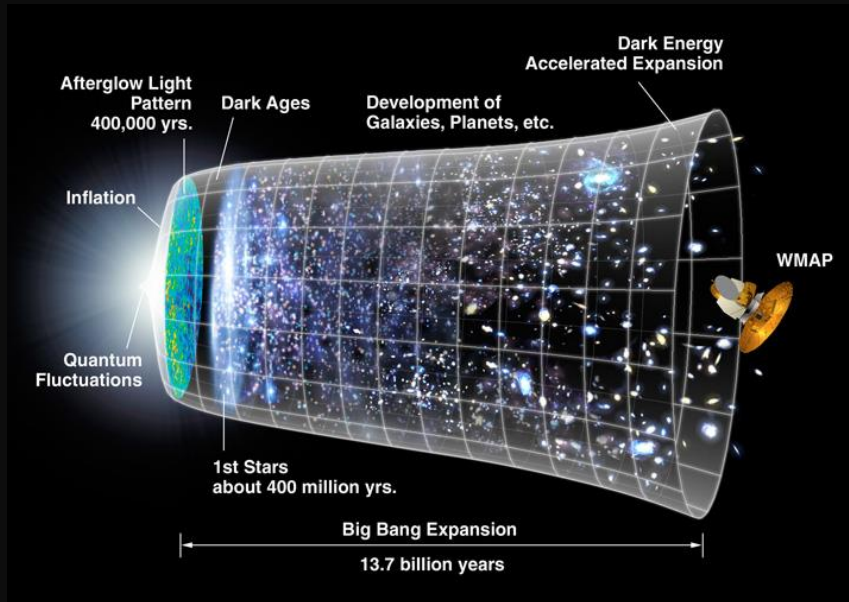# Testing Gravity in the Cosmic Web

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Modifying General Relativity

What caused the late-time acceleration?

If it is a cosmological constant, it is very small compared to the scale of gravity: $\Lambda \approx 10^{-120} M_{pl}{}^2$

$$G_{\mu\nu} = R_{\mu\nu} - \frac{1}{2} g_{\mu\nu} R \ [+?] = 8\pi G T_{\mu\nu} \ [-\Lambda g_{\mu\nu}?]$$

Change: geometry – "modified gravity", matter – "dark energy"

Screening the Fifth Force

- GR well-tested on small scales but not cosmological scales

  - *Chameleon*: in f(R) gravity, make mass of scalar field large in high density <u>environments</u>
  - *Symmetron*: change scalar field coupling to matter
  - *Vainshtein*: in massive gravity, galileon, and braneworld (DGP) models, derivative self-interactions hide fifth force, depending on <u>dimensionality</u> of the system (see Bloomfield, Burrage, & Davis 2014)

- I will look at the cosmic web and environmental dependence of *chameleon* and *Vainshtein* screening
  - (BF+ 2014, 1404.2206; BF+ 2015, 1503.06673)

Simulations

LCDM   nDGP   F4
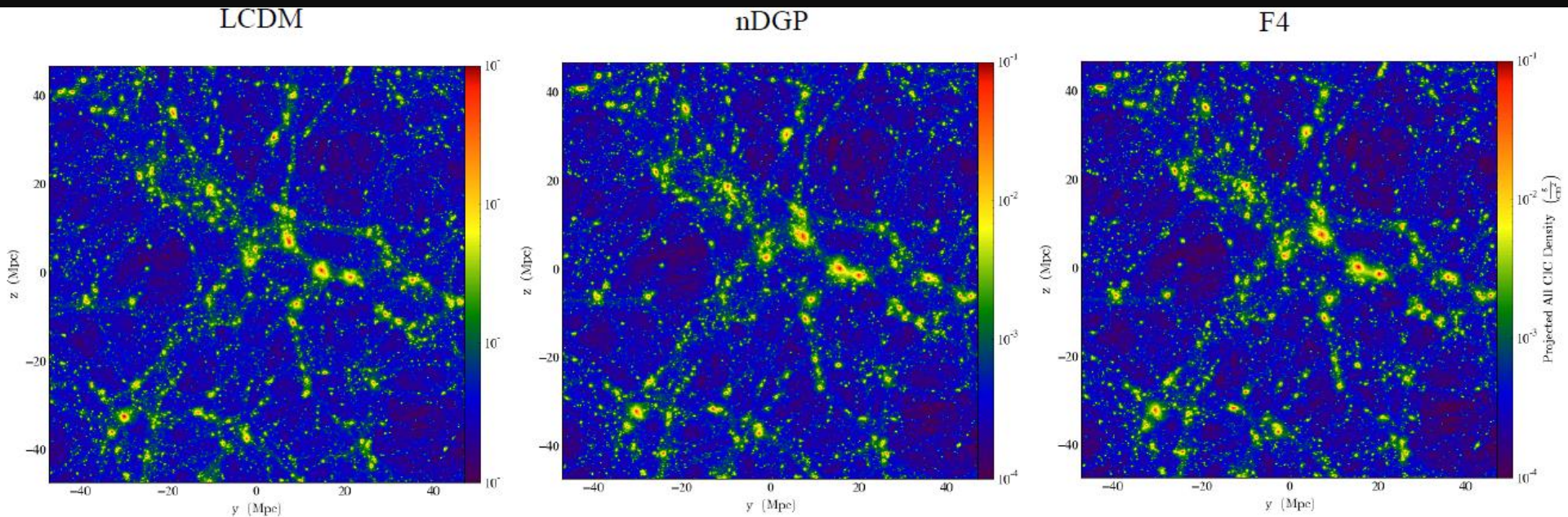
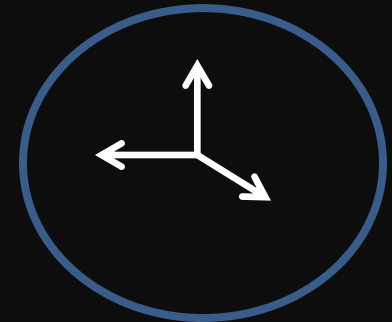- Cosmic web of dark matter particles identified with ORIGAMI (BF+ 2012, 1201.2353)
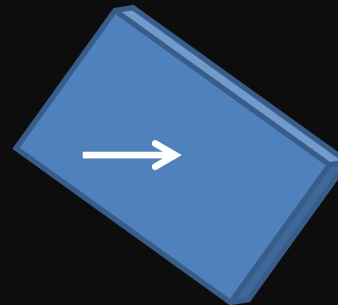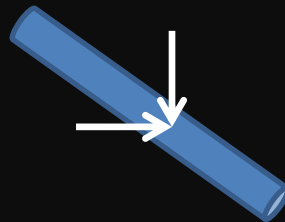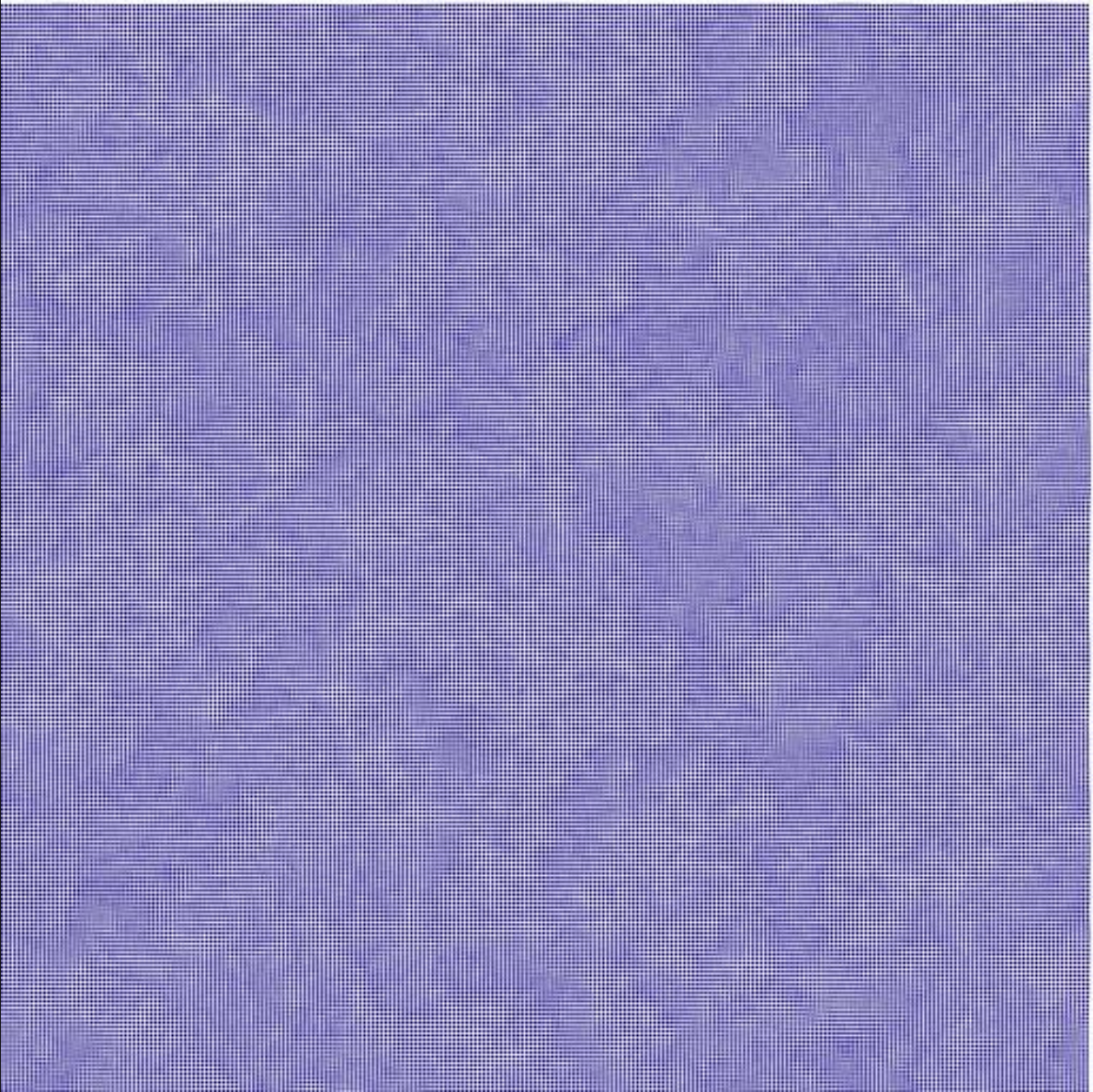
The ORIGAMI Cosmic Web
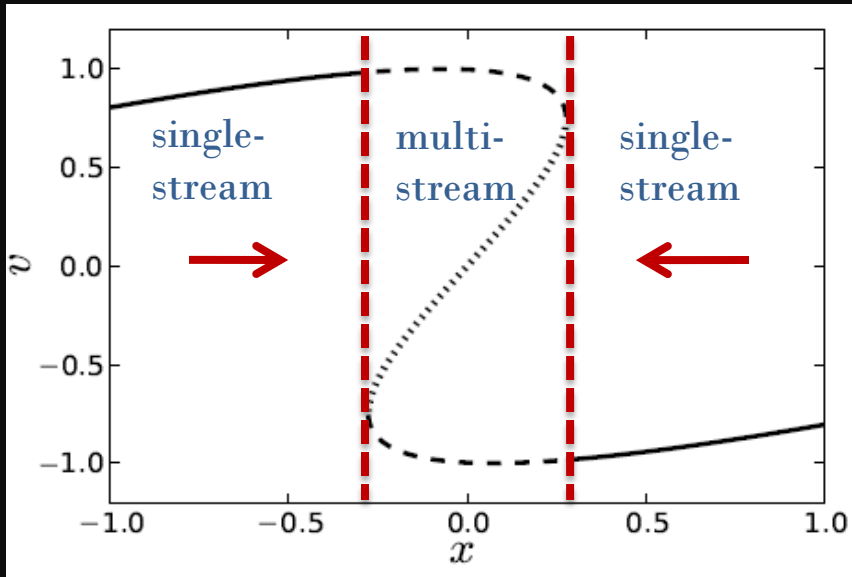
Find the phase-space folds by looking for simulation particles that are out of order along orthogonal axes
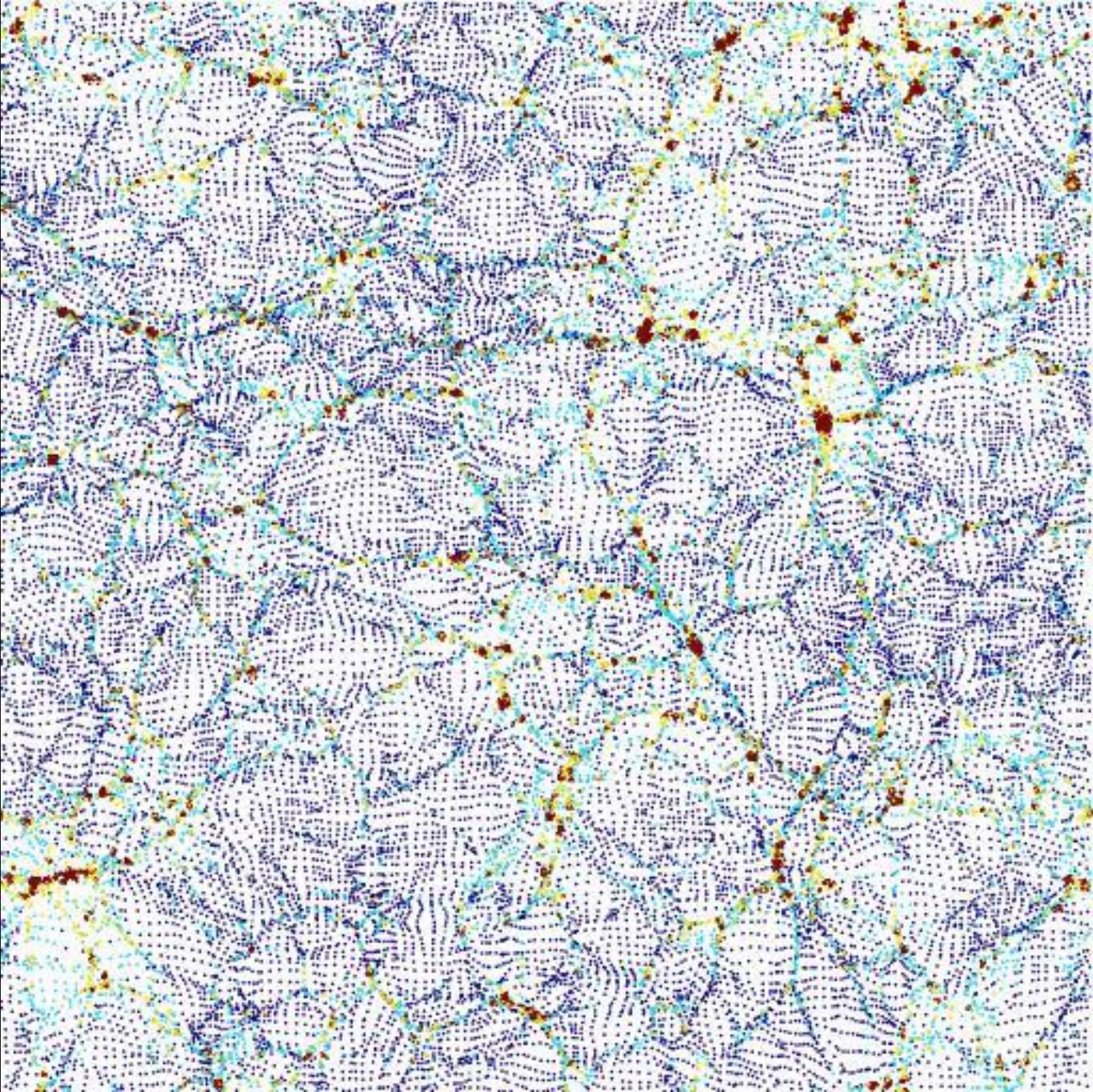
(Falck, Neyrinck, & Szalay 2012, 1201.2353)

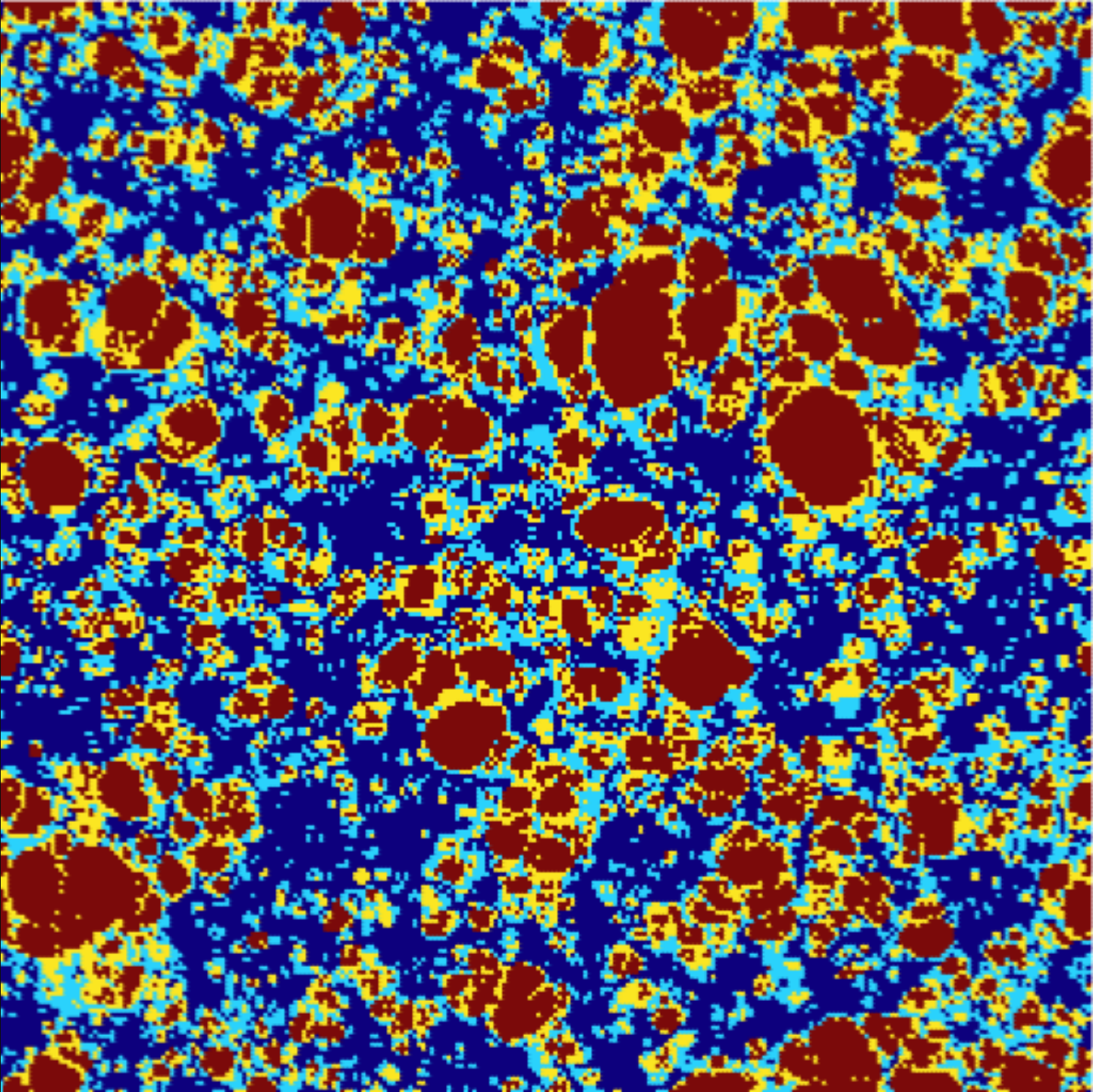Halos collapse along 3 axes, Filaments 2, Walls 1, and Voids 0

Halo
Filament
Wall
Void

Halo
Filament
Wall
Void

Halo
Filament
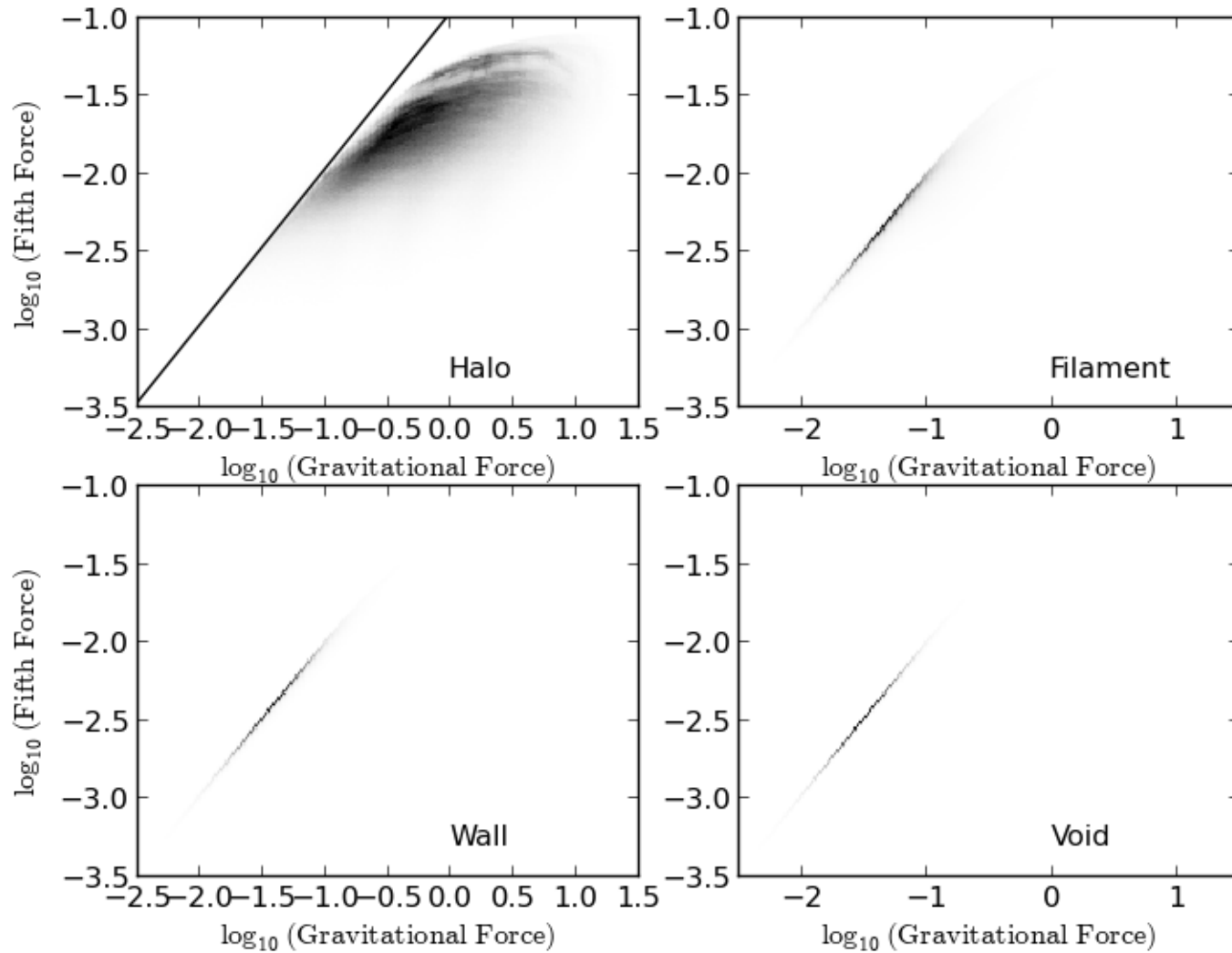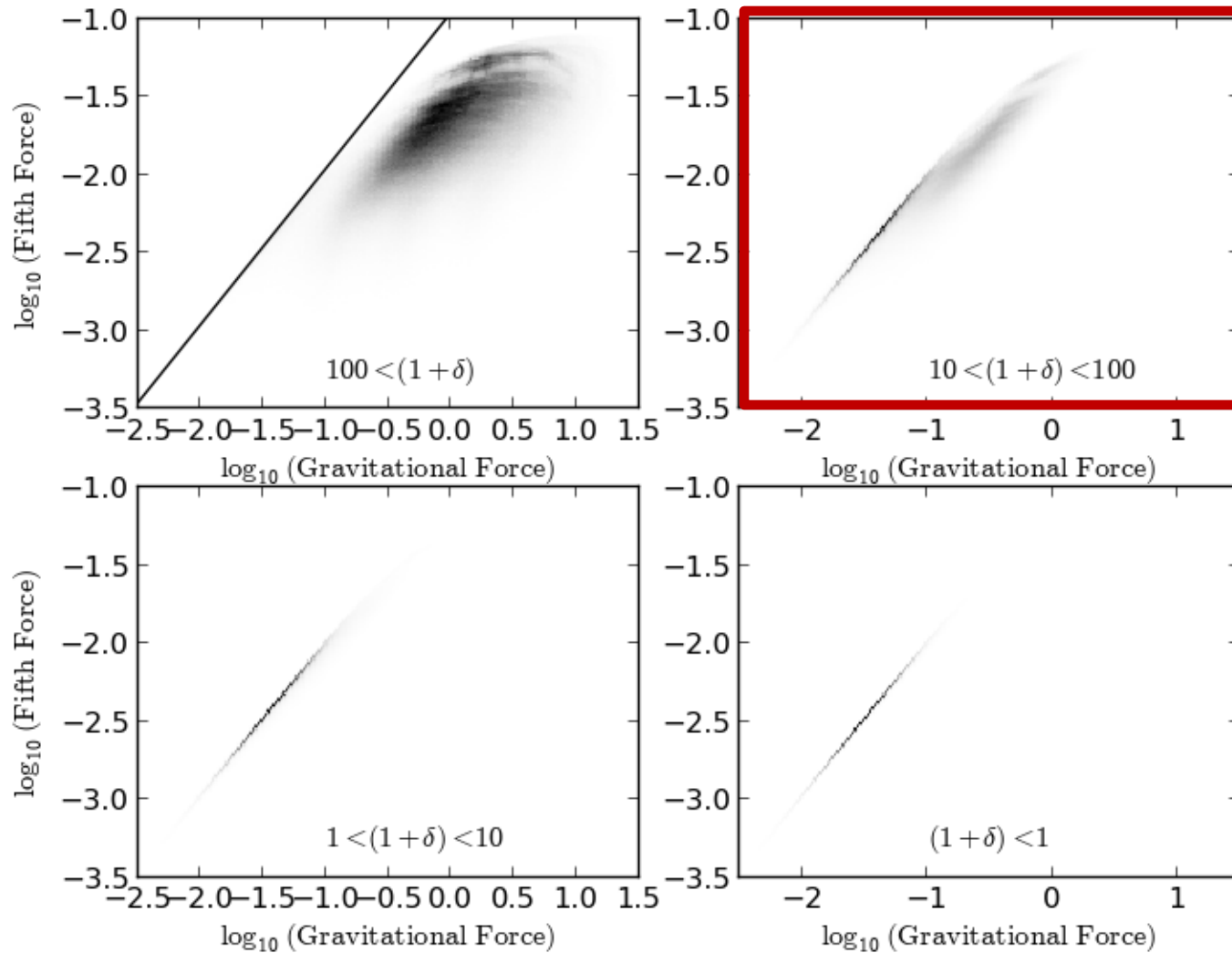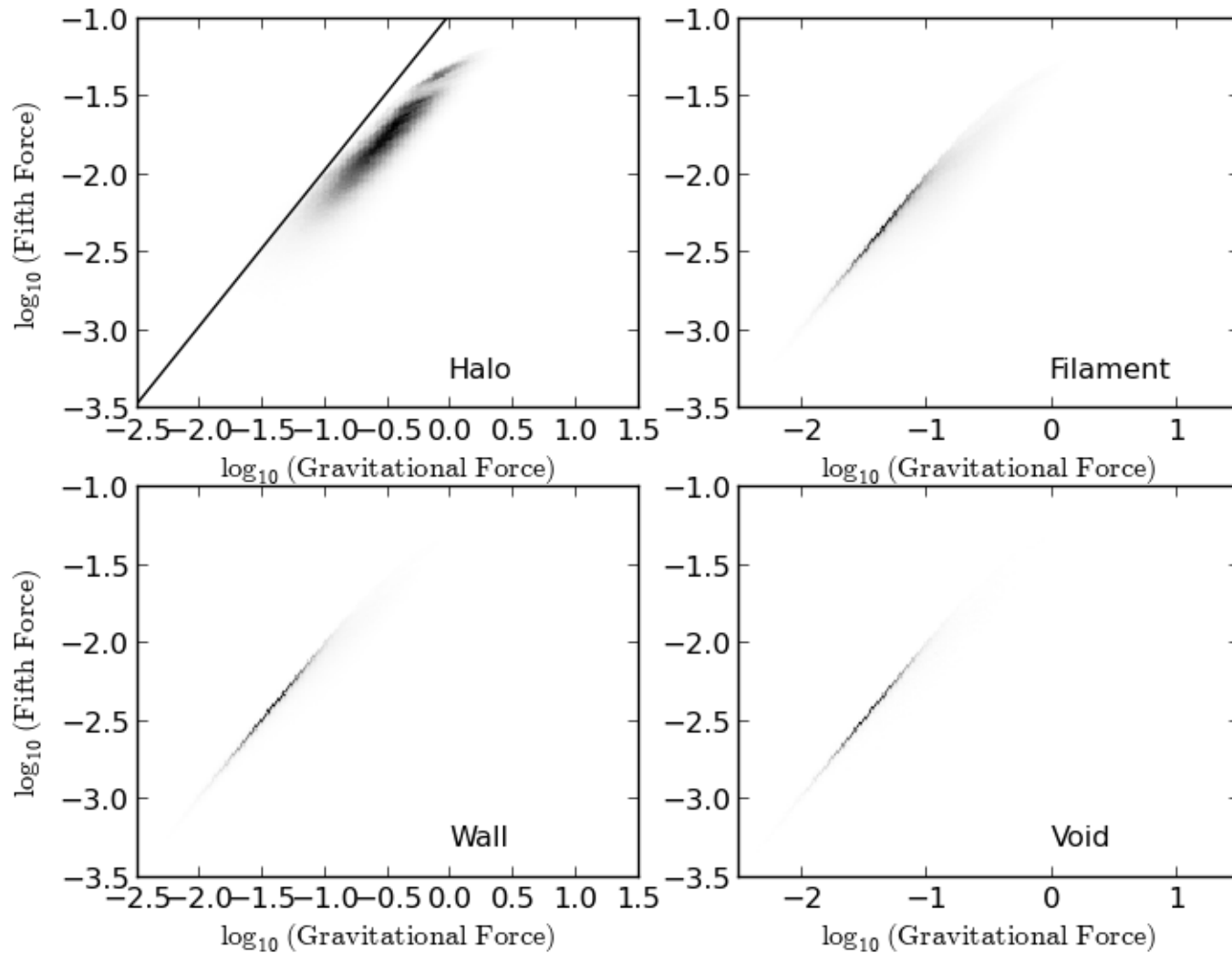Wall
Void

Vainshtein Screening of Dark Matter Particles

Vainshtein Screening of Dark Matter Particles
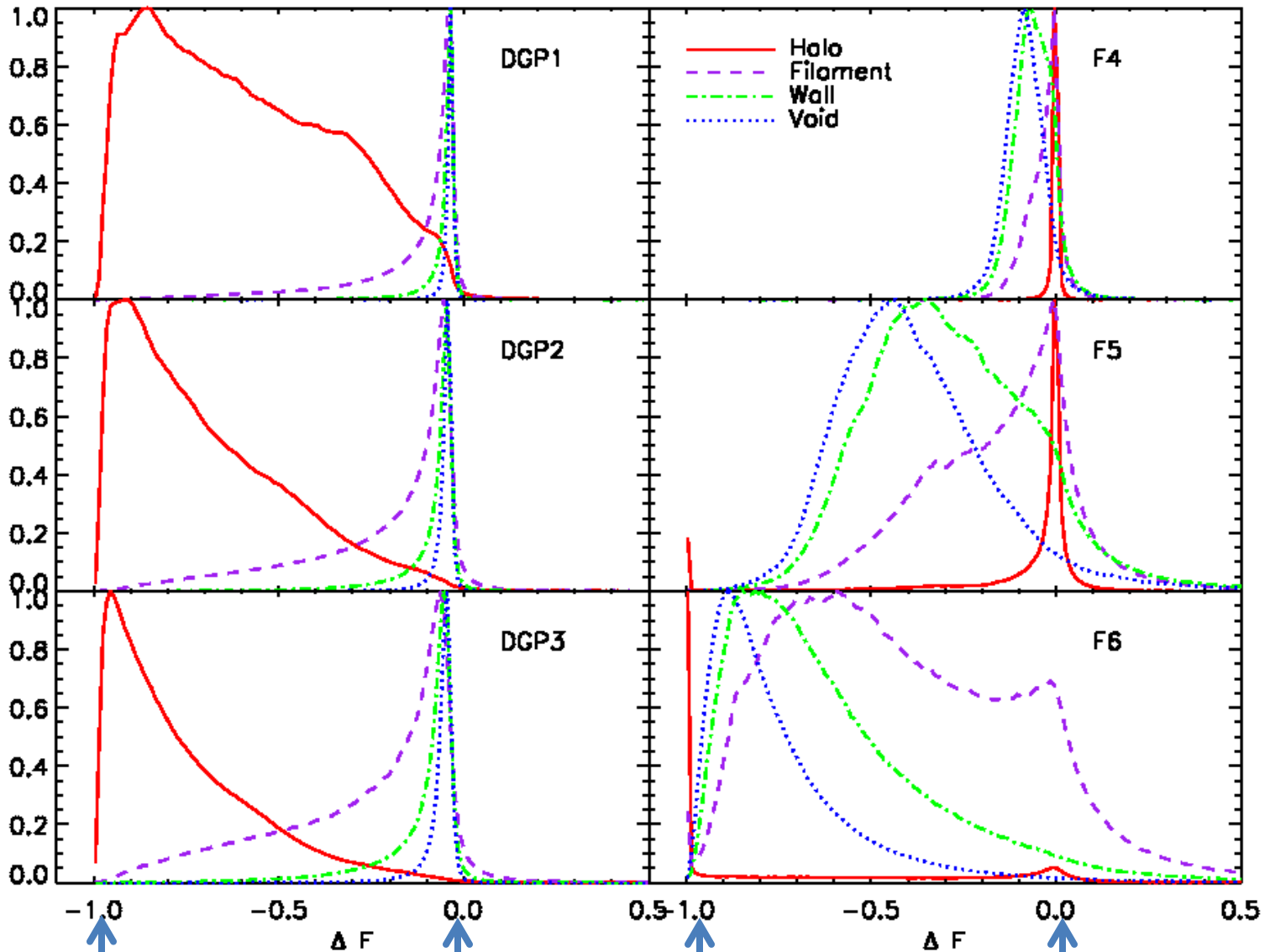
Vainshtein Screening of Dark Matter Particles

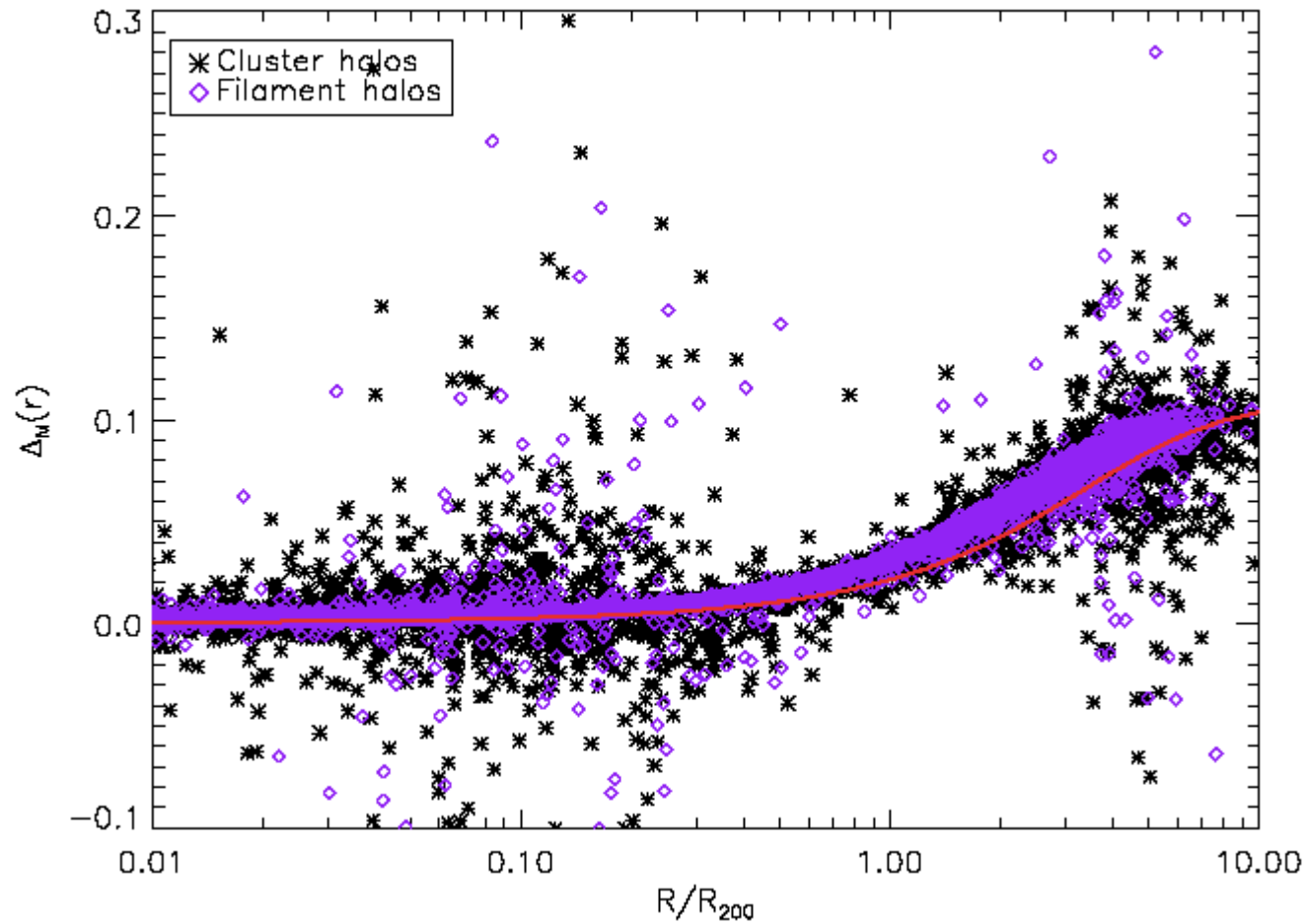# Vainshtein

Chameleon

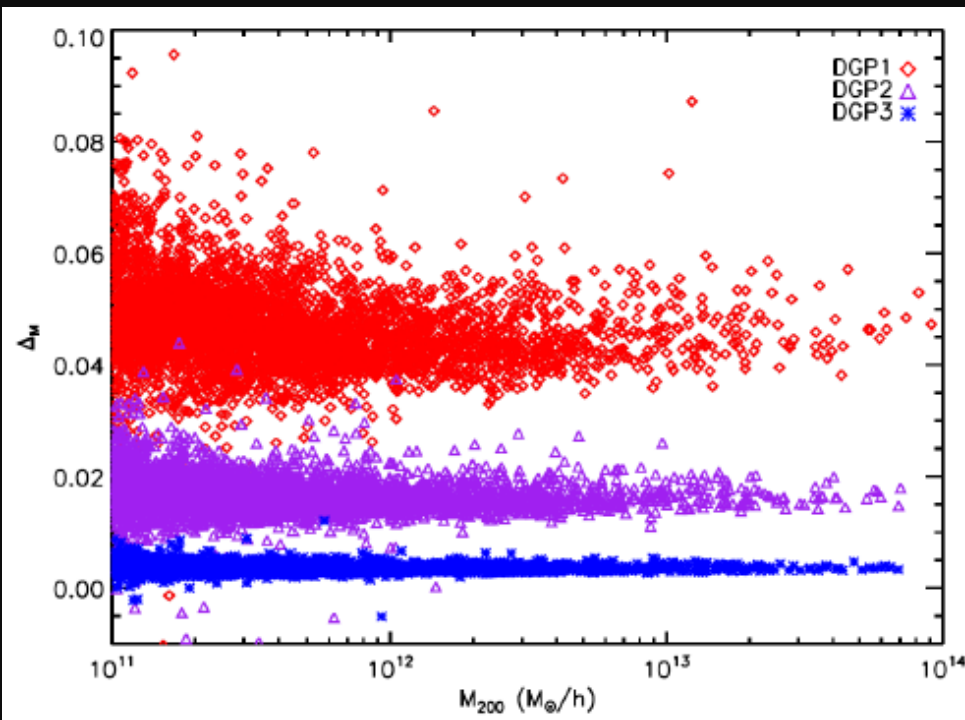screened   unscreened   screened   unscreened
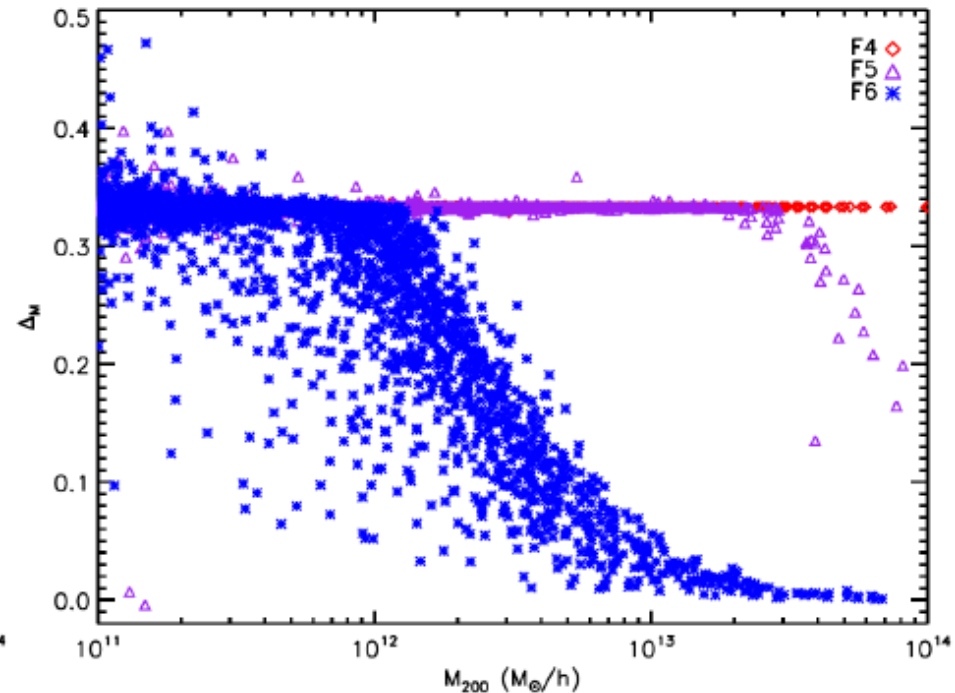
Vainshtein Screening Profile

Screening vs. Halo Mass

Vainshtein

Chameleon

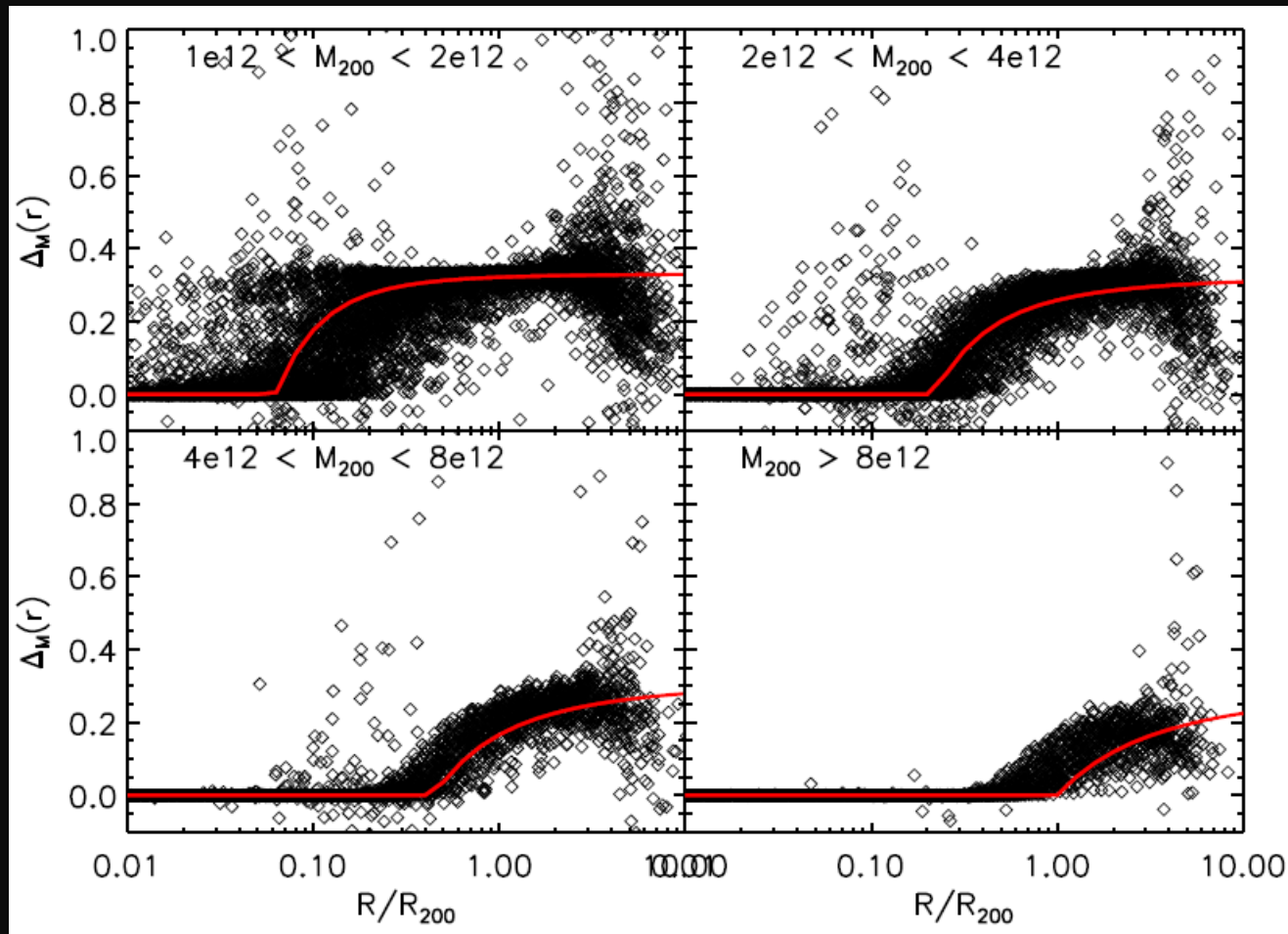Linear (unscreened) $\Delta_M = 0.2$ (red), 0.11 (purple), 0.03 (blue)
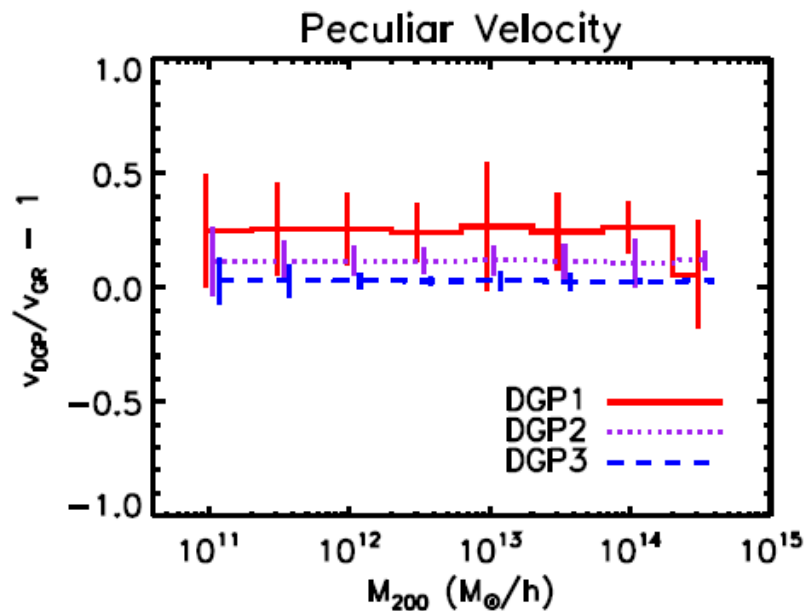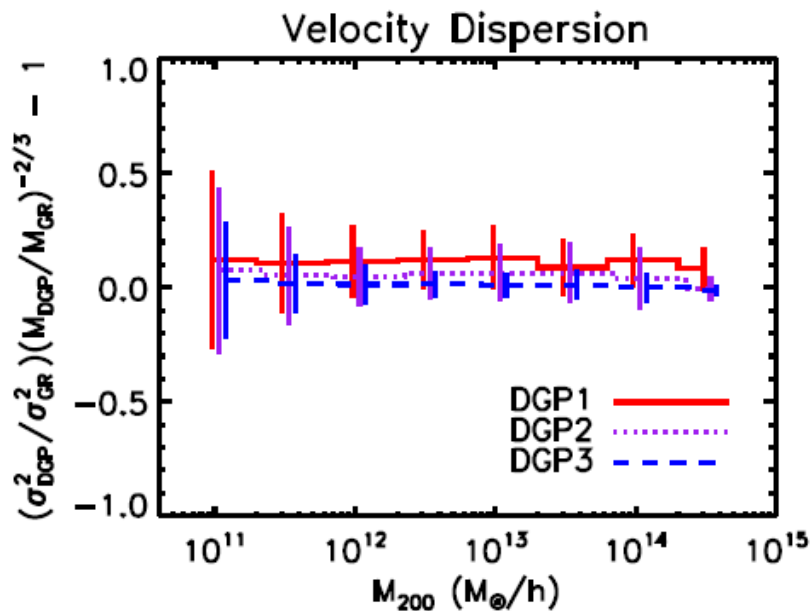
Linear (unscreened) $\Delta_M = 0.33$

(see also Schmidt 2010, 1003.0409)

Chameleon Screening Profiles

Fifth Force / Gravitational Force

Vainshtein

Velocity Dispersion

$\left(\sigma^2_{DGP}/\sigma^2_{GR}\right)\left(M_{DGP}/M_{GR}\right)^{-2/3} - 1$

M_{200} $(M_\odot/h)$

DGP1
DGP2
DGP3

Peculiar Velocity

$v_{DGP}/v_{GR} - 1$

M_{200} $(M_\odot/h)$

DGP1
DGP2
DGP3

Chameleon

Velocity Dispersion

$\left(\sigma^2_{FR}/\sigma^2_{GR}\right)\left(M_{FR}/M_{GR}\right)^{-2/3} - 1$

M_{200} $(M_\odot/h)$

F4
F5
F6

Peculiar Velocity

$v_{FR}/v_{GR} - 1$

M_{200} $(M_\odot/h)$

F4
F5
F6
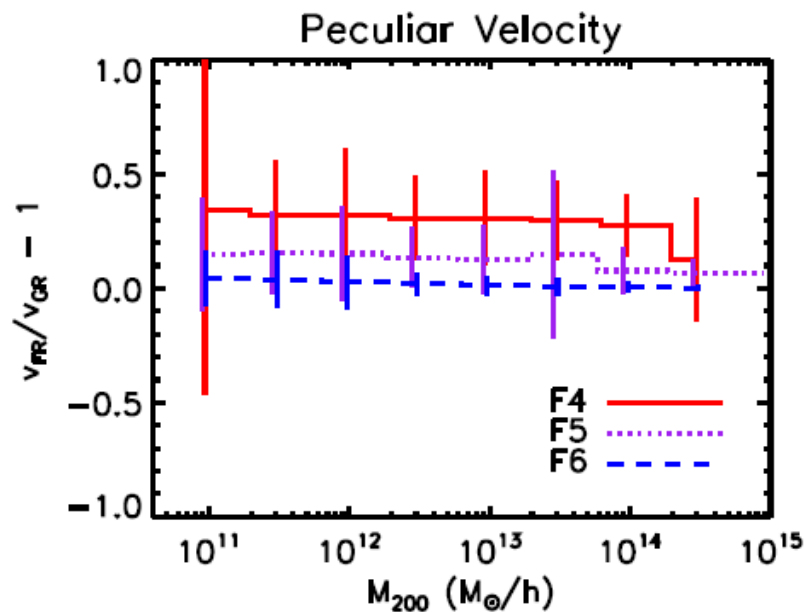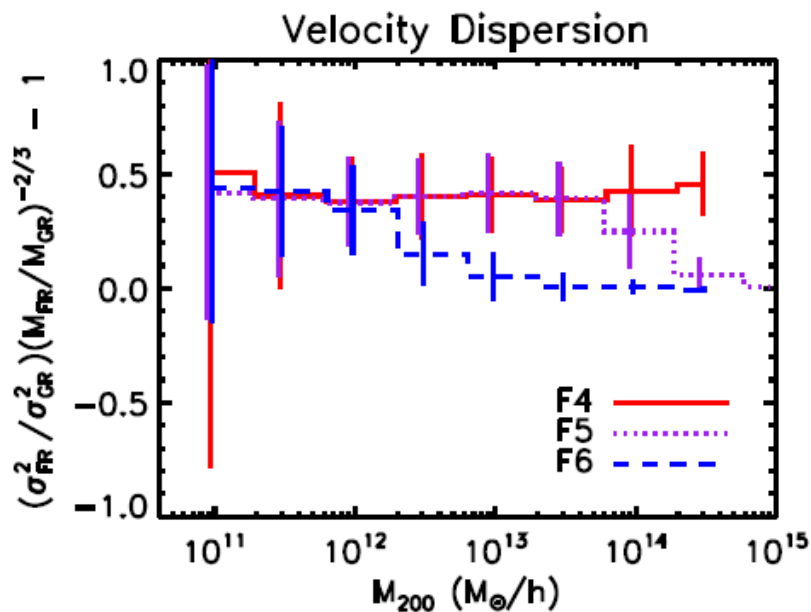
Screening vs. Environmental Density
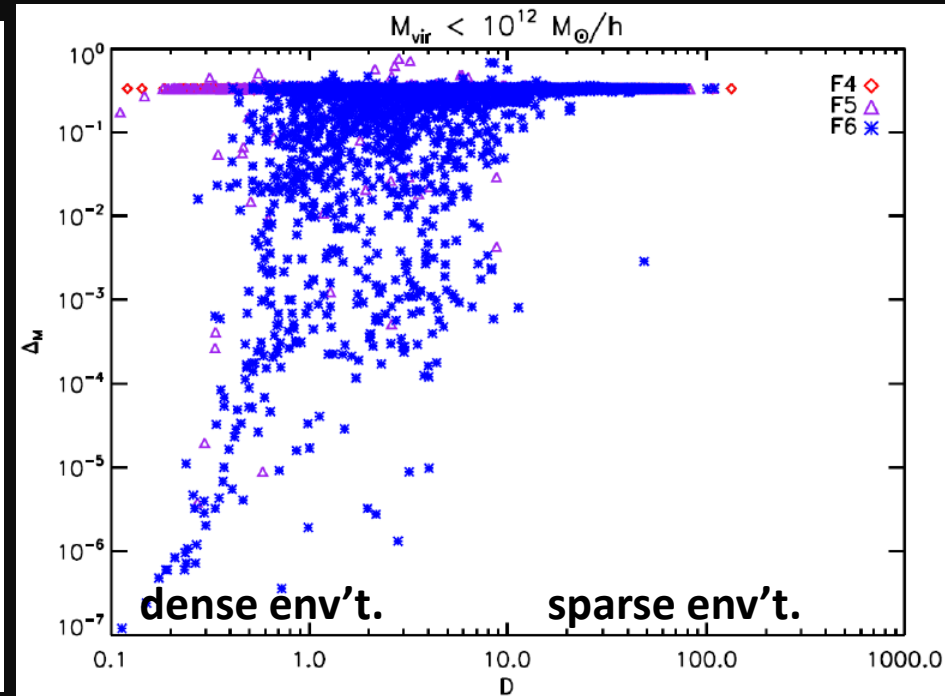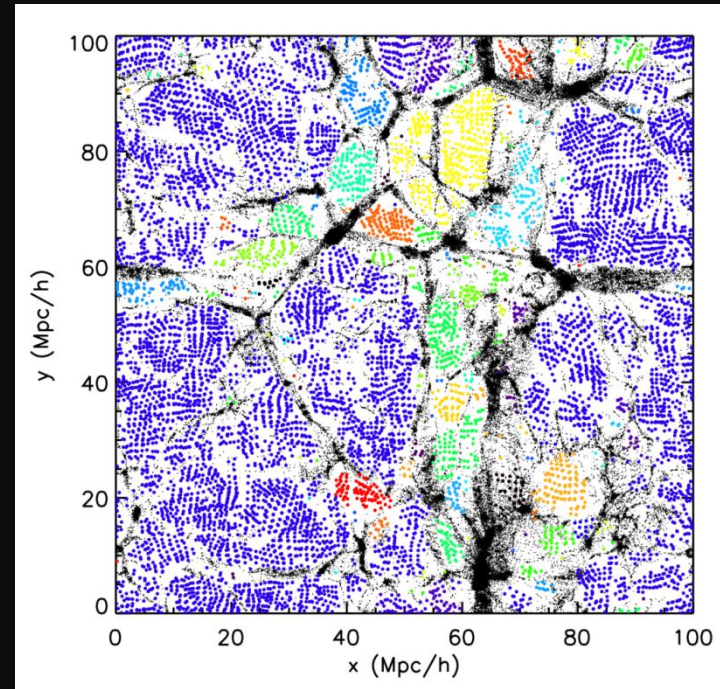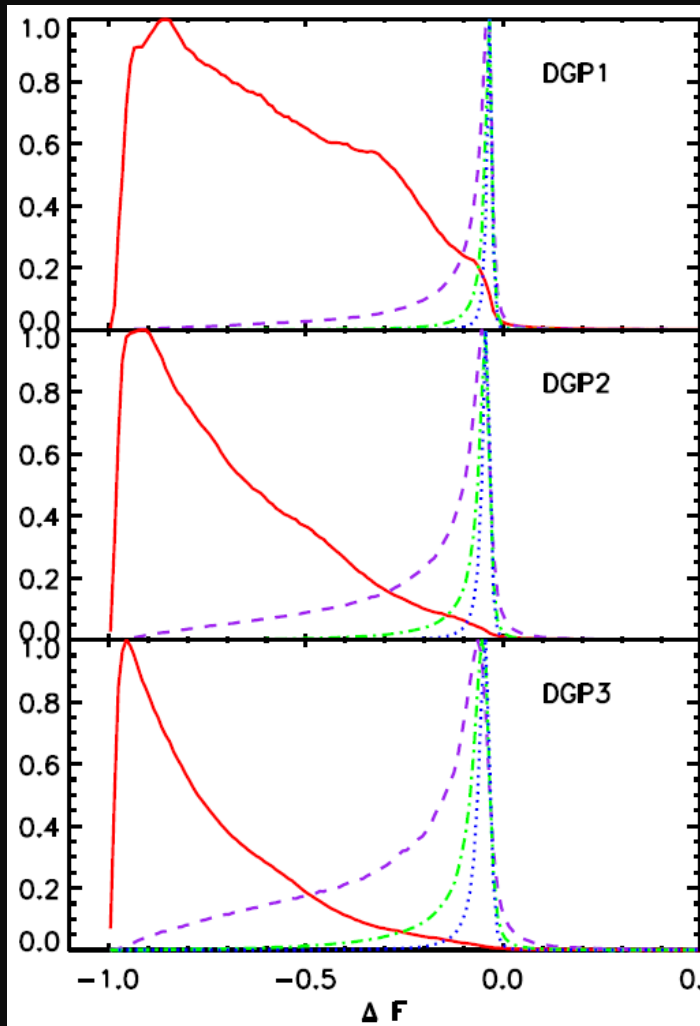
Vainshtein
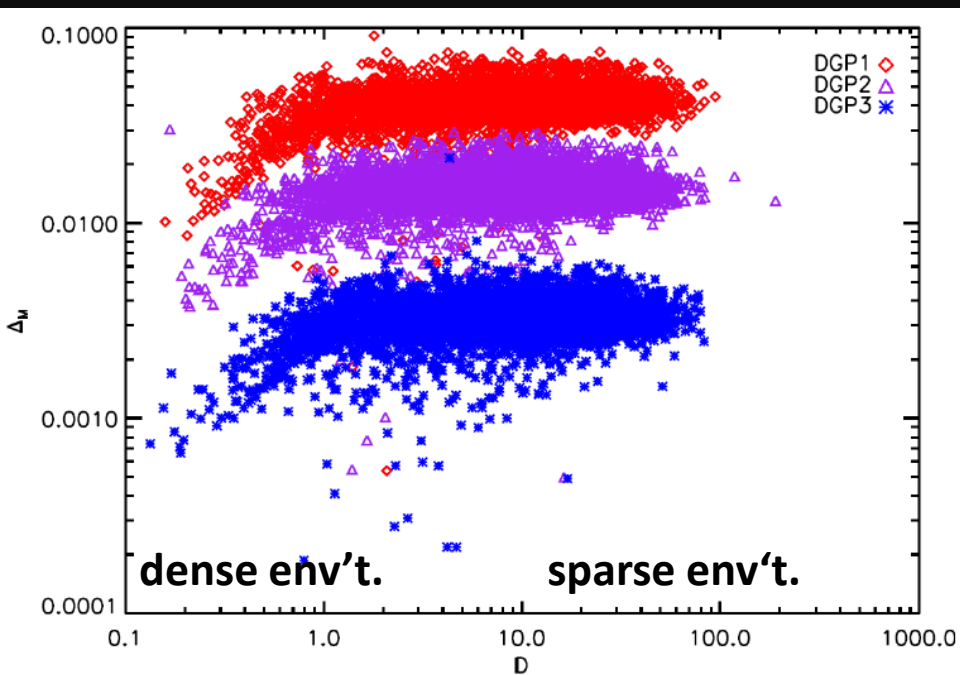
Chameleon

Linear (unscreened) $\Delta_M = 0.2$
(red), 0.11 (purple), 0.03 (blue)

Linear (unscreened) $\Delta_M = 0.33$

(see also Zhao et al. 2011, 1105.0922)

What about voids?

But single-stream regions not surrounded on all sides by walls & filaments – *single-stream voids percolate* (Falck & Neyrinck 2015, 1410.4751)

Summary

- ORIGAMI identifies cosmic web by finding folds in phase space
  - (Falck, Neyrinck, & Szalay 2012, 1201.2353)

- The *Vainshtein mechanism* depends on cosmic web morphology of dark matter particles, not mass or environment
  - (Falck, Koyama, Zhao, & Li 2014, 1404.2206)

- The *chameleon mechanism* depends on mass and environment, not cosmic web
  - (Falck, Koyama, & Zhao 2015, 1503.06673)

- Single-stream regions (voids) *percolate,* not surrounded by walls
  - (Falck & Neyrinck 2015, 1410.4751)