Assembly bias in the cosmic web

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MNRAS 476 (2018)
with C.Pichon, C.Cadiou, S.Codis, K.Kralijc, Y.Dubois
and earlier works

Analytical Methods – IHP, September 2018

About ICTP-EAIFR

- East African Institute for Fundamental Research
- A new ICTP partner institute in Kigali, Rwanda, within Univ of Rwanda
- A science hub for Africa
- Students, resident scientists, visitors and scientific activities
- In close collaboration with ICTP in Trieste

About ICTP-EAIFR

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Introduction

- PART I. Assembly bias from conditional excursion sets
- PART II. Work in progress on extrema statistics for LSS

Introduction

- Assembly bias (“there’s more to a halo than its mass...”) is somewhat of an obvious statement. The opposite would be surprising
- Surprisingly difficult to find the optimal variables to parametrize it
- Most quantities have unexpected behaviors in some regime
- Because halos are not isolated, their position in the cosmic web is an obvious candidate to explain the diversity of hosted galactic populations
- Observationally relevant: surveys (VIPERS, COSMOS, GAMA) find different mean colors as a function of the distance to the cosmic web

Excursion set theory

DM halos form out of patches in the initial conditions that:

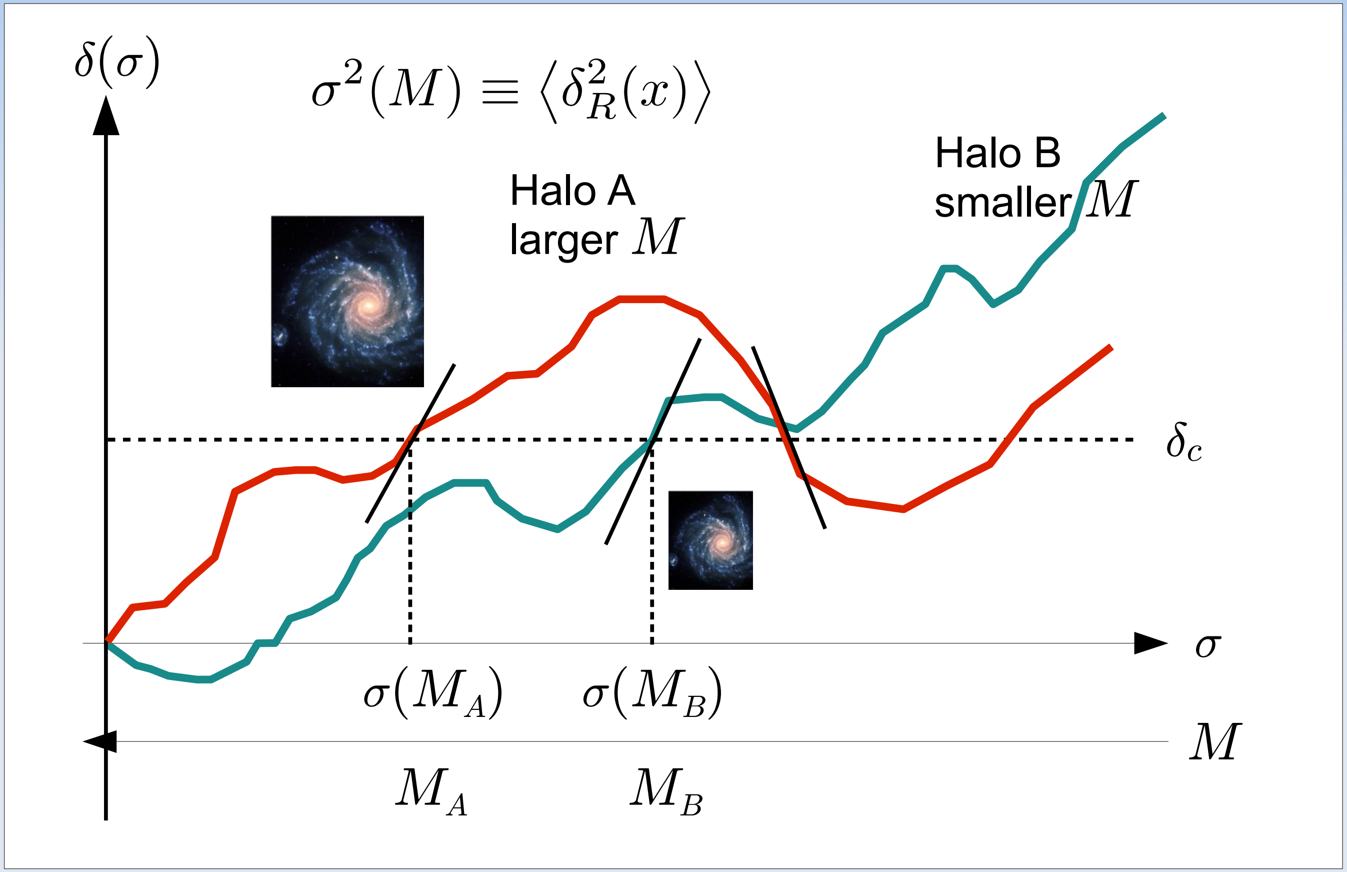
- are overdense “enough” to collapse by today (“enough” inferred from spherical collapse, $\delta_c = 1.686$ in vanilla models)
- are not contained in larger patches of the same density (“no cloud-in-cloud”)

$$\delta_R(\mathbf{x}) \equiv \int \frac{\mathrm{d}^3k}{(2\pi)^3}\, e^{i\mathbf{k}\cdot\mathbf{x}}\, W_{\mathrm{TH}}(kR)\, \delta_{\mathrm{lin}}(\mathbf{k}) \geq \frac{\delta_c}{D(z)}$$

- described as random walks of mean density field reaching a threshold (solution of Langevin equation with colored noise)
- abundance modeled as first-passage PDF with correlated steps
- close analogies with (P)BHs and stochastic inflation

Excursion set theory

- At each position $\mathbf{x}$, $\delta_R(\mathbf{x})$ draws a trajectory as R changes



- Scale σ of first crossing fixes M $(= 4\pi R^3 \rho/3)$
- First crossing is always upwards (positive slope)

From first crossing to upcrossing

- Abundance of halos $n_h(M)$ $\longleftrightarrow$ first crossing pdf $f(\sigma)$
- But steps are correlated (not Markovian walks): $f(\sigma)$ is not known
- However, correlations make zig-zags unlikely. Can relax **FIRST** into **UPWARDS.** Probability that $\delta = \delta_c$ and $\delta' \equiv \mathrm{d}\delta/\mathrm{d}\sigma \geq 0$

$$f_{\rm up}(\sigma) = \int_0^\infty \mathrm{d}\delta'\, \delta'\, p(\delta', \delta = \delta_c)$$

MM & Sheth (2012)

- For Gaussian field:

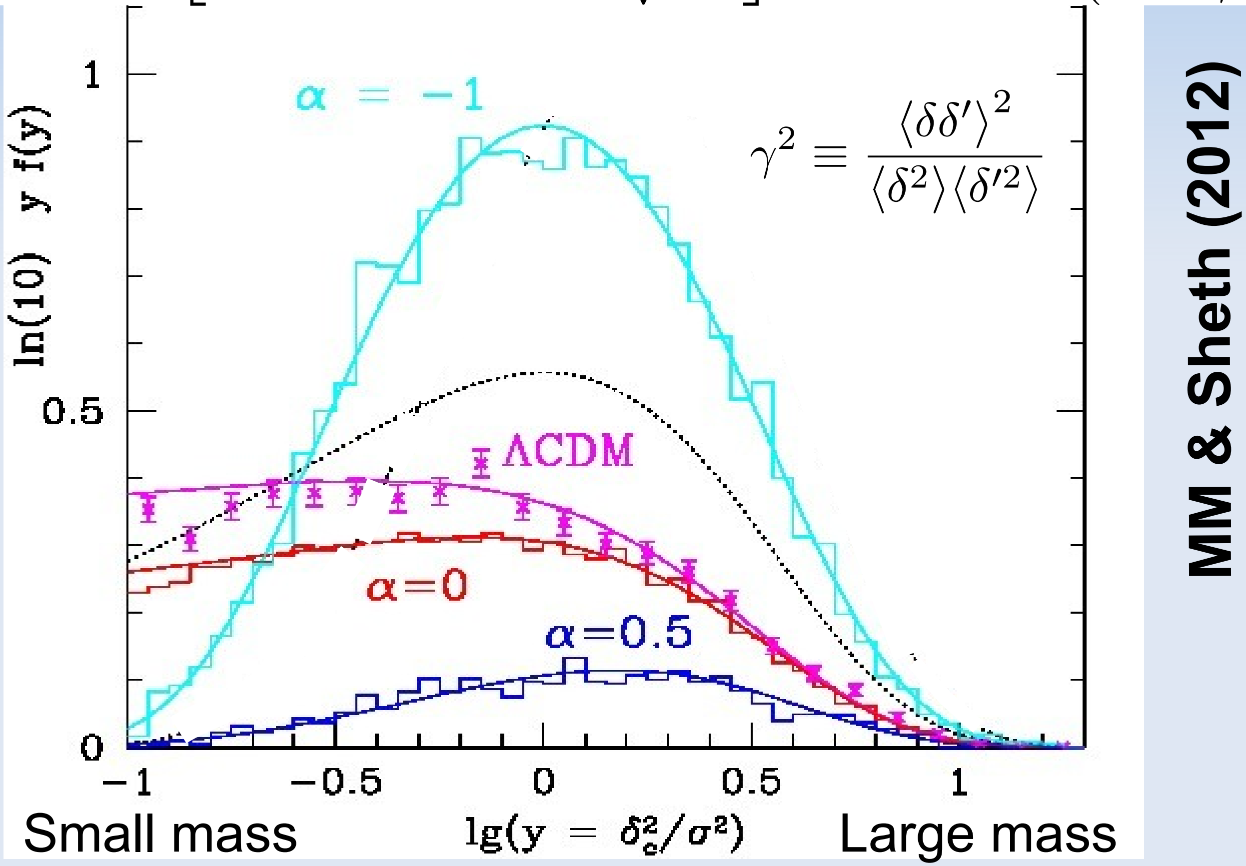
$$f_{\rm up}(\sigma) = f_{\rm PS}(\sigma)\left[\frac{1+\mathrm{erf}(X)}{2} + \frac{e^{-X/2}}{X\sqrt{2\pi}}\right], \qquad X^2 \equiv \frac{\gamma^2\delta_c^2}{(1-\gamma^2)\sigma^2}$$

Bond et al. (1991)

- Very accurate approximation! (also in NG case) **MM & Sheth (2012-2014)**

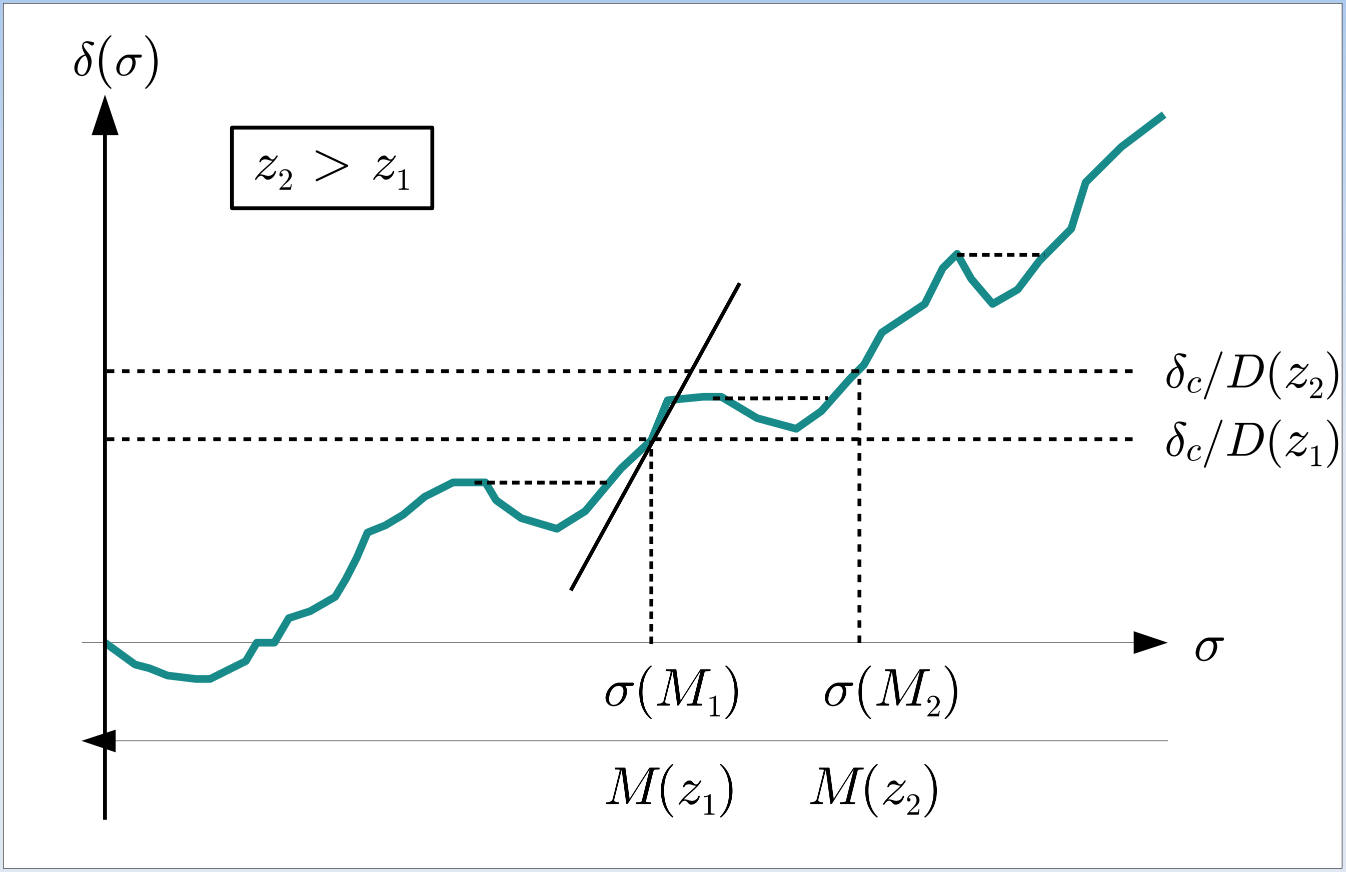
Upcrossing distribution

$$f_{\rm up}(s) = f_{\rm PS}(s)\left[\frac{1+{\rm erf}(X)}{2} + \frac{e^{-X/2}}{X\sqrt{2\pi}}\right], \qquad X^2 \equiv \frac{\gamma^2\delta_c^2}{(1-\gamma^2)s}$$



Check against exact first crossing of Monte Carlo walks (histograms) with various power spectra and generic barrier $b = \delta_c + \alpha s$. Dotted line is Bond et al. (sharp-k)

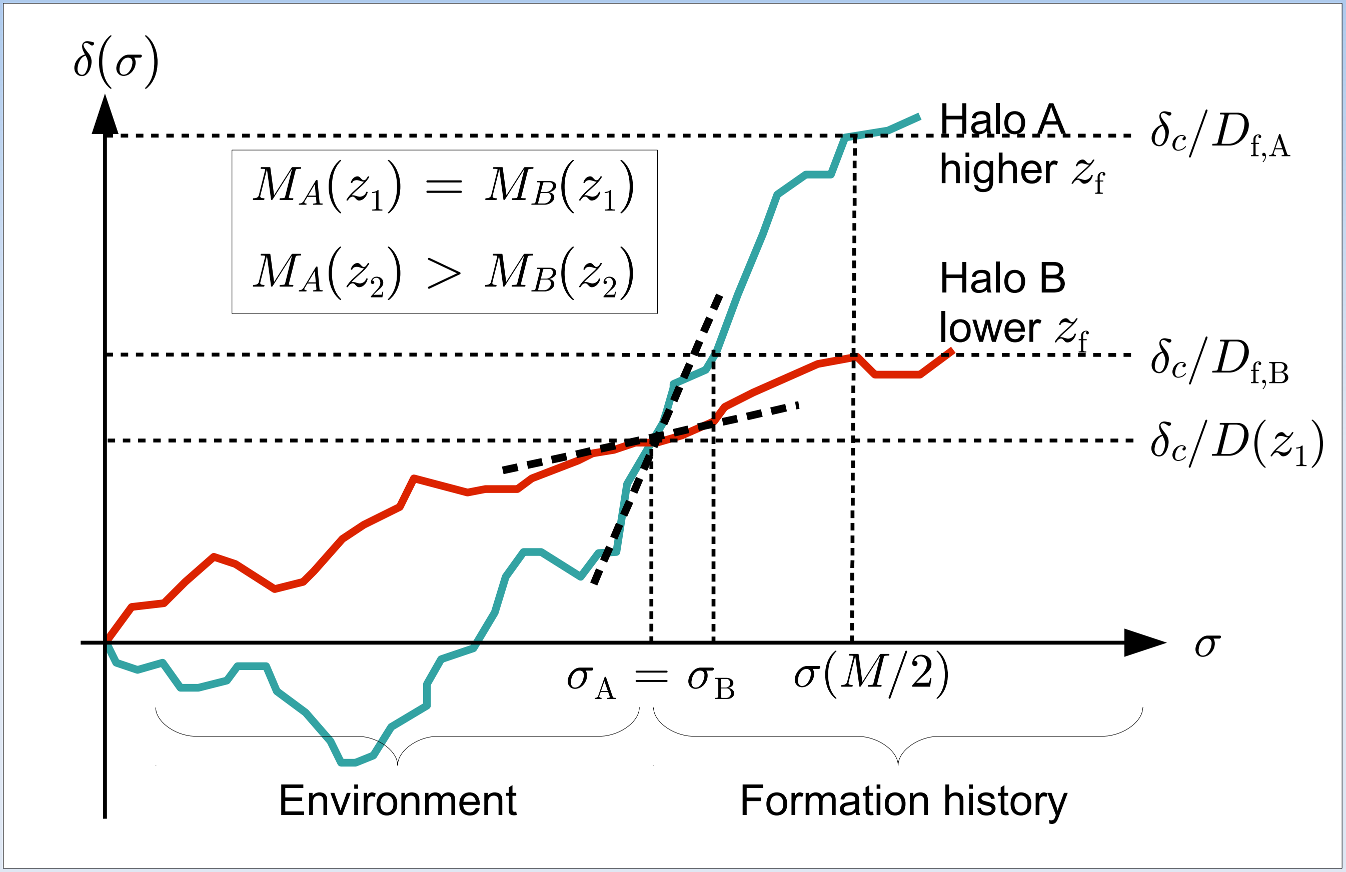
Formation history



- As threshold drops with time, first crossing moves/jumps to larger M
- Continuous growth of M is accretion, finite jumps are mergers. Whole formation history $M(z)$ in the trajectory. Slope gives 1/accretion rate.

Lacey and Cole (1993)

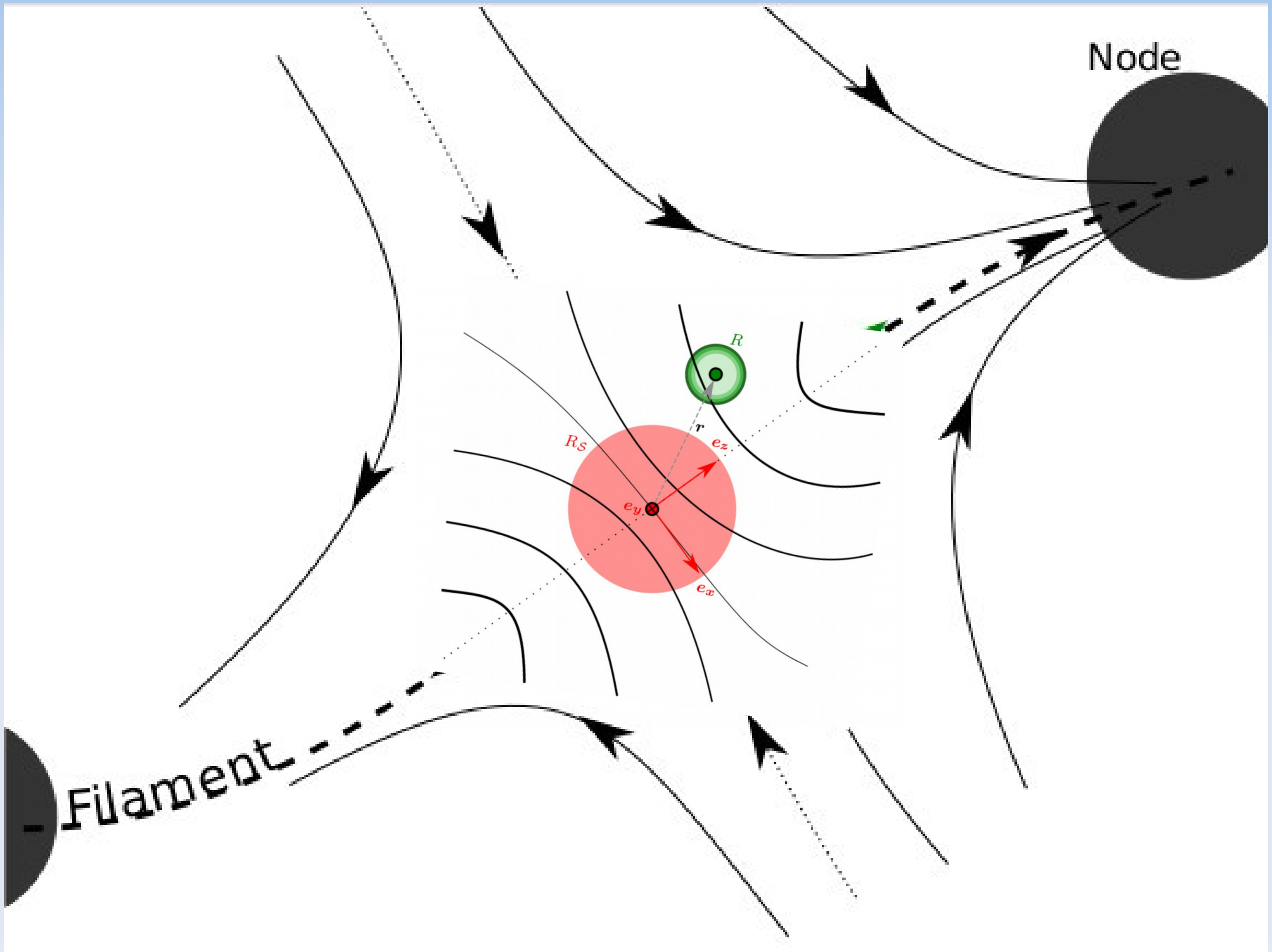
Accretion rate and formation time



- Same mass at z_1, but σ_A varies less with z : slower accretion. At $\sigma(M/2)$ halo A crosses a higher threshold : forming earlier
- But sharp turns are unlikely: B prefers denser environment than A (not so for uncorrelated steps). Assembly bias!

Dalal et al. (2008)

Saddle point of the potential



Saddle point of the potential

- Mean potential in sphere of radius R_s $$\phi_s = -\int \frac{\mathrm{d}^3k}{(2\pi)^3} \frac{\delta(\mathbf{k})}{k^2} \frac{3j_1(kR_s)}{kR_s}$$

- One neg. eigenvalue of shear: $$q_{ij} \equiv \frac{\nabla_i \nabla_j \phi_s}{\sigma^2(R_s)} = \frac{\delta_{ij}}{3}\nu_s + \bar{q}_{ij}$$

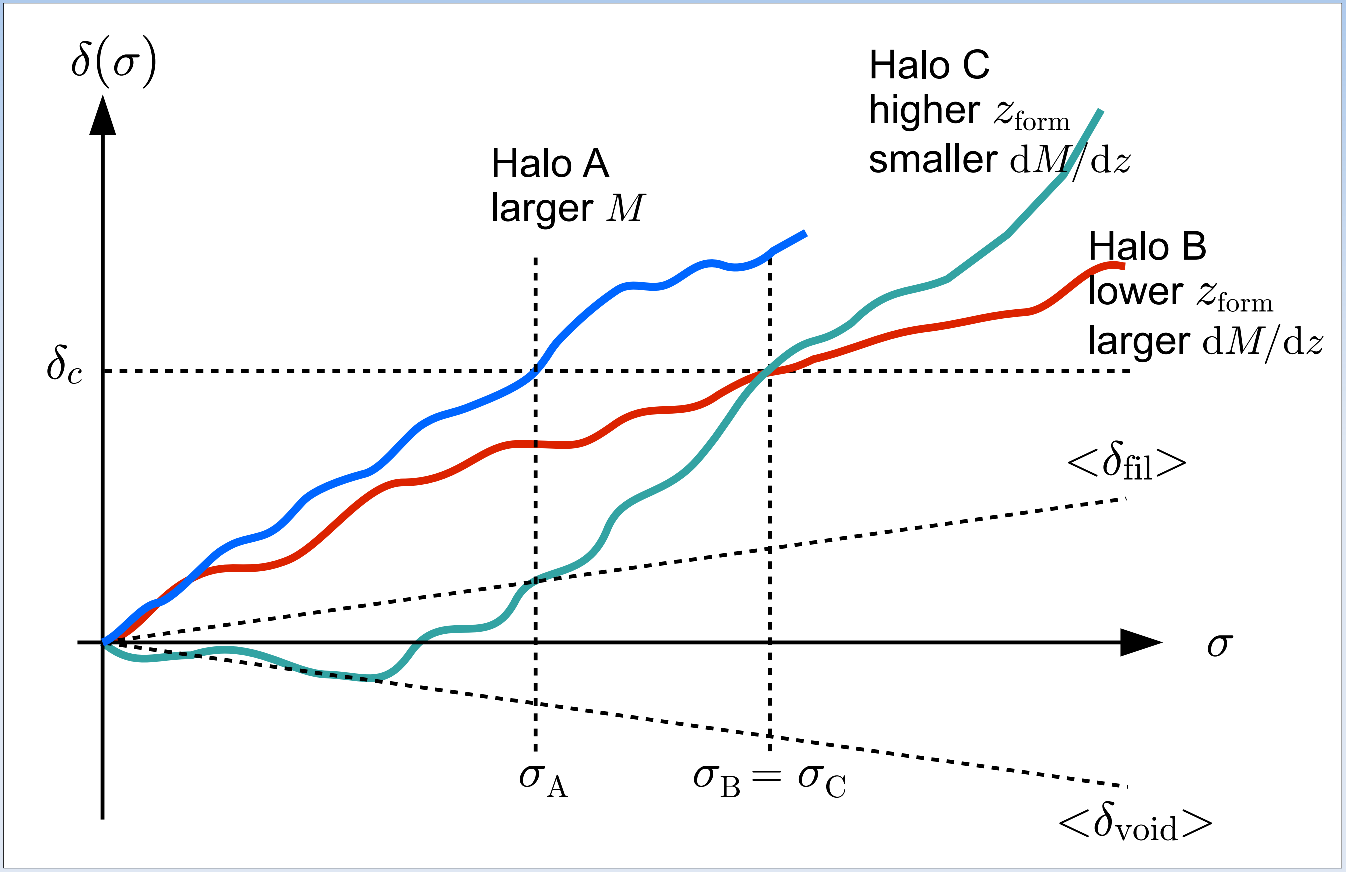
- Anisotropic conditional mean density (at fixed finite distance):

$$\langle \delta_R(\mathbf{r}) | \mathrm{saddle} \rangle = \xi_{00}(r)\nu_s - 5\xi_{20}(r)\frac{3\hat{r}_i \bar{q}_{ij} \hat{r}_j}{2} ,$$

anisotropy

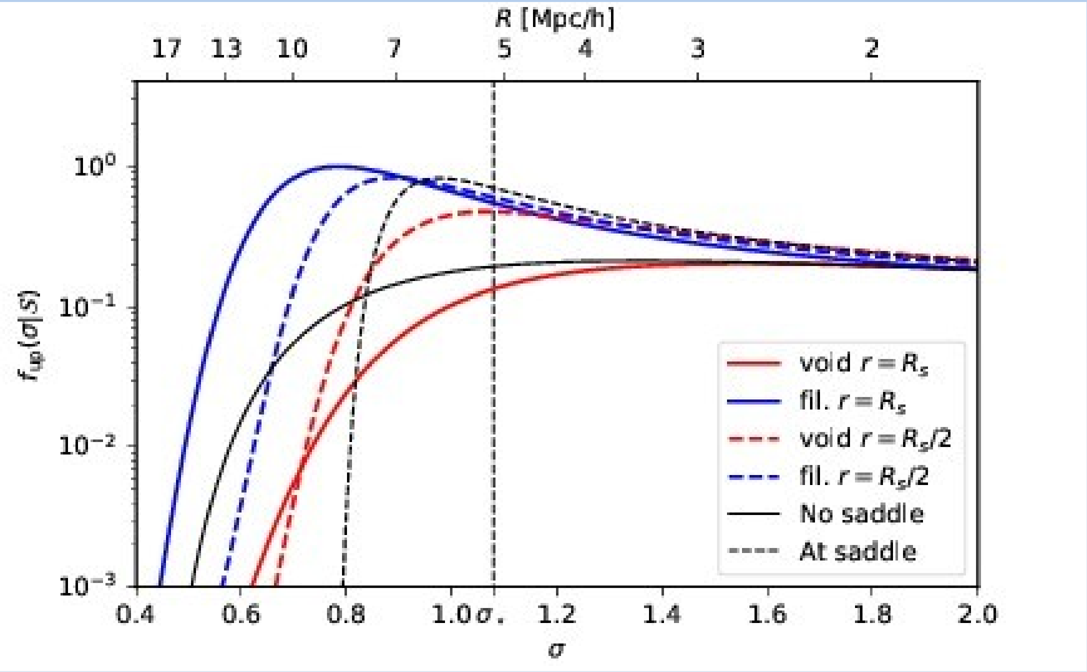
- Saddles of the potential are saddles of the conditional mean of δ. Outflowing direction (filament) has higher mean density.

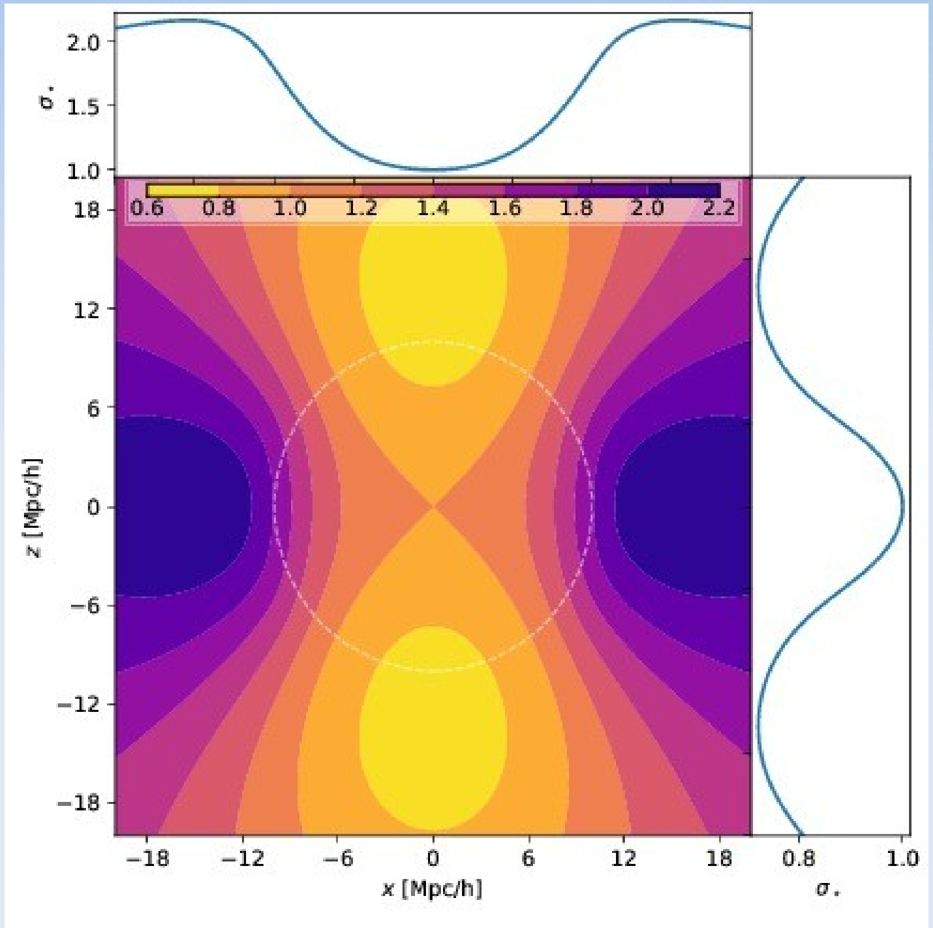
Assembly bias



- Halo A (filament): large $\langle \delta | S \rangle$, more likely, smaller σ, larger M
- Halo B (filament): low $\langle \delta | S \rangle$, less likely, larger σ, smaller M
- Halo C (void): same σ as B, shallow slope, low accr., early forming

Assembly bias

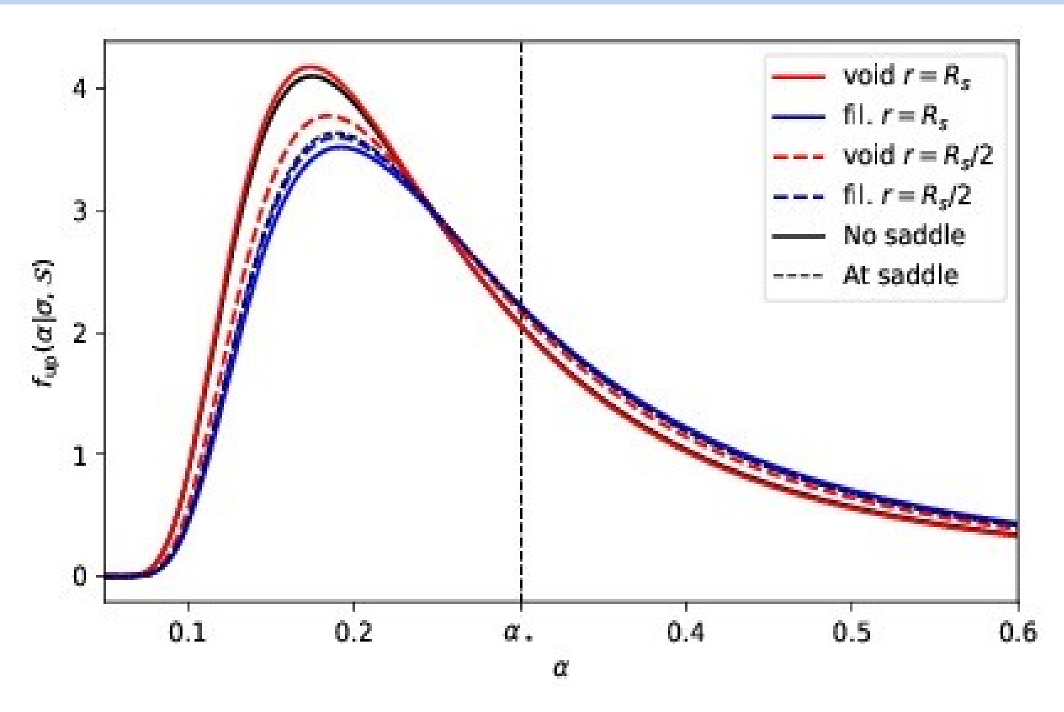


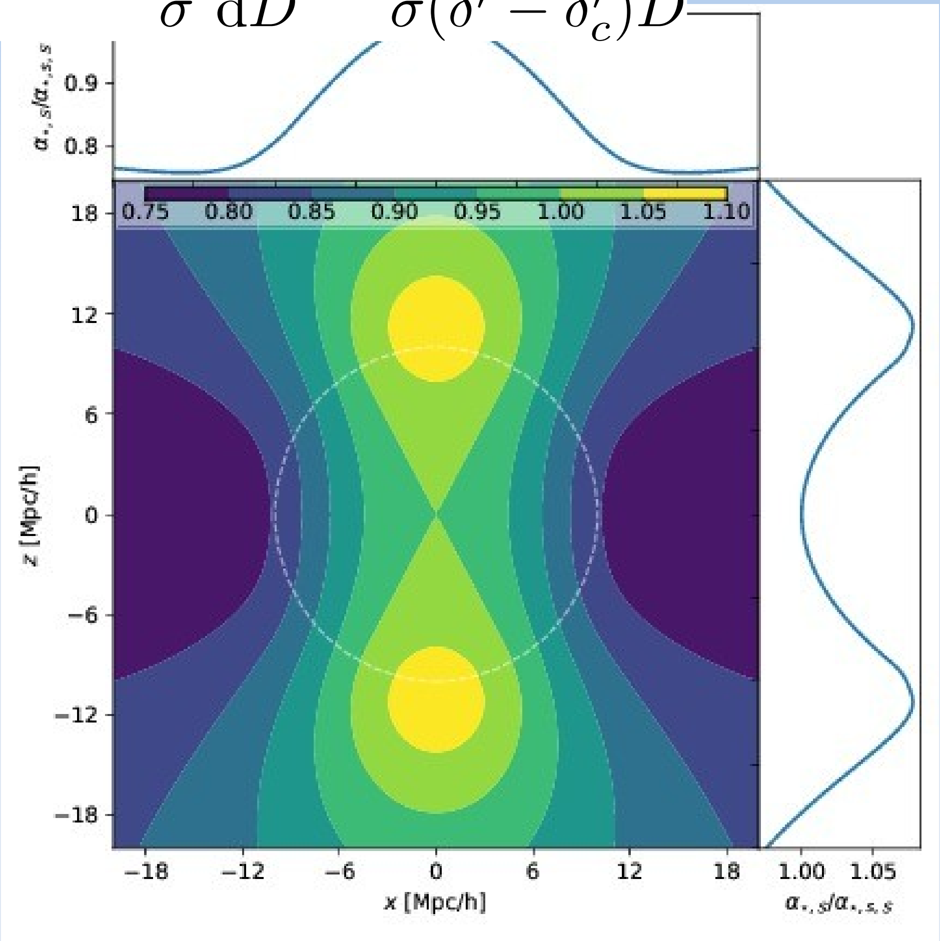


- Saddle point of typical mass too.
- Max of $\sigma_\star$ and min of $M_\star$ along the filament. Moving away from nodes, halos are less massive

Assembly bias

$$\frac{\mathrm{d}(\delta-\delta_c)}{\mathrm{d}\sigma(D)}\frac{\mathrm{d}\sigma}{\mathrm{d}D}=-\frac{\delta_c}{D^2} \qquad \alpha\equiv-\frac{D}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}D}=\frac{\delta_c}{\sigma(\delta'-\delta_c')D}$$



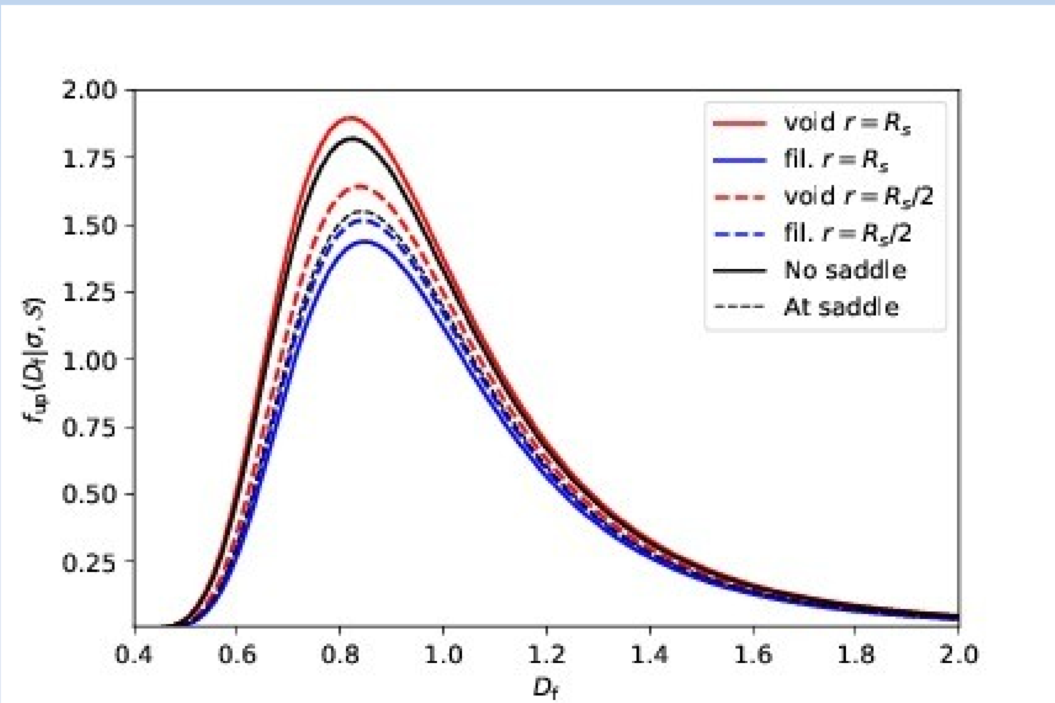


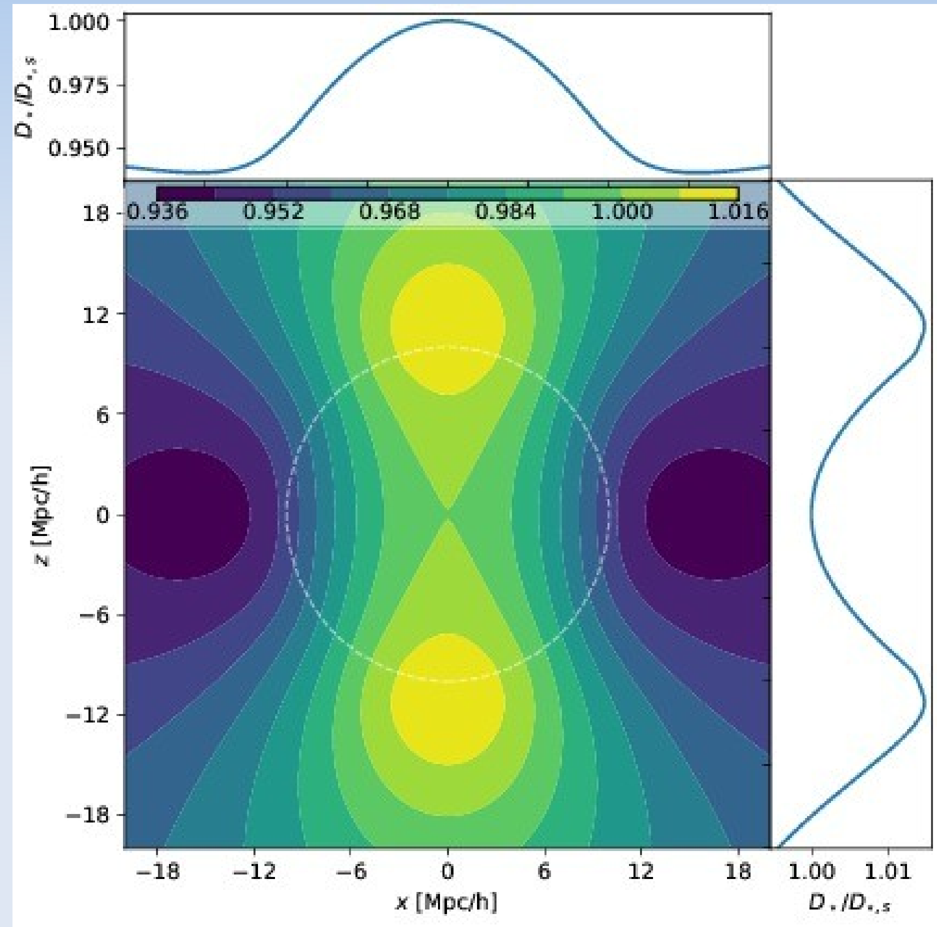
PDF of α has typical accretion rate $\alpha_\star$

- Slowly accreting halos (small $\alpha_\star$) are more likely in voids
- Larger $\alpha_\star$ near saddle point and even larger near nodes

Assembly bias

$$\frac{\delta_c}{D_{\rm form}} \equiv \delta(\sigma(M/2))$$

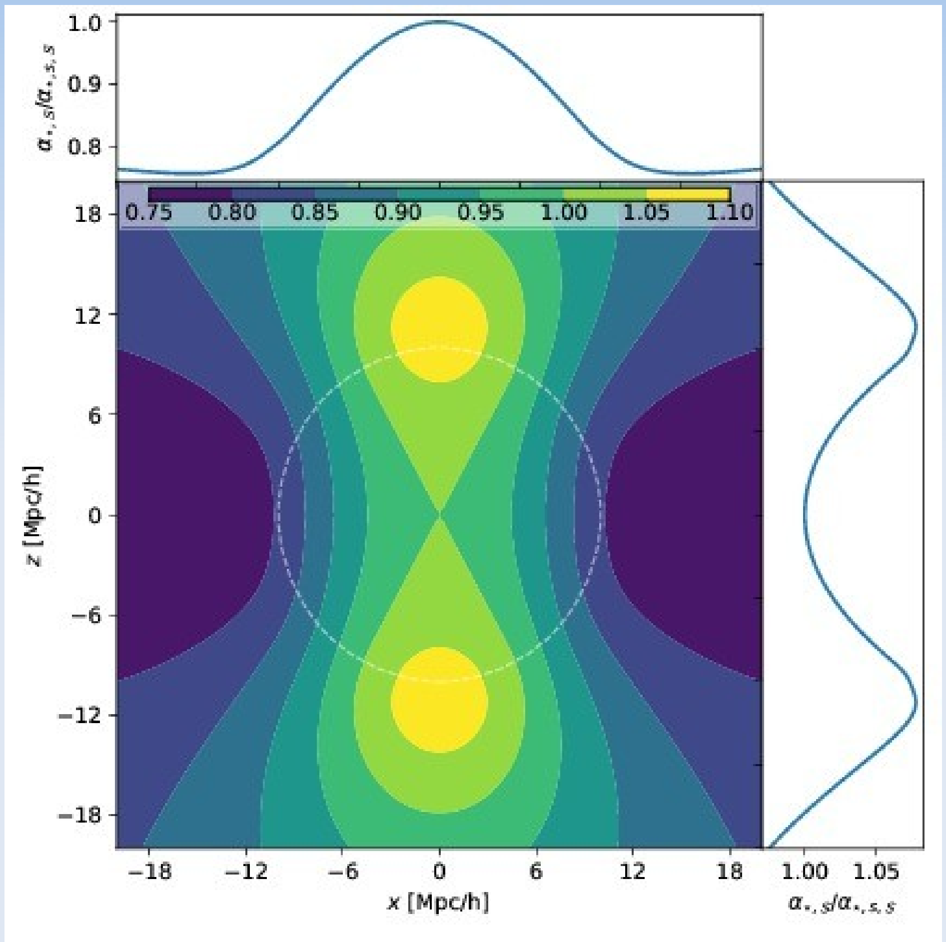




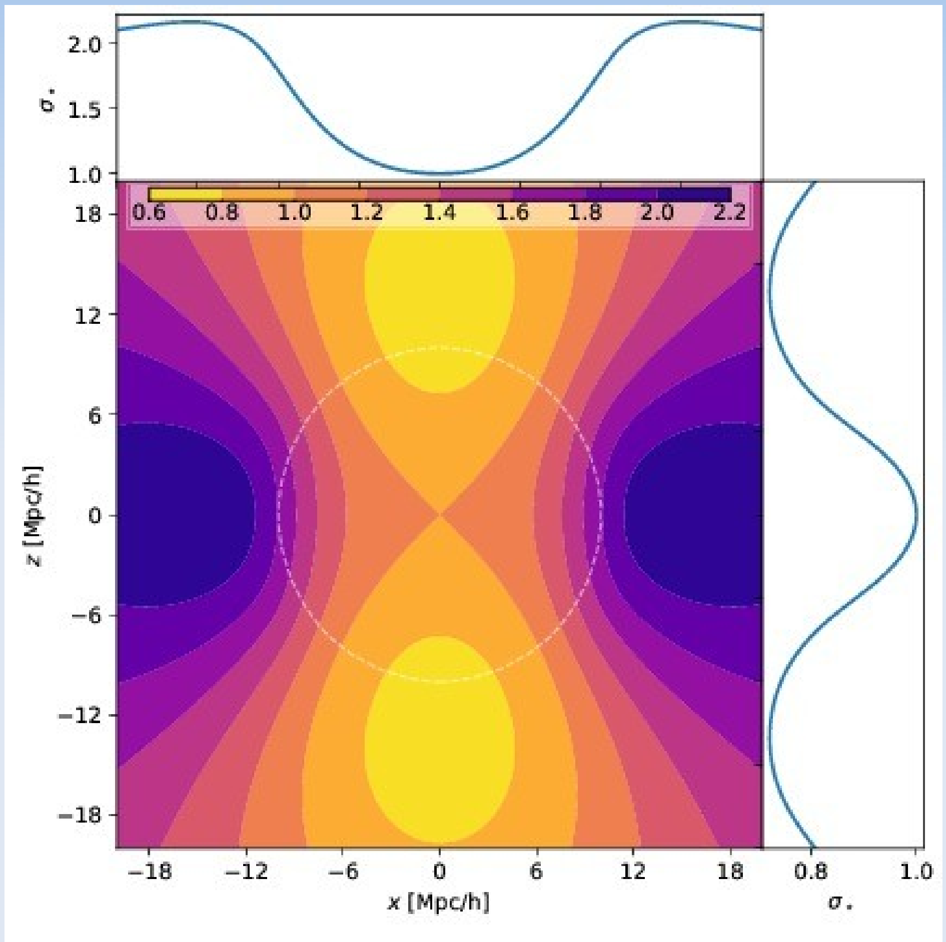
PDF of D has typical formation time $D_\star$

- Early forming halos (small $D_\star$) are more likely in voids
- Larger $D_\star$ near saddle point and even larger near nodes

Assembly bias



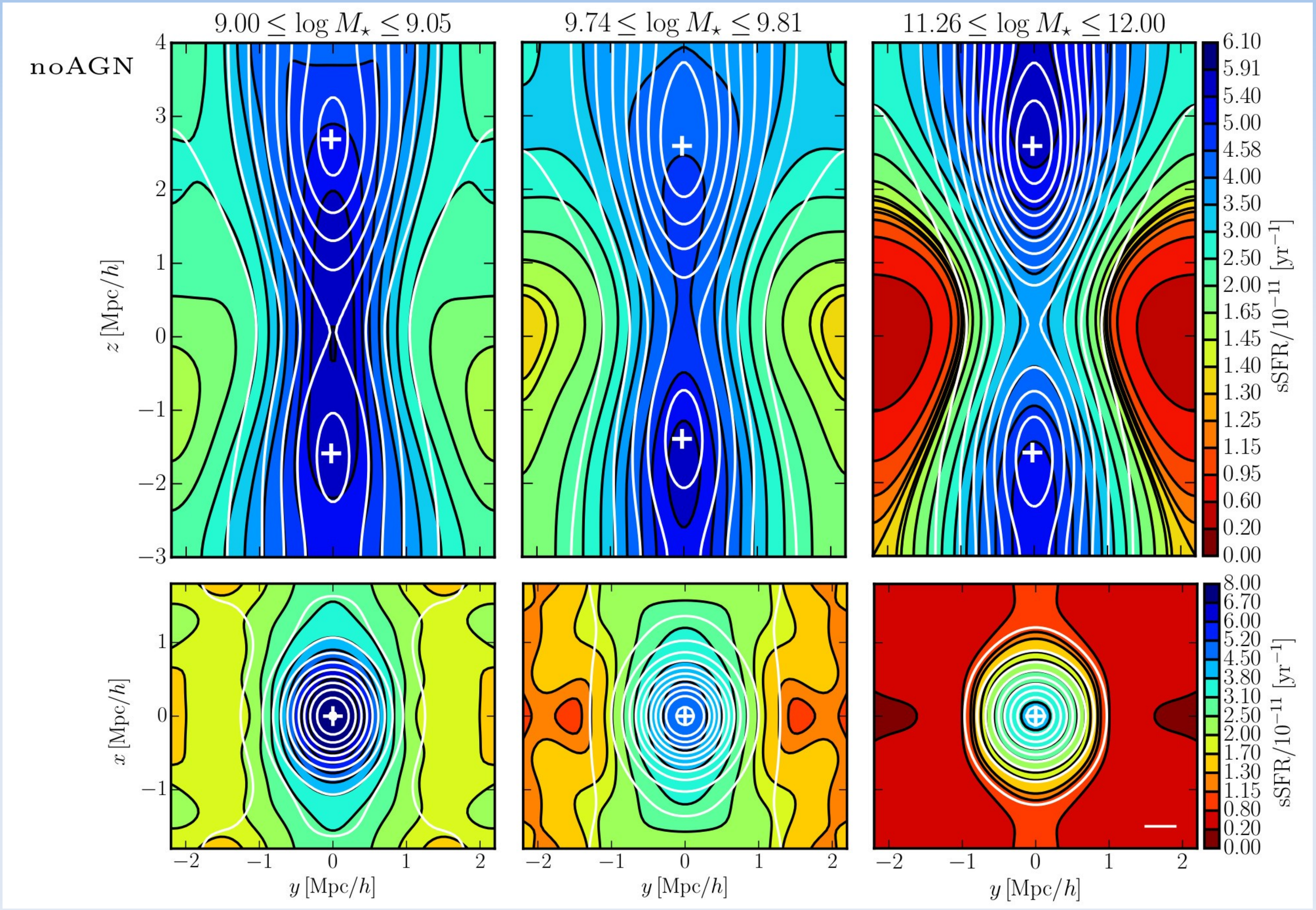
Typical accretion rate



Typical mass

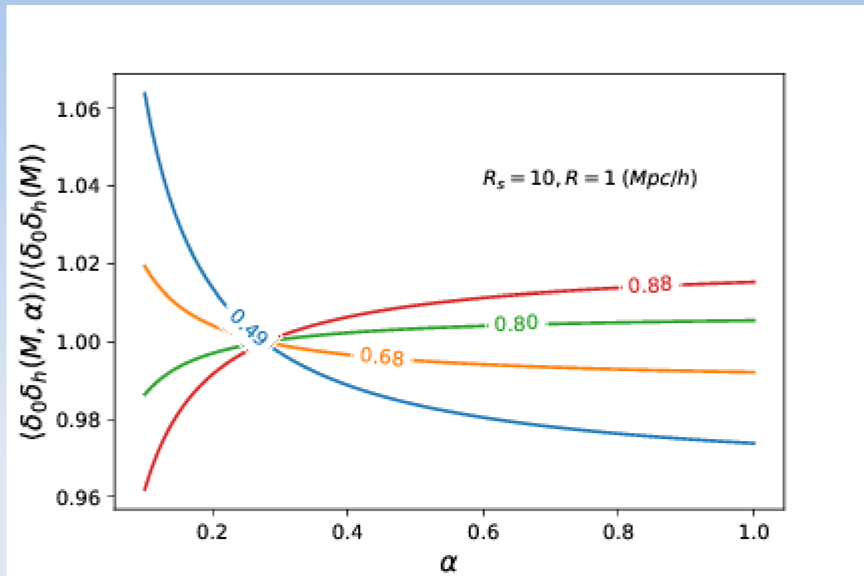
- Saddle point of $\alpha_\star$ and of $D_\star$. Away from nodes, halos form earlier and accrete less today. Different level surfaces (and ≠ from mass)

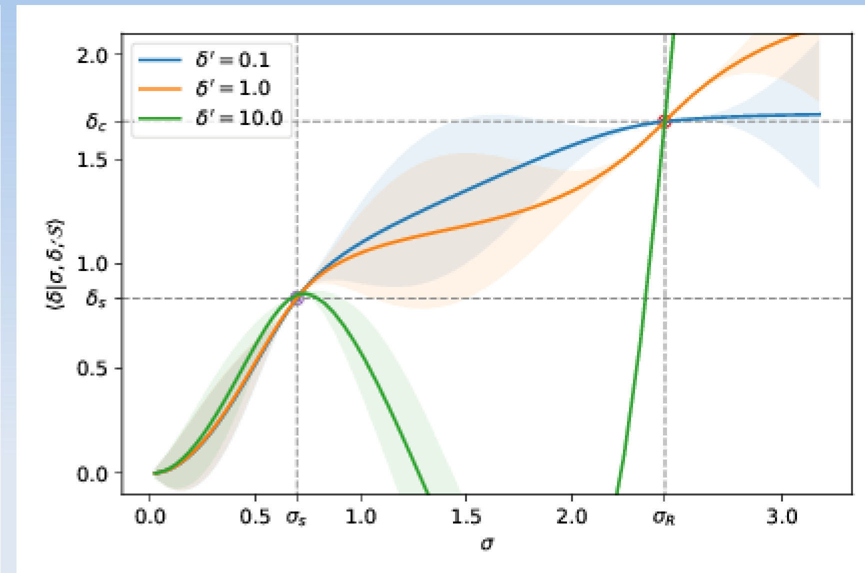
Assembly bias



Kraljic++ (in prep)

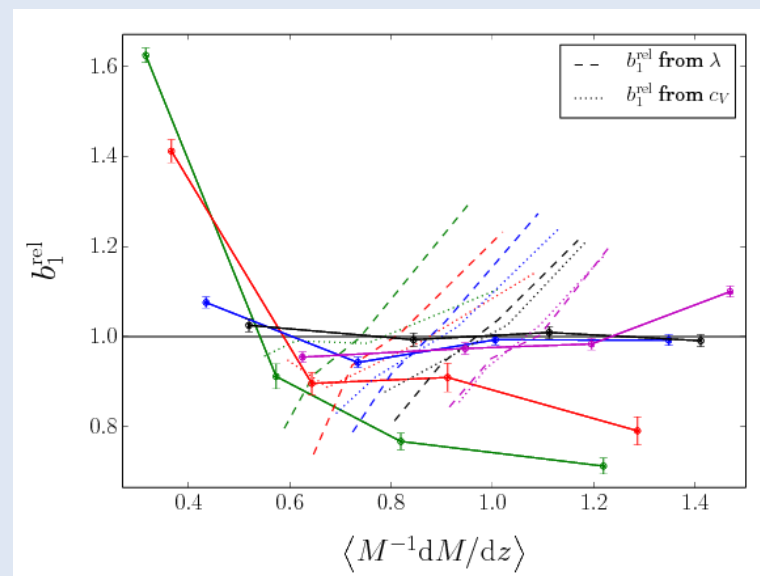
Large-scale bias near a filament





MM++ (2017)

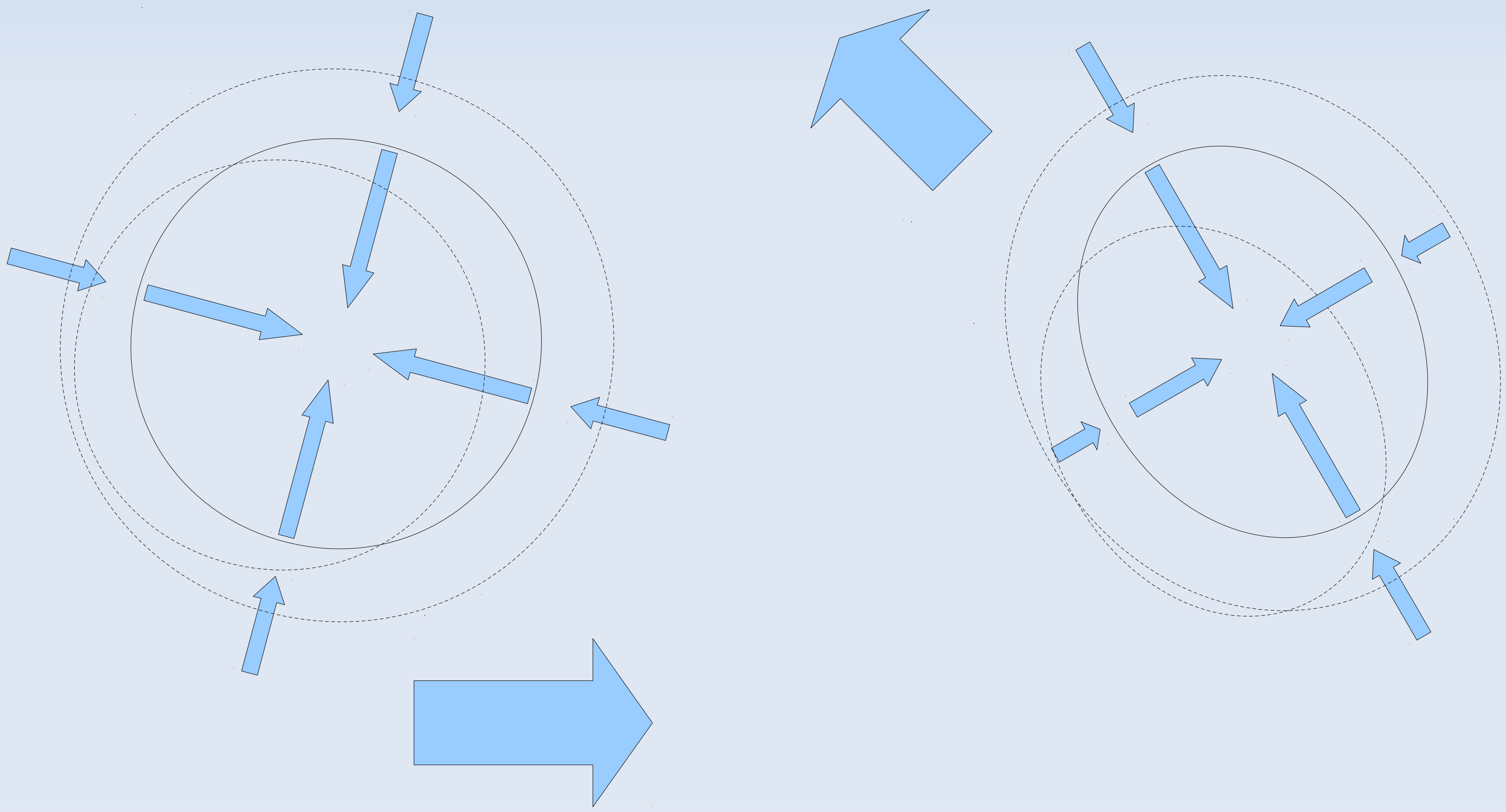
- Near the filament center halos with small accretion rate are more biased, opposite near the nodes
- Consequence of inversion in the constrained excursion set walks
- Similar qualitative trend as found in N-body



Lazeyras, MM, Schmidt (2016)

What's next?

Halos as centers of convergence of the velocity field



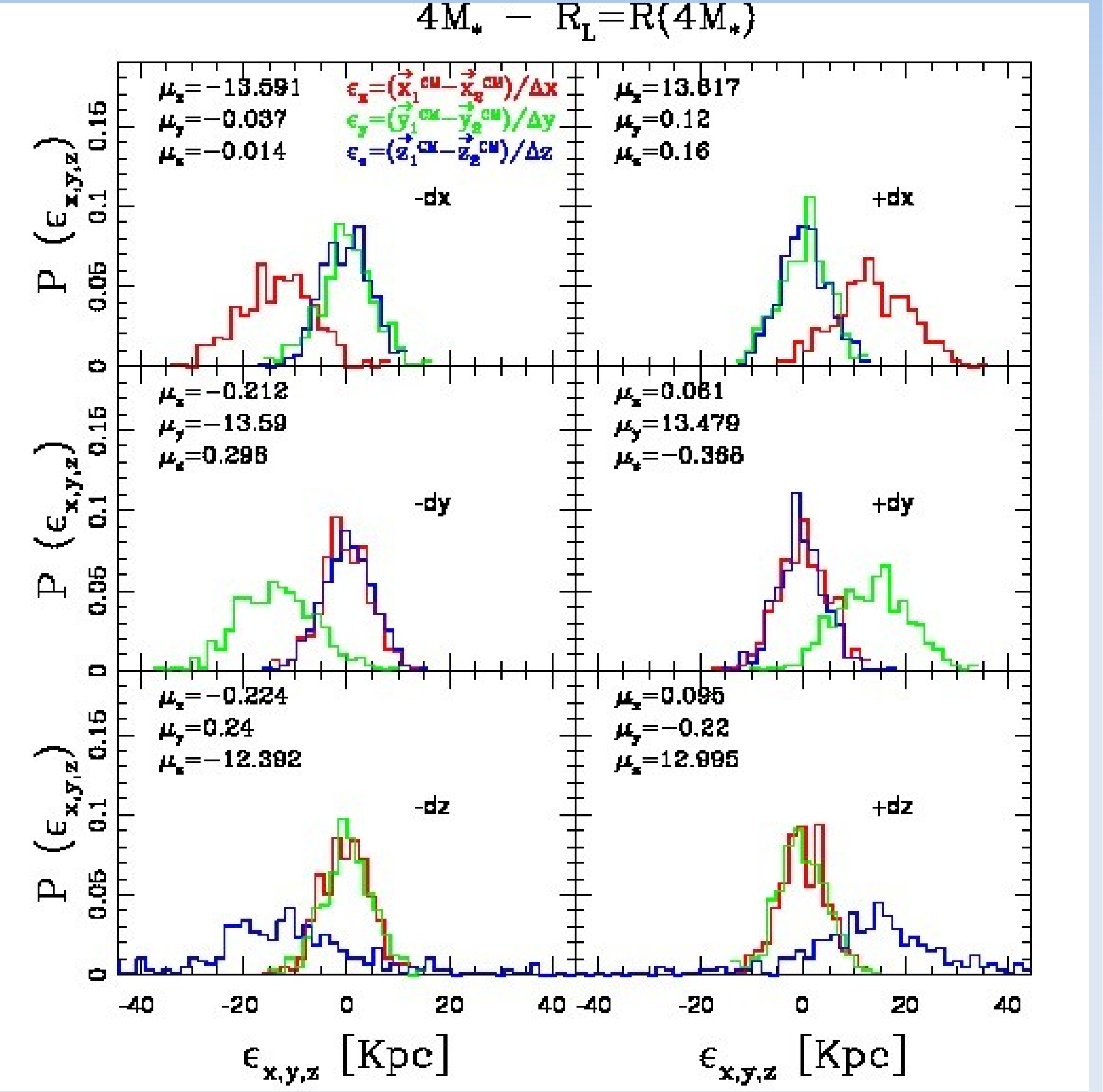
What's next?

- Halos as minima of the density of binding energy ϵ
- Replace $\nabla_i\delta$ = 0 with $\nabla_i\epsilon = 0$, -$\nabla_i\nabla_j\delta$ with ζ_{ij} = -$\nabla_i\nabla_j\epsilon$
- Identified by spheres with null dipole moment. That is, set the origin of the coordinates on the center of mass.
- TH filter: $$\zeta_{ij} \equiv -\nabla_i\nabla_j\epsilon = \int \frac{\mathrm{d}^3k}{(2\pi)^3}\frac{k_ik_j}{k^2}\delta(\mathbf{k})\frac{\partial W_{\mathrm{TH}}(kR)}{\partial R}$$
- Describes change of δ as any axis shrinks. Triaxial excursion sets!
- pos definite ζ_{ij} means that infall time from any direction decreases with distance
- No problem of divergences, unlike δ

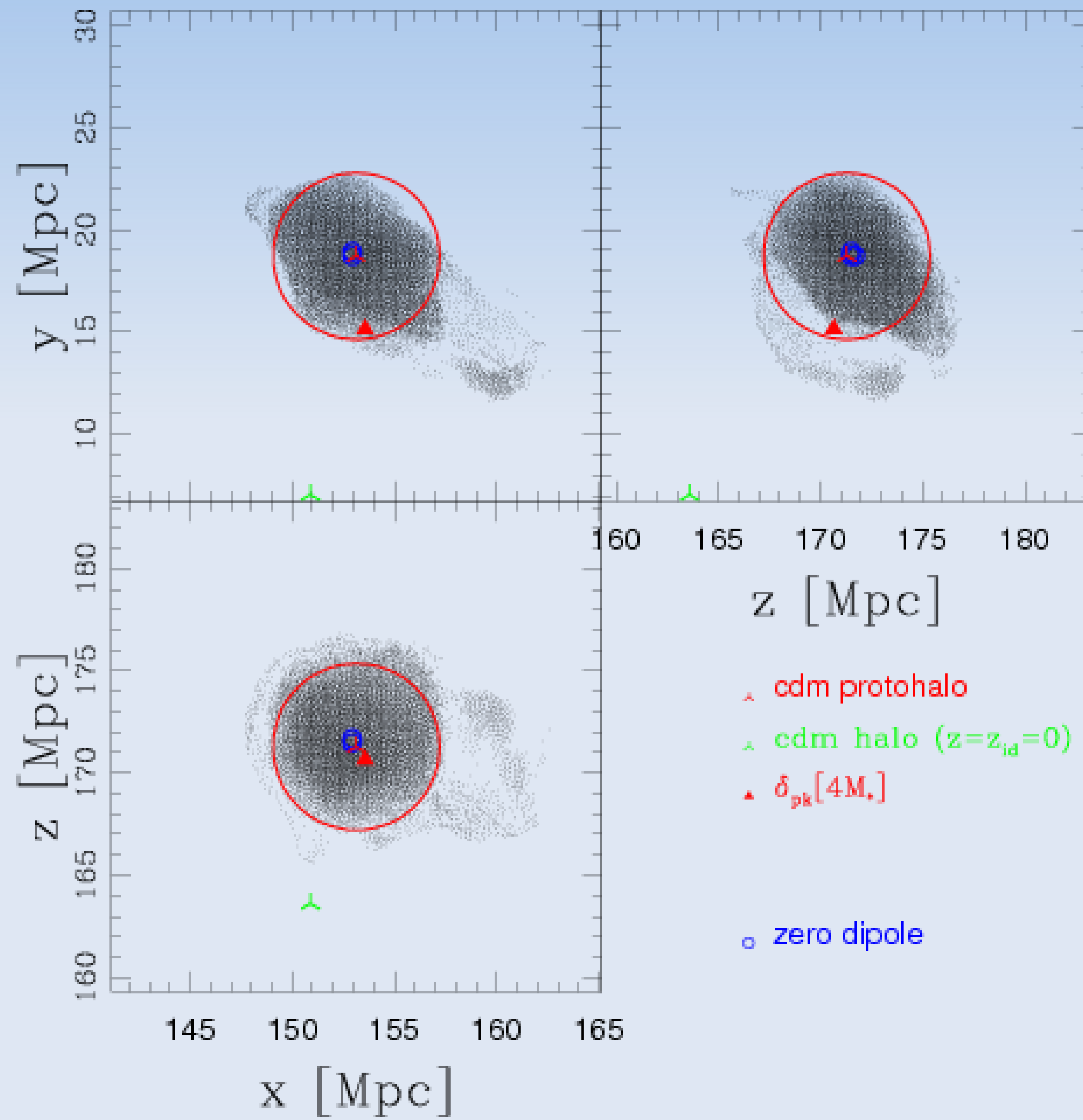
M.Musso (in prep)

What's next?

- The center of mass of a sphere of Lagrangian radius near the center of mass of the protohalo moves in the direction opposite to the displacement
- $\nabla_i \epsilon = 0$ at the center of mass of the protohalo
- $\nabla_i \nabla_j \epsilon$ is indeed neg. definite



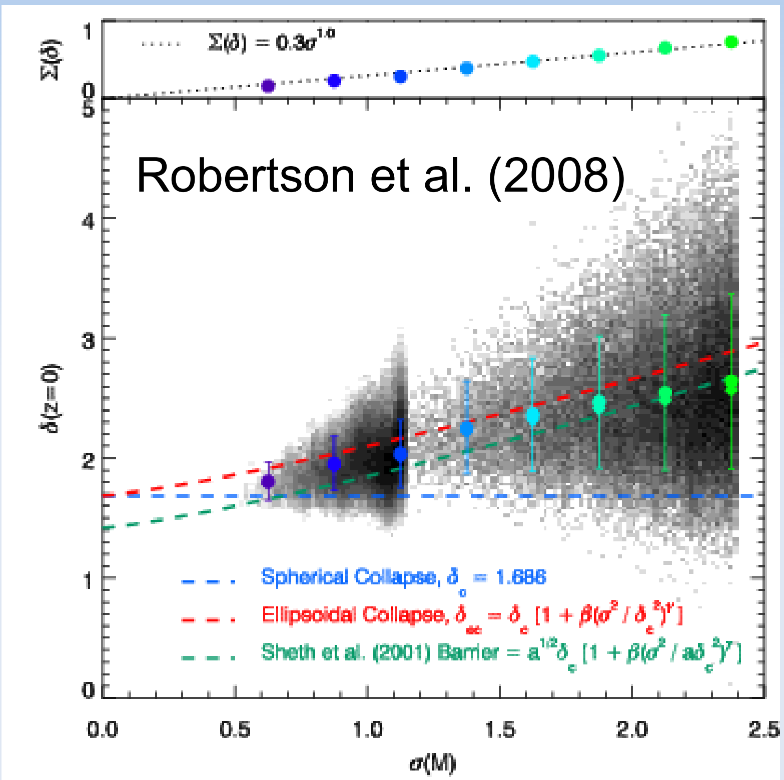
What's next?

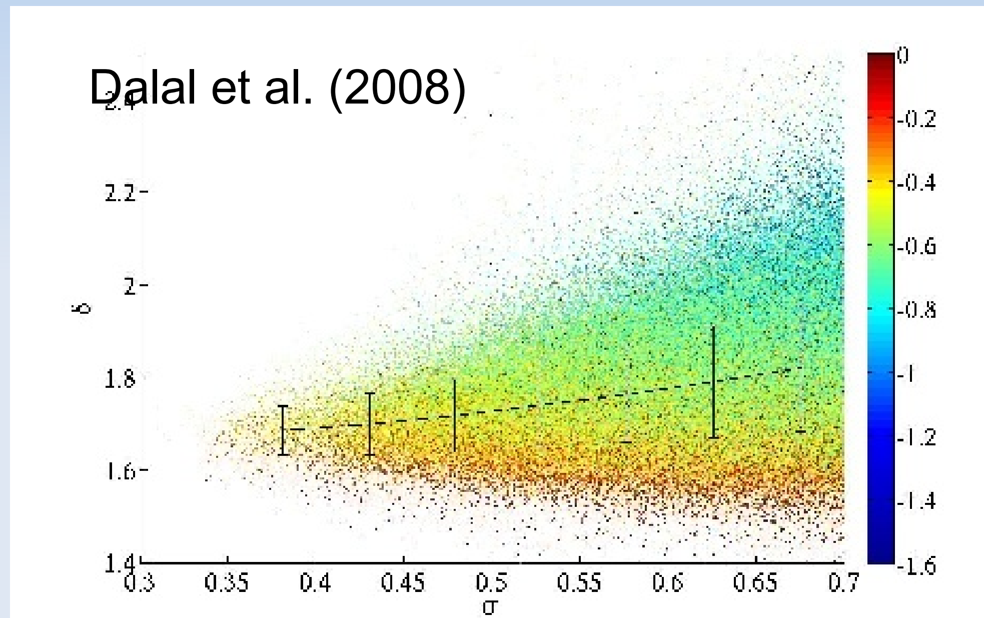


y [Mpc]
z [Mpc]
x [Mpc]
cdm protohalo
cdm halo (z=z_id=0)
δ_pk[4M*]
zero dipole

The "not-so-critical" density?

- At small mass, barrier becomes "stochastic" and scale-dependent





- Main culprits for the scatter: shear, ellipticity, velocity dispersion. (See also Borzyszkowski, Ludlow & Porciani). Need a model!
- Different types prefer different $\mathrm{d}b/\mathrm{d}\sigma$
- At equal σ (mass) they select different slopes (accr. rates)

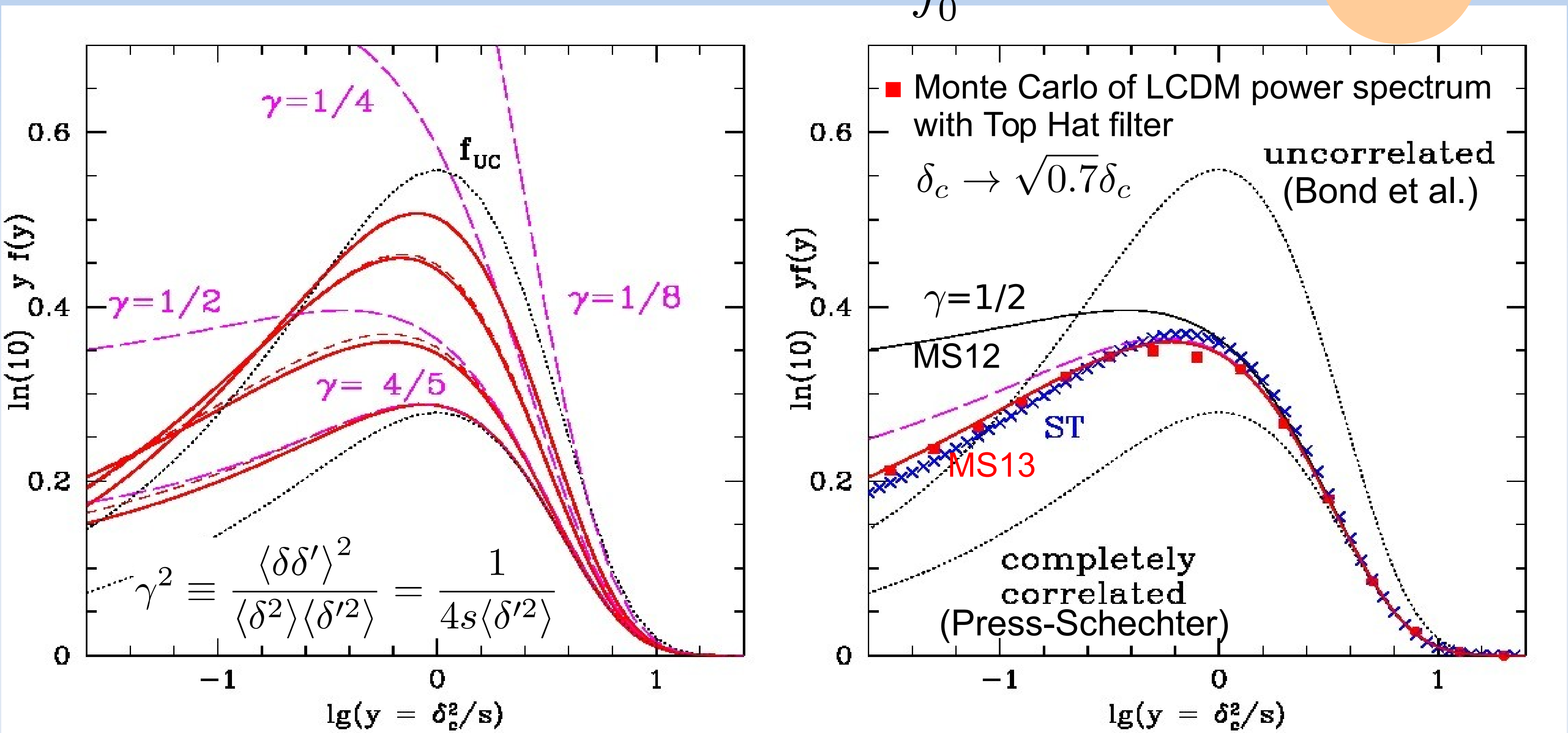
Conclusions

- Excursion sets allow to model accretion rates and formation times
- Qualitatively correct prediction of the distribution of secondary halo properties in the cosmic web after conditioning on the proximity to stationary points of the potential
- Saddles define a local metric for the various halo properties. The position in the cosmic web is part of assembly bias
- Accretion (plus AGN feedback...) is a key ingredient to understand galaxy colors. Correlation with angular momentum induced by tidal torques may be used to mitigate the problem of intrinsic alignments
- Need better models with clear dynamical content to improve accuracy and control the errors. Halos as minima of the potential are a very promising candidate.
- Voids? PBHs?

Thanks!!

Solution by back substitution

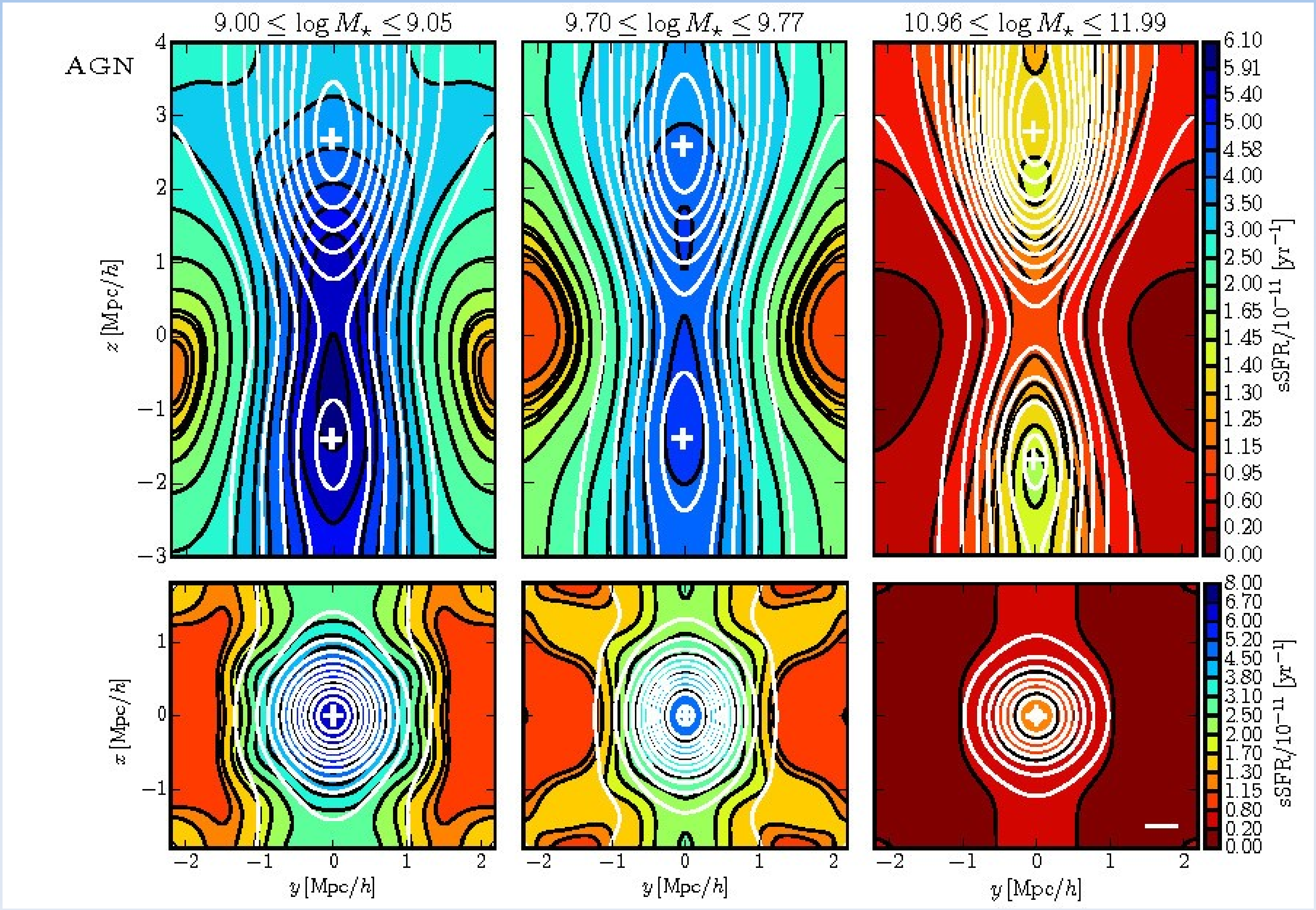
- An even better approx: $p(\delta_s \geq b) = \int_0^s \mathrm{d}S f(S) p(\delta_s \geq b|\mathrm{up}, S)$



MM & Sheth (2013)

- Upcrossing captures $f(s)$ for all $P(k)$, filters and barriers. Yet, the mass function works only if $\delta_c \to .84\ \delta_c$. There is a flaw in the ansatz!

Assembly bias



Kraljic++ (in prep)