from tidal interactions of galaxies to weak lensing - problem or possibility?

institute seminar, Observatoire de la Côte d'Azur, Nice

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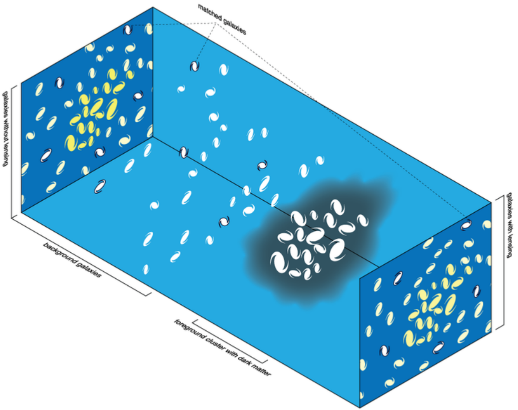
outline

weak lensing



theory of weak lensing, source: wikipedia

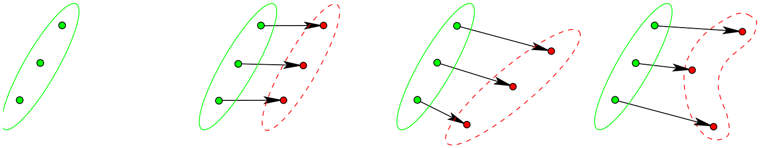
- weak lensing measures fluctuations in the metric by distortions of light bundles from distant galaxies

cosmology and weak lensing

strong lensing cluster Abell-2218 (NASA/STScI)

- gravitational lensing: deflection of light bundles by potentials in the large-scale structure
- **weak** effect: percent changes in the ellipticity

weak lensing basics



$\varphi = \text{const}$ $\varphi \propto \theta$ $\varphi \propto \theta^2$ $\varphi \propto \theta^3$

influence of gravitational fields on the shape of galaxies

- light deflection can
  1. change the apparent position of a galaxy by $\partial_i\Phi$
  2. shear the image of a galaxy by tidal shear $\partial_i\partial_j\Phi$
  3. bend the image of a galaxy by grav. flexions $\partial_i\partial_j\partial_k\Phi$
- particular interest: trace of the tidal shear, because it's related to density of (dark) matter, $\kappa \sim \mathrm{tr}(\partial_i\partial_j\Phi) = \partial_i\partial^i\Phi = \Delta\Phi = \delta$

parameter sensitivity

- let's look at the weak lensing spectrum

$$C_\kappa(\ell) = \int_0^{\chi_H} \frac{d\chi}{\chi^2} \left[\frac{3\Omega_m}{2\chi_H^2} G(\chi)\chi \frac{D_+}{a}\right]^2 P_\delta(k = \ell/\chi)$$

which is the Fourier-transformed correlation function $\langle\kappa(\theta)\kappa(\theta')\rangle$

1. strength gravitational coupling: Ω_m
2. rate of growth of gravitational potentials: Ω_m and w
3. relation between observed redshift and comoving distance: Ω_m and w
4. amplitude of density fluctuations: σ_8
5. balance of flucutations between large and small scales n_s
6. shape of $P_\delta(k)$: Ω_m and h, smaller influence by Ω_b

- in the easiest case, lensing determines 5 parameters
- parameter dependences are **very nonlinear** (leading to non-Gaussian likelihoods) and there are **degeneracies**

in a world with perfect lensing...

- weak lensing observable: correlations between shapes of galaxies due to correlated distortion
- alternatively: no correlation between shapes without lensing
- observed lensing spectra

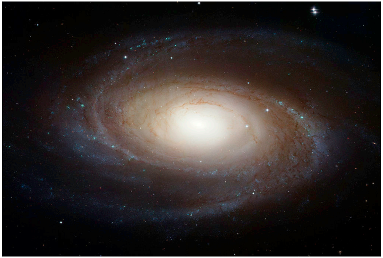
$$C^{\gamma}_{E,ij}(\ell) \rightarrow C^{\gamma}_{E,ij}(\ell) + \frac{\sigma_{\epsilon}^2}{\bar{n}}\delta_{ij} \tag{1}$$

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

galaxy shapes...

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

spiral galaxies: tidal torquing

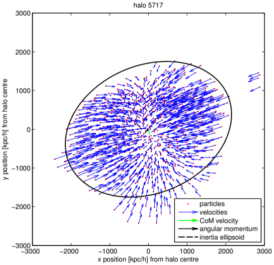


spiral galaxy M81, source: NASA

- non-constant displacement mapping across protogalaxy
- tidal forces $\partial^2_{ij}\Phi$ set protogalactic cloud into rotation
- in addition: anisotropic deformation
- gravitational collapse: separates protogalaxy from the density field and defines volume for integration of shear flows

spiral galaxies

tidal torquing simulations



particle velocities around a forming halo

- non-minimal coupling of haloes to the tidal shear field
- angular momentum $L_i \propto \epsilon_{ijk} I_{jl} \partial^2_{lk} \Phi$
- analytic treatment possible, tidal shear correlation functions

tidal torquing in Zel'dovich-approximation

- current model: galactic haloes acquire angular momentum by tidal shearing (Peebles 1969, White 1984)

$$\vec{L} \simeq \varrho_0 a^5 \int_{V_L} d^3q(\vec{q} - \bar{q}) \times \dot{\vec{x}} \tag{2}$$

- tidal shearing can be described in Zel'dovich approximation

$$\vec{x}(\vec{q}, t) = \vec{q} - D_+(t)\nabla\Phi(\vec{q}) \rightarrow \dot{\vec{x}} = -\dot{D}_+\nabla\Phi \tag{3}$$

- expand gravitational acceleration around the centre of mass of the halo: $\partial_i\Phi(\vec{q}) = \partial_i\Phi(\bar{q}) + \partial^2_{ij}\Phi(\bar{q})\,(\vec{q} - \bar{q})^j$
- 2 relevant quantities: inertia I_{ij} and shear $\partial^2_{ij}\Phi$

$$L_i = a^2\dot{D}_+ \sum_{jk} \varepsilon_{ijk} \sum_l I_{jl}\, \partial^2_{lk}\Phi \tag{4}$$

- tidal shear $\partial^2_{ij}\Phi$, derived from the potential Φ, $\Delta\Phi \propto \delta$

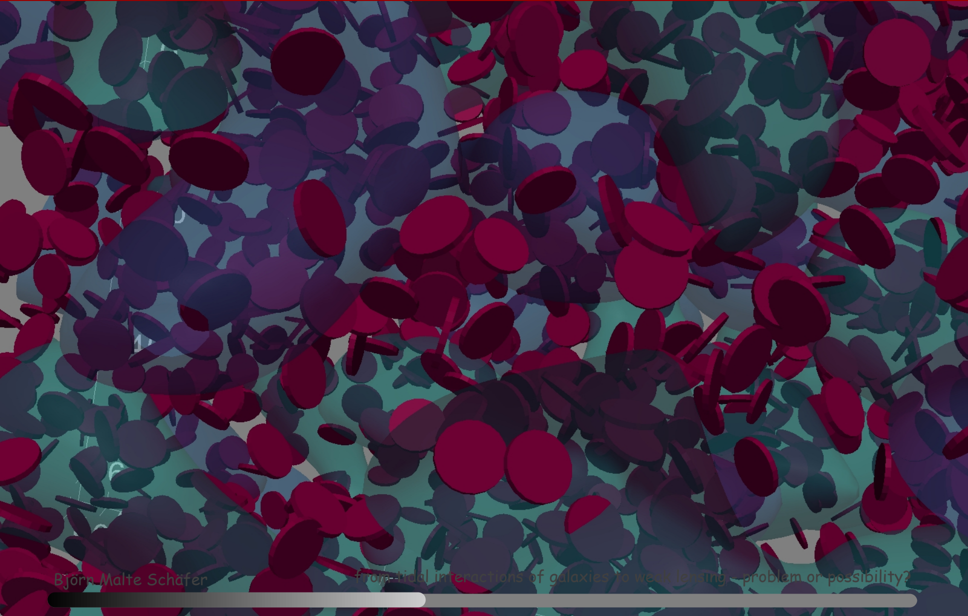
theory of quadratic alignments

- halo angular momentum $\vec{L}$ generated by tidal shearing $\partial^2_{ij}\Phi$: logic is $\delta \rightarrow \Phi \rightarrow \partial^2\Phi \rightarrow \vec{L} \rightarrow \hat{L} \rightarrow \epsilon$
- angular momentum direction tilts the disk and changes complex shape $\epsilon = \epsilon_+ + i\epsilon_\times$:

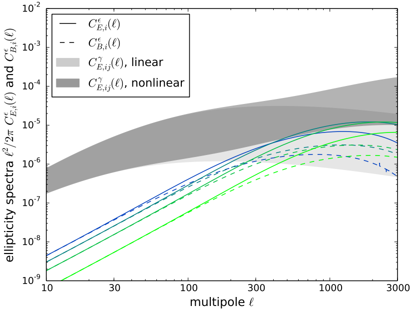
$$\epsilon_+ = \frac{\hat{L}_y^2 - \hat{L}_x^2}{1 - \hat{L}_z^2} \quad \text{and} \quad \epsilon_\times = 2\frac{\hat{L}_x\hat{L}_y}{1 + \hat{L}_z^2}$$

  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 $\partial^2_{ij}\Phi$

disk orientation



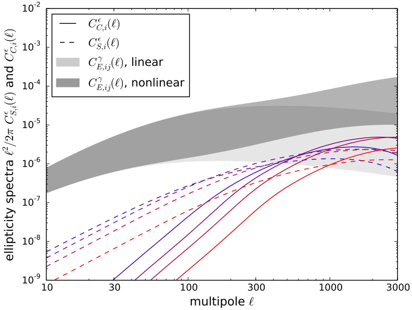
intrinsic shape E- and B-mode



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

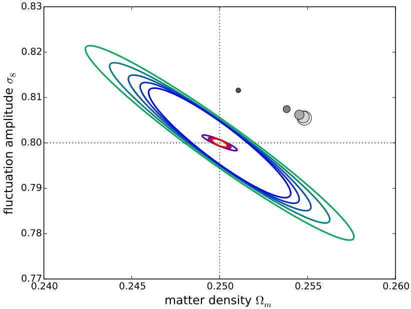
intrinsic shape C- and S-mode



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

- tomographic spectra for Euclid
- 2 new observables, spectra similar, cross-spectrum steeper at low ℓ

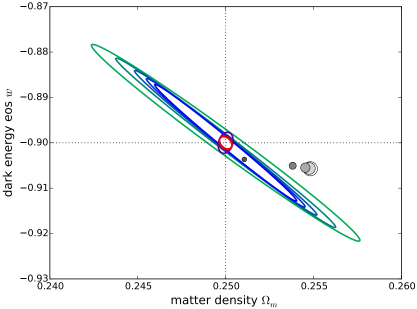
estimation biases Ω_m and σ_8



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

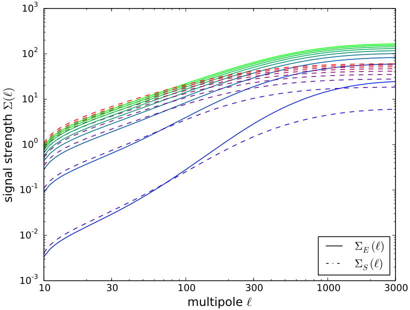
estimation biases Ω_m and w



estimation biases and statistical errors on Ω_m and w

- Euclid 7-bin tomography: w is biased negative
- dark energy could be mistaken for Λ

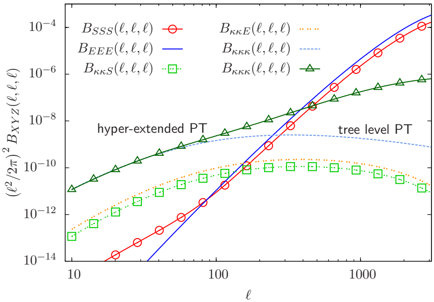
observability of the shape spectra



s/n-ratio for measuring $C^{\epsilon}_{E}(\ell)$ and $C^{\epsilon}_{S}(\ell)$ with Euclid

- all 4 spectra are observable with Euclid, tomography boosts signal
- few 10σ of significance → measurement of the alignment parameter with percent error

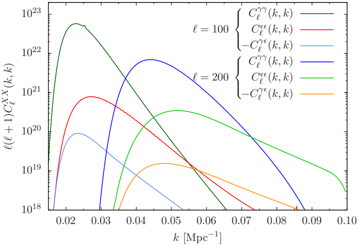
intrinsic shape bispectra



intrinsic alignment bispectra $B^\epsilon(\ell,\ell,\ell)$ for Euclid

- shape bispectra, simplified alignment model
- different configuration dependence compared to lensing
- surprisingly strong, confirms earlier results on simulations

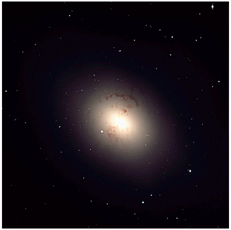
3d ellipticity alignments



3d intrinsic alignment and lensing spectra $C_\ell^\epsilon(k,k)$

- incorporate intrinsic alignments into the 3d weak lensing formalism
- for quadratic (theory) and linear (theory and numerics) alignments

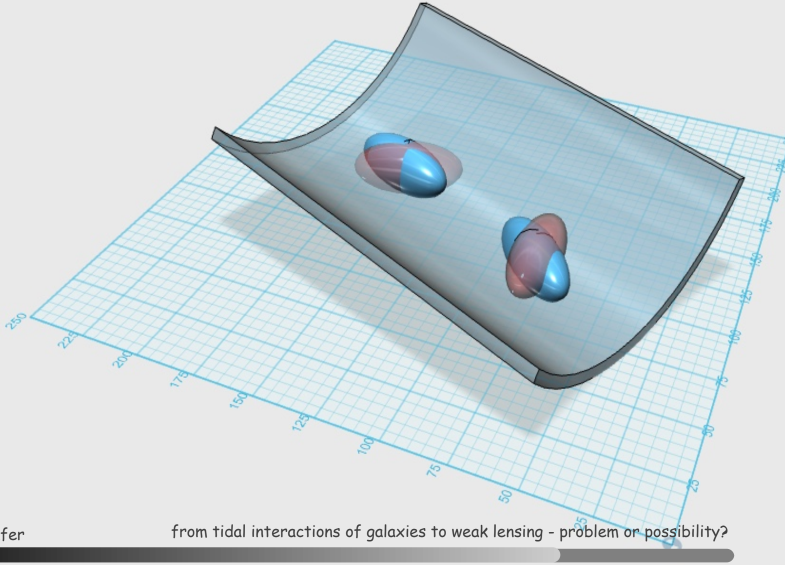
elliptical galaxies: tidal shearing



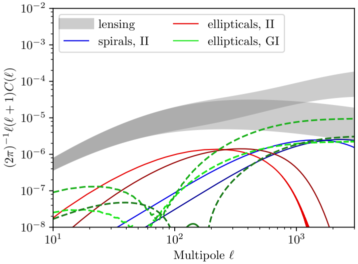
elliptical galaxy NGC 1316, source: ESO

- stars are in virial equilibrium with the dark matter
- tidal field $\partial^2_{ij}\Phi$ distorts the equipotential surfaces, effect proportional to $1/\sigma^2$ (nice catch: lensing measures $\partial^2_{ij}\Phi/c^2$)
- new model, linear relation $\varepsilon \propto \partial^2_{ij}\Phi$ from Jeans-equilibrium, single parameter: "Hooke-constant"

elliptical galaxies



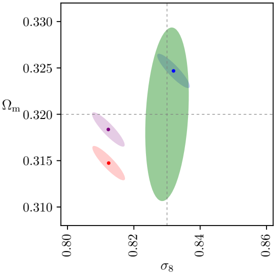
elliptical galaxies: intrinsic alignment spectra



linear and quadratic alignments in comparison to weak lensing

- amplitude fixed to comply with CHFTLenS
- cross correlation between weak lensing and intrinsic alignment (GI-terms)
- alternative alignment models
  - based on vorticity? ellipticity depends on $\vec{\omega} = \nabla \times \vec{\upsilon}$?
  - directly in the initial conditions? ellipticity reflects $\partial^2_{ij}\delta$?

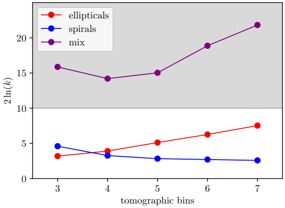
composite alignment model



composite alignment model vs. gravitational lensing

- IAs models affect lensing spectra on different angular scales
- they bias cosmological parameters in different ways, strongest effect on Ω_m and σ_8
- typical ratio: $q = 0.7$ spiral galaxies, $1 - q = 0.3$ elliptical galaxies

evidence for ΛCDM



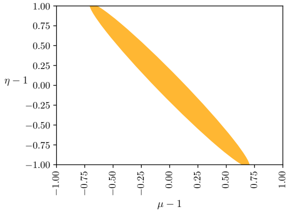
loss of Bayesian evidence

- Bayesian evidence ratio B for ΛCDM from weak lensing (Euclid) with a CMB-prior $p(\theta_\mu)$ (Planck)

$$B = \frac{\int d^n\theta\, p(\theta_\mu)\, \mathcal{L}_t(\theta_\mu)}{\int d^n\theta\, p(\theta_\mu)\, \mathcal{L}_w(\theta_\mu)}, \quad (5)$$

- loss of evidence due to shift of the best fit point

testing gravity with intrinsic alignments



bounds on η and μ (preliminary)

- weakly perturbed FLRW-metric

$$ds^2 = \left(1 + \frac{2\Phi}{c^2}\right)c^2 dt^2 - a^2(t)\left(1 - \frac{2\Psi}{c^2}\right) \tag{6}$$

  with two Bardeen-potentials Φ and Ψ
- relativistic particles are sensitive to $\Phi + \Psi$, nonrelativistic particles just to Φ
- ratio Φ/Ψ from combining lensing and IAs

intrinsic alignments are...

- serious contaminant in lensing surveys
  - spectra (2d, tomographic, 3d) and bispectra
  - intrinsic shape spectra can be measured with Euclid
  - parameter estimation biases are significant
  - there are many ways to distinguish lensing and IA
- chance to discover new things
  - no extra cost: same observable as weak lensing
  - insight into galaxy formation processes of spiral galaxies
  - virial equilibrium of elliptical galaxies: reaction to tidal fields
  - measurement of tidal fields on galaxy scales: gravity theories?
- opportunity for Euclid:
  - significance of intrinsic alignments: few 10σ
  - measurement of alignment model parameters at the %-level

many thanks: Philipp Merkel, Tim Tugendhat and Robert Reischke