Probing Anisotropic Expansion With Weak-Lensing

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Introduction

Motivation

- Homogeneity and isotropy on large scales is foundational to modern cosmology
- Some dark energy, modified gravity models lead to large-scale anisotropies
- Fundamentally, this assumption must be tested
- Renewed interest in anisotropic cosmologies (e.g. SN Ia measurements, CMB dipole)
  $\implies$ Can use weak lensing to probe anisotropies
- Formalism developed by Pitrou, Pereira, & Uzan to estimate B-mode shear generated by anisotropies [arXiv:1503.01125], [arXiv:1503.01127]
- Incorporate non-linear corrections and tomography into results of Pitrou et al.

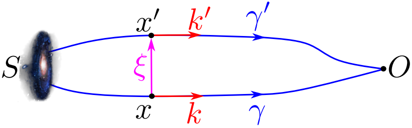
Lensing Formalism

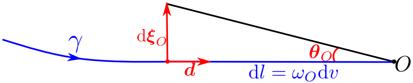
Lensing distortions

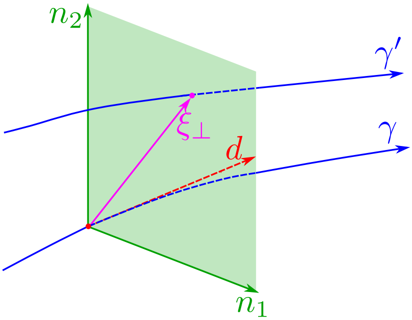
Jacobi matrix

- Observed angular size $\longmapsto$ physical separation

$$\xi^A\big|_S \propto \mathcal{D}^A{}_B\, \theta^B\big|_O$$







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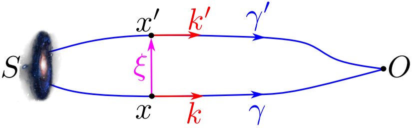
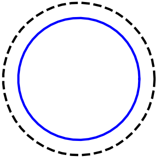


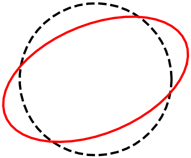
$$\mathcal{D} \approx \bar{D}_A \left[\overbrace{\begin{pmatrix} 1-\kappa & 0 \\ 0 & 1-\kappa \end{pmatrix}}^{\text{Convergence}} + \underbrace{\begin{pmatrix} 0 & -\psi \\ \psi & 0 \end{pmatrix}}_{\text{Rotation}} + \overbrace{\begin{pmatrix} -\gamma_1 & \gamma_2 \\ \gamma_2 & \gamma_1 \end{pmatrix}}^{\text{Shear}} \right]$$

- Weak lensing: κ, $\gamma \ll 1$ and $\dot{\psi} = \mathcal{O}(\gamma^2)$
  $\implies$ Ignore rotation (usually)

Convergence:



Shear:



E-modes, B-modes, and multipoles

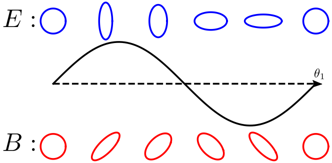
- Expand κ in spherical harmonics

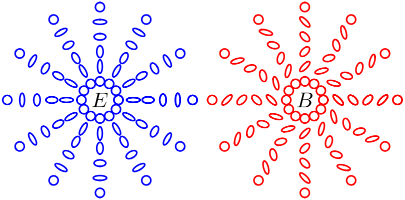
$$\kappa = \sum_{\ell,m} \kappa_{\ell m} Y_{\ell m}$$

- Expand γ in spin-weighted spherical harmonics

$$\gamma^{\pm} = \gamma_1 \pm i\gamma_2 = \sum_{\ell,m} (E_{\ell m} \pm iB_{\ell m}) Y^{\pm 2}_{\ell m}$$

- E =even parity, B =odd parity
- No B-modes on large scales (FLRW)*





Anisotropic Spacetime

Bianchi-I universes

Metric

$$\mathrm{d}s^2 = a^2(-\mathrm{d}\eta^2 + \gamma_{ij}\mathrm{d}x^i\mathrm{d}x^j)$$

- $a =$ scale factor, $\gamma_{ij} =$ spatial metric
- Hubble rate: $\mathcal{H} \equiv \frac{a'}{a}$
- Spatial shear: $\sigma_{ij} \equiv \frac{1}{2}\gamma'_{ij}$

Dark Energy

$$T^{de}_{\mu\nu} = (\rho_{de}+P_{de})u_\mu u_\nu + P_{de}g_{\mu\nu} + \Pi_{\mu\nu}$$

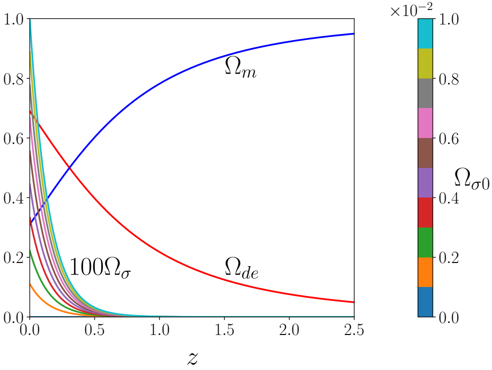
Anisotropic stress

- EoS: $P_{de} = -\rho_{de}$
- Anisotropic stress model: $\Pi^i{}_j \propto \Omega_{de} W^i_j$

Evolution

$$\mathcal{H}^2 = \frac{1}{3}\kappa a^2 \rho + \frac{1}{6}\sigma^2$$

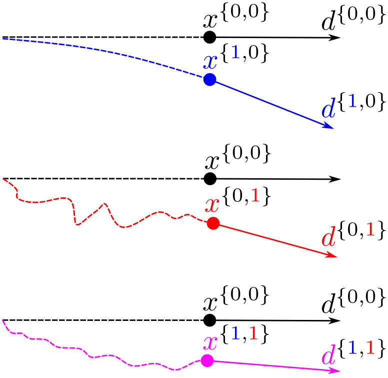
$$(\sigma^i{}_j)' = -2\mathcal{H}\sigma^i{}_j + \kappa \Pi^i{}_j$$



Weak shear limit and perturbation scheme

Perturbed metric

$$\mathrm{d}s^2 = a^2\Big[-(1+2\Phi)\mathrm{d}\eta^2 + 2\bar{B}_i \mathrm{d}x^i \mathrm{d}\eta + (\gamma_{ij} + h_{ij})\mathrm{d}x^i \mathrm{d}x^j \Big]$$



Perturbation scheme

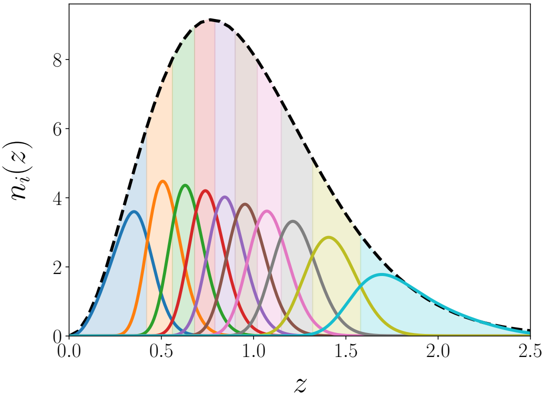
- Treat $\sigma_{ij}/\mathcal{H} \ll 1$ as perturbation along with scalar-vector-tensor (SVT) perturbations
- SVT: Φ, $\bar{B}^i$, $h_{ij} = -2\Psi\left(\gamma_{ij} + \frac{\sigma_{ij}}{\mathcal{H}}\right) + 2E_{ij}$
- Two-fold perturbation $\{n, m\}$ for shear and SVT*:

$$X^{\{n,m\}} = \underbrace{X^{\{0,0\}}}_{\text{FLRW}} + \overbrace{\delta X^{\{0,1\}}}^{\text{SVT}} + \underbrace{\delta X^{\{1,0\}}}_{\text{Shear}} + \overbrace{\delta X^{\{1,1\}} + \ldots + \delta X^{\{n,m\}}}^{\text{Shear+SVT}}$$

Results

Euclid tomography

- Lensing projects/flattens observables
- Tomography regains some projected info.
- Euclid:
  - 10 equi-populated bins $10^{-3} \leq z \leq 2.5$
  - Convolve underlying distribution $n(z)$ with photometric error $p_{\mathrm{ph}}(z_{\mathrm{p}}|z)$



Angular power spectra

Order $\{1, 0\}$

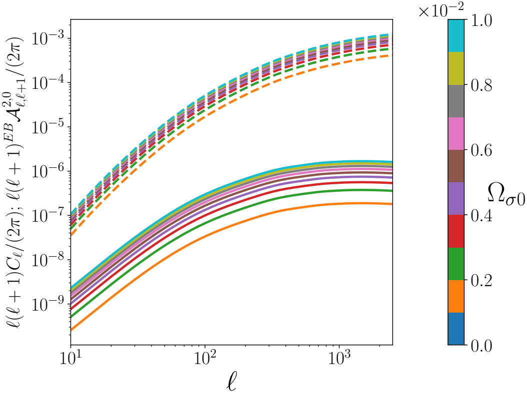
- $\gamma \sim \frac{\sigma}{\mathcal{H}}$
- Fully deterministic
  $\implies$ no power spectrum

Order $\{0, 1\}$

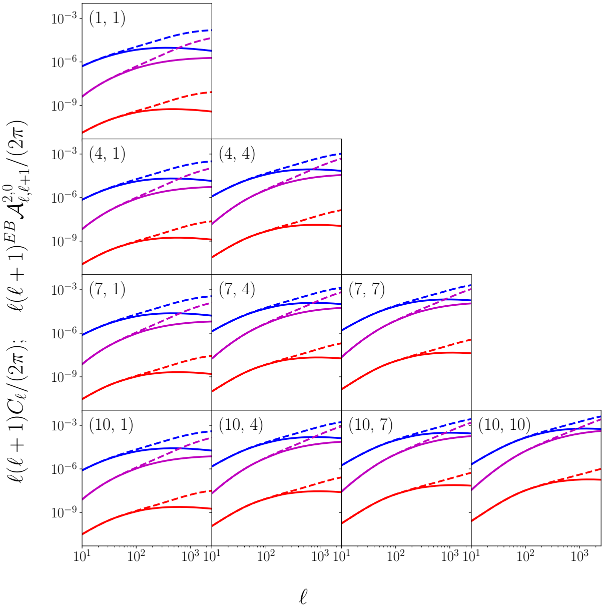
- First order in scalars
  $\implies$ only E-modes
- Auto: $C_\ell^{EE} \sim \varphi^2$
- CLASS: $P(k)$, $T_\varphi(\eta, k)$, HALOFIT

Order $\{1, 1\}$

- Post-Born couples σ and scalars
  $\implies$ Non-zero B-modes!
- Auto: $C_\ell^{BB} \sim \left(\frac{\sigma}{\mathcal{H}}\right)^2 \varphi^2$
- Cross: $\left\langle B_{\ell m} E^*_{\ell \pm 1 m'} \right\rangle \sim \left(\frac{\sigma}{\mathcal{H}}\right) \varphi^2$
  $\implies$ off-diagonal (parity)



Angular power spectra



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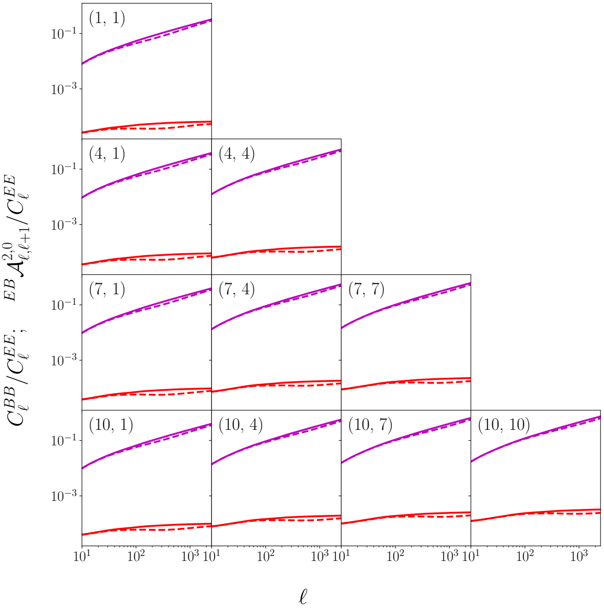

Conclusion

Concluding remarks

Summary

- Lightning review of lensing formalism
- Applied perturbation scheme and results Pitrou et al.
  $\implies$ incorporated tomography and non-linear corrections
- B auto- and E-B cross-correlations can be used together in order to constrain late-time anisotropic expansion
- Should construct appropriate estimators for cross-correlations

Outlook

- Investigate other B-mode sources (IA, clustering, GW,...)
- Beyond Limber? Forecasting?
- Weak lensing is of immense importance to upcoming surveys
- Hope to place constraints on $\sigma/\mathcal{H}$ at the percent level

Questions?