Mapping the dark universe with cosmic magnification

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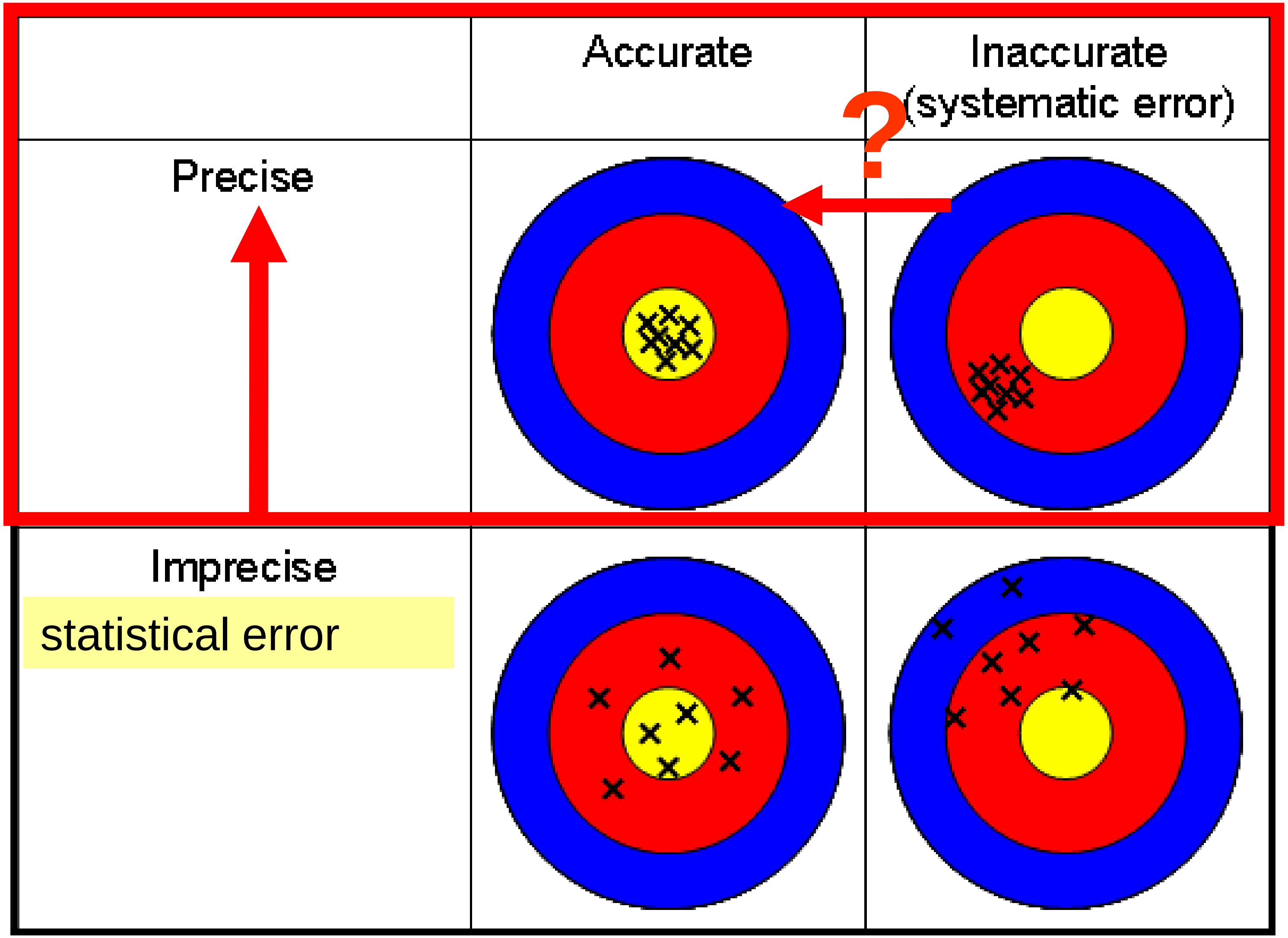
All the hard works are done by my student Yang Xinjuan （杨新娟）！

From **precision** to **accuracy**



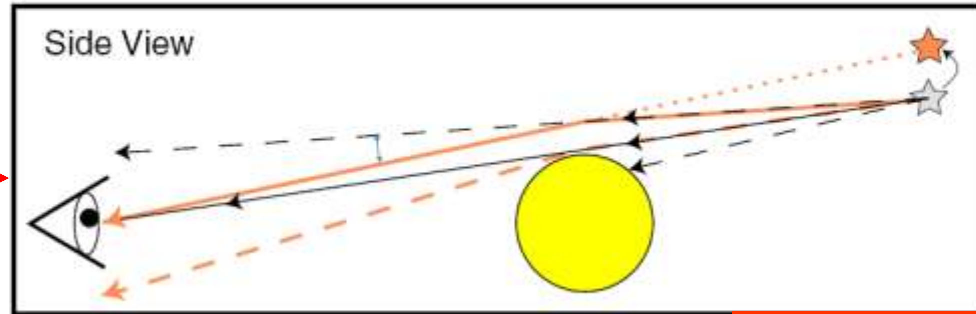
Outine of the talk

- The great power of weak lensing
- Daunting obstacles in cosmic shear cosmology
- Cosmic magnification as an alternative
  - overcome the intrinsic clustering
  - Galaxy stochasticity? Flux measurement error? Dust extinction?

Gravitational lensing: generic consequence of metric gravity

General covariance+ equivalence principle

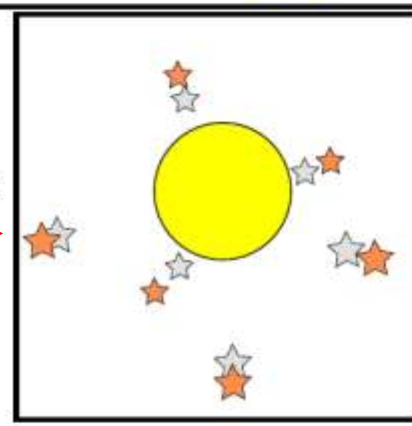
Light deflected in perturbed space-time



GR field equation

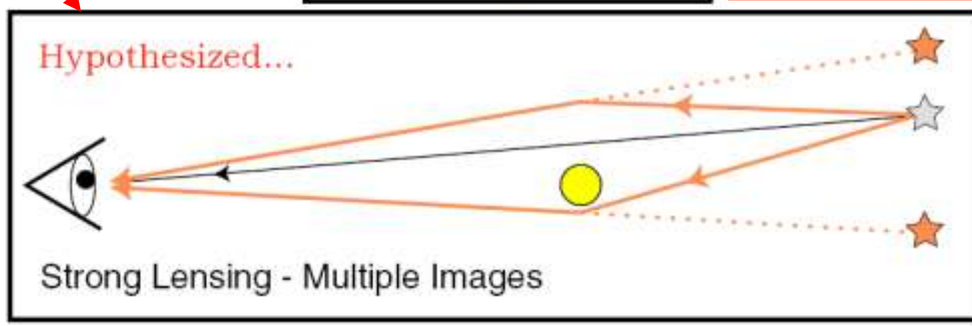
Deflection-matter/energy

View from Earth



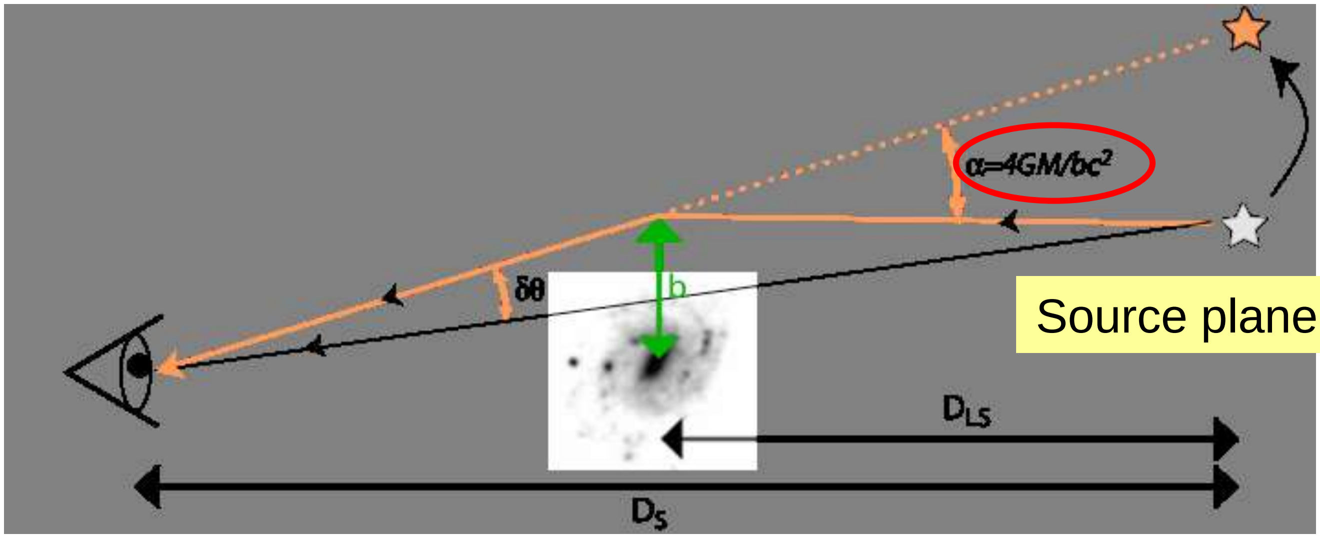
Weak lensing：
- Solar eclipse(1919）
- Galaxy cluster（1990）
- Blank sky（2000）

Strong lensing (1979一)



Micro-lensing

Gravitational lensing



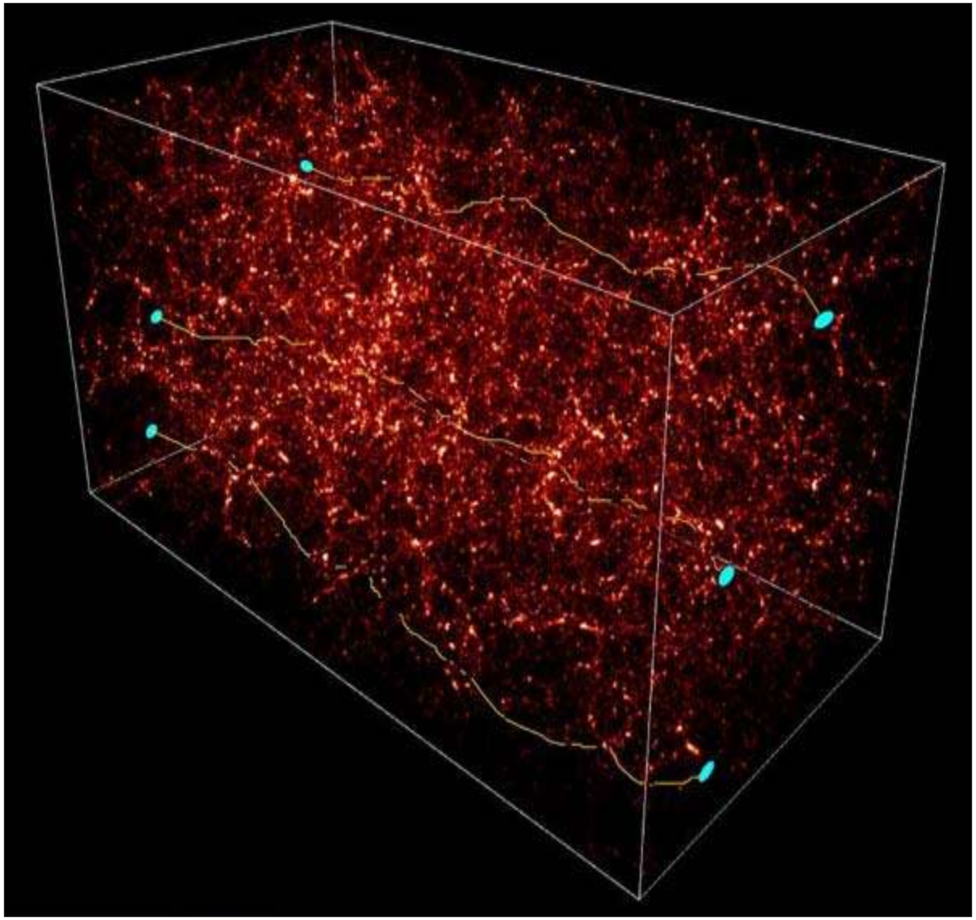
convergence

$$\frac{\partial \theta^I}{\partial \theta_S} = \begin{pmatrix} 1-\kappa-\gamma_1 & \gamma_2 \\ \gamma_2 & 1-\kappa+\gamma_1 \end{pmatrix}$$

shear

To the first order approximation, the matrix is symmetric and the convergence and shear are equivalent

Weak gravitational lensing



All matter along the line of sight contributes

$$\kappa(\hat{n}) = \int \delta(\chi, \hat{n})\ W(\chi, \chi_s)\frac{d\chi}{dz}dz$$

Weak lensing as a probe of precision cosmology

Probe dark matter, dark energy, gravity and neutrino

Structure (nonlinear) growth factor

$$\frac{l^2 C_l}{2\pi} = \frac{\pi}{l}\int_{observer}^{source} \Delta^2\left(k=\frac{l}{x_L}, z_i\right) D^2\left(k=\frac{l}{x_L}, z\right) W^2(x_L, x_S)\, dz_L$$

Measurable

Linear fluctuations

Probe initial fluctuations and test inflation

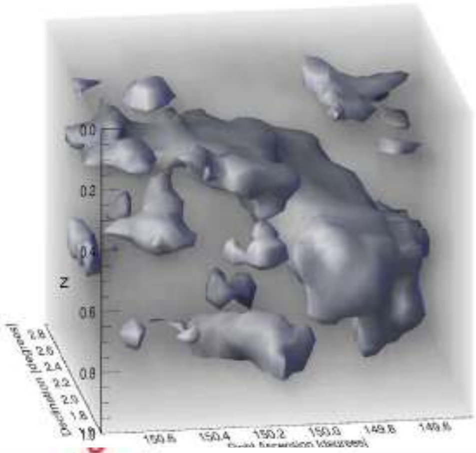
Lensing kernel

Probe the geometry of the universe

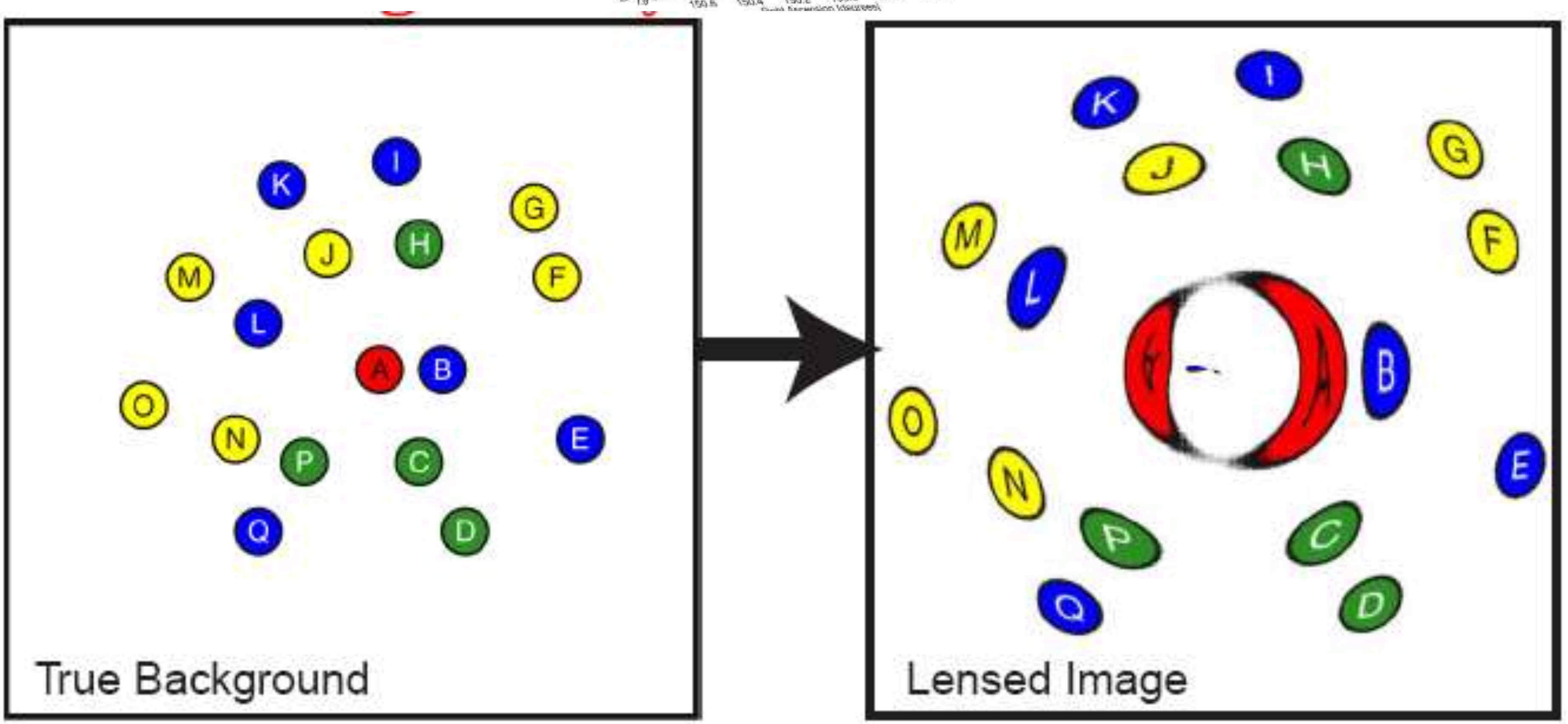
CMB vs. Lensing

Primary CMB	Weak Lensing
Robust measurements: **WMAP, PLANCK, CMB-Pol, etc.**	**Precision measurements:** **CFHTLS, DES, Euclid,LSST, Pan-STARRS, SKA, WFIRST, etc.**
Robust theory **baryon+lepton physics** **Linear, Gaussian** **Accuracy: better than 1%**	**Robust theory:** **Gravity** **Nonlinear, Non-Gaussian** **N-body simulations (+hydro)**
Information: **C_l ($l<3000$)** **$z_{cmb}=1100$ ---2D**	**Information:** **C_l ($l<\sim10^4$), $B(l_1,l_2,l_3)$, etc.** **z=1100, 10, 6-0 ----3D**

Mapping the dark universe with cosmic shear



cosmic shear



CFHTLS: Fu et al. 2007

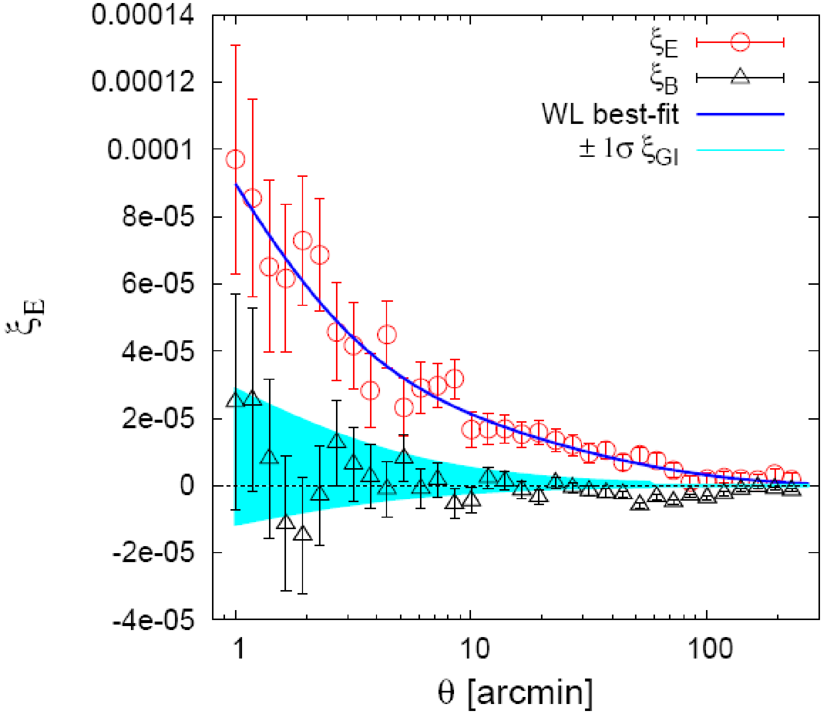


Fig. 14. The measured ξ_E and ξ_B (open symbols and error bars) with the lensing-only best-fit curve (solid blue line) and the allowed fractional $\pm 1\sigma$-contribution of ξ_{GI} to the total signal (shaded cyan region).

COSMOS
Schrabback et al. 2009

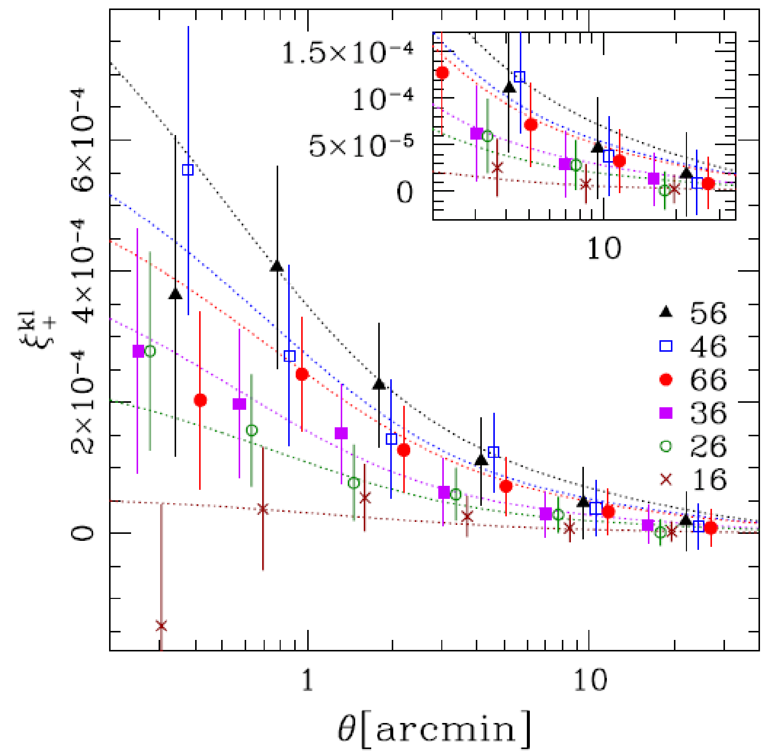
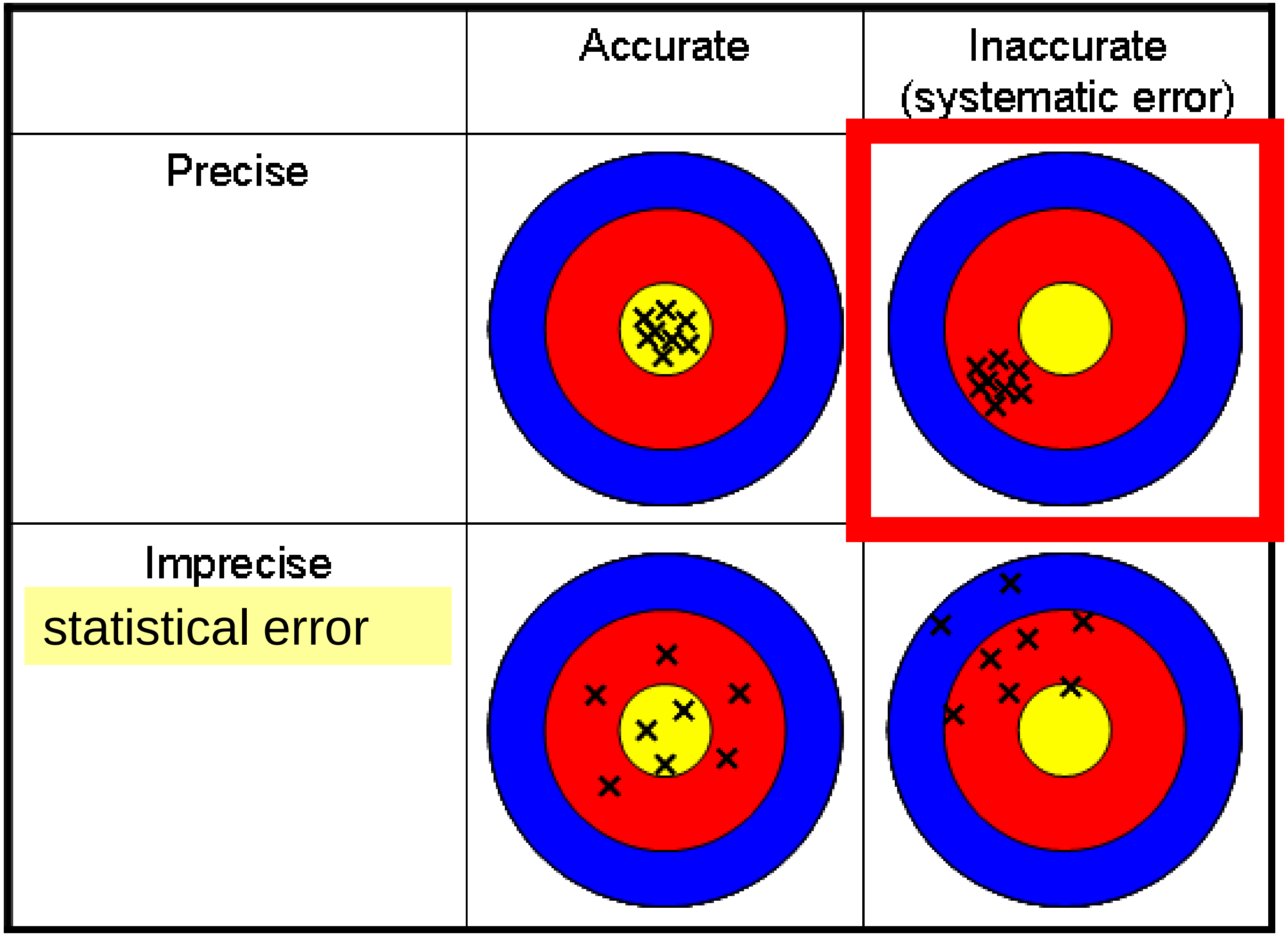


Fig. 7. Shear-shear cross-correlations ξ_+^{k6} between bins 1 to 6 and bin 6, where points are plotted at their *effective* θ, weighted within one bin according to the θ-dependent number of contributing galaxy pairs. The curves indicate ΛCDM predictions for our reference cosmology with $\sigma_8 = 0.8$. Corresponding points and curves have been equally offset along the x-axis for clarity. The error-bars correspond to the square root of the diagonal elements of the full ray-tracing covariance. Note that the points are substantially correlated both between angular and redshift bins, leading to the smaller scatter than naively expected from the error-bars.

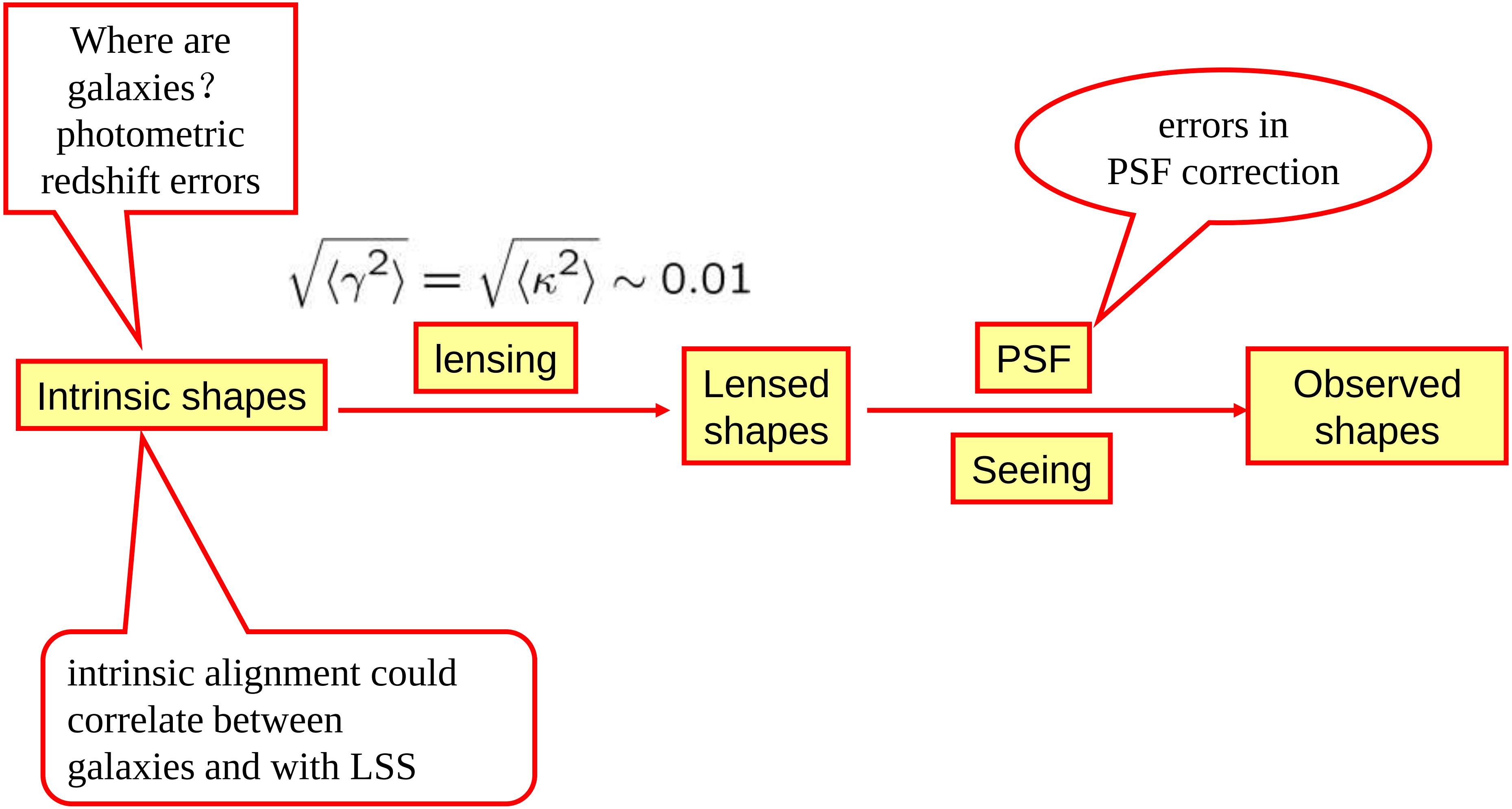
Systematics, systematics, systematics



Challenge to cosmic shear cosmology

- **Systematical errors in measurement**
  - PSF/seeing
  - Intrinsic alignment (II and GI)
  - Photometric redshift errors
- **Systematical errors in modeling**
  - Nonlinearity and non-Gaussianity in the matter and metric perturbation
  - Baryons (non-gravitational interaction)
  - High order corrections
    - Born correction, lens-lens coupling, reduced shear, etc.
  - Sampling bias
    - Source-lens coupling, close-pair exclusion, etc.

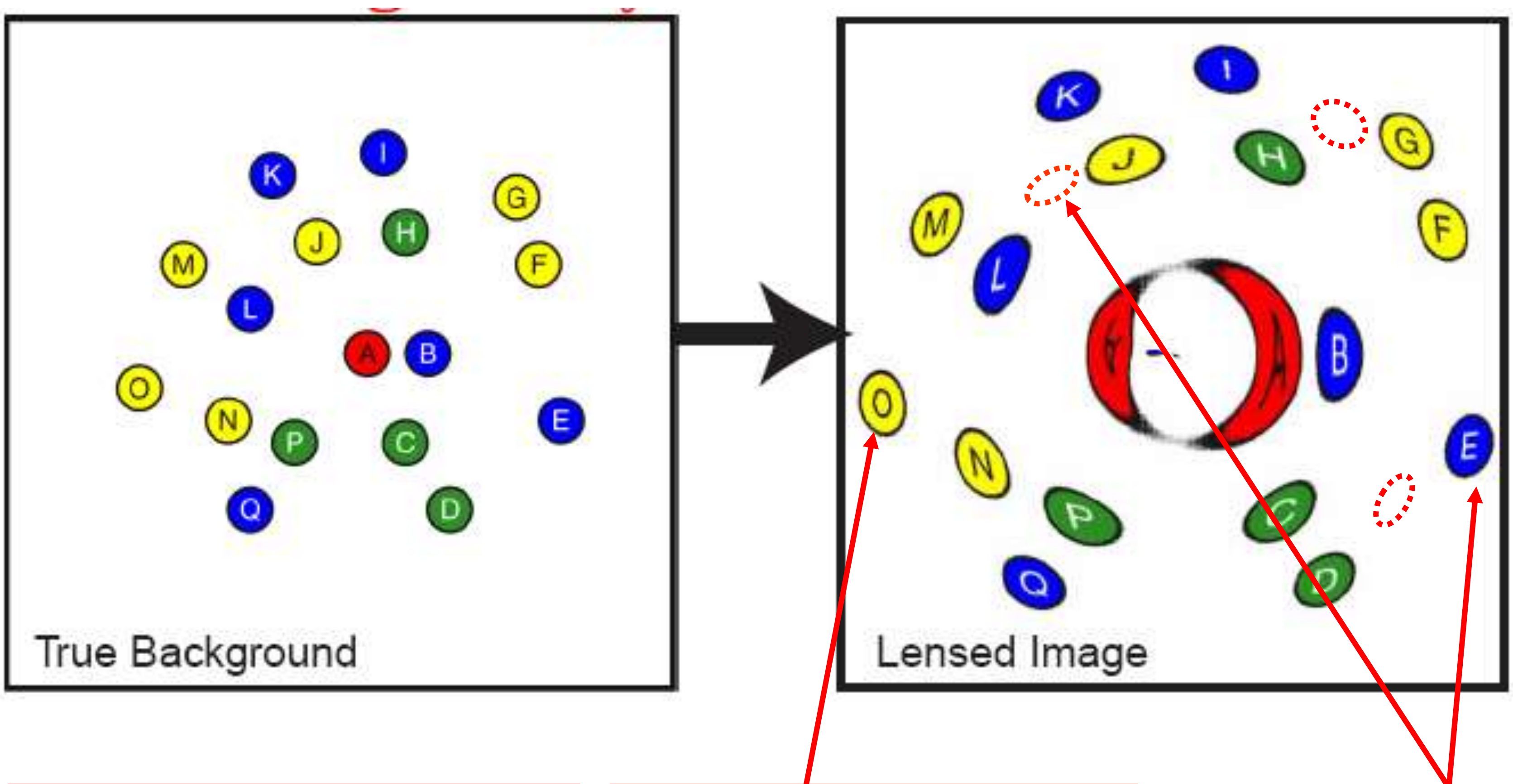
Major systematical errors in measurement



Works at SHAO on reducing lensing systematics

- Galaxy intrinsic alignment
  - Measurement and modeling: Okumura & Jing, 2010; Okumura, Jing & Li, 2010
  - Self-calibration: ZPJ, 2010a; ZPJ, 2010b
    - Extended to 3pt by Troxel & Ishak, 2011, 2012
- Photometric redshift error
  - Self-calibration: ZPJ, Pen & Bernstein, 2010
- The influence of baryons
  - Jing, ZPJ, et al. 2006 (see also Zhan & Knox 2004)
- High order corrections
  - Lens-lens coupling, Born correction, reduced shear: Dodelson & ZPJ, 2005
  - Source-lens coupling: Yu Yu, ZPJ, et al. 2012, in preparation
- Non-Gaussianity
  - Gaussianization technique: Yu Yu, ZPJ, et al. 2011, 2012

Other observable consequences



Anistropies and non-Gaussianities in cosmic backgrounds. Measure the deflection field

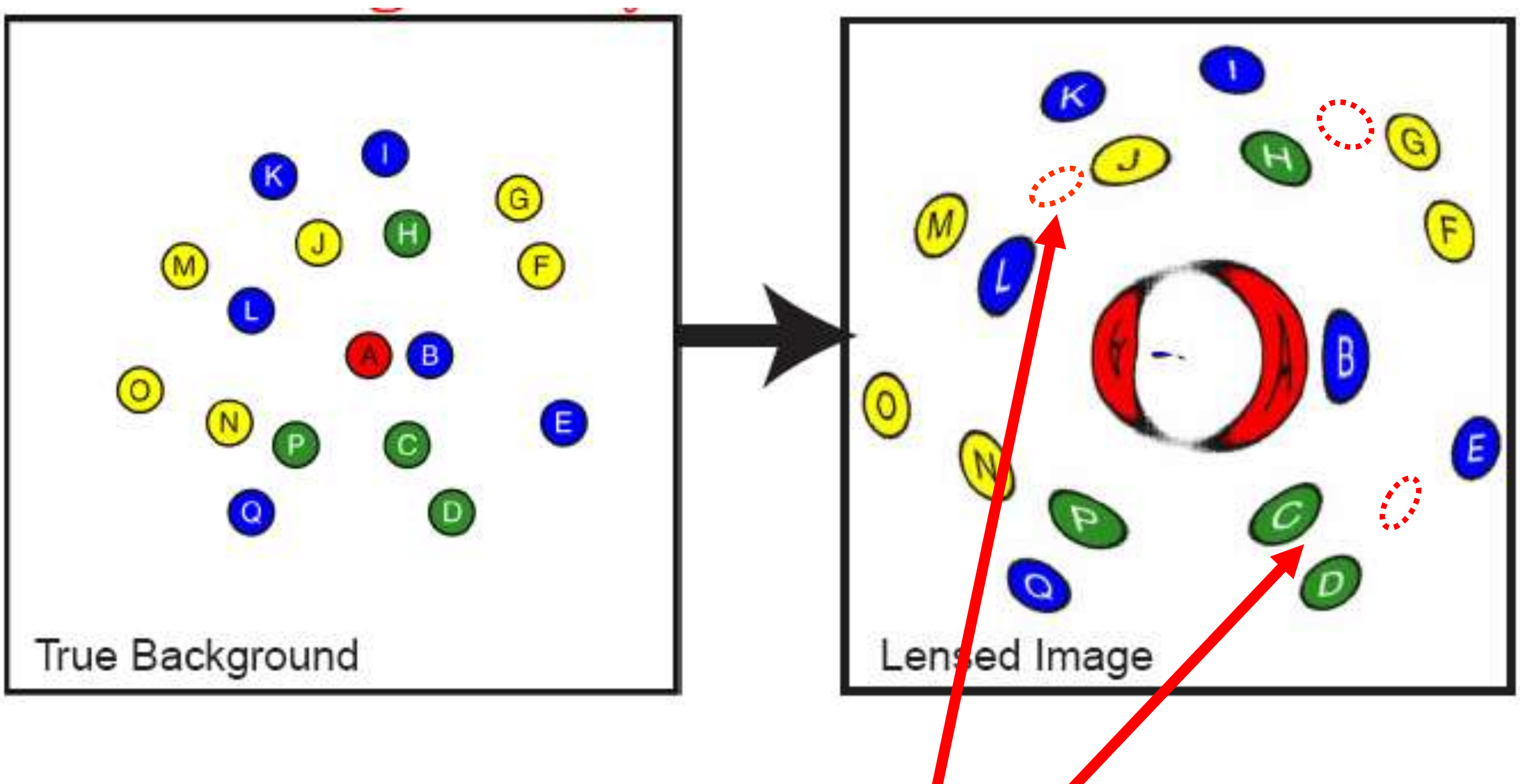
Magnification in flux e.g. SN Ia, fundamental plane. Measure the amplification～kappa

cosmic magnification in galaxy number distribution. Measure the amplification ~ kappa

Alternatives to cosmic shear

- **Lensing of cosmic backgrounds (CMB/21cm)**
  - **Seljak & Zaldarriaga, Zaldarriaga & Seljak 1998;Hu & Oakamoto 2002; Cooray 2004; Pen 2004; Zahn & Zaldarriaga 2006; Mandel & Zaldarriaga 2006; Lu et al. 2007; Das et al. 2011 (First CMB lensing measurement!)**
  - **CMB lensing-LSS measurement: e.g. Smith, Zahn & Dore 2007; Hirata et al. 2008**
  - **Problem: fixed source distance (with source redshift z=10-1100): hard to do tomography; 21cm lensing, non-Gaussianity problem!**
- **Magnification induced fluctuations in SN Ia flux and the galaxy fundamental plane and the size bias**
  - **Cooray et al. 2006; Dodelson & Vallinotto 2006; Bertin & Lombard 2006; Jonsson et al. 2010; Huff & Graves, 2011; Kronborg et al. 2011; Schmidt et al. 2011;**
  - **Problem: ZPJ & Corasaniti 2007 for contaminations by dust extinction; Photometry error**
- **Cosmic magnification (magnification bias): lensing induced fluctuation in galaxy number density distribution**
  - **Scrantan et al. 2005; Menard et al. 2009; Hilderbrandt et al. 2009; Wang et al. 2011**
  - **Problem: what measured is lensing-galaxy cross correlation, with an unknown galaxy bias: hard to do cosmology**
  - **Our solution (ZPJ & Pen, 2005; Yang & ZPJ, 2011;Yang et al. 2012)**

Cosmic Magnification



$$N^L(>F) = N(>F/\mu)/\mu \simeq N(>F)(1+2(\alpha-1)\kappa)$$

$$\alpha = -d\ln N(>F)/d\ln F$$

Cosmic magnification vs. cosmic shear

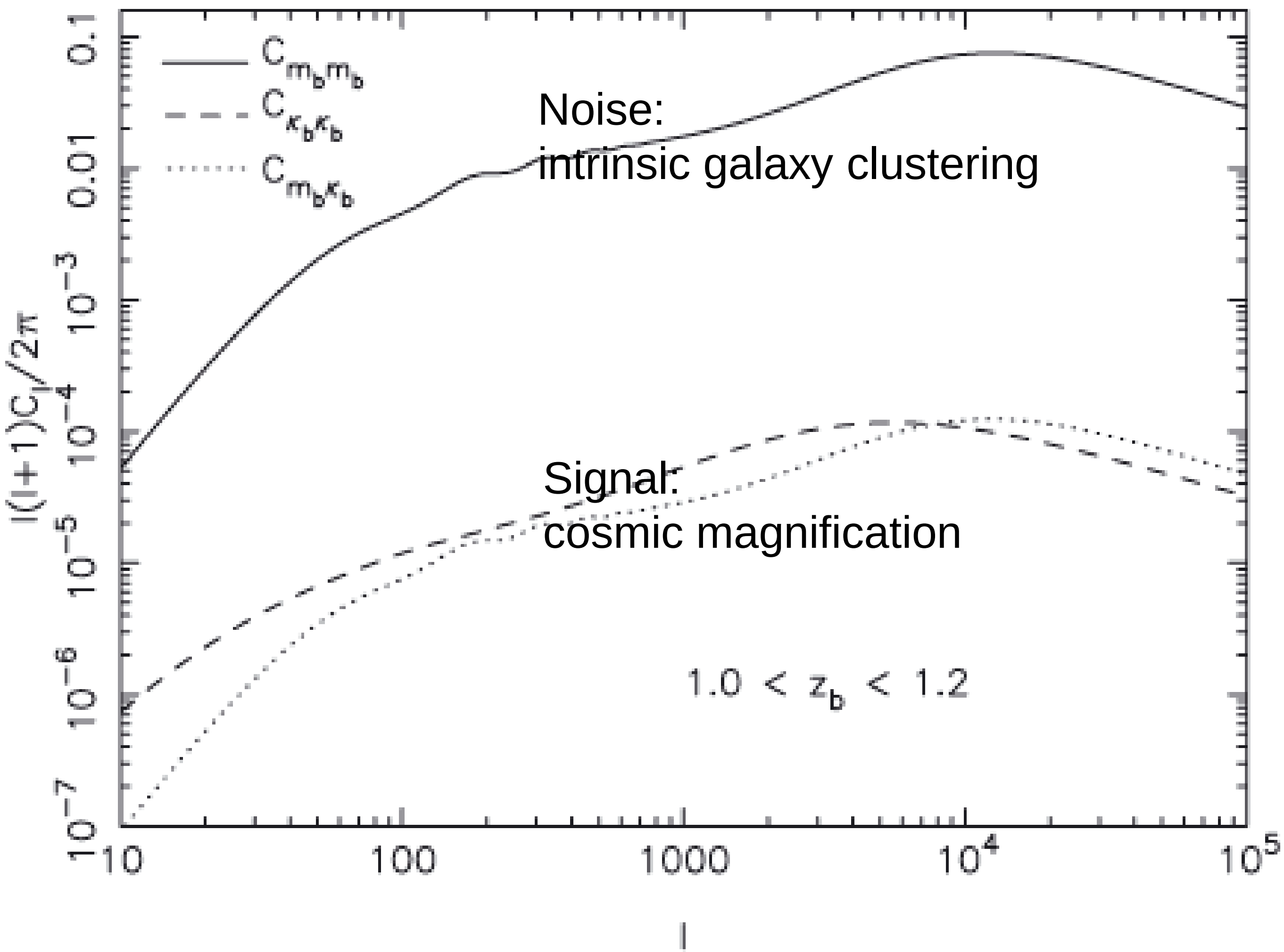
Observable signal noise

$$\delta_g^L = g\kappa + \delta_g$$ intrinsic clustering

$$\gamma^o = \gamma + I$$ intrinsic alignment

$$g \equiv 2(\alpha - 1)$$

Intrinsic clustering overwhelmes cosmic magnification



Cosmic magnification statistics

$$\delta_g^L = 2(\alpha - 1)\kappa + \delta_g$$

$\delta_g >> \kappa$

Cross correlation of foreground and background galaxies

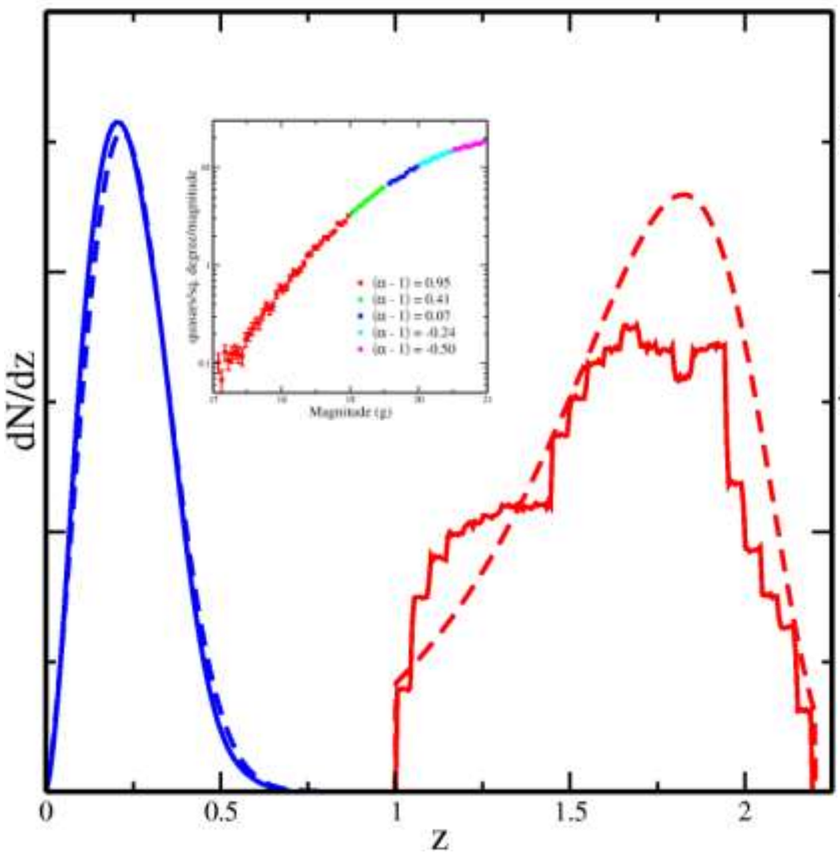
$$\begin{aligned} w(\theta) &= \langle \delta^f(\mathbf{x}) \delta^b(\mathbf{x}+\theta) \rangle \\ &\simeq \langle \delta_g^f 2(\alpha - 1)\kappa^b \rangle \end{aligned}$$

SDSS galaxy-quasar cross correlation

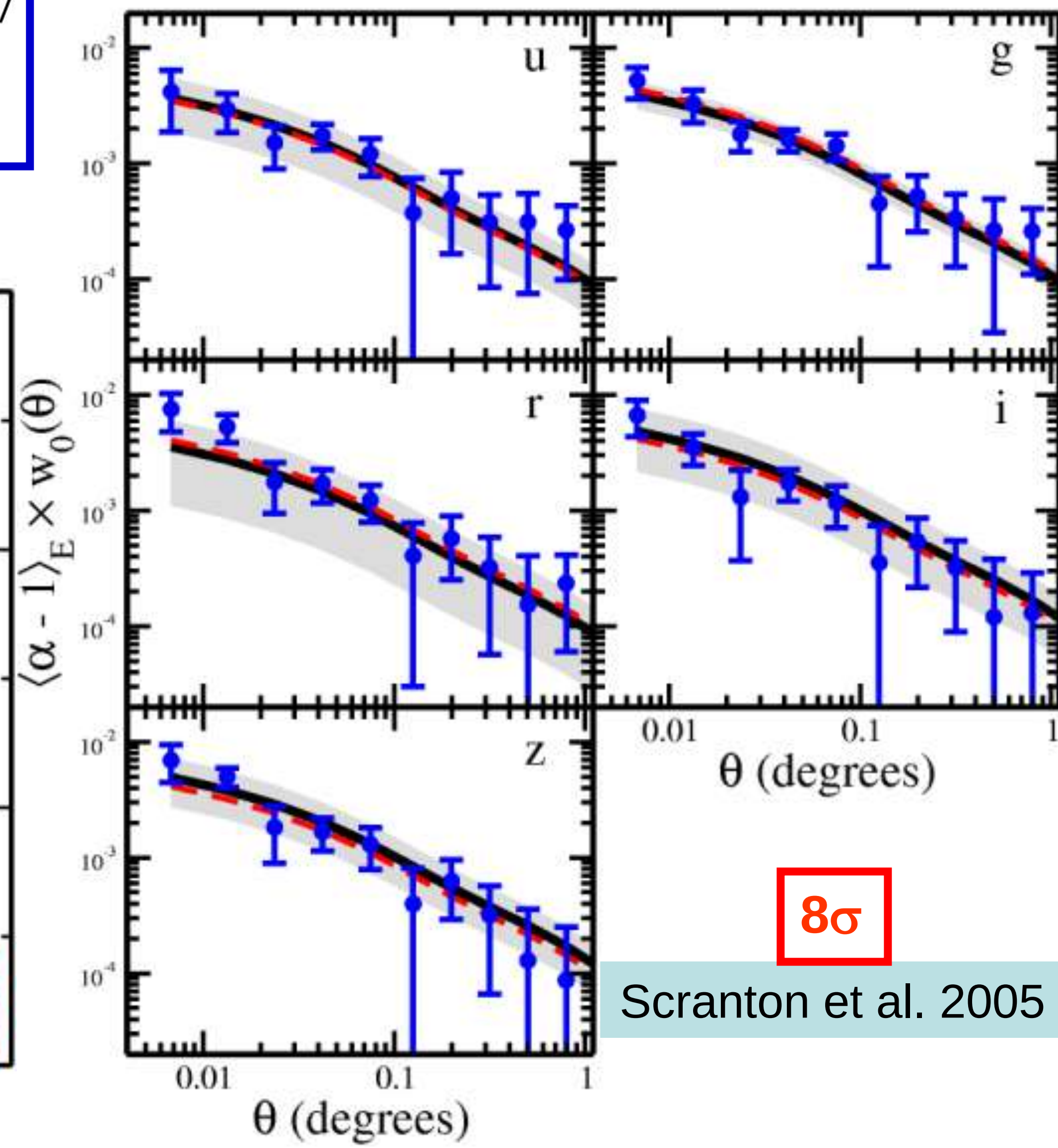
$$
\begin{aligned}
w(\theta) &= \langle \delta^f(\mathbf{x})\delta^b(\mathbf{x}+\theta)\rangle \\
&\simeq \langle \delta_g^f 2(\alpha - 1)\kappa^b\rangle
\end{aligned}
$$

1.3E7 galaxies

2E4 quasars



Weighting quasars by their α-1
(Menard & Bartelmann 2002)



8σ

Scranton et al. 2005

Problems

- Major problem: what measured is the lensing-galaxy cross correlation, subject to galaxy bias which is hard to model robustly. **Severely limits it cosmological applications!**

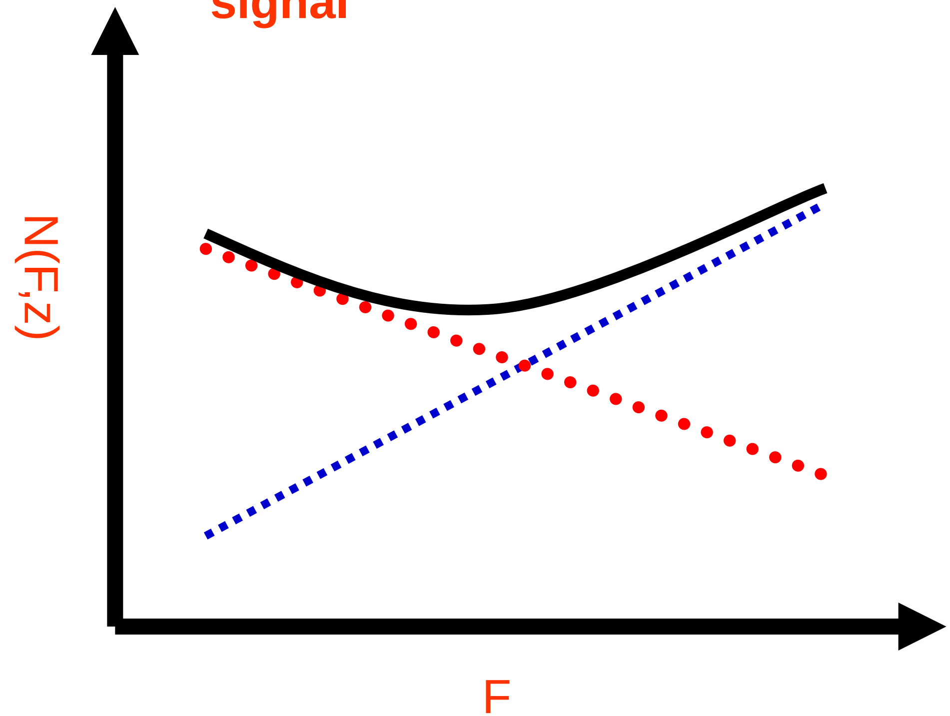
- Minor: the \alpha-1 weighting is not optimal. The optimal weighting is $W(F) = \alpha(F) - 1 + \lambda b_g(F)$
  - For a BigBOSS-like survey, S/N can improve by ~20%
  - For a CFHTLS-like survey, S/N can improve by ~100%
  - Yang Xiaofeng & ZPJ, 2011, MNRAS Letters

Seperate the cosmic magnification from the intrinsic clustering

$$\delta_g^L = 2(\alpha - 1)\kappa + \delta_g$$

signal **noise**

- δ_g has different dependence on flux, which can be inferred from the measured correlations
- The key to eliminate the intrinsic clustering



ZPJ & Pen 2005, PRL

An example

Bright galaxies: $\delta_g^L(B) = \kappa + \delta_g$

Faint galaxies: $\delta_g^L(F) = -\kappa + \delta_g$

$$\kappa = \frac{\delta_g^L(B) - \delta_g^L(F)}{2}$$

Oversimplified!

(1) The galaxy bias varies with flux

(2) This flux dependence is unknown

For a given redshift bin, split galaxies into flux bins

galaxy overdensity at the i-th flux bin. Knowns

The cosmic magnification coefficient in the i-th flux bin. Knowns

$$\delta_i^L = b_i \delta_m + g_i \kappa$$

Galaxy bias of the i-th flux bin. Unknowns

Matter fluctuation. Unknowns.

Lensing convergence. Unknowns

A minimal variance linear estimtator

$$\hat{\kappa} = \sum_i w_i \delta_i^L$$

1. Eliminate the galaxy clustering $\sum_i w_i b_i = 0$

2. Recover the lensing signal $\sum_i w_i g_i = 1$

3. Minimize shot noise

$$\left\langle \left| \sum_i w_i \delta_i^{\mathrm{L}} - \kappa \right|^2 \right\rangle = \left\langle \left| \sum_i w_i \delta_i^{\mathrm{shot}} \right|^2 \right\rangle = \sum_i \frac{w_i^2}{\bar{n}_i} .$$

The solution

$$\hat{\kappa} = \sum_i w_i \delta_i^L$$

$$w_i = \frac{\bar{n}_i}{2}(\lambda_1 g_i + \lambda_2 b_i) \ . \qquad (13)$$

Here, the two Lagrangian multipliers $\lambda_{1,2}$ are given by

$$\lambda_1 \quad = \quad -\frac{2\sum \bar{n}_i b_i^2}{(\sum \bar{n}_i b_i g_i)^2 - \sum \bar{n}_i b_i^2 \sum \bar{n}_i g_i^2} \ ,$$

$$\lambda_2 \quad = \quad \frac{2\sum \bar{n}_i b_i g_i}{(\sum \bar{n}_i b_i g_i)^2 - \sum \bar{n}_i b_i^2 \sum \bar{n}_i g_i^2} \ . \qquad (14)$$

Yang Xinjuan & ZPJ, 2011, MNRAS

How to measure the galaxy bias?

- Yang & ZPJ 2011 proposed an iterative method to measure the galaxy bias.
- It works at intermediate redshift, but fails at low and high redshift.

- Yang, ZPJ et al. 2012 found a way to measure the galaxy bias, while simultaneously measuring the lensing power spectrum.

Solving for unknows

Measurements: cross power spectra between i-th and j-th flux bins

$$\bar{C}_{ij}(\ell) = \left\langle \delta_i^{\rm L}(\ell)\delta_j^{\rm L}(-\ell) \right\rangle$$
$$= b_i b_j C_{\rm m} + g_i g_j C_\kappa + (g_i b_j + g_j b_i) C_{{\rm m}\kappa},$$

Intrinsic clustering — lensing — lensing-galaxy cross correlation

Invariant under the followin transformation. No unique solution!

$$\begin{aligned} b_i &\rightarrow Ab_i + Bg_i, \\ C_{\rm m} &\rightarrow A^{-2}C_{\rm m}, \\ C_{{\rm m}\kappa} &\rightarrow A^{-1}C_{{\rm m}\kappa} - A^{-2}BC_{\rm m}, \\ C_\kappa &\rightarrow A^{-2}B^2C_{\rm m} - 2A^{-1}BC_{{\rm m}\kappa} + C_\kappa. \end{aligned}$$

The remody

We manage to group the above unknowns into new variables $\hat{b}_i$ and $\hat{C}_\kappa$, where

$$\hat{b}_i \equiv \sqrt{C_{\rm m}}\left(b_i + g_i \frac{C_{{\rm m}\kappa}}{C_{\rm m}}\right) \tag{4}$$

and

A miltiplicative error of order 0.1%. negligible

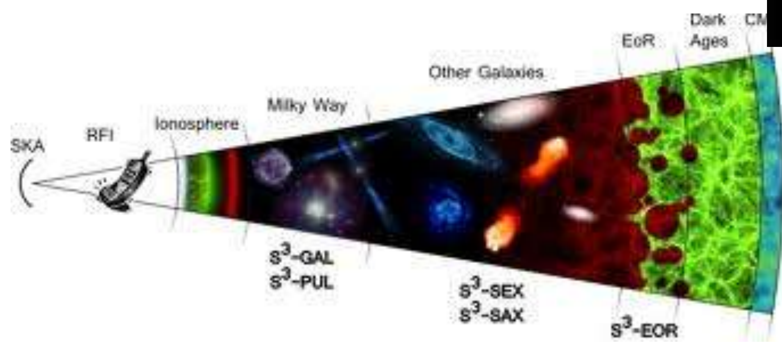
$$\hat{C}_\kappa \equiv C_\kappa (1 - r^2_{{\rm m}\kappa})\ ; \quad r^2_{{\rm m}\kappa} \equiv \frac{C^2_{{\rm m}\kappa}}{C_{\rm m} C_\kappa} \tag{5}$$

Under these new notations,

$$\bar{C}_{ij} = \hat{b}_i \hat{b}_j + \hat{C}_\kappa g_i g_j\ . \tag{6}$$

The above equations have unique solution!

Concept study against the Square Kilometer Array (SKA)



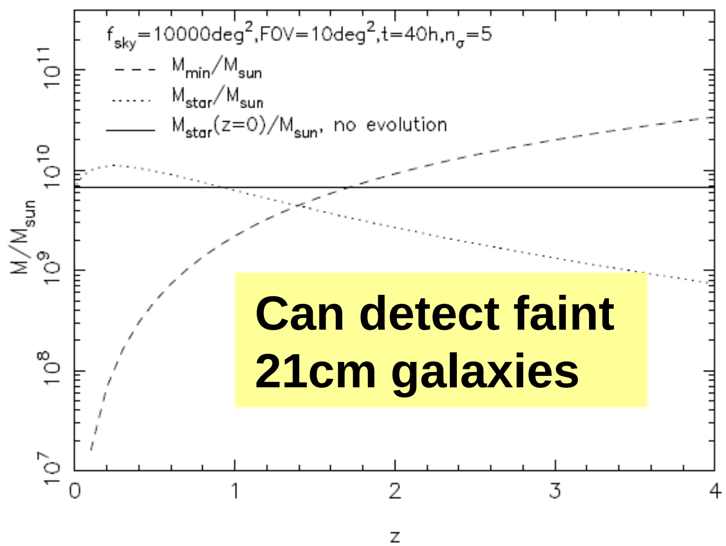


Figure A1. The redshift evolutions of HI mass limit (dashed line) and the characteristic mass in model C (dotted line). The characteristic mass in non-evolution model is plotted by the solid line.

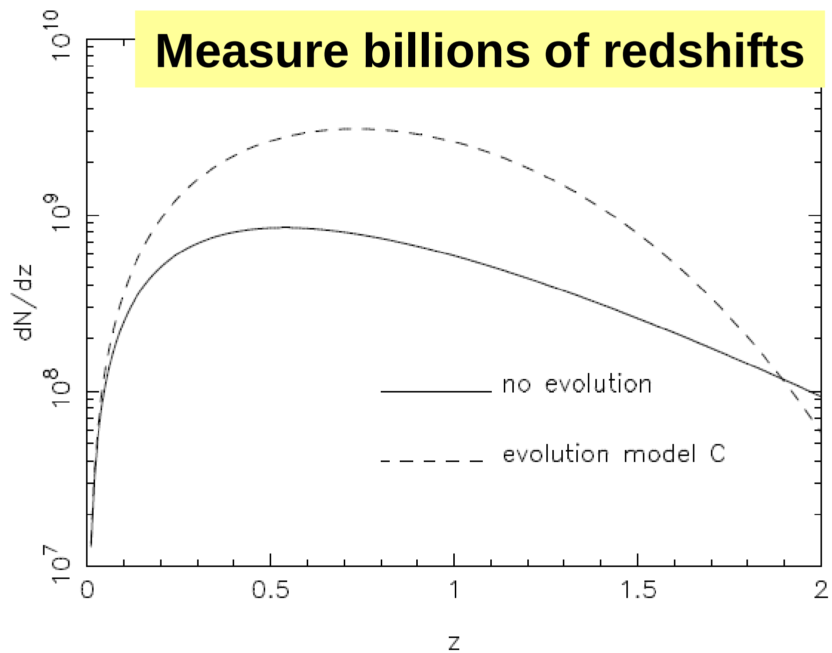
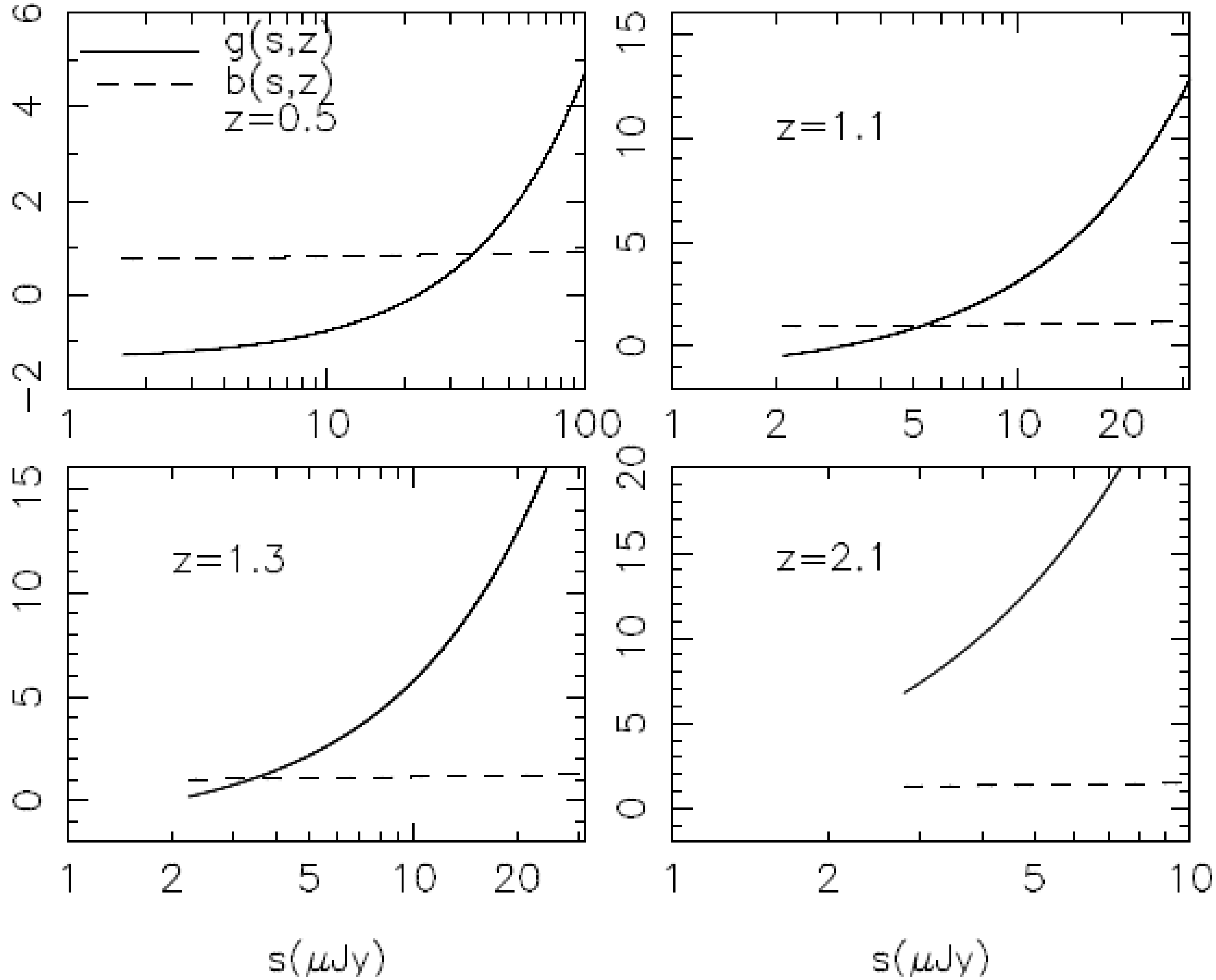


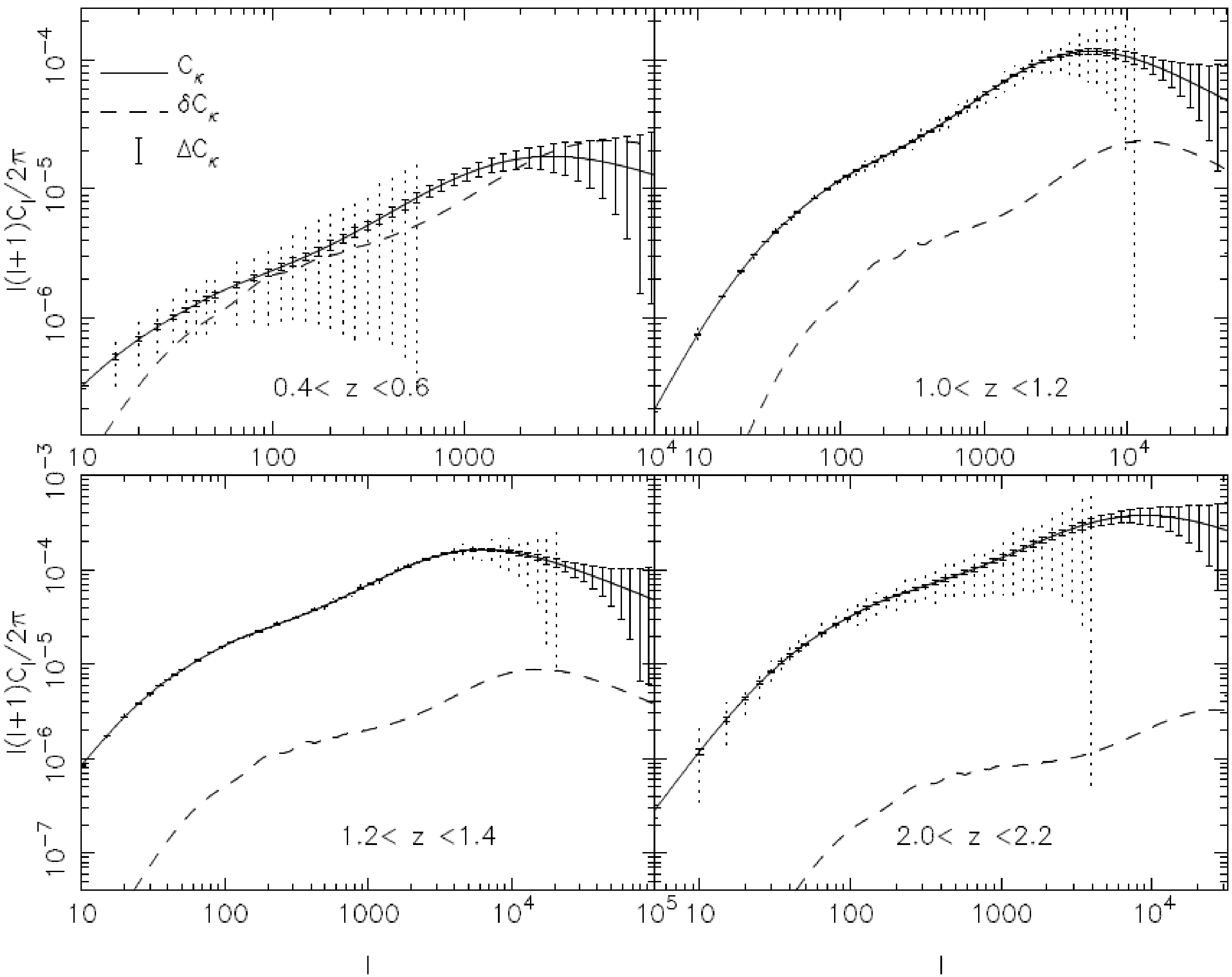
Figure A2. The redshift distributions of HI galaxies for no-evolution model and evolution model C.

Cosmic magnification and galaxy clustering are indeed different in flux dependence



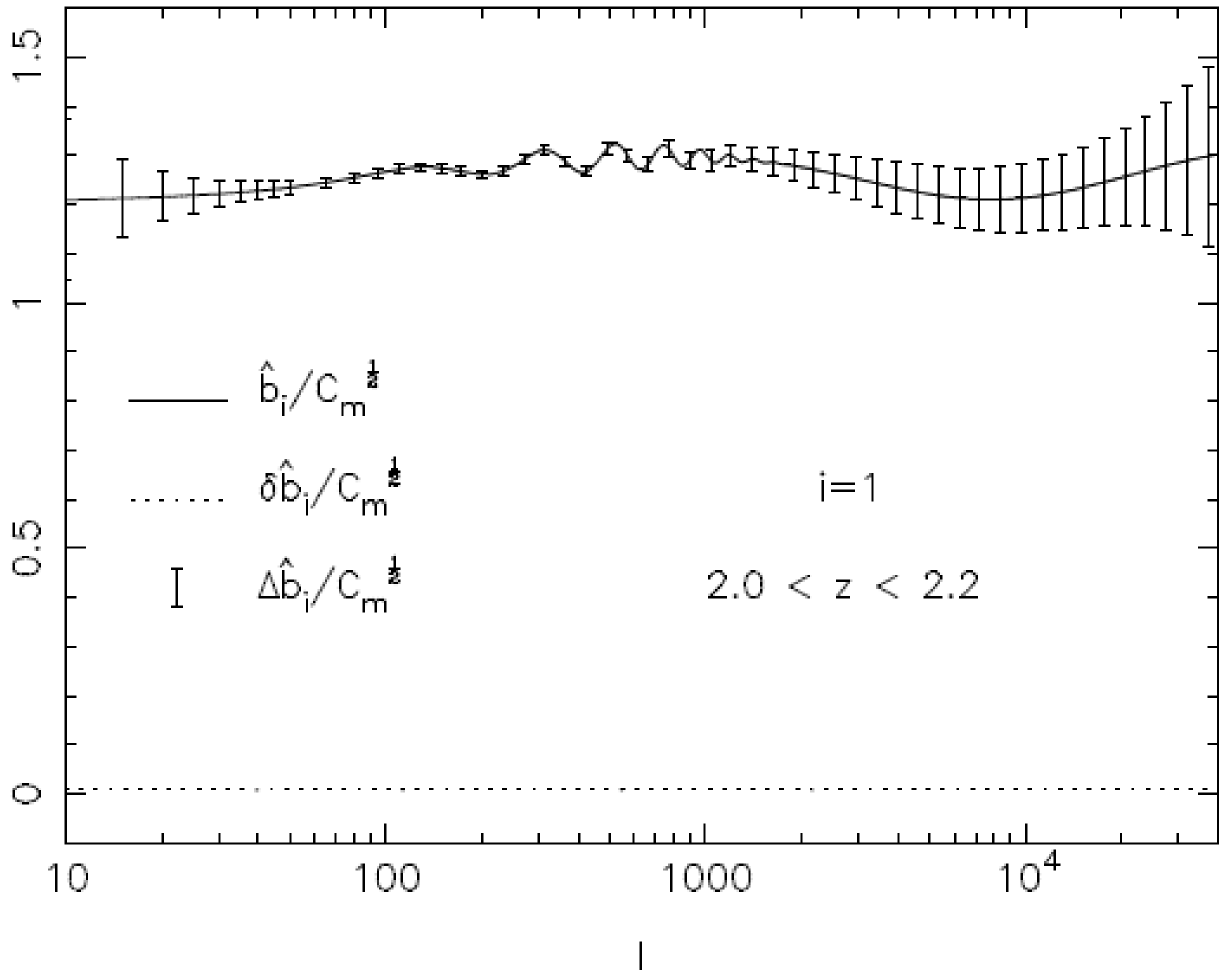
Forecast for SKA

Lensing auto power spectrum reconstruction



Yang Xinjuan, ZPJ, et al. 2012

The galaxy bias is solved too



- From lensing power spectrum reconstruction to lensing map reconstruction

Reconstructed lensing map at high redshift

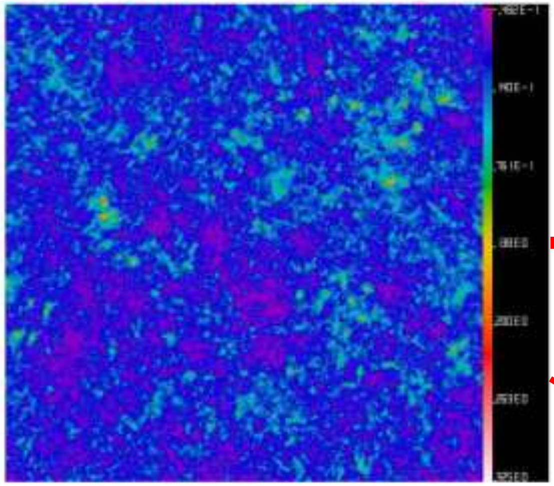
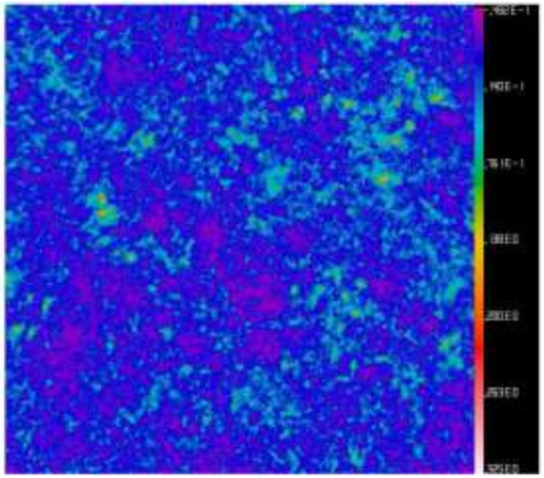


Fig. 2.— A κ map in the N-body simulation of a $\Omega_0 = 0.4$ ΛCDM cosmology. The map width is 3.18 degree and has 2048^2 pixels. The scale is in units of κ. The skewness of the distribution is apparent. Decreasing the cosmological density while maintaining the same variance forces structures to become more linear, and thus more skewed.

Measure lensing statistics: auto power spectrum bispectrum, cluster finding

Cross power spectrum Cross bispectrum, etc.

Reconstructed lensing map at low redshift



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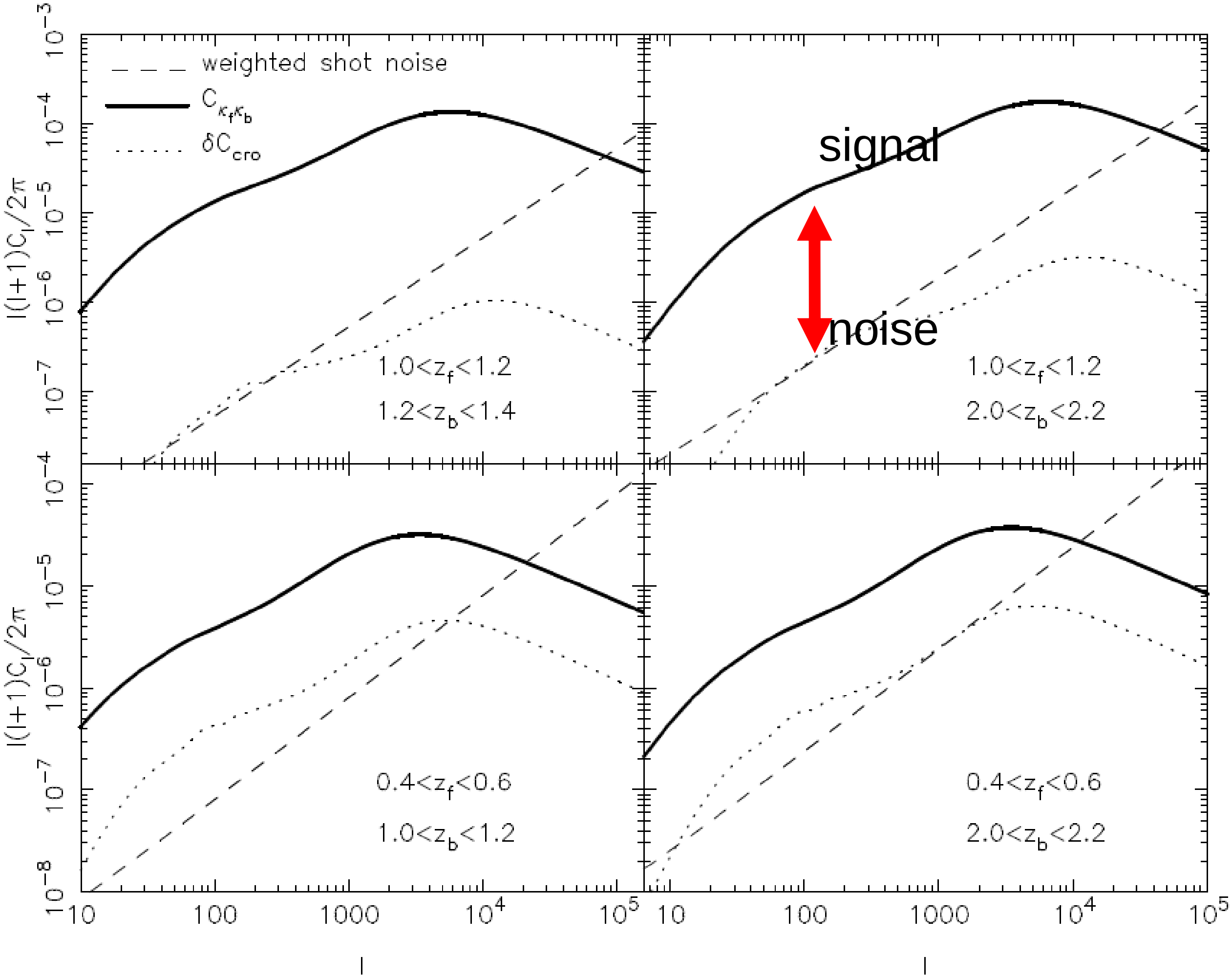
Measure lensing statistics: auto power spectrum bispectrum, cluster finding

Measuring statistics beyond the lensing auto power spectrum: e.g. peak statistics, cross power spectrum between redshift bins



Weak lensing reconstruction through cosmic magnification

- **Advantages:**
  - **No shape measurements. No PSF/intrinsic alignment errors.**
  - **Enable spectroscopic redshift surveys such as BigBOSS and SKA to measure lensing**
    - **Huge gain in science: multiple probes to the dark universe**
    - **Huge gain in measurement: photo-z is no longer a problem**
  - **Robust against photometry errors and dust extinction**
    - **Surprising but true!**

Systematical bias in flux calibration： not a problem

$$s^O = s\mu \times (1+p)\,.$$

$$n(s)dsdA = n^O(s^O)ds^O d(A\mu)$$

We circumvent this problem by defining another galaxy flux distribution function n^P, given by $n(s)ds = n^P(s^P)ds^P$ in which $s^P \equiv s(1+p)$. We then have

$$n^O(s^O) = \frac{1}{\mu^2} n^P\left(\frac{s^O}{\mu}\right) \simeq n^P(s^O)(1+g_P\kappa) \qquad \text{(A24)}$$

Here, $g_P \equiv 2(-d\ln n^P/d\ln s^P|_{s^O} - 2)$.

It is now clear that the cosmic magnification expression is still applicable, as long as we replace the intrinsic galaxy distribution n with n^P and replace g with g_P. Furthermore, since $\langle\mu\rangle = 1$ and $\langle(\mu-1)^2\rangle = O(10^{-3})$, $\langle n^O(s^O)\rangle = \langle n^P(s^O)\rangle$ to a good approximation. Under this limit, $g_P \simeq 2(-d\ln n^O/d\ln s^O - 2)$, an observable.

Random error in flux measurement: not a problem

$$\delta_g^O = \delta_g + g_P \kappa + \left(1 + \frac{g}{2}\right)(p - \langle p \rangle)$$

Different flux and angular dependence allowing for unbiased lensing reconstruction with the presence of flux measurement error (flux calibration, dust extinction, etc.)

Future works

- **Dealing with the galaxy stochasticity, the dominant systematical error**
  - **Research shows that stochasticity has limited degrees of freedom**
  - **The cross correlation covariance matrix can be well described by the first two eigen-modes**

- **Testing against mock catalog generated by N-body simulations (300-1200 Mpc/h, 512^3-3000^3 particles)**

- **Applying to real data**
  - **existing: CFHTLS/COSMOS**
  - **future: BigBOSS, DES, Euclid, KDUST, LSST, SKA**