Gravitational Redshift from Galaxy Clusters (Relativistic approach)

Enea Di Dio

ED, Castello & Bonvin, arXiv:2503.11585

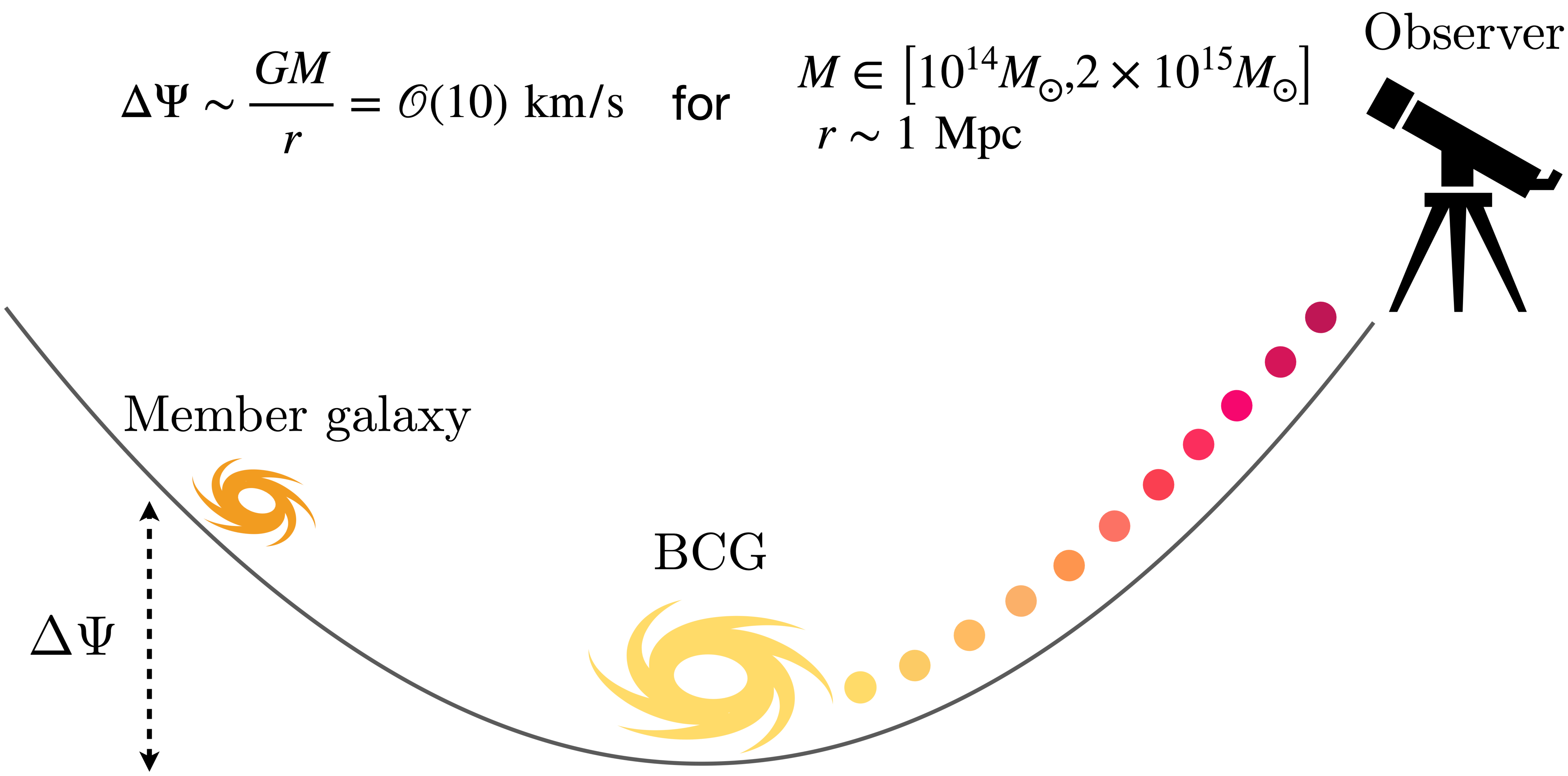
UNIVERSITÉ DE GENÈVE

Swiss Cosmology Days

Zurich, June 6th

Small scales to detect relativistic effects

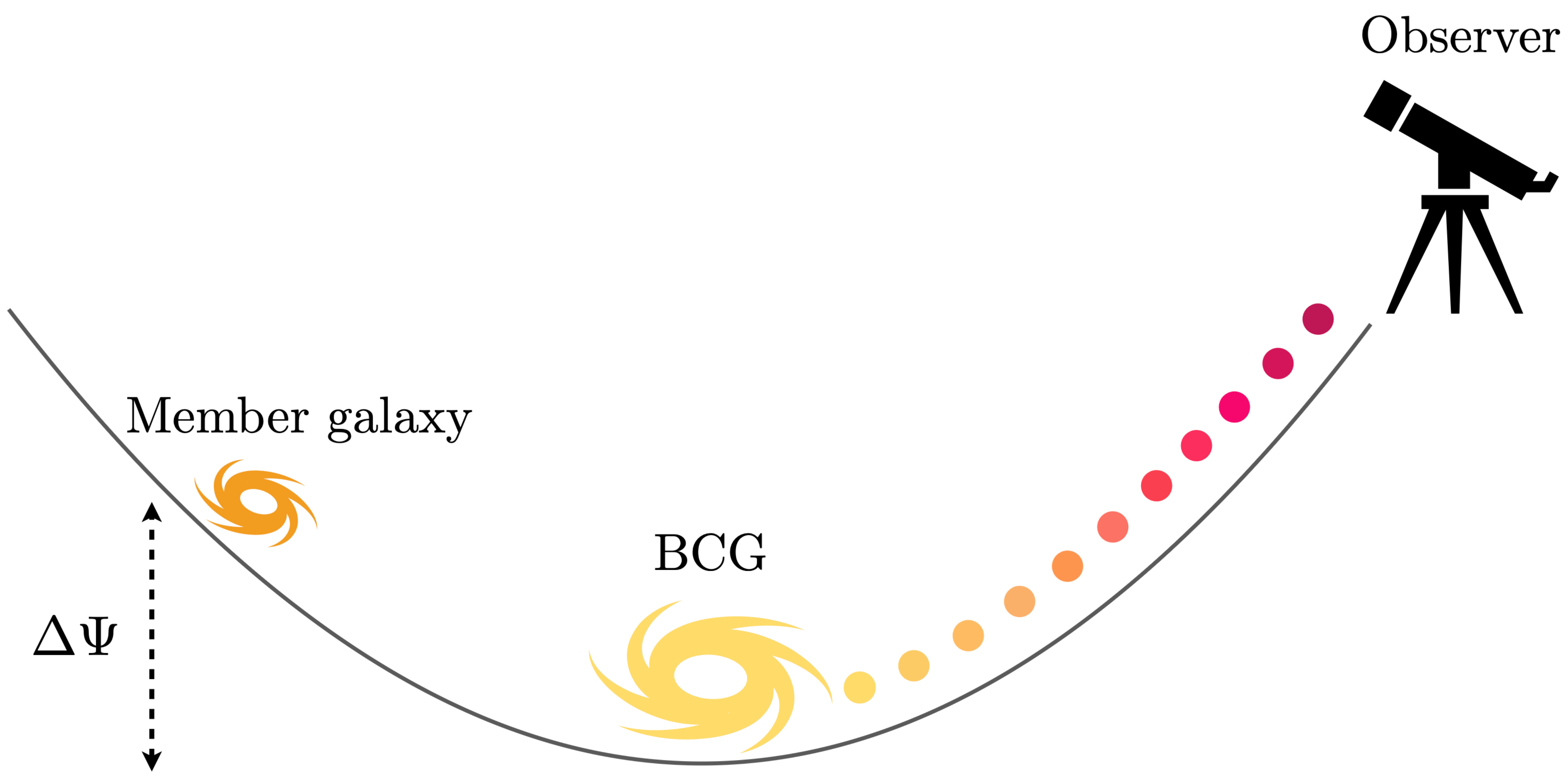
$$\Delta\Psi \sim \frac{GM}{r} = \mathcal{O}(10)\ \mathrm{km/s} \quad \text{for} \quad \begin{matrix} M \in [10^{14} M_\odot, 2\times 10^{15} M_\odot] \\ r \sim 1\ \mathrm{Mpc} \end{matrix}$$

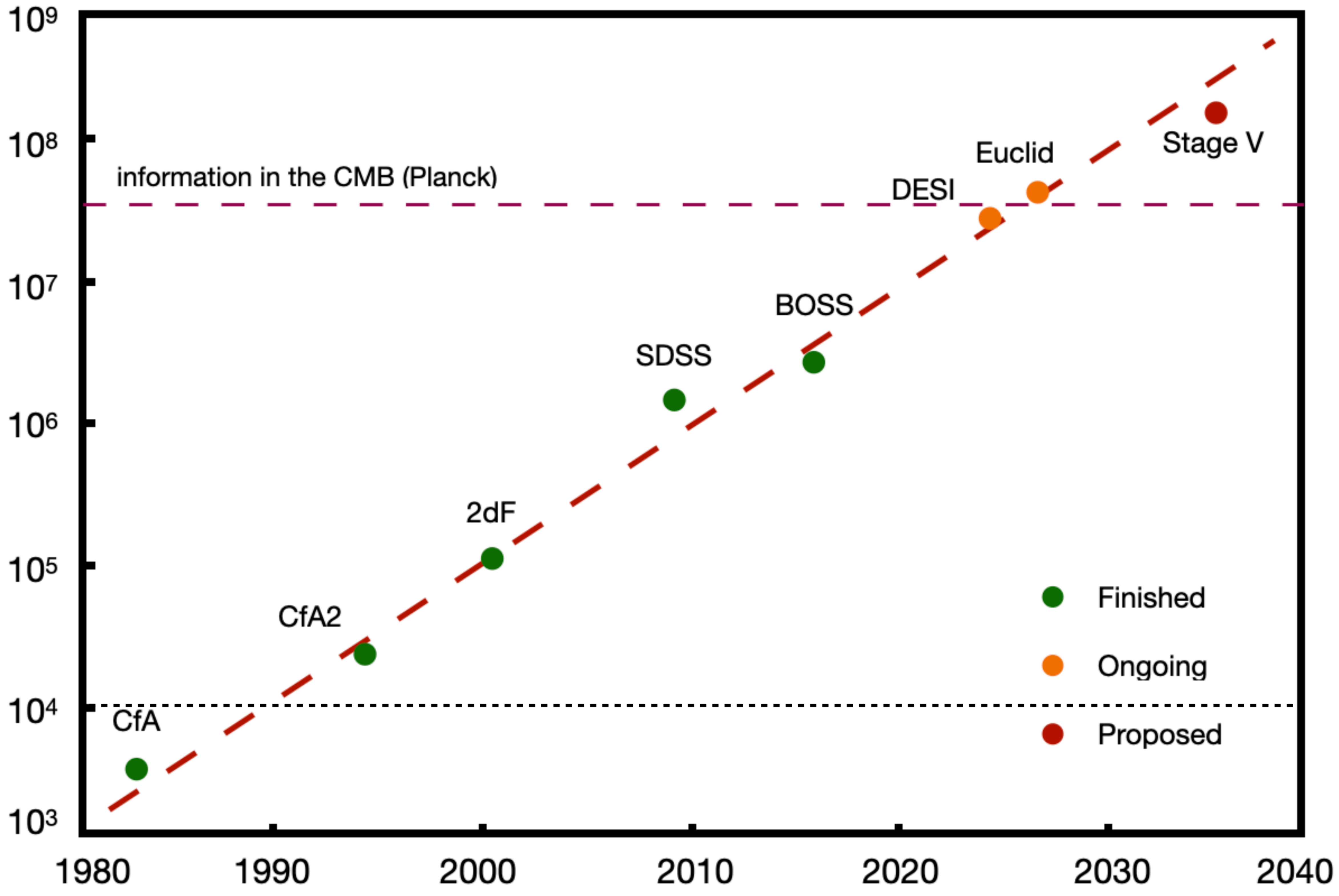


Small scales to detect relativistic effects

We want to detect a redshift of about 10 km/s, where the typical dispersion is of the order 1000 km/s

- signal is 2 order of magnitude smaller than the noise
- we need at least 10^4 galaxies





Credits: Marko Simonovic

First Detection

Letter | Published: 28 September 2011

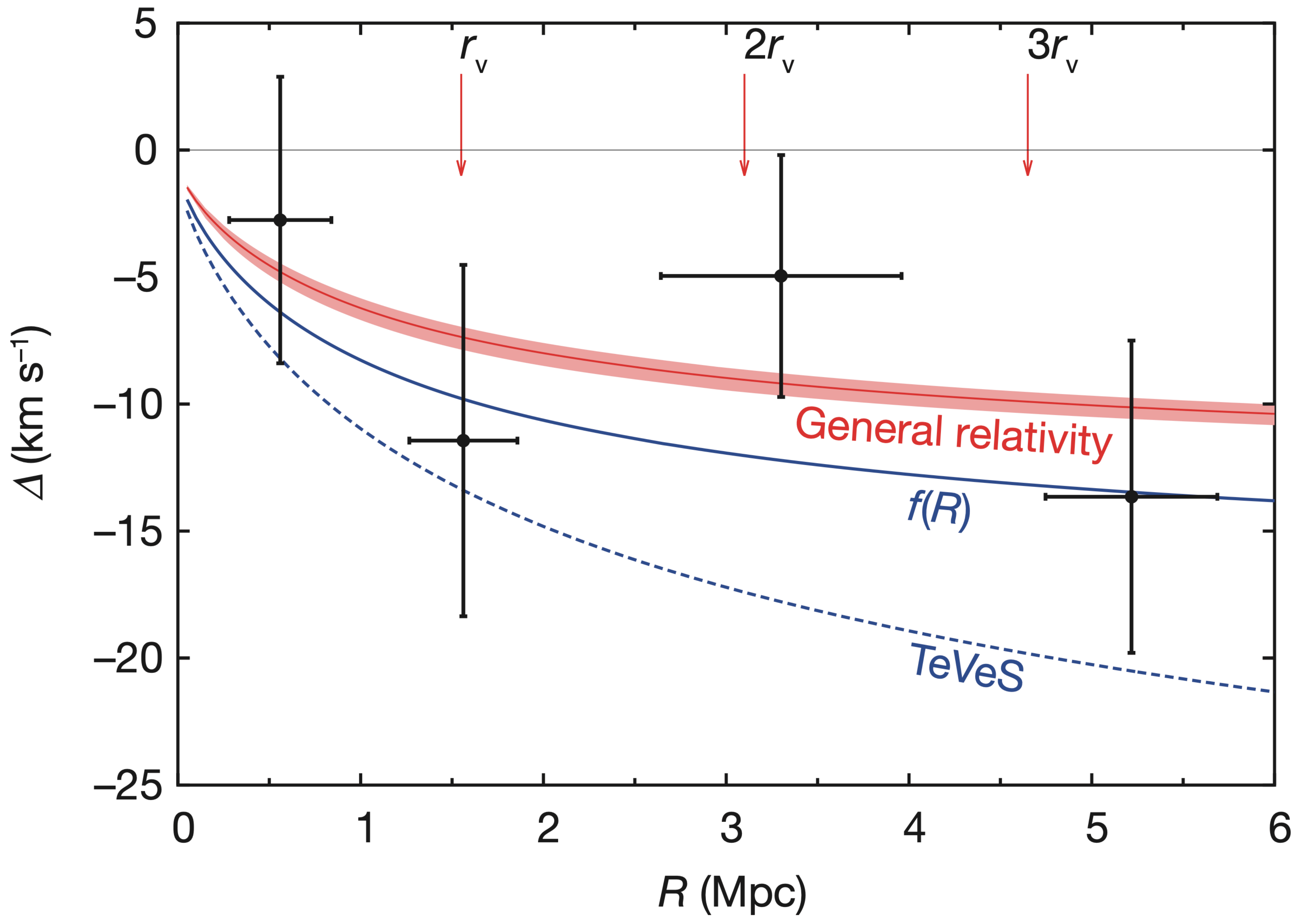
Gravitational redshift of galaxies in clusters as predicted by general relativity

Radosław Wojtak, Steen H. Hansen & Jens Hjorth

Nature 477, 567–569 (2011) | Cite this article

to allow for detection of gravitational redshift at a confidence level of nearly 3σ (see Supplementary Information).

Our final sample comprises 7,800 clusters with the mean redshift of 0.24 and on average 16 galaxies with spectroscopic redshift per cluster. Those clusters with less than 5 redshifts were not included into the sample. As the final step we combine redshift data of all clusters into one. The velocity diagram of the resulting composite cluster is shown in Supplementary Fig. 1.



$$\Delta z \equiv \frac{z - z_c}{1 + z_c} \sim -\Delta v_{\parallel} - \Delta\Psi \Rightarrow \langle \Delta z \rangle = -\Delta\Psi$$

Only gravitational redshift?

$$\Delta z \equiv \frac{z - z_c}{1 + z_c} \sim -\Delta v_{\parallel} - \Delta\Psi \Rightarrow \langle \Delta z \rangle = -\Delta\Psi$$

Galaxy clusters are the largest virialized objects in the universe

Virial Theorem

$$2\langle T \rangle = \langle V \rangle \Rightarrow \Psi \sim v^2$$

Transverse Doppler

Zhao, Peacock, Li [arXiv:1206.5032]

$$\Delta z \equiv \frac{z - z_c}{1 + z_c} \sim -\Delta v_{\parallel} + -\Delta\Psi + \frac{\Delta v^2}{2} \Rightarrow \langle \Delta z \rangle = -\Delta\Psi + \frac{\langle \Delta v^2 \rangle}{2}$$

How to include all the terms relevant at cluster scales?

Weak-field approximation ➡ $\delta \sim \left(k/H\right) v \sim \left(k/H\right)^2 \Psi$

Measurements

cluster mass function

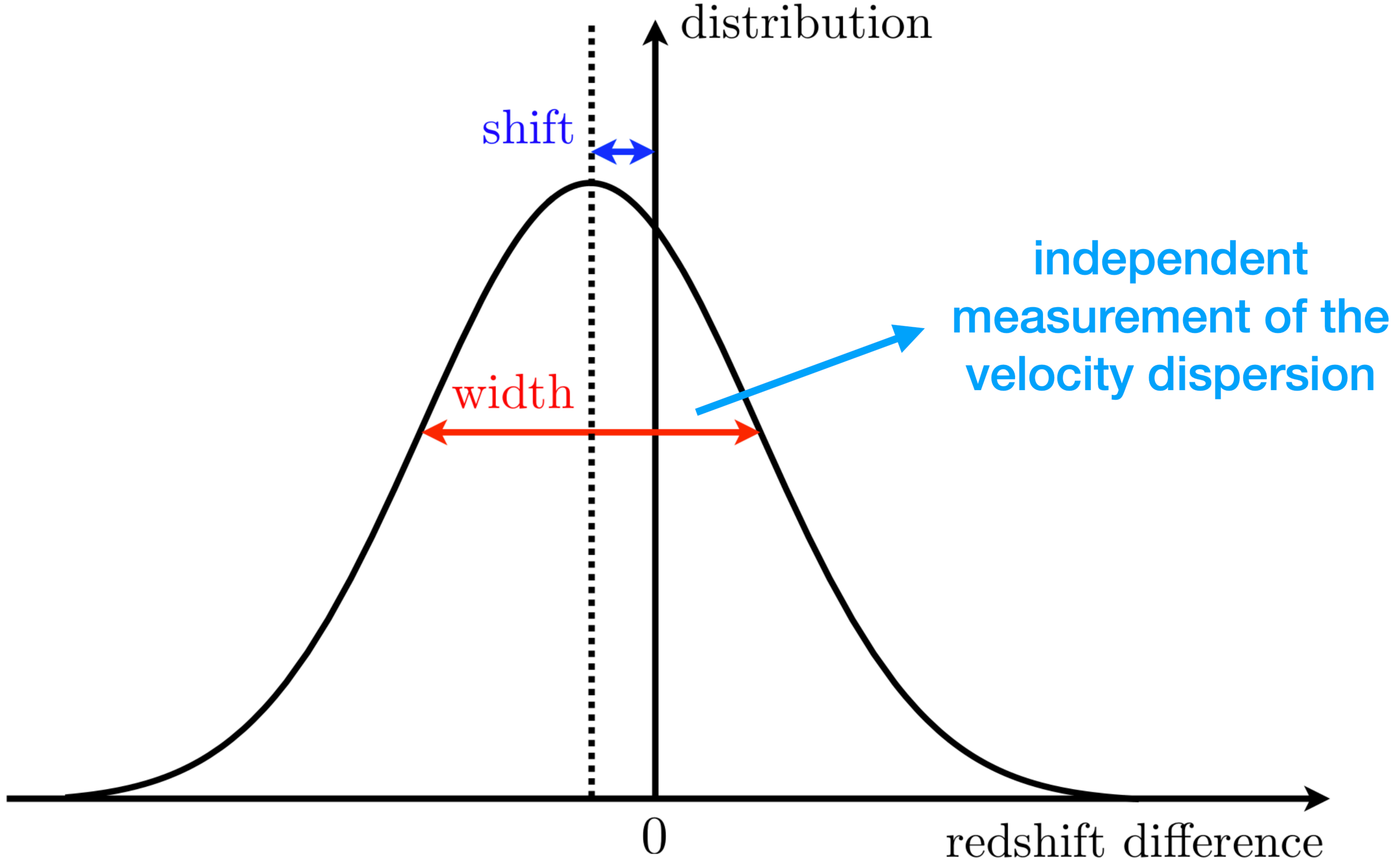
gravitational redshift

kinematical corrections

background evolution

$$\langle\overline{\Delta z}\rangle^{\text{stack}}_{R_\perp} = \frac{\int dM \frac{dN}{dM} \int dr_e \rho_g^{\text{real}}\left(\eta_e, r_e, \bar{L}_*, M\right)\left[-\Delta\Psi + \sigma_v^2\left(\frac{3}{2} - \mathcal{R}\right) + \frac{1}{2} r_e^2 \mathcal{H}_e^2\left(1 - 2\mathcal{B} - \frac{\dot{\mathcal{H}}_e}{\mathcal{H}_e^2}\right)\right]}{\int dM \frac{dN}{dM} \int dr_e \rho_g^{\text{real}}\left(\eta_e, r_e, \bar{L}_*, M\right)}$$

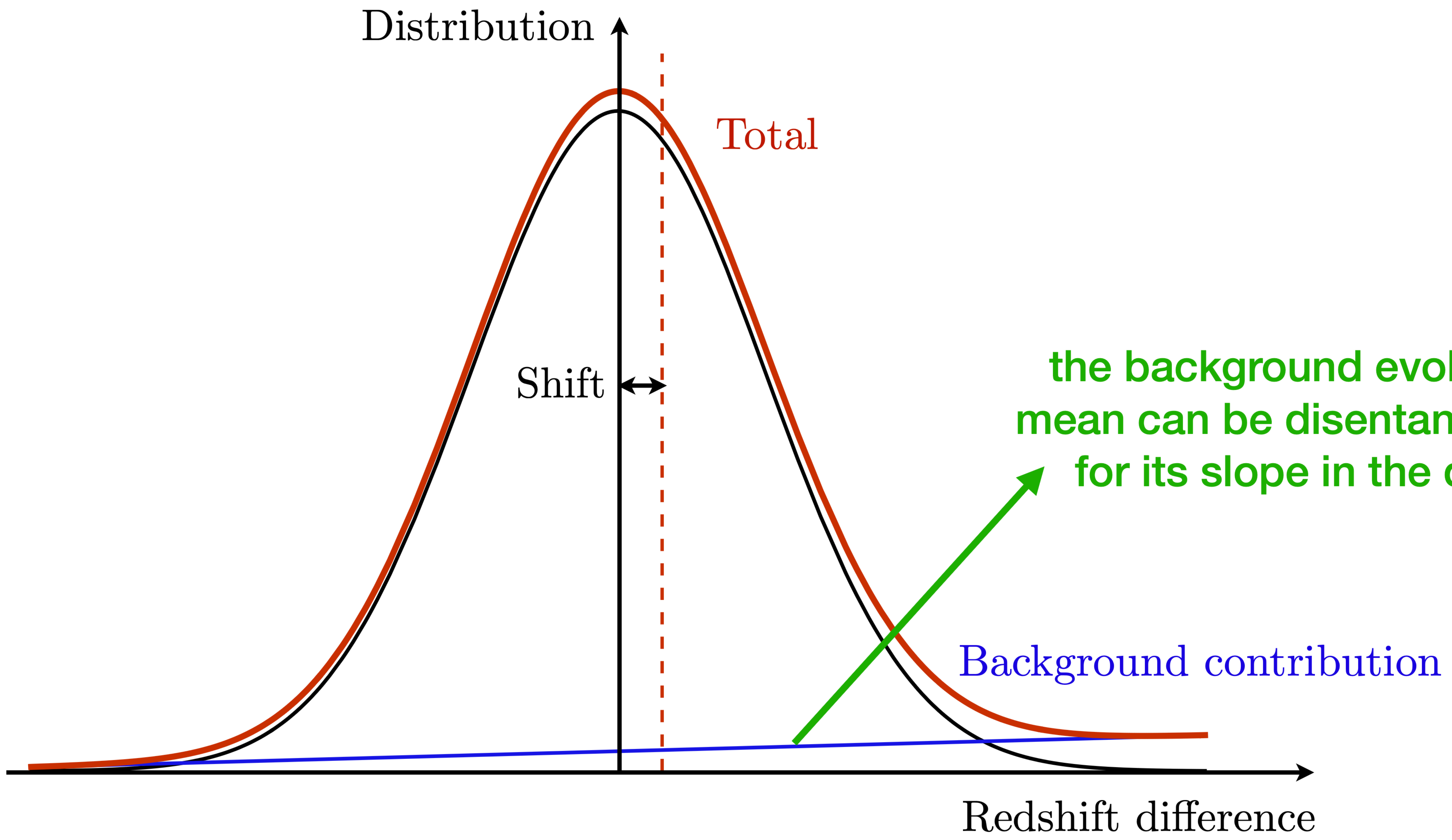
$$+\mathcal{O}\left(\epsilon_{\mathcal{H}}^3\right) \,, \qquad (3.1)$$



Measurements

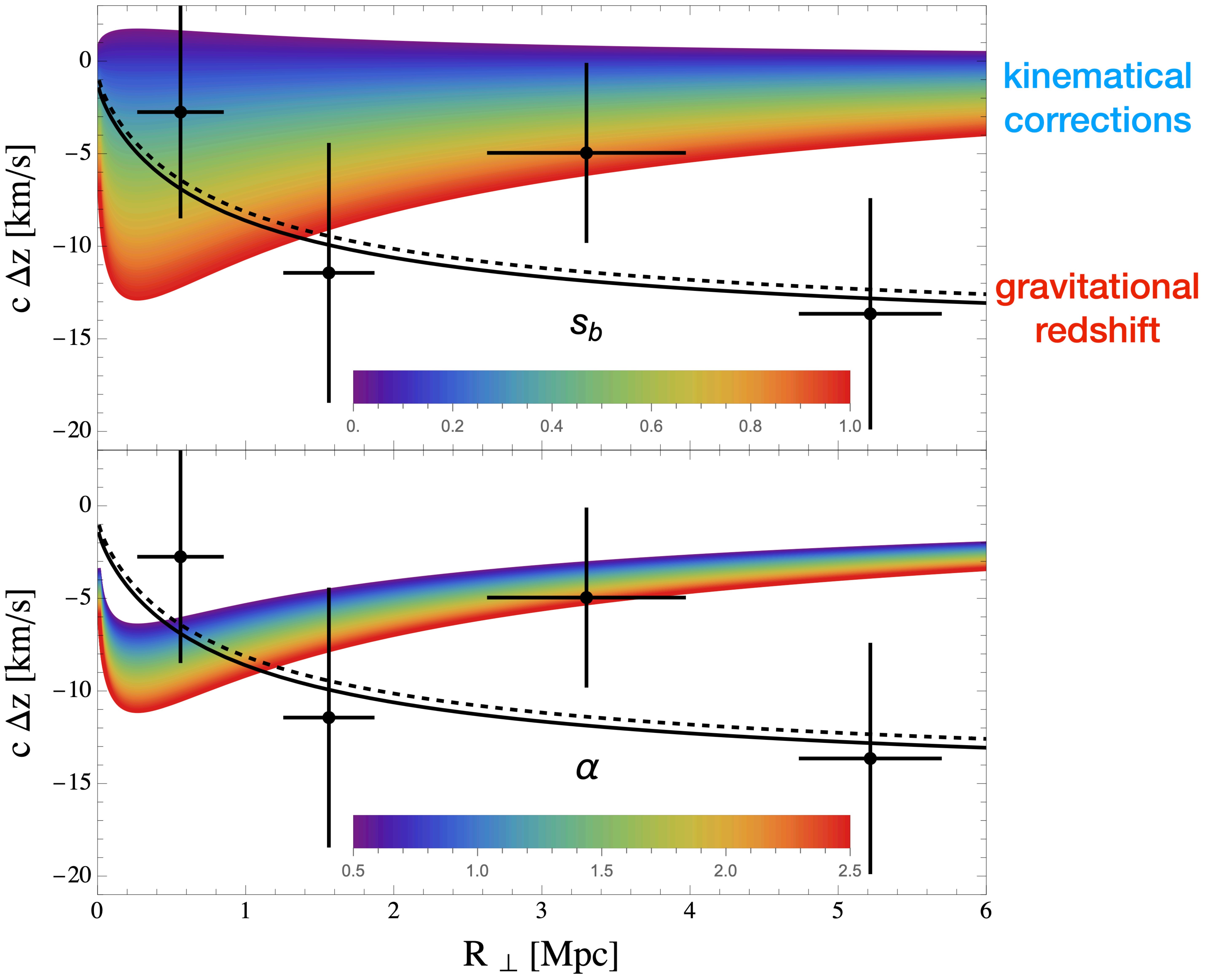
cluster mass function — gravitational redshift — kinematical corrections — background evolution

$$\langle\overline{\Delta z}\rangle^{\text{stack}}_{R_\perp} = \frac{\int dM \frac{dN}{dM} \int dr_e \rho_g^{\text{real}}\left(\eta_e, r_e, \bar{L}_*, M\right)\left[-\Delta\Psi + \sigma_v^2\left(\frac{3}{2} - \mathcal{R}\right) + \frac{1}{2} r_e^2 \mathcal{H}_e^2\left(1 - 2\mathcal{B} - \frac{\dot{\mathcal{H}}_e}{\mathcal{H}_e^2}\right)\right]}{\int dM \frac{dN}{dM} \int dr_e \rho_g^{\text{real}}\left(\eta_e, r_e, \bar{L}_*, M\right)} + \mathcal{O}\left(\epsilon_{\mathcal{H}}^3\right) \quad (3.1)$$



the background evolution on the mean can be disentangled by fitting for its slope in the distribution

Gravitational redshift and kinematical effects



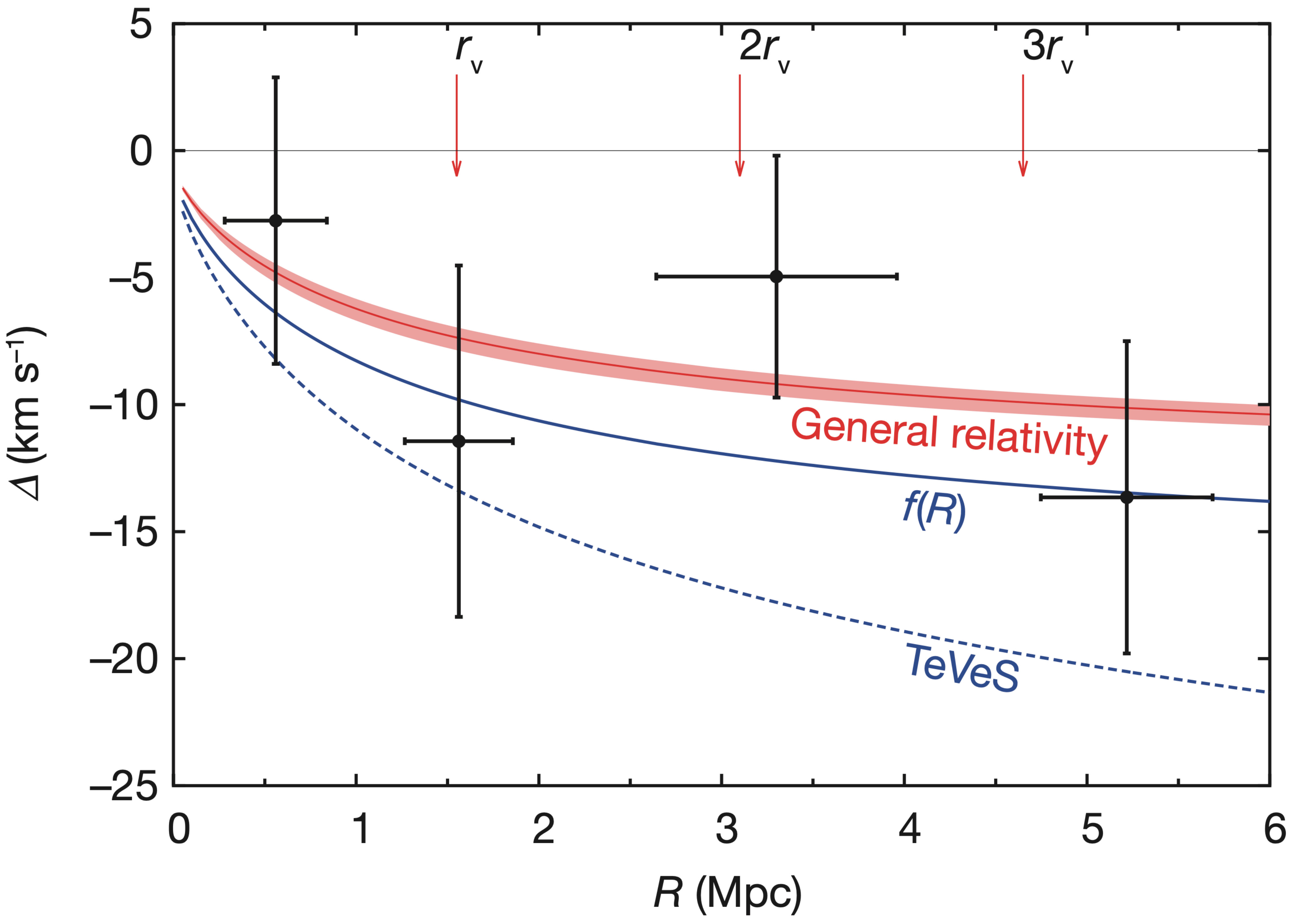
Test of Gravity

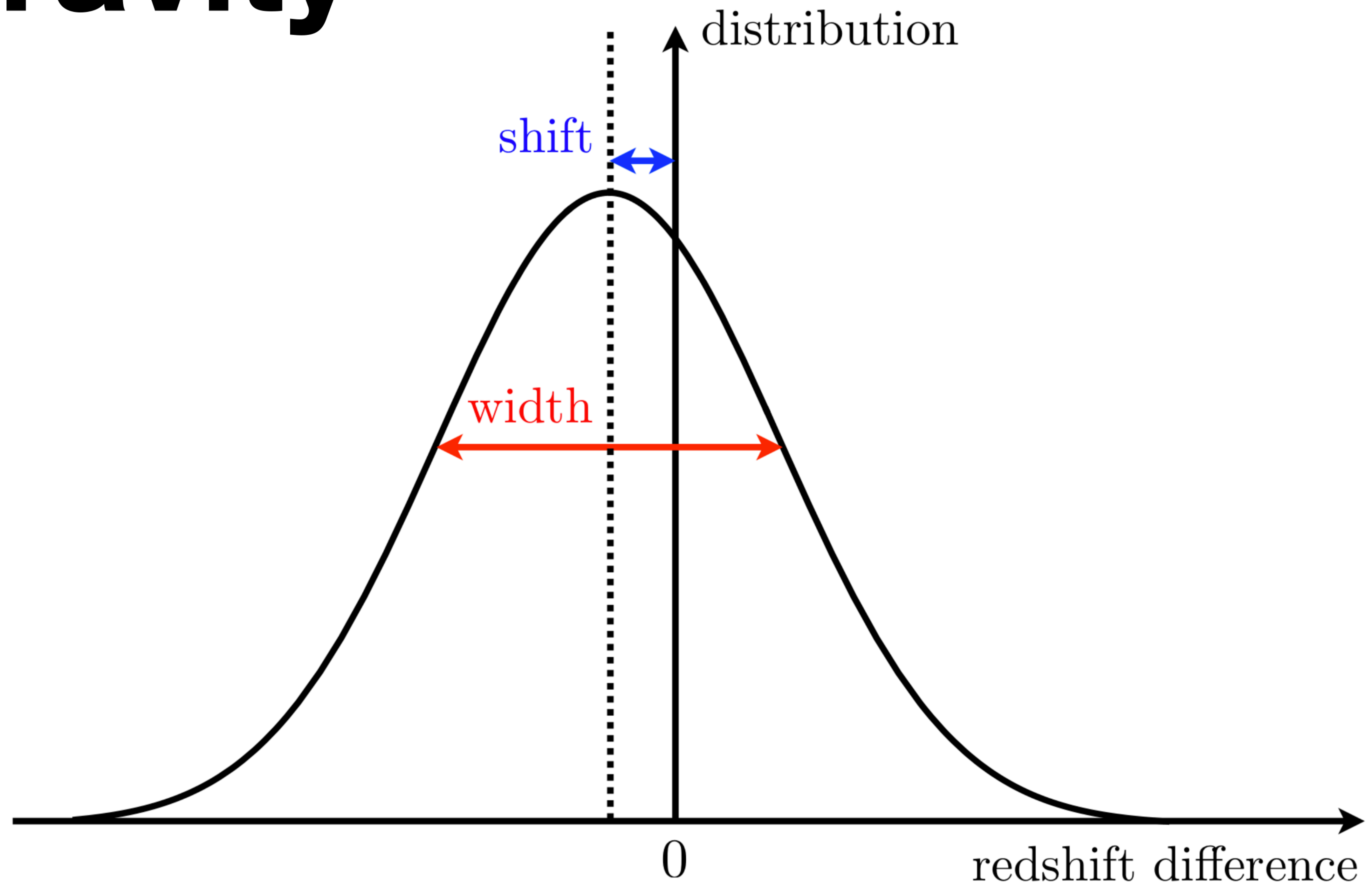
Letter | Published: 28 September 2011

Gravitational redshift of galaxies in clusters as predicted by general relativity

Radosław Wojtak, Steen H. Hansen & Jens Hjorth

Nature **477**, 567–569 (2011) | Cite this article





Gravitational potential + velocity dispersion

velocity dispersion

+ theory of gravity

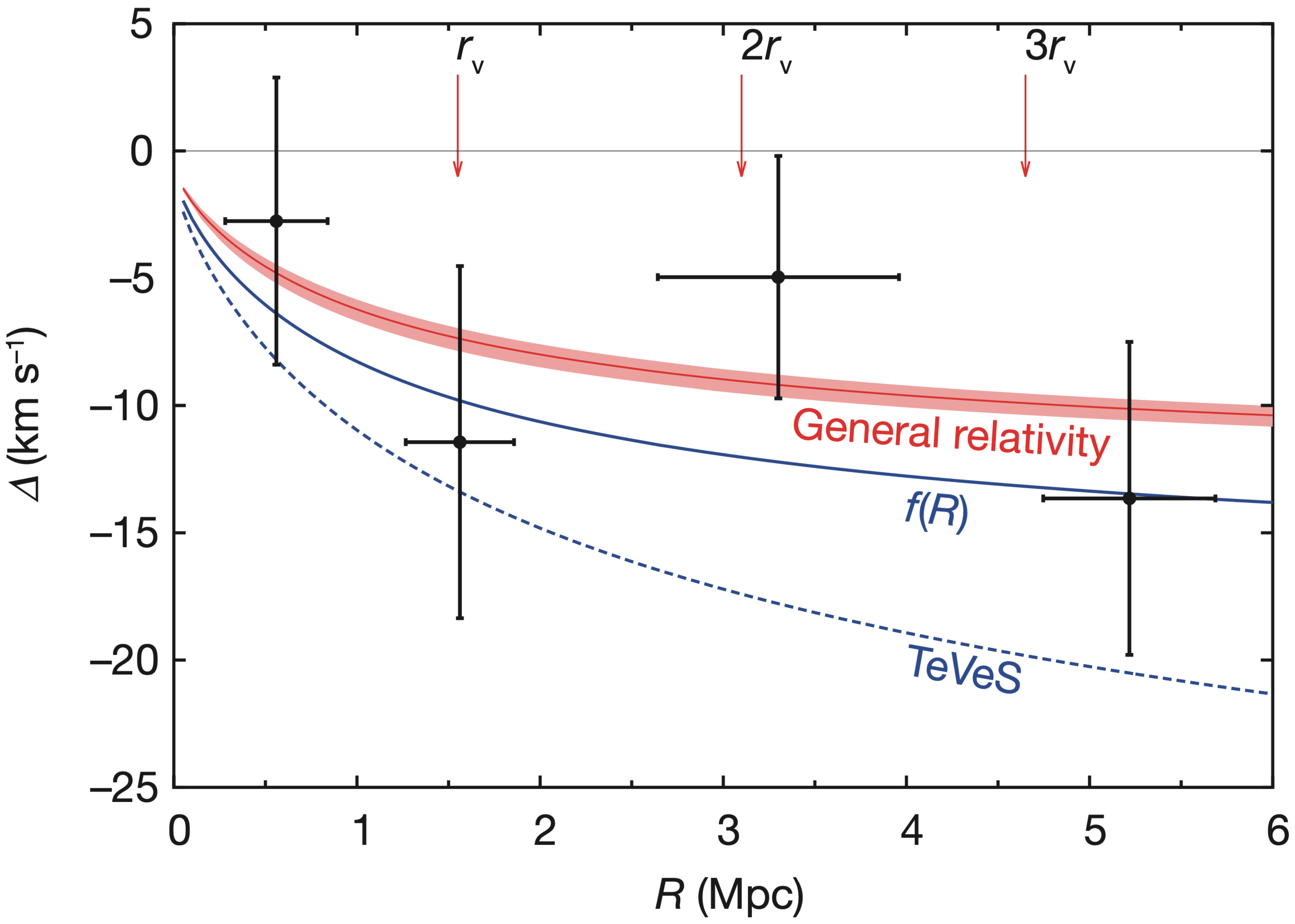
Future Directions

Letter | Published: 28 September 2011

Gravitational redshift of galaxies in clusters as predicted by general relativity

Radosław Wojtak, Steen H. Hansen & Jens Hjorth

Nature **477**, 567–569 (2011) | Cite this article



geodesic motion for massless particles

Gravitational redshift

both sourced by Ψ

velocity dispersion

geodesic motion for massive particles

Test of the Equivalence Principle

Conclusions

- Relativistic effects have been detected on cluster scales
- We developed a full relativistic description on the redshift difference observable up to second order in the weak-field expansion
- Kinematical effects are comparable to gravitational redshift
- Gravitational redshift and cluster dynamics can be used to test the equivalence principle at Mpc scales