Why and how test gravity?

(on cosmological scales)

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

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Collaborators: Boajiu Li (Durham), Maciek Bilicki (Leiden), Kazuya Koyama (Portsmouth), Ben Bose (en route to Geneva), Noam Libeskind (Potsdam), Adi Nusser (Haifa)

This project has received funding from the European Union’s Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie grant agreement No. 748525.

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Why and how test gravity?

(on cosmological scales)

OUTLINE:

- **Standard model of cosmology (abridged)**
- **General Relativity – basics and the current status**
- **Beyond GR (why and how) – Modified Gravity**
- **MG Screening**
- **Observational effects of beyond GR**
- **Troubles**
- **Outlook and the future**

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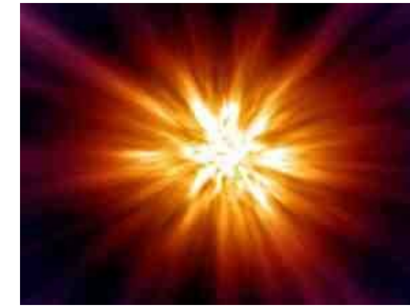
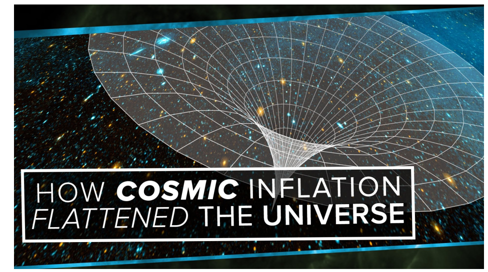
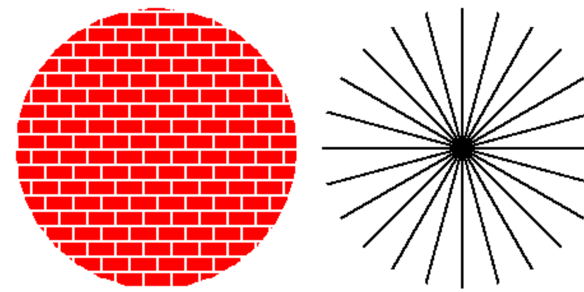
Standard model of cosmology: core assumptions



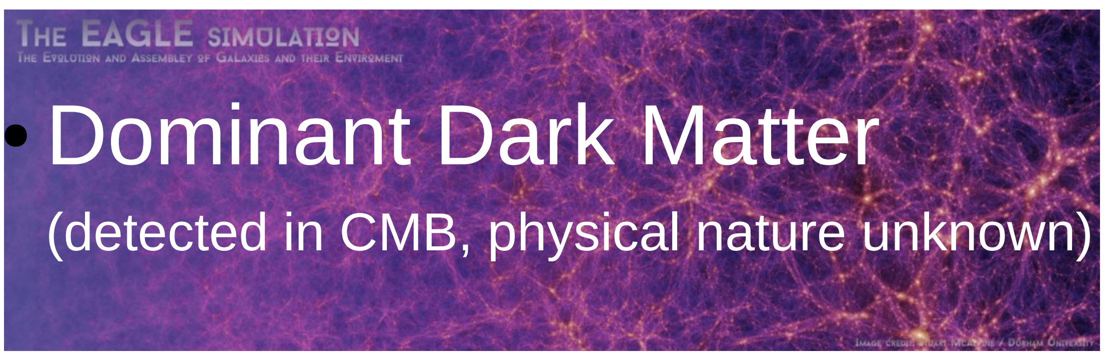
- Hot relativistic Big Bang



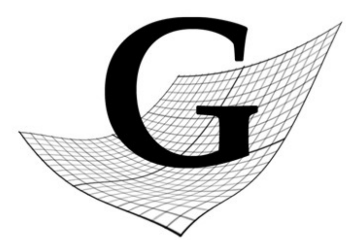
- Gaussian initial conditions
  (adiabatic, Inflation)



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



- Dominant Dark Matter
  (detected in CMB, physical nature unknown)



Gravity

- 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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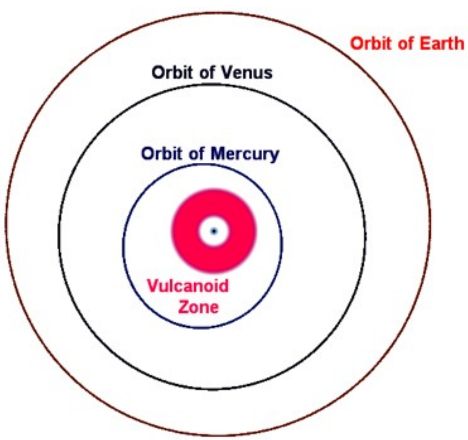
Paving the road to new paradigm

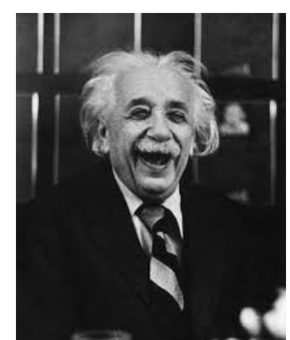
In 1859 **Urbain Le Verrier** showed that slow precession of Mercury's orbit perihelion could not be explained by Newton's theory of gravity.



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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Avoid comparing apples to oranges

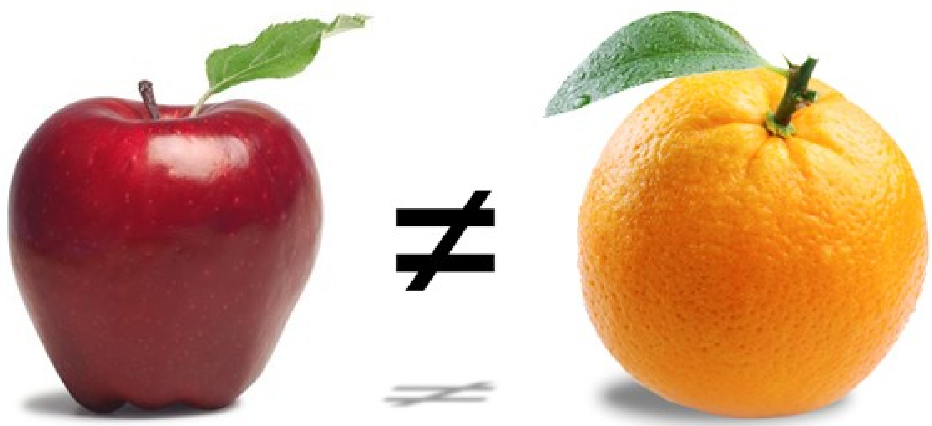
A **test** of GR cannot be simply described only by **single scale** parameter. Any metric theory of gravity might experience different behaviour in two parameter space – **curvature scale** and **potential strength**.

Kretschmann scalar
(e.g. for Swartzschild metric)

$$\xi = \left(R^{\alpha\beta\gamma\delta}R_{\alpha\beta\gamma\delta}\right)^{1/2} = \sqrt{48}\,\frac{GM}{r^3c^2}$$

Newtonian potential
(e.g. for a particle orbiting a point mass)

$$\epsilon \equiv \frac{GM}{rc^2}$$



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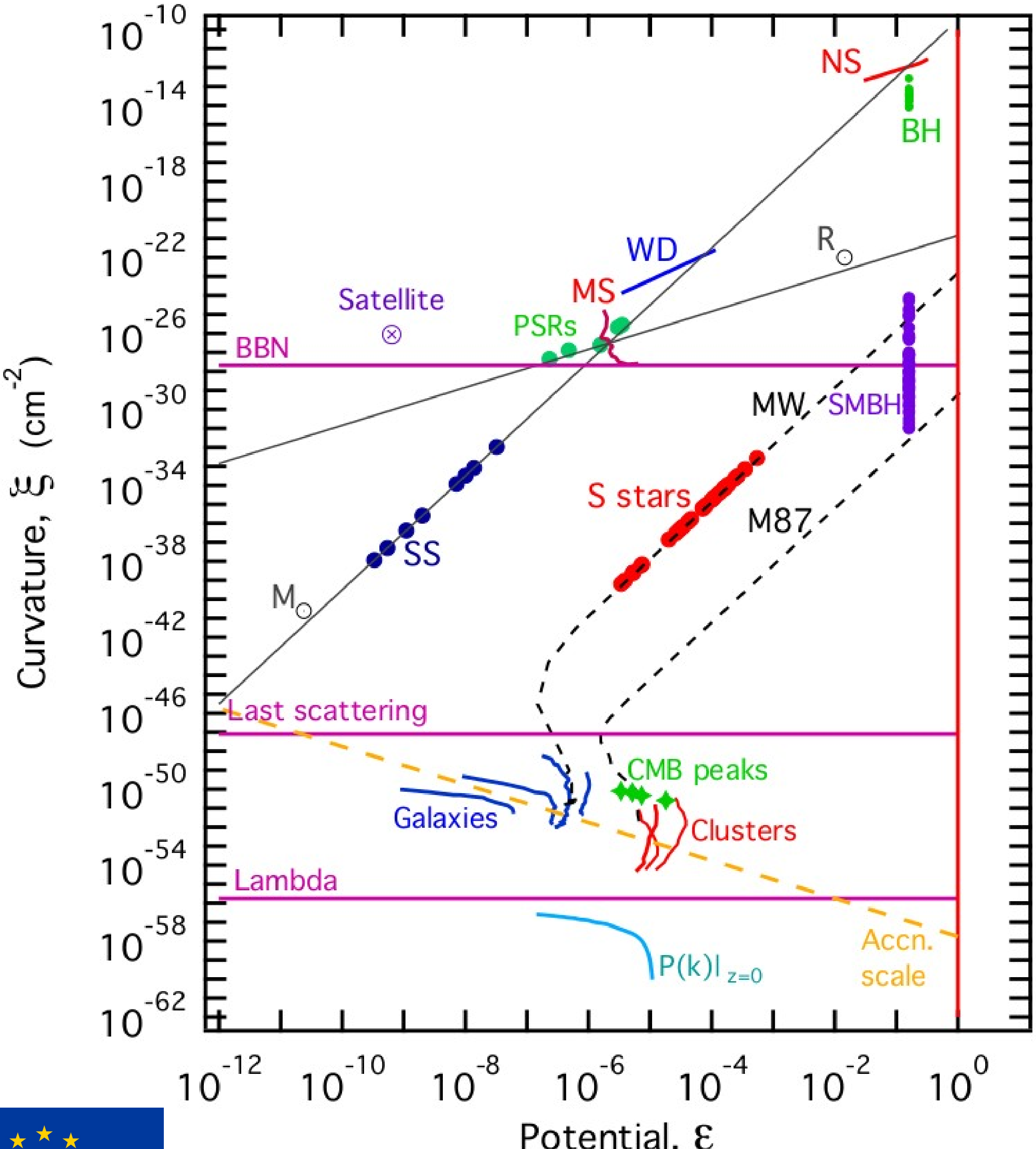

Different astrophysical objects probe different parts on 2D parameter plane.

From Baker et al. ApJ 802, 63, 2015

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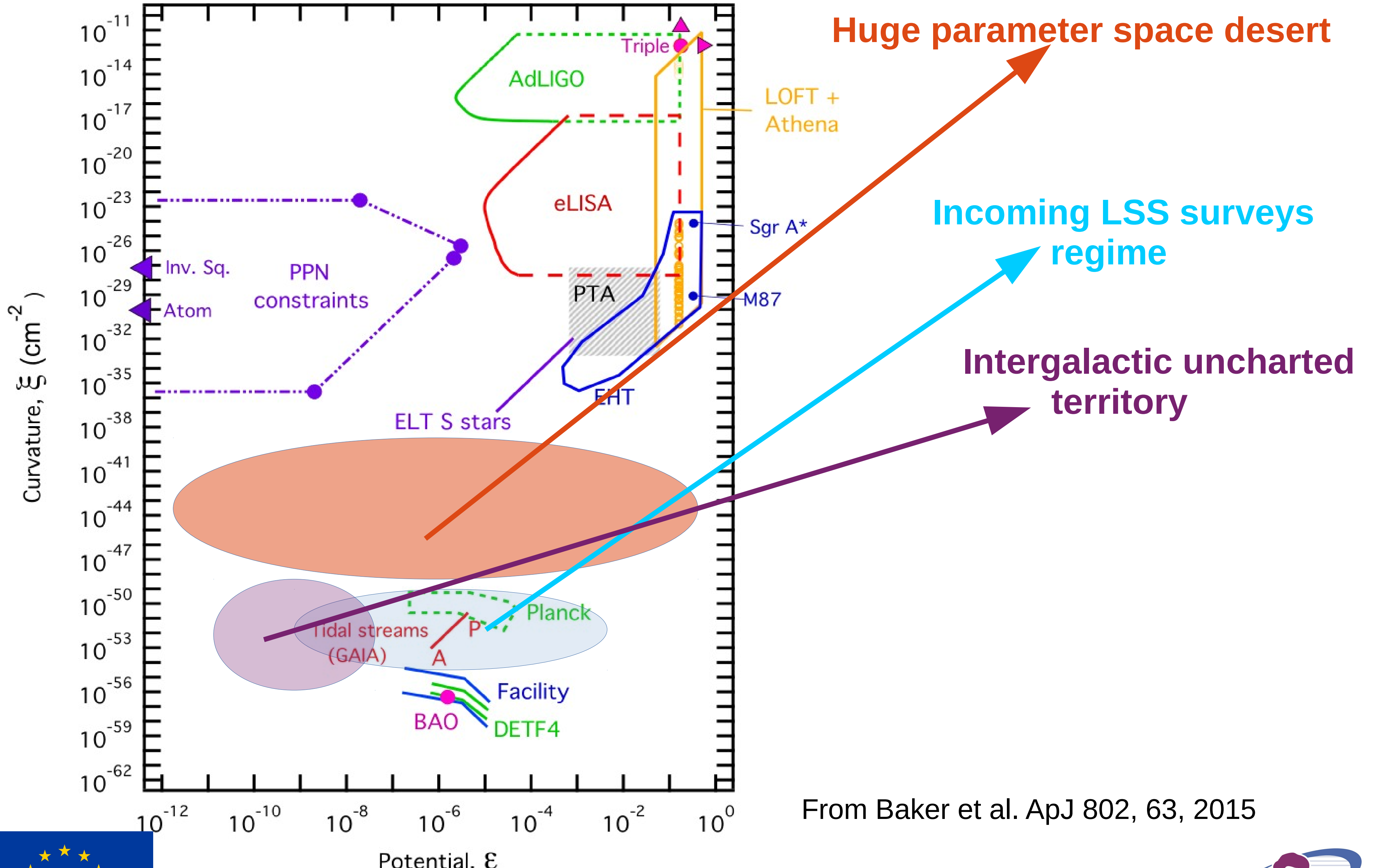
Uncharted territory – parameter desert



From Baker et al. ApJ 802, 63, 2015

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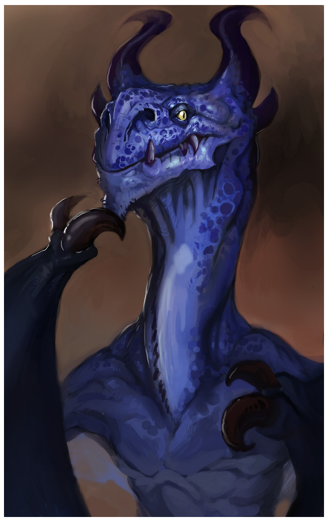
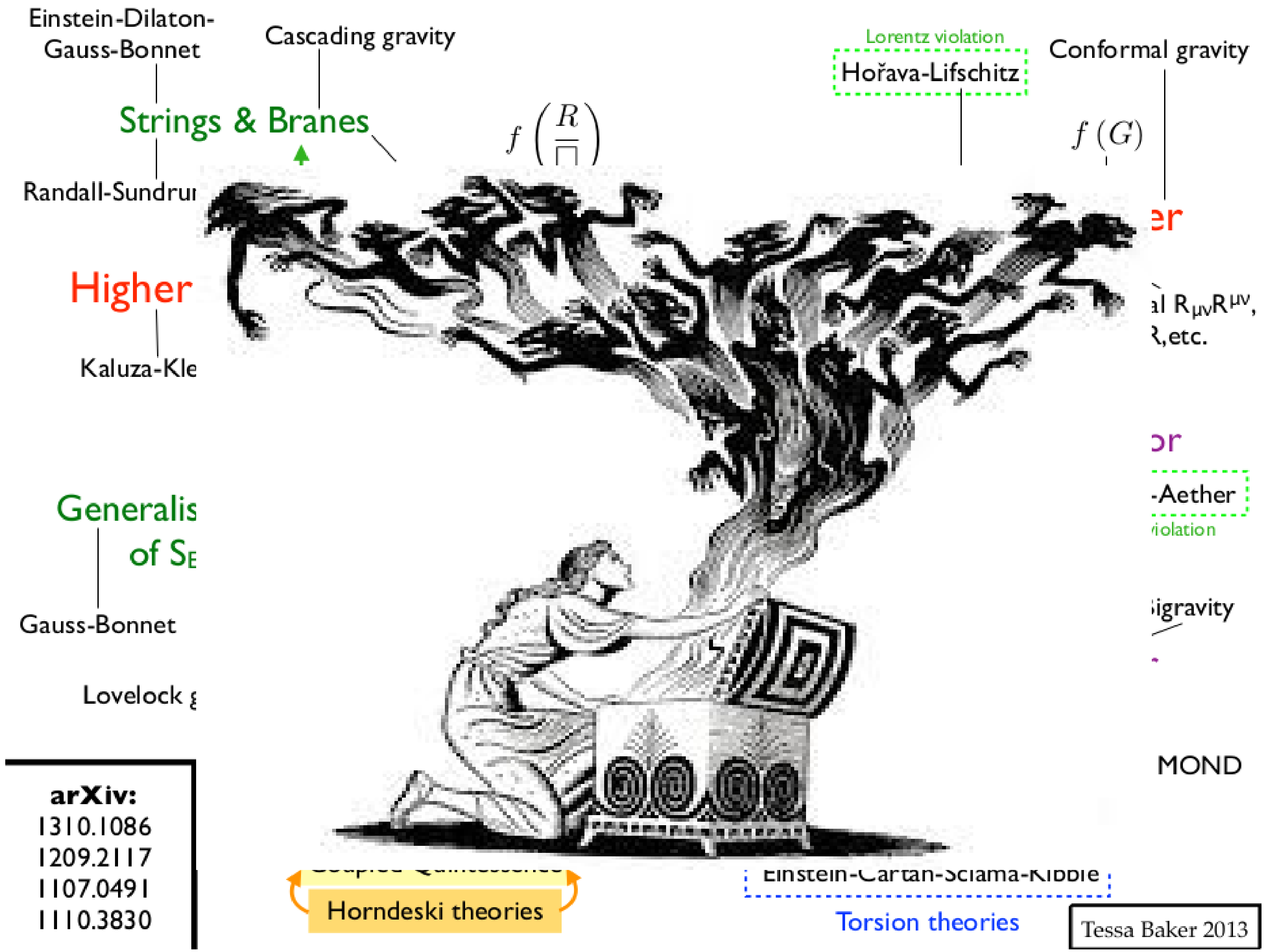
Charting MG. From GR to the land of dragons

Diagram of Modified Gravity plethora of treasure trove





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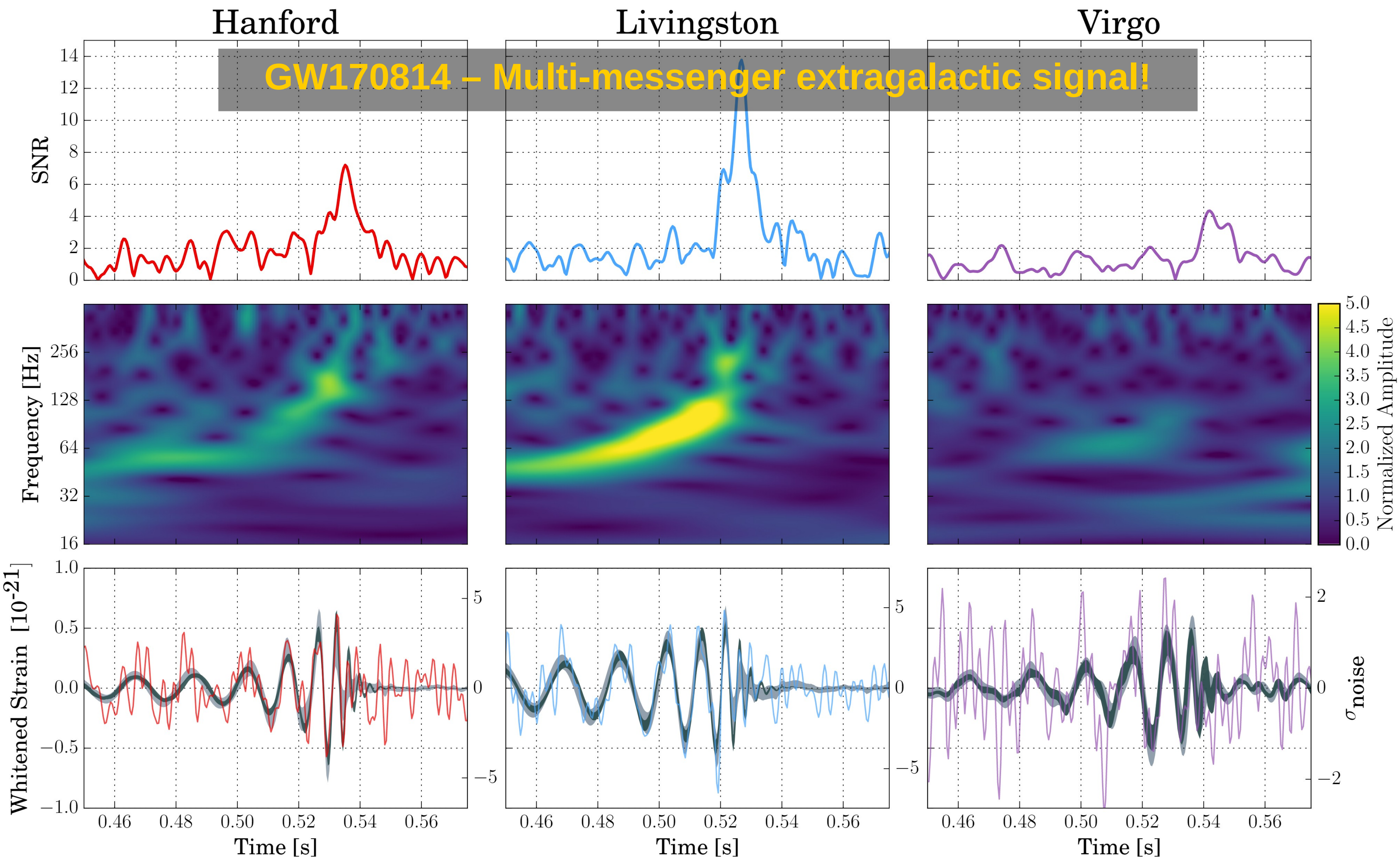
GW helped to clear the stage a bit



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Kilonova discovery – clearing the stage

Diagram of M[illegible] treasure trove

	$c_g = c$	$c_g \neq c$
Horndeski	General Relativity quintessence/k-essence [42] Brans-Dicke/$f(R)$ [43, 44] Kinetic Gravity Braiding [46]	quartic/quintic Galileons [13, 14] Fab Four [15, 16] de Sitter Horndeski [45] $G_{\mu\nu}\phi^\mu\phi^\nu$ [47], Gauss-Bonnet
beyond H.	Derivative Conformal ([20]) [18] Disformal Tuning ([22]) DHOST with $A_1 = 0$	quartic/quintic GLPV [19] DHOST [20, 48] with $A_1 \neq 0$
	Viable after GW170817	Non-viable after GW170817

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Beyond GR, or how to accelerate?

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m\right]$$

→ No acceleration

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\Lambda}{8\pi G}\right]$$

→ Standard GR based LCDM

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f\left(\nabla_\mu\varphi\nabla^\mu\varphi\right)\right]$$

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(R)\right]$$

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(\varphi)R + \frac{w(\varphi)\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

→ Modified gravity (MG)!

GR curvature term

Particle physics and DM

Stuff that accelerates

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Beyond GR, or how to accelerate?

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m\right]$$

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\Lambda}{\ldots}\right]$$

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + \frac{\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f\left(\nabla_\mu\varphi\nabla^\mu\varphi\right)\right]$$

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$$S = \int d^4x \sqrt{-g}\left[\frac{R}{16\pi G} + \mathcal{L}_m + f(\varphi)R + \frac{w(\varphi)\nabla_\mu\varphi\nabla^\mu\varphi}{2} + V(\varphi)\right]$$

Extra degrees of freedom (DOF)

GR curvature term

Particle physics and DM

Stuff that accelerates

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Charting MG. Screening is the trick!

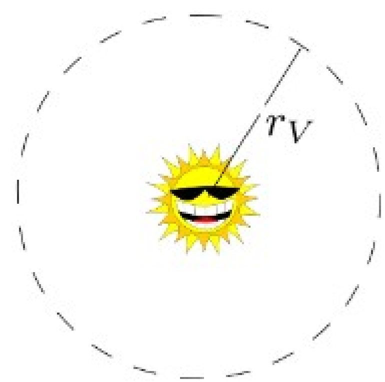
Accelerates the Universe (no need for Lambda)
Has the same or similar expansion history as LCDM
Produce **DIFFERENT** growth of structure history

chameleon sreening family

The 5th force is suppressed by the chameleon mechanism. This is environmentally dependent (local density)

Galileon/DGP gravity family

The 5th force is suppressed by the Vainshtein mechanism – no dependence on the environment



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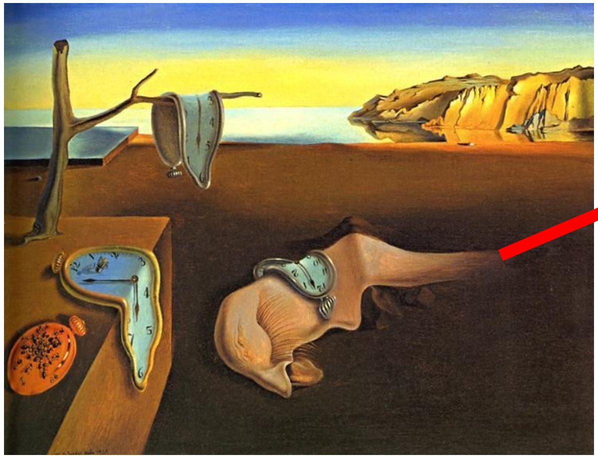
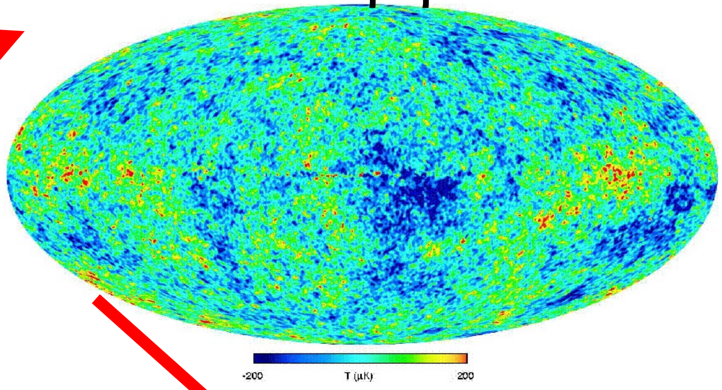
MG is even more non-linear then GR

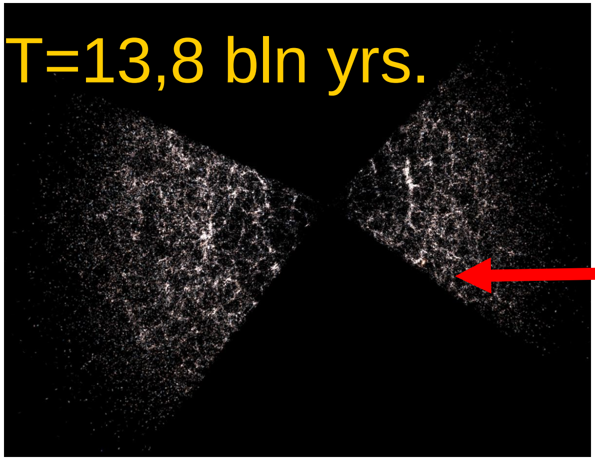
To model and study the growth of cosmic structures we need high-res N-body simulations

T=380,000 yrs.

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







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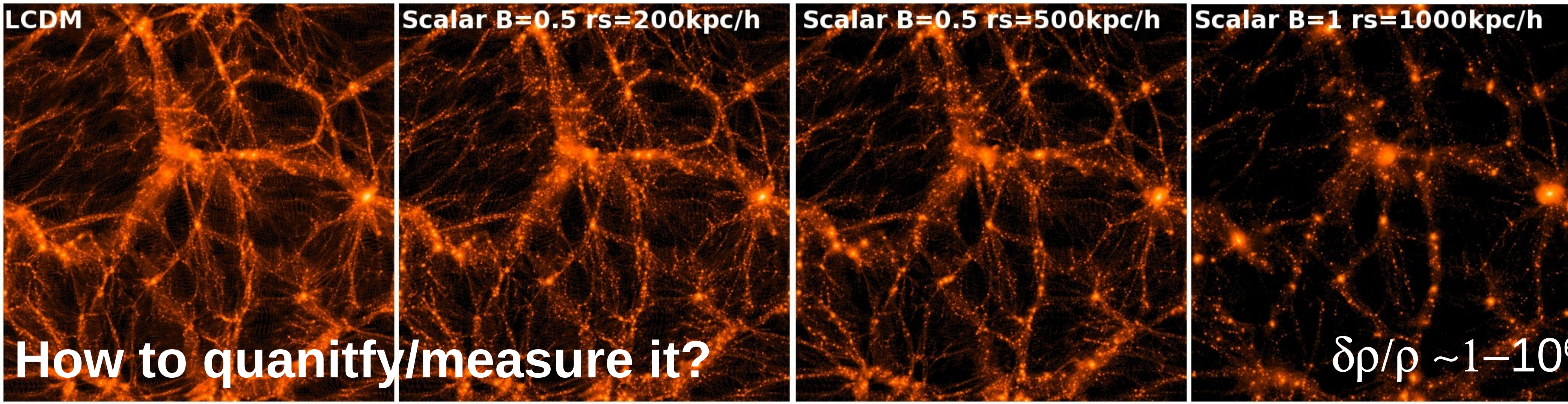
Beyond GR – looking for cosmological effects



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

Power spectrum of density fluctuations

Linear evolution equation for density perturbations.

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

Linear growth rate: f

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

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

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MG predict ehnaced growth of structures

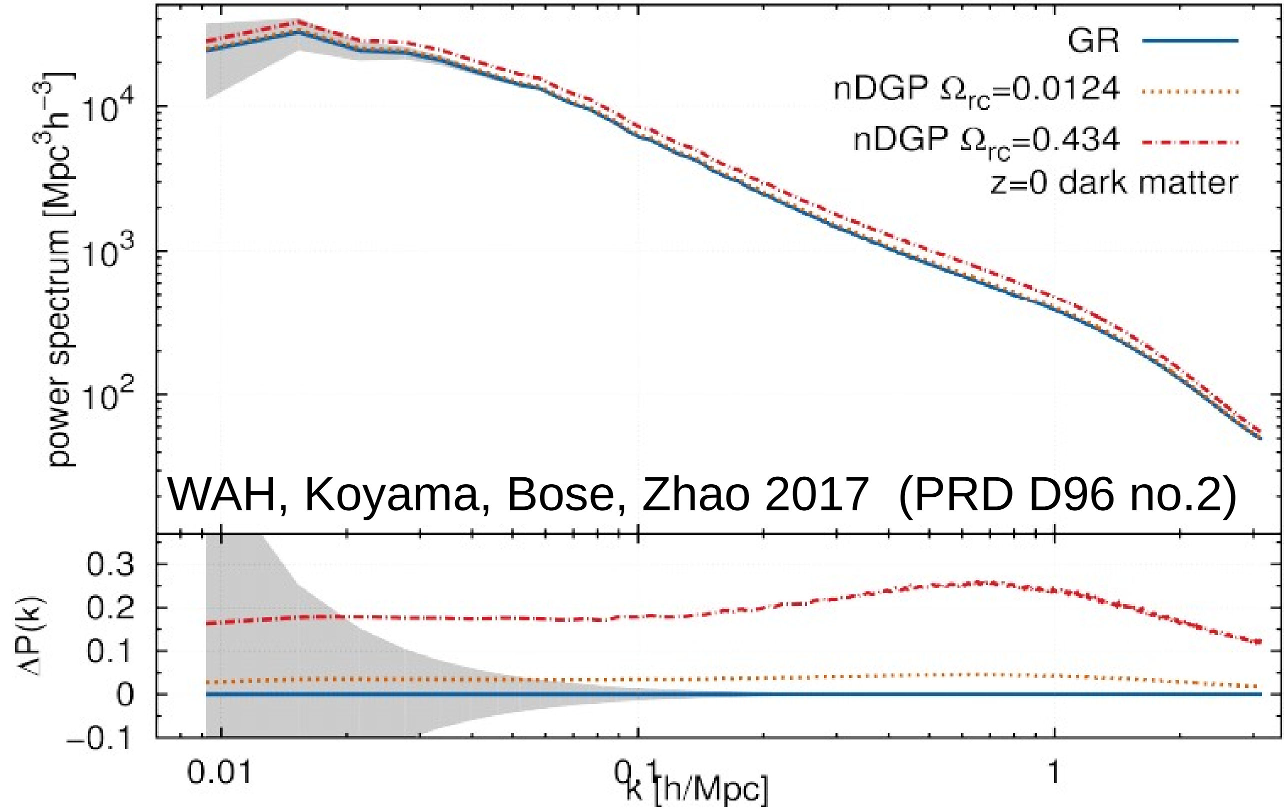

FIG. 5. The matter density power spectrum computed at $z = 0$ for our fiducial GR model (solid line) and two nDGP flavours (dotted and dashed-dotted lines). The shaded region illustrate the cosmic variance error. The bottom panel illustrates the fractional difference of both MG models w.r.t. the GR case.

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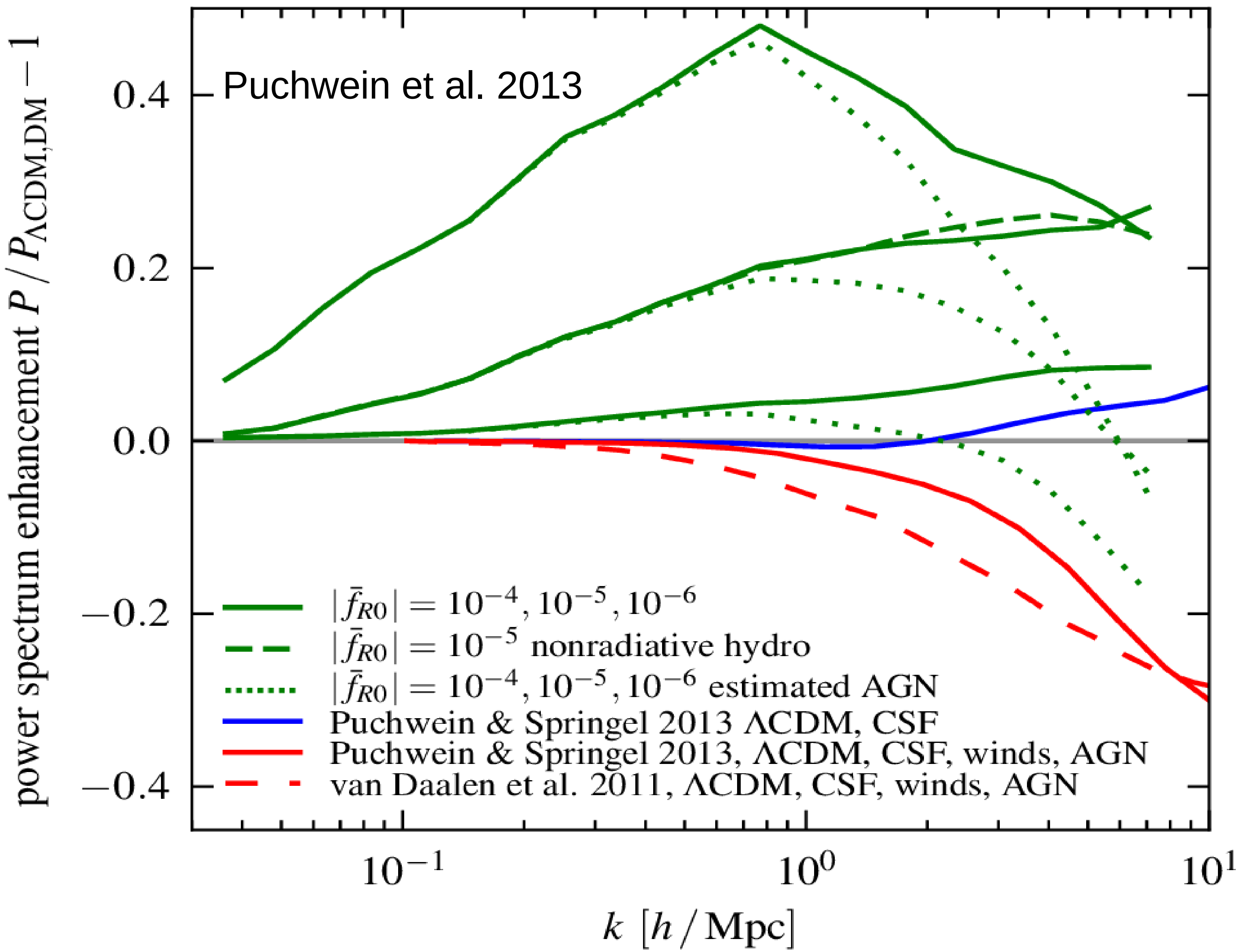
Do not trust baryons, they make up everything (more complicated!)



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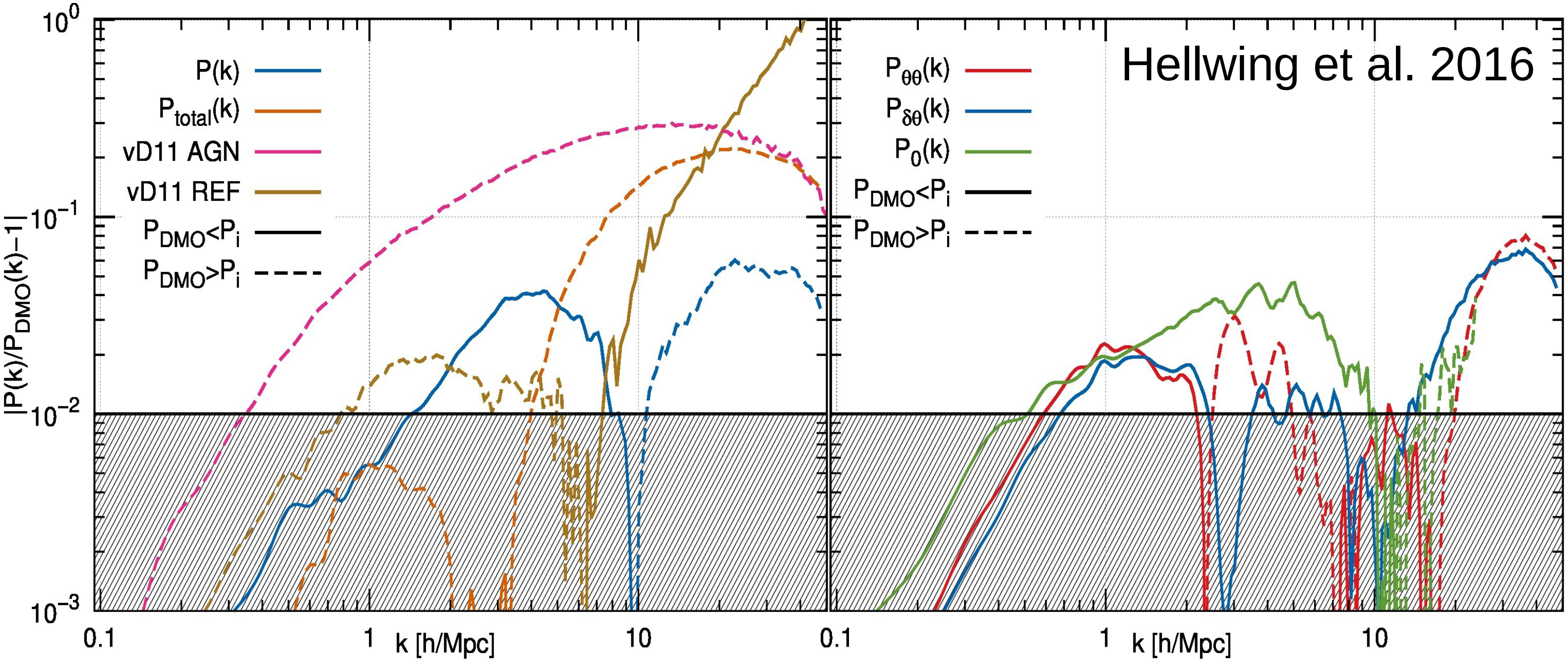

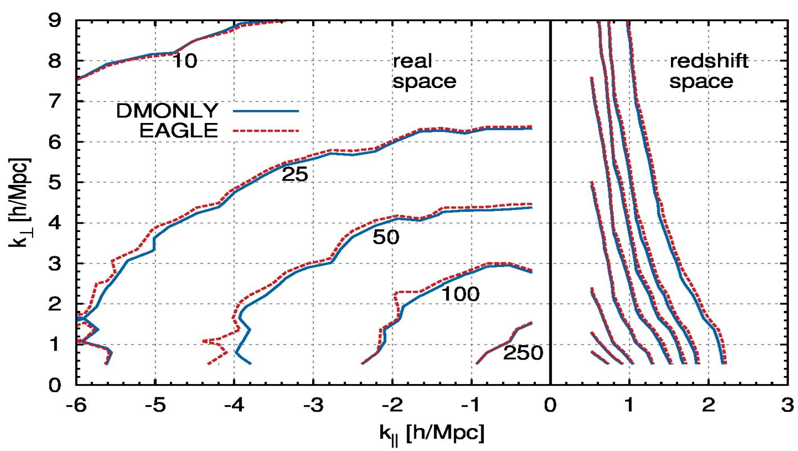

Baryons
accelerating business

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Galaxies are not helping... since they're biased!

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MARIE CURIE ACTIONS

RSD and the conspiracy of the damping tail

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

where

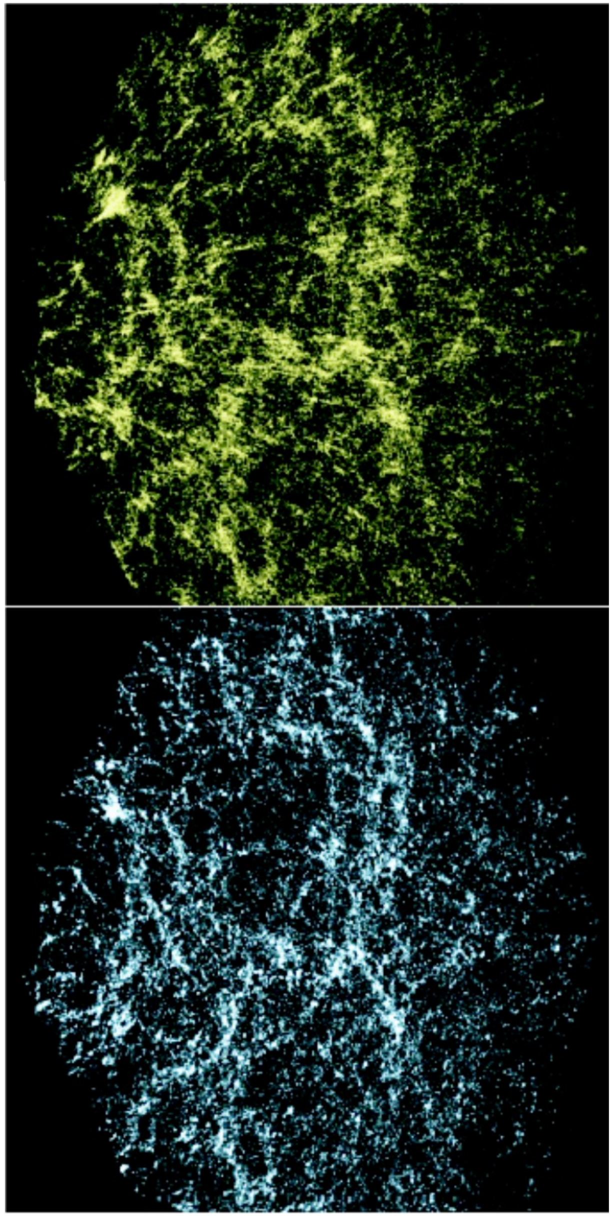
$$D(k\mu\sigma_v) = \begin{cases} \exp[-(k\mu\sigma_v)^2] \\ 1/[1+(k\mu\sigma_v)^2] \end{cases}$$

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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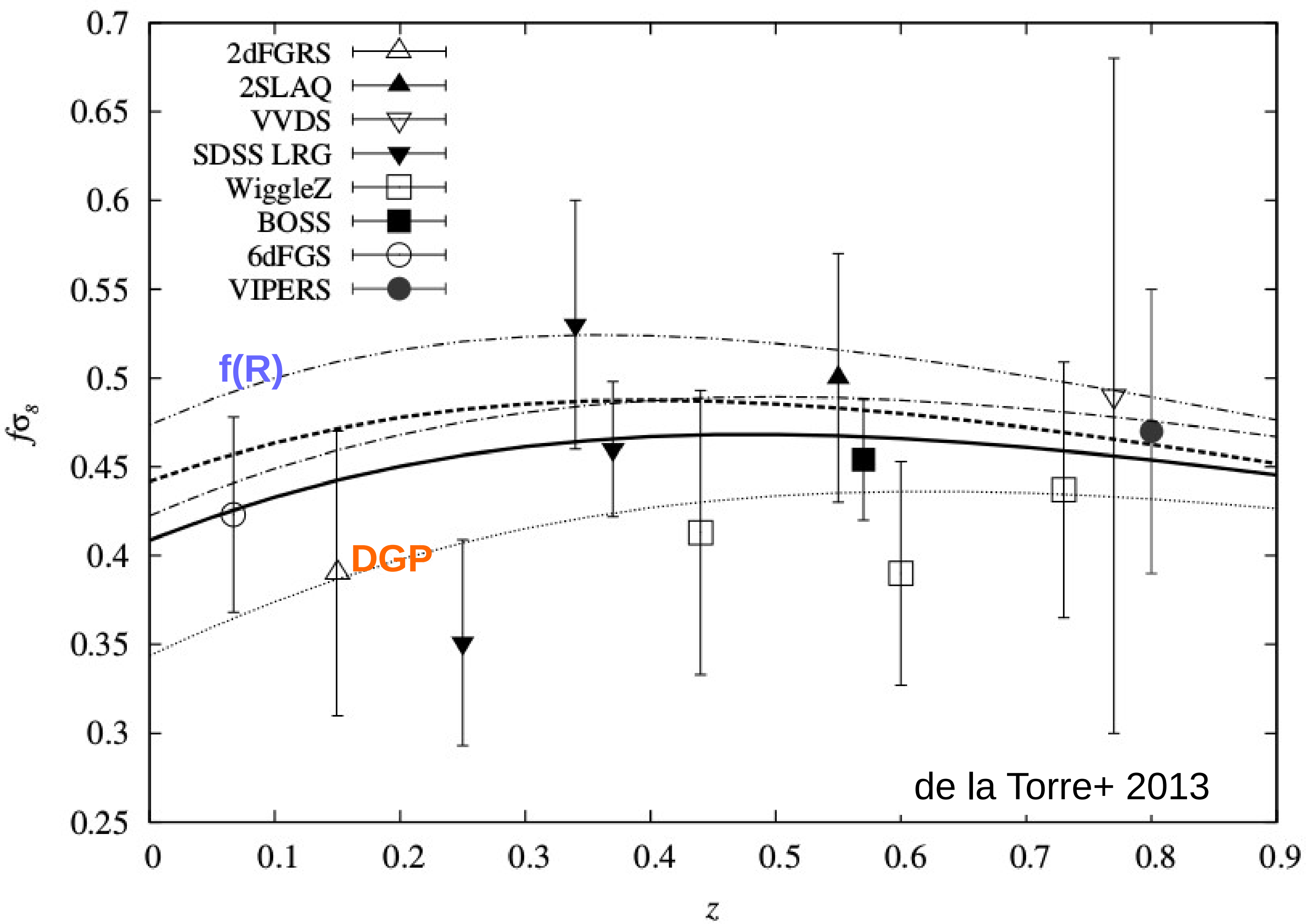

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Signal modeling is degenerated with assumed gravity!

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

where

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

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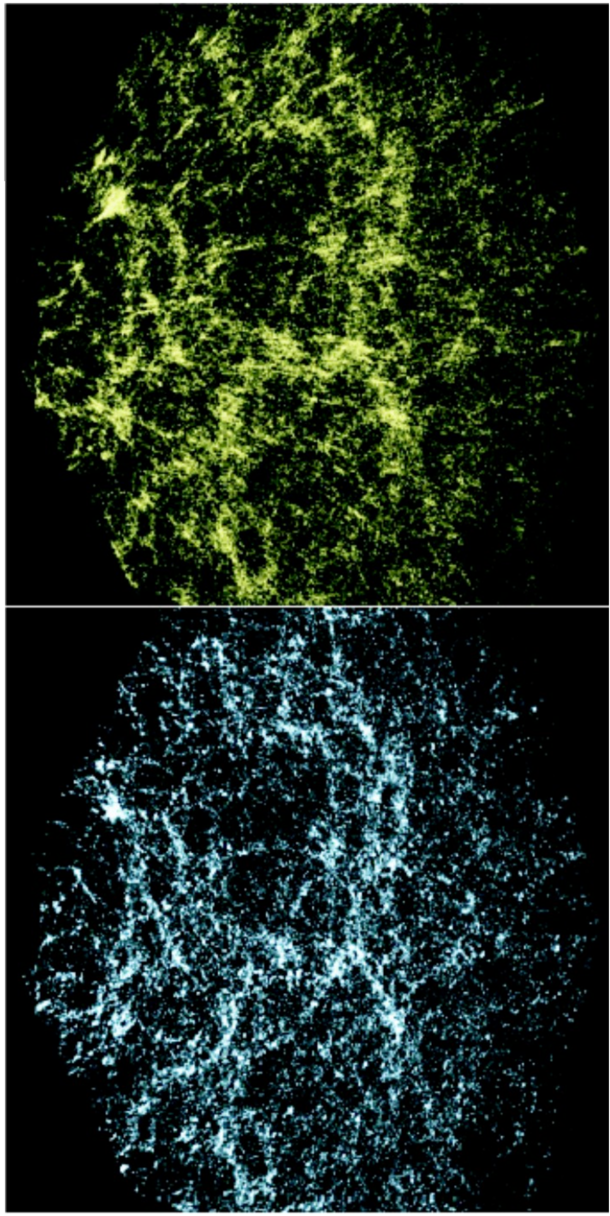

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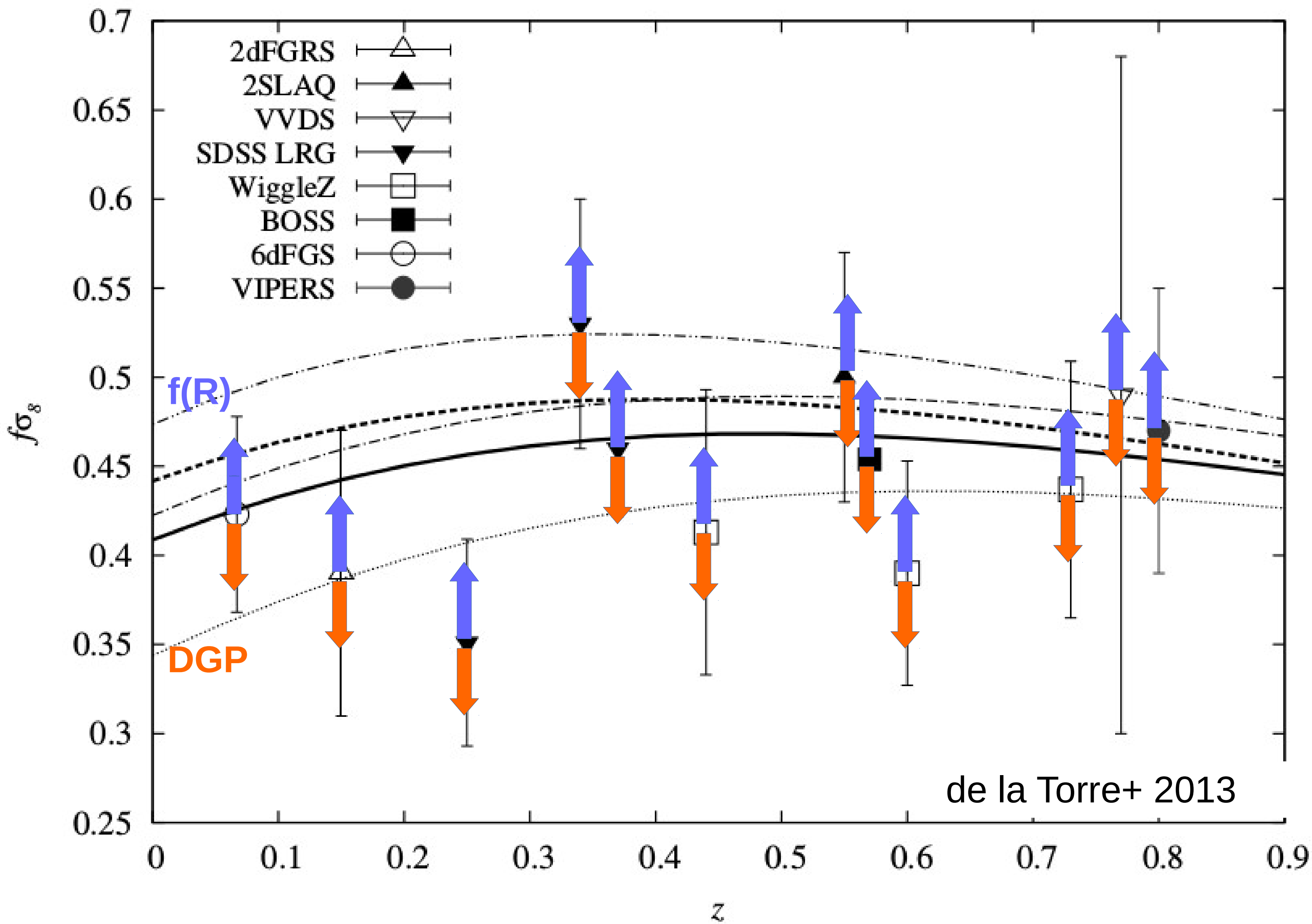

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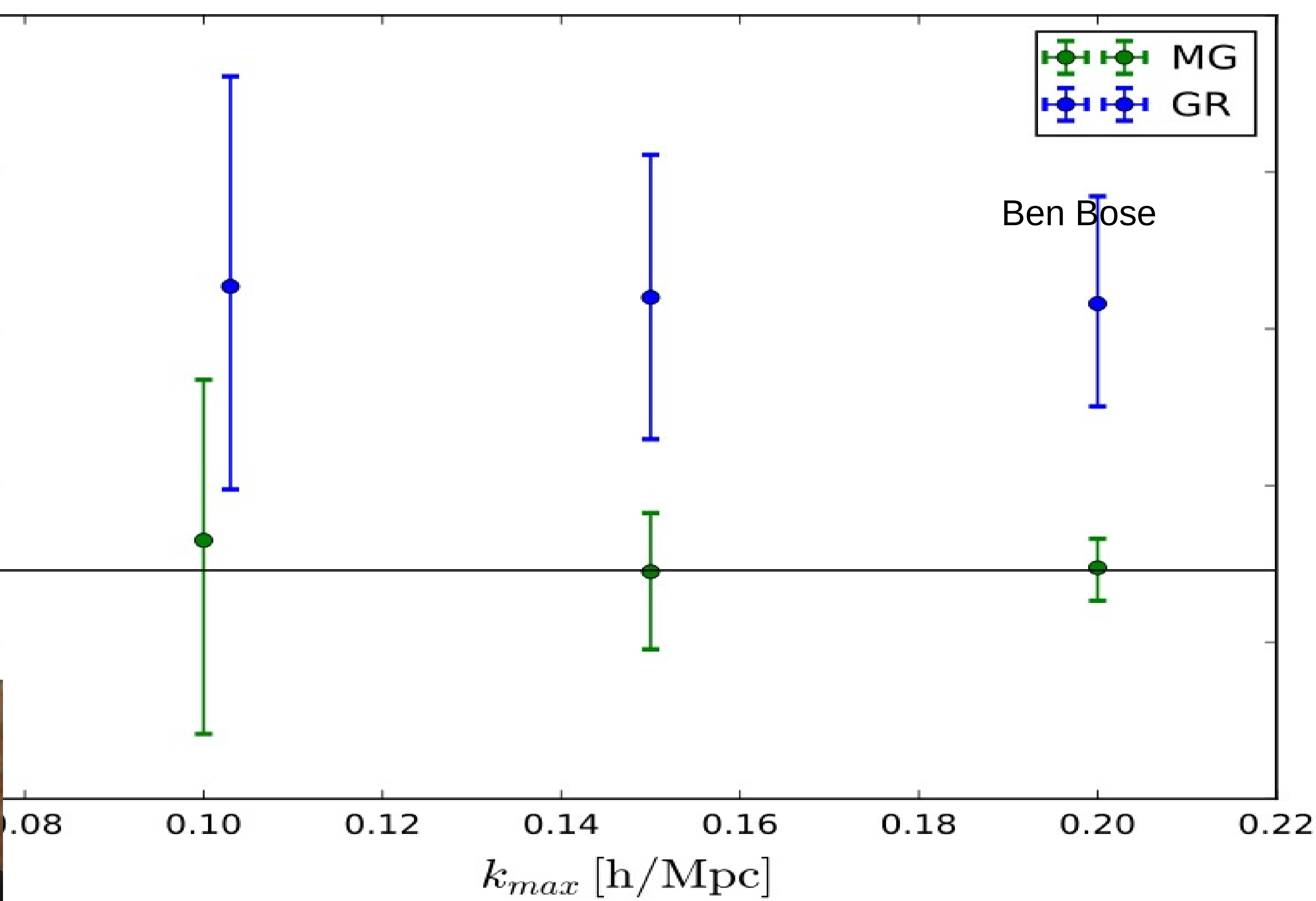
Gravity agnostic modeling leads to theoretical bias



Ben Bose

Bose, Koyama, WAH, Zhao, Winther 2017

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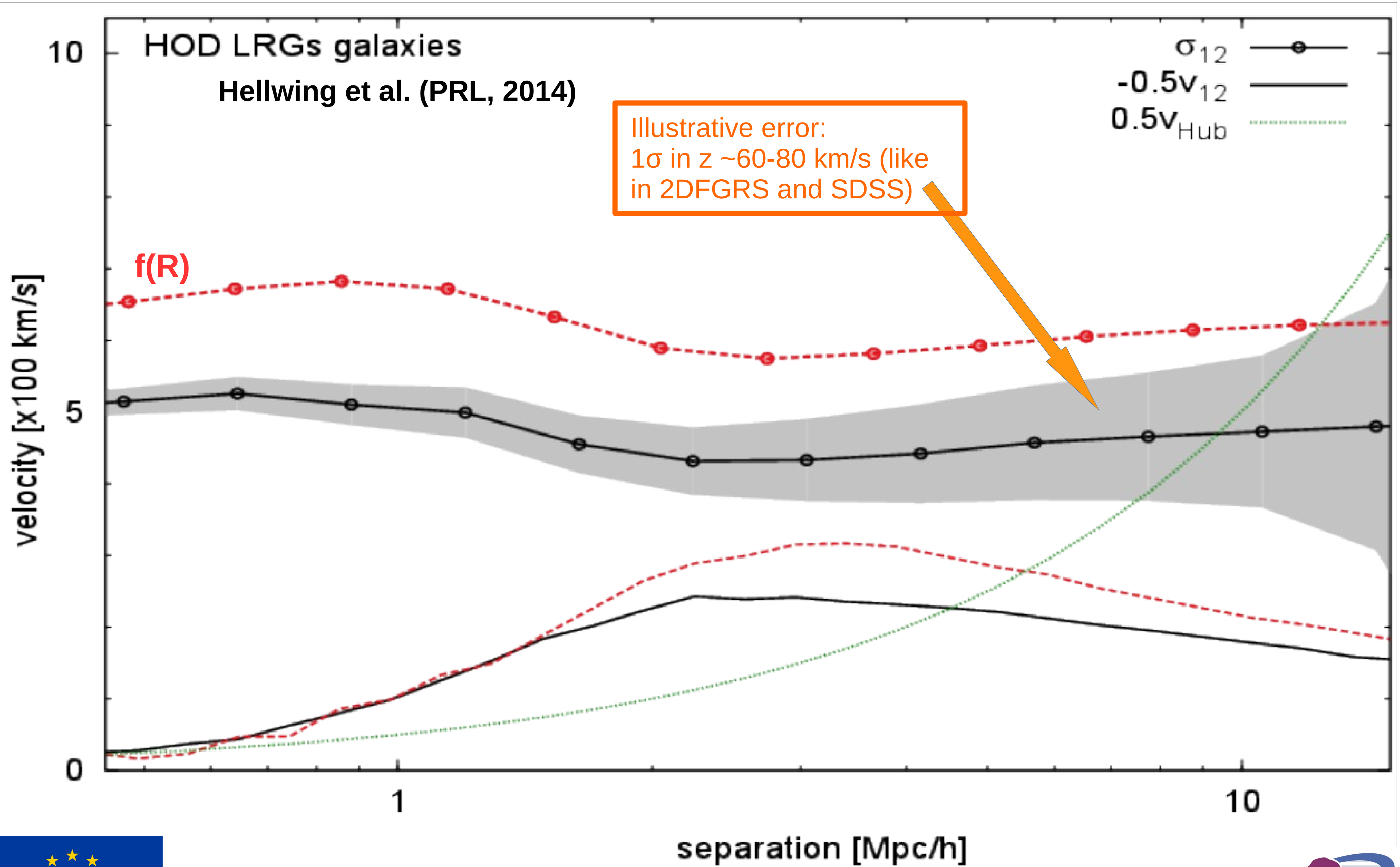
What about direct velocities data?



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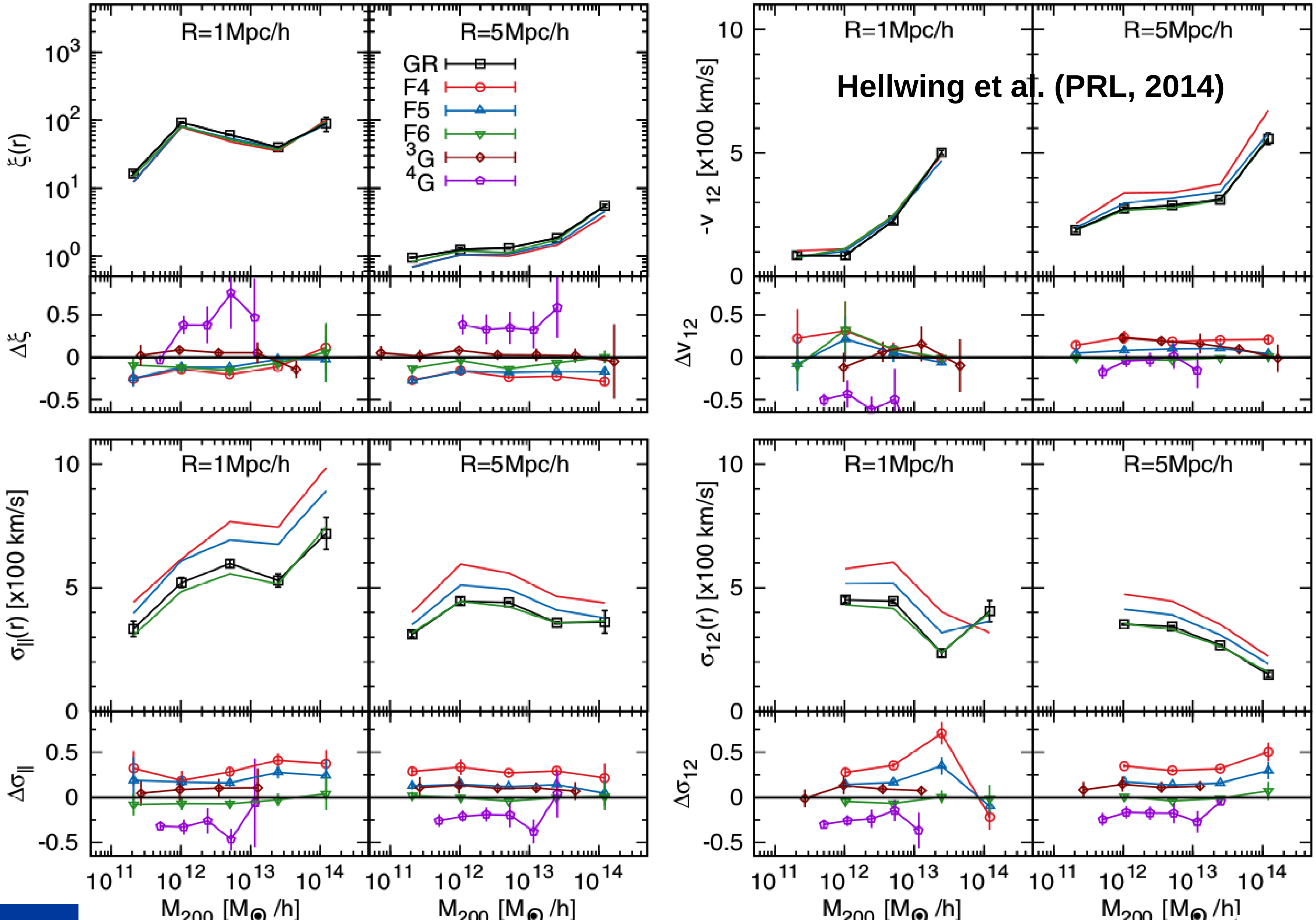

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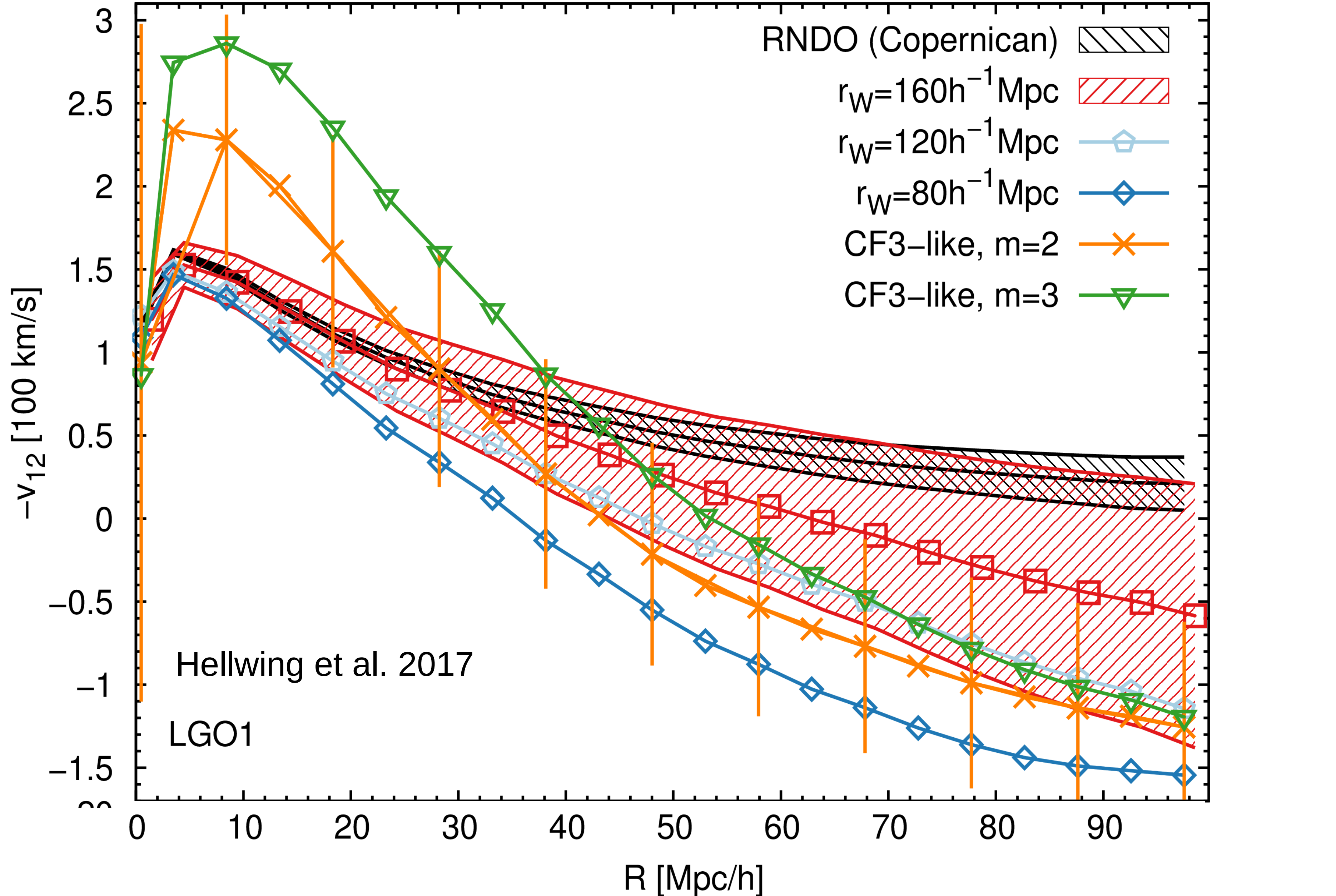
Signal is model independent but there are big systematics



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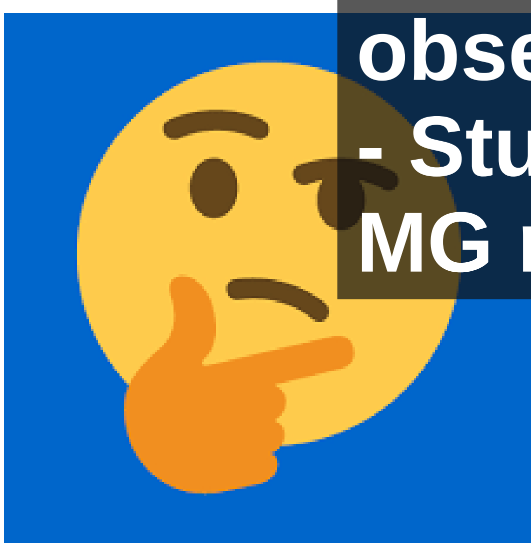
Cosmo gravity probes list of bad deeds

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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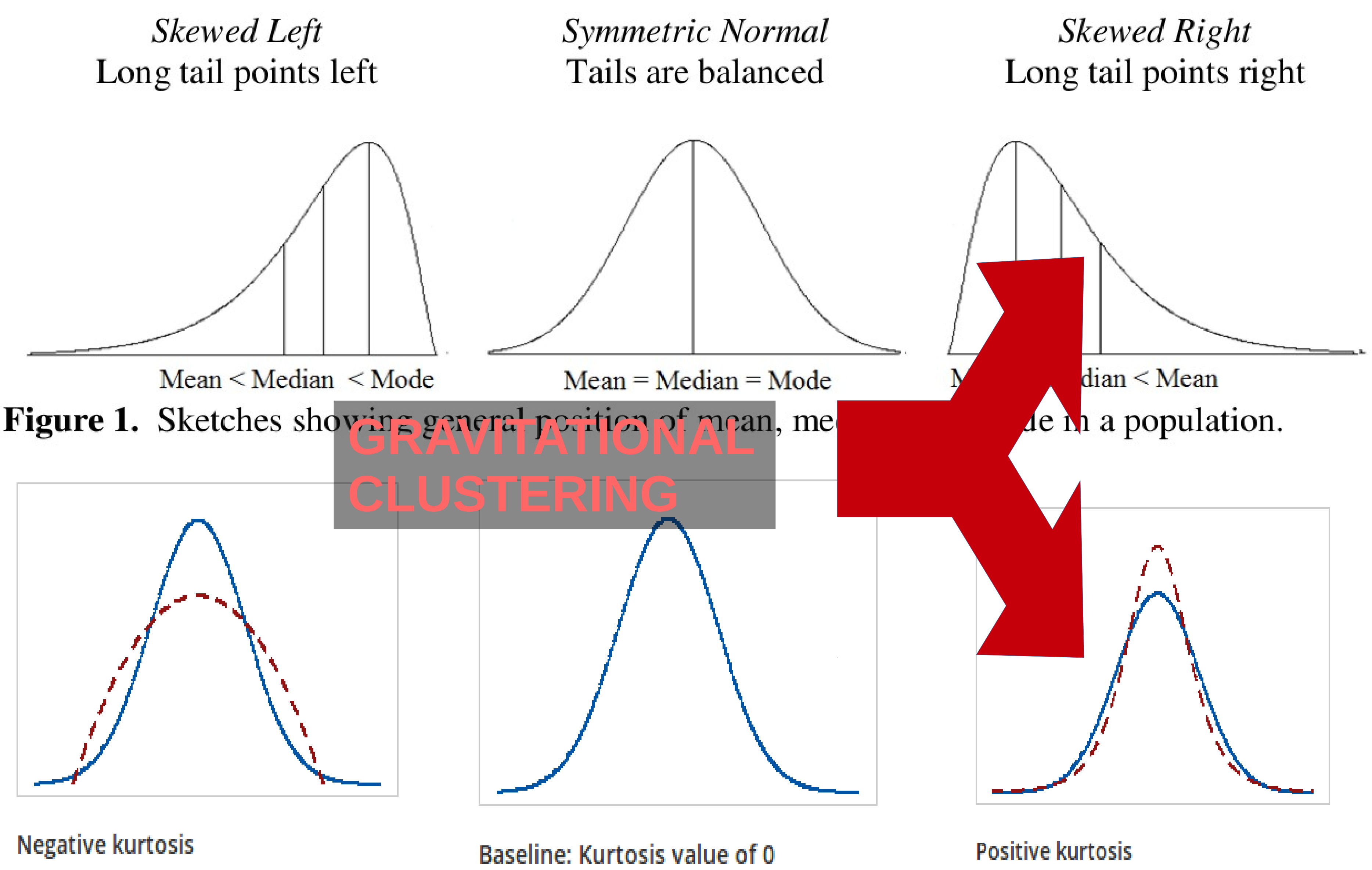
Non-standard GR tests: clustering amplitudes



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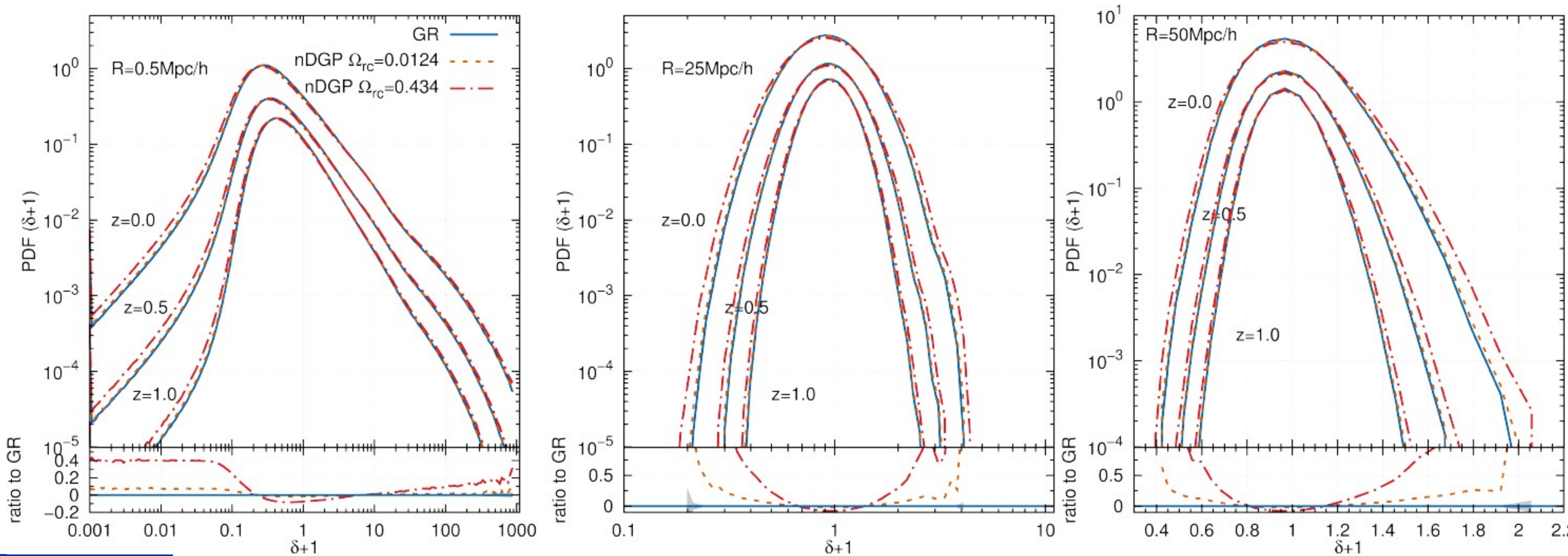
Non-standard GR tests: clustering amplitudes

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

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



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

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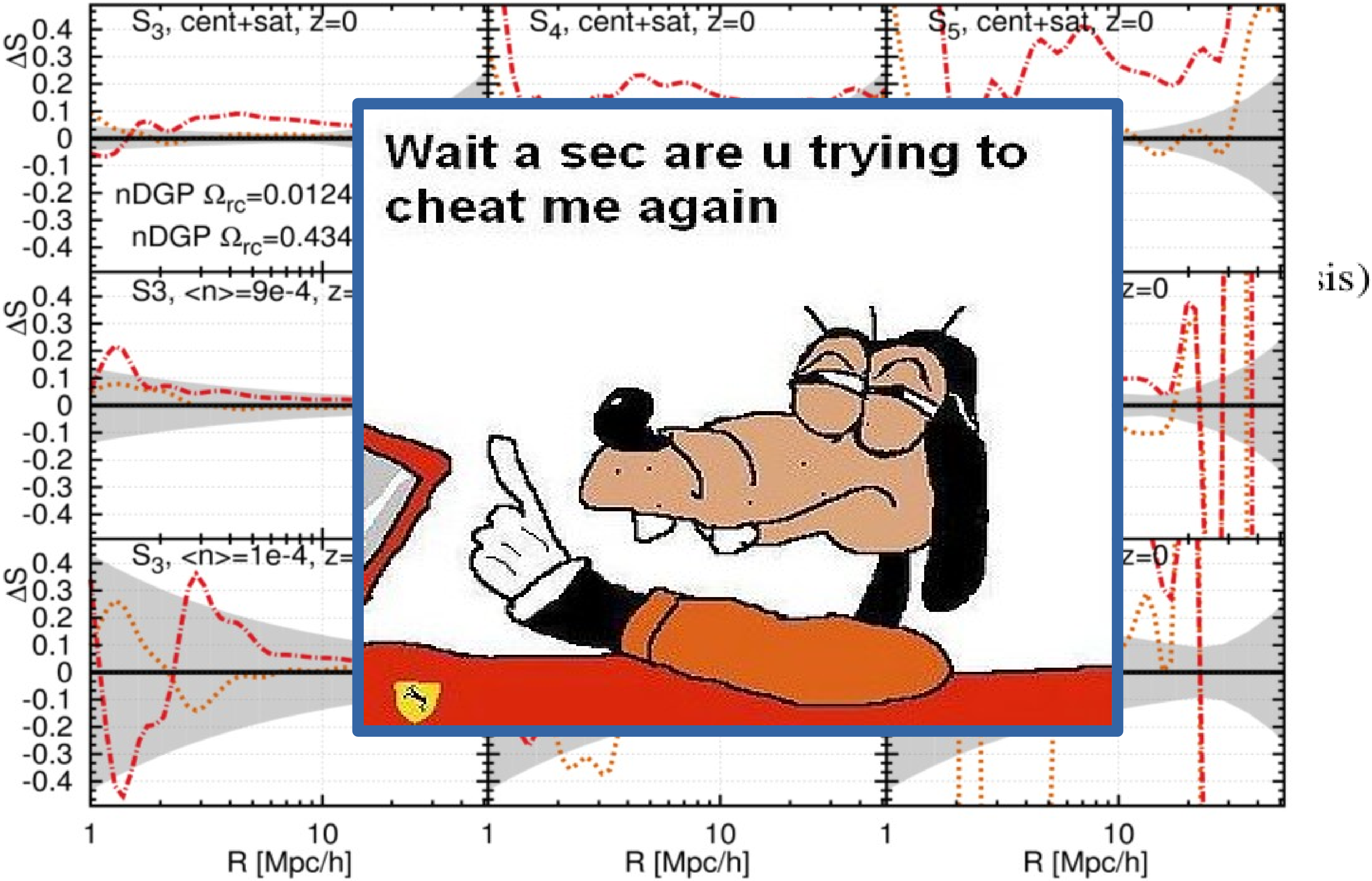
MARIE CURIE ACTIONS

Non-standard GR tests: clustering amplitudes



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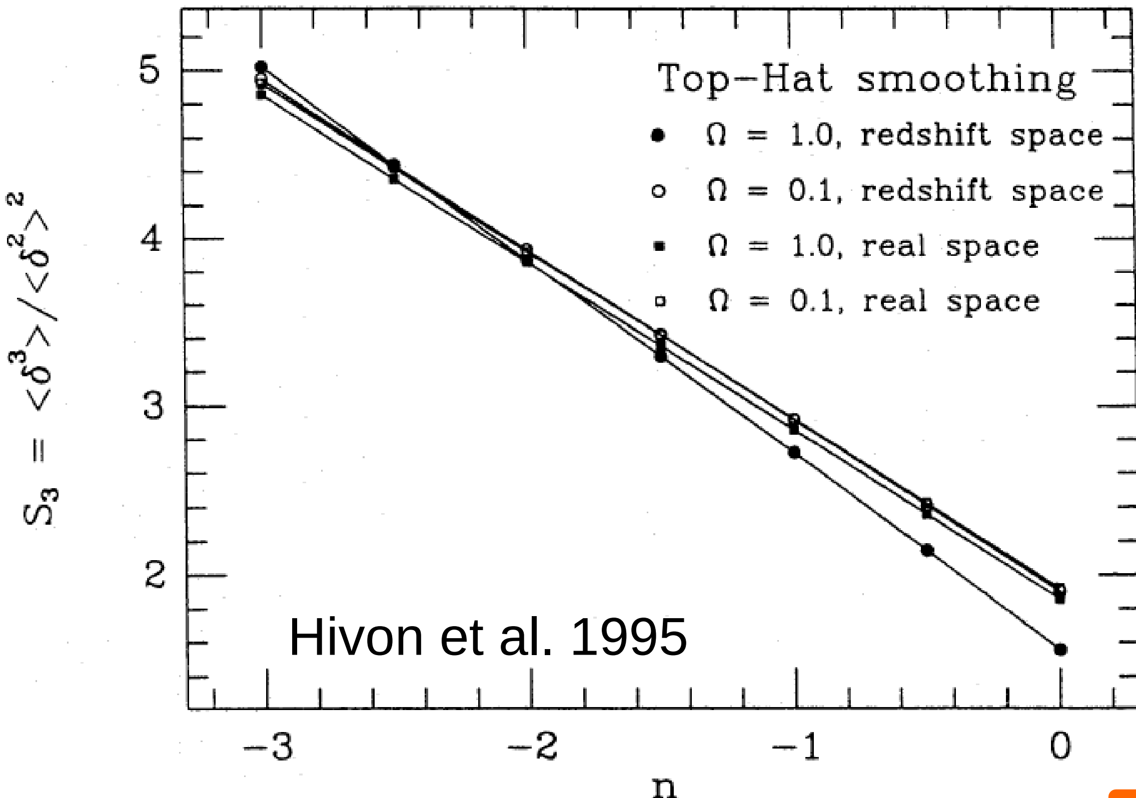
MARIE CURIE ACTIONS

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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MARIE CURIE ACTIONS

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!

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MARIE CURIE ACTIONS