Shear Peak Statistics

What is it, and how can we measure it?

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With Jan Kratochvil, Morgan May and others...

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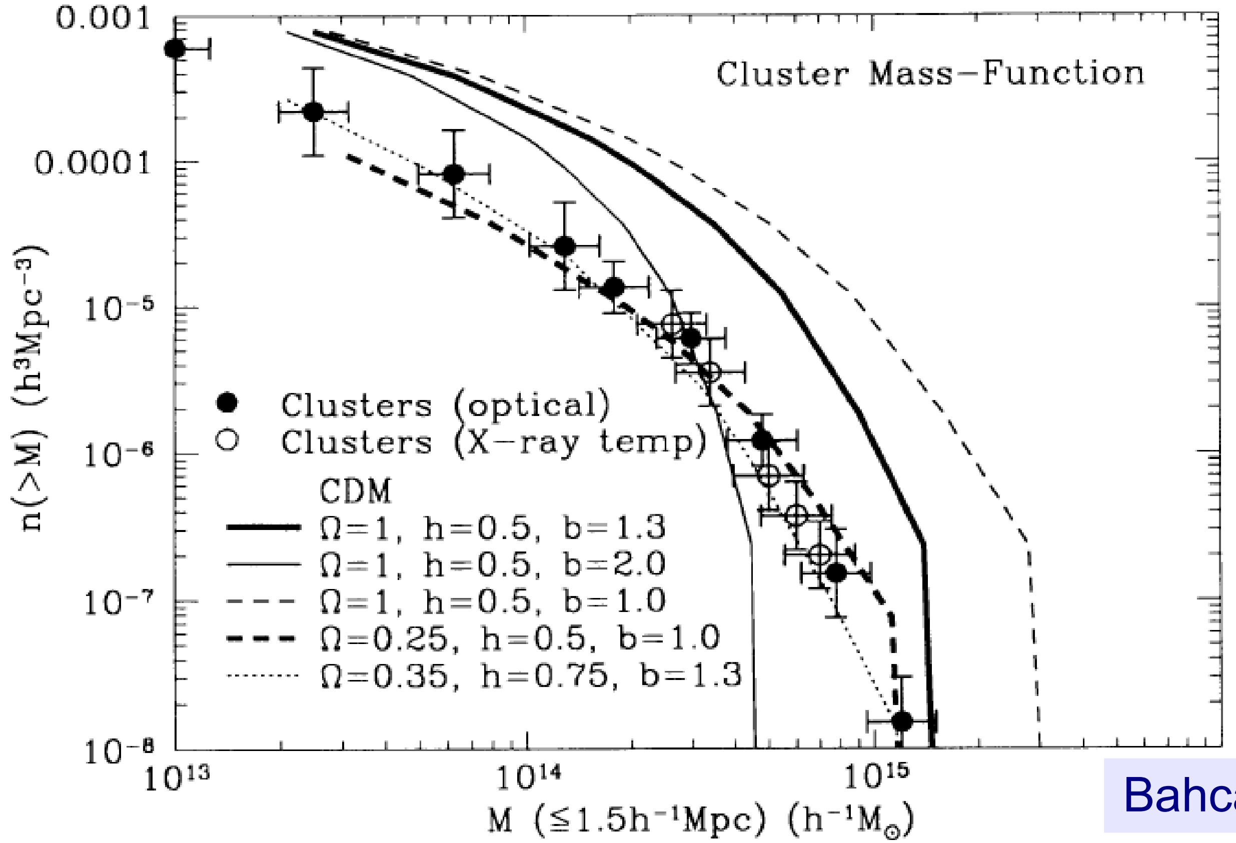
Cosmology with cluster counts

- We've seen many examples this week of how information from galaxy clusters can be used to constrain cosmological models.



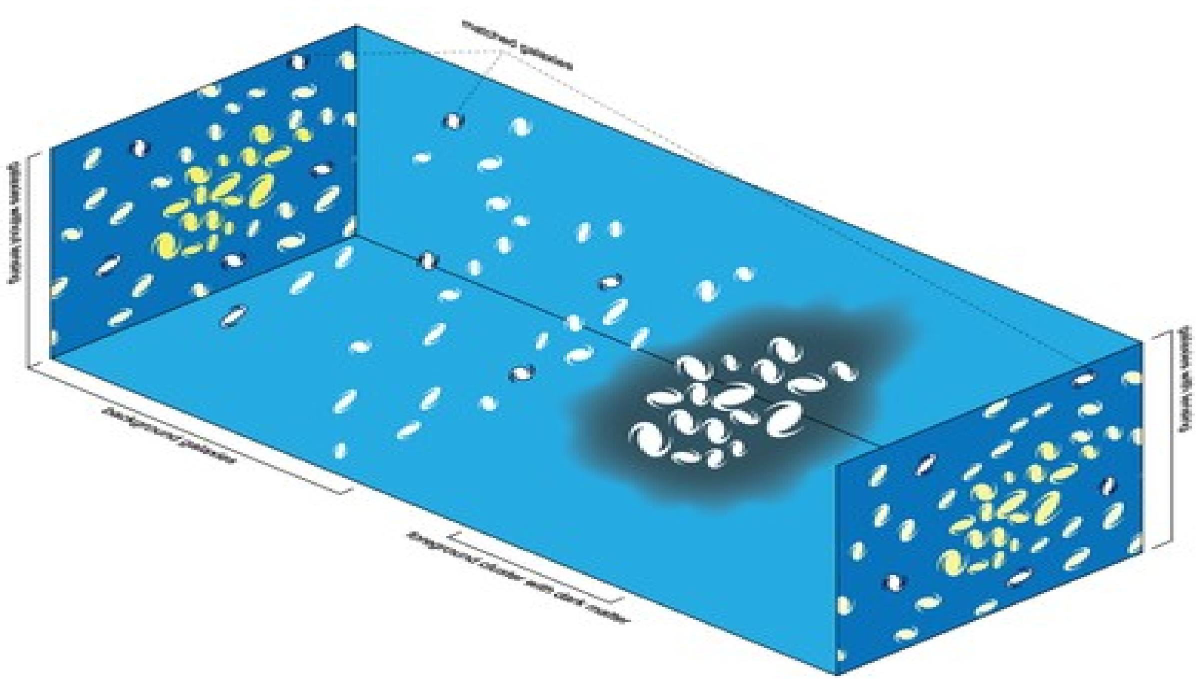
Bahcall & Cen 1992

Cosmology with cluster counts

- We've seen many examples this week of how information from galaxy clusters can be used to constrain cosmological models.
- Sensitive to cosmological parameters:
  - Total matter density of the universe (Ω_m),
  - Normalisation of the power spectrum (σ_8),
  - Evolution of equation of state of dark energy (*w*).
- Clusters can be detected and measured by x-ray observations, SZ effect and **weak lensing**.
- Work is on-going to fit these different measurements into a coherent picture.

Clusters and weak lensing

- Tidal gravitational field of matter along the line-of-sight causes shear field to be tangentially aligned around projected matter-density peaks.
- Shapes of background galaxies are sheared tangentially around foreground cluster mass.



Clusters and Weak Lensing

- Can use this effect to identify clusters (as well as weigh them!)
  - Detection method independent of luminous properties of galaxies, therefore independent detection of clusters compared to x-ray, SZ selection (Schirmer+ 2007, Dietrich+ 2007).
  - Could find “dark” clusters that are otherwise undetectable...
- **But!** Cluster sample selected in this way has both a low purity and a low completeness.
  - Some “clusters” are projections of random over-densities .
  - Some real clusters align with projected under-densities.

Shear Peaks

- These spurious peaks do contain cosmological information about the structure of matter density in the universe

  → **count peaks, instead of clusters, to constrain models of cosmology!**

  - (eg Marian+ 2009, Kratochvil+ 2009, Dietrich+Hartlap 2009).
- Can avoid the ambiguities inherent in cluster mass estimation and simulation.
- Early work concentrated on high-significance peaks, but recent work has shown that low- and medium-significance peaks contain the majority of the cosmological constraining power (Kratochvil+ 2009, Yang+ 2011).

How do we measure shear peaks?

- It's hard to make analytic predictions for peak counts (see Maturi+ 2009 for approach based on gaussian random fields) so we usually use cosmological simulations:

  1) N-body simulation.
  2) Ray-trace to get shear fields at different redshifts.
  3) Trace shear field with model galaxies.
  4) Calculate expected shear peak statistics for different cosmologies.
  5) Compare to measurements from real data to constrain cosmological parameters.

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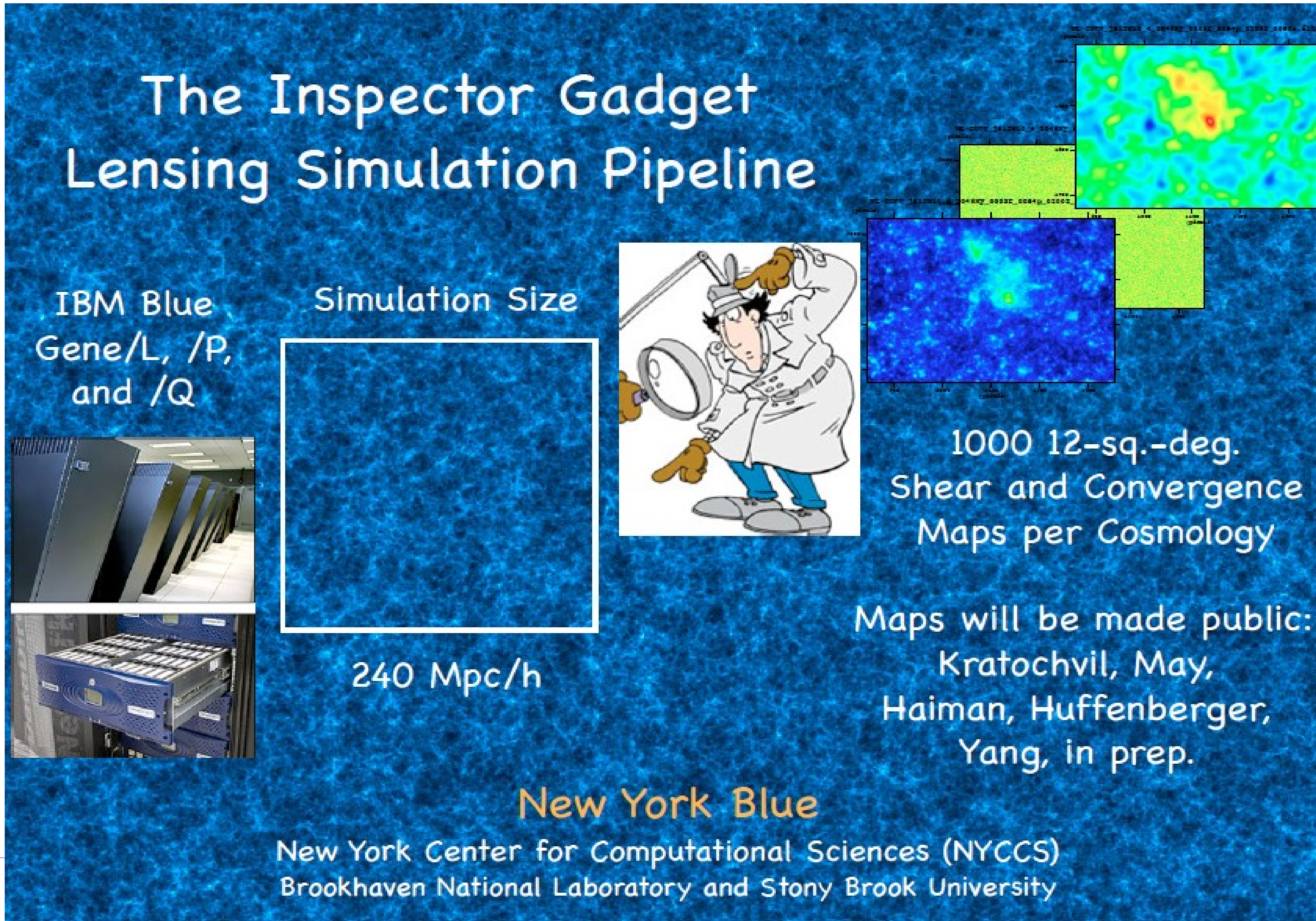
Ray-traced N-body simulations

- Produced by Jan Kratochvil (Kratochvil+ 2011).
- 512^3 particles in box with co-moving size $240h^{-1}$ Mpc → resolution of 7.4×10^9 M_0/h per dark matter particle.
- Ray-tracing uses 2048x2048 rays:
  - Produce maps of shear and convergence at z = [1.0, 1.5, 2.0].
  - Represents 12 square degrees (close to LSST footprint).
- Use 500 realisations of each of the 8 cosmologies.

Identifier	σ_8	w	Ω_m	Ω_Λ
Primary	0.798	-1.0	0.26	0.74
Auxiliary	0.798	-1.0	0.26	0.74
Om23	0.798	-1.0	0.23	0.77
Om29	0.798	-1.0	0.29	0.71
w12	0.798	-1.2	0.26	0.74
w08	0.798	-0.8	0.26	0.74
si75	0.750	-1.0	0.26	0.74
si85	0.850	-1.0	0.26	0.74

Ray-traced N-body simulations



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Tracer galaxies

- It's not enough to use model galaxies with some distribution in ellipticity.
- Should use galaxies with realistic properties, that match observed quantities:
  - redshift, ellipticity, magnitude, size, number density ...
- Need to account for measurement errors!
  - Distortion in galaxy shape from PSF.
  - Depends on galaxy properties!
- Shape measurement method also introduces uncertainties
  - Imperfect PSF correction.

→ **Use the LSST Image Simulator to determine these parameters**

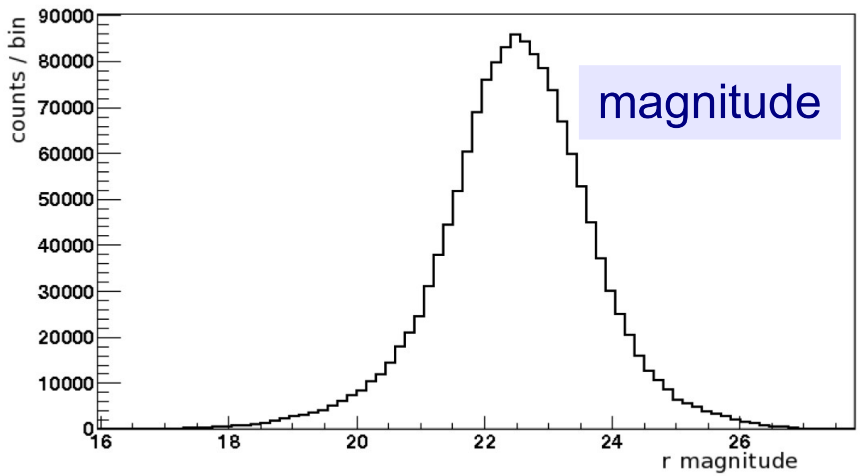
LSST Image Simulator

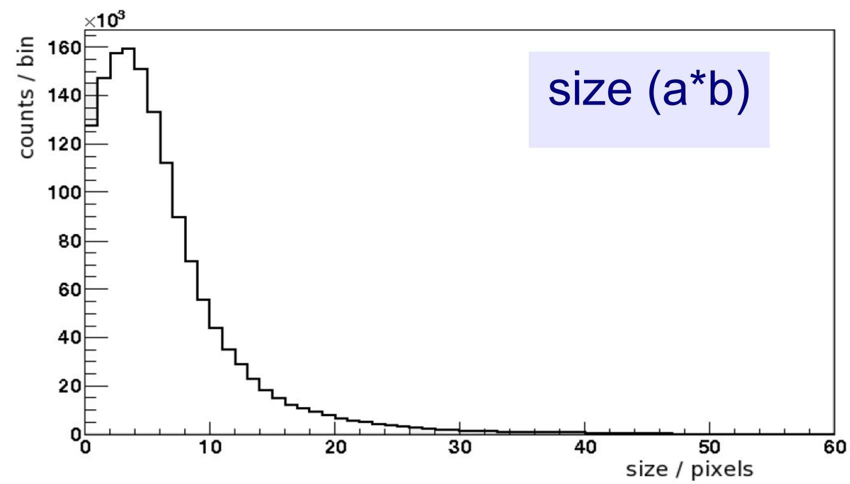
- Custom-made software to simulate LSST system.
- Input catalogues contain stars, galaxies etc with positions and properties based on observational data.
- Photons drawn from sources and ray-traced through atmosphere, telescope optics, camera and readout system.
- Regularly updated to include latest LSST design specifications and improved models of astronomical sky.
- Recent papers using ImSim: Chang+ 2012a and Chang+ 2012b.

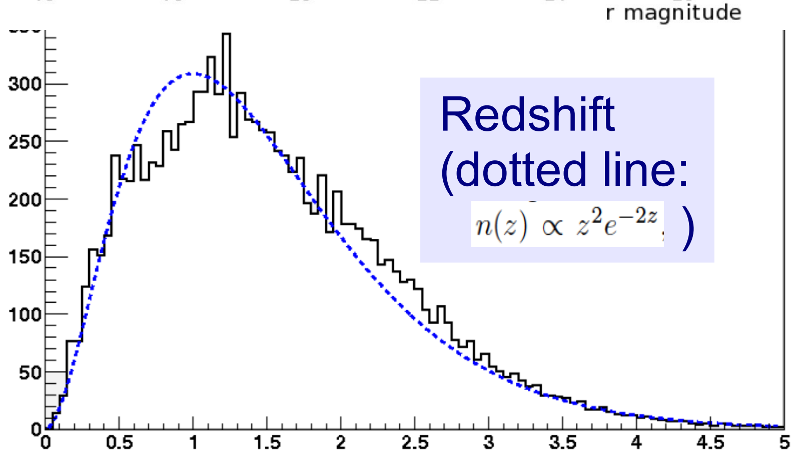
/Users/djbard/Documents/talks/LSST/Davis 26th April 2012/movie_peterson.mpeg

LSST Image Simulator: sources

- Make use of LSST input catalogue of sources to define tracer galaxies characteristics → galaxies drawn from catalogues based on Millenium simulation...







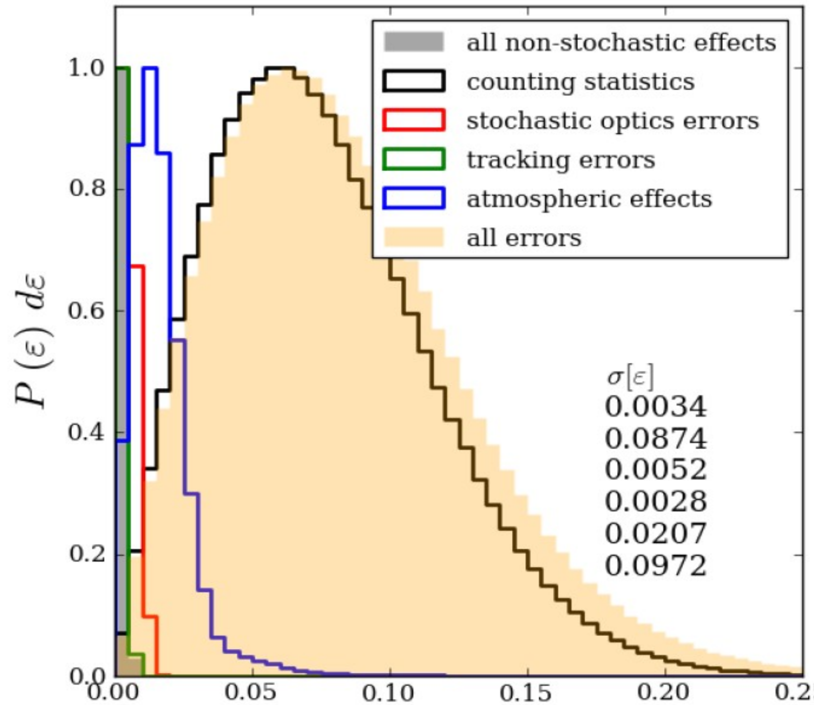
- ...matched to data from Coil+ 2004, and compilation of deep survey data from U. Durham.

http://astro.dur.ac.uk/ nm/pubhtml/counts/counts.html

LSST Image Simulator: PSF

- Contributions to shape distortion from atmosphere and instrumental effects (see Chang+ 2012a for details) based on LSST site measurements and design specifications.

- Non-stochastic effects: optics design, charge diffusion, pixelisation effects, optics perturbations, sensor surface warping...
  - Scales with size of galaxy.
- Stochastic effects: atmosphere, optics, tracking, counting statistics...
  - Scales with galaxy size and SNR.



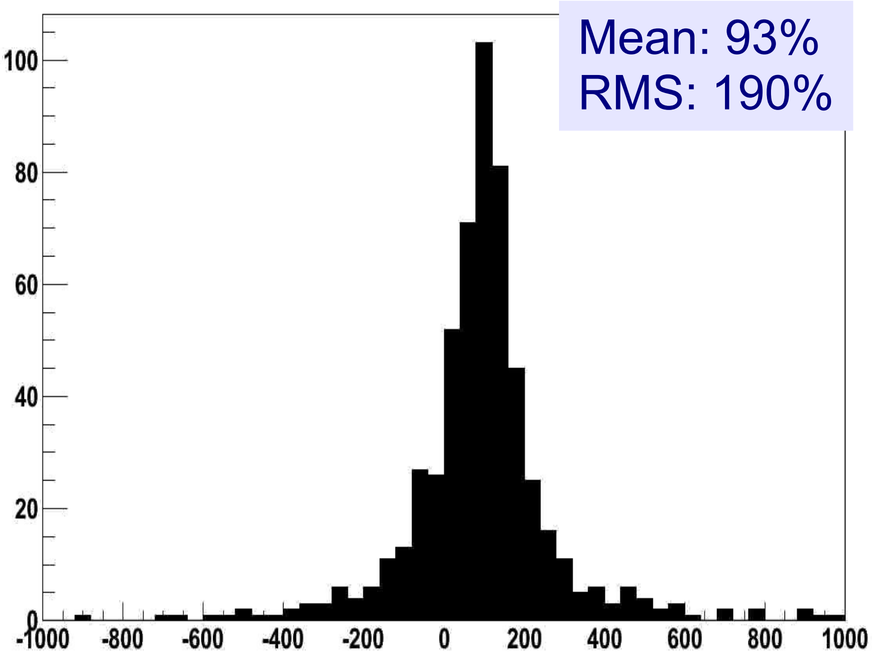
distortion introduced to ellipticity measurement

LSST Image Simulator: measurement error

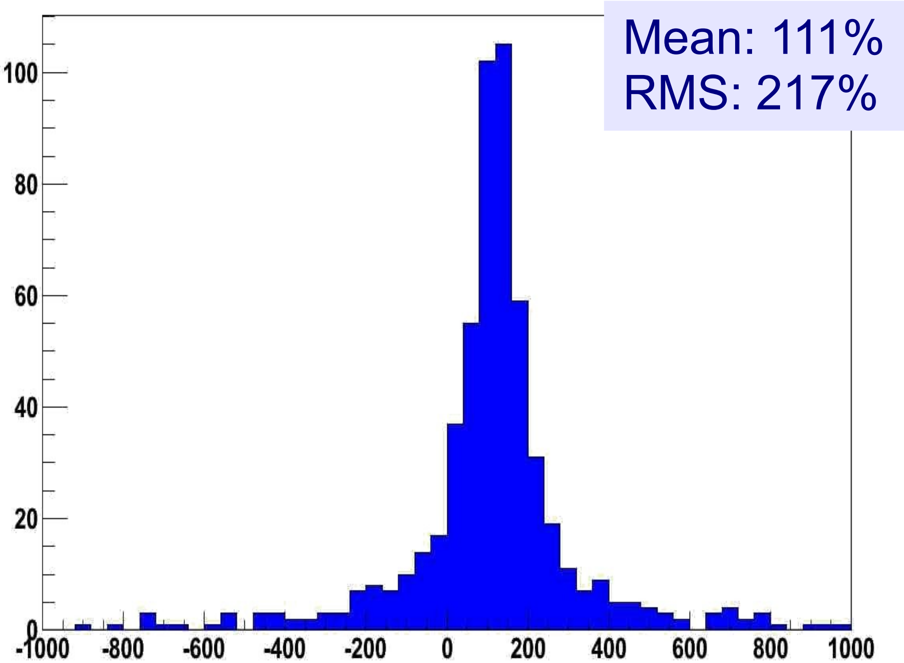
- Need to include uncertainty on shape measurement of galaxy, including imperfect PSF correction.
- Simulate large numbers of LSST images with shear applied:
  - Stars and galaxies in 15 second r-band exposure.
  - Use KSB to measure PSF-subtracted galaxy shapes for each image.
  - Average measured galaxy shapes over 100 exposures of the same field, which have 100 different atmospheric conditions (median seeing 0.6”). This corresponds to roughly 10 year stack of WL-quality data from LSST.
- Compare input shear to measured shear.
- Resulting shear measurement error depends on galaxy SNR (as seen in Leauthaud+ 2007) .

LSST Image Simulator: measurement error

- Average over all galaxies to remove effect of shape noise – what remains is the error due to PSF and measurement effects:



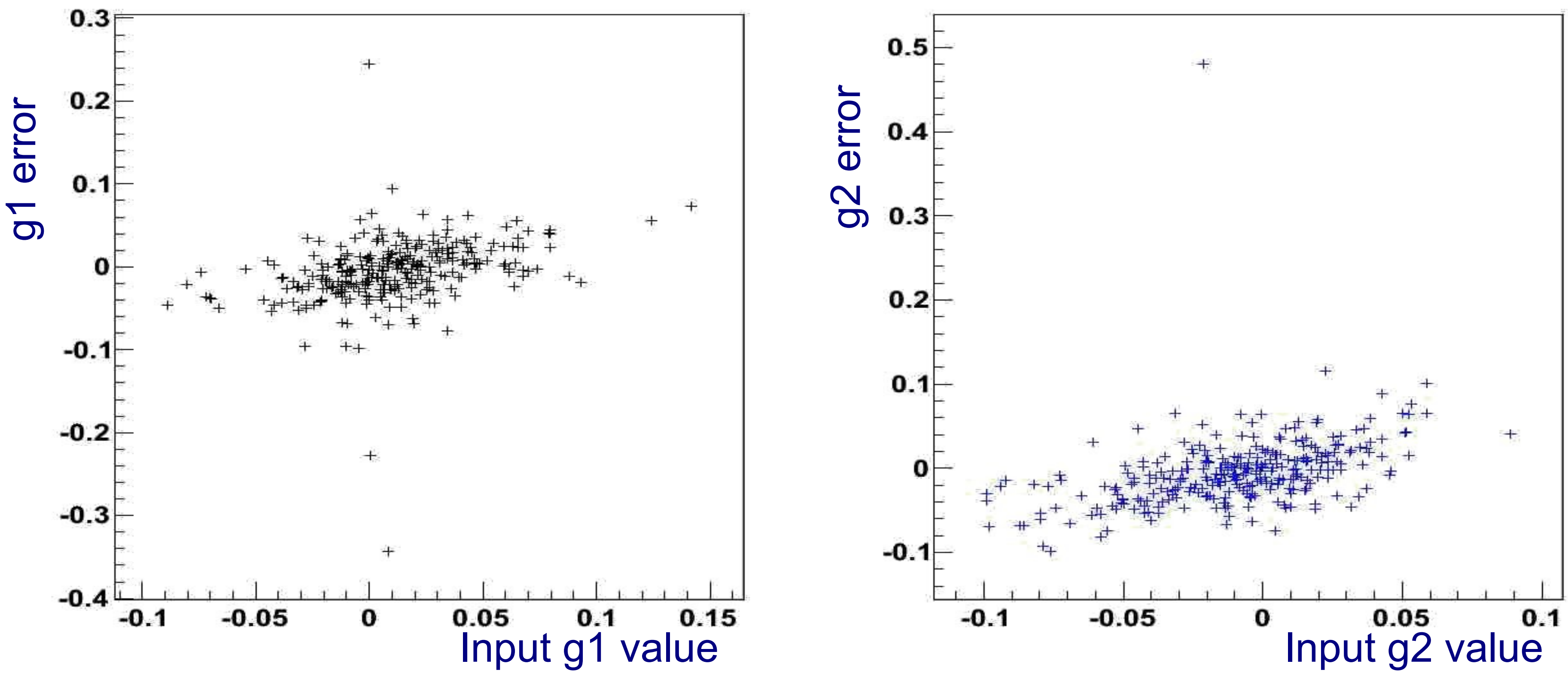
Error on g1 (%)



Error on g2 (%)

LSST Image Simulator: measurement error

- Can look at error on shear measurement as a function of input shear values.



- Clear correlation of measurement error with input shear value.

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Aperture Mass

- Define aperture mass as weighted integral over tangential components of shear: $M_{\rm ap}(\boldsymbol{\theta}_0) = \int_{\mathrm{sup}Q} \mathrm{d}^2\theta\, Q(\vartheta)\gamma_{\rm t}(\boldsymbol{\theta};\boldsymbol{\theta}_0)$
- Q is a weighting function – if it follows the expected shear profile of a mass peak then aperture mass is a matched filter for detecting mass peaks.
- In practice, shear is sampled by galaxies so sum over galaxy shapes. Can calculate noise directly from data, so we count peaks in map of SNR: $\hat{S}(\boldsymbol{\theta}_0) = \frac{\sqrt{2}\sum_i Q(\vartheta_i)\varepsilon_{i\rm t}}{\sqrt{\sum_i Q^2(\vartheta_i)\varepsilon_i^2}}$
- Define "peak" as pixels above a SNR threshold having 8-connectivity.

Aperture Mass

- Define aperture mass as weighted integral over tangential components of shear: $M_{\rm ap}(\boldsymbol{\theta}_0) = \int \mathrm{d}^2\theta\, Q(\vartheta)\gamma_{\rm t}(\boldsymbol{\theta};\boldsymbol{\theta}_0)$

We have 500 realisations of each of 8 different cosmological simulations in 3 different redshift bins, and each map is traced by ~1.5 million galaxies! Calculation is relatively light, but must be repeated billions of times
→ GPU computing!
(Bard + Bellis, in prep)

- …s the expected shear … mass is a matched
- …axies so sum over … directly from data, so we count peaks in map of SNR:

$$\hat{S}(\boldsymbol{\theta}_0) = \frac{\sqrt{2}\sum_i Q(\vartheta_i)\varepsilon_{i\rm t}}{\sqrt{\sum_i Q^2(\vartheta_i)\varepsilon_i^2}}$$

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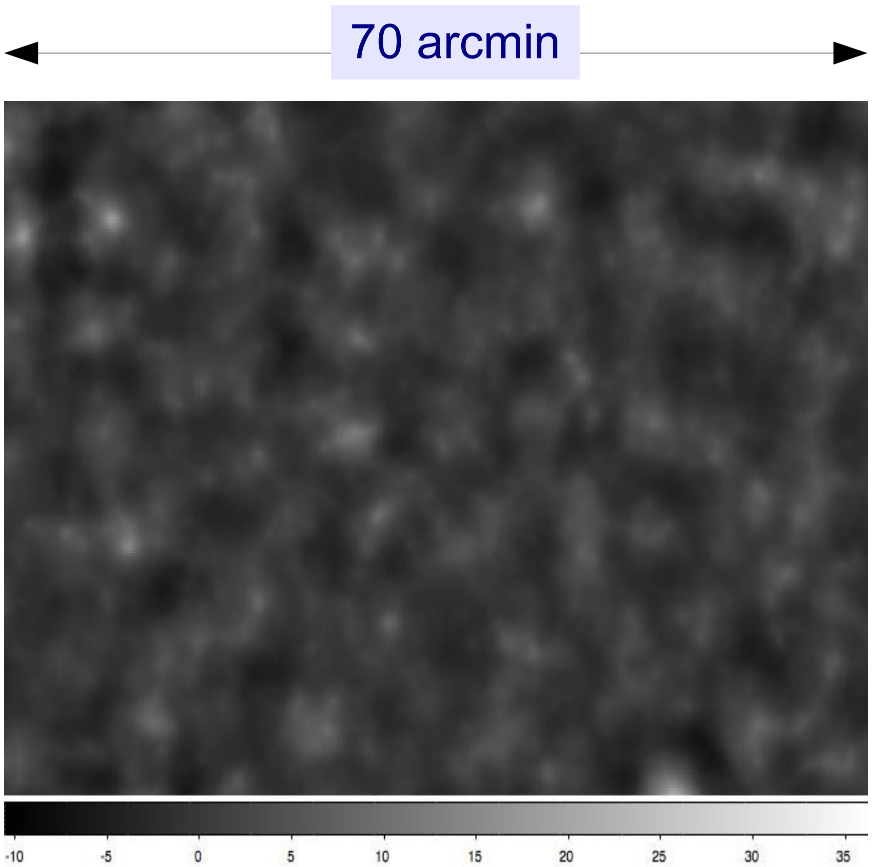
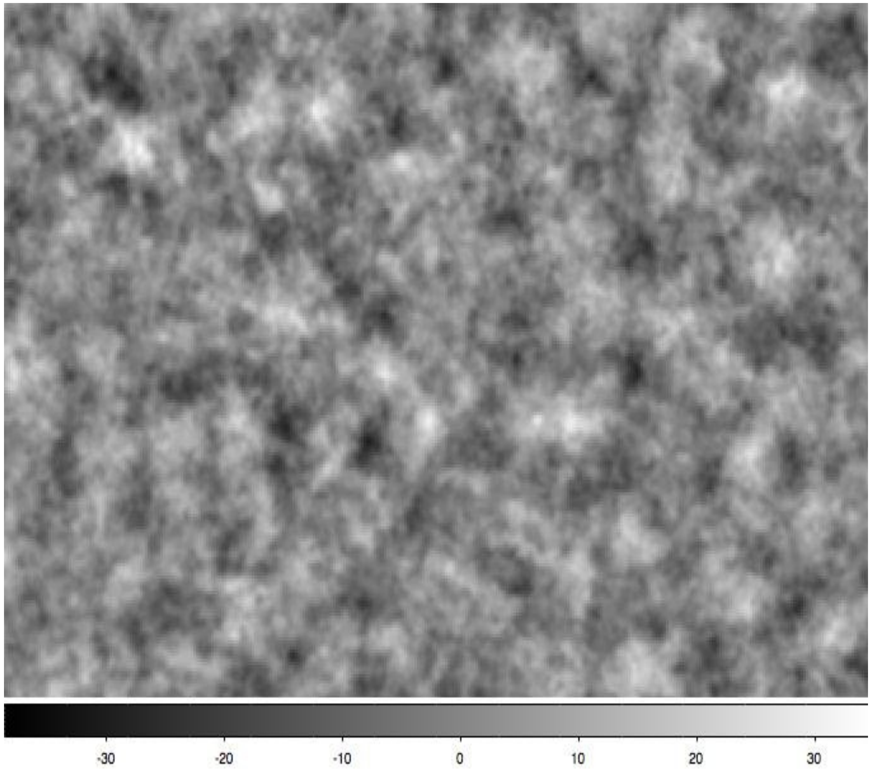
Aperture Mass



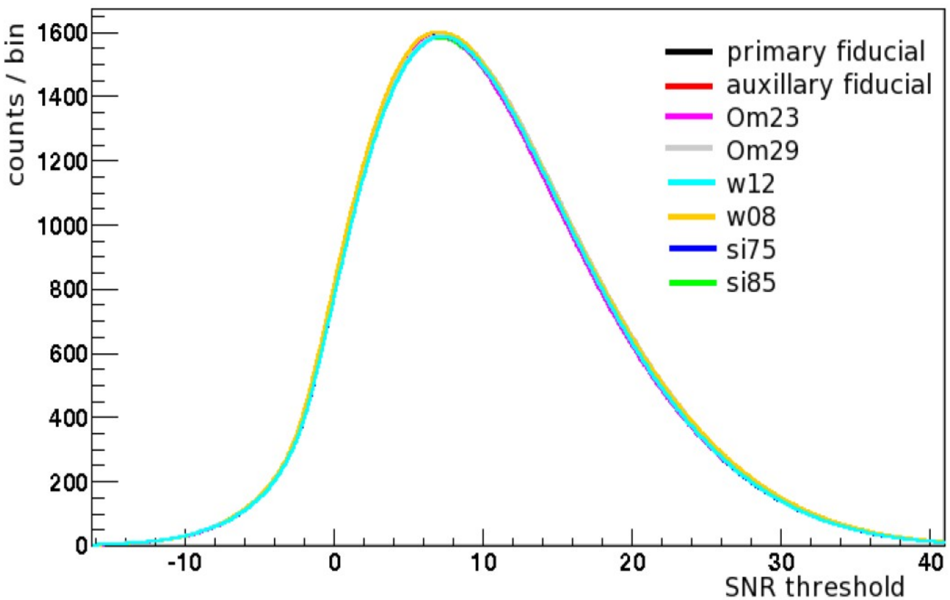


- Aperture mass with no shape noise, no measurement errors.

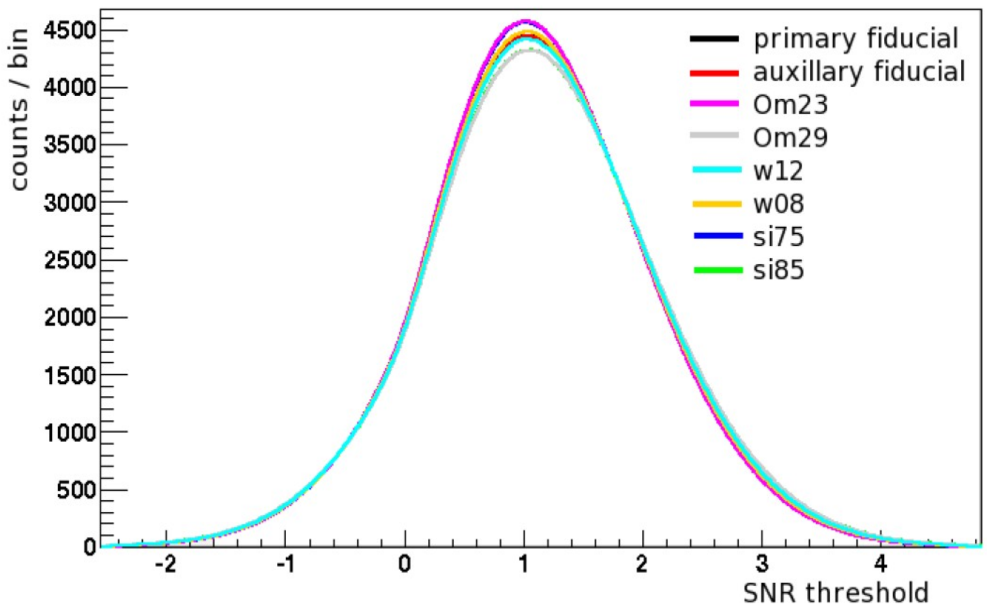
- Aperture mass **with** shape noise and errors.

Peak Counts

- Peak counts above SNR threshold



- No error on shear measurement

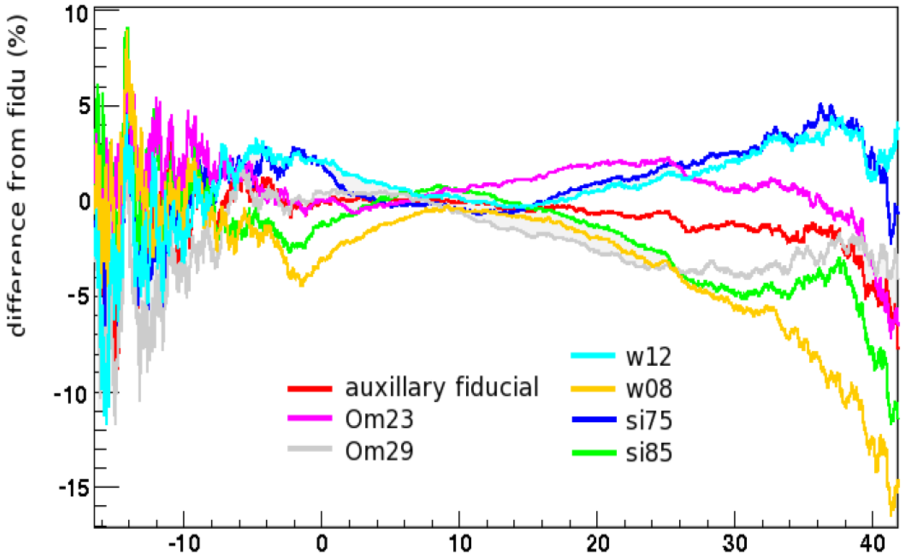


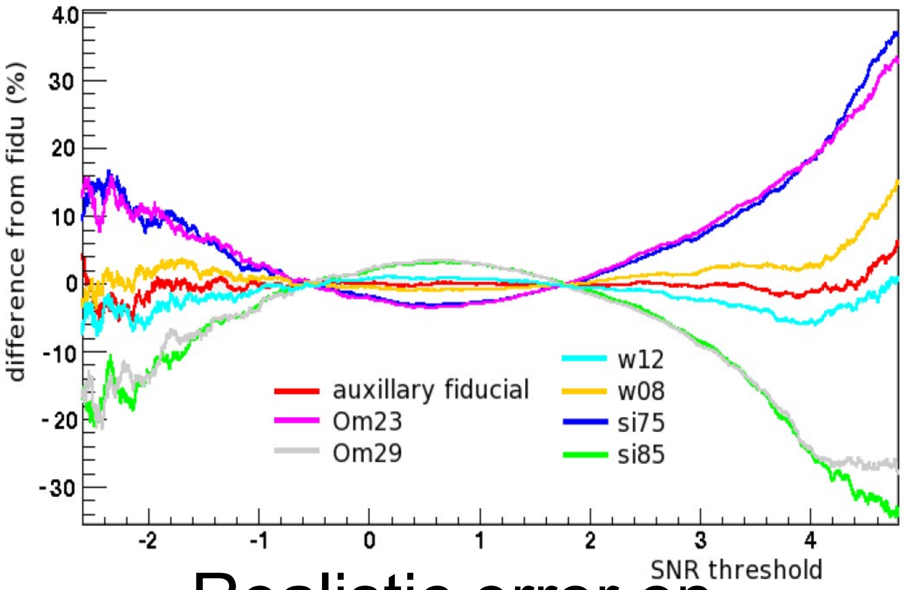
- Realistic error on shear measurement

- Addition of errors reduces peak significance, but does not destroy cosmological significance.

Peak Counts

- Peak counts above SNR threshold, as a % difference from fiducial cosmology.





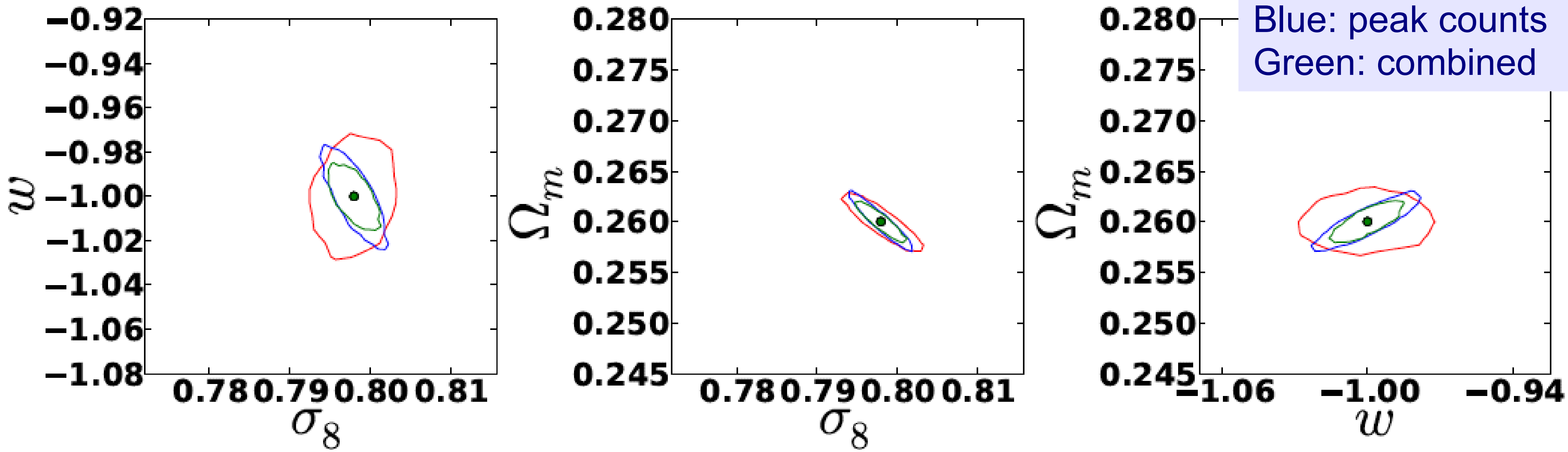
- No error on shear measurement
- Realistic error on shear measurement

- Addition of errors reduces peak significance, but does not destroy cosmological significance.

Cosmological constraints

- Constraints from peak counts, power spectrum (from aperture mass maps), and combination of both for **no errors**.
- 68% confidence contours, scaled to LSST ten-year survey.

Red: power spectrum
Blue: peak counts
Green: combined



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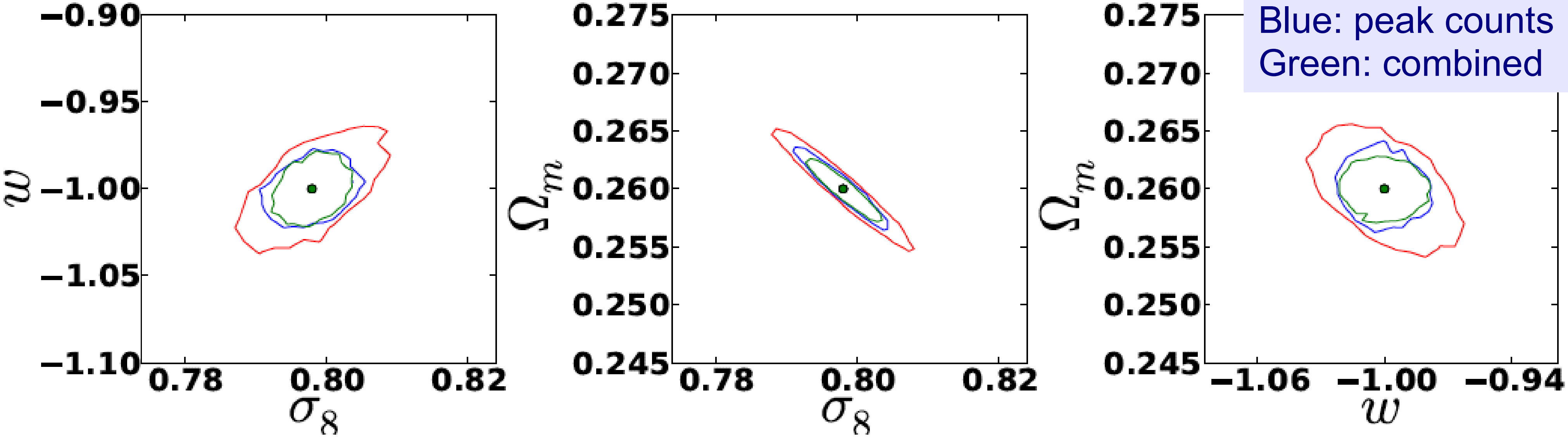


- Even in the presence of realistic measurement errors, there remains information in peak counts beyond the power spectrum!

What else can we do with this?

- We can use this framework to develop shear peak techniques:
  - Find optimal combination of filter functions to extract maximal cosmological information in the presence of realistic errors.
  - Explore tomographic measurements.
- Understand, quantify and mitigate the impact of different sources of systematic error:
  - Masked areas.
  - Varying depth of a survey.
  - Image quality.
  - PSF deconvolution techniques.

Conclusions

- Shear peak counts are a very useful probe of cosmology.
  - Can be used in combination with other measurements of the shear power spectrum.
- Adding realistic measurement errors does not destroy the cosmological information in peak counts.
- Need to use realistic galaxies to trace simulations if we're going to use shear peaks to constraint cosmological parameters!
- LSST Image Simulator is a powerful tool for these studies.

Extra Slides

Aperture Mass: Filter

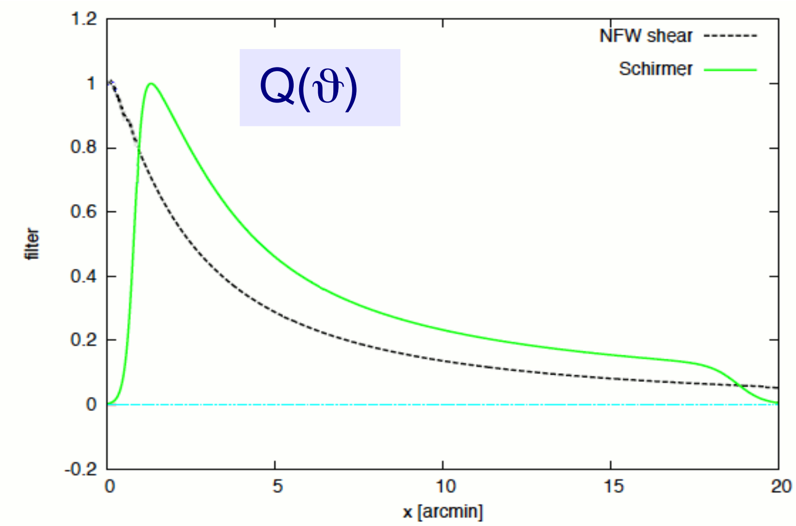
- Use filter proposed by Schirmer+ 2007:

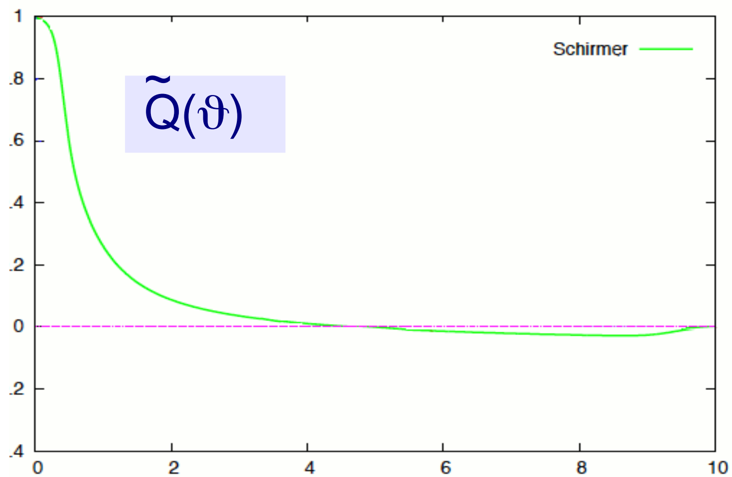
$$Q_{\rm NFW}(x; x_{\rm c}) \propto \frac{1}{1 + {\rm e}^{6-150x} + {\rm e}^{-47+50x}} \frac{\tanh(x/x_{\rm c})}{x/x_{\rm c}}$$

- Roughly and NFW profile with exponential cutoffs as $x \to 0$ and $x \to \infty$, $x=\theta_i/\theta_{max}$, where θ_{max} gives the radius to which the filter is tuned and $x_c = 0.15$.

- Can transform to convergence space using:

$$M_{\rm ap}(\boldsymbol{\theta}_0) = \int_{\sup Q} {\rm d}^2\theta\, Q(\vartheta)\gamma_{\rm t}(\boldsymbol{\theta}; \boldsymbol{\theta}_0)$$





From Maturi+ 2009