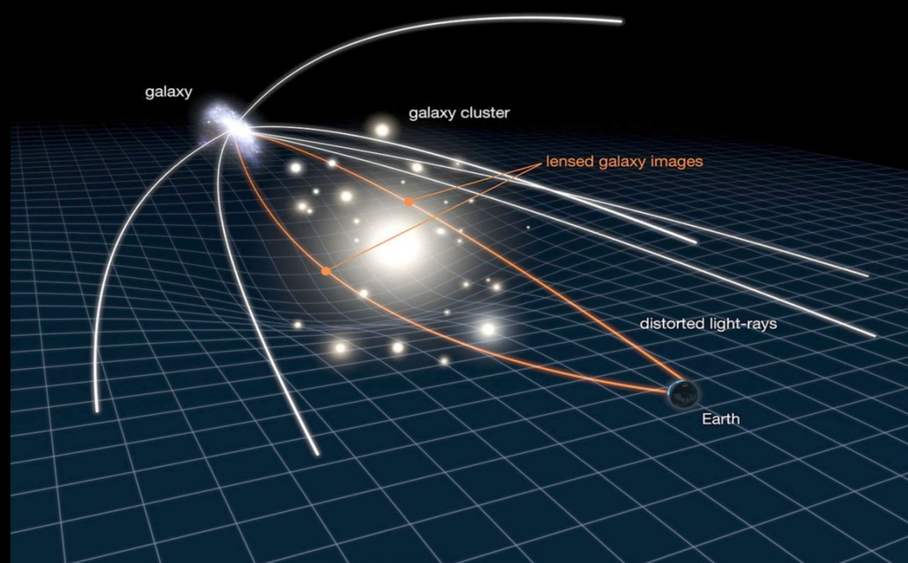
Weak Lensing & Modified Gravity:
A 'Plug-and-Play' Approach



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University of Oxford

Canadian Association of Physicists Congress 2014
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Image: NASA / ESA

Why Modify Gravity?

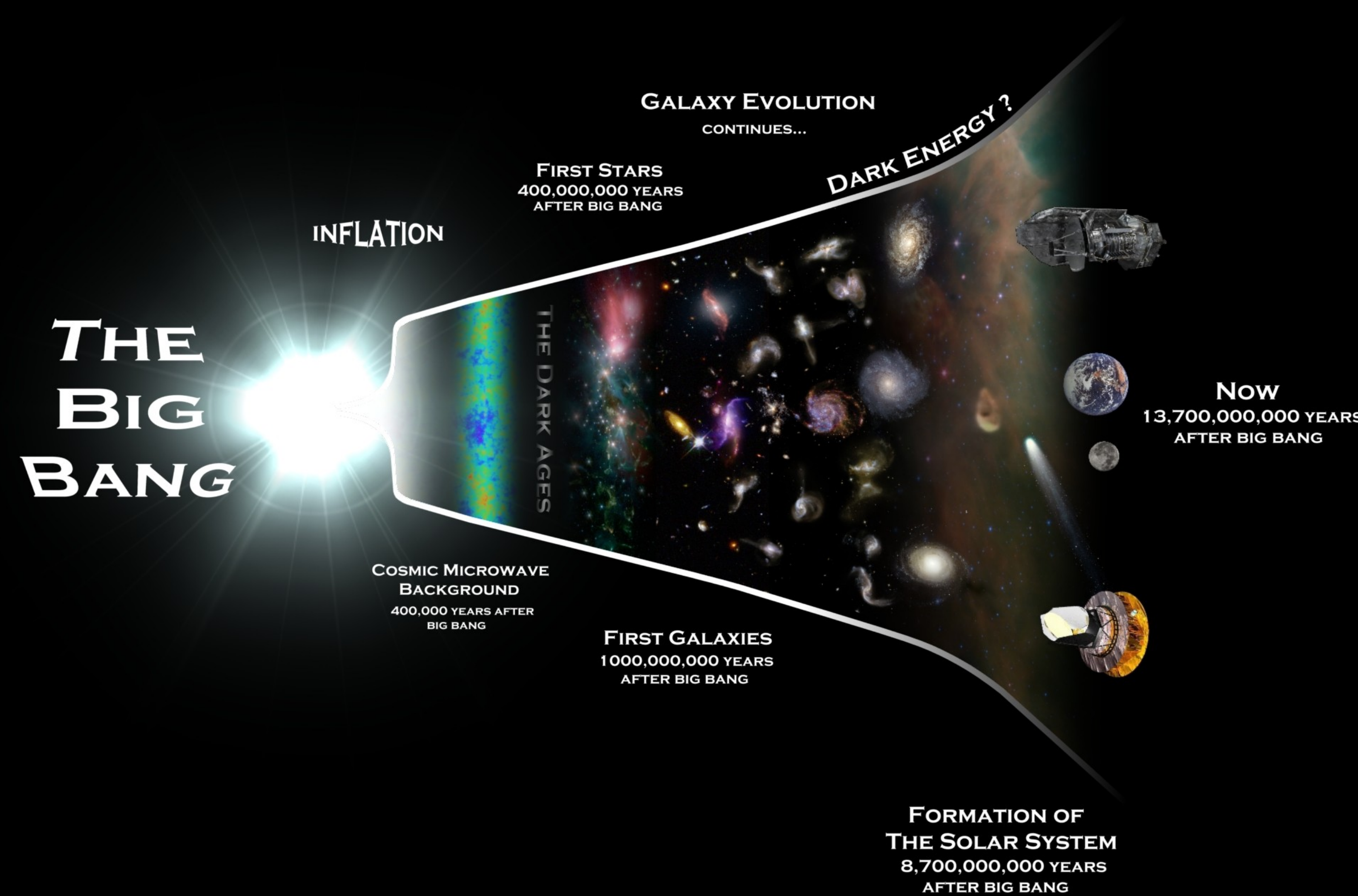

Image: Rhys Taylor, Cardiff University

Parametrizing Modified Gravity

$$ds^2 = a(\tau)\left(-(1+2\Psi)d\tau^2 + (1-2\Phi)(dx^2+dy^2+dz^2)\right)$$

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In modified gravity (quasistatic limit):

$$2\nabla^2\Phi = 8\pi G a^2 \mu(a,k) \bar{\rho}_M \Delta_M \qquad \frac{\Phi}{\Psi} = \gamma(a,k)$$

Gravitational Lensing

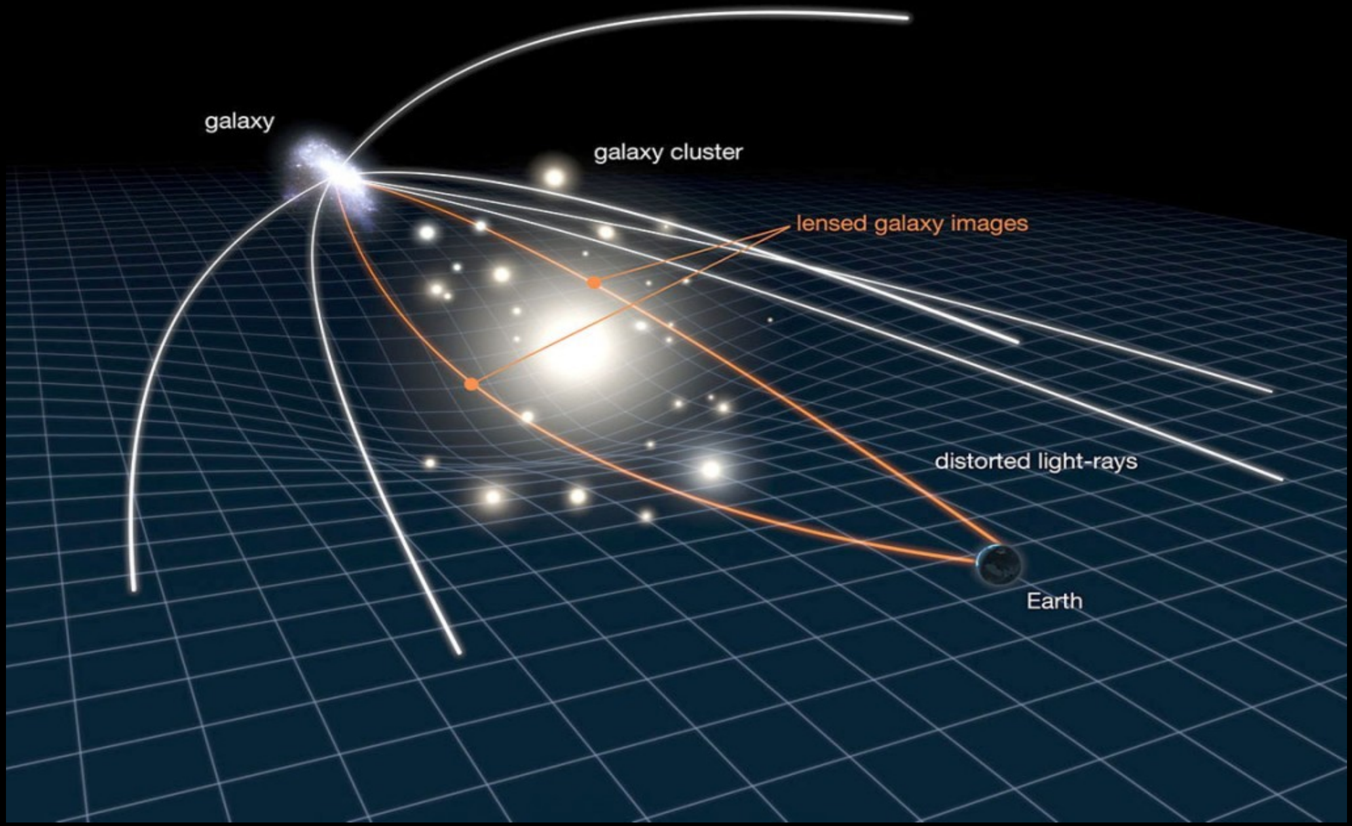
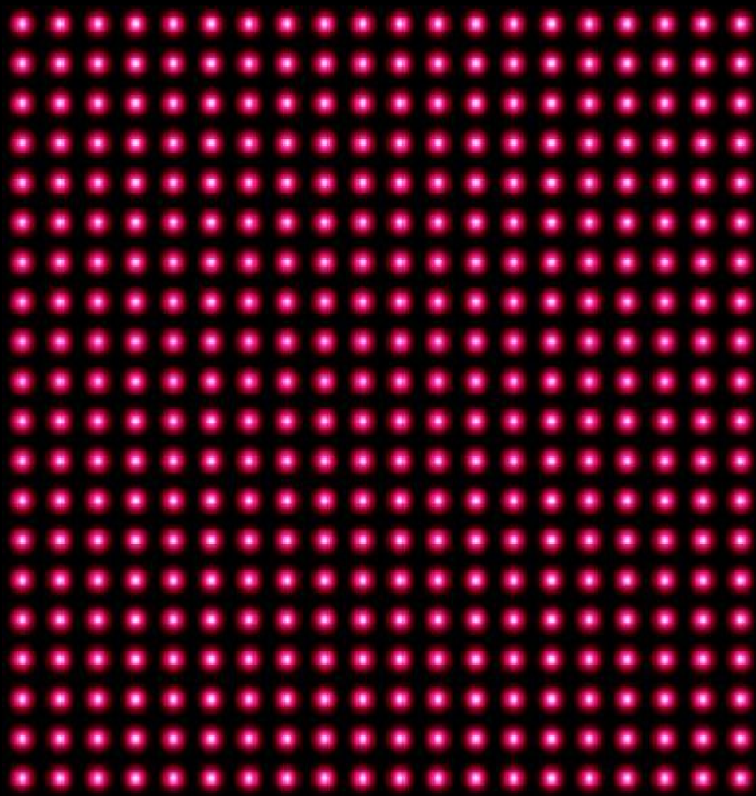


Image: NASA / ESA

Weak Gravitational Lensing: Shear and Convergence



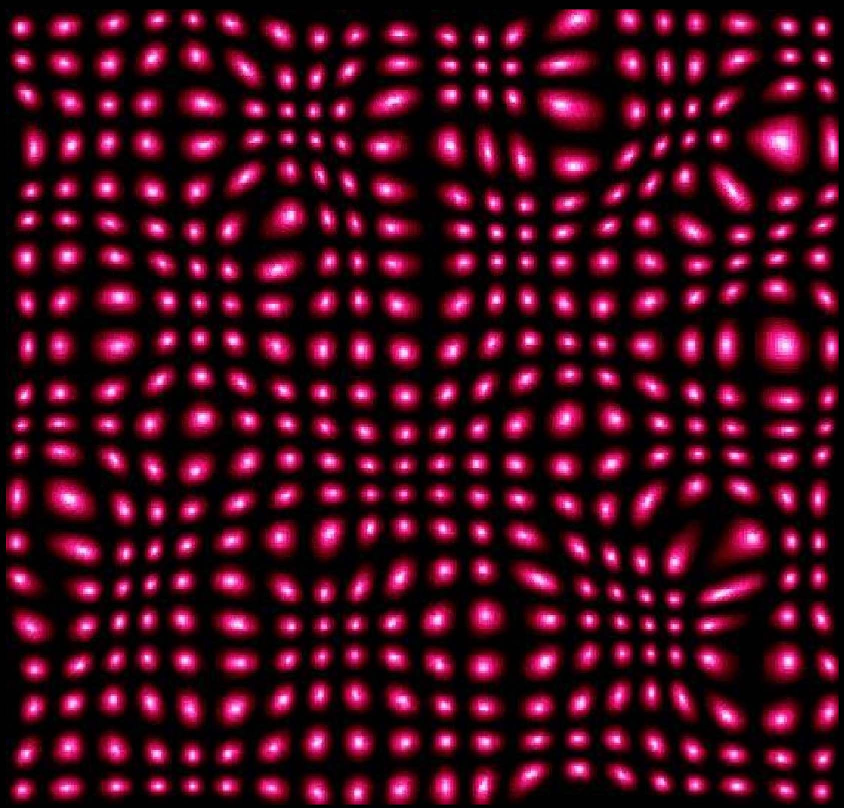


Image: iCosmo group (http://gravitationallensing.pbworks.com)

The Linear Response Approach

Baker, Ferreira, Skordis, 2014. 1310.1086

Recall:

$$2\nabla^2\Phi = 8\pi G a^2 \mu(a,k)\bar{\rho}_M \Delta_M \qquad \frac{\Phi}{\Psi} = \gamma(a,k)$$

The Linear Response Approach

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Recall:

$$2\nabla^2\Phi = 8\pi G a^2 \mu(a,k)\bar{\rho}_M \Delta_M \qquad \frac{\Phi}{\Psi} = \gamma(a,k)$$

Define:

$$\mu(a,k) = 1 + \delta\mu(a,k)$$
$$\gamma(a,k) = 1 + \delta\gamma(a,k)$$
$$w(a,k) = -1 + \beta(a,k)$$

Effects of modifying gravity

$$\delta\mu(a,k) \neq 0, \delta\gamma(a,k) \neq 0$$

- $\Psi \neq \Phi$
- Poisson Equation
- Evolution of overdensities

$$\beta(a,k) \neq 0$$

- Hubble parameter
- Conformal distances
- Evolution of overdensities

Convergence in Modified Gravity

$$P_\kappa(\ell) = \int_{-\infty}^{0} d\mathrm{x}\,\frac{9}{16}\frac{g(\mathrm{x})^2}{\chi_{\mathrm{GR}}(\mathrm{x})^2} P_M^{\mathrm{GR}}(k)\, D_{\mathrm{GR}}^2(\mathrm{x})\mathcal{H}_{\mathrm{GR}}^3(\mathrm{x})\Omega_M^{\mathrm{GR}}(\mathrm{x})^2$$

$$\times\left[1+\frac{3}{2}\left(\int_0^{\mathrm{X}} d\bar{\mathrm{x}}\beta(\bar{\mathrm{x}})\right)\left[1-\Omega_M^{GR}(\mathrm{x})\right]+2\delta\mu(\mathrm{x})-\delta\gamma(\mathrm{x})+2\delta_\Delta(\mathrm{x})\right.$$

$$\left.+\left(2\frac{\partial\ln G(\chi(\mathrm{x}))}{\partial\ln\chi(\mathrm{x})}-\frac{\partial\ln(P_M^0(k)/k^4)}{\partial\ln k}\right)\Bigg|_{\chi_{\mathrm{GR}}(\mathrm{X})}\frac{\delta\chi(\mathrm{x})}{\chi_{\mathrm{GR}}(\mathrm{X})}\right]_{k=\frac{\ell}{\chi(\mathrm{x})}}$$

$$\mathrm{x} = \ln(a)$$

Convergence in Modified Gravity

$$P_\kappa(\ell) = \int_{-\infty}^{0} d\mathrm{x}\, \frac{9}{16} \frac{g(\mathrm{x})^2}{\chi_{\mathrm{GR}}(\mathrm{x})^2} P_M^{\mathrm{GR}}(k)\, D_{\mathrm{GR}}^2(\mathrm{x}) \mathcal{H}_{\mathrm{GR}}^3(\mathrm{x}) \Omega_M^{\mathrm{GR}}(\mathrm{x})^2$$

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$$\left. + \left(2\frac{\partial \ln G(\chi(\mathrm{x}))}{\partial \ln \chi(\mathrm{x})} - \frac{\partial \ln(P_M^0(k)/k^4)}{\partial \ln k}\right)\Bigg|_{\chi_{\mathrm{GR}}(\mathrm{X})} \frac{\delta\chi(\mathrm{x})}{\chi_{\mathrm{GR}}(\mathrm{x})}\right]_{k = \frac{\ell}{\chi(\mathrm{x})}}$$

$F_{\mathrm{GR}}(\mathrm{X}, \ell)$: Kernel Term (GR only)

Convergence in Modified Gravity

$$P_\kappa(\ell) = \int_{-\infty}^{0} d\mathrm{x}\, \frac{9}{16} \frac{g(\mathrm{x})^2}{\chi_{\mathrm{GR}}(\mathrm{x})^2} P_M^{\mathrm{GR}}(k)\, D_{\mathrm{GR}}^2(\mathrm{x}) \mathcal{H}_{\mathrm{GR}}^3(\mathrm{x}) \Omega_M^{\mathrm{GR}}(\mathrm{x})^2$$

$$\times \left[1 + \frac{3}{2} \left(\int_0^{\mathrm{X}} d\bar{\mathrm{x}} \beta(\bar{\mathrm{x}}) \right) [1 - \Omega_M^{GR}(\mathrm{x})] + 2\delta\mu(\mathrm{x}) - \delta\gamma(\mathrm{x}) + 2\delta_\Delta(\mathrm{x}) \right.$$

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$\delta S(\mathrm{x}, \ell)$: Source Term
(Linear Deviations from GR)

Weak Lensing and the Growth Rate

(Scale Independent & $\beta(\mathrm{x}) = 0$)

For Weak Lensing:

$$\delta S(\mathrm{x}) = 1 + 2\delta\mu(\mathrm{x}) - \delta\gamma(\mathrm{x})$$

$$+3\int_0^{\mathrm{X}} (\delta\mu(\mathrm{x}') - \delta\gamma(\mathrm{x}'))I(\mathrm{x},\mathrm{x}')\Omega_M^{GR}(\mathrm{x}')d\mathrm{x}'$$

For the Linear Growth Rate of Structure:

$$\delta S(\mathrm{x}) = 1 + \delta\mu(\mathrm{x}) - \delta\gamma(\mathrm{x})$$

Baker, Ferreira, Skordis, 2014. 1310.1086

Weak Lensing and the Growth Rate

(Scale Independent & $\beta(\mathrm{x}) = 0$)

For Weak Lensing:

$$\delta S(\mathrm{x}) = 1 + 2\delta\mu(\mathrm{x}) - \delta\gamma(\mathrm{x}) + 3\int_0^{\mathrm{X}} (\delta\mu(\mathrm{x}') - \delta\gamma(\mathrm{x}'))I(\mathrm{x}, \mathrm{x}')\Omega_M^{GR}(\mathrm{x}')d\mathrm{x}'$$

→ $2\Sigma(\mathrm{x})$

(Typically assumed constrained by WL)

For the Linear Growth Rate of Structure:

$$\delta S(\mathrm{x}) = 1 + \delta\mu(\mathrm{x}) - \delta\gamma(\mathrm{x})$$

→ $\tilde{\mu}(\mathrm{x})$

(Constrained by growth rate)

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Weak Lensing and the Growth Rate

(Scale Independent & $\beta(\mathrm{x}) = 0$)

For Weak Lensing:

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For the Linear Growth Rate of Structure:

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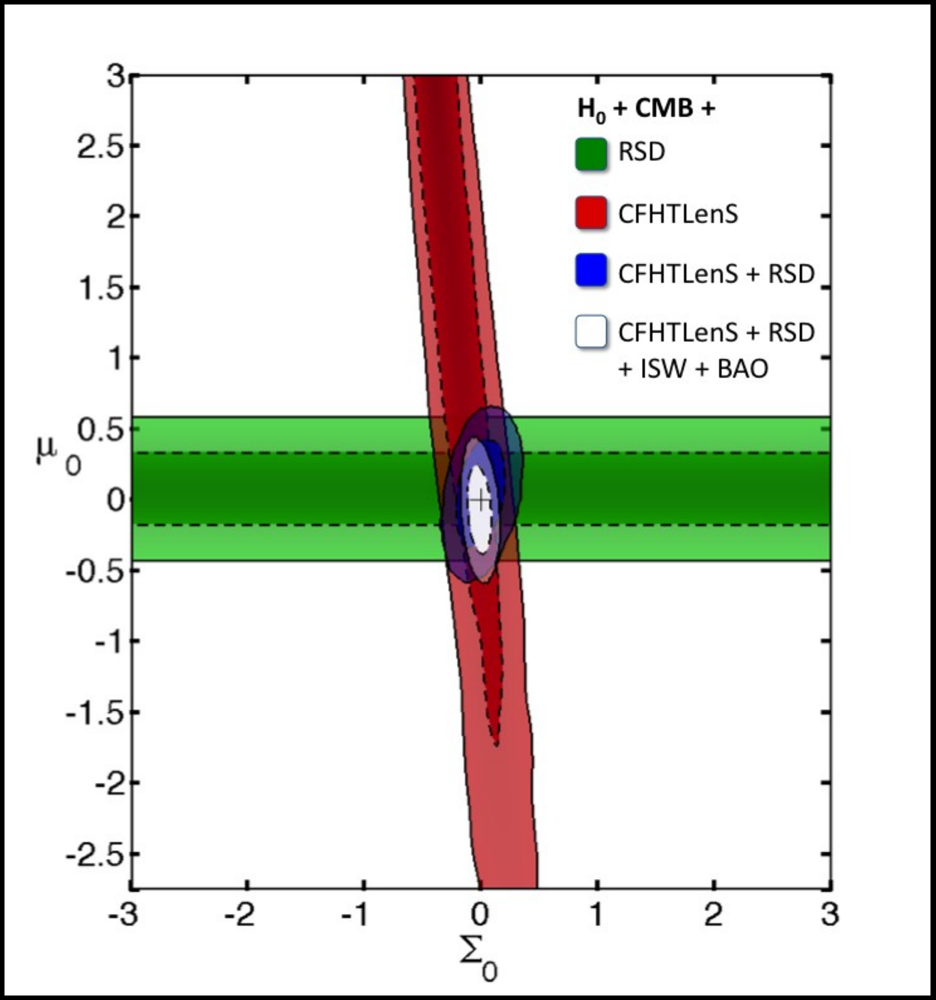
What is the effect of this term?

Current Constraints



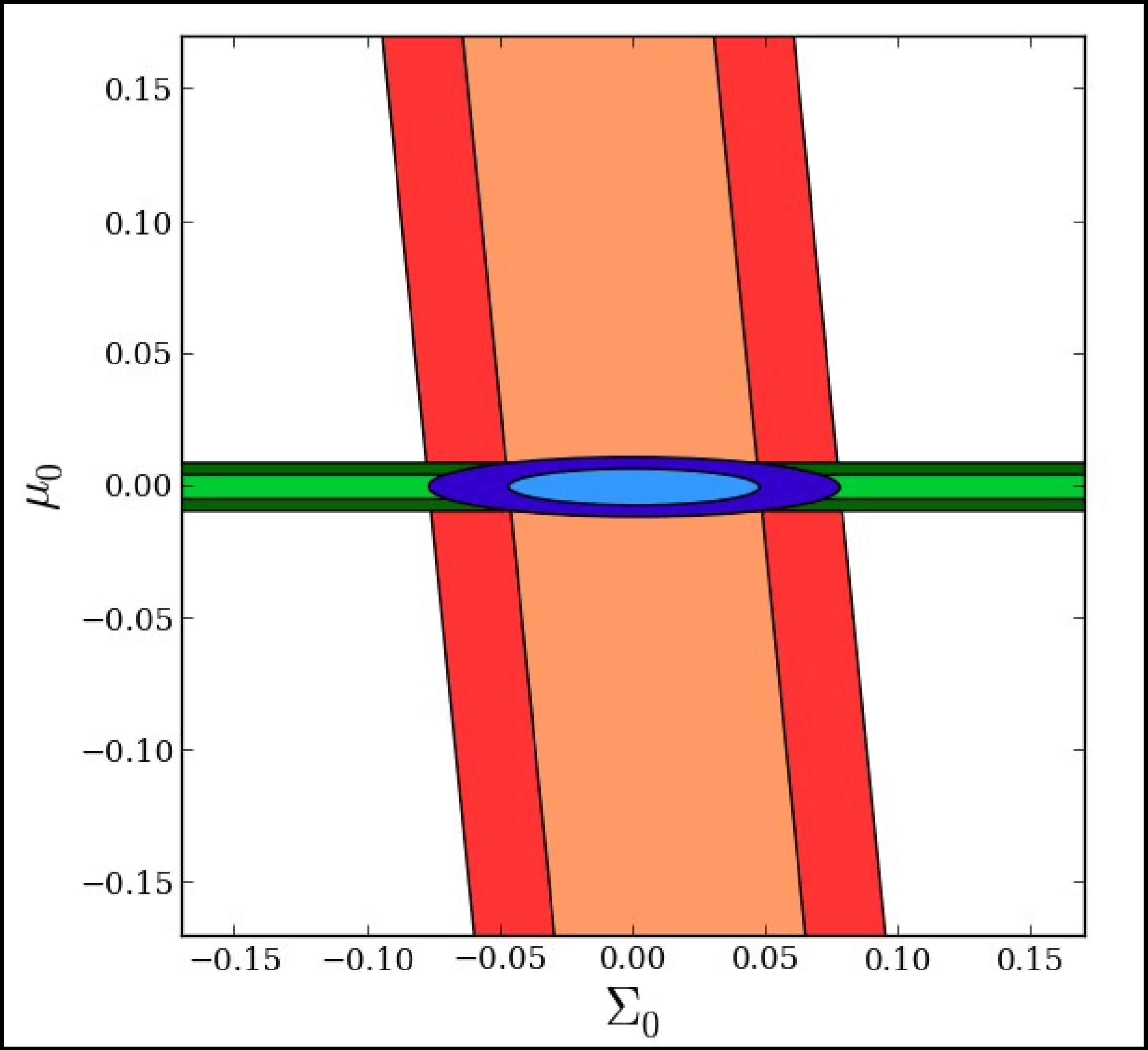
$$\tilde{\mu}(x) = \mu_0 \frac{\Omega_\Lambda(x)}{\Omega_\Lambda(x=0)}$$

$$\Sigma(x) = \Sigma_0 \frac{\Omega_\Lambda(x)}{\Omega_\Lambda(x=0)}$$

Image: CFHTLenS: Simpson et. al. 2012, 1212.3339

Forecast Constraints

From a Dark Energy Task Force 4 Type Survey
(Preliminary)



$$\tilde{\mu}(\mathrm{x}) = \mu_0 \frac{\Omega_\Lambda(\mathrm{x})}{\Omega_\Lambda(\mathrm{x}=0)}$$

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Forecast Constraints

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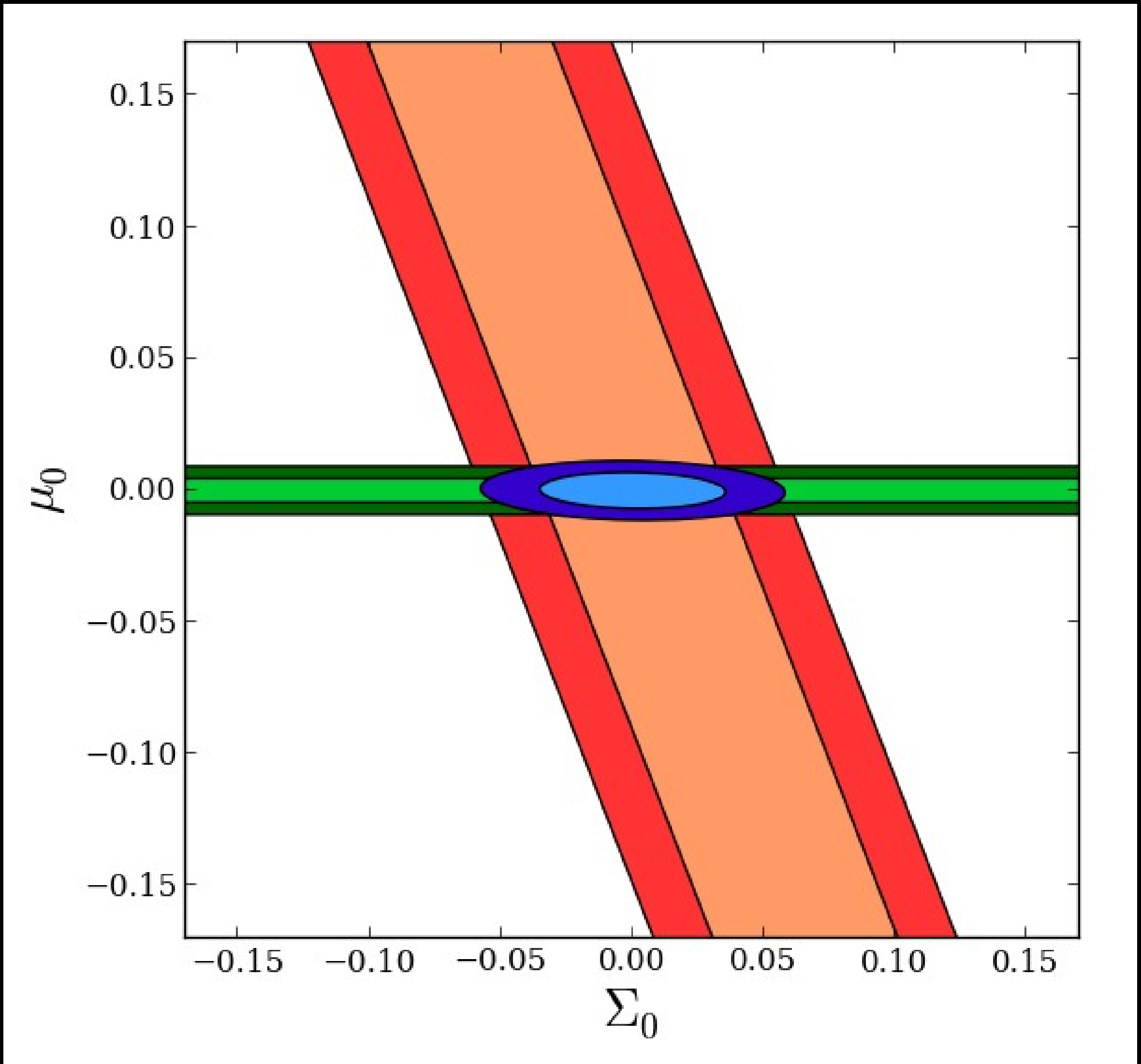

$$\tilde{\mu}(x) = \mu_0$$

$$\Sigma(x) = \Sigma_0$$

Summary

- We find an instructive expression for $P_\kappa(l)$ using the Linear Response Approach.
- We use it to understand parameter degeneracies between weak lensing and the growth rate in modified gravity.
- We make constraint forecasts for next-generation surveys.

Current & Future Work

- Consider the case where $\beta(\mathrm{x}) \neq 0$
- Consider constraints on specific modified gravity theories.

Acknowledgements

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Thank you for listening.