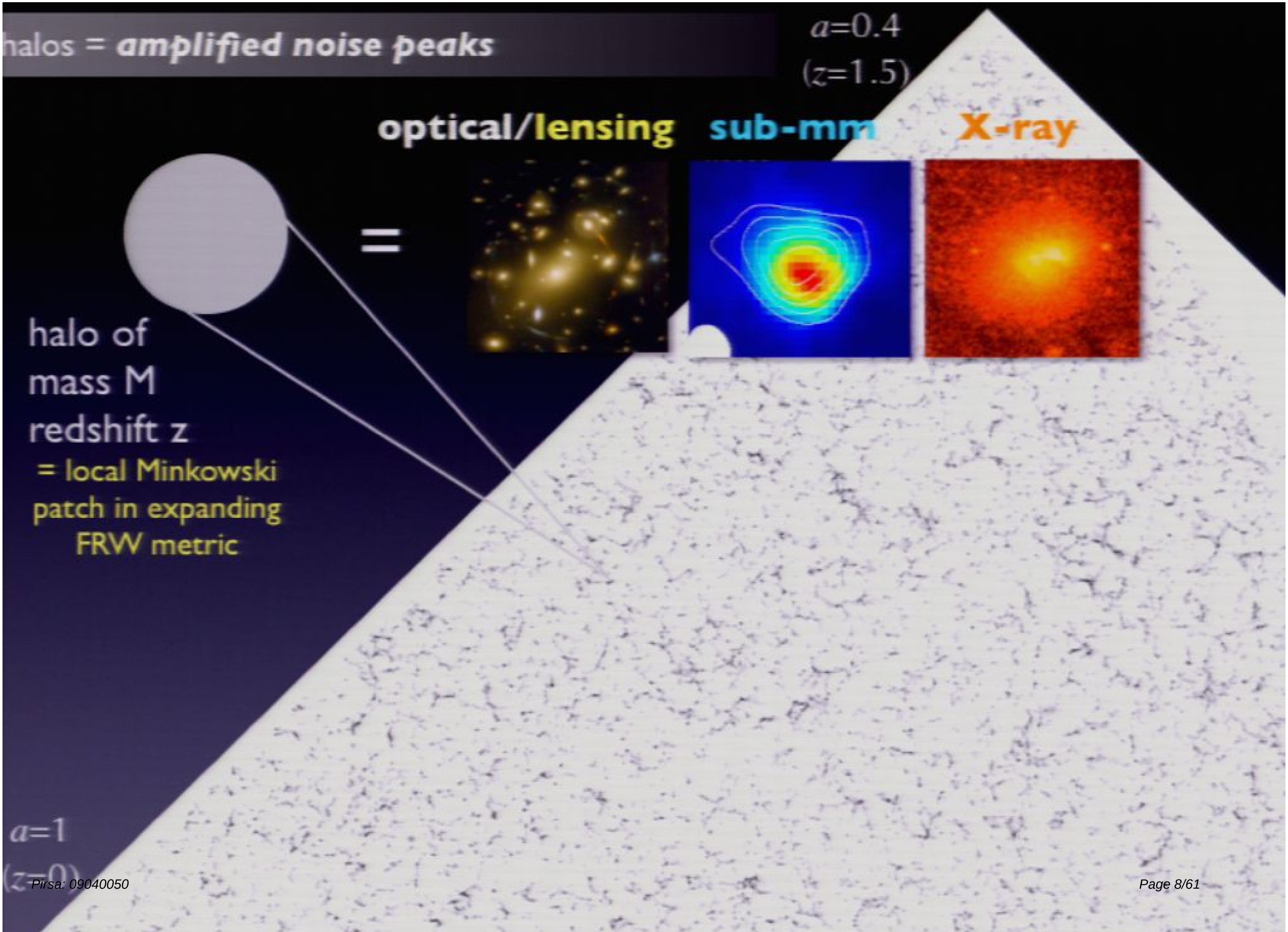
halos = amplified noise peaks
a=0.4
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optical/lensing
sub-mm
X-ray
=
halo of
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Cluster counting is challenged by

1. 3D halo mass is not directly observable
   need one or more signals to serve as a mass proxy

2. The universe is a big place
   projection along Gpc sight-line affects cluster properties

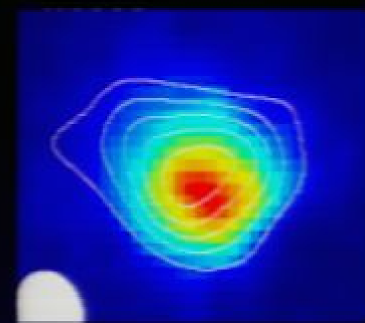
3. Require theory to map counts to cosmological parameters
   N-body simulation calibration needs baryonic extension

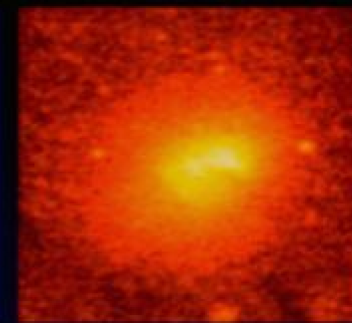
4. Cluster redshifts (~10k of them!) needed
   rely on photometric rather than spectroscopic z's

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

Select a halo sample based on some signal, s_1.

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

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

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

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

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

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

SDSS maxbcg analysis

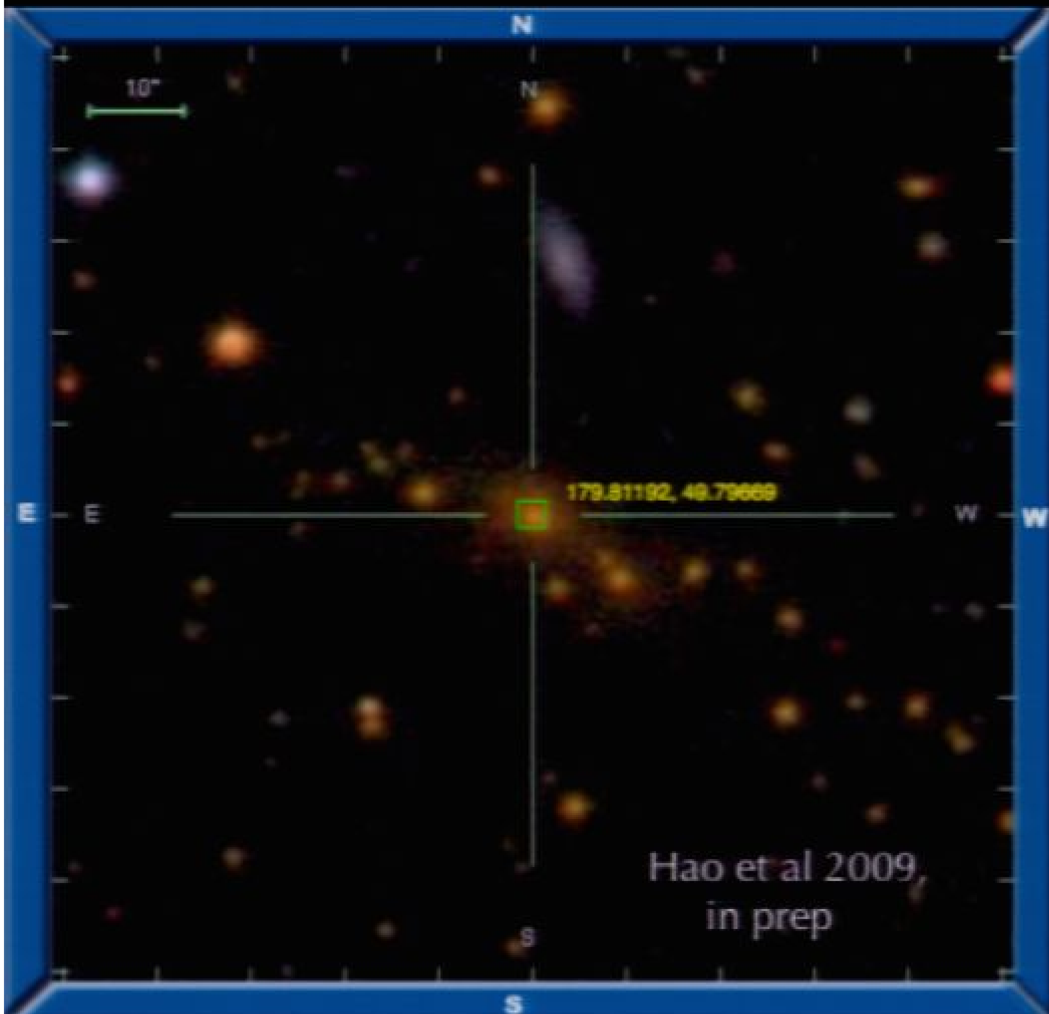
SDSS maxbcg analysis

~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:

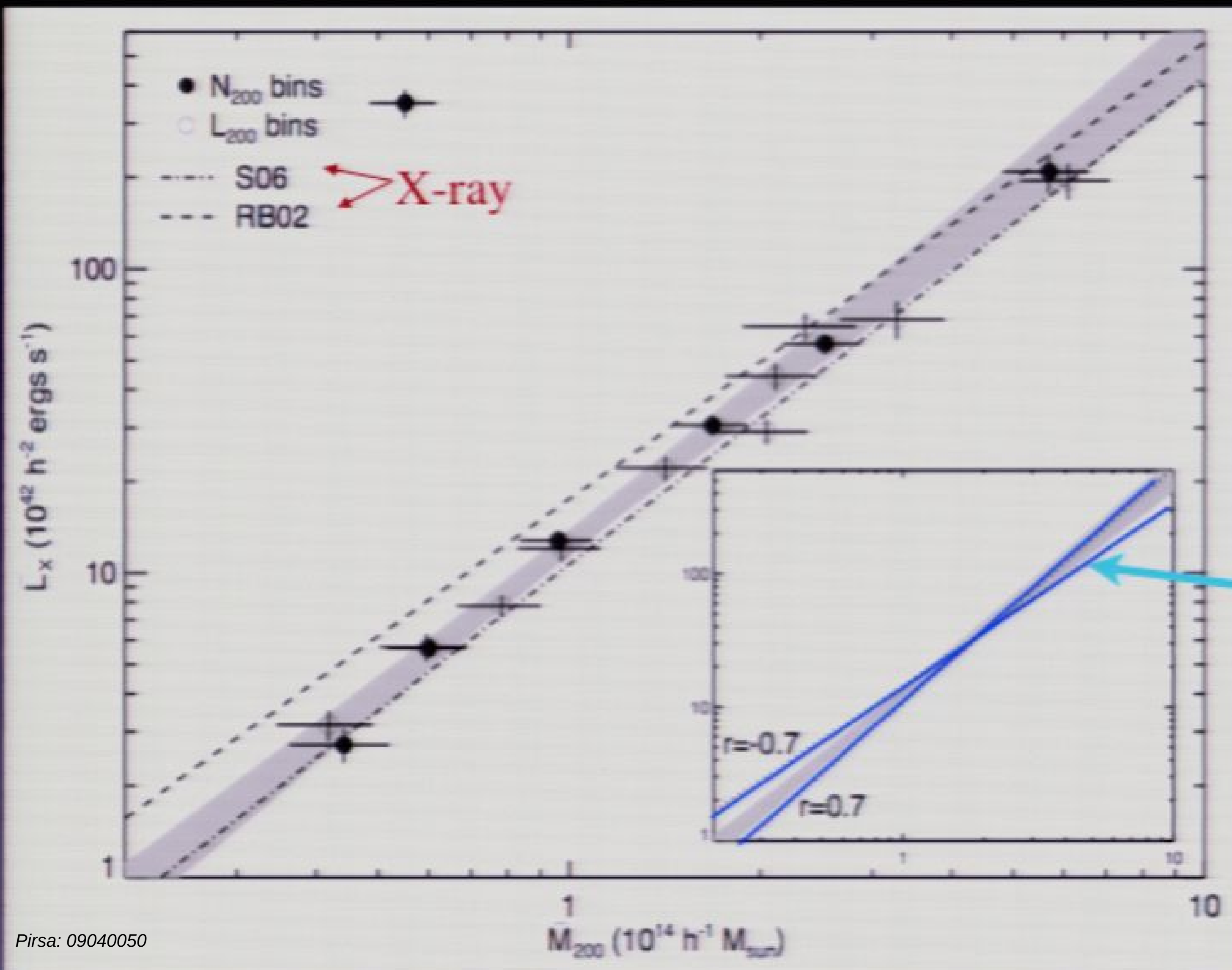
- ★ stacked weak lensing masses
  Johnston etal 2007; Sheldon etal 2007
- ★ velocity dispersion–richness
  Becker et al 2007
- ★ X-ray luminosity–richness
  Rykoff et al 2008a
- ★ X-ray luminosity–lensing mass
  Rykoff et al 2008a
- ★ improved richness estimator
  Rozo et al 2008a
- ★ scatter in mass–richness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

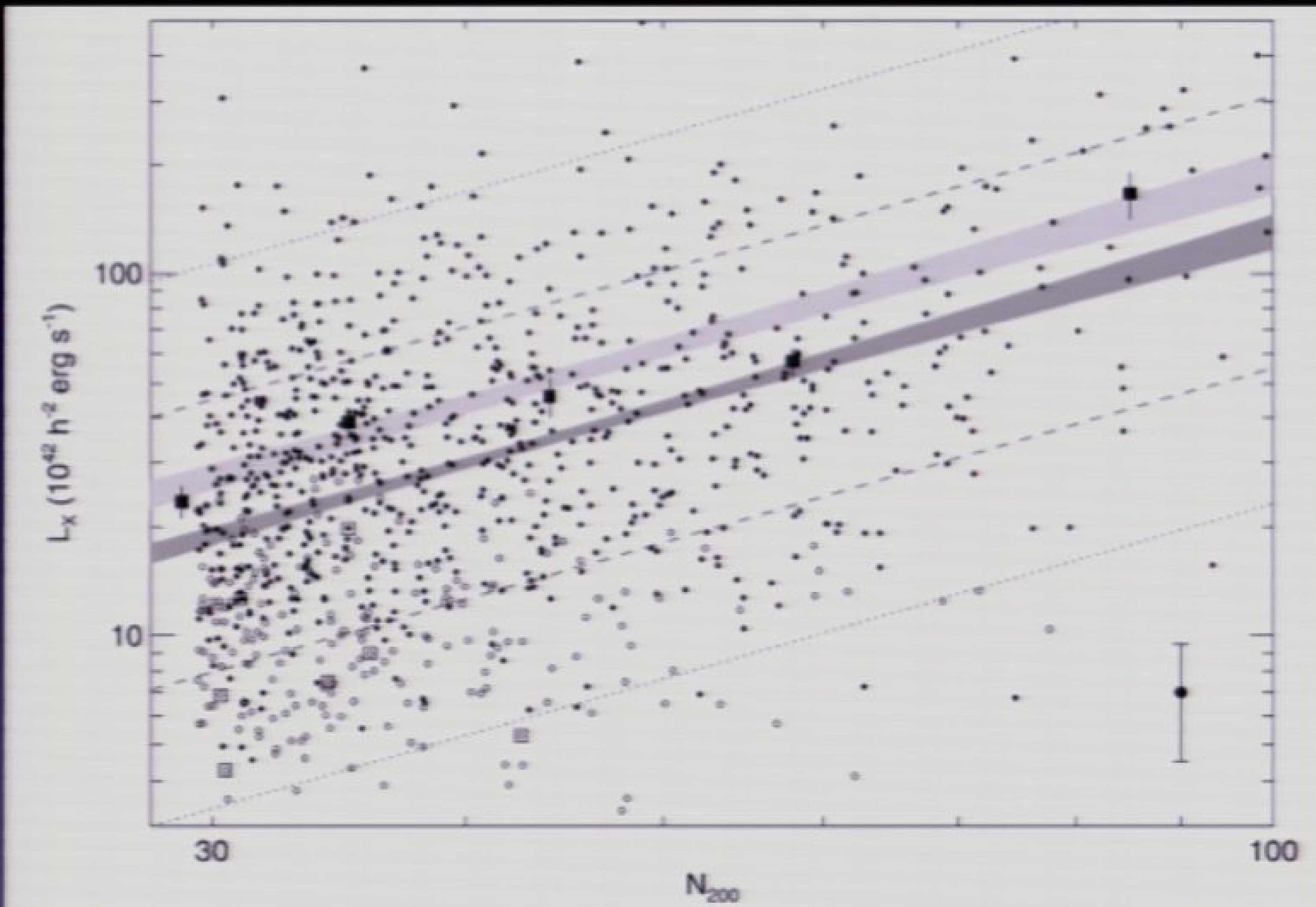
slope = 1.6 ± 0.1

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



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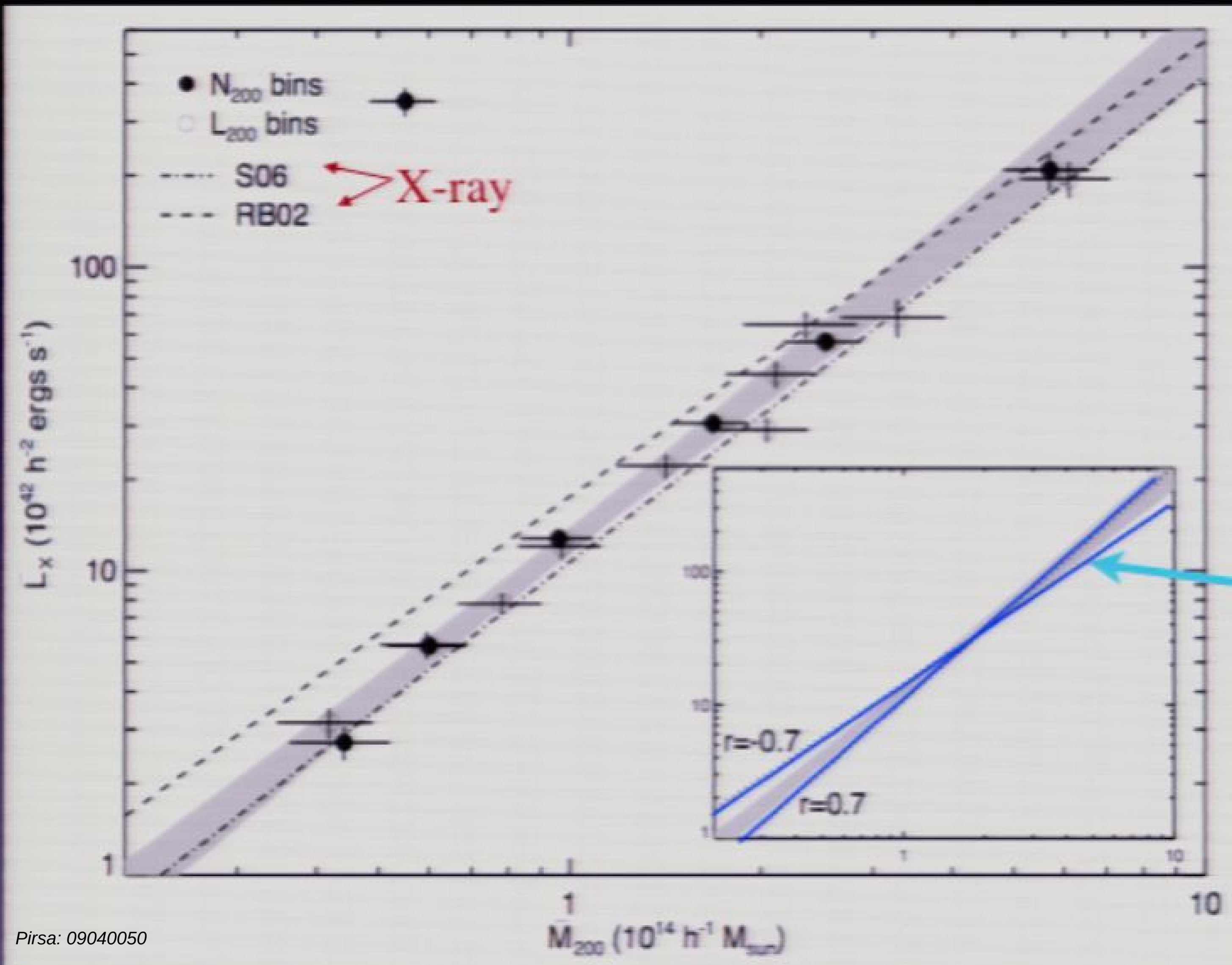

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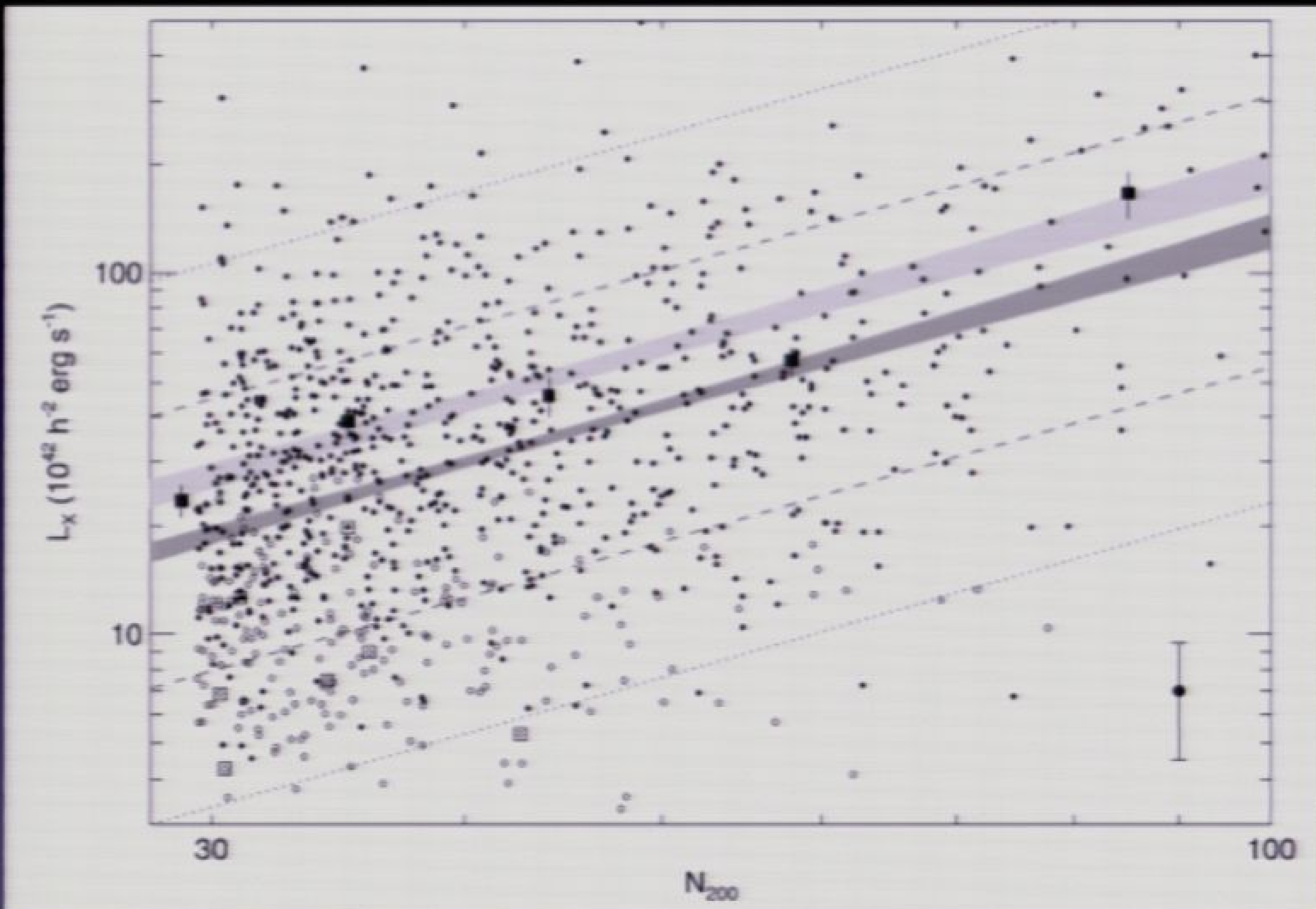

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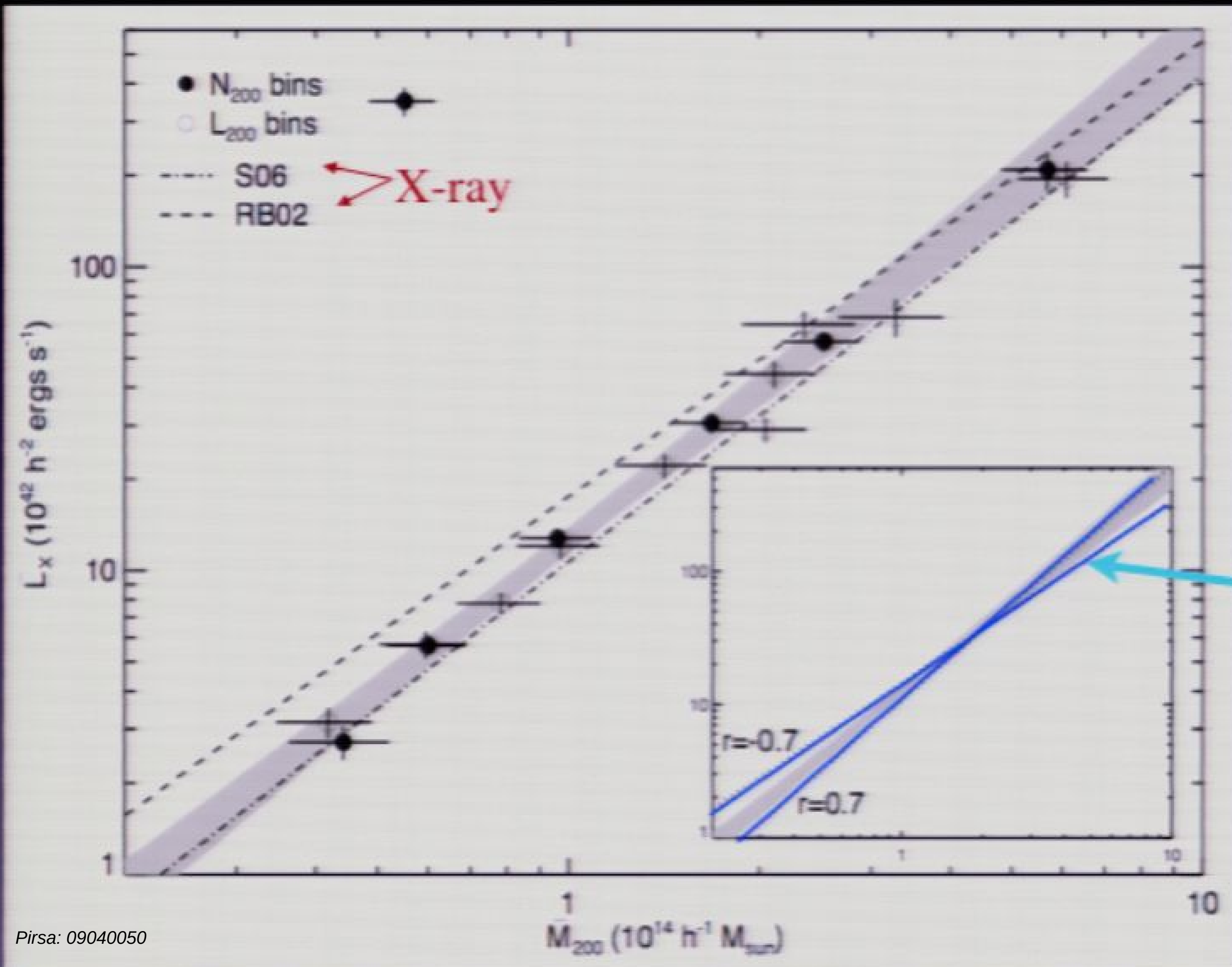

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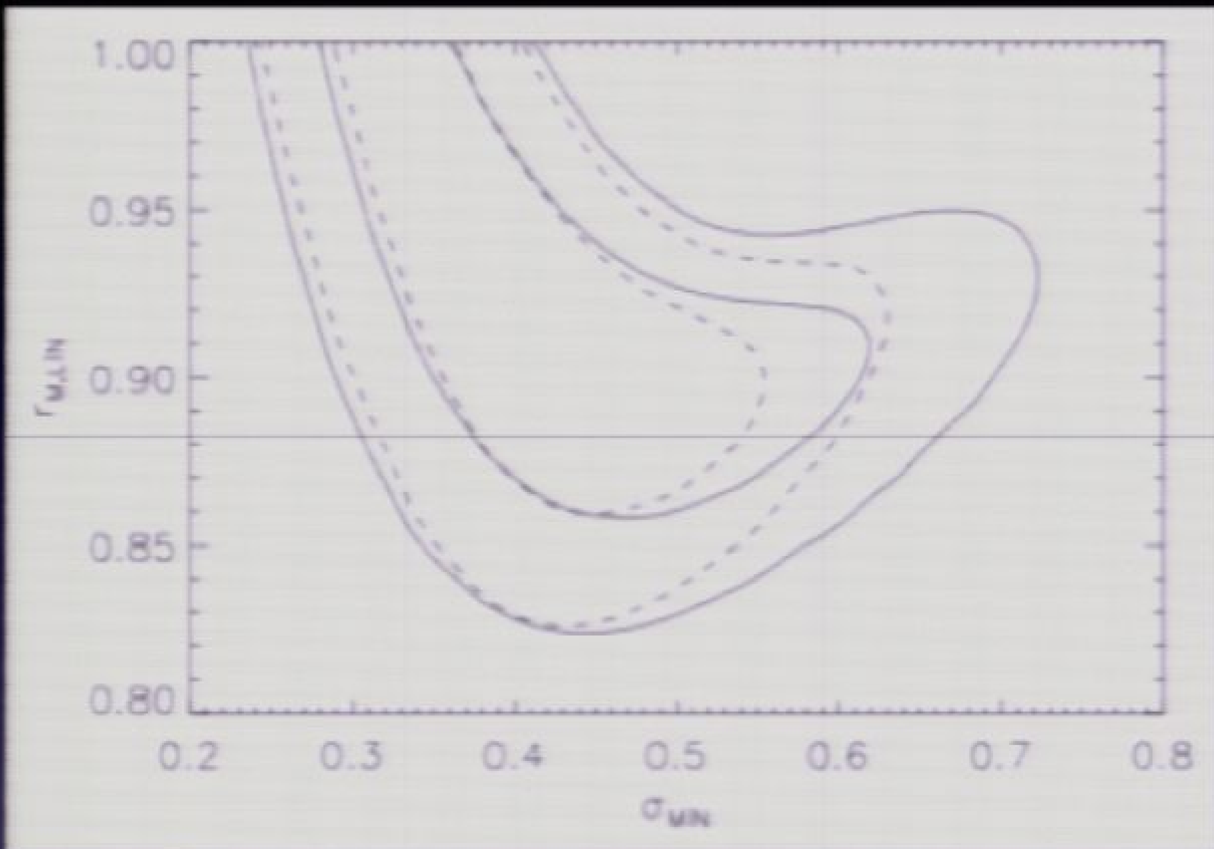
first measurement of property covariance for clusters

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

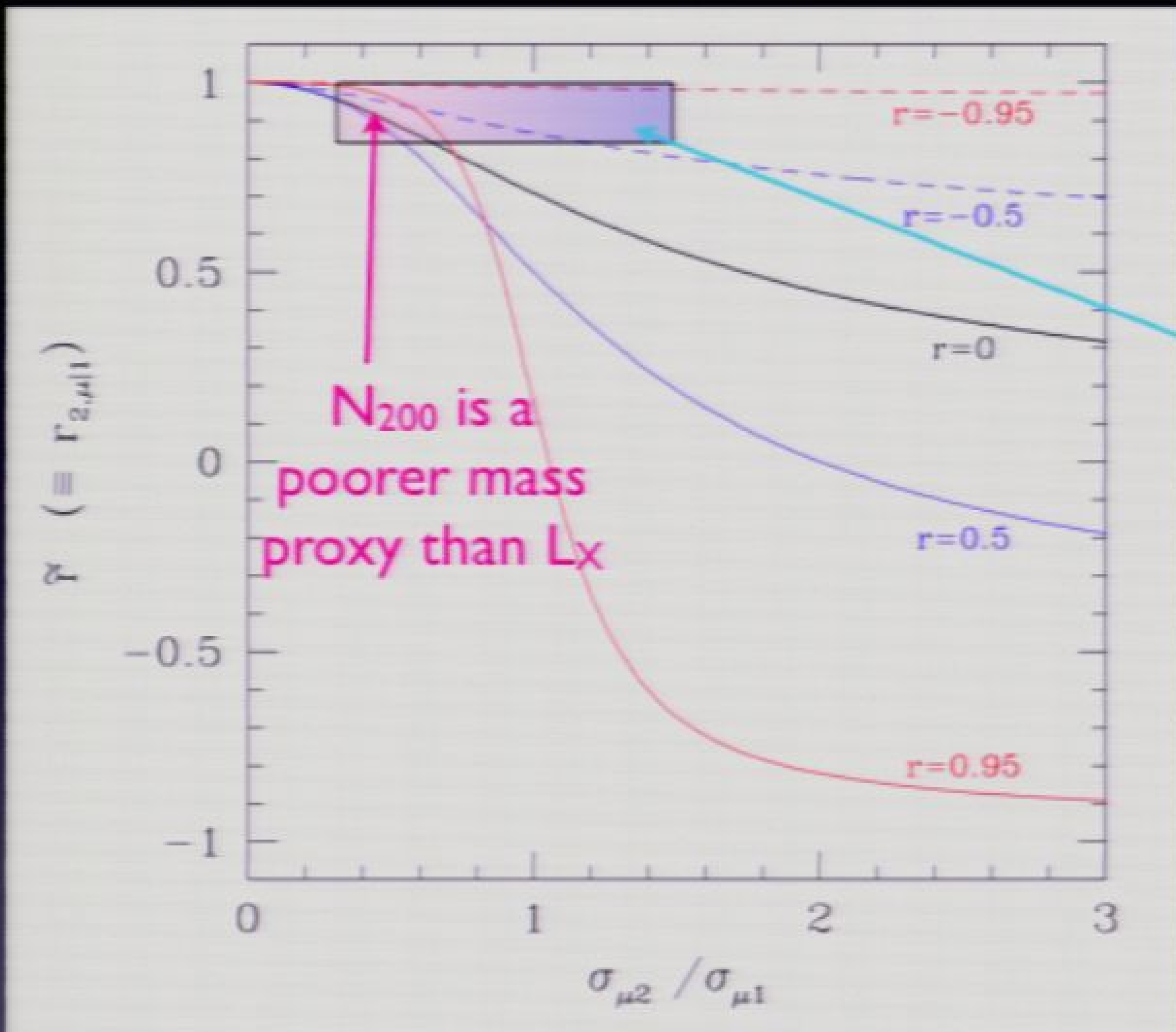
L_X–M_{500} scaling

slope, norm, scatter

Vikhlinin et al 2008

what does a large covariance in mass and Lx mean?

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



N200 is a better mass proxy and N200 and Lx 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
$\langle \ln N_{200} \vert M_1 \rangle$	flat	unrestrictive
$\langle \ln N_{200} \vert M_2 \rangle$	flat	unrestrictive
$\sigma_{N_{200}\vert M}$	[0.1,1.5]	unrestrictive
β	1.00 ± 0.06; [0.5, 1.5]	restrictive

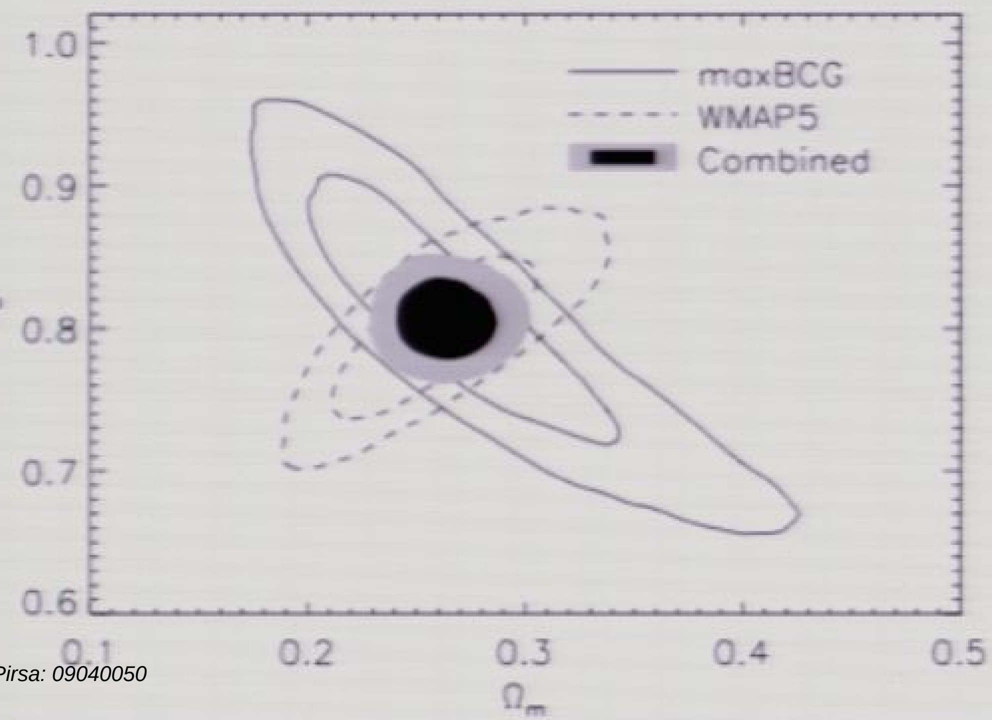


TABLE 4
BEST FIT MODEL

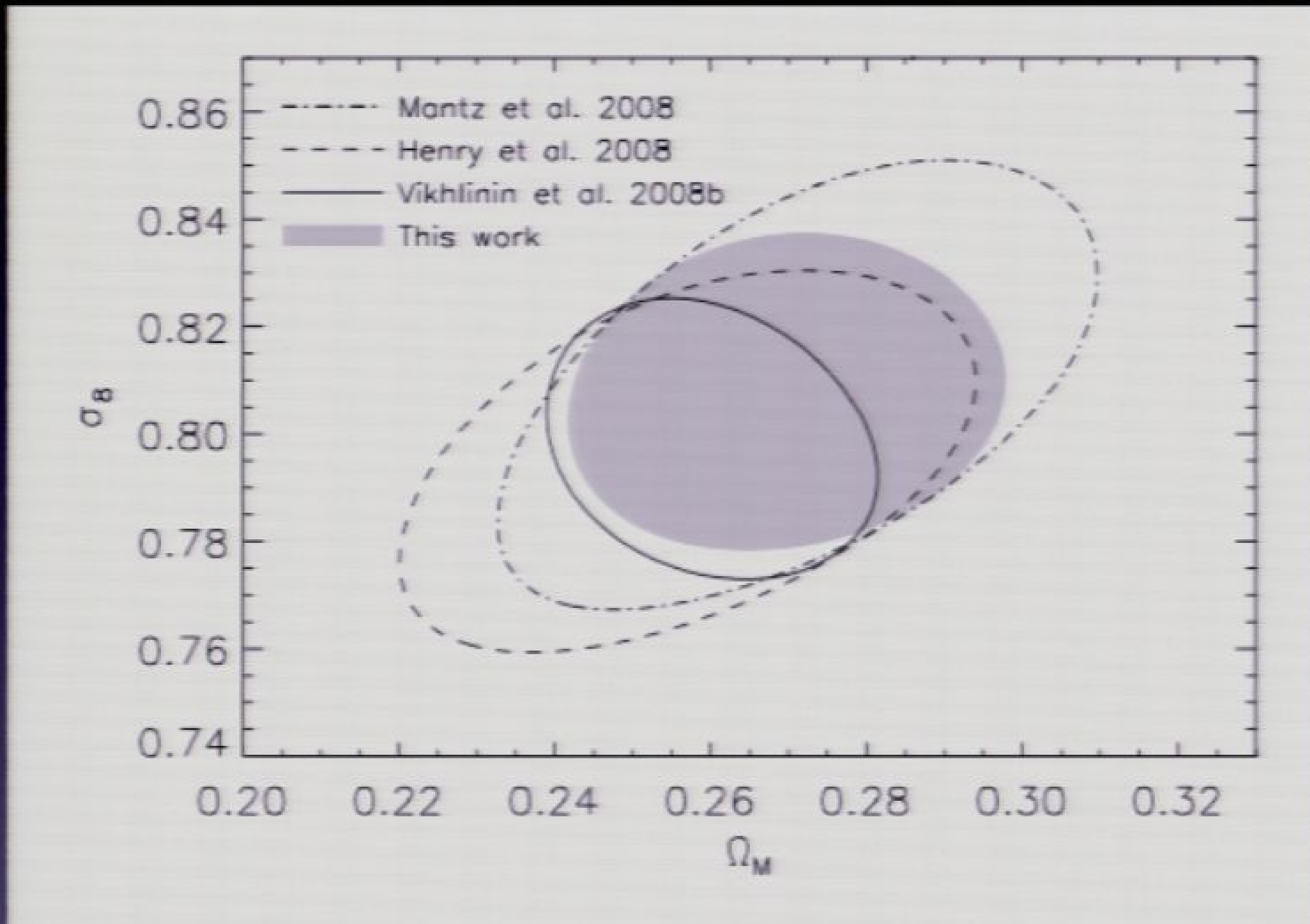
Parameter[a]	maxBCG	maxBCG+WMAP5[b]
σ_8	0.804 ± 0.073	0.807 ± 0.020
Ω_m	0.281 ± 0.066	0.269 ± 0.018
$\langle \ln N_{200} \vert M_1 \rangle$	2.47 ± 0.10	2.48 ± 0.10
$\langle \ln N_{200} \vert M_2 \rangle$	4.21 ± 0.19	4.21 ± 0.13
$\sigma_{N_{200}\vert M}$	0.357 ± 0.073	0.348 ± 0.071
β	1.016 ± 0.060	1.013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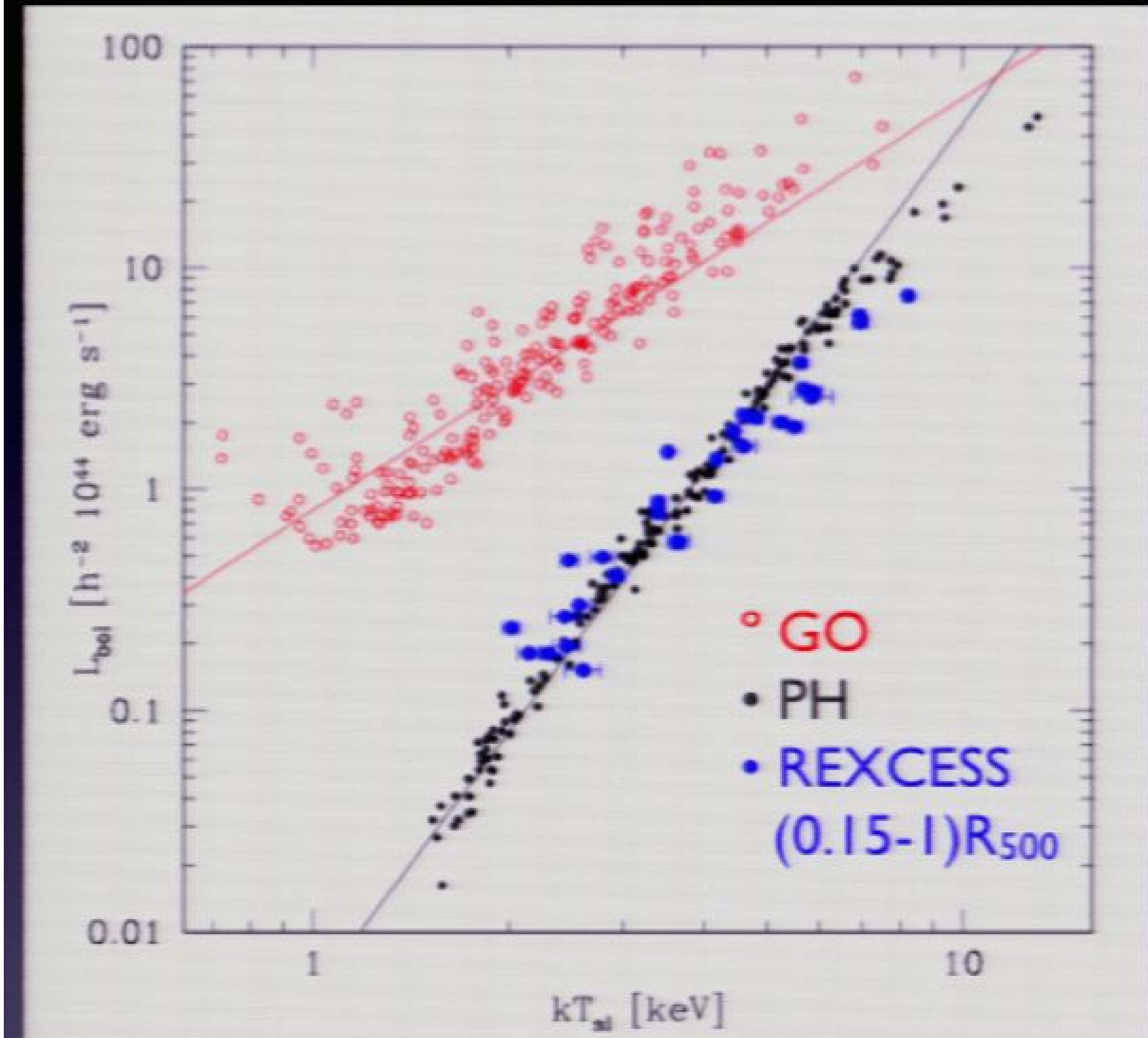
Millennium Gas Simulations (MGS)

Millennium Gas Simulations



GADGET-2 resimulations of Millennium Sim volume

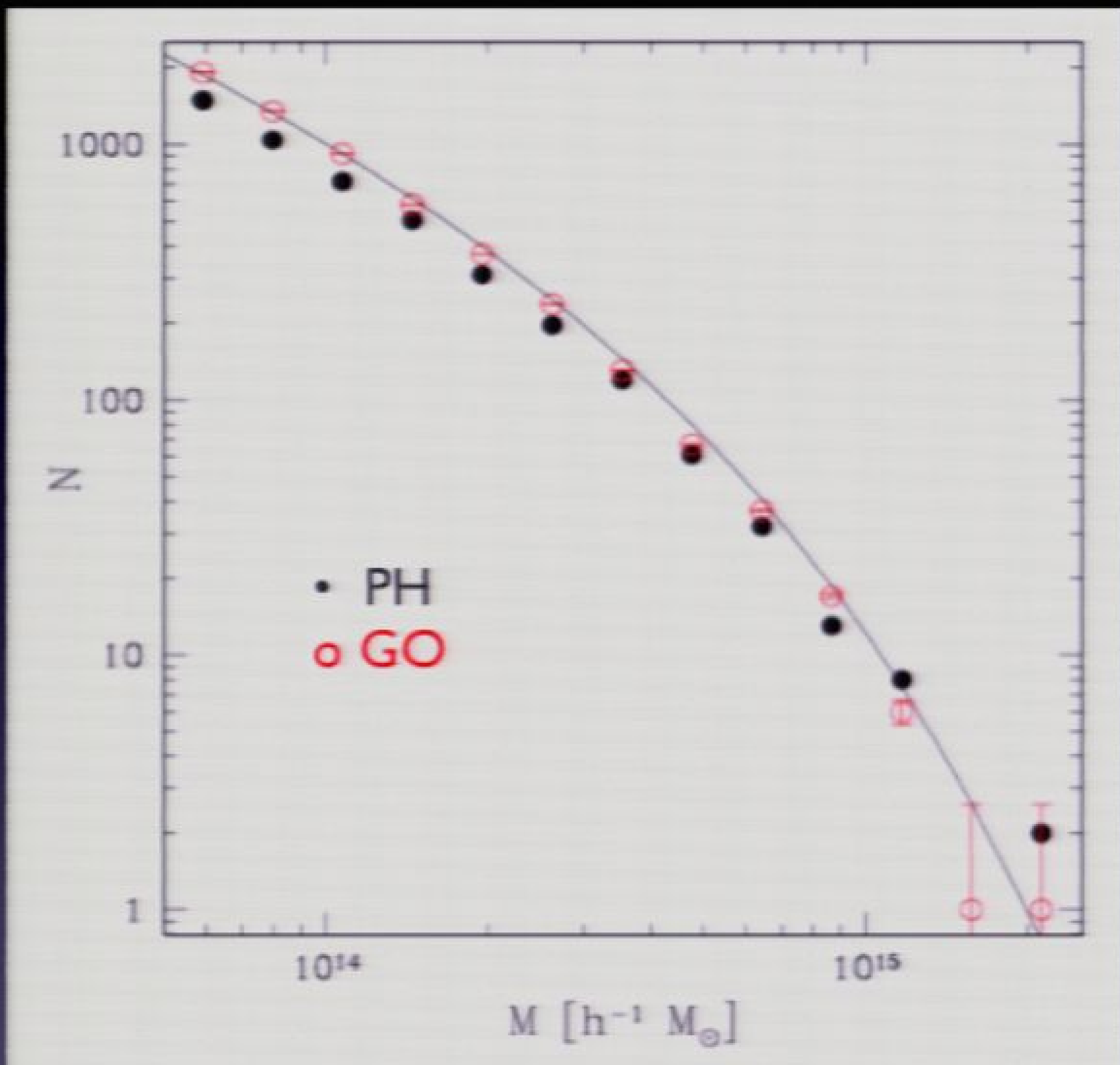
- 500 Mpc/h
- 1e9 gas+DM particles
- m_p(DM) ~ 1.4e10 Msun
- 25 kpc/h softening
- same cosmology as MS

physical treatments:

GO: gravity only

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

MGS massive halo yield

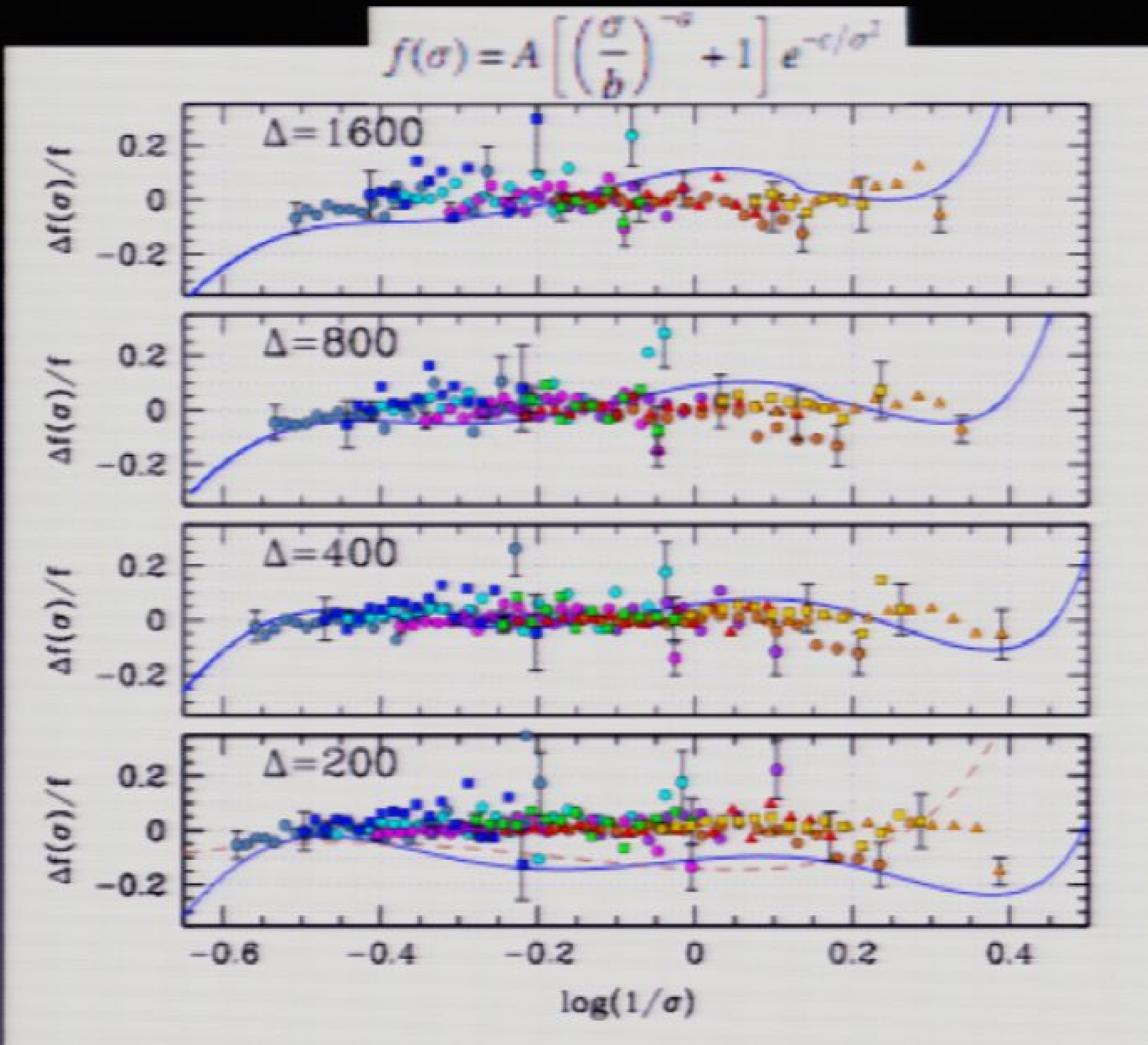


halos at z=0 with
$M_{200} \geq$ 5e13 Msun/h:

4474 (PH)
5612 (GO)

halo space density from large N-body simulations

Tinker et al (2008)



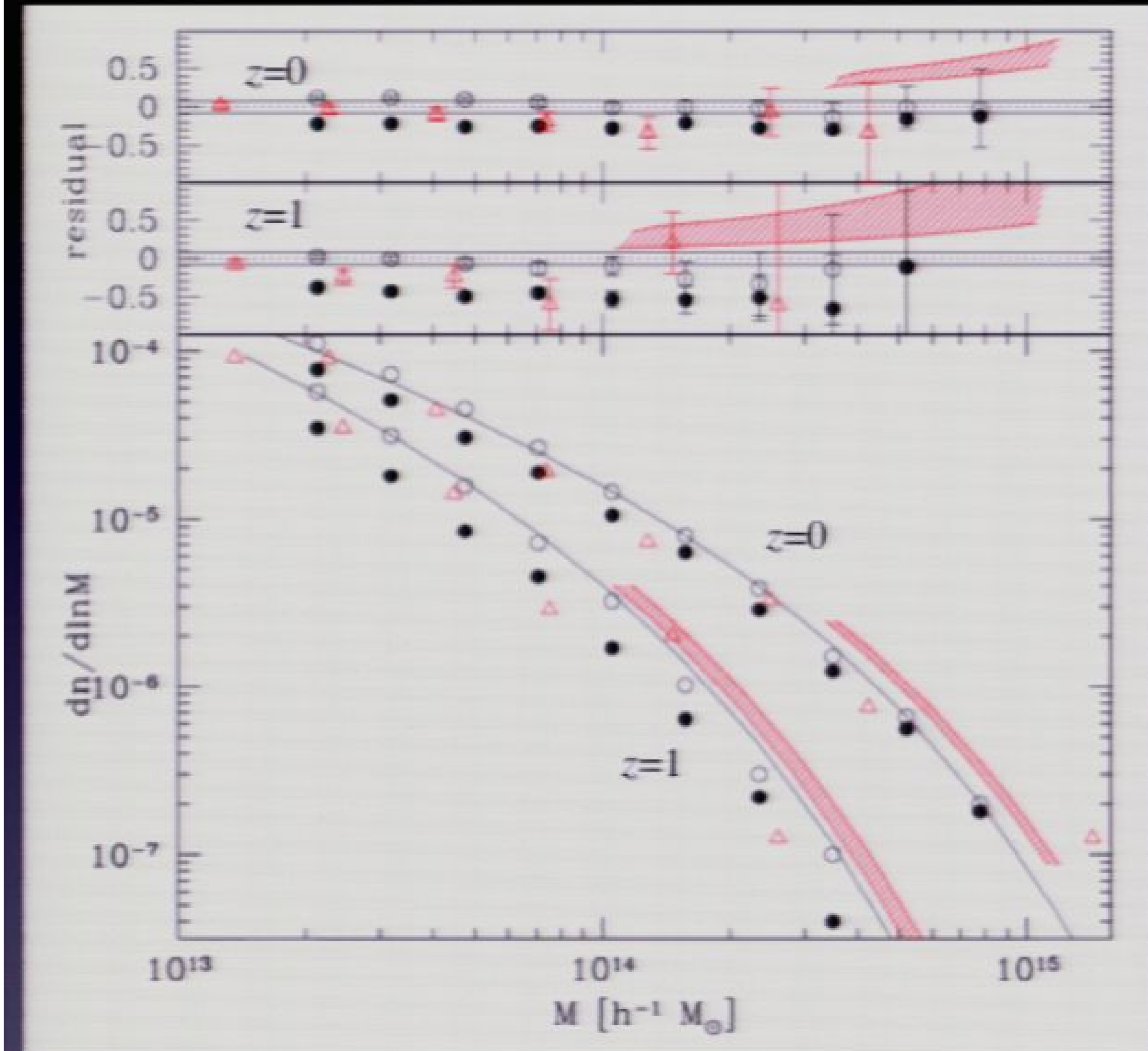
22 N-body simulations with N ≥ 512^3

– 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 0809.2805

– 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

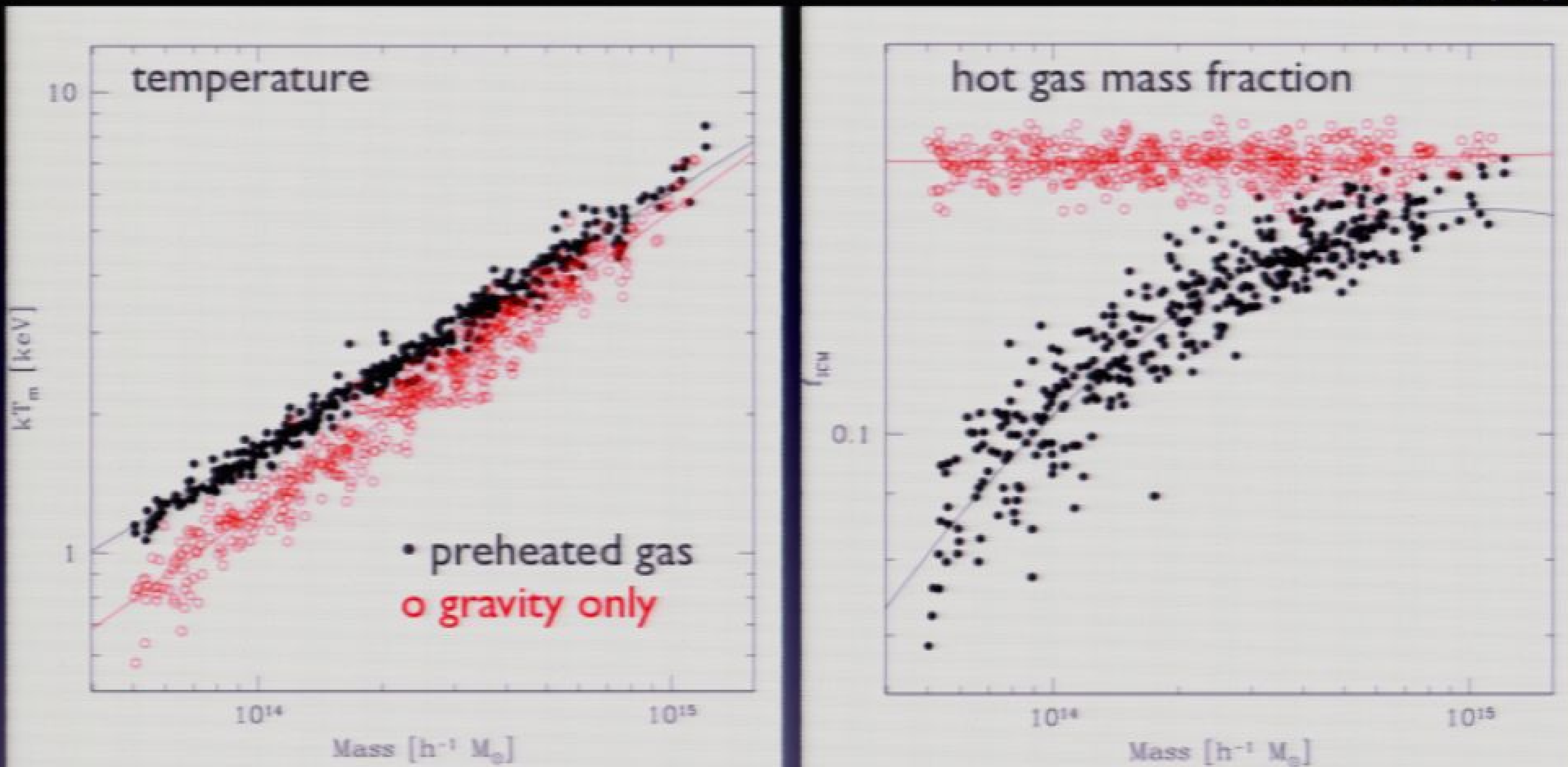
• MGS-preheat

Δ ART-gravity only

ART-cool/star/feedback

halo scalings from Millennium Simulation with gas dynamics treatments

Stanek et al, in prep



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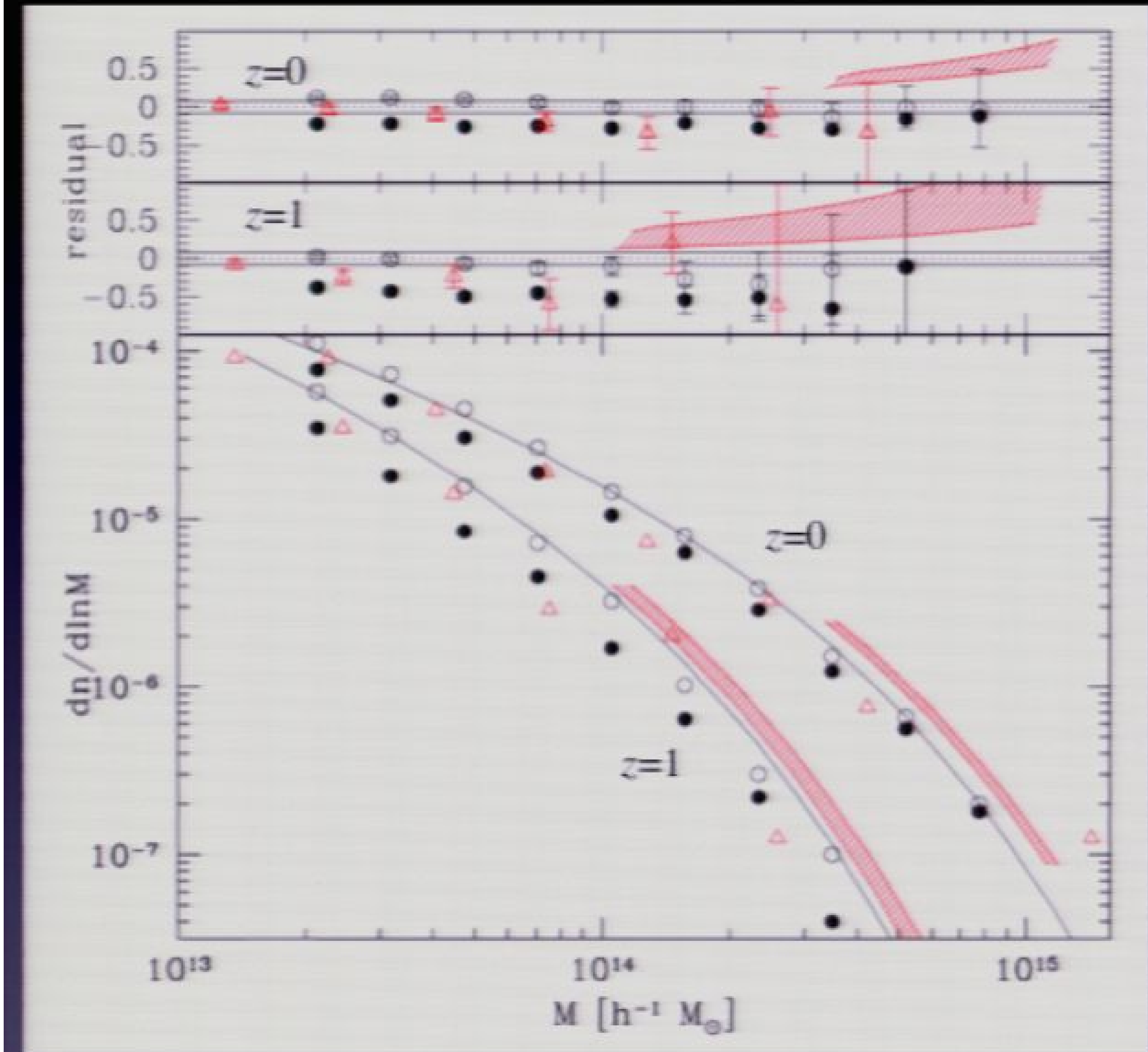

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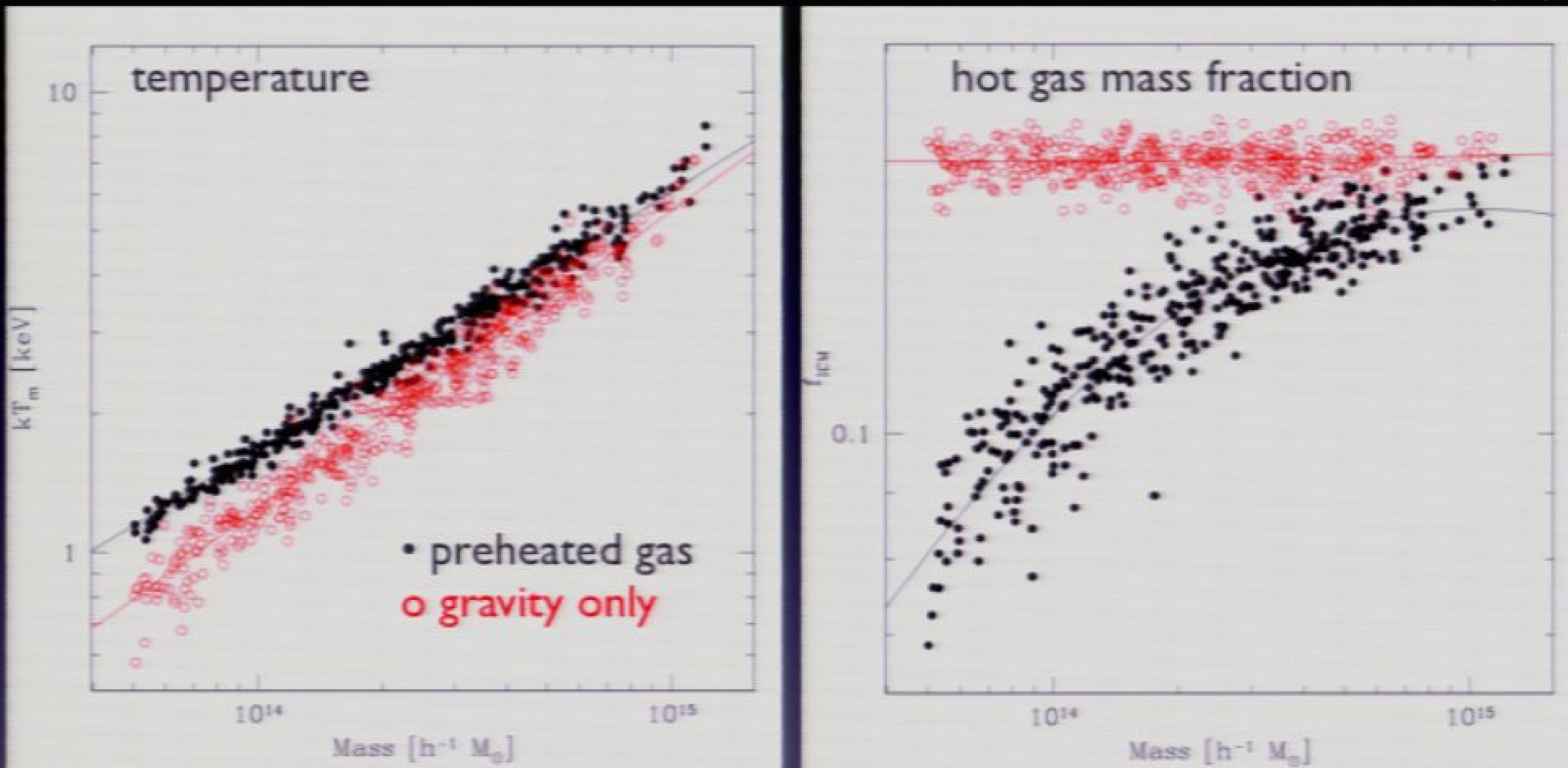

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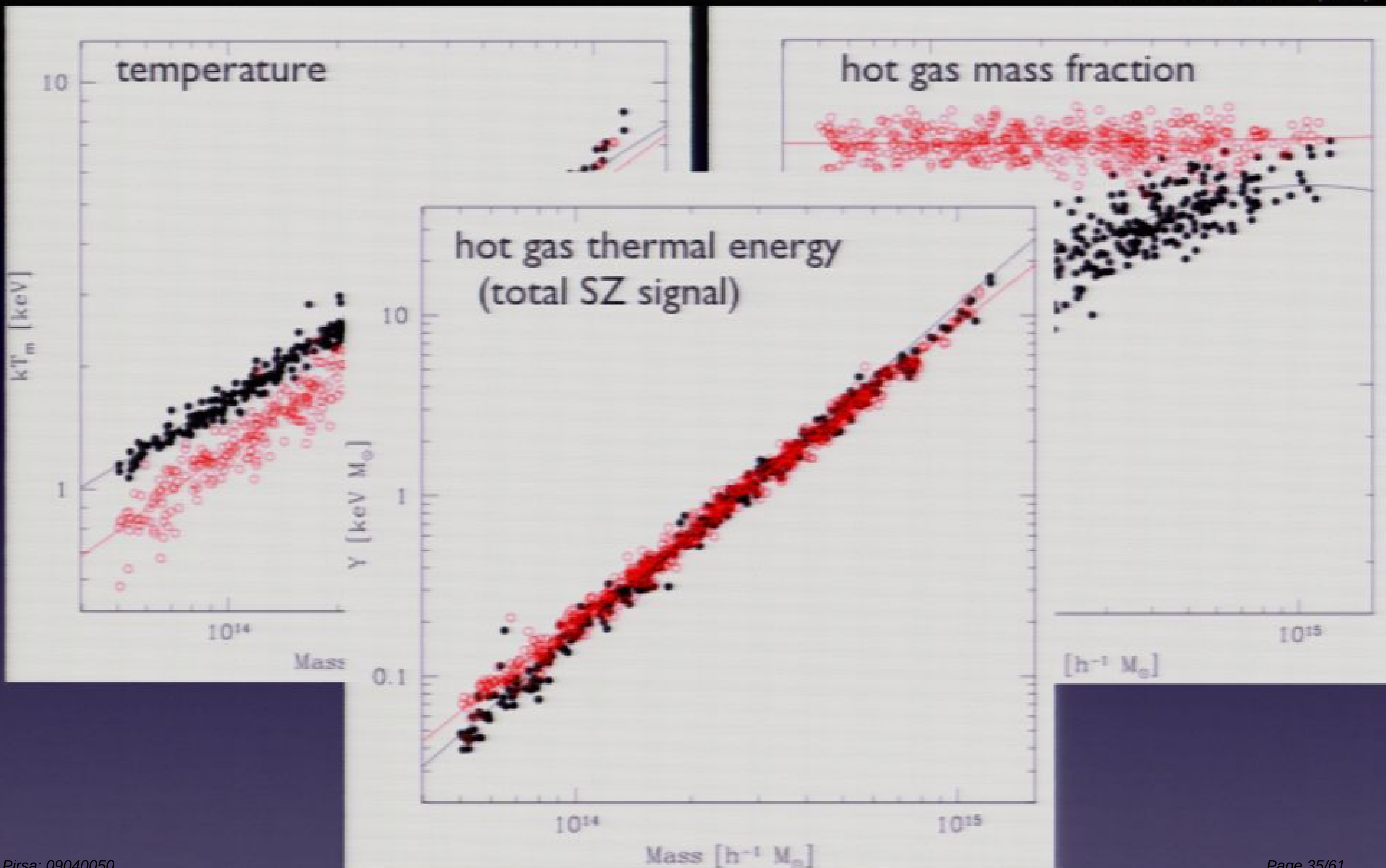
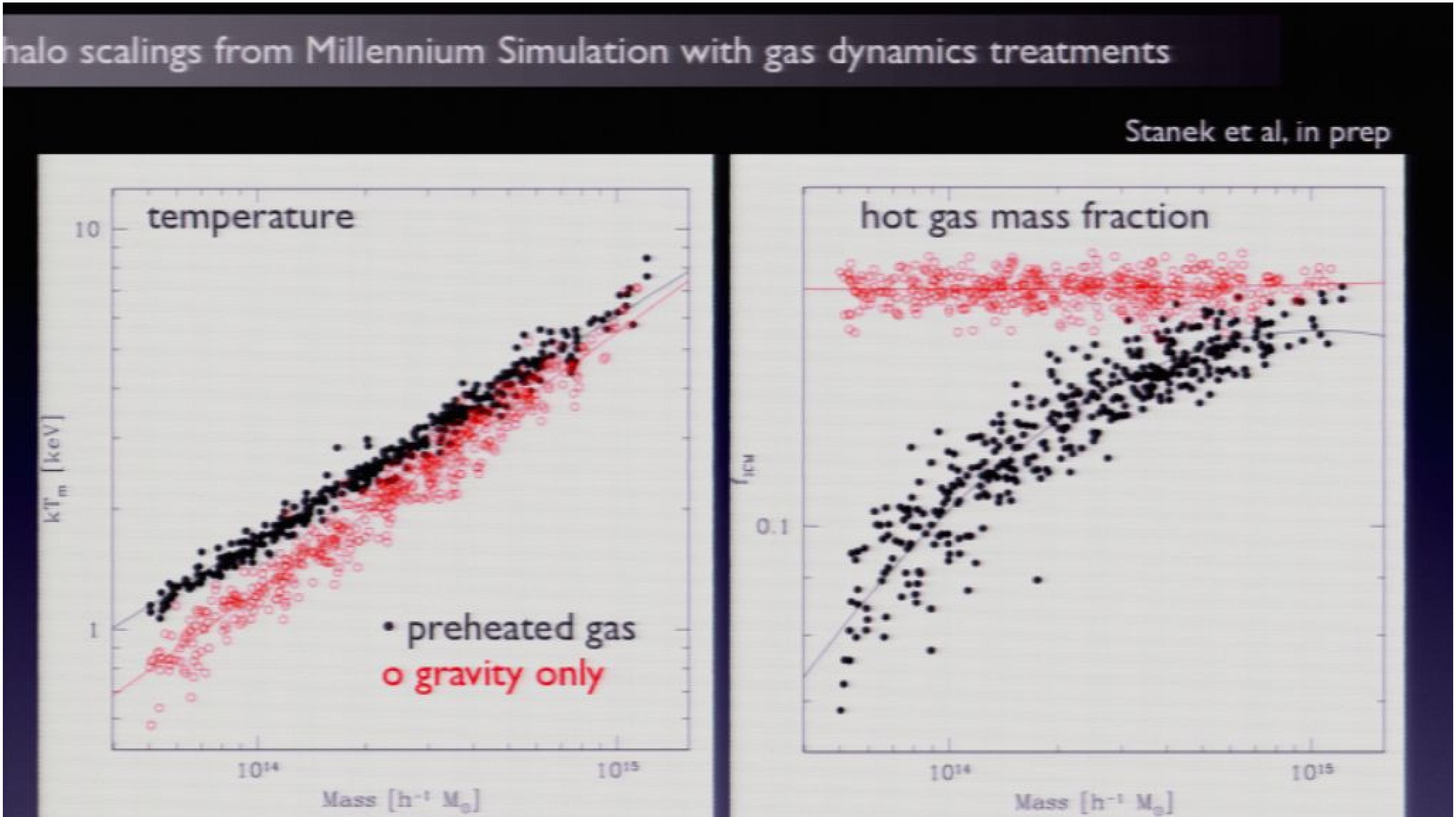
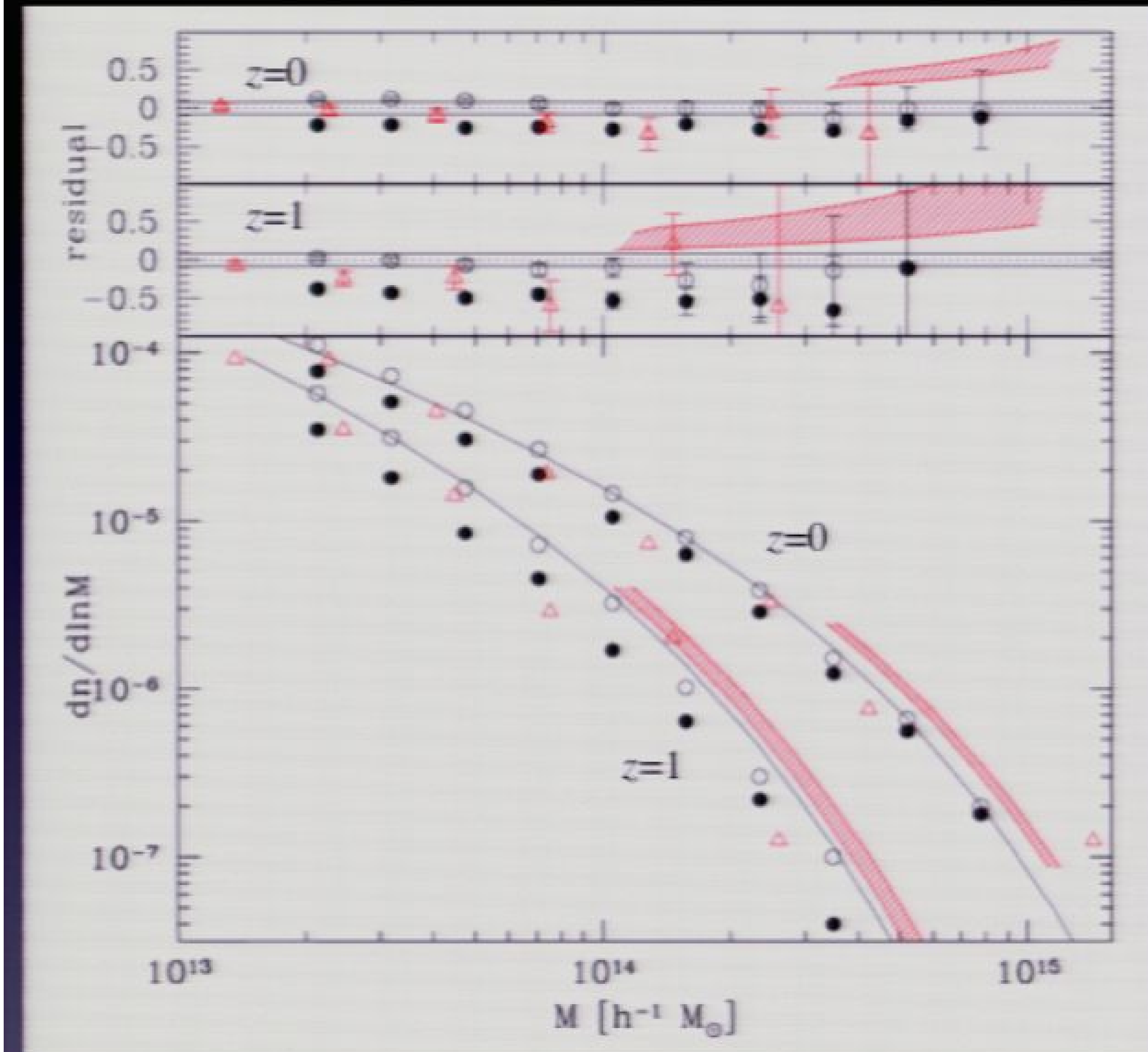



halo scalings from Millennium Simulation with gas dynamics treatments
Stanek et al, in prep
temperature
10
1
kT_m [keV]
• preheated gas
o gravity only
10^{14}
10^{15}
Mass [h^{-1} $M_\odot$]
hot gas mass fraction
0.1
f_{ICM}
10^{14}
10^{15}
Mass [h^{-1} $M_\odot$]

sensitivity of halo space density to baryon physics



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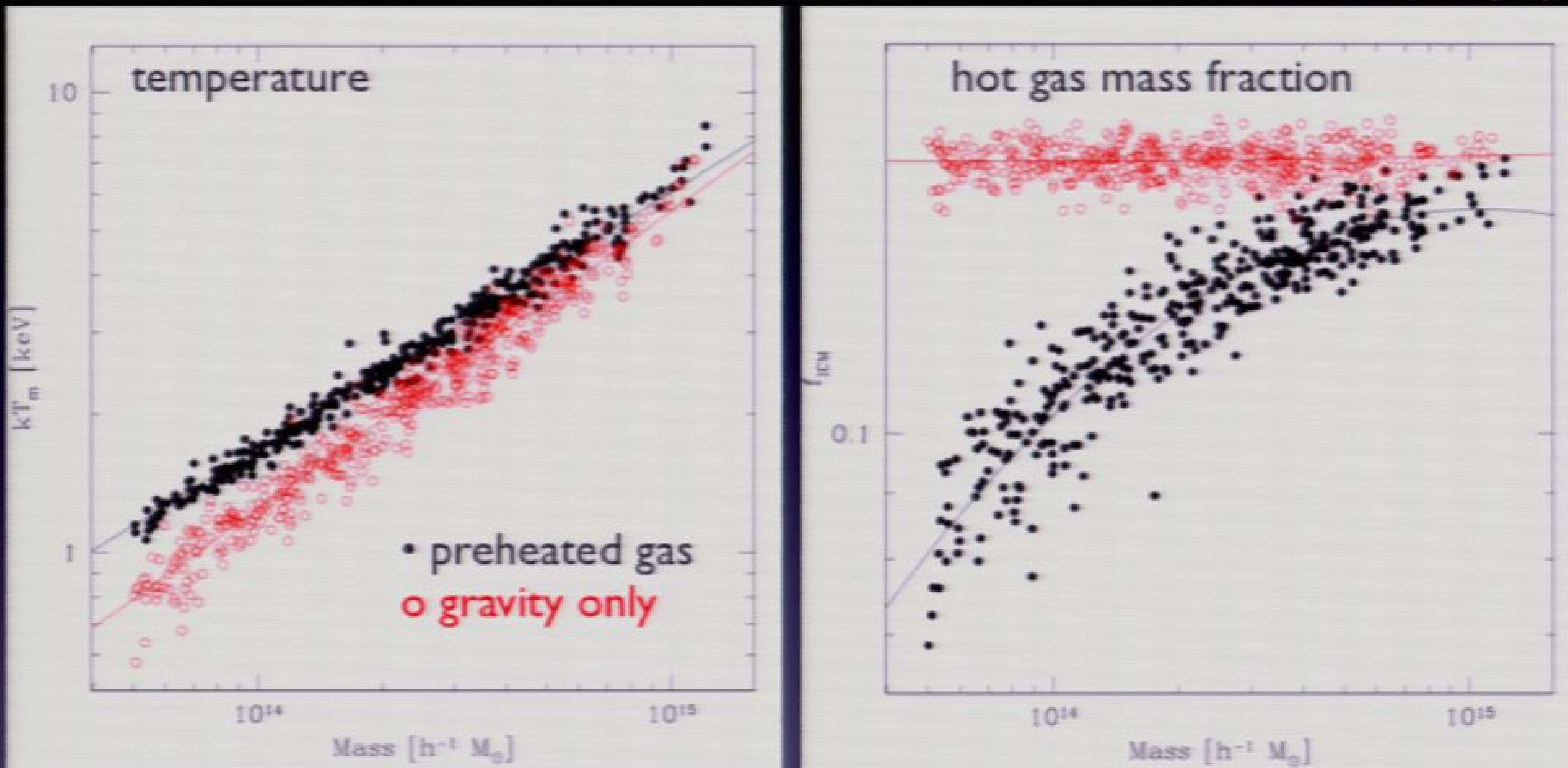

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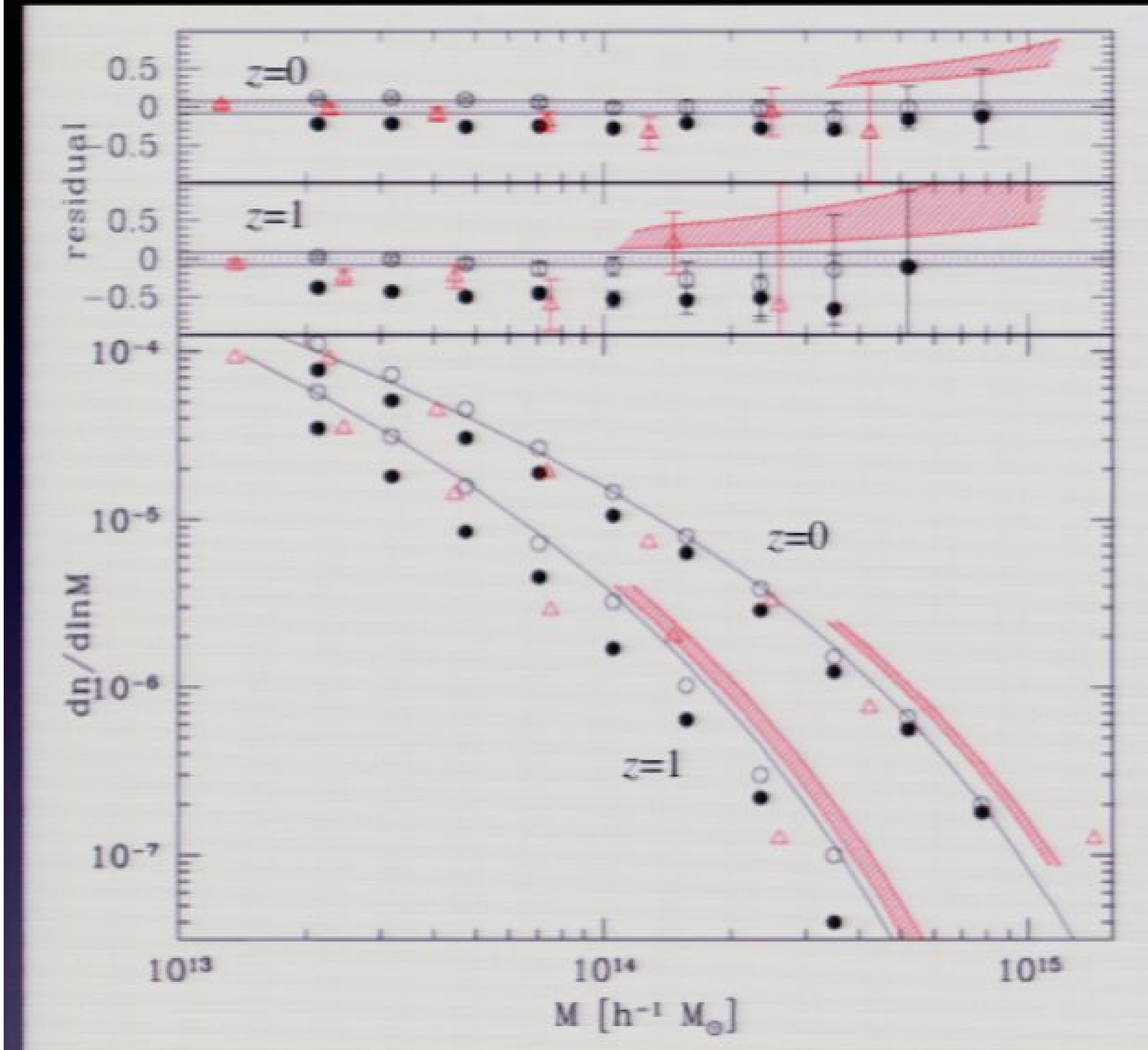

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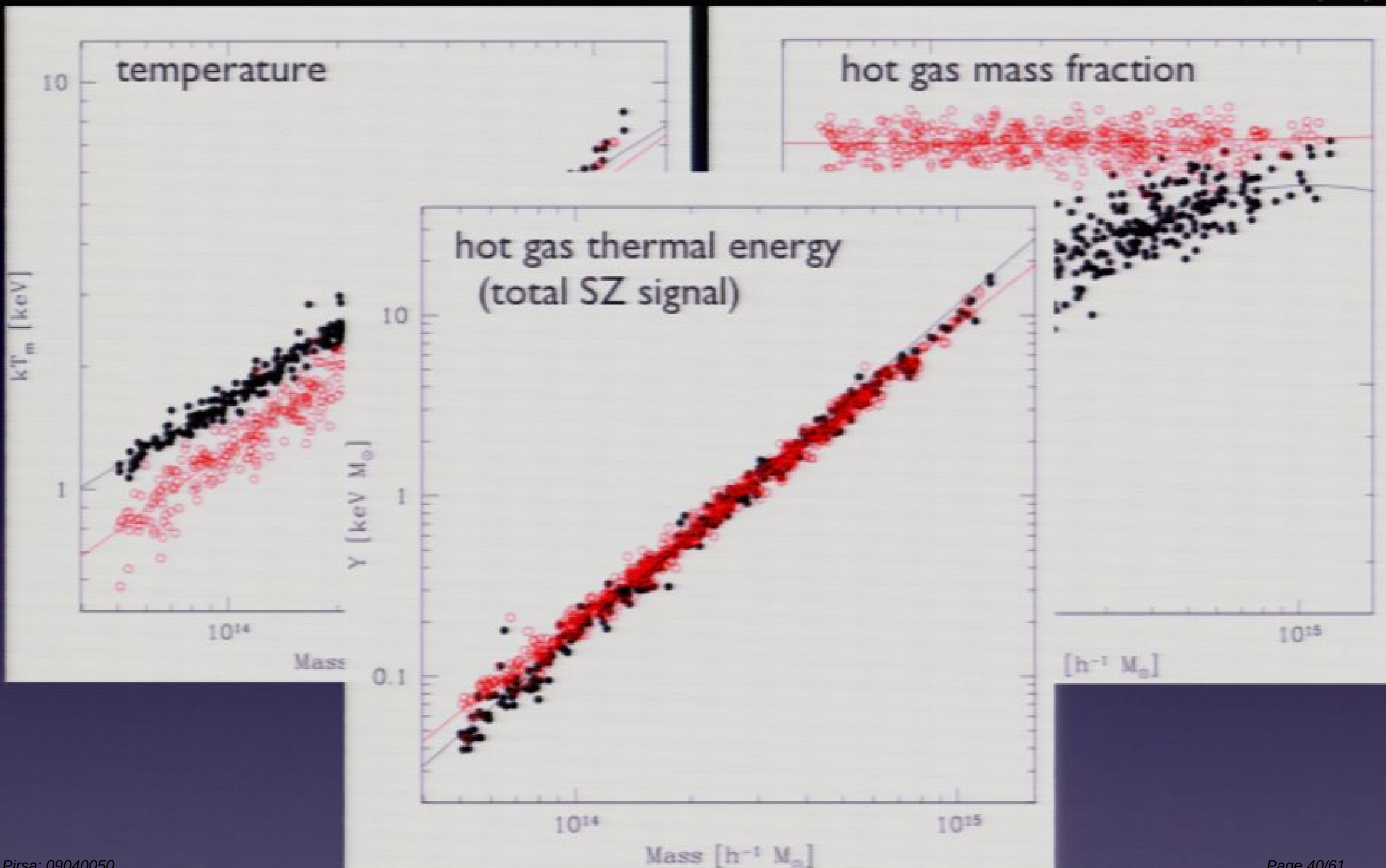

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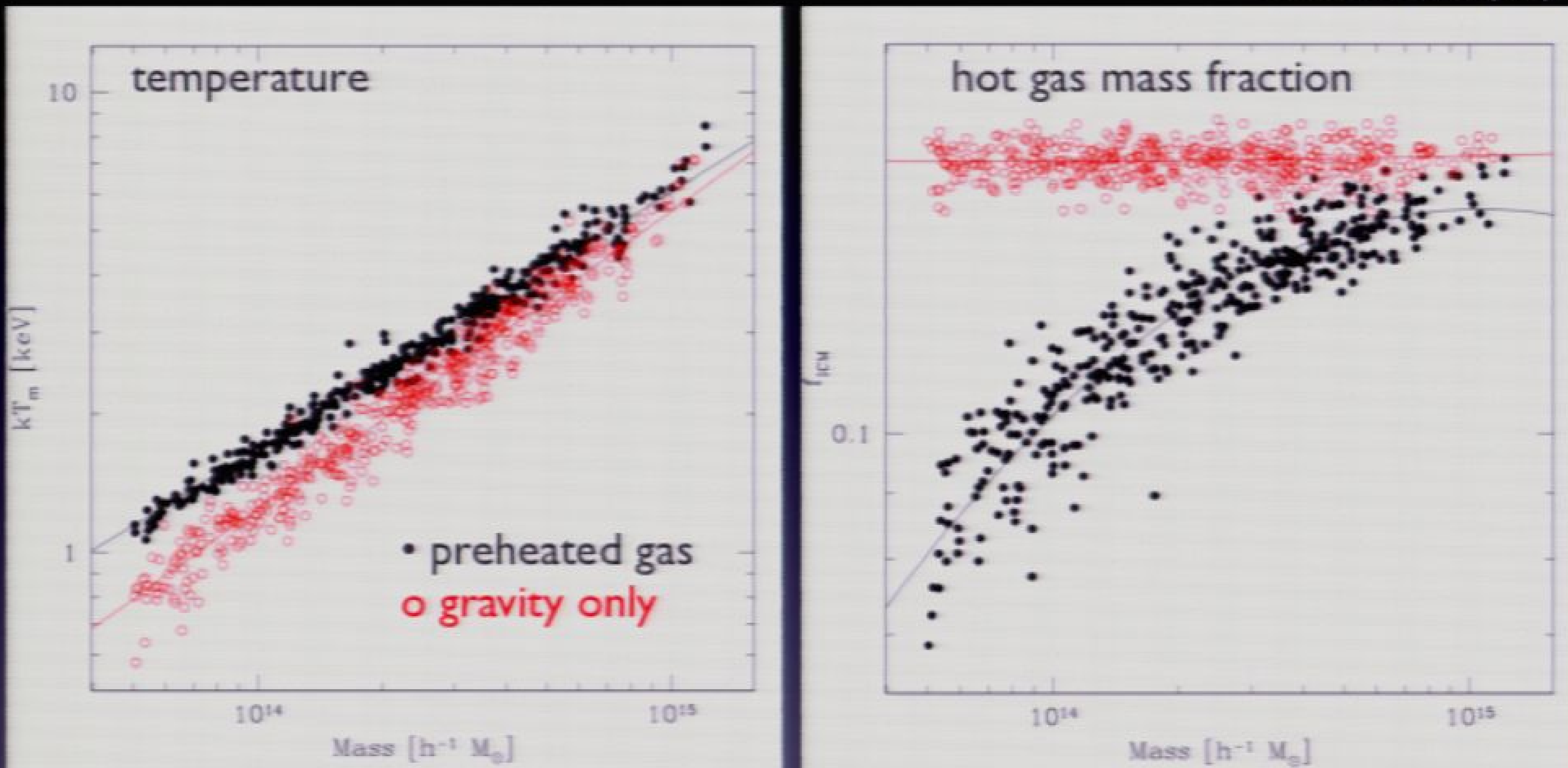
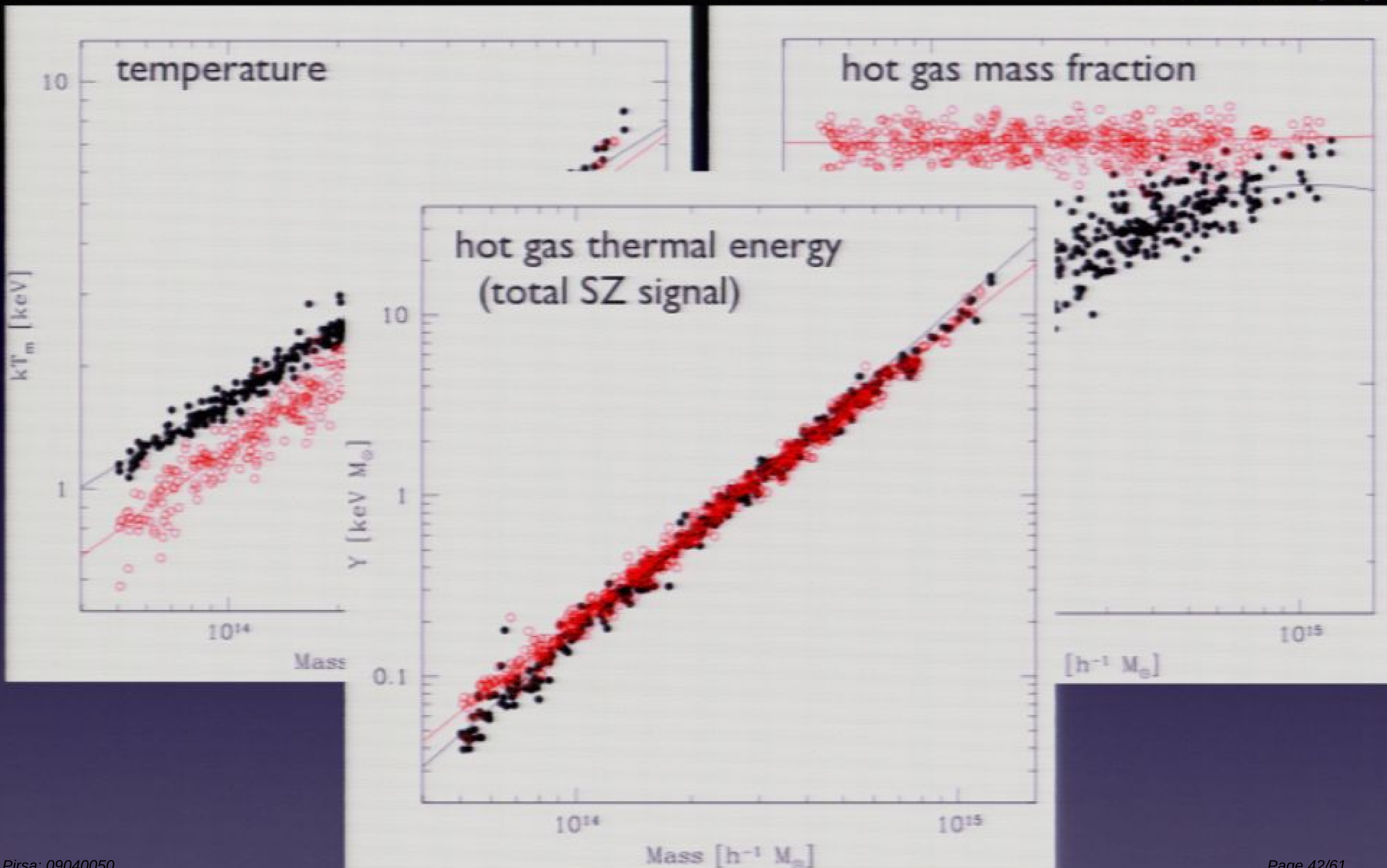
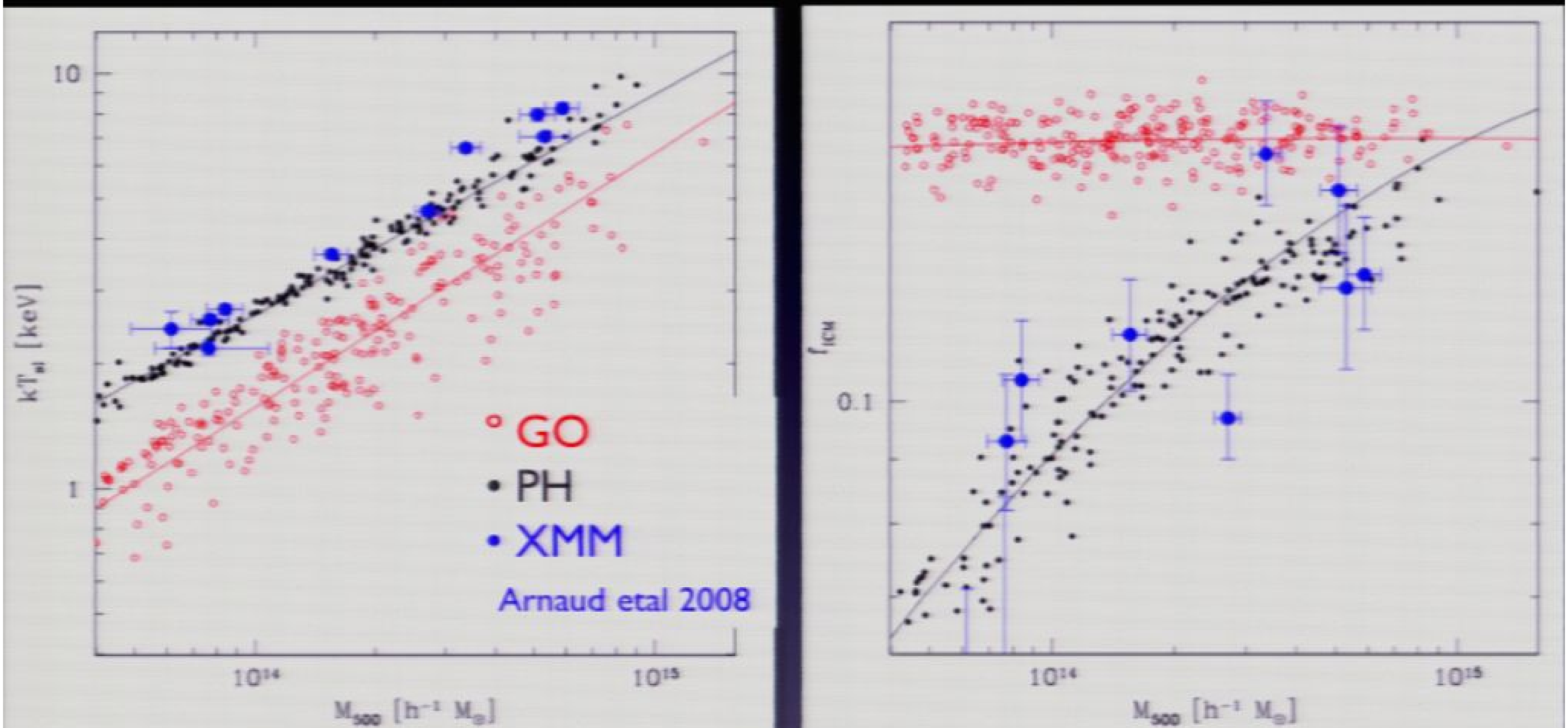


halo scalings from Millennium Simulation with gas dynamics treatments

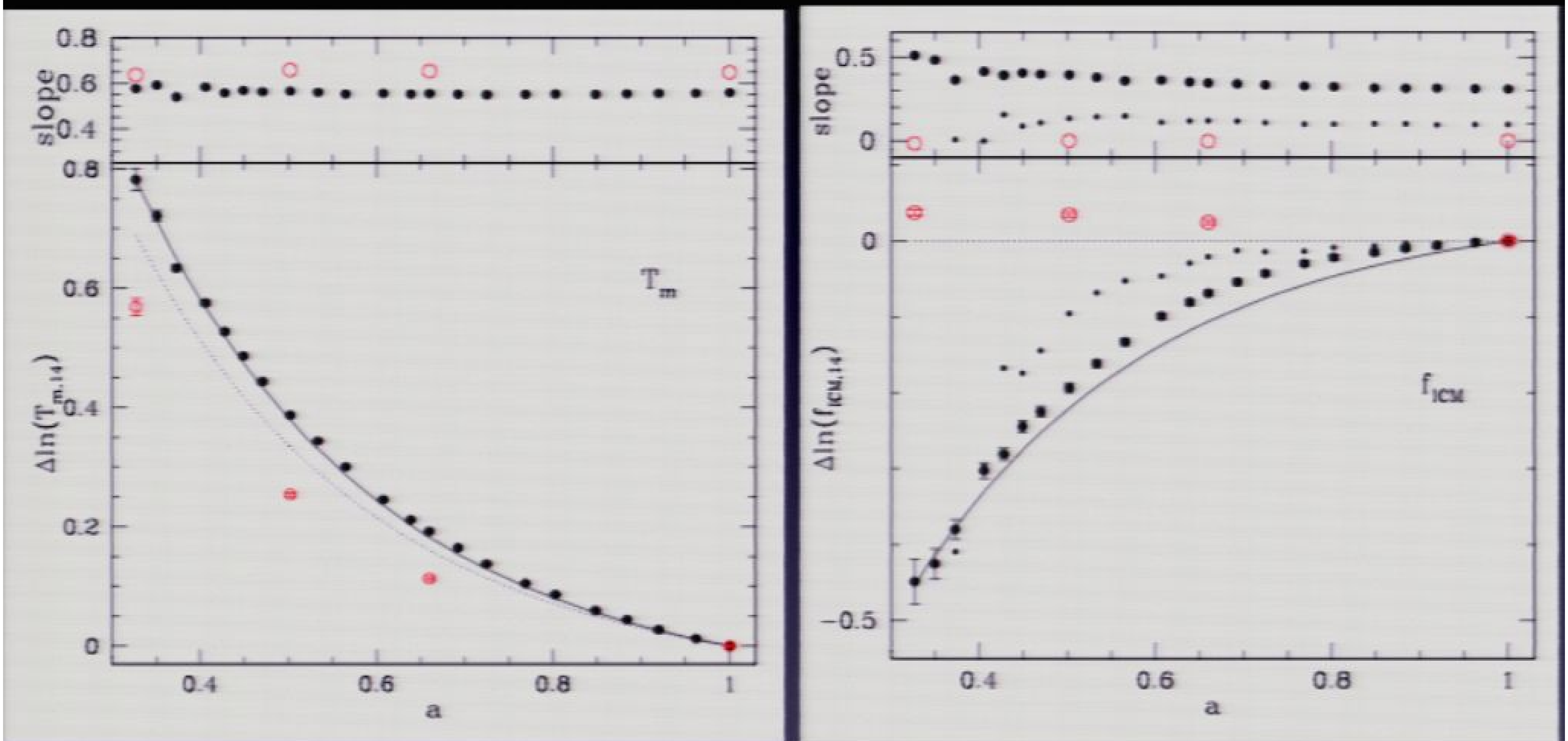
Stanek et al, in prep



MGS comparison to observations



MGS evolution of scaling relation slope and intercept



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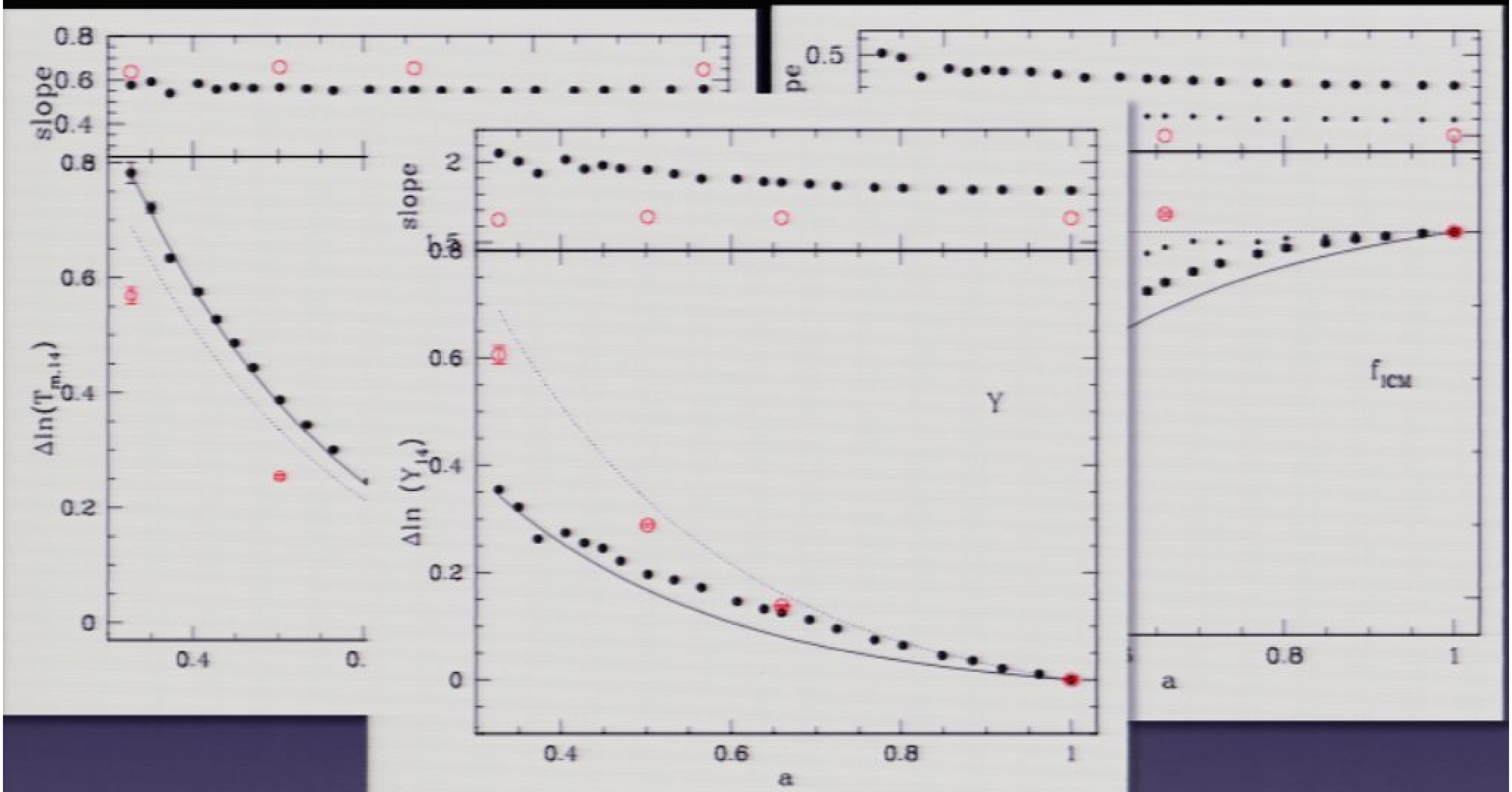
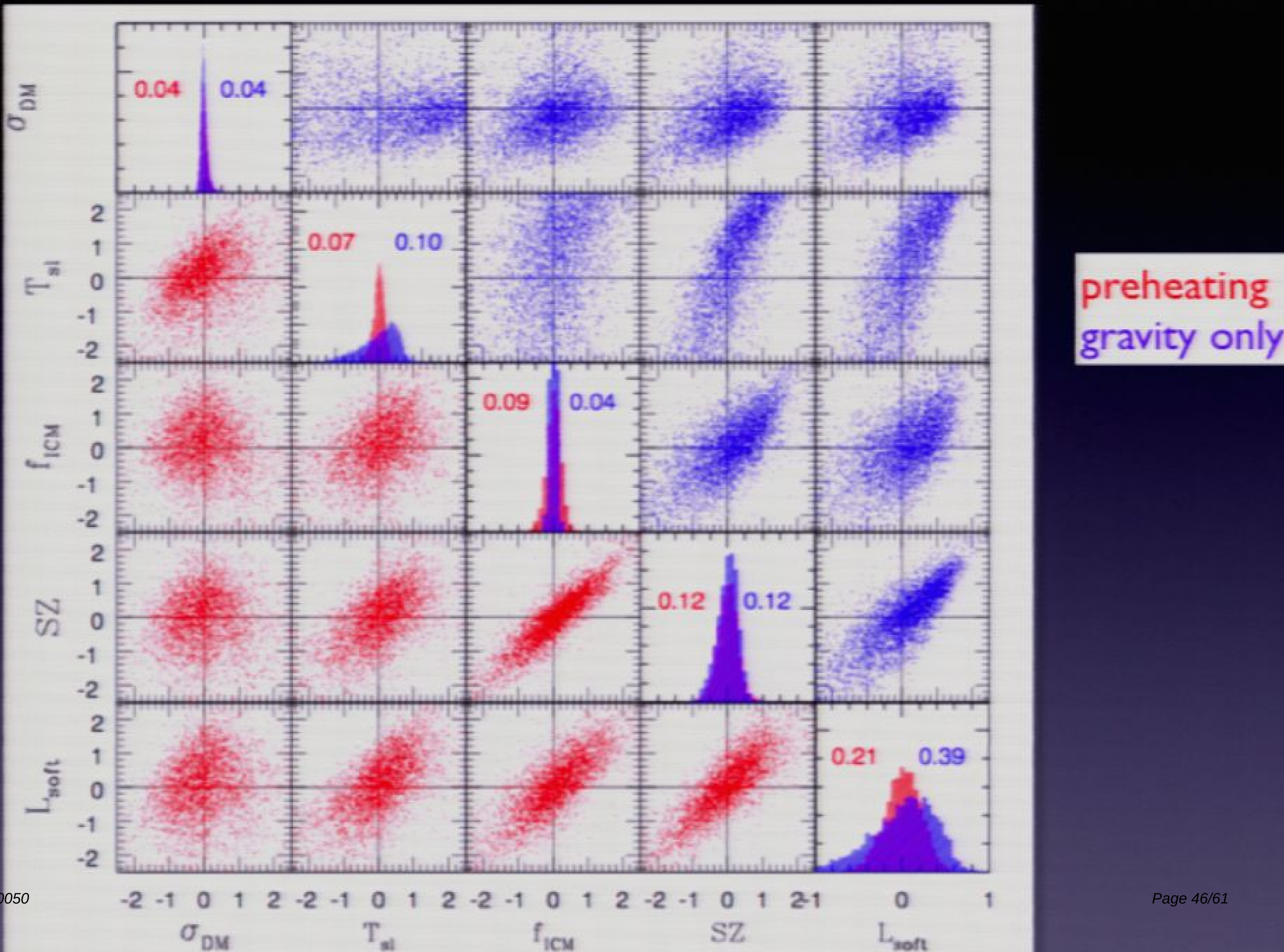


covariance of multiple signals at fixed halo mass



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.

blah

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

★ total mass is affected 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, ficm and T (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%)

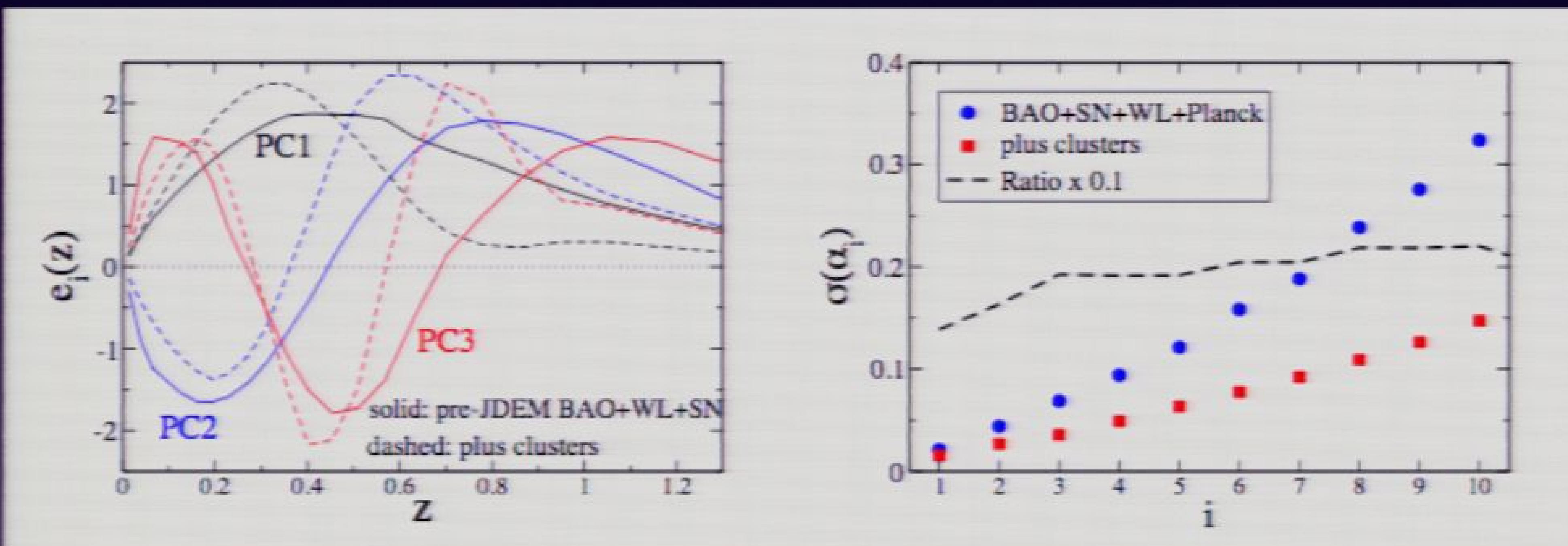
Fisher forecasts

Fisher analysis of value of cluster counts and clustering

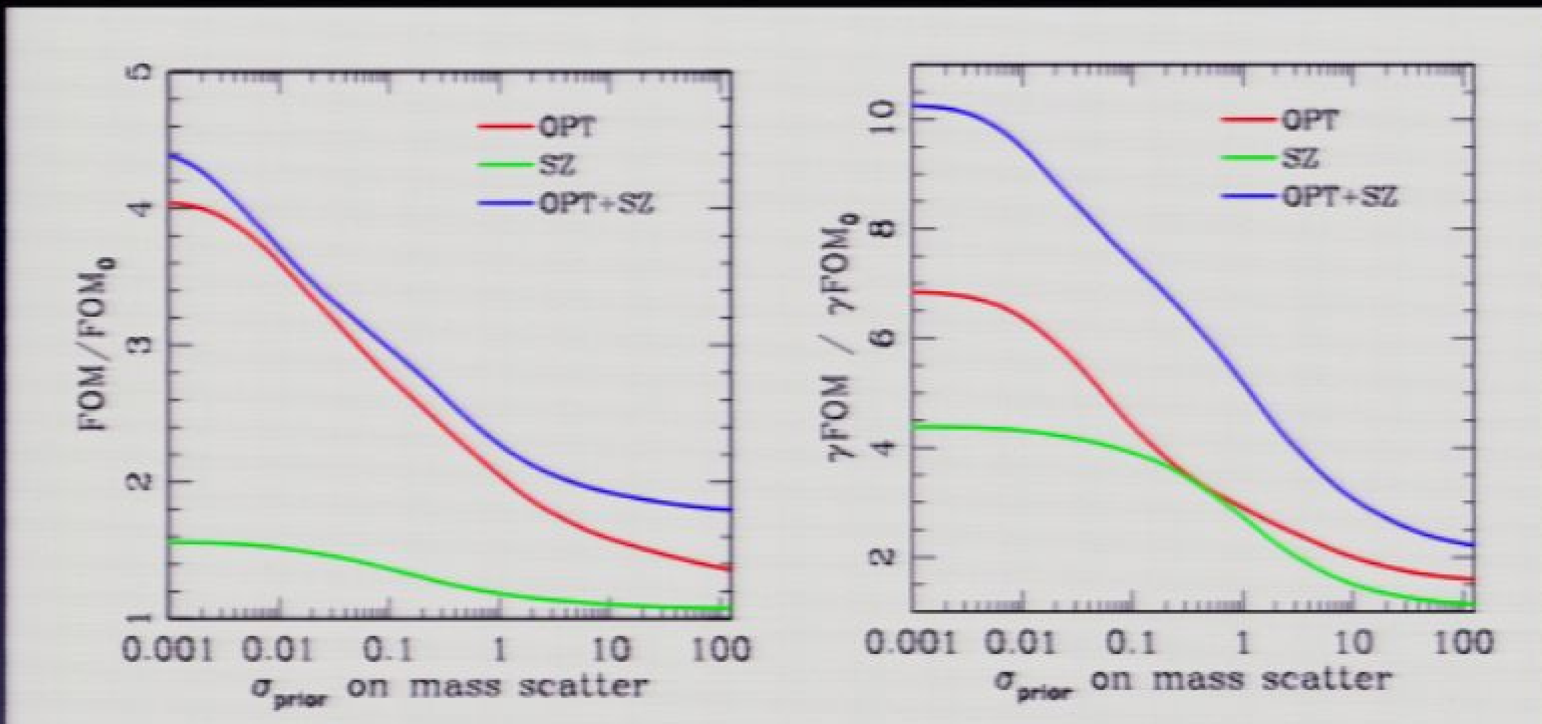
Cunha, Huterer
Frieman, 0904.1589

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

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



additional improvements from prior in Mobs proxy



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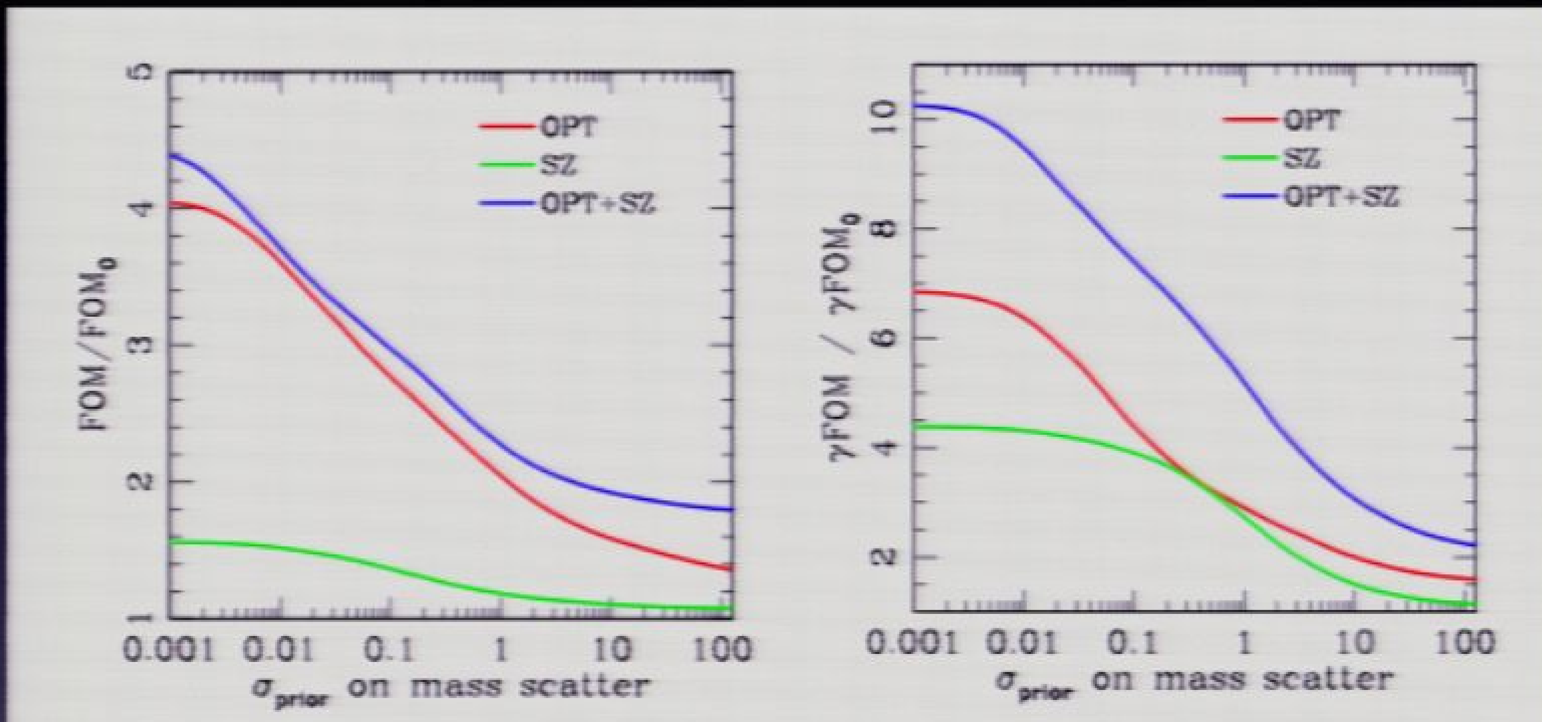


further exploration into Mobs and Mass Function/Bias

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

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

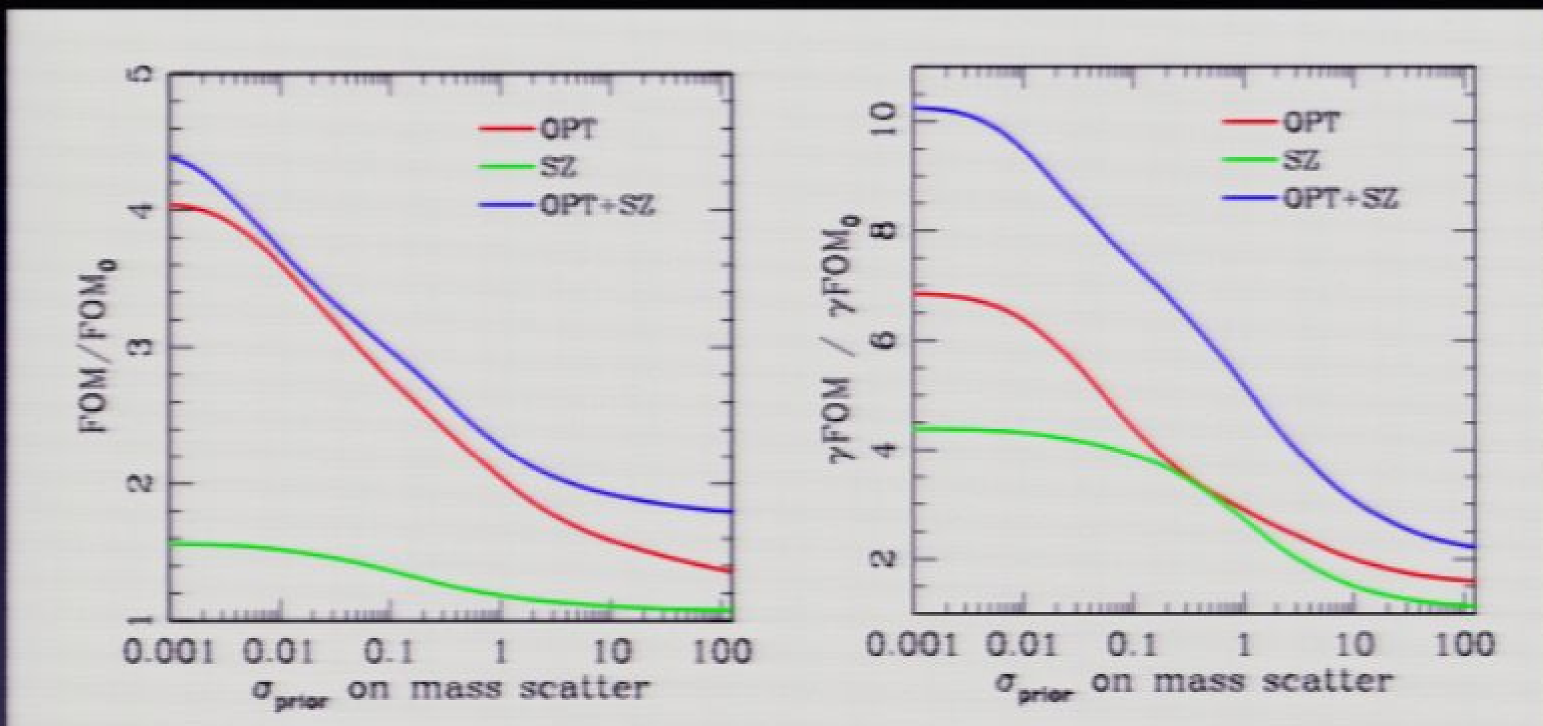
$$a(z) = a_0(1+z)^{a_z} \quad (18)$$

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

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

additional improvements from prior in Mobs proxy



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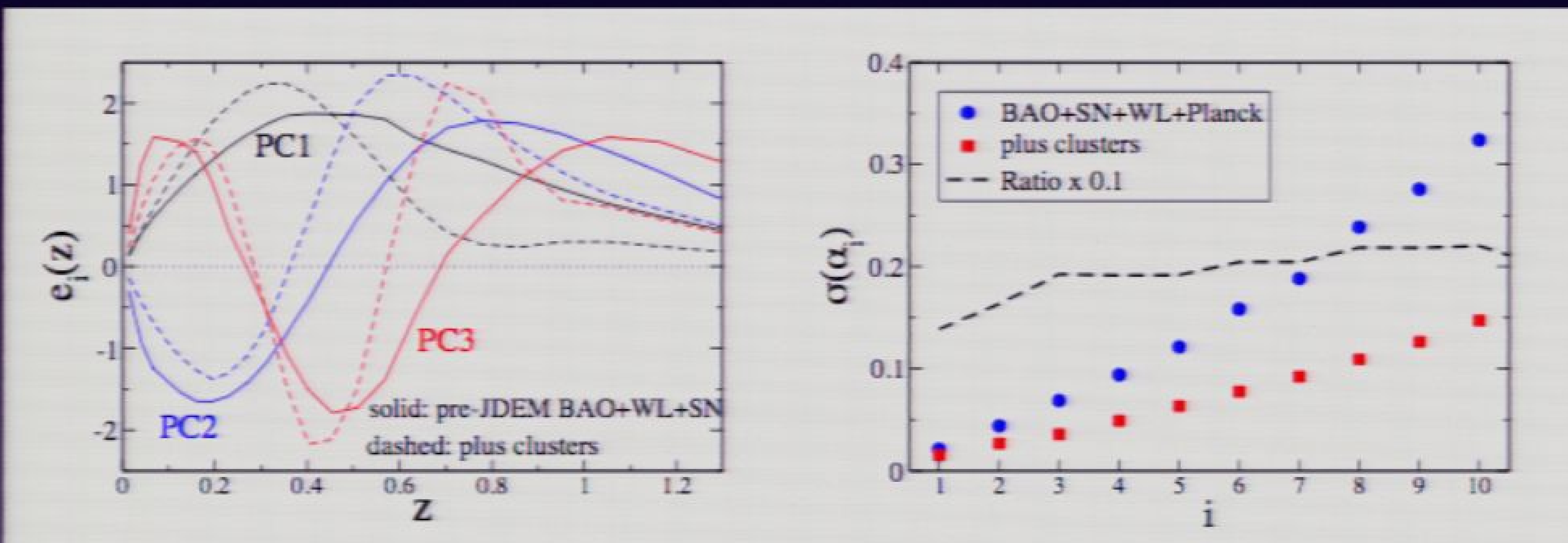

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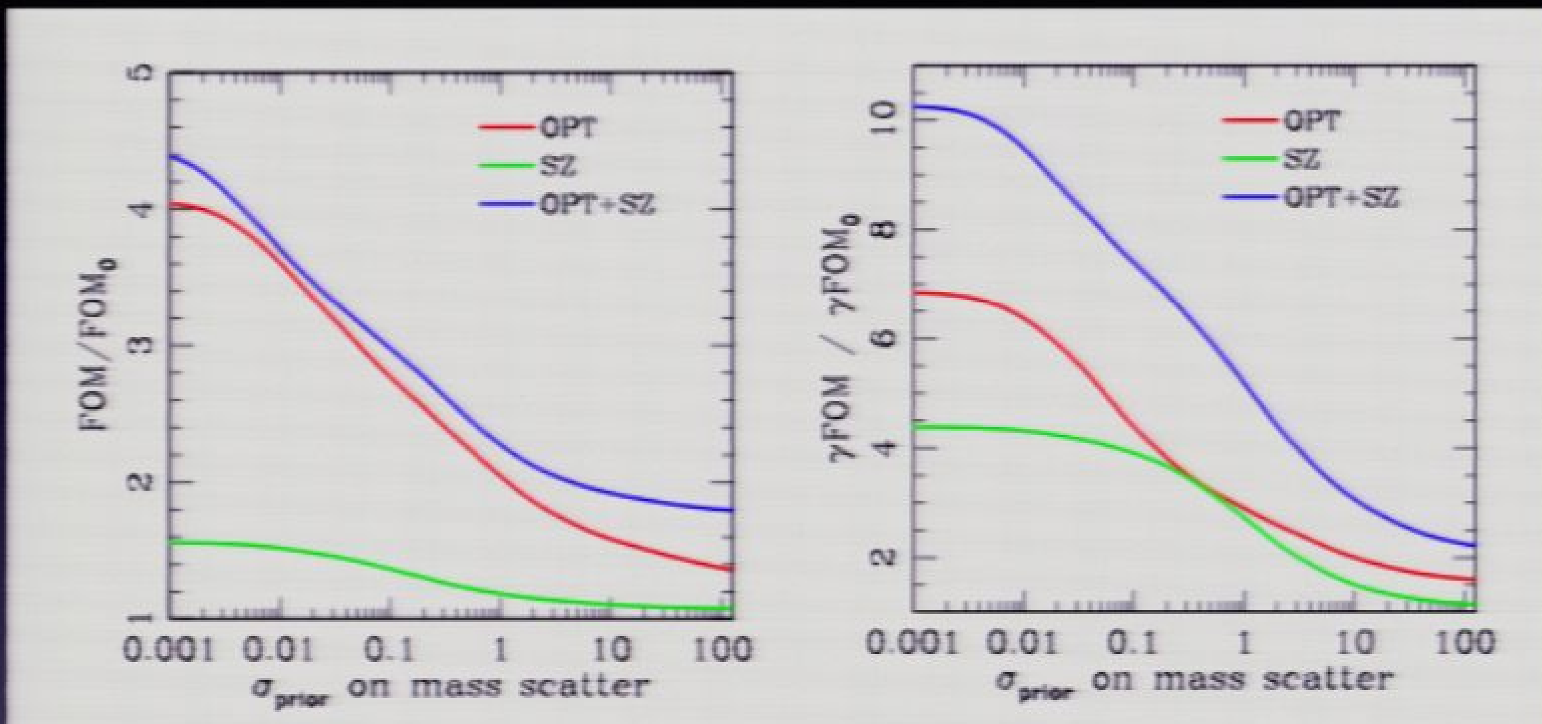

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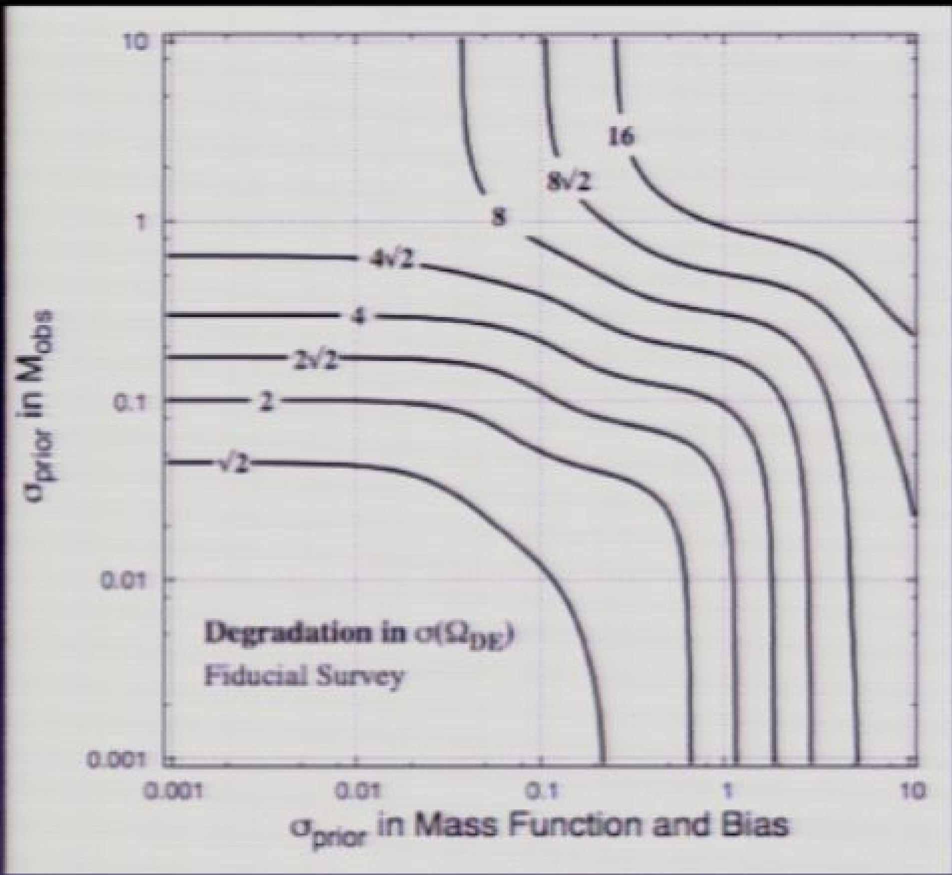
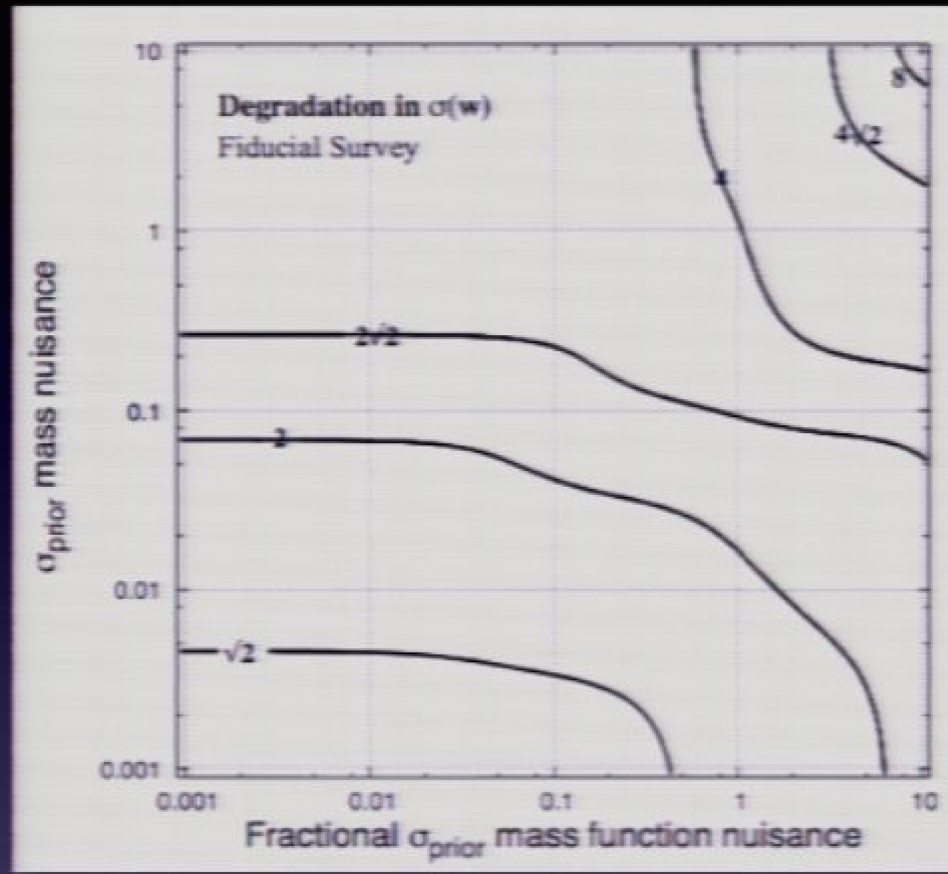
sensitivity to Mobs and Mass Function/Bias priors





the 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 ~24th mag

Repeated observations of 40 deg^2

Development and schedule

Construction: 2007-2011

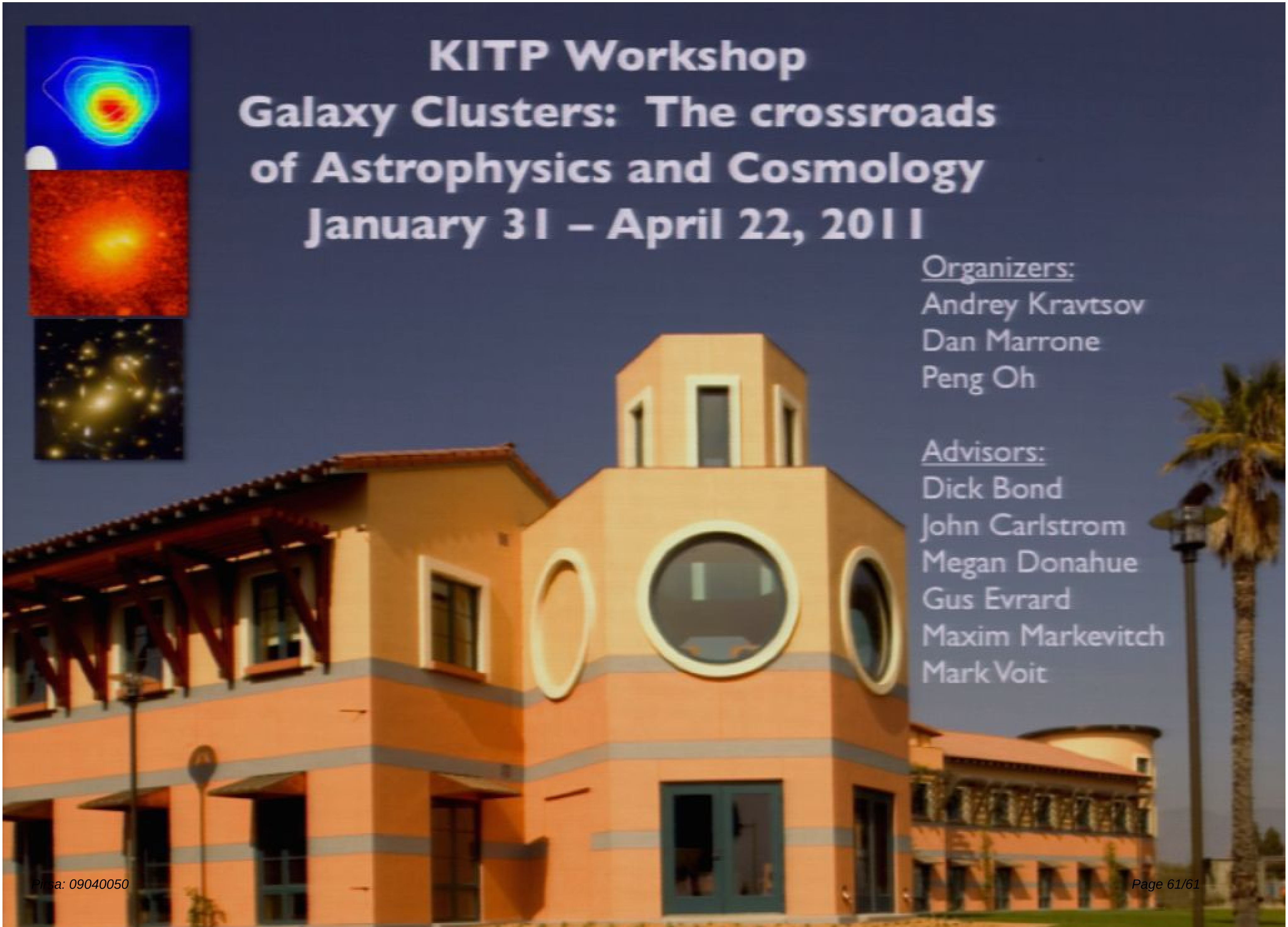
- New 3 deg^2 camera on Blanco 4m, Cerro Tololo
- Data management system at NCSA

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