Cosmic shear

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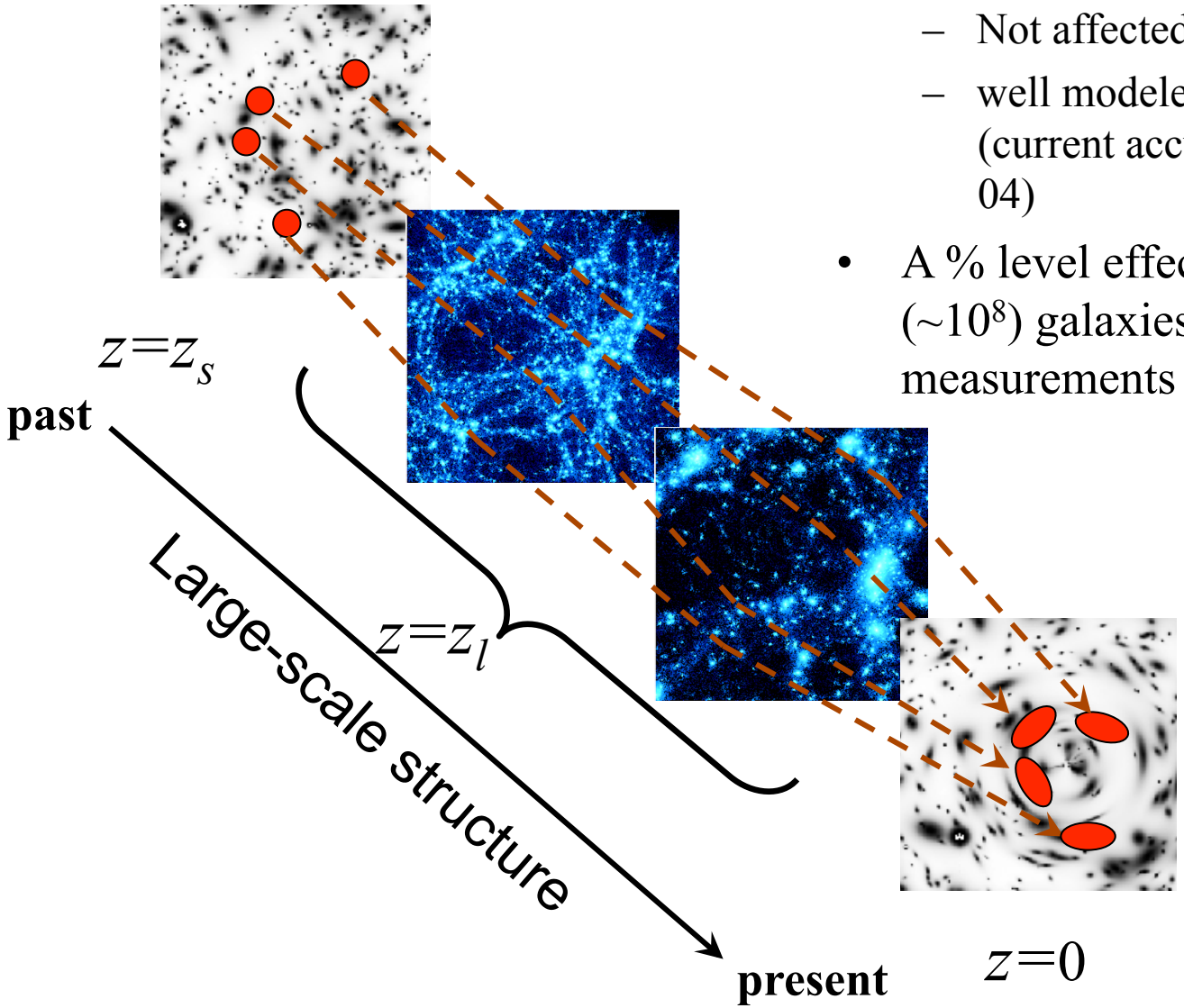
Cosmology on the Beach, Jan 15th 2010

Cosmic shear=cosmological weak lensing



- Arises from total matter clustering
  - Not affected by galaxy bias uncertainty
  - well modeled based on simulations (current accuracy, <10% White & Vale 04)
- A % level effect; needs numerous (~10^8) galaxies for the precise measurements

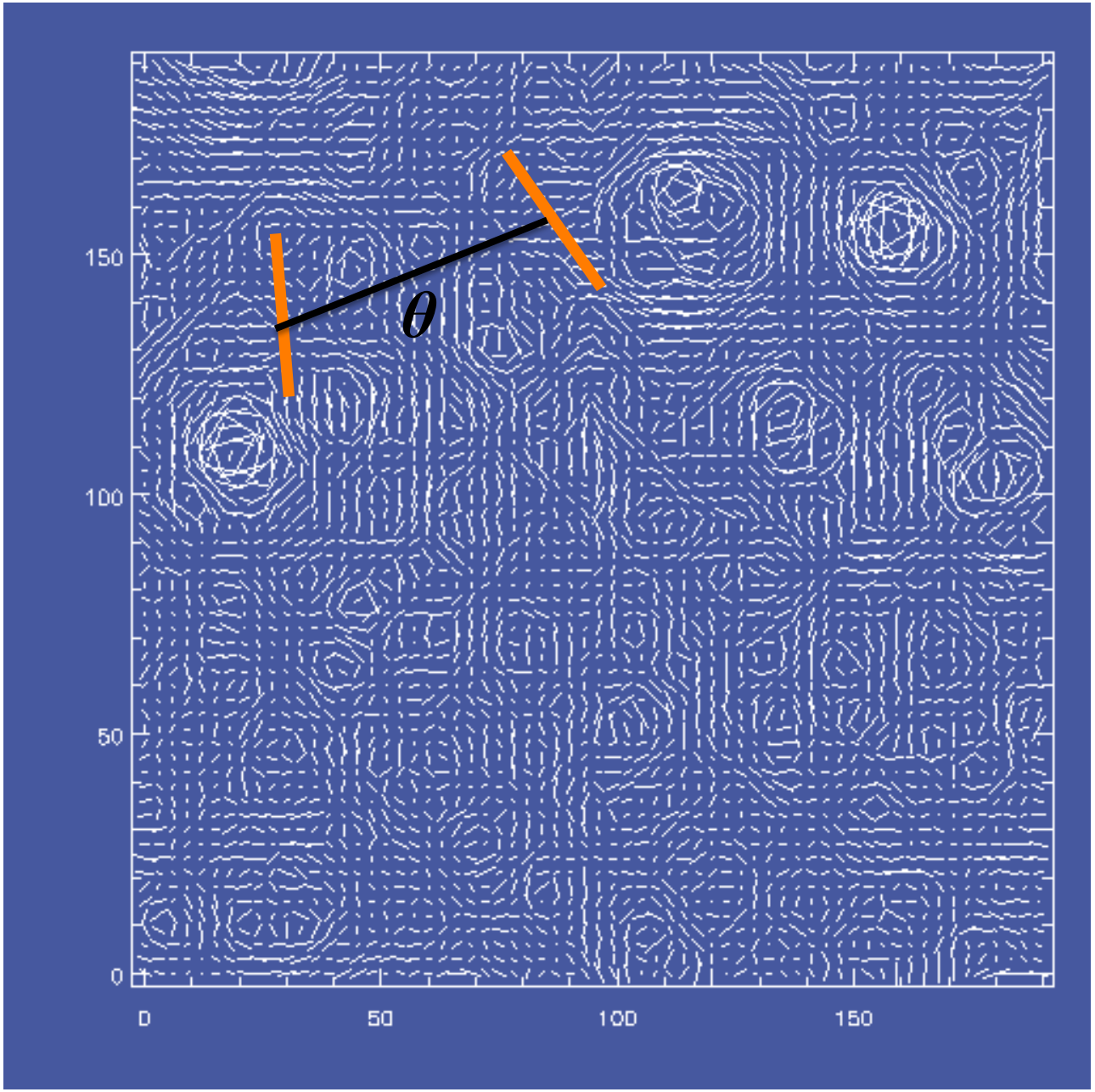
observables

$$\gamma = \frac{a-b}{a+b}$$

$$\gamma_1 = \gamma \cos 2\varphi$$

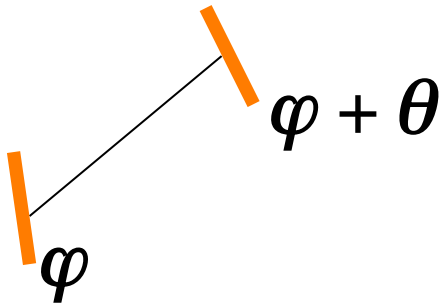
$$\gamma_2 = \gamma \sin 2\varphi$$

Measurement method



- Correlated images of distant galaxies over all angular scales
- Use images of all distant galaxies
- Correlation function method to measure the cosmic shear signals
- The lowest one is 2pt function

Cosmic shear observables: 2pt correlations



$$\xi_\gamma(\theta) = \left\langle \gamma(\varphi)\gamma^*(\varphi+\theta)\right\rangle \overset{F.T.}{\Leftrightarrow} C_\gamma(l)$$

Cosmological information is contained in statistical correlations.

Lensing correlations given by projection of the mass power spectrum:

$$\left\langle \gamma\ \gamma^*\right\rangle(\theta, z_s) = \int dz\ W^2(z, z_s) \int dk\ P_\delta(k,z)\ F(k,\theta,z)$$

First detection made in 2000: Van Waerbeke+, Kaiser+, Bacon+, Wittman+

Cosmic shear sensitivity to cosmology

$$\gamma(\boldsymbol{\theta}) \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

for a source galaxy at z_s

- Lensing efficiency function: W_{gl}
  - Overall amplitude is propotional to Ω_{m}, i.e. Ω_{de} if combined with CMB or a flat universe is *a prior* assumed
  - Sensitive to Hubble expansion through d_{A}, i.e. DE
  - Depends on source redshift – main uncertainty in cosmic shear measurements if redshift info is not available
- Mass clustering part: δ
  - Sensitive to primordial power spectrum (amplitude and shape)
  - Redshift history of the growth rate is sensitive to DE, and neutrino mass if combined with CMB information

Gravitational instability

- Density perturbation field of total matter (mainly CDM) in the linear regime

$$\boxed{\delta_m(\boldsymbol{x},z) \equiv \frac{\rho_m(\boldsymbol{x},z) - \bar{\rho}_m(z)}{\bar{\rho}_m(z)} = D(z)\delta_m(\boldsymbol{x}, z \approx 1000)}$$

- The 2nd-order diff. eqn. to govern the redshift evolution of density pert.: (FRW eqns + linearized Einstein eqns.)

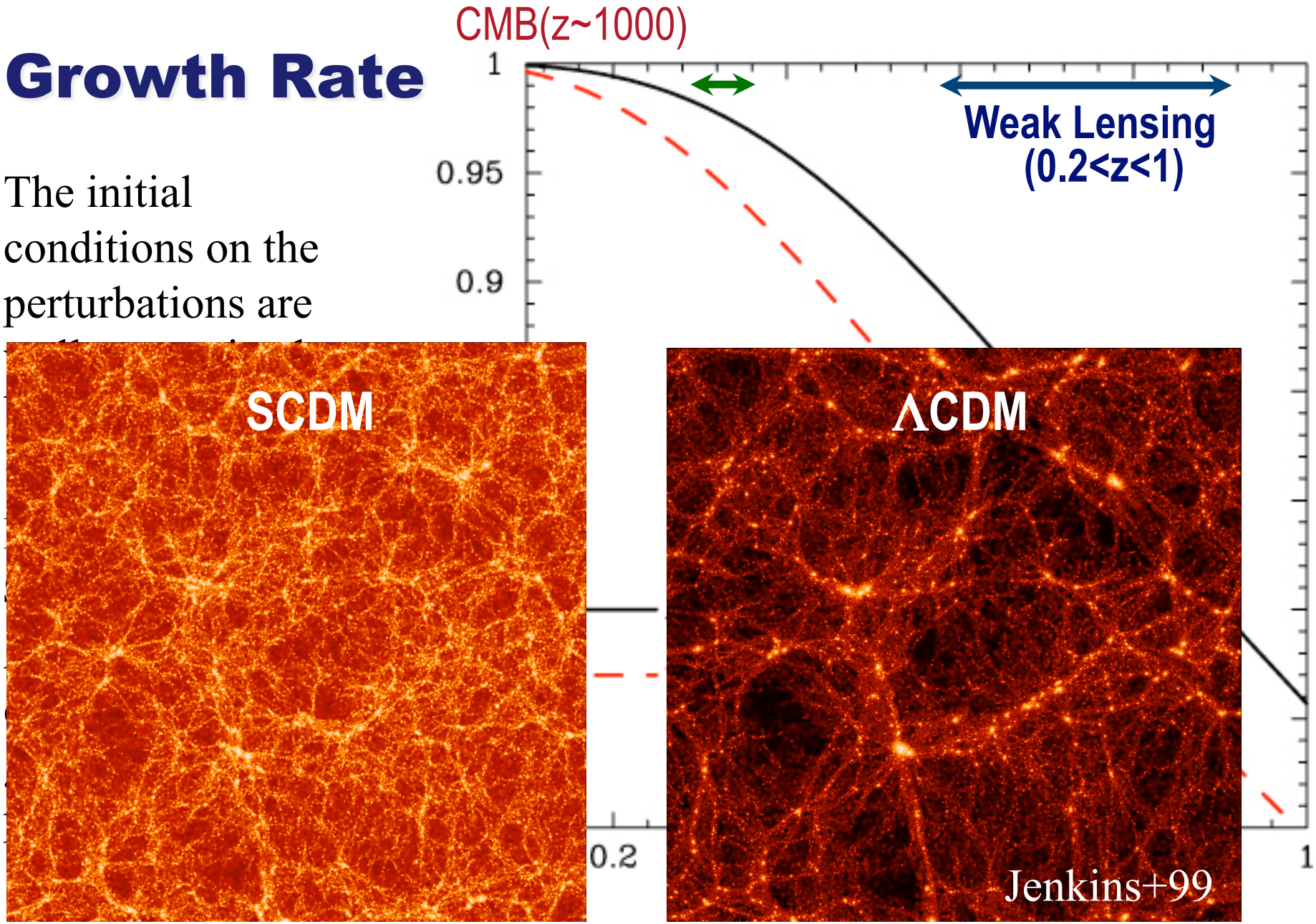
$$\boxed{\ddot{D} + 2H\dot{D} - 4\pi G\bar{\rho}_m D = 0}$$

where $H^2(z) \equiv \left(\frac{\dot{a}}{a}\right)^2 = H_0^2\left[\underbrace{\Omega_{\mathrm{m0}}(1+z)^3}_{\text{matter(CDM+baryon+ν)}} + \underbrace{\Omega_{\mathrm{de0}}(1+z)^{3(1+w)}}_{\text{Dark energy}}\right]$ $(\Omega_{\mathrm{m0}} + \Omega_{\mathrm{de0}} = 1)$

- Cosmic acceleration suppresses the amplification of the density perturbation at low redshifts

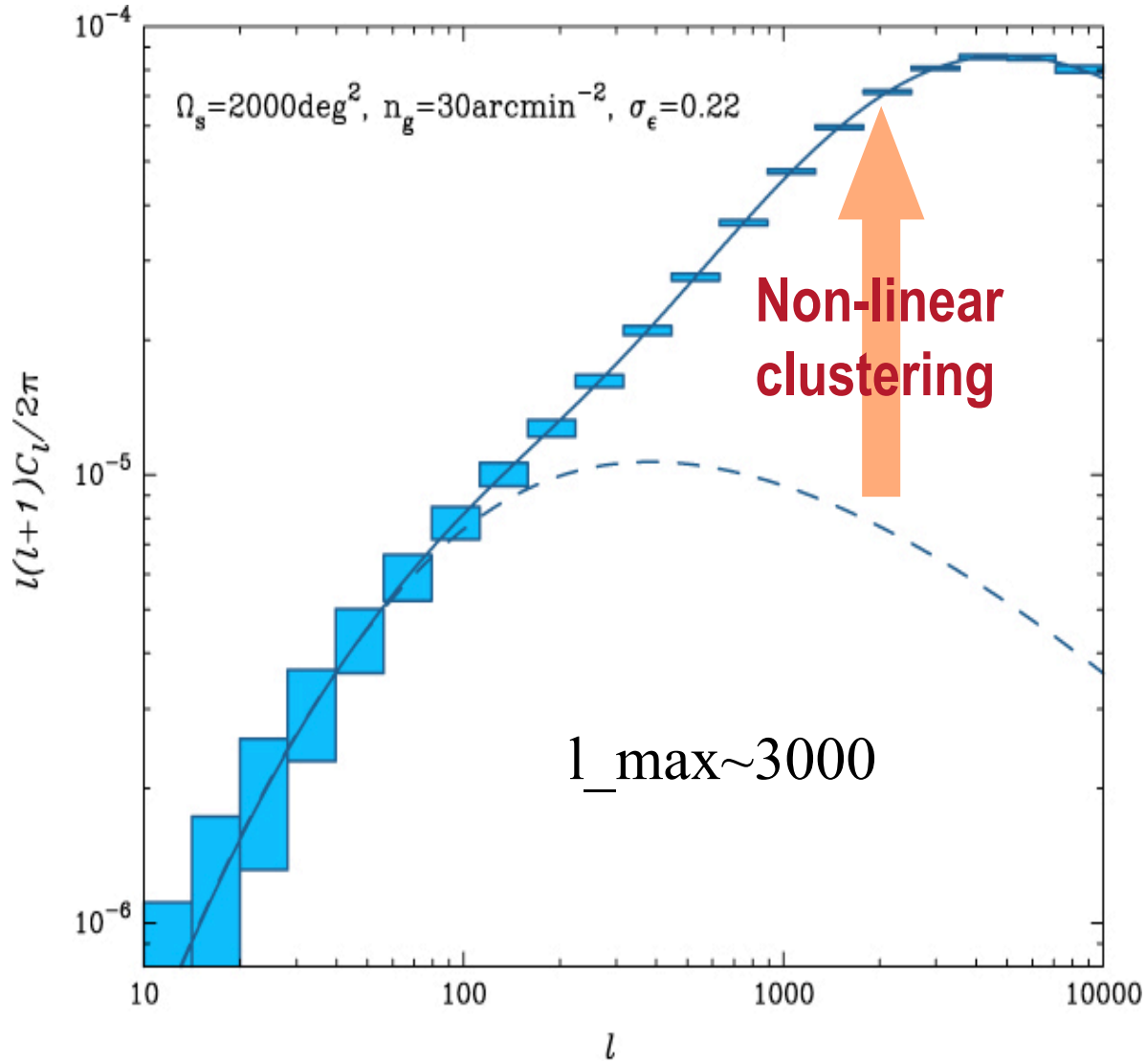
Growth Rate

- The initial conditions on the perturbations are

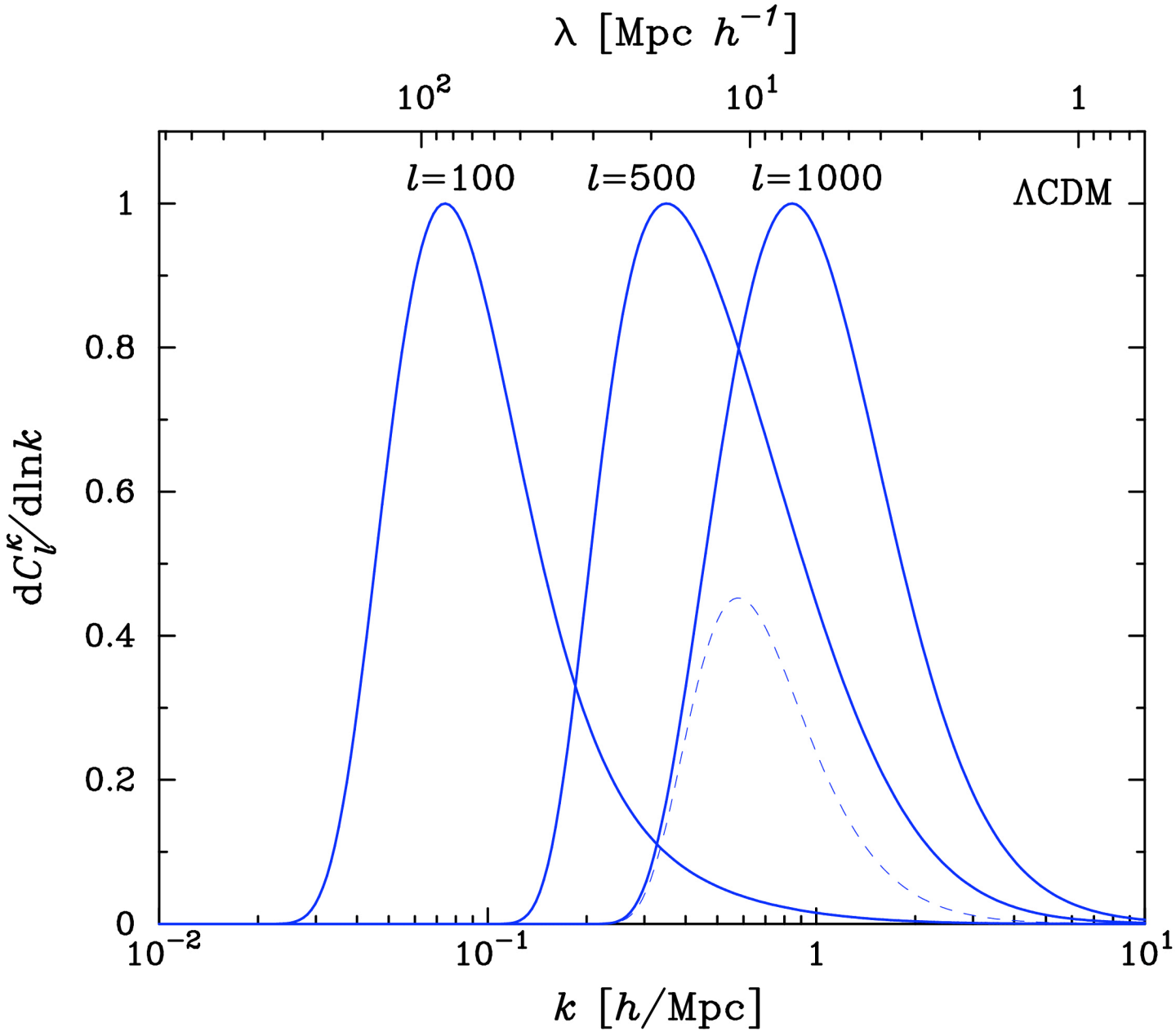


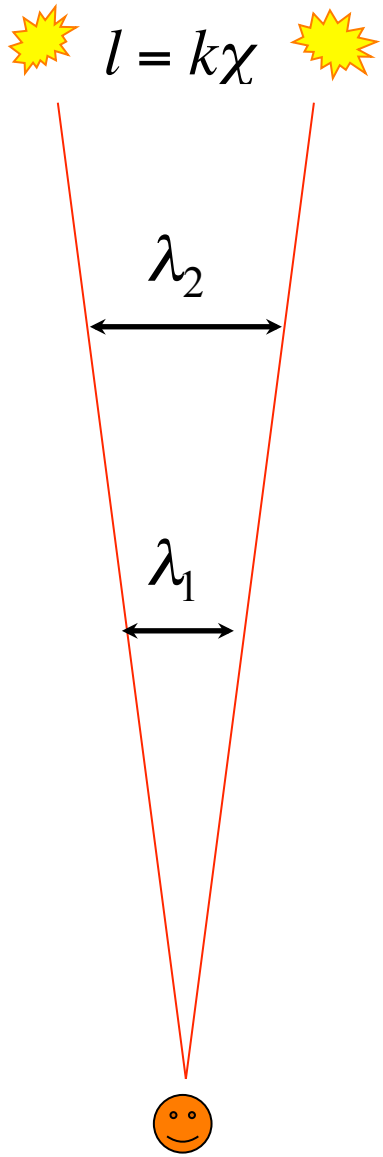
Lensing power spectrum: nonlinear boost

- Most of WL signal is from small angular scales, where the non-linear clustering boosts the lensing signals by an order of magnitude (Jain & Seljak97).
- Large-scale structures in the non-linear stage are non-Gaussian by nature.
- Baryonic physics: l>10^3 (see Zentner et al. 08)

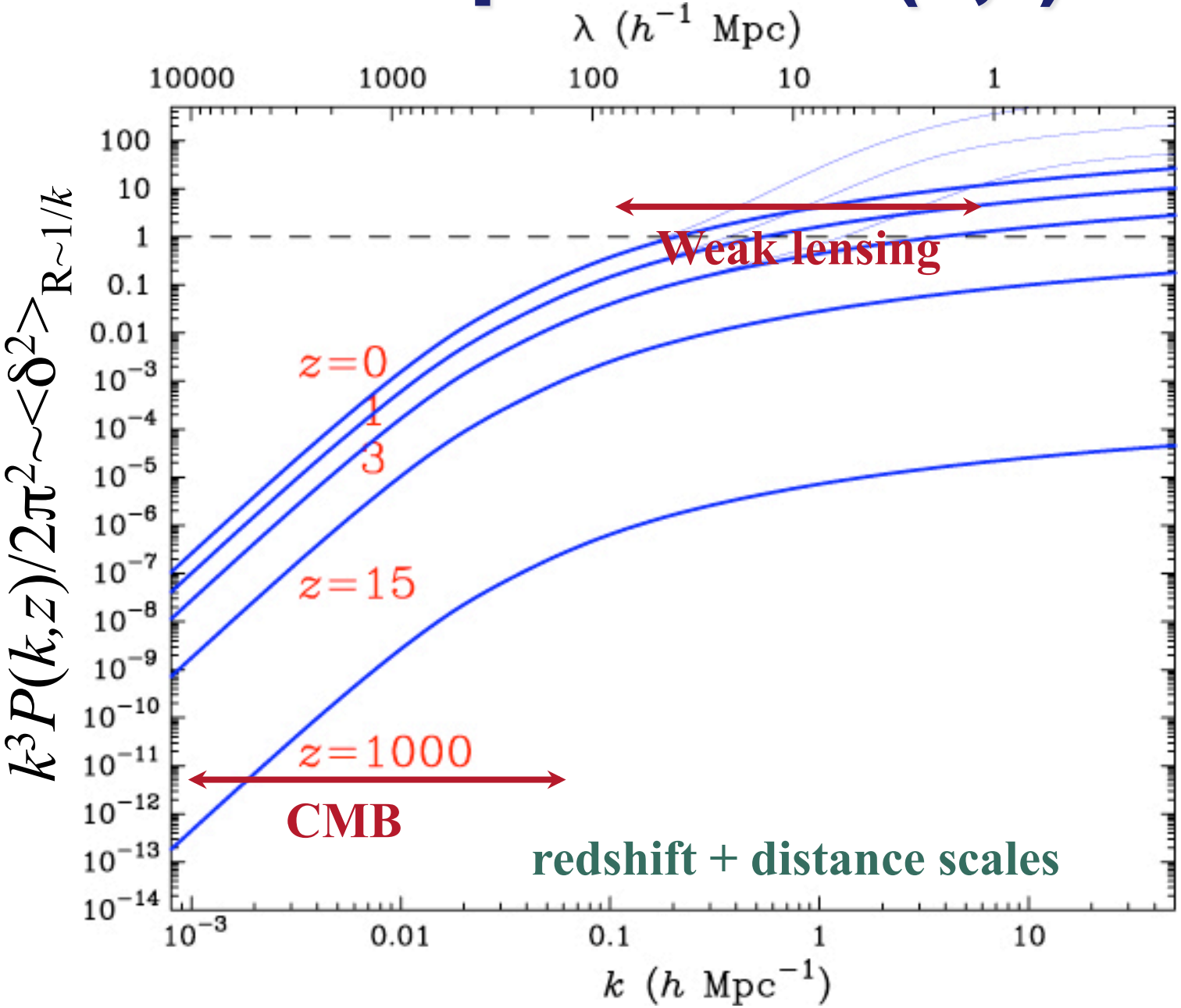


Projection effect (2D⇔3D)



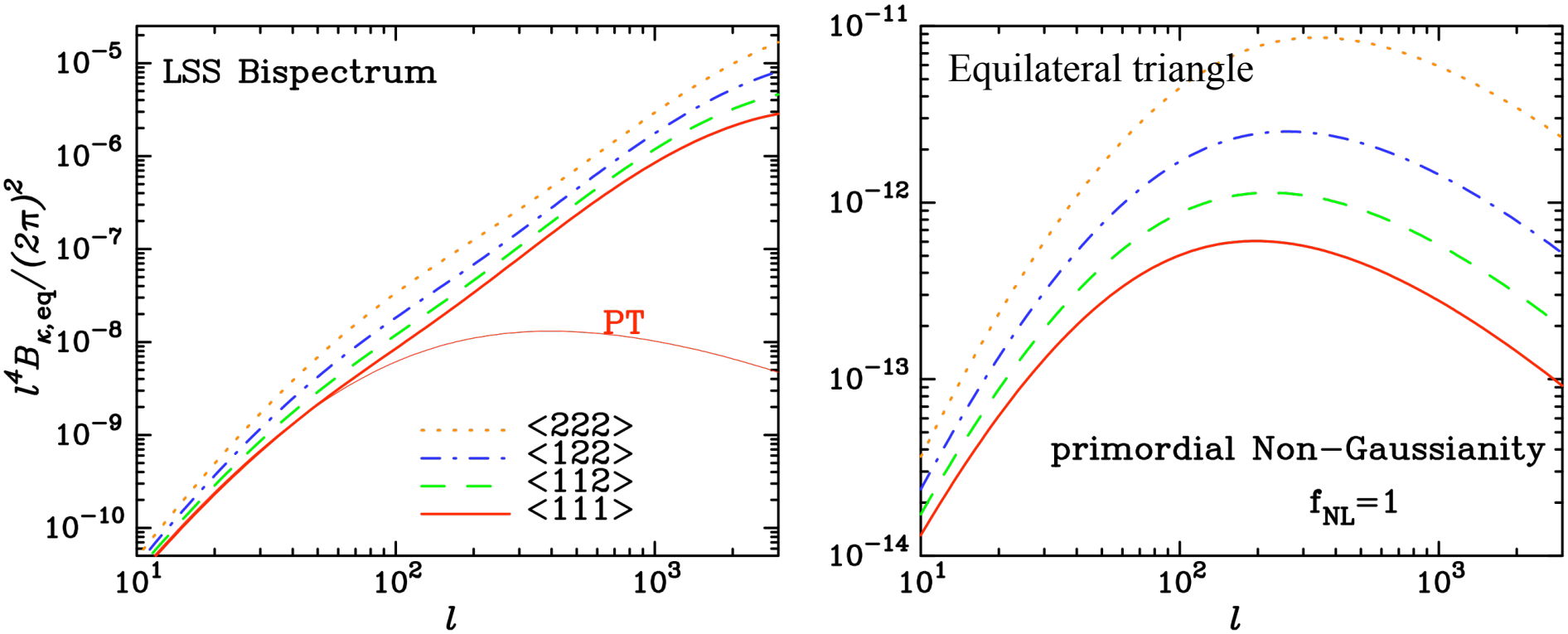


Power spectrum P(k,z)



Lensing bispectrum: primordial NG measurable from lensing?

MT & Jain 04



- The primordial NG biaspectrum is obscured by the nonlinear clustering bispectrum due to projection
- Weak lensing not powerful to constrain f_NL

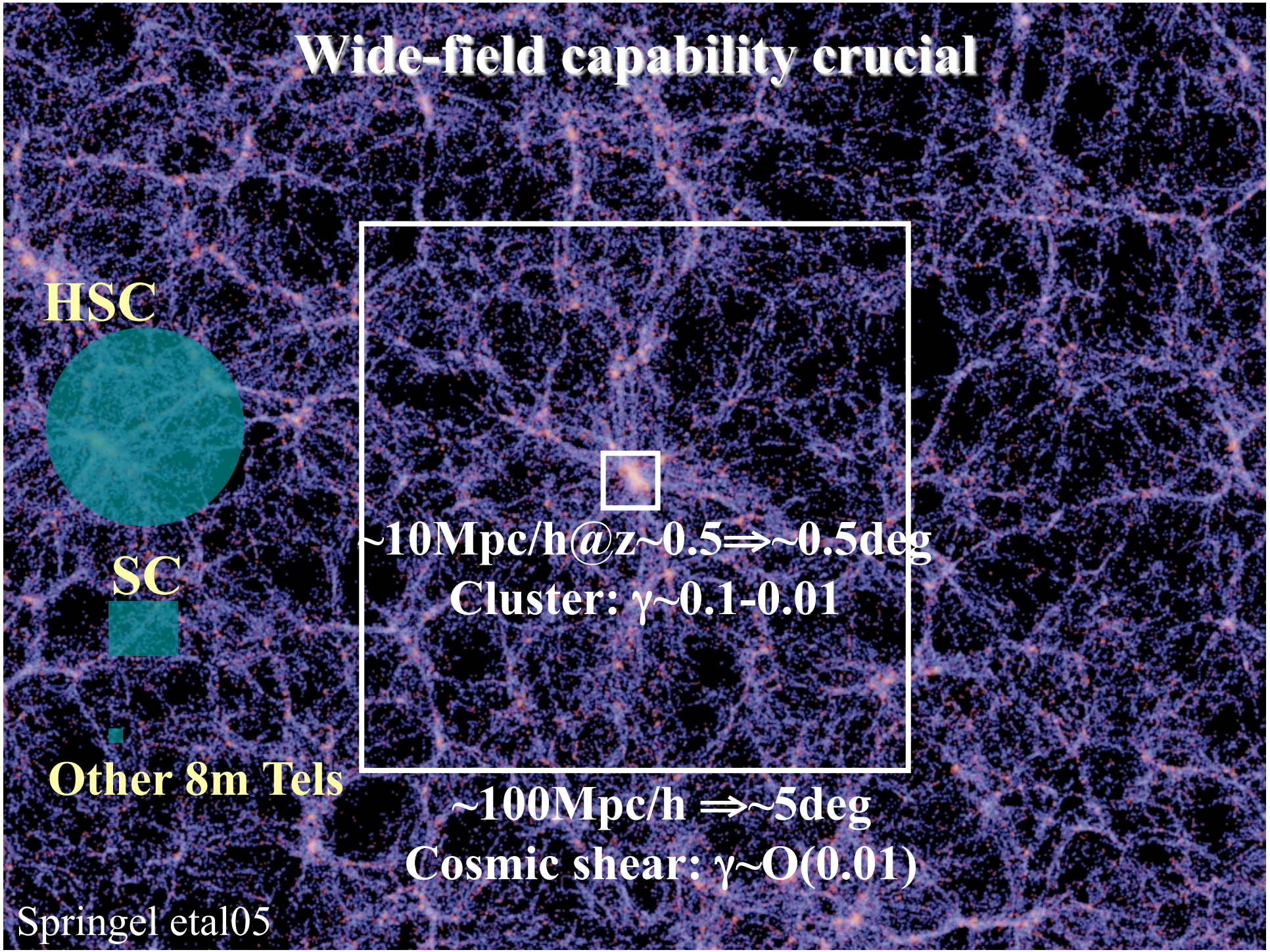
Wide-field lensing surveys

- Ongoing survey
  - CFHT Legacy Survey: Ω_s~200 deg^2, n_g~20 arcmin^-2

- Stage-III surveys (5-year time scale)
  - KIDS (2008?-): Ω_s~1500 deg^2, n_g~10 arcmin^-2
  - Pan-STARRS (2009-): Ω_s~30000 deg^2, n_g~4 arcmin^-2
  - DES (2011-): Ω_s~5000 deg^2, n_g~10 arcmin^-2
  - Subaru (2011-): Ω_s~2000 deg^2, n_g~30 arcmin^-2

- Stage-IV surveys (10-year time scale): *ultimate survey*
  - LSST (2016?-): Ω_s~20000 deg^2, n_g~50 arcmin^-2
  - SNAP/JEDM (20??-): Ω_s~4000 deg^2, n_g~100 arcmin^-2
  - EUCLID (20??-): Ω_s~20000 deg^2, n_g~100 arcmin^-2

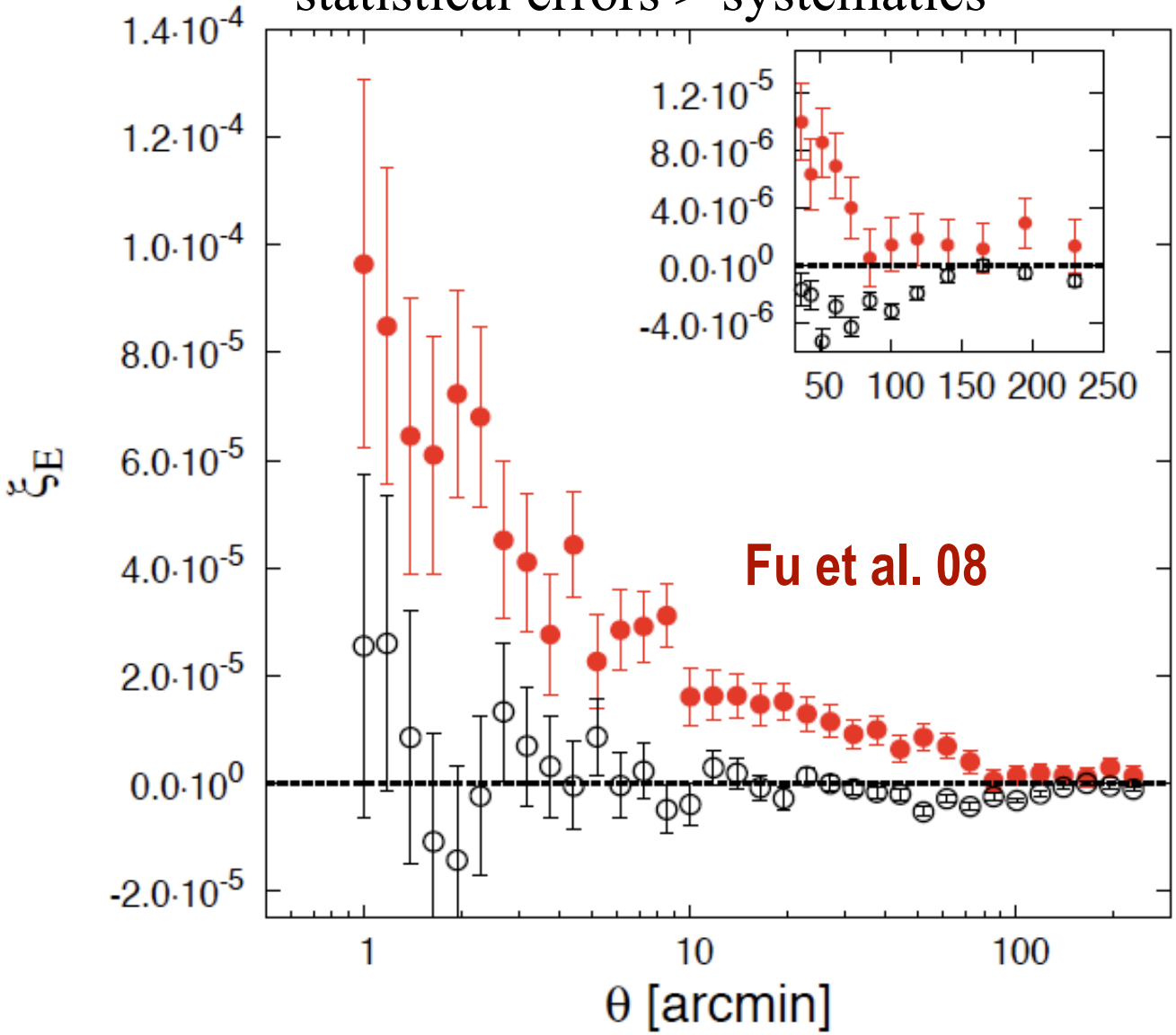
Wide-field capability crucial



Springel etal05

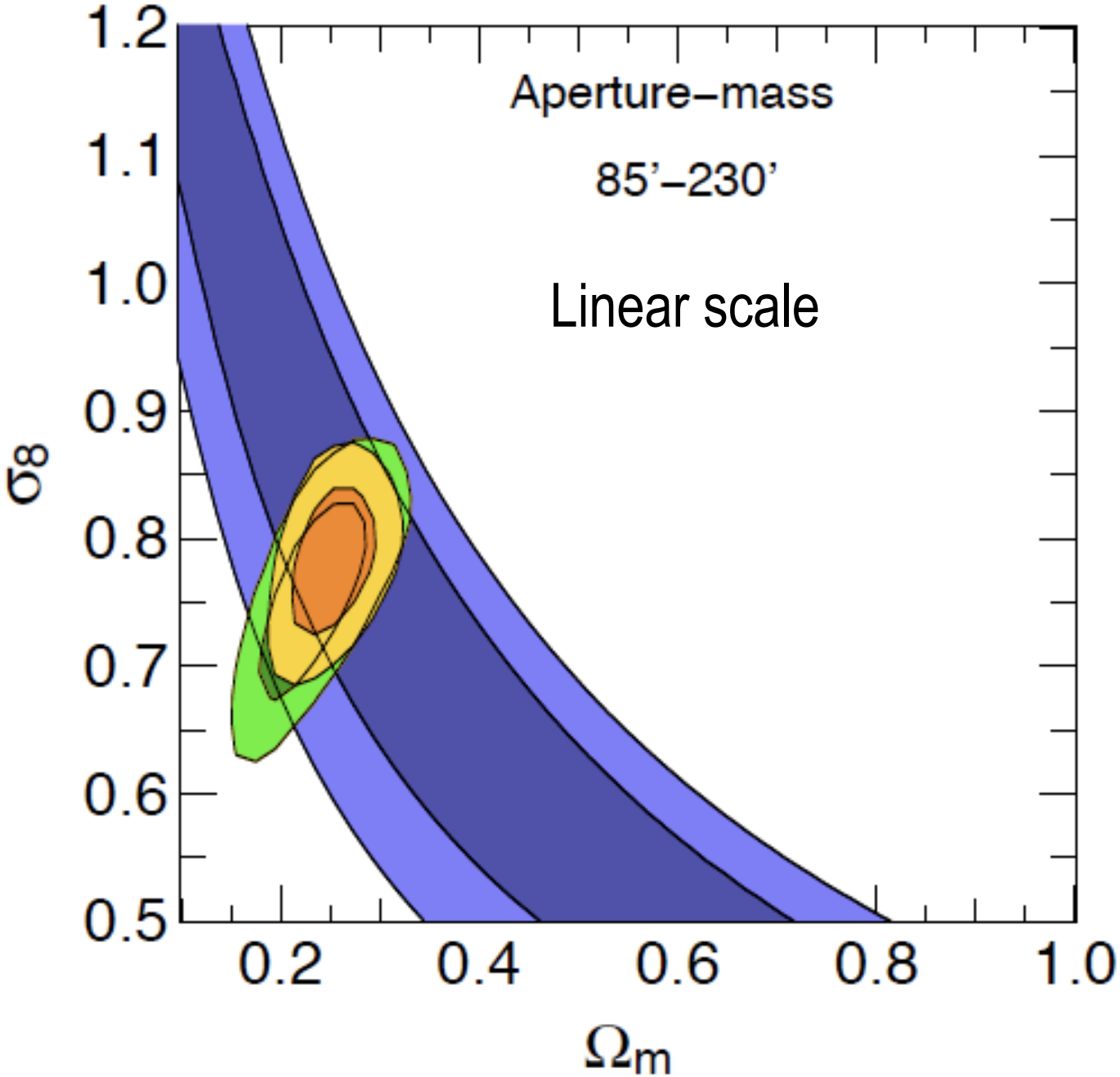
The state-of-art: CFHT WL Survey

statistical errors > systematics



- ~60 sq deg^2 (effective area: ~30 sq. deg^2)
- *i*'_AB~24.5, <z>~0.9
- Calibrate source redshift with the CFHT deep survey and the VVSD
- **~20σ detection,** over a range of few arcminutes to a few degrees
- 170 deg^2 results will be released this year?

Cosmological constraints



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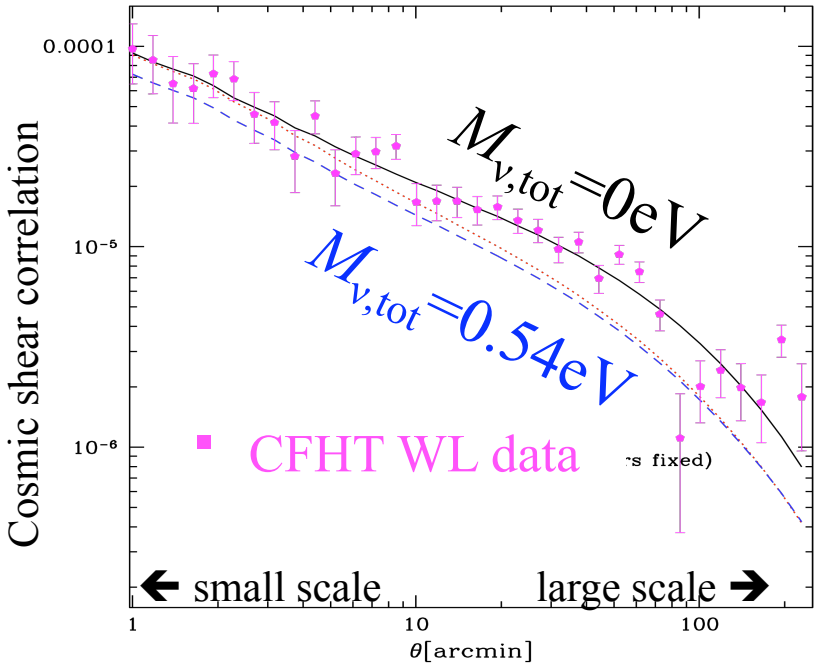
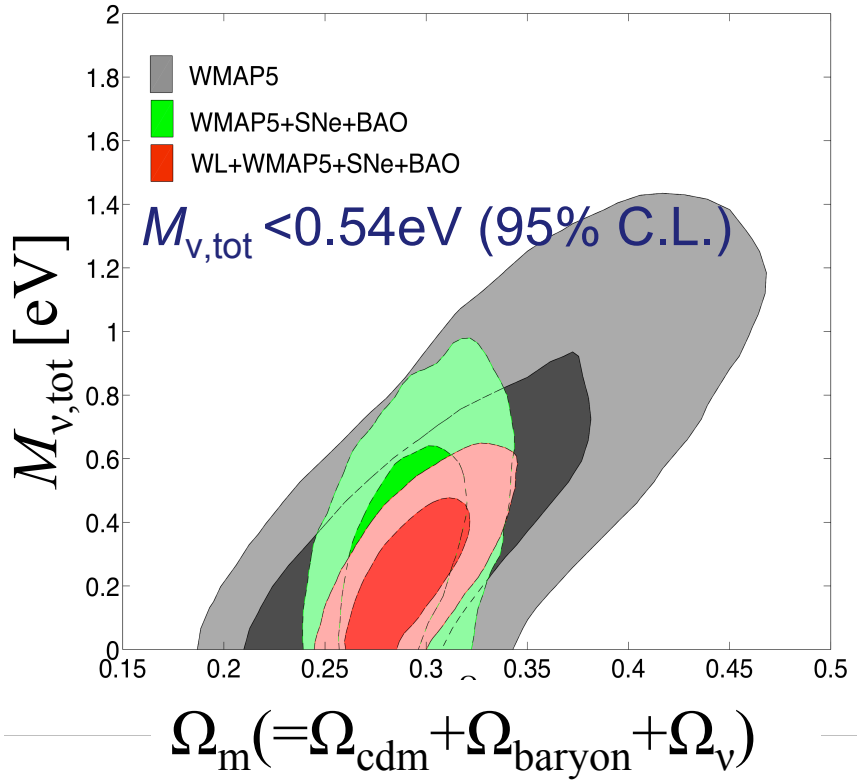
Neutrino mass

Ichiki, MT, Takahashi 09

- Apply the NL model of P(k) to CFHT weak lensing data (~60deg^2)
- WL directory probes total matter (free of galaxy bias)
- Even though the data is from a small sky coverage (60deg^2), the total mass M_nu is constrained as M_nu,tot <0.54eV (WMAP5+SN +BAO)

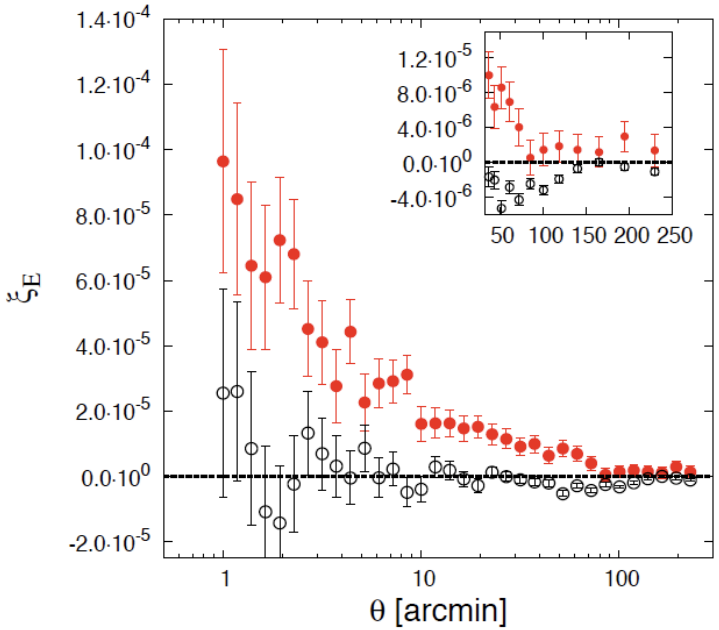




Q: Real-space vs. Fourier space?

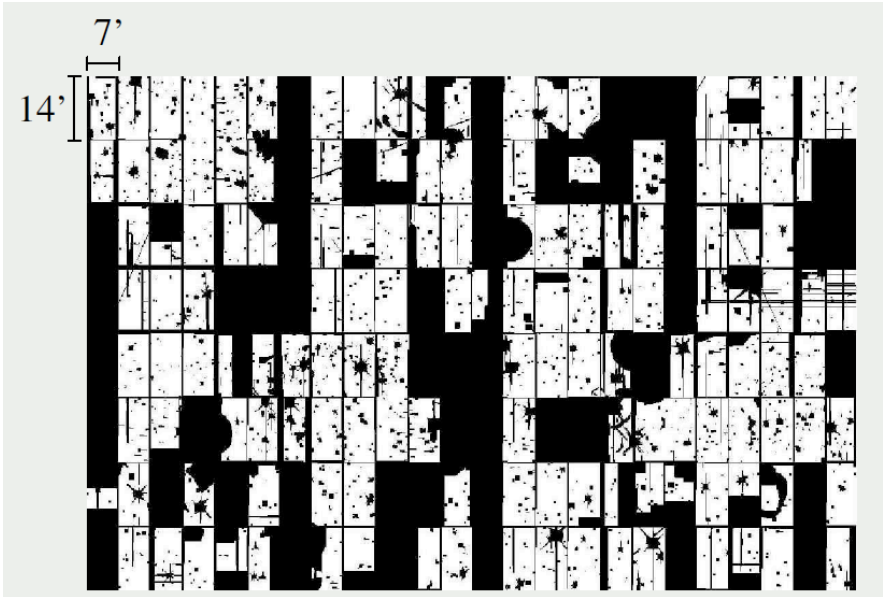
The previous studies use correlation function measurements

Correlation function and power spectrum are theoretically equivalent



Real-space

- *Pros*: handle complex survey geometry
- *Cons*: different bins highly correlated (complex covariance matrix).

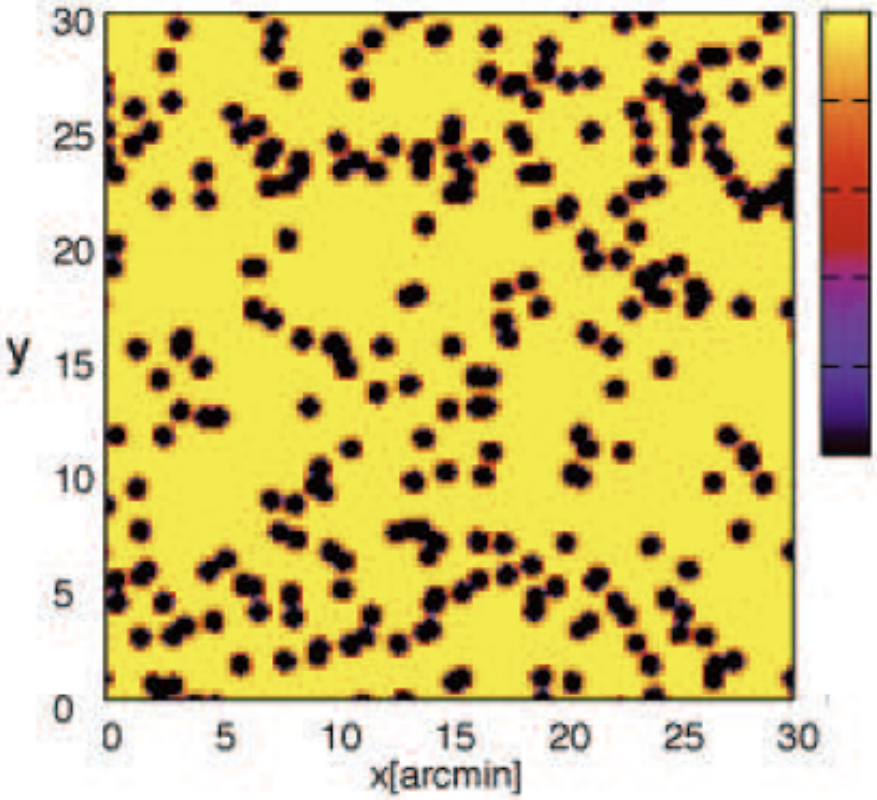


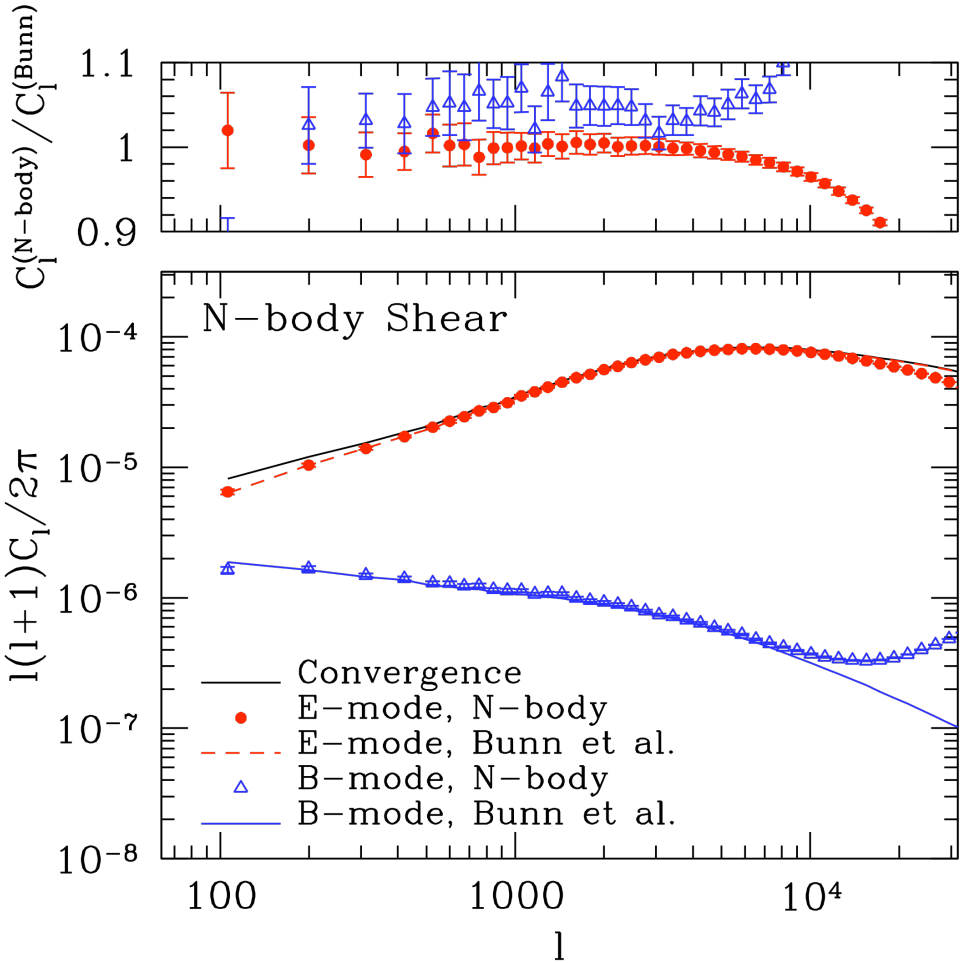
Fourier-space

- *Pros*: easy to interpret theoretically
- *Cons*: difficult to measure from a complex survey geometry

Power spectrum reconstruction

Hikage, MT, Spergel in prep.

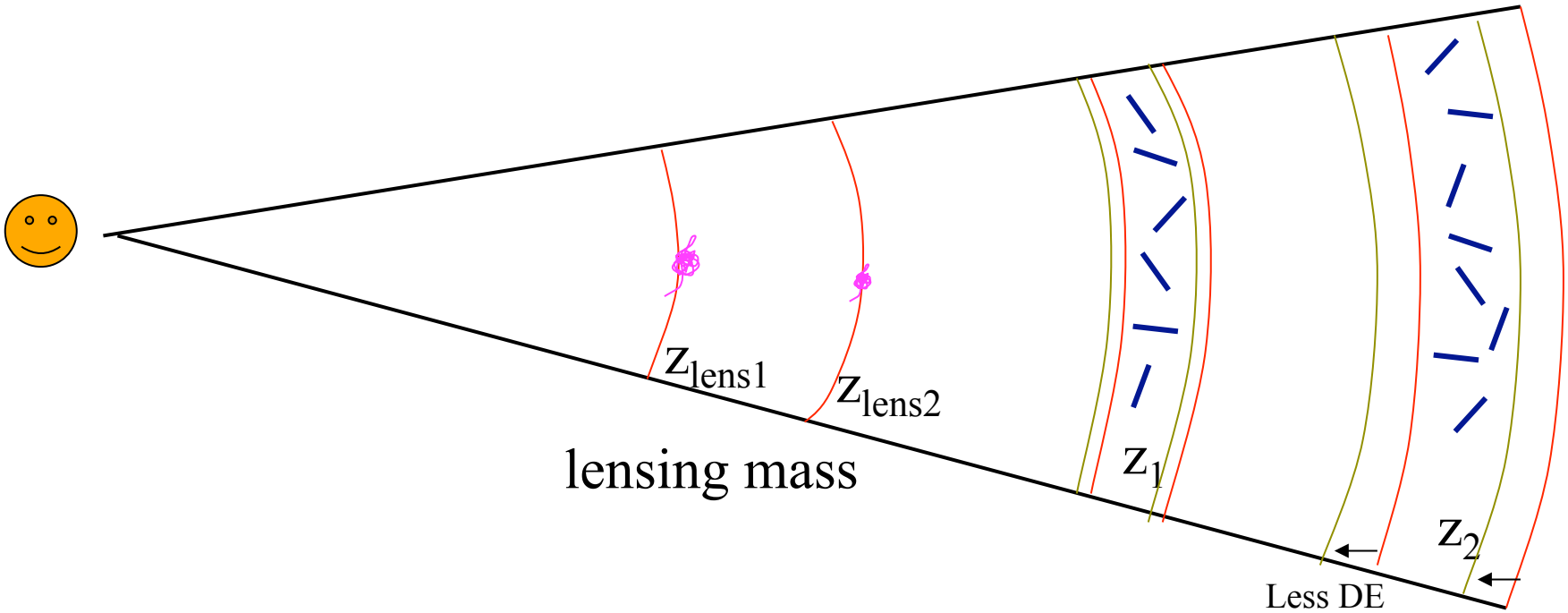




- E-mode power spectrum reconstruction from simulated lensing maps with masking (bright stars) → so far seems feasible!
- B-mode leakage due to a finite sky seems be correctable

Lensing tomography

(Hu 99; Huterer 02; Refregier et al. 03; MT & Jain 04)



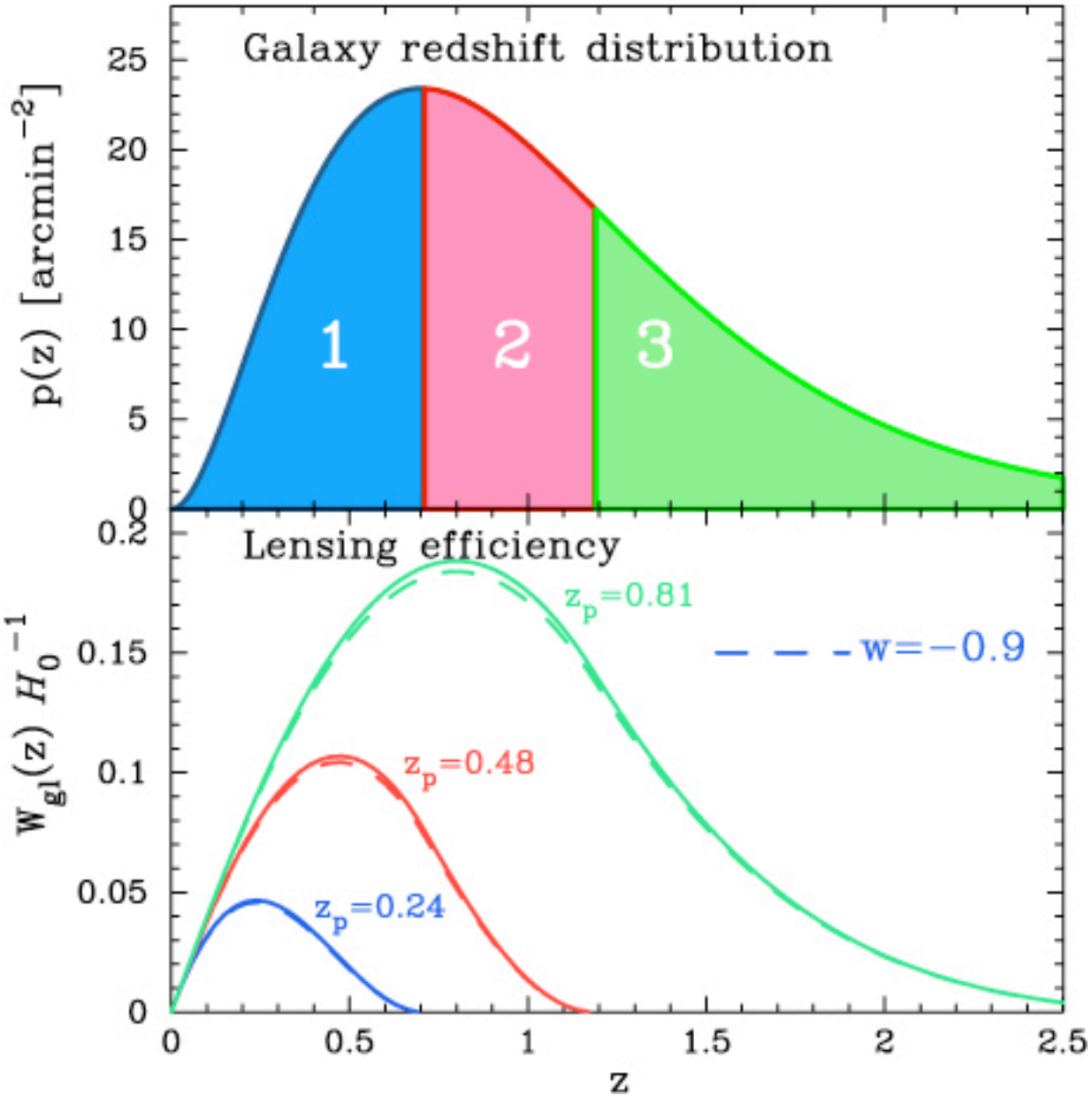
Adding redshift information!

Shear at z_1 and z_2 given by integral of growth function & distances over lensing mass distribution ➡ Lensing tomography probes expansion kinematics and growth of structure

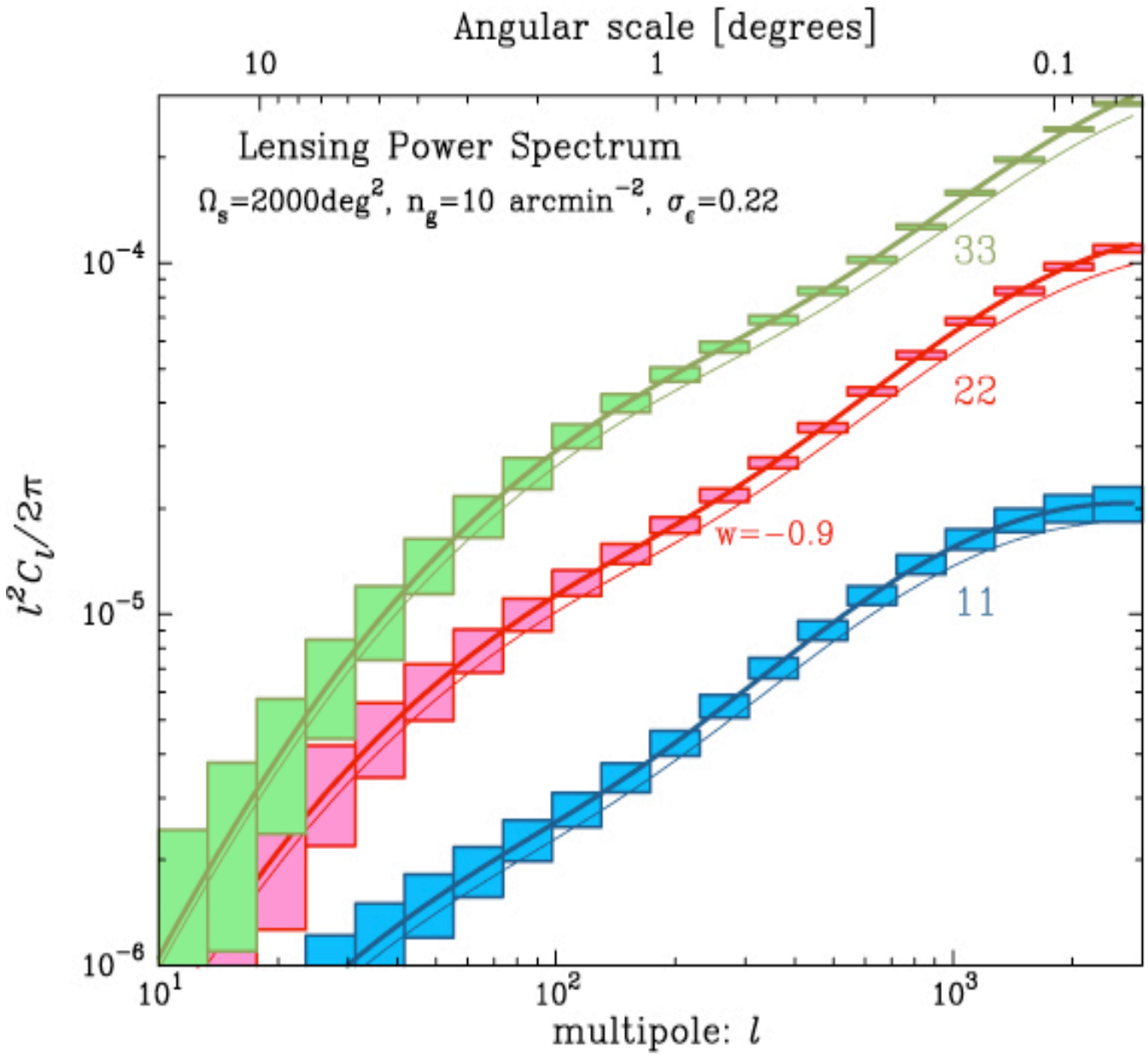
Lensing Tomography

- Subdivide source galaxies into several bins based on photo-z derived from multi-colors (4 or 5 colors for HSC)
- Adds some ``depth'' information to lensing – improve cosmological paras (including DE)

(Hu 99; Huterer 02; Refregier et al. 03; MT & Jain 04)

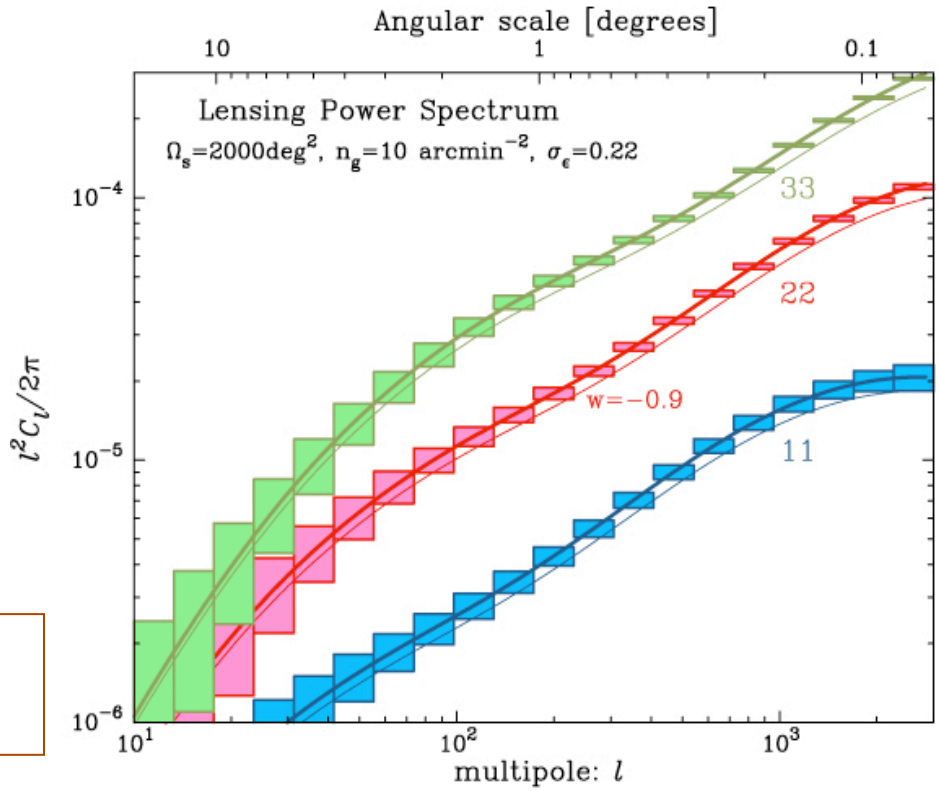


Tomographic Lensing Power Spectrum



- WL + photo-z
- Tomography allows to extract redshift evolution of the lensing power spectrum.
- A maximum multipole used should be like l_max<3,000
- ~10^7×(V/1000 deg^2) Fourier modes

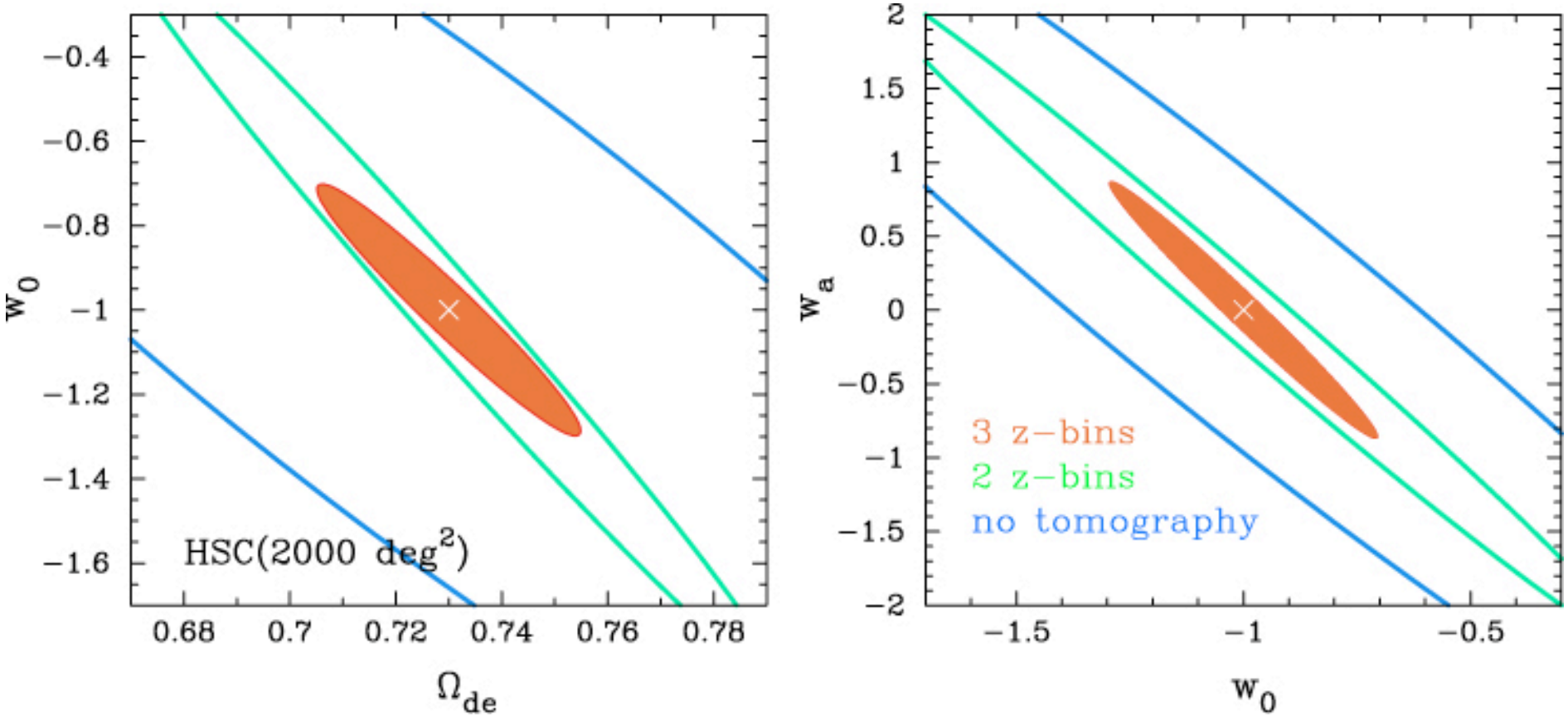
Tomographic Lensing PS (contd.)



$$\gamma \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

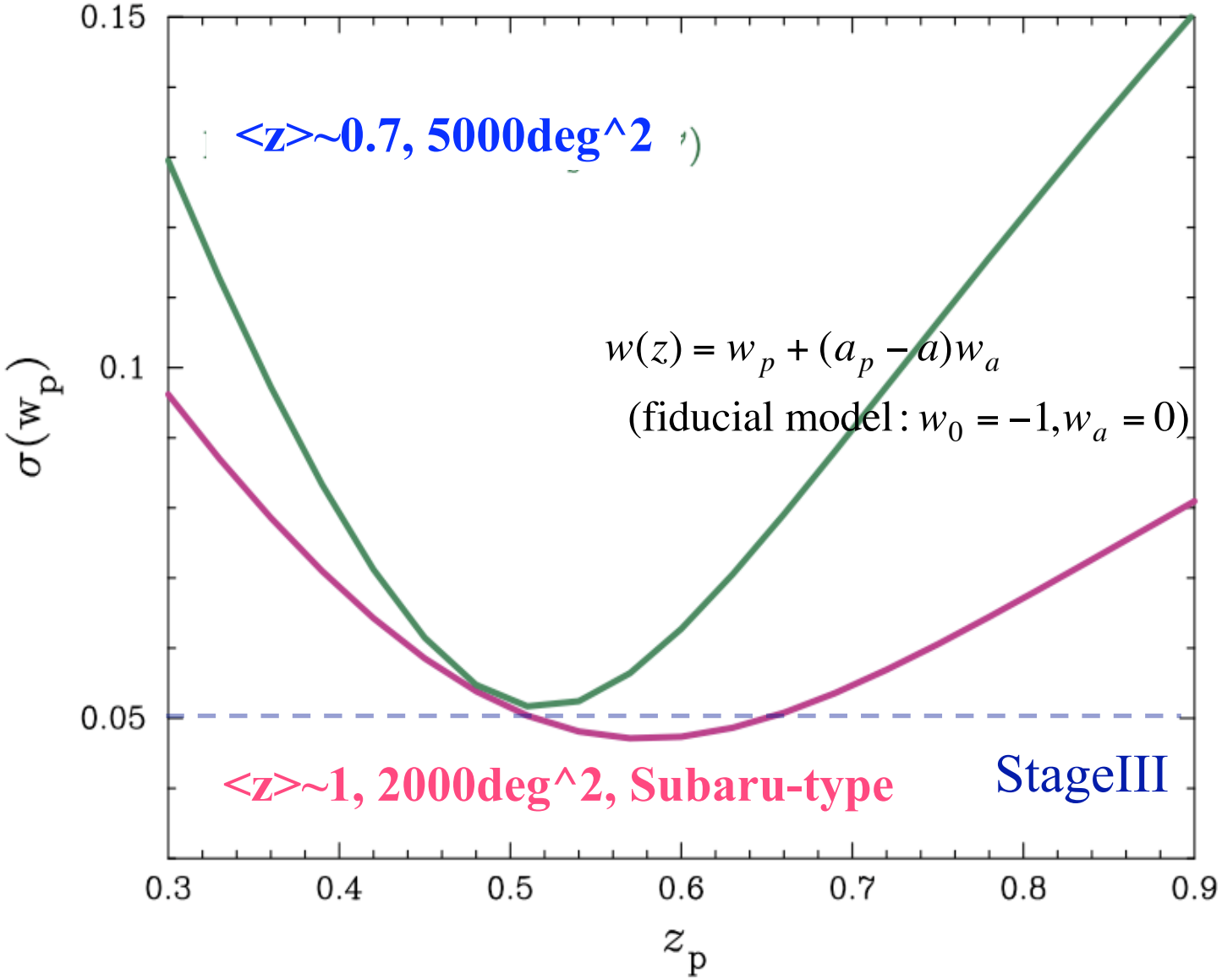
- Lensing PS has a less feature shape, not like CMB
  - Can't better constrain inflation parameters (n_s and alpha_s) than CMB
  - Need to use the **lensing power spectrum amplitudes** to do cosmology: the amplitude is sensitive to A_s, Ω_{de0} (or Ω_{m0}), w(z).

Lenisng tomography (condt.)



- WLT can be a powerful probe of DE energy density and its redshift evolution.
- Need 3 z-bins at least, if we want to constrain DE model with 3 parameters (Ω_de,w0, wa)
- Less improvement using more than 4 z-bins, for the 3 parameter DE model
- SNAP-type survey can constrain w(z_i) at ~4 different redshift bins (Albrecht & Bernstein 07)

Deep vs. Shallow Survey



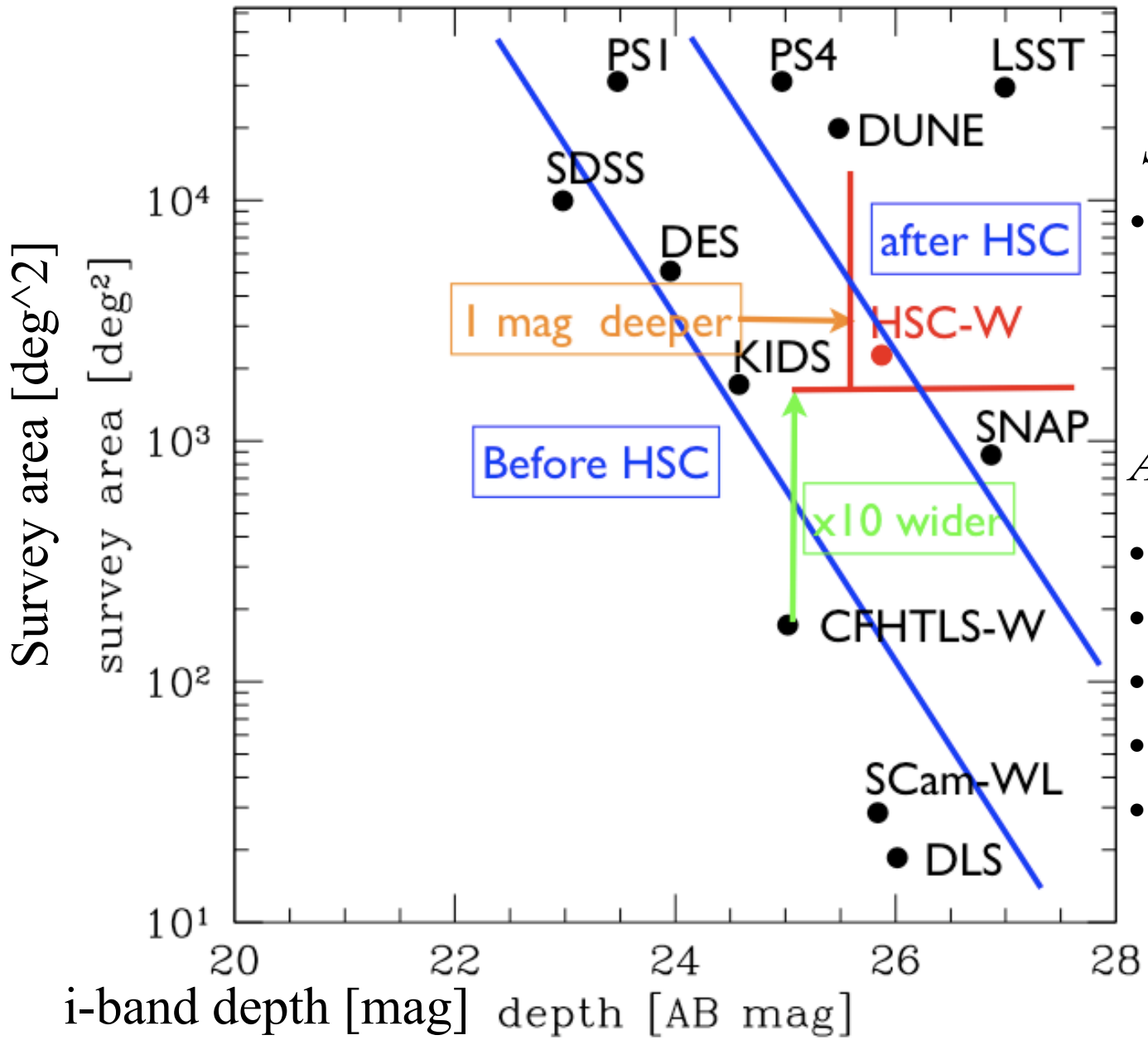
-For a fixed obs. time, a wider area more powerful for DE

-A deeper survey allows sensitivity to DE over a wider redshift range

-E.g., if w≠-1 around z~0.7, HSC could probe

-Note: high-z BAO survey can probe w at z>1

Survey parameters



Science drivers

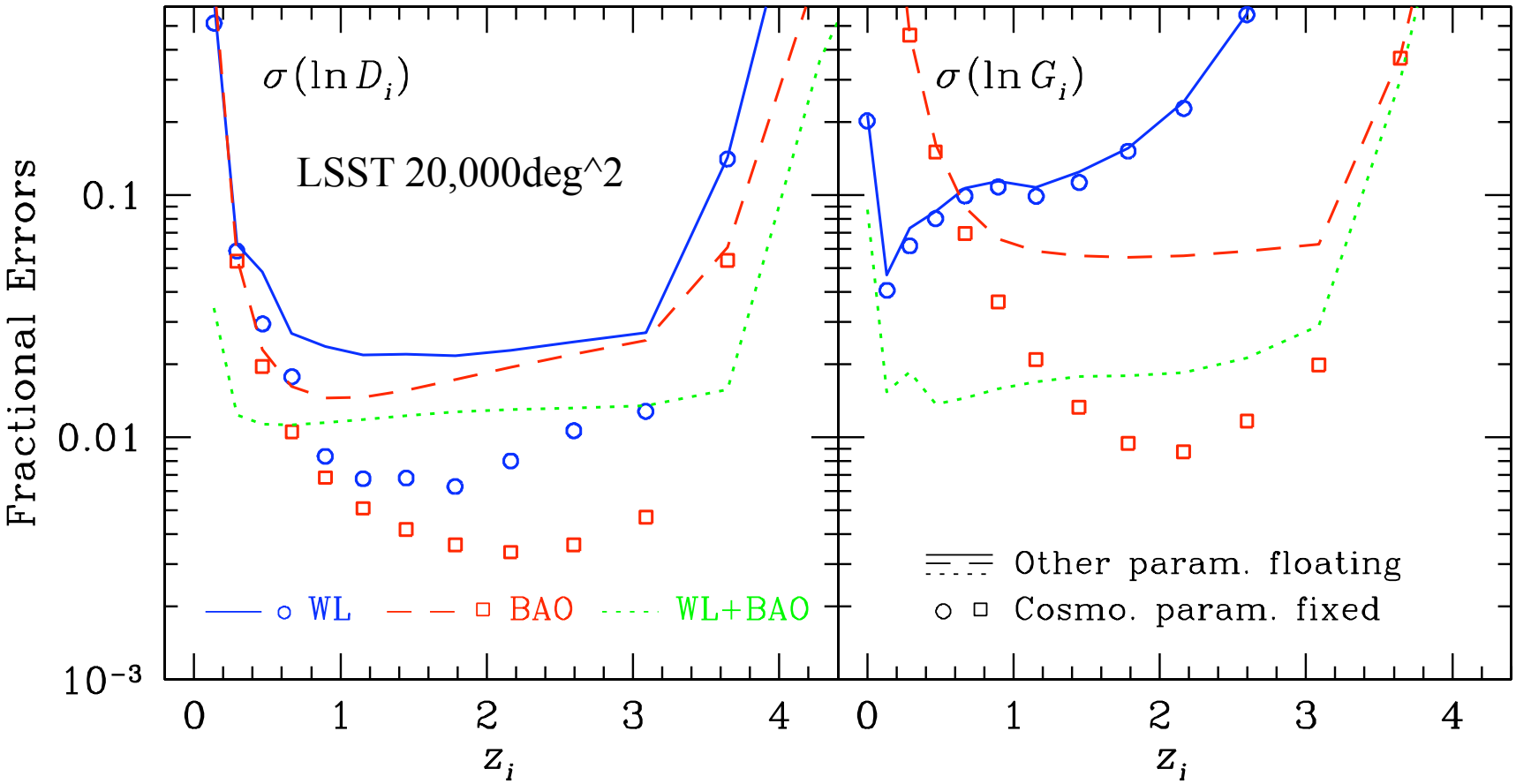
- Weak lensing
  - DE, DM

Auxiliary sciences

- Clusters
- High-z QSOs
- Strong lensing
- Galaxy evoution
- Milky Ways (dwarf satellites)

Growth rate reconstruction

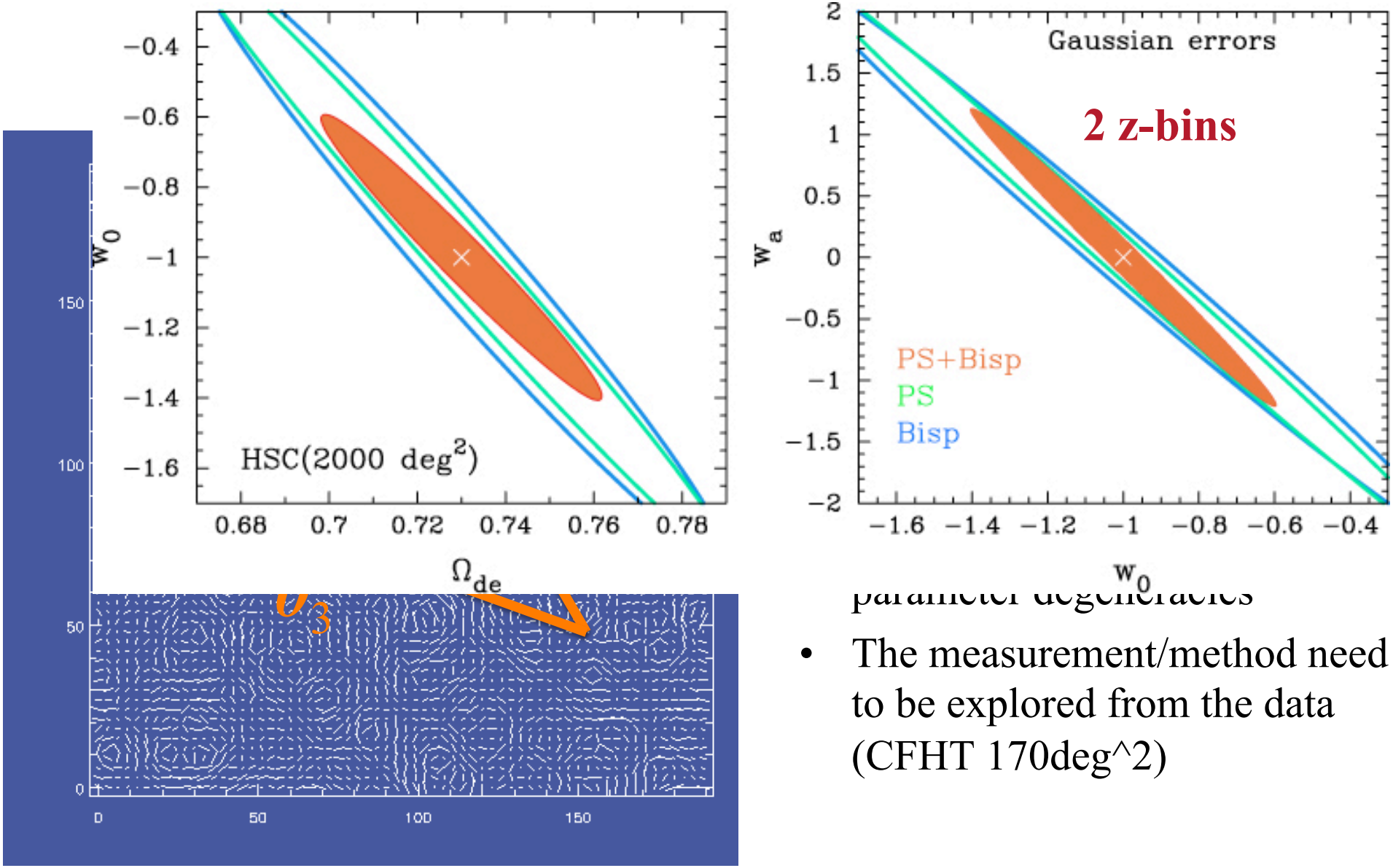
Zhang, Knox, Tyson 08



- Combining BAO+SNe (geometrical probe) with WL (geometrical + growth) allows a reconstruction of growth rate
- The plot above: photo-z BAO (20 z-bins, lmax=3000) + WL(10 z-bins, lmax=2000) allows a % accuracy reconstruction of G_i?

2pt + 3pt

MT & Jain 04

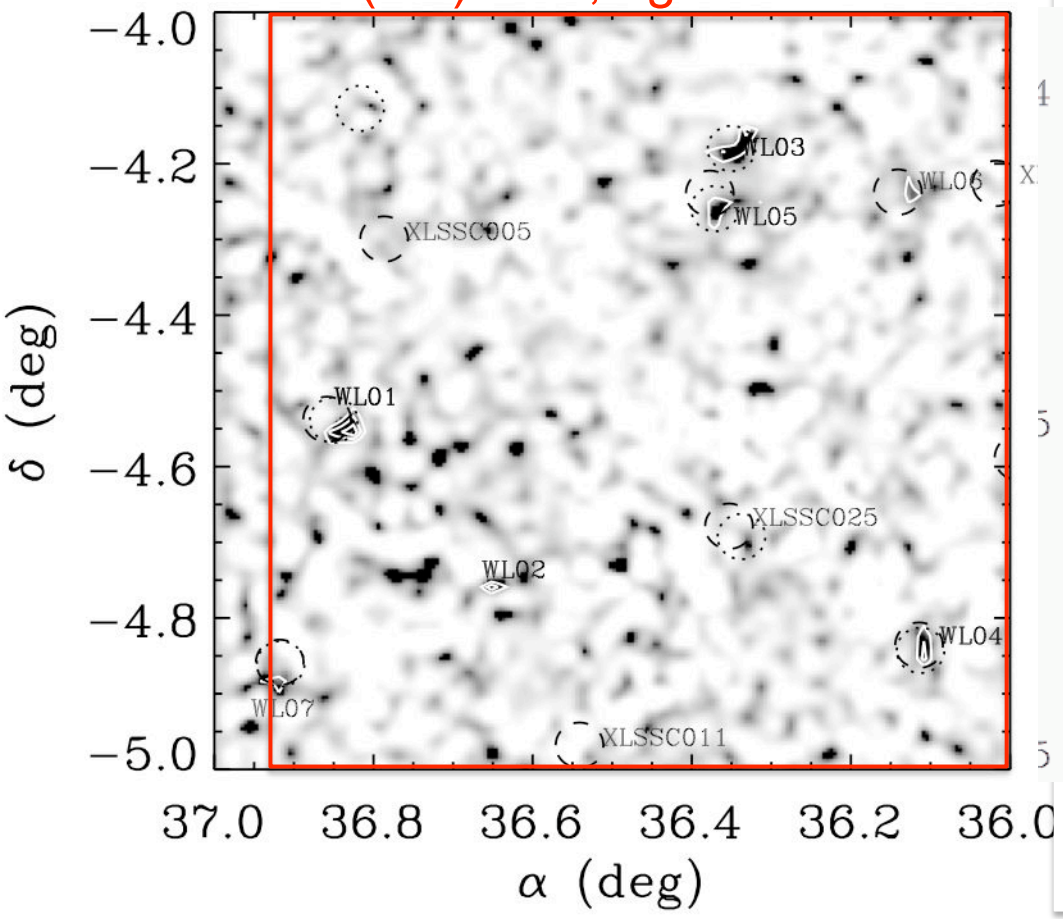


parameter degeneracies

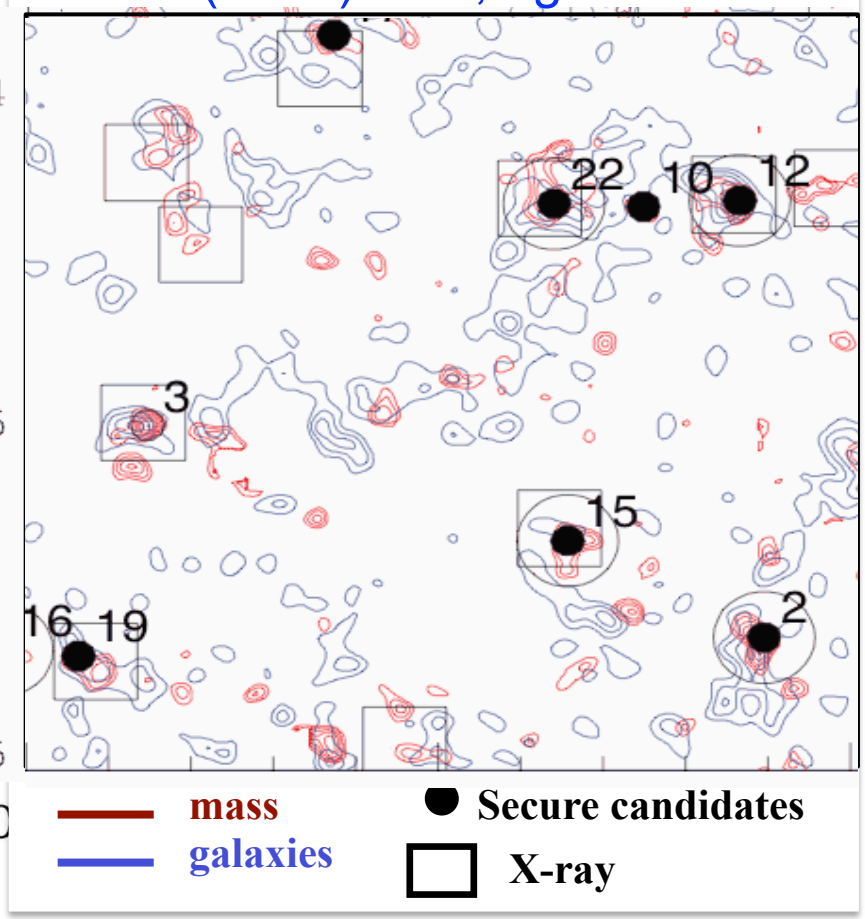
- The measurement/method need to be explored from the data (CFHT 170deg^2)

Blind lensing cluster survey

CFHT (4m): 37h, ng~30/arcmin^2



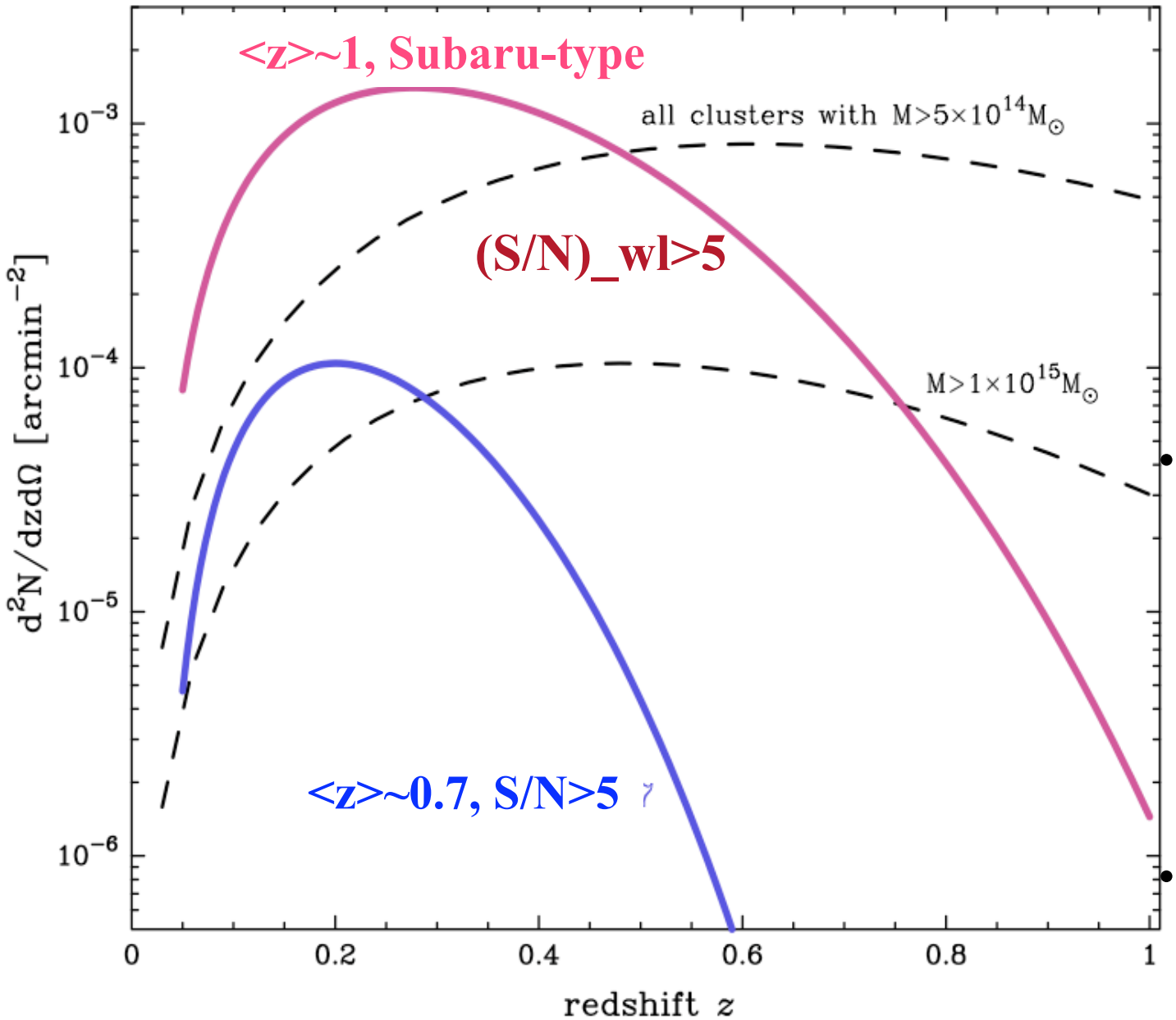
Subaru(8.2m):0.5h, ng~35/arcmin^2



$$\left(\frac{S}{N}\right)^2 \propto \bar{n}_g$$

- Deeper data has a better sensitivity to studying lensing of clusters (out to higher redshifts)

Deep vs. Shallow



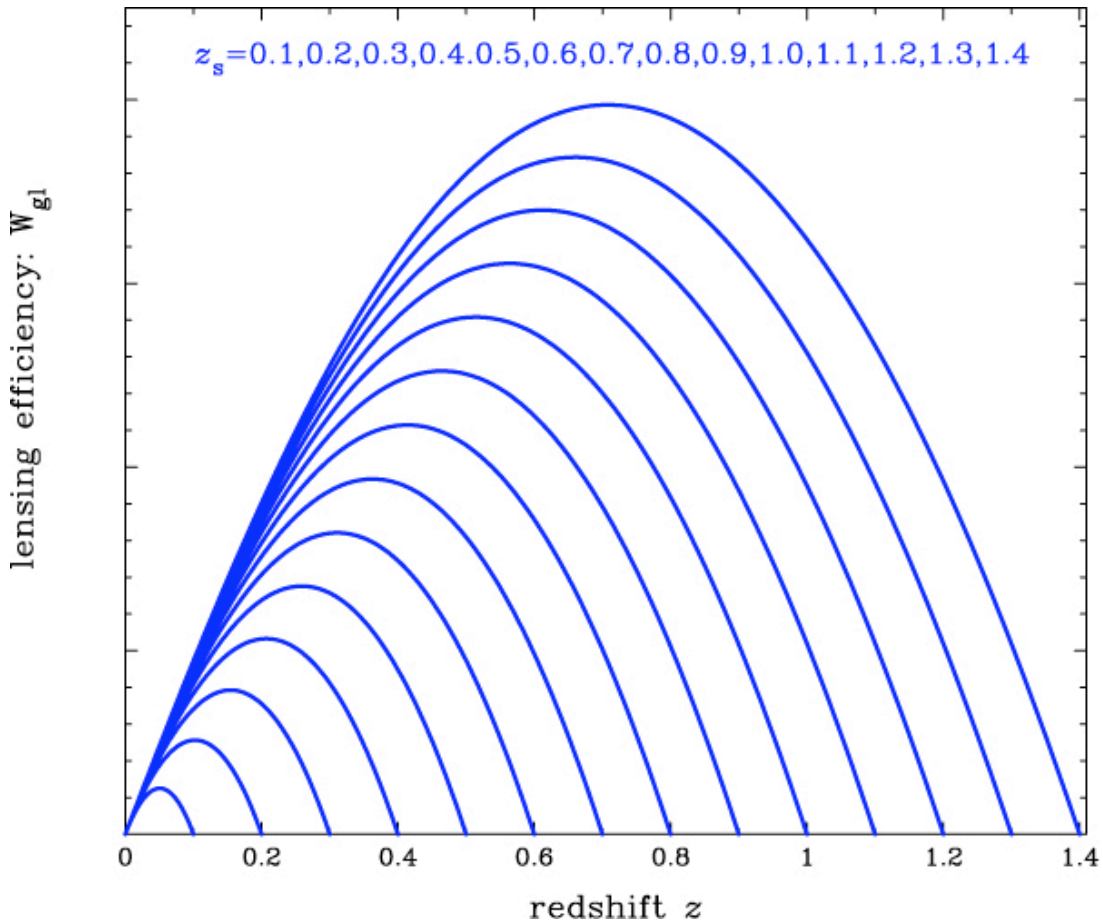
Expected redshift distribution of lensing clusters

- A deeper survey allows to find more clusters at each *z* and over a wider redshift coverage up to z~1
- *Synergy with SZ survey*

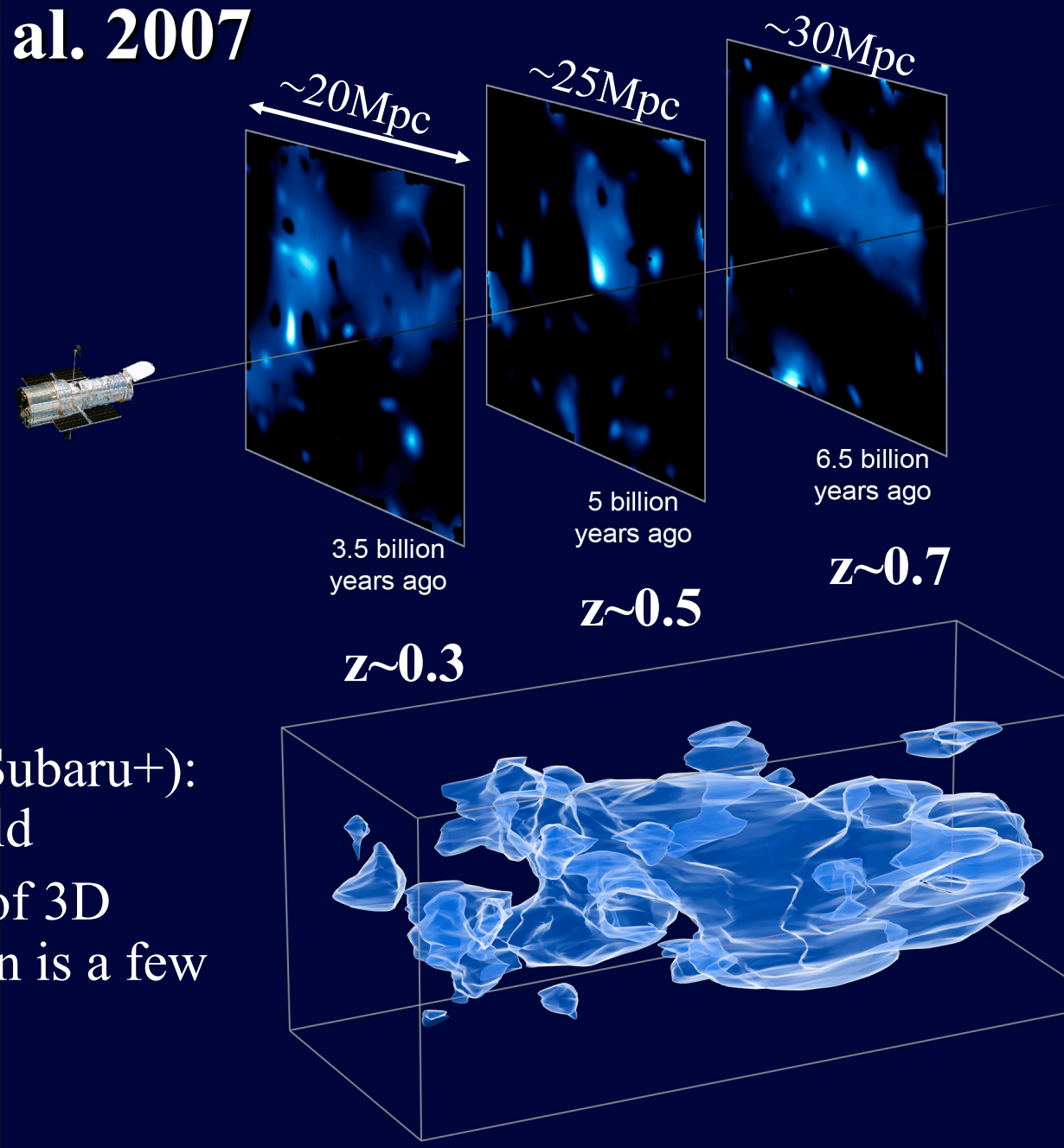
3D mass reconstruction

$$\gamma \propto \Omega_{m0} \int_0^{z_S} dz_L \frac{d_{LS}(z_L, z_S) d_L(z_L)}{d_S(z_S)} \delta(z_L, \boldsymbol{\theta})$$

- If source redshifts (z_s) and cosmology are known (fairly accurately), measuring shear as a function of z_s and angular position allows a 3D mass reconstruction (*real* tomography!)
- A direct test of CDM hierarchical clustering scenario



Massay et al. 2007



- COSMOS (HST+Subaru+): ~1.7 sq. degree field
- Spatial resolution of 3D mass reconstruction is a few 10Mpc

Systematic errors

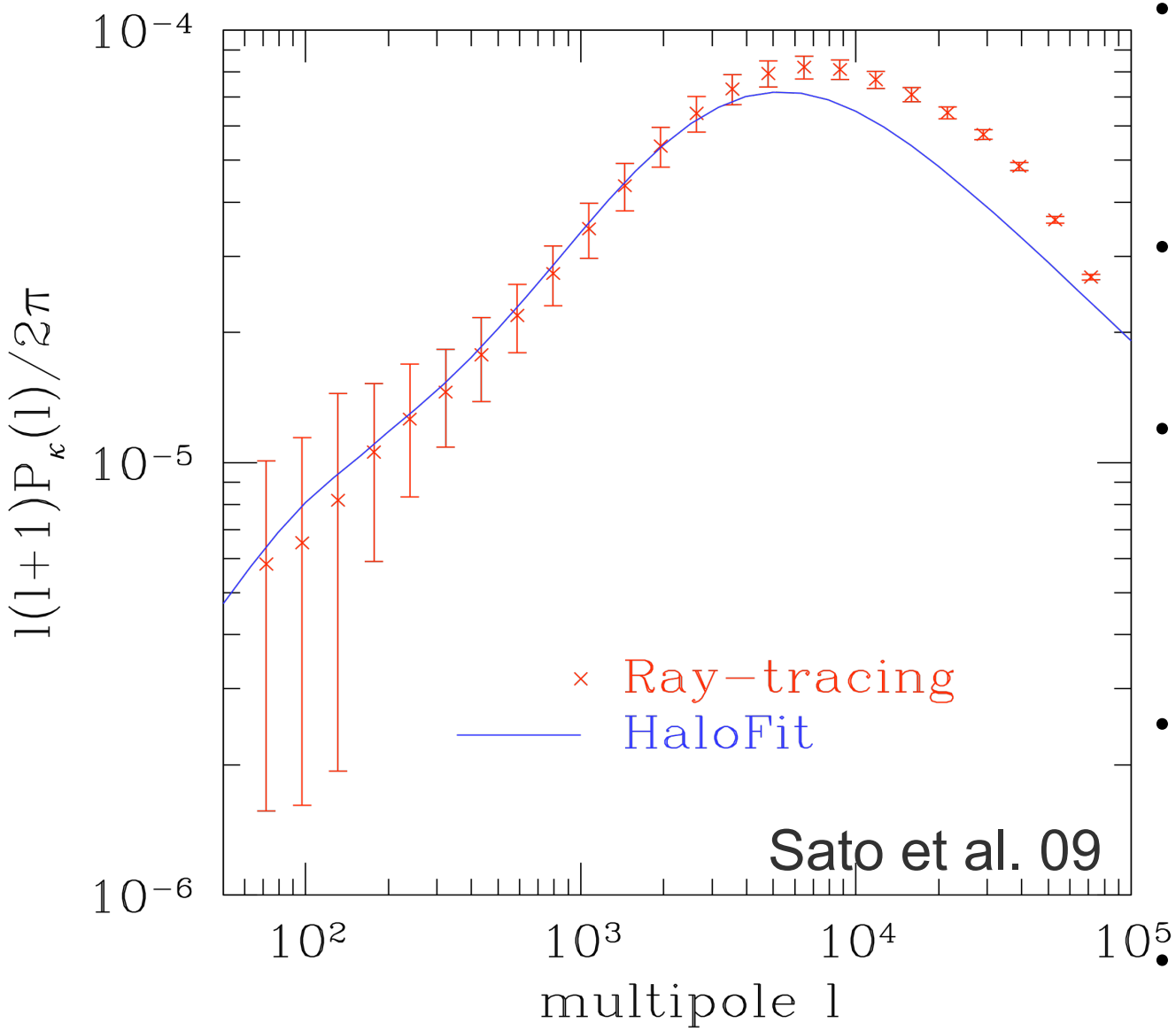
- Nonlinearities of structure formation
  - Model predictions: a few % of P(k) at k~1/Mpc
  - Non-Gaussian errors

- Systematic issues in the measurements

$$\gamma_+^{\rm obs}(\theta_i) = \gamma_+^{\rm cluster}(\theta_i) + \gamma_+^{\rm LSS}(\theta_i) + \varepsilon_+(\theta_i) + {\rm sys.}$$

  - Cosmic shear is quadratic, so systematic errors can be additive
  - Photo-z, a bias in the mean redshift needs to be smaller than 1%: photometric calibration, removing outliers, a training spectroscopic sample
  - Intrinsic alignments: requirements on photo-z
  - Shape measurements: e.g. a bias in multiplicative factor needs to be smaller than 1%

Nonlinear power spectrum



- Sato et al. used 1000 ray-tracing simulations to estimate the average power spectrum
- A few % accuracy, within reach to the requirement
- Differ from the fitting formula results, at ell>2000 (also White & Vale 04; Hilbert et al. 08)
- Consistent with other simulations, e.g. "Coyote" (Heitmann et al.08,09)
- Baryonic effects?
  - Cluster + WL

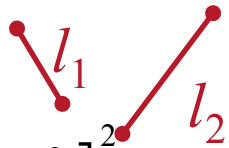
Non-gaussian errors

- Most of lensing signals are from non-linear scales: the errors are non-Gaussian
- PS covariance describes *correlation* between the two spectra of multipoles l_1 and l_2 (White & Hu 00; Cooray & Hu 01), providing a more realistic estimate of the measurement errors
- The non-Gaussian errors for PS arise from the 4-pt function of mass fluctuations in LSS
- The shot noise contributes only to the Gaussian part

$$\mathrm{Cov}[P(l_1),P(l_2)] = \langle P(l_1),P(l_2)\rangle - P(l_1)P(l_2)$$

$$= \langle$$

$$\rangle -$$



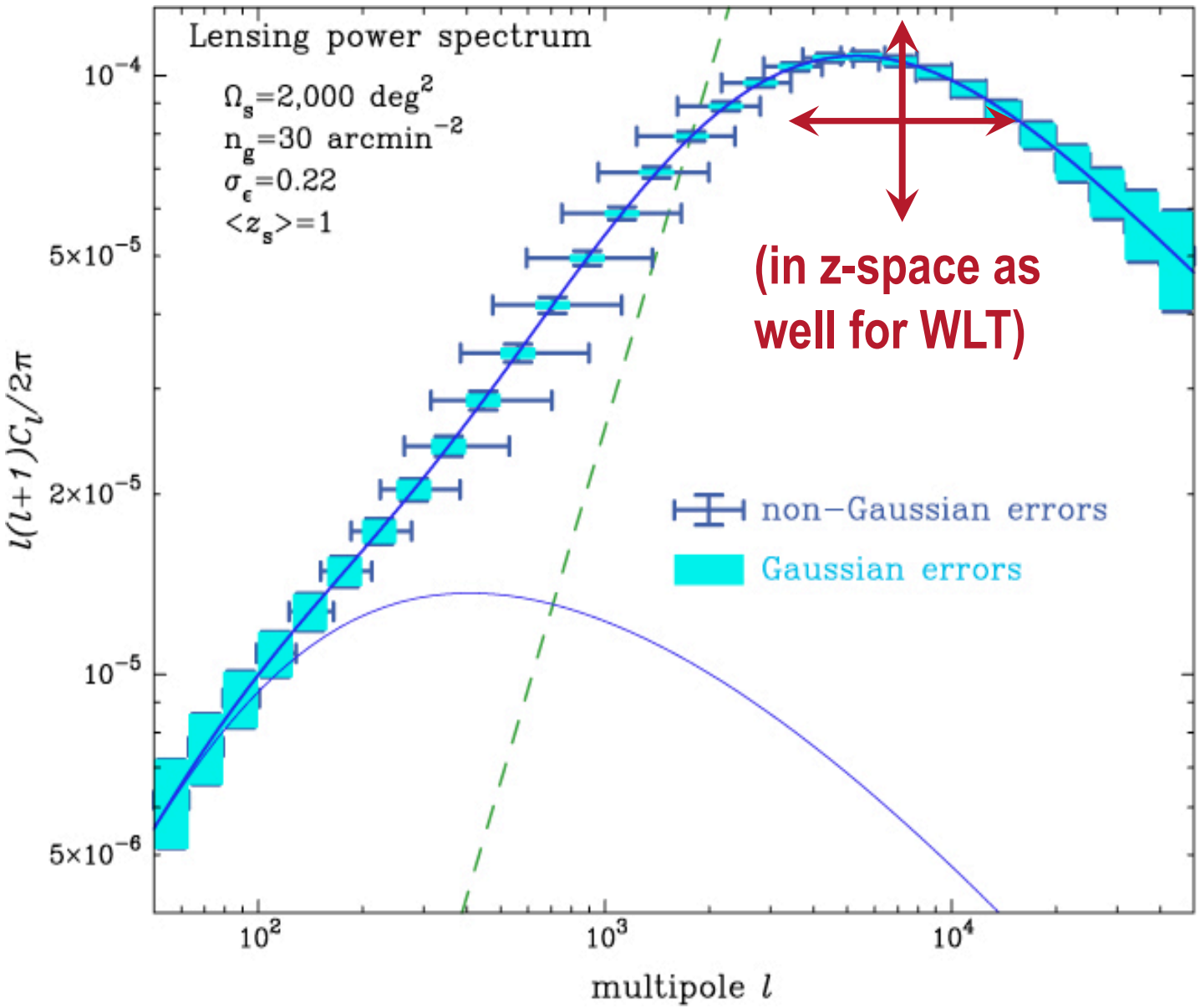
Gaussian errors →

$$= \frac{\delta_{l_1 l_2}}{f_{\mathrm{sky}} l_1 \Delta l_1}\left[P(l_1) + \frac{\sigma_\varepsilon^2}{n_g}\right]^2$$

Non-Gaussian errors →

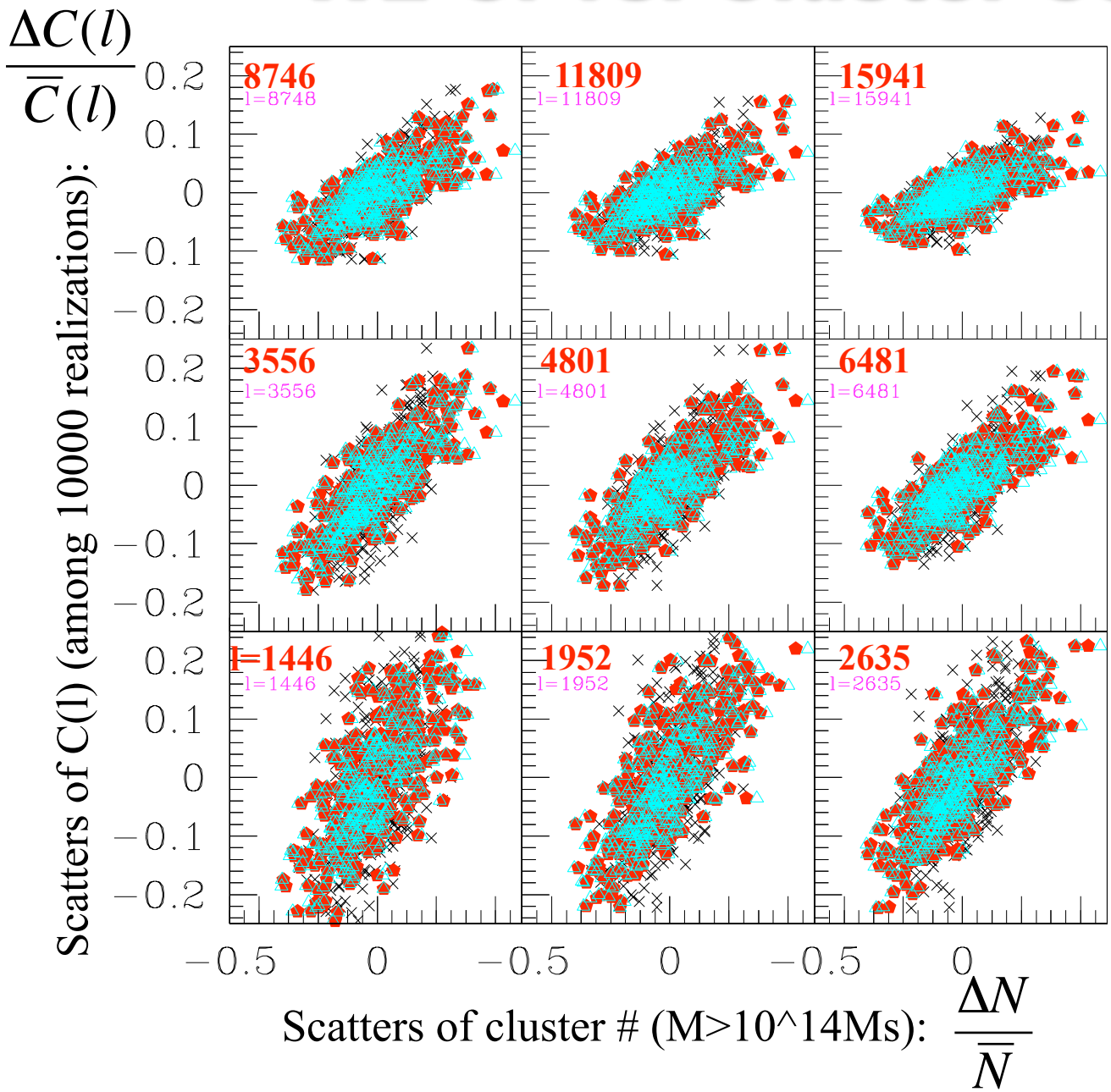
$$+ \frac{1}{4\pi f_{sky}} \int_{l_1} \frac{d^2 \boldsymbol{l}_1'}{2\pi l_1 \Delta l_1} \int_{l_2} \frac{d^2 \boldsymbol{l}_2'}{2\pi l_2 \Delta l_2} T(\boldsymbol{l}_1', -\boldsymbol{l}_1', \boldsymbol{l}_2', -\boldsymbol{l}_2')$$

Power spectrum with NG errors



- The band powers btw different ells are highly correlated (also see Kilbinger & Schneider 05)
- NG increases the errors by up to a factor of 2 over a range of l~1000
- ell<100, >10^4, the errors are close to the Gaussian cases

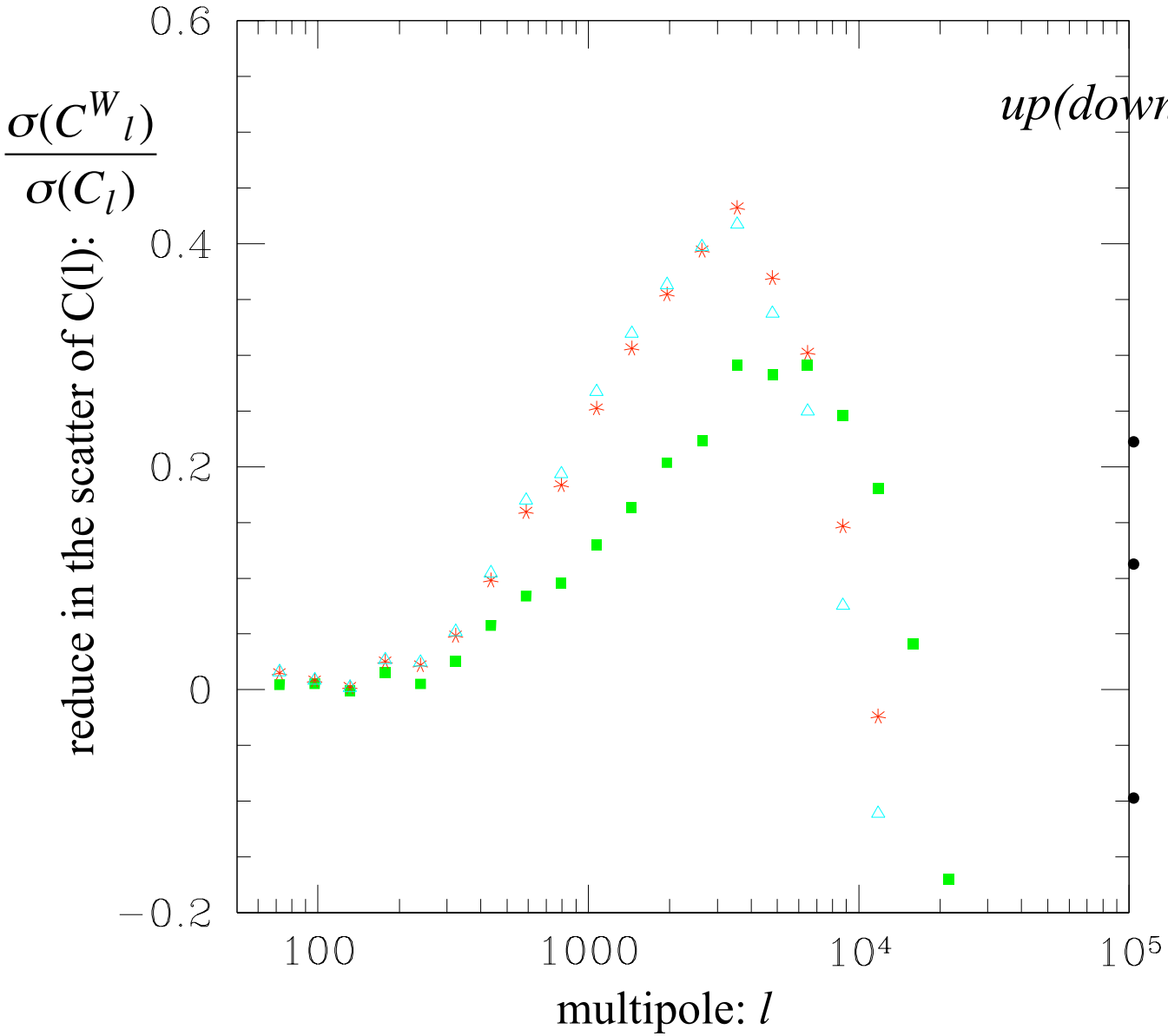
WL Cl vs. Cluster counts



- WL band powers at each ell are correlated with # of massive clusters in the surveyed region (mainly with >10^14Ms at z~0.2)

TSZ+ in prep.

WL Cl vs. Cluster counts (contd.)



up(down)-weighted estimator

$$\hat{C}_l^W = \frac{1}{1 + c\,\frac{\Delta N}{\bar{N}}}\,\hat{C}_l$$

- Clusters are easy to find (especially up to z~0.2)
- A knowledge of cluster # helps WL power spectrum measurements? (e.g. WL + SZ surveys)
- A 50% reduce in the PS scatter at l~3000

TSZ+ in prep.

Halo sample variance in WL covariance (Sato et al. 09)

- Halo model picture: the lensing power spectrum on small angular scales is given by

$$C_l = \int_0^{\chi_s} d\chi \frac{d^2V}{d\chi d\Omega} \int dM \frac{dn}{dM} \tilde{C}_l(M)$$

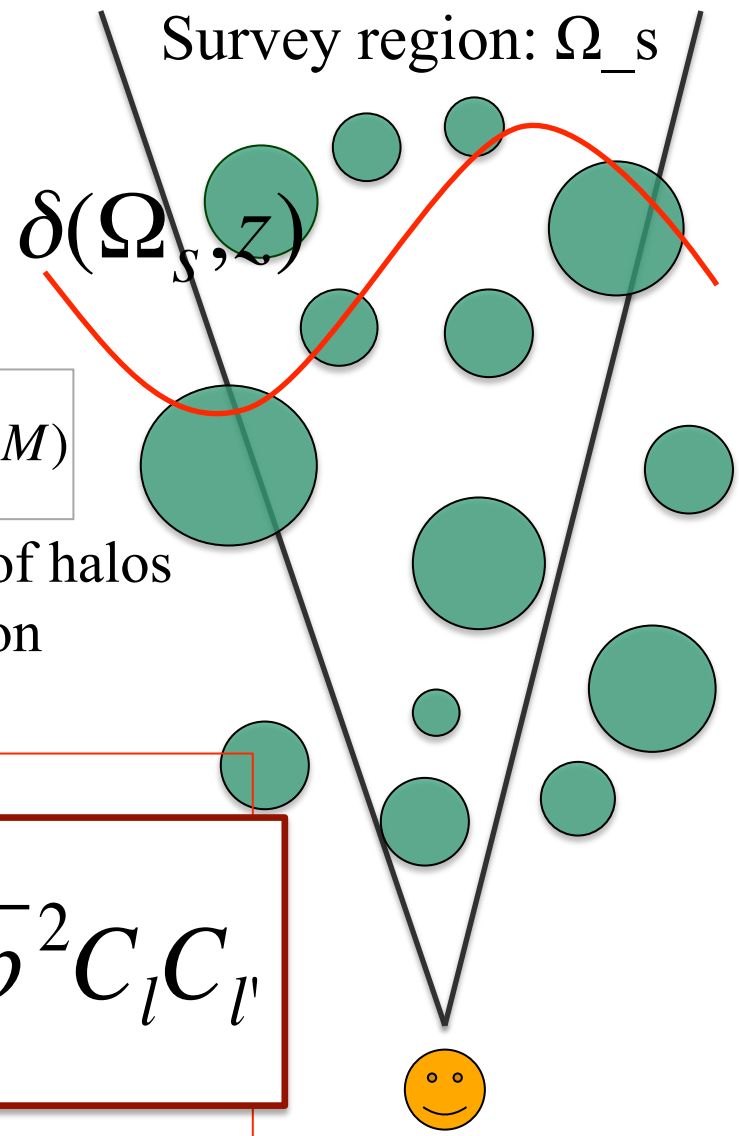
However, what is observed for a finite area survey is rather

$$C_l^{\Omega_s} = \int_0^{\chi_s} d\chi \frac{d^2V}{d\chi d\Omega} \int dM \frac{dn}{dM} \left[1 + b(M)\delta_m(\chi;\Omega_s)\right] \tilde{C}_l(M)$$

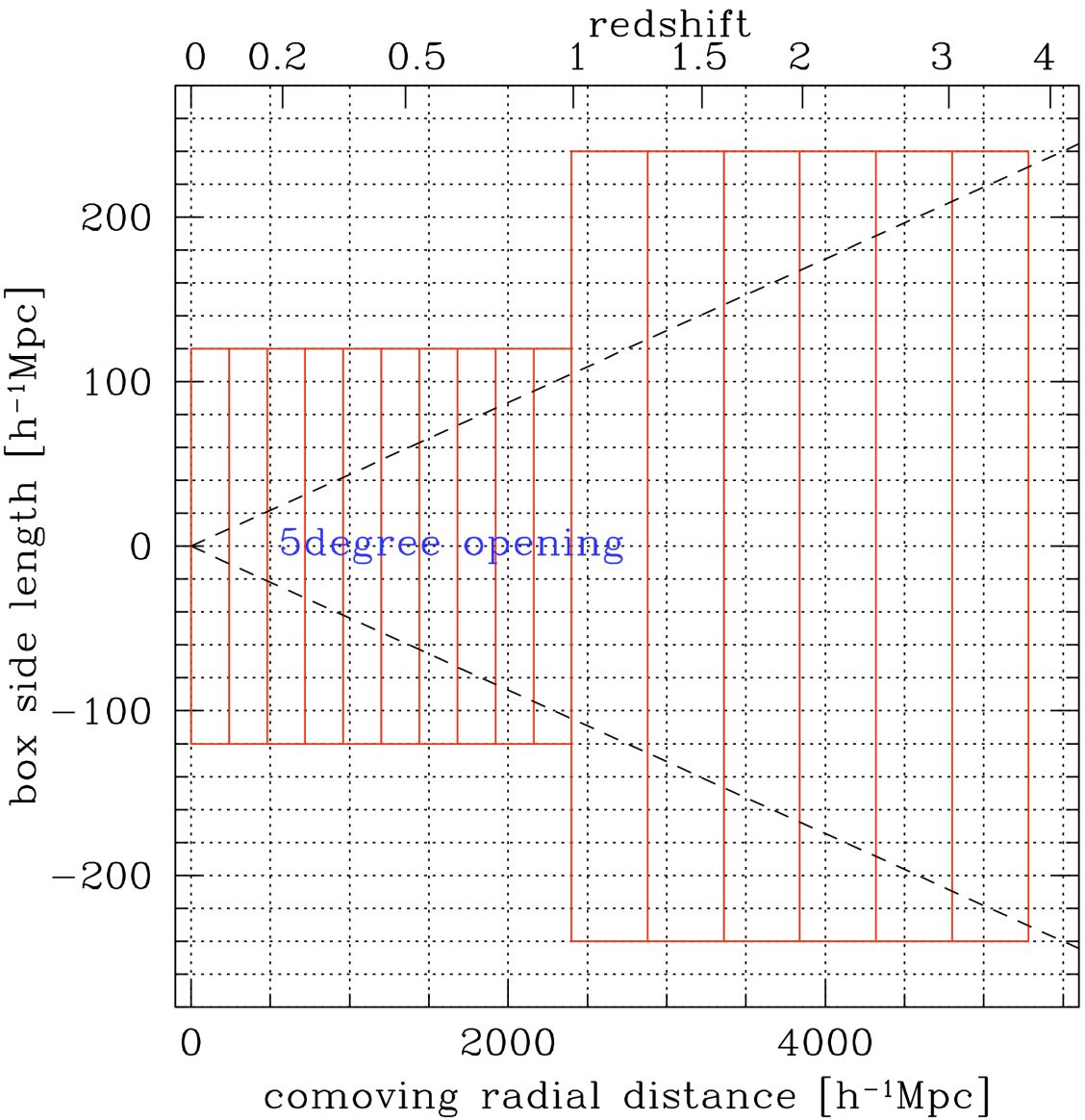
where $b(M)\delta_m(\chi;\Omega_s)$ is the number fluctuations of halos with mass M at redshift z(χ) for this survey region

$$\langle C_l^{\Omega_s} \rangle = C_l$$

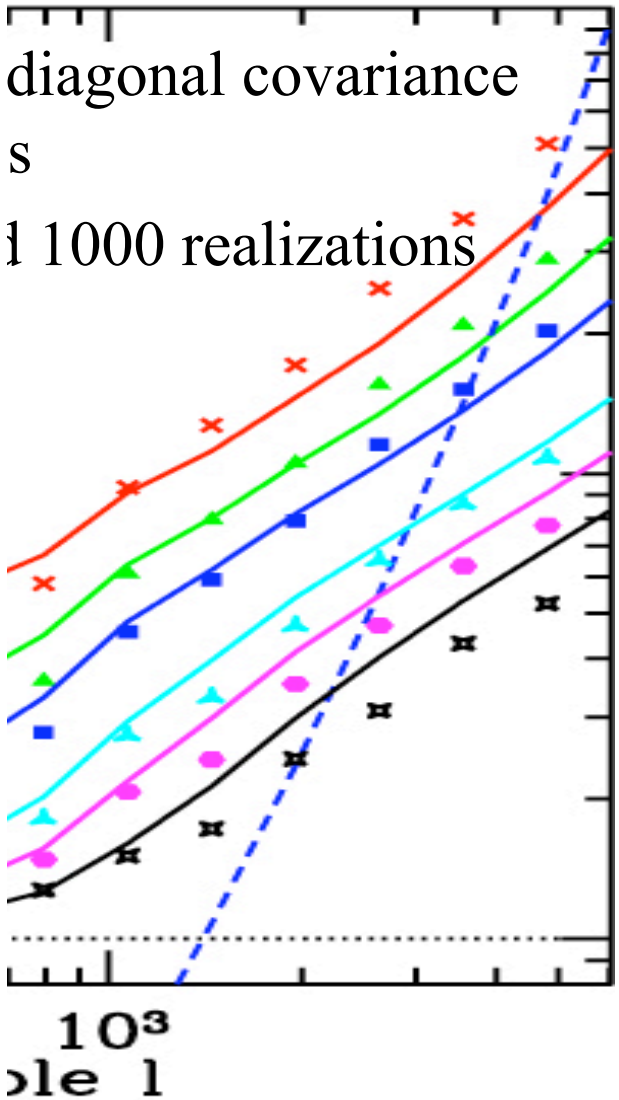
$$\mathrm{Cov}[C_l^{\Omega_s}, C_{l'}^{\Omega_s}]^{\mathrm{HSV}} \sim \sigma_m^2(\Omega_s)\bar{b}^2 C_l C_{l'}$$



WL covariance: halo model and simulations



Sato et al. 09



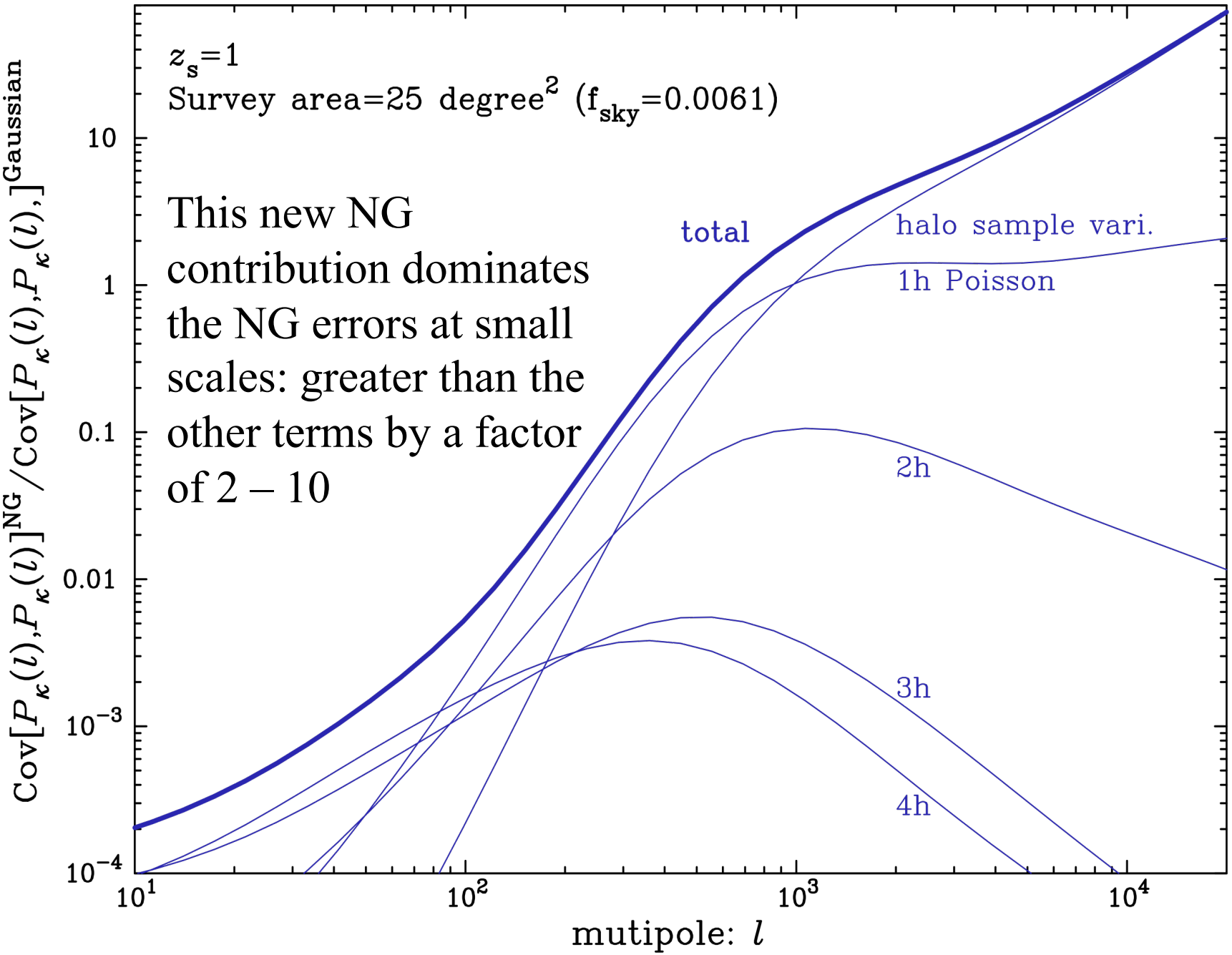
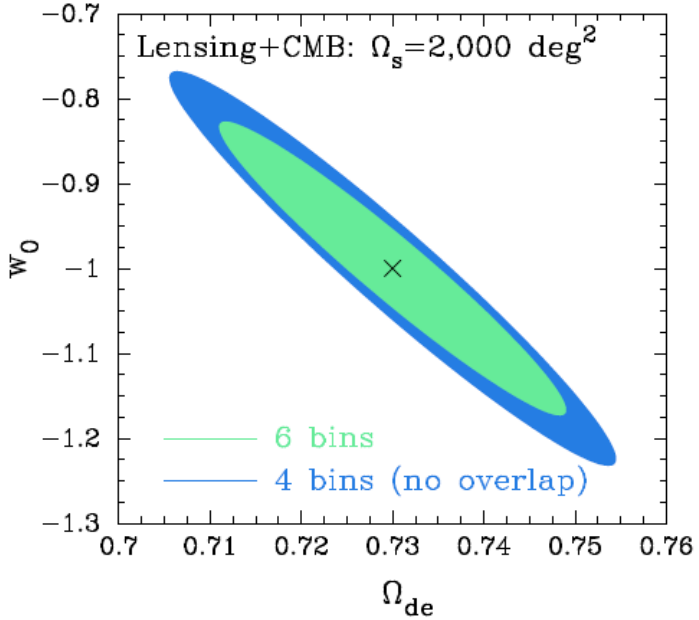
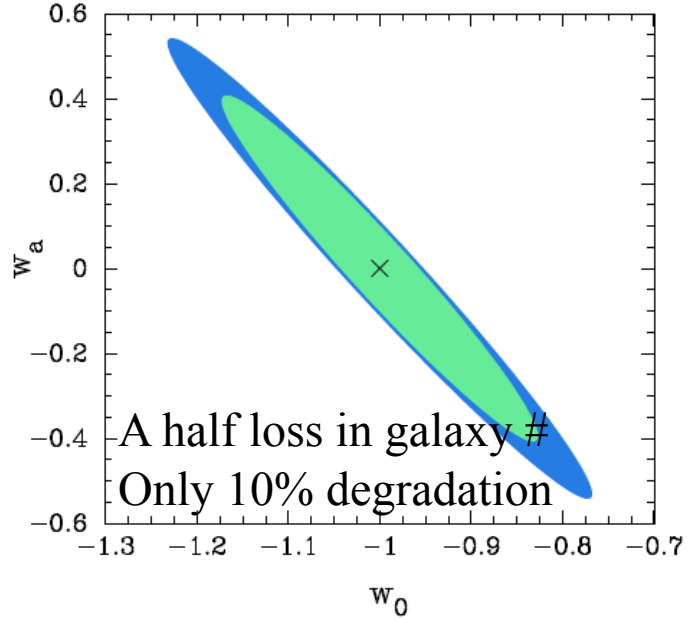
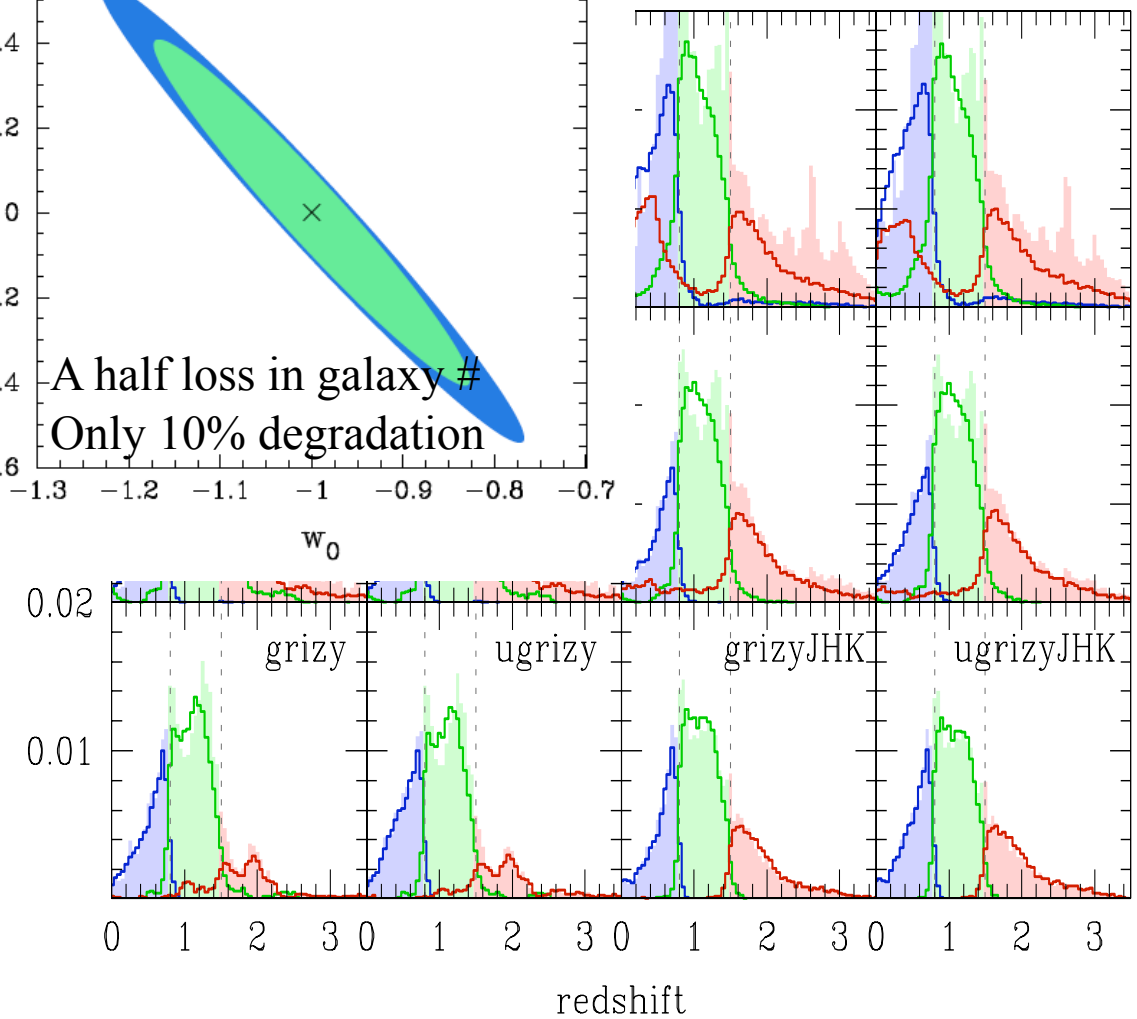

z_s=1
Survey area=25 degree^2 (f_{sky}=0.0061)
This new NG contribution dominates the NG errors at small scales: greater than the other terms by a factor of 2 – 10
total
halo sample vari.
1h Poisson
2h
3h
4h
$\mathrm{Cov}[P_\kappa(l),P_\kappa(l)]^{\mathrm{NG}}/\mathrm{Cov}[P_\kappa(l),P_\kappa(l),]^{\mathrm{Gaussian}}$
mutipole: l
10
1
0.1
0.01
10^{-3}
10^{-4}
10^1
10^2
10^3
10^4

Photo-z errors







- *Remark*: WL not shot-noise limited. Need to define a good photo-z sub-sample
  - E.g. 1/2 of galaxies can be discarded without much degradation in the constraining power (Jain, Connolly, MT 07)

Nishizawa, MT+ in prep.

Massive data coming!

- Wide-area SZ surveys: Planck, SPT, ACT
- Optical surveys: Subaru (2012-), DES (2012-)
- Synergy between optical and SZ surveys looks very, very, very promising!
  - Lensing: cluster lensing, cosmic shear, CMB lensing
  - Combining different probes (lensing, cluster counting)
- In 5 years, BOSS data available
  - Cross-correlation with LRG or Ly-alpha forests
  - Combining BAO, SZ and lensing even further improves various aspects of these methods (cosmology, systematics, …)
- Secure goal: neutrino mass $\boldsymbol{0.1}eV$ feasible from SZ+lensing +BOSS?
- Inflation parameters and primordial non-Gaussianity?

Summary: Lecture III

- Cosmic shear (weak lensing via large-scale structure) is sensitive to cosmology
  - Via the *3D power spectrum amplitudes* (growth + normalization) and the *lensing geometrical factor*
  - Combining with geometrical probes (SN + BAO) may allow to *test gravity* on cosmological scales
- The cosmic shear correlations have been detected at high significance by many groups
  - The systematics seem to be under control for a current 100deg^2-size survey
  - Need a more careful study to understand several systematics before upcoming surveys (Subaru Hyper Suprime-Cam survey, DES)
  - Fourier space vs. Real space?
- Combining cosmic shear and clusters looks useful (MT & Bridle 07)
  - Clusters can be found from the same imaging data
  - Combining the two can improve the power of constraining cosmology
  - The scatters in band powers of cosmic shear spectrum seem mainly from the sample various of clusters in the surveyed region

Many Thanks!