Constraints on Dark Energy from Future Weak Lensing Surveys

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Dark Energy

- **The expansion of the universe is accelerating**

  - discovered by looking at distant Supernovae in 1998

  - confirmed recently by studying the CMB, clusters.

- **Three different explanations**

  1. vacuum has finite (nonzero) energy density
  2. “dark energy”: a new uniform component of the universe with large negative pressure
  3. general relativity fails on cosmological scales

- **Commonly regarded “most important problem in physics”**

  - accounts for ~70 percent of total energy in the universe

Dark Energy

- **Characterizing dark energy**

  - equation of state $p = w\,\rho$

  - vacuum: $w=-1$ *vs* dark energy or non-GR: $w=w(t) \neq -1$

- **Universe is "flat": no spatial curvature (CMB)**

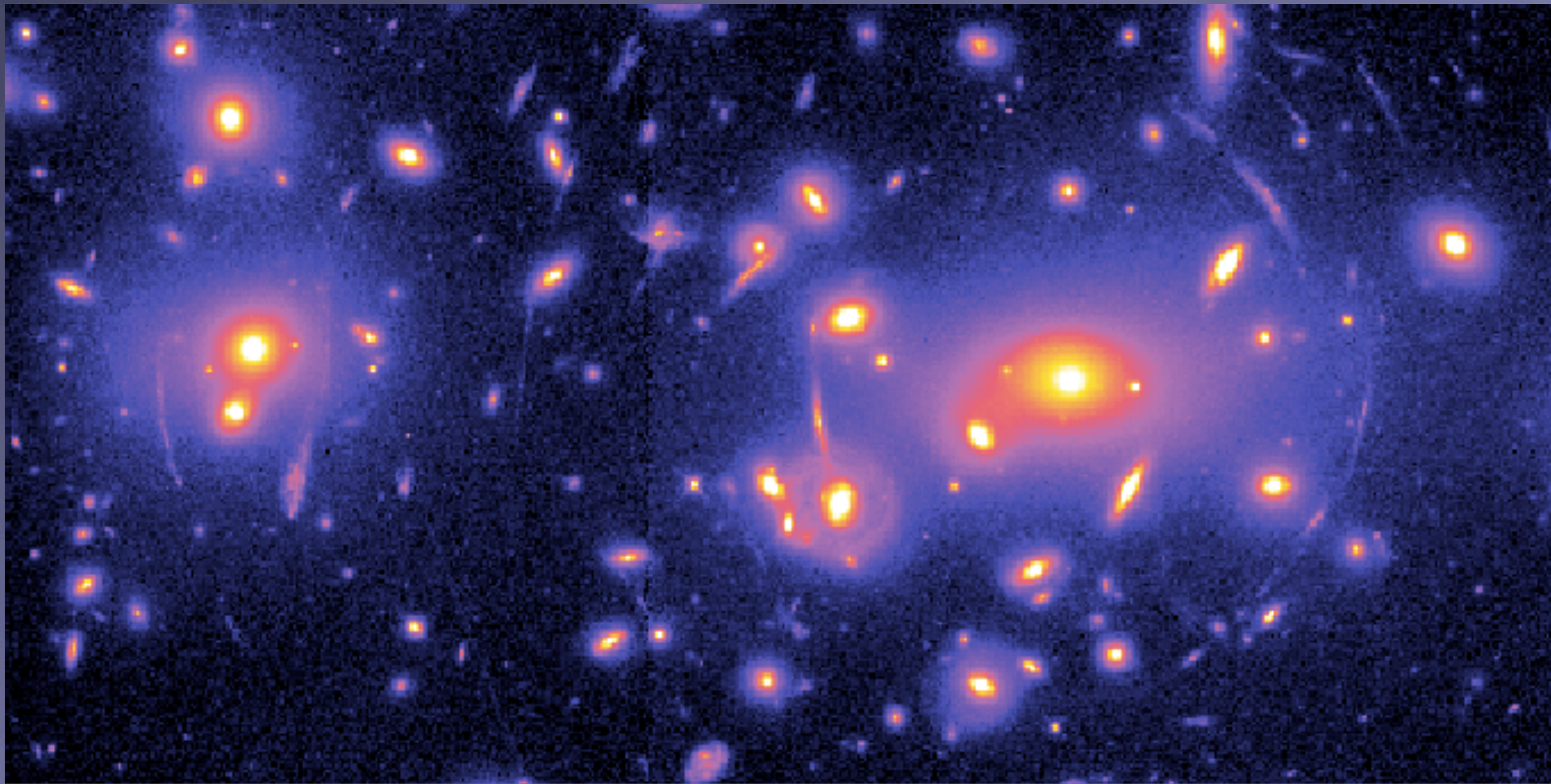
  - fixes energy density ρ. Need to measure w

  - w affects: (i) evolution of expansion rate

    (ii) growth of structure

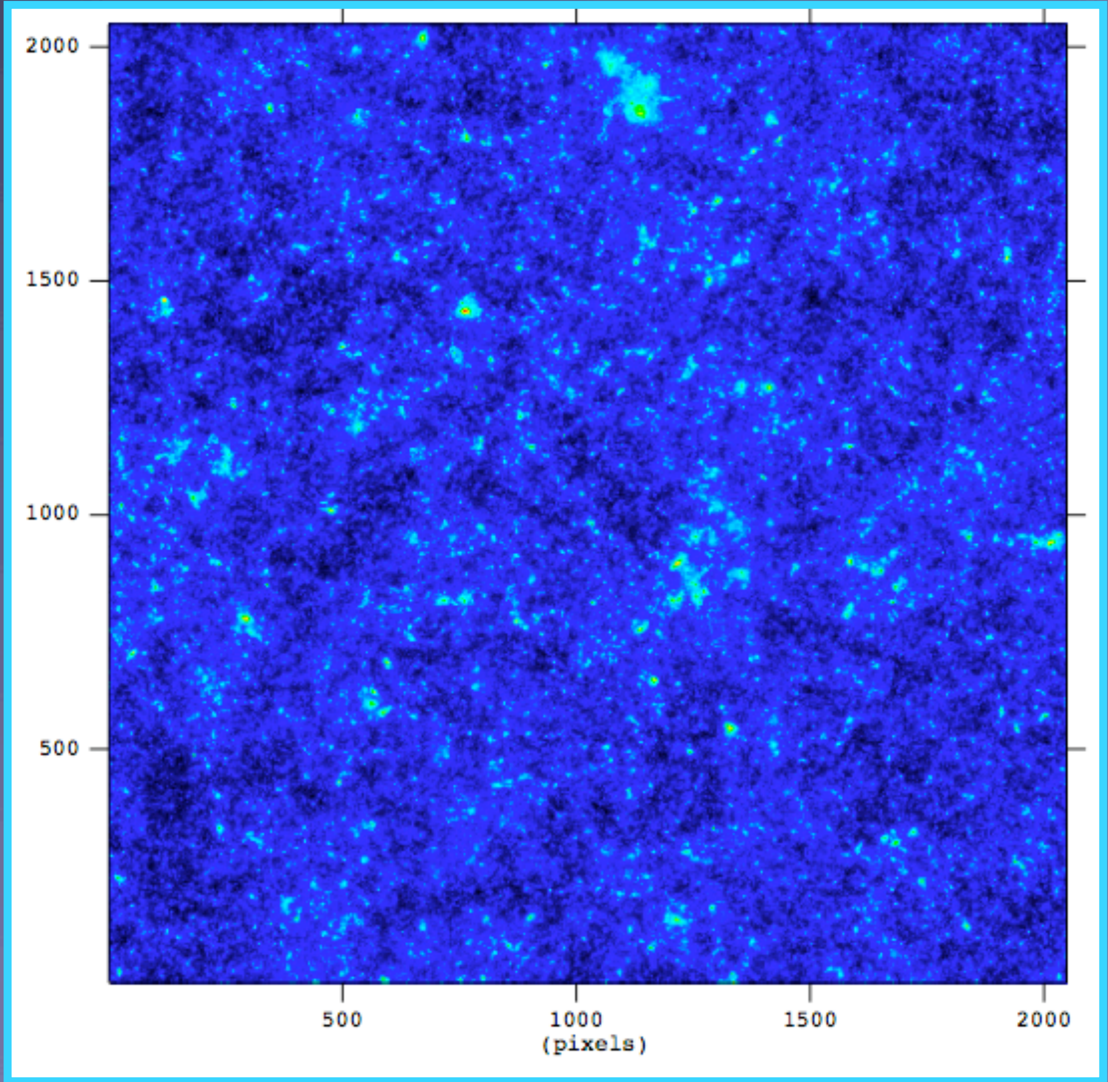
- **Solution will come from astronomers: no small-scale effect**

A tool: Weak Gravitational Lensing



Simulated Map of Weak Lensing

3×3 deg^2 ; 1 $amin^2$ pixels



Extracting information from WL maps

- **Traditional statistic**:

  - (tomographic) two-point correlation function C_l

  - depends on w, linear regime analytically predictable

- **Question:** is there significant information in the non-linear regime beyond "usual" LSS statistics ?

  1. Statistical power of *dN/dz* (cluster counts)
  2. Complementarity of *dN/dz* and C_l

Forecasts for Future

- Several large ($\gtrsim$1,000 sq. deg) WL surveys forthcoming:
  (e.g. Pan-STARRS, KIDS, DES, LSST)
- Shear power spectrum and related large-scale statistics
  (e.g. Kaiser 1992; Jain & Seljak 1997; Hu 1999, 2002; Huterer 2002; Refregier et al. 2004; Abazajian & Dodelson 2003; Takada & Jain 2004; Song & Knox 2004)
  E.g. $\sigma(w_0)$=0.06; $\sigma(w_a)$=0.1 from 11-paramater fit to tomographic shear power spectrum (LSST) + *Planck*
- Comparable statistical errors from cluster number counts
  (e.g. Wang et al. 2004, 2005; Fang & Haiman 2007; Takada & Bridle 2007; Marian & Bernstein 2006, 2008)
  E.g. $\sigma(w_0)$=0.04; $\sigma(w_a)$=0.09 from 7-paramater fit to ~200,000 shear-selected cluster counts (LSST) + *Planck*

Adding Non-Linear Info

- Cluster counts and shear power spectrum can be considered independent observables – high synergy

  Covariance changes parameter-estimates by < few %

  (Fang & Haiman 2007; Takada & Bridle 2007)

- However, selection effects are (probably) a showstopper in a WL survey alone, due to projection effects

  Filter-dependent trade-off between *completeness* and *purity*: "best compromise" values are ~70% for both

  (e.g. White et al. 2002; Hamana et al. 2005; Hennawi & Spergel 2005)

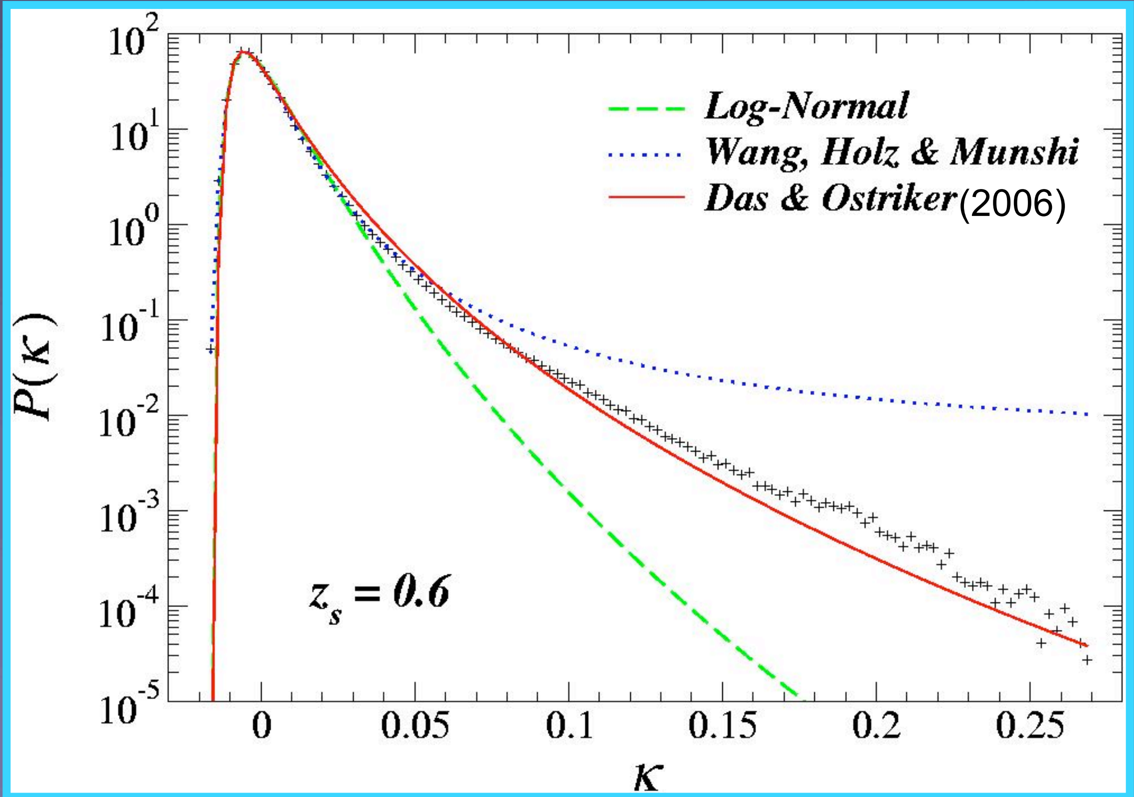
- Why not define observable immune to projection effects?

  historical reason: cosmology-dependence of halo mass function calculable from Press-Schechter

Fractional Area of "Hot Spots"

Wang, Haiman & May (2009)

- A simple statistic: one-point function of convergence
  i.e. fraction of sky above a fixed threshold $\kappa > \kappa_T = \nu\sigma_N$
  "analytically" calculable, analogous to mass function:



cosmology dependence only through $\langle\kappa^2\rangle$ and κ_{min}

$F = \int_{\nu\sigma} P(\kappa)d\kappa$

Simulations by M.White (2005)

Peak counts

- Another simple statistic: # of shear peaks, regardless of whether or not they correspond to true bound objects
  as a function of height, redshift and angular size
  Kratochvil, Haiman, Hui & May (2009)

- Fundamental questions about “false” (non-cluster) peaks:
  1. How does N(peak) depend on cosmology ?
  2. What is the field-to-field variance ΔN(peak) ?

- Requires simulations

N-body Simulation Details

- pure DM (no baryons, neutrinos, or radiation)
- public code GADGET-2, modified to handle $w_0 \neq -1$
- fiducial ΛCDM cosmology from *WMAP5*:
  $(w_0, \Omega_\Lambda, \Omega_m, H_0, \sigma_8, n) = (-1.0, 0.74, 0.26, 0.72, 0.79, 1.0)$
- fix *primordial* amplitude $\Delta^2_R = 2.41\times10^{-9}$ at $k = 0.002$ Mpc^{-1}
  (σ_8=0.79 vs. 0.75)
- two alternative cosmologies, differ only in w_0= -0.8 or -1.2
- 512^3 box, size $200h^{-1}$ Mpc, z_{in}=60, $M_{DM}=4.3\times10^9\,M_\odot$
- gravitational softening length ε_{Pl} = $7.5h^{-1}$ kpc
- output particle positions every $70h^{-1}$ comoving Mpc
- runs performed at NSF TeraGrid and at Brookhaven

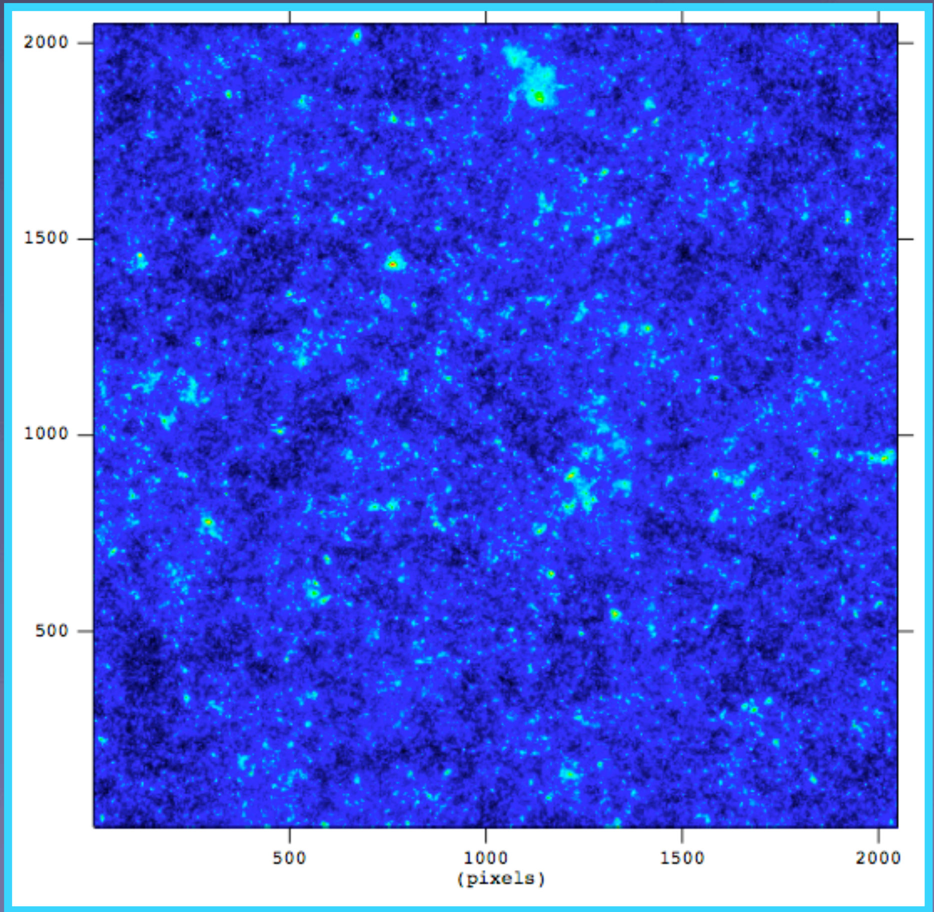
Simulating Weak Lensing Maps

- Ray-tracing
  - compute 2D potential (2048×2048) in each lens plane
  - implement algorithm to follow rays (Hamana & Mellier 2001)
  - compute shear (γ), convergence (κ) and reduced shear (μ)
- Mock "observational" parameters
  - gaussian 1-component shear noise from intrinsic ellipticity:
    $\sigma_\gamma=0.15+0.035z$ (Song & Knox 2004)
  - $n_{gal}=30$ arcmin^{-2} background galaxies, at $z_s = 1, 1.5,$ and 2
  - smooth κ-map with 2D finite Gaussian 0.25 - 30 arcmin
  - use 3×3 deg^2 smoothed convergence maps
- Identifying peaks
  - find all local maxima, record their height

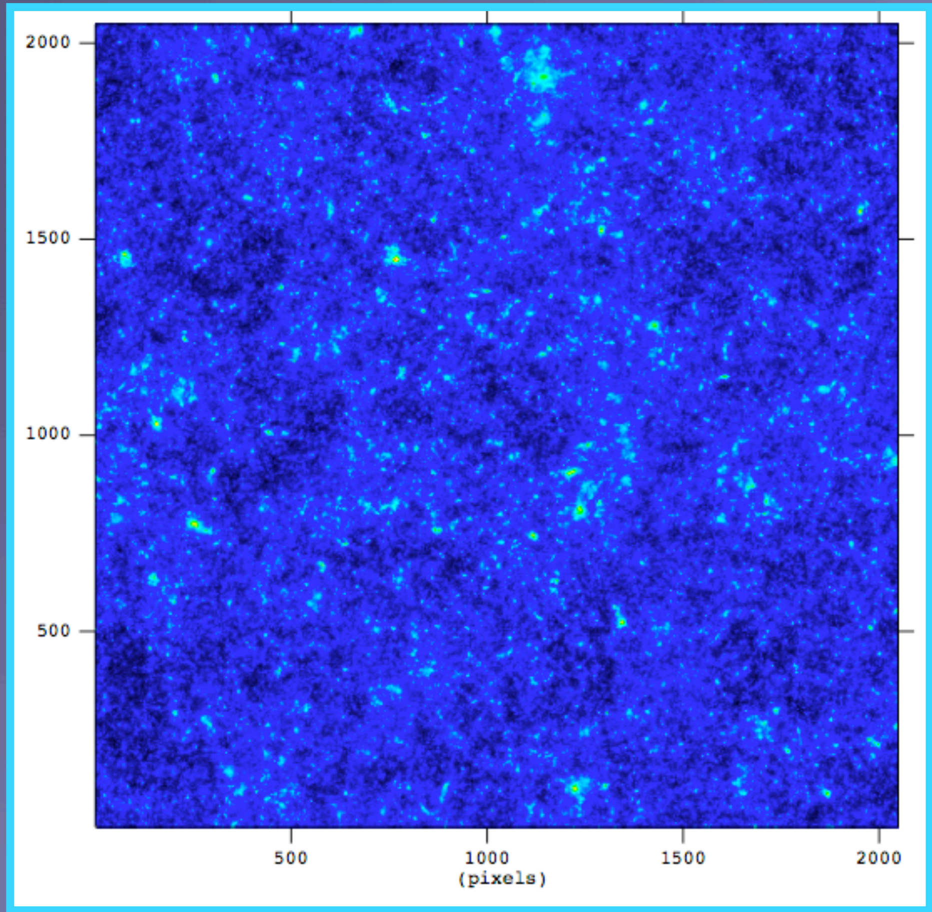
Example

raw convergence map (3×3 deg^2 ; 2048×2048 pixels)

w=-1



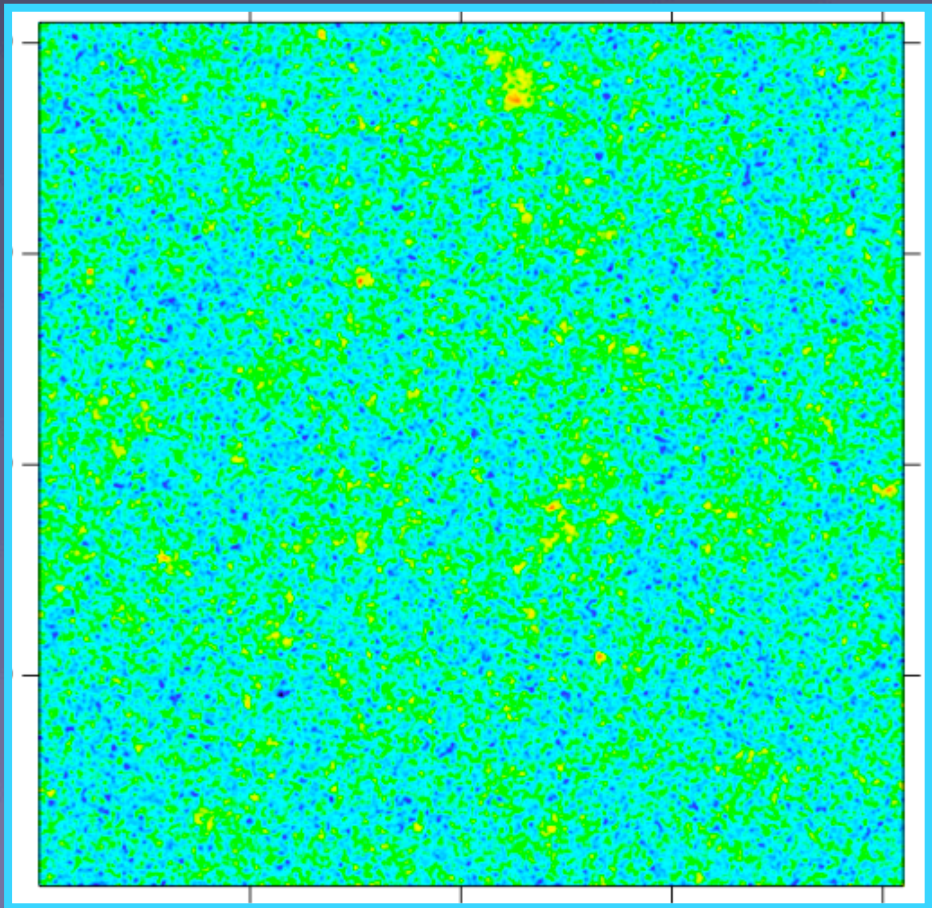
w=-0.8



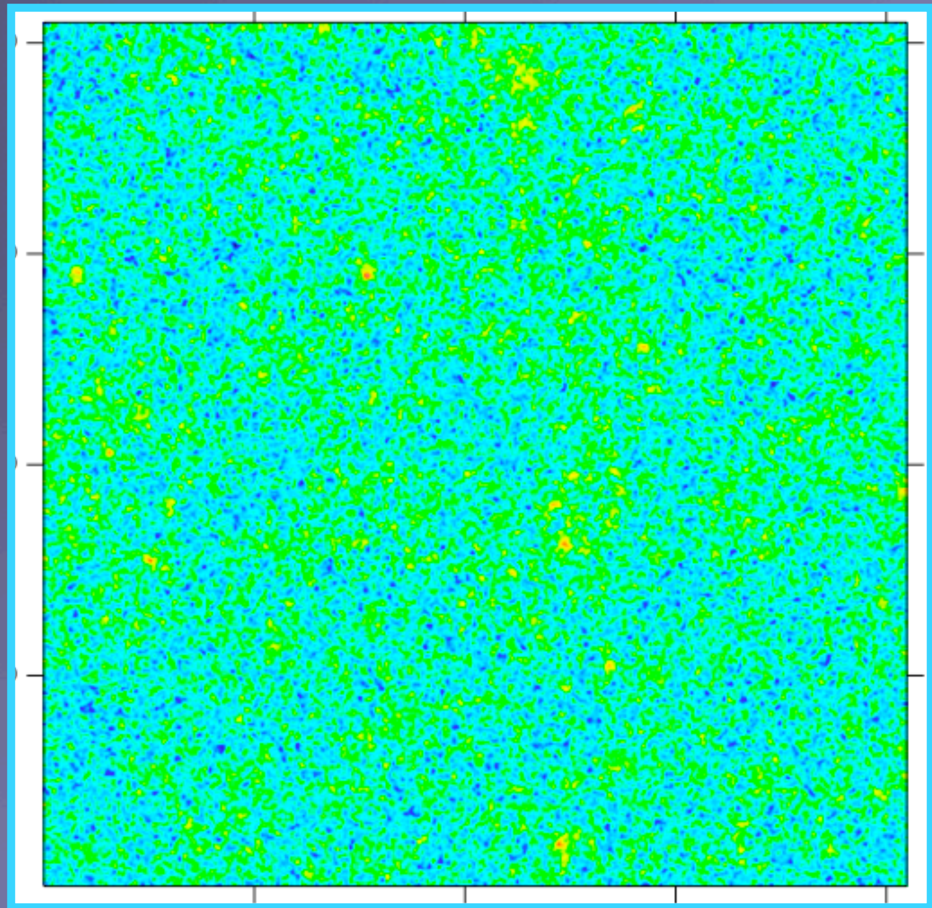
Example

convergence map with ***noise*** and 1-arcmin ***smoothing***

w=-1



w=-0.8



Basic Results

- 3×3 deg^2 field, smoothing with 1-arcmin, galaxies at $z_s=2$

- Expectations based on clusters with $\kappa_G \geq 4.5\sigma_\kappa$
  (Fang & Haiman 2007)
  N(clusters) = 150 ± 25 for $w=-1$
  N(clusters) = 103 ± 21 for $w=-0.8$
  ➔S/N≈2σ *mostly coming from change in* σ_8

- Total peak counts above same threshold [w/no noise]
  N(peaks) = 576 ± 86 [230 ± 42] for $w=-1$
  N(peaks) = 547 ± 85 [186 ± 37] for $w=-0.8$
  ➔S/N≈0.3σ : (i) smaller difference, (ii) larger variance

- Total peak counts (all peaks):
  N(peaks) = 11,622 ± 62 for $w=-1$
  N(peaks) = 11,562 ± 62 for $w=-0.8$

Statistical Methodology

- Covariance matrix for number of binned, tomographic peaks:

$$C^m_{i,j} \equiv \frac{1}{R-1}\sum_{r=1}^{R}\left[N^m_i(r) - \overline{N}^m_i\right]\left[N^m_j(r) - \overline{N}^m_j\right]$$

  - R=500 realizations in cosmology *m* (rotate/shift/slice box)
  - *i = 15 (height) x 3 (source redshift) = 45 bins*

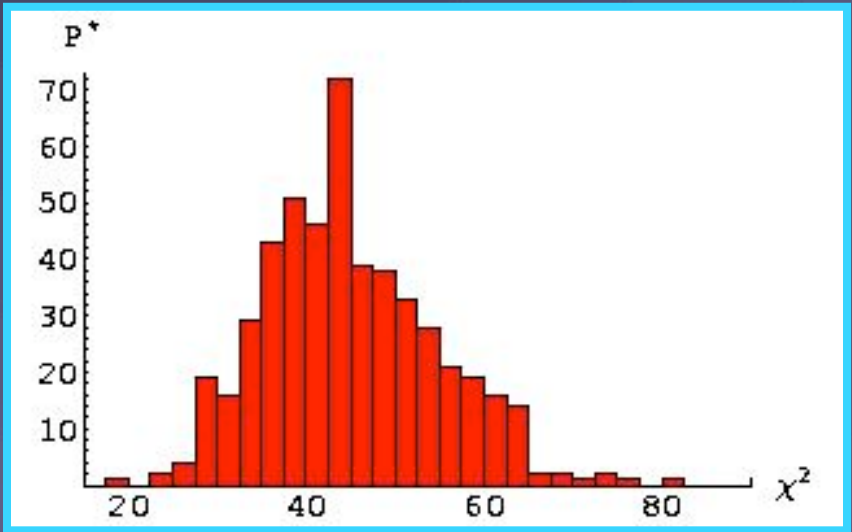
- Compute "χ^2 " between test (*m*) and fiducial (*n*) cosmology:

$$\chi^{2;m,n}(r) \equiv \sum_{i,j=1}^{45}\left[N^m_i(r) - \overline{N}^n_i\right]\left[C^n_{i,j}\right]^{-1}\left[N^m_j(r) - \overline{N}^n_j\right]$$

- Compute likelihood at which cosmology *m* can be distinguished from cosmology *n*:
  - given by overlap between two distributions $\chi^{2;m,n}$ and $\chi^{2;n,n}$

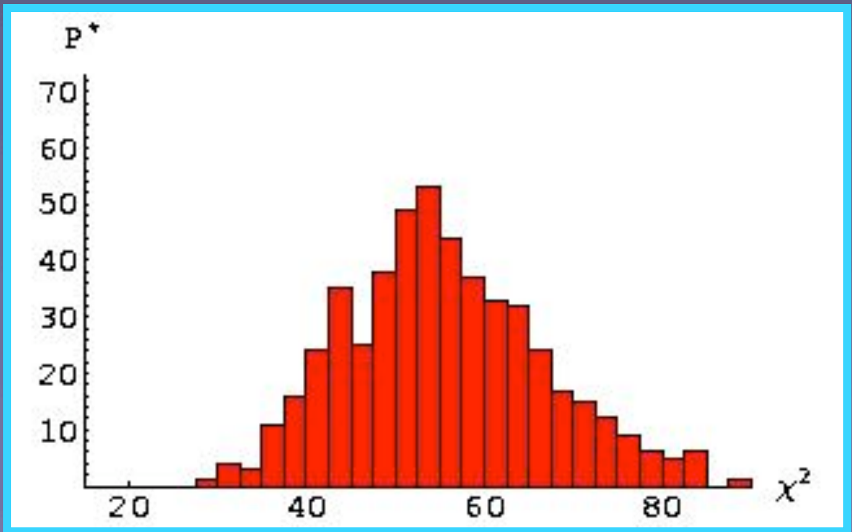
Chi Square Distributions

3 redshift bins, 15 peak height bins, 0.5 arcmin smoothing



w = -1 versus w = -1

$\langle\chi^2\rangle$=44.89



w=-0.8 versus w=-1

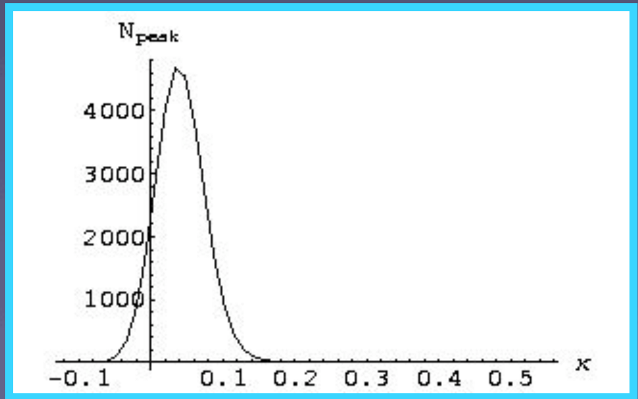
$\langle\chi^2\rangle$=55.51

$\rightarrow \Delta \langle\chi^2\rangle \approx 10$

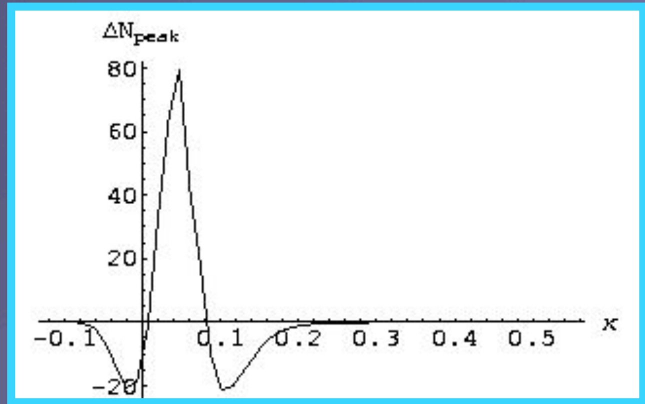
or 85% confidence

Which peaks dominate constraints?

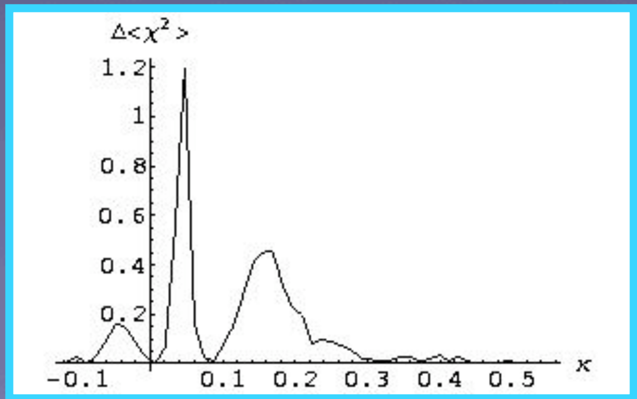
- smoothing with 0.5 arcmin, galaxies at z_s=2
- w=-1 more peaks at high+low ends (DE dominates later)
- w=-0.8 peaks are more sharply peaked
- medium height ($\kappa \approx 0.04$, or 2σ) peaks dominate the total χ^2



Total # of peaks



Difference in N_{peak}



Contribution to χ^2

Conclusions

- Number of shear peaks in 9 deg^2 has statistically significant ($\sim 1.5\sigma$) difference between w=-0.8 and w=-1.0
- Encouraging, since # of peaks is a robust observable
- Similar to cluster dN/dz, but most of the information comes from lower (non-cluster) peaks
- Just a first step: we need suite of simulations to address degeneracies when other parameters are included

Question for the Audience

- We do not know a-priori how changes in w affect map
- Peak counts may <u>not</u> capture most of the information
- **Can we use some 'artificial neural network' approach?**

  - simulate maps in different cosmologies "training sets"

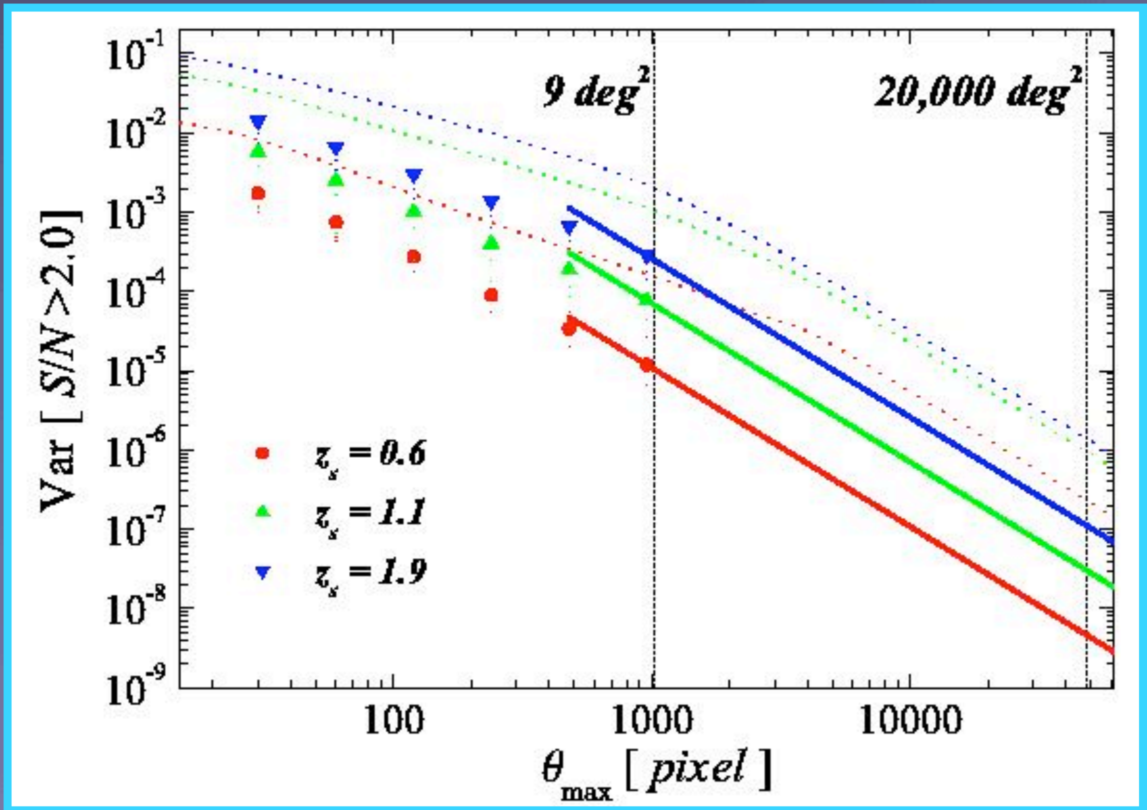
  - algorithm itself should come up with a discriminator

  - problem(?): small training sets (100 realizations/model)

The End

Fractional Area of "Hot Spots"

- Forecast *p* constraint (S/N) from Fisher matrix - need:
  cosmology-dependence (S): $d\langle F\rangle / dp$ ✓
  variance (N): $\langle F^2\rangle$?
- Full covariance matrix from log-normal model *vs* simulations



$i \in \{\kappa\text{-threshold, galaxy redshift}\}$

$C_{ij} = \langle F(\kappa_i, z_i)\, F(\kappa_j, z_j)\rangle$

Simulations by M.White (2005)

Constraints from "Hot Spots"

- Fiducial 7-parameter flat ΛCDM cosmology (~*WMAP)*:

  $(\Omega_{DE}, \Omega_m h^2, \Omega_b h^2, w_0, w_a, \sigma_8, n_s) = (0.72, 0.14, 0.024, -1, 0, 0.9, 1)$

- Assume LSST-like survey parameters:

  * $\Delta\Omega$ = 20,000 deg^2 ; n_g = 40 gal/deg^2 ; σ_ε= 0.3
  * 1-arcmin smoothing
  * three redshift bins: z_g = 0.6, 1.1, 1.9
  * seven convergence bins: ν = 2, 2.5, 3, 3.5, 4, 4.5, 5 $(\kappa=\nu\sigma_G)$

- Six Nuisance parameters:

  * σ_G = free parameter in each z-bin with 0.01-1% priors
  * κ_{bias} = free parameter in each z-bin with 0.05-1% priors

- Planck Priors $(\Omega_m h^2, \Omega_b h^2, n_s)$

- Ref: noise from intrinsic ellipticity (σ_G=0.023) vs. smoothed convergence field at z=(0.6, 1.1, 1.9): σ=0.01, 0.017, 0.025

Results from “Hot Spots”

- Constraints approaching those expected from cluster dN/dz
- DETF figure of merit:

  $(\Delta w_0\ \Delta w_a)^{-1} = 180$ (pessimistic) vs 760 (optimistic)
- Nonlinear info - complementary to shear power spectrum

TABLE 1

CALIBRATED COSMOLOGICAL PARAMETER CONSTRAINTS FROM LSST USING THE FRACTIONAL AREA STATISTIC AND ADDING PLANCK PRIORS: $\Delta\Omega_m h^2 = 0.0012$, $\Delta\Omega_b h^2 = 0.00014$, AND $\Delta n_s = 0.035$. FOR THE PESSIMISTIC SCENARIO, WE ADOPT 1% PRIORS ON THE ADDITIVE AND MULTIPLICATIVE ERRORS ALREADY ACHIEVED BY CURRENT SURVEYS. FOR THE OPTIMISTIC SCENARIO, WE ADOPT 0.01% AND 0.05% PRIORS ON THE ADDITIVE AND MULTIPLICATIVE ERROR RESPECTIVELY, WHICH IS THE GOAL OF FUTURE SURVEYS.

Parameter Constraints	LSST ($\mathcal{F}$)	LSST ($\mathcal{F}$) + Planck (priors)
Pessimistic		
Δw_p	0.094	0.022
z_p	0.50	0.94
Δw_0	0.55	0.12
Δw_a	1.6	0.25
$\Delta\Omega_{DE}$	0.046	0.0095
$\Delta\sigma_8$	0.047	0.0080
Optimistic		
Δw_p	0.028	0.012
z_p	0.60	0.60
Δw_0	0.16	0.043
Δw_a	0.42	0.11
$\Delta\Omega_{DE}$	0.015	0.0038
$\Delta\sigma_8$	0.031	0.0029

Results: statistical significance

- $w=-0.8$ distinguishable at 85% confidence from $w=-1.0$
  70% chance for 68% CL
  26% chance for 95% CL

- covariance has small effect overall (cuts high-χ^2 tail)

- co-adding several smoothing scales gives only modest (~10%) improvement over single best scale (~0.5 arcmin – smaller than best cluster case)

- scaling from $3 \times 3 = 9$ deg^2 to 20,000 deg^2 :
  rough guess:
  significance $\sqrt{(20,000/9)}=50$ times better
  1.5σ constraint on w_0 is $\Delta w_0 = 0.2/50 = 0.004$