SORBONNE UNIVERSITÉ
CRÉATEURS DE FUTURS DEPUIS 1257

Institut Lagrange de Paris

The impact of the large scale structure of the Universe on dark matter halo and galaxy formation

L'impact des grandes structures de l'Univers sur la formation des halos de matière noire et des galaxies

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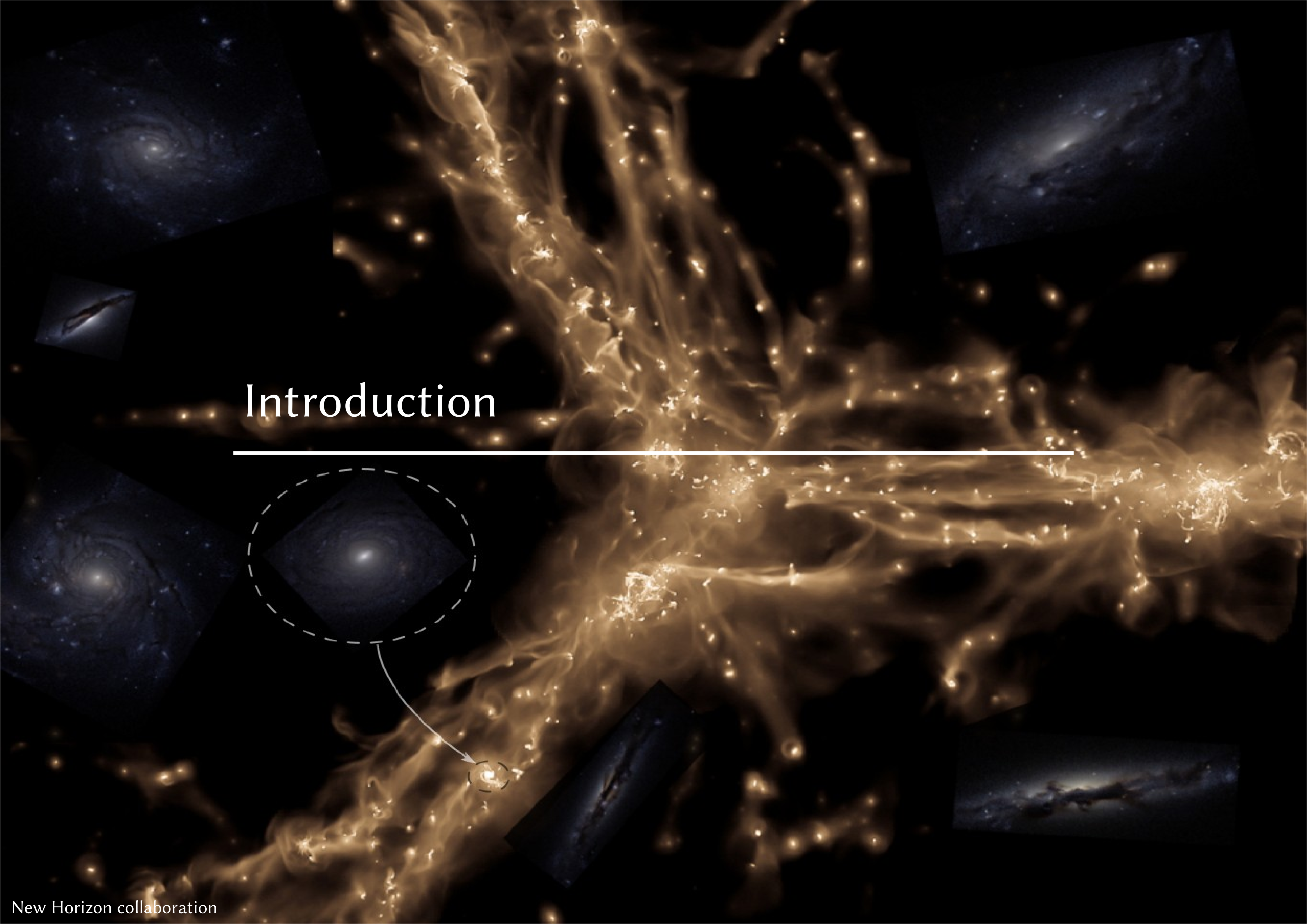
Corentin Cadiou

Institut d'Astrophysique de Paris

Under the direction of C. Pichon & Y. Dubois

26/09/2019

Introduction



New Horizon collaboration


Different size, mass, colour, morphology, ...
Can we explain this diversity?
Images: Hubble Space Telescope

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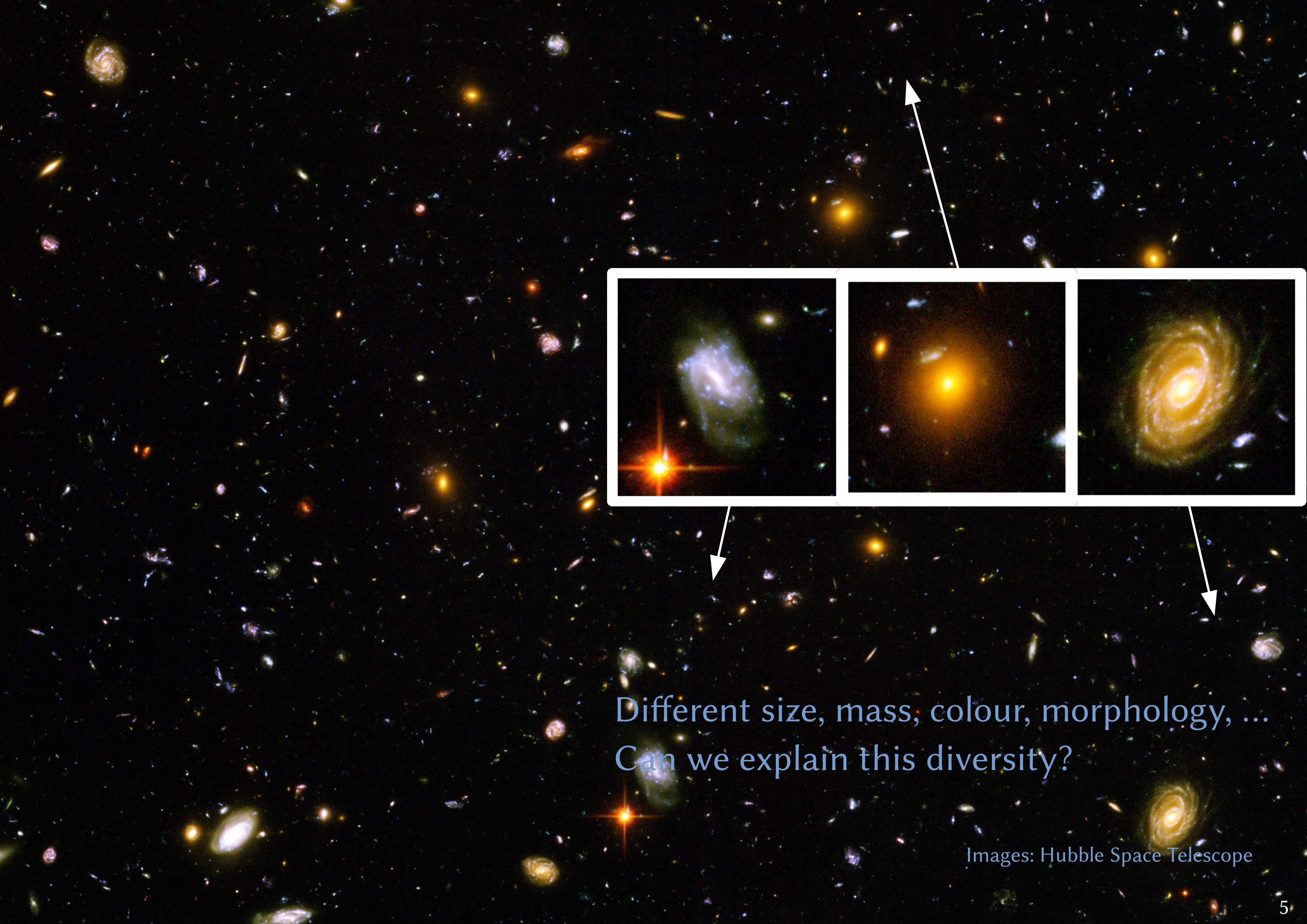
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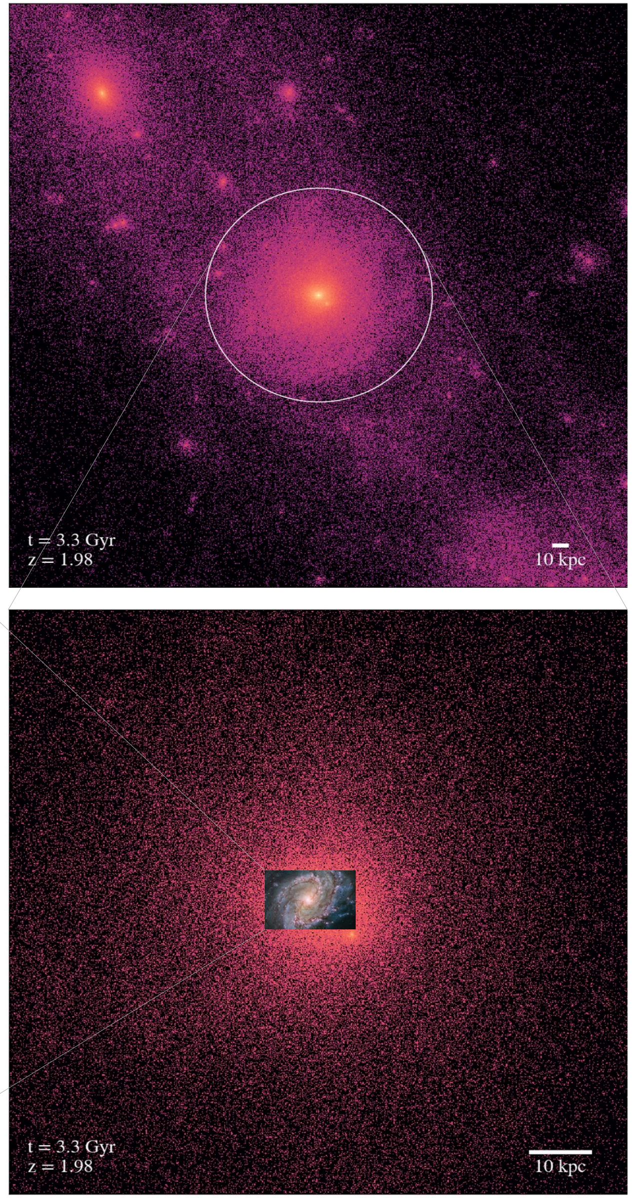
What is a galaxy made of?

- Dark matter halo (90-99%)

M83 galaxy.



Projected density from numerical simulations.
Cadiou+in prep.

What is a galaxy made of?

- Dark matter halo (90-99%)
- Gas (~1-10%)

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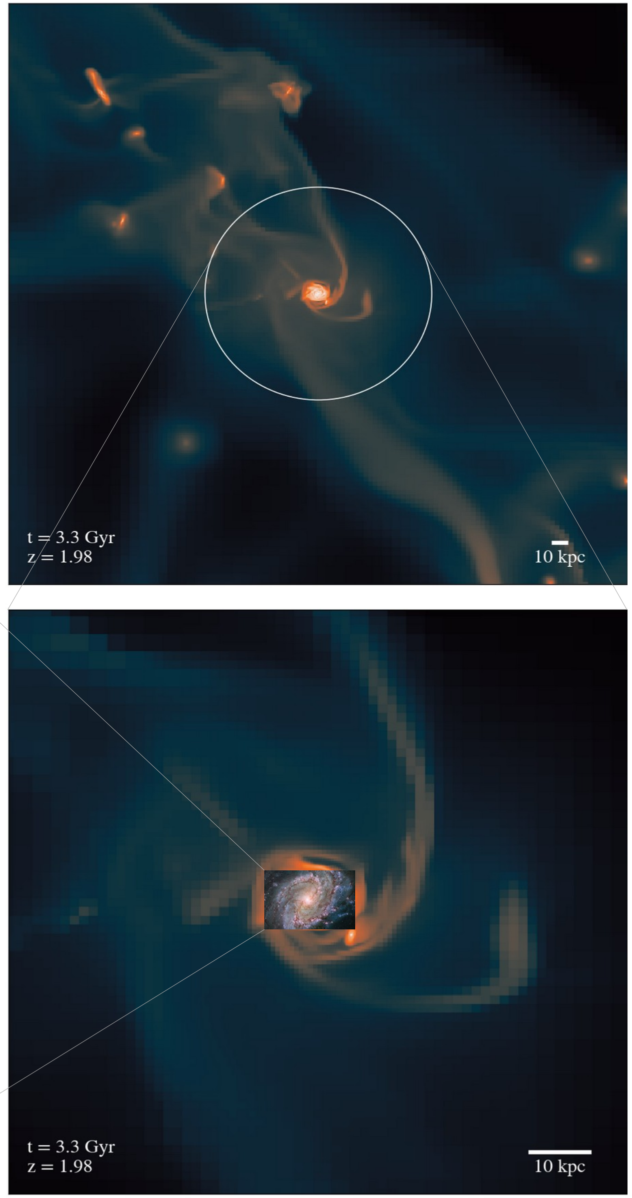

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What is a galaxy made of?

- Dark matter halo (90-99%)
- Gas (~1-10%)
- Stars (~1-10%)

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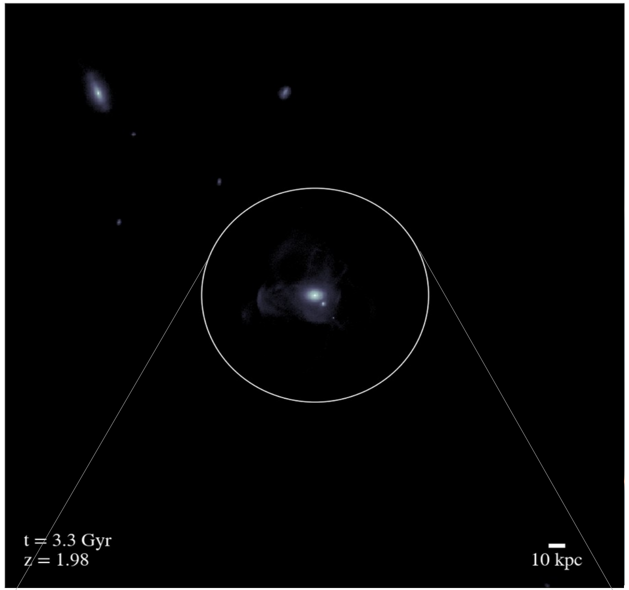

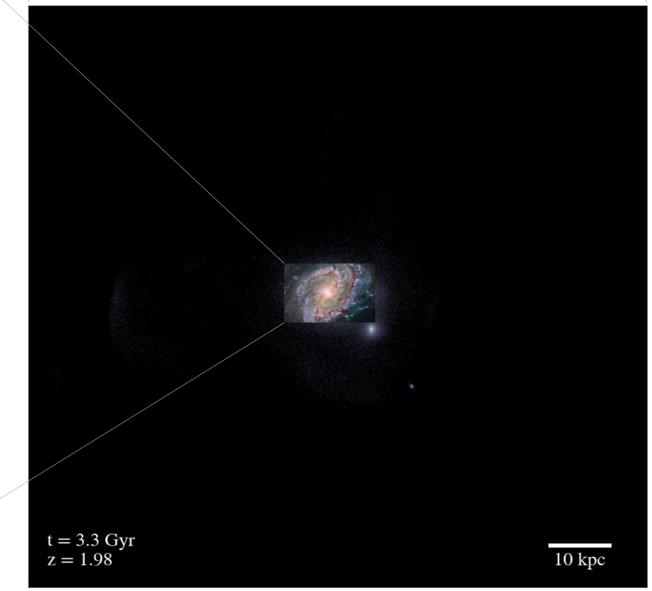

Projected density from numerical simulations.
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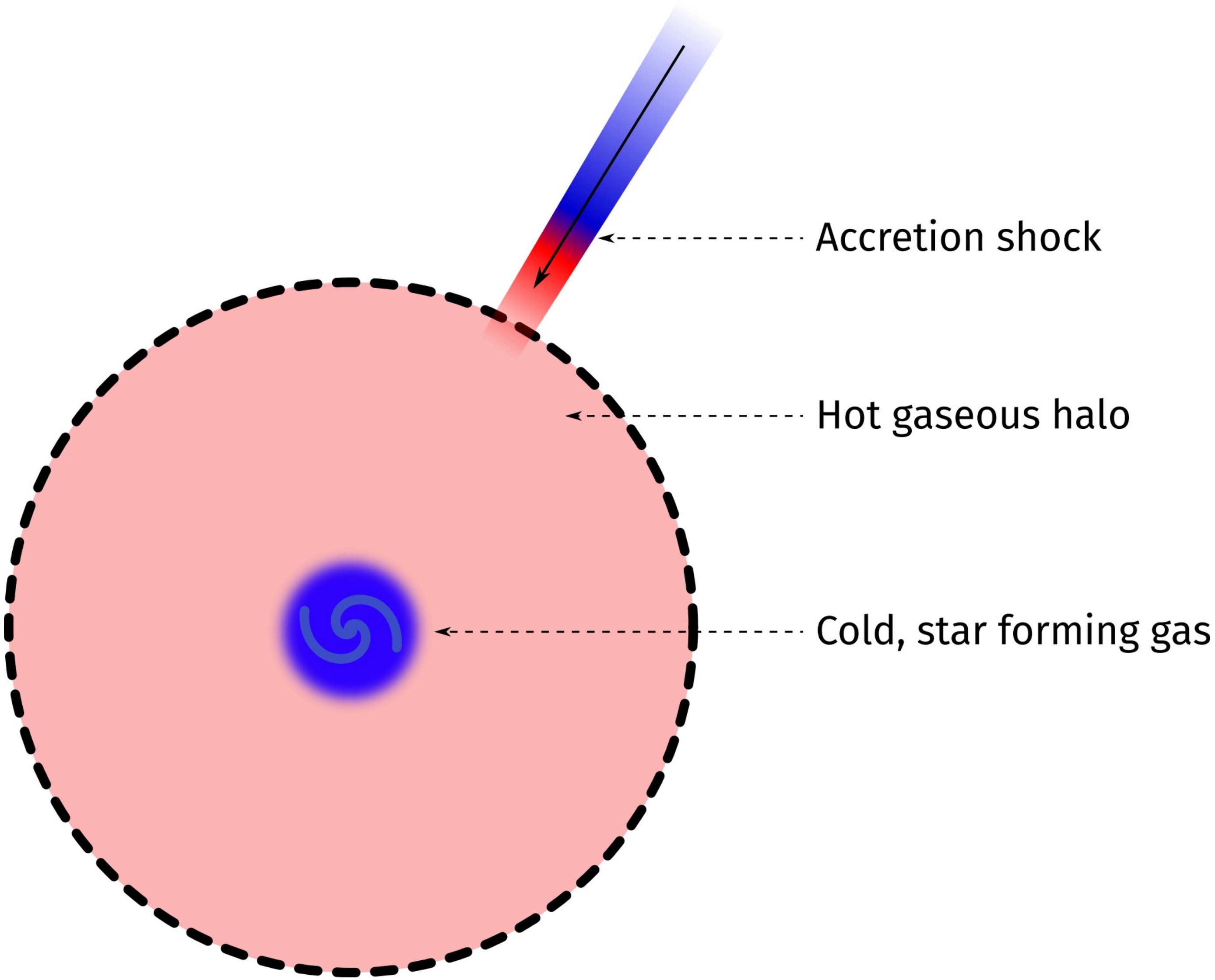
The "classical model" of galaxy formation

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

Halo & galaxy properties:

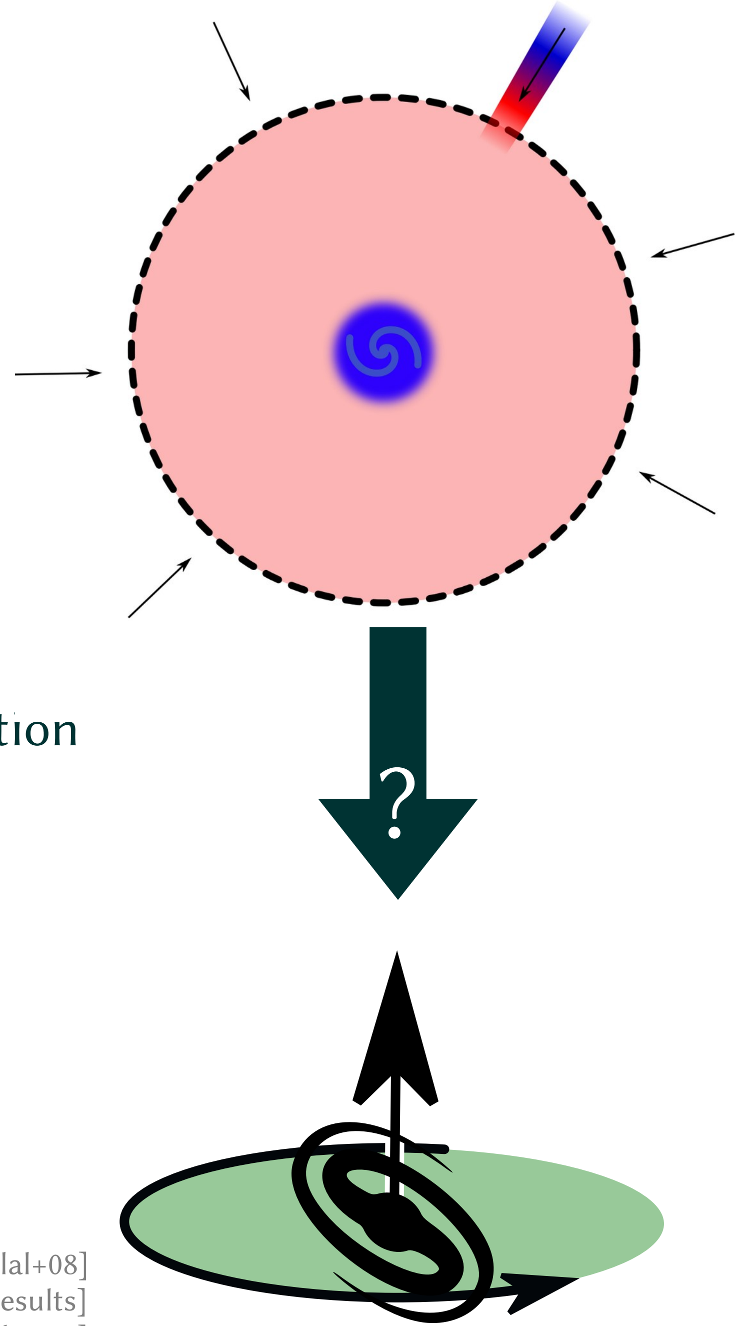
→ driven by halo mass + density



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

Possible improvements of the classical model

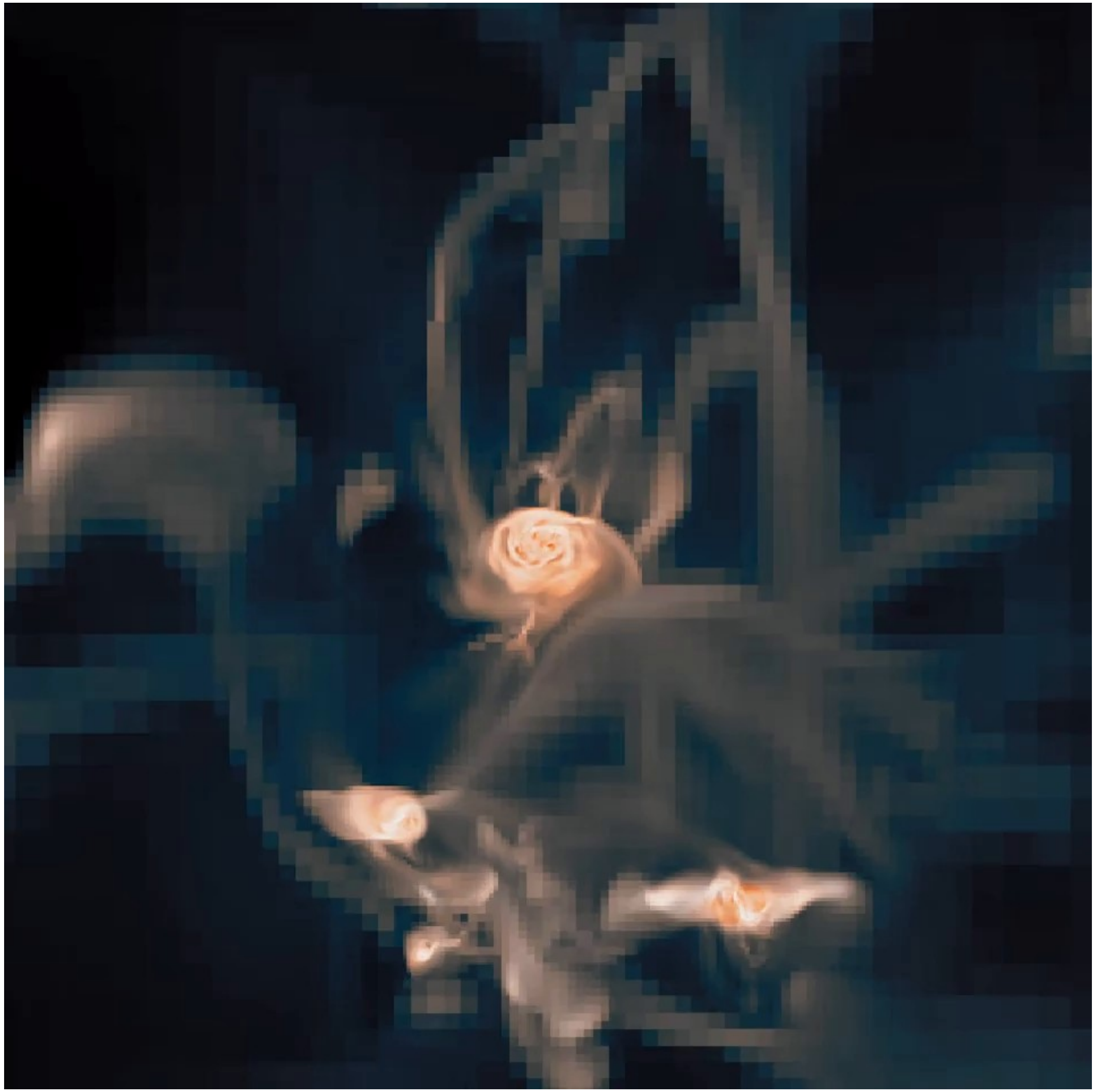
- How do galaxies acquire their **angular momentum**?
  [White+84, beyond TTT?]
- **Assembly bias**:
  - *"The clustering of dark haloes depends not only on their mass but also on their assembly history"* [Croton+07]
  - Call for extra parameters entering halo & galaxy formation



→ Need to study galaxy and halo formation, constrained to their environment.

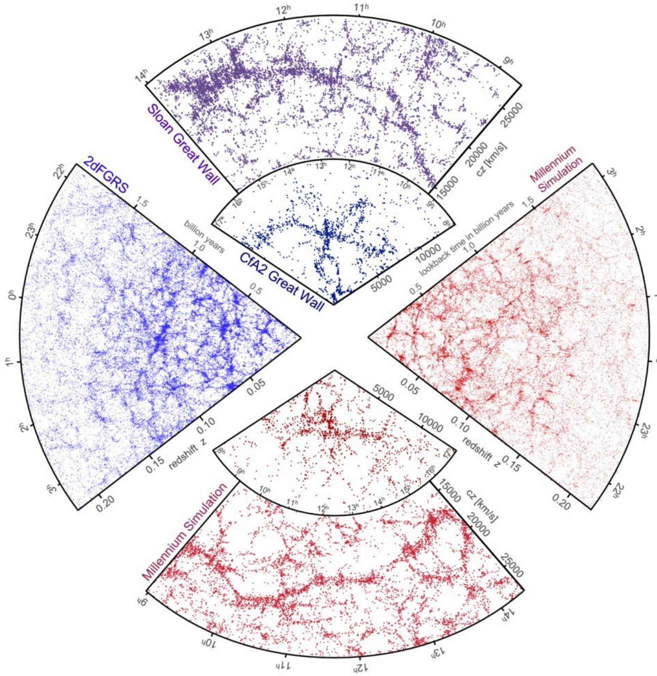
[Assembly bias: Croton+07; Gao&White 07; Dalal+08]
[Galactic conformity: Weinmann+06; Hartley+15; Kawinwanichakij+16, see Peng+10, for different results]
[AM acquisition: TTT: Hoyle 49; Peebles 69; Doroshkevich 70; White 84, Codis+15]

Defining the environment



- Galaxies are embedded in a large-scale environment
- Nodes, filaments, walls, voids

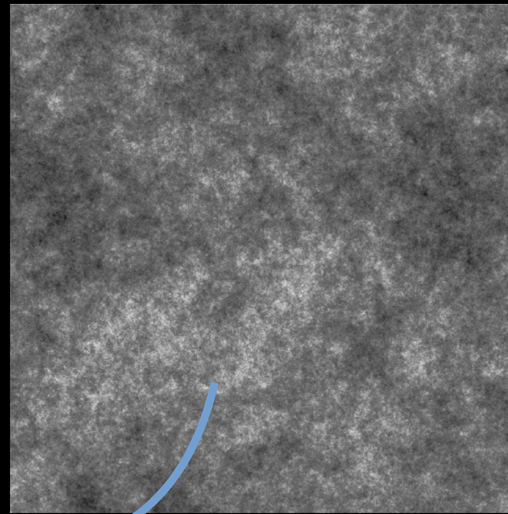
  → the **cosmic web**



The cosmic web in observations (blue) and simulations (red). Springel+2006

[Cosmic web: Klypin & Shandarin 93, Bond+96; Pogosyan+96]
[CfA, de Lapparent+86; SDSS, Abazajian+03; HectoMAP, Hwang+16]

(Increased contrast by 10,000)



Projected gas maps of a
hydrodynamical simulation
(**Cadiou**+in prep.)
Coloured regions are hot
Bright regions are dense

[Zel'dovich 70, Bond&Myers 96, Bernardeau+02]

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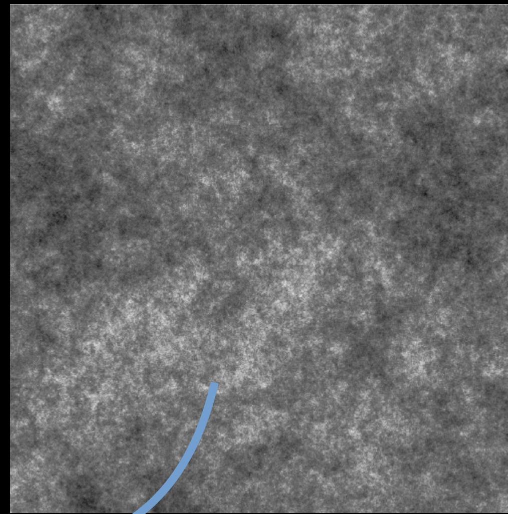

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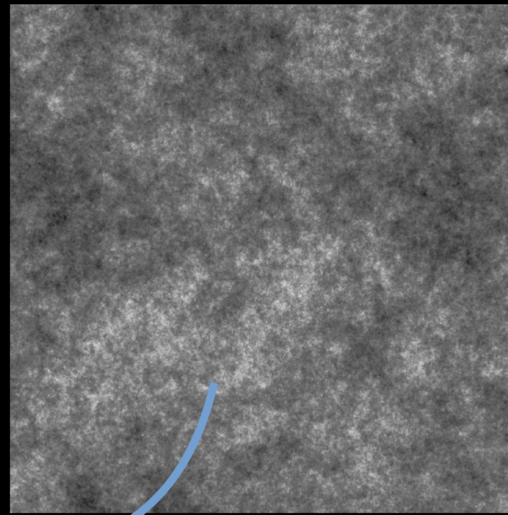

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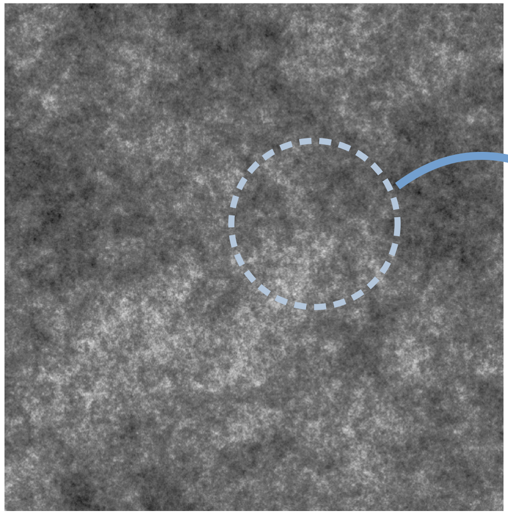
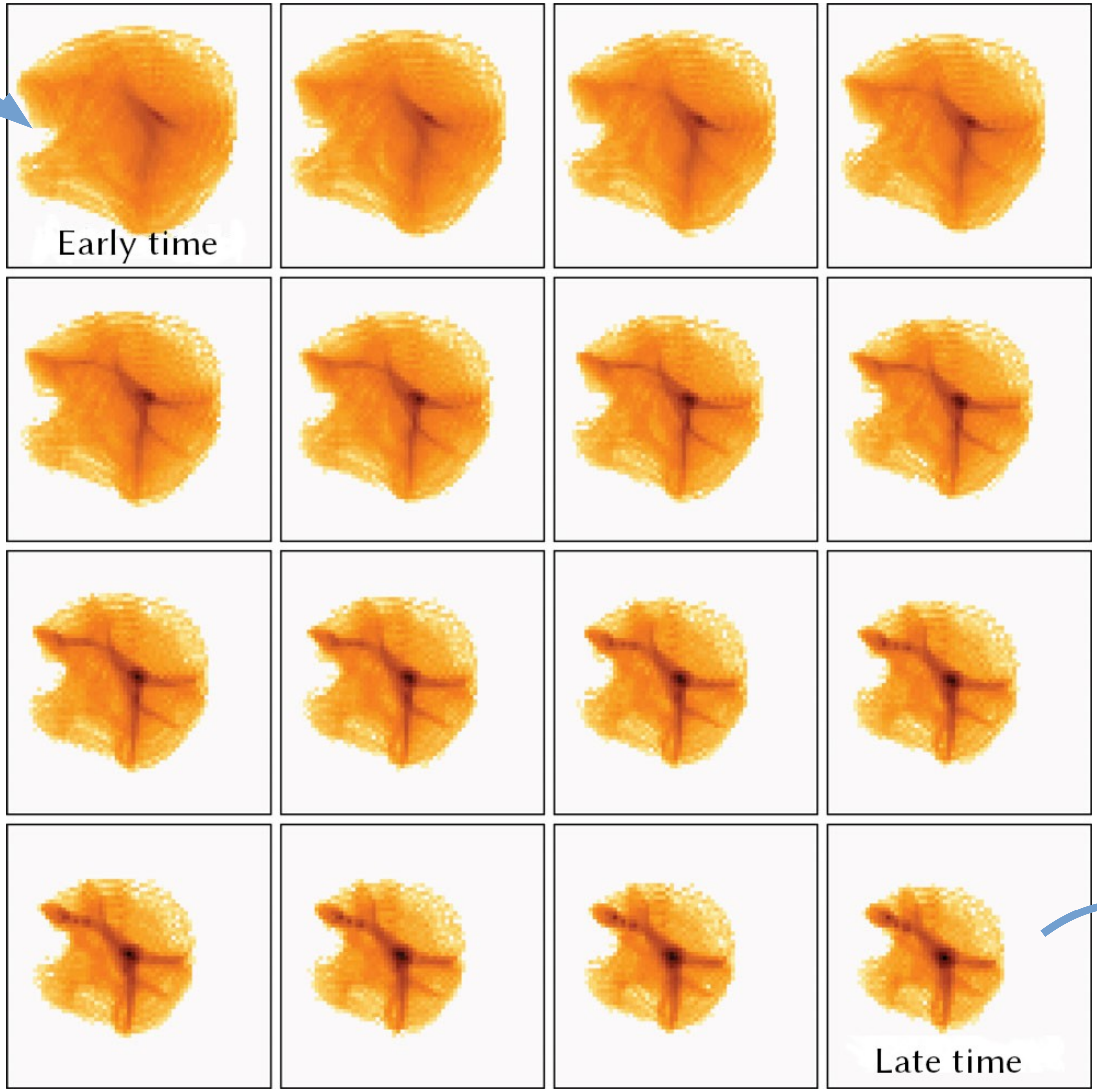
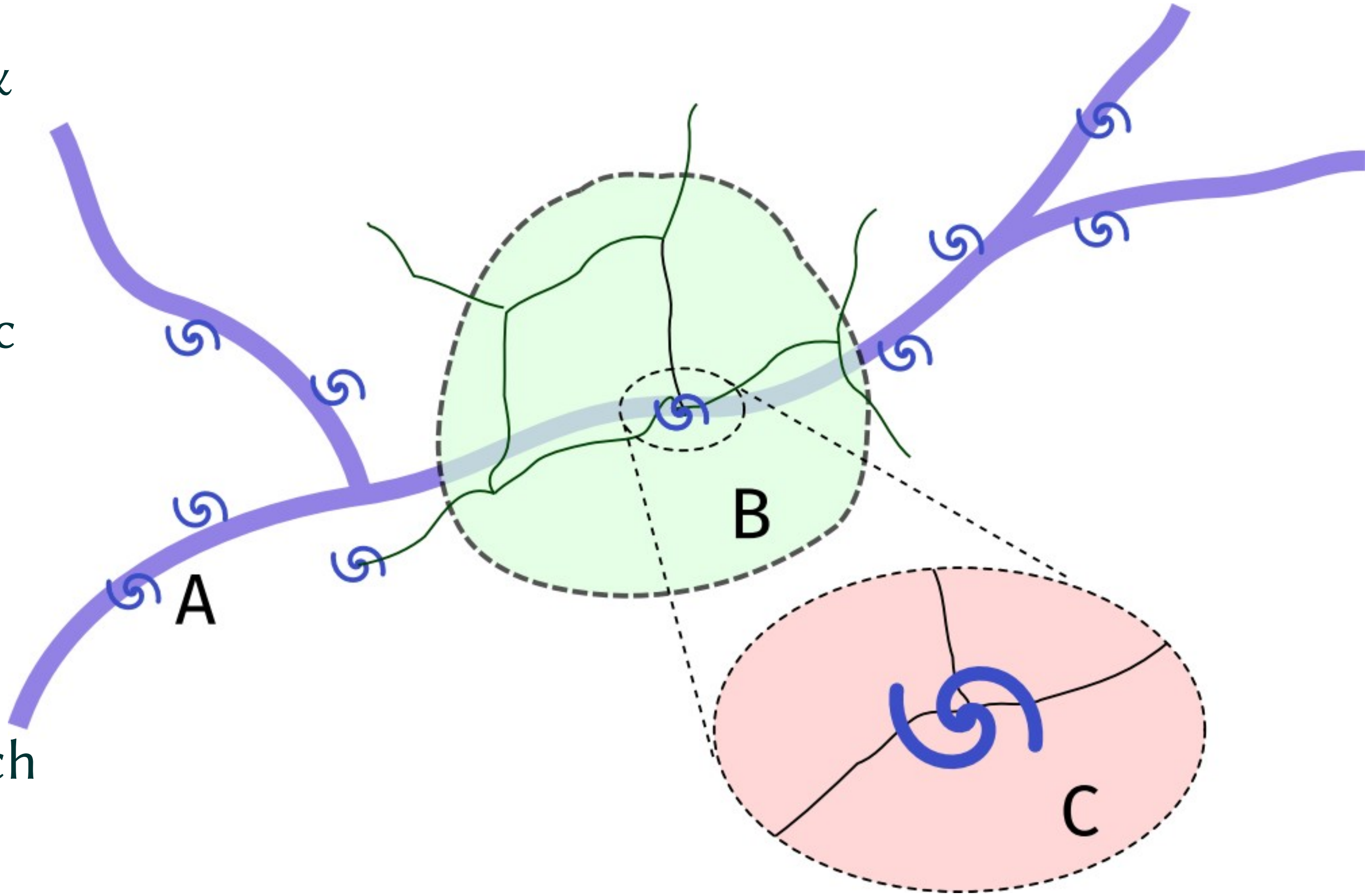
Lagrangian patch





[Pichon+11]

- Effect of cosmic web on halo & galaxy formation?
  On galaxy morphology?
- Compact description of cosmic web and its evolution?



Three-scales approach

- A: larger than Lagrangian patch
- B: in Lagrangian patch
- C: galaxy formation scale

Open questions

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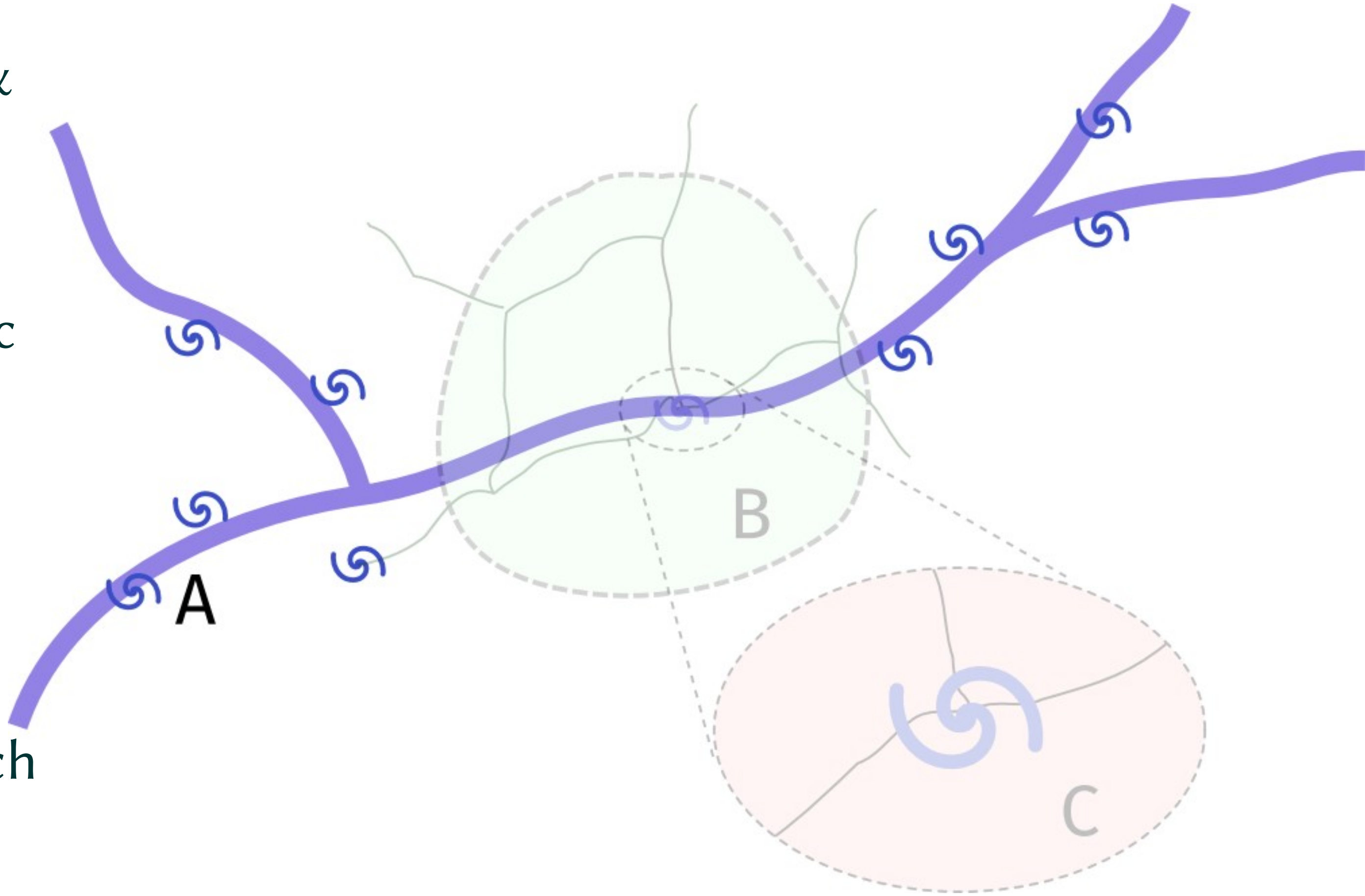

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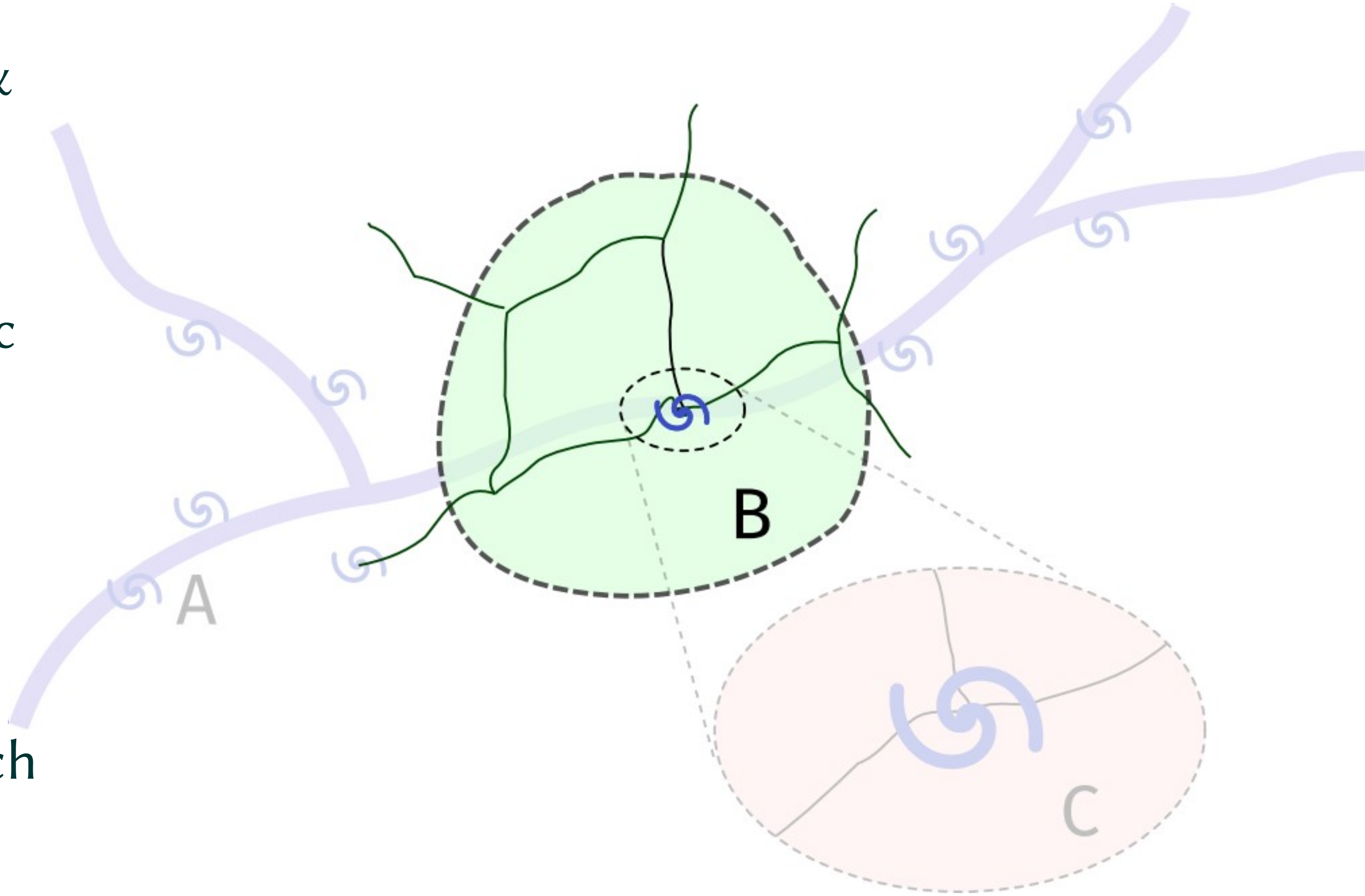

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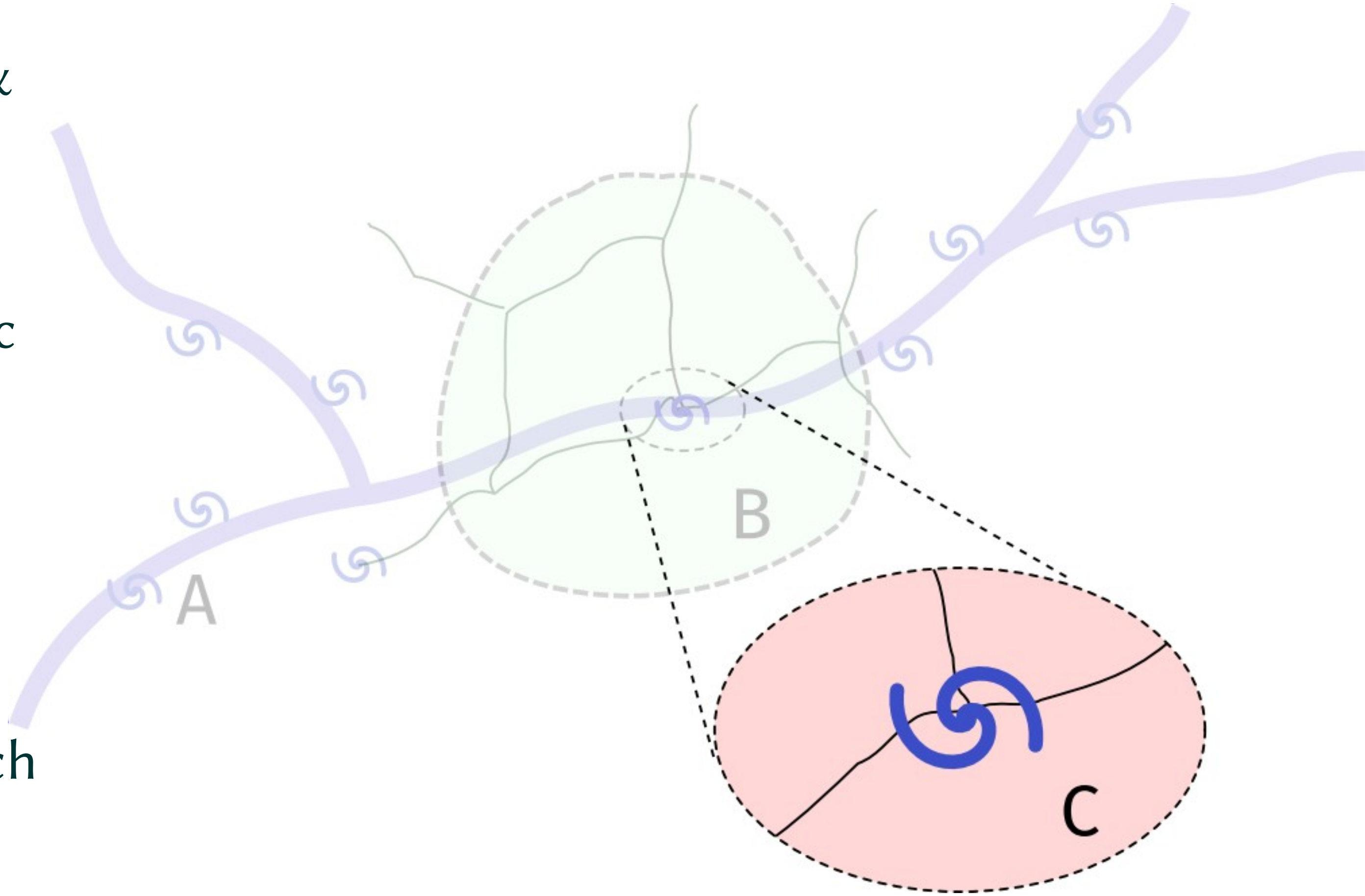

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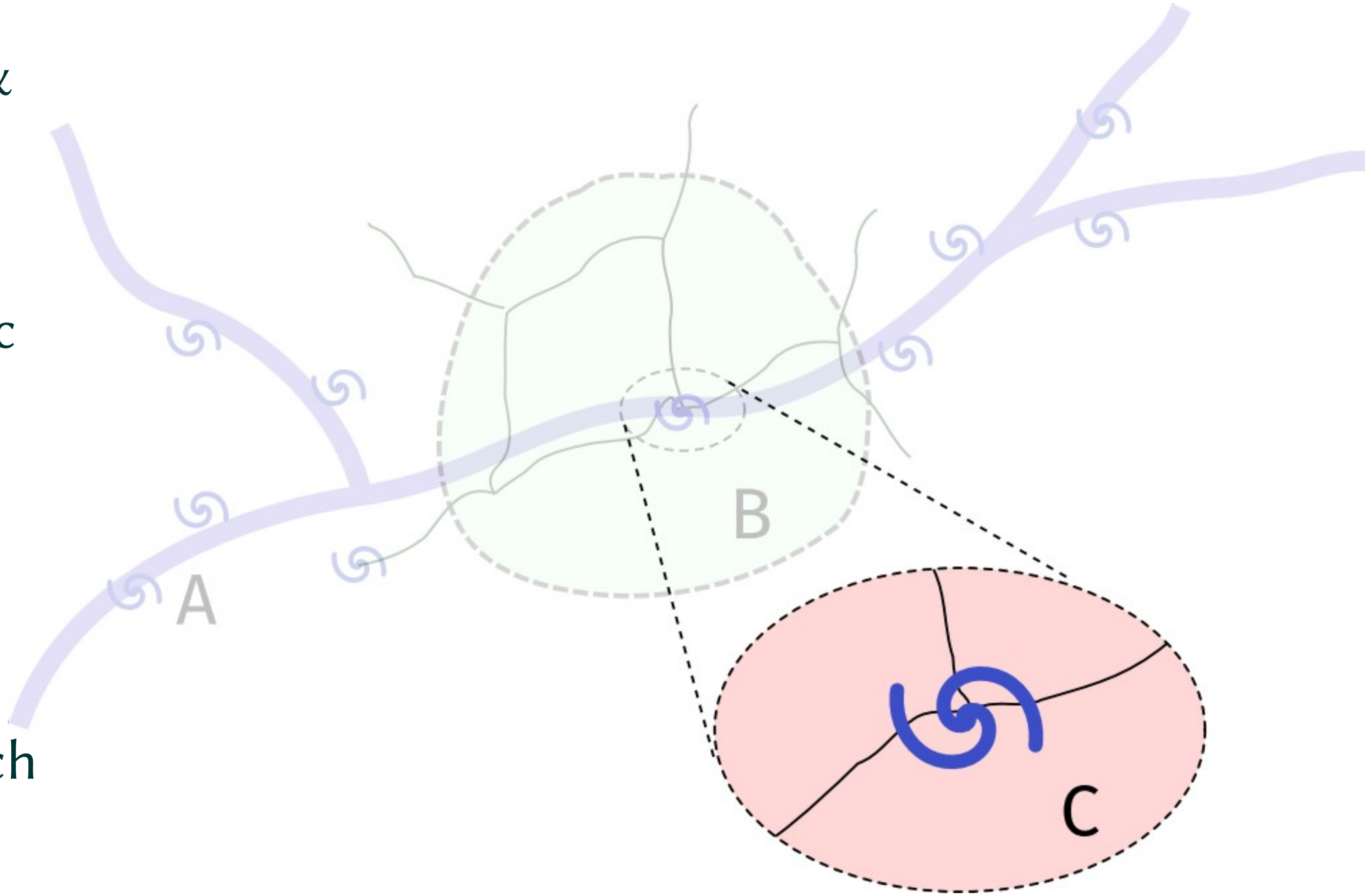

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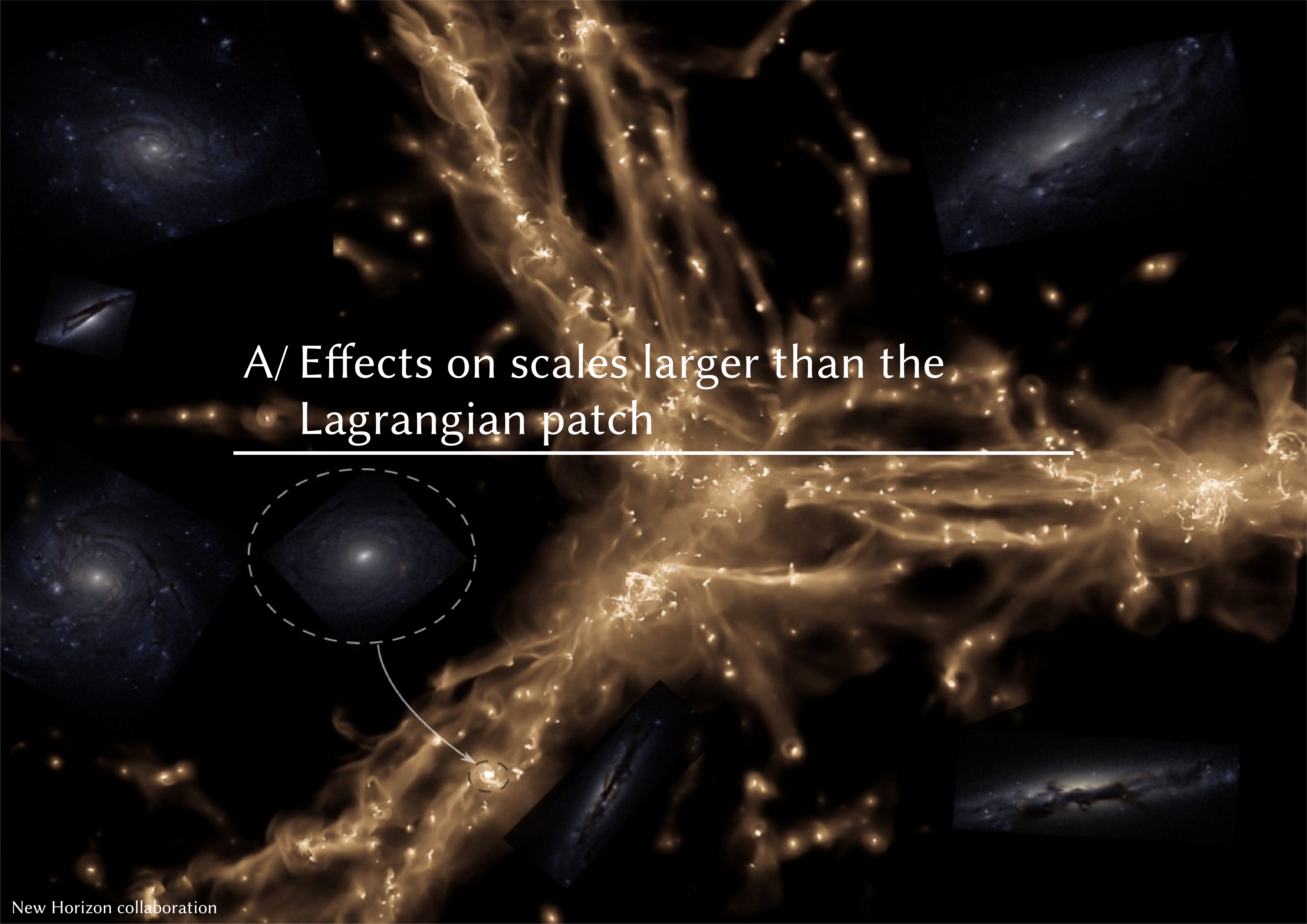
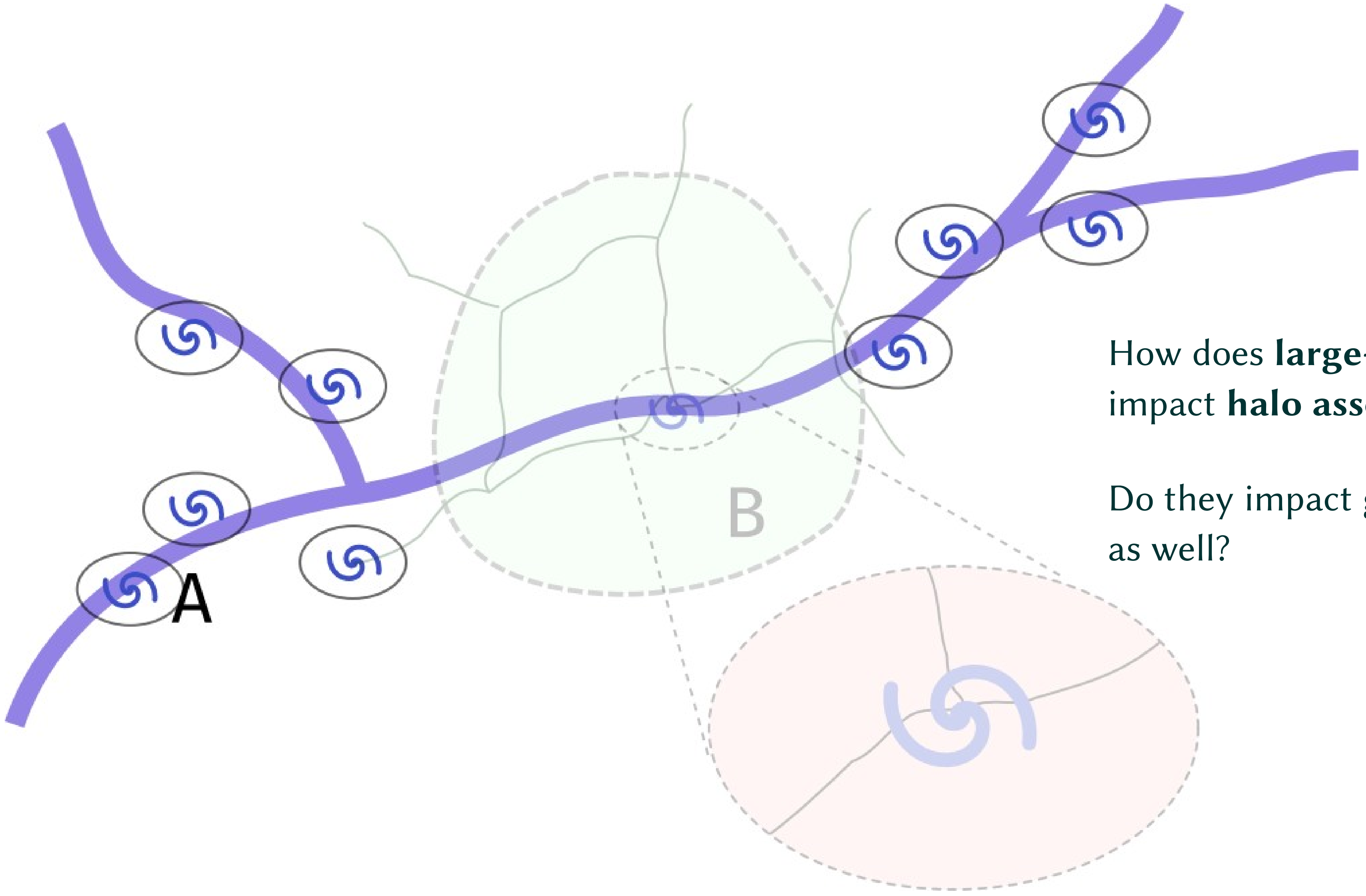
A/ Effects on scales larger than the Lagrangian patch



New Horizon collaboration

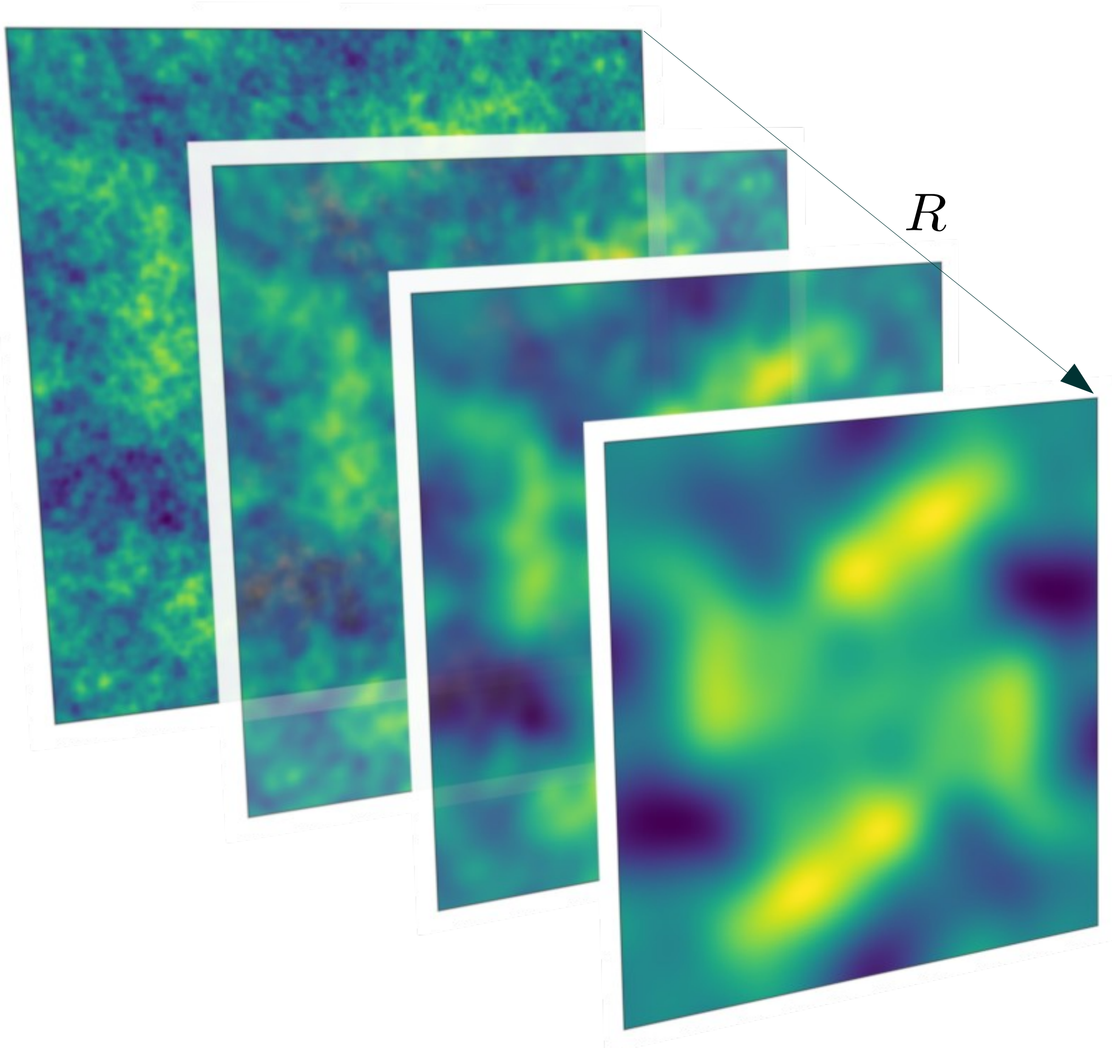
Effect of filament on halo properties



How does **large-scale filaments** impact **halo assembly**?

Do they impact **galactic assembly bias** as well?

Excursion set theory



- Large overdensities $\longrightarrow$ early collapse

$$\delta(R) = \frac{\delta_c}{D(z)}$$

- Large Lagrangian patches $\longrightarrow$ large halos

$$M(R) = \frac{4\pi}{3}\bar{\rho}R^3$$

δ ~ proxy for time of formation

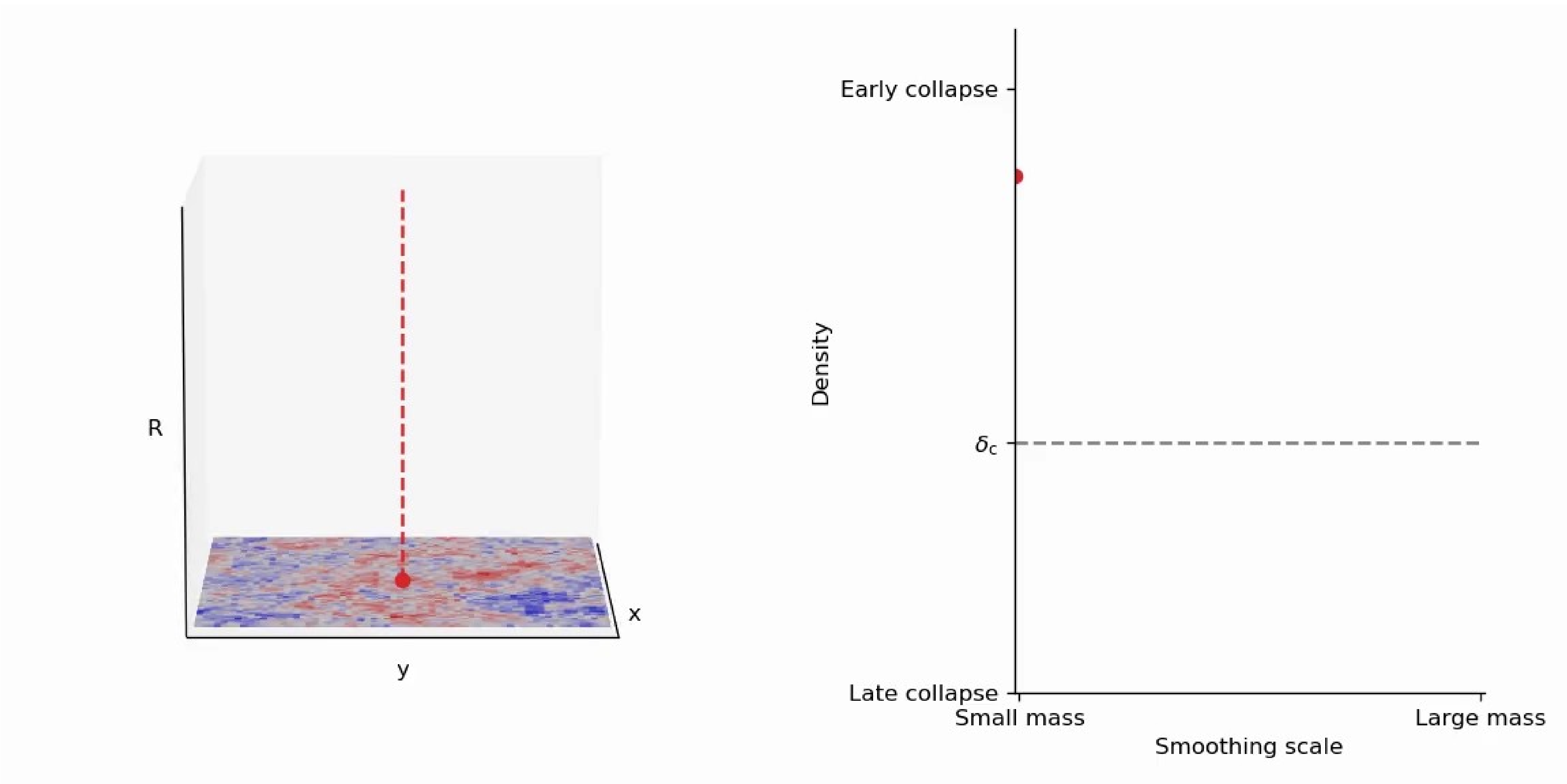
R ~ proxy for halo mass

$\longrightarrow$ We can predict halo properties from the initial conditions

δ_c = 1.68, D(z) is the linear growth factor,
R is the smoothing scale

[Press&Schechter 74; Bond+91; Musso&Sheth14]

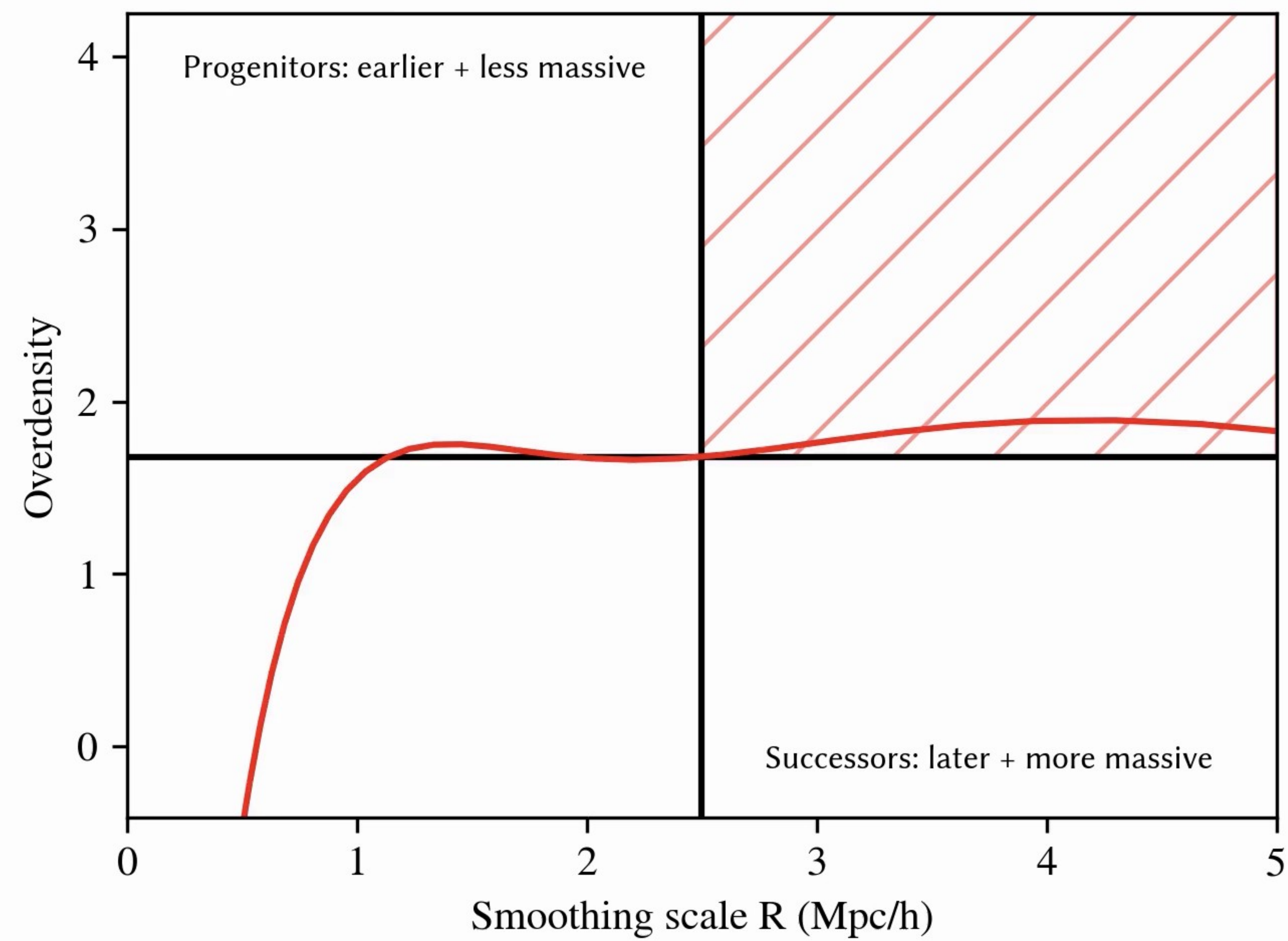
Excursion set theory



Finding the largest collapsing mass

Early formation

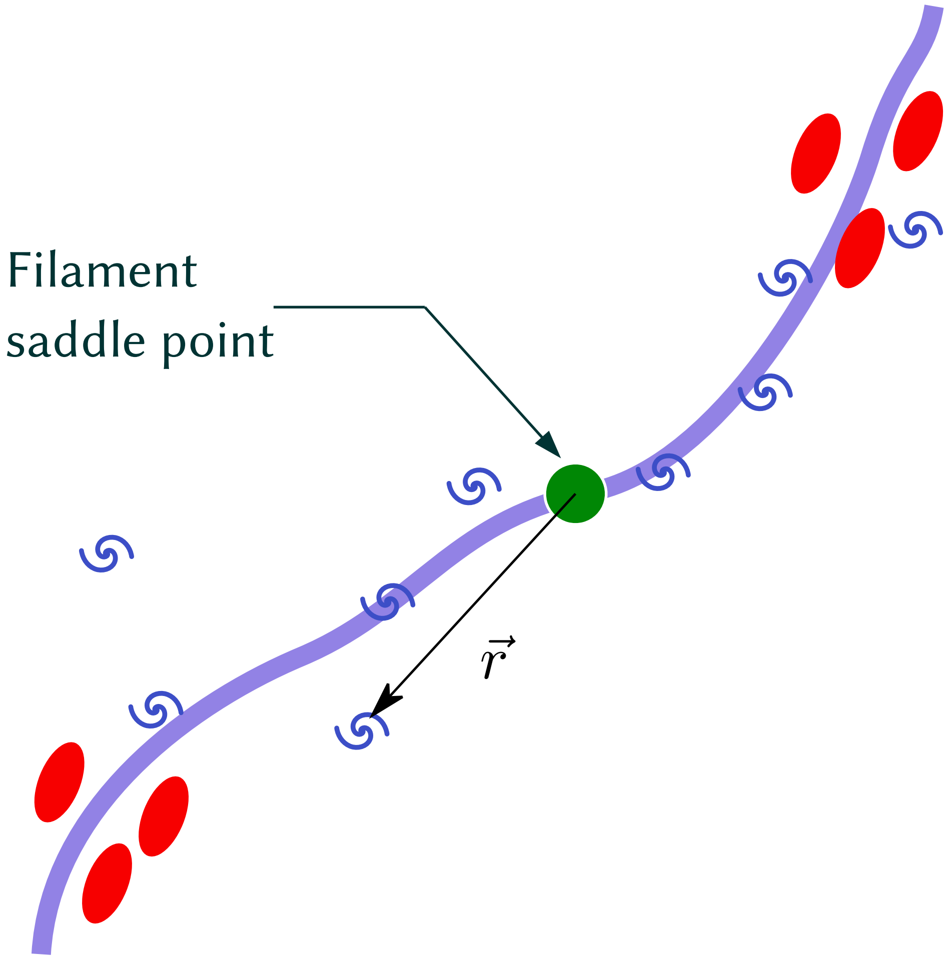
Late formation



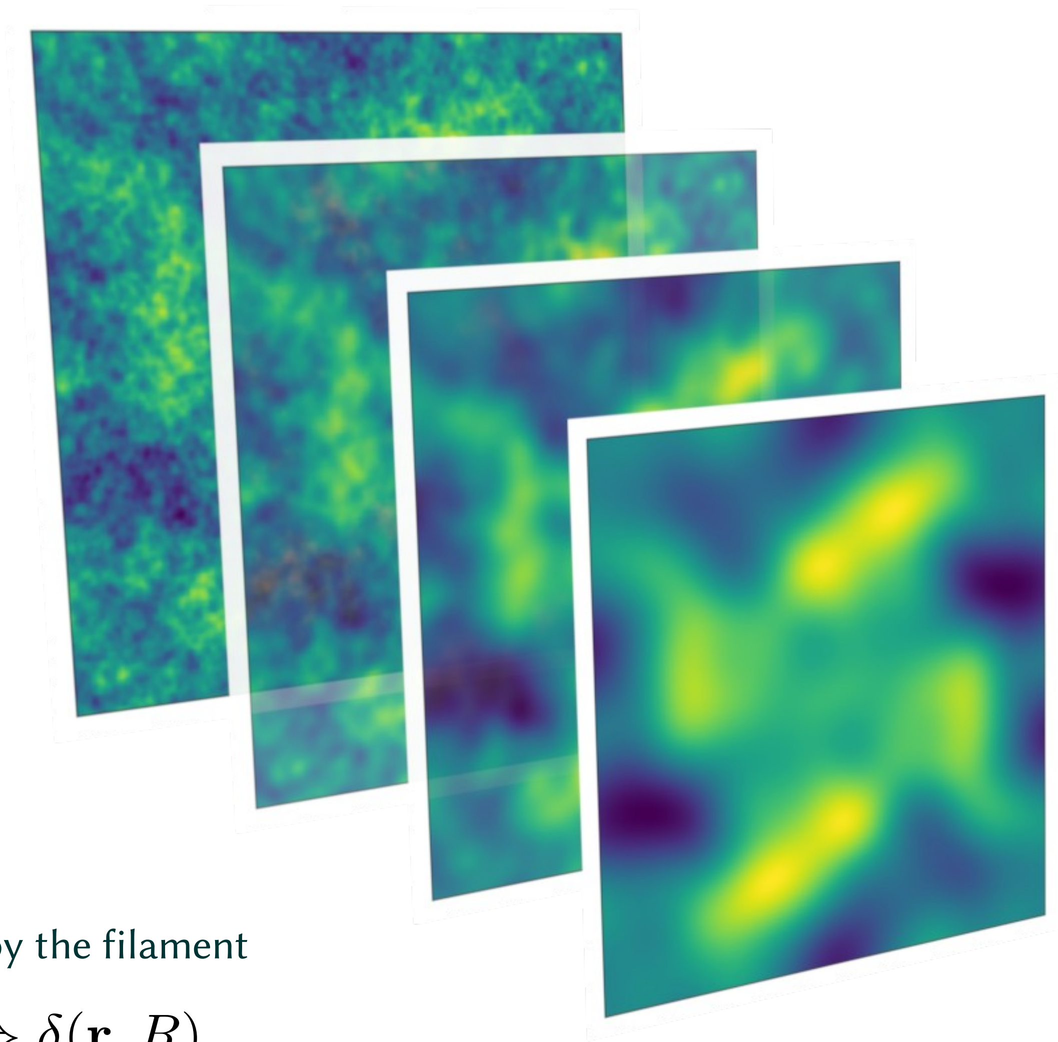
Small mass

Large mass

Constrained excursion set theory



+



Both the density and its variance are impacted by the filament

$$\delta(R) \Rightarrow \delta(\mathbf{r}, R)$$

$$\sigma(R) \Rightarrow \sigma(\mathbf{r}, R)$$

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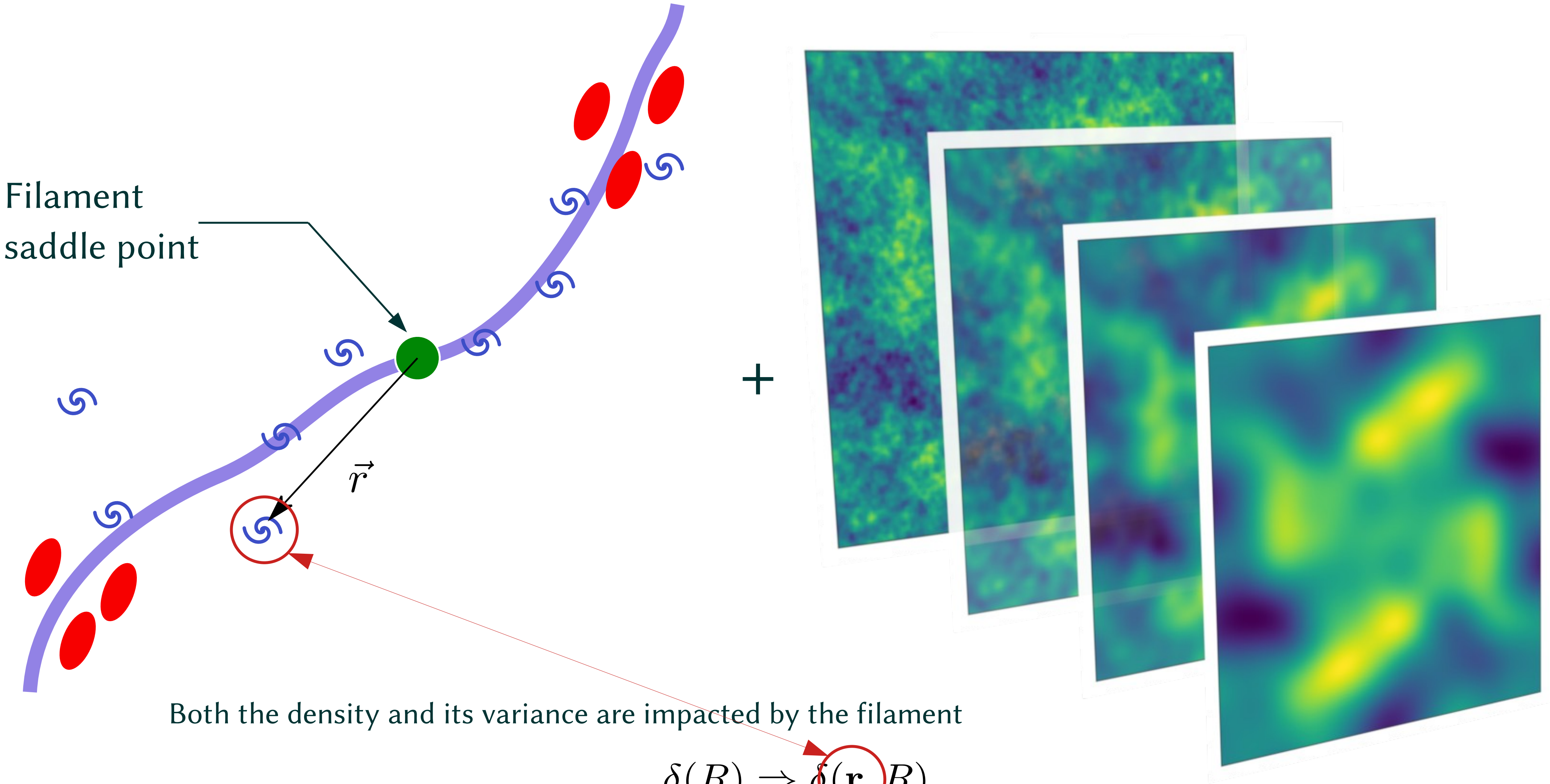

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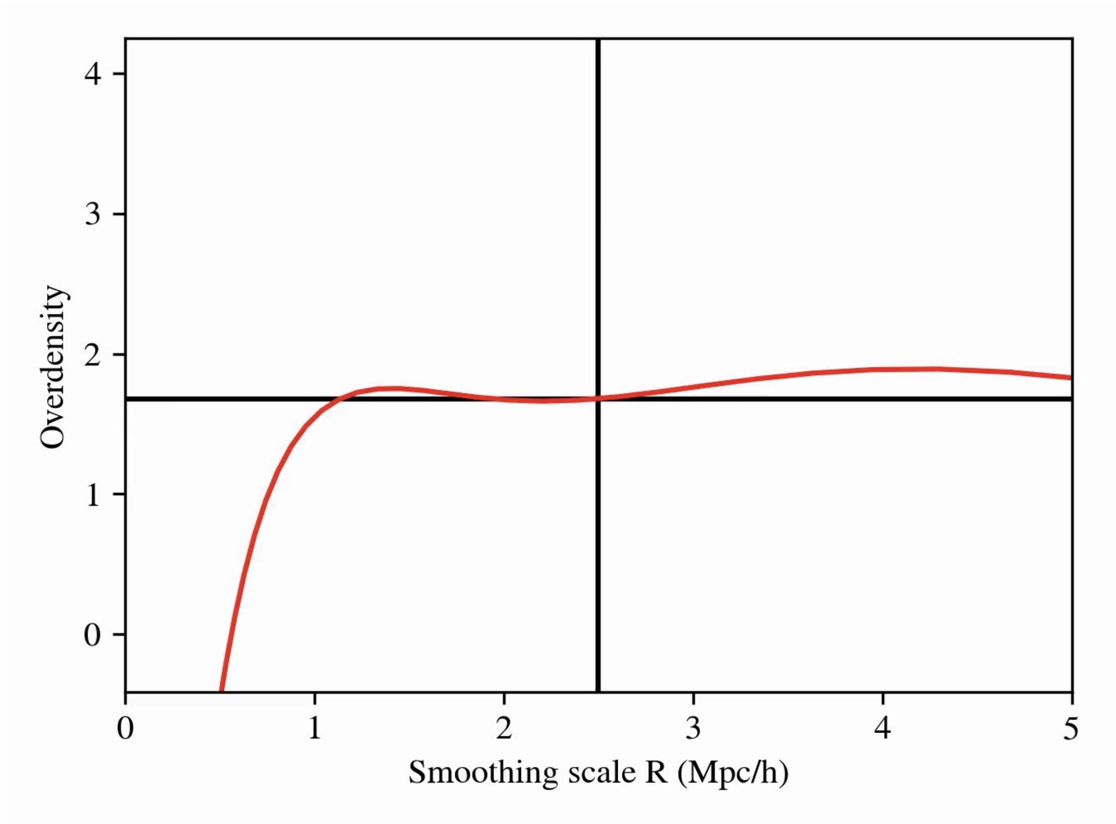
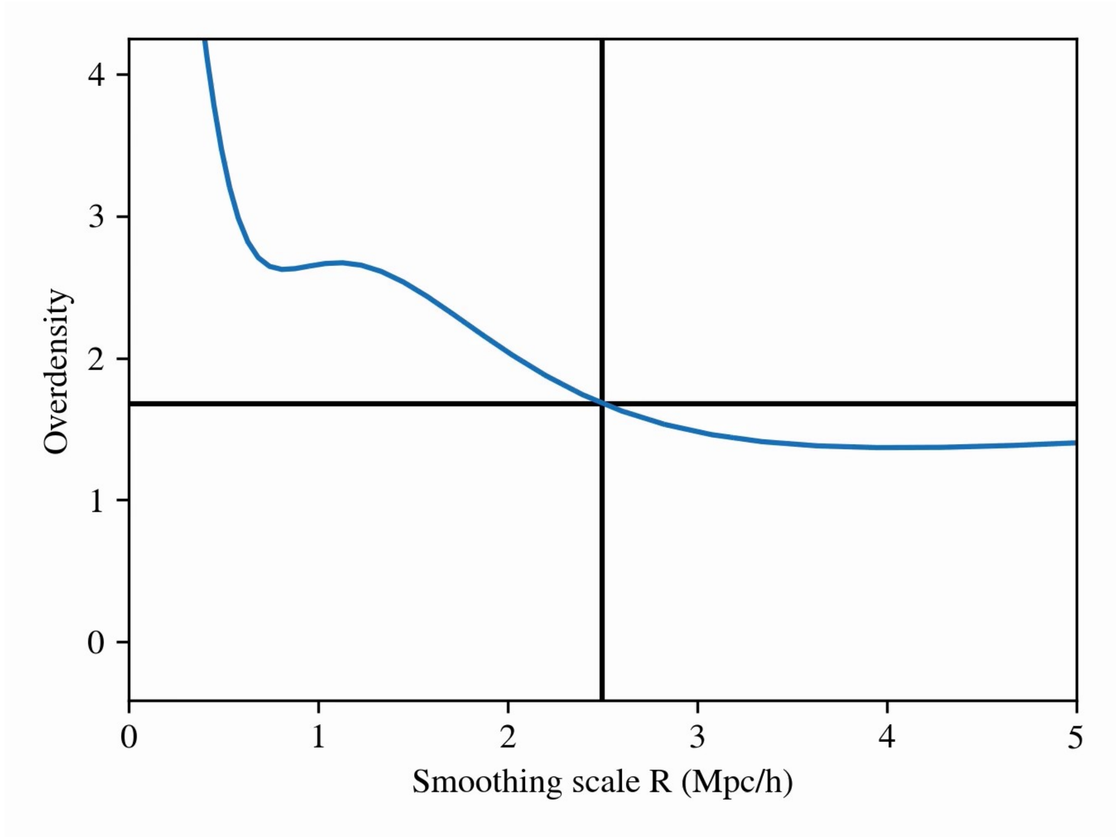
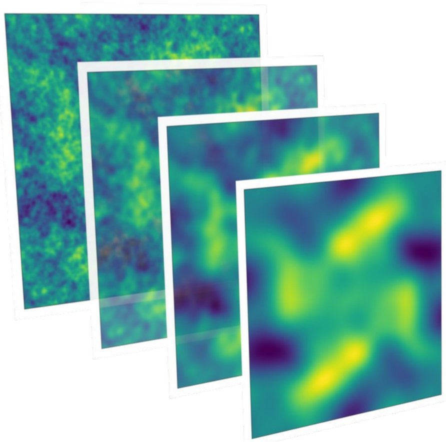
With filamentary constrain

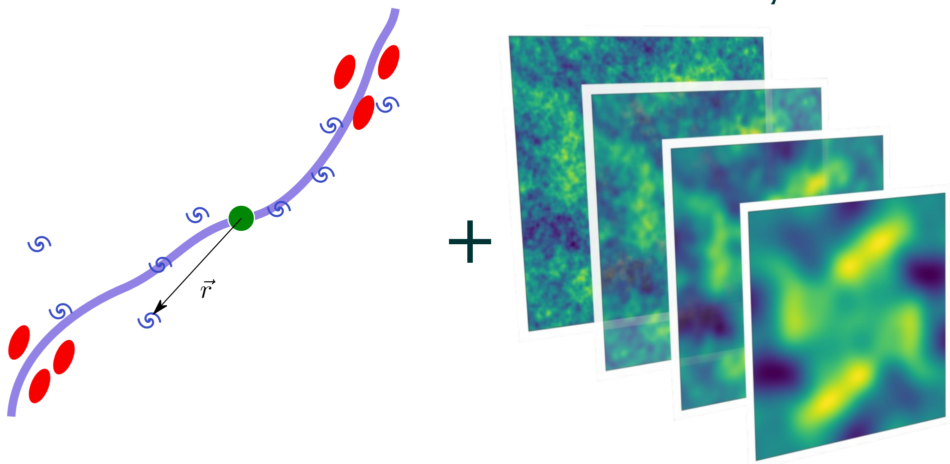




Standard excursion set theory



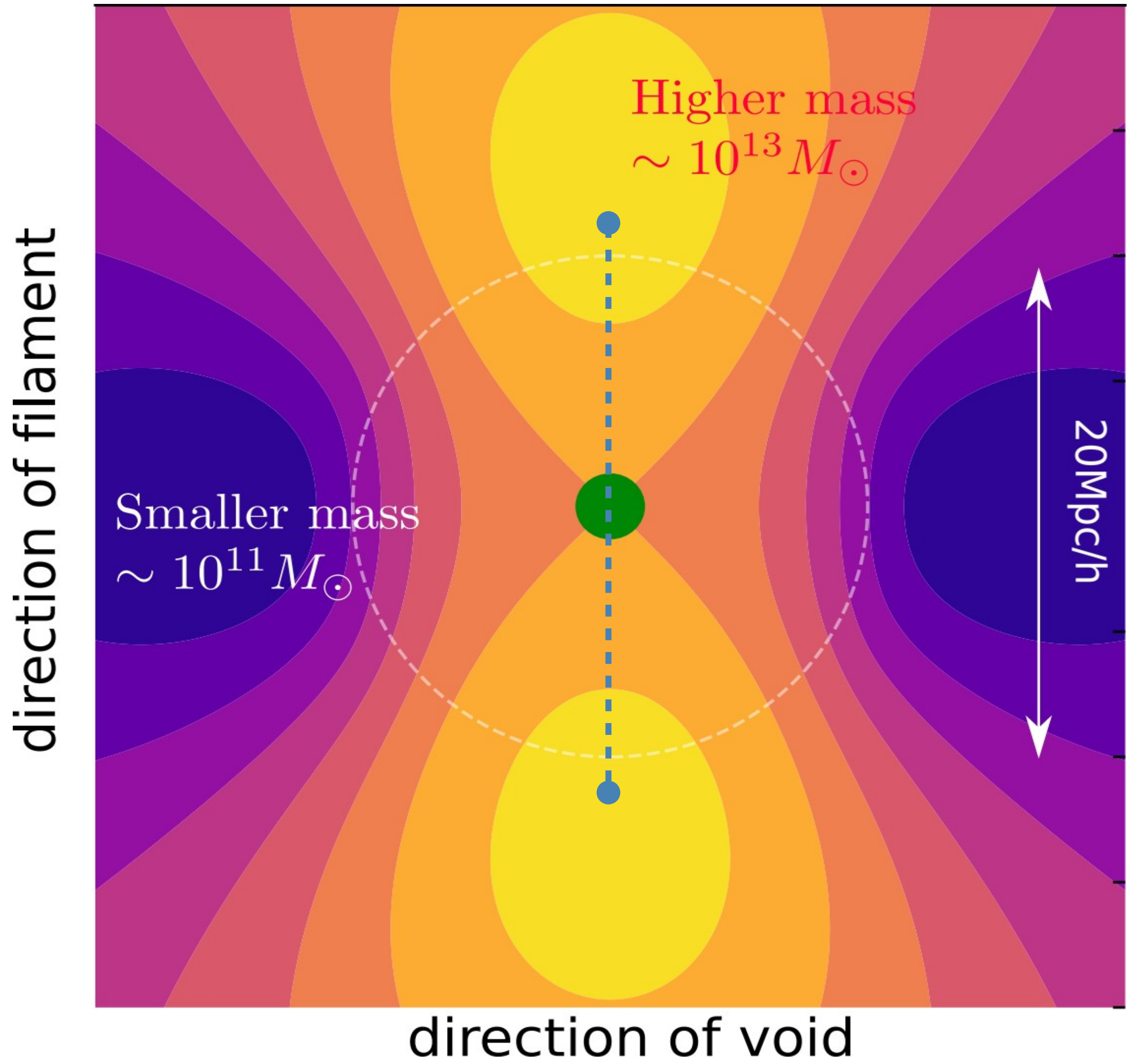
Constrained excursion set theory



Halos in nodes (resp. filament)

- are **more massive**,
- **form later**, and
- **accrete more**

than those in filaments (resp. voids).



Typical halo mass

Analytical predictions (Musso, **Cadiou**+2018)

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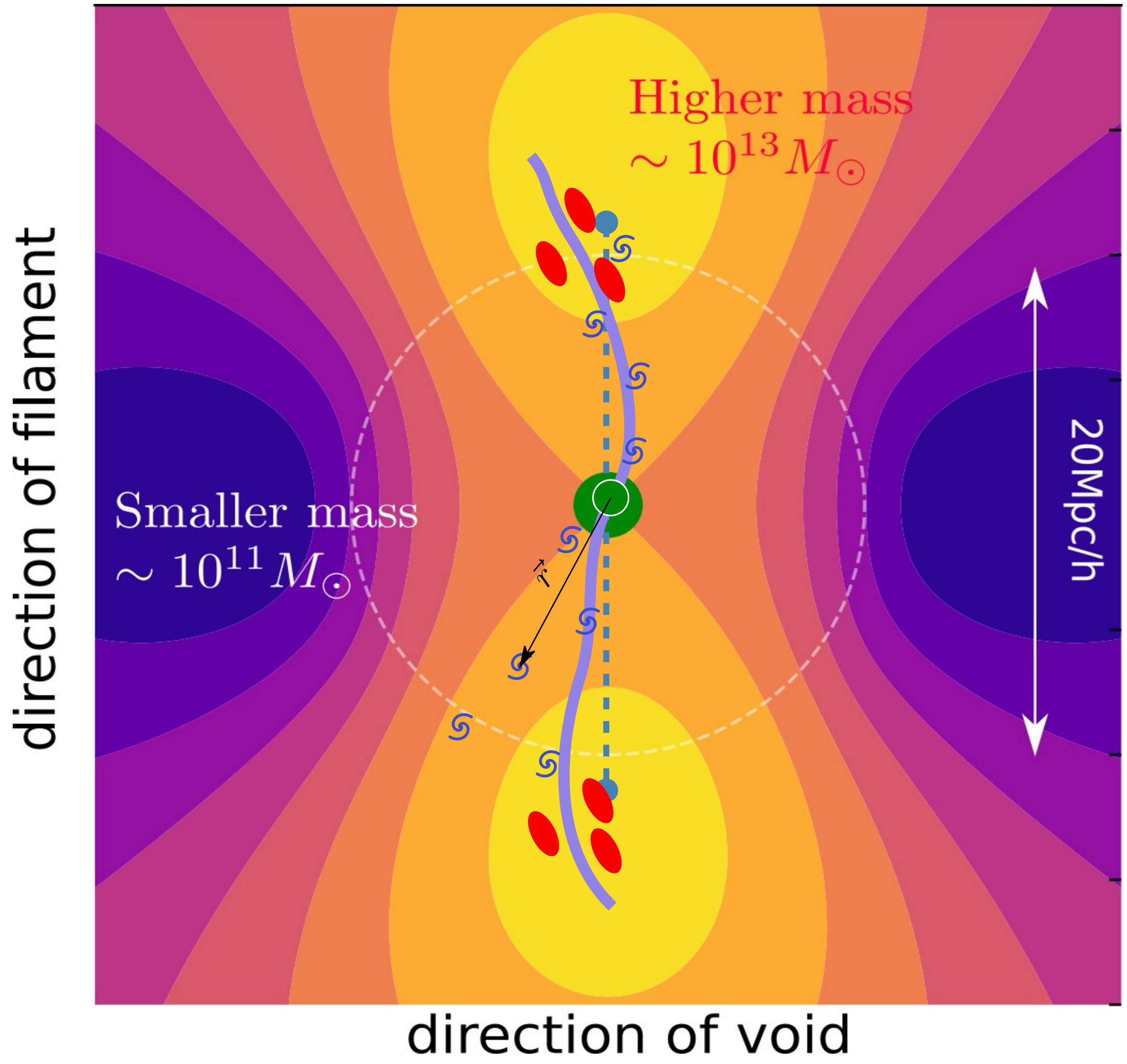

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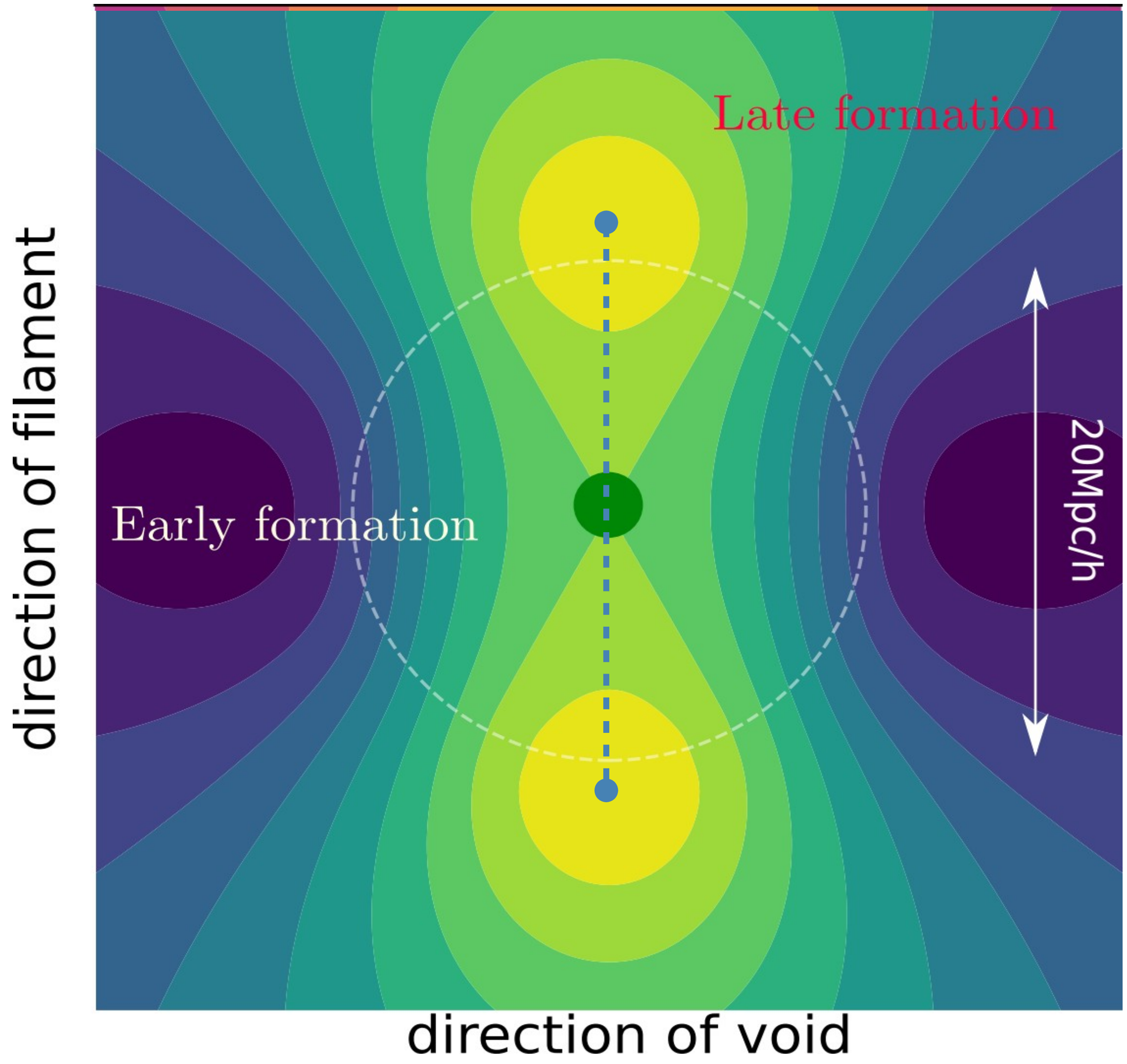

Typical formation time at fixed mass

Halos in nodes (resp. filament)

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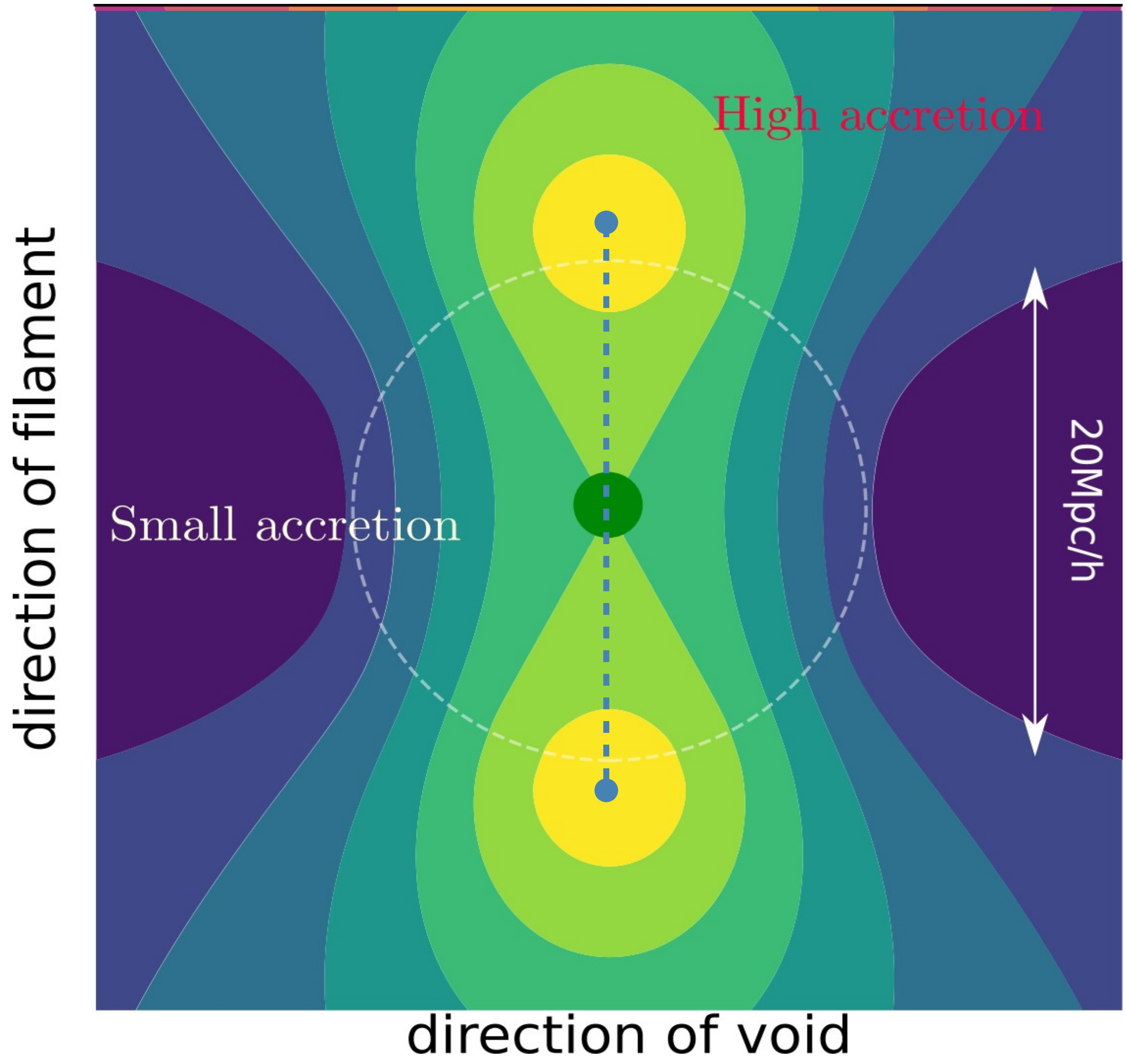

Typical accretion rate at fixed mass

Analytical predictions (Musso, **Cadiou**+2018)

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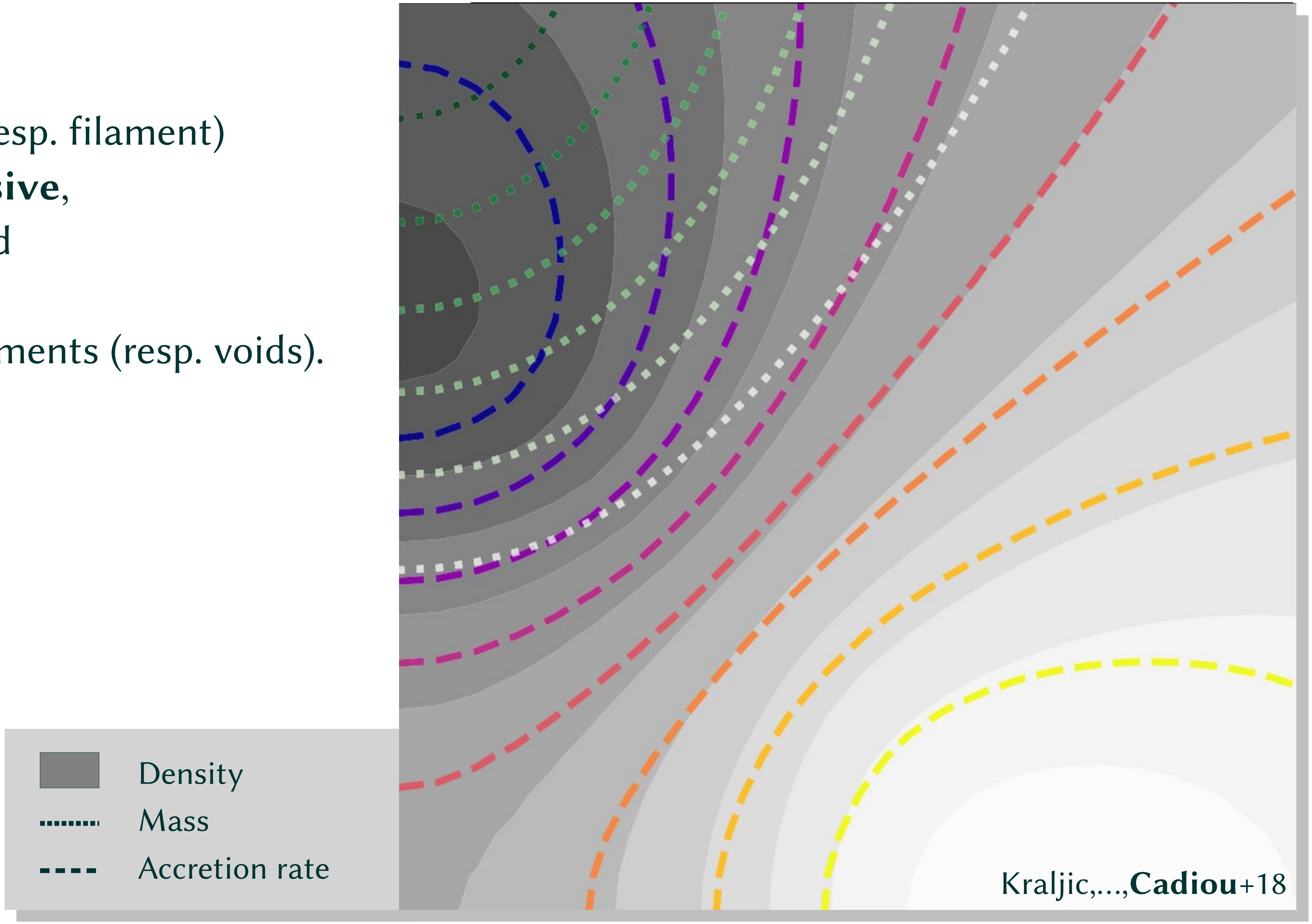

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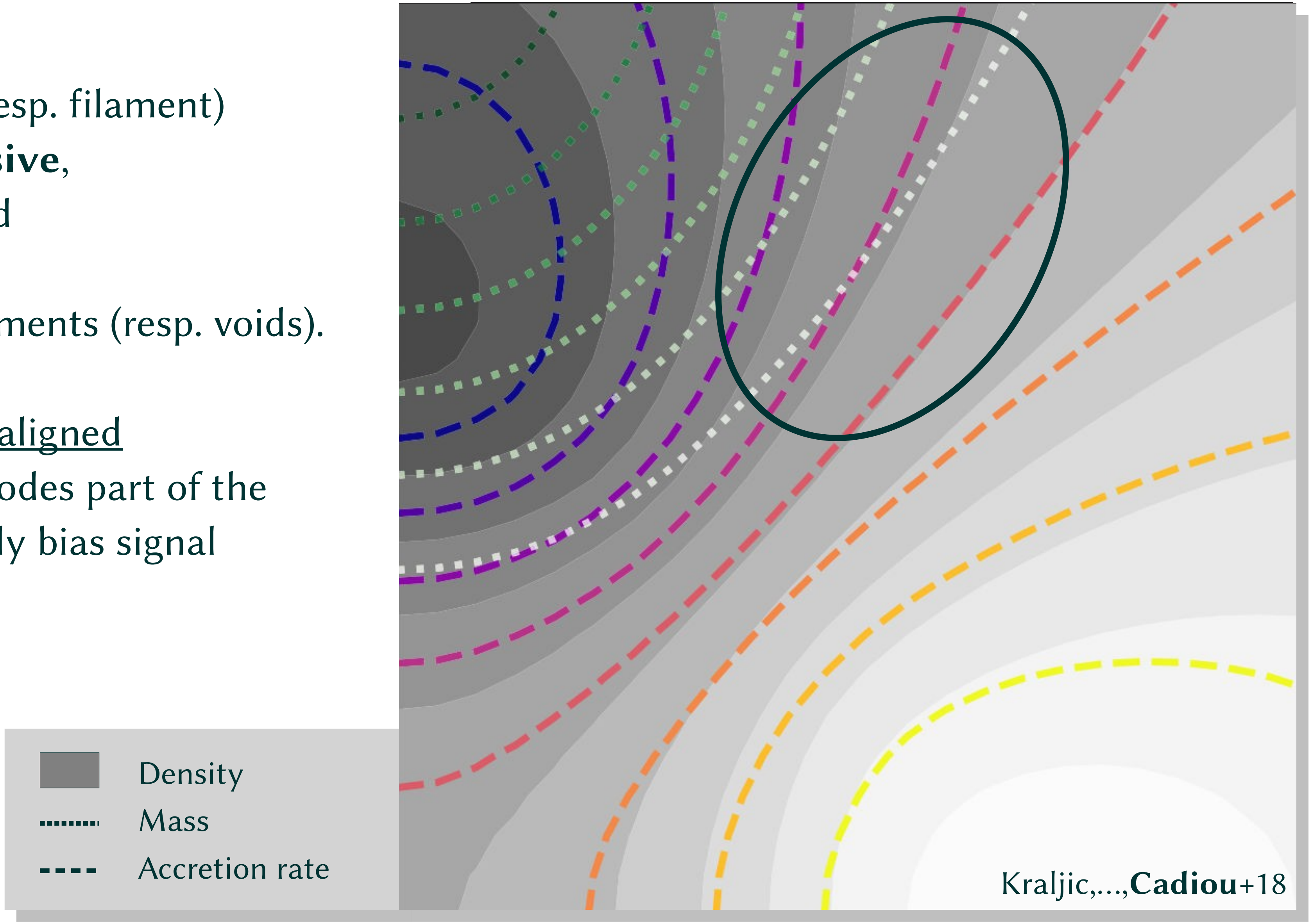
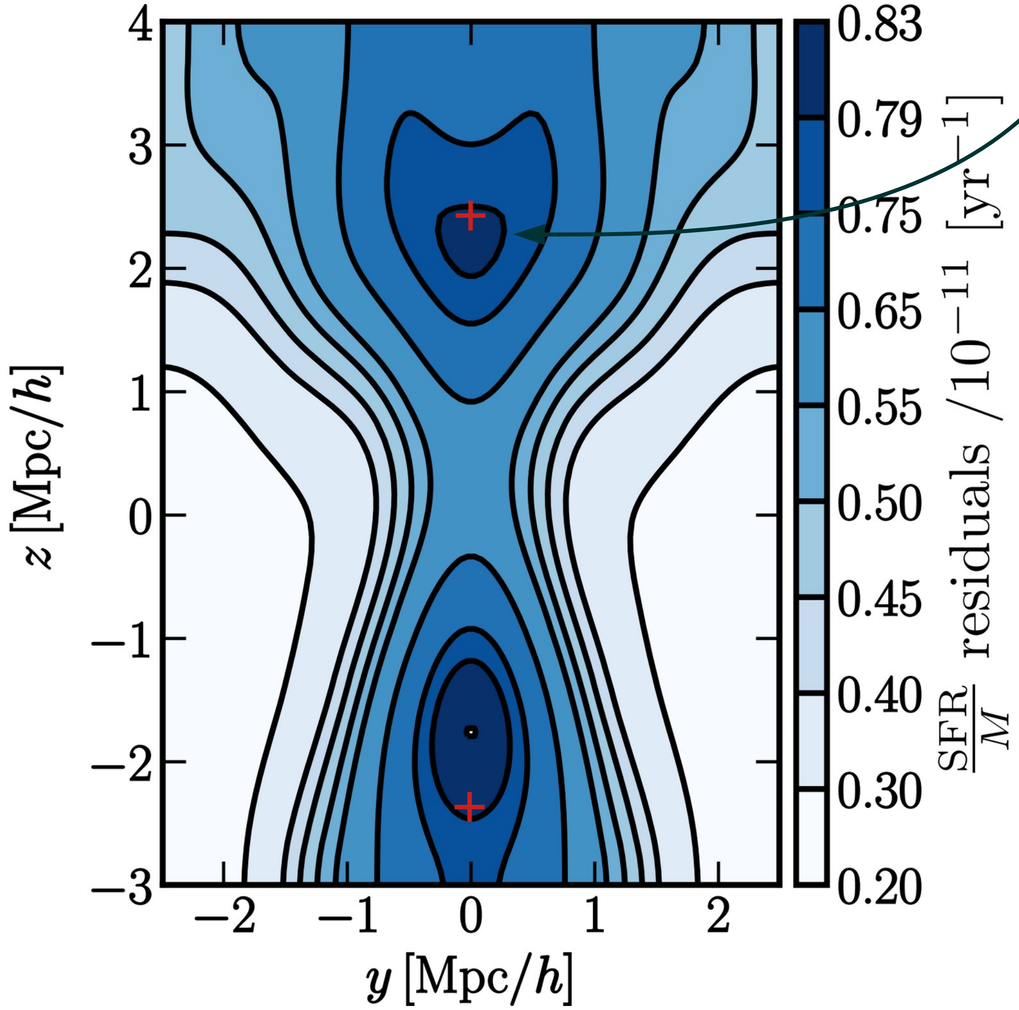
<u>Contours are misaligned</u>

$\longrightarrow$ Filament encodes part of the **halo** assembly bias signal



Results for galaxies from simulations

Higher star formation rate than cosmic trend

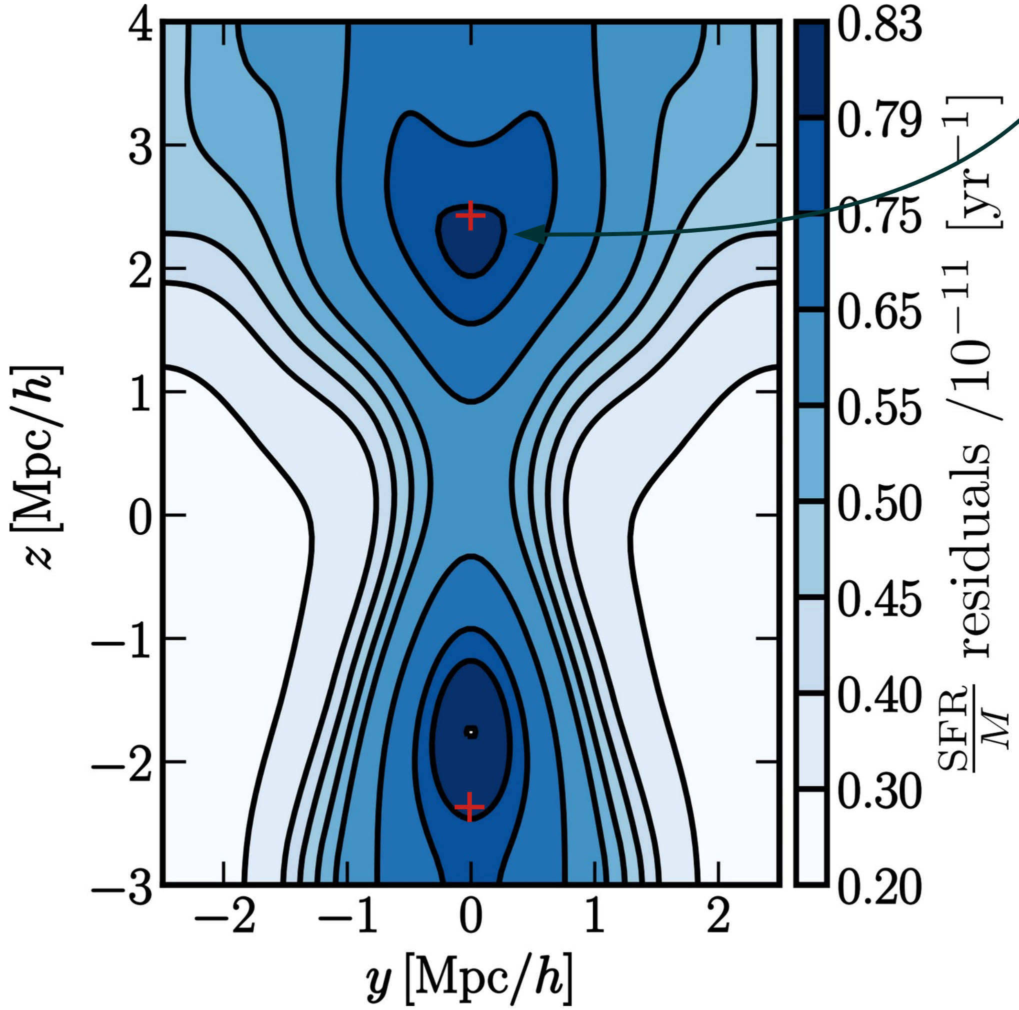


- Measurements for galaxies in Horizon-AGN simulation
- Mean trend in M, ρ removed
- Signal is at % levels

Specific star formation rate, mass and density effects removed.
Kraljic...Cadiou...+19

[HAGN: Dubois+14, 16]
[See Alam+19 for different conclusions]

Higher star formation rate than cosmic trend



- Measurements for galaxies in Horizon-AGN simulation
- Mean trend in M, ρ removed
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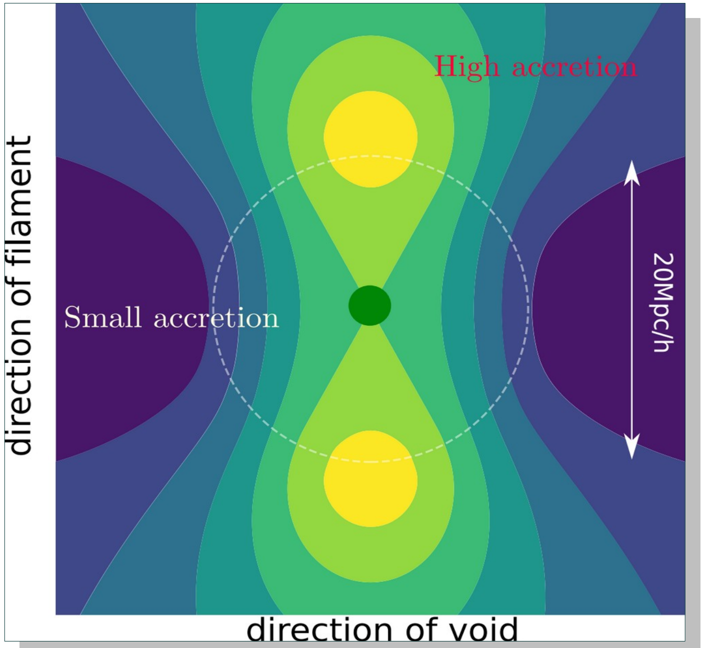
→ Filament encodes part of the **galaxy** assembly bias signal

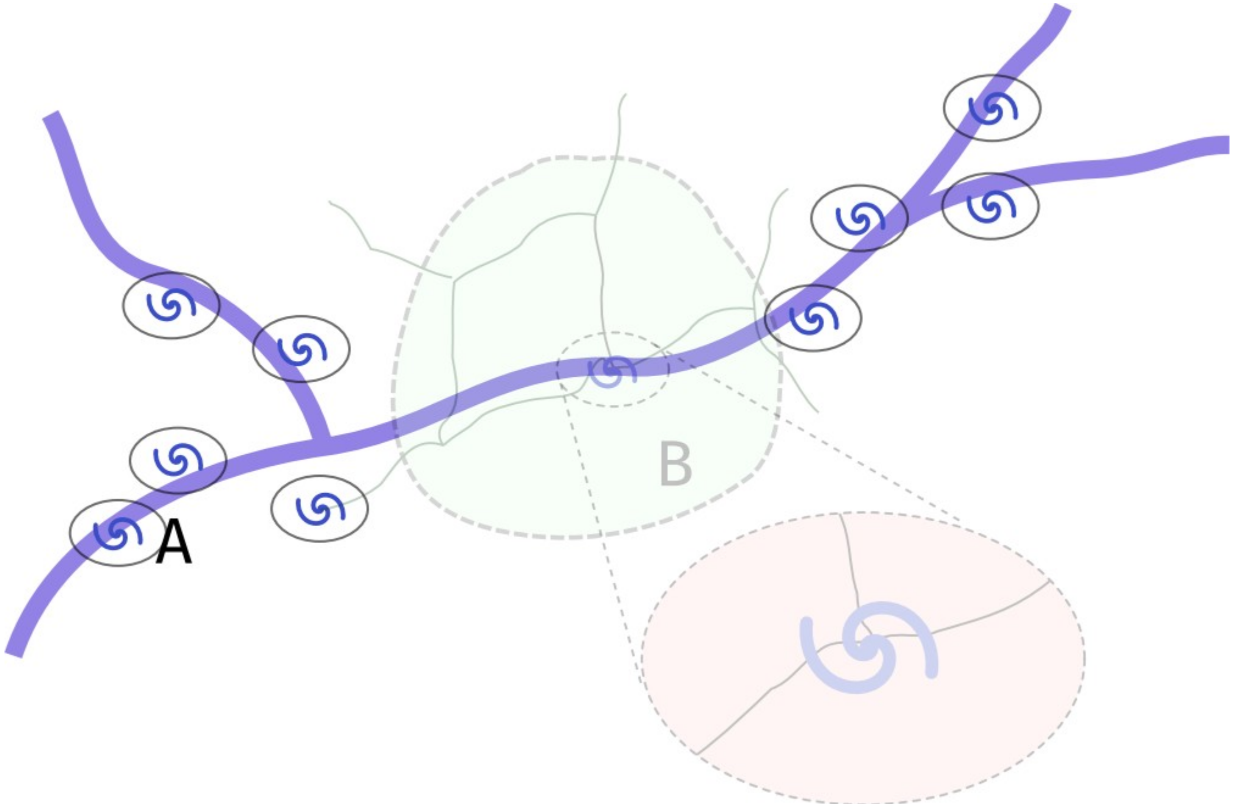
Similar results found in COSMOS [Laigle+17], GAMA [Kraljic,...,**Cadiou**+18]

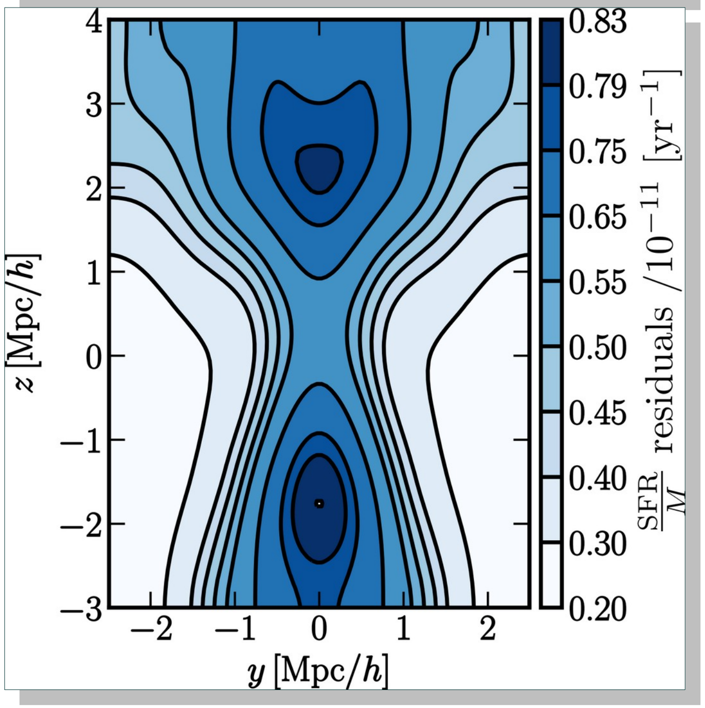
Specific star formation rate, mass and density effects removed.
Kraljic...Cadiou...+19

[HAGN: Dubois+14, 16]
[See Alam+19 for different conclusions]

- **Conditional** excursion set theory to take into account large-scale environment
- Filamentary structure has an impact on
  - **Halo** assembly bias [**Musso, Cadiou+18**]
  - **Galaxy** assembly bias [**Kraljic, ..., Cadiou+18,19**]

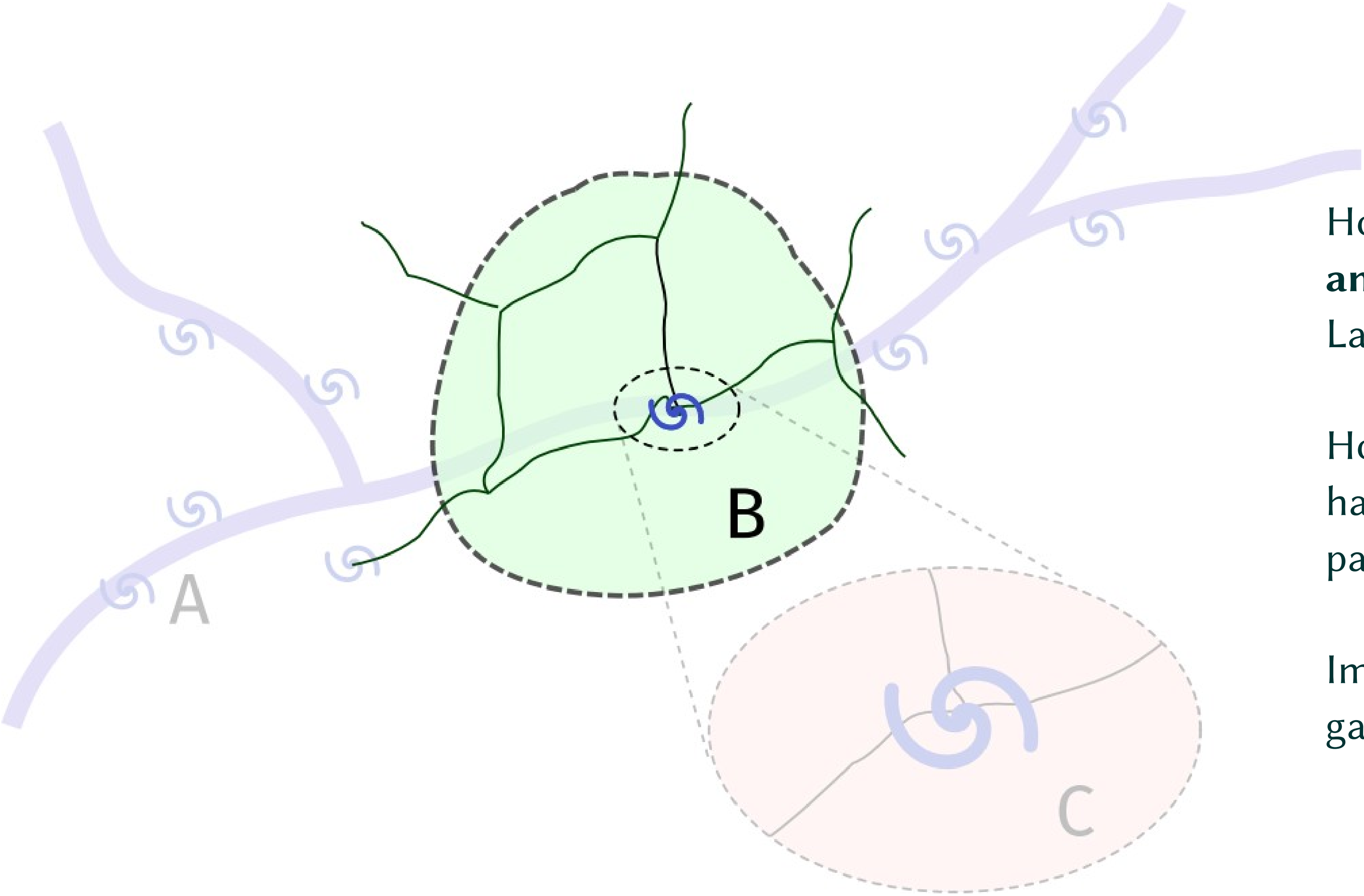







B/ The effect of the cosmic web within the Lagrangian patch
New Horizon collaboration

Effect of the cosmic web on assembly



How is matter **accreted anisotropically** within the Lagrangian patch?

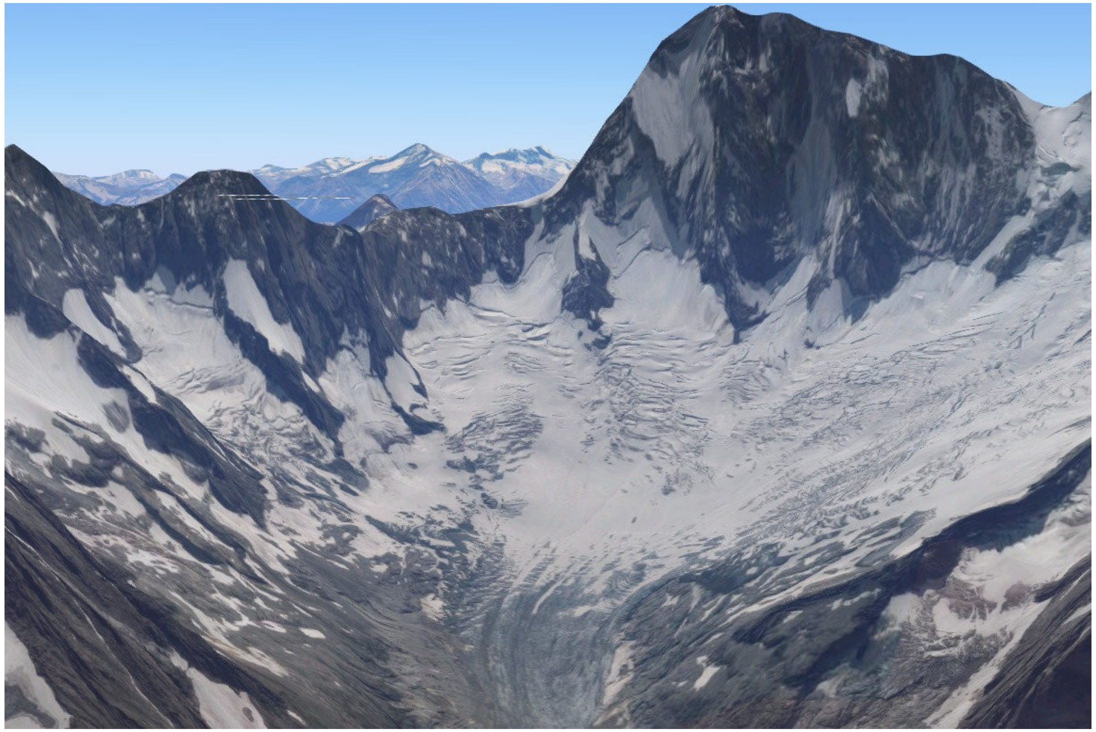
How to describe **special events** happening within the Lagrangian patch?

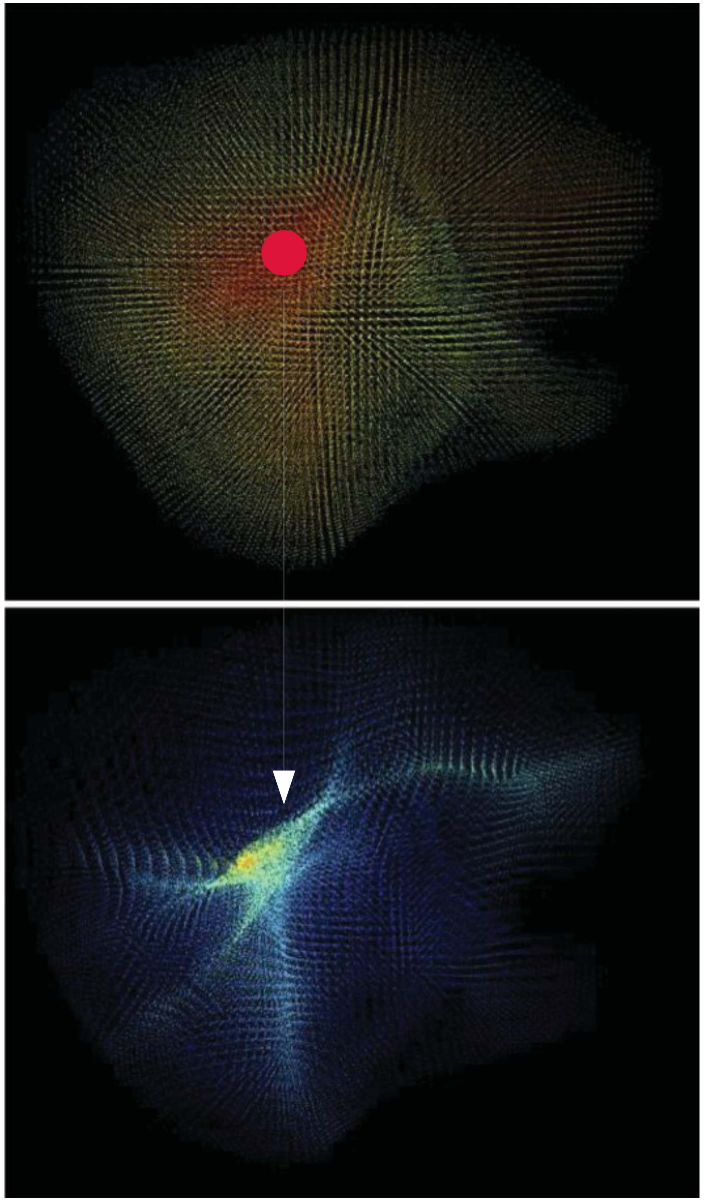
Impact of **filament merger** on galactic assembly?

→ Need to go beyond merger trees: describe evolution of the cosmic web

Compressing the cosmic web

- Proto-halos ~ maxima
- Proto-filaments ~ filament saddle points
- Proto-walls ~ wall-saddle point
- Proto-voids ~ minima





Early time

Late time

Dark matter density in numerical simulation.

[Peak-patch picture: BBKS+86]

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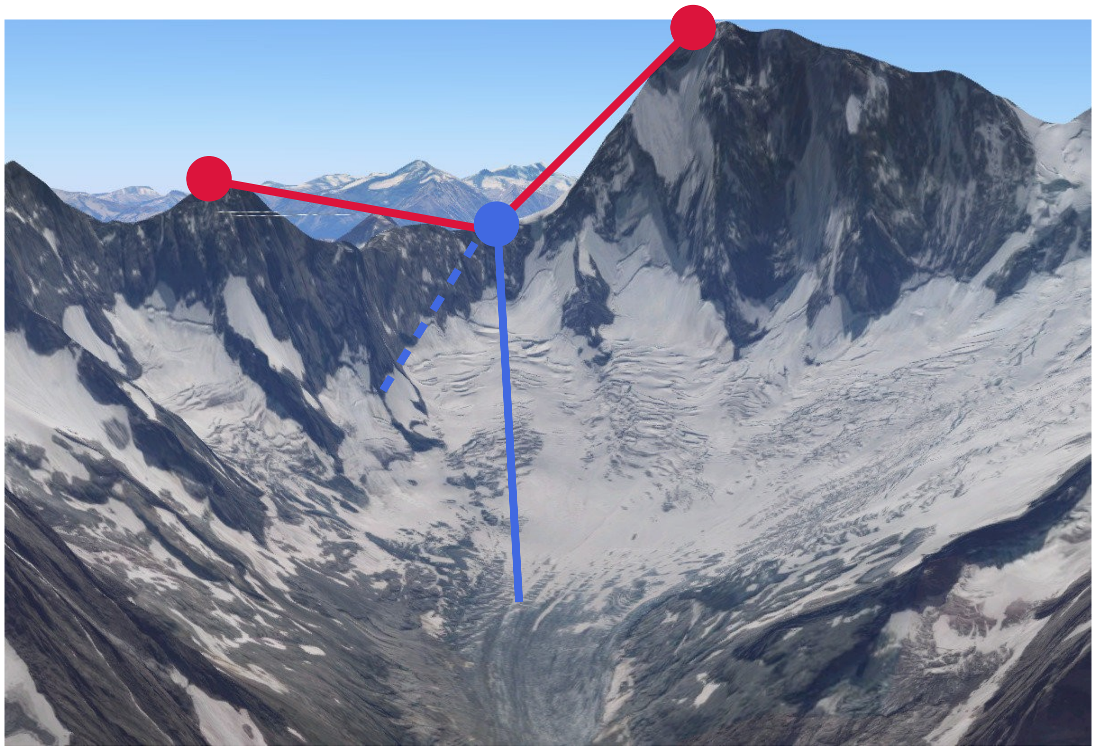

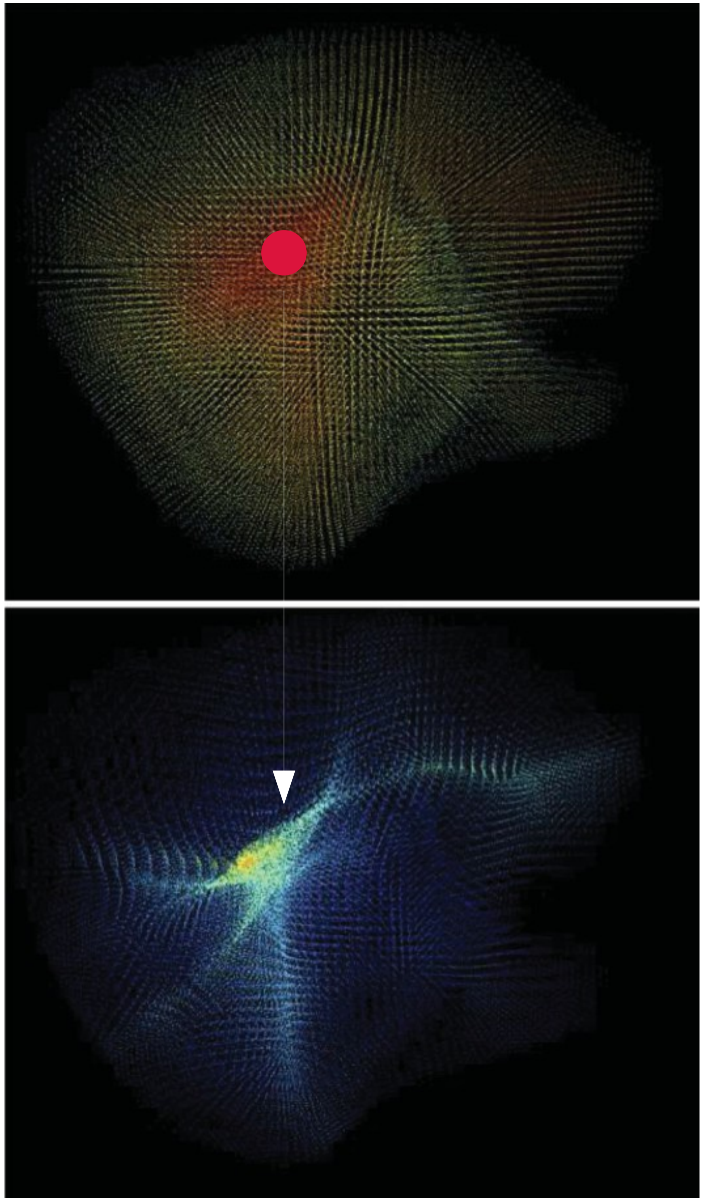

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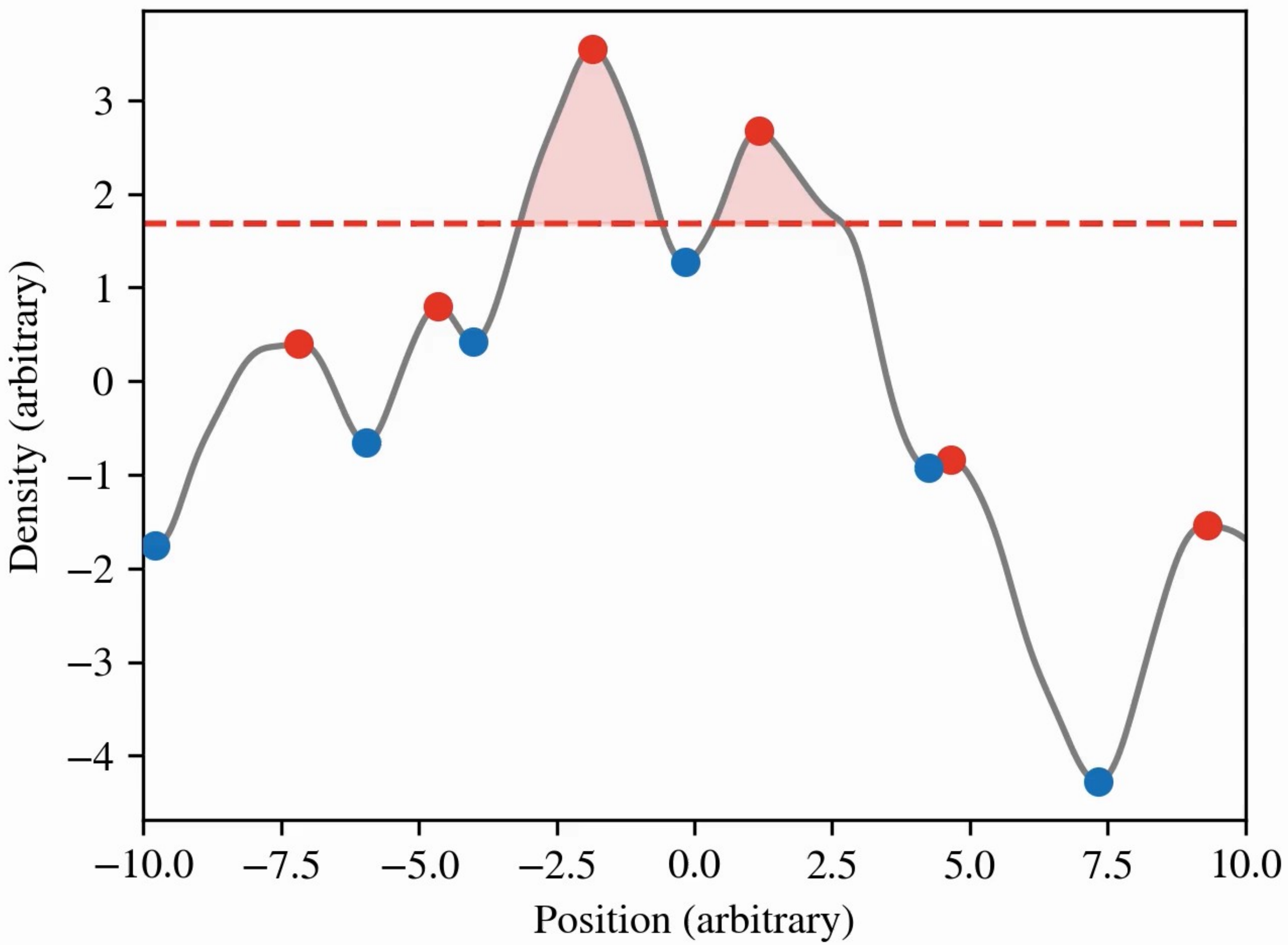

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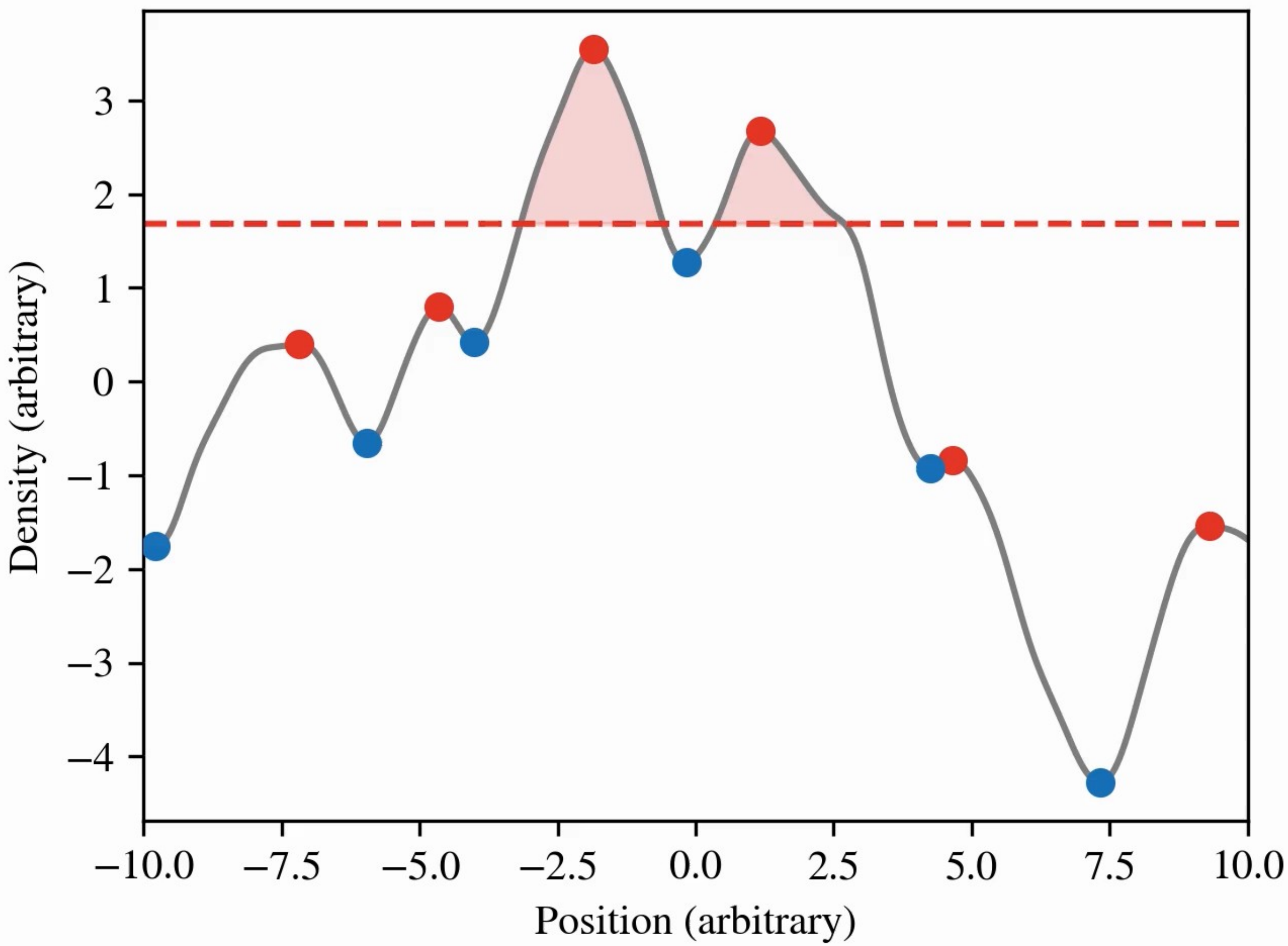

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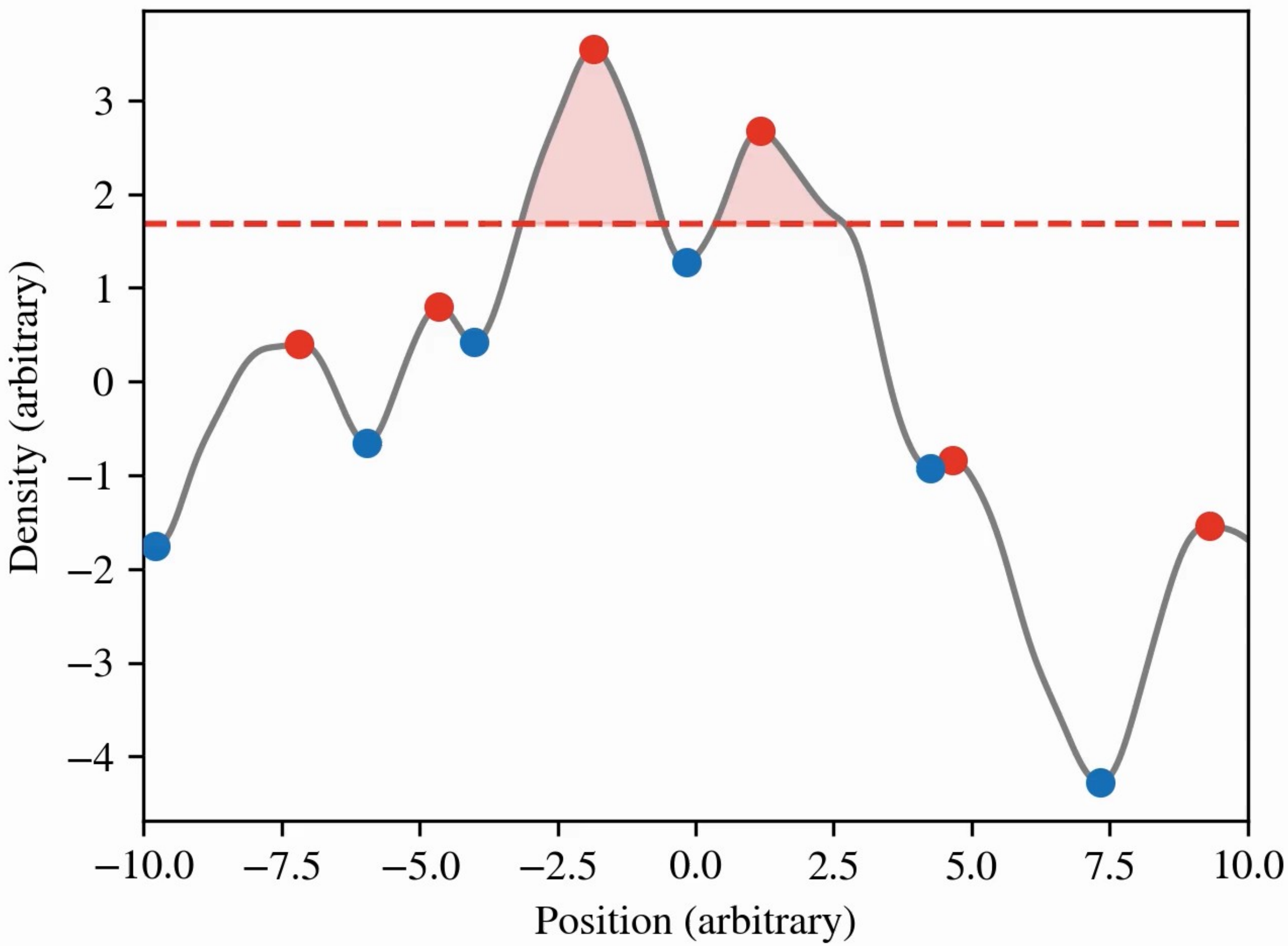
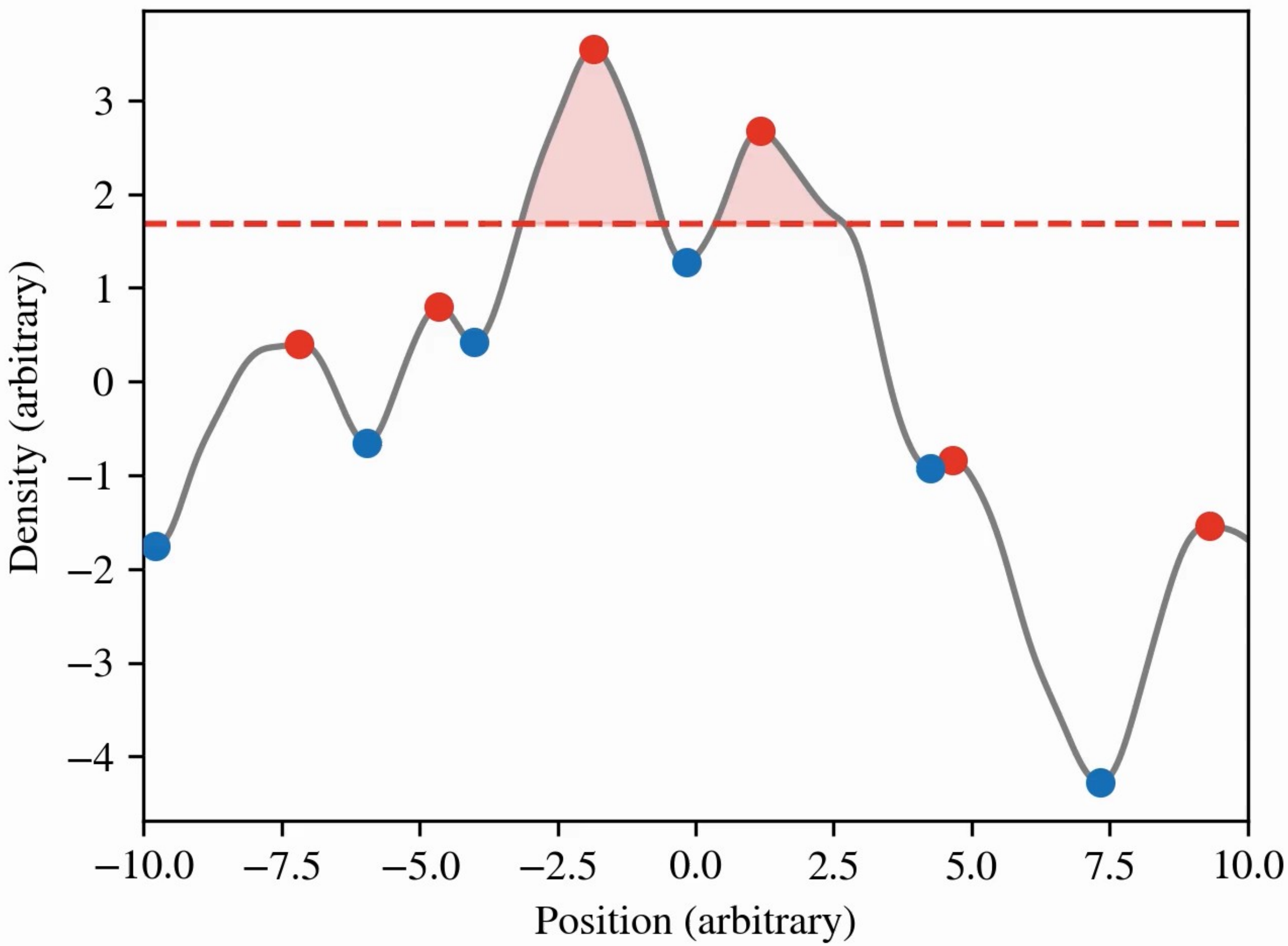
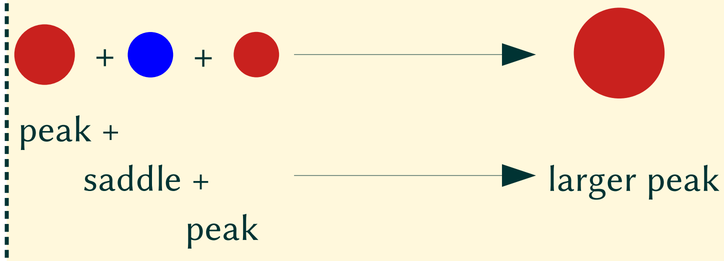


peak +
saddle +
peak
→ larger peak

In the initial conditions (Lagrangian space)

Critical events – 1+1D case

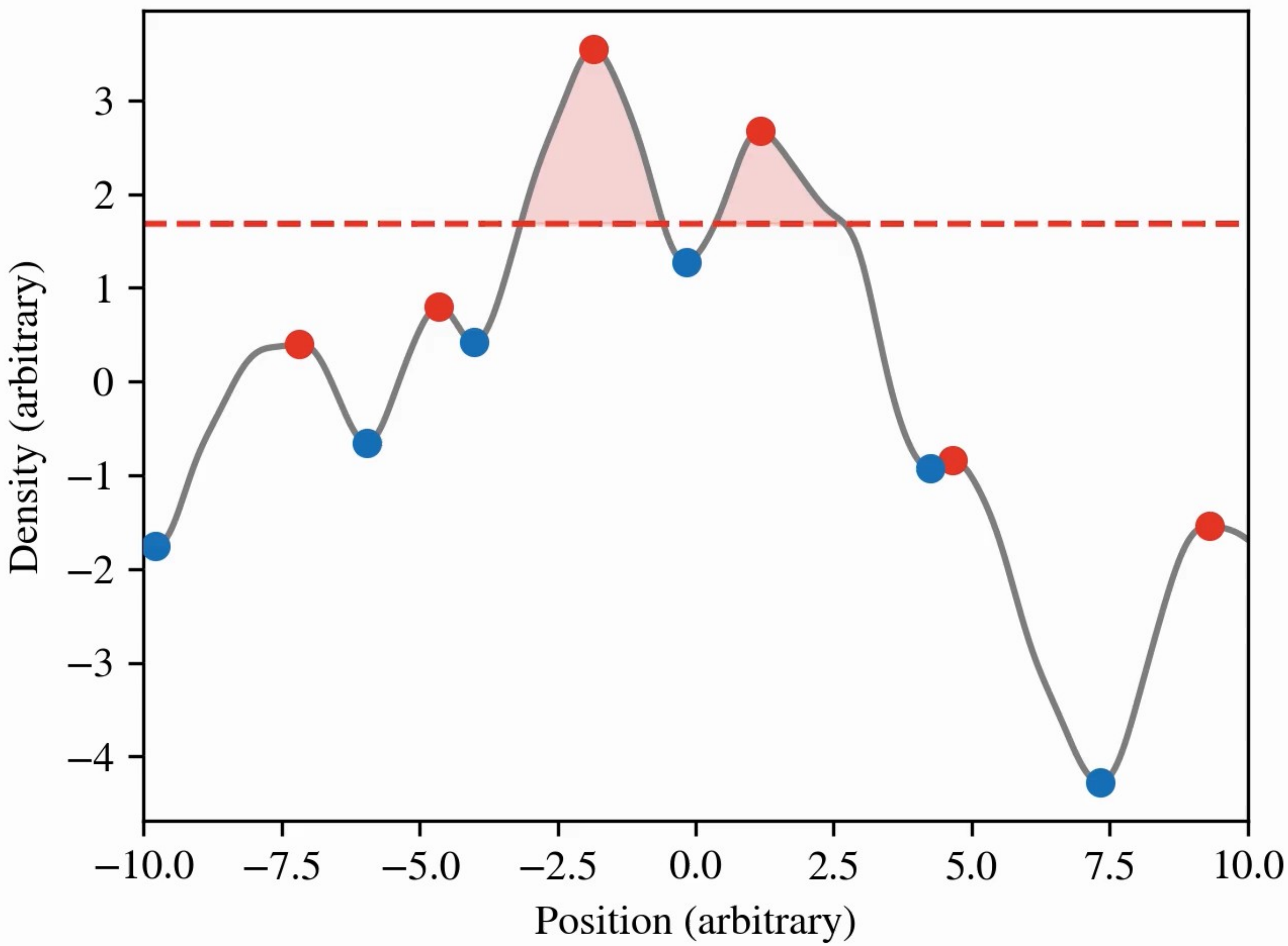




In the initial conditions (Lagrangian space)

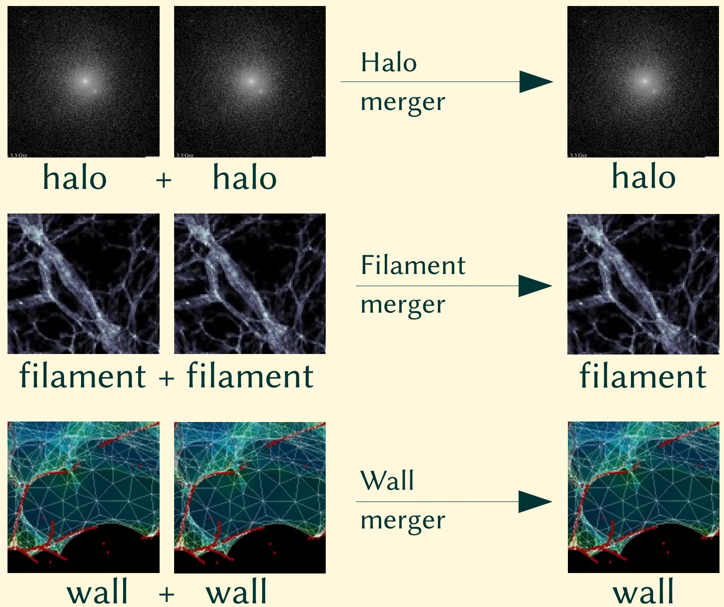
In “real space” (Eulerian space)

Critical events – 1+1D case



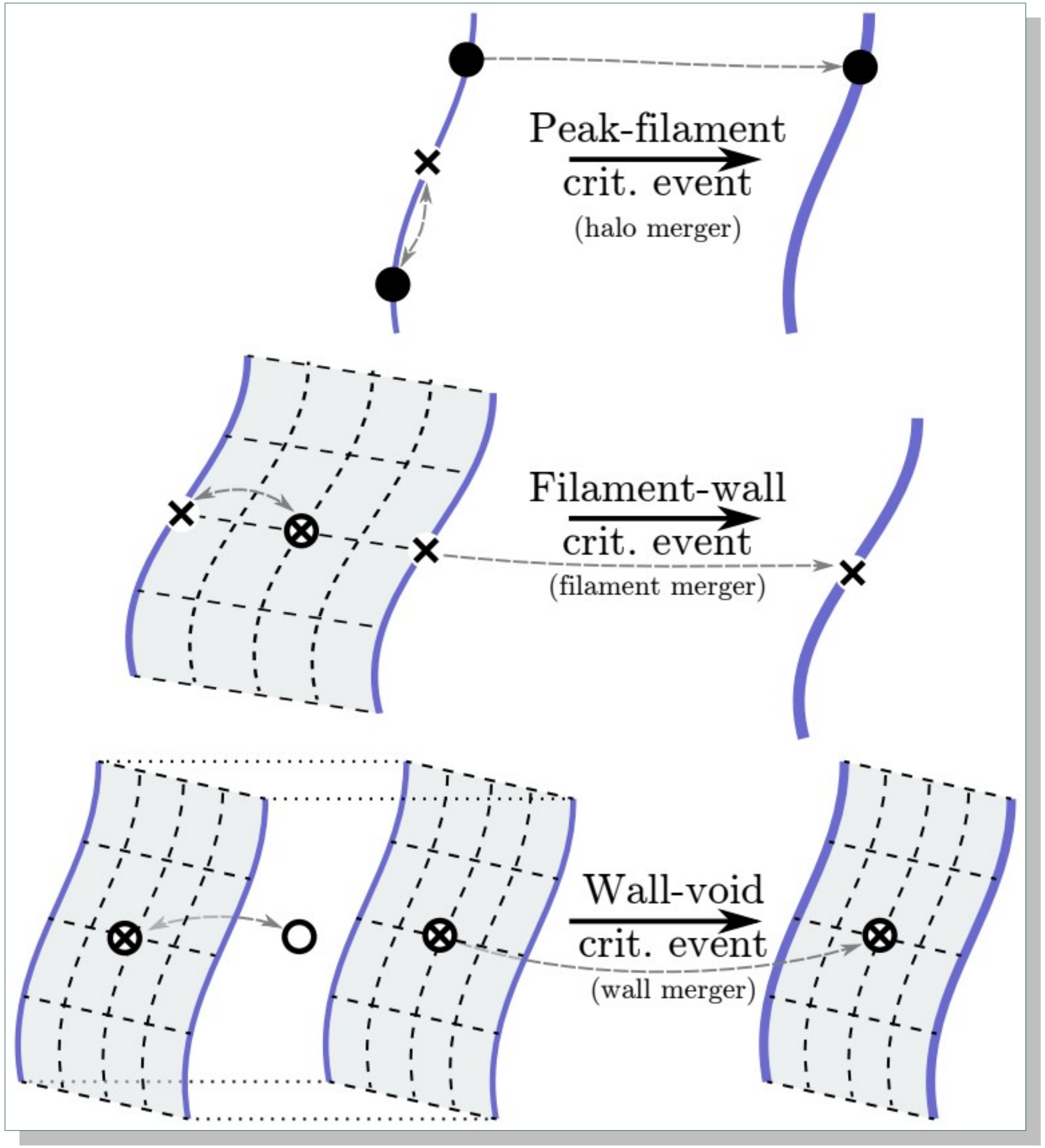
peak +
saddle +
peak
→ larger peak

In the initial conditions (Lagrangian space)



In "real space" (Eulerian space)

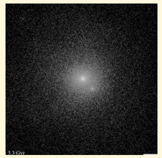
Critical events – 3+1D case



peak +
saddle +
peak

larger peak

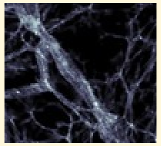
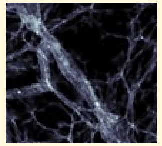
In the initial conditions (Lagrangian space)

halo + halo

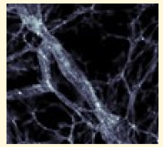
Halo merger

halo

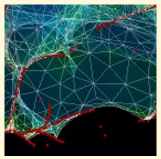
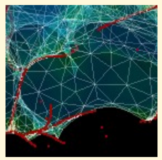
 

filament + filament

Filament merger

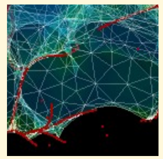


filament

wall + wall

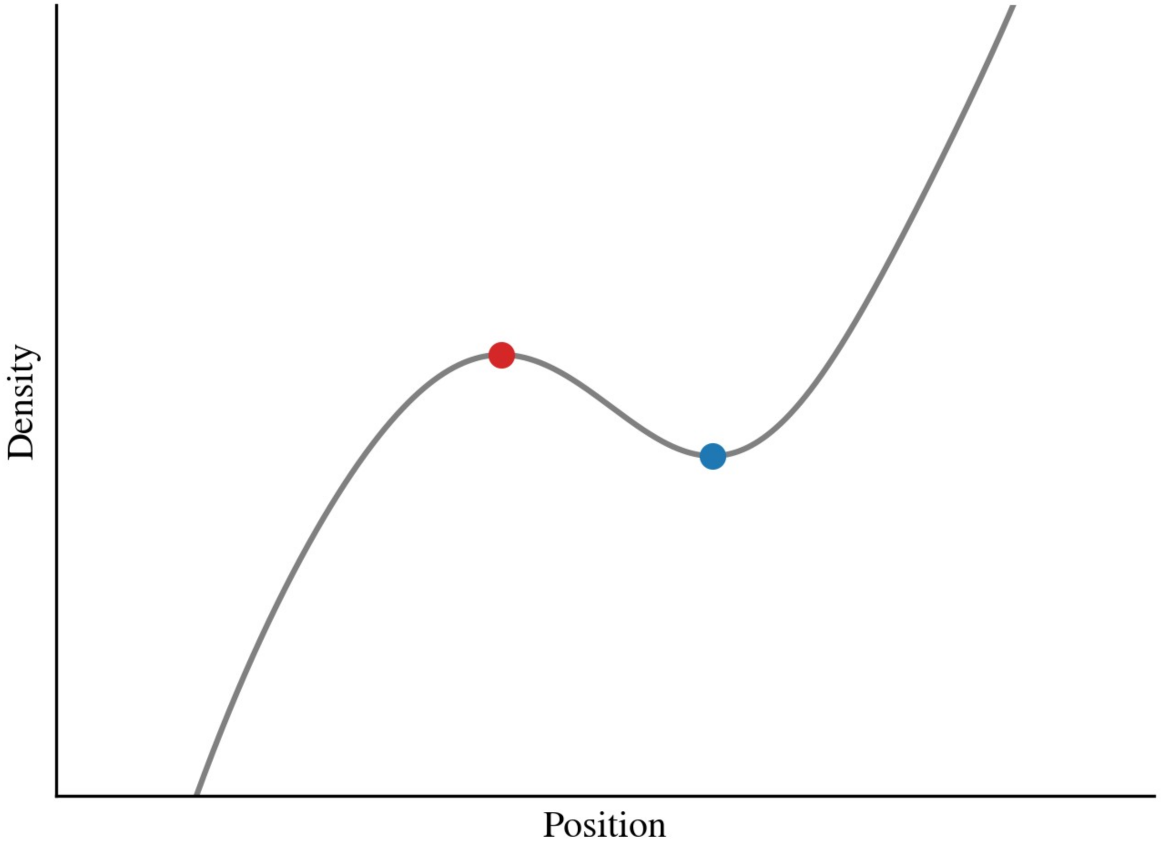
Wall merger



wall

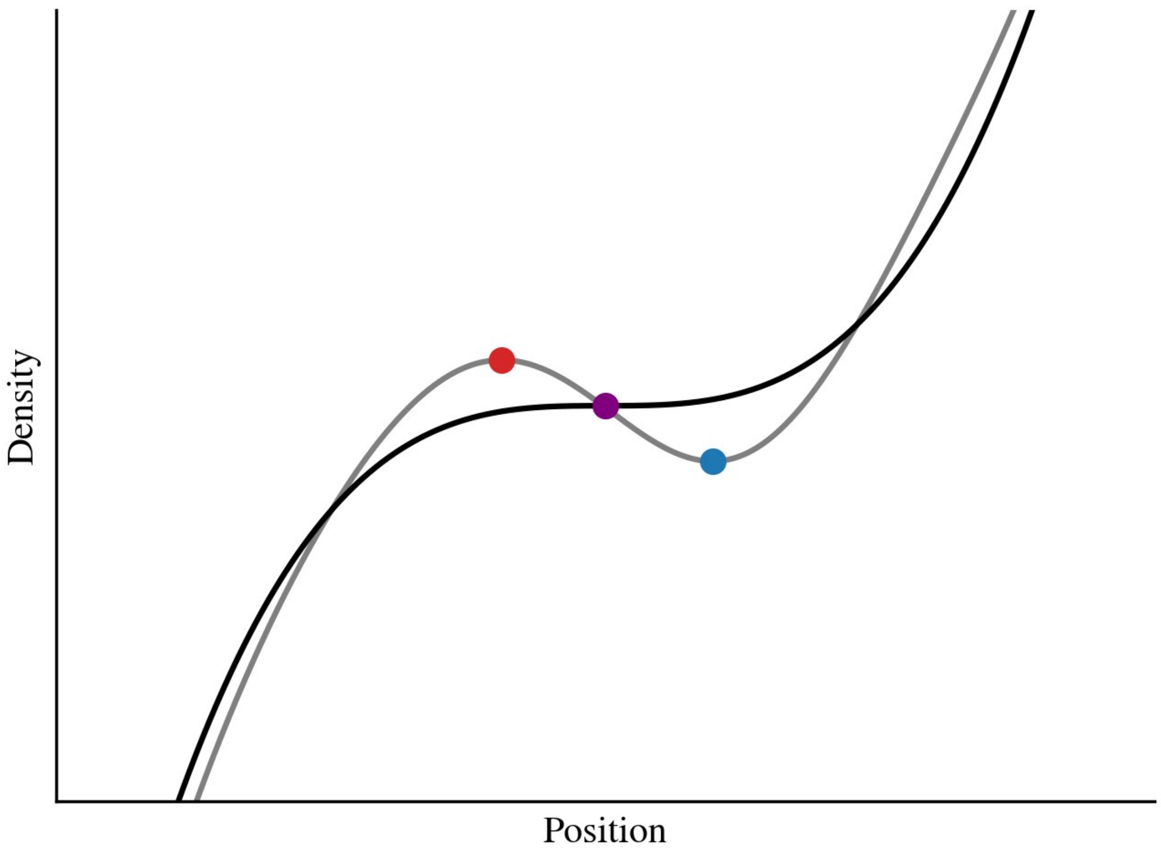
In “real space” (Eulerian space)

Analytical prediction



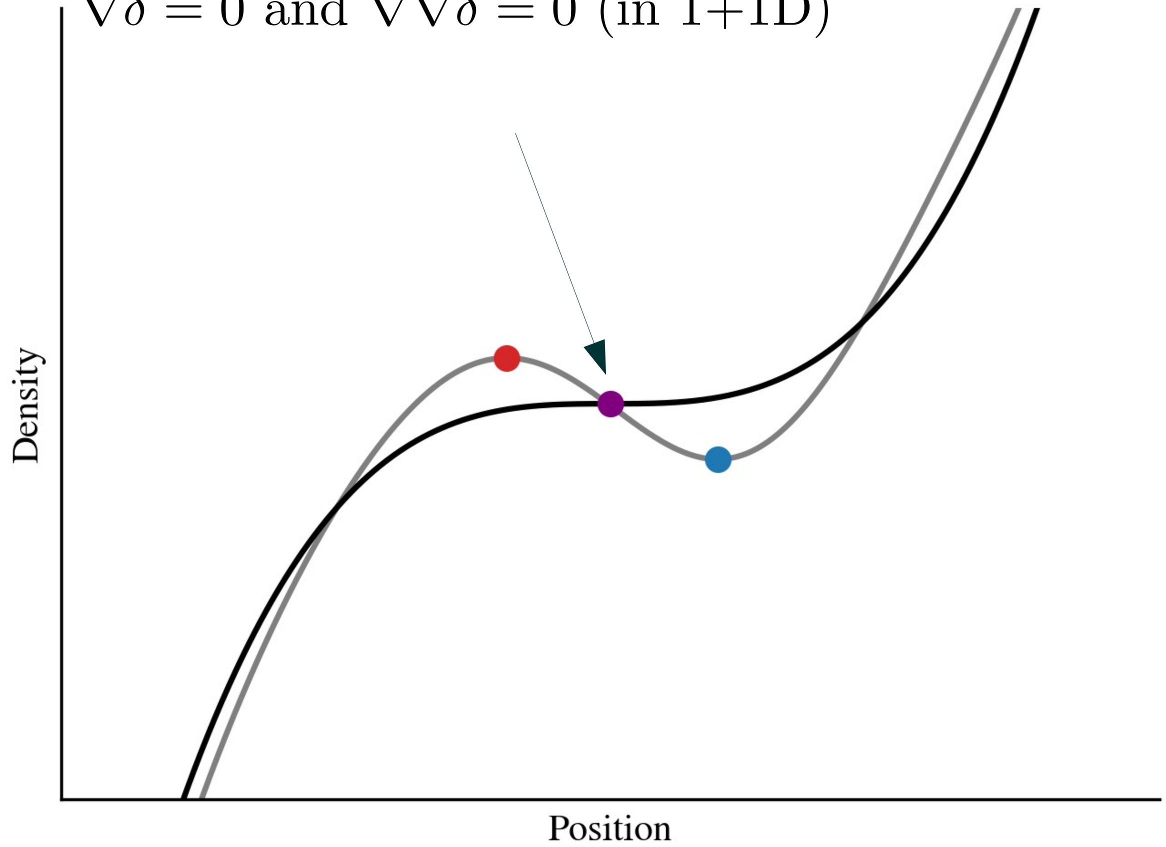
[See also Manrique&Salvador 95, 96, Hanami+01]

Analytical prediction



[See also Manrique&Salvador 95, 96, Hanami+01]

$\nabla\delta = 0$ and $\nabla\nabla\delta = 0$ (in 1+1D)



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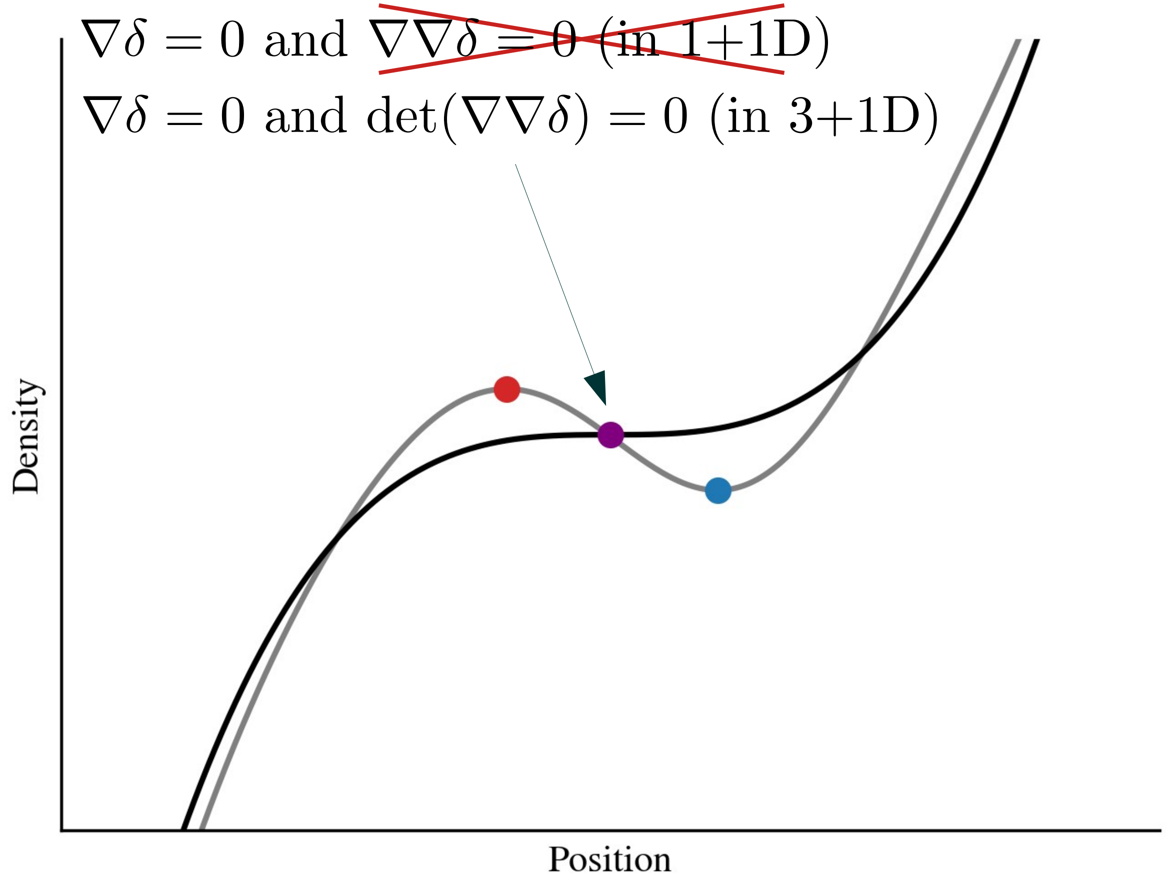
Analytical prediction



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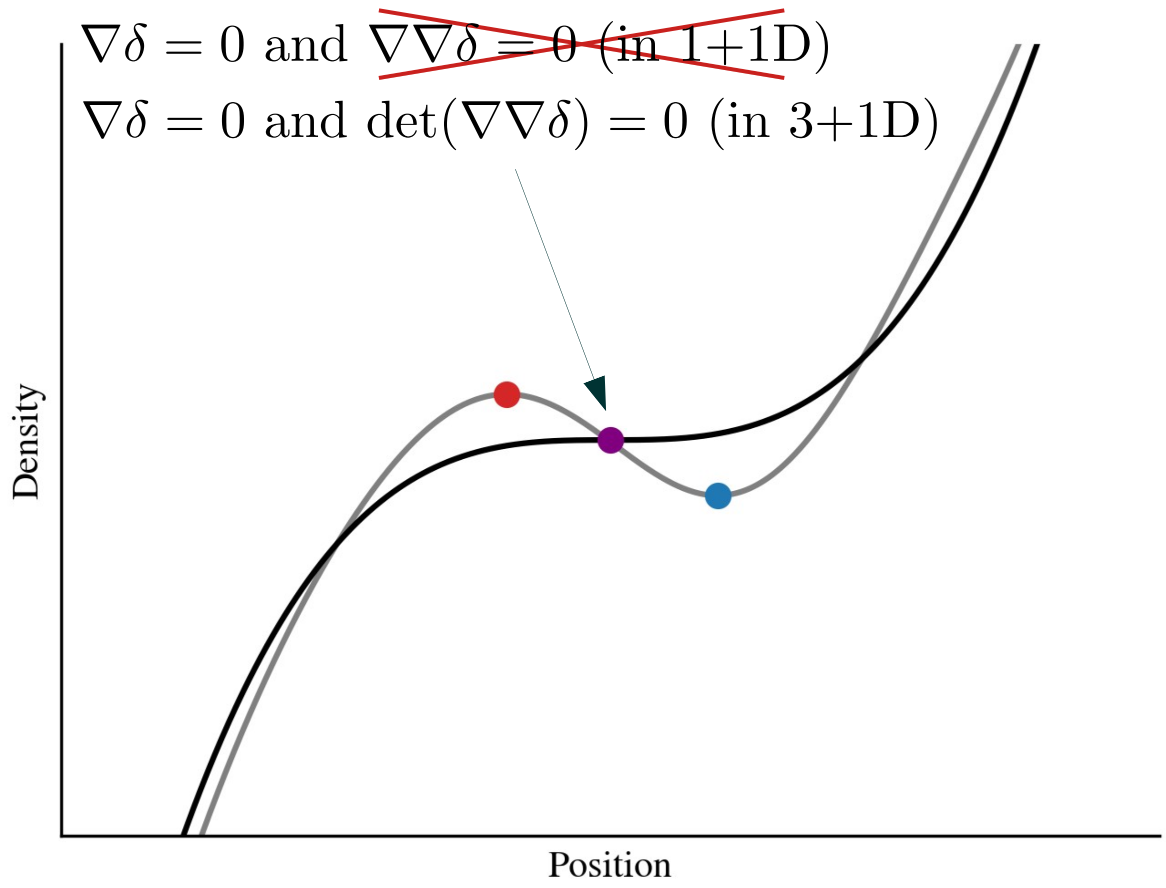
Analytical prediction

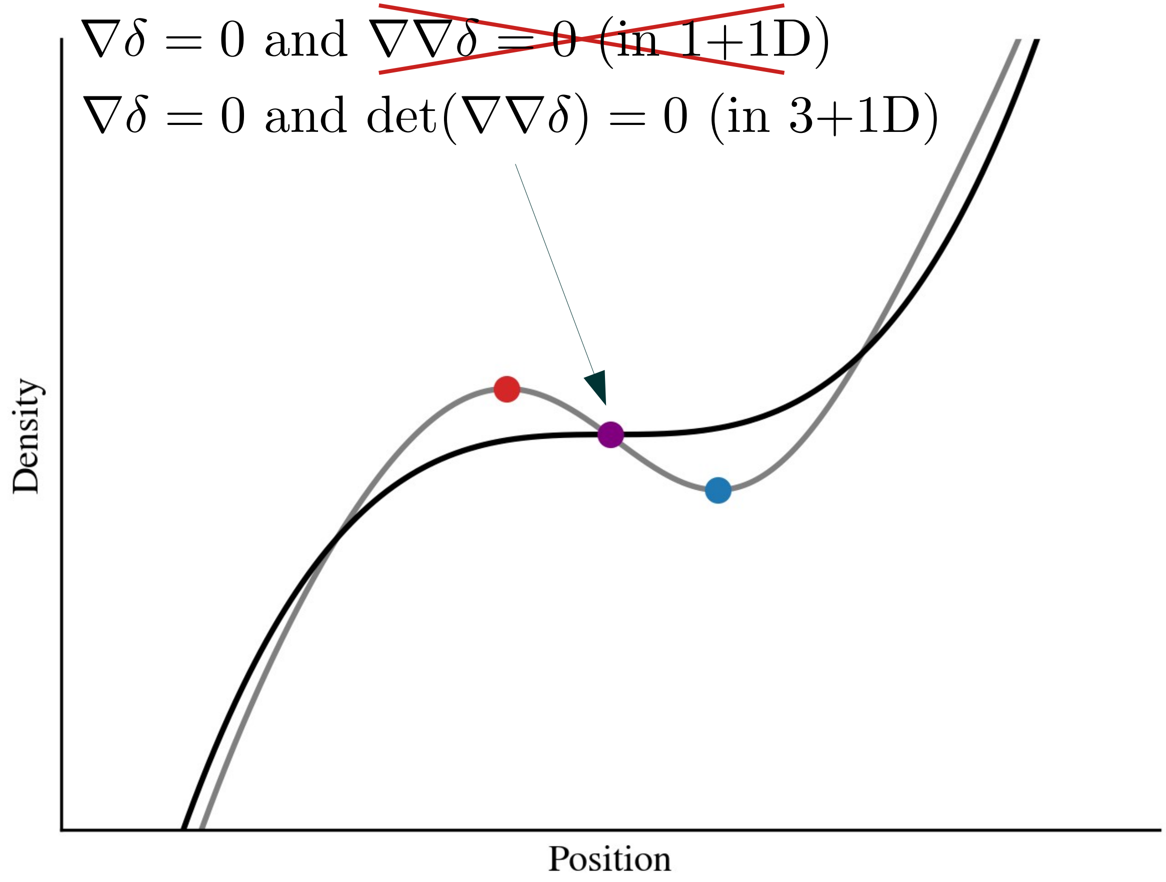


Number count derived from $\mathrm{PDF}(\boxed{\delta, \nabla\delta, \nabla\nabla\delta}, \nabla\nabla\nabla\delta)$

Critical point condition – 10 variables

[See also Manrique&Salvador 95, 96, Hanami+01]

Analytical prediction



Critical *event* condition – 10+10 variables

Number count derived from $\mathrm{PDF}(\delta, \nabla\delta, \nabla\nabla\delta, \nabla\nabla\nabla\delta)$

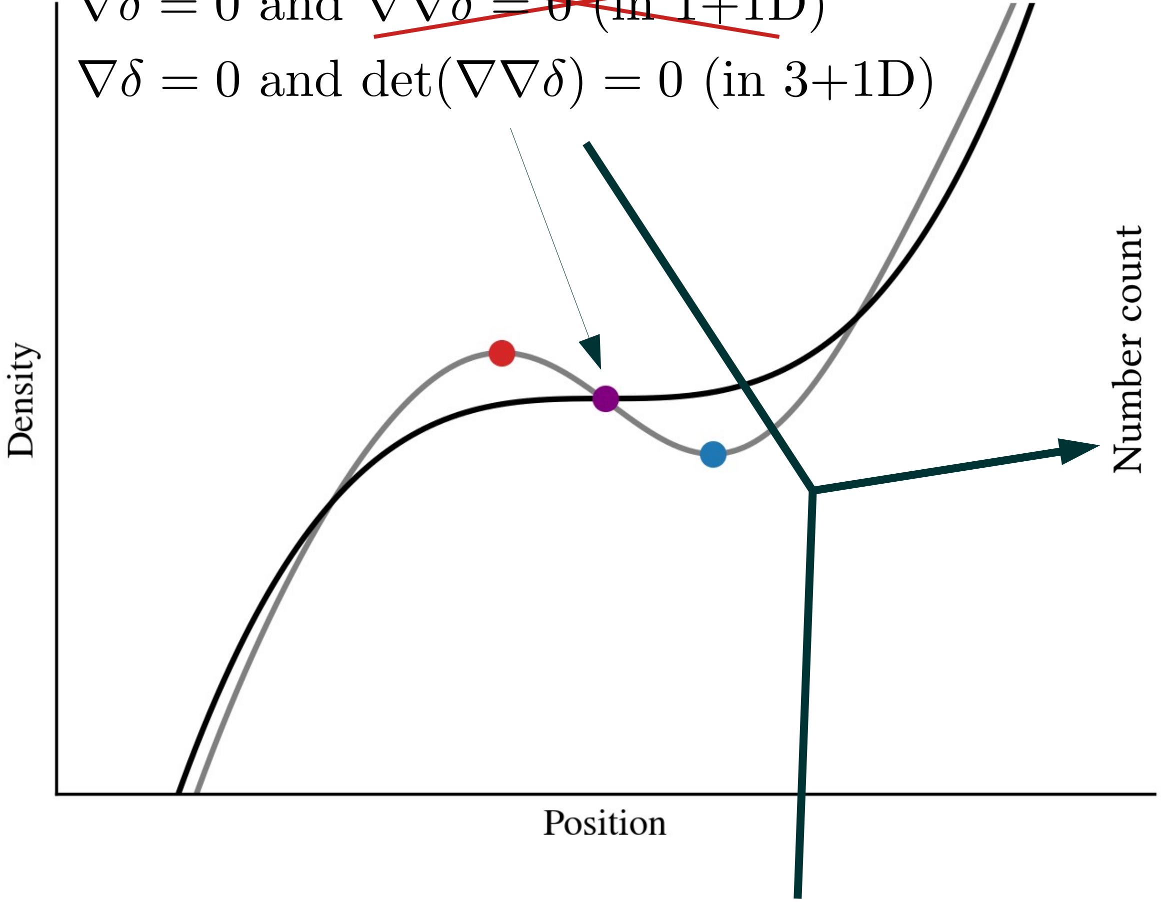
Critical point condition – 10 variables

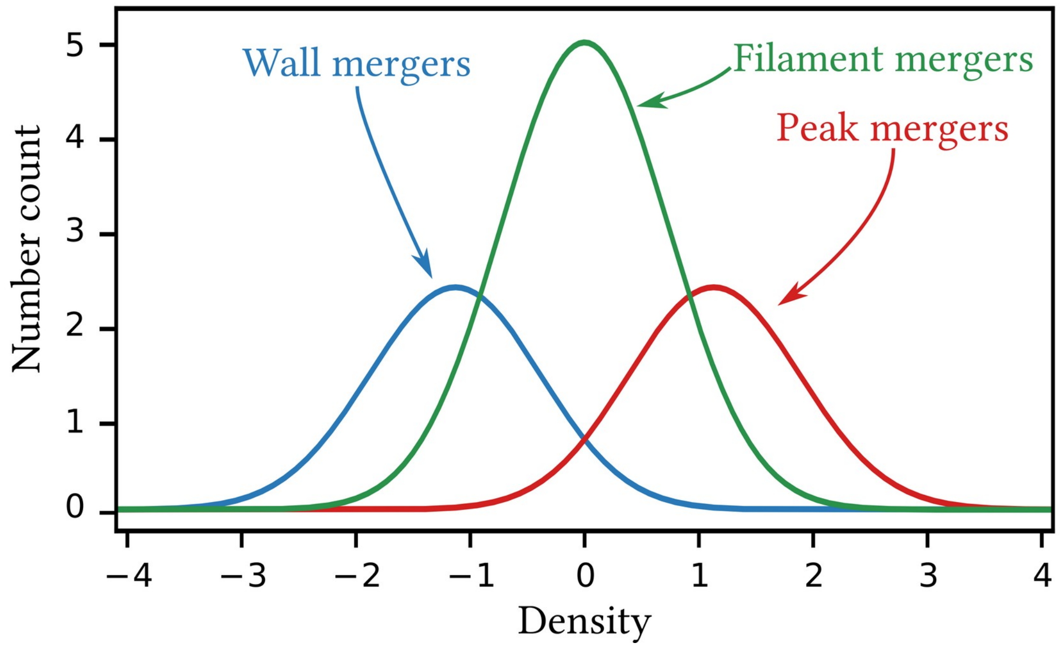
[See also Manrique&Salvador 95, 96, Hanami+01]

Analytical prediction

$\nabla\delta = 0$ and $\cancel{\nabla\nabla\delta = 0 \text{ (in 1+1D)}}$

$\nabla\delta = 0$ and $\det(\nabla\nabla\delta) = 0$ (in 3+1D)





Number count from theory (solid)

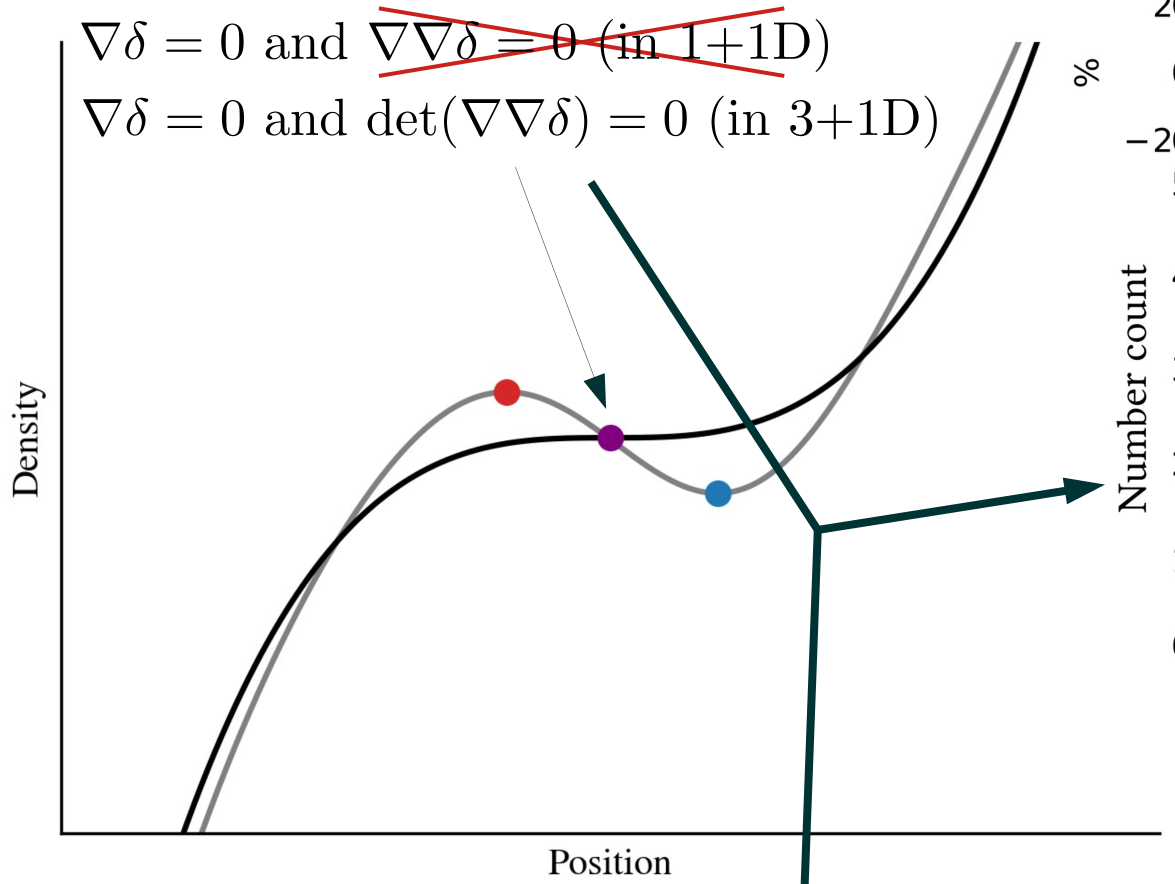
Critical *event* condition – 10+10 variables

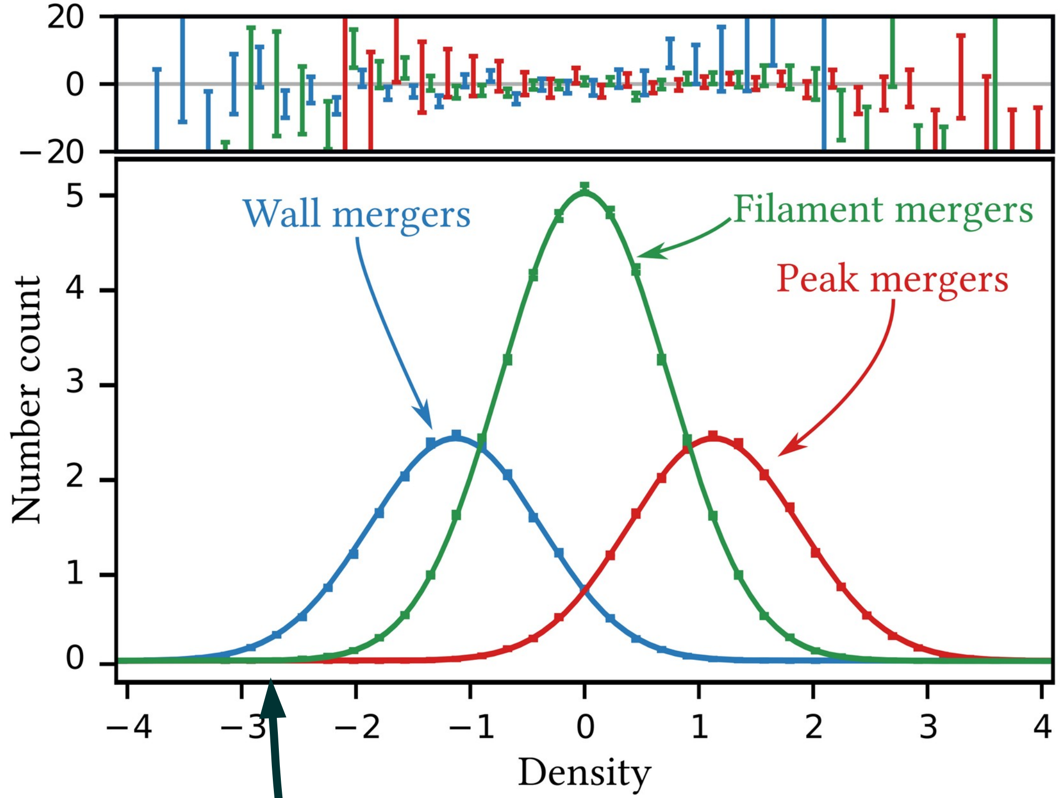
Number count derived from $\mathrm{PDF}(\delta, \nabla\delta, \nabla\nabla\delta, \nabla\nabla\nabla\delta)$

Critical point condition – 10 variables

[See also Manrique&Salvador 95, 96, Hanami+01]

Analytical prediction





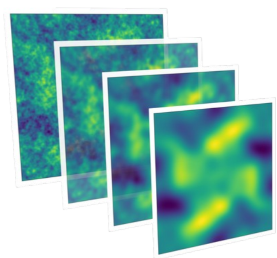
Number count from theory (solid) and numerical (symbols)

Critical *event* condition – 10+10 variables

Number count derived from $\mathrm{PDF}(\delta, \nabla\delta, \nabla\nabla\delta, \nabla\nabla\nabla\delta)$

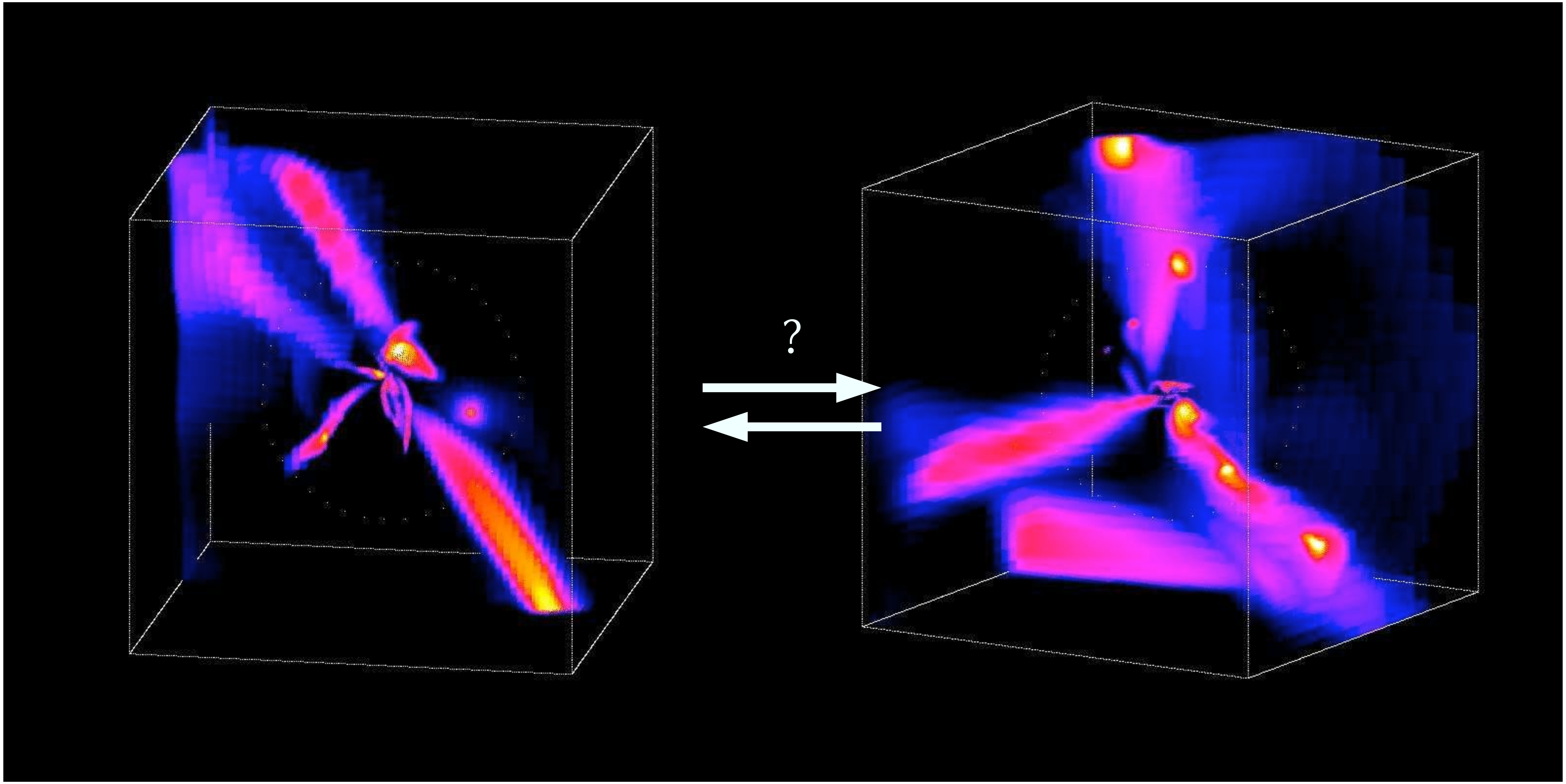
Critical point condition – 10 variables

Measurements in generated random fields
→ <u>numerical estimator</u>



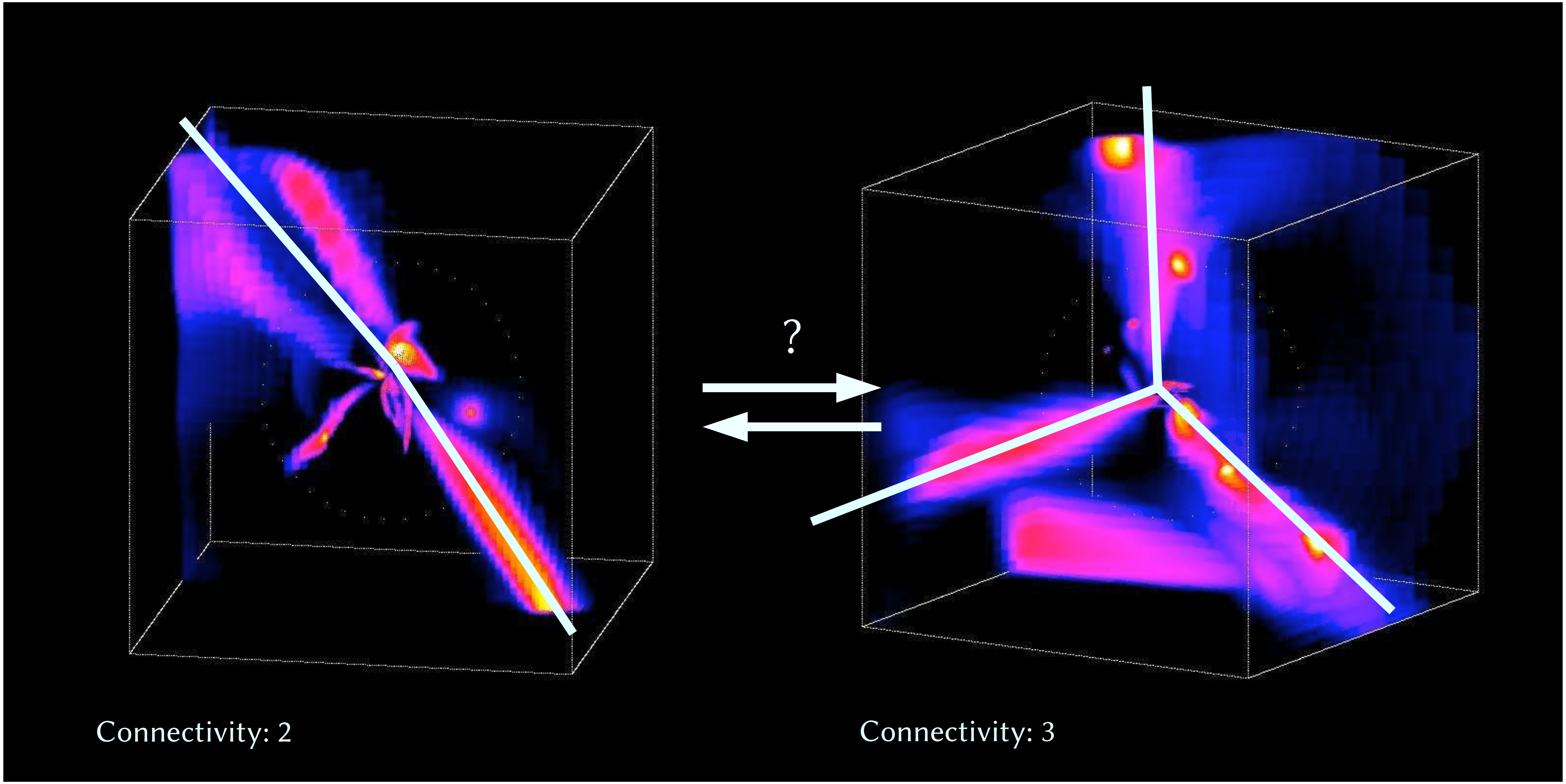
[See also Manrique&Salvador 95, 96, Hanami+01]

On the problem of connectivity



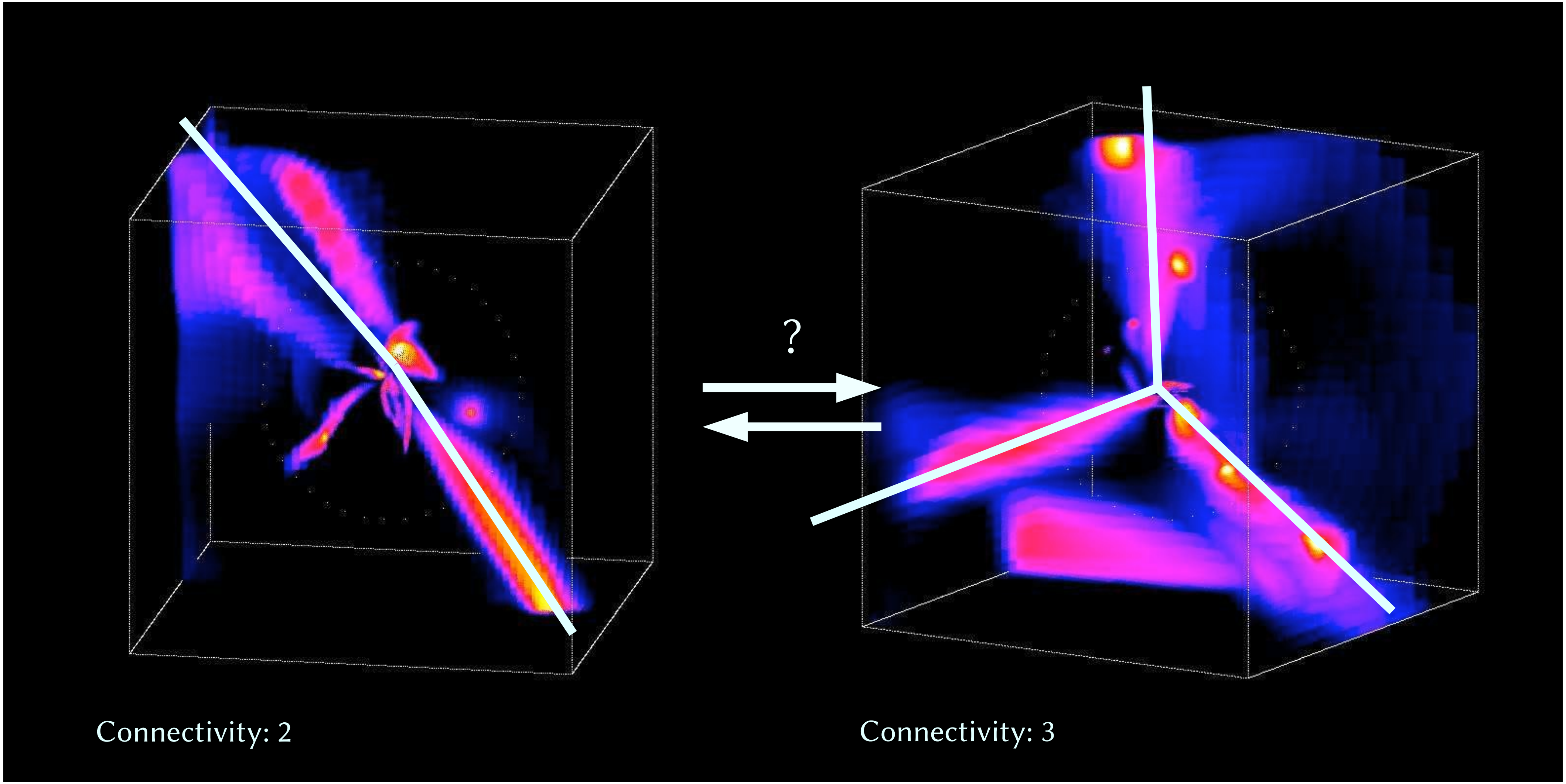
[Dekel+09; Codis+18 for predictions of the connectivity]

On the problem of connectivity



[Dekel+09; Codis+18 for predictions of the connectivity]

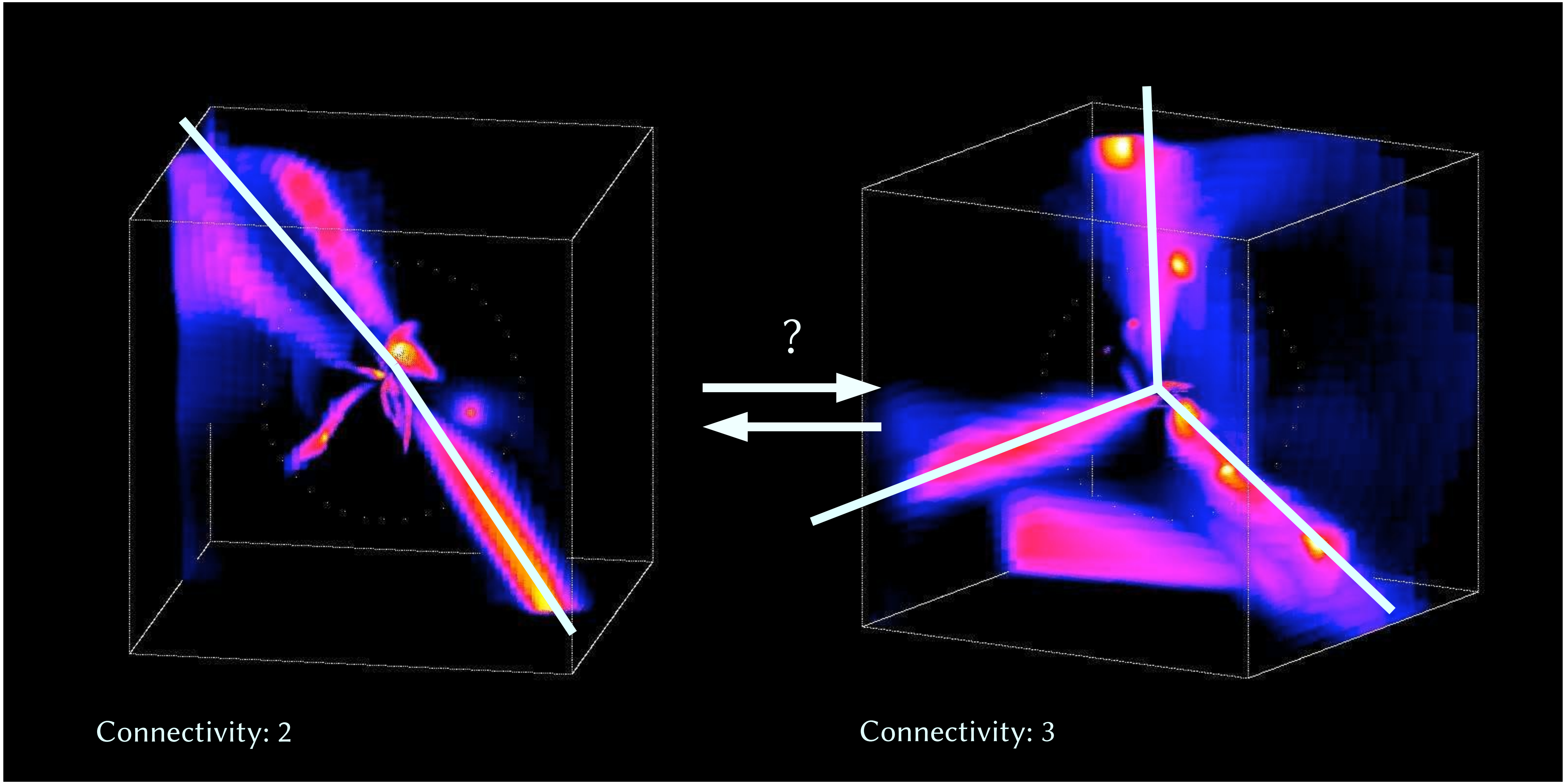
On the problem of connectivity



How does **connectivity** evolve with cosmic web? Why 3 filaments?

[Dekel+09; Codis+18 for predictions of the connectivity]

On the problem of connectivity



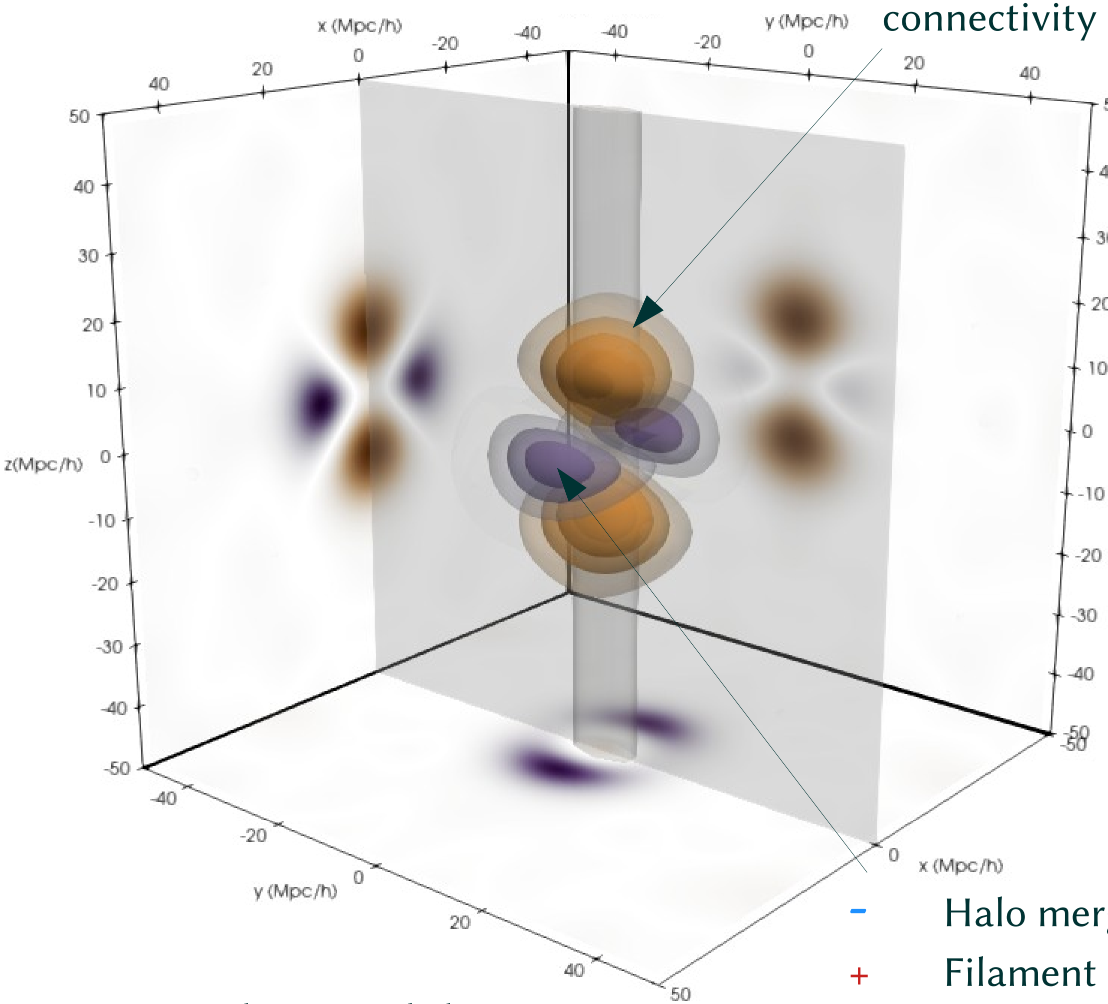
How does **connectivity** evolve with cosmic web? Why 3 filaments?

→ Rely on random realisation + filamentary constrain + numerical estimator

[Dekel+09; Codis+18 for predictions of the connectivity]

Connectivity evolution across the cosmic web

+ Halo mergers
- Filament mergers
→ Towards higher connectivity

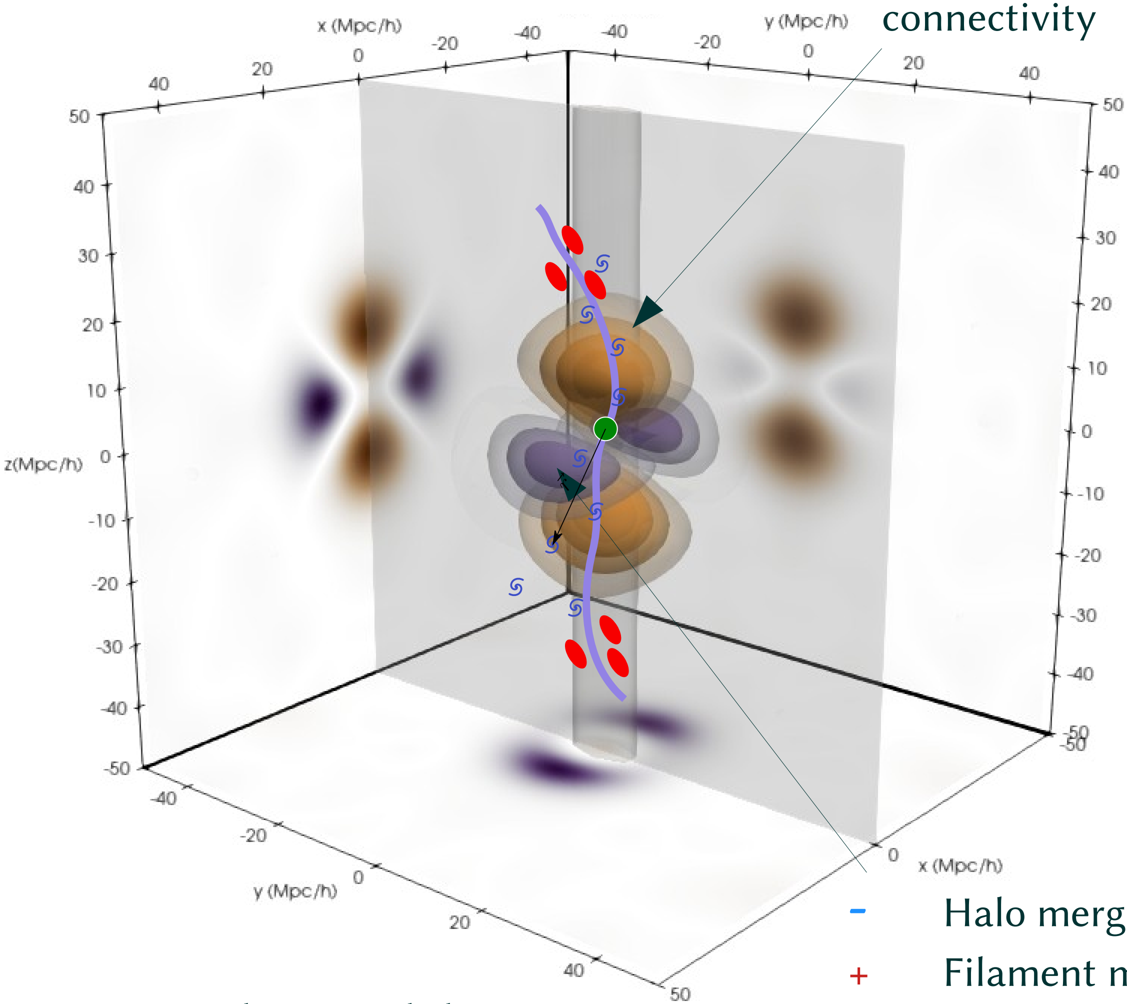


- Halo mergers
+ Filament mergers
→ Towards lower connectivity

Filament-to-halo merger rate, computed numerically. Cadiou+in prep

[Connectivity: Codis+18]

Connectivity evolution across the cosmic web



+ Halo mergers
- Filament mergers
⟶ Towards higher connectivity

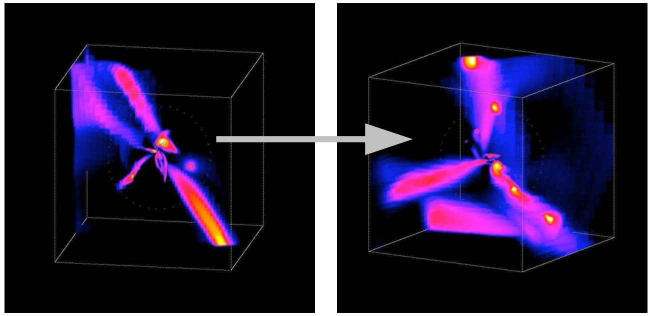
- Halo mergers
+ Filament mergers
⟶ Towards lower connectivity

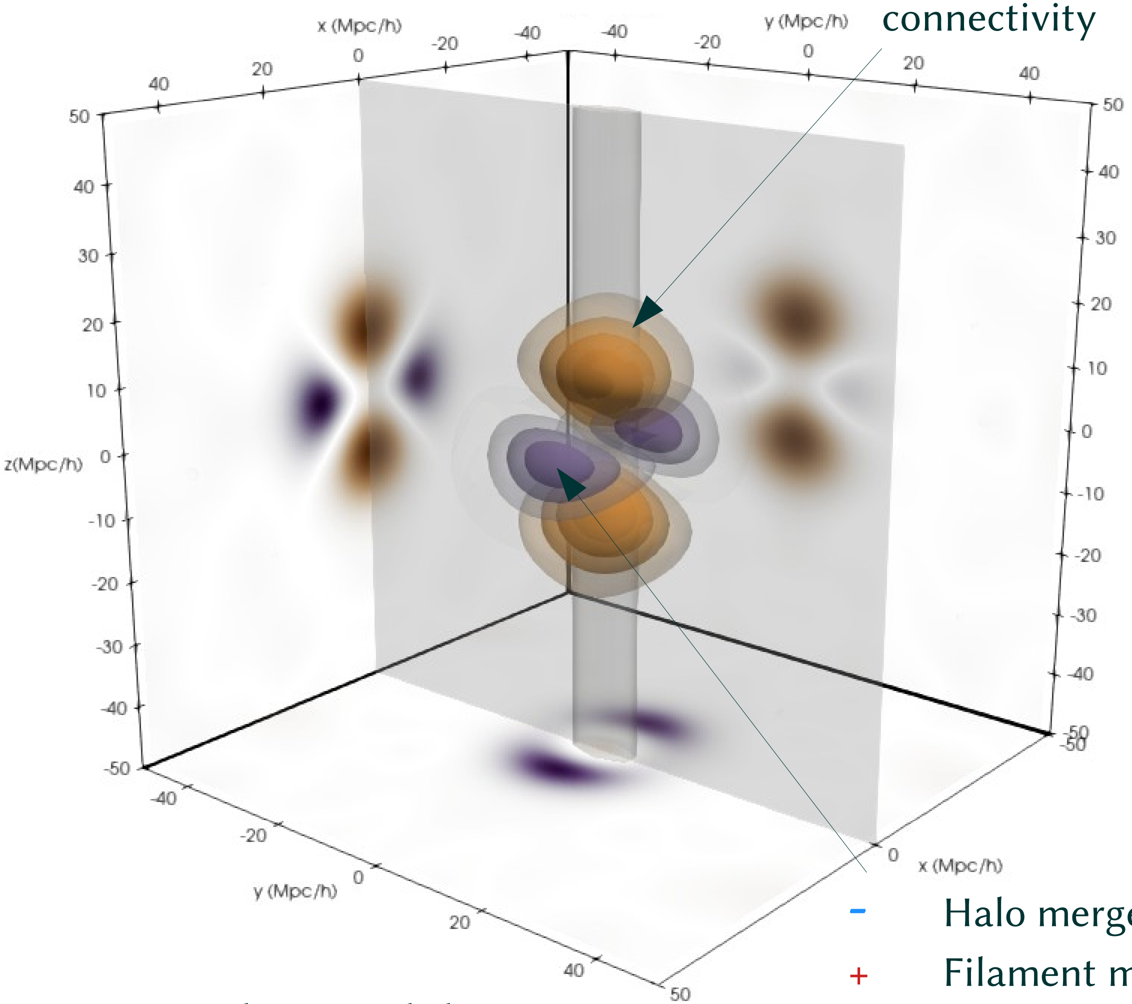
Filament-to-halo merger rate, computed numerically. Cadiou+in prep

[Connectivity: Codis+18]

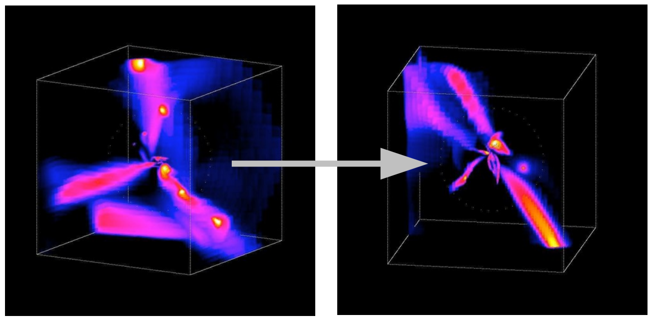
Connectivity evolution across the cosmic web

- \+ Halo mergers
- \- Filament mergers
- ⟶ Towards higher connectivity





- \- Halo mergers
- \+ Filament mergers
- ⟶ Towards lower connectivity

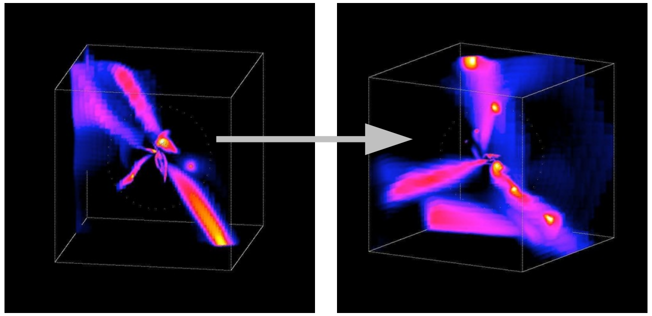


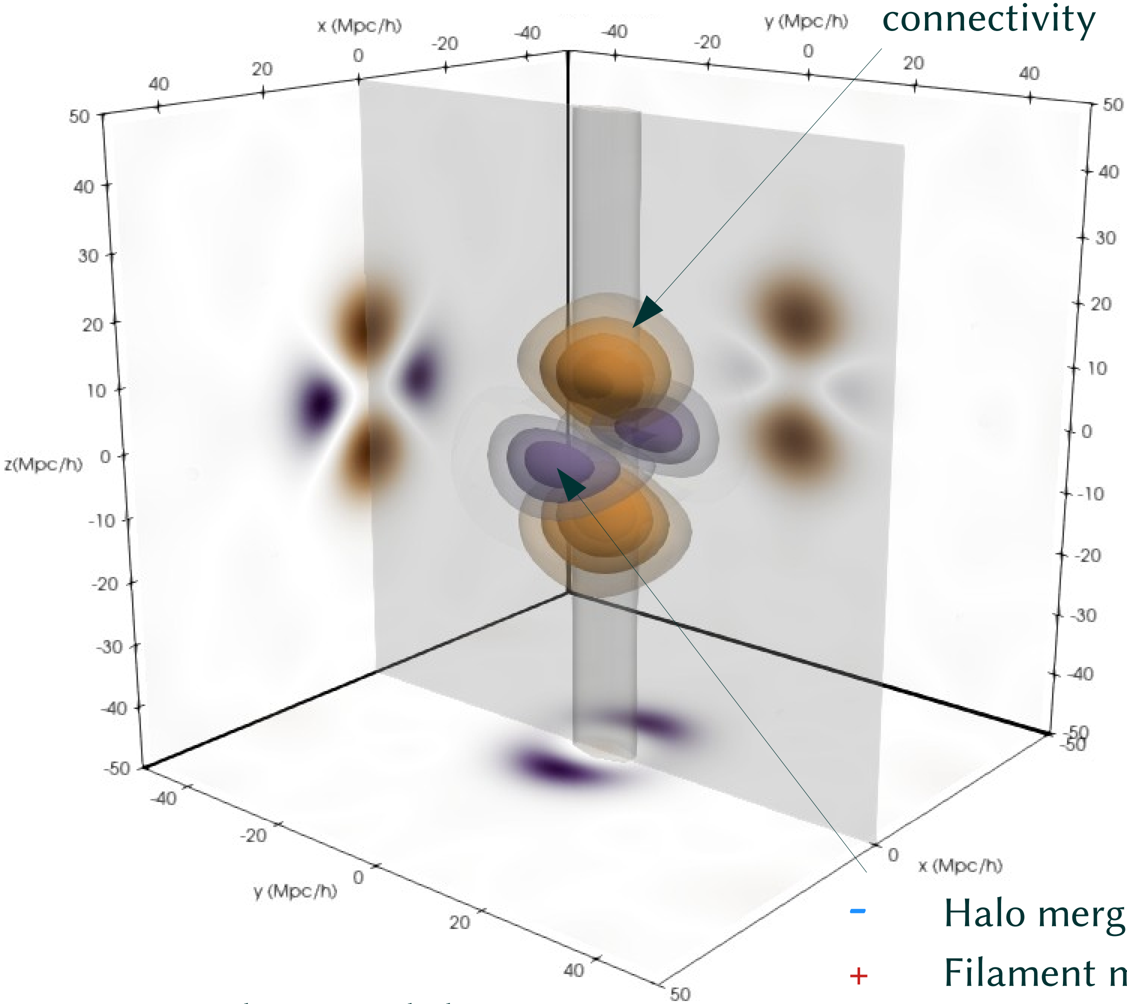
Filament-to-halo merger rate,
computed numerically.
Cadiou+in prep

+ Halo mergers

- Filament mergers

→ Towards higher connectivity





At **fixed smoothing scale**, in nodes

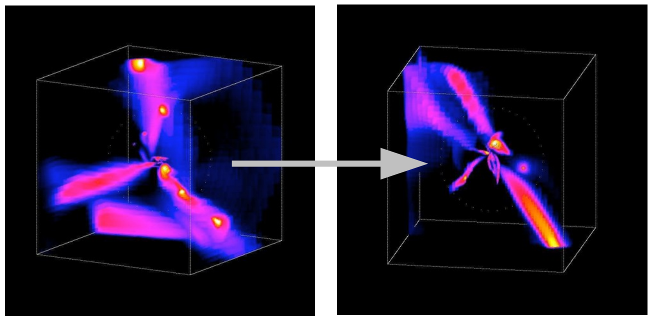
- more halo mergers,
- less filament mergers,
- <u>growing</u> towards higher connectivity,

than in voids.

- Halo mergers

+ Filament mergers

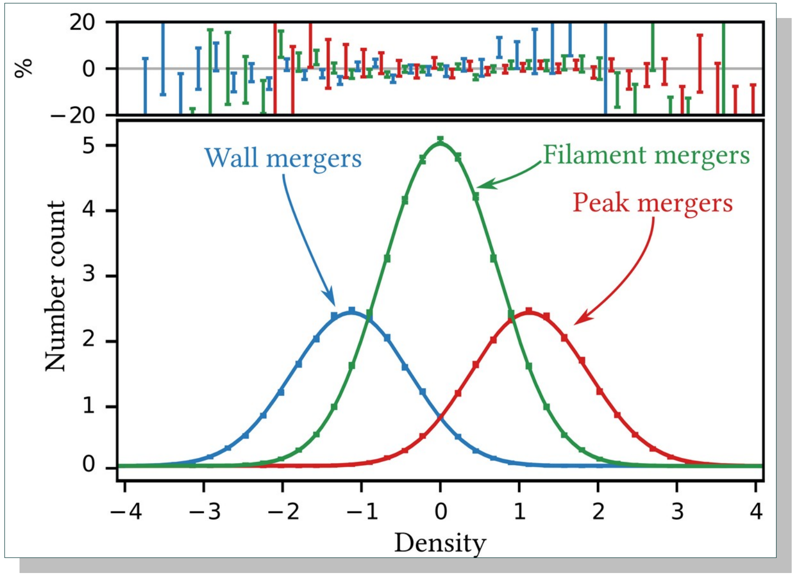
→ Towards lower connectivity

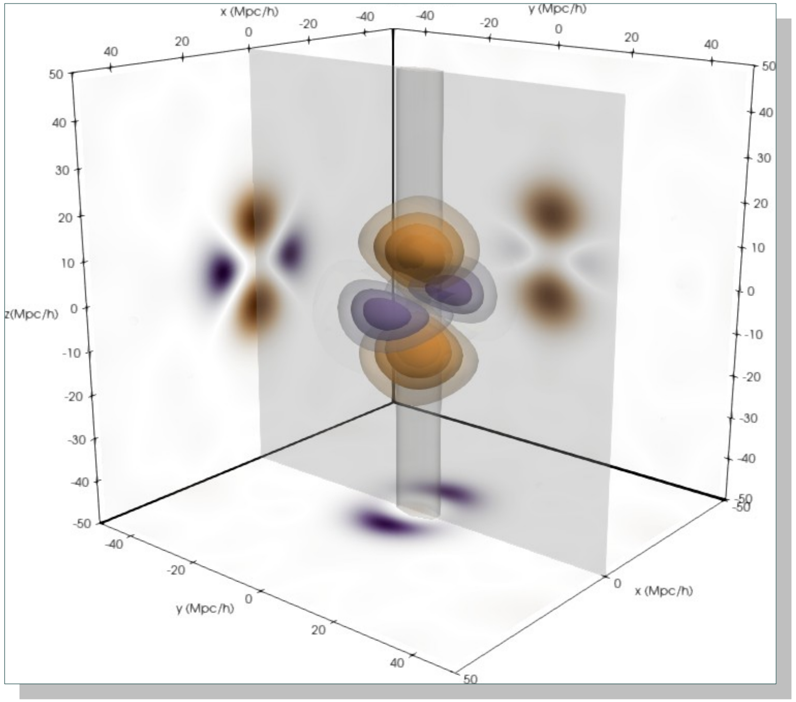


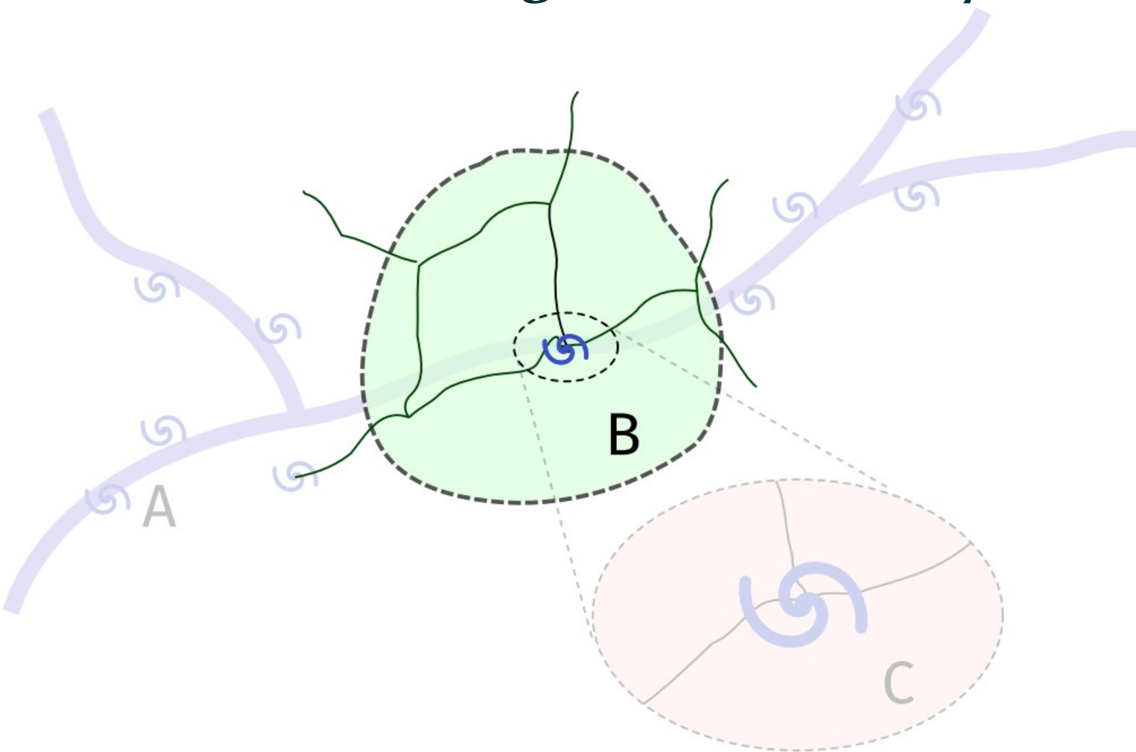
Filament-to-halo merger rate, computed numerically. Cadiou+in prep

[Connectivity: Codis+18]

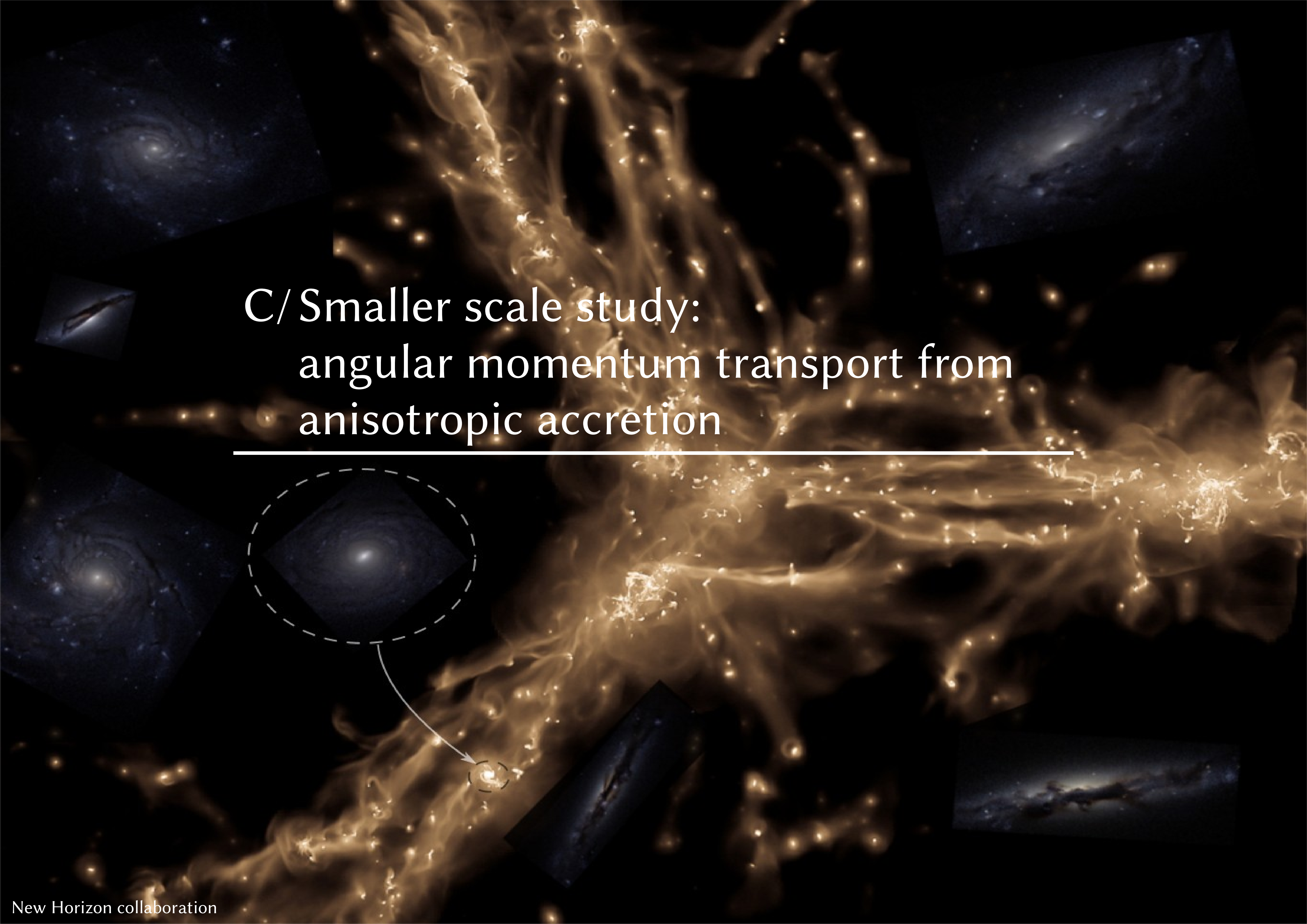
- Critical events
  - ✔ Derived theoretical expectations
  - ✔ Theory checked against random realisations
  - ✔ Can be used in numerical simulations
- Capture halo mergers *but also* **filament mergers**
- Typical assembly impacted by larger-scale environment ⟶ **higher connectivity in nodes**



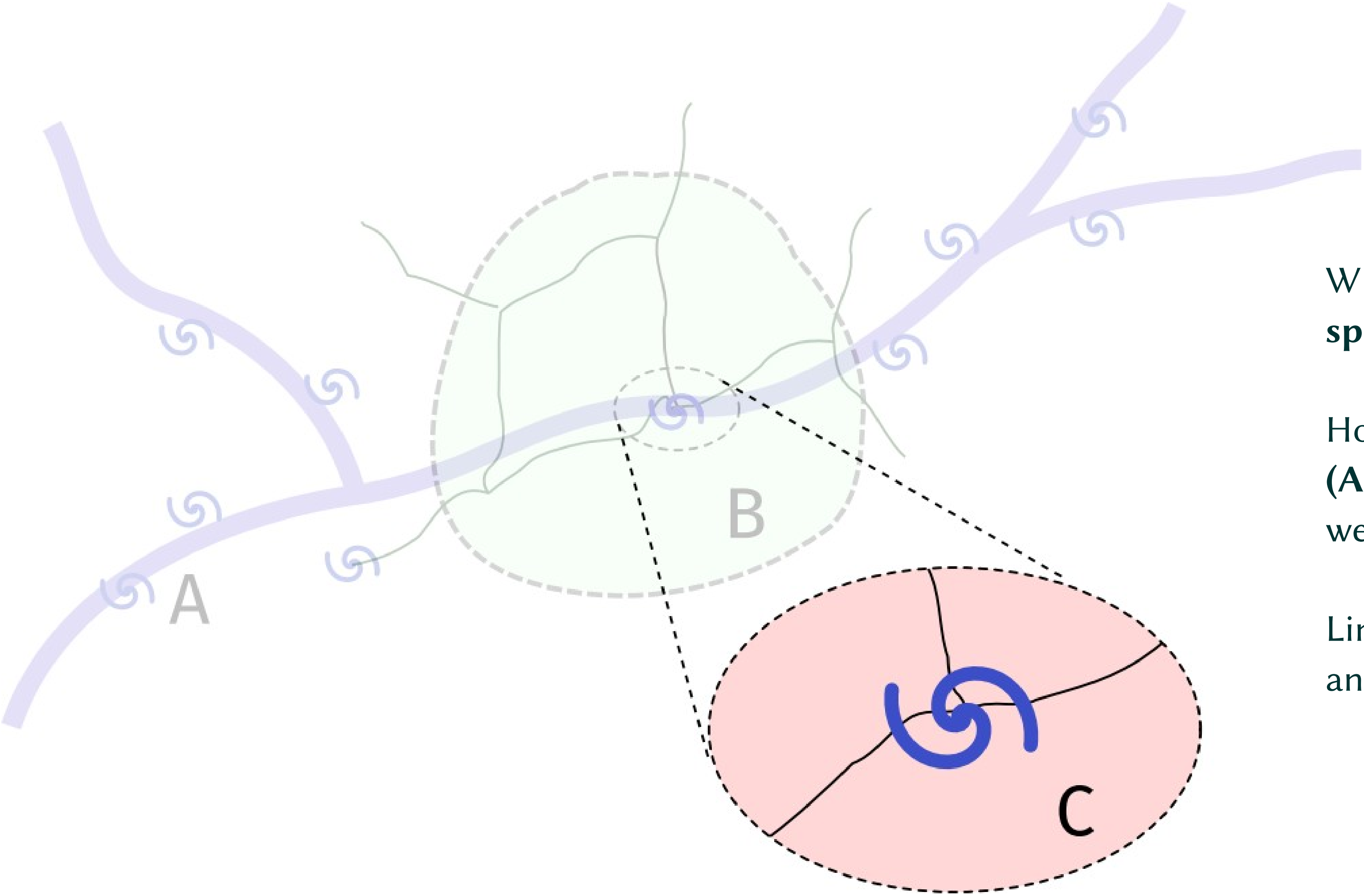




C/ Smaller scale study: angular momentum transport from anisotropic accretion



New Horizon collaboration



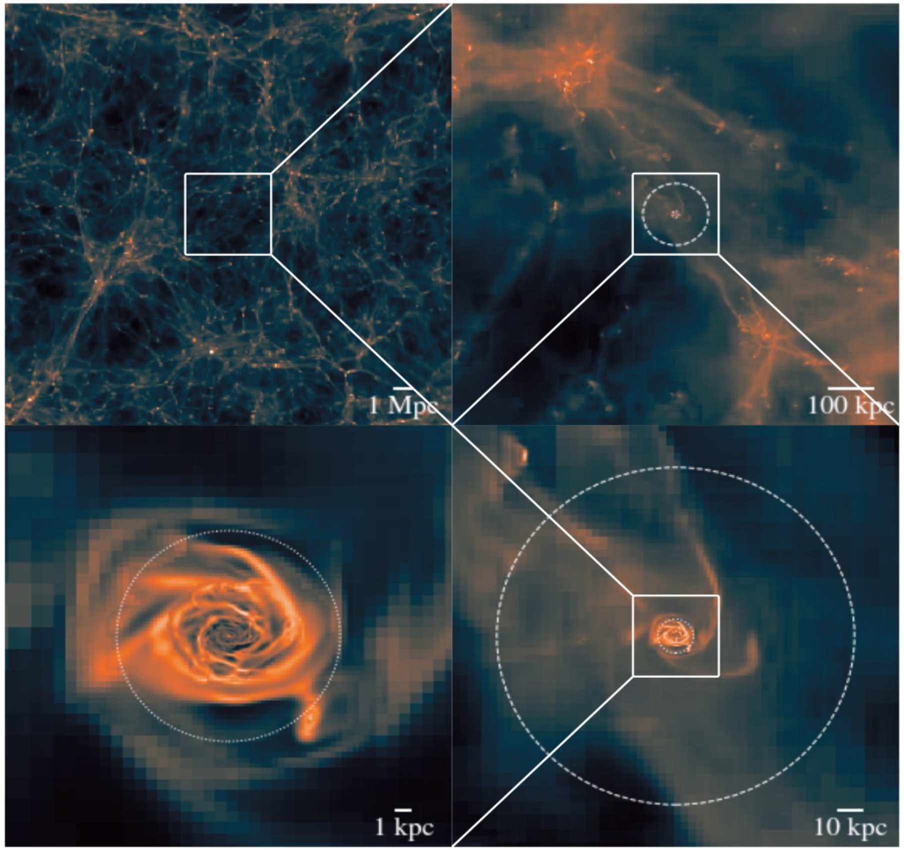
What is the **origin of galactic spin**?

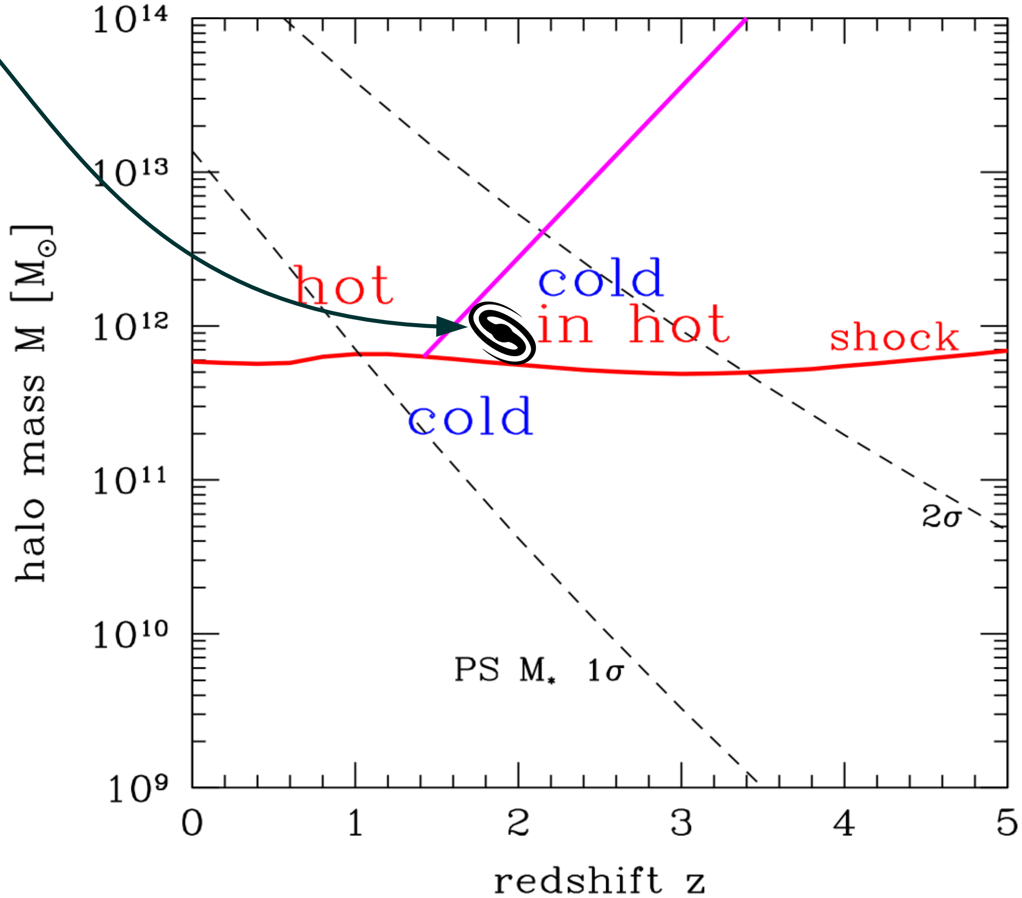
How is **angular momentum (AM) transported** from cosmic web to the galaxy?

Link between **large-scale AM** and **galactic AM**?

[Large-scale AM: given by TTT. Hoyle 49; Peebles 69; Doroshkevich 70; White 84, Codis+15]

- 6 halos of $M=10^{12}\,M_\odot$ at $z=2$
- Focus on cold flows ⟶ main source of angular momentum
- RAMSES, 30pc resolution



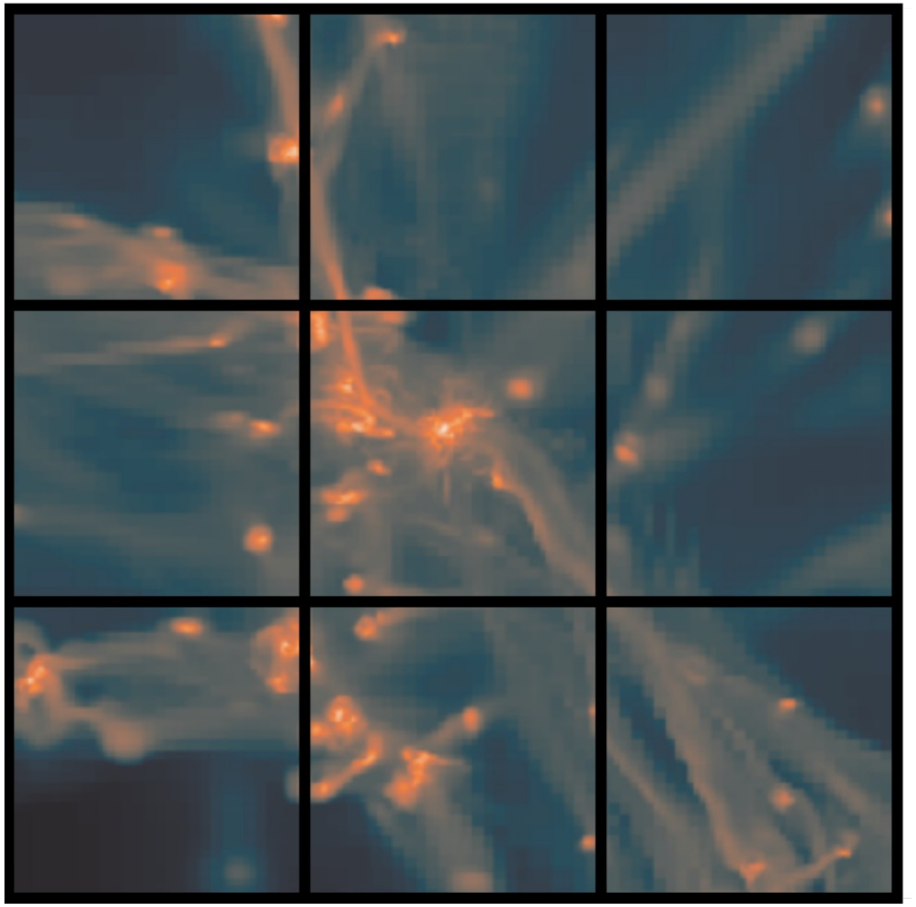


Two modes of gas accretion. Dekel & Birnboim 06

[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

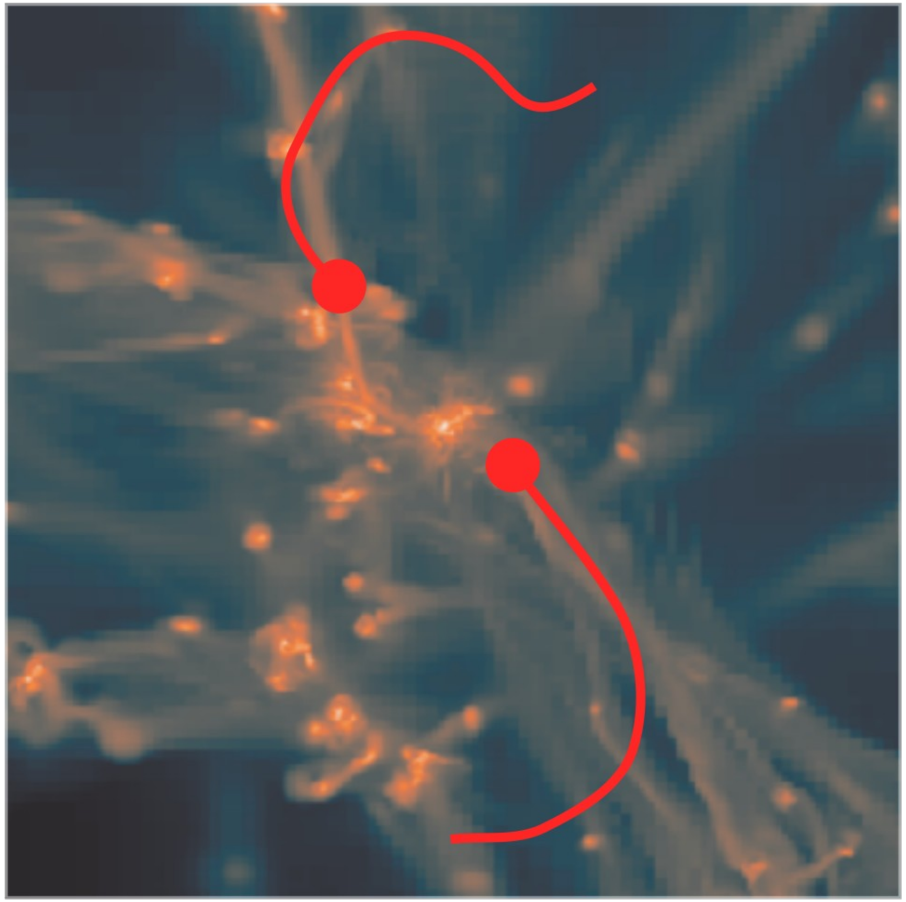


Grid-based approach (*AMR*):

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

Ex: Art, <u>Ramses</u>, Enzo, ...

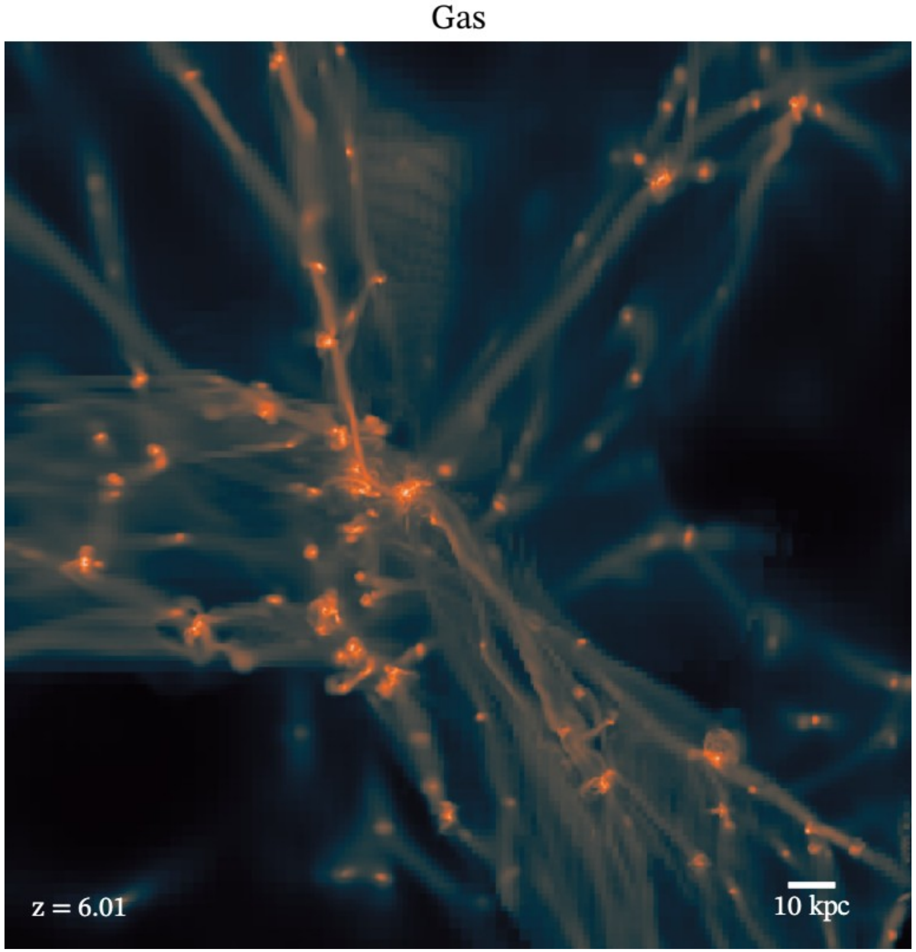
Lagrangian method



Particle-based approach (*SPH*):

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

Ex: GADGET, Gasoline, ...

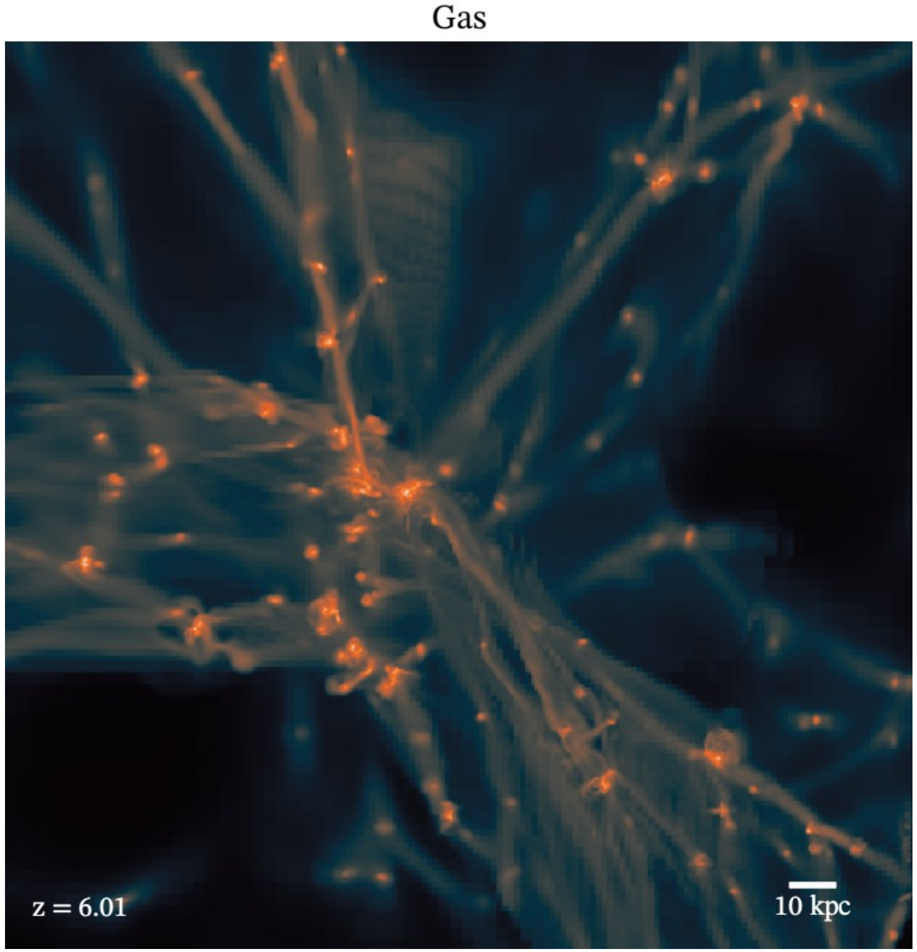


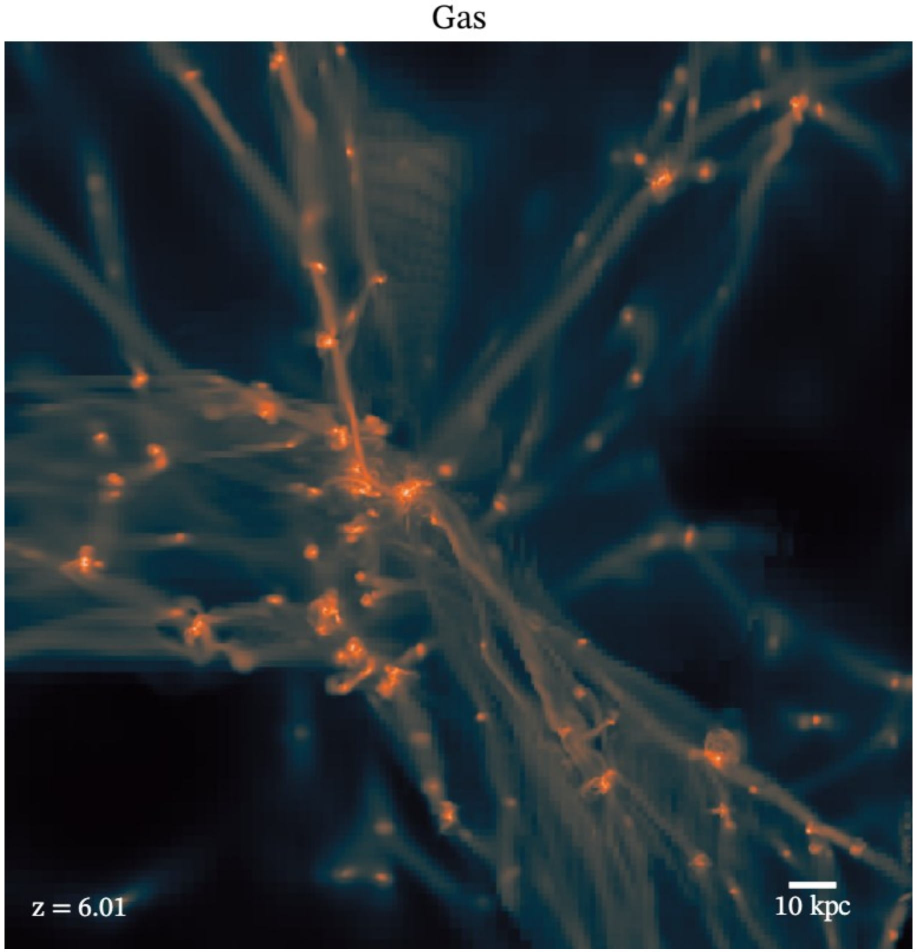
To follow gas accretion: need the Lagrangian history of the gas

- past temperature,
- past position.

In grid-based codes:
$\longrightarrow$ achieved with Lagrangian tracer particles

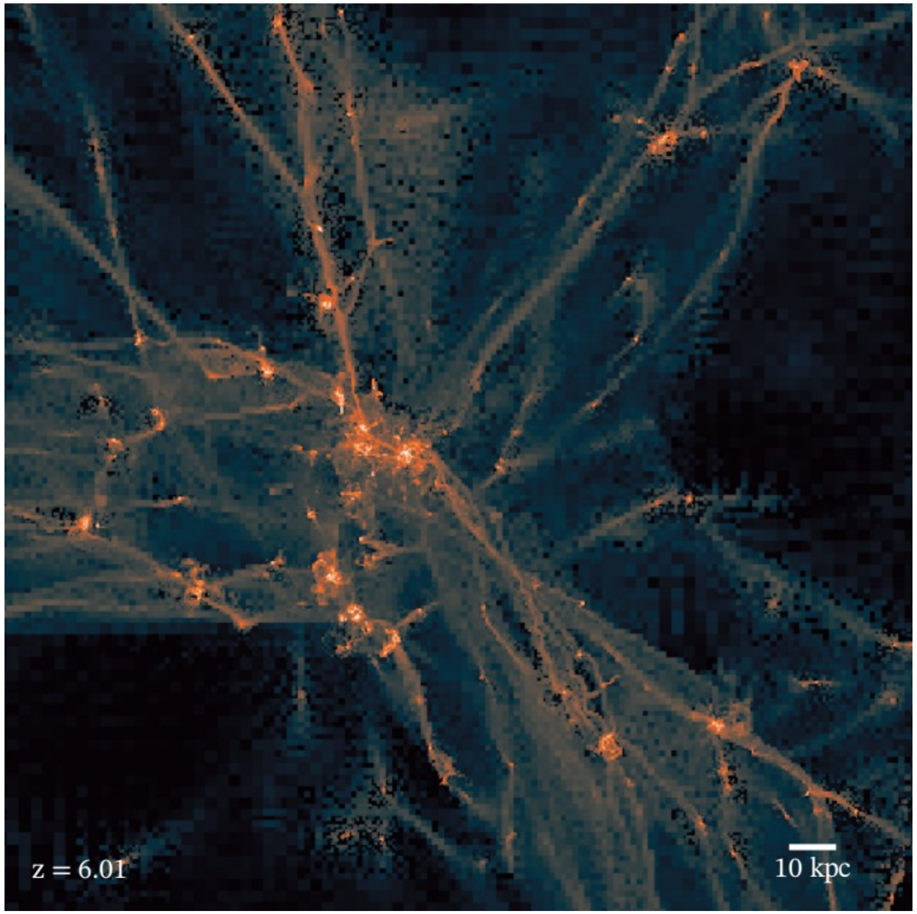
Monte Carlo tracer particles in grid-based code



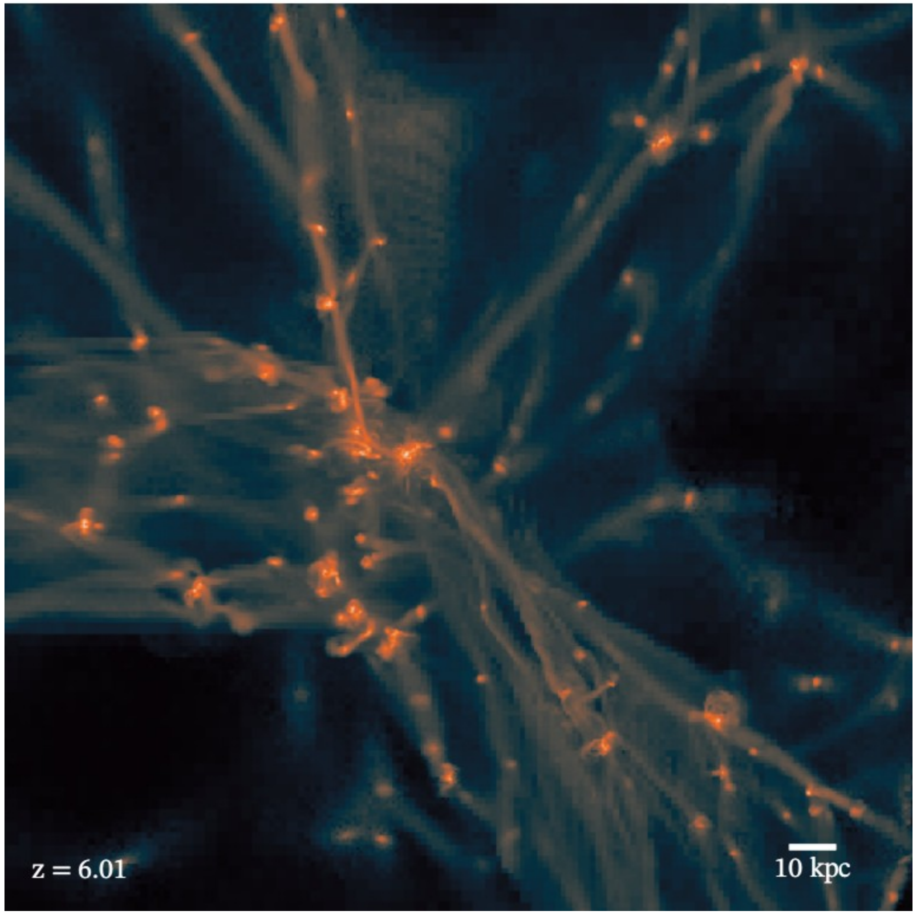


Monte Carlo tracer particles in grid-based code

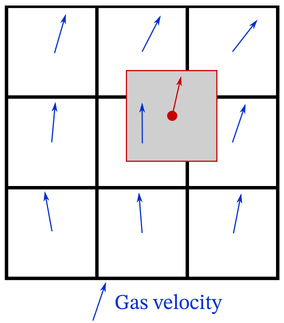
Velocity Advected Tracers



MC Gas Tracers

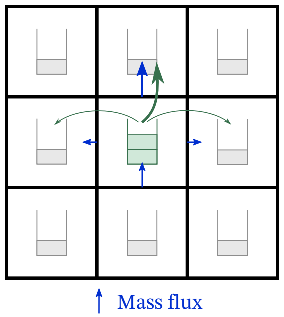


Velocity-advected method



Using linear interpolation of velocity

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



Monte-Carlo approach: moving with probability

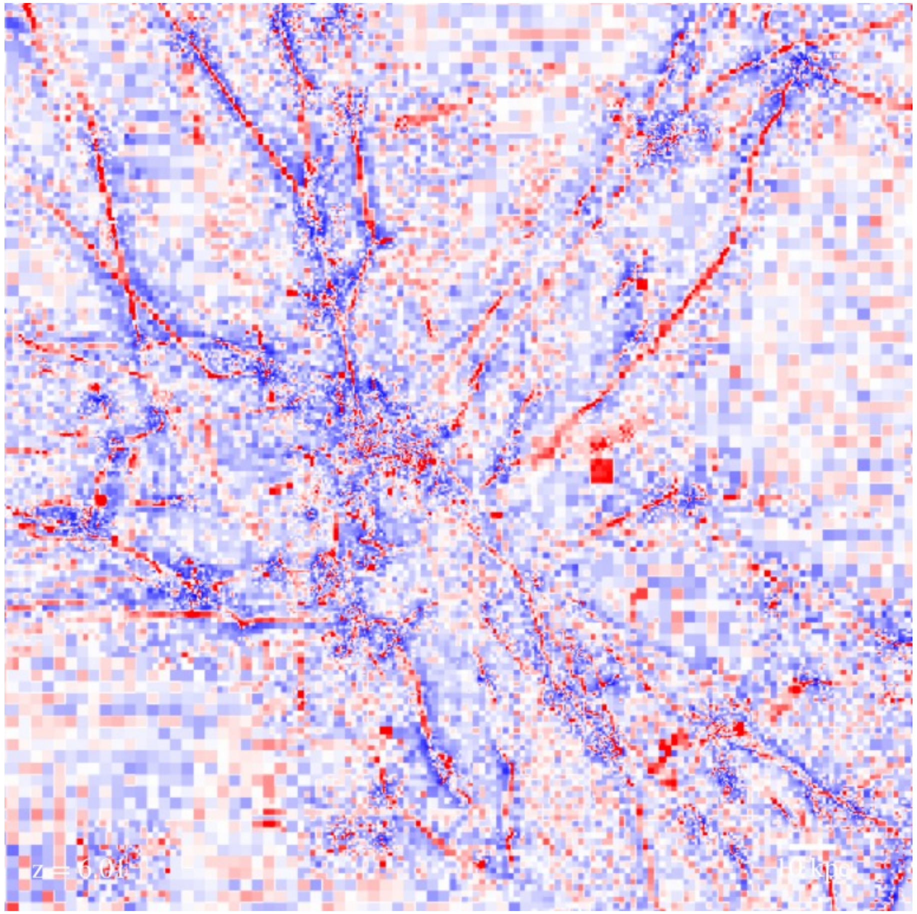
$$p = \Delta M/M$$

M mass of cell

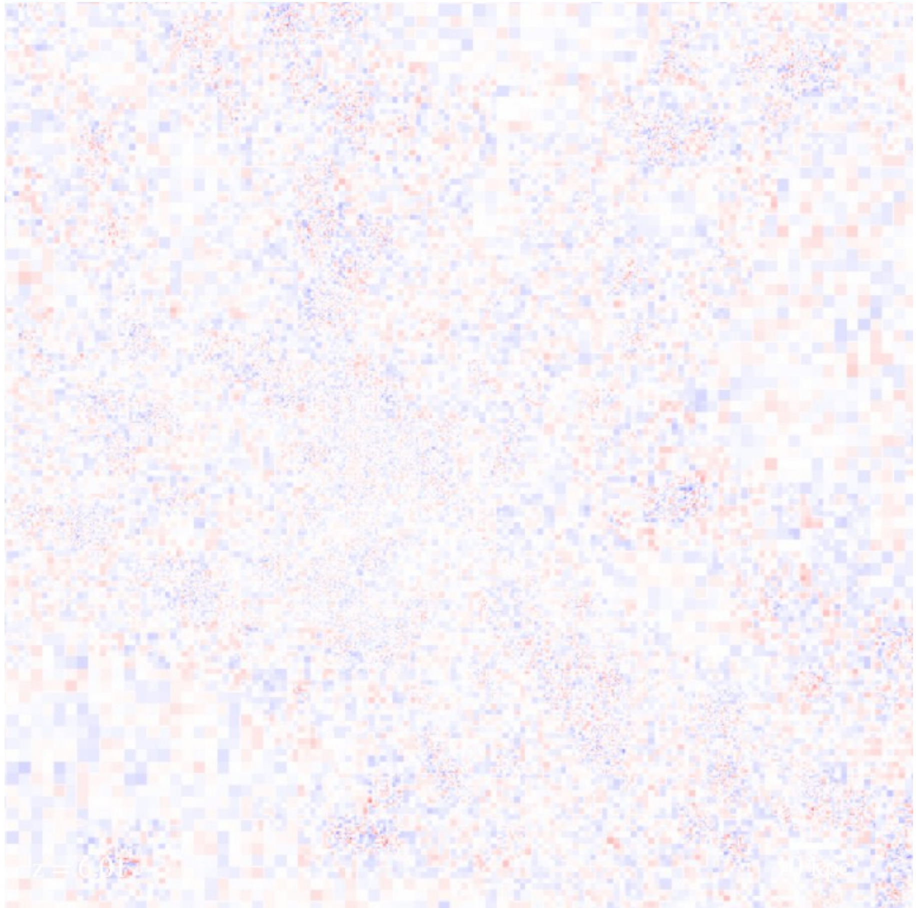
ΔM mass flux

Monte Carlo tracer particles in grid-based code

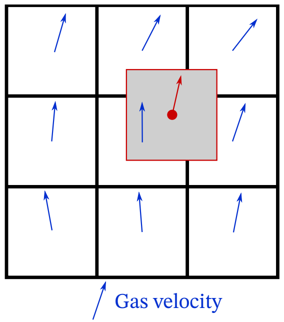
Velocity Advected Tracers



MC Gas Tracers



Velocity-advected method



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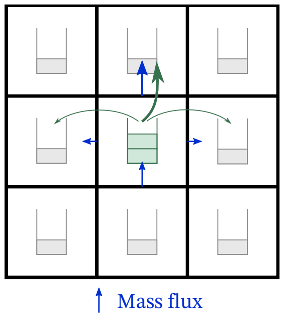

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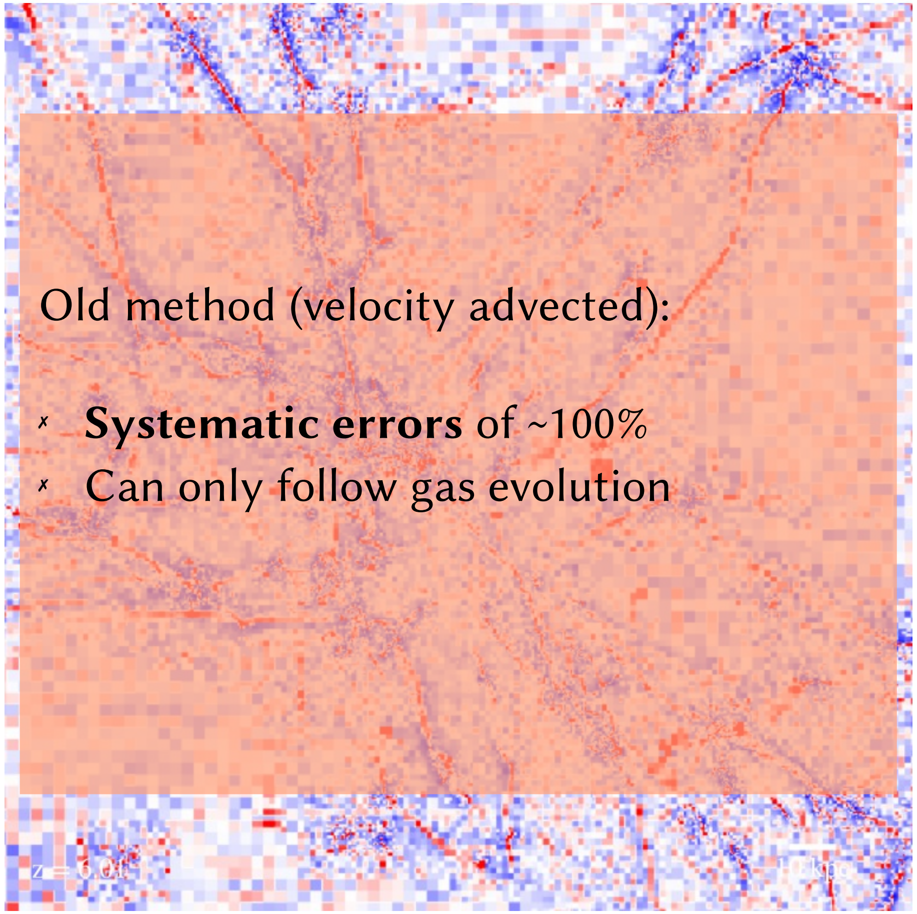
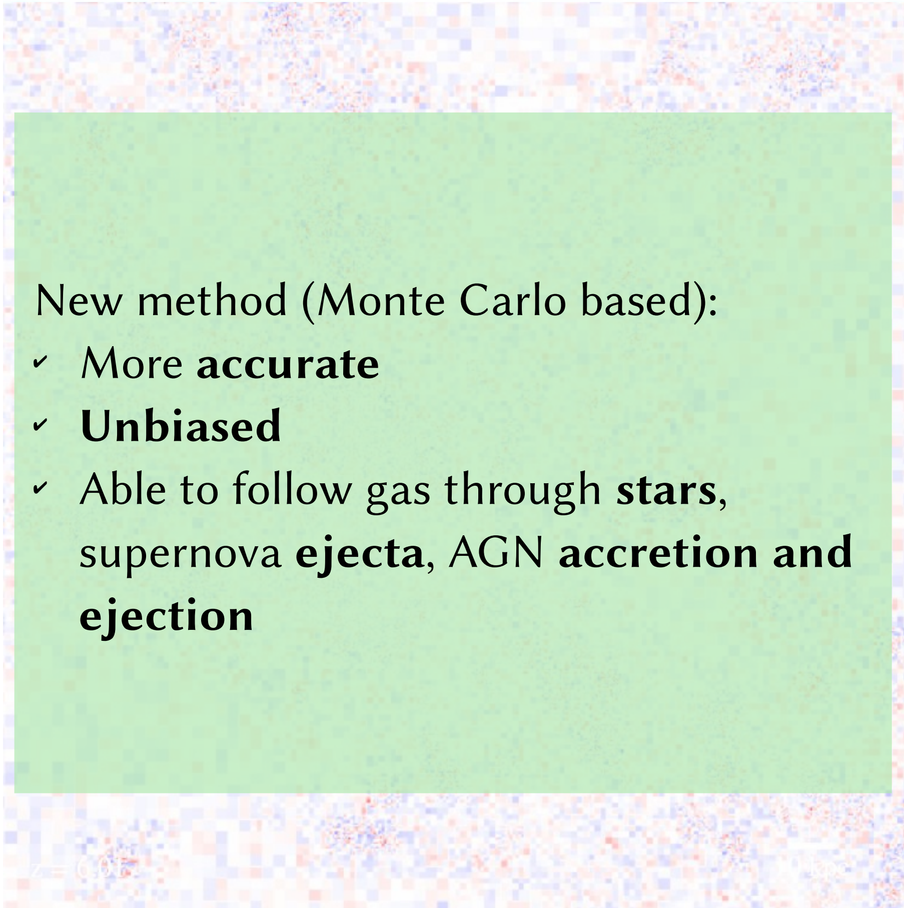
Velocity Advected Tracers



Old method (velocity advected):

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

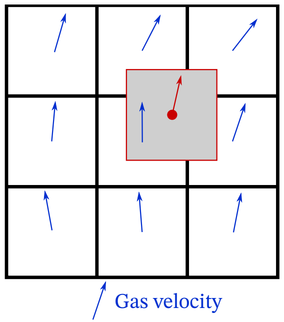
MC Gas Tracers



New method (Monte Carlo based):

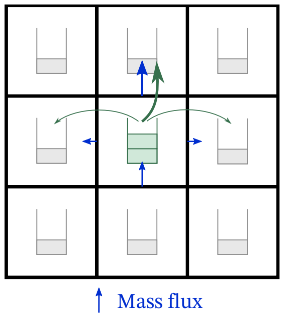
- ✓ More **accurate**
- ✓ **Unbiased**
- ✓ Able to follow gas through **stars**, supernova **ejecta**, AGN **accretion and ejection**

Velocity-advected method



Using linear interpolation of velocity

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

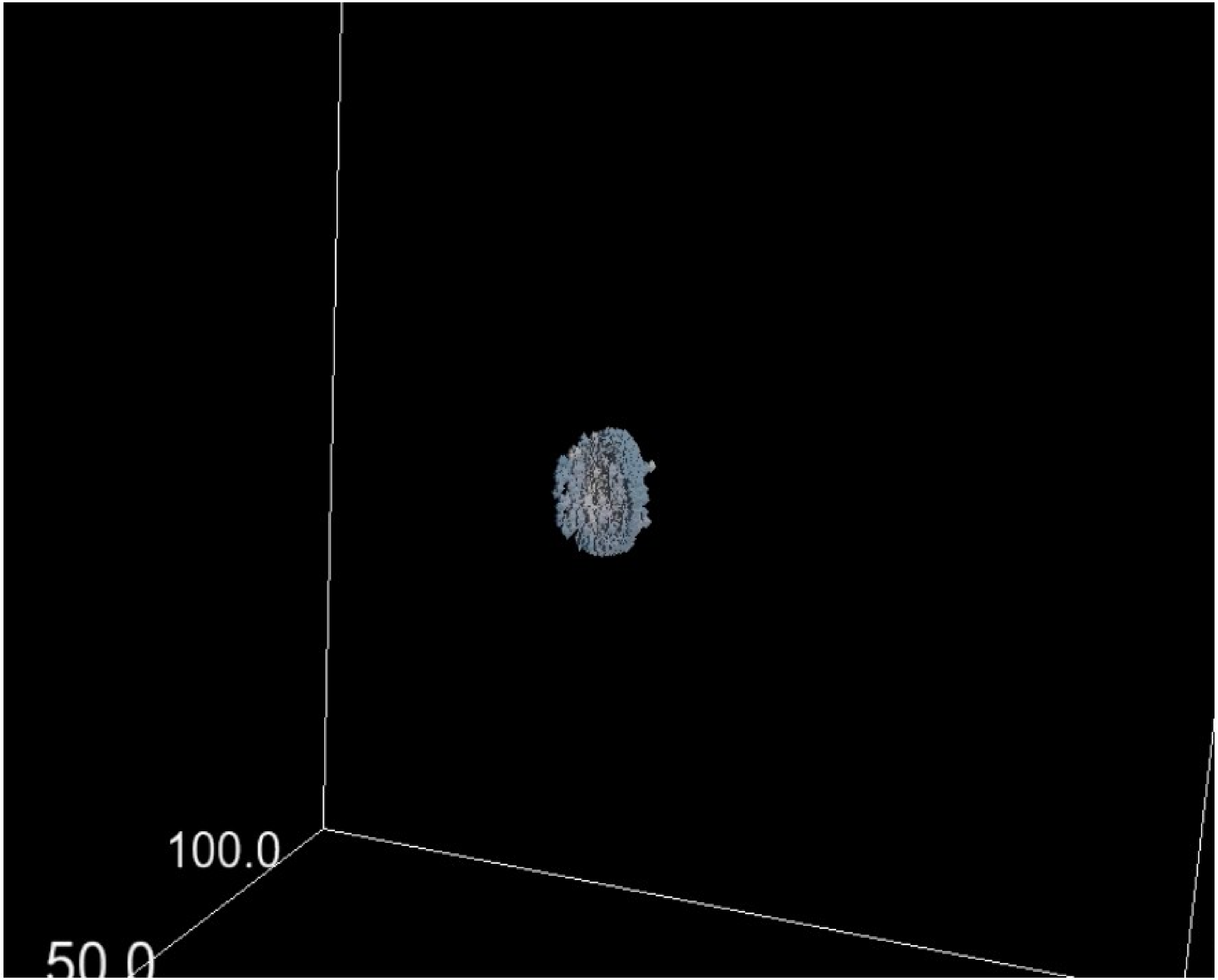


Monte-Carlo approach:
moving with probability

$$p = \Delta M / M$$

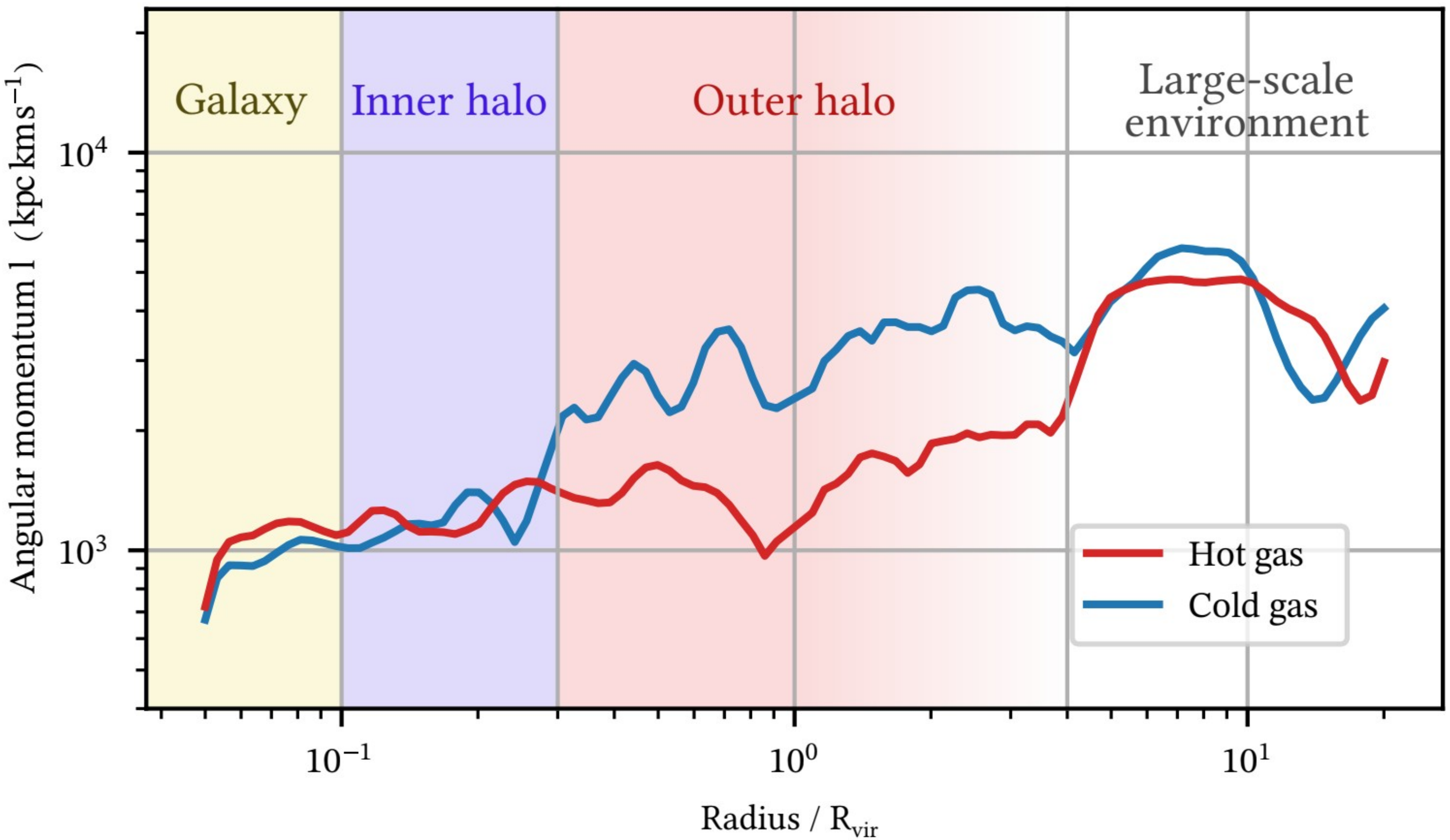
M   mass of cell
ΔM   mass flux

Tracking gas accretion using tracer particles



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

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



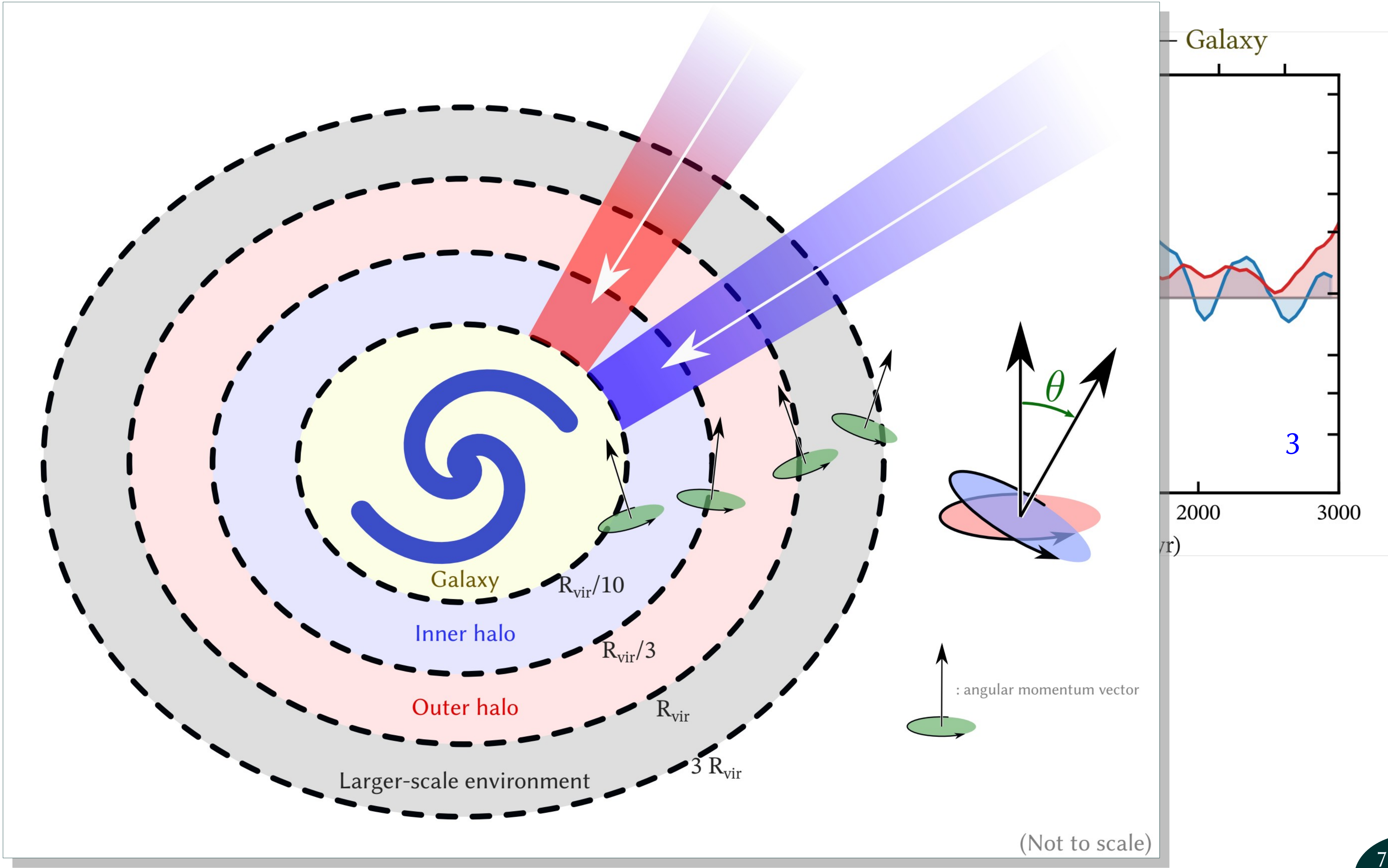
Angular momentum magnitude of the cold and hot-accreted gas. **Cadiou+in prep**

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

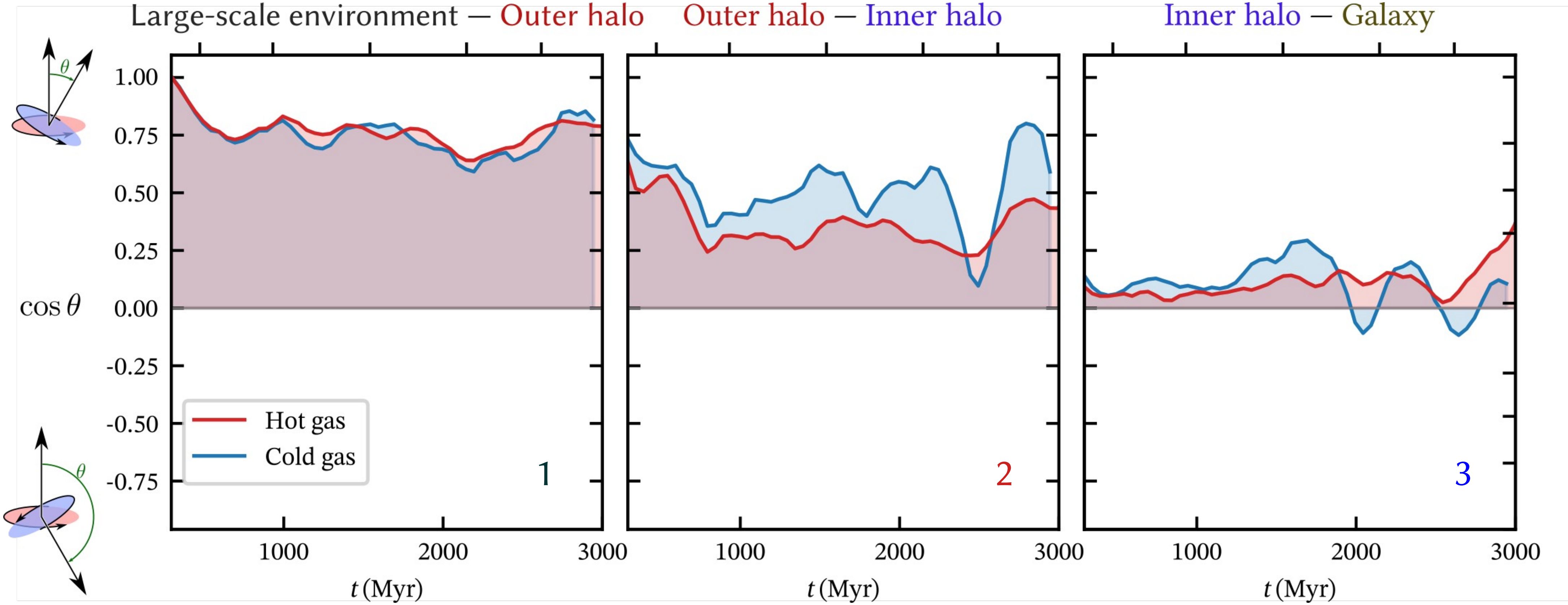
Hot gas: retains its angular momentum to **outer halo**

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

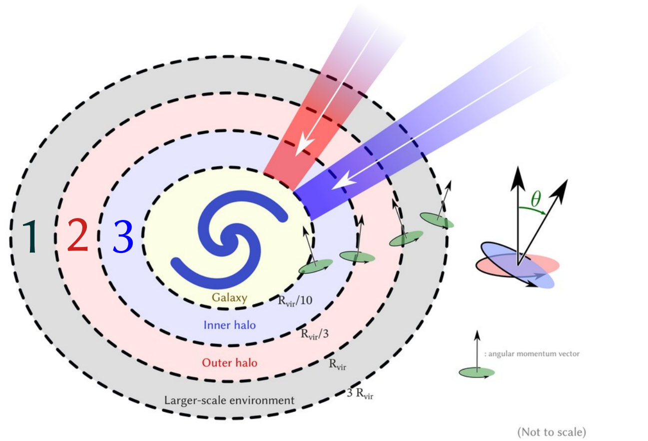
Angular momentum alignment



Angular momentum alignment



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



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

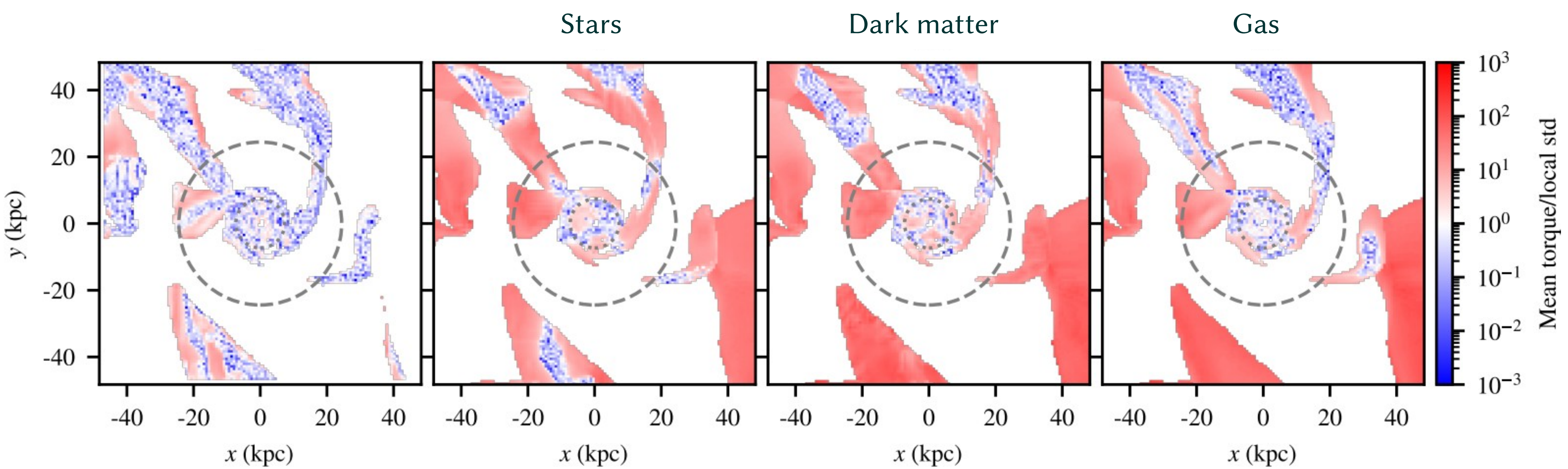
Hot gas: aligned down to **inner halo**

Pressure torques

- High-frequency variations
- Low <u>overall</u> contribution

Cause of angular momentum variation in cold-accreted gas?

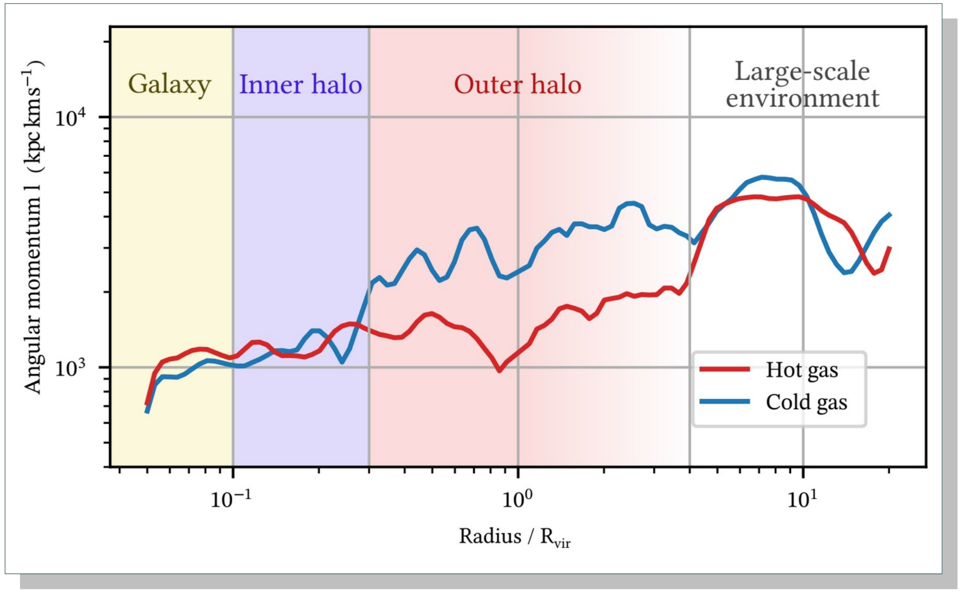
Pressure torques **Gravitational torques**

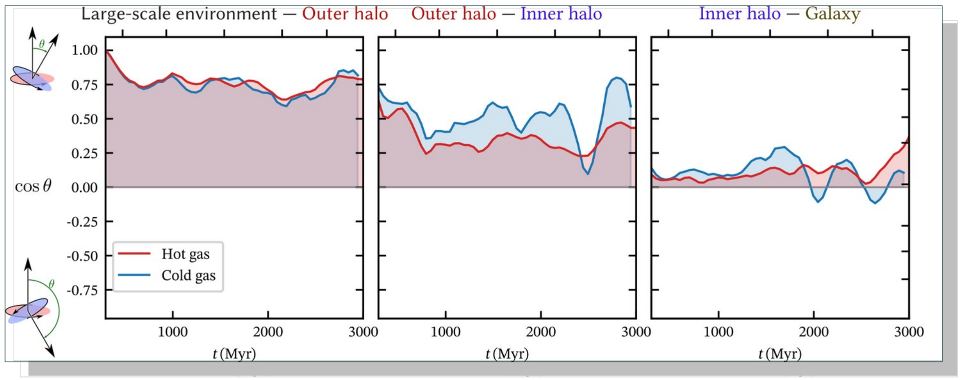


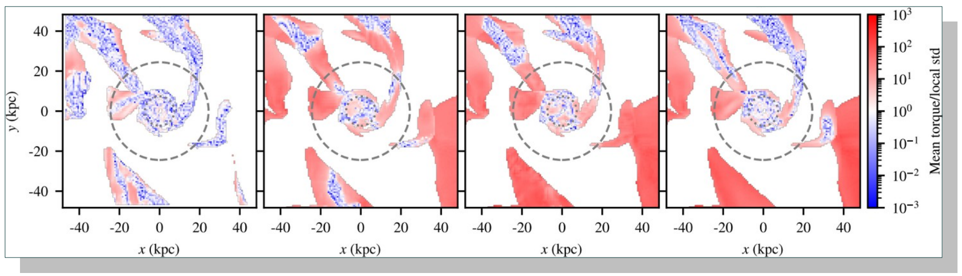
- High-frequency variations
- Low overall contribution

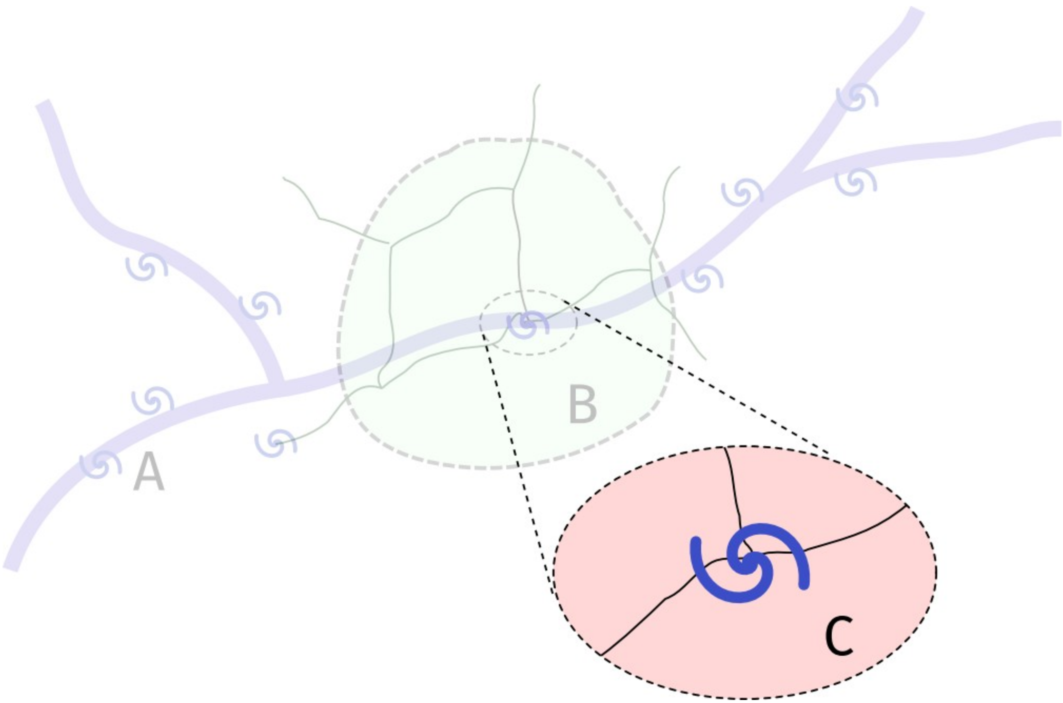
- Long wavelength variations
- Globally dominating
  - → Dark matter in outer halo
  - → Stars close to disk

- Different evolution of angular momentum of cold/hot accreted gas
- **Pressure** torques → average out
- **Gravitational** torques → globally dominant
  - **Dark matter** torques in **outer halo**
  - **Stellar** torques in **disk**

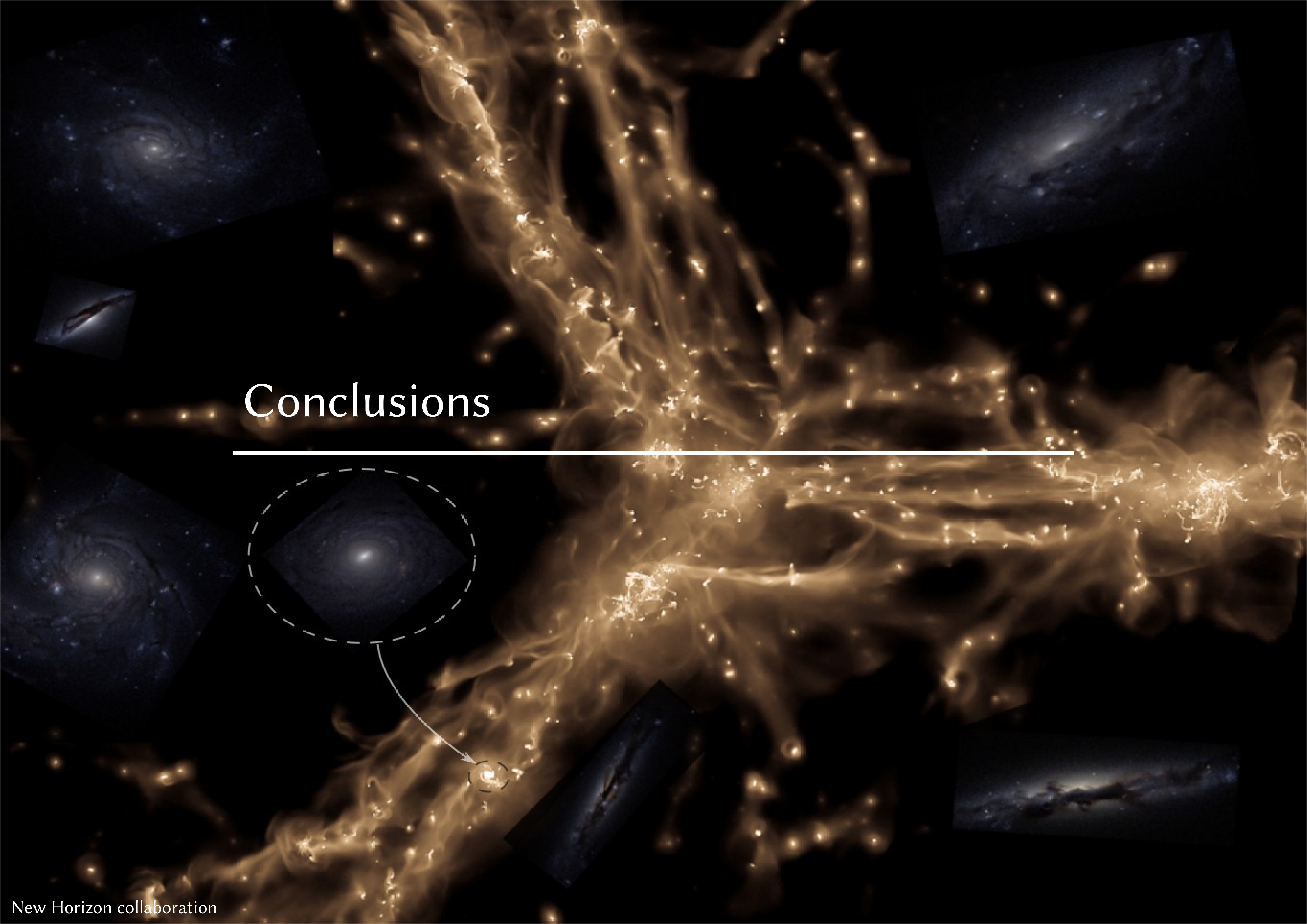








Conclusions



New Horizon collaboration

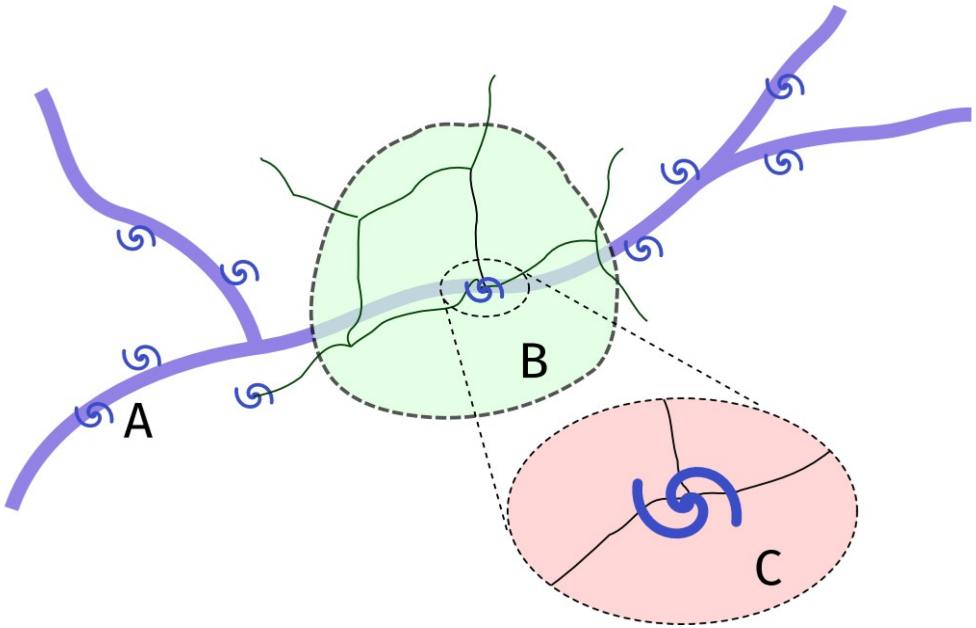
Conclusions

Cosmic web does **influence** dark matter halo & galaxy formation

- Large-scale filament → explain part of assembly bias signal
- Within Lagrangian patch → growing higher connectivity close to nodes
- Galactic scales → large-scale angular momentum transported to inner regions
  → gravity-driven

Cosmic web **evolution** best described in terms of

- Critical events:
  → halo mergers,
  → filament mergers,
  → wall mergers.

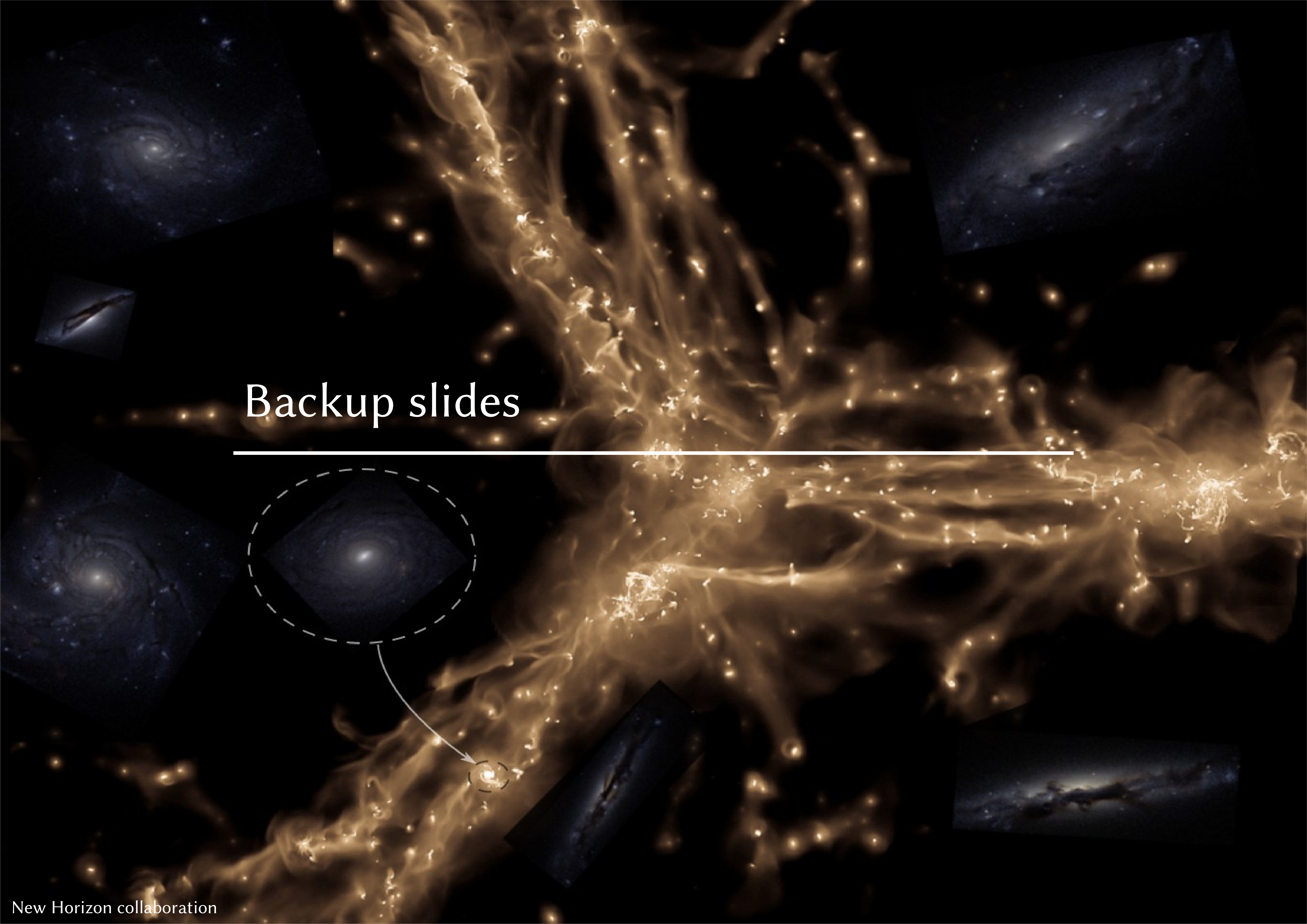


→ **Anisotropic corrections** on top of classical model

Discussions

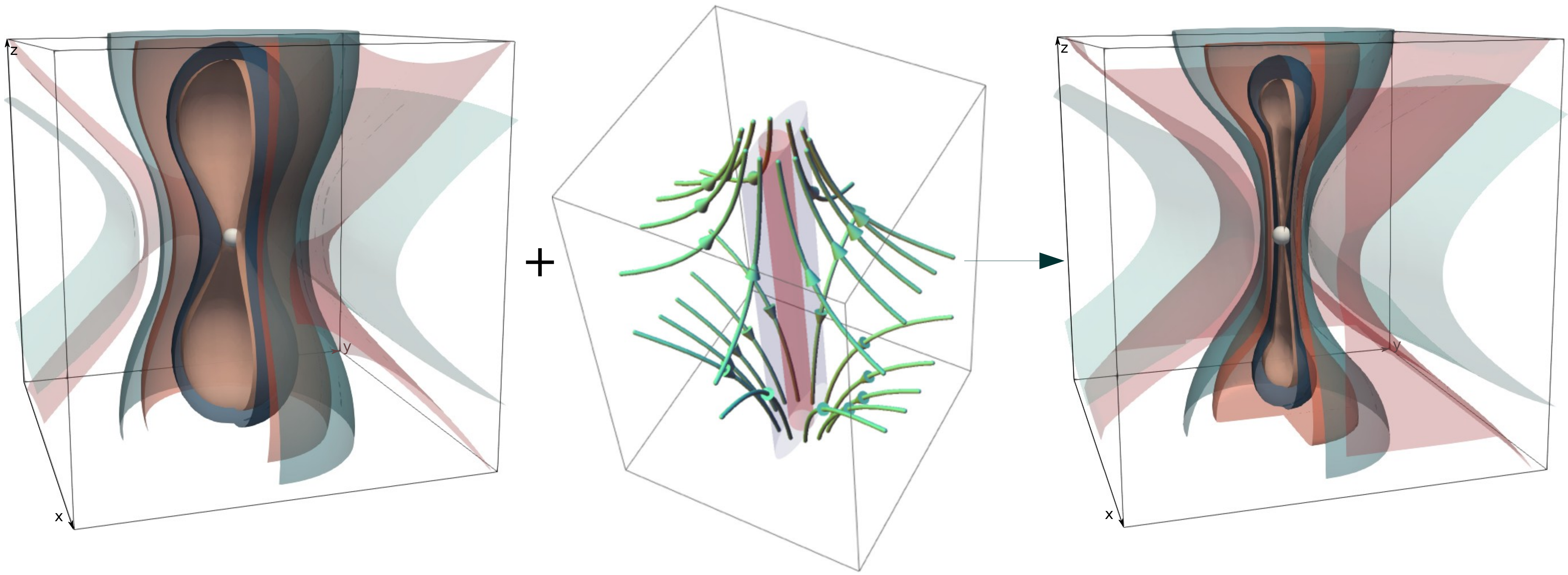
- Tidal interactions $\longrightarrow$ extend constrained excursion set theory
  $\longrightarrow$ *constrained* ellipsoidal collapse?
  [Hahn & Paranjape 14; Ludlow+14; Castorina+16; Ramakrishnan+19]
- Predict galaxy morphology *from initial conditions*
  $\longrightarrow$ use augmented merger tree (with filament & wall mergers)?
  [Extending SAMs, see Benson+10 for review]
  $\longrightarrow$ use machine learning; critical points as *compression* of information
- Galactic properties
  $\longrightarrow$ filament merger $\Longrightarrow$ spin flip *via* cold flows?
  $\longrightarrow$ control galactic spin from initial conditions?
  [Roth+16; Rey&Pontzen 17]
  $\longrightarrow$ control AGN activity from initial conditions?
  [Porqueres+18; Man+19; Huang+19]

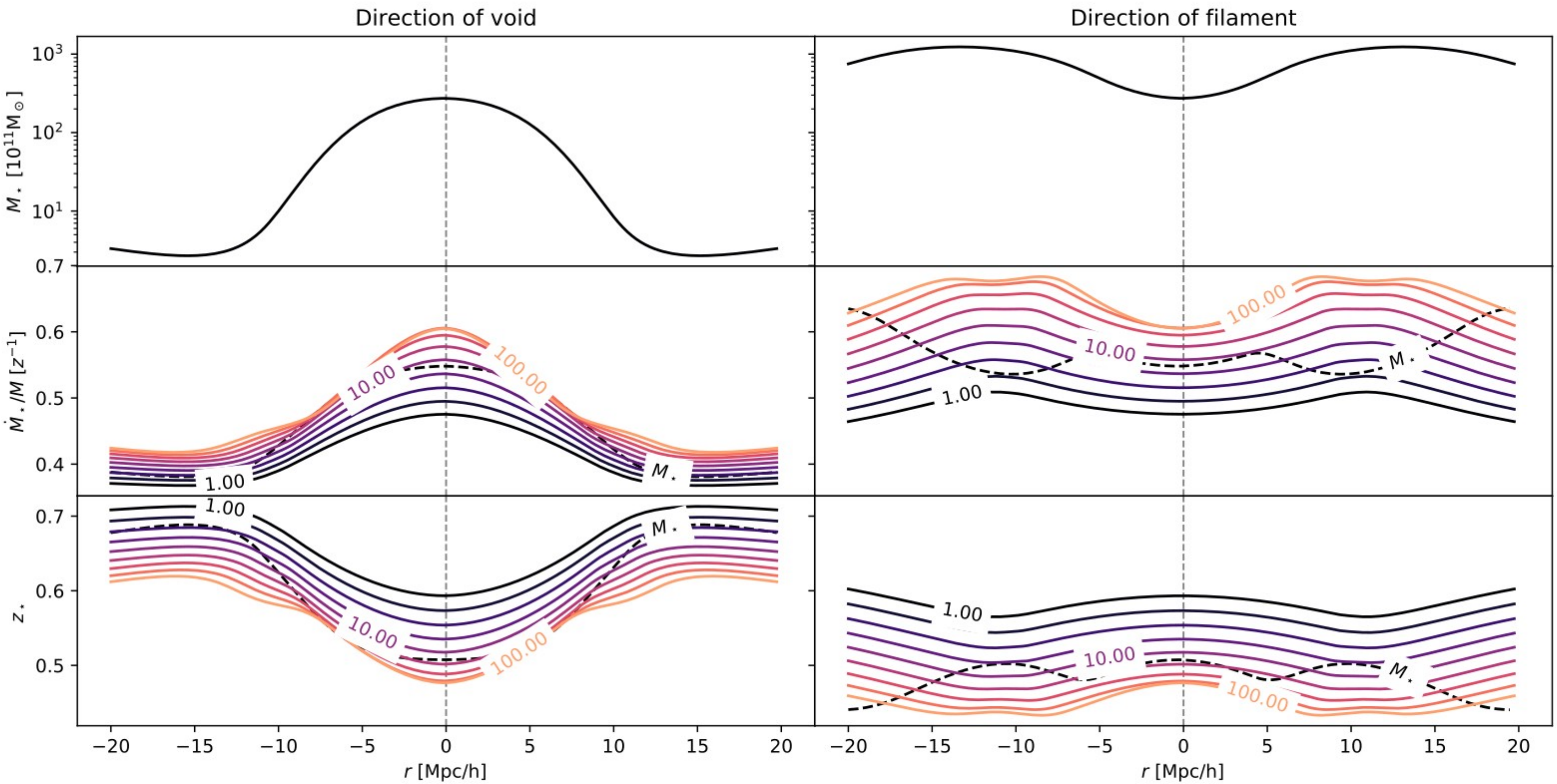
Backup slides



New Horizon collaboration

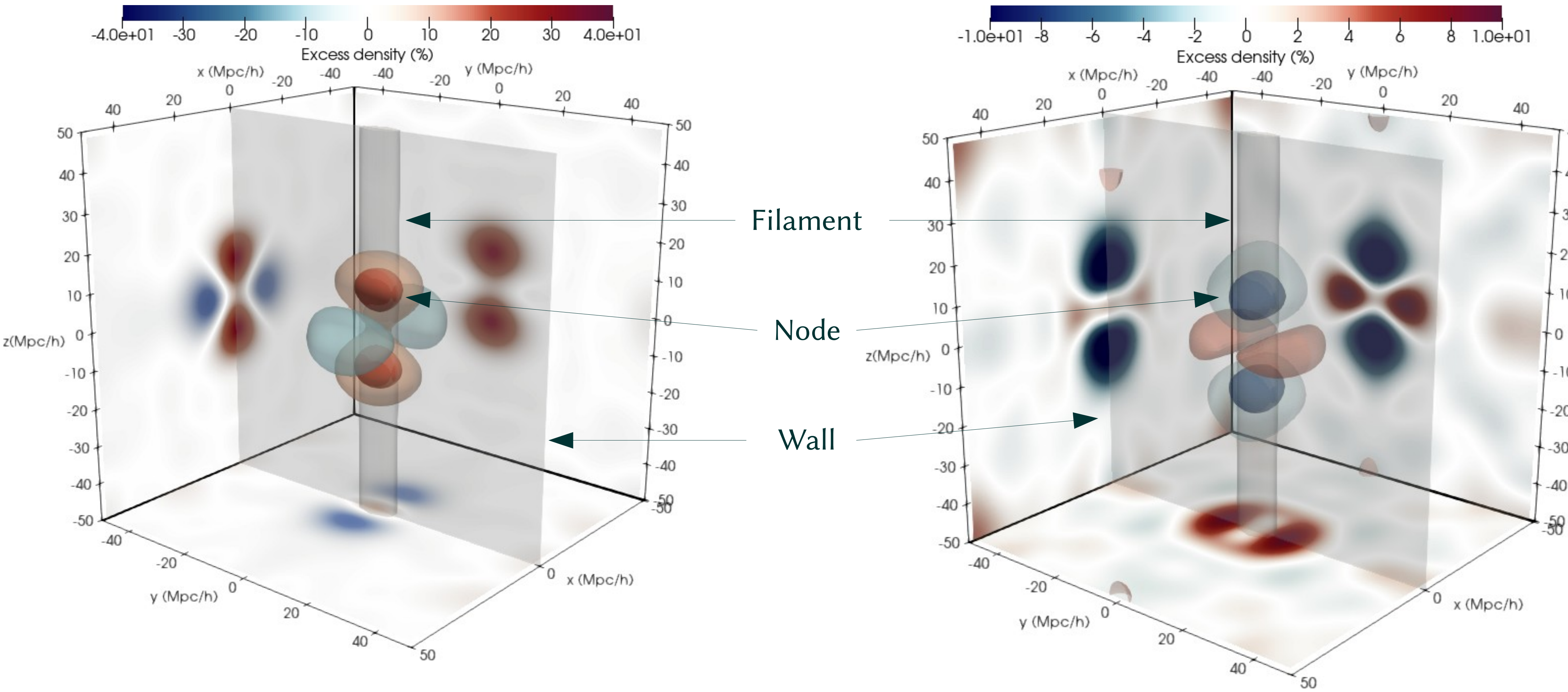
Accounting for Zel'dovich displacement





Typical mass (top), specific accretion rate (middle) and formation redshift (bottom) in the direction of the void (left) and the filament (top).

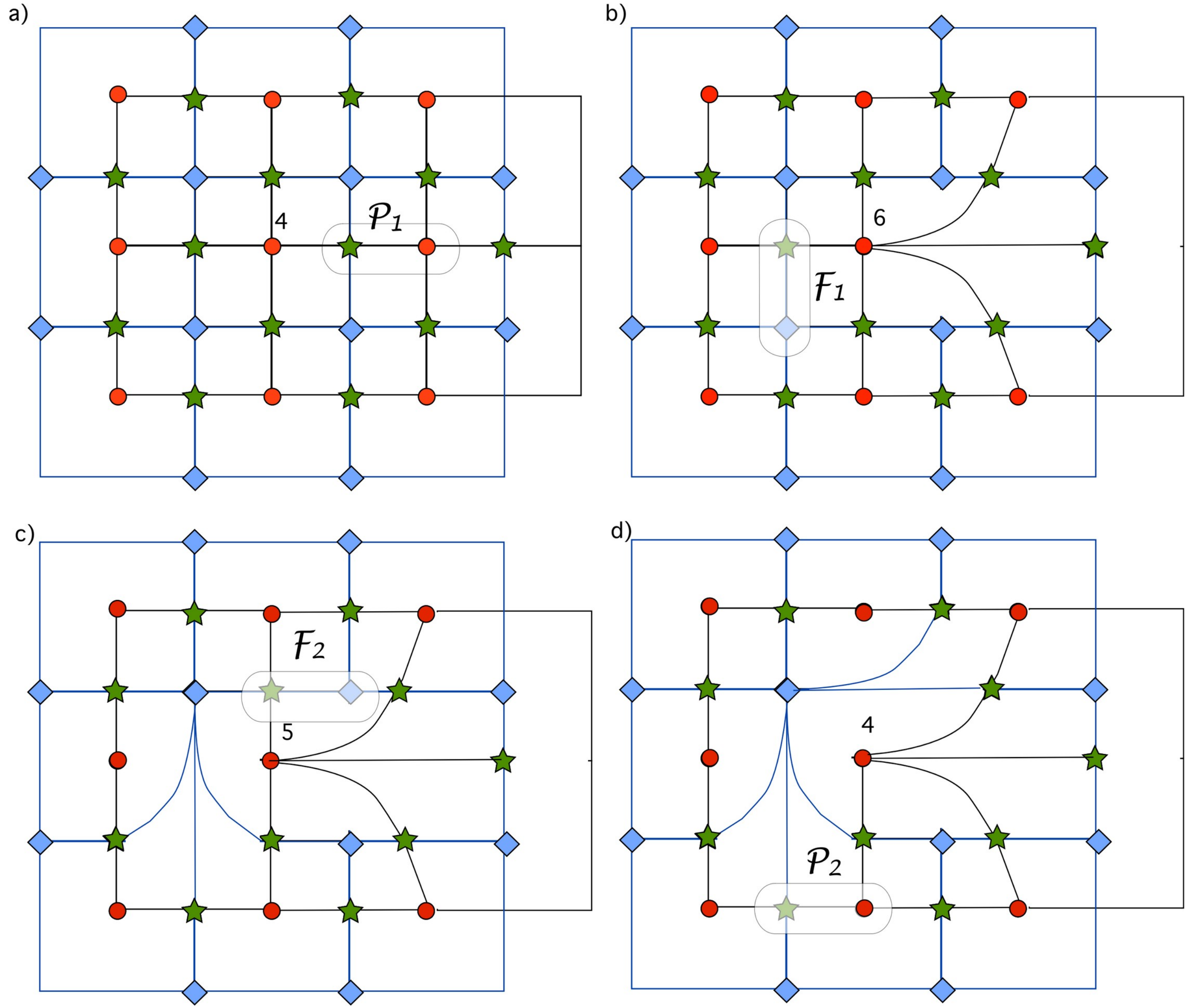
Merger rate at **fixed** final mass around filament



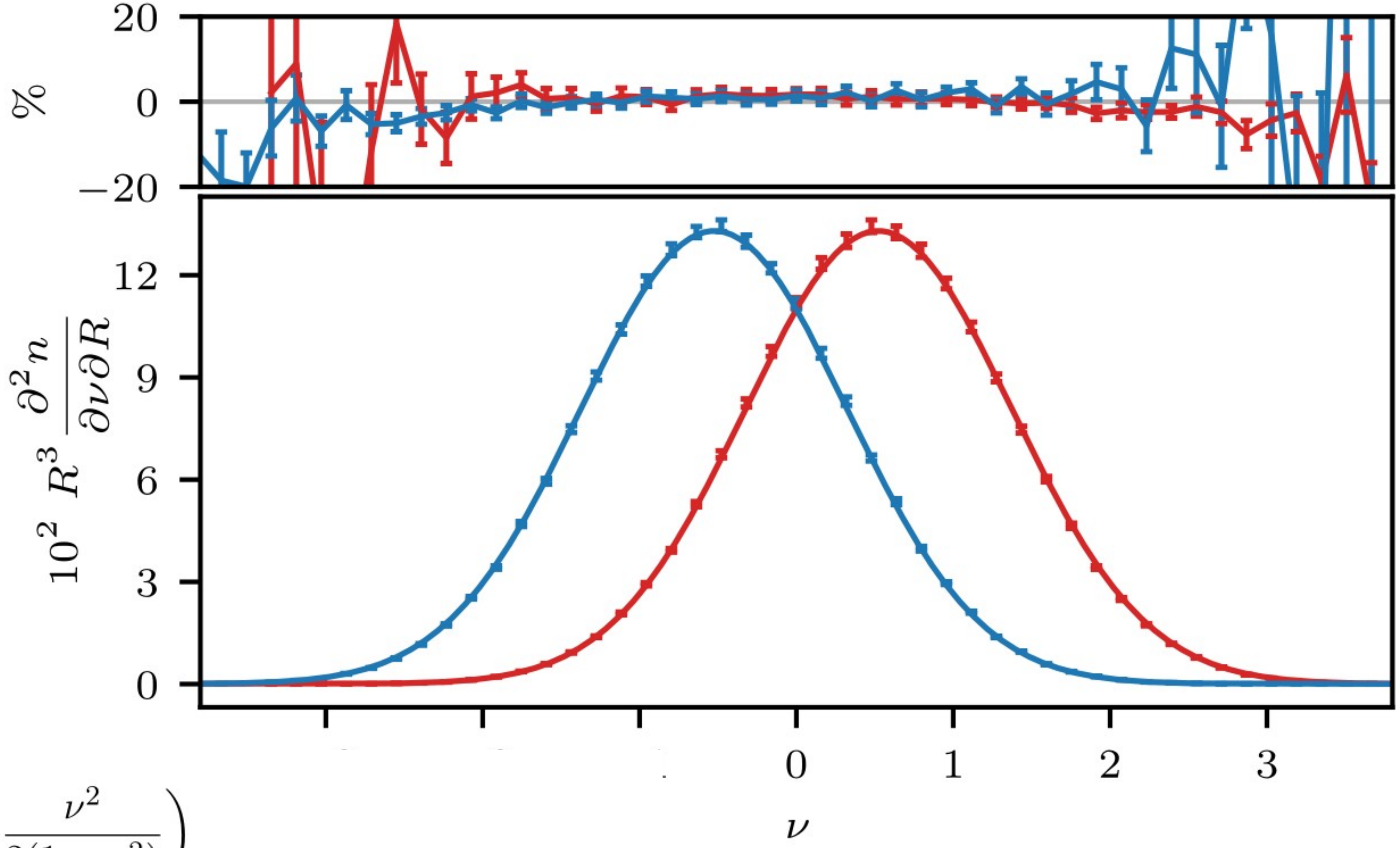
Halo merger excess density

Filament merger excess density

Connectivity and critical events – 2+1D case



Typical evolution of the connectivity and corresponding critical points.

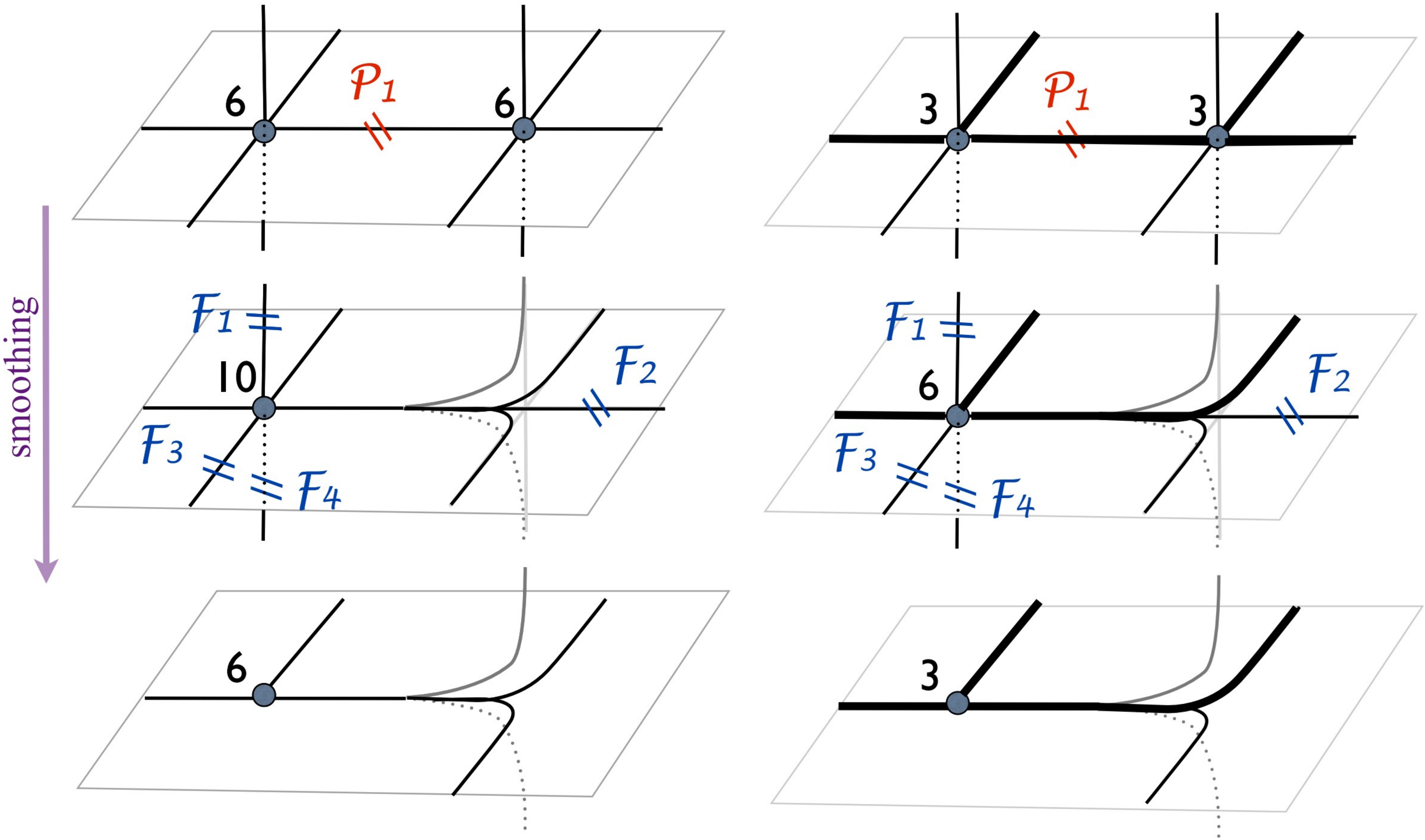


$$\frac{\partial^2 n}{\partial R \partial \nu} = \frac{R C_{\rm odd}}{\tilde{R}^2 R_*^2} \left[\frac{4\gamma\nu\sqrt{1-\gamma^2}}{(3-2\gamma^2)^2} \exp\left(-\frac{\nu^2}{2(1-\gamma^2)}\right) \right.$$
$$\left. + \frac{\sqrt{8\pi}(2\gamma^4+\gamma^2(\nu^2-5)+3)}{(3-2\gamma^2)^{5/2}} \mathrm{erfc}\left(\frac{-\gamma\nu}{\sqrt{4\gamma^4-10\gamma^2+6}}\right) \exp\left(-\frac{3\nu^2}{6-4\gamma^2}\right)\right],$$

with

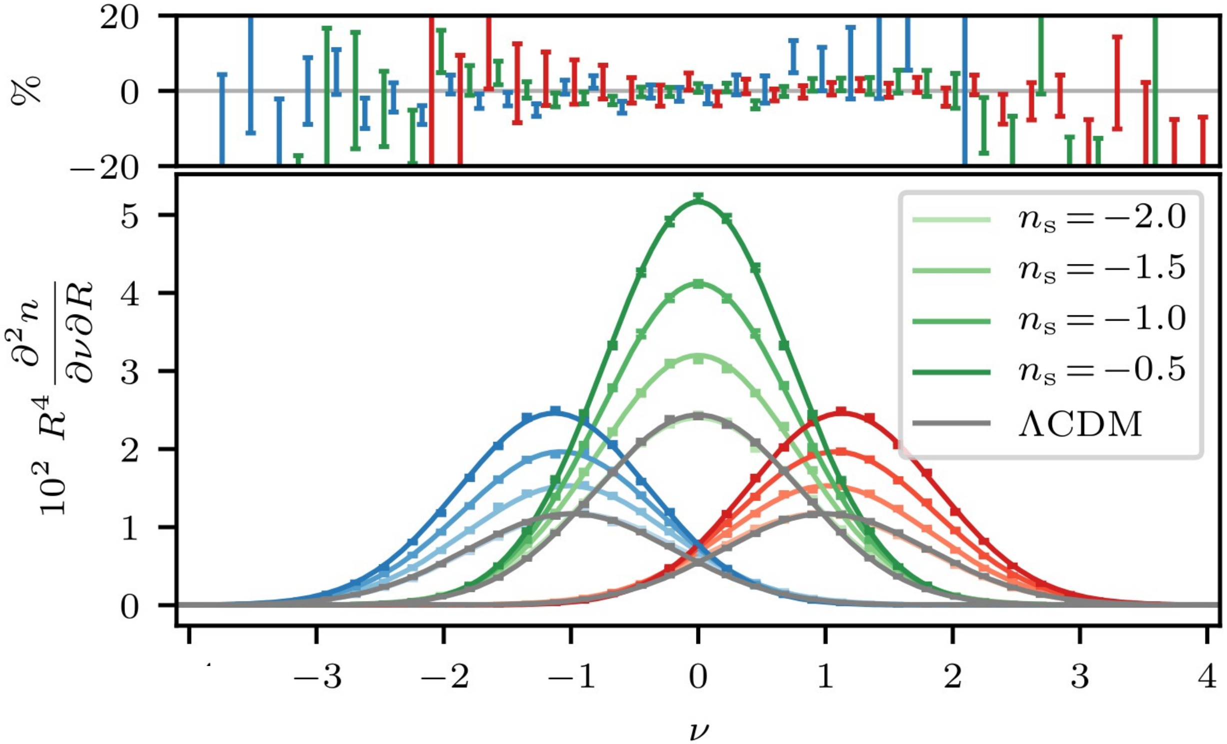
$$C_{\rm odd} = \frac{\hat\gamma + 3\hat\gamma^2 \tan^{-1}(3\hat\gamma)}{4\pi^2}, \text{ given } \hat\gamma = \sqrt{1-\tilde\gamma^2}\,.$$

Connectivity and critical events – 3+1D case



Typical evolution of the connectivity and corresponding critical points.

$$\frac{\partial^2 n}{\partial R \partial \nu} = \frac{2\pi^2 R}{\tilde{R}^2 R_*^3} C_{\rm odd} C_{j,\rm even}(\nu)$$



$$C_{\rm odd} = \frac{\sqrt{27}(1-\tilde{\gamma}^2)}{\sqrt{50\pi^5}} \left(\frac{2}{\sqrt{21(1-\tilde{\gamma}^2)}} + \tan^{-1} \frac{\sqrt{21(1-\tilde{\gamma}^2)}}{2} \right),$$

$$C_{1,\rm even}(\nu) = \sum_{i=1,6,9} c_{1,i} \exp\left(-\frac{\nu^2}{2\,(1-\gamma^2/i)}\right),$$

$$C_{2,\rm even}(\nu) = c_{2,6} \exp\left(-\frac{\nu^2}{2(1-5\gamma^2/6)}\right),$$

with

$$c_{1,1} = \frac{3\sqrt{\frac{5}{2}}\gamma\sqrt{1-\gamma^2}\nu\left(275\gamma^4+30\gamma^2\left(2\nu^2-23\right)+351\right)}{\pi^{3/2}\left(9-5\gamma^2\right)^4},$$

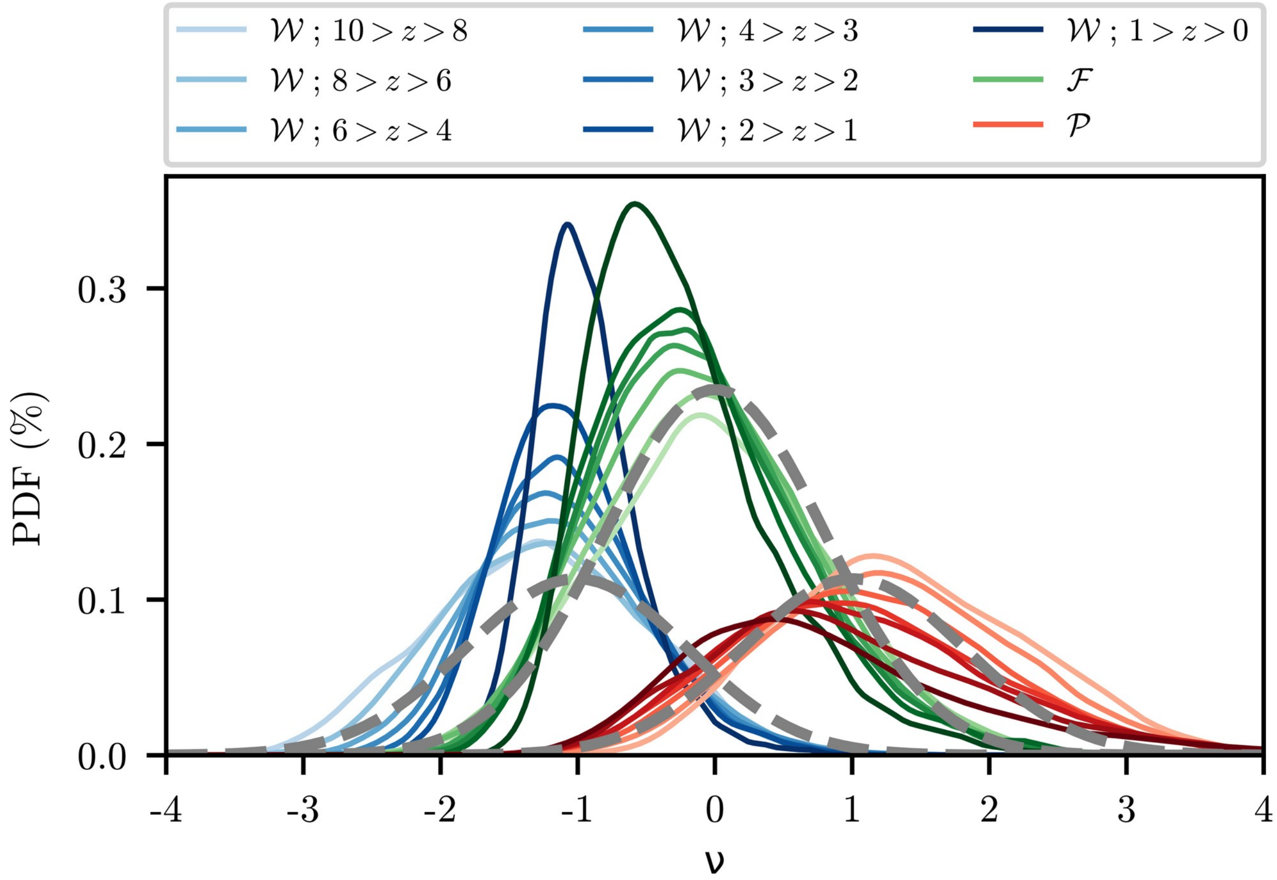
$$c_{1,6} = -\frac{\operatorname{erf}\left(\frac{\gamma\nu}{\sqrt{2}\sqrt{5\gamma^4-11\gamma^2+6}}\right)+1}{\sqrt{5}\pi\sqrt{6-5\gamma^2}},$$

$$c_{2,6} = \frac{2}{\pi\sqrt{30-25\gamma^2}},$$

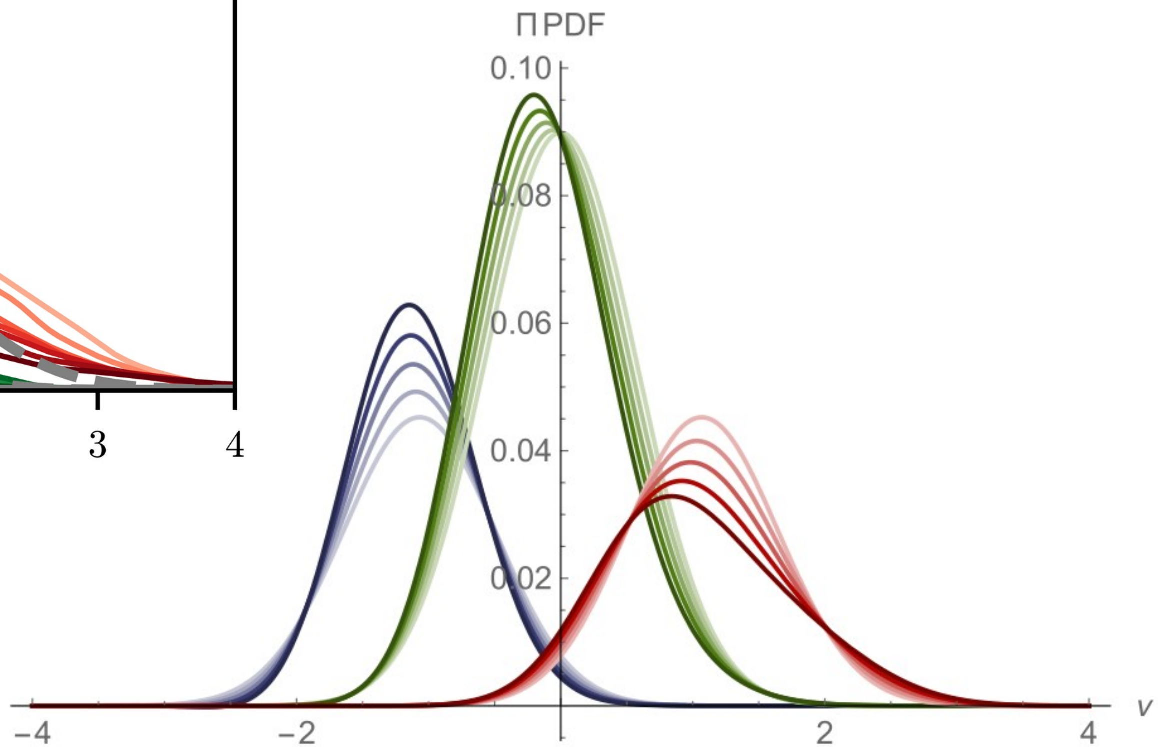
$$c_{1,9} = \frac{\operatorname{erf}\left(\frac{\sqrt{2}\gamma\nu}{\sqrt{5\gamma^4-14\gamma^2+9}}\right)+1}{4\pi\sqrt{5}\left(9-5\gamma^2\right)^{5/2}} \left(\frac{3600\gamma^4\nu^4}{\left(9-5\gamma^2\right)^2} + \frac{120\gamma^2\left(27-35\gamma^2\right)\nu^2}{9-5\gamma^2} + 575\gamma^4 - 1230\gamma^2 + 783\right).$$

Typical evolution of the connectivity and corresponding critical points.

Comparison with N-body simulations

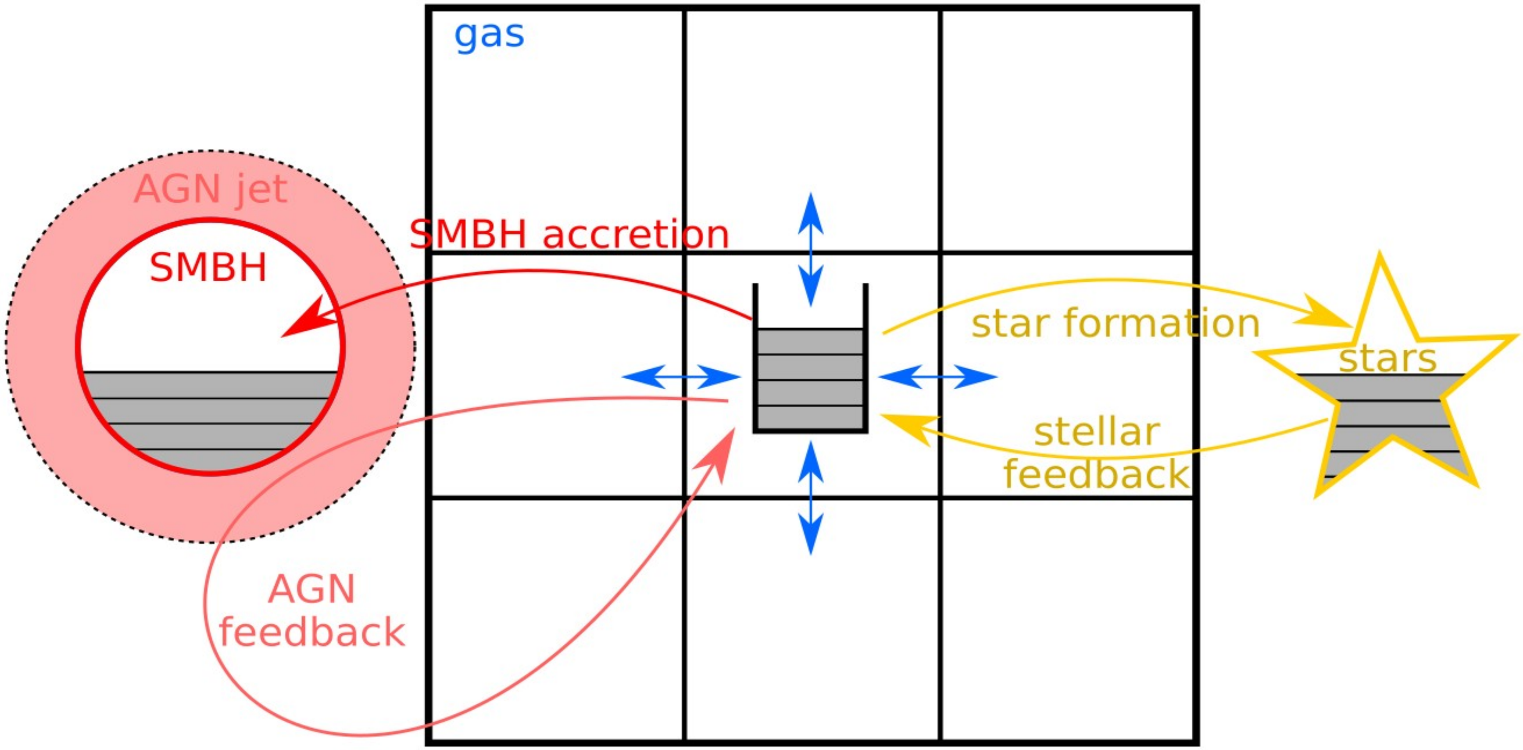


Critical event number counts (solid) in N-body simulations.



Analytical prediction of number counts at first-order in non-gaussianity.

Monte Carlo tracers

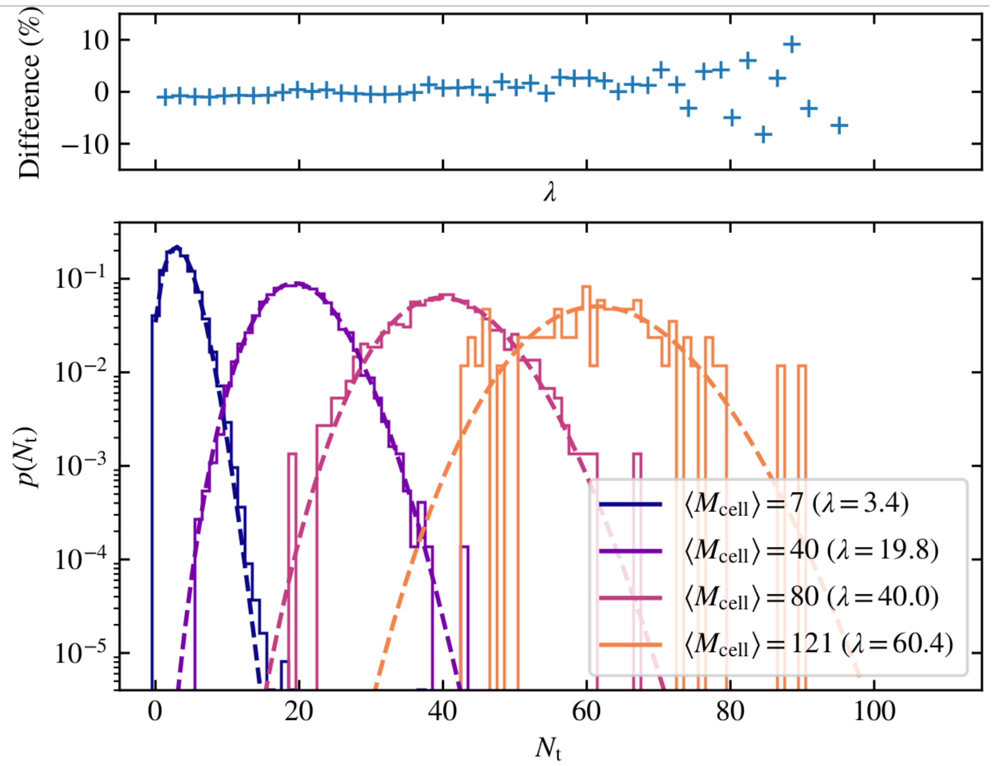


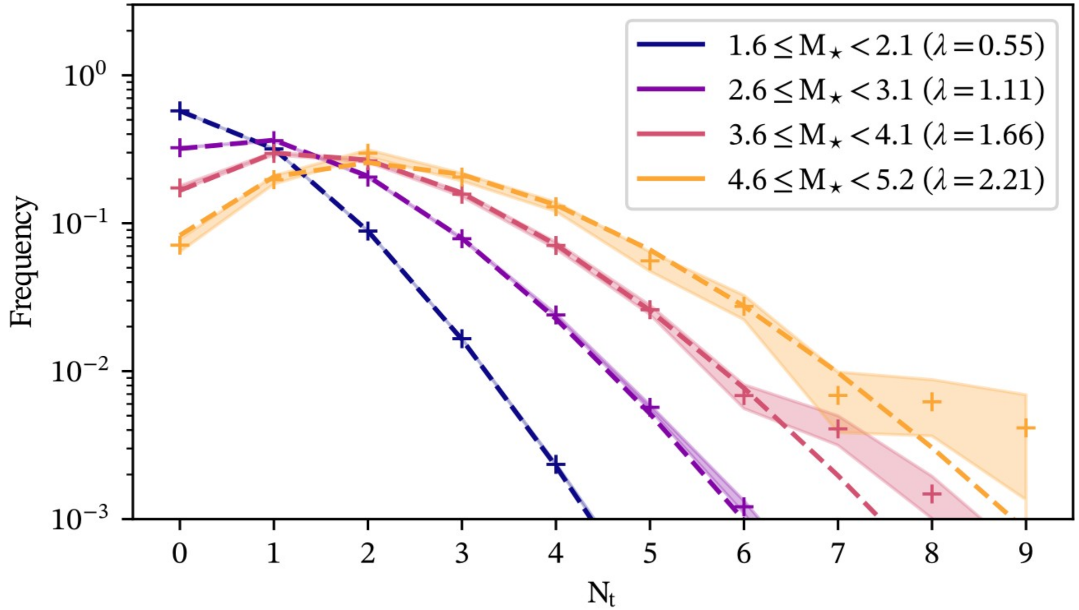
$$p_{ij} = \frac{\Delta M_{ij}}{M_{ij}}$$

- M_{ij}:
  - Mass flux between cells
  - Newly-created star mass
  - Stellar feedback
  - Black hole accretion

- M:
  - Cell mass
  - Cell mass
  - Star mass
  - Cell mass

Distribution of tracer particles



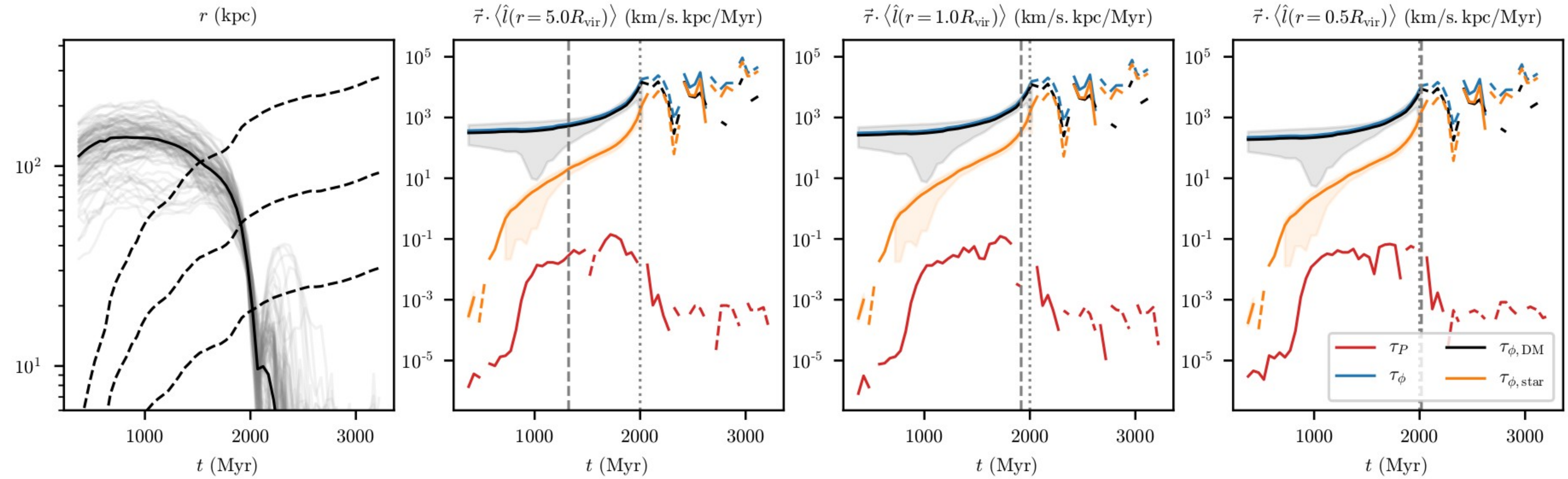


Gas tracer number density per **cell** mass bins

Star tracer particle number density per **star** mass bins

→ Number density consistent with Poisson distribution

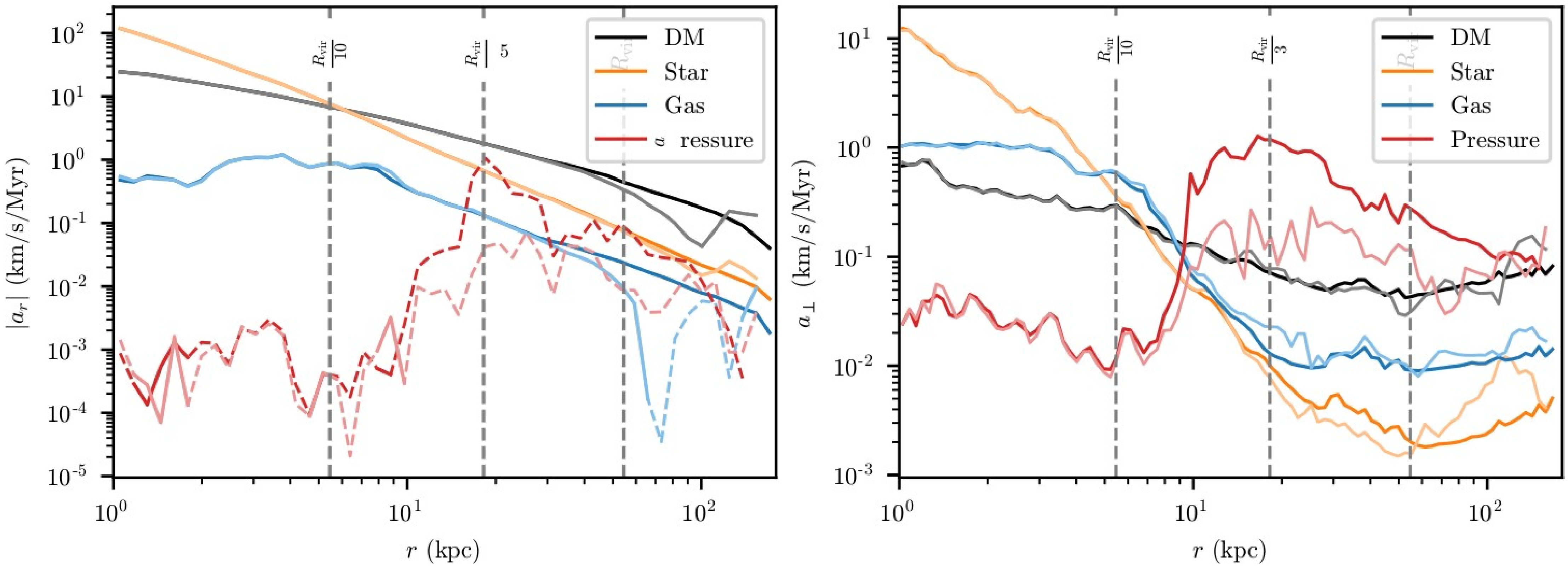
Torque along Lagrangian trajectory



Radius and mean torque magnitudes as a function of accretion time.

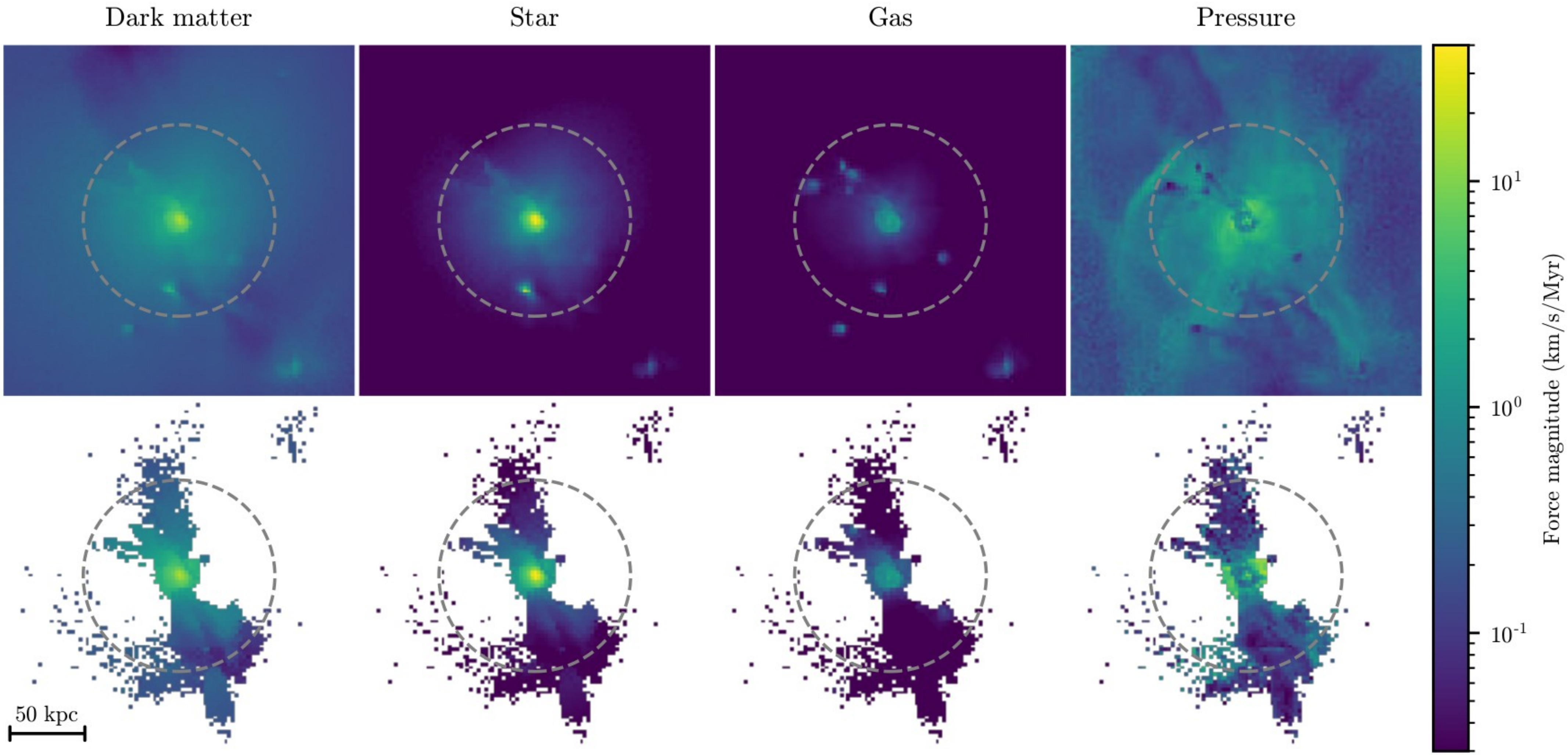
Acceleration profiles

Acceleration profiles



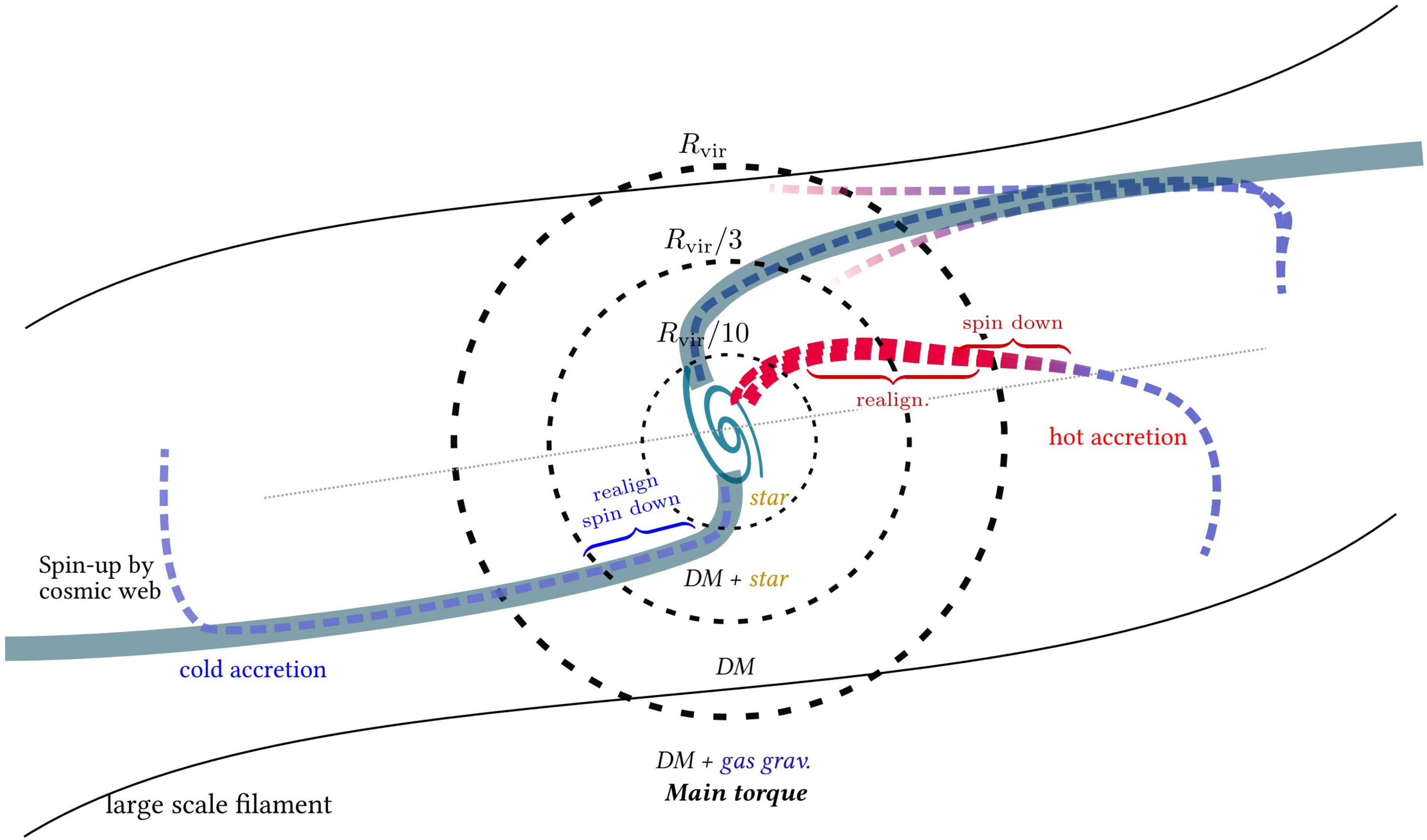
Acceleration profiles of one halo for the hot (dark) and cold-accreted (light) gas.

Acceleration profiles



Force projections around one halo for the hot (top) and cold-accreted (bottom) gas.

Conclusion AM acquisition



AM of cold gas

- **Amplitude** conserved down to **inner halo**
- **Alignment** ————————————————————

AM of hot gas

- **Amplitude** conserved up to **virial shock**
- **Alignment** preserved down to **inner halo**