Cosmology of gravity theories beyond General Relativity

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LECTURE 3

Cosmological probes of Modified Gravity

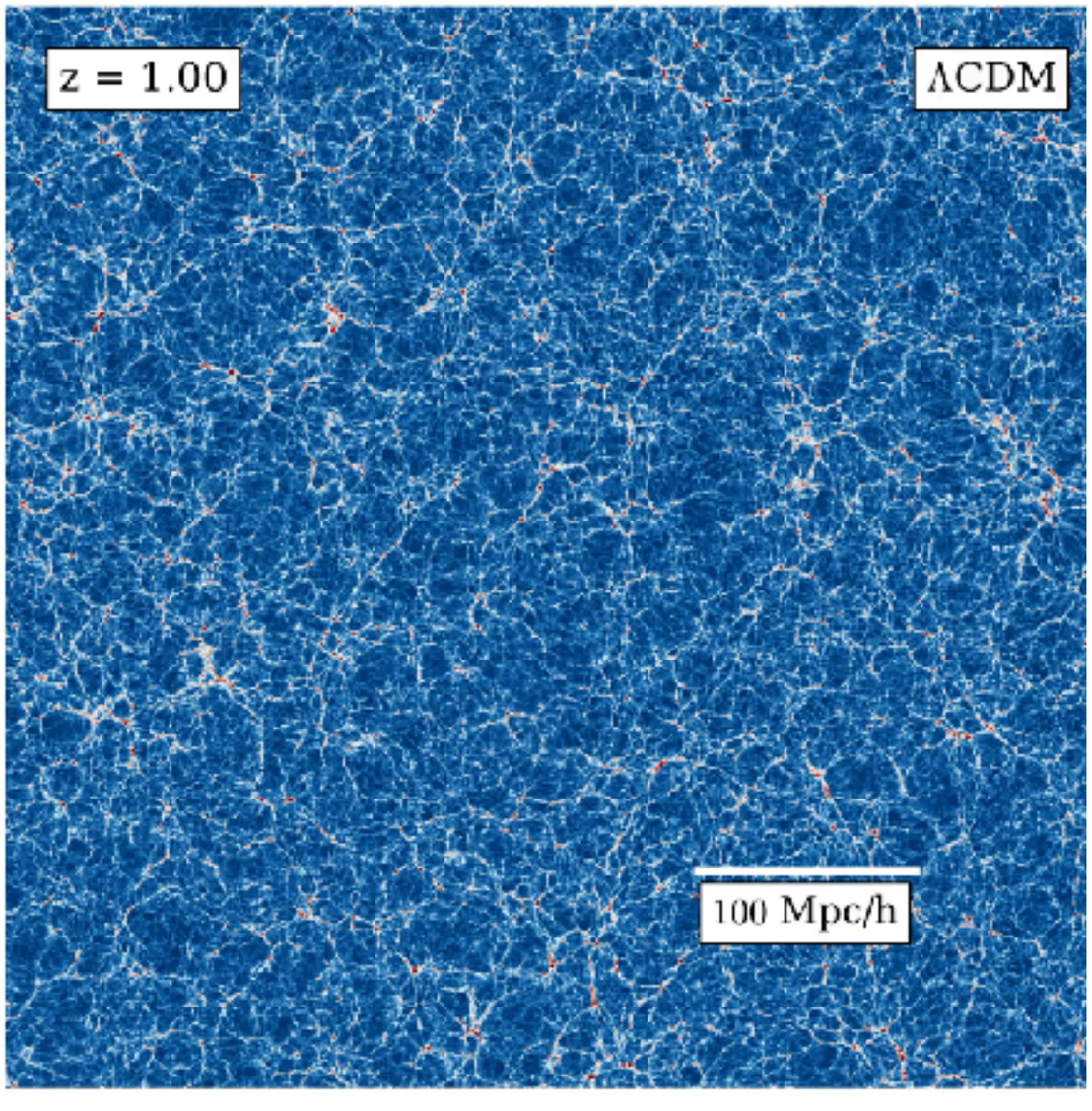
Structure formation probes deviations from GR

(Christiansen, Adamek, Hassani, DFM)

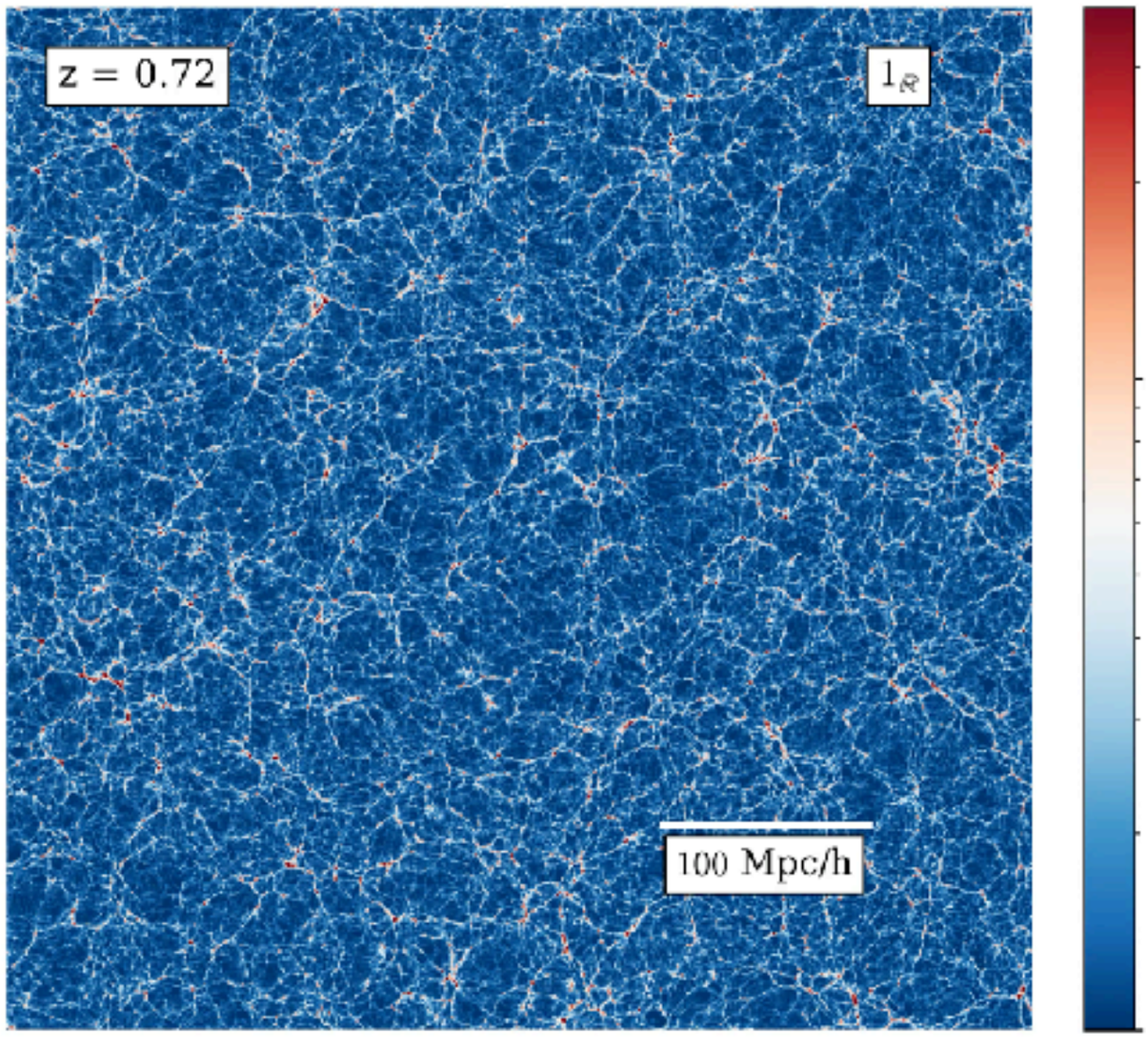
$$\ddot{\mathbf{x}} = -\nabla\Psi_N - f(\phi)\nabla\phi$$

GR — Fifth Force

General Relativity



Modified Gravity (Symmetron)



Implementing extra-degrees of freedom into N-body codes

General relativity

$$\begin{cases} G_{\alpha\beta} = 8\pi G T_{\alpha\beta} + \Lambda & \Leftarrow \text{Relation between geometry and energy} \\ \nabla^{\alpha} T_{\alpha\beta} = 0 & \Leftarrow \text{Conservation of energy} \end{cases}$$

Modified gravity:

$$\begin{cases} G_{\alpha\beta} = 8\pi G T_{\alpha\beta} + f(\phi) \\ \nabla^{\alpha} T_{\alpha\beta} = g(\phi, \partial_a \phi) \\ \Box\phi = h(T_{\alpha\beta}, \phi, \partial_a \phi) \end{cases}$$

N-Body codes and parameters

- *N*-body code of ISIS/RAMSES

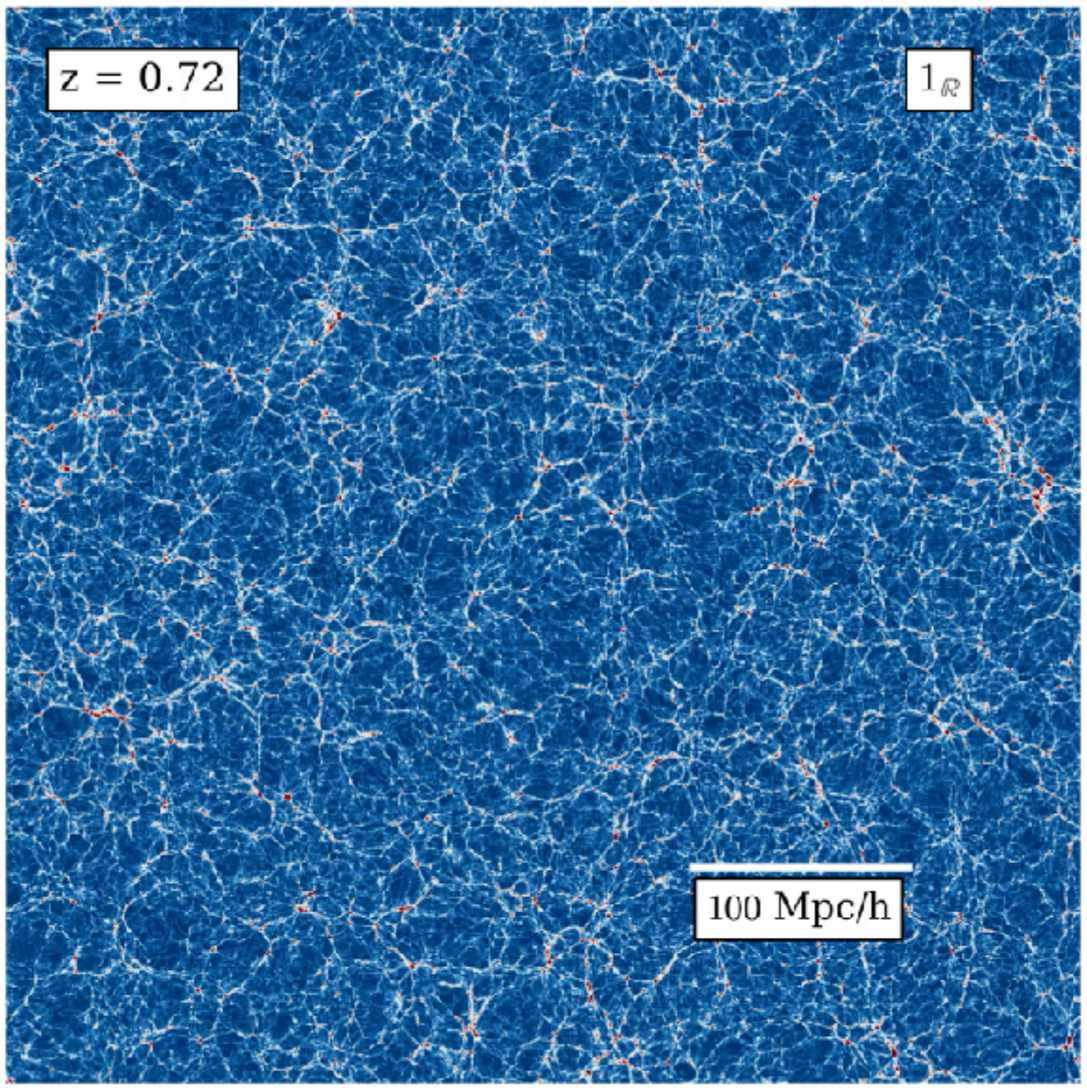
Structure formation dependence on the coupling and range

$$\frac{G_{\rm eff}(r)}{G} = 1 + 2\beta^2 e^{-r/\lambda_\phi}$$

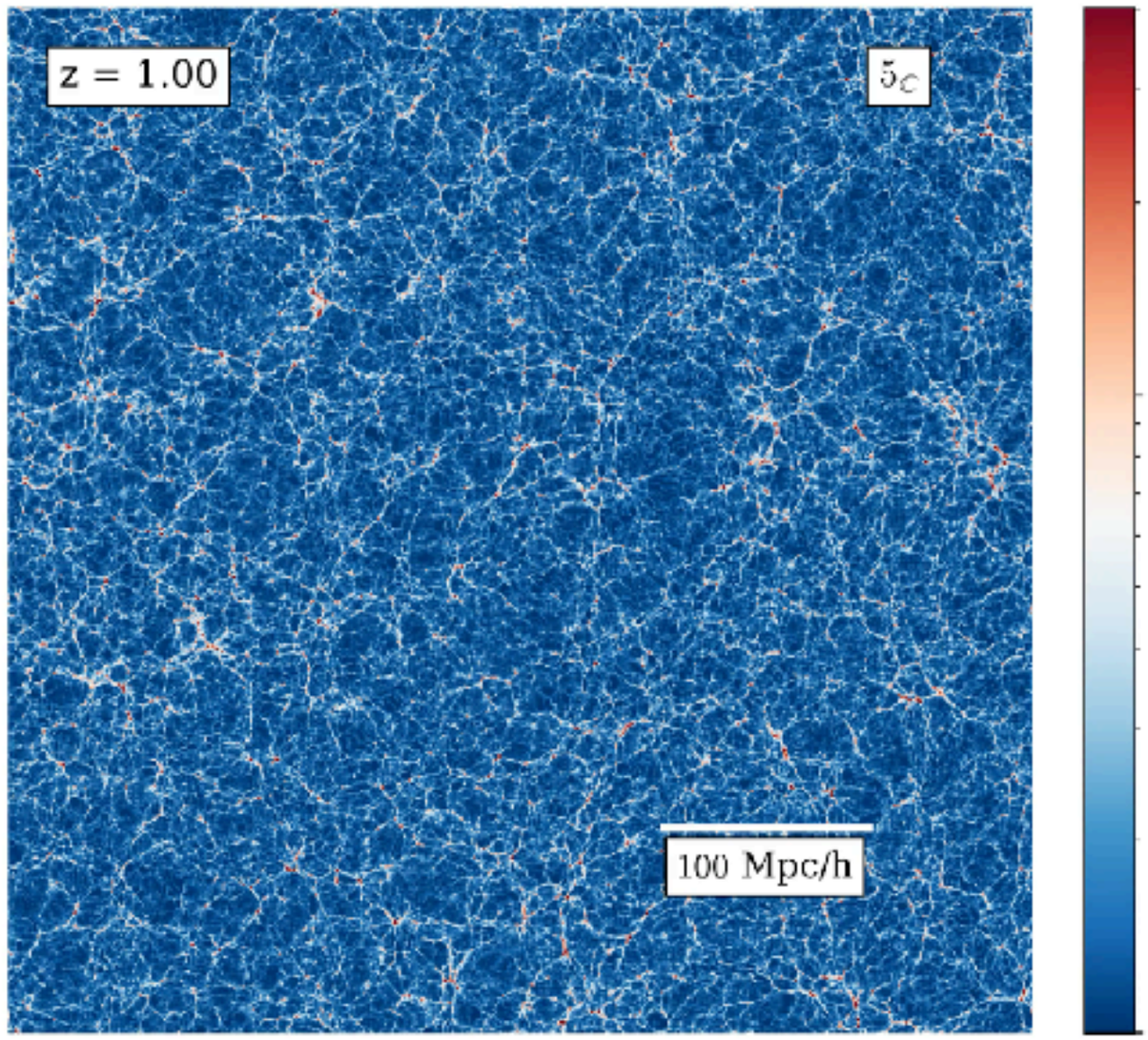
(Christiansen, Adamek, Hassani, DFM)

bigger deviations from GR

Modified Gravity (weak coupling)

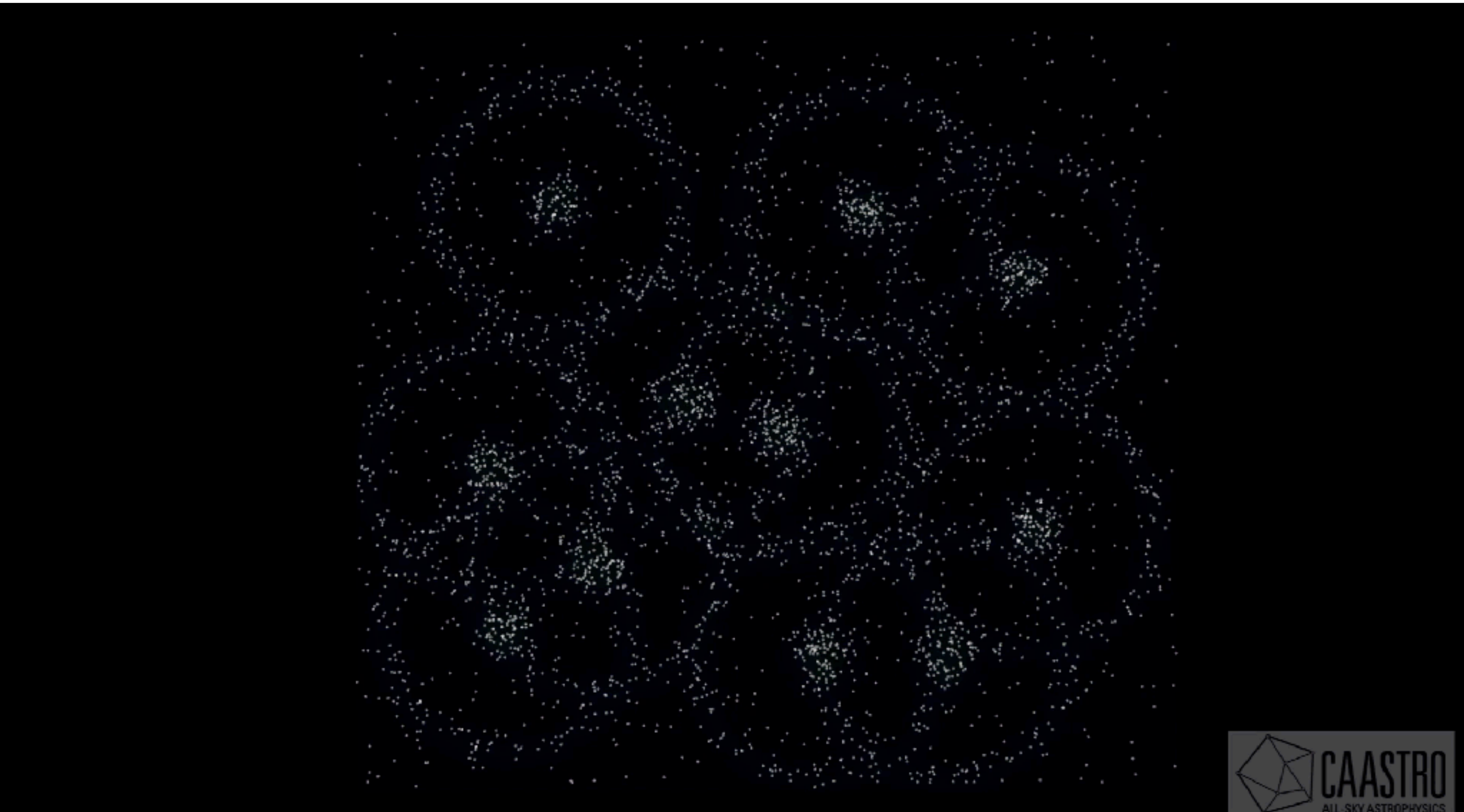


Modified Gravity (Strong coupling)

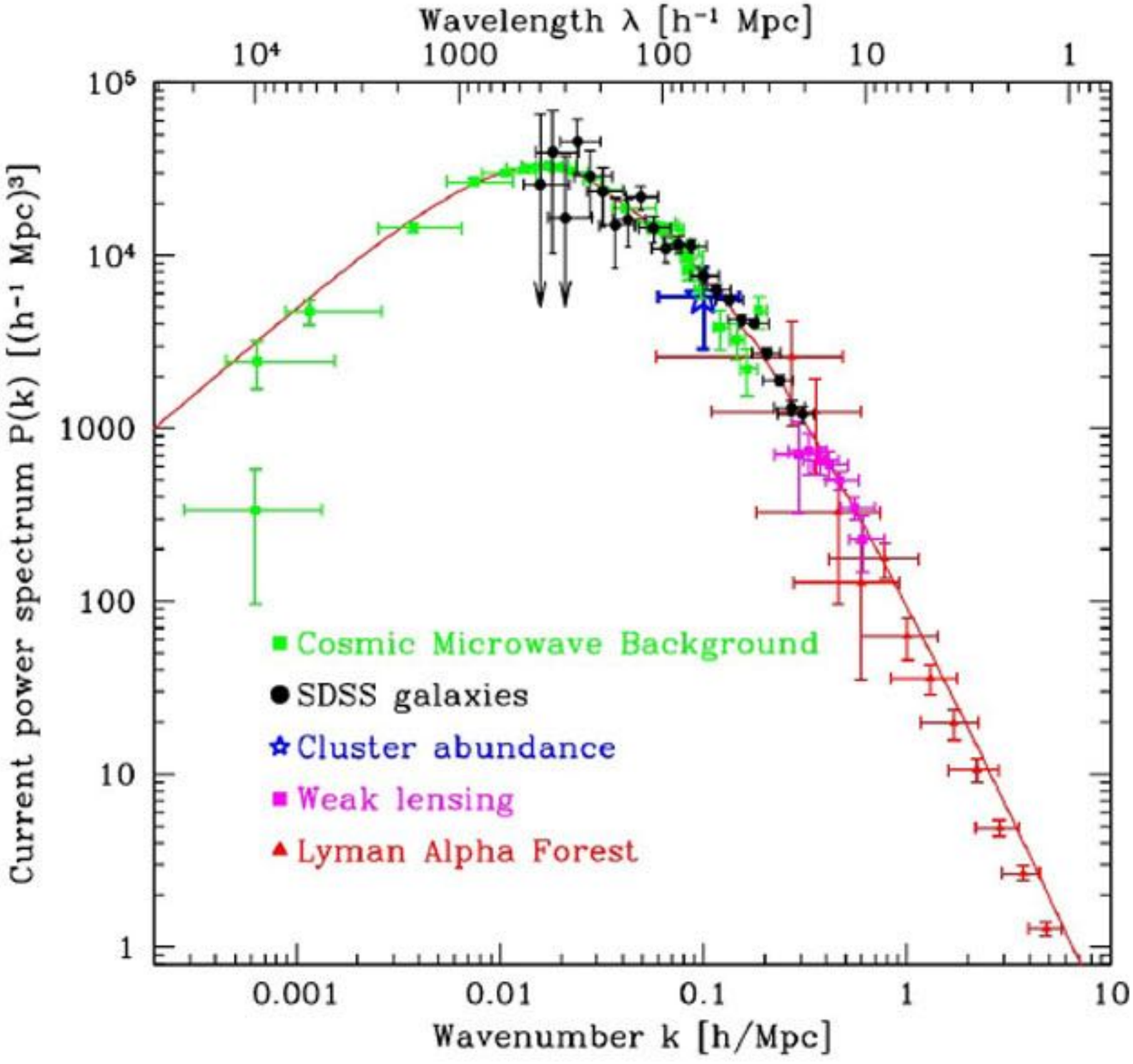


Galaxy correlation function measures degree of clustering of galaxies

Power spectrum is the Fourier transform of the correlation function



Power Spectra



Tegmark

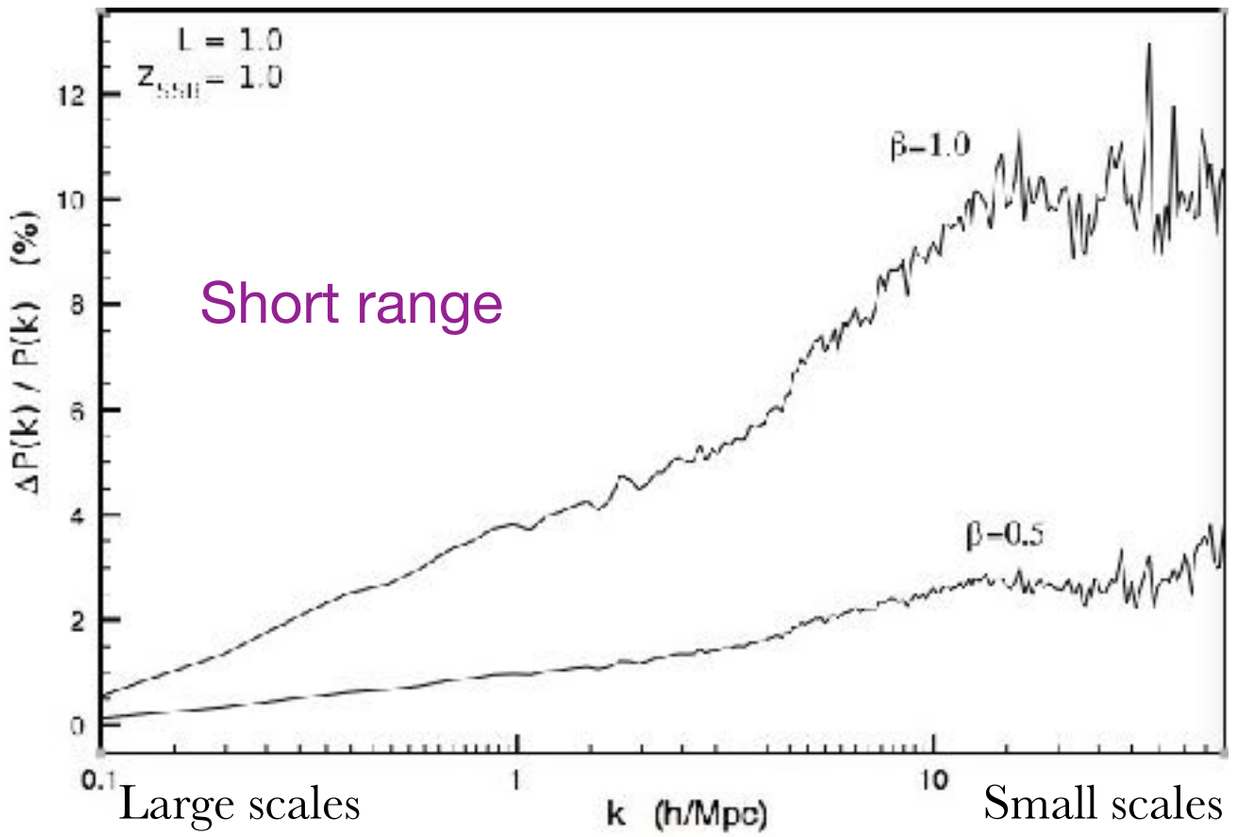
Non-screened (Massive) Modified Gravity

$$\frac{G_{\rm eff}(r)}{G} = 1 + 2\beta^2 e^{-r/\lambda_\phi}$$

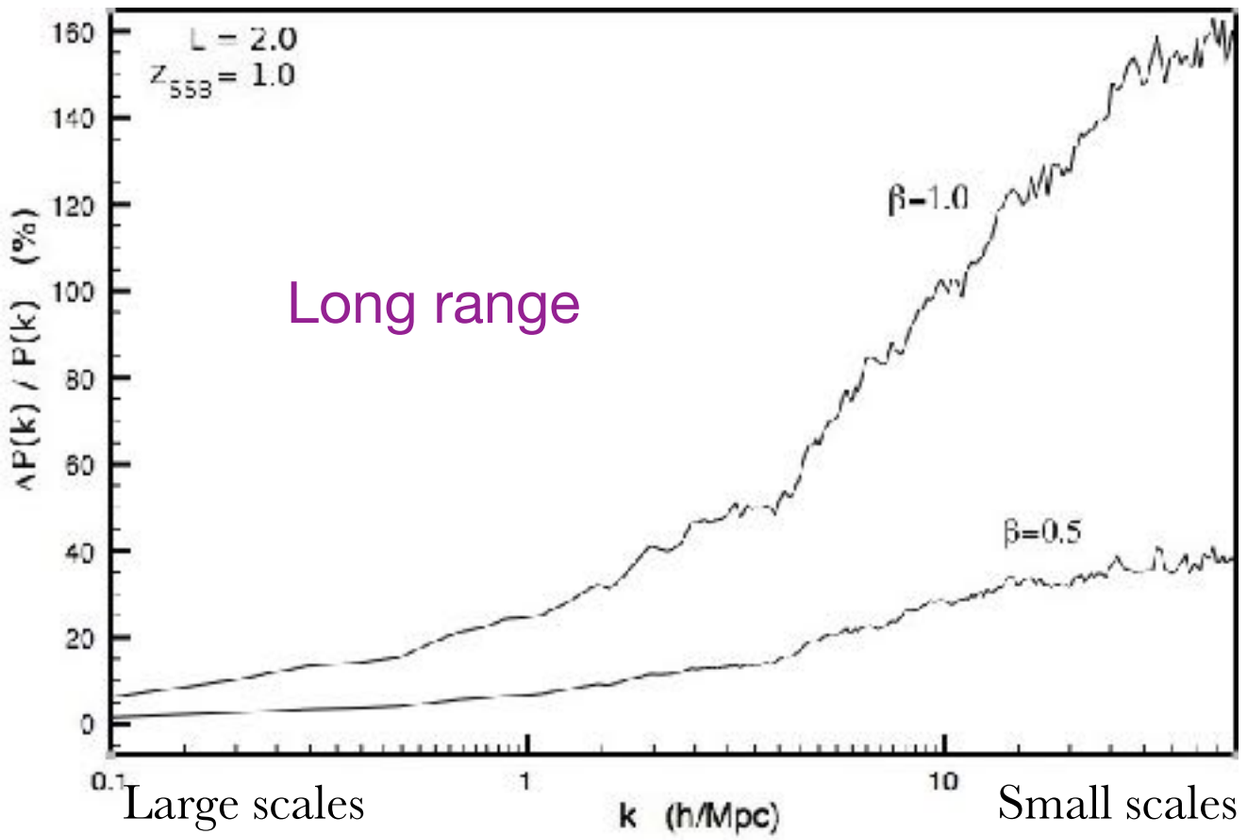
$$\frac{G_{\rm eff}}{G} = \begin{cases} 1 & r \gg \lambda_\phi \\ 1+2\beta^2 & r \ll \lambda_\phi \end{cases}$$

Stronger coupling -> bigger deviations from LCDM

Larger range -> large scale deviations from LCDM



Short range



Long range

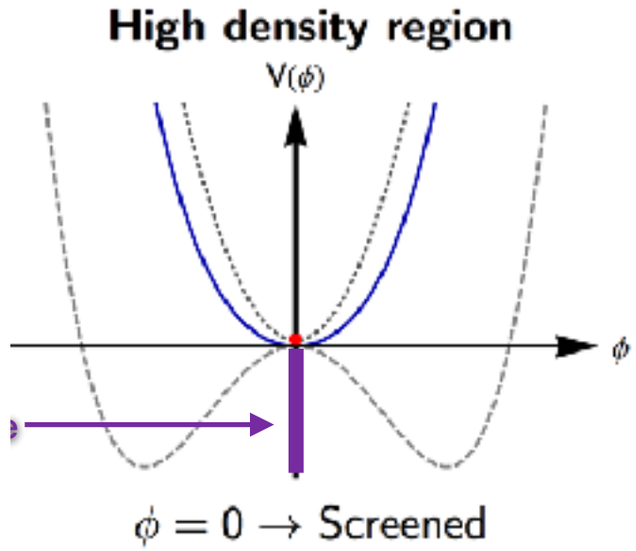
Scales larger than range of force: recovers GR

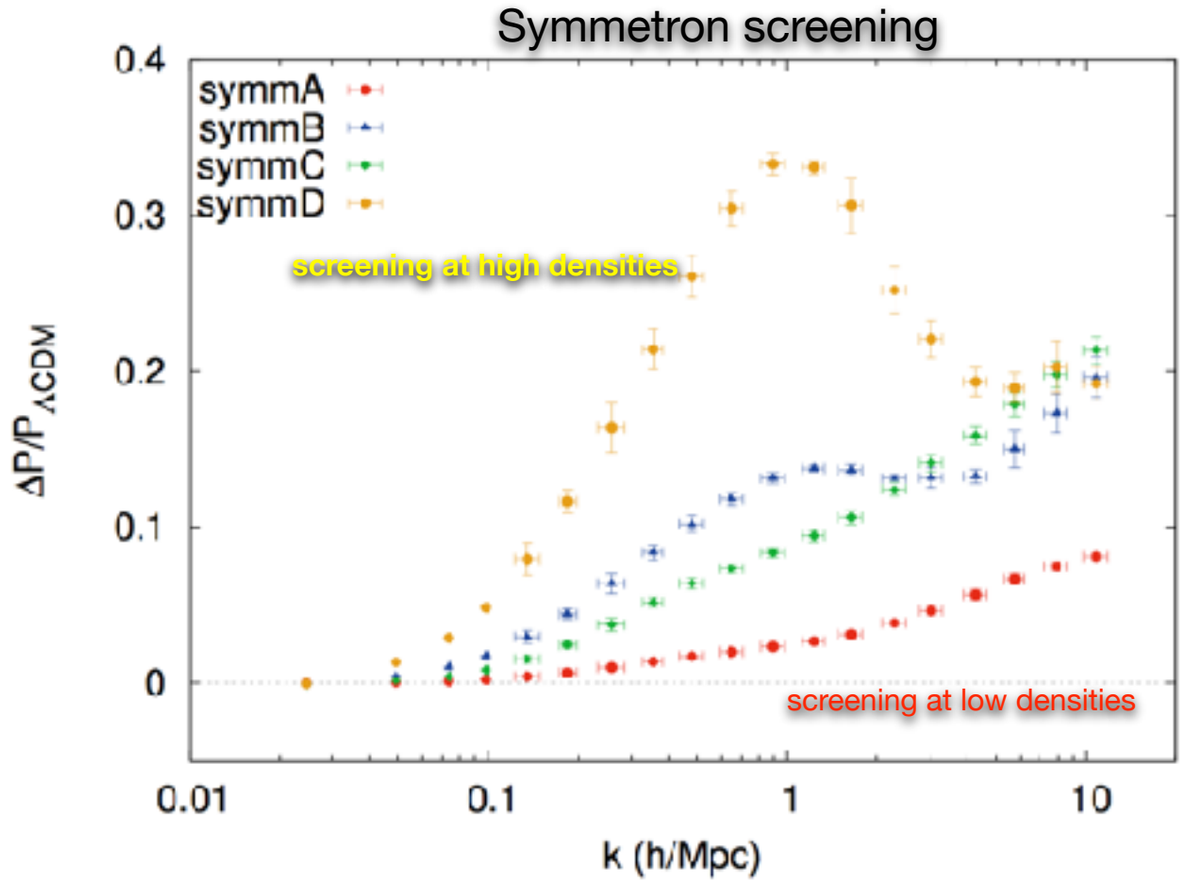
Background and LSS indistinguishable from GR

Llinares, DFM & Winther, ApJ

Structure formation dependence on the screening scale

$$\frac{G_{\rm eff}}{G} = 1$$



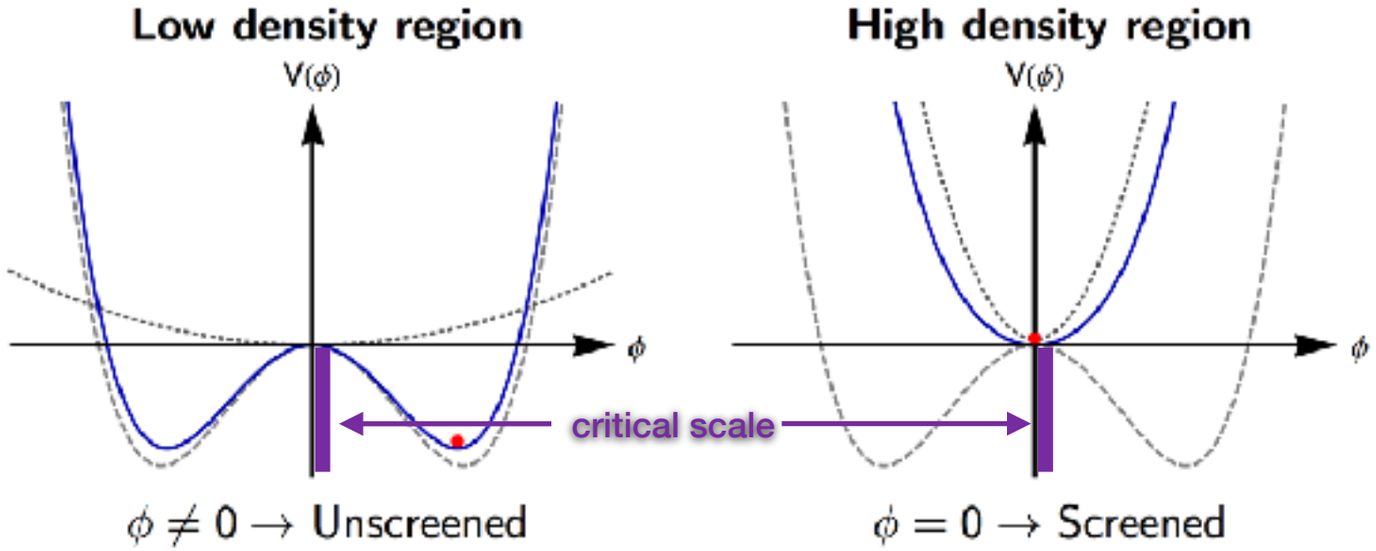


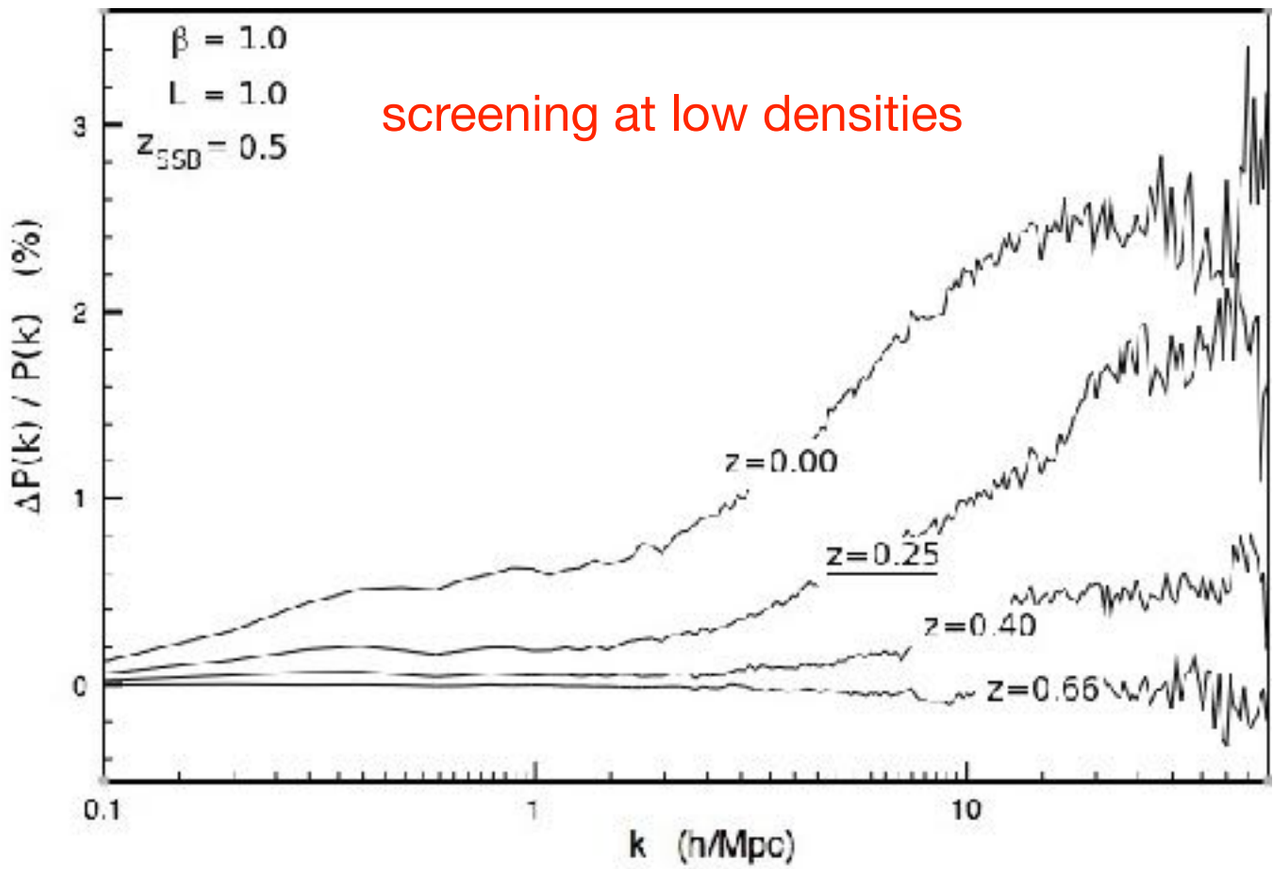
screening at high densities => deviations from GR easier to detect

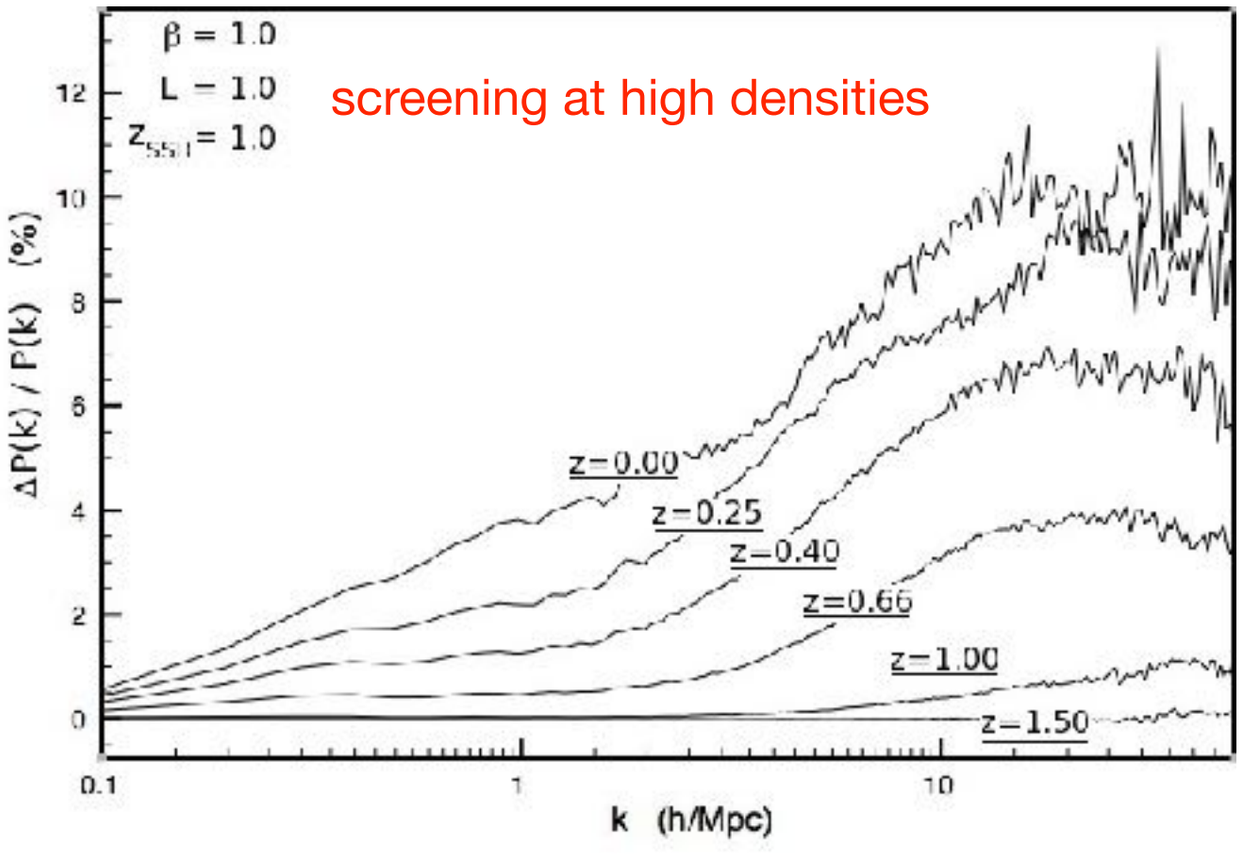
Gronke, Llinares, DFM, A&A

Probing the critical screening density with Tomography

$$\frac{G_{\rm eff}}{G} = 1 + \frac{2\beta^2\phi^2/\phi_0^2}{1 + \frac{a^2}{\lambda_\phi^2 k^2}}$$



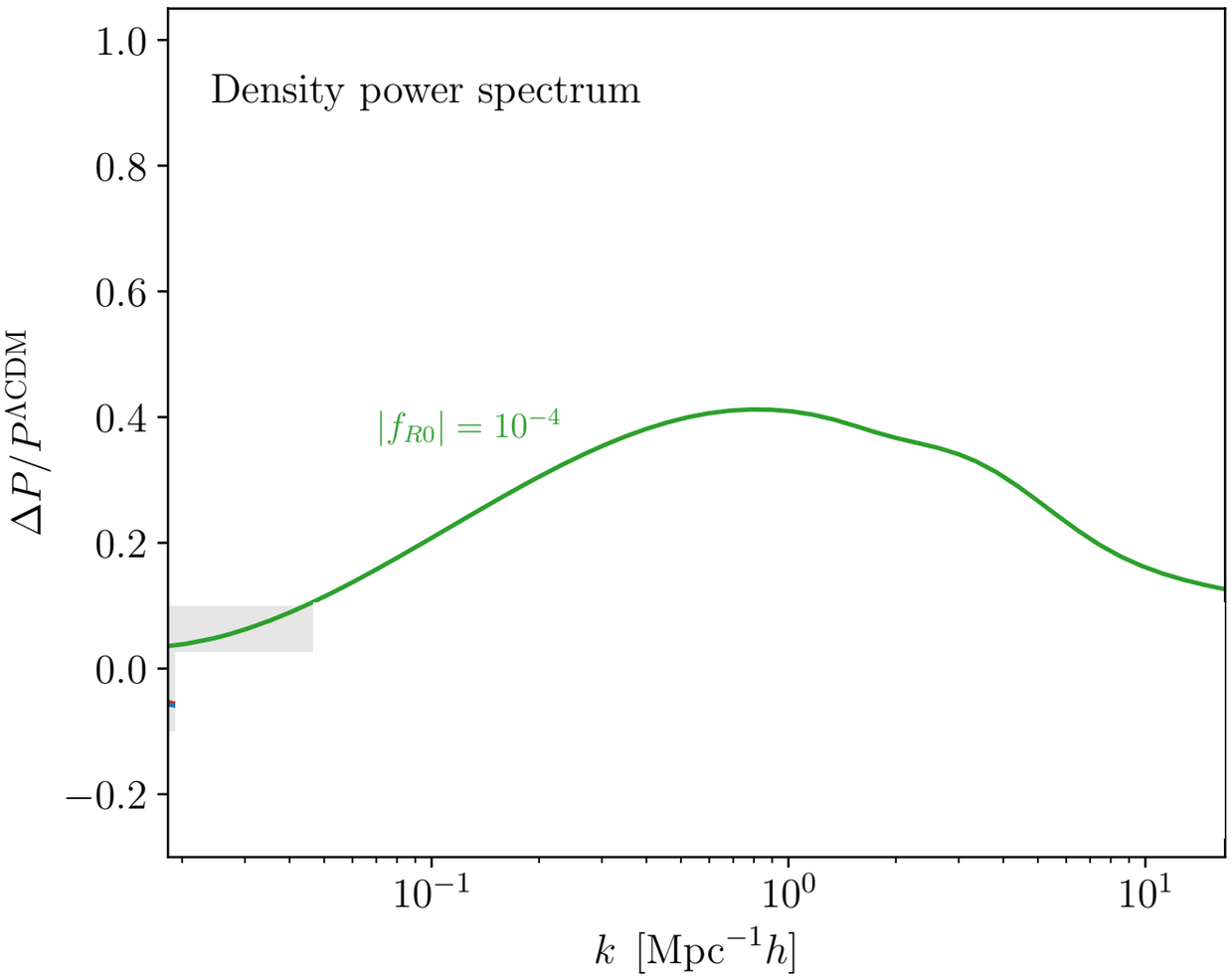




Screening at higher densities => fifth force acts for longer time

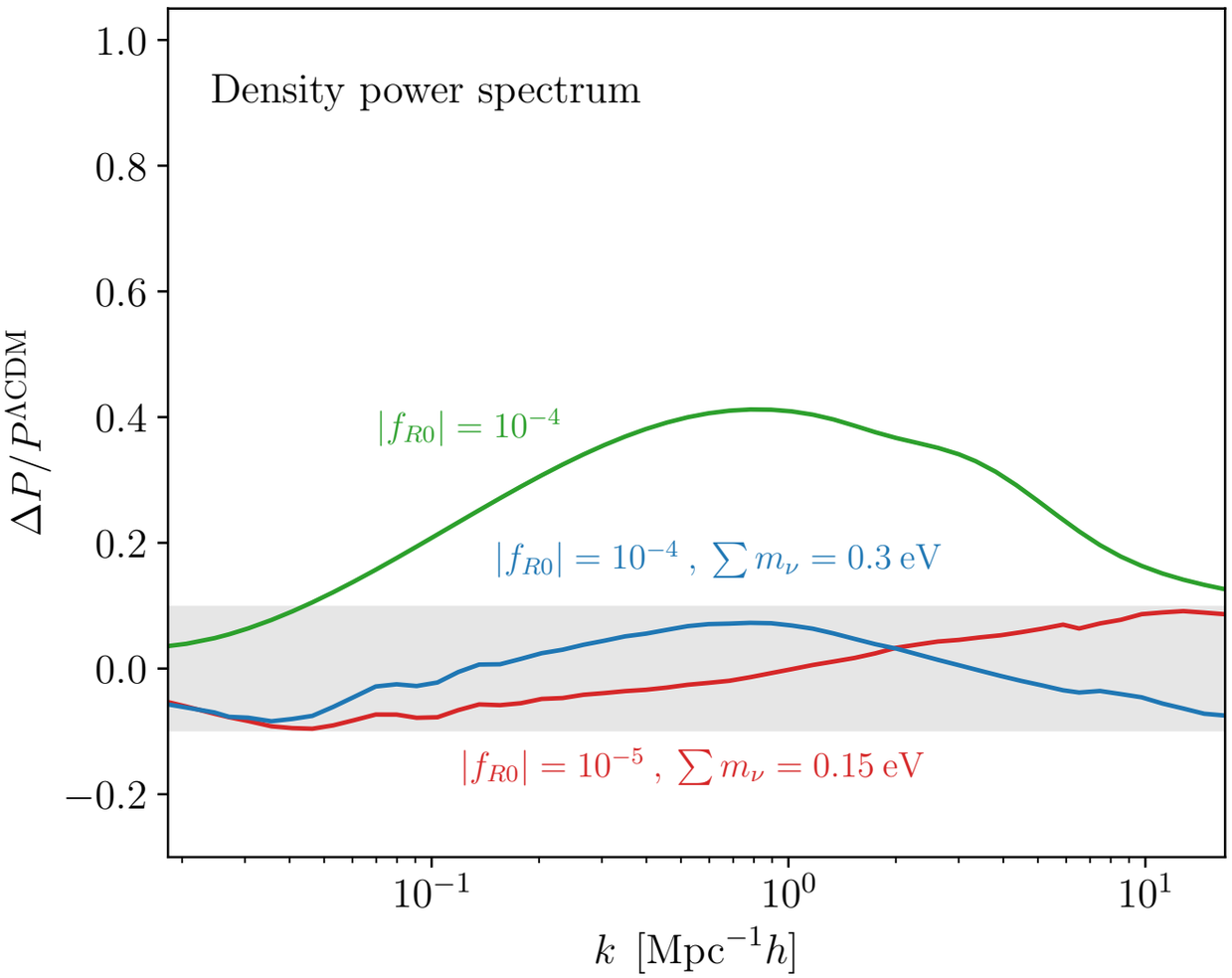
Llinares, DFM & Winther, ApJ

Matter Power Spectrum as a probe of Modified Gravity



Hagstotz, Gronke, DFM A&A

Neutrinos masses degenerated with Modified Gravity



Hagstotz, Gronke, DFM A&A

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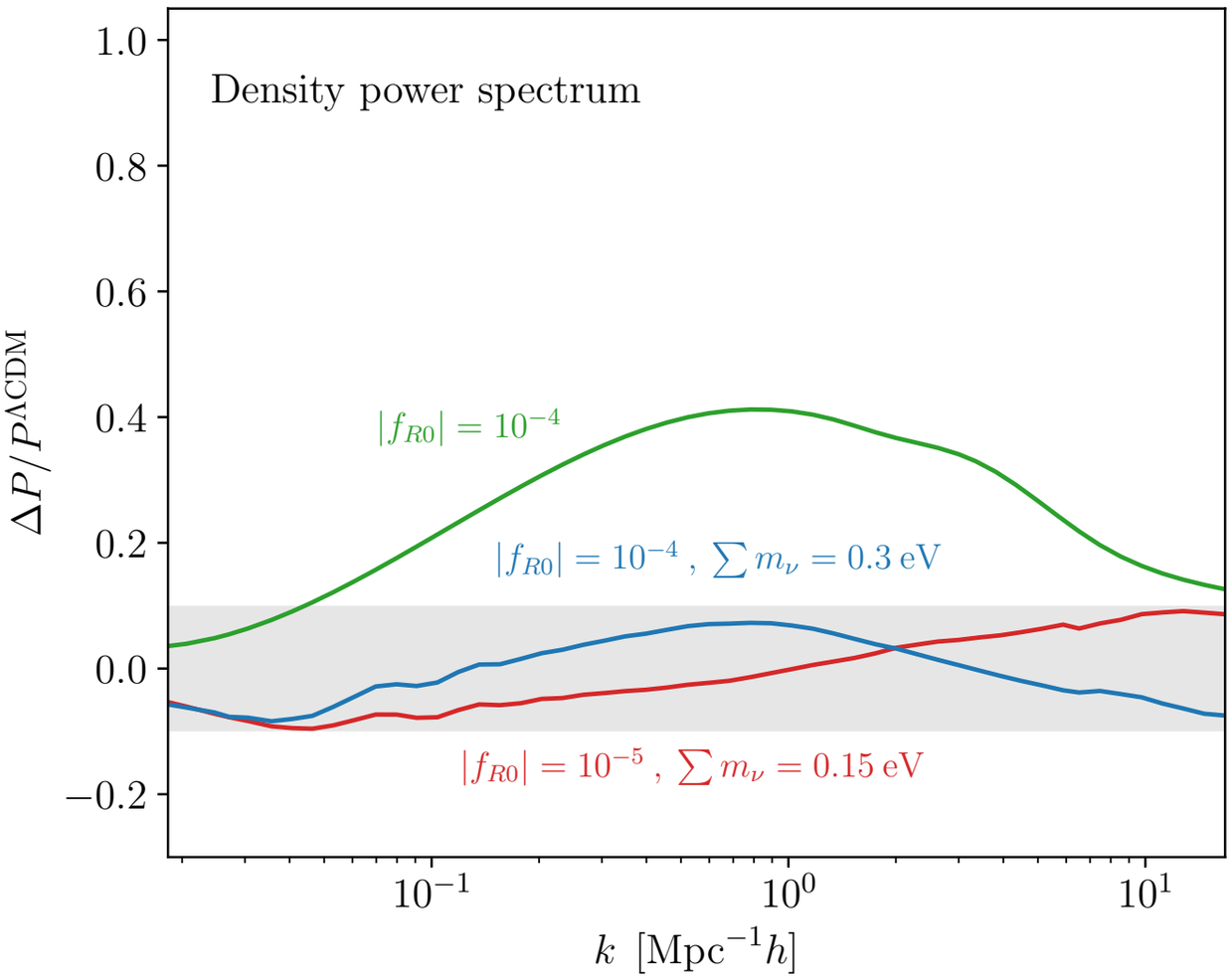
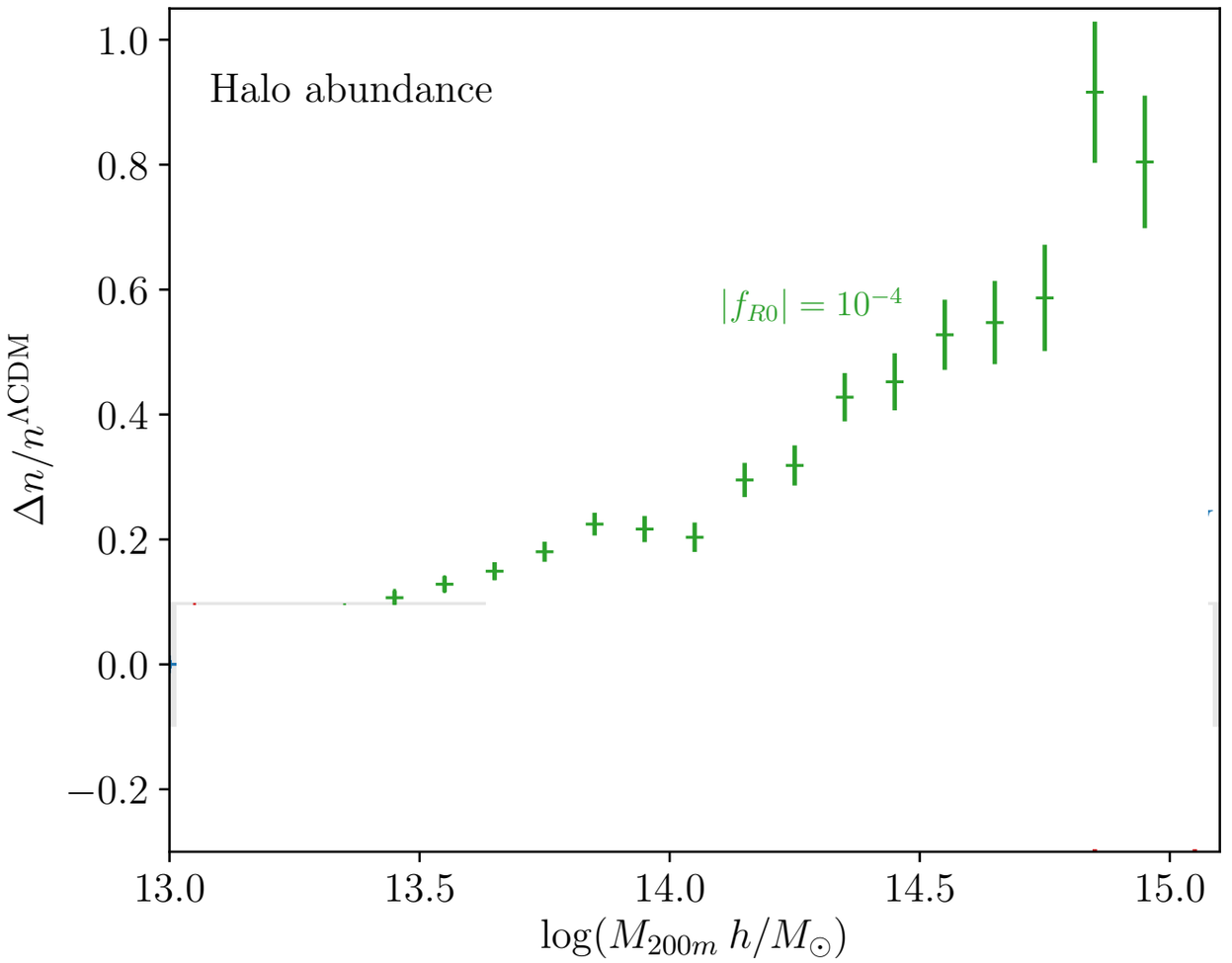
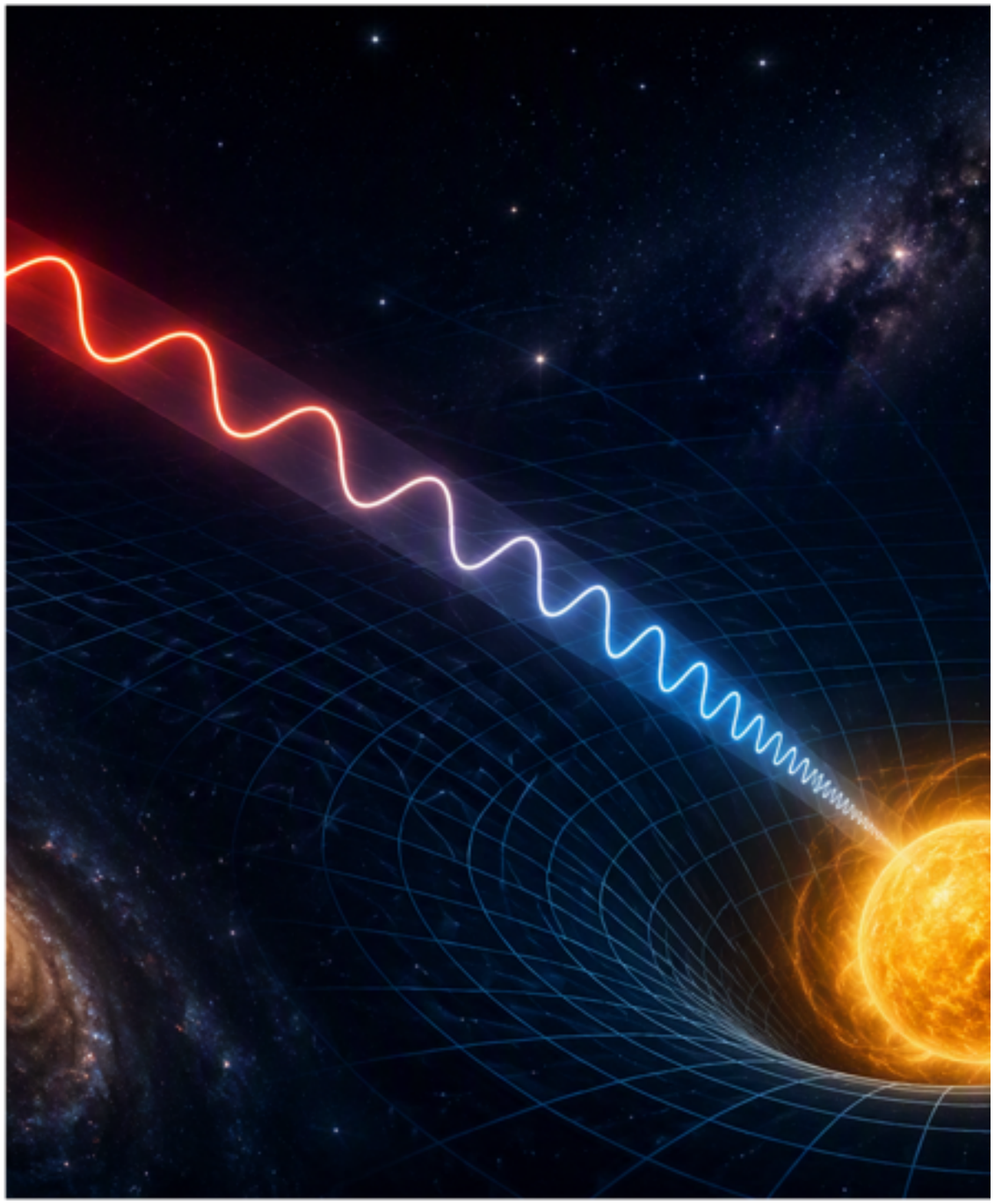




Large deviation caused by modified gravity growth counteracted by massive neutrinos

Hagstotz, Gronke, DFM A&A

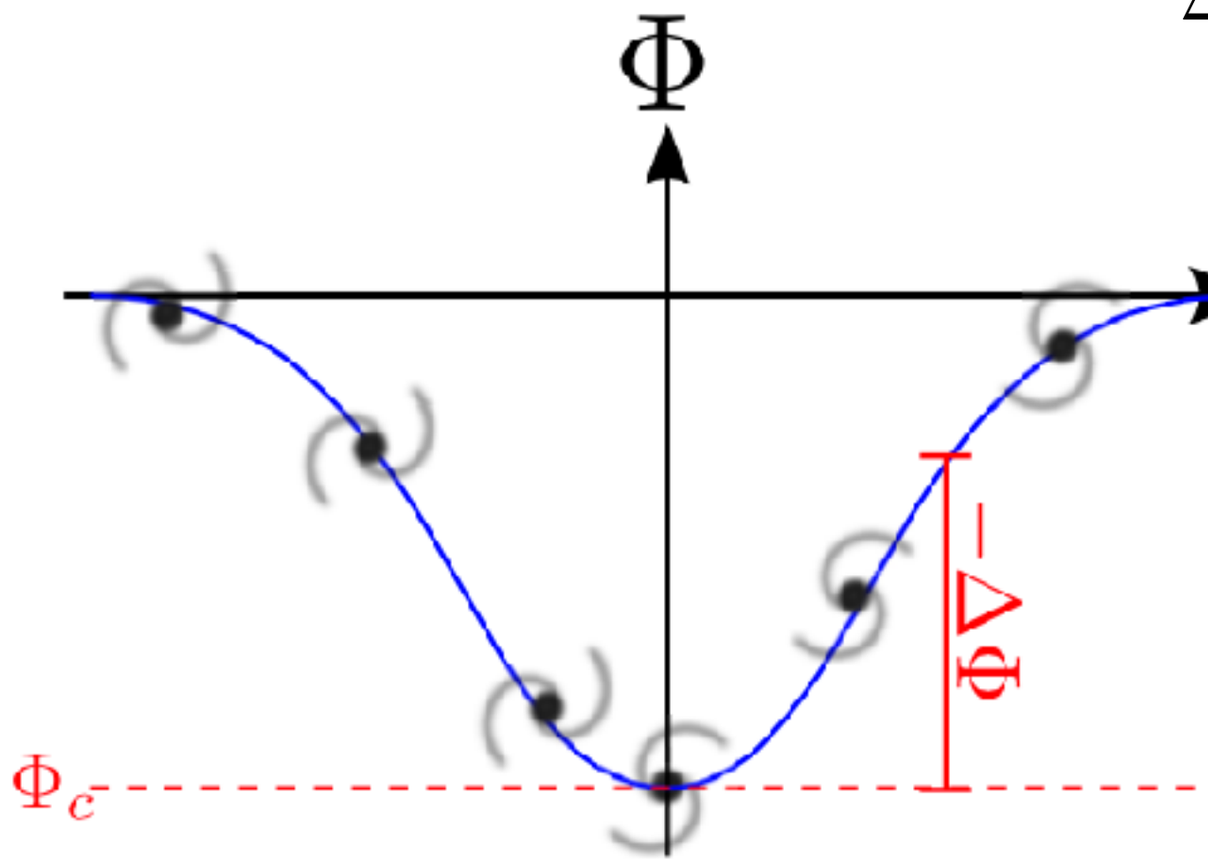
Gravitational redshift



photons climbing out
of the potential well
are redshifted

Gravitational redshift in clusters

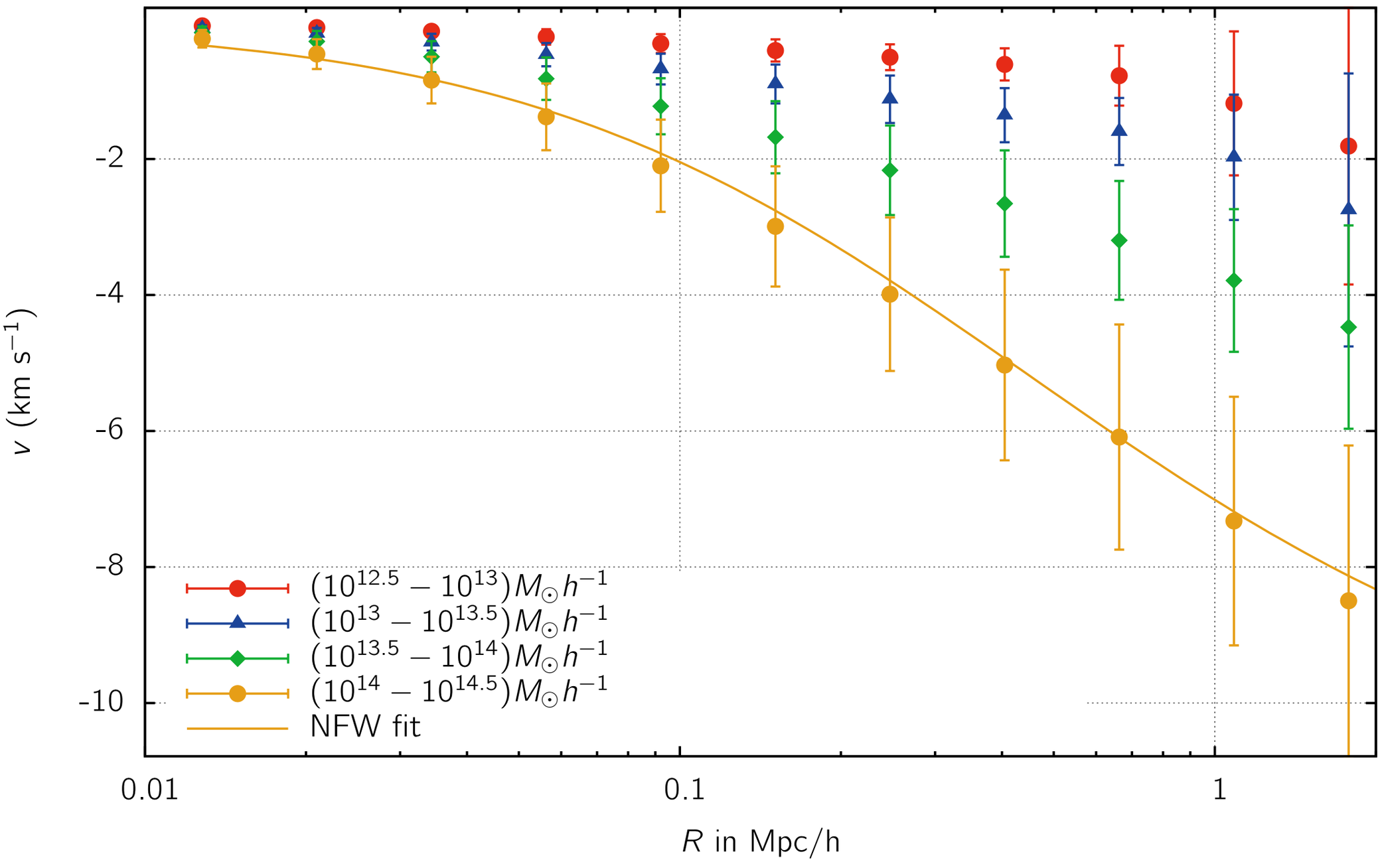
$$\Delta z_{\rm gr}(r) \equiv z_{\rm sat}(r) - z_{\rm cen} \simeq \frac{\Phi_c - \Phi(r)}{c^2}$$



Measurement of $\Delta\Phi(r)$

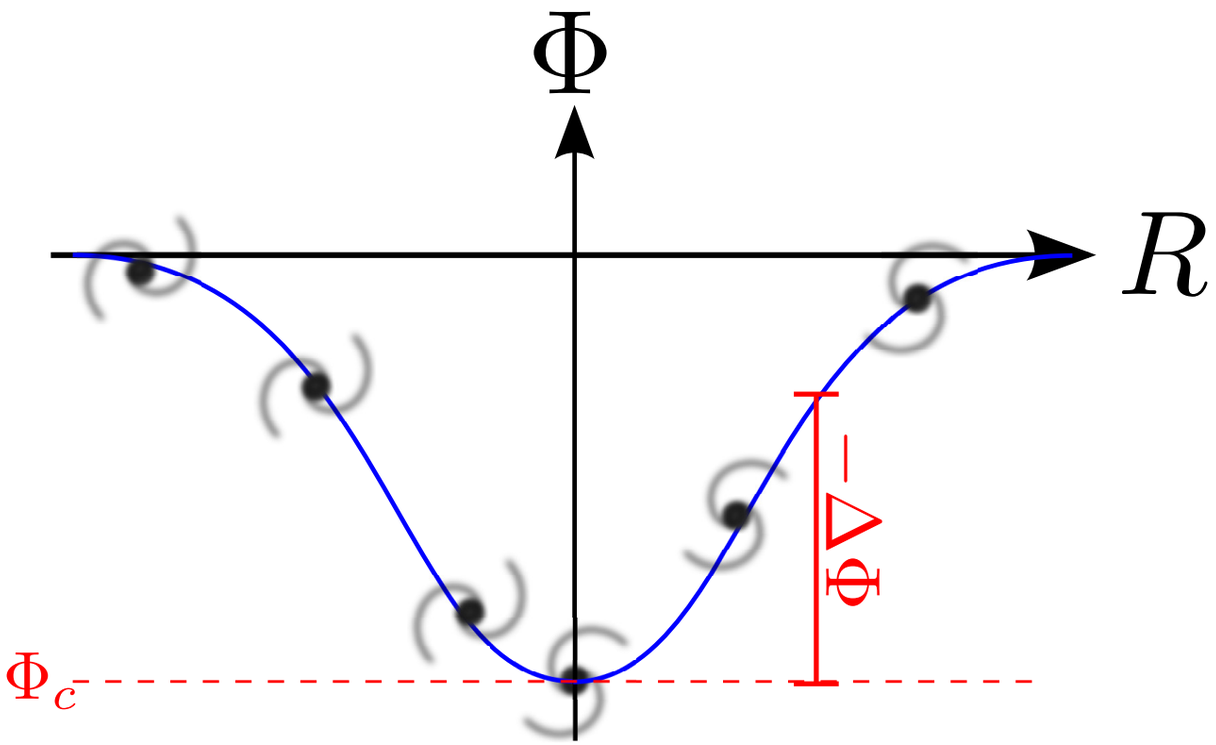
Gravitational redshift of a cluster for ΛCDM

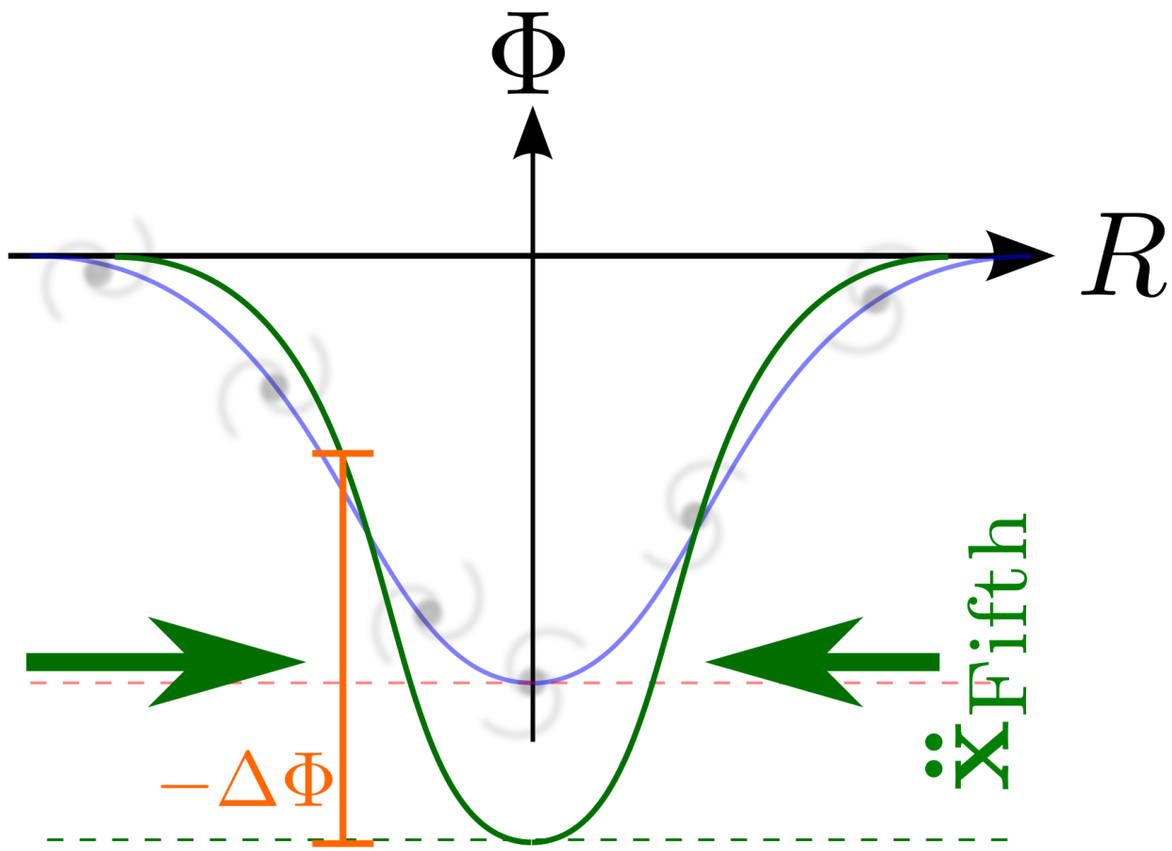
$$v_g \equiv \left|\frac{\Delta\Phi}{c}\right| = \left|\frac{\Phi_c - \Phi}{c}\right|$$



→ Same for all models & parameters and use relative deviation

Expected results

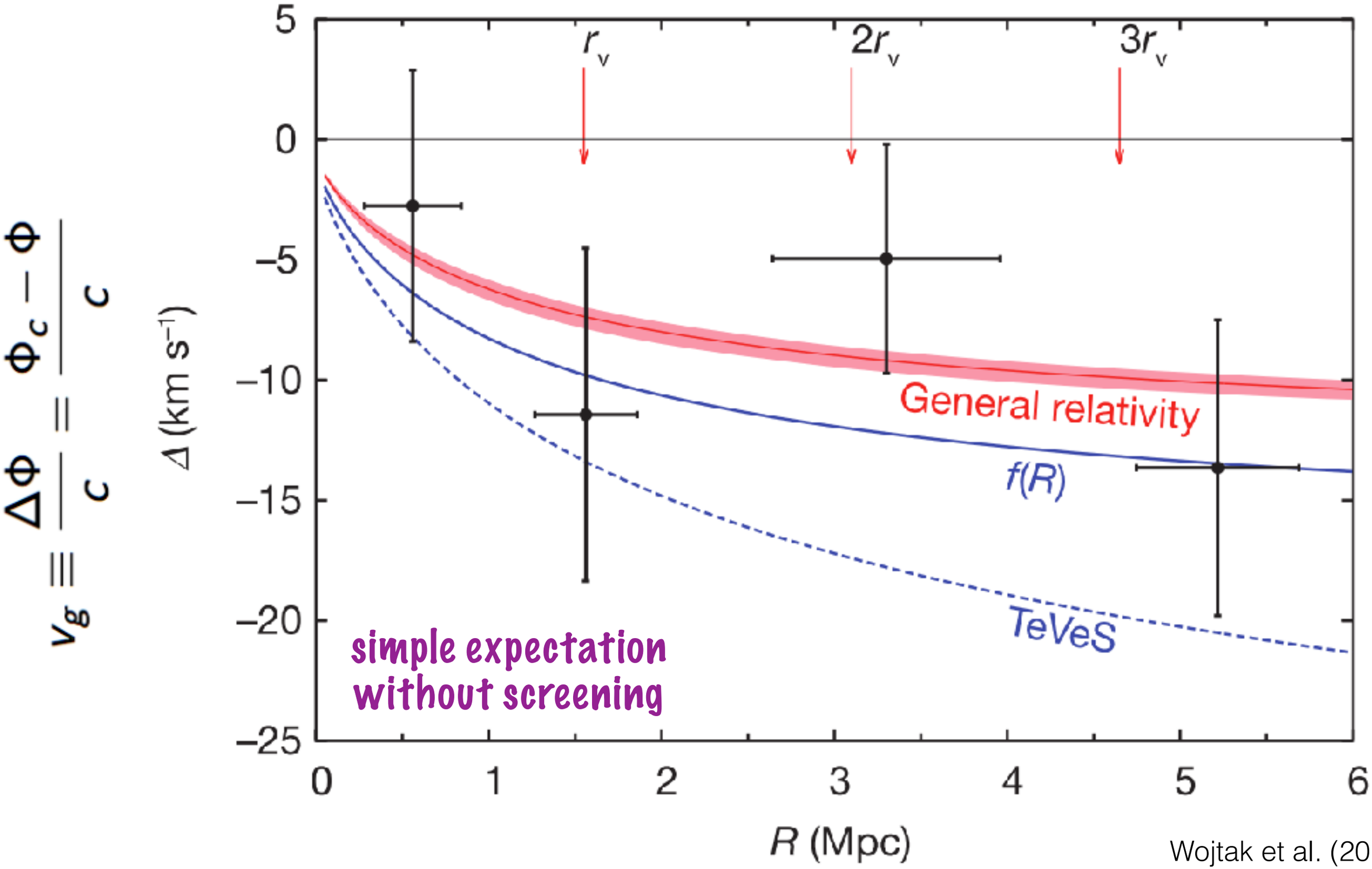




$$|\Delta\Phi_{\Lambda CDM}| \quad < \quad |\Delta\Phi_{mod}|$$

$$\xrightarrow{\text{expected}} (\text{Relative deviation})\frac{V_{g,mod}}{V_{g,\Lambda CDM}} - 1 > 0$$

Gravitational redshift measurements



Wojtak et al. (2011)

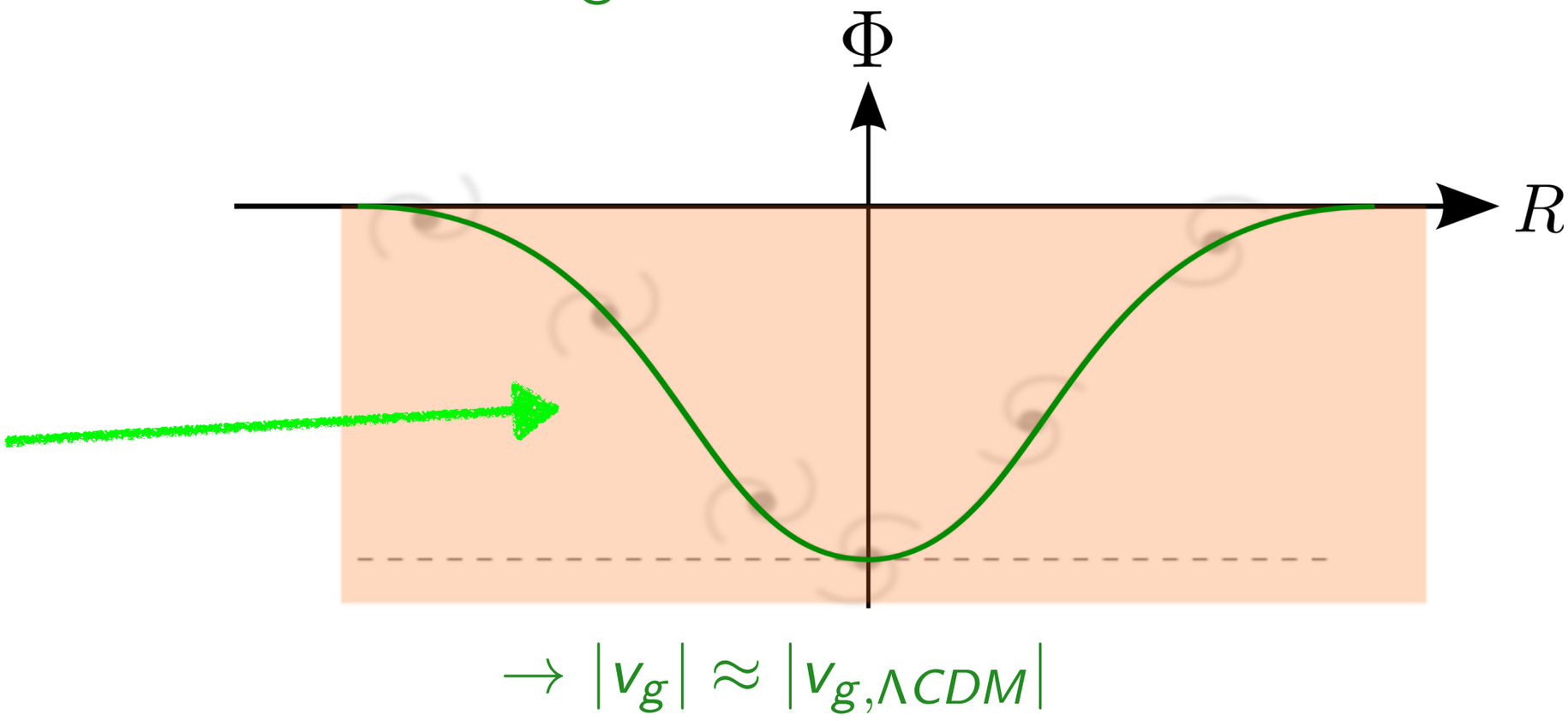
The three screening regimes

- Full screening

fofr4~24 Mpc

fofr5~7 Mpc

fofr6~2 Mpc



$$\rightarrow |v_g| \approx |v_{g,\Lambda CDM}|$$

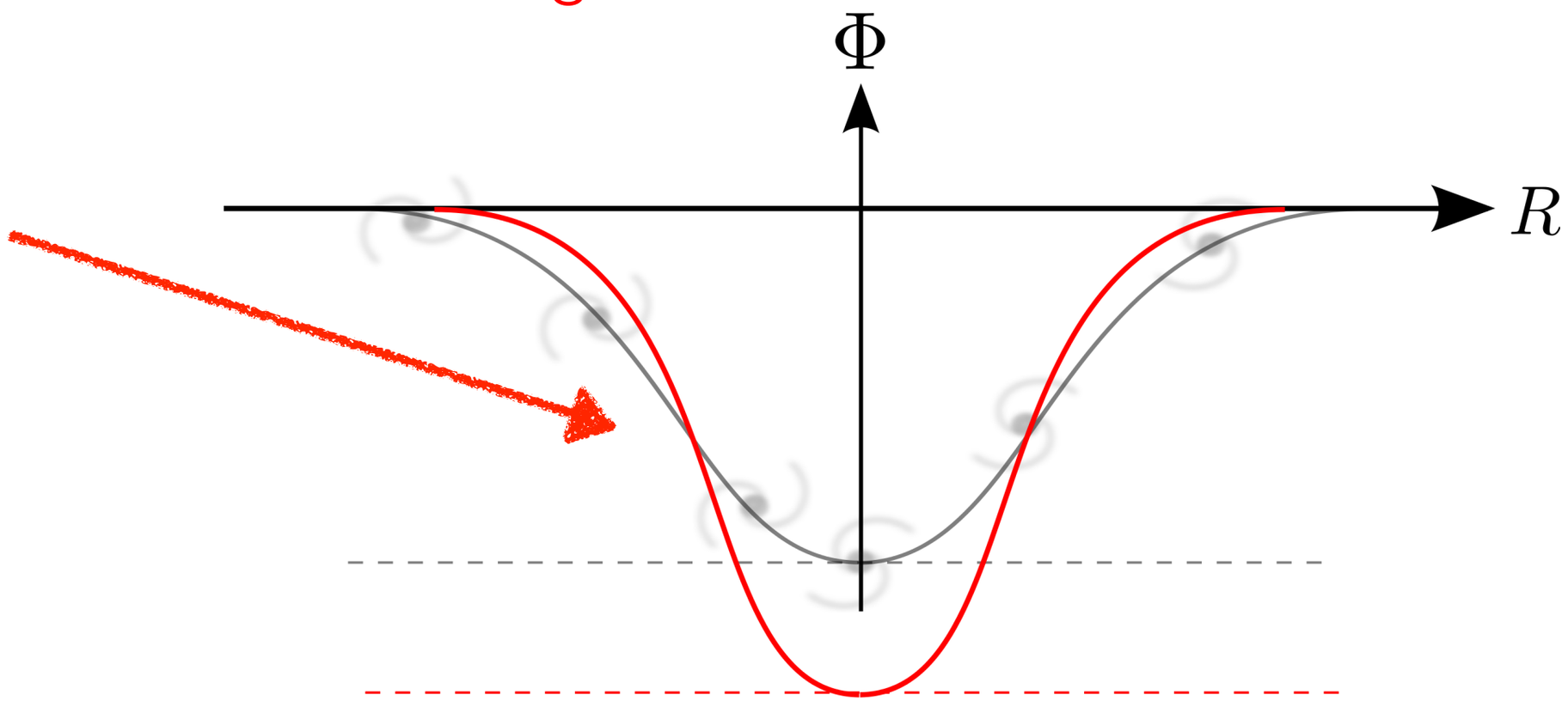
The three screening regimes

- No screening

fofr4~24 Mpc

fofr5~7 Mpc

fofr6~2 Mpc



$\rightarrow |v_g| > |v_{g,\Lambda CDM}|$

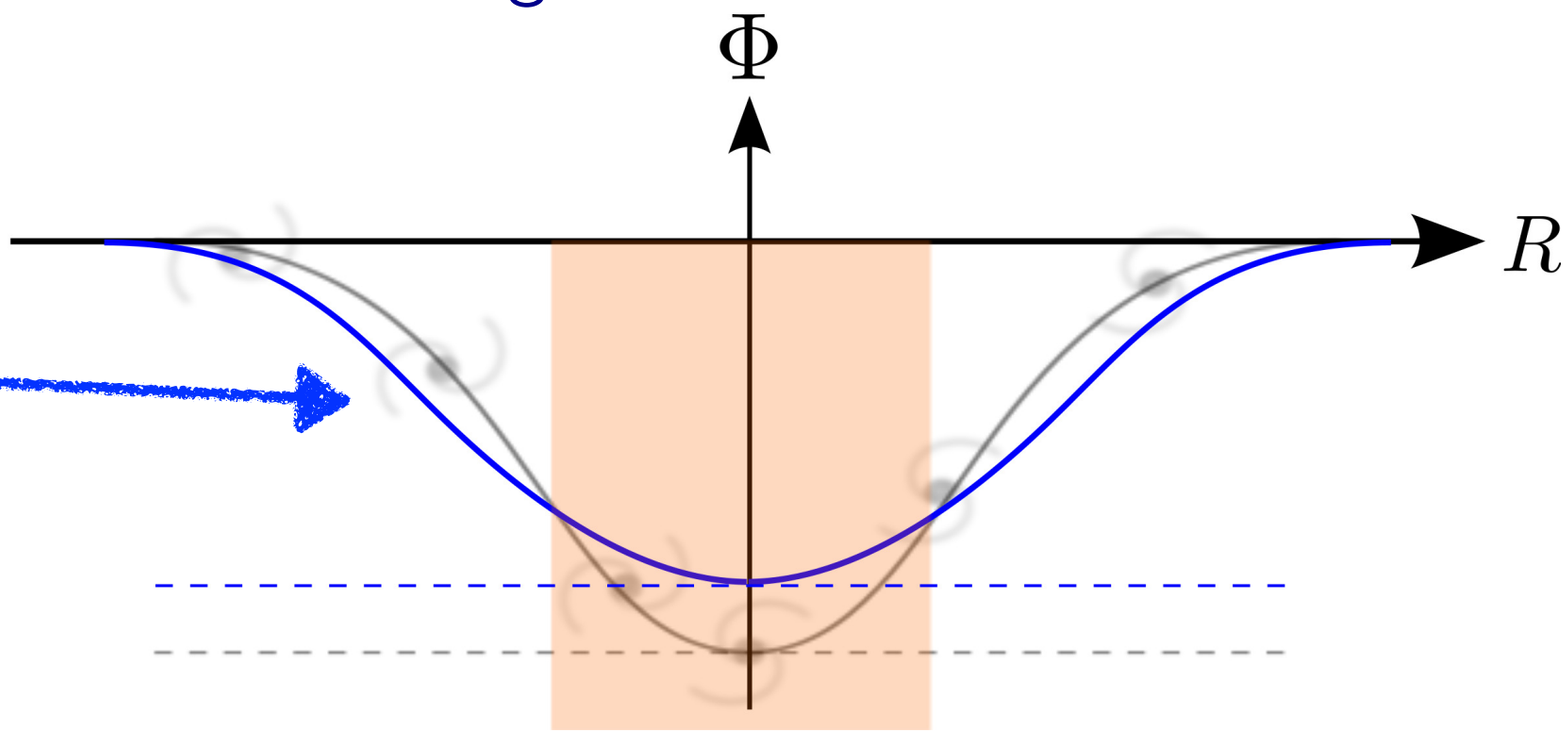
The three screening regimes

- Partial screening

fofr4~24 Mpc

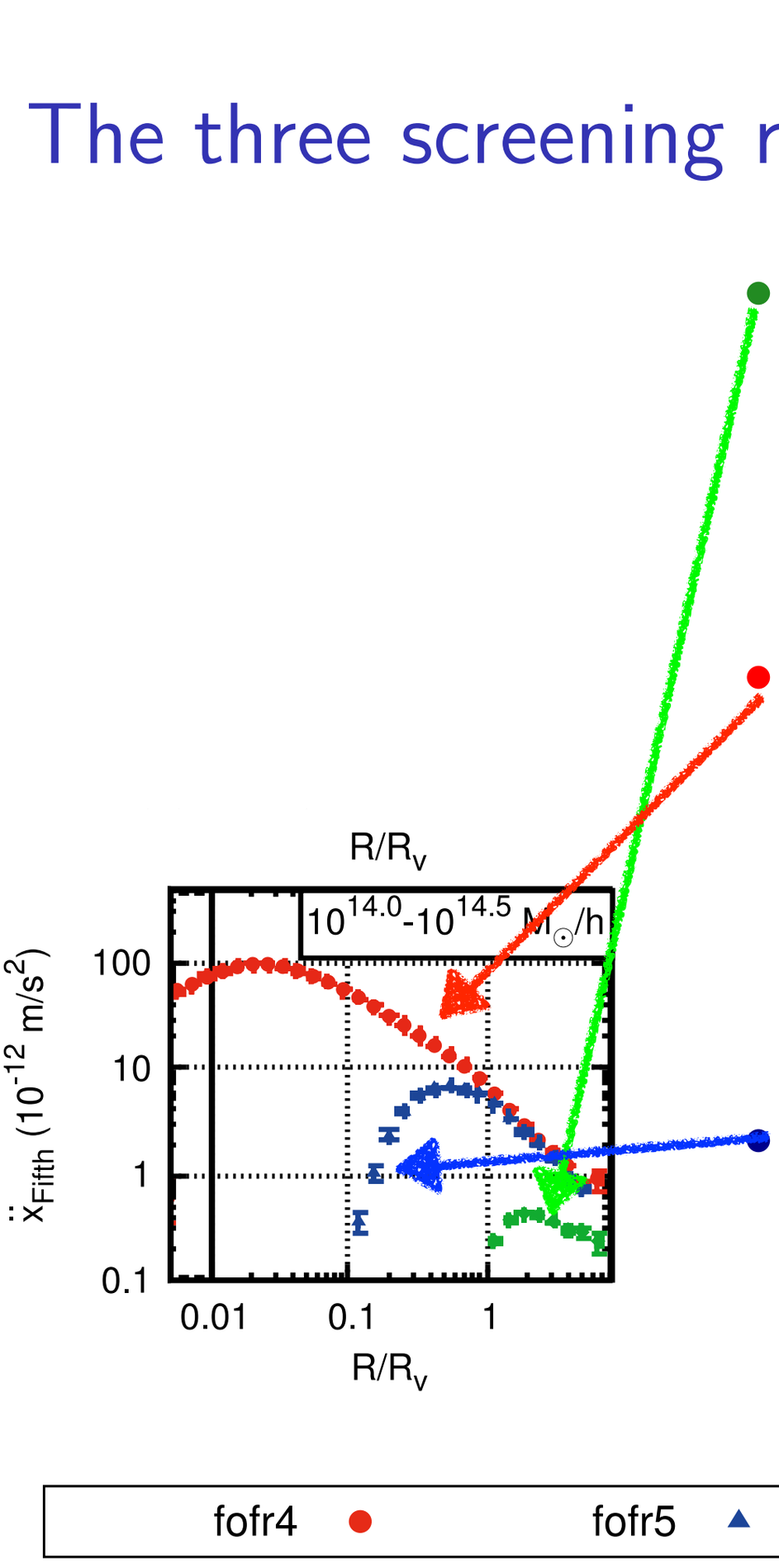
fofr5~7 Mpc

fofr6~2 Mpc

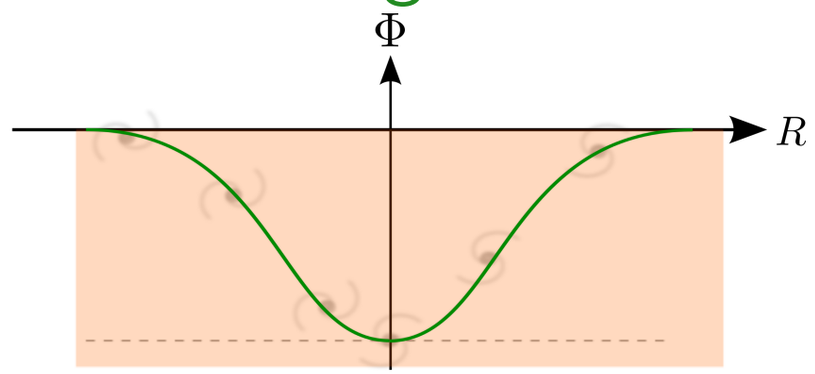


$\rightarrow |v_g| < |v_{g,\Lambda CDM}|$

The three screening regimes – Overview

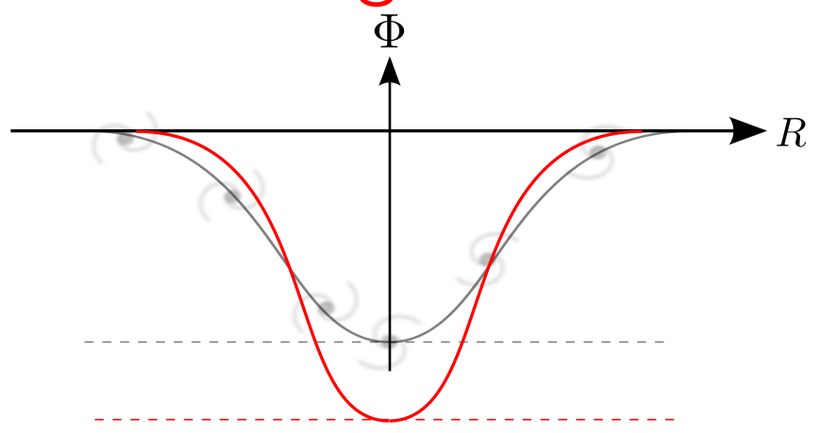


Full screening



$\rightarrow |v_g| \approx |v_{g,\Lambda CDM}|$

No screening



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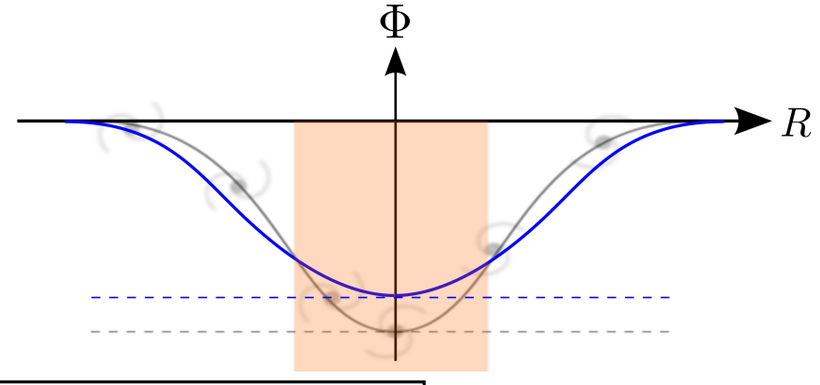
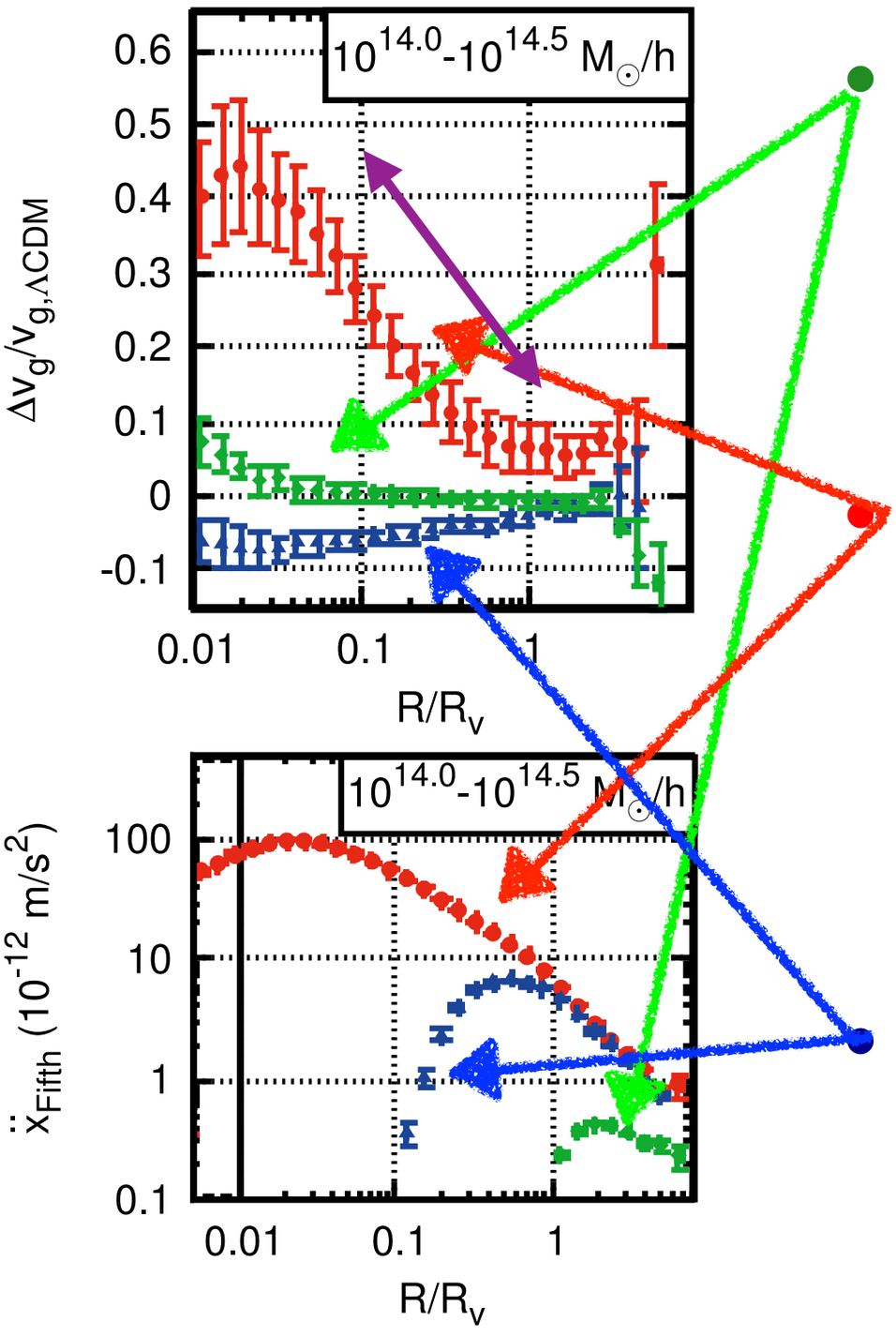
Partial screening



$\rightarrow |v_g| < |v_{g,\Lambda CDM}|$

Gronke, DFM, Winter, A&A

The three screening regimes – Overview



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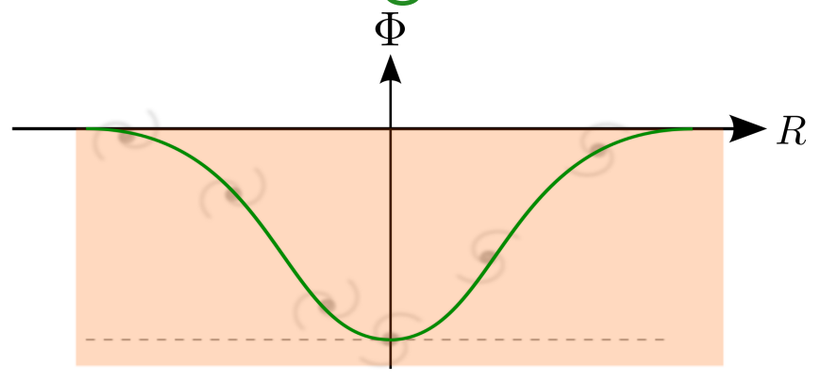

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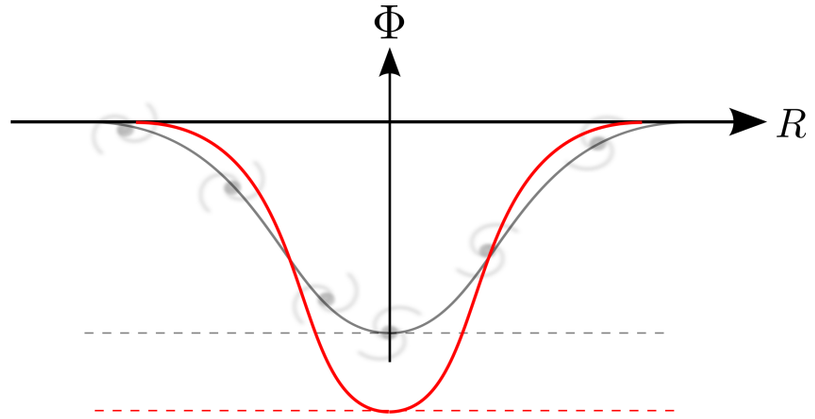

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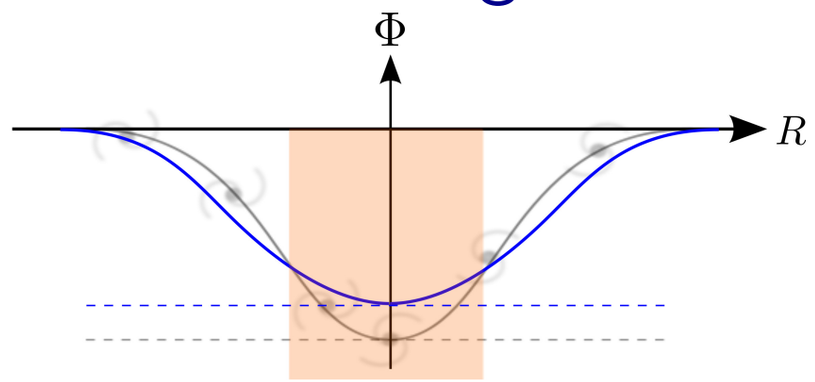
Partial screening



$\rightarrow |v_g| < |v_{g,\Lambda CDM}|$

Gronke, DFM, Winter, A&A