The origin of angular momentum: from cosmic web to galaxy formation

Corentin Cadiou
@KITP | 7 Feb 2023

LUNDS UNIVERSITET

erc

DiRAC

The origin of angular momentum: from cosmic web to galaxy formation

SP What is the origin of angular momentum in high redshift galaxies?

The origin of angular momentum in high redshift galaxies is not yet fully understood and is an area of active research in astrophysics. The prevailing theory is that angular momentum is acquired through a process called tidal torquing, where interactions with nearby galaxies and large-scale structures in the early universe cause a transfer of angular momentum to the protogalactic gas. This results in the formation of rotating disks, which then give rise to spiral and elliptical galaxies. However, other mechanisms, such as gas accretion and mergers with other galaxies, may also play a role in shaping the angular momentum of high redshift galaxies.

Corentin Cadiou
@KITP | 7 Feb 2023

LUNDS UNIVERSITET

erc

DiRAC

The origin of angular momentum: from cosmic web to galaxy formation

SP What is the origin of angular momentum in high redshift galaxies?

The origin of angular momentum in high redshift galaxies is not yet fully understood and is an area of active research in astrophysics. The prevailing theory is that angular momentum is acquired through a process called tidal torquing, where interactions with nearby galaxies and large-scale structures in the early universe cause a transfer of angular momentum to the protogalactic gas. This results in the formation of rotating disks, which then give rise to spiral and elliptical galaxies. However, other mechanisms, such as gas accretion and mergers with other galaxies, may also play a role in shaping the angular momentum of high redshift galaxies.

LUNDS UNIVERSITET

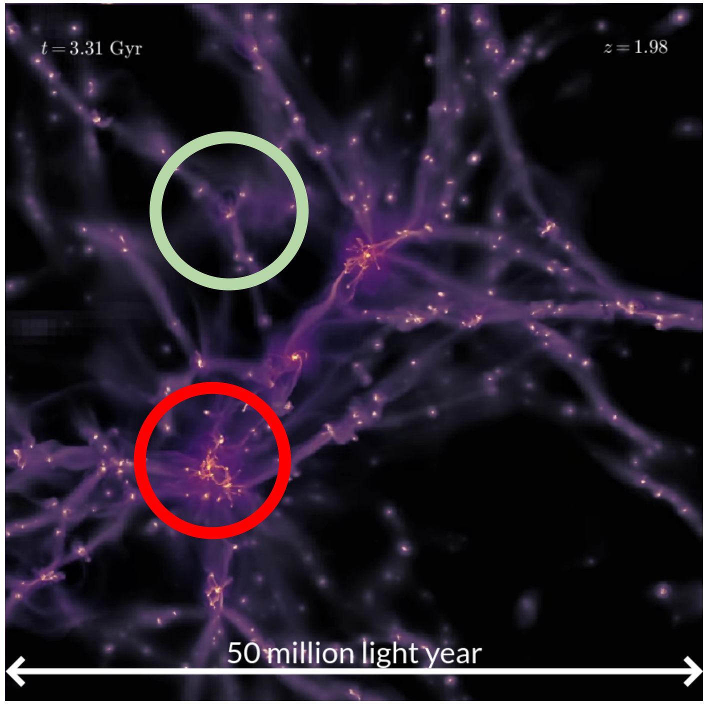
Corentin Cadiou
@KITP | 7 Feb 2023

erc

DiRAC

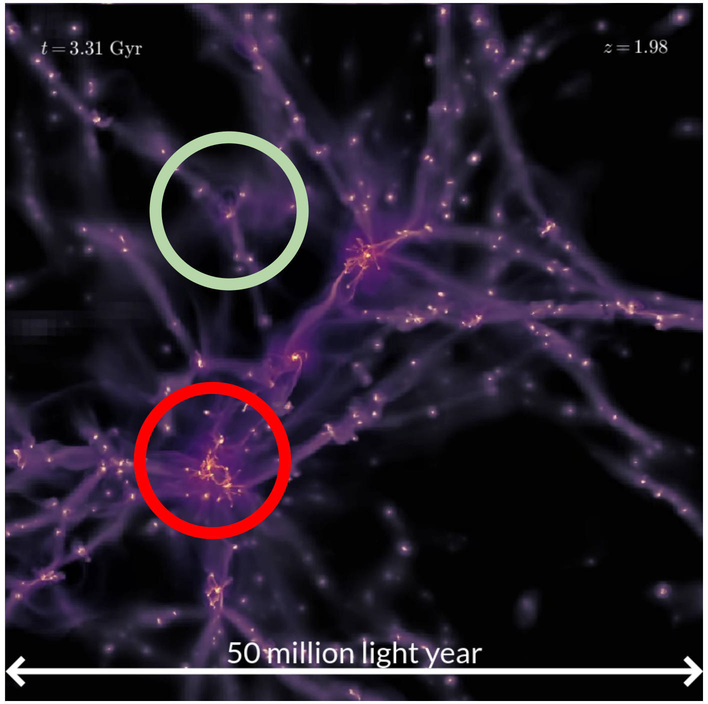
The effects of environment on halo properties

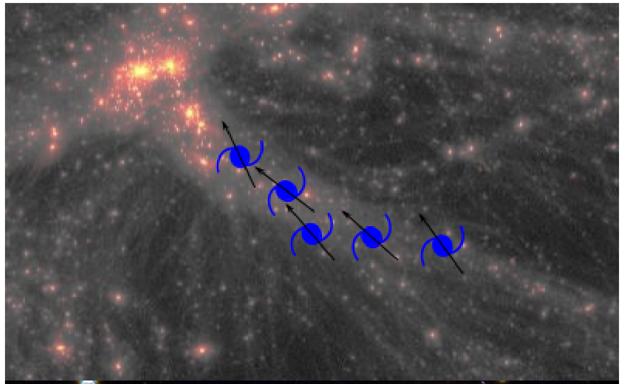
- $M_{\rm DM}$(node) > $M_{\rm DM}$(fil) > $M_{\rm DM}$(void), higher clustering



The effects of environment on halo properties

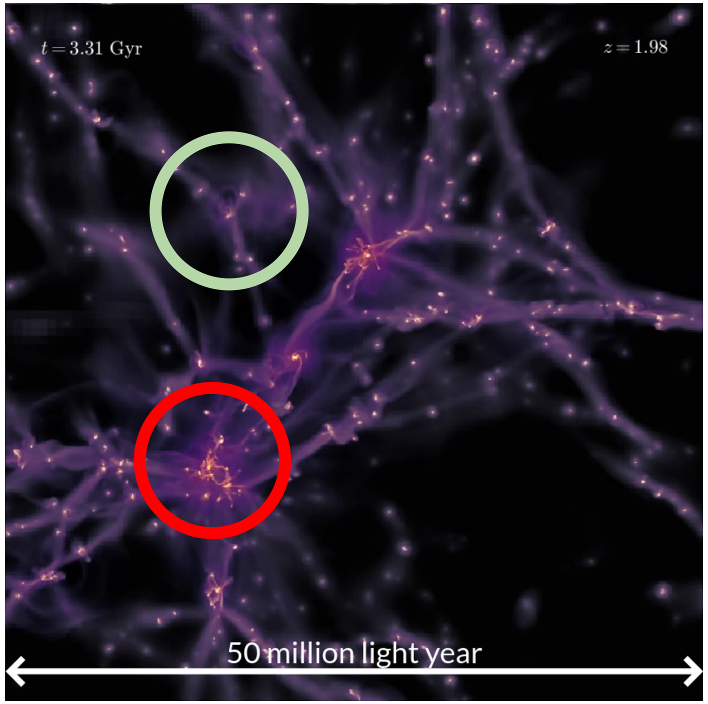
- $M_{\rm DM}$(node) > $M_{\rm DM}$(fil) > $M_{\rm DM}$(void), higher clustering
- spins align with cosmic web ⇒ issue for weak lensing

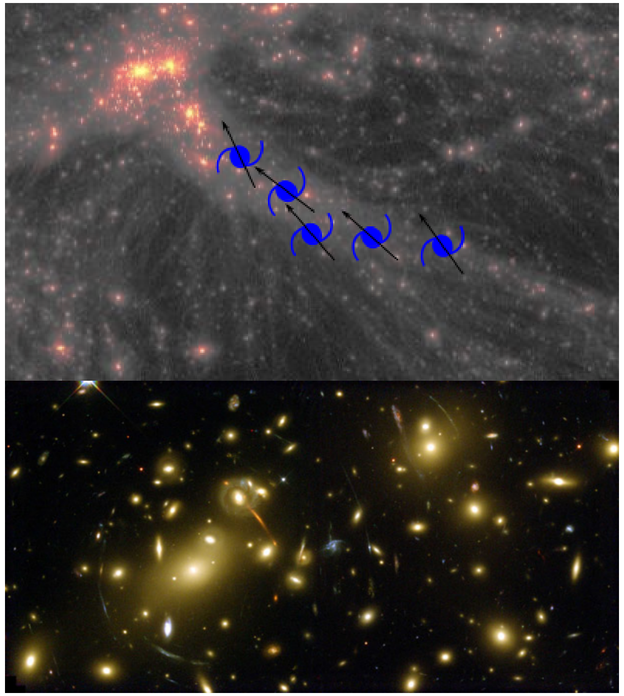


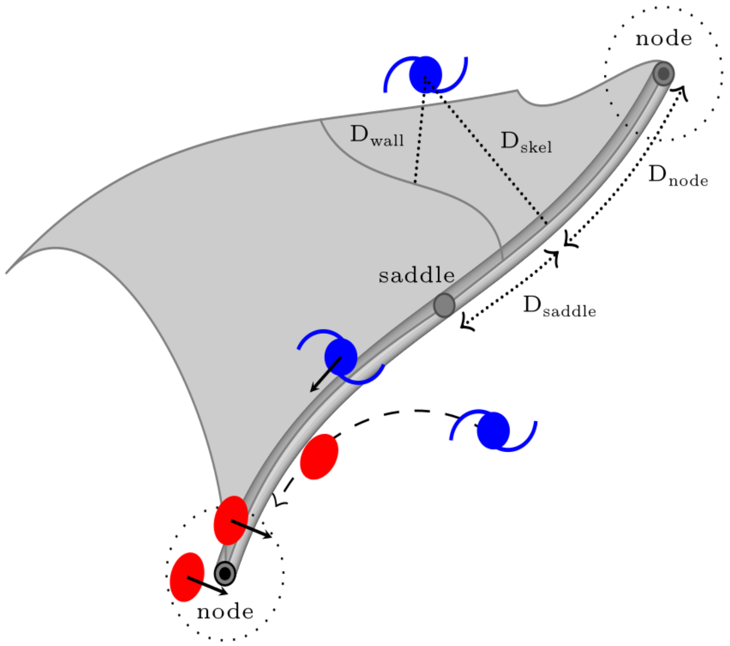


The effects of environment on halo properties

- M_{DM}(node) > M_{DM}(fil) > M_{DM}(void), higher clustering
- spins align with cosmic web ⇒ issue for weak lensing
- v/σ(fil) > v/σ(void) ⇒ bias in galaxy formation



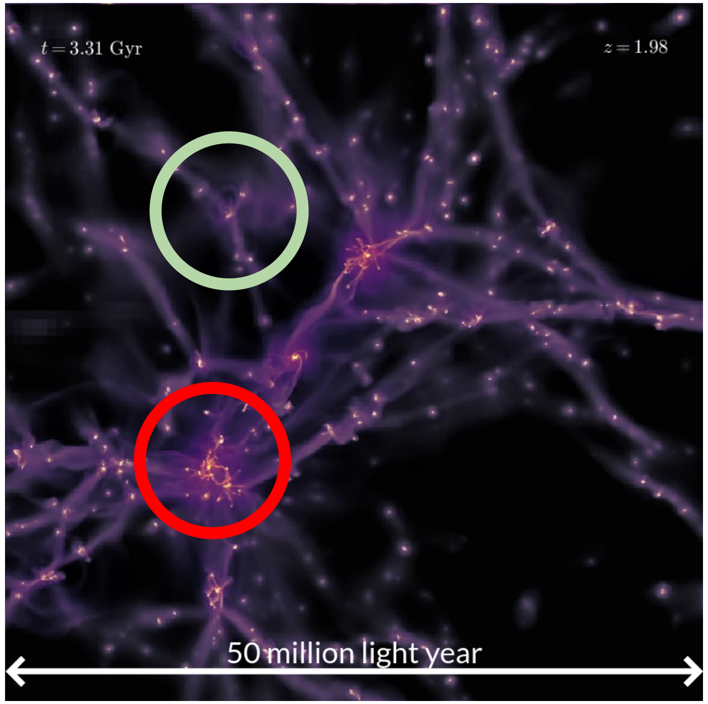


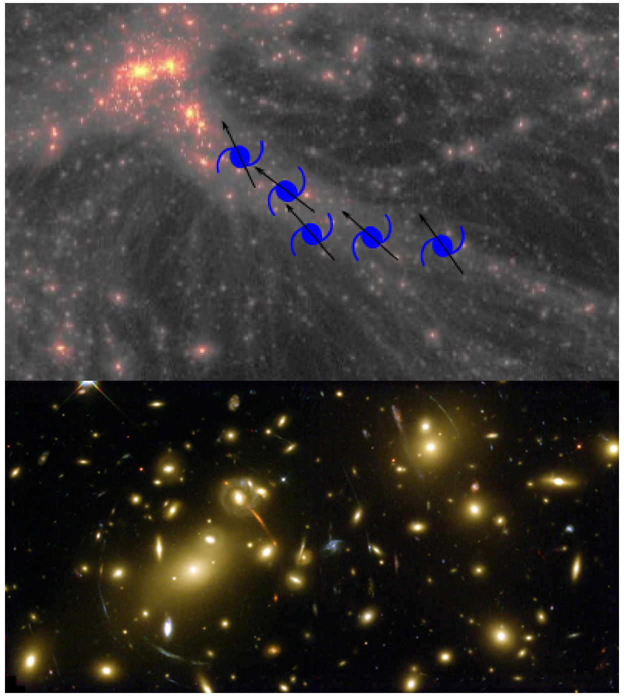


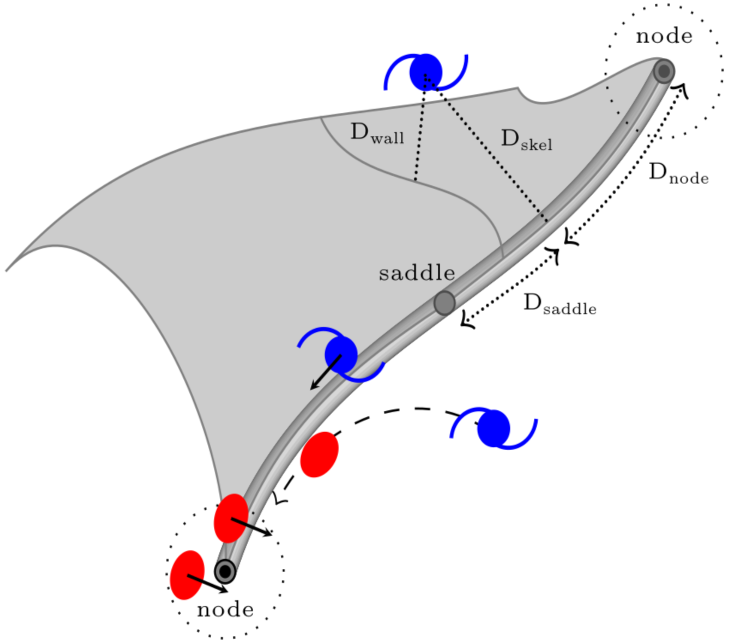
Kraljic+18 [see also Laigle15, Song+21,…]

The effects of environment on halo properties

- $M_{\rm DM}$(node) > $M_{\rm DM}$(fil) > $M_{\rm DM}$(void), higher clustering
- spins align with cosmic web ⇒ issue for weak lensing
- v/σ(fil) > v/σ(void) ⇒ bias in galaxy formation
- ….







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

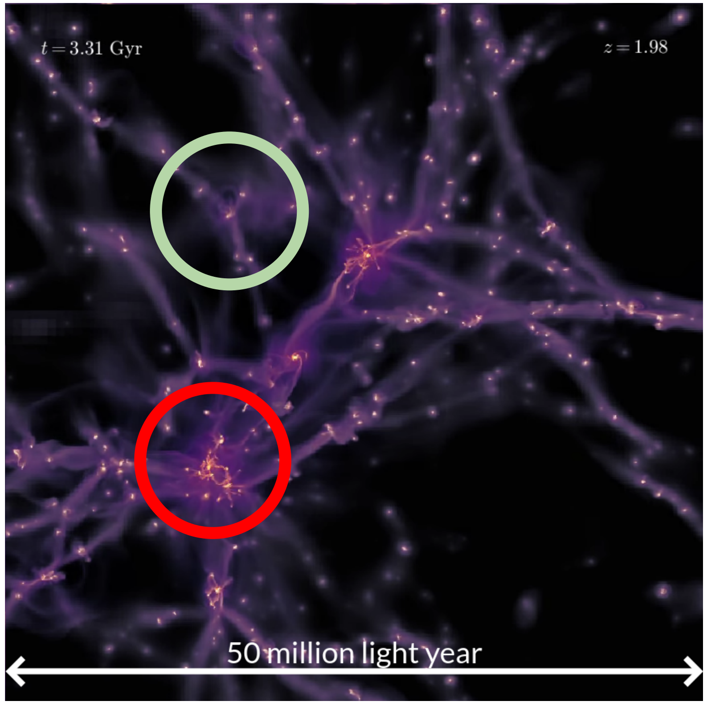
The effects of environment on halo properties

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?

The effects of environment on halo properties

Isotropic effects

Kaiser bias, cluster vs. groups, ...

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

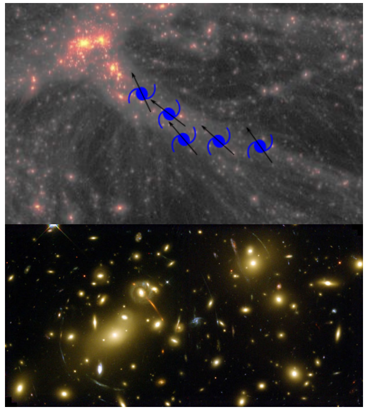
Mass regulated

An-isotropic effects

Intrinsic alignment, formation of disks?

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

Angular momentum regulated?



The effects of environment on halo properties

Isotropic effects

Kaiser bias, cluster vs. groups, ...

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

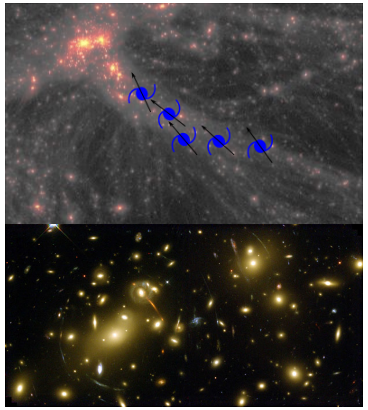
Mass regulated

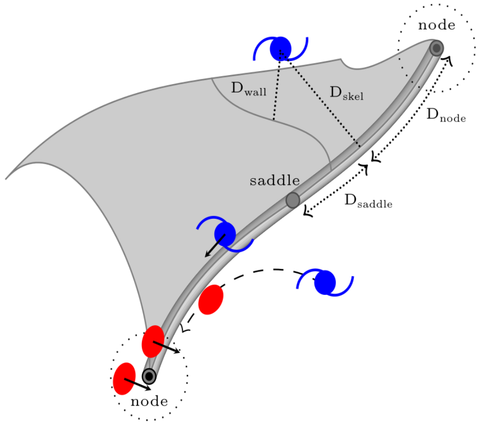
An-isotropic effects

Intrinsic alignment, formation of disks?

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

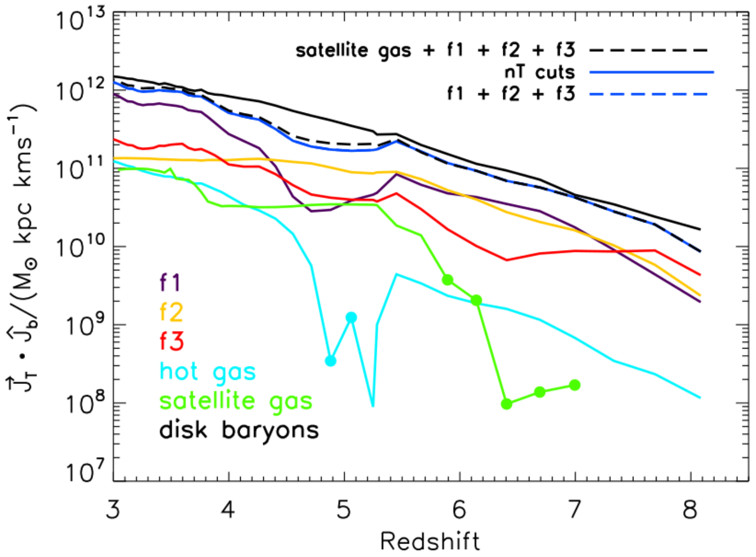
Angular momentum regulated?



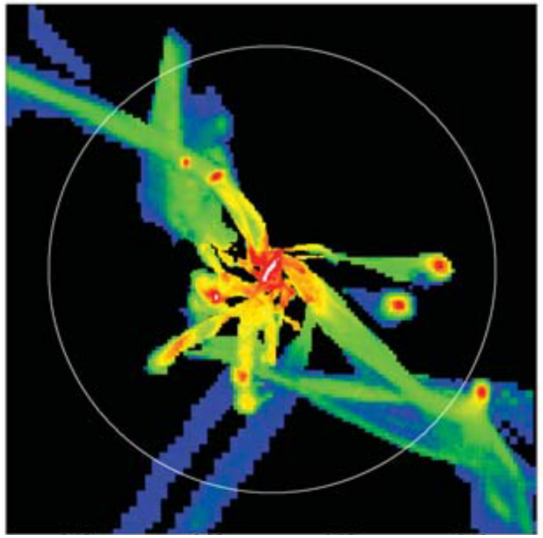


Angular momentum: bridging galaxies to cosmology?

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

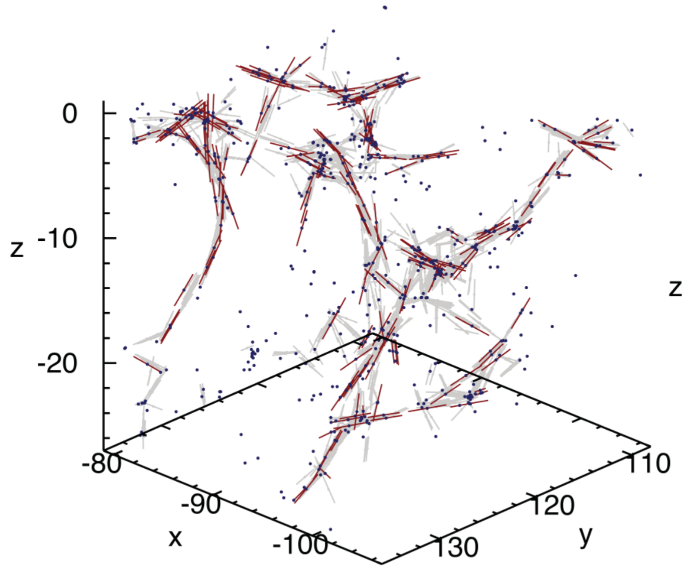


Tillson+15



Dekel&Birnboim 06

Lower-*zs*:
intrinsic alignment problem

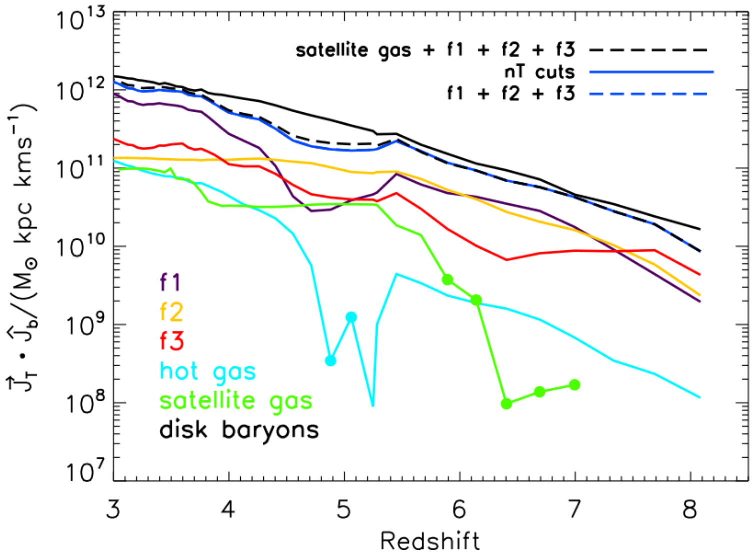


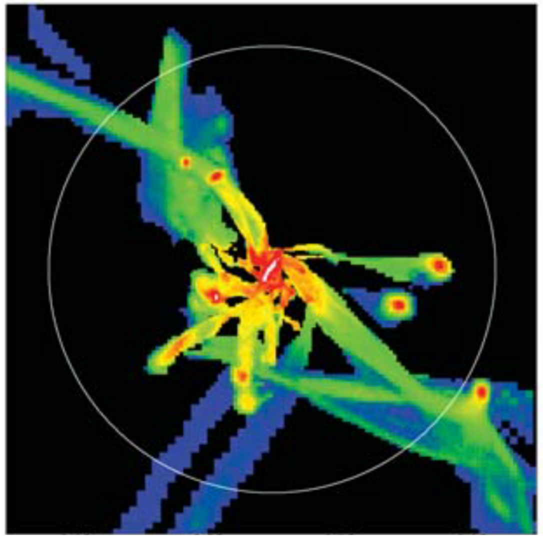
Tempel+13

[AM: Dekel & Birboim 06; Stewart+11; Kim+11; Pichon+11; Codis+12; Danovich+12,15; Stewart+13; Codis+15; Prieto+15; Tillson+15; Stewart+17, Cadiou+21,...]

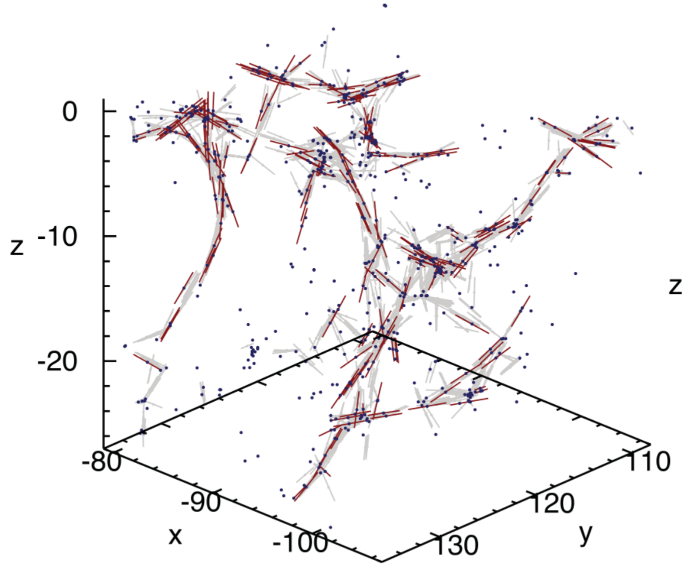
Angular momentum: bridging galaxies to cosmology?

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





Lower-zs:
intrinsic alignment problem



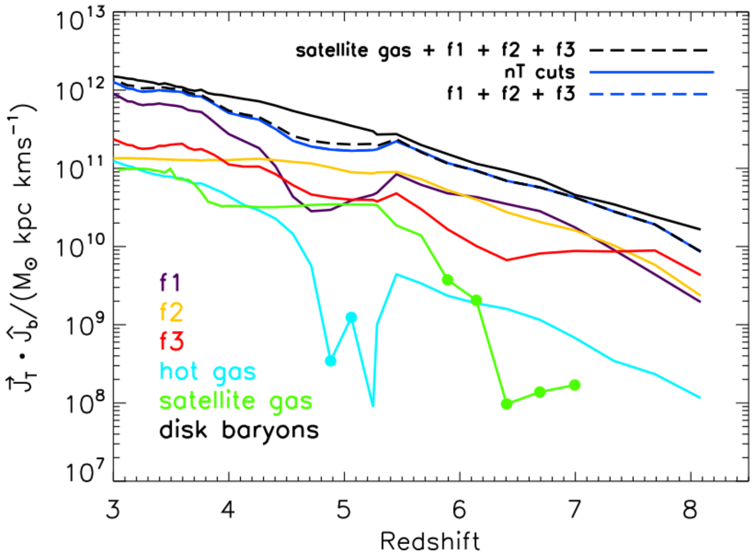
Tillson+15 Dekel&Birnboim 06 Tempel+13

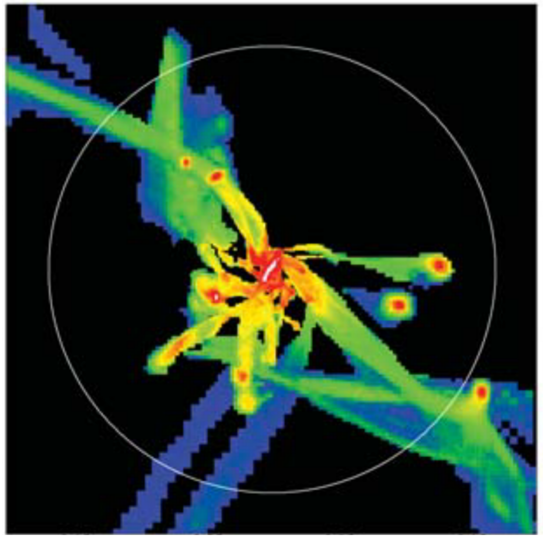
How do we study these effects?

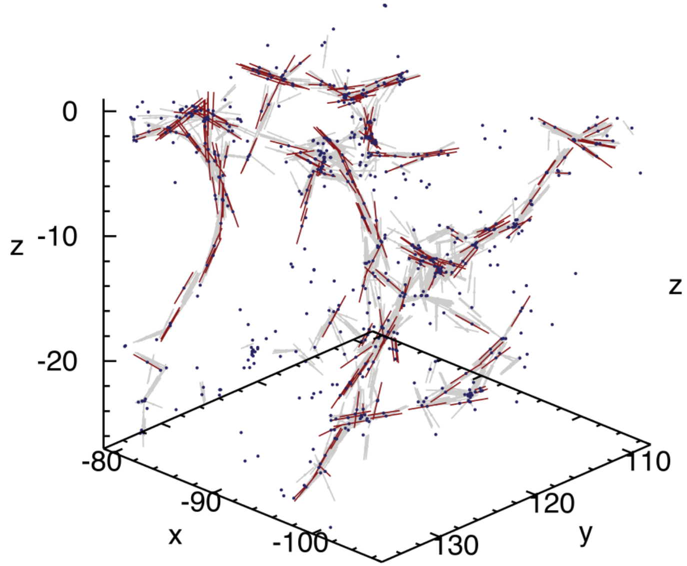
Angular momentum: bridging galaxies to cosmology?

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

Lower-zs:
intrinsic alignment problem







Tillson+15 Dekel&Birnboim 06 Tempel+13

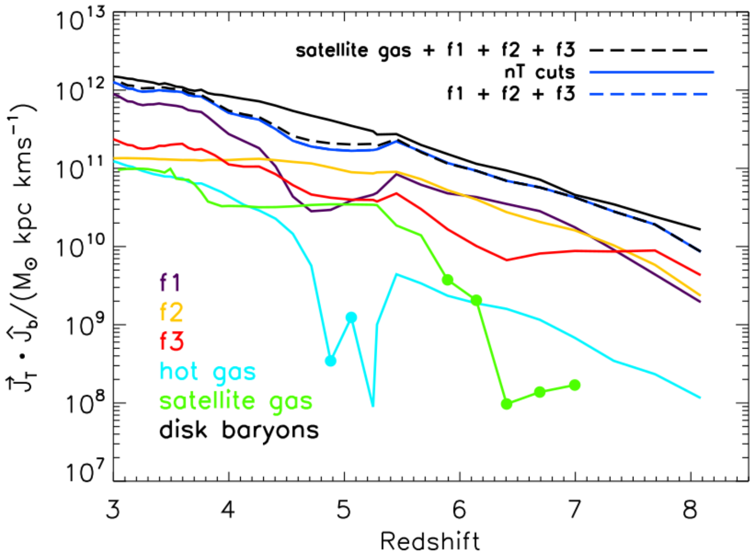
How do we study these effects?

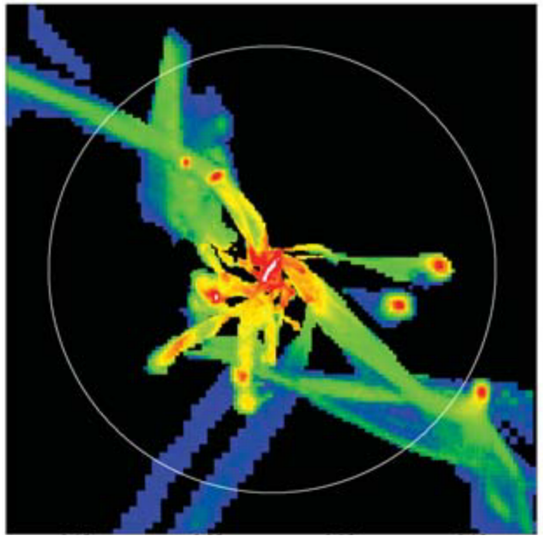
Large volumes

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

Angular momentum: bridging galaxies to cosmology?

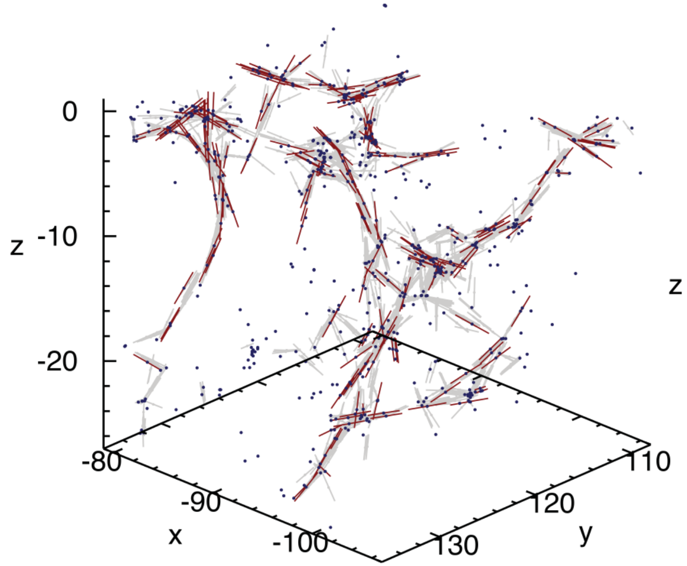
High-z:
most of mass + AM flow along filaments





Tillson+15 Dekel&Birnboim 06

Lower-zs:
intrinsic alignment problem

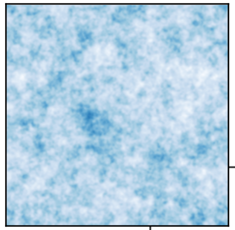


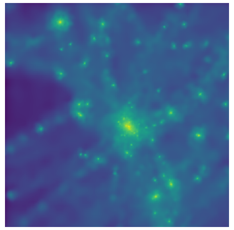
Tempel+13

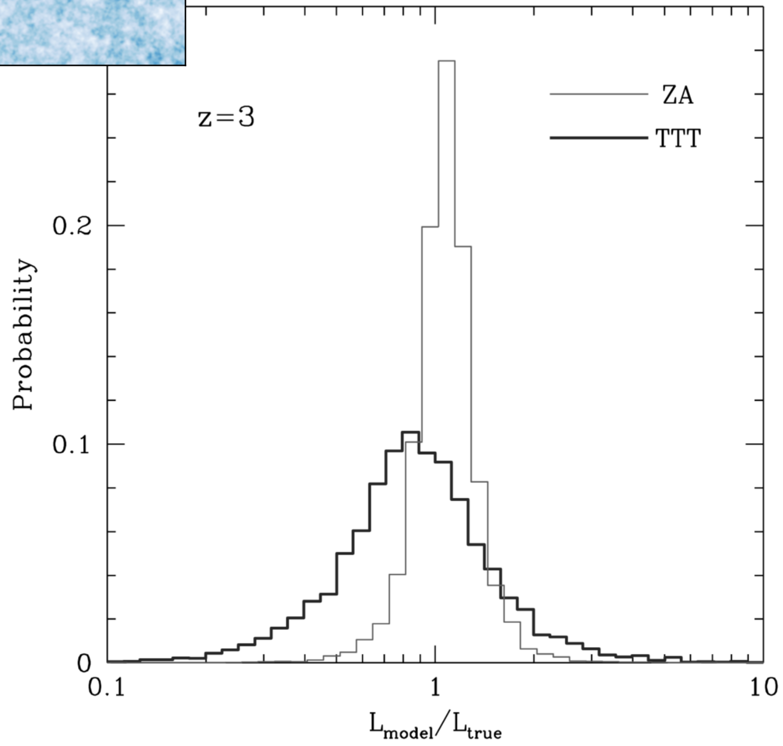
How do we study these effects?

Large volumes	This talk
sample $p(M_\star, M_{\rm DM}, \mathbf{J}, d_{\rm fil}, \dots)$	sample $p(\mathbf{J} \mid M_\star, M_{\rm DM}, d_{\rm fil}, \dots)$

Angular momentum: where are we?



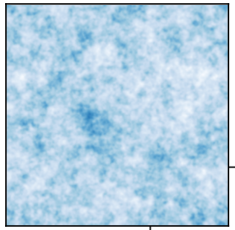


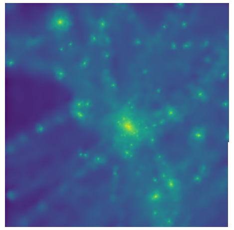


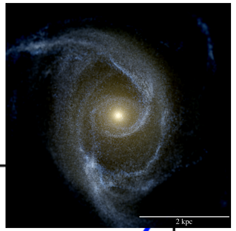
Porciani+02

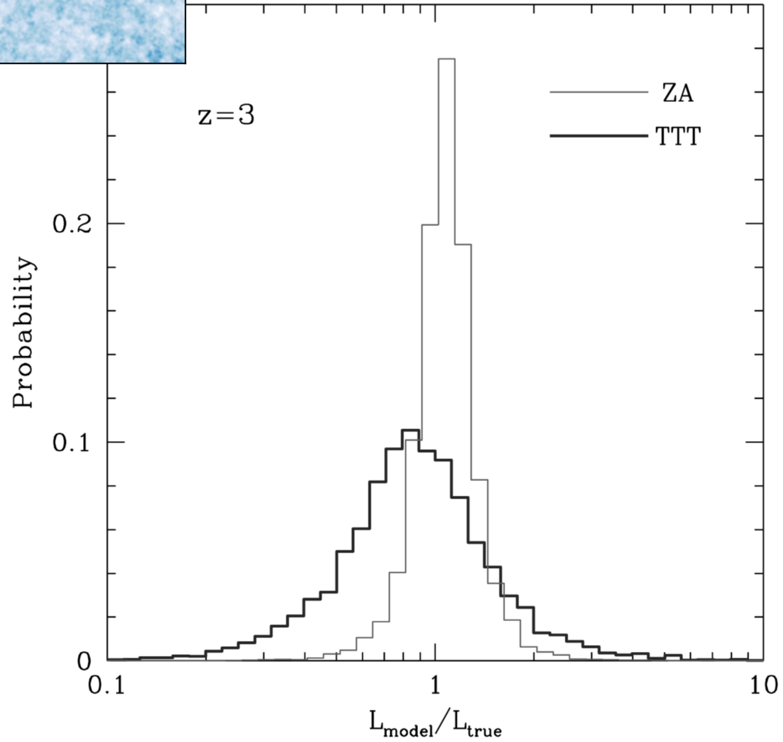
Predictions for $j_{\rm DM}$ remain qualitative

Angular momentum: where are we?

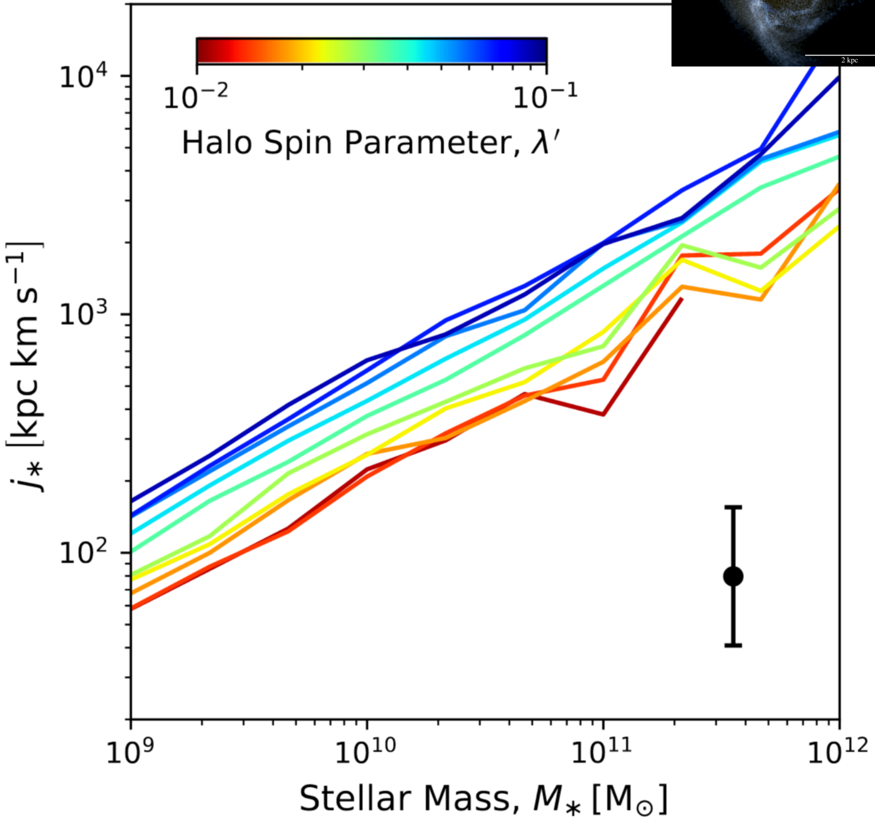








Porciani+02

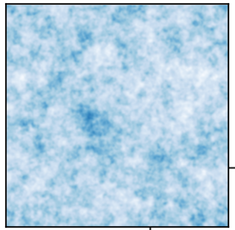


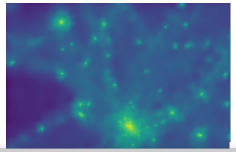
Rodriguez-Gomez+22

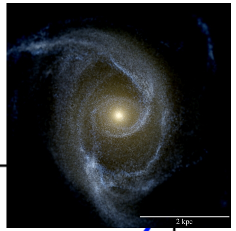
Predictions for $j_{\rm DM}$ remain qualitative

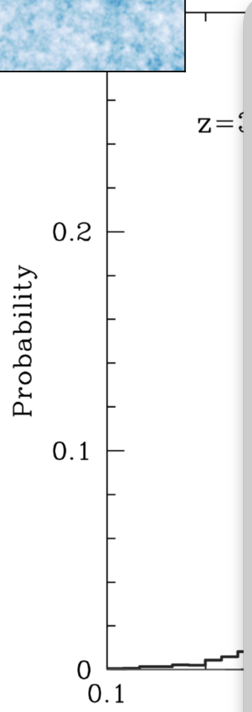
$j_{\rm DM} - j_\star$
weak correlation
(statistically strong)

Angular momentum: where are we?









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

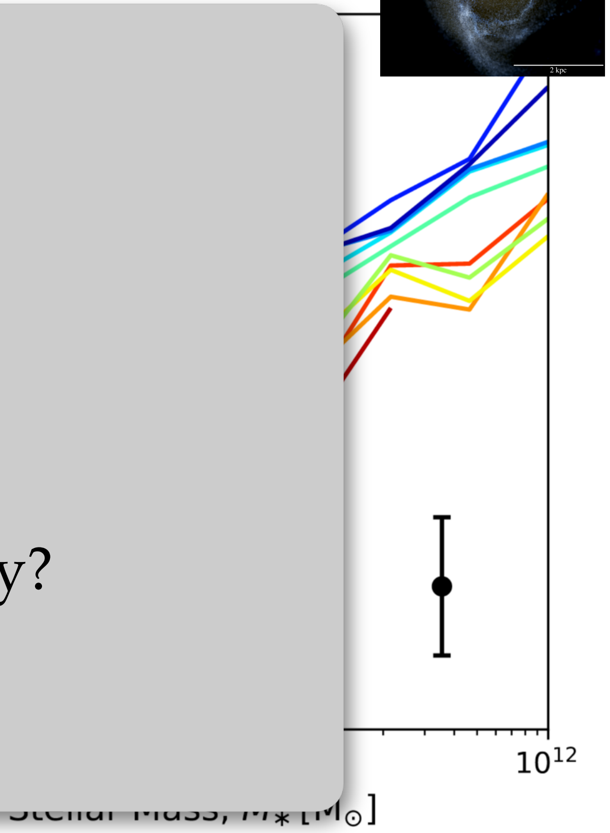
   Can we do better than statistical correlations?

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

   Can we spin a simulated galaxy up?

3. Where is the CW / galaxy boundary?

   Need detailed sims of the CGM



Porciani+02

Rodriguez-Gomez+22

Predictions for j_{DM} remain qualitative

$j_{\mathrm{DM}} - j_{\star}$
weak correlation
(statistically strong)

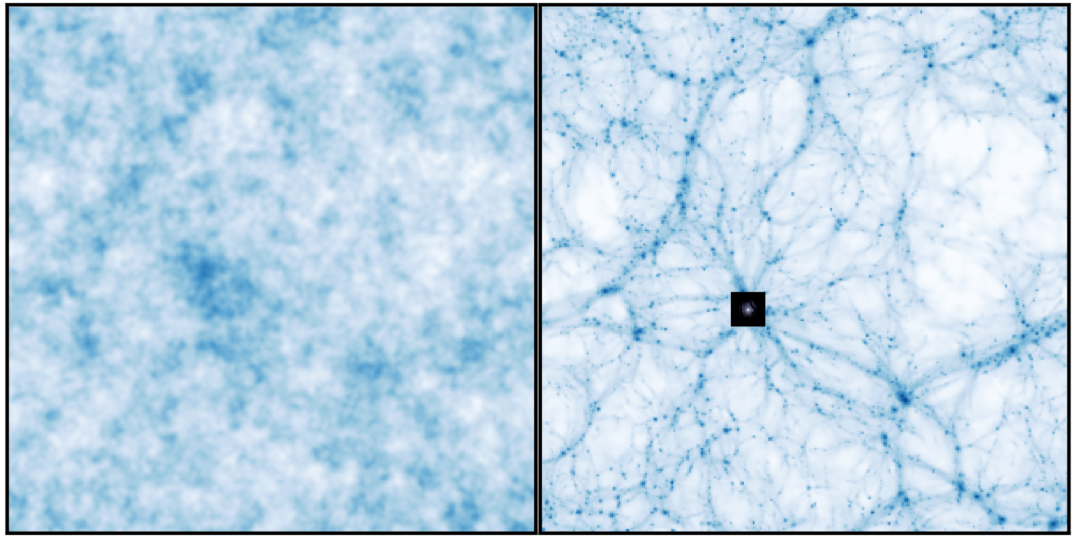
Is j_{DM} chaotic or our theory poor?

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

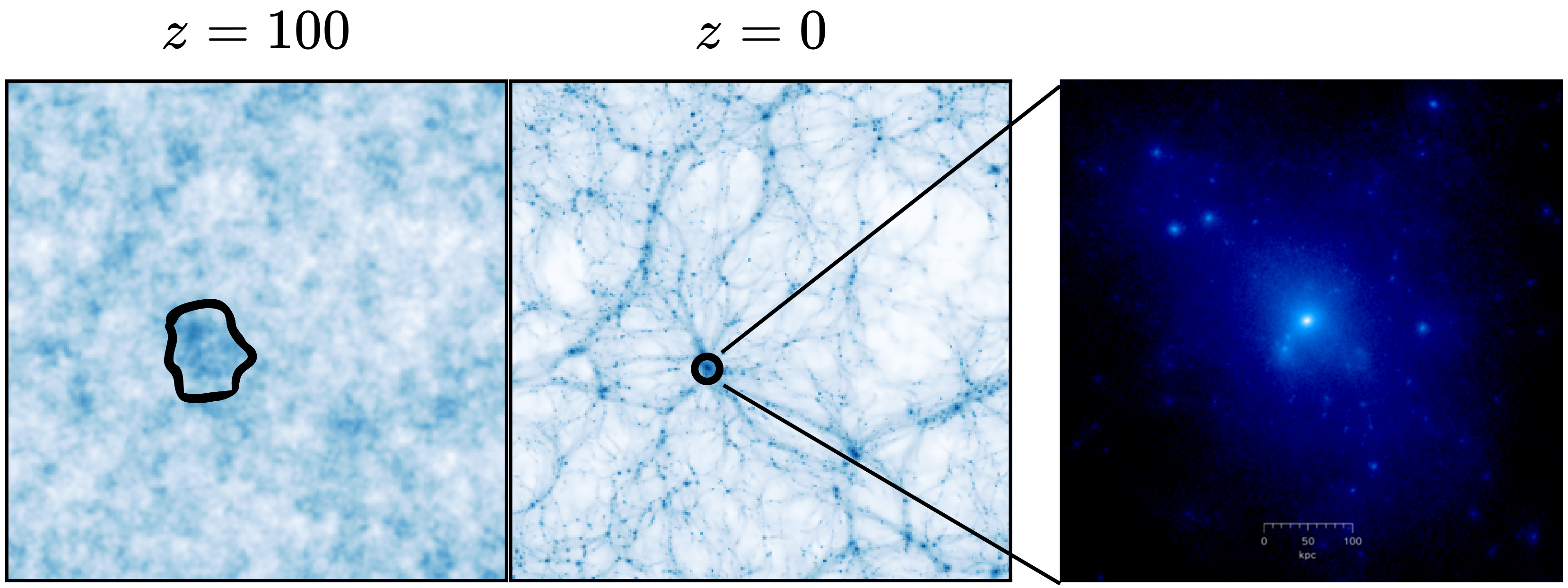
CC+21a, arXiv: 2012.02201

Predicting angular momentum

$z = 100$ $z = 0$



Predicting angular momentum



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

Note: vanishes at 1st order in a sphere

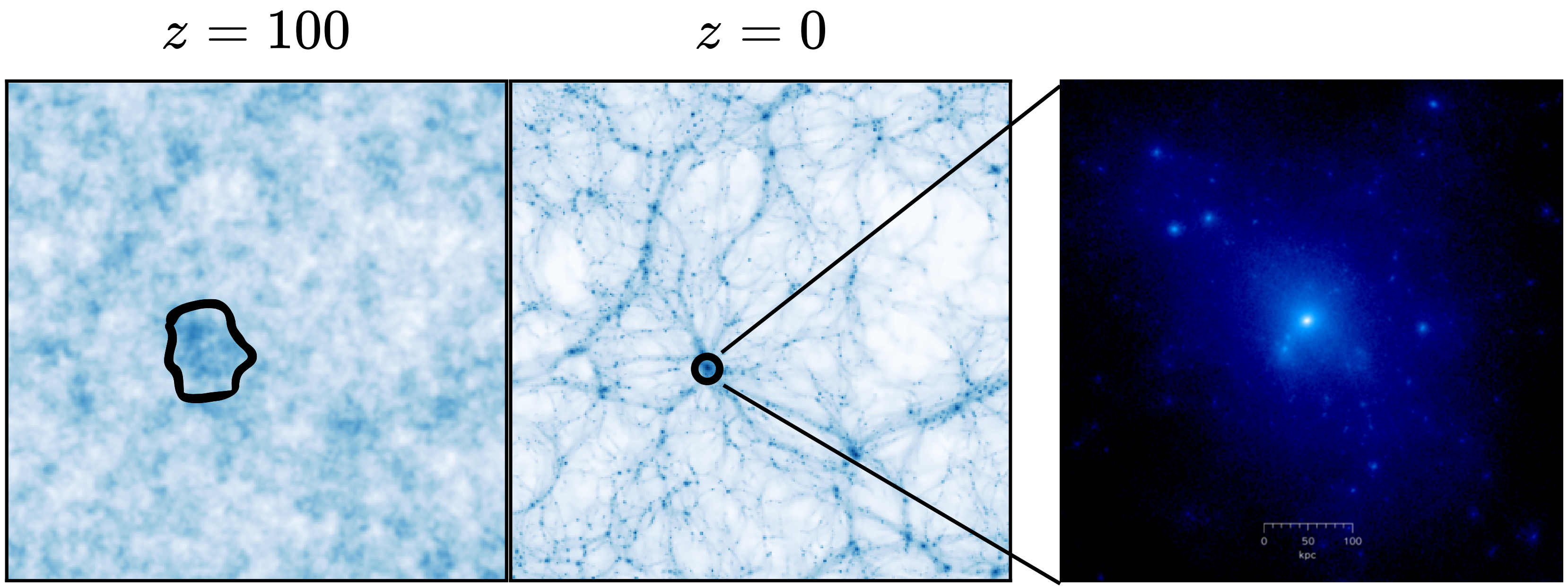
$$\int_{\Gamma} \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla\phi = \int_{\partial\Gamma} \phi(q)(\mathbf{q} - \bar{\mathbf{q}}) \times \mathrm{d}\mathbf{S}$$

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

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

[White 84]

Predicting angular momentum



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

Position w.r.t. center

Note: vanishes at 1st order in a sphere

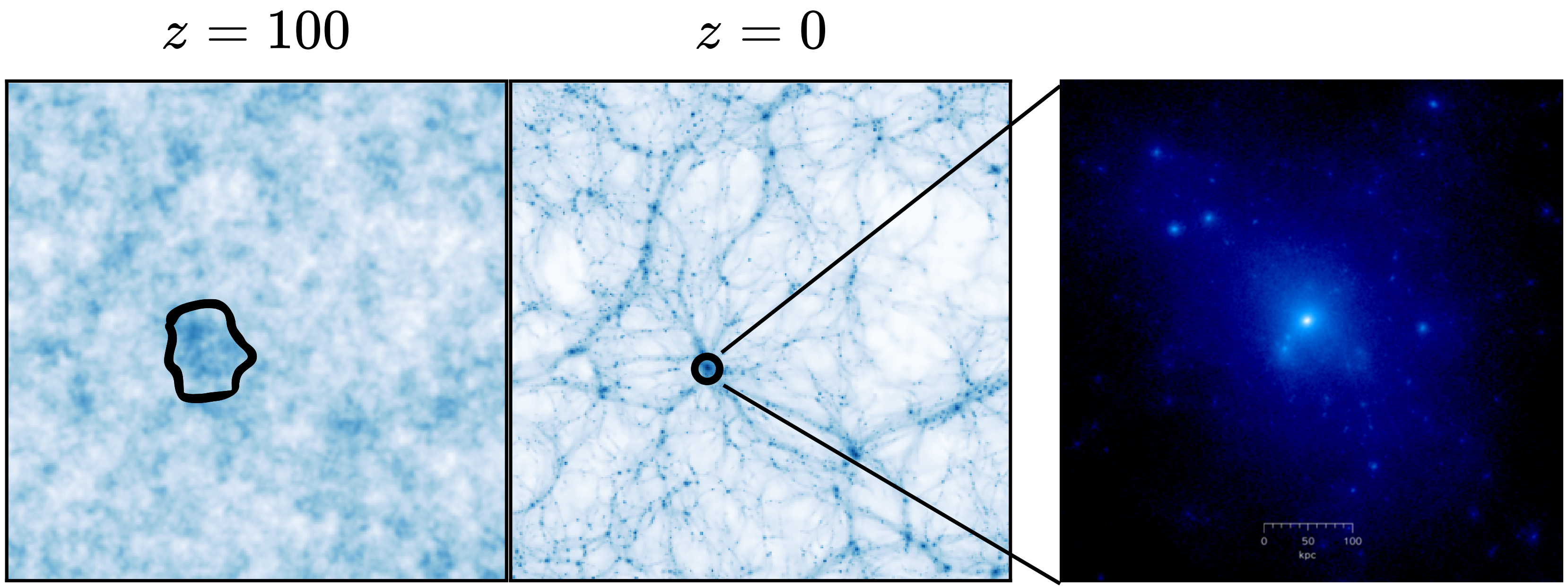
$$\int_\Gamma \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla\phi = \int_{\partial\Gamma} \phi(q)(\mathbf{q} - \bar{\mathbf{q}}) \times \mathrm{d}\mathbf{S}$$

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

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

[White 84]

Predicting angular momentum



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

Position w.r.t. center

Velocity

Note: vanishes at 1st order in a sphere

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

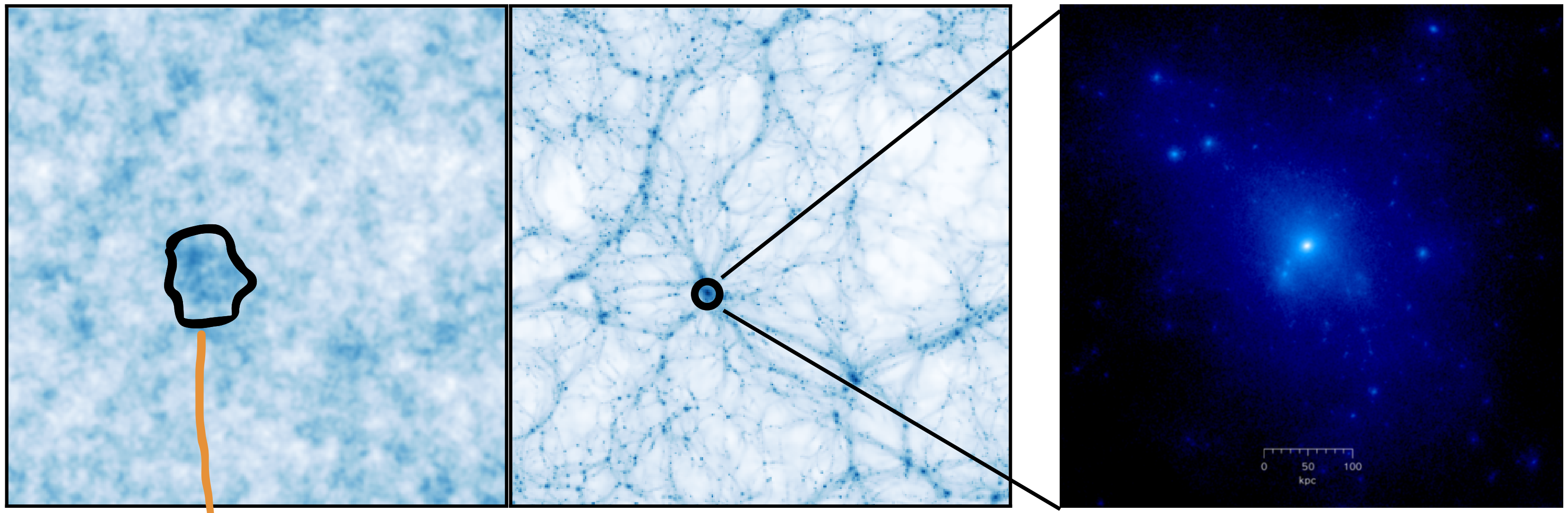
Note: the following is a (**poor**) approximation:

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

[White 84]

Predicting angular momentum

$z = 100$ $\qquad$ $z = 0$



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

Position w.r.t. center

Velocity

Note: vanishes at 1st order in a sphere

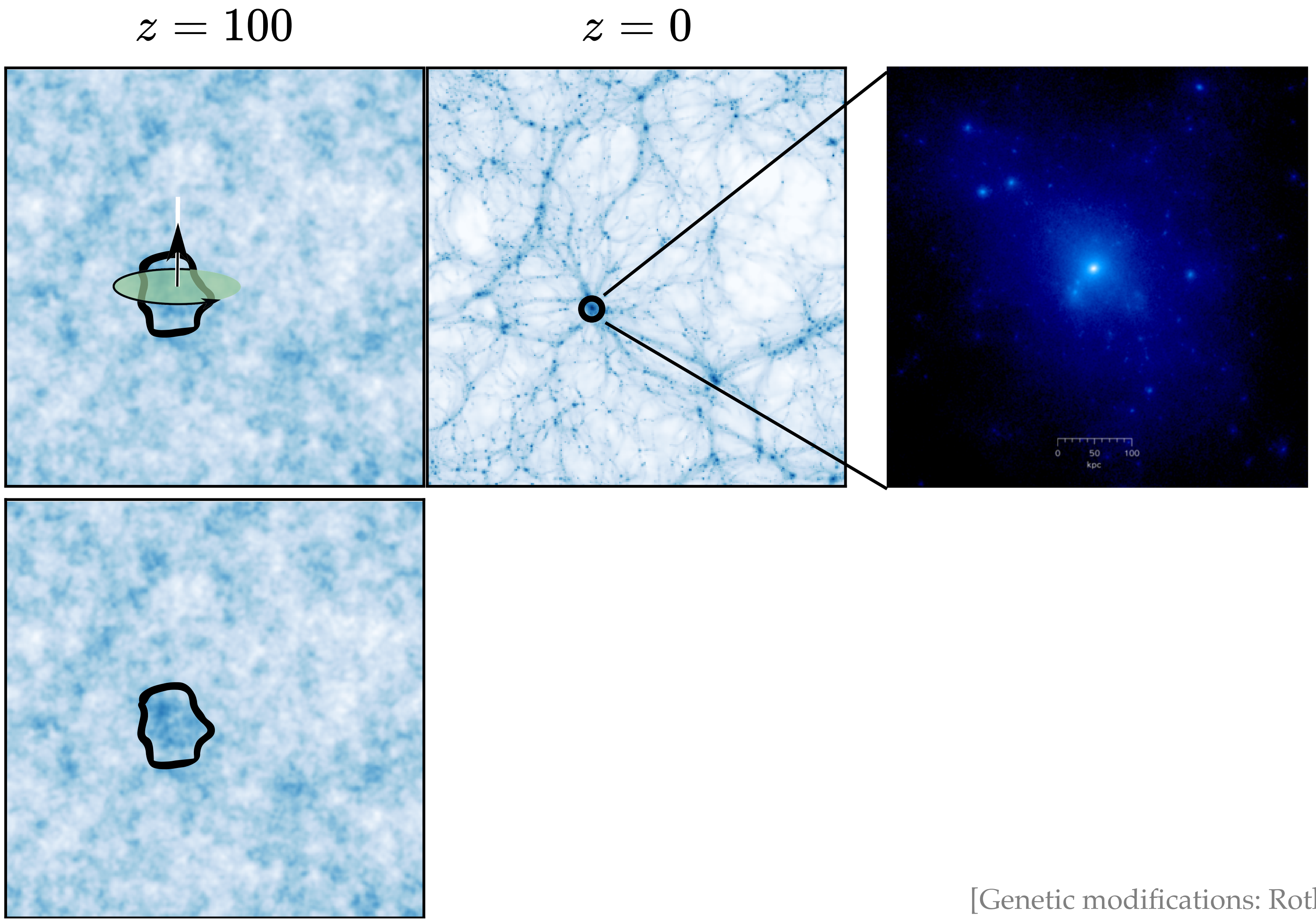
$$\int_\Gamma \mathrm{d}^3 q (\mathbf{q} - \bar{\mathbf{q}}) \times \nabla\phi = \int_{\partial\Gamma} \phi(q)(\mathbf{q} - \bar{\mathbf{q}}) \times \mathrm{d}\mathbf{S}$$

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

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

[White 84]

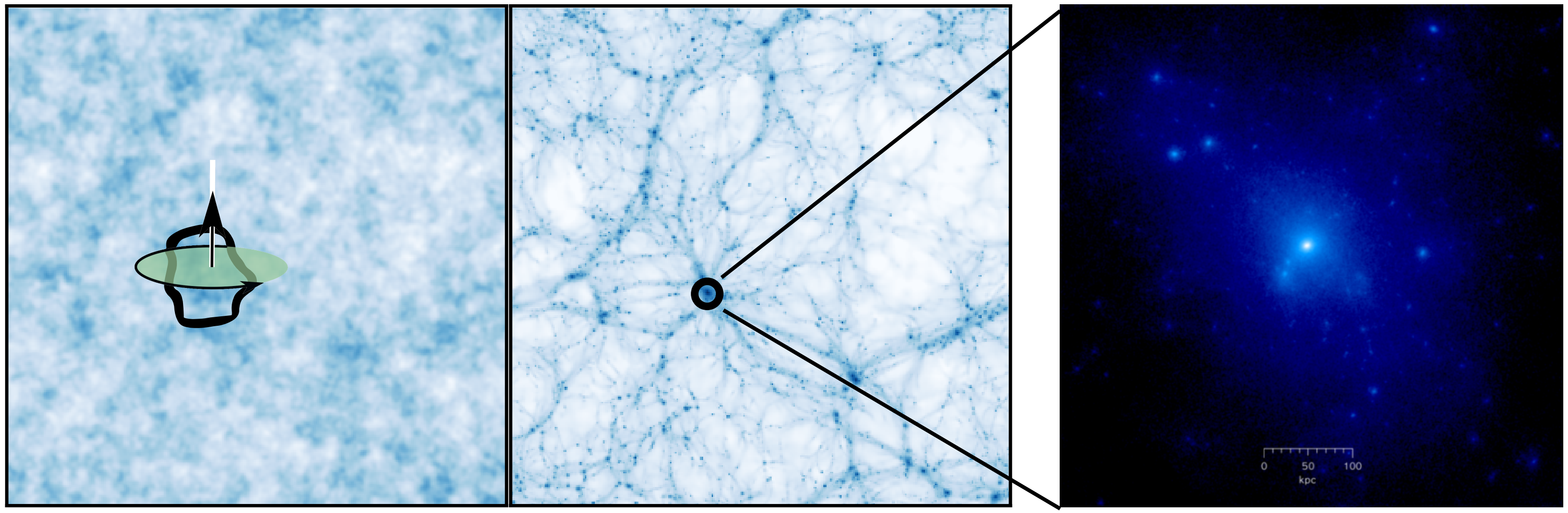
Predicting angular momentum

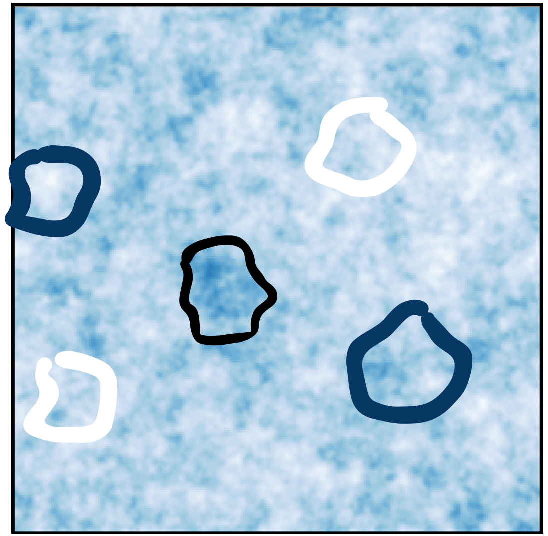


[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum

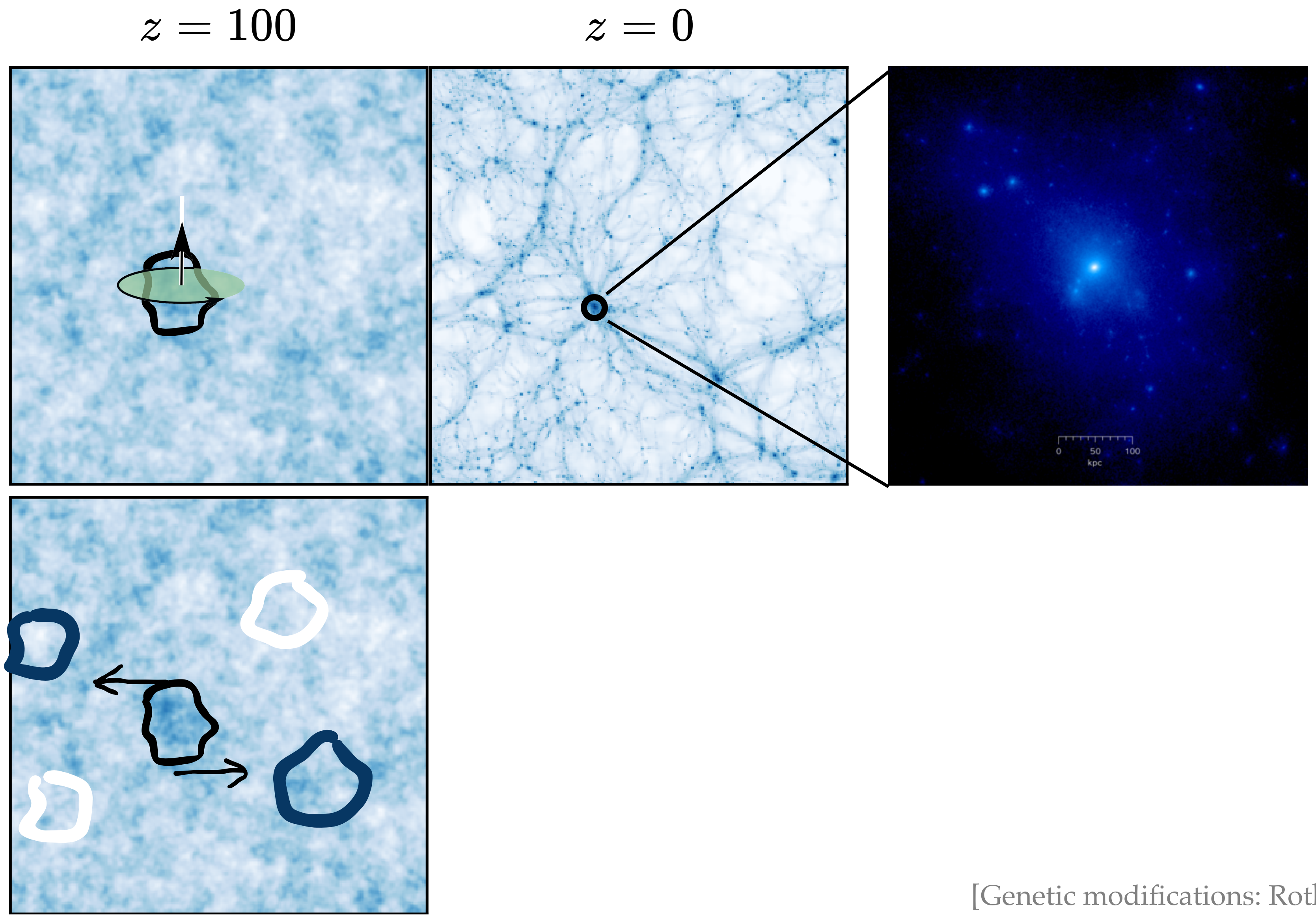
$z = 100$ $z = 0$





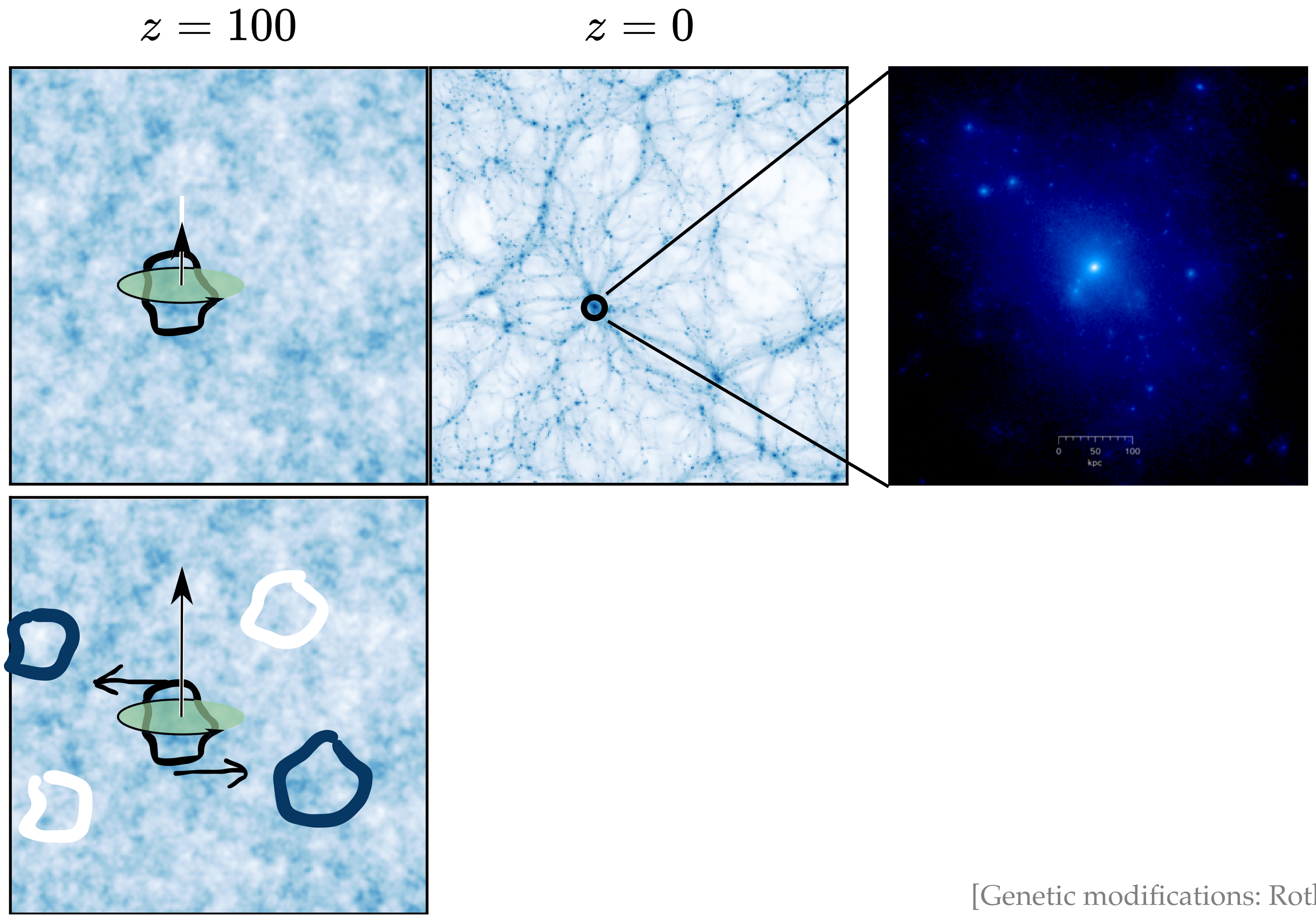
[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum



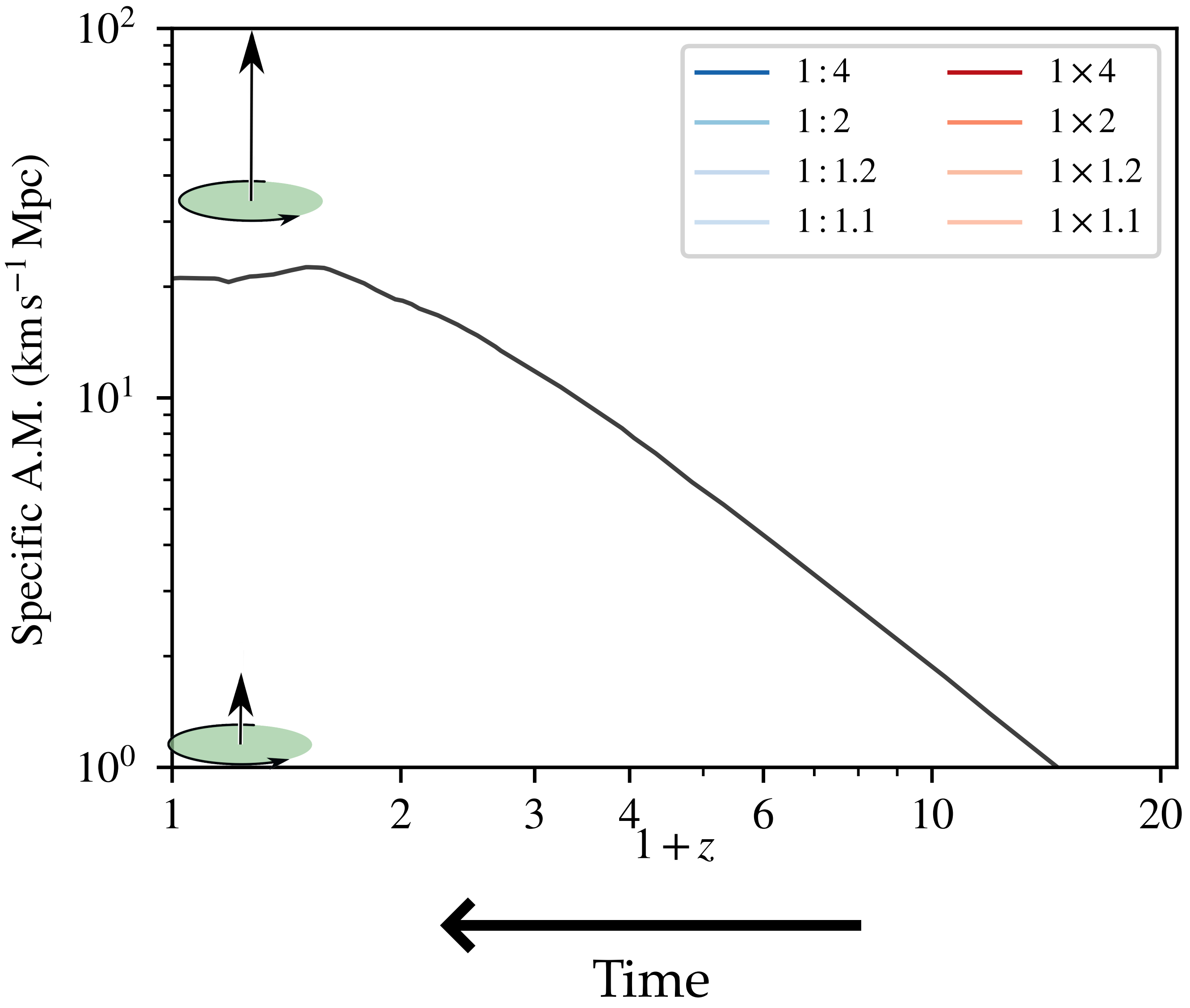
[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

Predicting angular momentum

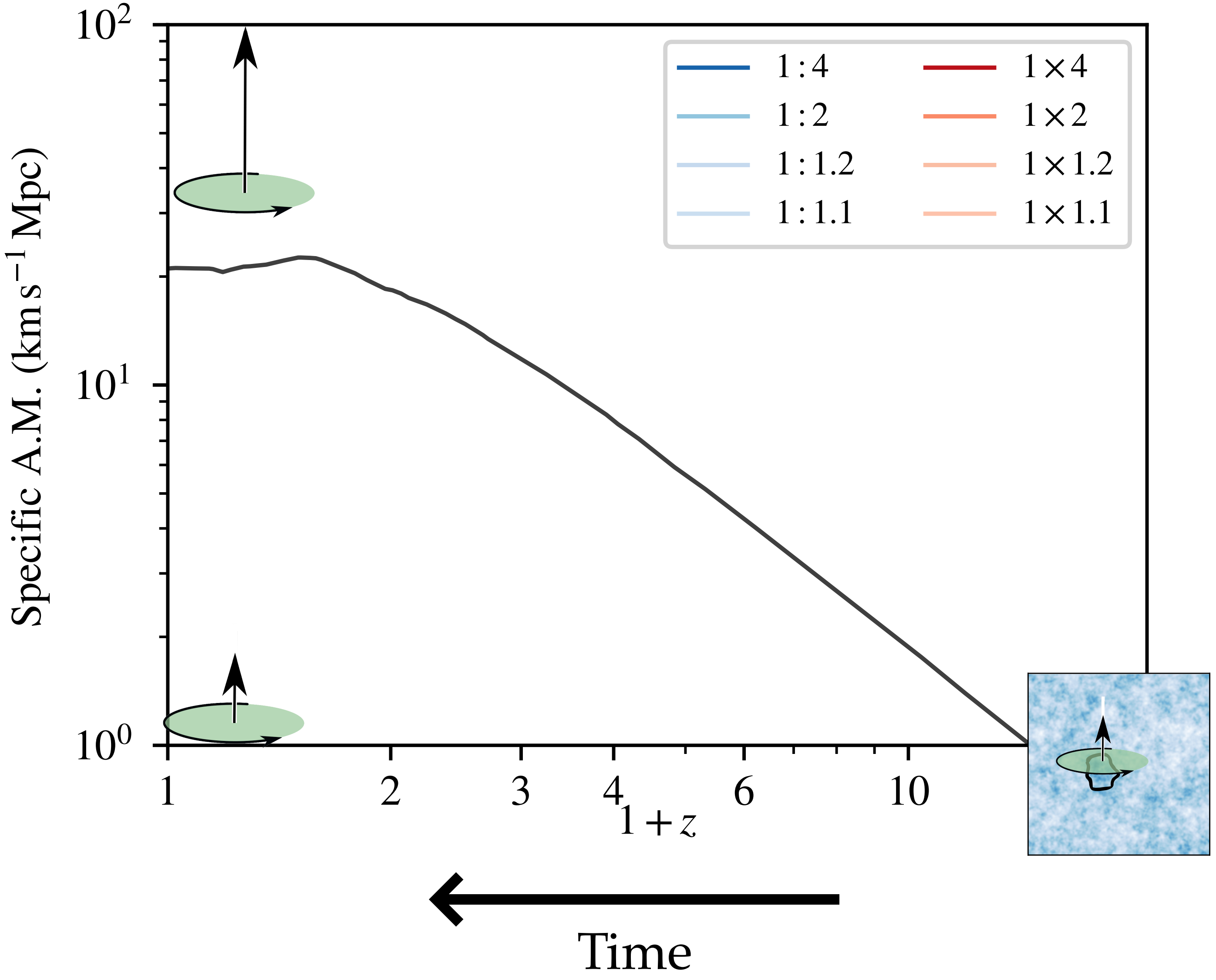


[Genetic modifications: Roth+16, see also Rey&Pontzen 18, Stopyra+20]

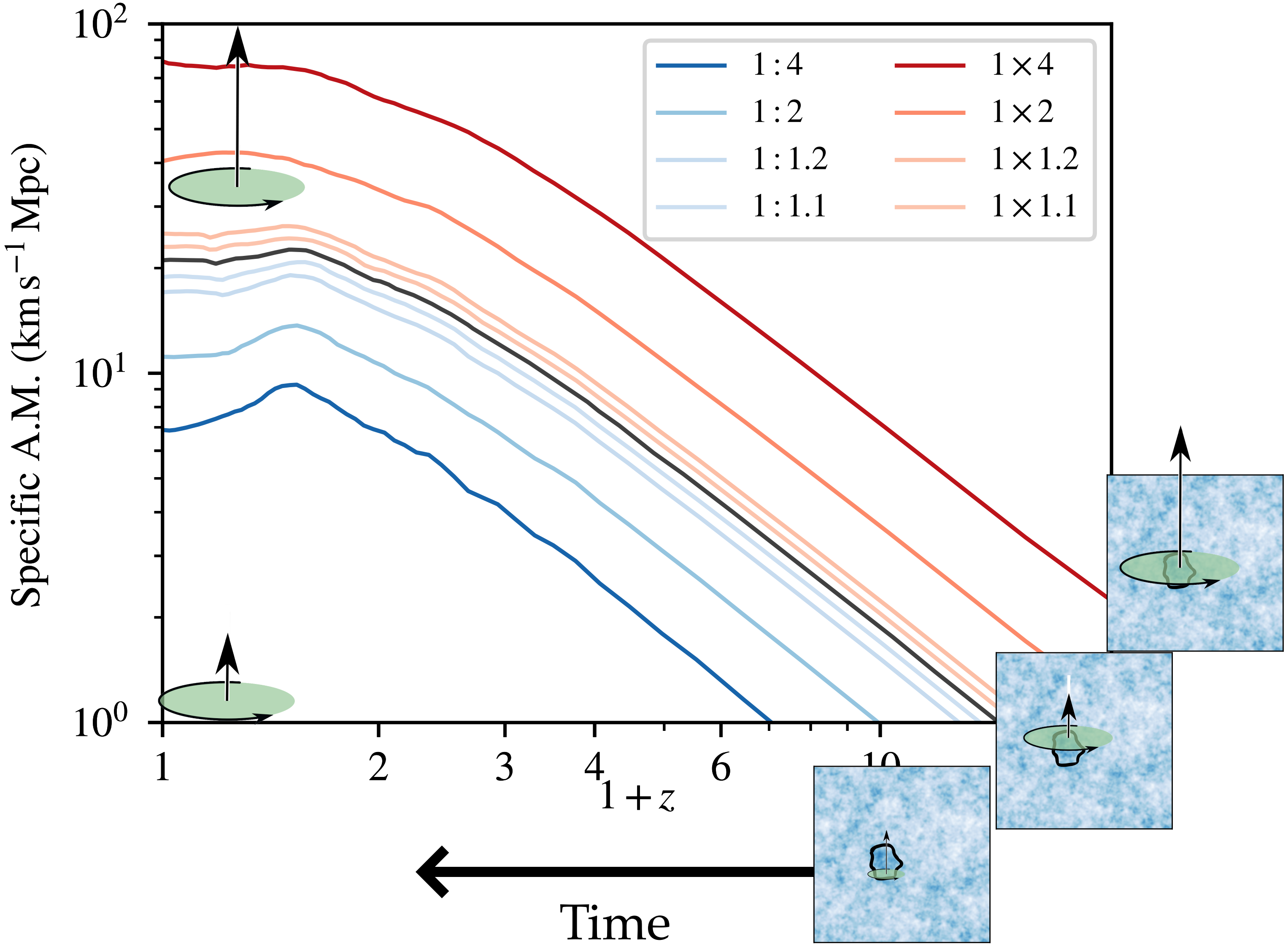
Predicting angular momentum



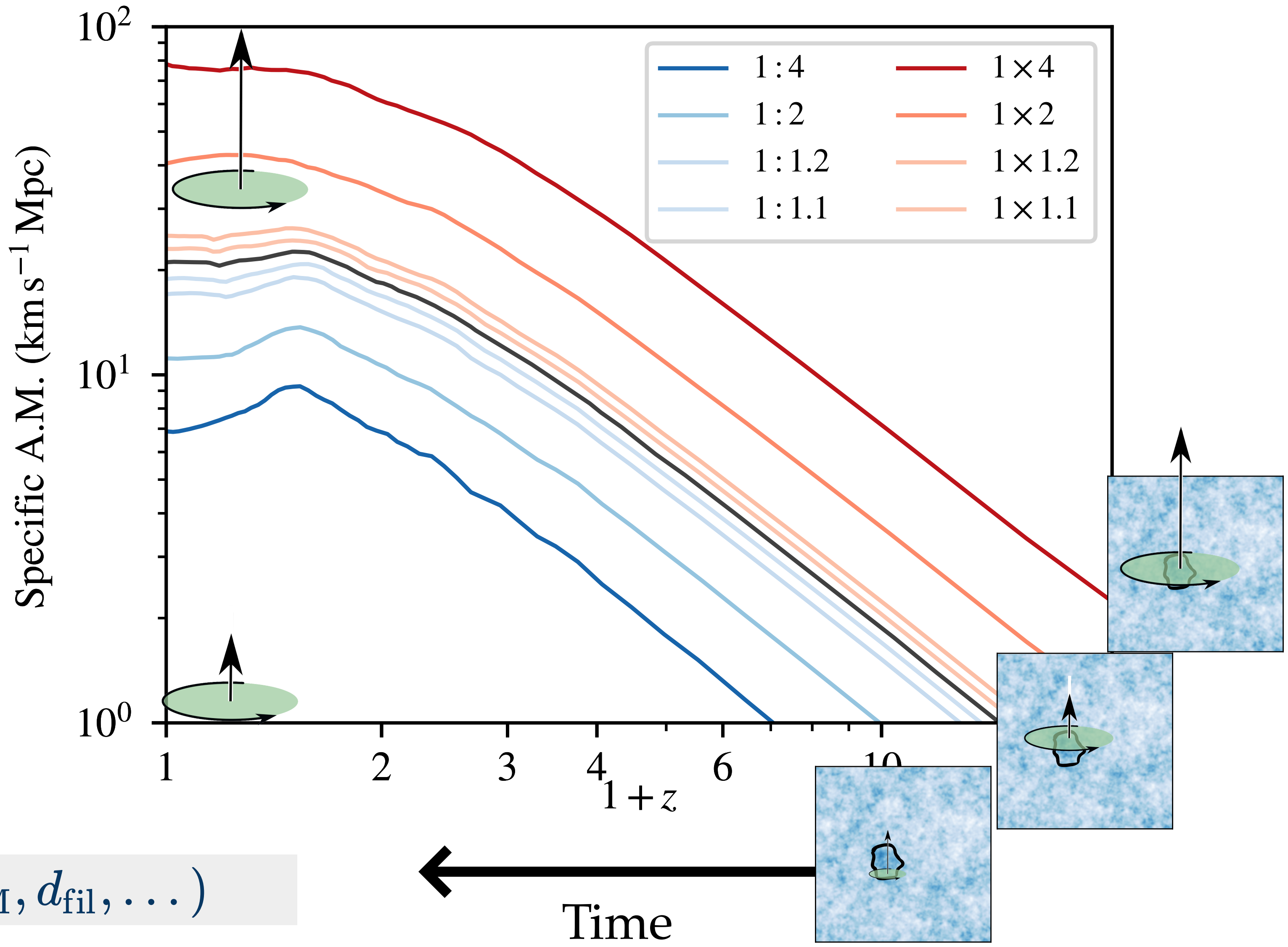
Predicting angular momentum



Predicting angular momentum

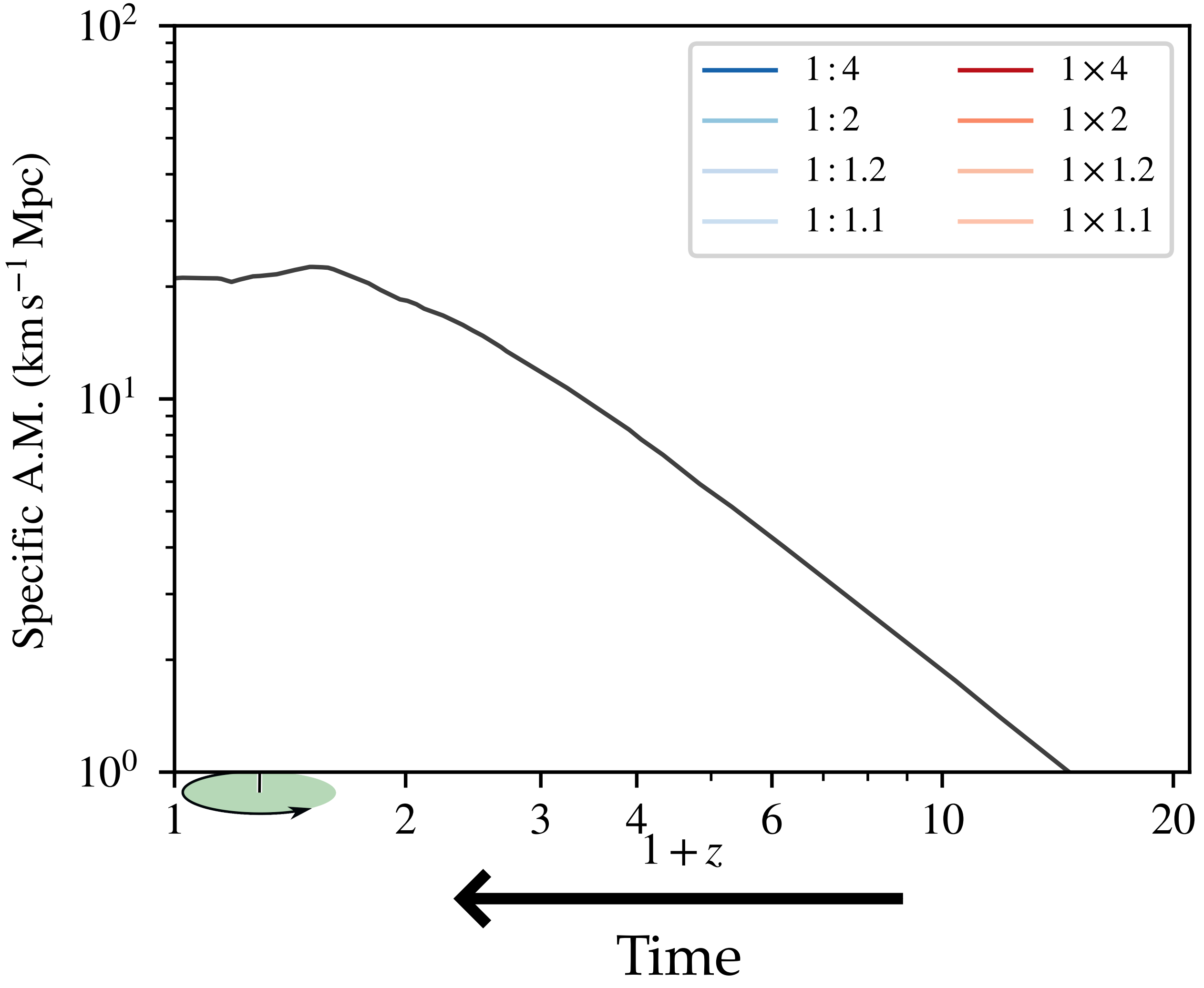


Predicting angular momentum

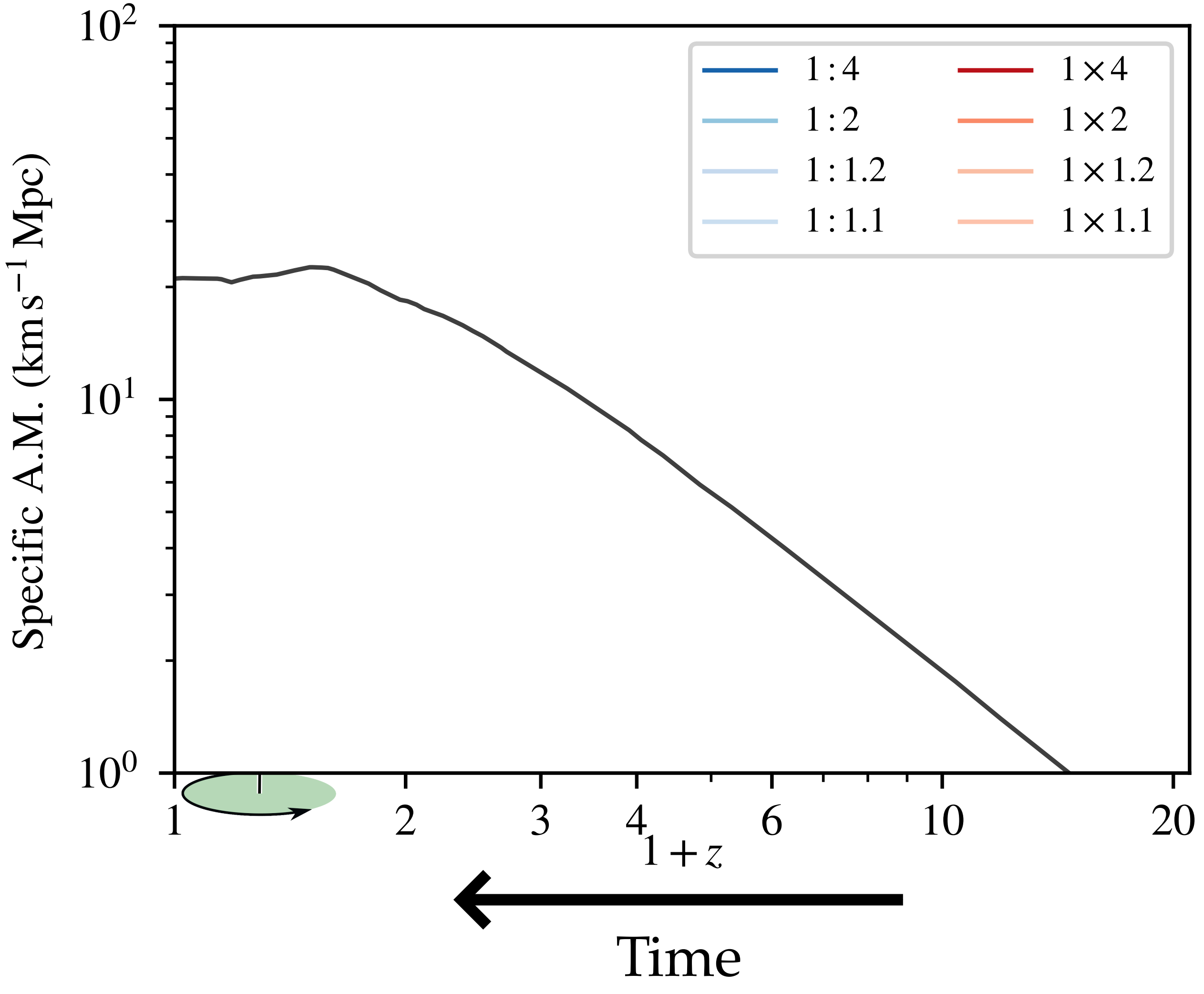


Sampling $p(\mathbf{J}|M_{\rm DM}, d_{\rm fil}, \dots)$

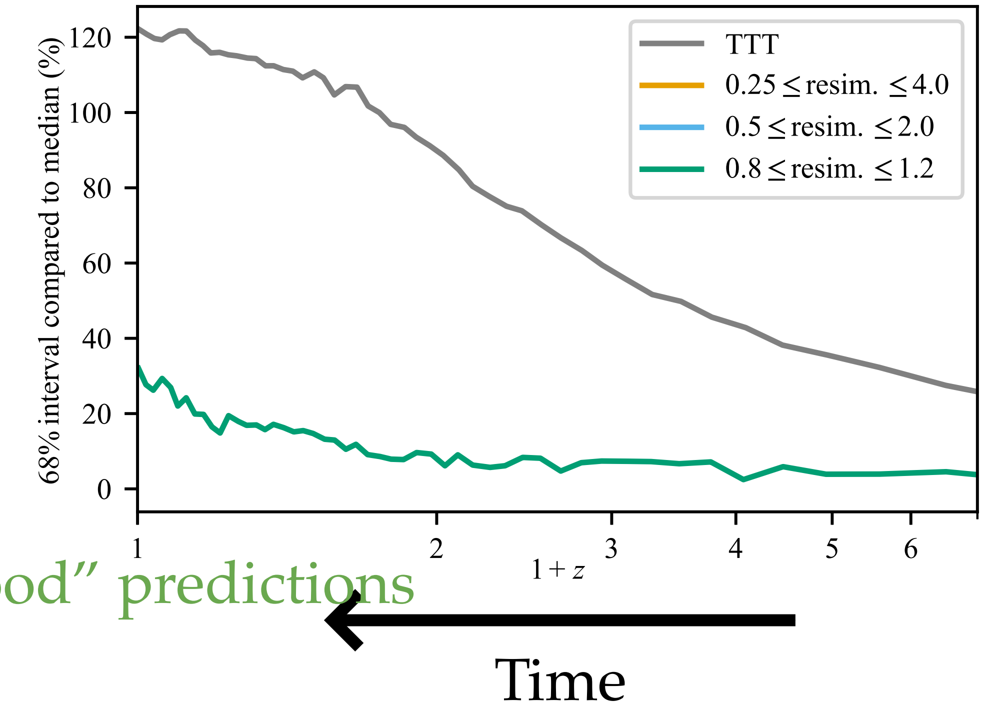
Predicting angular momentum



Predicting angular momentum

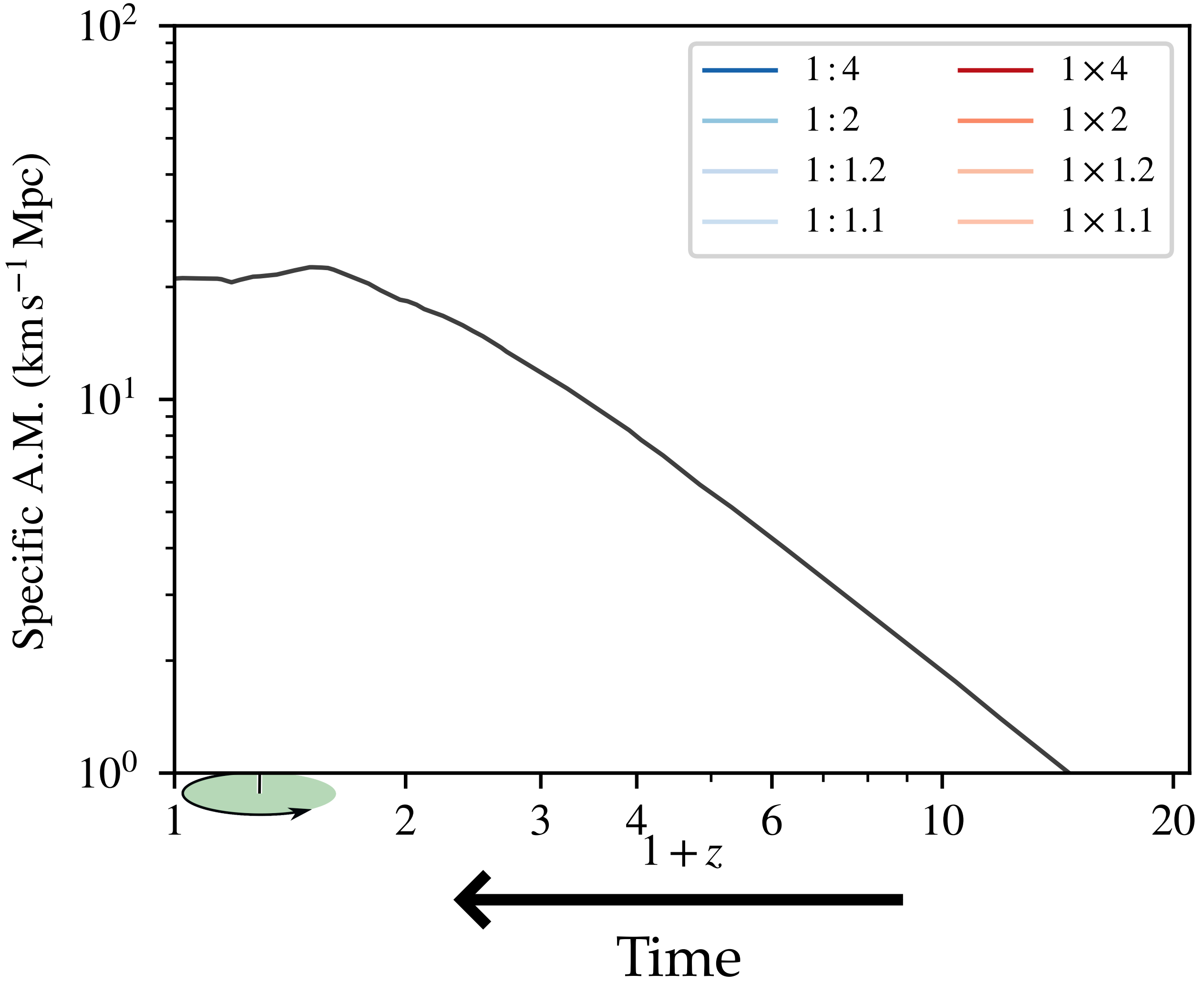


“Poorer” predictions

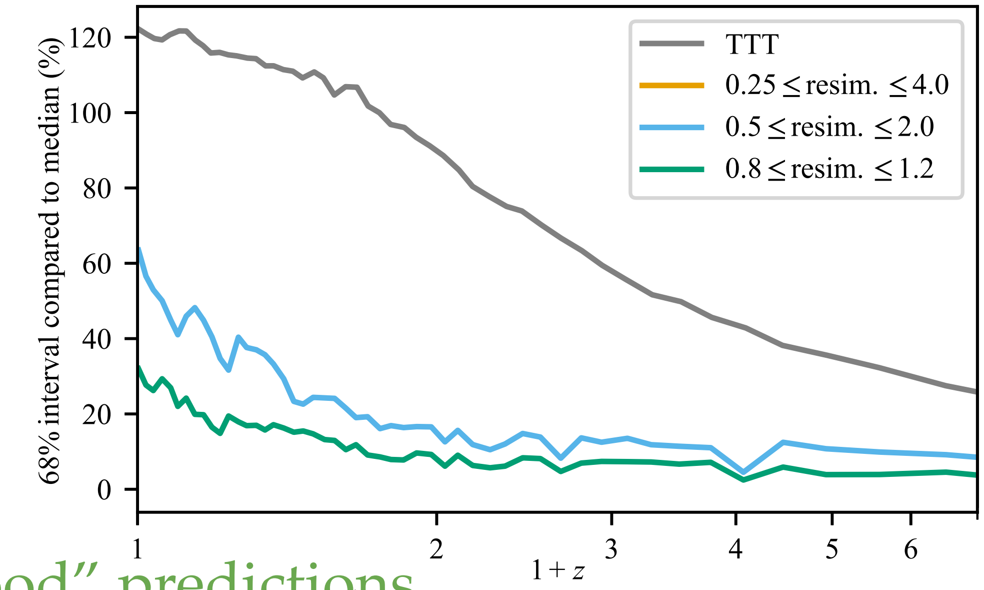


“Good” predictions

Predicting angular momentum



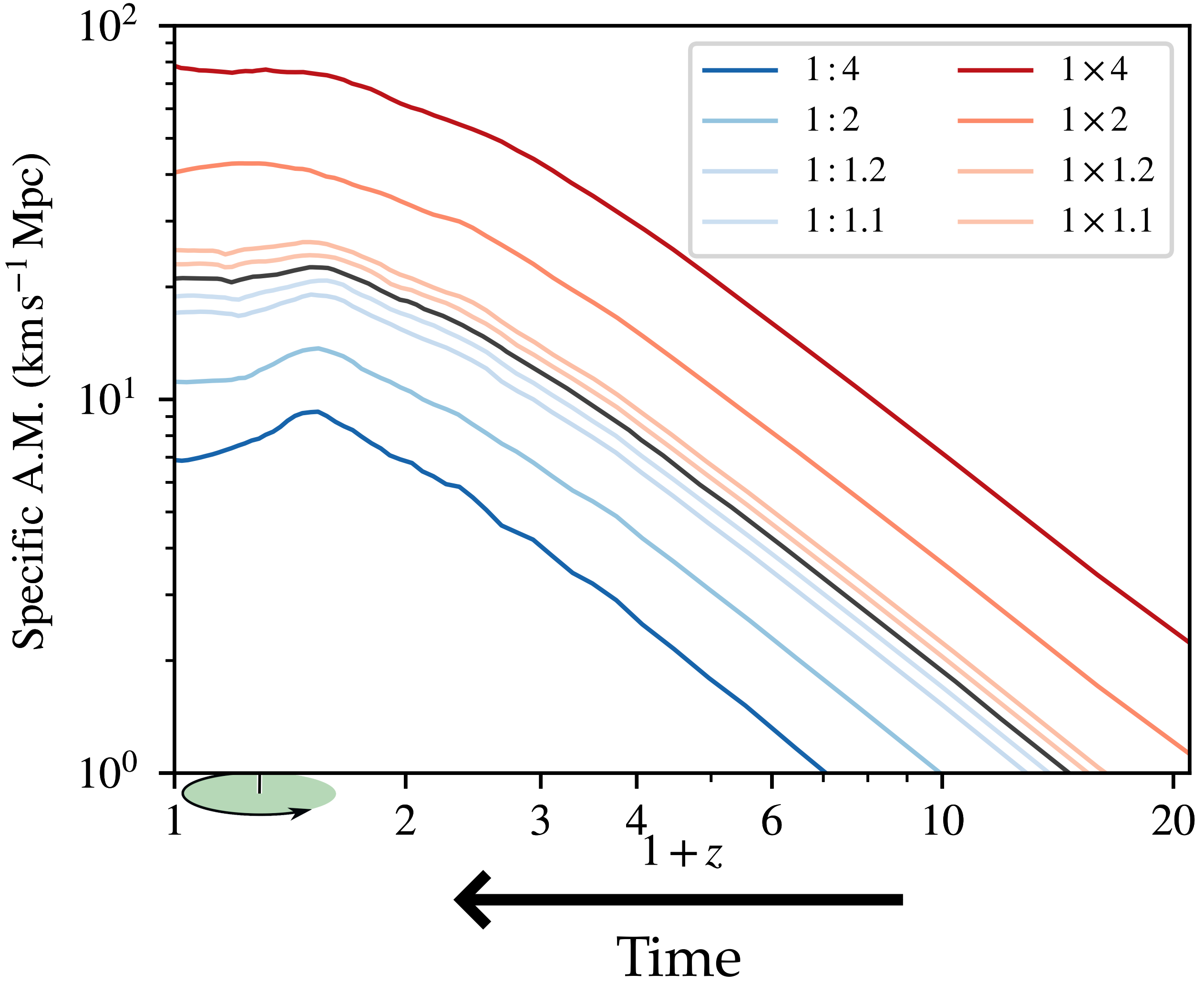
"Poorer" predictions



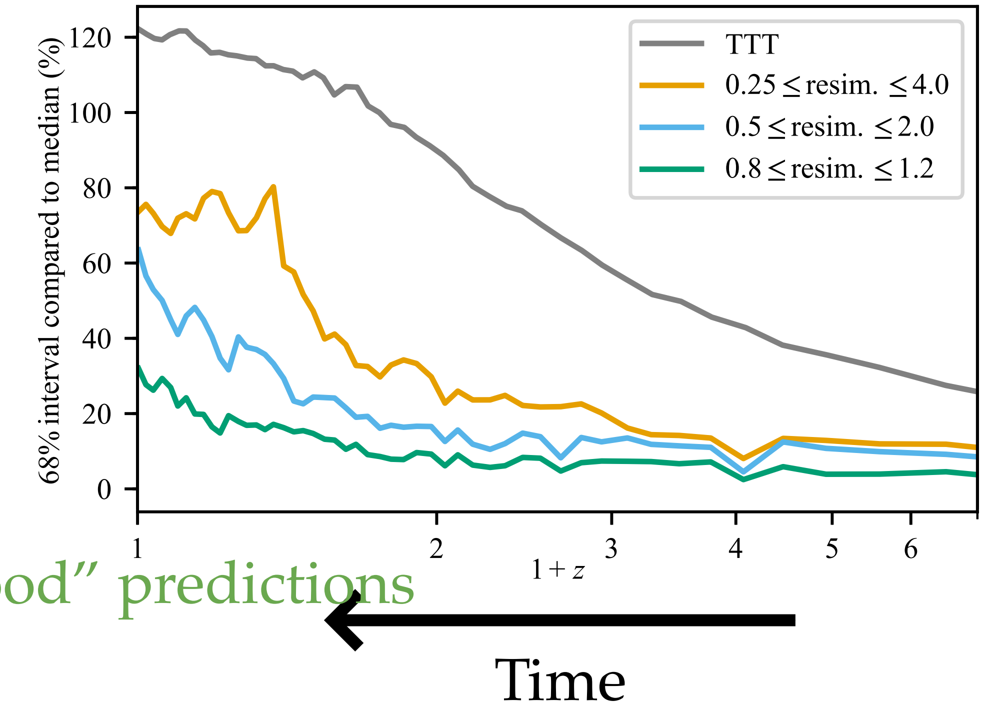
"Good" predictions

Time

Predicting angular momentum

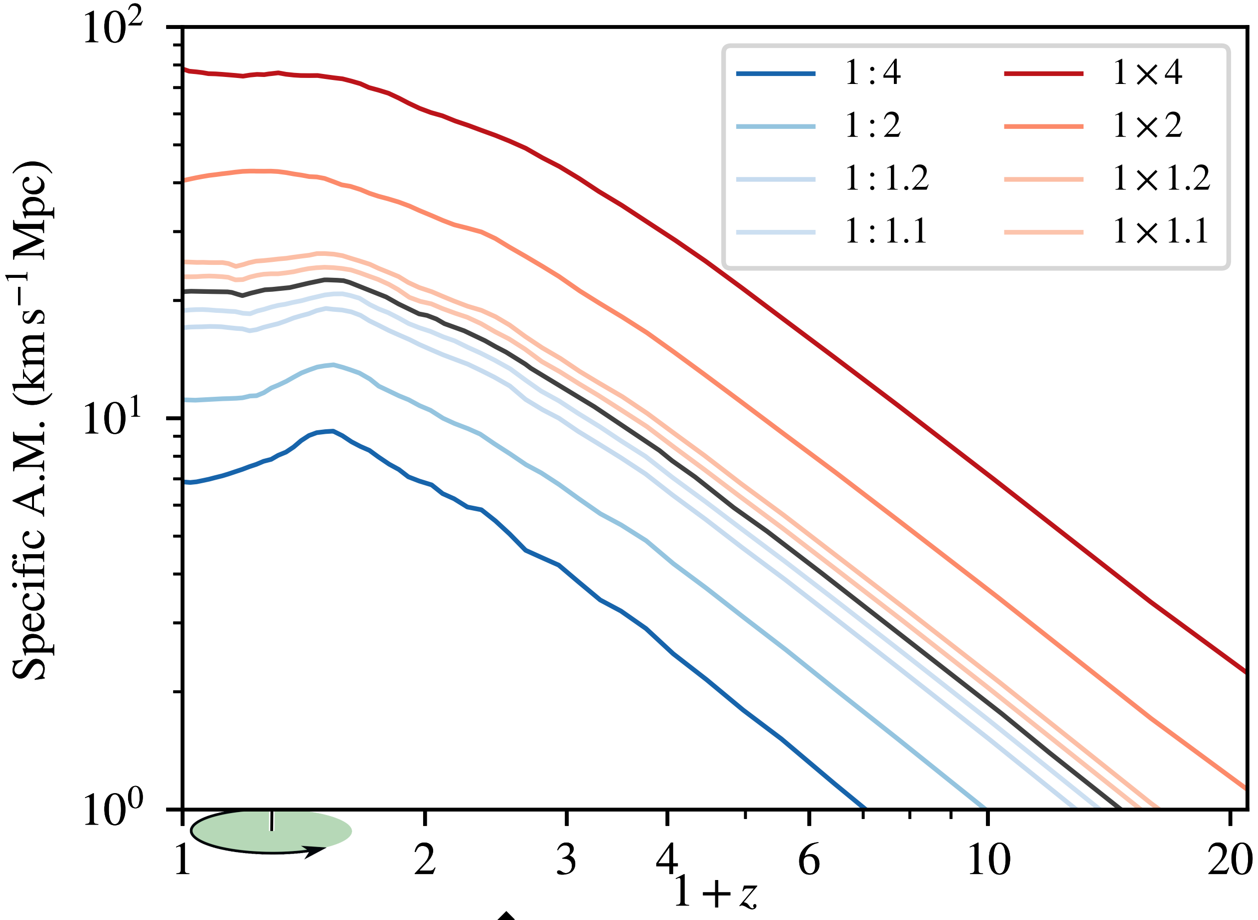


"Poorer" predictions



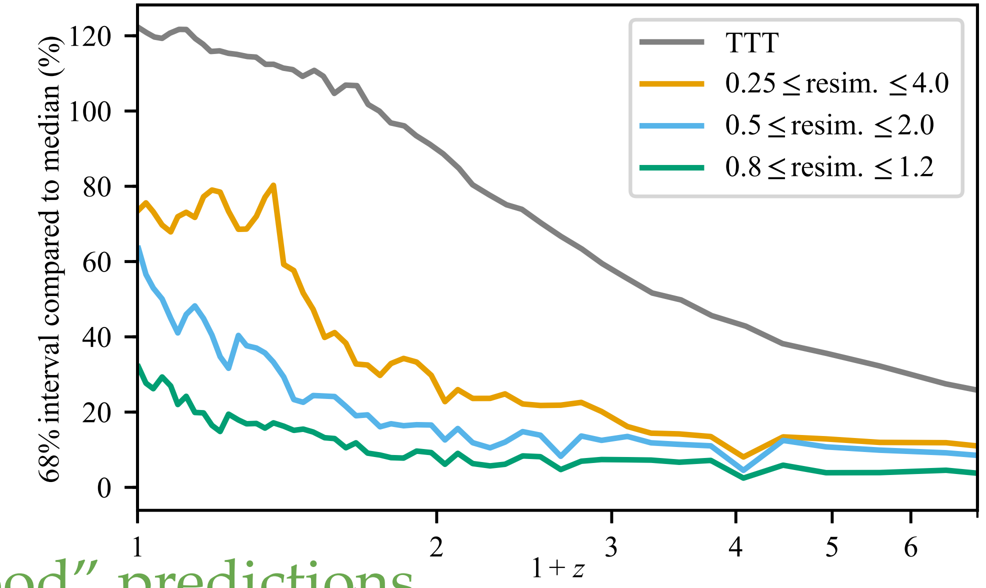
"Good" predictions

Predicting angular momentum



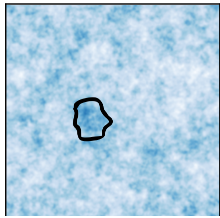
Time

"Poorer" predictions

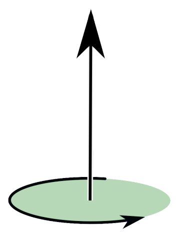


"Good" predictions

Time



Predicting angular momentum



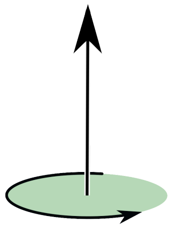
✅ AM of **fixed** DM **regions** responds ~linearly (so is not chaotic!)

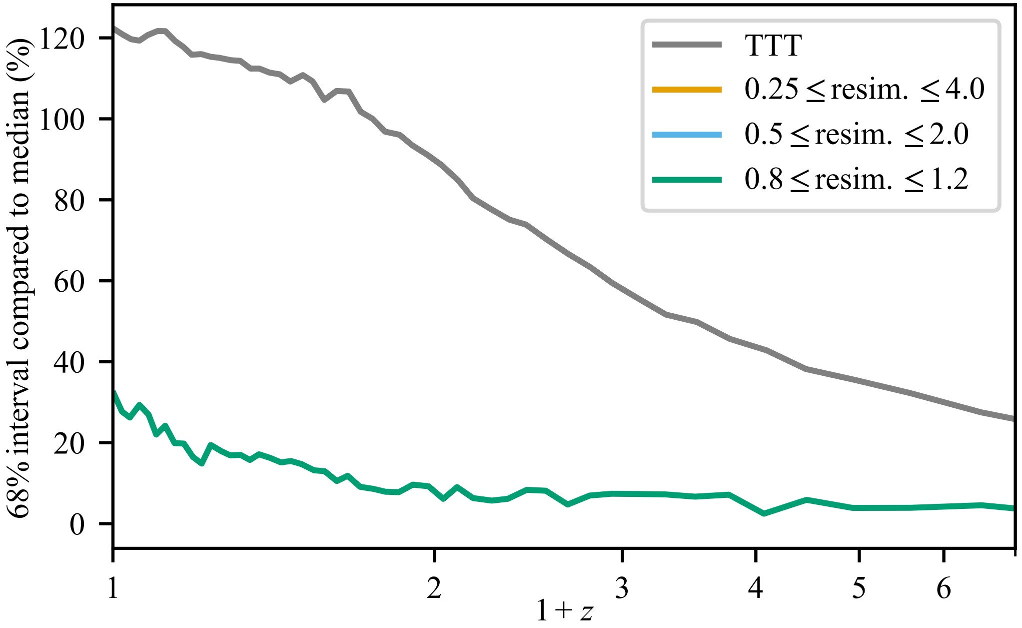
Improve theory?
Good model of Lagrangian patch boundaries (cf. M. Musso future talk)

or

Find more robust definition of AM?

Predicting angular momentum





✅ AM of **<u>fixed</u>** DM **<u>regions</u>** responds ~linearly (so is not chaotic!)

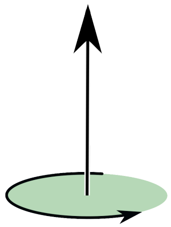
Improve theory?

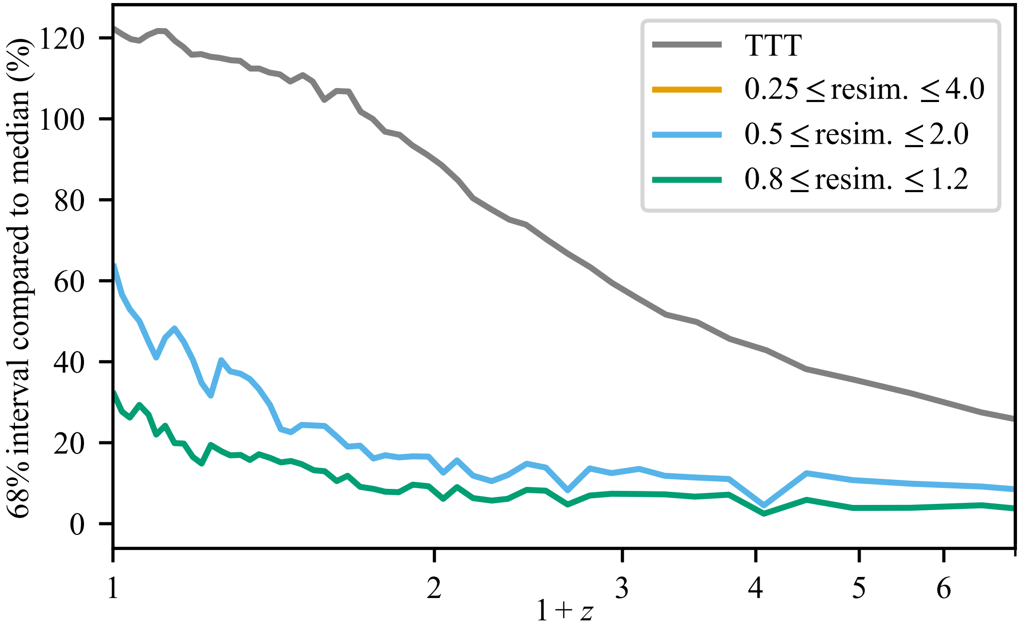
Good model of Lagrangian patch boundaries (cf. M. Musso future talk)

or

Find more robust definition of AM?

Predicting angular momentum





✅ AM of **fixed** DM **regions** responds ~linearly (so is not chaotic!)

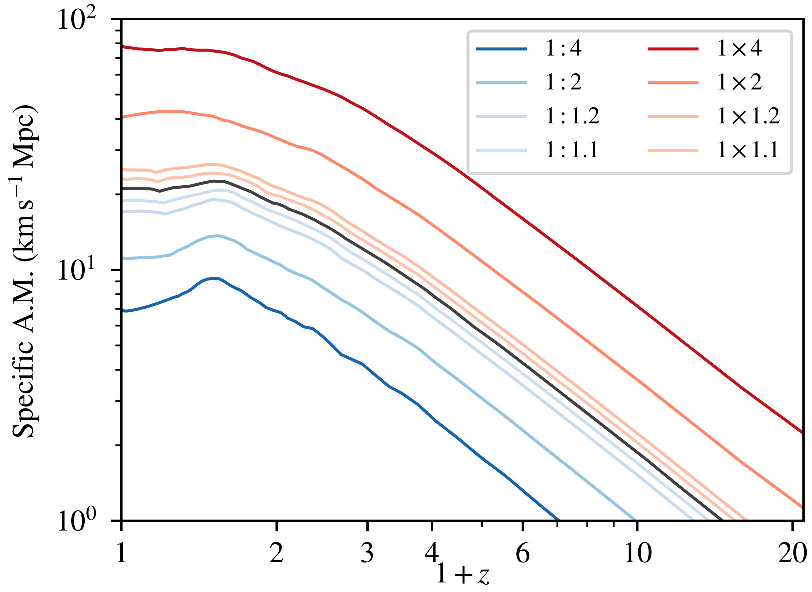
Improve theory?

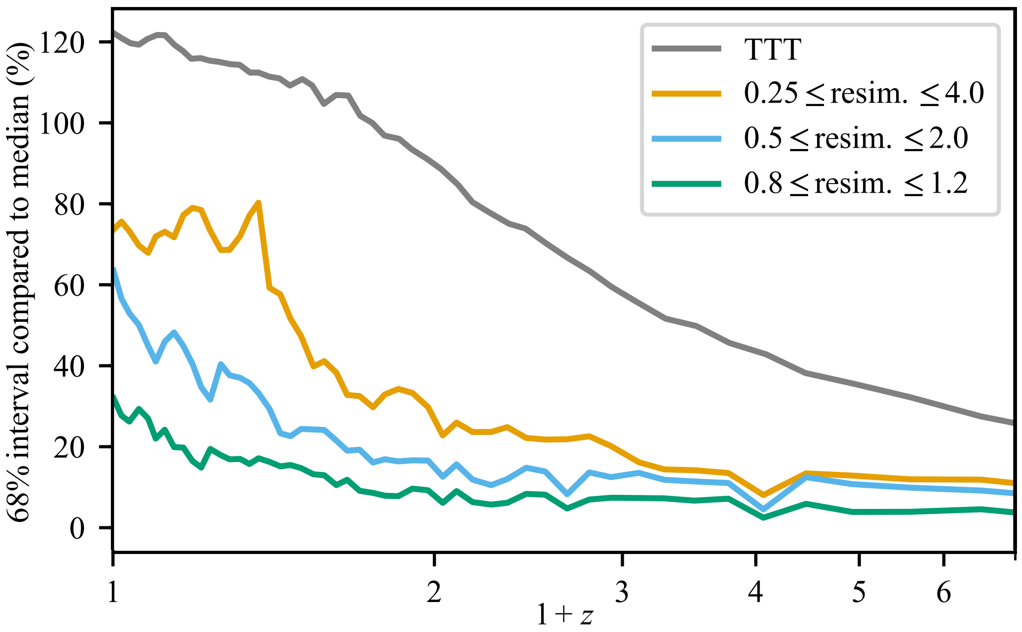
Good model of Lagrangian patch boundaries (cf. M. Musso future talk)

or

Find more robust definition of AM?

Predicting angular momentum





✅ AM of **fixed** DM **regions** responds ~linearly (so is not chaotic!)

Improve theory?

Good model of Lagrangian patch boundaries (cf. M. Musso future talk)

or

Find more robust definition of AM?

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

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

CC+22, arXiv: 2206.11913

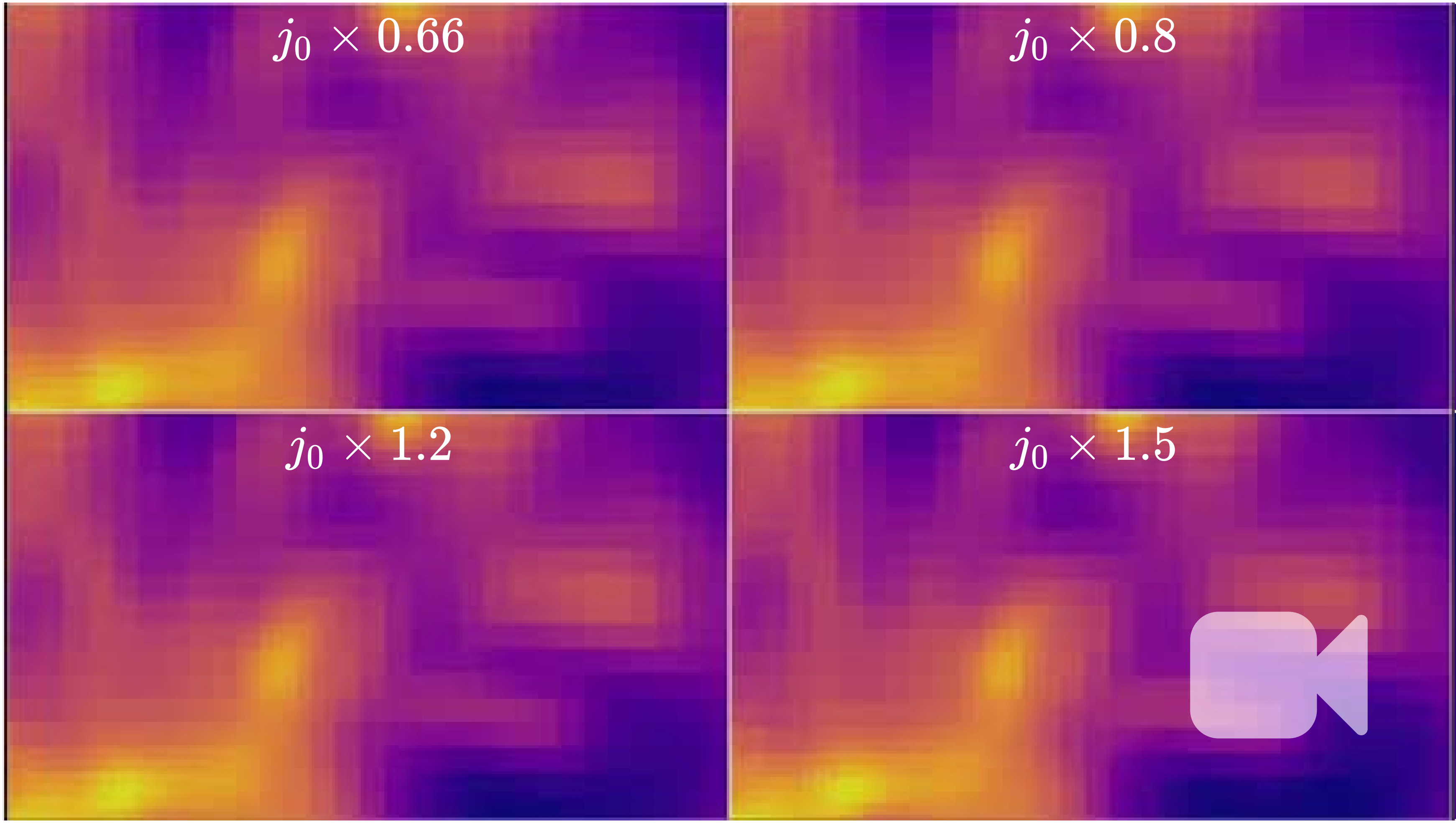
Main idea: stars are deeper in potential well so less sensitive to what happens at large scales

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

Baryon angular momentum

Full hydro simulations (10Mh @ DiRAC):

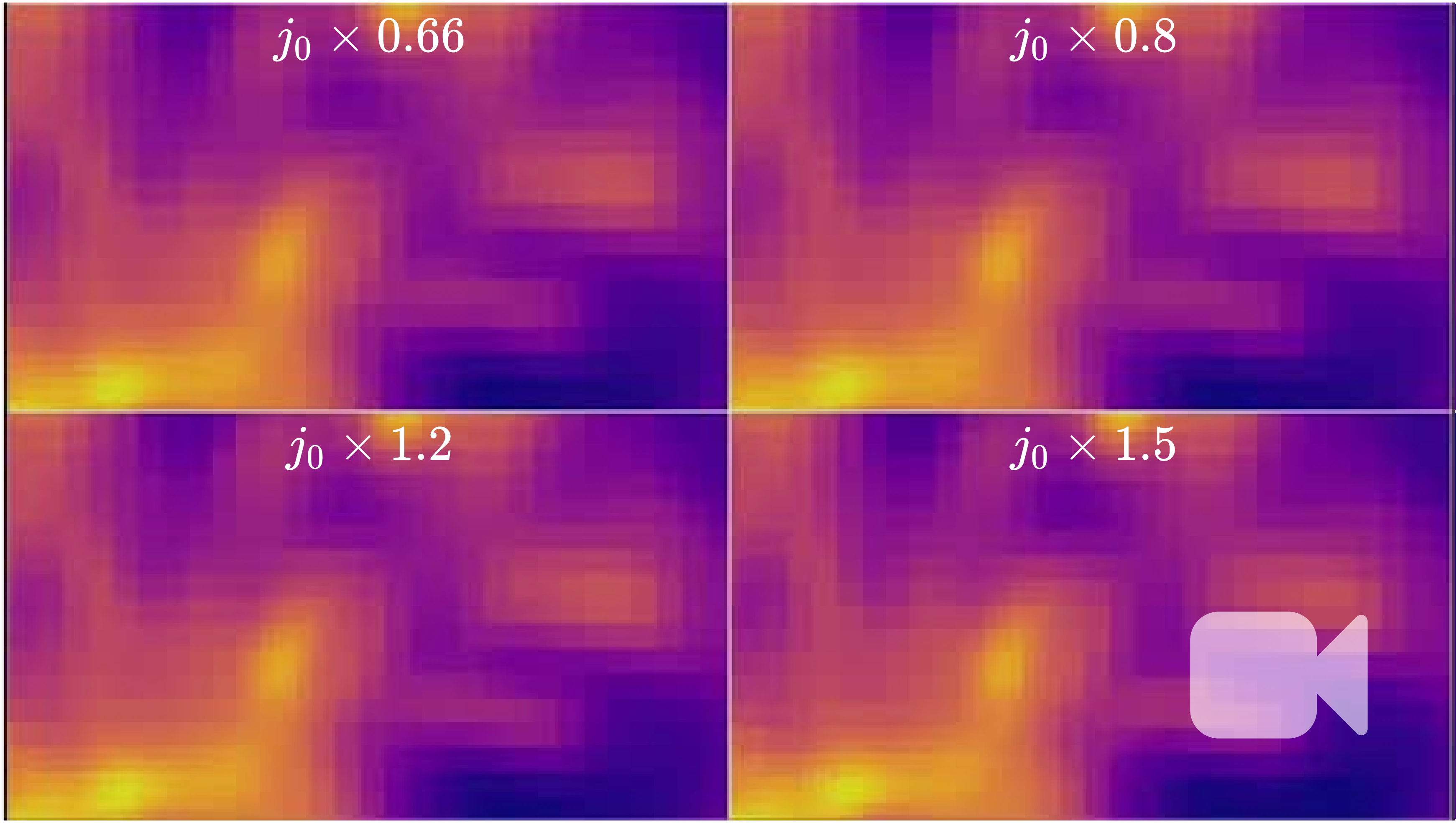
- Resolve disk height $\Delta x = 35$ kpc
- $z \geq 2$, $M_{200c} = 10^{12}$ $M_\odot$
- SF + AGN & SN feedback
- **Tracer particles CC+19**
- 3 galaxies, 5× scenario each



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

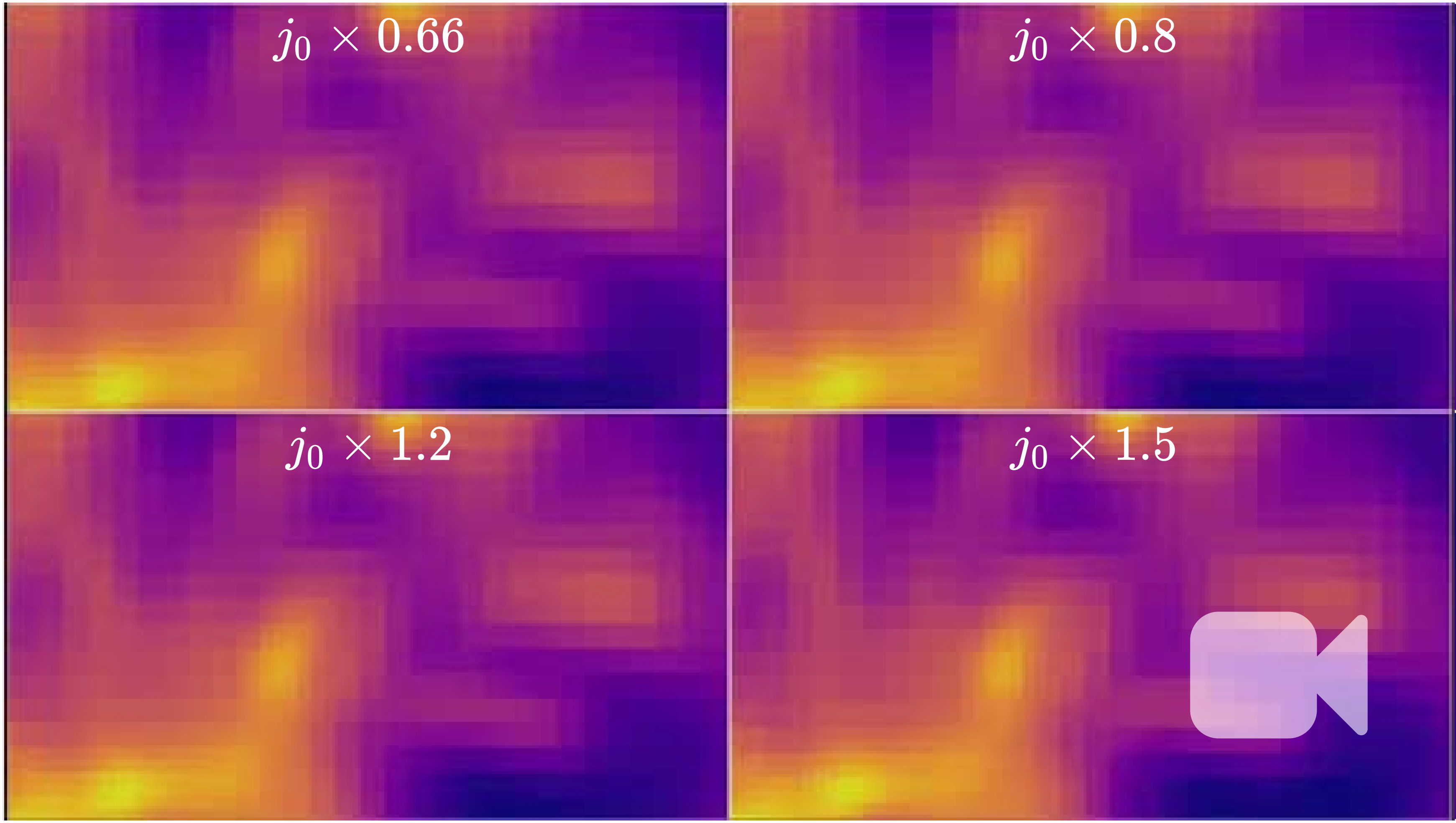


Sampl*ing* $p(\mathbf{J}|M_\star, M_{\rm DM}, d_{\rm fil}, \ldots)$

Baryon angular momentum

Full hydro simulations (10Mh @ DiRAC):

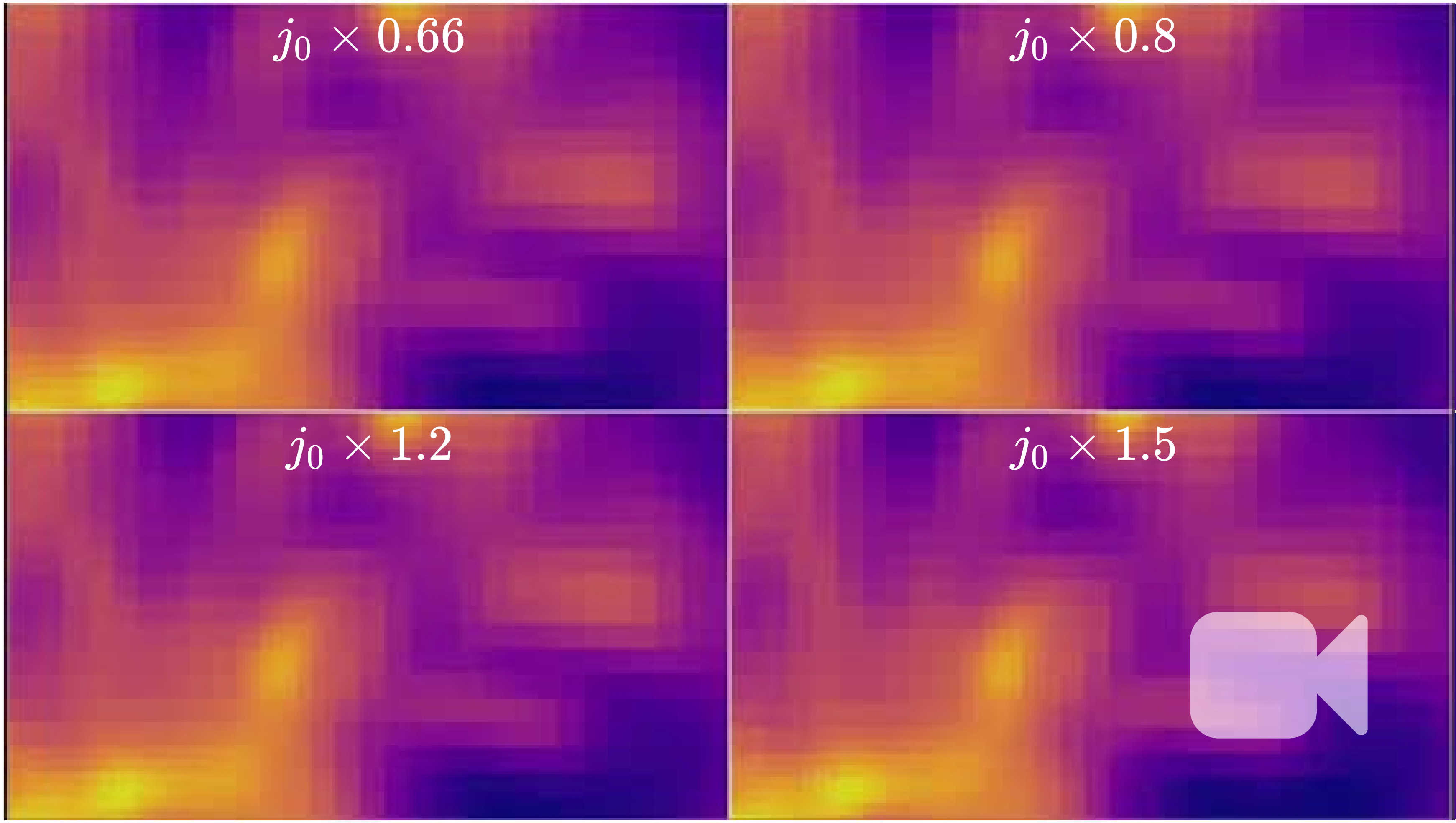
- Resolve disk height $\Delta x = 35$ kpc
- $z \geq 2$, $M_{200c} = 10^{12}$ $M_\odot$
- SF + AGN & SN feedback
- **Tracer particles CC+19**
- 3 galaxies, 5× scenario each



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

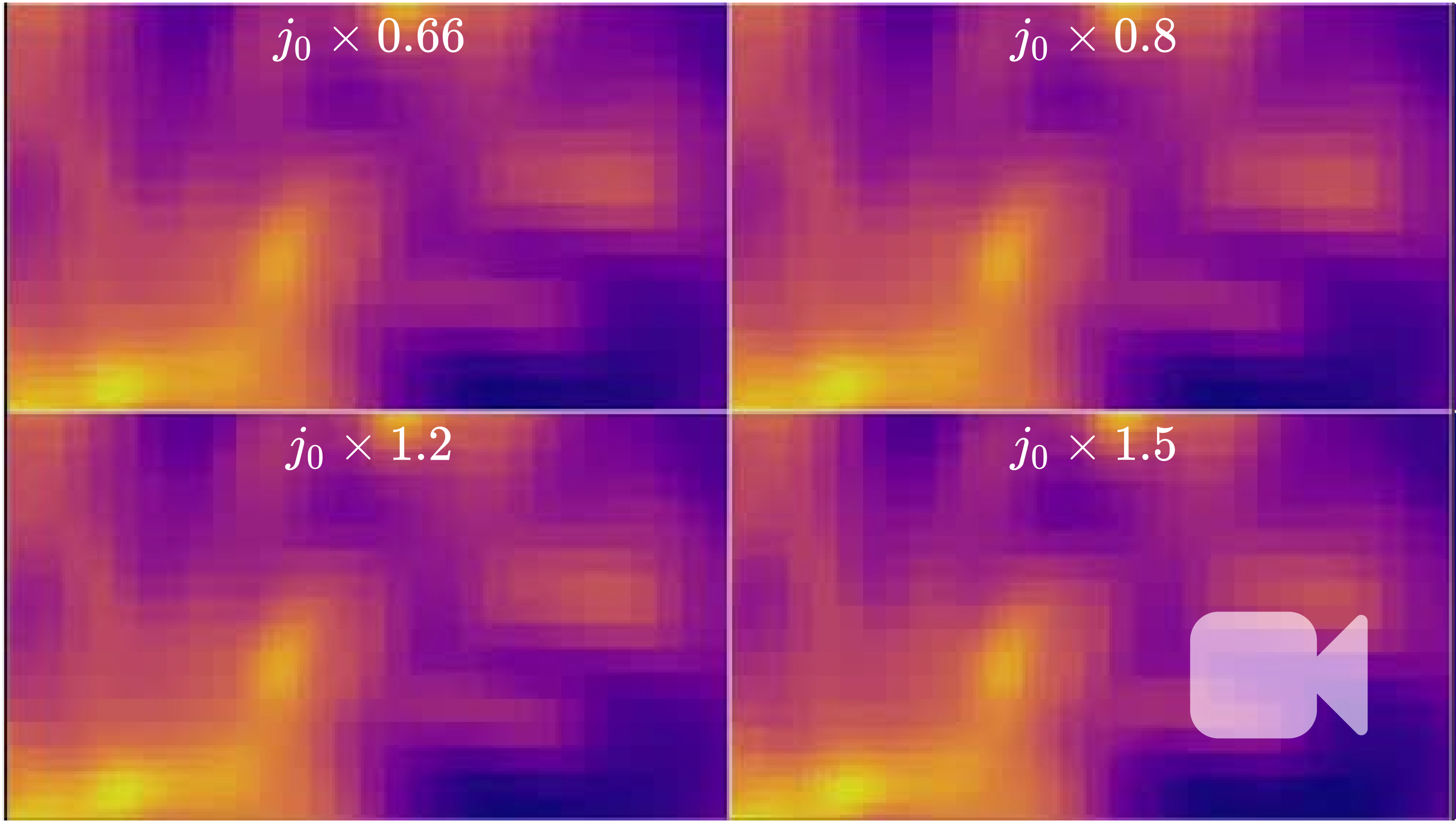


Sampl*ing* $p(\mathbf{J}|M_\star, M_{\rm DM}, d_{\rm fil}, \dots)$

Baryon angular momentum

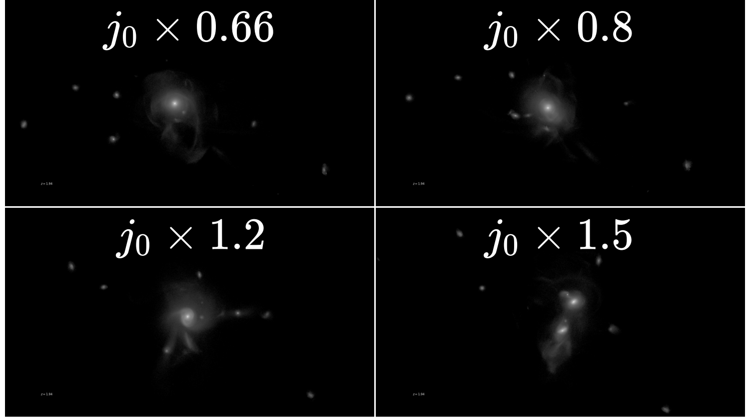
Full hydro simulations
(10Mh @ DiRAC):

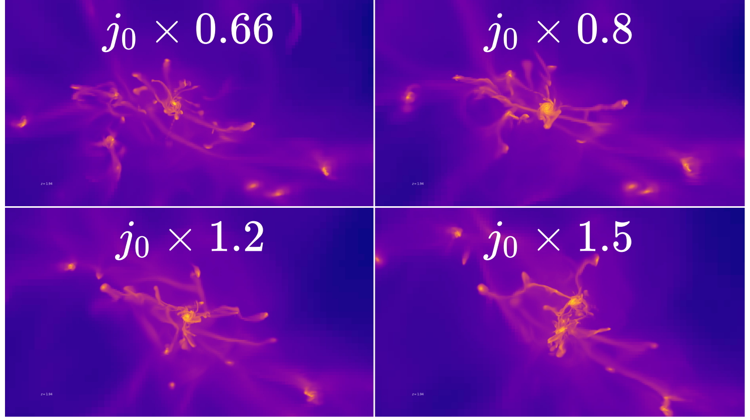
- Resolve disk height
  $\Delta x = 35$ kpc
- $z \geq 2$, $M_{200c} = 10^{12}$ M$_\odot$
- SF + AGN & SN feedback
- **Tracer particles**
  CC+19
- 3 galaxies, 5× scenario each

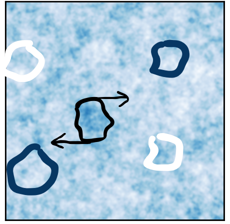


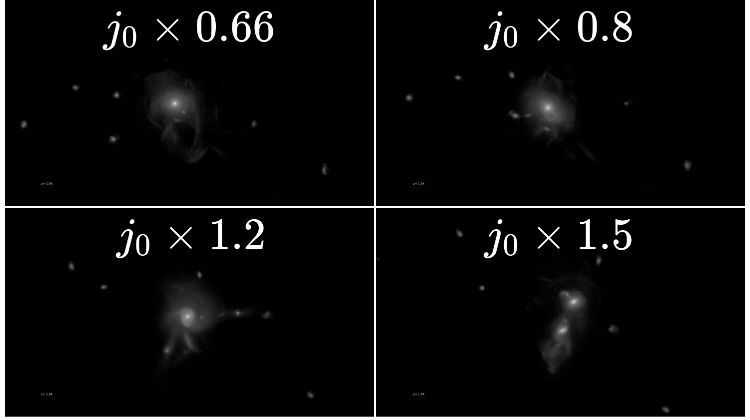
Sampl*ing* $p(\mathbf{J}|M_\star, M_{\rm DM}, d_{\rm fil}, \dots)$

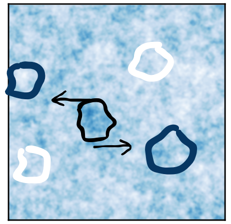
… by delaying/hastening time of last major merger

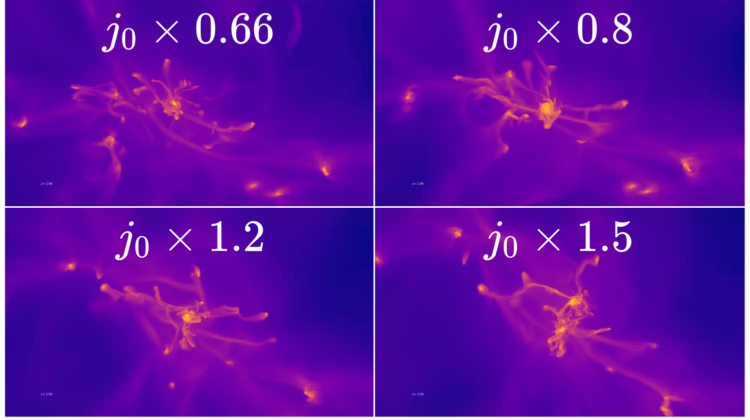

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$

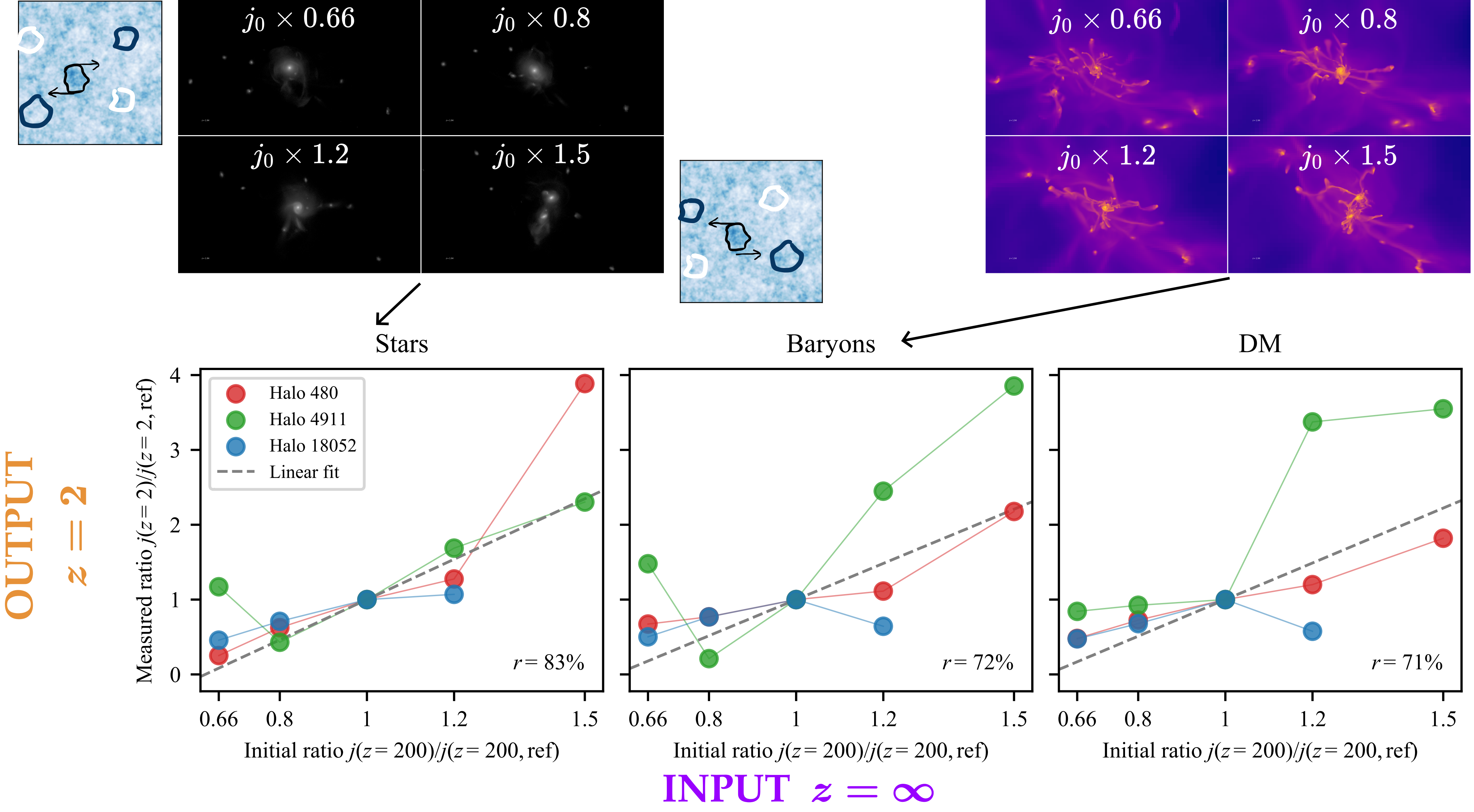

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$



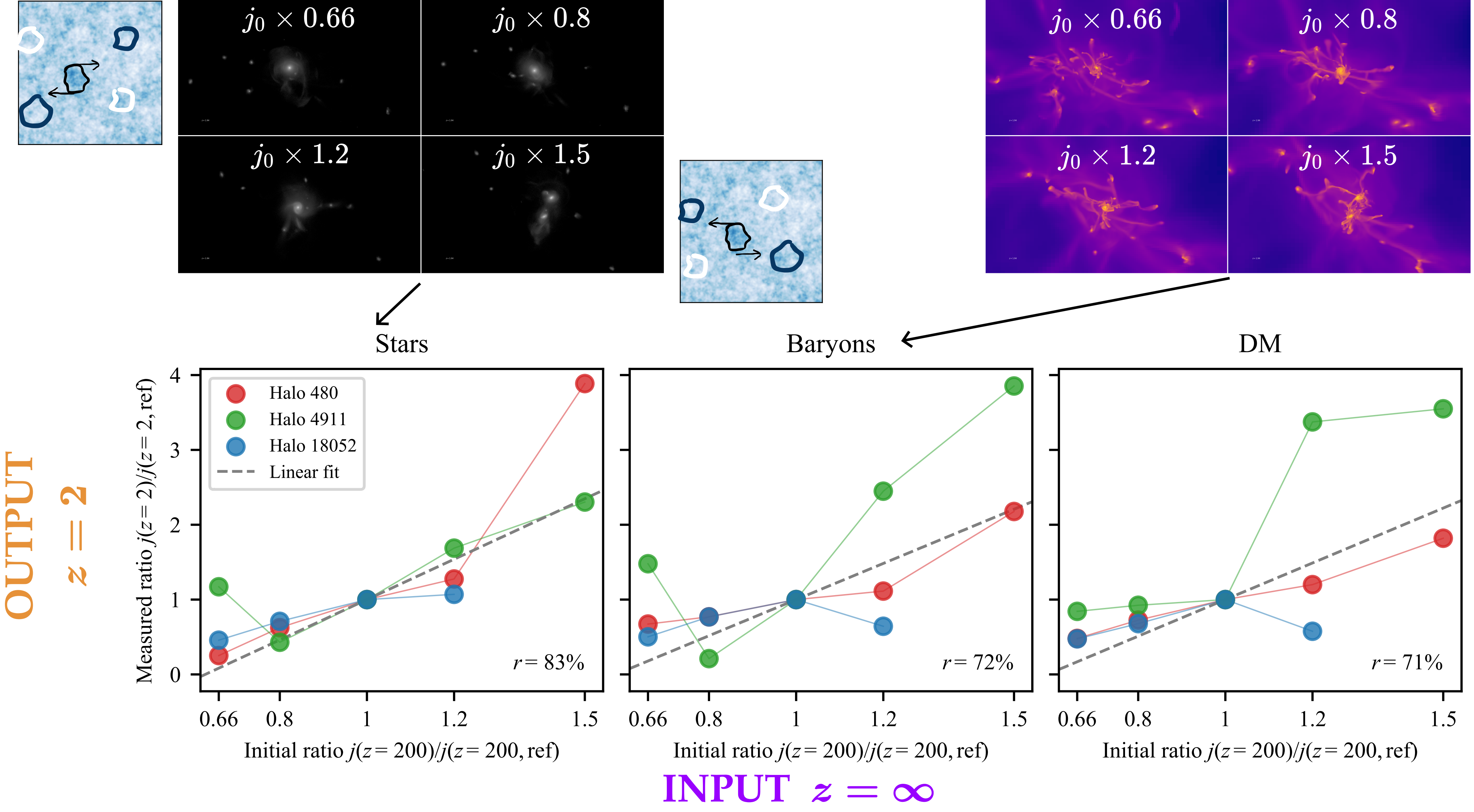

$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$




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

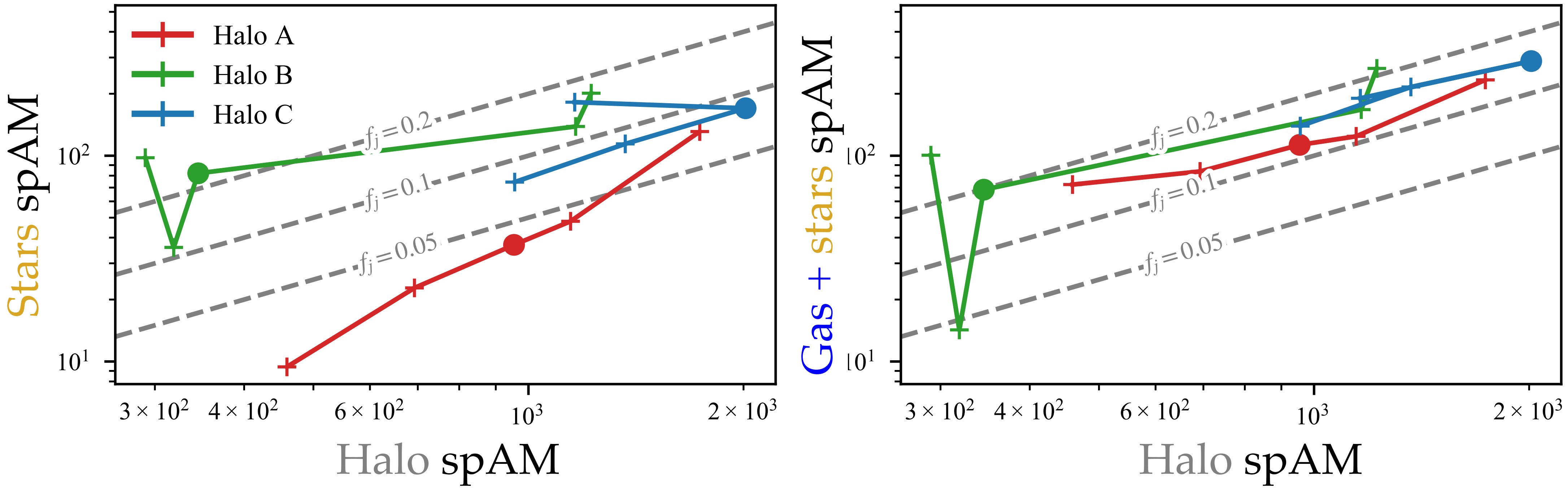


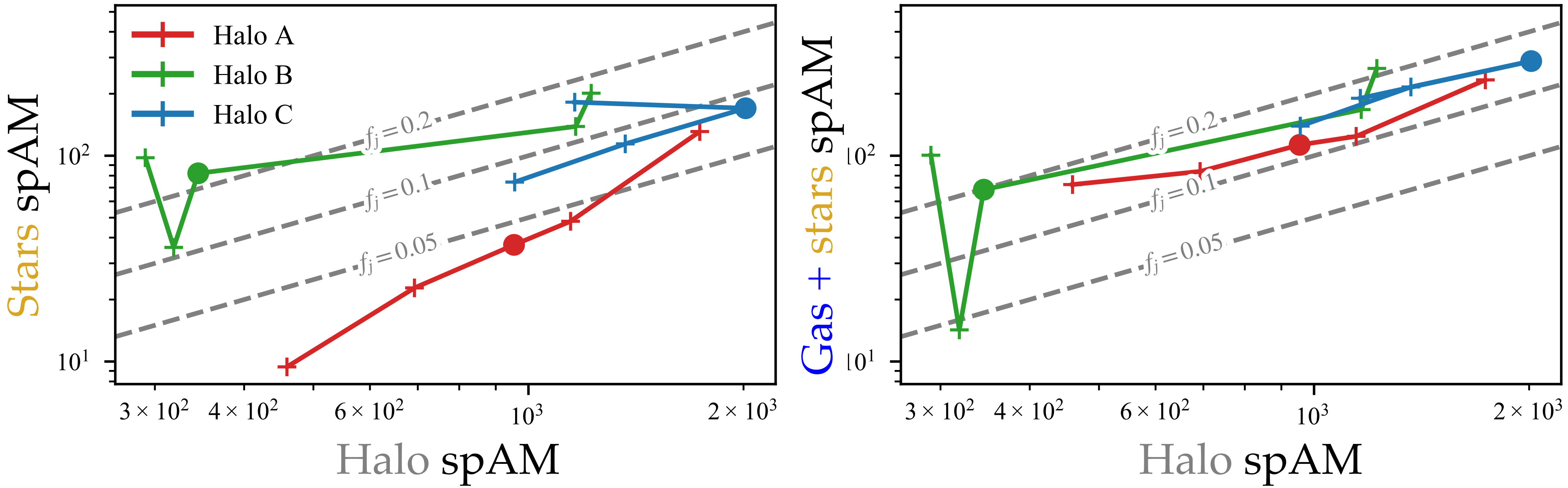
$j_0 \times 0.66$
$j_0 \times 0.8$
$j_0 \times 1.2$
$j_0 \times 1.5$
Stars
Baryons
DM
Halo 480
Halo 4911
Halo 18052
Linear fit
Measured ratio $j(z=2)/j(z=2,\mathrm{ref})$
Initial ratio $j(z=200)/j(z=200,\mathrm{ref})$
$r = 83\%$
$r = 72\%$
$r = 71\%$
OUTPUT $z = 2$
INPUT $z = \infty$



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

✅ Useful to make sense out of e.g. JWST data


Halo A
Halo B
Halo C
Stars spAM
Halo spAM
fj=0.2
fj=0.1
fj=0.05
Gas + stars spAM



✅ **Changes** in baryon spAM $\propto$ **changes** in Halo spAM

$$\lambda_{\rm DM} \xrightarrow[f_j]{} \lambda_{\rm baryon} \xrightarrow[\rm SF+fb]{} \lambda_\star$$

❗ Per-galaxy fluctuation of $\lambda_\star/\lambda_{\rm DM}$

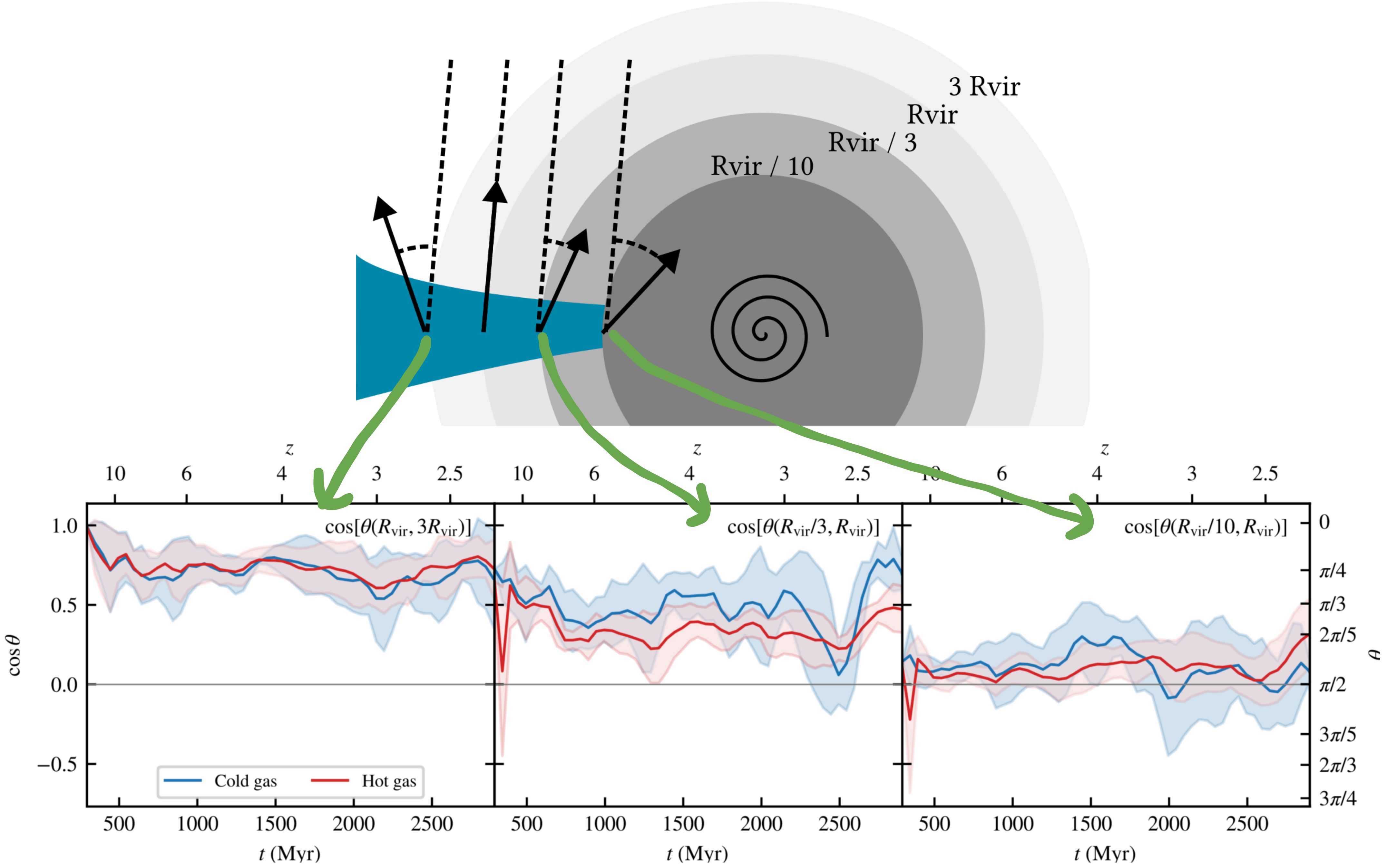
$\Rightarrow$ cannot be captured with HOD modelling (cf. Boryana Hadzhiyska talk this morning)

Where is the CW — galaxy boundary?

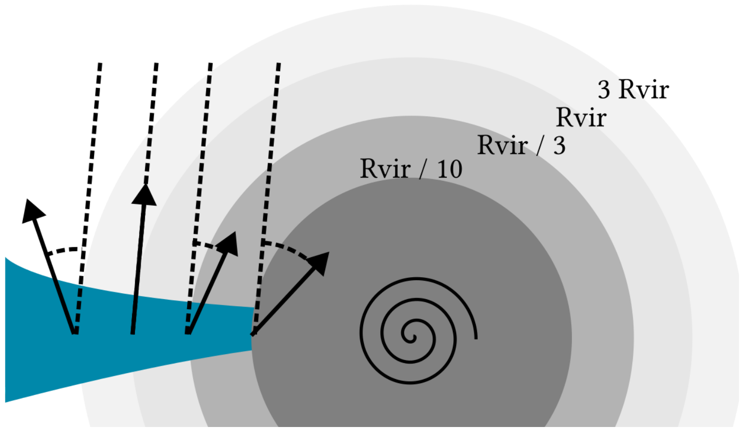
Spoiler: probably within the CGM

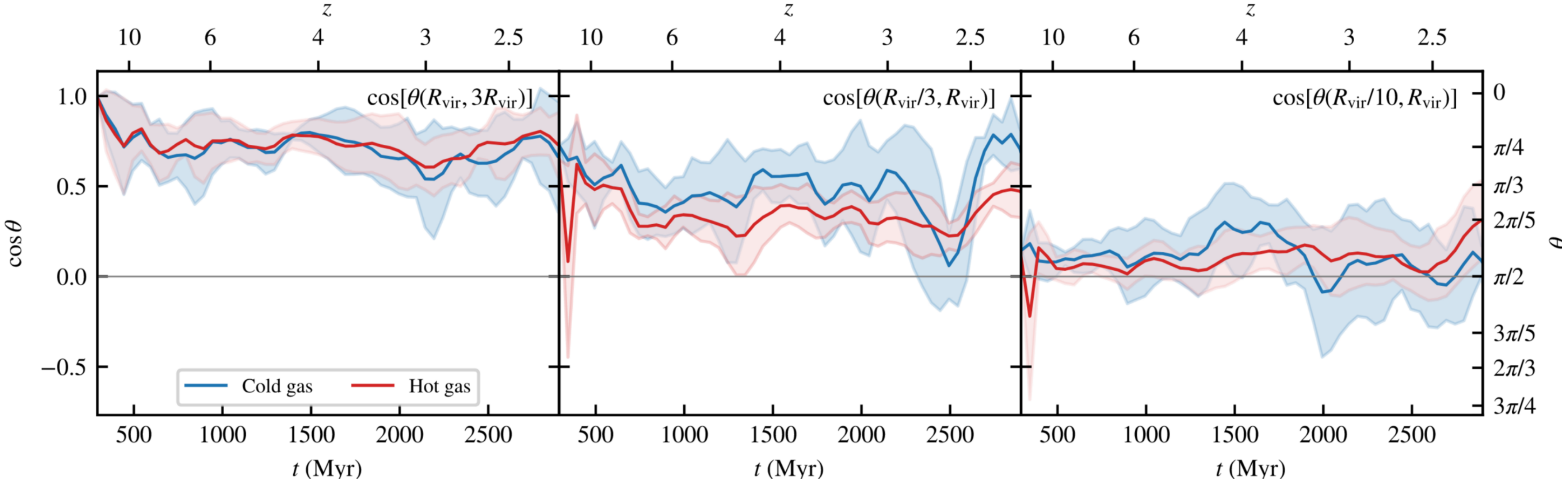
CC+Pichon+Dubois, 21, arXiv: 2110.05384

By no means complete review!



[See also Danovich+15, Prieto+17]



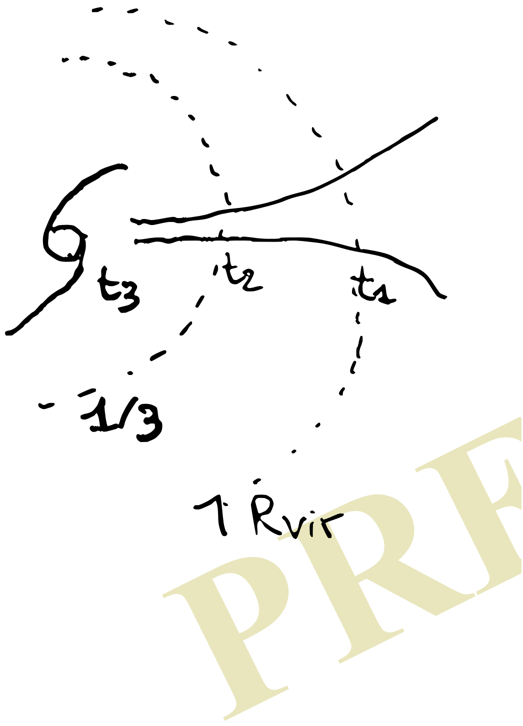


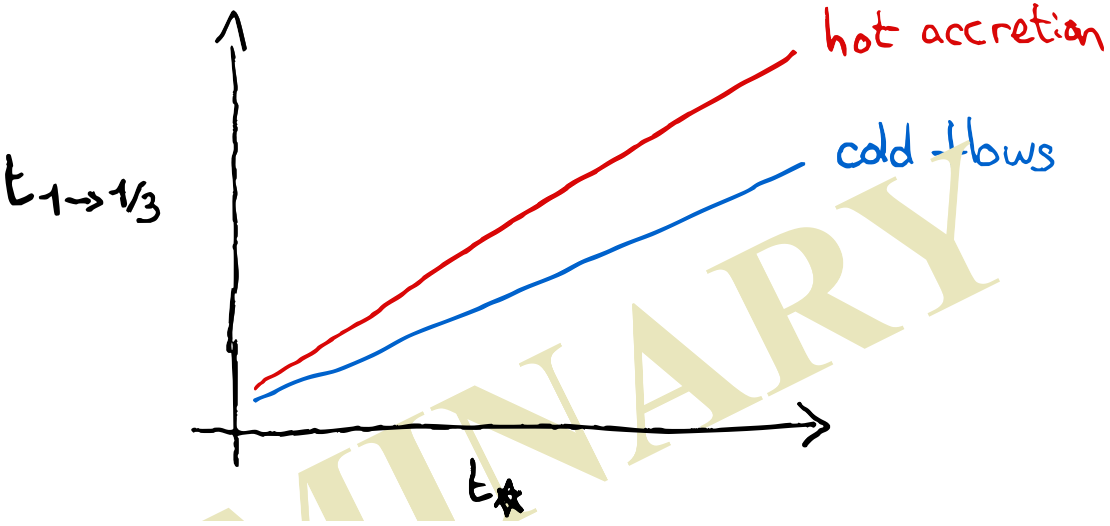
✅ Most of re-alignment happens in the CGM $0.1 \leq \frac{r}{R_{\rm vir}} \leq 0.3$

The longer gas remains in CGM, the more it realigns with disk

[See also Danovich+15, Prieto+17]

Ongoing work by Z. Kocjan (looking for a PhD in the US!)

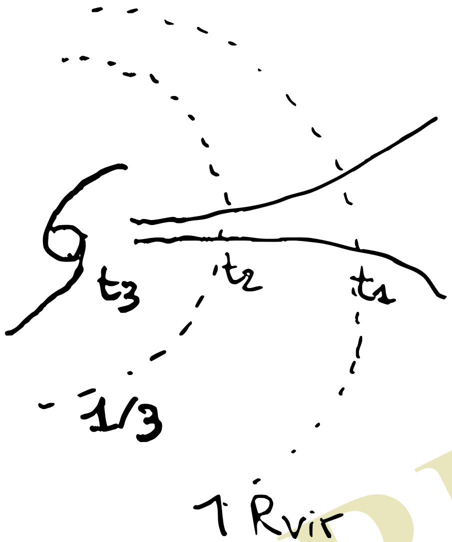


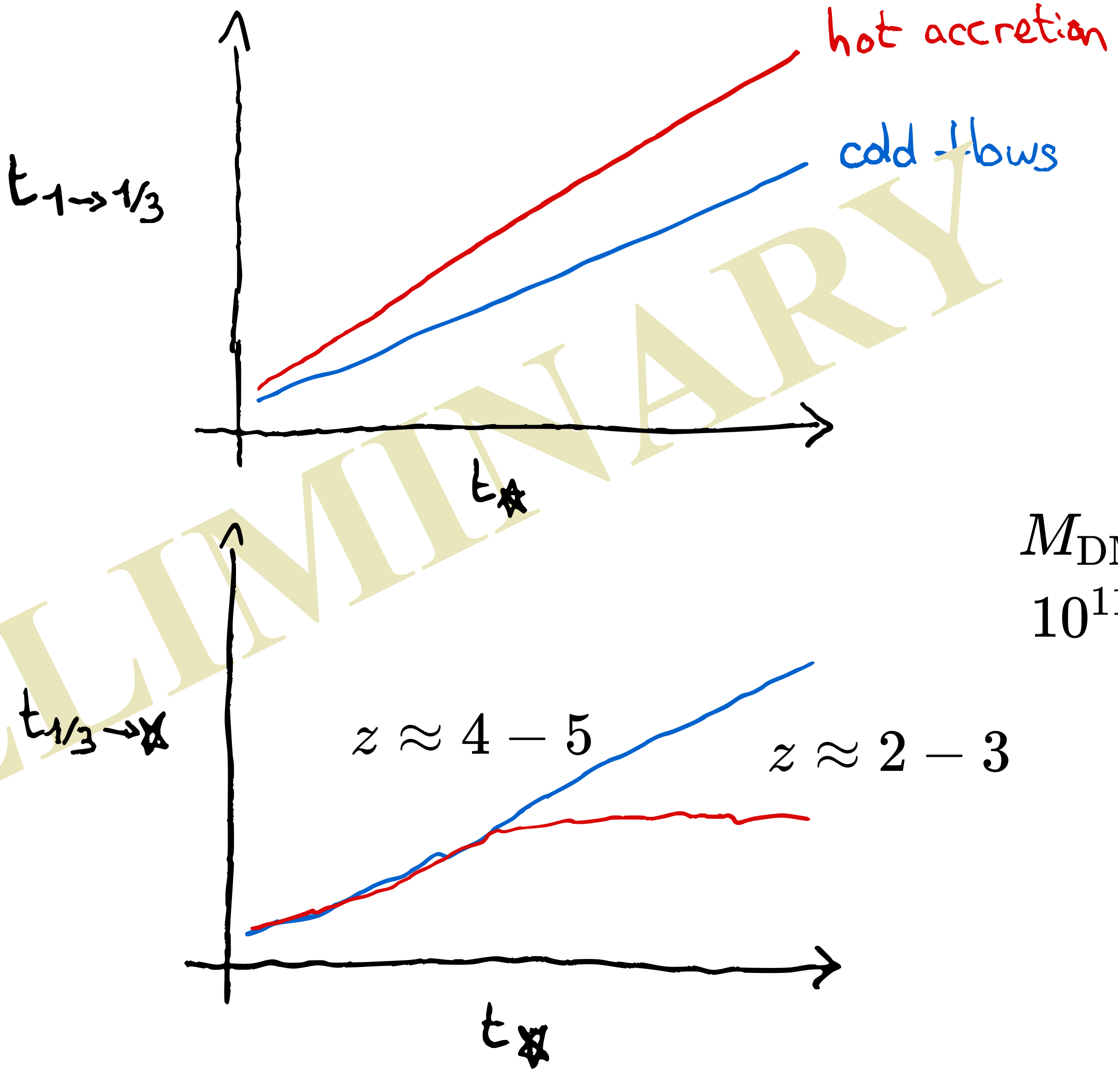


Filamentary accretion ~ Cold flow = $T \leq 10^5$K for $0.3R_{\rm vir} < r < 2R_{\rm vir}$

[Kocjan, CC+ in prep]

Ongoing work by Z. Kocjan (looking for a PhD in the US!)





$M_{\rm DM}(z=2) \approx 10^{11} - 10^{12} M_\odot$

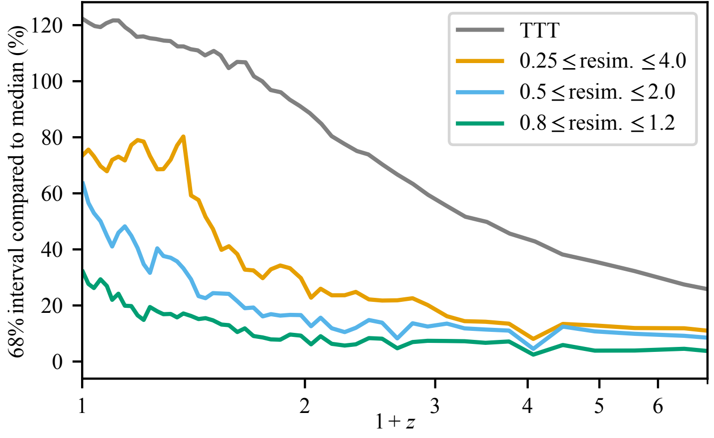
Filamentary accretion ~ Cold flow = $T \leq 10^5$K for $0.3R_{\rm vir} < r < 2R_{\rm vir}$

Not *necessarily* fast-track to star formation ⇒ lose connection to CW?

[Kocjan, CC+ in prep]

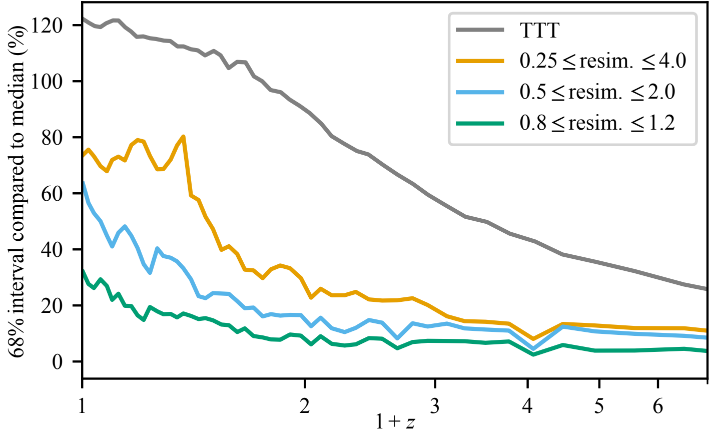
Conclusion & outlook

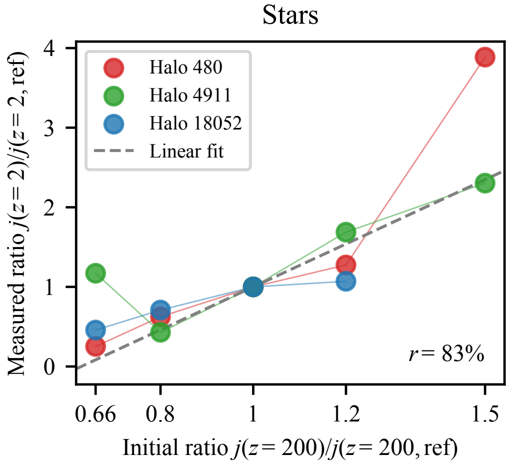
Conclusion & outlook



Conclusion & outlook

1. j_{DM} responds linearly to perturbations
   Good accuracy (few ~10%) achievable for **individual halos** in principle iff correct growth rate+boundary

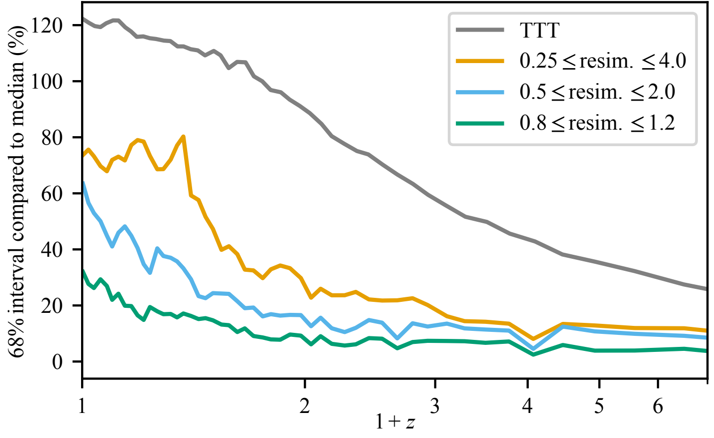


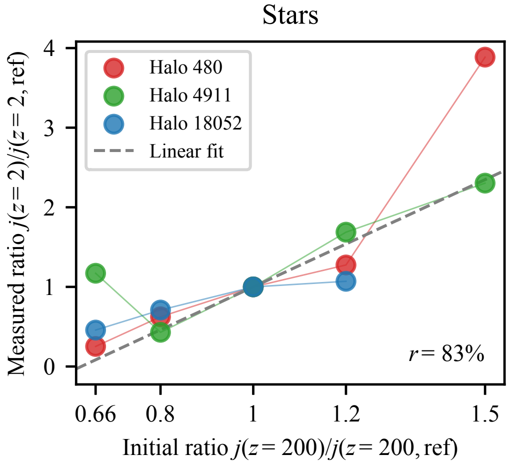


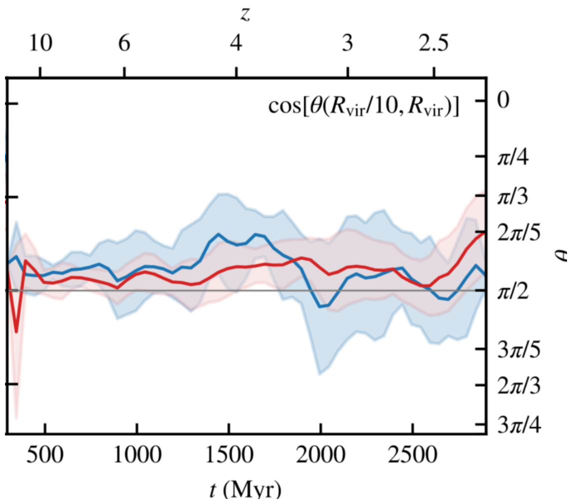
Conclusion & outlook

1. $j_{\rm DM}$ responds linearly to perturbations
   Good accuracy (few ~10%) achievable for **individual halos** in principle iff correct growth rate+boundary

2. $j_{\rm gal}$ retain memory of the cosmic web
   Galaxies may be less stochastic than expected
   Intrinsic alignment to be expected
   Galactic spin & DM spins are (partially) independent at level of individual galaxies







Conclusion & outlook

1. $j_{\rm DM}$ responds linearly to perturbations
   Good accuracy (few ~10%) achievable for **individual halos** in principle iff correct growth rate+boundary

2. $j_{\rm gal}$ retain memory of the cosmic web
   Galaxies may be less stochastic than expected
   Intrinsic alignment to be expected
   Galactic spin & DM spins are (partially) independent at level of individual galaxies

3. Boundary CW → galaxy formation: CGM
   Buffer zone: transition from gravity-dominated to baryon-dominated regime