Secondary Anisotropies

&

Data Analysis

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Based on Hu & Dodelson 2002

Secondary Anisotropies

- Perturbation of CMB
- Photons interact with matter, energy, space
- Two Types
  - Gravitational effects
  - Scattering off electrons

Gravitational Anisotropies

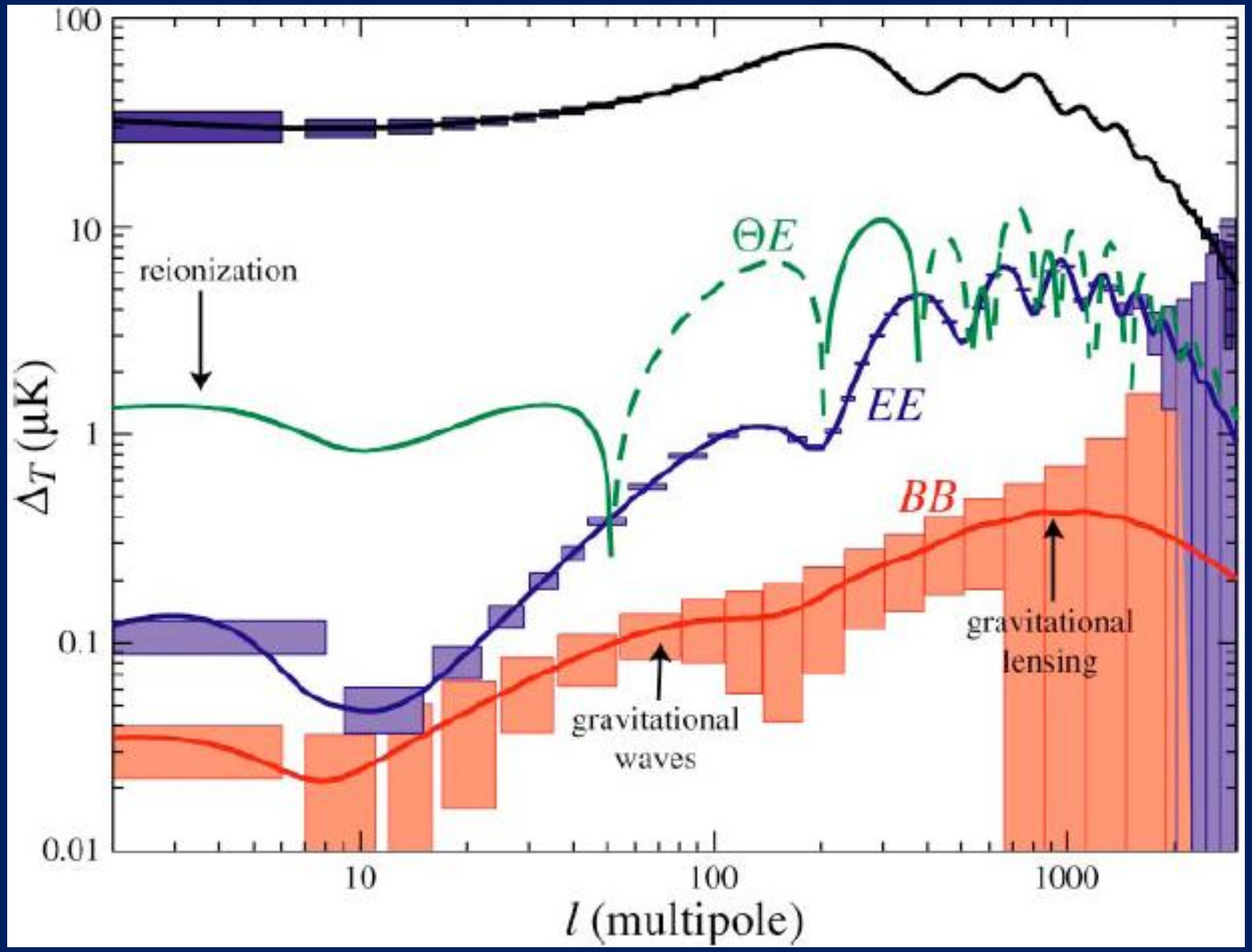
- Integrated Sachs-Wolfe Effect: ISW video
  - Photons gravitationally redshifted
  - Expansion of universe alters potential
  - Suppressed at large *l*
- Rees-Sciama Effect:
  - Nonlinear regime of ISW
  - Potential also affected by bulk motion

Gravitational Anisotropies

- Gravitational waves
  - Variation of metric of spacetime
  - Quadrupolar temperature distortion
  - Generates polarization
  - Suppressed at large *l*
- Gravitational lensing
  - Smooths acoustic power spectrum
  - Generates *B*-mode polarization

Scattering Anisotropies

- Peak Suppression
  - Anisotropies reduced by scattering
  - Less suppression at larger angular scales
- Large-angle Polarization
  - Extra bump in *E*-polarization spectrum


100
10
1
0.1
0.01
Δ_T (μK)
10
100
1000
l (multipole)
reionization
ΘE
EE
BB
gravitational
waves
gravitational
lensing

Scattering Anisotropies

- Doppler Effect
  - Highly suppressed by cancellation of modes
- Density modulations
  - Caused by dark matter halos and clusters
- Ionization modulation

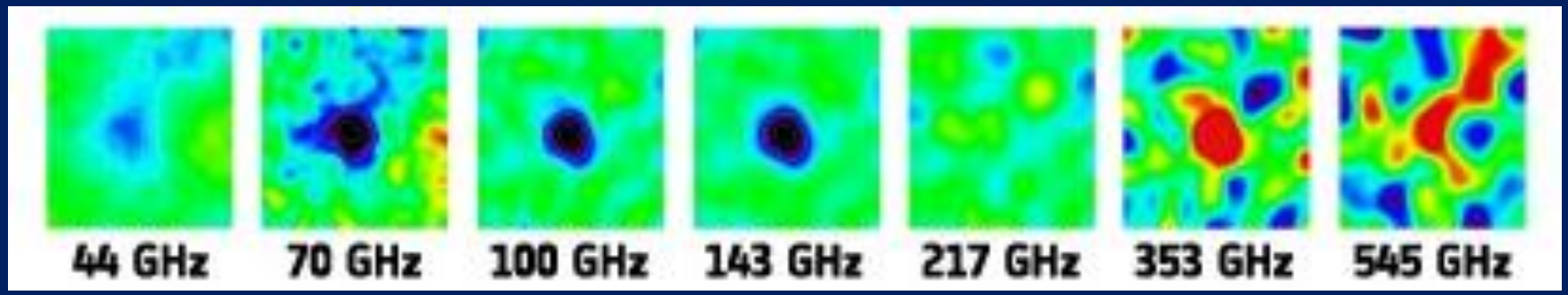
Scattering Anisotropies

- Sunyaev-Zel'dovich effect
  - Inverse Compton scattering
  - Thermal vs kinetic SZ effect
  - Large source of secondary anisotropies
  - Separable from power spectrum

Question: Can it be used to detect high redshift clusters?

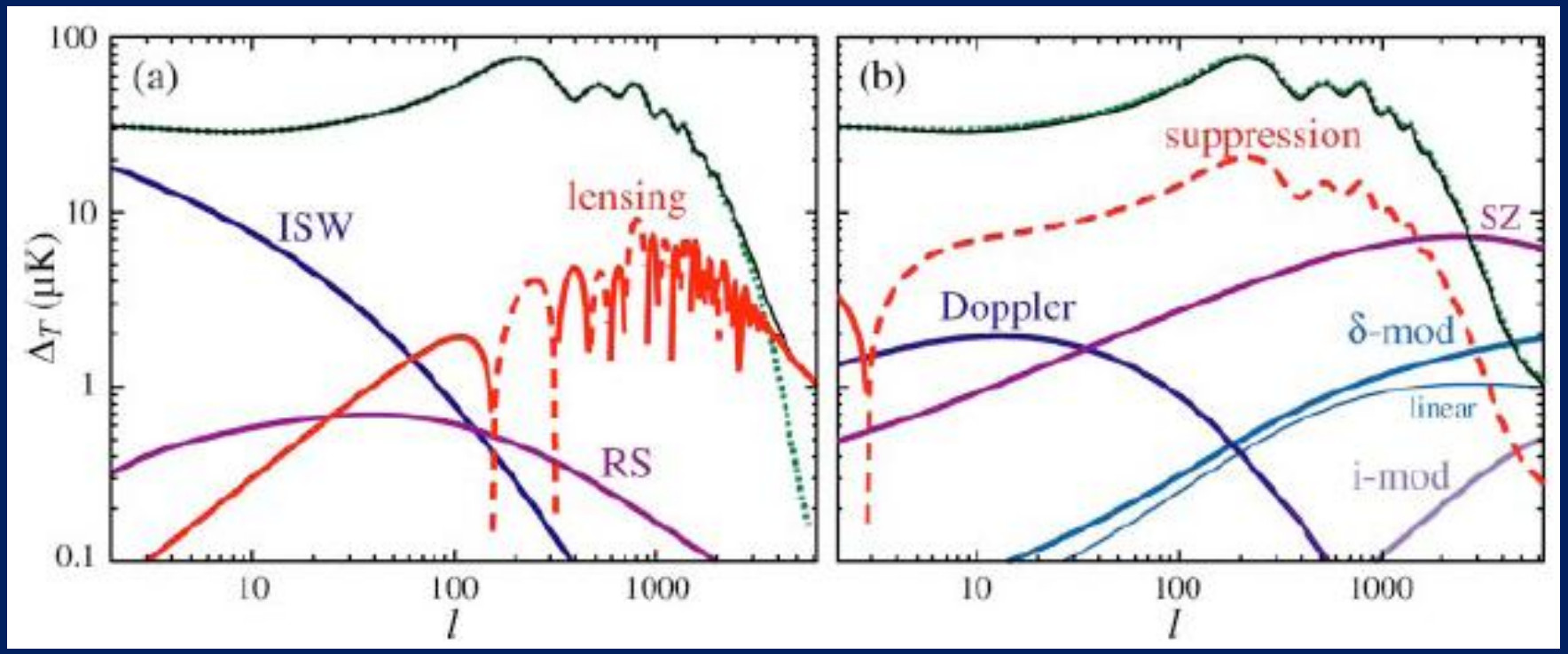
Detecting Clusters with SZ Effect

- Planck: European CMB mission
- Excess photons at high energy
- Deficit of photons at low energy



Abell 2319 in different bands

Secondary Anisotropy Summary



Data Analysis

- Data -> Map -> Power Spectrum -> Cosmological Parameters
- Each step uses likelihood function
- Gaussian assumption compresses data

Data to Map

- Data = Signal + Noise
- Noise estimated from data

$$\mathcal{L}_\Theta(d_t) = \frac{1}{(2\pi)^{N_t/2}\sqrt{\det \mathbf{C}_d}} \exp\left[-\frac{1}{2}(d_t - P_{ti}\Theta_i)\, C^{-1}_{d,tt'}(d_{t'} - P_{t'j}\Theta_j)\right]$$

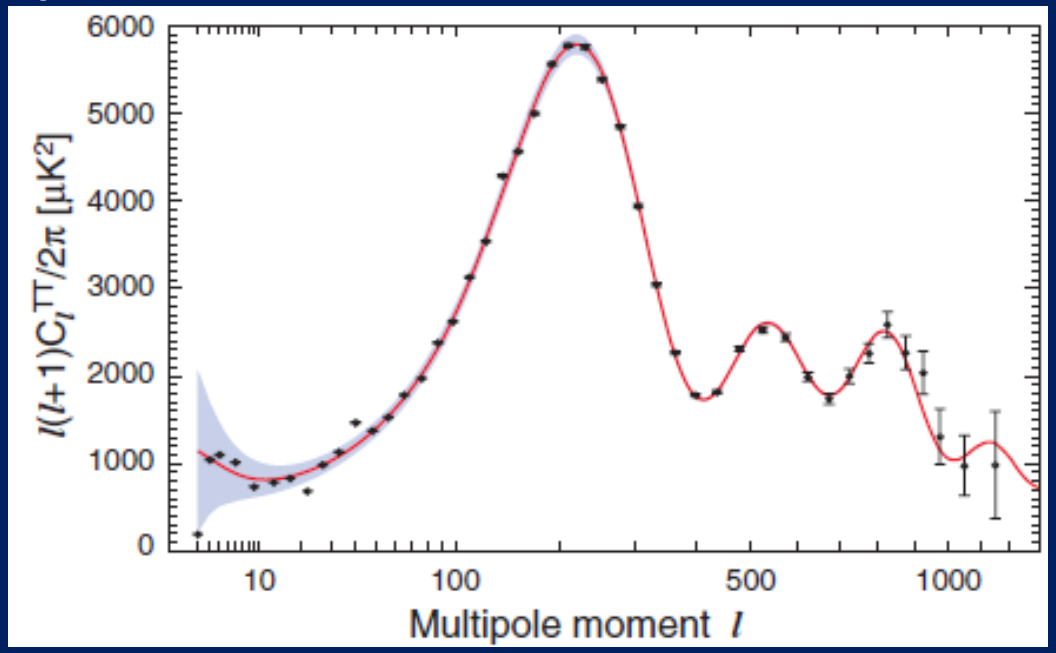
- Goal is to maximize likelihood function
- Foreground separated with other likelihood function

Map to Bandpower

- Maximize another likelihood function

$$\mathcal{L}_B(\Theta_i) = \frac{1}{(2\pi)^{N_p/2}\sqrt{\det \mathbf{C}_\Theta}} \exp\left(-\frac{1}{2}\Theta_i C^{-1}_{\Theta,ij}\Theta_j\right)$$

- No analytical solution, brute force not feasible



Bandpower to Cosmological Parameters

- Likelihood function (yawn)

$$\mathcal{L}_c(\hat{B}_a) \approx \frac{1}{(2\pi)^{N_c/2}\sqrt{\det \mathbf{C}_B}} \exp\left[-\frac{1}{2}(\hat{B}_a - B_a)C^{-1}_{B,ab}(\hat{B}_b - B_b)\right]$$

- 10^{10} data points -> ~10 parameters

WMAP Results

- Larson et al. 2011: Seven year results

Parameter	7-year Fit	
Fit parameters		
$10^2\Omega_b h^2$	$2.258^{+0.057}_{-0.056}$	Physical baryon density
$\Omega_c h^2$	0.1109 ± 0.0056	Physical cold dark matter density
Ω_Λ	0.734 ± 0.029	Dark energy density ($w = -1$ unless otherwise noted - see below)
$\Delta^2_{\mathcal{R}}$	$(2.43 \pm 0.11) \times 10^{-9}$	Amplitude of curvature perturbations, $k_0 = 0.002$ Mpc^{-1}
n_s	0.963 ± 0.014	Spectral index of density perturbations, $k_0 = 0.002$ Mpc^{-1}
τ	0.088 ± 0.015	Reionization optical depth
Derived parameters		
t_0	13.75 ± 0.13 Gyr	Age of the universe (Gyr)
H_0	71.0 ± 2.5 km/s/Mpc	Hubble parameter, $H_0 = 100h$ km s^{-1} Mpc^{-1}
σ_8	0.801 ± 0.030	Amplitude of density fluctuations in linear theory, 8 h^{-1} Mpc scale
Ω_b	0.0449 ± 0.0028	
Ω_c	0.222 ± 0.026	
$z_{\rm eq}$	3196^{+134}_{-133}	Redshift of matter-radiation equality
$z_{\rm reion}$	10.5 ± 1.2	Redshift of reionization

LikelihoodPlots