Constraining the stochastic gravitational wave background using cosmic shear B-mode

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+possibly HSC collaborators

Accelerating the universe in the Dark, March 2019@Kyoto

The Stochastic GW Background

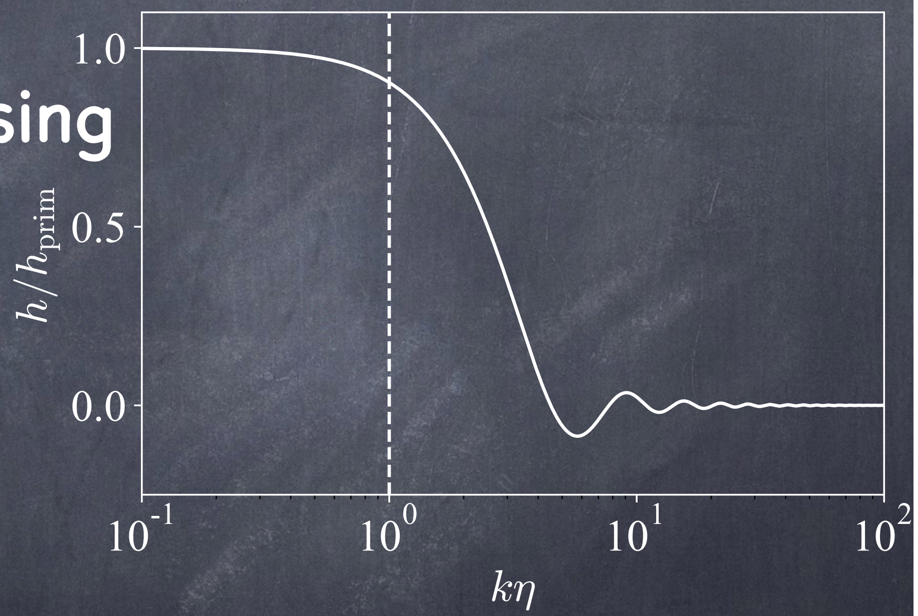
- GWs in the expanding universe
  - tensor perturbation $ds^2 = a^2(\eta)[-d\eta^2 + (\delta_{ij} + h_{ij})dx^i dx^j]$

    $$h''_{ij} + 2\mathcal{H}h'_{ij} + k^2 h_{ij} = 0$$

  - decay after the horizon crossing

    $$h_{ij}(\eta) \propto T_T(k,\eta) = 3\frac{j_1(k\eta)}{k\eta}$$

  - oscillation in subhorizon



- Sources of the stochastic GW background (SGWB)
  - Astrophysics: unresolved compact binary (BH, NS…)
  - Cosmology: inflation, phase transition, cosmic string…

Properties of the SGWB

- Characterized by its statistical properties
  - Isotropic, stationary…
  - Frequency spectrum

- Energy density parameter of the SGWB
  - Energy density of the SGWB

$$\rho_{\rm GW} \equiv \frac{1}{64\pi G a^2}\langle (h'_{ij})^2 + (\nabla h_{ij})^2 \rangle$$

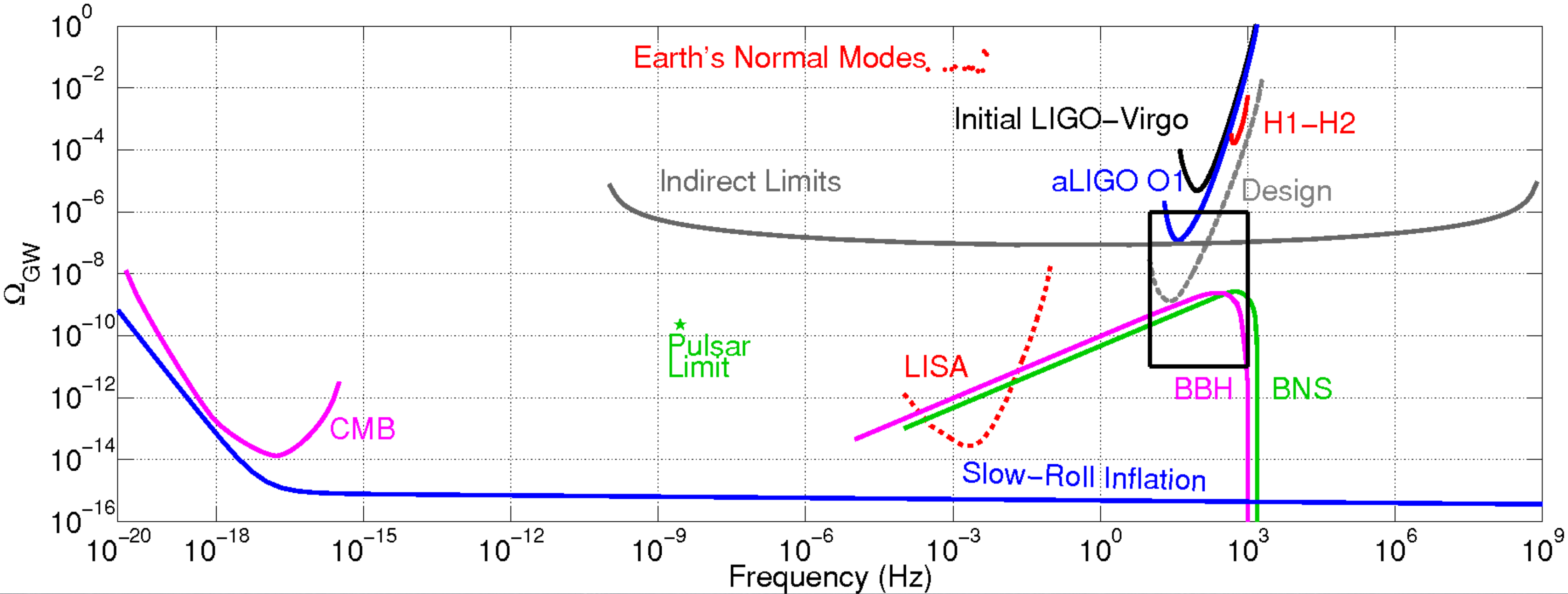
  - Energy density per unit log frequency or wavenumber

$$\Omega_{\rm GW}(f) \equiv \frac{1}{\rho_{\rm crit}}\frac{d\rho_{\rm GW}(f)}{d\ln f} = \frac{1}{12}\left(\frac{k}{H_0}\right)^2 \Delta_h^2(k) \qquad \Delta_h^2(k) = \frac{k^3 P_h(k)}{2\pi^2}$$

  - $\Omega_{\rm GW} h^2$ is independent of the H_0

Current constraints on SGWB

LIGO&Virgo collaboration 2017

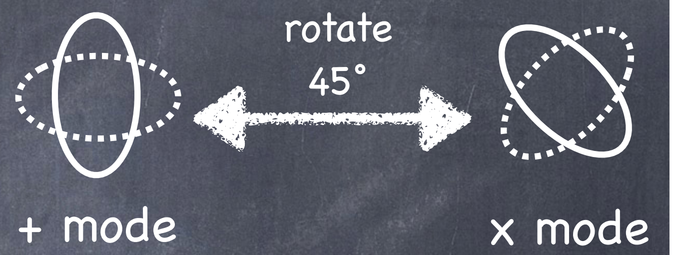


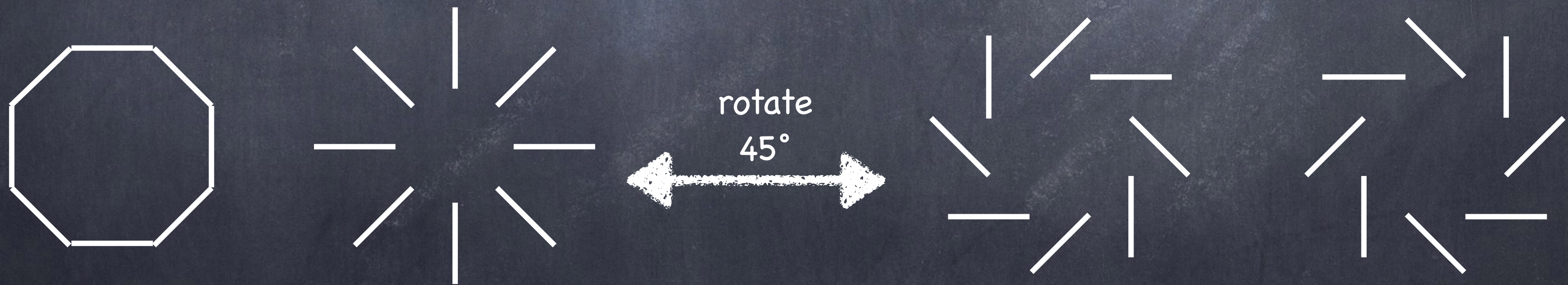
- Detection methods
  - CMB temperature/polarization anisotropy (Gpc)
  - Pulsar Timing Array (pc)
  - Laser interferometer experiments (km)

Cosmic shear as a probe of GW

Kaiser&Jaffe 1996, Dodelson+ 2003, Schmidt&Jeong 2012

- Galaxy shape(shear): spin-2 -> E/B decomposition
- Weak lensing: Bending light by metric perturbations
  - Scaler perturbation -> only EE
  - Tensor perturbation -> both EE&BB





E-mode (Parity even) B-mode (Parity odd)

- B-mode shear is a unique signature of GWs

B-mode power spectrum from GWs

$$C_\ell^{BB}(\chi_1,\chi_2) = \frac{1}{\pi}\int d\ln k\ \underbrace{\Delta_h^2(k)}_{\text{GW power}} F_\ell^B(k,\chi_1)F_\ell^B(k,\chi_2) \qquad \Delta_h^2(k) = \frac{k^3}{2\pi^2}P_h(k)$$

$$F_\ell^B(k,\chi) = -\frac{1}{4}\Bigg[\underbrace{T_T(k,\eta_0)\left(\mathrm{Im}\ \hat{Q}_1(x)\frac{j_\ell(x)}{x^2}\right)_{x=0}}_{\text{observer term}} + \underbrace{T_T(k,\eta_0-\chi)\left(\mathrm{Im}\ \hat{Q}_1(x)\frac{j_\ell(x)}{x^2}\right)_{x=k\chi}}_{\text{source term}}\Bigg]$$

Schmidt&Jeong 2012

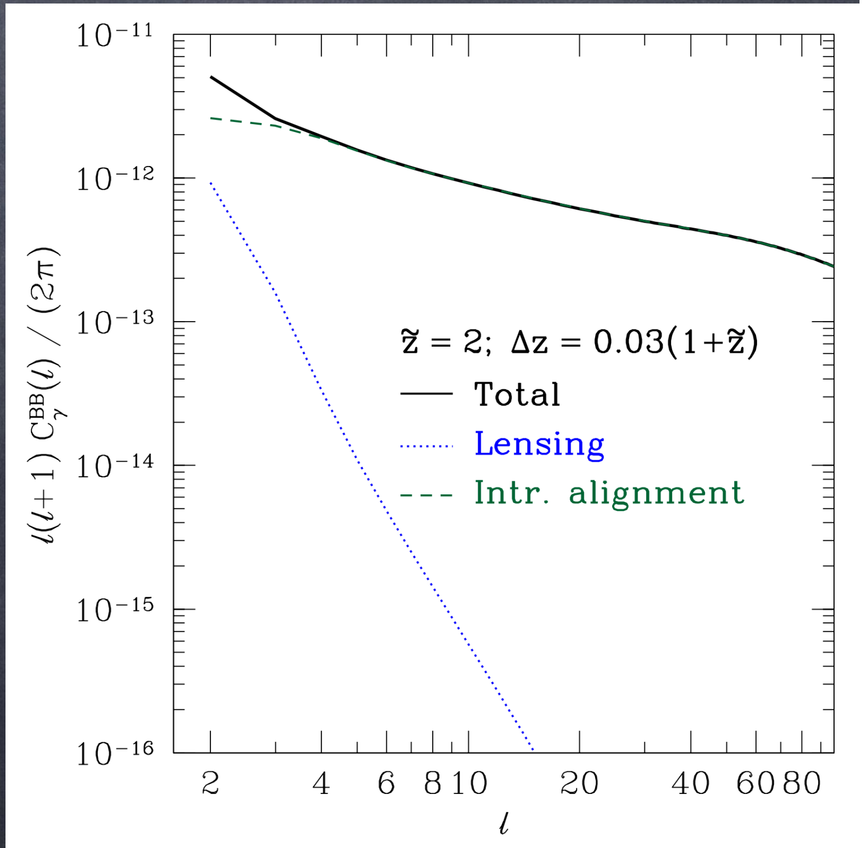
$$\underbrace{+\int_0^\chi \frac{d\tilde\chi}{\tilde\chi}\, T_T(k,\eta_0-\tilde\chi)\left(\mathrm{Im}\ \hat{Q}_2(x)\frac{j_\ell(x)}{x^2}\right)_{x=k\tilde\chi}}_{\text{lensing term}}$$

- For GWs from the inflation
  - flat spectrum

$$\Delta_h^2(k) = \frac{k^3}{2\pi^2}P_h(k) = \Delta^2_{T,\mathrm{pivot}}\left(\frac{k}{k_{\mathrm{pivot}}}\right)^{n_T}$$

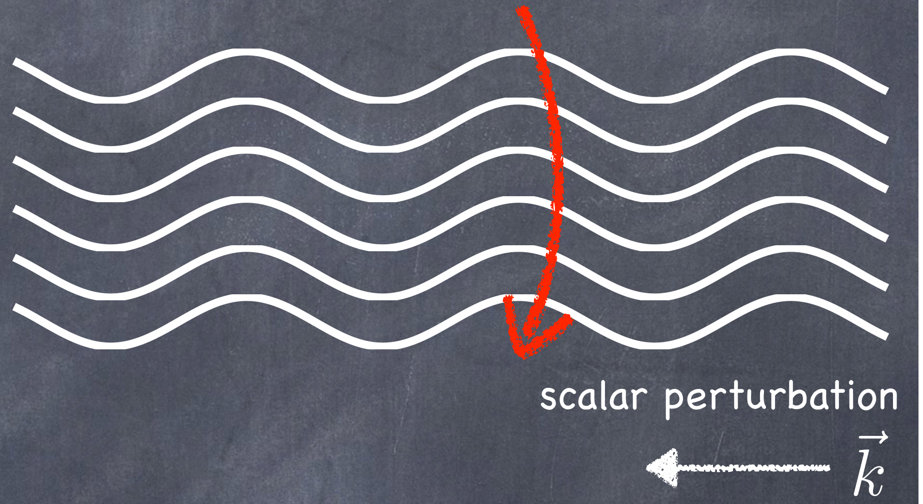
$$n_T = -r/8, \quad r = 0.2$$

  - very steeply falling with l

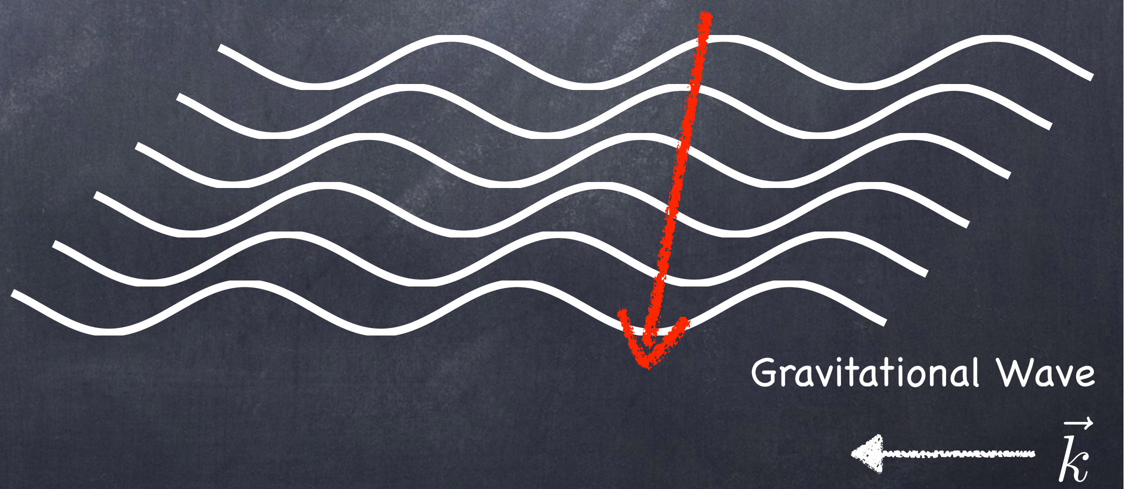


Weak lensing by density/GW

- Lensing by scalar perturbation
  - static
  - deflect light coherently along the line of sight(LOS)



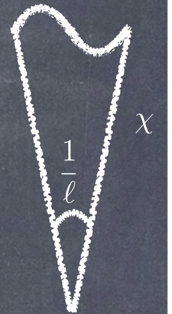
- Lensing by GW
  - propagating!
  - cancellation of lensing effect along the LOS



B-mode signal from GWs

✘ Limber approximation: contribution from only $k\chi \sim \ell$

$$\int k^2 dk\, \underline{P_h(k;\chi,\chi')} j_\ell(k\chi) j_\ell(k\chi') \quad \simeq \quad \frac{\pi}{2\chi^2}\delta_D(\chi-\chi')P_h\left(k=\frac{\ell+1/2}{\chi};\chi,\chi'\right)$$



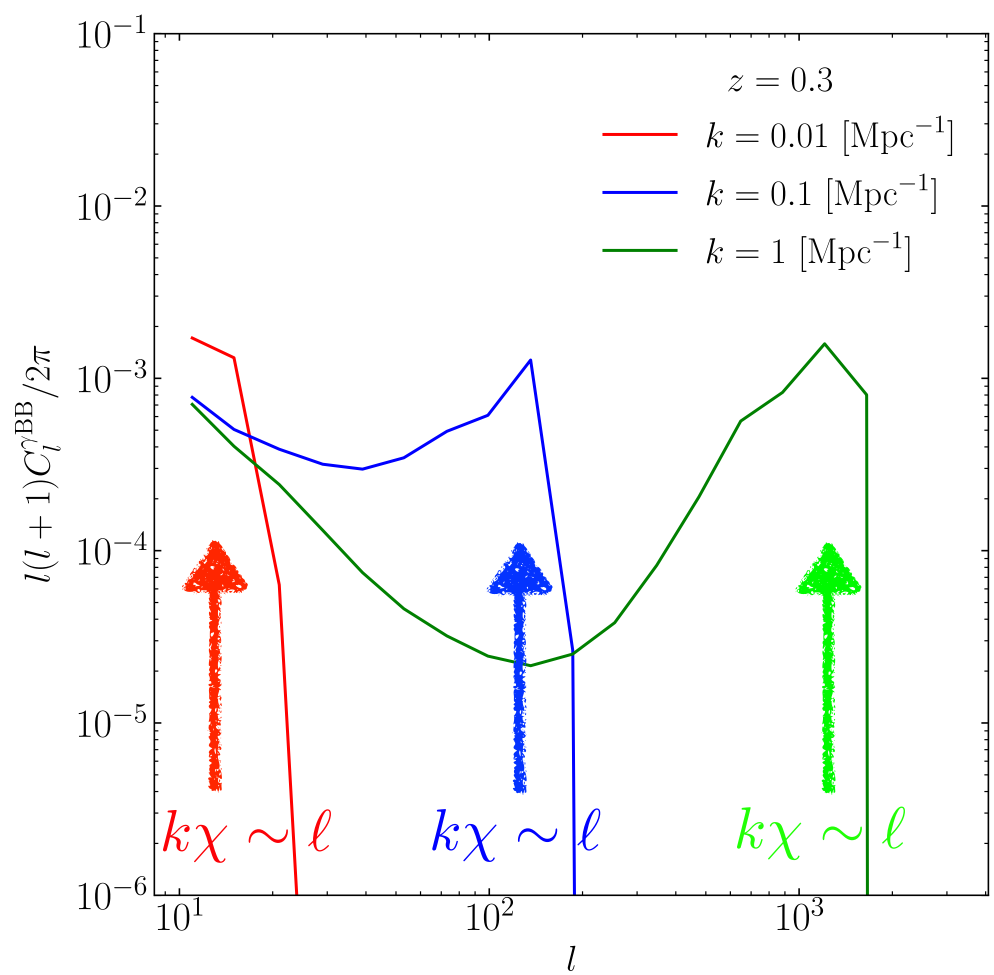
highly oscillatory function

$$P_h(k;\chi,\chi') = T_T(k\chi)T_T(k\chi')P_{T0}(k)$$

$$T_T(k\chi) \propto \frac{j_1(k\chi)}{k\chi} \quad \text{in M.D.}$$

- different from scalar case
- due to the high oscillation of tensor transfer func.
- require careful calculation

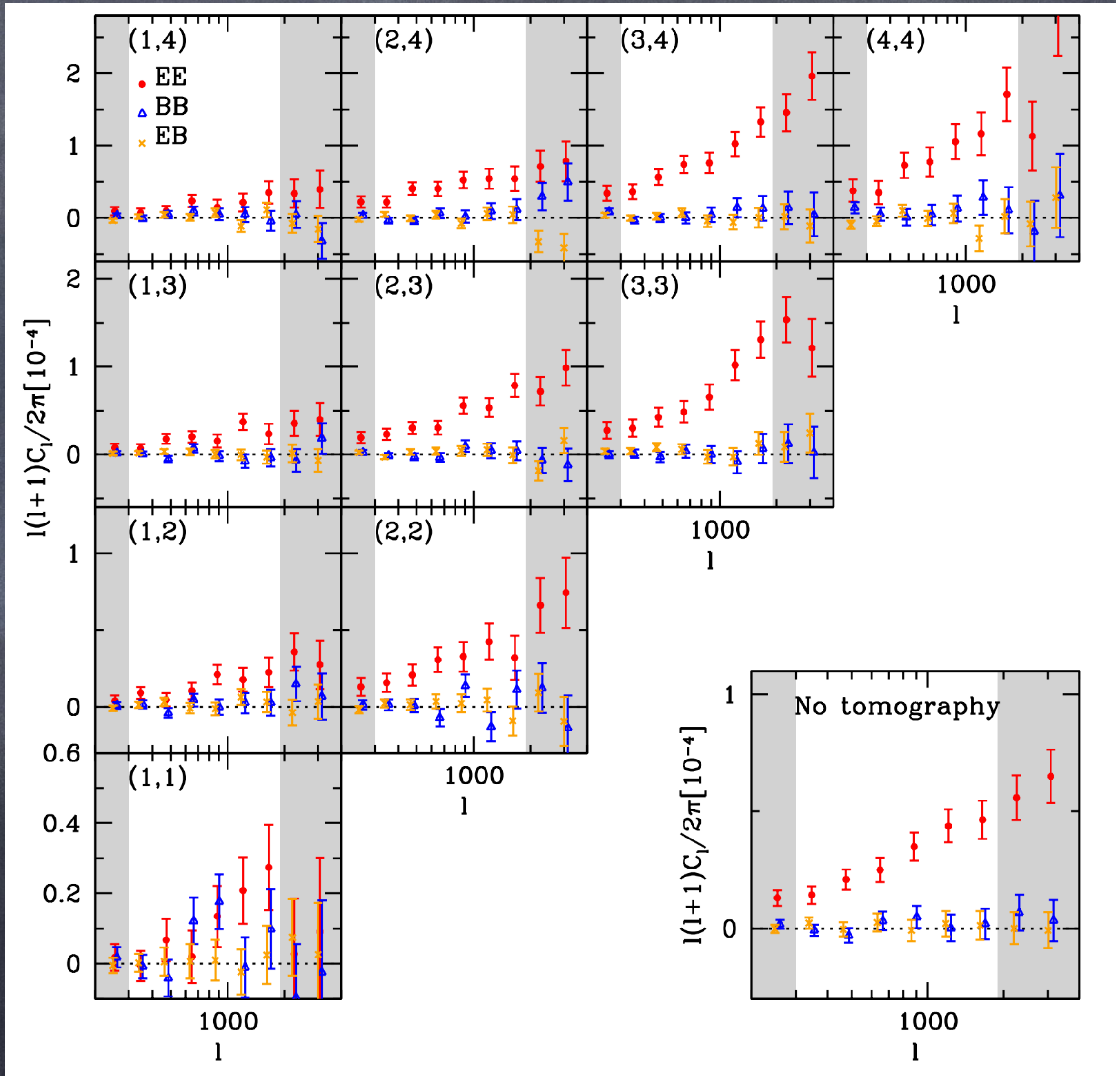
- low-l can probe short-mode



HSC first-year data

Higake+ 2018

- E-mode
  - from scalar mode
  - constrain cosmological parameters
    (Hikage-san's talk)
- No B-mode
  - $\Delta[\ell(\ell+1)C_\ell^{BB}/2\pi] \simeq 10^{-5}$
  - can put upper limit on $\Omega_{\rm GW}$



Method

- Cosmic shear B-mode signal in the HSC survey (model)

$$C_\ell^{(ij)} = \frac{1}{\pi} \int d\ln k \; \Delta_h^2(k) \; \bar{F}_\ell^{(i)}(k) \bar{F}_\ell^{(j)}(k)$$

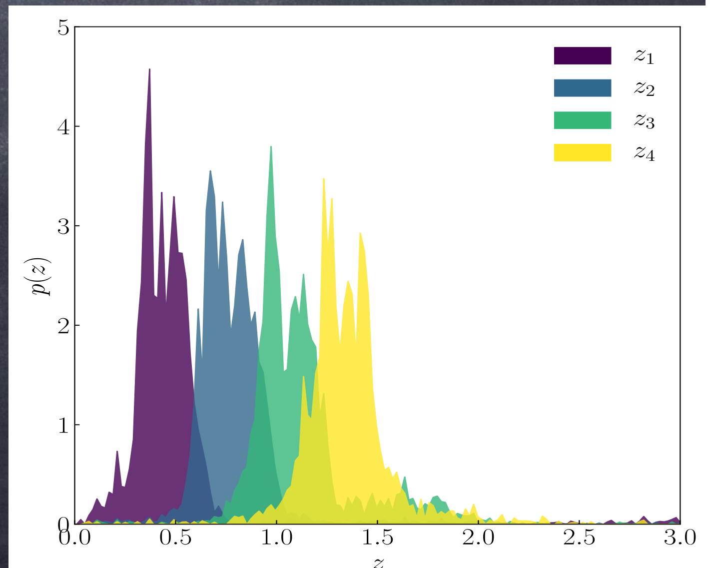
- Tensor power spectrum: step-type

$$\Delta_h^2(k) = \begin{cases} \Delta_h^{2\;(i)} & (k_{\rm min}^{(i)} \le k < k_{\rm min}^{(i+1)}) \\ 0 & (\text{otherwise}) \end{cases}$$

  - independent of GW sources

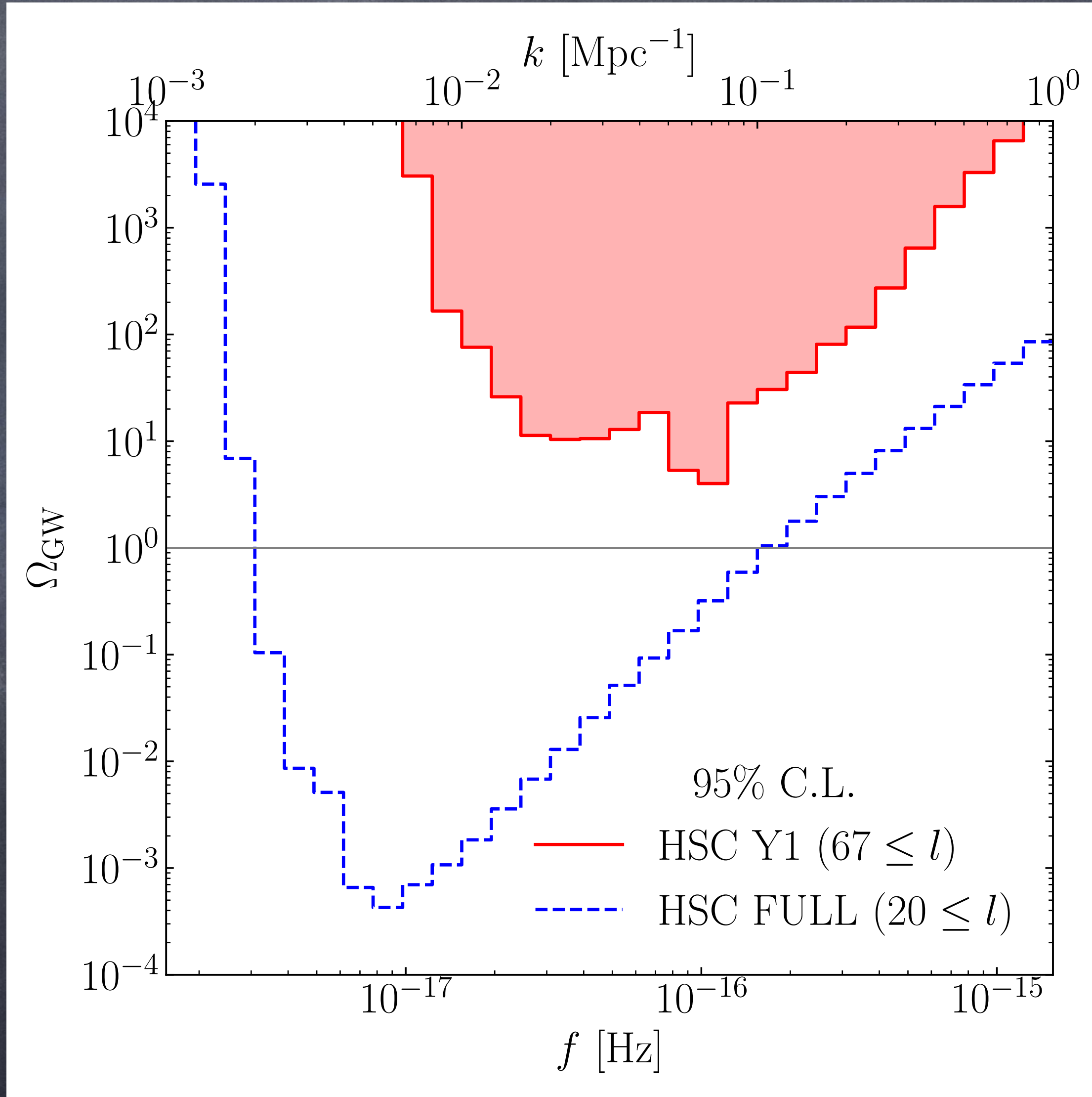
- Redshift distribution: $p_i(\chi)$
  - four redshift(photo-z) bins
  - averaged kernel

$$\bar{F}_\ell^{(i)}(k) = \int d\chi \; p_i(\chi) F_\ell(k,\chi)$$



Constraints from the HSC

- constraints are around Gpc~Mpc scale
  - galaxy separation
- HSC Y1: $\Omega_{\rm GW} \lesssim 1$
  - 140 deg², l > 67
- HSC full: $\Omega_{\rm GW} \lesssim 10^{-3}$
  - 1400 deg², l > 20



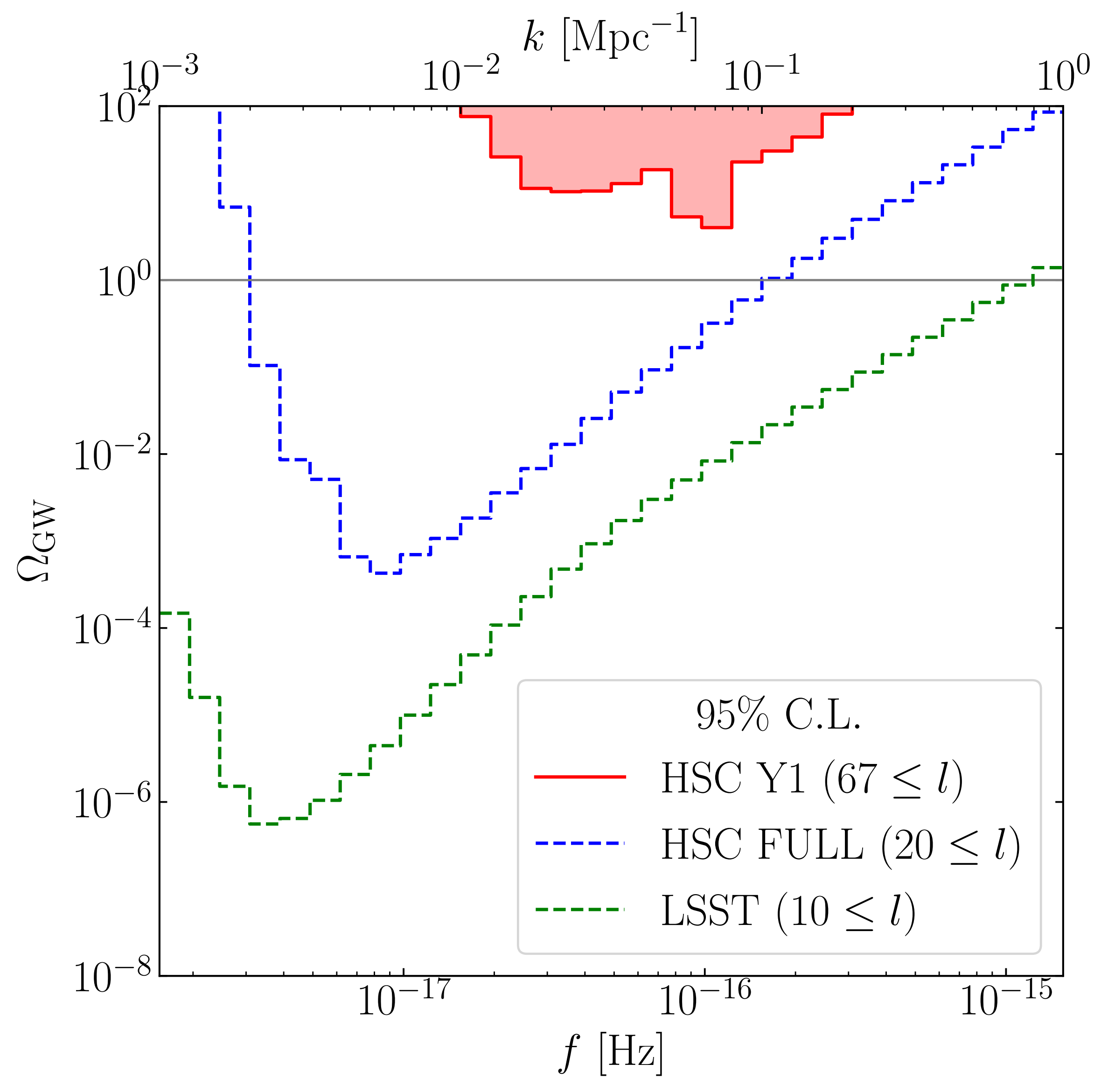
Future prospect (e.g. LSST)

- To reduce errors
  - sky coverage
  - number density

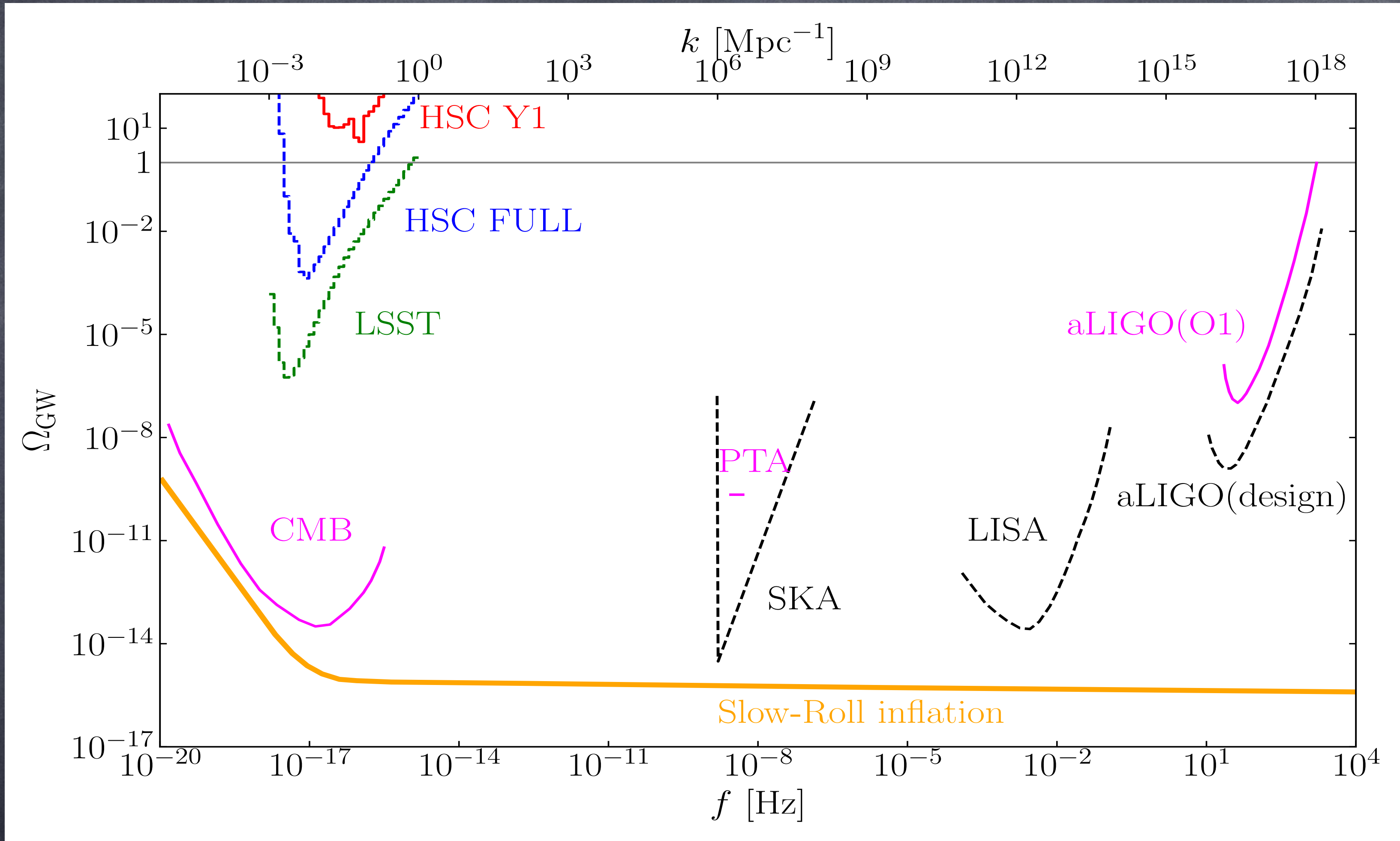
    $$\mathrm{Cov} \propto (f_{\mathrm{sky}} \bar{n}_g)^{-1}$$

- effect of decaying
  - high redshift
  - low multipole
- LSST: $\Omega_{\mathrm{GW}} \lesssim 10^{-6}$
  - $f_{\mathrm{sky}} \sim 0.5, \ \bar{n}_{g,\mathrm{total}} \sim 40 \ \mathrm{arcmin}^{-2}$

    $z < 3, \ \ell \geq 10$



Comparison with other results



- Weak lensing can constrain GWs generated after recombination/reionization

Summary & Future works

- Weak lensing by GWs produces B-mode cosmic shear
- With the HSC full data, we can constrain $\Omega_{\rm GW} \lesssim 10^{-3} @ 10^{-17}\ {\rm Hz}$
- Future survey(e.g. LSST) will constrain $\Omega_{\rm GW} \lesssim 10^{-6}$
- Future works:
  - Removing higher-order contributions (cf. delensing)
  - Intrinsic Alignments by GWs   Schmidt&Jeong 2012, Pajer+ 2013b
  - Cross correlation with CMB

Backup