the integrated Sachs-Wolfe effect

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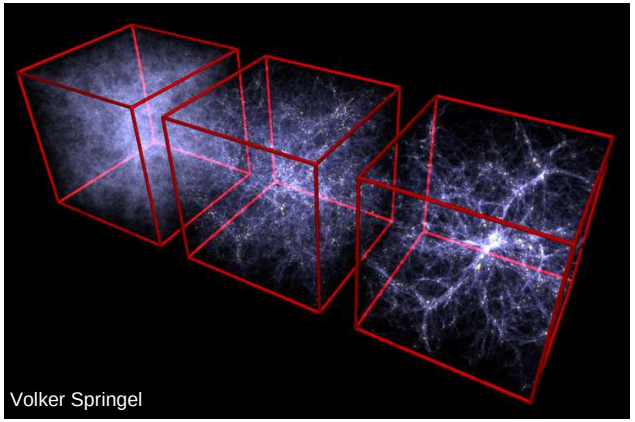
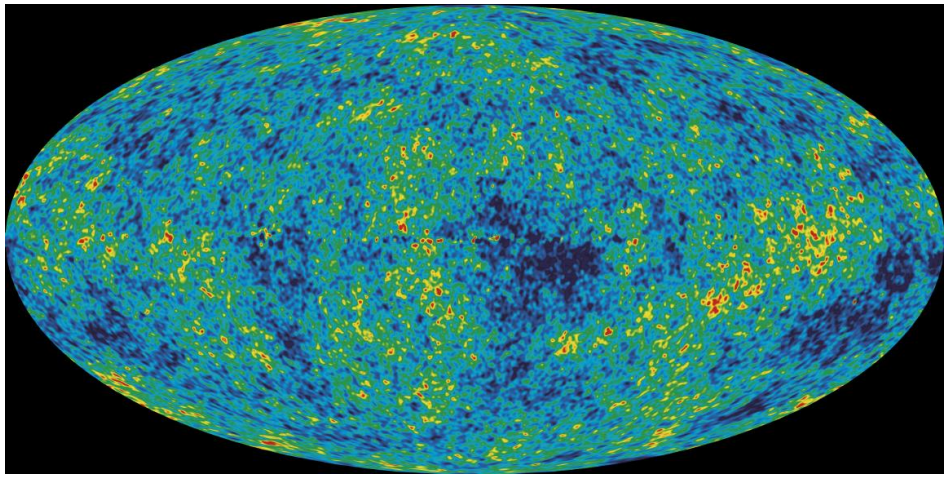
outline

introduction: paradigm of structure formation



- cosmological standard model (ΛCDM): structures form by
  - Newtonian gravitational instability of
  - Gaussian, adiabatic inflationary initial fluctuations in the
  - (collisionless) cold dark matter field
  - on a flat **accelerating** expanding background
- open questions in structure formation
  - determination of **cosmological parameters** from growth
  - **nonlinear structure formation** and interplay with dark energy
  - **collective dynamics** of dark matter particles (e.g. angular momenta)

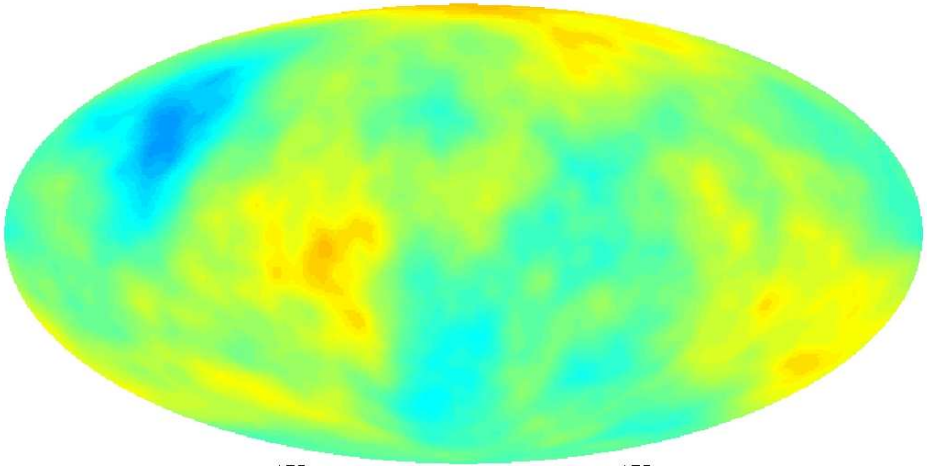
cosmic microwave background



CMB sky map from WMAP

- CMB: relic radiation from the formation of hydrogen atoms
- potential and velocity fluctuations at the time of last scattering
- fluctuation statistics allows precision determination of cosmology

secondary CMB anisotropies



reconstructed iSW map by B. Barreiro

- secondary anisotropies
  - gravitational interaction:
    CMB lensing, int. Sachs-Wolfe effect, Rees-Sciama effect
  - Compton scattering:
    Sunyaev-Zel'dovich effect (thermal, kinetic), Ostriker-Vishniac effect
- iSW-effect is special
  - keeps Planckian photon spectrum → cross correlation technique
  - primary CMB fluctuations are a noise source → total $s/n \simeq 10$

cosmic structure formation 1

- cosmological structures growth by gravitational amplification of seed fluctuations in the early universe
- hydrodynamic, self-gravitating phenomenon:
  - **equation of continuity**: no particles lost or generated

$$\frac{\partial}{\partial t}\rho + \mathrm{div}(\rho\vec{v}) = 0 \tag{1}$$

  - **Euler equation**: tracks momentum evolution

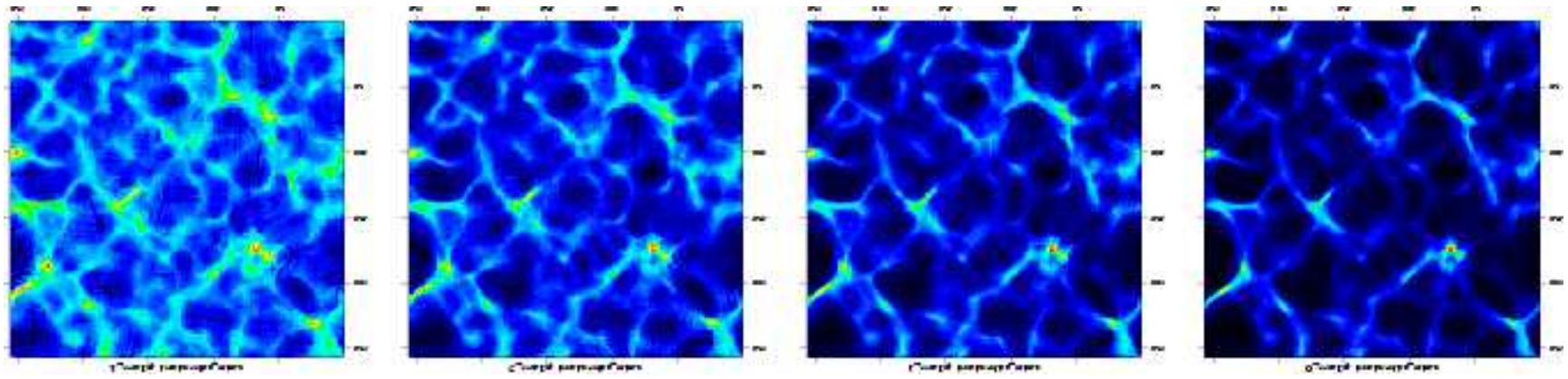
$$\frac{\partial}{\partial t}\vec{v} + (\vec{v}\nabla)\vec{v} = -\nabla\Phi \tag{2}$$

  - **Poisson-equation**: generates potential from density

$$\Delta\Phi = 4\pi G\rho \tag{3}$$

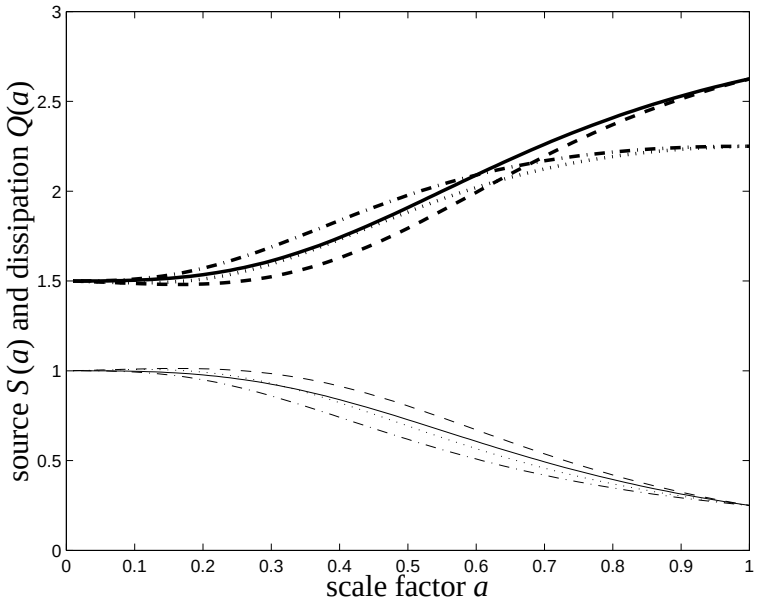
- three major difficulties
  - 2 nonlinearities
  - CDM is collisionless: no microscopic relaxation mechanisms
  - gravity is non-saturating (binding energy/particle diverges)

cosmic structure formation 2

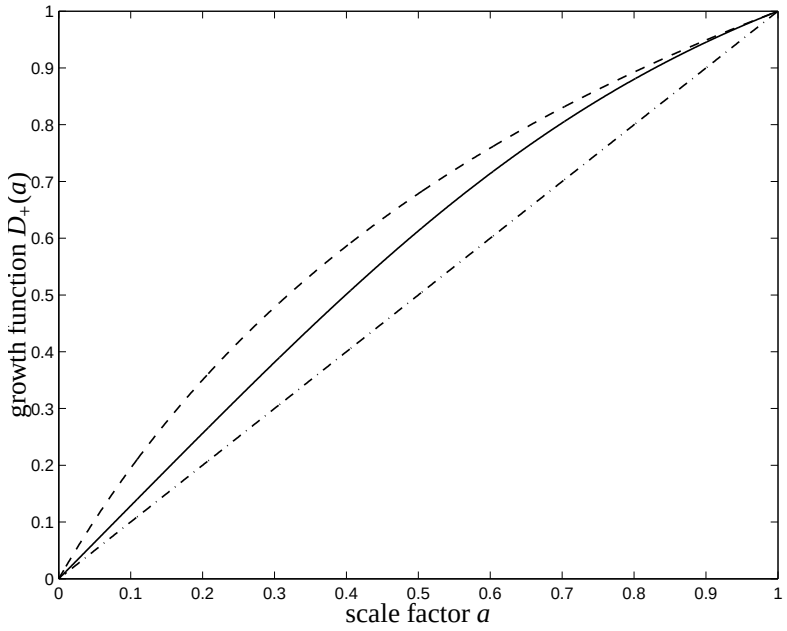


- cosmological structures grow by gravitational amplification of seed fluctuations in the early universe
- expanding background has an important influence:
  - $t_{\mathrm{dyn}} < t_{\mathrm{Hubble}}$: structure grows
  - $t_{\mathrm{Hubble}} < t_{\mathrm{dyn}}$: structure stops growing
- accelerating background: arbitrary small t_{Hubble} reached sometime, stops structure formation

linear regime: growth equation $\delta(\vec{x}, a) = D_+(a)\delta_0(\vec{x})$



terms in growth equation

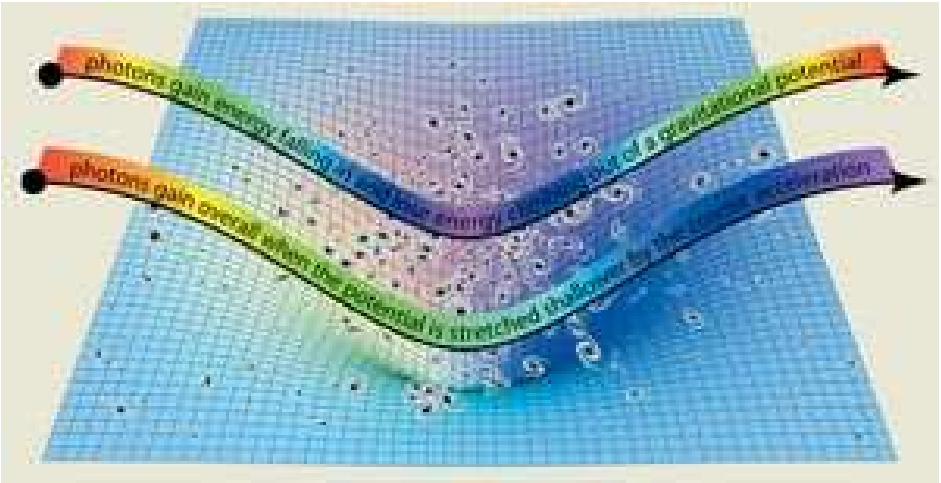


growth equation $D_+(a)$

- combine continuity, Euler- and Poisson-eqn. for differential equation:

$$\frac{\mathrm{d}^2 D_+(a)}{\mathrm{d}a^2} + \frac{1}{a}\left(3 + \frac{\mathrm{d}\ln H}{\mathrm{d}\ln a}\right)\frac{\mathrm{d}D_+(a)}{\mathrm{d}a} = \frac{3\Omega_m(a)}{2a^2}D_+(a)$$

integrated Sachs-Wolfe effect

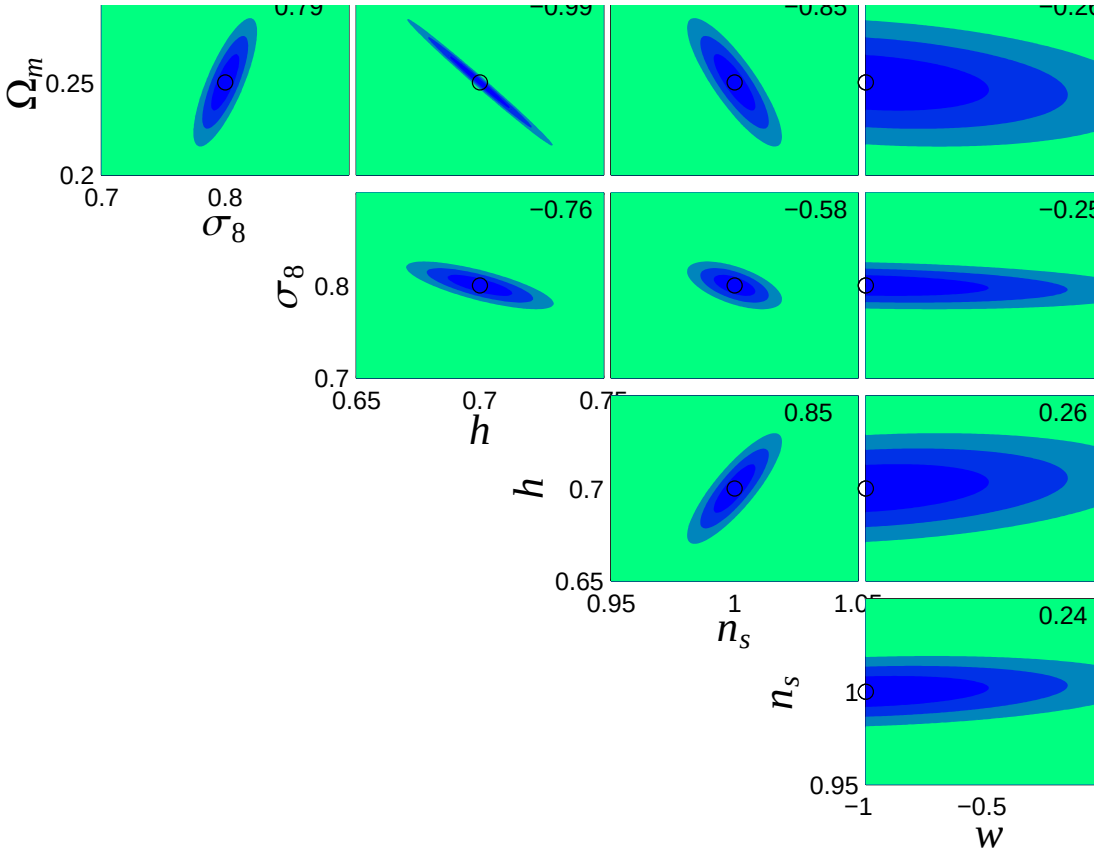


- gravitational interaction of CMB photons with time-varying potentials
- sensitive to the **growth** of structures
  - measures line of sight integrated $\dot{\Phi}$

$$\tau \propto \int \mathrm{d}\chi \, a^2 H(a) \frac{\mathrm{d}}{\mathrm{d}a} \frac{D_+}{a} \, \Phi \tag{4}$$

  - vanishes in SCDM, where $D_+(a) = a \rightarrow$ presence of fluids with $w \neq 0$!
- measurement: cross-correlation with a large-scale structure tracer

parameter sensitivity

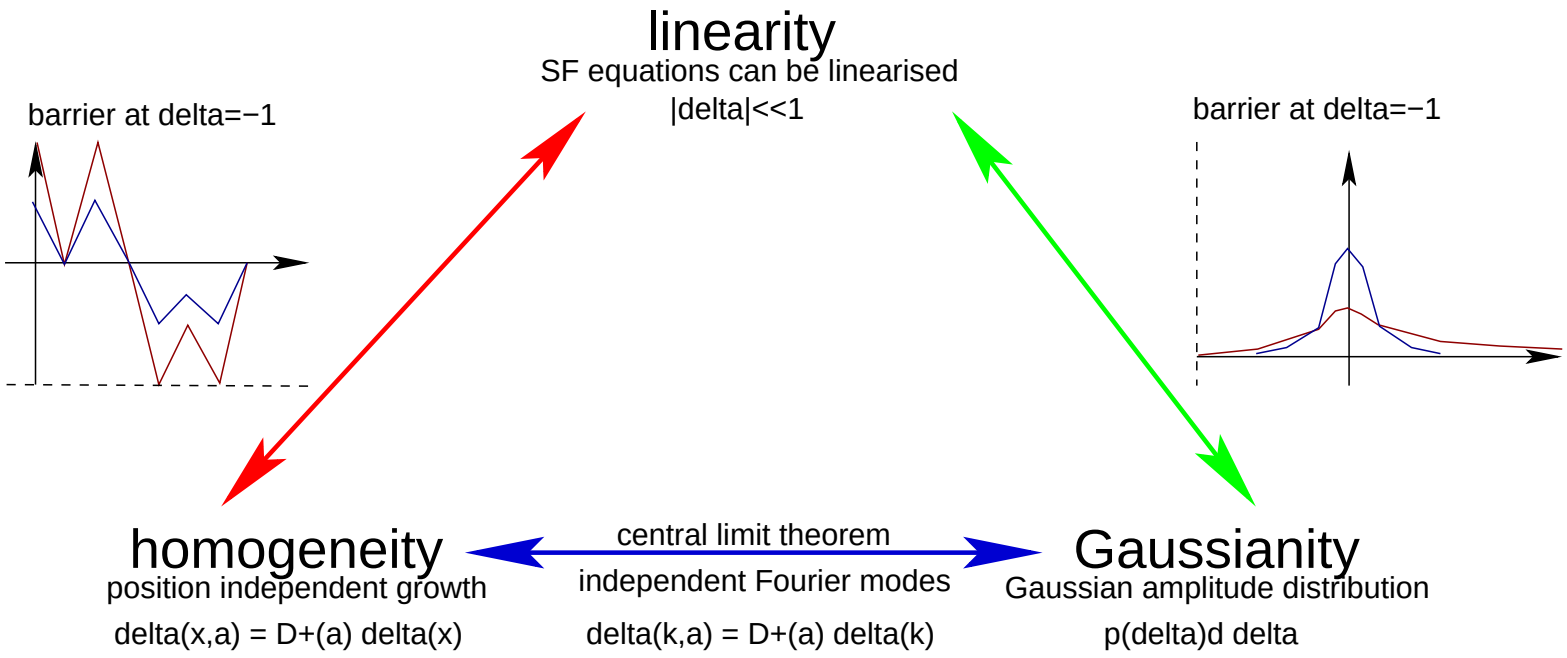


ideal measurement: PLANCK combined with EUCLID

- CMB priors on Ω_m, σ_8, n_s and h from PLANCK
- 10% accuracy on $\Omega_{\rm DE}$, 20% accuracy on w

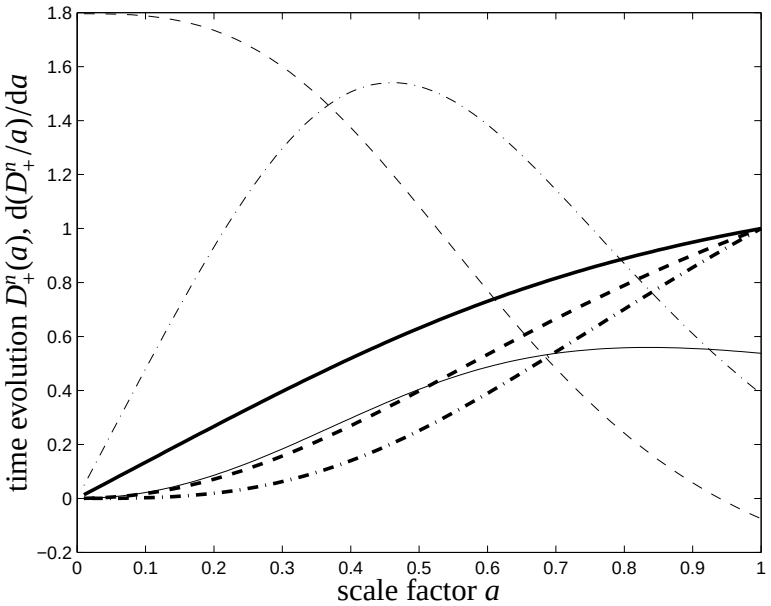
nonlinear structure formation

- linearity, homogeneity and Gaussianity imply each other
- mode coupling - can be described in perturbation theory

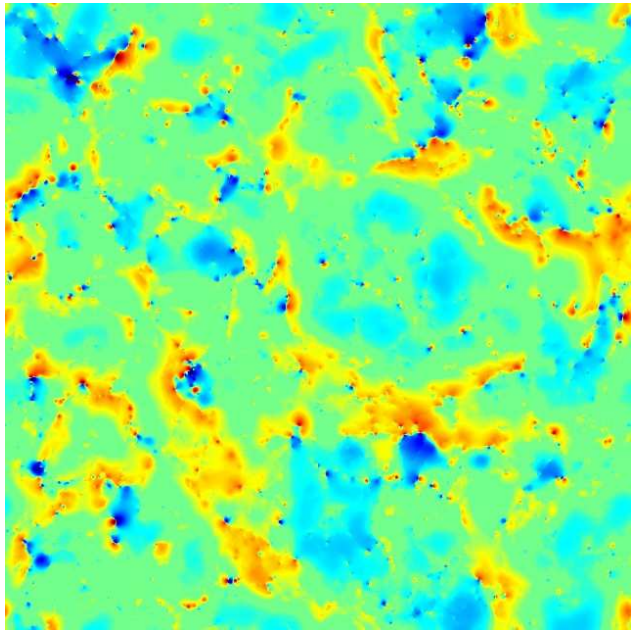


- linear growth: conserves Gaussianity (any statistical property)
- nonlinearities cause the emergence of non-Gaussian features

Rees-Sciama effect



evolution of density field + potential

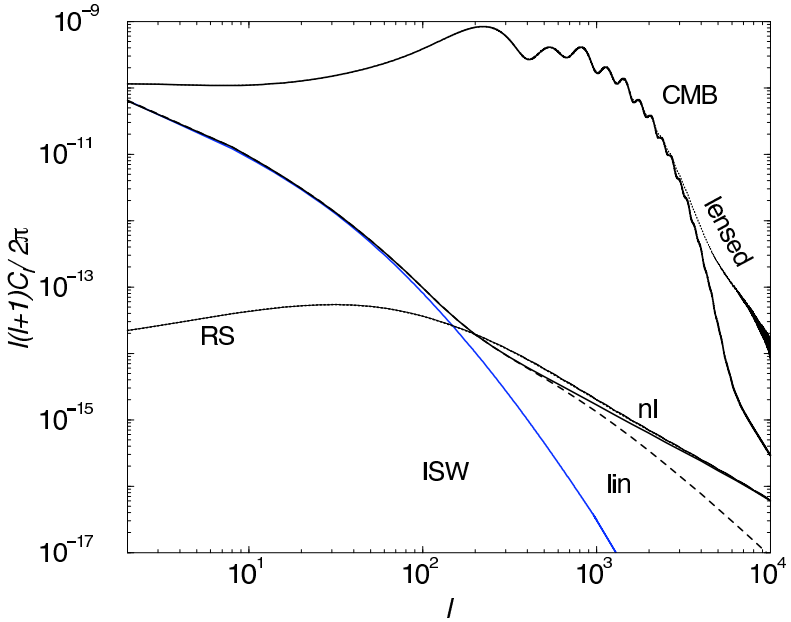


simulated RS-field (V. Springel)

- iSW-effect from nonlinear structures
- nonlinear corrections to iSW-spectrum at high ℓ
- 3rd order perturbation theory needed, $\delta(\vec{x}, a) = \sum_n D_+^n(a)\delta^{(n)}(\vec{x})$

spectrum of the Rees-Sciama effect

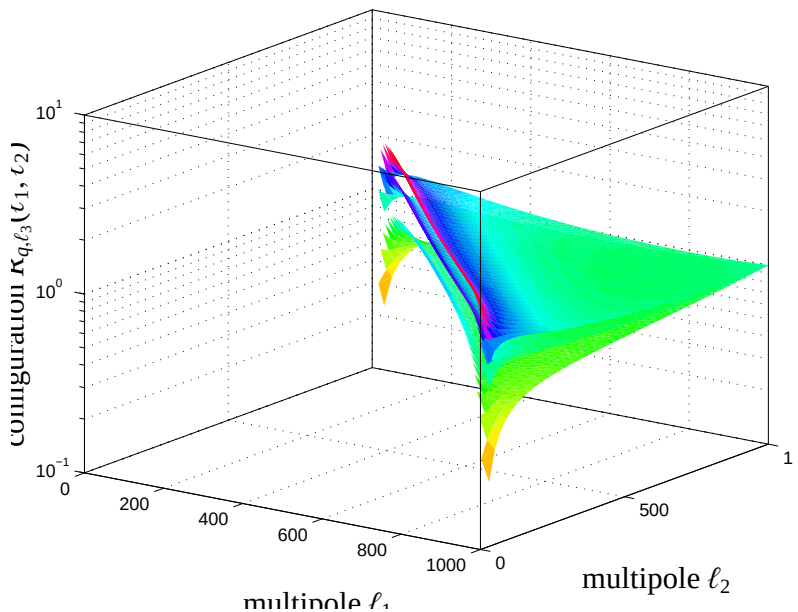
- use mode coupling for $\delta^{(2)}$, decompose with Wick-theorem



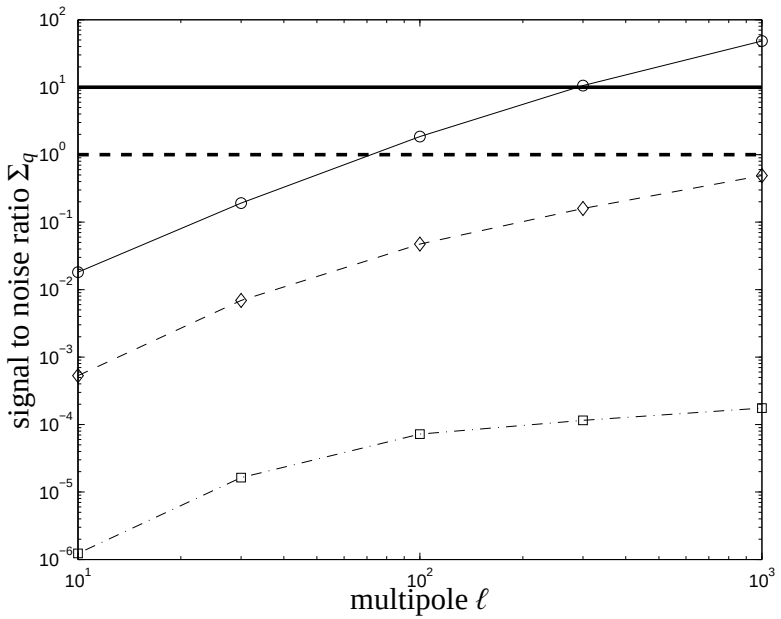
source: Cooray + Sheth 2002

- RS-spectrum much flatter than iSW-spectrum, cross-over at $\ell = 100$
- signal/noise ratio for RS-effect: only 2σ!

Rees-Sciama effect: non-Gaussianities



configuration dependence



signal/noise ratio increase with ℓ

- mixed bispectra between iSW-effect and galaxy overdensity $\langle \tau^q \gamma^{3-q} \rangle$
- cross-correlation of PLANCK with EUCLID yields 0.6σ
- extention to trispectrum? very technical!

open questions

- iSW-effect needs precise understanding of biasing models → bias time evolution, scale-dependence, non-locality, stochasticity?
- usage of unbiased tracers such as weak cosmic shear?
- iSW-effect is so far only detected at low redshift → correlation of iSW with CMB lensing?
- iSW-effect from individual objects → accretion rates or void dynamics
- Rees-Sciama effect → spectrum too weak, bispectrum too small, other non-Gaussian quantifiers?
- distinguishing with the iSW-effect between curved cosmologies and dark energy is possible, in combination with other structure formation probes