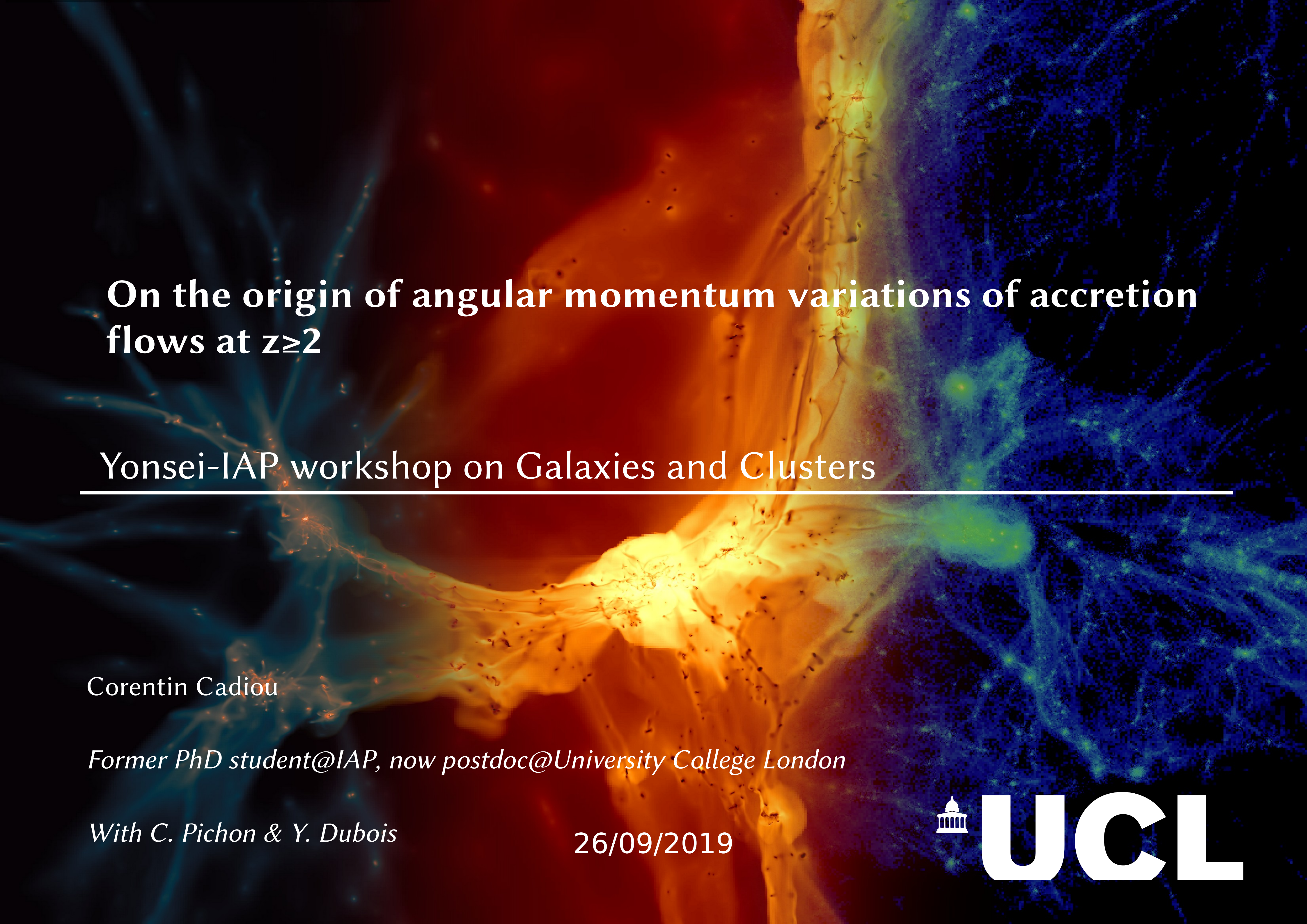


# On the origin of angular momentum variations of accretion flows at z≥2

## Yonsei-IAP workshop on Galaxies and Clusters


Corentin Cadiou

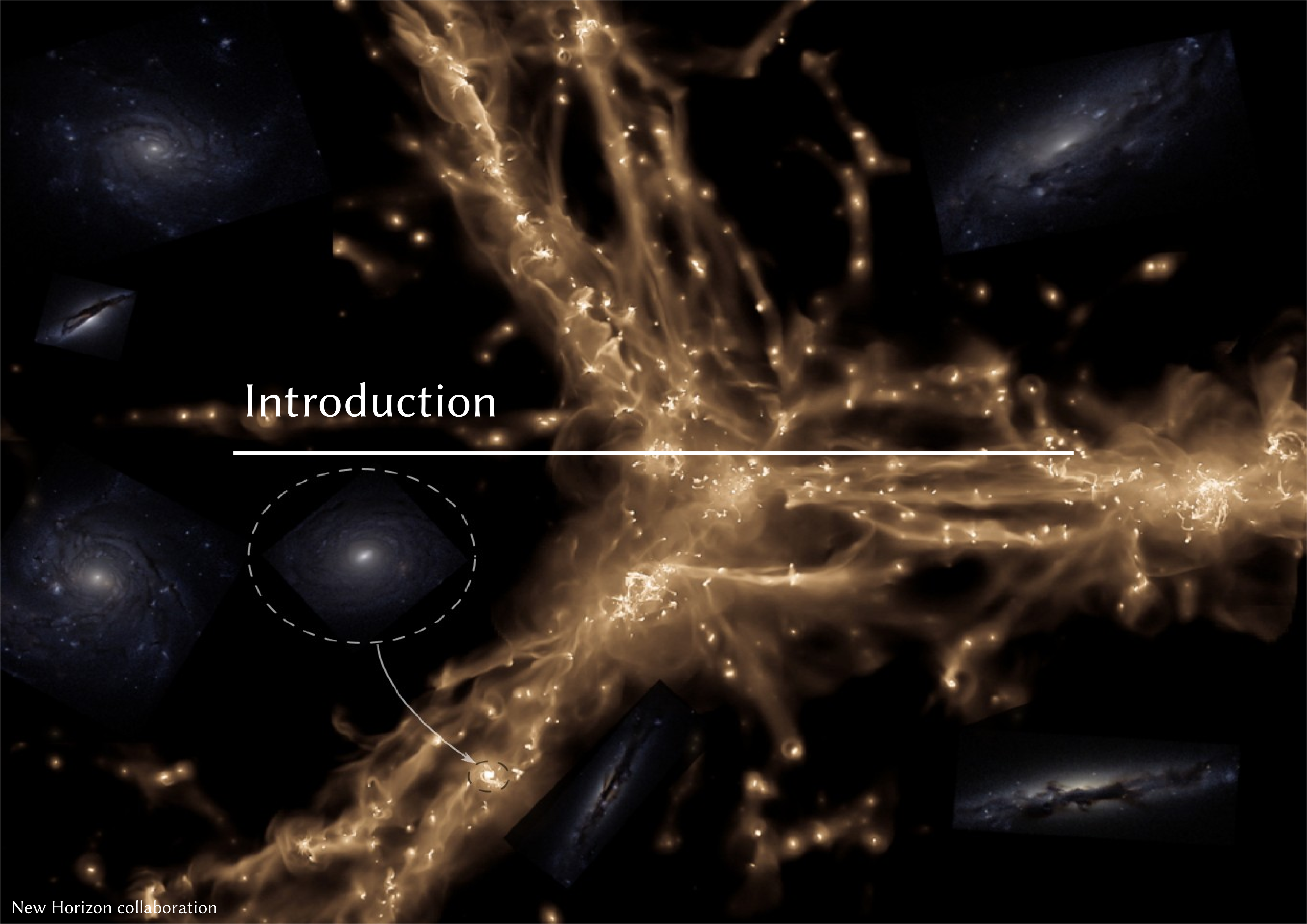
*Former PhD student@IAP, now postdoc@University College London*

*With C. Pichon & Y. Dubois*


26/09/2019

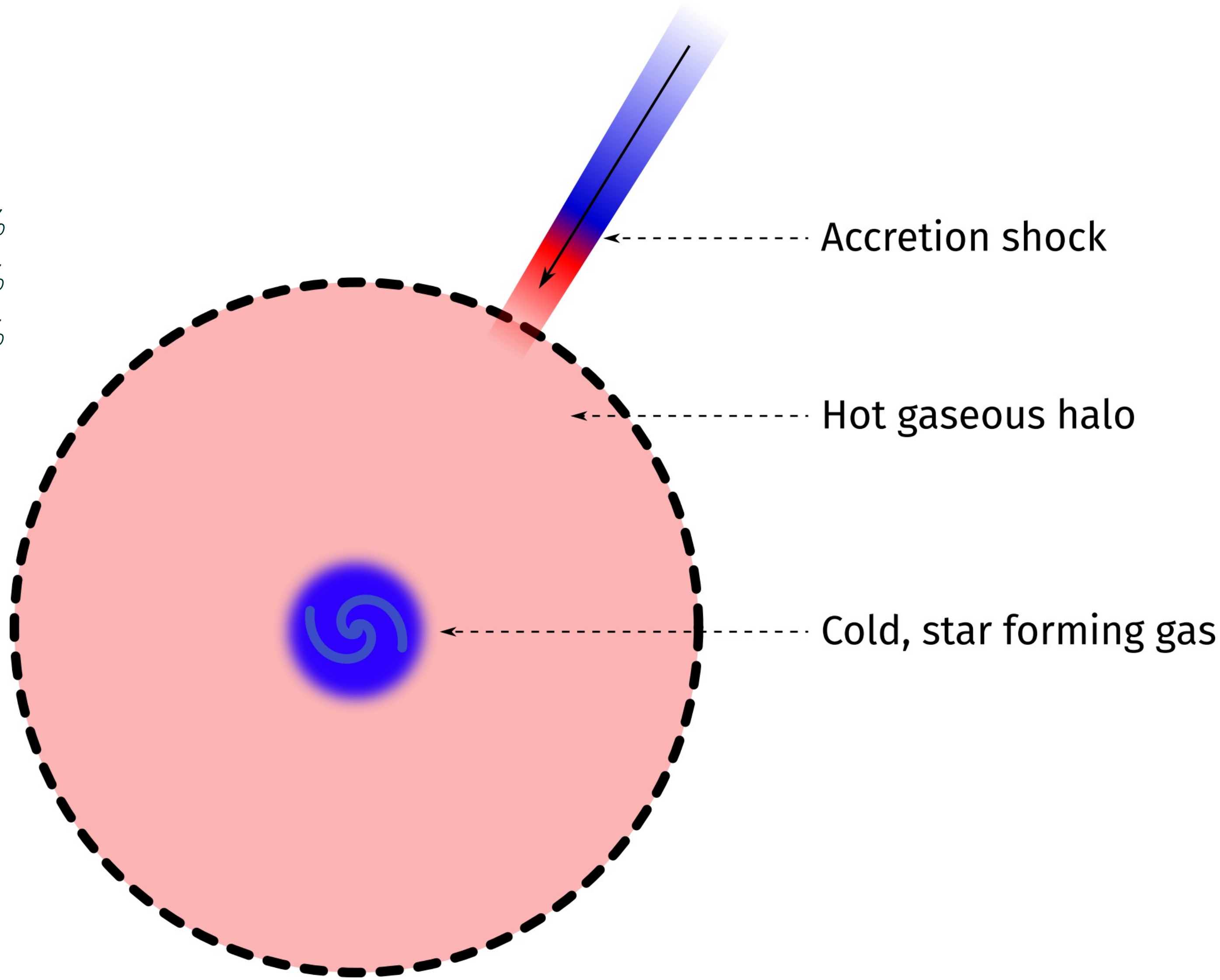
UCL

# Introduction



New Horizon collaboration

1) Gas falls onto halo made of:
   - → dark matter ~ 90%
   - → previously accreted gas ~<10%
   - → galaxy ~<10%
2) heats at virial radius,
3) and cools at the center




**Accretion:**

→ mostly *anisotropic*

→ struggle for vectorial qties (ex. AM)

[White&Rees 78; White&Frenk 91; Kauffmann+93; Cole+94; Mo+98; Cole+00; Bower+06; Guo+10]

# Linking galaxy formation to their environment

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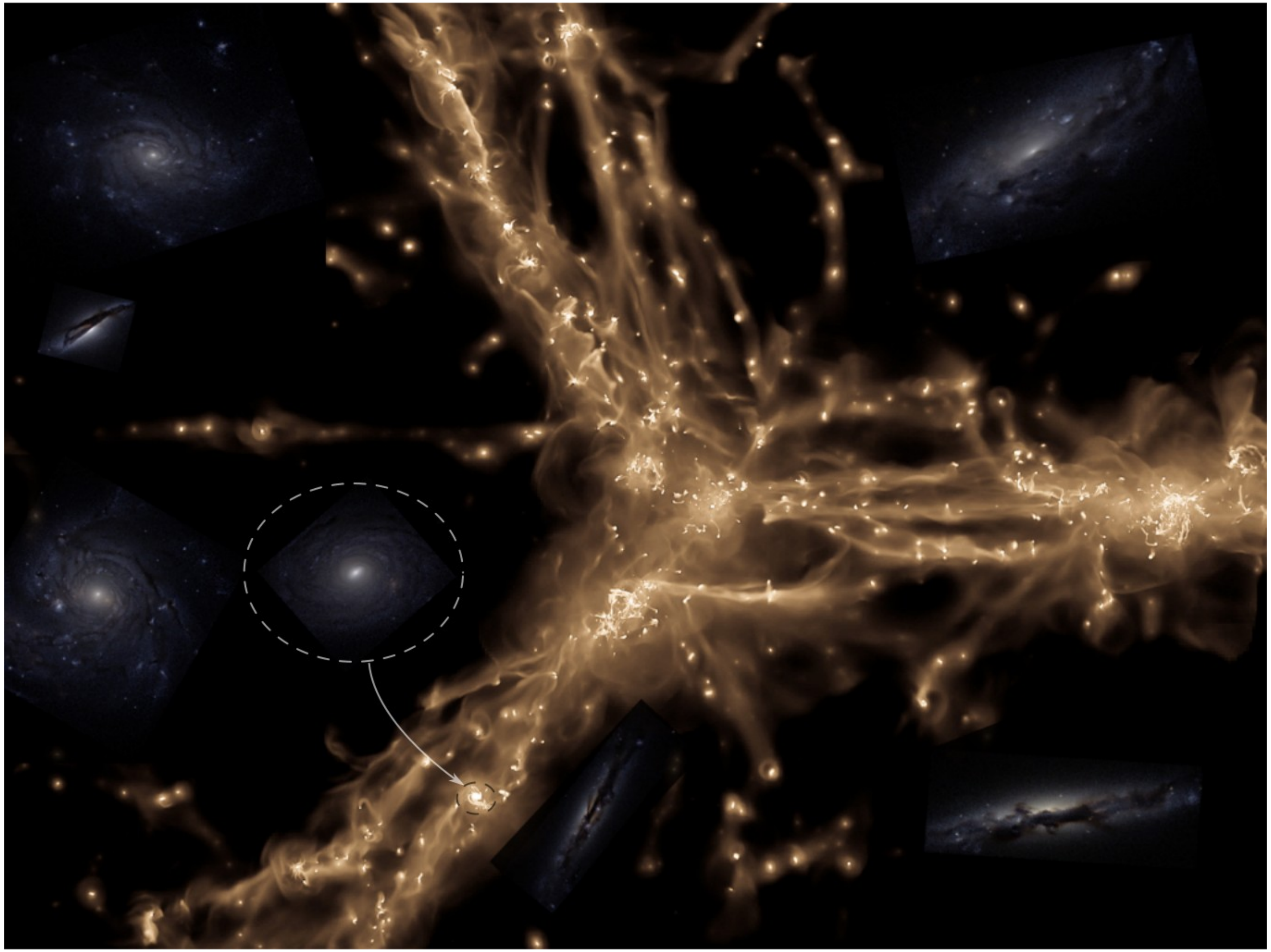
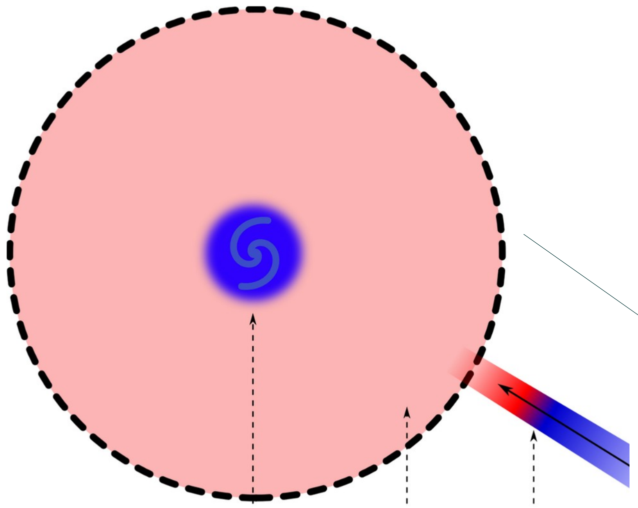


Two ingredients:

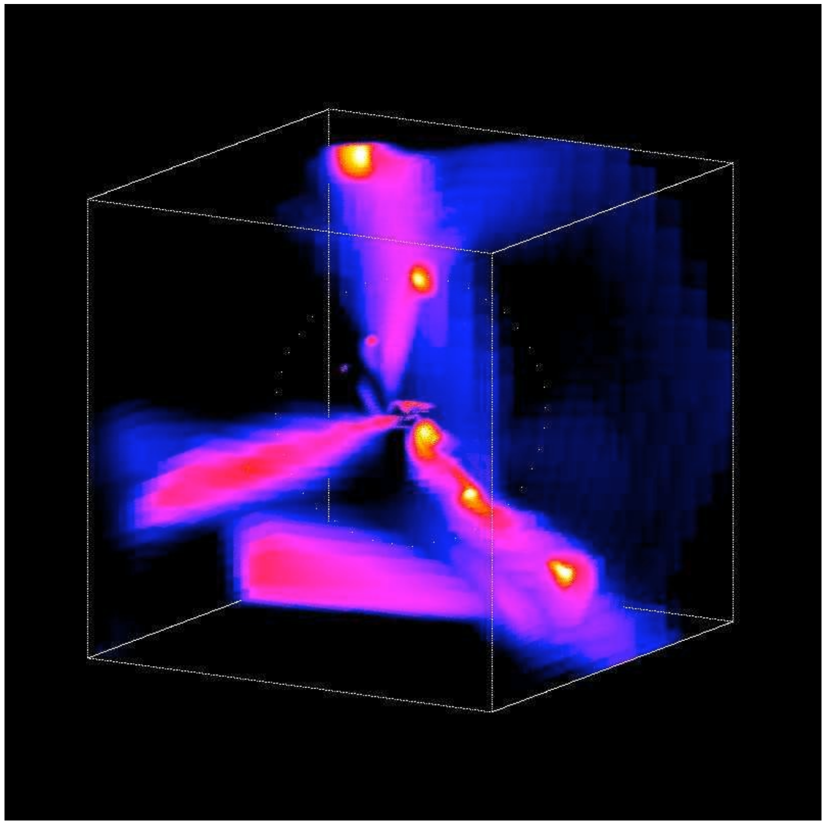
- Galaxies...
- ... cosmic web
  (⟹ D. Pogosyan talk)

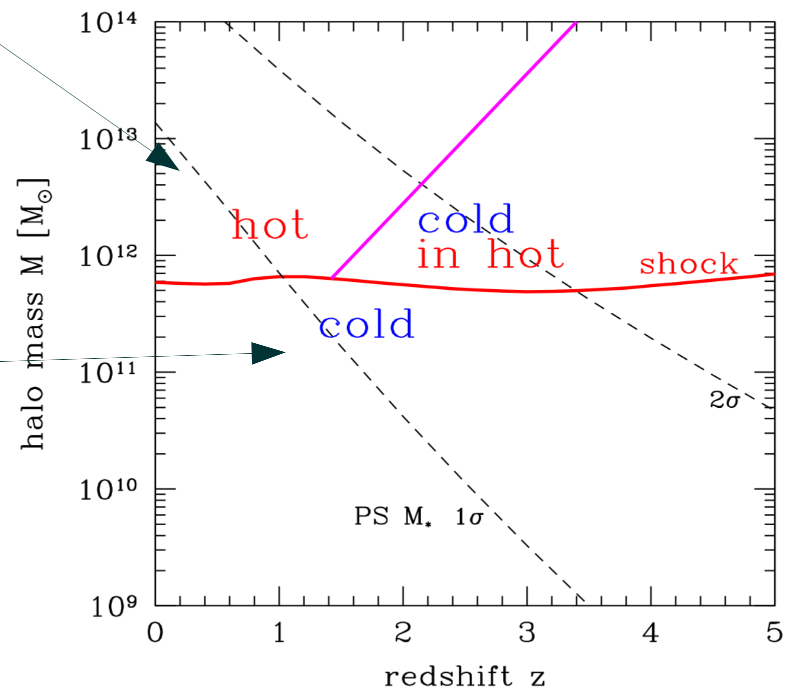
Link between the two?
(⟹ K. Kraljic talk)

Missing piece in galaxy formation model!



- Two modes of accretion: hot (classical) and cold (never shock-heated)
- Cold accretion: dominant at small mass, high z






[Dekel&Birnboim 06, Dekel+09]
[AM studies: Pichon+11; Kimm+11; Stewart+13,17]

# Improving classical model: cold flows

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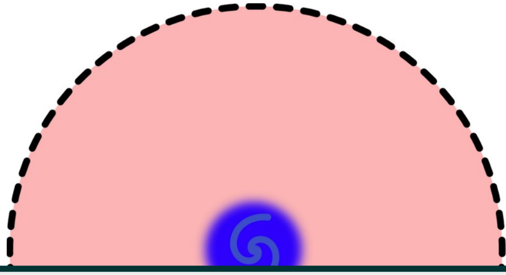
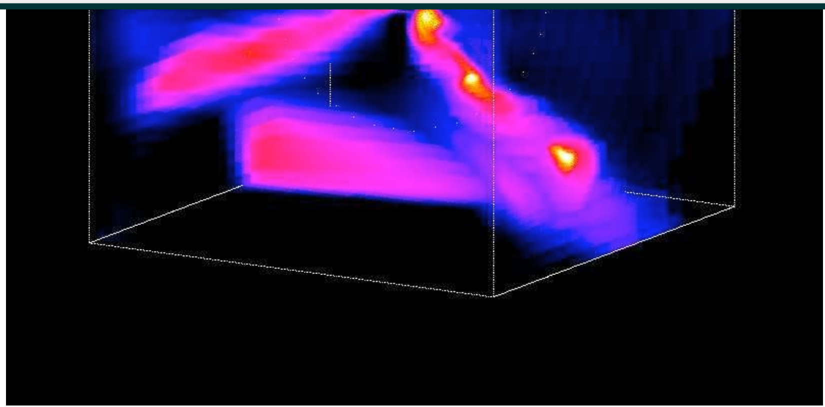
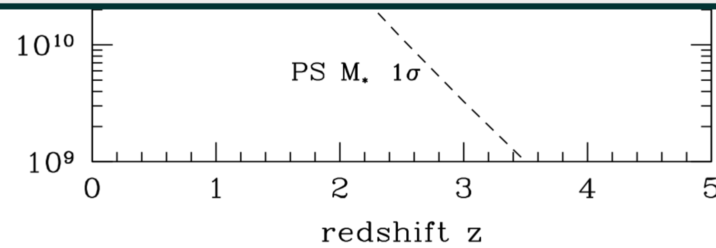


- Two modes of accretion: hot (classical) and cold (never shock-heated)

To understand link with large-scale structures
$\Longrightarrow$ understand kinematics + dynamics of cold flows






[Dekel&Birnboim 06, Dekel+09]
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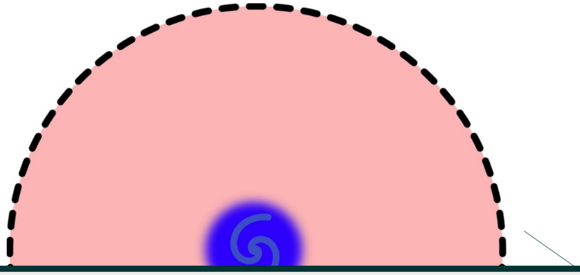

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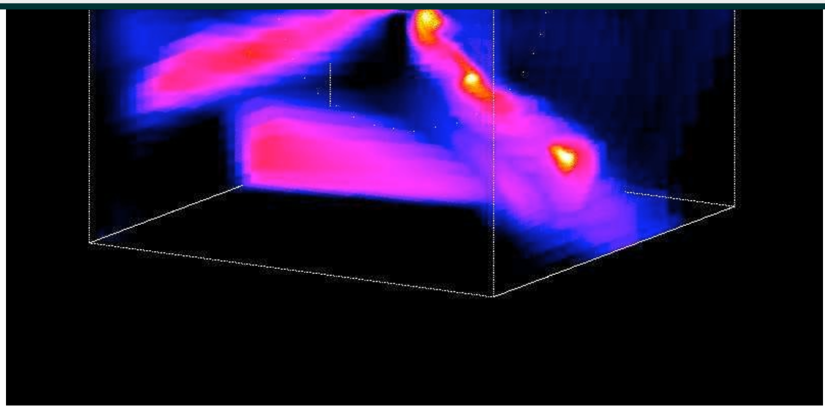
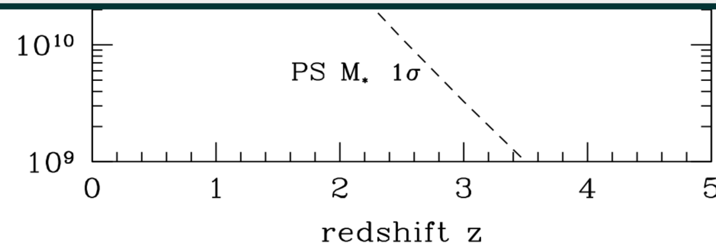
1) Shock-capturing simulation



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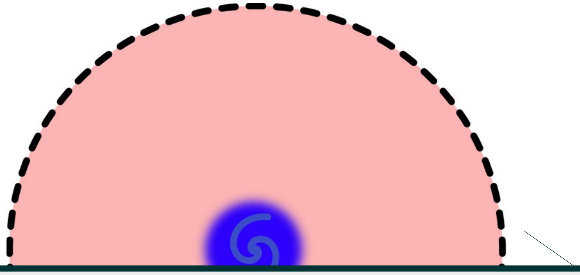
# Improving classical model: cold flows





- Two modes of accretion: hot (classical) and cold (never shock-heated)

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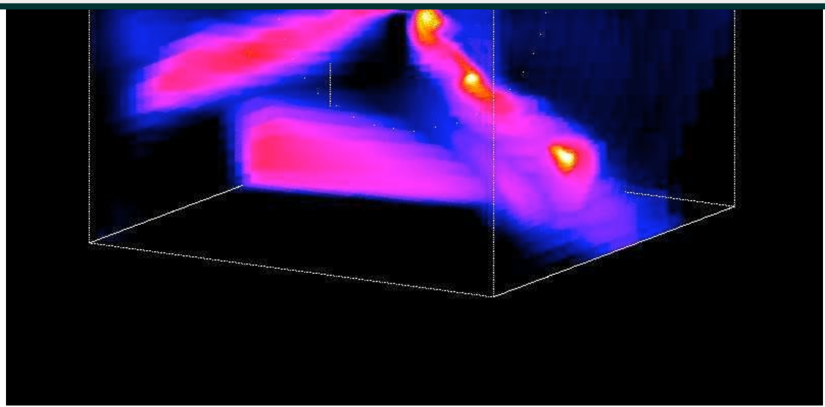

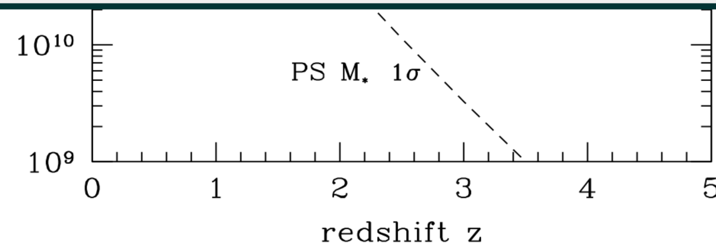


[Dekel&Birnboim 06, Dekel+09]

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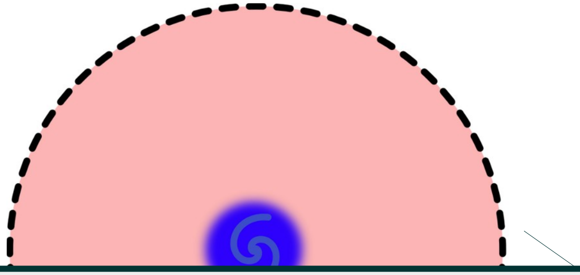
# Improving classical model: cold flows

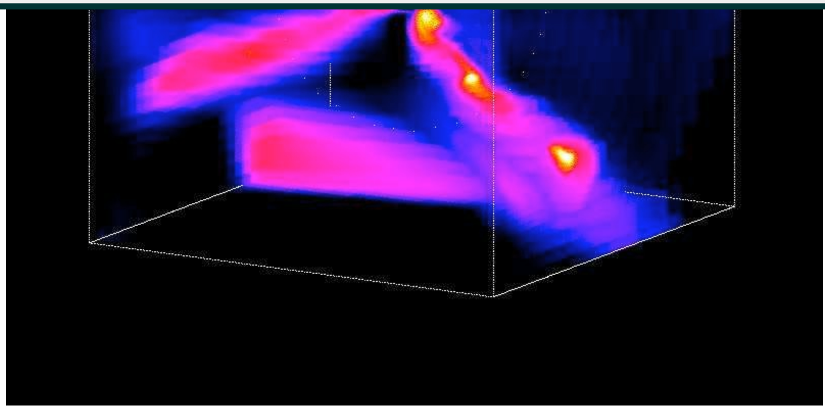


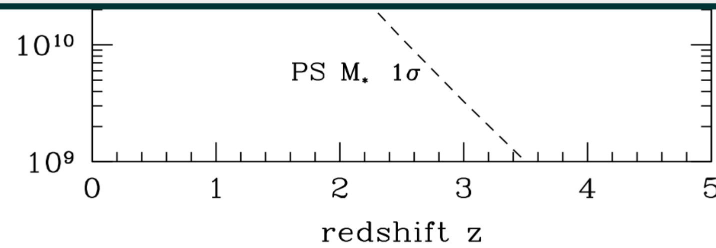


- Two modes of accretion: hot (classical) and cold (never shock-heated)

To understand link with large-scale structures
$\Longrightarrow$ understand kinematics + dynamics of cold flows

1) Shock-capturing simulation
2) Lagrangian history of the accreted gas
3) Disk formation $\Longrightarrow$ study AM acquisition






[Dekel&Birnboim 06, Dekel+09]
[AM studies: Pichon+11; Kimm+11; Stewart+13,17]

# Cosmic web, angular momentum and tides

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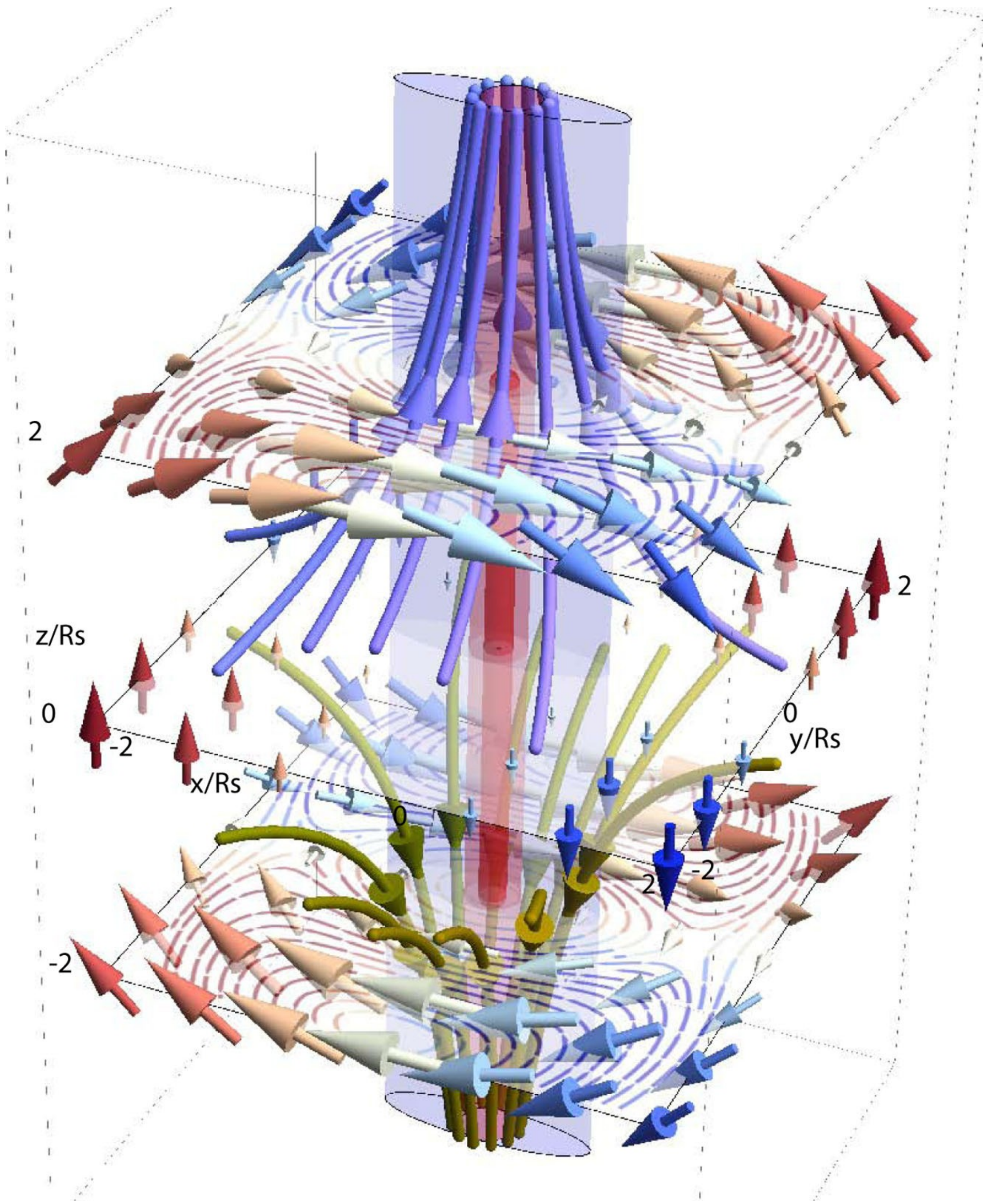
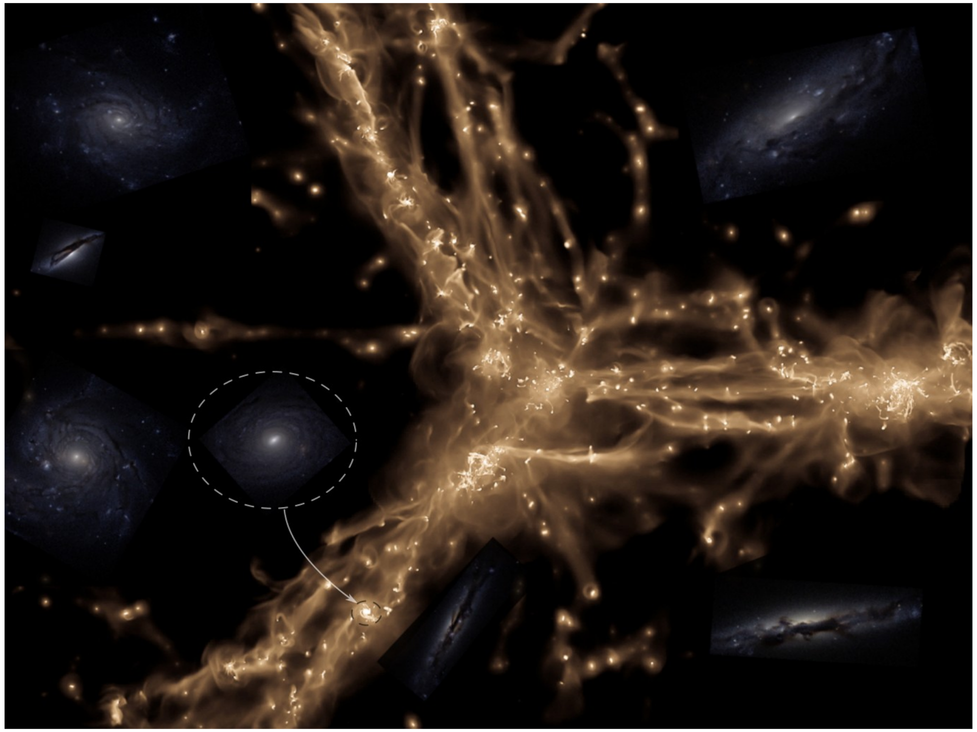



From Codis, Pichon, Pogosyan 2015

- *Prior* to accretion
  AM acquisition via tidal torques with cosmic web
- Most of AM brought along filament
- How much ends up in galaxy?



[TTT: Hoyle 49; Peebles 69; Doroshkevich 70; White 84; Catelan&Theuns 96; Crittenden+01]
[AM accretion: Pichon+11; Kimm+11; Stewart+13; Stewart+17]

# (Some) open questions on AM of cold-flows

- Is the angular momentum advected to disk? Exchanged before *via* torques? Study **kinematics**

[See e.g. Danovich+15, Tillson+15]

# (Some) open questions on AM of cold-flows

- Is the angular momentum advected to disk? Exchanged before *via* torques? Study **kinematics**
- Importance of **dynamical** effects?
  - Pressure torques?
  - Gravitational torques?

[See e.g. Danovich+15, Tillson+15]

# (Some) open questions on AM of cold-flows

- Is the angular momentum advected to disk? Exchanged before *via* torques? Study **kinematics**
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- Cold flows as bridge between
  - Cosmic web $\longrightarrow$ AM acquisition
  - Galaxy $\longleftarrow$ AM transport, link to star formation

  True of false?

[See e.g. Danovich+15, Tillson+15]

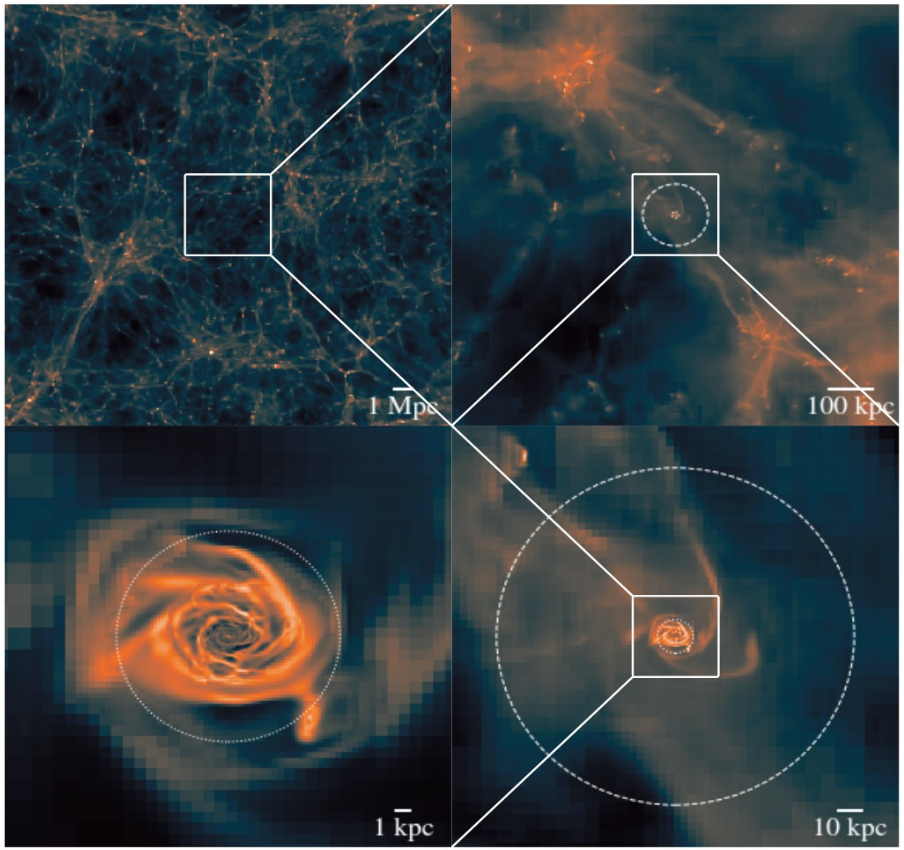
# (Some) open questions on AM of cold-flows

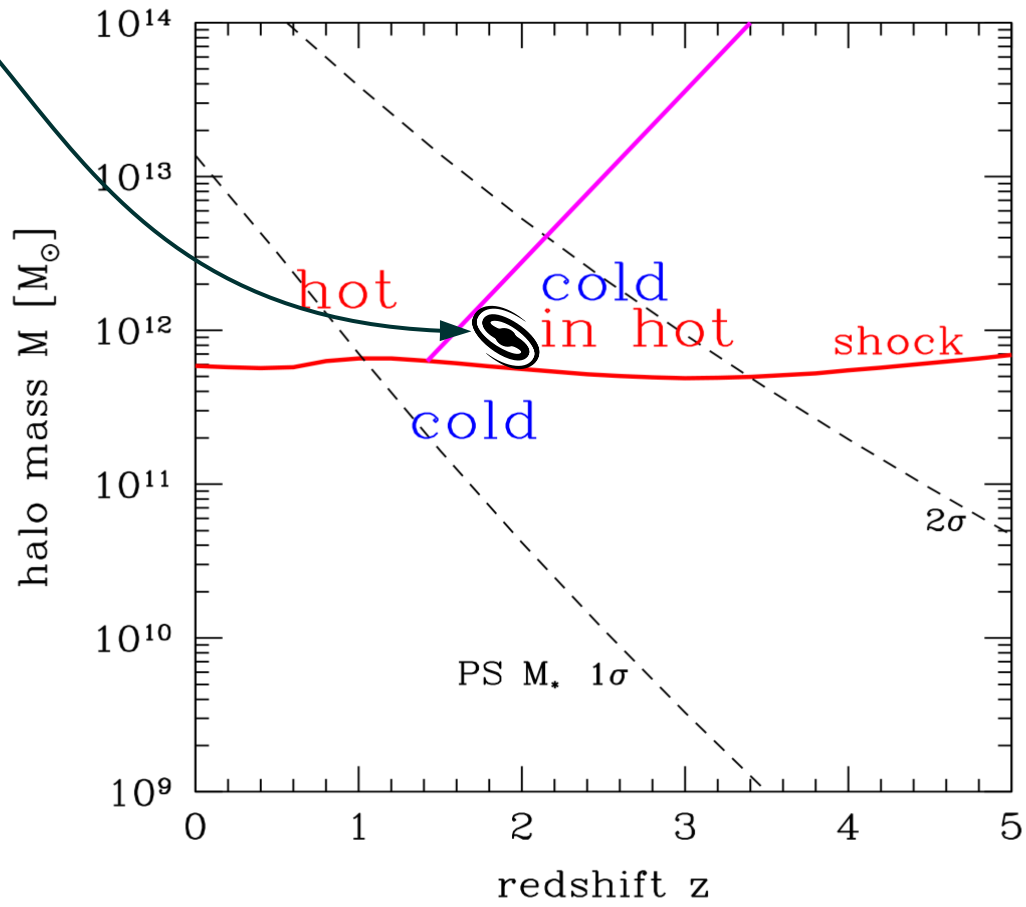
- Is the angular momentum advected to disk? Exchanged before *via* torques? Study **kinematics**
- Importance of **dynamical** effects?
  - Pressure torques?
  - Gravitational torques?
- Cold flows as bridge between
  - Cosmic web ⟶ AM acquisition
  - Galaxy ⟵ AM transport, link to star formation

  True of false?
- Cosmic filaments ↔ cold flows ↔ galaxies
  - What is the link (if any)?
  - Use cosmic web prediction to infer properties of galaxies? (spin alignment, morphology, star formation rate, angular momentum distribution, ...)

[See e.g. Danovich+15, Tillson+15]

- 6 halos of $M \sim 10^{12}\,M_\odot$ at $z=2$
- 30pc resolution
- Focus on cold flows
- Which code to use?



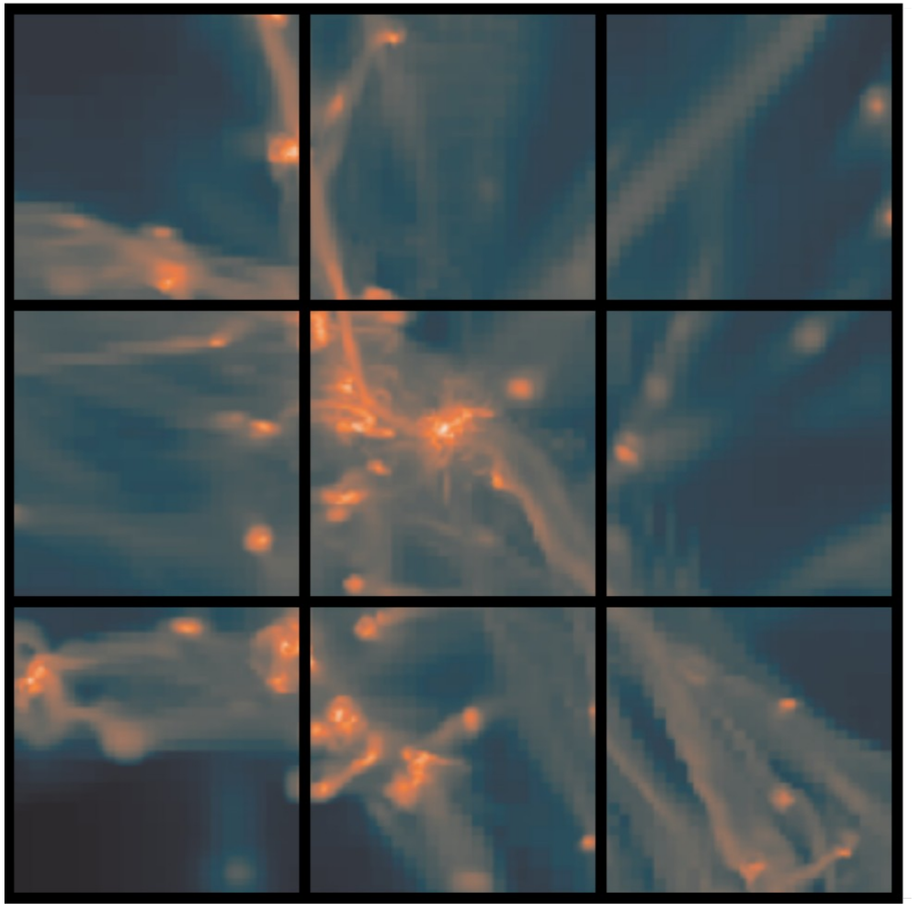

Two modes of gas accretion. Dekel & Birnboim 06

[Ramses: Teyssier 02]
[Cold flows: Dekel & Birnboim 06; Kereš+05; Ocvirk+08; Nelson+13]
[AM transport: Pichon+11; Kimm+11; Stewart+13; Stewart+17]

# Eulerian & Lagrangian codes



Eulerian method

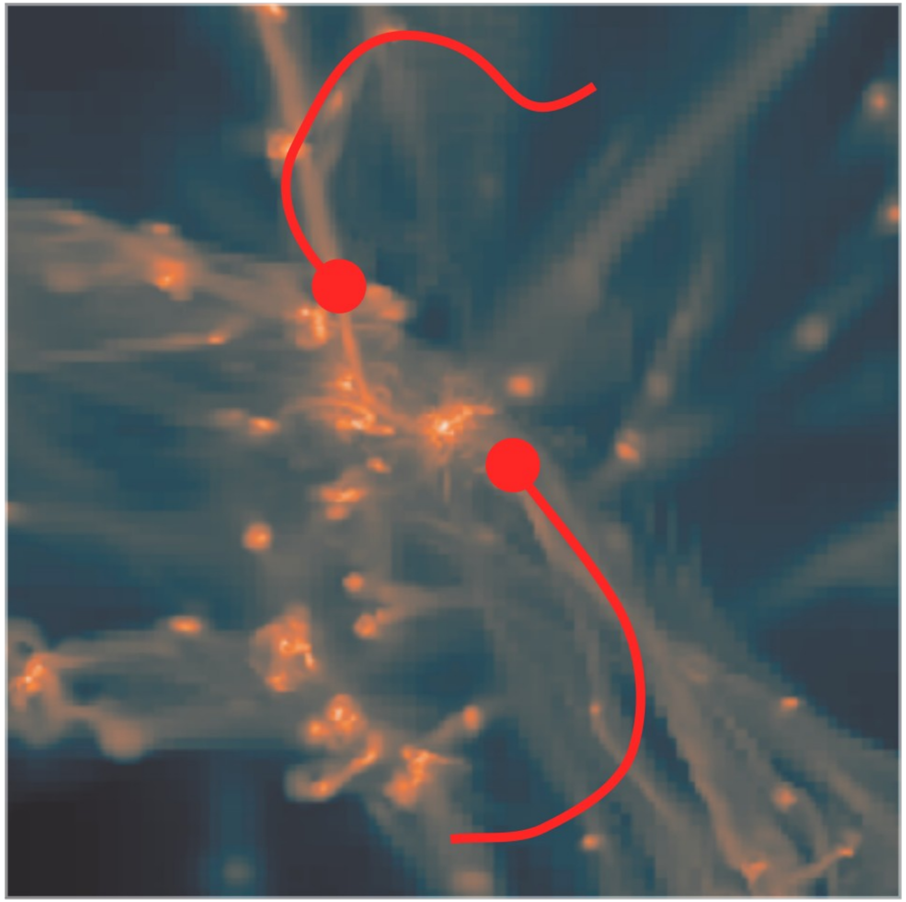


Grid-based approach (*AMR*):

- Base elements: cell
- Cells of “fixed **volume**”
- Naturally shock-capturing

Ex: Art, RAMSES, Enzo, …

Lagrangian method

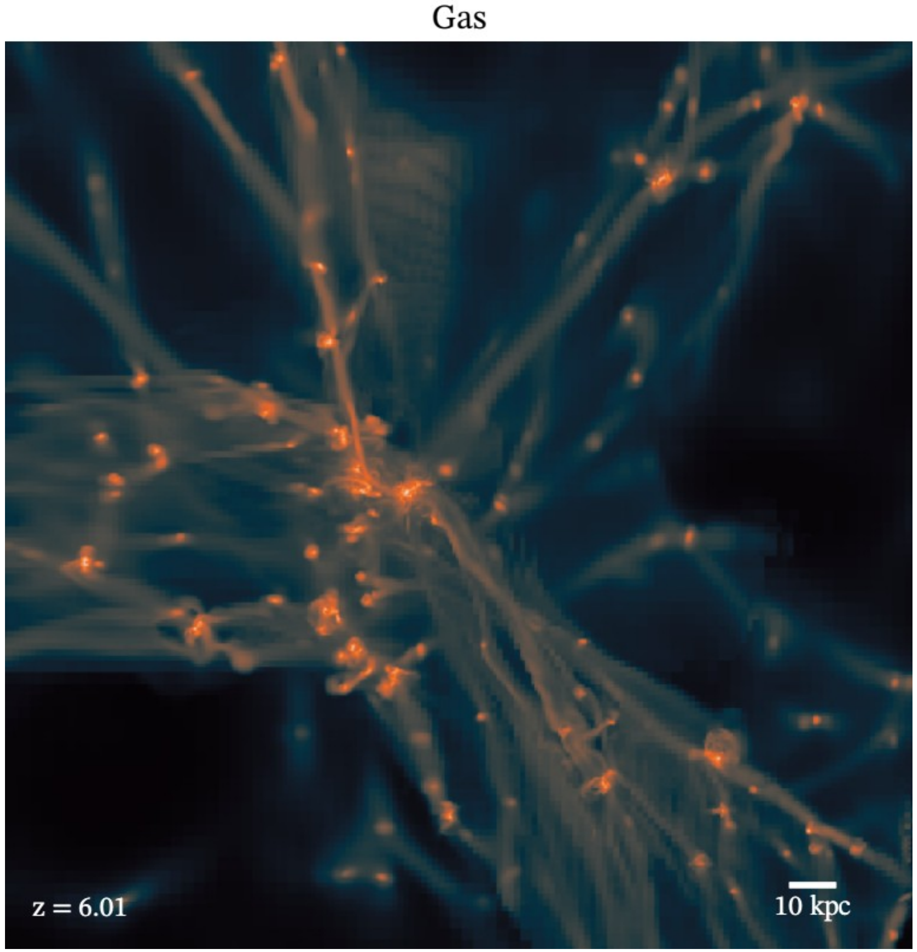


Particle-based approach (*SPH*):

- Base elements: particle
- Particles of fixed **mass**

Ex: GADGET, Gasoline, …

# Monte Carlo tracer particles in grid-based code




To follow gas accretion: need the Lagrangian history of the gas

- past temperature,
- past position.

In grid-based codes:
→ achieved with Lagrangian tracer particles

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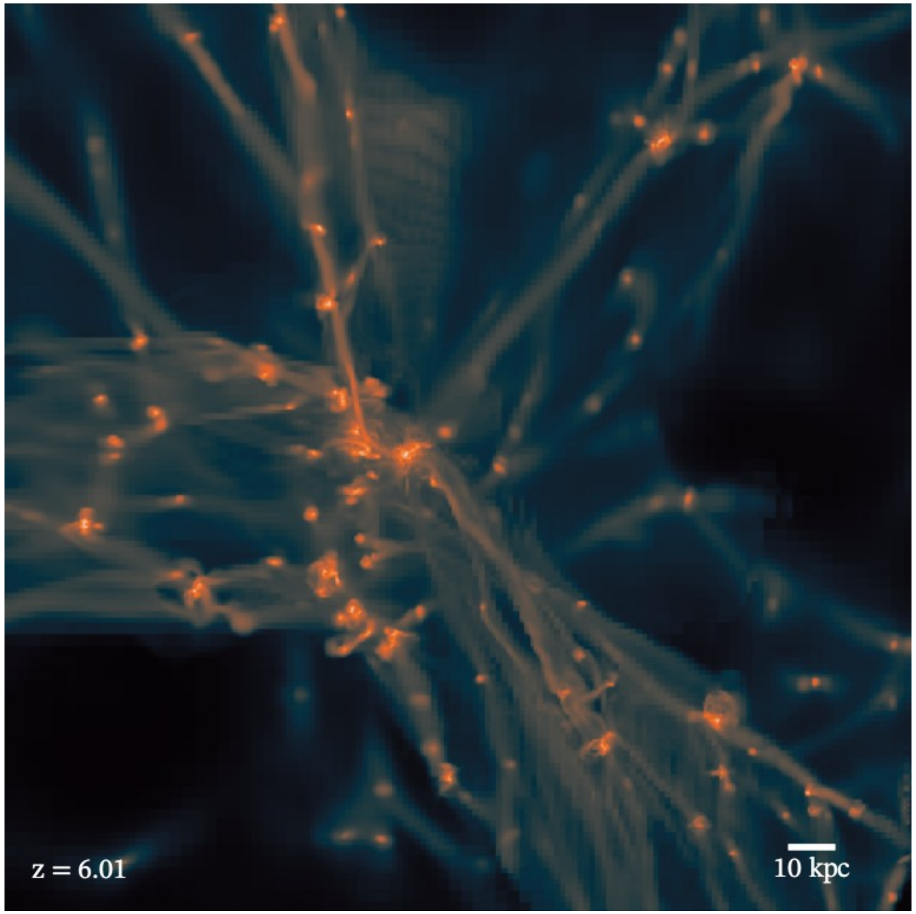
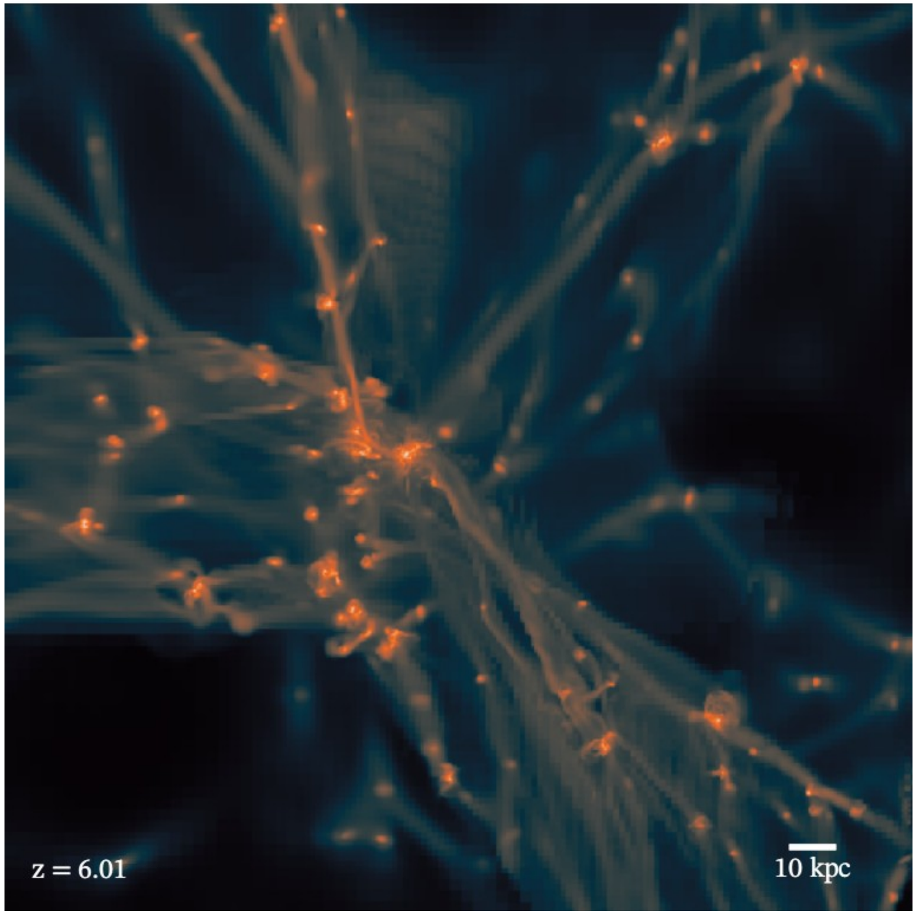
Gas




Gas



# Monte Carlo tracer particles in grid-based code

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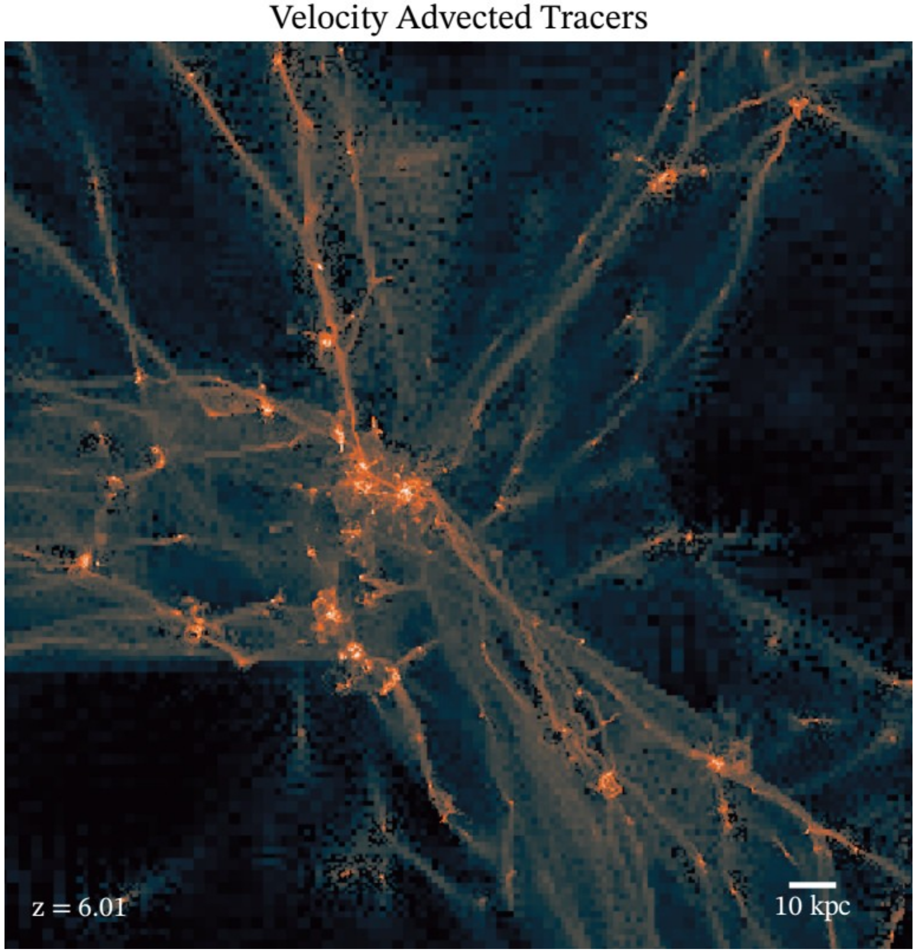
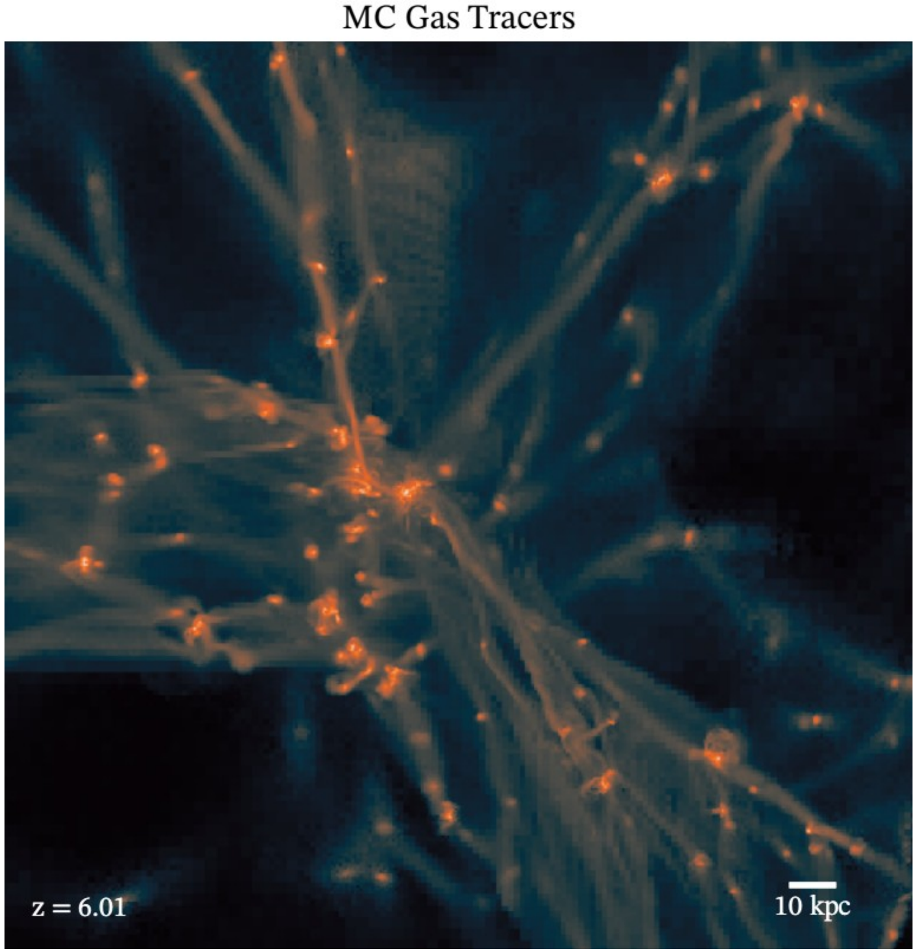
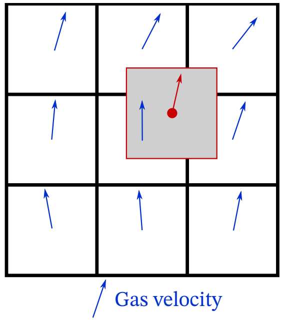


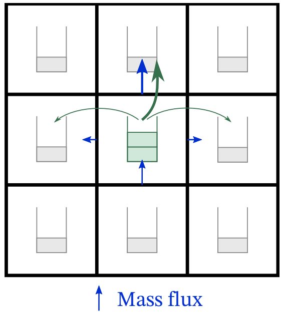




## Velocity-advected method




Using linear interpolation of velocity

## Monte Carlo method (Genel+13, **Cadiou+19**)



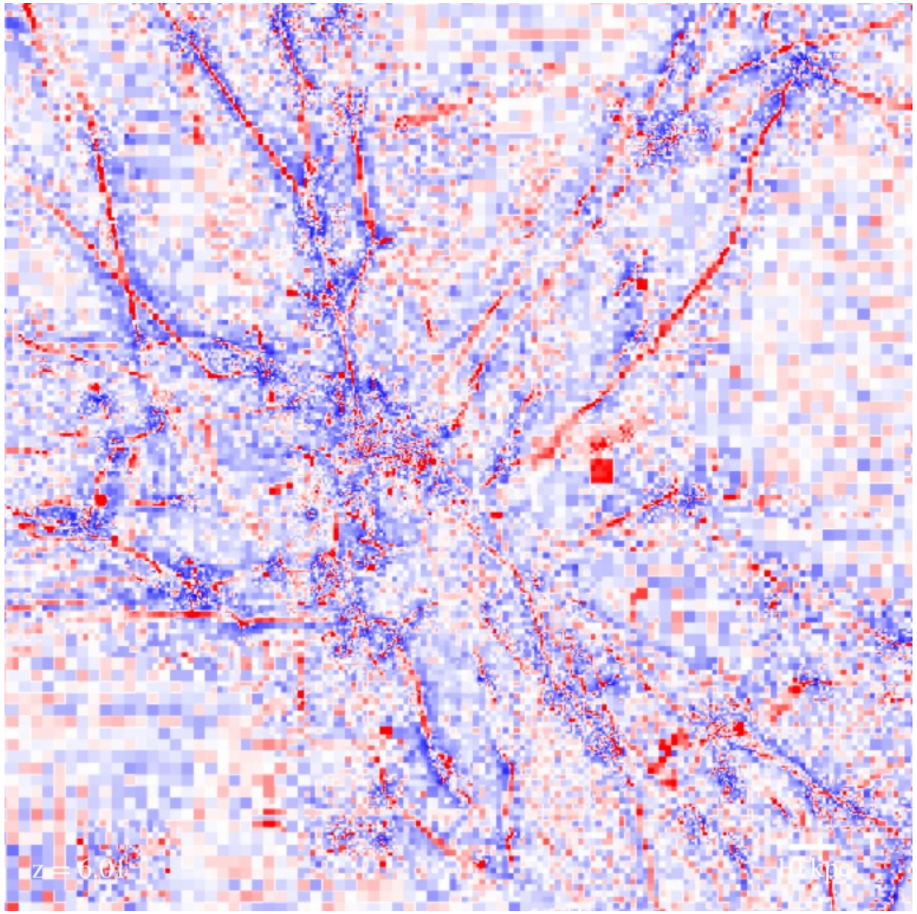

Monte-Carlo approach: moving with probability

$$p = \Delta M / M$$

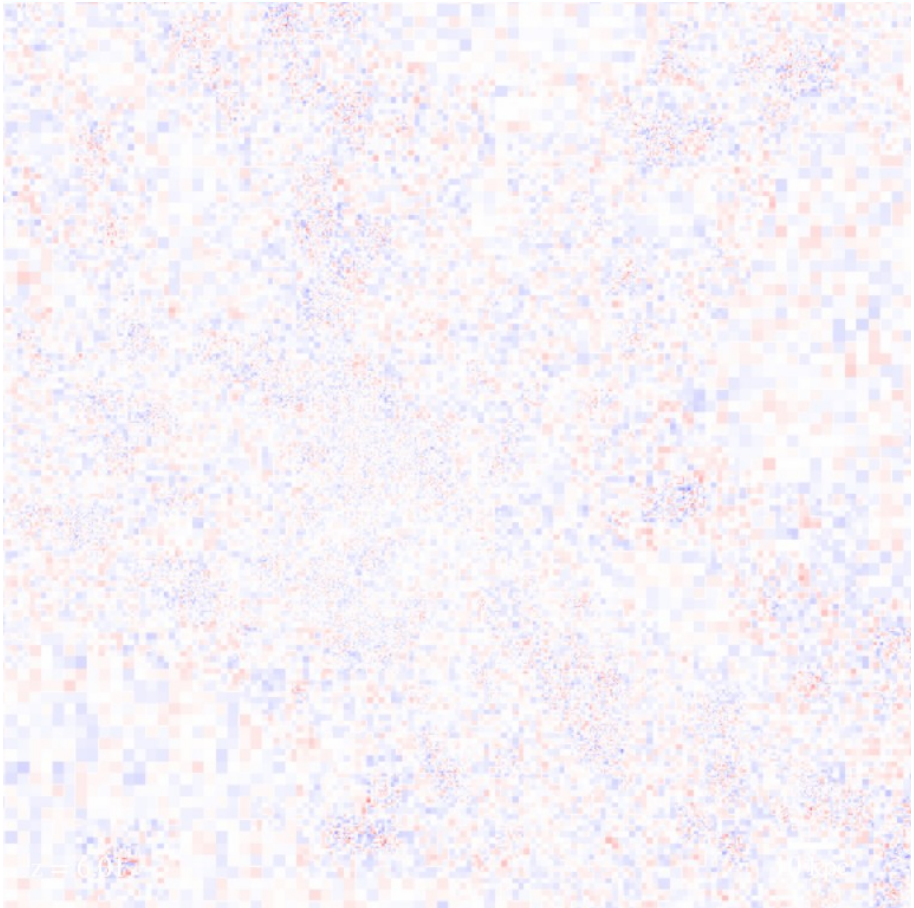
M mass of cell

ΔM mass flux

Velocity Advected Tracers



MC Gas Tracers



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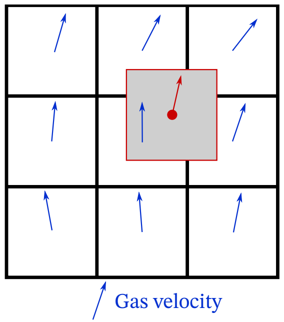


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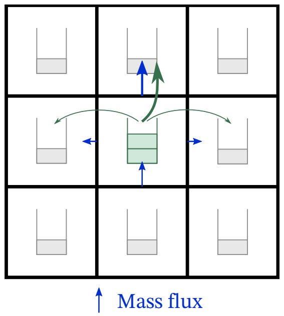


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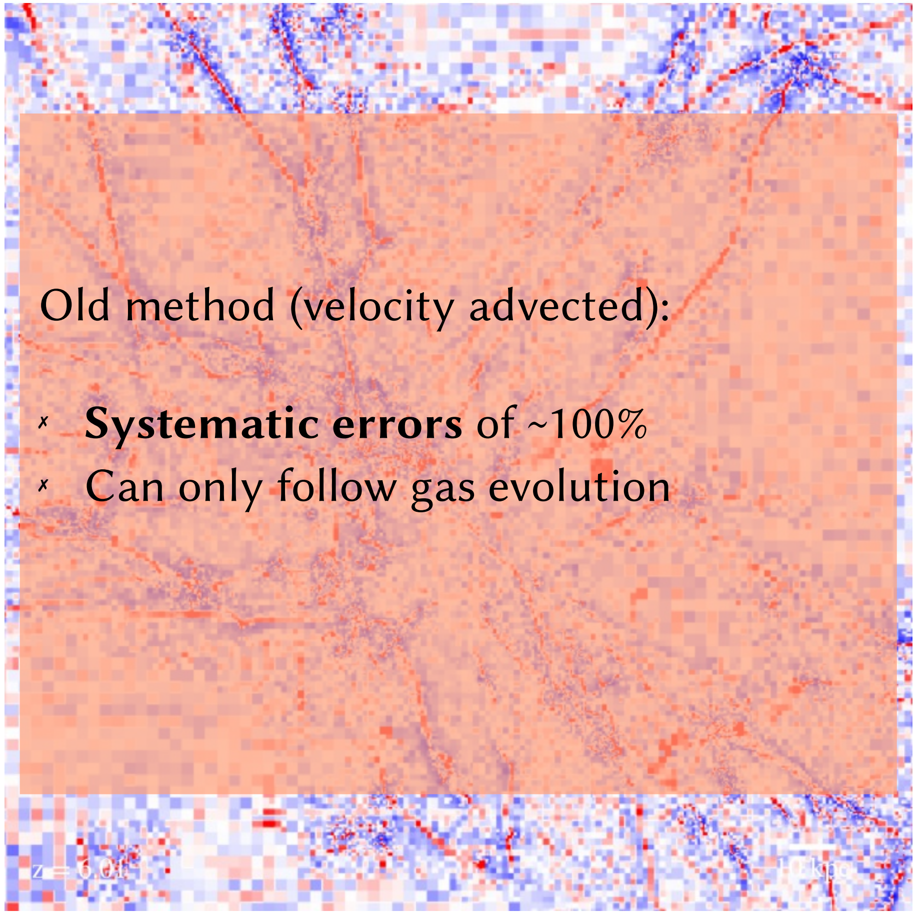
# Monte Carlo tracer particles in grid-based code

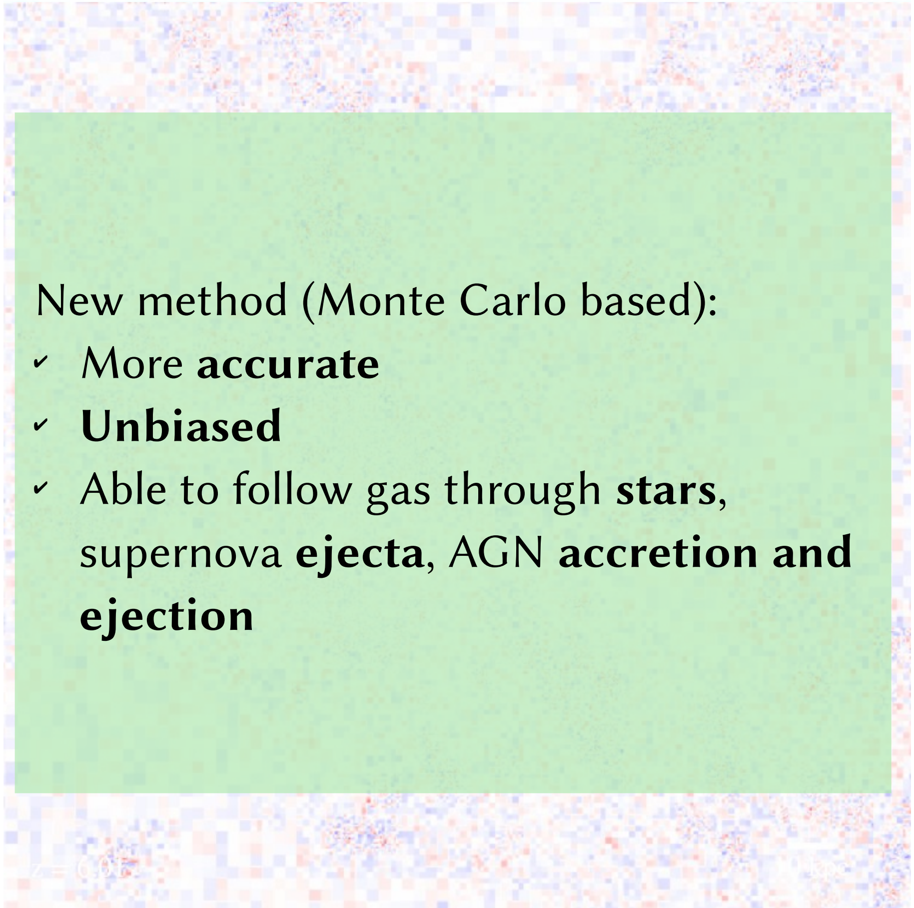
Velocity Advected Tracers



Old method (velocity advected):

- ✗ **Systematic errors** of ~100%
- ✗ Can only follow gas evolution

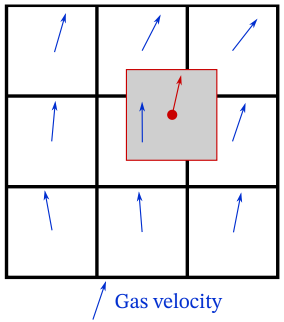
MC Gas Tracers



New method (Monte Carlo based):

- ✓ More **accurate**
- ✓ **Unbiased**
- ✓ Able to follow gas through **stars**, supernova **ejecta**, AGN **accretion and ejection**

## Velocity-advected method

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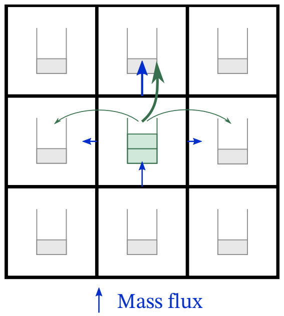
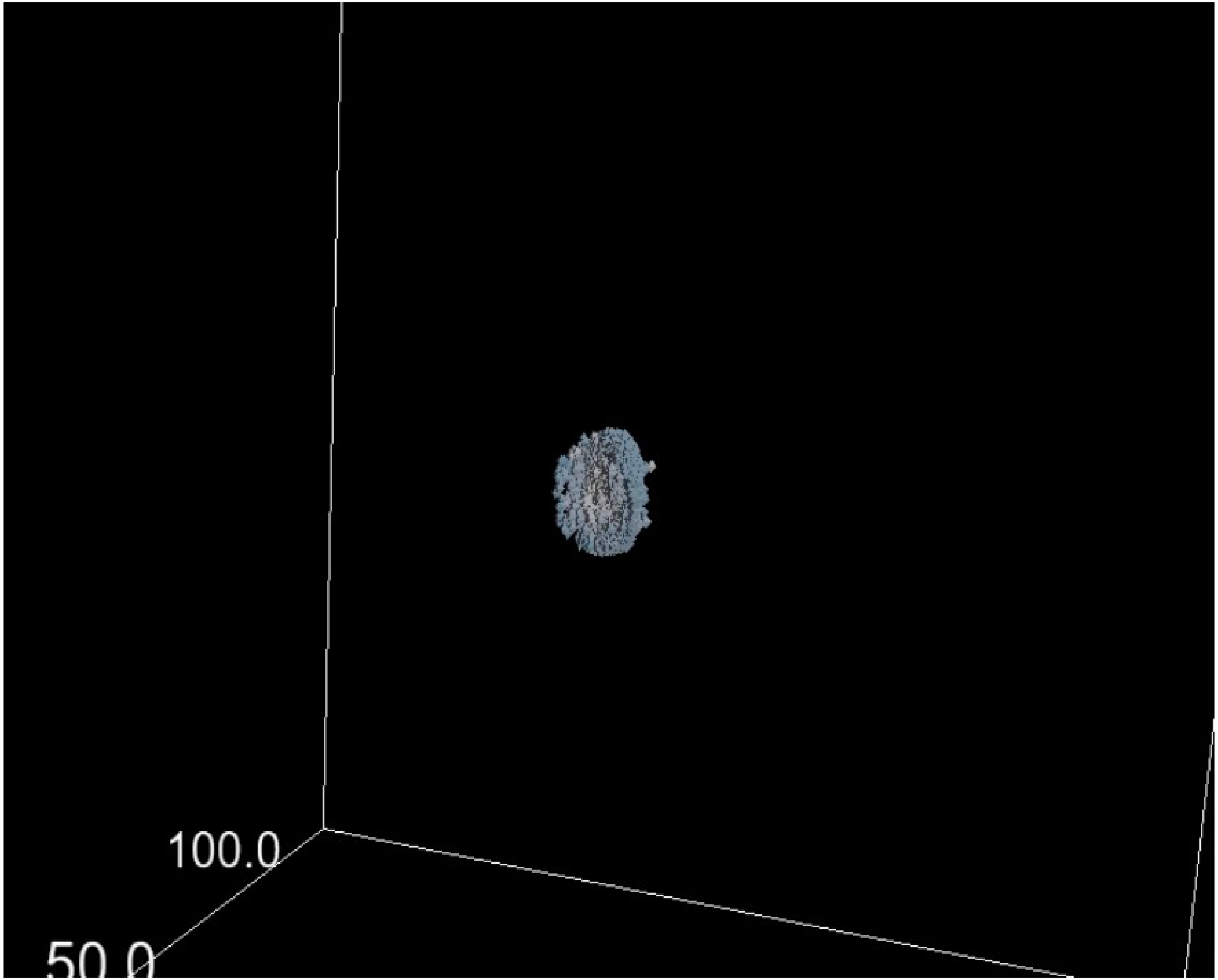



Monte-Carlo approach:
moving with probability

$$p = \Delta M/M$$

M mass of cell
ΔM mass flux

# Tracking gas accretion using tracer particles

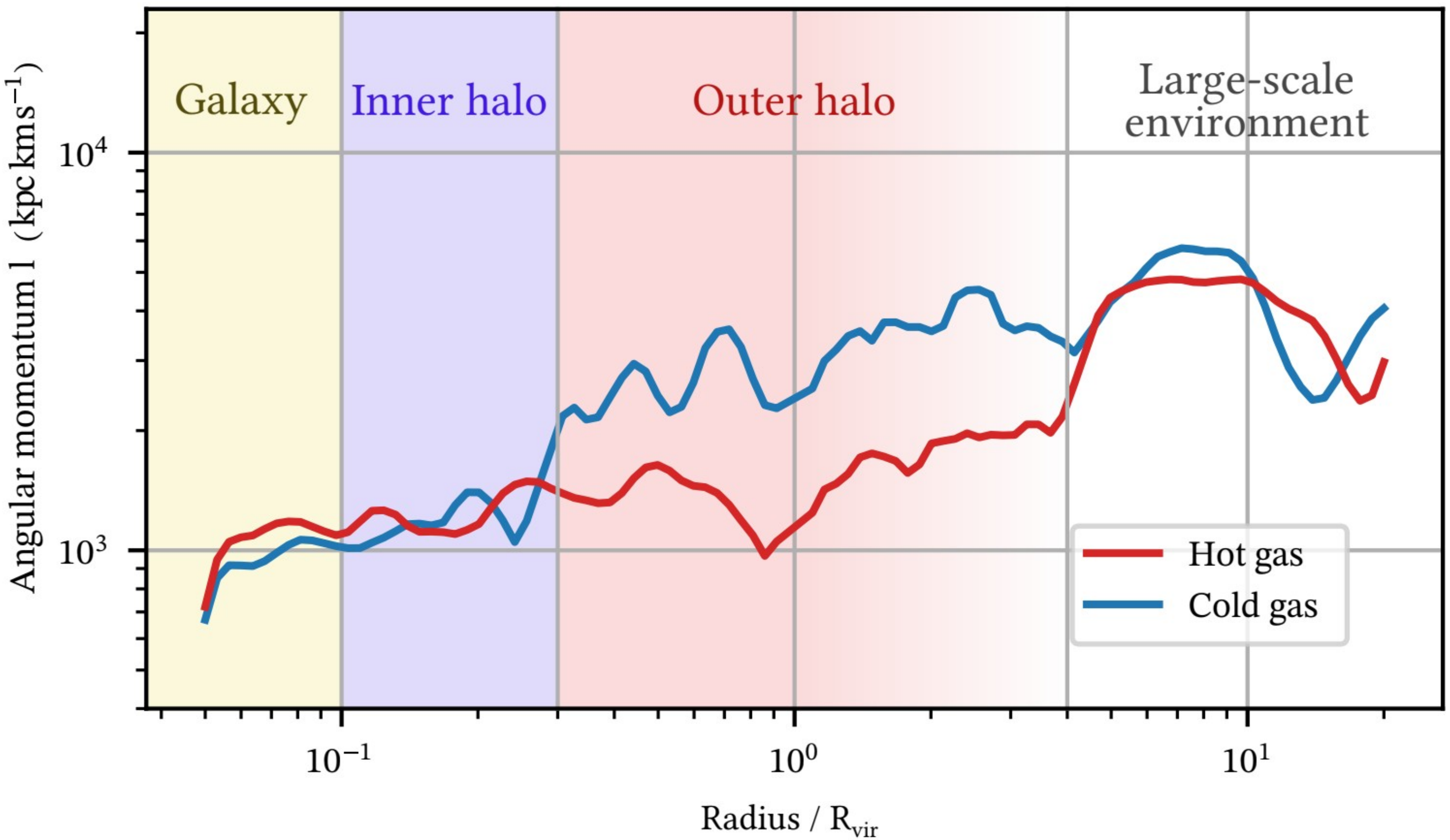



Gas tracer particles traced backward in time. Cadiou+in prep

**Baryon selection:**

- $T_{max} \leq 2.5\ 10^5$K while in gas phase
- Never accreted on any satellite
- End up in central galaxy (gas + stars)

Significant fraction (~50%) of gas accreted via anisotropic filamentary accretion

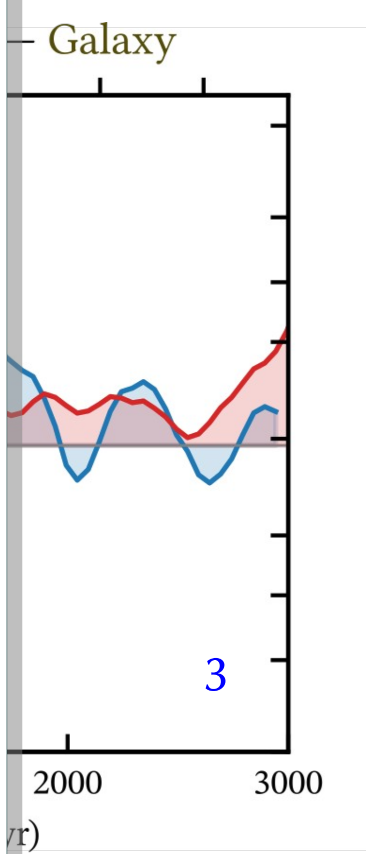


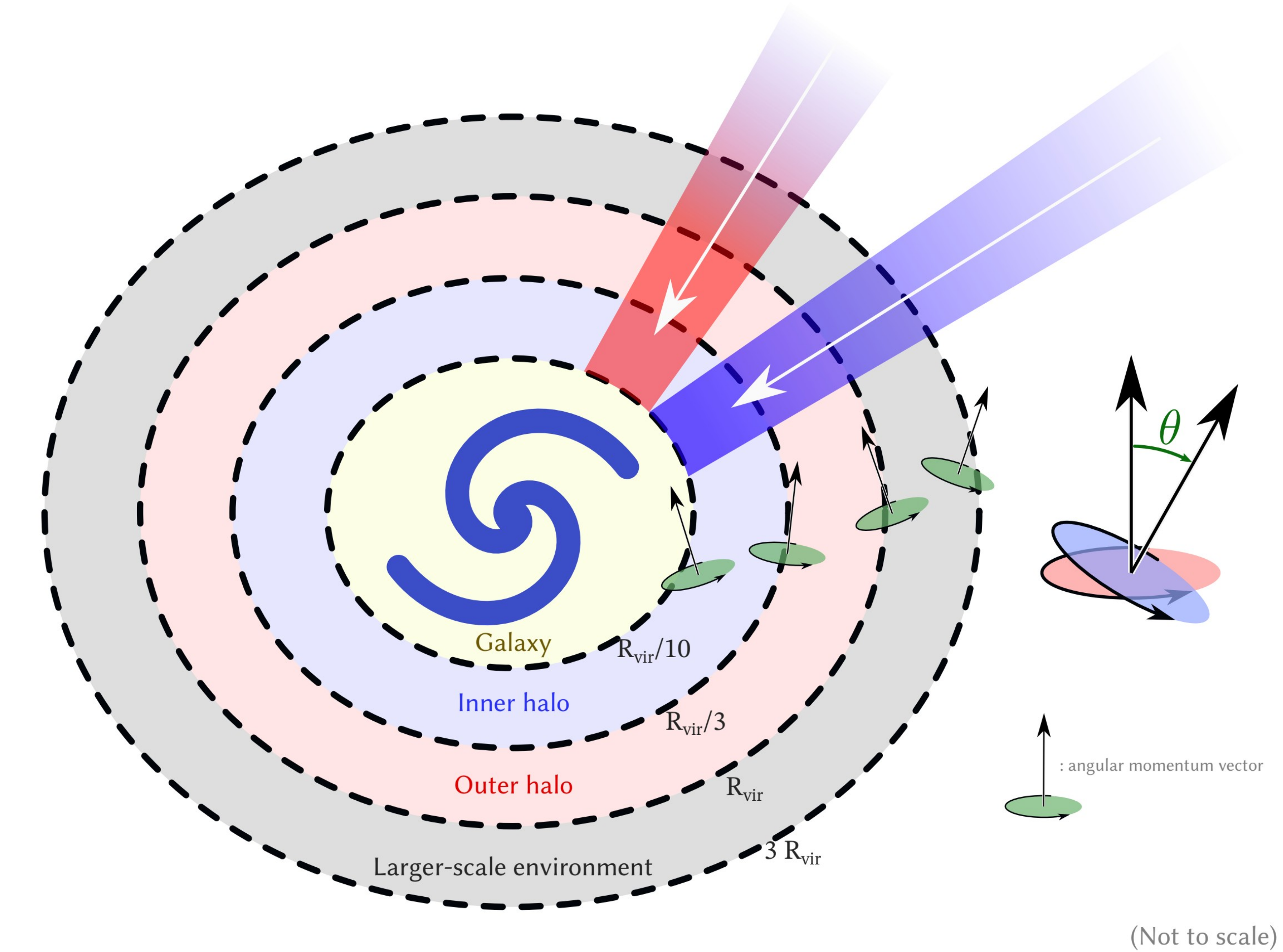

Angular momentum magnitude of the cold and hot-accreted gas. **Cadiou+in prep**

Cold gas: retains its angular momentum to **inner halo**

Hot gas: retains its angular momentum to **outer halo**

[See also Kimm+11, Dubois+12, Danovich+15, Tillson+15, Stewart+17]


Galaxy
2000
3000
3
r)


Galaxy
$R_{vir}/10$
Inner halo
$R_{vir}/3$
Outer halo
$R_{vir}$
Larger-scale environment
$3\ R_{vir}$
$\theta$
: angular momentum vector
(Not to scale)

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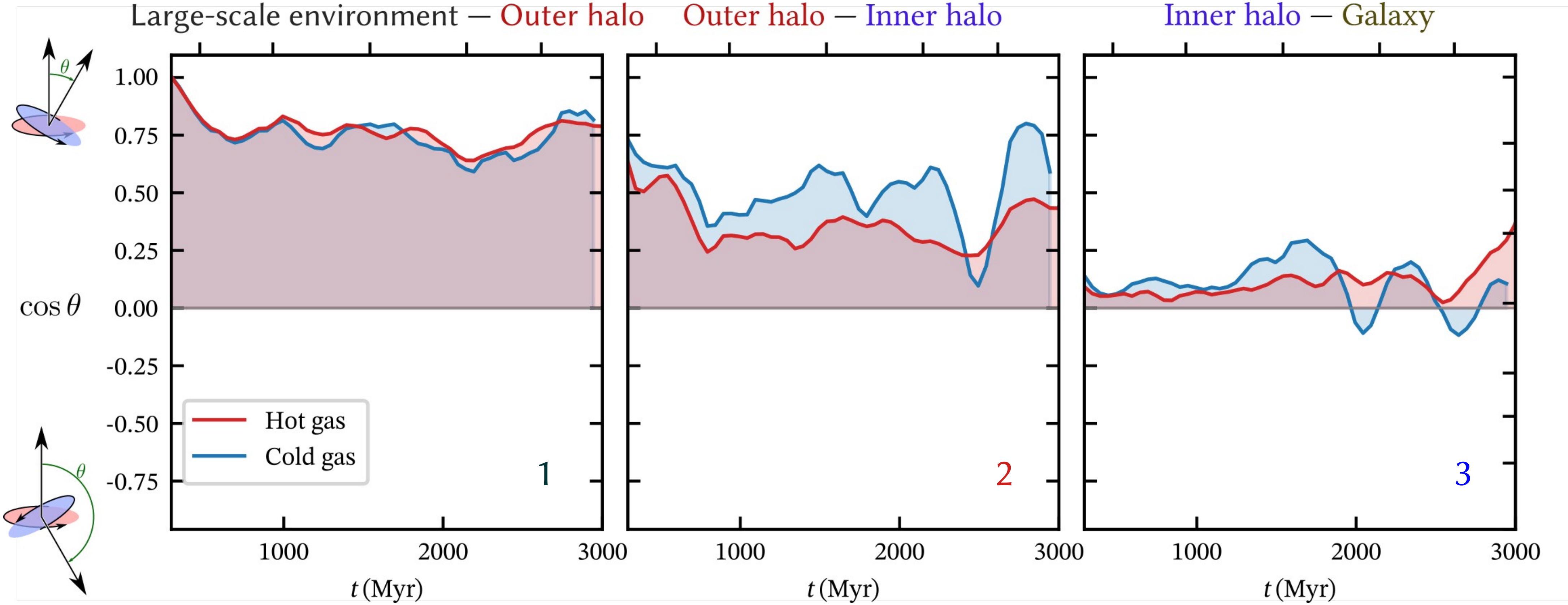
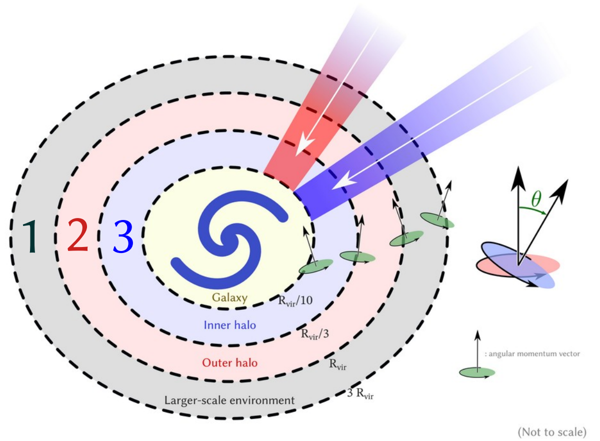



Angular momentum alignment of the cold and hot-accreted gas. Cadiou+in prep

Cold gas: well-aligned down to **inner halo**

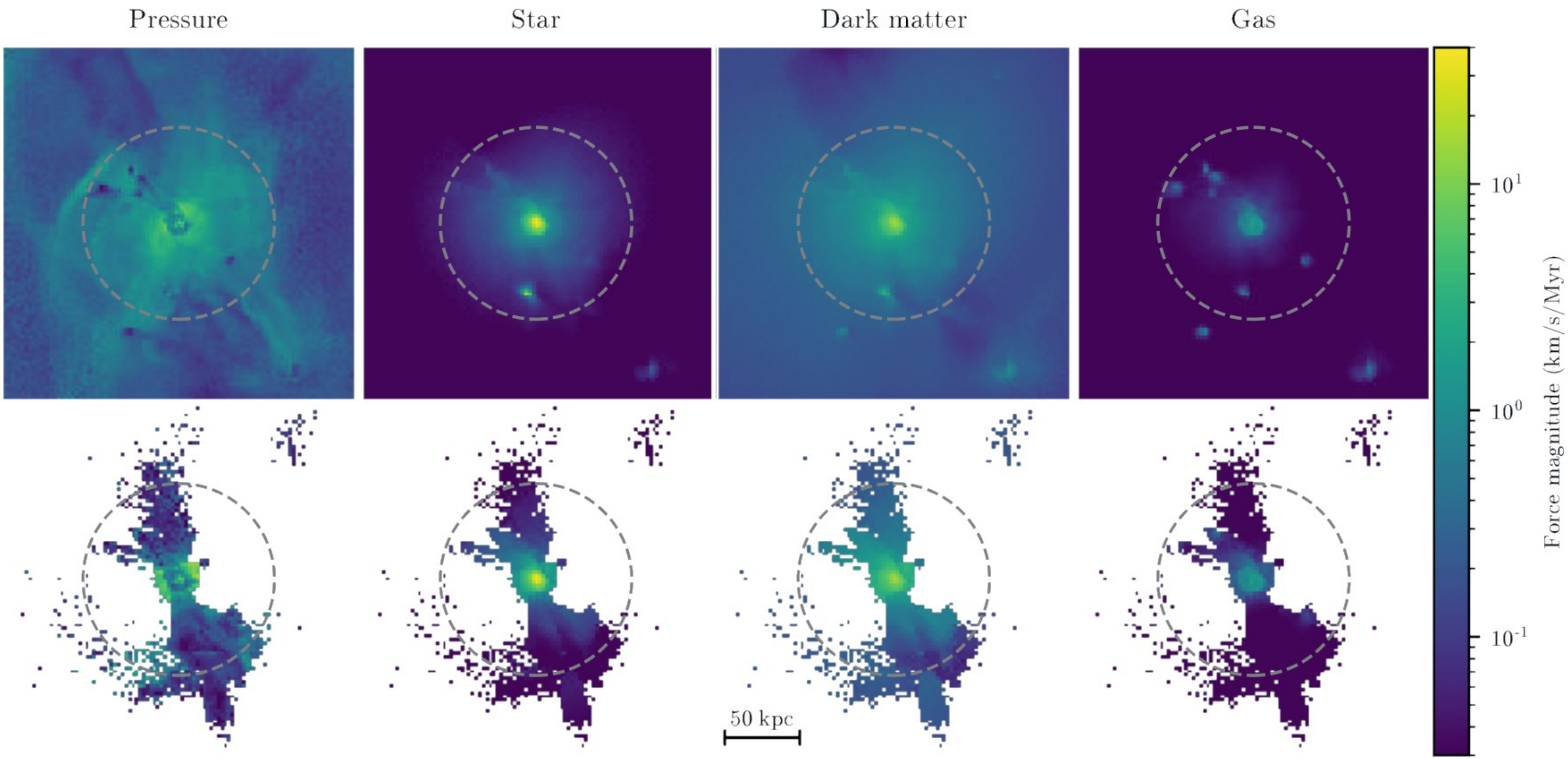
Hot gas: aligned down to **inner halo**



# What is causing angular momentum variation?

*Need to focus on torques to study dynamics*

$$\frac{\mathrm{d}\vec{l}}{\mathrm{d}t} = \underbrace{\vec{\tau}_{\mathrm{pressure}}}_{-\nabla P/\rho} + \underbrace{\vec{\tau}_{\mathrm{star}} + \vec{\tau}_{\mathrm{DM}} + \vec{\tau}_{\mathrm{gas}}}_{-\nabla \phi}$$

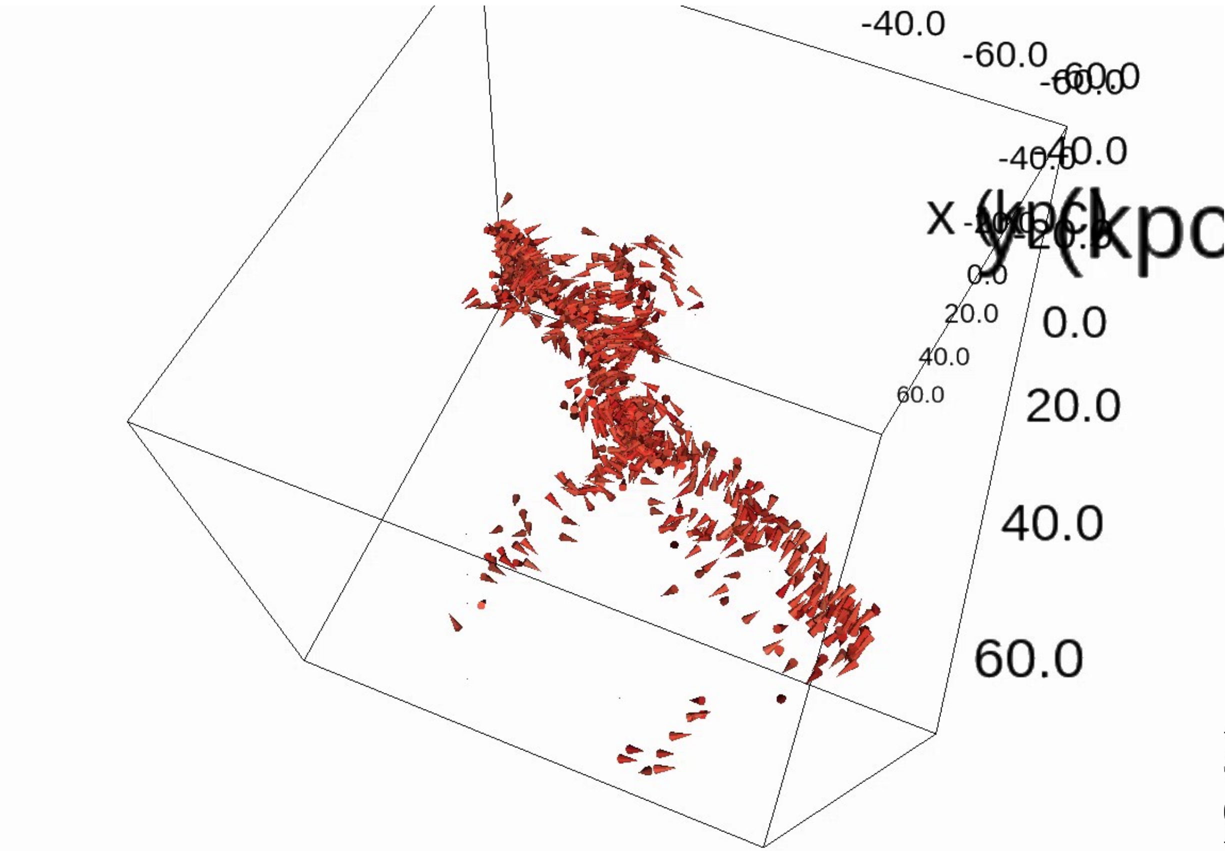



In projections: pressure + DM torques in outer regions
pressure + DM + star torques close to galaxy

[Similar to Danovich+15, Prieto+17]

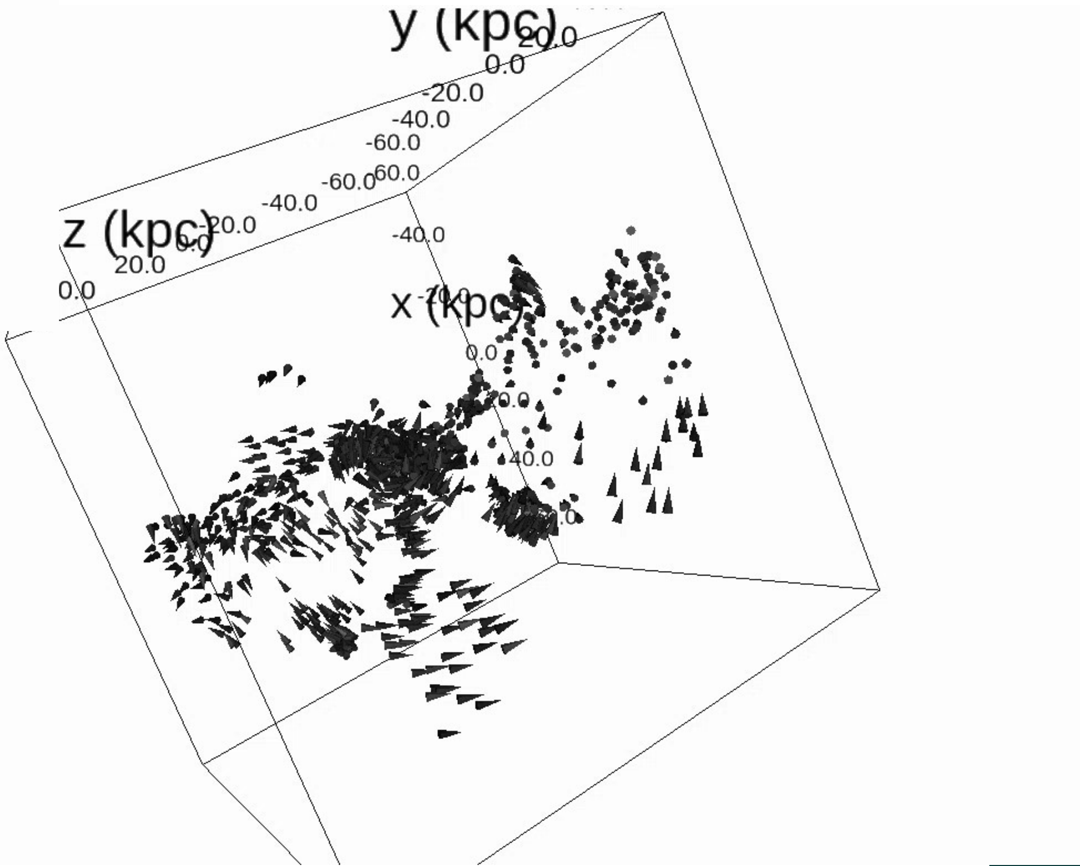
# Spatial structure of the torques?






Pressure torques
⟶ no spatial coherence

DM torques
⟶ spatial coherence

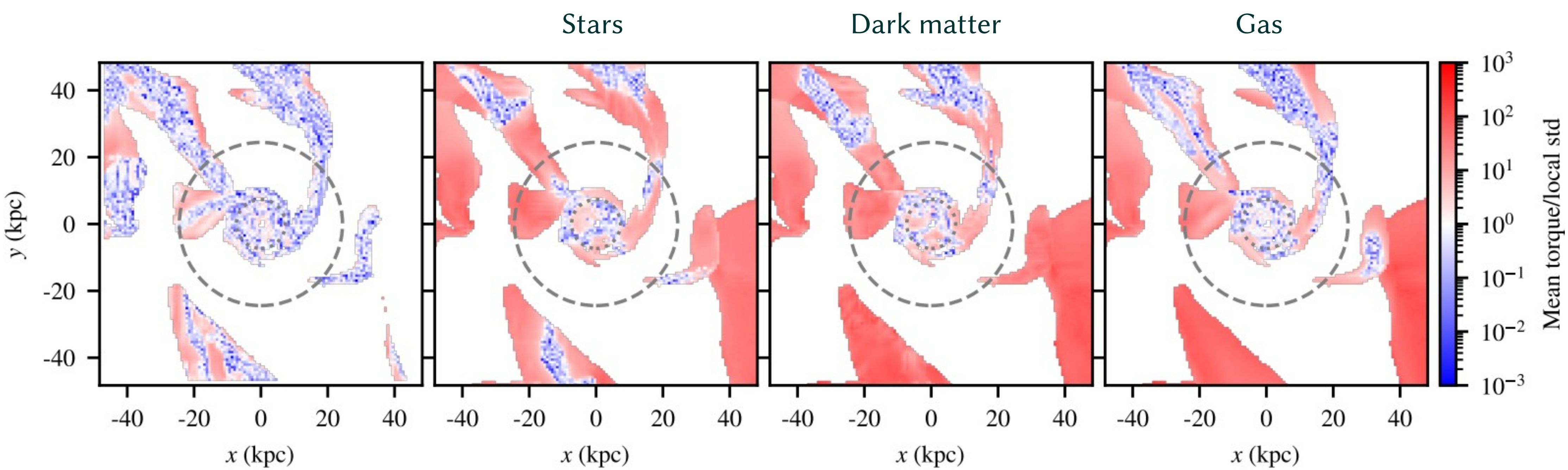


**Pressure torques**


- High-frequency variations
- Low overall contribution

# Cause of angular momentum variation in cold-accreted gas?

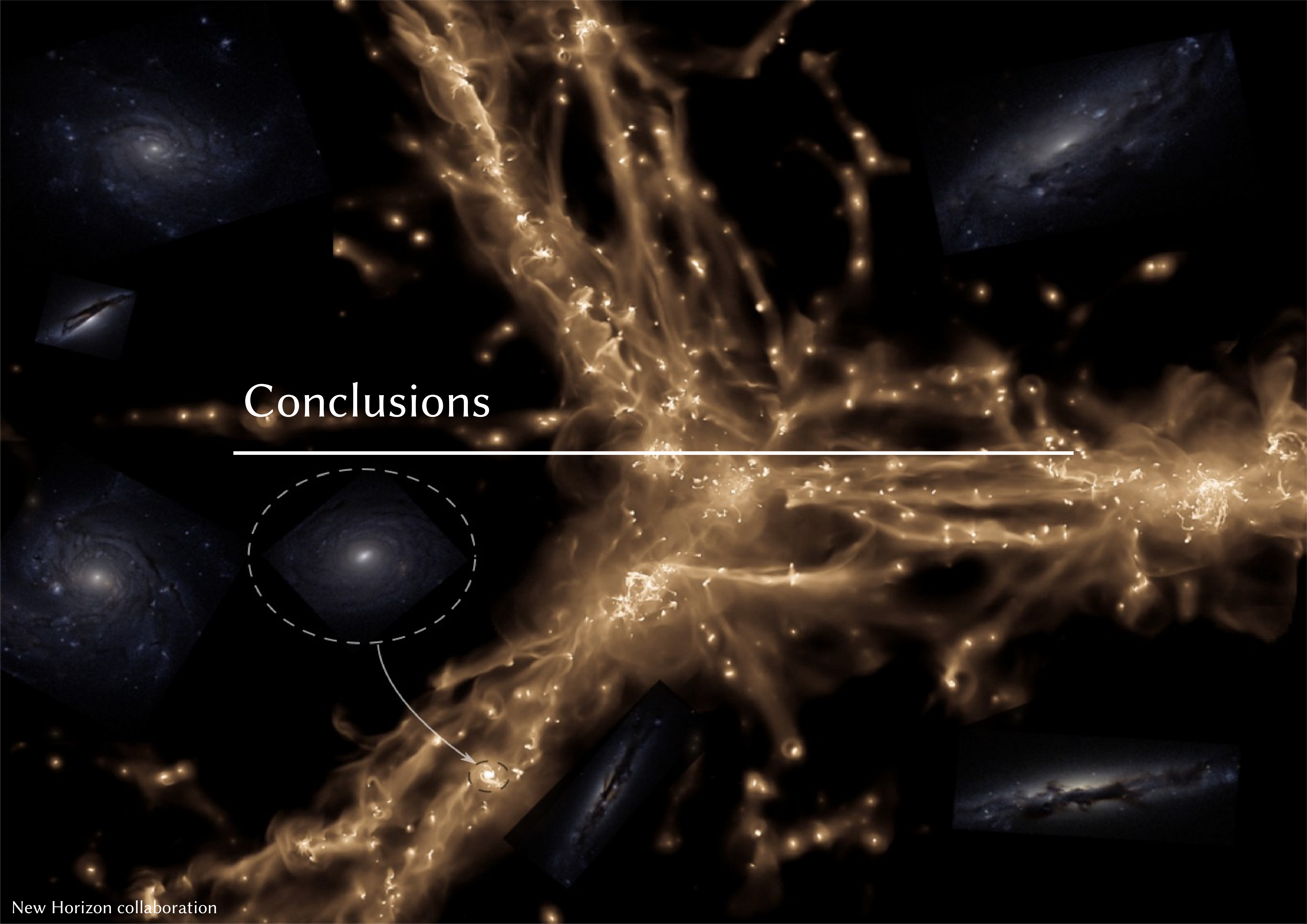
**Pressure torques** **Gravitational torques**




- High-frequency variations
- Low overall contribution

- Long wavelength variations
- Globally dominating
  - → Dark matter in outer halo
  - → Stars close to disk

# Conclusions



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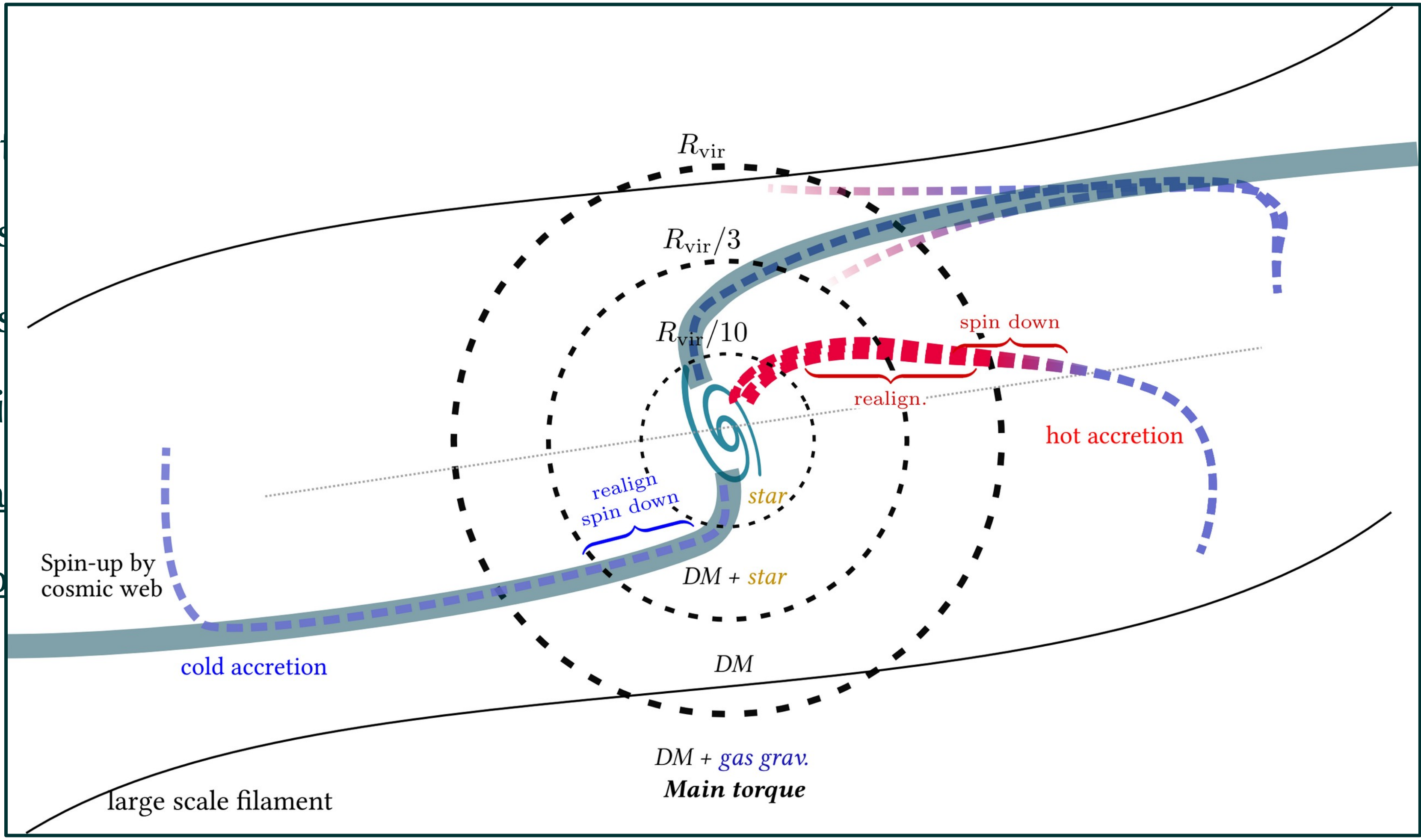
## Cold gas

- Kinematics:
  - Conservation of magnitude to disk
  - Conservation of orientation to disk
- Dynamics:
  - Local: grav torques ~ pressure torques
  - Global average:
    grav torques >> pressure torques

## Hot gas

- Kinematics:
  - Conservation of magnitude to inner halo
  - Orientation $\longrightarrow$ inner halo/disk
- Dynamics:
  - Pressure torques > grav torques
  - Global average?
    *TODO*

- Kinemat
  - Cons … inner halo
  - Cons … k
- Dynami
  - Loca … es
  - Glob
    grav



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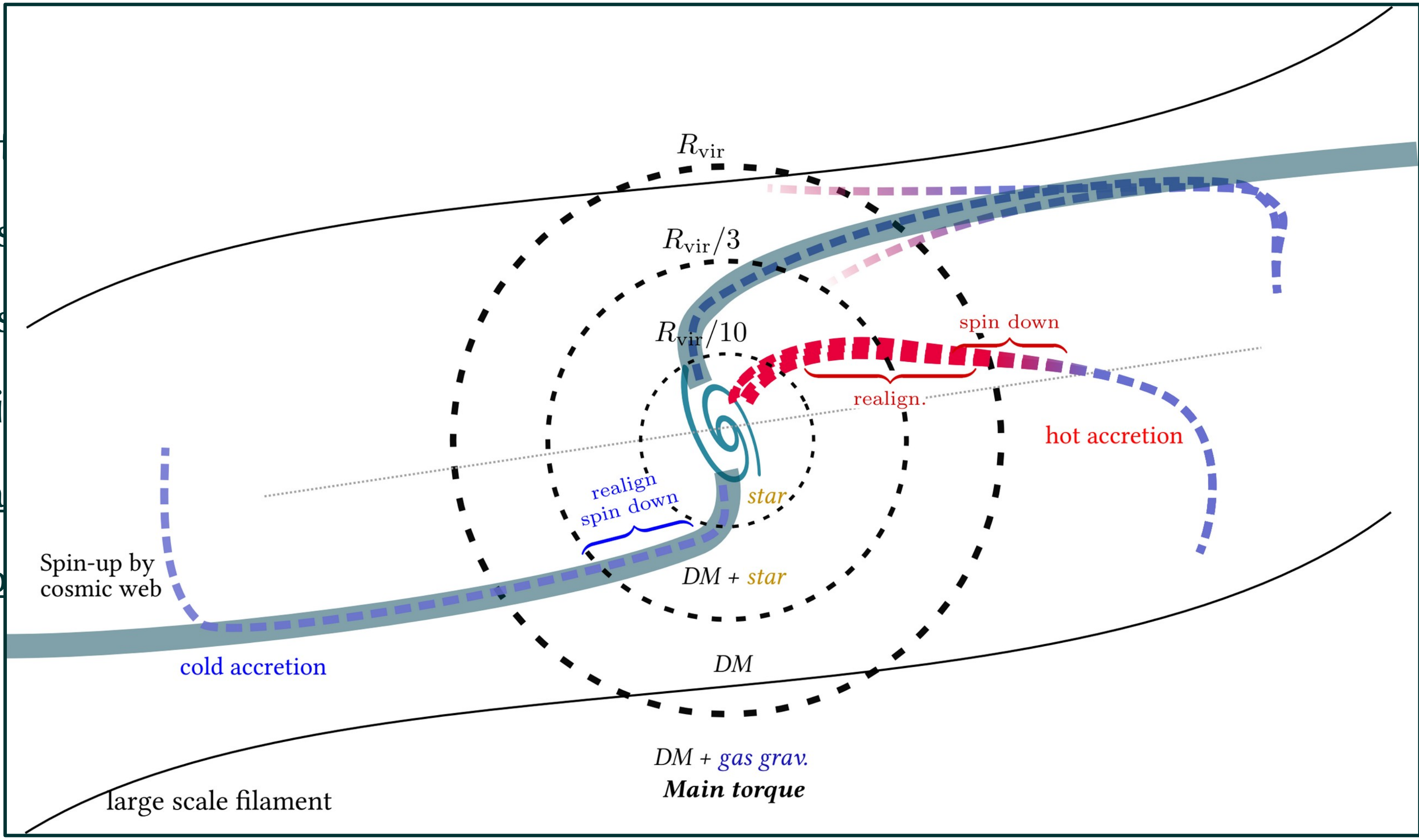


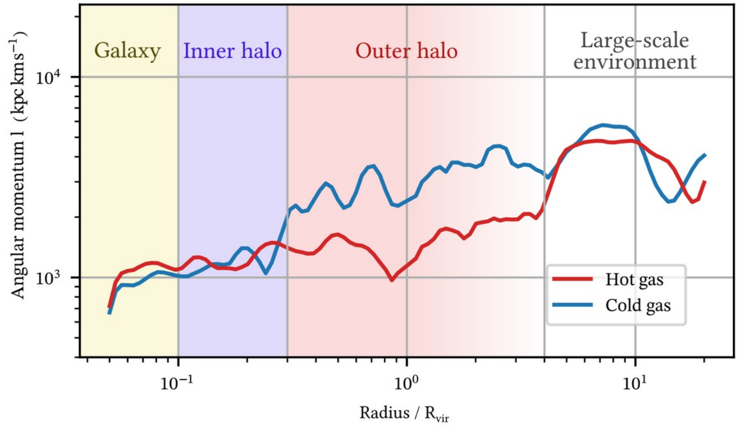

Cold flows

⟹ transport AM from cosmic web to galaxy

⟹ require fine analysis (now possible with tracer particles! available upon request)ll

# Discussion

- Why different temperature evolution ⟹ different AM evolution?
  - Cooling time vs. infall time vs. torquing time [WIP]



# Discussion

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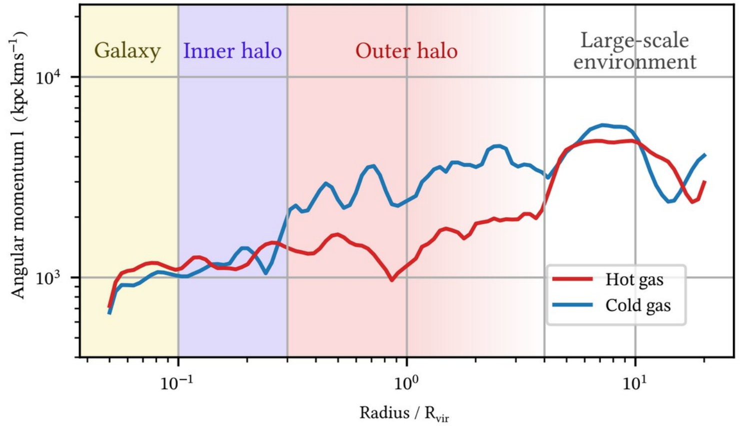
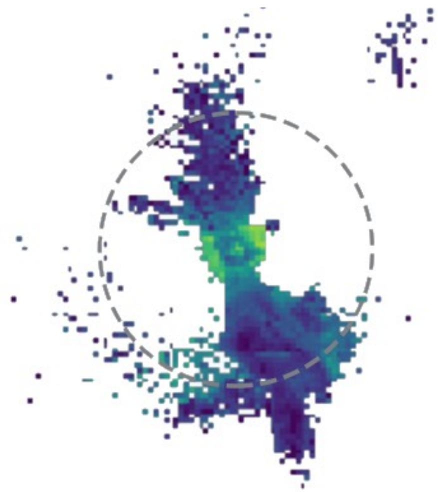
  - Stripping of filamentary gas? (*decrease* AM inflow)
  - Entrain hot gas (*increase* AM inflow) [Mandelker+19]



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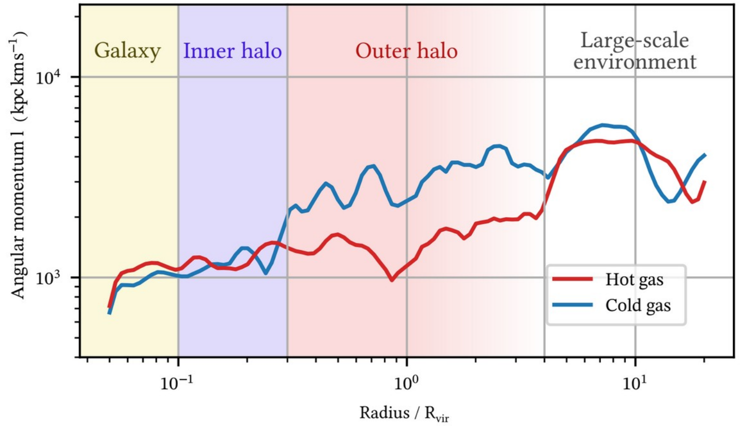


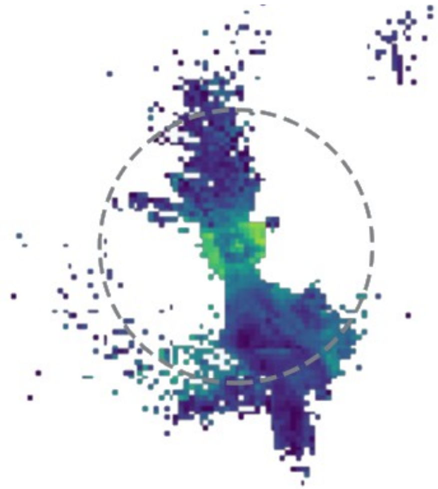

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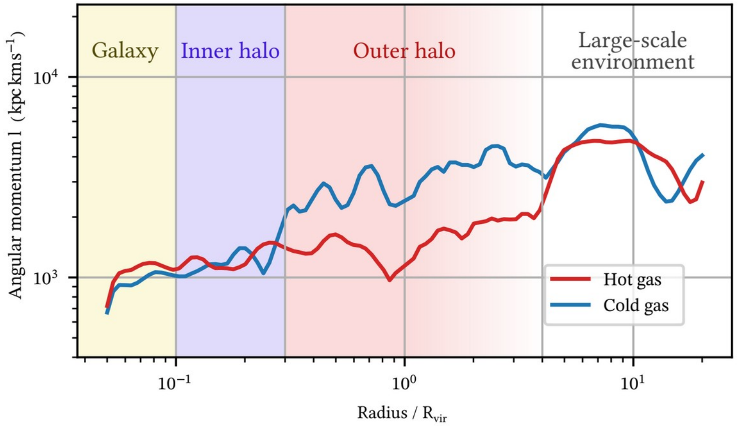
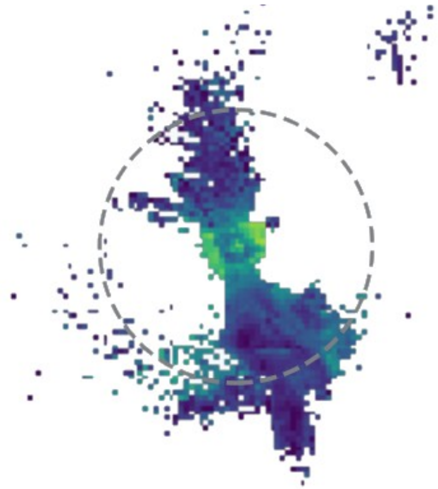
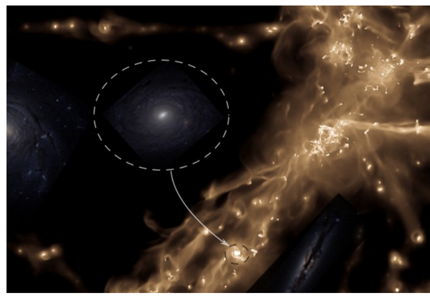
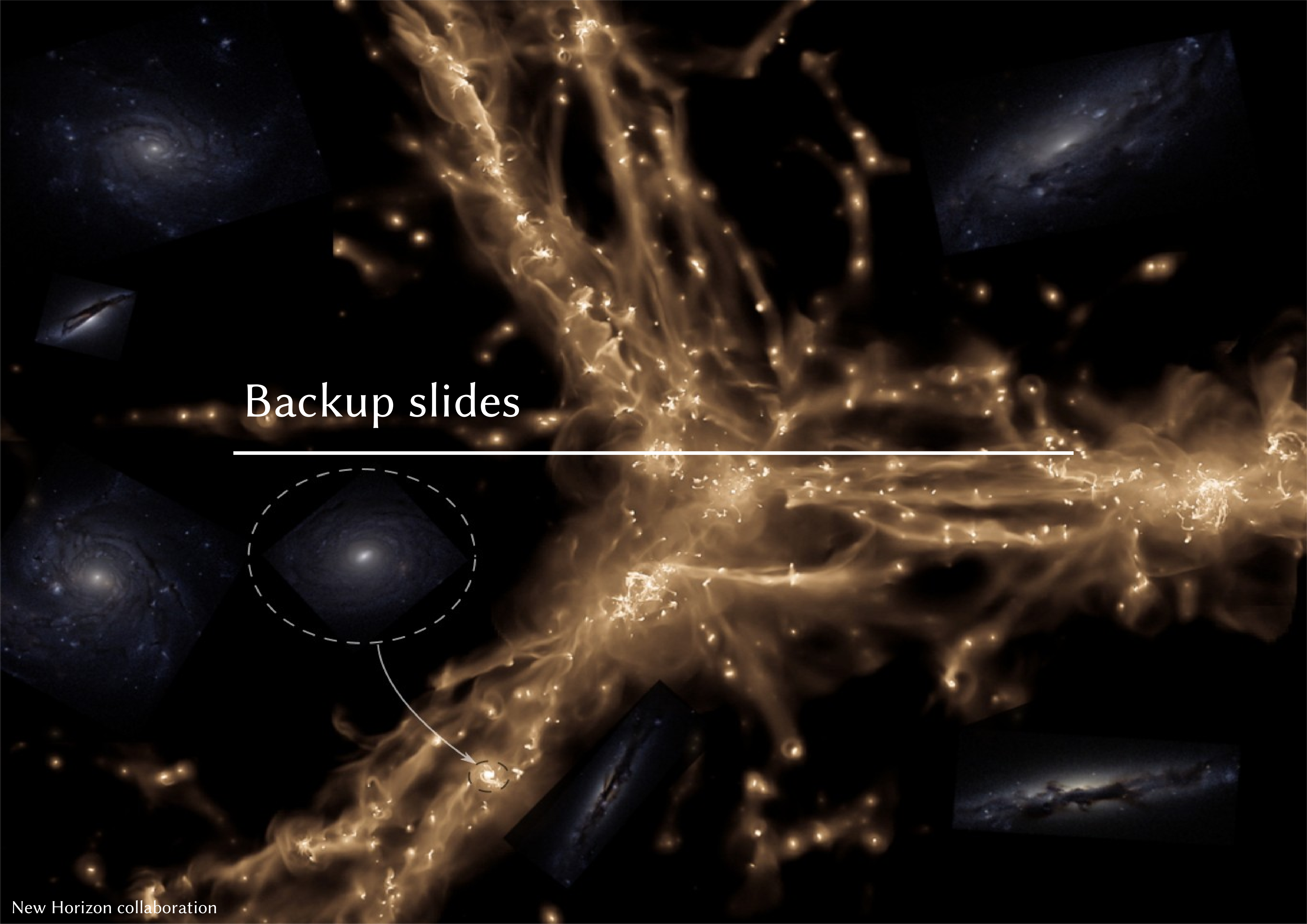
  - Effect of feedback on AM?
  - Understand pressure ring / disk connection (need high-res simulation)
- Cosmic web and galaxies
  - Low-mass/high-z $\longrightarrow$ cold-accretion dominated $\longrightarrow$ alignment retained to disk?
  - What if filament disappears? [Another story, talk to me or Christophe about this!]





# Backup slides



New Horizon collaboration