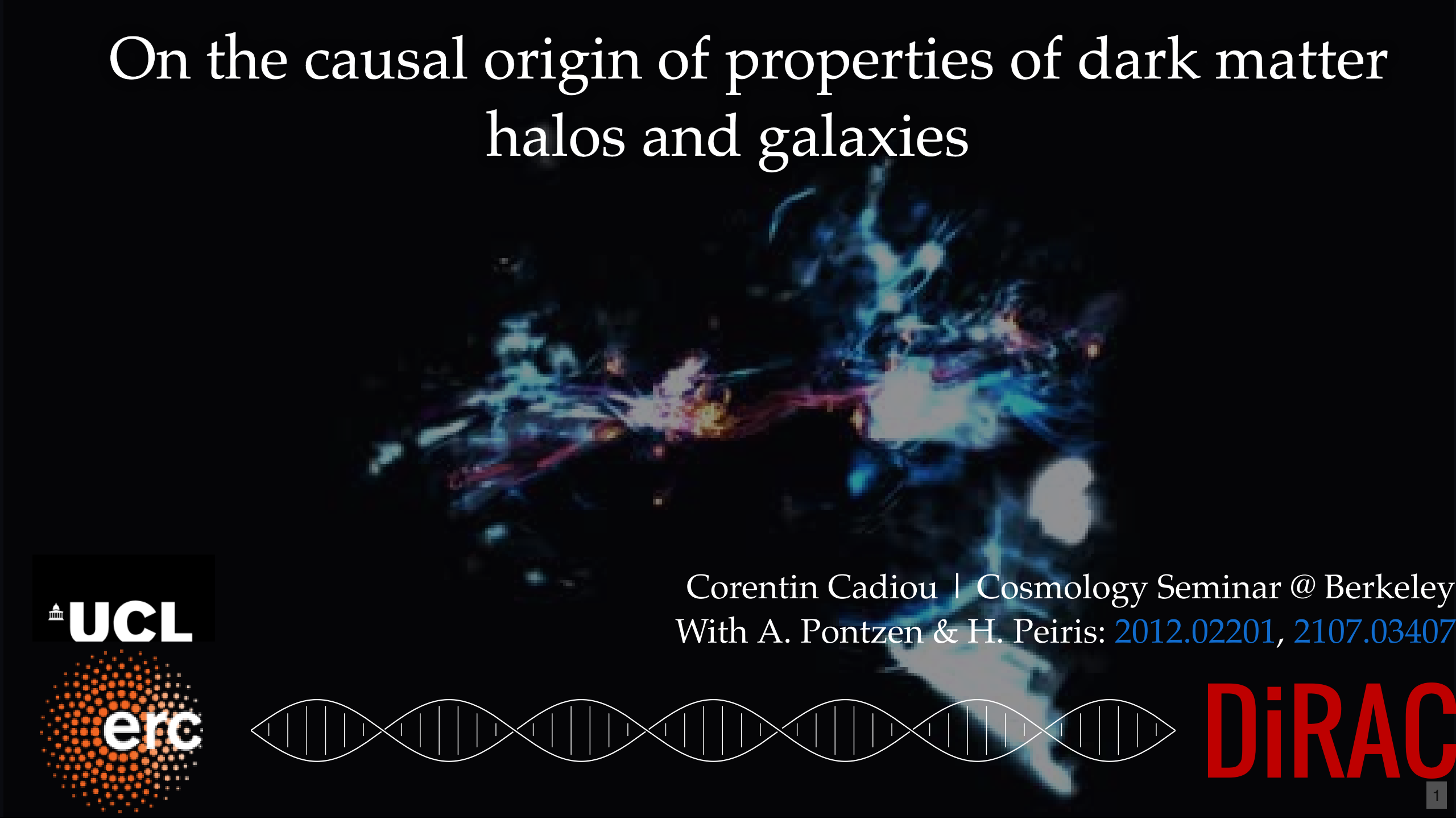
On the causal origin of properties of dark matter halos and galaxies



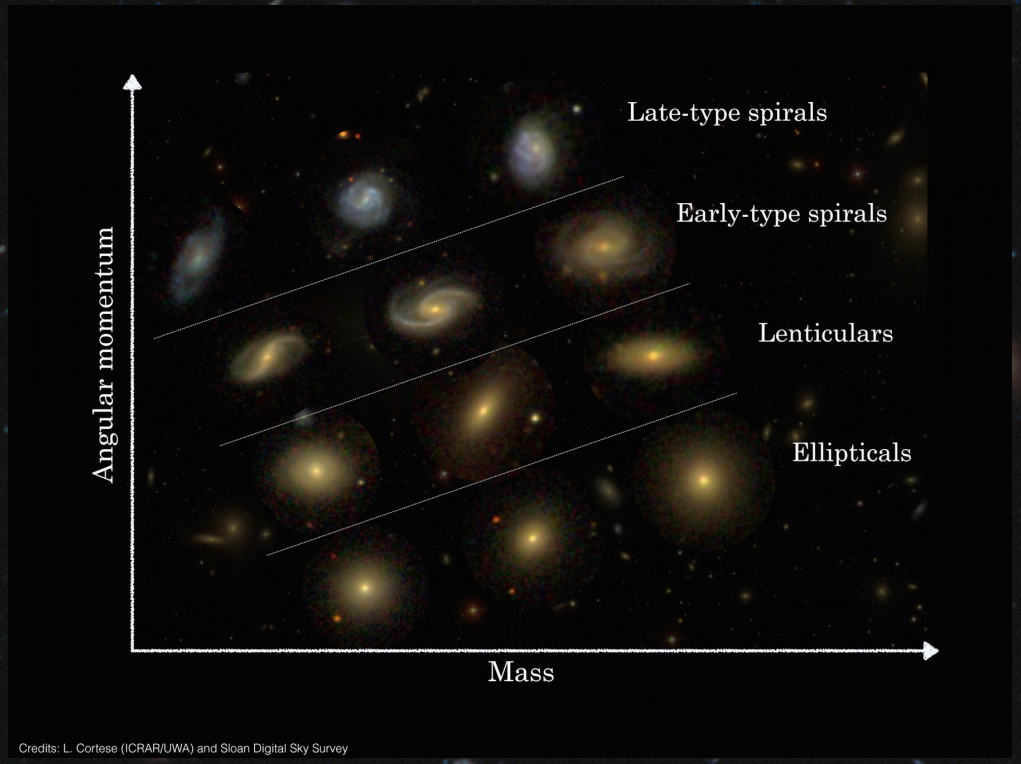
Corentin Cadiou | Cosmology Seminar @ Berkeley
With A. Pontzen & H. Peiris: 2012.02201, 2107.03407

UCL

erc

DiRAC

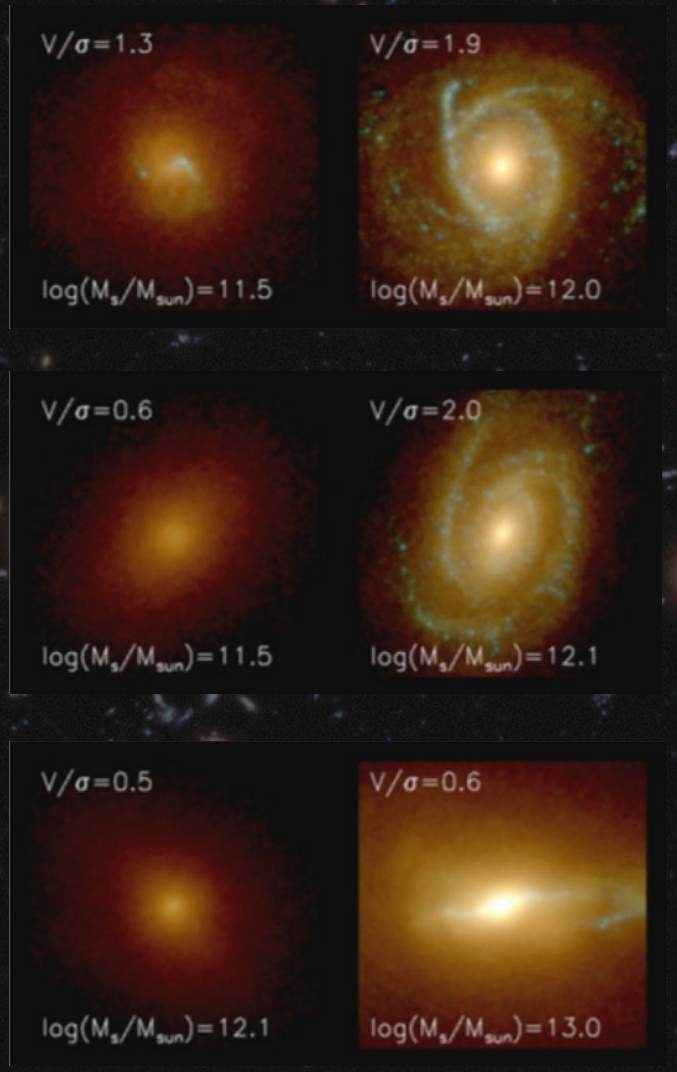
Galaxy formation



[L. Cortese; SDSS.]

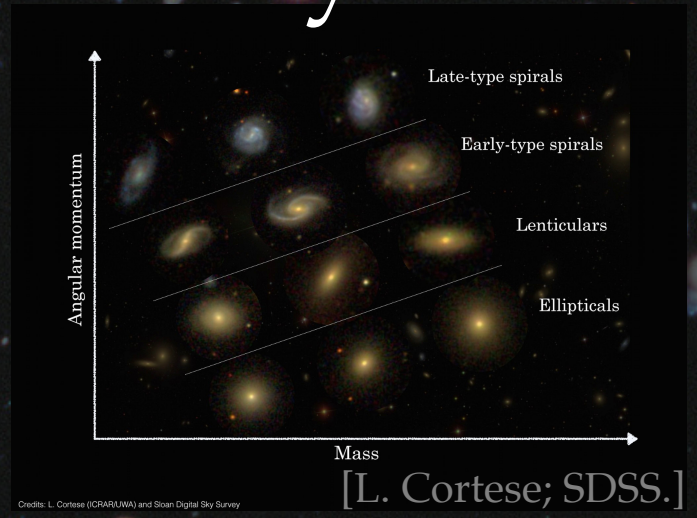
Origin of morphological diversity at fixed mass?

AGN no AGN



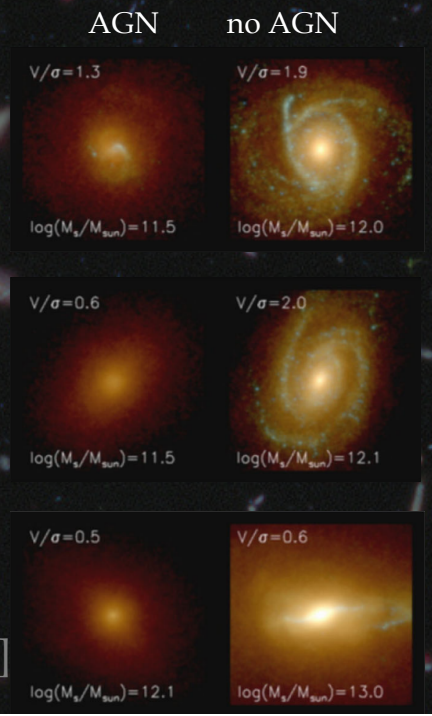
[Dubois+16]

Galaxy formation



[L. Cortese; SDSS.]

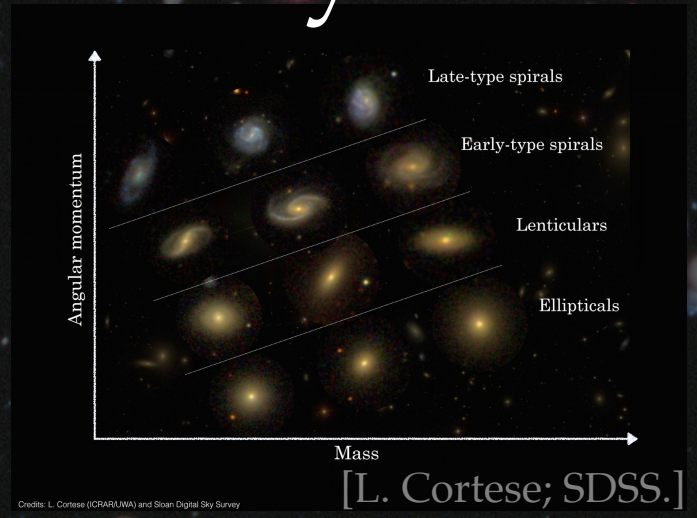
Origin of morphological diversity at fixed mass?



[Dubois+16]

[Kraljic+ in prep]

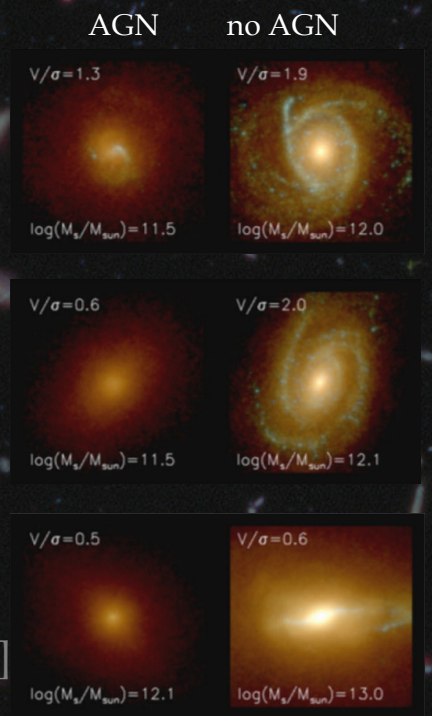
Galaxy formation



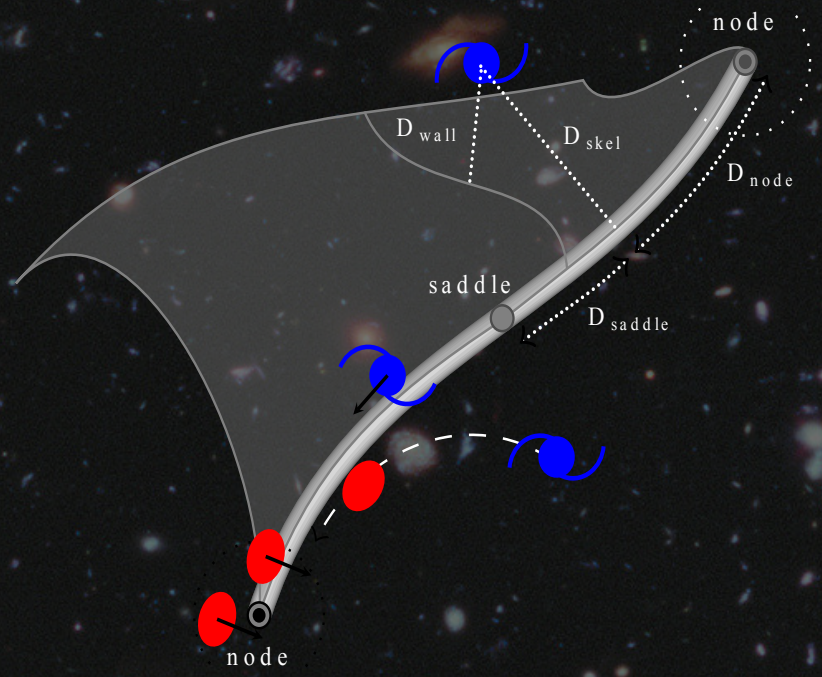
[L. Cortese; SDSS.]

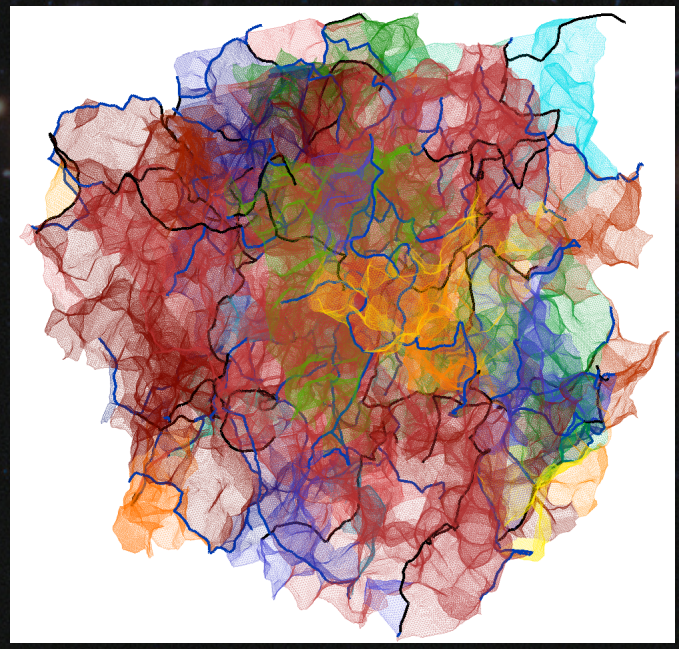
Origin of morphological diversity at fixed mass?

How to explain environmental effects?



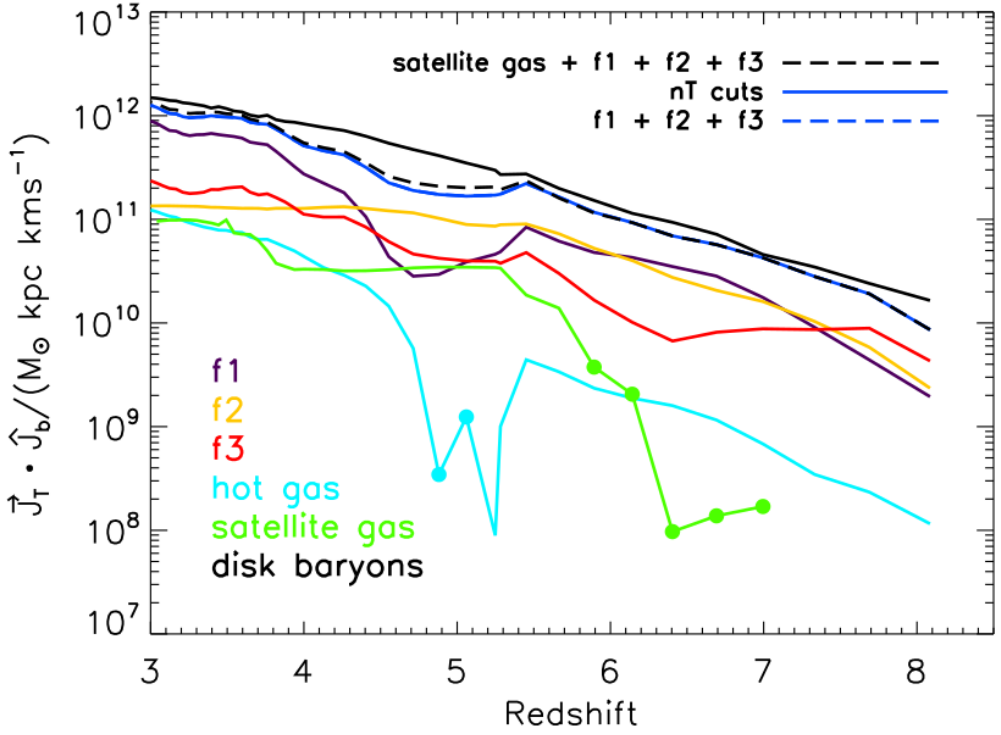
[Dubois+16]



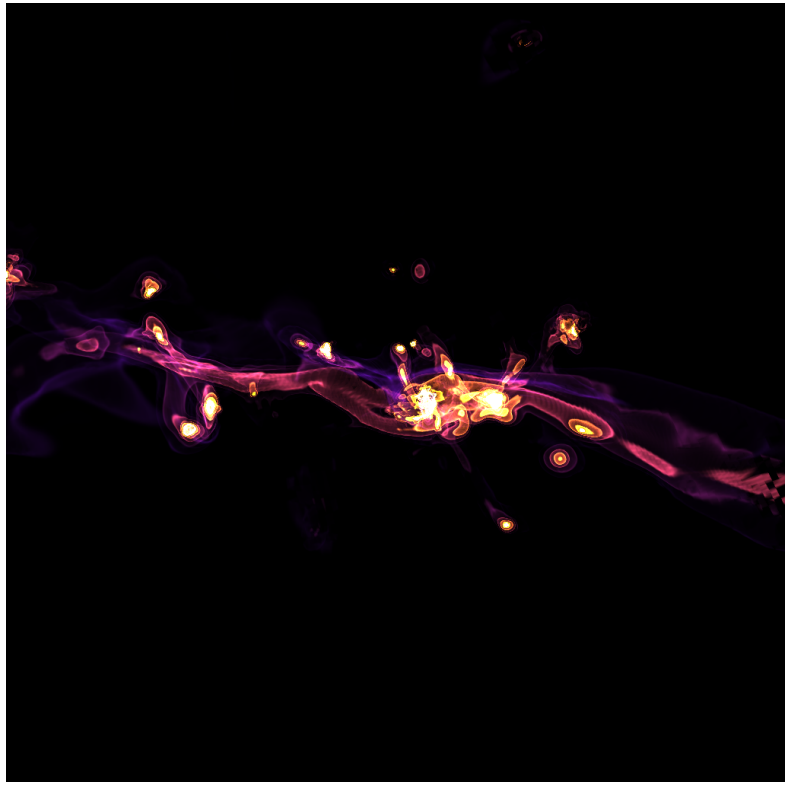


[Kraljic+ in prep]

Galaxy formation in cosmology: the role of the environment



Tillson+15

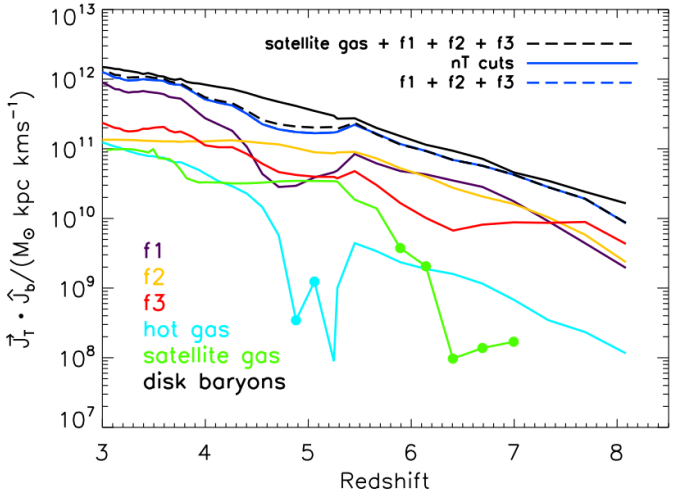


Cadiou+21c

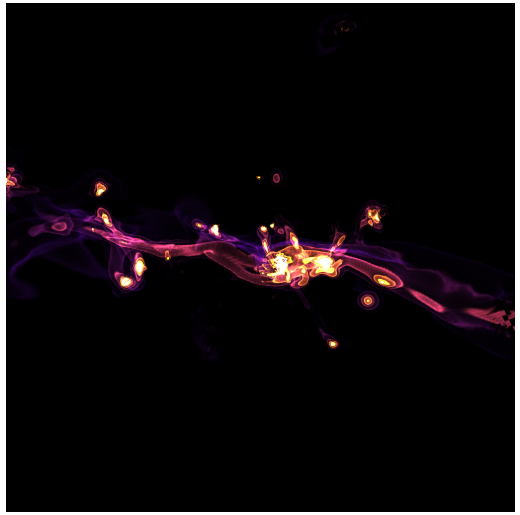
High-z, most of the gas + AM flows along filamentary structures… connected to cosmic web

[also Dekel & Birboim 06, Danovich+15]

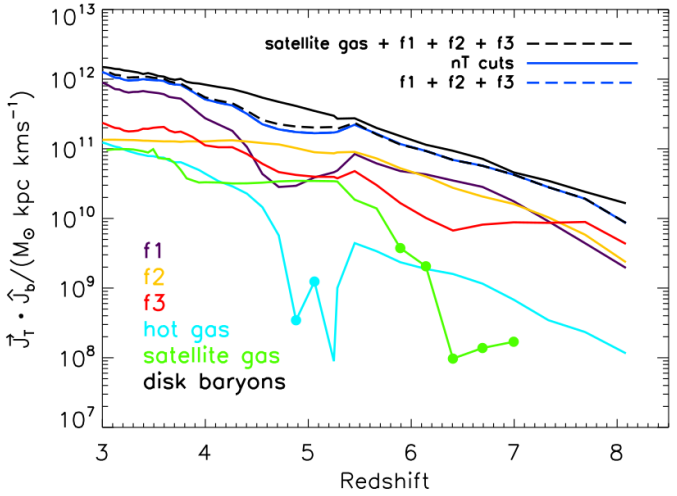
Galaxy formation in cosmology: the role of the environment



Environmental effects:

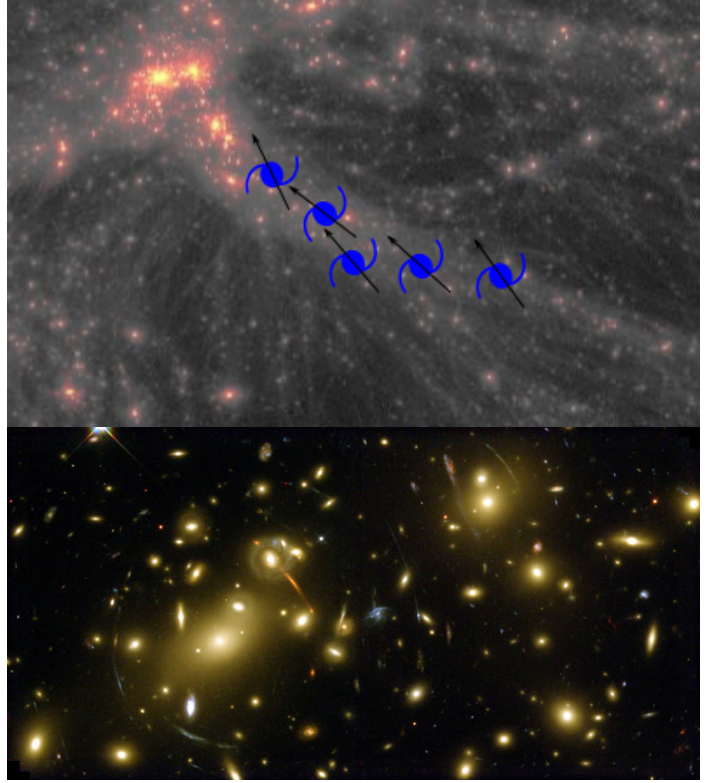


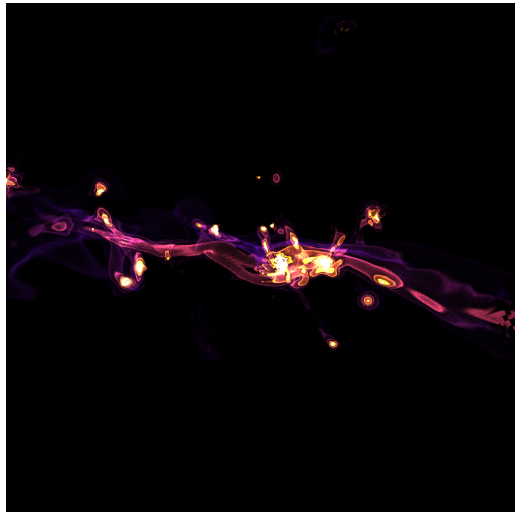
Galaxy formation in cosmology: the role of the environment



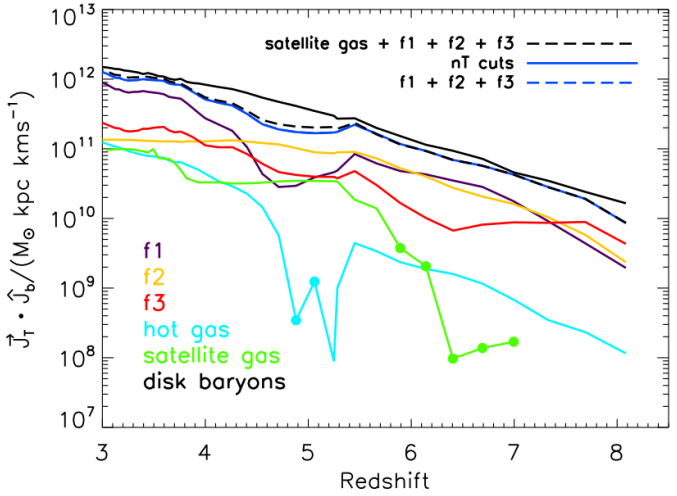
Environmental effects:

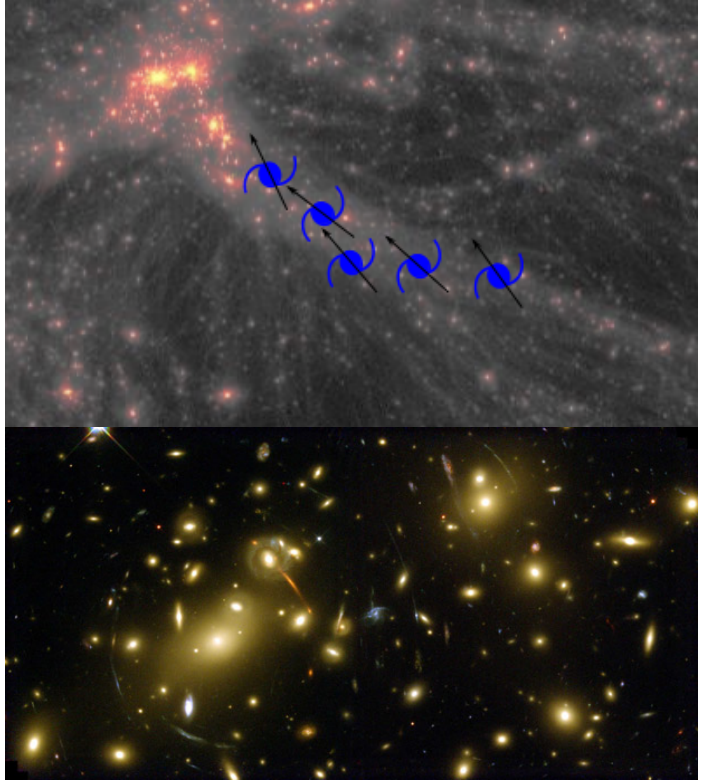
- source of "pollution" in weak lensing surveys
  ⇒ intrinsic alignment





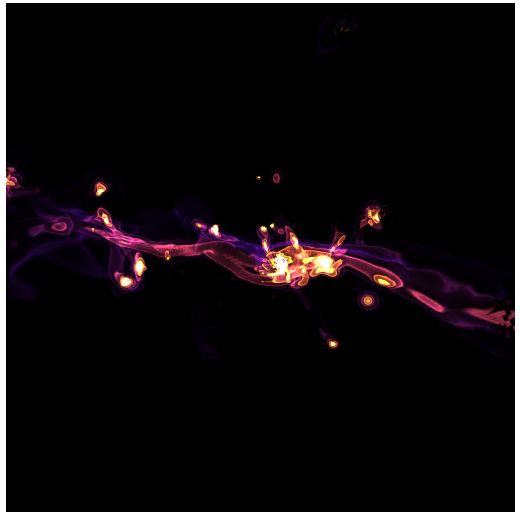
Galaxy formation in cosmology: the role of the environment



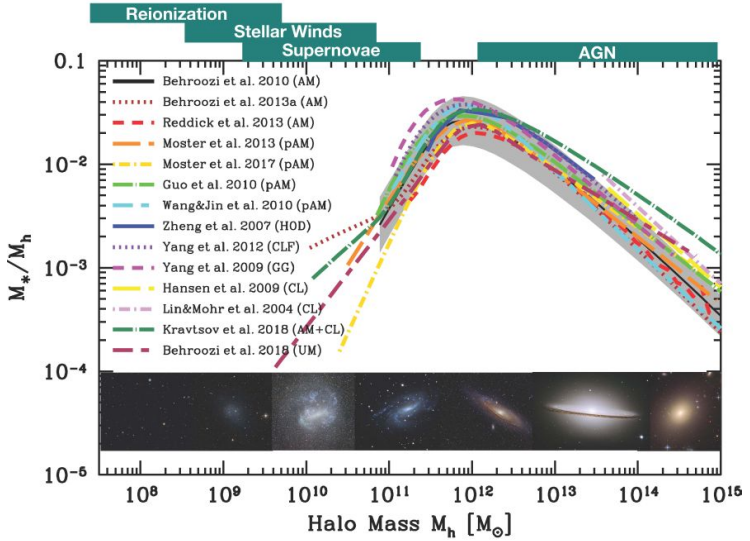


Environmental effects:

- source of "pollution" in weak lensing surveys
  ⇒ intrinsic alignment



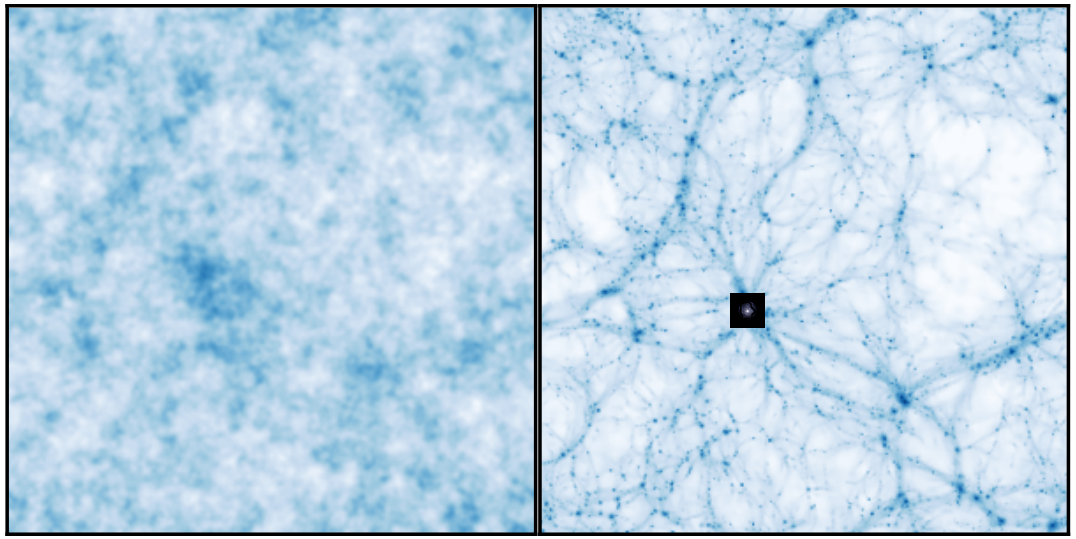
- extra parameters in semi-analytical models
  ⇒ galaxy-halo correlation



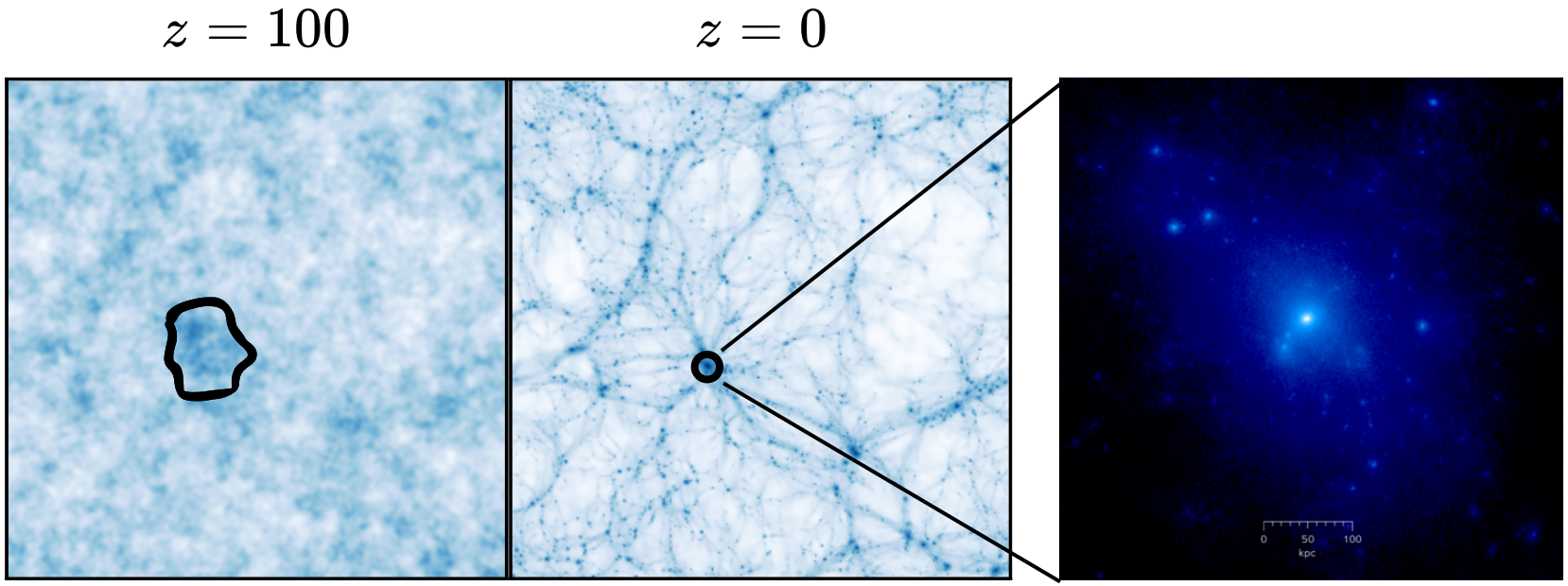
The origin of angular momentum

Predicting angular momentum

$z = 100$ $z = 0$



Predicting angular momentum

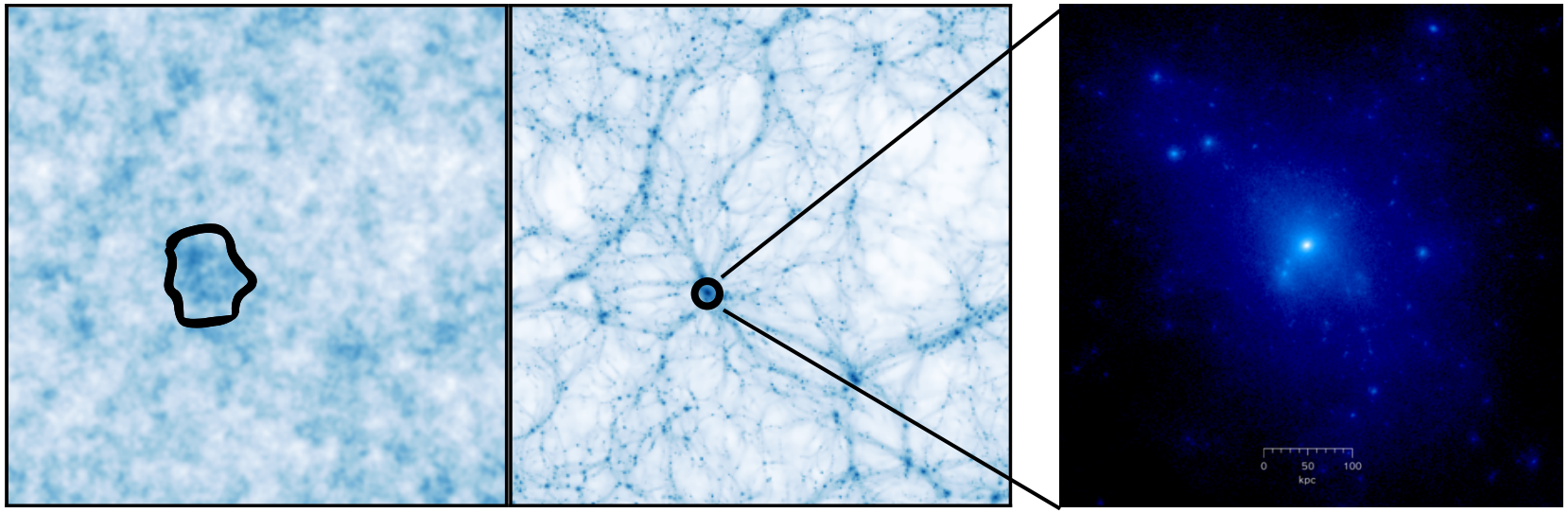


$$\mathbf{L}_{\text{lin.}} \propto \int_{\bigcirc} \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla \phi$$

[White 84]

Predicting angular momentum

$z = 100$ $z = 0$

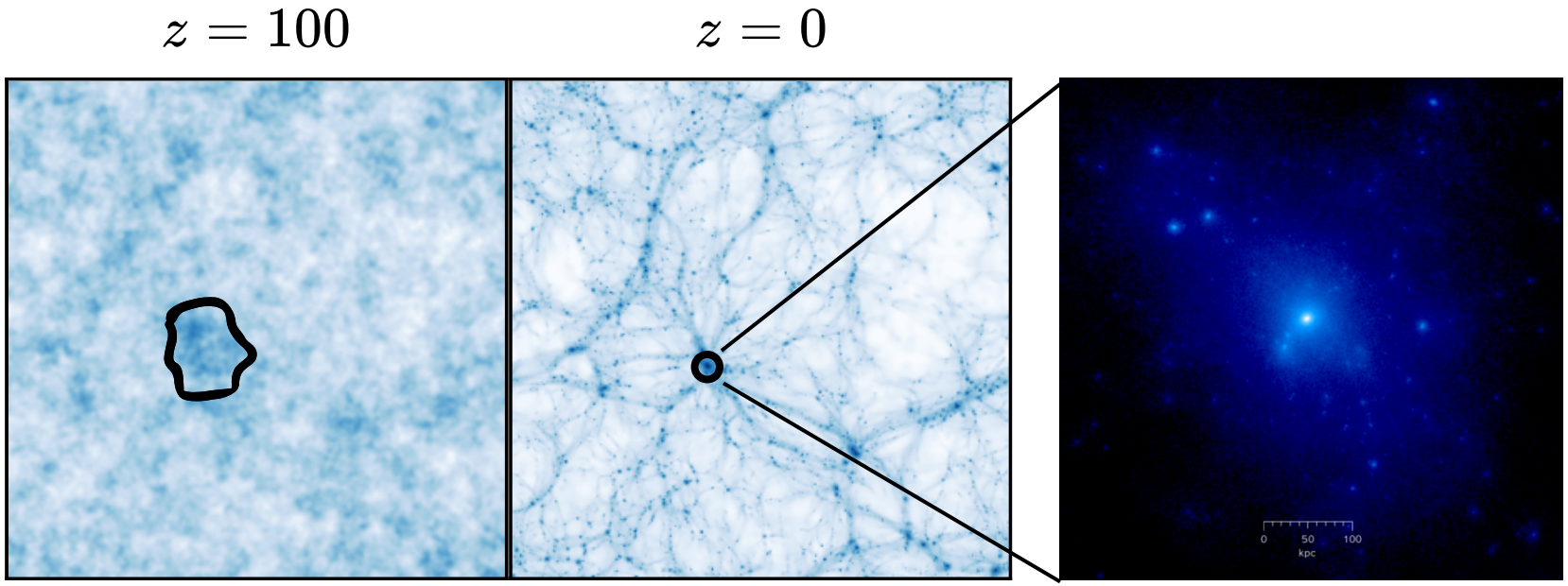


$$\mathbf{L}_{\text{lin.}} \propto \int_{\bigcirc} \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla \phi$$

Position w.r.t. center

[White 84]

Predicting angular momentum



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

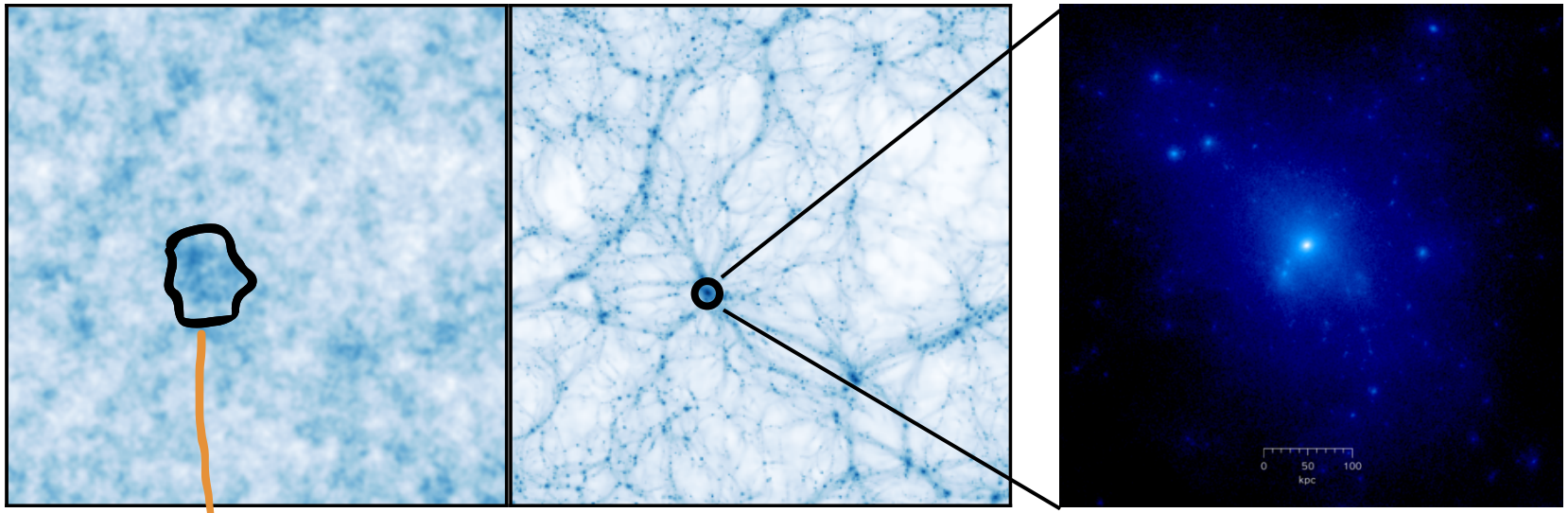
Position w.r.t. center

Velocity

[White 84]

Predicting angular momentum

$z = 100$ $z = 0$



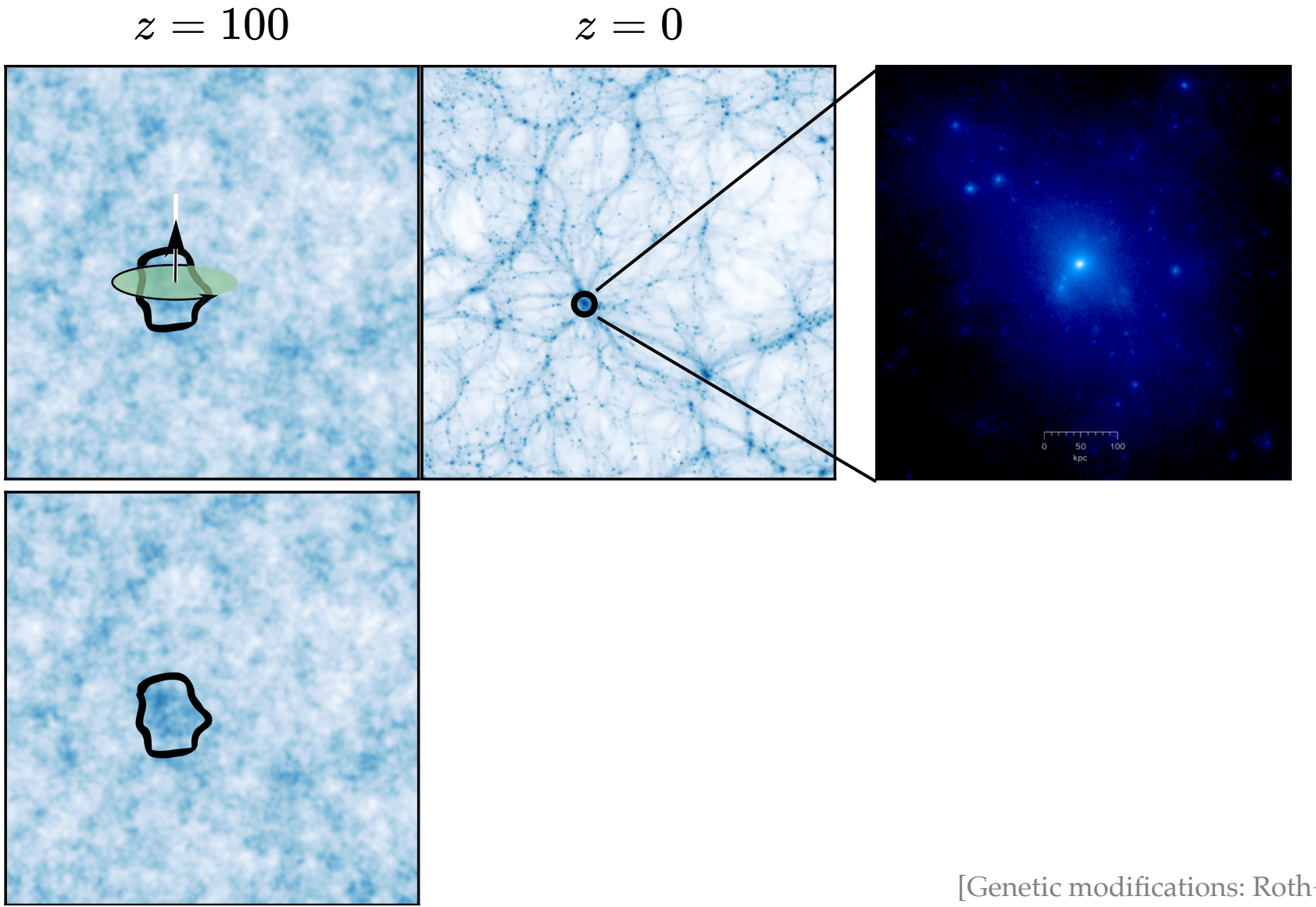
$$\mathbf{L}_{\text{lin.}} \propto \int_{\bigcirc} \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla\phi$$

Position w.r.t. center

Velocity

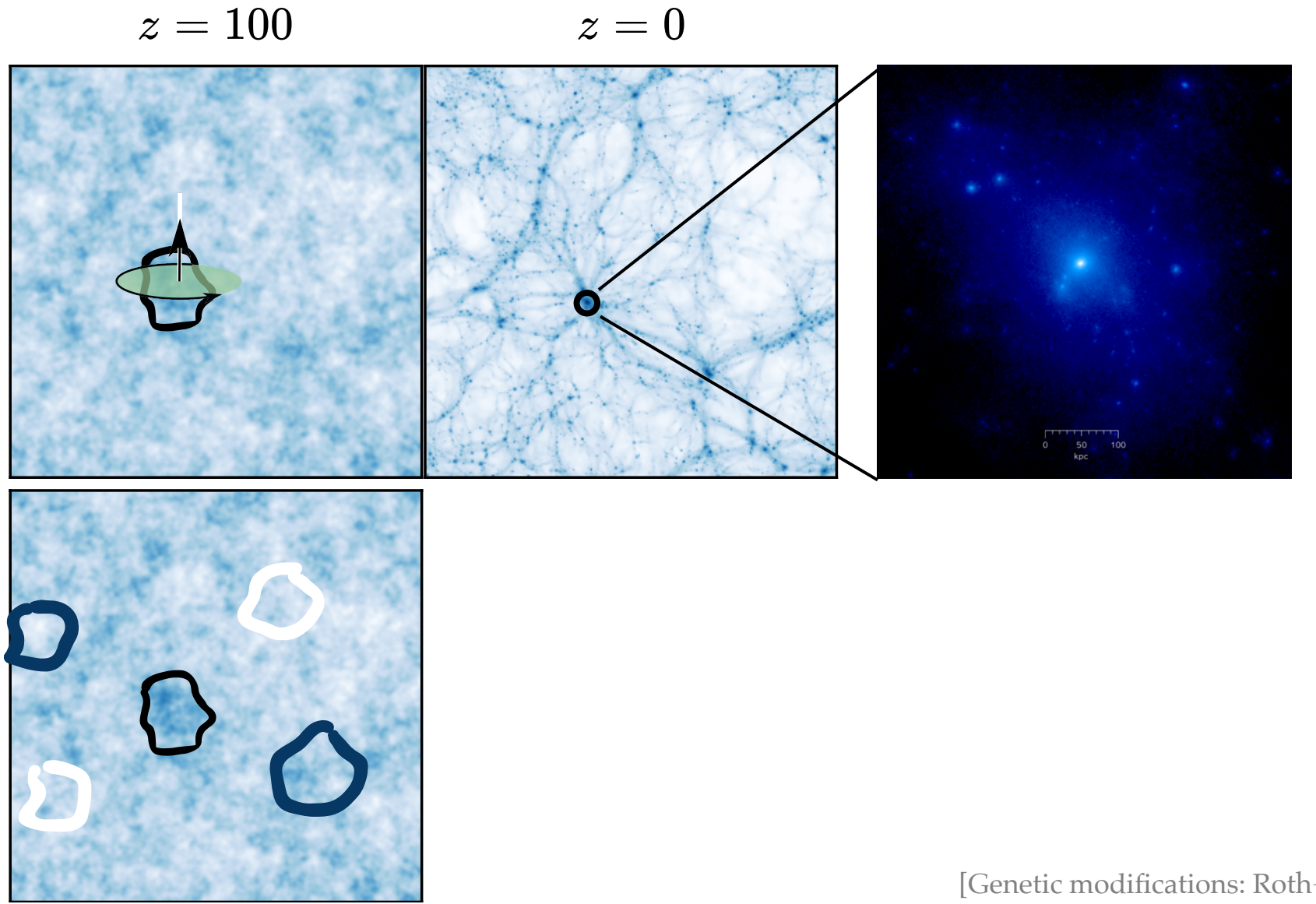
[White 84]

Predicting angular momentum



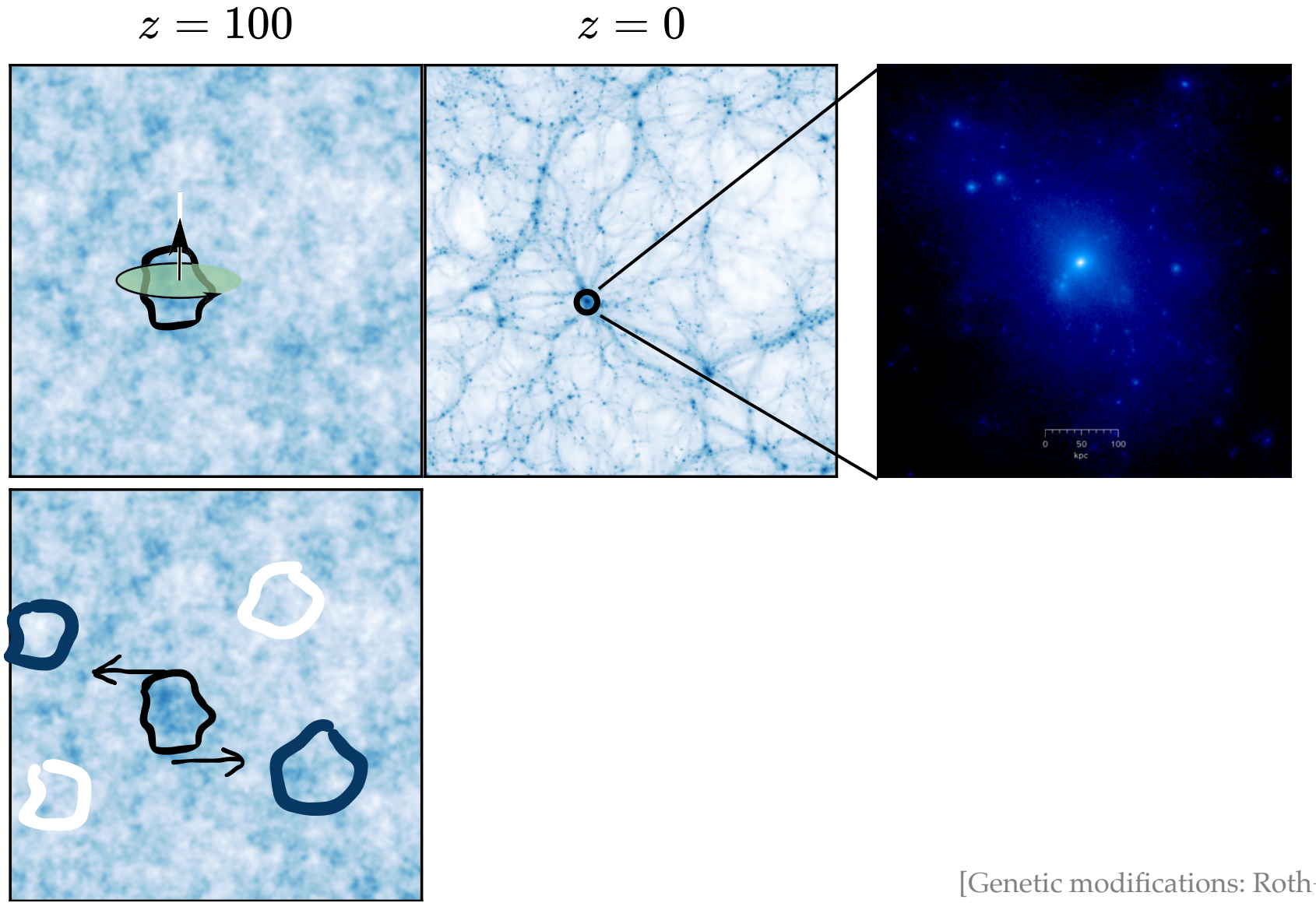
[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum



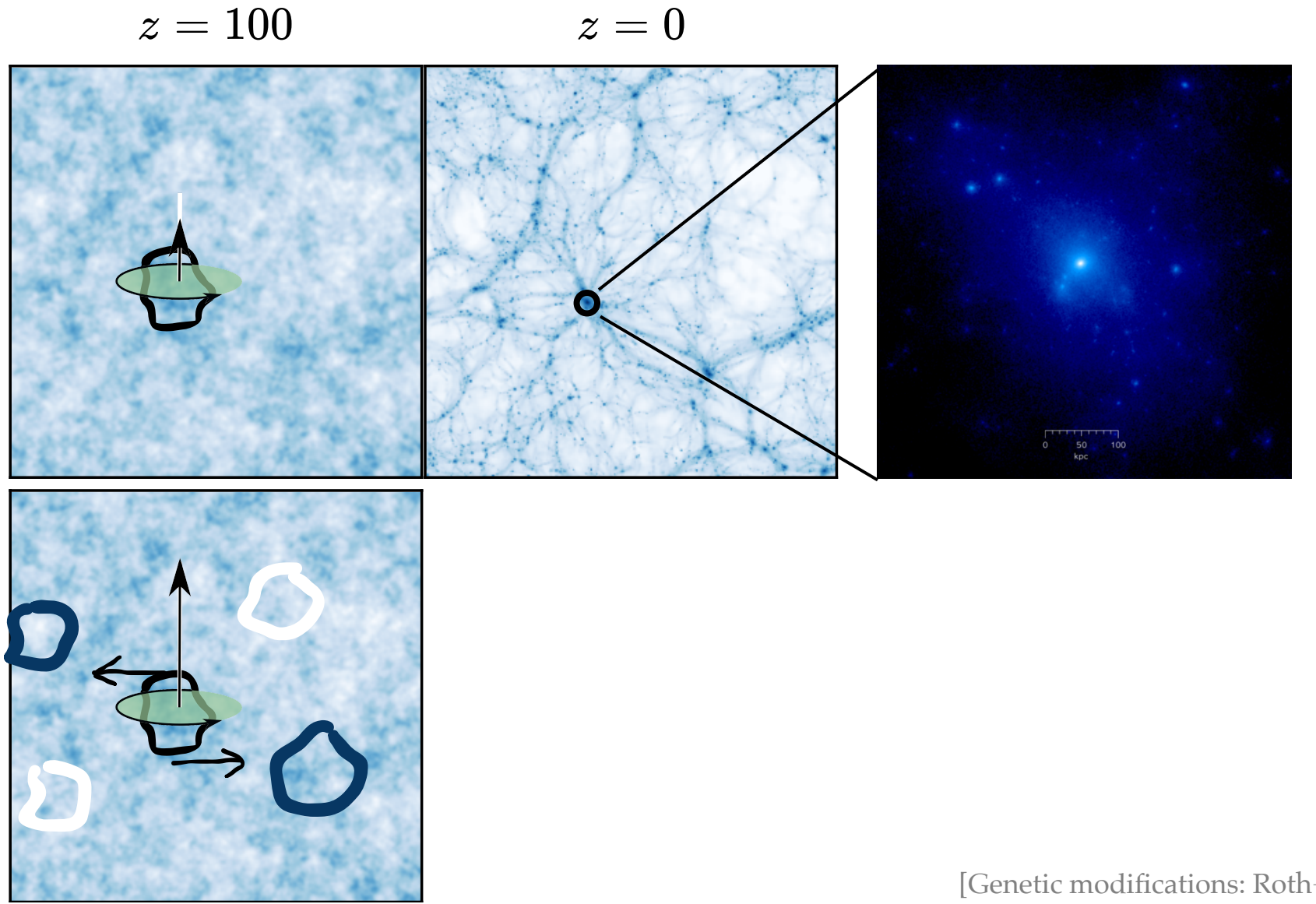
[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum



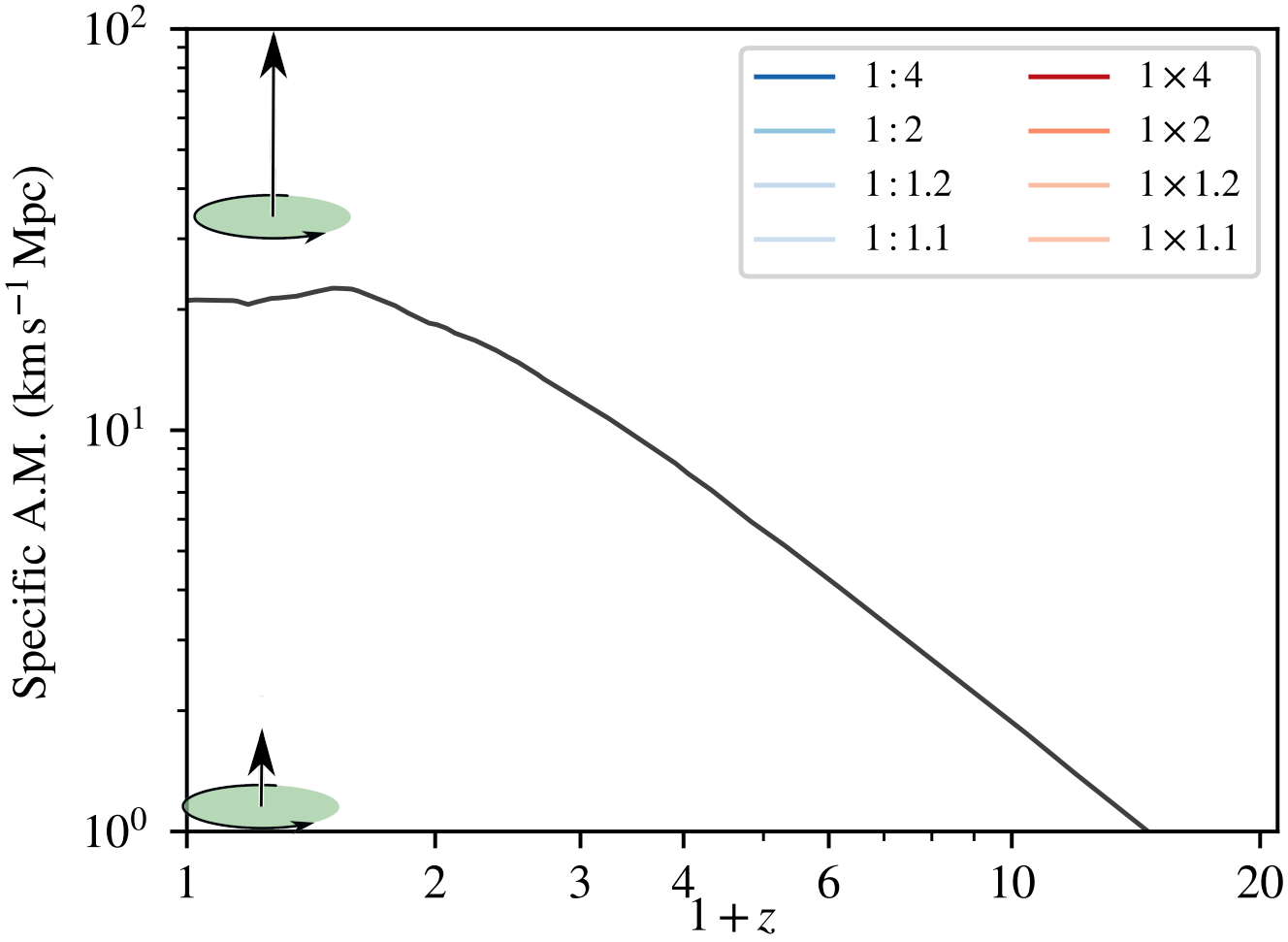
[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum

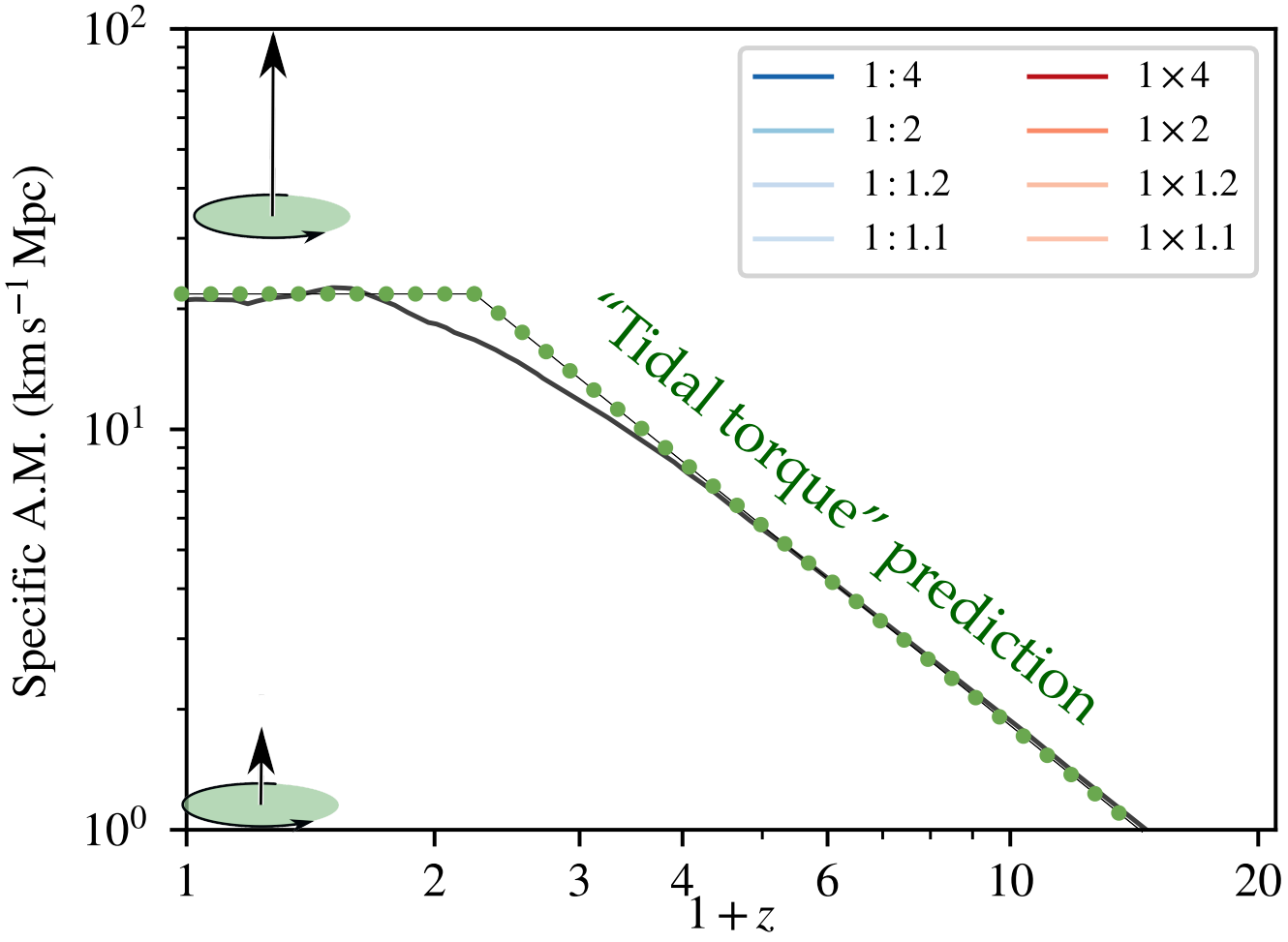


[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

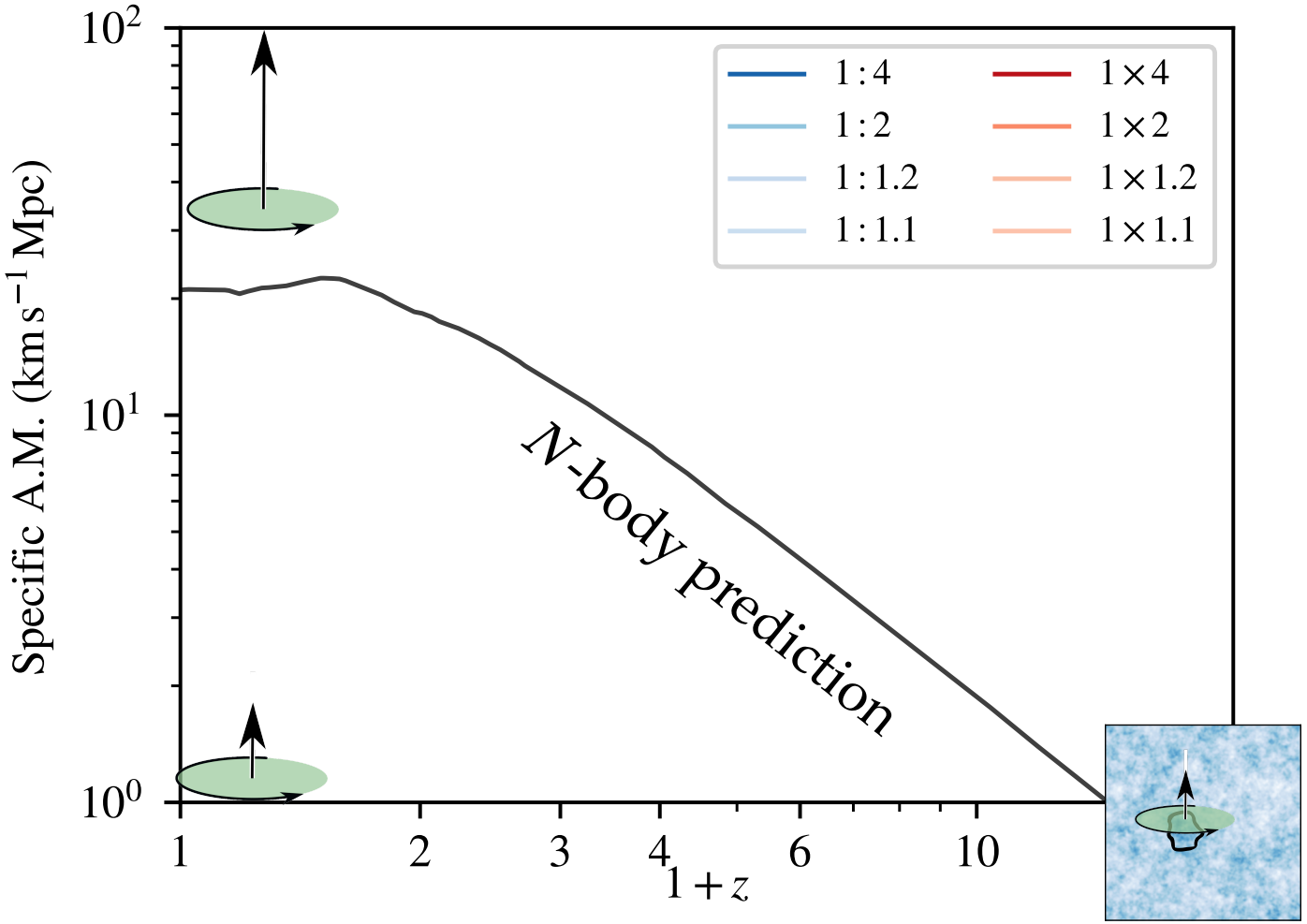
Predicting angular momentum



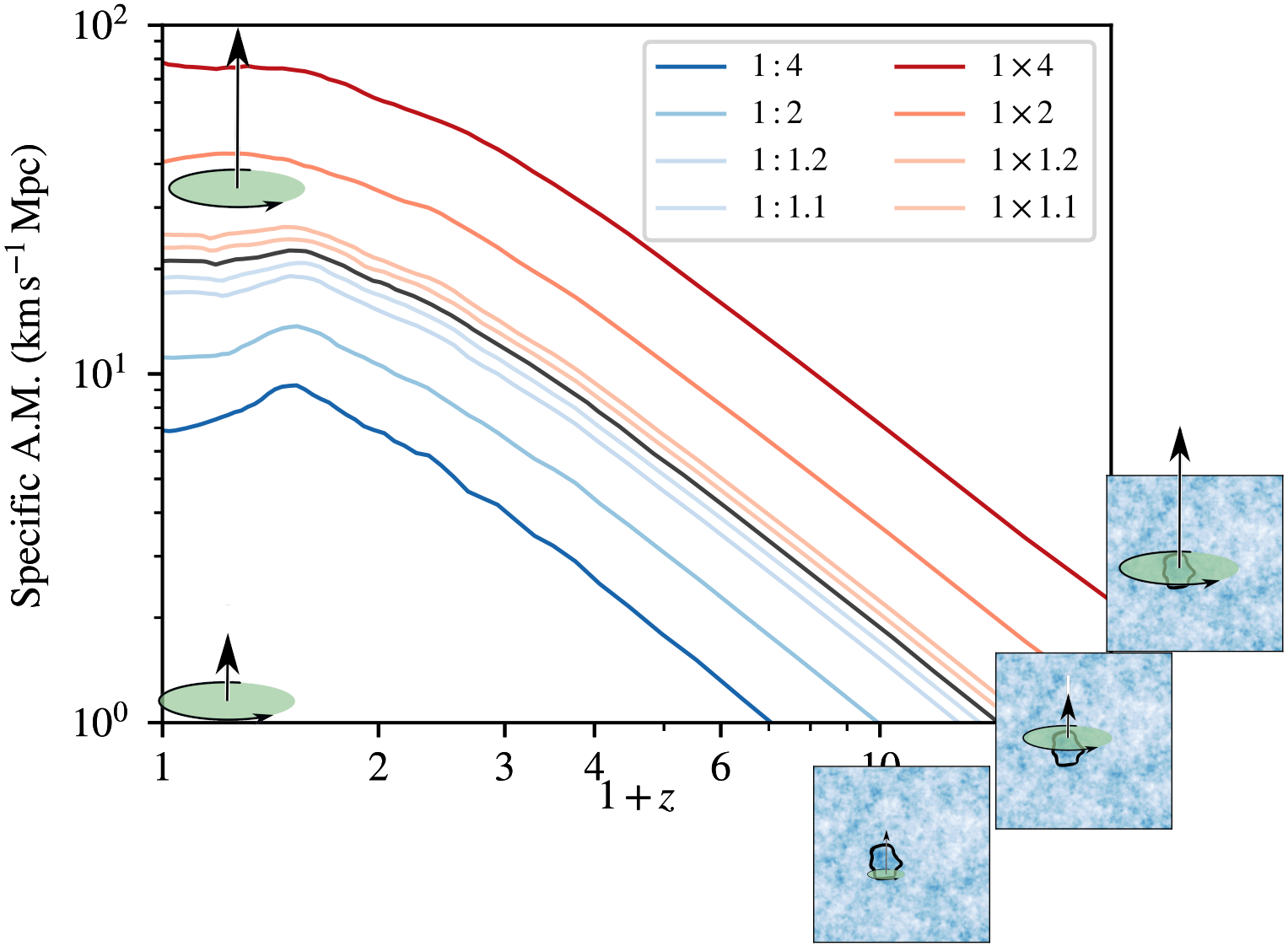
Predicting angular momentum



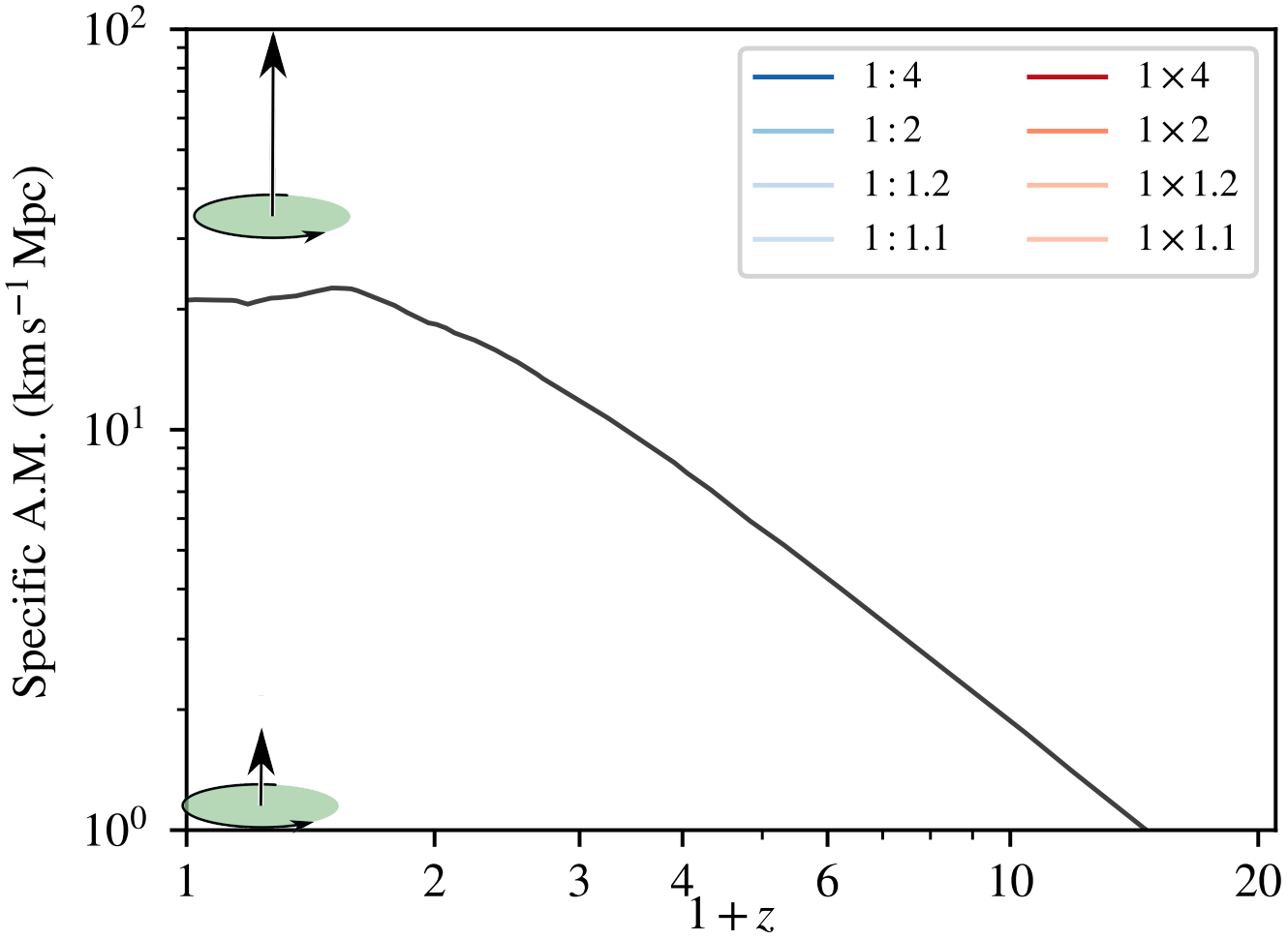
Predicting angular momentum



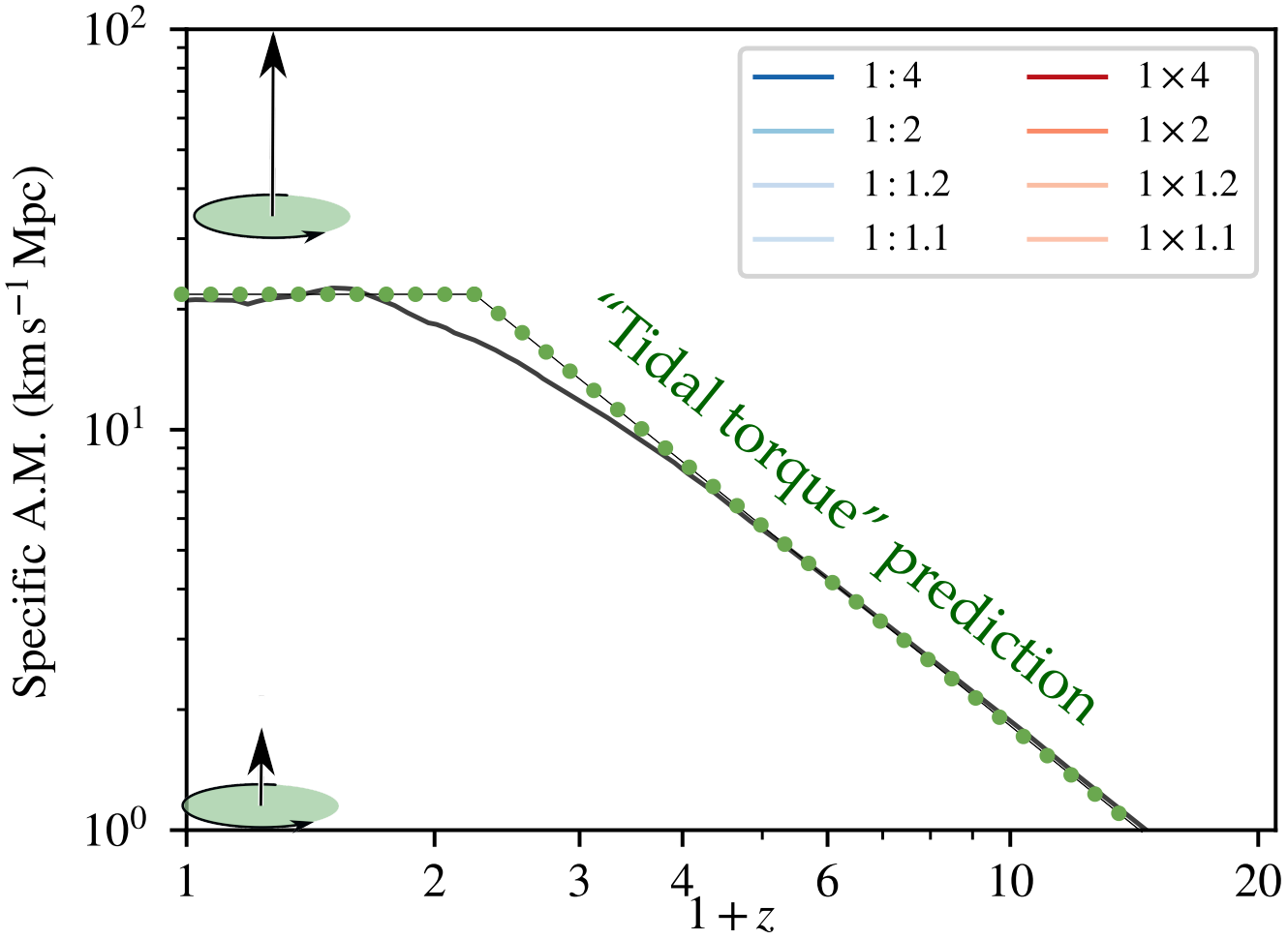
Predicting angular momentum

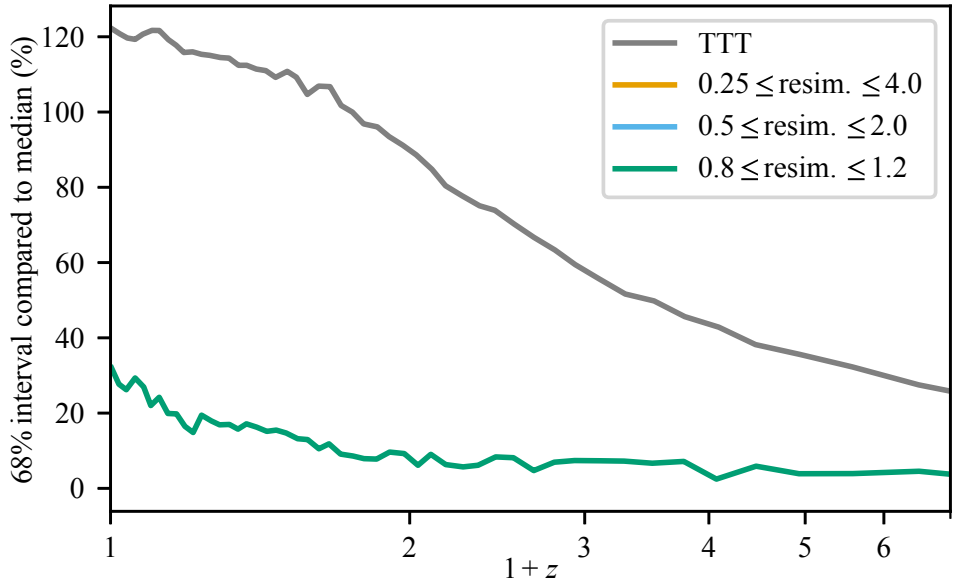


Predicting angular momentum

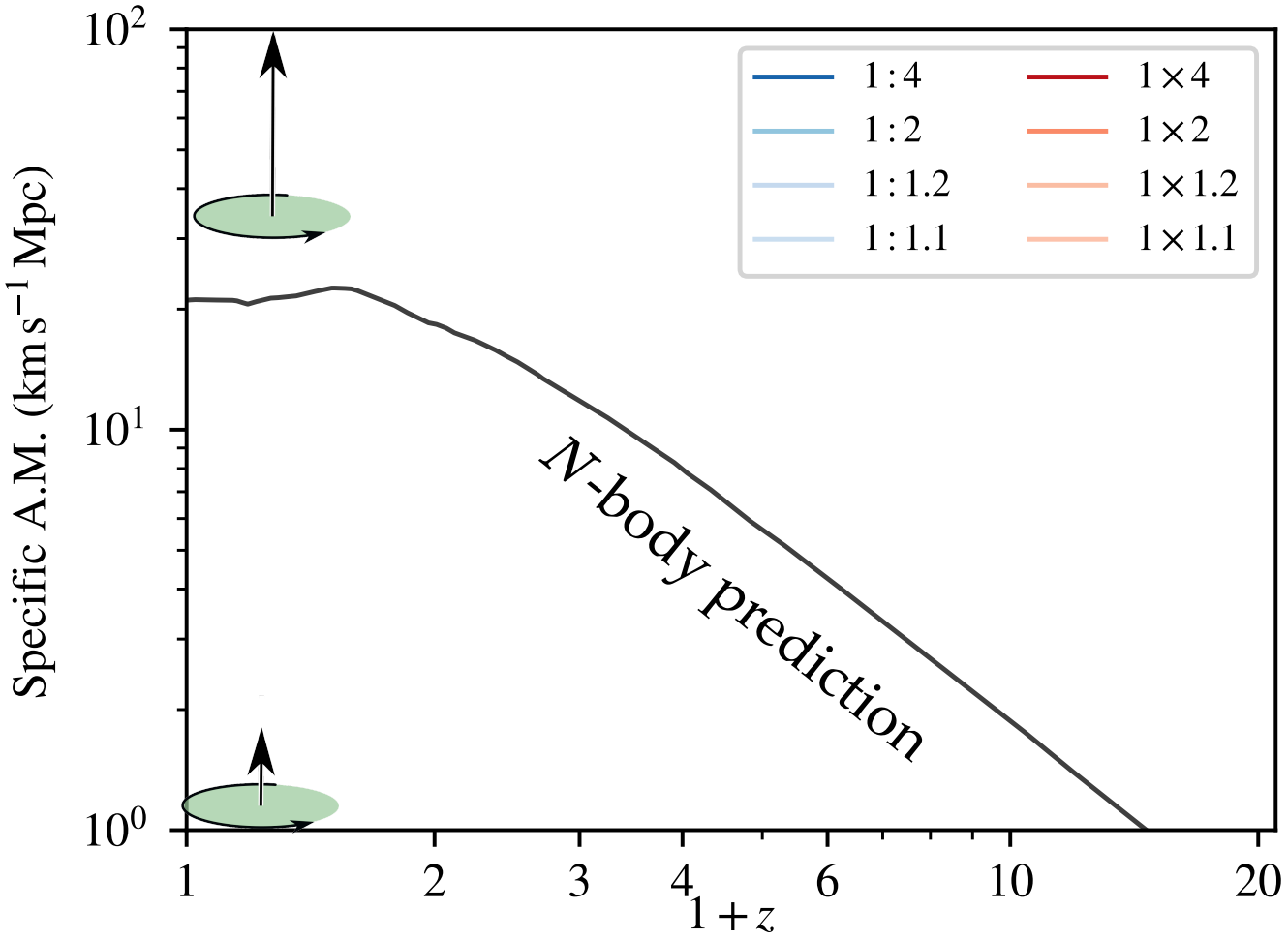


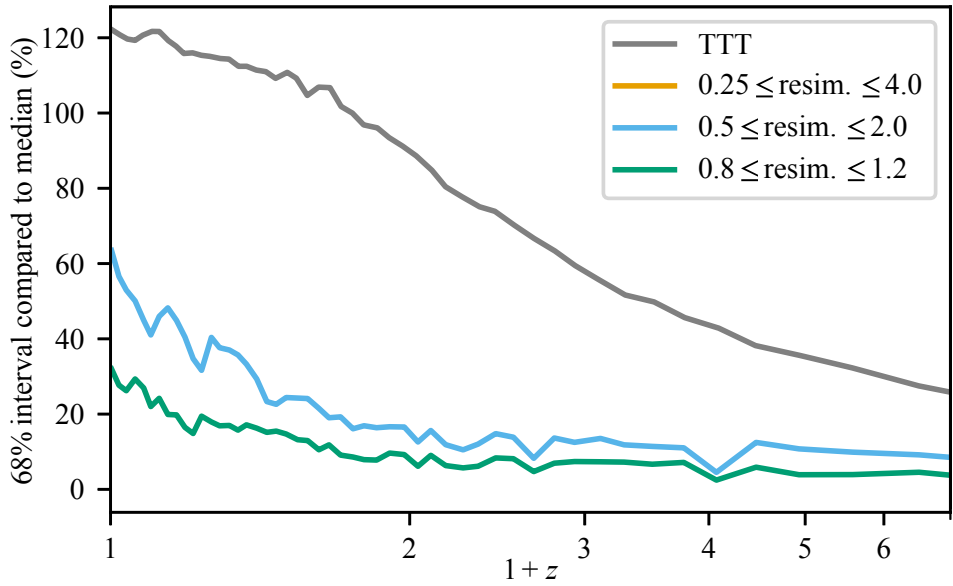
Predicting angular momentum



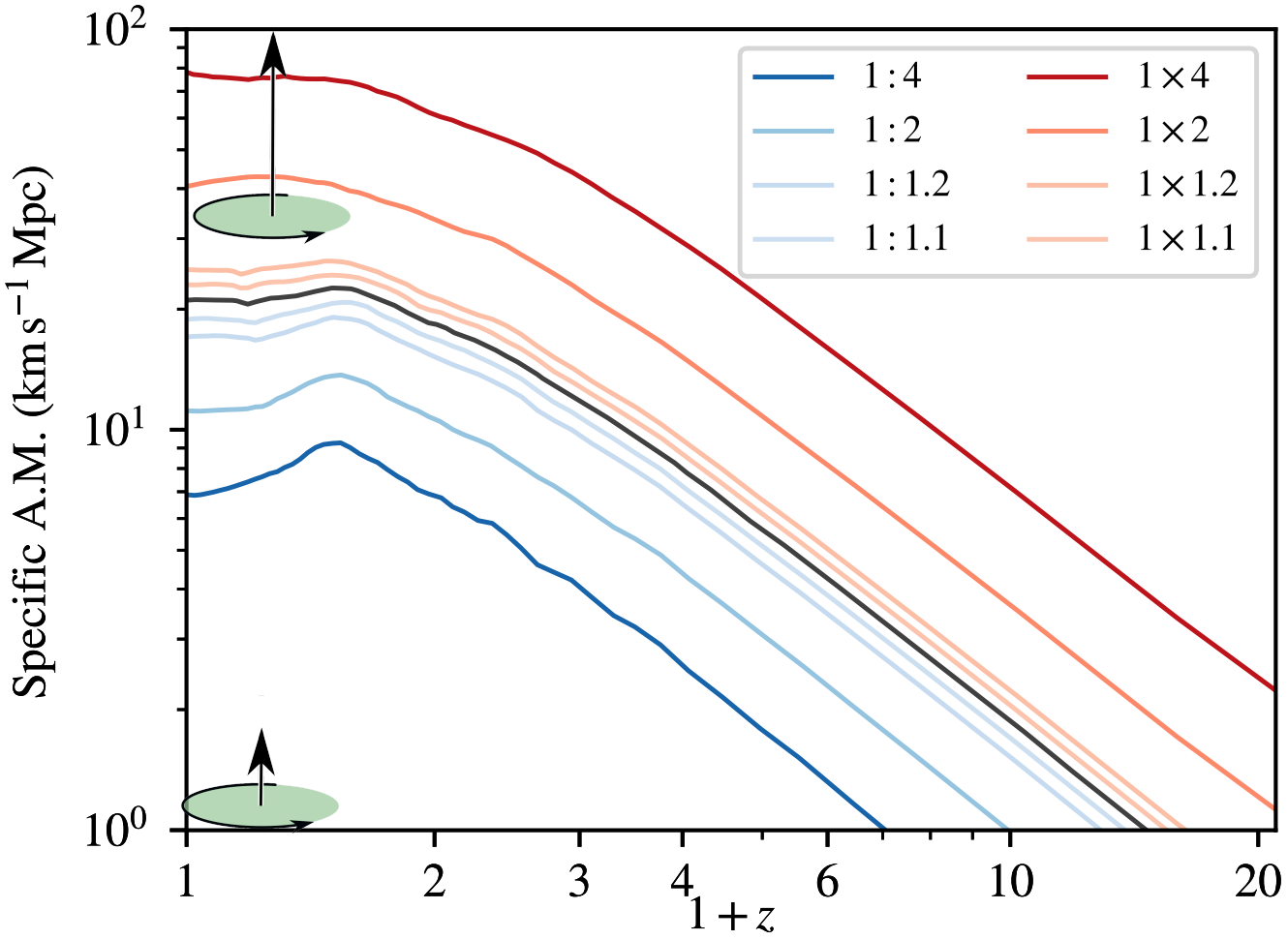


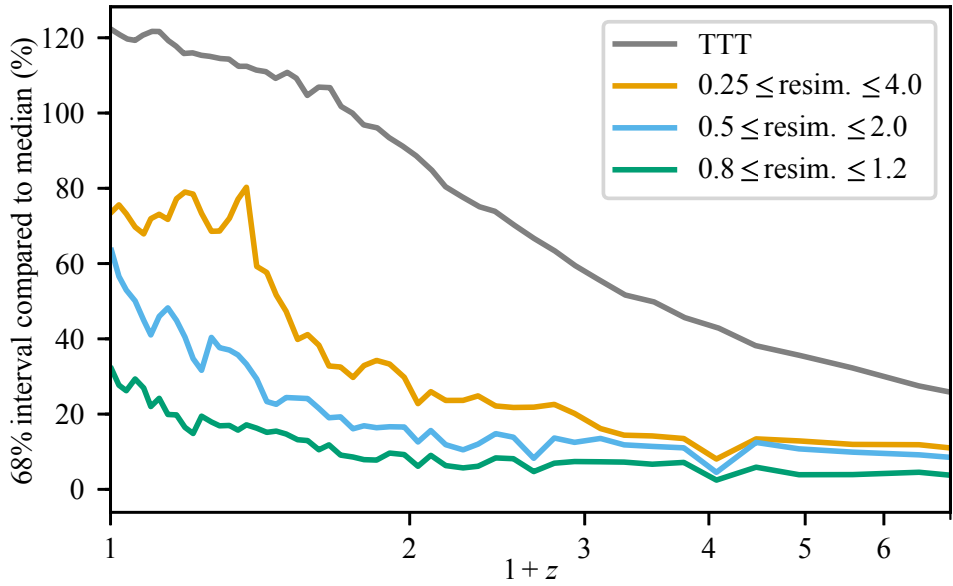
Predicting angular momentum





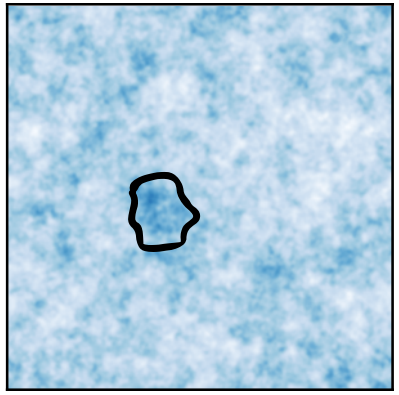
Predicting angular momentum





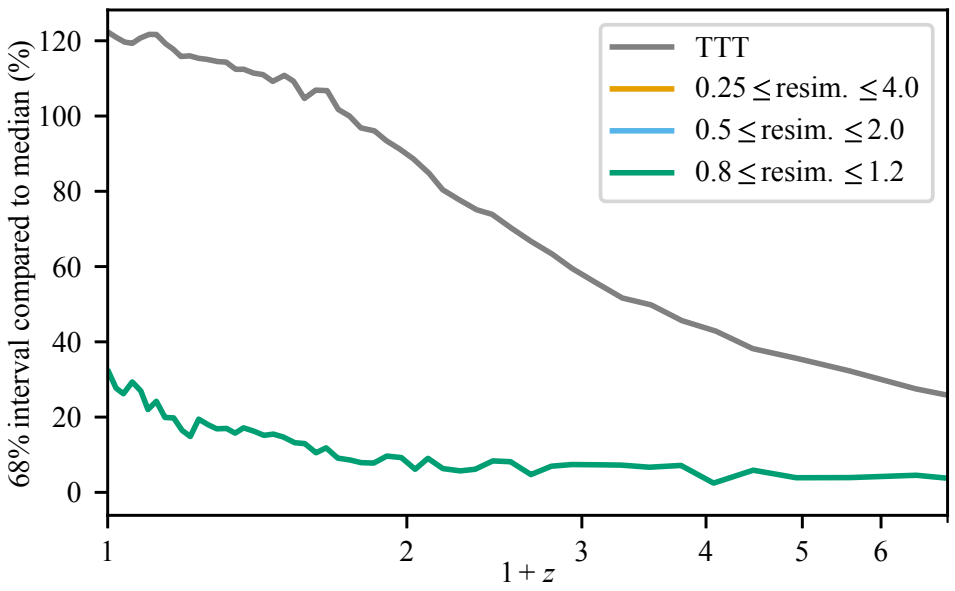
Predicting angular momentum

- Angular momentum of individual regions *can* be predicted accurately.

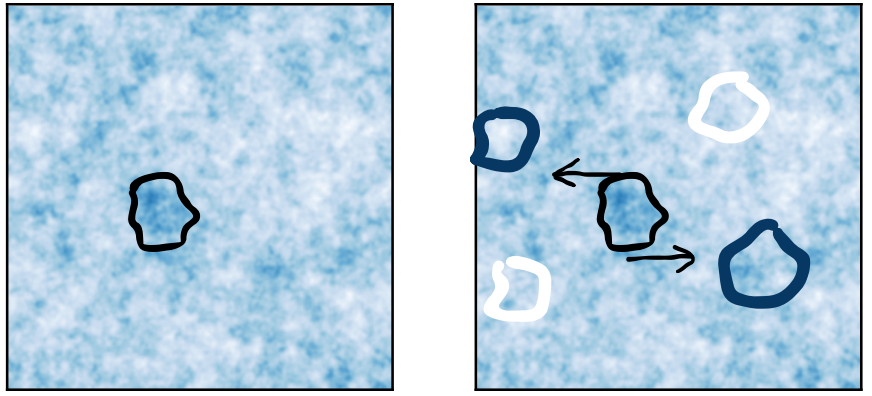


[On patch boundaries: see Lucie-Smith+18]

Predicting angular momentum

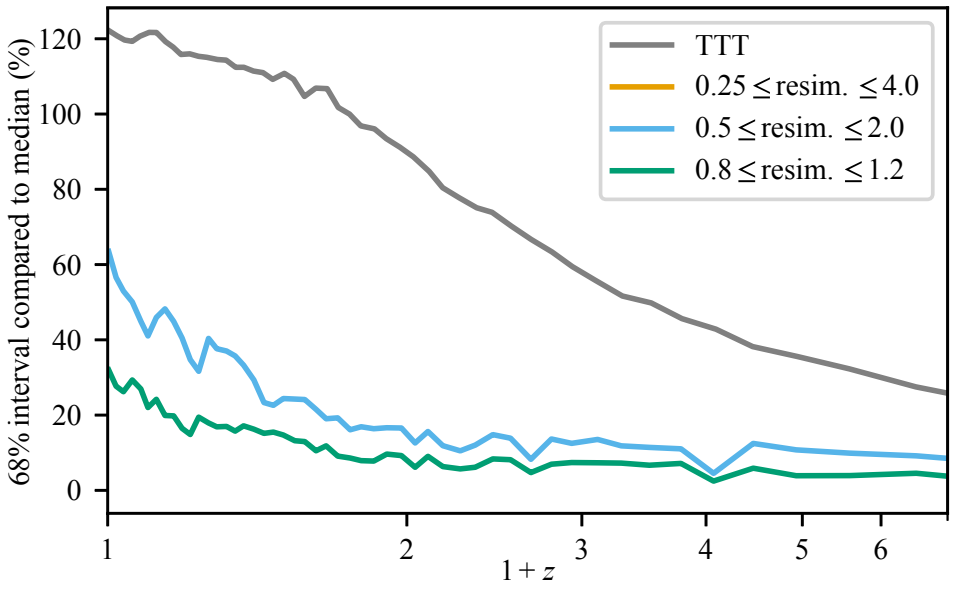


- Angular momentum of individual regions *can* be predicted accurately.
- AM of *halos* ⇒ requires boundaries of patch



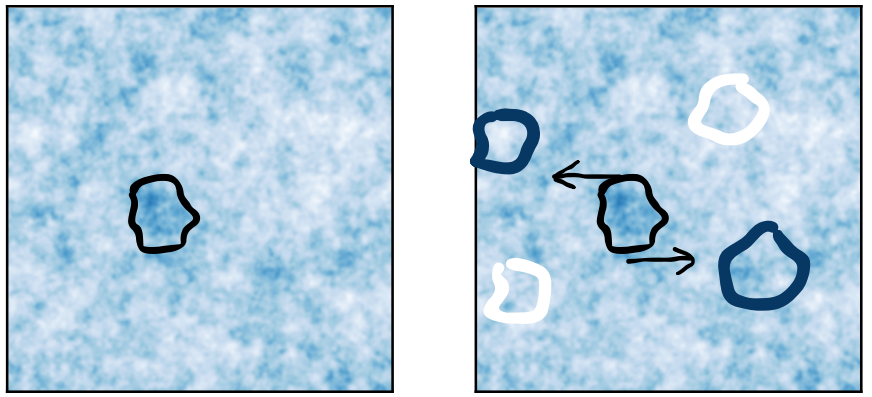
[On patch boundaries: see Lucie-Smith+18]

Predicting angular momentum



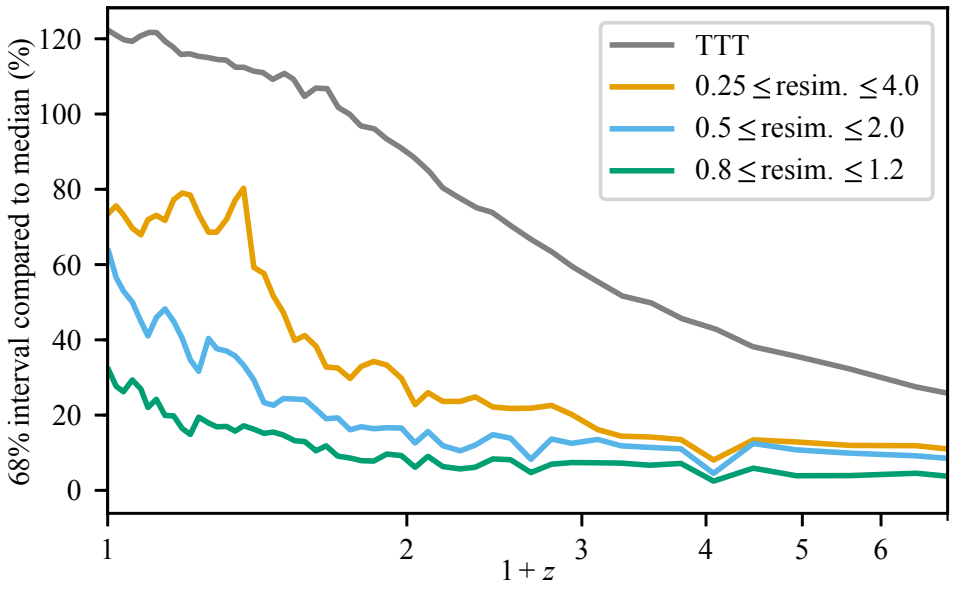
$$\mathbf{L}_{\text{lin.}} \propto \int_{\text{patch}} \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla \phi$$

- Angular momentum of individual regions *can* be predicted accurately.
- AM of *halos* ⇒ requires boundaries of patch



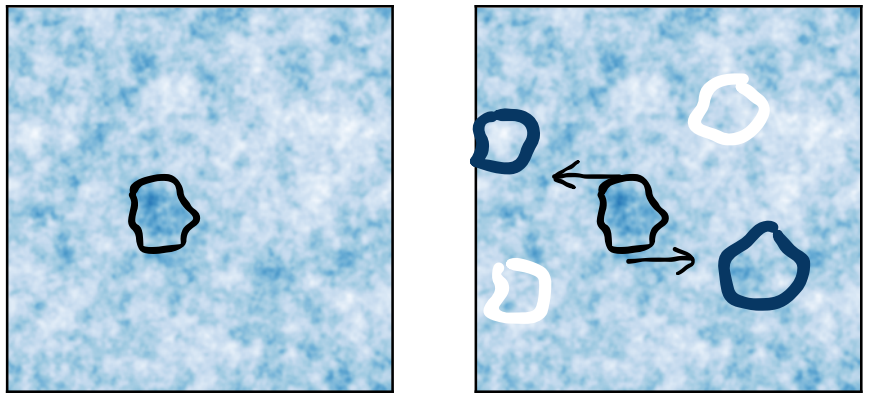
[On patch boundaries: see Lucie-Smith+18]

Predicting angular momentum



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

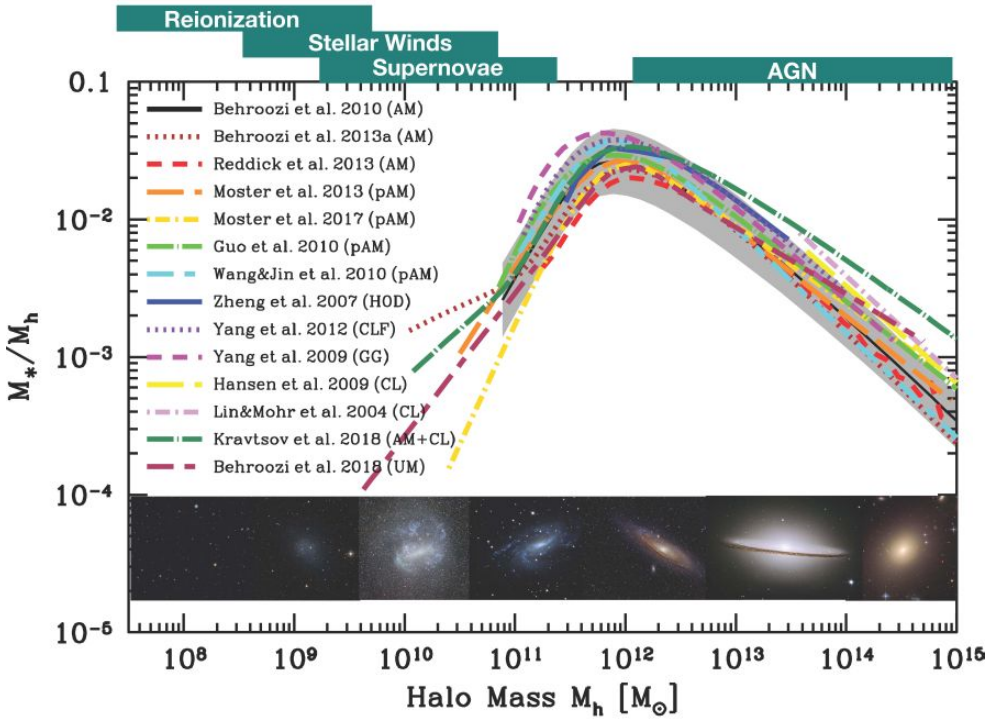
- Angular momentum of individual regions *can* be predicted accurately.
- AM of *halos* ⇒ requires boundaries of patch



[On patch boundaries: see Lucie-Smith+18]

Can we control *baryonic* angular momentum?

Can we control *baryonic* angular momentum?

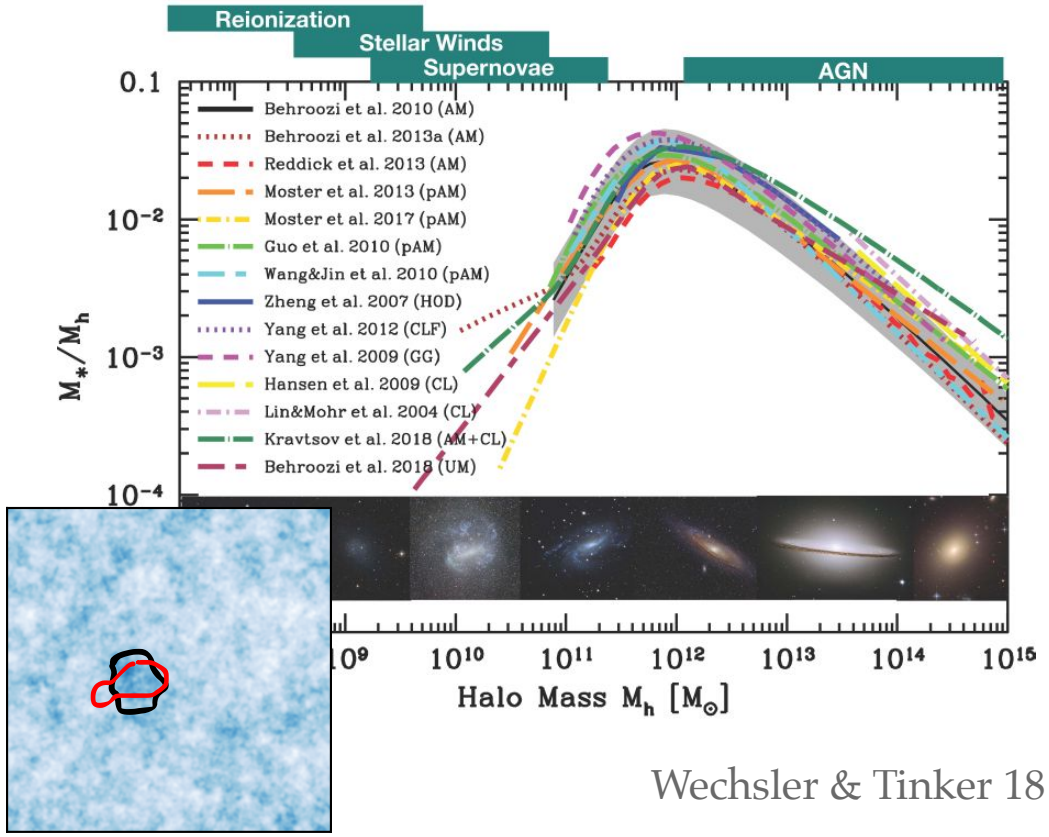


Wechsler & Tinker 18

$$M_\star/M_{\rm h} \ll \Omega_b/\Omega_m$$

$\Rightarrow$ baryons & DM stem from different regions

Can we control *baryonic* angular momentum?

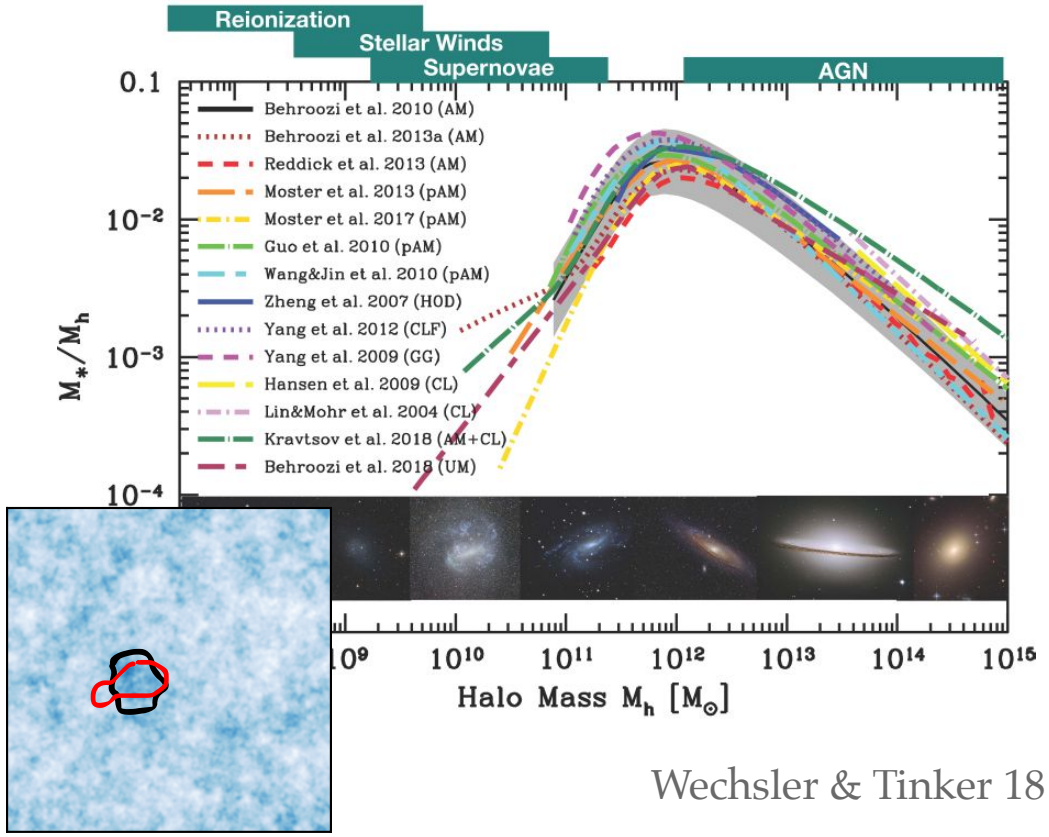


Wechsler & Tinker 18

$$M_\star/M_{\rm h} \ll \Omega_b/\Omega_m$$

$\Rightarrow$ baryons & DM stem from different regions

Can we control *baryonic* angular momentum?



Wechsler & Tinker 18

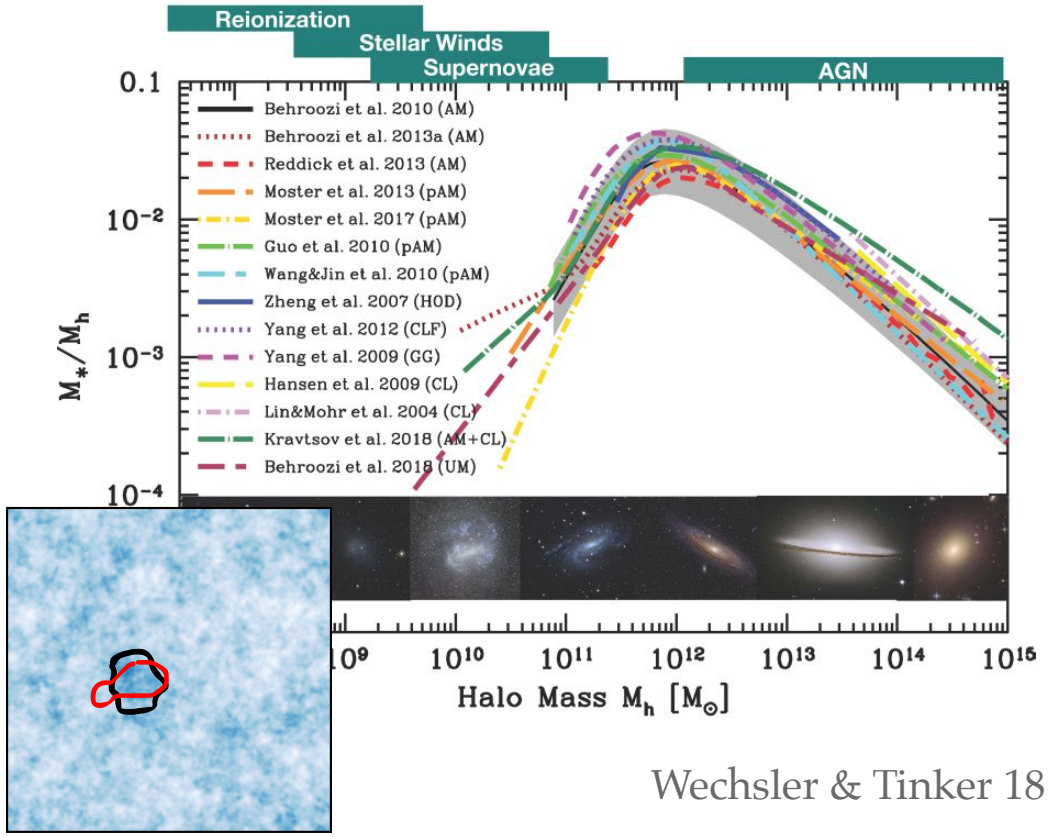
$M_\star/M_{\rm h} \ll \Omega_b/\Omega_m$

⇒ baryons & DM stem from different regions

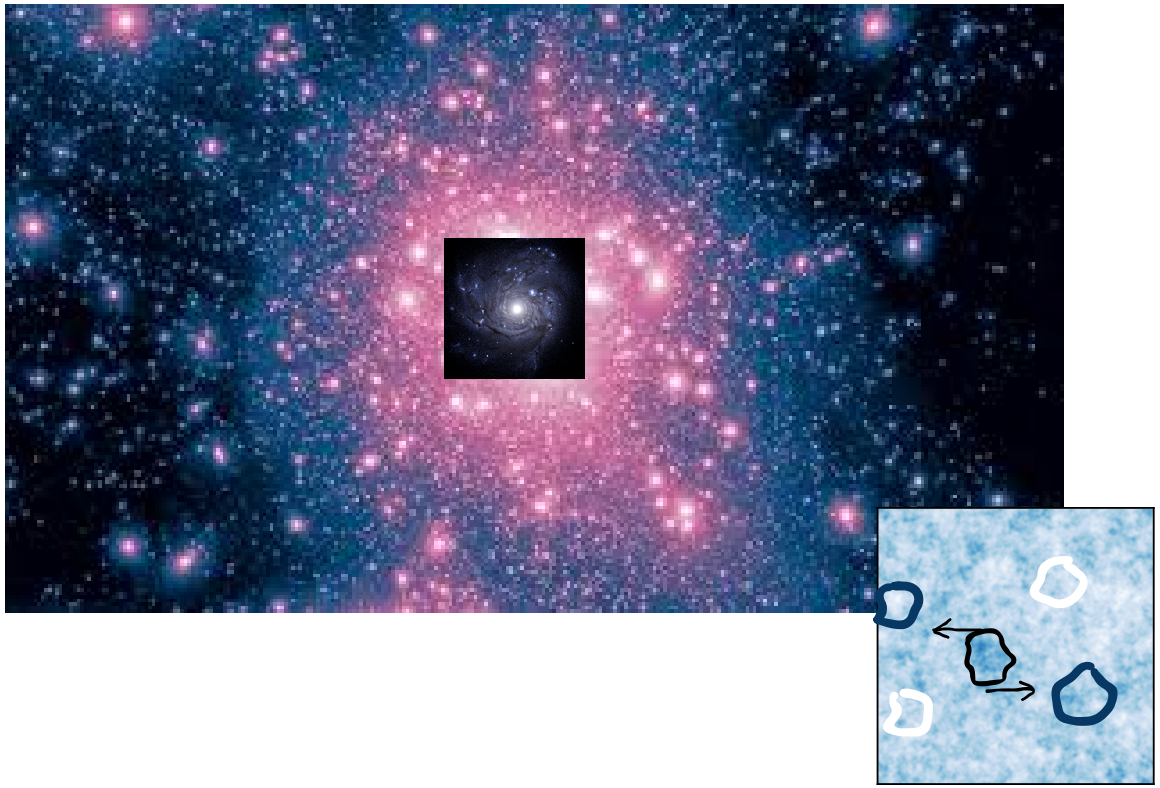
Baryons more strongly bound

⇒ less prone to being ejected

Can we control *baryonic* angular momentum?



Wechsler & Tinker 18



$M_\star/M_{\rm h} \ll \Omega_b/\Omega_m$

⇒ baryons & DM stem from different regions

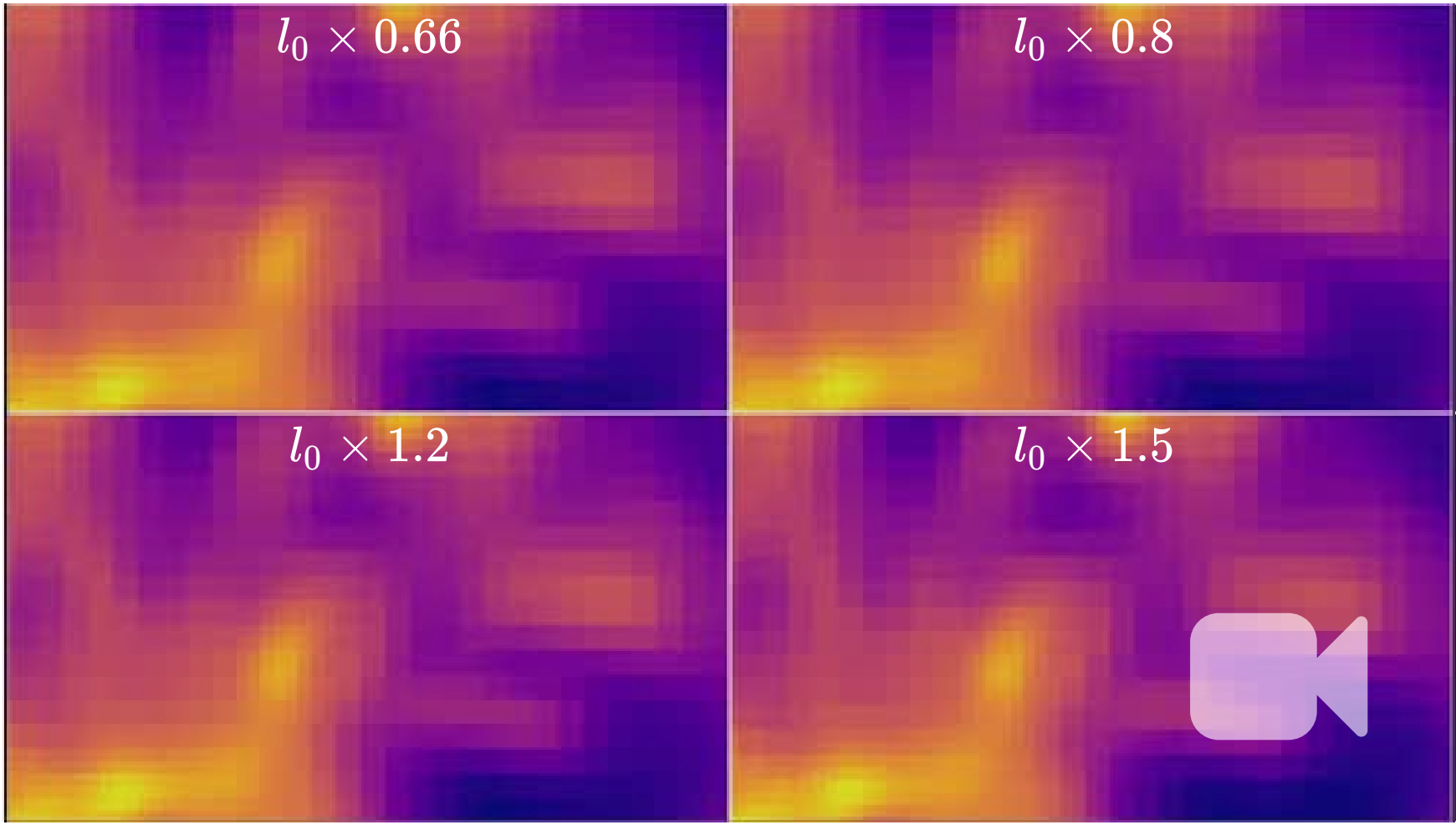
Baryons more strongly bound

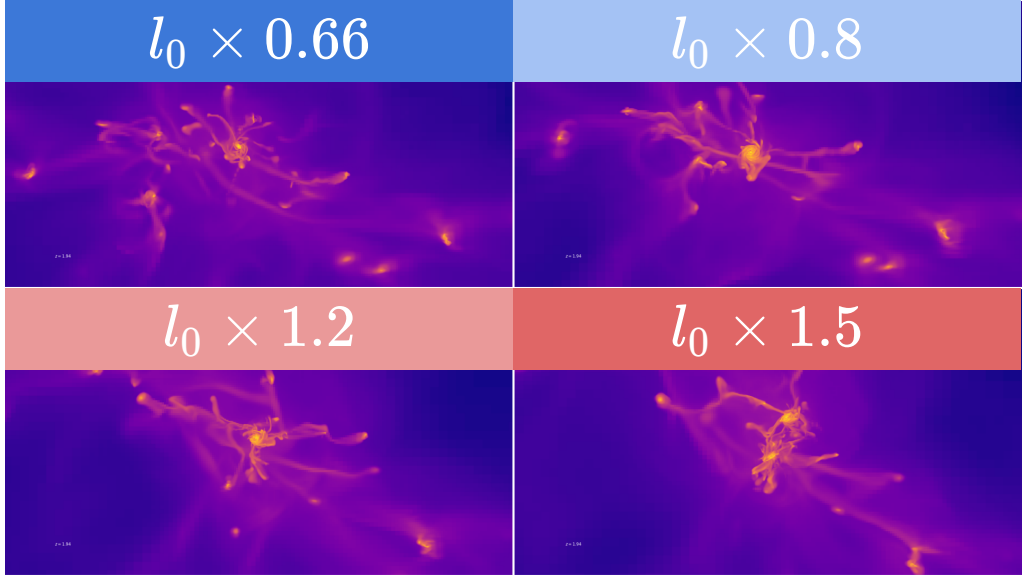
⇒ less prone to being ejected

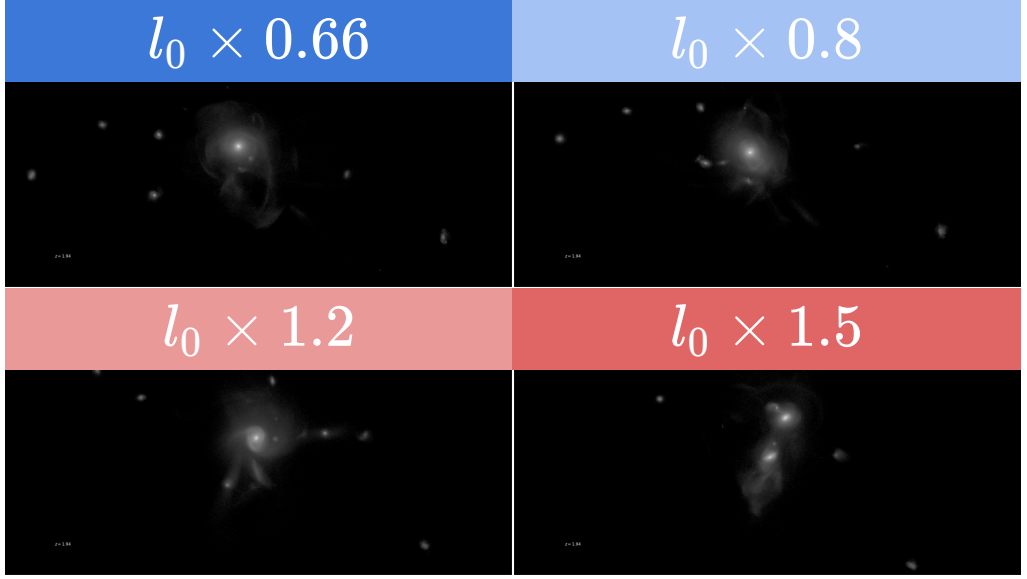
Baryon angular momentum

Simulations (9Mh @ DiRAC):

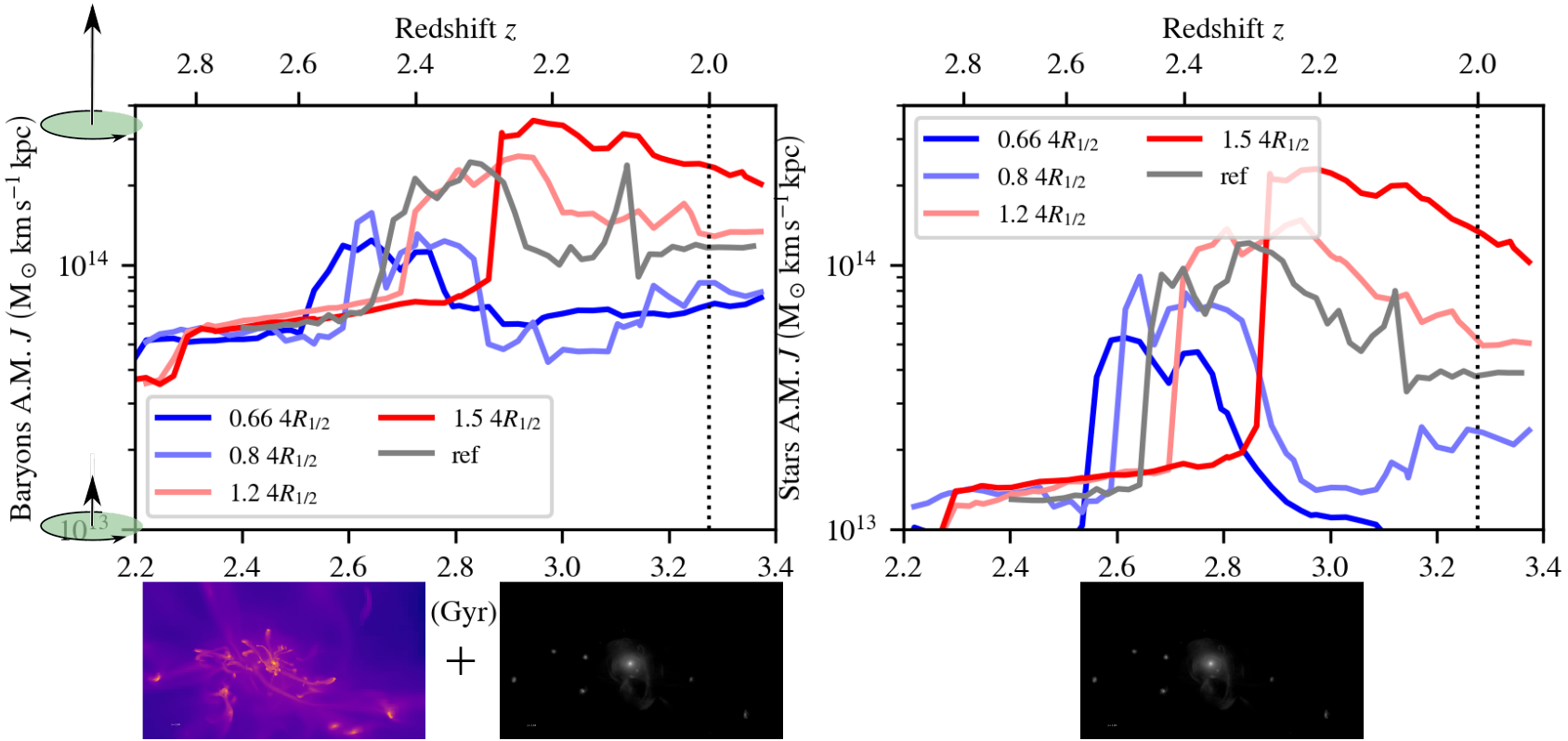
- Resolve disk height
  $\Delta x = 35$ kpc
- $z \geq 2$, $M_{200c} = 10^{12}$ $M_\odot$
- SF + AGN & SN feedback
- Modify $l(z = 2)$
- **Tracer particles**
  Cadiou+19

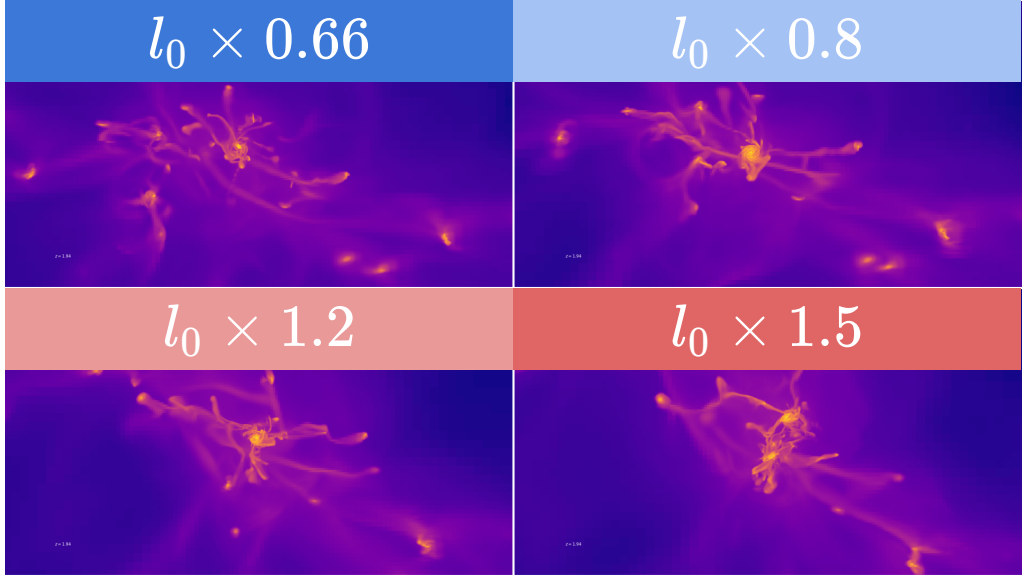


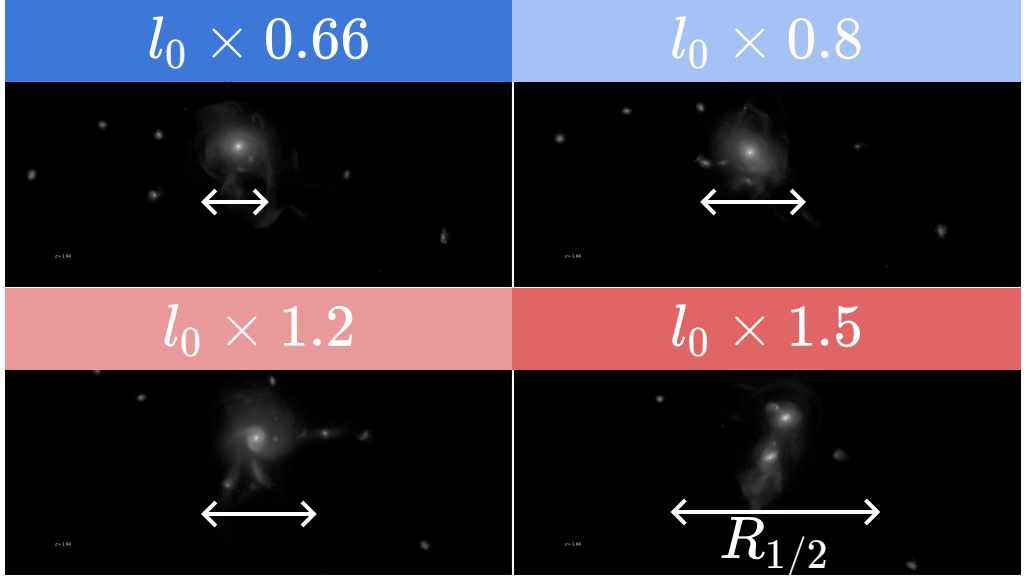


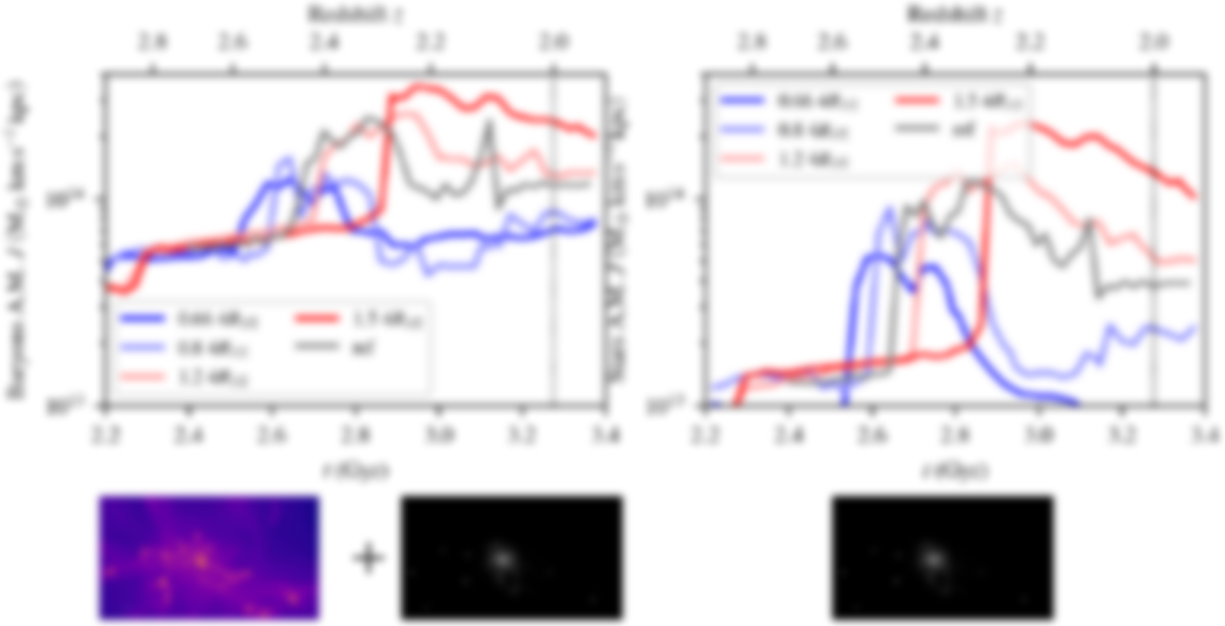


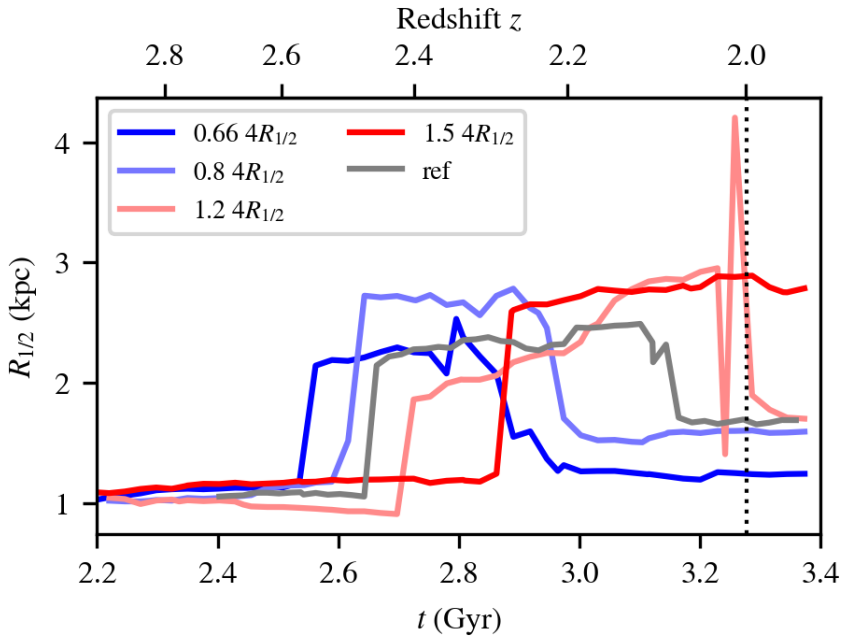
Angular momentum of the baryons / stars within $R_{\rm vir}$

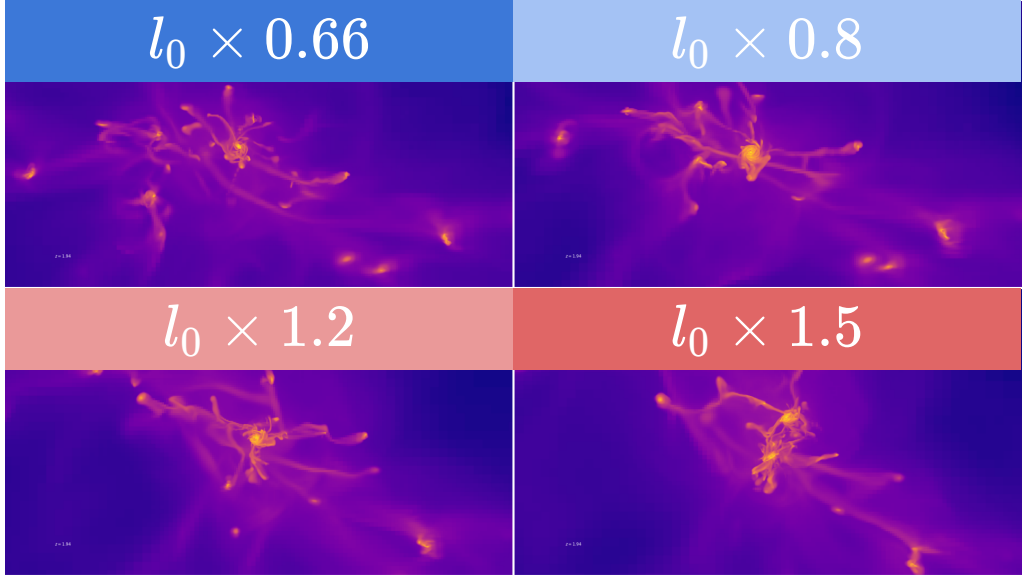


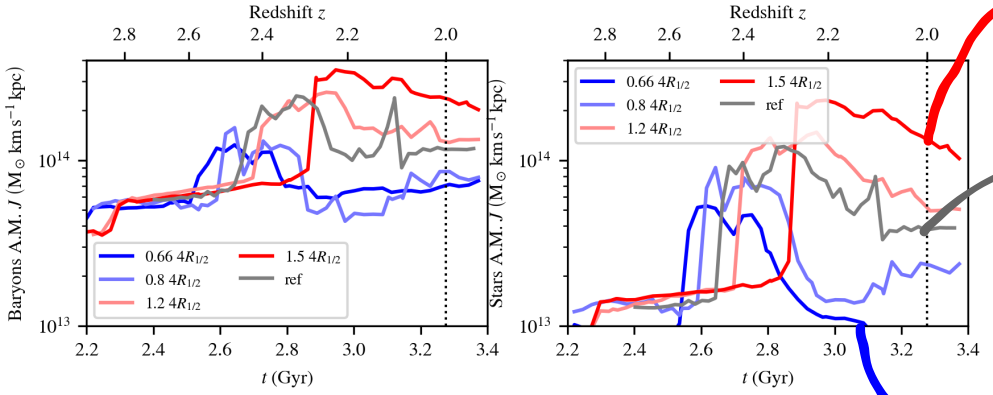

$l_0 \times 0.66$
$l_0 \times 0.8$
$l_0 \times 1.2$
$l_0 \times 1.5$


$l_0 \times 0.66$
$l_0 \times 0.8$
$l_0 \times 1.2$
$l_0 \times 1.5$
$R_{1/2}$

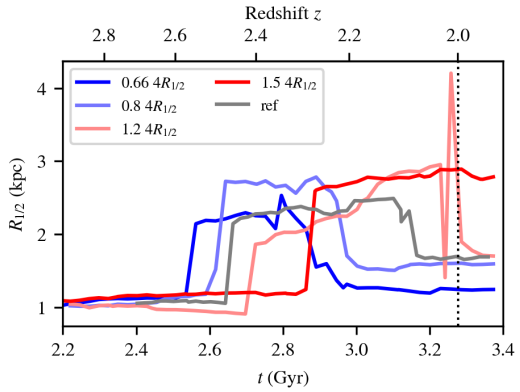


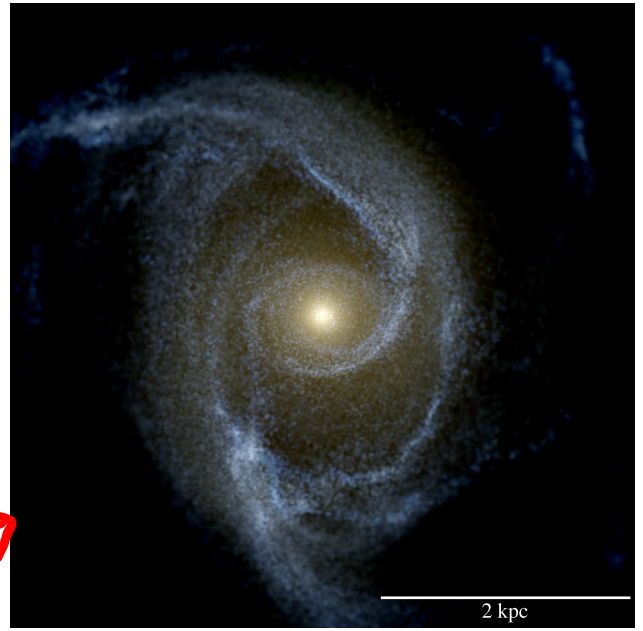

Redshift z
2.8
2.6
2.4
2.2
2.0
0.66 $4R_{1/2}$
0.8 $4R_{1/2}$
1.2 $4R_{1/2}$
1.5 $4R_{1/2}$
ref
$R_{1/2}$ (kpc)
1
2
3
4
2.2
2.4
2.6
2.8
3.0
3.2
3.4
t (Gyr)

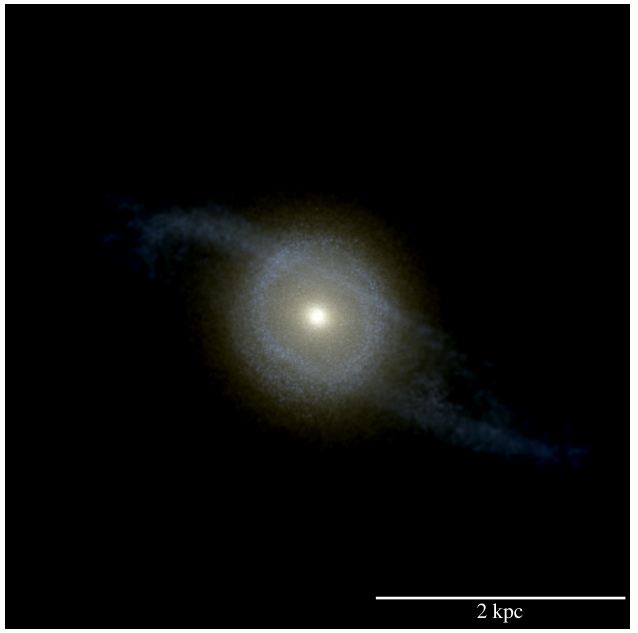

$l_0 \times 0.66$
$l_0 \times 0.8$
$l_0 \times 1.2$
$l_0 \times 1.5$

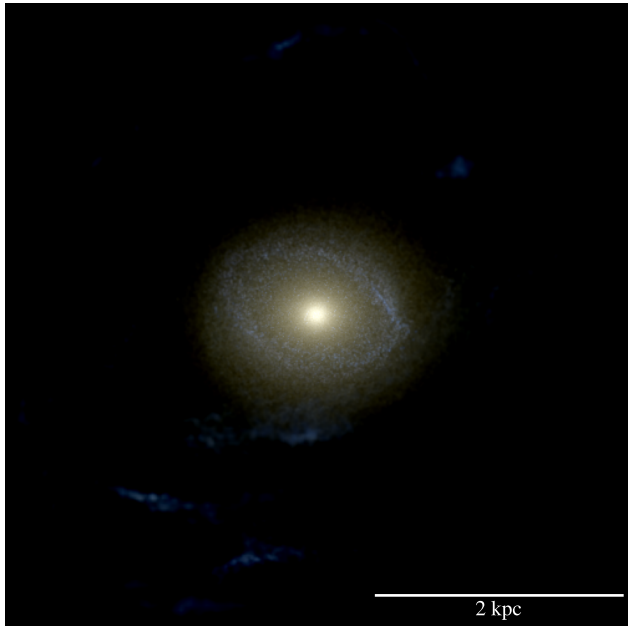

Redshift z
2.8 2.6 2.4 2.2 2.0
Baryons A.M. J ($M_\odot$ km s^{-1} kpc)
10^{14}
10^{13}
0.66 $4R_{1/2}$
0.8 $4R_{1/2}$
1.2 $4R_{1/2}$
1.5 $4R_{1/2}$
ref
2.2 2.4 2.6 2.8 3.0 3.2 3.4
t (Gyr)

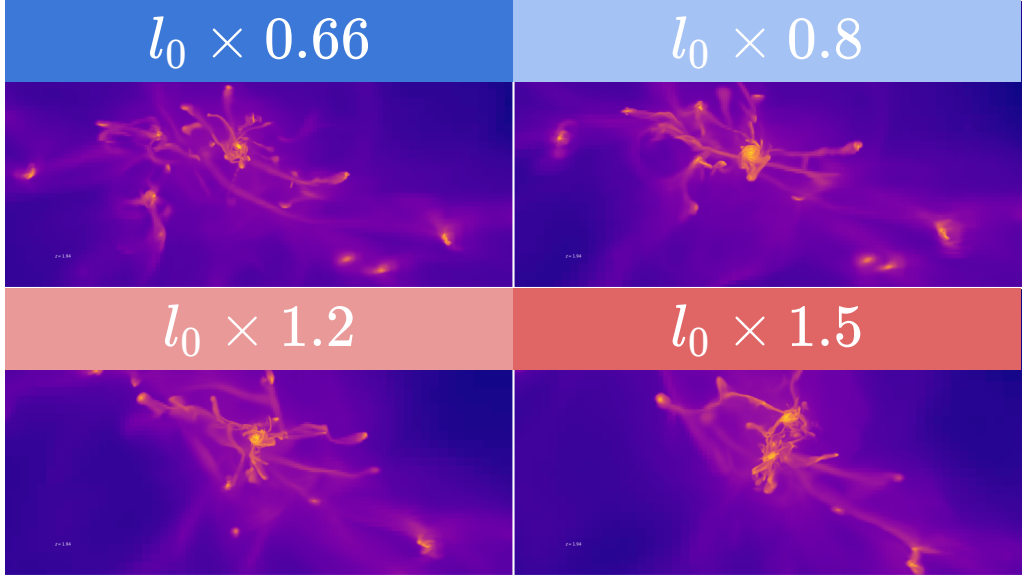
Redshift z
2.8 2.6 2.4 2.2 2.0
Stars A.M. J ($M_\odot$ km s^{-1} kpc)
10^{14}
10^{13}
0.66 $4R_{1/2}$
0.8 $4R_{1/2}$
1.2 $4R_{1/2}$
1.5 $4R_{1/2}$
ref
2.2 2.4 2.6 2.8 3.0 3.2 3.4
t (Gyr)

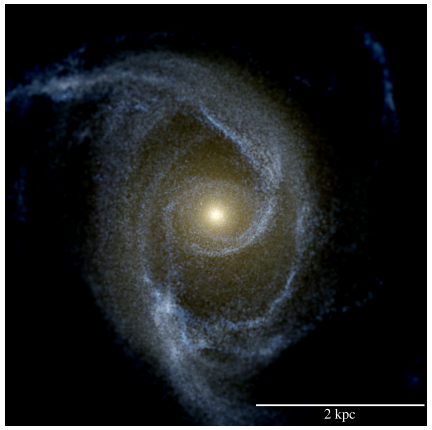

Redshift z
2.8 2.6 2.4 2.2 2.0
$R_{1/2}$ (kpc)
4
3
2
1
0.66 $4R_{1/2}$
0.8 $4R_{1/2}$
1.2 $4R_{1/2}$
1.5 $4R_{1/2}$
ref
2.2 2.4 2.6 2.8 3.0 3.2 3.4
t (Gyr)

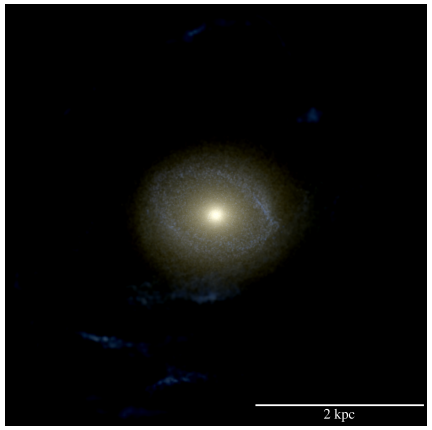

2 kpc

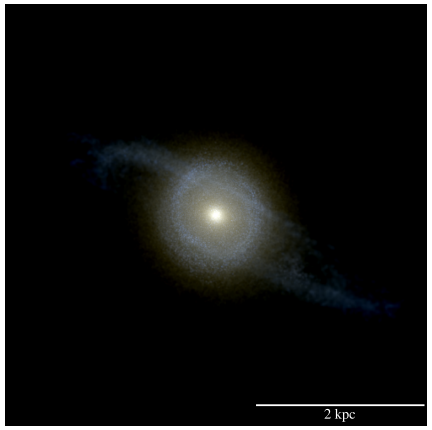

2 kpc


2 kpc

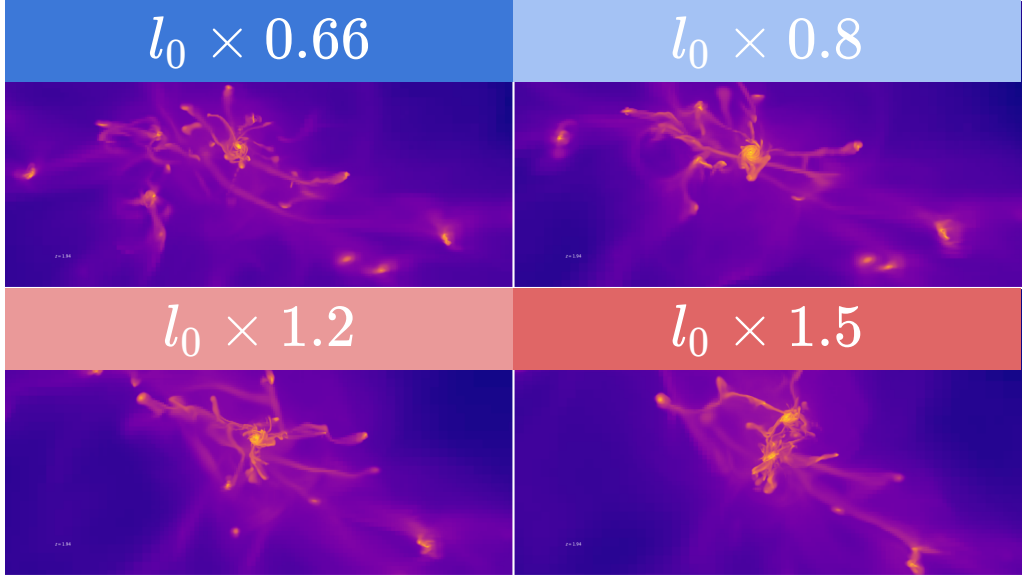


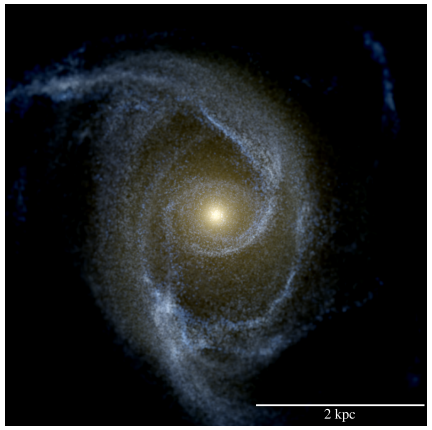


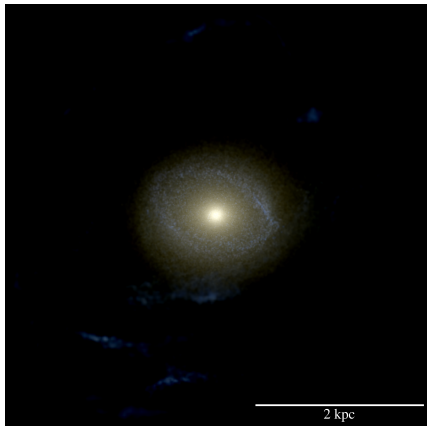


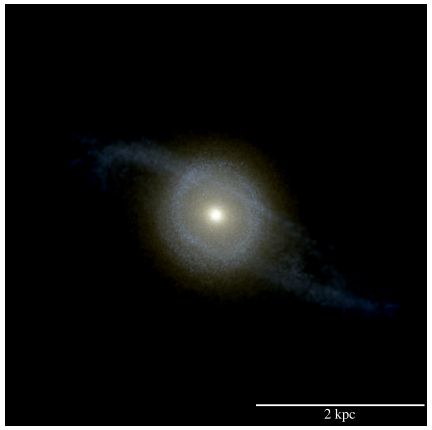


- AM of *baryons* originates from initial conditions…

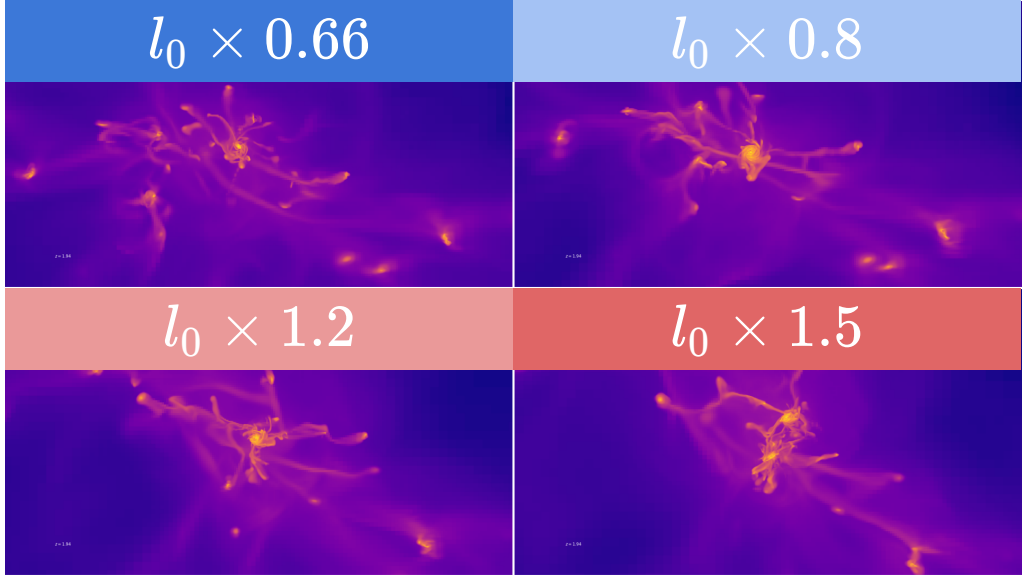


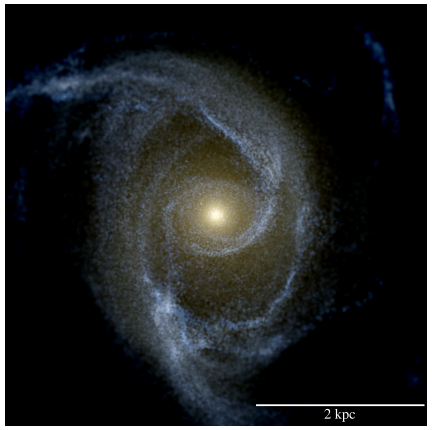


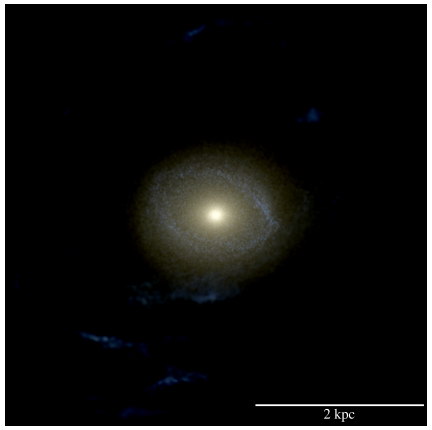


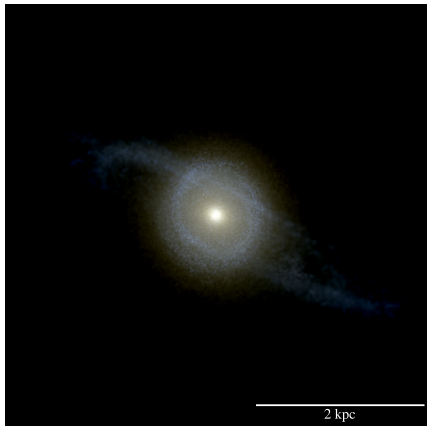


- AM of *baryons* originates from initial conditions…
- can be controlled…

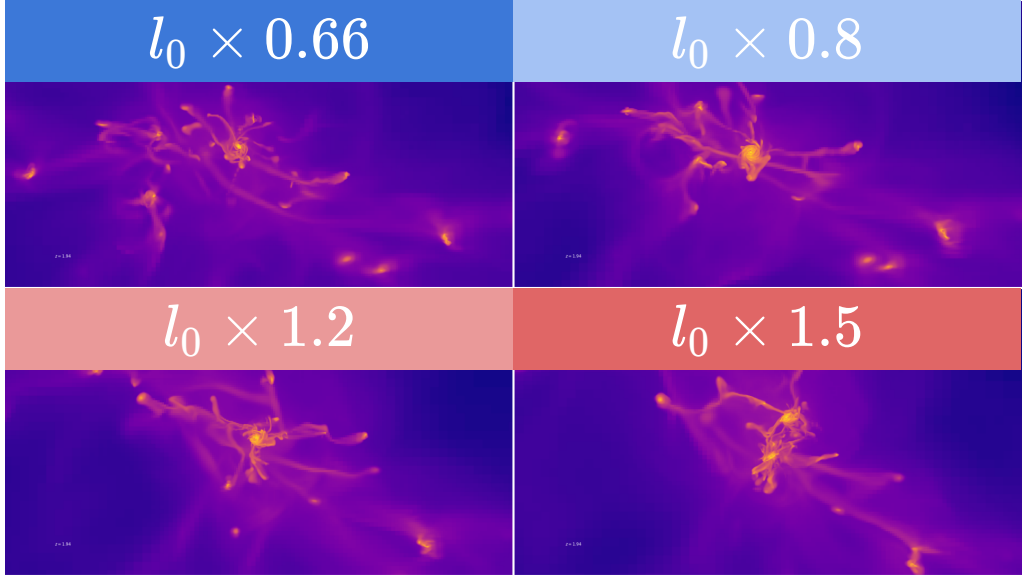


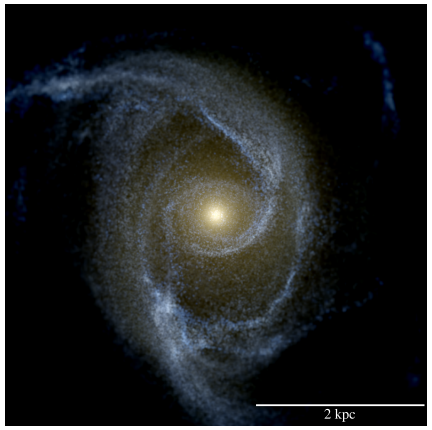


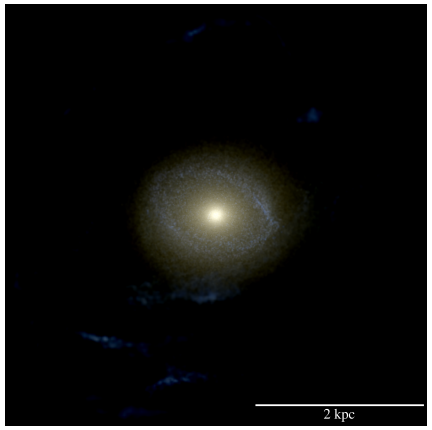


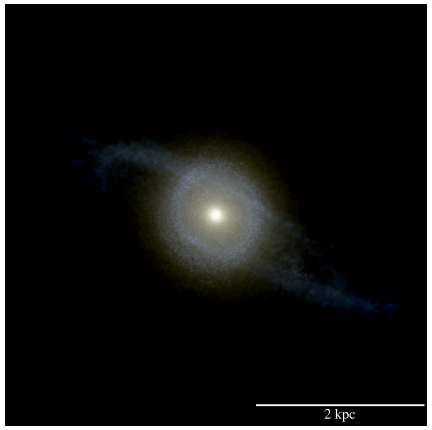


- AM of *baryons* originates from initial conditions…
- can be controlled…
- and regulate galaxy morphology





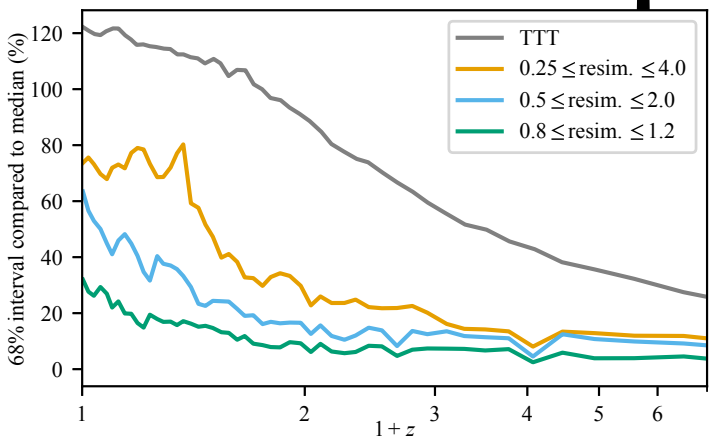




- AM of *baryons* originates from initial conditions…
- can be controlled…
- and regulate galaxy morphology
- *Negligible* AGN/SN global self-regulation

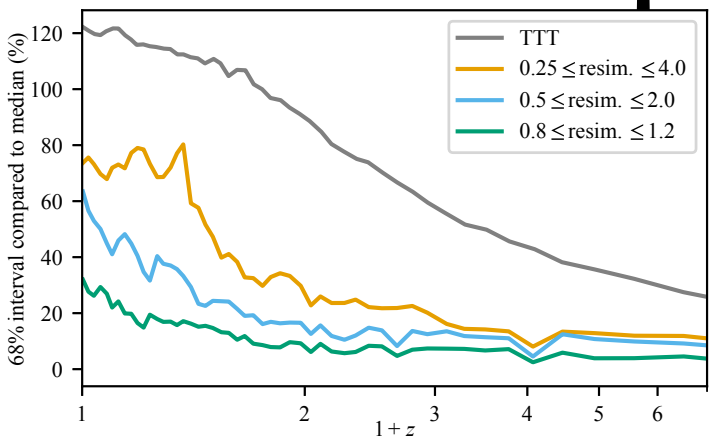
Temporary conclusions

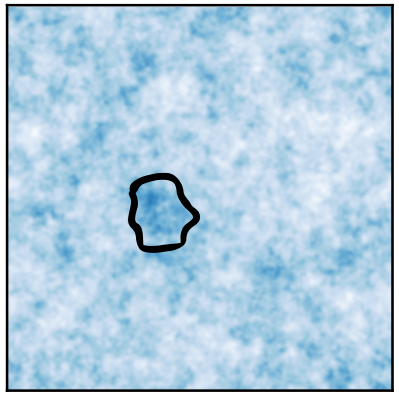
Temporary conclusions



- angular momentum is predictable

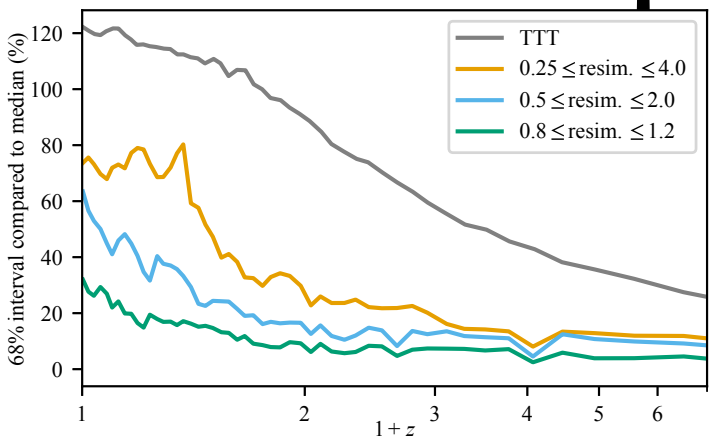
Temporary conclusions

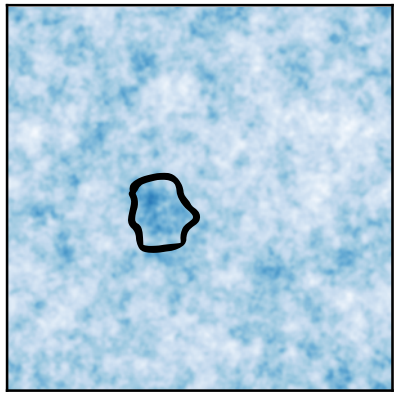


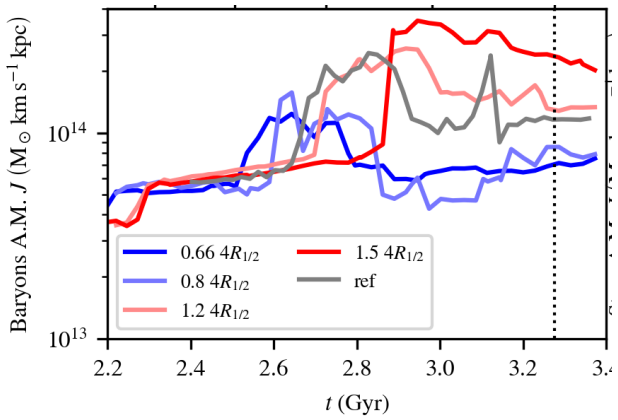


- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)

Temporary conclusions

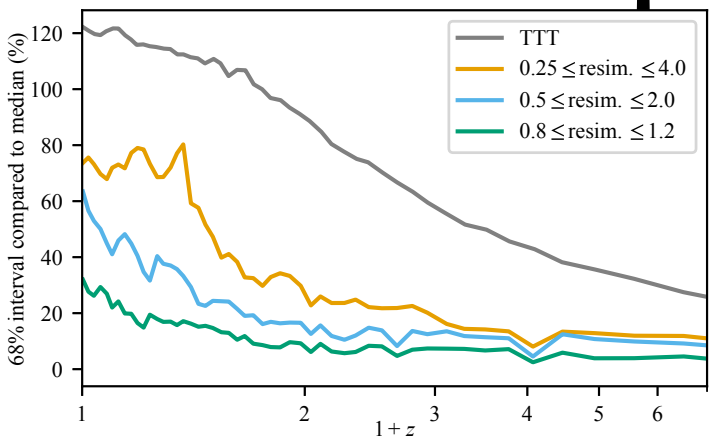


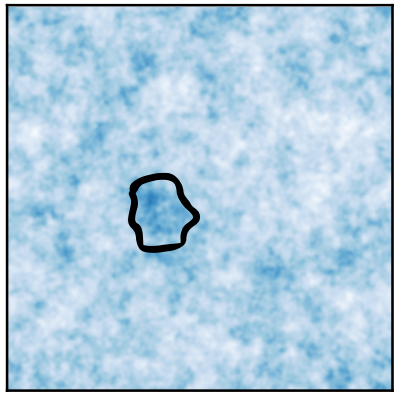


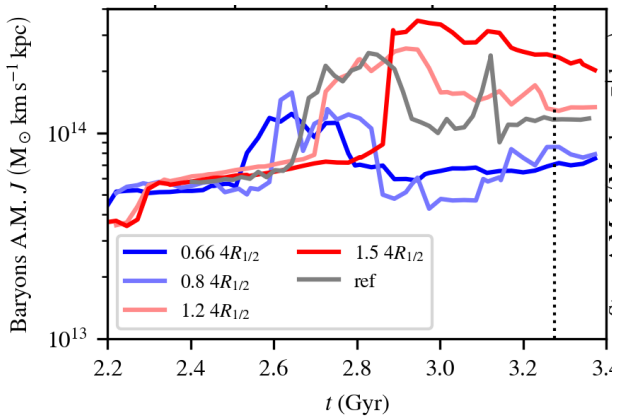


- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* appear to be simpler!
  ⇒ good news for weak lensing predictions
  ⇒ key to understand morphology

Temporary conclusions



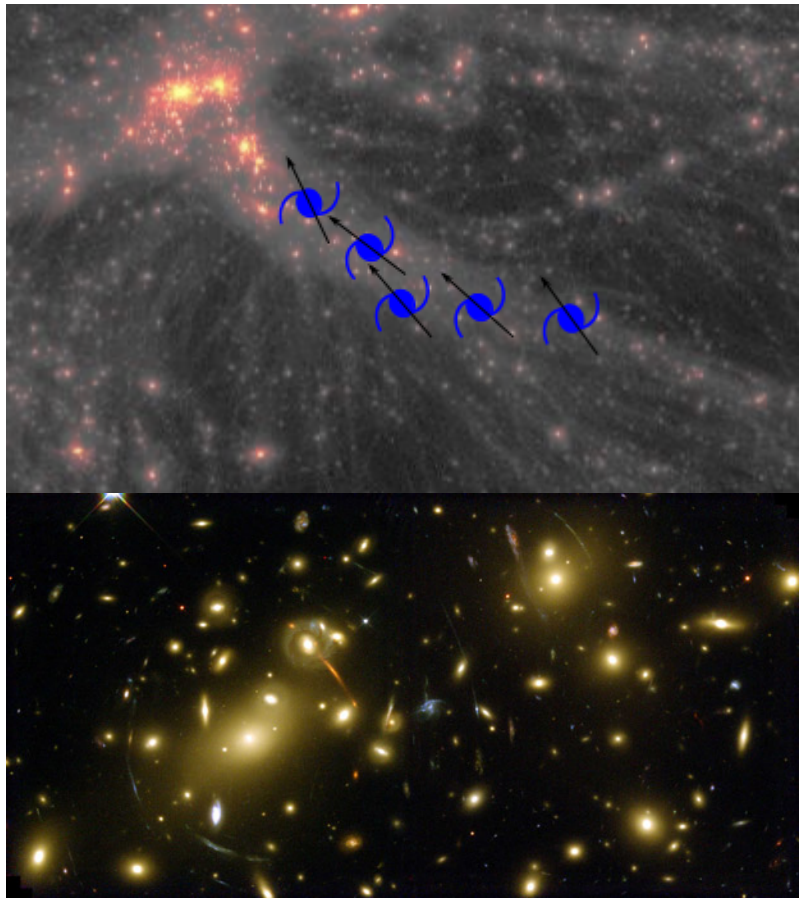




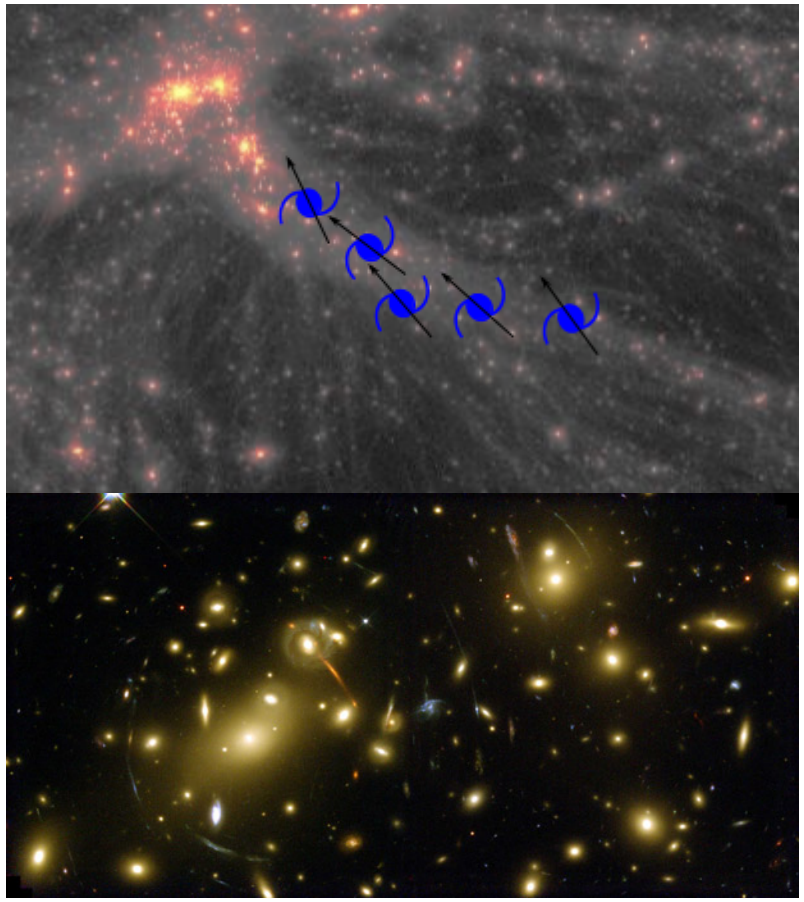
- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* appear to be simpler!
  ⇒ good news for weak lensing predictions
  ⇒ key to understand morphology
- but why do some objects grow their AM faster/slower?

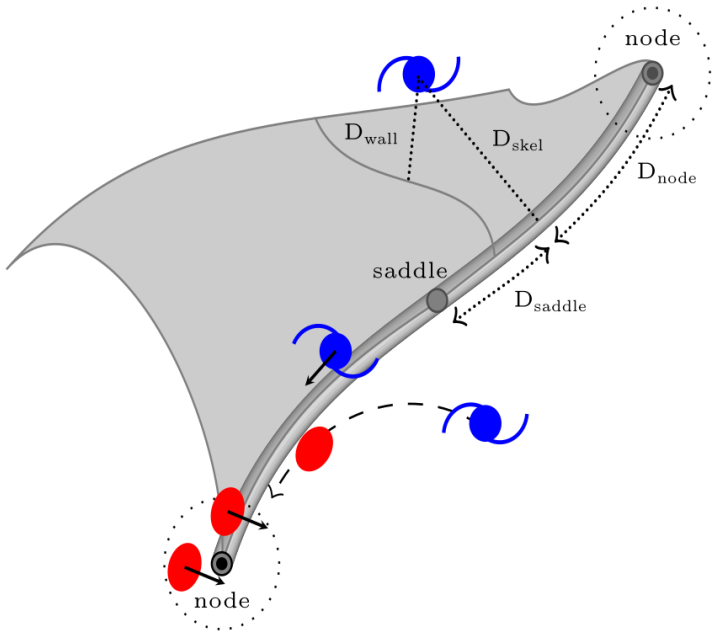
The effect of environment on halo properties

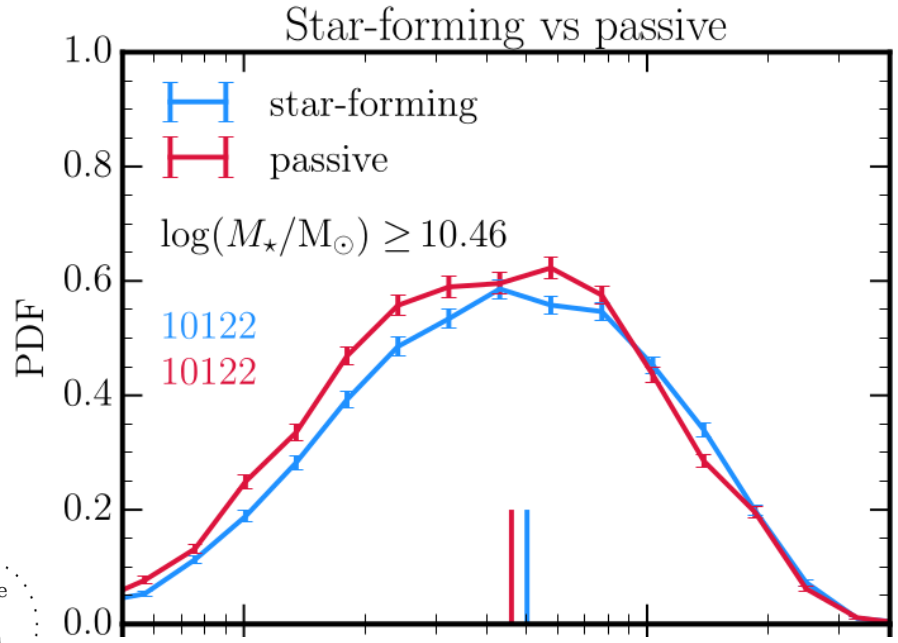
The effect of environment on halo properties



The effect of environment on halo properties

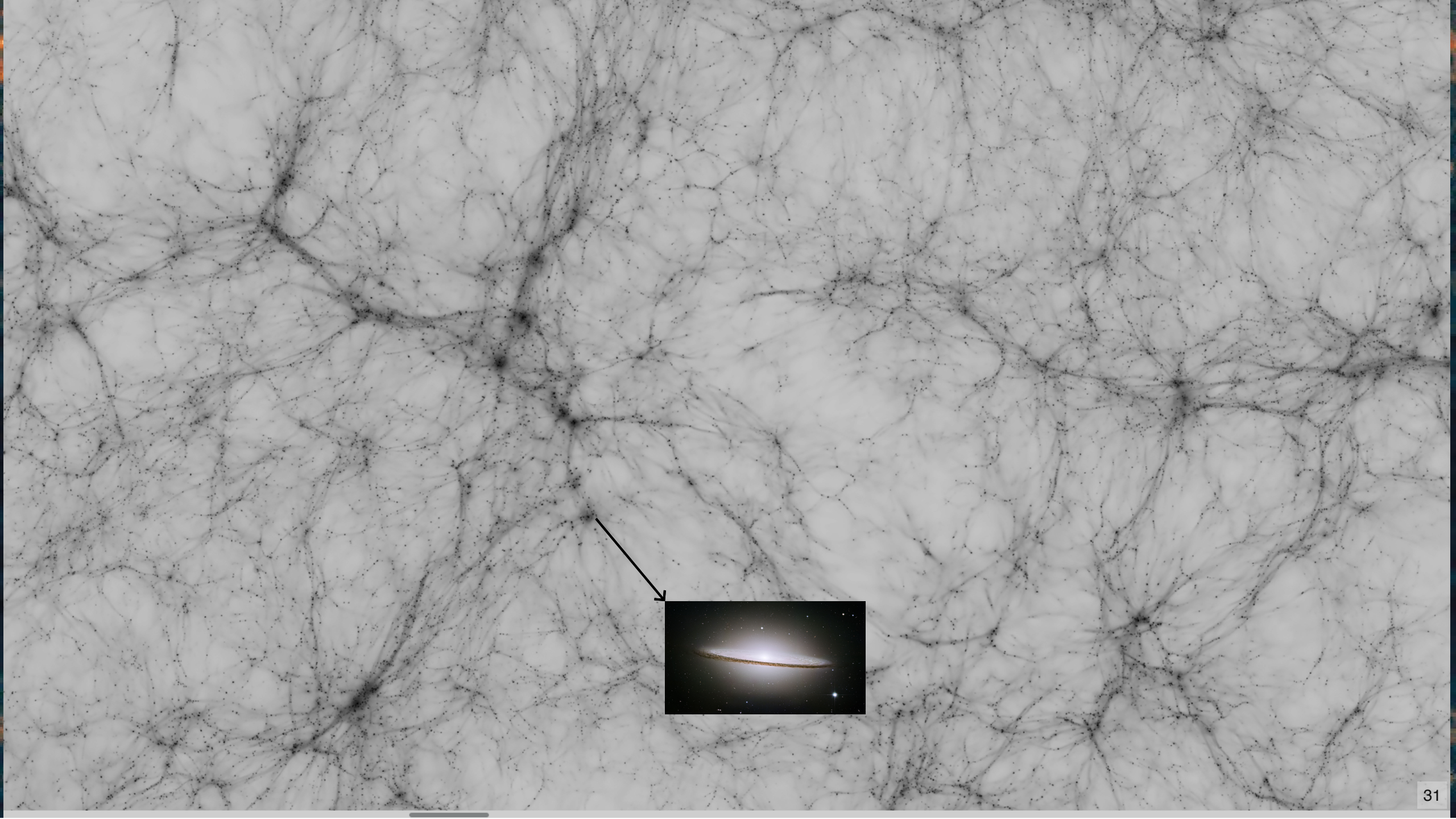






Distance to filament

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

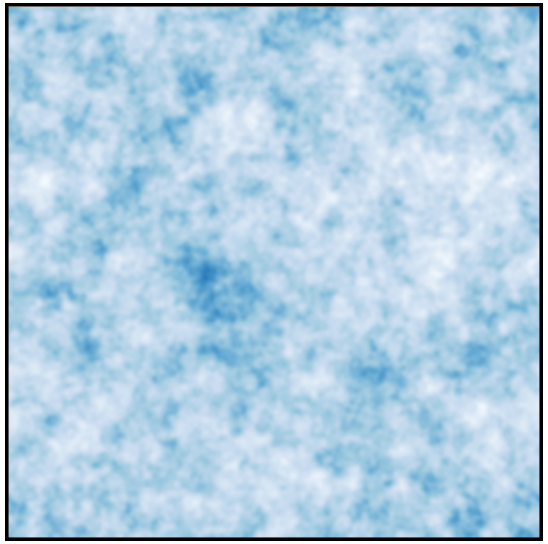


What if the galaxy had formed here instead?

What if the galaxy had formed here instead?

or here?

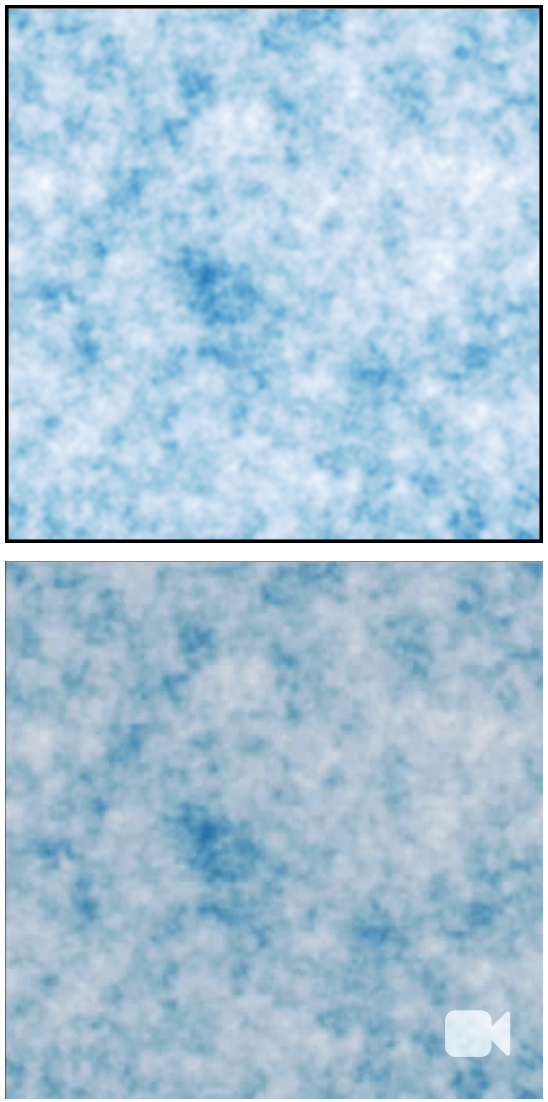
The “splicing” technique



1. Generate ICs

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

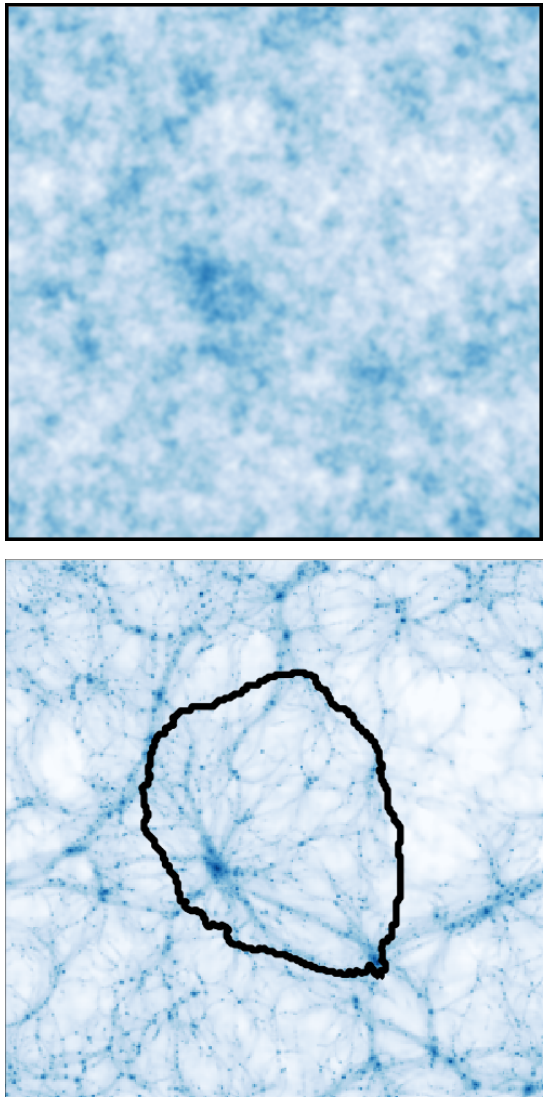
The “splicing” technique



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

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

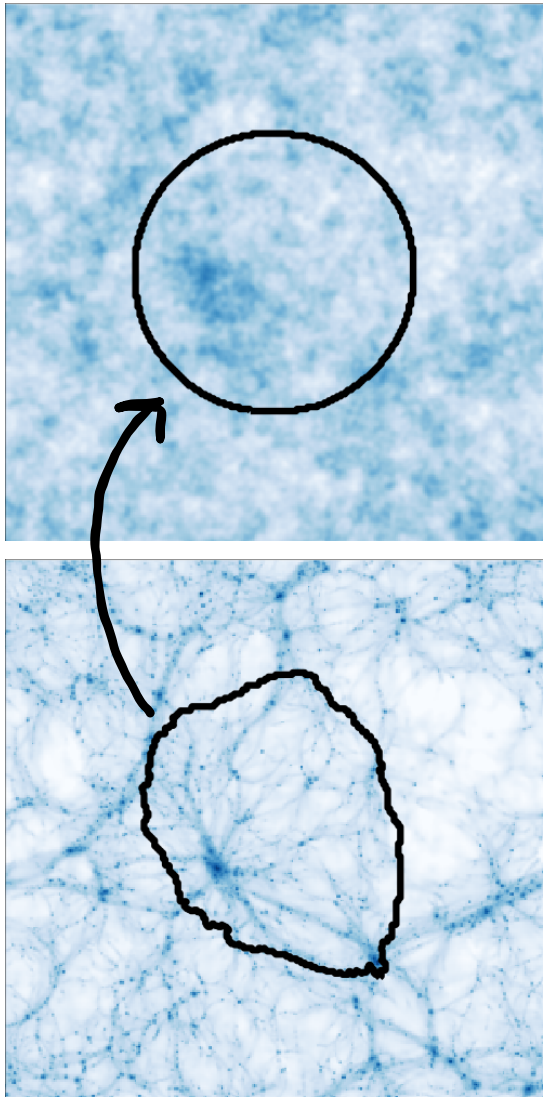
The “splicing” technique



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

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

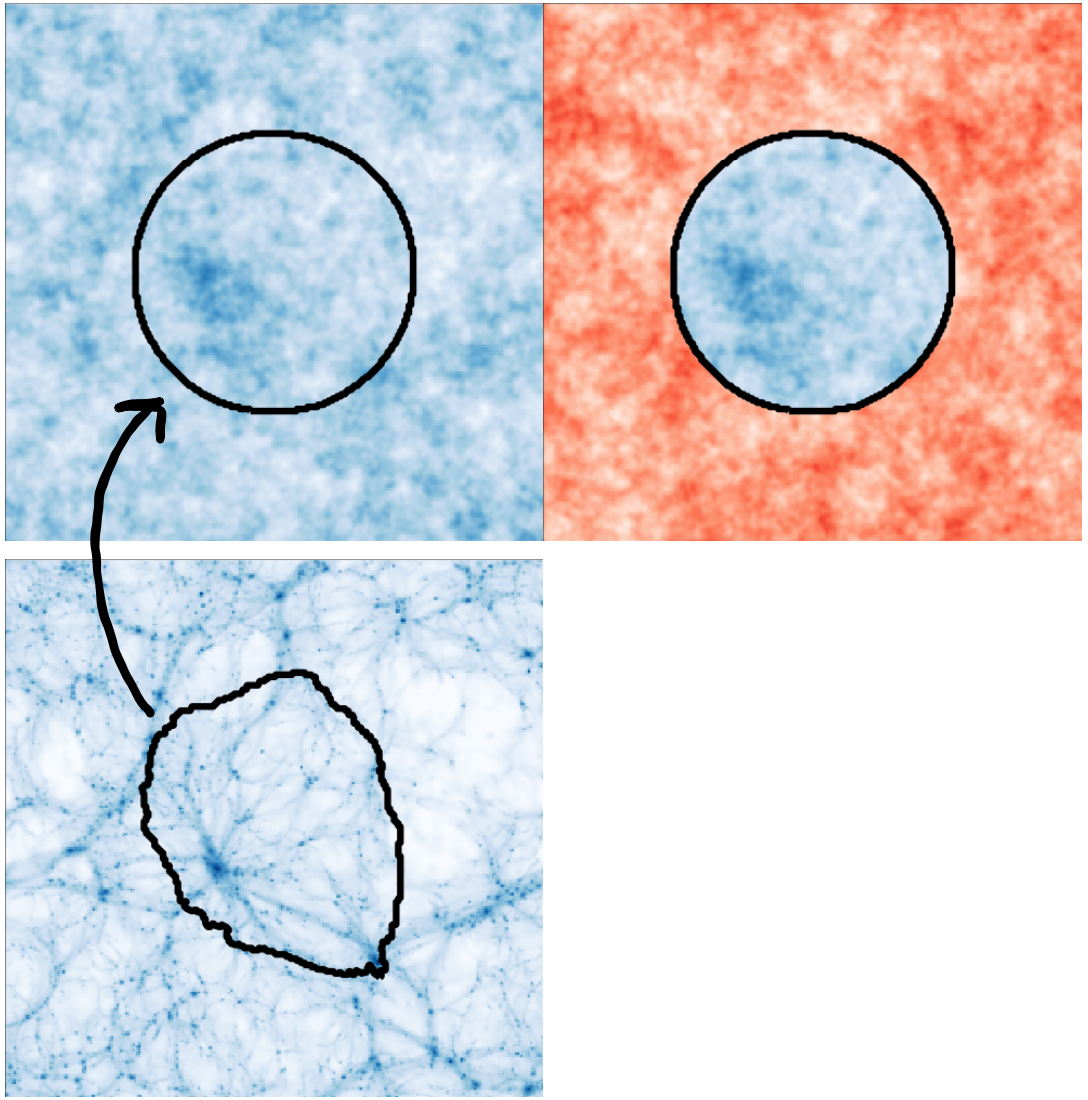
The “splicing” technique



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

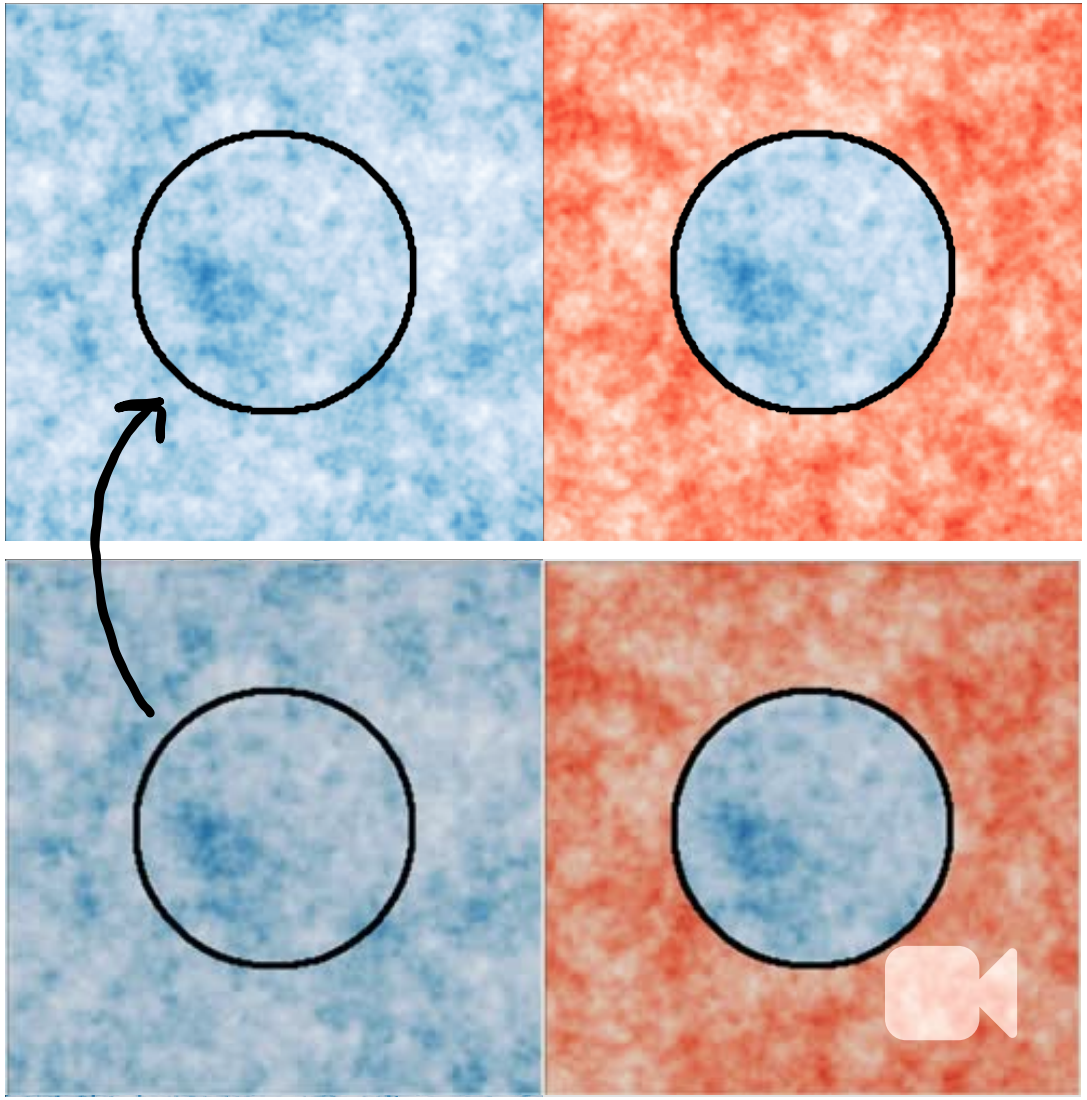
The “splicing” technique



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

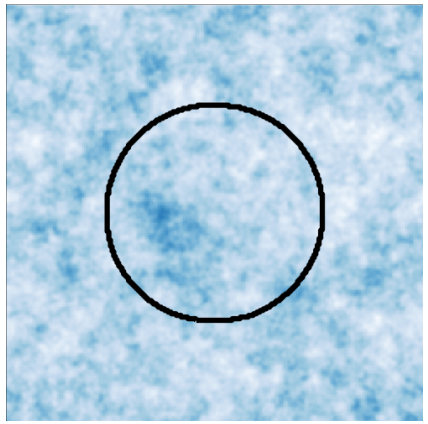
The “splicing” technique



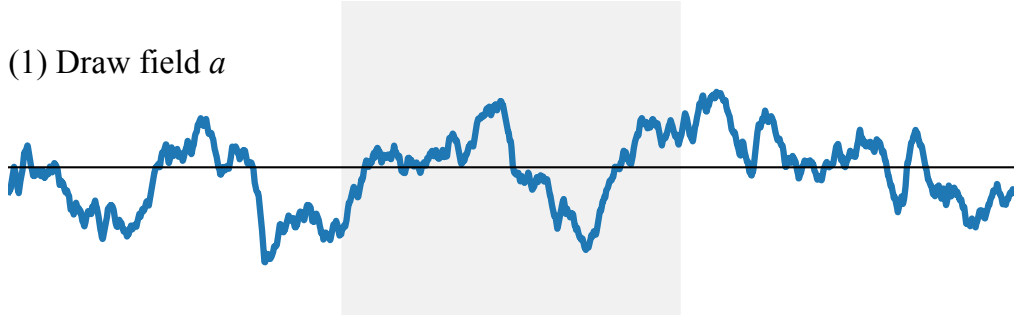
1. Generate ICs
2. Integrate (N-nody)
3. Select region of interest
4. Trace back to ICs
5. “Splice”
6. Integrate again

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

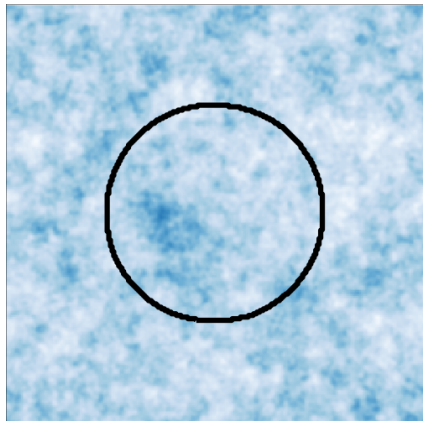
Splicing in 1D

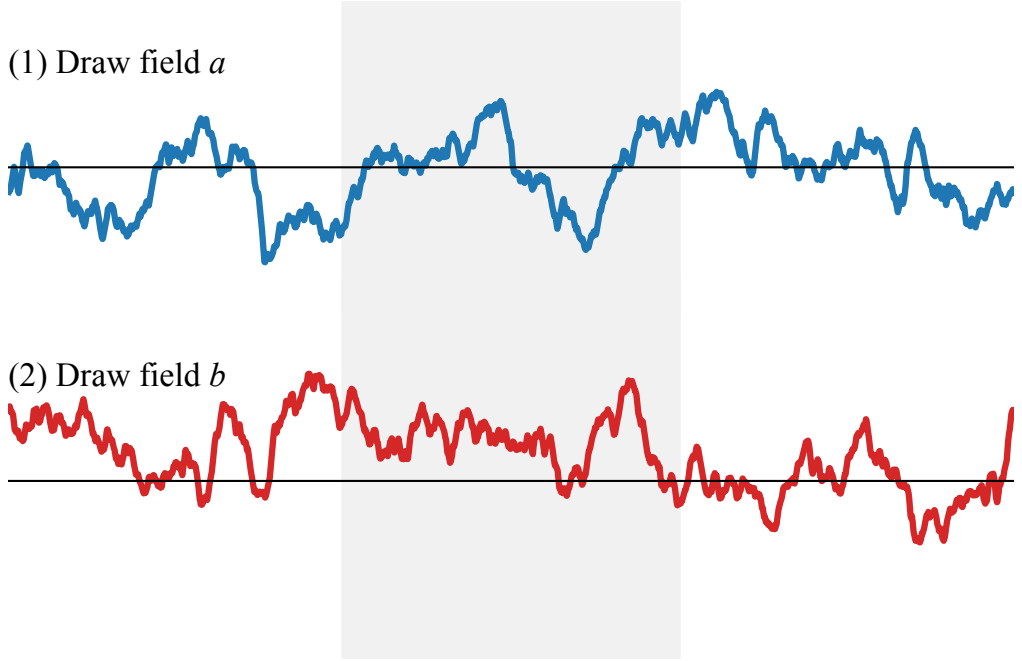


(1) Draw field *a*

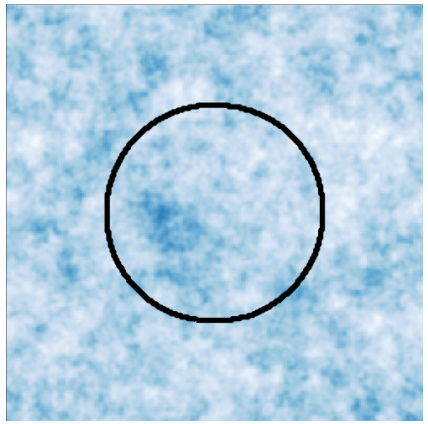


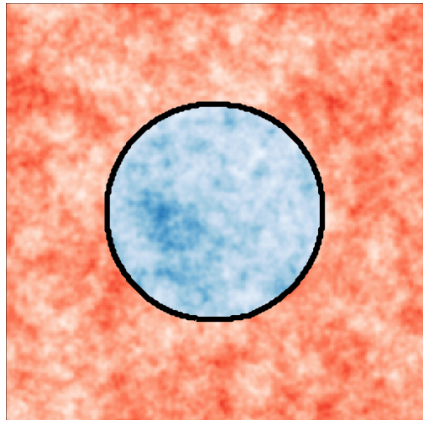
Splicing in 1D

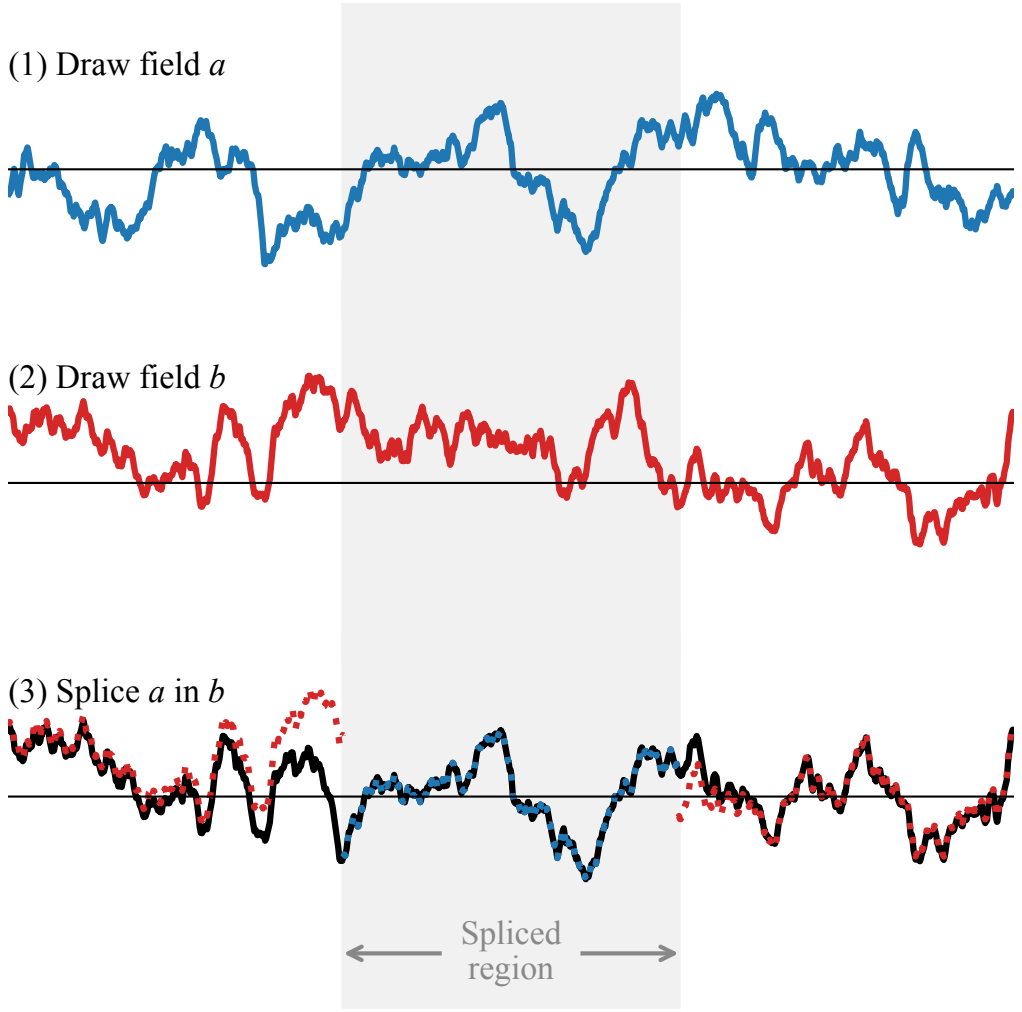




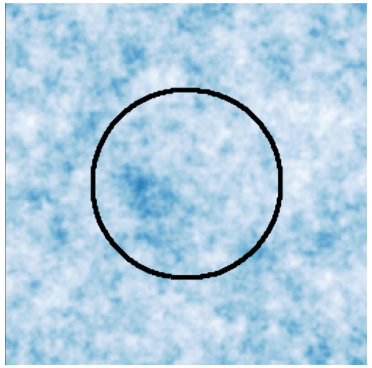
Splicing in 1D

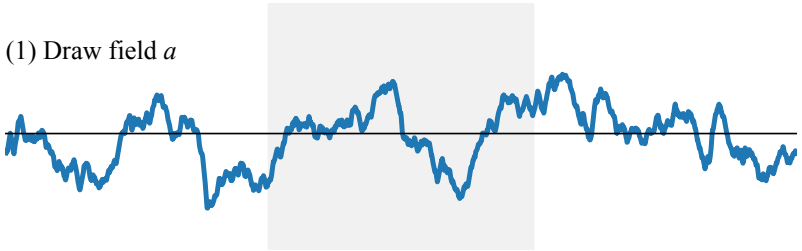






Splicing in 1D





Most likely* field f with

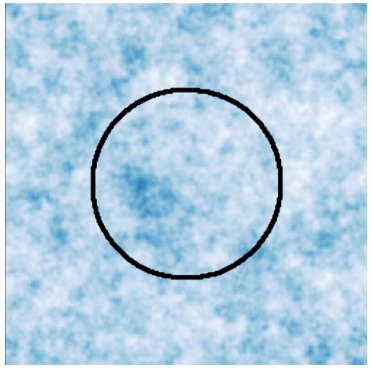
- **same** value in spliced region (a),
- as close as possible outside (b)

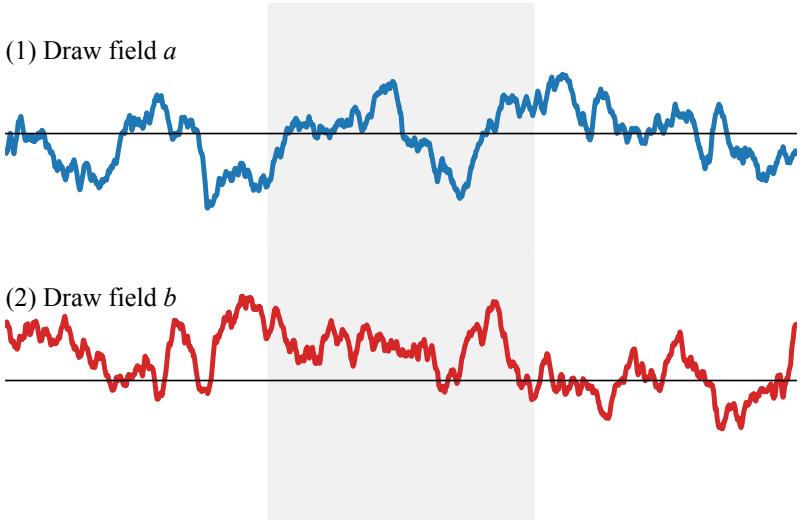
Mathematically f is solution of:

$f = a$ in Γ

minimizes $\mathcal{Q} = (b - f)^\dagger \mathbf{C}^{-1}(b - f)$ outside Γ

Splicing in 1D





Most likely* field f with

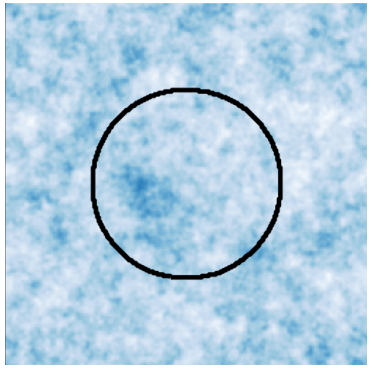
- **same** value in spliced region (a),
- as close as possible outside (b)

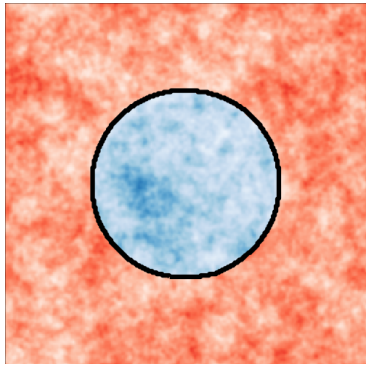
Mathematically f is solution of:

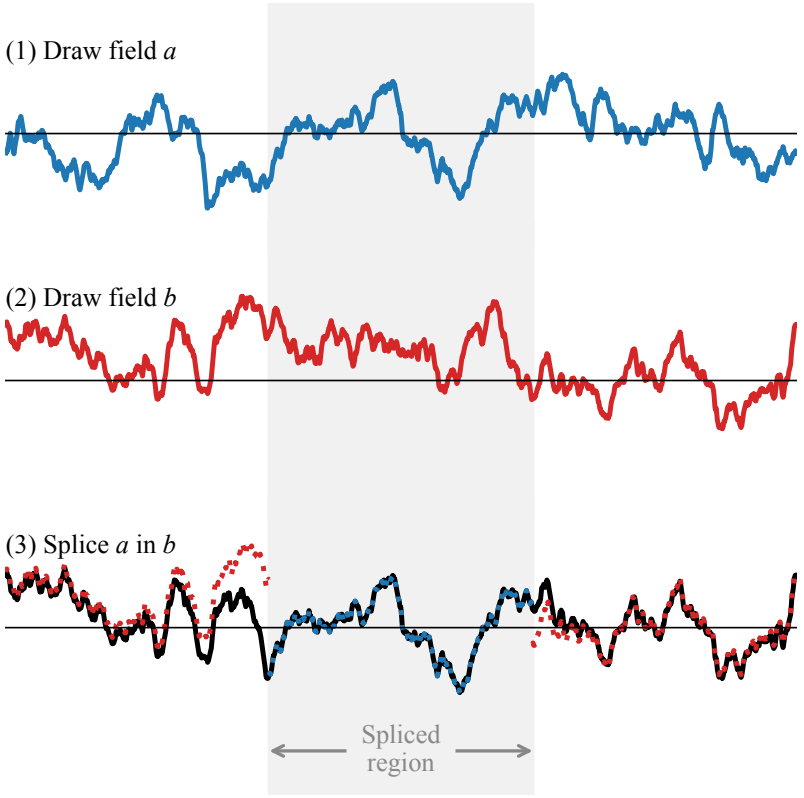
$f = a$ in Γ

minimizes $\mathcal{Q} = (b - f)^\dagger \mathbf{C}^{-1}(b - f)$ outside Γ

Splicing in 1D







Most likely* field f with

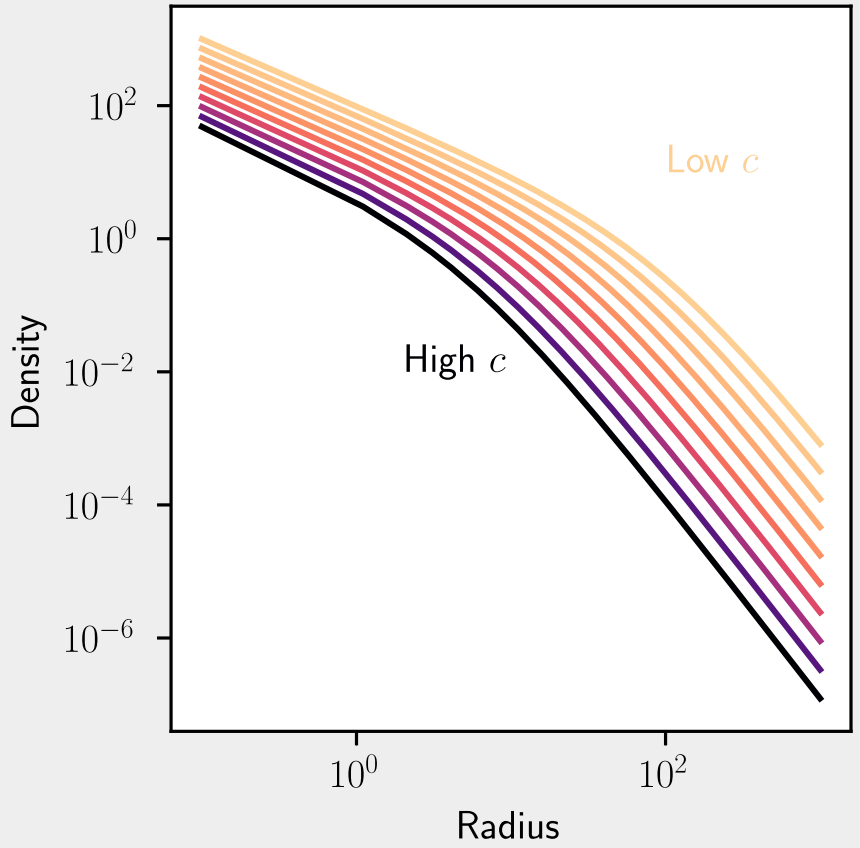
- **same** value in spliced region (a),
- as close as possible outside (b)

Mathematically f is solution of:

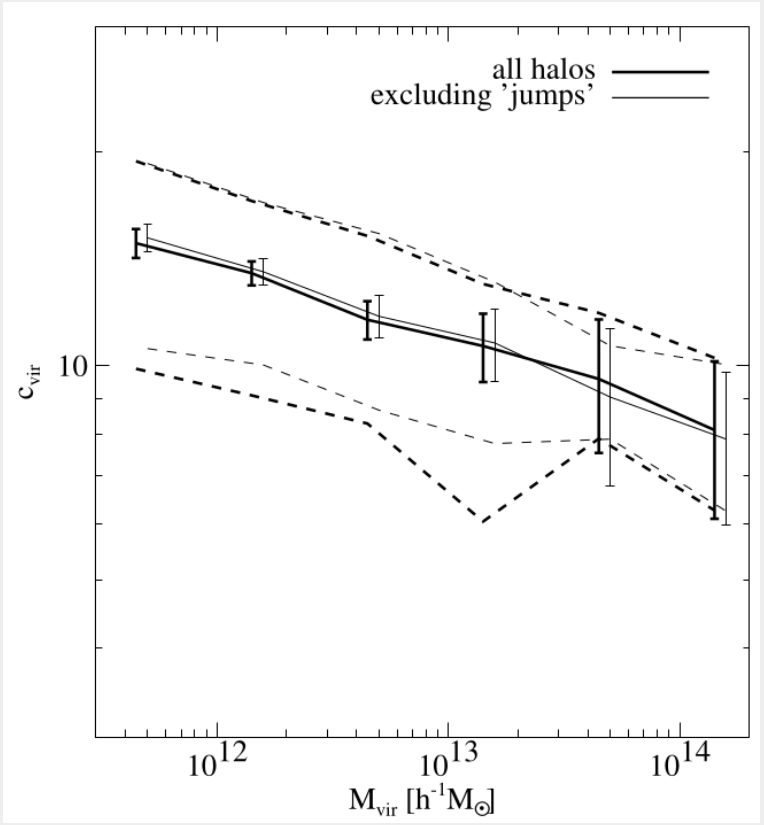
$f = a$ in Γ

minimizes $\mathcal{Q} = (b - f)^\dagger \mathbf{C}^{-1} (b - f)$ outside Γ

The causal origin of DM halo concentration

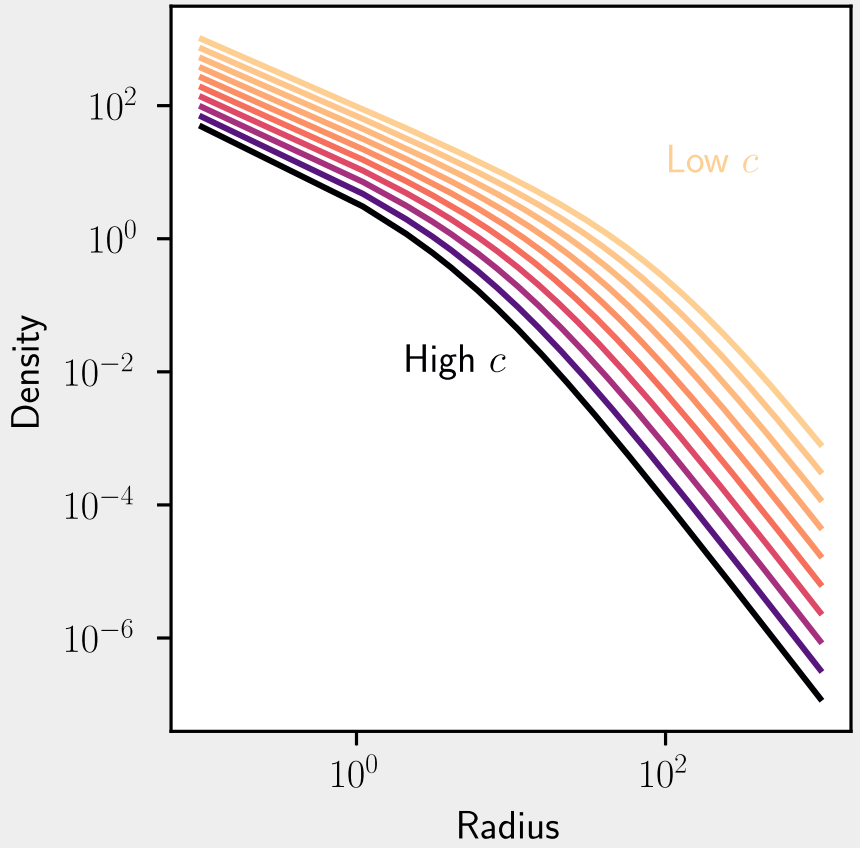


$$\rho_{\rm DM}(r) = \frac{\rho_0}{\frac{r}{R_{\rm vir}/c}\left(1+\frac{r}{R_{\rm vir}/c}\right)^2}$$

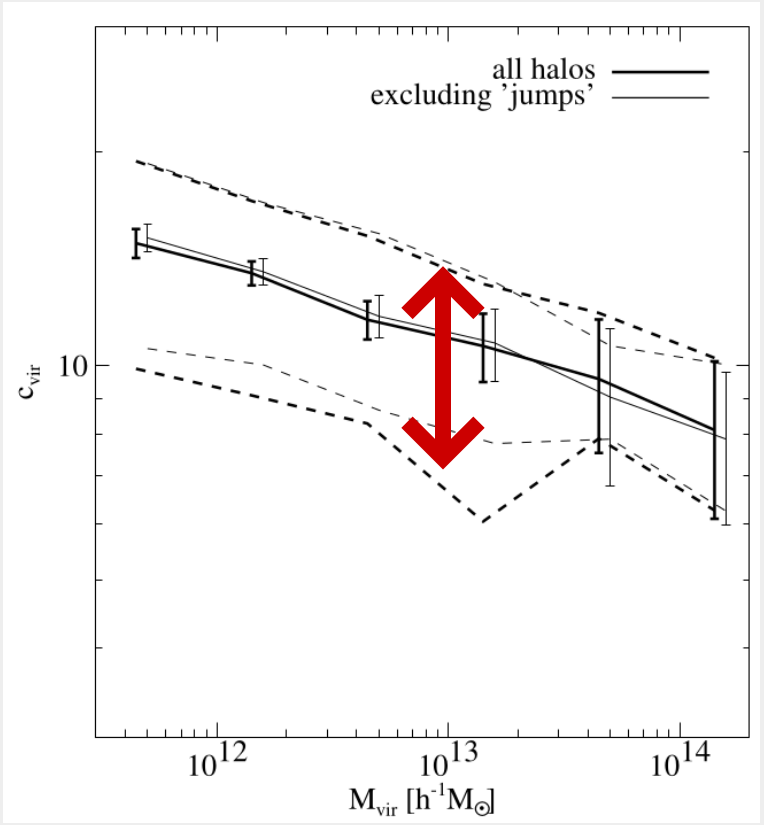


Wechsler+02

The causal origin of DM halo concentration



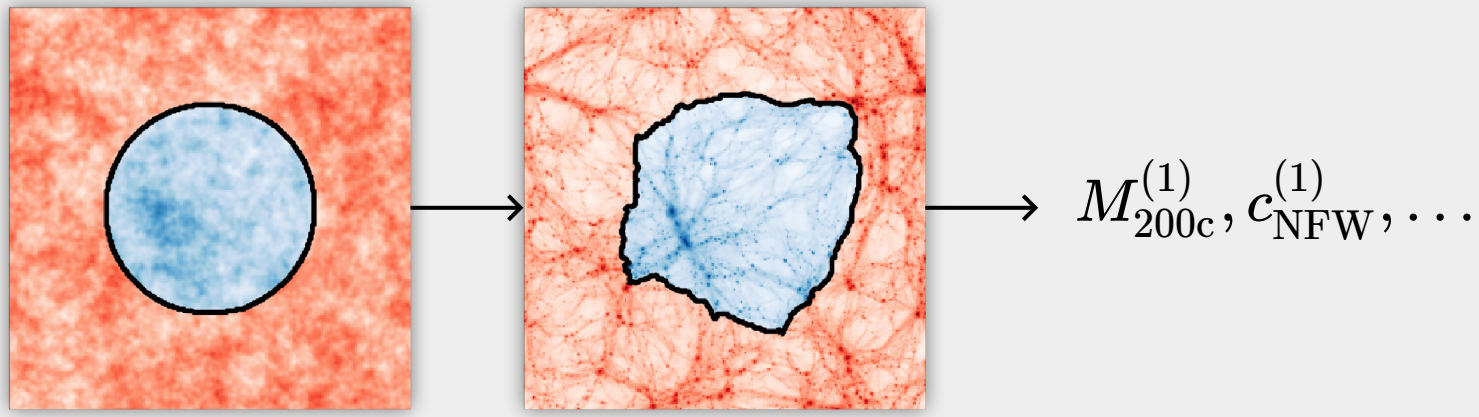
$$\rho_{\rm DM}(r) = \frac{\rho_0}{\frac{r}{R_{\rm vir}/c}\left(1+\frac{r}{R_{\rm vir}/c}\right)^2}$$



Wechsler+02

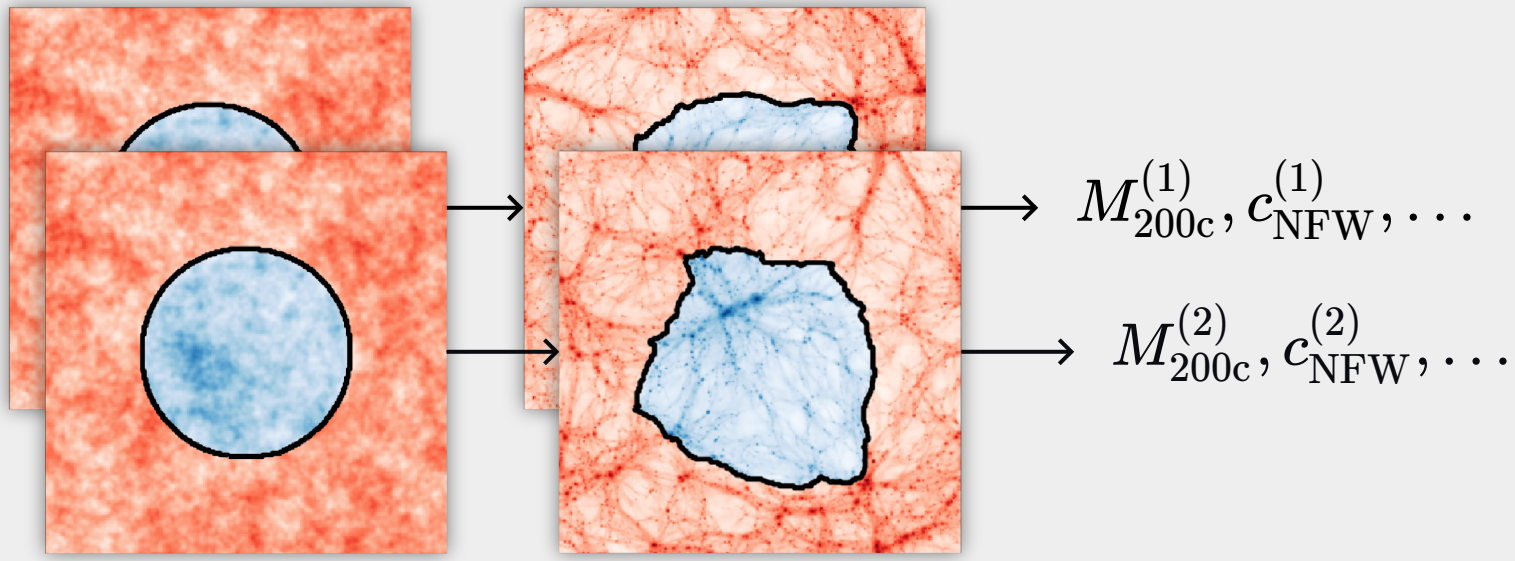
Origin of scatter at fixed $M_{\rm vir}$?

The causal origin of DM halo concentration

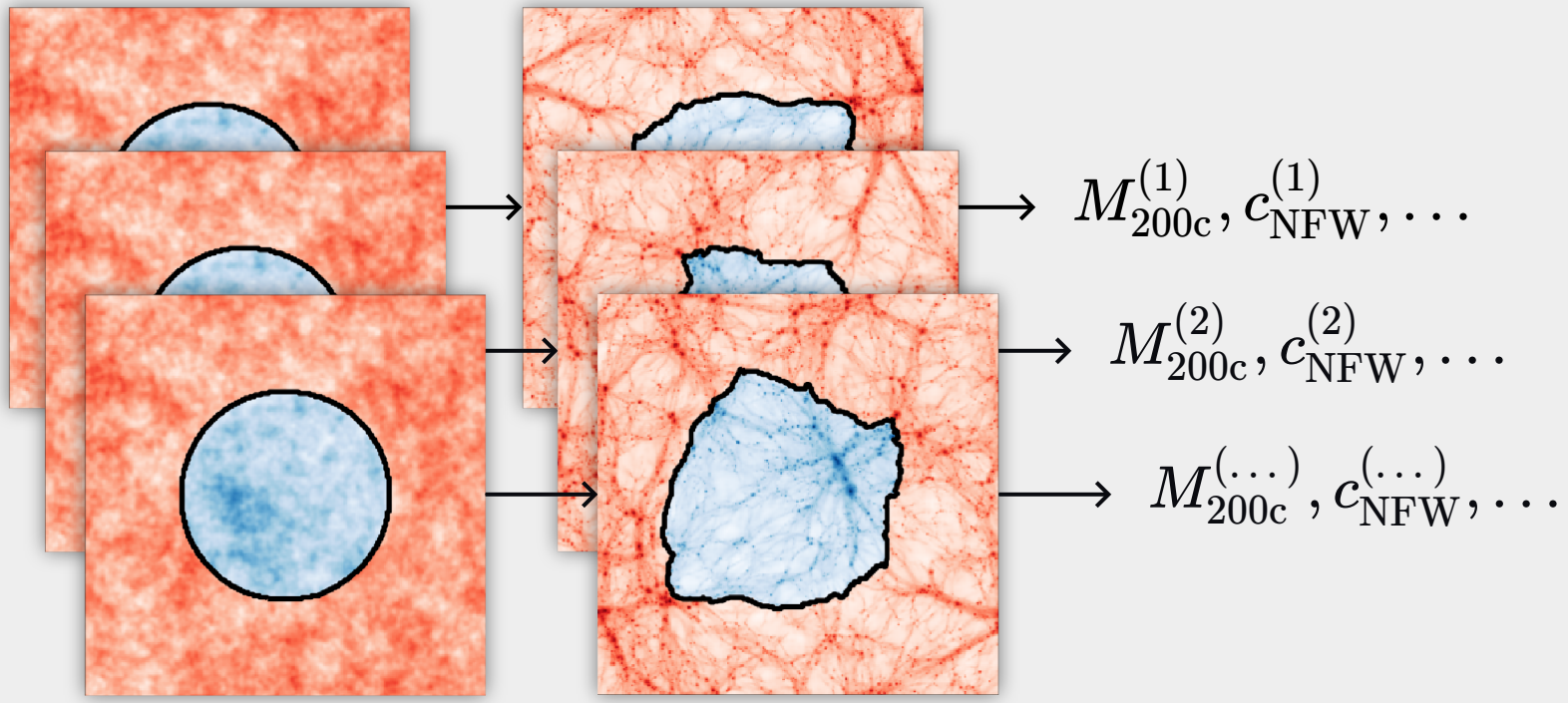


$$M_{200\mathrm{c}}^{(1)}, c_{\mathrm{NFW}}^{(1)}, \ldots$$

The causal origin of DM halo concentration



The causal origin of DM halo concentration

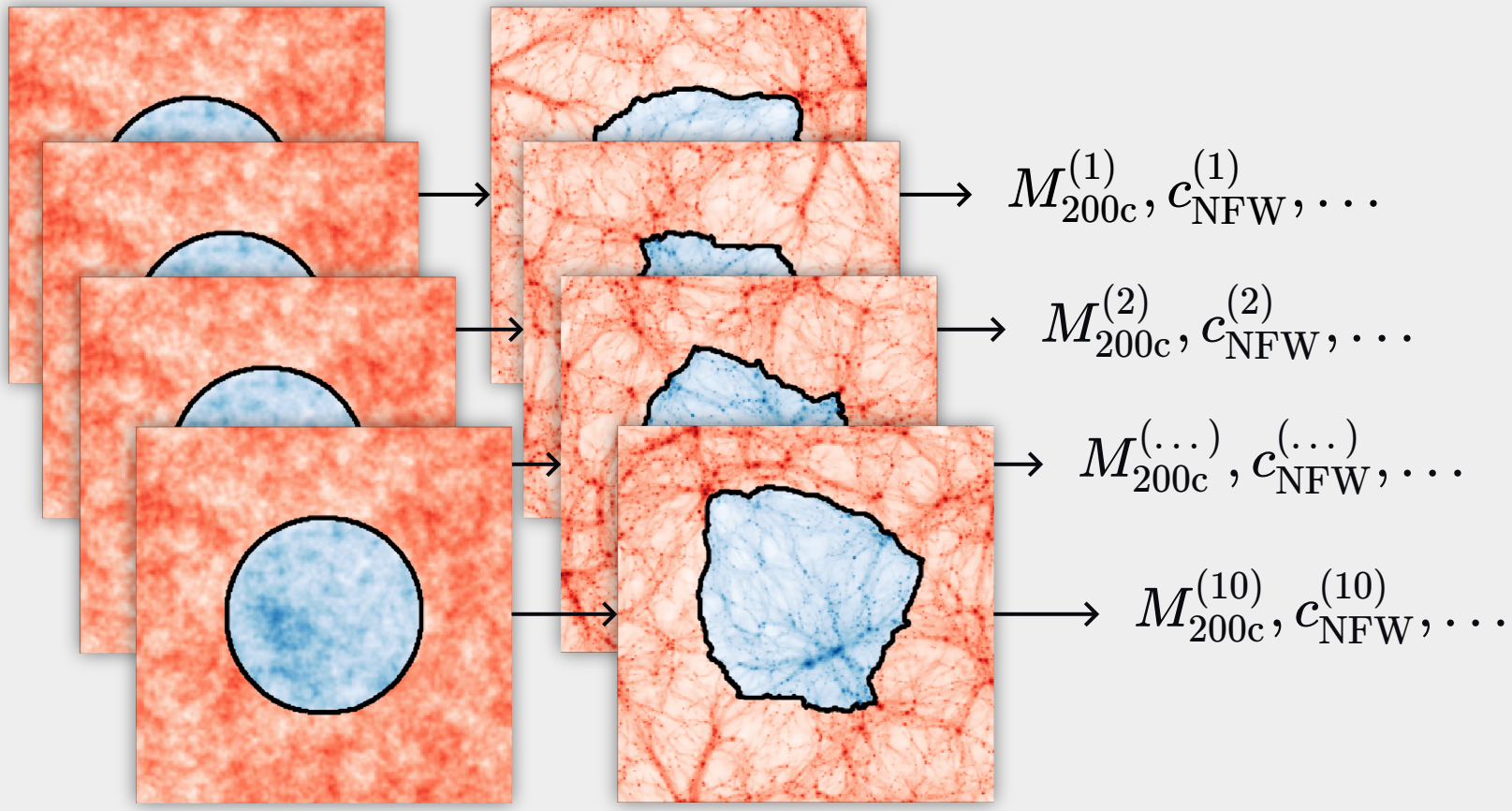


$$M_{200c}^{(1)}, c_{NFW}^{(1)}, \ldots$$

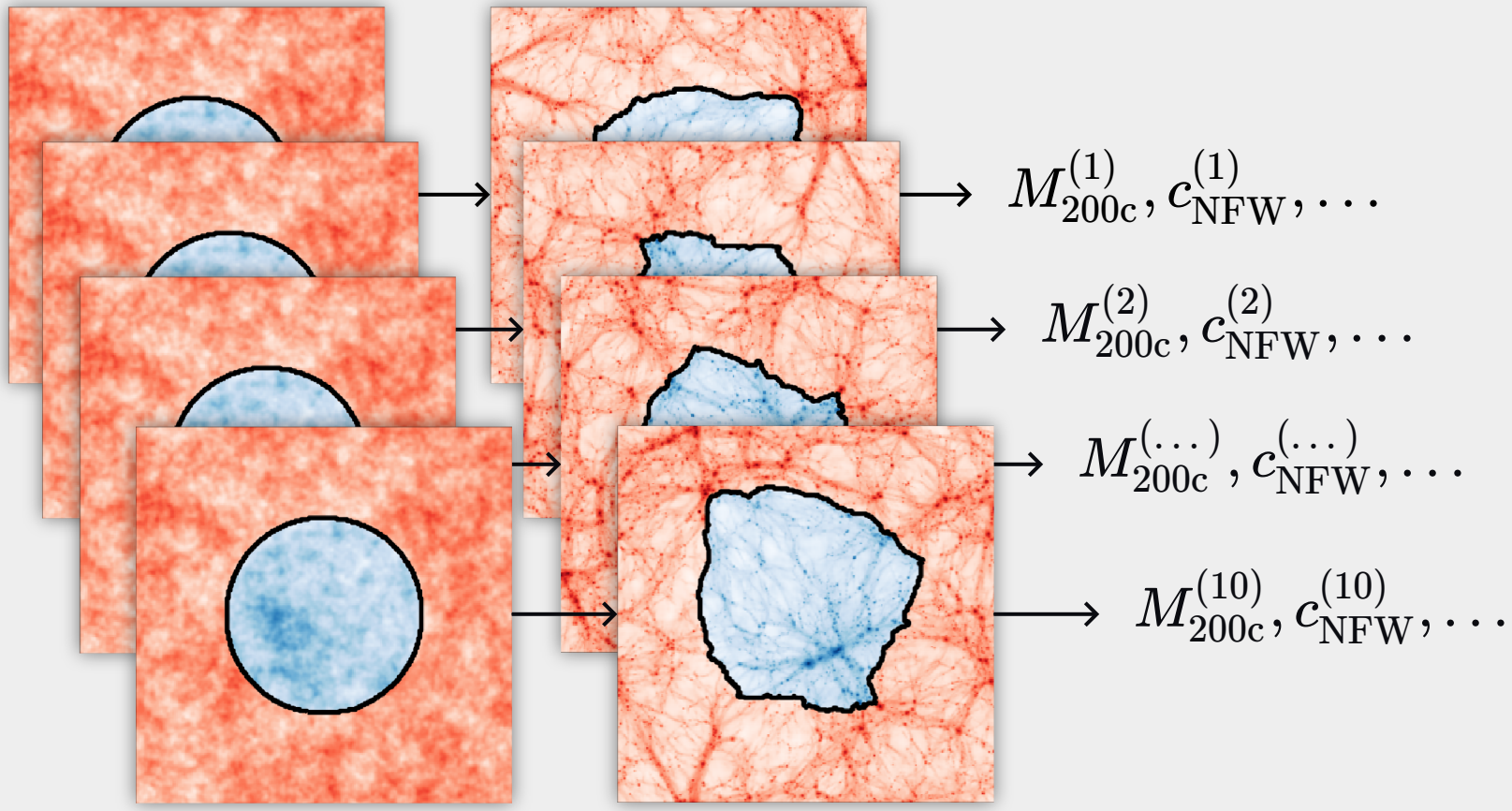
$$M_{200c}^{(2)}, c_{NFW}^{(2)}, \ldots$$

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

The causal origin of DM halo concentration



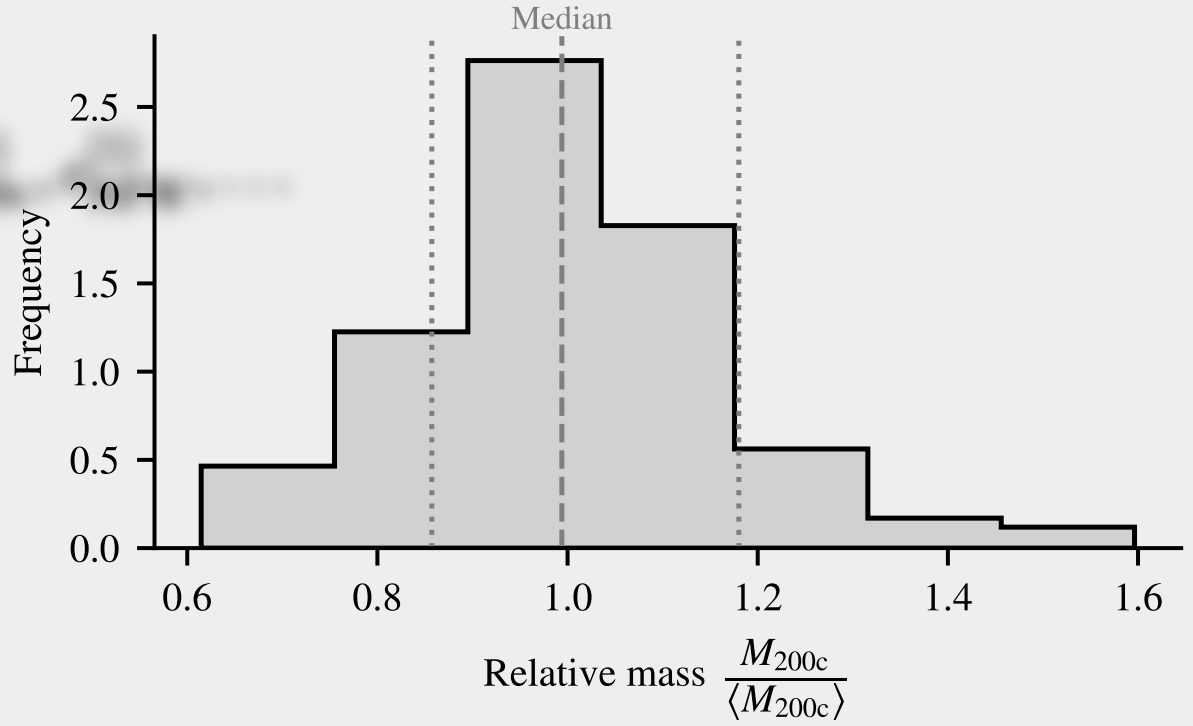
The causal origin of DM halo concentration



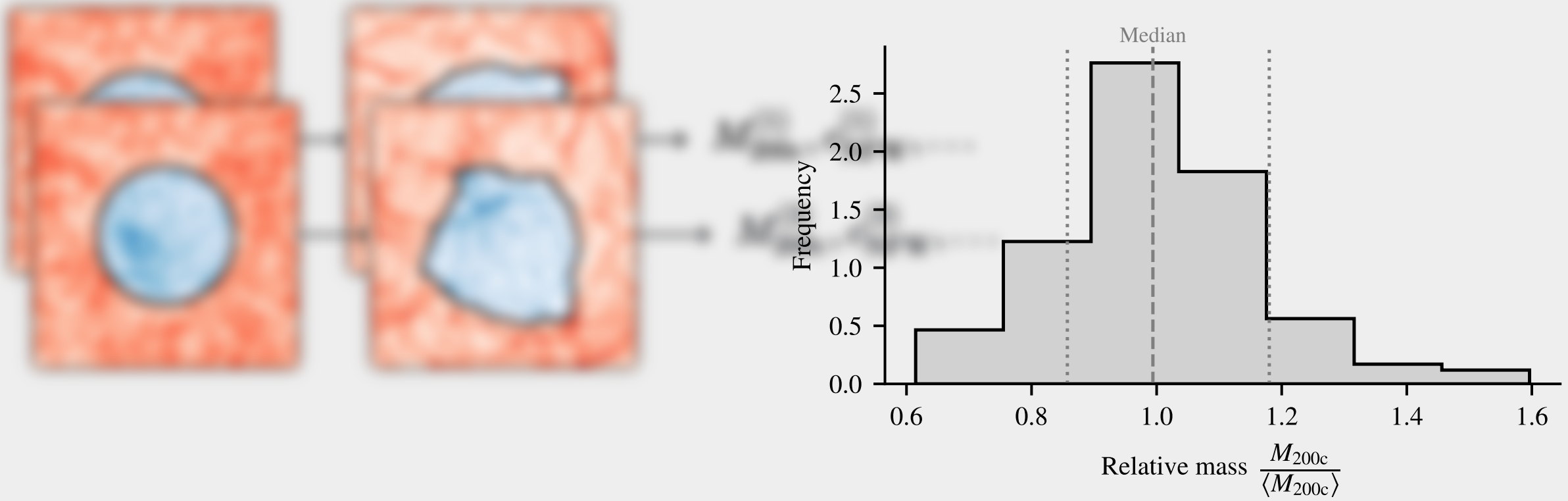
Same halo in 10× different environments

Repeat experiment for 7 halos (70 realisations in total)

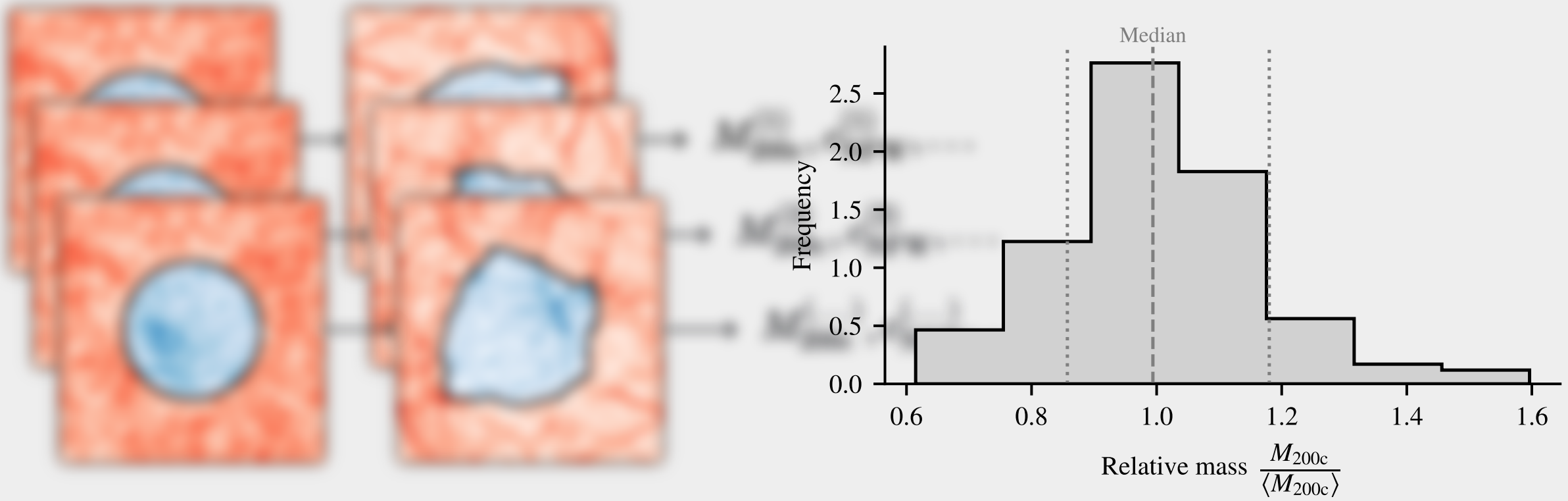
The causal origin of DM halo concentration



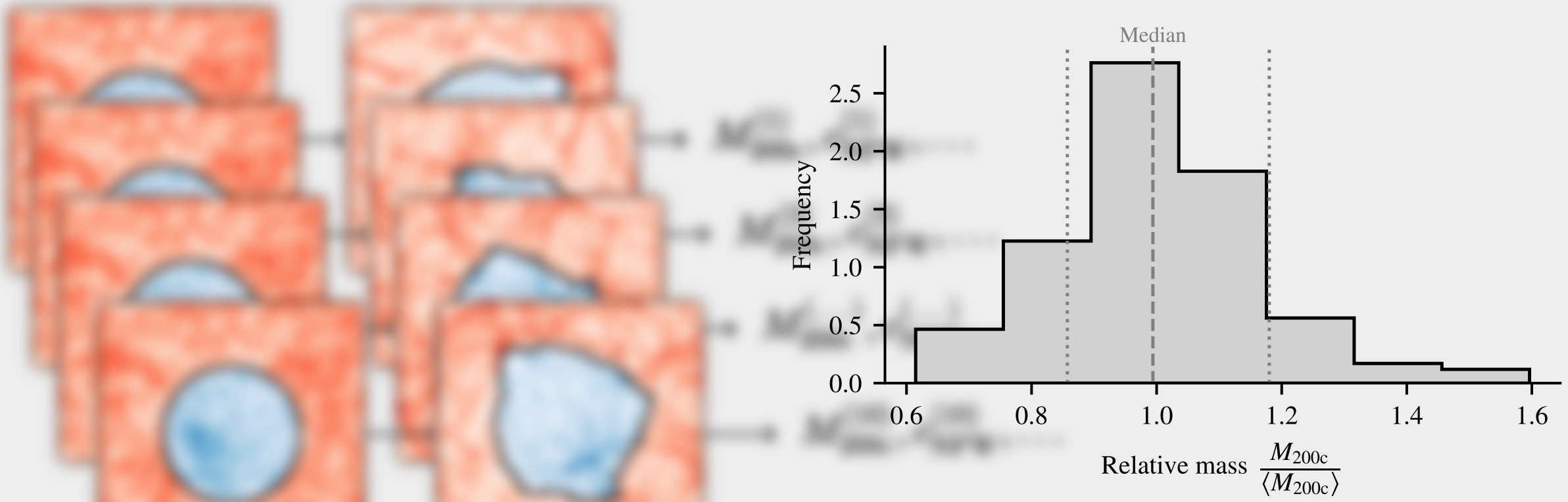
The causal origin of DM halo concentration



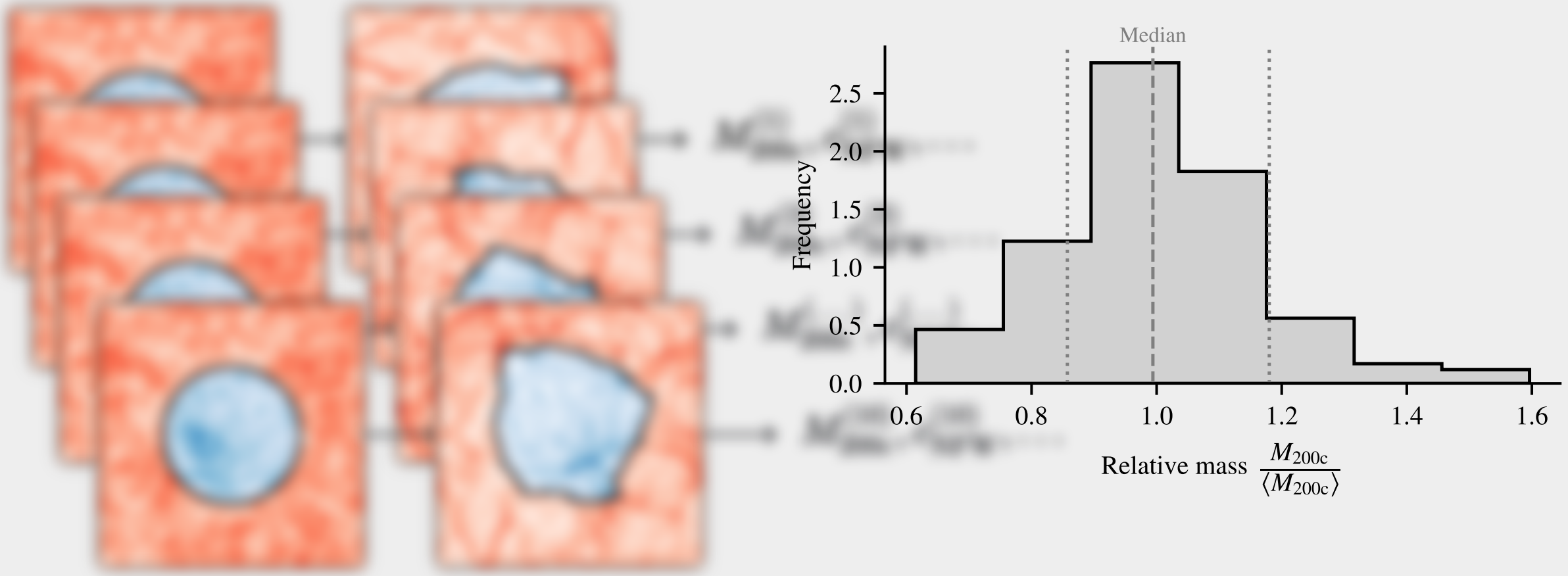
The causal origin of DM halo concentration



The causal origin of DM halo concentration



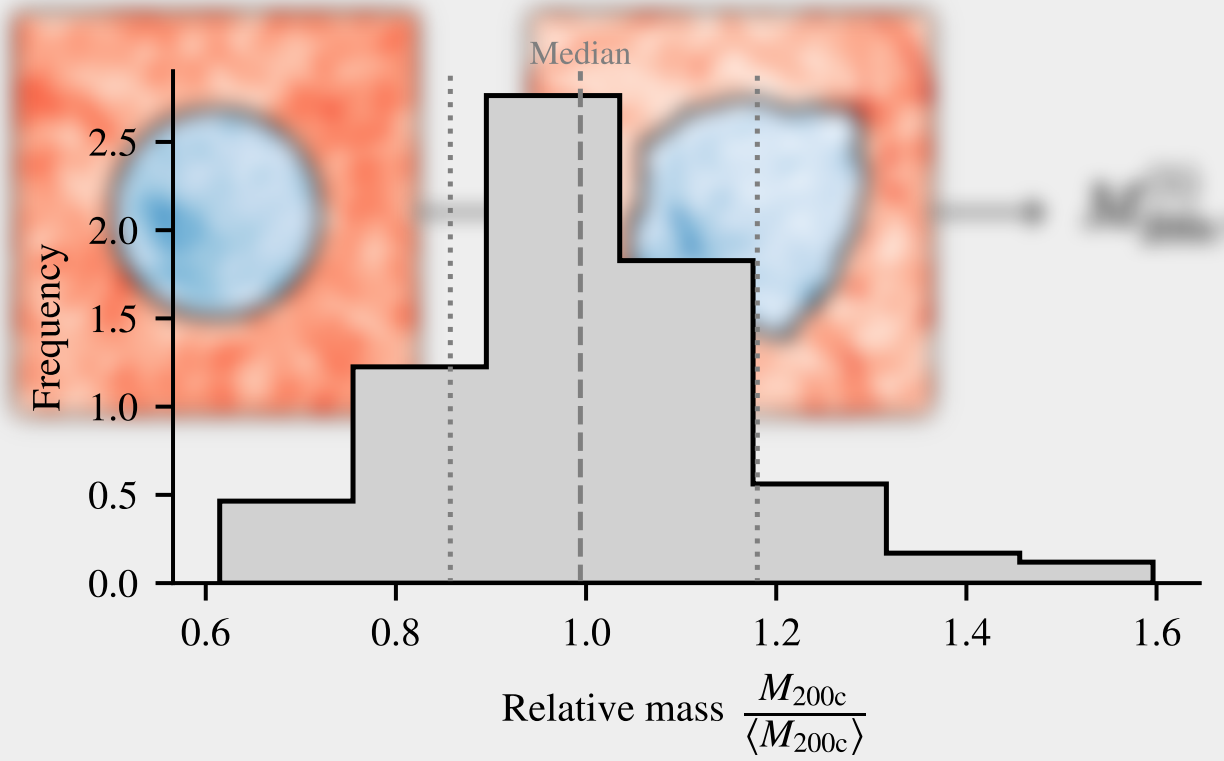
The causal origin of DM halo concentration

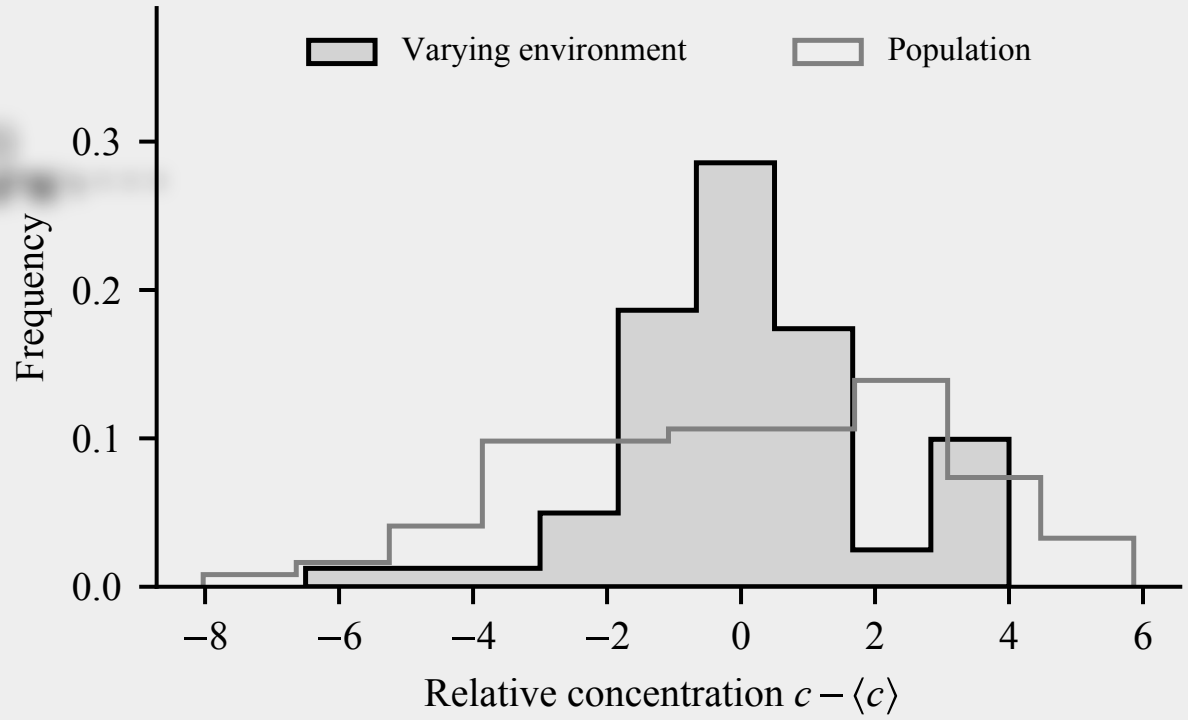


Same halo in 10× different environments

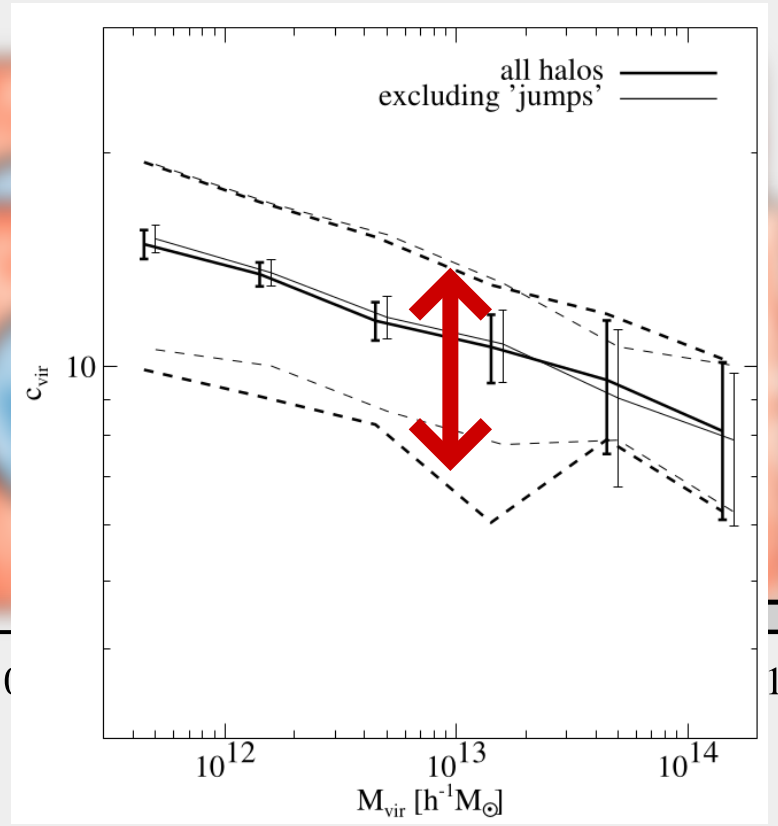
Repeat experiment for 7 halos (70 realisations in total)

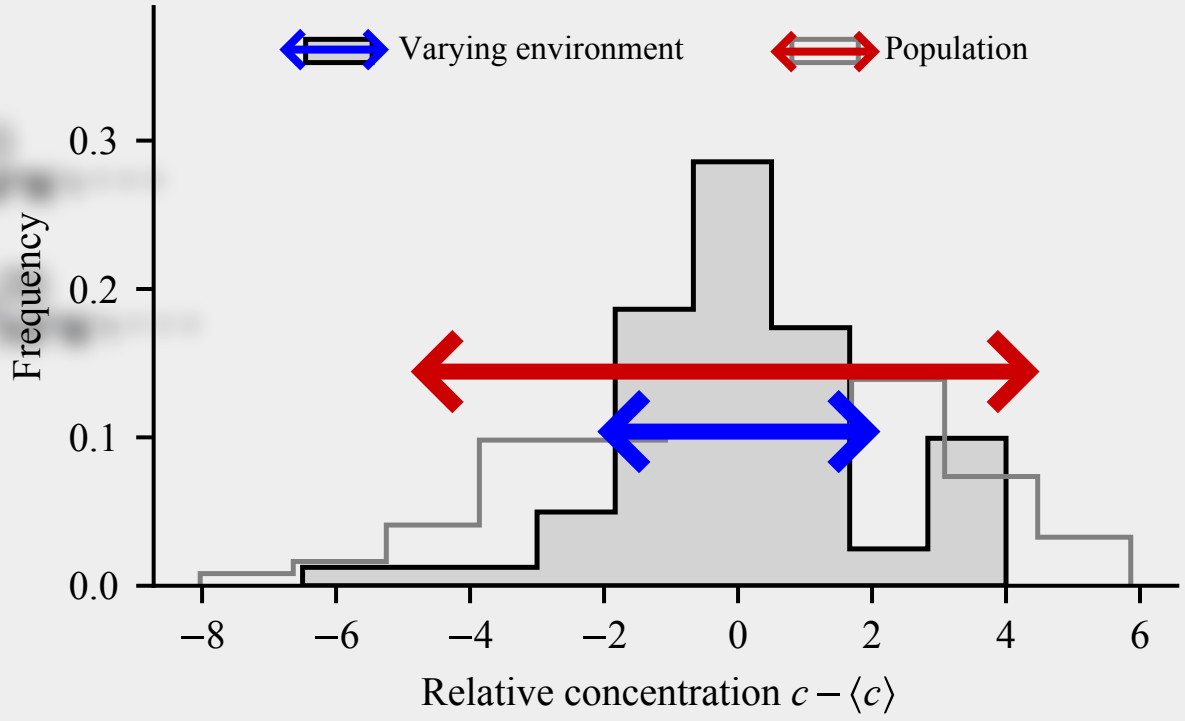
The causal origin of DM halo concentration



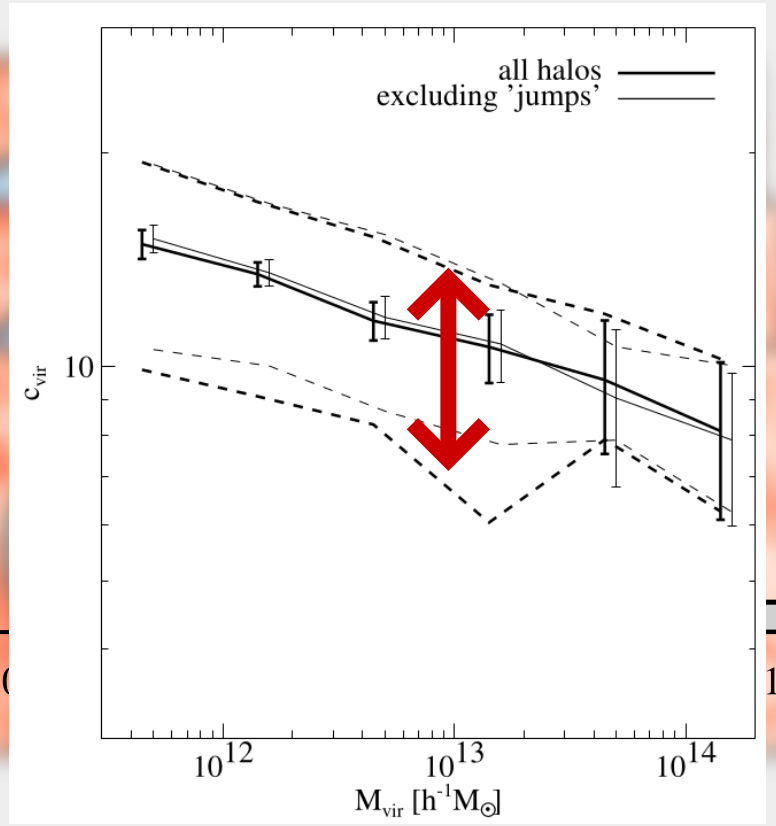


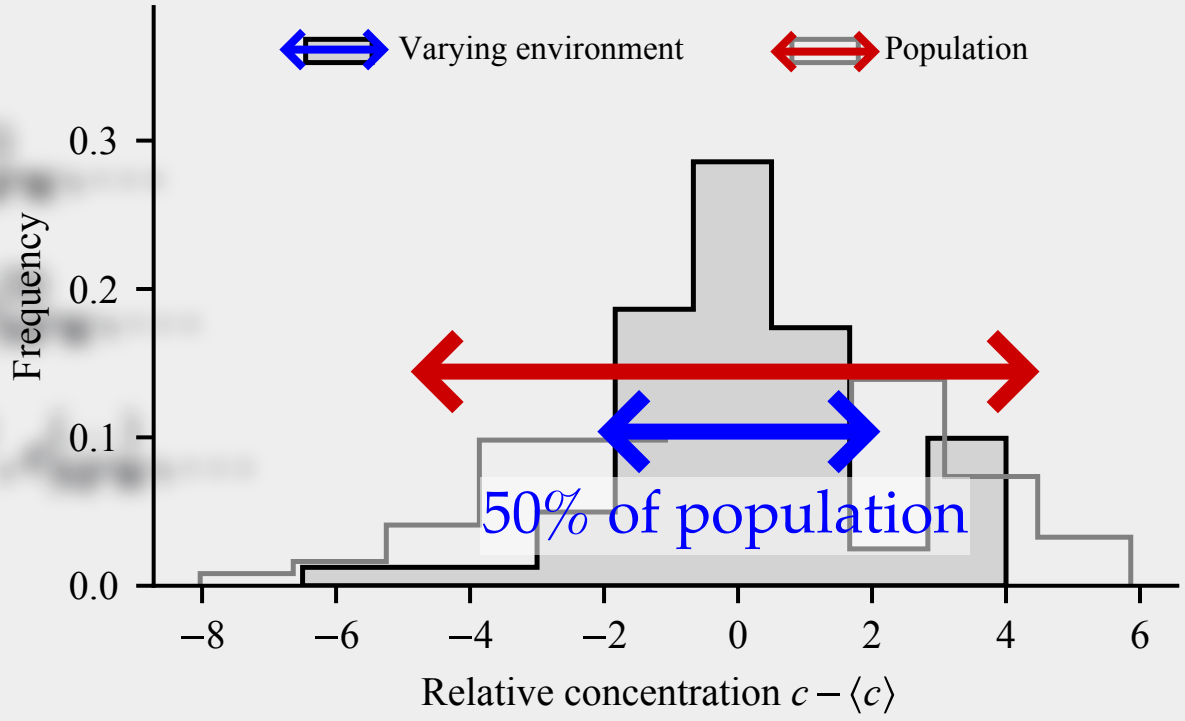
The causal origin of DM halo concentration



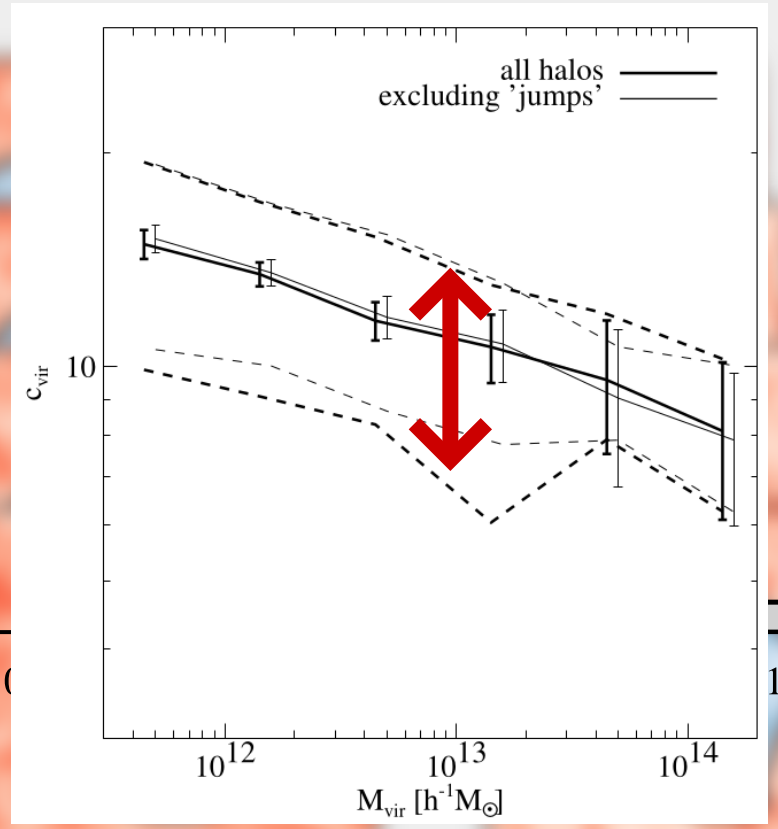


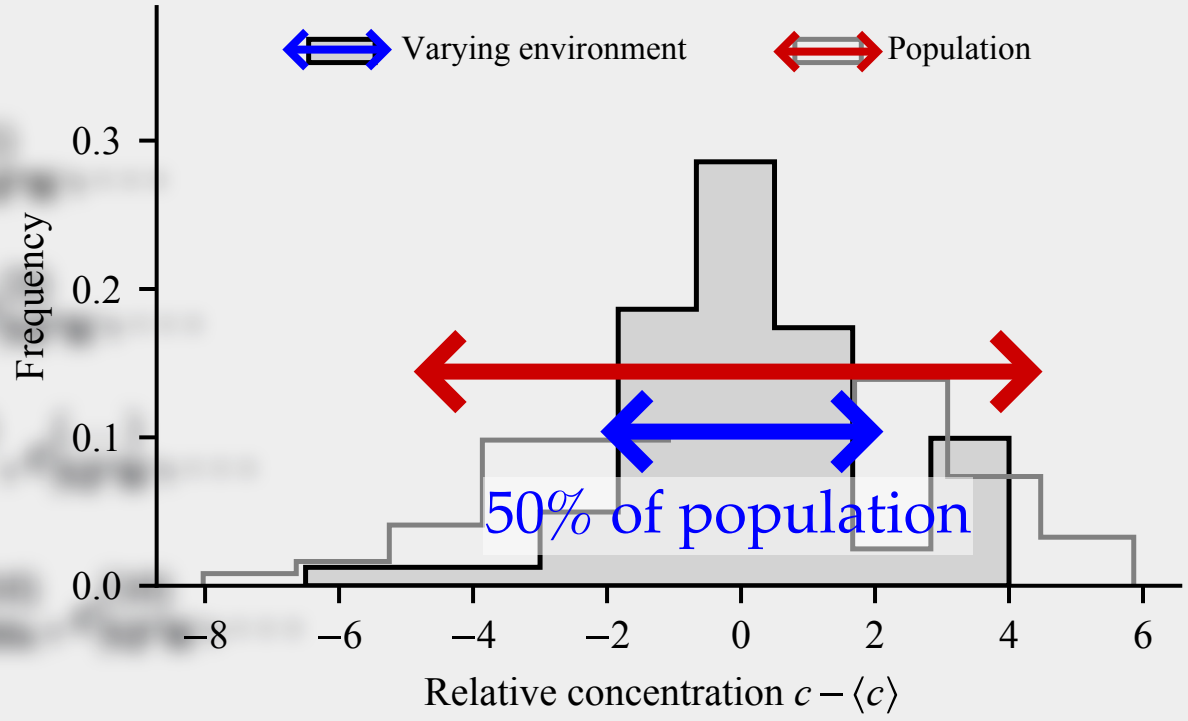
The causal origin of DM halo concentration



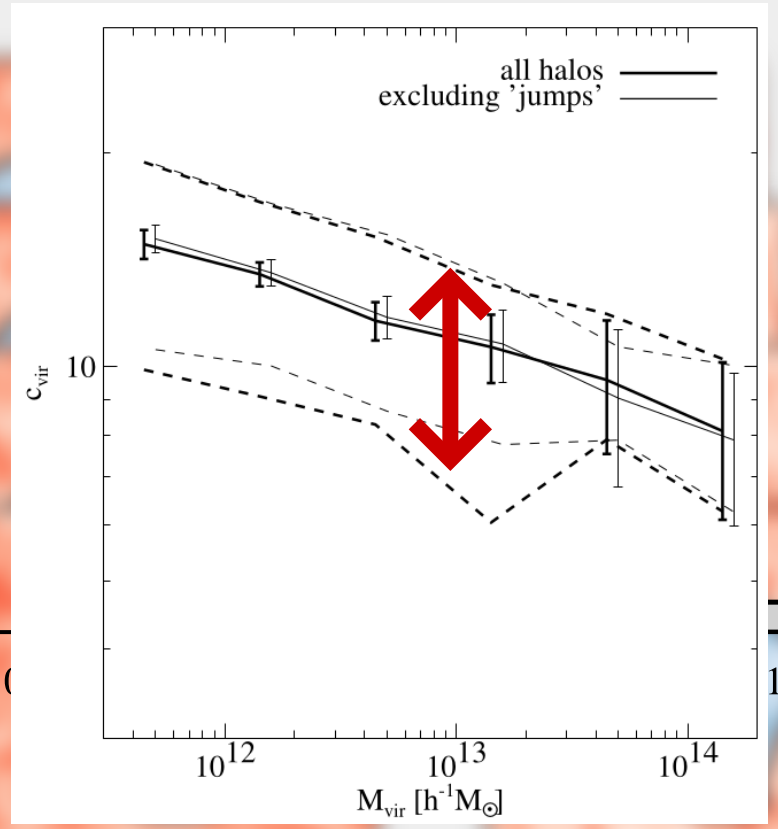


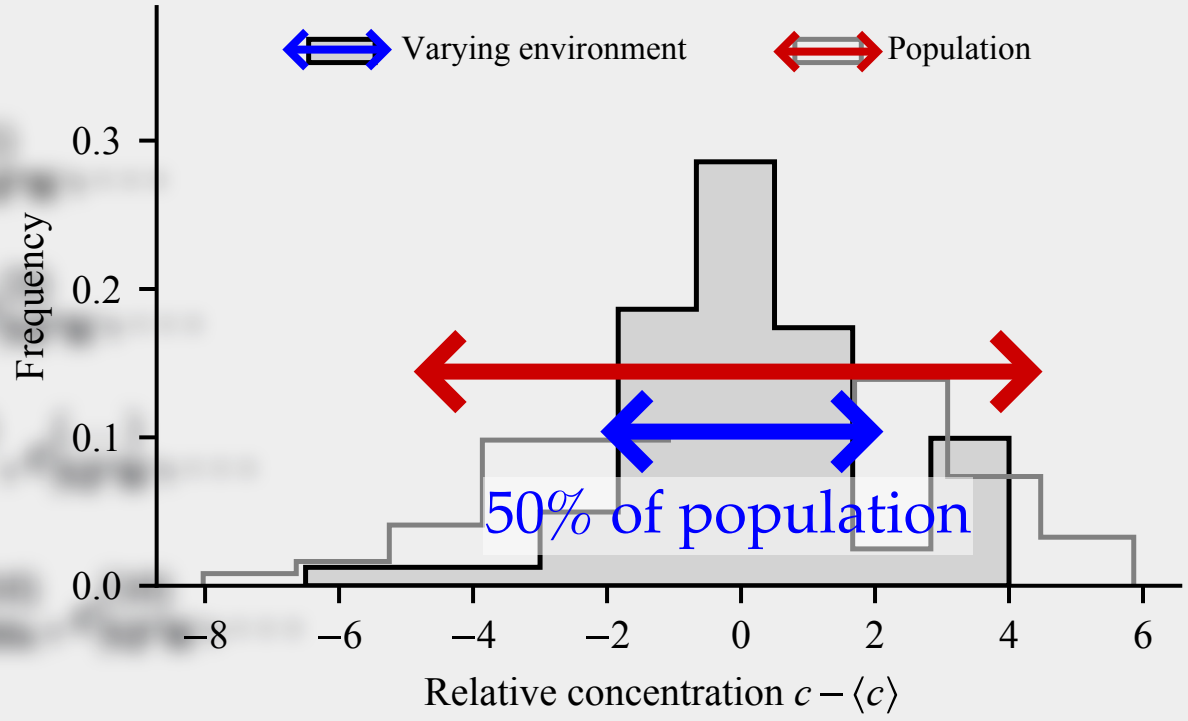
The causal origin of DM halo concentration





The causal origin of DM halo concentration





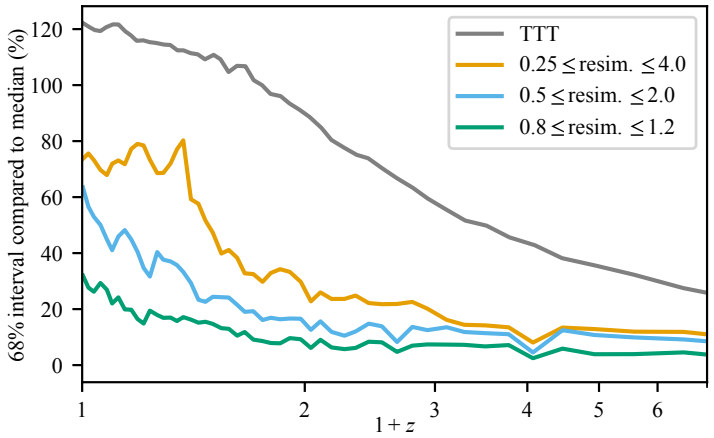
Same halo in 10× different environments

Repeat experiment for 7 halos (70 realisations in total)

Conclusion & outlook

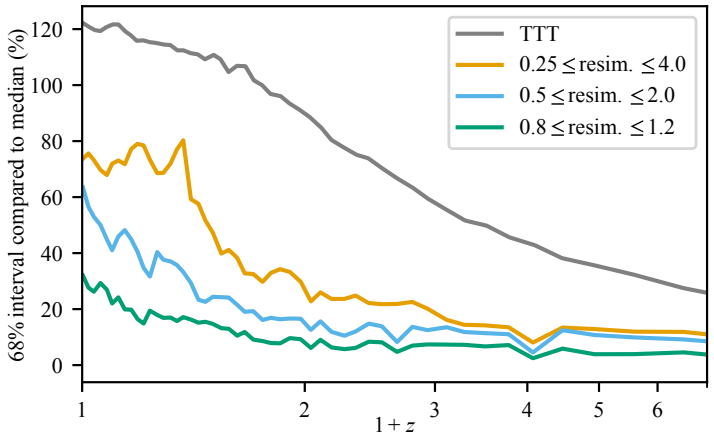
Conclusion & outlook

Conclusion & outlook



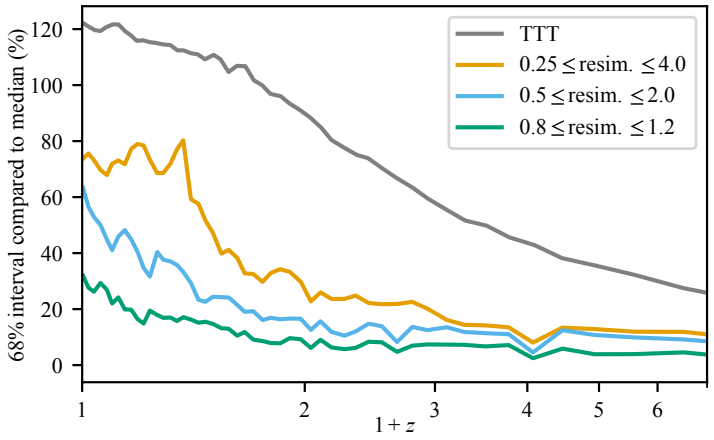
- angular momentum is predictable

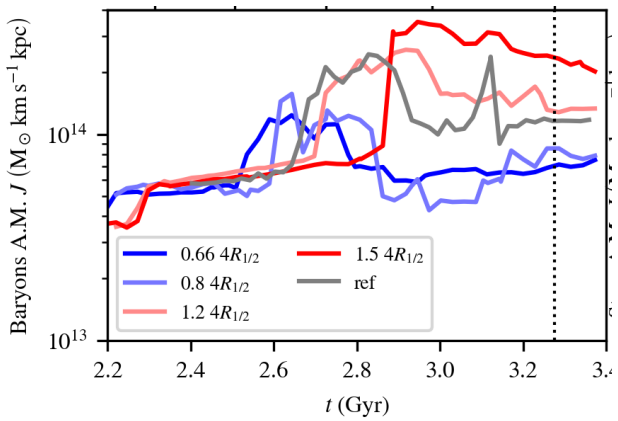
Conclusion & outlook



- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)

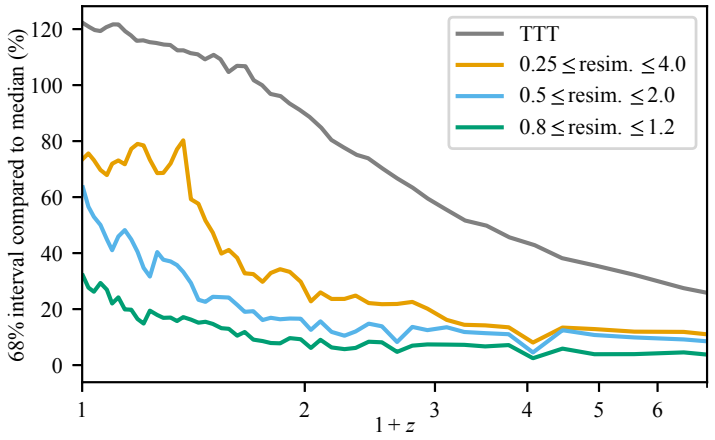
Conclusion & outlook

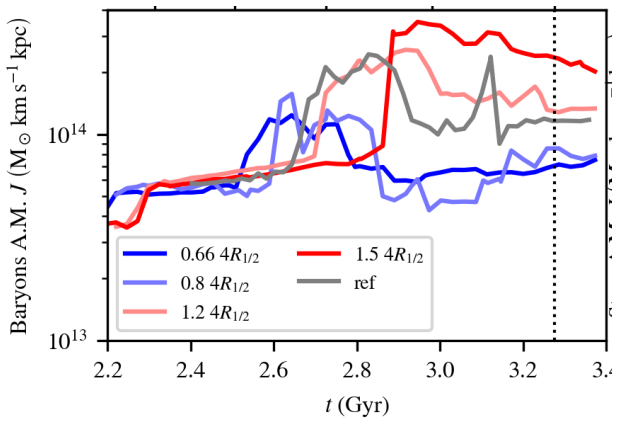


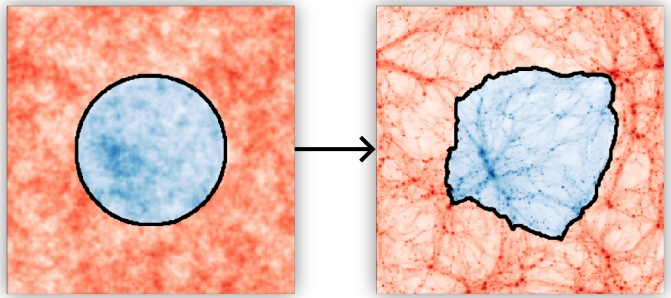


- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* can be controlled!
  ⇒ weak lensing predictions easier than expected?
  ⇒ role in setting morphology

Conclusion & outlook

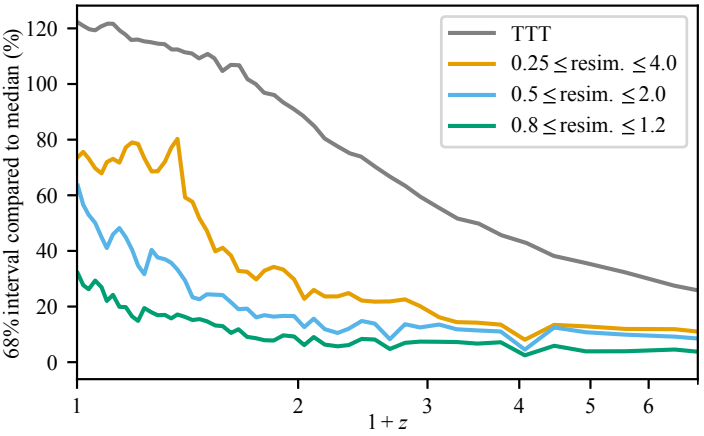


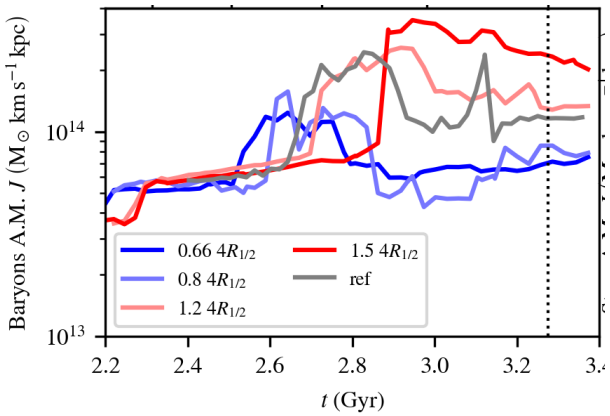


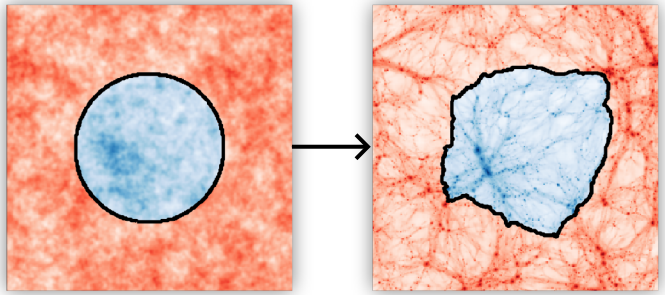


- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* can be controlled!
  ⇒ weak lensing predictions easier than expected?
  ⇒ role in setting morphology
- environmental effects can have *dramatic* impact on halo formation
  ⇒ 50% of concentration scatter due to env.
  ⇒ similar impact on galaxy formation?

Conclusion & outlook



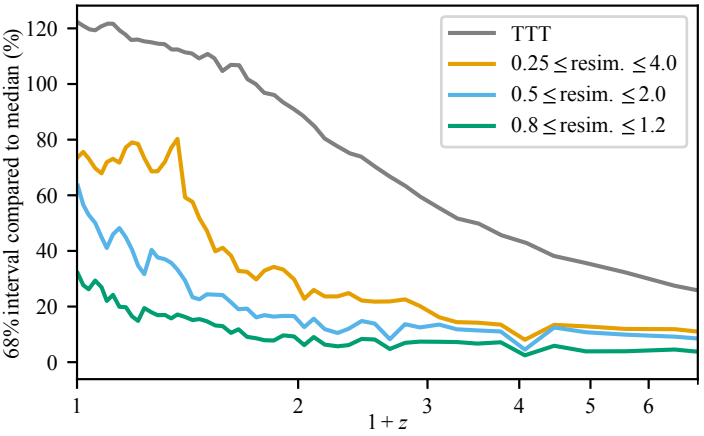


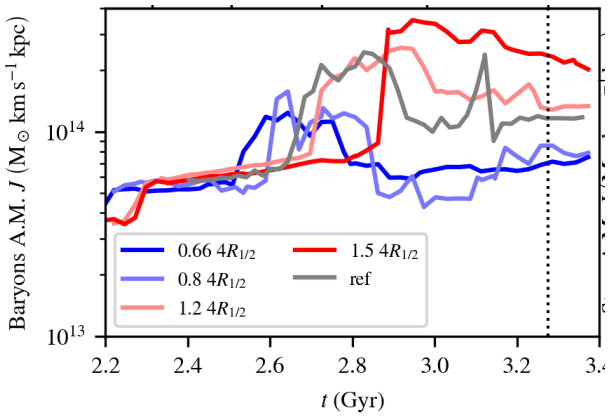


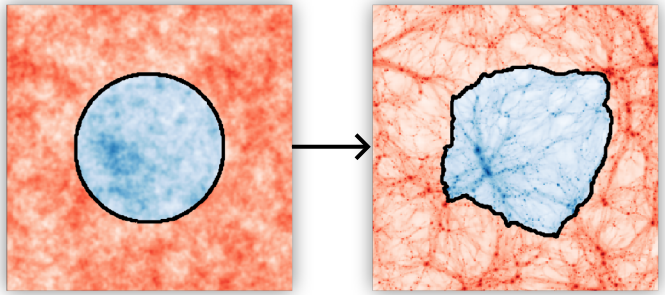
Questions?

More infos in Cadiou+21a,b,c (2012.02201, 2107.03407, 2110.05384)

Conclusion & outlook





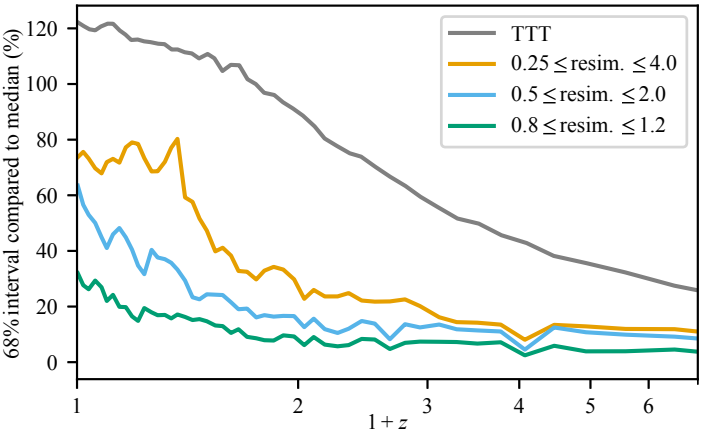


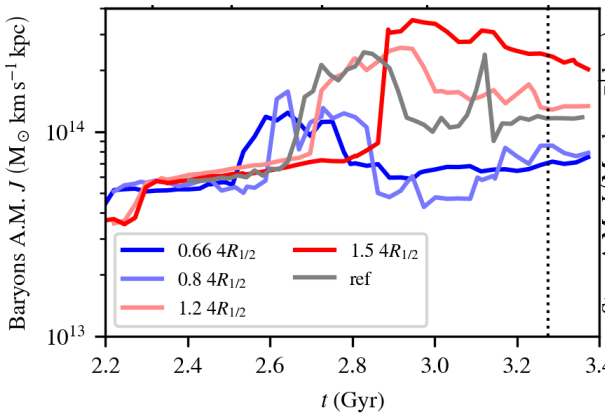
- angular momentum is predictable

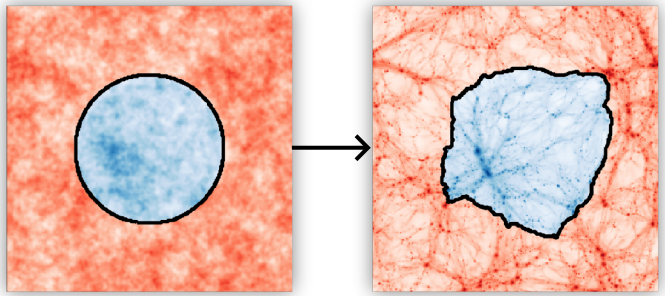
Questions?

More infos in Cadiou+21a,b,c (2012.02201, 2107.03407, 2110.05384)

Conclusion & outlook





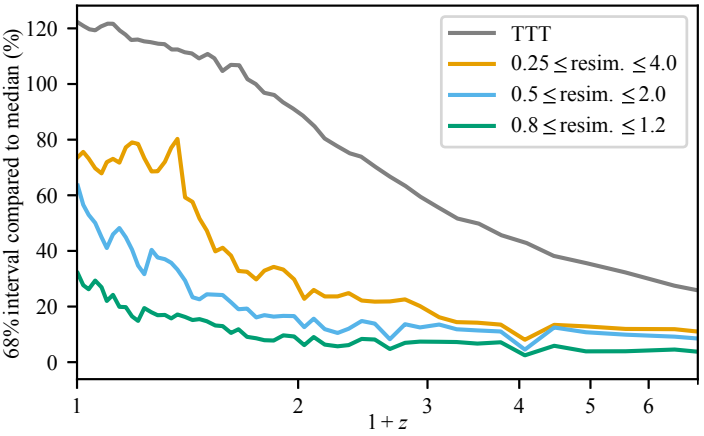


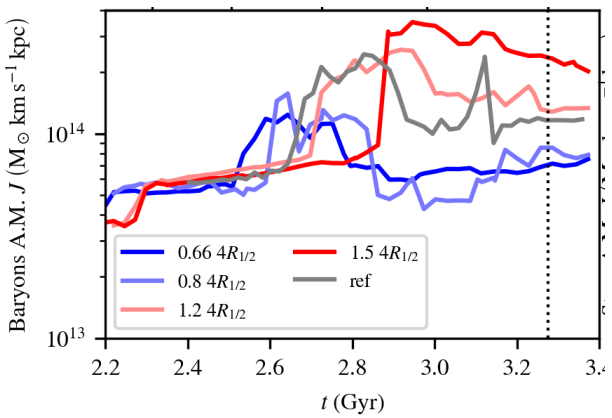
- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)

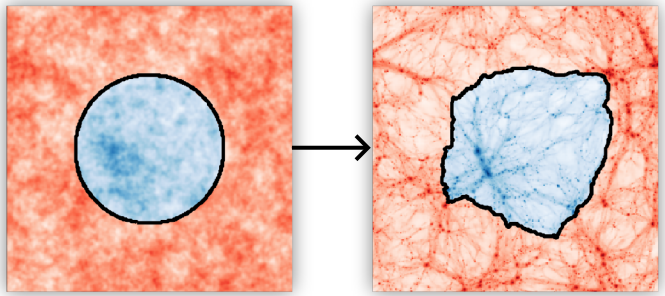
Questions?

More infos in Cadiou+21a,b,c (2012.02201, 2107.03407, 2110.05384)

Conclusion & outlook





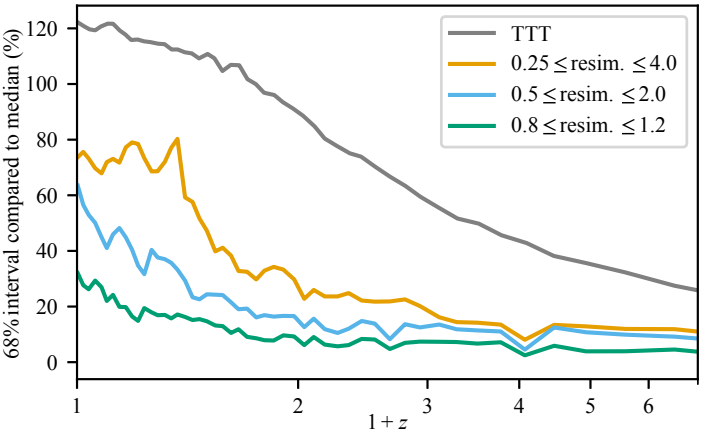


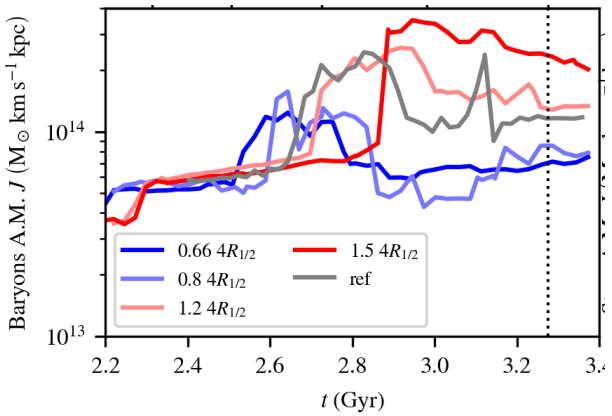
- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* can be controlled!
  ⇒ weak lensing predictions easier than expected?
  ⇒ role in setting morphology

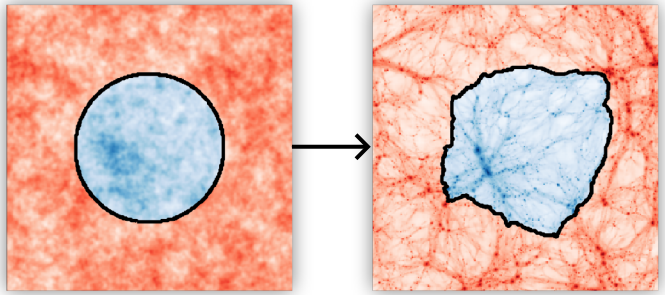
Questions?

More infos in Cadiou+21a,b,c (2012.02201, 2107.03407, 2110.05384)

Conclusion & outlook



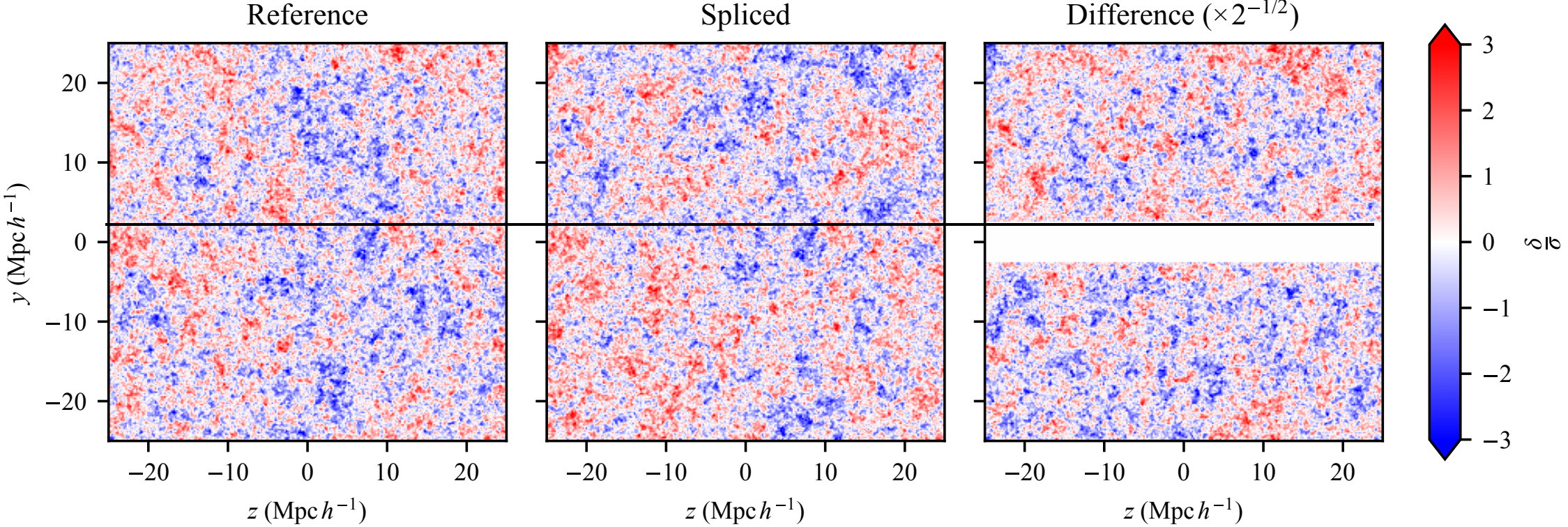




- angular momentum is predictable
- *boundary* of halos in the ICs is a *hard* problem
  ⇒ limits practicality of predictions (for now)
- *baryons* can be controlled!
  ⇒ weak lensing predictions easier than expected?
  ⇒ role in setting morphology
- environmental effects can have *dramatic* impact on halo formation
  ⇒ 50% of concentration scatter due to env.
  ⇒ similar impact on galaxy formation?

Questions?

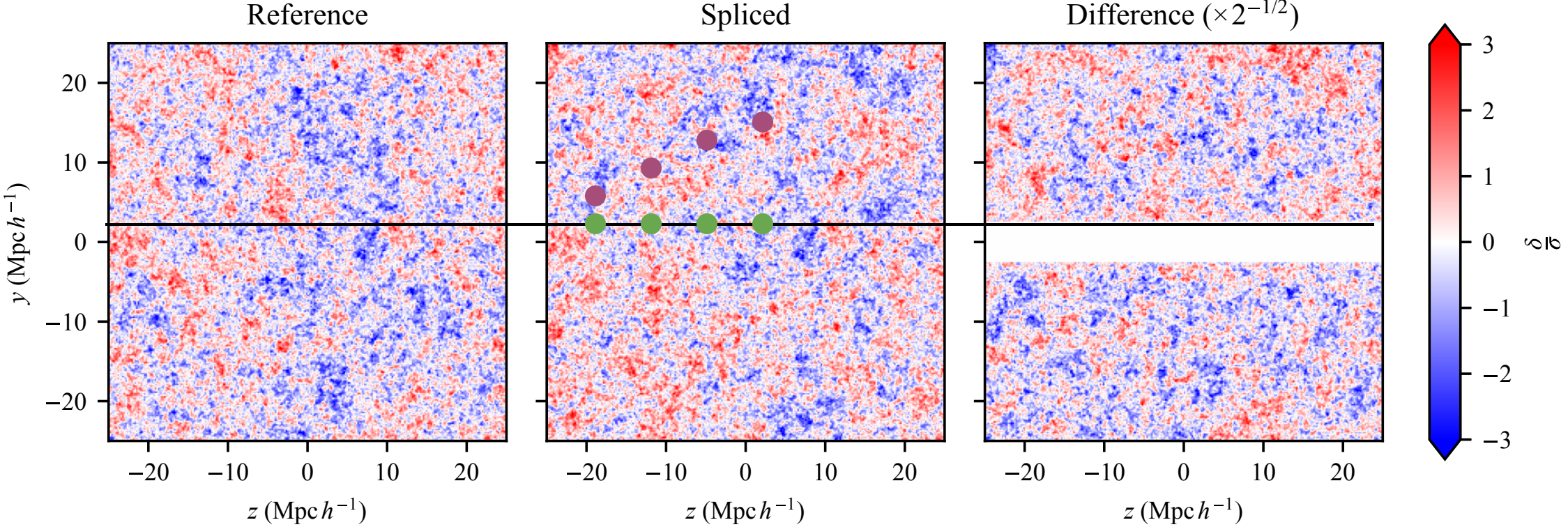
More infos in Cadiou+21a,b,c (2012.02201, 2107.03407, 2110.05384)



Verify that

$$\xi_{\text{lin}}(r) \sim \left\langle \underbrace{\delta(x=d)}_{\text{in}} \underbrace{\delta(x=d+r)}_{\text{out}} \right\rangle$$

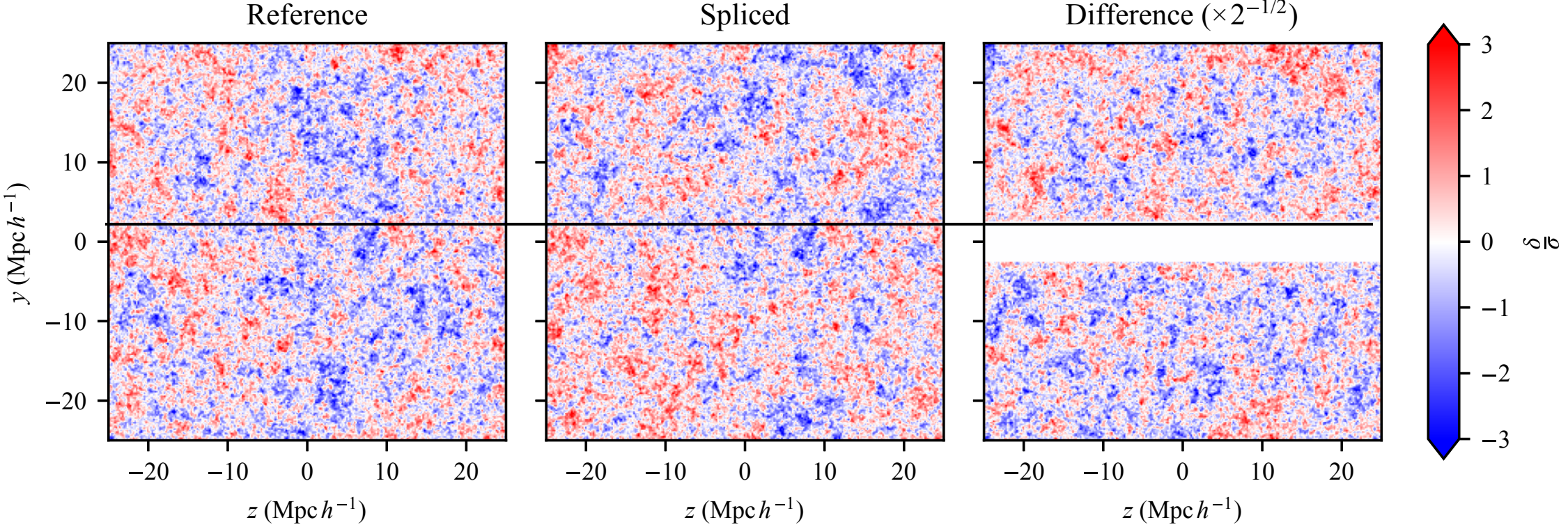
is the same in spliced / ref simulation.



Verify that

$$\xi_{\text{lin}}(r) \sim \left\langle \underbrace{\delta(x=d)}_{\text{in}} \underbrace{\delta(x=d+r)}_{\text{out}} \right\rangle$$

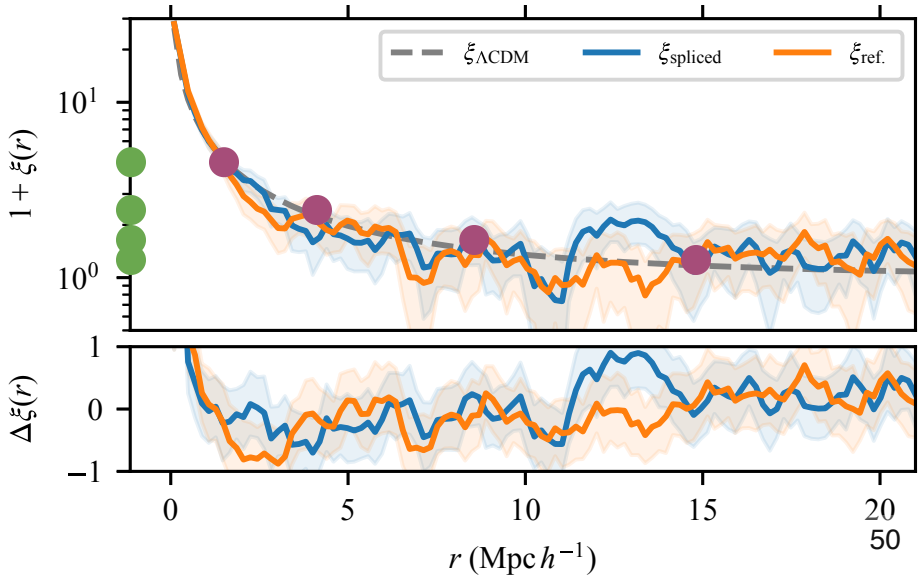
is the same in spliced / ref simulation.



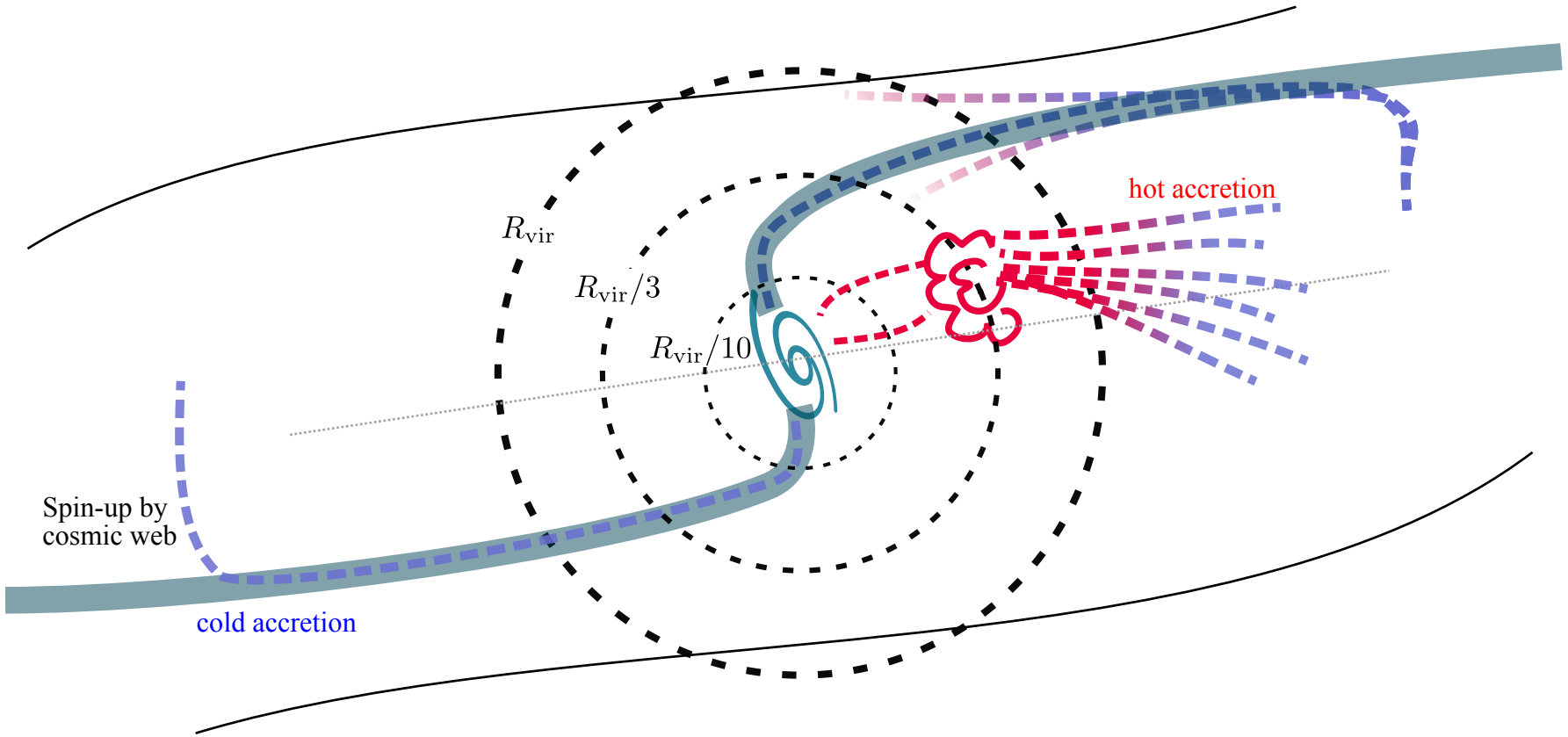
Verify that

$$\xi_{\rm lin}(r) \sim \left\langle \underbrace{\delta(x=d)}_{\text{in}} \underbrace{\delta(x=d+r)}_{\text{out}} \right\rangle$$

is the same in spliced / ref simulation.

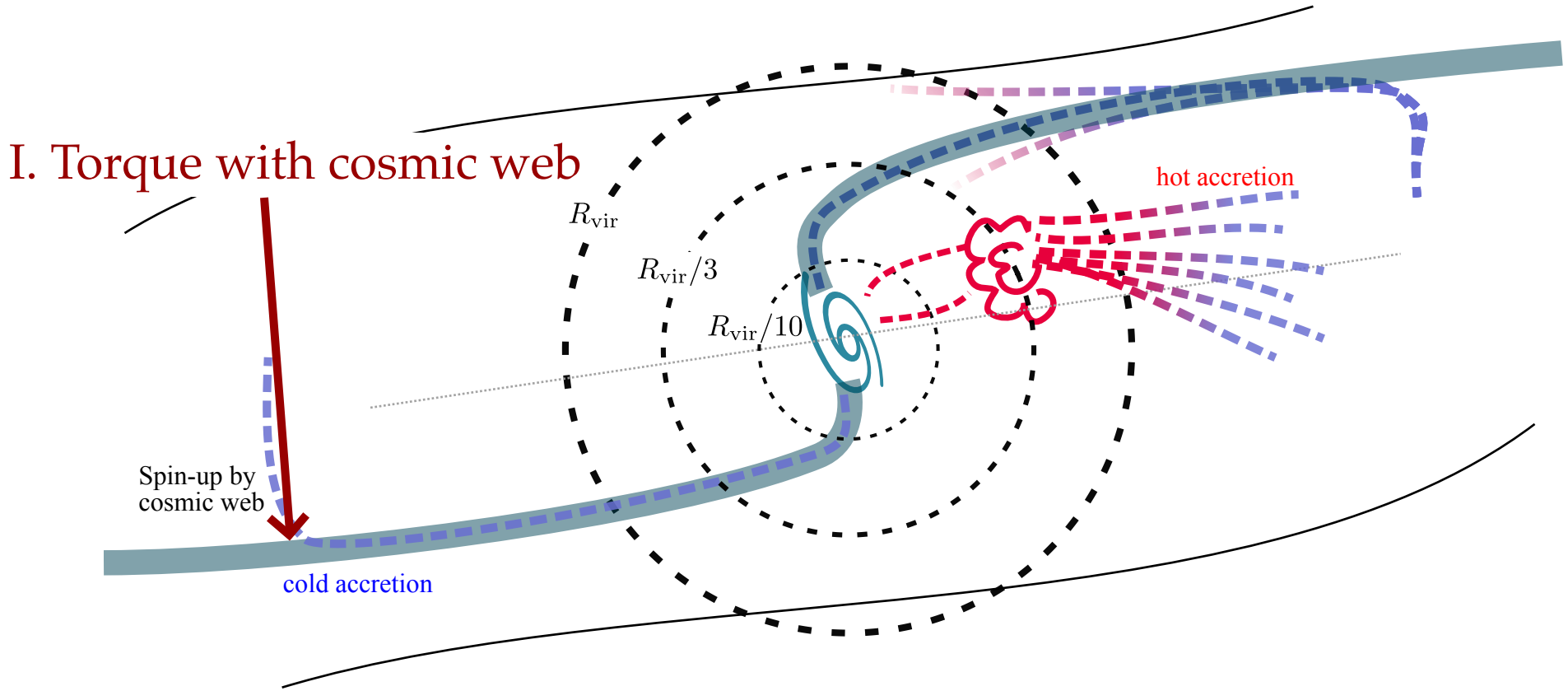


The origin of high z angular momentum



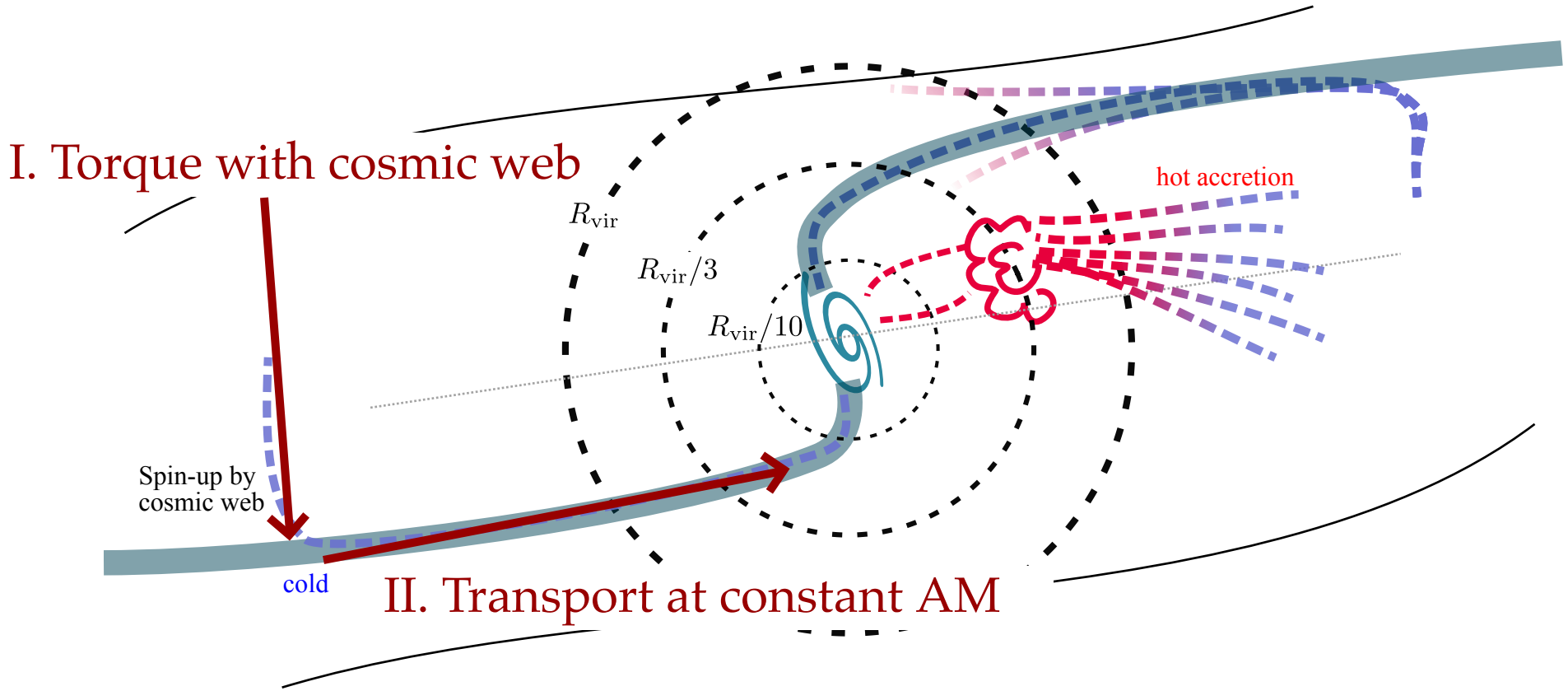
[Danovich+15]

The origin of high z angular momentum



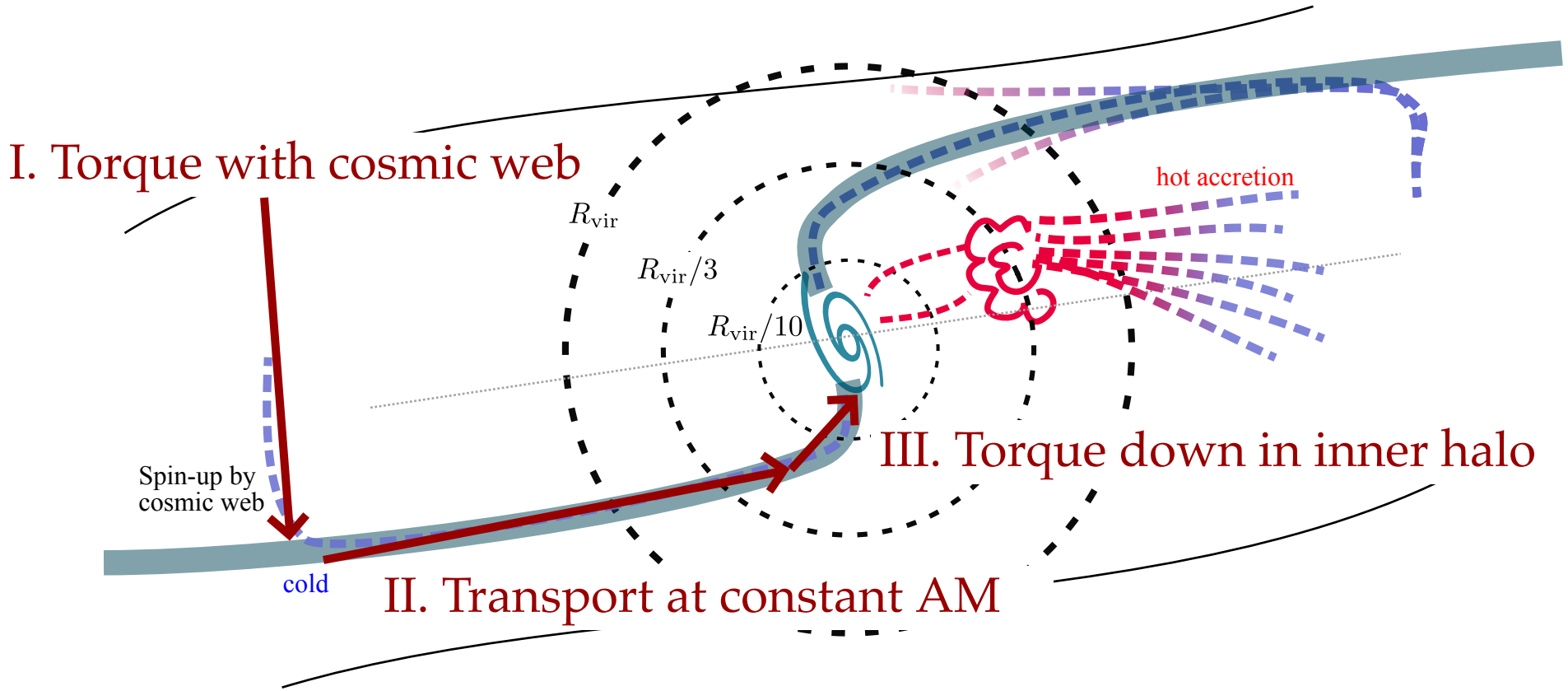
[Danovich+15]

The origin of high z angular momentum



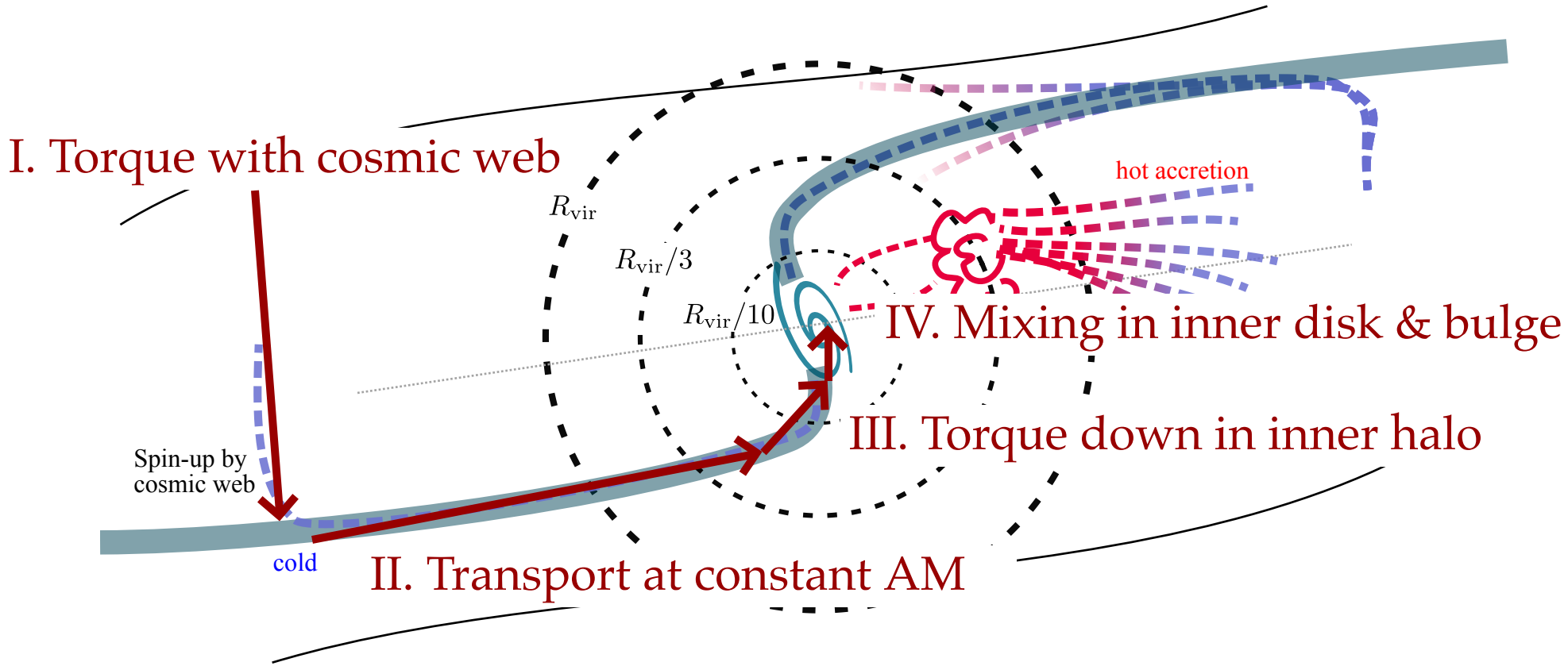
[Danovich+15]

The origin of high z angular momentum



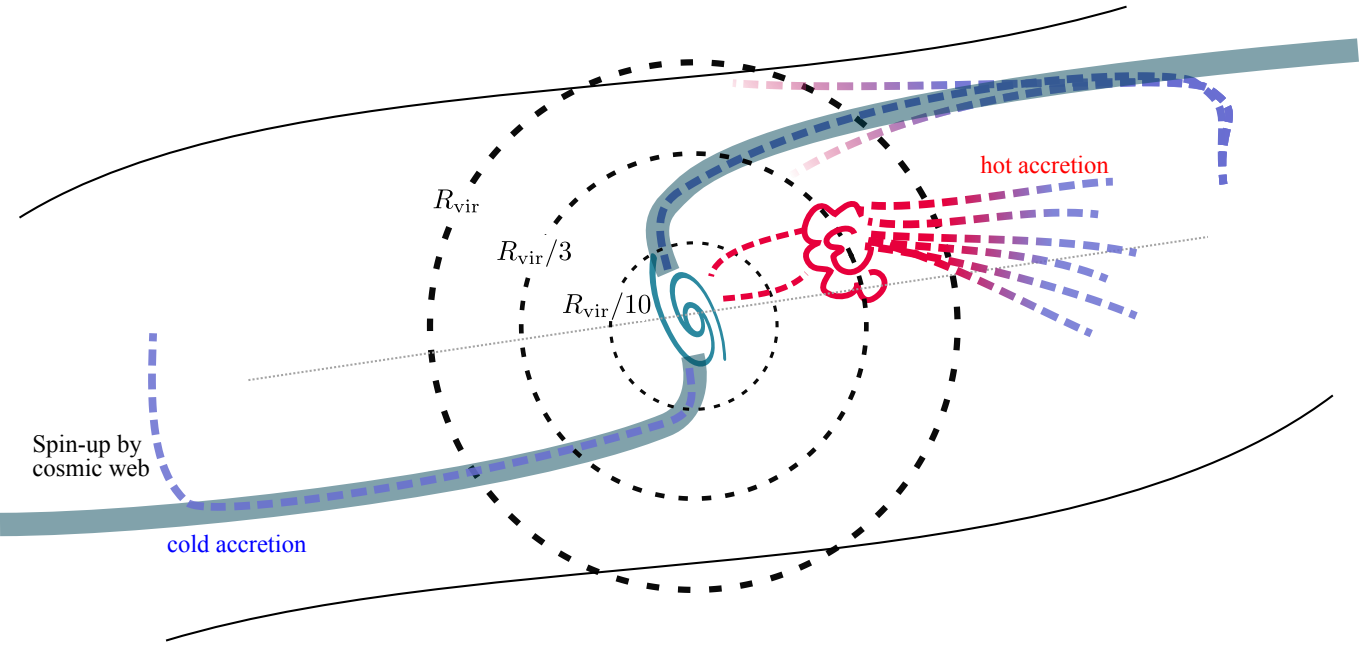
[Danovich+15]

The origin of high z angular momentum



[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

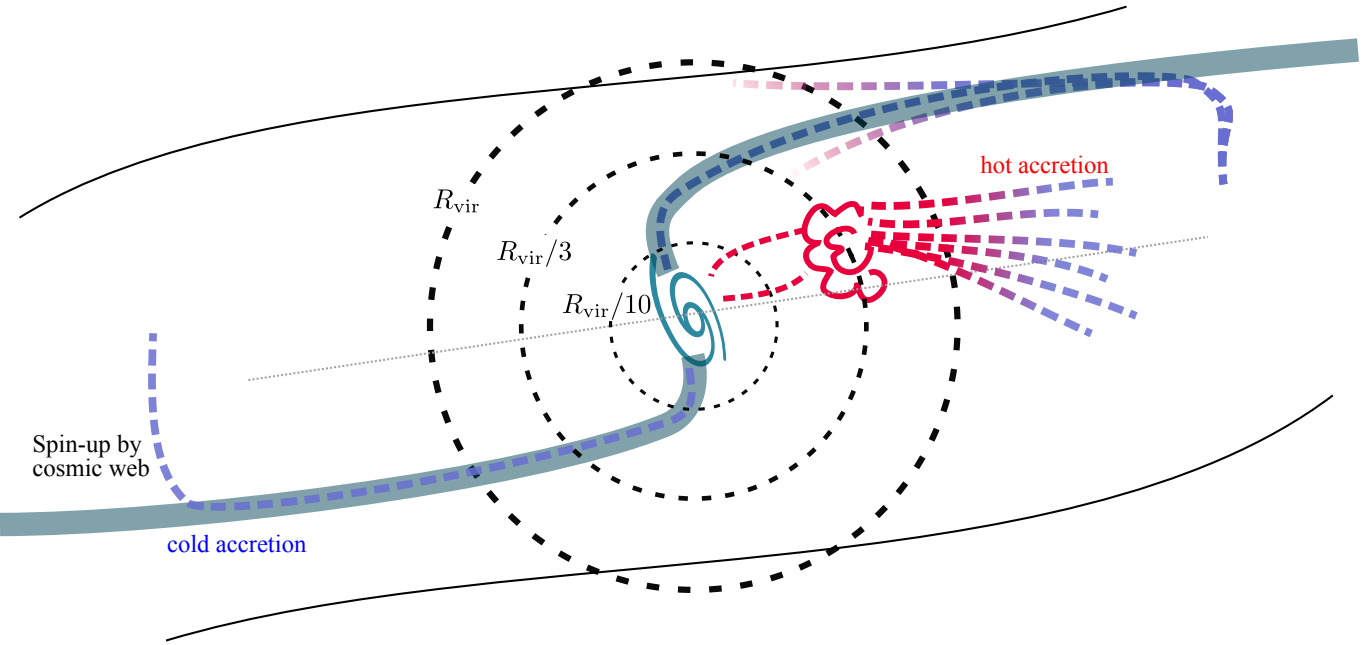
II. Transport at constant AM

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

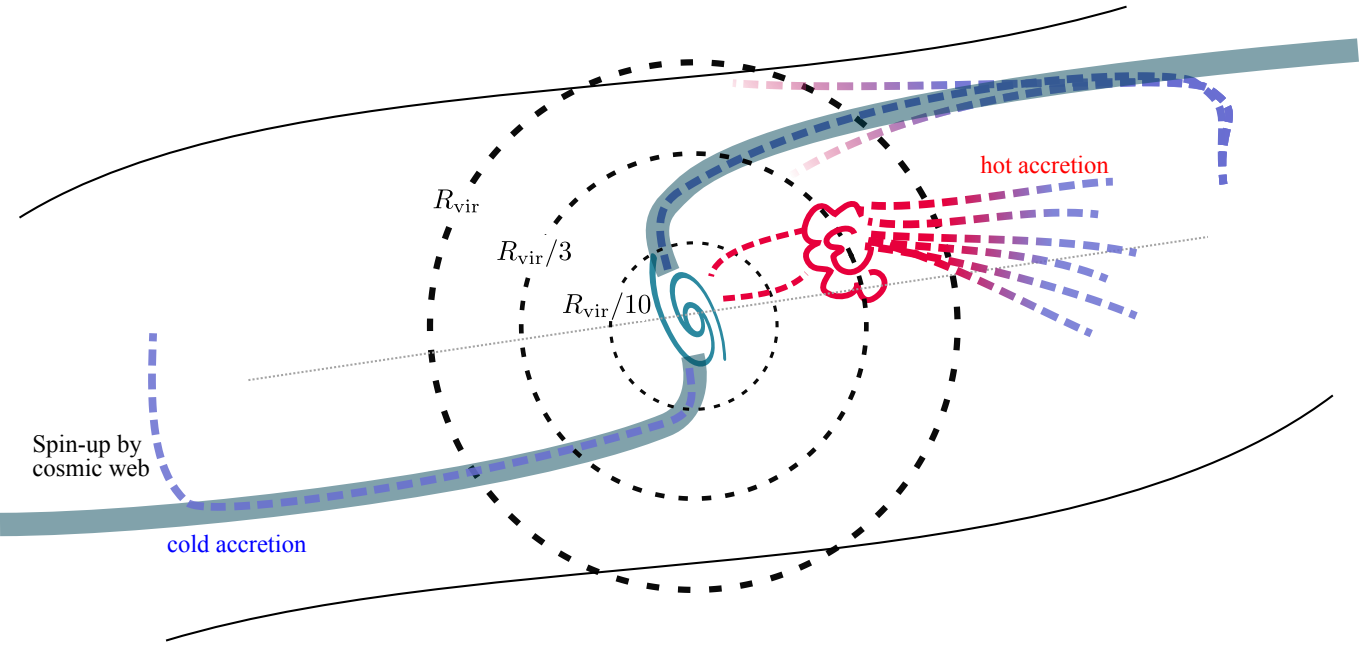
Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

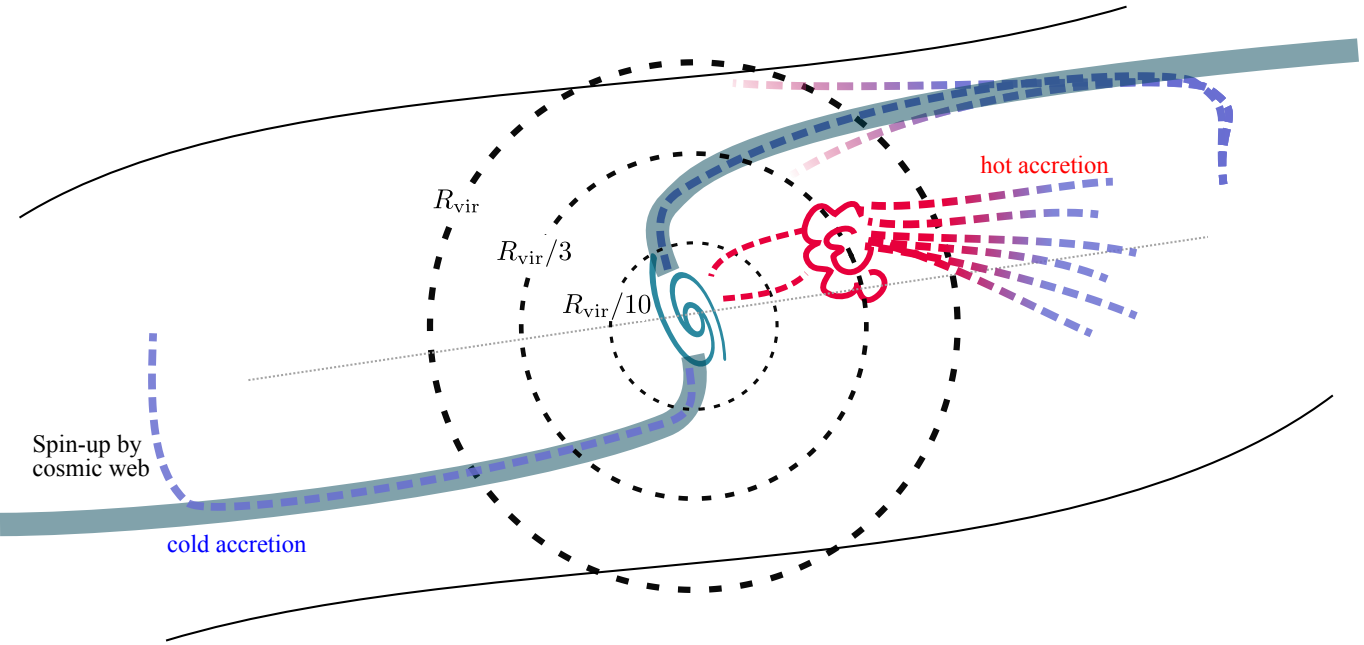
Origin of torque down (pressure or gravity)?

Loss of link with cosmic AM?

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

Origin of torque down (pressure or gravity)?

Loss of link with cosmic AM?

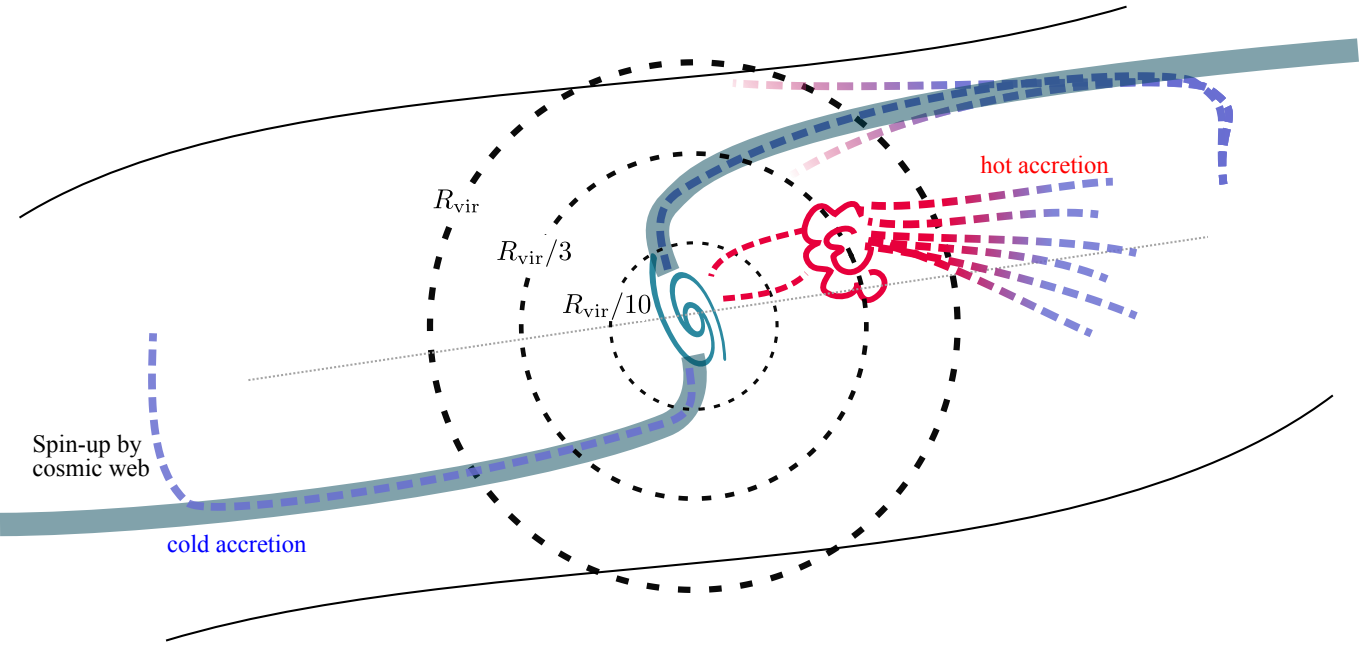
IV. Mixing in inner disk & bulge

Fraction that ends up in disk vs. IGM?

Influence of galactic physics?

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

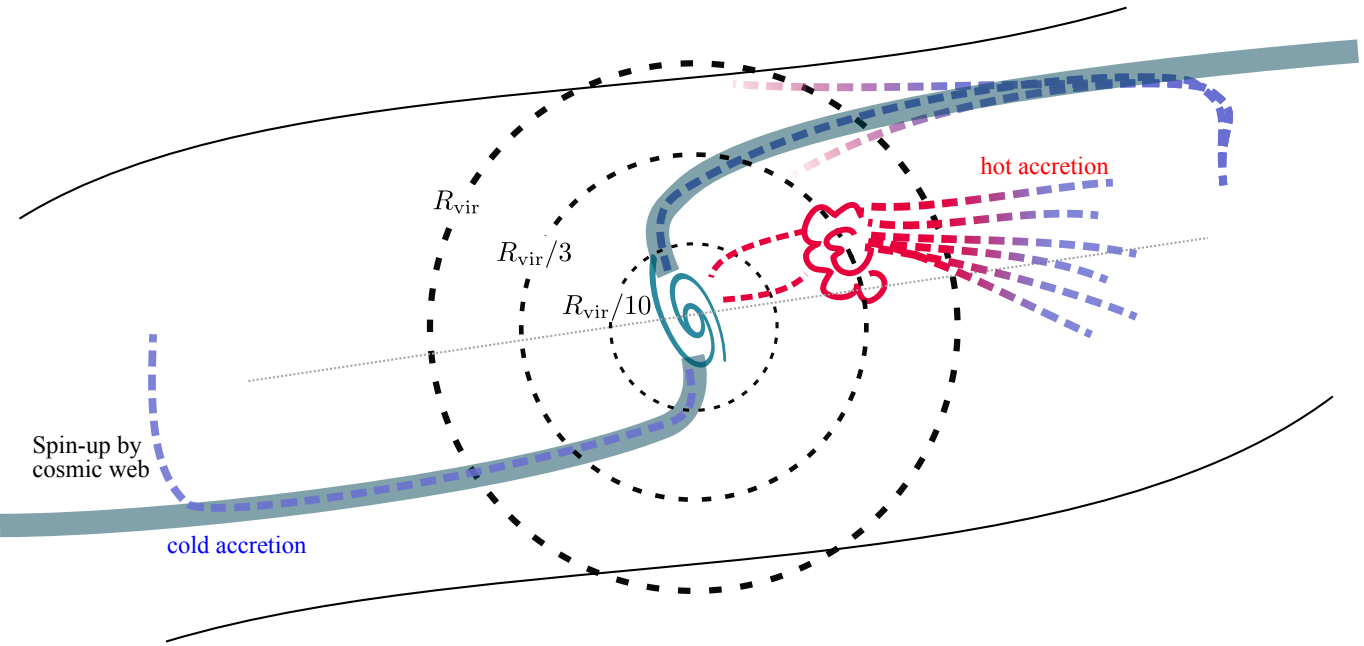
II. Transport at constant AM

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

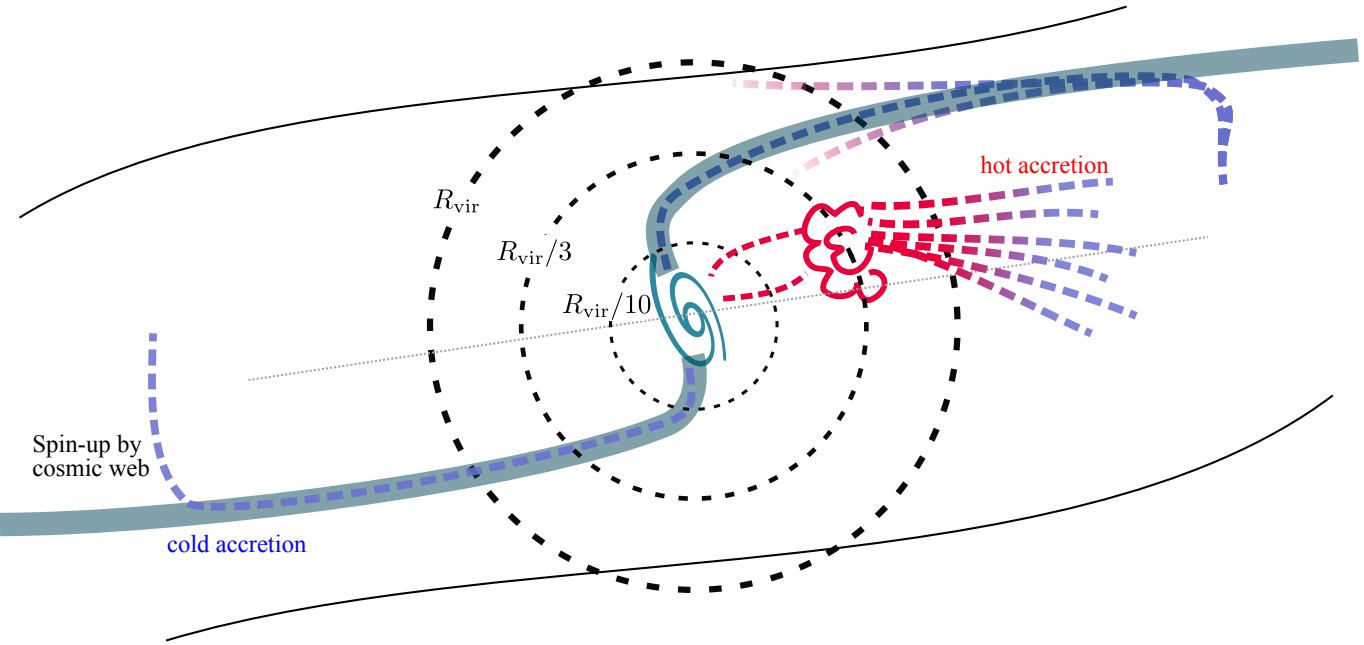
Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

Origin of torque down (pressure or gravity)?

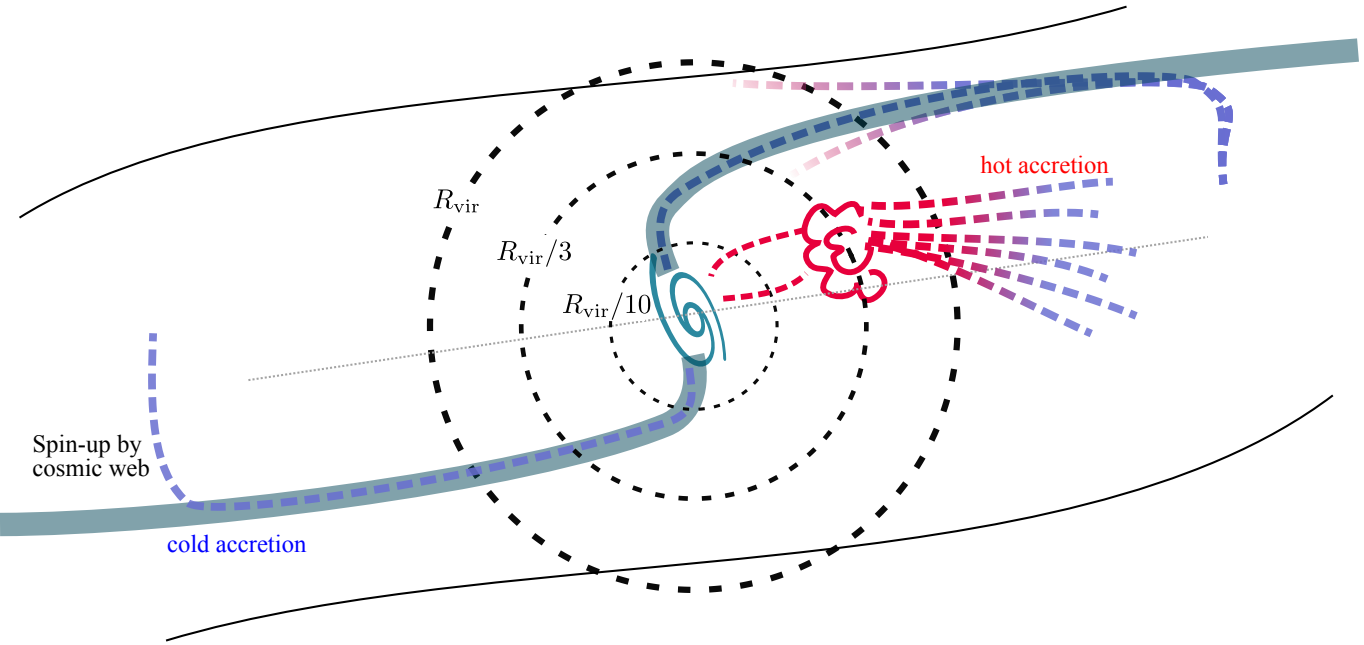
Loss of link with cosmic AM?

See Cadiou+21c

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

Origin of torque down (pressure or gravity)?

Loss of link with cosmic AM?

See Cadiou+21c

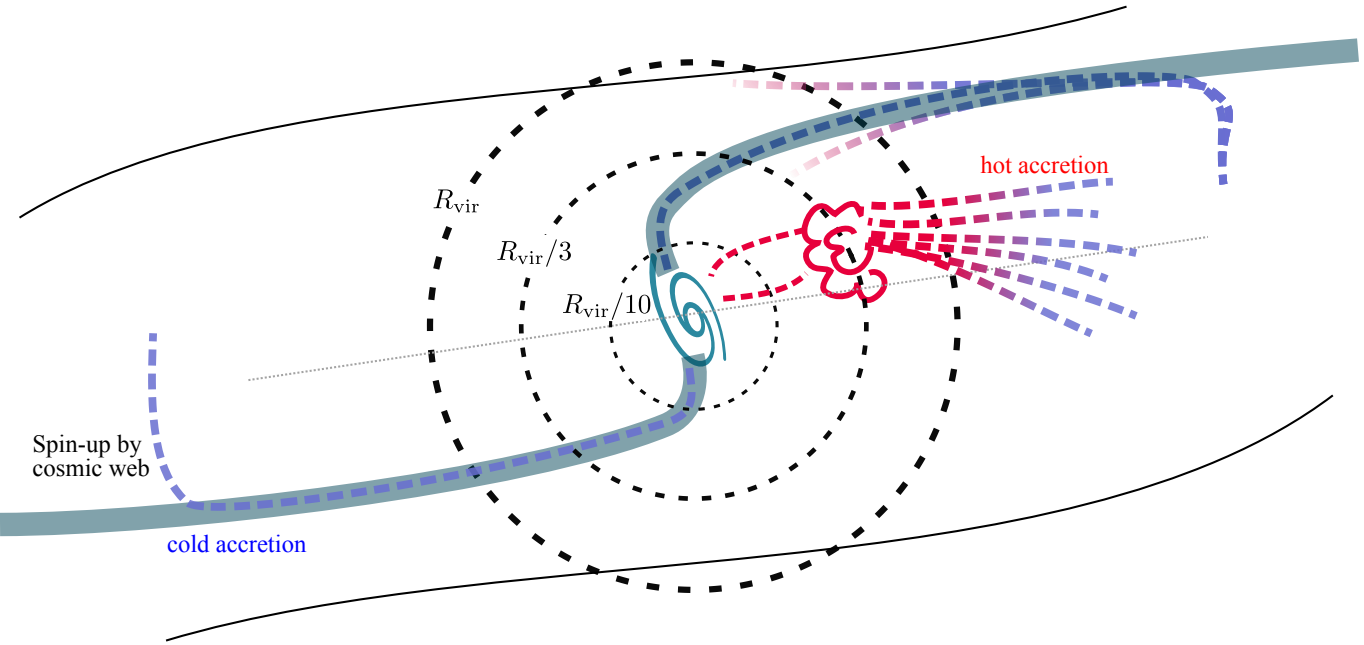
IV. Mixing in inner disk & bulge

Fraction that ends up in disk vs. IGM?

Influence of galactic physics?

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

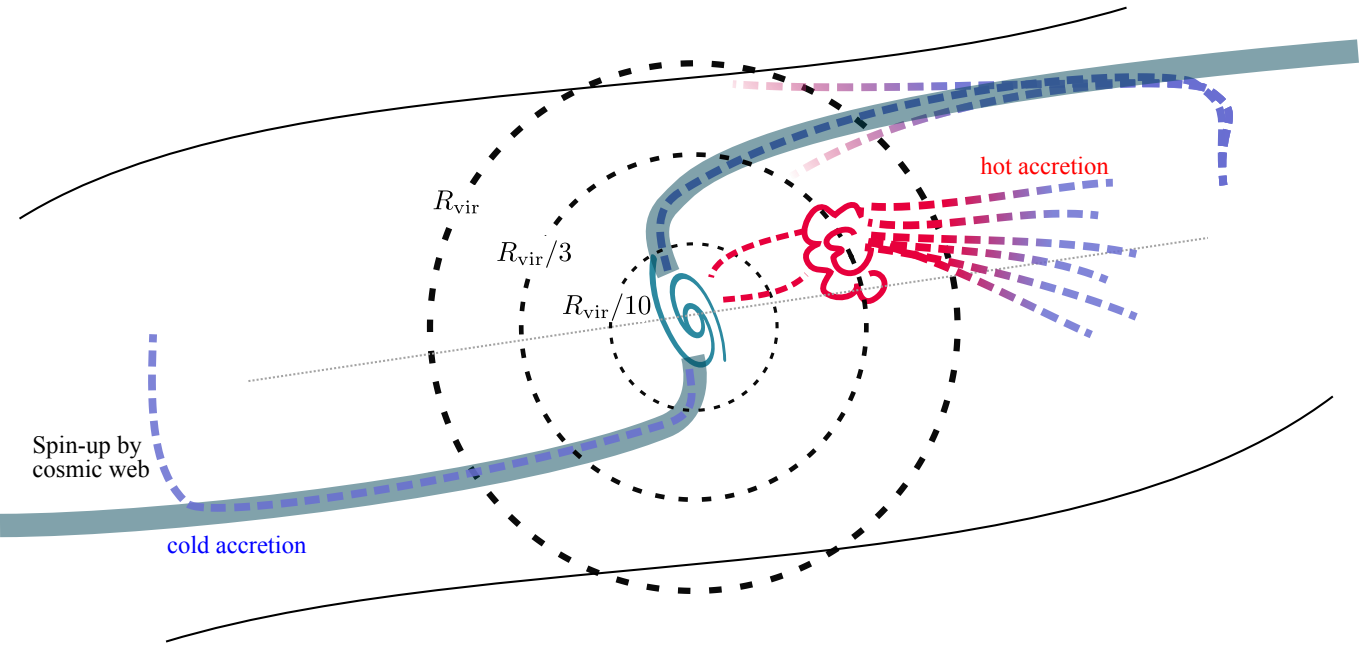
II. Transport at constant AM

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

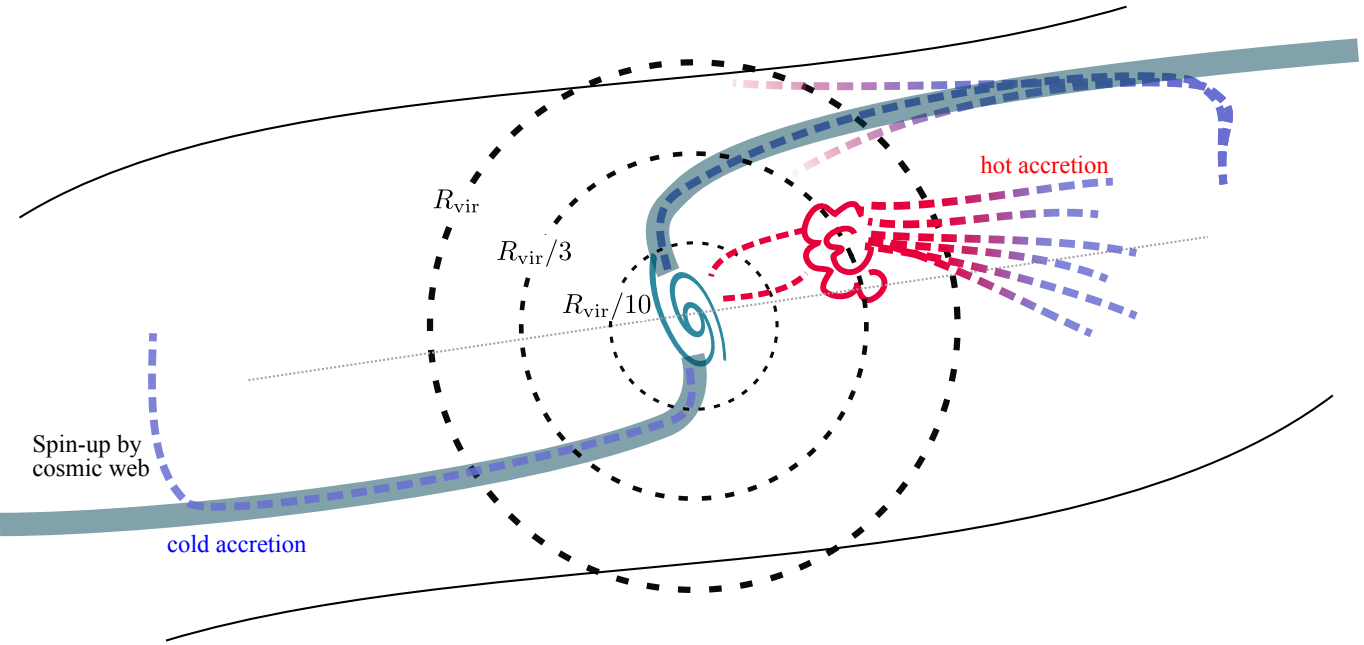
Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

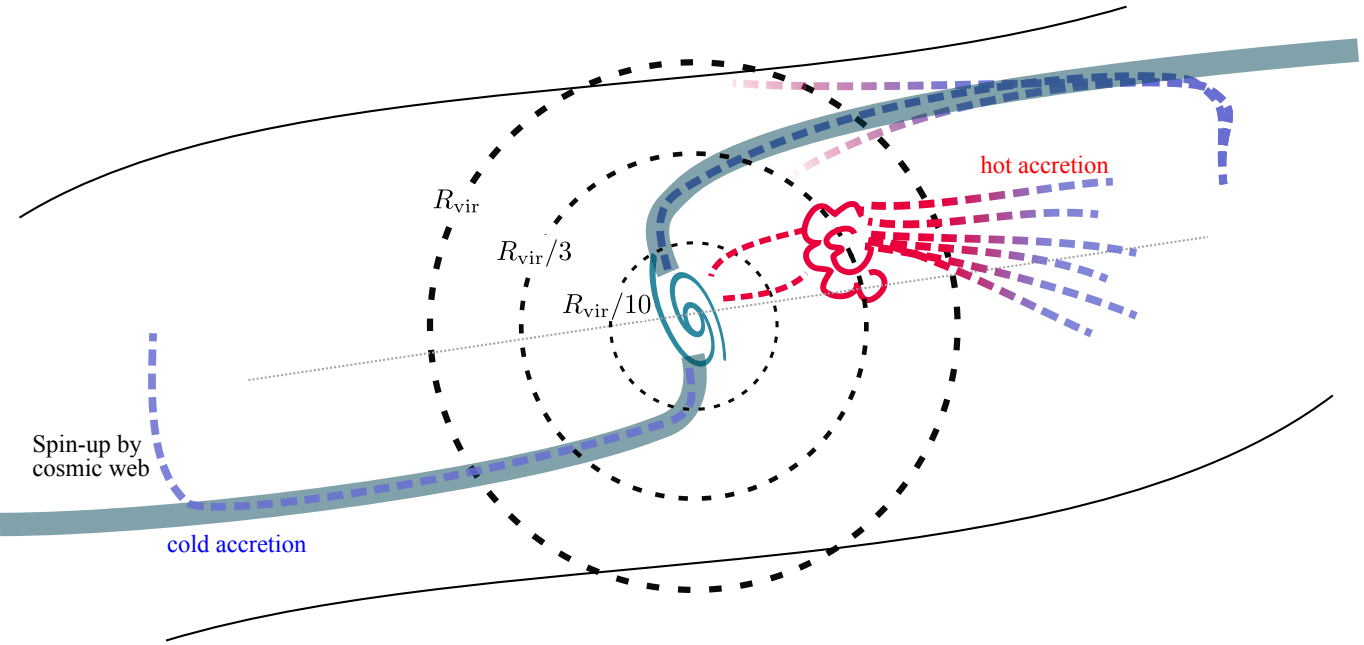
Origin of torque down (pressure or gravity)?

Loss of link with cosmic AM?

IV. Mixing in inner disk & bulge

[Danovich+15]

The origin of high z angular momentum



I. Torque with cosmic web

Predict pre-accretion AM?

Alignment with environment?

II. Transport at constant AM

Same evolution in cold/hot accretion modes?

III. Torque down in inner halo

Origin of torque down (pressure or gravity)?

Loss of link with cosmic AM?

IV. Mixing in inner disk & bulge

Fraction that ends up in disk vs. IGM?

Influence of galactic physics?

[Danovich+15]