The cosmic web: flows and gravity

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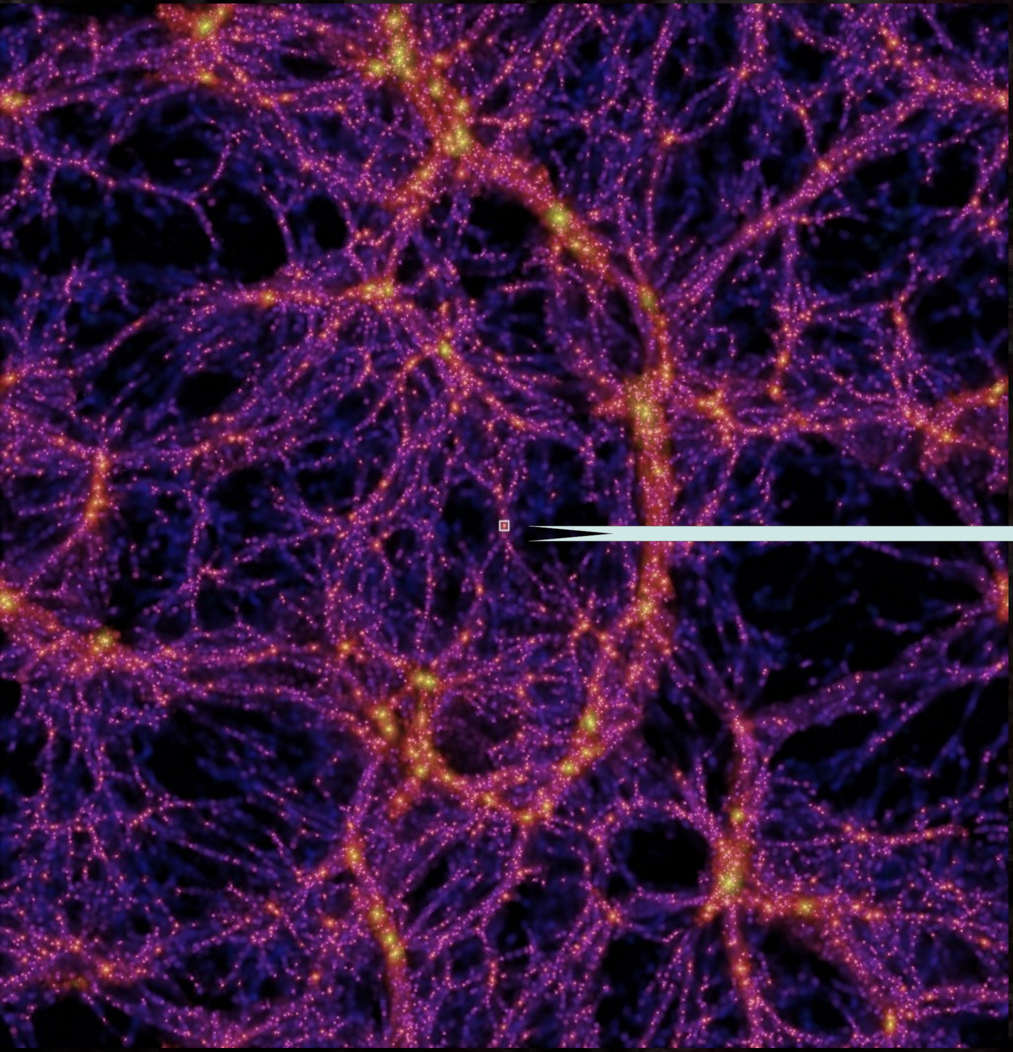
IAU 308, Zeldovich 100, Tallinn 2014

THE COSMIC WEB
a home for haloes and galaxies woven within



Aquarius simulation

THE COSMIC WEB

Forming processes:

Hierarchical structure formation

Anisotropic collapse

skewness of the density distribution

Underlying Physics:

Nature of Gravity

Physics Of DM

Background Expansion History (DE/ModGrav)

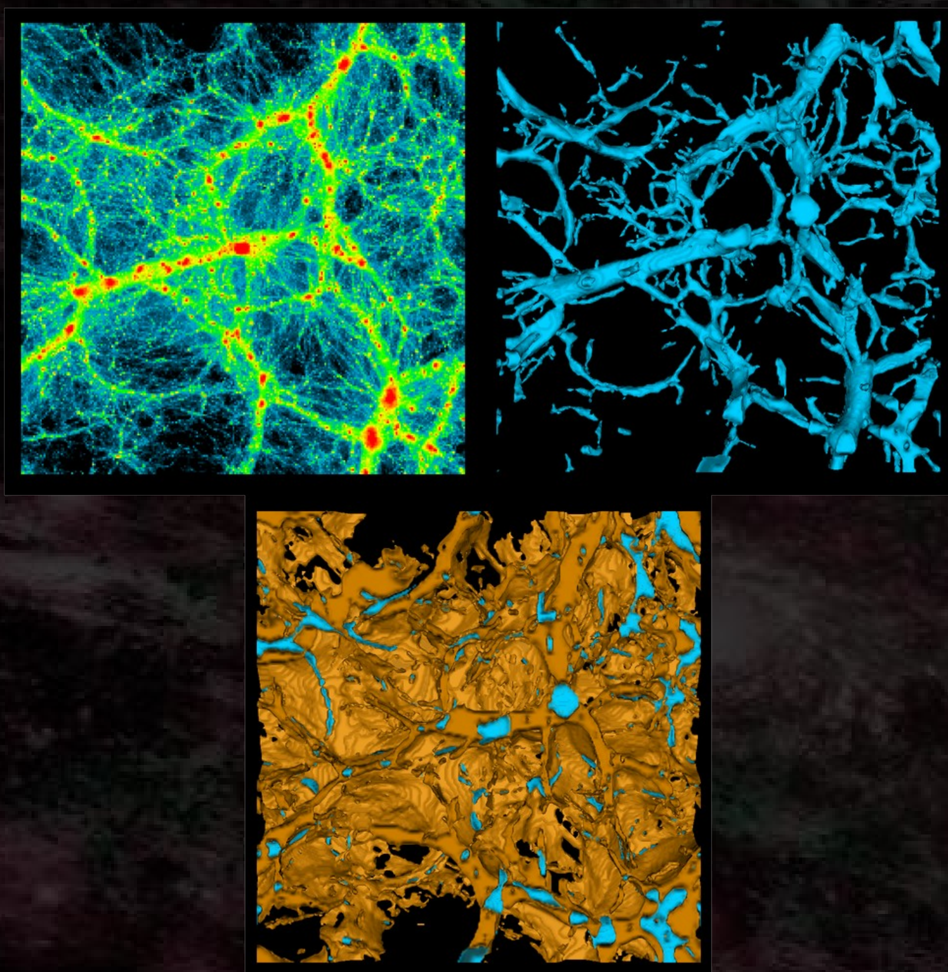
Resulting properties:

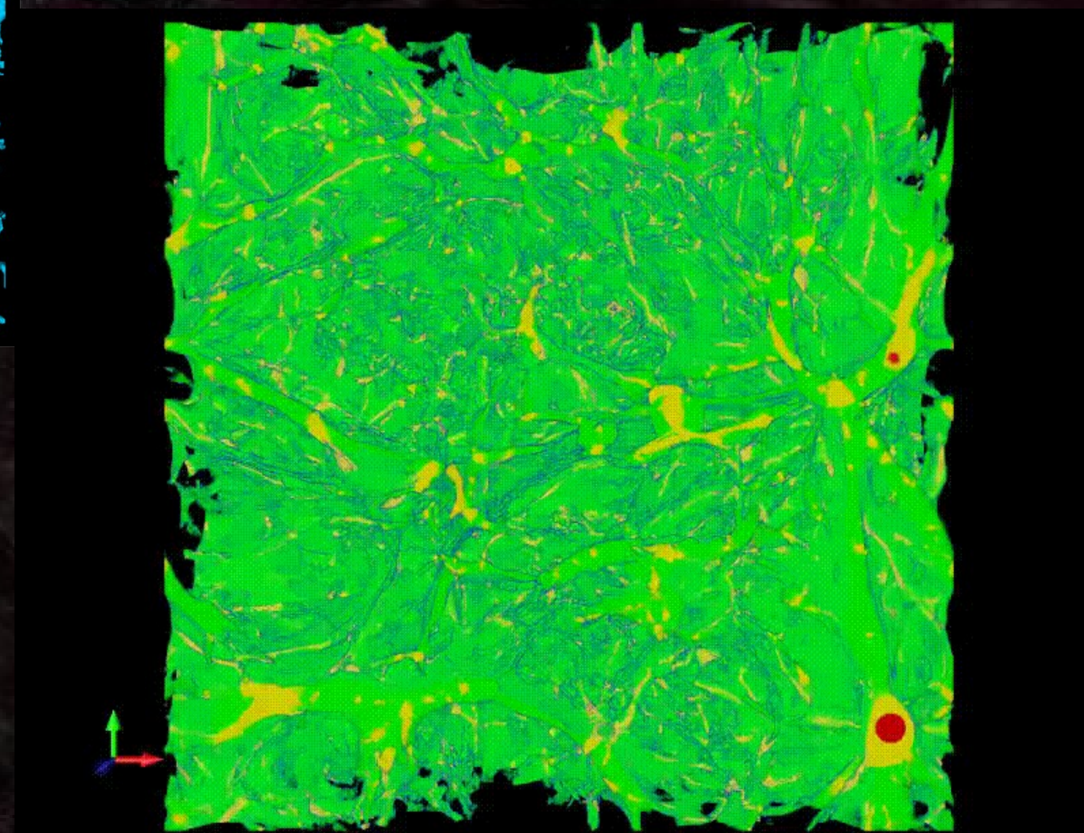
Multi-scale character

Web-like patterns

Volume dominance of The Voids

Unveiling the Cosmic WEB in Millennium 2

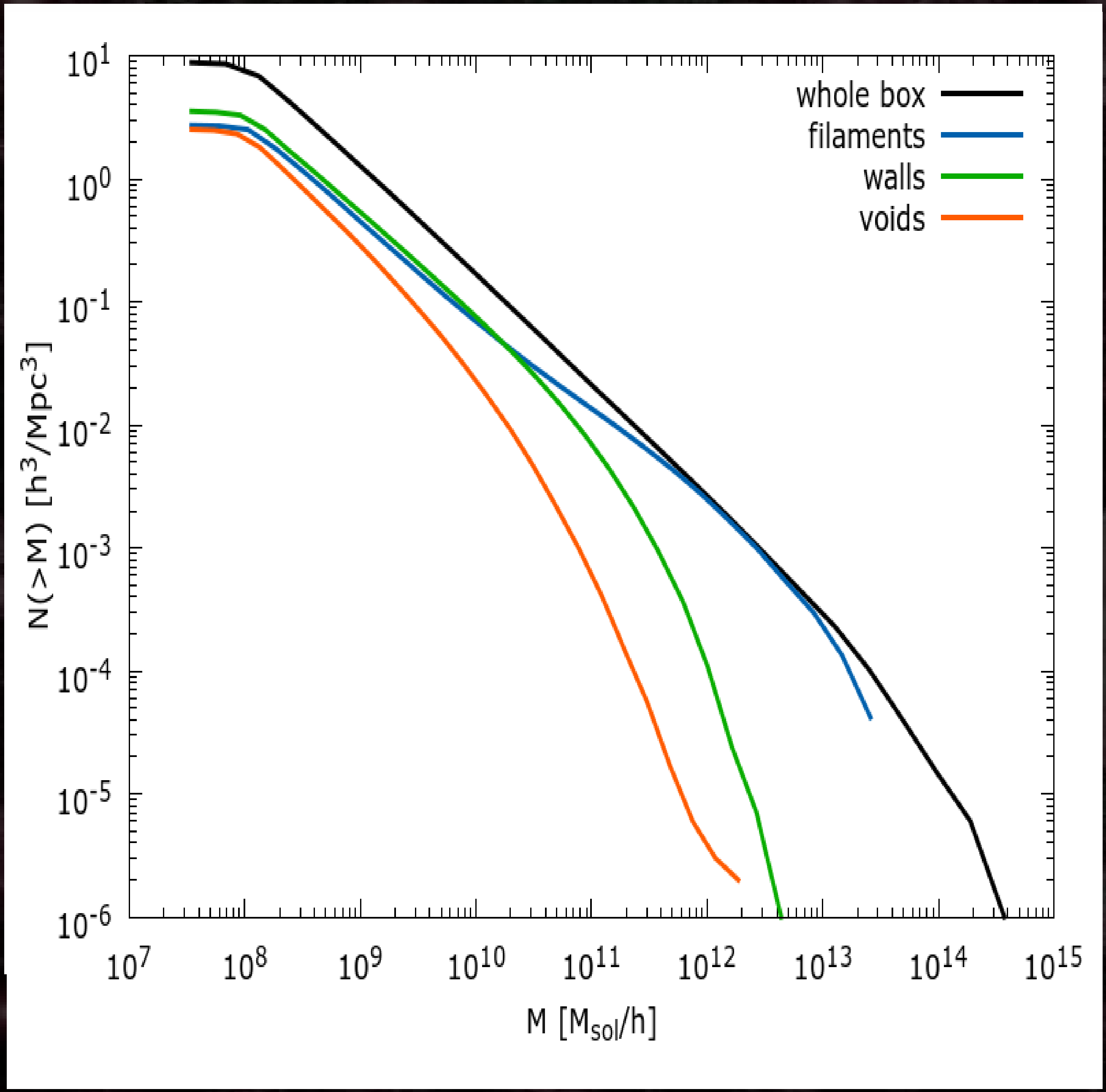




MS2 - Boylan-Kolchin et al.

THE COSMIC WEB

Who is living where?



- The mass – environment relation

- The clustering bias induces mass-environment bias

- If MW is a wall-nation galaxy it is already rare (<~10 %)

Pairwise velocities – cosmic dance of galaxies

Pairwise velocities. The mean pairwise relative velocity of galaxies (or *pairwise streaming velocity*), v_{12}, reflects the "mean tendency of well-separated galaxies to approach each other" [28]. This statistic was introduced by Davis & Peebels [29] in the context of the kinetic BBGKY theory which describes the dynamical evolution of a system of particles interacting through gravity. In the fluid limit its equivalent is the pair density-weighted relative velocity,

$$\mathbf{v}_{12}(r) = \langle \mathbf{v}_1 - \mathbf{v}_2 \rangle_\rho = \frac{\langle (\mathbf{v}_1 - \mathbf{v}_2)(1+\delta_1)(1+\delta_2) \rangle}{1+\xi(r)}$$

line-of-sight pairwise velocity dispersion, $\sigma_{12}^2(r) = \int \xi(R)\sigma_p^2(R)dl / \int \xi(R)dl$. Here r is the projected galaxy separation, $R = \sqrt{r^2+l^2}$, and the integration is taken along the line-of-sight within $l \pm 25h^{-1}$ Mpc. The quantity σ_p^2 is the line-of-sight centred pairwise dispersion, defined as [31]

$$\sigma_p^2 = \frac{r^2\sigma_\perp^2/2 + l^2(\sigma_\parallel^2 - v_{12}^2)}{r^2+l^2}. \quad (2)$$

BBGKY=Bogoliubov–Born–Green–Kirkwood–Yvon hierarchy

(LSS, eq. [71.6]). For models with Gaussian initial conditions, the solution of the pair conservation equation is well approximated by (Juszkiewicz, Springel, & Durrer 1998b)

$$v_{12}(r) = -\frac{2}{3}Hrf\bar{\bar{\xi}}(r)[1+\alpha\bar{\bar{\xi}}(r)], \quad (2)$$

$$\bar{\xi}(r) = (3/r^3)\int_0^r \xi(x)x^2dx \equiv \bar{\bar{\xi}}(r)[1+\xi(r)]. \quad (3)$$

Modified gravity – pairwise velocities

$$\mathbf{v}_{12}(r) = \langle \mathbf{v}_1 - \mathbf{v}_2 \rangle_\rho = \frac{\langle (\mathbf{v}_1 - \mathbf{v}_2)(1+\delta_1)(1+\delta_2) \rangle}{1+\xi(r)}$$

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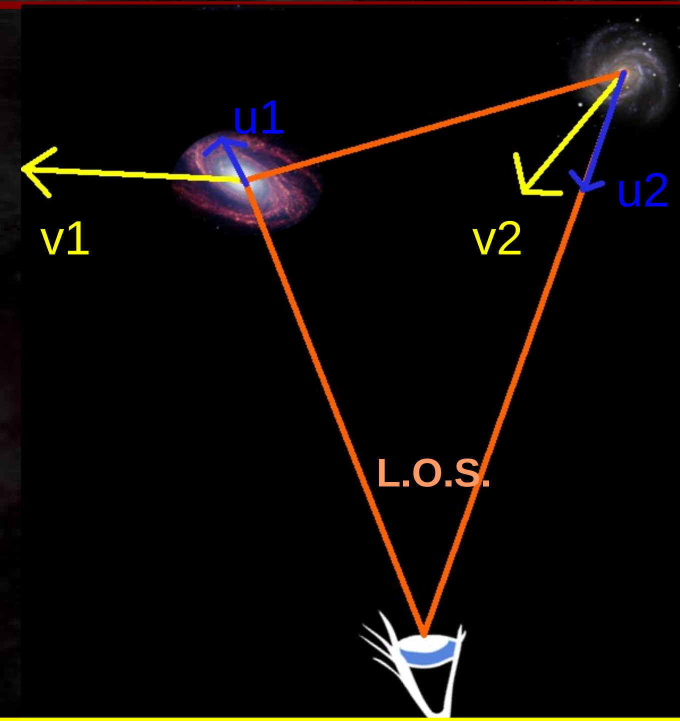


$$\xi'(\sigma,\pi) = \xi_0(s)P_0(\mu) + \xi_2(s)P_2(\mu) + \xi_4(s)P_4(\mu)$$

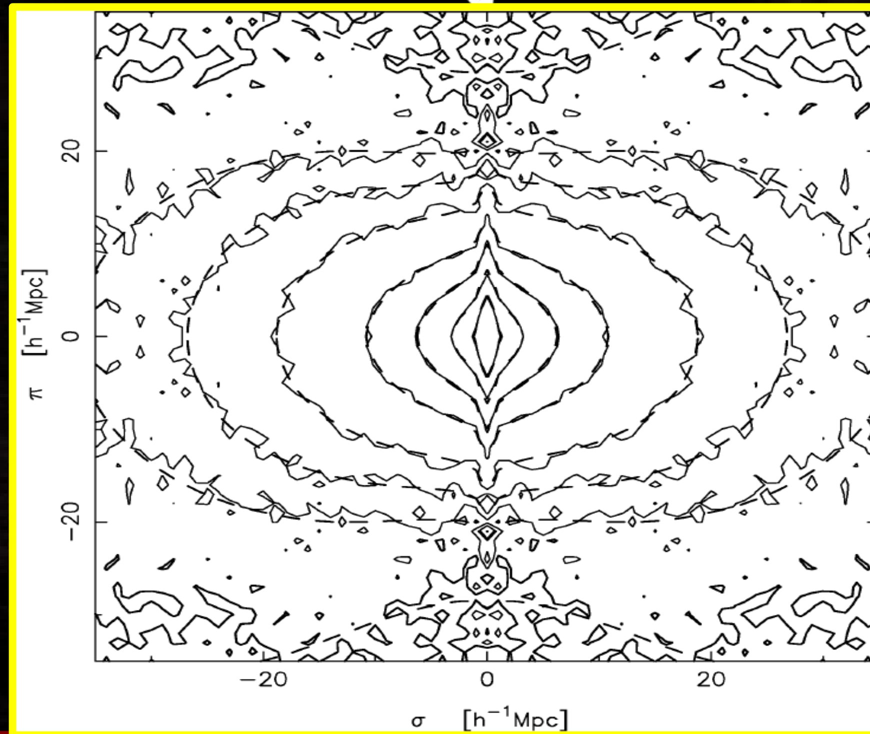
$$\xi_0(s) = \left(1 + \frac{2\beta}{3} + \frac{\beta^2}{5}\right)\xi(r)$$

$$\xi_2(s) = \left(\frac{4\beta}{3} + \frac{4\beta^2}{7}\right)\left(\frac{\gamma_r}{\gamma_r - 3}\right)\xi(r)$$

$$\xi_4(s) = \frac{8\beta^2}{35}\left(\frac{\gamma_r(2+\gamma_r)}{(3-\gamma_r)(5-\gamma_r)}\right)\xi(r).$$

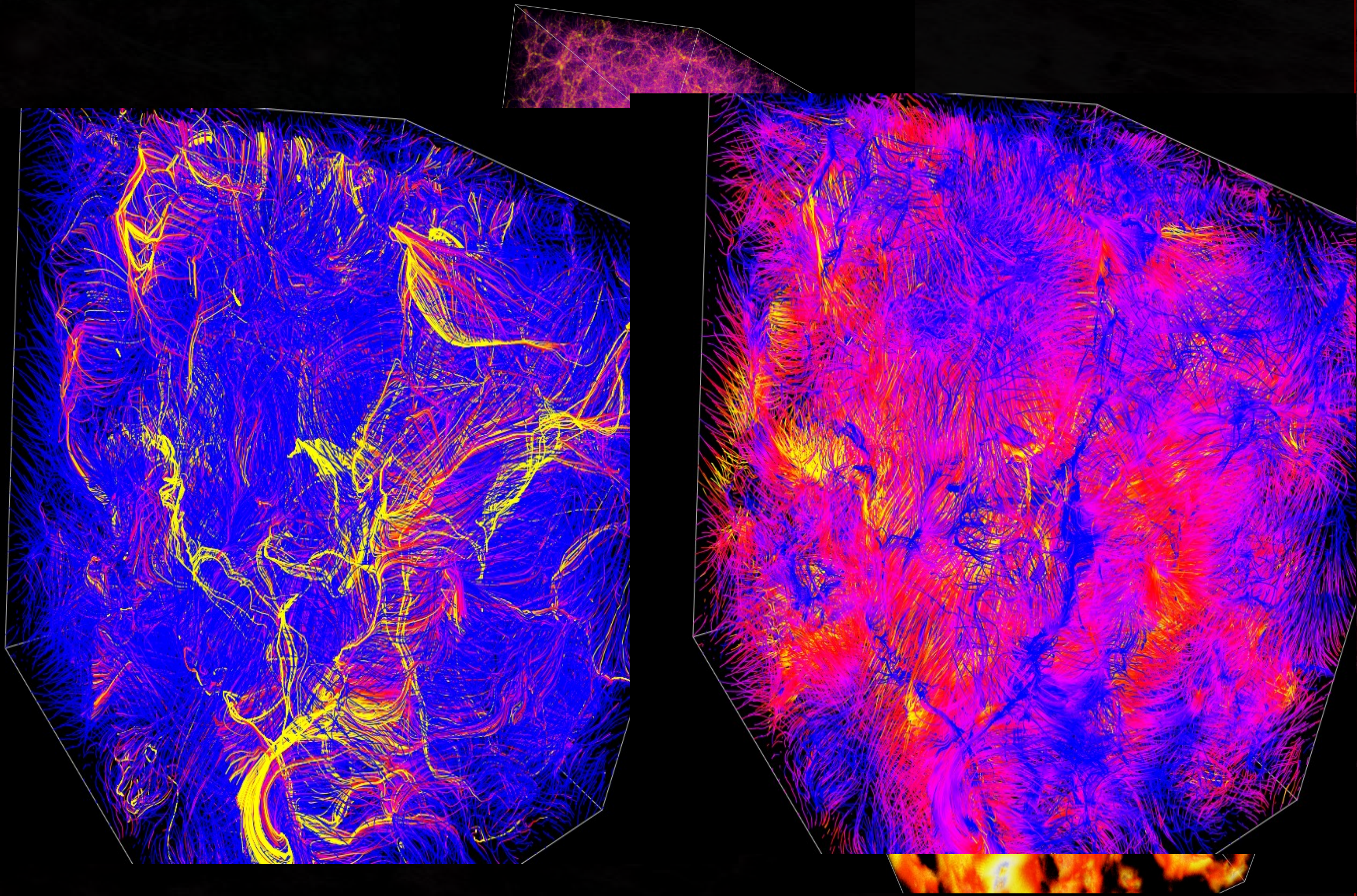
$$\xi(\sigma,\pi) = \int_{-\infty}^{\infty} \xi'(\sigma, \pi - v/H_0) f(v)\, \mathrm{d}v.$$

$$f(v) = \frac{1}{a\sqrt{2}} \exp\left(-\frac{\sqrt{2}|v|}{a}\right)$$



Hawkins et al. 2003

Pairwise velocities – cosmic dance of galaxies



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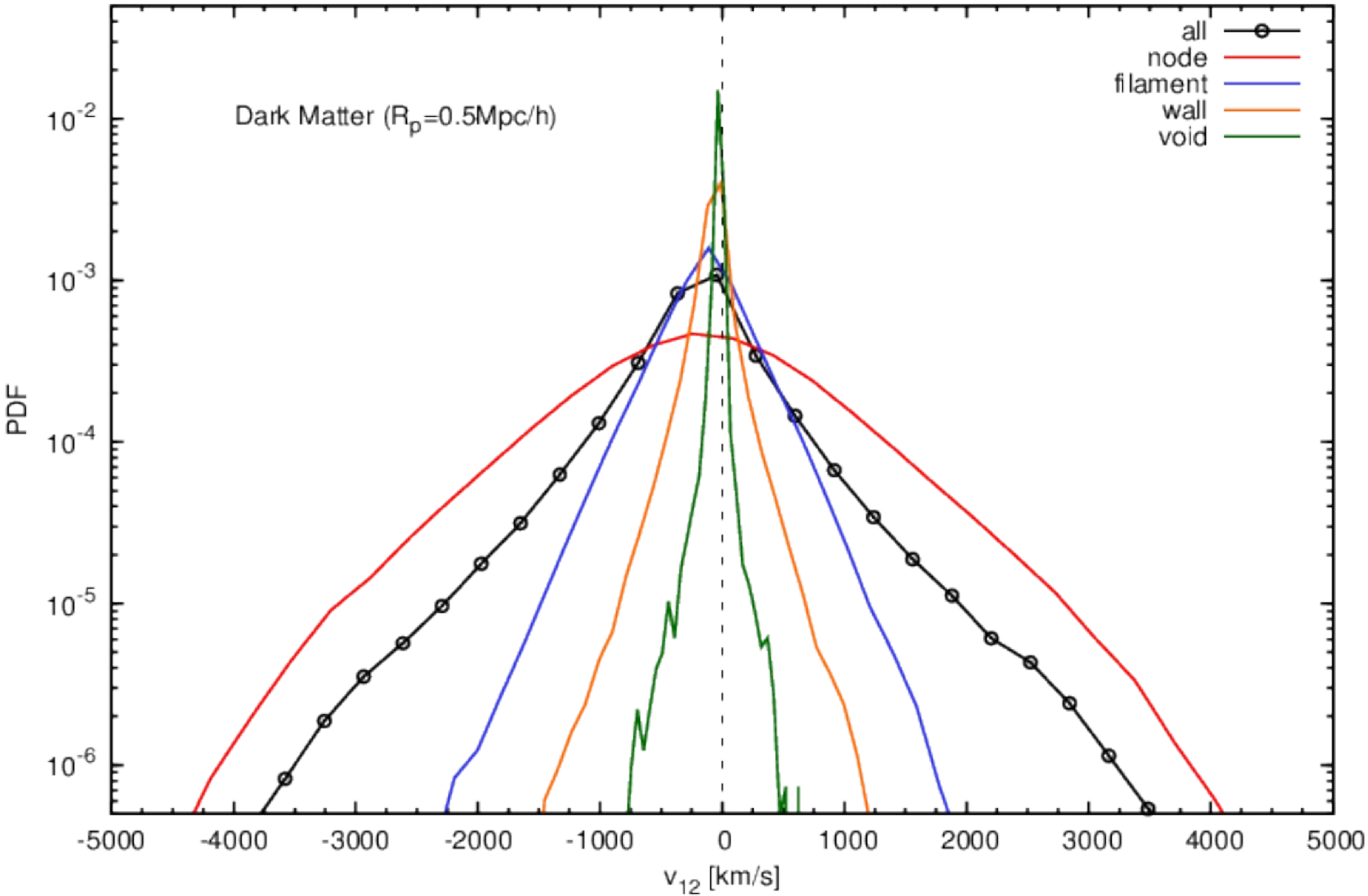

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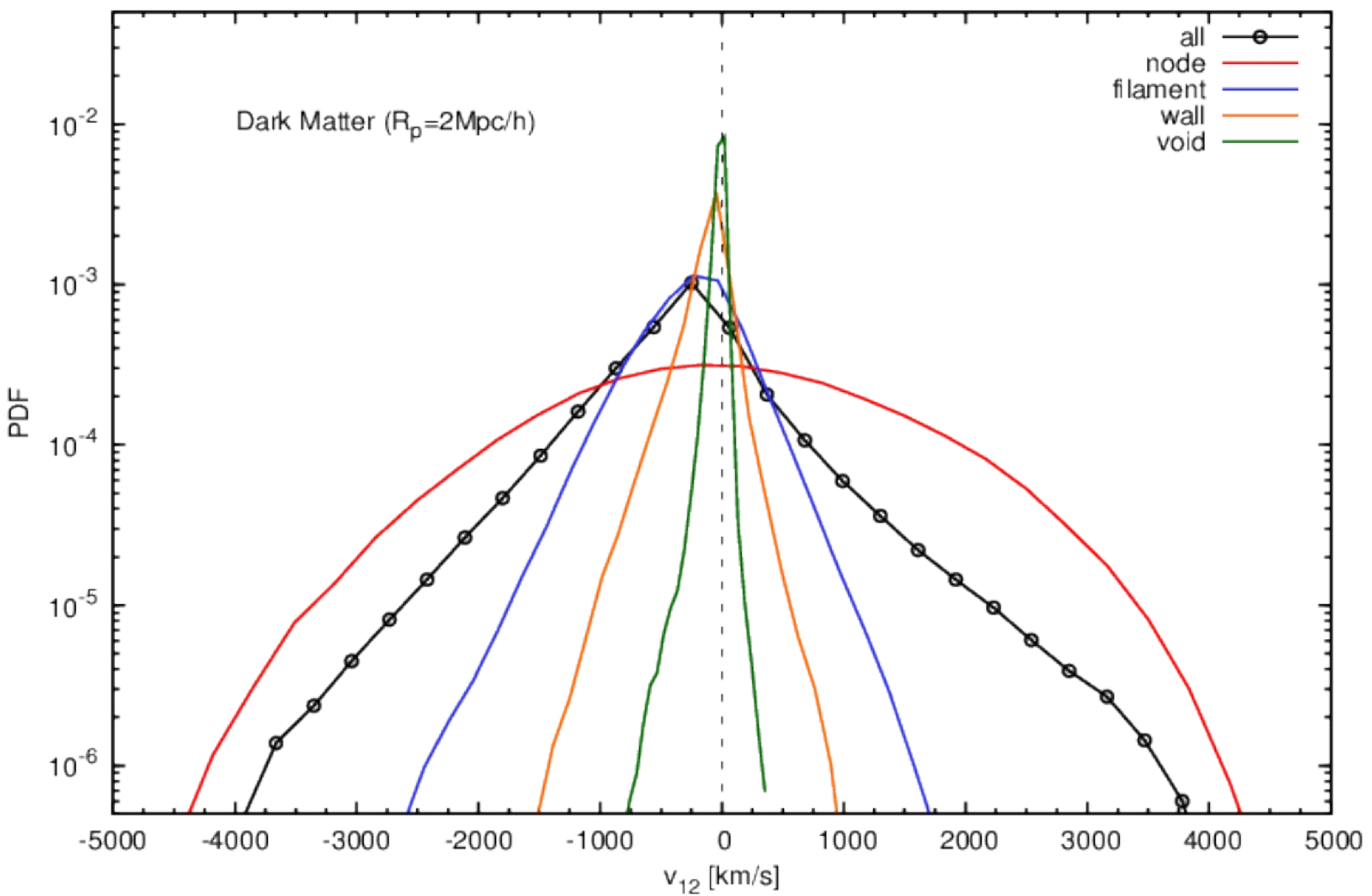

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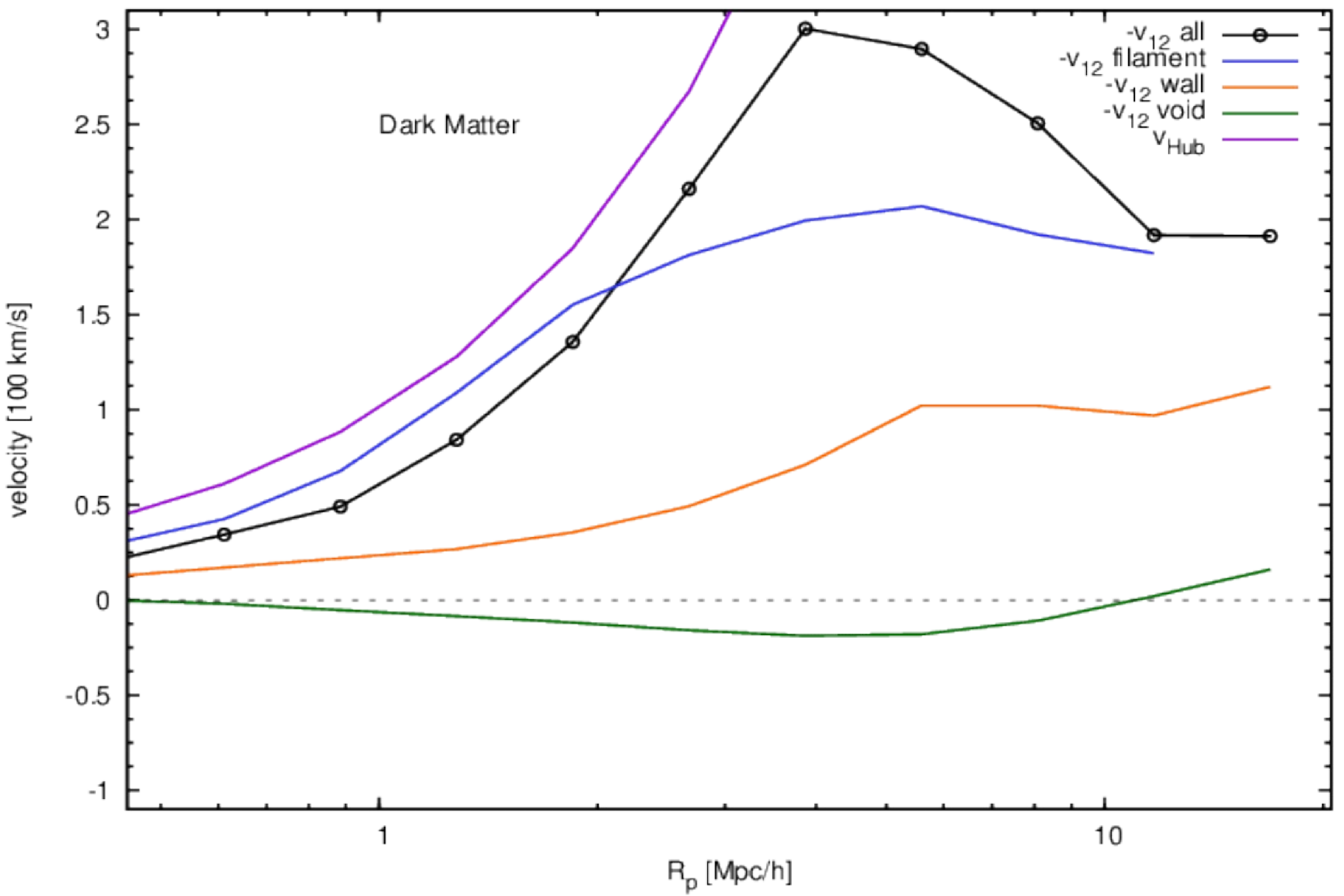

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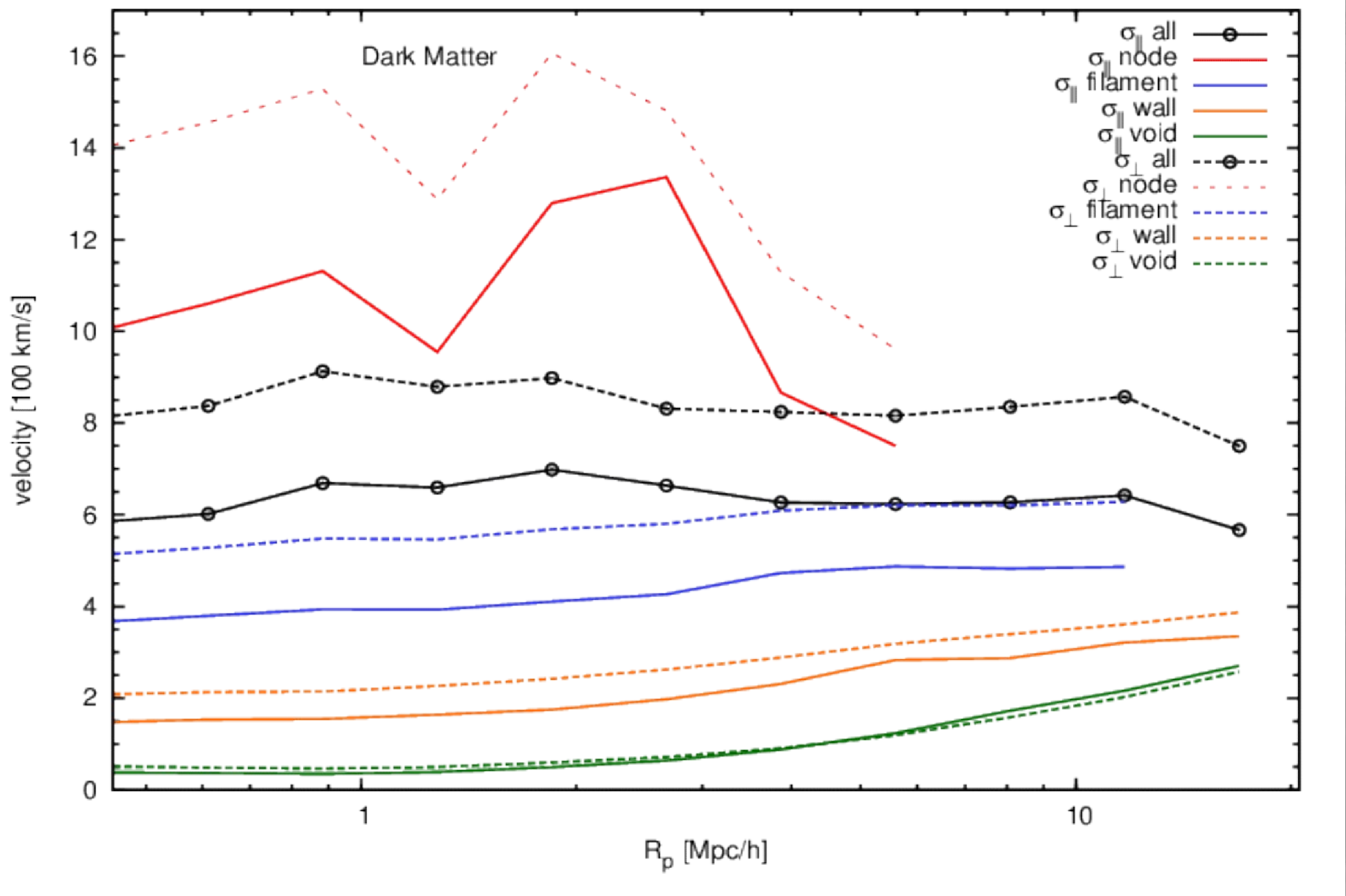

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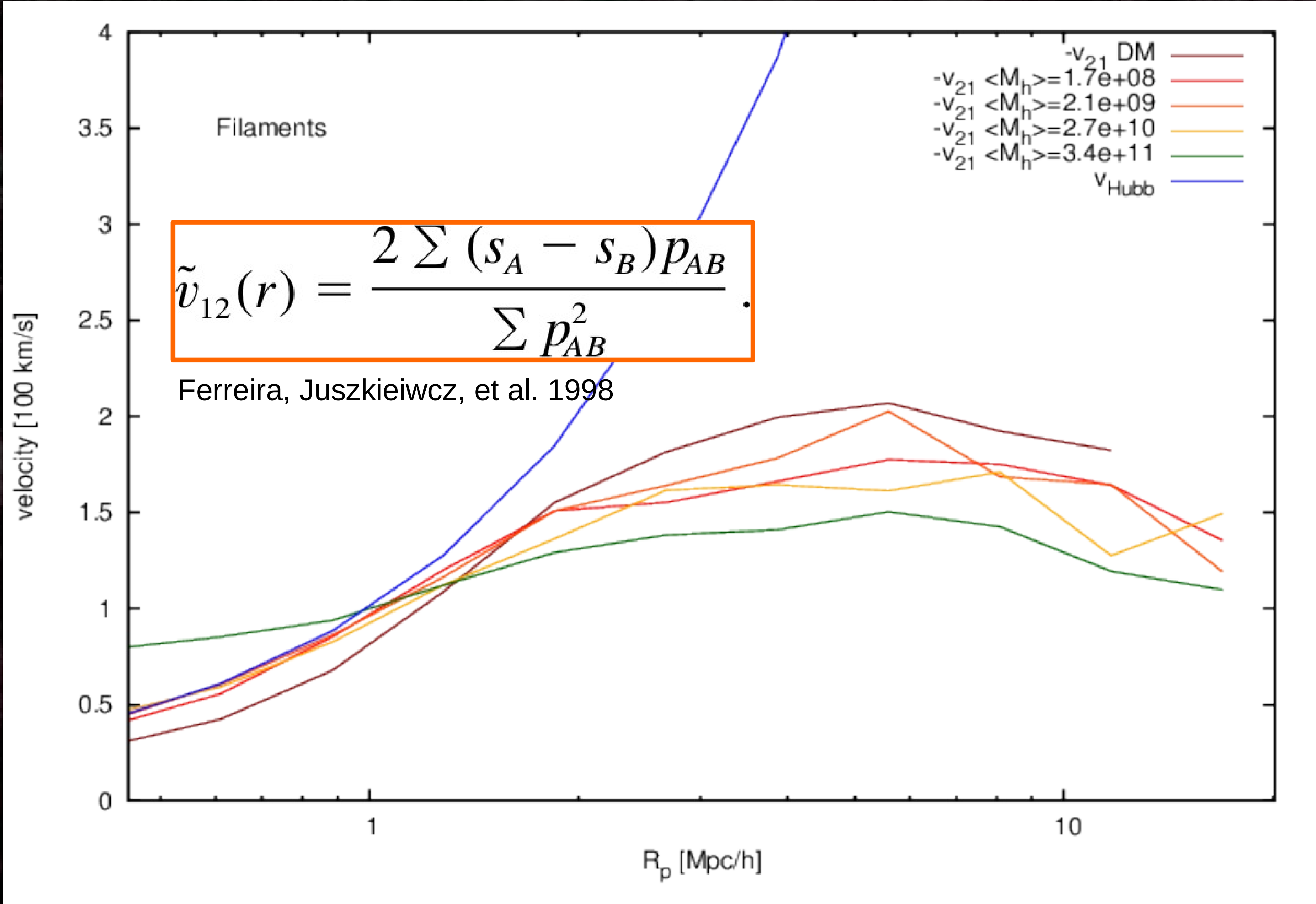

$$\tilde{v}_{12}(r) = \frac{2 \sum (s_A - s_B) p_{AB}}{\sum p_{AB}^2}.$$

Ferreira, Juszkieiwcz, et al. 1998

ModGrav – why bother?

Cosmic acceleration

Pure dark energy models

GR + unknown 'Dark Energy' with repulsive gravity.

Modified gravity models

Modifications to GR can accelerate the Universe.

Basic requisites:

- Preserve the standard past radiation and matter dominated eras
- Cannot modify gravity in the solar system, where GR is very successful.

Global expansion – possible scenarios

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

→ **No acceleration**

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

→ **Standard LCDM model**

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

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

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

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GR curvature term

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GR curvature term

Particle physics and DM

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GR curvature term

Particle physics and DM

Stuff that accelerates

The f(R)-gravity model

The Ricci scalar R in the Eisenstein-Hilbert action is generalised to a function of R. f_R=df(R)/dR is the extra scalar degree of freedom, dubbed as scalaron.

The Poisson and scalaron equations for growth of structure:

$$\nabla^2\Phi = \frac{16\pi G}{3}a^2\delta\rho_{\rm M} + \frac{a^2}{6}\delta R(f_R),$$

$$\nabla^2\delta f_R = -\frac{a^2}{3}[\delta R(f_R) + 8\pi G\delta\rho_{\rm M}],$$

Hu & Sawicki(2007) parameterization:

$$f(R) = -m^2\frac{c_1(-R/m^2)^n}{c_2(-R/m^2)^n+1},$$

$$m^2 \equiv \Omega_m H_0^2,$$

$$f_R \approx -n\frac{c_1}{c_2^2}\left[\frac{m^2}{-R}\right]^{n+1}$$

Effectively two free parameters of the f(R) gravity:

$$\xi \equiv \frac{c_1}{c_2^2}$$

and n. We consider simulations with $|fR_0|$=1e-4,1e-5 F4,F5,etc

The Galileon origins

Galilean shift transformation

$$\partial_\mu \varphi \longrightarrow \partial_\mu \varphi + b_\mu$$

In 4D Minkowski

There are only 5 theoretically acceptable galilean-invariant Lagrangians.

Nicolis et al. (2009)
(Over 400 citations)

After covariantization
(Defayet et al. 2009)

Vainshtein mechanism suppresses modifications on small scales.

Vainshtein (1972)

Acceleration of the Universe after radiation and matter domination.

De Felice & Tsujikawa (2010)

The Galileon model

$$S = \int d^4x\sqrt{-g}\left[\frac{R}{16\pi G} - \frac{1}{2}\sum_{i=1}^{5} c_i\mathcal{L}_i - \mathcal{L}_m\right] \qquad M^3 \equiv M_{\rm Pl}H_0^2$$

$$\mathcal{L}_1 = M^3\varphi,$$

Potential term; not interesting

$$\mathcal{L}_2 = \nabla_\mu\varphi\nabla^\mu\varphi,$$

$$\mathcal{L}_3 = 2\Box\varphi\nabla_\mu\varphi\nabla^\mu\varphi/M^3,$$

Cubic Galileon (c4=c5=0)

Quartic Galileon (c5=0)

$$\mathcal{L}_4 = \nabla_\mu\varphi\nabla^\mu\varphi\left[2(\Box\varphi)^2 - 2(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi) - R\nabla_\mu\varphi\nabla^\mu\varphi/2\right]/M^6,$$

$$\mathcal{L}_5 = \nabla_\mu\varphi\nabla^\mu\varphi\left[(\Box\varphi)^3 - 3(\Box\varphi)(\nabla_\mu\nabla_\nu\varphi)(\nabla^\mu\nabla^\nu\varphi) + 2(\nabla_\mu\nabla^\nu\varphi)(\nabla_\nu\nabla^\rho\varphi)(\nabla_\rho\nabla^\mu\varphi) - 6(\nabla_\mu\varphi)(\nabla^\mu\nabla^\nu\varphi)(\nabla^\rho\varphi)G_{\nu\rho}\right]/M^9.$$

Quintic Galileon (Most general)

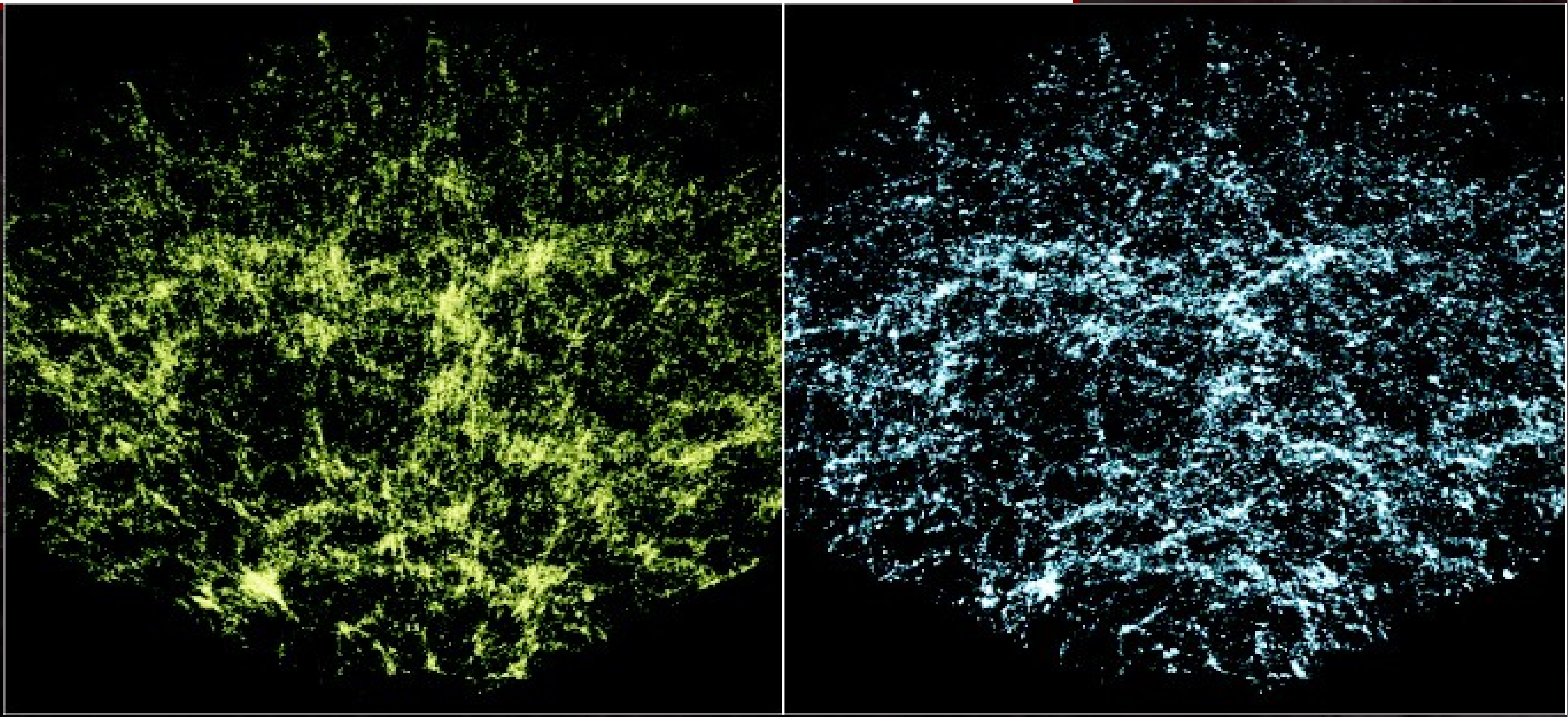
RSD power spectrum and the conspiracy of the damping tail

$$P^s(k,\mu) =$$
$$\left(P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\theta\theta}(k)\right) \times e^{-(fk\mu\sigma_v)^2}$$

where σ_v is the 1D linear velocity dispersion given by

$$\sigma_v^2 = \frac{1}{3}\int \frac{P_{\theta\theta}(k)}{k^2}\mathrm{d}^3k.$$

Scoccimarro 2004 (PRD 70,8)



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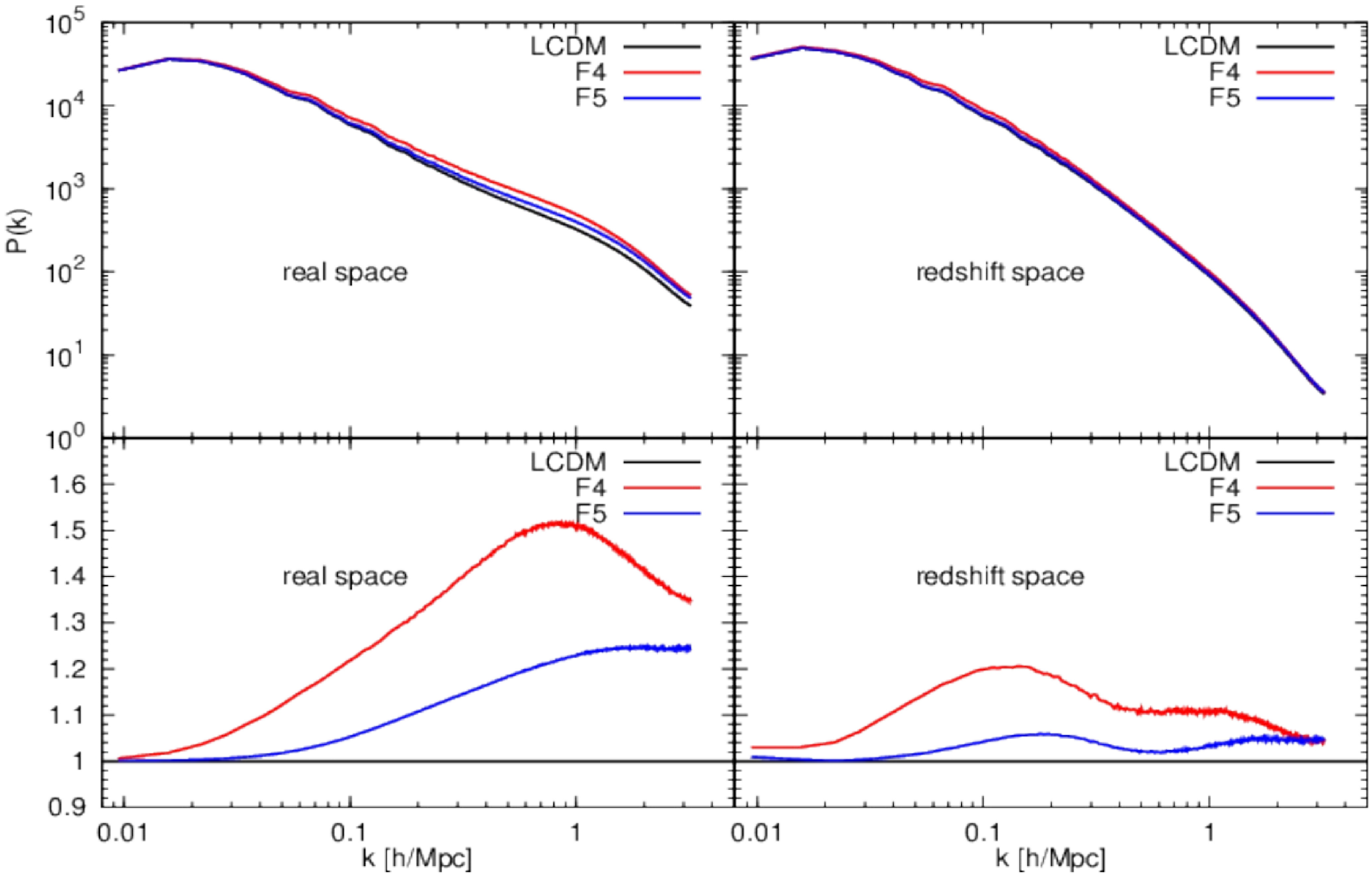
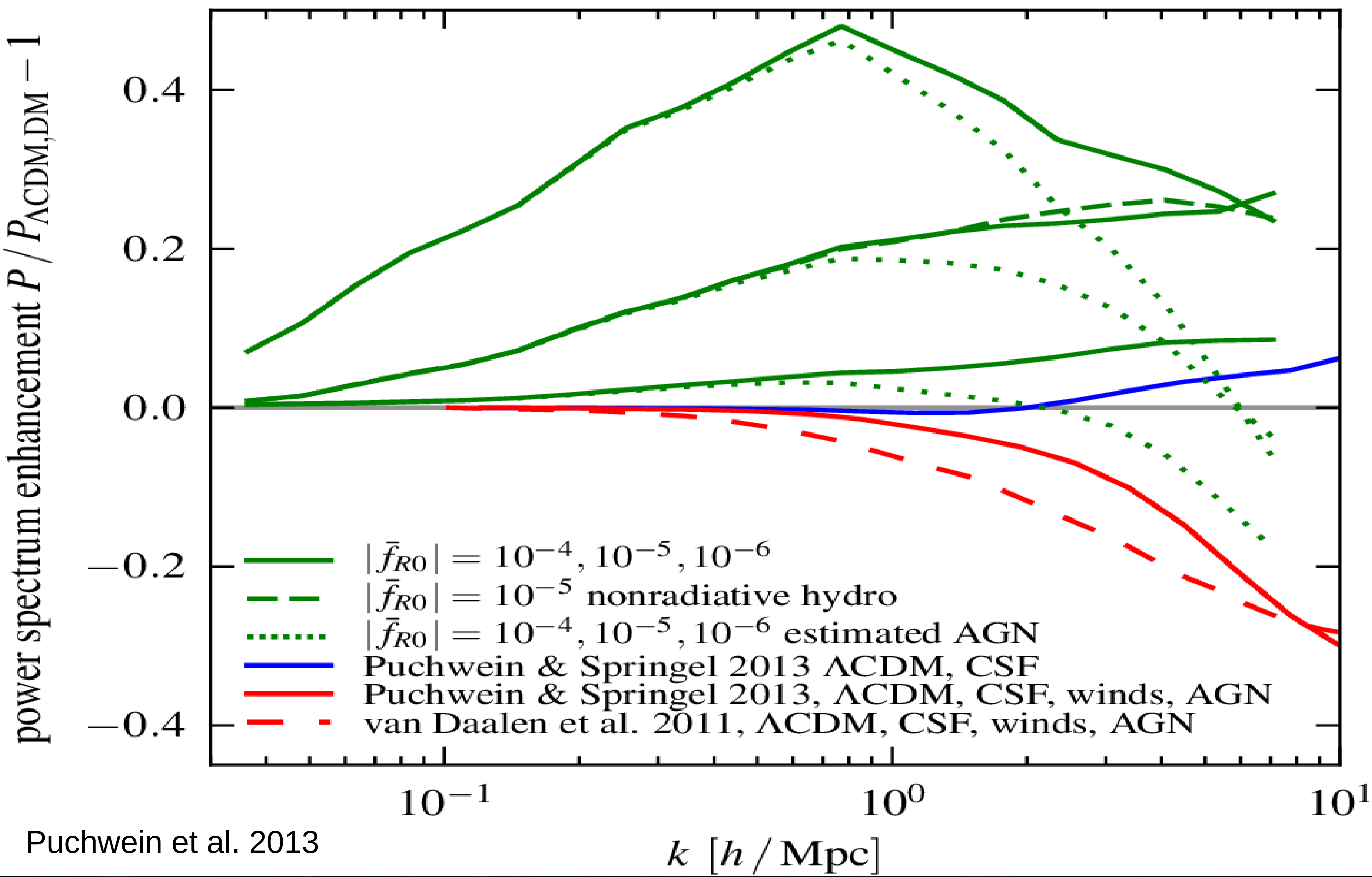


The spatial clustering signal gets diminished in the redshift space!

Baryons make everything more complicated...



Puchwein et al. 2013

The clustering enhancement is degenerate with baryonic feedbacks

Cosmic gravitational instability and velocity-density relation

verse. On very large, linear scales, the relation between the density contrast δ and the peculiar velocity v in comoving coordinates can be expressed in differential form,

$$\delta(\boldsymbol{r}) = -(H_0 f)^{-1} \nabla \cdot \boldsymbol{v}(\boldsymbol{r}), \quad (1)$$

Here f = dln D+/dln a=a/D+ dD/da

or in integral form,

Peebles ansatz:
f=f(Ω)~Ω^0.6
Modern version: f~Ω^0.55

$$\boldsymbol{v}(\boldsymbol{r}) = \boldsymbol{g}(\boldsymbol{r}). \quad (2)$$

Expressing the differential form in Fourier space yields:
<θ^2>=f^2<δ^2>, or
Pθθ(k) = f^2P(k), here θ = div v

Here,

$$\boldsymbol{g}(\boldsymbol{r}) \equiv H_0 f \int \frac{d^3\boldsymbol{r}'}{4\pi} \frac{\delta(\boldsymbol{r}')(\boldsymbol{r}' - \boldsymbol{r})}{|\boldsymbol{r}' - \boldsymbol{r}|^3} \quad (3)$$

ModGrav Smoking gun? ArXiv:1401.0706

A clear and measurable signature of modified gravity in the galaxy velocity field

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Institute for Computational Cosmology, Department of Physics, Durham University, South Road, Durham DH1 3LE, UK

The velocity field of dark matter and galax
cosmic history. We show that the low-order m
powerful diagnostic of the laws of gravity on c

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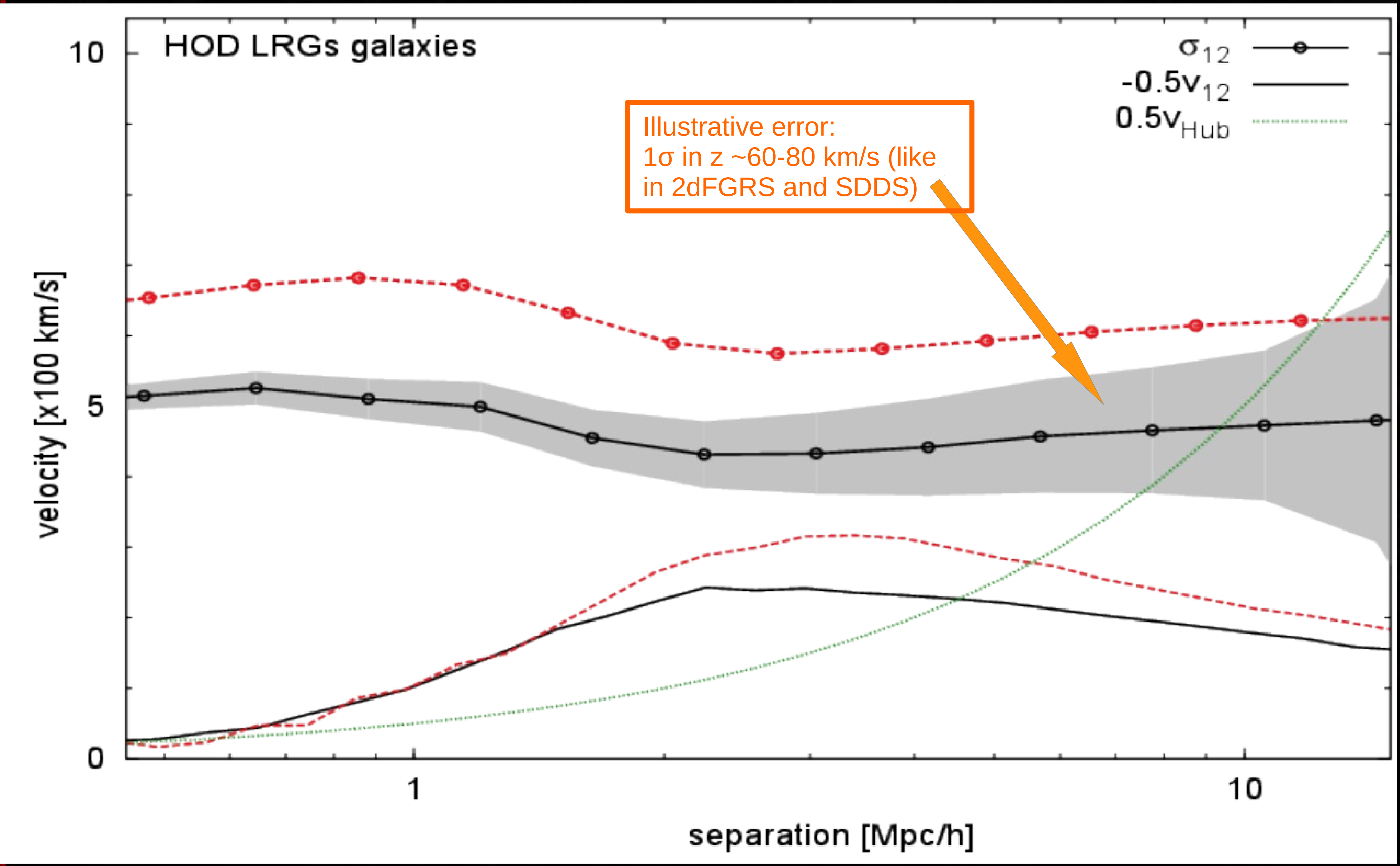
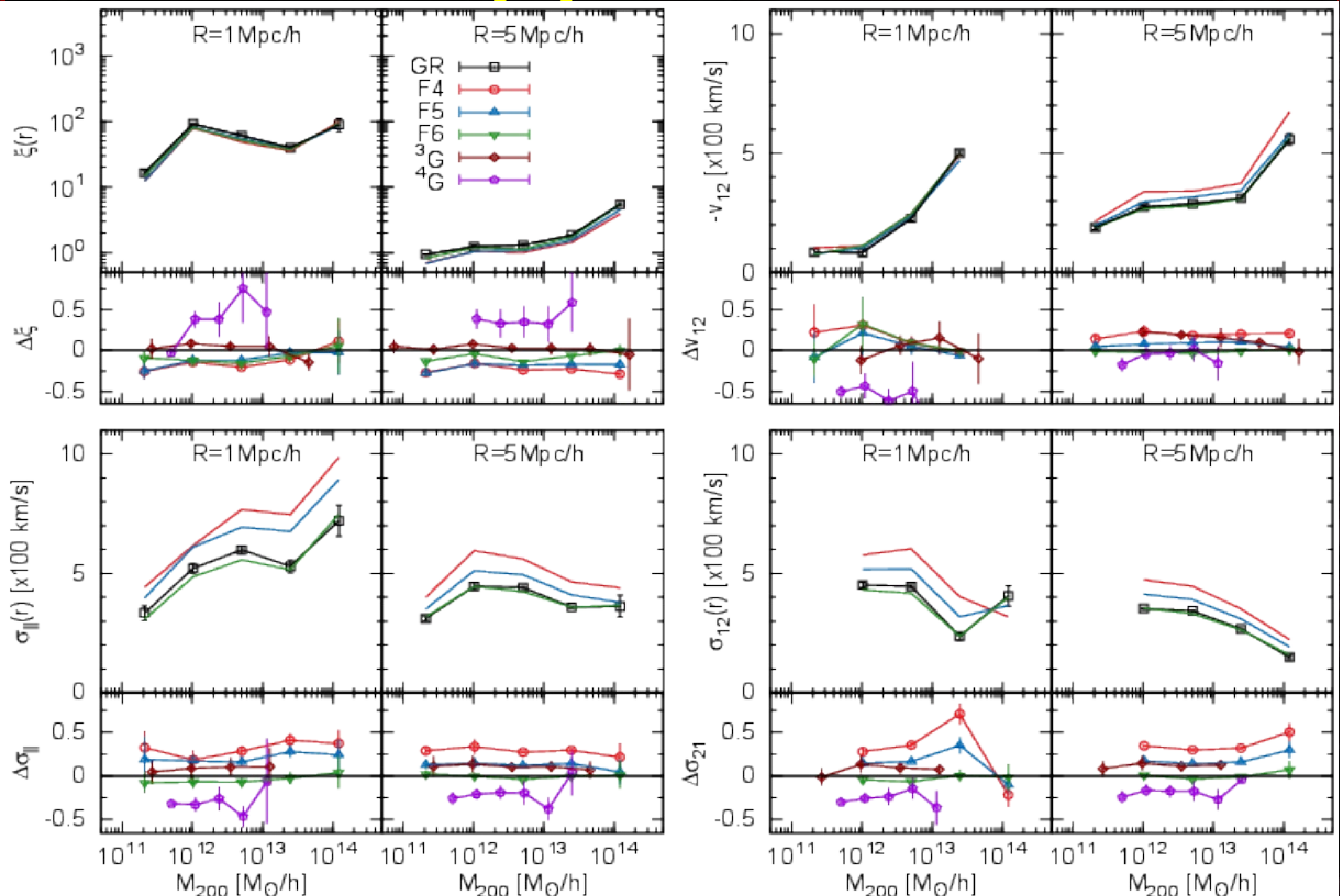


Hellwing et al. (2014,PhRL) ArXiv:1401.0706

A smoking gun for ModGrav?



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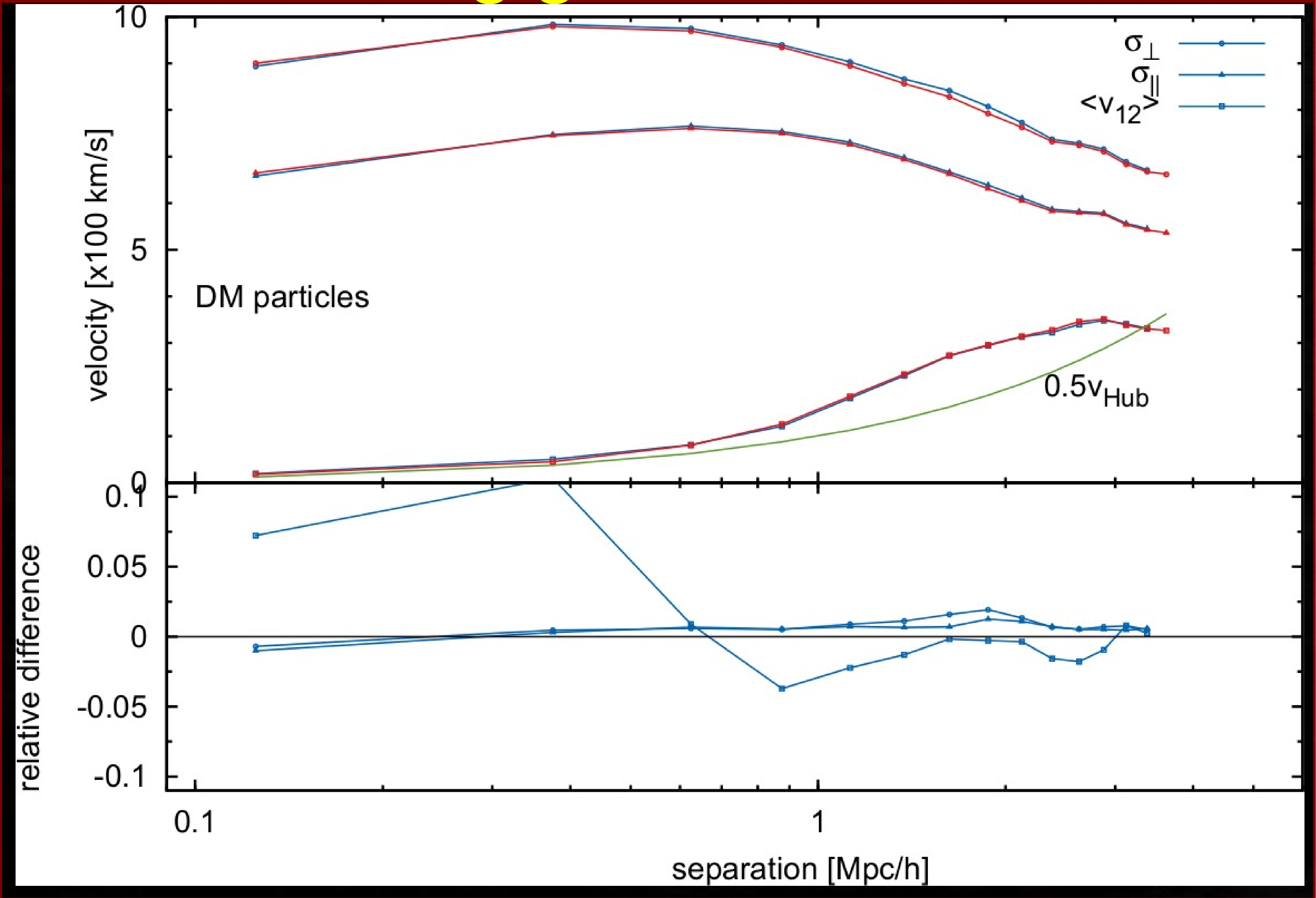

Modified gravity – pairwise velocities

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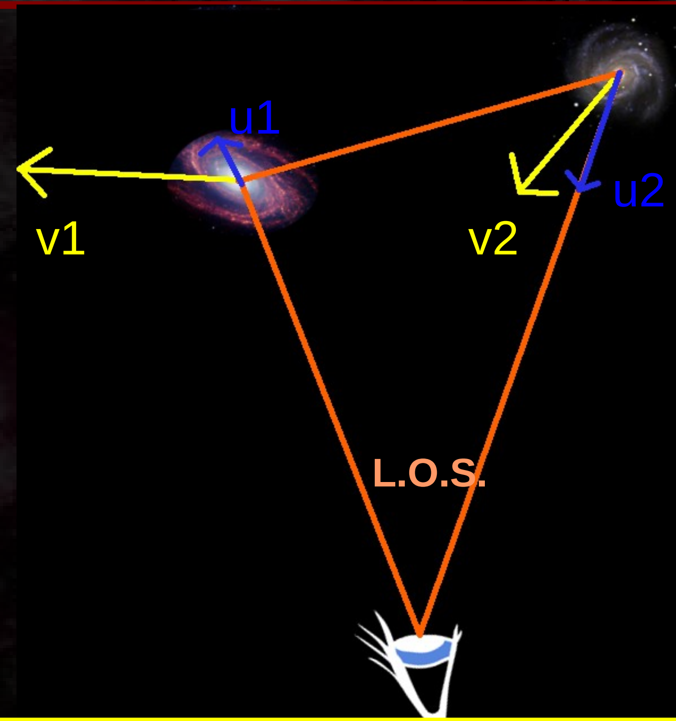

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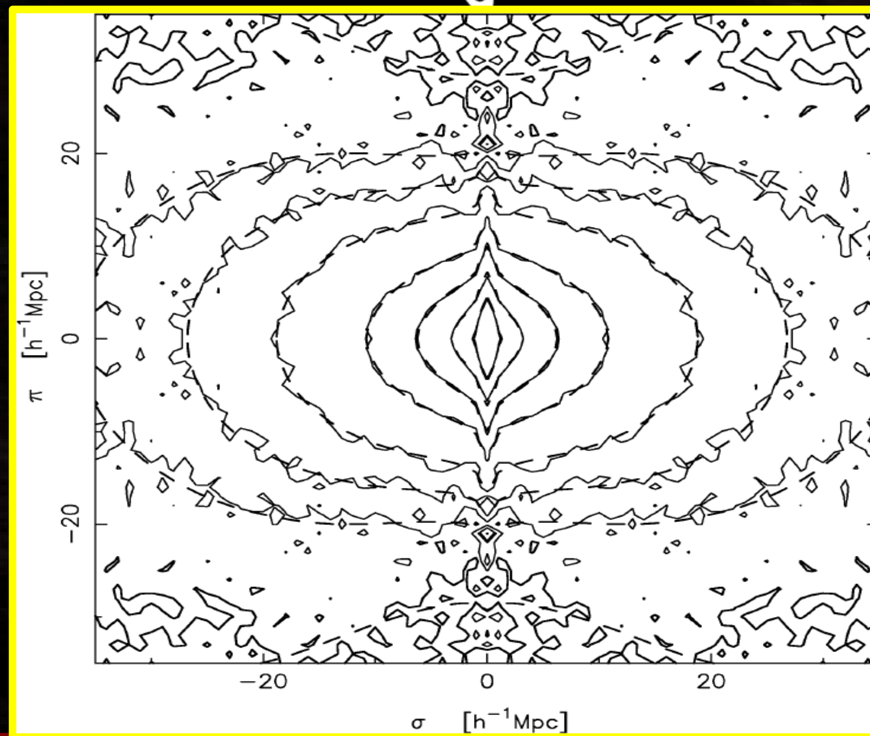
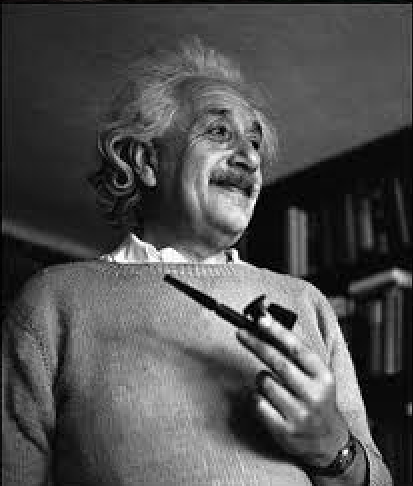
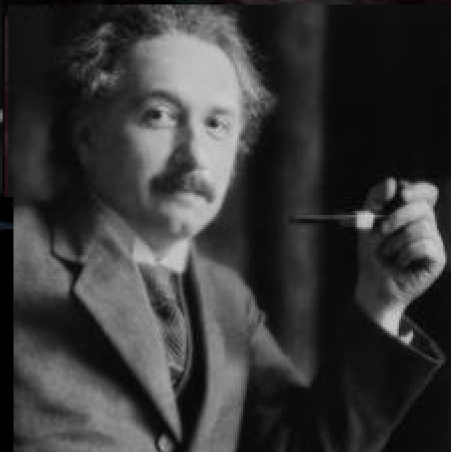
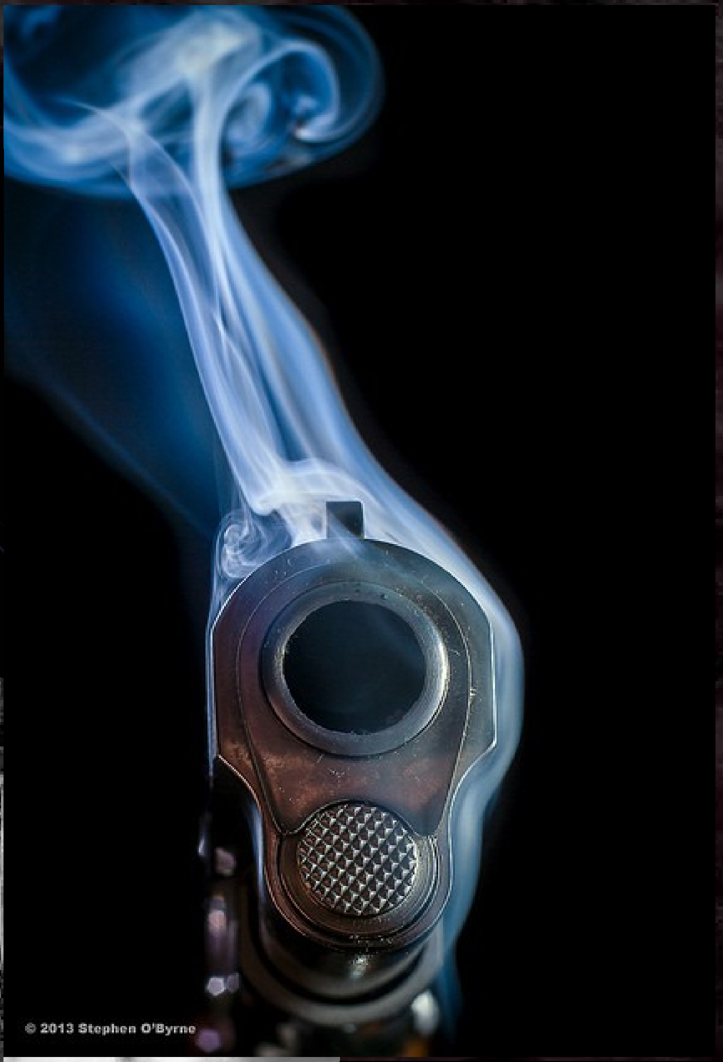


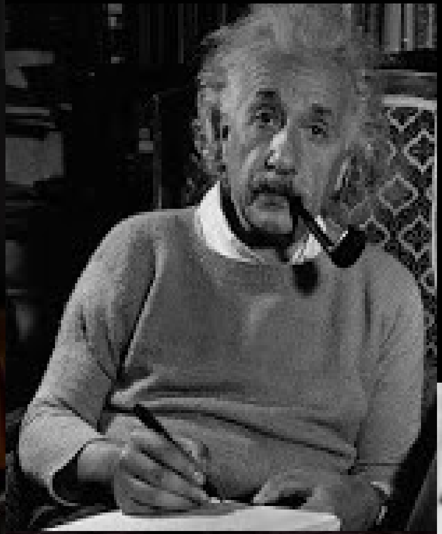
Hawkins et al. 2003

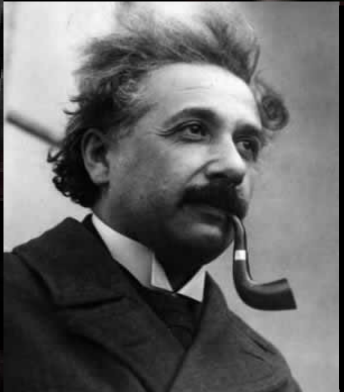
Modified gravity – the smoking gun!











Conclusions

- The LSS/Cosmic Web environment is much more complicated than just background density
- The Cosmic Web is a *REAL* existing entity which manifests itself in strongly different cosmic flows in different morphological elements
- The pairwise velocity distribution gets it's non-Gaussian character mostly due to galaxy/halo motions in walls and filaments
- The dynamics of the Cosmic Web embodied in large-scale galaxy distribution is rich source of cosmological information and potentially powerful tool to study Universe

ANNOUNCEMENT Check your conference schedule for the summer of 2015 – The 1st Roman Juszkiewicz Symphosium, Warsaw, Summer 2015