Measurements of Dark Energy

Lecture 3: Concordance with the Growth of Structure

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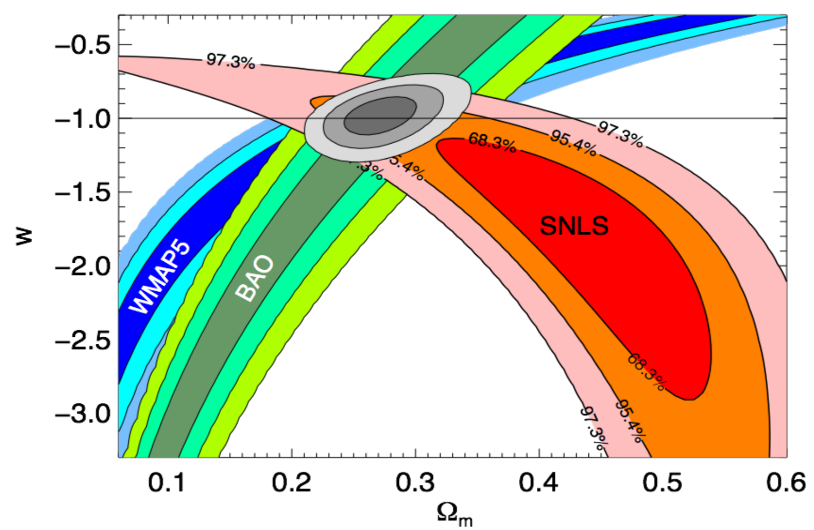
Recap of Lecture 2

Expansion history now constrained by CMB, SNe, cluster gas fractions and BAO – all “kinematic” probes, measuring distance

Entering systematics-dominated regime, big plans for future

Clear that best – and most convincing - constraints come from combining multiple independent datasets with different parameter degeneracies

What else is sensitive to the presence of Dark Energy?



Plan

1) Growth of structure – another way to probe dark energy

2) The cluster mass function

3) Weak lensing by large scale structure: cosmic shear

4) Closing thoughts - concordance

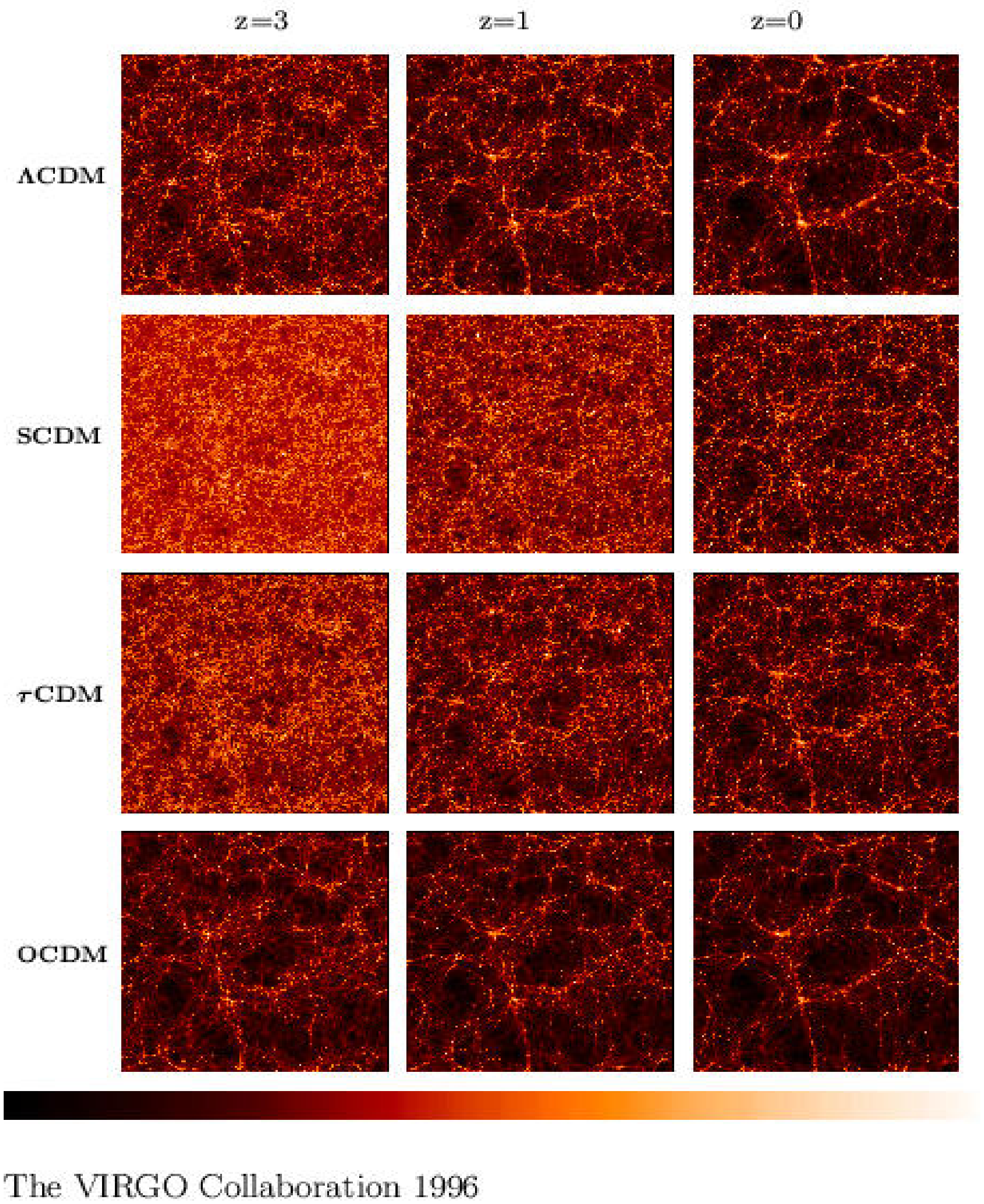
1) Structure formation in the presence of Dark Energy

Growth of Large-scale Structure

Cosmological simulations very well-established, informing analytic formulae describing structure growth

Expansion slows gravitational collapse

Structure growth is a probe of dark energy – and we can use simulations to check for systematics



Density perturbations

Fluctuations in matter density are enhanced by gravity over time

Convenient to describe their growth in Fourier space – linear perturbation theory to describe them while small:

$$\delta_m(x,t) \equiv \frac{\delta\rho_m(x,t)}{\bar{\rho_m}}$$

$$\frac{\partial^2 \delta_k}{\partial t^2} + 2H(t)\frac{\partial \delta_k}{\partial t} - 4\pi G\rho_m\delta_k = 0$$

Expansion of the universe counters (linear) collapse

“Hubble Drag” is enhanced when expansion is accelerating

Density perturbations

Can put all time dependence of perturbations into "linear growth factor" g(t) by rescaling them relative to their value at some early time – g then obeys same differential equation as before

Solution for growing mode is:

$$g(a) \propto \frac{H(a)}{H_0} \int_0^a \frac{da}{\left[\Omega_m a^{-1} + \Omega_X a^2 \exp\left[3 \int_{\log a}^0 (1+w) d \log a\right] + \Omega_k\right]^{\frac{3}{2}}}$$

Quite different from distance integrals – plus modified gravity would lead to different perturbation theory result...

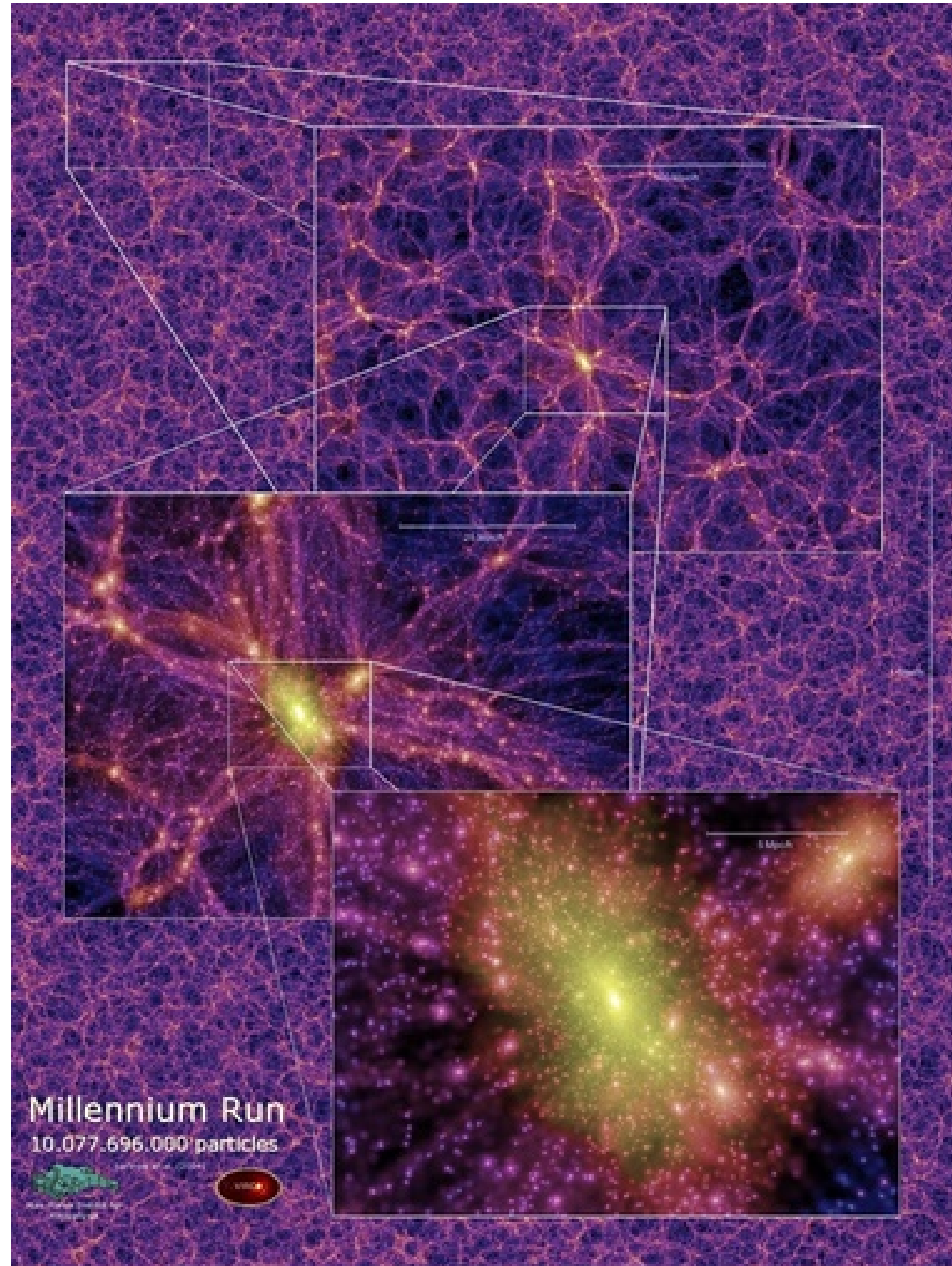
Use power spectrum to describe statistics of fluctuations – even beyond linear regime:

$$P(k,t) \propto \langle \delta_k^2(t) \rangle$$

Non-linear perturbations

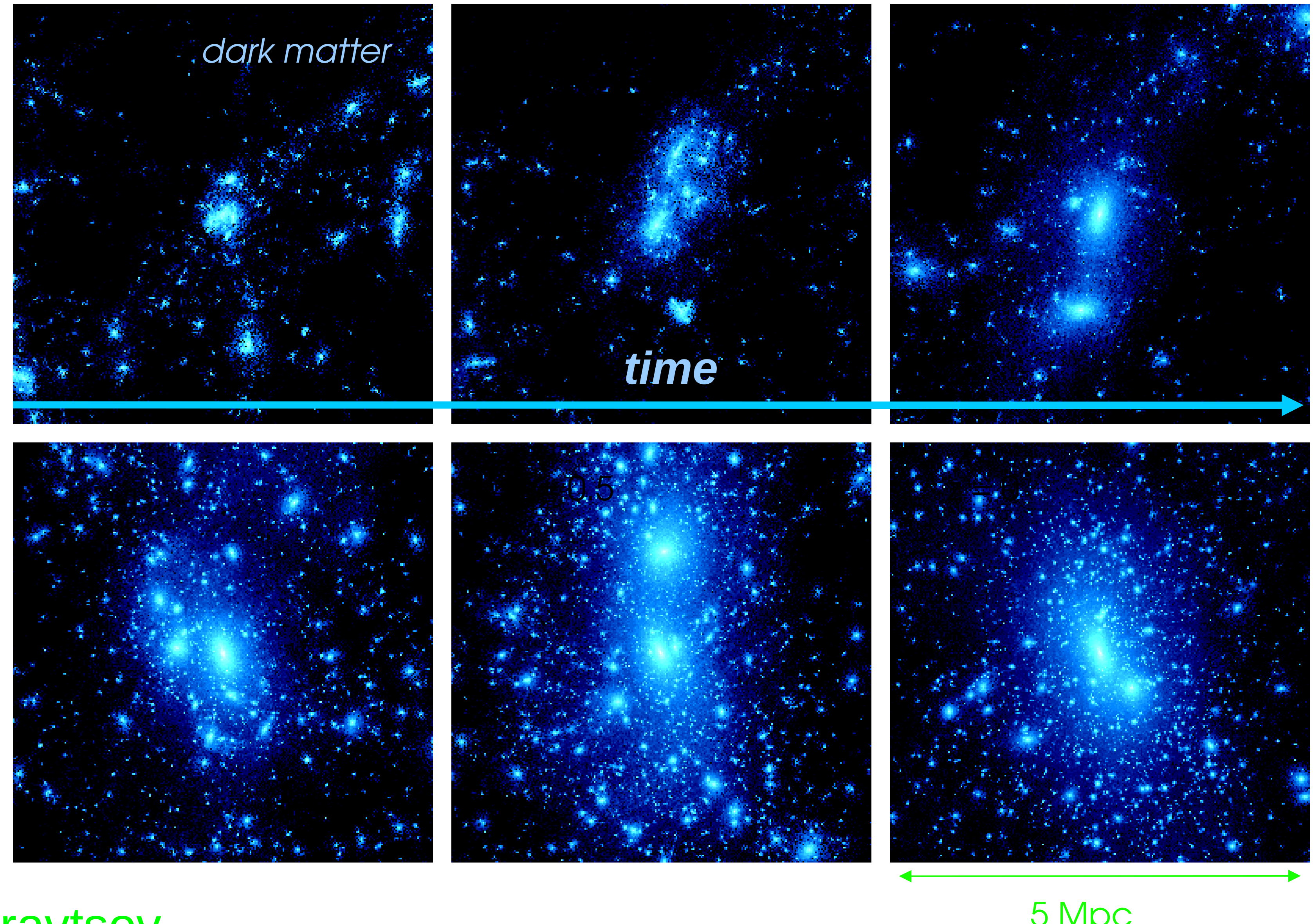
When fluctuation grows to ~1 , non-linear collapse occurs, and (after some violent relaxation) a bound object forms

To characterise this process accurately we use numerical simulations – fitting formulae can be derived to describe object abundances and properties



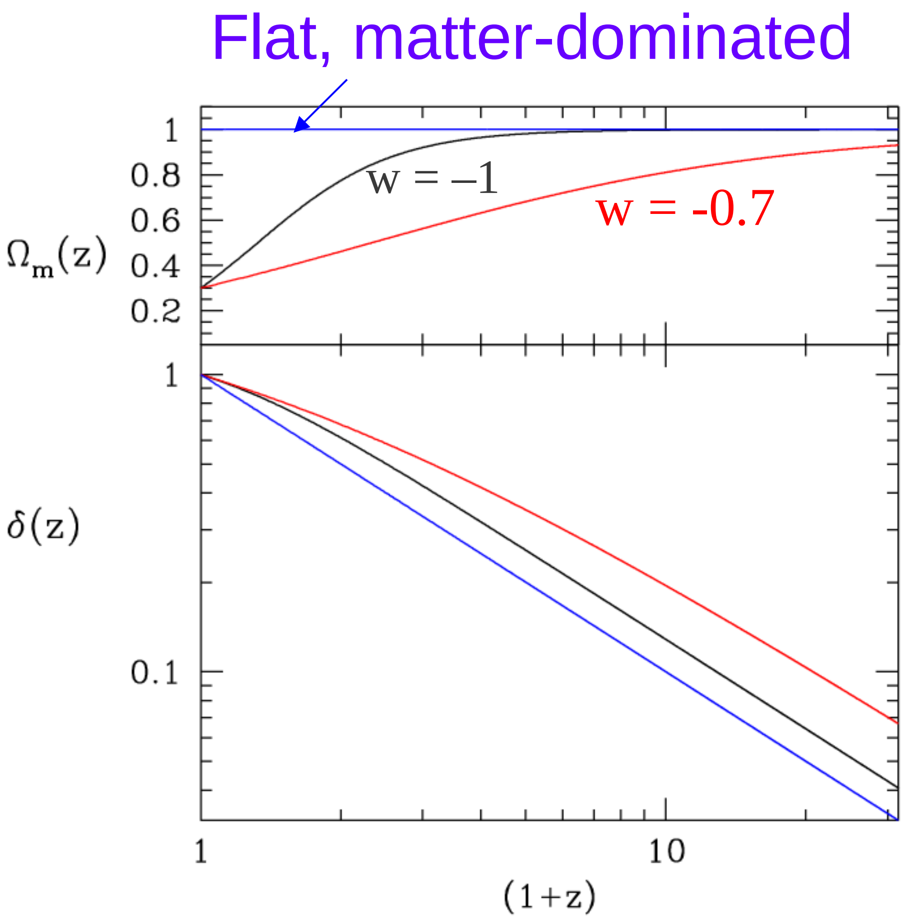
Cluster formation

"Violent relaxation" now seen in simulations as hierarchical merging – clusters of galaxies are fairly well-understood

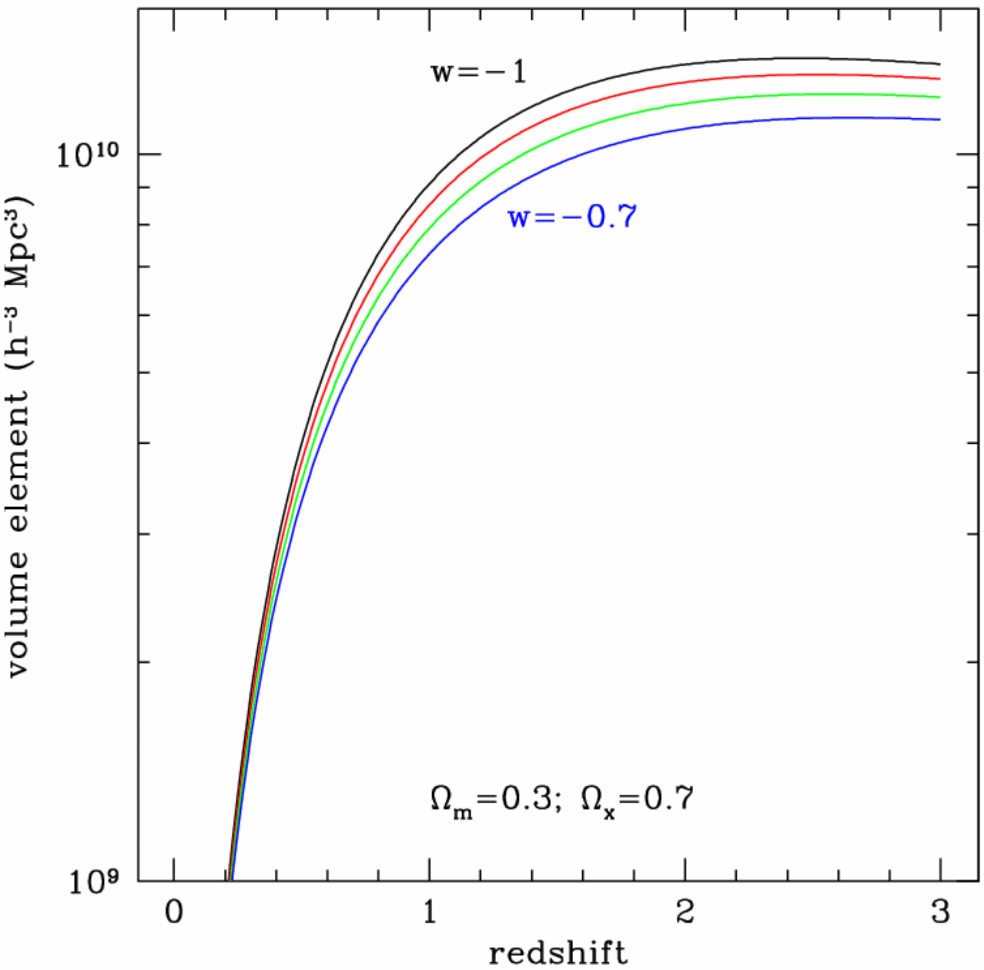


Kravtsov

Growth of Density Perturbations



Volume Element



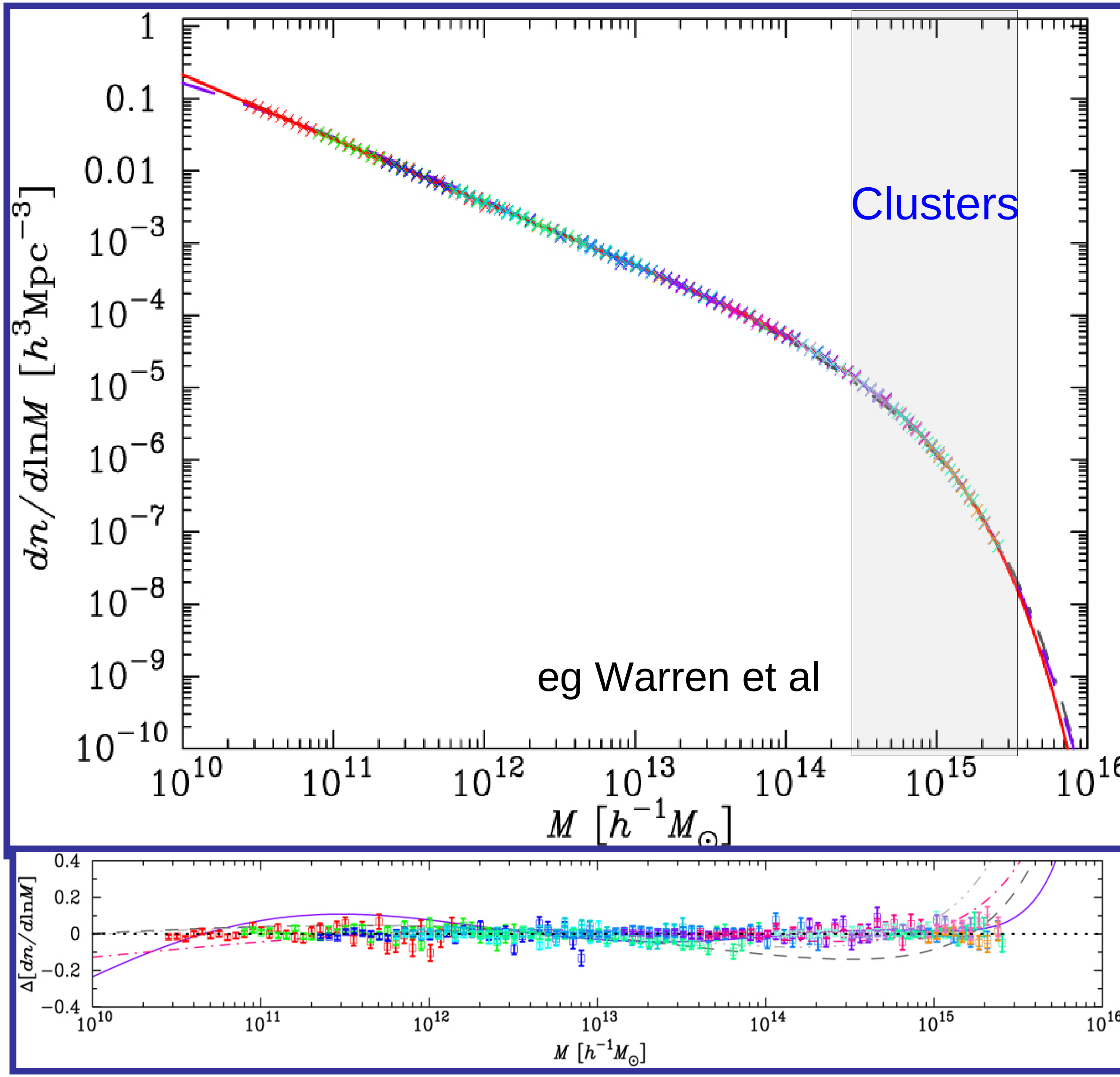
Raising *w* at fixed Ω_{DE}: decreases growth rate of density perturbations, and also decreases volume element (Increasing Dark Energy density at fixed w has similar effect)

2) The Cluster Mass Function

Collapsed objects: halo abundance

Gravitationally bound structure (eg cluster of galaxies) built up by hierarchical merging – most massive objects form late and are least numerous

Mass is dominated by dark matter halo – **number density of halos as a function of mass** can be estimated analytically (Press & Schechter), or **more accurately from numerical simulations**



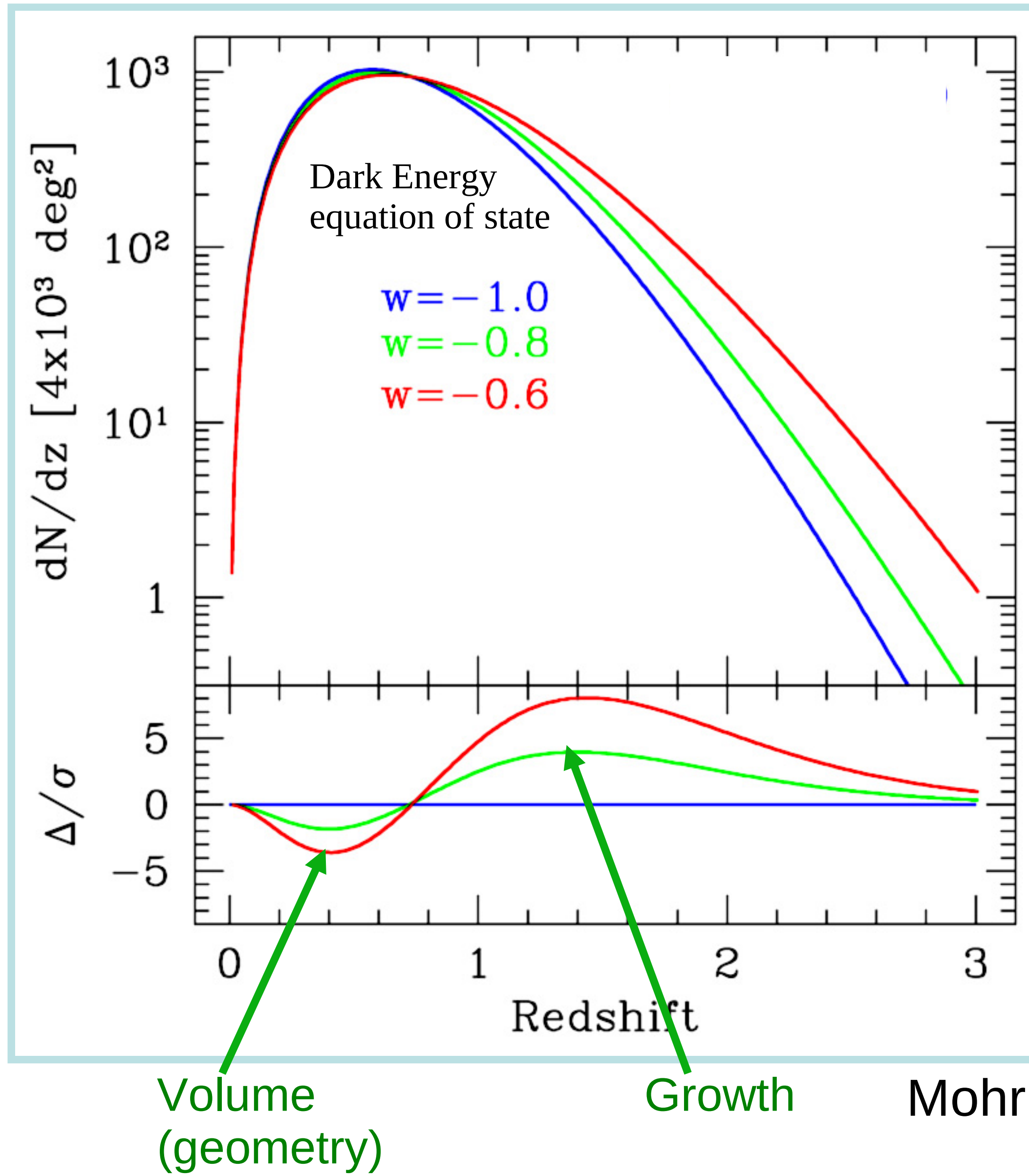
Clusters and Dark Energy

Suppose we could find all clusters above a known mass threshold:

Integrate mass function to get differential number counts:

$$\frac{dN}{dzd\Omega} = n(z)\frac{dV}{dzd\Omega}$$

Count clusters as a function of redshift, probe dark energy

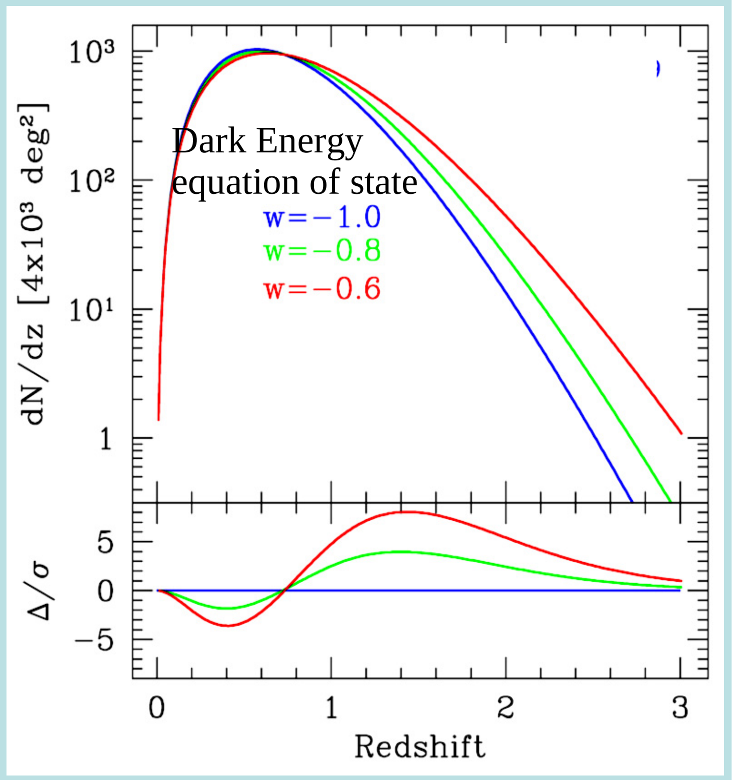


Mohr

Clusters and Dark Energy

Requirements:

* Model mass function (from sims)
* Clean sample of clusters with well-defined mass threshold
* Redshift estimates for each
* Observable mass proxy “O” and its pdf: Pr(O|M,z)



Predicted number counts (eg in bins):

$$\frac{d^2N(z)}{dz d\Omega} = \frac{r^2(z)}{H(z)} \int_0^\infty f(O,z)dO \int_0^\infty p(O|M,z)\frac{dn(z)}{dM}dM$$

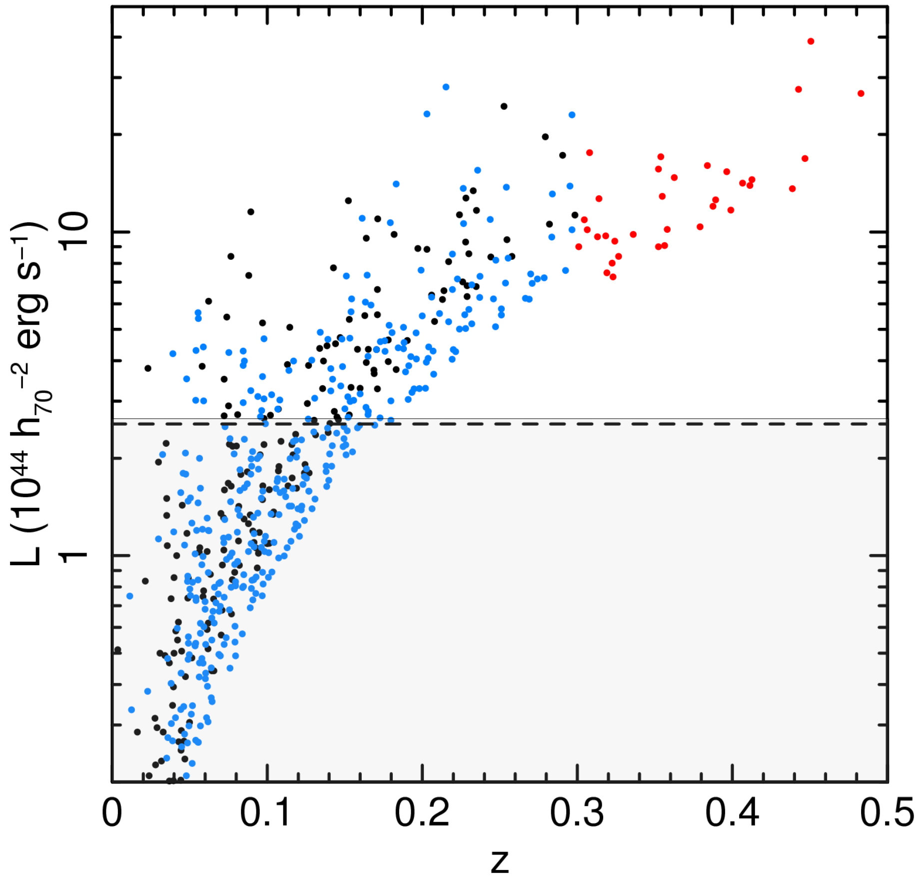
Counts Volume Selection by O M-O relation Mass function

In practice, do not have to integrate over mass – but n(z) shows DE effects well

Mantz et al 2009

X-ray Luminosity Function

238 clusters selected by their X-ray emission from BCS, REFLEX and MACS surveys



Known redshifts!

Mantz et al 2009

X-ray Luminosity Function

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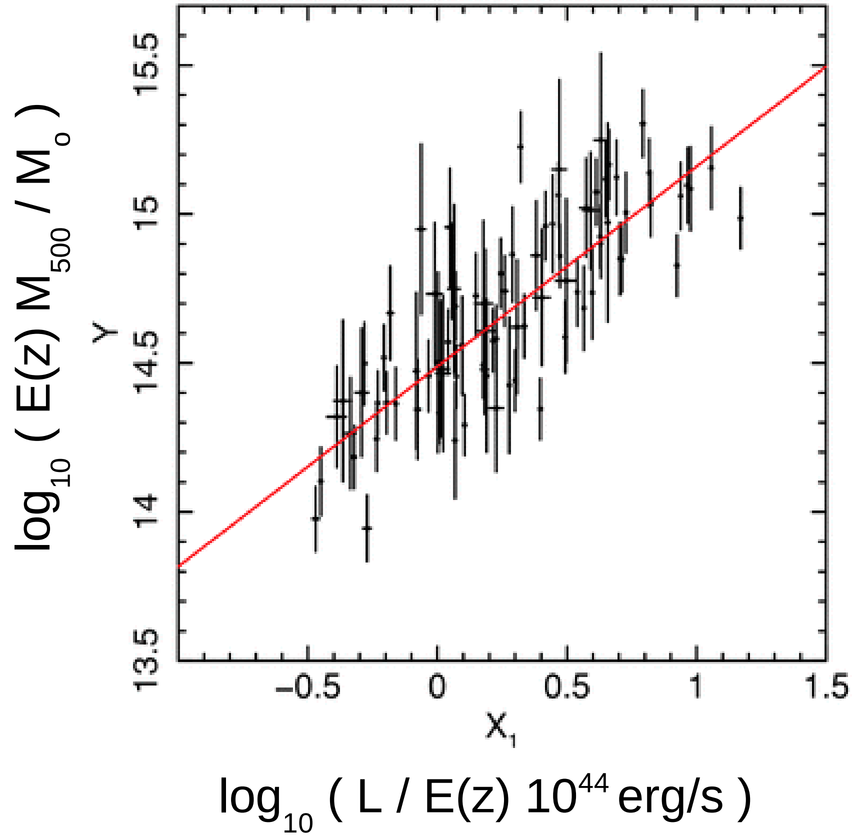
Observable mass proxy is luminosity – correlates with mass. Explore with 94 cluster training set observed at high resolution and depth



Mantz et al 2008

Mantz et al 2009

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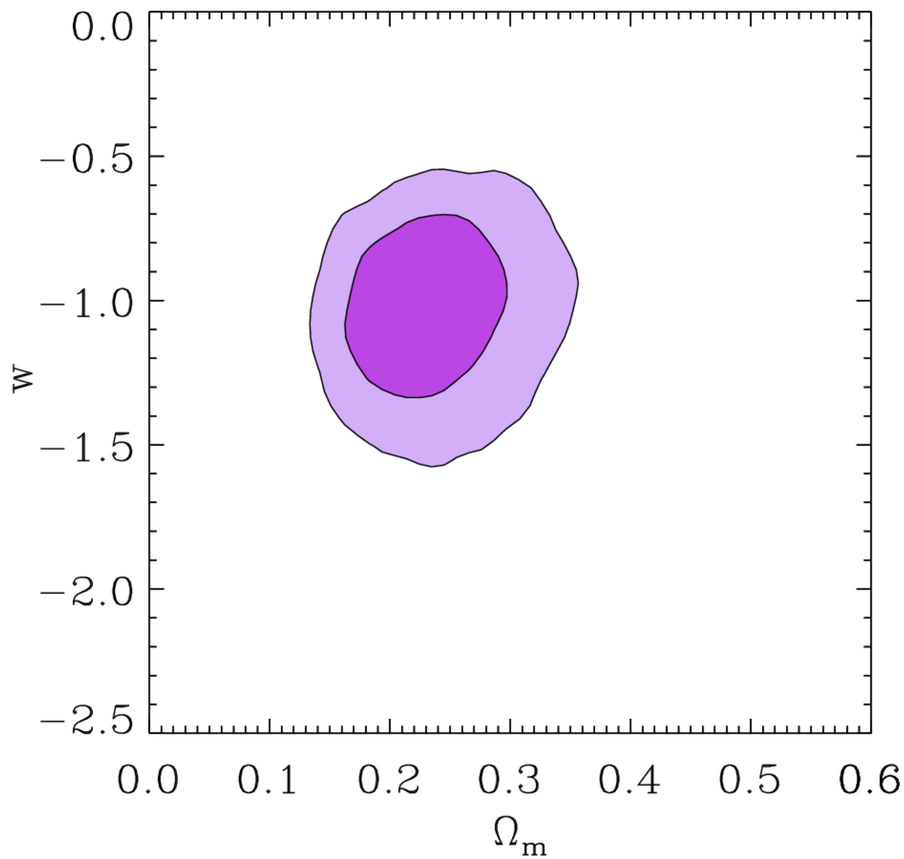
Extend L-M relation to all clusters – fit for cosmological parameters and scaling relation simultaneously. Training set provides prior pdfs on nuisance parameters



Flat geometry
- How does it compare?

They also marginalise out uncertainty in mass function!

Mantz et al 2009

X-ray Luminosity Function

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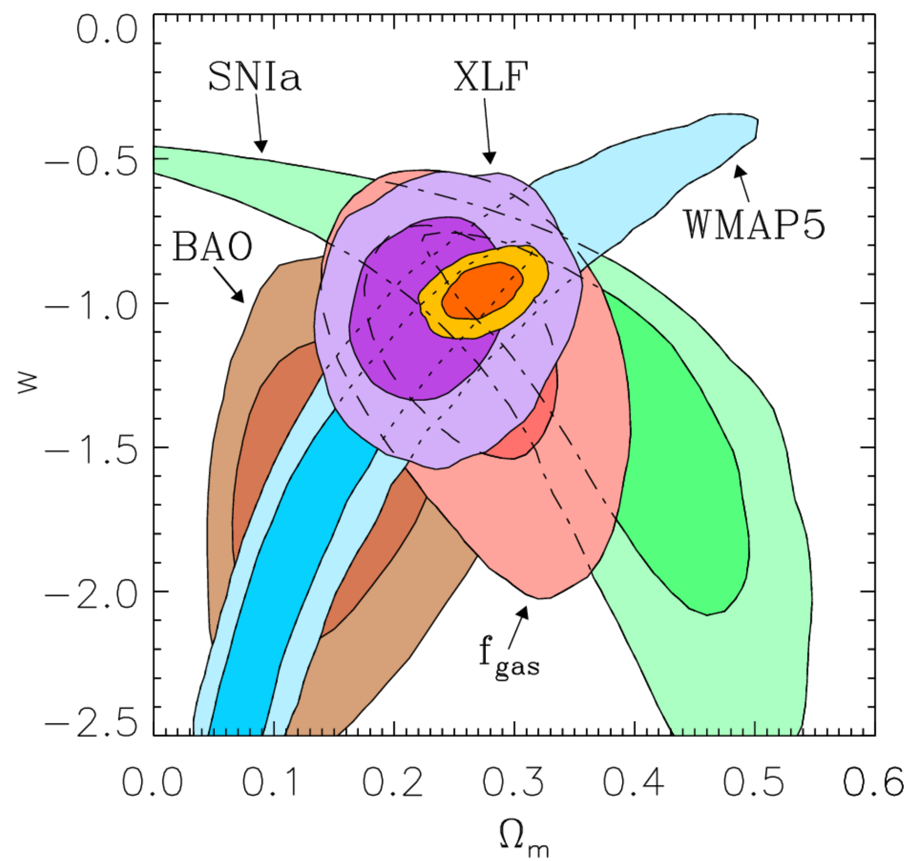


Flat geometry

Overall:
w = -0.96 +/- 0.06

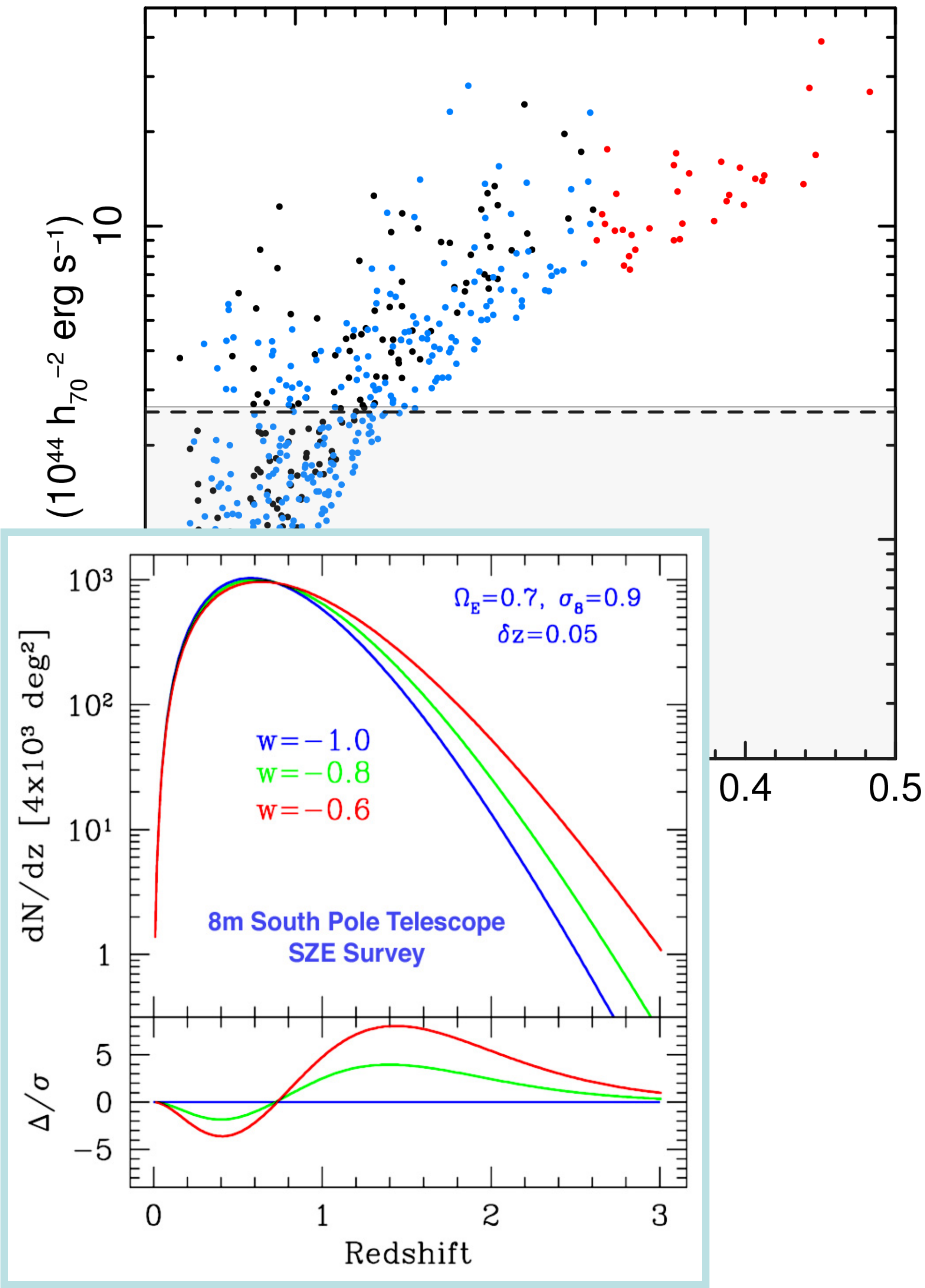
Next steps

X-ray surveys (eg Mantz et al) and optical surveys (see eg Rozo et al for SDSS work) restricted so far to low redshift (eg z < 0.5 for Mantz sample)

Need clusters at higher z for greater leverage on Dark Energy

Programme:

- Find more high-z clusters
- Measure their redshifts
- Measure their masses



Cluster Selection

4 possible techniques for cluster selection:

- Optical galaxy concentration
- Weak Lensing
- Sunyaev-Zel'dovich effect (SZE)
- X-ray

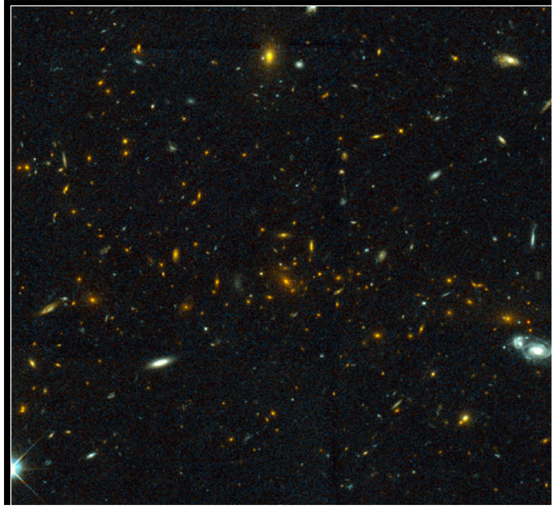
Lensing potentially cleanest in terms of mass-observable – no surveys big enough yet

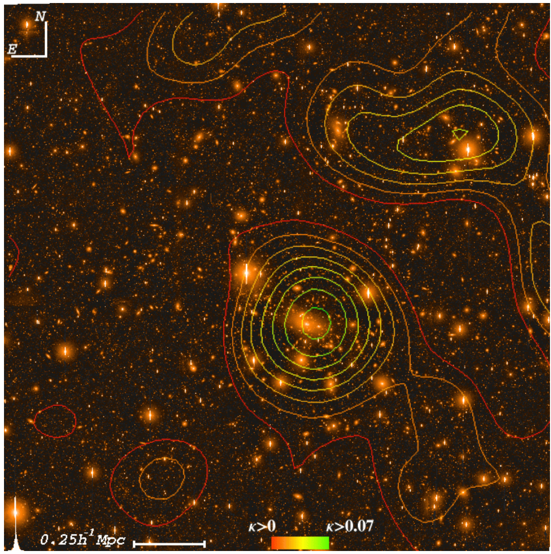
Good results from X-ray and optical (eg SDSS) so far – eROSITA to provide more X-ray clusters

SZE very promising

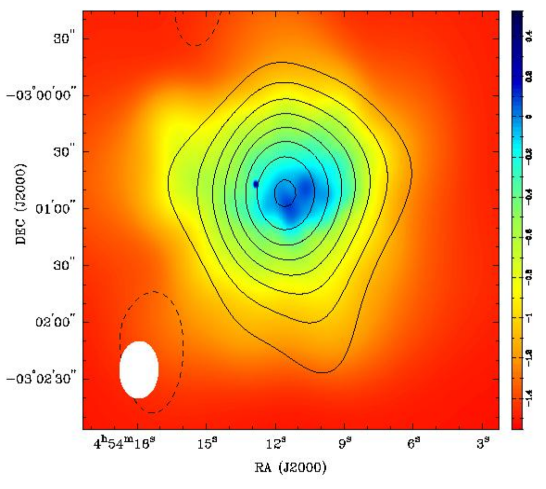
X-rays just needs a deeper survey

- Cross-compare selection to control systematic errors

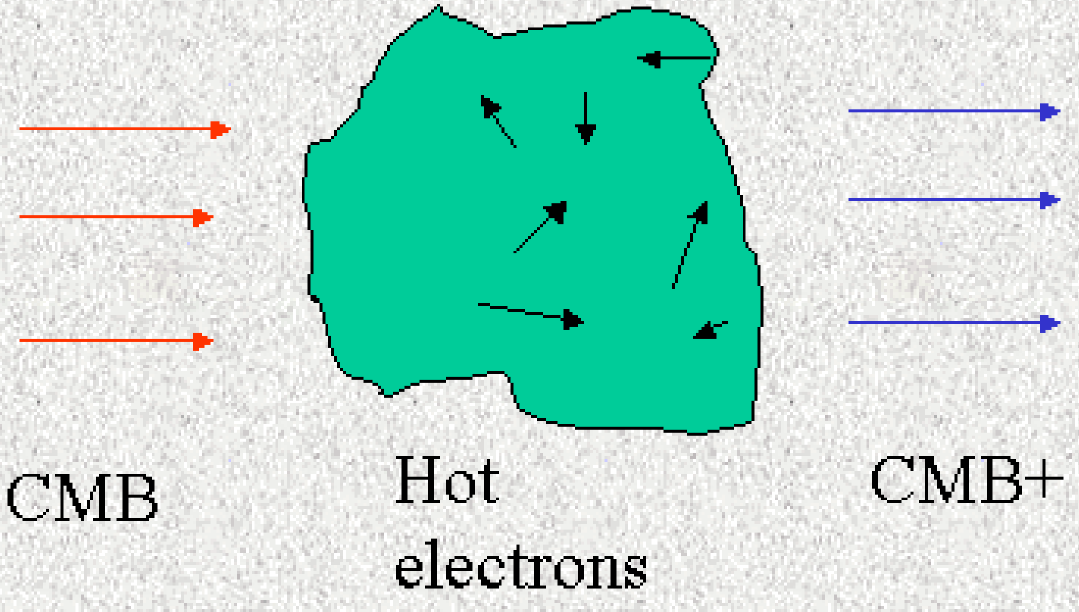




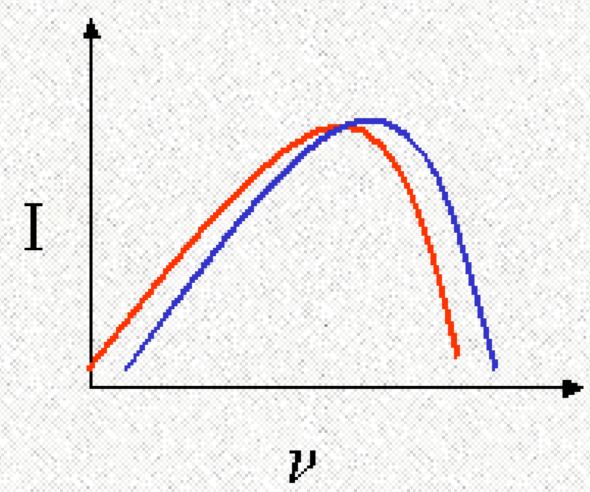
MS 0451−03: S−Z Effect Contours, Chandra ACIS Color Scale



Sunyaev-Zel'dovich Effect



Observe a **decrement** in the CMB below 220GHz



$$F_{SZ} = g(\nu)Y = g(\nu)\int\int n_e\left(\frac{kT_e}{m_e c^2}\right) dl\, d\Omega$$

$$F_{SZ} \sim M_{\rm gas} T_{\rm gas}$$

Note: SZ surface brightness is *independent of z:* clusters get (somewhat) smaller but flux still high

Holder

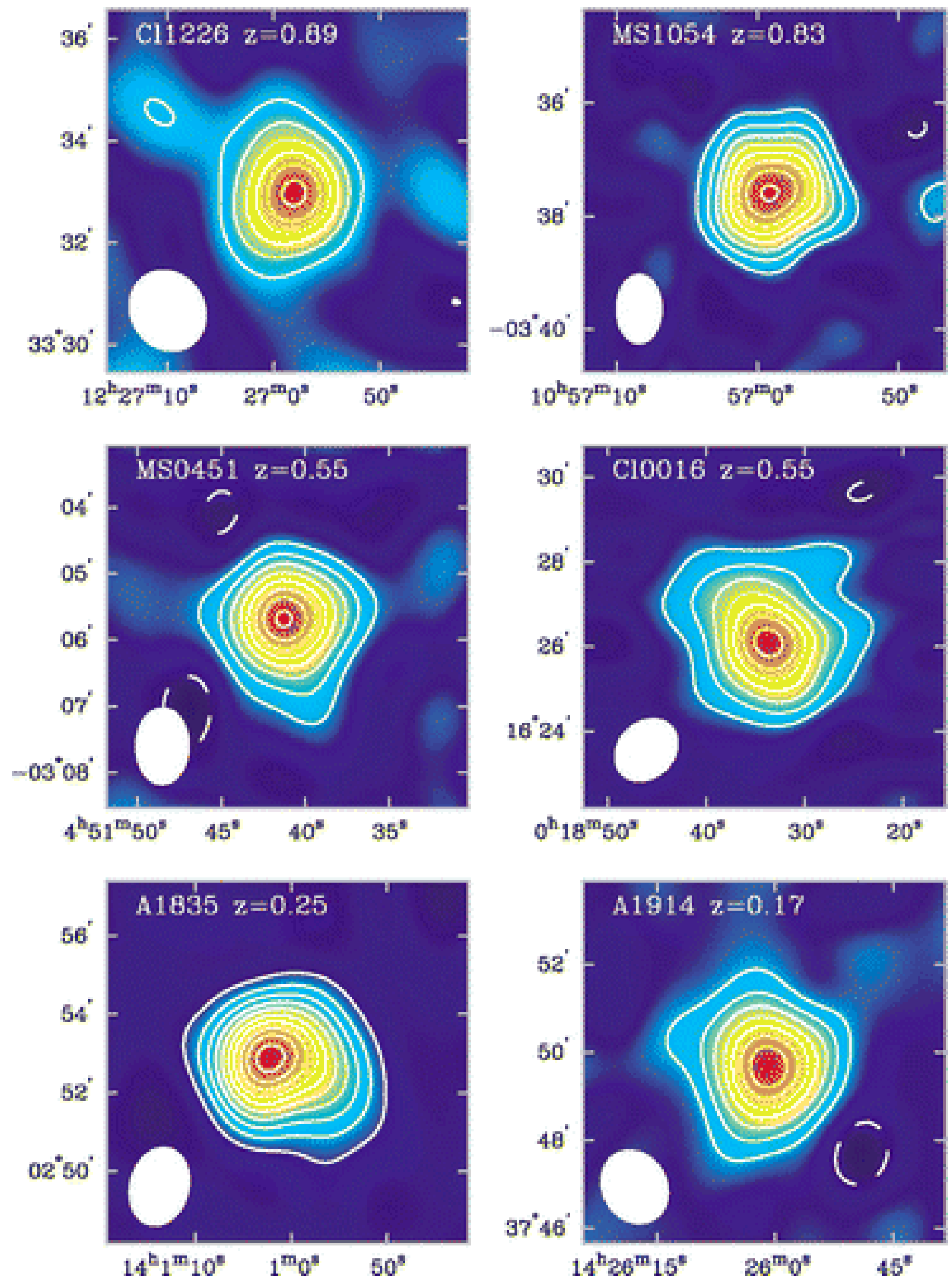
Clusters observed in SZ retain visibility to high redshift

Emission from galaxies (optical) and hot gas (X-rays) falls off rapidly with z

• mass-observable relations become very uncertain
• optical confusion, projection effects a problem

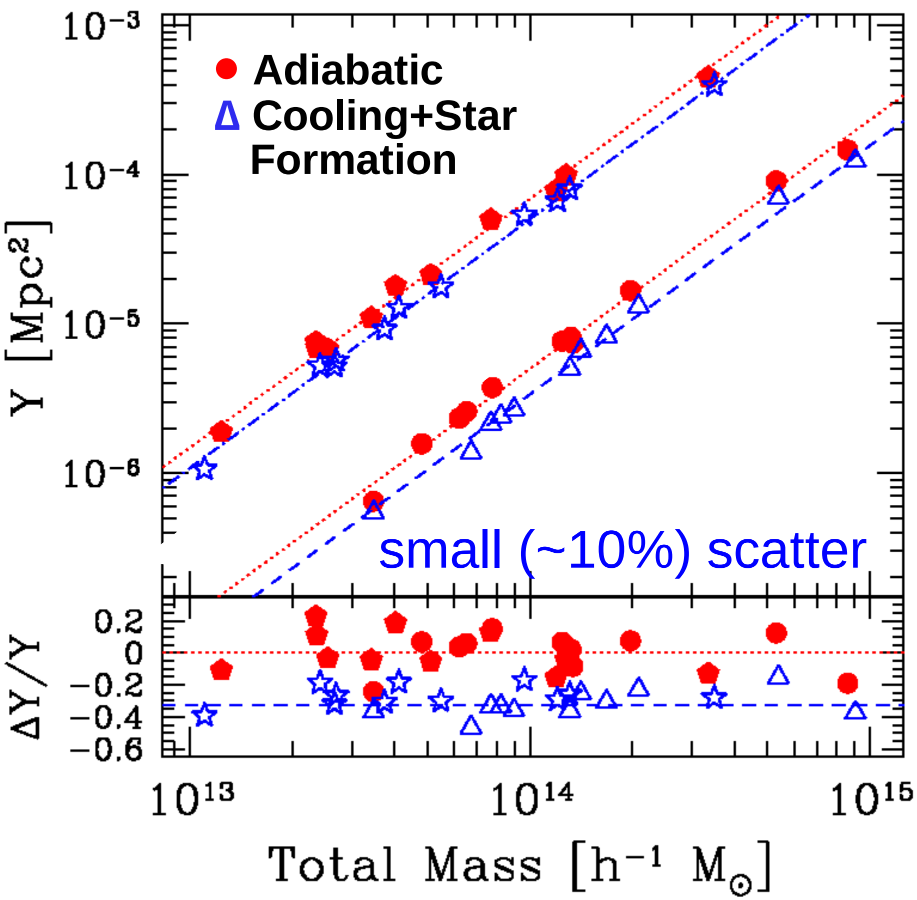
Combine SZ (detection, M) with optical data for photometric redshifts – how good is SZ as a mass proxy?

(Potentially additional mass information through optical richness)



Carlstrom et al

SZ flux vs. Cluster Mass



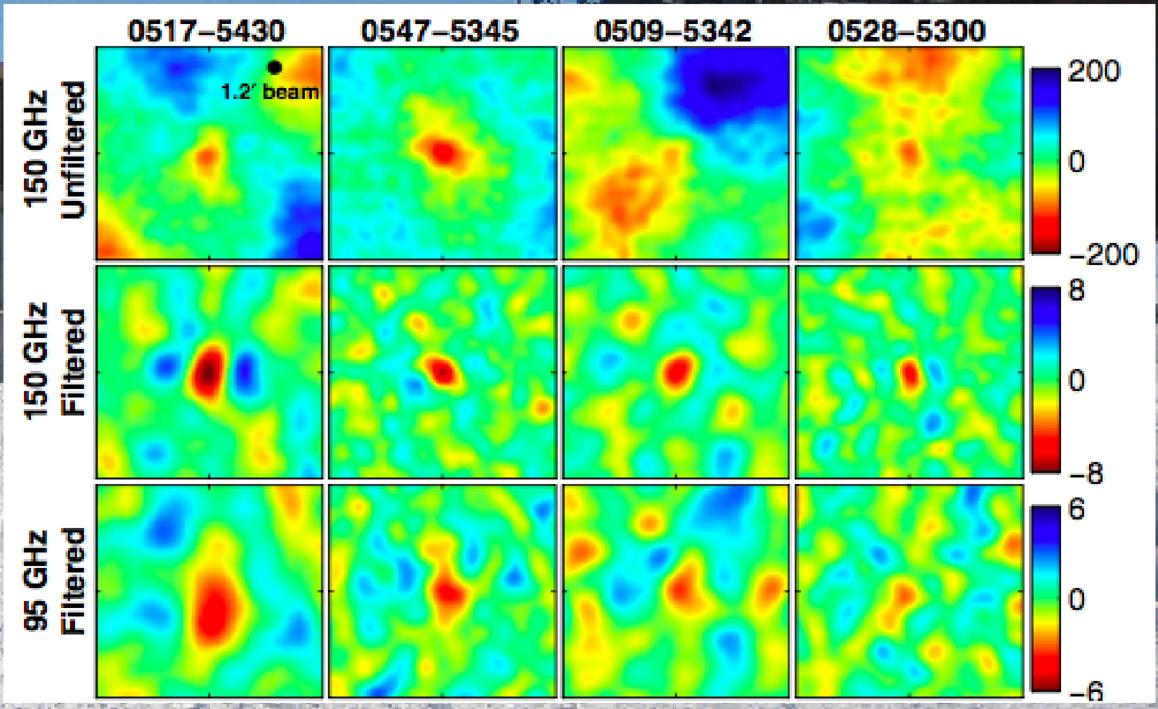
Calibration with simulations:

Integrated SZE flux decrement depends only on cluster energy, insensitive to details of gas dynamics/galaxy formation in the cluster core → robust scaling relations, 10% scatter

The South Pole Telescope

Competition: **ACT**
http://www.physics.princeton.edu/act

10m dish
operating at 95, 120 and 225 GHz
40 sq deg published so far
First 3 SZ clusters detected!
Final survey 1000 sq deg



Staniszewski et al 2009
http://pole.uchicago.edu/

Precision Cosmology with Clusters?

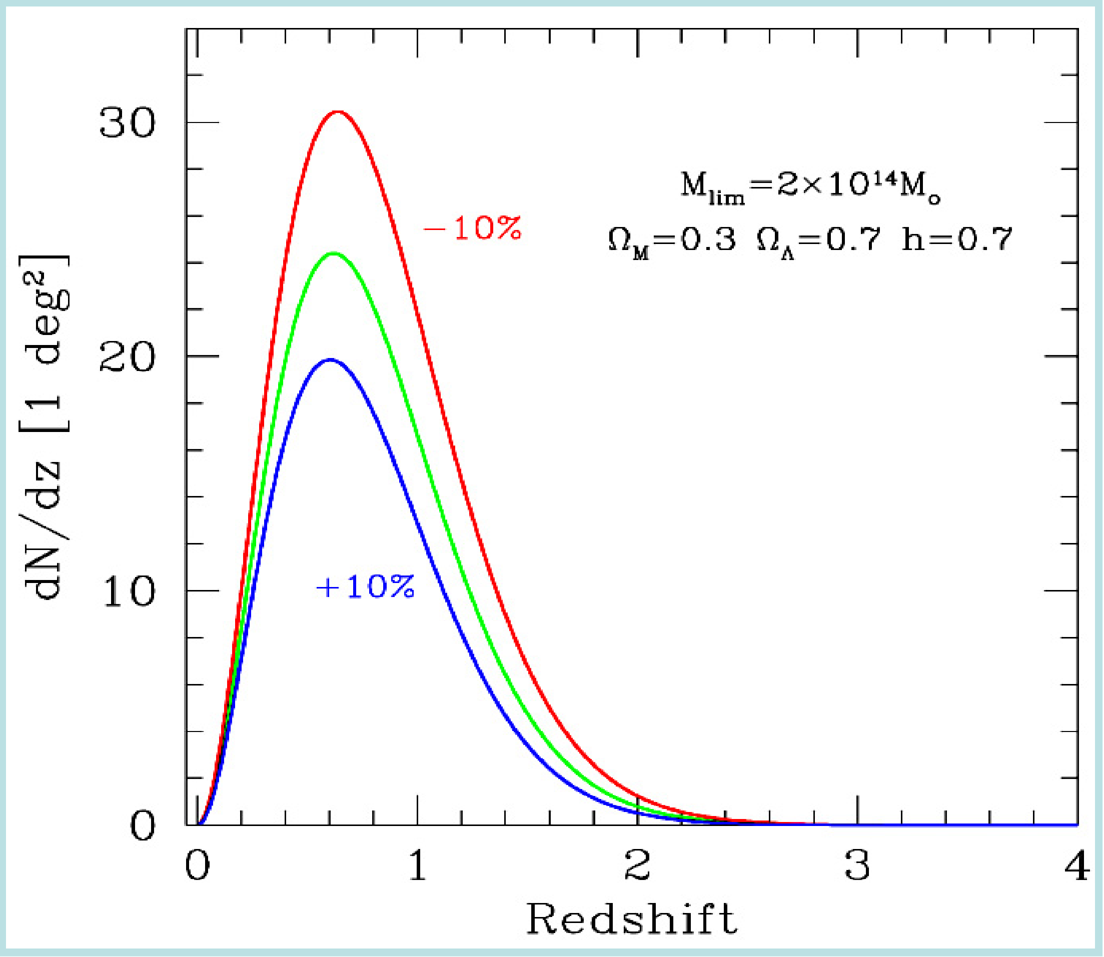
Uncertainty in mass-observable relation can dwarf effects of dark energy

Mass threshold needs to be characterised really well – and scatter marginalised out...

• Detailed mock maps and catalogues to understand detection completeness

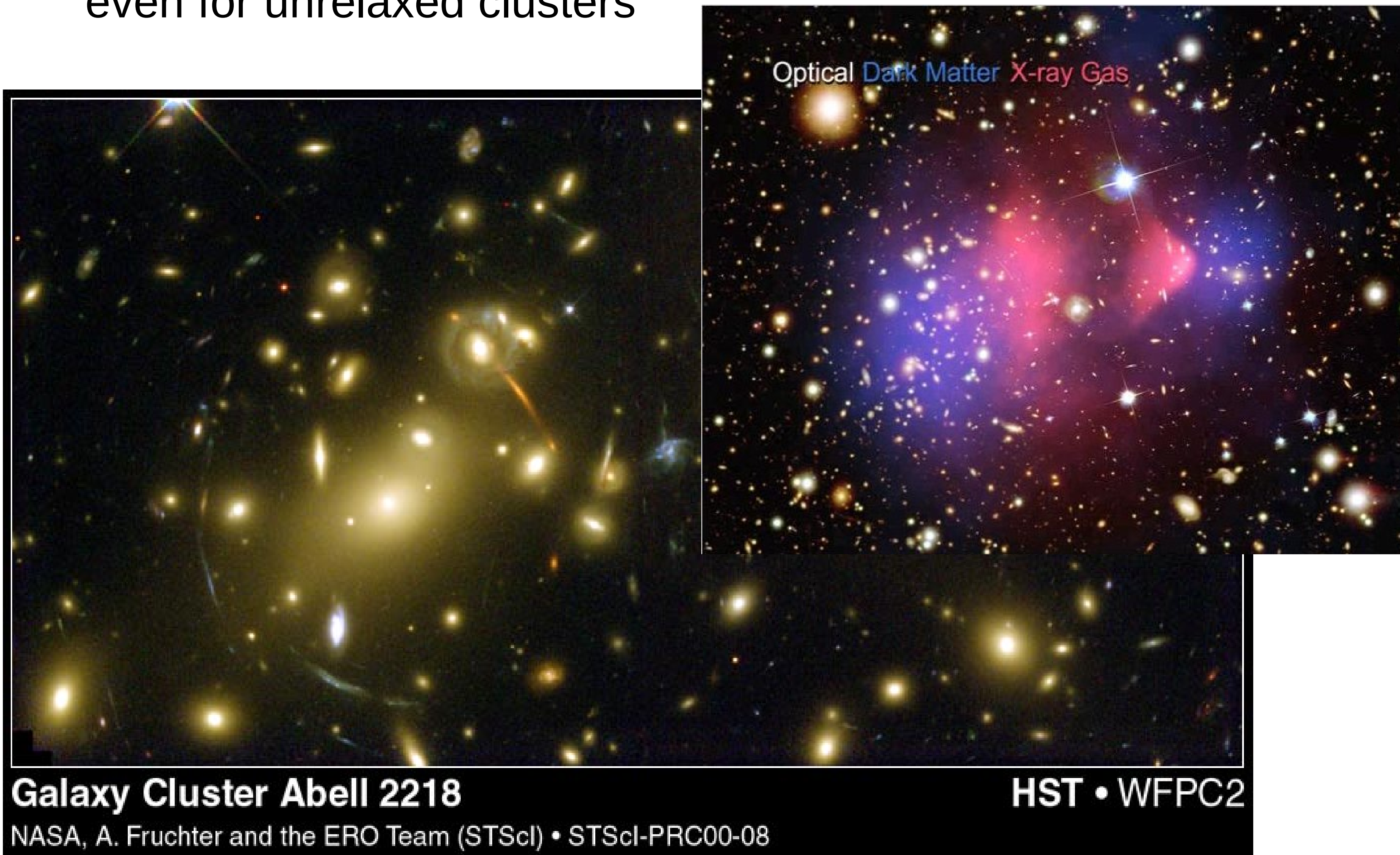
• Multiple, accurate mass measurements

Sensitivity to Mass Threshold

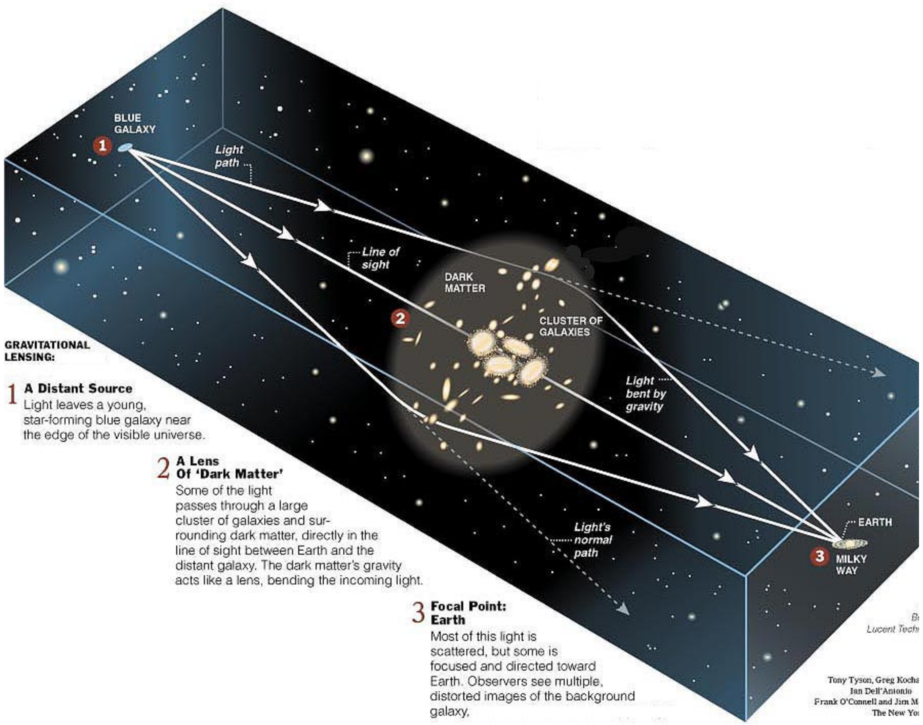


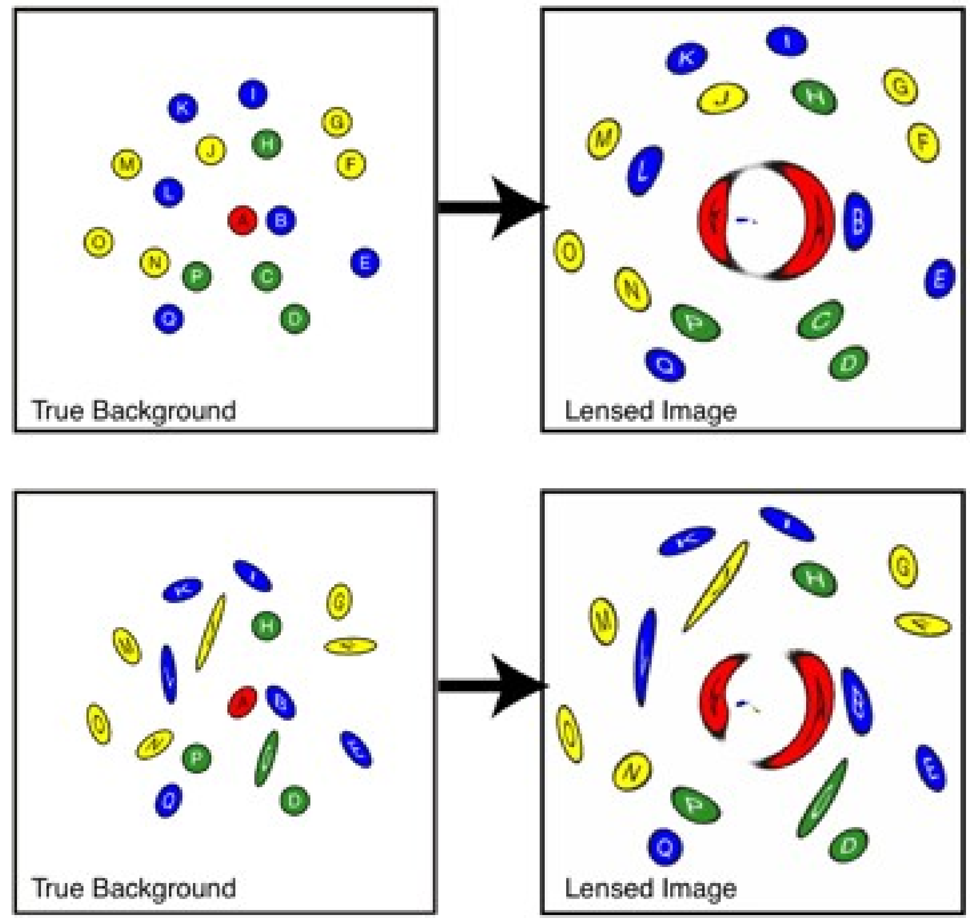
Cluster mass measurement

Gravitational lensing can provide accurate mass estimates even for unrelaxed clusters



Cluster mass measurement





Strong lensing helps but is not always present – weak lensing always is

Measure galaxy ellipticities, predict them from mass model

Cluster mass measurement

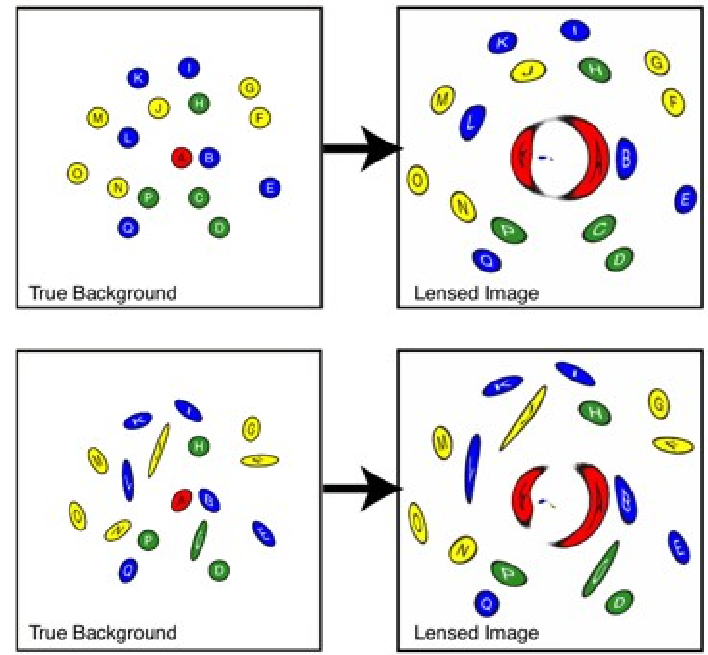
Average (complex) ellipticity is zero:

$$\langle \epsilon \rangle \approx \gamma$$

For spherical cluster, shear is

$$\gamma(R) = \frac{\bar{\Sigma}(< R) - \Sigma(R)}{\Sigma_{\rm crit}}$$

Projected mass overdensity

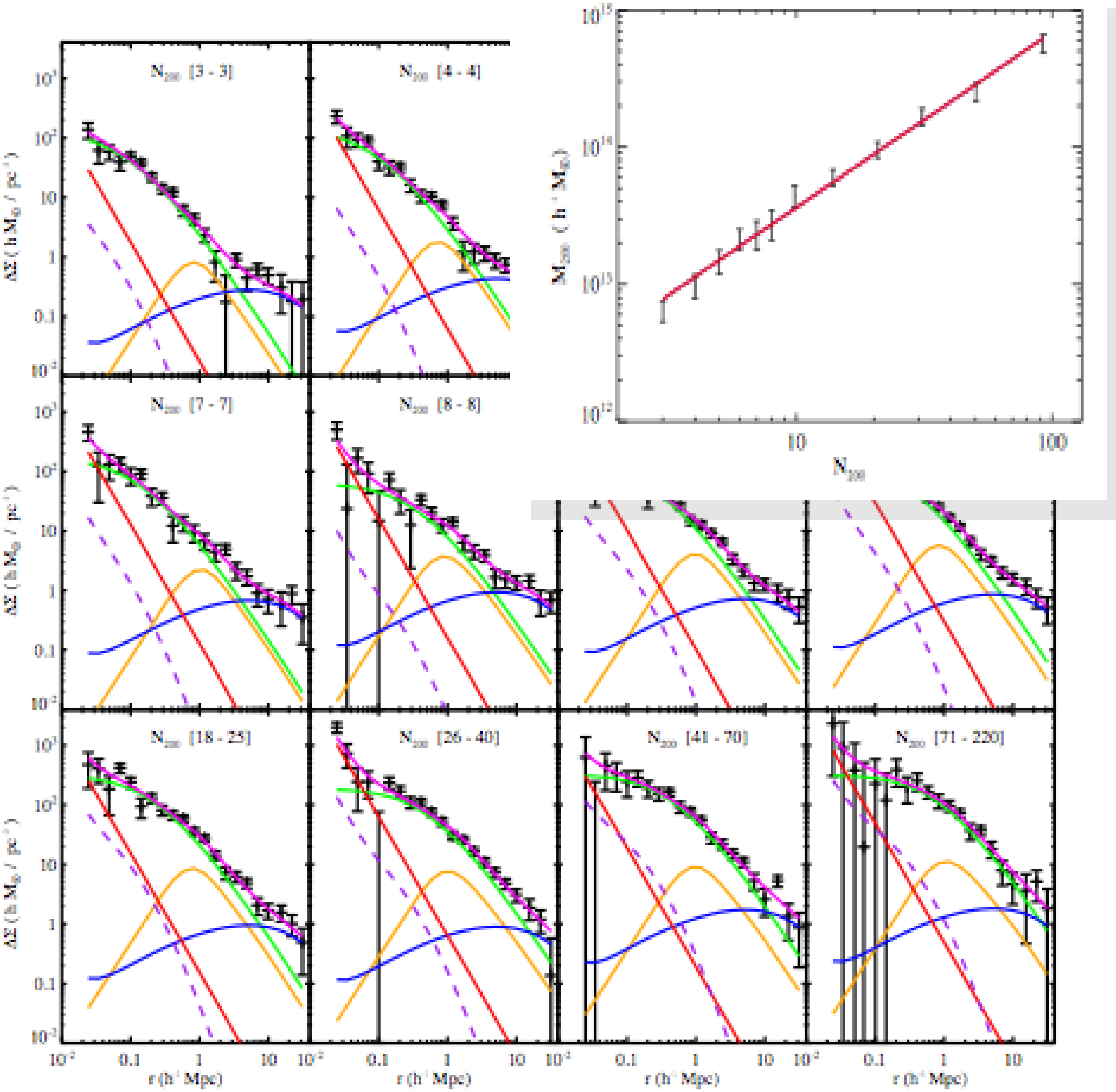


Individual clusters' masses precision limited to +/- 10^{14} M_o by mass along line of sight (Hoekstra et al 2001)

“Stacking” clusters shear signals together enforces symmetry, and averages both ellipticity and LOS noise down

Fine for observable – mass relation

SDSS cluster mass profiles



Johnston et al 2007

130,000 groups and clusters, stack measured shears for clusters in bins of N, the number of galaxies within virial radius

Fit resulting overdensity profile with multi-component model, separate out part that corresponds to cluster mass (as defined in simulations)

Result:
Calibrated N-M relation for optical clusters
Could repeat for Y-M...

The Dark Energy Survey

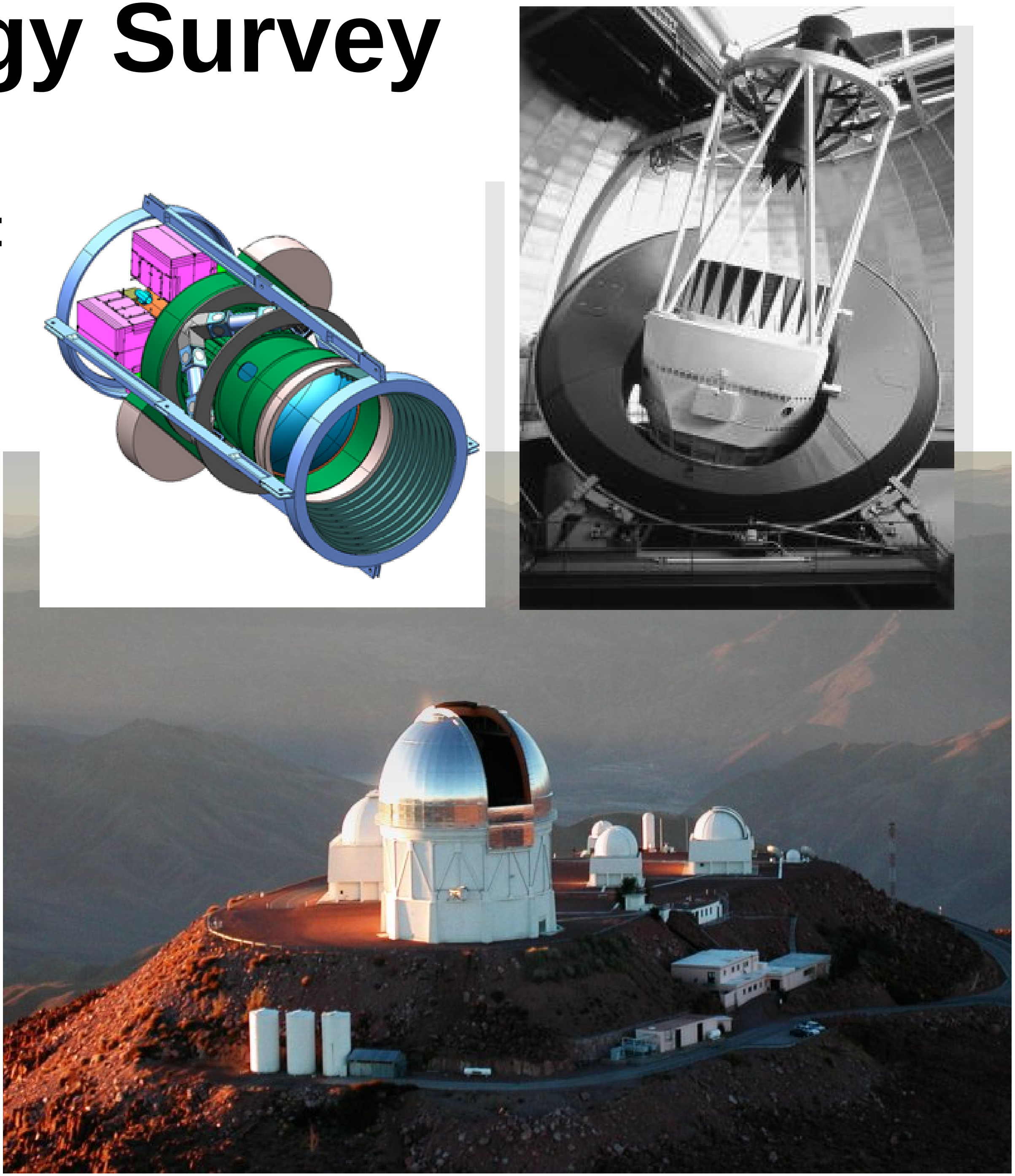
Study Dark Energy using
4 complementary techniques:

I. Cluster Counts

II. Weak Lensing

III. Baryon Acoustic Oscillations

IV. Supernovae



New 3 deg^2 camera for Blanco telescope at CTIO, Chile

Re-fit optics...

- 5000 deg^2 *g, r, i, z,Y*
  9 deg^2 repeat (SNe)
- 5-year, 525-night survey
  2011-2016

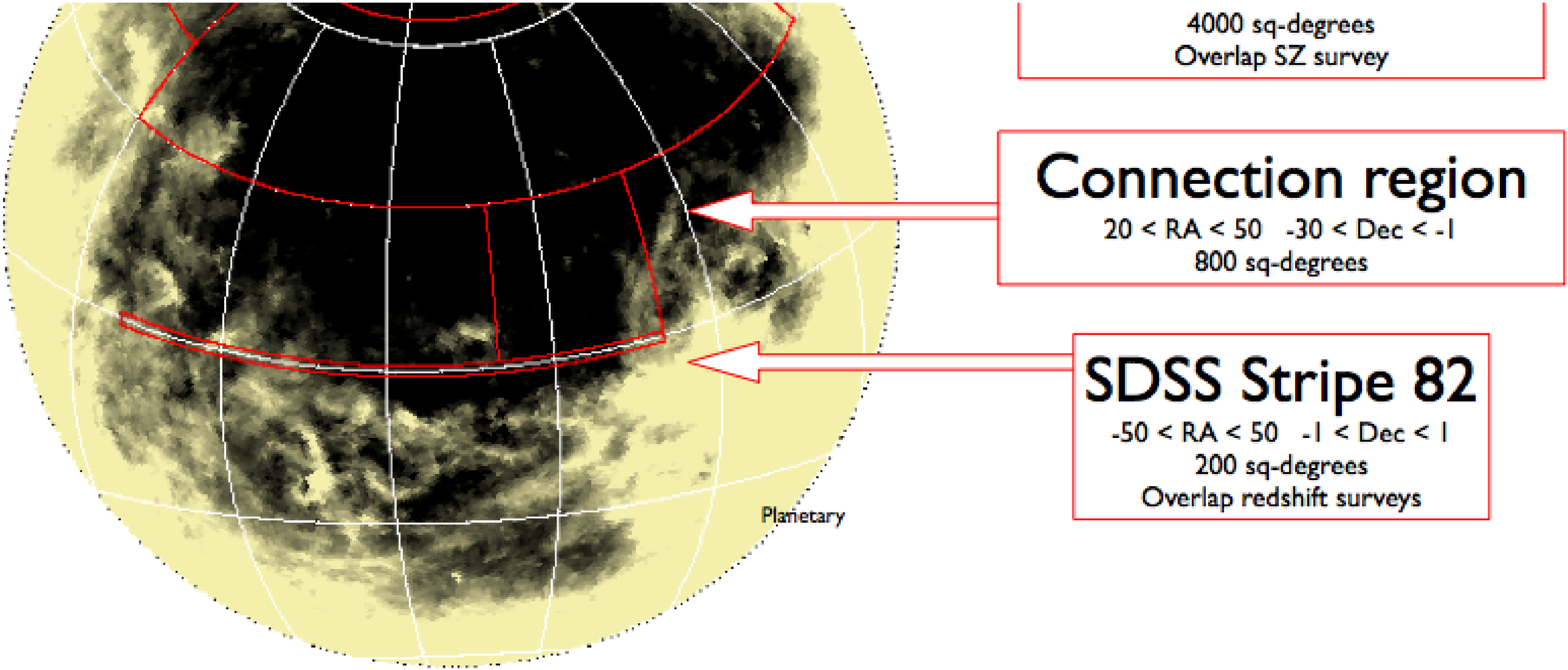
https://www.darkenergysurvey.org

DES & SPT for clusters

Original mission:

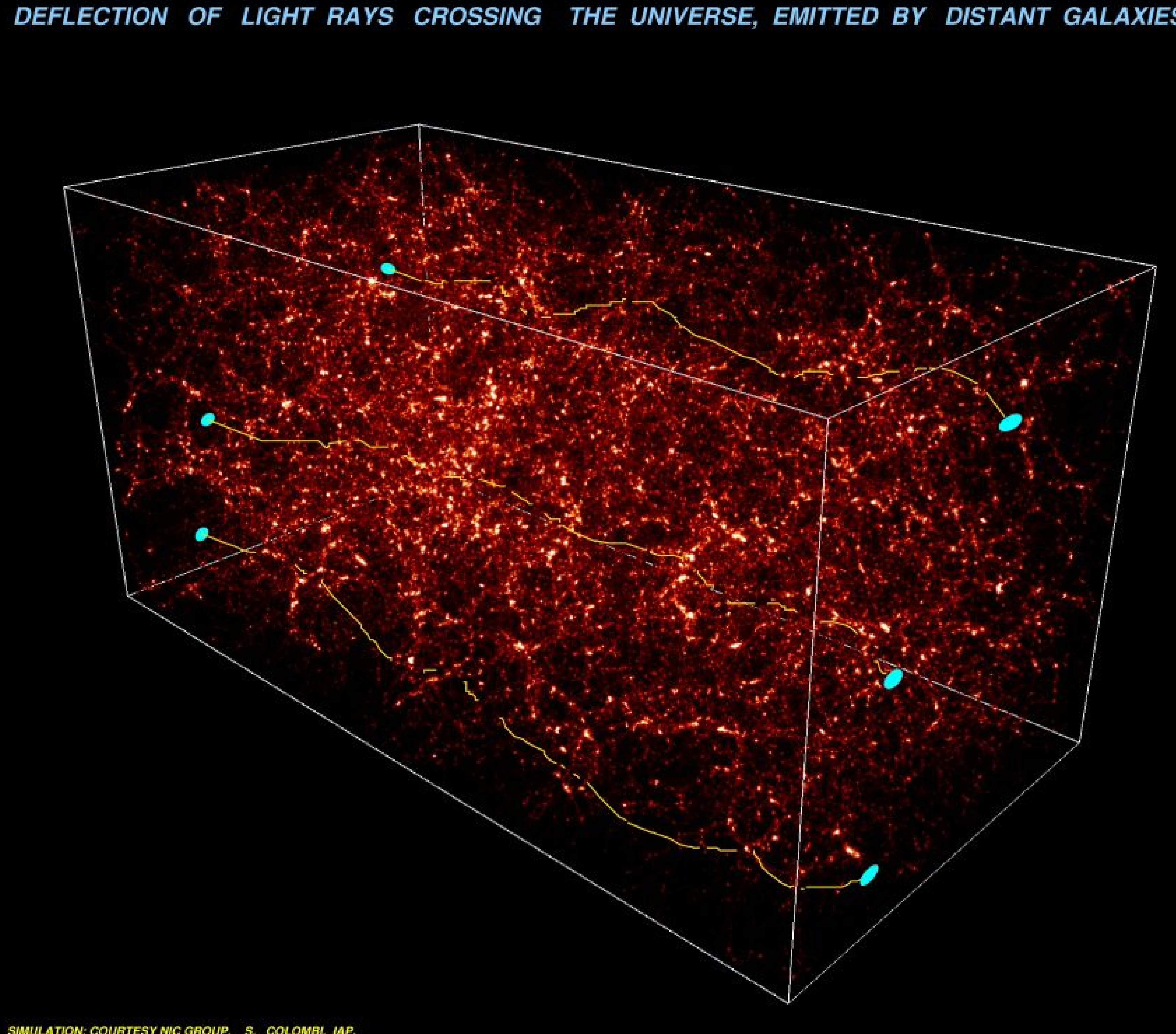
provide **photometric redshifts for SPT clusters**

4000 of 5000 sq deg survey area overlaps with SPT surveyable area

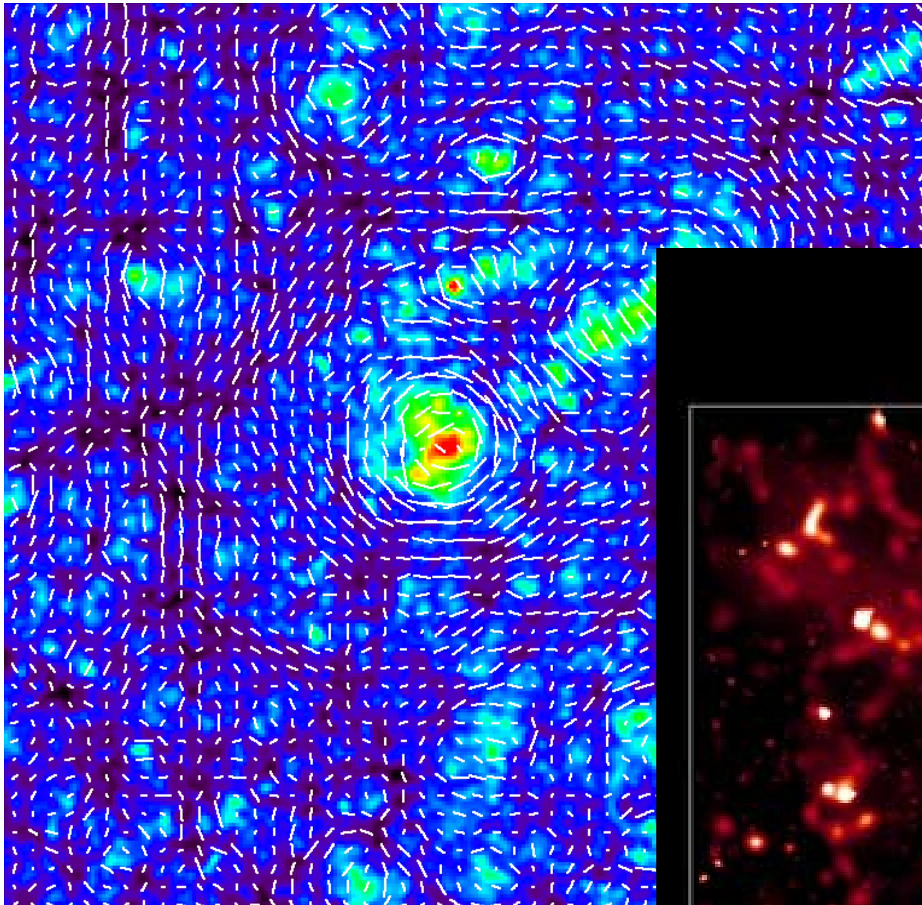


3) Weak lensing by large-scale structure

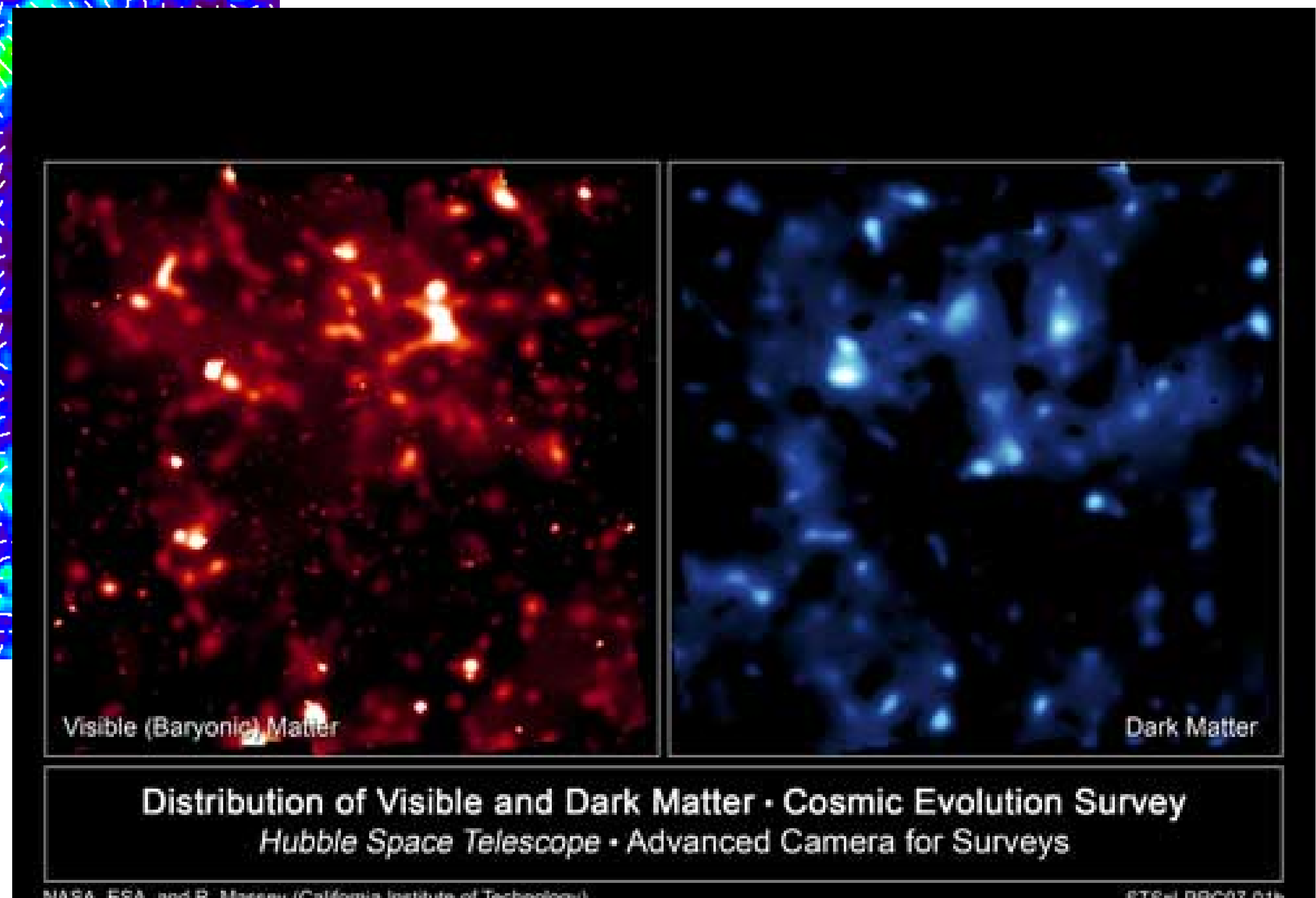
Weak Lensing by Everything



Weak lensing: shear traces mass



Shear field from numerical simulation of large scale structure (eg Jain & Seljak)



Can reconstruct maps like this – if data are very high quality

eg HST/COSMOS

Both shear and surface density are second derivatives of the projected gravitational potential – so are related by a convolution enabled by FFT (Kaiser & Squires 1993)

Weak Lensing signals

Intrinsic galaxy shapes are uncorrelated, so average shape is round. $\langle e_{intrinsic} \rangle = 0$

Main part of statistical error is variance of galaxy shapes:

- Width of intrinsic ellipticity distribution is ~ 0.3
- Uncertainty in shear estimate is $\sim 0.3/(N^{1/2})$
- The lower mass the structure, the more background galaxies you need
- COSMOS data: 40 galaxies per sq arcmin, map clusters

Shear	Galaxies Needed	Example
10%	100	Rich Clusters
3%	1000	Normal Clusters
1%	10,000	Galaxy Halos
0.3%	100,000	Field Lensing

Jarvis

Cosmic shear

Mass maps are instructive – but cosmological information is better extracted from *cosmic shear statistics*

- identify lens plane and source plane galaxies (preferably by redshift)
- measure background galaxy ellipticities
- combine (noisy) ellipticities into noisy shear statistics

Correlation function: $$\xi_{\pm}(\theta) = \left\langle \gamma_1(\boldsymbol{\phi})\gamma_1(\boldsymbol{\phi}+\boldsymbol{\theta}) \pm \gamma_2(\boldsymbol{\phi})\gamma_2(\boldsymbol{\phi}+\boldsymbol{\theta}) \right\rangle$$

2-point – there are more...

$$\xi_{\times}(\theta) = \left\langle \gamma_1(\boldsymbol{\phi})\gamma_2(\boldsymbol{\phi}+\boldsymbol{\theta}) + \gamma_2(\boldsymbol{\phi})\gamma_1(\boldsymbol{\phi}+\boldsymbol{\theta}) \right\rangle$$

Shear variance:

$$\left\langle |\gamma|^2 \right\rangle(R) = \frac{1}{2}\int \frac{\theta^2}{R^2}\xi_+(\theta) S_+\left(\frac{\theta}{R}\right)$$

circular aperture, radius R

Aperture mass:

$$M_{\rm ap} = \int Q(R)\gamma_T(x,y)\,dx\,dy$$

circular aperture, radius R

Cosmic shear

These statistics can be predicted given a matter power spectrum (computed from cosmological parameters, non-linear transfer fitting functions etc)

For example, the observed aperture mass can be derived via a weighted integral of the shear correlation functions:

$$M_{\mathrm{ap}}^2(R) = \frac{1}{2}\int \frac{\theta^2}{R^2}\left[\xi_+(\theta)T_+\left(\frac{\theta}{R}\right) + \xi_-(\theta)T_-\left(\frac{\theta}{R}\right)\right]$$

The predicted aperture mass is this integral of the power spectrum:

$$M_{\mathrm{ap}}^2(R) = \frac{1}{2\pi}\int \ell d\ell P_\kappa(\ell)\frac{(\ell R)^4}{4}\mathrm{e}^{-(\ell R)^2}$$

Example: CTIO Weak Lensing Survey

Jarvis et al (2006)

12 “random” fields

High galactic latitude, low extinction

Each field is 2.5º x 2.5º

Total area ~ 75 square degrees

Total of 1.8 million usable galaxies: 7 per sq arcmin!

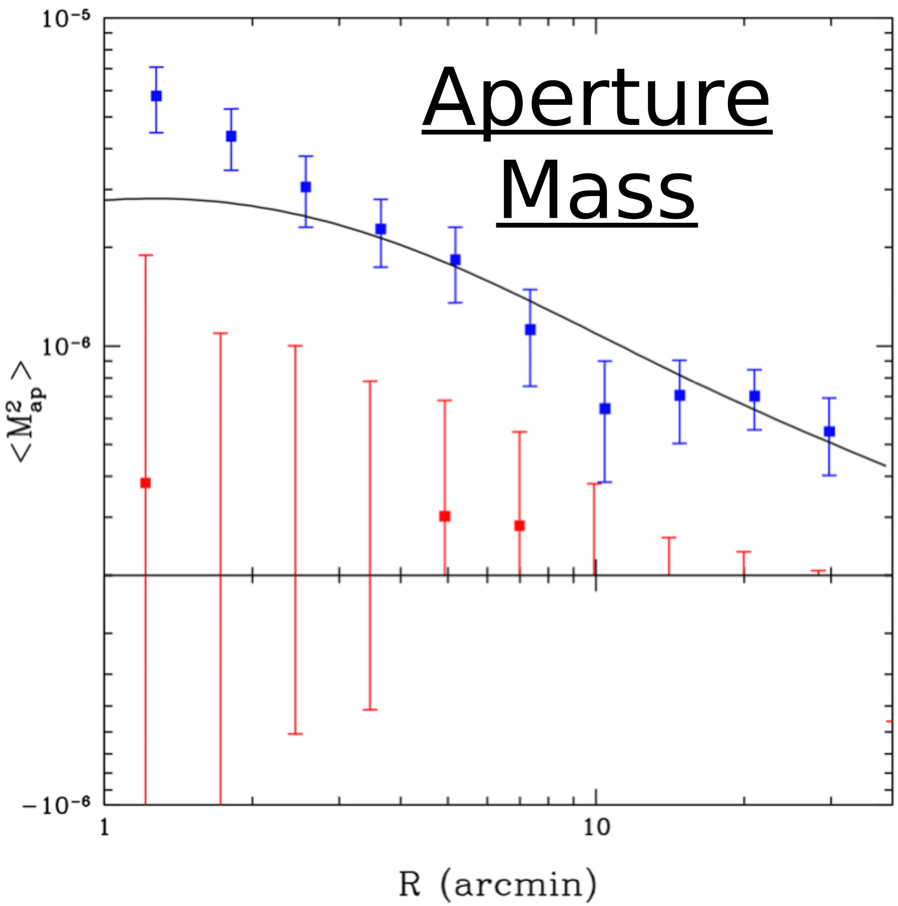
Same telescope as for DES
 - but old Mosaic camera and optics...

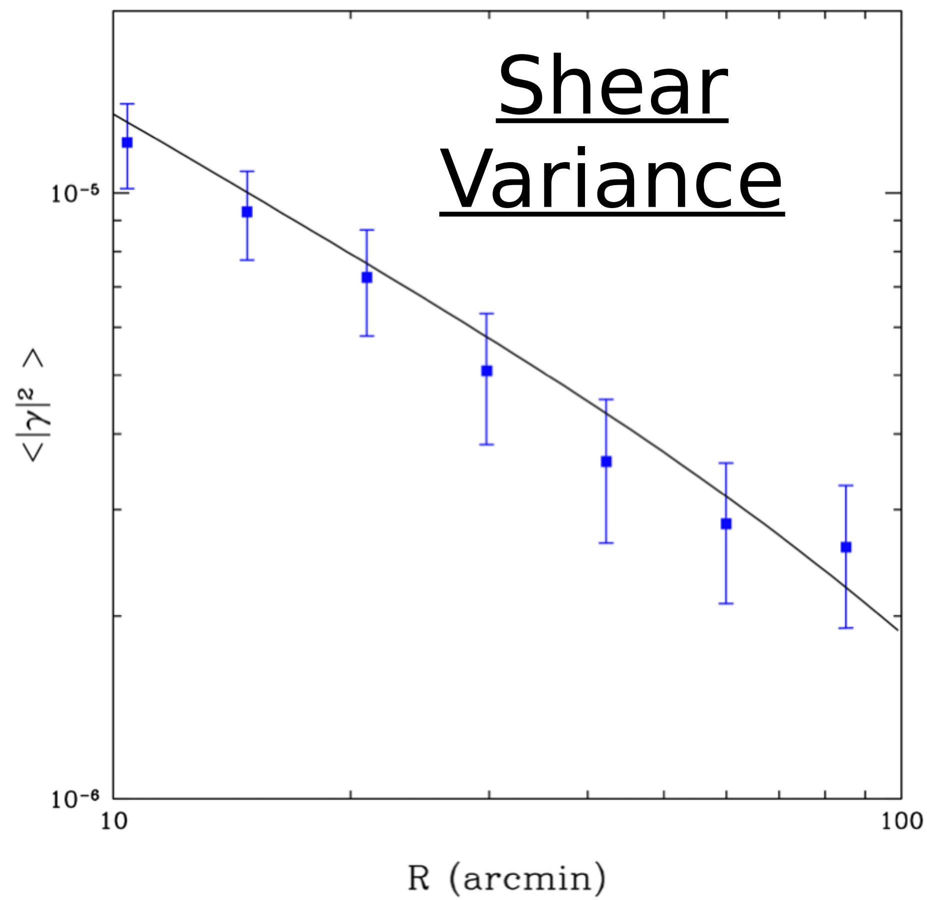
Useful range: 19 < m < 23 (R band)

Galaxies in this magnitude range peak at z ~ 0.5

Most sensitive to Dark Matter at z ~ 0.25

Lensing Statistics





Blue = E-mode
Red = B-mode

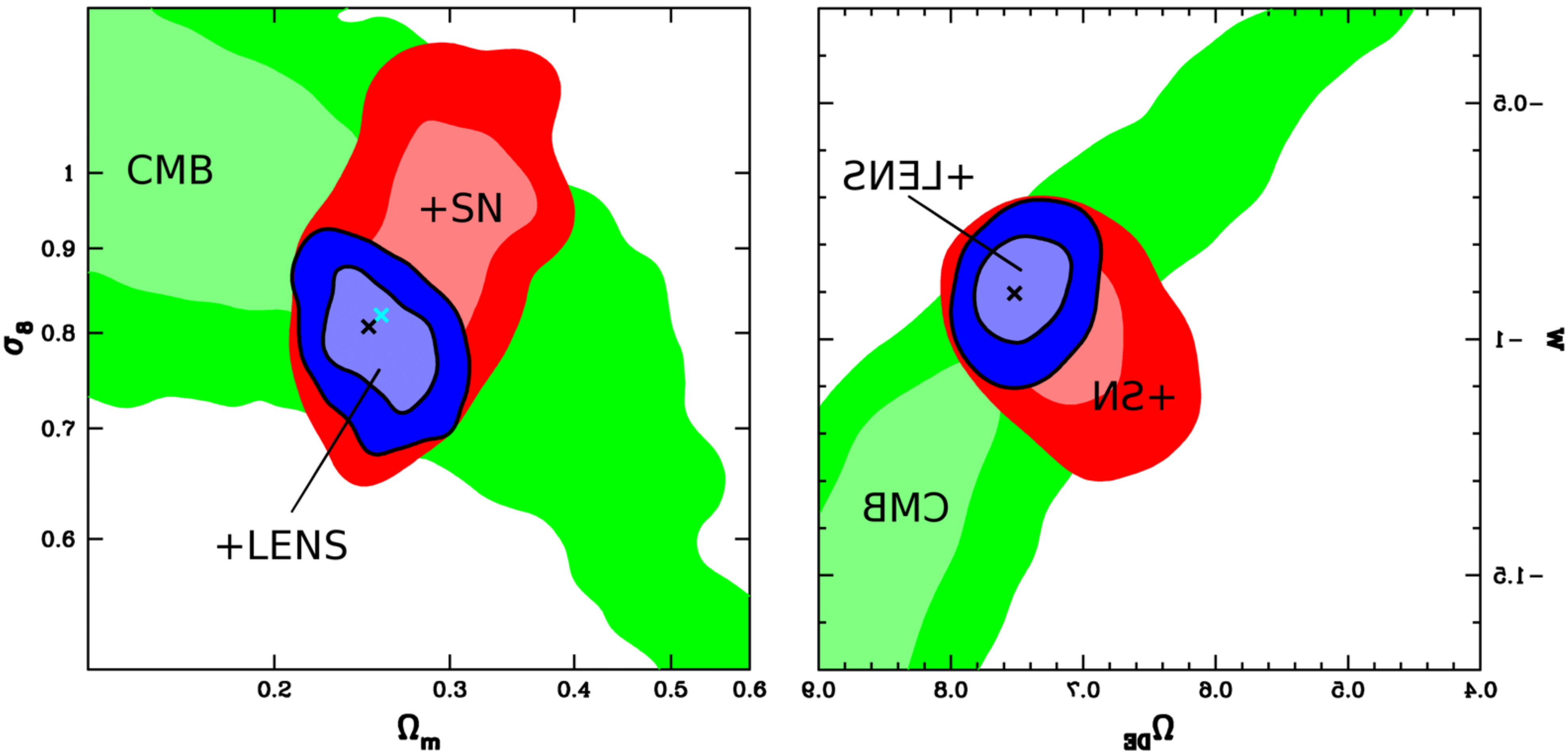
Blue = E-mode + B-mode

$$M_{ap}^2(R) = \frac{1}{2}\int \frac{\theta^2}{R^2}\left[\xi_+(\theta)T_+\left(\frac{\theta}{R}\right) + \xi_-(\theta)T_-\left(\frac{\theta}{R}\right)\right]$$

Change this + to – to get imaginary aperture mass – should be zero if there is only lensing and no systematics

Parameter constraints

Flat geometry, $-3 < w < 0$ $w_a = 0$



2D marginalized $\Omega_m = 0.25$ $\Omega_{\mathrm{DE}} = 0.75$

posterior peaks: $\sigma_8 = 0.81$ $w = -0.90$

Systematic uncertainties

Empirical approach:

- B-mode: add, subtract, re-analyse
- Source redshift distribution (use different redshift survey, re-analyse)
- Overall calibration of shear estimates (<5%)
- Non-linear prediction (Smith et al cf. Peacock-Dodds)

Fully marginalized (95% c.l.) parameter estimates:

Green = statistical
Red = systematic

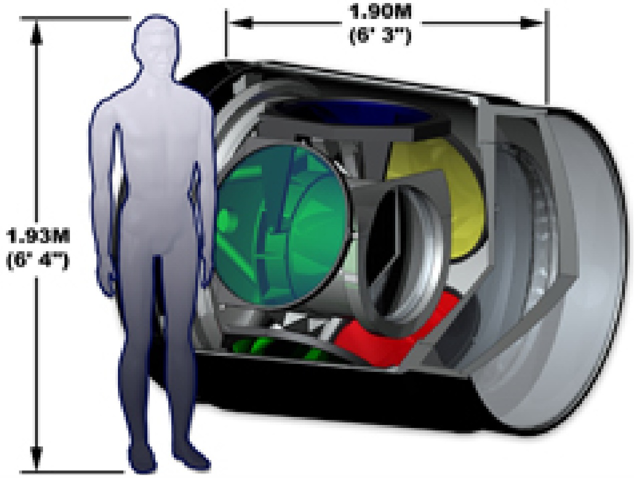
Current WL measurements are statistics limited – but future ones will not be

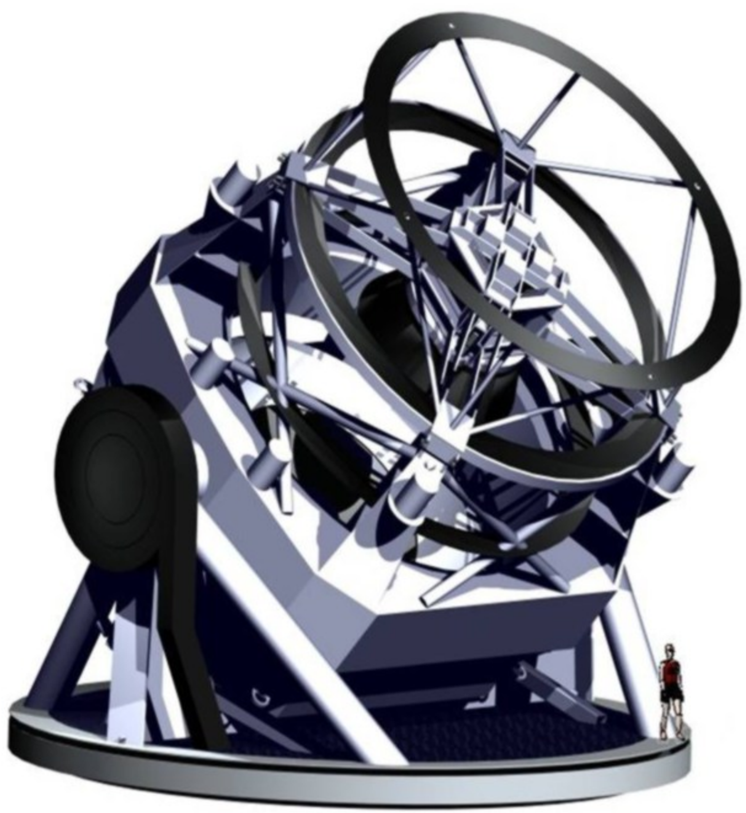
$$\Omega_m = 0.25^{+0.05+0.02}_{-0.04-0.01}$$

$$\sigma_8 = 0.79^{+0.11+0.06}_{-0.10-0.04}$$

$$w = -0.89^{+0.14+0.02}_{-0.16-0.05}$$

LSST





High etendue survey telescope:
- 6.5m effective aperture
- 10 sq degree field, 3Gpc camera
- **20000 sq deg survey (½ sky)**
- 6 filters, UgrizY
- Cadence ~ 10 days, interleaved
- 24 mag in 30 seconds
- 3 month seasons, 10 year survey
- Site: Cerro Pachon, Chile:
  0.7" median seeing
- Pipeline processing (static and difference imaging) to catalogue level: observing = data mining
- 15Tb per night, Database ~ 10 Pb
- **~ 2 billion galaxies**
- **First light: 2014, Survey 2016-26**

Weak Lensing with LSST

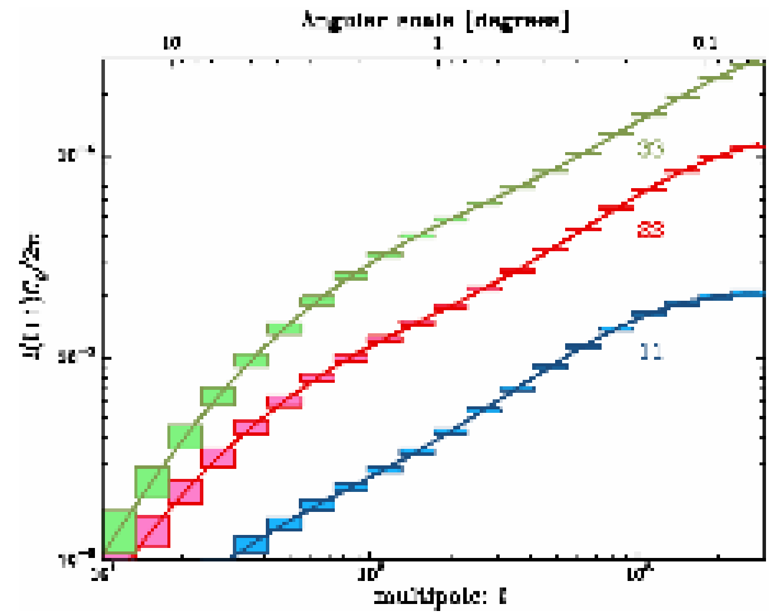
200 images per field per filter in 10 years
20,000 sq deg
2 billion galaxies
19 < m < 27 (r band)
Photo-zs to z = 3

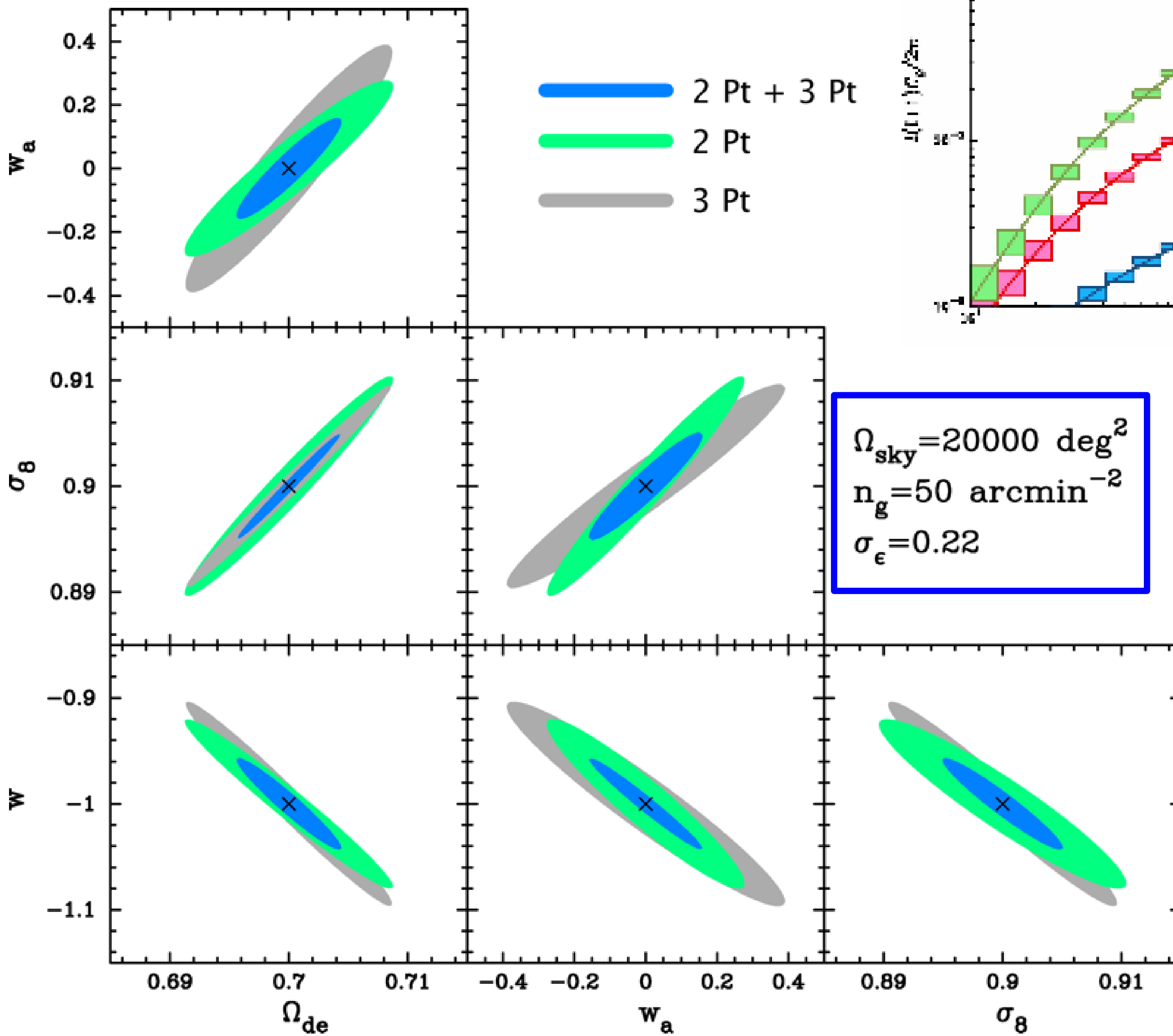
Statistical Errors:

- About 1000 times as many galaxies as CTIO, so S/N increase by a factor of 30.
- Greater depth in z will increase signal by ≈ 1.5.
- Photometric redshifts allow for **tomography** studies
  - Measure lensing as a function of lens redshift
  - Cross-correlation gives differential measurement of structure growth
  - Increase S/N on cosmological parameters by ≈ 2-3.

- Net: **statistical errors should drop by factor of over 100**.
- Expected uncertainty on w_{pivot} ≈ 1%, w to 4% or so
- Tomography will provide interesting constraints on DE evolution, w_a potentially to < 20%

Prospects for LSST





Ω_{sky}=20000 deg^2
n_g=50 arcmin^{-2}
σ_ϵ=0.22

Best case scenario

Internal combinations to improve constraints, consistency check

Systematic Errors in Weak Lensing

Next generation weak lensing experiments (eg DES) and “Stage IV” experiments (eg JDEM, LSST) should provide very high precision

They will instead be limited systematic errors – how well will we need to know what we know?

A whistle-stop tour:

- “Multiplicative” shear errors: shape estimation
- “Additive” shear errors: PSF anisotropy
- Photometric redshift calibration
- Intrinsic alignments
- Theory errors: non-linear P(k), baryonic mass

Go back and look at how the CTIO analysis was done – and how it can be improved

Shape estimation

Kaiser, Squires & Broadhurst (1995):

- Galaxy and stellar ellipticities from weighted second moments of surface brightness
- Derive polarisability matrices to correct for PSF smearing and shearing, and for the fact that round galaxies are sheared more than elliptical
- Apply noisy matrices to noisy data to get shear estimates

Reconvolution (Bernstein & Jarvis 2002, CTIO)

- Convolve the image with a kernel which removes the anisotropic effect of the PSF - kernel is calculated for each star and kernel is interpolated across the image.
- Correct for the dilution analytically

Deconvolution (Bernstein & Jarvis 2002, Nakajima et al)

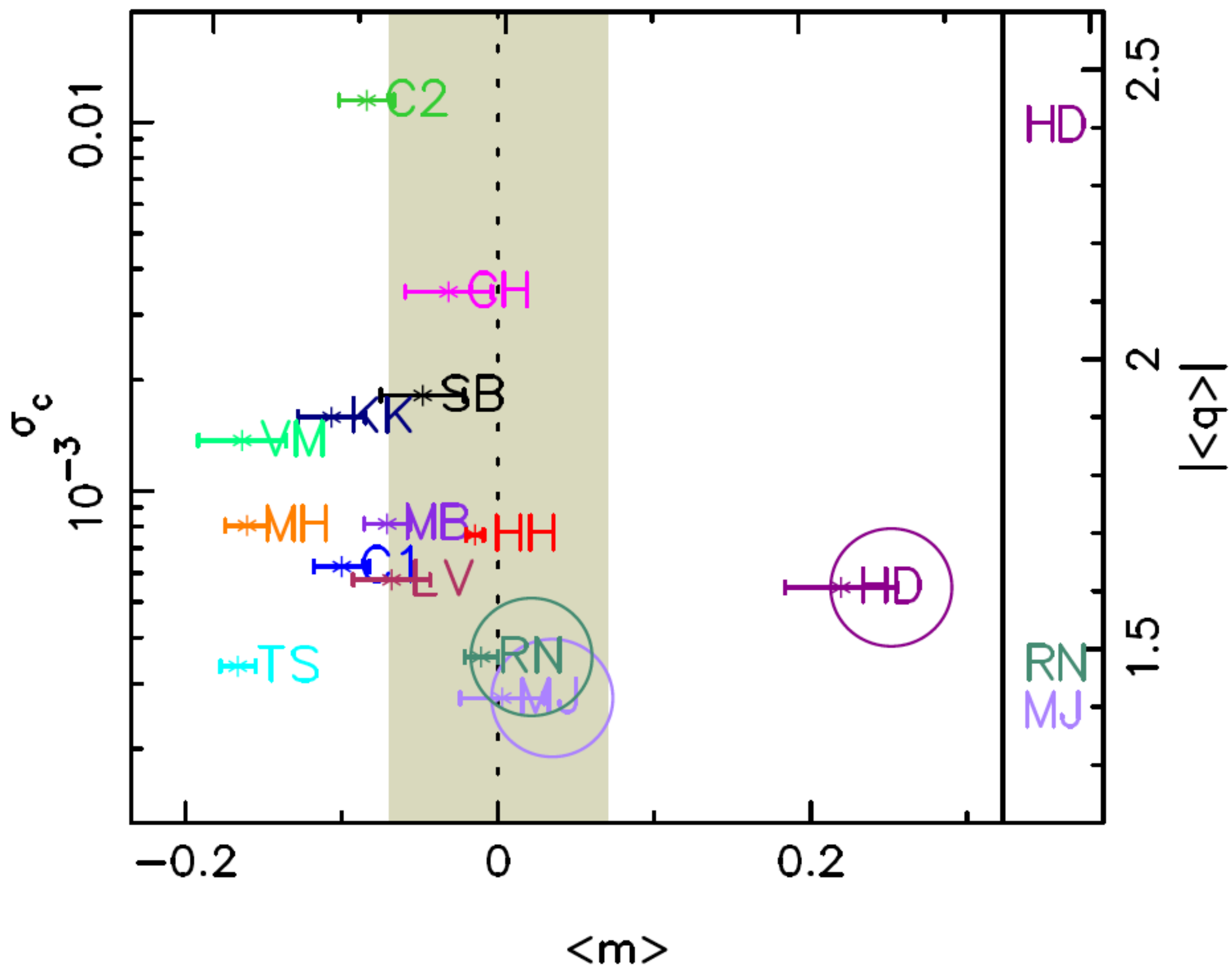
- Fit star images with suitable basis functions to get PSFs
- Fit galaxy images with basis functions convolved with interpolated PSF to get underlyinggalaxy shape

Shape estimation

Various methods compared in community-wide blind test on simulated images “STeP”, Heymans et al

Re/Deconvolution schemes ("MJ", “RN”) work very well

Shear calibration m (ratio of output to input shear) is currently feasible at the ~1% level (m ~ 0.01)

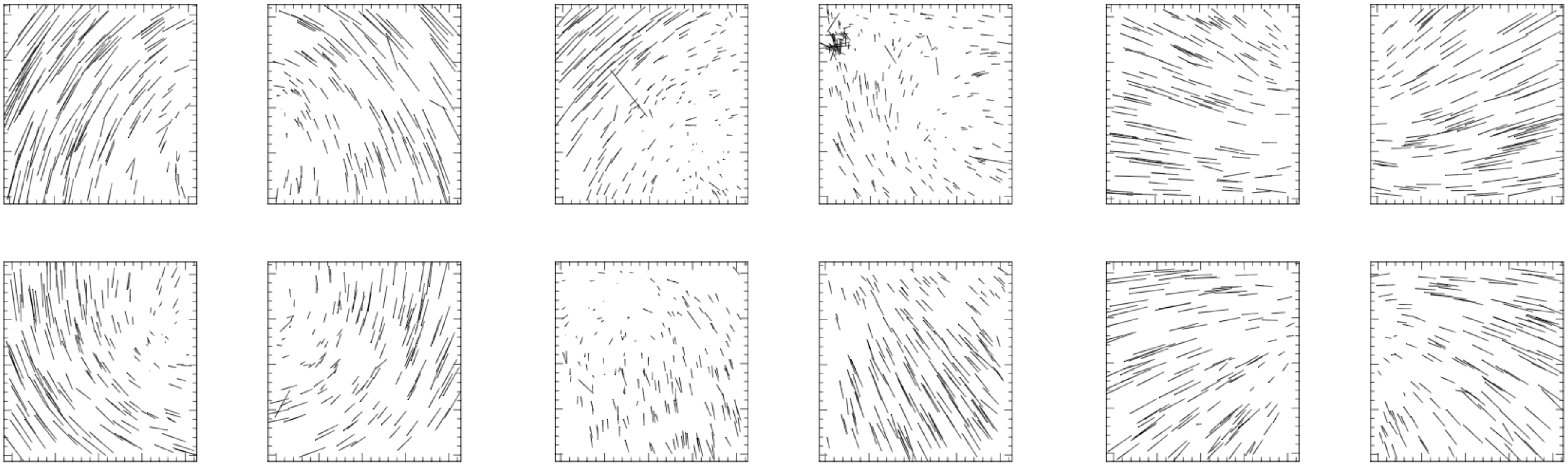


LSST requires x10 improvement to avoid degradation in DE parameters

Basis functions? Need for speed...

PSF Correction

Measure PSF at few stars / sq arcmin, need to interpolate to galaxy positions – “residual PSF anistropy”



Focus too low Focus (roughly) correct Focus too high

- Atmosphere provides random pattern, telescope distortions are repeatable: multiple exposures to beat former
- Interpolation scheme: PCA captures aberrations efficiently
- Can use multiple exposures of different fields to build model

Jarvis & Jain 2005

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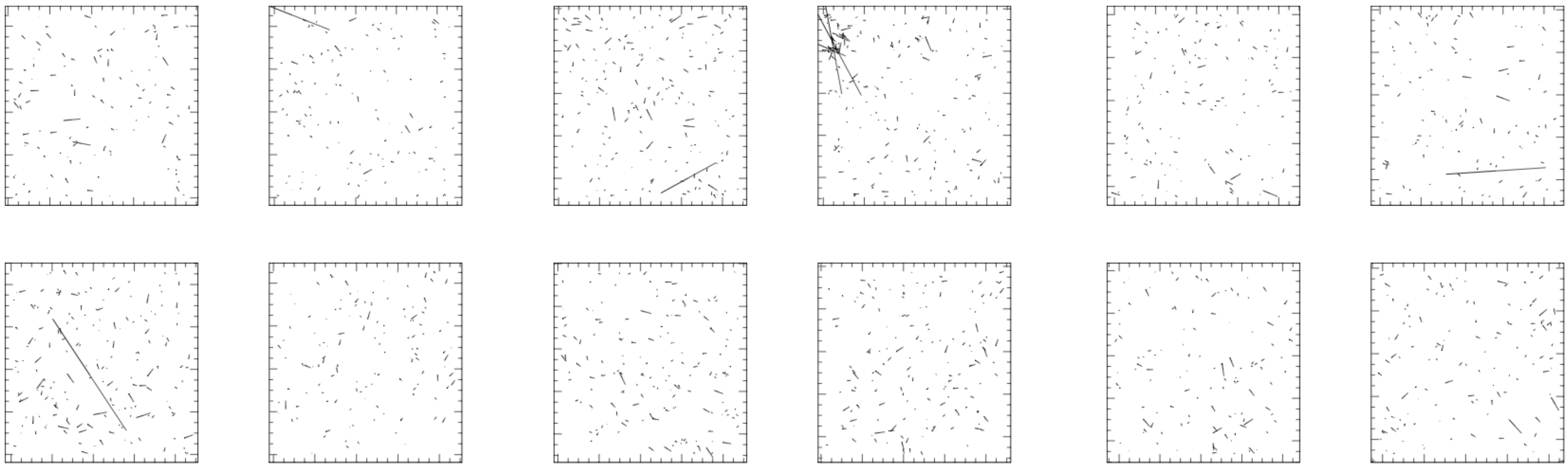


Focus too low   Focus (roughly) correct   Focus too high

- Atmosphere provides random pattern, telescope distortions are repeatable: multiple exposures to beat former
- Interpolation scheme: PCA captures aberrations efficiently
- Can use multiple exposures of different fields to build model

telescope design!

200 with LSST

Jarvis & Jain 2005

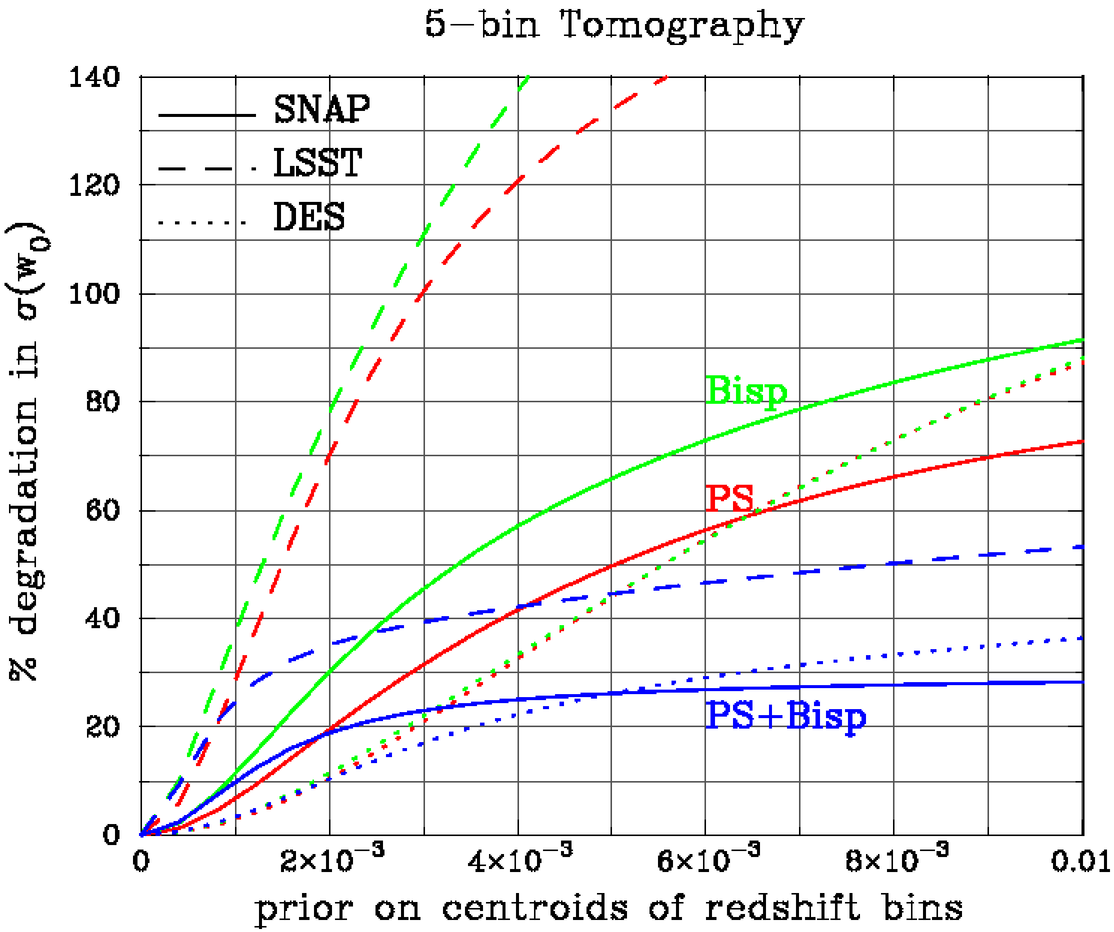
Photo-z calibration

Photo-zs needed for accurate tomagraphy (splitting lenses and sources into bins) – distribution within bin needs to be known to +/- 0.003 (Huterer et al)

Implies need for calibration survey (spectroscopy) with > 100,000 faint galaxy redshifts per bin

Some self-calibration will be possible (infer bin centres with DE parameters) at the loss of some precision

Note importance of multiple PS techniques



Can we reduce the spectroscopic sample by a factor of 10 using angular correlations?

Intrinsic alignments

Suppose we have some other mechanism for making galaxies appear sheared:

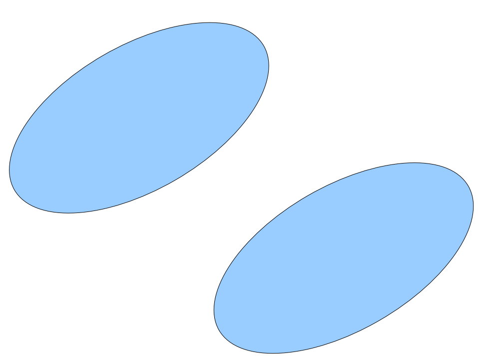
$$\epsilon = \gamma_0 + \gamma_I + \gamma_G$$

Before, we had that ellipticities told us about gravitational lensing by large scale structure:

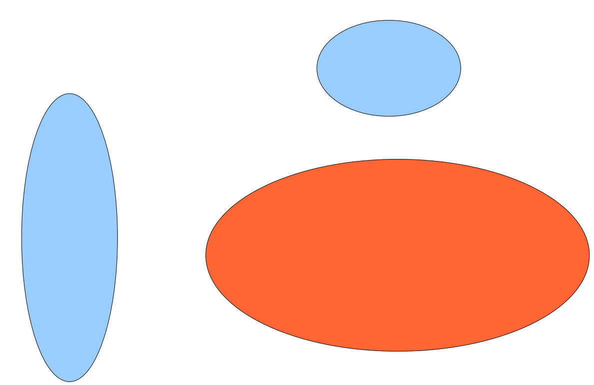
$$\langle \epsilon\epsilon \rangle = \langle \gamma_G \gamma_G \rangle$$

New terms in the correlation function:

$$\langle \gamma_I \gamma_I \rangle$$



$$\langle \gamma_G \gamma_I \rangle$$

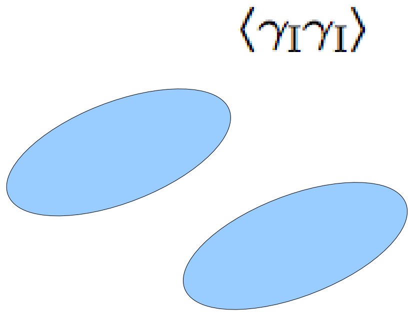


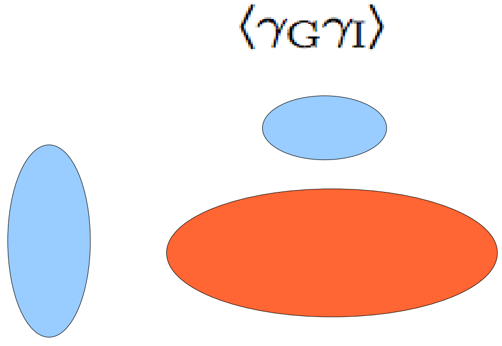
Intrinsic alignments

Intrinisic-intrinsic effect has been measured (Brown et al 2002) Only important for physically-associated sources at small angular separations – downweight using photo-z information (few % if not removed, King, Heymans)

GI term is more insidious – gets worse with lens-source separation (few % in P(k) normalisation). Possible to trade precision for geometrical correction; need to learn how to use more information from images (typing) (Joachimi & Schneider, King)

Both put additional demands on the photo-z accuracy: x 3





Theory systematics

Power spectrum needs to be computed very accurately at small scales, where growth is non-linear

Program: “halo models” for groups and clusters calibrated to improved simulations, including dark energy - ongoing!

Cosmological simulations with realistic baryon effects are demanding: main problem is on small cluster scales.
Re-simulations and observations can constrain halo models well

Internal structure of group and cluster halos is interesting! Fitting for eg the concentration-mass relation simultaneously with DE parameters tells us about dark matter as well as dark energy

Degradation in w would be ~20% (Zentner)

Weak Lensing with LSST

Work is cut out preparing for LSST WL survey:

Biggest task is the spectroscopic calibration survey – look to combine with other science projects for this

Angular correlation function idea needs testing – promising

Information from previous generation will be important:

• Number of wide field cameras being used for lensing, informing design of LSST optics to minimise shear estimation errors
• DES will constrain GI and II power spectra, reveal new problems

Pessimistic and optimistic DETF models: FoM 30-450(!)

Weak Lensing from Space

Reference mission for JDEM includes weak lensing survey too

also Euclid in Europe – very similar approach

10,000 sq deg survey, NIR imaging with ~ HST/2 resolution (1.5m telescope, 0.2" pixels?)

Higher density of measurable sources possible from space – but trade depth for survey speed, and need to worry harder about non-linear structures?

Measure shapes in stable imaging, combine with ground-based optical photometry for photo-zs

Use BAO/SN spectroscopic elements to carry out a matched redshift survey to calibrate the photo-zs

Pessimistic and optimistic DETF models: FoM 100-300

No plots available for reference mission   but different experiments are good

DES parameter forecasts

Assumptions:

Clusters: SPT selected

σ_8=0.75, z_{max}=1.5,

WL masses

BAO: l_{max}=300

WL: l_{max}=1000

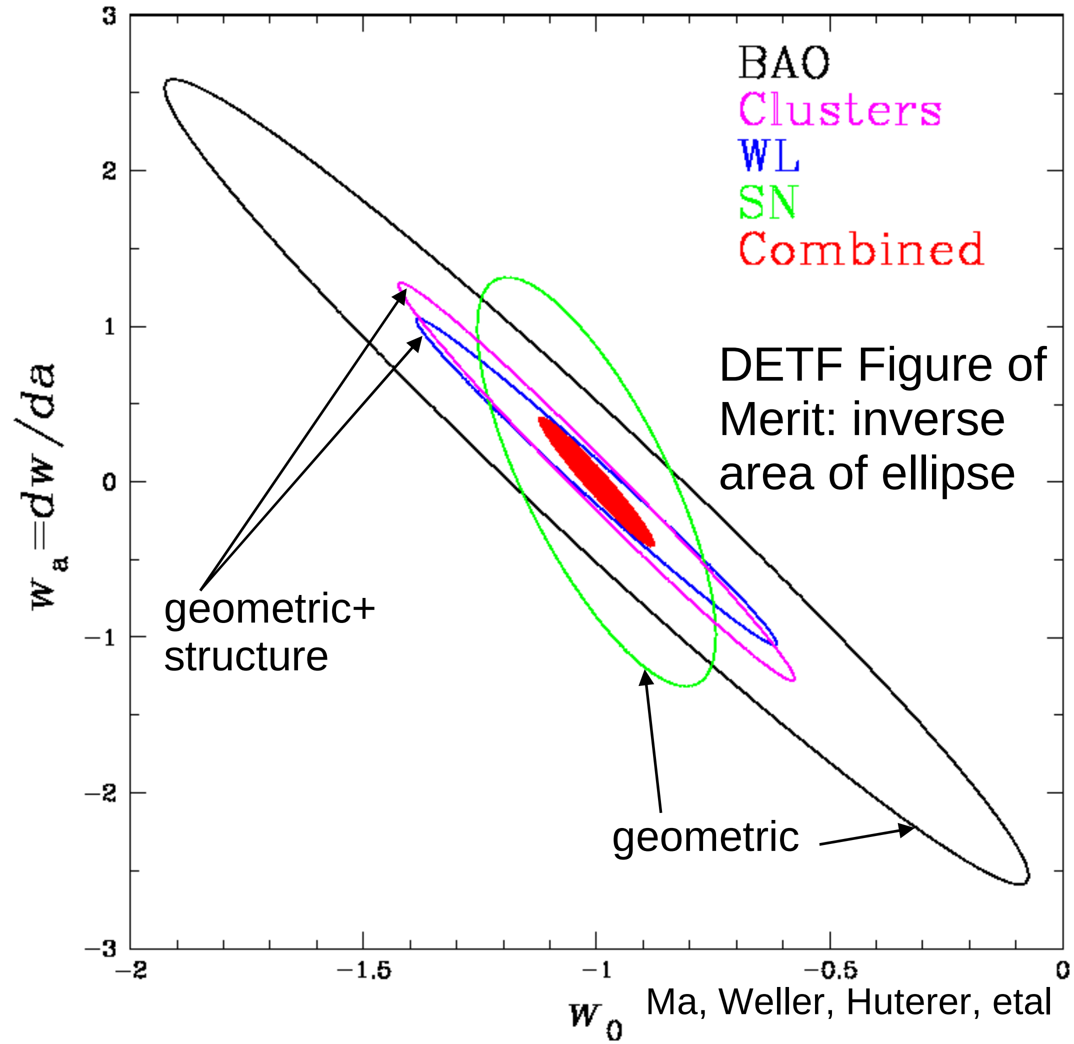
only 2-point function

Statistical + photo-z systematic errors only

Spatial curvature, galaxy bias marginalized over

Planck CMB prior

$w(z) = w_0 + w_a(1-a)$ 68% CL



Ma, Weller, Huterer, etal

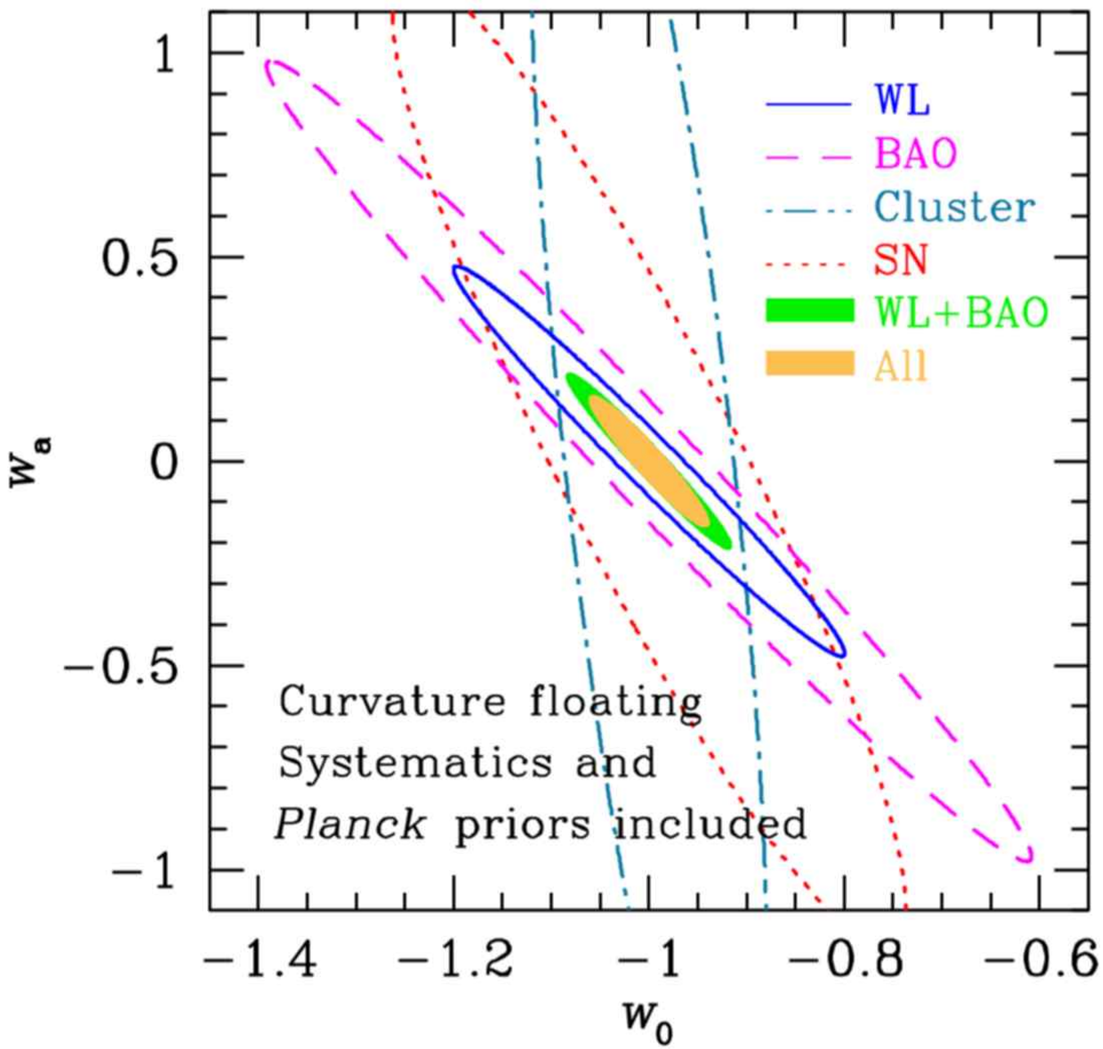
w to 20%, wa to 40%

LSST

Multi-filter imaging survey enables
same 4 Dark Energy measurements:
DES++

• photo-z BAO
• tomographic weak lensing
• SNe lightcurves
• cluster detection and redshifts

Figure from LSST Science Book, due out this Fall

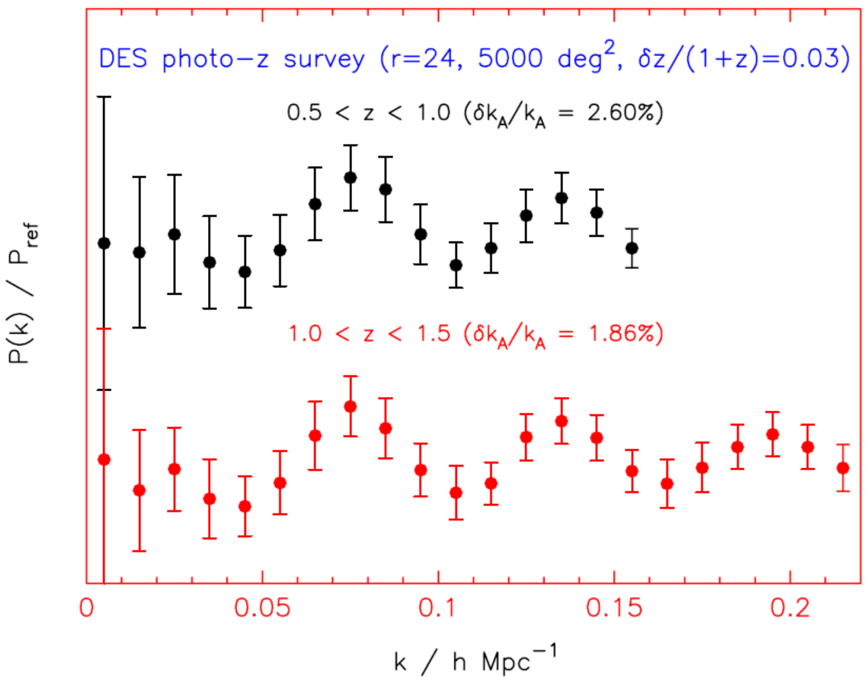


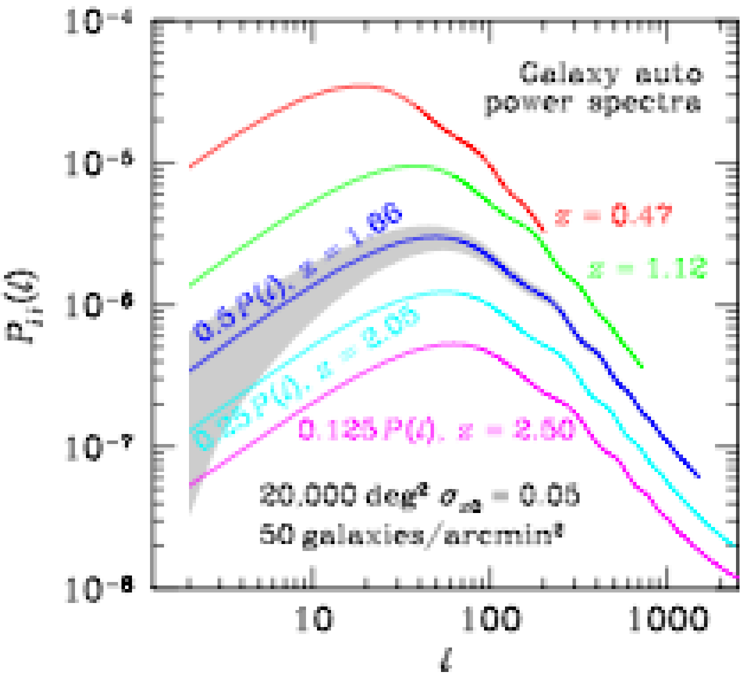
w to ~5-10%, wa to ~ 20%

LSST and DES BAO?

Michael's question...

Both DES and LSST plan BAO surveys, following Padmanabhan et al in SDSS

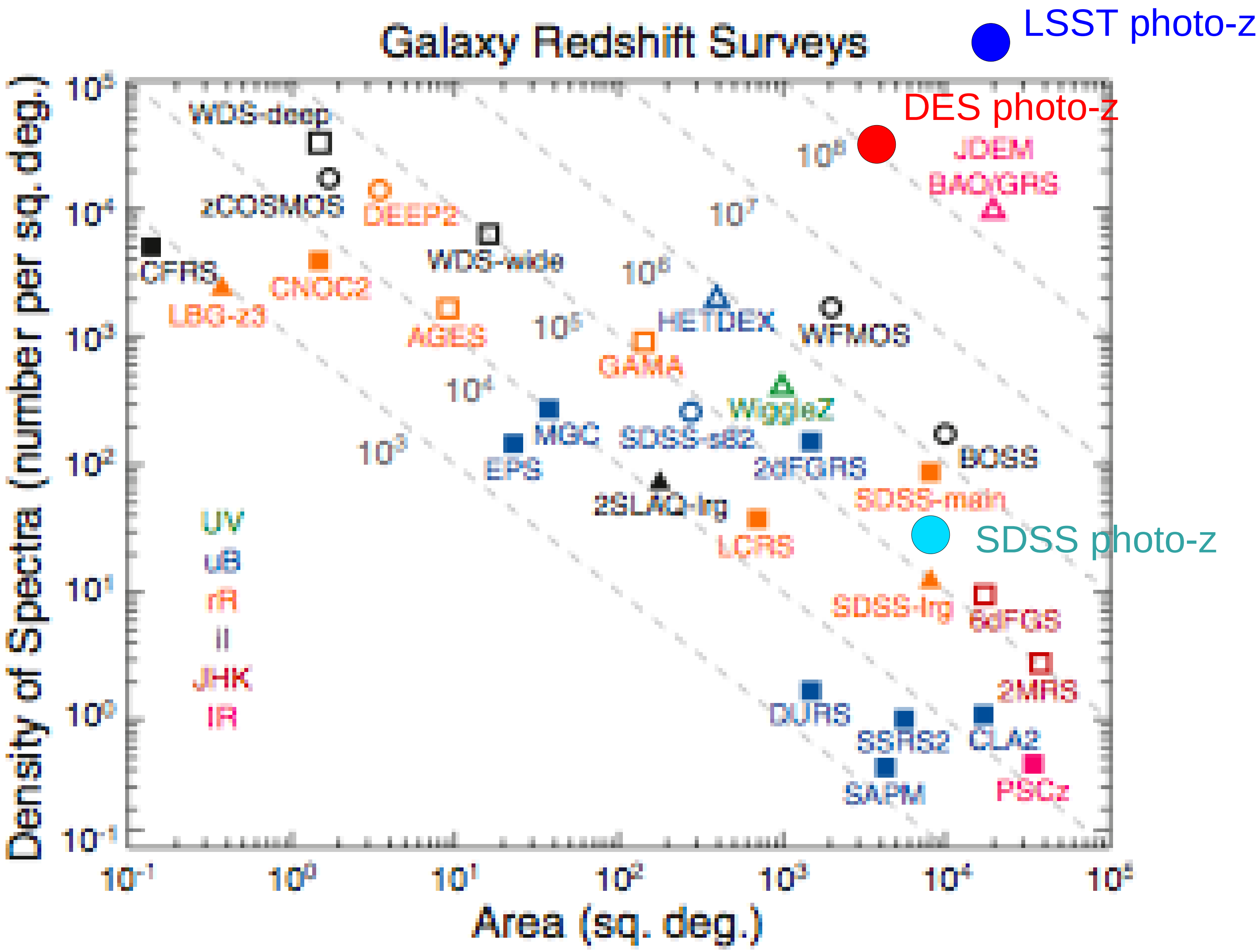




DES: 5000 sq deg, 200million galaxies?

LSST: 20,000 sq deg, 4billion galaxies?

LSST and DES BAO?



4) Final thoughts

Concordance

The natural goal of any joint analysis - but there's an issue:

What if the maximum posterior PDF point becomes known as "the right answer"?

Scientists take pride in their objectivity -

Do we need to take **_groupthink_** about the values of cosmological parameters seriously?

Otherwise known as "experimenter bias"

Testing Groupthink with Cosmologists?

Groupthink (Janis 1971)

"A mode of thinking that people engage in when they are deeply involved in a cohesive in-group, when the members' strivings for unanimity override their motivation to realistically appraise alternative courses of action."

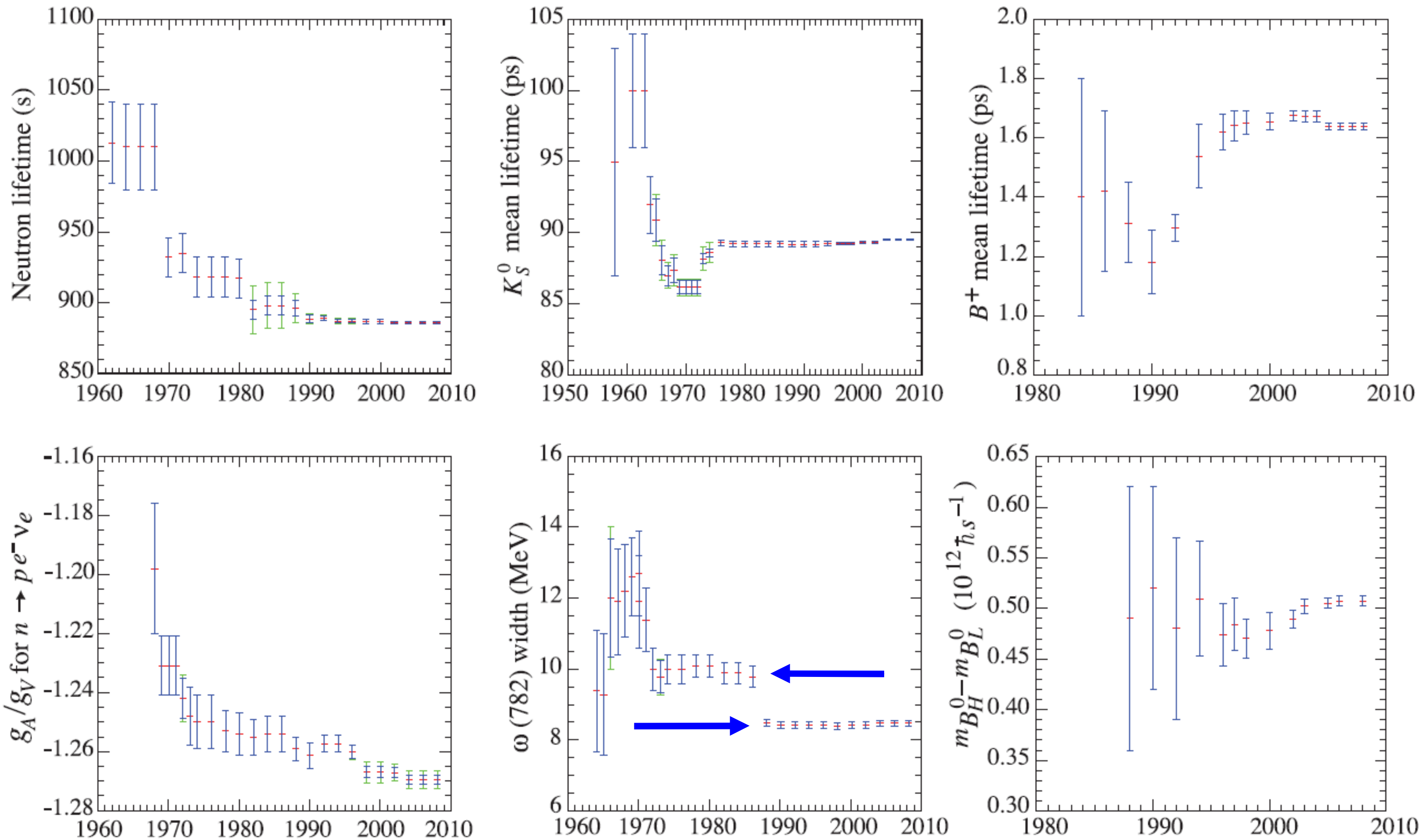
How to test this social psychology theory?
Esser (1998) suggests that

"*The ideal decision task for groupthink research should possess several characteristics. It should be* ***important, difficult, and involving for the subjects.*** *Subjects should possess the knowledge and technical skills required for the decision. Specific task-related information should be provided to the subjects or available to them. The task should* ***allow for multiple alternative solutions to be generated, and no single solution, if presented, should be readily perceived as 'correct.'*** *The task should* ***require discussion and information exchange*** *to reach a good decision. Finally, a (preferably objective) method for assessing decision quality should be available."*

Watching cosmologists would be a pretty good psychosocial groupthink experiment

Parameter Convergence

Particle physicists have been worrying about groupthink for years:

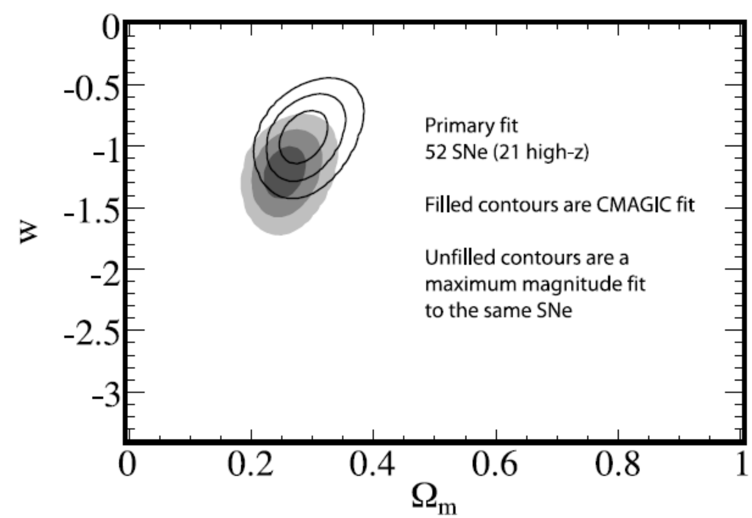


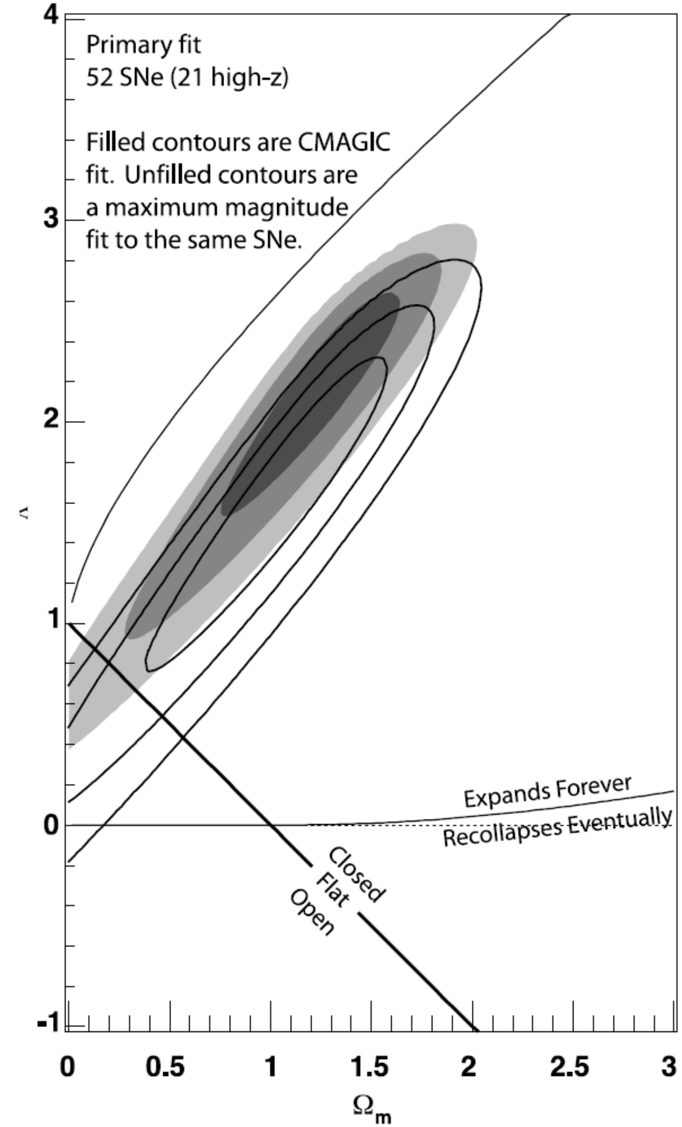
Review of Particle Physics (2008) measured quantities (with errors) vs publication date

Blind Analysis in Cosmology

Learning from particle physicists: ***blind analysis***

Conley et al (2006) explored their systematic errors by varying cuts, methods etc and repeating the cosmological fit - *including a random and unknown offset to the cosmological parameters*





"One of the lessons of blind analyses is that 1.5-sigma disagreements occur in science more frequently than our intuition, developed from exposure to nonblind experiments, often expects."

Accurate Cosmology

Blind analysis is one important approach that needs extending to more generalised cosmological analyses

- Dataset combination is required for measurements in cosmological dynamics - and especially for testing Modified GR against Dark Energy

- It's also a very good way of revealing unforeseen systematic errors!

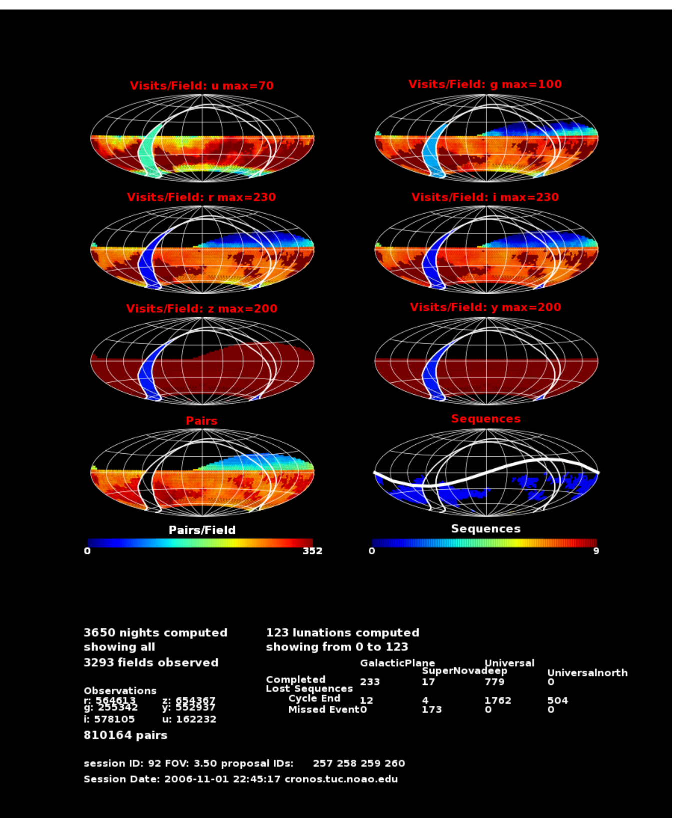
How to disentangle the two will take some subtle experimental design -

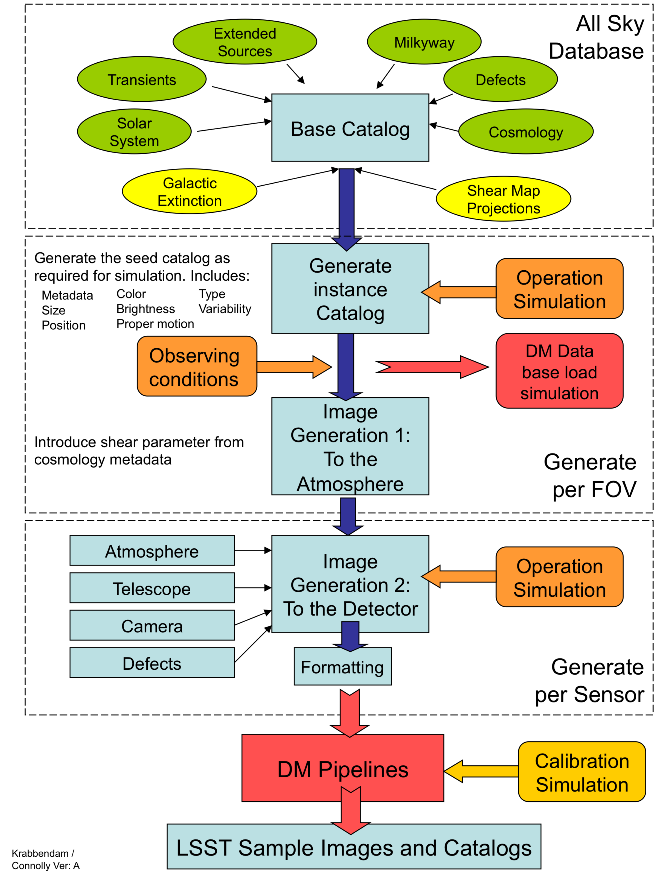
including **detailed end-to-end simulations of datasets...**

LSST simulator

OpSim:

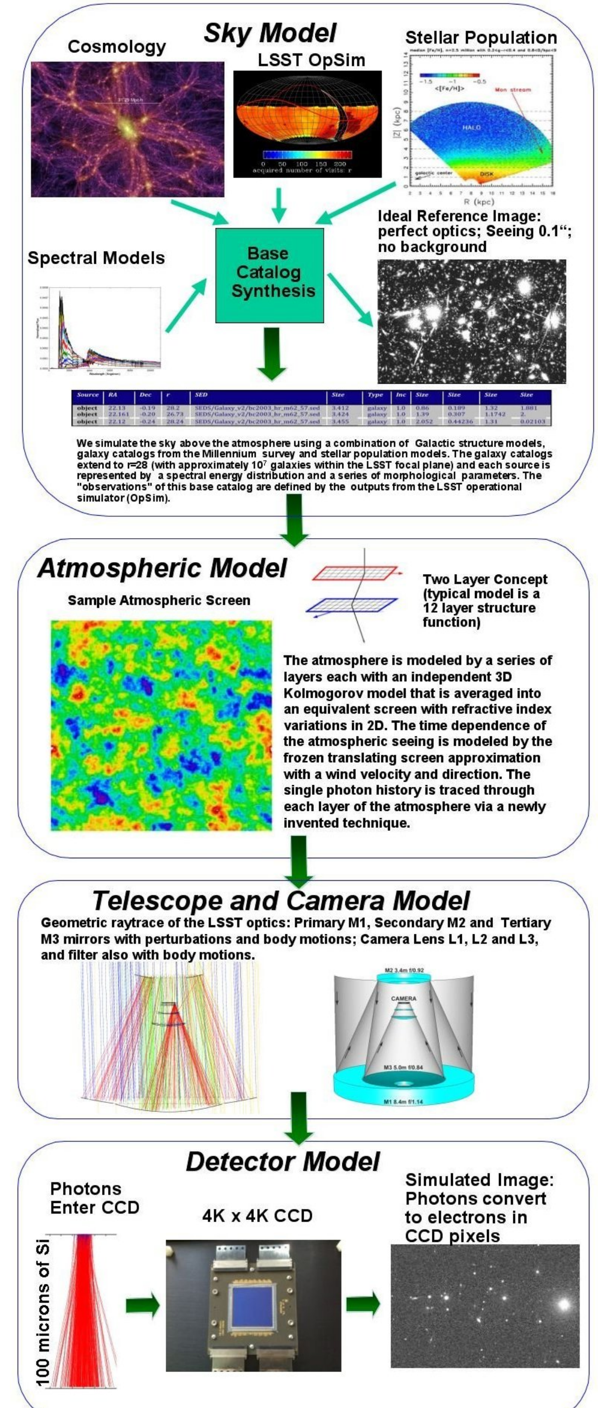
Simulate **observing conditions** (seeing, sky brightness, moon phase, downtime etc) over **mock scheduled 10 year survey** (including dynamic field selection)





ImSim:

Given **observing conditions,** simulate **mock images** for analysis, by **tracing photons from model astrophysical sources through to the detectors**



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How to disentangle the two may take some subtle experimental design - including detailed end-to-end simulations of datasets, **analogous to HEP Monte Carlos?**

Cosmology is a good field for particle physicists!