Frontier Cosmology with Galaxy Clusters

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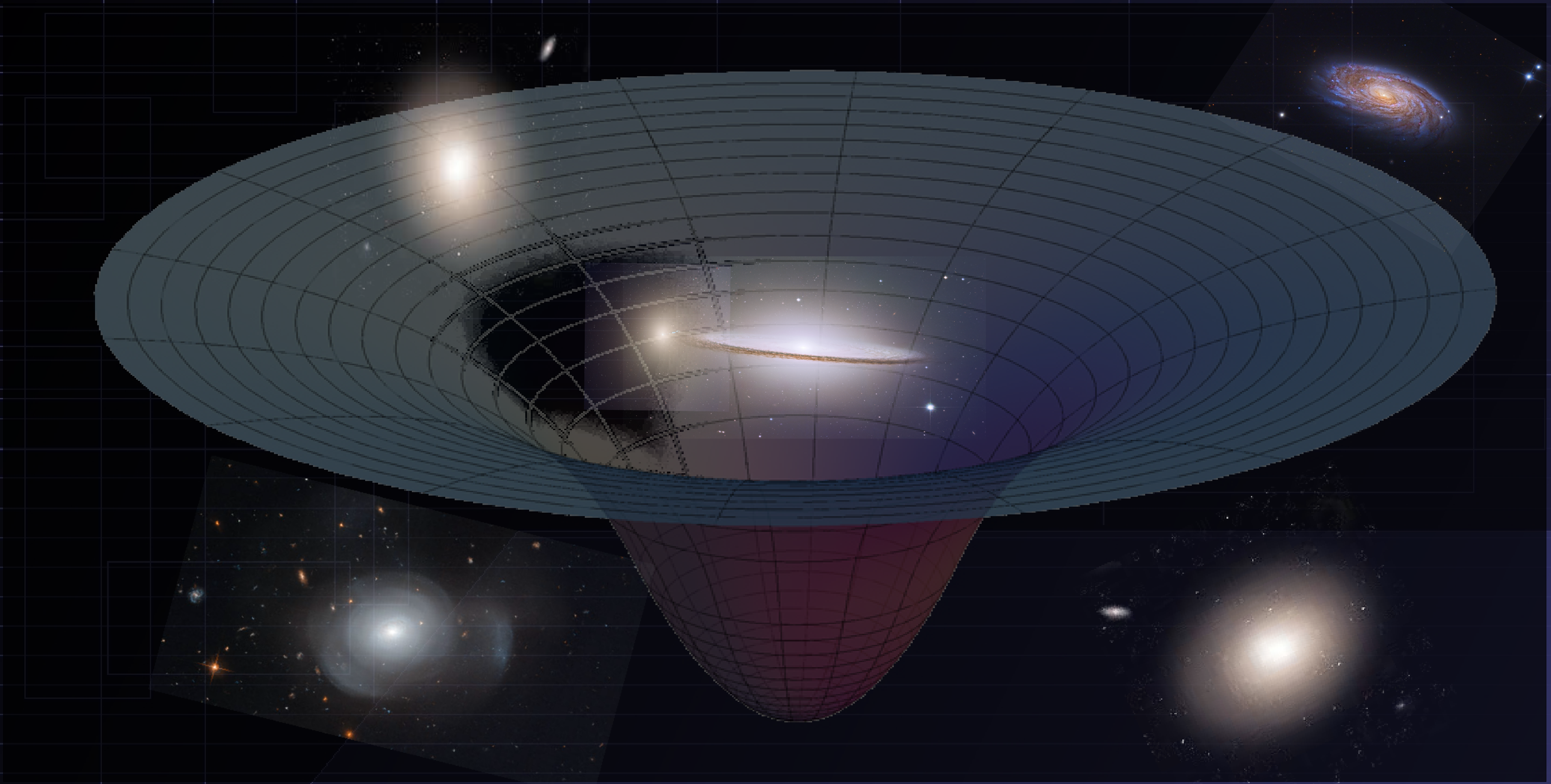


What Roles Do Galaxy Clusters Play in Cosmology

- Counting Statistics
  - Simple:

    Mass functions

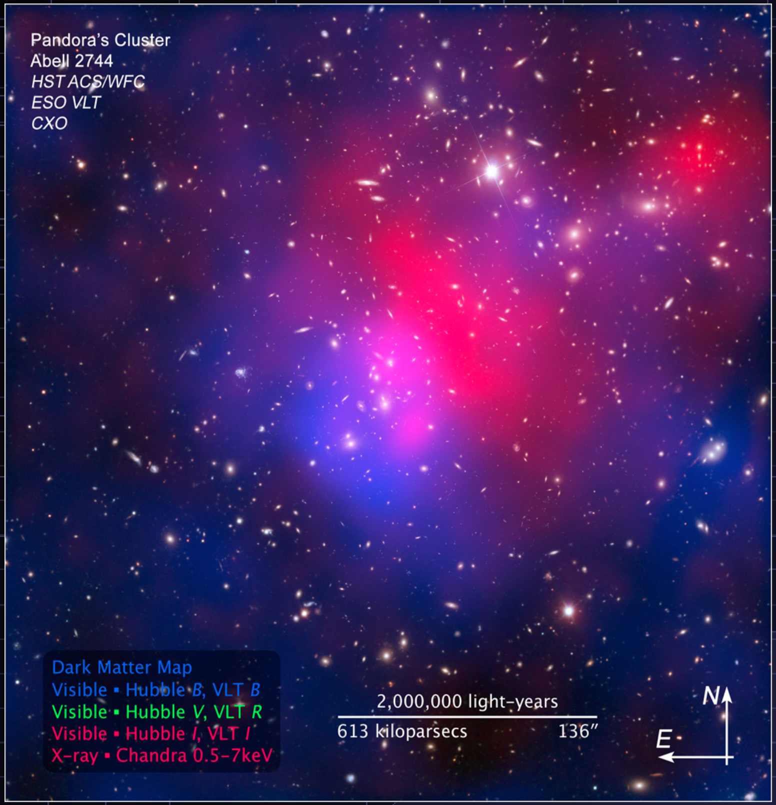
    Hi-z, high mass
  - Spatial:

    high mass peaks

    2pt and/or P(k)

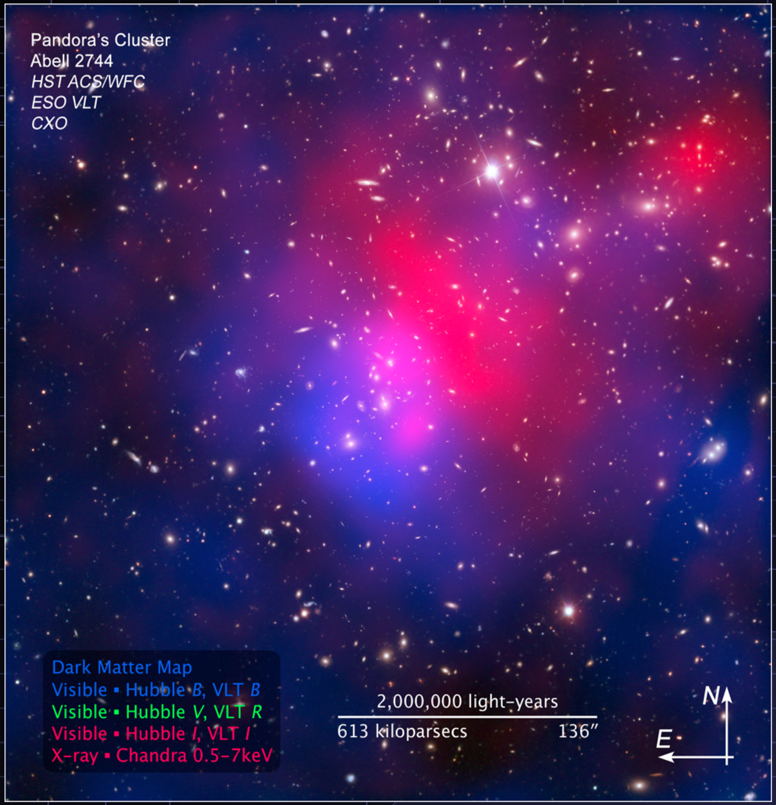
- Seeding the Growth of Structure
  - Hierarchical structure formation
  - Simplified baryons
  - Laboratories for galaxy evolution

All clusters provide us the opportunity to directly or indirectly measure their *gravitational potentials*



- Lensing
- Dynamics
- Emission of the intra-cluster medium
- Scattering of the ICM

Use the most direct measures of the *gravitational potential* in clusters for frontier cosmology



- Lensing
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The Role of the Potential and Gravity

$$\Delta f = \nabla^2 f = \nabla \cdot \nabla f$$

$$\Delta f = \sum_{i=1}^{n} \frac{\partial^2 f}{\partial x_i^2}$$

The Laplacian Δf(x,y,z) of a function at a position x,y,z is the rate at which the ***average*** of the function deviates from f(x,y,z) as the distance increases. Zeros in the Laplacian define “edges”.

$$\left(\frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}\right)\varphi(x,y,z) = f(x,y,z).$$

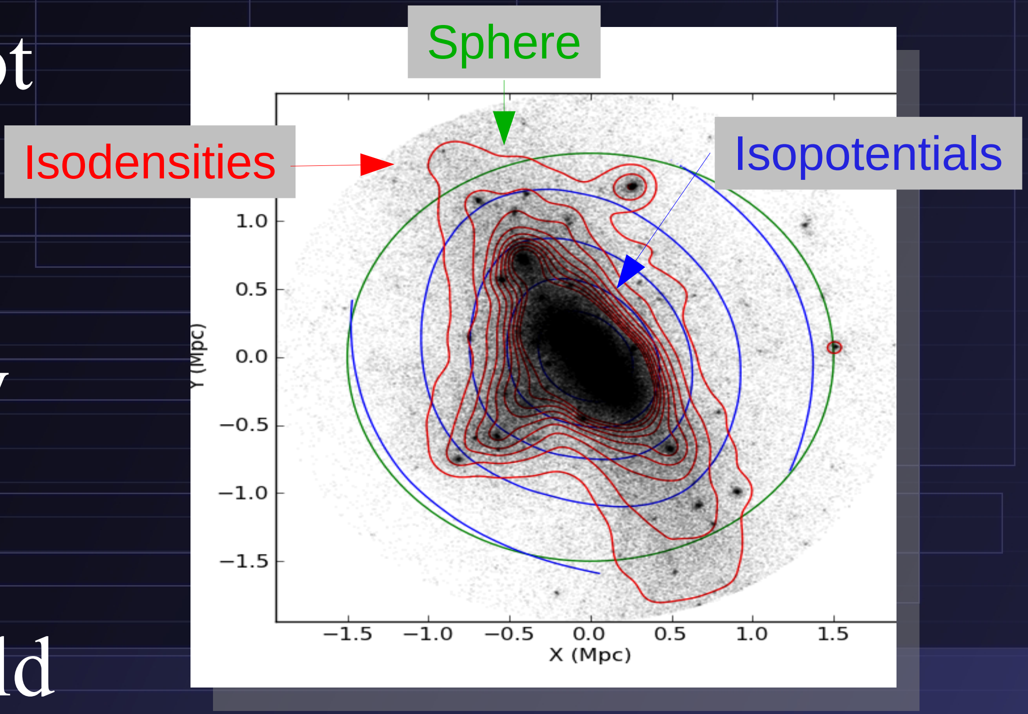
We apply Gauss's Law to a gravitational field and then the Laplacian to the resulting scalar potential field (LHS). The result is Poisson's Eq:

$$\nabla \cdot \mathbf{g} = -4\pi G\rho,$$

$$\nabla^2 \Phi = 4\pi G\rho.$$

Density and Potential in N-body Halos

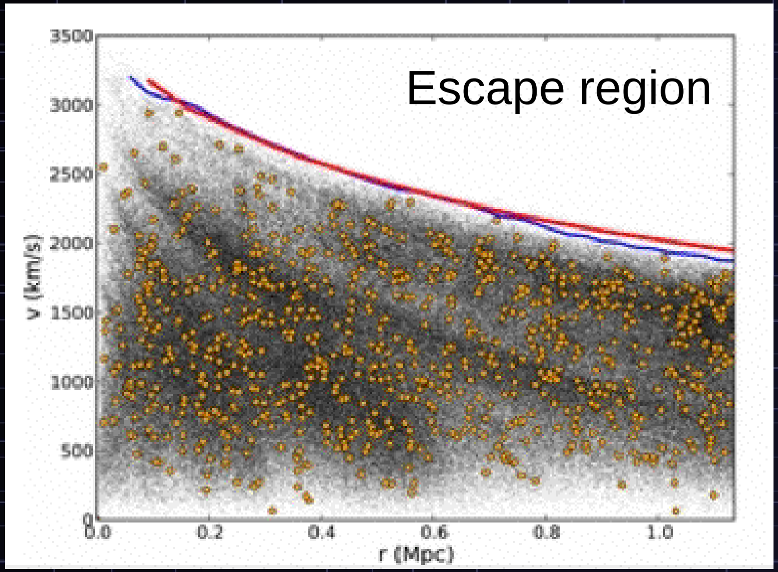
- Cluster-sized dark matter halos are not spherical in their density
- But they are nearly spherical in their local gravitational potential scalar field



From Escape Velocity to Mass: the radius-velocity phase space of clusters

$$\nabla^2\Phi = 4\pi G\rho.$$

$$v_{\rm esc}^2(r) = -2\Phi(r).$$

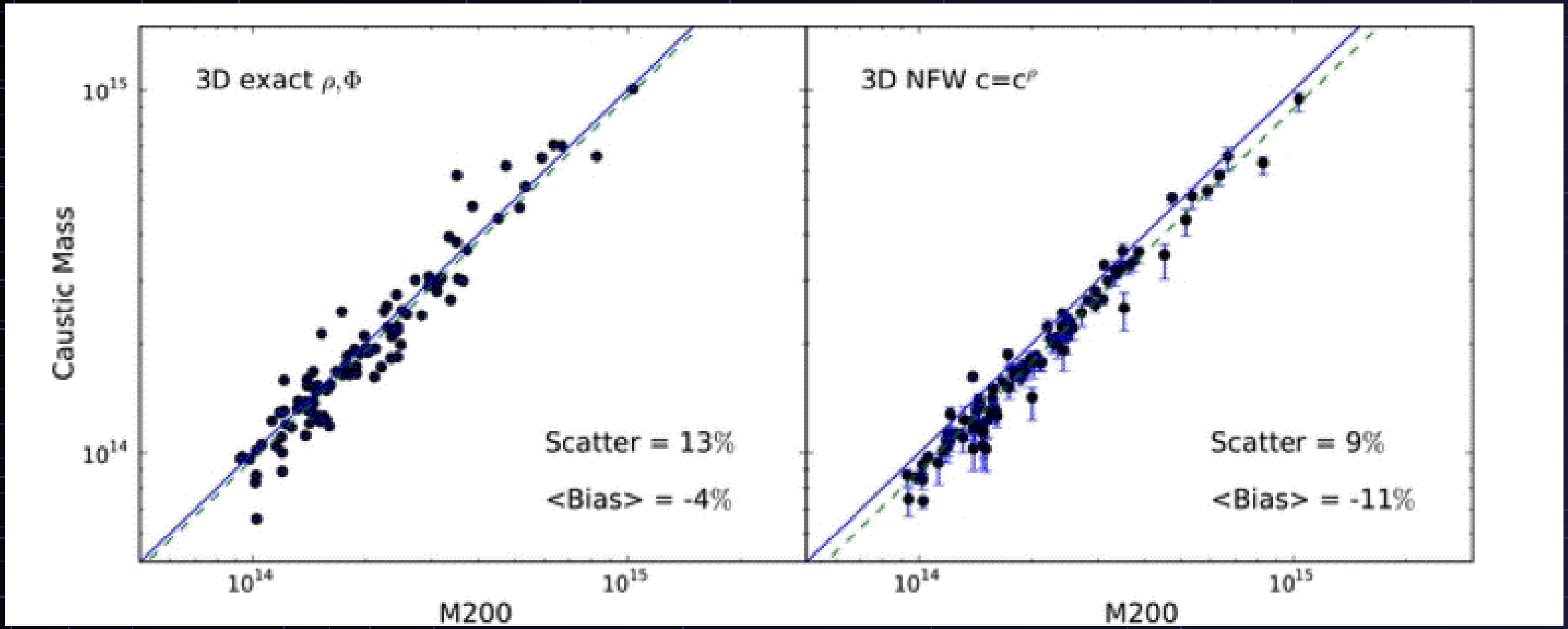


Gifford, Miller, Kern 2013

Wu et al.

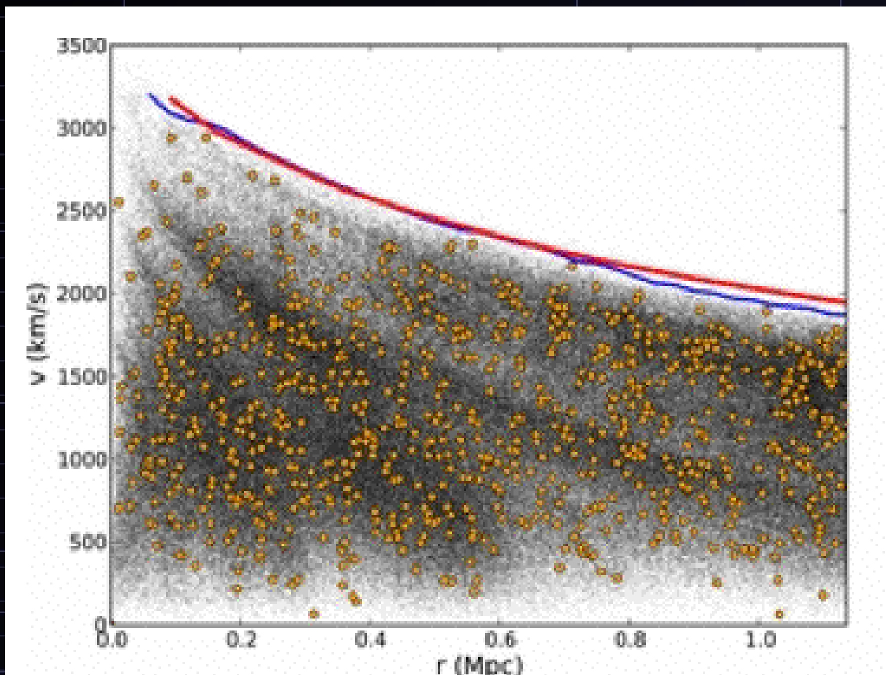
$$GM(<R) = \int_0^R \hat{\mathcal{F}}(r) v_{\rm esc}^2(r) dr,$$

Escape Velocity Mass of N-body Halos

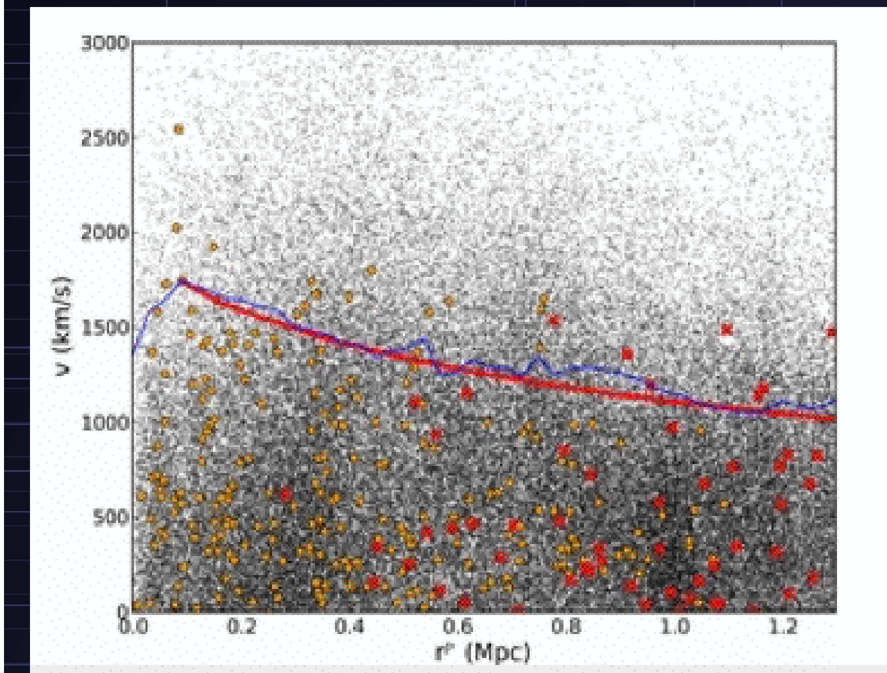


Gifford, Miller, Kern 2013

Projection and the Escape Velocity

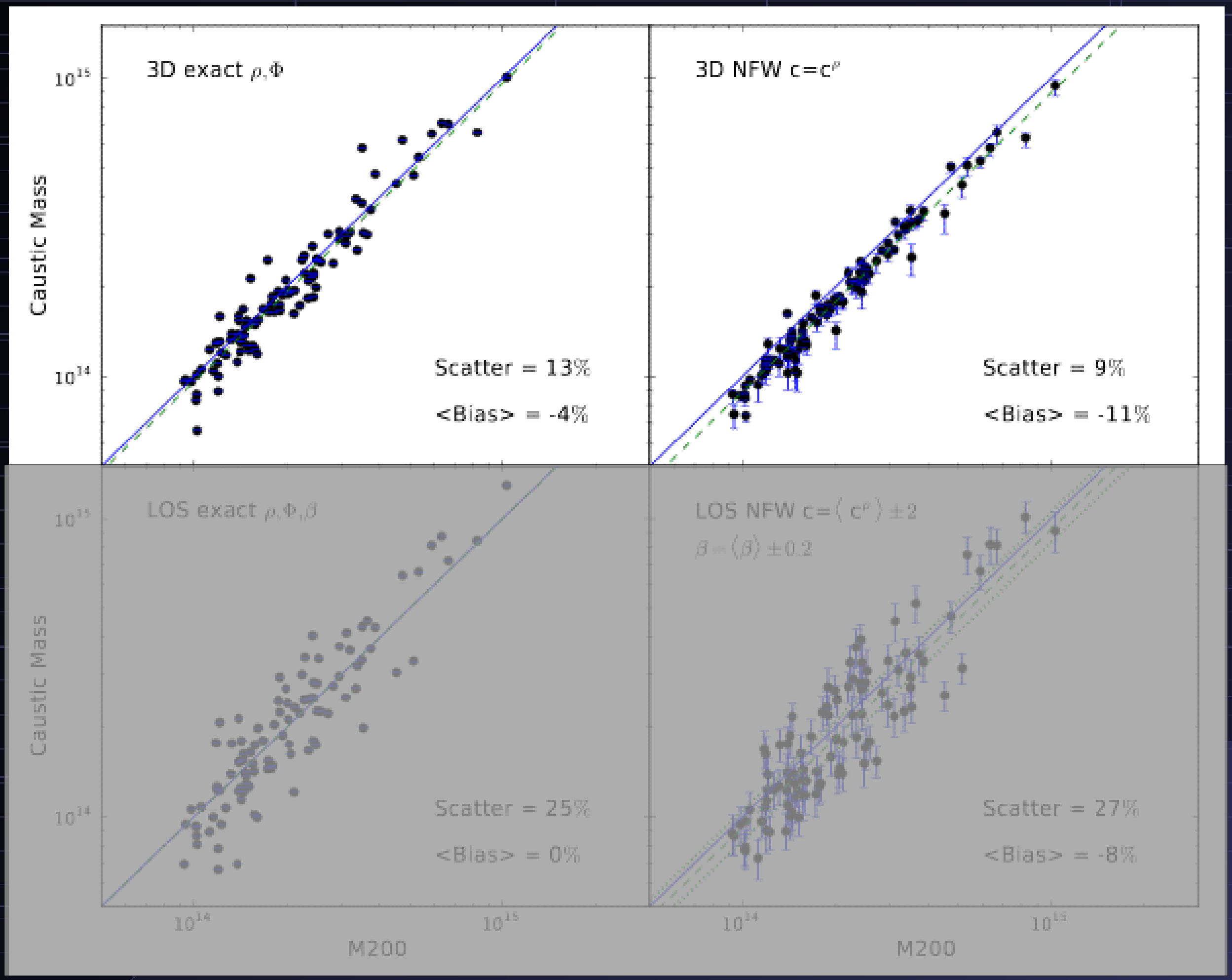


3D



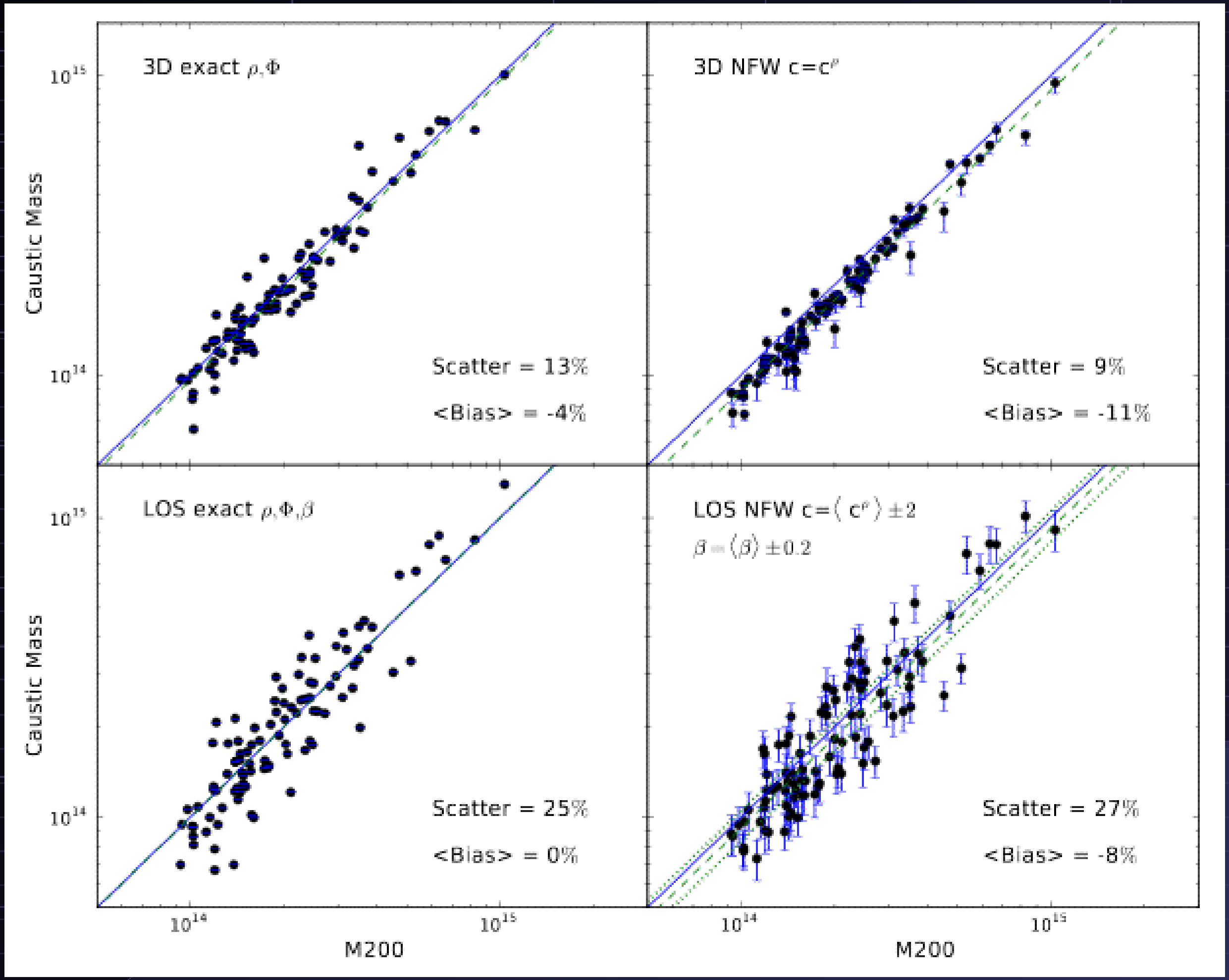
2D

Projected Escape Velocities



Gifford & Miller 2013

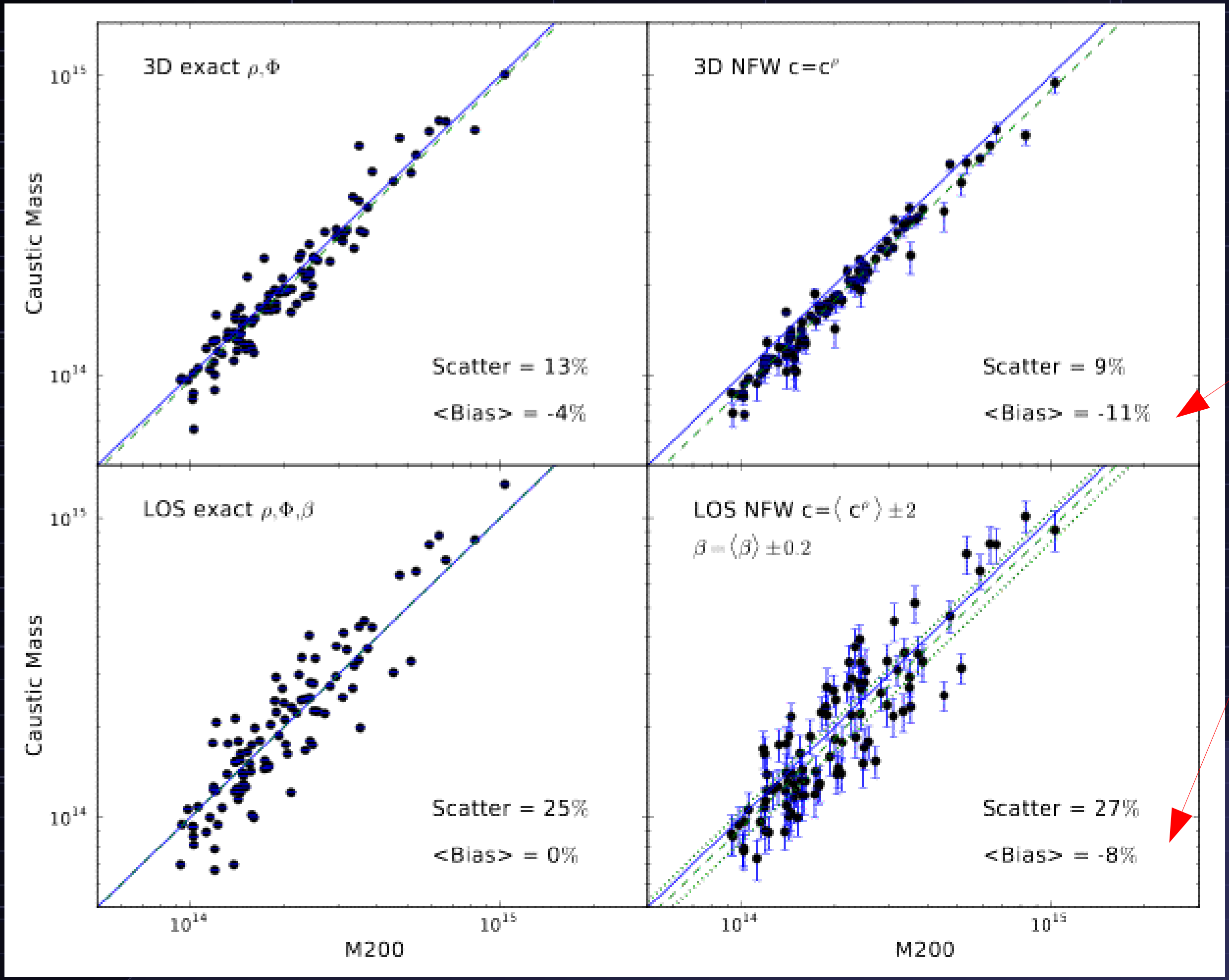
Projected Escape Velocities



Gifford & Miller 2013

Projected Escape Velocities

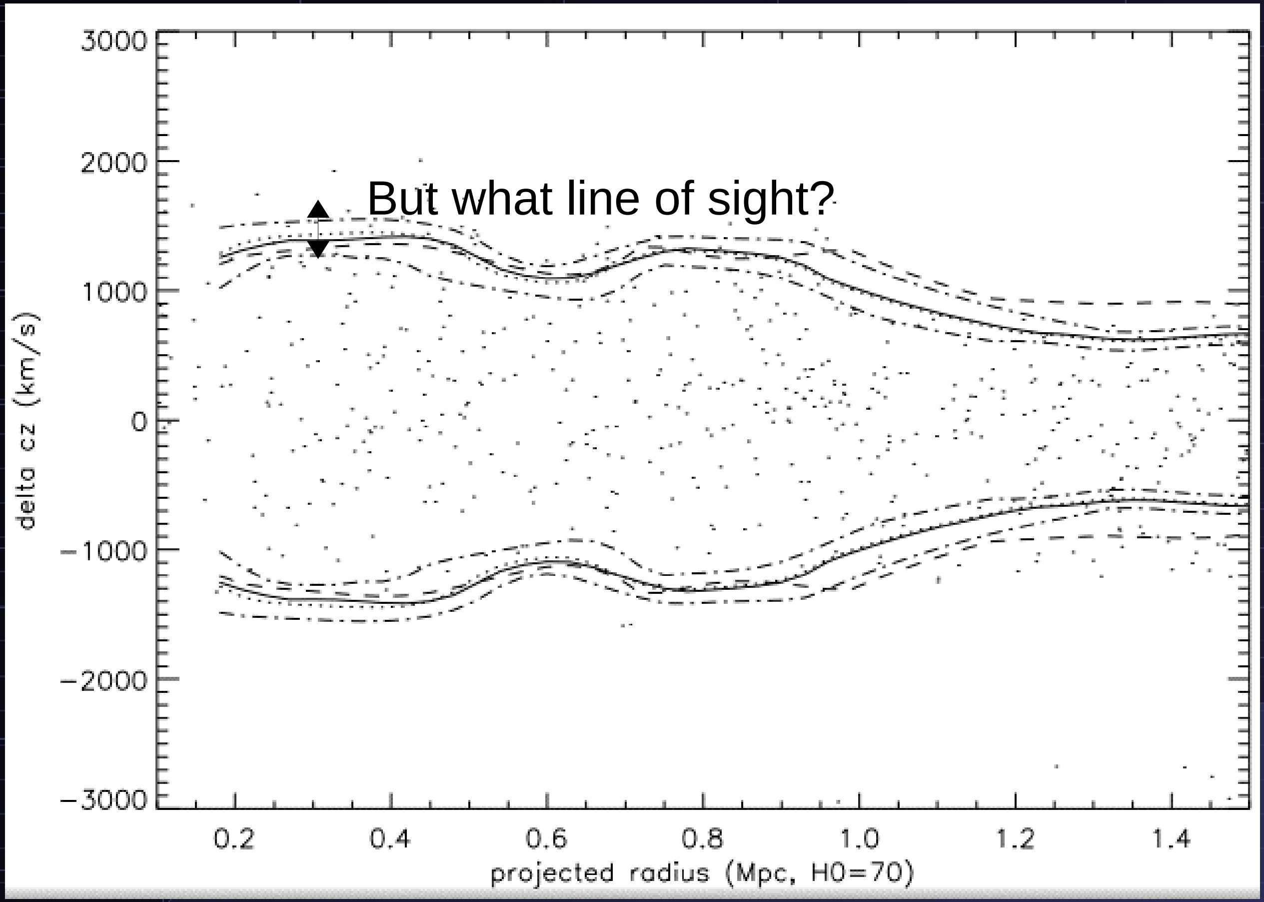
Spherical NFW potential



Shape bias

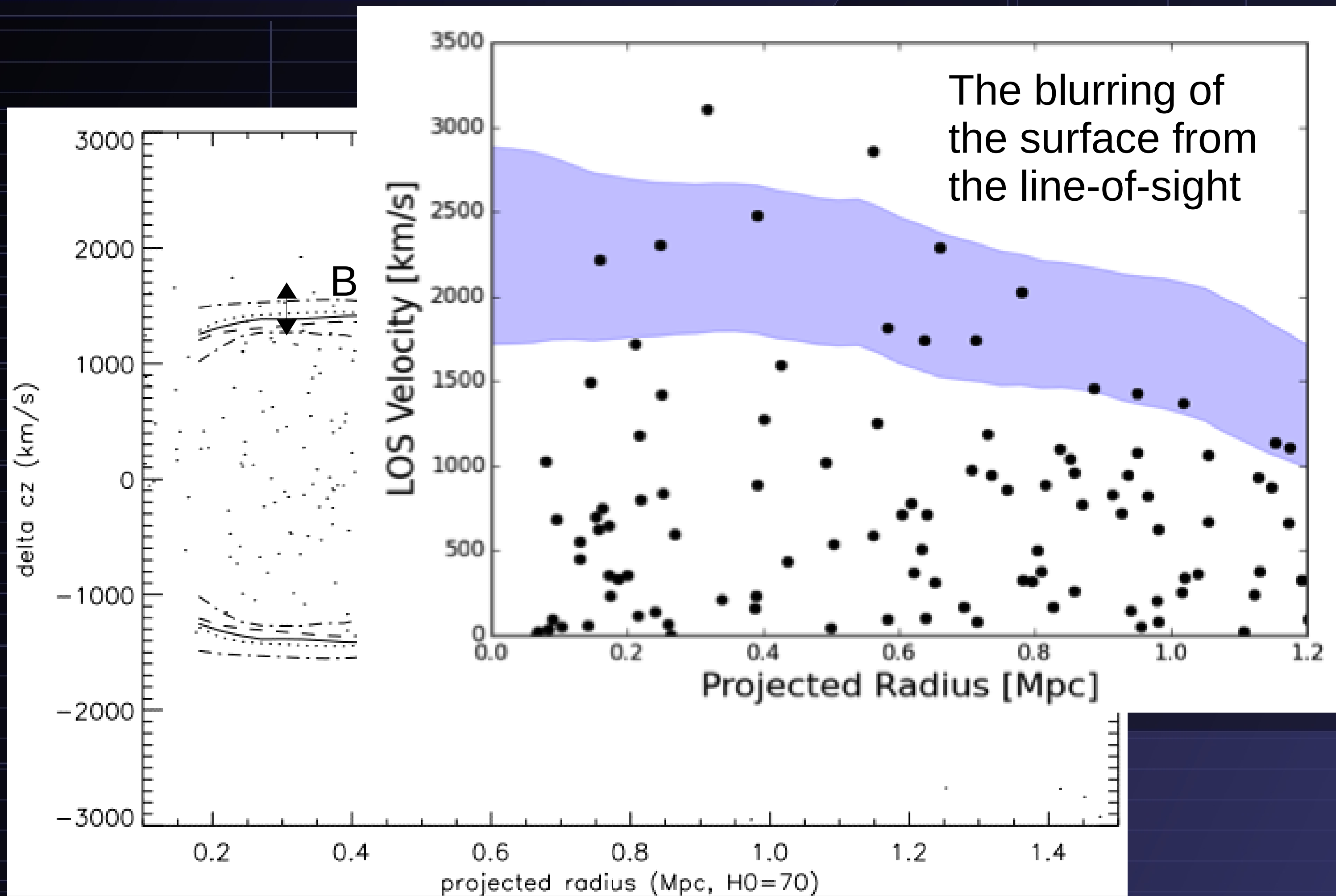
Gifford & Miller 2013

The Virgo Cluster: Real data

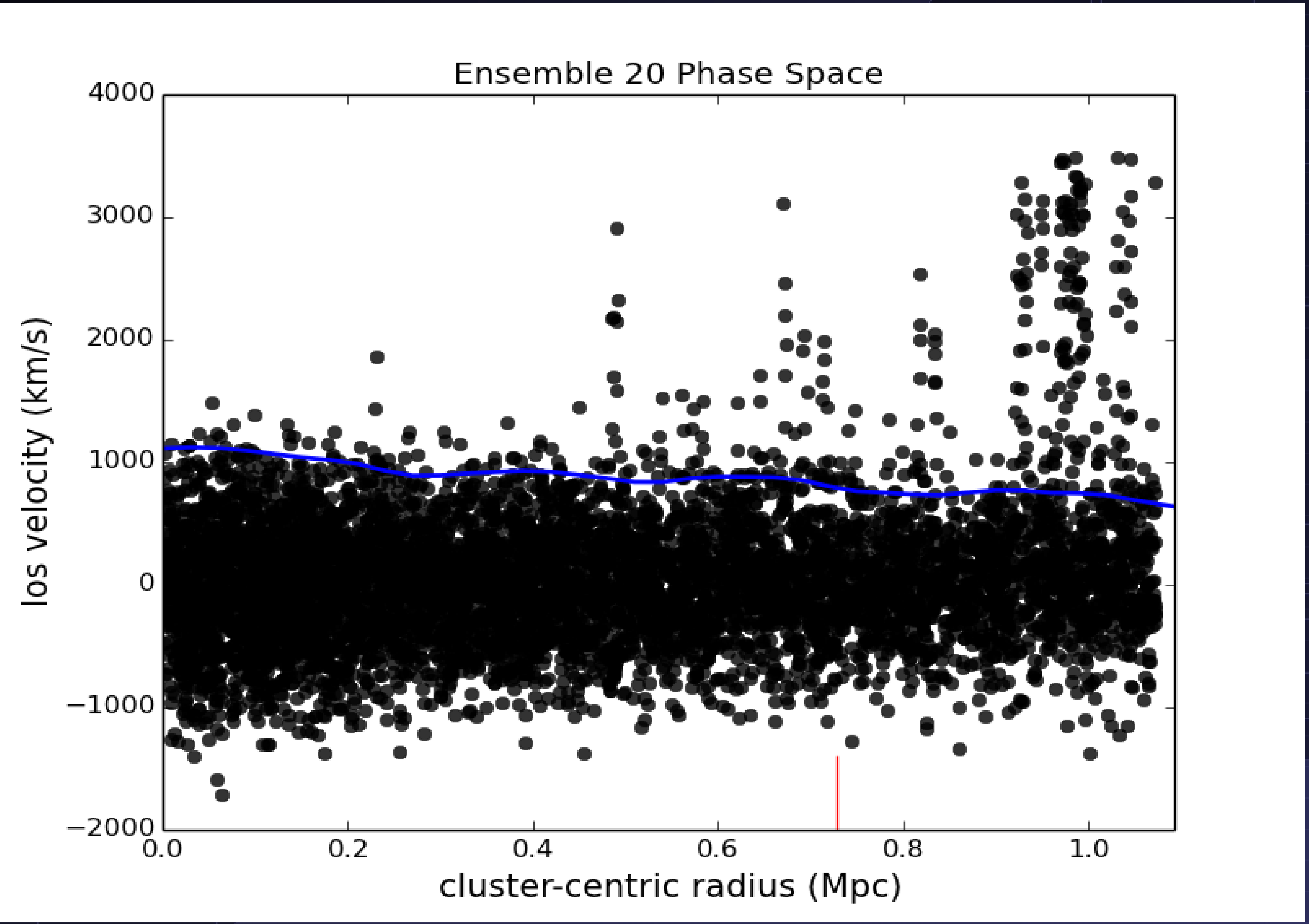


The Virgo Cluster: Real data

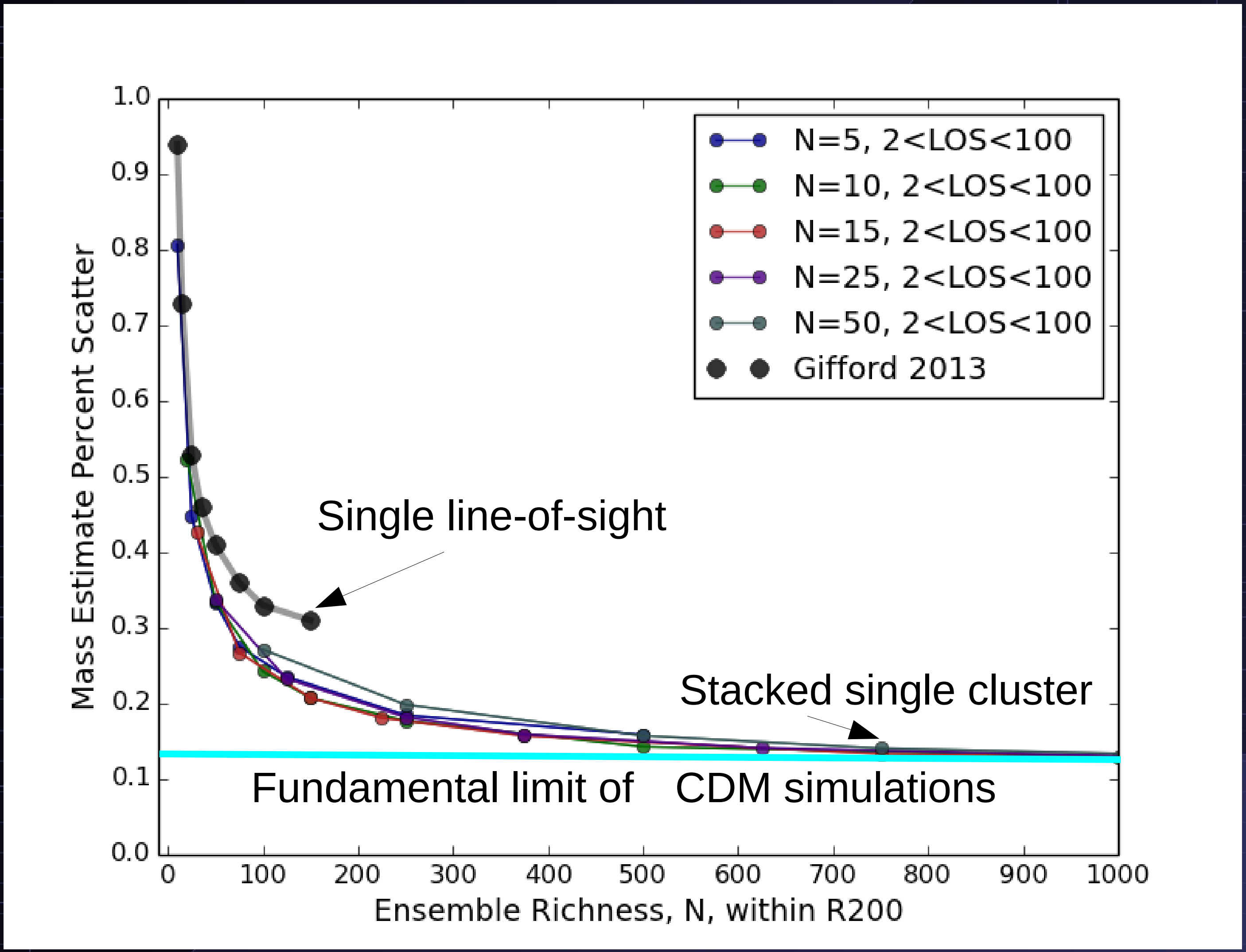
Simulations



An ensemble phase space-2D

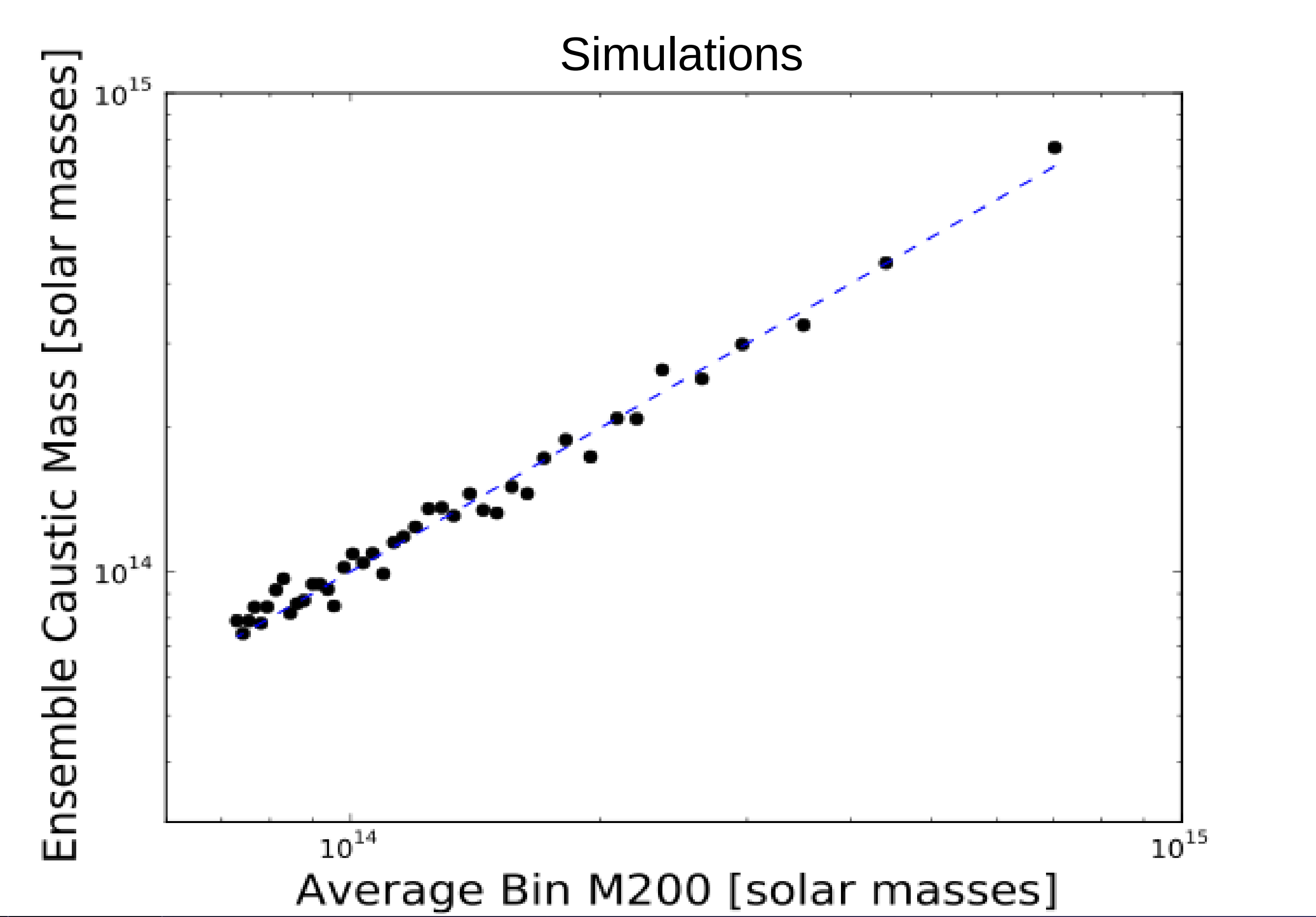


Solution to the line-of-sight issues: Stacking



Gifford, Kern,Miller 2015

Stacking based on a bin averaged optical mass indicator (richness): 5% mass scatter, 0% bias



Frontier Cosmology with Galaxy Clusters

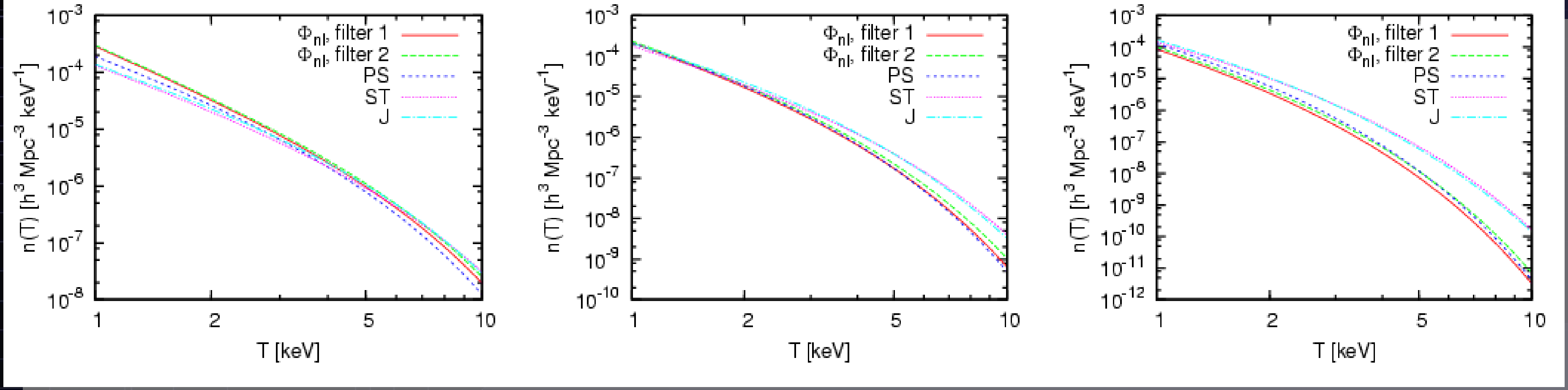
New directions

- ~~1. Direct mass estimates via their potentials~~
- 2. The “Potential Abundance” Function
- 3. Constraining
- 4. Testing gravity (alternatives to Dark Energy)

Part 2: Cosmology directly via the potential instead of the mass density

Angrick and Bartelmann 2009

$$\Delta\Phi_c(a) = \frac{3}{2} H_0^2 \Omega_{m0} \frac{\delta_c(a)}{a}. \qquad n(\Phi) = \int_{\Delta\Phi_c}^{\infty} d(\Delta\Phi)\tilde{n}(\Phi, \Delta\Phi), \qquad P_\Phi(k) = \frac{9}{4} \frac{\Omega_{m0}^2}{a^2} \frac{H_0^4}{k^4} P_\delta(k).$$



Linking the Potential from Photons and Dynamics

From the observed density (weak lensing)

$$\rho(r) = \frac{\rho_0}{(r/r_s)(1+r/r_s)^2}$$

NFW

To the inferred mass profile

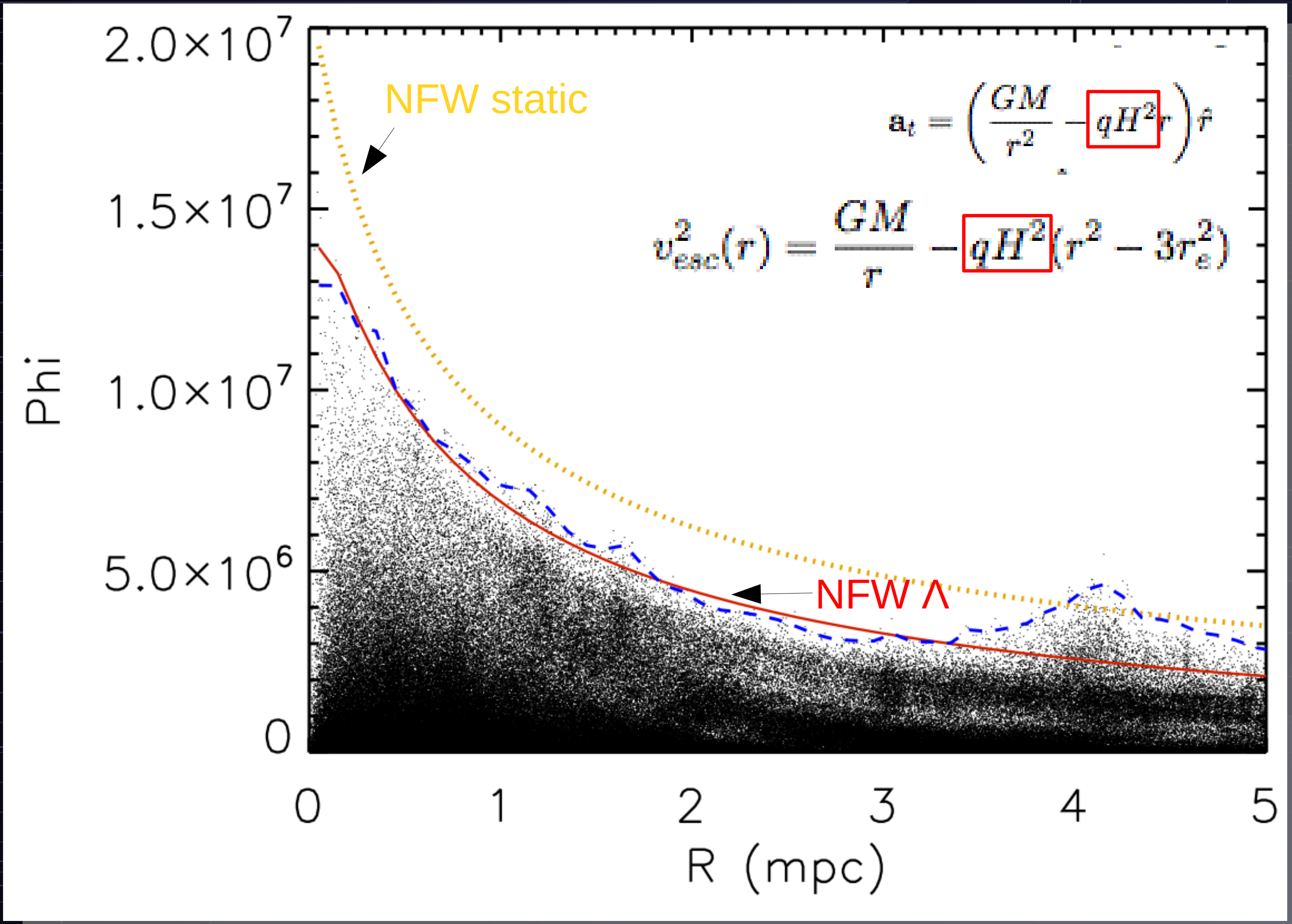
$$M(<r) = 4\pi\rho_0 r_s^3\left[\ln\left(1+\frac{r}{r_s}\right) - \frac{r/r_s}{1+r/r_s}\right]$$

To the potential via the Poisson equation

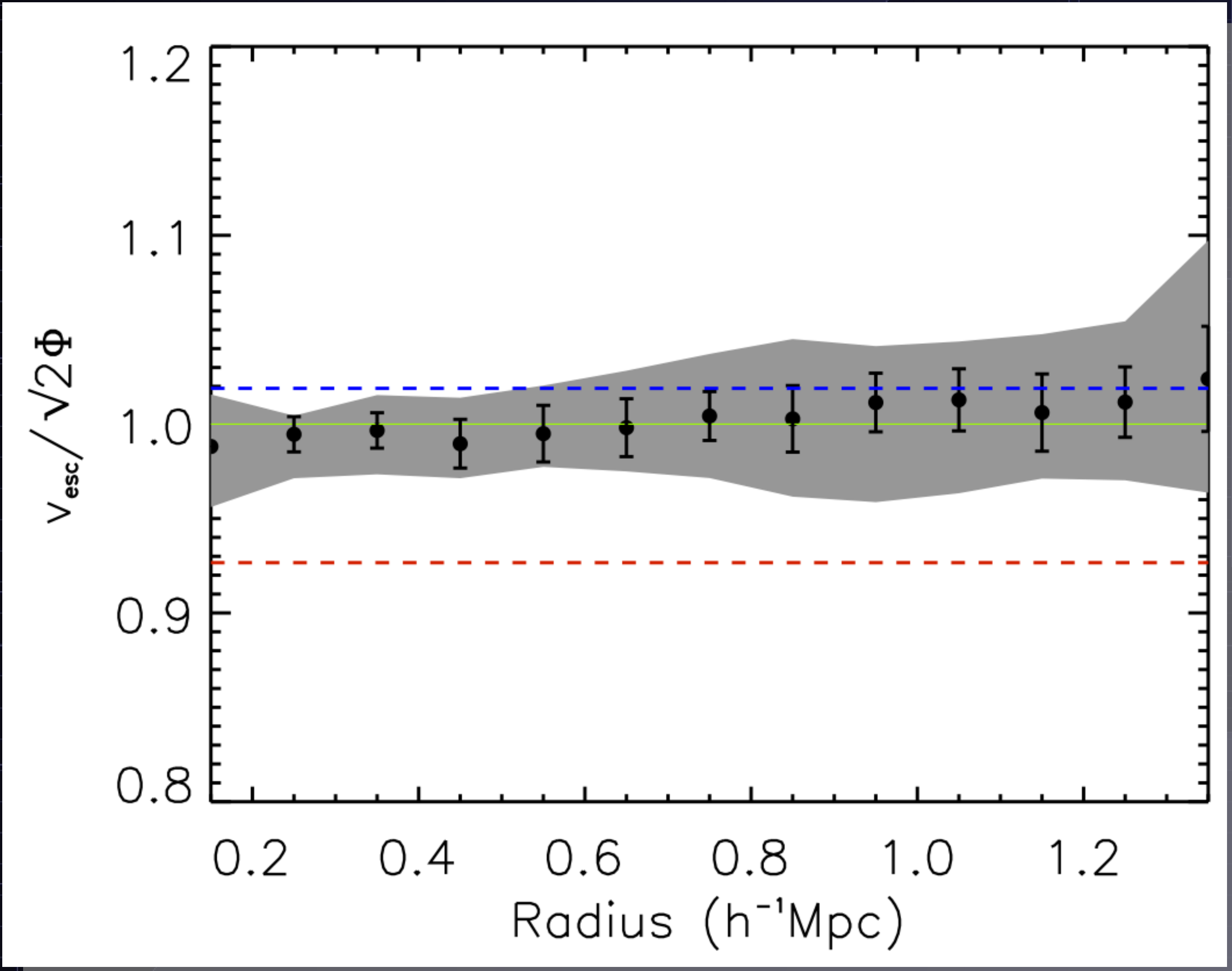
$$\Phi_{GR}(r) = \frac{-4\pi G\rho_s r_s^2 \ln(1+r/r_s)}{r/r_s} + \Phi_0$$

$$\Phi(r) = -\frac{1}{2}v_{esc}^2(r)$$

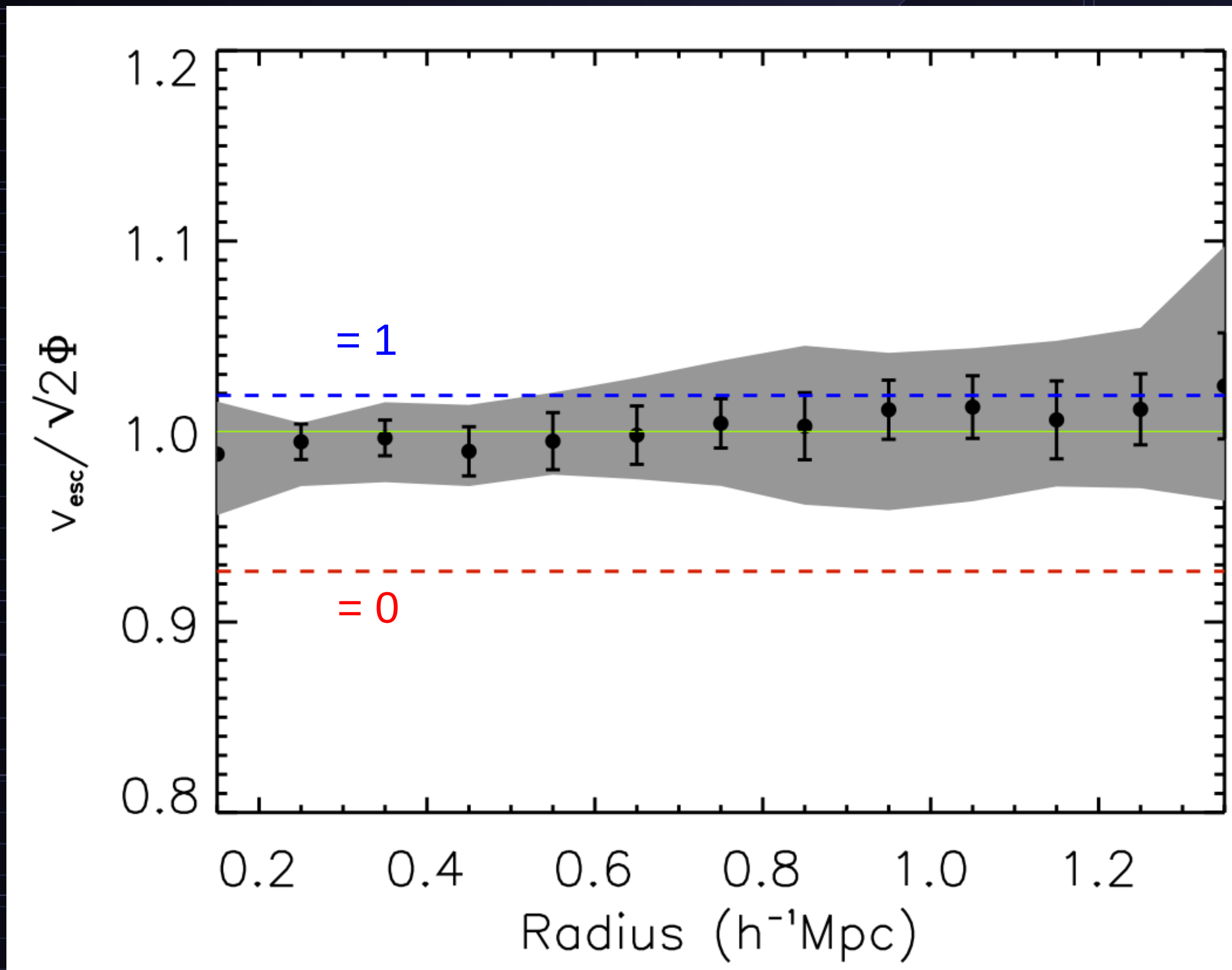
Enter: the expanding Universe



Part 3: Constraining the acceleration of the Universe



Part 3: Constraining the acceleration of the Universe



Testing gravity in low density regions and on Mpc Scales

modify the **left hand side** of Einstein Field Equations:

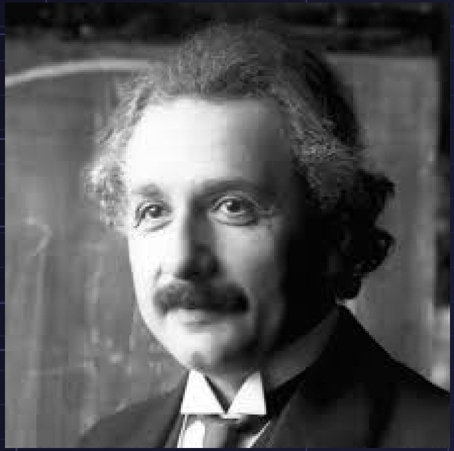
$$\nabla^2 \Phi = 4\pi G \varrho$$

geometry = mass, energy

$$G_{\mu\nu} = 8\pi G \left(T_{\mu\nu}^{M} + T_{\mu\nu}^{DE}\right)$$

formally equivalent to...

$$G_{\mu\nu} + \underline{\qquad} = 8\pi G \, T_{\mu\nu}^{M}$$



$$G_{\mu\nu} + f_R R_{\mu\nu} - \left(\tfrac{1}{2} f - \Box f_R\right) g_{\mu\nu} - \nabla_\mu \nabla_\nu f_R = 8\pi G \, T_{\mu\nu}$$

modified gravitational potential in f(R) gravity

Equation of motion for scalar field:

$$\nabla^2 \delta f_R = (1/3) [-(8\pi G) \delta \rho + \delta R(f_R)]$$

Modified Poisson equation:

$$\nabla^2 \Phi = (16\pi G/3) \delta \rho - (1/6) \delta R(f_R)$$

Combine…

modified gravitational potential:

$$\Phi = \phi_N - ½ \delta f_R$$

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modified gravitational potential in f(R) gravity

Equation of motion for scalar field ($f_R \equiv df(R)/dR$):

$$\nabla^2 \delta f_R = (1/3)\,[-(8\pi G)\,\delta\rho + \delta R(f_R)]$$

Perturbation from background value today (f_{R0}):

$$\delta f_R = f_R - f_{R0}$$

Quote modification "strength" as value of f_{R0}:

$$|f_{R0}| = 0 \equiv \text{LCDM ("GR")}$$

$$|f_{R0}| = 10^{-6} \equiv \text{FR6}$$

$$|f_{R0}| = 10^{-5} \equiv \text{FR5}$$

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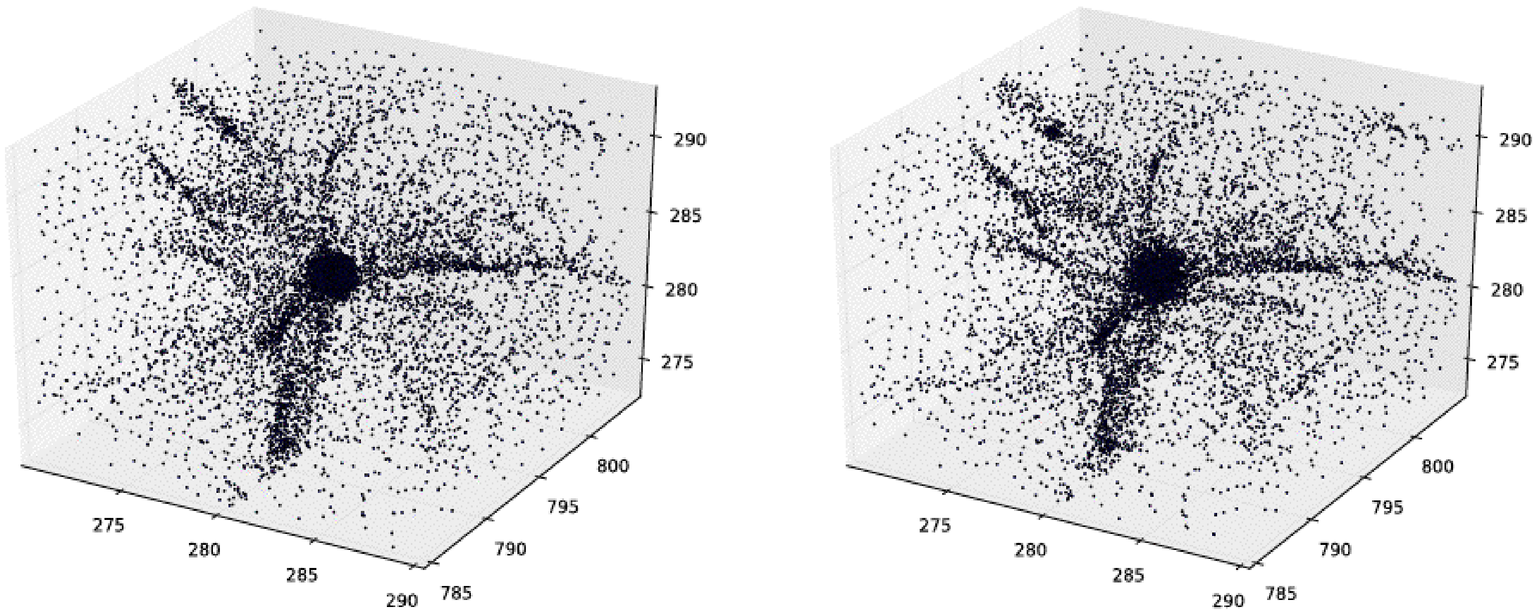
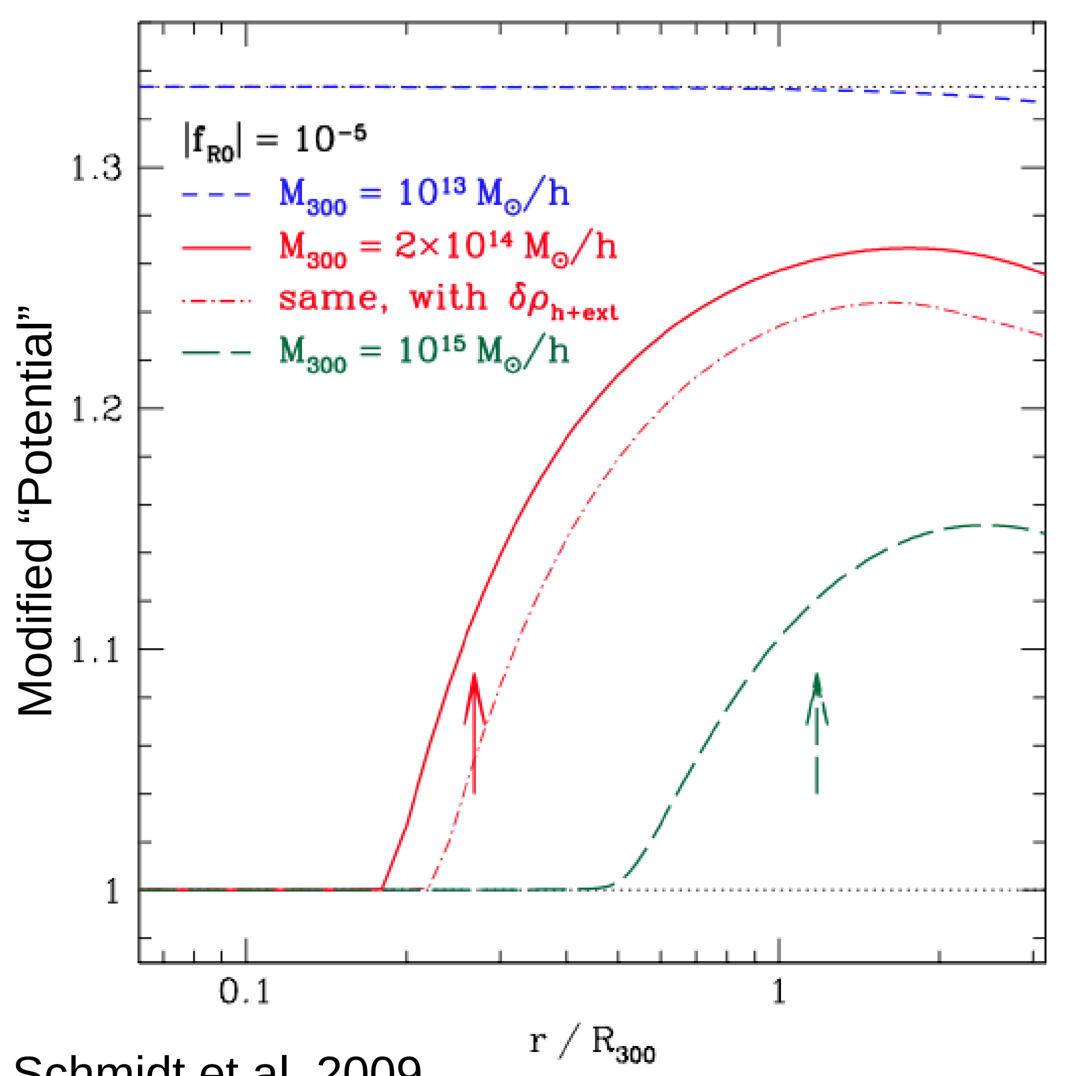
same galaxy cluster in two different universes…



LCDM/GR **Chameleon f(R) gravity**

N-body simulations
by Kazuya Koyama, Gong-Bo Zhao, Baojiu Li

The Gravitational Potential Profile in f(R) Gravity: Screening

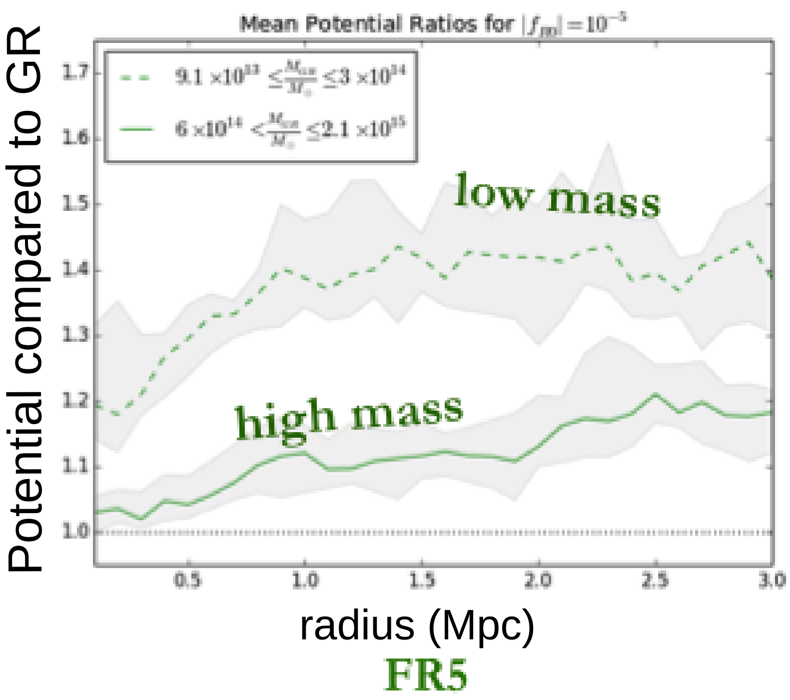


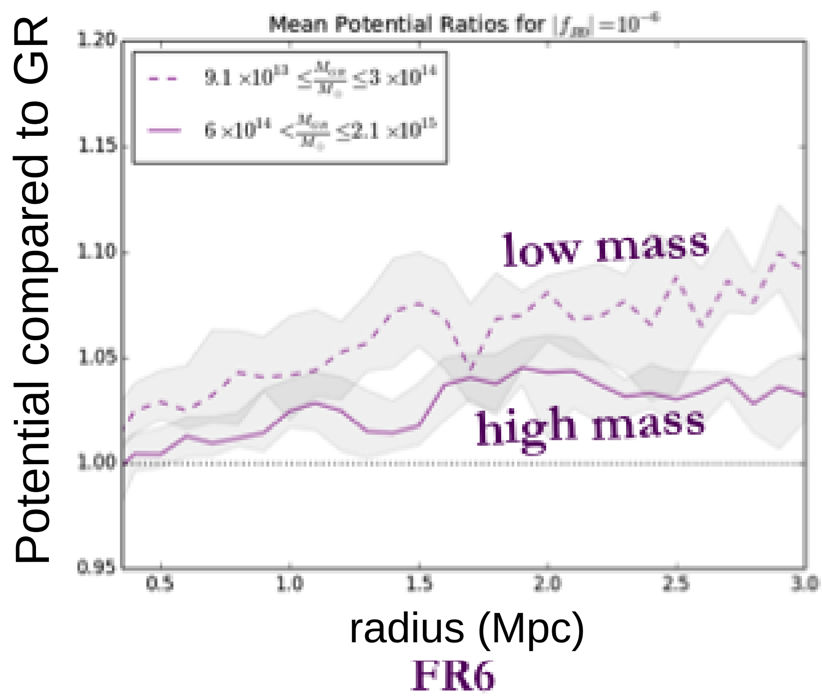
Schmidt et al. 2009

Clusters: scale and size

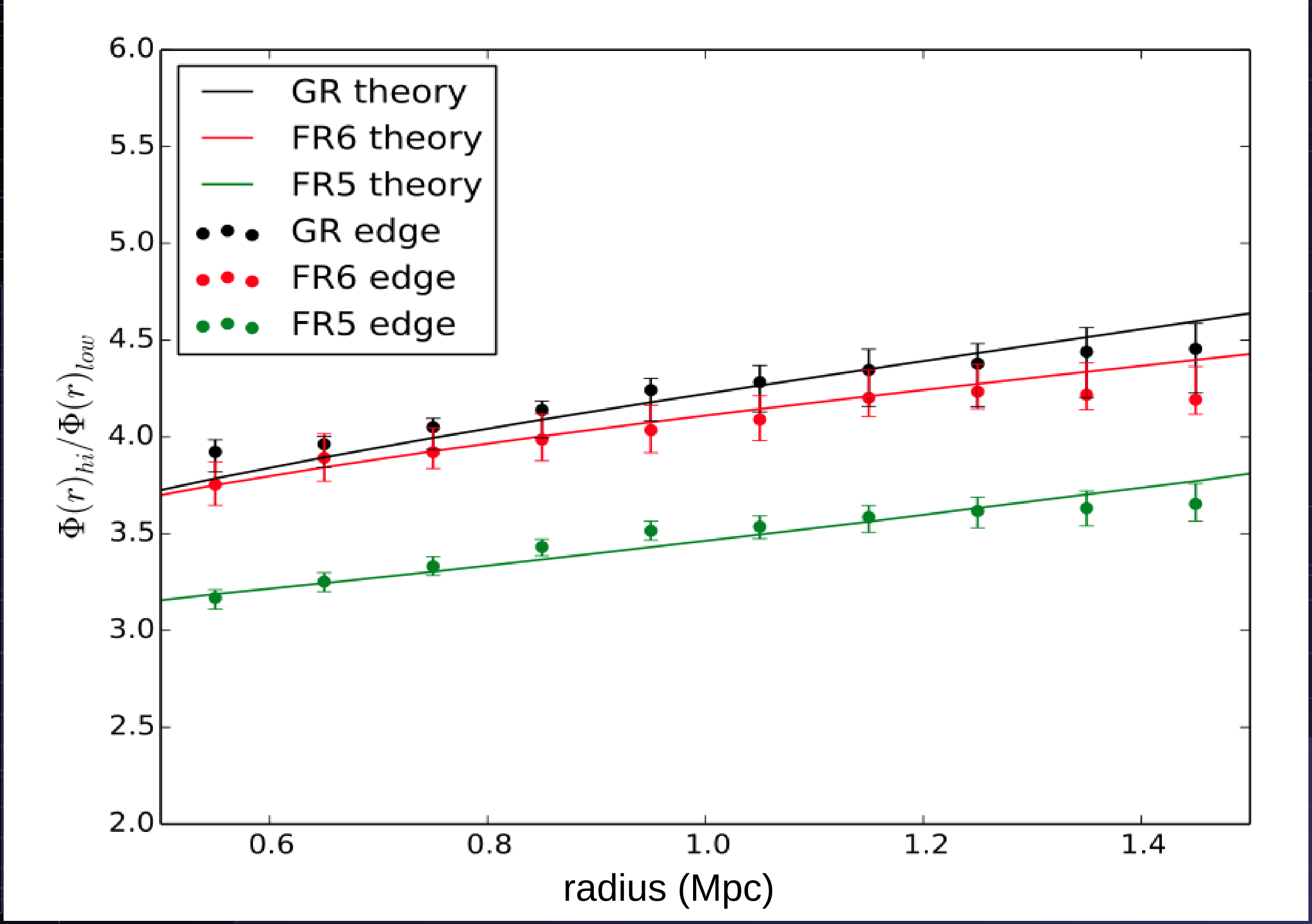
Stark, Miller, Koyama et al.

High mass clusters are *screened* vis-à-vis **low mass clusters** in f(R) gravity, but not in GR





Part 4: Testing Alternatives to



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