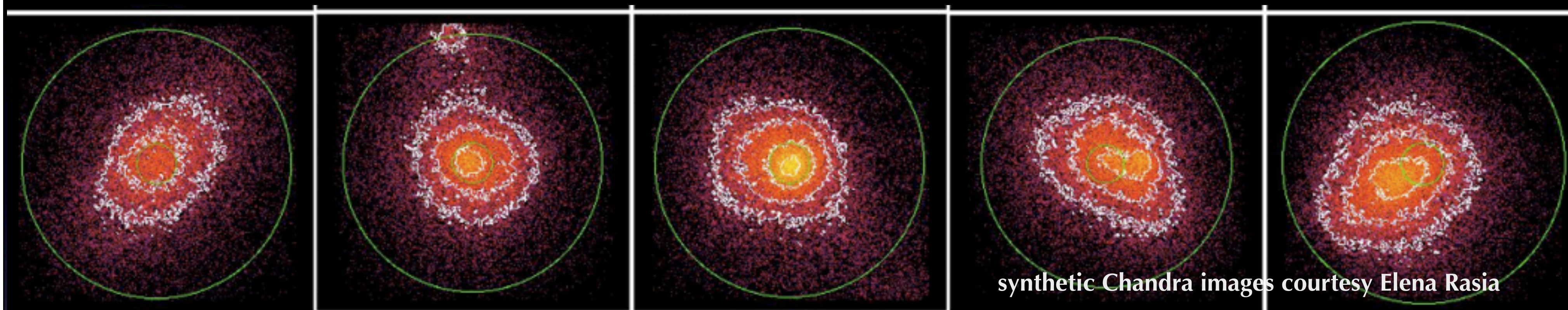
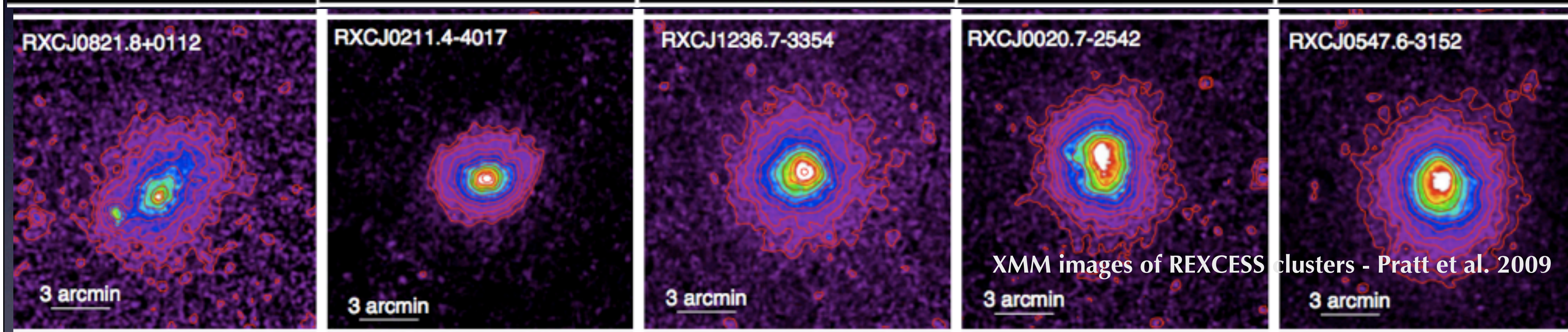
# Galaxy Clusters at the Crossroads

## of Astrophysics + Cosmology

## of Theory + Computation + Observation



synthetic Chandra images courtesy Elena Rasia




XMM images of REXCESS clusters - Pratt et al. 2009

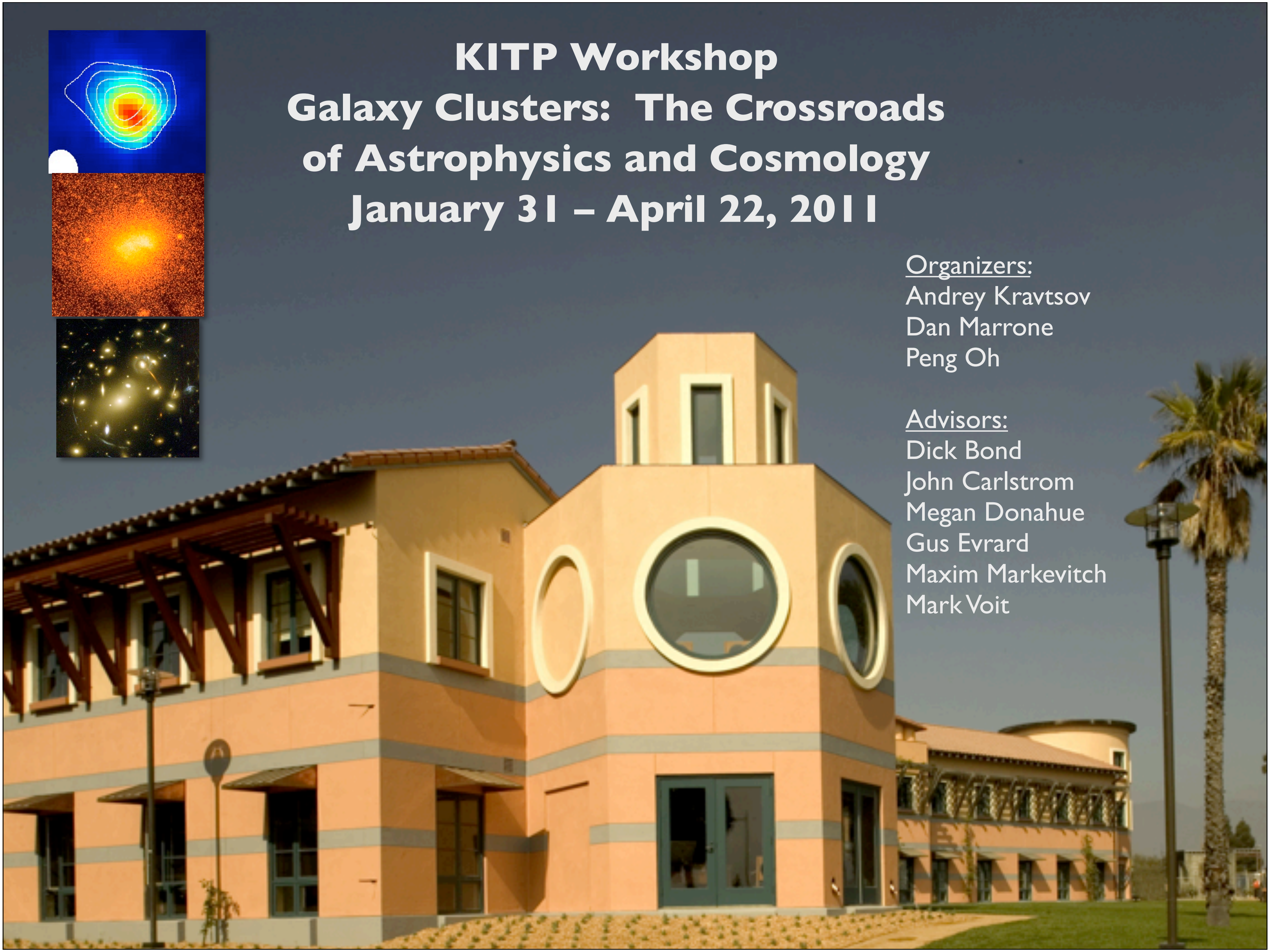

**August (Gus) Evrard**

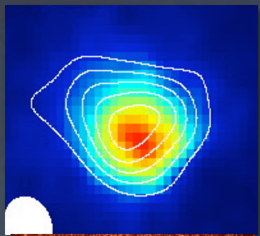
Arthur F. Thurnau Professor

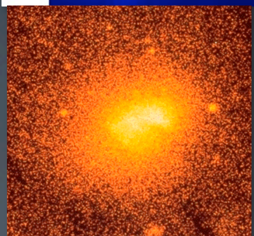
Departments of Physics and Astronomy

Michigan Center for Theoretical Physics

University of Michigan


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





# KITP Workshop
# Galaxy Clusters: The Crossroads of Astrophysics and Cosmology
## January 31 – April 22, 2011

Organizers:
Andrey Kravtsov
Dan Marrone
Peng Oh
Mark Voit

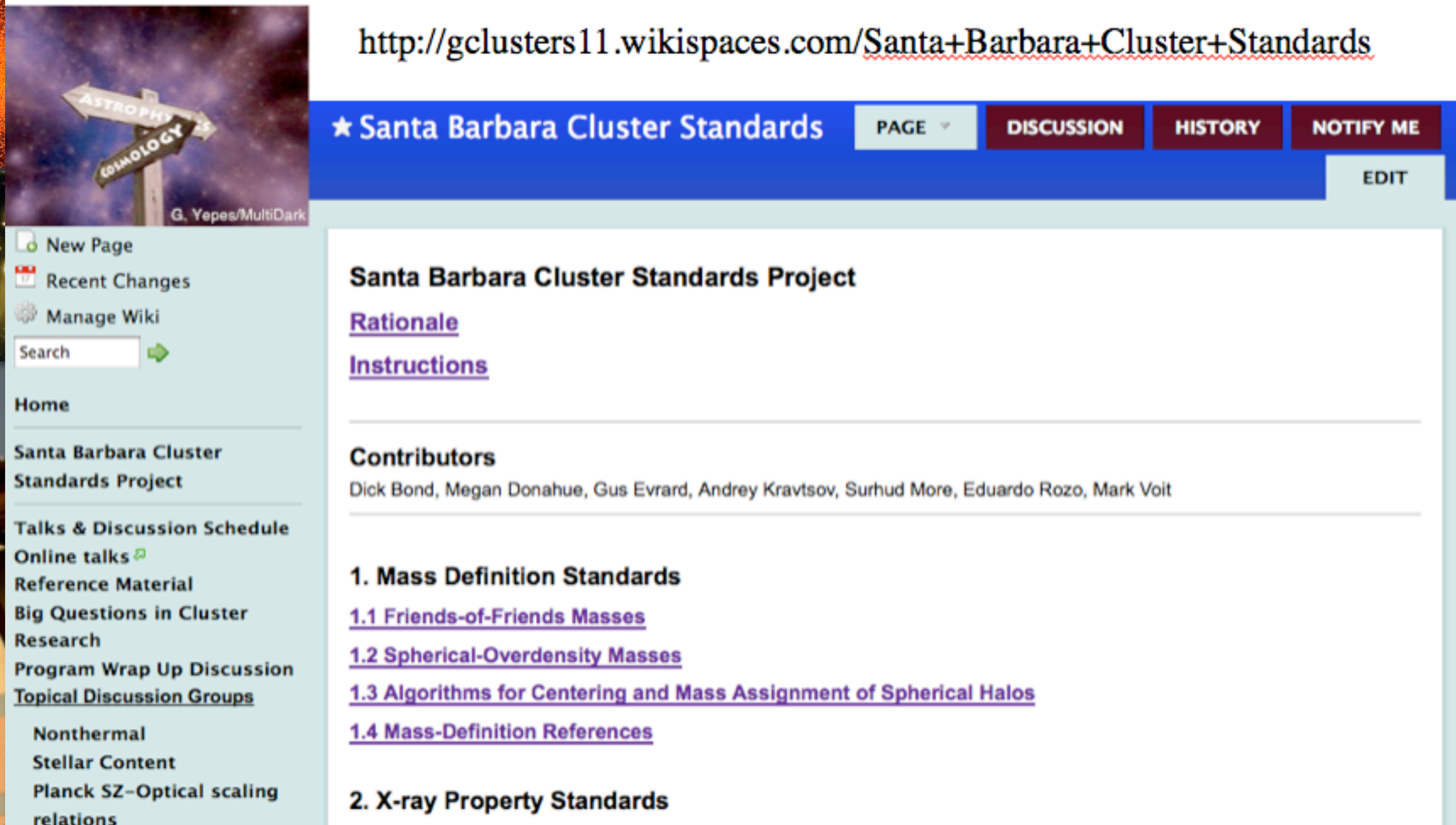
# STANDARDS

# KITP Workshop

## Galaxy Clusters: The Crossroads

# `Santa Barbara cluster' standards movement

http://gclusters11.wikispaces.com/Santa+Barbara+Cluster+Standards



## basic steps to study dark energy (DE) with large-scale structure

1. produce a large survey of a class of cosmic objects to z≥1, using a class that enables statistical tracing of dark matter

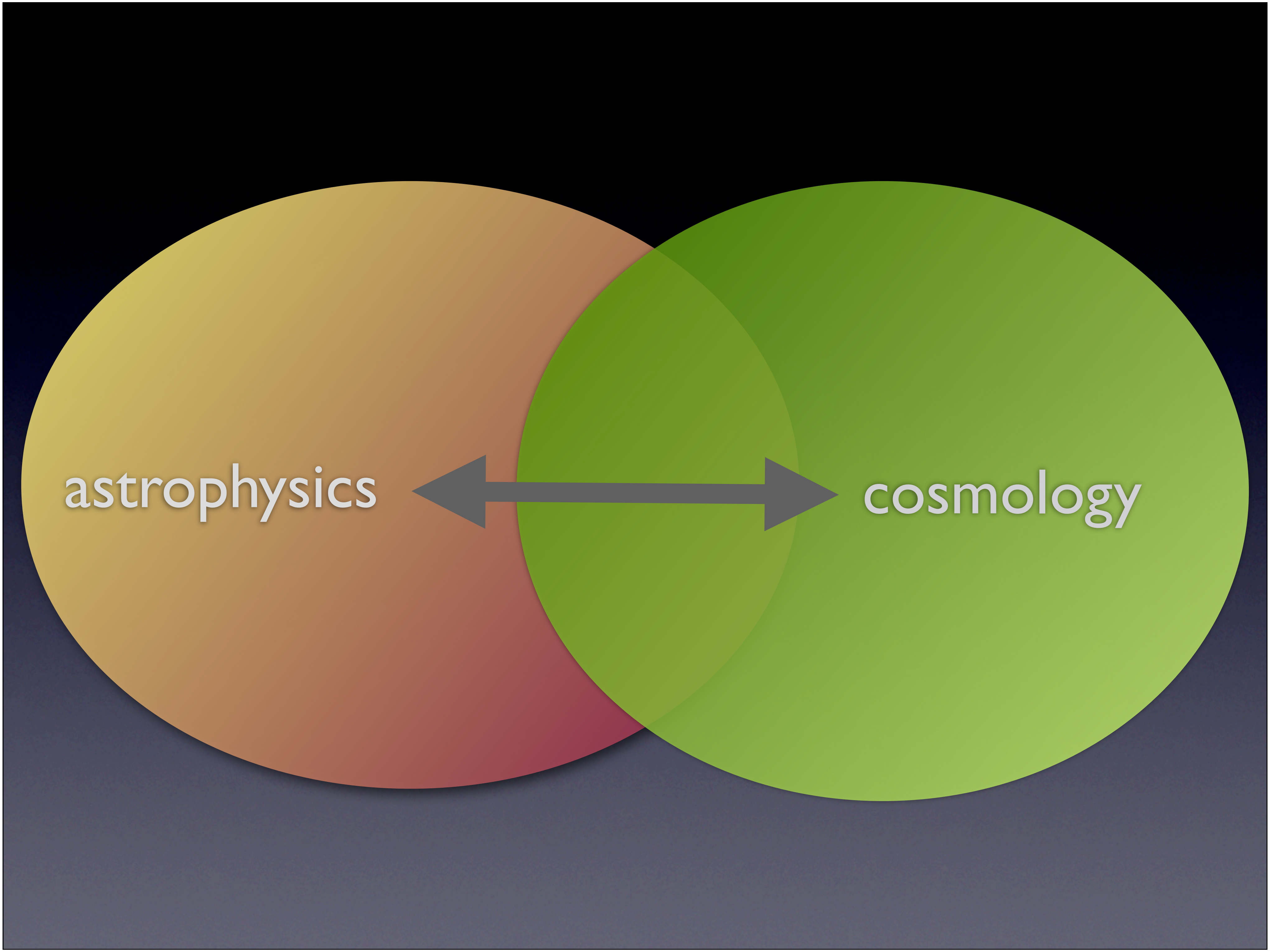
   – extract statistics, $\mathbf{y}_i$, for DE test method *i* (e.g., BAO, WL, CL)

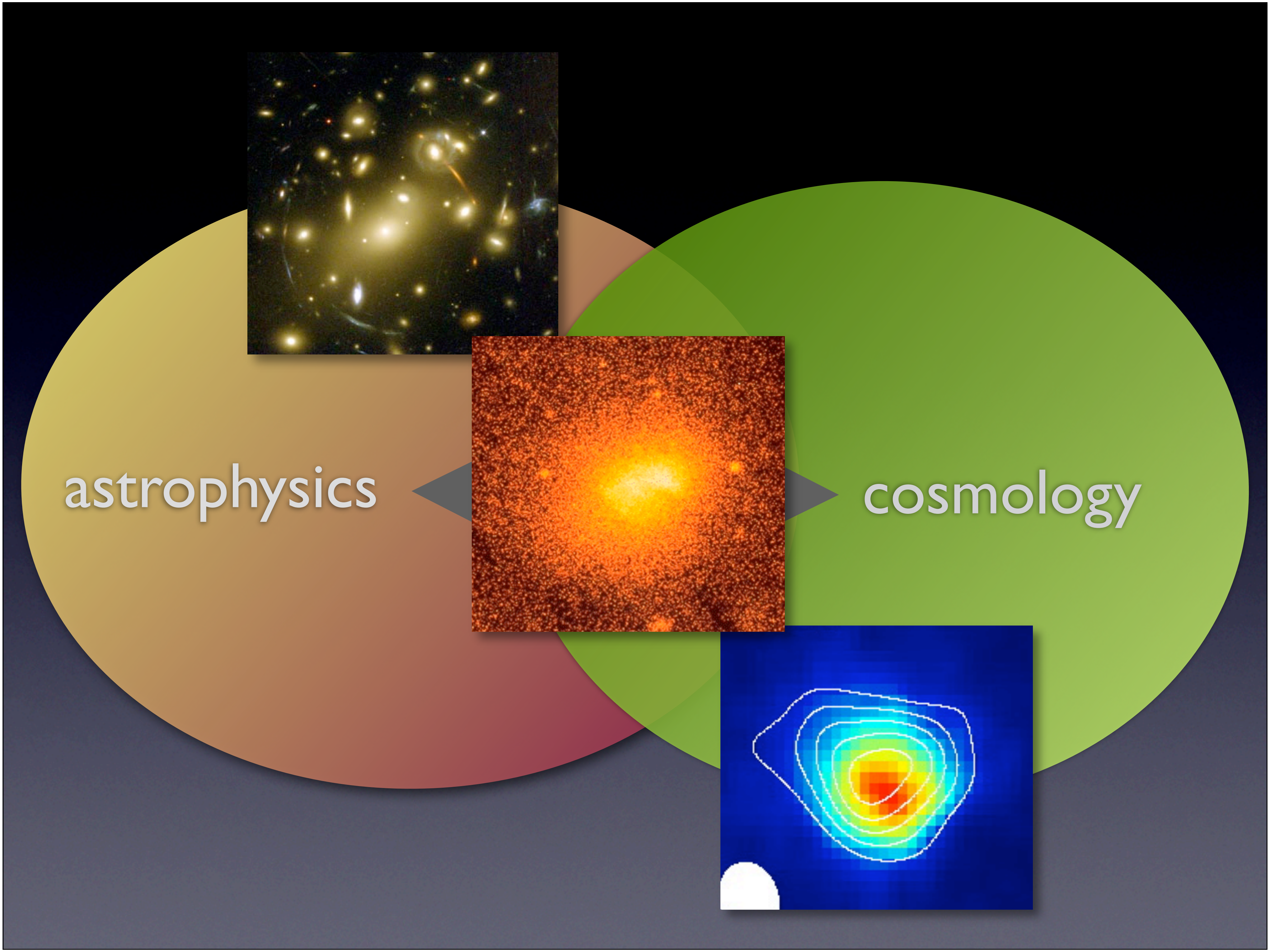
2. compute model expectations for object survey statistics

   – calculate likelihood, $p(\mathbf{y}_i \mid \theta, \alpha)$, over cosmological params, $\theta$, and within an assumed astrophysical model, $\alpha$, for the specific object class use

3. perform the likelihood analysis, marginalizing over (or just fixing) $\alpha$

   – extract cosmological constraints, $p(\theta)$


astrophysics
cosmology


astrophysics
cosmology

<u>*Survey-specific*</u> simulations enable ***key capabilities:***

* to extract unbiased statistical signals, $\mathbf{y}_i$, from the raw object catalog

* to predict statistical expectations, $p(\mathbf{y}_i \mid \theta, \alpha)$ for a variety of models

* to calculate the expected signal covariance, $\mathrm{COV}(\mathbf{y}_i , \mathbf{y}_j)$

# eRosita simulation posters

## List of Posters

| | | | |
|---|---|---|---|
| | **eROSITA Hard- and Software** | | |
| 1 | Brunner | Hermann | Simulating the eROSITA all-sky survey: exposure, sensitivity, and source detection strategies |
| 2 | Freyberg | Michael | Calibration of eROSITA, on-ground and in-orbit |
| 3 | Guglielmetti | Fabrizia | The Background-Source separation algorithm - A feasibility study for the eROSITA mission |
| 4 | Kreykenbohm | Ingo | The eROSITA pre-processing and NRTA software |
| 5 | Lamer | Georg | eROSITA source detection and sensitivity |
| 6 | Perinati | Emanuele | The radiation environment in L-2 orbit :implications on the non-X-ray background of the eROSITA pn-CCD cameras |
| 7 | Schmid | Christian | Simulated eROSITA Sky |
| 8 | Wille | Michael | Recognition of bad pixels on charge-coupled devices in the eROSITA Near Real Time Analysis |
| | **Galaxy Clusters and Cosmology** | | |
| 9 | Borm | Katharina | Expected Properties of eROSITA Galaxy Clusters |
| 10 | Borozdin | Konstantin | Studying Dark Energy with eRosita |
| 11 | Burenin | Rodion | Cosmological parameters from the measurements of galaxy cluster mass function in combination with other cosmological data |

# cosmology
# from counts and clustering
# of massive halos

## basic ingredients for cluster cosmology

1. halo space density (aka, *mass function*), d$n$(>$M$, $z$)/d$V$
   – well calibrated (~5% in d$n$) by (dark matter only) simulations

2. two-point spatial clustering of halos (aka, *bias function*), $b(M, z)$
   – similarly well calibrated

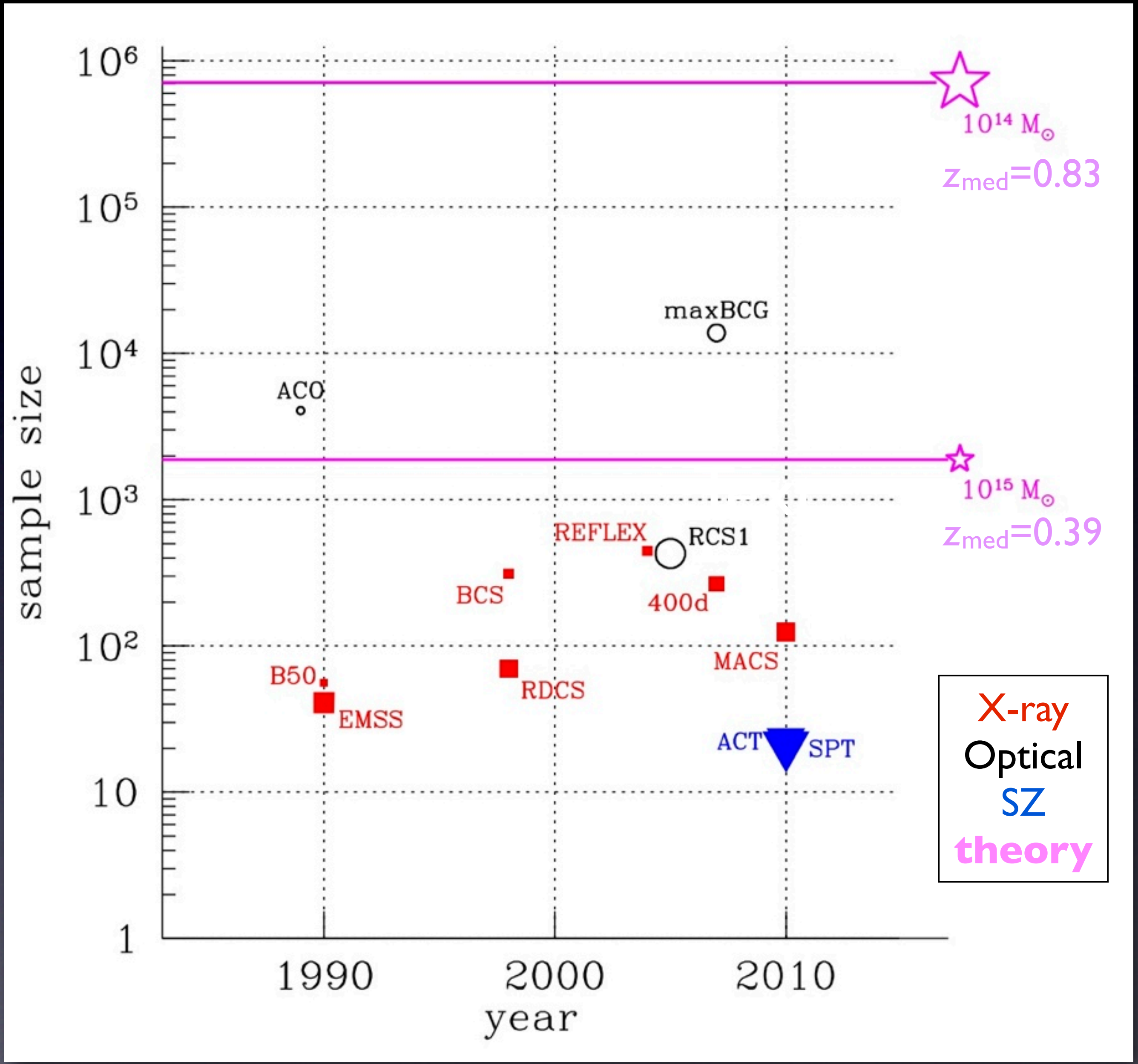
3. population model for signal, $S$, used to identify clusters, $p(S \mid M, z)$
   – power-law with log-normal deviations (typically self-calibrated)
   – projection effects (signal-dependent) $S_{\mathrm{observed}} \neq S_{\mathrm{intrinsic}}$

4. selection model for signal, $S$
   – completeness (missed clusters)
   – purity (false positives)

## observable signal choices for surveys: pros and cons

| Signal | Pros | Cons |
|---|---|---|
| X-ray | • spatially compact signal (relative to other methods)<br>• hot thermal ICM is unique to clusters<br>• 40+ year science history | • expensive (space-based)<br>• flux confusion from AGN<br>• surface brightness dimming<br>• most sources will have moderate S/N |
| Optical | • inexpensive (*free* with any galaxy survey!)<br>• old, `red sequence' galaxies reside in massive halos<br>• 80+ year science history | • confusion from line-of-sight projection<br>• moderate S/N (Poisson statistics for $N \geq 10$)<br>• galaxy formation! |
| Sunyaev-Zel'dovich | • inexpensive (*free* with any CMB survey)<br>• nearly redshift-independent signal | • point source confusion<br>• l-o-s projected confusion with low angular resolution<br>• moderate S/N for most |

# cluster samples today are sparse relative to massive halos on the sky

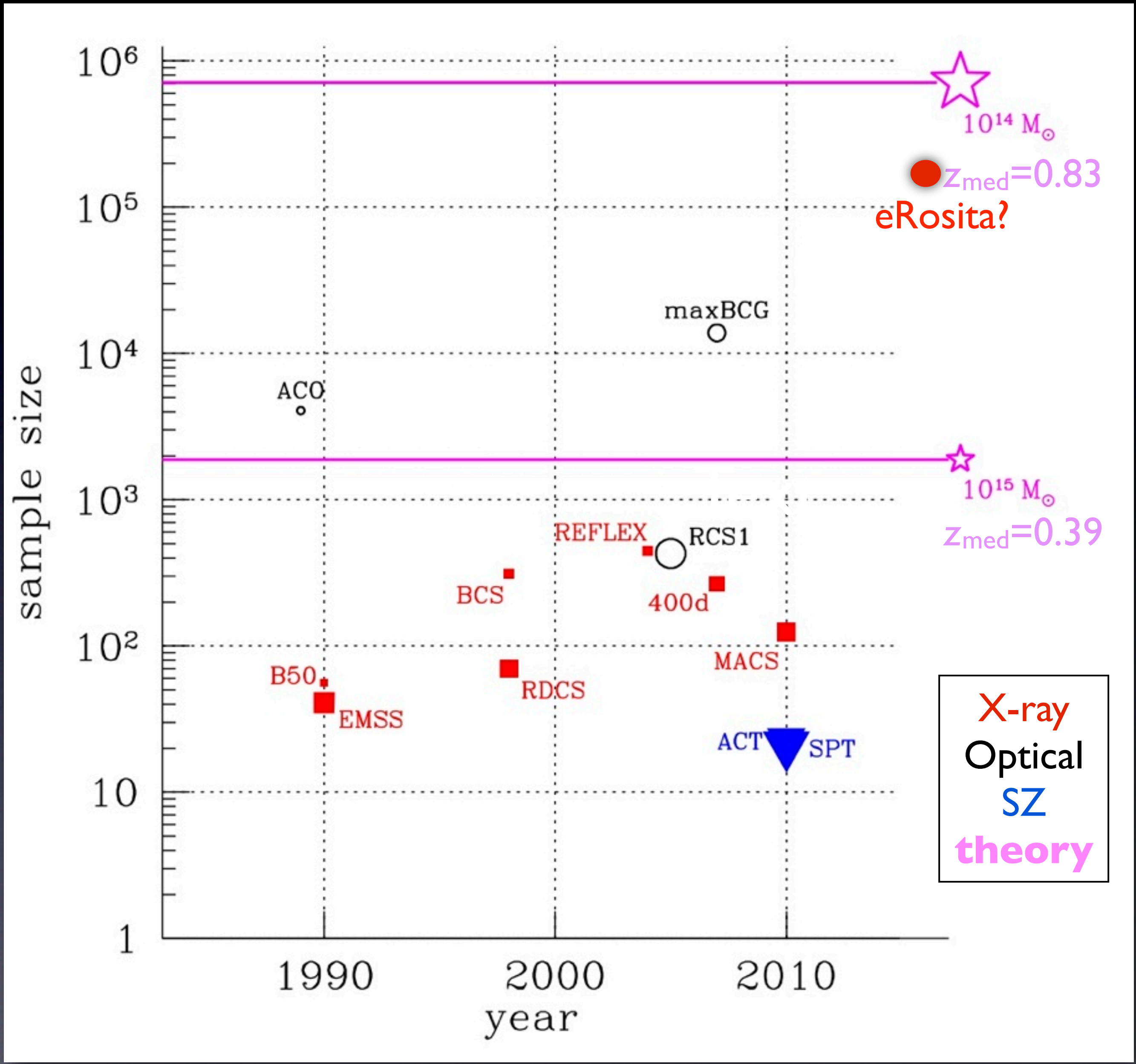



Allen, Evrard & Mantz 2011

symbol size scales with median redshift

Halo mass scale is $M_{200m}$ (h = 0.7)

# cluster samples today are sparse relative to massive halos on the sky



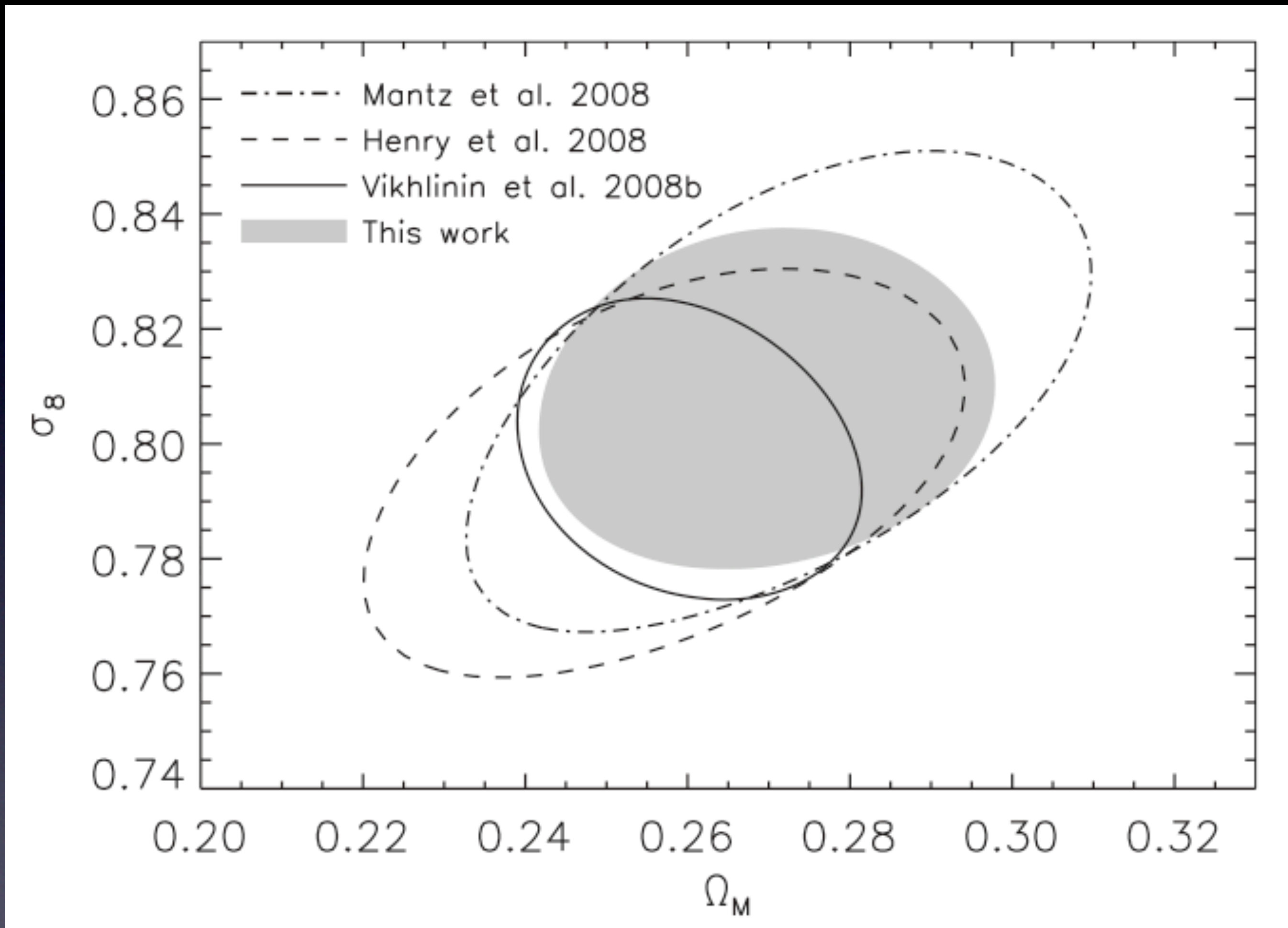

Allen, Evrard & Mantz 2011

symbol size scales with median redshift

Halo mass scale is $M_{200m}$ (h = 0.7)

## consistent cosmology from existing optical and X-ray samples

Rozo et al 2010




optical: maxBCG
(shaded)
~14,000 clusters

X-ray: 400d, BCS
(lines)
~100 clusters

***systematics limited !***

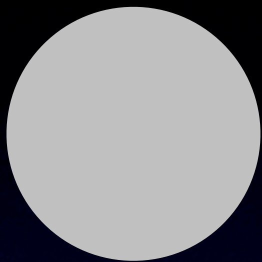
## how hard is counting? Major systematic error sources for cluster cosmology

1. 3D halo mass is not directly observable
   – what is the form of signal likelihood, $p(\boldsymbol{S} \mid M, z)$ ?

2. The universe is a big place
   – how does projection along Gpc sight-line distort the signal, $\boldsymbol{S}$ ?

3. Baryons (17% of matter) are dynamically complex on Mpc scales
   – how significant are the decaying modes excited by baryon hydrodynamics in LSS formation?

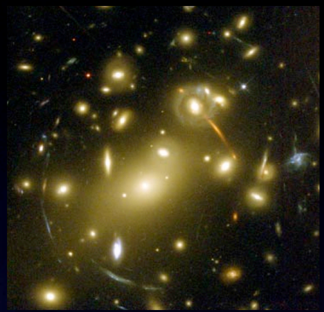
## massive halo phenomenology:  observable signal likelihoods



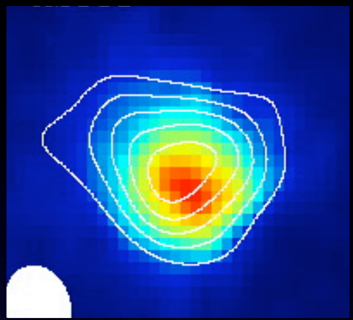
halo of
mass M
redshift z

=

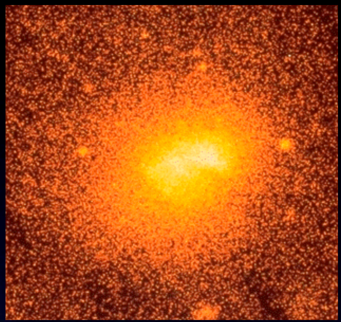
**optical/lensing**



**sub-mm**



**X-ray**



# "Astrophysics 101"

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

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

## PL+LN covariance model for halo signals

# 1 A Local Model for Multivariate Counts

Consider a mass function described locally as a power-law in mass with slope $-\alpha$. Specifically, using $\mu \equiv \ln M$, define the mass function, $n(\mu, z)$, as the likelihood of finding a halo at redshift $z$ in the mass range $\mu$ to $\mu + d\mu$ within a small comoving volume $dV$,

$$dp \equiv n(M,z)\, d\ln M\, dV = AM^{-\alpha} d\ln M\, dV = A\, e^{-\alpha\mu}\, d\mu\, dV. \tag{1}$$

piecewise power-law mass function

The local slope, $\alpha$, and amplitude, $A$, implicitly depend on mass and redshift in a manner dependent on cosmology (*e.g.*, Tinker et al. 2008).

Consider a set of $N$ halo properties, $S_i \in \{N_{\rm gal}, L_{\rm X}, T_{\rm X}, M_{\rm gas}, Y_{\rm X}, Y_{\rm SZ}, \cdots\}$, let $\mathbf{s}$ be a vector containing their logarithms,

$$s_i = \ln(S_i) \tag{2}$$

Assume that the mass scaling behavior of these properties are power-laws, so that the mean ln(signal) for a mass–complete sample scales as

$$\bar{\mathbf{s}}(\mu, z) = \mathbf{m}\mu + \mathbf{b}(z). \tag{3}$$

assumed form of signal-mass relation

The elements of vector $\mathbf{m}$ are the slopes of the individual mass-observable relations. (Note that, at some fixed epoch, we can always choose units such that the intercepts $b_i(z) = 0$.)

Assume that ln(signal) deviations about the mean are Gaussian, described by a likelihood

$$p(\mathbf{s}|\mu) = \frac{1}{(2\pi)^{N/2}|\Psi|^{1/2}} \exp\left[-\frac{1}{2}(\mathbf{s}-\bar{\mathbf{s}})^{\dagger}\Psi^{-1}(\mathbf{s}-\bar{\mathbf{s}})\right], \tag{4}$$

where the covariance matrix has elements

$$\Psi_{ij} \equiv \langle (s_i - \bar{s}_i)(s_j - \bar{s}_j)\rangle, \tag{5}$$

and the brackets denote an ensemble average over a (large) mass–complete sample.

# PL+LN covariance model for halo signals

## 1.1 Multivariate Space Density

The space density as a function of the multivariate properties, $\mathbf{s}$, is found by the convolution, $n(\mathbf{s}) = \int d\mu\, n(\mu)\, p(\mathbf{s}|\mu)$. Using equations (1) and (4), the result is

$$n(\mathbf{s}) = \frac{A\Sigma}{(2\pi)^{(N-1)/2}|\Psi|^{1/2}} \exp\left[-\frac{1}{2}(\mathbf{s}^\dagger \Psi^{-1}\mathbf{s} - \frac{\bar{\mu}^2(\mathbf{s})}{\Sigma^2})\right], \tag{6}$$

where $\Sigma^2$ is the **multi-property mass variance** defined by

$$\Sigma^2 = (\mathbf{m}^\dagger \Psi^{-1}\mathbf{m})^{-1}, \tag{7}$$

and the mean mass is

$$\bar{\mu}(\mathbf{s}) = \frac{\mathbf{m}^\dagger \Psi^{-1}\mathbf{s}}{\mathbf{m}^\dagger \Psi^{-1}\mathbf{m}} - \alpha\Sigma^2, \tag{8}$$

$$\equiv \bar{\mu}_0(\mathbf{s}) - \alpha\Sigma^2. \tag{9}$$

The first term, $\bar{\mu}_0(\mathbf{s})$, is the mean mass for the case of a flat mass function, $\alpha = 0$, which corresponds to the mass expected from inverting the input log-mean relation.

The second term, $\alpha\Sigma^2$, represents the mass shift induced by asymmetry in the convolution when $\alpha > 0$. (Low mass halos scattering up outnumber high mass systems scattering down.) Note that **the magnitude of this effect scales with the variance**, not the rms deviation.

Applying Bayes' theorem in the form $p(\mu|\mathbf{s}) = p(\mathbf{s}|\mu)n(\mu)/n(\mathbf{s})$ leads to the result that the set of masses selected by a specific set of properties is Gaussian in the log with mean given by equation (9) and variance, equation (7).

← **exact** form for multi-signal space density (eq. 6)

← mean mass selected by signals is biased low (Malmquist bias) (eq. 9)

# PL+LN covariance model for halo signals

### 1.1.1 Explicit expressions for the one-variable case

For a single property, $s \equiv \ln(S)$, with slope, $m$, and logarithmic scatter at fixed mass, $\sigma$, the mass variance at fixed $S$ is

$$\Sigma^2 \;=\; \left(\frac{\sigma}{m}\right)^2. \tag{10}$$

The mean mass for a sample complete in $S$ is

$$\bar{\mu}(s) \;=\; \frac{s}{m} - \alpha\Sigma^2. \tag{11}$$

The property space density function is

$$n(s)\,ds = (A/m)\,\exp\{-\alpha\left(\frac{s}{m} - \alpha\Sigma^2/2\right)\}\,ds, \tag{12}$$

which is a power-law in the original property, $n(S) \propto S^{-(\alpha/m)}$.

Note that the effective shift in mass, $\alpha\Sigma^2/2$, is half that in the expression above. These expressions are consistent, in that they address different questions. Equation (11) gives the mean ln(mass) of a signal-selected sample while equation (12) gives the ln(mass) value that matches the local space density – in number per volume per ln(S) – of halos with property value, $S$.

# PL+LN covariance model for halo signals

### 1.1.1 Explicit expressions for the one-variable case

For a single property, $s \equiv \ln(S)$, with slope, $m$, and logarithmic scatter at fixed mass, $\sigma$, the mass variance at fixed $S$ is

$$\Sigma^2 = \left(\frac{\sigma}{m}\right)^2. \quad (10)$$

The mean mass for a sample complete in $S$ is

$$\bar{\mu}(s) = \frac{s}{m} - \alpha\Sigma^2. \quad (11)$$

The property space density function is

$$n(s)\,ds = (A/m)\,\exp\{-\alpha\left(\frac{s}{m} - \alpha\Sigma^2/2\right)\}\,ds, \quad (12)$$

which is a power-law in the original property, $n(S) \propto S^{-(\alpha/m)}$.

Note that the effective shift in mass, $\alpha\Sigma^2/2$, is half that in the expression above. These expressions are consistent, in that they address different questions. Equation (11) gives the mean ln(mass) of a signal-selected sample while equation (12) gives the ln(mass) value that matches the local space density – in number per volume per ln(S) – of halos with property value, $S$.

cosmology

# PL+LN covariance model for halo signals

### 1.1.1 Explicit expressions for the one-variable case

For a single property, $s \equiv \ln(S)$, with slope, $m$, and logarithmic scatter at fixed mass, $\sigma$, the mass variance at fixed $S$ is

$$\Sigma^2 = \left(\frac{\sigma}{m}\right)^2. \tag{10}$$

The mean mass for a sample complete in $S$ is

$$\bar{\mu}(s) = \frac{s}{m} - \alpha\Sigma^2. \tag{11}$$

The property space density function is

$$n(s)\,ds = (A/m)\,\exp\{-\alpha\left(\frac{s}{m} - \alpha\Sigma^2/2\right)\}\,ds, \tag{12}$$

which is a power-law in the original property, $n(S) \propto S^{-(\alpha/m)}$.

Note that the effective shift in mass, $\alpha\Sigma^2/2$, is half that in the expression above. These expressions are consistent, in that they address different questions. Equation (11) gives the mean ln(mass) of a signal-selected sample while equation (12) gives the ln(mass) value that matches the local space density – in number per volume per ln(S) – of halos with property value, $S$.

cosmology

astrophysics

# PL+LN covariance model for halo signals

### 1.1.2 Explicit expressions for the two-variable case

For two properties, we introduce the correlation coefficient, $r \equiv \langle \delta_1 \delta_2 \rangle$, of the normalized deviations, $\delta_i \equiv (s_i - \bar{s}_i)/\sigma_i$, and write the covariance matrix,

$$\Psi = \begin{pmatrix} \sigma_1^2 & r\sigma_1\sigma_2 \\ r\sigma_1\sigma_2 & \sigma_2^2 \end{pmatrix},$$

and its inverse,

$$\Psi^{-1} = (1-r^2)^{-1} \begin{pmatrix} \frac{1}{\sigma_1^2} & -\frac{r}{\sigma_1\sigma_2} \\ -\frac{r}{\sigma_1\sigma_2} & \frac{1}{\sigma_2^2} \end{pmatrix}.$$

The mass variance is now a harmonic mixture

$$\Sigma^{-2} = (1-r^2)^{-1} \left( \sigma_{\mu 1}^{-2} + \sigma_{\mu 2}^{-2} - 2r\sigma_{\mu 1}^{-1}\sigma_{\mu 2}^{-1} \right), \quad (13)$$

where $\sigma_{\mu i} = \sigma_i / m_i$ is the mass scatter at fixed signal $S_i$.

The zero-slope mean mass is

$$\bar{\mu}_0(s_1, s_2) = \frac{(s_1/m_1)\sigma_{\mu 1}^{-2} + (s_2/m_2)\sigma_{\mu 2}^{-2} - r(s_1/m_1 + s_2/m_2)\sigma_{\mu 1}^{-1}\sigma_{\mu 2}^{-1}}{\sigma_{\mu 1}^{-2} + \sigma_{\mu 2}^{-2} - 2r\sigma_{\mu 1}^{-1}\sigma_{\mu 2}^{-1}}, \quad (14)$$

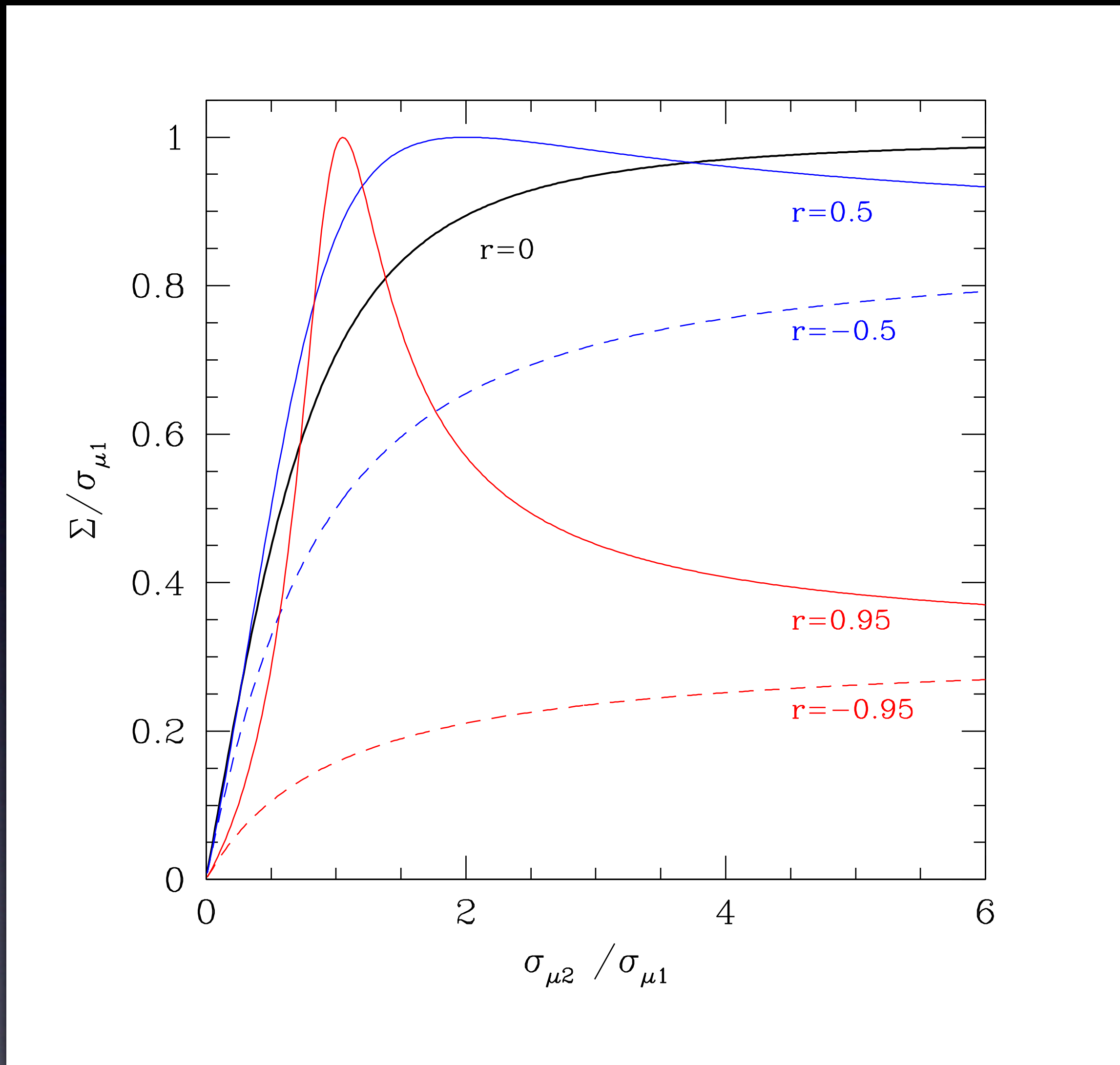
and the **joint space density** is

$$n(s_1, s_2) = \frac{A\Sigma}{\sqrt{2\pi(1-r^2)}\sigma_1\sigma_2} \exp\left[ -\alpha\bar{\mu}_0 + \frac{\Sigma^2}{2}\left( \alpha^2 - \frac{(s_1/m_1 - s_2/m_2)^2}{\sigma_{\mu 1}^2 \sigma_{\mu 2}^2} \right) \right]. \quad (15)$$

The first two terms in the exponent are analogous to those in the 1D expression, equation (12). For "reasonable" choices of $(S_1, S_2)$ pairs — meaning values that pick out comparable mass scales, $s_1/m_1 \sim s_2/m_2$ — the space density remains effectively power-law. The third term in the exponent suppresses the number density for unreasonable pairings of $s_1/m_1$ and $s_2/m_2$, those lying out in the wings of the bivariate Gaussian.

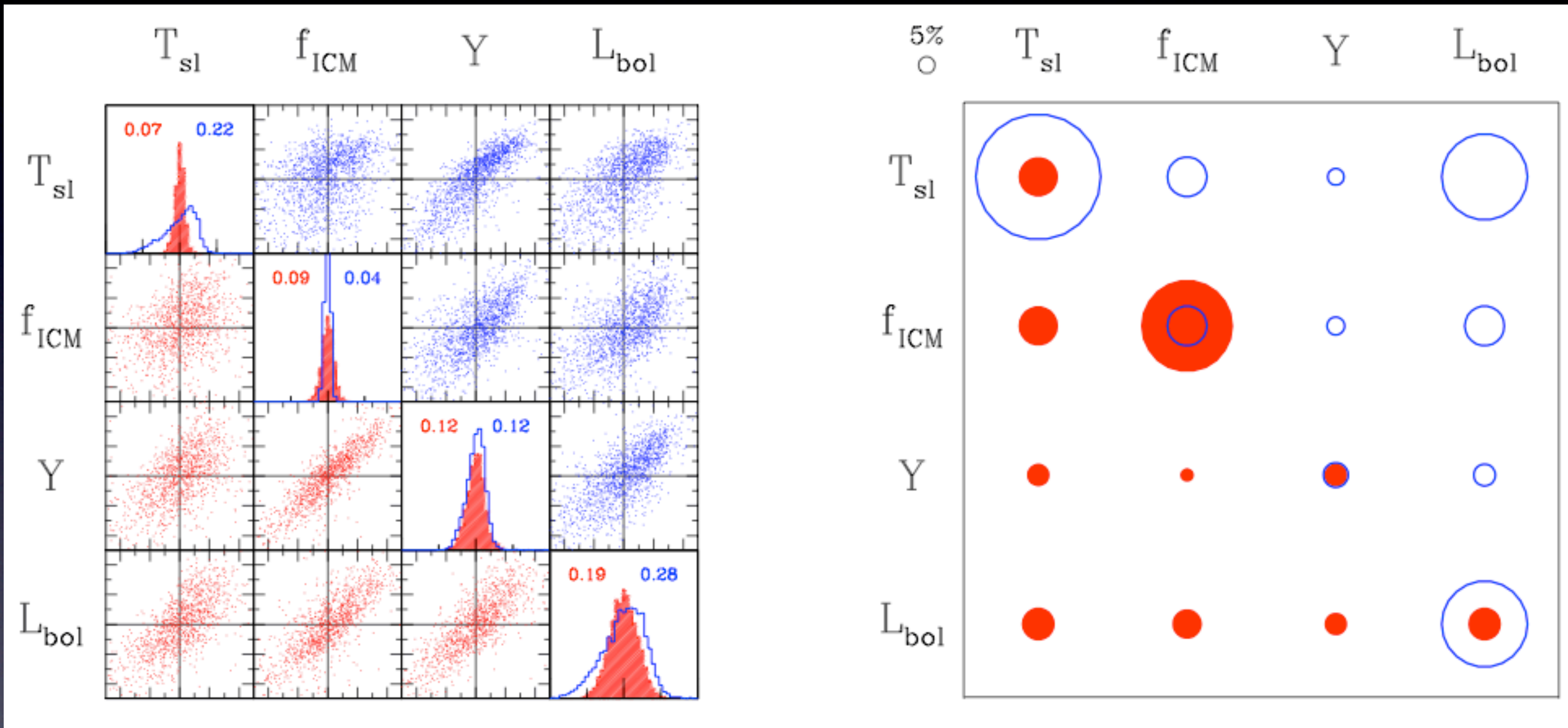
anti-correlated signals best for mass selection

# mass scatter for two-property joint selection



# mass scatter for hot gas observables from Millennium Gas Simulations

Allen, Evrard & Mantz 2011
Stanek et al 2010




preheating (200 kev-cm$^2$ @z=4)
gravity only

# PL+LN covariance model for halo signals

## 1.2 Property-selected samples

For a halo sample selected with some property, $s_1$, we can now use Bayes' theorem to find the joint probability of those halos having a second property, $s_2$, and mass, $\mu$. The result can be expressed as a bivariate Gaussian in terms of the two-element vector, $\mathbf{t} = [s_2\ \mu]$,

$$p(\mathbf{t}|s_1) = \frac{1}{(2\pi)|\tilde{\Psi}|^{1/2}} \exp\left[-\frac{1}{2}(\mathbf{t}-\bar{\mathbf{t}})^\dagger \tilde{\Psi}^{-1}(\mathbf{t}-\bar{\mathbf{t}})\right], \tag{16}$$

where the mean mass, $\bar{\mu}(s_1)$, is defined by equation (11) and the mean of the non-selection property is given by

$$\bar{s}_2(s_1) = m_2\left(\bar{\mu}(s_1) + \alpha r \sigma_{\mu 1}\sigma_{\mu 2}\right). \tag{17}$$

Note that, if $r < 0$, the non-selected property mean can be "doubly" biased low relative to a simple $m_2(s_1/m_1)$ expectation, with one shift coming from the extra $(-\alpha\Sigma^2)$ term in the mean mass and the second coming from the second term in the above expression.

The covariance in $s_2$ and $\mu$ at fixed $s_1$ is given by

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

where the variance in $s_2$ at fixed $s_1$ is

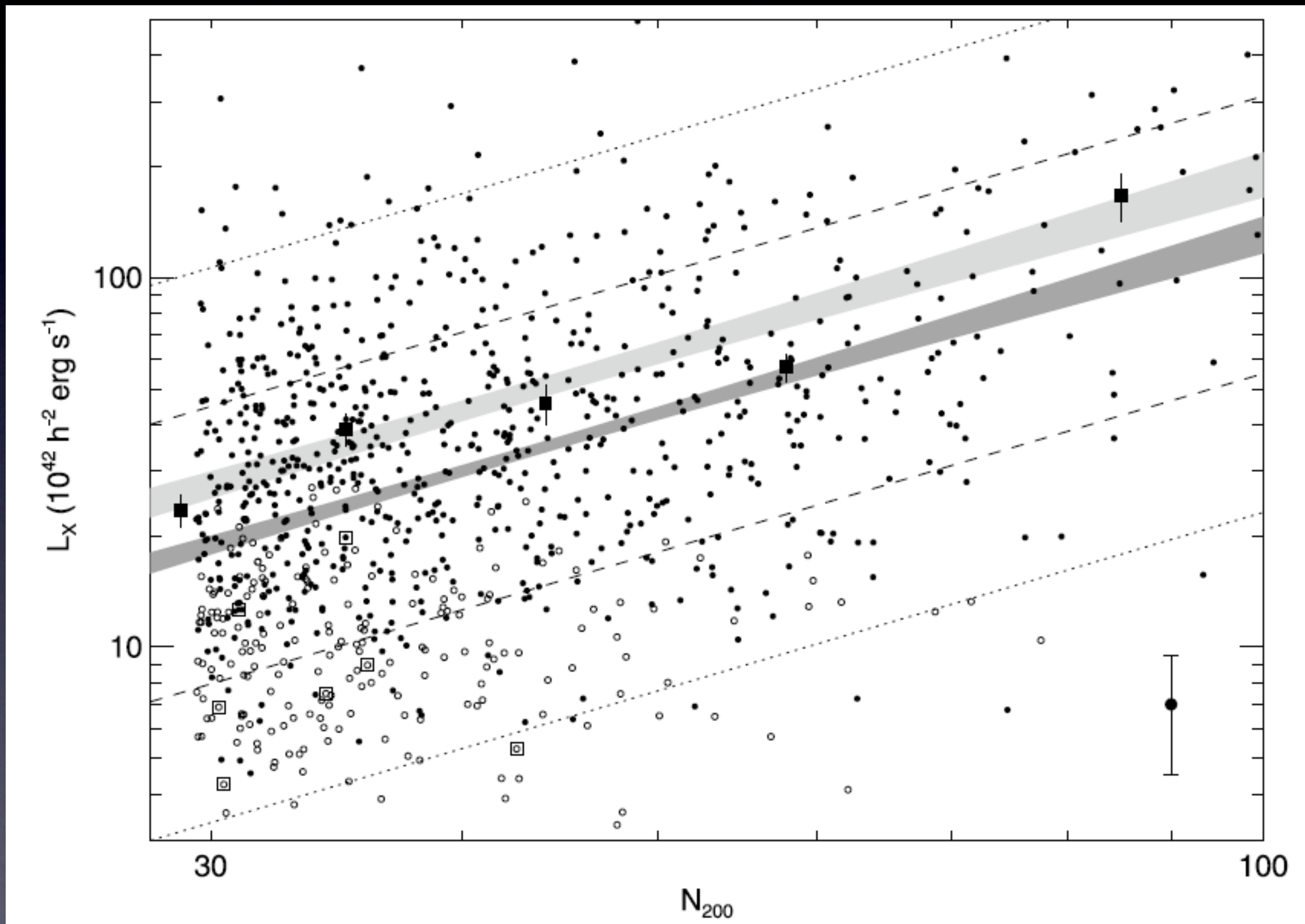
$$\sigma_{21}^2 = m_2^2\left(\sigma_{\mu 1}^2 + \sigma_{\mu 2}^2 - 2r\sigma_{\mu 1}\sigma_{\mu 2}\right). \tag{18}$$

future program: combine large samples to extract signal covariance

# RASS analysis of maxBCG sample

Rykoff et al 2008a

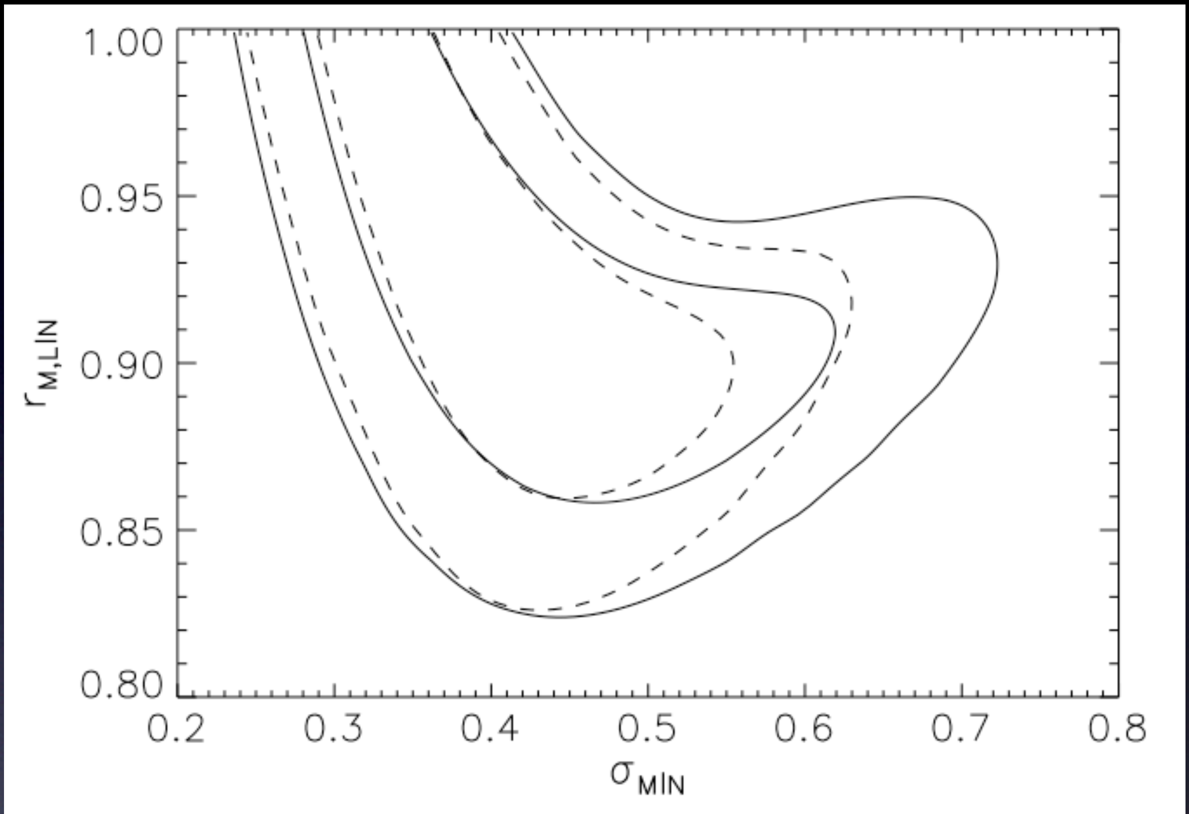
variance in Lx at fixed Ngal $\sigma_{\ln L_X \mid N_{gal}} = 0.83 \pm 0.03$



# first measurement of property covariance for clusters

Rozo et al 2009

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

# PL+LN covariance model for halo signals

expect large covariance if optical selection has larger mass scatter than X-ray

The $s_2$–mass correlation coefficient, $\tilde{r}$, depends on both the intrinsic property correlation, $r$, as well as the ratio of scatter in mass for the two properties,

$$\tilde{r} \;=\; \frac{\sigma_{\mu 1}/\sigma_{\mu 2} - r}{\sqrt{1 - r^2 + (\sigma_{\mu 1}/\sigma_{\mu 2} - r)^2}}. \qquad (19)$$

If the selection property is an excellent mass proxy ($\sigma_{\mu 1} \to 0$), then $\tilde{r} \to -r$.

If the selection property is a much poorer mass proxy compared to the second property, then $\tilde{r} \to 1$, irrespective of the intrinsic correlation, $r$.

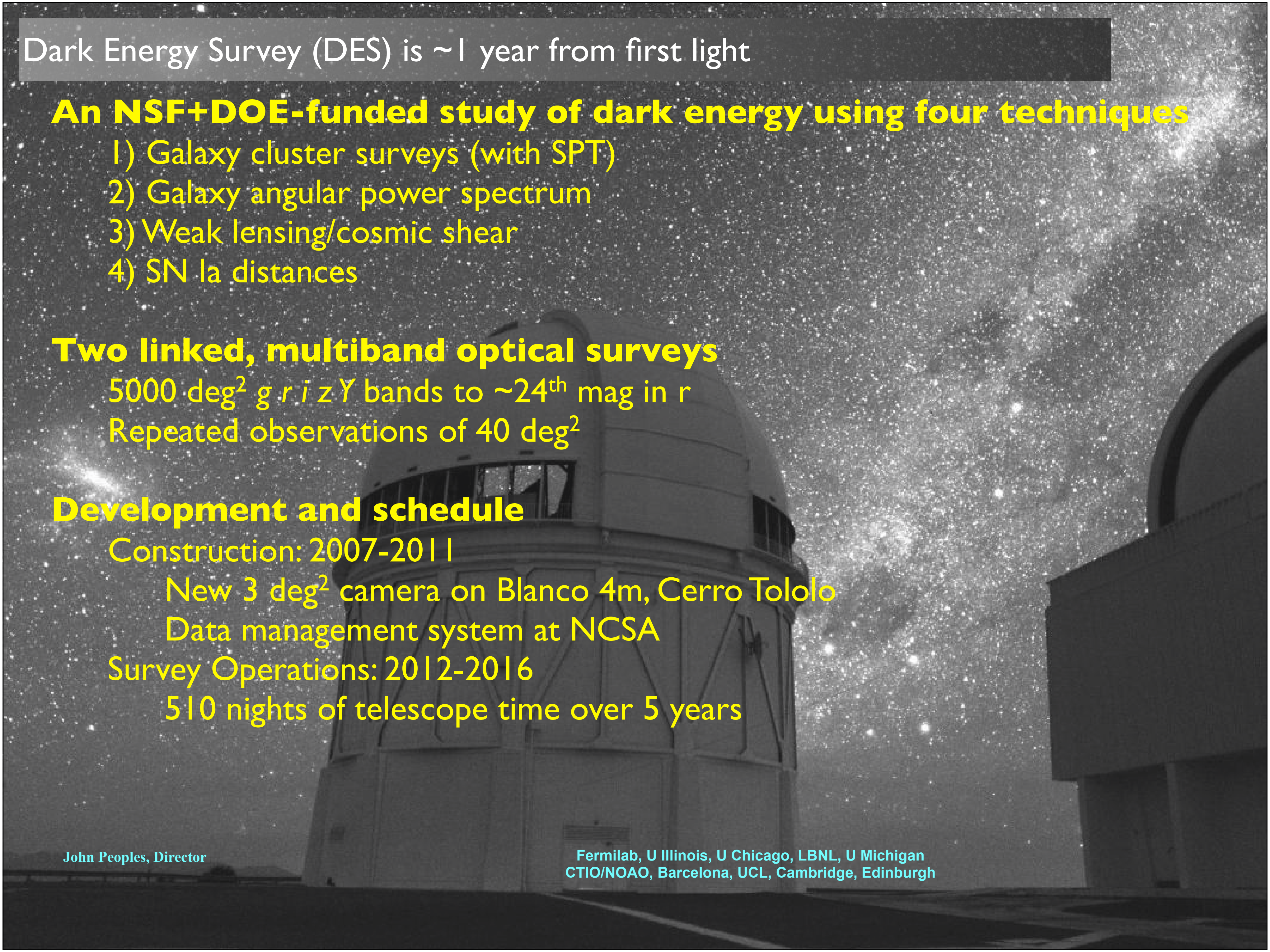
## benefits of large, overlapping cluster samples

1. Test basic model component with cross-signal abundance matching
   – e.g., true halo mass for Nth-ranked cluster identified with signal 1 must agree with the estimate for a sample selected with signal 2

2. Constrain signal covariance at fixed halo mass
   – mean and variance of signal 2 binned in signal 1

3. Astrophysical models make explicit joint signal predictions
   – e.g., $< \ln Y_{SZ} >$ should dependent linearly on $< \ln M_{gas} >$ and $< \ln T_X >$

# DES Simulation Support



## Dark Energy Survey (DES) is ~1 year from first light

**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 Y* bands to ~24$^{th}$ mag in r

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: 2012-2016

- 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

## DES Simulation Working Group: **Blind Cosmology Challenge**

3M SU TeraGrid-XSEDE allocation (TACC ranger) + 120 Tb storage (IU HPSS)

6-12 cosmological models

– full sky surveys of DM structure to z~6 (variable mass rez.)
built from four $2048^3$ N-body sims. of nested volumes (1-6 Gpc/h)

+ empirically-tuned galaxy catalog, ADDGALs (R. Wechsler, M. Busha)

+ weak lensing shear (M. Becker)

+ synthetic image generation for ~200 sq deg including multiple detector-telescope-sky effects (H. Lin)

*source code to be made available on bitbucket repository*

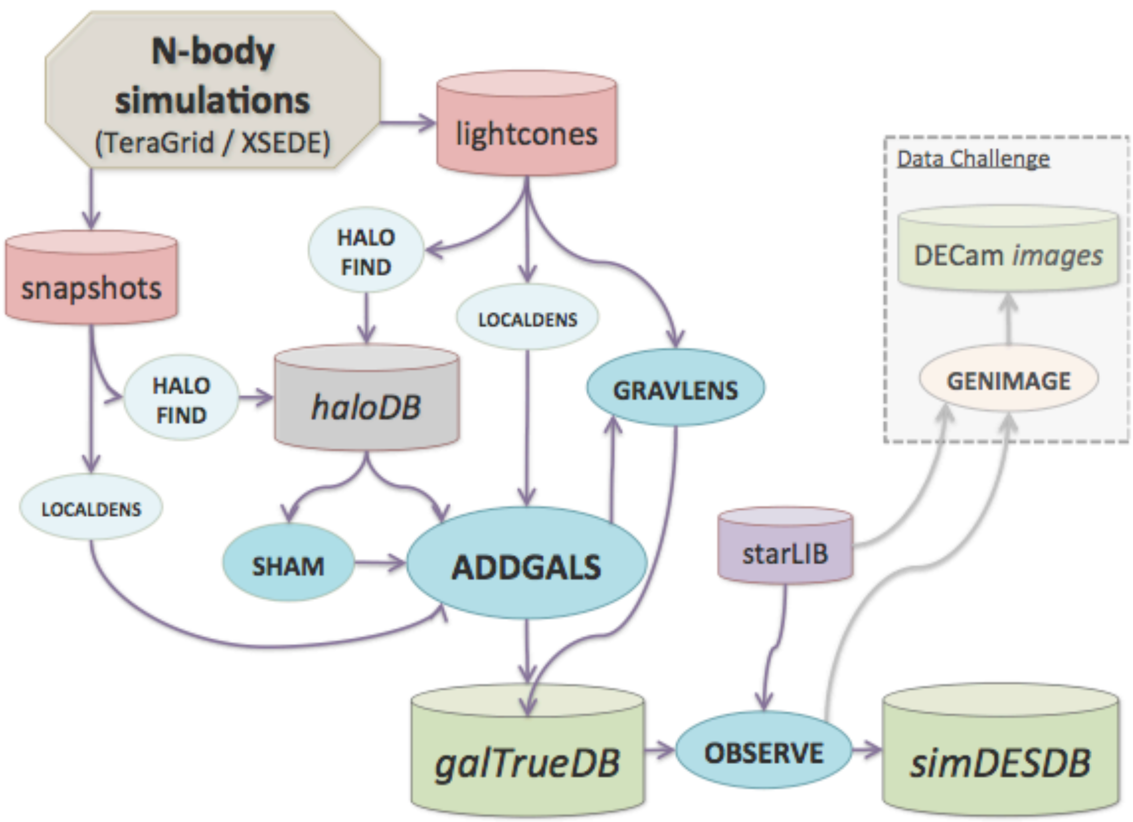
GOALS:

* validate science pipelines used by DE science teams
* provide testbed for characterizing systematic error sources
* assist planning for follow-up observations

# simulation workflow to support DES analysis

DARK ENERGY SURVEY

## Cosmic Sky Machine (COSMA)




Catalog Simulations

M. Becker (Chicago)
M. Busha (Zurich)
B. Erickson (Michigan)
A. Evrard (Michigan)
A. Kravtsov (Chicago)
R. Wechsler (Stanford)

Image Simulations

H. Lin (Fermilab)
Nikolai Kuropatkin (Fermilab)
+ DES Data Management

## simulation workflow to support DES analysis

Risa Wechsler, DES Penn Collaboration Mtg, 11 Oct 2011

DARK ENERGY SURVEY

# BCC simulation pipeline

1. Decide on a cosmological model (first one WMAP7. rest TBD.)
2. Initial conditions, run simulation, output light cone, run halo finder, validate (Busha, Erickson, Becker)
3. Add galaxies (Busha, Wechsler)
4. Run validation tests (Hansen, Busha, Wechsler, others)
5. Calculate shear at all galaxy positions (Becker)
6. Add shapes, lens (magnify & distort) galaxies (Dietrich)
7. Add stars (Santiago)
8. Determine mask (Swanson), including varying photometric depth & seeing, foreground stars
9. Blend galaxies (Hansen)
10. Determine photometric errors (Busha, Lin), incorporating mask information
11. Misclassify stars and galaxies (Sevilla, Hansen, Santiago)
12. Determine photometric redshifts (Busha, Cunha, Gerdes, etc)
13. Provide a lensed galaxy catalog in the DESDM database with:

ra, dec, mags, magerrors, photoz's, p(z), size, ellipticity, star/galaxy probability, seeing

☆ grey steps already implemented in v3.02 (220 sq. degrees) and/or for BCCv0.1

☆ **Science working groups do analysis!**

# simulation workflow to support DES analysis



DARK ENERGY SURVEY

## BCC "observed" information

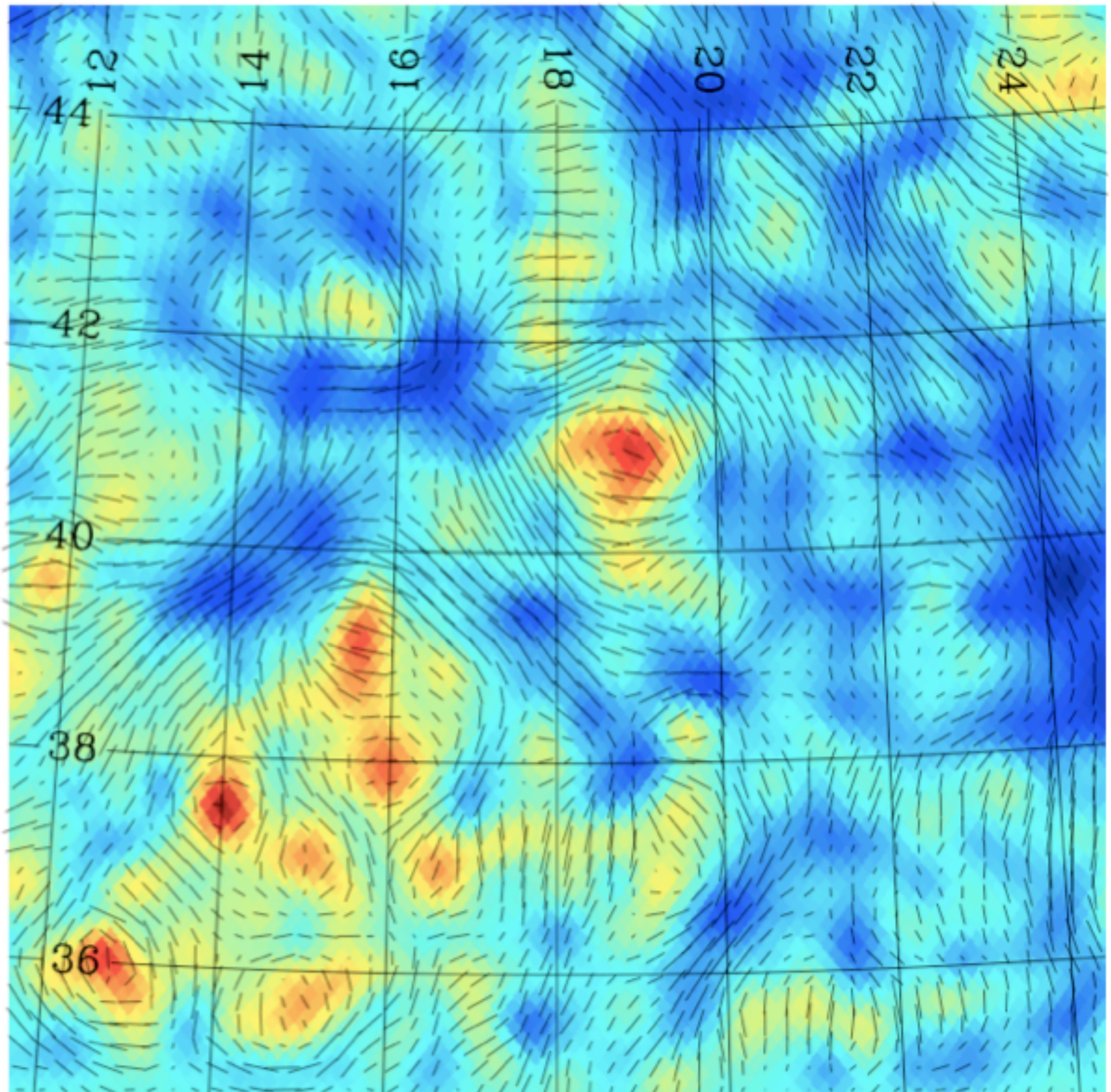
**Available now for v3.02**

- RA: Right ascension (lensed).
- DEC: Declination (lensed).
- MAG_[UGRIZY]: The observed DES magnitudes with photometric errors applied to LMAG.
- MAGERR_[GRIZY]: Estimated photometric errors for each band.
- EPSILON: Observed ellipticity.
- SIZE: Observed size (FLUX_RADIUS).
- PGAL: Probability that the object is a galaxy.
- PHOTOZ_GAUSSIAN: Estimated photo-$z$ using a gaussian PDF with $\sigma = 0.03/(1+z)$.
- ZCARLOS: Redshift estimate from zCarlos code.
- PZCARLOS: ARRAY of $p(z)$ in bin of $\Delta z = 0.02$.
- ARBORZ: Redshift estimate from ArborZ code.
- ARBORZ_ERR: Redshift errorestimate from ArborZ code.
- PZARBOR: ARRAY of $p(z)$ in bin of $\Delta z = 0.032$.
- ANNZ: Redshift estimate from ANNz code.
- ANNZ_ERR: Redshift error estimate from ANNz code.

+ vista magnitudes

- Is there additional information we should be providing?

# HEALPix-based map of DC6B 200 deg$^2$ convergence and shear fields




***Colors indicates convergence ∝ surface mass density; redder ==> higher density***

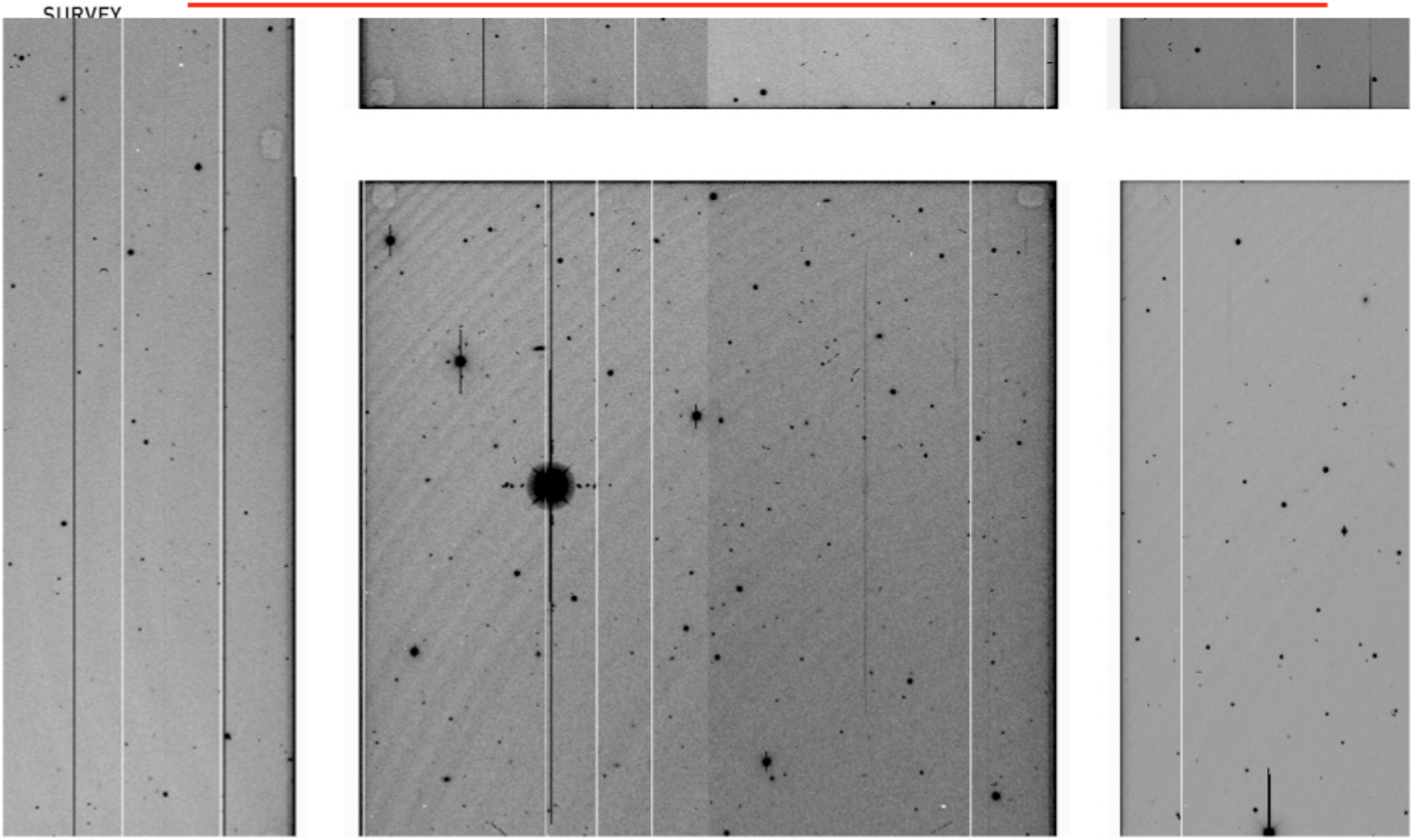
***Black "whiskers" show shear field due to gravitational lensing***

***Figure from M. Becker***

DARK ENERGY SURVEY

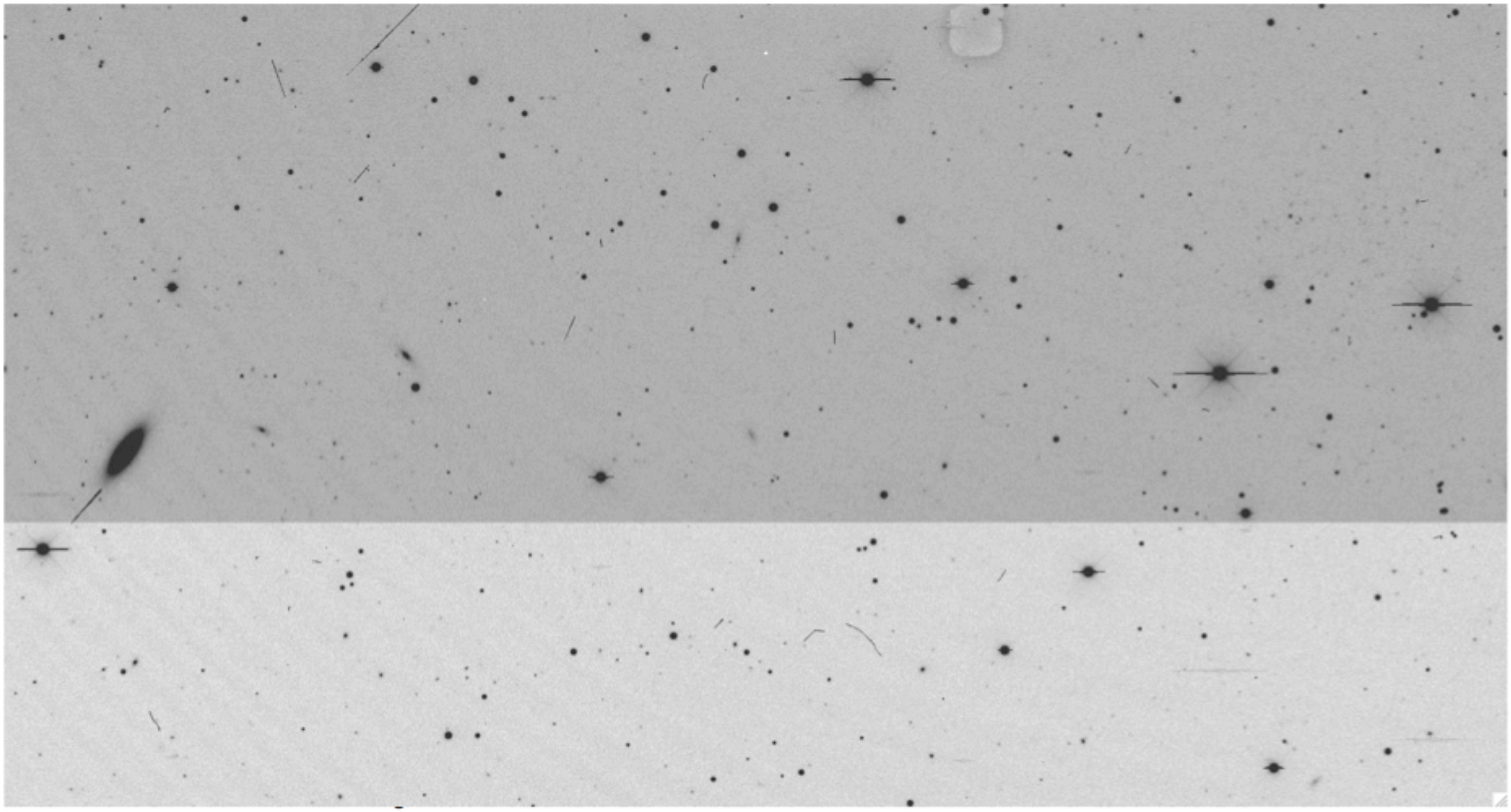
# Close-up of raw simulated images

## Note bright star artifacts, cosmic rays, cross talk, glowing edges, flatfield (“grind marks”, tape bumps), bad columns, 2 amplifiers/CCD



DARK ENERGY SURVEY

# Example DC6B image using profile galaxies: Part of raw r-band image of one CCD



# Same r-band image after bias subtraction and flatfielding (cosmic rays can be removed but left in here)

DARK ENERGY SURVEY