Weak gravitational lensing of CMB

(Recent progress and future prospects)

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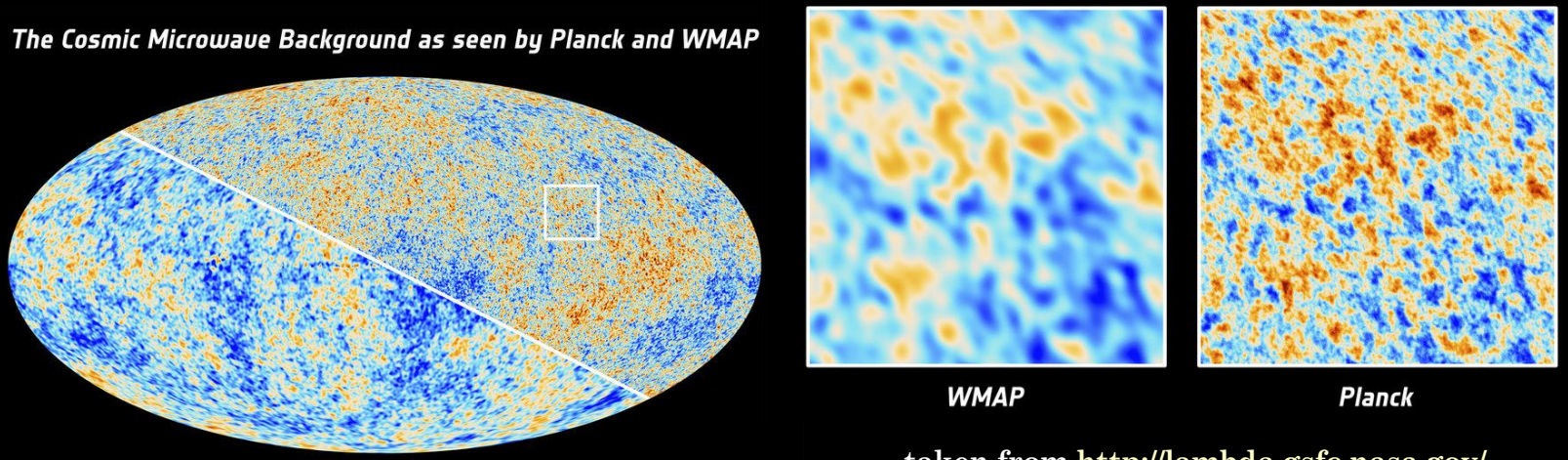
Cosmic Microwave Background (CMB)

- **Precise measurements of CMB fluctuations**



taken from http://lambda.gsfc.nasa.gov/

  - ✓ **The energy components of Universe is well described by flat ΛCDM model**

- **Cosmology can now focus on more advanced and fundamental issues !**
  - ✓ **dark energy**
  - ✓ **dark matter**
  - ✓ **mass of neutrinos**
  - ✓ **primordial gravitational waves**
  - ✓ **cosmic strings**
  - ✓ **primordial non-Gaussianity**
  - ⋮

Cosmological probes

- ✓ CMB temperature/ polarizations
- ✓ Type-Ia Super Novae
- ✓ Baryon Acoustic Oscillations
- ✓ Cluster abundance
- ✓ 21cm brightness temperature
- ✓ Weak Lensing

⋮

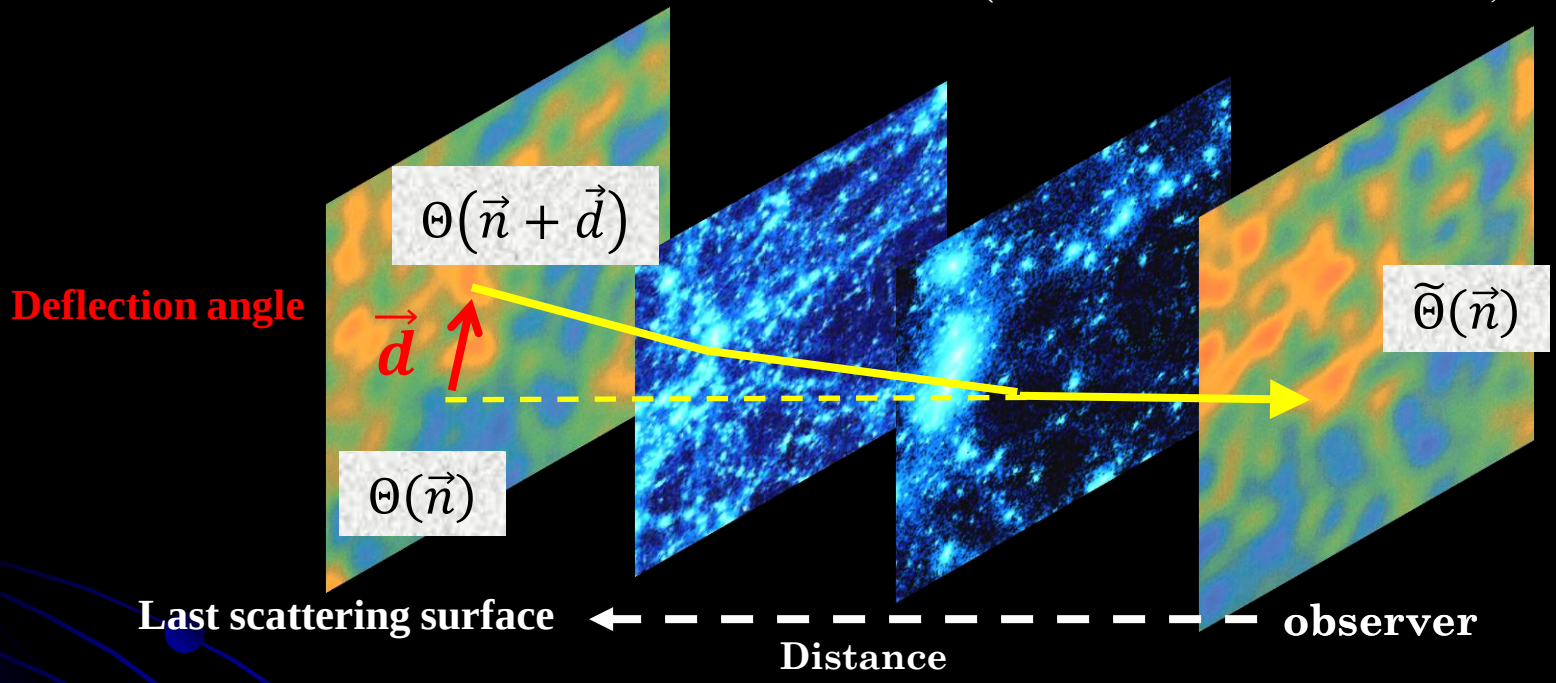
Compared to other observables, weak lensing is …

- ✓ sensitive to both geometry and density fluctuations
- ✓ free from galaxy bias ← (Important for "accurate" cosmology)
- ✓ for CMB lensing, the properties of source (CMB) is well known

CMB Lensing

- **CMB Lensing = distortion of spatial pattern of CMB anisotropies**

(Reviews : Lewis&Challinor'06, Hanson+'10)



- **Lensed anisotropies**

$$\tilde{\Theta}(\vec{n}) = \Theta\left(\vec{n} + \vec{d}(\vec{n})\right)$$

Lensing potential ϕ

Gravitational potential

$$\nabla\left(-2\int_0^{\chi_s} d\chi \frac{\chi_s - \chi}{\chi\chi_s}\overline{\psi(\eta_0 - \chi, \chi\vec{n})}\right)$$

Dark Energy/ Massive Neutrinos

- Evolution of gravitational potential is affected by the properties of **dark energy** (or modified gravity), **massive neutrinos**, etc

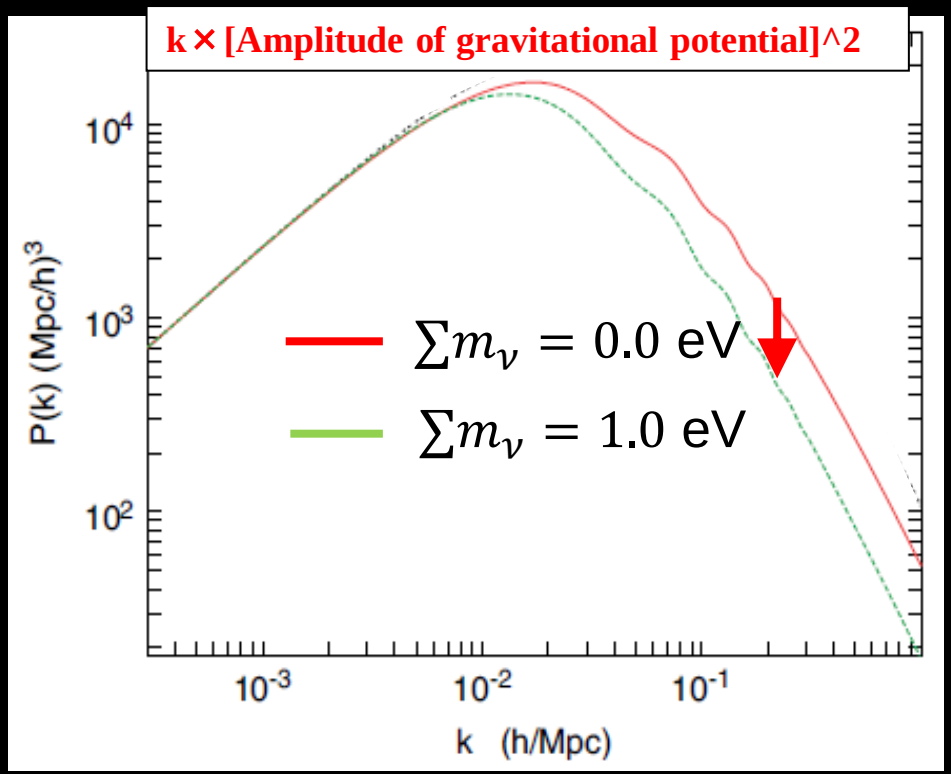
Massive neutrinos

✓ At small scales, the density fluctuations of neutrinos do not grow, because of their velocity dispersion

↓

Massive neutrinos do not contribute to the gravitational clustering, and the gravitational potential becomes weak

(for details, see, e.g., Lesgourgues & Pastor'13)

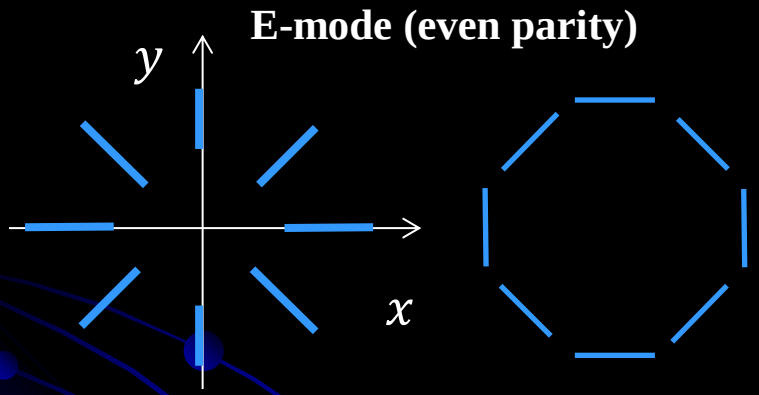


Other motivations to measure CMB lensing

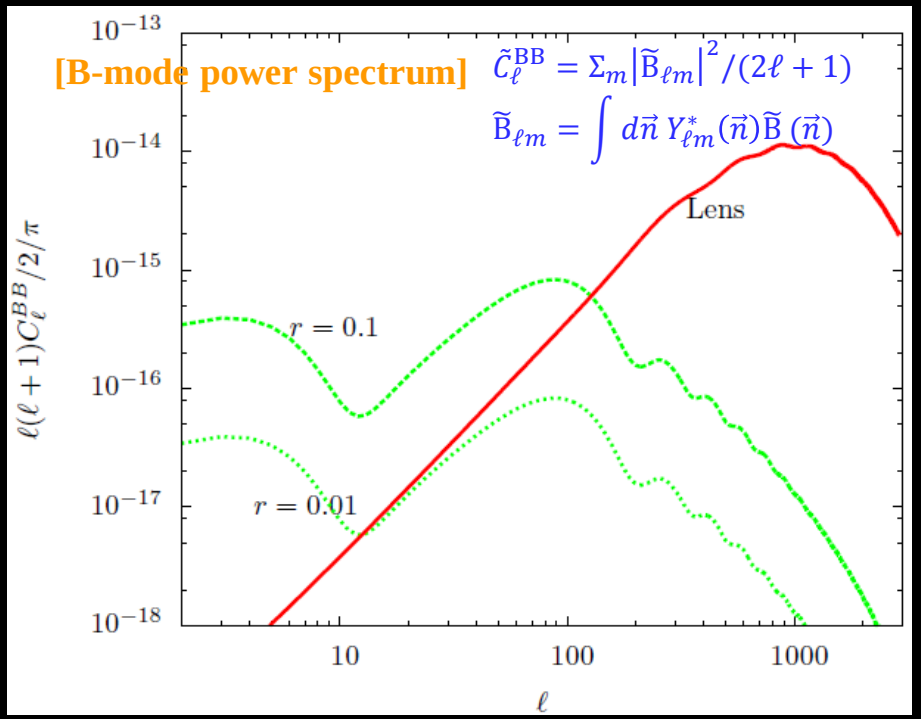
✓ CMB Lensing generates **B-mode polarization** and **secondary non-Gaussianity**

Significant contamination for a detection of primordial GWs / primordial non-Gaussianity

- **CMB polarizations**



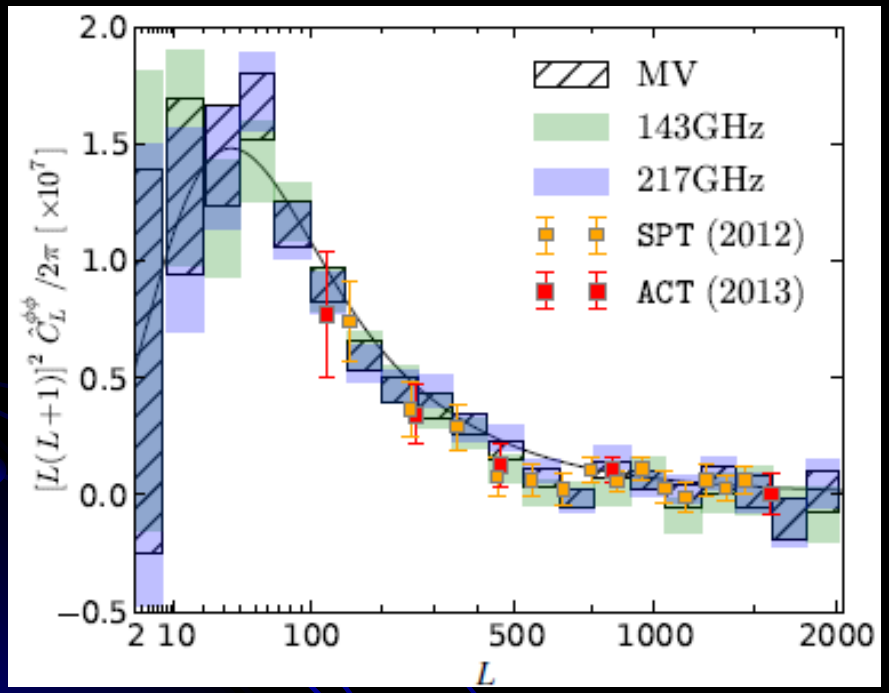
Primordial GWs

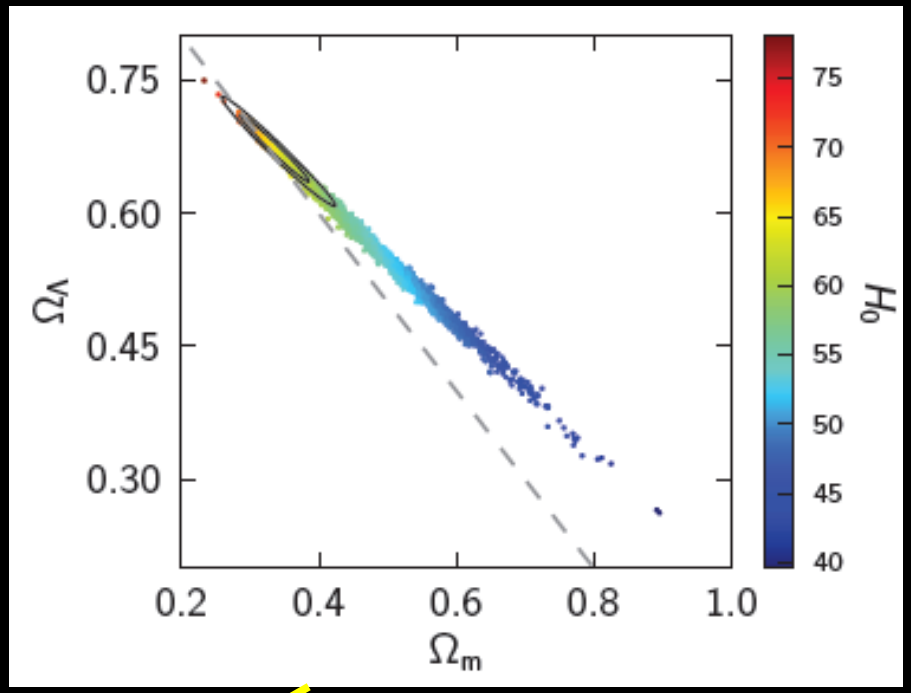


e.g., Knox+'02, Kesden+'02, Smith+'09

Recent detections

- **CMB lensing signals are detected from several CMB experiments**
  - ✓ 2011: **First detection !** from Atacama Cosmology Telescope (**ACT**) + WMAP (Das+'11)
  - ✓ 2012: Detection from South Pole Telescope (**SPT**) + WMAP (van Engelen+'12)
  - ✓ 2013: Detection with ~25σ !! from **Planck** (**see also Planck 2013 results XVII**)



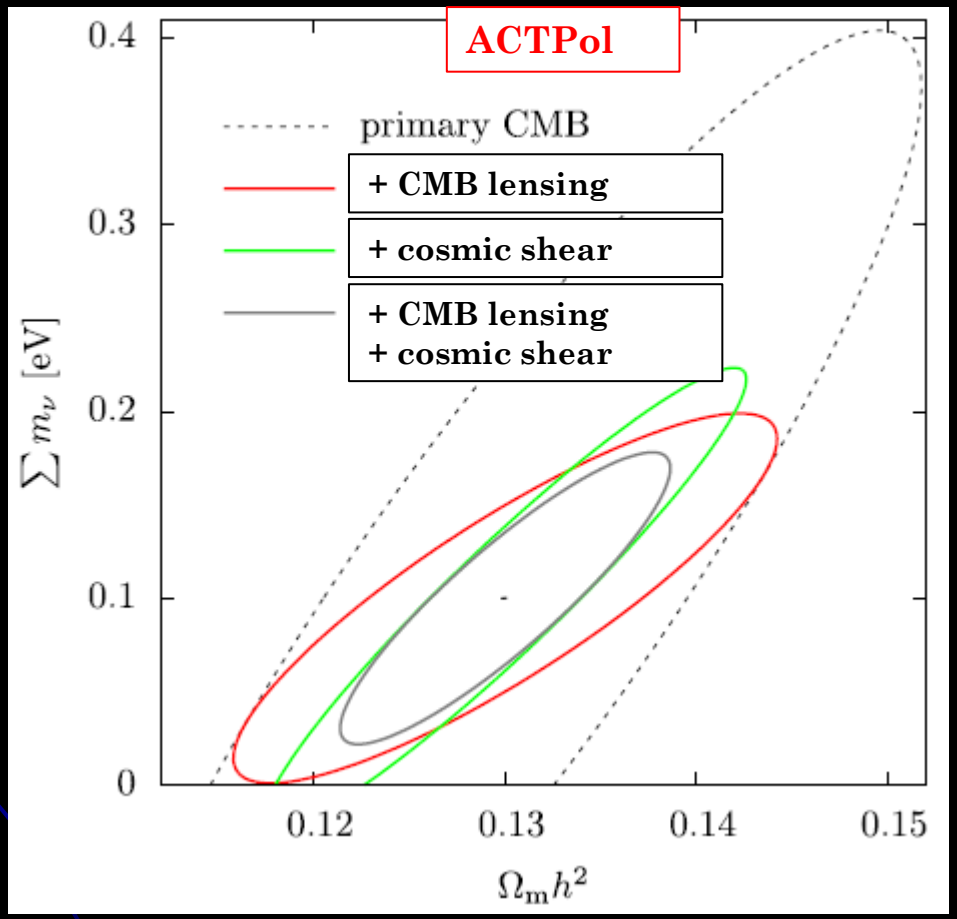


- ✓ Lensing signals significantly improve the constraints on cosmological parameters
- ✓ Lensing still do not have enough sensitivity to constrain e.g. mass of neutrinos …

Future prospects

- **CMB experiments** Planck(Pol), SPTpol, PolarBear, ACTPol, Polar, LiteBird, CMBPol...

expected 1σ-constraints TN+'10



- ✓ **Lensing signals would be measured with enough precision to probe, e.g., dark energy and massive neutrinos**

Summary

- **CMB lensing as a cosmological probe**
  - ✓ **CMB lensing has sensitivity to probe massive neutrinos, dark energy, etc.**
  - ✓ **Measurement of CMB lensing is also important to probe primordial GWs and primordial non-Gaussianity**
- **Near future**
  - ✓ **Recent CMB lensing detection is from temperature maps, but polarization data from upcoming experiments would *significantly* improve the current constraints from CMB lensing**
  - ✓ **Practical methods of lensing measurement from polarization are required**

Short summary of lensing reconstruction

➢ History

- **Reconstruction technique**

  - Basic ideas for quadratic estimator
  (e.g., Seljak'97; Seljak&Zaldarriaga'98; Hu&Okamoto'02; Okamoto & Hu'03; Lewis+'11)

  - Maximum-likelihood estimator **(Hirata&Seljak'03a,b; Hanson+'09)**

  - Curl mode estimator **(Cooray+'05; TN+'12)**

- **Estimating lensing power spectrum,** C_ℓ^{xx}
  (e.g., Kesden&Cooray'03; Cooray&Kesden'04; Hanson+'10; TN+'13)

- **Method in practical cases (masking, inhomogeneous noise, etc.)**
  (e.g., Carvalho&Tereno'11; Hanson+'11; TN+'13)

➢ Future

- **Method in practical cases for polarization**
- **Importance of higher-order statistics**