Testing modified gravity with cosmic voids and compensated structures

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DARKMOD workshop

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l'Observatoire de Paris | LUTH
Laboratoire de l'Univers et de ses Théories

USPC
Université Sorbonne Paris Cité

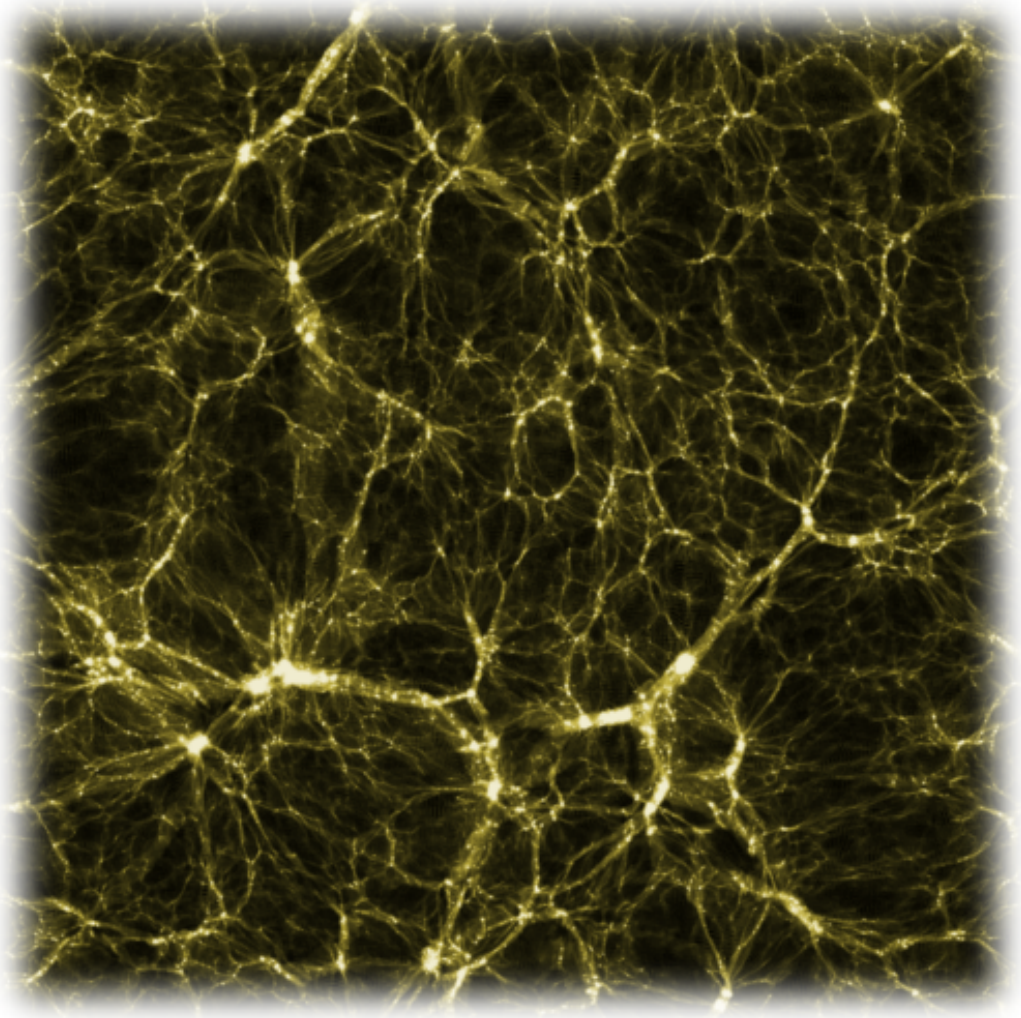
LSS as cosmological probes

The structuration of the Universe

Structuration of the Universe

Slice of 162 h^{-1}Mpc from DEUS simulations

- full matter field (DM)
- halos
- filaments
- cosmic voids : $\rho_m < \bar{\rho}_m$.



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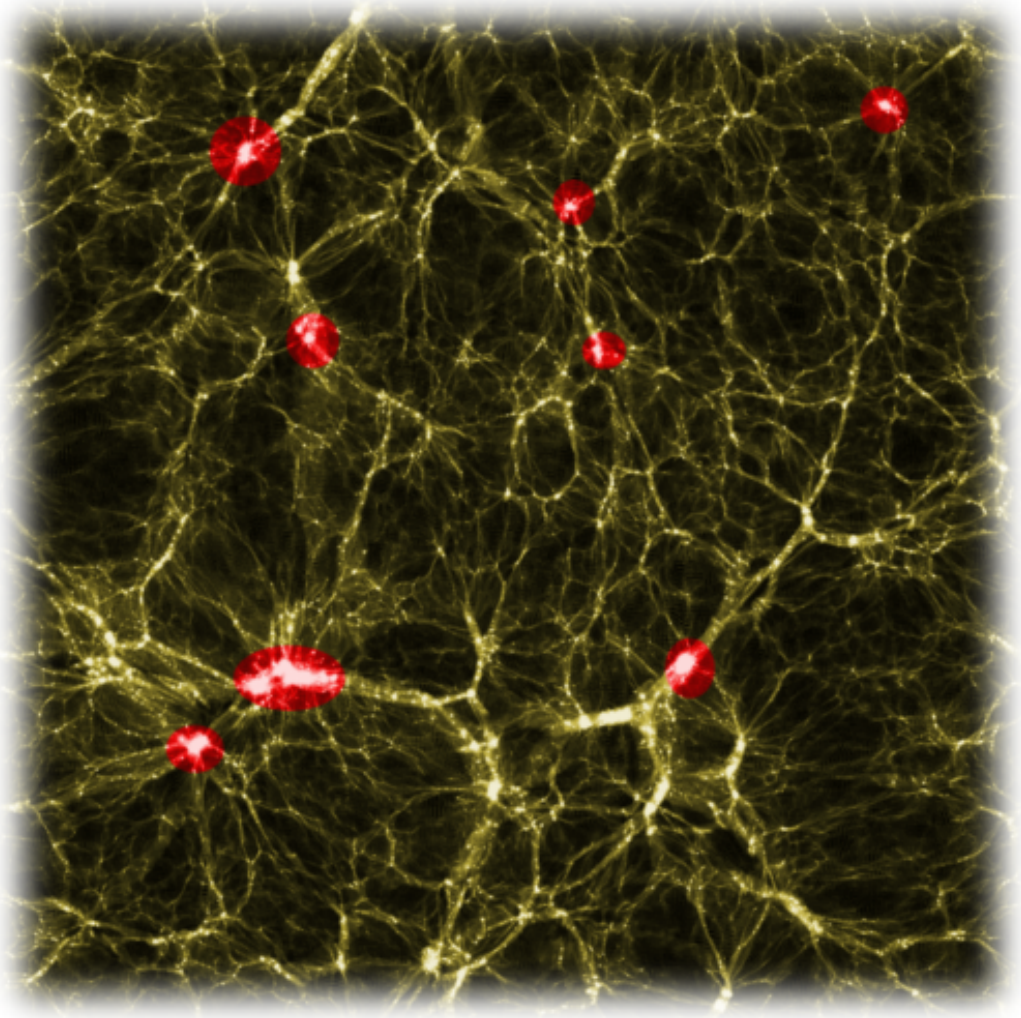

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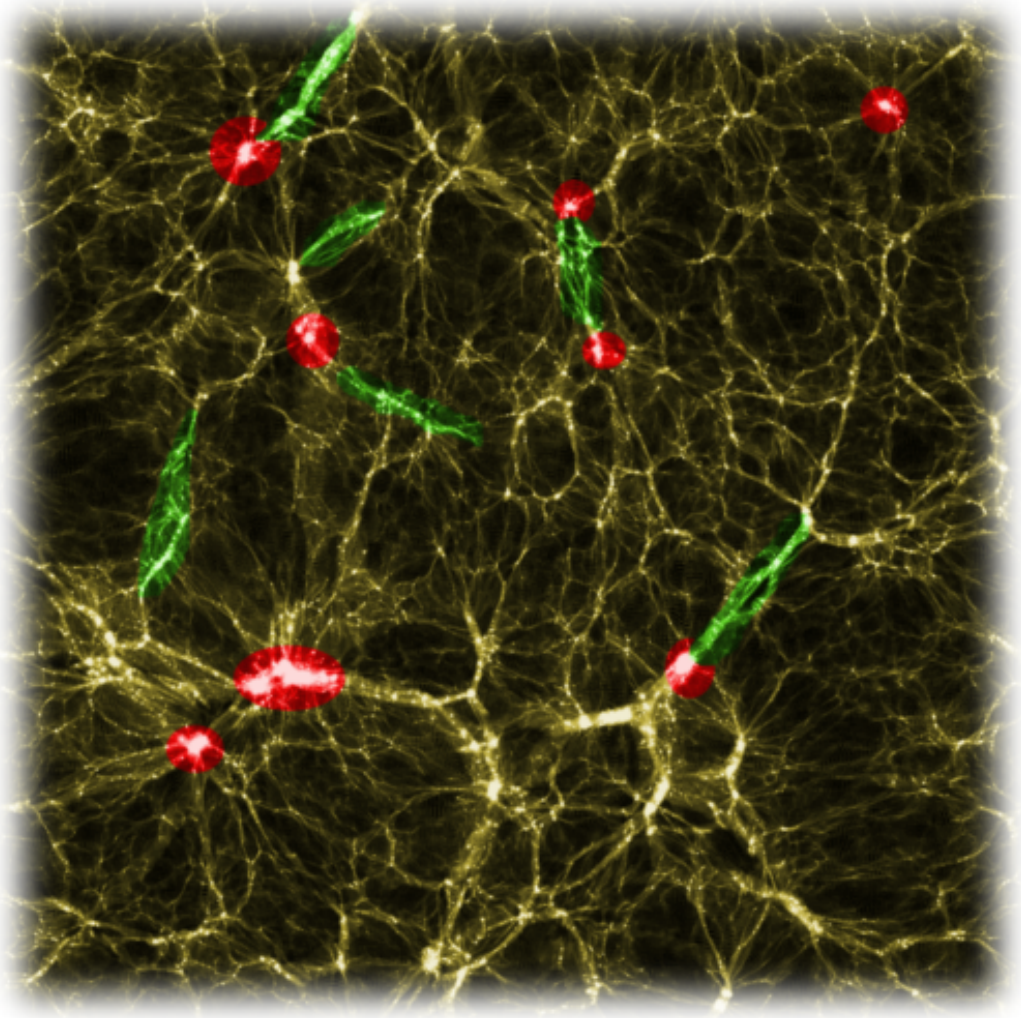

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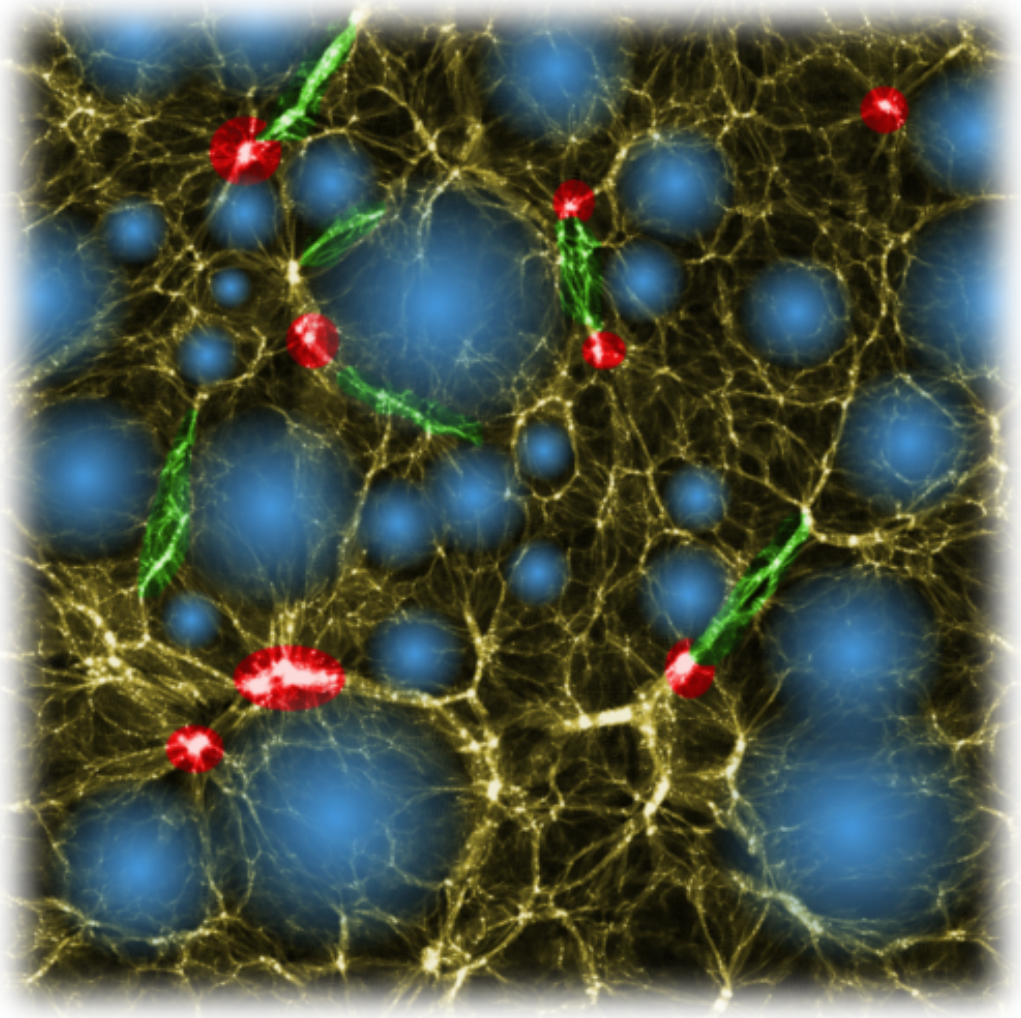

LSS as cosmological probes

The structuration of the Universe

Cosmic Voids

- Emptiest regions in the Universe
- Majority of the volume $\sim 95\%$
- Typical "compensated" profiles
- Almost spherical, tend to sphericity (Bertschinger, 1995; Sheth and van de Weygaert, 2004)
- Particularly sensitive to DE !

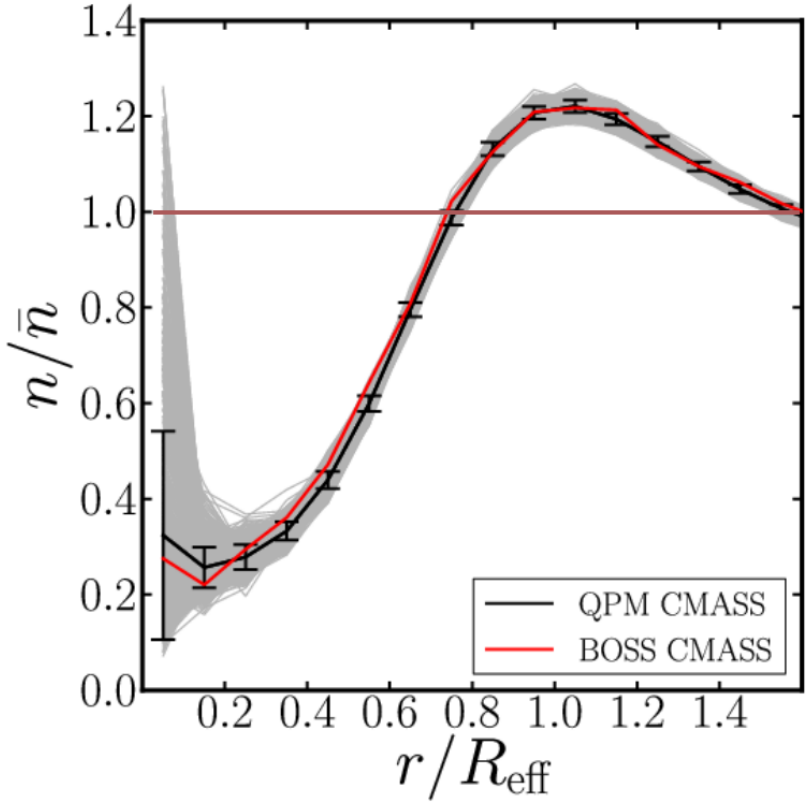

Figure: Observable void radial profile traced by galaxies (Mao et al., 2017)

Introducing CoSpheres

The structuration of the Universe

To constrain efficiently cosmology

Need a **prediction** to compare to ...

- Simple approach : top-hat profile (Sheth and van de Weygaert, 2004)
- Parametric approach (Hamaus et al., 2014)
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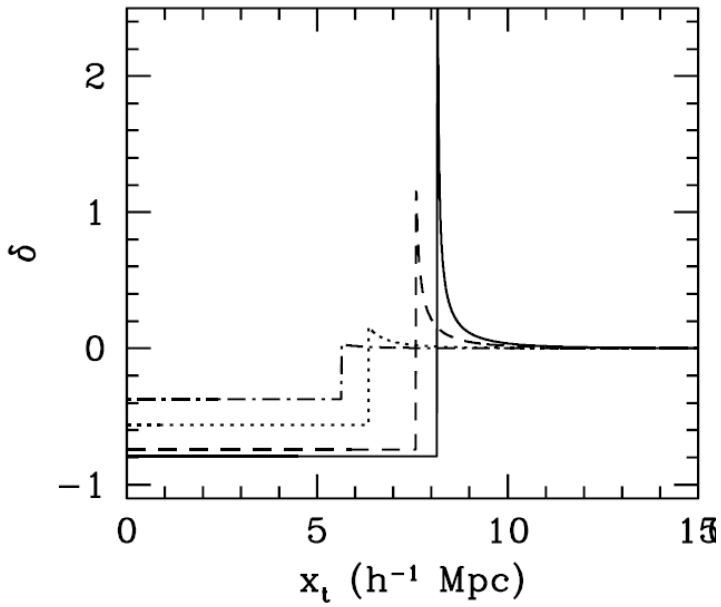

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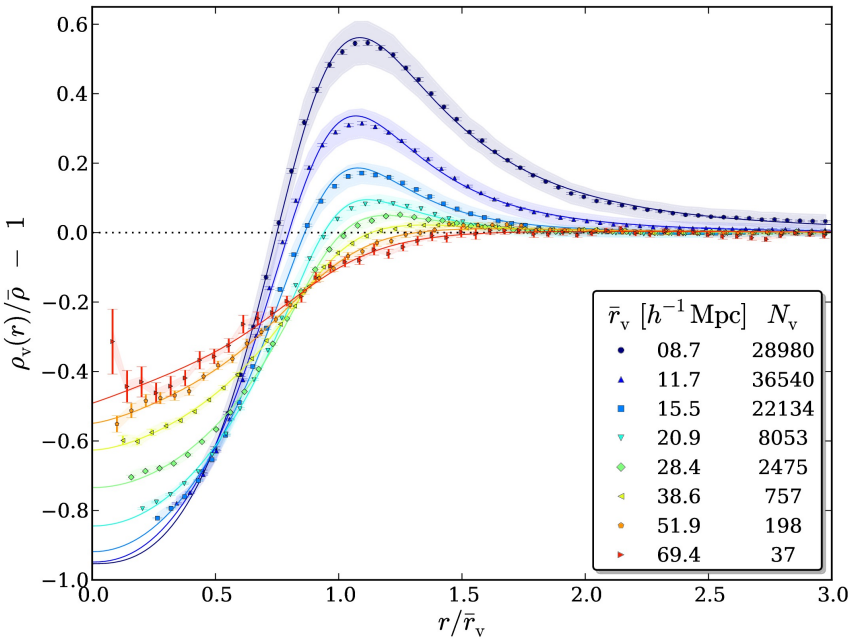

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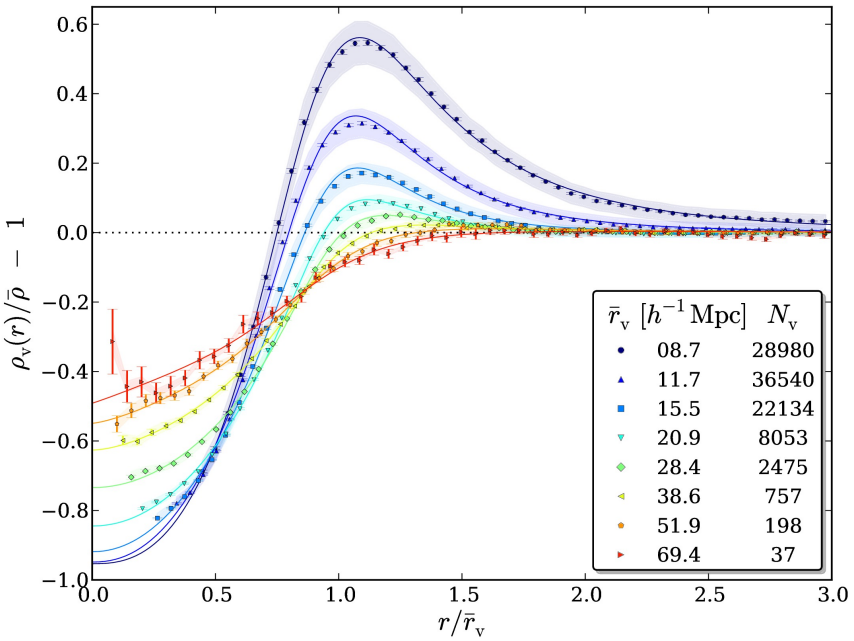
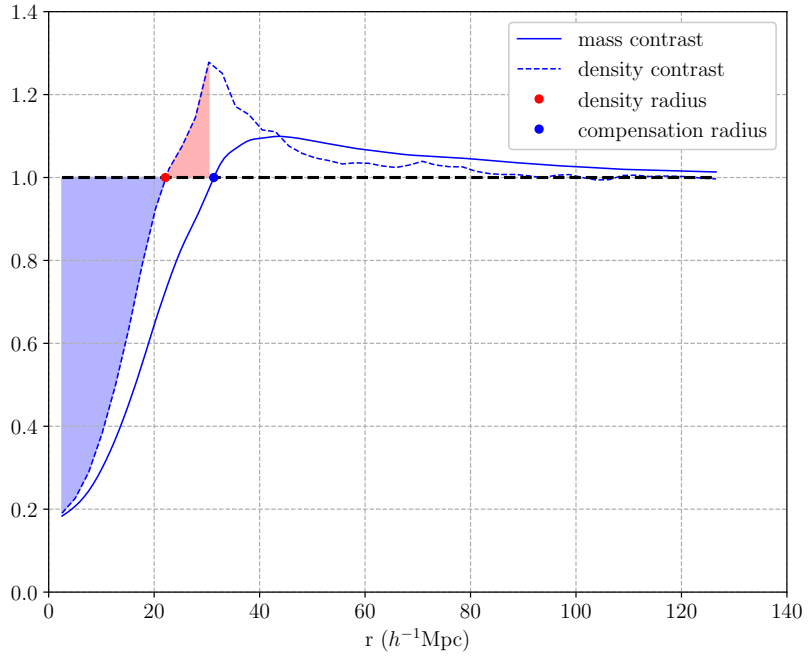


Introducing CoSpheres

CoSpheres in numerical simulations

Spherical profiles around extrema in numerical simulations ($z = 0$)



density contrast $\delta(r)$

$$\delta(r) = \frac{\rho(r)}{\bar{\rho}} - 1$$

Mass contrast $\Delta(r)$

$$\Delta(r) = \frac{M(r)}{4\pi/3\bar{\rho}r^3} - 1$$

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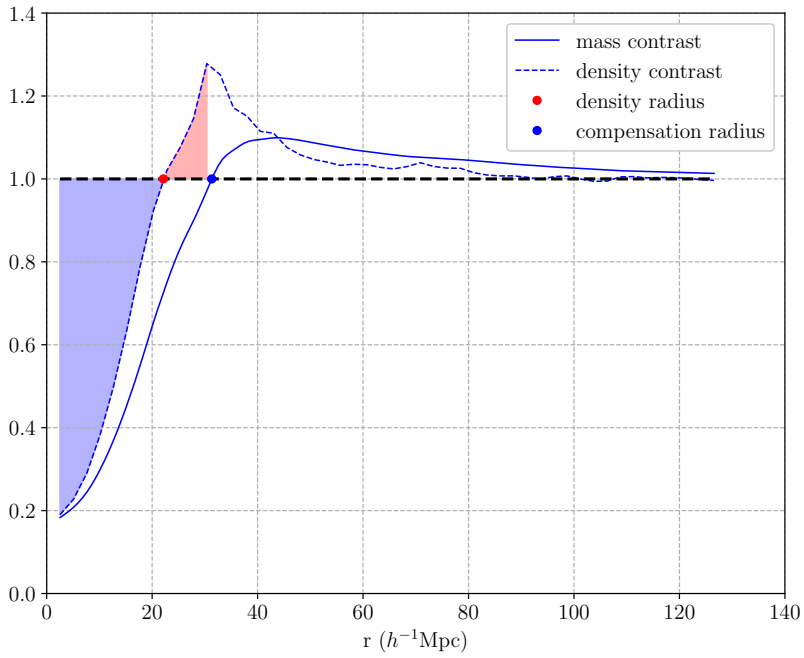

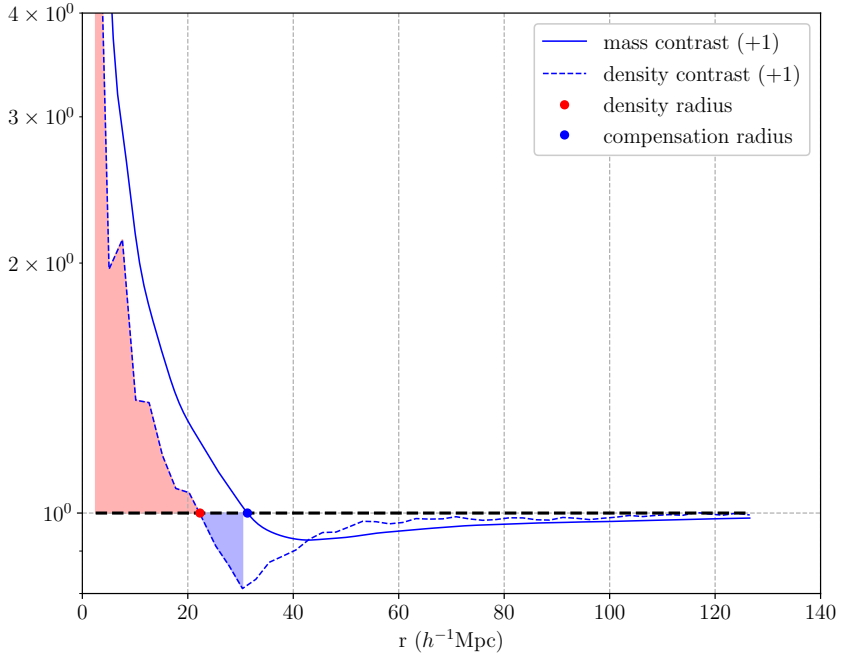

Introducing CoSpheres

Defining CoSpheres

Defining **CoSpheres**

Compensated **Sphe**rical **re**gions (arXiv:1709.04490)

- Isotropy on large scale + stacking $\Longrightarrow$ sphericity
- Centred on local extrema of $\delta(\boldsymbol{x})$
- Mass conservation $\Longrightarrow$ compensated profiles

$$\forall \quad \text{extrema} \quad \exists R_1 \quad \text{the } \textbf{compensation radius}, \quad \boxed{\Delta(R_1) = 0} \quad (1)$$

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Average (mass contrast) profiles at $z = 0$ for various R_1

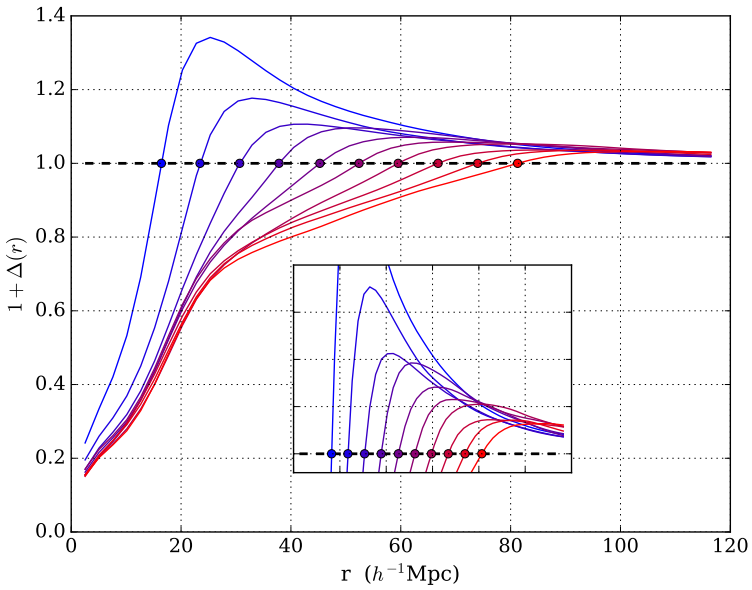


Figure: Compensated profiles around minima = cosmic voids

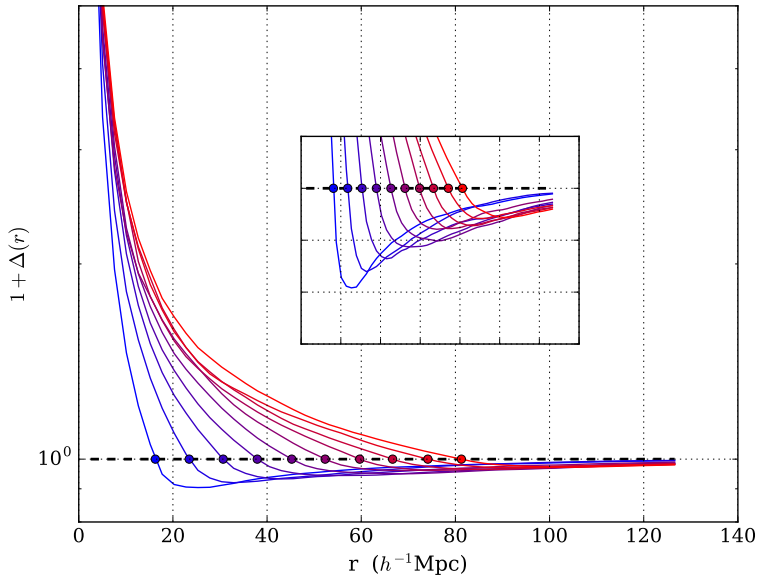
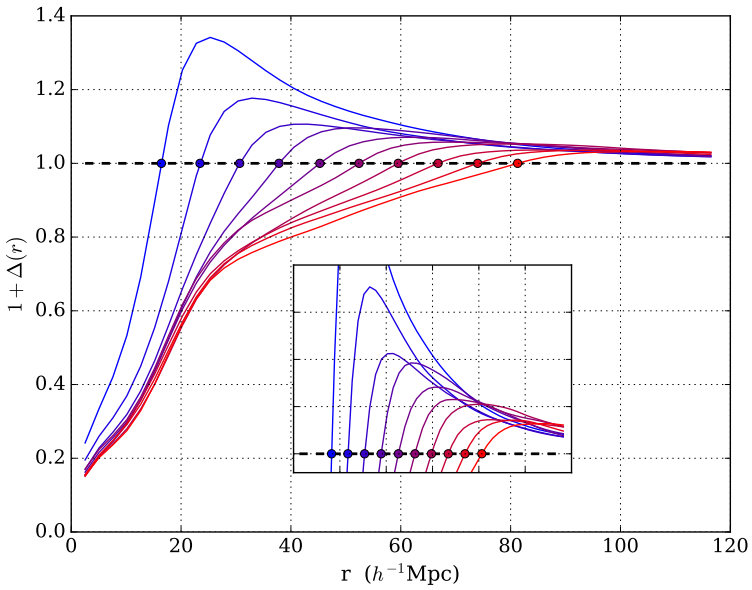


Figure: Compensated profiles around maxima = DM halos

Introducing CoSpheres

Defining CoSpheres

goal : model these cosmic structures $\Longrightarrow$ study the imprint of DE/MG



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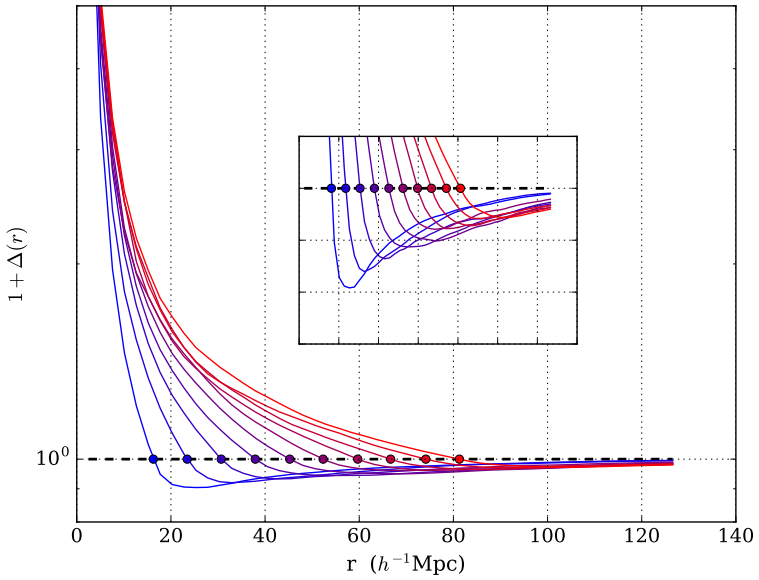

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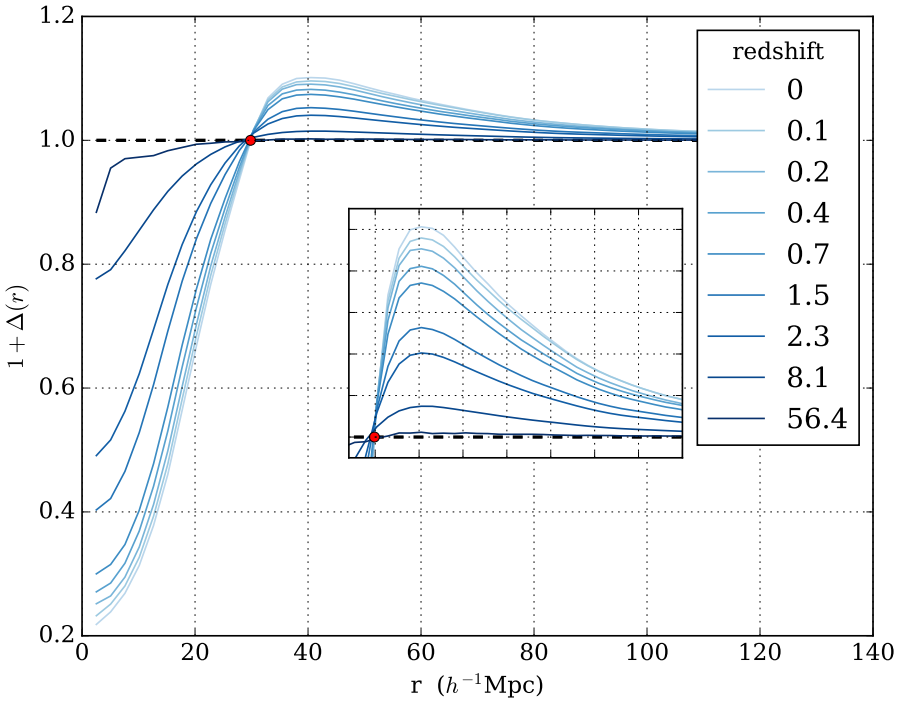
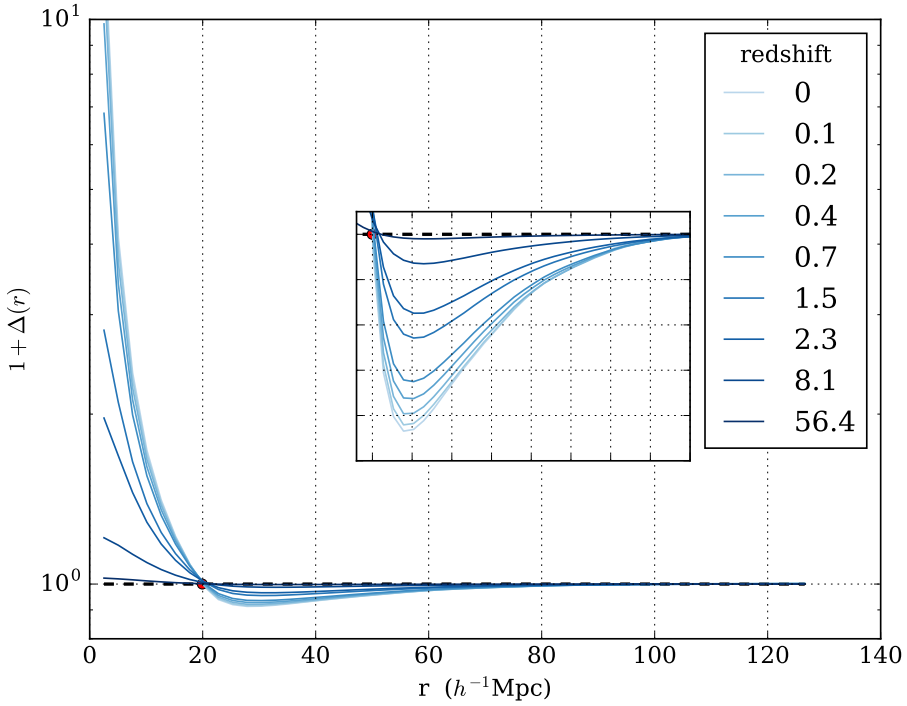
Bubble Universes ...

Defining CoSpheres

Dynamical evolution of these structures





Bubble Universes ...

Defining CoSpheres

From numerical simulations, CoSpheres are

- generated within the **primordial** (Gaussian) Universe
- conserving their comoving R_1 !

- R_1 isolates spheres whose *averaged* density $\langle \rho \rangle \equiv \bar{\rho}$
- $\Longrightarrow$ $R_1(t) \propto a(t)$
- $\Longrightarrow$ CoSphere $\equiv$ spatially bounded replicas of the Universe

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Reconstructing these regions in Gaussian Random Field

Defining CoSpheres

Constrained GRF

Must implement :

- Extrema constrains (Bardeen et al., 1986)
- Compensation constrains

leads to ...

- average profile $\langle \delta | \boldsymbol{C} \rangle (\boldsymbol{x})$
- parameters distribution

$\Longrightarrow$ **theoretical predictions** (in GRF at least ...)

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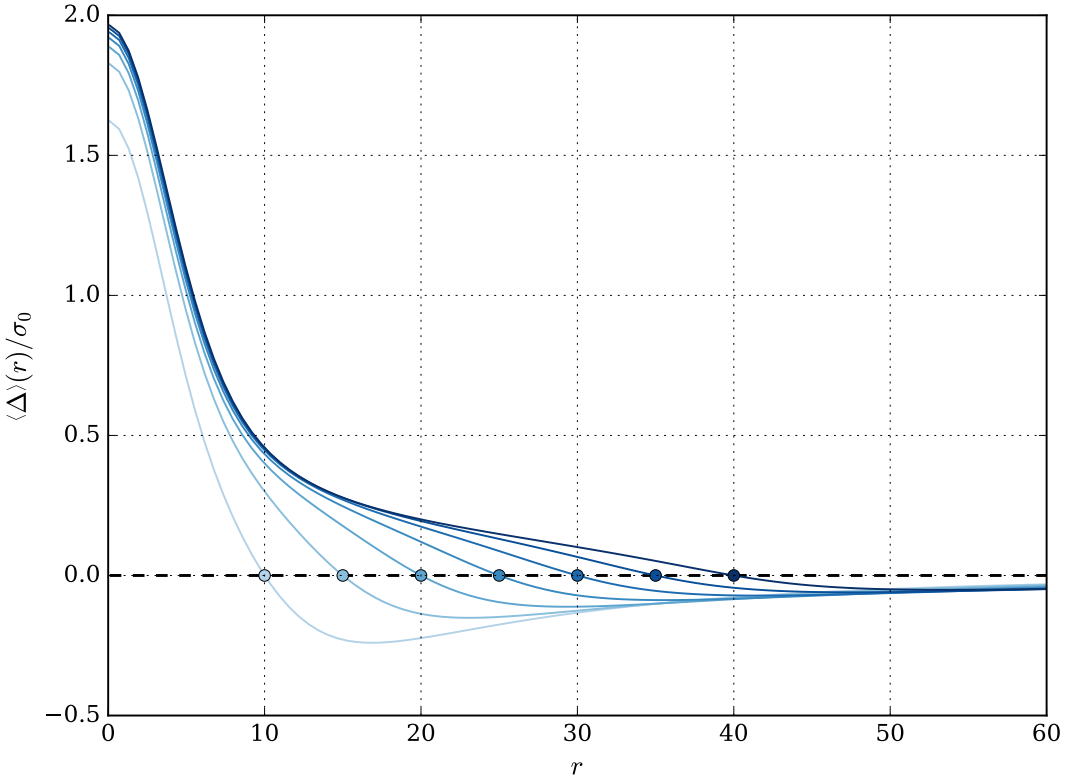

Figure: Theoretical average CoSphere profile in GRF

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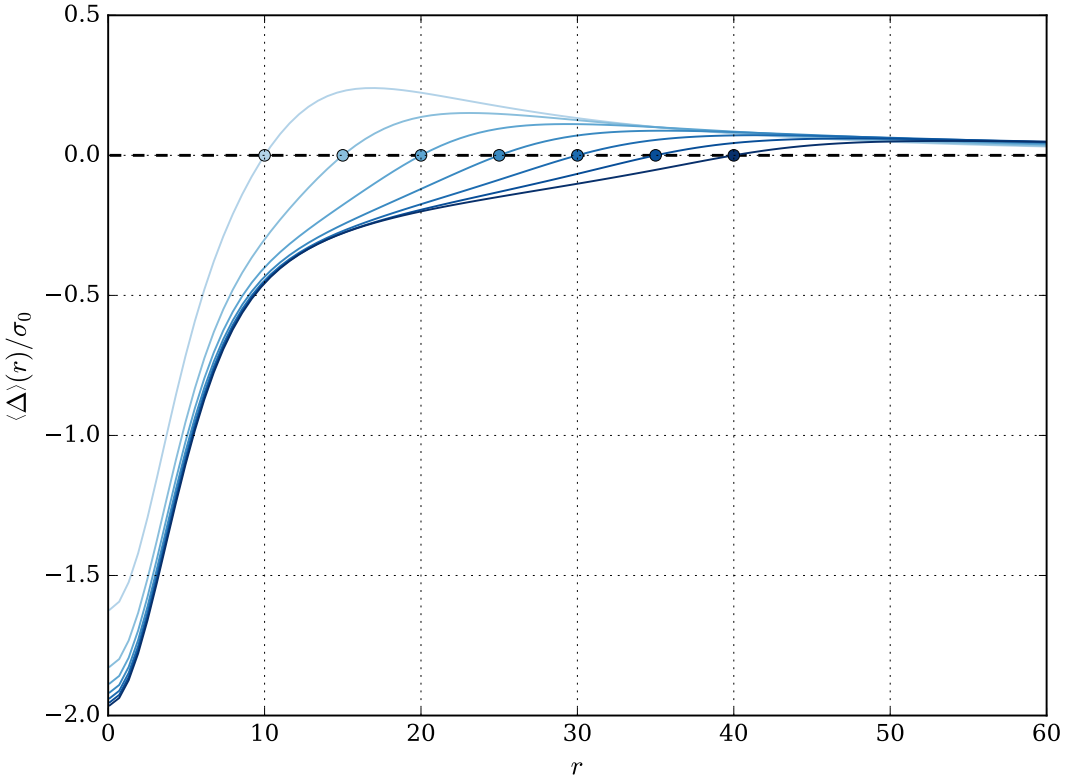

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Primordial statistics of Cospheres

Back to GRF

Cosphere's statistics

GRF : parameter statistics. Particularly, the pdf of $\delta(R_1) = \delta_1$ (for each R_1)

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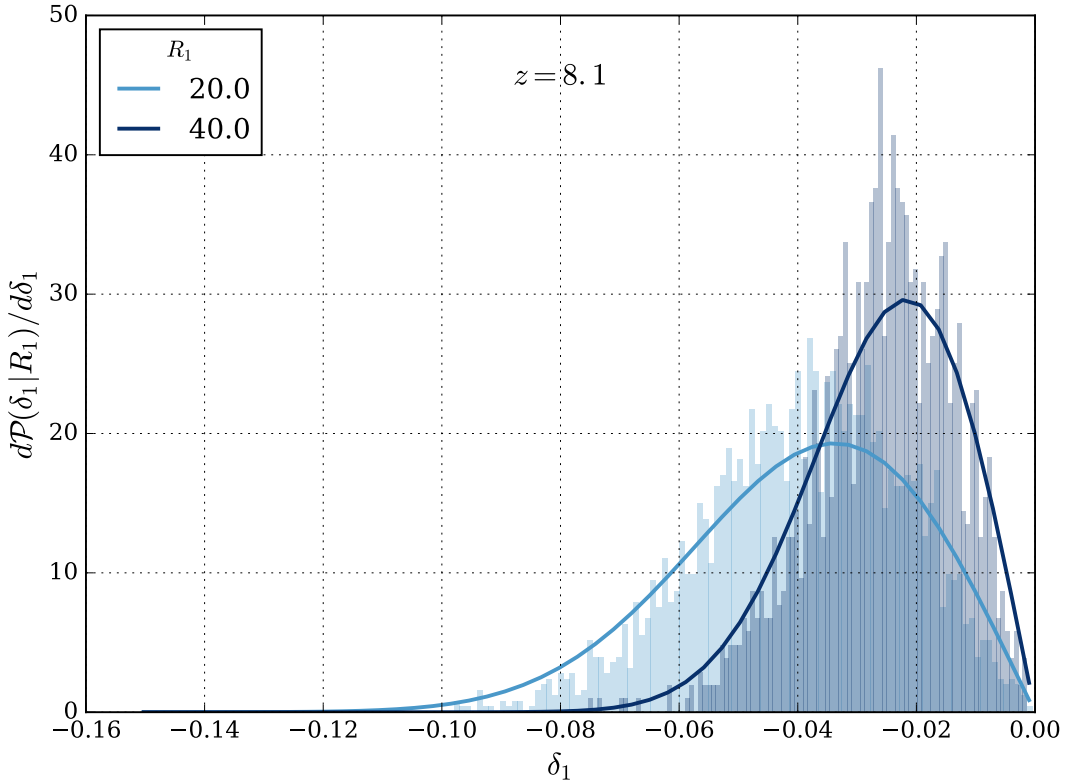

Figure: Comparison between Cosphere prediction and numerical simulations

Gravitational dynamics of CoSphere

From CMB to non linearly structures Universe

From $z \simeq 1100$ to $z = 0$ ...

Question

What is the appropriate dynamics ?

Answer

Spherical symmetry $\Longrightarrow$ Lagrangian **Spherical** collapse

- non linear dynamics
- easiest symmetry ...

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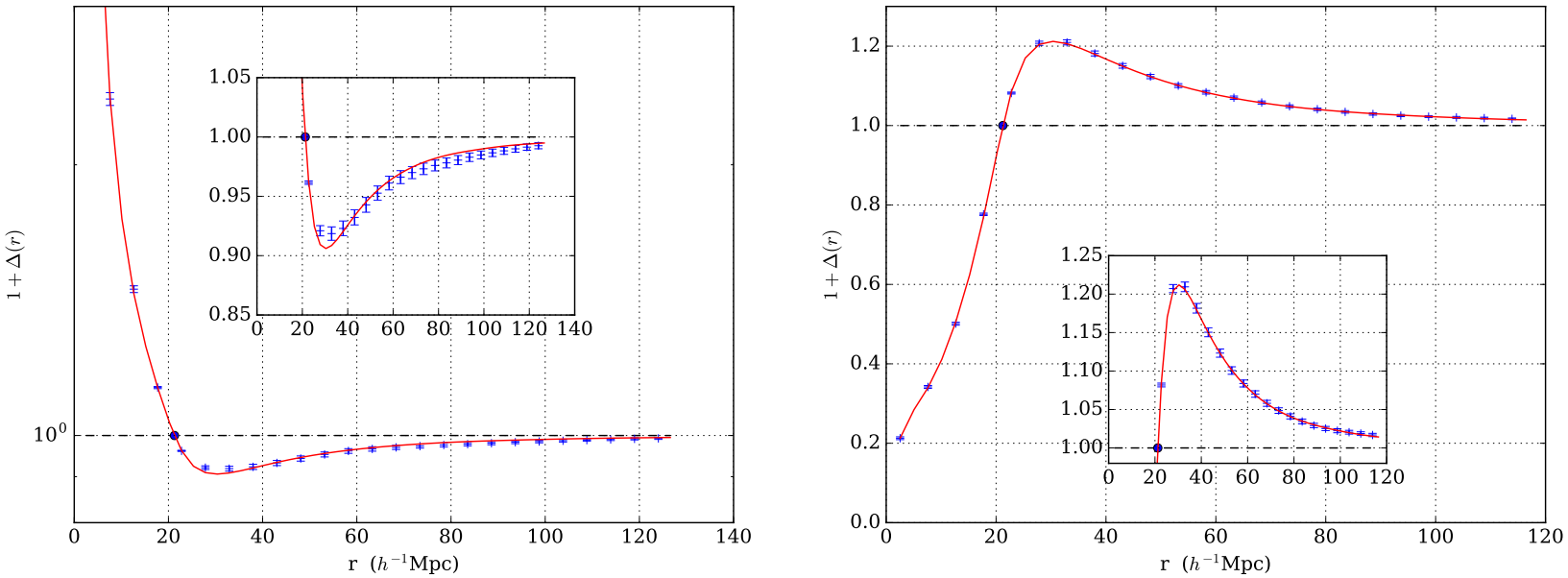

Figure: reconstruction of mass profiles at $z = 0$ for $R_1 = 20\ h^{-1}$Mpc. Blue : numerical simulation, red : CoSphere reconstruction

Beyond ΛCDM

MG behavior

From ΛCDM to Modified Gravity (Horndeski model in QSA)

Background effects

MG ⇔ effective *Dark Energy* with $w_{de}(t)$.

BUT : possible *Phantom crossing* $w_{de}(t) < -1$

Effects on LSS

$ds^2 = (1+2\Psi)dt^2 - a^2(t)(1-2\Phi)d\boldsymbol{x}^2$

Einstein equations :

$$k^2\Phi = -4\pi G\mu(a,k)a^2\bar{\rho}\delta$$
$$\Psi = \gamma(a,k)\Phi$$

with $\mu = \gamma = 1$ in GR

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Spherical collapse in Modified Gravity

Spherical Lagrangian dynamic in MG

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$$\text{Geodesic equation : } \ddot{\chi} + 2H\dot{\chi} = -\frac{1}{a^2}\nabla\Phi$$

$$\text{in real space : } \nabla^2\Phi = 4\pi G\bar{\rho}_m\left[\delta * \tilde{\mu}\right] \tag{2}$$

$$\text{with } \tilde{\mu} = \underbrace{\frac{G_0}{G}}_{\text{1 in GR}}\delta_D^{(3)}(r) + \underbrace{\frac{G_\infty - G_0}{G}\frac{1}{4\pi\lambda^2}\frac{e^{-\frac{r}{\lambda}}}{r}}_{\text{0 in GR}} \tag{3}$$

and

$$G_\infty(a) = p_4^{-1}(a)G, \quad G_0(a) = p_3(a)p_5^{-1}(a)G, \quad \lambda(a) = \sqrt{p_5(a)p_4^{-1}(a)}$$

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Dynamical equation in MG

$$\boxed{\frac{\partial^2 \mathcal{R}}{\partial \tau^2} + \frac{1}{\sqrt{2\Omega_m}} \frac{\partial \mathcal{R}}{\partial \tau} = \underbrace{\frac{G_{eff}}{G}}_{1 \text{ in GR}} \left(\mathcal{R} - \frac{1+\Delta_i}{\mathcal{R}^2} \right)} \tag{4}$$

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$G_{eff}(r,t)$: complex problem !

A fitting function for CoSpheres

$$G_{eff}(r,t) = G_\infty \left[1 - (1 + xe^{-x})\right] + G_0(1+x)e^{-x}, \quad \text{with} \quad x = 0.56 \times \frac{r}{\lambda}$$

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Beyond ΛCDM

A toy model : $f(R)$ gravity

An example : $f(R)$ gravity

$$S = \frac{1}{2\kappa}\int d^4x\sqrt{-g}\left(R + \underbrace{f(R)}_{0 \text{ in GR}}\right) + S_m[\psi_m, g_{\mu\nu}] \tag{6}$$

with (Hu and Sawicki, 2007)

$$f(R) = f_0\frac{\xi+1}{\xi+\left(\frac{R_0}{R}\right)^n}, \quad \text{with} \quad R_0 = R|_{z=0}\,, \quad f_0 = -2\Lambda \tag{7}$$

Parametrized by

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Spherical Collapse

$$\begin{cases} G_0 = 4/3G \\ G_\infty = G \end{cases} \tag{9}$$

At first order in $f_R^0 \ll 1$,

$$\lambda \propto \sqrt{|f_R^0|} \left[\frac{a^3 \Omega_m(a)}{4 - 3\Omega_m(a)} \right]^{\frac{n+2}{2}}$$

and

$$w_{de} + 1 \simeq -f_R^0 \times [...]$$

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$$\lambda \propto \sqrt{|f_R^0|}\left[\frac{a^3\Omega_m(a)}{4-3\Omega_m(a)}\right]^{\frac{n+2}{2}}$$

and

$$w_{de} + 1 \simeq -f_R^0 \times [...]$$

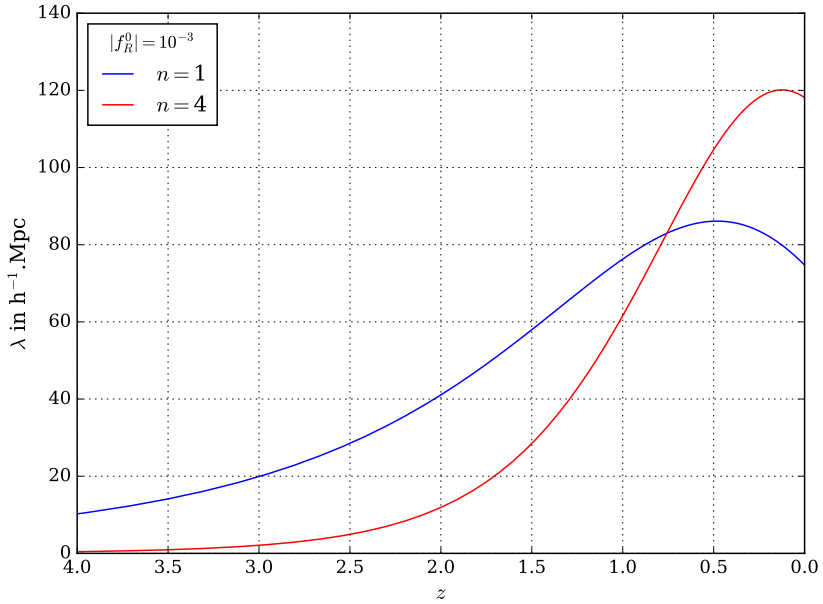

Figure: Evolution of $\lambda(z)$ for $|f_R^0| = 10^{-3}$ and $n = 1$ or $n = 4$

Beyond ΛCDM

A toy model : $f(R)$ gravity

Spherical Collapse

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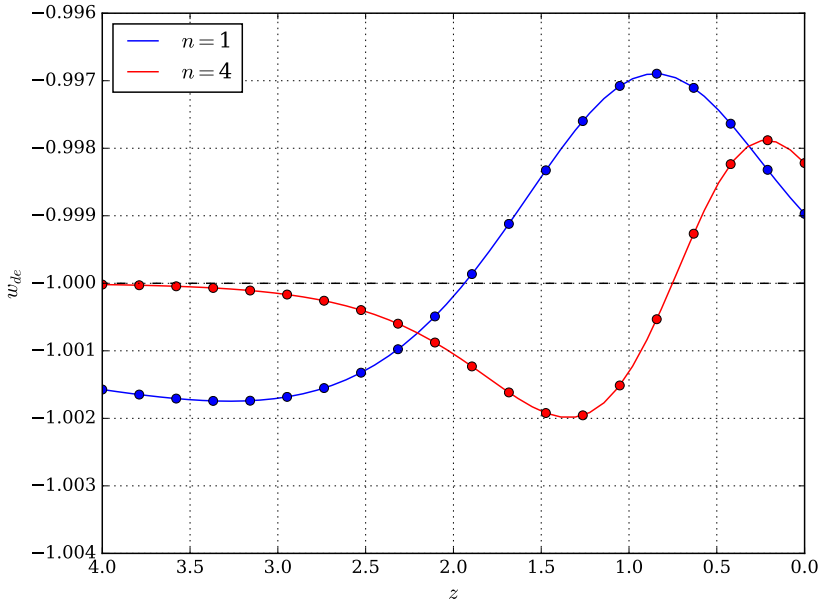

Figure: Evolution of $w_{de}(z)$ for $\left|f_R^0\right| = 10^{-3}$ and $n = 1$ or $n = 4$

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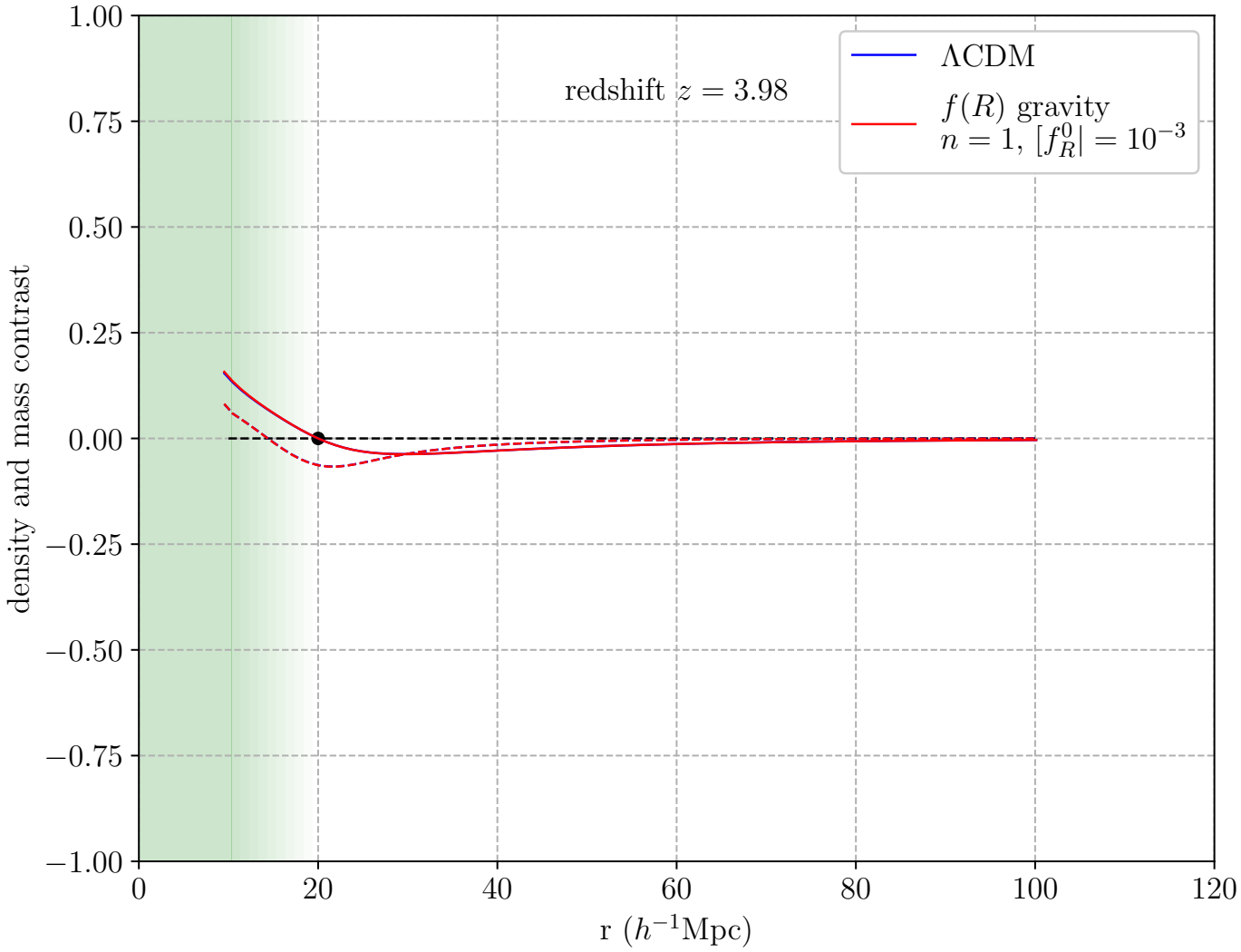

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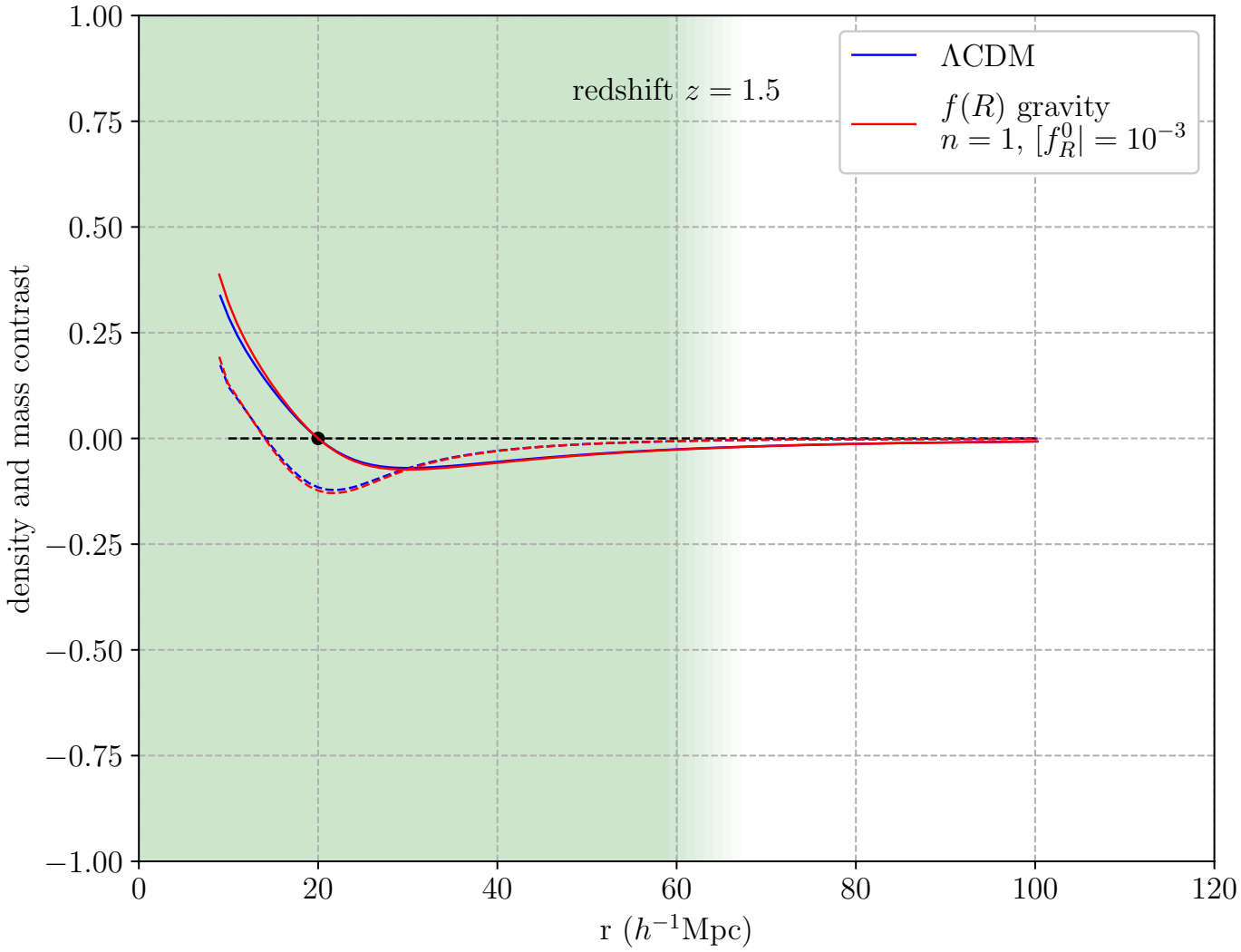

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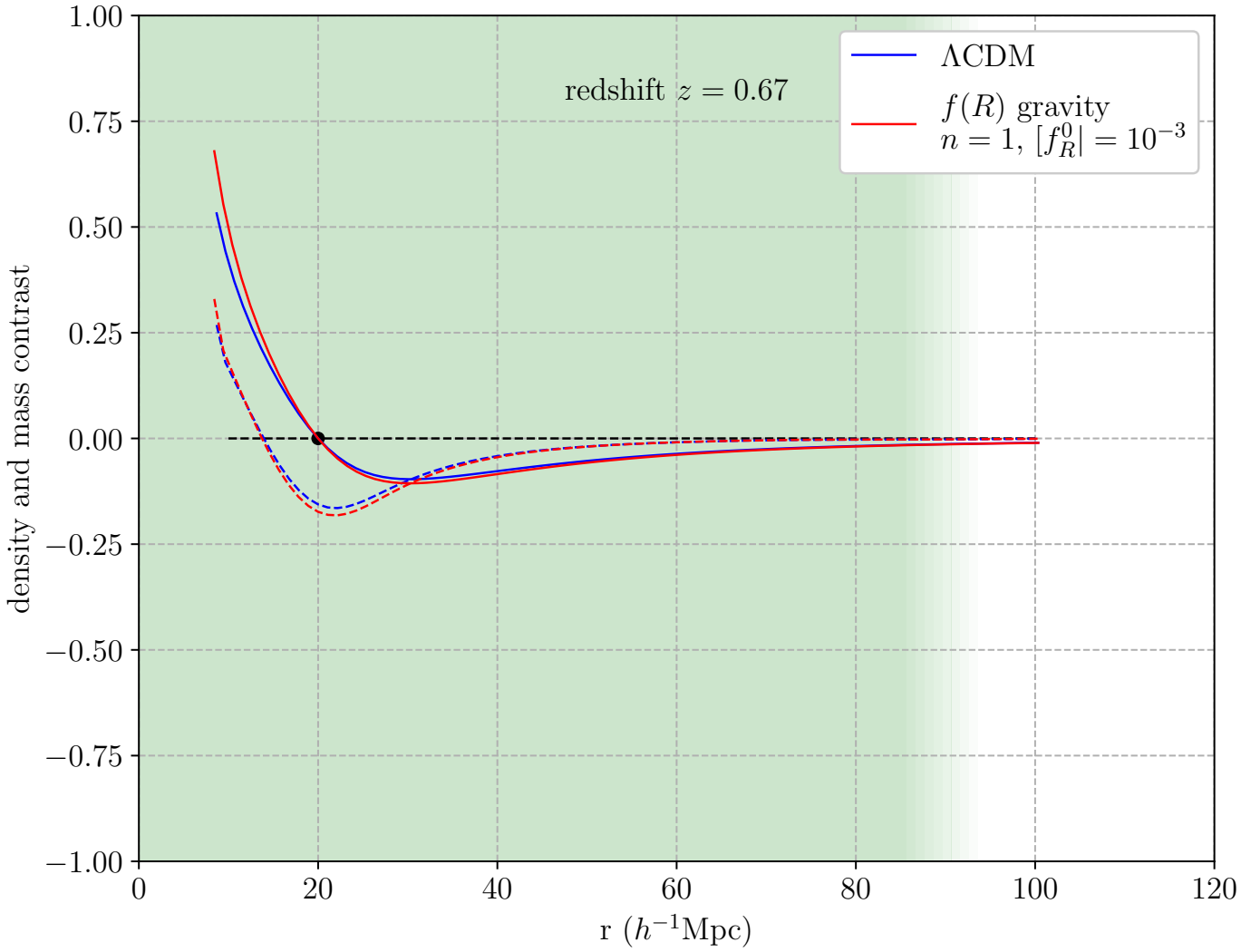

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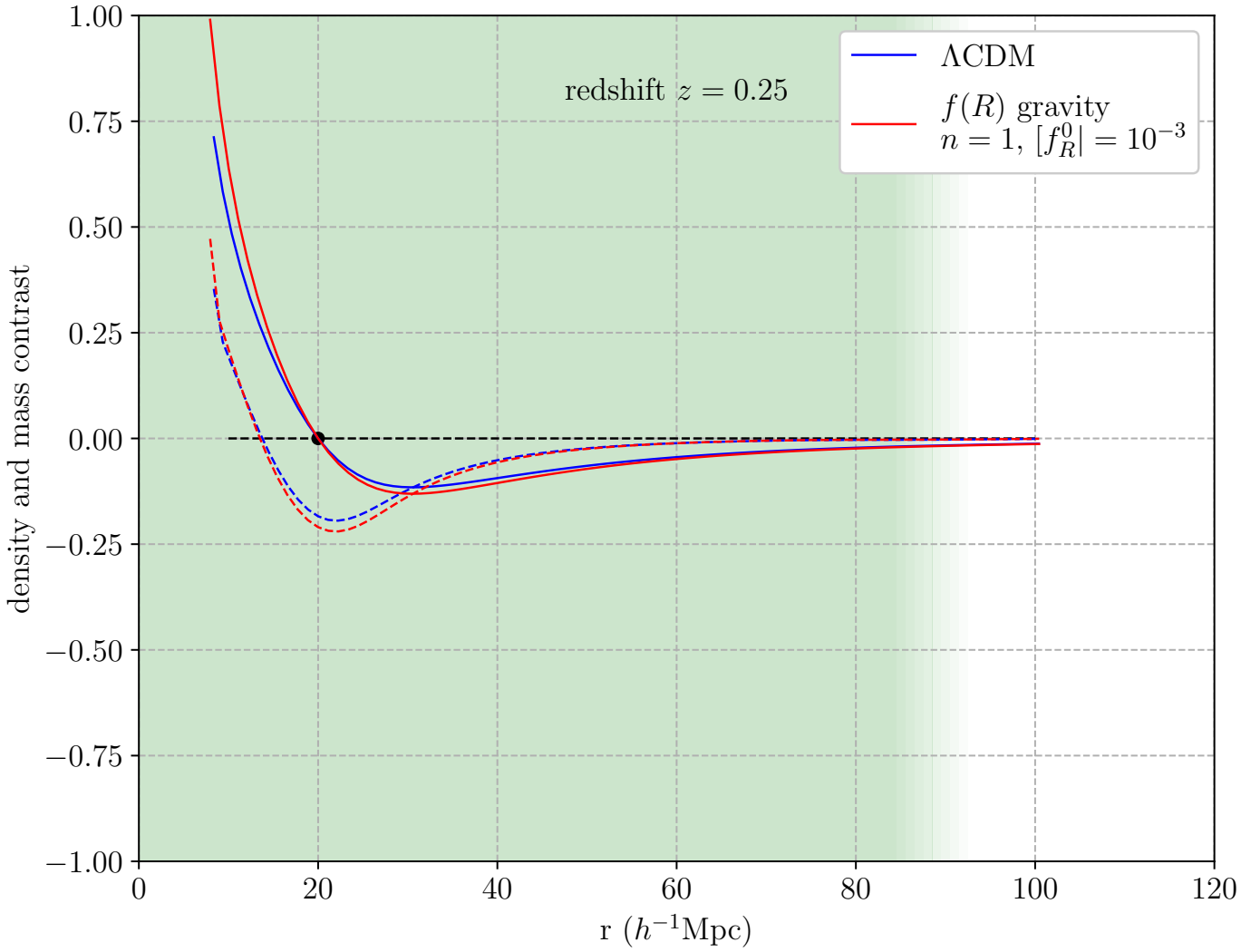

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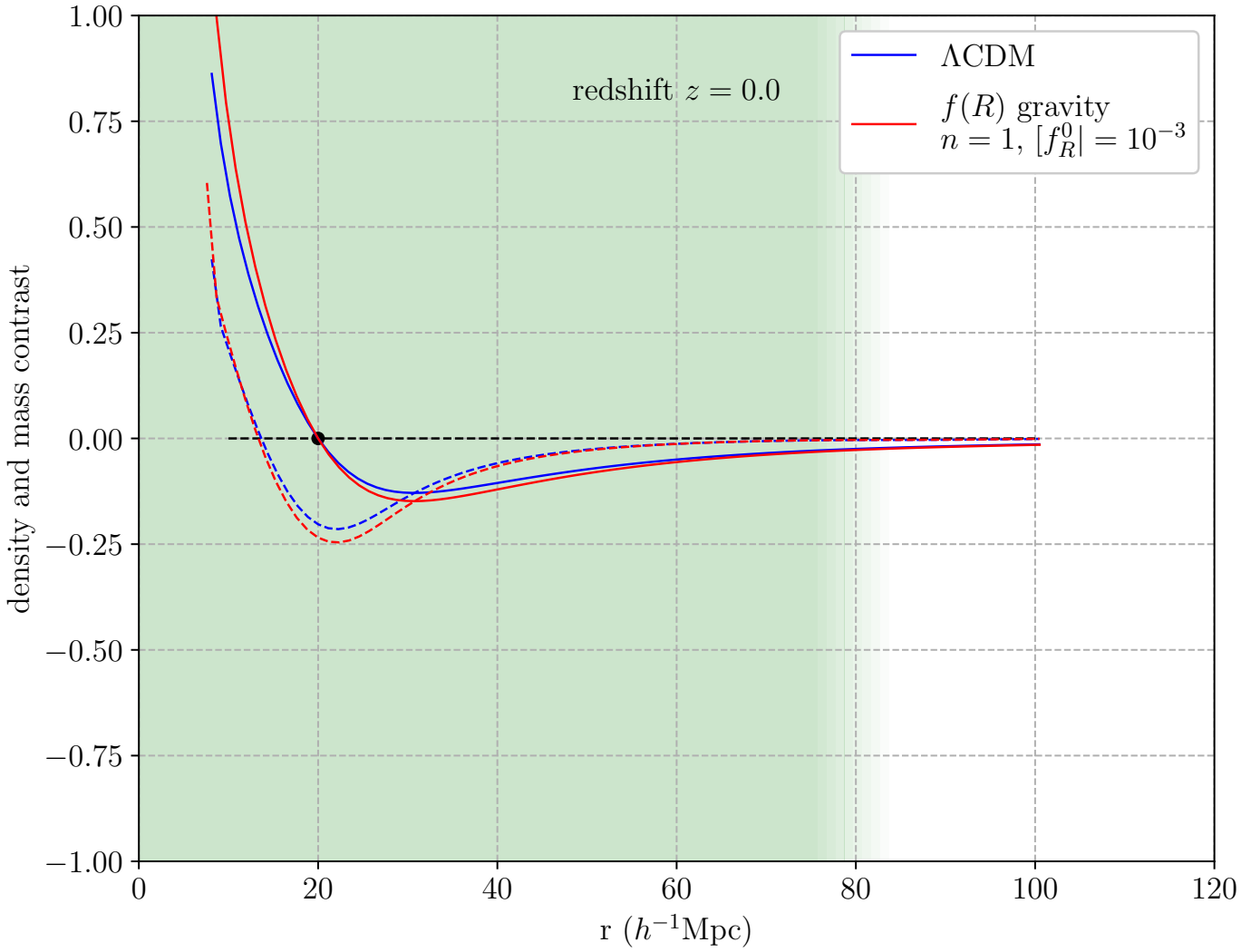

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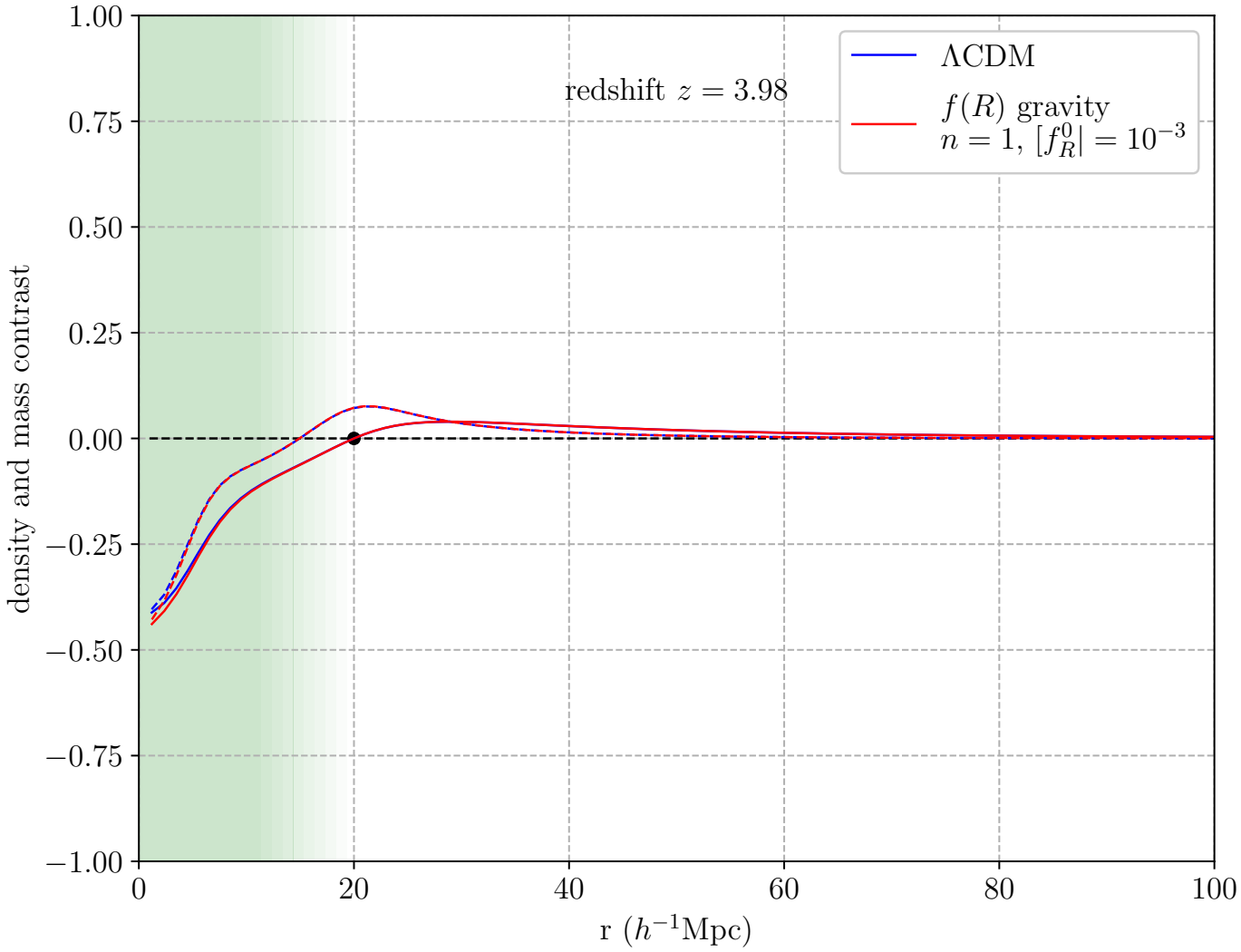

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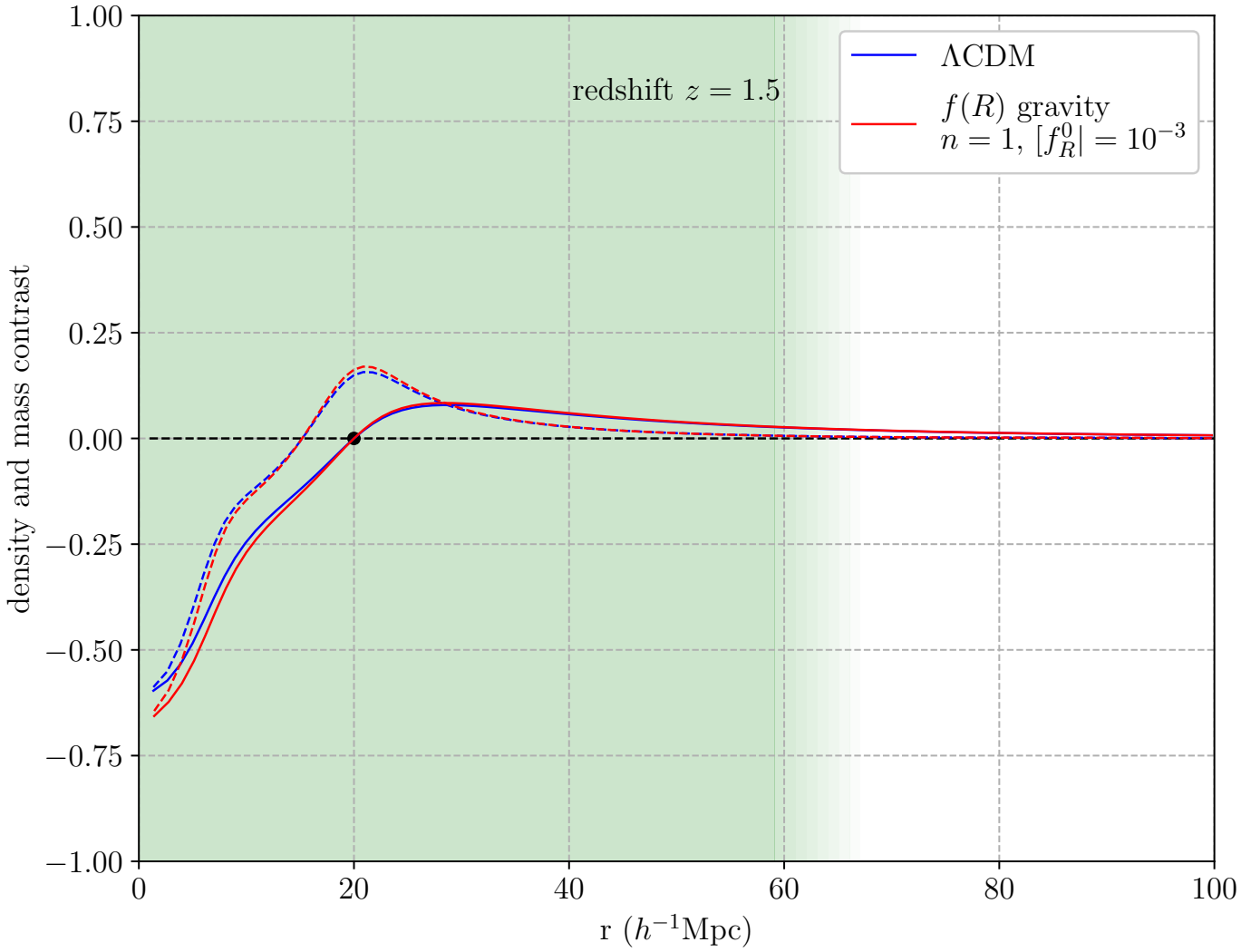

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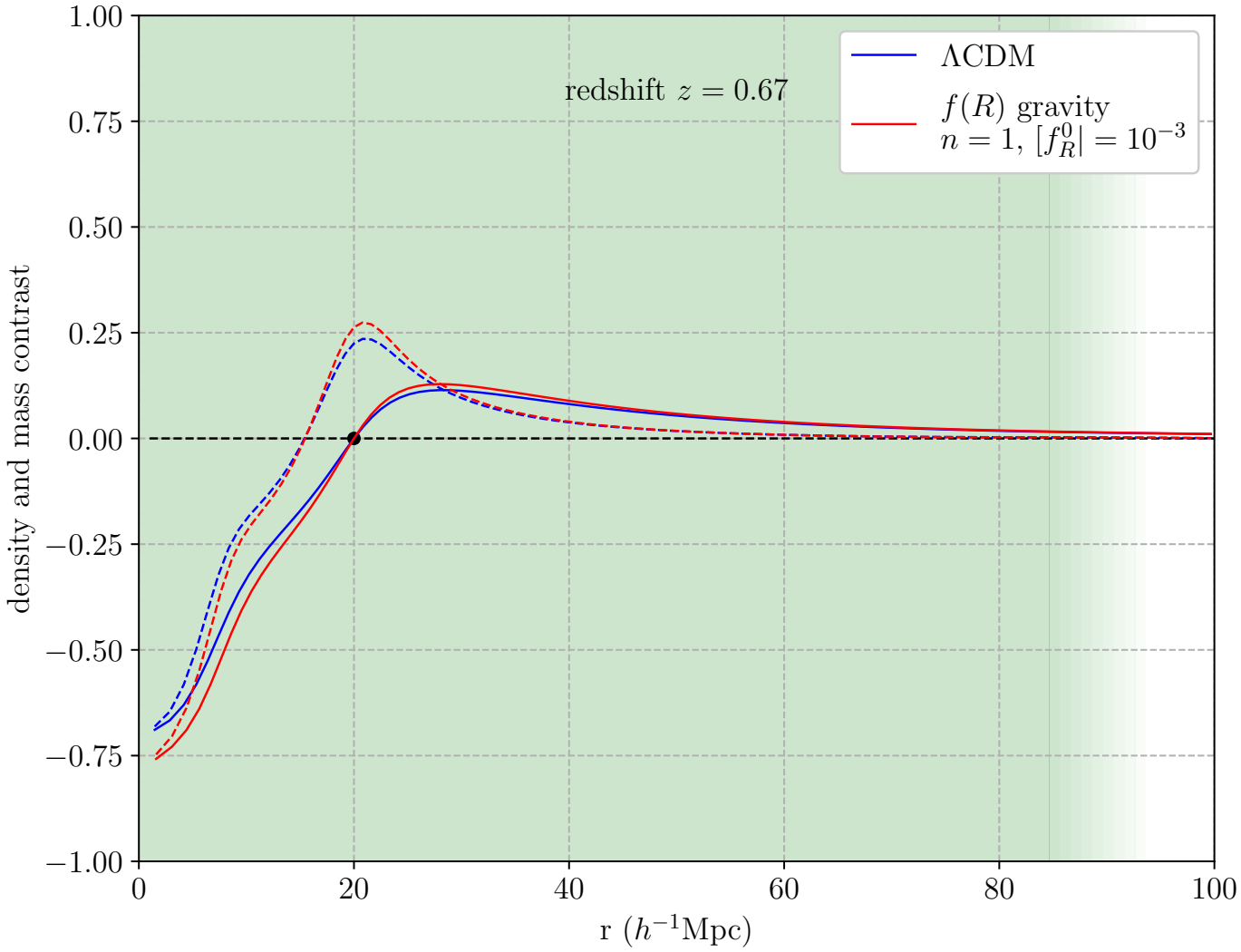

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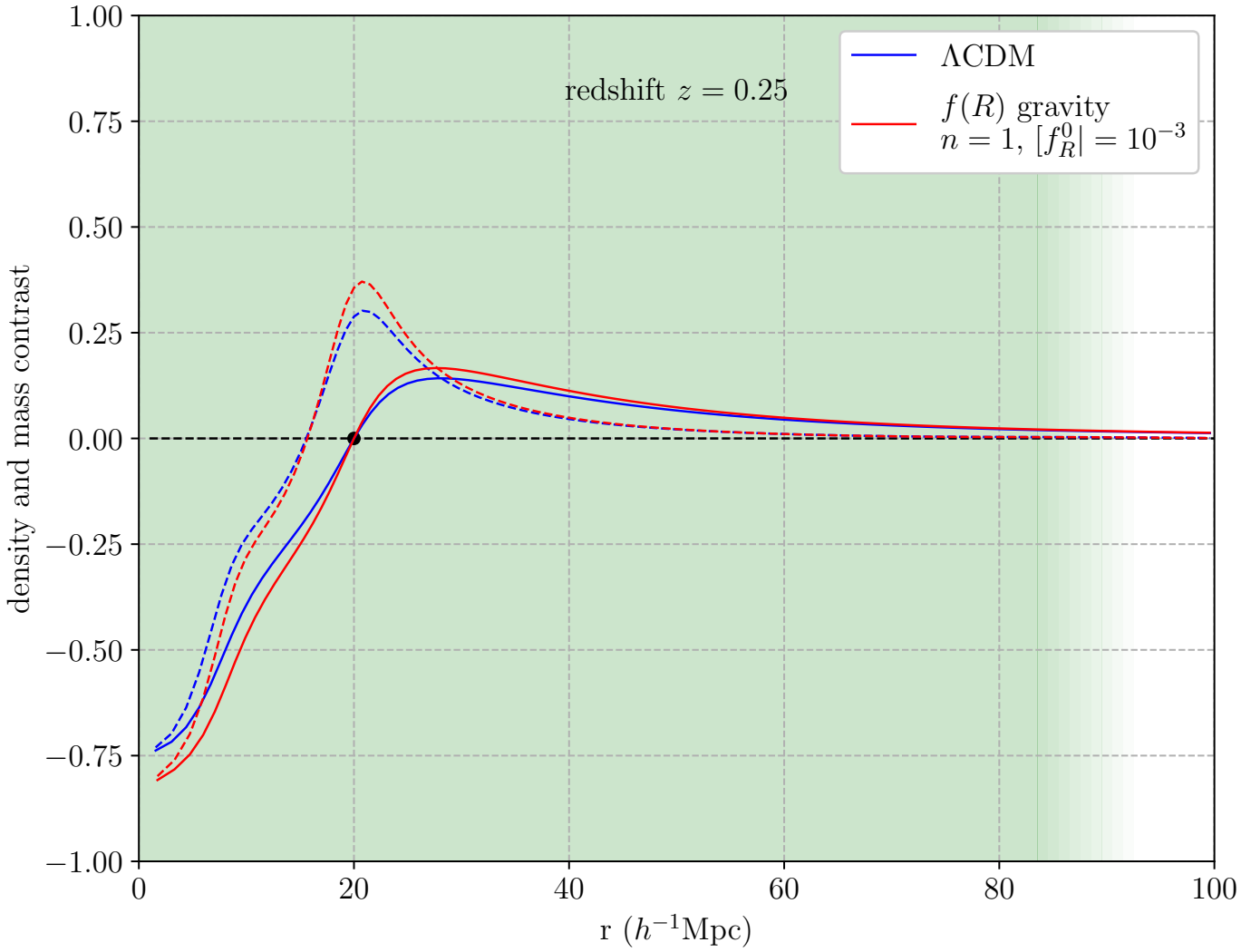

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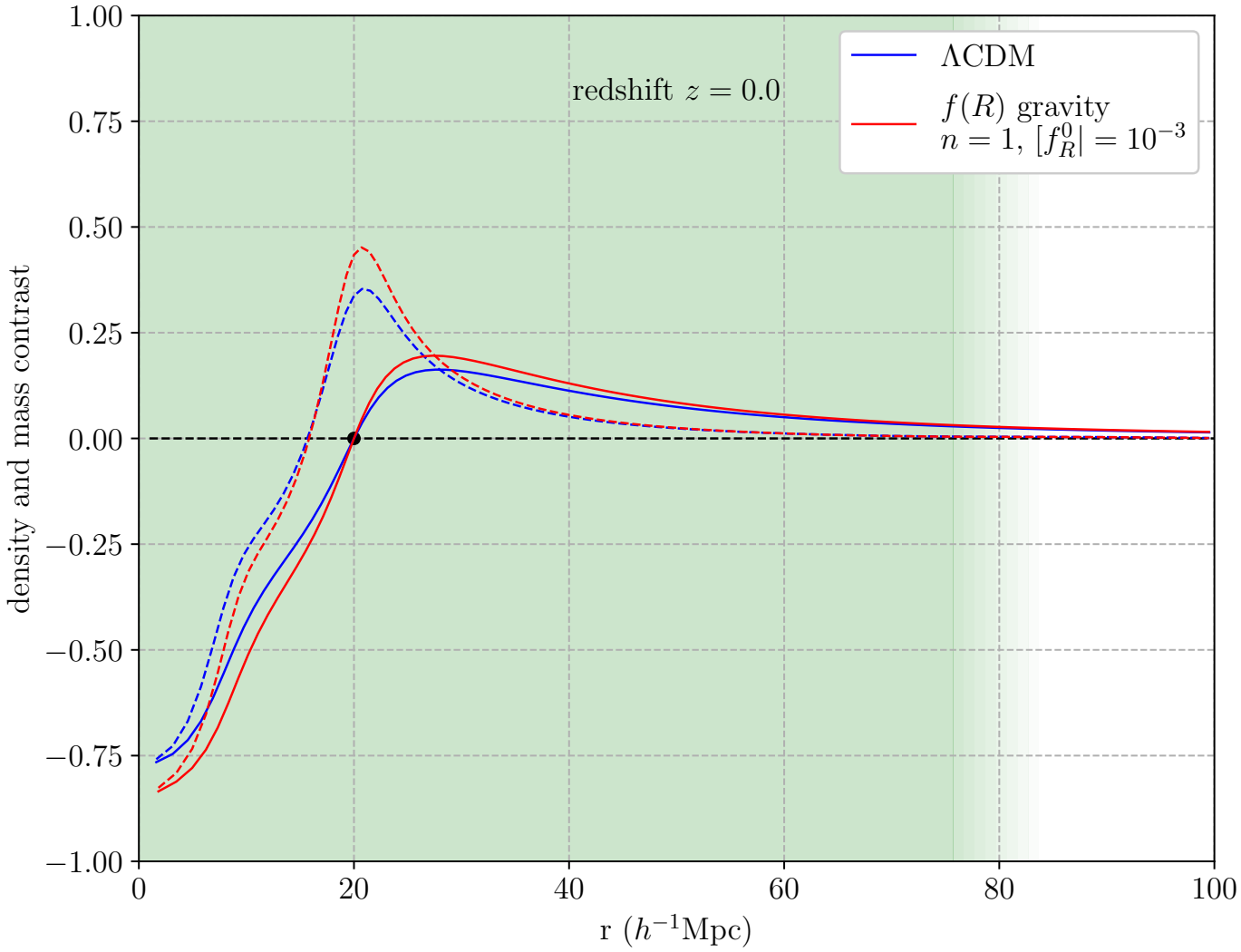

Beyond ΛCDM
Probing modified Gravity

How can you probe MG with CoSpheres ?

Use predictions !

- $\delta(R_1)$ distribution
- $\langle \delta(R_1) | R_1 \rangle$
- linear growth rate at $r = R_1$ (using RSD)

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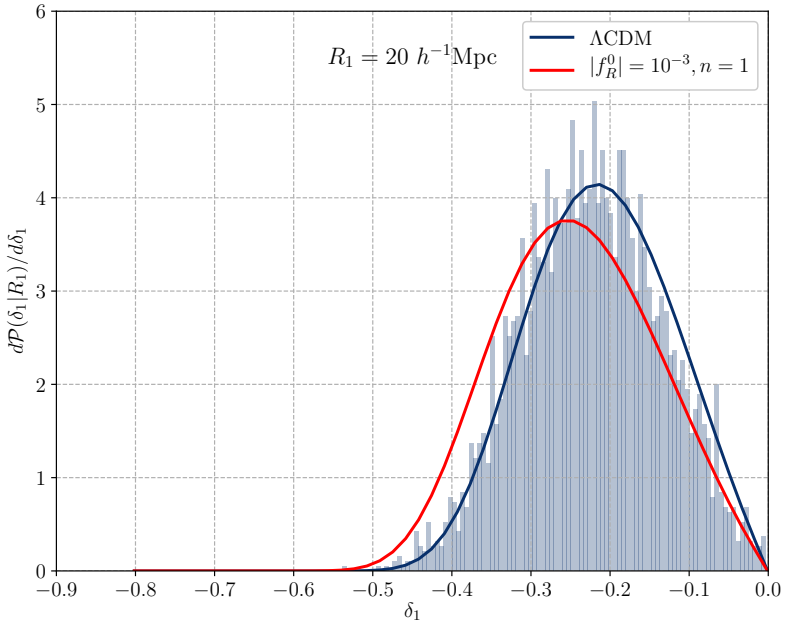

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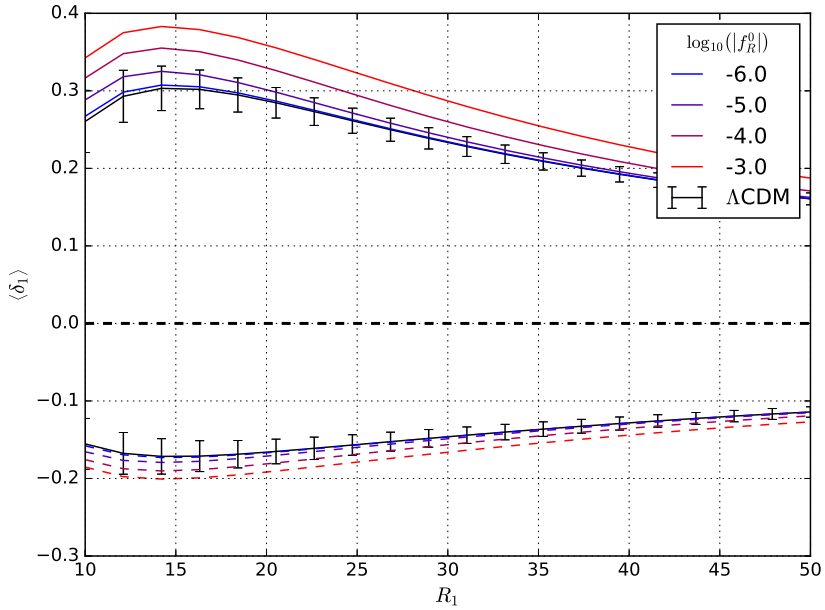

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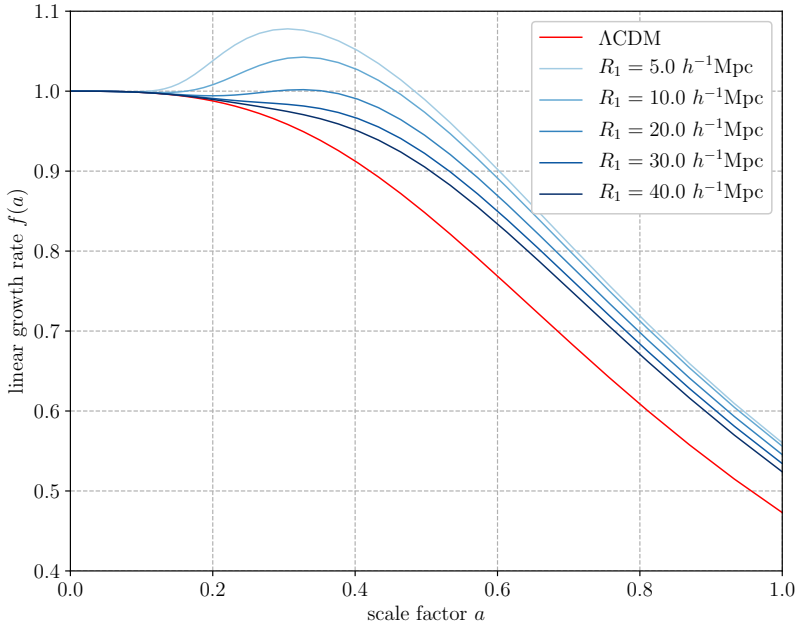

Conclusion

Goal

It is possible to have a **prediction** for cosmic void profiles and statistics ?

Short answer

yes $\Longrightarrow$ define CoSpheres (GRF to $z = 0$ through spherical collapse)

Is it useful ?!

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next : use this formalism on real galactic survey ...

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Thank you for your attention !