When do cosmic peaks, filaments or walls merge?
A theory of critical events in a multi-scale landscape

In collaboration with C. **Pichon**, S. **Codis**, M. Musso, D. **Pogosian**, et al.

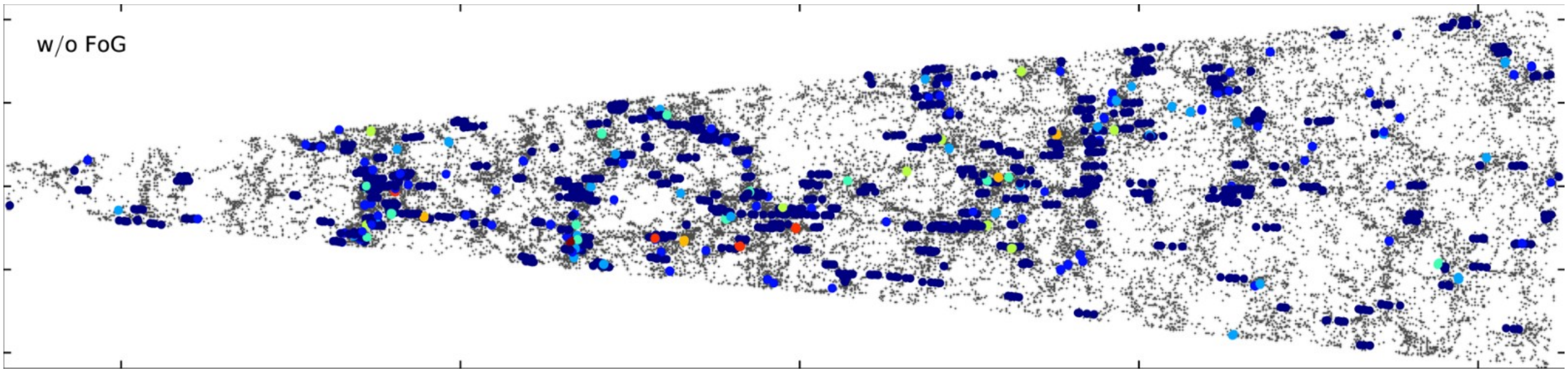
arXiv:2003.04413

New Horizon collaboration

Motivation(s)

- Unique time in terms of data... DESI, *Euclid*, LSST ⟶ millions of datapoints to play with!
  - Better "halo" model to understand data (White 78, Cooray&Sheth 2002)
    - Origin of spin alignment? Origin of spin of galaxies?
    - Origin of scatter in star-to-halo ratio?
    - Origin of morphology diversity?
  - Extract relevant information about cosmic web (CW)

0^{th} order:	mass
1^{st} order:	local density
2^{nd} order:	"assembly bias"
	cosmic web anisotropies?



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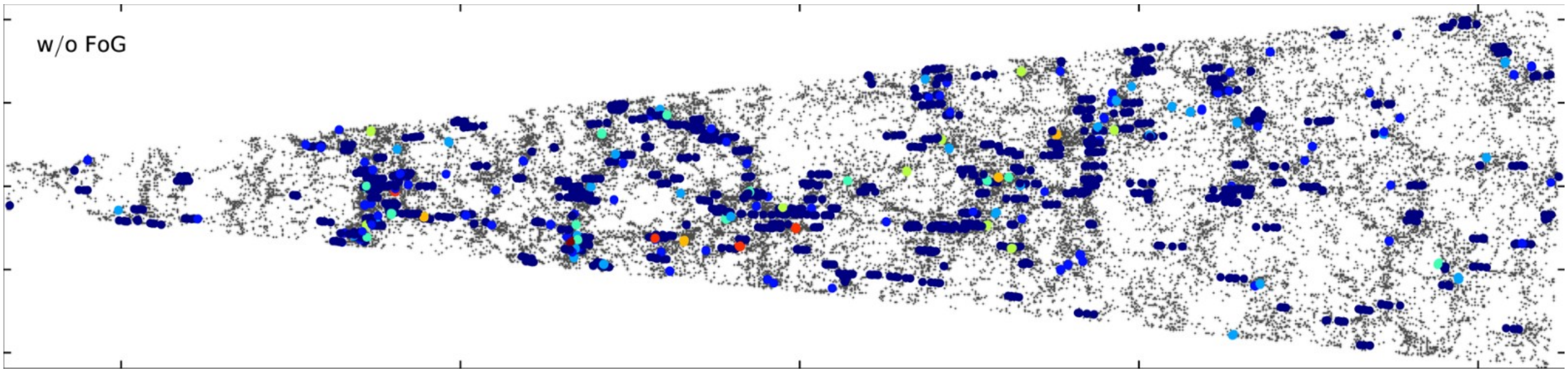

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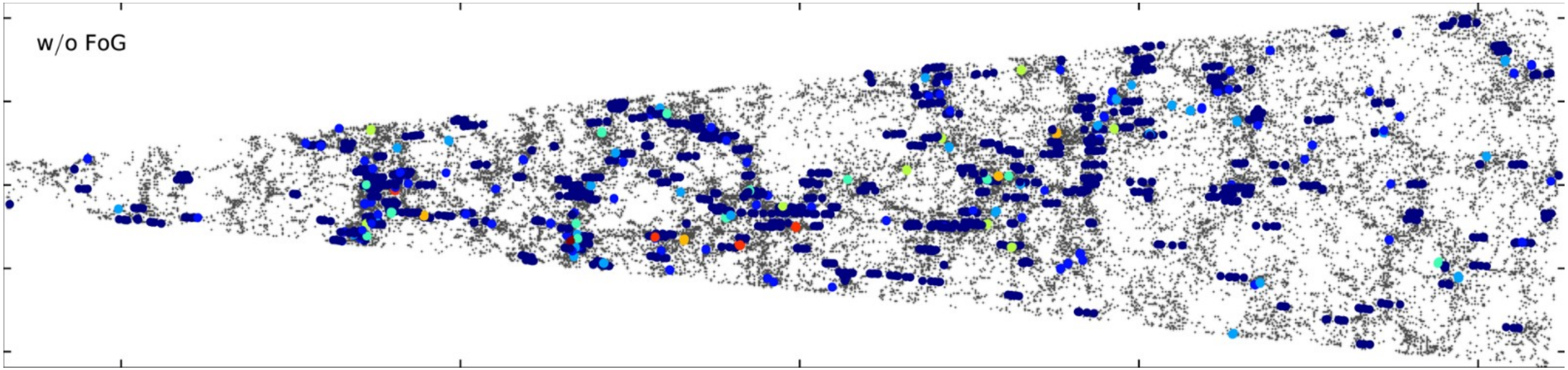

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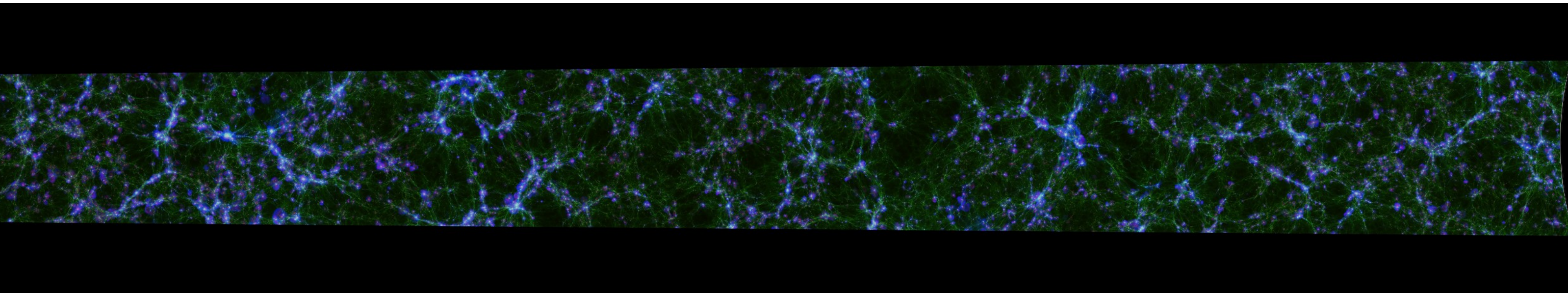
Motivation(s)

- Unique in terms of (numerical) experiment ⟶ exascale, *i.e.* billions of datapoints to generate
  - How to not be trampled by amount of data?
  - How to compare to observations?
  - What matters and what does not?

→ Use *physically motivated* summary statistics



Slice through the Horizon simulation – not yet exascale, but working on it!

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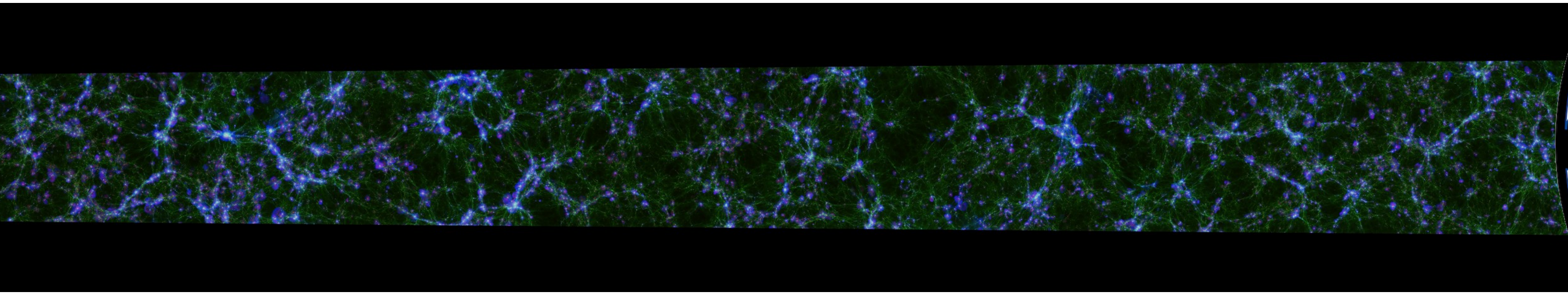
⟹ **Need a way to encode evolution of anisotropy leading to structure formation…**
… in a compact way



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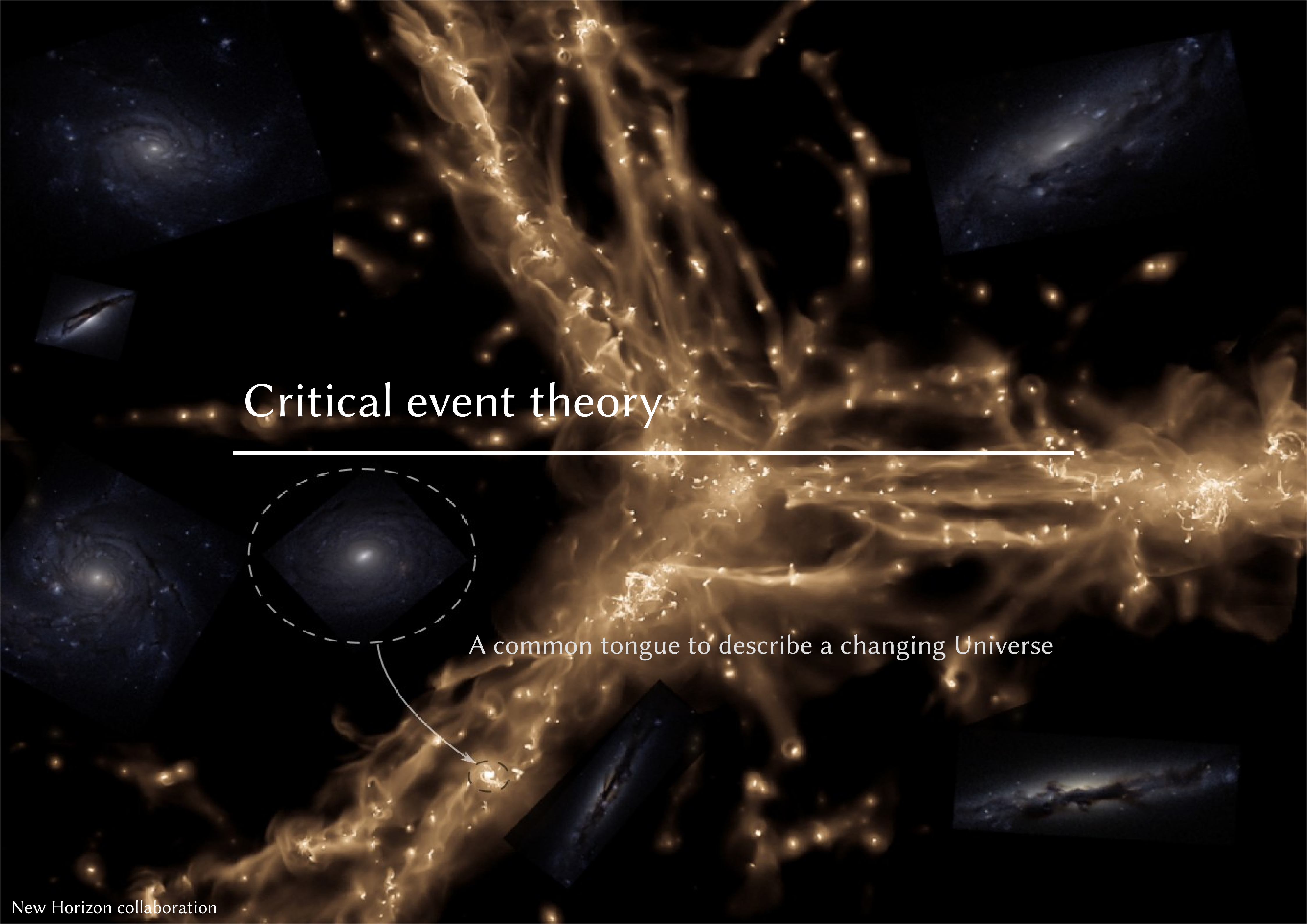
Critical event theory

New Horizon collaboration

Critical event theory

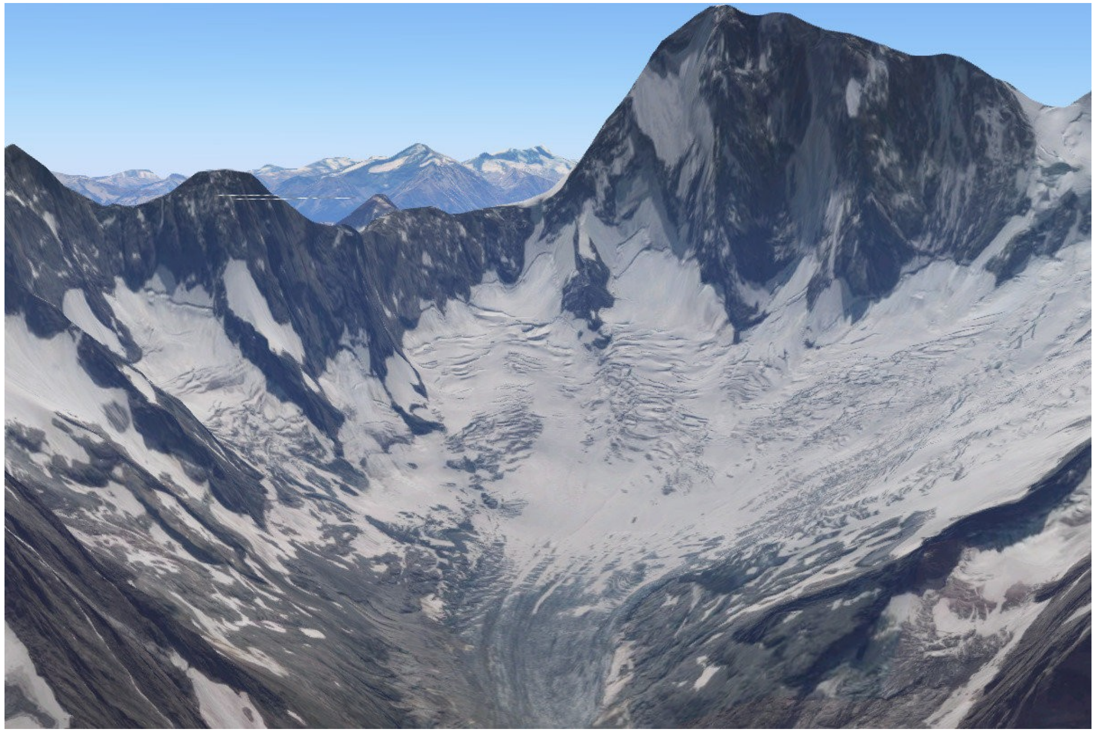
A common tongue to describe a changing Universe

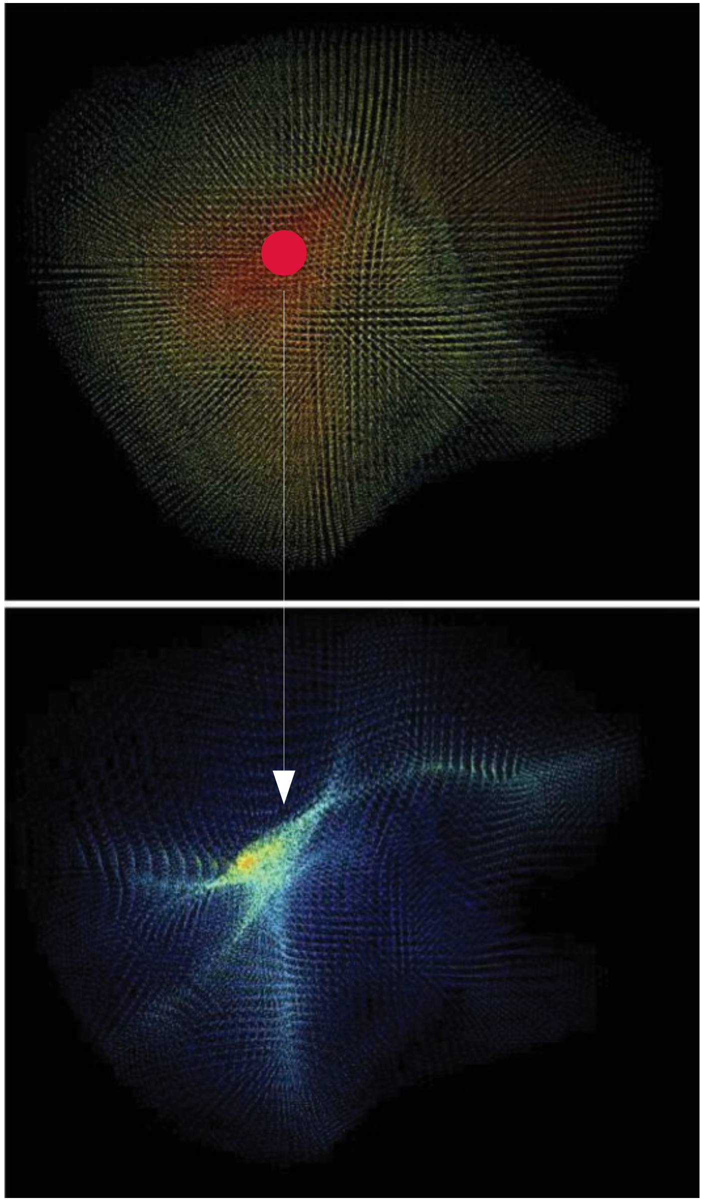


New Horizon collaboration

Inheriting from BBKS – critical *point* theory

- 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]
[Skeleton theory: Pogosyan+09, ...]

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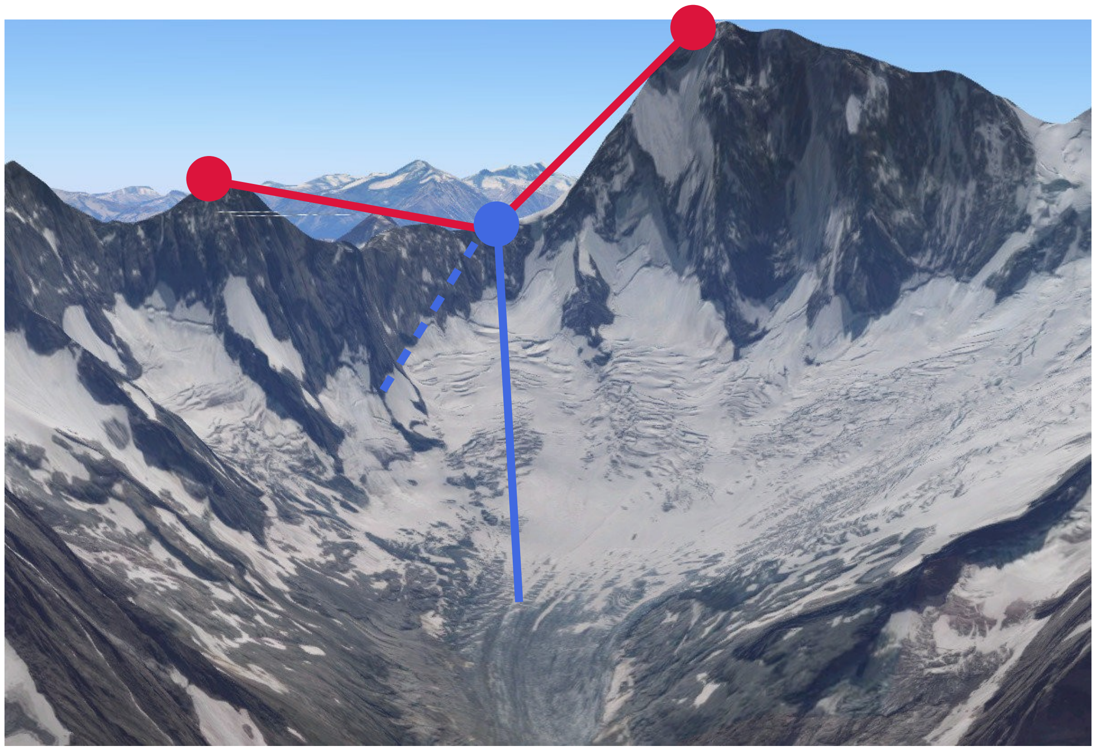

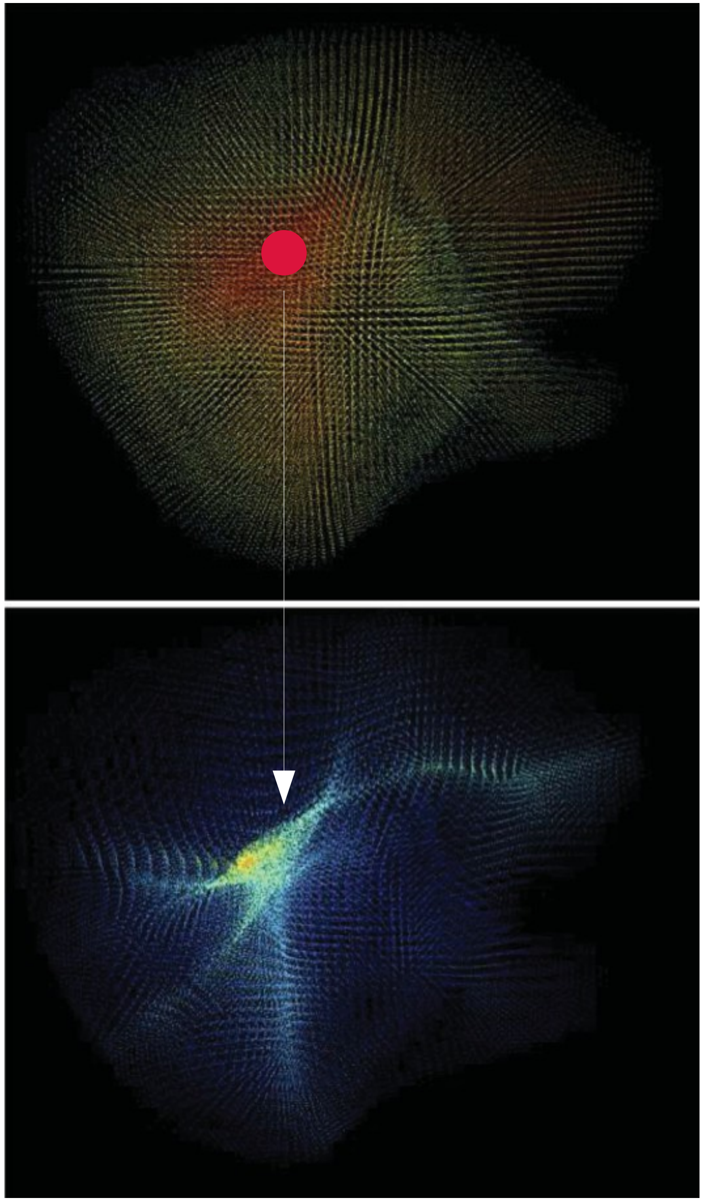

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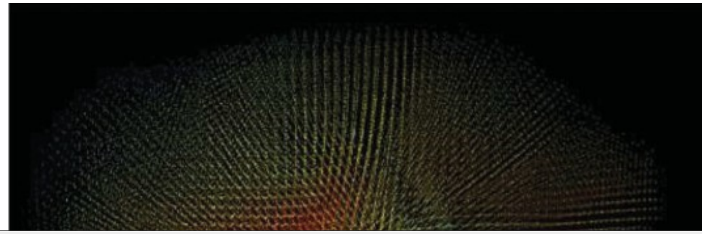
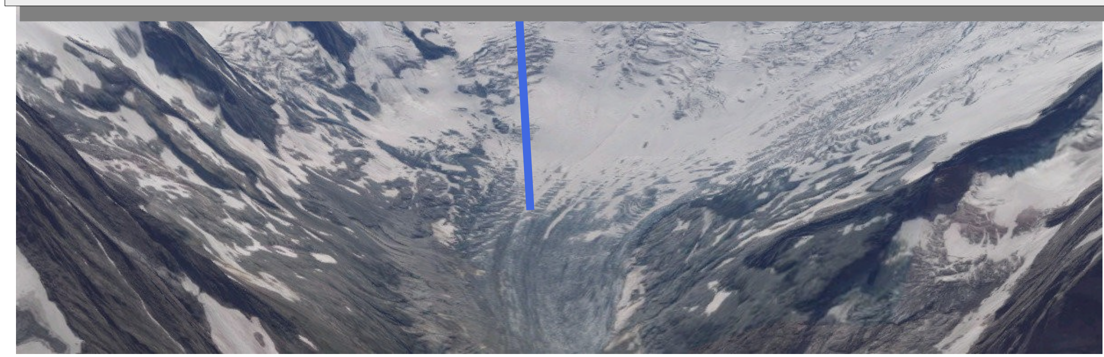
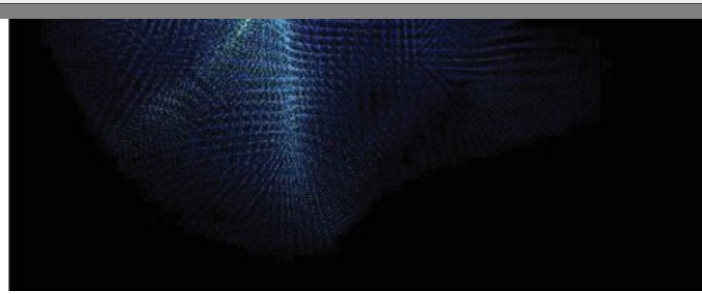


Early

Critical points:

N-dimensional field $\longrightarrow$ compressed in finite set of points in N dim at scale R





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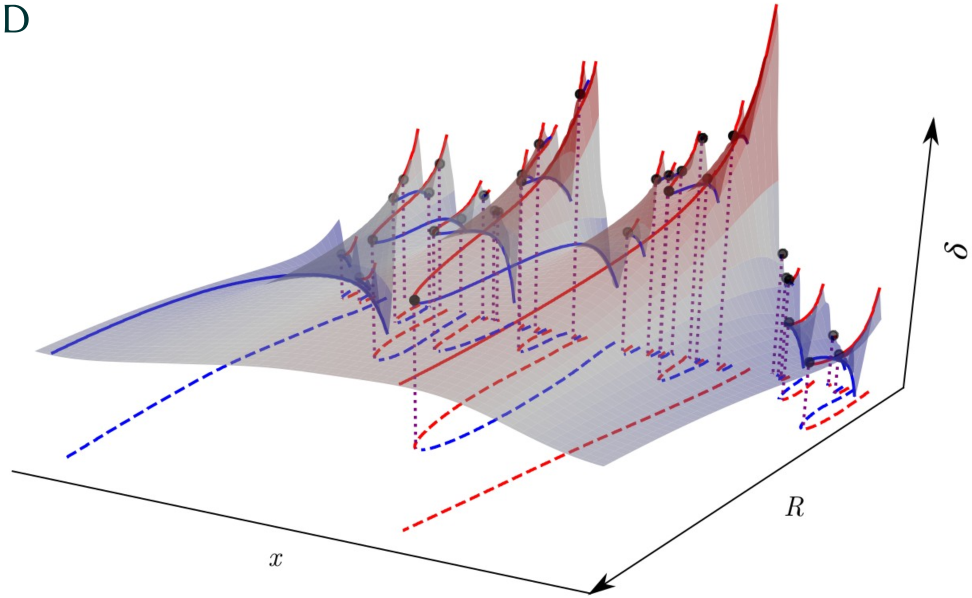
Inheriting from BBKS – critical *event* theory

1+1D



BBKS (peak theory):

Halos form out of peaks

High δ $\longrightarrow$ early formation

High R $\longrightarrow$ high mass

$\Longrightarrow$ multi-scale analysis (different R)

$\longrightarrow$ mass as a function of time

- ✗ Answer depends on scale considered
- ✗ Continuous information (*i.e.* $M(z)$)

[Skeleton tree: Hanami+01]

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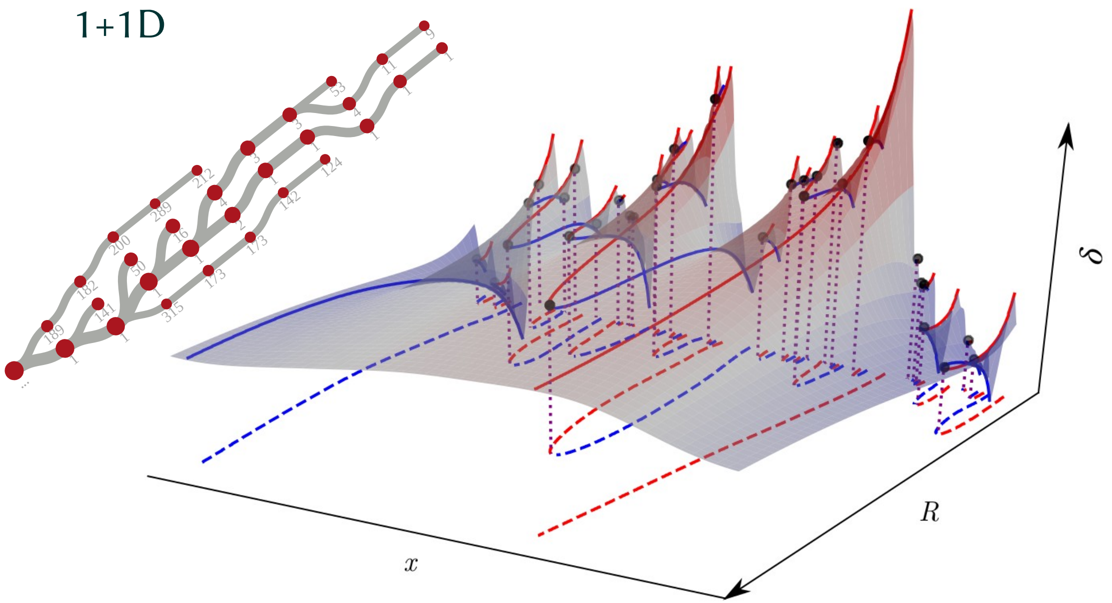

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$$“\ \frac{\partial \mathrm{BBKS}(M(R),t)}{\partial R}\ ”$$

$\Longrightarrow$ Spot peaks disappearing

- ✔ Scale intrisic to theory!
- ✔ Efficient compression (*i.e.* $(M(z),z)$)
- ✔ Applicable to peaks, filaments, walls, voids

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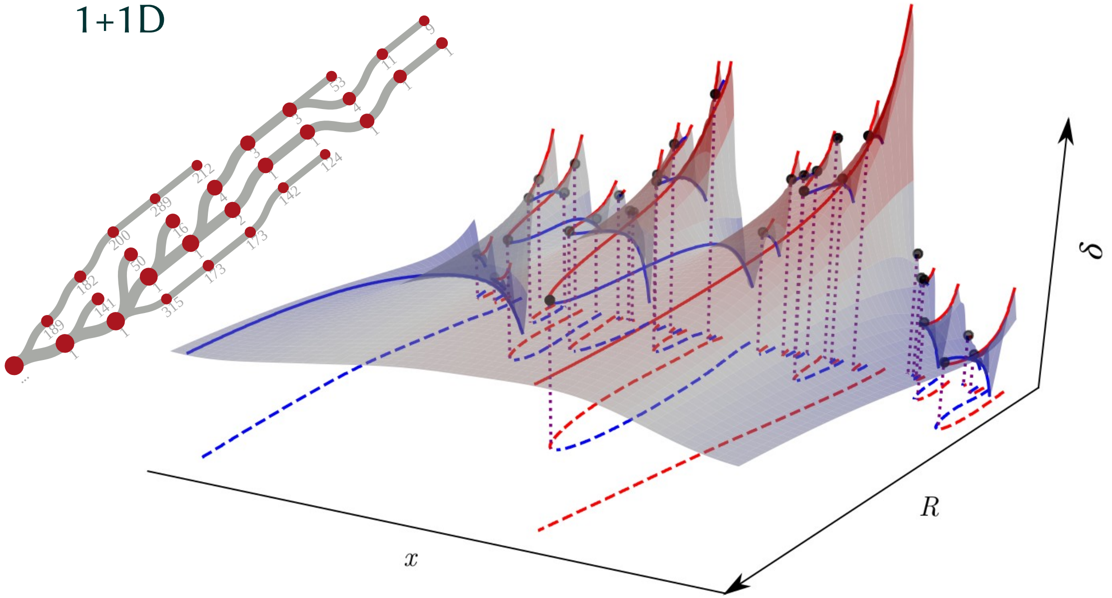
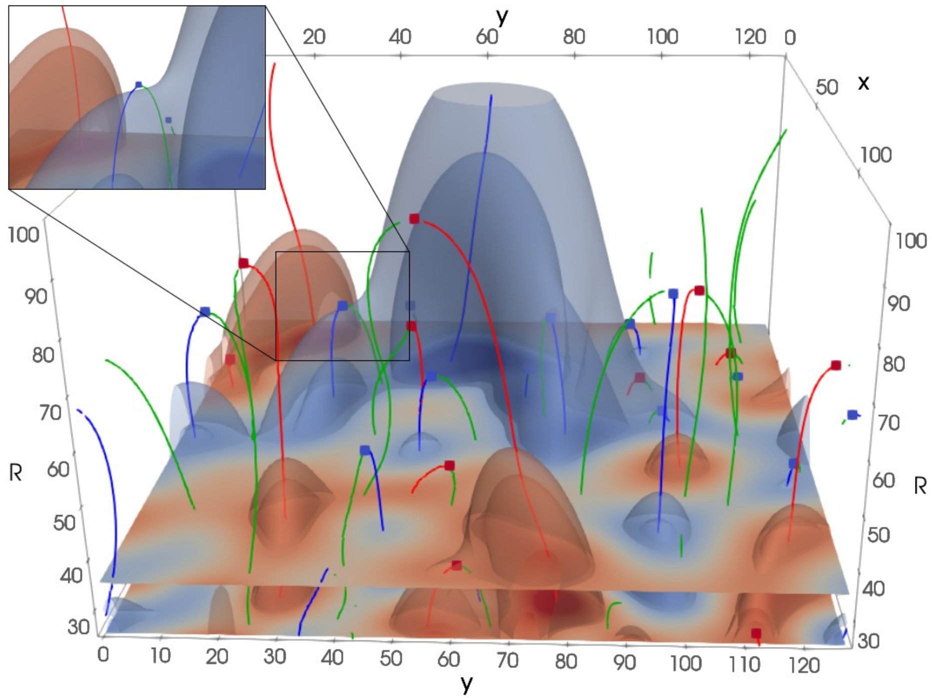


2+1D



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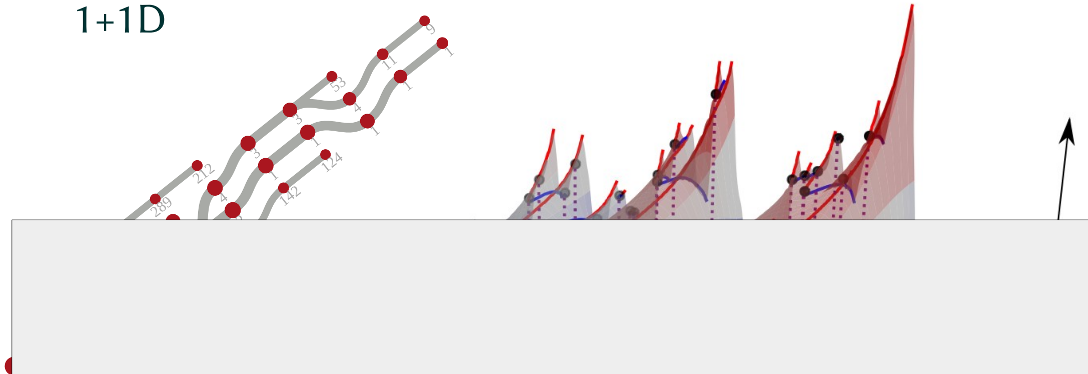

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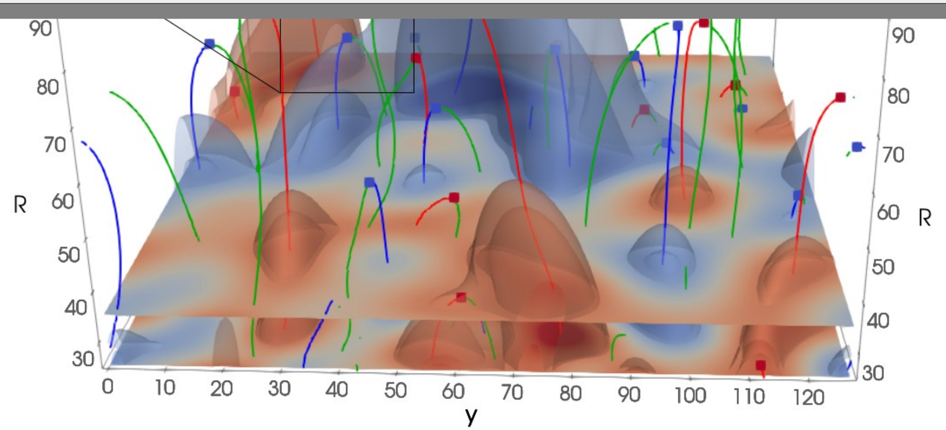

$$\partial R$$

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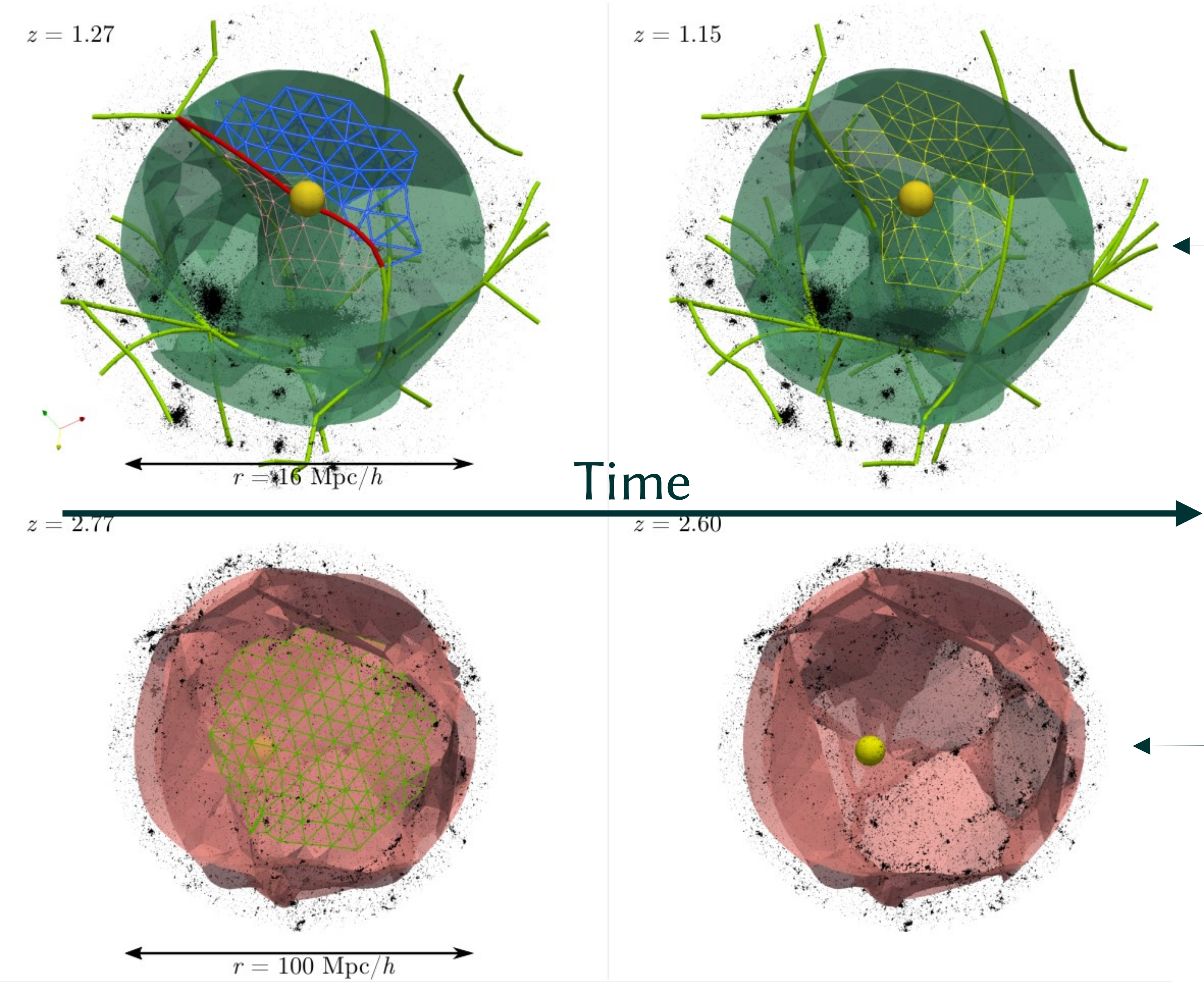
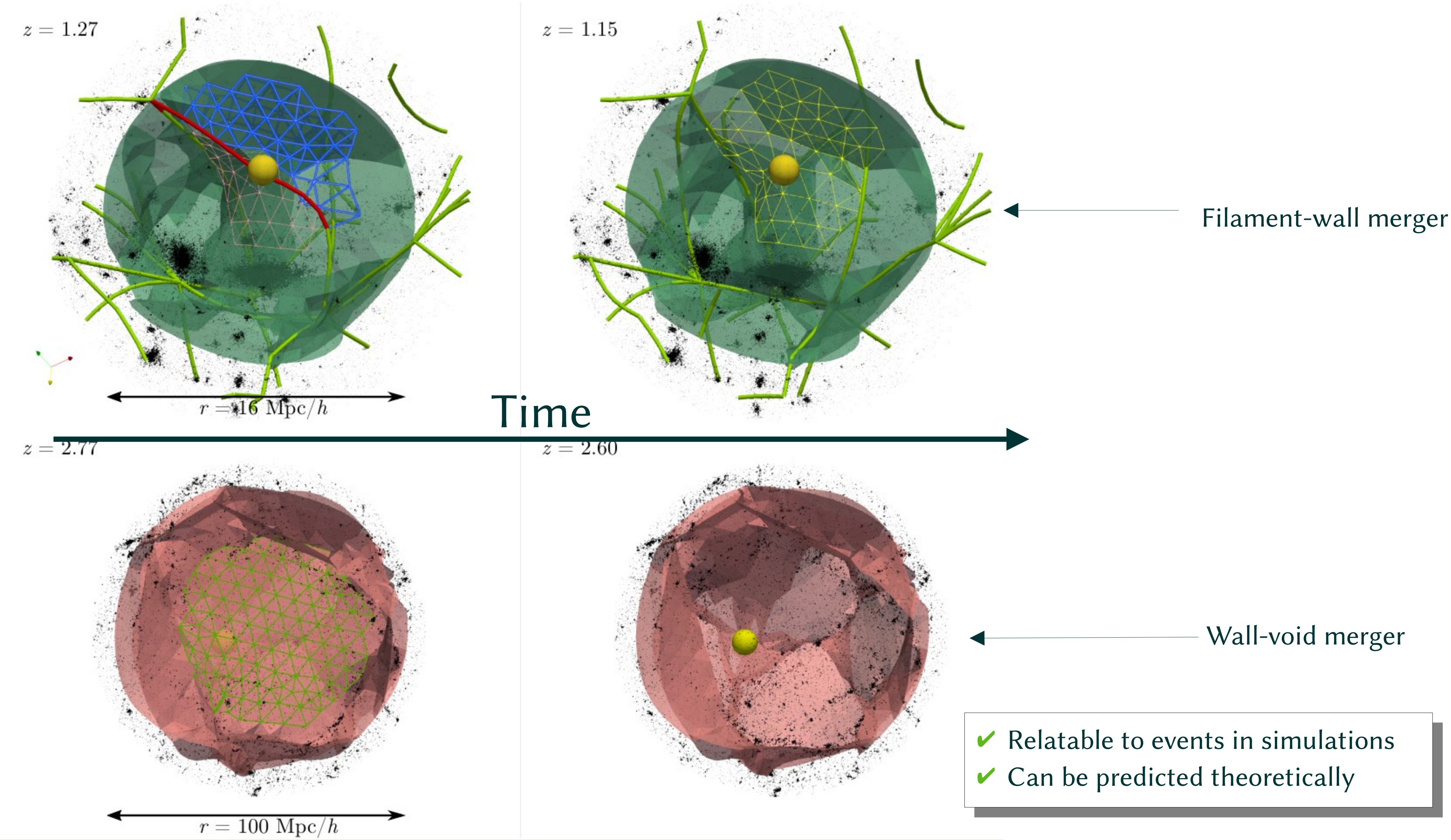
Detection in simulations



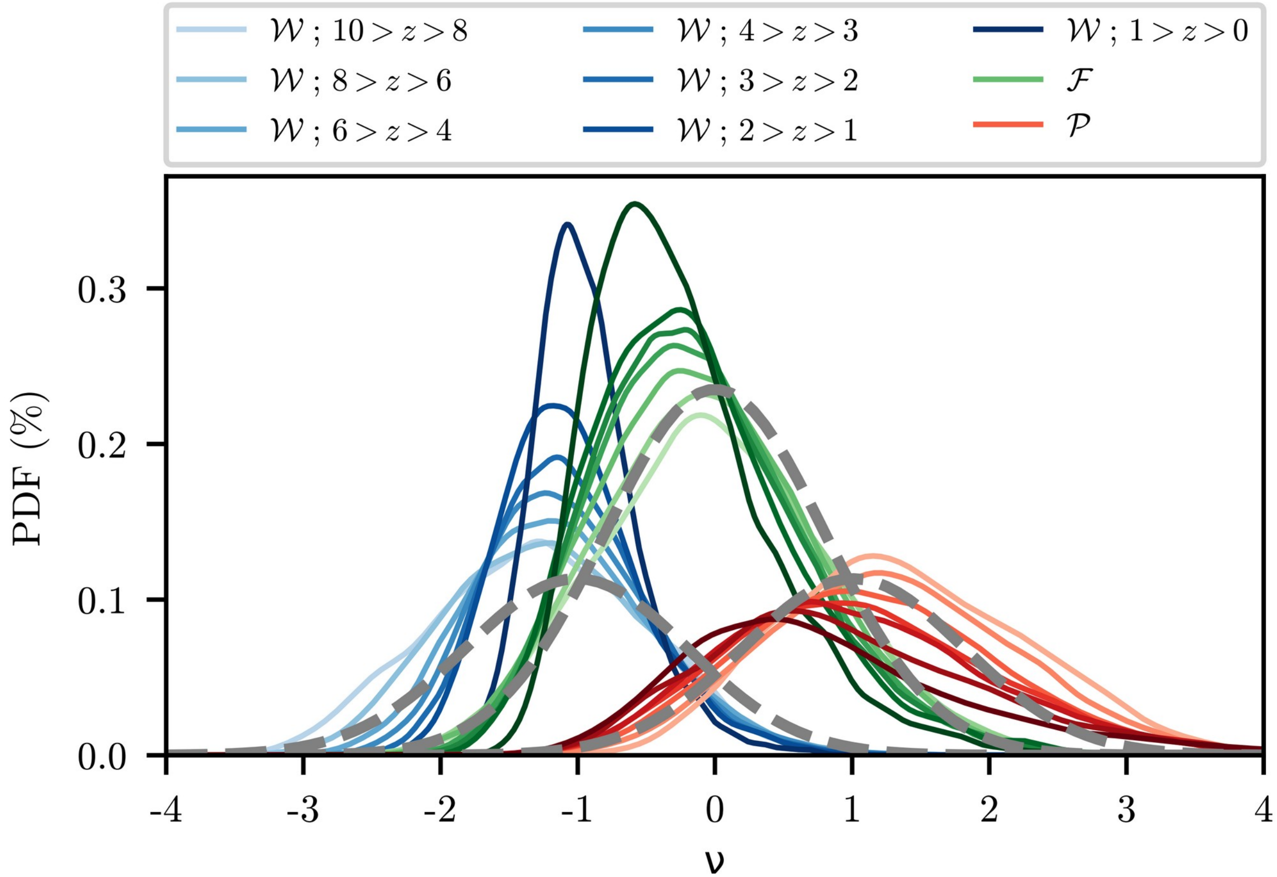
Filament-wall merger

Wall-void merger

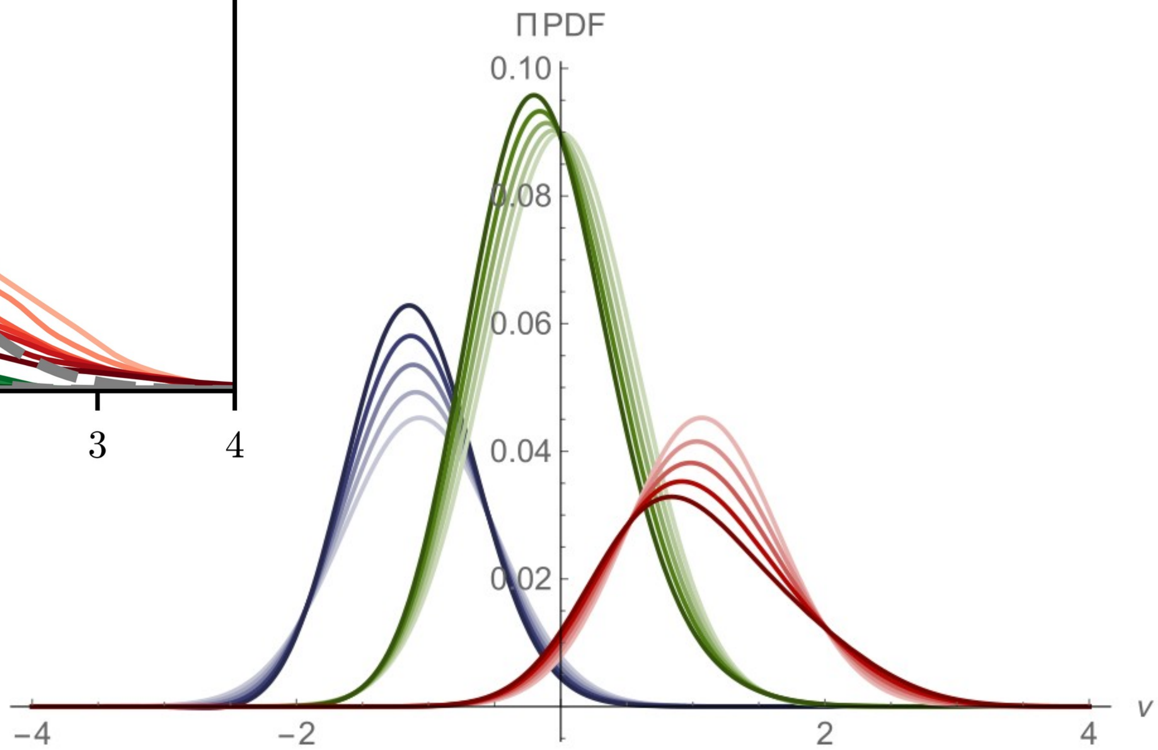


- ✔ Relatable to events in simulations
- ✔ Can be predicted theoretically

Comparison with N-body simulations



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



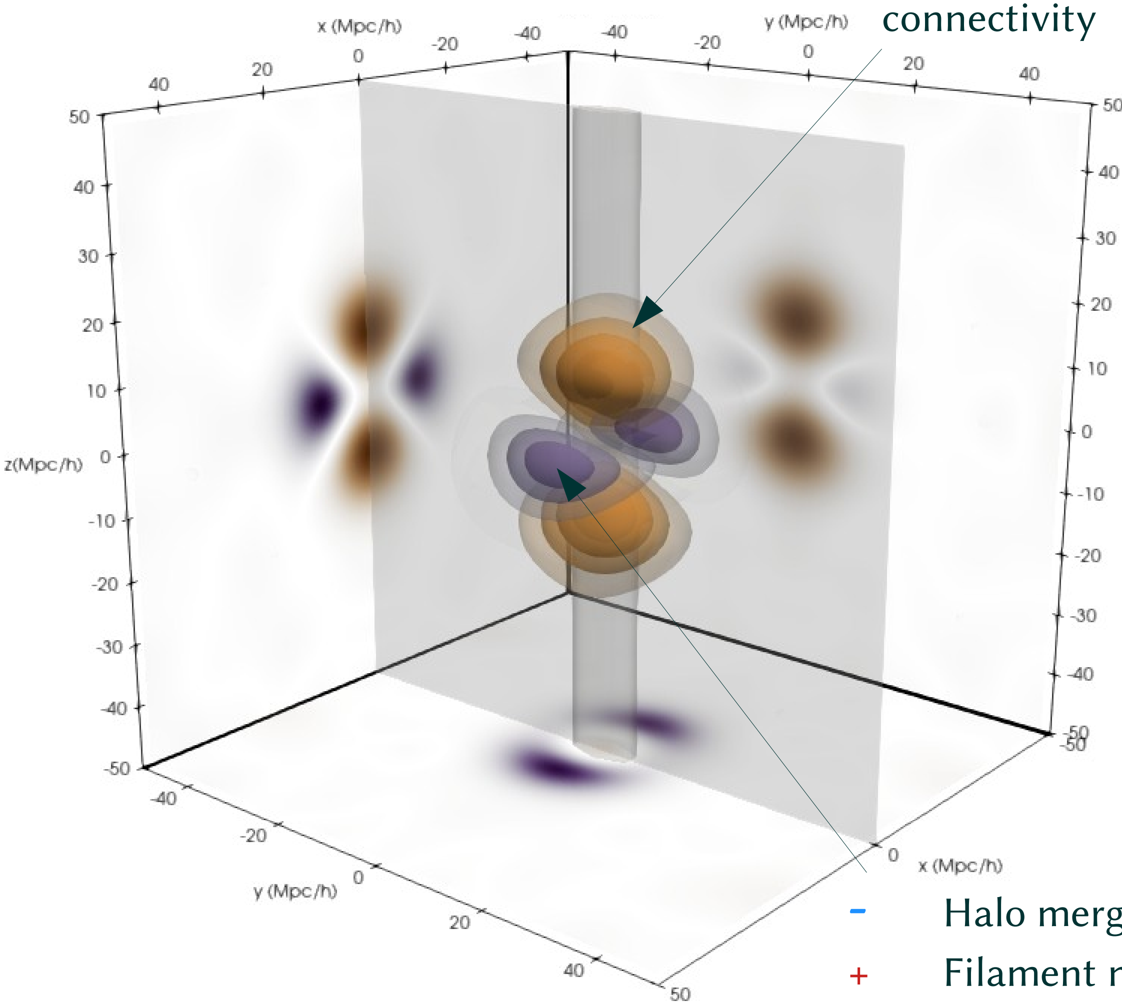
Analytical prediction of number counts at first-order in non-gaussianity.

Connectivity evolution across the cosmic web

\+ Halo mergers

\- Filament mergers

→ Towards higher connectivity



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Predicted filament-to-halo merger rate

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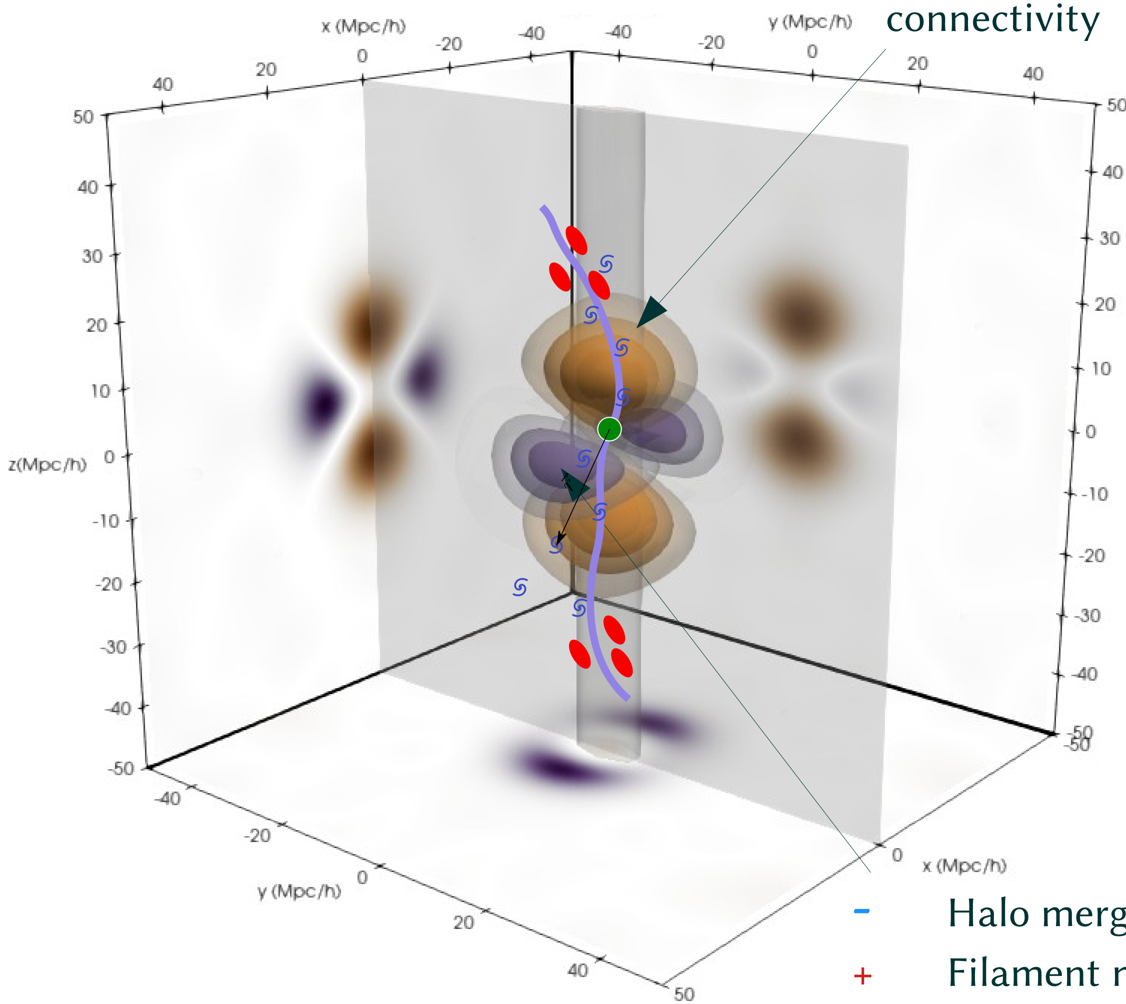

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[Connectivity: Codis+18]

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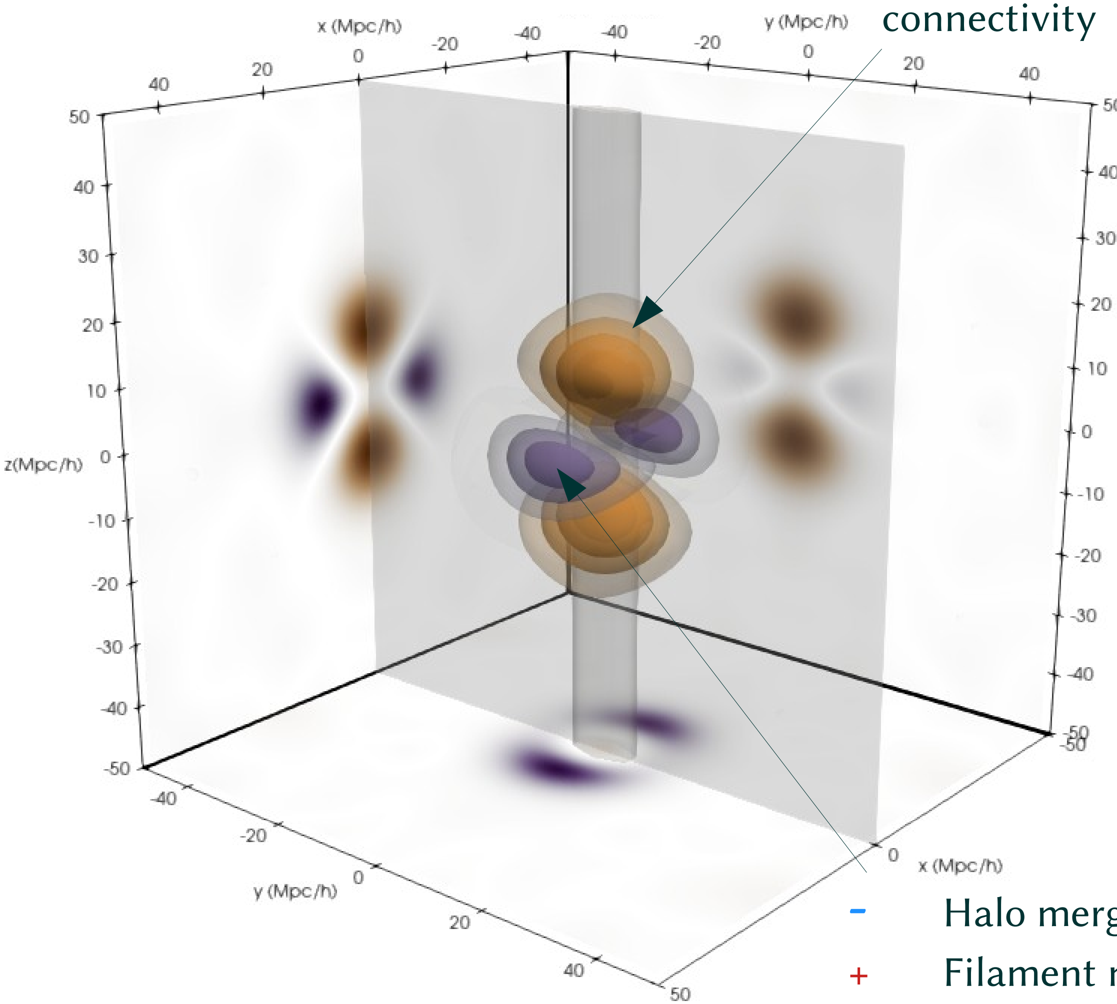

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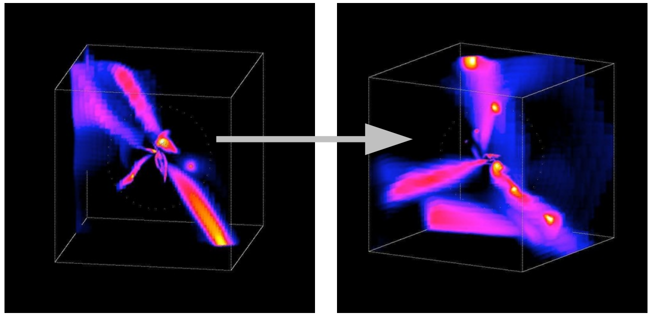

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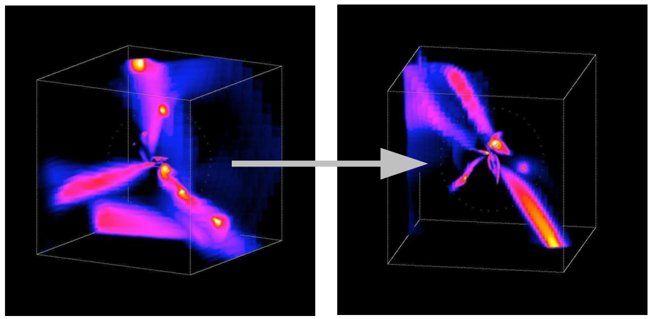

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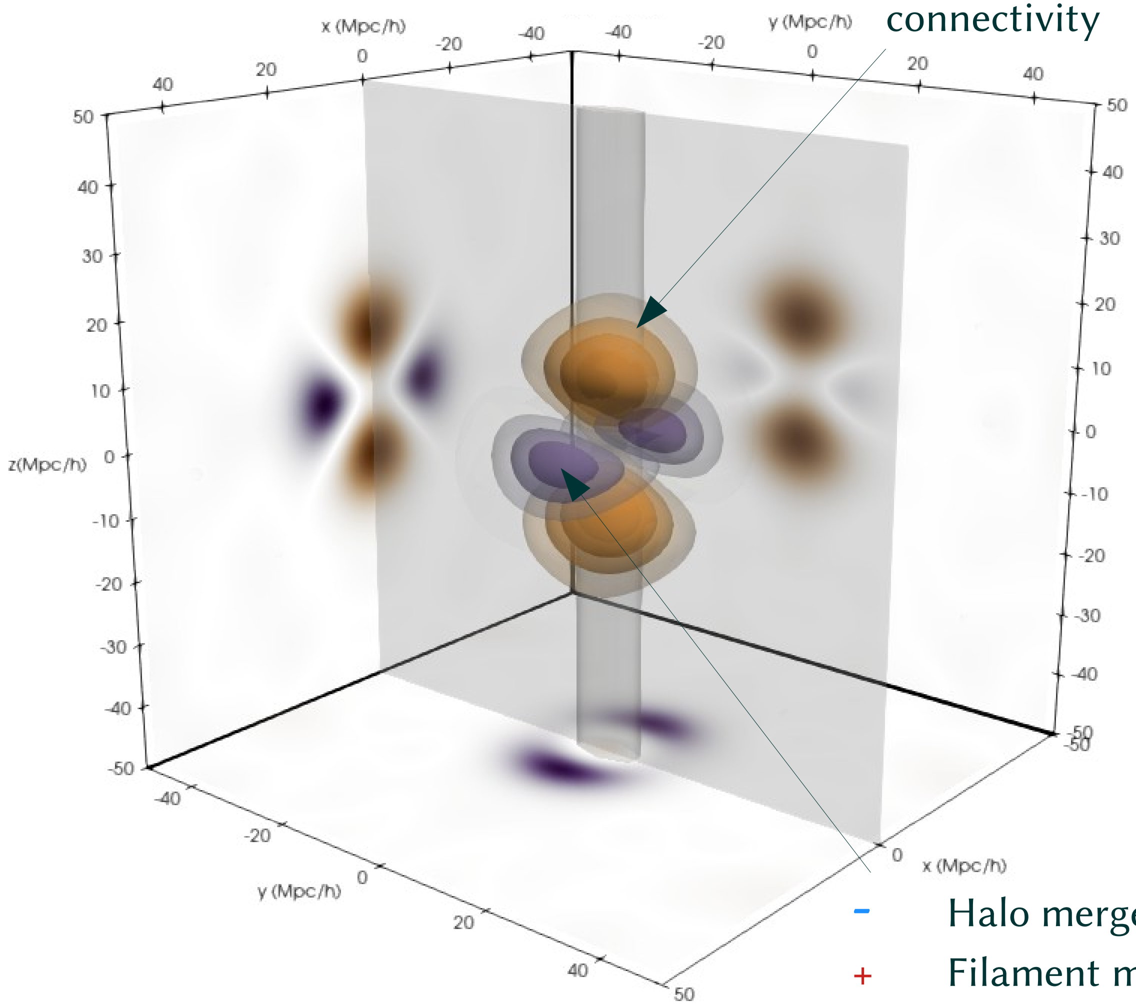

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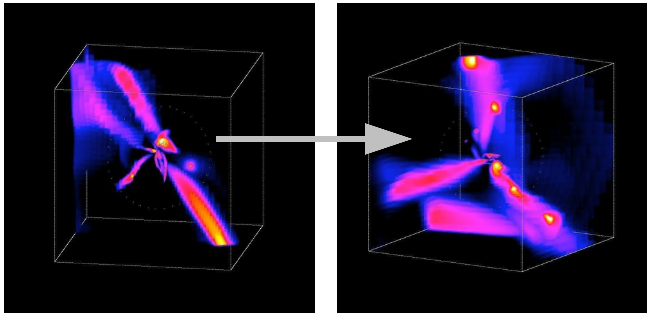
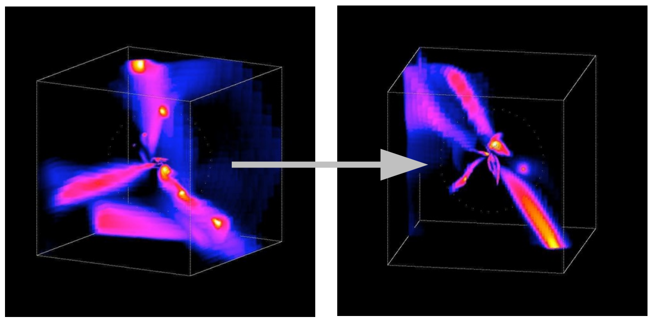


At **fixed smoothing scale**, in nodes
⇒ growing towards higher connectivity, than in voids.

- Halo mergers
+ Filament mergers
→ Towards lower connectivity



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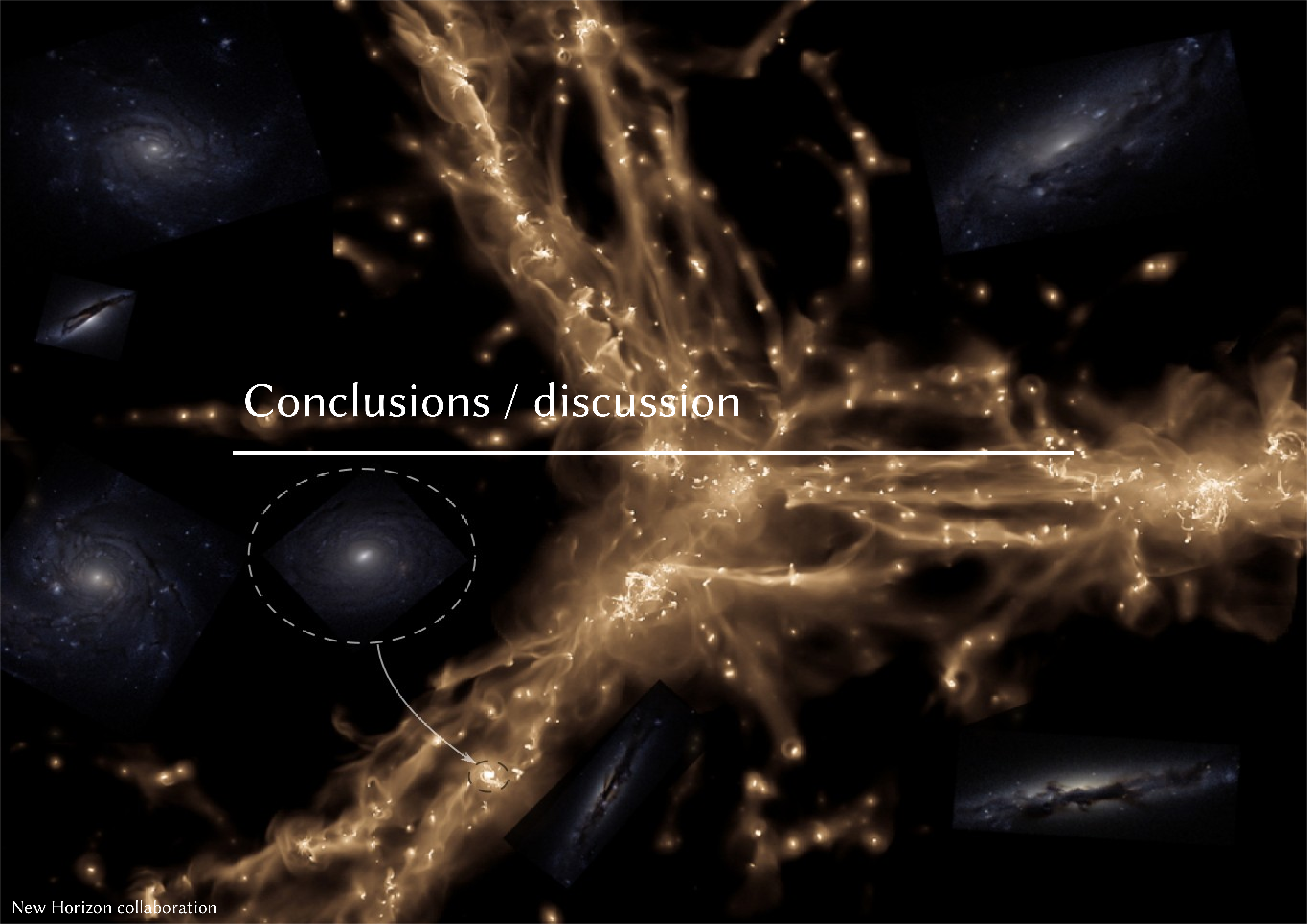
Conclusions / discussion



New Horizon collaboration

Conclusion

Key points:

- ✔ Describes full change of topology of galactic infall (+ consistent w/ connectivity)
  - ➔ Halo mergers
  - ➔ **Filament mergers + wall (or void) mergers**
- ✔ Very efficient compression
  - ➔ 3D continuous space ⟶ finite set of points in 4D

Achievements

- ✔ Derived theoretical expectations
- ✔ Can be used in numerical simulations
- ✔ Extension to non-linearities (modified gravity or non-linear Universe)
- ✔ Many applications:
  - ✔ Study of assembly bias
  - ✔ Merger rates in mass, time space
  - ✔ Alternative cosmological probe

Future

- Assign mass and time?
- Use as input to machine learning / halo model