Testing Gravity with Large-Scale Structure
(i.e., the leftovers)

Fabian Schmidt
Caltech

Ringberg, 6/29/12

Outline

- **Phasespace of clusters: an extension of "E_G" to non-linear scales**

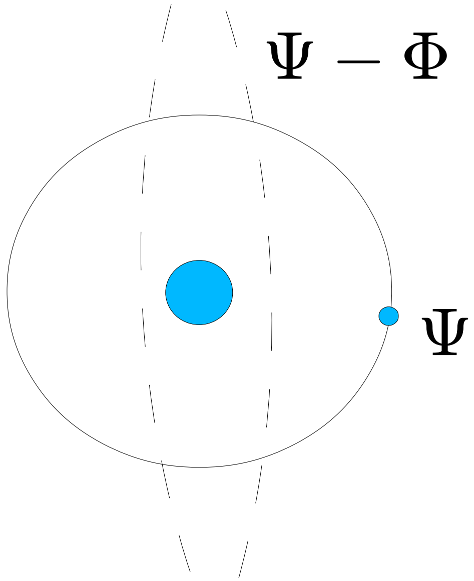
- **Some remarks on the Vainshtein mechanism**

"Direct" Tests of Gravity

- **Compare (non-rel.) dynamics with lensing:**

$$\Psi = \Psi_N + \frac{1}{2}\phi$$

$$\Psi - \Phi = \Psi_N - \Phi_N$$



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Schwab et al, Smith 09
FS, 2010

X-ray; SZ; galaxy dynamics in clusters;
dynamics within galaxies

“Direct” Tests of Gravity

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  - *Linear regime:* redshift distortions vs weak lensing

    r > 50 Mpc/h

    Zhang et al 08, Reyes et al 2010

  - *Non-linear regime:* dynamical mass vs lensing mass

    r < 5 Mpc/h

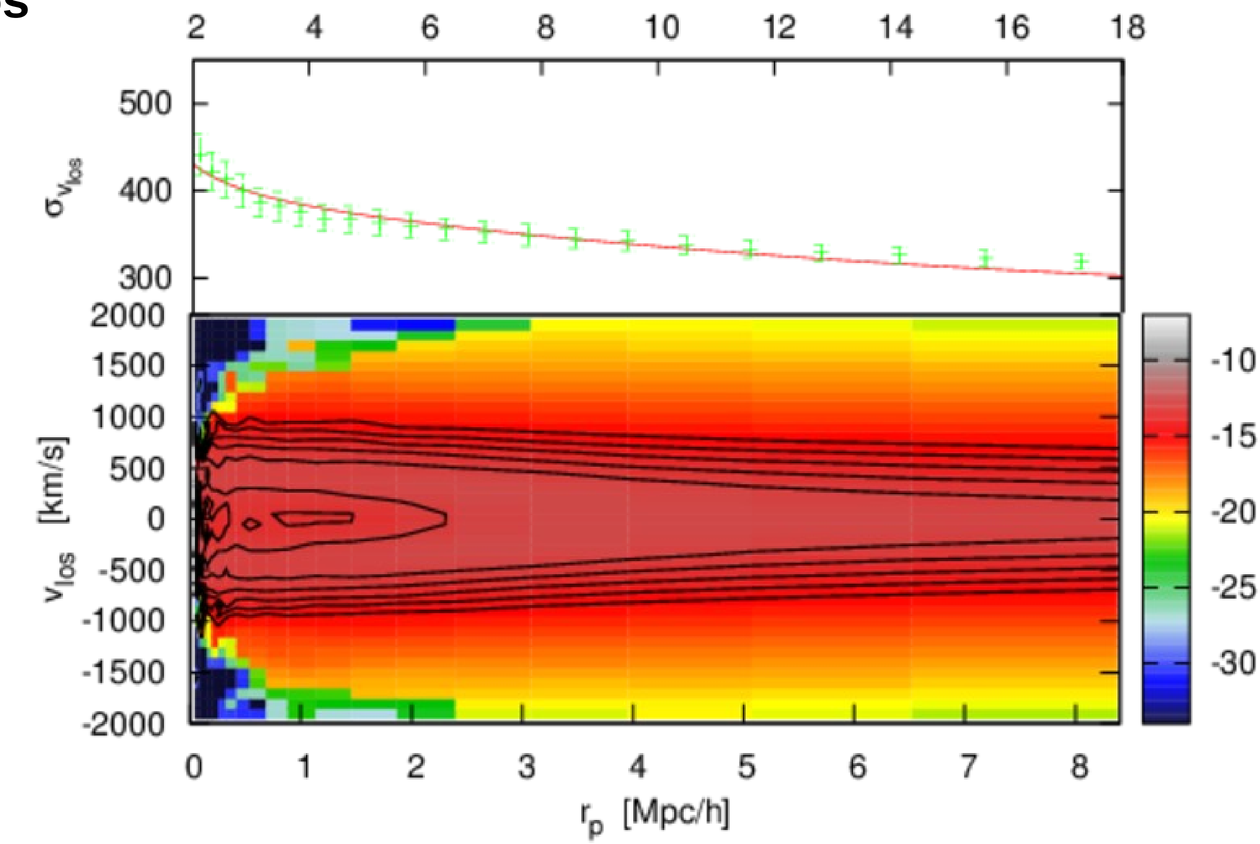
    Schwab et al, Smith 09
    FS, 2010

Phase-Space around Clusters

Distribution of V_{los} as function of r_{perp}

Measured from spectroscopic galaxy sample

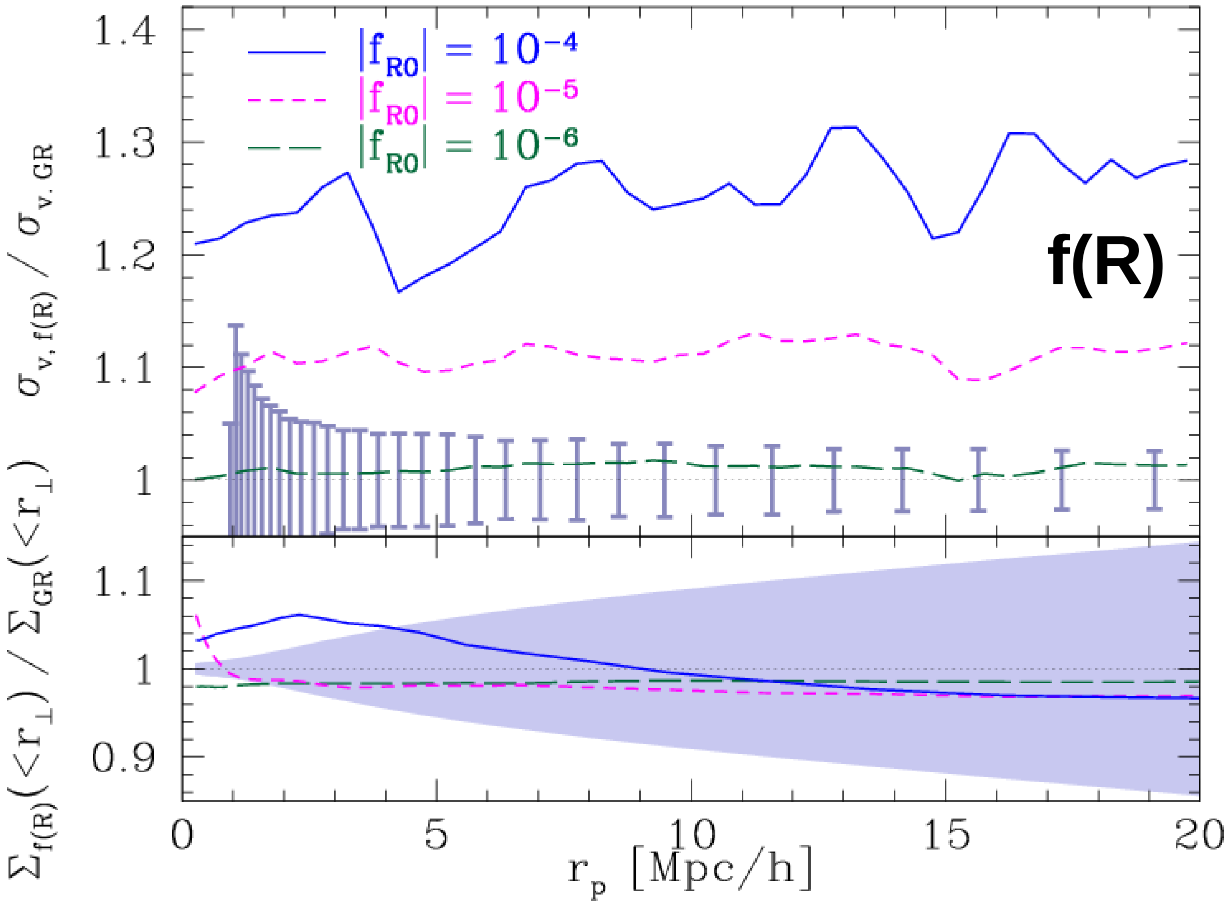
Density distribution measured from lensing



Lam et al, 2012

Phase-Space around Clusters

- **RMS dispersion of V_{los} as function of r_{perp}**



Stronger effect than virial scaling

$$\propto \sqrt{G_{\rm eff}/G}$$

Eventually approaching linear scaling

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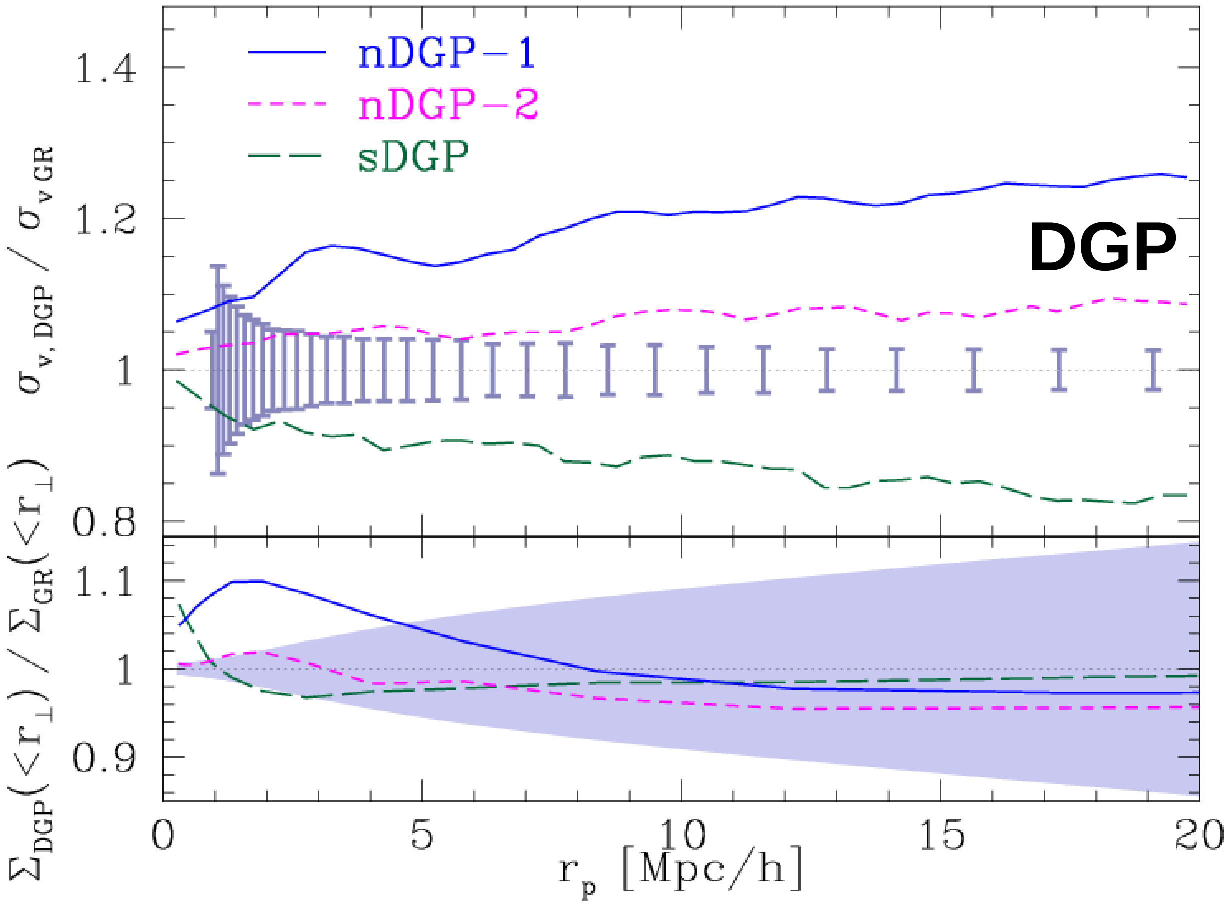

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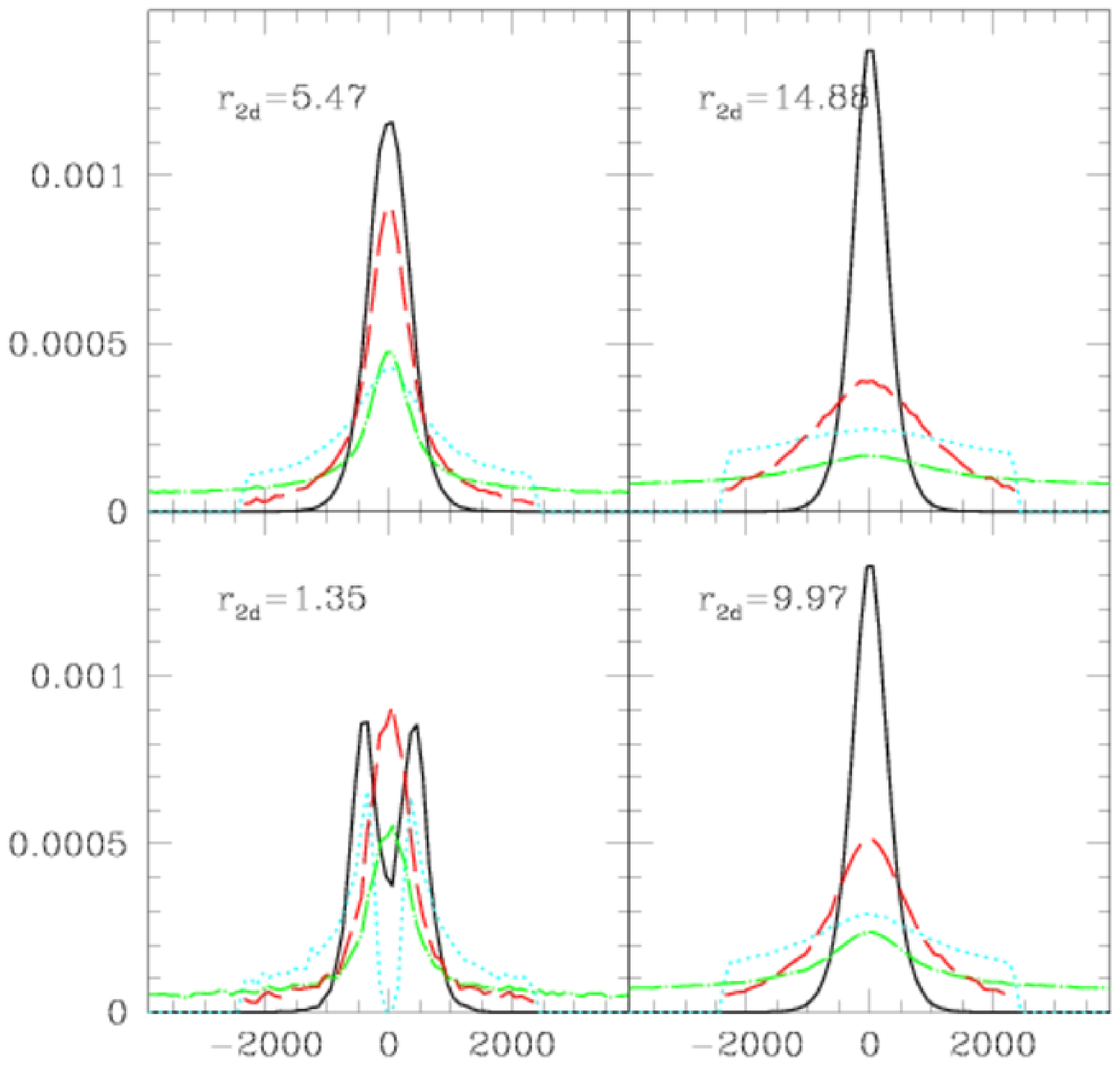
Challenge: Hubble flow

- **Increasingly difficult towards larger r_p**
- **Complementary to redshift distortions**
  - Black: velocities only
  - Red: including Hubble flow



Vainshtein mechanism

- **DGP (+Galileons, massive gravity, ...) evades Solar System through non-linear interactions of the scalar d.o.f.:**

$$\nabla^2\varphi + \frac{r_c^2}{3\beta\, a^2}\left[(\nabla^2\varphi)^2 - (\nabla_i\nabla_j\varphi)(\nabla^i\nabla^j\varphi)\right] = \frac{8\pi\, G\, a^2}{3\beta}\delta\rho$$

Quasi-static approximation: sub-horizon scales

Non-linear interactions

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- **Hard: non-linear in derivatives of φ**
  - No superposition principle
  - Fully non-linear (as opposed to quasi-linear)

Non-linear interactions

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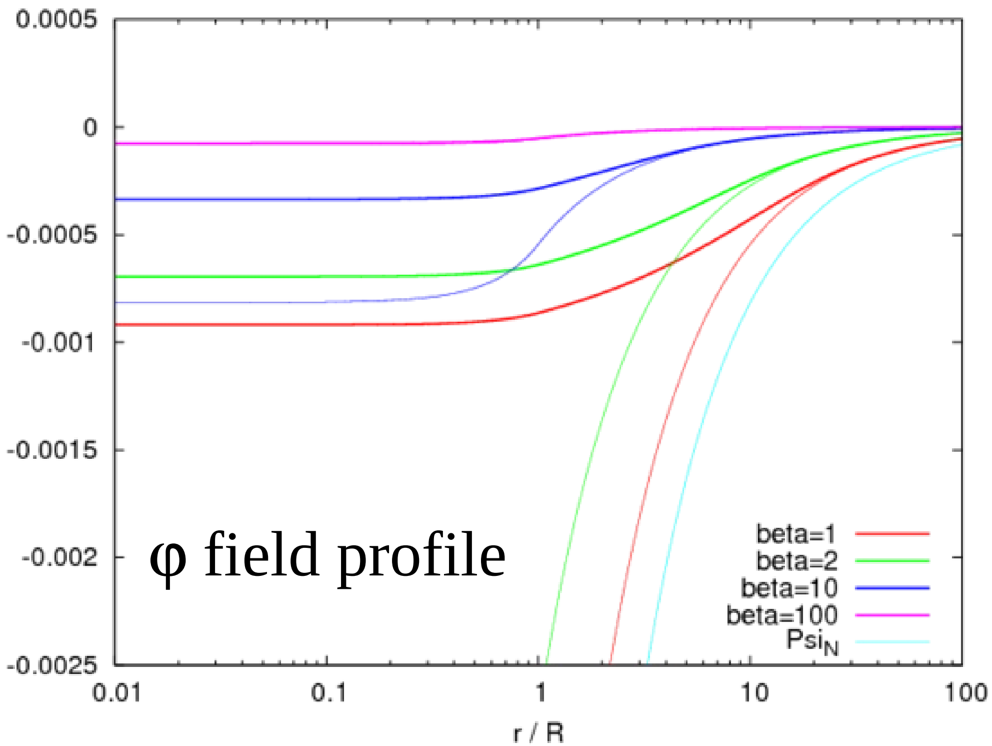
- **Two analytically solvable cases:**
  - **1. Plane wave:** $\varphi \sim e^{i\mathsf{k}\cdot\mathsf{x}} \Rightarrow -k^2\varphi = \frac{8\pi G a^2}{3\beta}\delta\rho$

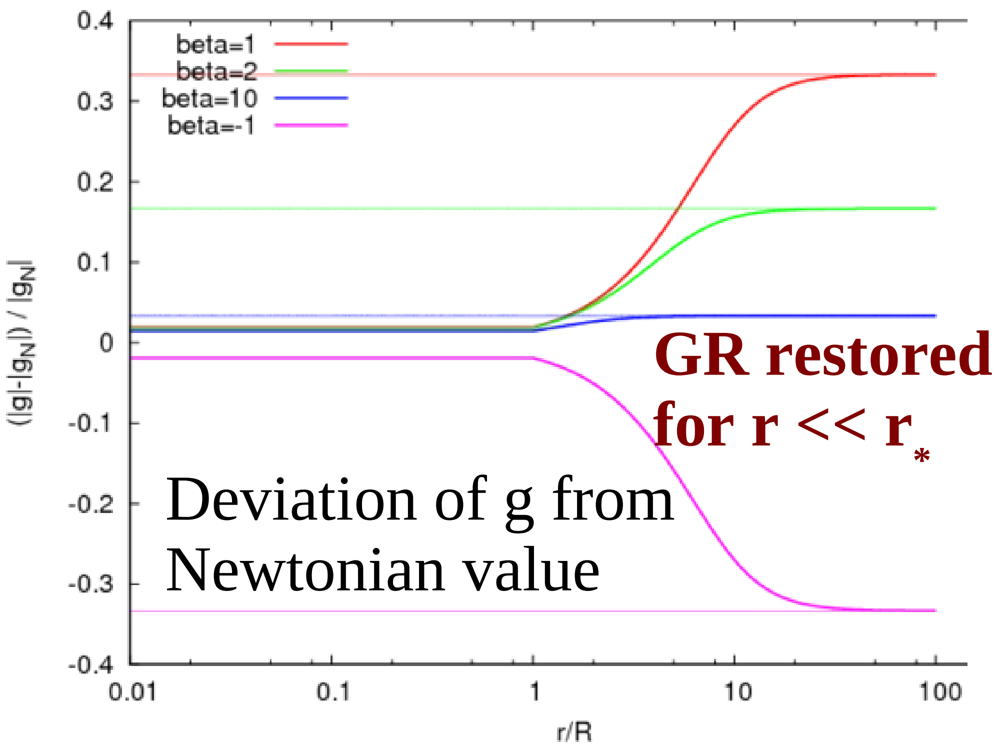
    Non-linearity cancels !

  - **2. Spherically symmetric mass**

Vainshtein mechanism

- **Spherical mass:**
  - Field suppressed within characteristic scale, *Vainshtein radius:* $r_* \propto (r_c^2\, r_s)^{1/3}$





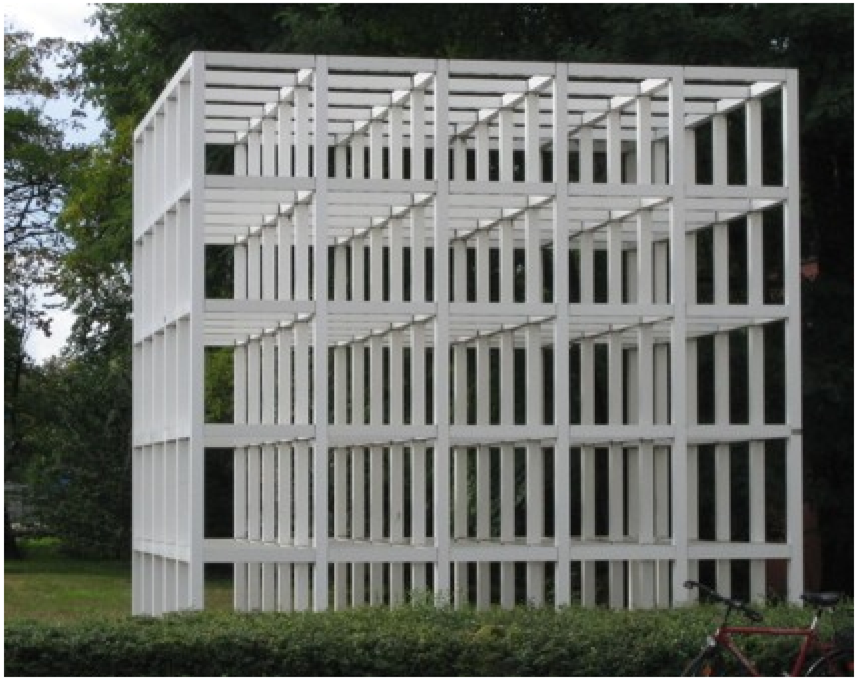
Simulating Modified Gravity

Self-consistent solution of field & particles

- ***Particle-mesh code:***
  - "particles" stand for chunks of dark matter (in phase space)
  - Density and potential are evaluated on cubic grid N_g^3
  - Typically,

$$N_p = (256 - 512)^3$$

$$N_g = 512$$



Main task: solve for potential

- **Newtonian potential Ψ_N:**
  - Obtained via Fourier transform of density
- **Brane-bending mode φ:**
  - Quasistatic approx.: no time derivatives
  - Non-linear relaxation scheme
    - Parallelized with multi-grid acceleration
- **Finally:** $\Psi = \Psi_N + \frac{1}{2}\varphi$
- **Currently no working AMR implementation**

Solving for brane-bending mode

- **Write φ equation as:** $L(\varphi) = f$
  - All quantities discretized on grid: $\varphi(x, y, z) \rightarrow \varphi_{i,j,k}$

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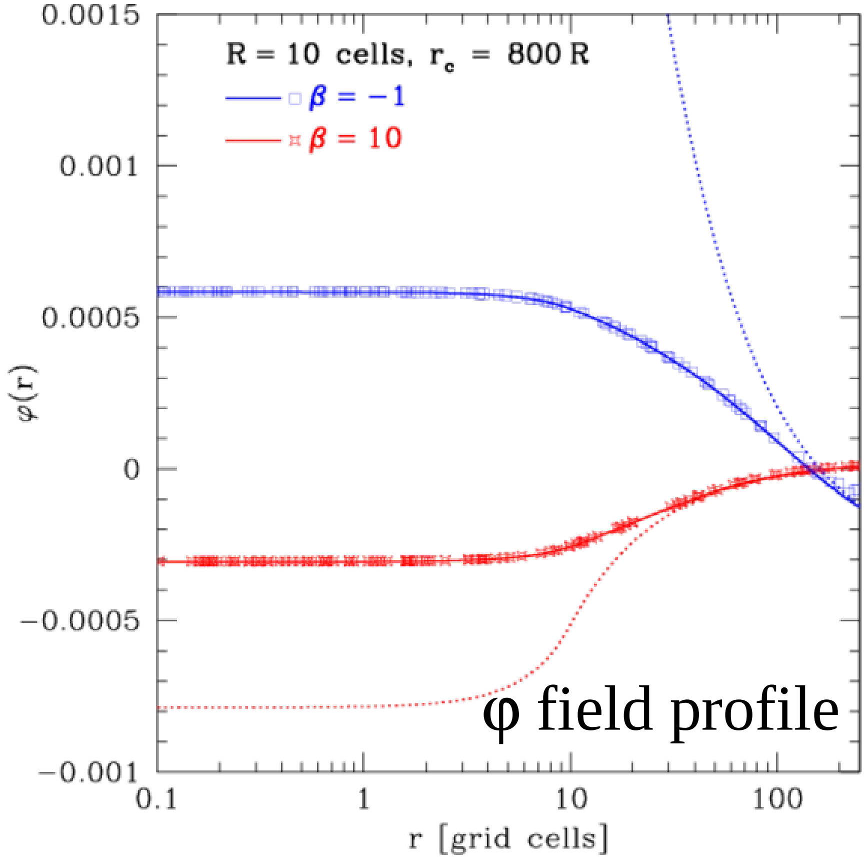
  - In our case, L is non-linear, hence use Newton's method to guess solution:

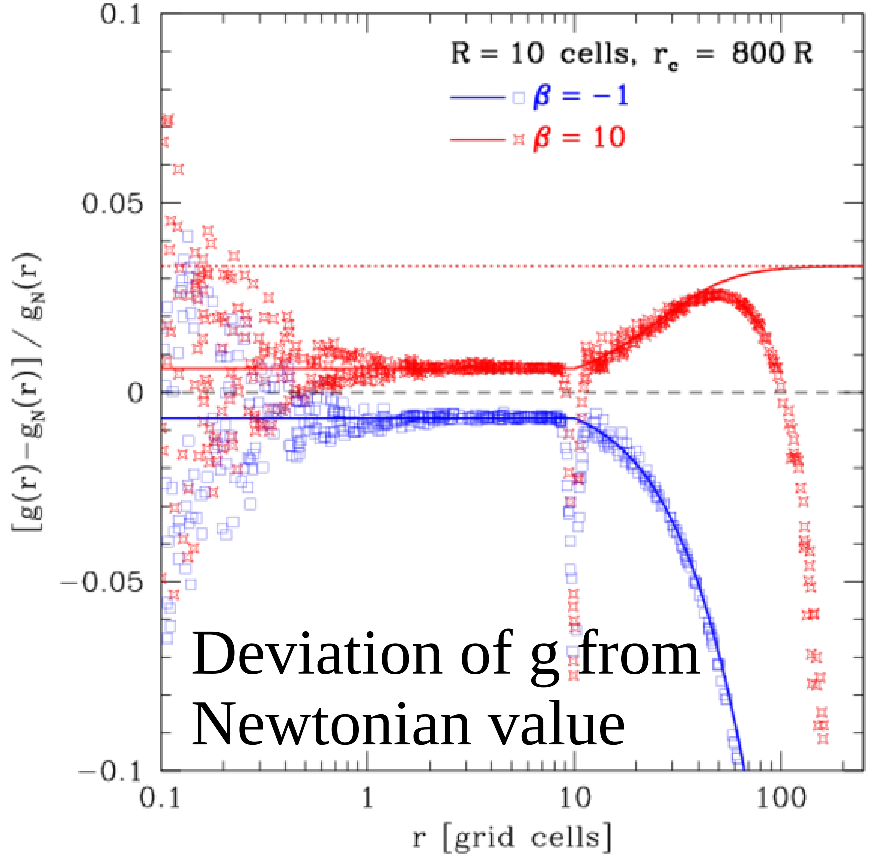
$$\varphi_{i,j,k} \leftarrow \frac{L(\ldots, \varphi_{i,j,k}, \ldots) - f_{i,j,k}}{\partial L / \partial \varphi_{i,j,k}}$$

Newton-Gauss-Seidel

Code Tests

- **Spherical mass (top-hat profile):**
  - Compare with analytical solution

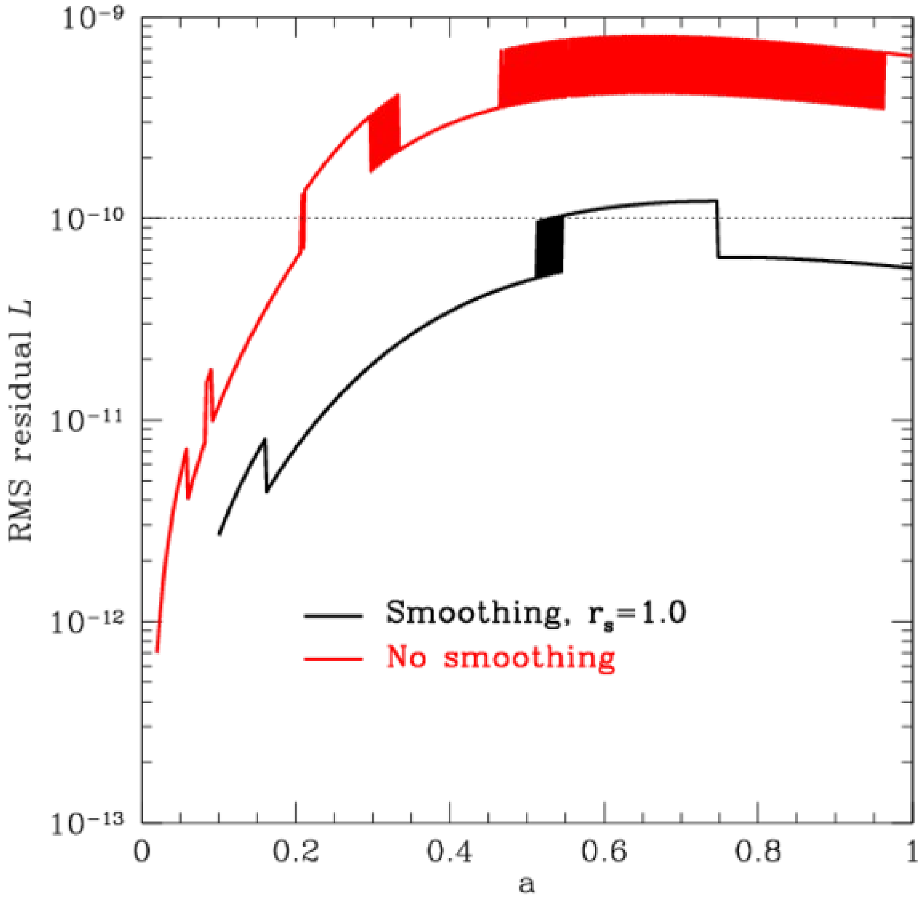




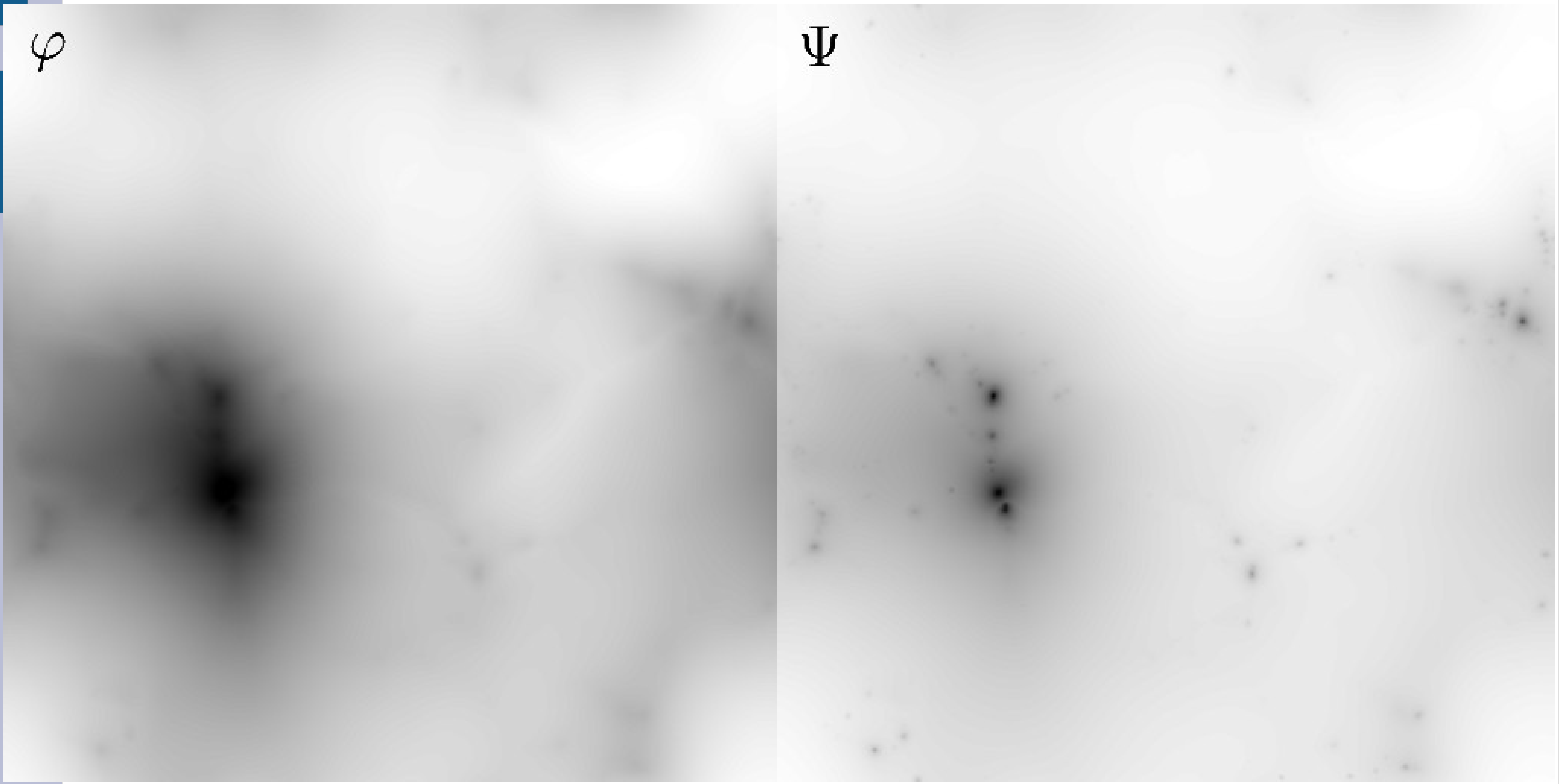
Convergence issues in cosmological simulations

- **Non-linearities + particle noise increase residuals**
  - r_* for particle ~ cell size
- **Two tricks:**
  - Increase number of particles
  - Smooth RHS of φ eqn

Gaussian filter radius 1 grid cell

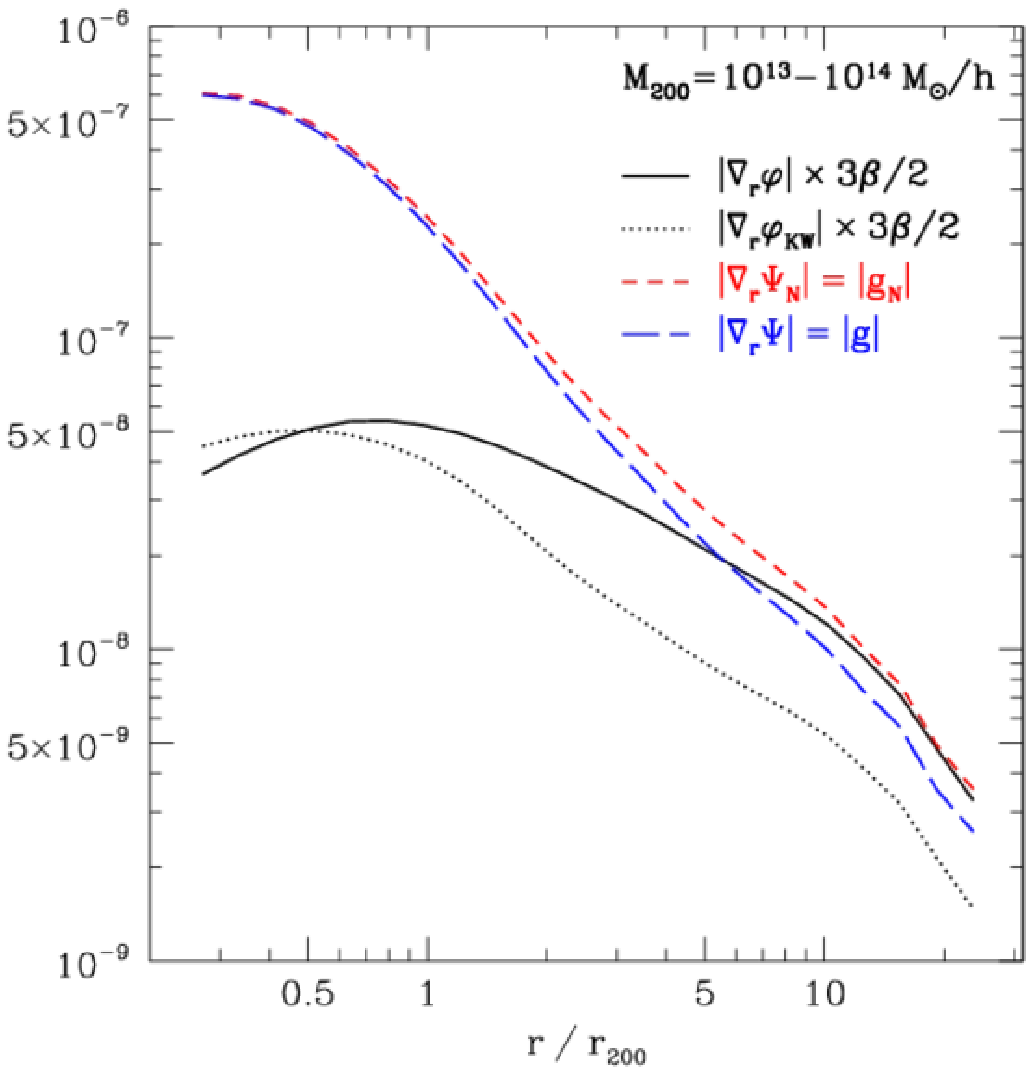


Vainshtein in action



Slices through cosmological simulation (64 Mpc/h, z=0)

Non-linear suppression of brane-bending mode



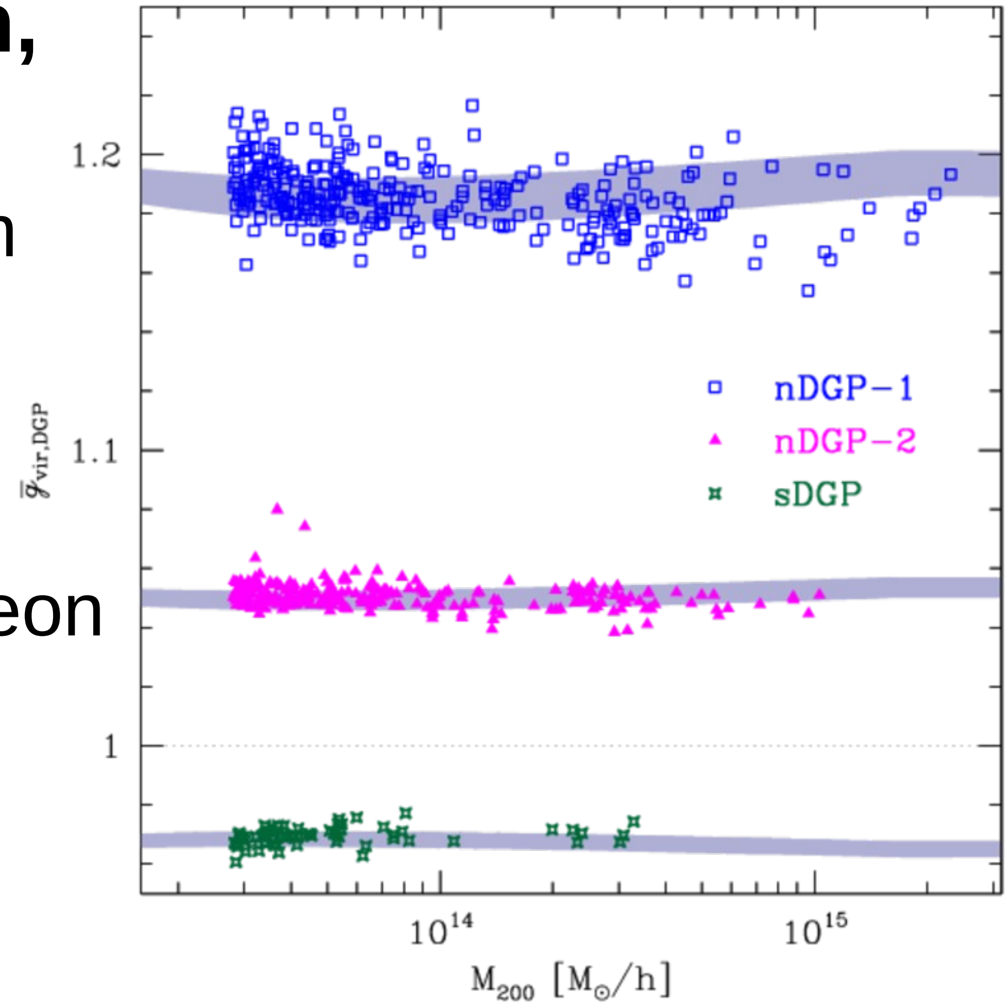
Average halo profiles:

- *brane-bending mode*
- *acceleration* in **DGP** and **GR**

GR is restored inside halos

Dynamical vs Lensing Mass

- **Mass-weighted average of force modification, vs halo mass**
  - Vainshtein mechanism *mass-independent*
  - Small effects due to profile evolution
  - Orthogonal to chameleon effect



Conclusions

- **Phasespace around massive halos:** a possible avenue to measuring velocities on intermediate scales (few – 30 Mpc) – complementary to RSD
- **Vainshtein mechanism:** a challenge to simulators...