Angular momentum and galaxy formation

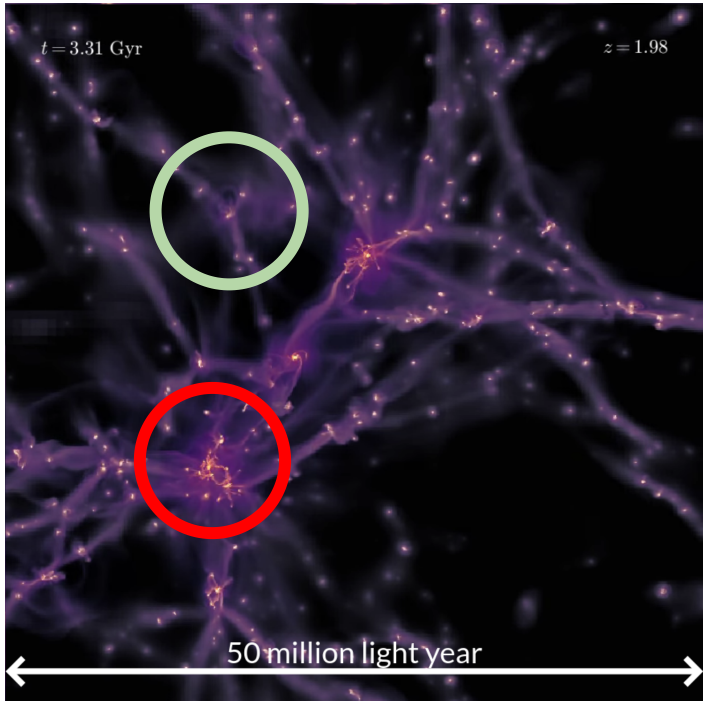
replacing galaxies in their cosmological environment

Corentin Cadiou

KITP Cosmic Web program 2023

The effects of environment on halo properties

- $M_{\mathrm{DM}}(\mathrm{node}) > M_{\mathrm{DM}}(\mathrm{fil}) > M_{\mathrm{DM}}(\mathrm{void})$, higher clustering



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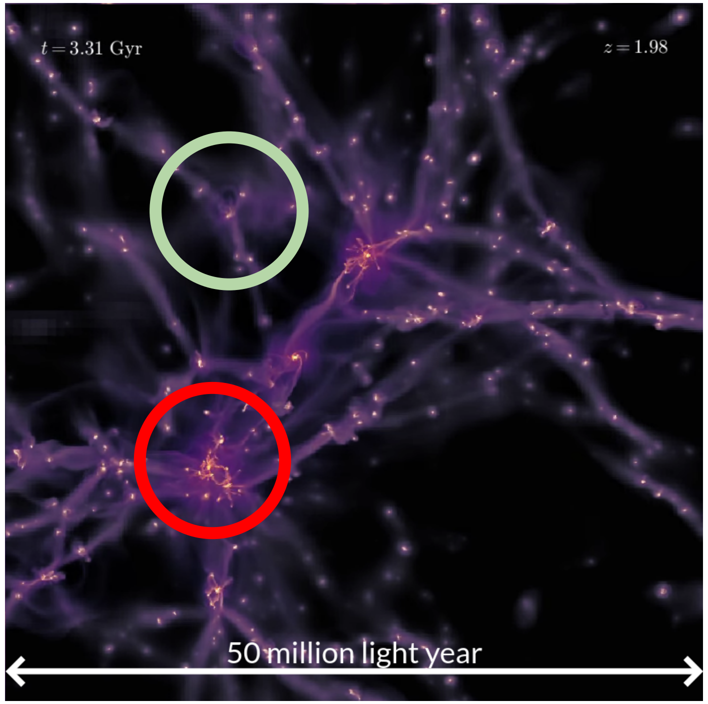

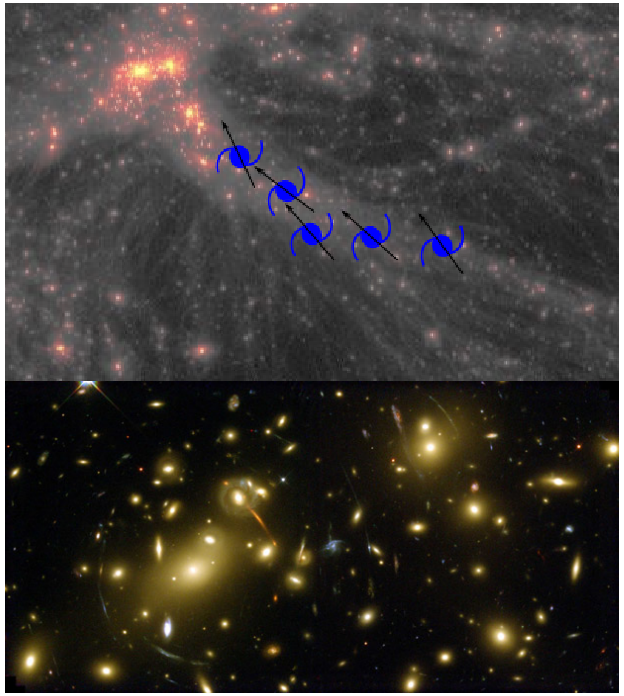

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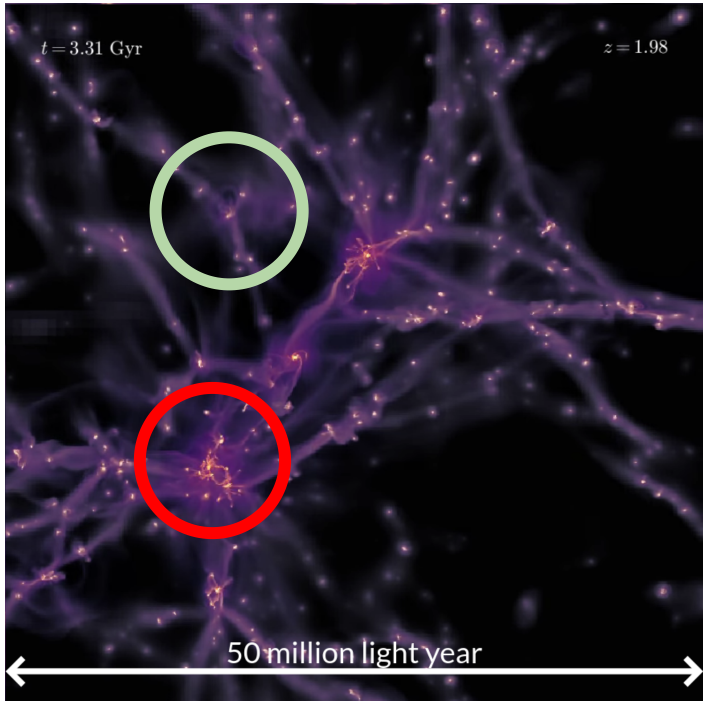

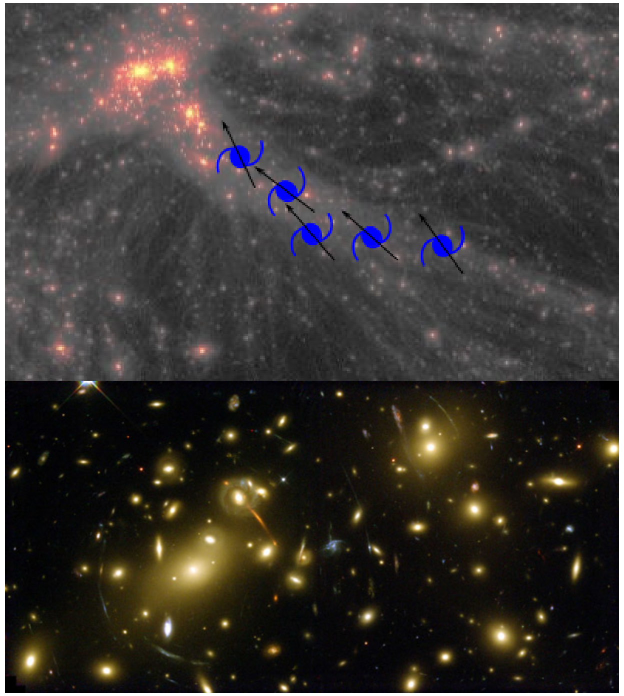

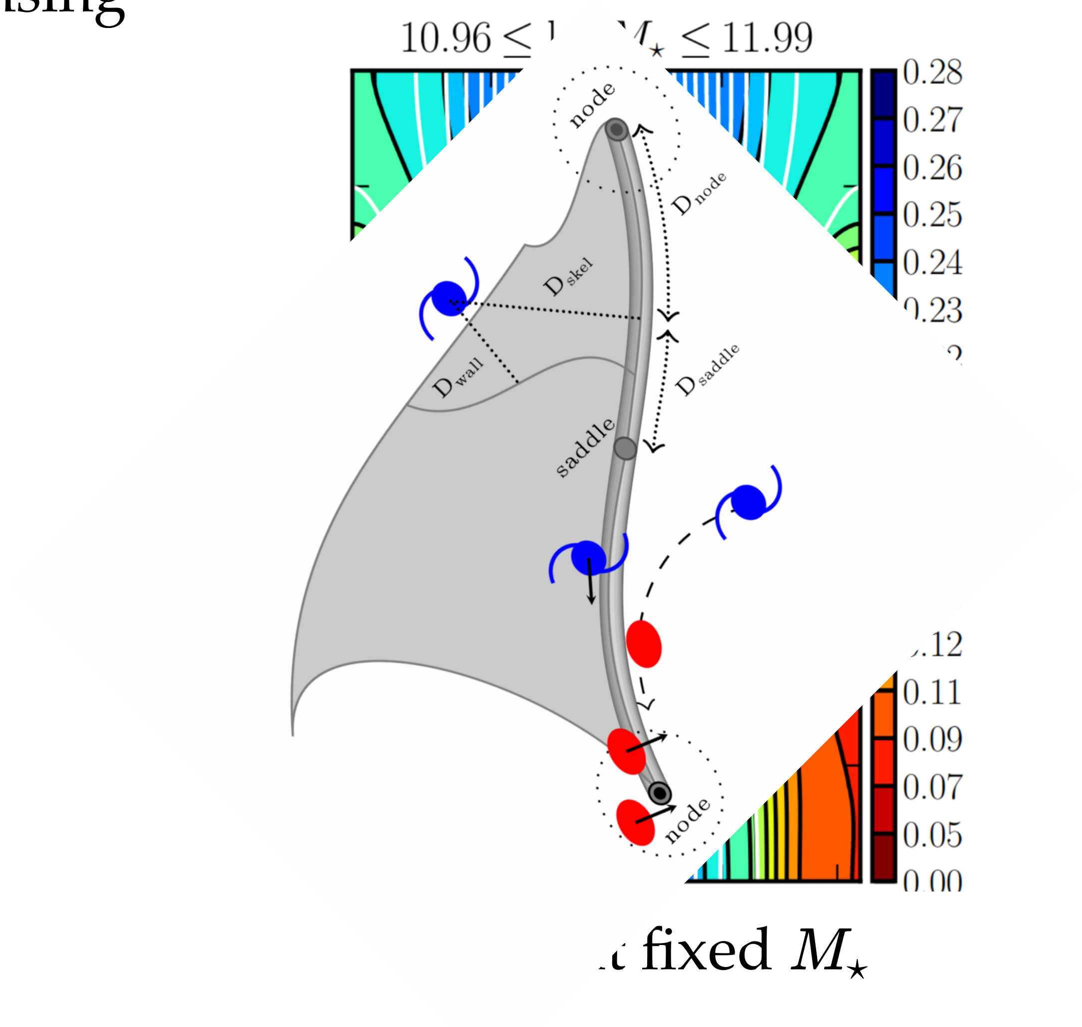

Kraljic+18 [see also Laigle15, Song+21,...]

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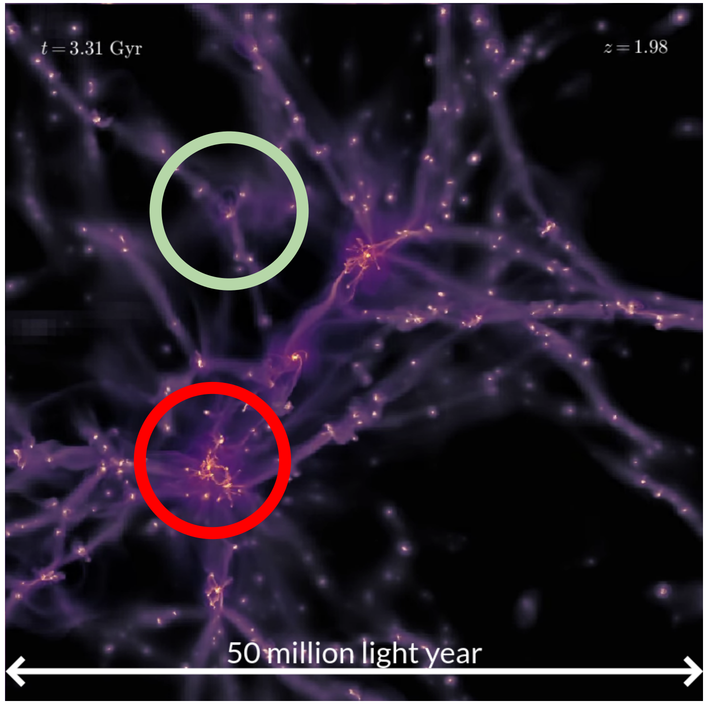

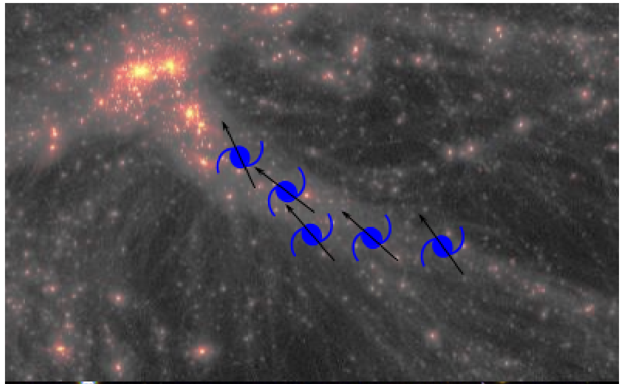

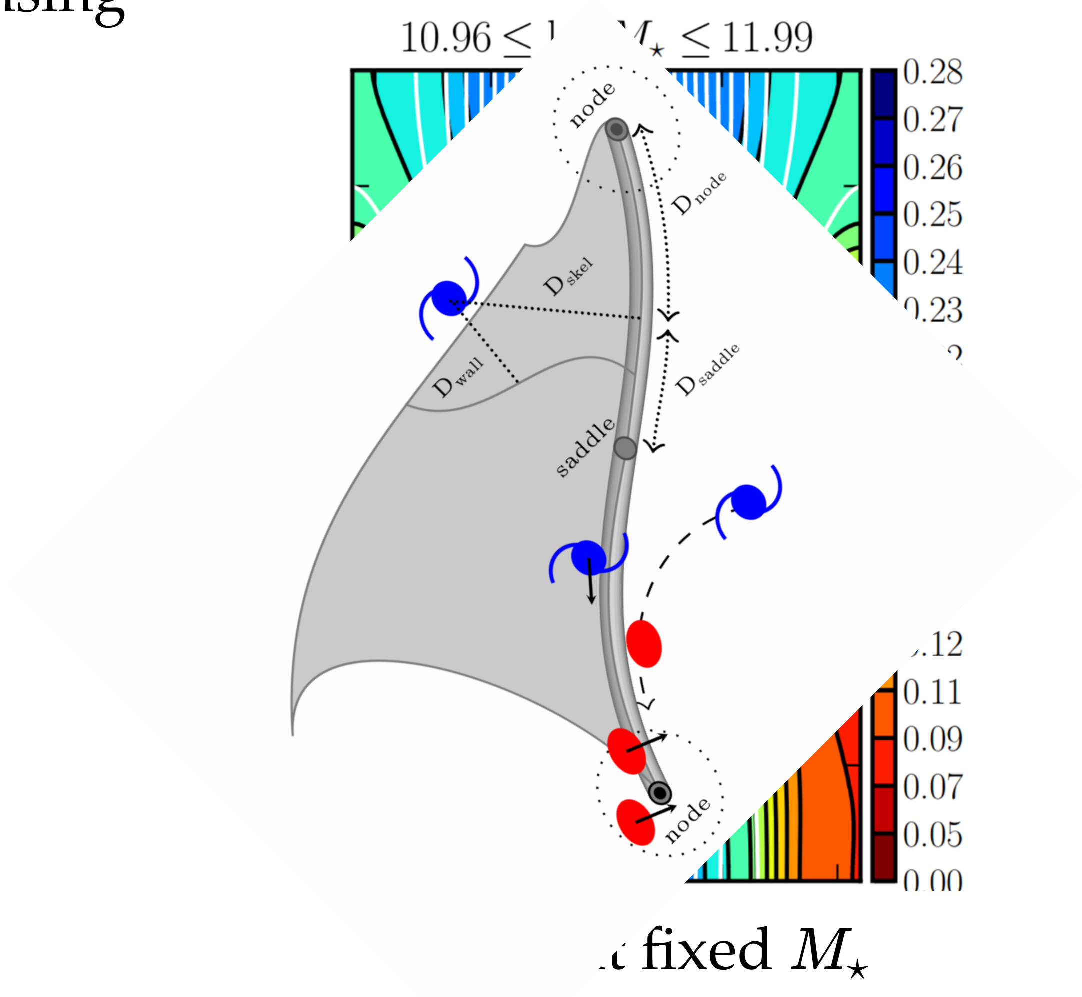

fixed $M_\star$

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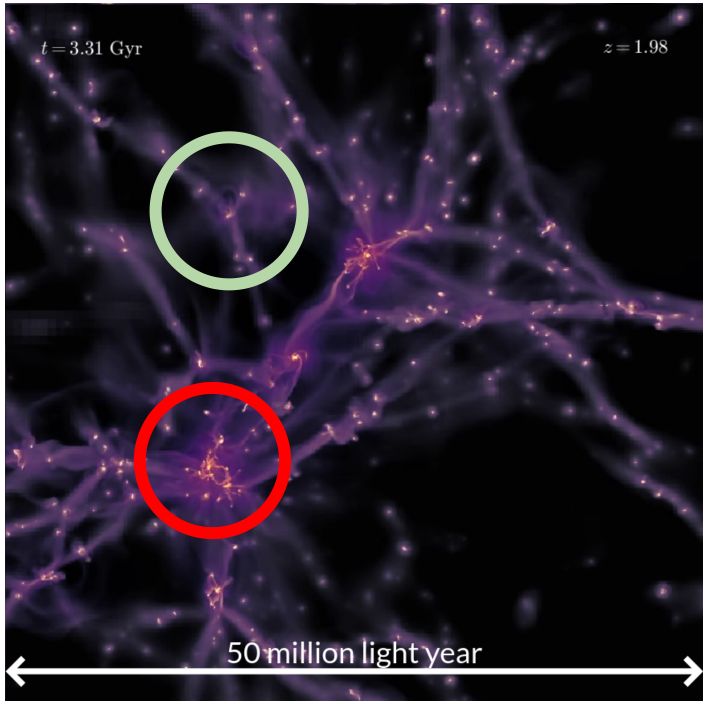

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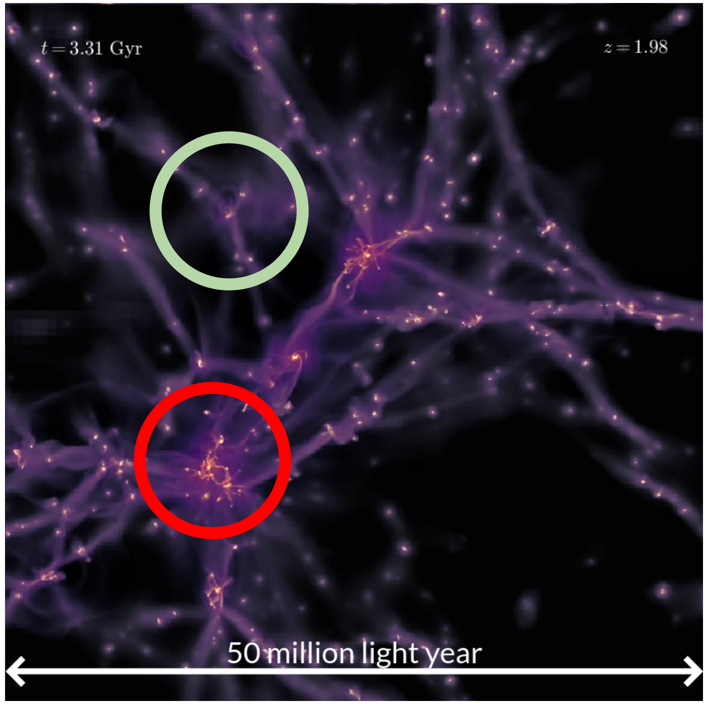

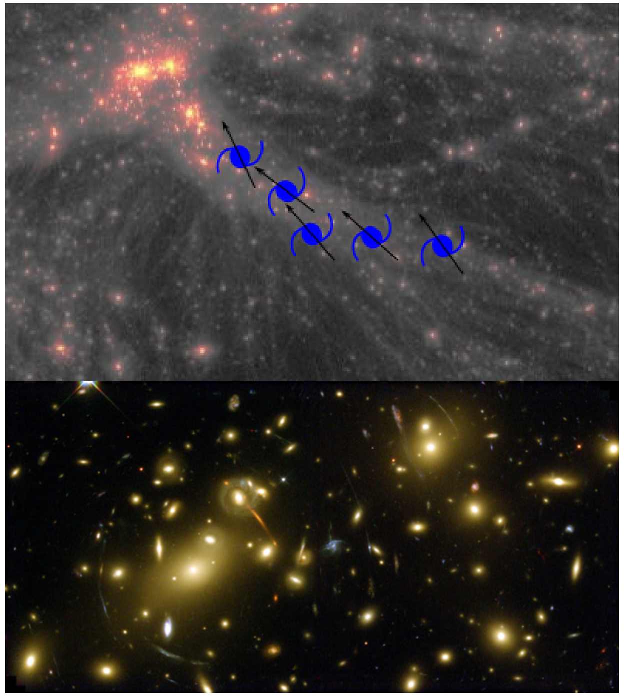

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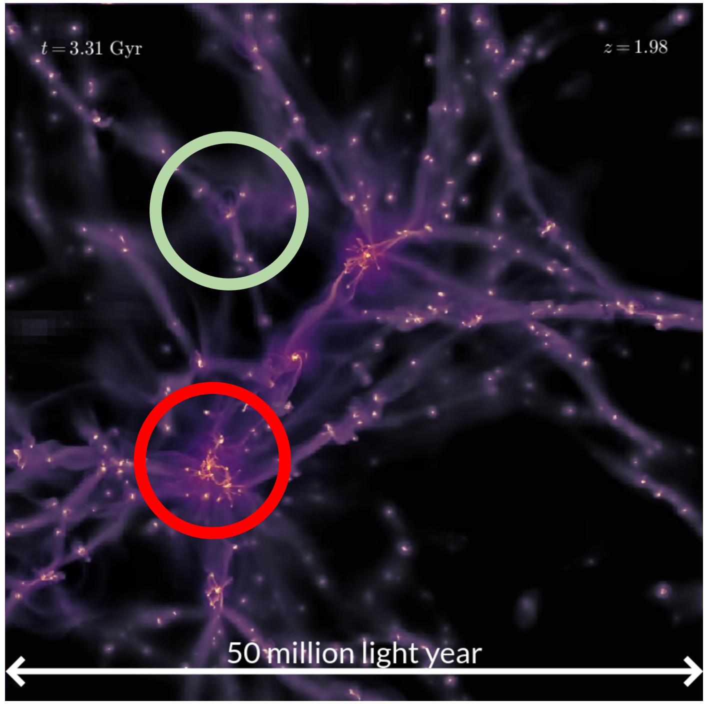

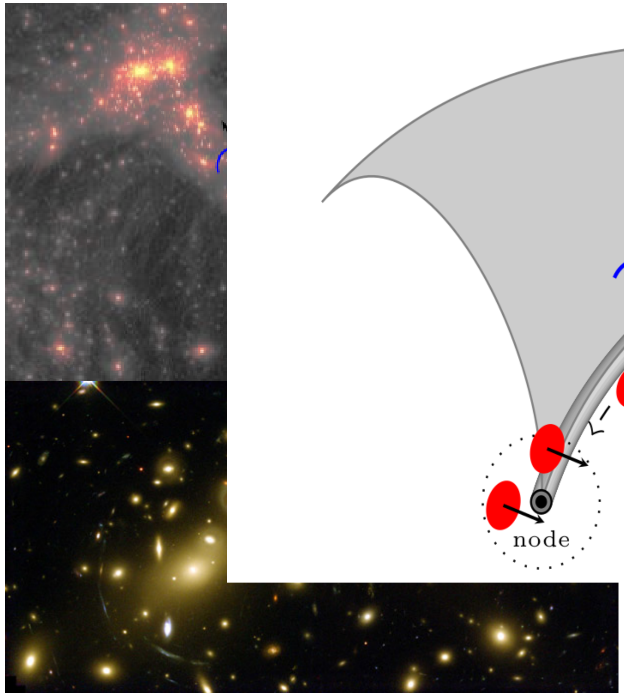

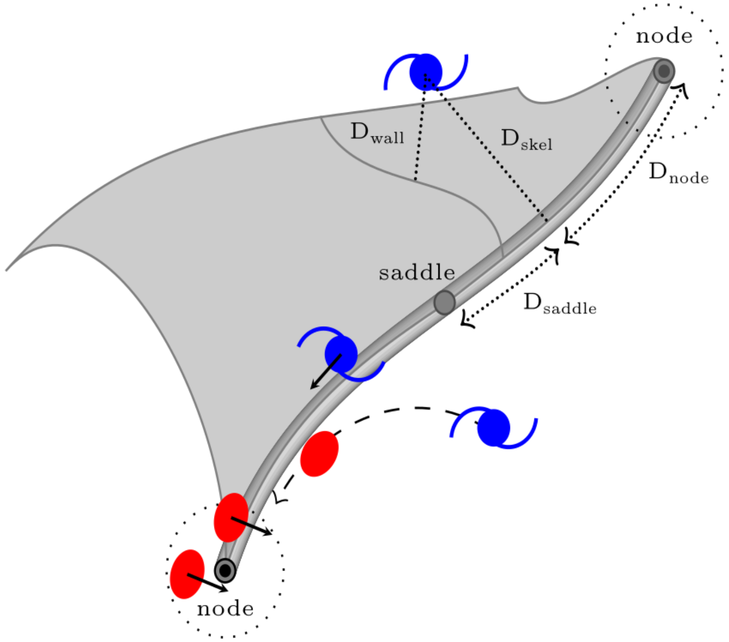

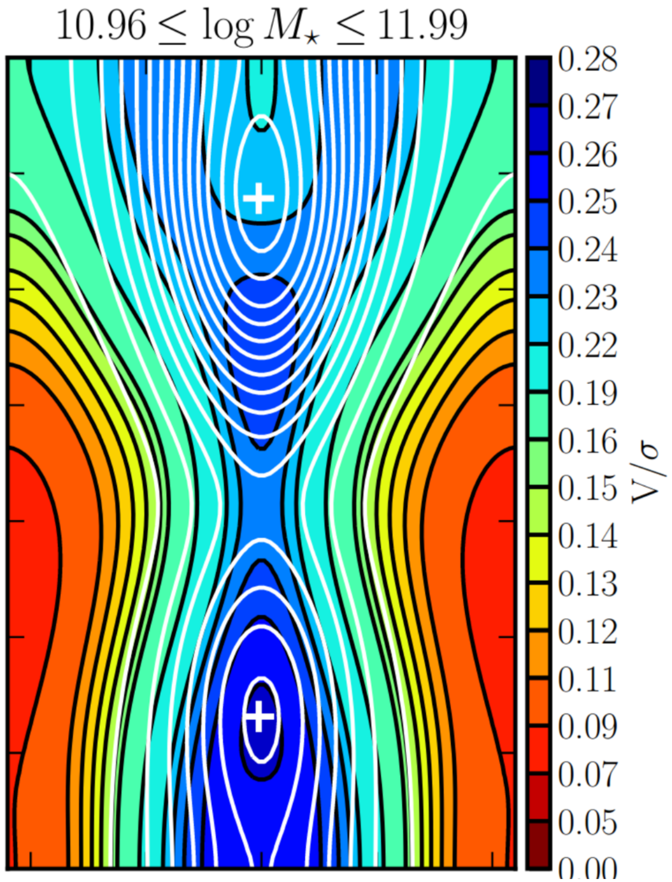

v/σ at fixed $M_\star$

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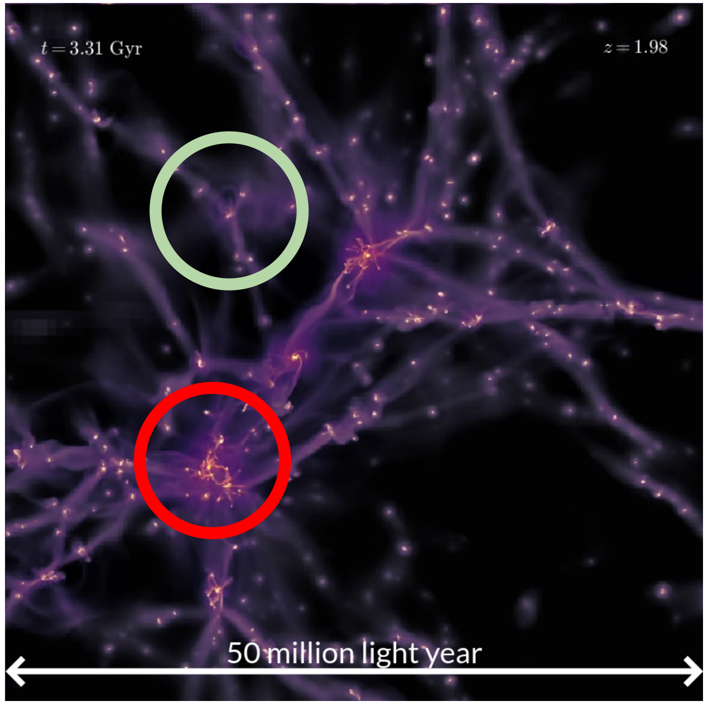

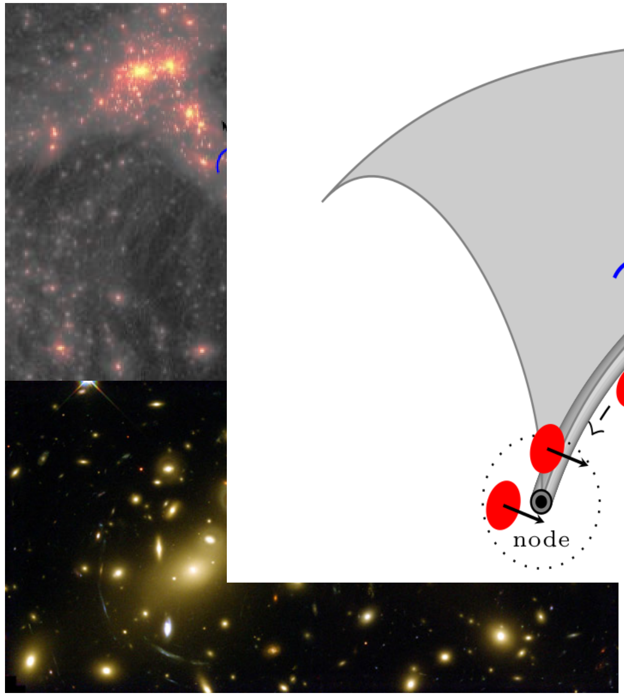

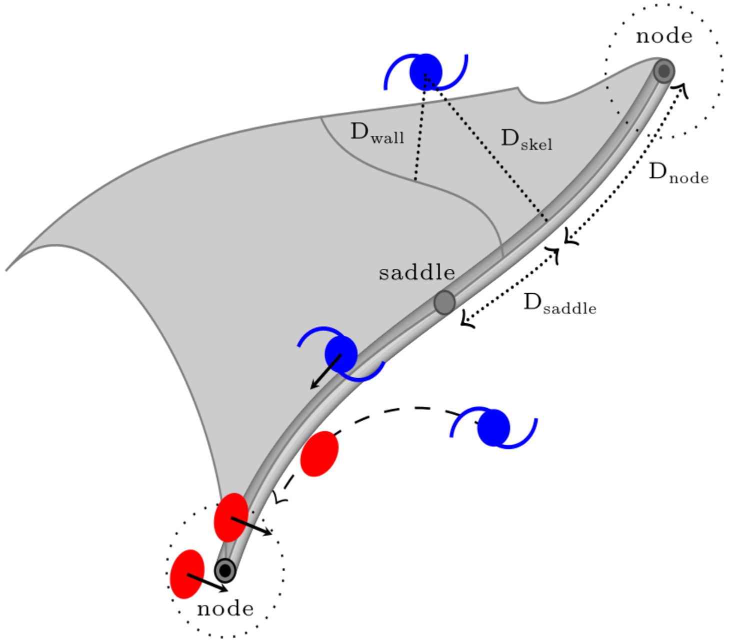

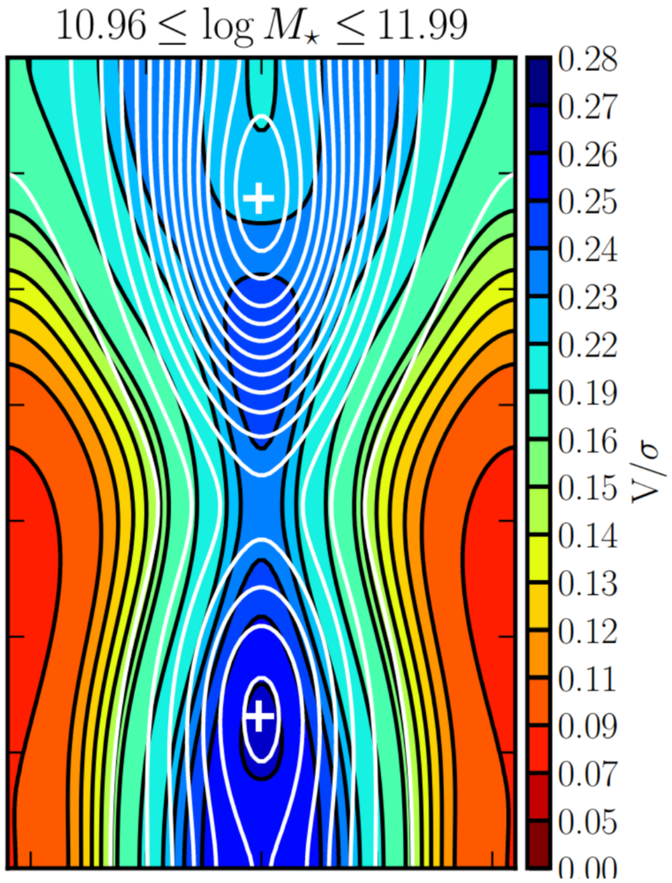

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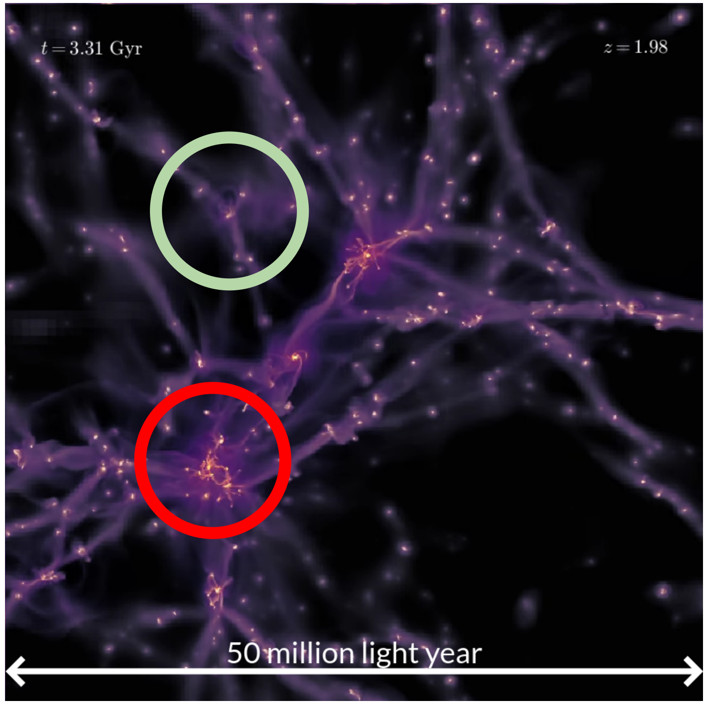
Isotropic effects

Kaiser bias, cluster vs. groups, ...

<u>From theory:</u> $M \propto \int \mathrm{d}^3 R \rho$

Mass regulated



An-isotropic effects

Intrinsic alignment, formation of disks?

<u>From theory:</u> $J \propto \int \mathrm{d}^3 R \nabla \phi$

Angular momentum regulated?

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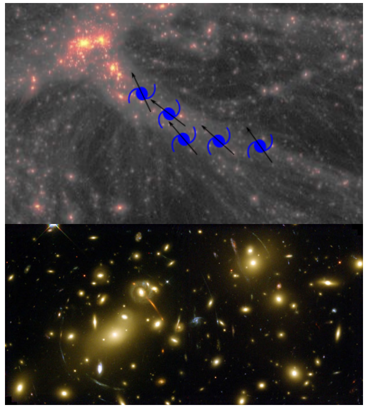

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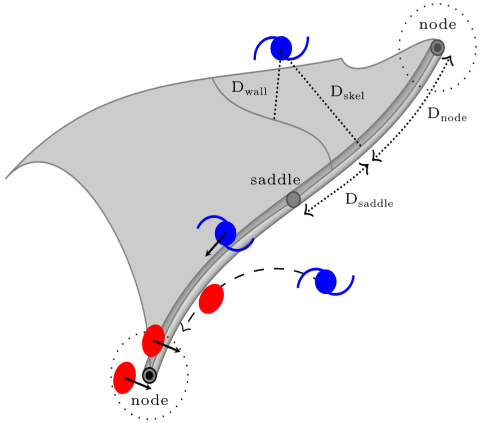
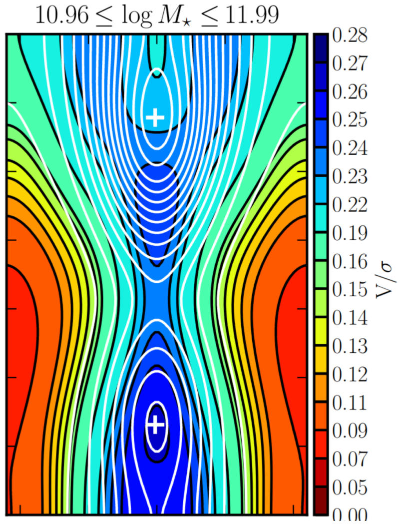
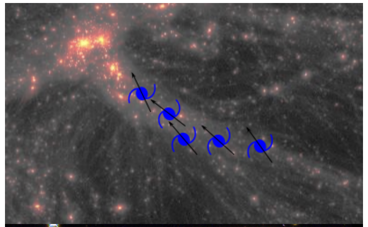


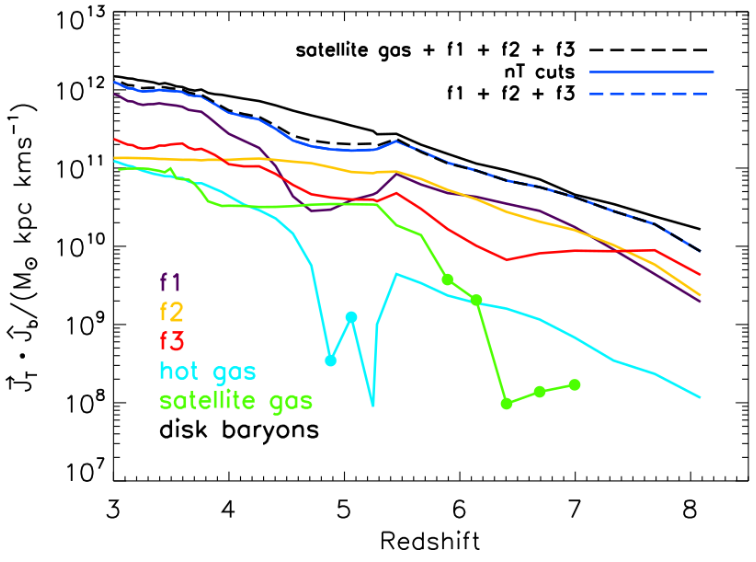




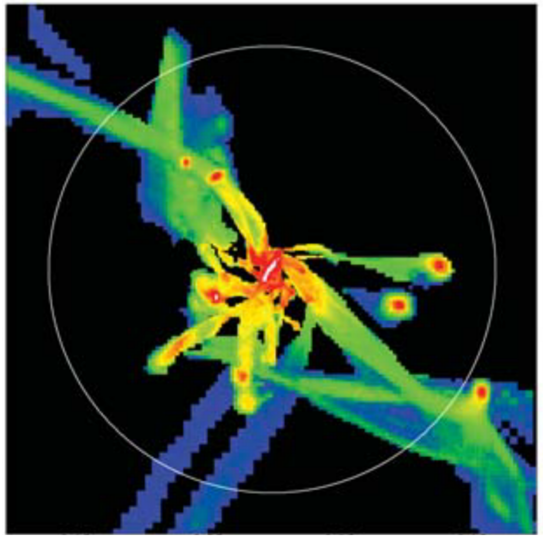
Angular momentum: bridging galaxies to cosmology?

High-*z*:
most of mass + AM flow along filaments

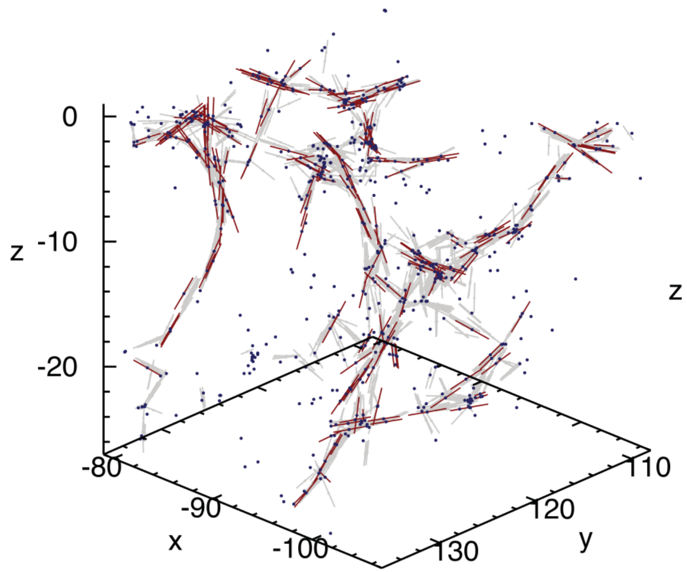
Lower-*zs*:
intrinsic alignment problem



Tillson+15



Dekel&Birnboim 06



Tempel+13

[also Dekel & Birboim 06, Danovich+15, Cadiou+21c]

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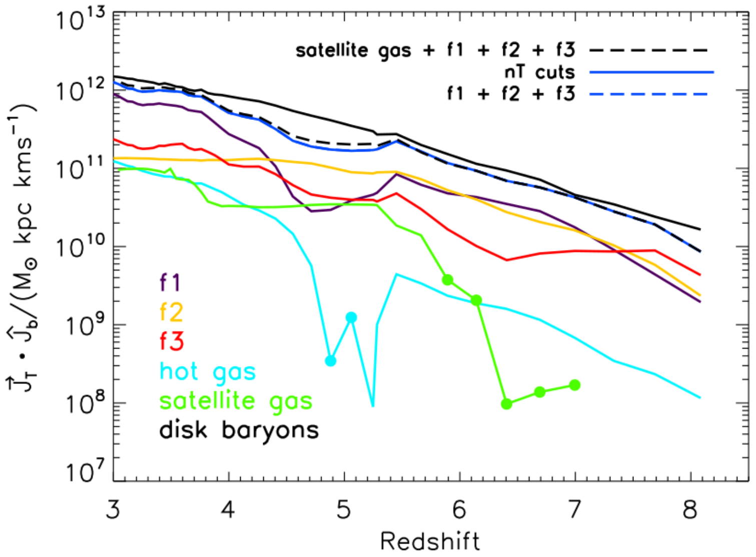

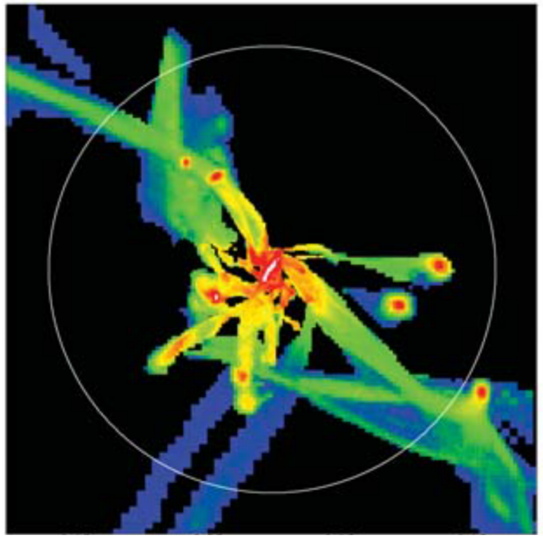

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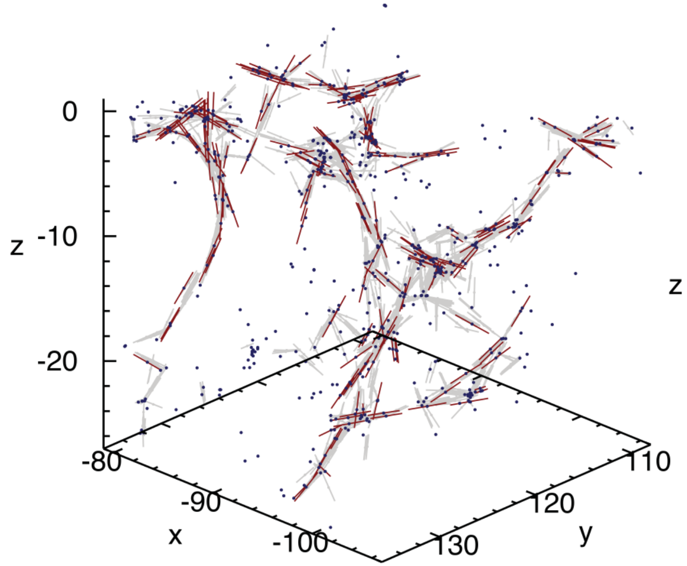

Tillson+15 Dekel&Birnboim 06 Tempel+13

How do we detect these effects?

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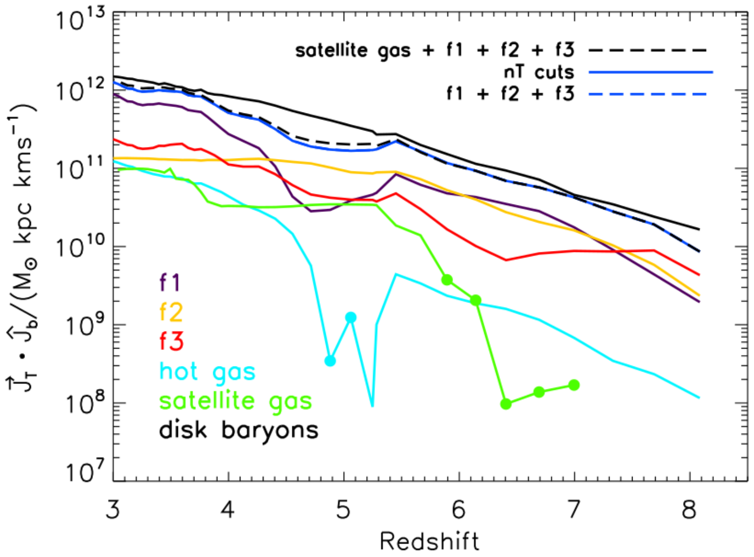

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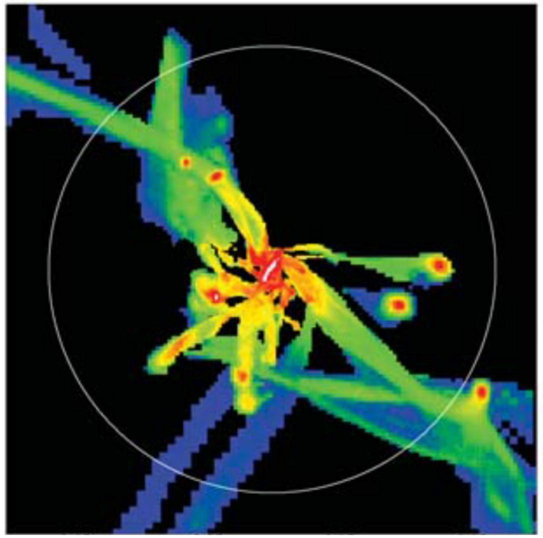

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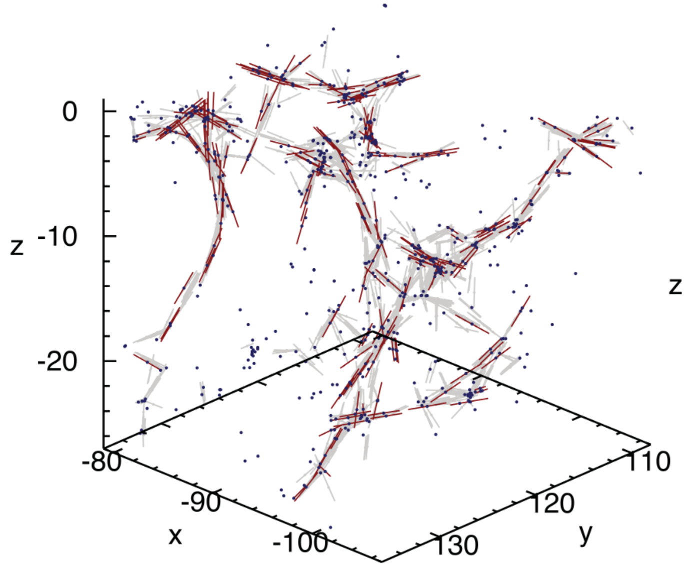

Tempel+13

How do we detect these effects?

Large volumes

sample $p(M_\star, M_{\rm DM}, \mathbf{J}, d_{\rm fil}, \dots)$

[also Dekel & Birboim 06, Danovich+15, Cadiou+21c]

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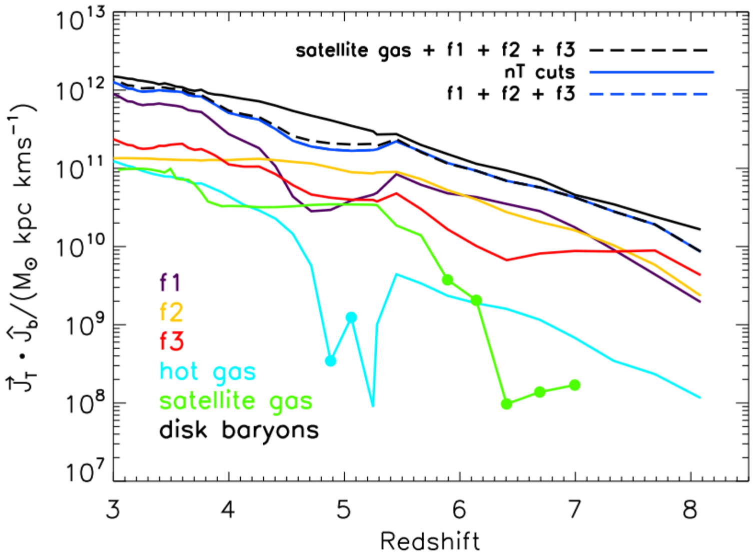

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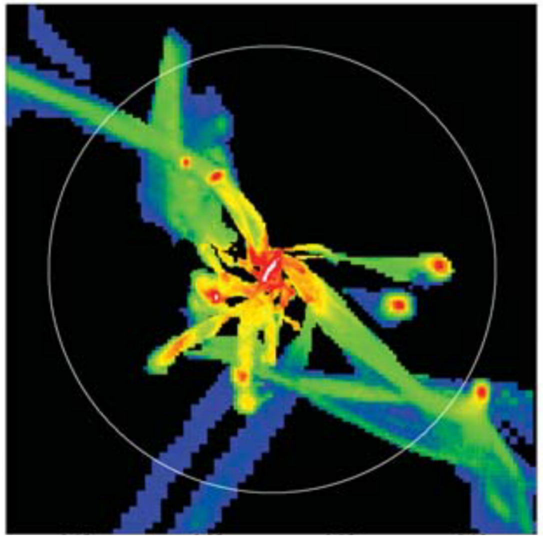

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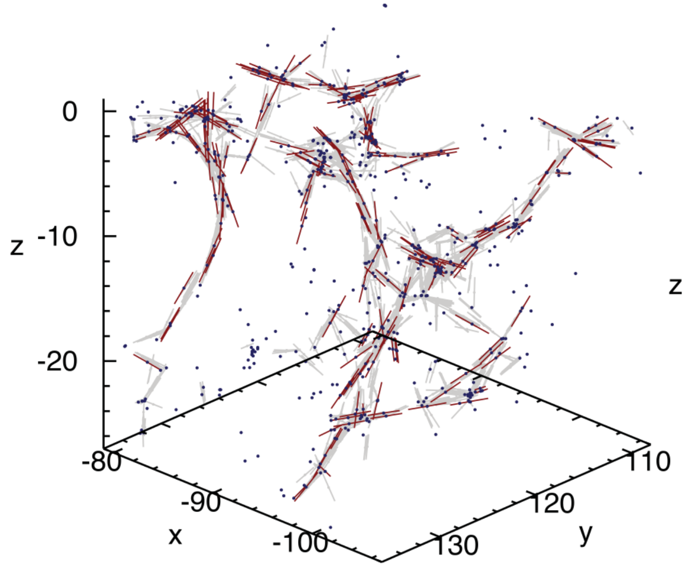

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This talk

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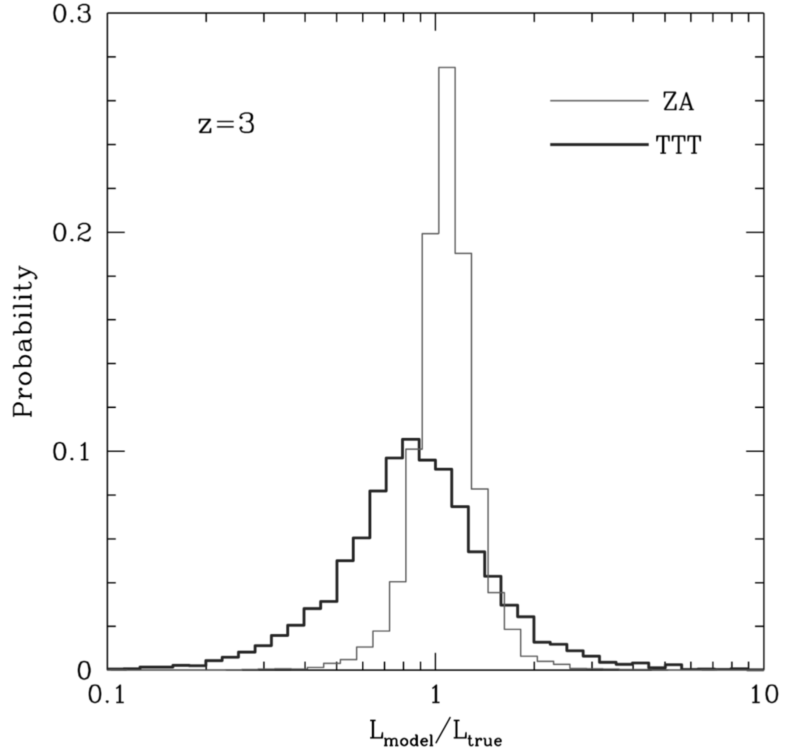
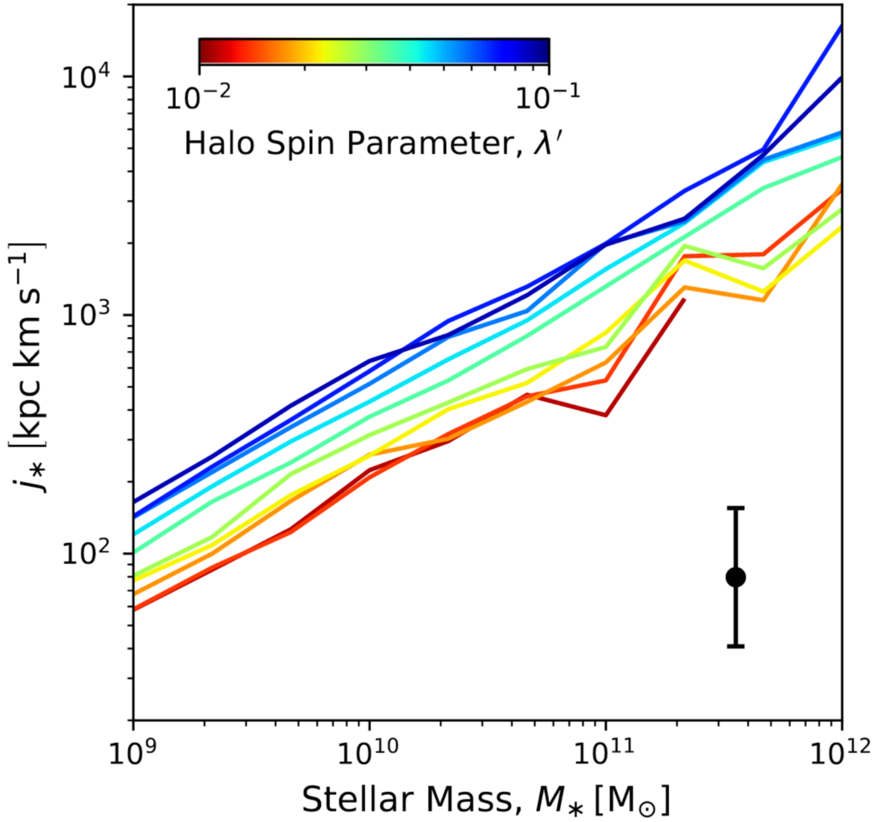
Angular momentum: where are we?



Porciani+02

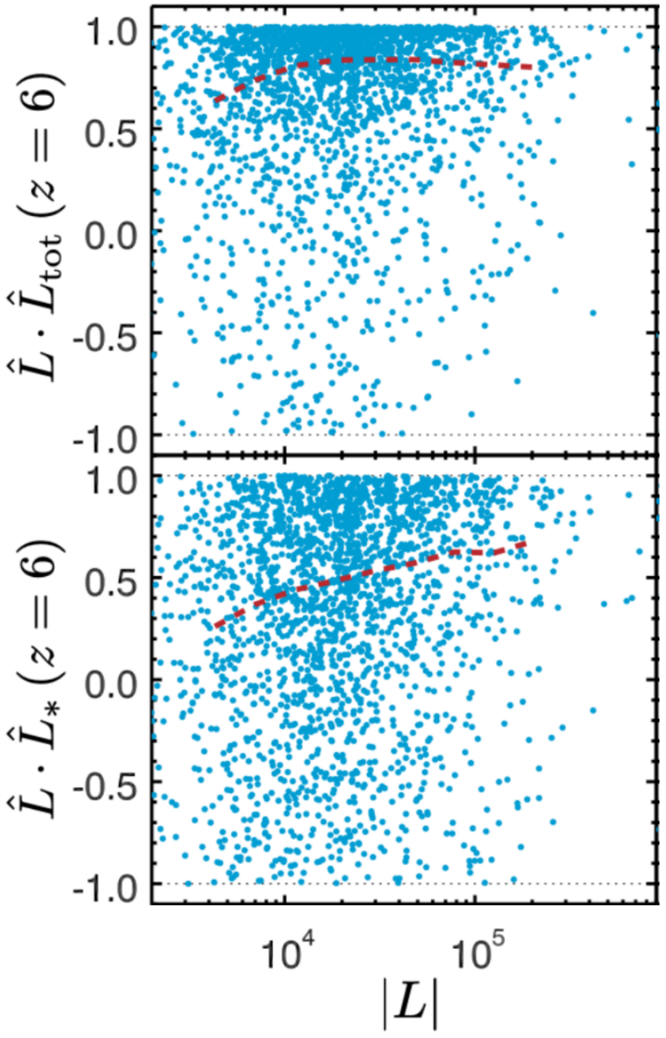
Predictions for $j_{\rm DM}$ remain qualitative



Rodriguez-Gomez+22

$j_{\rm DM} - j_\star$

strong detection of weak correlation



Adapted from Park+22

Angular momentum: where are we?

1. Is $j_{\rm DM}$ chaotic or our theory poor?

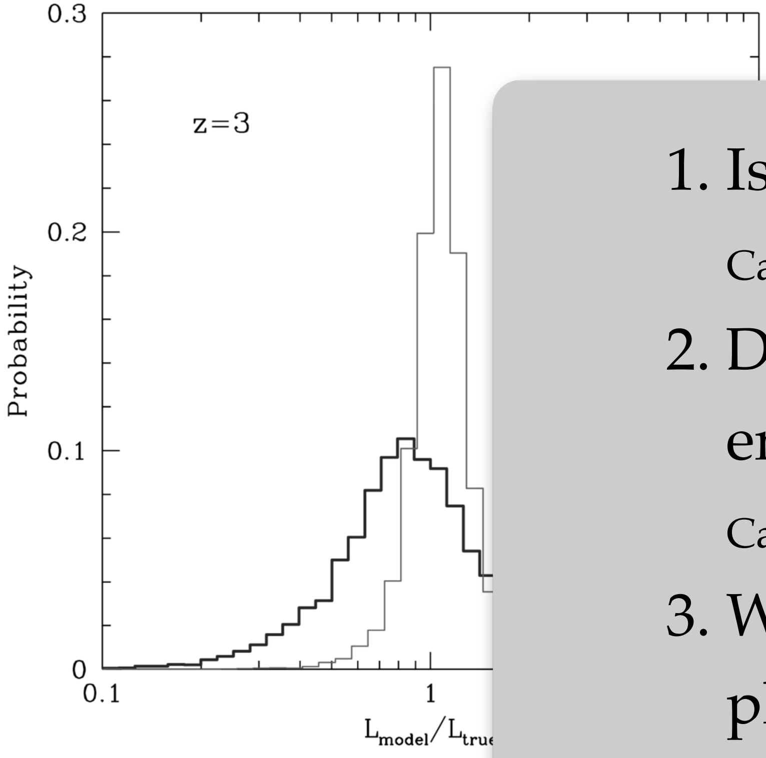
   Can we do better than statistical correlations?

2. Do $j_{\rm gal}$ retain memory of their environment?

   Can we spin a simulated galaxy up?

3. What effect does anisotropic environment play in DM/gal formation?

   Can we simulate a galaxy in ≠environments?



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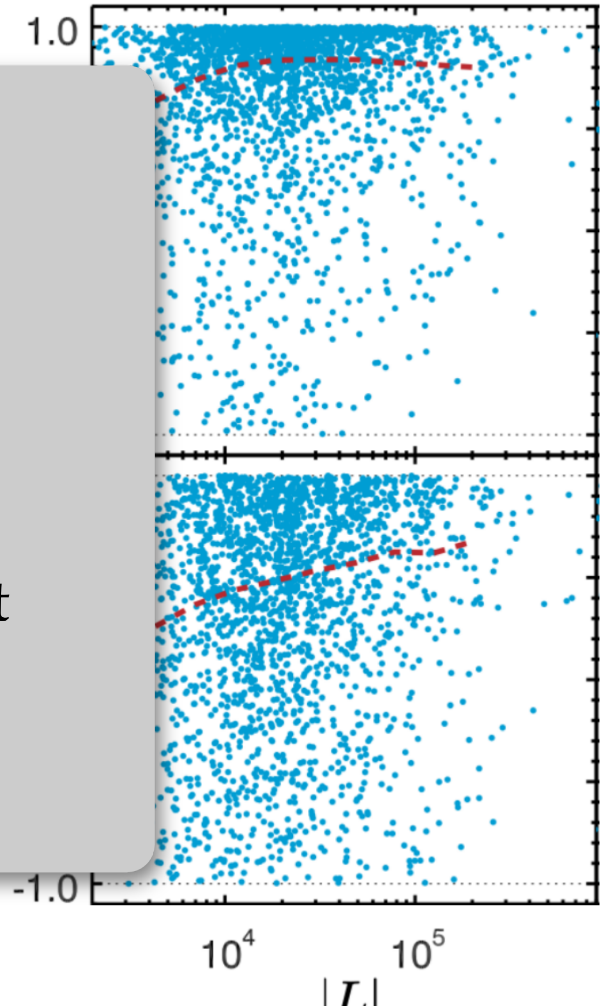

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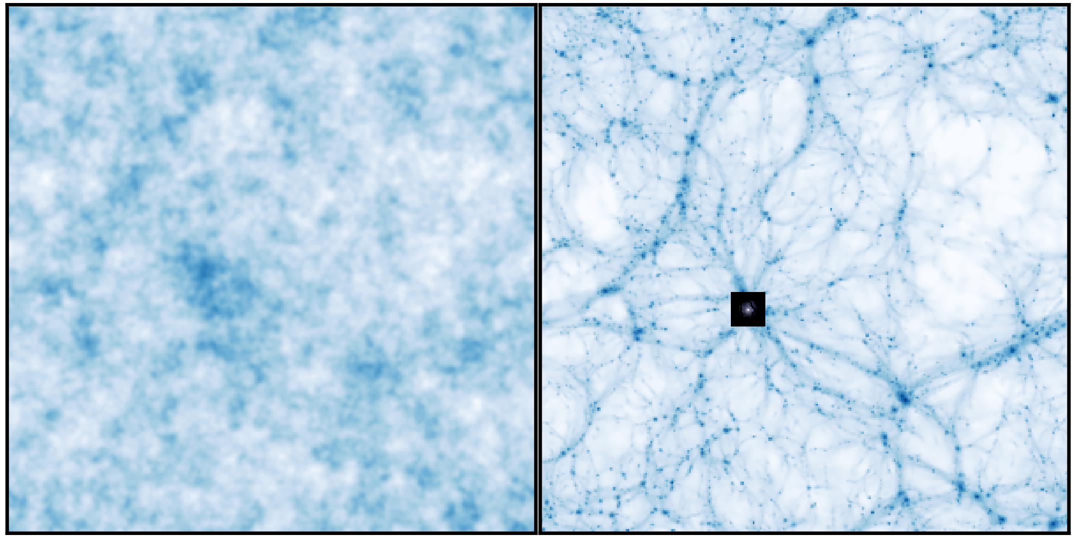
Is $j_{\rm DM}$ chaotic or our theory poor?

First controlled experiment of testing tidal torque theory for **individual halos**

CC+21a, arXiv: 2012.02201

Predicting angular momentum

$z = 100$ $z = 0$



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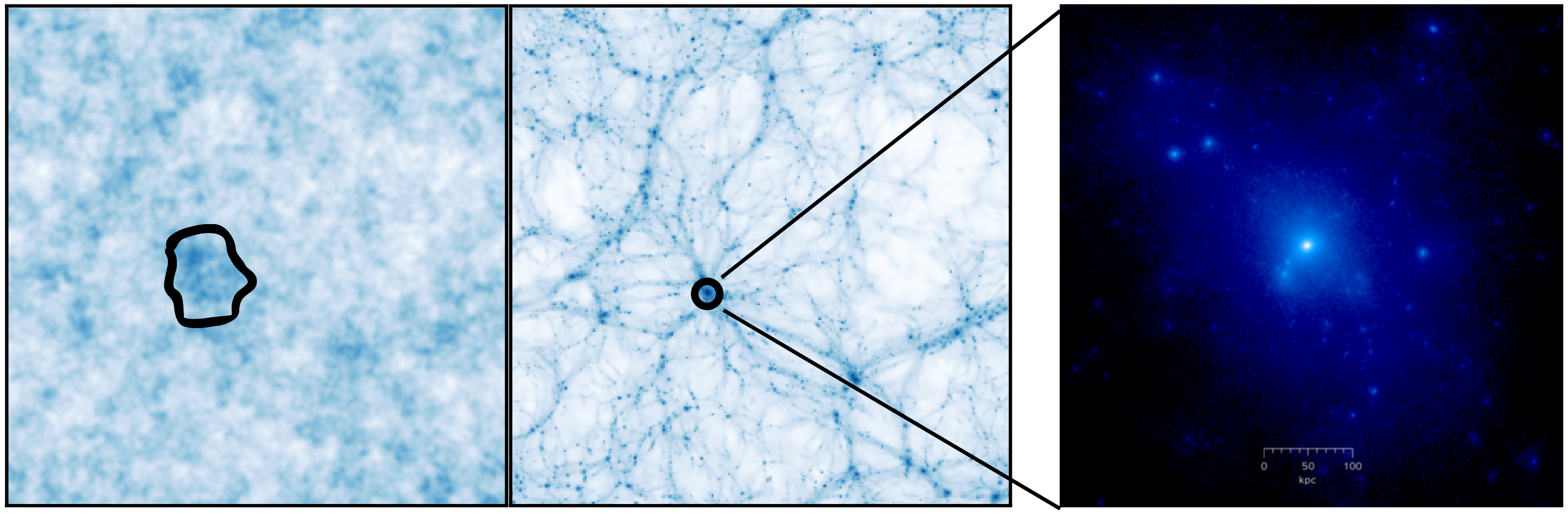

$$\mathbf{L}_{\text{lin.}} \propto \int \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla \phi$$

Note: vanishes at 1st order in a sphere

$$\int_\Gamma \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla \phi = \int_{\partial\Gamma} \phi(q)(\mathbf{q} - \bar{\mathbf{q}}) \times \mathrm{d}\mathbf{S}$$

Note: the following is a (**poor**) approximation:

$\mathbf{L} \propto \epsilon_{ijk} T_{jl} I_{lk},$ with T the tidal tensor and I the inertia tensor

[White 84]

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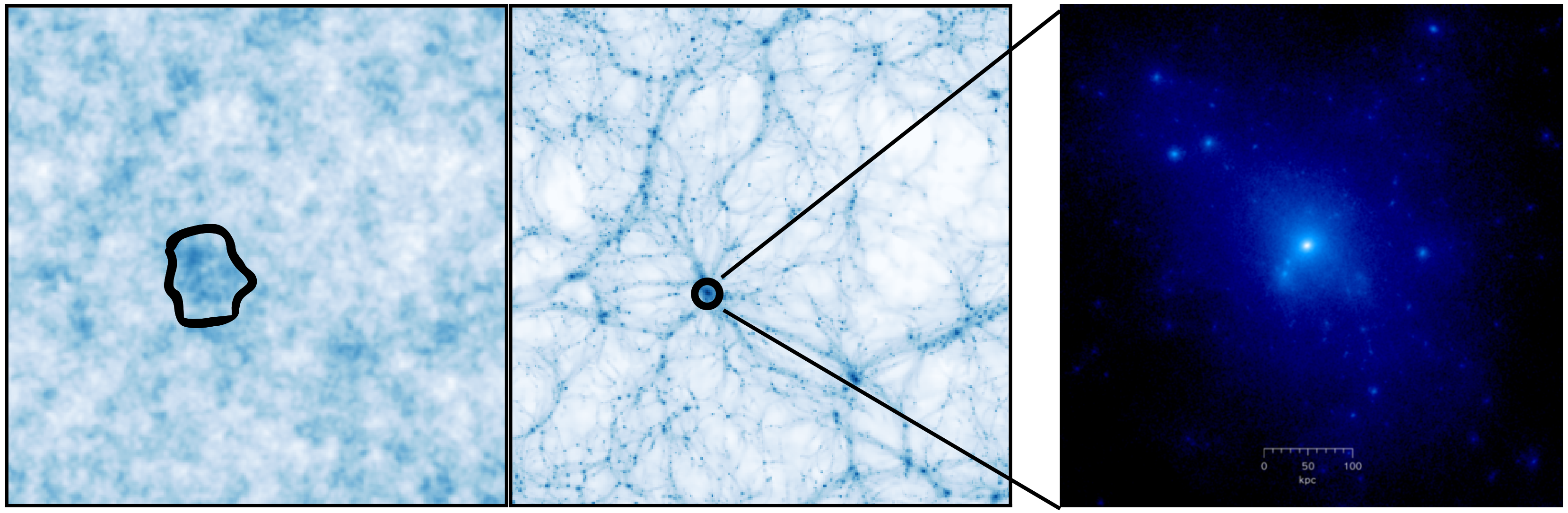

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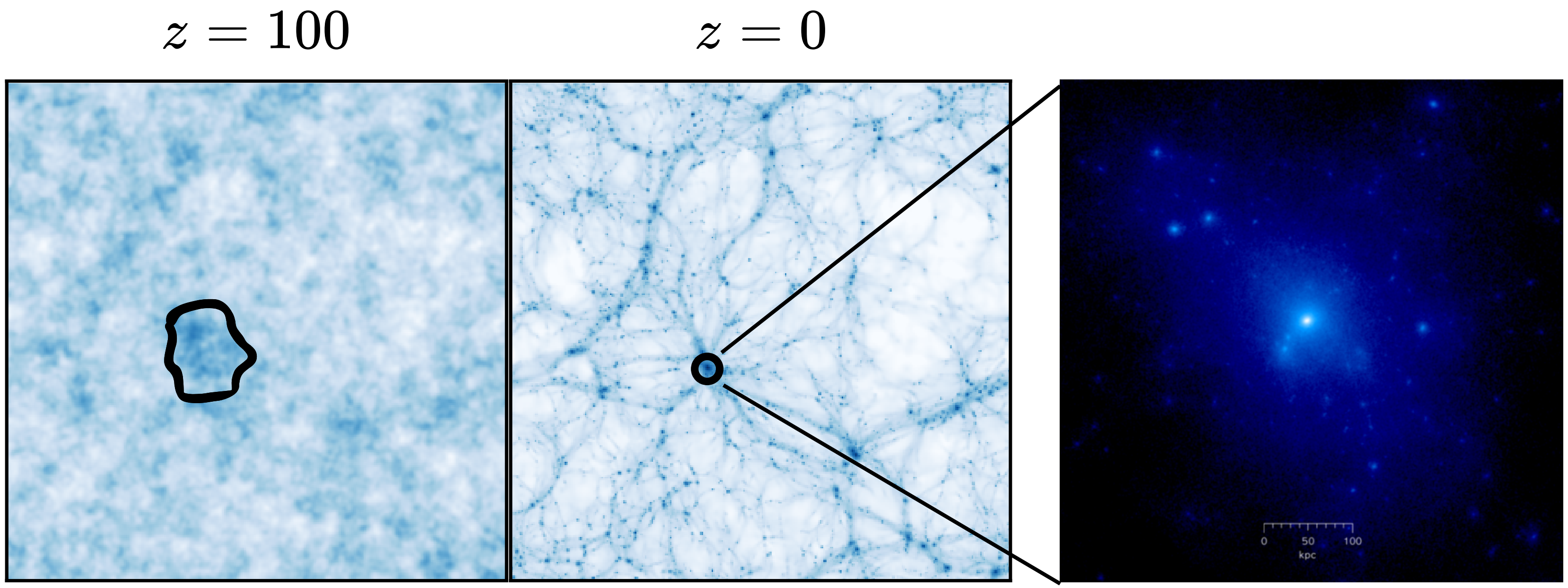

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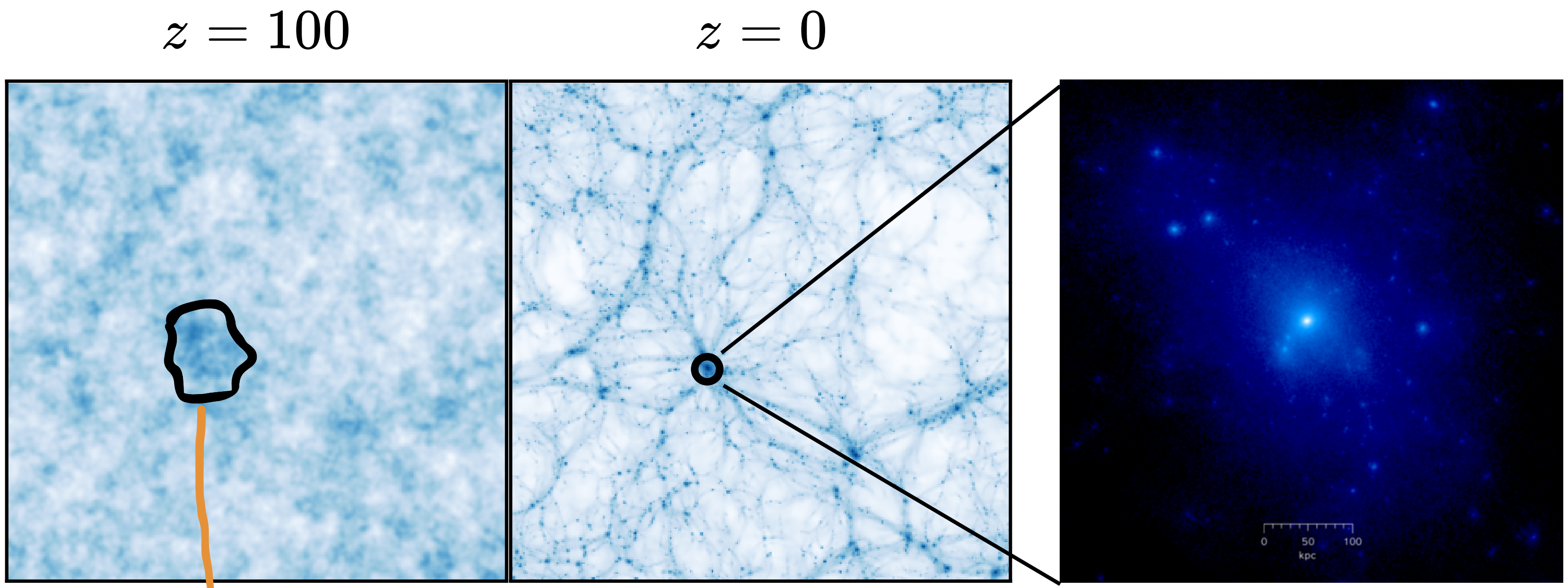

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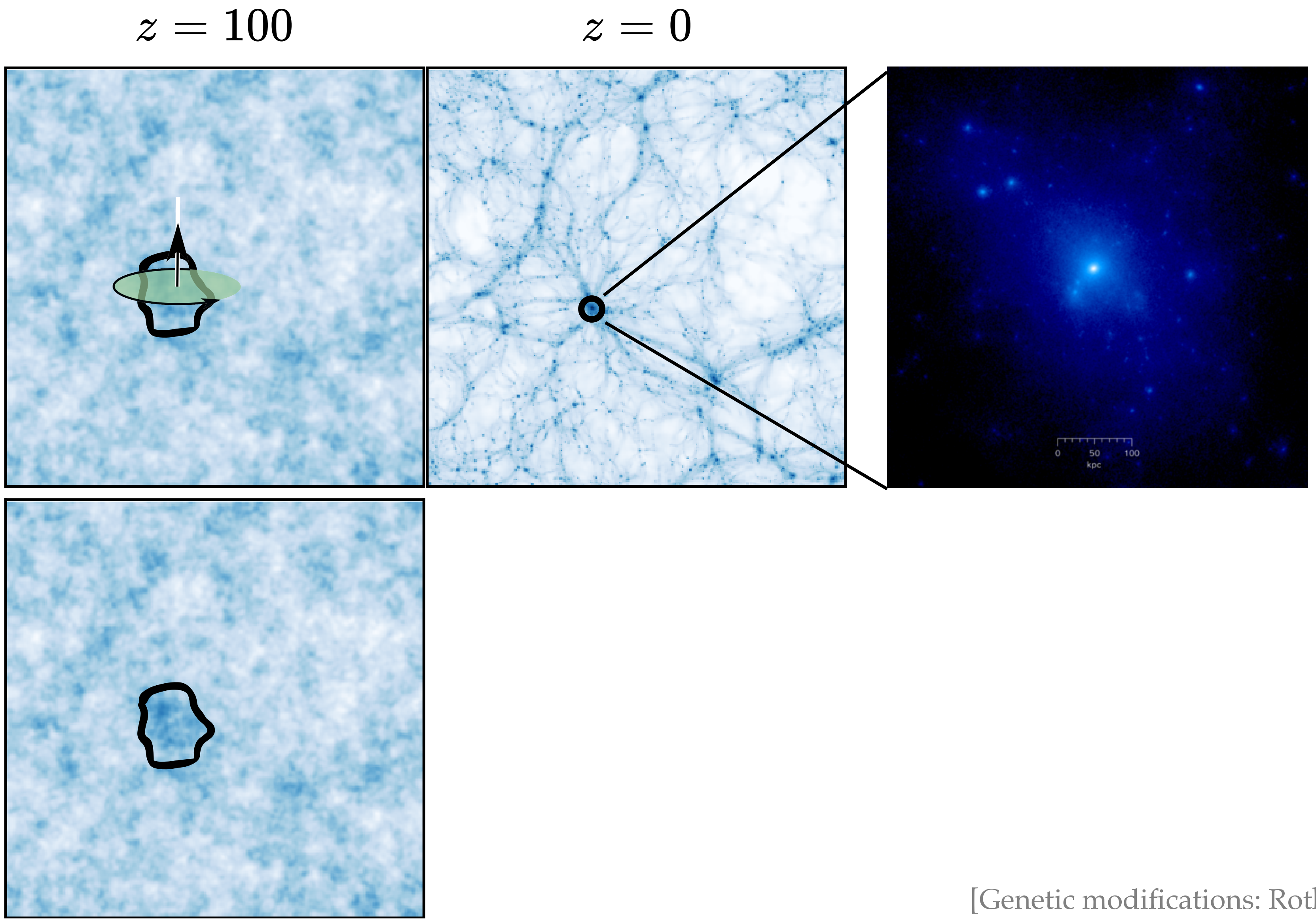

[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

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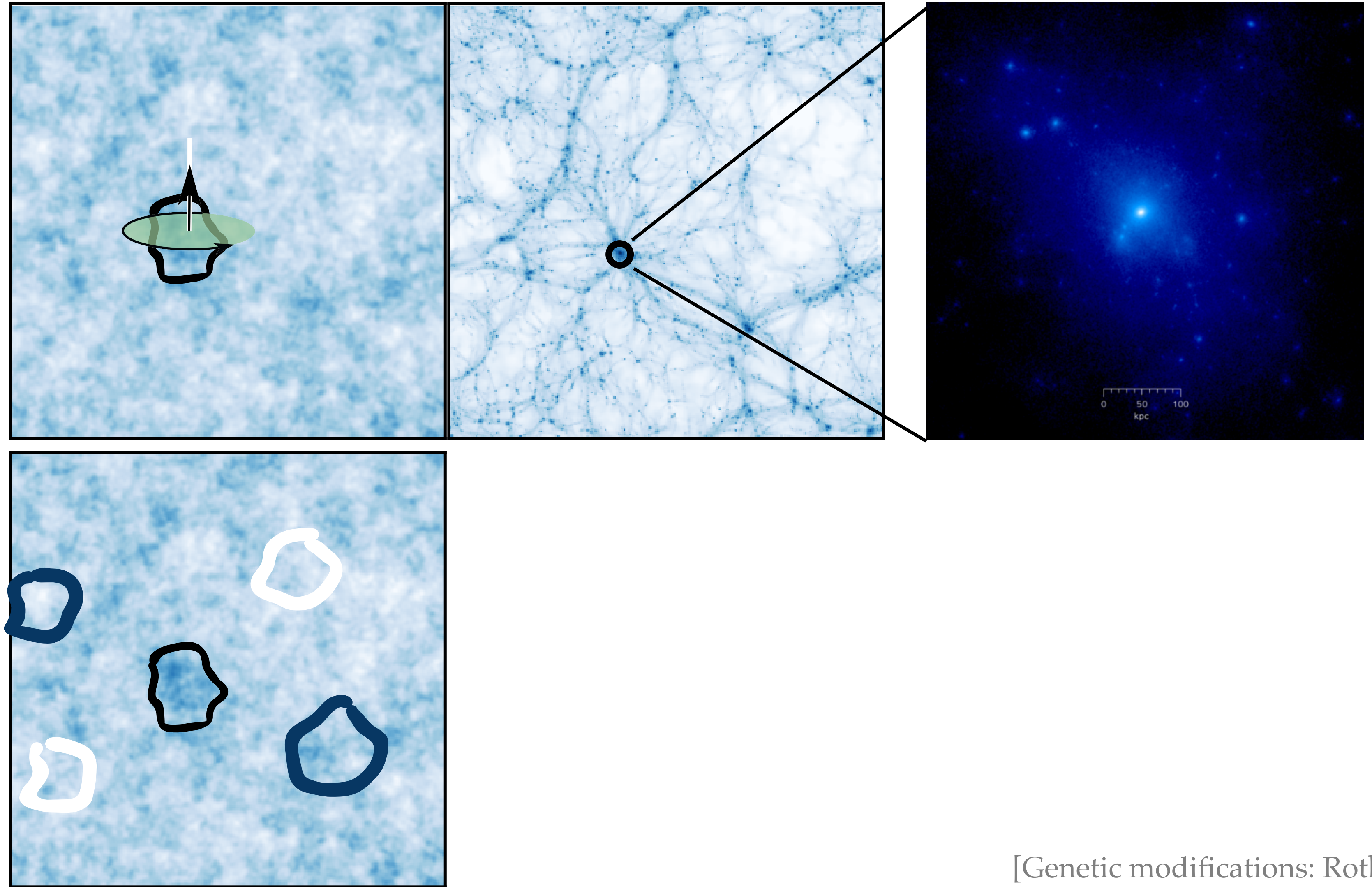

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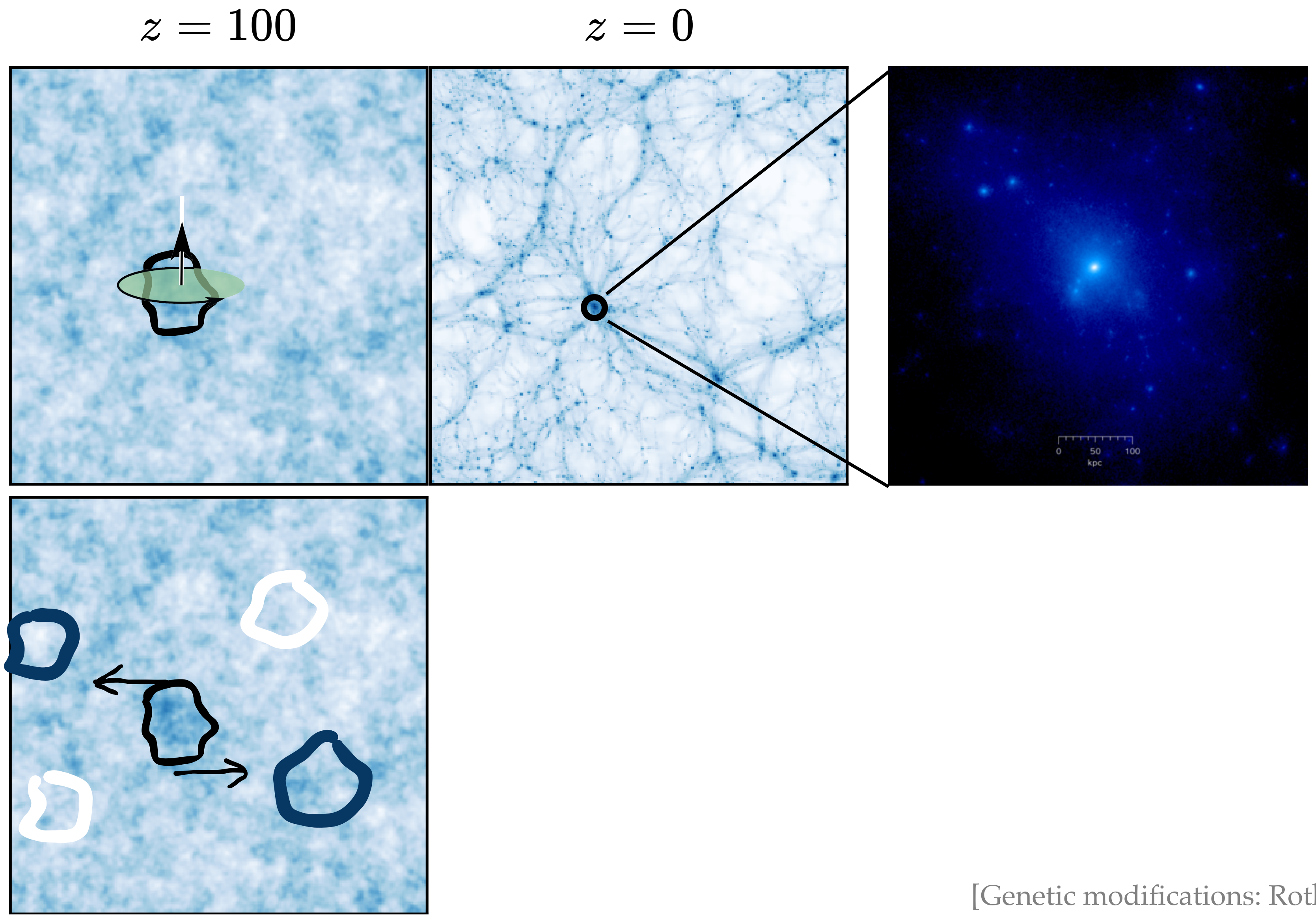

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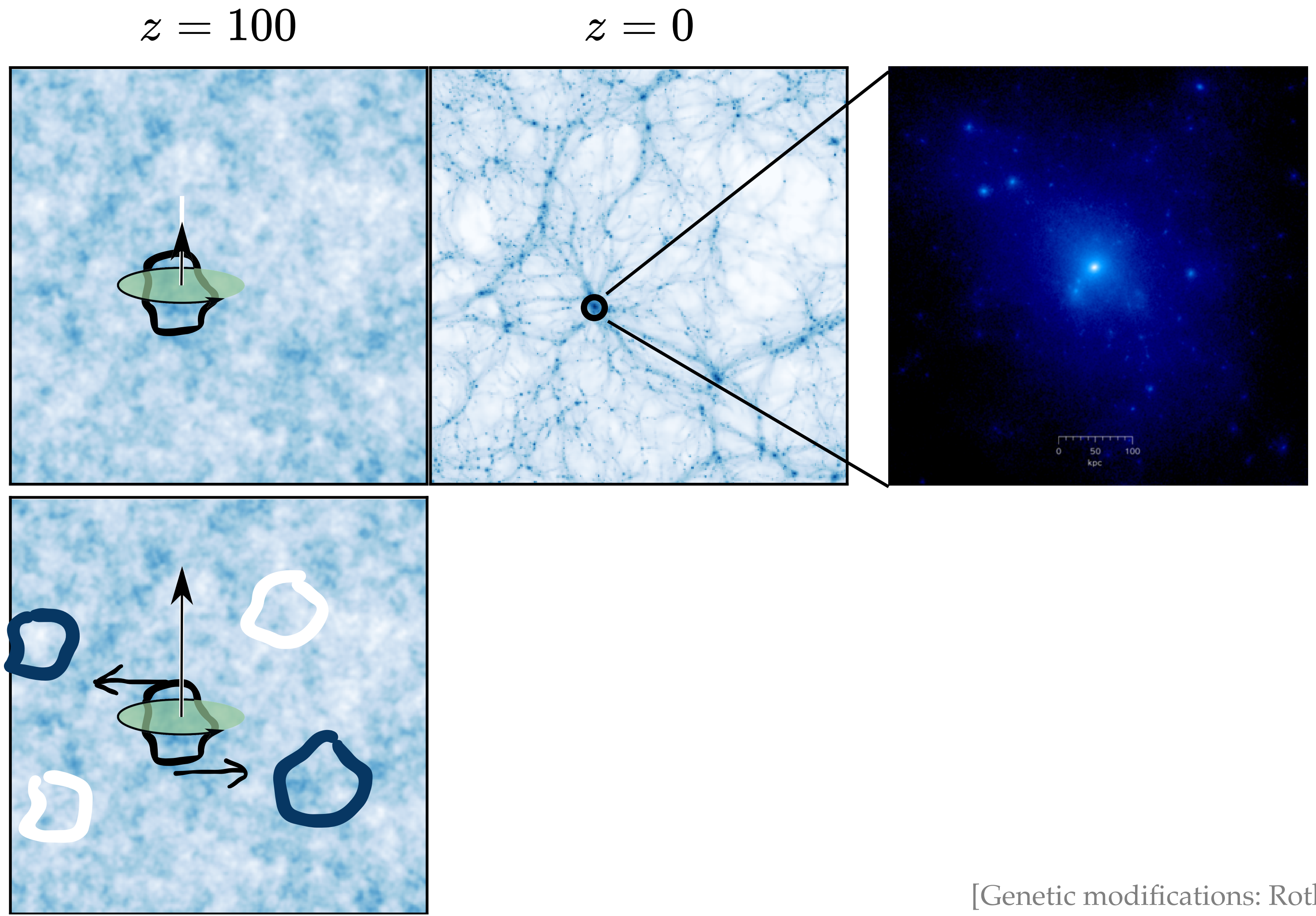

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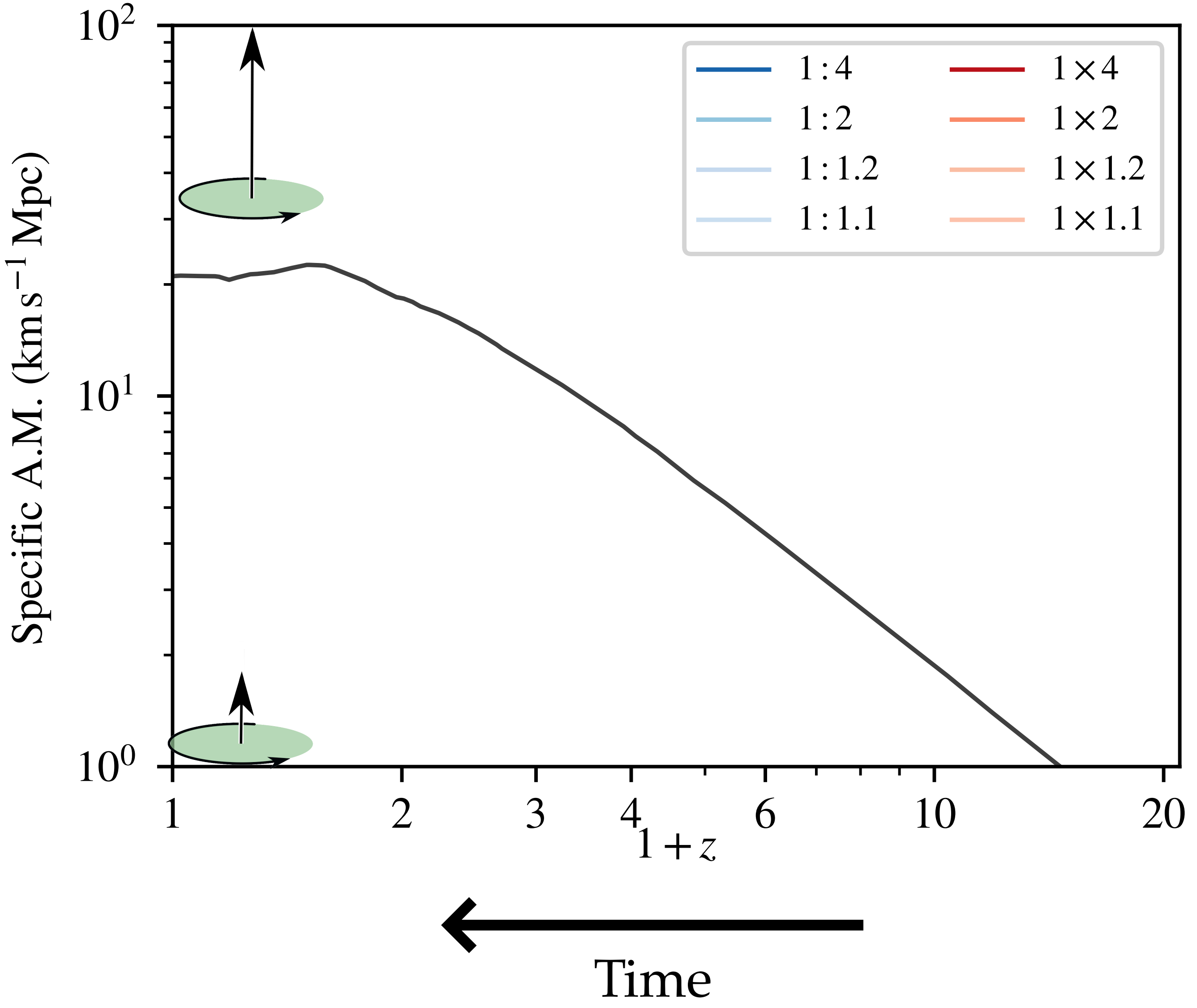
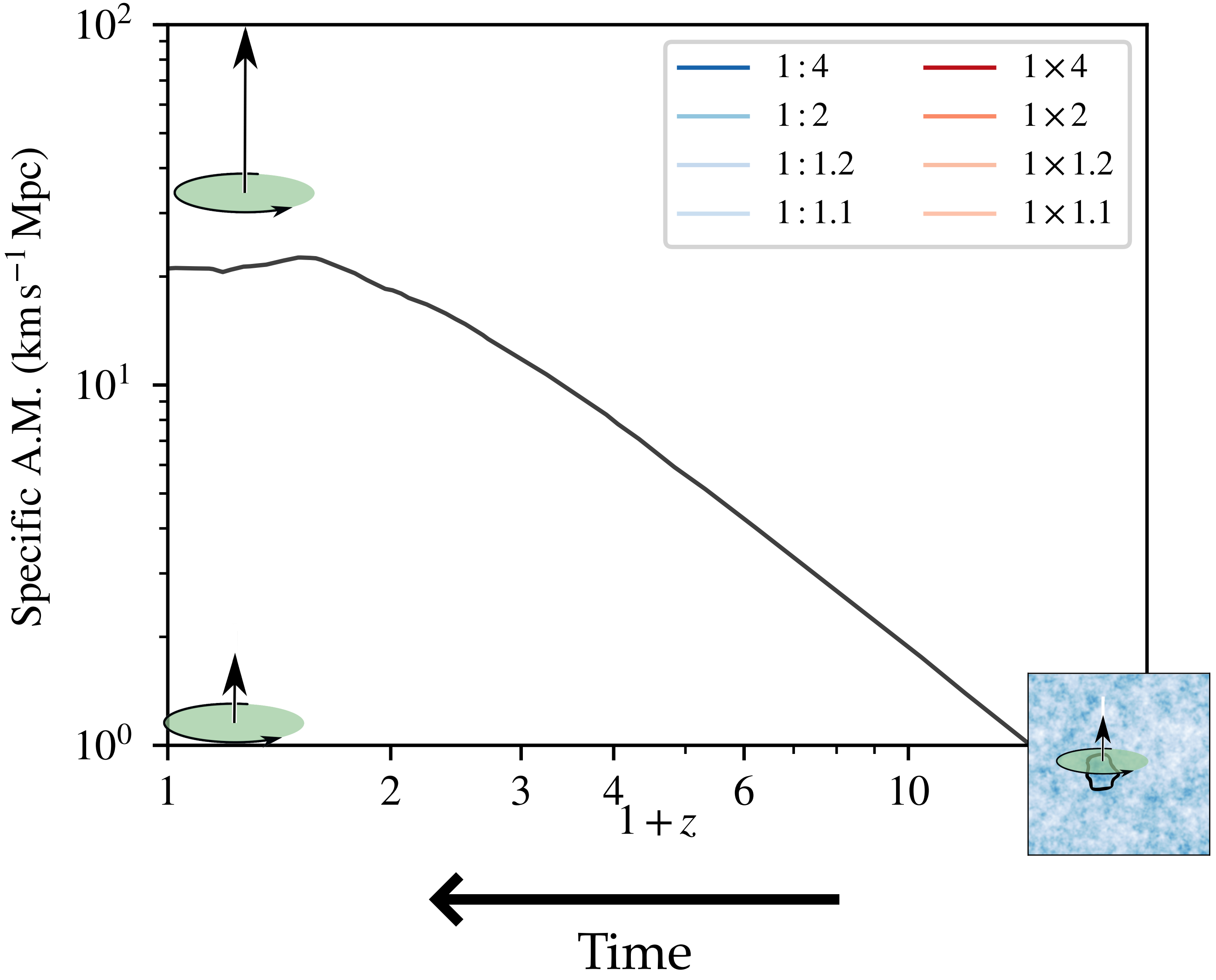
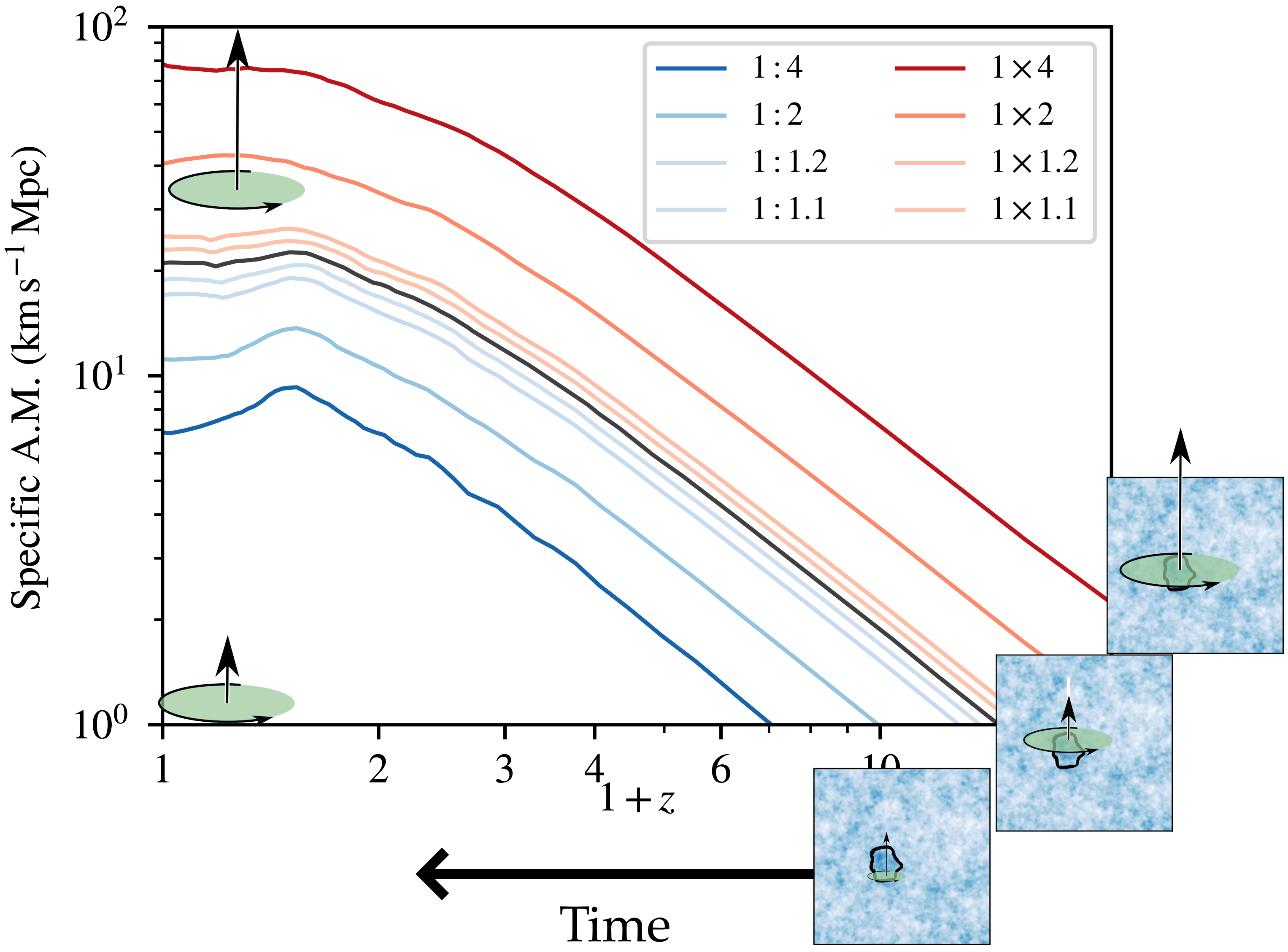


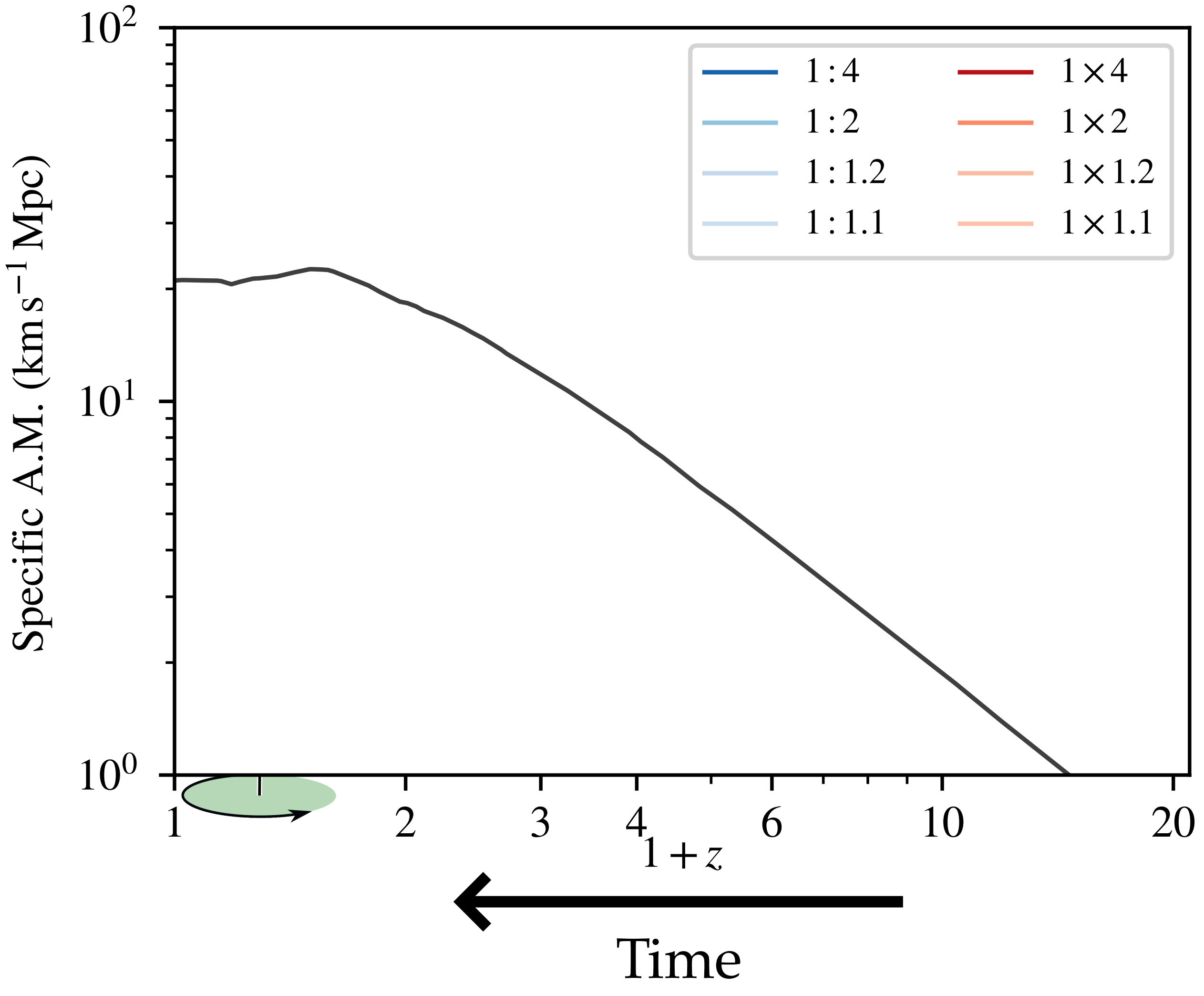
Predicting angular momentum



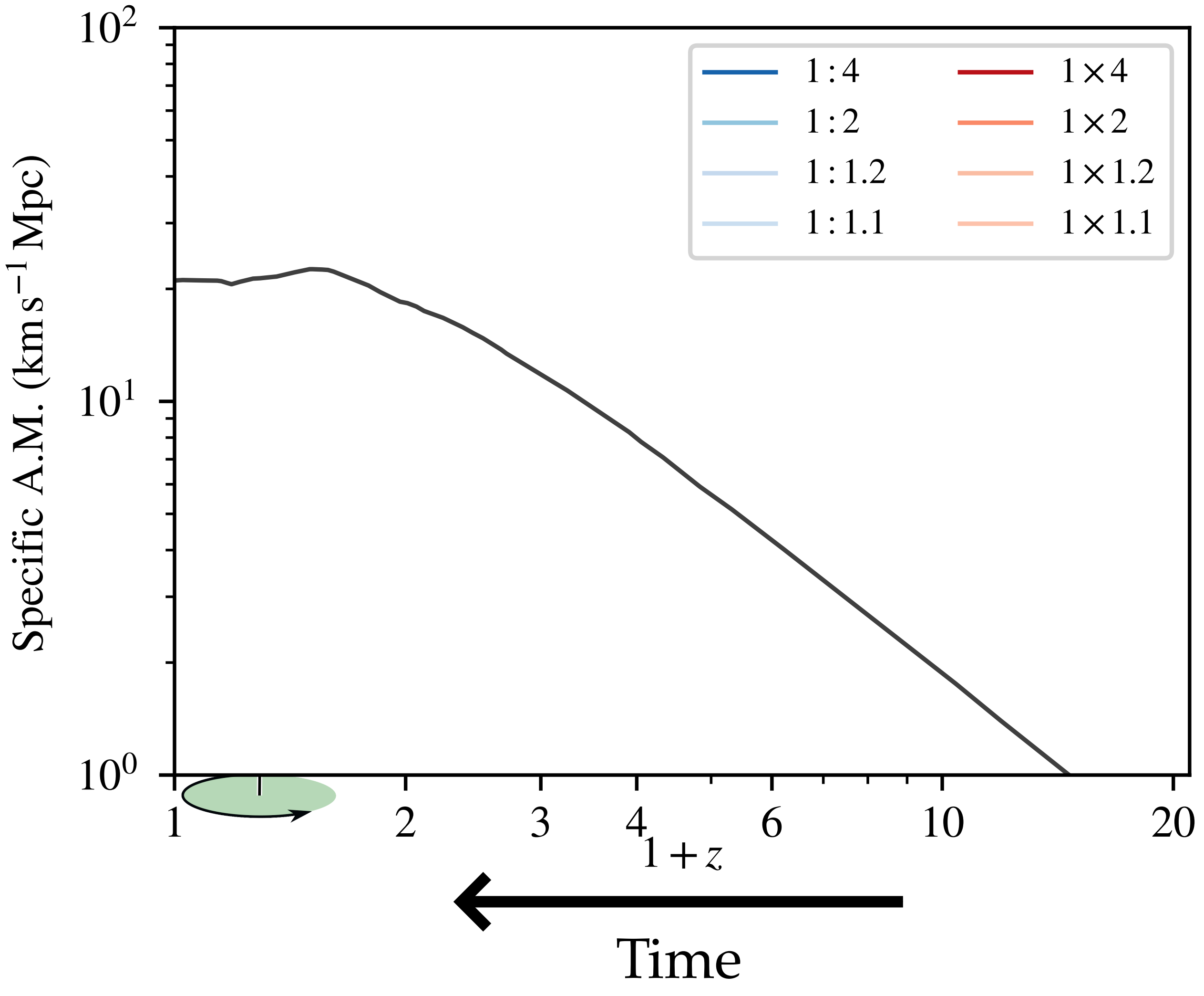
Predicting angular momentum



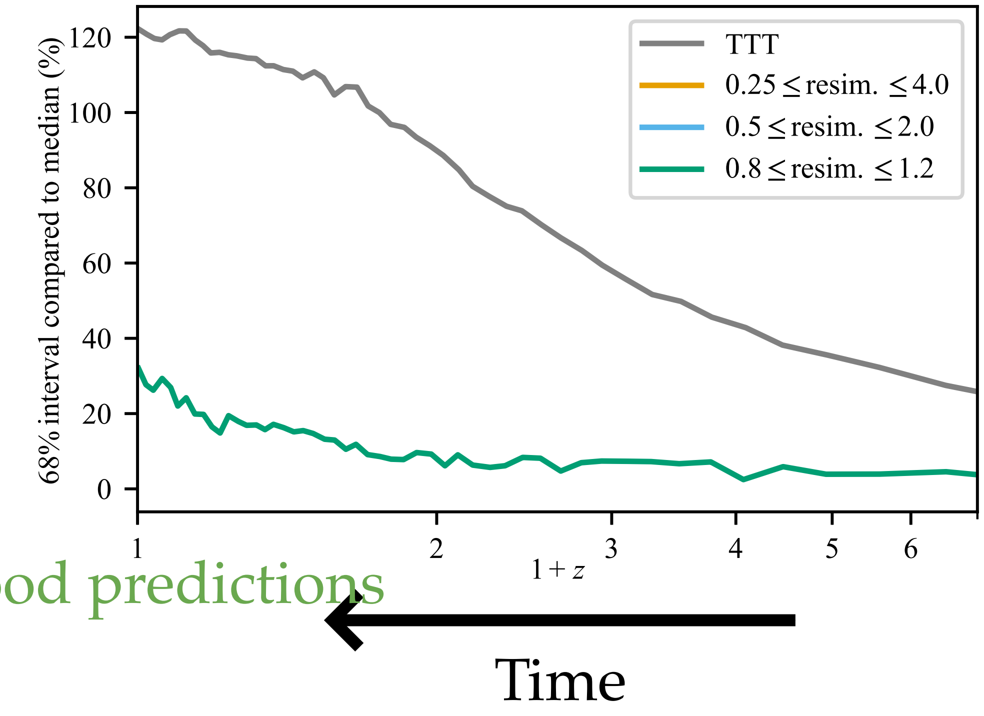
Predicting angular momentum



Predicting angular momentum

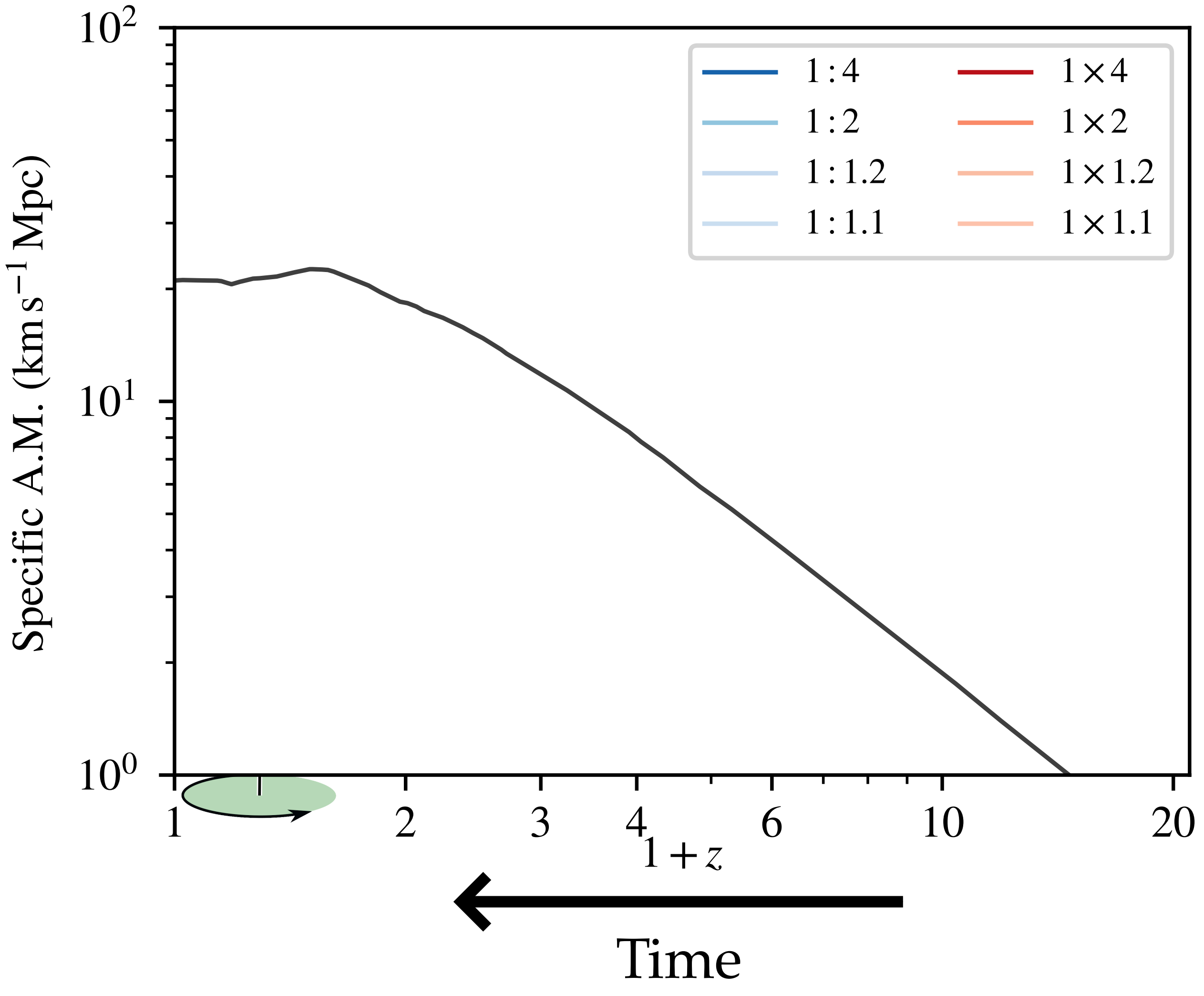


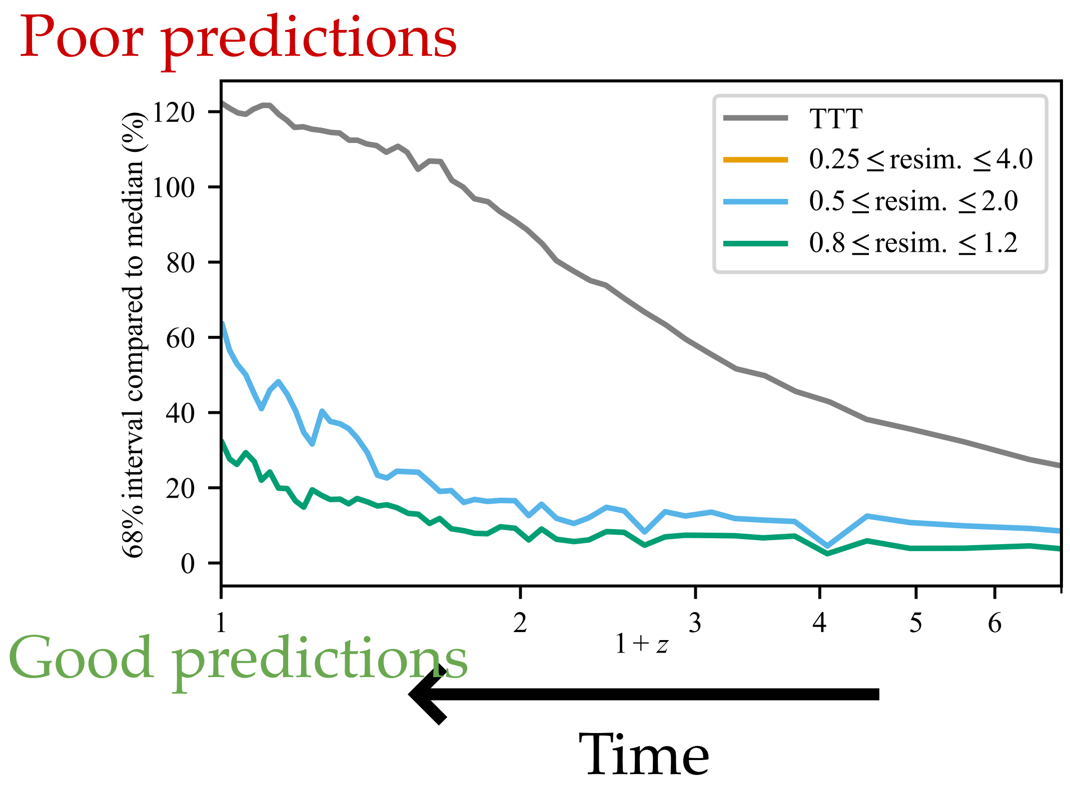
Poor predictions



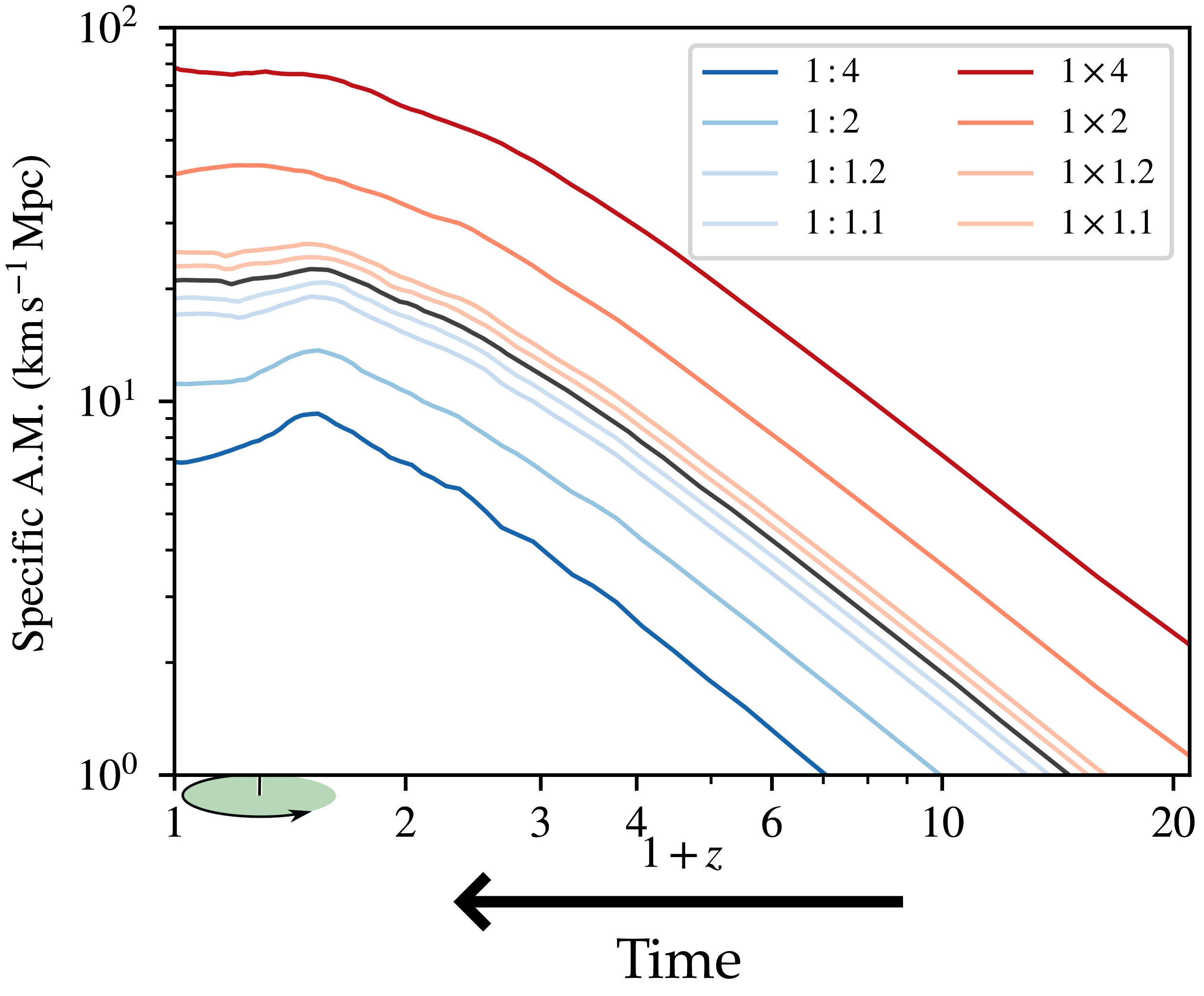
Good predictions

Predicting angular momentum

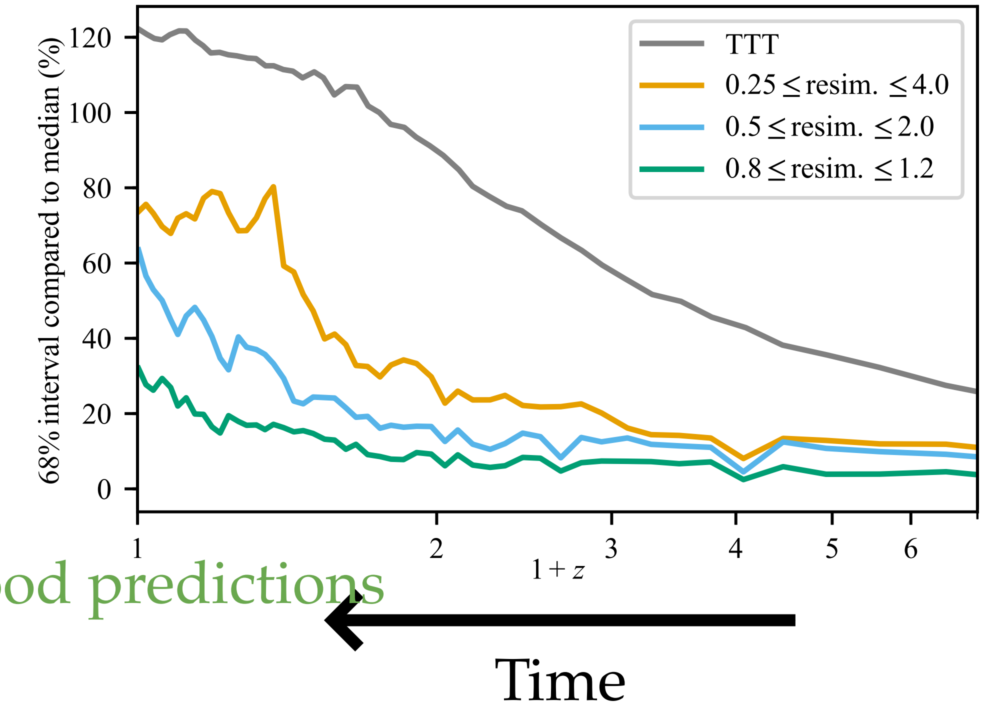




Predicting angular momentum

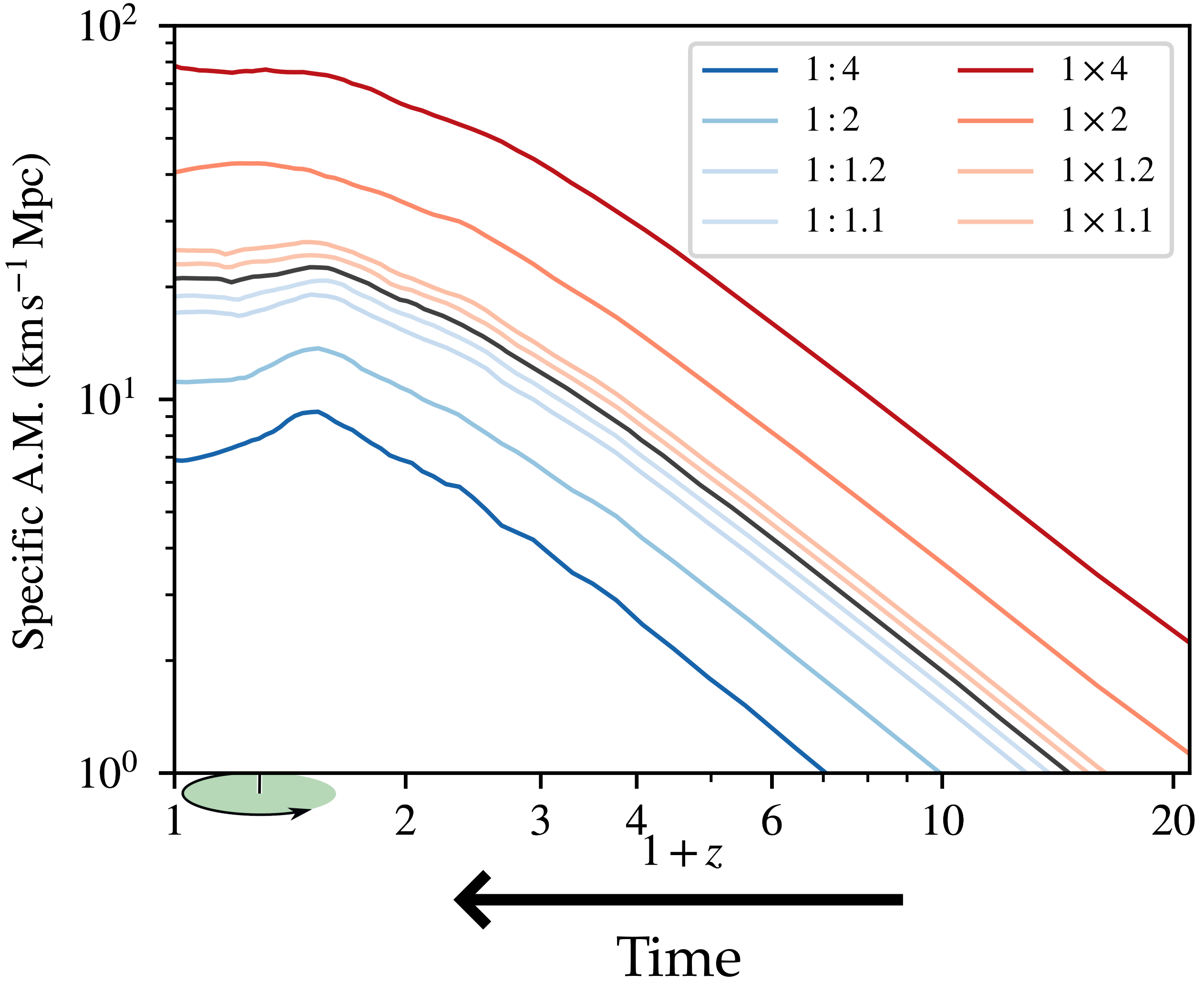


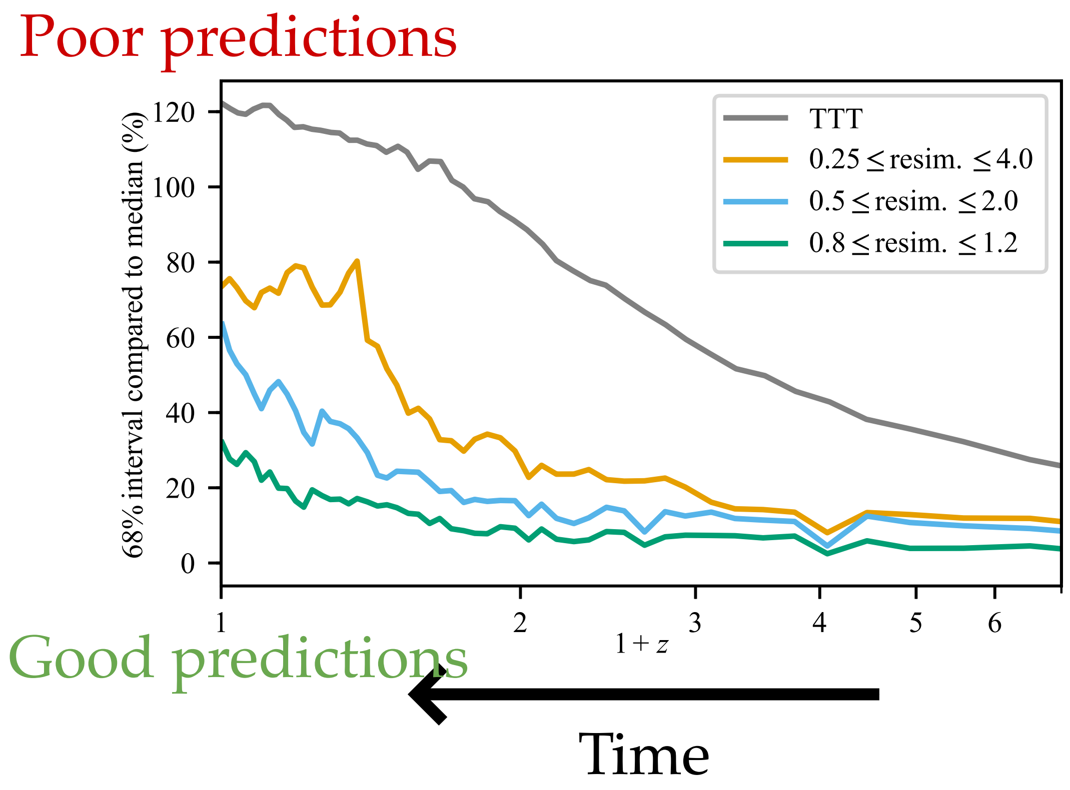
Poor predictions



Good predictions

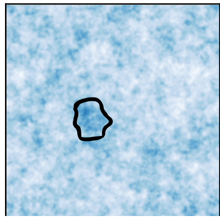
Predicting angular momentum





✅ AM of **<u>fixed</u>** DM **<u>regions</u>** can be predicted (so is not chaotic!)

Improve theory? Need good model of Lagrangian patch boundaries



Do $j_{\rm gal}$ retain memory of the environment?

First **controlled experiment** of angular momentum accretion on **individual galaxies**

CC+22, arXiv: 2206.11913

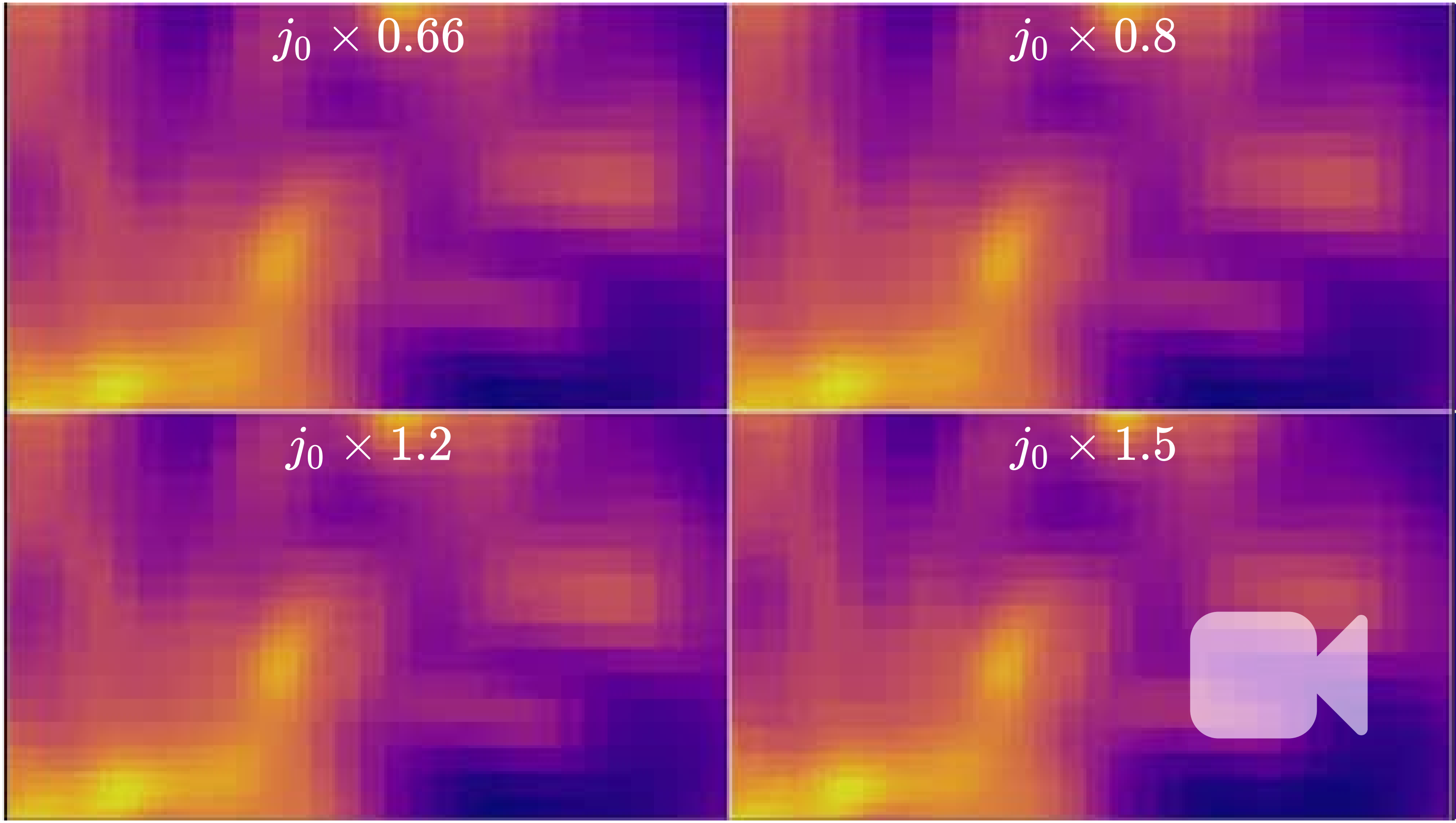
Main idea: stars are deeper in potential well so less sensitive to what happens at large scales

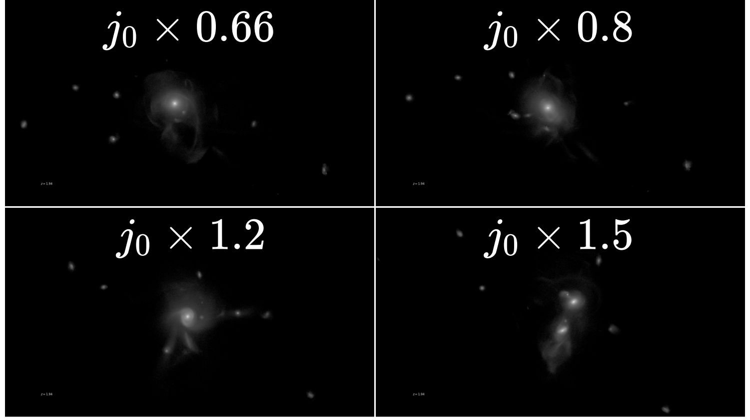
$\Rightarrow$ *stellar* Lagrangian patch should be more stable to perturbations

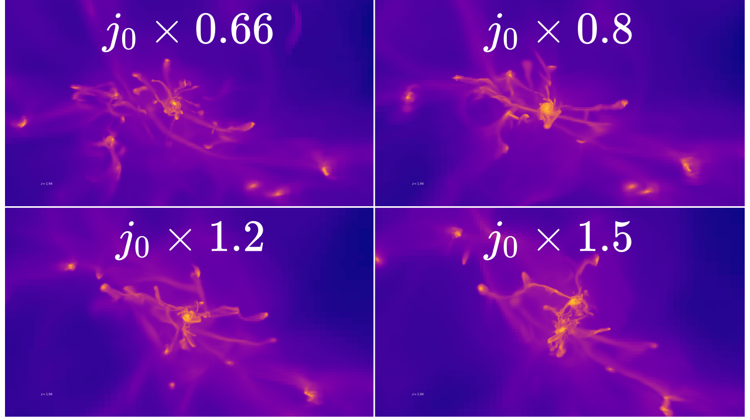
Baryon angular momentum

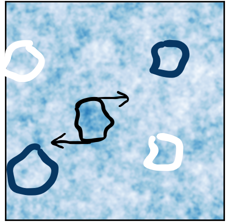
Full hydro simulations (10Mh @ DiRAC):

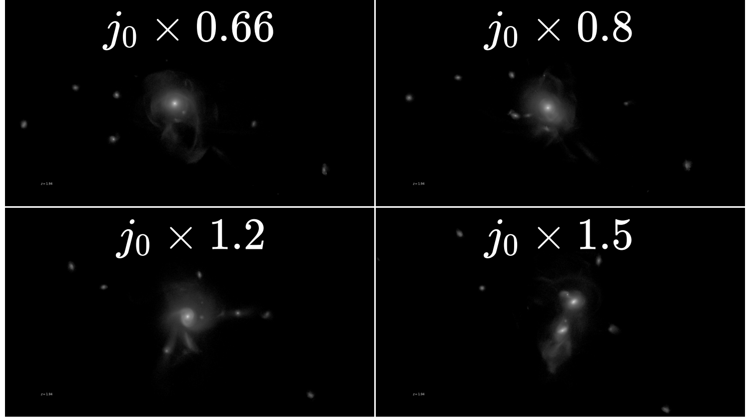
- Resolve disk height $\Delta x = 35$ kpc
- $z \geq 2$, $M_{200c} = 10^{12}$ $M_\odot$
- SF + AGN & SN feedback
- **Tracer particles** **CC**+19
- 3 galaxies, 5× scenario each

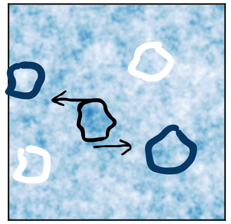


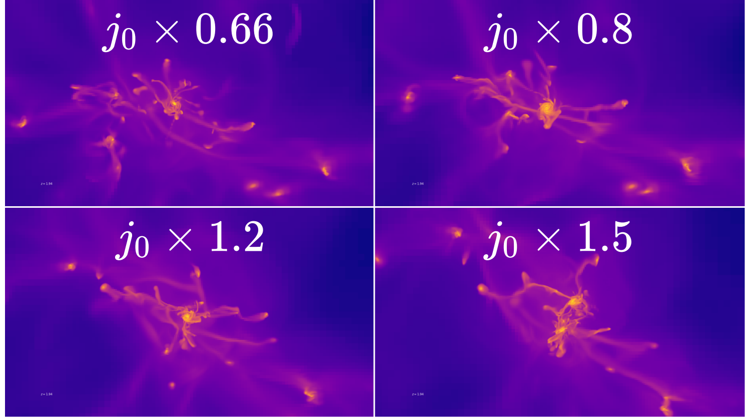

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$

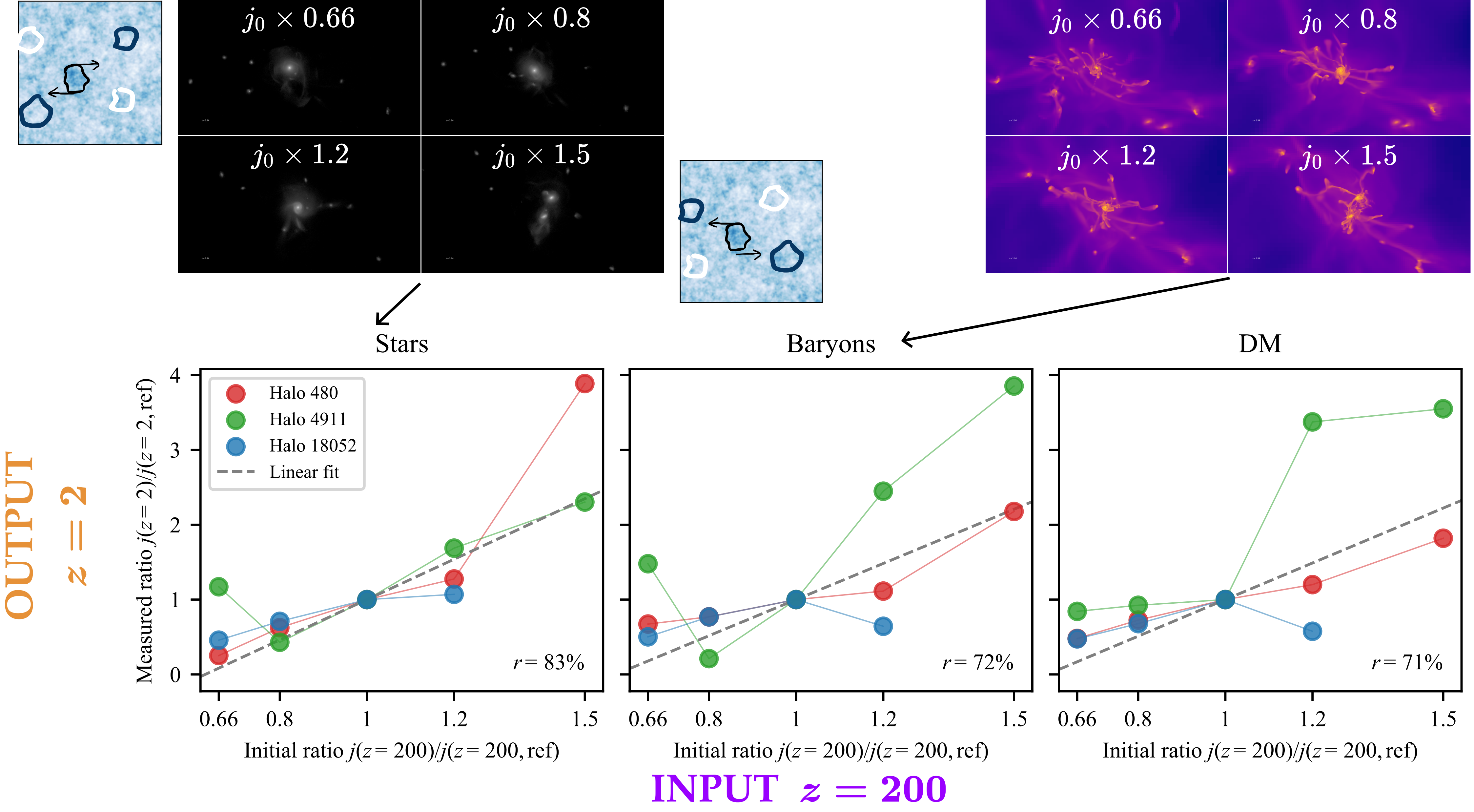

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$



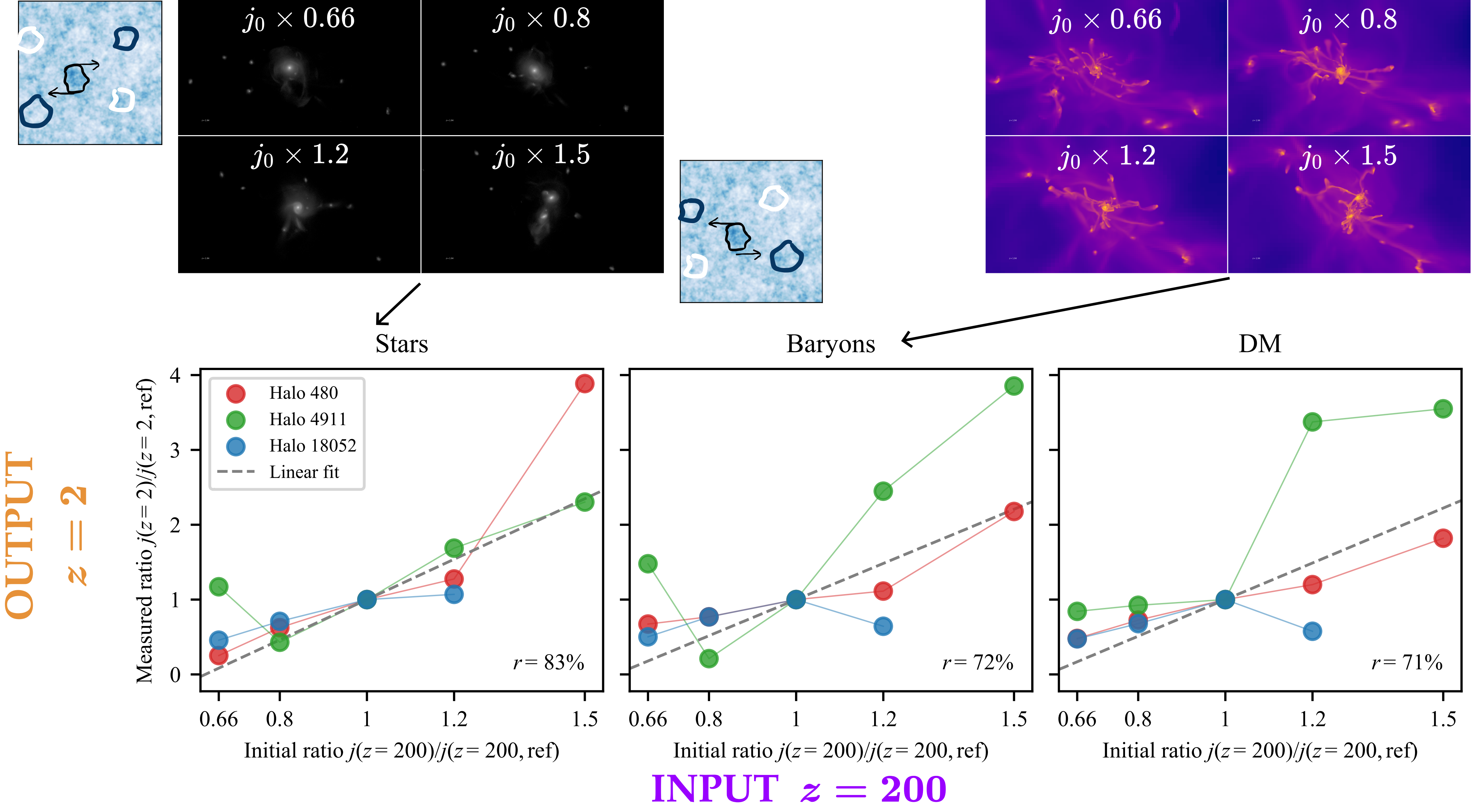

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$




$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$

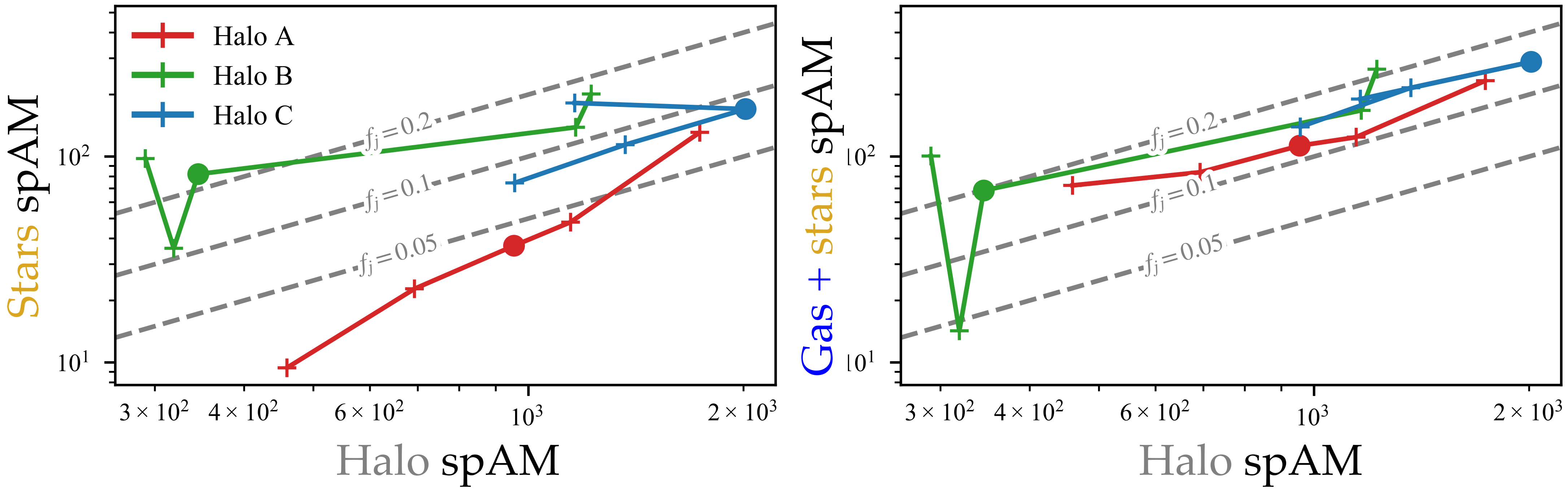


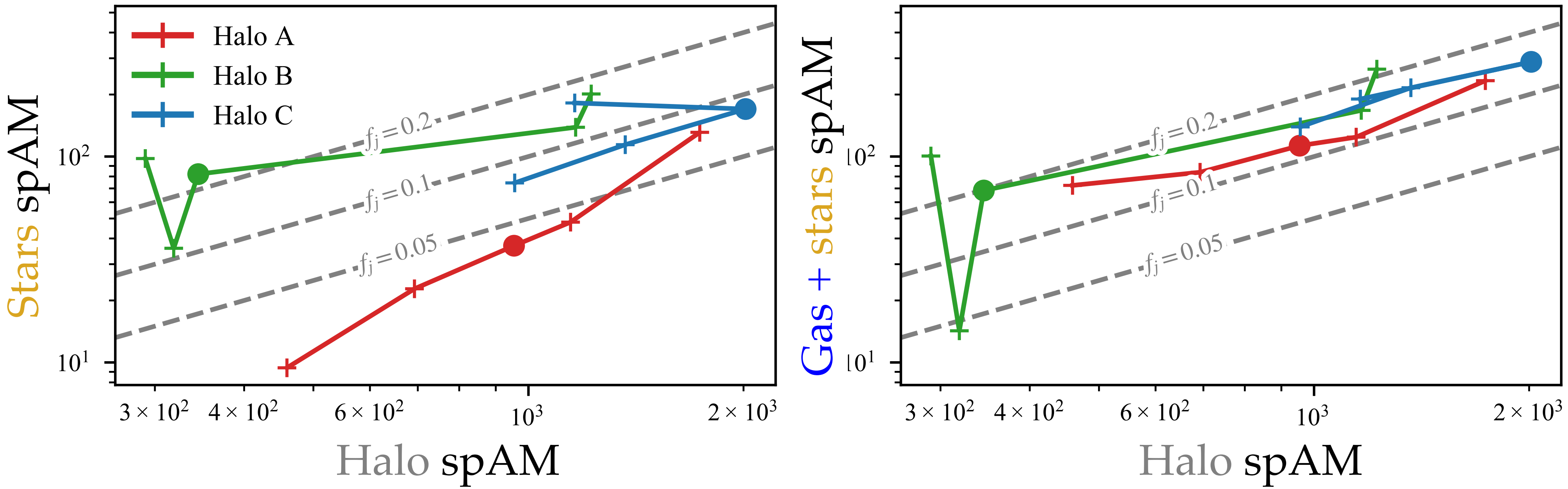
$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$
$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$
Stars
Baryons
DM
Halo 480
Halo 4911
Halo 18052
Linear fit
Measured ratio $j(z=2)/j(z=2, \text{ref})$
$r = 83\%$
$r = 72\%$
$r = 71\%$
Initial ratio $j(z=200)/j(z=200, \text{ref})$
Initial ratio $j(z=200)/j(z=200, \text{ref})$
Initial ratio $j(z=200)/j(z=200, \text{ref})$
OUTPUT $z = 2$
INPUT $z = 200$



✅ **Stellar** AM driven by (past) tides with the cosmic web (which can be predicted)

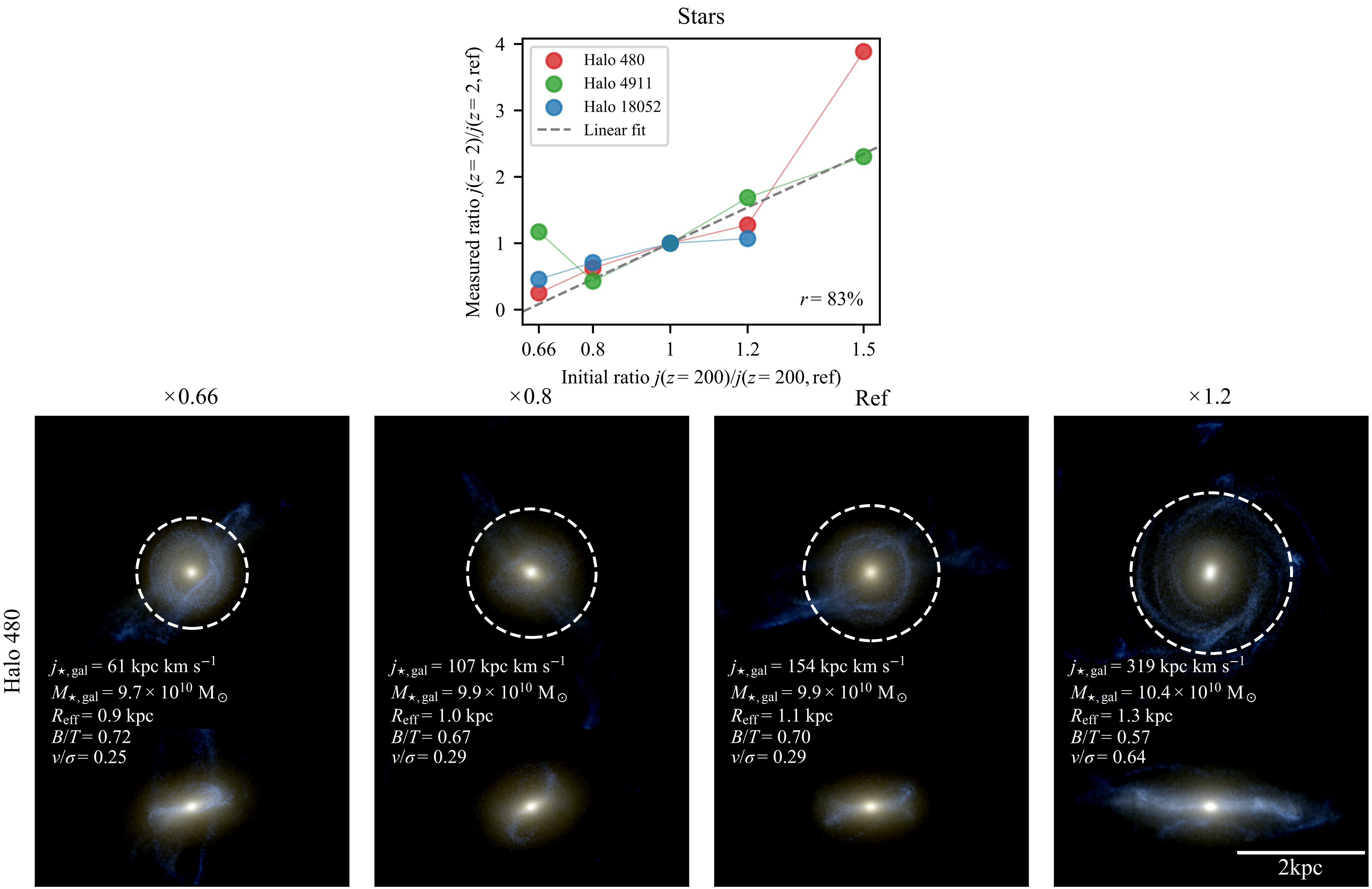
More complex for DM / baryons


Halo A
Halo B
Halo C
Stars spAM
Gas + stars spAM
Halo spAM
Halo spAM

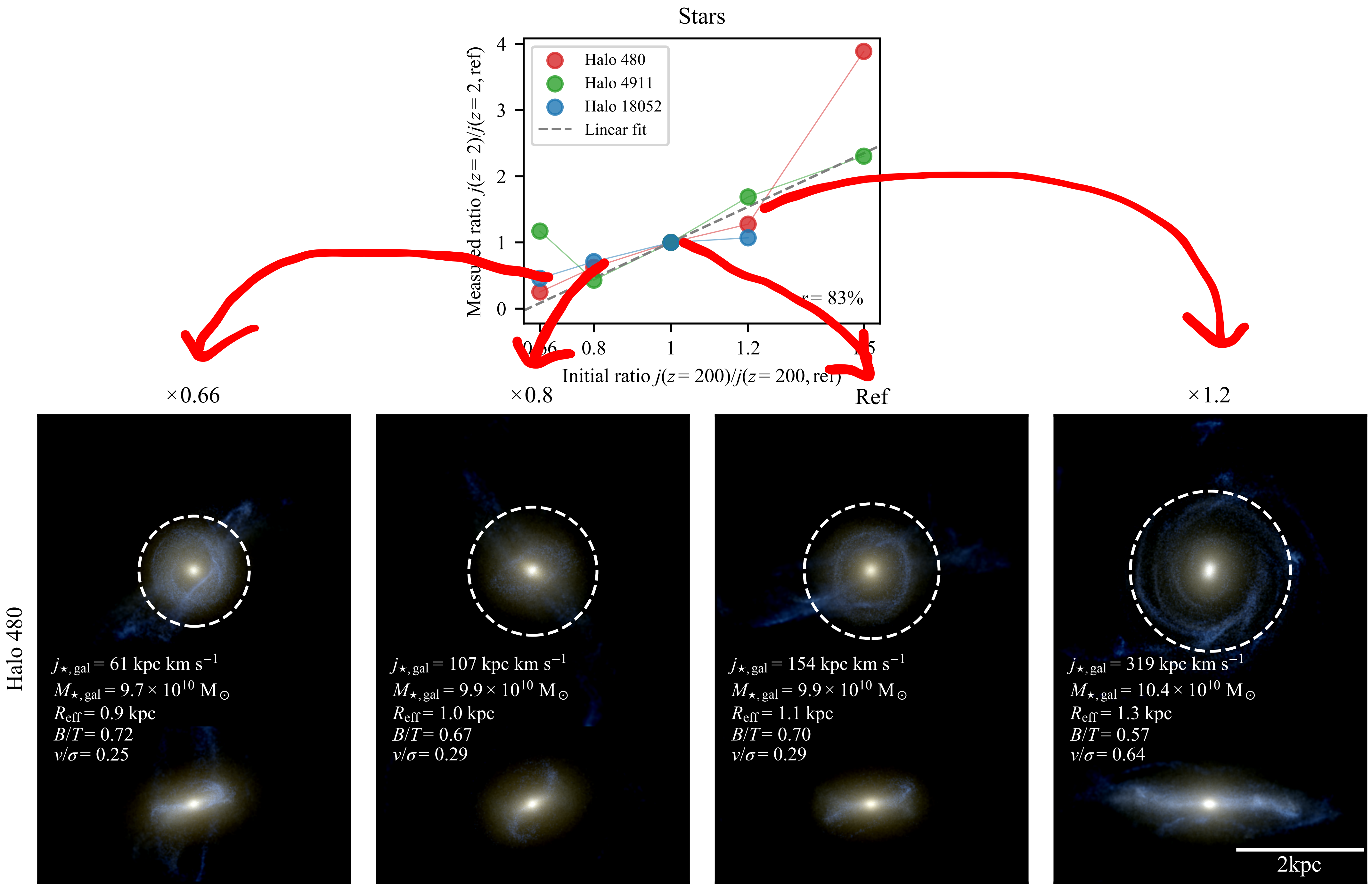


✅ **Changes** in baryon spAM ~ **Changes** in Halo spAM

Insight: matter in the outskirts (mostly gas & DM) dominate spAM magnitude (& direction?)



Stars
Measured ratio $j(z=2)/j(z=2, \mathrm{ref})$
Initial ratio $j(z=200)/j(z=200, \mathrm{ref})$
Halo 480
Halo 4911
Halo 18052
Linear fit
$r = 83\%$
0.66
0.8
1
1.2
1.5
0
1
2
3
4
×0.66
×0.8
Ref
×1.2
Halo 480
$j_{\star,\mathrm{gal}} = 61$ kpc km s^{-1}
$M_{\star,\mathrm{gal}} = 9.7\times10^{10}$ M$_\odot$
$R_{\mathrm{eff}} = 0.9$ kpc
$B/T = 0.72$
$v/\sigma = 0.25$
$j_{\star,\mathrm{gal}} = 107$ kpc km s^{-1}
$M_{\star,\mathrm{gal}} = 9.9\times10^{10}$ M$_\odot$
$R_{\mathrm{eff}} = 1.0$ kpc
$B/T = 0.67$
$v/\sigma = 0.29$
$j_{\star,\mathrm{gal}} = 154$ kpc km s^{-1}
$M_{\star,\mathrm{gal}} = 9.9\times10^{10}$ M$_\odot$
$R_{\mathrm{eff}} = 1.1$ kpc
$B/T = 0.70$
$v/\sigma = 0.29$
$j_{\star,\mathrm{gal}} = 319$ kpc km s^{-1}
$M_{\star,\mathrm{gal}} = 10.4\times10^{10}$ M$_\odot$
$R_{\mathrm{eff}} = 1.3$ kpc
$B/T = 0.57$
$v/\sigma = 0.64$
2kpc


Stars
Halo 480
Halo 4911
Halo 18052
Linear fit
Measured ratio j(z = 2)/j(z = 2, ref)
Initial ratio j(z = 200)/j(z = 200, ref)
0.8
1
1.2
0
1
2
3
4
= 83%
×0.66
×0.8
Ref
×1.2
Halo 480
$j_{\star,\mathrm{gal}}$ = 61 kpc km s^{-1}
$M_{\star,\mathrm{gal}}$ = 9.7 × 10^{10} M$_\odot$
R_eff = 0.9 kpc
B/T = 0.72
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$j_{\star,\mathrm{gal}}$ = 107 kpc km s^{-1}
$M_{\star,\mathrm{gal}}$ = 9.9 × 10^{10} M$_\odot$
R_eff = 1.0 kpc
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$M_{\star,\mathrm{gal}}$ = 9.9 × 10^{10} M$_\odot$
R_eff = 1.1 kpc
B/T = 0.70
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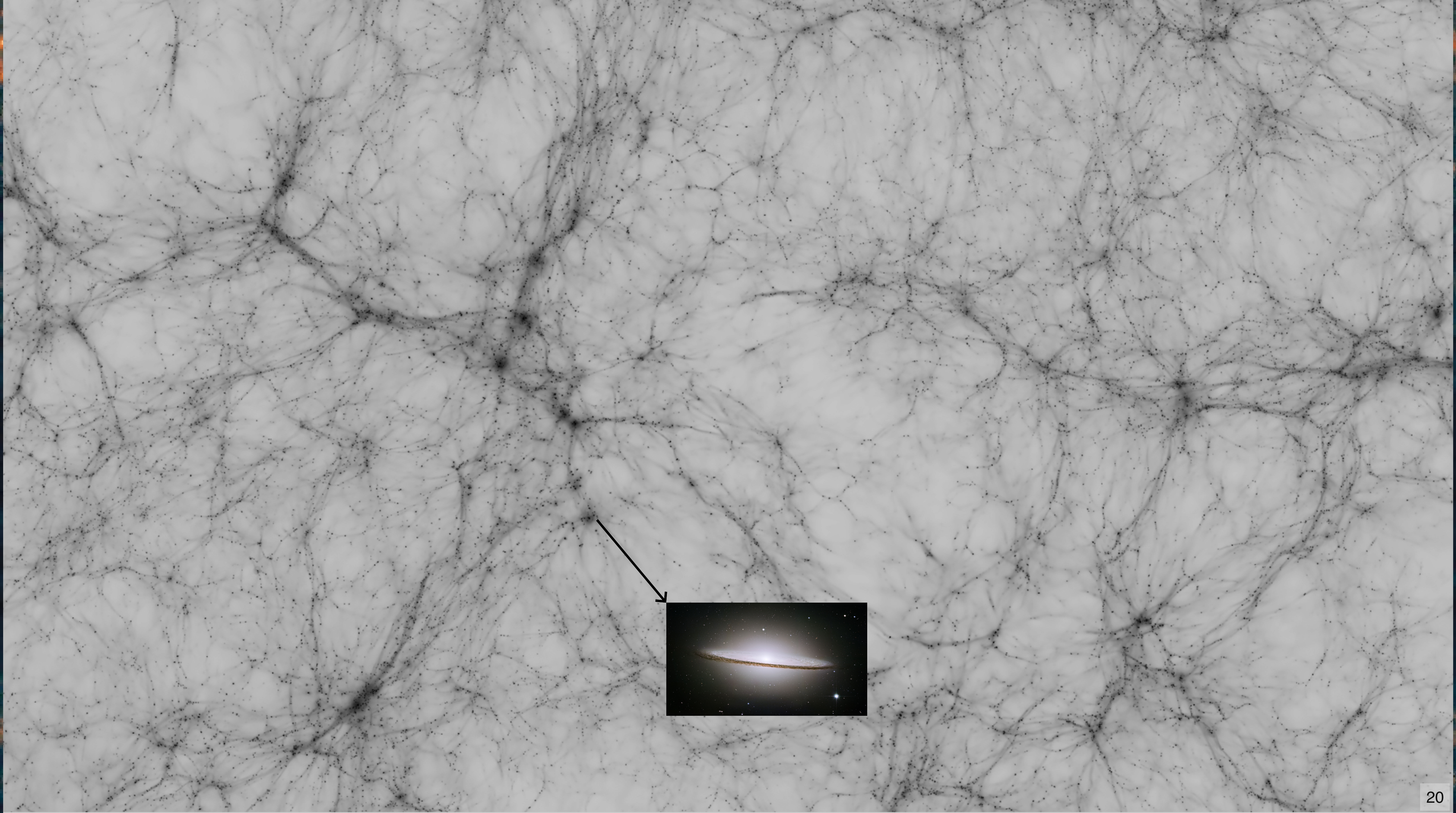
$j_{\star,\mathrm{gal}}$ = 319 kpc km s^{-1}
$M_{\star,\mathrm{gal}}$ = 10.4 × 10^{10} M$_\odot$
R_eff = 1.3 kpc
B/T = 0.57
v/σ = 0.64
2kpc

Effect(s) of anisotropic env DM / gal formation?

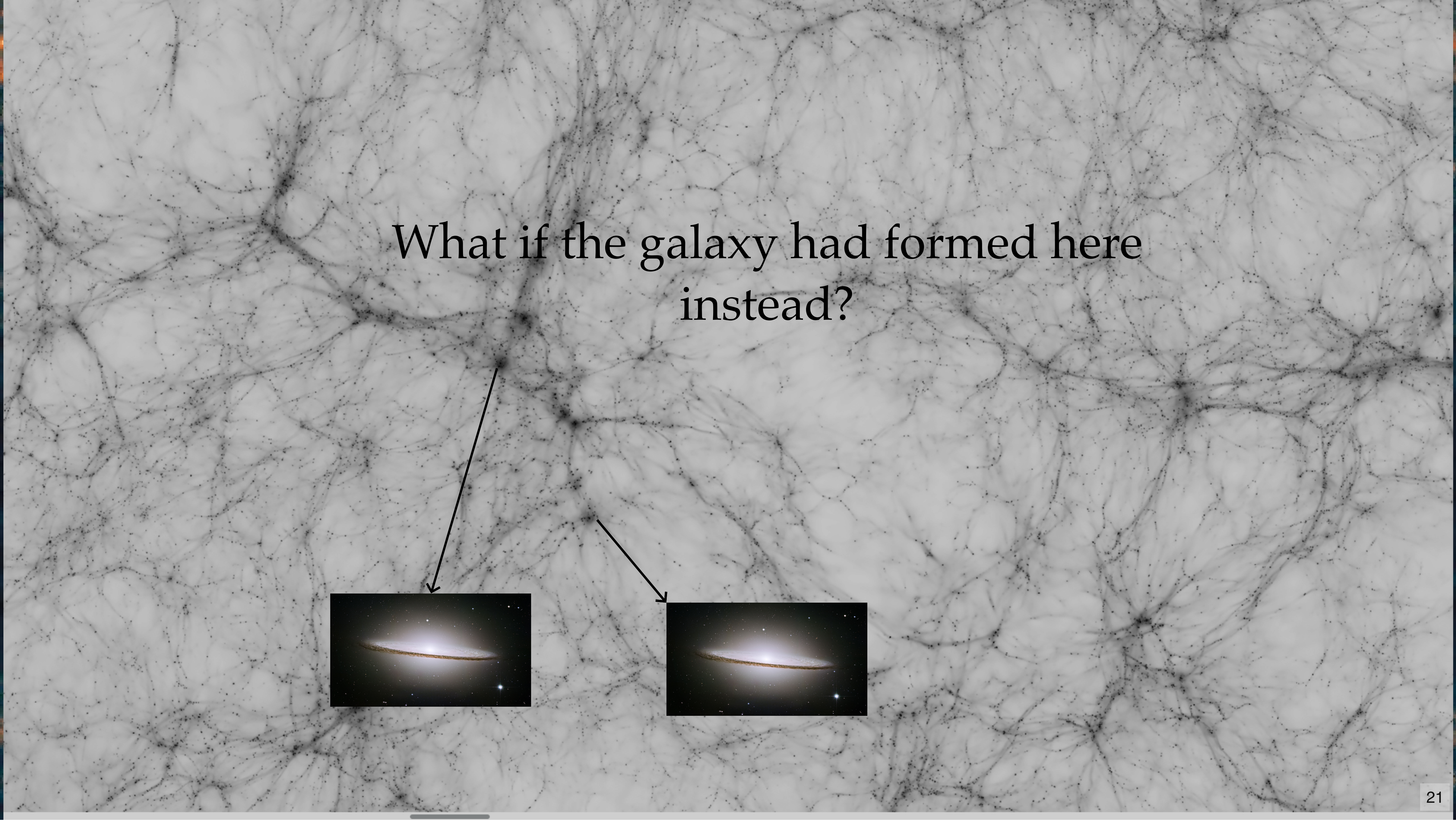
Study **same object**, **different environment**.

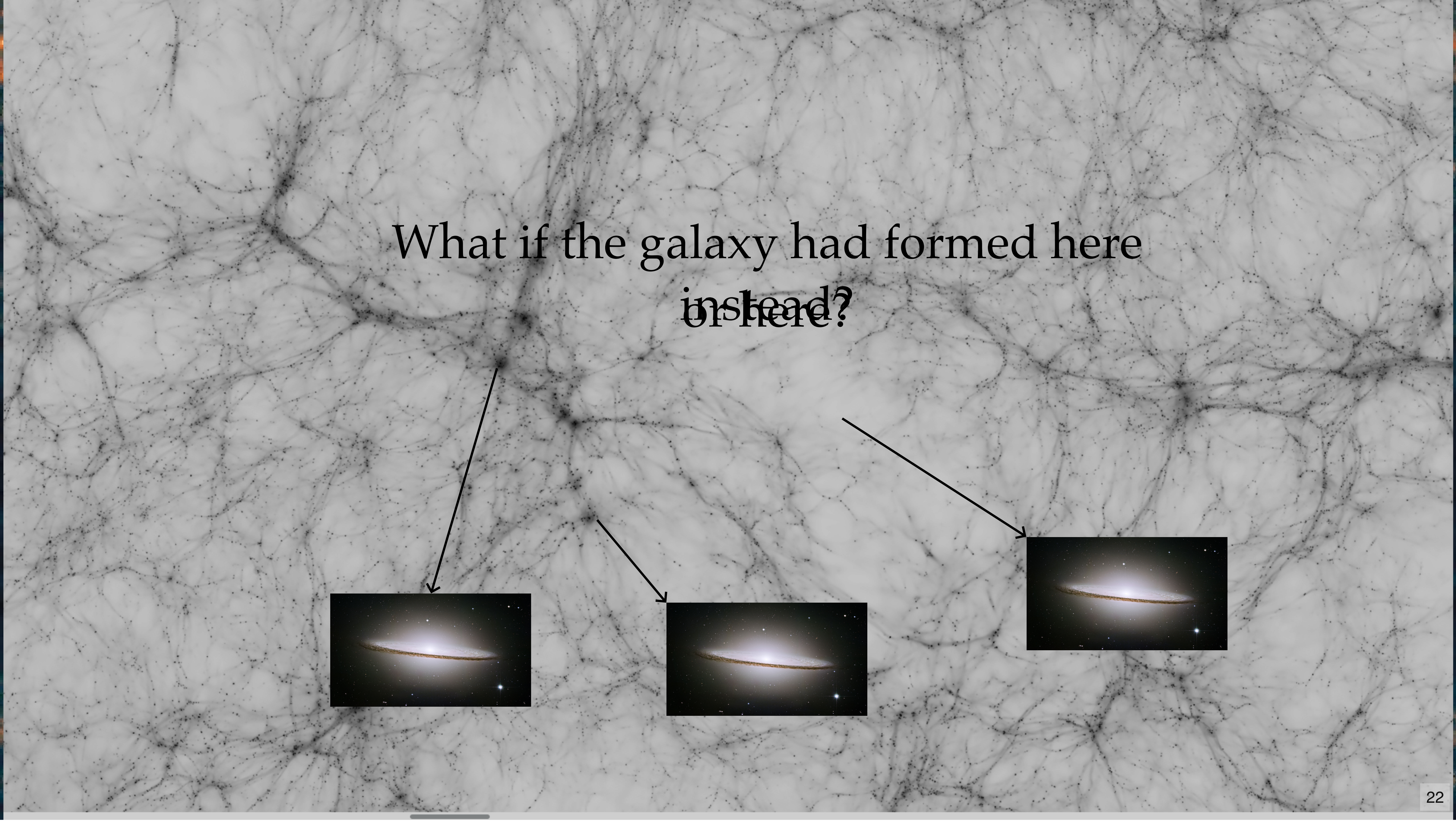
CC+21, arXiv: 2107.03407

Cosmic web drives AM acquisition... what scales? what's affected?

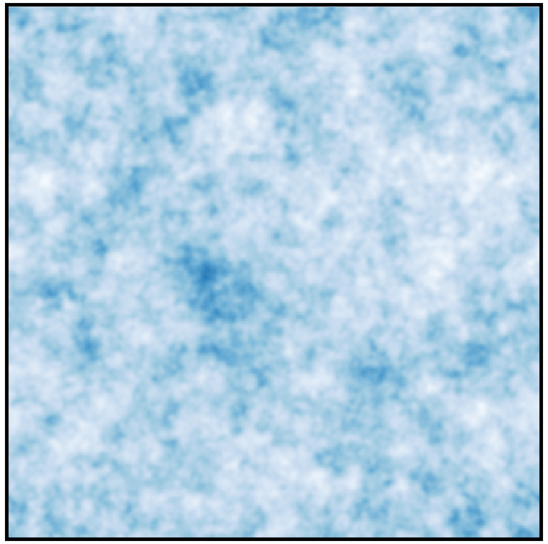


What if the galaxy had formed here instead?




What if the galaxy had formed here
instead?
or here?

The "splicing" technique

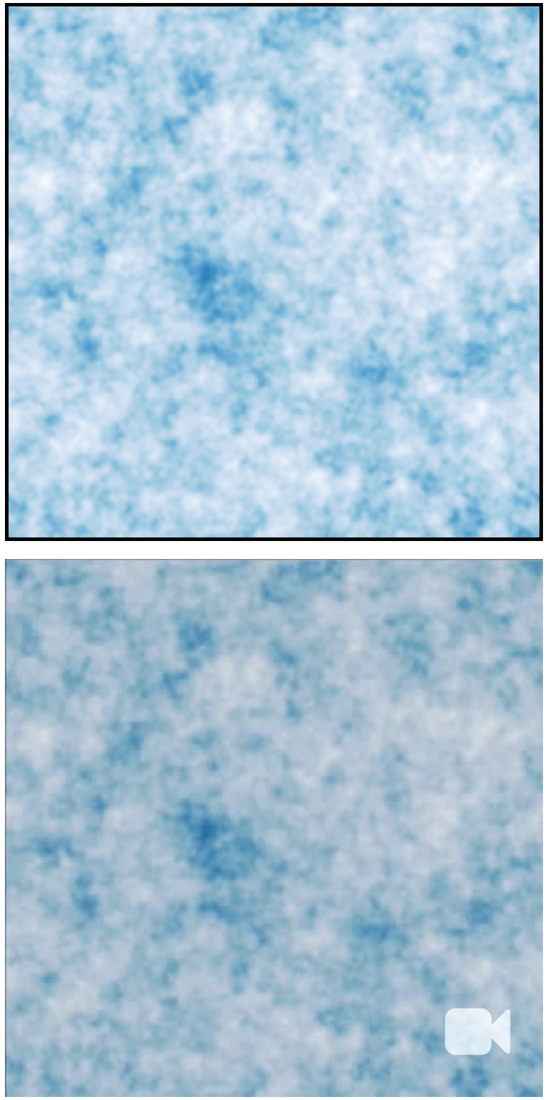


1. Generate ICs

Splicing: equivalent of constraining field **at all points** in spliced region

The “splicing” technique

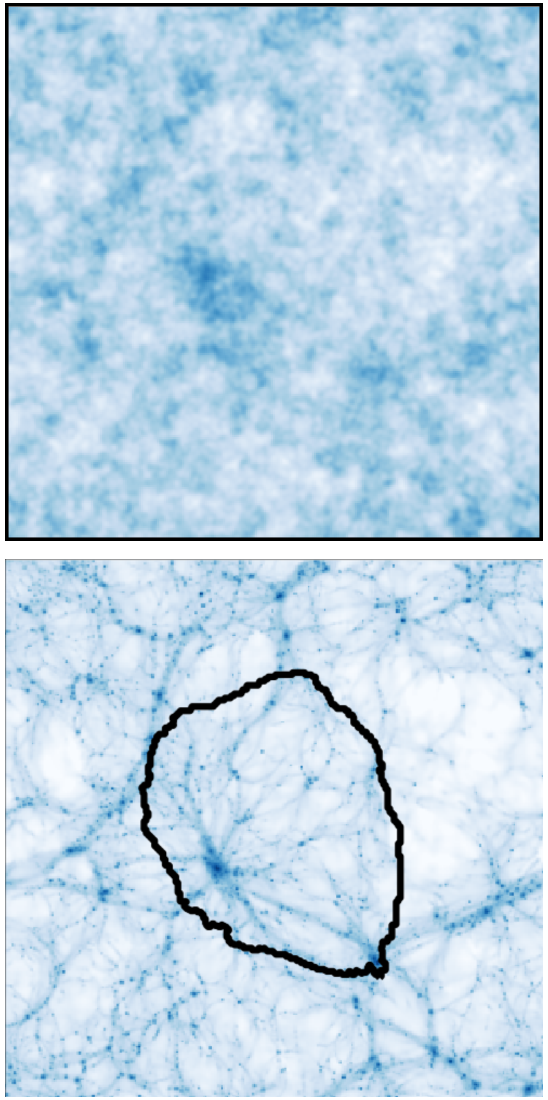
t



1. Generate ICs
2. Integrate (N-nody)

Splicing: equivalent of constraining field **at all points** in spliced region

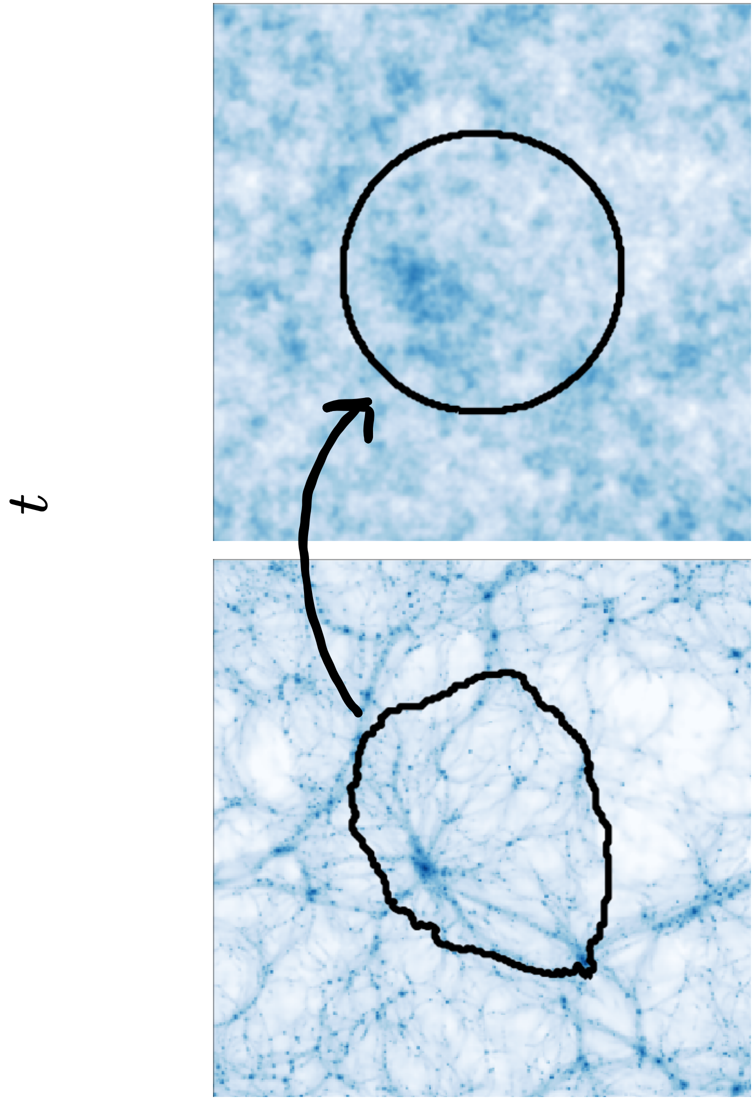
The “splicing” technique



1. Generate ICs
2. Integrate (N-nody)
3. Select region of interest

Splicing: equivalent of constraining field **at all points** in spliced region

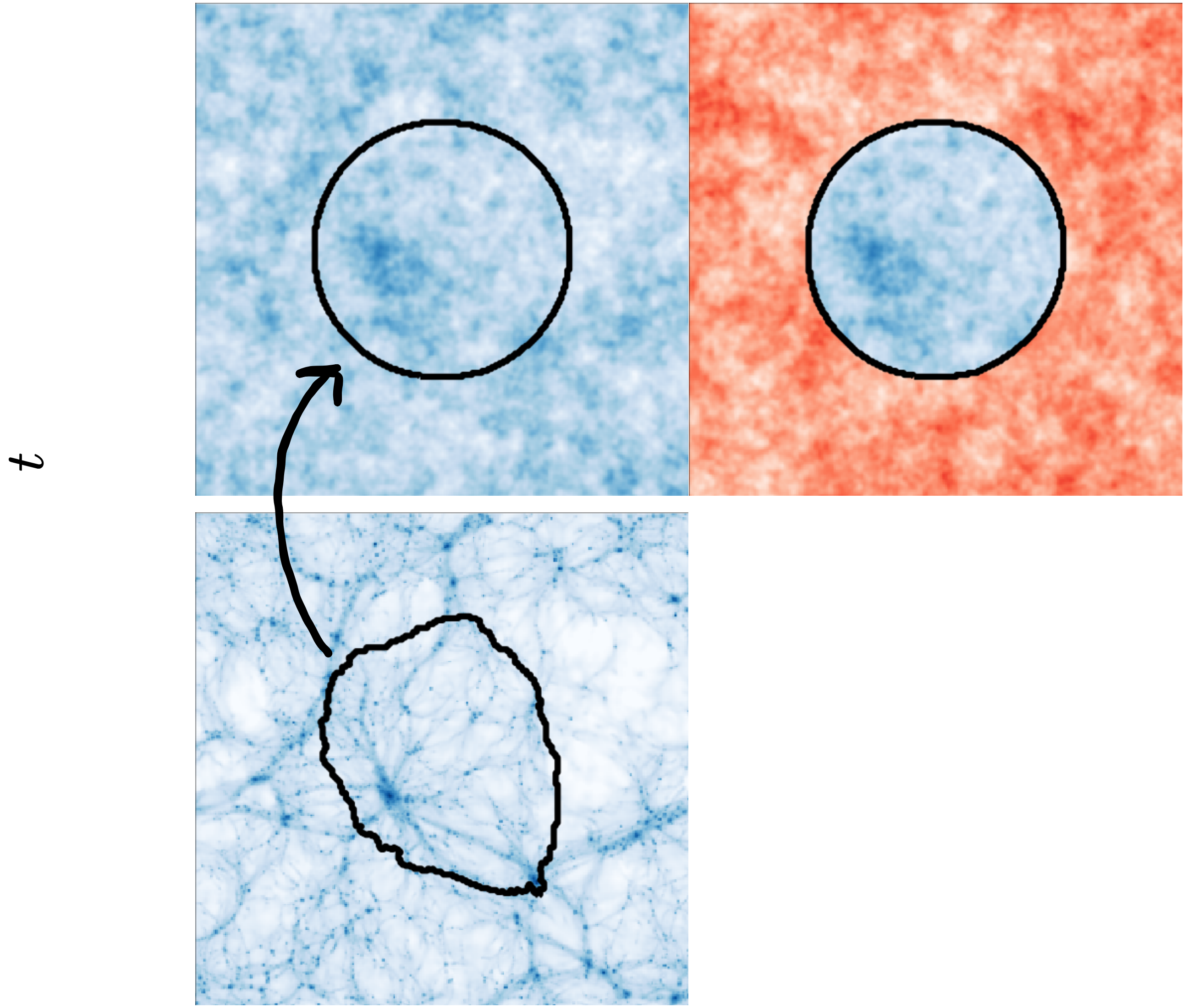
The "splicing" technique



1. Generate ICs
2. Integrate (N-nody)
3. Select region of interest
4. Trace back to ICs

Splicing: equivalent of constraining field **at all points** in spliced region

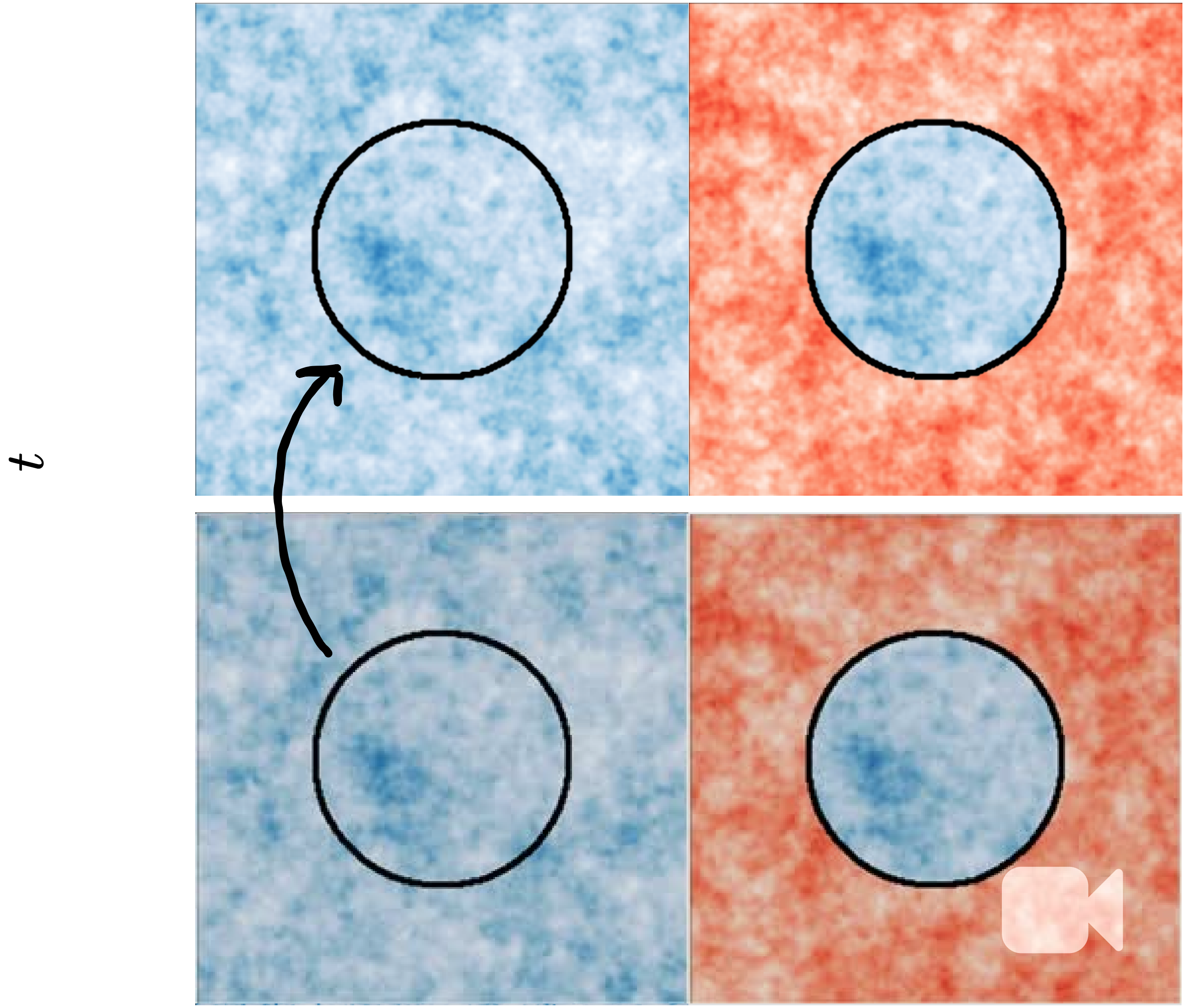
The "splicing" technique



1. Generate ICs
2. Integrate (N-nody)
3. Select region of interest
4. Trace back to ICs
5. "Splice"

Splicing: equivalent of constraining field **at all points** in spliced region

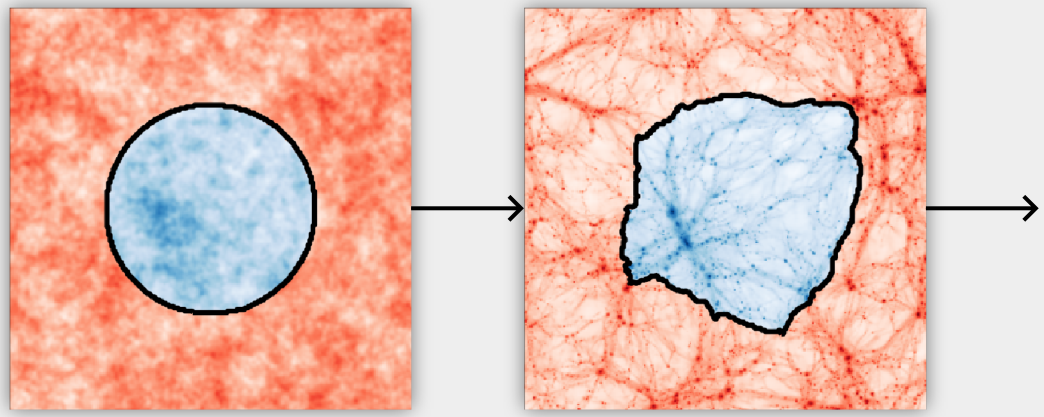
The "splicing" technique



1. Generate ICs
2. Integrate (N-nody)
3. Select region of interest
4. Trace back to ICs
5. "Splice"
6. Integrate again

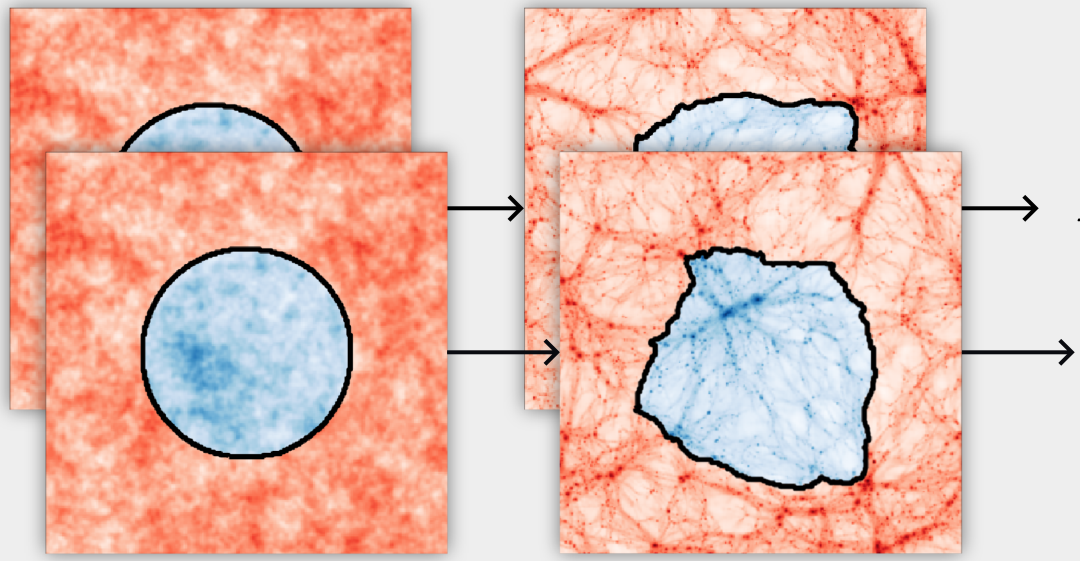
Splicing: equivalent of constraining field **at all points** in spliced region

The causal origin of DM halo concentration



$M_{200c}^{(1)}, c_{NFW}^{(1)}, \ldots$

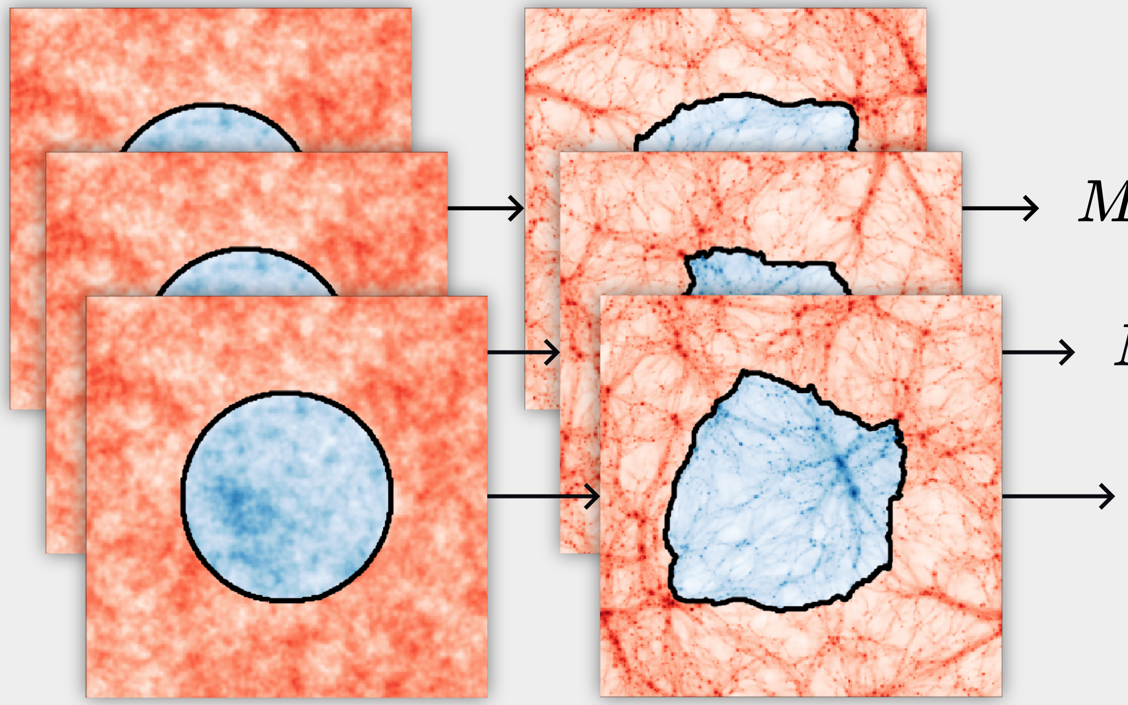
The causal origin of DM halo concentration



$$M_{200c}^{(1)}, c_{\mathrm{NFW}}^{(1)}, \ldots$$

$$M_{200c}^{(2)}, c_{\mathrm{NFW}}^{(2)}, \ldots$$

The causal origin of DM halo concentration

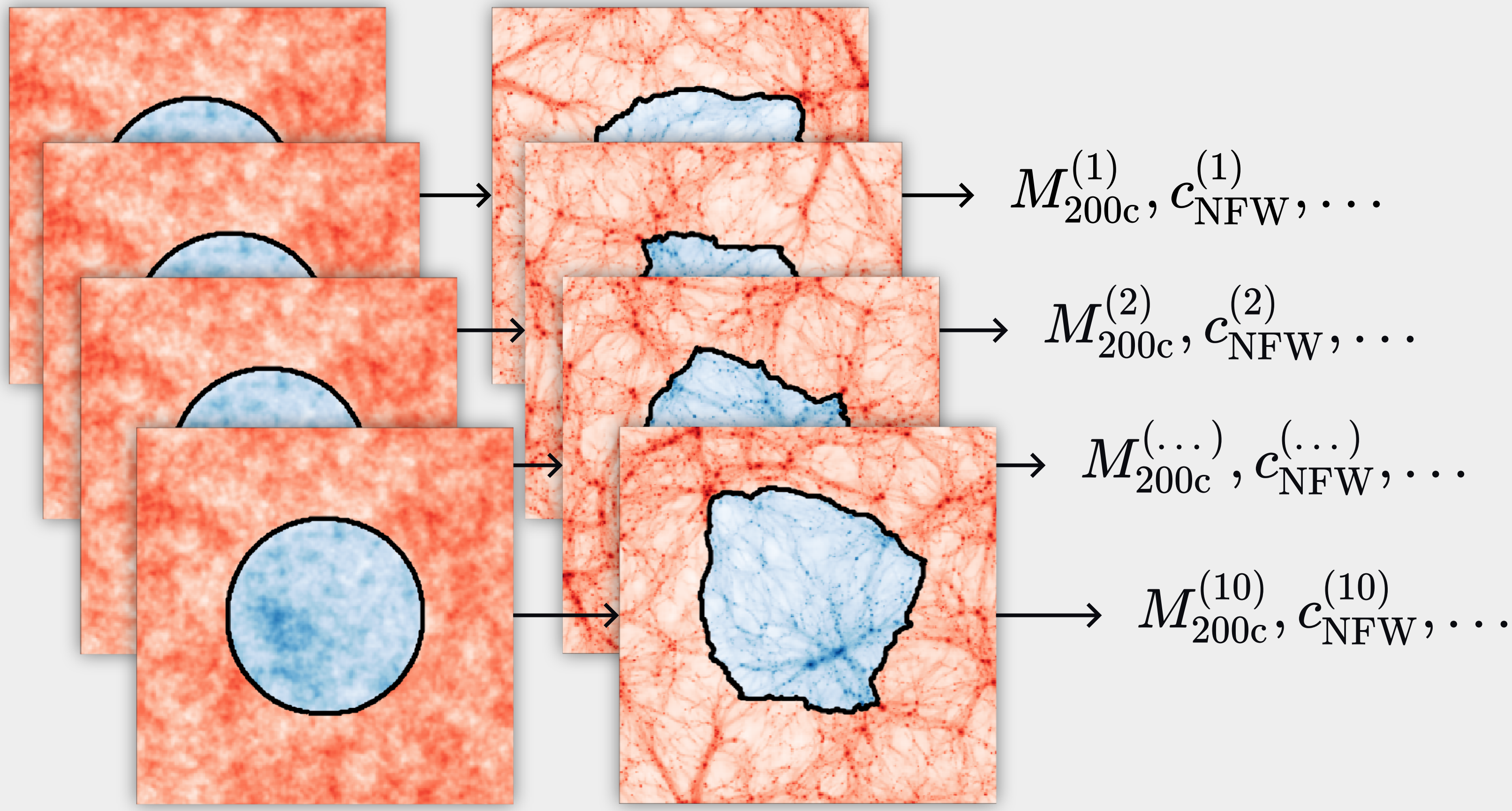


$M_{200c}^{(1)}, c_{\mathrm{NFW}}^{(1)}, \ldots$

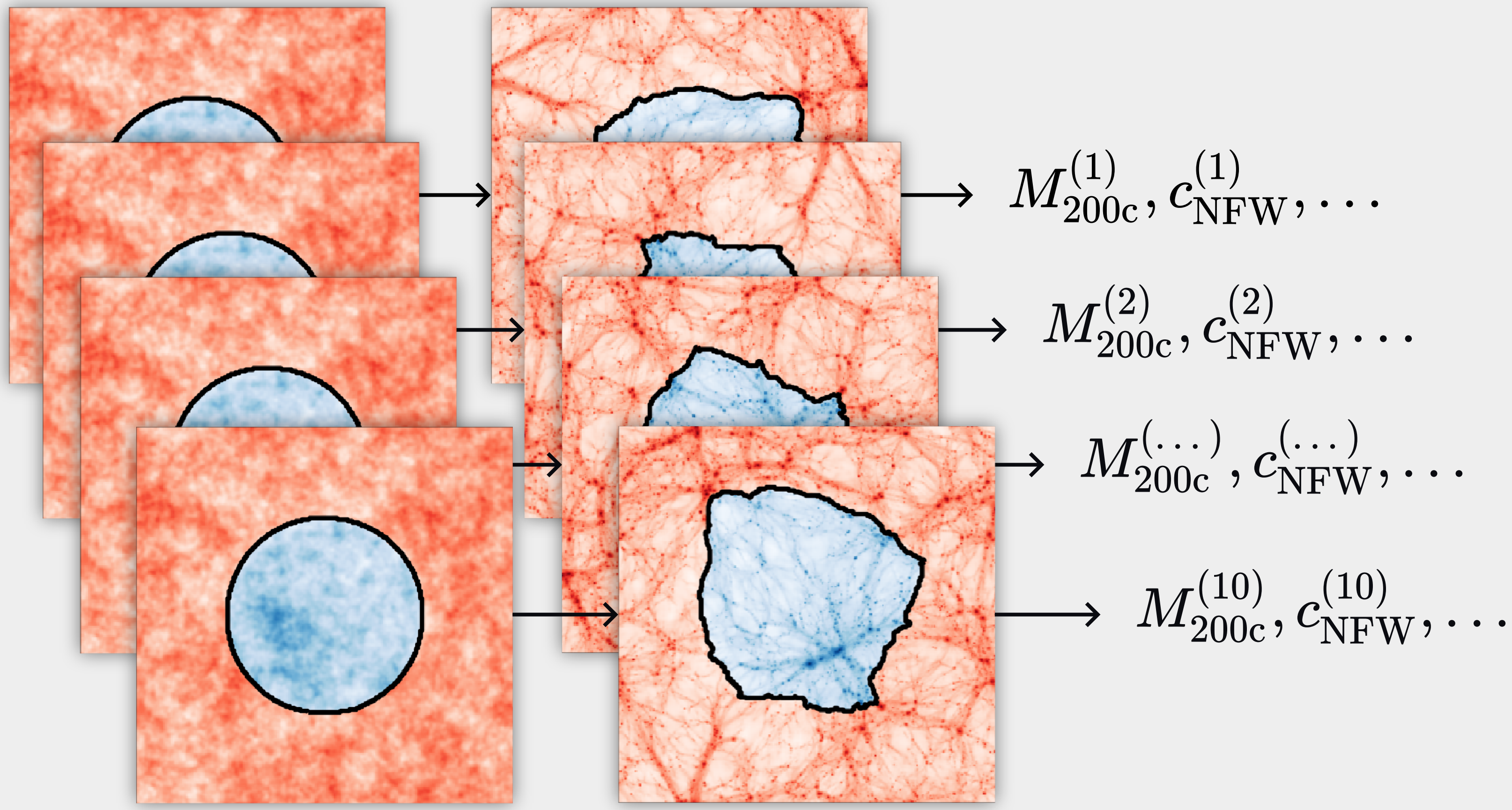
$M_{200c}^{(2)}, c_{\mathrm{NFW}}^{(2)}, \ldots$

$M_{200c}^{(\ldots)}, c_{\mathrm{NFW}}^{(\ldots)}, \ldots$

The causal origin of DM halo concentration



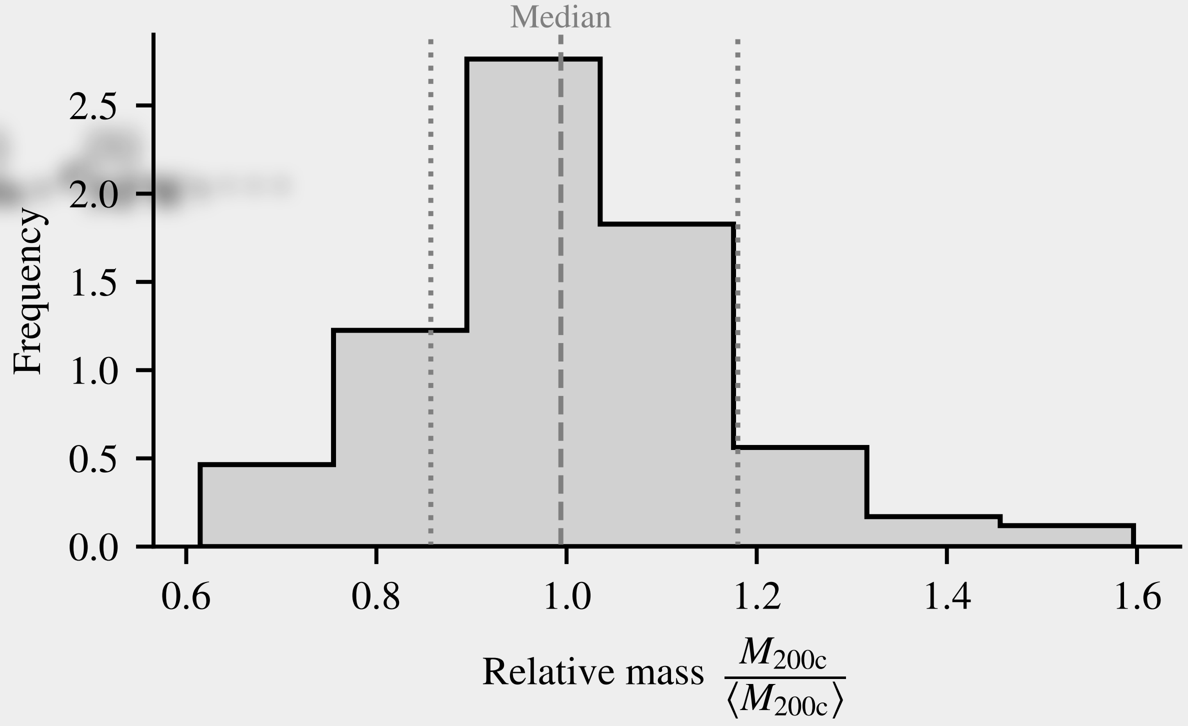
The causal origin of DM halo concentration



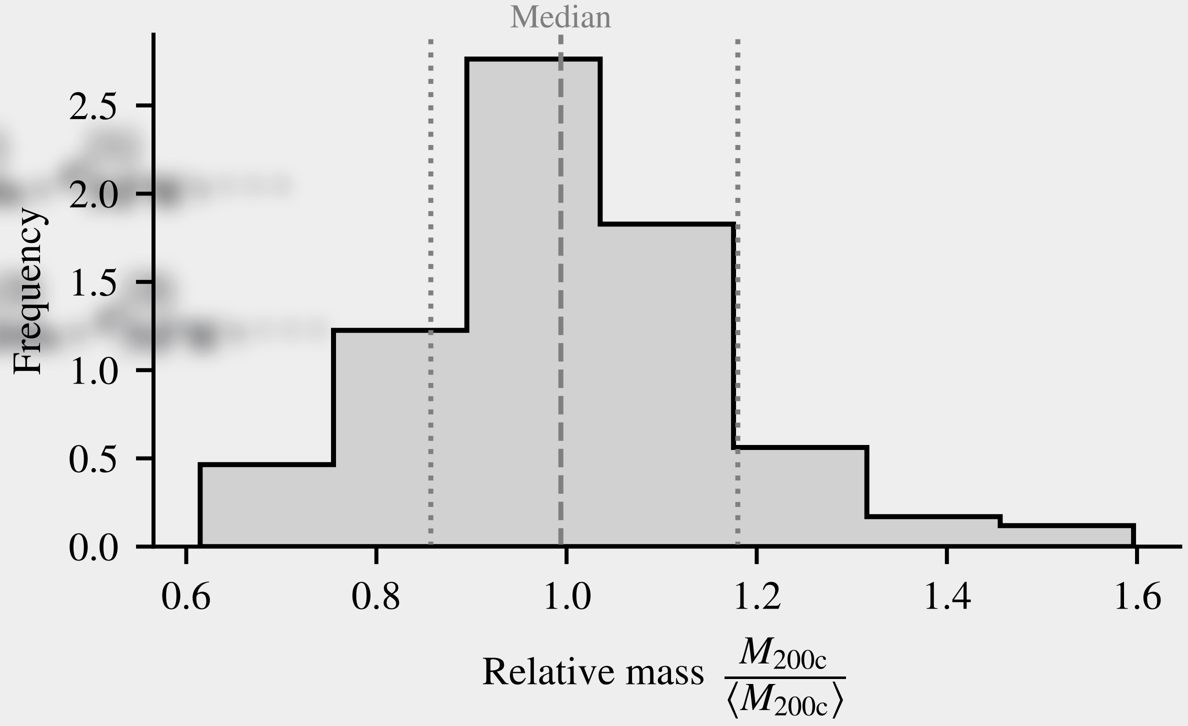
Same halo in 10× different environments

Repeat experiment for 7 halos (70 realisations in total)

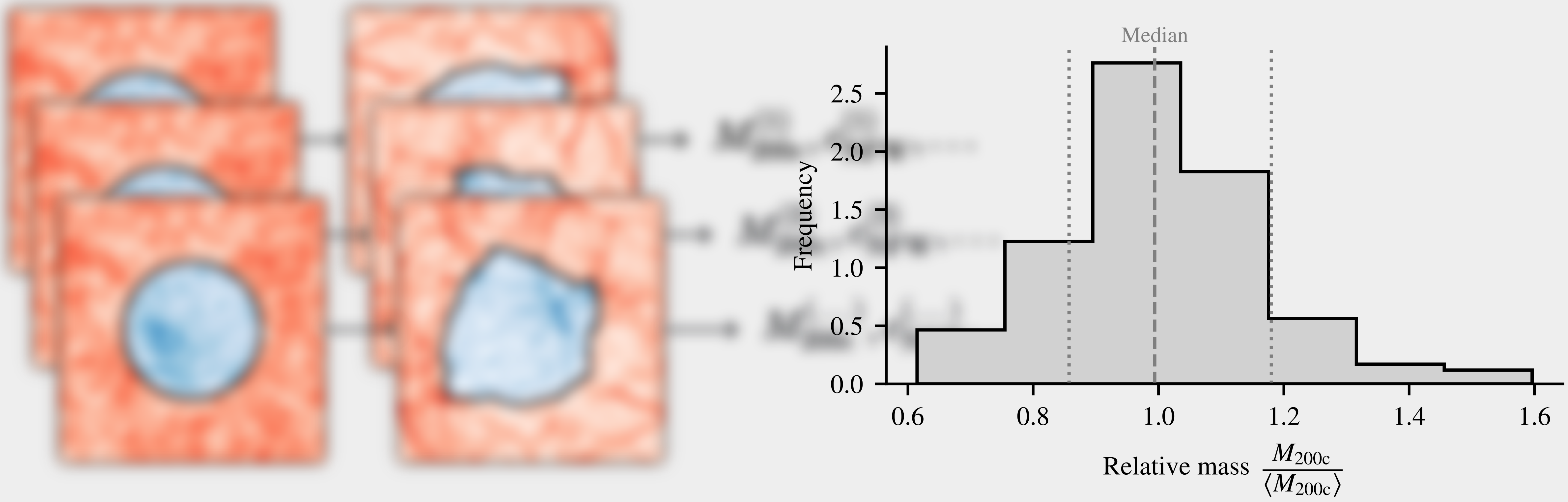
The causal origin of DM halo concentration



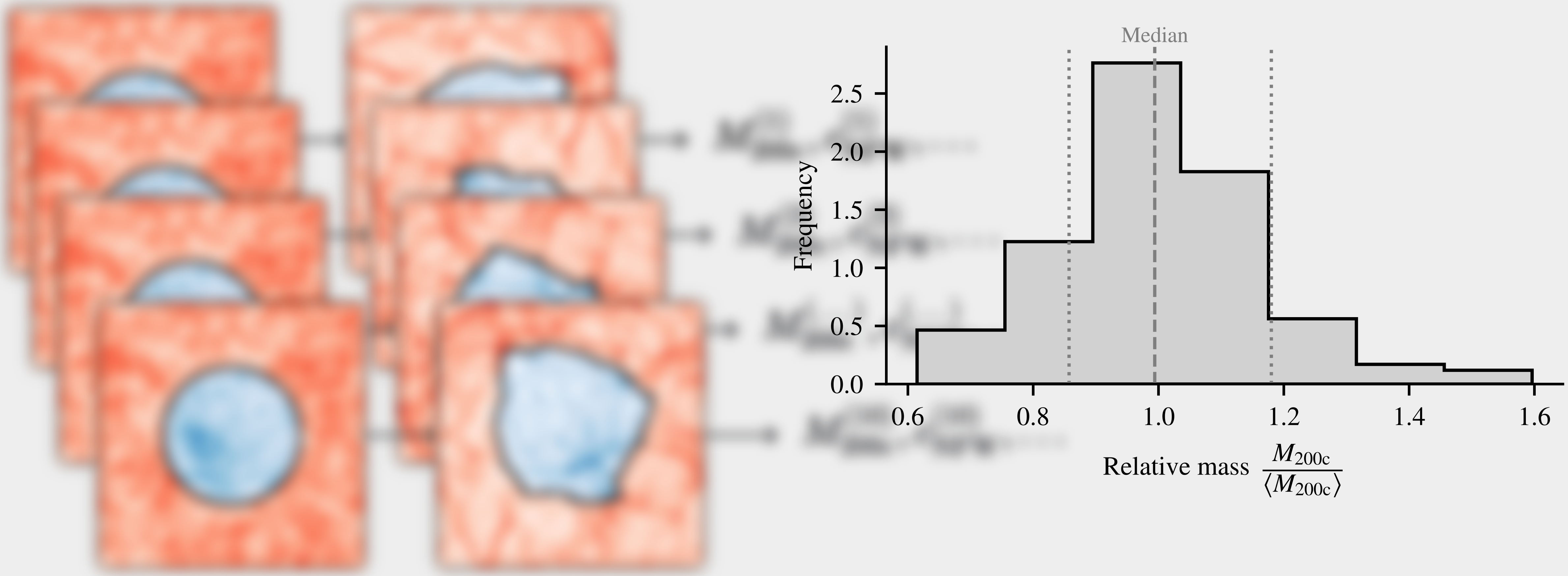
The causal origin of DM halo concentration



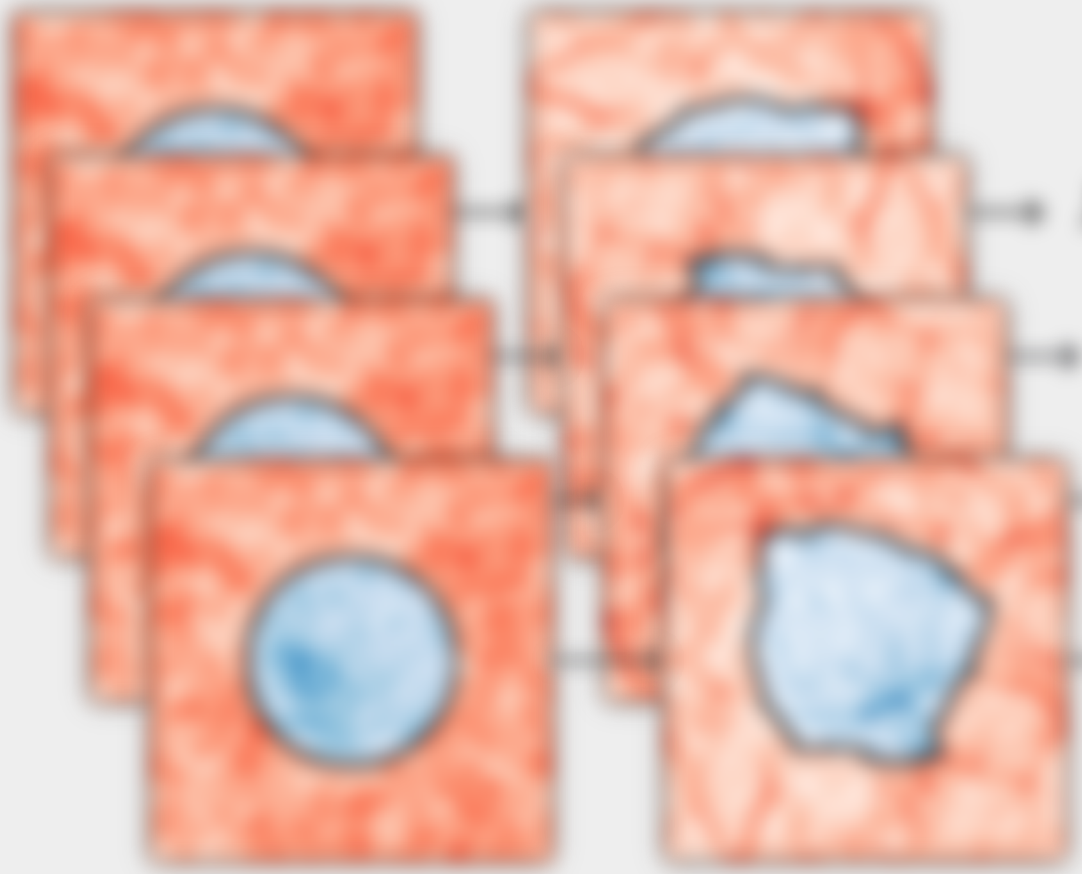
The causal origin of DM halo concentration

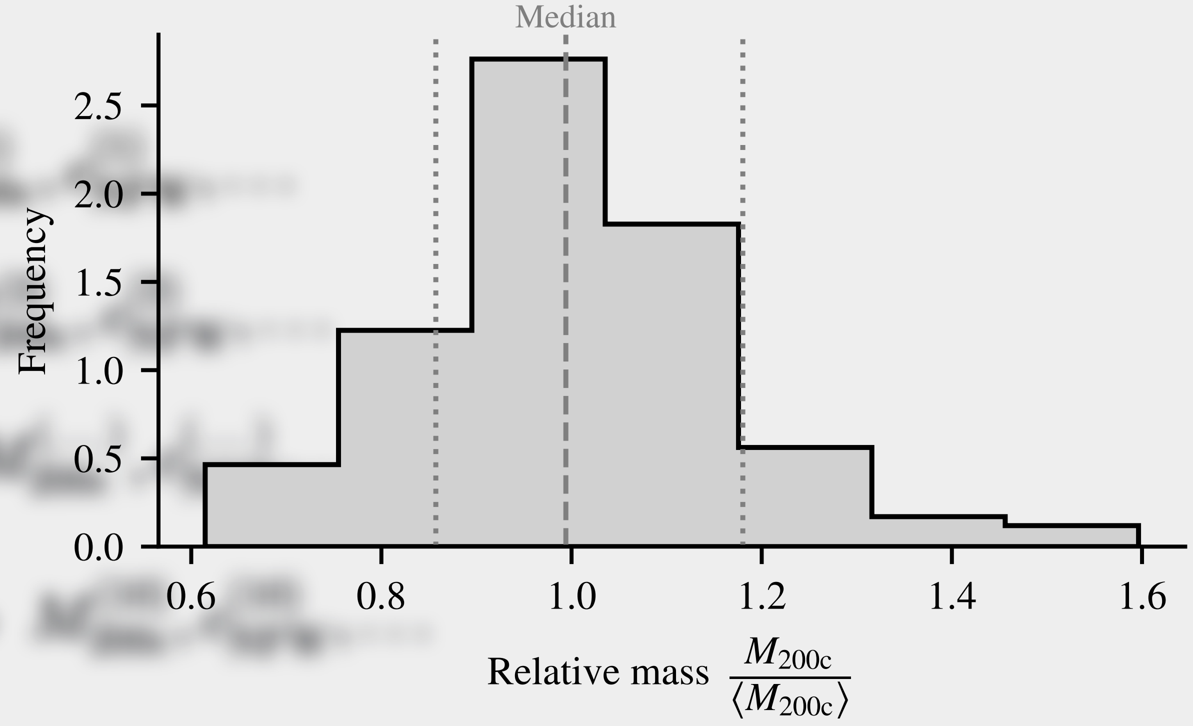


The causal origin of DM halo concentration



The causal origin of DM halo concentration





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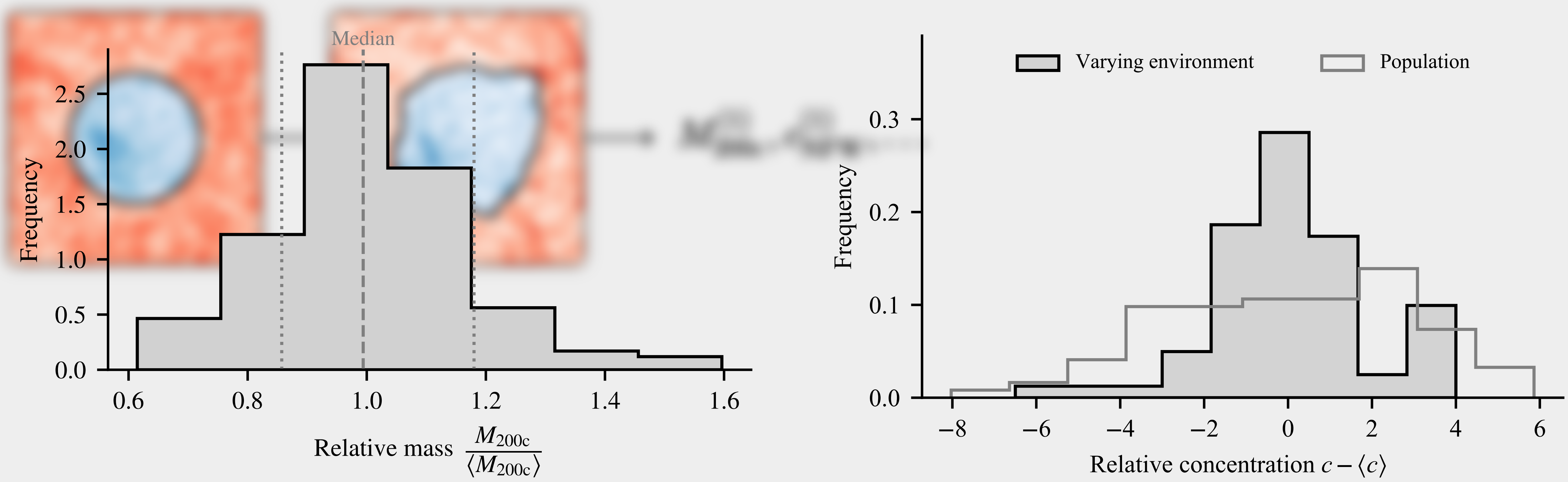
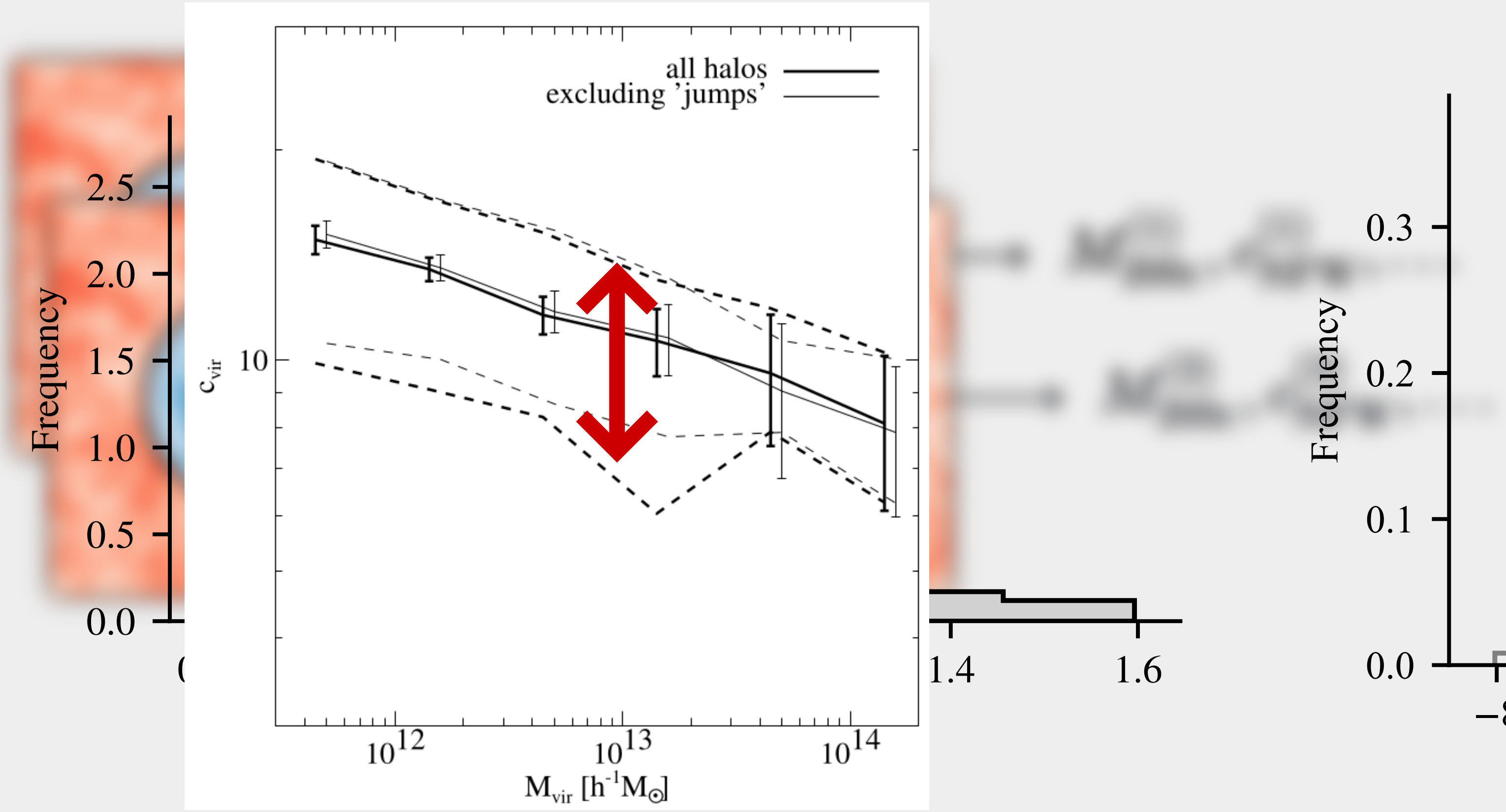
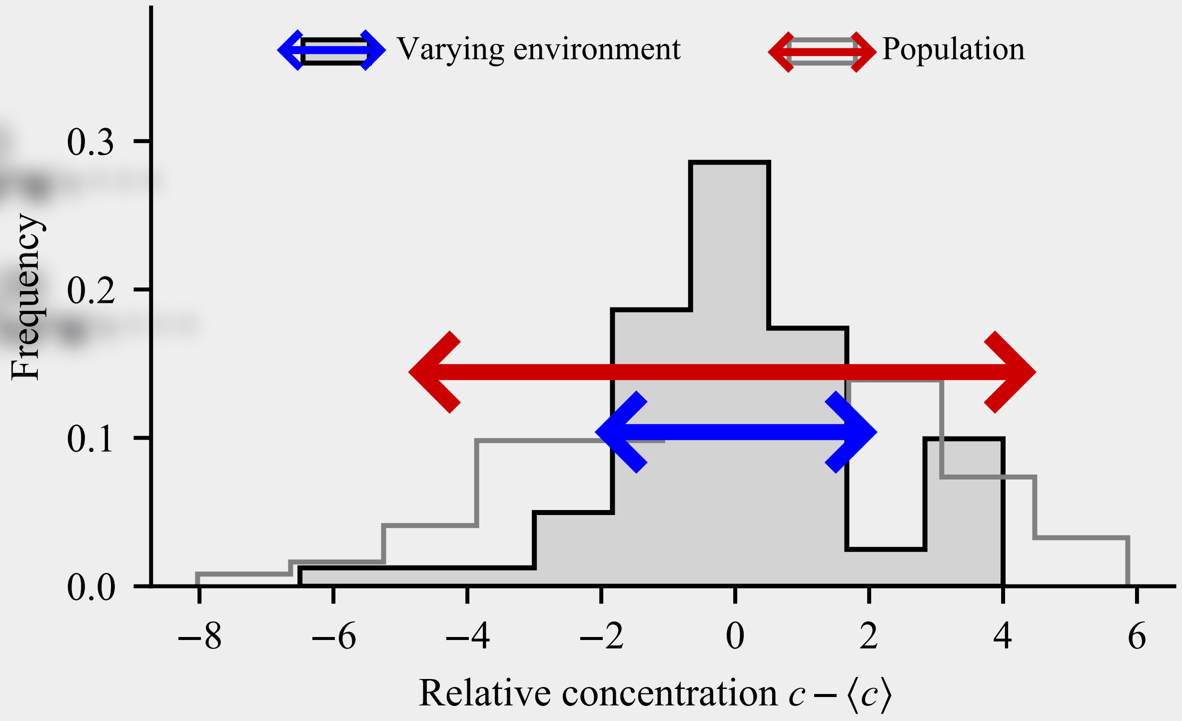
The causal origin of DM halo concentration

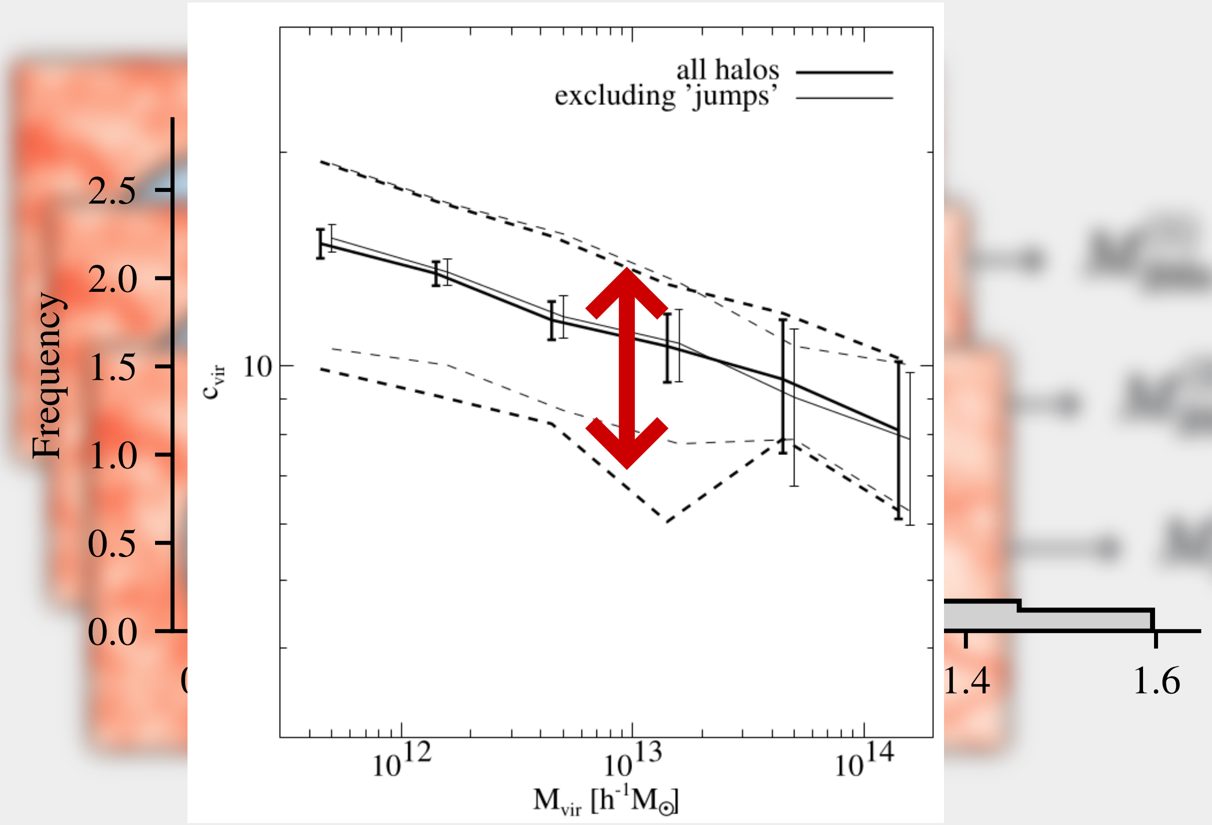


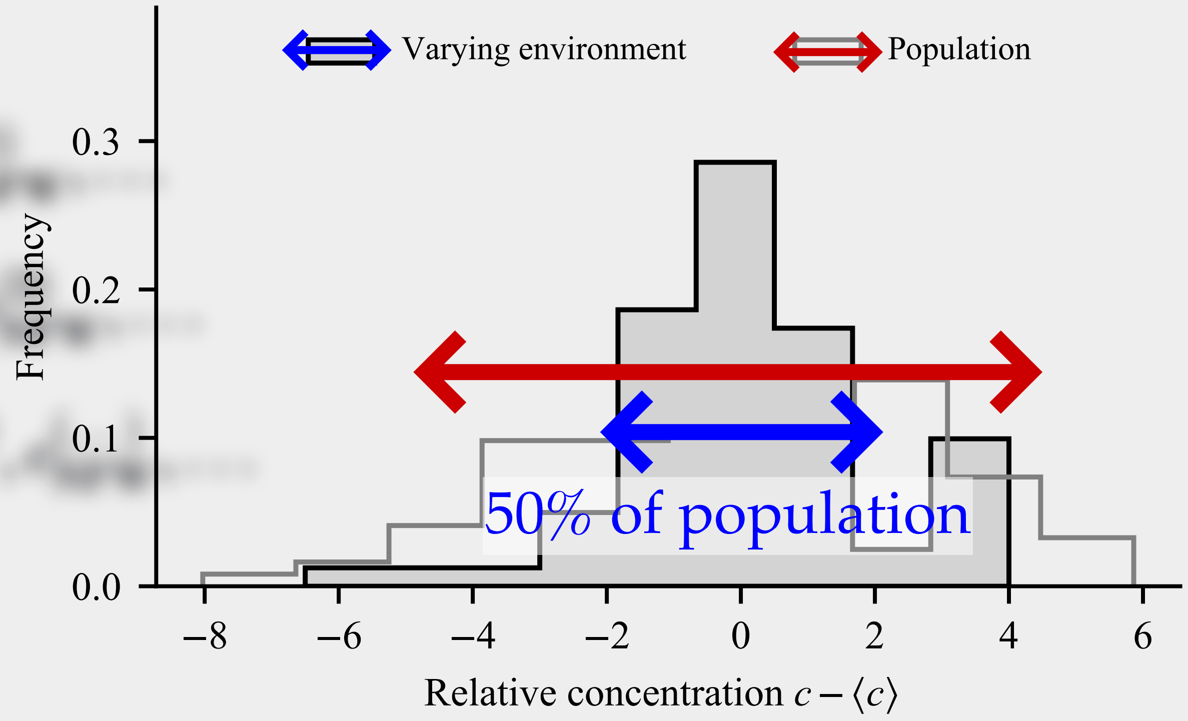
The causal origin of DM halo concentration



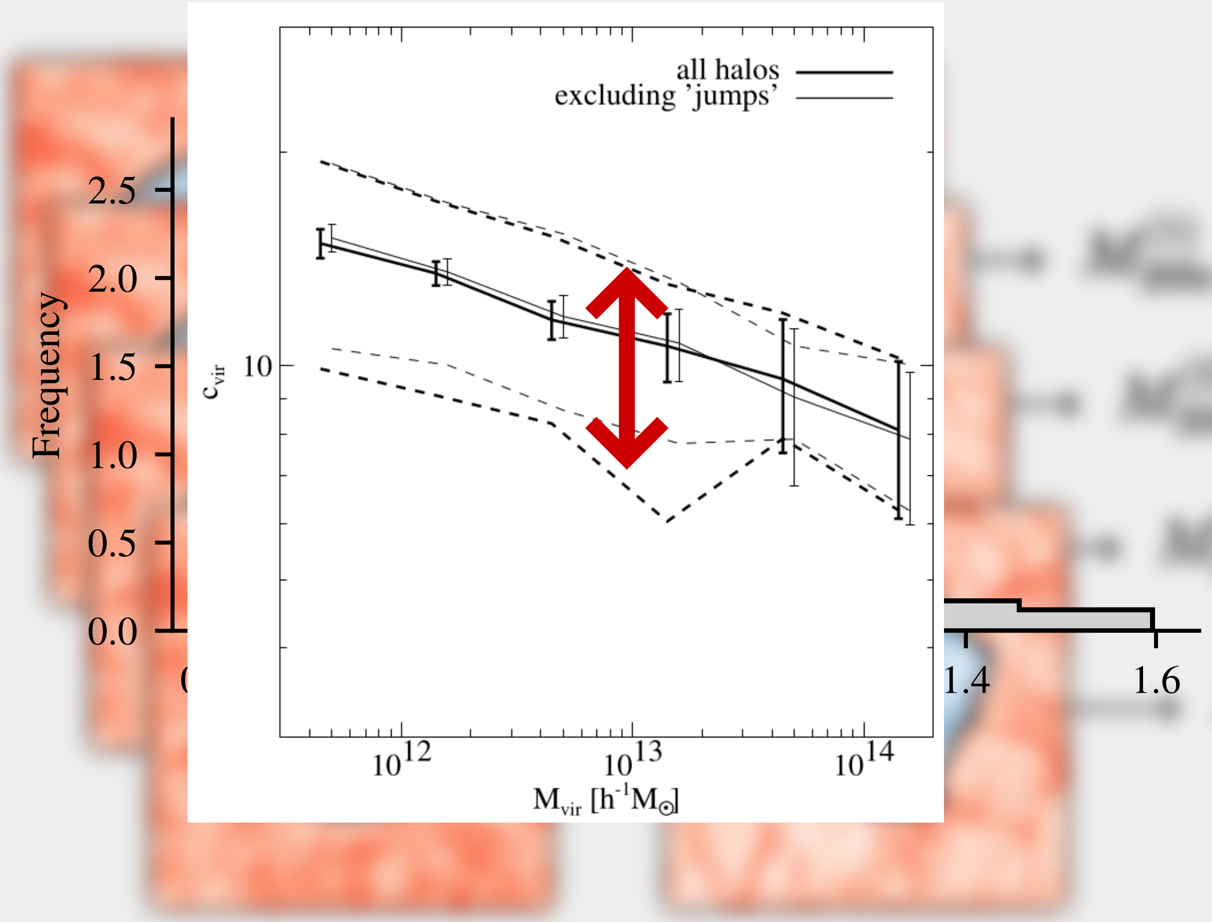


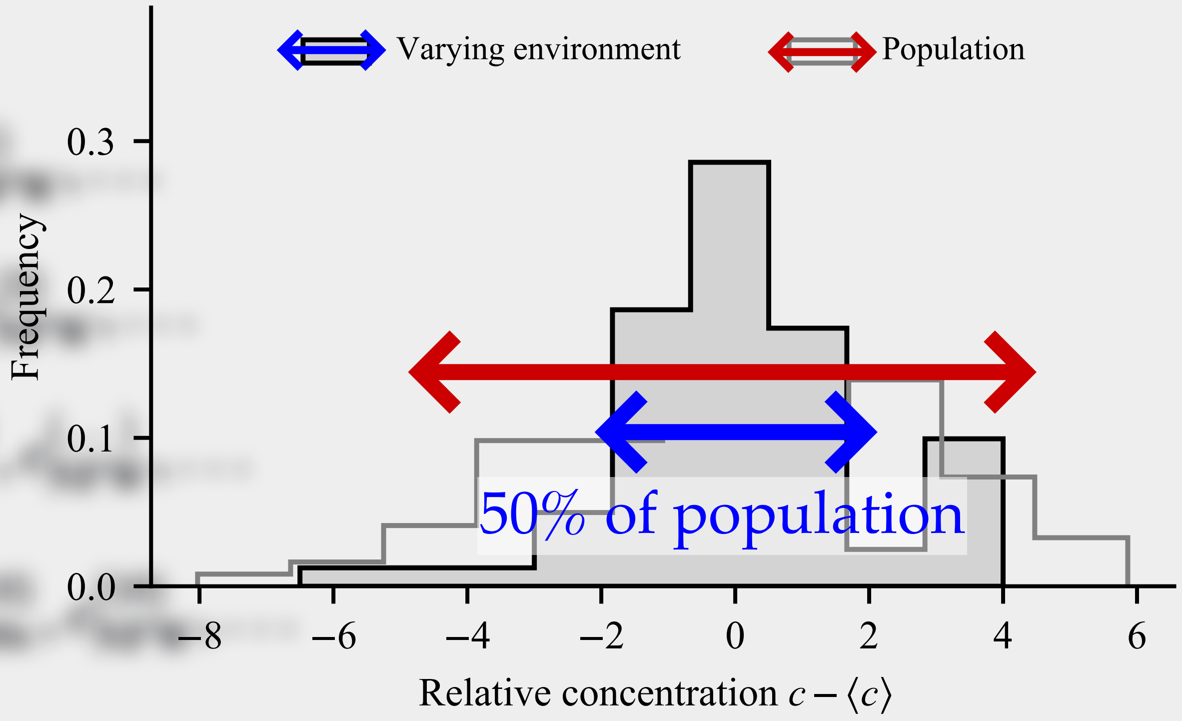
The causal origin of DM halo concentration



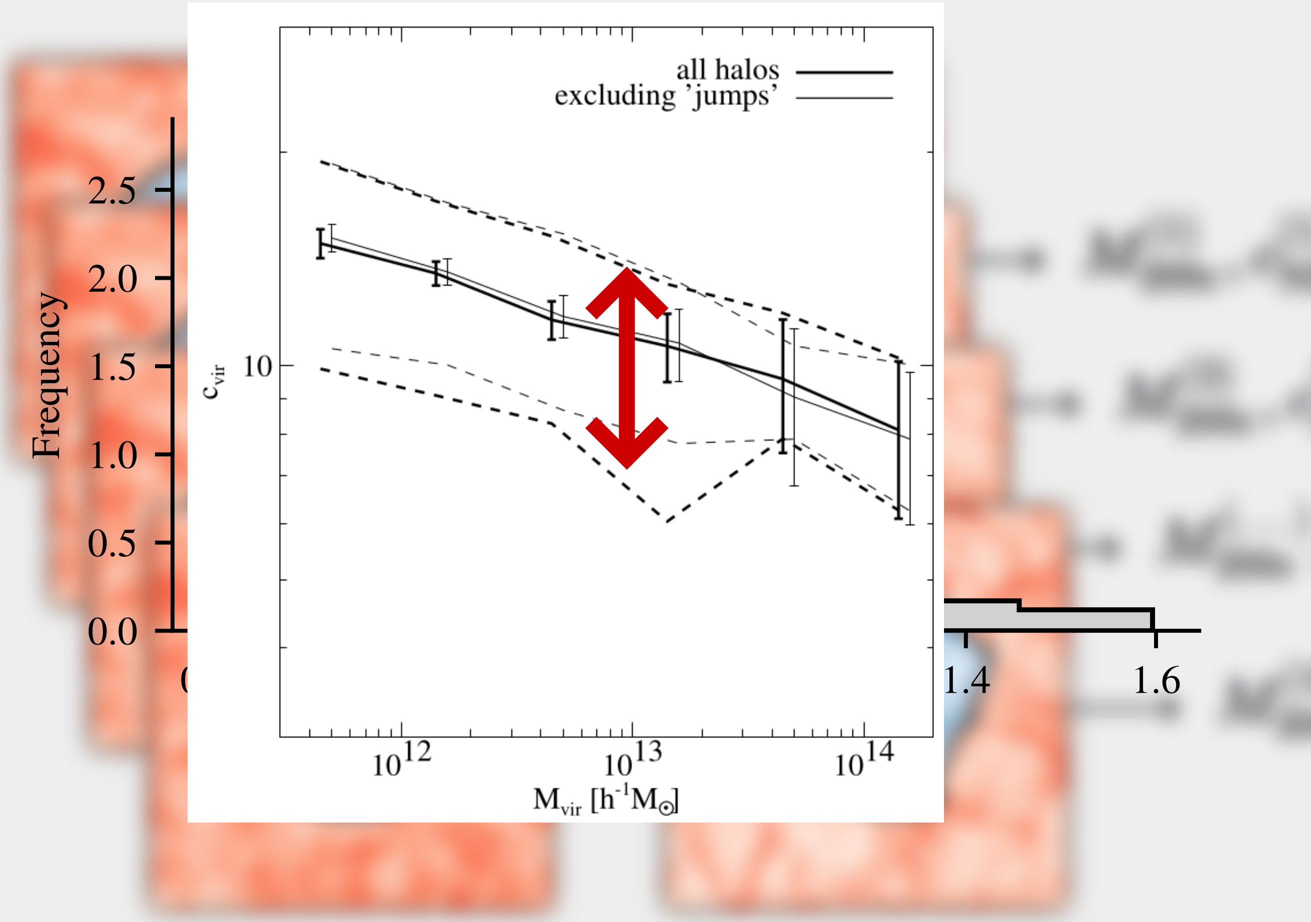


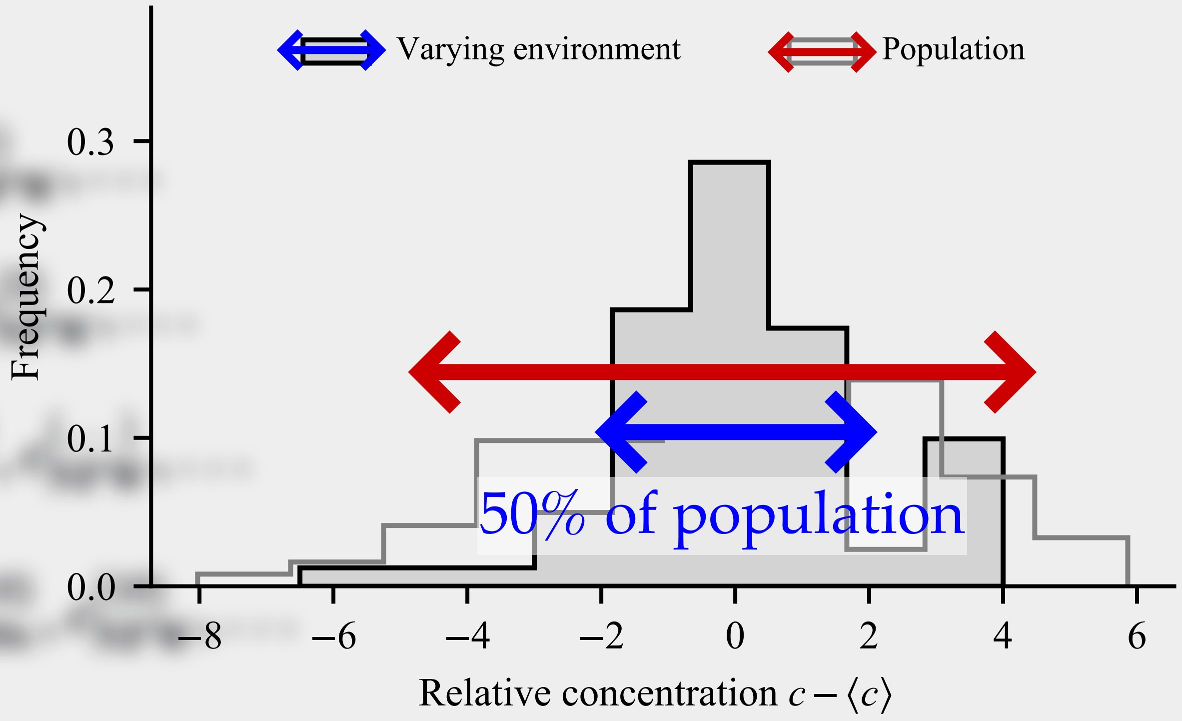
The causal origin of DM halo concentration





The causal origin of DM halo concentration





Same halo in 10× different environments

Repeat experiment for 7 halos (70 realisations in total)

Conclusion & outlook

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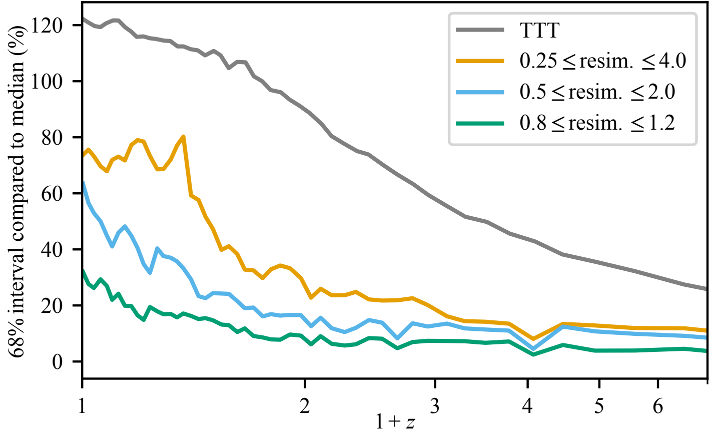
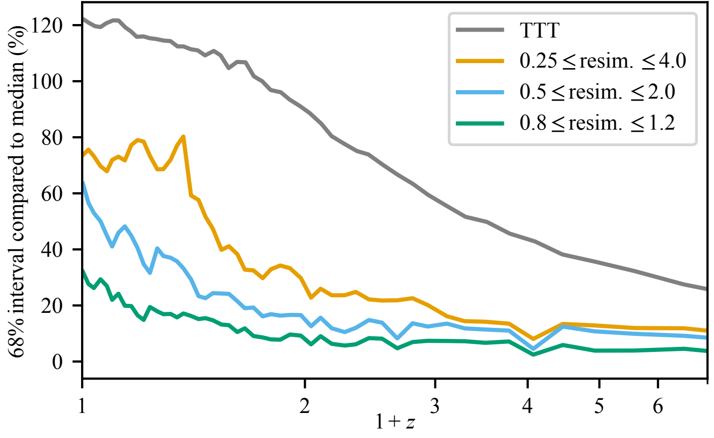
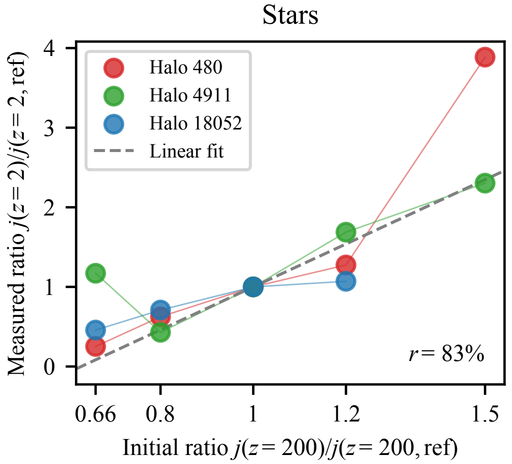


Conclusion & outlook

1. Is $j_{\rm DM}$ chaotic or our theory poor?
   Poor theory! Good accuracy (few ~10%) achievable for **individual halos** in principle.





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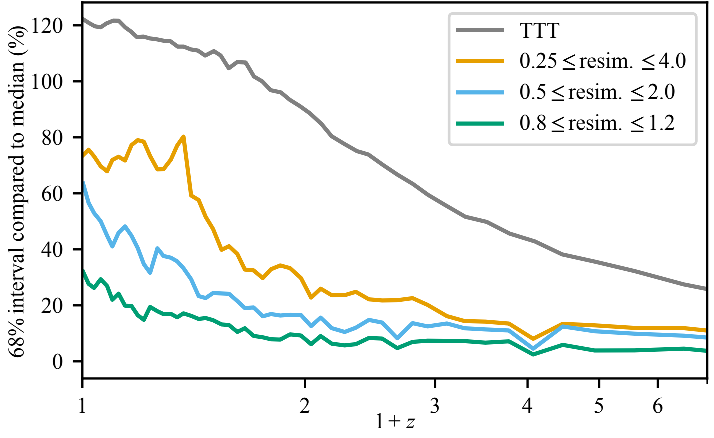
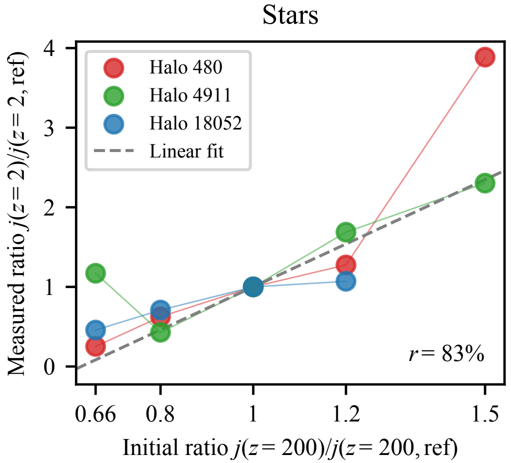
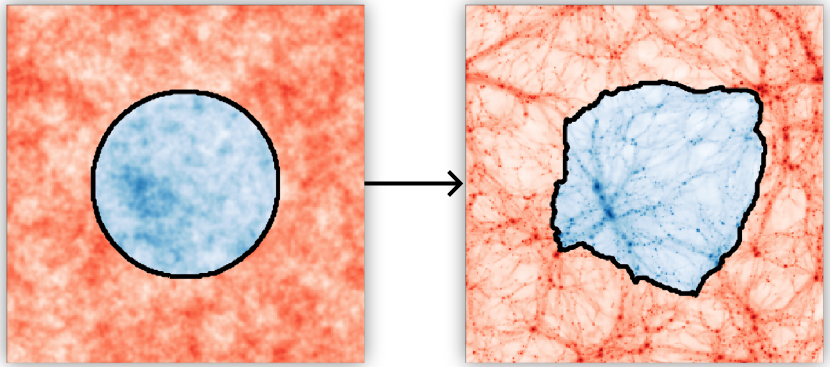
2. Do j_{gal} retain memory of their environment?
   Individual galaxies retain memory of env, can be controlled in simulations!
   Galaxies may be less stochastic than expected







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3. What effect does anisotropic environment play in DM formation?

   Changing env **causes**

   ⇒ ~15% change in mass

   ⇒ 50% of population scatter for concentration

   Very promising for intrinsic alignment studies!