Surface brightness fluctuations in Intrinsic Alignment and Area-metric Spacetimes

Cosmology from Home 2022

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Motivation: Etherington Distance Duality

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$D_L(z)$: luminosity distance

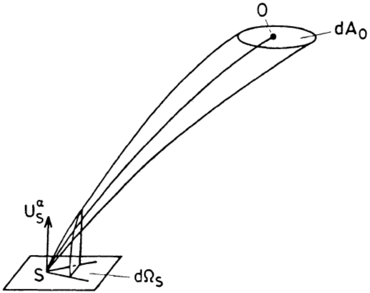

Figure: See [Schneider,Ehlers,Falco (93)]

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$D_A(z)$: angular diameter distance

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$D_L(z)$: luminosity distance

$D_A(z)$: angular diameter distance

Universal for metric spacetimes!

$\Rightarrow$ Important observational quantity to test for new physics

see [Basset & Kunz (04)] and [Schuller & Werner (17)] for instance

$\Rightarrow$ Focus on different geometries

$\Rightarrow$ Similar phenomenology for classical astrophysical effects? $\rightarrow$ Intrinsic Alignment!

Structure

- Surface brightness fluctuations in linear alignment model

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- Basic ideas about area-metric geometry

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- Basic ideas about area-metric geometry
- Surface brightness fluctuations in area-metric lensing

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- Surface brightness fluctuations in linear alignment model
- Basic ideas about area-metric geometry
- Surface brightness fluctuations in area-metric lensing
- Numerical comparison of the spectra

Intrinsic Alignment

General Idea: Local alignment of galaxies in the tidal fields of the large scale structure → linear model for elliptical galaxies
(See [Hirata et. al. (07), Hirata & Seljak (10)] for instance)

Important systematic error in weak lensing

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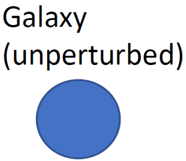

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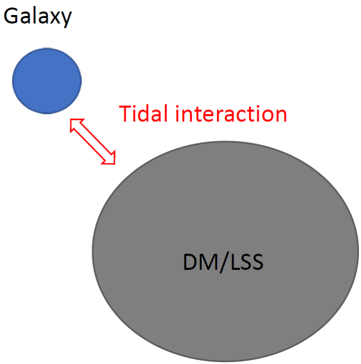

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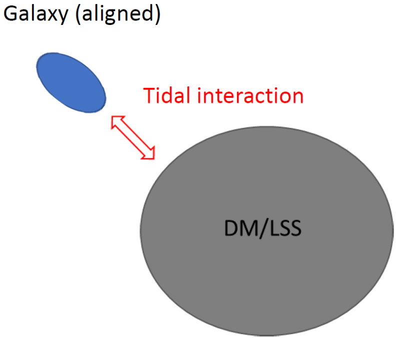

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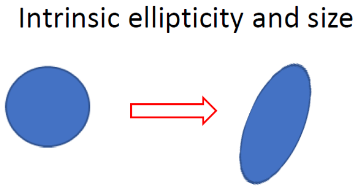

See [Ghosh, Durrer & Schäfer (22)]

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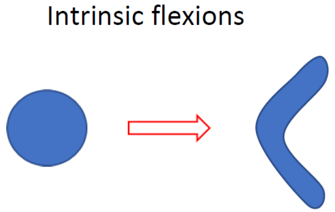

See `https://doi.org/10.1093/mnras/stab3680`

Linear alignment model

Based on Jeans-equilibrium

(see [Hirata et. al. (07), Hirata & Seljak (10), Piras et. al. (18), Ghosh, Durrer & Schäfer (22)])

$$\sigma^2 \partial_r \ln\left(\rho(r)\right) = -\partial_r \Phi$$

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In unperturbed situation solved by

$$\rho(r) = \bar{\rho} \exp\left(-\frac{\Phi(r)}{\sigma^2}\right) = \frac{N_{\text{stars}}}{A} \exp\left(-\frac{\Phi(r)}{\sigma^2}\right)$$

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$$N_{\mathrm{stars}} = \int \mathrm{d}^2 r \rho\left(r\right) = \int \mathrm{d}^2 r \frac{N_{\mathrm{stars}}}{A} \exp\left(-\frac{\Phi(r)}{\sigma^2}\right)$$

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$\Rightarrow$ Measure for cross section area:

$$A = \int \mathrm{d}^2 r \exp\left(-\frac{\Phi(r)}{\sigma^2}\right) = \int_0^{2\pi} \mathrm{d}\phi \int_0^{\infty} \mathrm{d}r \; r \exp\left(-\frac{\Phi(r)}{\sigma^2}\right)$$

Linear alignment model

Quadrupolar perturbation in tidal field ...

$$\Phi(r) \rightarrow \Phi(r) + \frac{1}{2}\partial_a\partial_b \left.\Phi\right|_{r=0} r^a r^b$$

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$$\Phi(r) \;\rightarrow\; \Phi(r) + \frac{1}{2}\partial_a\partial_b\, \Phi\big|_{r=0}\, r^a r^b$$

... lead to a density profile perturbation

$$\rho'(r) = \frac{N_{\text{stars}}}{A'} \exp\left(-\frac{\Phi(r)}{\sigma^2}\right)\left(1 - \frac{1}{2\sigma^2}\partial_a\partial_b\Phi r^a r^b\right)$$

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and according size/area change

$$A' = \int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\mathrm{d}r\;r\exp\left(-\frac{\Phi(r)}{\sigma^2}\right)\left(1-\frac{1}{2\sigma^2}\partial_a\partial_b\Phi r^a r^b\right).$$

while the number of stars stays the same

Intrinsic surface brightness fluctuations

With the proportionality $F \propto N_{\text{stars}}$, the surface brightness $I(r) \propto \rho(r)$ and

$$\bar{I} = \frac{F}{A}$$

$\Rightarrow$ Surface brightness fluctuations

$$\frac{\delta\bar{\rho}}{\bar{\rho}} = \frac{-\delta A}{A'} = \frac{\delta\bar{I}}{\bar{I}} = \frac{1}{2\sigma^2}\frac{\int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\mathrm{d}r\, r\exp\left(-\Phi(r)/\sigma^2\right)\partial_a\partial_b\Phi r^a r^b}{\int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\mathrm{d}r\, r\exp\left(-\Phi(r)/\sigma^2\right)}$$

Explicit evaluation of integrals leads to

$$\Rightarrow \quad \frac{\delta\bar{I}}{\bar{I}} \propto D_{IA}\frac{\Delta\Phi}{c^2}$$

Alignment parameter $D_{IA} \propto \frac{c^2}{\sigma^2} r_{\text{scale}}^2$

Intrinsic surface brightness spectrum

With $\Delta \to -\ell^2/\chi^2$ and Limber approximation:

$$II: \quad C_{AB}^{\delta\bar{I}/\bar{I}\,\delta\bar{I}/\bar{I}}(\ell) \propto \ell^4 D_{\mathrm{IA}}^2 \int_0^{\chi_H} \frac{\mathrm{d}\chi}{\chi^2} W_{\varphi,A} W_{\varphi,B} P_{\Phi\Phi}(k = \ell/\chi)$$

Weighting function

$$W_{\varphi,A}(\chi) = \frac{1}{\chi^2} p(z(\chi))\, \Theta(\chi - \chi_A)\, \Theta(\chi_{A+1} - \chi) \frac{\mathrm{d}z}{\mathrm{d}\chi'} \frac{D_+(a)}{a}$$

with $P_{\Phi\Phi}(k = \ell/\chi) \propto k^{n_s - 4} T(k)^2$

and $p(z) \propto \left(\frac{z}{z_0}\right)^2 \exp\left[-\left(\frac{z}{z_0}\right)^\beta\right]$ with $\beta = 3/2$ and $z_0 = 0.64$

(See [Laureijs et. al. (11)])

Premetric Electrodynamics

General linear electrodynamics which allows for vacuum birefringence [Hehl & Obdukov (03)]

$$S_{\mathrm{GLE}}\left[A; G\right) = -\frac{1}{8}\int d^4x\omega_G \boldsymbol{G}^{\boldsymbol{abcd}} F_{ab}F_{cd}$$

with volume element $\omega_G = 1/24\left(\epsilon_{abcd}G^{abcd}\right)^{-1}$ and area-metric $\boldsymbol{G}^{\boldsymbol{abcd}}$

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Compare with Maxwell:

$$S_{\text{Maxwell}}[A; G) = -\frac{1}{4}\int d^4x\sqrt{-\det g}\,g^{ac}g^{bd}F_{ab}F_{cd}$$

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Principal polynomial:

$$P^{abcd}k_ak_bk_ck_d = -\frac{1}{24}\omega_G^2\epsilon_{uvpq}\epsilon_{rstu}G^{uvr(a}G^{b|ps|c}G^{d)qtu}k_ak_bk_ck_d$$

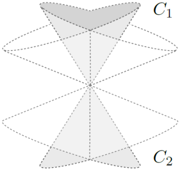

Figure: See [Duell et. al. (18)]

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Find according gravity theories via Gravitational Closure/Constructive Gravity [Duell et. al. (18)]

EM Conservation in AM

Covariant energy momentum conservation via Gotay Marsden tensor

→ generalized concept of energy momentum conservation for arbitrary geometries

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$$\partial_b \left(\omega_G N^b \right) = 0$$

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→ generalized concept of energy momentum conservation for arbitrary geometries

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$$\partial_b \left(\omega_G N^b \right) = 0$$

... instead of

$$\frac{1}{\sqrt{-\det g}} \partial_b \left(\sqrt{-\det g} N^b \right) = 0 \quad \Rightarrow \quad \nabla_a N^a = 0$$

for metric case.

→ replace $\sqrt{-\det g}$ with ω_G for volume measure!

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Weakly birefringent space-times:

$$G^{abcd} = \eta^{ac}\eta^{bd} - \eta^{ad}\eta^{bc} - \sqrt{-\mathrm{det}\eta}\epsilon^{abcd} + H^{abcd}$$

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Weakly birefringent space-times:
Effectively metric photon propagation with

$$P^{ab} = \eta^{ab} + h^{ab}$$

and conservation wrt. ω_G
$\Rightarrow \nabla_a N^a \neq 0$
⇒ Photon excess μ_{vio} for line of sight integration
$\rightarrow F' \propto F \left(1 + \mu_{\text{vio}}\right)$.

See [Schuller & Werner (17)] for more details

Surface brightness fluctuations

This leads to:

- Violation of Etherington distance duality $D_L' = D_L/\sqrt{1+\mu_{\rm vio}}$

  $\Rightarrow D_L = \frac{(1+z)^2 D_A}{\sqrt{1+\mu_{\rm vio}}}$
  See [Schuller & Werner (17)]

- Violation of surface brightness conservation in lensing
  $I\left(O\right) = I_{\rm GR}\left(O\right)\left(1+\mu_{\rm vio}\right) = \left(1+\mu_{\rm vio}\right) I(S)\left(1+z\right)^{-4}$

$$\Rightarrow \quad \frac{\delta I}{I} = \frac{I(O) - I(O)_{\rm GR}}{I(O)_{\rm GR}} = \mu_{\rm vio}$$

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From CG the solution for a point mass source leads to the effective potential

$$\Phi_{\mathrm{eff}}\,(\vec{r}) = -\frac{GM}{c^2\,|\vec{r}-\vec{r}_M|}\,(1+\delta\exp\left(-\eta\,|\vec{r}-\vec{r}_M|\right))$$

See [Schneider et al.(17), Alex(20)] for more details

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$$\Rightarrow \quad \frac{\delta I}{I} = \frac{I(O) - I(O)_{\text{GR}}}{I(O)_{\text{GR}}} = \mu_{\text{vio}}$$

In this case

$$\mu_{\text{vio}} = \frac{3\delta GM}{c^2}\left(\frac{\exp\left(-\eta|\vec{r}_{\text{S}} - \vec{r}_{\text{M}}|\right)}{|\vec{r}_{\text{S}} - \vec{r}_{\text{M}}|} - \frac{\exp\left(-\eta|\vec{r}_{\text{O}} - \vec{r}_{\text{M}}|\right)}{|\vec{r}_{\text{O}} - \vec{r}_{\text{M}}|}\right)$$

See [Schuller & Werner (17)]

Surface brightness fluctuation

For continuous mass distribution $\rho(\vec{r})$ and average over different sources and directions:

$$\overline{\frac{\delta I}{I}}\left(\vec{\theta}\right) = -3\delta \int_0^{\chi_H} \mathrm{d}\chi \, p\left(z(\chi)\right) \Theta\left(\chi_A - \chi\right) \frac{\mathrm{H}\left(\chi\right)}{c} D_+(a) \frac{\Phi_{\mathrm{Y}}(\chi\vec{\theta}, \chi)}{c^2}.$$

with

$$\delta \frac{\Phi_{\mathrm{Y}}(\vec{r_S})}{c^2} = -\frac{\delta G}{c^2} \int \mathrm{d}^3 r' \rho(\vec{r}') \left(\frac{\exp(-\eta|\vec{r_{\mathrm{S}}} - \vec{r}'|)}{|\vec{r_{\mathrm{S}}} - \vec{r}'|} \right)$$

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Linear limit: Comoving Poisson equation

$$\left(\Delta a^{-2} - \eta^2\right)\frac{\Phi_{\mathrm{Y}}(\chi\vec{\theta},\chi)}{c^2} = \frac{3\Omega_{m_0}}{2\chi_H^2}\delta_c(\chi\vec{\theta},\chi)a^{-3},$$

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In Fourier space the Yukawa field equation becomes

$$-\left(k^2a^{-2}+\eta^2\right)\frac{\tilde{\Phi}_\mathrm{Y}\left(k,\chi\right)}{c^2} = \frac{3\Omega_{m_0}}{2\chi_H^2}\tilde{\delta}_c\left(k,\chi\right)a^{-3}$$

with $k=\ell/\chi$

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In Fourier space the Yukawa field equation becomes

$$\Rightarrow \quad \frac{\tilde{\Phi}_\mathrm{Y}\left(k, \chi\right)}{c^2} = -\left(k^2 + \eta^2 a^2\right)^{-1} \frac{3\Omega_{m_0}}{2\chi_H^2} \tilde{\delta}_c\left(k, \chi\right) a^{-1}$$

with $k = \ell/\chi$

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For continuous mass distribution $\rho(\vec{r})$ and average over different sources and directions:

$$\frac{\overline{\delta I}}{I}\left(\vec{\theta}\right) = -3\delta \int_0^{\chi_H} \mathrm{d}\chi\, p\left(z(\chi)\right) \Theta\left(\chi_A - \chi\right) \frac{\mathrm{H}\left(\chi\right)}{c} D_+(a) \frac{\Phi_\mathrm{Y}(\chi\vec{\theta}, \chi)}{c^2}.$$

Then the line of sight averaged violation factor becomes

$$\begin{aligned}\frac{\widetilde{\overline{\delta I}}}{I}(\ell) =& 3 \int_0^{\chi_H} \mathrm{d}\chi p\left(z(\chi)\right) \Theta\left(\chi_A - \chi\right) \\ & \times \frac{\mathrm{H}\left(\chi\right)}{c} \frac{D_+(a)}{a} \delta\left(k^2 + \eta^2 a^2\right)^{-1} \frac{3\Omega_{m_0}}{2\chi_H^2} \tilde{\delta}_c(k, \chi)\end{aligned}$$

Surface brightness fluctuation spectra

With Limber approximation:

$$GG: \quad C_{AB}^{\delta\bar{I}/\bar{I}_Y\,\delta\bar{I}/\bar{I}_Y}(\ell) \propto 9\int_0^{\chi_H} \frac{\mathrm{d}\chi}{\chi^2} W_{Y,A}(\chi)\, W_{Y,B}(\chi) \times \delta^2 \frac{9\Omega_{m_0}^2}{4\chi_H^4}\left(k^2+\eta^2 a^2\right)^{-2} P_{\delta_c\delta_c}(k)$$

$$GI: \quad C_{AB}^{\delta\bar{I}/\bar{I}_Y\,\delta\bar{I}/\bar{I}}(\ell) \propto -\delta 3\ell^2 \int_0^{\chi_H} \frac{\mathrm{d}\chi}{\chi^2} D_{IA} W_{\varphi,A}(\chi) W_{Y,\mathrm{B}}(\chi) \times \frac{9\Omega_{m_0}^2}{4\chi_H^4} k^{-2}\left(k^2+\eta^2 a^2\right)^{-1} P_{\delta_c\delta_c}(k)$$

Weighting function $W_{Y,A}(\chi) = p(z(\chi))\,\Theta(\chi_A-\chi)\,\frac{\mathrm{H}(\chi)}{c}\frac{D_+(a)}{a}$,
$P_{\delta_c\delta_c}(k) \propto k^{n_s} T(k)^2$.

Numerical evaluation - Spectra

Choose values for δ, η via scale argument:

$$\delta \frac{\tilde{\Phi}_{Y}(k,\chi)}{c^2} = -\left(k^2 + \eta^2 a^2\right)^{-1} \frac{3}{2}\Omega_{m_0}\frac{\delta}{\chi_H^2}\tilde{\delta}_c(k,\chi)\, a^{-1}$$

with m multiples of the Hubble length:

$\eta = 1/(m\chi_H)$ and $\delta/\chi_H^2 = 1/(m^2\chi_H^2)$

Numerical evaluation - Spectra

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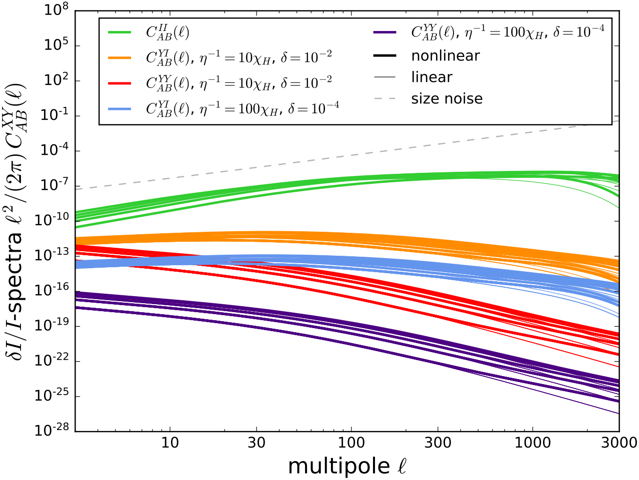
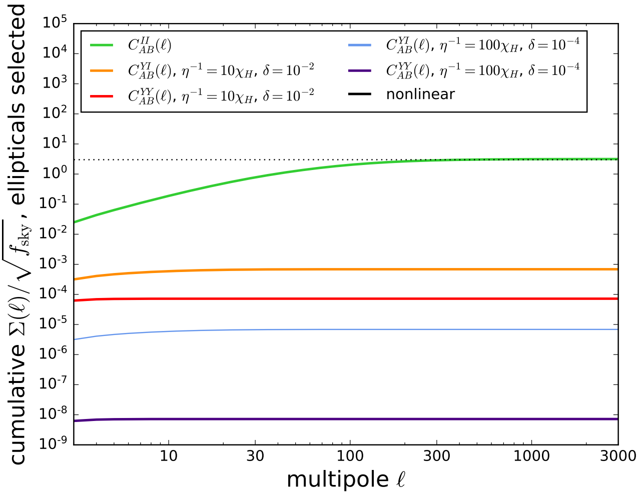


Numerical evaluation - cumulated S2N Σ^2

$(N_{\text{noise}})_{AB} = \sigma^2_{\text{size}} \frac{n_{\text{tomo}}}{\bar{n}} \delta_{AB}$ with $\sigma_{\text{size}} = 0.8$ and $\bar{n} = 3.545 \times 10^8 \text{sr}^{-1}$ (*Euclid*)

$$\Sigma^2 = \sum_\ell \frac{2\ell+1}{2} \text{tr}\left(\mathcal{C}^{-1} S\, \mathcal{C}^{-1} S\right)$$

$$\mathcal{C}_{AB}(\ell) = C_{AB}^{\delta\bar{I}/\bar{I}\,\delta\bar{I}/\bar{I}}(\ell) + C_{AB}^{\delta\bar{I}/\bar{I}_Y\,\delta\bar{I}/\bar{I}}(\ell) + C_{AB}^{\delta\bar{I}/\bar{I}_Y\,\delta\bar{I}/\bar{I}_Y}(\ell) + (N_{\text{noise}})_{AB}\,.$$



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Thank you very much for listening!

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Back-Up: Sérsic model for instrinsic alignment

With the proportionality $F \propto N_{\text{stars}}$ and the surface brightness $I(r) \propto \rho(r)$ and

$$\bar{I} = \frac{F}{A}$$

$\Rightarrow$ Surface brightness fluctuations

$$\frac{\delta\bar{\rho}}{\bar{\rho}} = \frac{-\delta A}{A'} = \frac{\delta\bar{I}}{\bar{I}} = \frac{1}{2\sigma^2}\frac{\int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\mathrm{d}r\; r\exp\left(-\Phi(r)/\sigma^2\right)\partial_a\partial_b\Phi r^a r^b}{\int_0^{2\pi}\mathrm{d}\phi\int_0^{\infty}\mathrm{d}r\; r\exp\left(-\Phi(r)/\sigma^2\right)}$$

Insert Sérsic model

$$\rho(r) \propto \exp\left(-\frac{\Phi(r)}{\sigma^2}\right) \hat{=} \exp\left(-b(n)\left[\left(\frac{r}{r_{\text{scale}}}\right)^{1/n} - 1\right]\right),$$

with $b(n) \approx 2n - \frac{1}{3}$ and n the Sérsic index
$\rightarrow$ Evaluate integrals in polar coordinates

Back-Up: Sérsic model for instrinsic alignment

$$\frac{\delta \bar{I}}{\bar{I}} = S_{\text{Sérsic}}(n) D_{IA} \frac{\Delta\Phi}{c^2}$$

Alignment parameter $D_{IA} = \frac{1}{2}\frac{c^2}{\sigma^2}\frac{1}{8} r_{\text{scale}}^2 b^{-2n} \frac{\Gamma(6n)}{\Gamma(4n)}$

$S_{\text{Sérsic}}(n) = 4\frac{\Gamma(4n)^2}{\Gamma(2n)\Gamma(6n)}$

With $\Delta \to -\ell^2/\chi^2$ and Limber approximation:

$$II: \quad C_{AB}^{\delta\bar{I}/\bar{I}\,\delta\bar{I}/\bar{I}}(\ell) = \ell^4 S_{\text{Sérsic}}(n)^2 D_{\text{IA}} \int_0^{\chi_H} \frac{\mathrm{d}\chi}{\chi^2} W_{\varphi,A} W_{\varphi,B} P_{\Phi\Phi}(k = \ell/\chi)$$

Weighting function

$$W_{\varphi,A}(\chi) = \frac{1}{\chi^2} p\left(z(\chi)\right) \Theta\left(\chi - \chi_A\right) \Theta\left(\chi_{A+1} - \chi\right) \frac{\mathrm{d}z}{\mathrm{d}\chi'} \frac{D_+(a)}{a}$$

$P_{\Phi\Phi}(k = \ell/\chi) \propto k^{n_S - 4} T(k)^2$

$p(z) \propto \left(\frac{z}{z_0}\right)^2 \exp\left[-\left(\frac{z}{z_0}\right)^\beta\right]$ with $\beta = 3/2$ and $z_0 = 0.64$ [Laureijs et. al. (11)]