Probing Gravity with Large-Scale Structure

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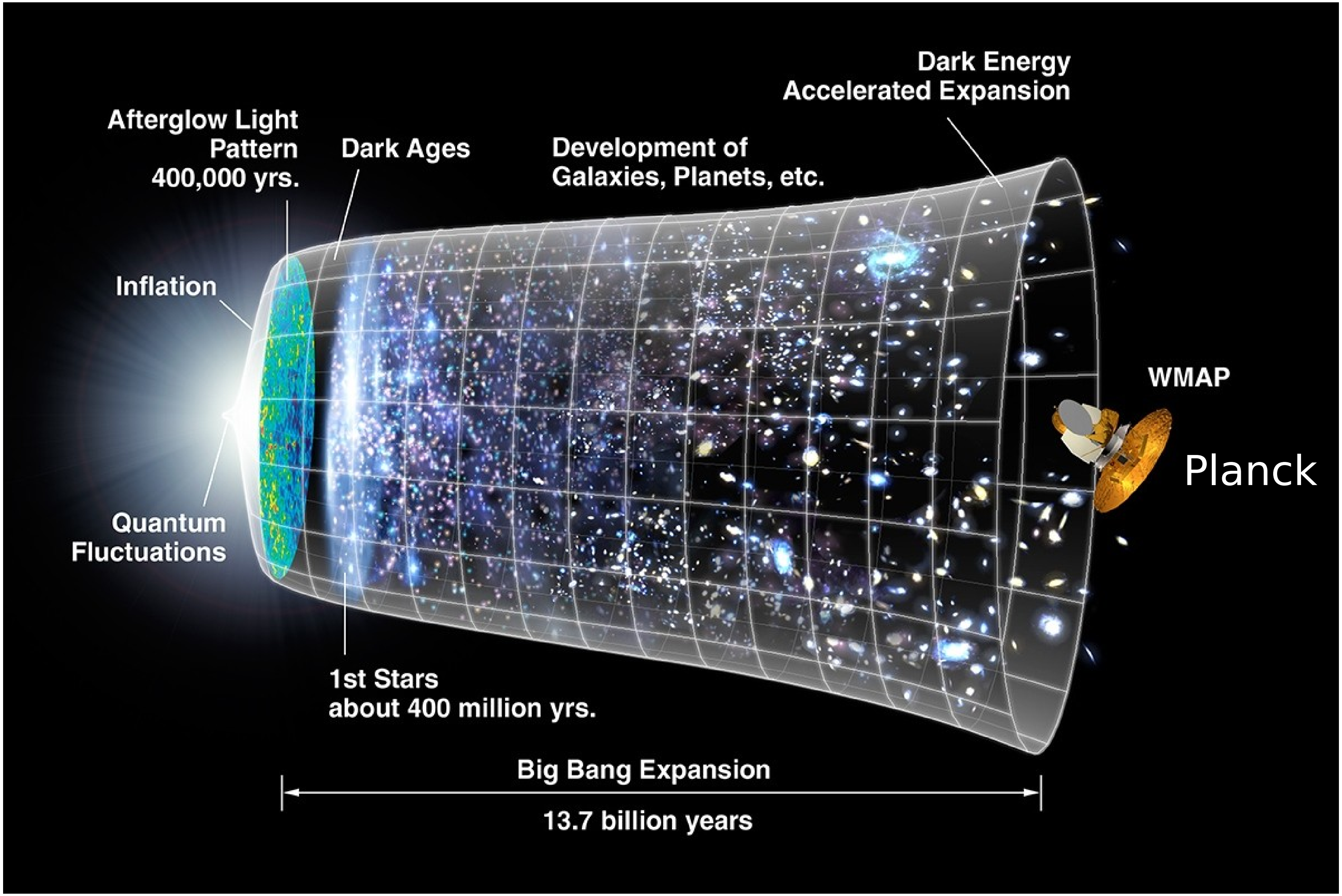
Caltech - TAPIR

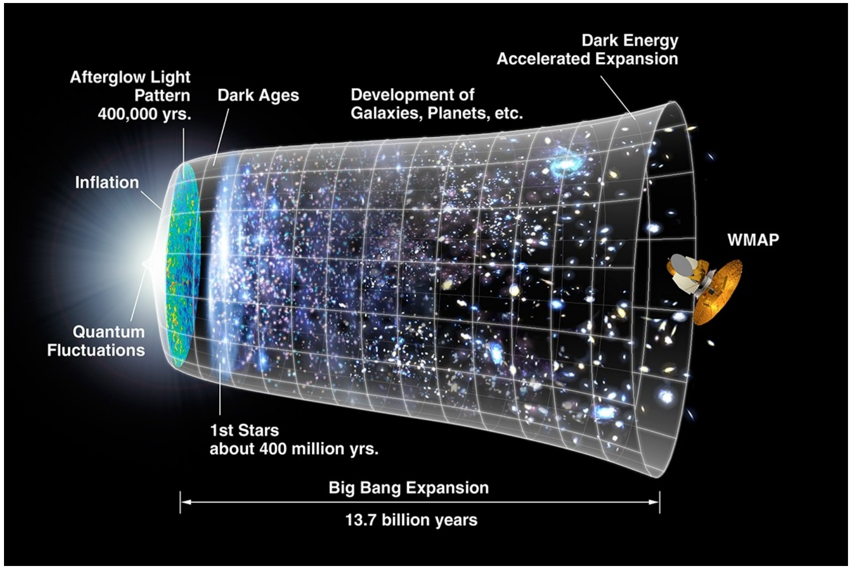
IPMU, 4/11/12

Pictorial History of the Universe



Motivation 1

- **Cosmology experiments are providing us with a wealth of information**
- **On scales > few Mpc, gravity is the only relevant force**
- **We *should* be using this information to test gravity...**



Motivation 2

- **The Universe is accelerating**
- **Physics behind acceleration is a big mystery**

Physics behind Acceleration

- **Modify any of the ingredients:**

Homogeneity & Isotropy
- FRW metric

General Relativity (GR)
- Friedmann Equation

Accelerating Universe

Stress-Energy Content
- Matter & Radiation

Physics behind Acceleration

- **Modify any of the ingredients:**

~~Homogeneity & Isotropy~~
~~- FRW metric~~

Violate Copernican principle

Accelerating Universe

General Relativity (GR)
- Friedmann Equation

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Physics behind Acceleration

- **Modify any of the ingredients:**

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Accelerating Universe

Stress-Energy Content
- Matter & Radiation

add
Dark Energy

Physics behind Acceleration

- **Modify any of the ingredients:**

Homogeneity & Isotropy
- FRW metric

~~General Relativity (GR)~~
~~- Friedmann Equation~~

Modified Gravity ?

Accelerating Universe

(focus of this talk)

Stress-Energy Content
- Matter & Radiation

Physics behind Acceleration

- **Minimal solution: cosmological constant Λ**

Homogeneity & Isotropy
- FRW metric

General Relativity (GR)
- Friedmann Equation

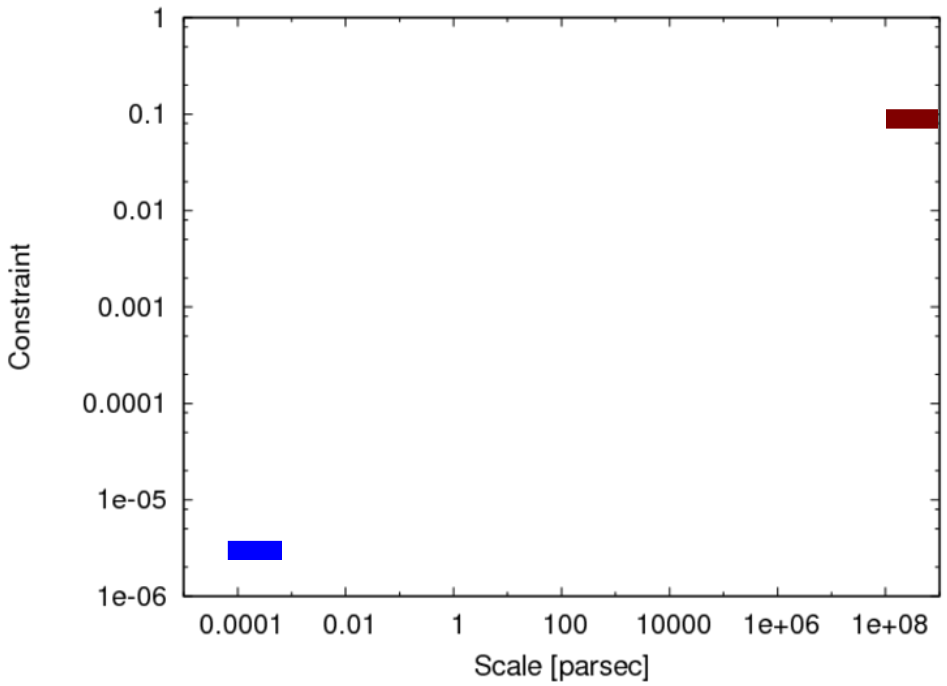
Accelerating Universe

Λ

Stress-Energy Content
- Matter & Radiation

Tests of Gravity: 6 years ago

- **Solar System**
  - Precision constraints from time delay
- **CMB (+SN, BAO)**
  - Model-dependent constraints (geometry, ISW)
  - Important for developing viable modified gravity models



Modified Gravity: Challenges

Theoretical Challenge:

- **How to evade Solar System (and CMB) constraints**

- **Idea: reduce to GR in high-curvature regime**
  - Applies to Early Universe as well as high-density regions today

Modified Gravity: Challenges

Observational Challenge:

- **How can we distinguish Modified Gravity from GR + Dark Energy ?**
  - (Almost) any expansion possible with Dark Energy

- **Beyond background: growth of structure**
  - Predictions straightforward in *linear regime*
  - *Non-linear regime* less so...
  - Will always compare modified gravity with Dark Energy model with *identical expansion history*

Probing gravity: linear vs nonlinear regime

Linear regime: ***CMB, Supernovae, BAO***

- Parametrizing gravity possible --> model-independent constraints
- Limited statistical/constraining power

Non-linear regime: ***weak lensing, cluster abundance,...***

- No general parametrization: specific *non-linearities of modified gravity* model important
- Wealth of observables, plenty of S/N

f(R) Gravity

- **Simplest workable modified gravity model**
- **Generalize Lagrangian of General Relativity:**

$$\mathcal{L}_g = \frac{1}{16\pi G}(R - 2\Lambda) \longrightarrow \frac{1}{16\pi G}(R + f(R))$$

- **Choose function with ΛCDM limit:**

$$f(R) = -2\Lambda \frac{R/R_c}{R/R_c + 1} \approx -2\Lambda - f_{R0}\frac{R_0^2}{R},$$

Hu & Sawicki, PRD 07

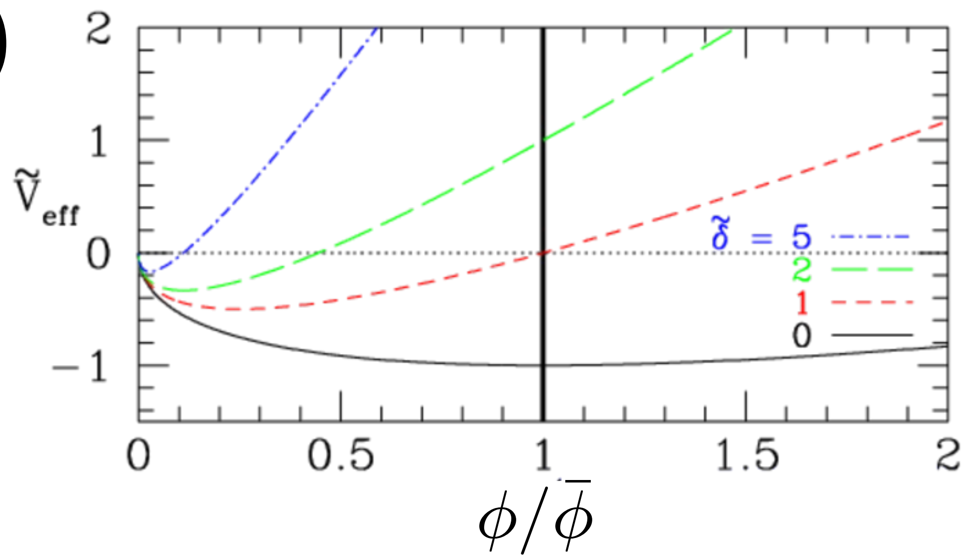
f(R) Gravity

- **f(R) model produces ΛCDM expansion history without true Λ**
  - Difference in H(z) of order $f_{R0} \ll 1$ (background field value today)
- **Equivalent to scalar-tensor theory**
  - Scalar field $f_R \equiv \frac{df}{dR}$ with universal coupling
  - Grav. force enhanced by 4/3 within $\lambda_C = \sqrt{3 f_{RR}}$
- ***Chameleon effect:* recover GR locally**
  - Scalar field decouples in high-density regions

Chameleon Mechanism

- **Consider scalar ϕ with equation of motion (static regime)**

$$\nabla^2\phi = \frac{\partial V(\phi)}{\partial\phi} + 8\pi G\rho$$
$$\equiv \frac{\partial V_{\rm eff}(\phi)}{\partial\phi}$$



  - GR restored in *sufficiently deep* potential wells:

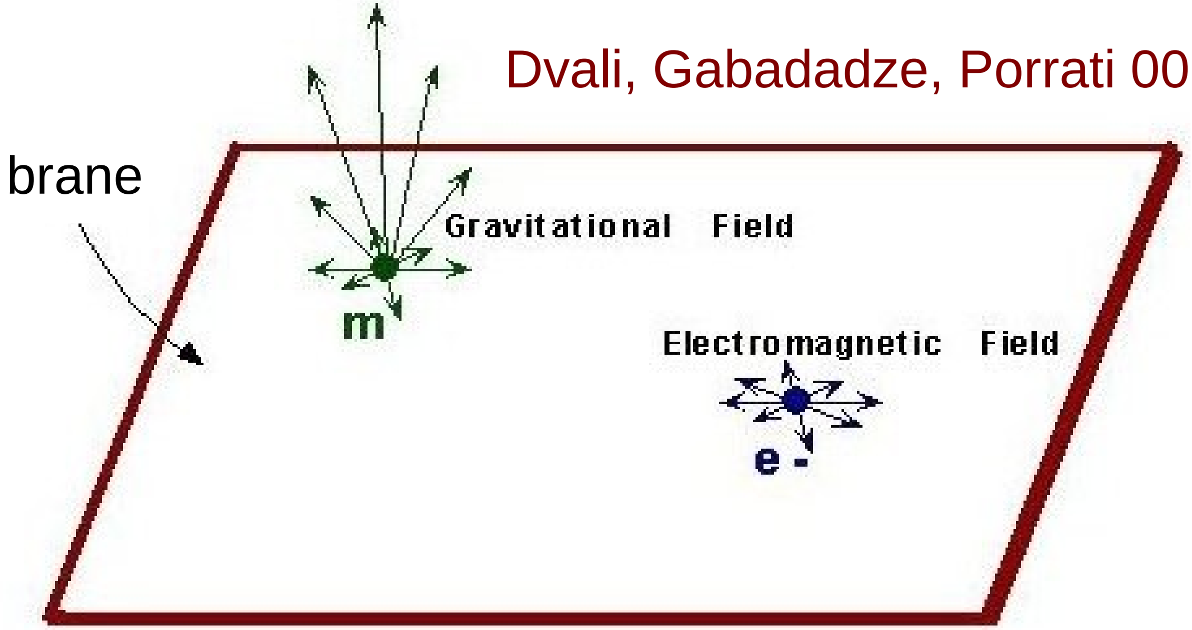
$$\Psi \gtrsim \frac{3}{2}\overline{\phi} = \frac{3}{2}\overline{f_R}$$ average (background) field

  - Must hold in Solar System

Working Example II: DGP

- **Dvali-Gabadadze-Porrati model:**
  - Matter / radiation confined to 4D brane in 5D Minkowski space
  - Action constructed to reduce to GR on small scales

Dvali, Gabadadze, Porrati 00



Working example II: DGP

- **Sub-horizon scales** $(\lesssim r_c,\, H^{-1})$**: effective scalar-tensor theory**
  - Massless field φ - *brane-bending mode*
  - $\varphi(\vec{x},t)$ quantifies displacement of brane in extra dimension

Brane-bending mode

- **Linearized solution:** $\varphi = \frac{2}{3\beta}\Psi_N, \quad \beta(a) \propto H\, r_c$
  - i.e. time-dependent G (grav. constant)

- **When $\delta\rho/\bar{\rho} \gtrsim 1$, non-linear interactions of φ important:**

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

- **Leads to screening of field at high densities: *Vainshtein mechanism***

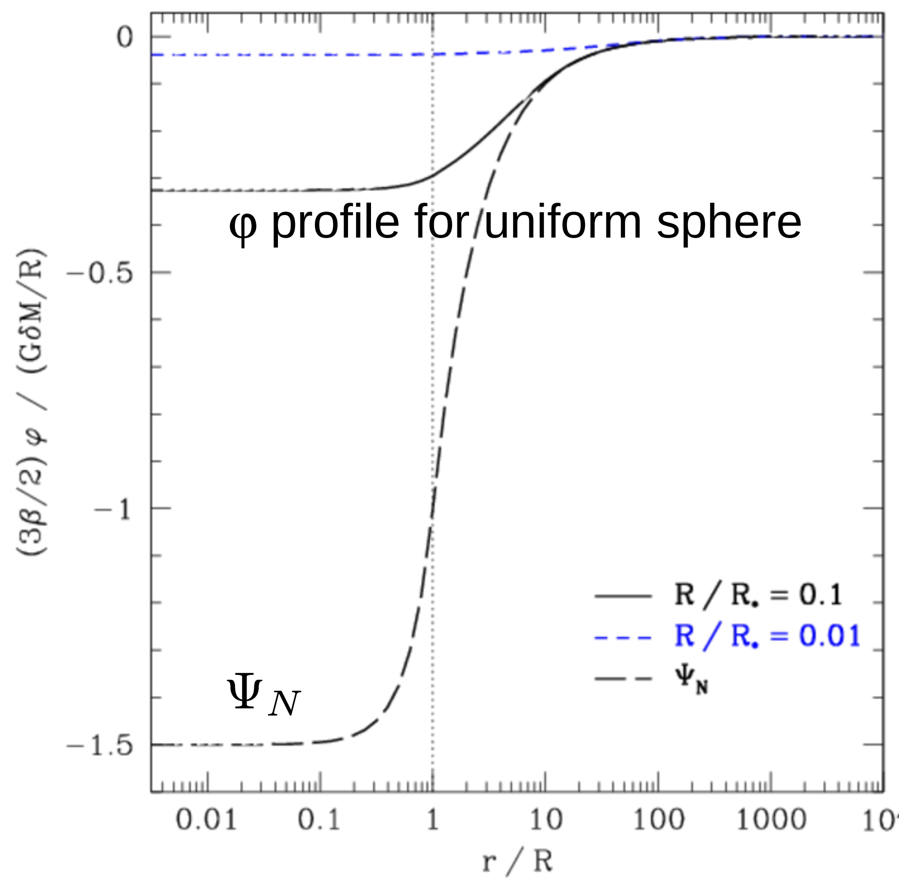
Vainshtein mechanism

- **For spherically symmetric object, φ is screened within**

$$r_*(r) = \left(\frac{16\,G\,M(<r)r_c^2}{9\beta^2}\right)^{1/3}$$

Vainshtein radius

  - Vainshtein mechanism operates at fixed *enclosed density*



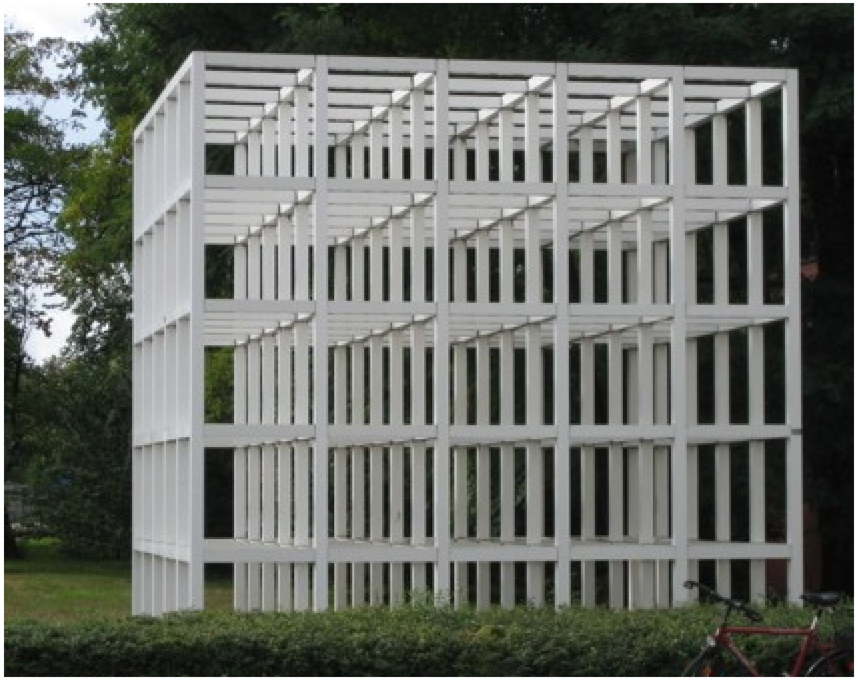
From Theory to Data

- **In order to confront these models with observations, need *accurate predictions***
  - Standard tool for virtually any large-scale structure measurement: *N-body simulations*
  - However: *Chameleon, Vainshtein* mechanisms generally active when $\delta\rho/\bar{\rho} \gtrsim 1$
- **Require self-consistent N-body simulations to predict observables on non-linear scales**
  - Signatures of screening mechanisms interesting to look for in their own right

Simulating Modified Gravity

- **Need self-consistent solution of nonlinear scalar field and dark matter**

- ***Particle-mesh code:***
  - Density and potential are evaluated on cubic grid
  - Given modified potential, propagation of particles unchanged

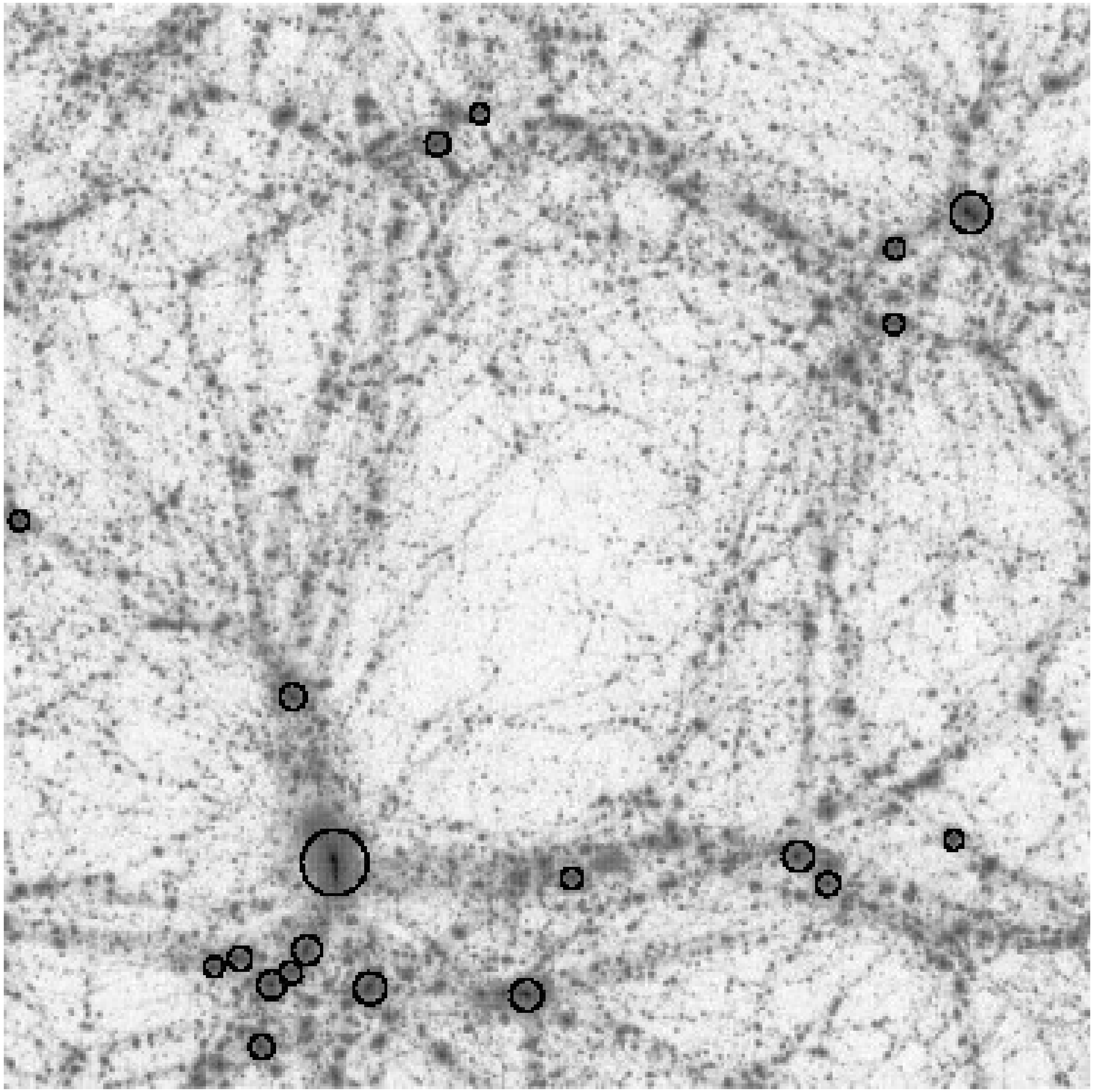


Main task: solve for potential

Oyaizu 08, FS 09a
Li, Zhao, Koyama 10

- **Newtonian potential Ψ_N:**
  - Obtained via Fourier transform of density
- **Scalar field φ:**
  - Non-linear relaxation scheme (Newton-Raphson)
    - Parallelized with multi-grid acceleration
- **Finally:** $\Psi = \Psi_N + \frac{1}{2}\varphi$
- **Non-linear relaxation *time-consuming:***
  - CPU time ~20x that of ordinary GR simulations

Results: Structure Formation

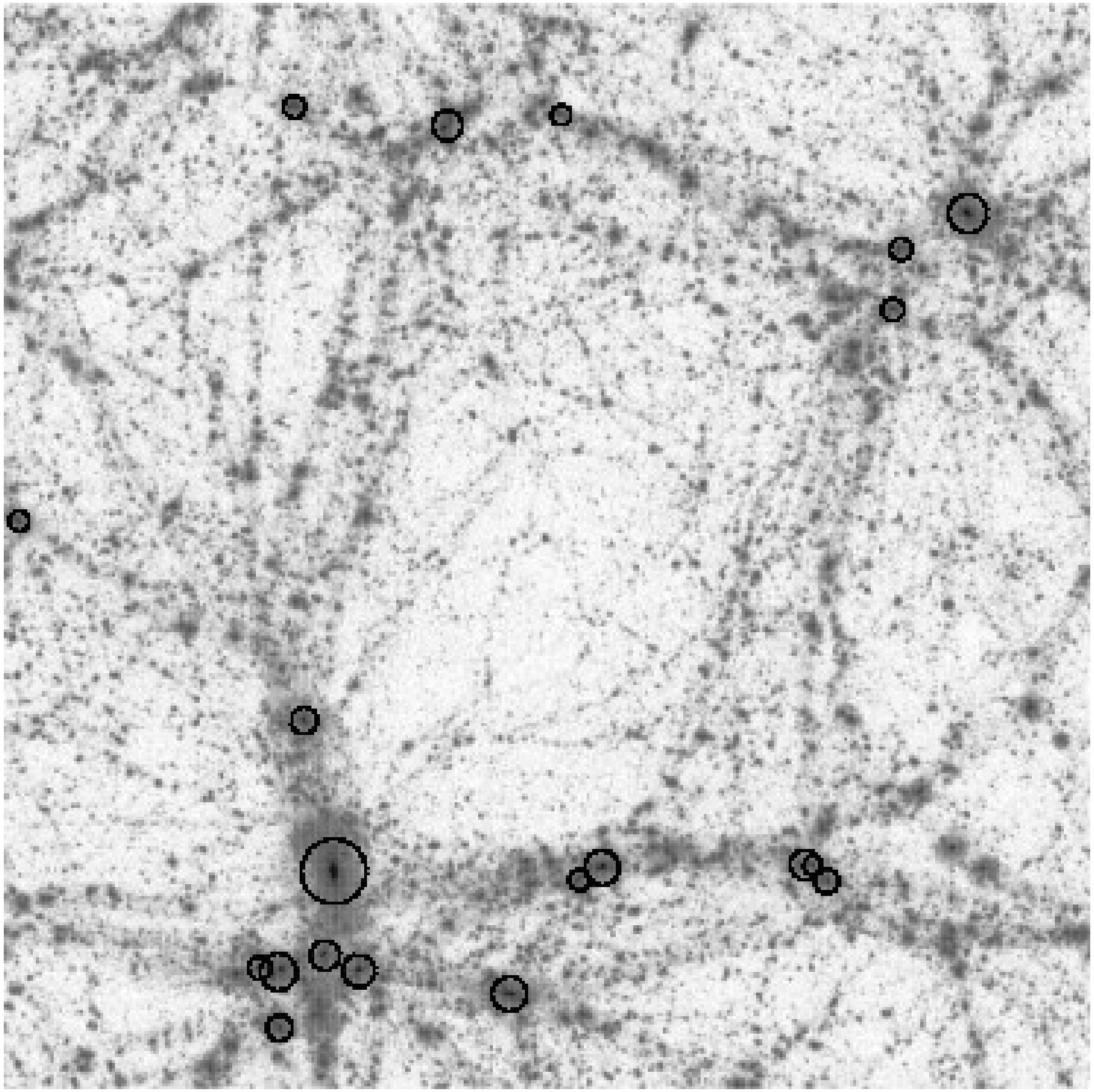


Slice through simulation at z=0, size: 64 Mpc/h

GR – ΛCDM

Circles: 20 most massive halos

Results: Structure Formation

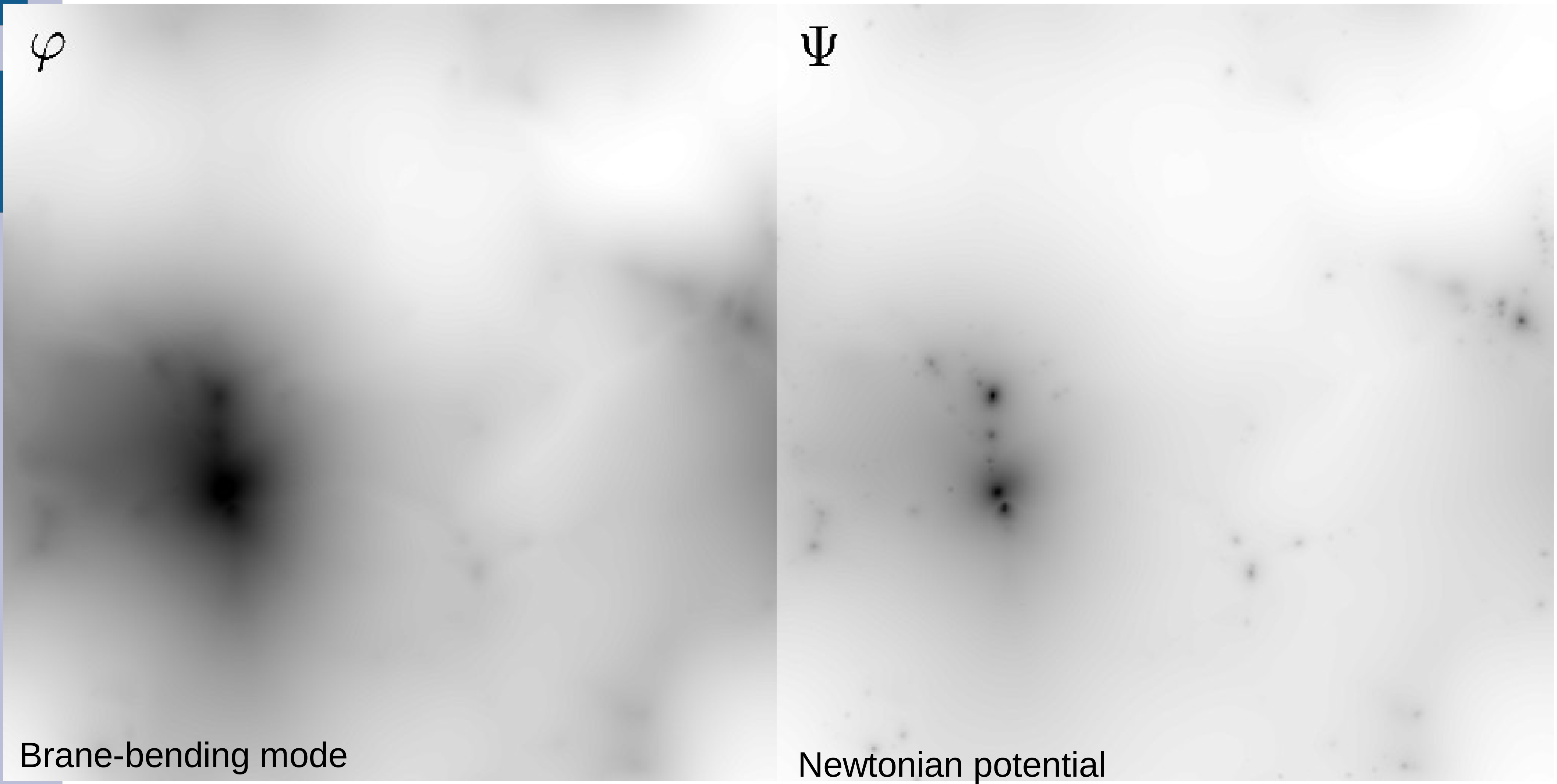


Slice through simulation at z=0, size: 64 Mpc/h

f(R) with $f_{R0} = 10^{-4}$

Circles: 20 most massive halos

Vainshtein in Action...



DGP simulation, 64 Mpc/h box, z=0

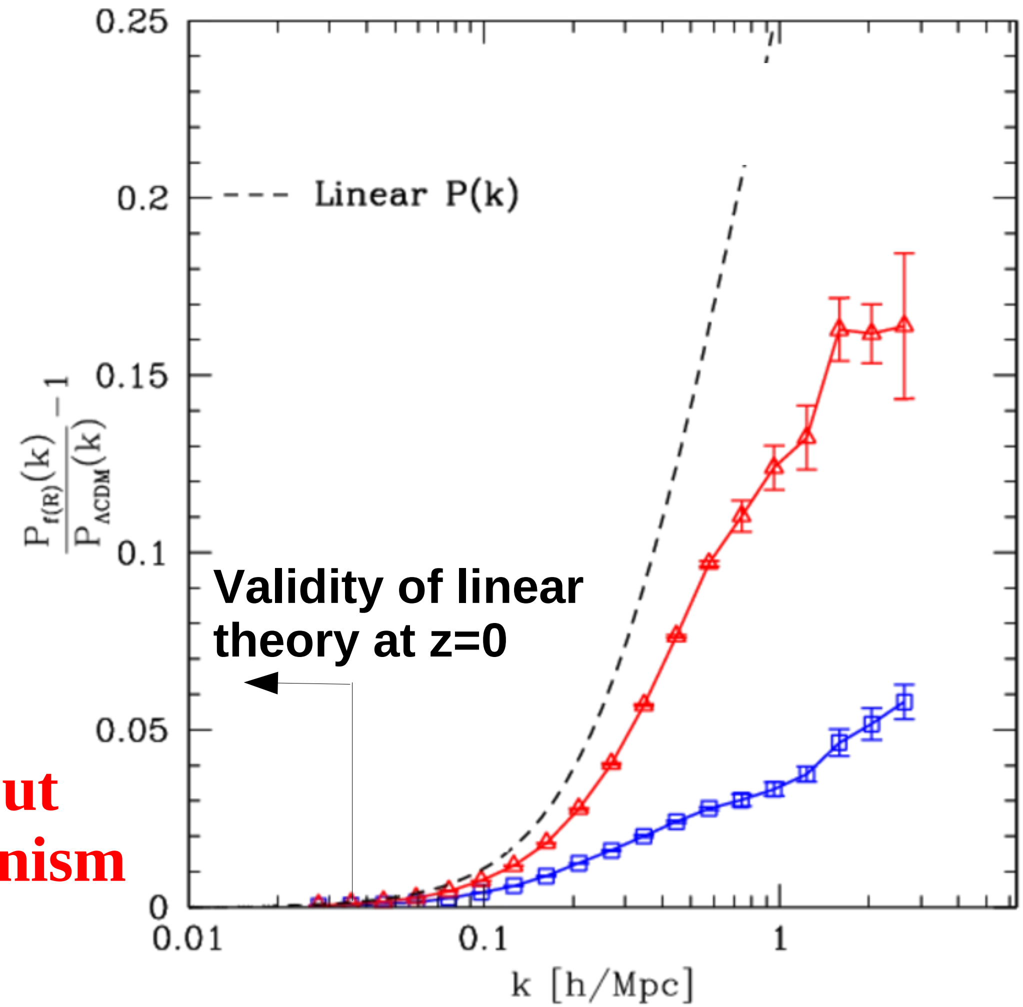
Linear vs Non-linear Scales...

– Relative deviation of matter power spectrum from ΛCDM

f(R)

$$|f_{R0}| = 10^{-6}$$

$$\lambda_C \approx 30\ Mpc$$



Full simulations

Simulations without chameleon mechanism

Linear vs Non-linear Scales...

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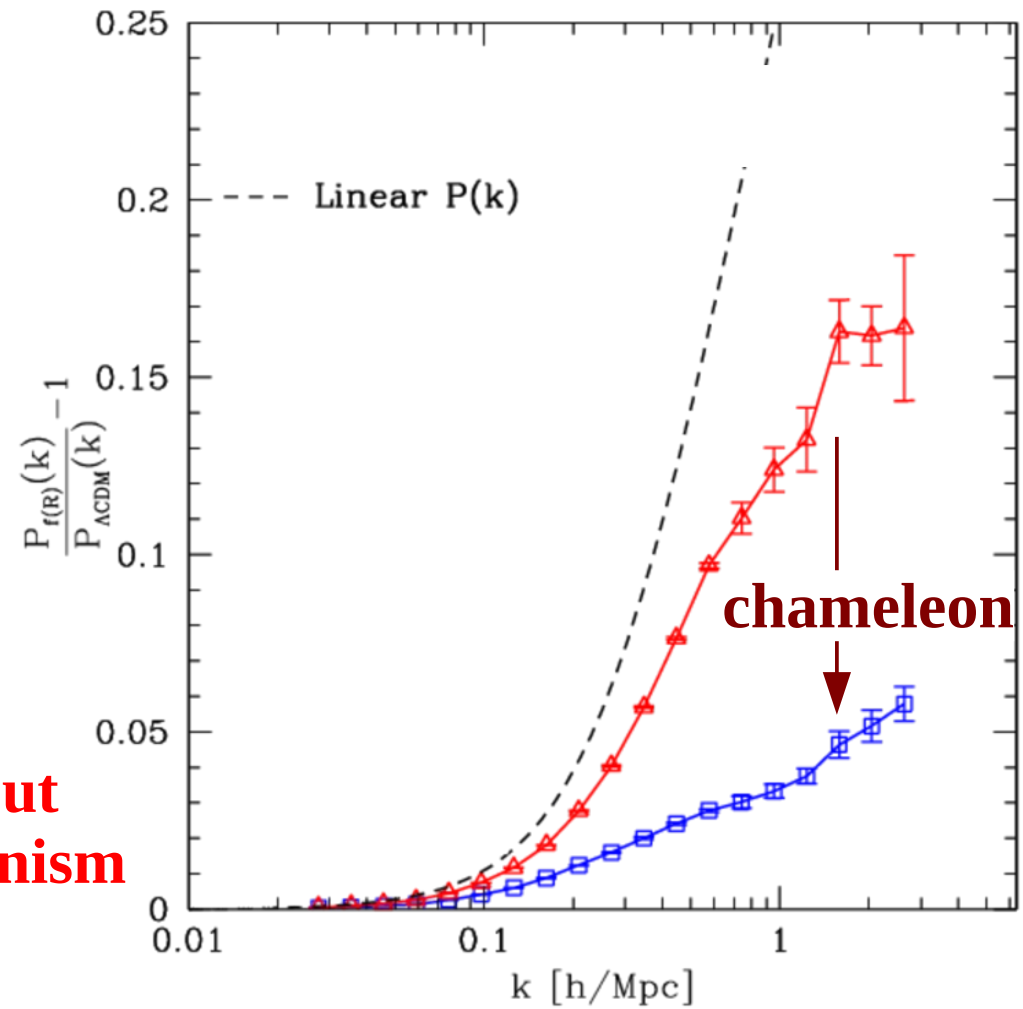
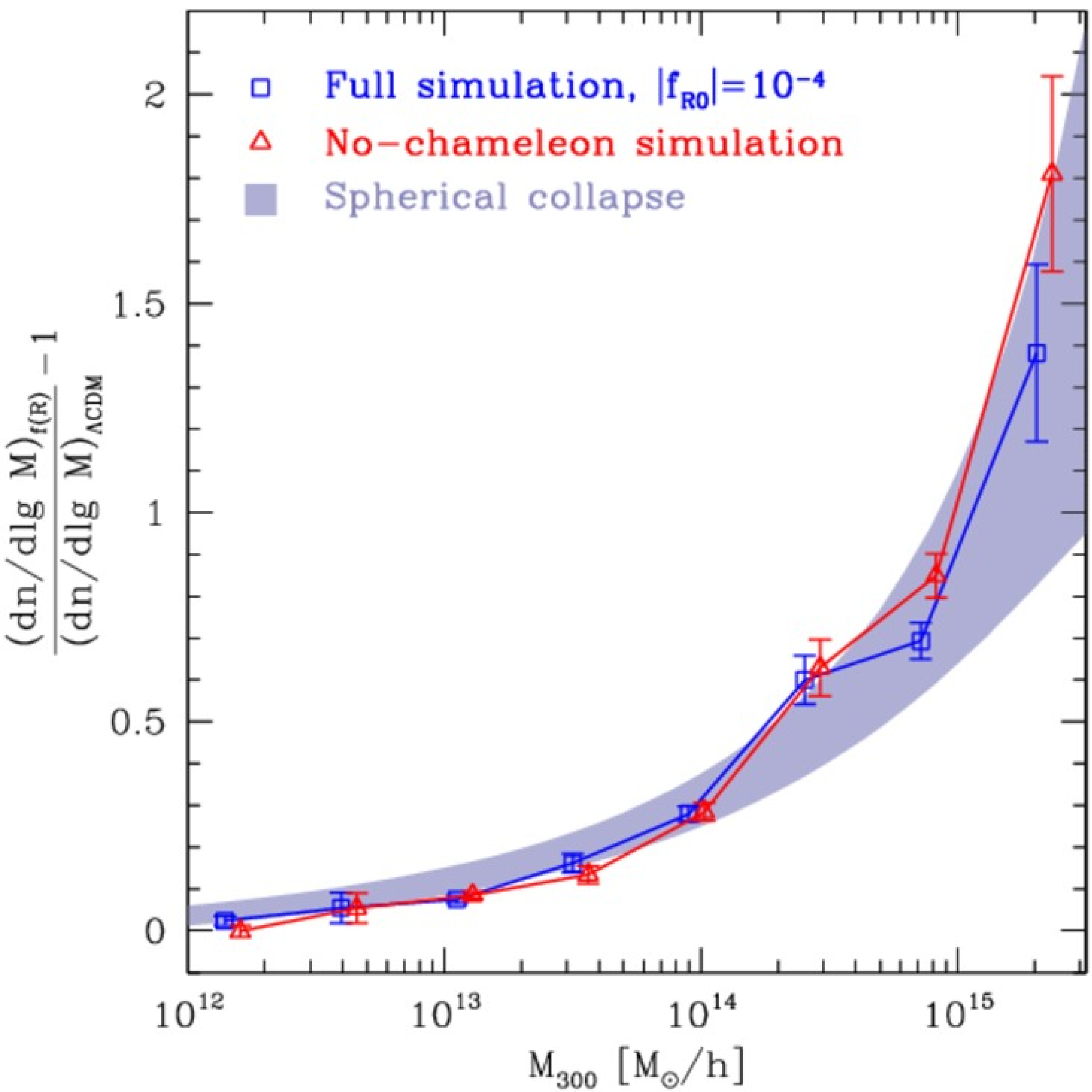


Abundance of Dark Matter Halos

- **Massive DM halos** $(M \gtrsim 10^{14}\, M_\odot)$ **observable as galaxy clusters**

- **Abundance "exponentially sensitive" to P(k) normalization**
  - Excellent probe of growth of structure (once observable – halo mass relation is known)

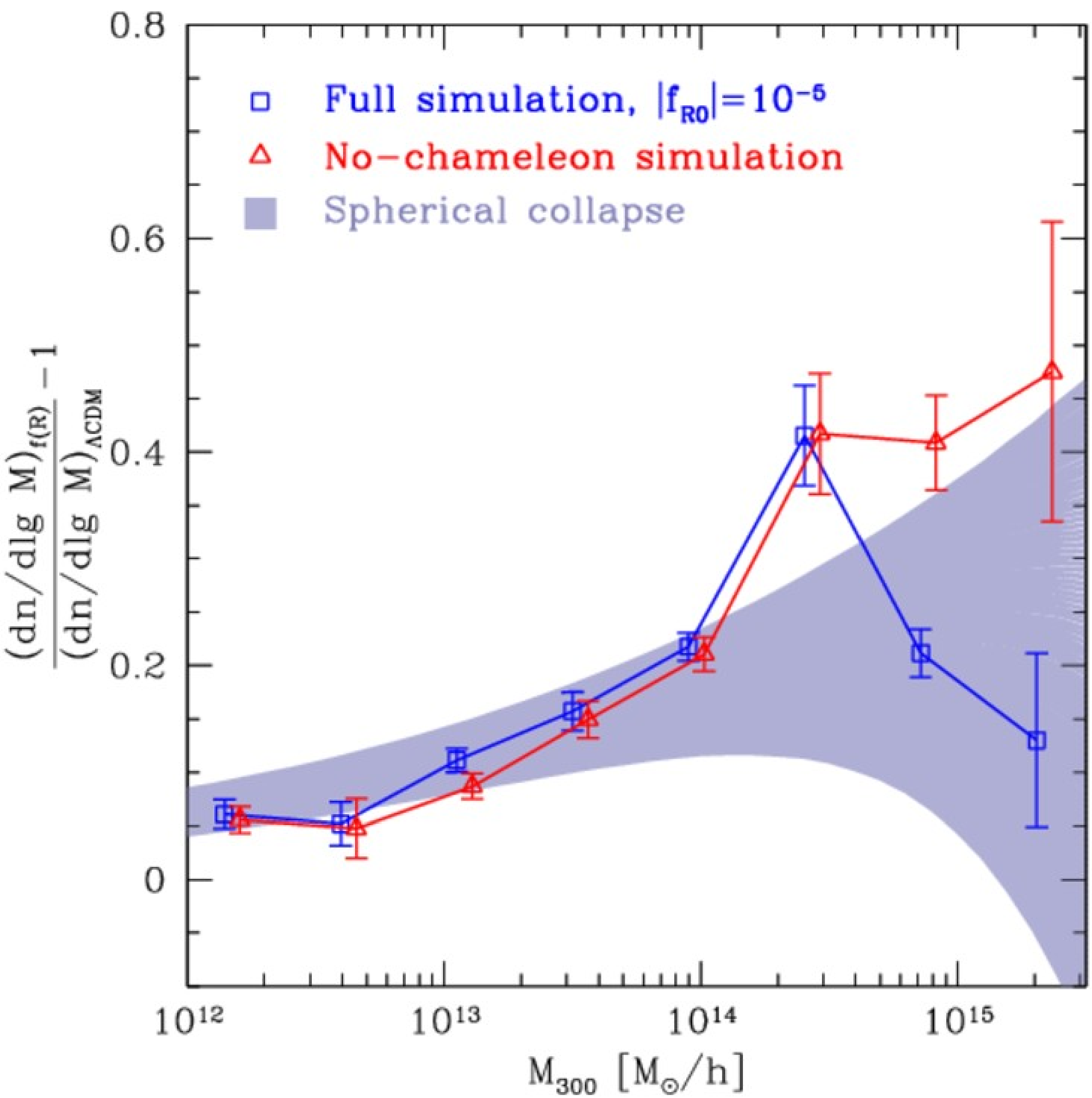
Halo Abundance in f(R)



- **Strong field (10^{-4}):**
  - Large enhancement at high masses (as expected)
  - Semi-analytical model works reasonably well
- **DGP qualitatively similar**

FS, Lima, Oyaizu, Hu, 2009

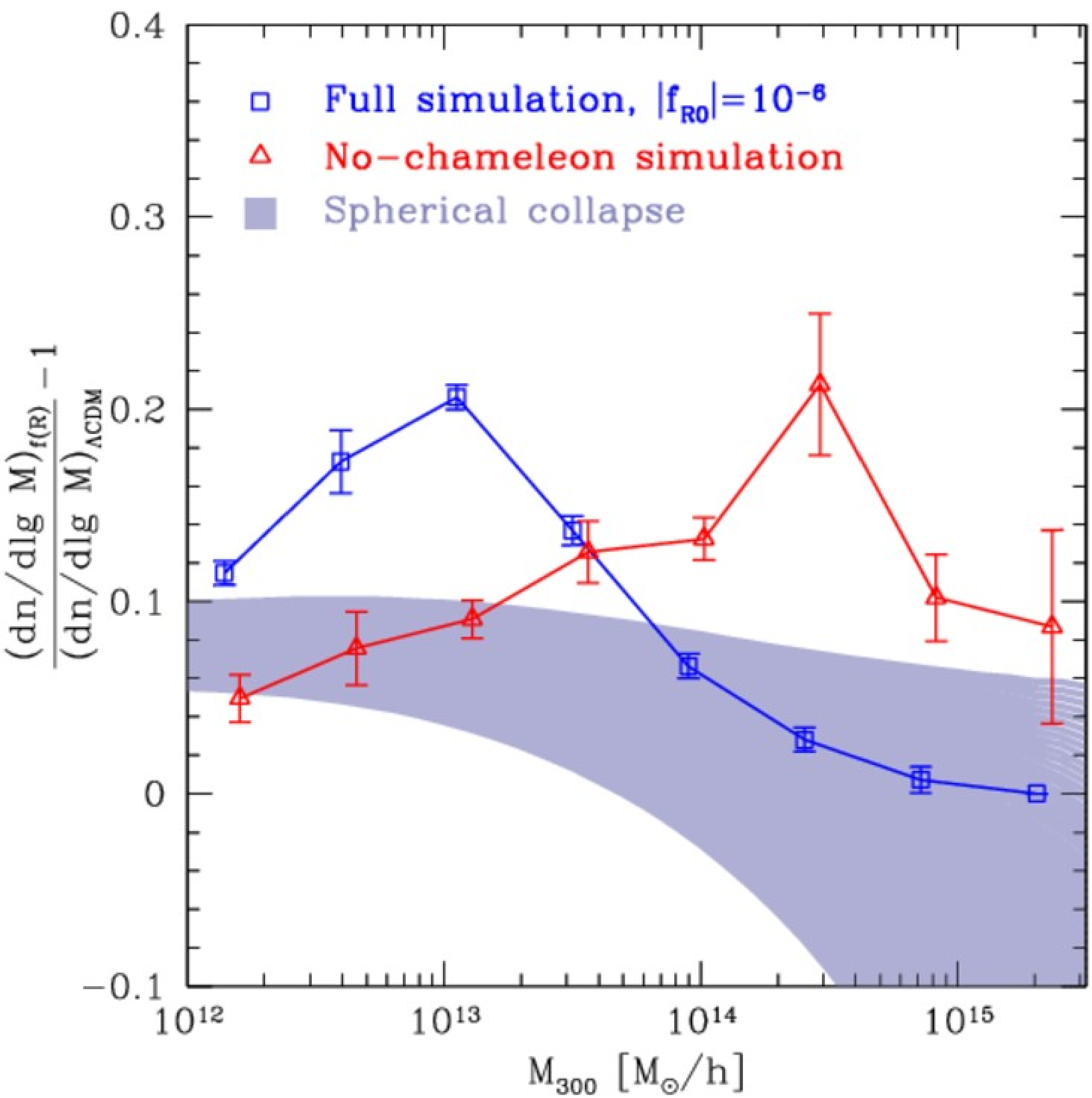
Halo Abundance in f(R)



- **Smaller field (10^{-5}):**
  - Background field comparable to typical potentials
  - Chameleon begins to act at highest masses

FS, Lima, Oyaizu, Hu, 2009

Halo Abundance in f(R)



- **Weak field (10^{-6}):**
  - Chameleon effect active at large masses
  - Abundance of clusters not a good probe anymore

FS, Lima, Oyaizu, Hu, 2009

Application: constraining f(R) with Cluster Abundance

- **X-ray clusters from ROSAT survey**
  - Observable: N(>M_0); ~35 clusters at z < 0.15
  - Mass-observable scatter probably smallest in X-rays
- **Treat f(R) effect as effective *σ_8 enhancement***
  - Spherical collapse model to predict scaling of f(R) effect with parameters
  - CMB constrains primordial normalization
  - SN, H_0, BAO break parameter degeneracies

FS, Vikhlinin, Hu 09

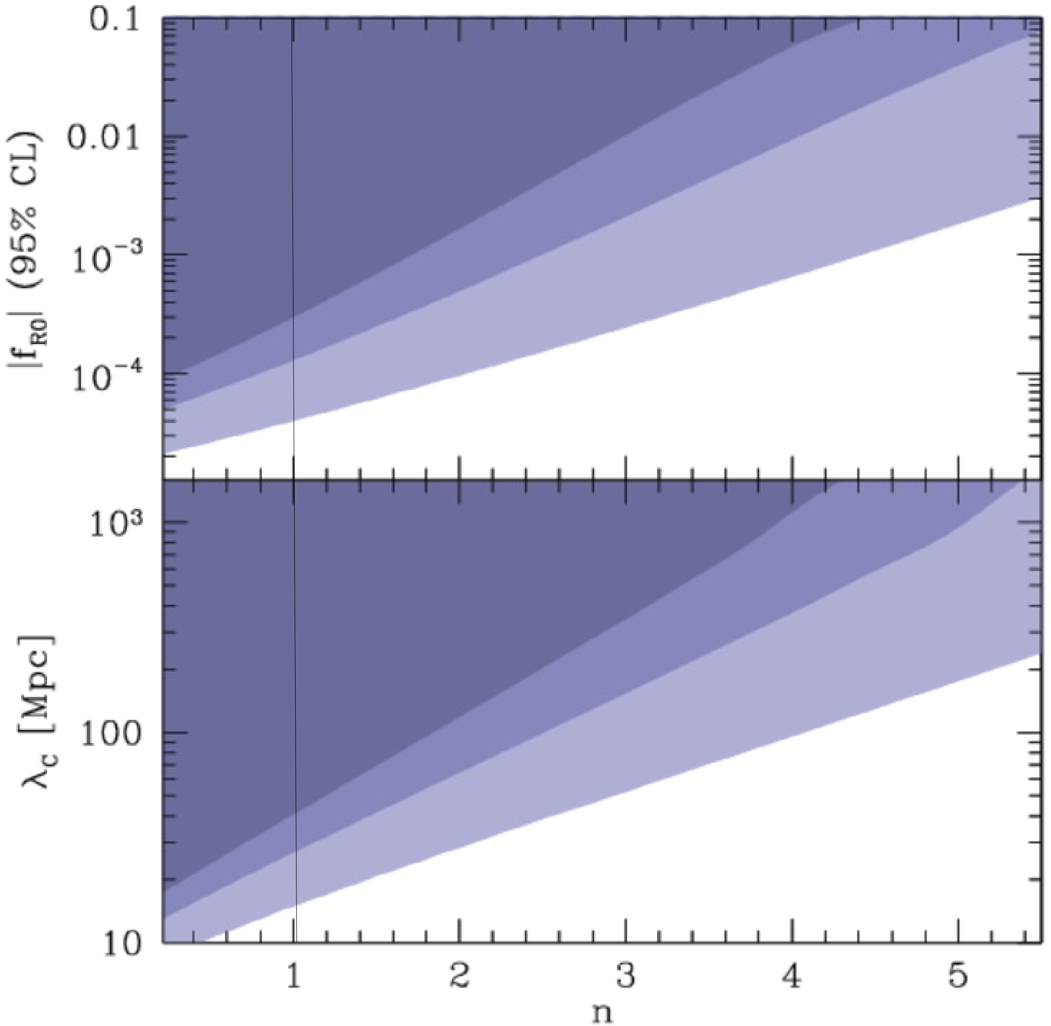
Application: constraining f(R) with Cluster Abundance

95% CL upper limit:

$$|f_{R0}| < 1.3 \times 10^{-4}$$

cf. constraints from linear regime: $|f_{R0}| \lesssim 0.1$

$$\lambda_C \lesssim 2000\mathrm{Mpc}$$



f(R) functional shape

FS, Vikhlinin, Hu 09
Ferraro, FS, Hu 10;
see also Lombriser et al, 10

Forecast for SZ cluster samples

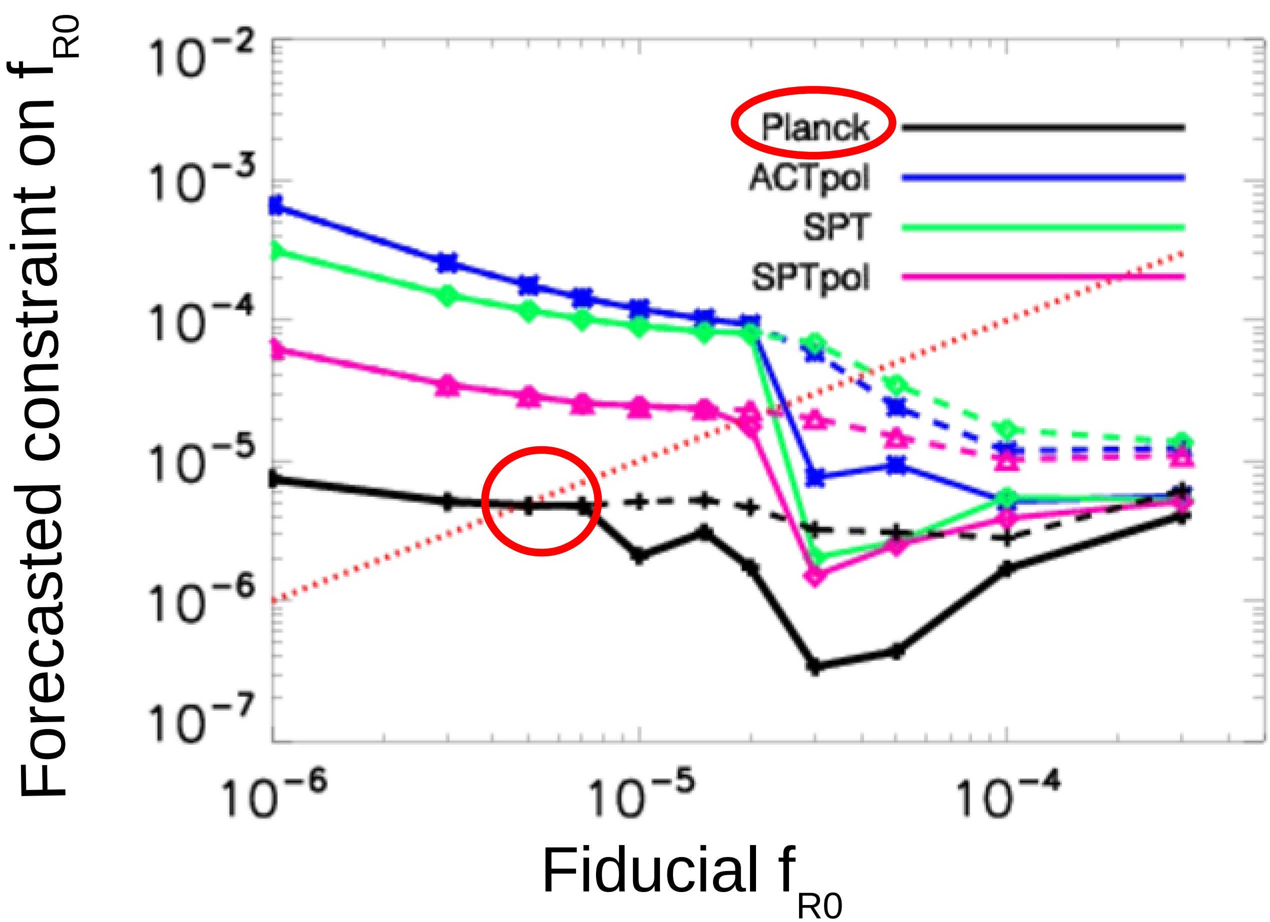
- **Significantly larger next generation cluster samples (> 1000)**
  - Number counts (dN/dz) and clustering (P(k)) of clusters
  - Self-calibration of bias & scatter in mass-observable relation
- **f(R) effects enter through**
  - Mass function
  - Halo bias & matter P(k)
  - Effect on dynamical mass (-> later)

Sph. Collapse + halo model

Mak, Pierpaoli, FS, Macellari

Planck SZ cluster constraints

- **Fischer-forecast as function of fiducial f_{R0}**

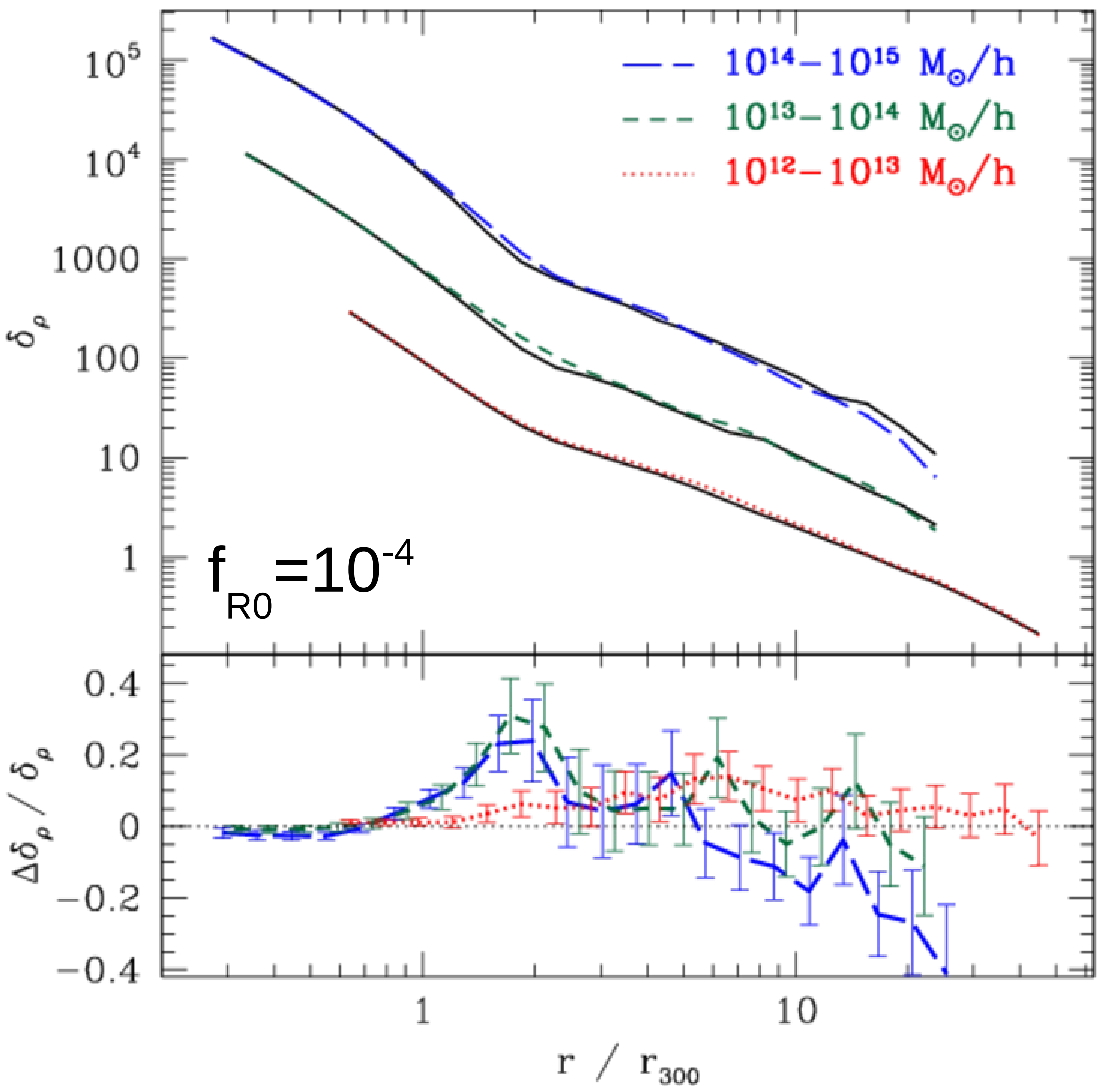


Fully marginalized, assuming flat ΛCDM background

Combination dN/dz+P(k) breaks degeneracies w/ nuisance parameters

Mak, Pierpaoli, FS, Macellari

Halo Density Profiles



- **Stacked halo profiles for ΛCDM and f(R)**
  - Inner halo profiles unchanged
  - Some effects in *infall* region
- **Observable through weak lensing**

FS et al., 09
Li et al., 10

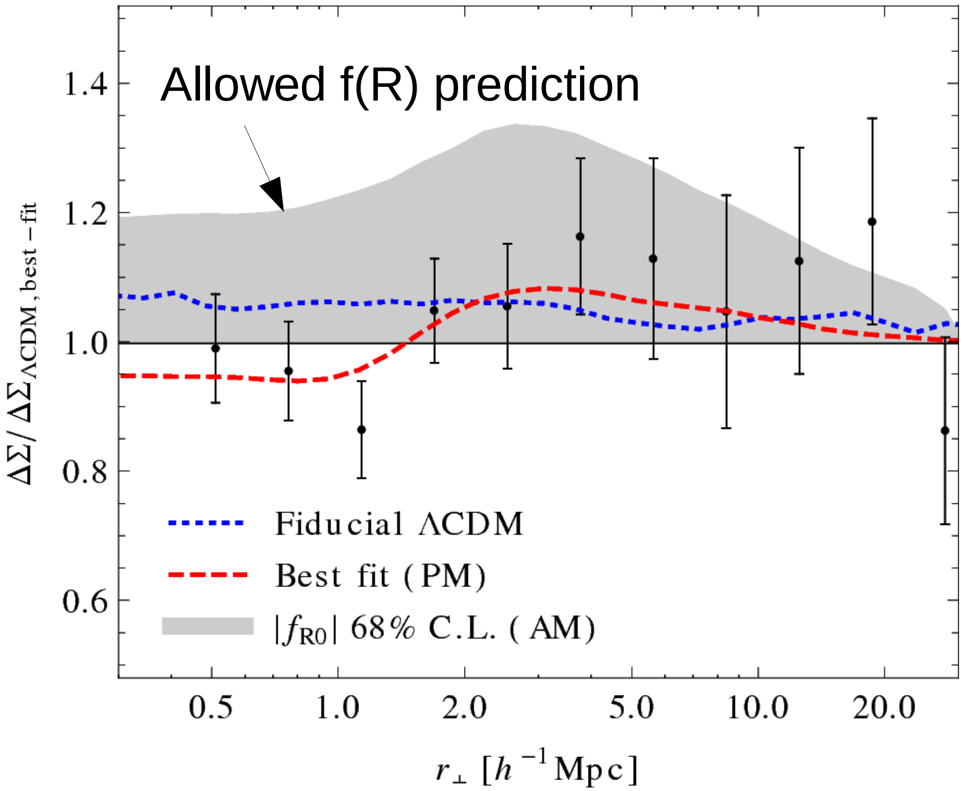
Halo Profiles through Weak Lensing Shear

- ***Measurement*** **of stacked halo density profiles**
  - From Sloan cluster (maxBCG) lensing Mandelbaum et al.
  - f(R) predictions through abundance matching
  - Marginalize over scatter

Fully marginalized 95% CL constraint:

$$|f_{R0}| < 0.0035$$

Lombriser, FS, et al., 11



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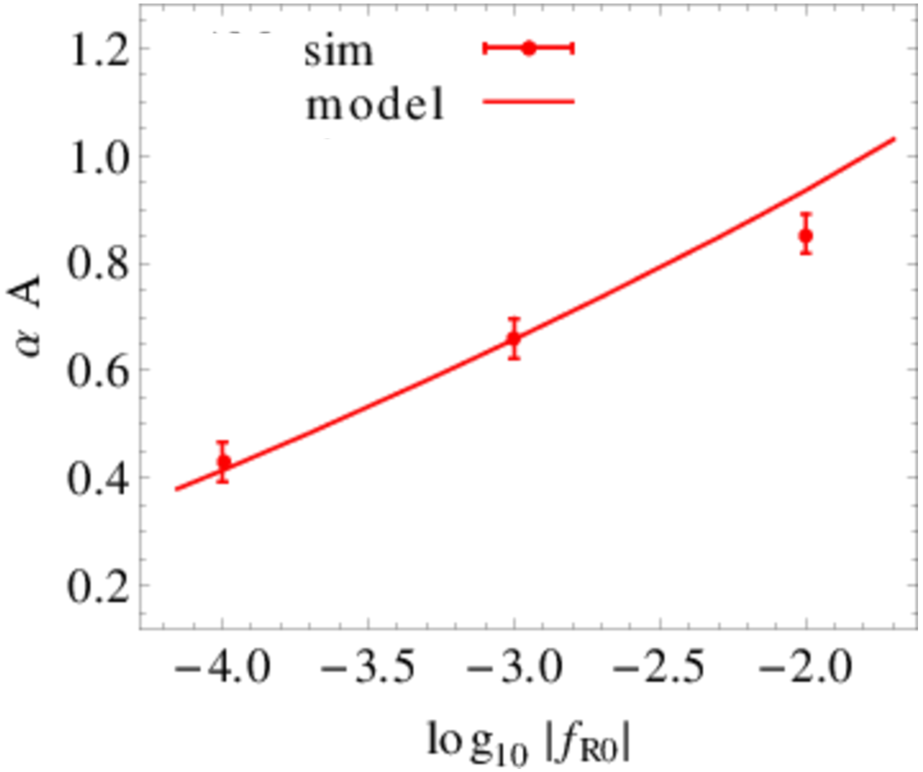
- ***Measurement*** **of stacked halo density profiles**
  - From Sloan cluster (maxBCG) lensing Mandelbaum et al.
  - f(R) predictions through abundance matching
  - Marginalize over scatter

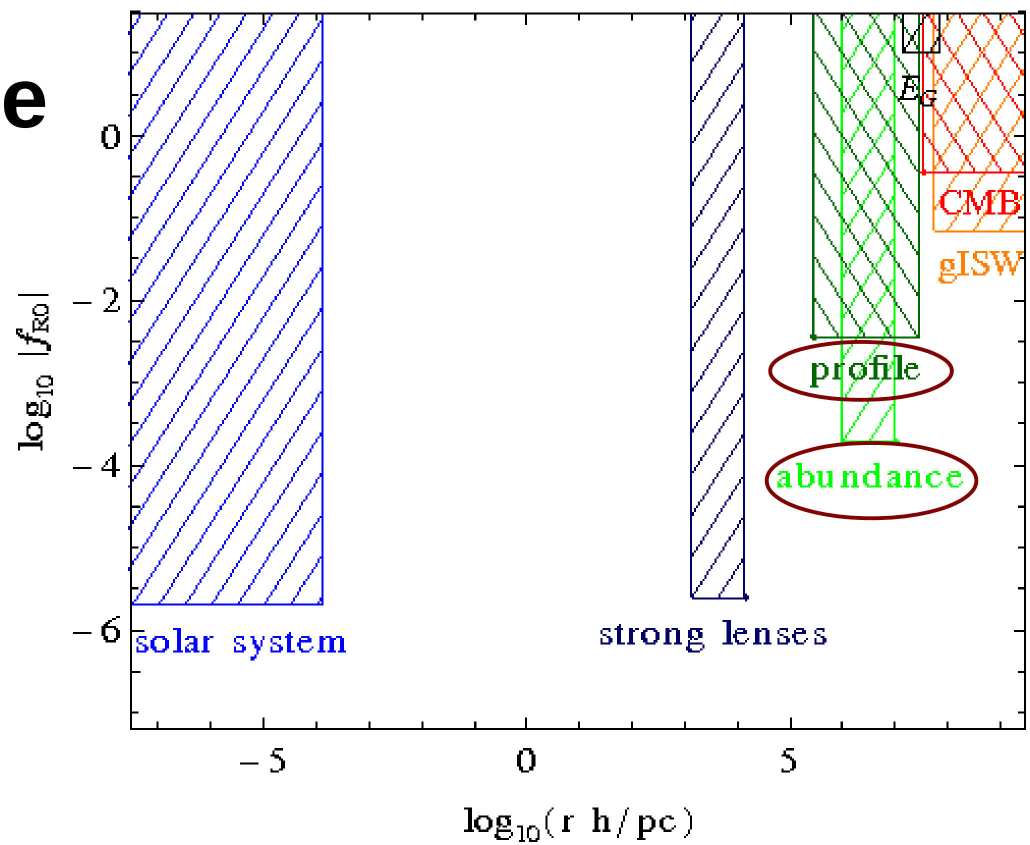
Weak scaling with f_{R0} - could become competitive soon, e.g. with DES

Lombriser, FS, et al., 11



Tests of Gravity: Today

- **Specifically: constraints on f(R)**
- **Large-scale structure filling in significant amounts of “white space” !**
- **Goal: constraints comparable to Solar System**



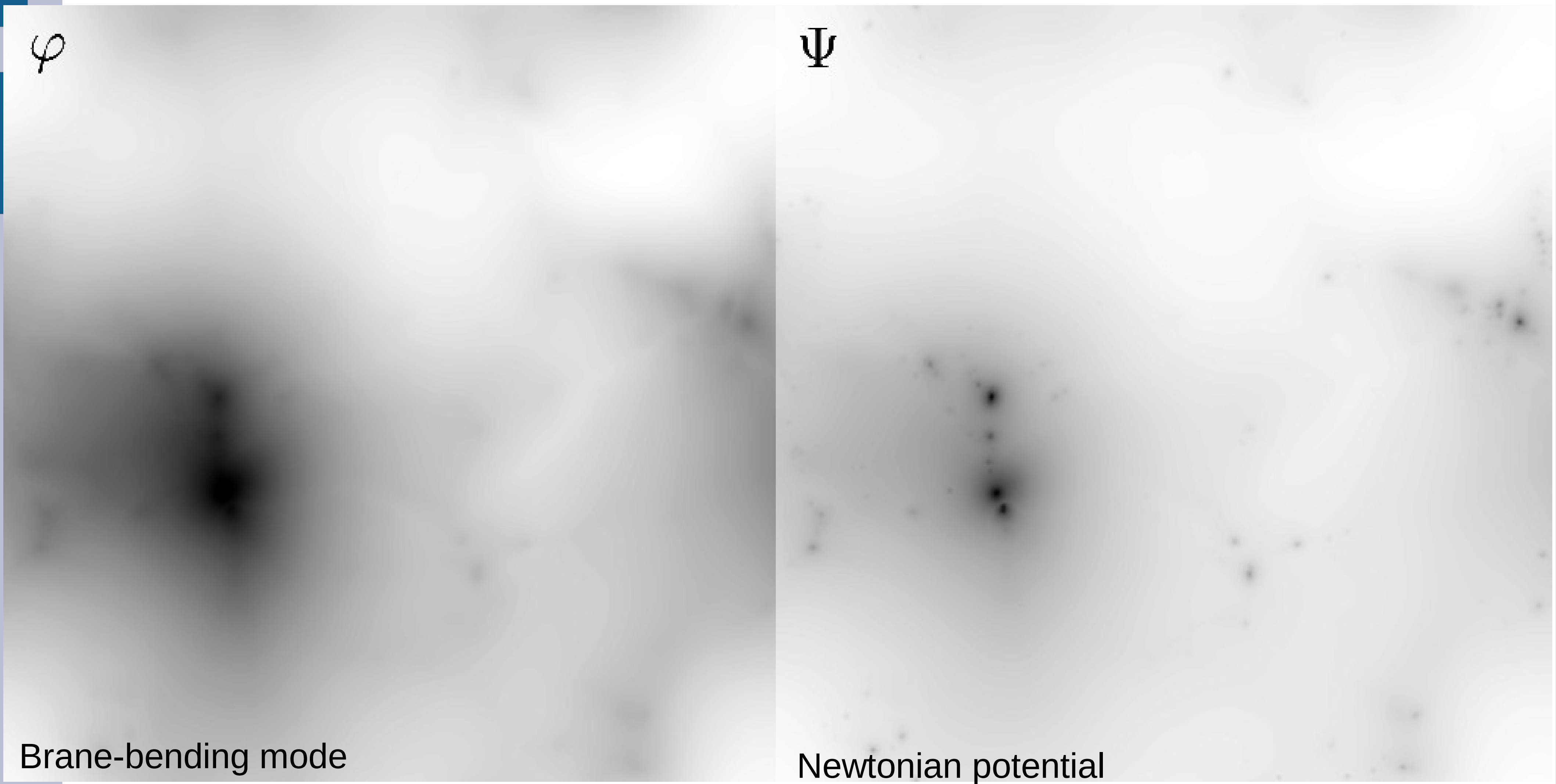
Lombriser, FS, et al., 11

Tests of Gravity: Today

- **Matter power spectrum, halo abundance, profiles: not specific to modified gravity**
  - Other non-standard ingredients can lead to similar effects (or cancel those of mod. gravity)
  - e.g., neutrinos, primordial non-Gaussianity, ...

- **We would like to have tests that *directly* target gravity**

Direct Tests of Gravity ?



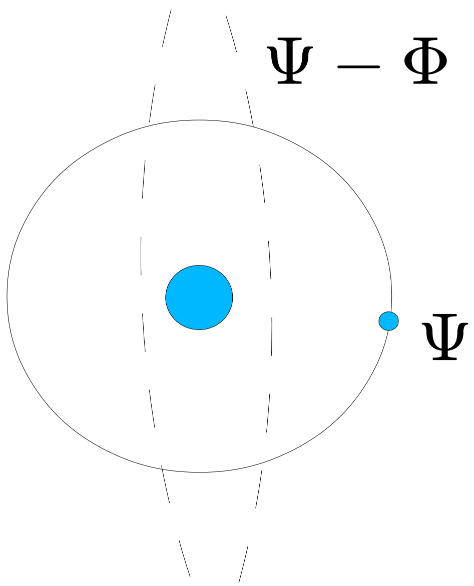
DGP simulation, 64 Mpc/h box, z=0

Direct Tests of Gravity ?

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

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

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



Direct Tests of Gravity ?

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

$$\Psi = \Psi_N + \frac{1}{2}\phi \qquad\qquad \Psi - \Phi = \Psi_N - \Phi_N$$

  - *Linear regime:* redshift distortions vs weak lensing

Zhang et al 08, Reyes et al 2010

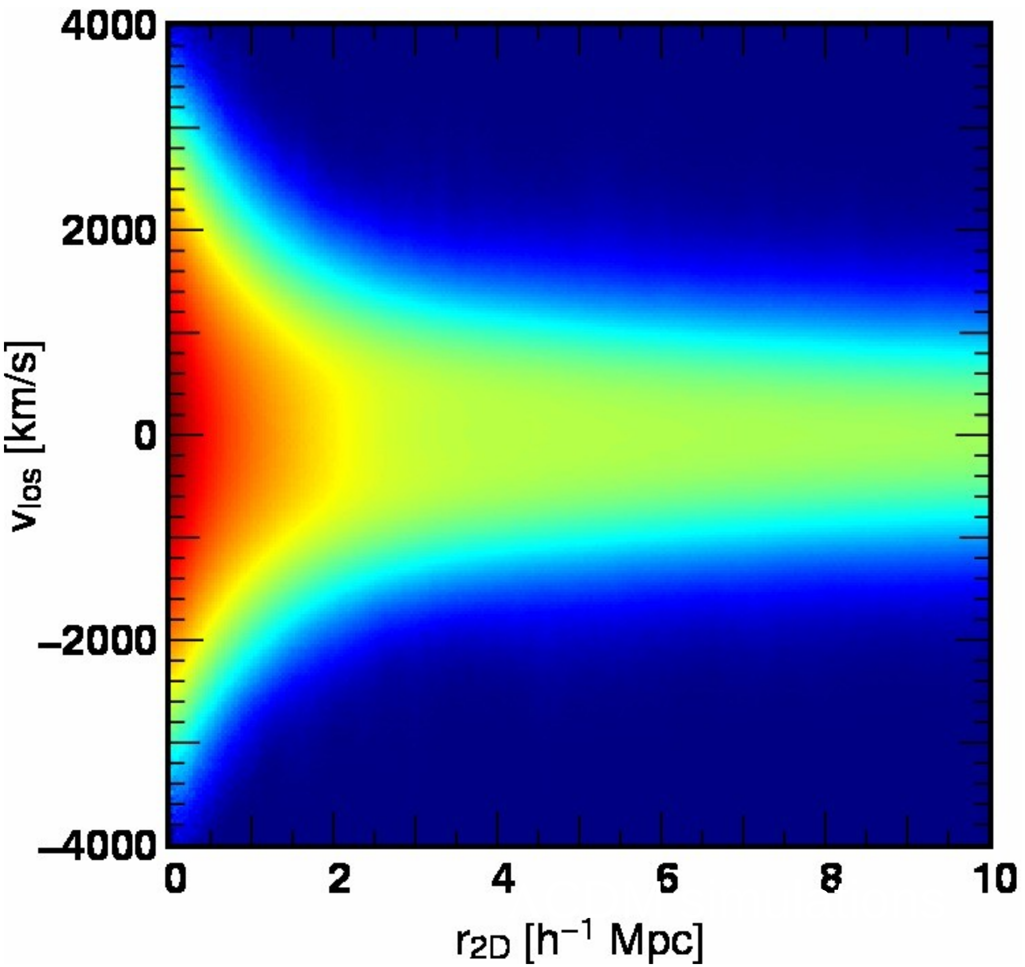
  - *Non-linear regime:* dynamical mass vs lensing mass

Schwab et al, Smith 09
FS, 2010

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

Phase-Space around Clusters

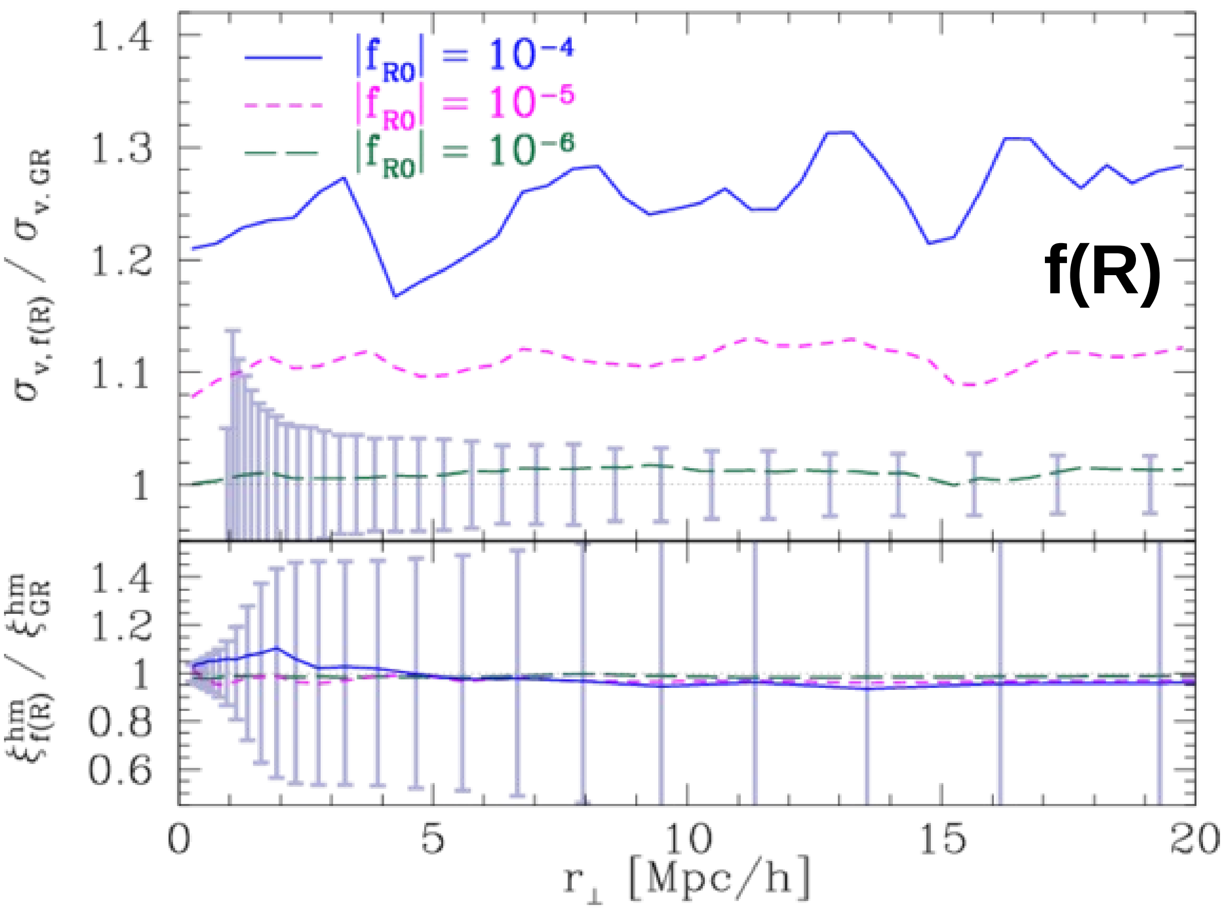
- **Distribution of V_{los} as function of r_{perp}**
  - Measured from spectroscopic galaxy sample
  - Density distribution measured from lensing



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

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

Lam et al, 2012

Conclusions

- **Large scale structure offers numerous ways to probe gravity**
  - Much more information on non-linear scales
  - Model-dependent constraints, though tests not model-dependent
- **f(R) and DGP predictions worked out**
  - More work on N-body codes necessary
- **Comparing *dynamics* with *lensing* allows for (semi-)direct test of gravity**
  - Effective for *any* scalar-tensor type models