The causal origin of the angular momentum and of the properties of galaxies

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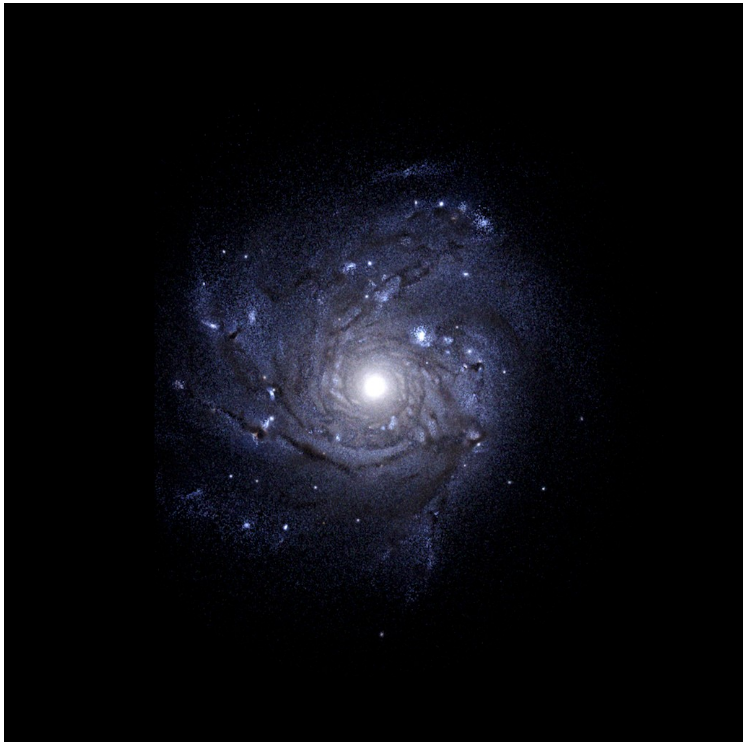
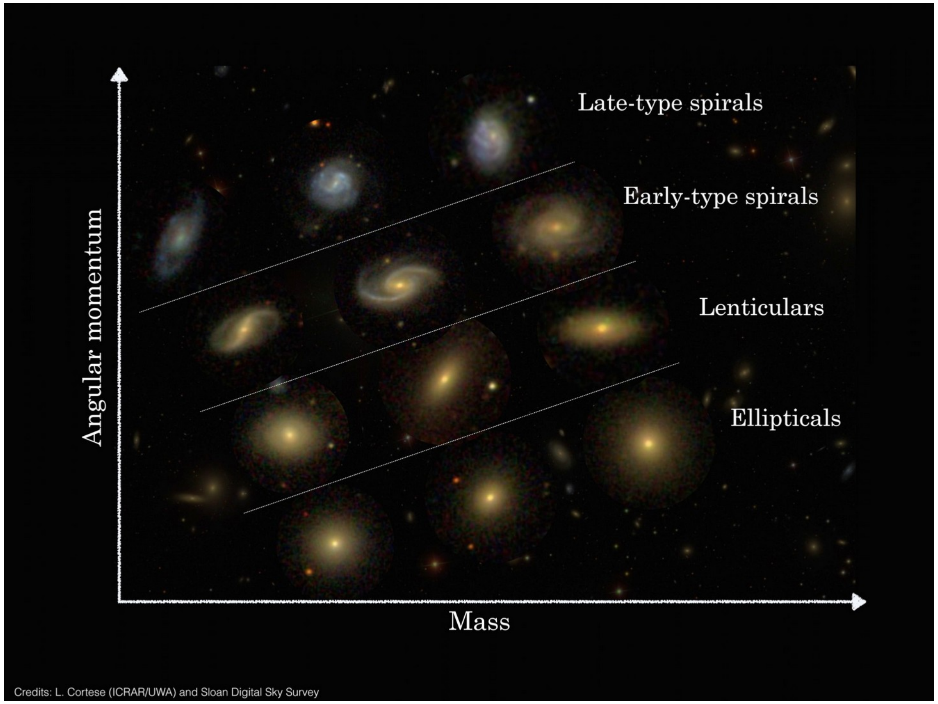
https://cphyc.github.io
Looking for job in 2022!



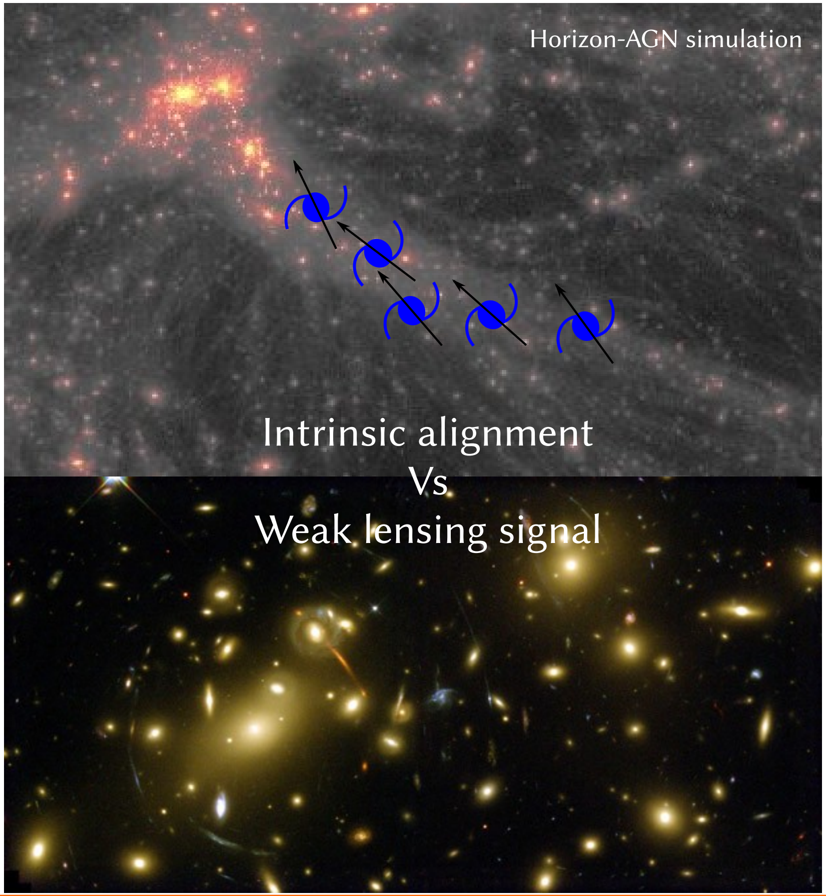
With A. Pontzen
& H. V. Peiris

Introduction

Cannot explain **morphological diversity** & **intrinsic alignment** without angular momentum



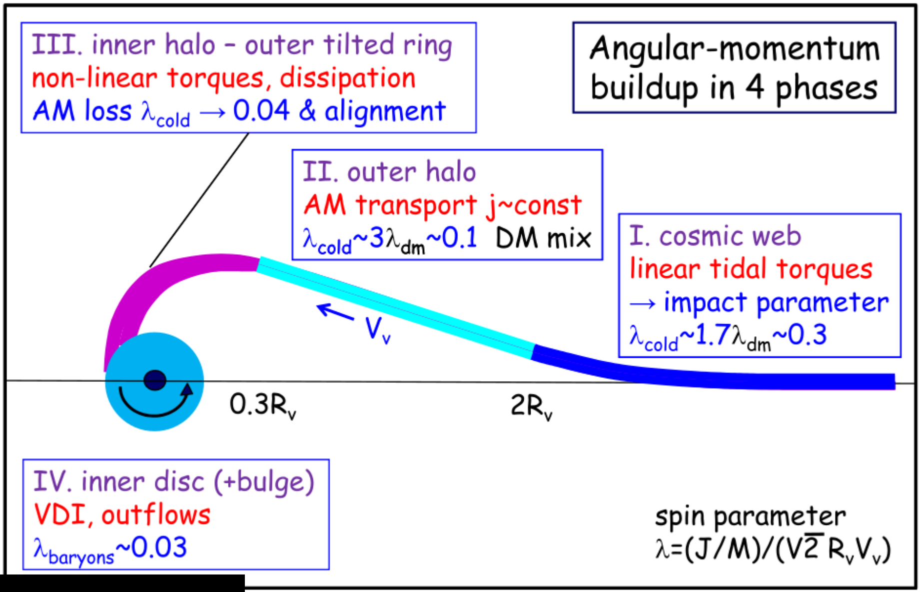
L. Cortese; SDSS.



+ subgrid physics: AGN, SN feedback, CRs, dust, ...

Origin of angular momentum

1) Early times: torquing with cosmic web
2) Transport at constant ~j
3) Torque down in inner halo
4) Mixing in inner disk & bulge



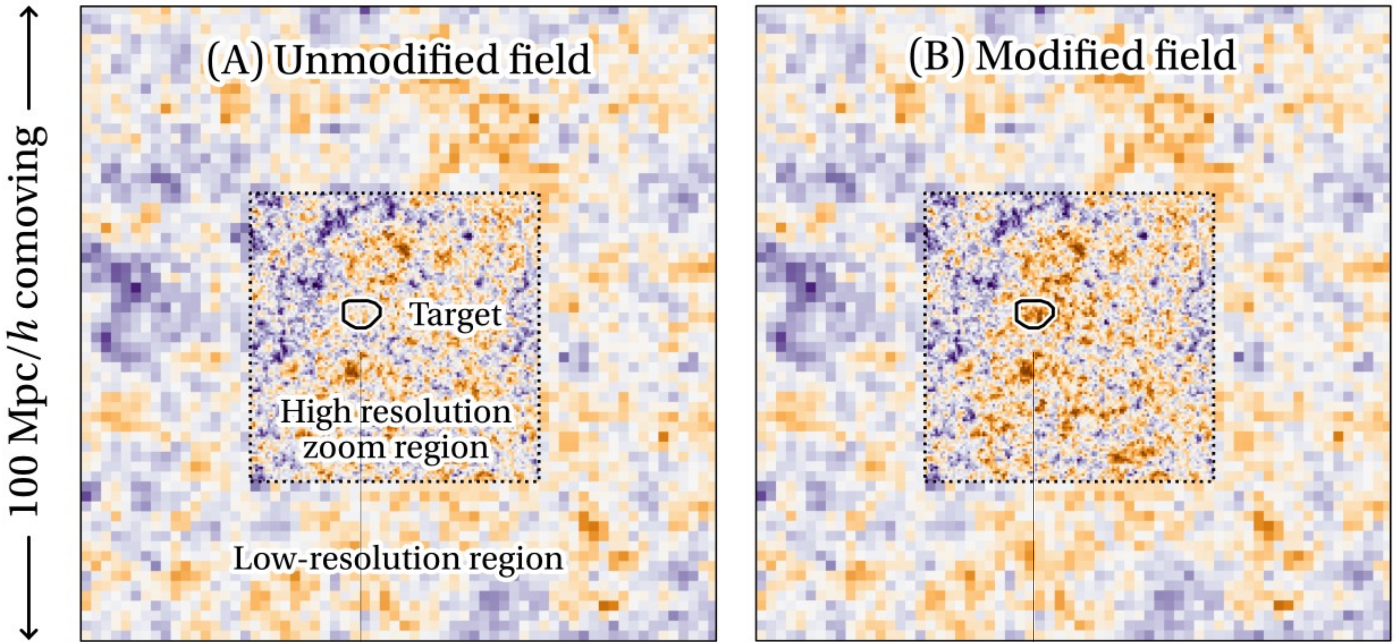
Danovich+15

Studying angular momentum

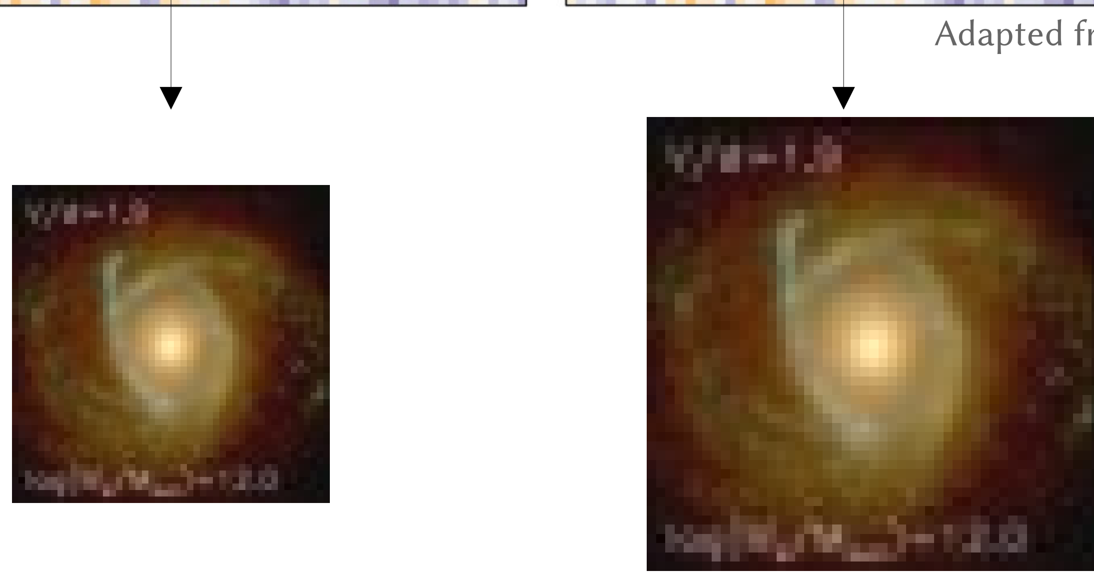
	Isolated sims	Large cosmo	Zoom
• Resolve the disk scale-height $\Delta x = 30$pc	×		×
• Cosmological setup		×	×
• Modify angular momentum accretion history			
• Modify cosmological environment			

Studying AM: a need for a fresh approach

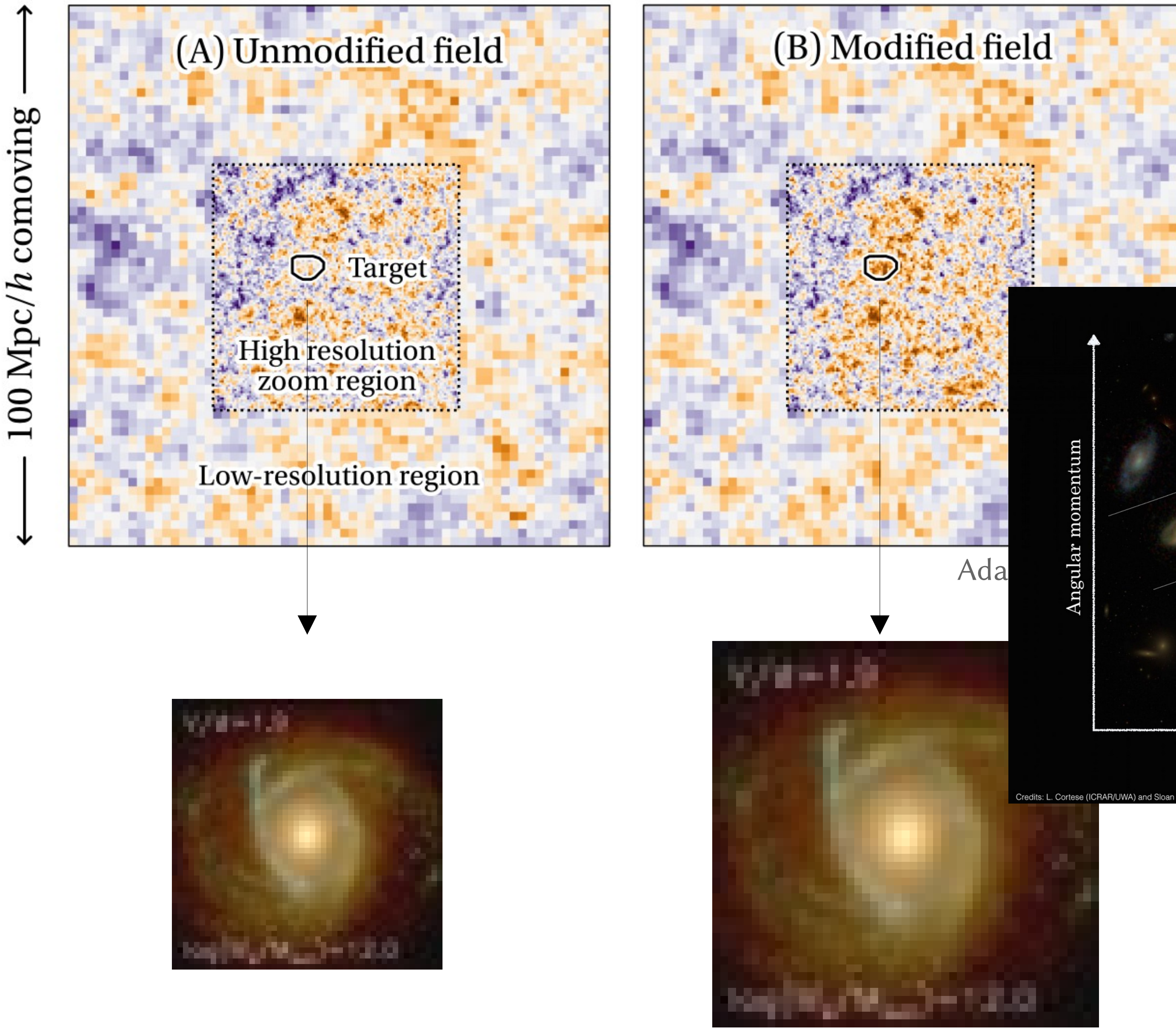
	Isolated sims	Large cosmo	Zoom	???
• Resolve the disk scale-height $\Delta x = 30$pc	×		×	×
• Cosmological setup		×	×	×
• Modify angular momentum accretion history				×
• Modify cosmological environment				



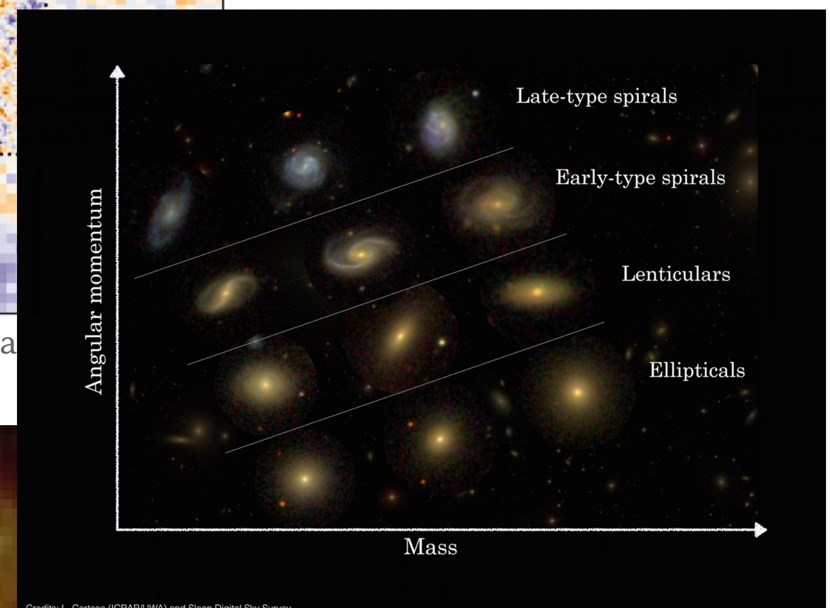
Adapted from Stopyra+20



GM: Roth+16, Rey&Pontzen 18



Ada

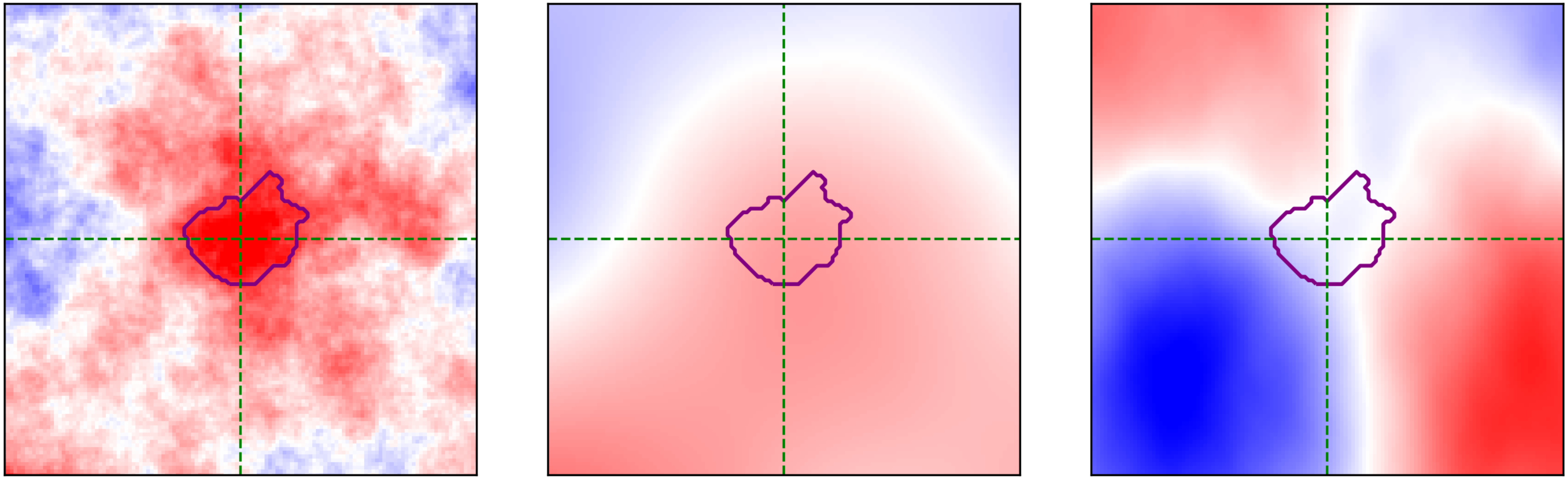


GM: Roth+16, Rey&Pontzen 18

In the ICs

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

$$\Delta\phi = 4\pi G\bar{\rho}(1+\delta)$$

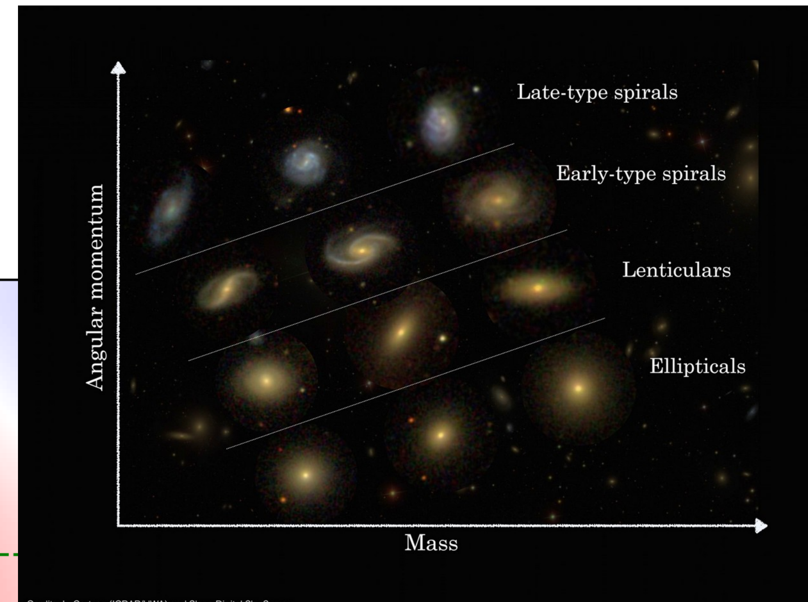


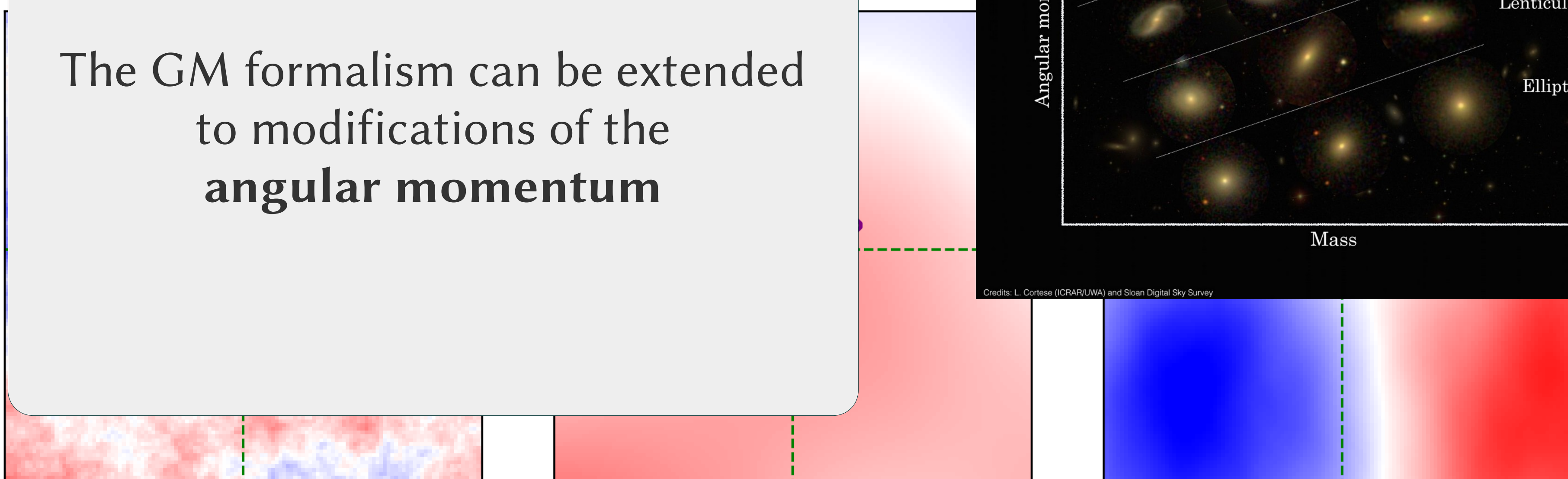
(1) Generate δ (2) Derive ϕ (3) Compute $\nabla_x\phi, \nabla_y\phi, \nabla_z\phi$

In the ICs

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

The GM formalism can be extended to modifications of the **angular momentum**

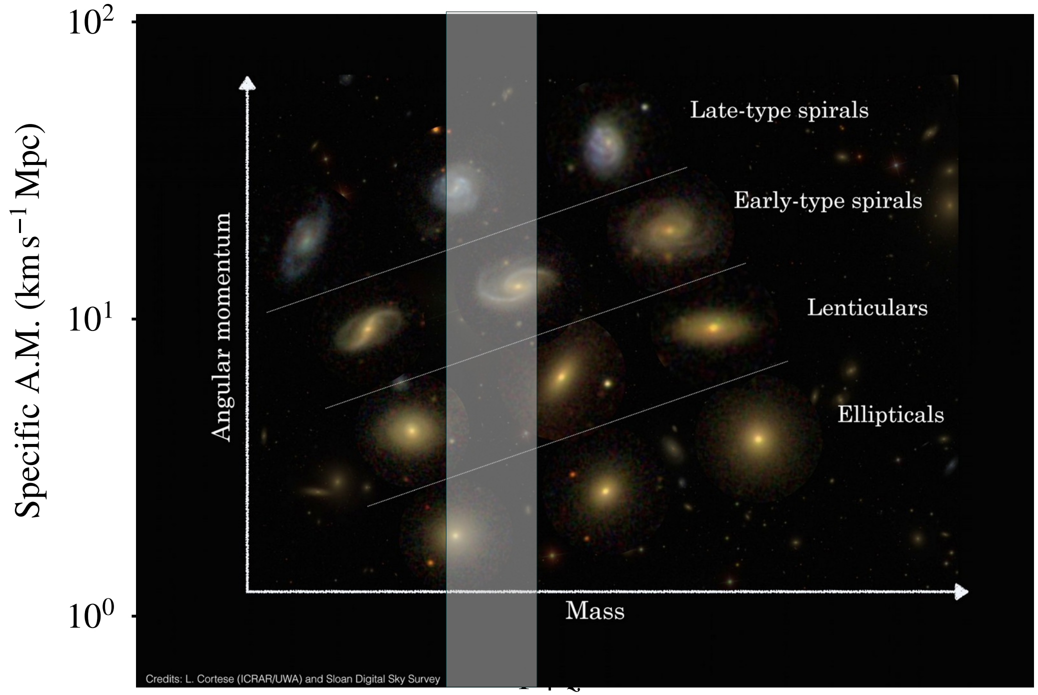




(1) Generate δ (2) Derive ϕ (3) Compute $\nabla_x\phi, \nabla_y\phi, \nabla_z\phi$

First step: DM only simulations

Same halo, same environment but ...



Classical DM-only setup
256^3 ICs
7 halos × 8 different AM*
50 Mpc/h box
AdaptaHOP halo finder

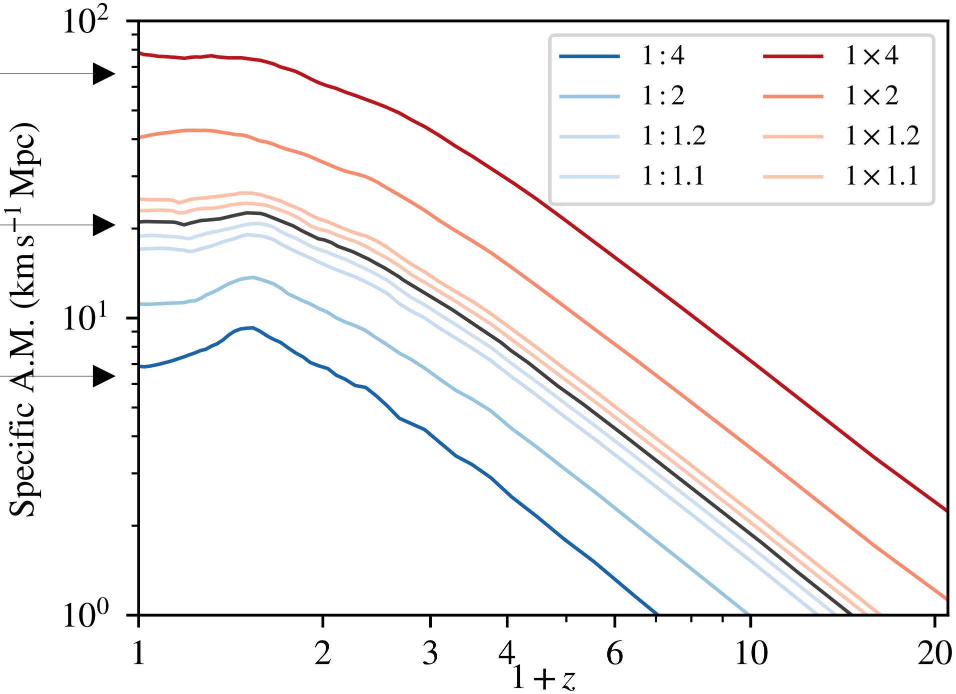
*: l_0 × 0.25, 0.5, 0.8, 0.9, 1.1, 1.2, 2, 4

Same halo, same environment but ...

... increased initial AM

Reference simu

... decreased initial AM



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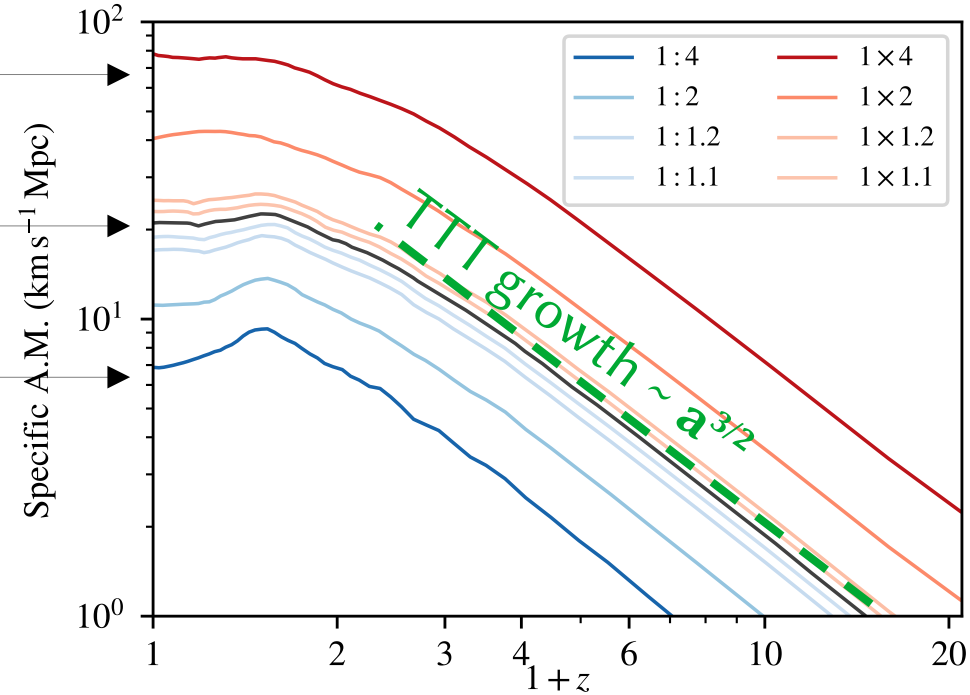

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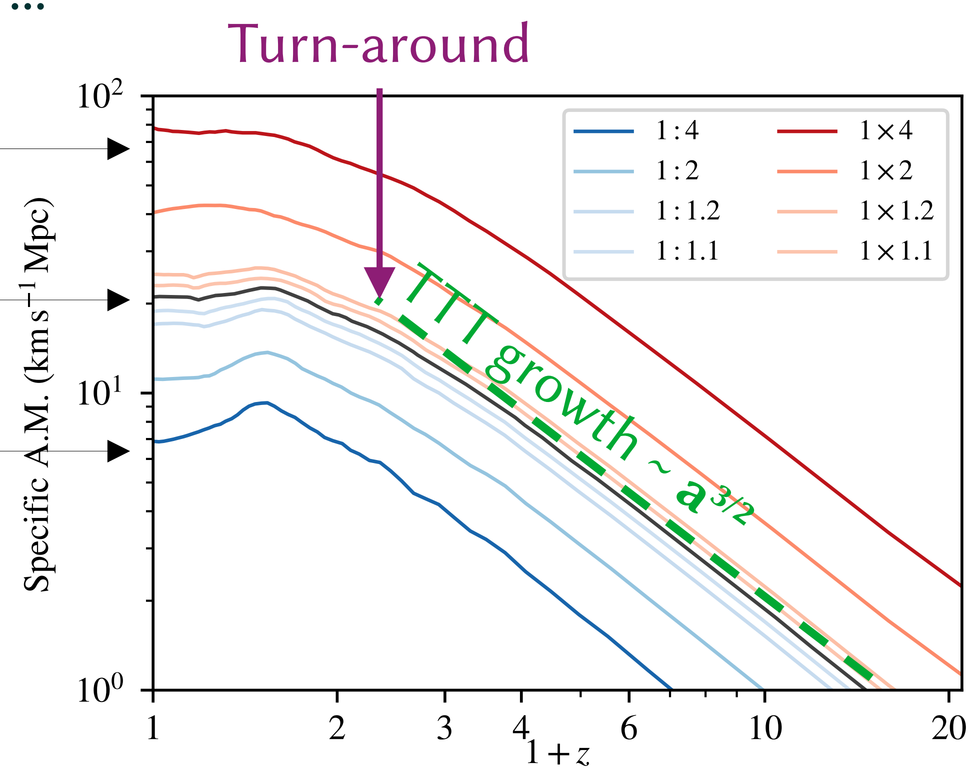

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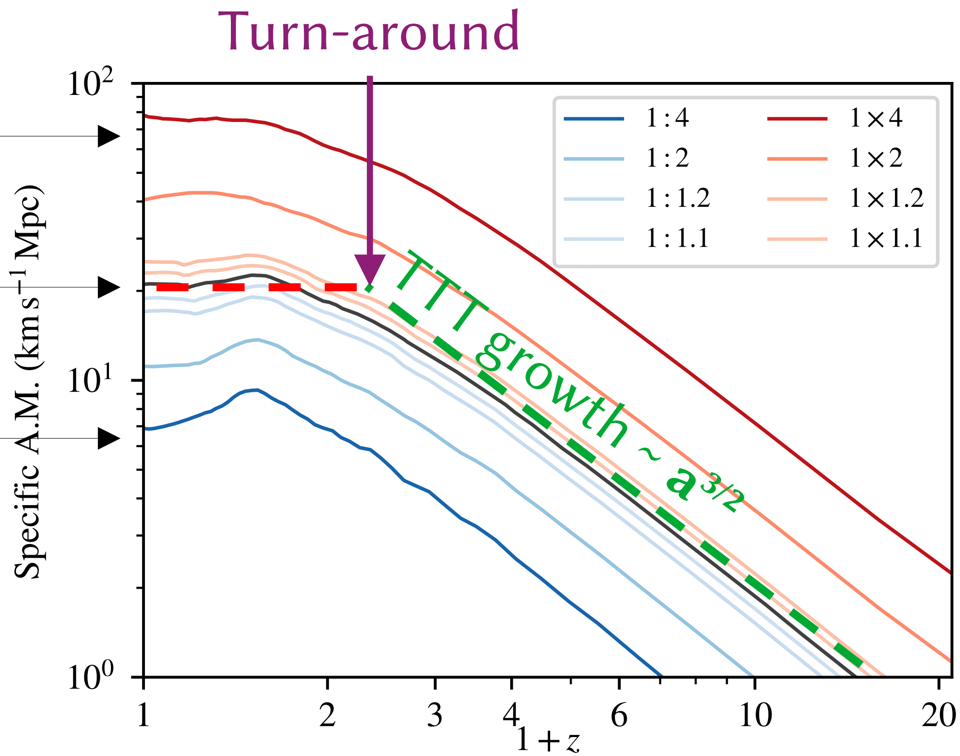

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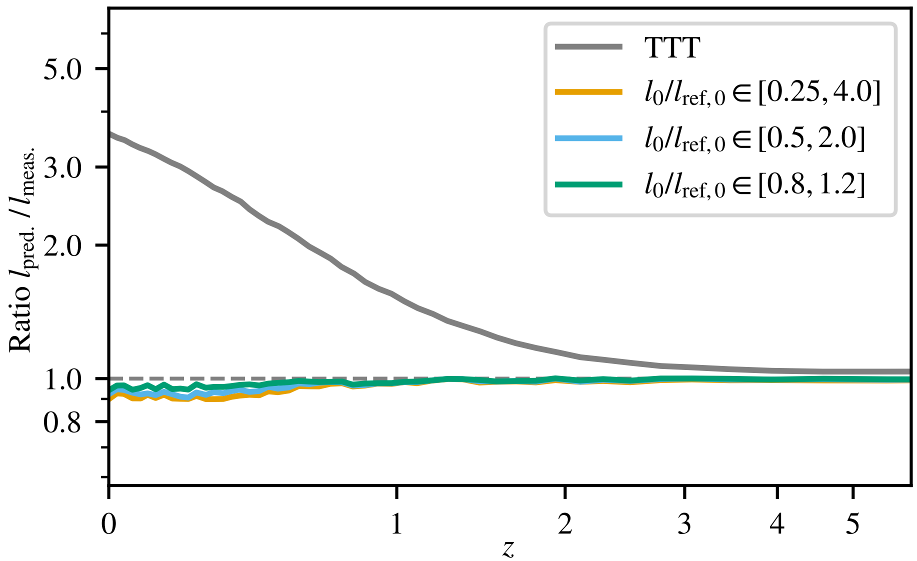
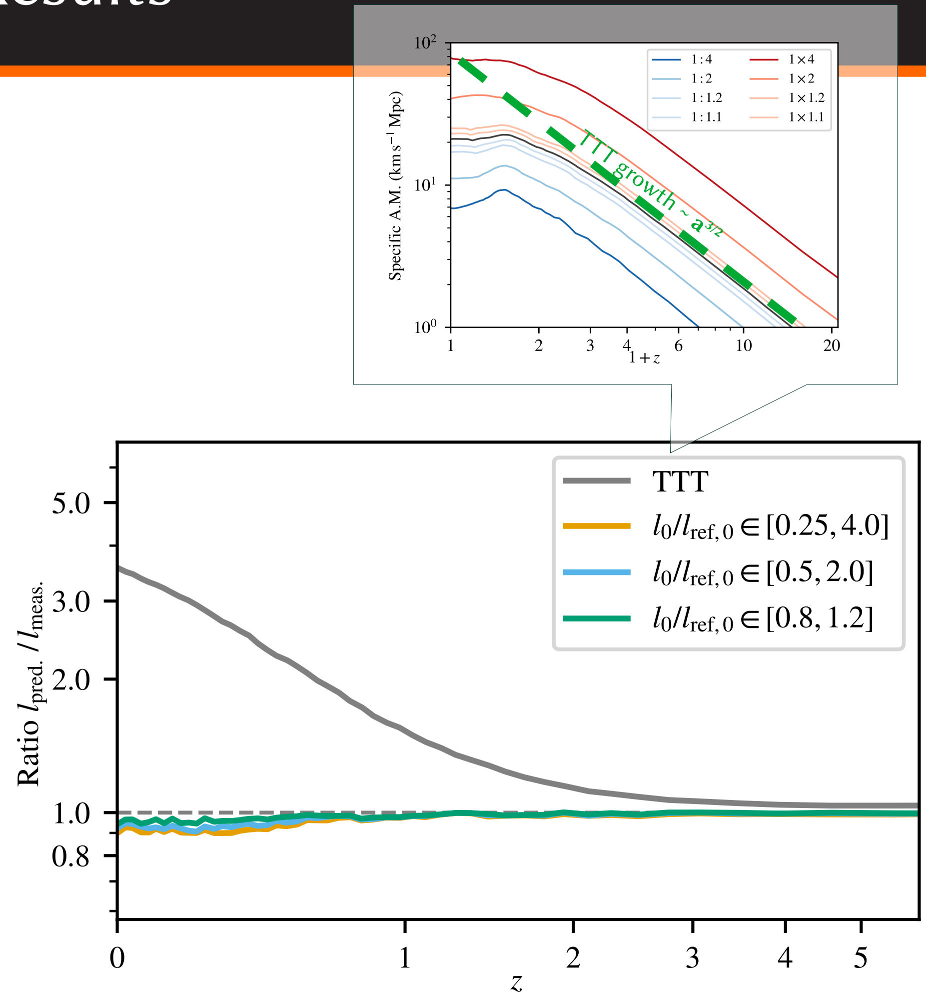


TTT
$l_0/l_{\text{ref},0} \in [0.25, 4.0]$
$l_0/l_{\text{ref},0} \in [0.5, 2.0]$
$l_0/l_{\text{ref},0} \in [0.8, 1.2]$
Ratio $l_{\text{pred.}}/l_{\text{meas.}}$
5.0
3.0
2.0
1.0
0.8
0
1
2
3
4
5
z



Specific A.M. (km s^{-1} Mpc)
$1+z$
1:4
1:2
1:1.2
1:1.1
1×4
1×2
1×1.2
1×1.1
TTT growth ~ $a^{3/2}$
Ratio $l_{\rm pred.}/l_{\rm meas.}$
z
TTT
$l_0/l_{\rm ref,0} \in [0.25, 4.0]$
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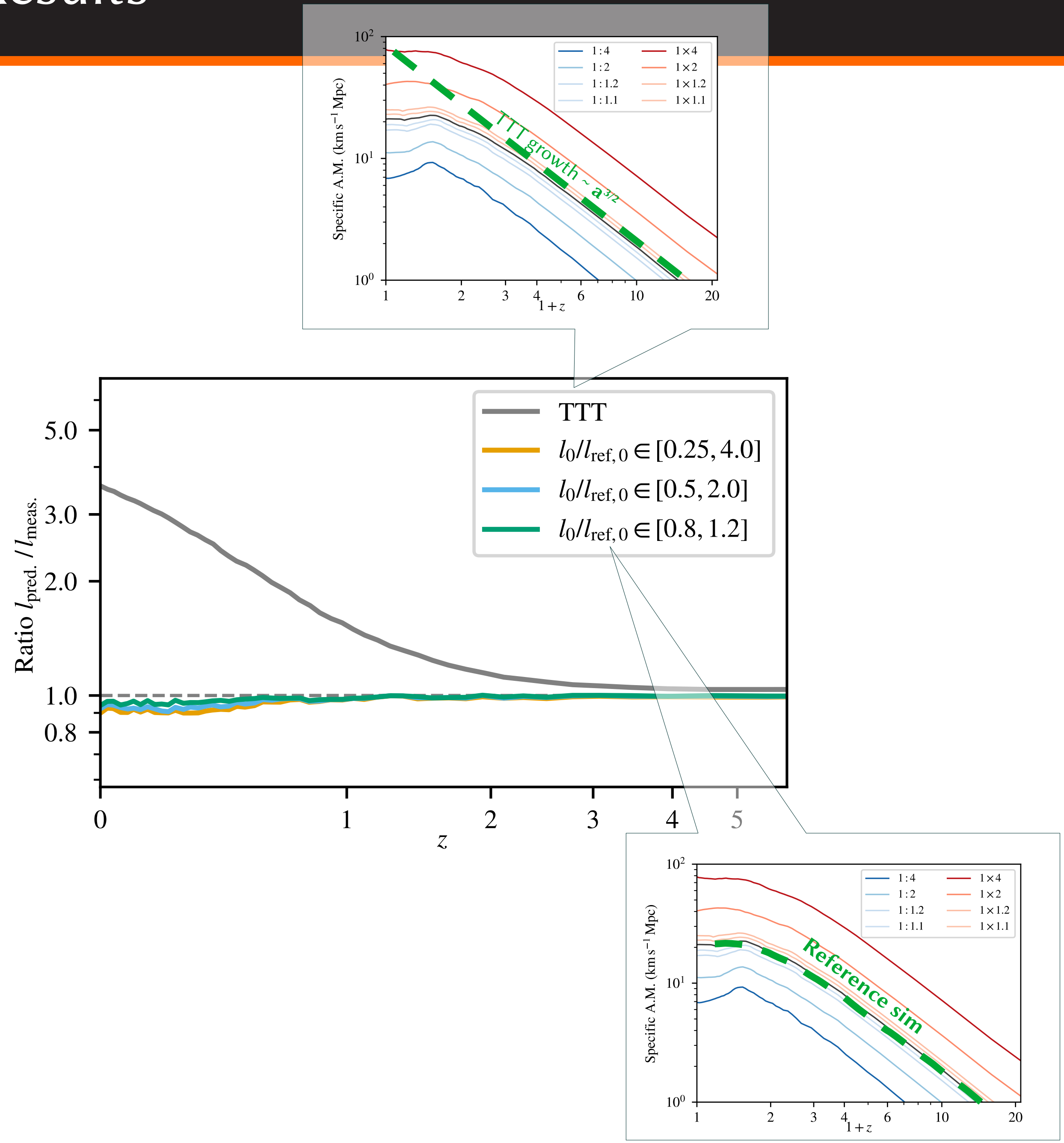
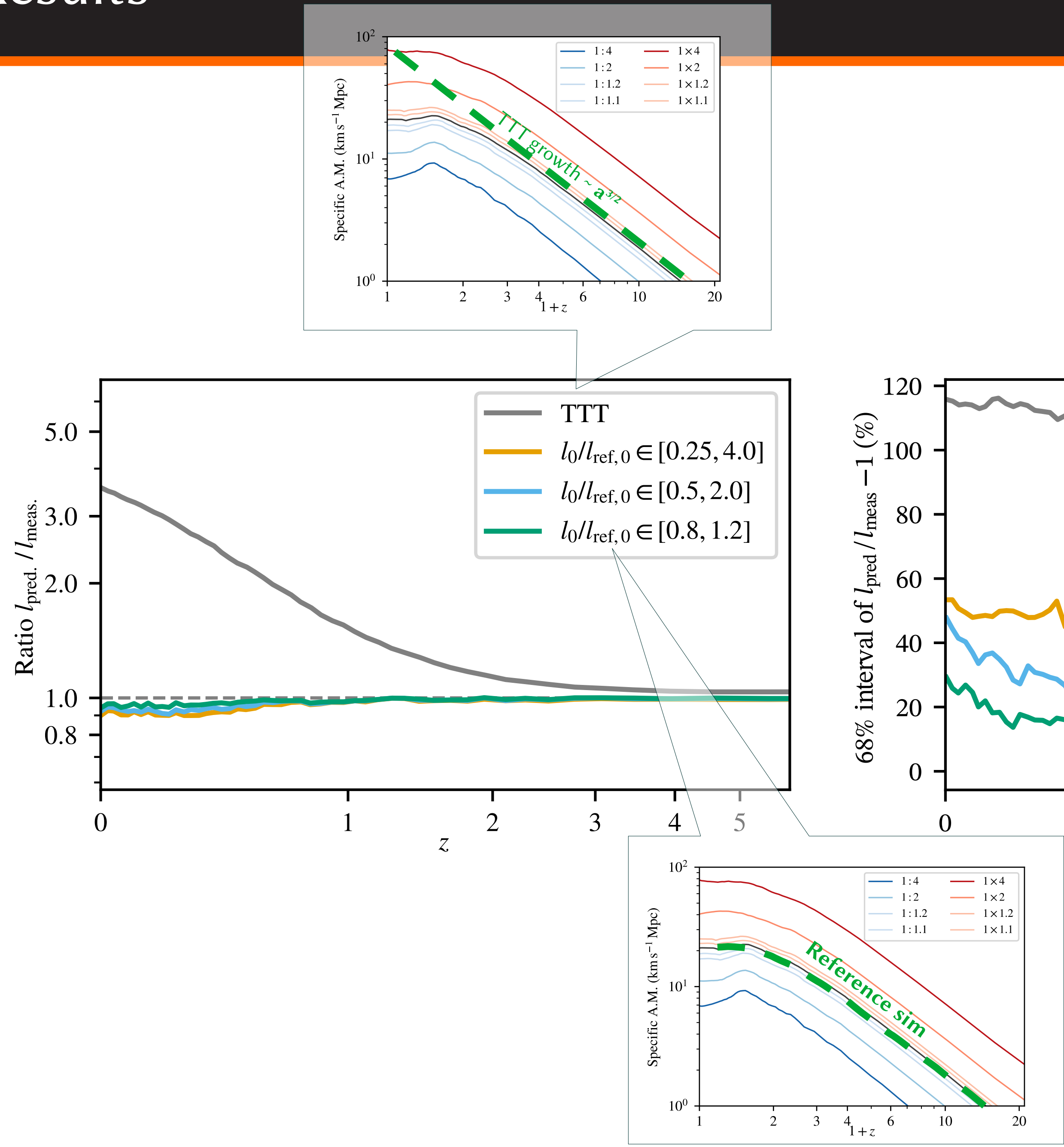

TTT growth ~ a^{3/2}
Reference sim
Specific A.M. (km s^{-1} Mpc)
1 + z
1 : 4
1 : 2
1 : 1.2
1 : 1.1
1 × 4
1 × 2
1 × 1.2
1 × 1.1
TTT
$l_0/l_{ref,0} \in [0.25, 4.0]$
$l_0/l_{ref,0} \in [0.5, 2.0]$
$l_0/l_{ref,0} \in [0.8, 1.2]$
Ratio $l_{pred.}/l_{meas.}$
z


Specific A.M. (km s^{-1} Mpc)
1 : 4
1 : 2
1 : 1.2
1 : 1.1
1 × 4
1 × 2
1 × 1.2
1 × 1.1
TTT growth ~ $a^{3/2}$
$1+z$
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TTT
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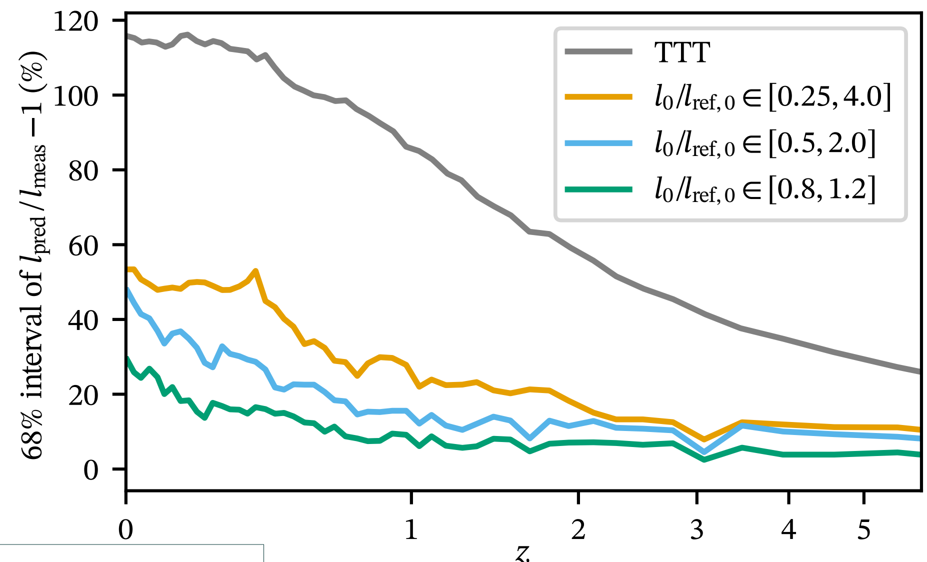
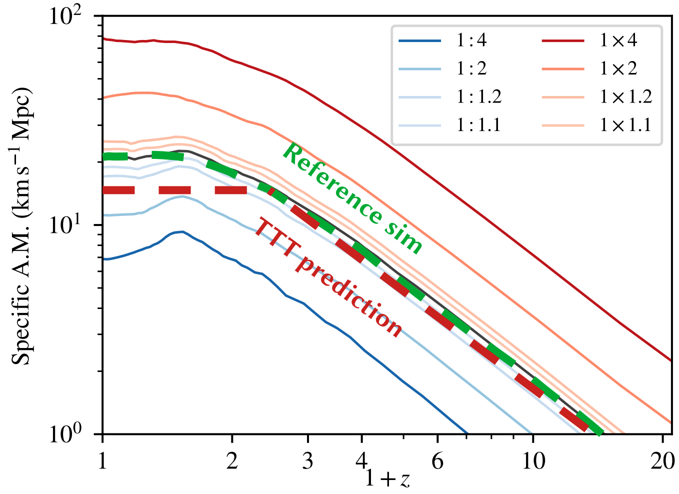
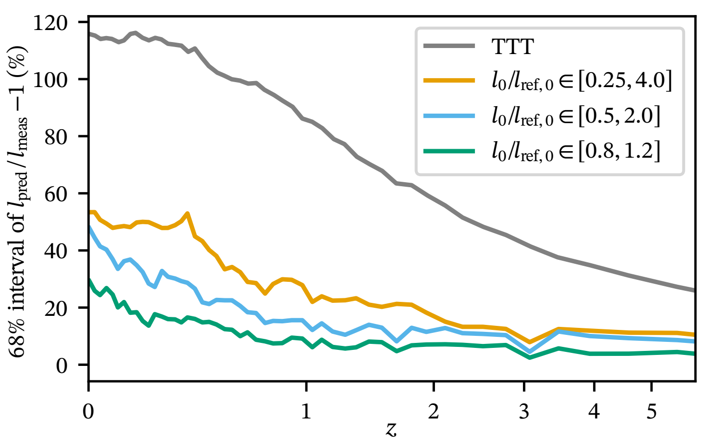
$l_0/l_{ref,0} \in [0.8, 1.2]$
z
Reference sim


68% interval of $l_{pred}/l_{meas} - 1$ (%)
TTT
$l_0/l_{ref,0} \in [0.25, 4.0]$
$l_0/l_{ref,0} \in [0.5, 2.0]$
$l_0/l_{ref,0} \in [0.8, 1.2]$
z

- Tested TTT for single DM halos
- AM of **set of particles** can be **predicted accurately** from initial conditions (not chaotic)
- Possible to improve theory ×4 by **predicting halo growth rate** (instead of universal growth rate)
- Apparent stochasticity of AM
  ~~⟹ due to chaos~~
  ⟹ due to **particle membership**



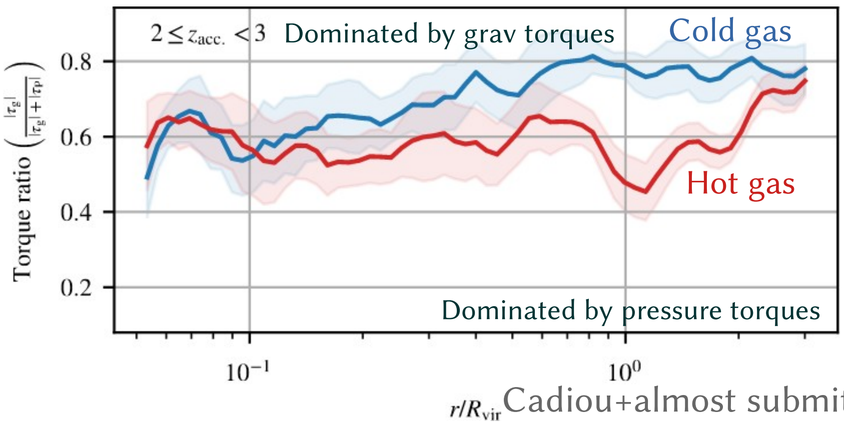


<u>Conclusion:</u>
AM & spin are predictable / *not* random
(⟹ systematic effects in lensing survey)

Second step: GM of baryons

- Apply same method to **baryon AM**
- Simulations (9Mh @ DiRAC):
  - Cosmological hydro $\Delta x = 35$pc
  - $z \geq 2$, $M_{200c} = 10^{12} M_\odot$
  - SF + AGN & SN feedback
  - RAMSES, Teyssier+02
    New Horizon model, Dubois+21
    Tracer particles, Cadiou+19
- Ansatz: accreted gas is…
  - slowed down by **pressure gradients**
    torqued down by **grav. torques**
  - Less sensitive to particle membership

ONGOING



Cadiou+almost submitted
[see also Prieto+16;
Danovich+15 for ≠ result]

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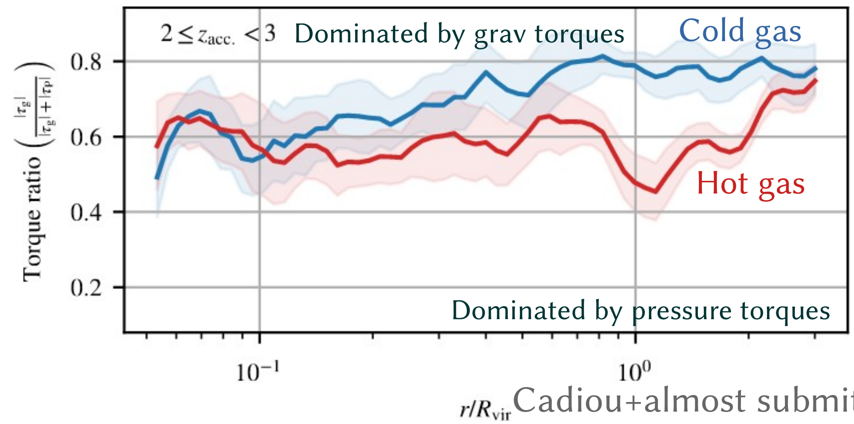

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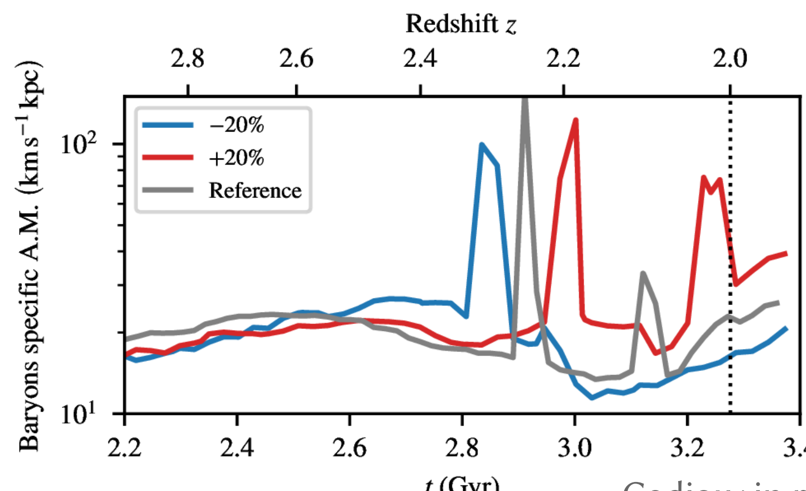


Cadiou+in prep

Second step: GM of baryons

- Appl
- Simu
  - C
  - z
  - S
  - I
    N
    T
- Ansa
  - s
    t
  - Less sensitive to particle membership

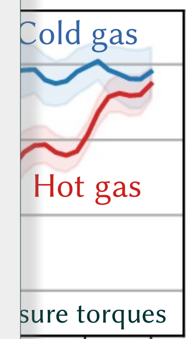
ONGOING

ONGOING

Very preliminary results

- AM of **galactic baryons** can be controlled/predicted from initial conditions
- AGN & SN feedback play small role in setting **baryon AM** at $z > 2$

Can now explore origin of galaxy spin & interplay with baryons



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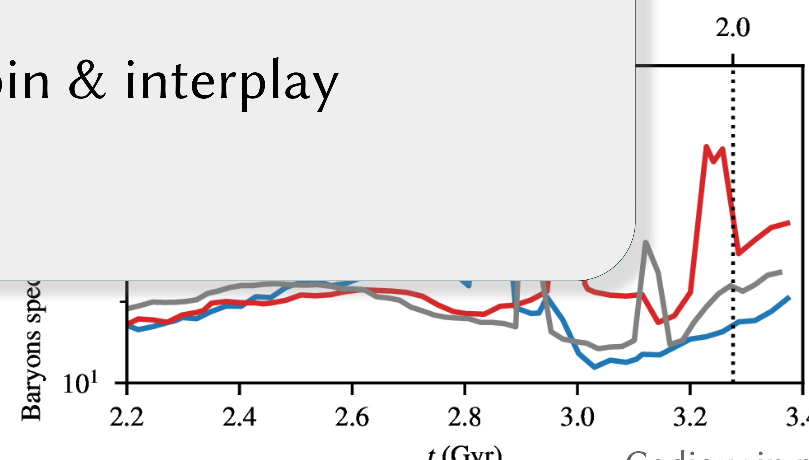

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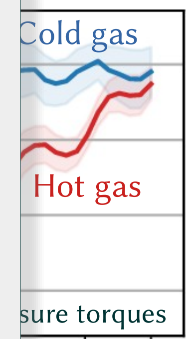

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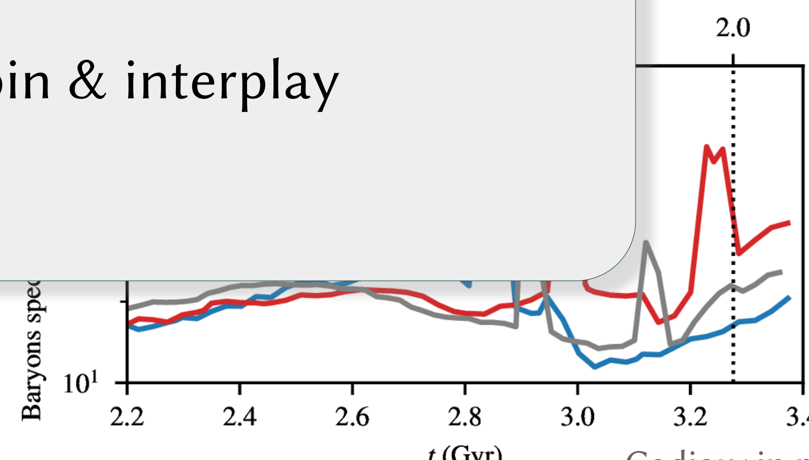

Cadiou+in prep

Introducing genetic modifications

	Isolated sims	Large cosmo	Zoom	GM of AM
• Resolve the disk scale-height $\Delta x = 30\text{pc}$	×		×	×
• Cosmological setup		×	×	×
• Modify angular momentum accretion history[1]				×
• Modify cosmological environment				

1: Cadiou+21a, arXiv: 2012.02201

	Isolated sims	Large cosmo	Zoom	GM of AM	???
Resolve the disk scale-height $\Delta x = 30\text{pc}$	×		×	×	×
Cosmological setup		×	×	×	×
Modify angular momentum accretion history[1]				×	
Modify cosmological environment					×

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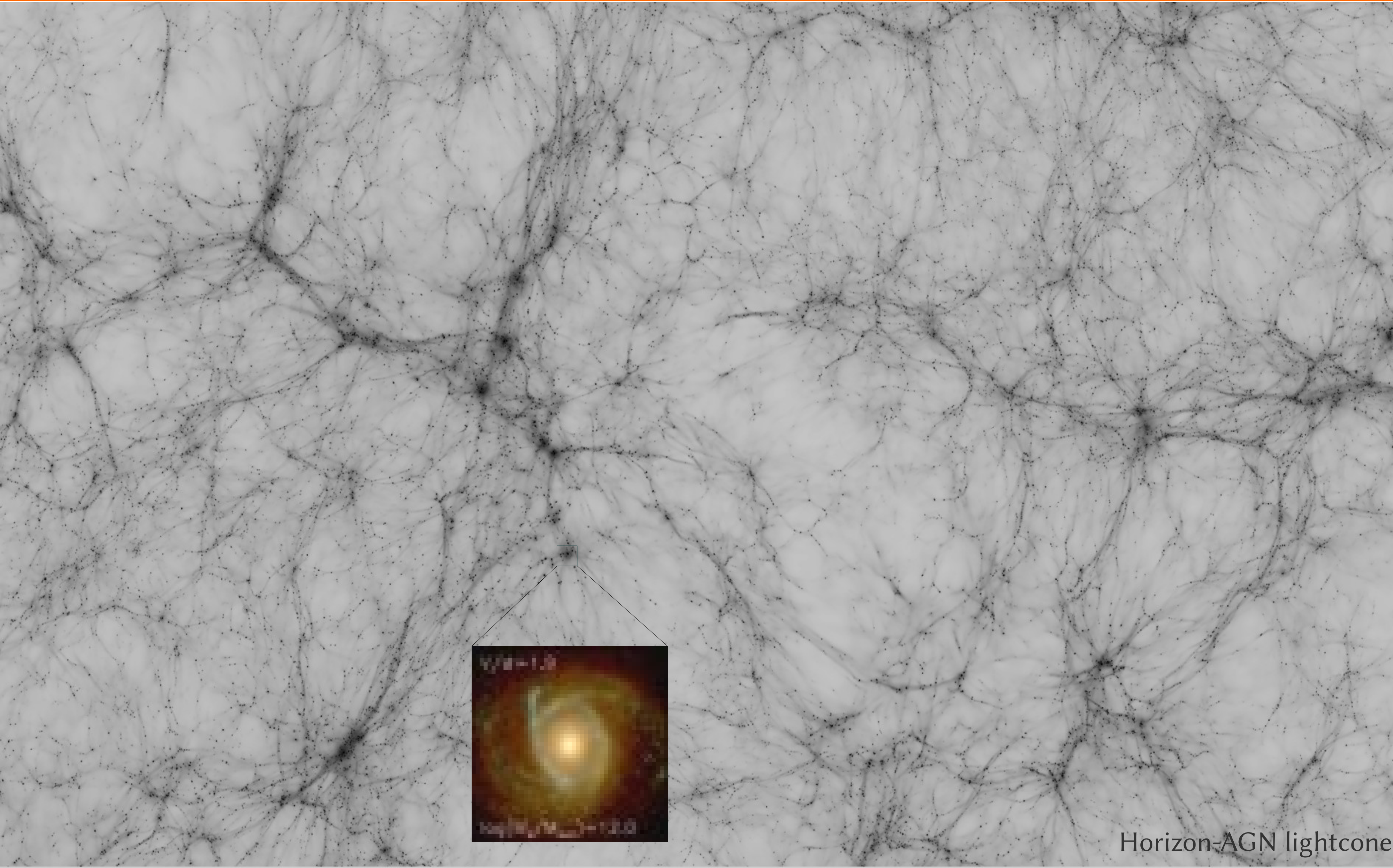
The effect of environment on AM

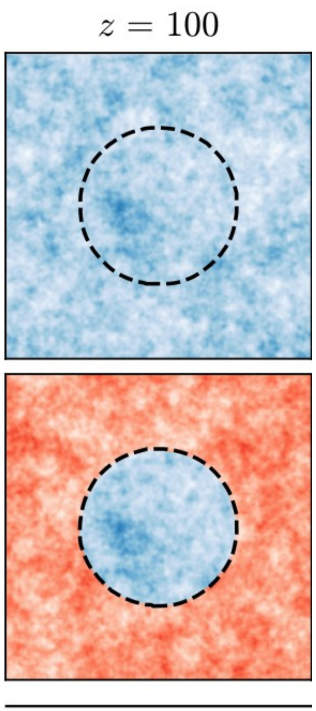
The splicing technique



What if the galaxy had formed here instead?

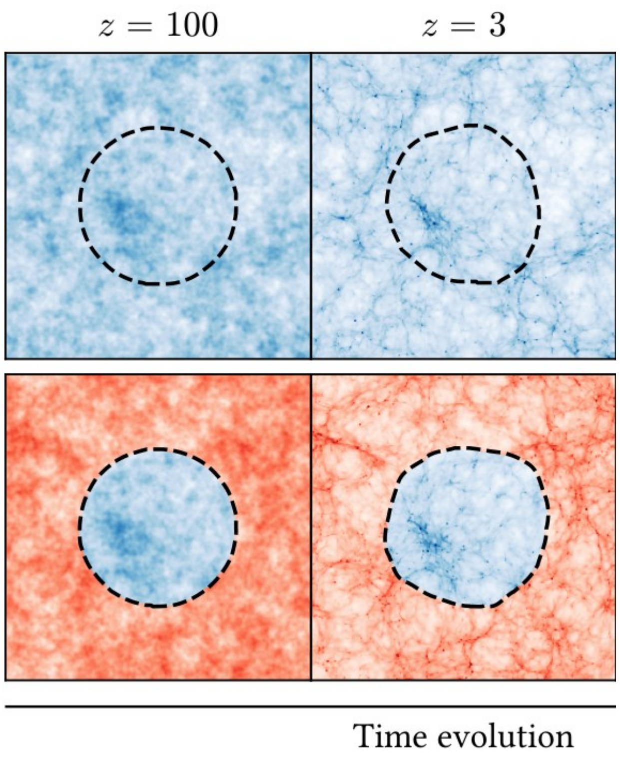

What if the galaxy had formed here instead?
Or here?
Horizon-AGN lightcone

In 3D



The “splicing technique”

In 3D



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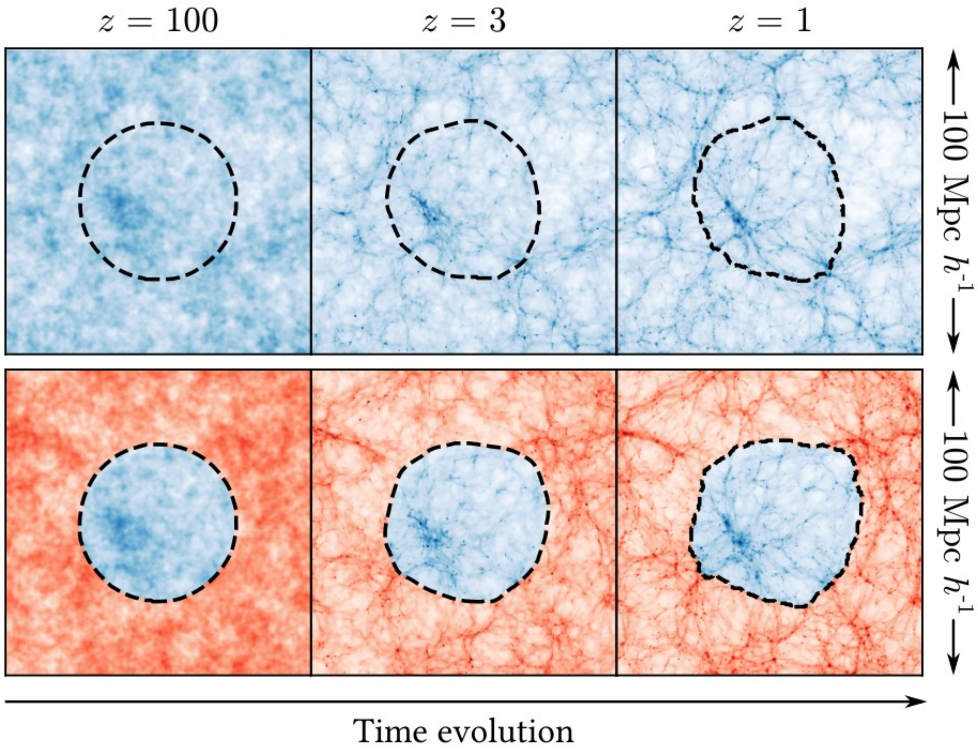

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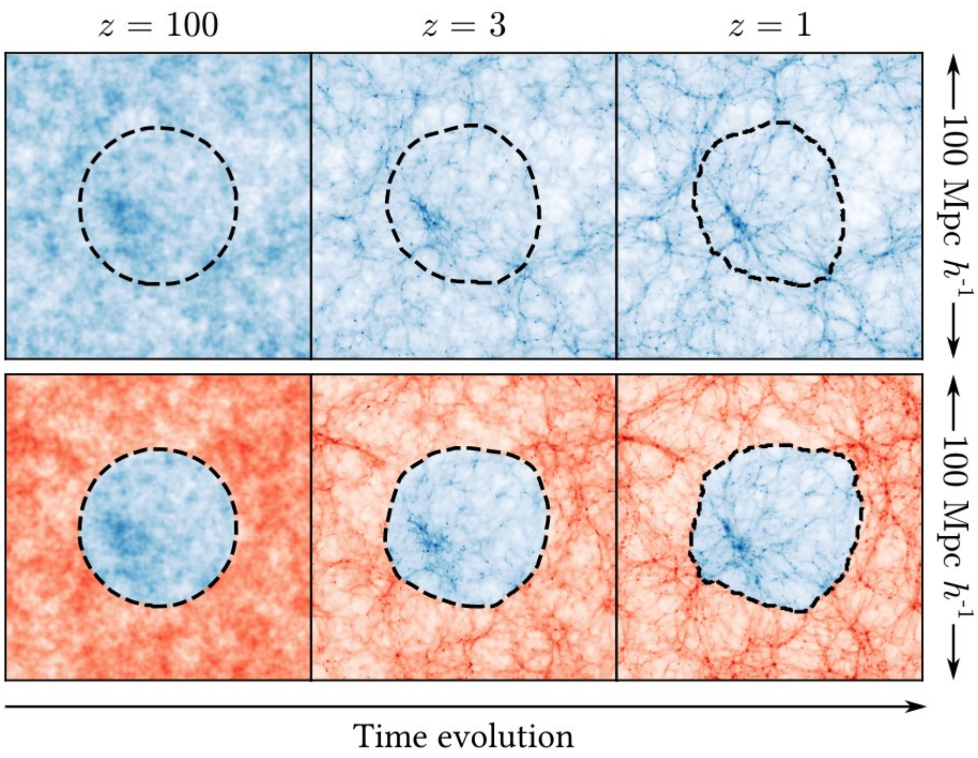
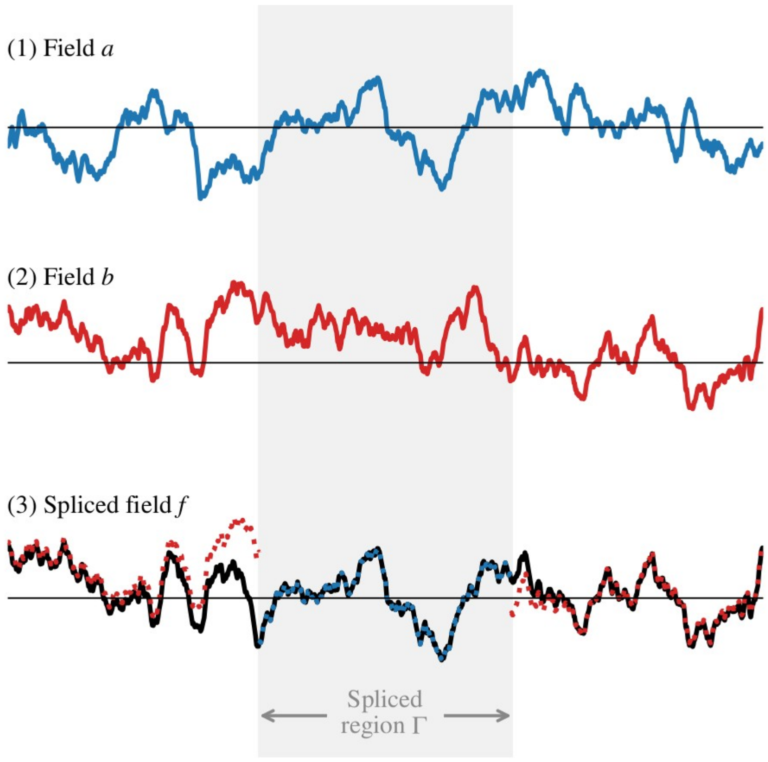
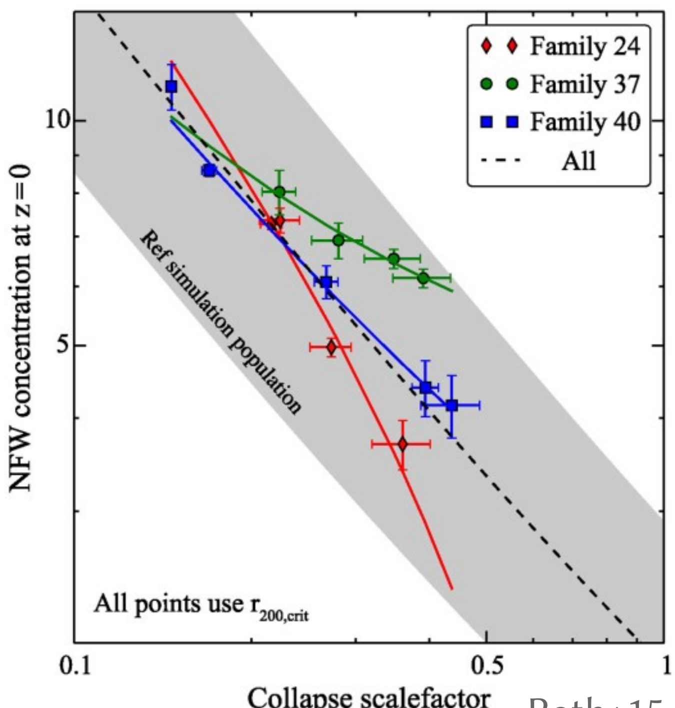


In 1D

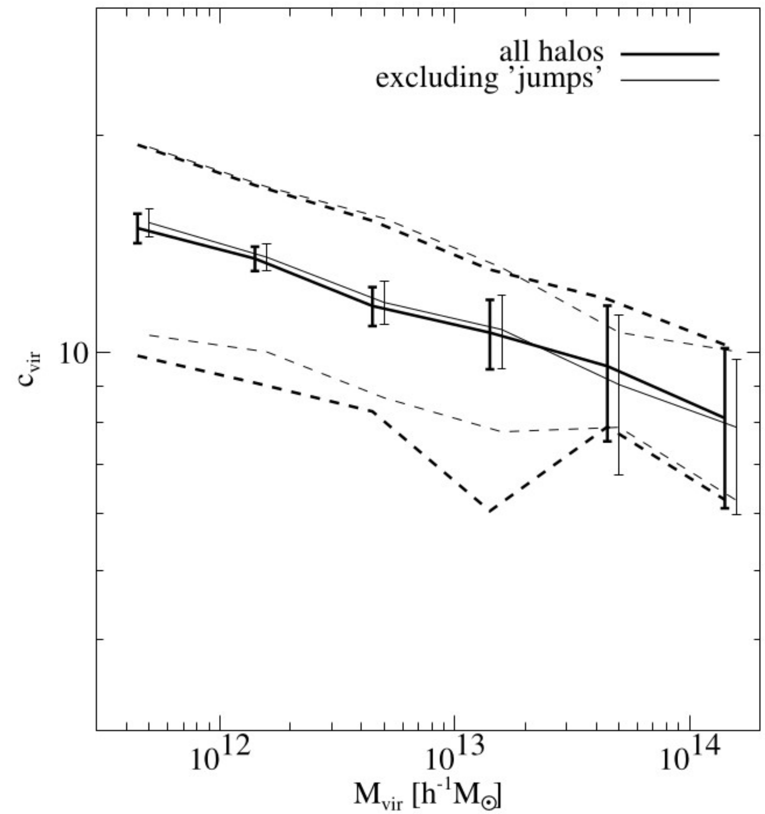


At fixed mass: scatter in *c* parameter

Hypothesis: scatter is due to different formation times.



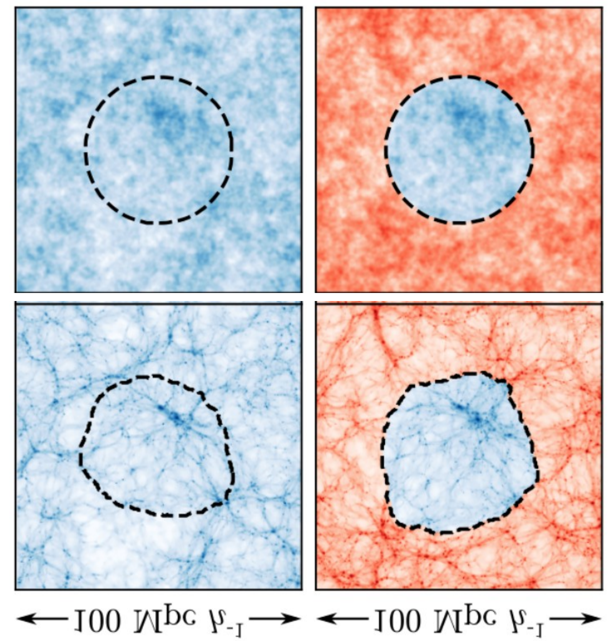
Roth+15



Wechsler+02

Procedure:

- Run simulation to $z = 0$
- Select halo and its particles
- Trace back to initial conditions ($z = 100$)
- "Cut" and "paste" into different environment
- Run simulation again & measure M_{200c} and c



More details in **Cadiou+21b**
"The causal effect of environment on halo mass and concentration"

Procedure:

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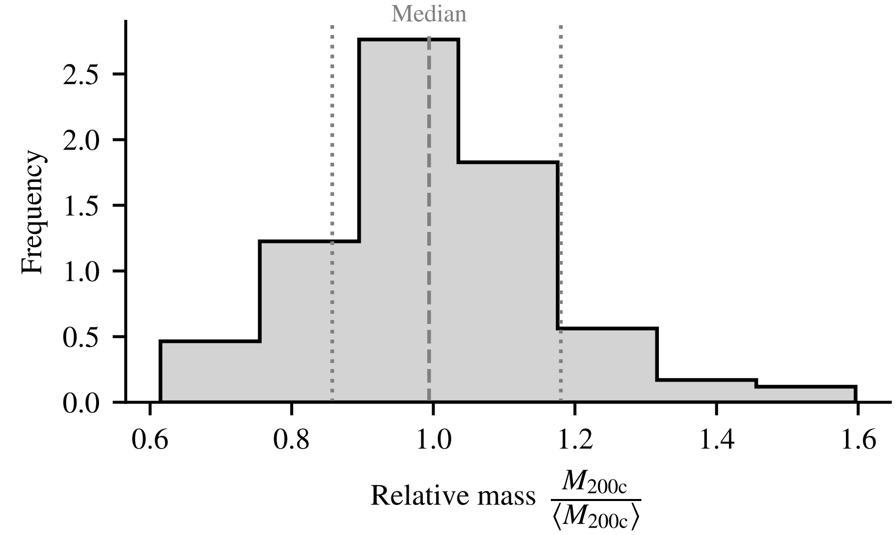
1) Small mass fluctuations (±20%) & 50% particles in common



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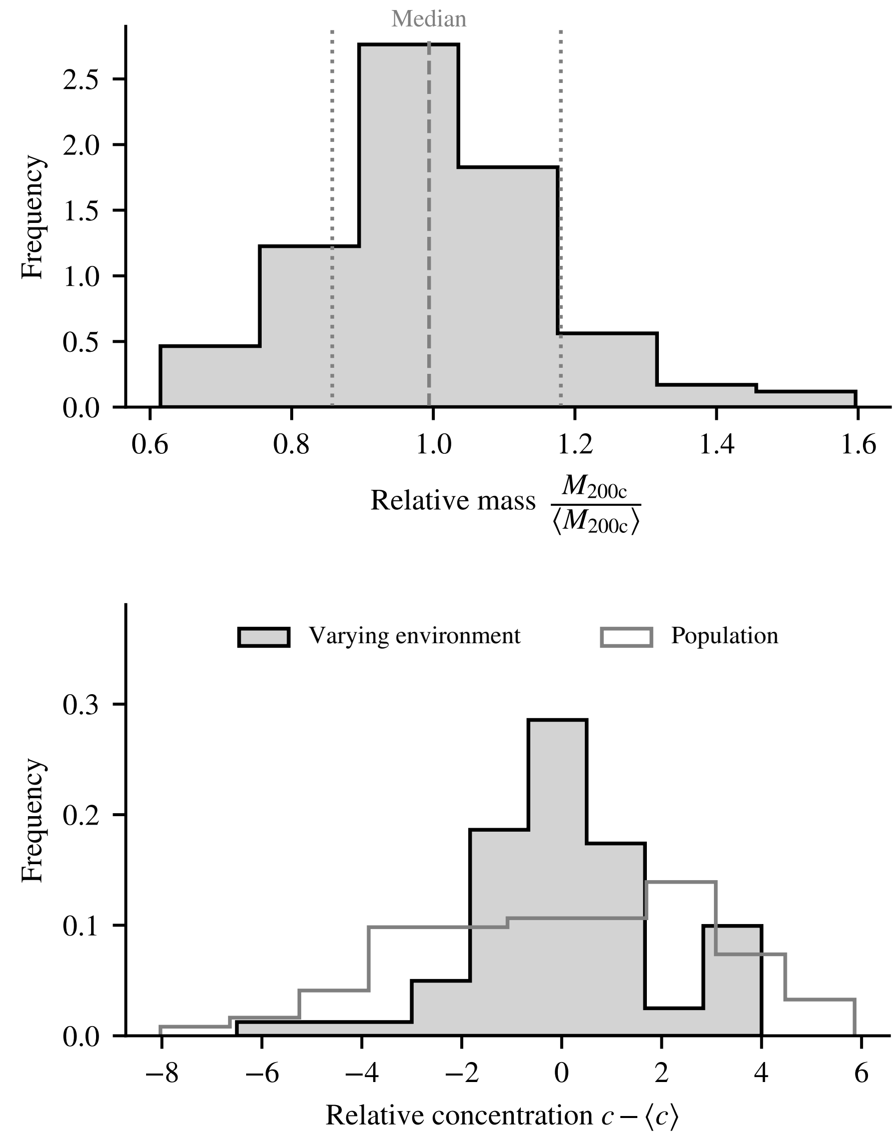
- Run simulation again & measure M_{200c} and c

1) Small mass fluctuations (±20%) & 50% particles in common
2) Large c fluctuations (~50% pop. fluctuations)



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UCL

	Isolated sims	Large cosmo	Zoom	GM of AM	Splicing
• Resolve the disk scale-height $\Delta x = 30$pc	×		×	×	×
• Cosmological setup		×	×	×	×
• Modify angular momentum accretion history[1]				×	
• Modify cosmological environment[2]					×

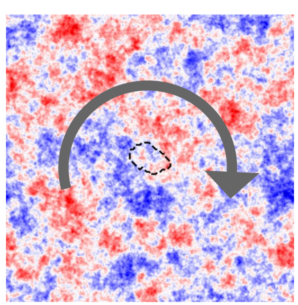
1: Cadiou+21a, arXiv: 2012.02201
2: Cadiou+21b, arXiv: 2107.03407

Conclusions

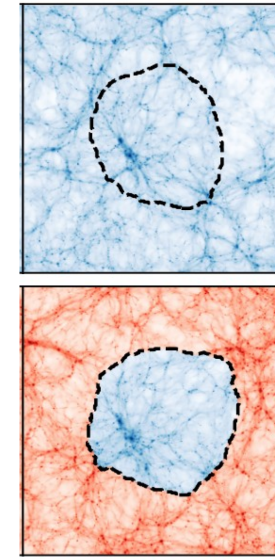
Conclusions / discussions

GM of angular momentum

- AM of DM is predictable (but edges of DM patch *not predictable*)
- With help from MC tracers (Cadiou+19) ⟹ applied to baryons
  - Spin self-regulation by SN/AGN?
  - Can spin-flips be triggered?
  - Formation of blue nuggets?
  - Link AM / SMBH growth?



Splicing method



- Spliced DM halos
  - Same mass
  - 100% ≠ environments
- Future sims:
  - Work as well for galaxies?
  - Filament quenching & spin-up Laigle+15, ..., Song+21
  - Link cosmic web ↔ galactic spins Kraljic+18,19, Laigle+18
- In g^{al}: useful to study env-driven effects (ex: biasing of same halo in ≠ env)

Cherry on the cake: everything readily usable in GENETIC (https://github.com/pynbody/genetIC) and RAMSES!

Bonus: new features in yt (since 2018)!

- Subdomain selection

```
ds = yt.load("output_00001",
    bbox=[[0.4]*3, [0.6]*3])
```

- Optimized-reader
  - AMR: 18s | hydro: 20s
  - AMR: 7s | hydro: 4.5s (reading zoomed region)
- (Easy) on-the-grid gradient computation

```
ds.r["gas", "pressure_gradient_magnitude"]
```

- Efficient particle projection (CIC) & grid interpolation (cell value at particle position)
- Supports RT, MHD, sinks, gravity
- Volume rendering, iso-surfaces, ray casting