Estimating B-mode polarization of CMB induced by gravitational lensing of intervening matter using ray-tracing simulation

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● Introduction

CMB polarization contains much information of the Early Universe (inflation).

Polarization has two modes（so called E&B-modes）

Scalar perturbation → only E-mode

tensor perturbation → E&B-modes

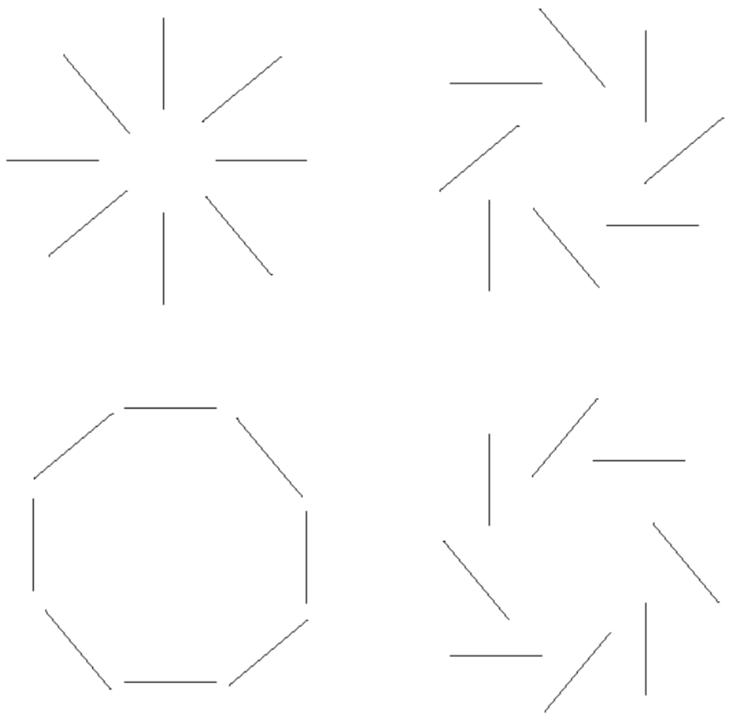
B-mode polarization is a probe of the primordial GWs generated during inflation.

However B-mode is not detected yet by current detectors such as WMAP, BICEP.

Next generation detectors (QUIET, LiteBIRD,,,) are planned to detect it.

Komatsu-san’s slide（CMB workshop 2010, in June, NAOJ）

E-mode and B-mode



E mode B mode

grad-type
even parity

curl-type
odd parity

- Gravitational potential can generate the E-mode polarization, but not B-modes.
- **Gravitational waves** can generate both E- and B-modes!

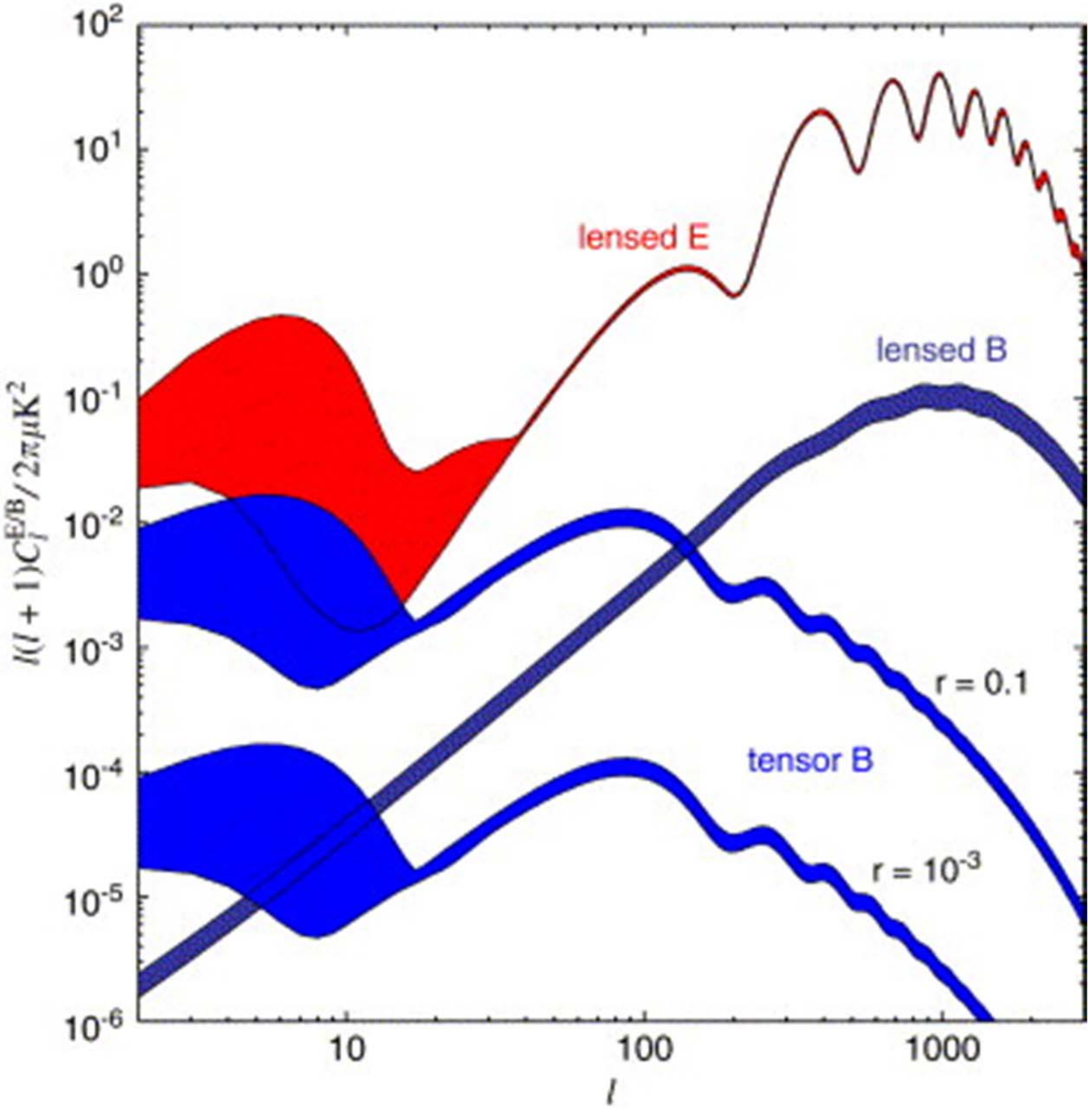
However, when CMB photons propagate through the Universe, the photons are scattered many times due to gravitational lensing by an inhomogeneous mass distribution in the Universe.

The gravitational lensing mixes E- & B-modes and generates secondary B-mode polarization which is major contamination when measuring the primordial B-mode signal.

So the CMB lensing is crucially important when measuring the primordial GWs from the CMB polarization.

（Lewis & Challinor 2006）

CMB Polarization power spectrum



r : scalar-to-tensor ratio

Recently I started studying this topic, so I do not have new results yet.

In this talk, I will talk about

1. **the related previous works**
2. **recent our work of ray-tracing simulation for galaxy lensing**
3. **my plan for investigating the CMB lensing**

If you have any comments or suggestions, please let me know and let us discuss after this session or at workshop dinner.

Financial support

My research is supported by the foundation (kobo-kenkyu) of the project Shinryoiki (the leader is Hazumi-san).

The purpose of the project is the detection of the primordial GWs in the CMB polarization using next generation detectors (QUIET, LiteBIRD,,,).

In order to study the basics of the CMB lensing:

1. I participated in CMB workshop 2010, NAOJ, June.

2. I invited two experts of CMB and weak lensing and hold seminars in August.

Kaiki Inoue-san（Kinki University）

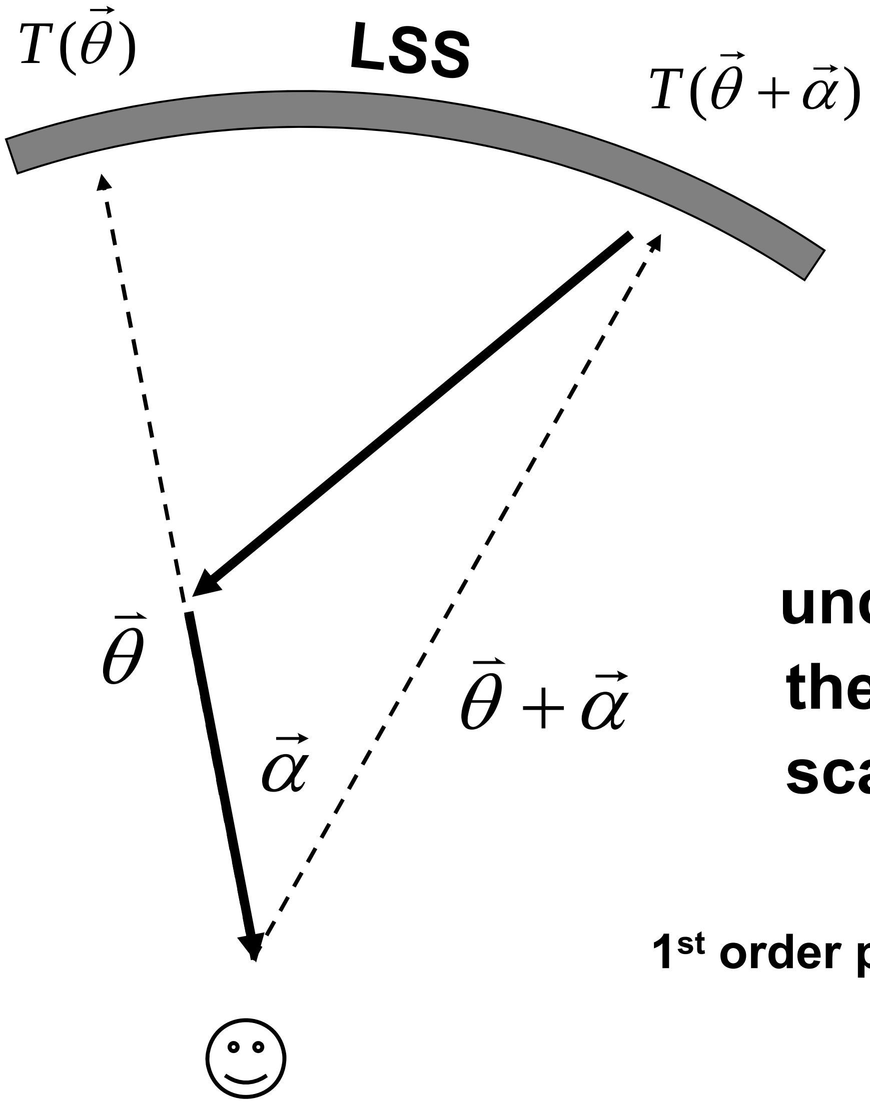
Title: “Evidence of Quasi-linear Super-structures in the CMB and Galaxy Distribution”

Masahiro Takada-san（IPMU）

Title: “Weak lensing of galaxy clusters using Subaru telescope（すばるデータによる銀河団弱重力レンズ効果の研究）”

supported by the Shinryoiki koubo-kenkyu

Basics of the CMB lensing （Lewis & Challinor 2006）



$$T(\vec{\theta}) \to \tilde{T}(\vec{\theta}) = T(\vec{\theta}+\vec{\alpha})$$

$\vec{\alpha}$: deflection angle

α～ a few arcmin

under the Born approximation the light ray from LSS is scattered once.

1st order perturbation of gravitational potential

under the Born approximation

$$\vec{\alpha}(\vec{\theta}) = \vec{\nabla}_{\theta}\psi(\vec{\theta})$$

$$\psi(\vec{\theta}) = -\int_0^{\chi_*} d\chi \frac{\chi_* - \chi}{\chi_* \chi} \Psi(\chi\vec{\theta}, \chi)$$

ψ : lensing potential

Ψ : gravitational potential

χ : comoving distance

χ_* : comoving distance to LSS

The gravitational potential is related to the density fluctuation via Poisson equation.

$$\nabla^2 \Psi = 4\pi G a^2 \overline{\rho} \delta$$

power spectrum of Ψ

$$\left\langle \Psi(\vec{k};\eta)\Psi^*(\vec{k}';\eta') \right\rangle = \frac{2\pi^2}{k^3} P_\Psi(k;\eta)\,\delta^{(3)}(\vec{k}-\vec{k}')\,\delta(\eta-\eta')$$

lensing potential as an expansion of spherical harmonics

$$\psi(\vec{\theta}) = \sum_{\ell,m} \psi_{\ell m} Y_{\ell m}(\vec{\theta})$$

$$\left\langle \psi_{\ell m} \psi^*_{\ell' m'} \right\rangle = C_\ell^\psi \,\delta_{\ell\ell'} \delta_{mm'}$$

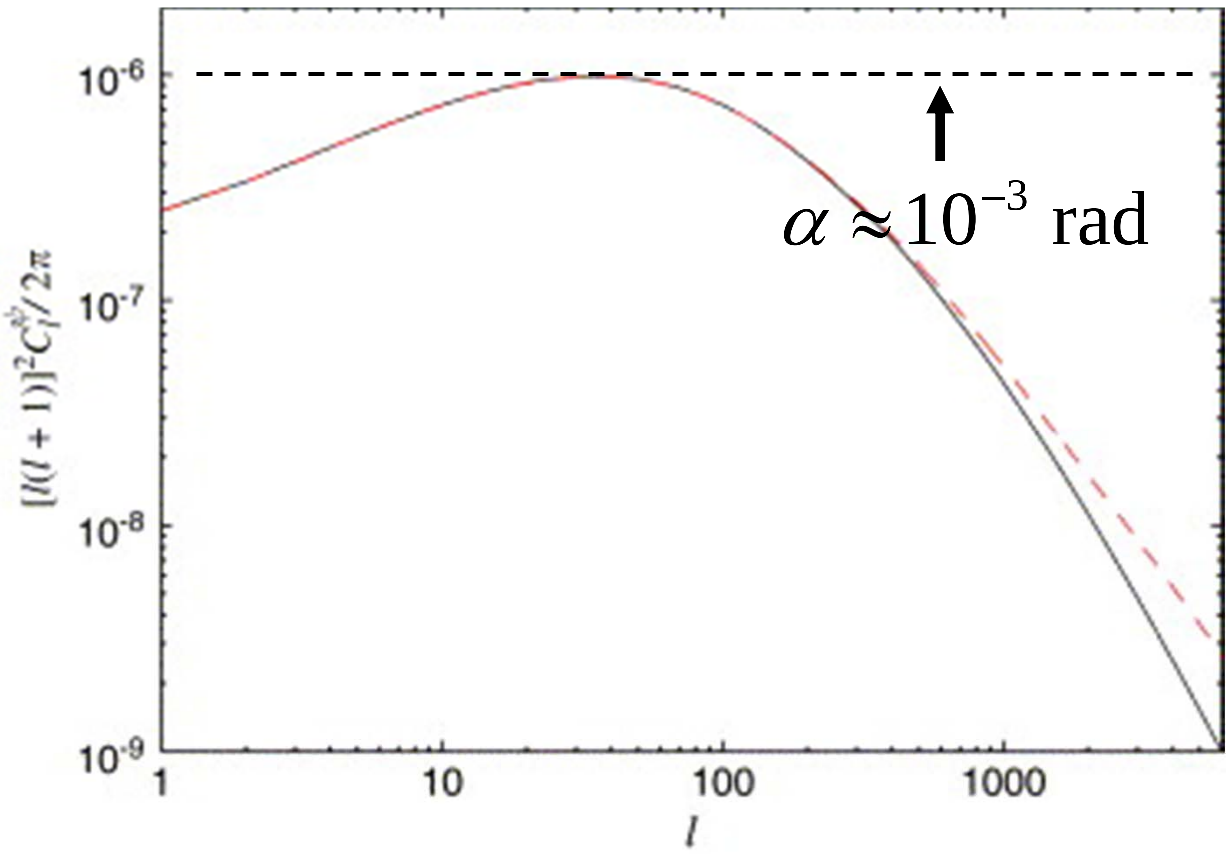
angular power spectrum of ψ

$$C_\ell^\psi = 16\pi \int \frac{dk}{k} \int d\chi\, P_\Psi(k,\chi) \left[j_\ell(k\chi) \right]^2 \left(\frac{\chi_* - \chi}{\chi_* \chi} \right)^2$$

Deflection angle α～ a few arcmin

Power spectrum of deflection angle α

$\langle \alpha^2 \rangle$



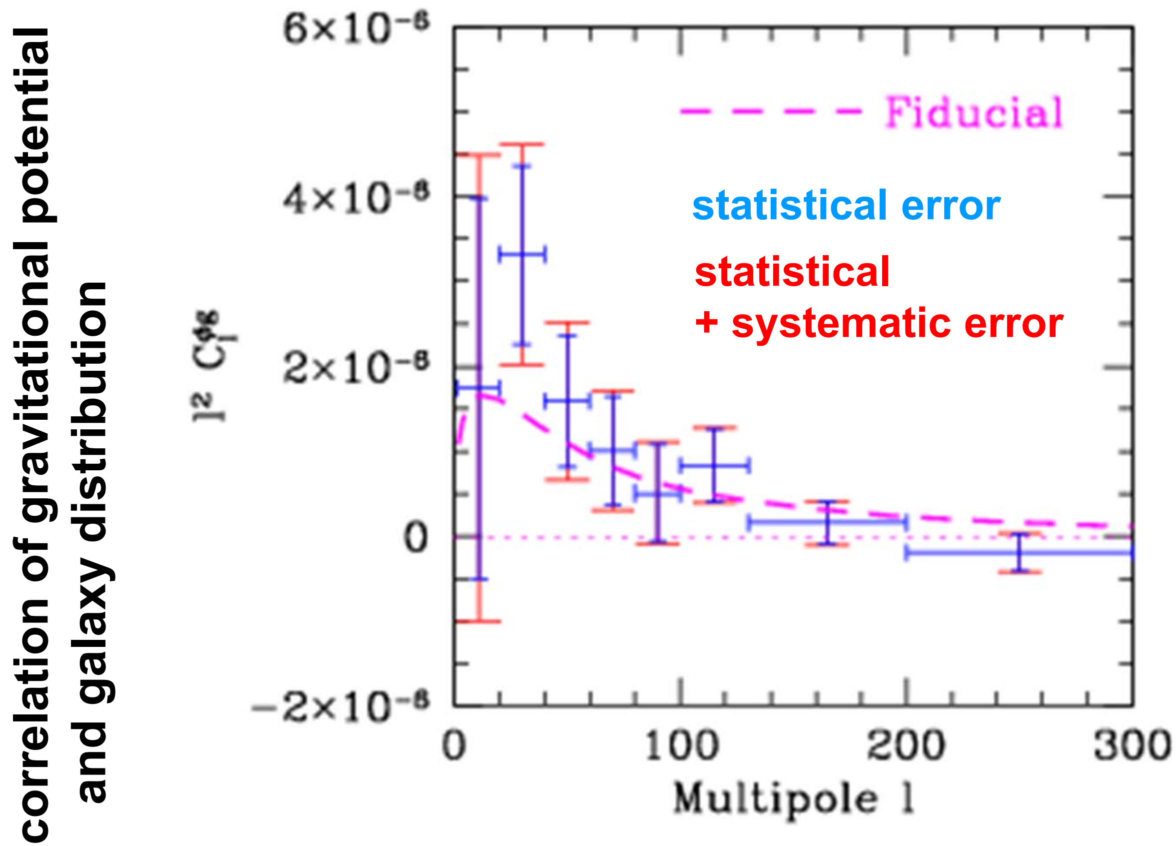
$$\int \frac{d\Omega}{4\pi} \langle \alpha^2 \rangle = \sum_{\ell,m} \frac{\ell(\ell+1)}{4\pi} C_\ell^{\psi} \approx \frac{[\ell(\ell+1)]^2}{2\pi} C_\ell^{\psi}$$

（Lewis & Challinor 2006）

Detection of CMB lensing

First detection reported by Smith+（2007）

Correlation of CMB (WMAP) and radio galaxy distribution



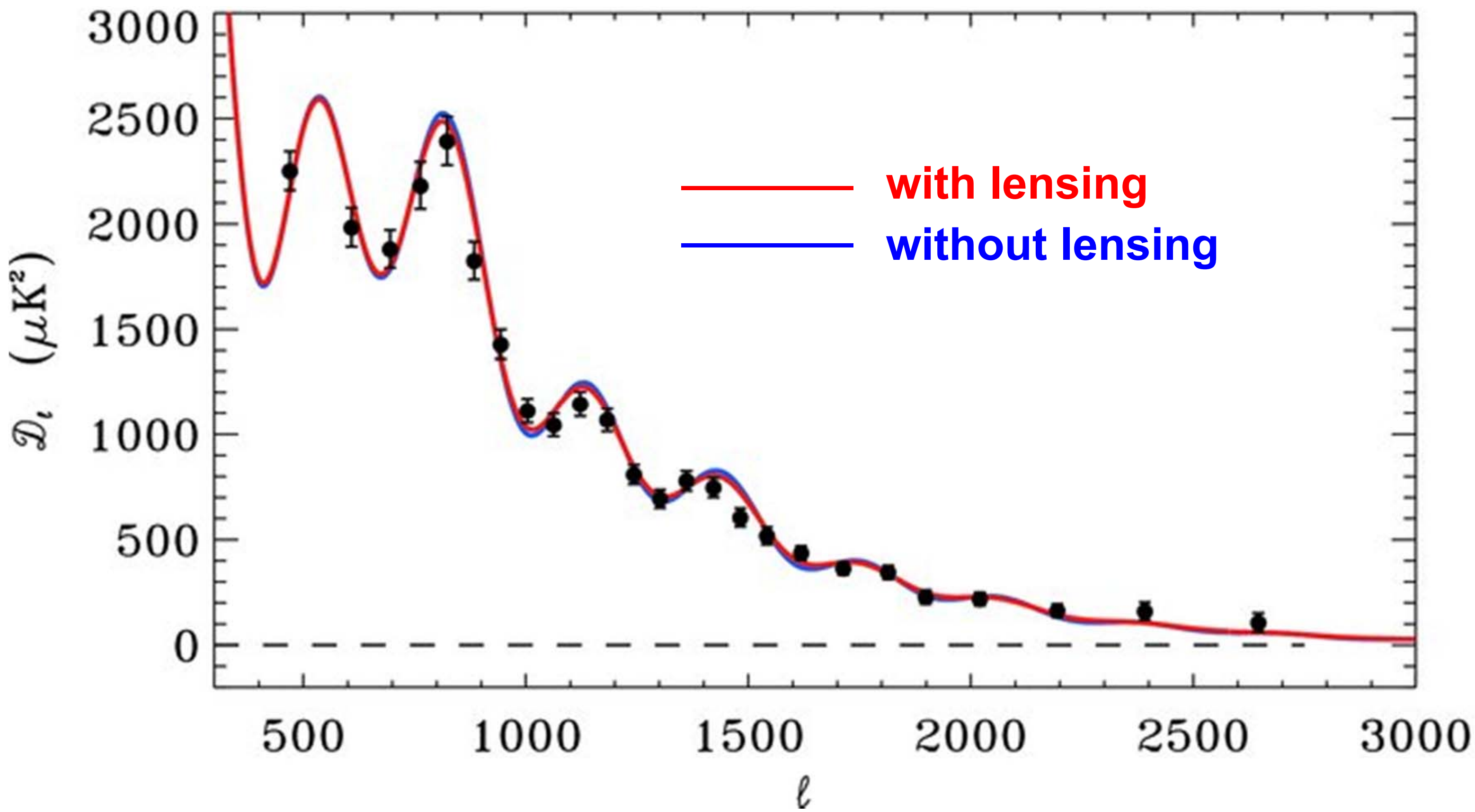
3.4σ detection

Hirata+ (2008) also did similar analysis and reported 2.5σdetection

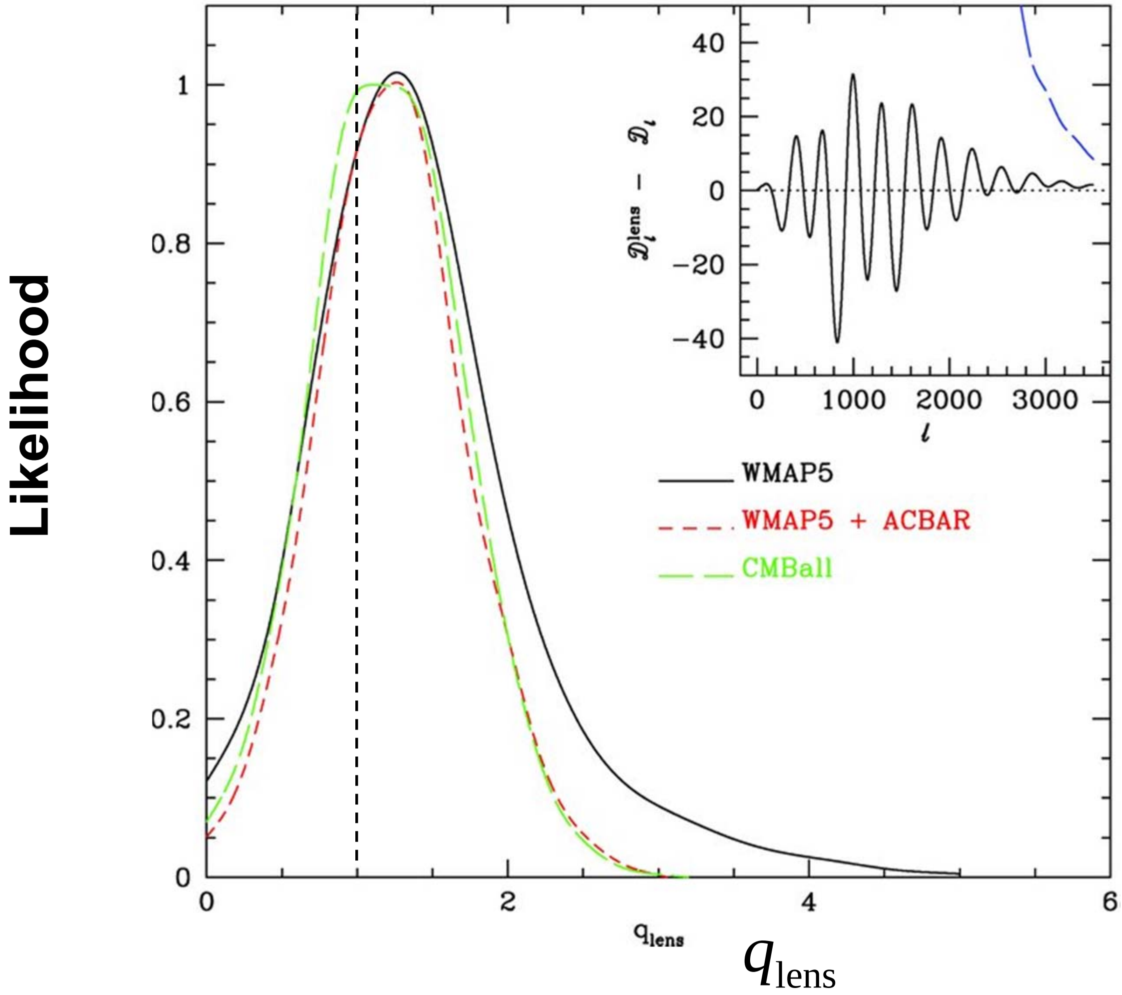
Lensing signature in CMB TT power spectrum

（Reichardt+ 2009）

ACBAR TT power spectrum



Lensing smears the acoustic oscillation



（Reichardt+ 2009）

>2σ detection

WMAP5+ACBAR

$$C_\ell = C_\ell^{\rm no-lens} + q_{\rm lens}\,\Delta C_\ell^{\rm lens}$$

$q_{\rm lens} = 1$ **: normal lensing case**

$q_{\rm lens} = 0$ **: no-lensing case**

Lensing signature in ACT data

（Das+ 2010）

ACT temperature power spectrum

with lensing

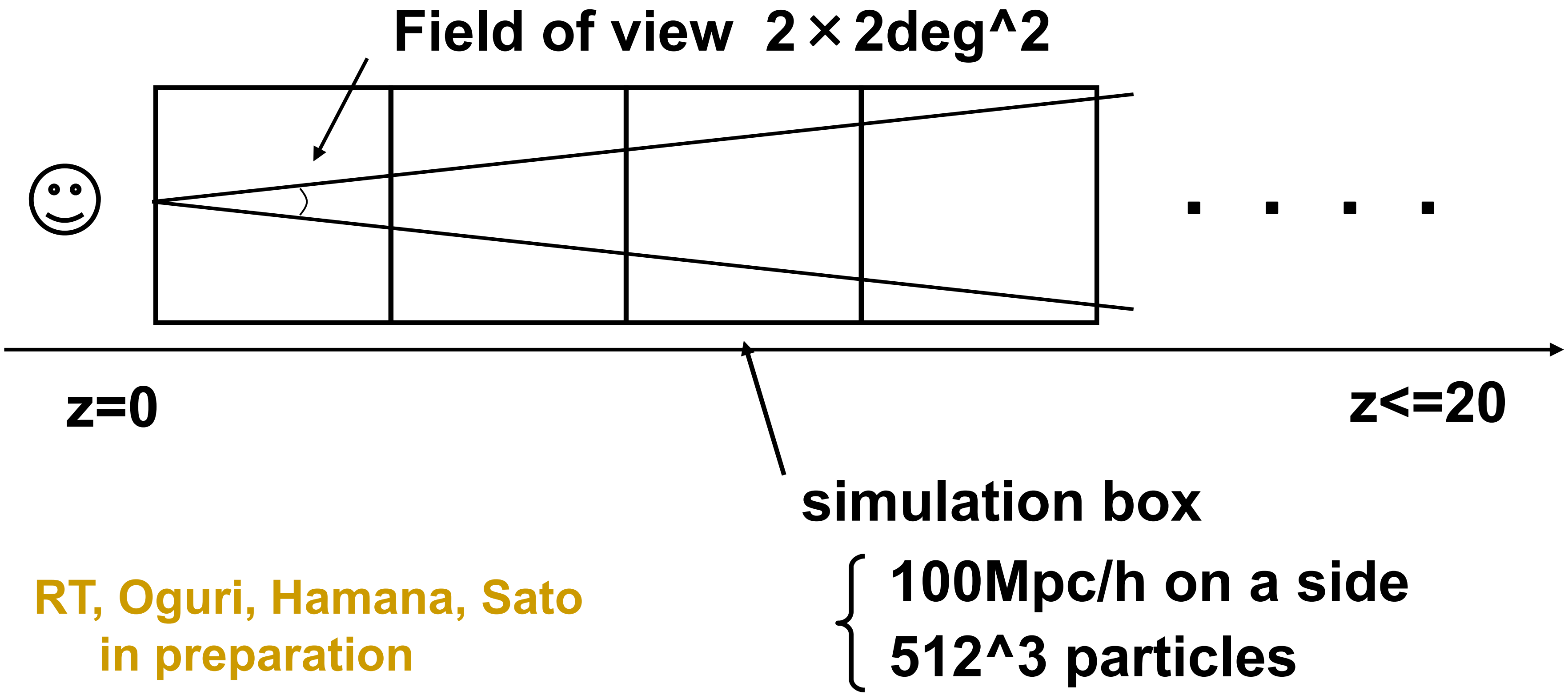
without lensing

2.8σ detection

Ray-tracing simulation for galaxy lensing

light-ray propagation through inhomogeneous mass distribution in the Universe

We reproduce the large scale structure of dark matter in each simulation box and calculate the light-ray path.



RT, Oguri, Hamana, Sato
in preparation

Ray-tracing simulation

We use freely publicly available codes :

1. **N-body simulation code of Gadget2 （Springel）**

   evaluate non-linear gravitational evolution of dark matter particles

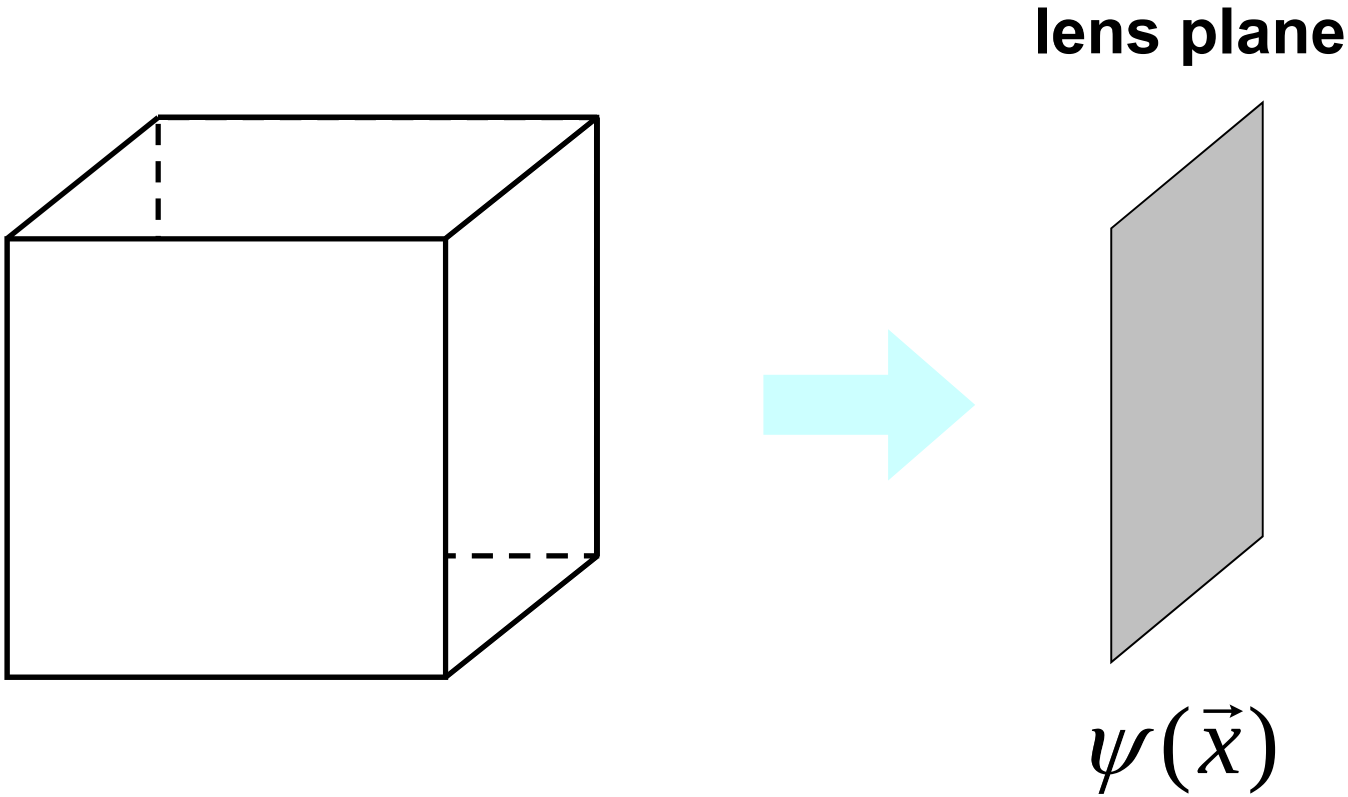
2. **Ray-tracing simulation code of Raytrix （Hamana）**

   calculate light ray path in inhomogeneous mass distribution

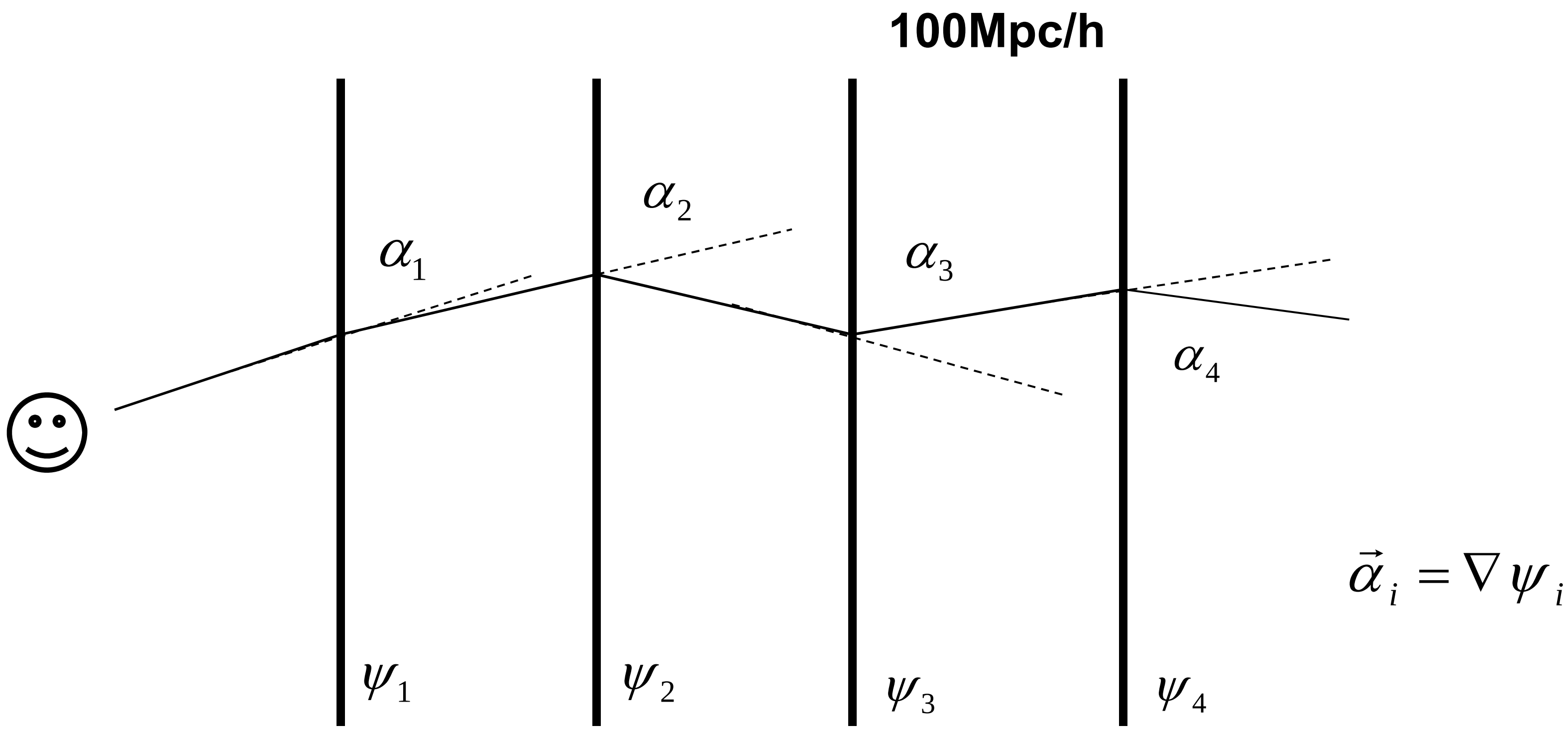
We did our calculation using the PC cluster at NAOJ

3D particle distribution is projected to 2D surface, and calculate the gravitational potential on the lens plane.

(thin lens approximation)



Lens planes



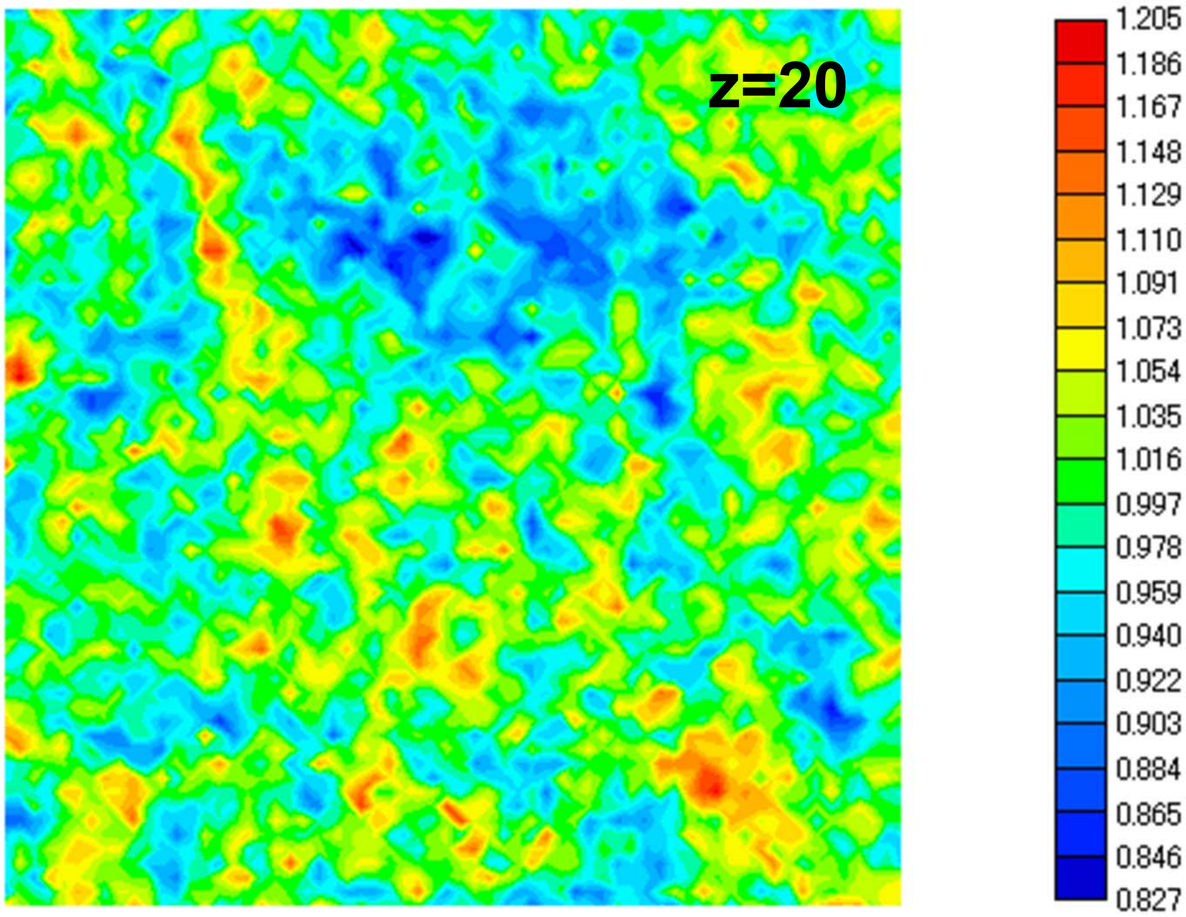
A light ray emitted from the observer is deflected at each lens plane

calculate the ray path up to the source plane

Example 1 Contour map of convergenceκ at z=20

$1+\kappa$

convergence κ: projected surface mass density



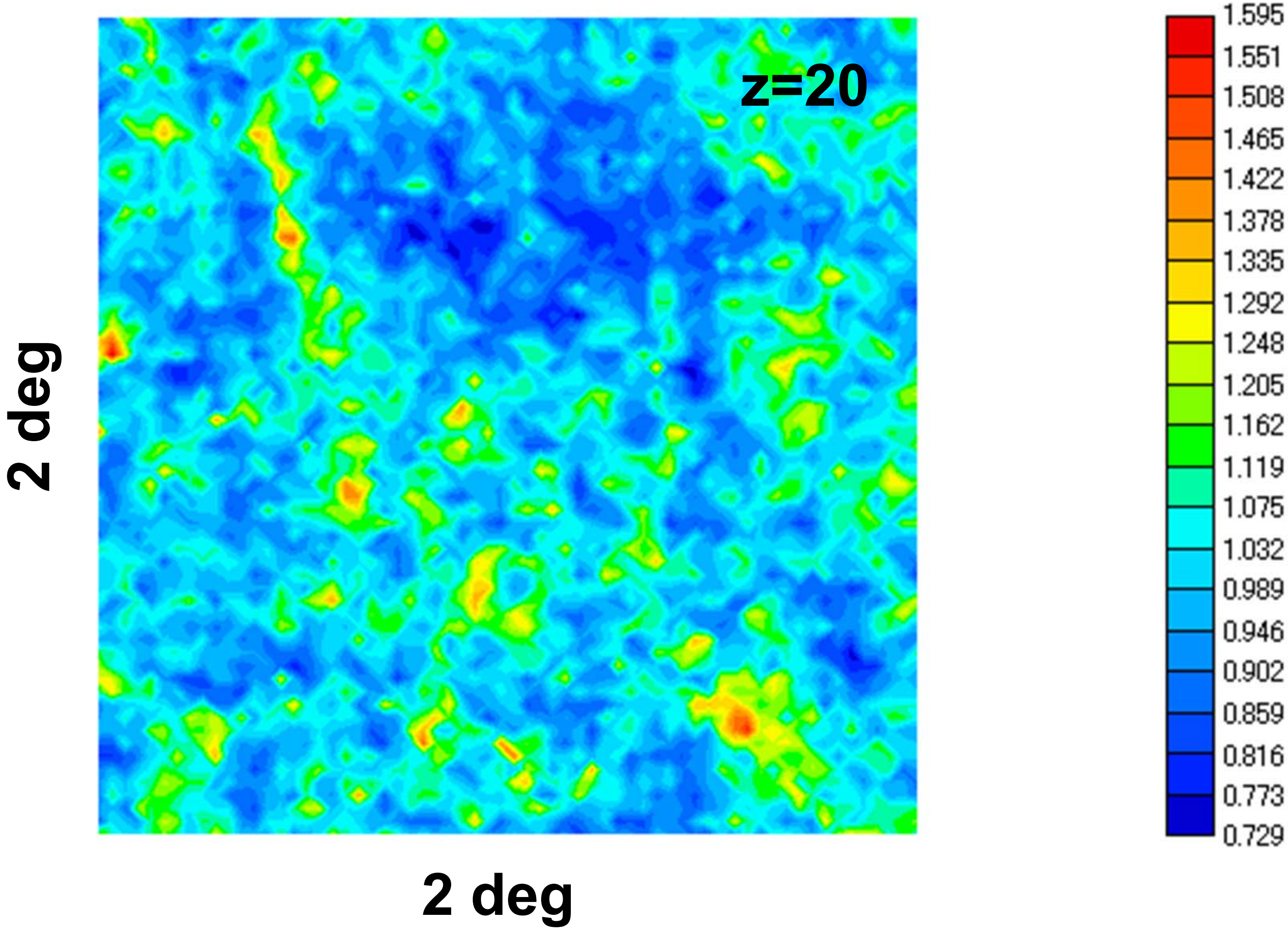
2 deg

2 deg

（RT, Oguri, Hamana Sato, in preparation）

grid size of gravitational potential = 0.8Mpc/h
angular resolution = 2 arcmin

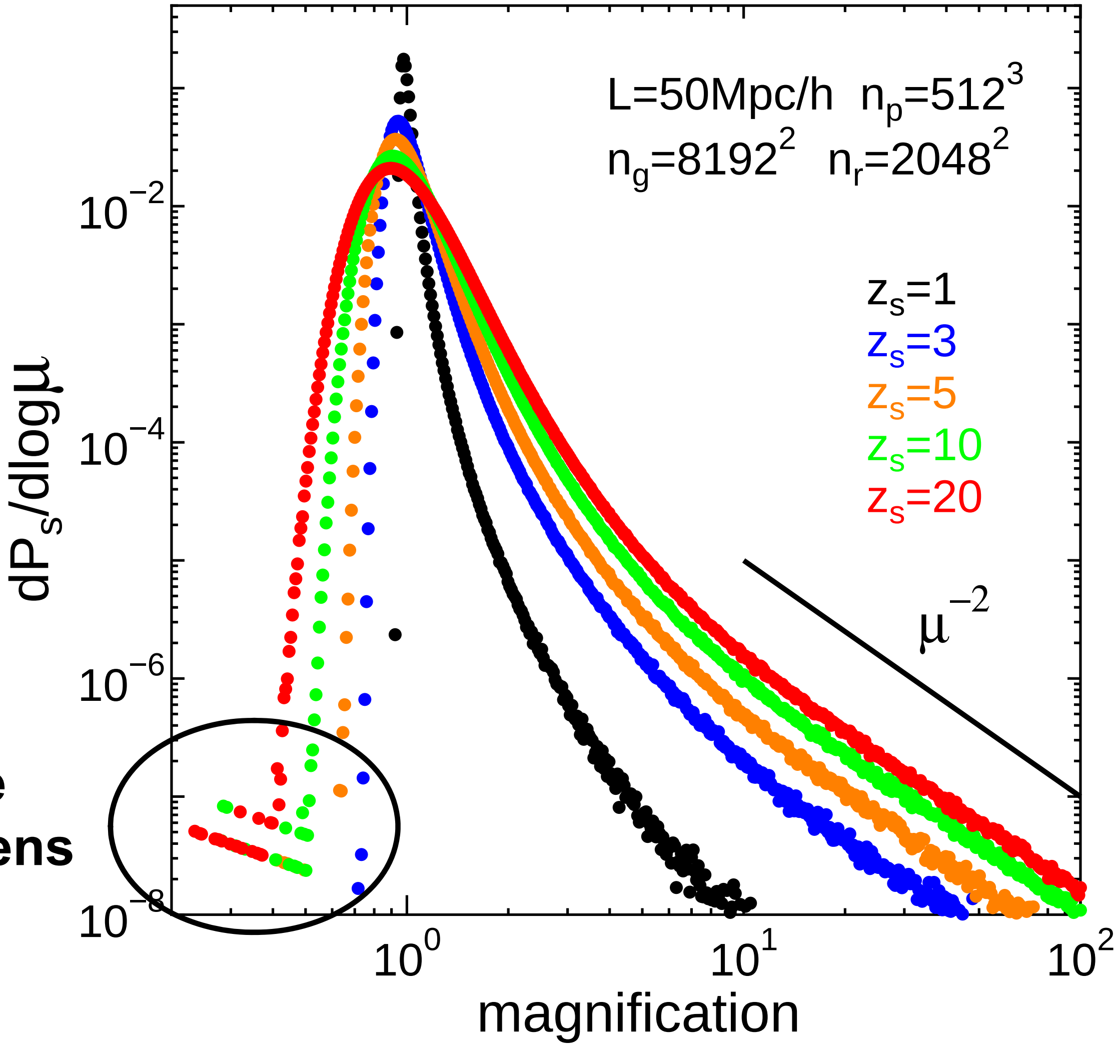
Example 2 Contour map of magnification at z=20



grid size of gravitational potential = 0.8Mpc/h
angular resolution = 2 arcmin

Magnification PDF

$$\frac{dP_S(\mu)}{d\log\mu}$$



faint image in strong lens

binning in logμ

My plan 1 for the CMB lensing :

primary CMB map ← publicly available code HEAPix

+

ray-tracing simulation

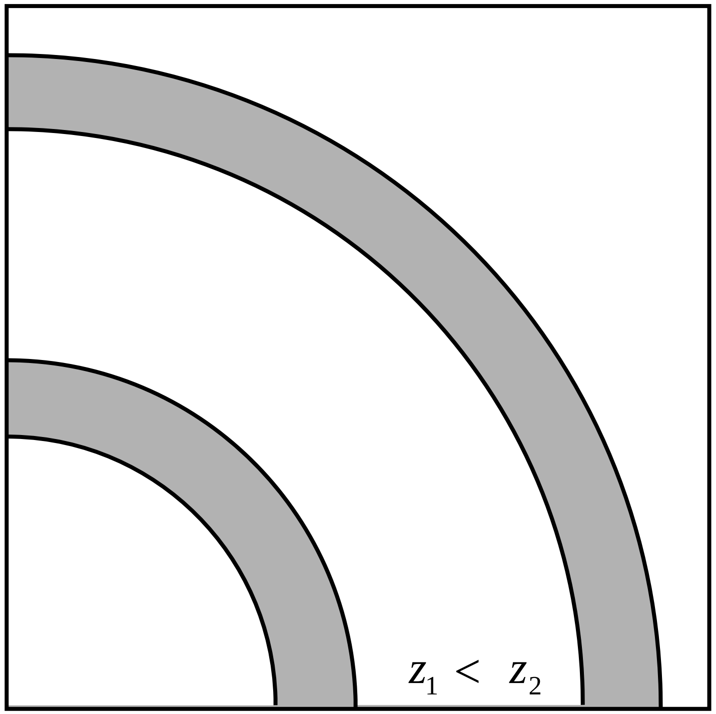
↓

lensed CMB map

My plan 2:

We need some modifications in the code to study the CMB lensing

flat lens plane → spherical shell



(Das & Bode 2008)

My plan 3:

primary CMB anisotropy obeys Gaussian

But, gravitational lensing induce non-Gaussianity

Because the foreground density fluctuation obeys non-Gaussian distribution in non-linear regime

Estimating Non-Gaussianity in lensed CMB

Covariance matrix

Dependence of shape of survey area

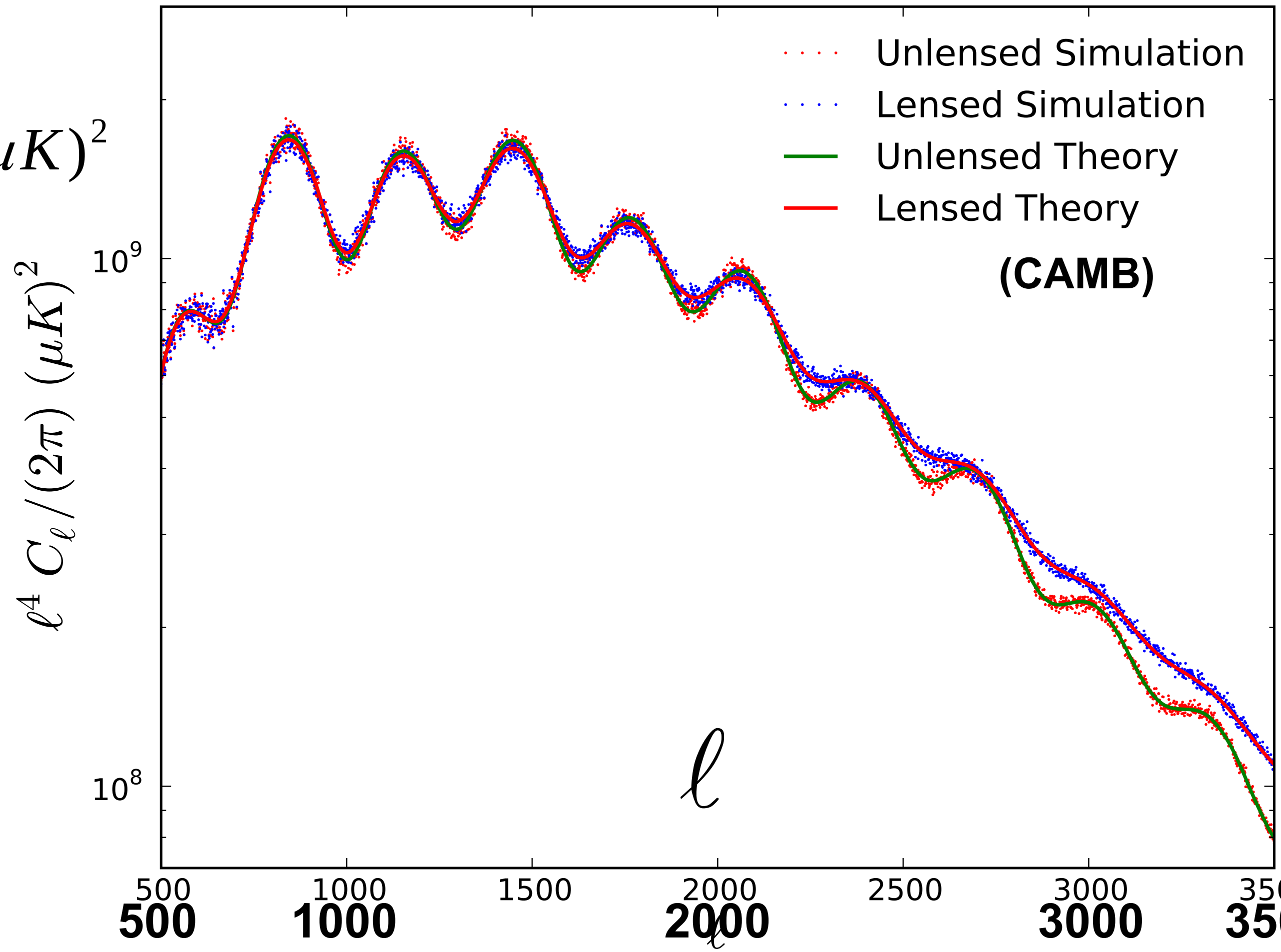
Ray-tracing simulation for CMB lensing

Sehgal, Bode, Das+ 2008,2010

FOV : 4π/ 8

They also discuss kinetic and thermal SZ

$\ell^4 C_\ell / (2\pi)\ (\mu K)^2$



500 1000 2000 3000 3500

ℓ

Carbone, Bartelmann, Springel+ 2008,2009

N-body simulation: Millennium simulation

Lensed E-&B-modes power spectra

slight excess (～10%) in power spectra due to non-linear clustering in Millennium simulation

Non-Gaussianity induced by lensing

No signature of non-Gaussianity in one point distribution function of T

three- or four- correlation function is better

Delensing

Estimate the gravitational lens potential from the CMB T, E and B maps,

and reduce the lensing noise in the B-mode （Hu 2001）

lensing contamination can be reduced by

～1/7（quadratic method） and

< 1/40（iterative method） （Seljak & Hirata 2004）

～1/10（quadratic method） （Knox & Song 2002）

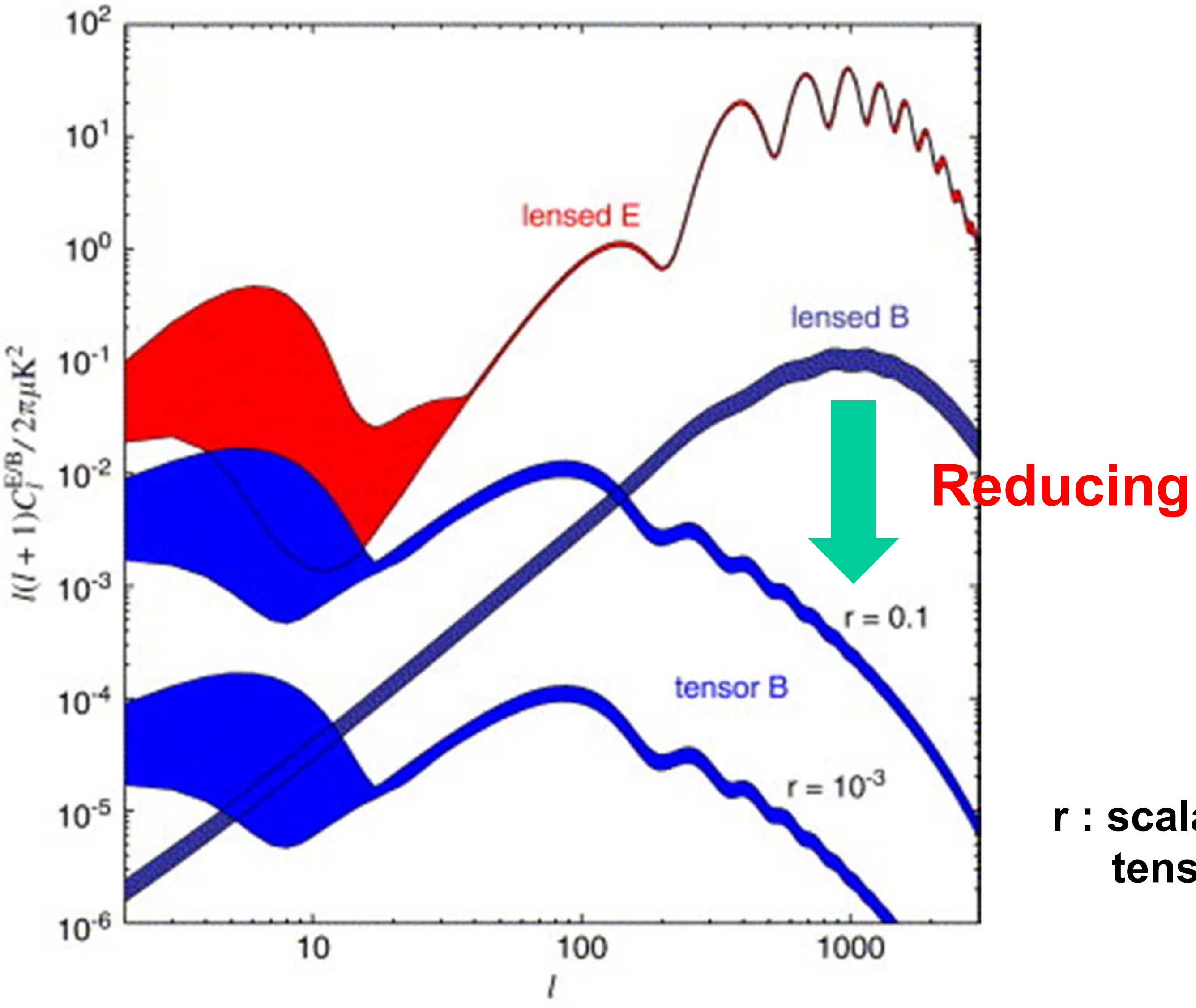
My plan 4:

understand their method

calculate how accurately reconstruct the lensing potential using the lensed CMB map

（Lewis & Challinor 2006）

CMB Polarization power spectrum

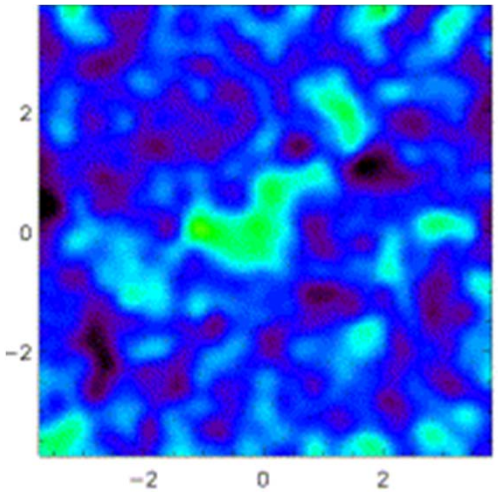


r : scalar-to-tensor ratio

Amblard, Vale & White 2004

reconstruction of convergence κ map

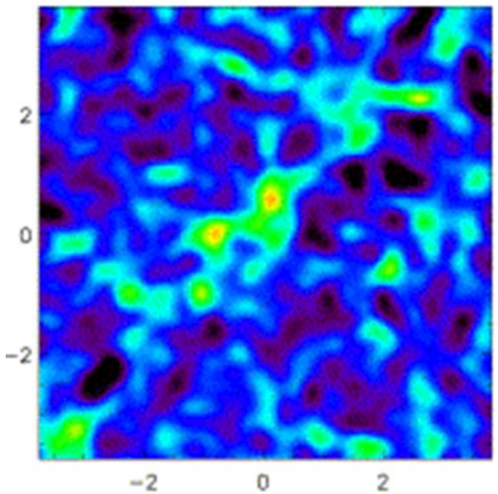
using N-body simulation



input κ map

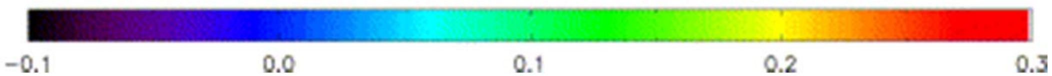
CMB ← Gaussian

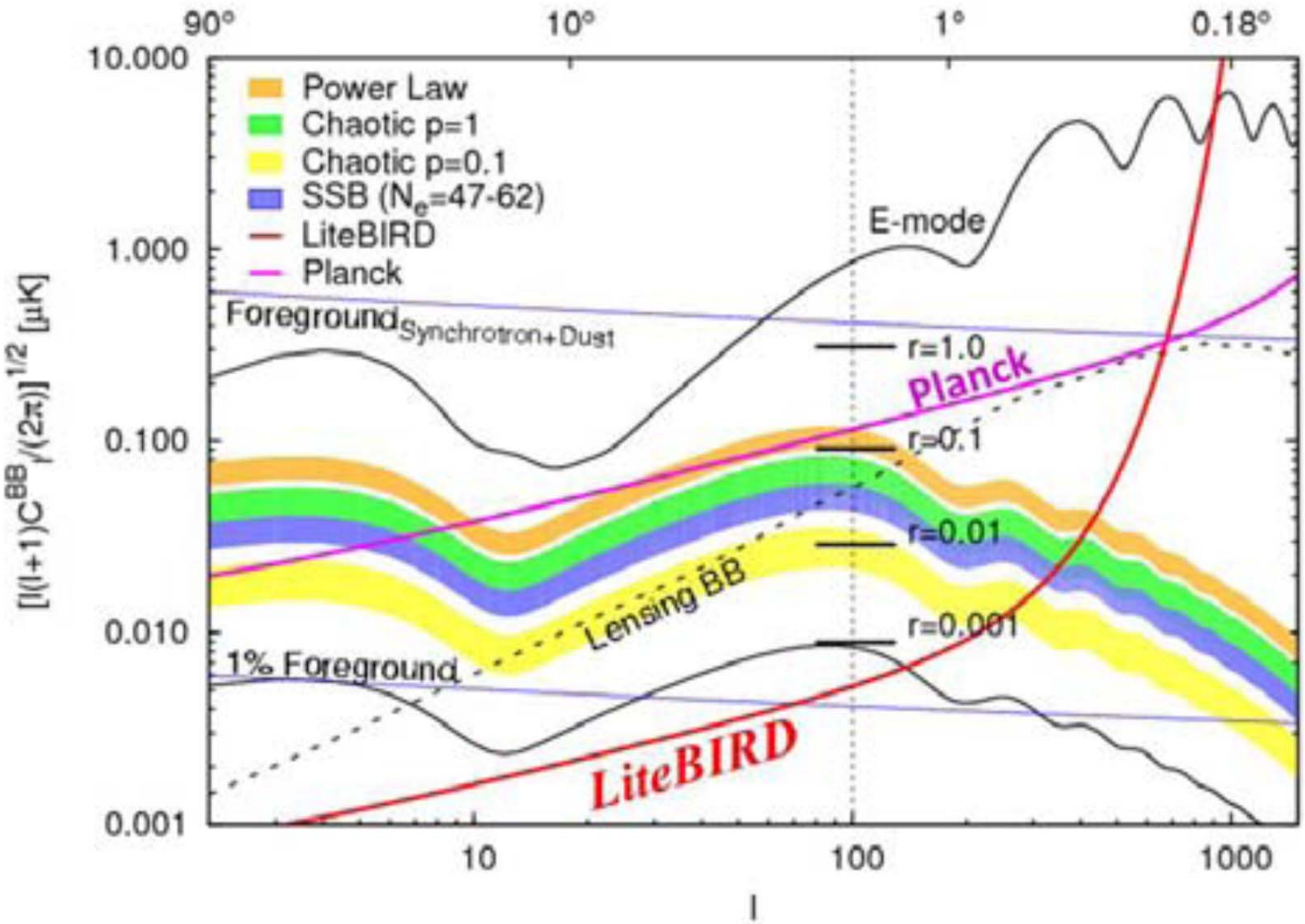
κ ← non-Gaussian



reconstructed κ map

can reconstruct the κ map within <50% error in the angular power spectrum of κ





90°
10°
1°
0.18°
10.000
1.000
0.100
0.010
0.001
10
100
1000
l
[l(l+1)C^BB_l/(2π)]^1/2 [μK]
Power Law
Chaotic p=1
Chaotic p=0.1
SSB (N_e=47-62)
LiteBIRD
Planck
E-mode
Foreground Synchrotron+Dust
r=1.0
Planck
r=0.1
r=0.01
Lensing BB
r=0.001
1% Foreground
LiteBIRD

（羽澄　2010）