# (Future) weak lensing constraints on chameleon modified gravity

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# Overview

- Introduction: Modified gravity
- Theoretical and Observational signatures;
  - Expansion history
  - Growth history
- Observational constraints;
  - Solar system
  - Weak lensing
    - Nonlinear regime: Perturbation theory
    - Nonlinear regime: Simulations
- Conclusions

# Introduction

$$S_{EH} = \int_M \sqrt{-g}\, d^4x \left[ \frac{R}{16\pi G} - L_m \right]$$

Cosmic acceleration

→ Dark energy

$$S_{EH} = \int_M \sqrt{-g}\, d^4x \left[ \frac{R}{16\pi G} - L_m - L_{de} \right]$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G \left( T_{\mu\nu} + T^{de}_{\mu\nu} \right)$$

$$3H^2 + \frac{k}{a^2} = 8\pi G \left( \rho_m + \rho_r + \rho_{de} \right)$$

Examples:
Cosmological constant
Quintessence
Chaplygin gas

# Introduction

$$S_{EH}=\int_M \sqrt{-g}\,\mathrm{d}^4x\left[\frac{\mathrm{R}}{16\pi\mathrm{G}}-\mathrm{L}_\mathrm{m}\right]$$

Cosmic acceleration

## Modified gravity

$$S_{MG}=\int_M \sqrt{-g}\,\mathrm{d}^4x\left[\frac{\mathrm{R}}{16\pi\mathrm{G}}+F\left(R,\phi,C^2,\ldots\right)-\mathrm{L}_\mathrm{m}\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R+M_{\mu\nu}\left[g,\partial g,\partial\partial g,\phi,..\right]=8\pi G T_{\mu\nu}$$

$$3H^2+\frac{k}{a^2}+B\left(H,\dot{\phi}\right)=8\pi G\left(\rho_m+\rho_r\right)$$

Examples:
Higher dimensional models
Weyl gravity
Scalar-tensor gravity

## Dark energy

$$S_{EH}=\int_M \sqrt{-g}\,\mathrm{d}^4x\left[\frac{\mathrm{R}}{16\pi\mathrm{G}}-\mathrm{L}_\mathrm{m}-\mathrm{L}_{de}\right]$$

$$R_{\mu\nu}-\frac{1}{2}g_{\mu\nu}R=8\pi G\left(T_{\mu\nu}+T^{de}_{\mu\nu}\right)$$

$$3H^2+\frac{k}{a^2}=8\pi G\left(\rho_m+\rho_r+\rho_{de}\right)$$

Examples:
Cosmological constant
Quintessence
Chaplygin gas

# Modified gravity

- Could the late time acceleration be attributed to additional gravitational degrees of freedom?
- Rather than the Einstein Hilbert action

$$S_{EH} = \int_{\mathrm{M}} \sqrt{-g}\,\mathrm{d}^4\mathrm{x}\left[\frac{R}{16\pi \mathrm{G}} - L_{\mathrm{m}}\right]$$

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = 8\pi G T_{\mu\nu}$$

- One could consider a generalized action of the form

$$S = \int \sqrt{-g}\, d^4x \left[\frac{R + f(R)}{16\pi G} - L_{\mathrm{m}}\right]$$

- Purely phenomenological; can different (toy) gravitational models fit the data?

# f(R) models

- f(R) gravity

$$S = \int \sqrt{-g}\, d^4x \left[ \frac{R + f(R)}{16\pi G} - L_{\mathrm{m}} \right]$$

- Field equations

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R + R_{\mu\nu} f_R - \frac{1}{2} g_{\mu\nu} f + [g_{\mu\nu}\Box - \nabla_\mu \nabla_\nu] f_R = 8\pi G T_{\mu\nu}$$

$$f_R = \frac{df}{dR}$$

General Relativity

- The equations now contain fourth order derivatives of the metric
- Can the additional terms drive late time acceleration?
  - There is a new, scalar degree of freedom that propagates

# Chameleon mechanism

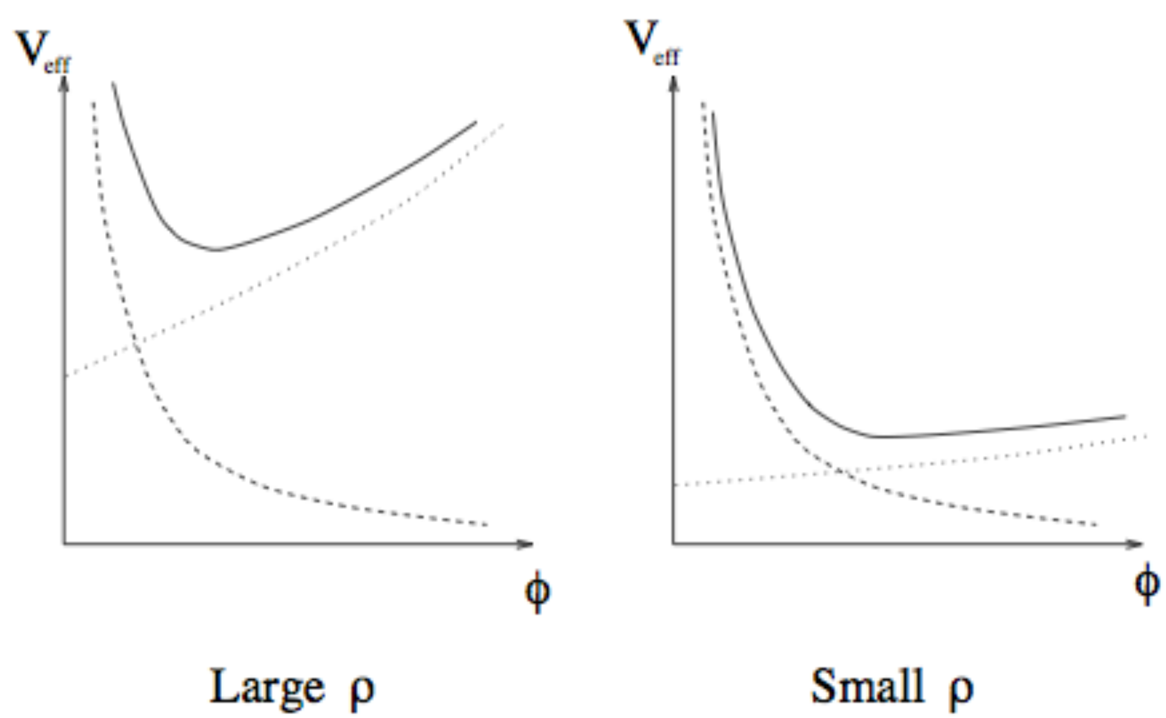
- Chameleon mechanism; the scalar field has a mass that depends on the 'background' energy density:

$$\Box\phi = \frac{dV}{d\phi} + \beta e^{\beta\phi}\rho_m \qquad V_{eff}(\phi) = V(\phi) + e^{\beta\phi}\rho_m$$

- In regions of high density, the 'effective' scalar field potential is very large and the field does not propagate.

- In regions of low density, the potential relaxes.

- The (only important) question; can the scalar field roll on cosmological scales?




- Khoury (2004)

# Modified gravity: Cosmology

- By taking an FRW metric ansatz, we can write down the modified Friedmann and acceleration equations

$$ds^2 = -dt^2 + a^2(t)\left[dr^2 + r^2(d\theta^2 + \sin^2\theta \, d\phi^2)\right]$$

$$3H^2 = 8\pi G(\rho_c + \rho_r) + 3(H^2 + \dot{H}) f_R - \frac{f}{2} - 3H\dot{f}_R$$

$$-2\dot{H} - 3H^2 = 8\pi G P_r + \ddot{f}_R + 2H\dot{f}_R + \frac{f}{2} - (\dot{H} + 3H^2) f_R$$

$$\dot{\rho}_c + 3H\rho_c = 0$$

$$\dot{\rho}_r + 4H\rho_r = 0$$

General Relativity

- We have the freedom to specify the f(R) function; we can reproduce any expansion history...

- Introduce an effective density

$$8\pi G\rho_f = 3(\dot{H} + H^2)\frac{\dot{f}}{\dot{R}} - \frac{f}{2} - 3aH^2\left(\frac{\dot{f}}{\dot{R}}\right)^{\cdot}$$

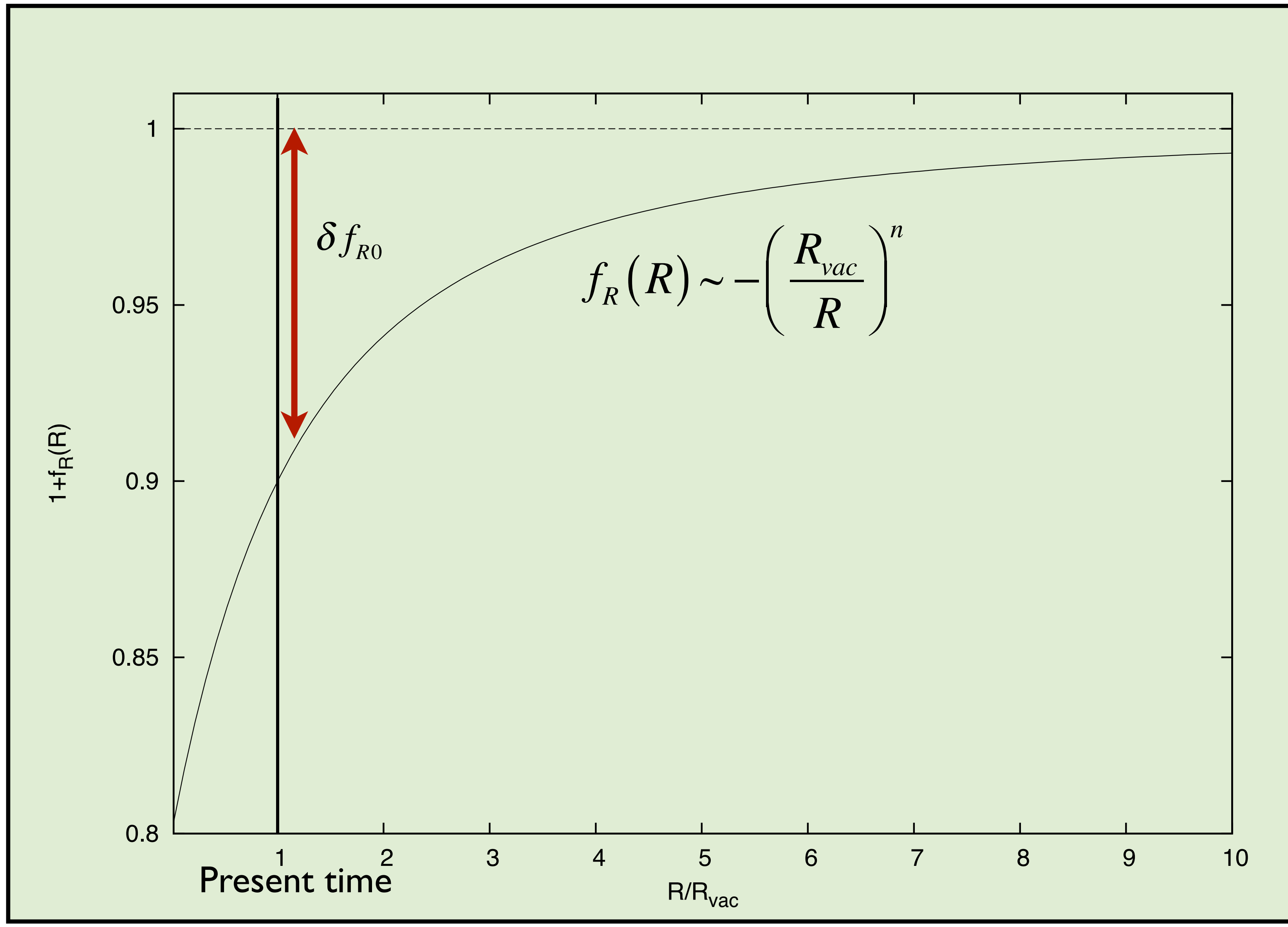
# Modified gravity: Constraints

- However, f(R) models are subject to stringent theoretical and observational constraints, which restricts the allowed expansion histories
- Theoretical constraints
  - No ghost $1 + f_R > 0$
  - No early time instability $f_{RR} > 0$
    - Dolgov Kawasaki (2004)
  - No cosmological constant $f(R = 0) = 0$
  - Return to GR at early times $R f_{RR} \to 0$ $R \to \infty$

# Modified gravity: Theoretical constraints

$$1+f_R$$

- The only viable functions are monotonic and asymptote to GR to the past.




- We can describe such a function with two 'modified gravity' parameters.

# f(R) models

- Simple parameterizations of the f(R) curve are considered

$$f(R) = -\frac{R_{vac}}{2}\frac{\lambda\left(R/R_{vac}\right)^n}{1+\lambda\left(R/R_{vac}\right)^n} \qquad \lambda > 1 \qquad n > 0$$

- Hu et al (2007)
- Starobinsky (2007)

- At large curvatures, $f(R) \simeq -\frac{R_{vac}}{2}\left(1-\lambda^{-1}\left(\frac{R_{vac}}{R}\right)^n\right)$

- At early times, viable models behave as the standard $\Lambda CDM$ model

- However, there is no true cosmological constant! Minkowski space is a vacuum solution to the field equations.

# f(R) models

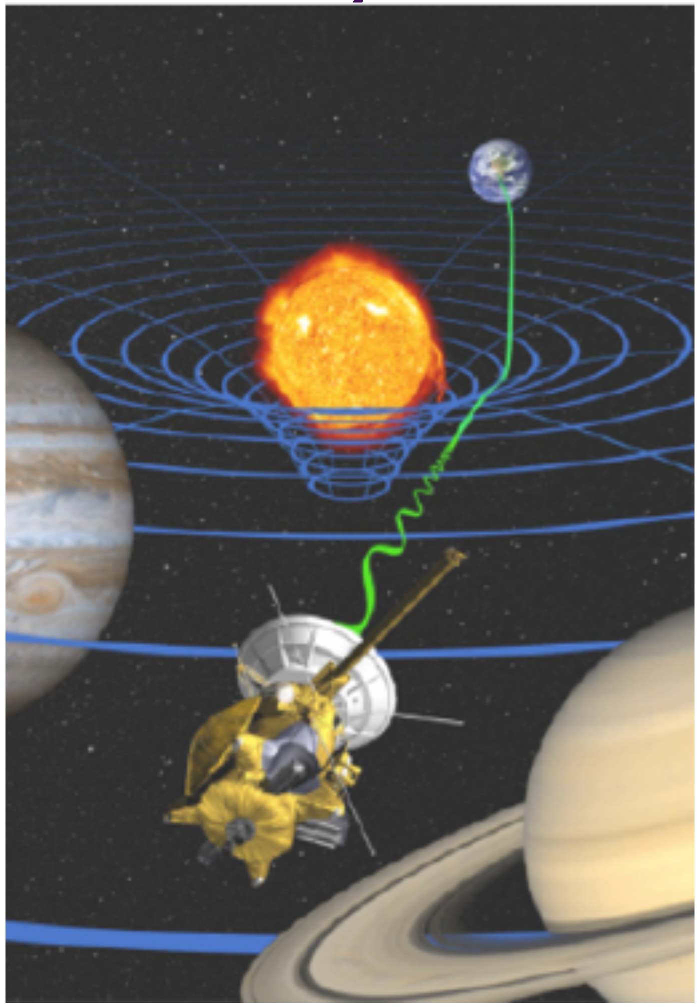
- Constraints on f(R) models;
  - Local, solar system tests of gravity
  - Cosmological signatures
    - Luminosity distance-redshift relation
    - CMB
    - Matter power spectrum

# Modified gravity: Observational constraints

- Gravity is well described by General Relativity in the solar system

$$g_{00} = -1 + 2U$$
$$g_{ij} = \left(1 + 2U + (\gamma - 1)U\right)\delta_{ij}$$

- Shapiro time delay measured by the Cassini probe



$$|\gamma - 1| < 2.3 \times 10^{-5}$$ B. Bertotti, L. Iess, P. Tortora (2003)

Effect due to modified gravity

- (Hu et al, 2007)

$$ds^2 = -\left[1 - 2A(r) + 2B(r)\right]dt^2 + \left[1 + 2A(r)\right]\left(dr^2 + r^2 d\Omega\right)$$

# Modified gravity: Observational constraints

$$\nabla^2 A \simeq -4\pi G\rho_m + \frac{1}{6}\left(8\pi G\rho_m - R\right)$$

$$\nabla^2 B \simeq \frac{1}{3}\left(8\pi G\rho_m - R\right)$$

$$\nabla^2 f_R \simeq -\frac{1}{3}\left(8\pi G\rho_m - R\right)$$

- Solving these equations corresponds to the following constraint: (Hu et al, 2007)

$$|\gamma - 1| < 2.3\times 10^{-5}$$

$$f_{\mathrm{R}}(R_{\mathrm{sol}}) \sim (\gamma - 1)\frac{GM_{\mathrm{s}}}{r_{\mathrm{s}}}$$

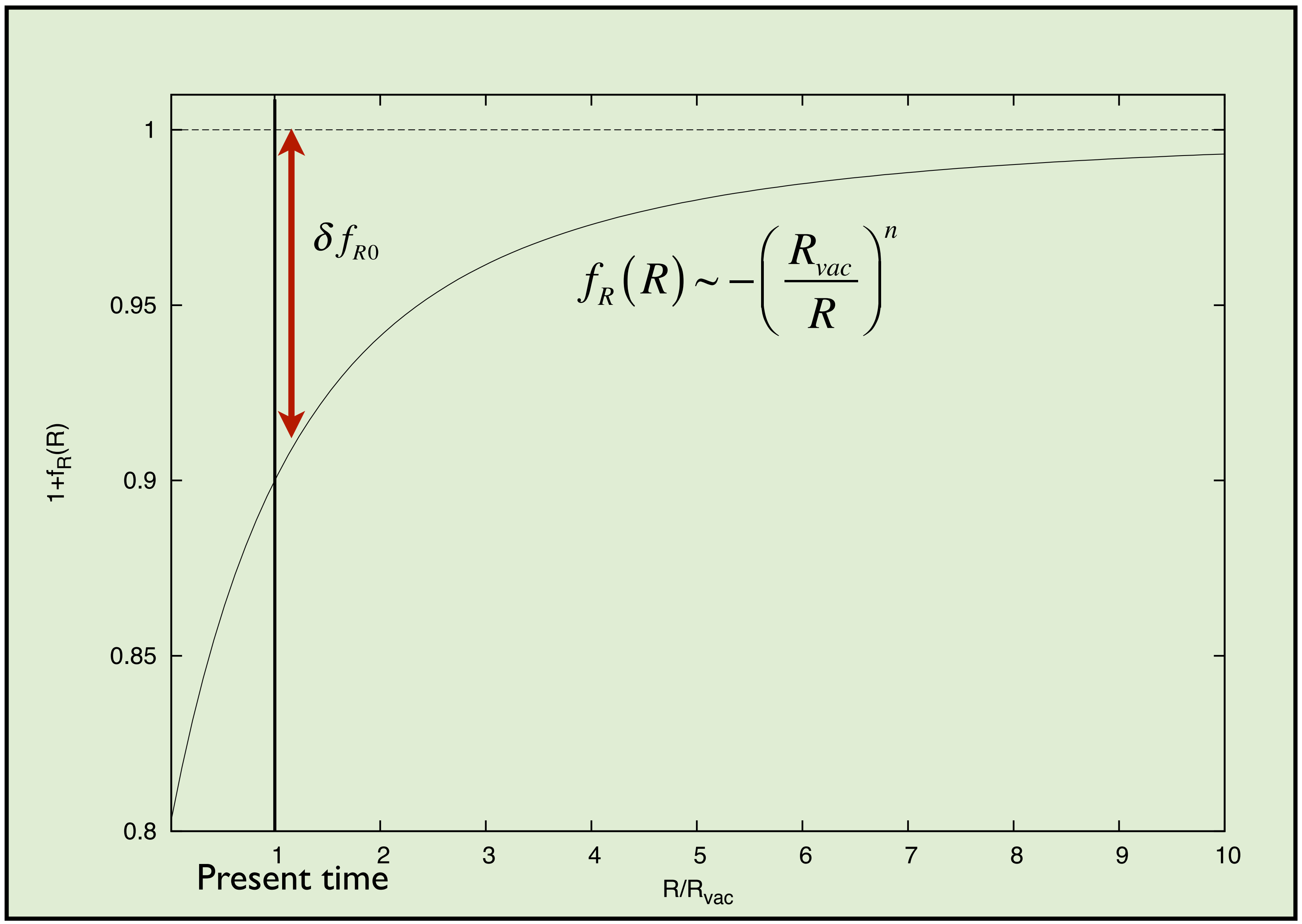
$$\frac{GM_{\mathrm{s}}}{r_{\mathrm{s}}} = 2.12\times 10^{-6}$$

$$R_{sol} \sim 8\pi G\rho_{sol}$$

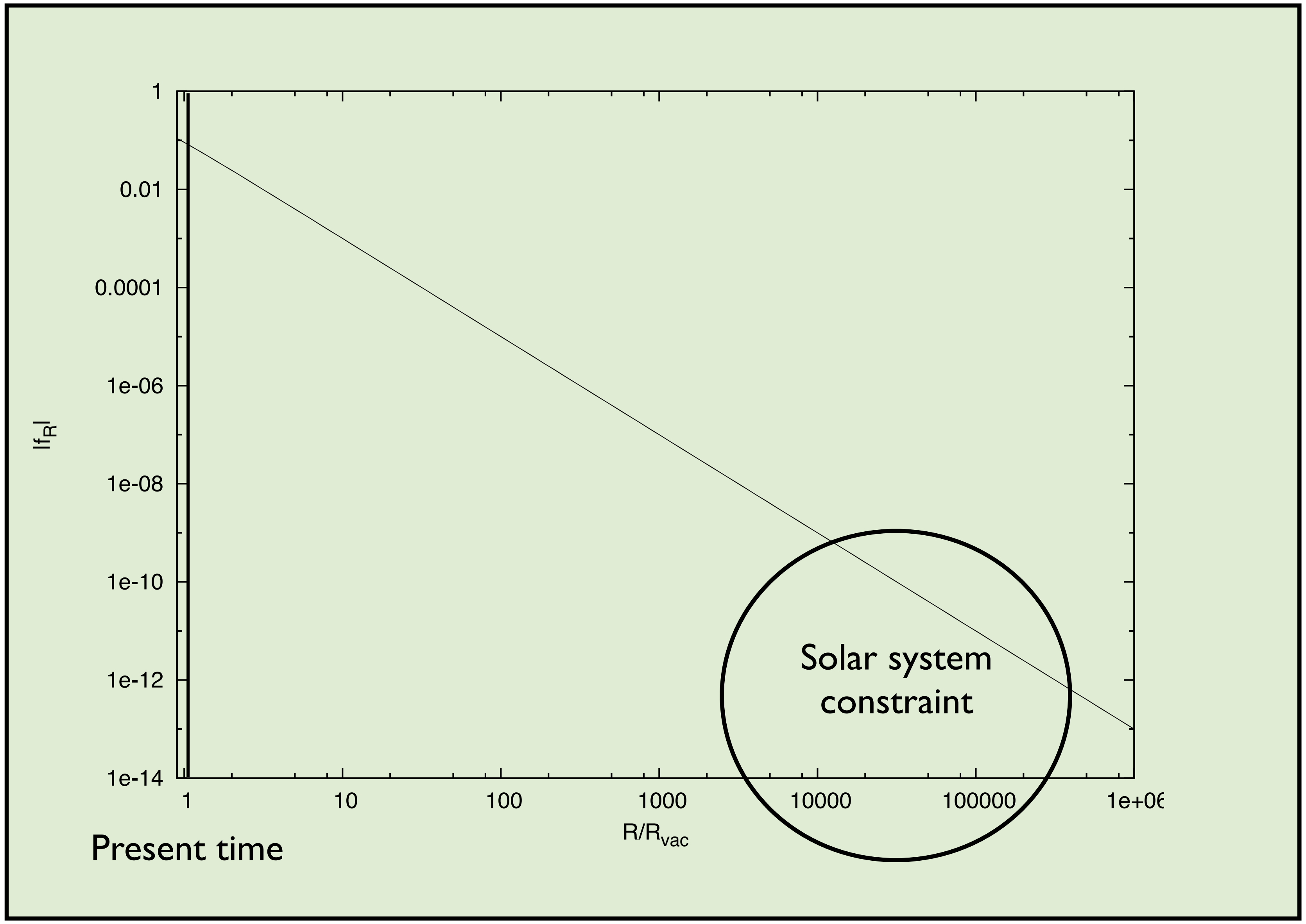
$$\rho_{sol} \sim 10^{-24}\, gcm^{-3} \qquad \rho_{crit} \sim 10^{-29}\, gcm^{-3}$$

$$|f_{\mathrm{R}}(R_{sol})| \sim \frac{R_{sol}}{M_{scal}^2} < 4.9\times 10^{-11}$$

# Modified gravity: Theoretical constraints



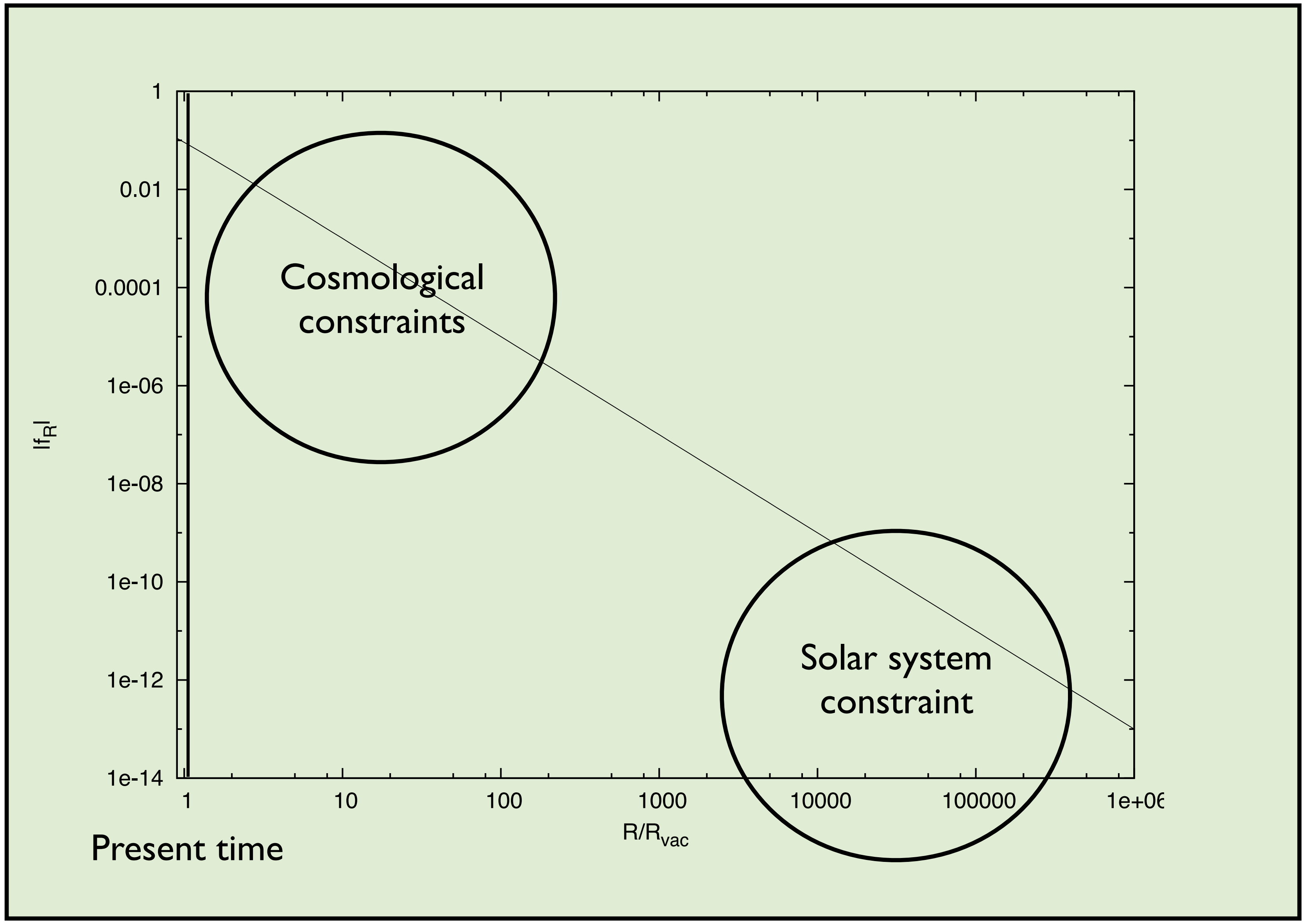
# Modified gravity: Observational constraints




$$\left|f_R(R)\right| \sim \left(\frac{R_{vac}}{R}\right)^n$$

$$n = 2$$

# Modified gravity: Observational constraints




$$|f_R(R)| \sim \left(\frac{R_{vac}}{R}\right)^n$$

$$n = 2$$

# f(R) models

- Constraints on f(R) models;
  - Local, solar system tests of gravity
  - Cosmological signatures
    - Luminosity distance-redshift relation
    - CMB
    - Matter power spectrum

# Observational signatures: Expansion history

- Background cosmology of f(R) models;

$$ds^2 = -dt^2 + a^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\theta^2 + \sin^2\theta d\phi^2)\right]$$

$$3H^2 = 8\pi G(\rho_c + \rho_r) + 3(H^2 + \dot{H})f_R - \frac{f}{2} - 3H\dot{f}_R$$

$$-2\dot{H} - 3H^2 = 8\pi G P_r + \ddot{f}_R + 2H\dot{f}_R + \frac{f}{2} - (\dot{H} + 3H^2)f_R$$

$$\dot{\rho}_c + 3H\rho_c = 0$$

$$\dot{\rho}_r + 4H\rho_r = 0$$

General Relativity

- Fourth order field equations. To simplify, we only consider the parameter range for which the 'quasi-static approximation' holds

$$f_{RR}(R_{GR}) \ll H_{GR}^2$$

$$f(R) = -\frac{R_{vac}}{2}\frac{\lambda(R/R_{vac})^n}{1+\lambda(R/R_{vac})^n}$$

# Observational signatures: Expansion history

- Background equations in the quasi-static approximation

$$3H^2 = 8\pi G(\rho_c + \rho_r + \rho_\Lambda) + \varpi_0 f_{RR} H^4$$

Model dependent constant of order unity

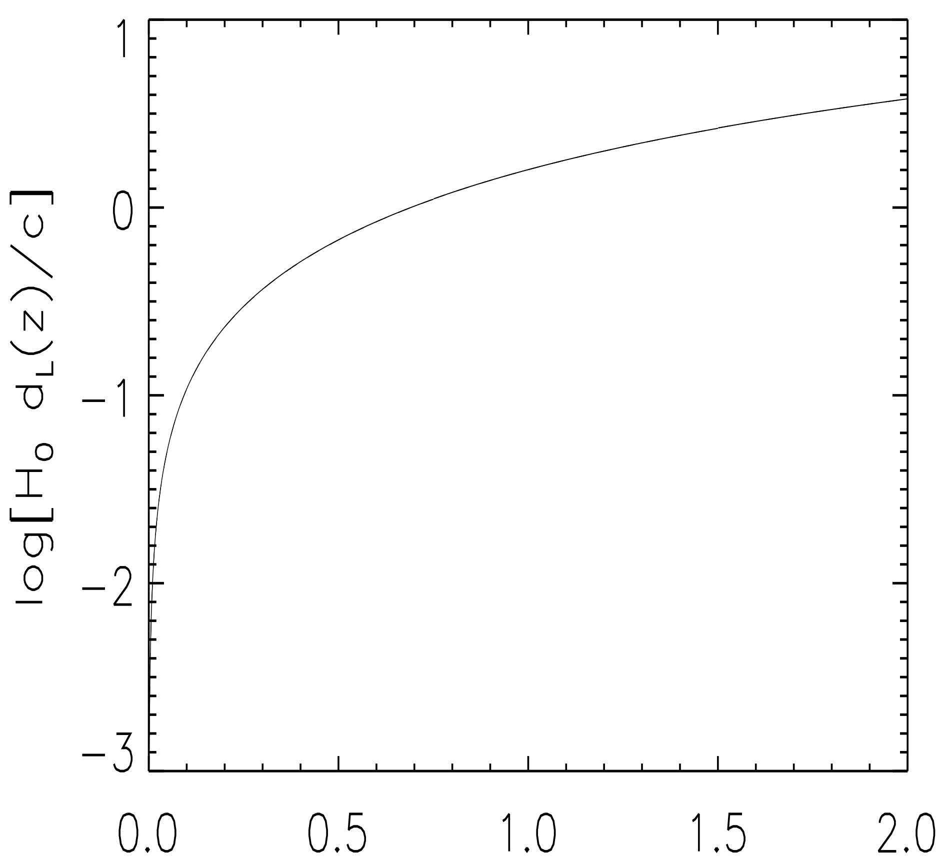
$$\dot{\rho}_r + 4H\rho_r = 0$$

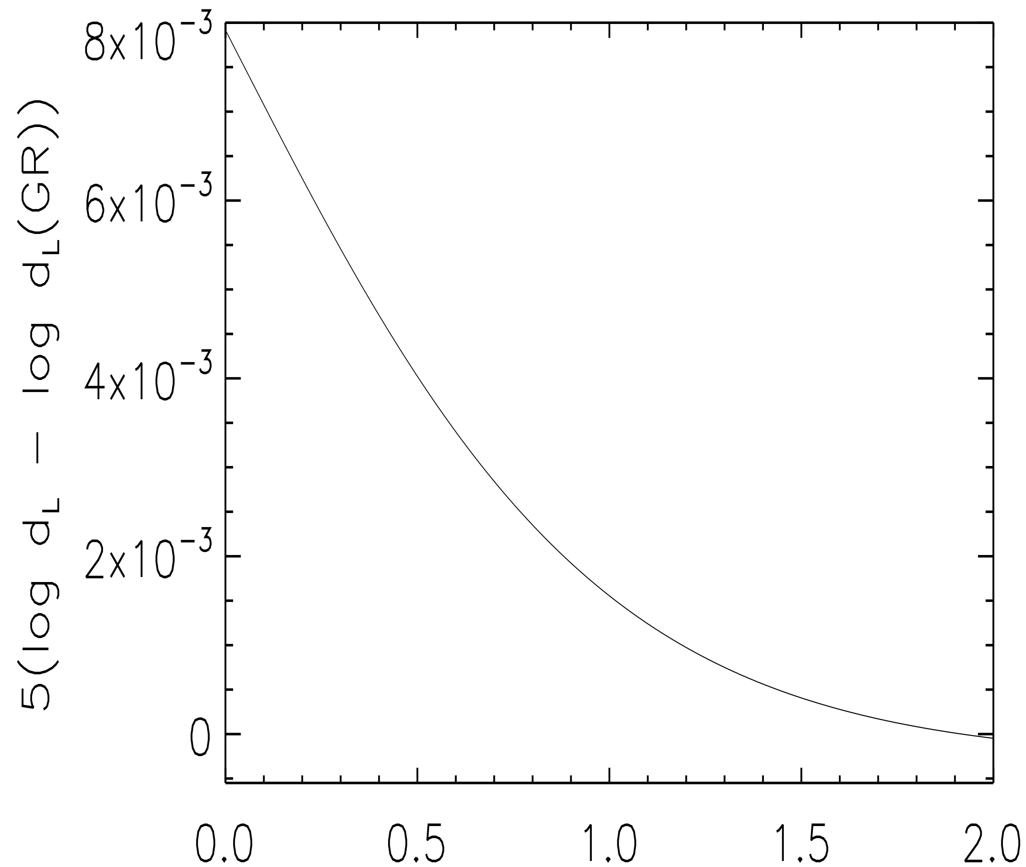
$$\dot{\rho}_c + 3H\rho_c = 0$$

$$f(R) = -\frac{R_{vac}}{2}\frac{\lambda(R/R_{vac})^n}{1+\lambda(R/R_{vac})^n}$$

$$\lambda \sim 10^3$$

$$d_L(z) = (1+z)\int_0^z \frac{cdz'}{H(z')}$$



# Observational signatures: Growth history

- Perturbation equations (scalar perturbations only, Newtonian gauge) Bean et al. 2006

$$ds^2 = a^2\left[-(1+2\psi)d\tau^2 + (1-2\phi)\gamma_{ij}dx^i dx^j\right]$$

$$\delta_c'' + H\delta_c' + k^2\psi - 3\phi'' - 3H\phi' = 0$$

$$\delta_\gamma'' + \frac{1}{3}k^2\delta_\gamma + \frac{4}{3}k^2\psi - 4\phi'' = 0$$

Fluid perturbation equations are unchanged

$$(1+f_R)(\psi-\phi) + f_{RR}\delta R = -\frac{3a^2}{2k^2}8\pi G\Sigma_i(\rho_i + p_i)\sigma_i$$

$$(1+f_R)\left[2k^2\phi + 6H(\phi' + H\psi)\right] + 3f_{RR}H'\delta R - (k^2 f_{RR} + 3Hf_{RR}')\delta R - 3Hf_{RR}\delta R' + f_R'(6H\psi + 3\phi') = -8\pi Ga^2\Sigma_i\rho_i\delta_i$$

$$\delta R = \frac{2}{a^2}\left[-6\frac{a''}{a}\psi - 3H\psi' + k^2\psi - 9H\phi' - 3\phi'' - 2k^2\phi\right]$$

# Modified gravity: Evolution of perturbations

- To solve these equations, we use the quasi-static limit
- At background level, the f(R) funtion satisfies

$$f_{RR} \ll H^2, \dot{H}$$

- The dominant contributions arise from terms involving

$$f_{RR}^{-1} = 3M^2 \qquad \frac{k^2}{a^2}$$

- Approximate equations

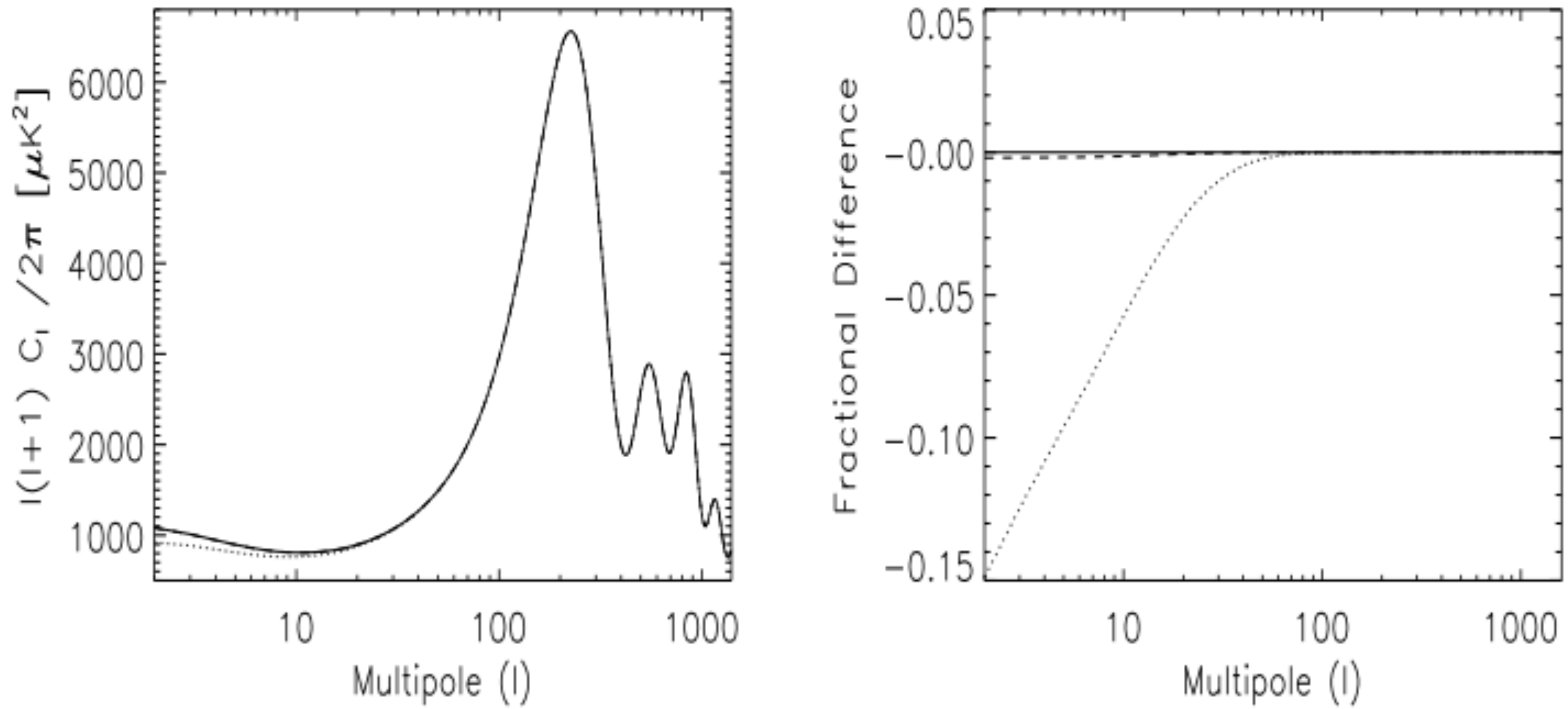
$$k^2\phi = -4\pi G Q(a,k) a^2 \delta_c \qquad Q = \frac{3a^2M^2 + 2k^2}{3a^2M^2 + 3k^2}$$

$$\psi = [1 + \eta(a,k)]\phi \qquad \eta = \frac{2k^2}{3a^2M^2 + 2k^2}$$

$$\ddot{\delta}_c + 2H\dot{\delta}_c - 4\pi G \rho_c \theta(a,k)\delta_c = 0 \qquad \theta = \frac{4k^2 + 3a^2M^2}{3k^2 + 3a^2M^2}$$

# Cosmological constraints: CMB

- CMB angular power spectrum;




$$\lambda \sim 10^3$$

$$f(R) = -\frac{R_{vac}}{2}\frac{\lambda (R/R_{vac})^n}{1+\lambda (R/R_{vac})^n}$$

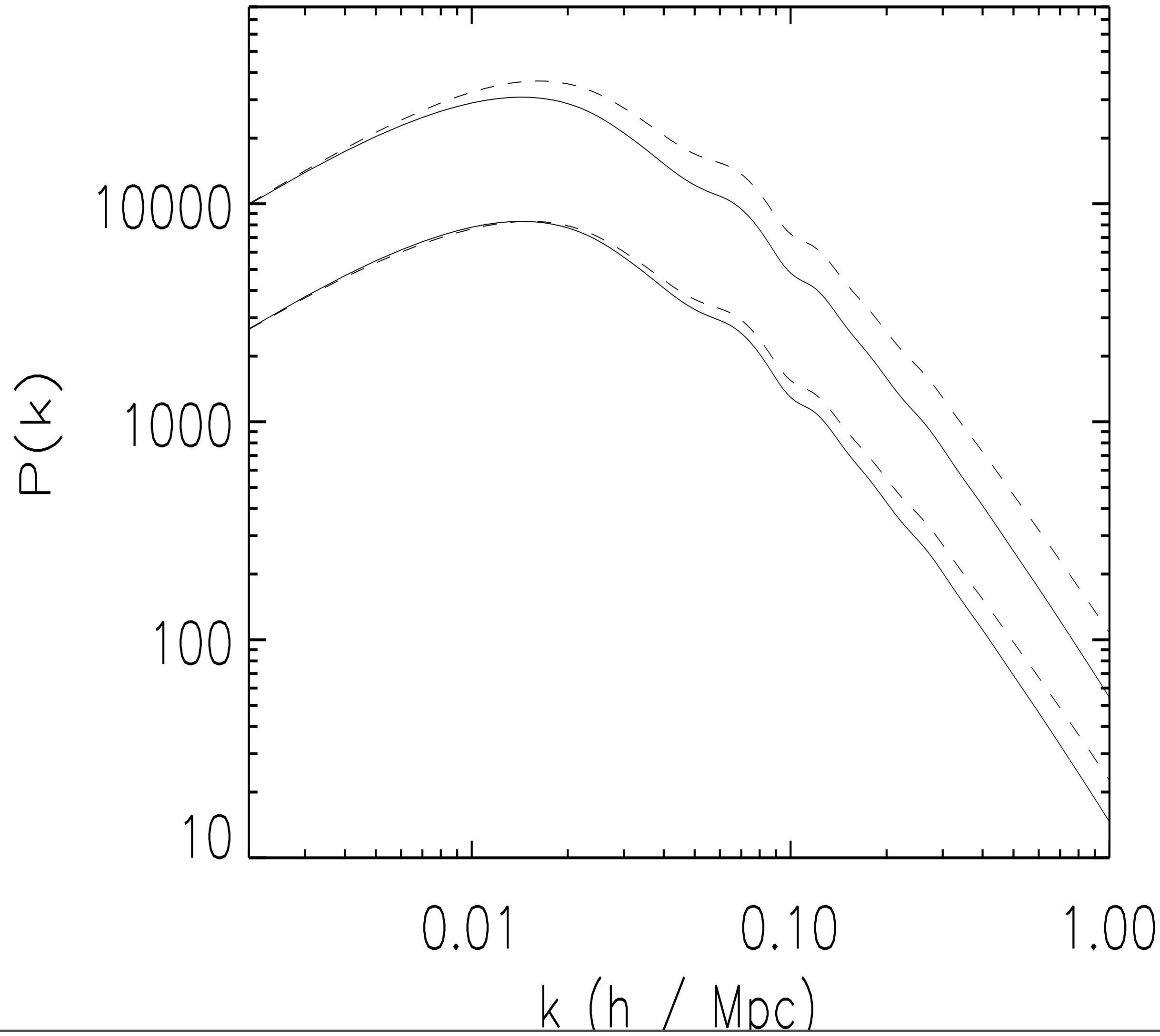
- Very low modified gravity signal in the angular power spectrum, even on large scales.

# Modified gravity: Perturbations

- The power spectrum is modified at late times
- $$P(z,k) = P_{\rm GR}(z=10,k)\left(\frac{\delta_{\rm c}(z,k)}{\delta_c(z=10,k)}\right)^2$$
- f(R) models generically lead to increased power at 'intermediate' scales

$$f(R) = -\frac{R_{vac}}{2}\frac{\lambda\left(R/R_{vac}\right)^n}{1+\lambda\left(R/R_{vac}\right)^n}$$

$$\lambda \sim 10^3$$

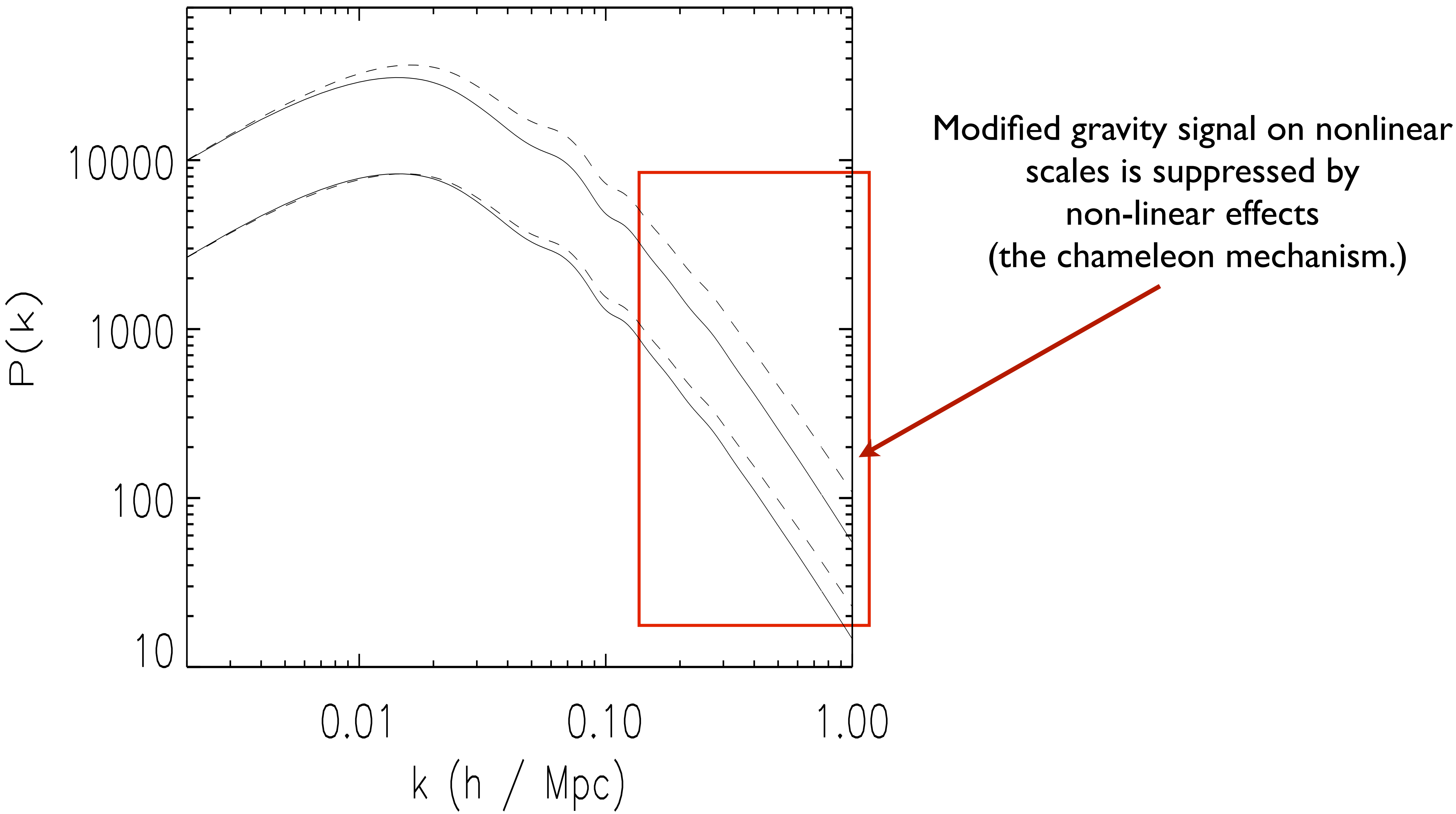


# Modified gravity: Constraints

- The growth history is far more sensitive to modified gravity than the expansion history
- Weak lensing will provide the most stringent constraints* (cluster number counts are exponentially sensitive to the amplitude of the matter power spectrum...)
- How well can future missions constrain these models?
- Euclid:
  - Full extra galactic sky survey with 1.2m telescope at L2
  - Optimised for weak gravitational lensing

- Measurements will be precise enough to reconstruct the growth history in several redshift bins, allowing us to reconstruct the metric potentials and hence constrain this class of modified gravity models.
- To maximize the constraining power of future surveys, we must also construct the non-linear power spectrum.

# Modified gravity: Weak lensing



# Modified gravity: Non-linear regime

- Use higher order perturbation theory for the mildly nonlinear regime

$$\Phi_a = \begin{pmatrix} \delta(\tau, \mathbf{k}) \\ -\theta(\tau, \mathbf{k}) \end{pmatrix} \qquad \tau = \log[a]$$

$$\frac{\partial \Phi_a(\tau, \mathbf{k})}{\partial \tau} + \Omega_{ab}\Phi_b(\tau, \mathbf{k}) = \int \frac{d^3\mathbf{k}_1 d^3\mathbf{k}_2}{(2\pi)^3}\delta^D(\mathbf{k} - \mathbf{k_1} - \mathbf{k}_2)\gamma_{abc}(\tau, \mathbf{k})\Phi_b(\mathbf{k}_1, \tau)\Phi_c(\mathbf{k}_2, \tau)$$

$$\Omega_{ab} = \begin{pmatrix} 0 & -1 \\ -\frac{4\pi G\rho_m}{H^2}\left(1 + \frac{k^2}{3a^2\Pi(a,\mathbf{k})}\right) & 2 + \frac{\dot{H}}{H^2} \end{pmatrix}$$

$$\Pi(a, \mathbf{k}) = \left(\frac{k^2}{a^2} + \frac{M^2}{3}\right)$$

$$\Phi_a = \Phi_a^{(1)} + \Phi_a^{(2)} + \Phi_a^{(3)} + \dots$$

$$P_{ab}(\mathbf{k}, \tau) = P_{ab}^{(11)}(\mathbf{k}, \tau) + P_{ab}^{(22)}(\mathbf{k}, \tau) + P_{ab}^{(13)}(\mathbf{k}, \tau) + \dots$$

$$\gamma_{112} = \frac{1}{2}\left(1 + \frac{\mathbf{k}_1.\mathbf{k}_2}{|\mathbf{k}_1|^2}\right)$$

$$\gamma_{121} = \frac{1}{2}\left(1 + \frac{\mathbf{k}_1.\mathbf{k}_2}{|\mathbf{k}_2|^2}\right)$$

$$\gamma_{222} = \frac{1}{2}\frac{\mathbf{k}_1.\mathbf{k}_2|\mathbf{k}_1 + \mathbf{k}_2|^2}{|\mathbf{k}_1|^2|\mathbf{k}_2|^2}$$

$$\gamma_{211} = -\frac{1}{12H^2}\left(\frac{8\pi G\rho_m}{3}\right)^2 \frac{(k_1 + k_2)^2}{a^2}\frac{M_2(a)}{\Pi(\tau, \mathbf{k}_{12})\Pi(\tau, \mathbf{k}_1)\Pi(\tau, \mathbf{k}_2)}$$

Higher order vertex functions

# Modified gravity: Non-linear regime

- Use higher order perturbation theory for the mildly nonlinear regime; closure relations

Taruya, Hiramatsu (2007)
Koyama, Taruya, Hiramatsu (2009)

$$(2\pi)^3\delta_D(\mathbf{k}+\mathbf{k}')R_{ab}(|\mathbf{k}|,\tau,\tau') = \langle \Phi_a(\mathbf{k},\tau), \Phi_b(\mathbf{k}',\tau')\rangle \qquad \tau > \tau'$$

$$(2\pi)^3\delta_D(\mathbf{k}-\mathbf{k}')G_{ab}(|\mathbf{k}|,\tau,\tau') = \left\langle \frac{\delta\Phi_a(\mathbf{k},\tau)}{\delta\Phi_b(\mathbf{k}',\tau')} \right\rangle \qquad \tau > \tau'$$

$$\Phi_a = \begin{pmatrix} \delta(\tau,\mathbf{k}) \\ -\theta(\tau,\mathbf{k}) \end{pmatrix}$$

$$\Lambda_{ab}(\mathbf{k},\tau)R_{bc}(|\mathbf{k}|,\tau,\tau') = 0$$

$$\Lambda_{ab}(\mathbf{k},\tau)G_{bc}(|\mathbf{k}|,\tau,\tau') = 0$$

$$\Lambda_{ab} = \delta_{ab}\frac{\partial}{\partial\tau} + \Omega_{ab}(\mathbf{k},\tau)$$

$$\Gamma_{abcd} = \delta_{ac}\delta_{bd}\frac{\partial}{\partial\tau} + \delta_{ac}\Omega_{bd}(k,\tau) + \delta_{bd}\Omega_{ac}(k,\tau).$$

$$\Gamma_{abcd}(\mathbf{k},\tau)P_{cd}(|\mathbf{k}|,\tau) = \int_{\tau_i}^{\tau} d\tau'' M_{as}(k,\tau,\tau'')R_{bs}(k,\tau,\tau'') + \int_{\tau_i}^{\tau} N_{as}(k,\tau,\tau'')G_{bs}(k,\tau,\tau'')$$

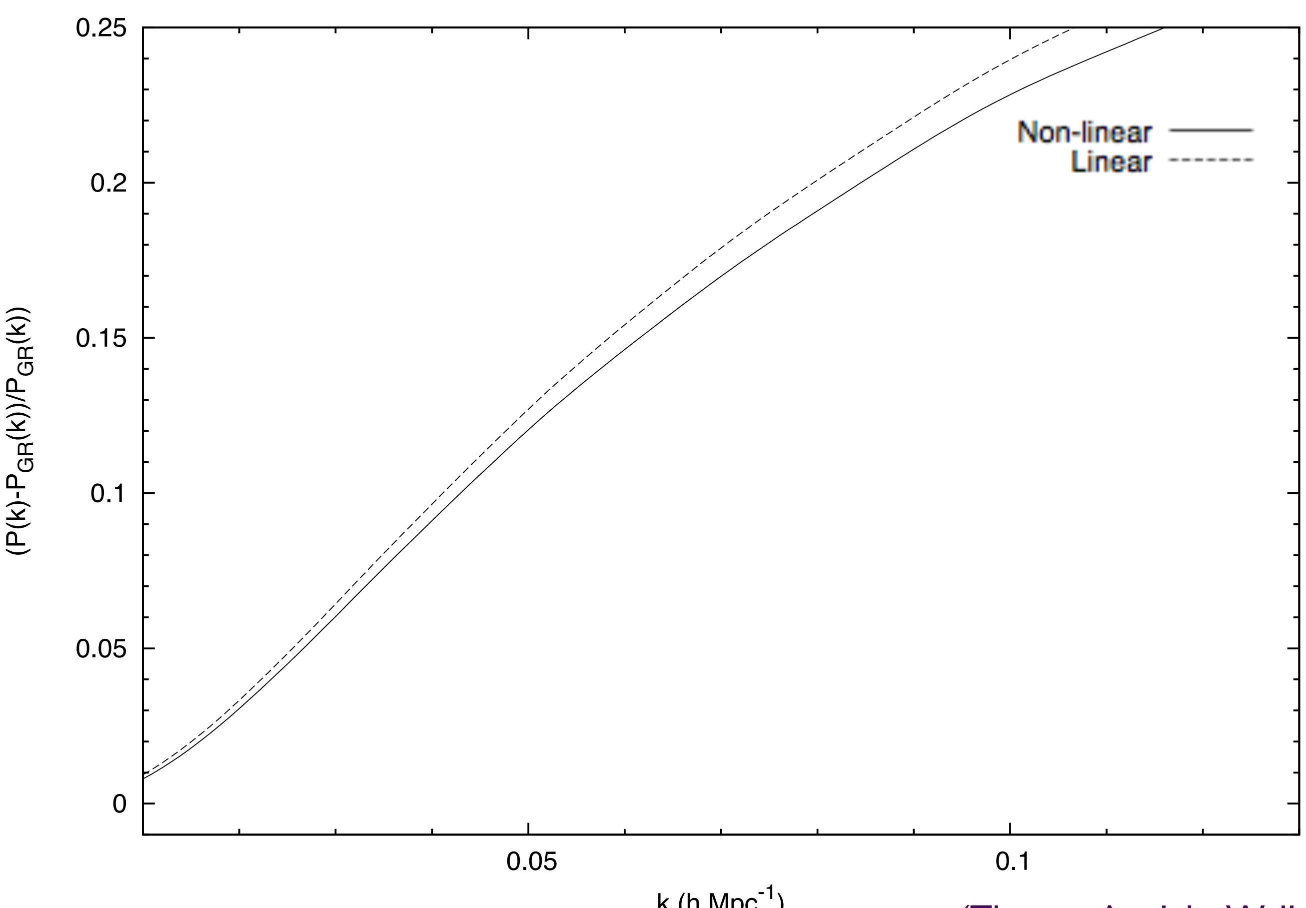
$$\gamma_{112}(\mathbf{k}_1,\mathbf{k}_2,\tau) = \frac{1}{2}\left(1 + \frac{\mathbf{k}_1.\mathbf{k}_2}{|\mathbf{k}_1|^2}\right)$$

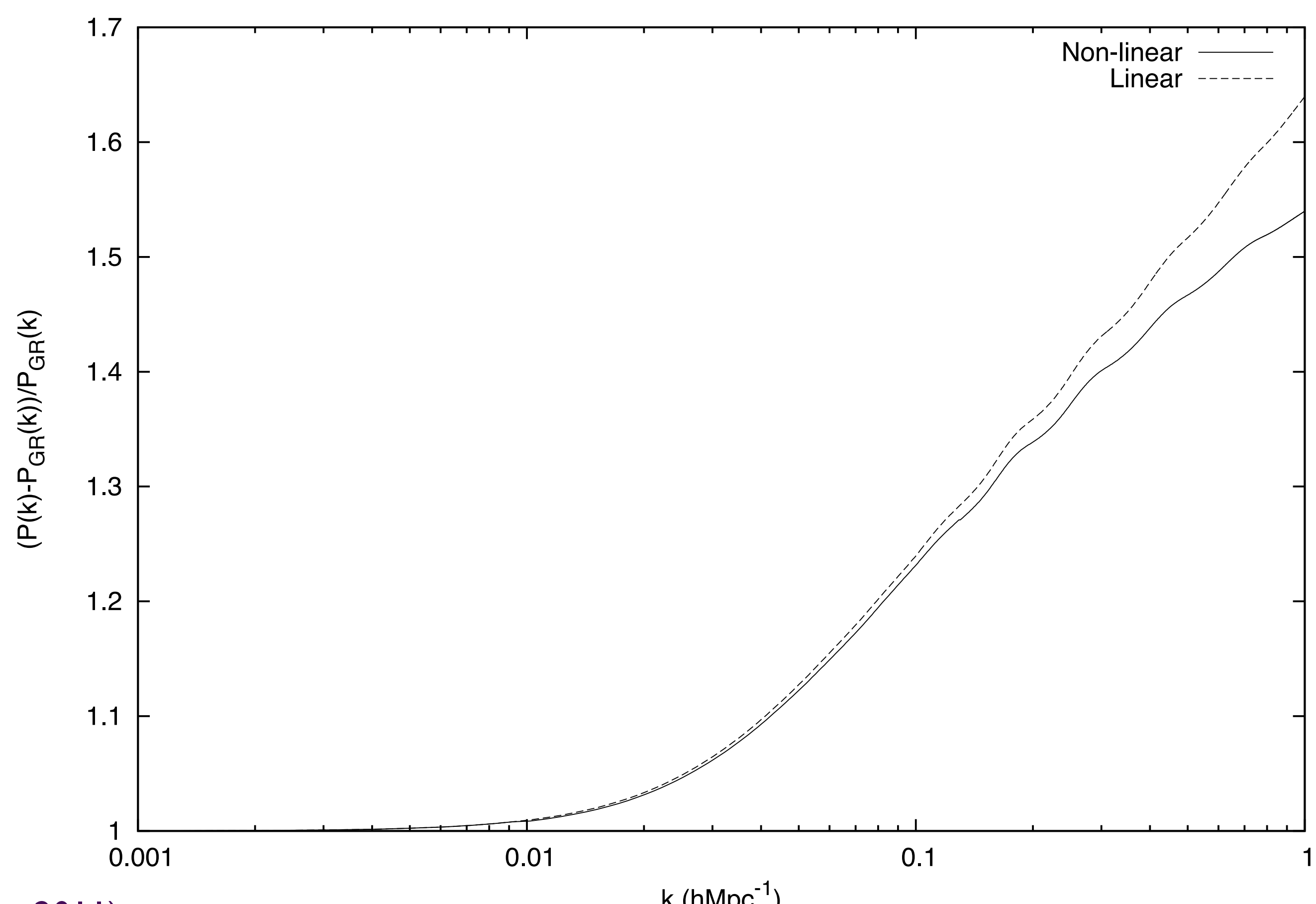
$$\gamma_{211}(\mathbf{k}_1,\mathbf{k}_2,\tau) = -\frac{1}{12H^2}\left(\frac{8\pi G\rho_{\rm m}}{3}\right)^2 \frac{(k_1+k_2)^2}{a^2}\frac{M_2(a)}{\Pi(\tau,\mathbf{k}_{12})\Pi(\tau,\mathbf{k}_1)\Pi(\tau,\mathbf{k}_2)}$$

- Extra terms; backreaction of the metric perturbations on the f(R) functional form (the chameleon mechanism!)

# Modified gravity: Non-linear regime

- We observe the effect of the chameleon mechanism in the mildly non-linear regime




(Thomas Appleby Weller, 2011)

- Can use the mildly non-linear regime to calibrate fully non-linear fitting formulas.

# Modified gravity: Non-linear regime

- Perturbation theory cannot be trusted above $k \sim 0.1\, h\, Mpc^{-1}$

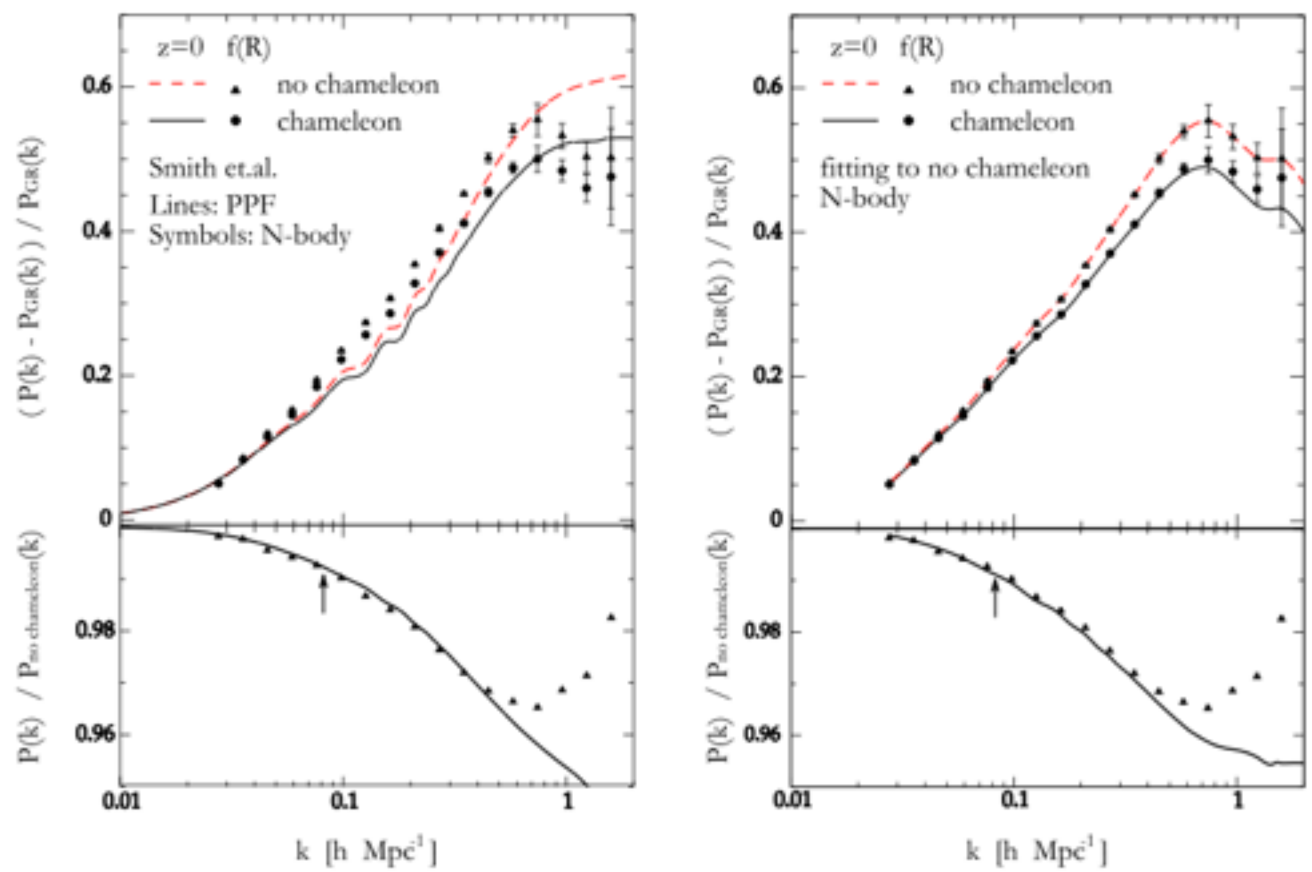
- Beyond this, we must use alternative approaches (N-body simulations,...?)

- The PPF formalism,

$$P(a,k) = \frac{P_{\rm no-cham}(a,k) + c_{\rm nl}(a)\Sigma^2(a,k)P_{\rm GR}(a,k)}{1 + c_{\rm nl}(a)\Sigma^2(a,k)}$$

Hu, Sawicki (2007)

- Requires simulations to calibrate!




Koyama, Taruya, Hiramatsu (2009)

# Modified gravity:
# Fisher matrix analysis

- How well can future missions constrain these models?
- Fisher matrix analysis
- Calculate the shear power spectrum for these models
- Take two cuts in the data

$$C_{ij}(l) = \frac{l^4}{4}\int d\chi \frac{W_i(\chi)W_j(\chi)}{\chi^6} P_{(\phi-\psi)}\left(\frac{l}{\chi},\chi\right)$$

  - Conservative $l_{cut} = 400$ (only consider the linear regime)
  - Include nonlinear physics $l_{cut} \sim 10000$ (using GR fitting function; used as an indication of possible gain due to using the nonlinear regime only!)
  - Parameterize the f(R) function as $f_{RR}(a) = \frac{M_0^{-2}}{3}\left(\frac{a^{-3}+4a_*^{-3}}{1+4a_*^{-3}}\right)^{-2\upsilon}$ $\quad M_0 > H_0 \quad \upsilon > \frac{1}{2}$

Euclid

$$F_{ij} = \sum_l \frac{\partial C}{\partial p_i}\mathrm{Cov}^{-1}\frac{\partial C}{\partial p_j}$$

$\sigma_z = \sigma_p(1+z)$, $\sigma_p = 0.03$

$$C_{ij}(l) = P_{ij} + \langle\gamma_{\rm int}^2\rangle\frac{\delta_{ij}}{\bar{n}_i}.$$

20'000 square degrees

40 gal/arcmin$^2$

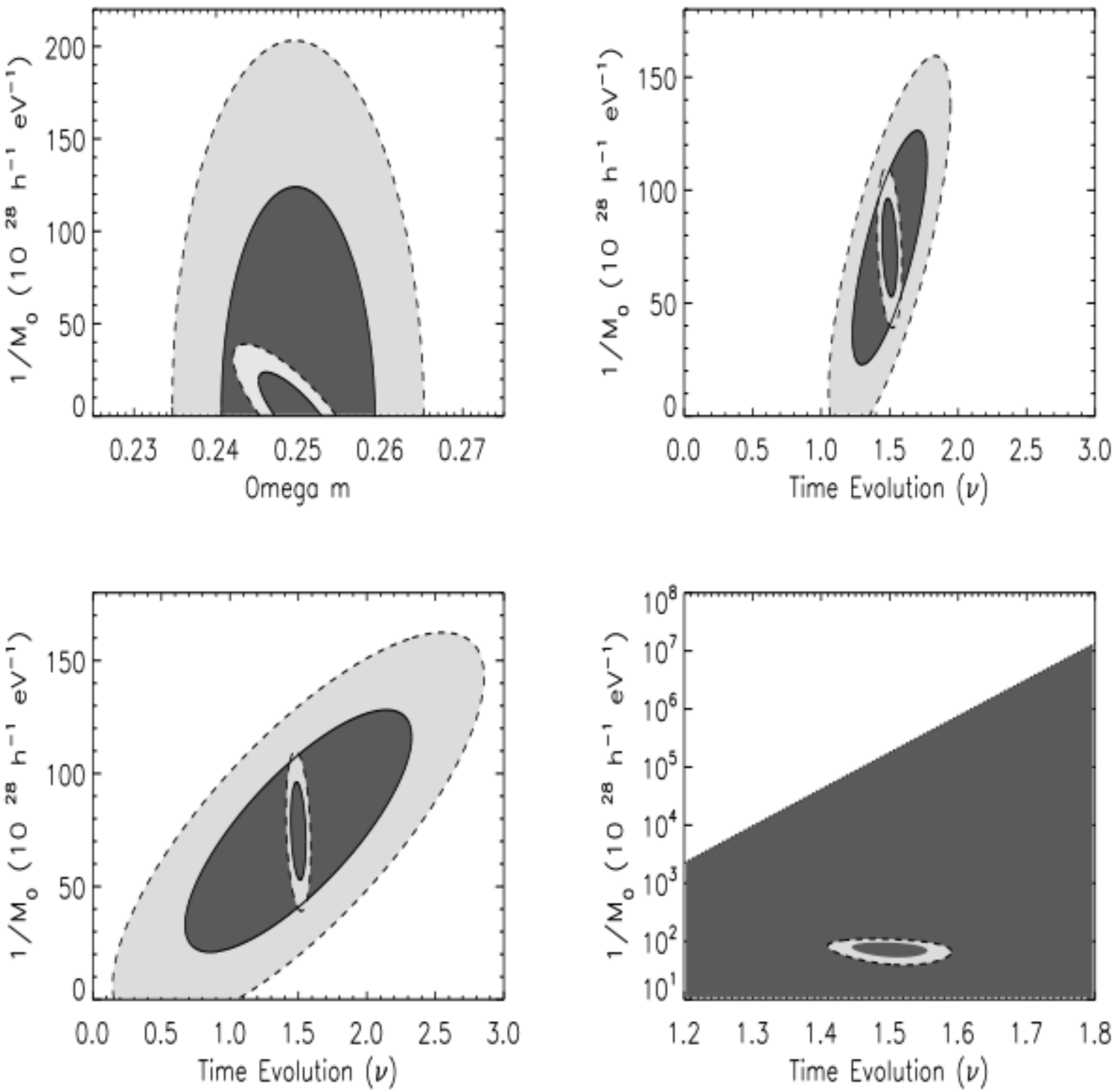
5 Tomographic bins

$n(z) \propto z^\alpha \exp[-(z/z_0)^\beta]$ $\quad z_{\rm m} = 0.9$

$z_0 = z_{\rm m}/1.412$, $\alpha = 2$, $\beta = 1.5$.

$\Omega_m$, $h$, $\ln(A_S)$, $\Omega_b$ and $n_s$

# Modified gravity: Forecast constraints




Fiducial values

$\Omega_{m0} = 0.25$
$\Omega_{b0} = 0.05$
$h = 0.7$
$n_s = 1.0$
$\log[A_s] = \log[2.34e-9]$
$M_0^{-1} = 0$
$\nu = 1.5$

$\Omega_{m0} = 0.25$
$\Omega_{b0} = 0.05$
$h = 0.7$
$n_s = 1.0$
$\log[A_s] = \log[2.34e-9]$
$M_0 = 10^2 H_0$
$\nu = 1.5$

$$f_{RR}(a) = \frac{M_0^{-2}}{3}\left(\frac{a^{-3} + 4a_*^{-3}}{1 + 4a_*^{-3}}\right)^{-2\nu}$$

# Modified gravity: Conclusion

- The expected constraints on f(R) models from future surveys are at least two orders of magnitude greater than current cosmological bounds.
- These constraints will be tighter than those obtained from local, solar system tests.
- We must be careful to analyse the nonlinear regime correctly!
- The parameter space must be explored in further detail to determine whether the scalar field can roll on cosmological scales.