Spherical collapse in Modified Gravity theories

Paul de Fromont

supervised by *Jean-Michel Alimi*

July 5, 2016

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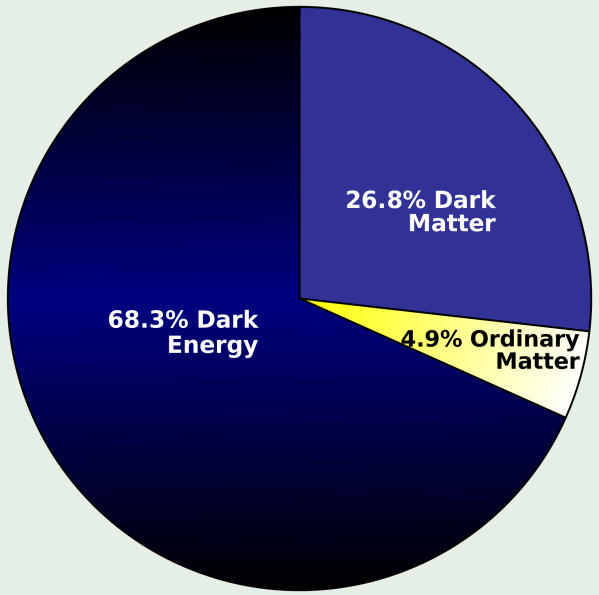
- Dark Energy
- cosmological constant Λ
  - $p = -\rho$
- dark fluid
  - $p = w\rho$ and $w < -1/3$
- quintessence
  - $p = w(a)\rho$ with $w(1) \sim -1$

The cosmic pie



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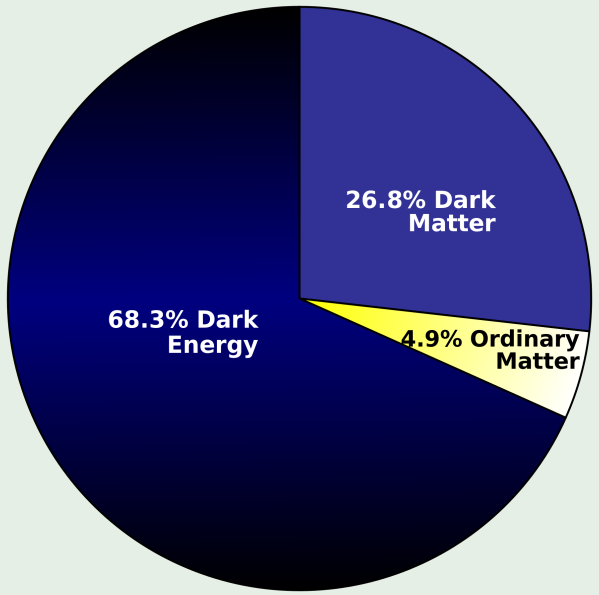

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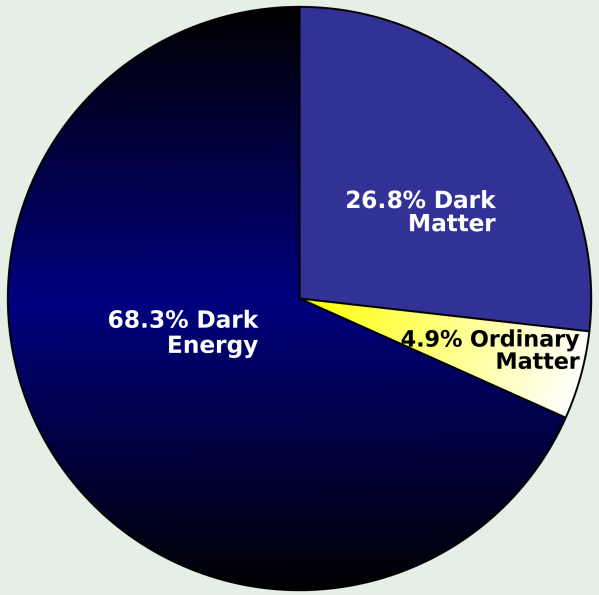

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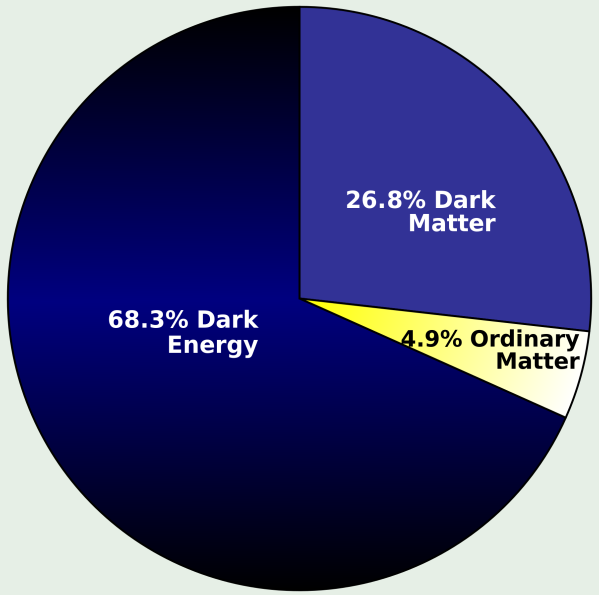

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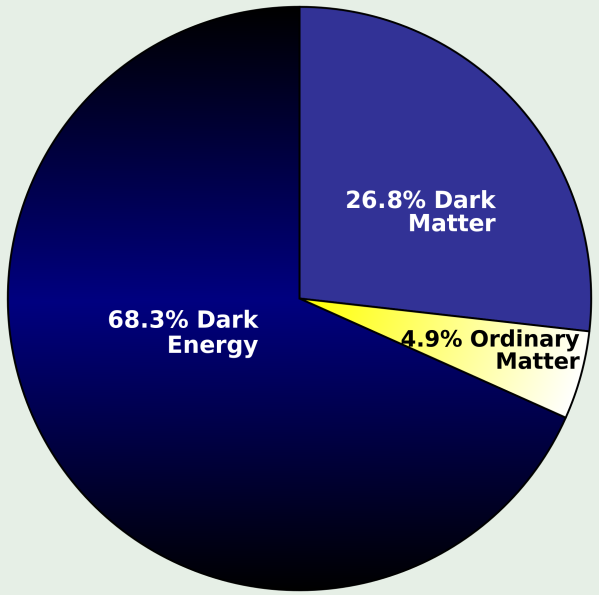

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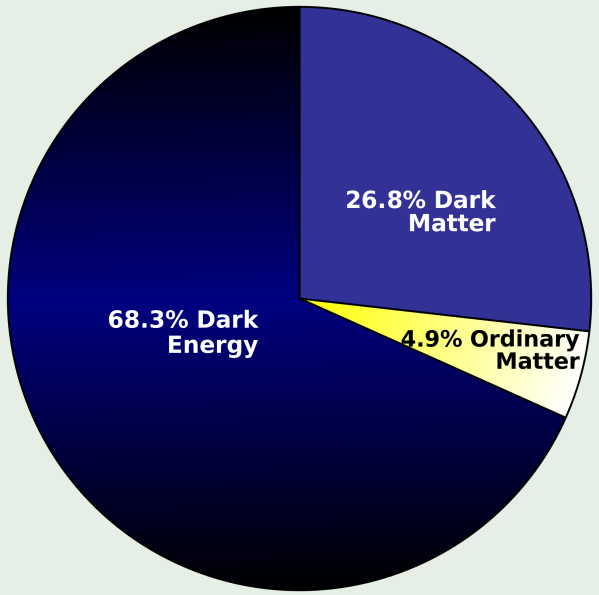

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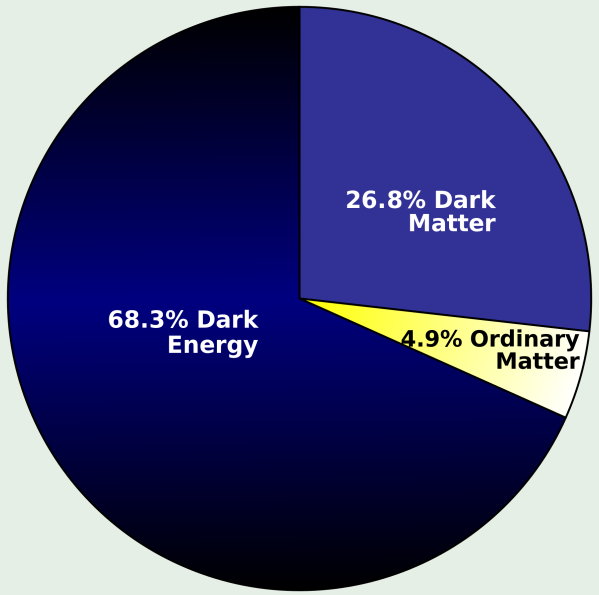

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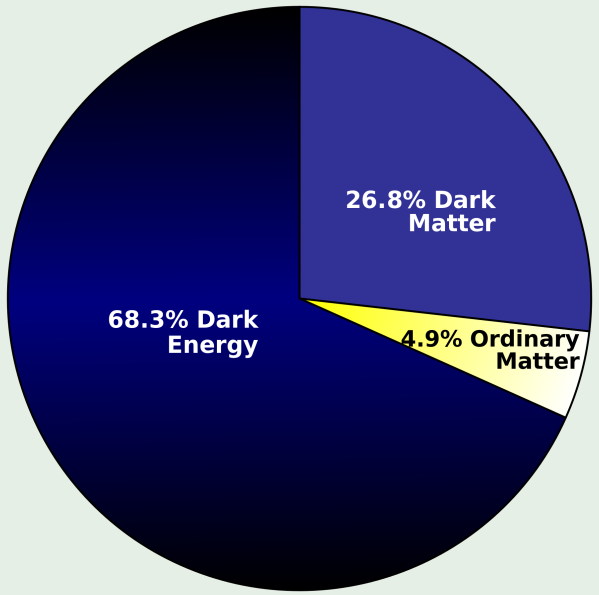

dark energy : new exotic fluid

$$R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R = \kappa T_{\mu\nu} \tag{1}$$

modified gravity : modifications of the geometrical term

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Outline

From the action point of view, Usual GR, introducing a new scalar field ϕ, minimally coupled to $g_{\mu\nu}$ (Quintessence)

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}R + S_m[\Psi; g] + S_{DE}[\phi, g] \tag{3}$$

leads to w :

$$w(\phi) = \frac{\dot{\phi}^2 - 2V(\phi)}{\dot{\phi}^2 + 2V(\phi)} \tag{4}$$

if $\dot{\phi}^2 \ll V(\phi)$, then $w \sim -1$!

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$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}R + S_m[\Psi; g] + S_{DE}[\phi, g] \quad (5)$$

to a non minimal coupling

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}F(\phi)R + S_m[\Psi; g] + S_{DE}[\phi, g] \quad (6)$$

results into

$$G_{\mu\nu} = \kappa\left[T^m_{\mu\nu} + T_{\mu\nu}(\phi)\right] \rightarrow F(\phi)G_{\mu\nu} = \kappa\left[T^m_{\mu\nu} + T_{\mu\nu}(\phi)\right] \quad (7)$$

known as Scalar-Tensor theories (Modified Gravity)

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What is the background dynamics ? Starting from the Einstein equation

$$F(\phi)G_{\mu\nu} = \kappa T^m_{\mu\nu} + \kappa T_{\mu\nu}(\phi) \tag{8}$$

FLRW metric $ds^2 = dt^2 - a^2(t)d\mathbf{x}^2$,

$$F(a)G_{\mu\nu}(a) = \kappa T^m_{\mu\nu}(a) + \kappa T_{\mu\nu}(a) \tag{9}$$

can be directly transposed to

$$G_{\mu\nu}(a) = \kappa T^m_{\mu\nu}(a) + \underbrace{\kappa T_{\mu\nu}(a) + G_{\mu\nu}(a)\left(1 - F(a)\right)}_{\kappa \tilde{T}_{\mu\nu}(a)} \tag{10}$$

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$$ds^2 = dt^2(1+2\Phi) - a^2 d\mathbf{x}^2(1-2\Psi) \quad (11)$$

$$\rho_m = \bar{\rho}_m(1+\delta) \quad (12)$$

$$\phi = \bar{\phi} + \delta\phi \quad (13)$$

and using

- Einstein equations
- scalar field *e.o.m.*
- assume that $\partial_t^2 \ll \nabla^2$ and $k \gg H = \dot{a}/a$

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This leads to

1. modified Poisson equation : $k^2\Phi = -\mu(a,k)\delta\rho$
2. in GR, $\mu(a,k) = G$
3. modified slip equation : $\Psi = \gamma(a,k)\Phi$
4. in GR $= \gamma = 1$

with

$$\mu = \frac{1 + p_3 k^2}{p_4 + p_5 k^2}, \qquad \gamma = \frac{p_1 + p_2 k^2}{1 + p_3 k^2} \tag{14}$$

with $p_i = p_i(a)$

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Conclusion : MG implies

- **background level** : Dark Fluid with $w(a)$
- **perturbed level** :
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Outline

Simple but powerful approach ! Newtonian **spherical** motion

$$\ddot{r} = \frac{\ddot{a}}{a} r - \nabla\Phi \tag{15}$$

With the Poisson equation

$$k^2\Phi = -\mu(a,k)\delta\rho \quad \underset{FT}{\Rightarrow} \quad \nabla^2\Phi = [\delta\rho * \tilde{\mu}] \tag{16}$$

$\tilde{\mu}$ can be written :

$$\tilde{\mu}(r) = \tilde{G}\delta_D^{(3)}(r) + (G_0 - \tilde{G})\frac{1}{4\pi R^2 r} e^{-\frac{r}{R}} \tag{17}$$

where

$$G_0 = \frac{1}{p_4}, \quad \tilde{G} = \frac{p_3}{p_5}, \quad R^2 = \frac{p_5}{p_4} \tag{18}$$

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basics on Spherical collapse

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1. $r \gg R(a)$: fully GR regime (usual GR), $G_N = G_0(a)$
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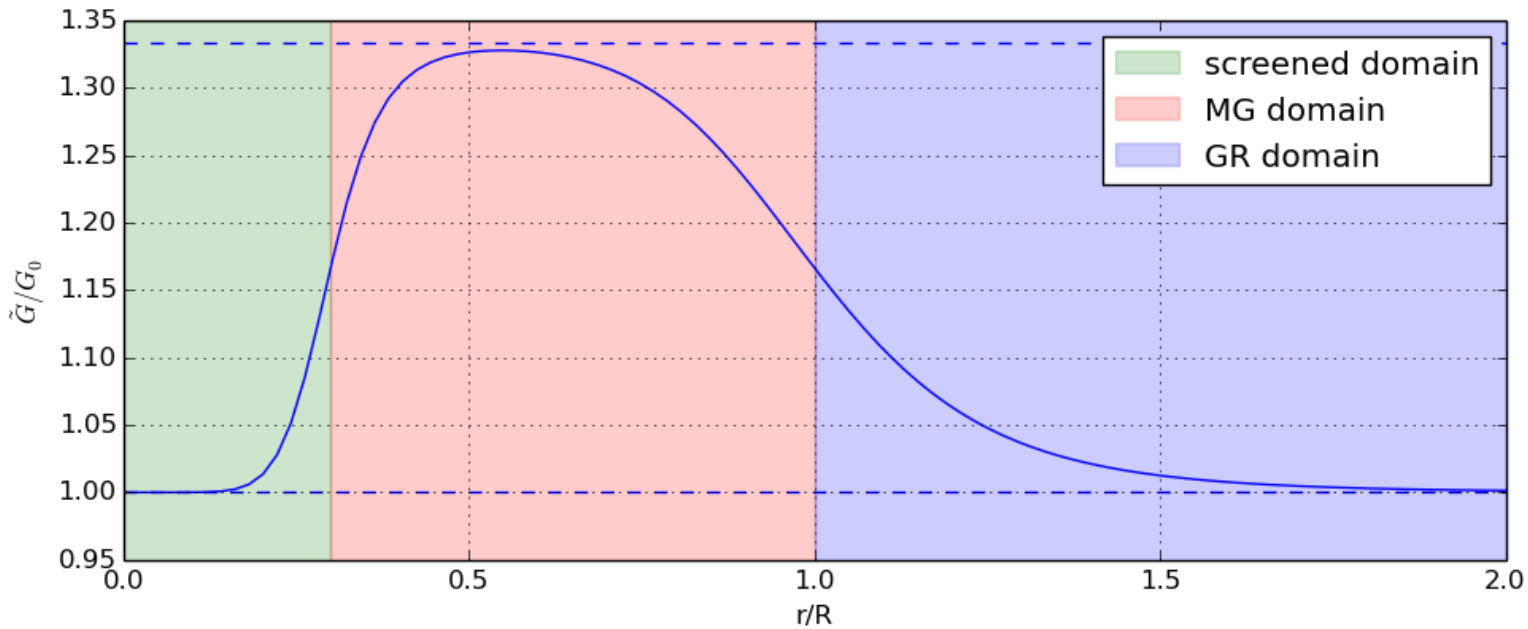

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1. its position $\chi(t) = r(t)/a(t)$
2. its mass (conserved) $M = \frac{4\pi}{3}\bar{\rho}_m^0 r_0^3 \left[1 + \Delta_0(r_0)\right]$

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Spherical Collapse
Large scale matter profiles

Question

We know the dynamics. We need initial realistic matter profiles !

Possible answer

Averaged large scale matter profiles around ... Halos and Cosmic Voids !

- analytically predicable (Gaussian primordial field)
- spherically averaged
- suitable for spherical collapse
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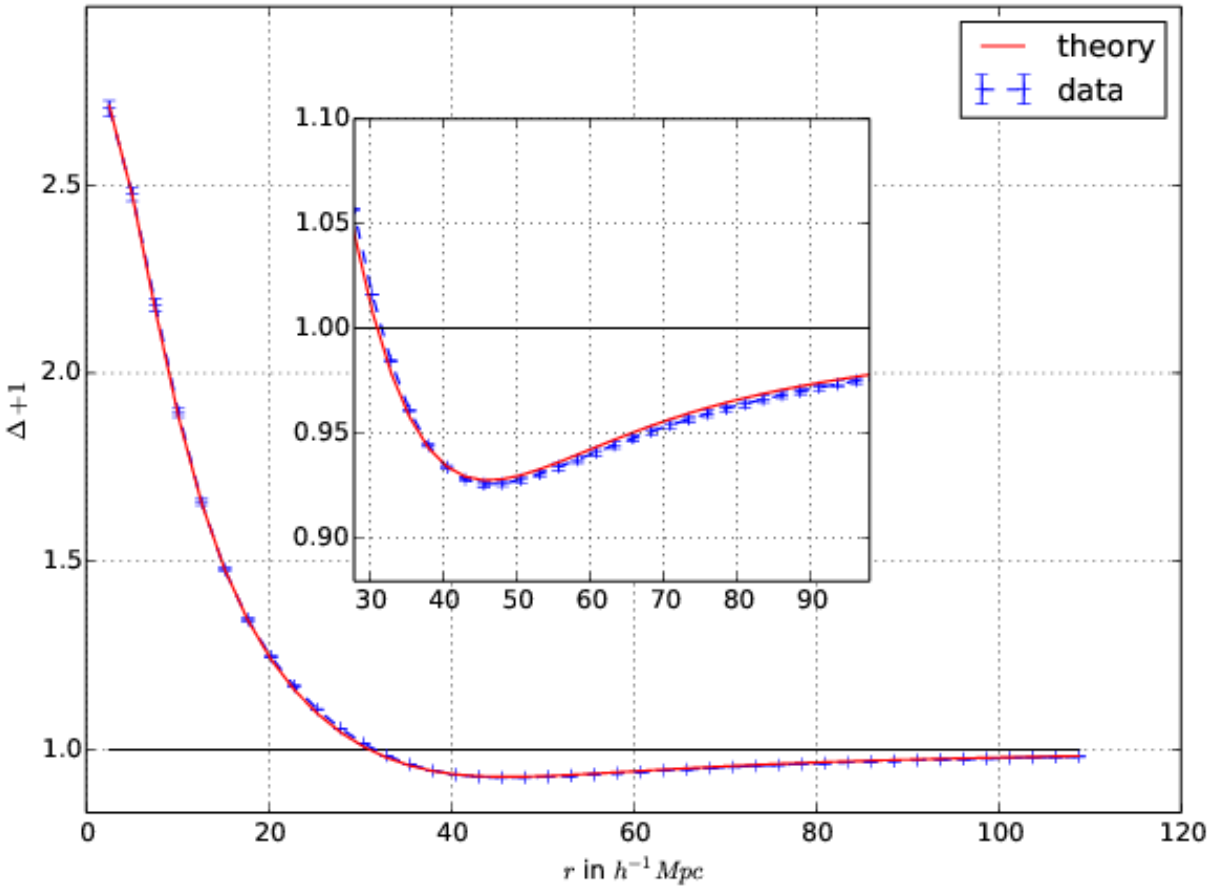

Figure : Mass contrast for $R_1 = 30\ h^{-1}Mpc$

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initial conditions (averaged profiles) the dynamics for every model

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A Modified gravity model ! Generic effective model : $f(R)$ Hu & Sawicki model (2007)

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\,(R + f(R)) + S_m[\Psi; g] \tag{20}$$

$$f(R) = f_0\frac{\gamma + 1}{\gamma + R_0/R} \tag{21}$$

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Spherical collapse in Modified Gravity
Mass profiles for halos

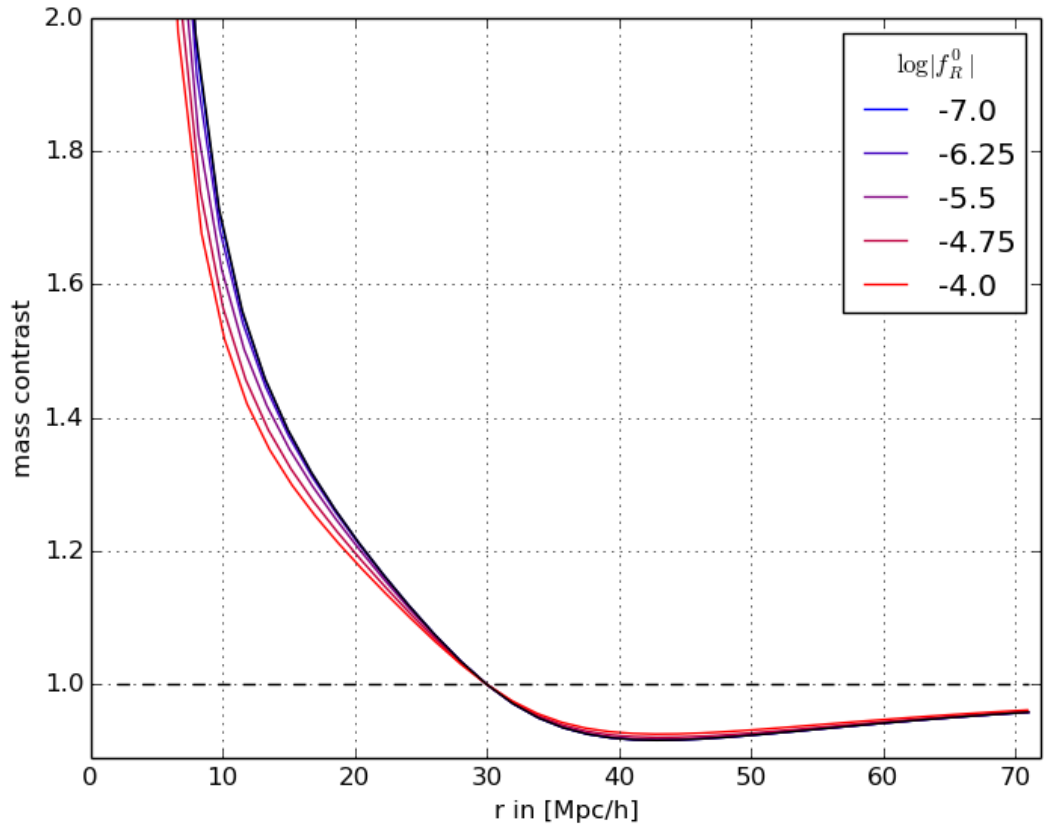
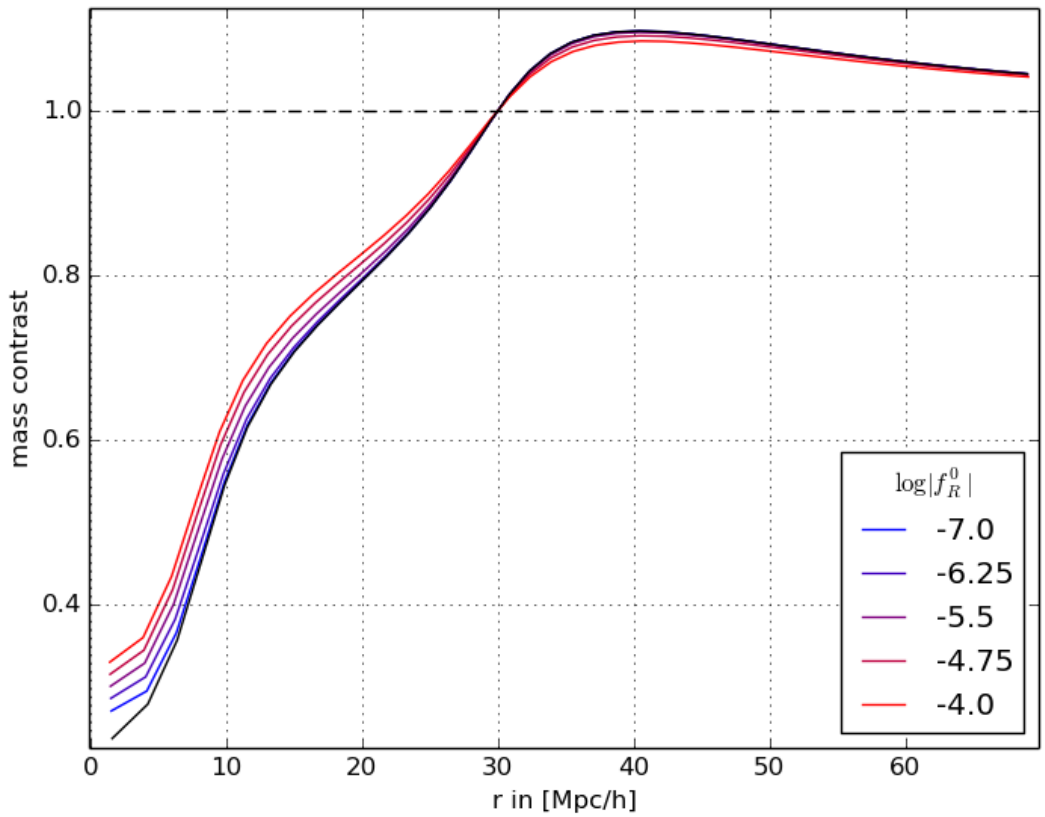


Figure : Mass contrast with various f_R^0 (ΛCDM for $f_R^0 \to 0$)

Spherical collapse in Modified Gravity
Mass profiles for Voids



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Spherical collapse in Modified Gravity
Exclusion contour

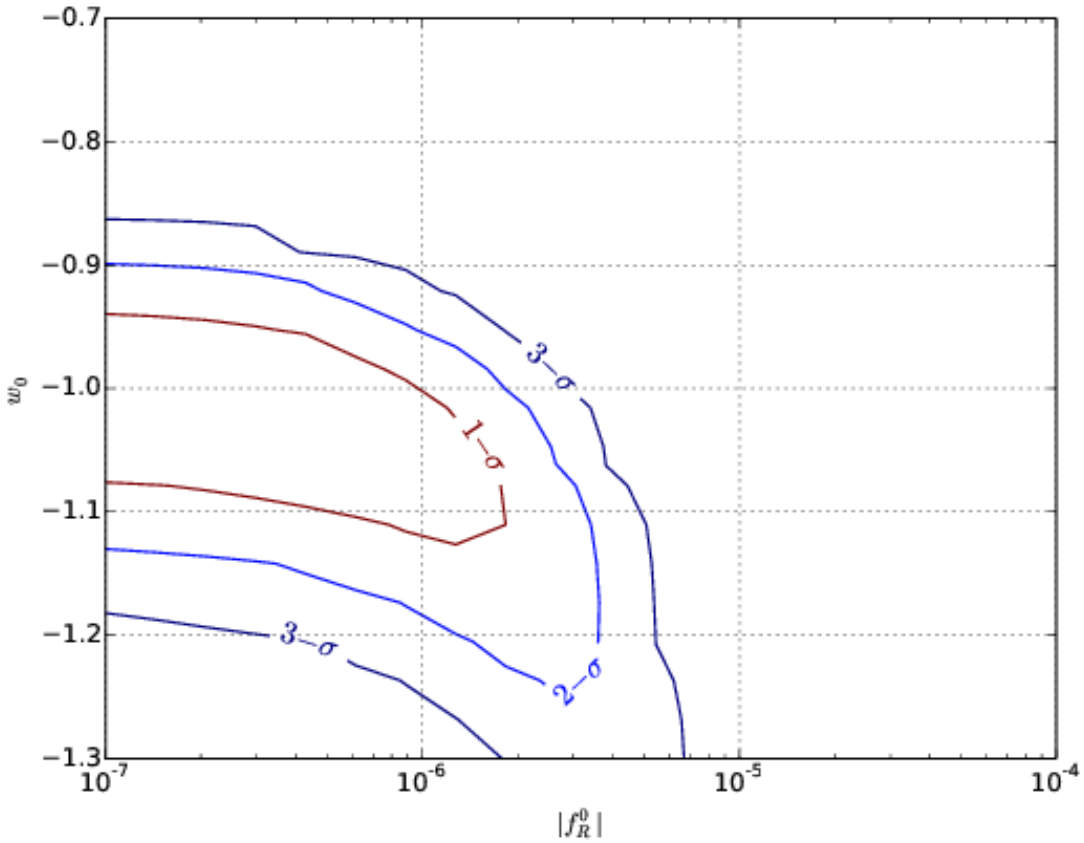

Figure : Exclusion region for w_0 and f_R^0

Spherical collapse in Modified Gravity
Exclusion contour

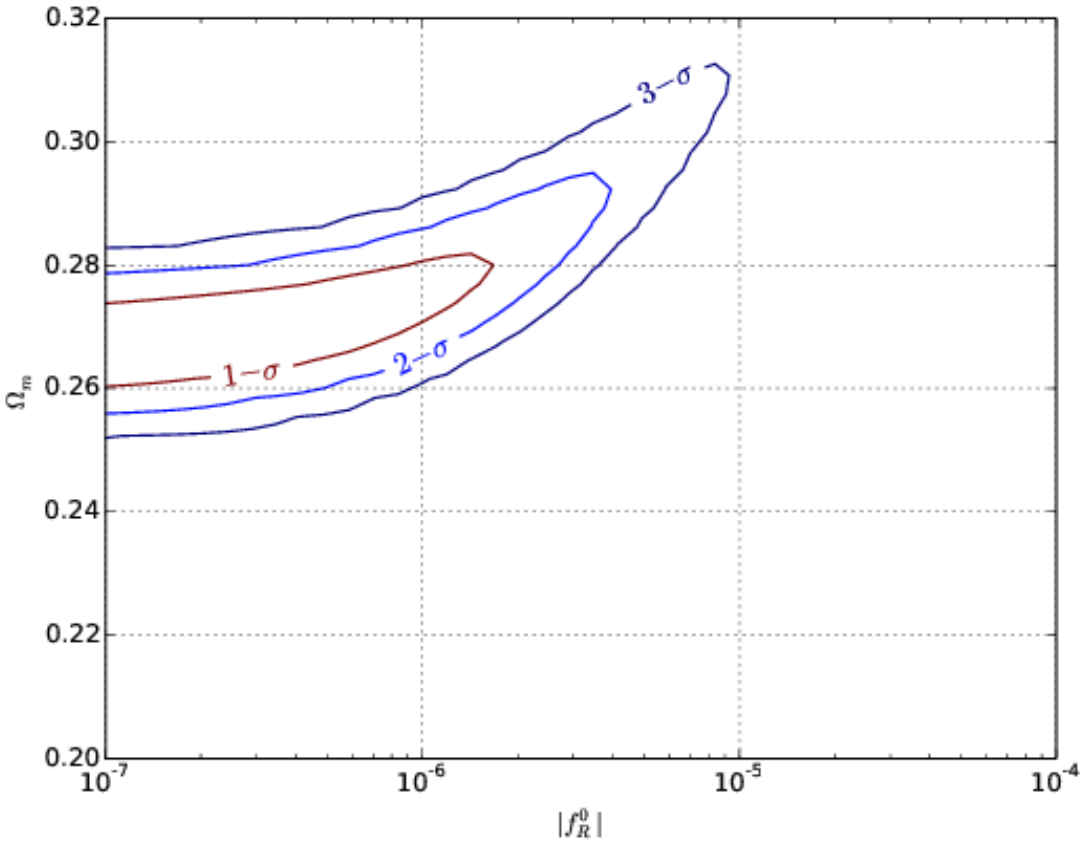

Figure : Exclusion region for Ω_m and f_R^0

Conclusion

- Modified gravity and Quintessence $\Rightarrow$ Dark Energy
- for background : MG $\equiv$ Quintessence
- Impact on LSS
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Thank you for your attention !