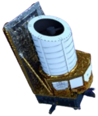
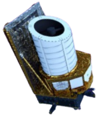
Cosmological parameter estimation with weak gravitational lensing

Susan Rissanen



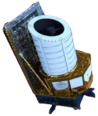
Overview



Motivation: the Euclid mission

- My task: test out a simple parameter estimation pipeline
- ESA's cosmology survey mission; mapping the Universe, abundant data
- Euclid is optimized to investigate some of the biggest mysteries in cosmology [1]
    - Shed light on the nature of dark matter and dark energy

Figure: Euclid's view of the Abell 2390 galaxy cluster featuring some lensing effects [2]

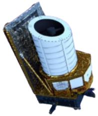


Cosmological parameters

- Properties of the Universe described by different cosmological parameters:

Parameter	Explanation
$\Omega_m = \Omega_b + \Omega_c$	Matter fraction, baryonic and (cold) dark matter.
σ_8	Amplitude of matter power spectrum fluctuations; ”clumpiness” of matter distribution, higher values mean stronger clustering.
$S_8 = \sigma_8\sqrt{\Omega_m/0.3}$	Derived parameter minimizing estimation degeneracies. Lensing depends on both matter amount Ω_m and clustering σ_8
Ω_Λ	Dark energy fraction; in a flat universe, $\Omega_\Lambda = 1 - \Omega_m$.

- My focus on matter content and distribution



Weak gravitational lensing

- Why weak lensing for cosmology?
  - Direct probe of total matter Ω_m and clustering σ_8
  - Evolution of the Universe with redshift of lensed galaxies
- Mass curves spacetime (assume GR) $\Rightarrow$ light bends around massive objects
- Galaxy images distorted $\Rightarrow$ amount and direction described by **shear**, γ

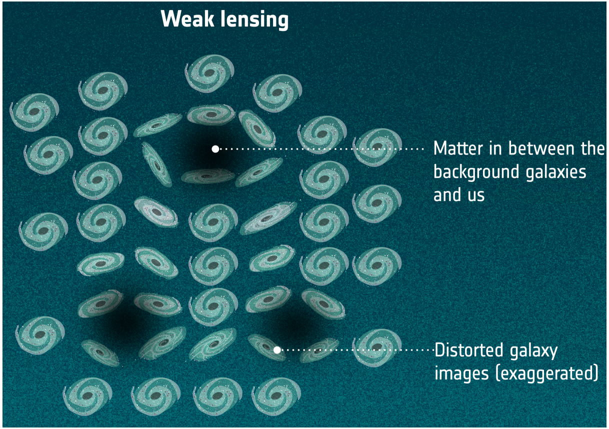
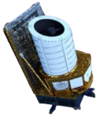


Figure: Weak lensing [3]



Shear components

- Complex number for mathematical convenience, $\gamma = |\gamma| \exp(2\mathrm{i}\phi)$
- Two components: tangential γ_t and cross component $\gamma_\times$, defined relative to the angular separation direction between galaxies as [5],
  $\gamma_t = -\mathbb{R}\mathrm{e}[\gamma \exp(-2\mathrm{i}\phi)]$,
  $\gamma_\times = -\mathbb{I}\mathrm{m}[\gamma \exp(-2\mathrm{i}\phi)]$
- Galaxy pair separated by an angular separation vector $\bar{\theta}$ making an angle ϕ (polar angle) with the horizontal axis

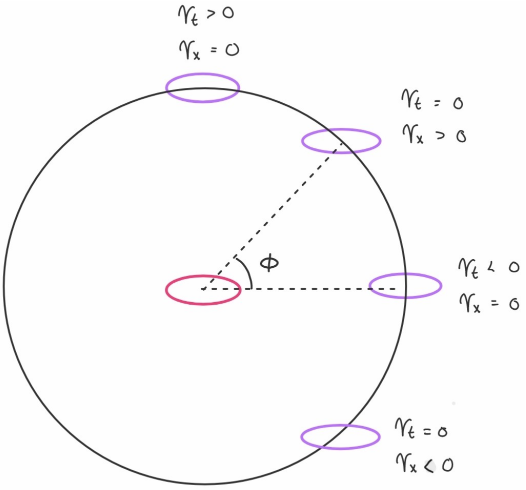
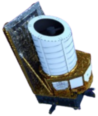


Figure: γ_t, $\gamma_\times$ separated by ϕ.



Cosmic shear

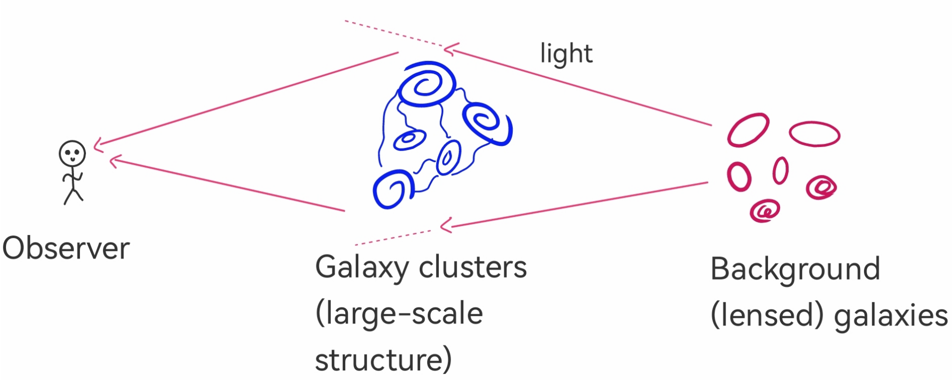
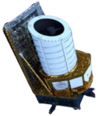
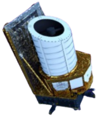


Figure: Cosmic shear: shear due to lensing from the gravitational influence of larger cosmic structures



Cosmic shear

- Similar advantages as weak gravitational lensing: sensitivity to matter content, matter distribution and evolution of the Universe with redshift
- Describing pairs of galaxies lining up relative to each other
- Weak lensing distortions detectable by statistically analyzing many sources $\Rightarrow$ correlation functions $\xi_{\pm}(\theta)$

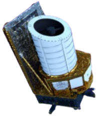


Cosmic shear correlation functions

- Correlation functions: how similarly or differently galaxy pairs point when you look at ensembles of galaxies [5]:

$$\xi_+(\theta) = \langle \gamma_t \gamma_t \rangle(\theta) + \langle \gamma_\times \gamma_\times \rangle(\theta) \tag{1}$$
$$\xi_-(\theta) = \langle \gamma_t \gamma_t \rangle(\theta) - \langle \gamma_\times \gamma_\times \rangle(\theta). \tag{2}$$

  - ξ_+: how often galaxy pairs have *aligned* shear components
  - ξ_-: how often galaxy pairs have *differences* in how their shear components are aligned



E- and B-modes

- The $\xi_{\pm}(\theta)$ can be decomposed into contributions from two sources: **E**- and **B**-modes
  - E-modes correspond to the true shear field
  - B-modes cannot originate from lensing, but are due to systematic errors or higher-order effects (intrinsic shapes and alignment of galaxies)
- Cleanly separating these modes is crucial to extract cosmological information from cosmic shear
  - Distinguish the true lensing signal from contaminants

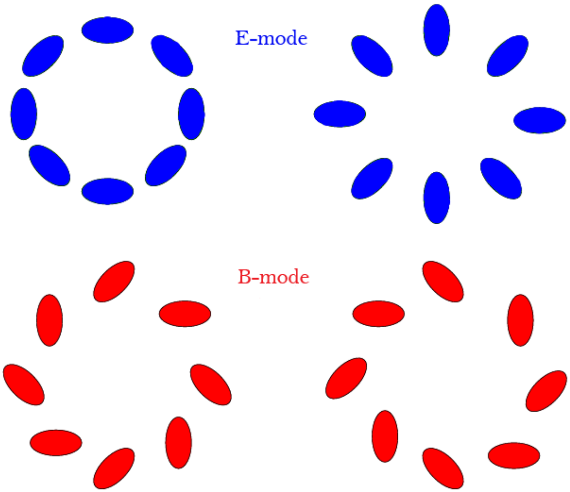
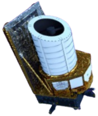
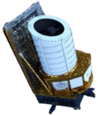


Figure: E- and B-modes of cosmic shear.



COSEBIs

- Different statistical measures developed to separate E- and B-modes, but all required measuring $\xi_{\pm}(\theta)$ down to arbitrarily small separation angles θ between galaxies, which is impractical
- Efficient mode separation: *Complete Orthogonal Sets of E- and B- mode integrals*, COSEBIs
- Fully retain the cosmological information from the shear signals in a finite angular interval and are very sensitive to cosmological parameters related to matter content and matter distribution



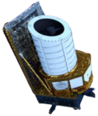
COSEBIs weight functions

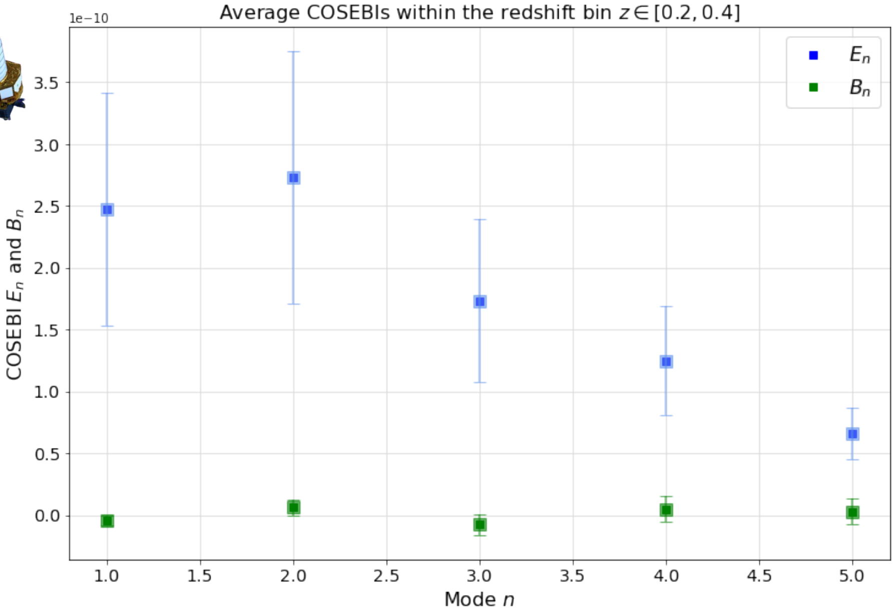
- Mathematically, COSEBIs are defined with $\xi_\pm(\theta)$ and their weight functions $T_{\pm n}(\theta)$ for n modes [6],

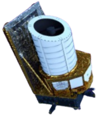
$$E_n = \frac{1}{2}\int_{\theta_{\min}}^{\theta_{\max}} d\theta\, \theta[\xi_+(\theta) T_{+n}(\theta) + \xi_-(\theta) T_{-n}(\theta)] \tag{3}$$

$$B_n = \frac{1}{2}\int_{\theta_{\min}}^{\theta_{\max}} d\theta\, \theta[\xi_+(\theta) T_{+n}(\theta) - \xi_-(\theta) T_{-n}(\theta)], \tag{4}$$

- COSEBIs can be linear or logarithmic depending on whether the $T_{\pm n}(\theta)$ are polynomials in θ or in $\ln\theta$
- Log-COSEBIs generally more efficient due to requiring 5 data points (modes) per redshift bin to get the same amount of cosmological information as in $\xi_\pm(\theta)$



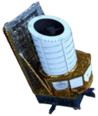

Average COSEBIs within the redshift bin $z \in [0.2, 0.4]$
1e−10
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
COSEBI E_n and B_n
E_n
B_n
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
Mode n



Parameter estimation

- Cosmological parameter estimation requires the use of Bayesian statistics, maximum likelihood estimation and Markov Chain Monte Carlo sampling.
- The data vector (E-modes, E_n) are compared to the values of theoretically predicted E-modes (E_n^{obs}), given a set of model parameters denoted by $\boldsymbol{\pi}$.
    - Additionally, a covariance matrix Cov_{mn} for E_n
- Essentially one minimizes the χ^2 function, given by [6],

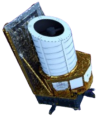
$$\chi^2 = \sum_{m,n=1}^{N} [E_m^{\mathrm{obs}} - E_m(\boldsymbol{\pi})]\mathrm{Cov}_{mn}^{-1}[E_n^{\mathrm{obs}} - E_n(\boldsymbol{\pi})]$$



Data pipeline

- Galaxy data from a single simulated catalog developed by the *Marenostrum Institut de Ciencies de l'Espai* (MICE) [4]
  - Contains the positions, redshifts, separation angle and shear
  - Not many simulations with shear publicly available $\Rightarrow$ a rough approximate Cov_{mn}
- Theoretical predictions and parameter estimation using `Cosmosis` [7]

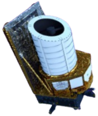
$$\boxed{\text{MICE catalog}} \xrightarrow[\textit{tomographic binning}]{} \boxed{\xi_\pm(\theta)} \xrightarrow{T^{\log}_{\pm n}} \boxed{\text{Data } E_n,\ B_n} \longrightarrow \boxed{\mathrm{Cov}_{mn}} \longrightarrow \boxed{\texttt{Cosmosis}} \longrightarrow \boxed{\text{Results}}$$

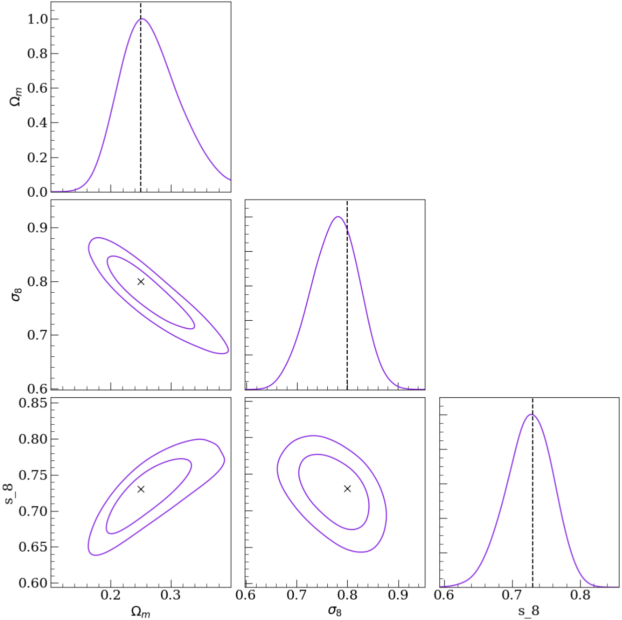


Results

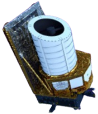
Parameter	Max Posterior	Mean $\pm$ Std	Median $\pm$68 CI
Ω_m	0.253	0.267 ± 0.047	$0.262^{+0.025}_{-0.021}$
σ_8	0.787	0.775 ± 0.045	$0.777^{+0.021}_{-0.022}$
S_8	0.723	0.725 ± 0.033	$0.727^{+0.015}_{-0.016}$
Ω_Λ	0.747	0.733 ± 0.047	$0.738^{+0.021}_{-0.025}$

- Model parameter values: $\Omega_m = 0.25$, $\sigma_8 = 0.8$, $S_8 = 0.73$ and $\Omega_\Lambda = 0.75$
- Only Ω_m, σ_8 sampled since $S_8 = \sigma_8\sqrt{\Omega_m}$ and in a flat universe $\Omega_\Lambda = 1 - \Omega_m$
- True values lie within about one std (1σ) of the means $\Rightarrow$ reasonably good
- Uncertainties relatively small, S_8 particularly well-constrained $\Rightarrow$ also good





Ω_m
σ_8
s_8
1.0
0.8
0.6
0.4
0.2
0.0
0.9
0.8
0.7
0.6
0.85
0.80
0.75
0.70
0.65
0.60
0.2
0.3
0.6
0.7
0.8
0.9
0.6
0.7
0.8
Ω_m
σ_8
s_8



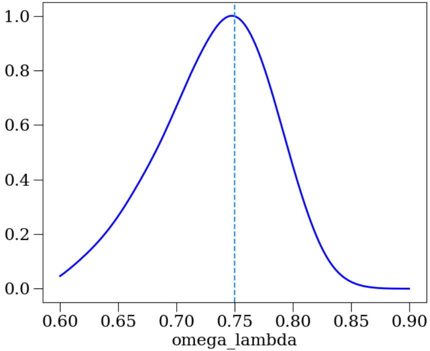


Figure: Ω_Λ posterior distribution plot

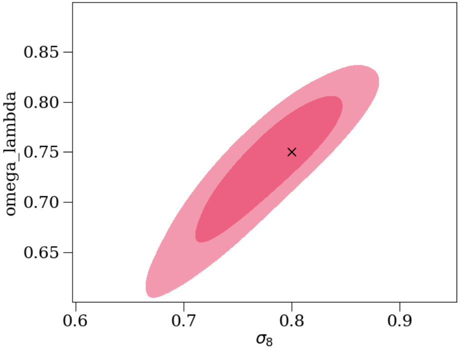
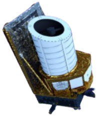
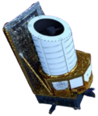


Figure: $\Omega_\Lambda - \sigma_8$ contour plots



Results discussion

- Results confirm that COSEBIs efficiently probe the matter parameters and yield accurate estimations for values of $\Omega_m, \Omega_\Lambda,$ S_8 and σ_8 (despite the lack of data)
- Degeneracy between Ω_m and σ_8 expected in weak lensing studies; cosmic shear is sensitive to their combination, S_8, the most
  - A lower Ω_m can be compensated for by a higher σ_8 and vice versa
  - More elliptic contour implies more correlation between the parameter pair; high correlation expected with Ω_m, σ_8
  - Smaller or tighter contours imply better constraints
- Combining weak lensing with other probes (CMB, galaxy clustering) can potentially improve results and degeneracies



Summary

- Dark matter and dark energy need to be studied more $\Rightarrow$ the Euclid mission
- Cosmic shear is a powerful tool for studying the matter distribution and evolution of the Universe
  - Sensitive to matter content, clustering and evolution of the universe
- Shear signal is not free of contaminants $\Rightarrow$ need to separate E- and B-modes $\Rightarrow$ COSEBIs
- Results suggest that COSEBIs indeed yield accurate results and do their job at separating E- and B-modes and confirm that the data processing and parameter estimation pipeline is solid even though Cov_{mn} was only approximate

Thank you!

Figure: Gravitational lensing meme drawn by my good friend ChatGPT

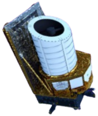
References I

[1] URL: https://www.esa.int/Science_Exploration/Space_Science/Euclid_overview.

[2] URL: https://www.esa.int/ESA_Multimedia/Images/2024/05/Closer_Euclid_view_of_Abell_2390.

[3] URL: https://www.esa.int/ESA_Multimedia/Images/2023/05/What_Euclid_will_measure_weak_lensing.

[4] P. Fosalba et al. “The MICE Grand Challenge light-cone simulation – III. Galaxy lensing mocks from all-sky lensing maps”. In: *Monthly Notices of the Royal Astronomical Society* 447.2 (Dec. 2014), 1319–1332. ISSN: 0035-8711. DOI: 10.1093/mnras/stu2464. URL: http://dx.doi.org/10.1093/mnras/stu2464.



References II

[5] Martin Kilbinger. “Cosmology with cosmic shear observations: a review”. In: *Reports on Progress in Physics* 78.8 (2015), p. 086901. URL: https://doi.org/10.1088%2F0034-4885%2F78%2F8%2F086901.

[6] Schneider, P., Eifler, T., and Krause, E. “COSEBIs: Extracting the full E-/B-mode information from cosmic shear correlation functions”. In: *A&A* 520 (2010), A116. DOI: 10.1051/0004-6361/201014235. URL: https://doi.org/10.1051/0004-6361/201014235.

[7] J. Zuntz et al. “CosmoSIS: Modular cosmological parameter estimation”. In: *Astronomy and Computing* 12 (2015), pp. 45–59. ISSN: 2213-1337. URL: https://www.sciencedirect.com/science/article/pii/S2213133715000591.