Probing the structure of spacetime: apples, light and waves

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outline:

1. lensing fundamentals
2. deflection spectra
3. spiral galaxies
4. shape spectra
5. elliptical galaxies

test particles falling through spacetime

- geodesics are paths through space time for freely falling (i.e. no inertial forces felt) particles

$$\frac{du^\alpha}{d\tau} + \Gamma^\alpha_{\mu\nu} u^\mu u_\nu = 0 \quad \text{and} \quad \frac{dk^\alpha}{d\lambda} + \Gamma^\alpha_{\mu\nu} k^\mu k^\nu = 0 \tag{1}$$

  Christoffel-symbol $\Gamma^\alpha_{\mu\nu}$: generates parallel transport

- massive particles follow time-like geodesics $g_{\mu\nu} u^\mu u^\nu = c^2$
- photons follow null-geodesics $g_{\mu\nu} k^\mu k^\nu = 0$
- geodesic equation minimises path length: Fermat- and Hamilton-principles

perturbed spacetime

- weakly perturbed Minkowski-spacetime

$$ds^2 = \left(1 + 2\frac{\Phi}{c^2}\right)c^2dt^2 - \left(1 - 2\frac{\Phi}{c^2}\right)\delta_{ij}dx^idx^j \qquad (2)$$

with the potential Φ, if $|\Phi| \ll c^2$

- slow, non-relativistic particles:

$$\int ds = S \simeq \int dt\, \frac{\Phi}{c^2} - \delta_{ij}u^iu^j/2 \qquad (3)$$

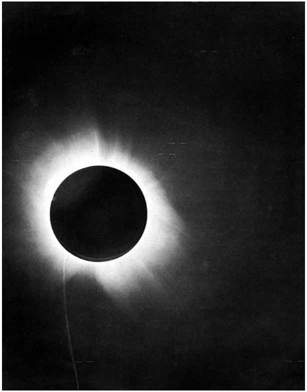
in the slow-motion limit, deflection is given by $-\partial_i\Phi$

- fast, relativistic particles $ds^2 = 0$

$$\frac{dx}{dt} = c' = \sqrt{\frac{1-2\Phi/c^2}{1+2\Phi/c2}}c \simeq (1-2\Phi/c^2)c \qquad (4)$$

deflection given by $-2\partial_i\Phi$

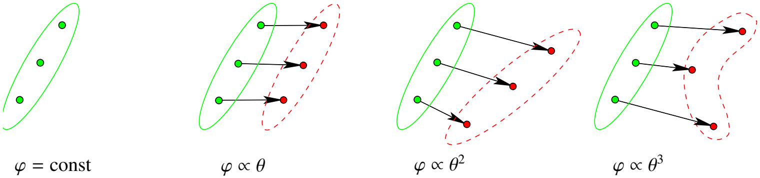
Eddington: Solar eclipse from 1919



Solar eclipse in 1919, observed by A. Eddington

- confirmed prediction from GR, deflection of 1.75 arcsec
- many reanalyses done since then, result holds up
- accesses of the unlensed situation possible!

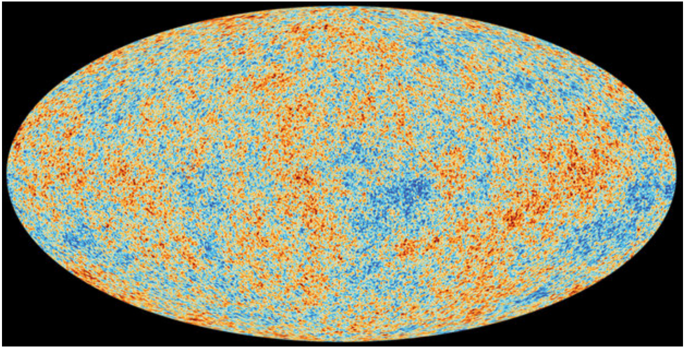
weak lensing basics



influence of gravitational fields on the shape of galaxies

- interaction of light with a potential can
  1. delay the arrival of photons by Φ
  2. change the apparent position of a galaxy by $\partial_i\Phi$
  3. shear the image of a galaxy by tidal fields $\partial_i\partial_j\Phi$
  4. bend the image of a galaxy by grav. flexions $\partial_i\partial_j\partial_k\Phi$
- particular interest: trace of the tidal shear: $\mathrm{tr}(\partial_i\partial_j\Phi) = \delta$, measures the density δ of (dark) matter

lensing in cosmology: on the CMB



all-sky map of the cosmic microwave background (ESA)

- **weak** effects: deflection typically arcmin
- unlensed situation never accessible

weak gravitational lensing

- photons follow null-geodesics $ds^2 = 0$ in a weakly perturbed metric
- in a radiation background (CMB, 21cm, CNB), the displacement of the position due to lensing matters
- photon number, energy and polarisation is conserved
- $T(\theta) \rightarrow T(\theta + \alpha)$ with lensing deflection α, follows from weak lensing potential $\alpha = \nabla\psi$
- lensing potential:

$$\psi(\theta) = 2\int_0^{\chi_{CMB}} d\chi\, W_\psi(\chi)\Phi \quad \text{with} \quad W_\psi(\chi) = \frac{\chi_{CMB} - \chi}{\chi_{CMB}\chi}\frac{D_+}{a}, \quad (5)$$

- with the CMB source plane at a distance $\chi_{CMB} = 10$ Gpc/h

two effects

- diffusive motion of one point relative to the other: on large scales
  - one point stays where it is, the other is changed at second order:

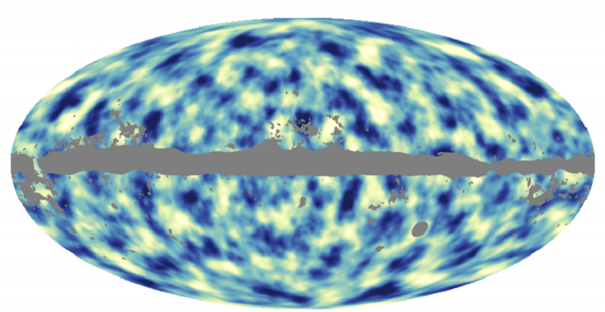
$$\langle T(\theta)T(\theta' + \alpha')\rangle = \langle T(\theta)T(\theta')\rangle + \frac{1}{2}\langle \alpha'_{i_0}\alpha'_{i_1}\rangle \partial'^2_{i_0 i_1}\langle T(\theta)T(\theta')\rangle \quad (6)$$

  - relevant quantity: variance $\langle \alpha^2 \rangle$
  - diffusive motion of one of the points
  - **frosted glass effect**, reduces structures (compare to Zel'dovich approximation)
- correlated deflection of the two points: on smaller scales
  - both points are changed at first order

$$\langle T(\theta + \alpha)T(\theta' + \alpha')\rangle = \langle T(\theta)T(\theta') + \langle \alpha_i \alpha'_j\rangle \partial_i \partial'_j \langle T(\theta)T(\theta')\rangle \quad (7)$$

  - relevant quantity: correlation function $\langle \alpha_i \alpha'_j \rangle$
  - coherent deflection of the two points

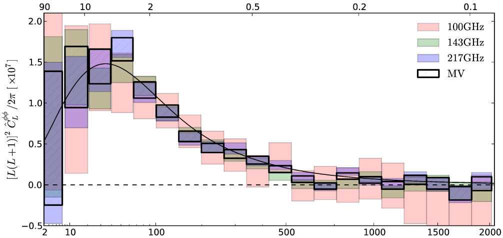
PLANCK weak lensing deflection map



reconstruction of the lensing potential by PLANCK

- CMB-lensing breaks homogeneity of the CMB
- reconstruction of the lensing potential by measuring correlations between different multipoles

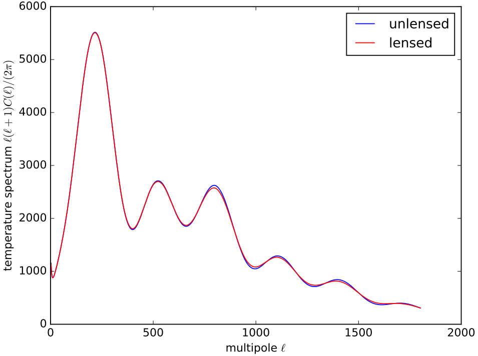
PLANCK weak lensing deflection spectrum



spectrum of the weak lensing deflection and ΛCDM-fit by PLANCK

- measured lensing deflection spectrum is a source of cosmological information: Ω_m, σ_8, shape of the CDM-spectrum
- consistency between different channels (selected close to the CMB-maximum)

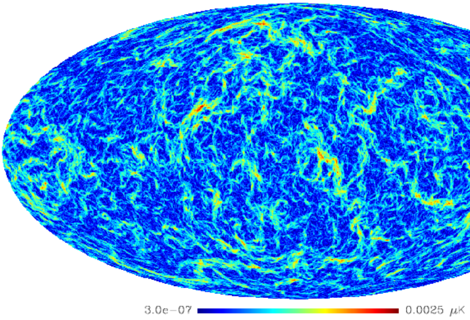
temperature spectrum of the CMB



lensed and unlensed CMB temperature spectra (from CAMB)

- CMB-lensing **decreases** the amount of structure in the CMB
- computation with the correlation function formalism

simulated deflection map



simulated convergence map including non-Gaussian structures by C. Carbone

- non-Gaussian structures even at high redshift
- Gaussian assumption of the characteristic function is flawed

lensing in cosmology: on galaxies

strong lensing cluster Abell-2218 (NASA/STScI)

- **weak** effects: percent changes in the ellipticity
- unlensed situation never accessible

in a world with perfect lensing...

- weak lensing observable: correlations $C_{\epsilon,ij}(\ell)$ between shapes of galaxies due to correlated distortion
- alternatively: no correlation between shapes without lensing
- observed lensing spectra

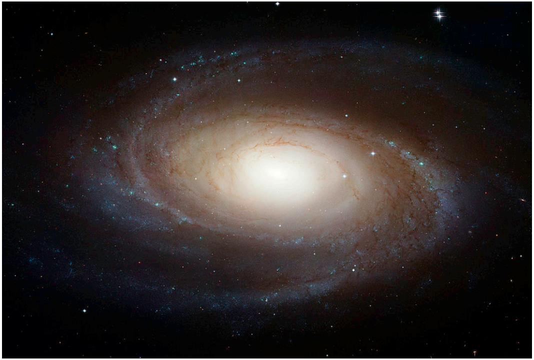
$$C^{\gamma}_{\epsilon,ij}(\ell) \rightarrow C^{\gamma}_{\epsilon,ij}(\ell) + \frac{\sigma_\epsilon^2}{\bar{n}}\delta_{ij} \quad (8)$$

with σ_ϵ^2 (shape noise) and $\bar{n}$ (galaxies per unit solid angle)

galaxy shapes...

are **not** uncorrelated due to galaxy formation processes! 2 primary mechanisms for spiral and elliptical galaxies based on tidal fields

spiral galaxies: tidal torquing



spiral galaxy M81, source: NASA

- non-constant displacement mapping across protogalactic cloud
- tidal forces $\partial^2_{ij}\Phi$ set protogalactic (dark matter) cloud into rotation

theory of quadratic alignments

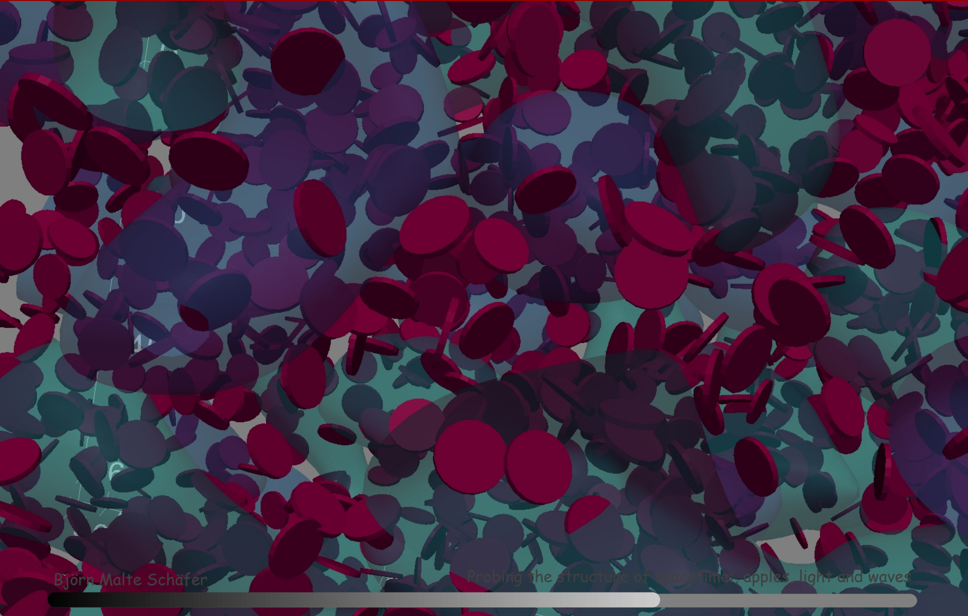
- halo angular momentum $\vec{L}$ generated by tidal shearing $\partial^2_{ij}\Phi$
- effective description with a conditional probability $p(\vec{L}|\partial^2_{ij}\Phi)d\vec{L}$
- angular momentum direction tilts the disc and changes complex shape $\epsilon = \epsilon_+ + i\epsilon_\times$:

$$\epsilon_+ = \frac{\hat{L}_y^2 - \hat{L}_x^2}{1+\hat{L}_z^2} \quad \text{and} \quad \epsilon_\times = 2\frac{\hat{L}_x\hat{L}_y}{1+\hat{L}_z^2}$$

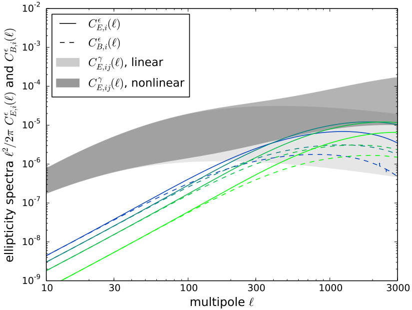
  with the angular momentum direction $\hat{L} = \vec{L}/L$
- prediction of 4 shape spectra: $C_E^\epsilon(\ell)$, $C_B^\epsilon(\ell)$, $C_C^\epsilon(\ell)$ and $C_S^\epsilon(\ell)$ including correlations of the scalar ellipticity $|\epsilon|^2 = \epsilon_+^2 + \epsilon_\times^2$ and cross-correlation with the E-mode
- effectively a single parameter a: alignment of $\vec{L}$ with $\partial^2_{ij}\Phi$

intrinsic ellipticity correlations

disc orientation



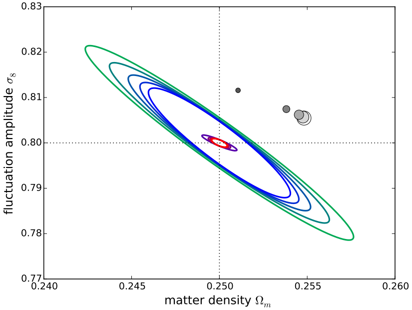
intrinsic shape correlations



shape spectra $C^{\varepsilon}_{E}(\ell)$ and $C^{\varepsilon}_{B}(\ell)$

- tomographic spectra for Euclid
- small scale correlations, similar to linear lensing, smaller than nonlinear lensing in all bins

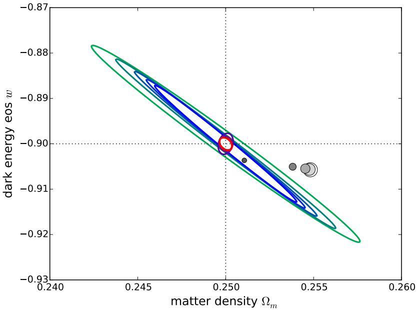
estimation biases Ω_m and σ_8



estimation biases and statistical errors on Ω_m and σ_8

- Euclid 7-bin tomography: σ_8 is biased high
- $2\ldots3\sigma$ in terms of the (marginalised) statistical error

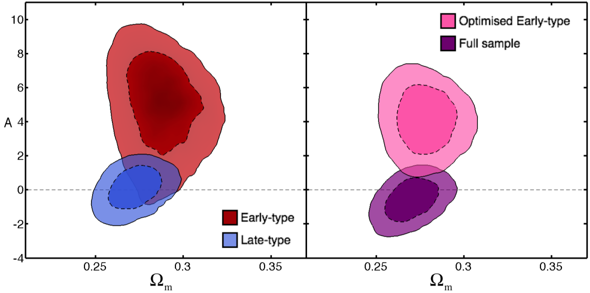
estimation biases Ω_m and w



estimation biases and statistical errors on Ω_m and w

- Euclid 7-bin tomography: w is not strongly affected
- that's from weak lensing data alone, you'll find it's different if other data is included

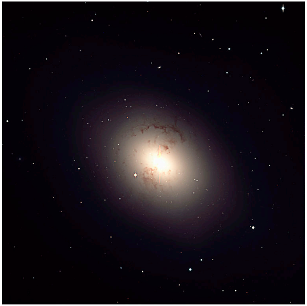
look at data



C. Heymans, arXiv:1303.1808

- measurement of alignments in CFHTLenS-data by C. Heymans
- no alignments on spiral galaxies (should not be able to do it with CFHTLenS-data)
- but alignment of ellipticial galaxies

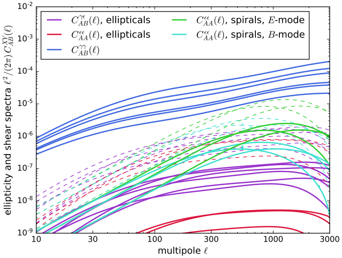
elliptical galaxies: tidal shearing



elliptical galaxy NGC 1316, source: ESO

- stars are in virial equilibrium in an NFW-halo
- tidal field $\partial^2_{ij}\Phi$ distorts the equipotential surfaces → shape change
- linear relation $\epsilon \propto \partial^2_{ij}\Phi$ from Jeans-equilibrium, single parameter is the velocity dispersion σ: "Hooke-constant"

elliptical galaxies: intrinsic alignment spectra



linear and quadratic alignments in comparison to weak lensing

- cross correlation between weak lensing and intrinsic alignment
- corresponding size-correlations, parallel to shape correlations?

summary

- 101 years of gravitational lensing
- lensing is a tool in cosmology, precision measurements of parameters and tests of cosmology
- many physical systems show lensing effects
- limited by intrinsic alignments: very interesting physical systems by themselves

many thanks to

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