Breaking cosmic degeneracies?
(with non-standard observables)

Wojciech “Voytek” Hellwing
Center for Theoretical Physics
in Warsaw
Polish Academy of Sciences

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Collaborators: Boajiu Li (Durham), Maciek Bilicki (Warsaw), Kazuya Koyama (Portsmouth), Ben Bose (Geneva),

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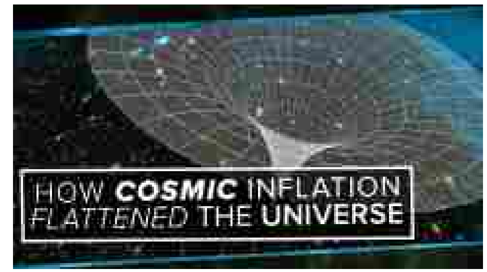
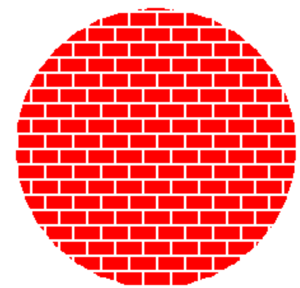
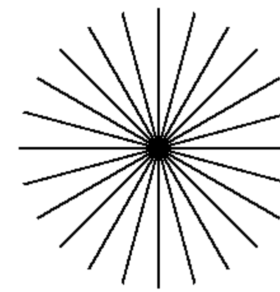
Standard model of cosmology: core assumptions

- Hot relativistic Big Bang

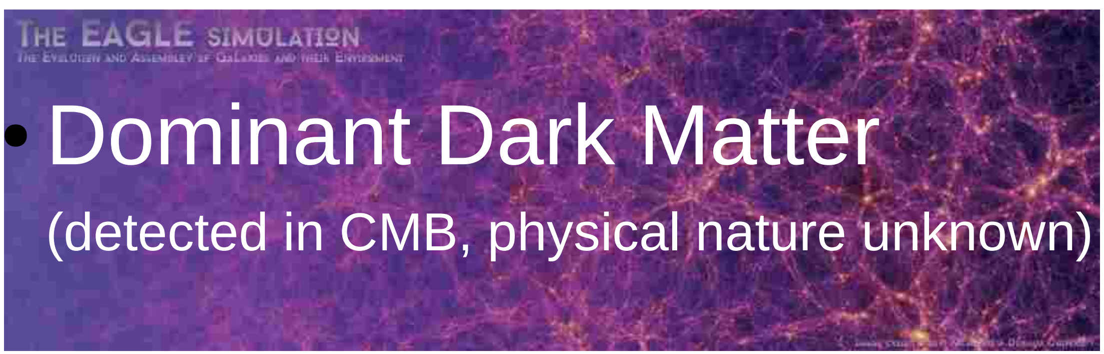


- Gaussian initial conditions
  (adiabatic, Inflation)



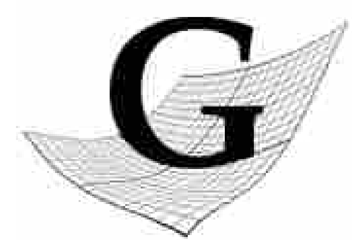


- global homogeneity and isotropy
  (early Universe ok, late-time under scrutiny)



- Dominant Dark Matter

  (detected in CMB, physical nature unknown)



- GR is theory of gravity on all scales
  (tested only on Solar System scales and strong-field regime)

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GR - a successful story (of metric)

General Relativity is a metric theory. Einstein field equations can be derived by varying the Einstein-Hilbert action integral with respect to metric.

GR curvature term

SM particles and dark matter

$$\frac{1}{16\pi G}\int d^4x\sqrt{-g}\,R(g) + \int d^4x\sqrt{-g}\,\mathcal{L}(g,\mathrm{matter})$$

Einstein's cosmological constant

$$+\ \frac{1}{8\pi G}\int \mathrm{d}^4x\sqrt{-g}\,\Lambda$$

metric of space time

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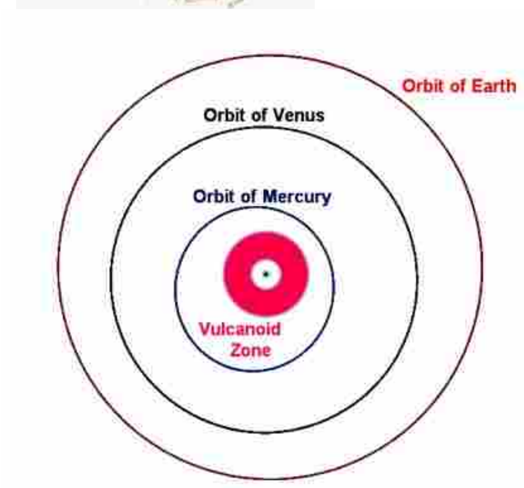
Paving the road to new paradigm

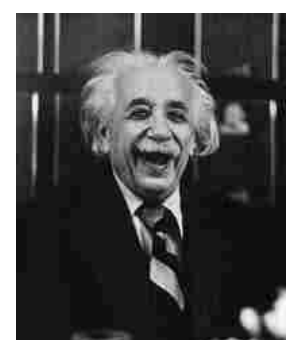
In 1859 **Urbain Le Verrier** showed that slow precession of Mercury's orbit perihelion could not be explained by Newton's theory of gravity.



A conjecture – hypothetical planet Vulcan as a cause of the anomaly.

Vulcan was never discovered.

Instead the Newtonian theory was improved to GR



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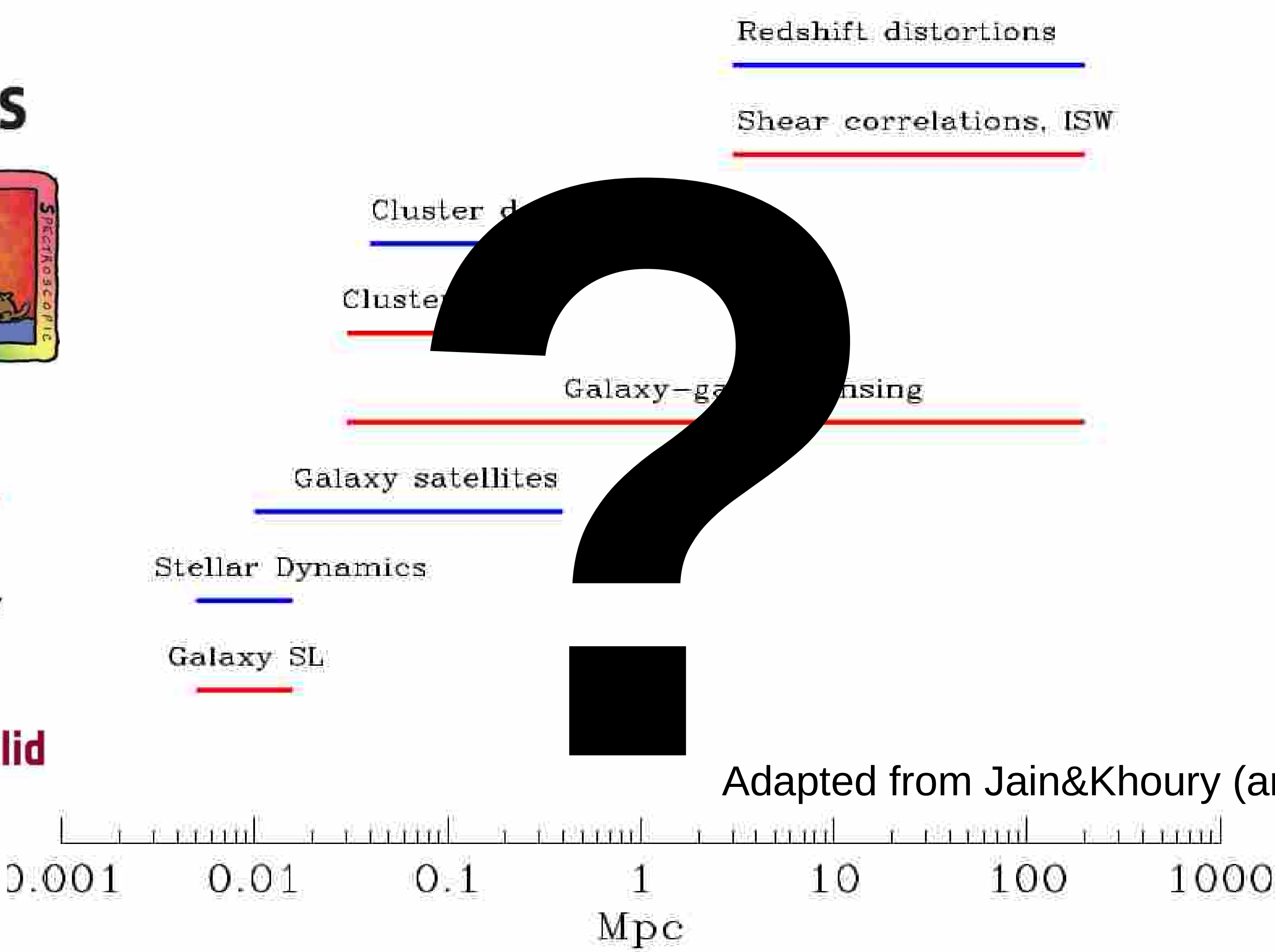
Testing GR/DE – bold task of XXI century extra-galactic astronomy



Adapted from Jain&Khoury (arXiv:1004.3294)

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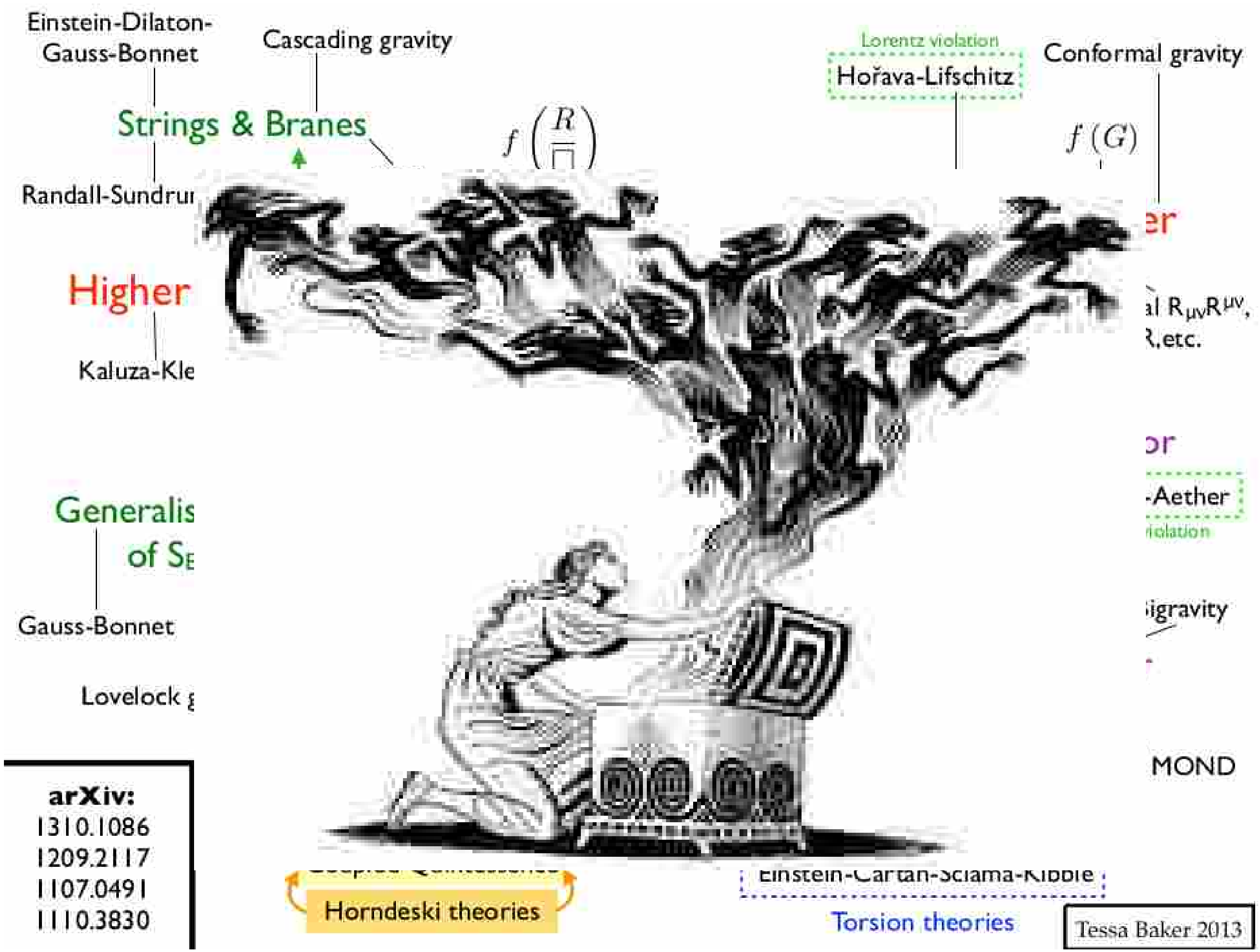
Charting MG. From GR to the land of dragons

Diagram of Modified Gravity plethora of treasure trove



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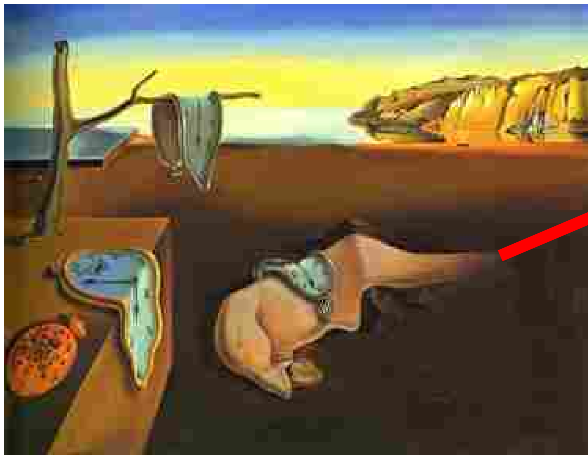
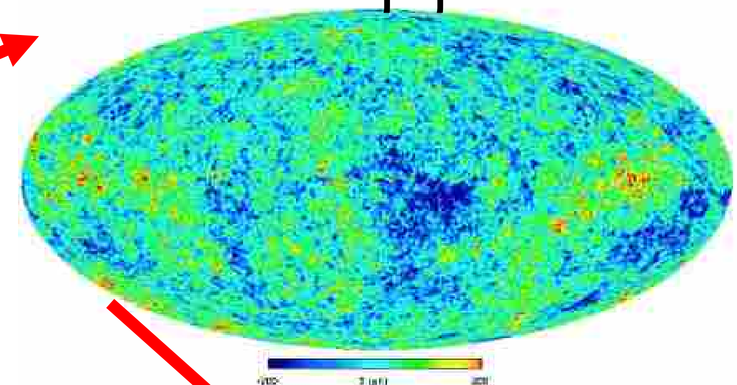
MG is even more non-linear then GR

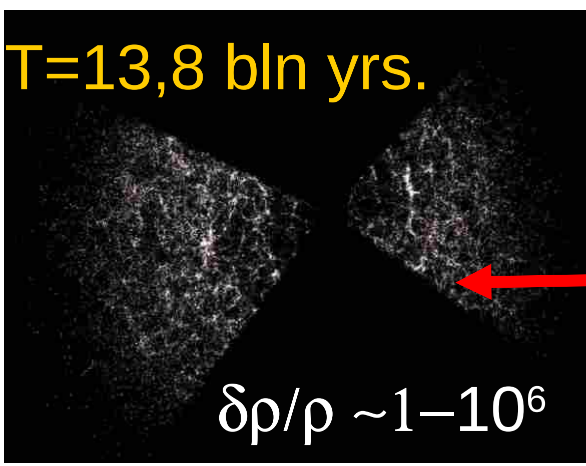
To model and study the growth of cosmic structures we need high-res N-body simulations



T=380,000 yrs.

$\delta\rho/\rho \sim 10^{-5}$





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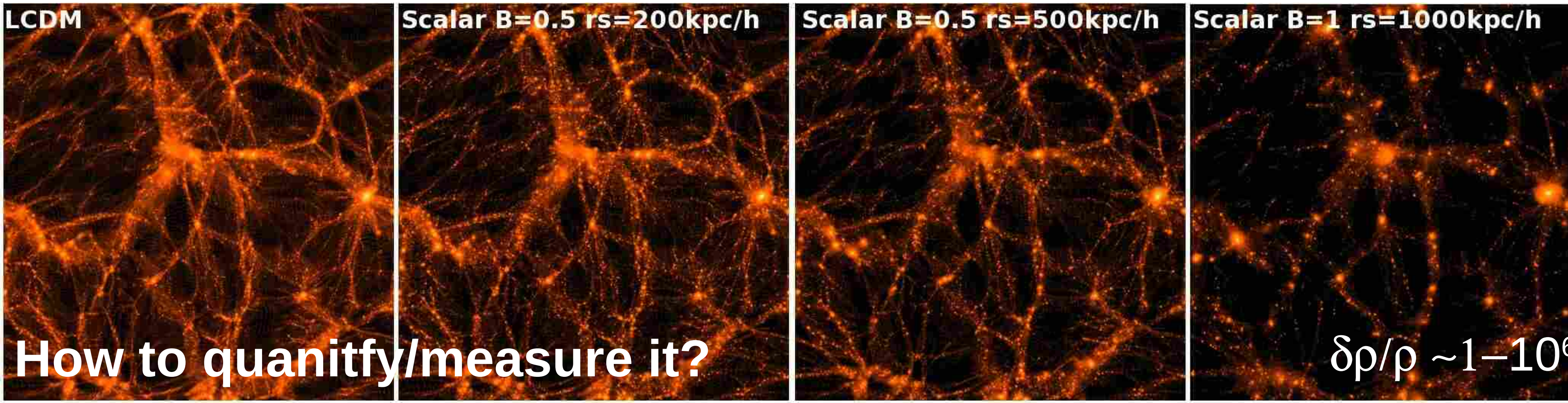
Beyond GR – looking for cosmological effects



$$P(k) = \langle |\delta_{\mathbf{k}}|^2 \rangle$$

Power spectrum of density fluctuations

Linear growth rate: f

$$f(z)\sigma_8(z) \propto \frac{dD}{da} a$$

$$f \equiv \frac{d \ln D}{d \ln a}$$

Linear evolution equation for density perturbations.

$$\frac{\partial^2 \delta_k}{\partial t^2} + 2\frac{\dot{a}}{a}\frac{\partial \delta_k}{\partial t} + \left(\frac{c_s^2 k^2}{a^2} - 4\pi G \rho_0\right)\delta_k = 0\,.$$

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MG predict ehnaced growth of structures

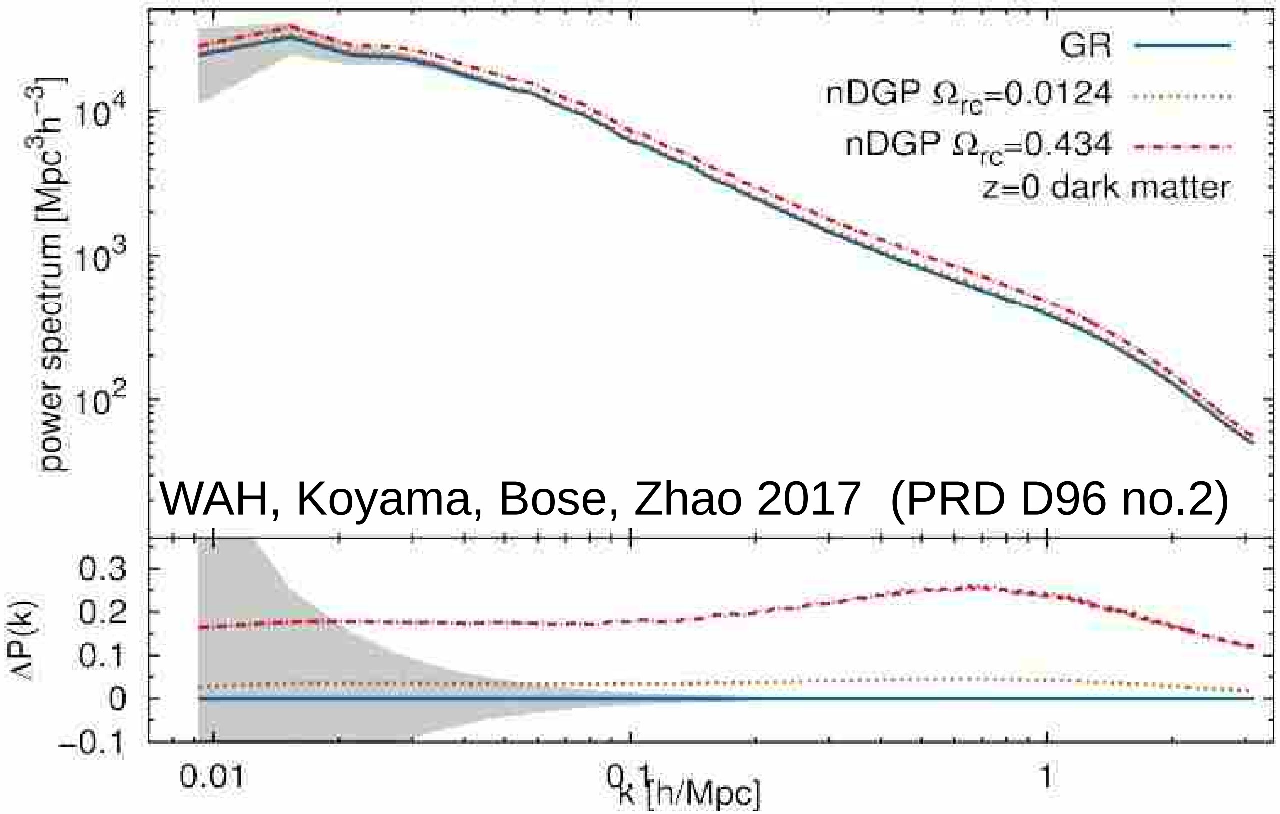

FIG. 5. The matter density power spectrum computed at $z = 0$ for our fiducial GR model (solid line) and two nDGP flavours (dotted and dashed-dotted lines). The shaded region illustrate the cosmic variance error. The bottom panel illustrates the fractional difference of both MG models w.r.t. the GR case.

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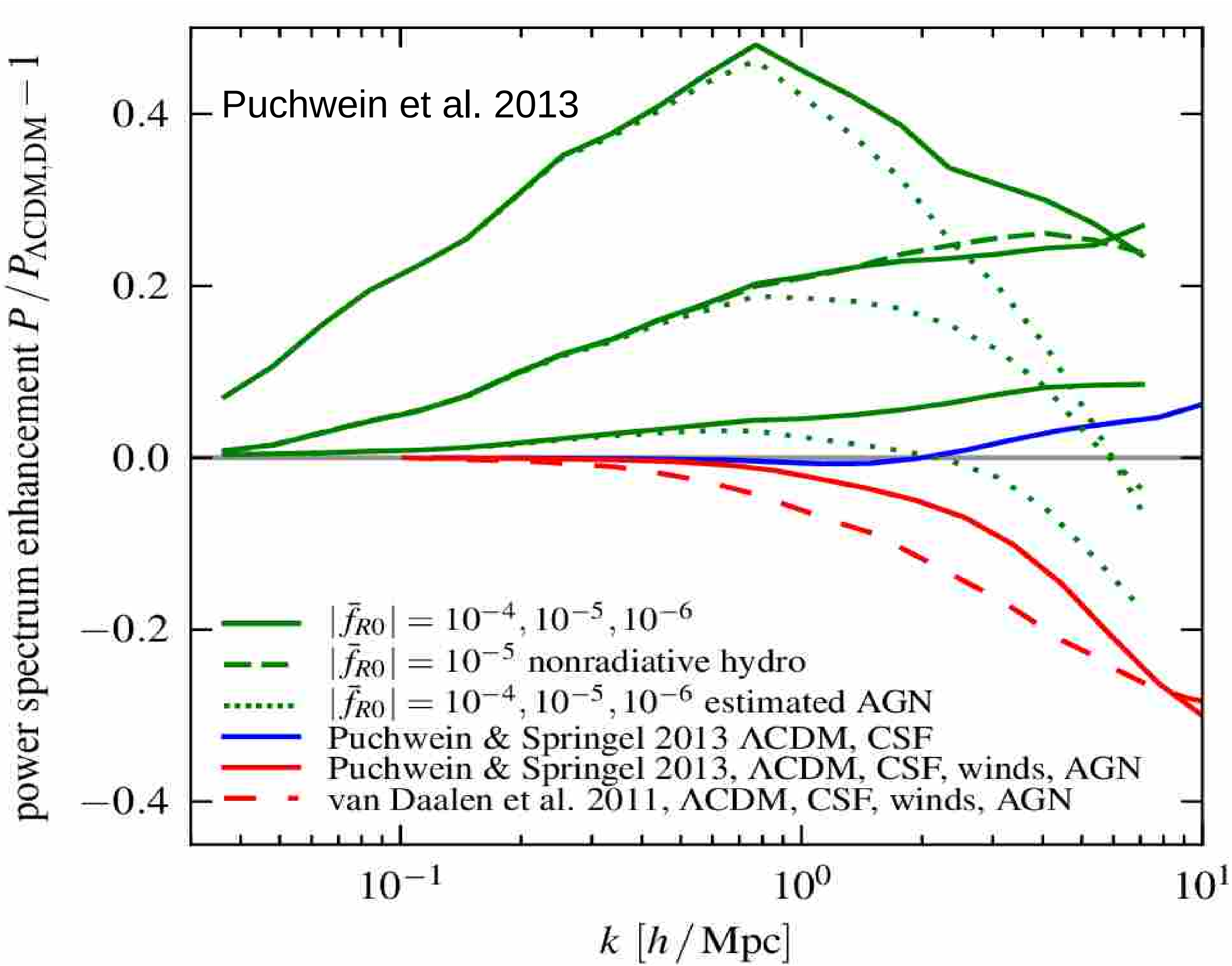
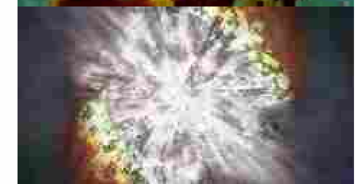
Do not trust baryons, they make up everything (more complicated!)





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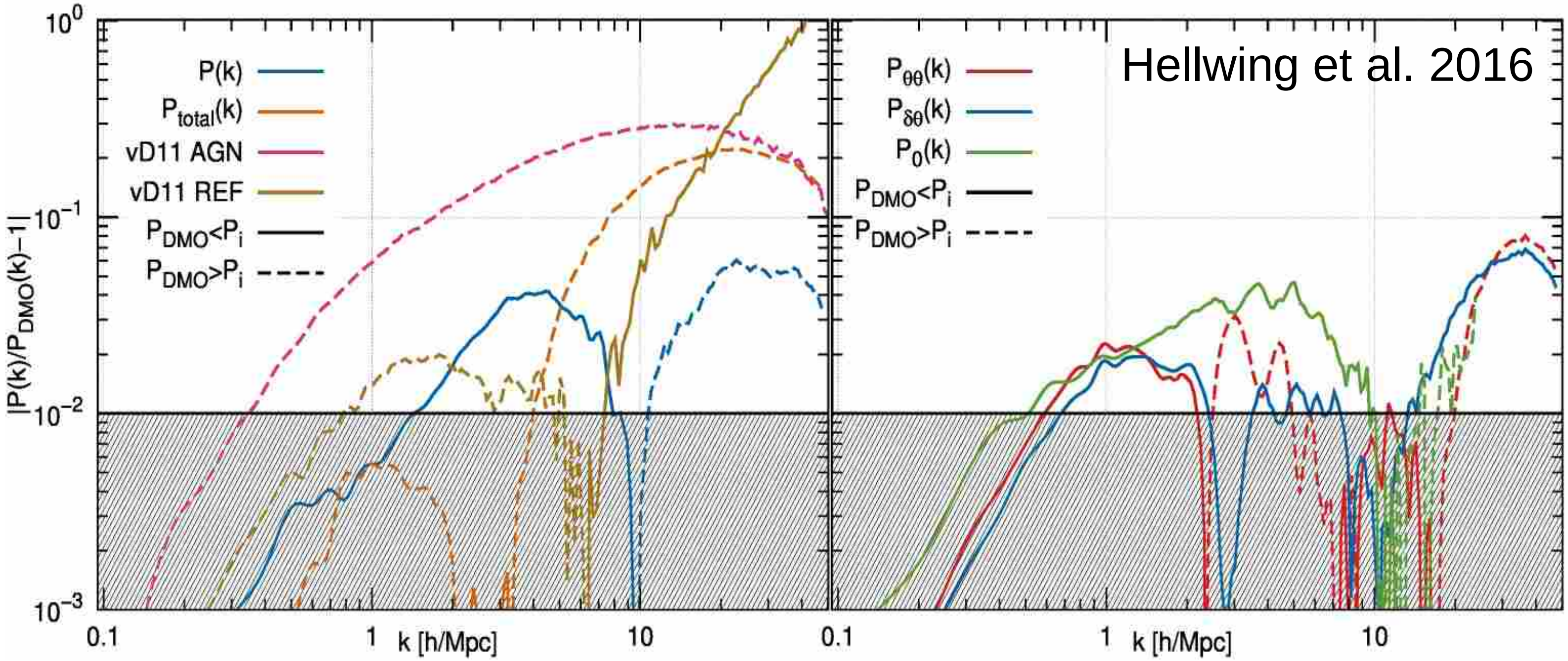

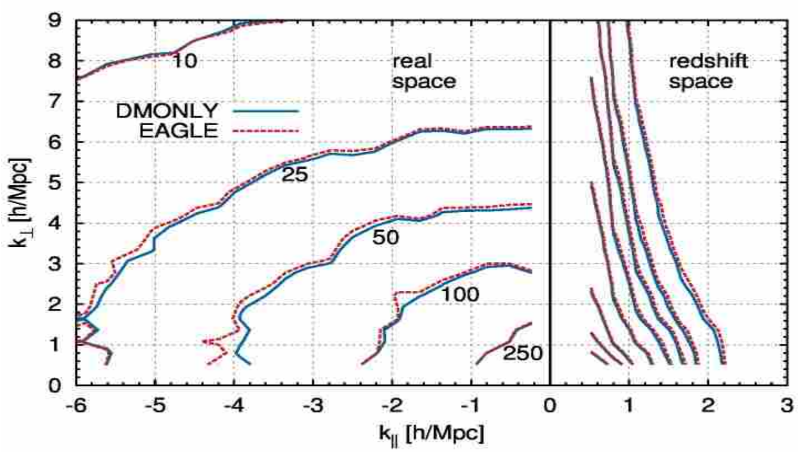

Baryons
accelerating business

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RSD and the conspiracy of the damping tail

$$P_g^s(k,\mu) = D(k\mu\sigma_v)P_K(k,\mu,b), \qquad (24)$$

where

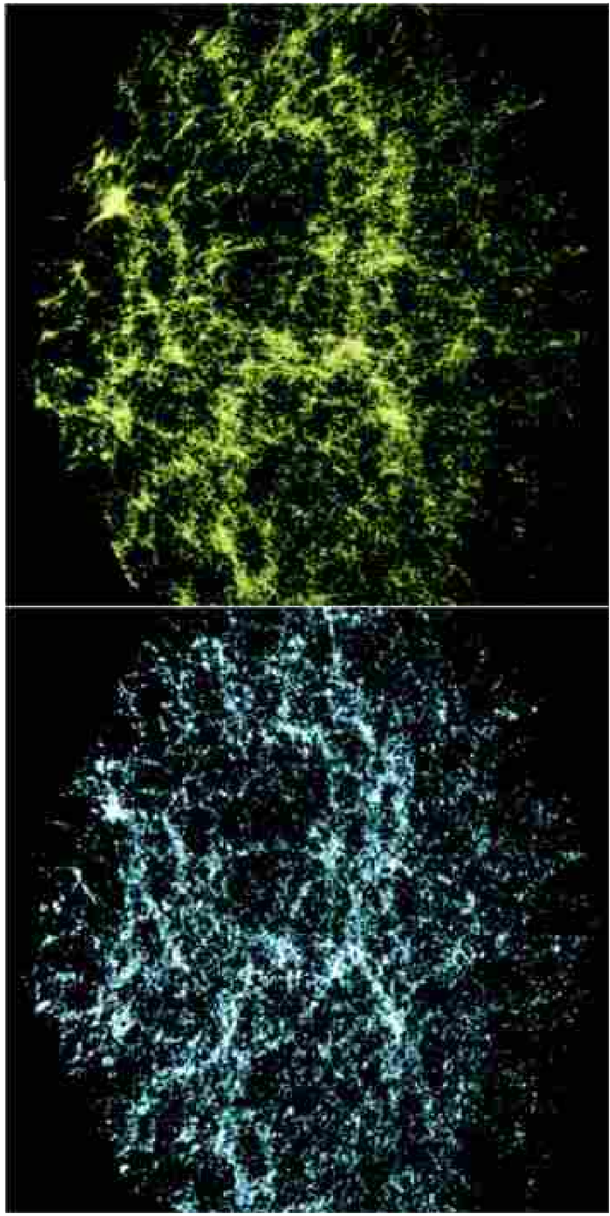
$$D(k\mu\sigma_v) = \begin{cases} \exp[-(k\mu\sigma_v)^2] \\ 1/[1+(k\mu\sigma_v)^2] \end{cases}$$

and

$$P_K(k,\mu,b) =$$

$$\begin{cases} b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\delta}(k) + \mu^4 f^2 P_{\delta\delta}(k) & \text{(mod. A)} \\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) + \mu^4 f^2 P_{\theta\theta}(k) & \text{(mod. B)} \\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) + \mu^4 f^2 P_{\theta\theta}(k) & \\ + C_A(k,\mu;f,b) + C_B(k,\mu;f,b) & \text{(mod. C)} \end{cases}$$

$$b(k) = \begin{cases} b_L \\ b_L b_{NL}(k) \end{cases} \quad .$$



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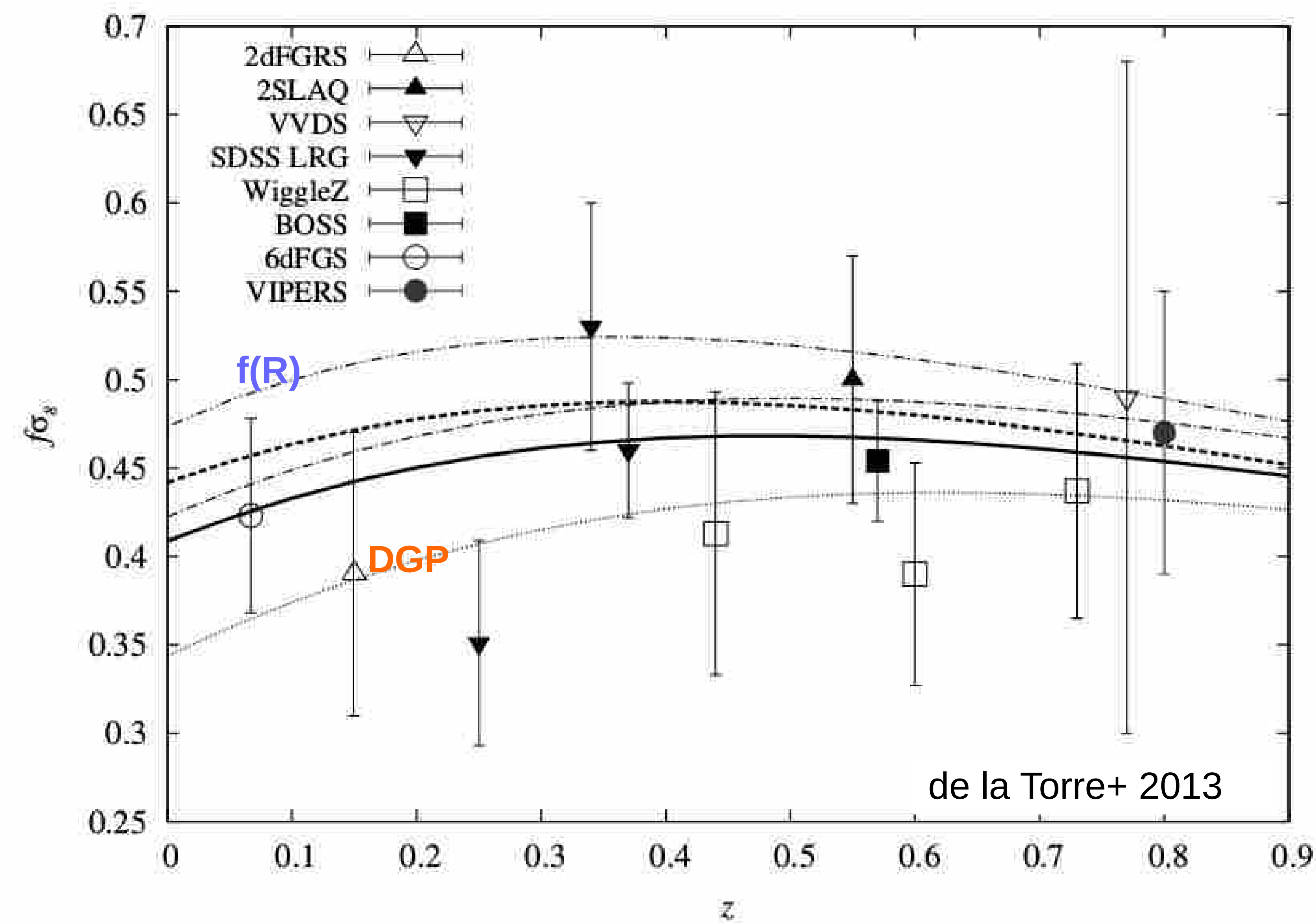

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Signal modeling is degenerated with assumed gravity!

$$P_g^s(k,\mu) = D(k\mu\sigma_v)P_K(k,\mu,b), \tag{24}$$

where

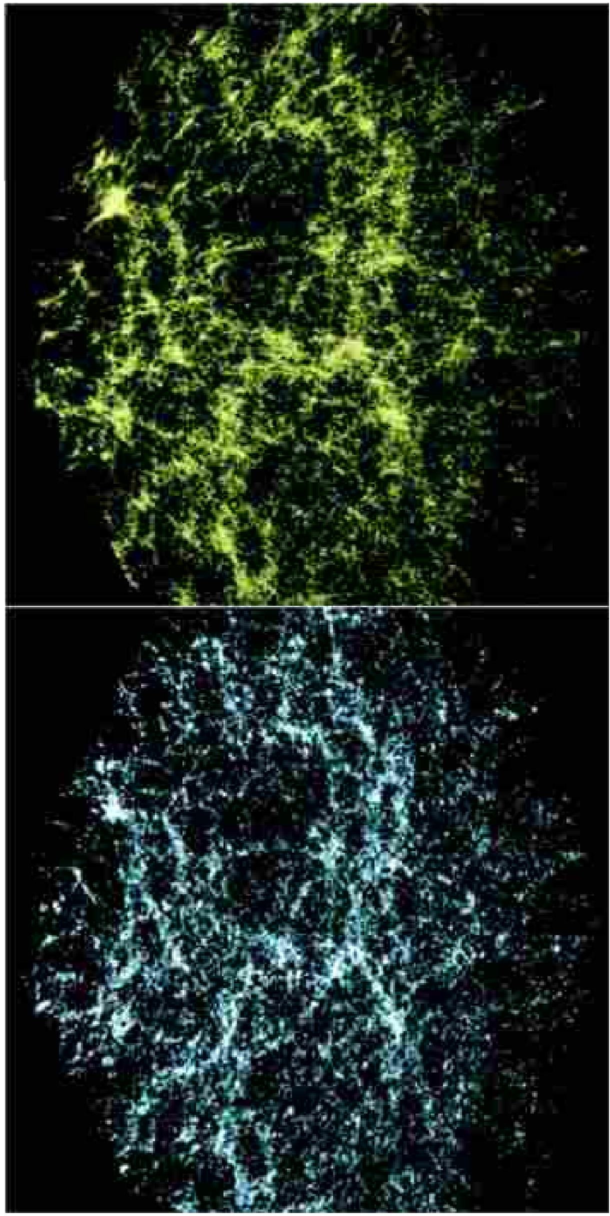
$$D(k\mu\sigma_v) = \begin{cases} \exp[-(k\mu\sigma_v)^2] \\ 1/[1+(k\mu\sigma_v)^2] \end{cases}$$

and

$$P_K(k,\mu,b) =$$

$$\begin{cases} b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\delta}(k) + \mu^4 f^2 P_{\delta\delta}(k) & \text{(mod. A)} \\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) + \mu^4 f^2 P_{\theta\theta}(k) & \text{(mod. B)} \\ b^2(k)P_{\delta\delta}(k) + 2\mu^2 f b(k) P_{\delta\theta}(k) + \mu^4 f^2 P_{\theta\theta}(k) & \\ + C_A(k,\mu;f,b) + C_B(k,\mu;f,b) & \text{(mod. C)} \end{cases}$$

$$b(k) = \begin{cases} b_L \\ b_L b_{NL}(k) \end{cases} .$$



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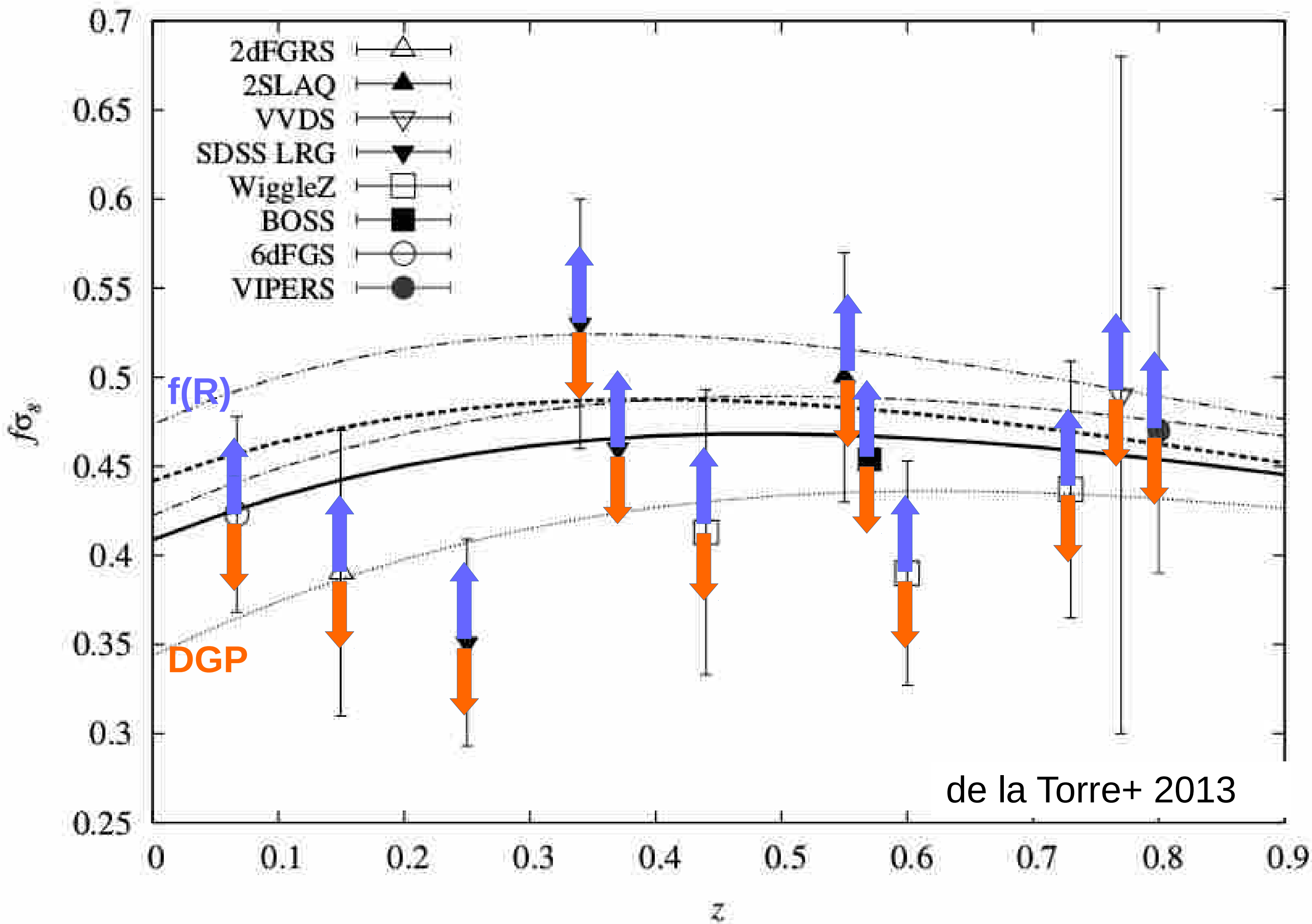

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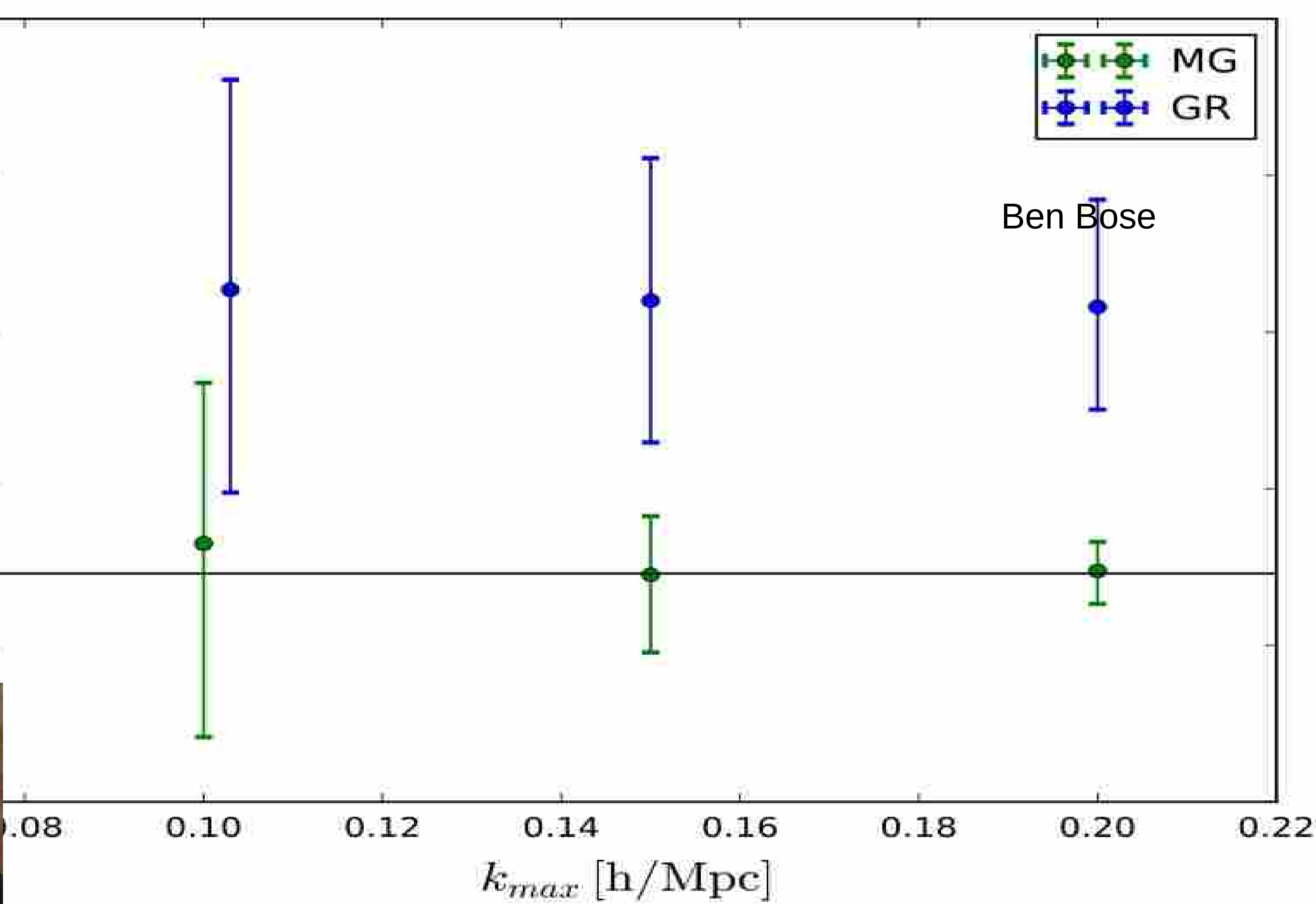
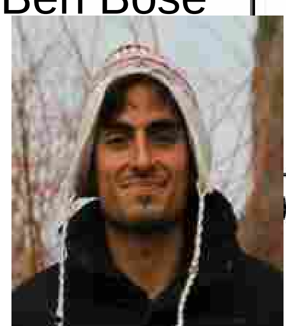
Gravity agnostic modeling leads to theoretical bias



Ben Bose

Ben Bose



Bose, Koyama, WAH, Zhao, Winther 2017

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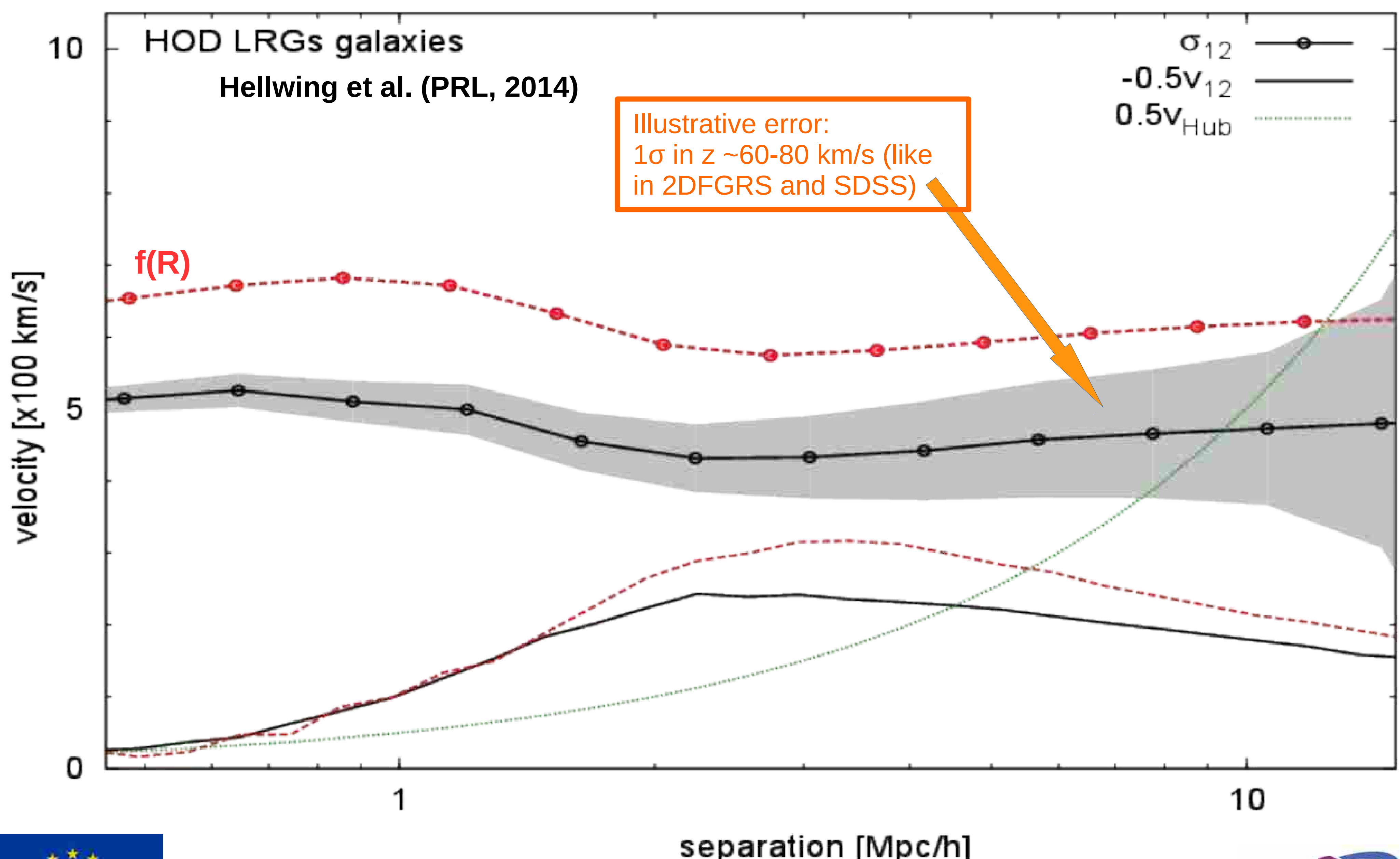
What about direct velocity data?



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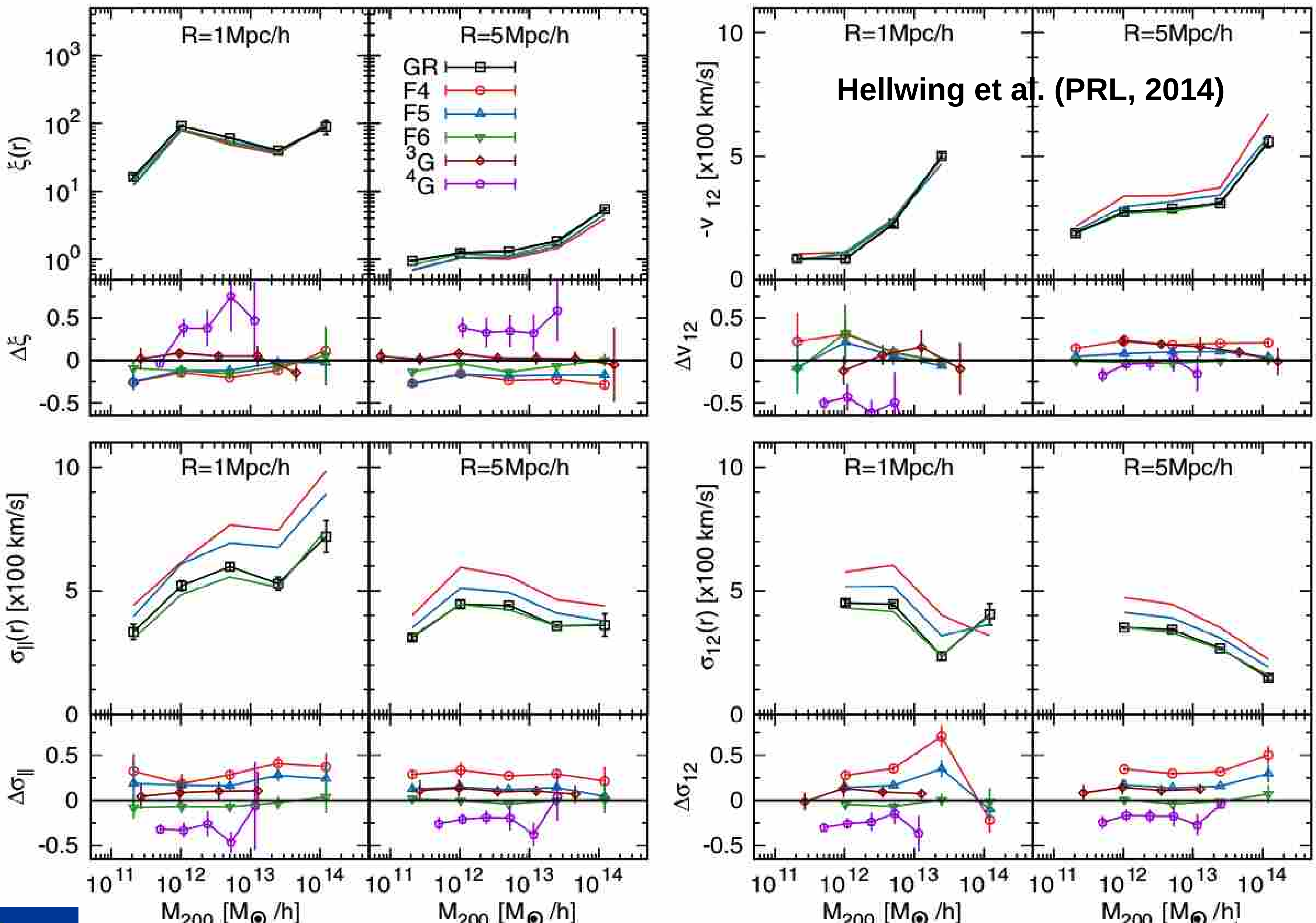
What about direct velocities data?



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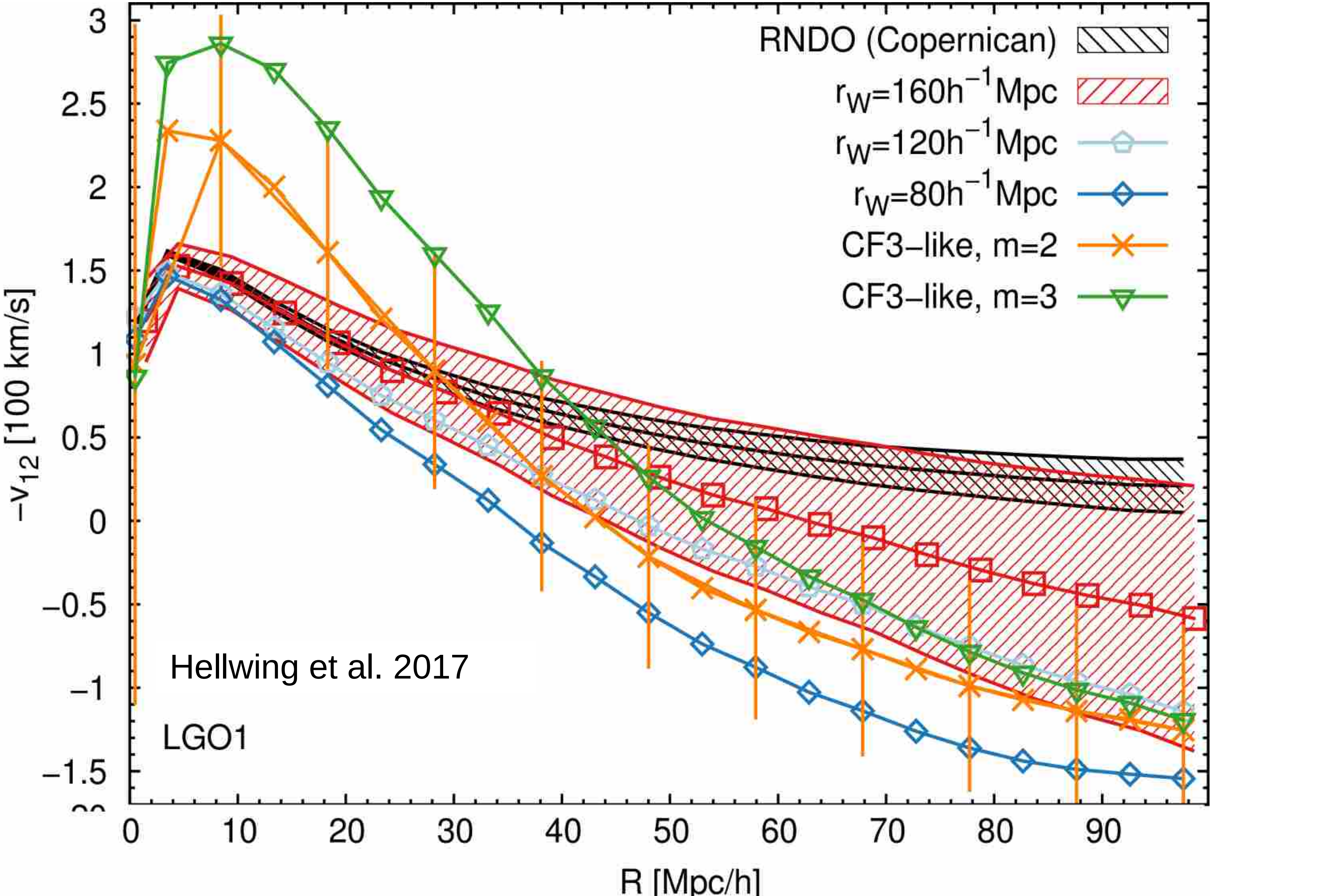
Signal is model independent but there are big systematics



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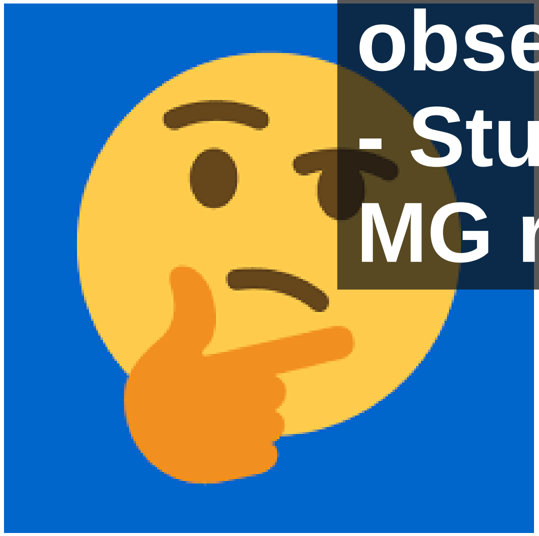
Cosmo gravity probes list of bad deeds

Theoretical bias prone
- Weak lensing statistics
- RSD clustering probes
- Cluster mass comparison

Solution?
- Look for model independent observable.. or/and
- Study galaxy formation in MG regime.



Baryonic degeneracies
- Weak lensing statistics
- LSS clustering probes
- Cluster mass comparison
- Galaxy satellite dynamics

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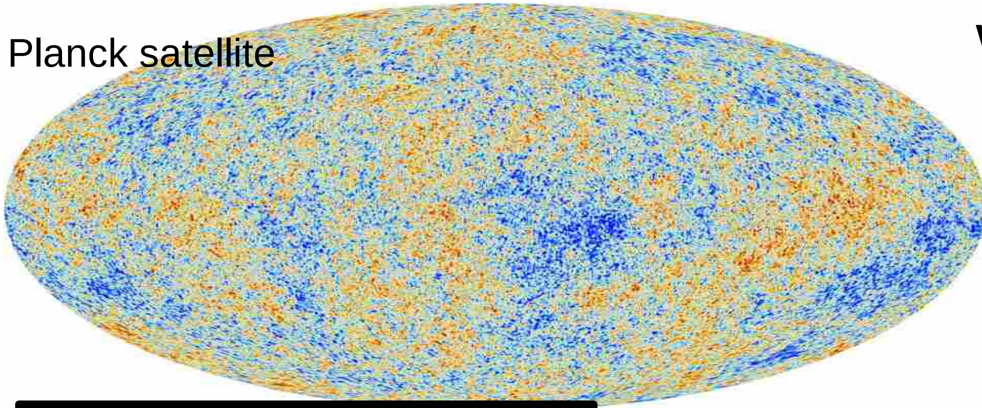
Cosmic density field: A Gaussian random field

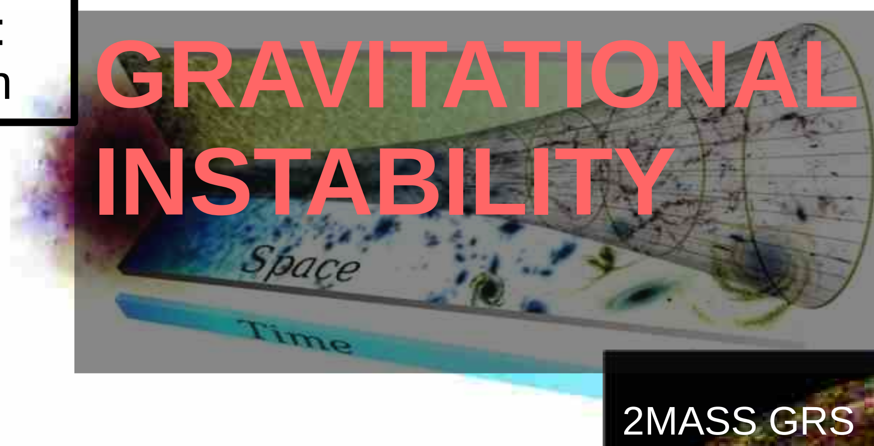


Wick's theorem for Gaussian fields

$$\langle \delta(\mathbf{k}_1)\dots\delta(\mathbf{k}_{2p+1})\rangle = 0$$

$$\langle \delta(\mathbf{k}_1)\dots\delta(\mathbf{k}_{2p})\rangle = \sum_{\text{all pair associations}} \prod_{p \text{ pairs (i,j)}} \langle \delta(\mathbf{k}_i)\delta(\mathbf{k}_j)\rangle$$

Primordial fluctuations:
Very close to Gaussian



Final galaxy distribution:
significantly non-Gaussian

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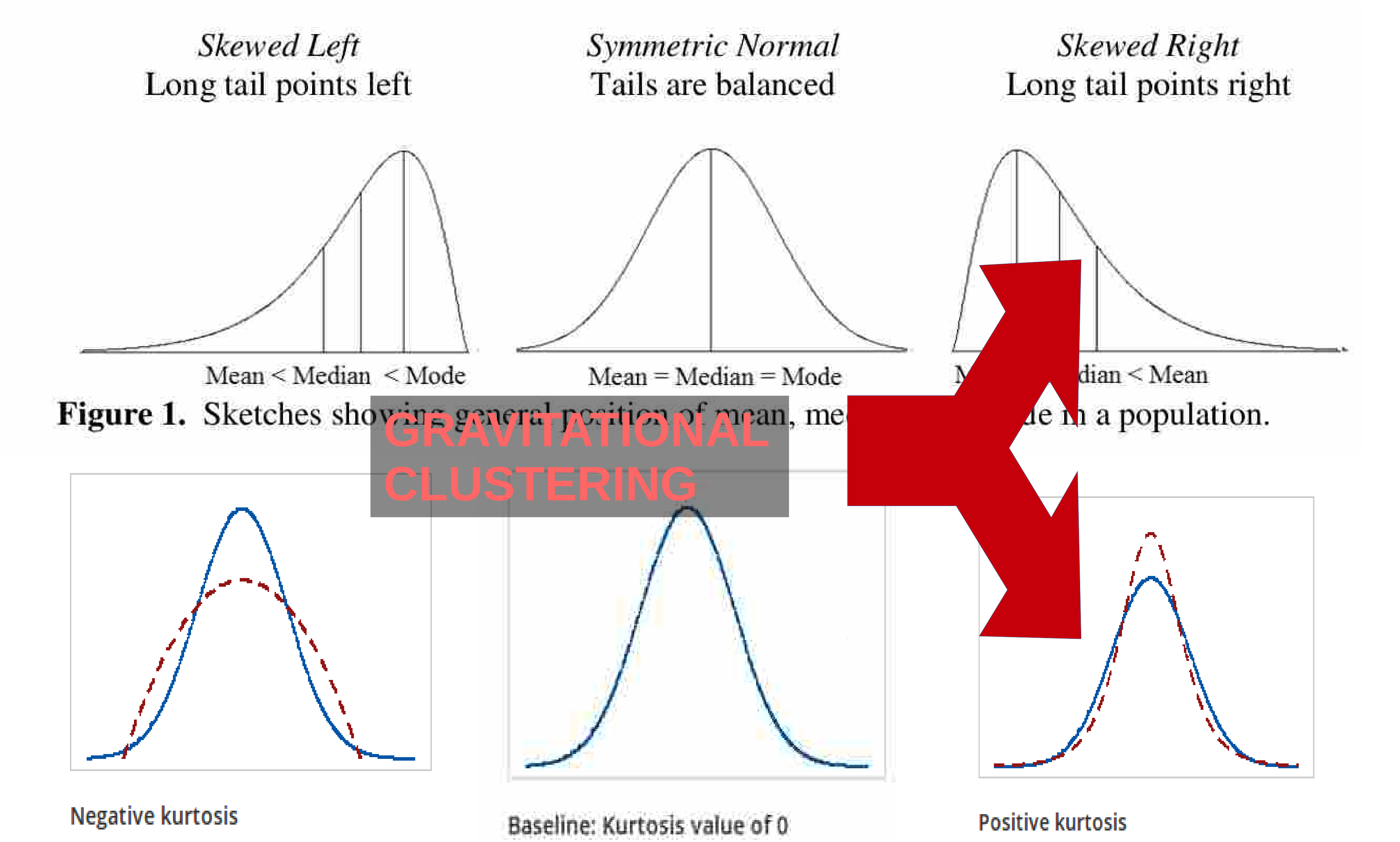
Non-standard GR tests: clustering amplitudes



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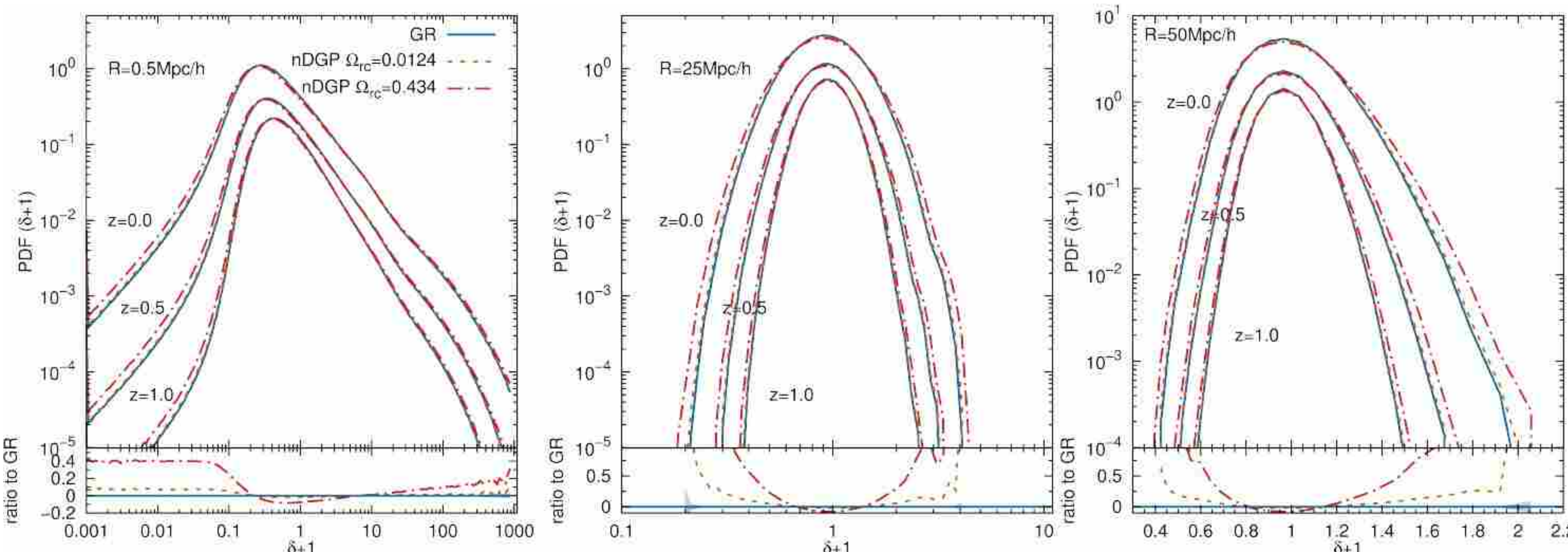
Non-standard GR tests: clustering amplitudes

$$S_n \equiv \frac{\langle \delta^n \rangle_c}{\langle \delta^2 \rangle_c^{n-1}}$$

$$\begin{aligned}
\langle \delta \rangle_c &= 0, \text{ (the mean)} \\
\langle \delta^2 \rangle_c &= \langle \delta^2 \rangle \equiv \sigma^2, \text{ (the variance)} \\
\langle \delta^3 \rangle_c &= \langle \delta^3 \rangle, \text{ (the skewness)} \\
\langle \delta^4 \rangle_c &= \langle \delta^4 \rangle - 3\langle \delta^2 \rangle_c^2, \text{ (the kurtosis)} \\
\langle \delta^5 \rangle_c &= \langle \delta^5 \rangle - 10\langle \delta^3 \rangle_c \langle \delta^2 \rangle_c \,.
\end{aligned}$$



WAH, Koyama, Bose, Zhao 2017 (arXiv:1703.03395)

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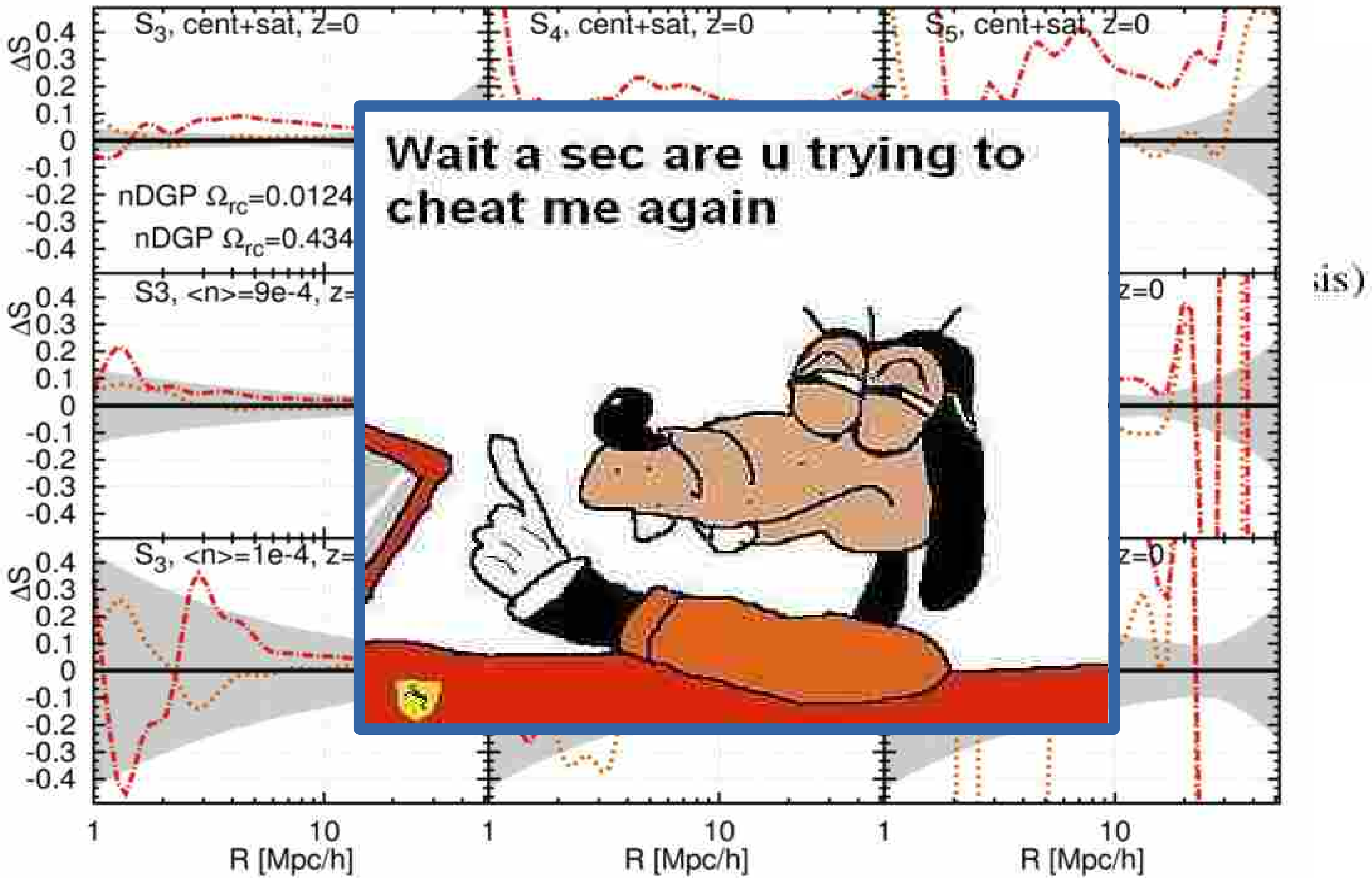

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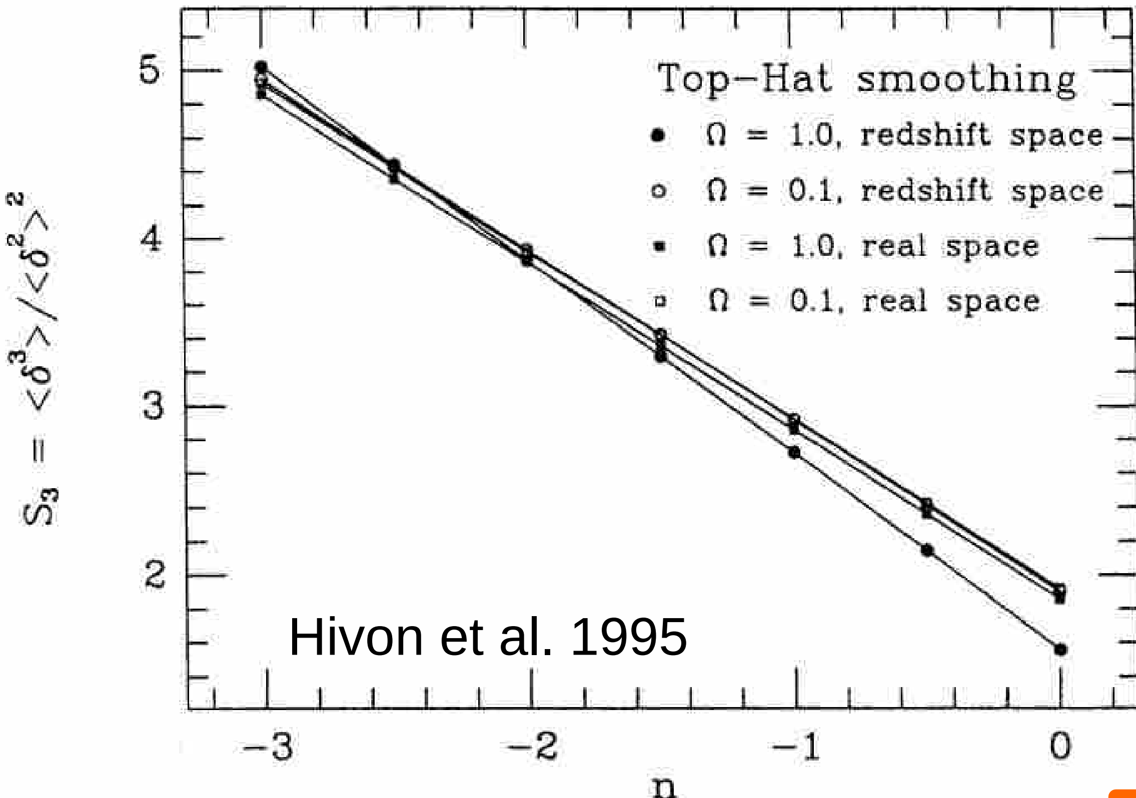
RSD mild for clustering amplitudes!



Skewness in real space

$$S_3 = \frac{34}{7} + \frac{6}{7}(\Omega^{-2/63} - 1) - (n+3)$$

Skewness in redshift space

$$S_{3,z} \simeq \frac{35.2}{7} - 1.15(n+3).$$

$$S_n \equiv \frac{\langle \delta^n \rangle_c}{\langle \delta^2 \rangle_c^{n-1}}$$

Both terms affected by RSD by similar amount (in mildly non-linear regime). Overall RSD effect largely **cancels out**!

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Take home messages

- Crucial to test GR on cosmological and intergalactic distances.

- Clean test (both for GR and MG) are hard to achieve: degeneracies leading to systematics effects.

- Outlook for difficult but cleaner methods (i.e. velocities, hierarchical clustering in RSD)

- Really need MG-hydro galaxy formation run to test most of the methods against baryonic effects (happened for f(R) → see Christian Arnold's work/talk!

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