The co-evolution of galaxies and the cosmic web over cosmic time

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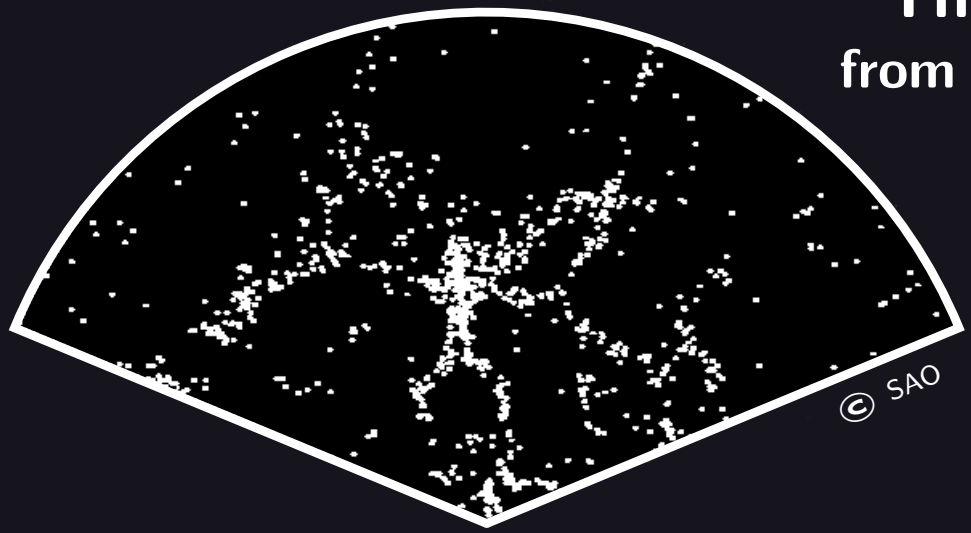
Observatoire **astronomique** de Strasbourg | ObAS

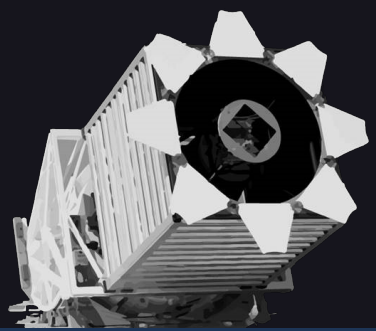
cnrs

The AtLAST-France workshop, 14 May 2025

The Cosmic web
from observations . . .

de Lapparent et al. 1986





Sloan Foundation Telescope

The Cosmic web
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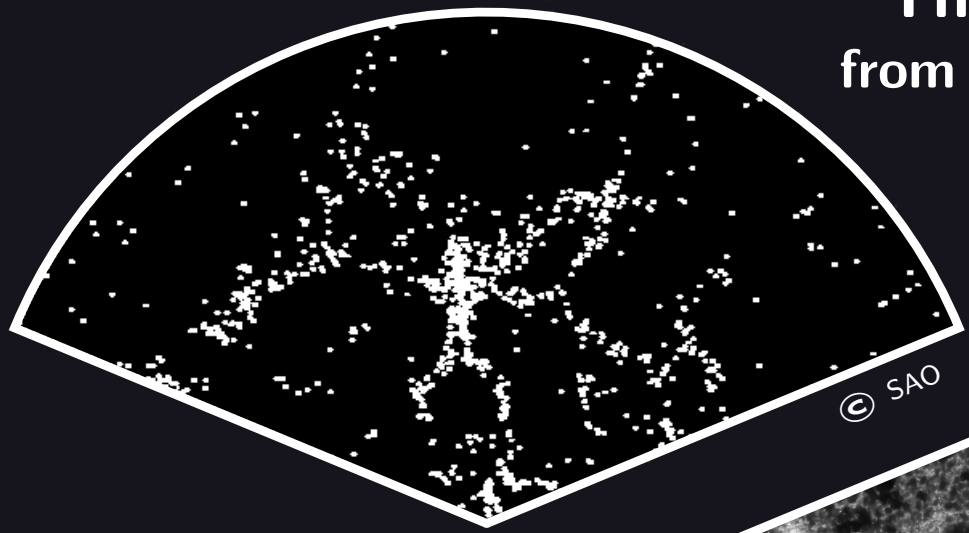
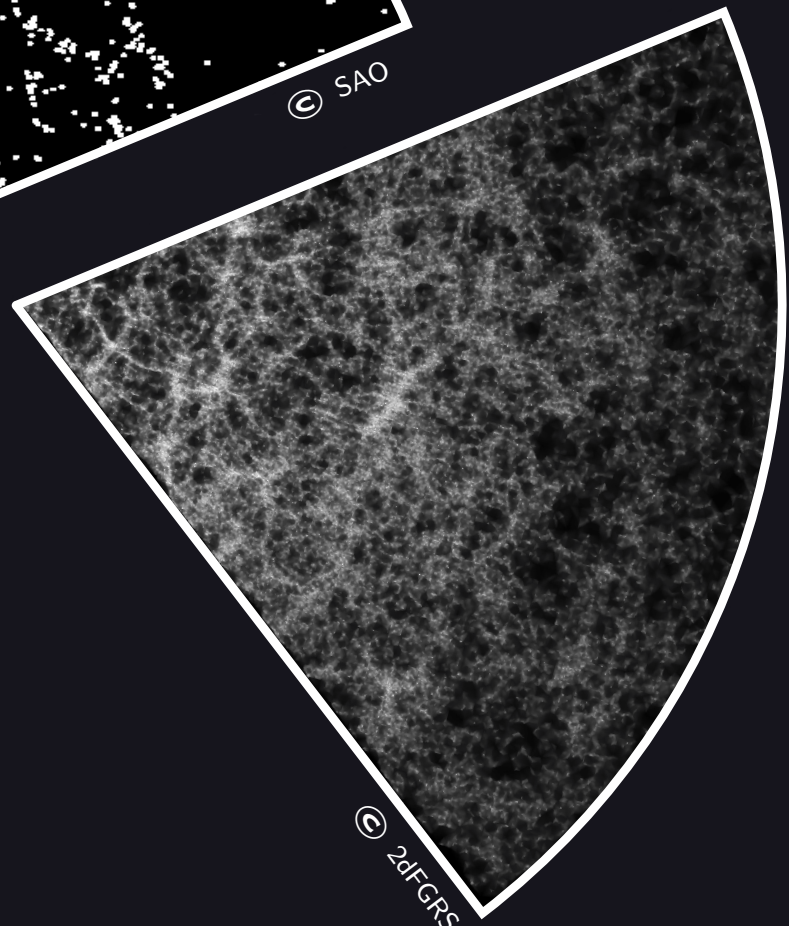
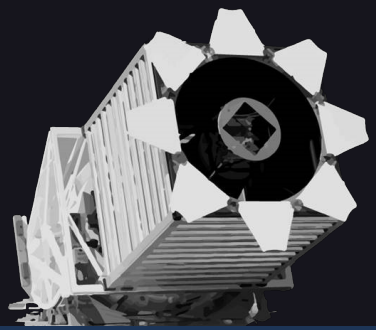
de Lapparent et al. 1986
Colless et al. 2003







Sloan Foundation Telescope

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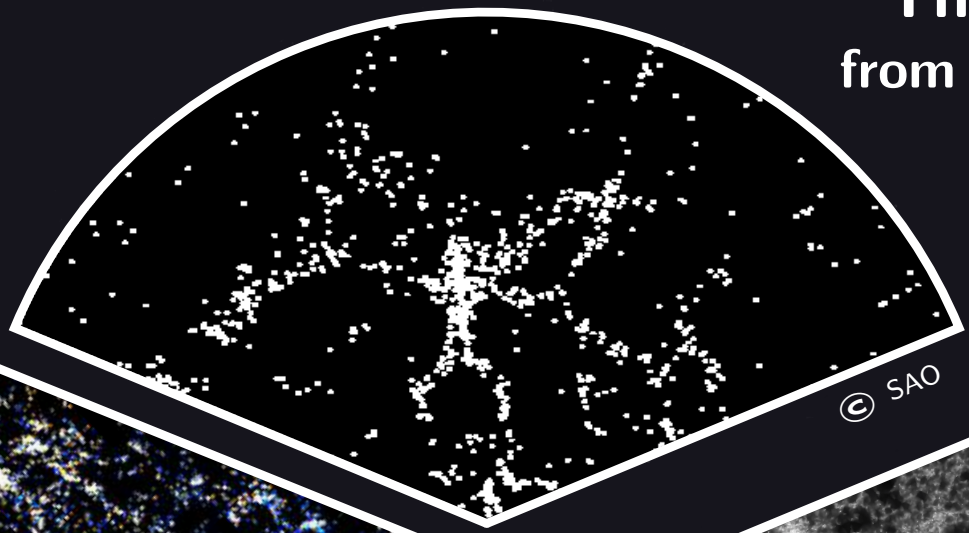
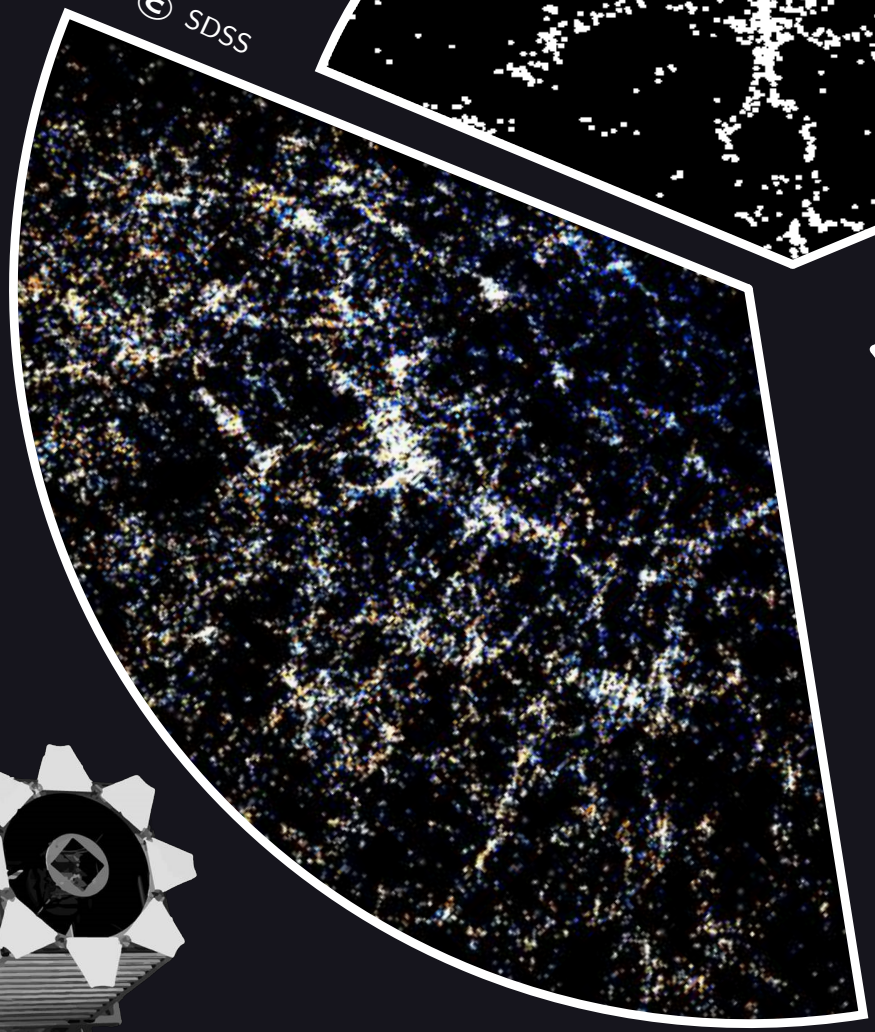
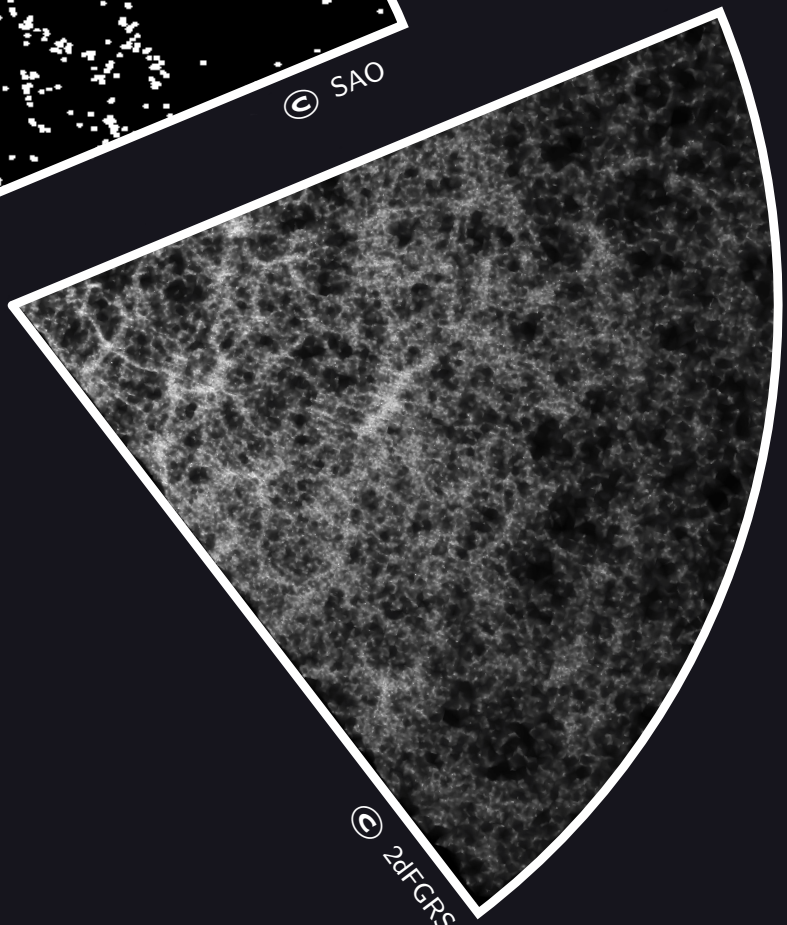
de Lapparent et al. 1986
Colless et al. 2003
Adelman-McCarthy et al. 2008





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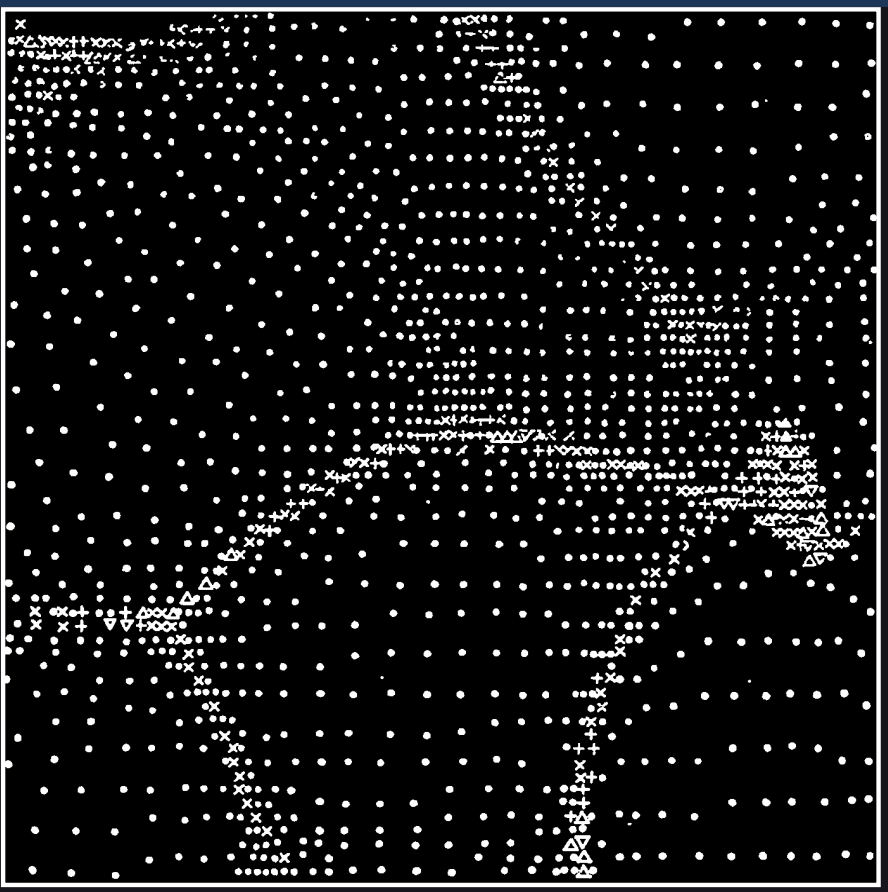

Doroshkevich & Shandarin 1978
Zel'dovich 1970

The Cosmic web
. . . to theory

Klypin & Shandarin 1993
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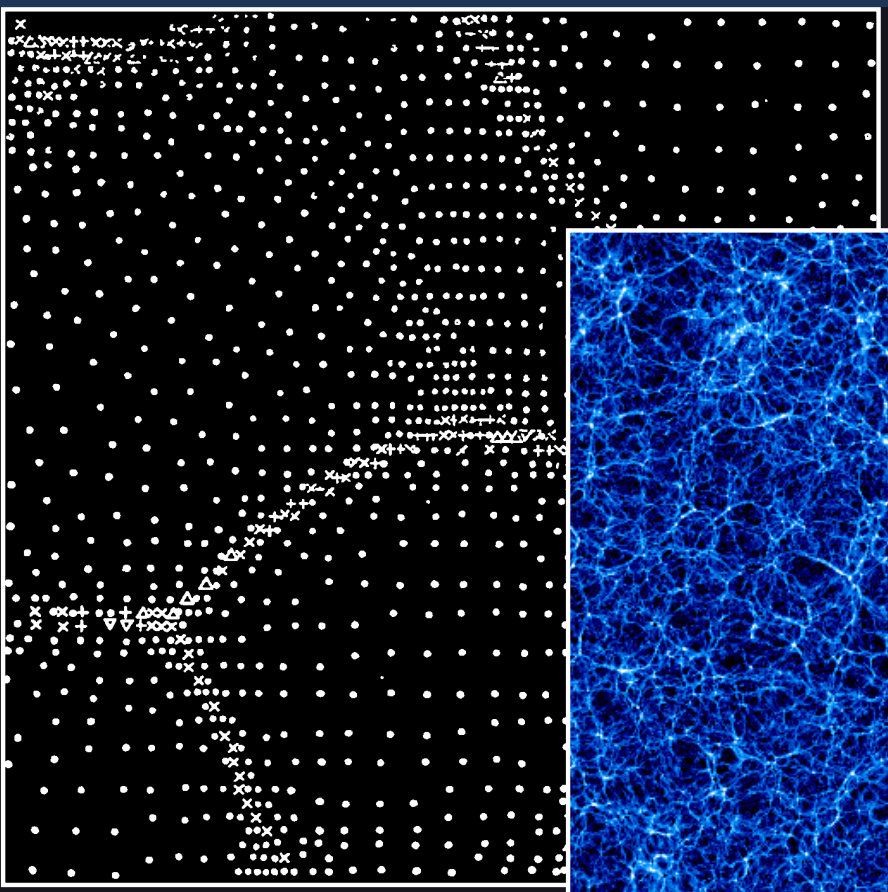

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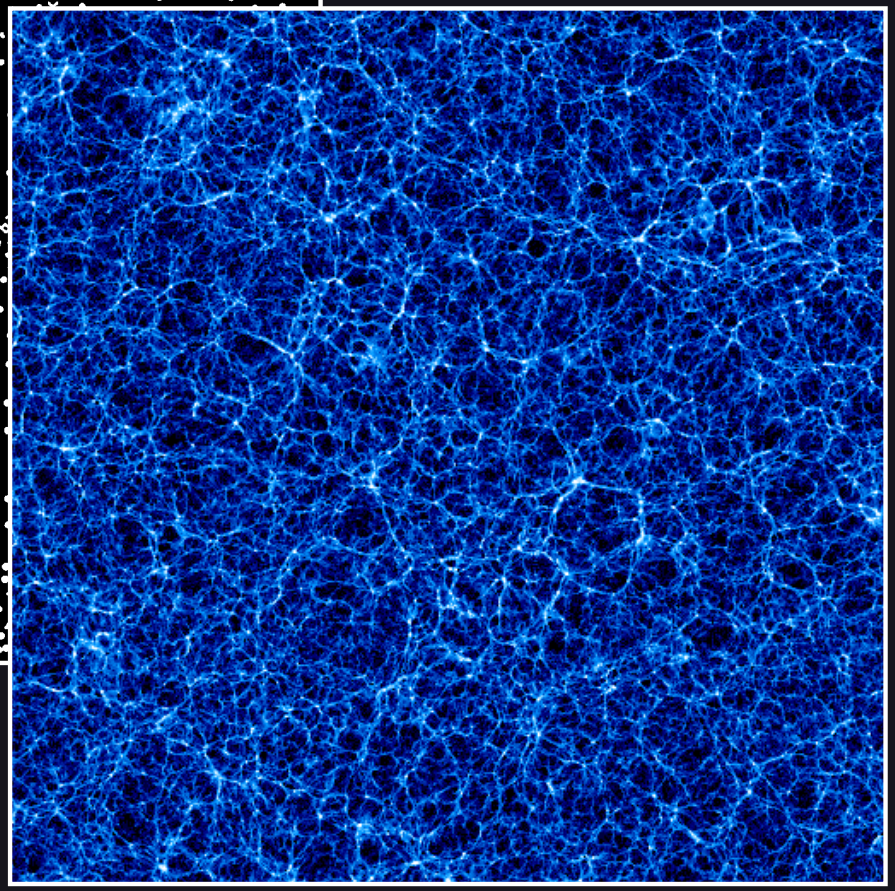

Marenostrum • Yepes et al. 2007

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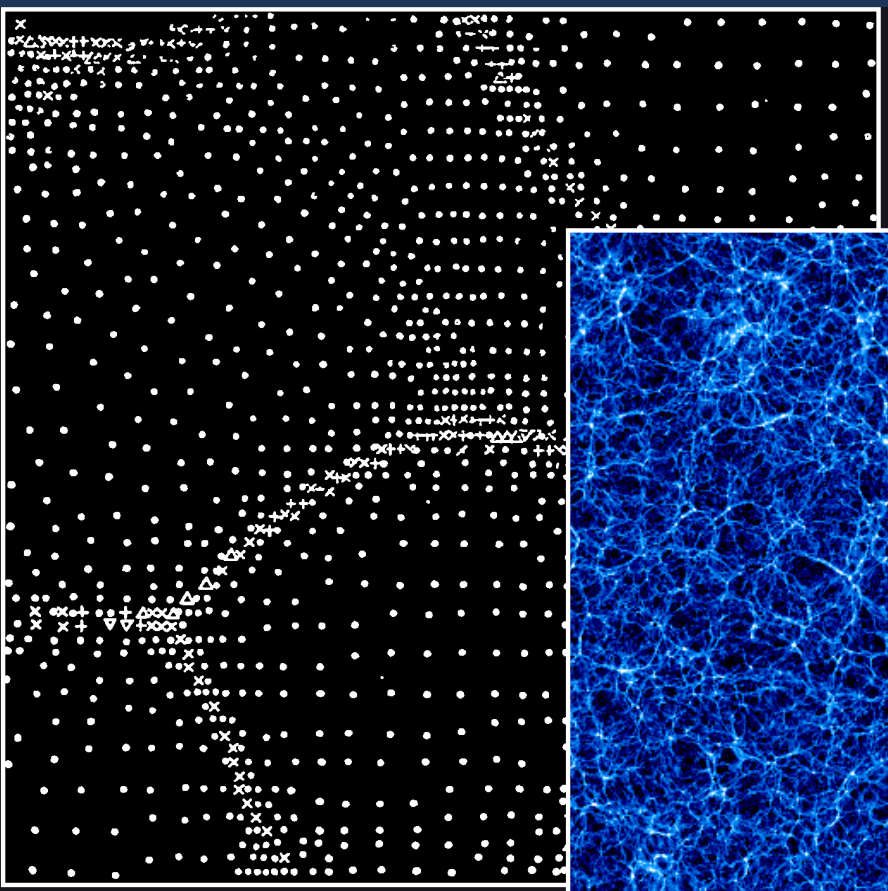

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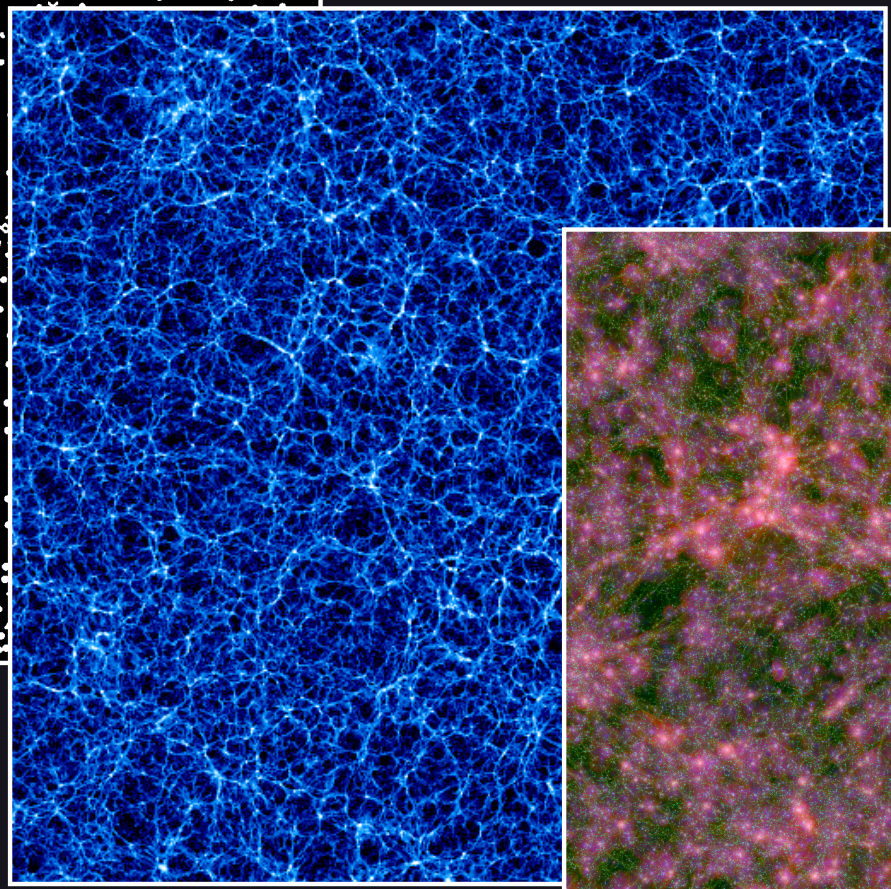
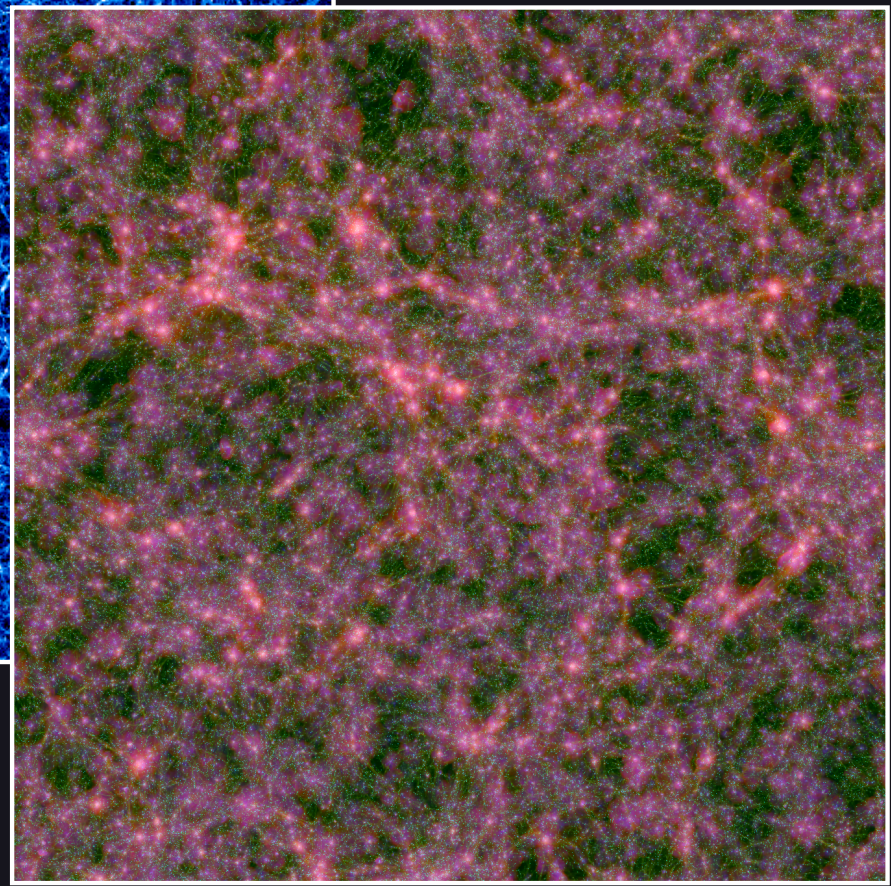


Marenostrum • Yepes et al. 2007



Horizon-AGN • Dubois et al. 2014

The Cosmic web

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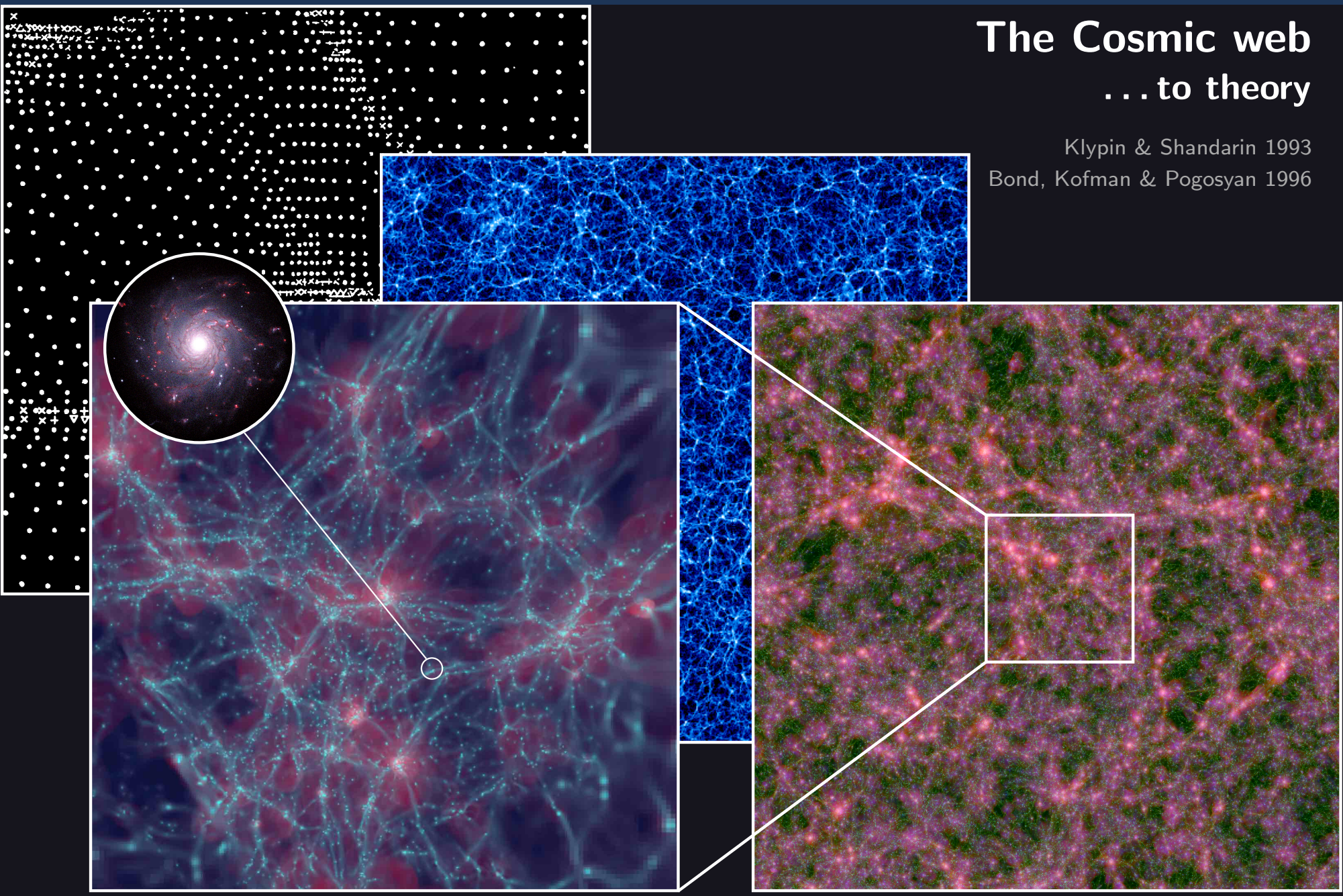

NewHorizon • Dubois et al. 2021

Horizon-AGN • Dubois et al. 2014

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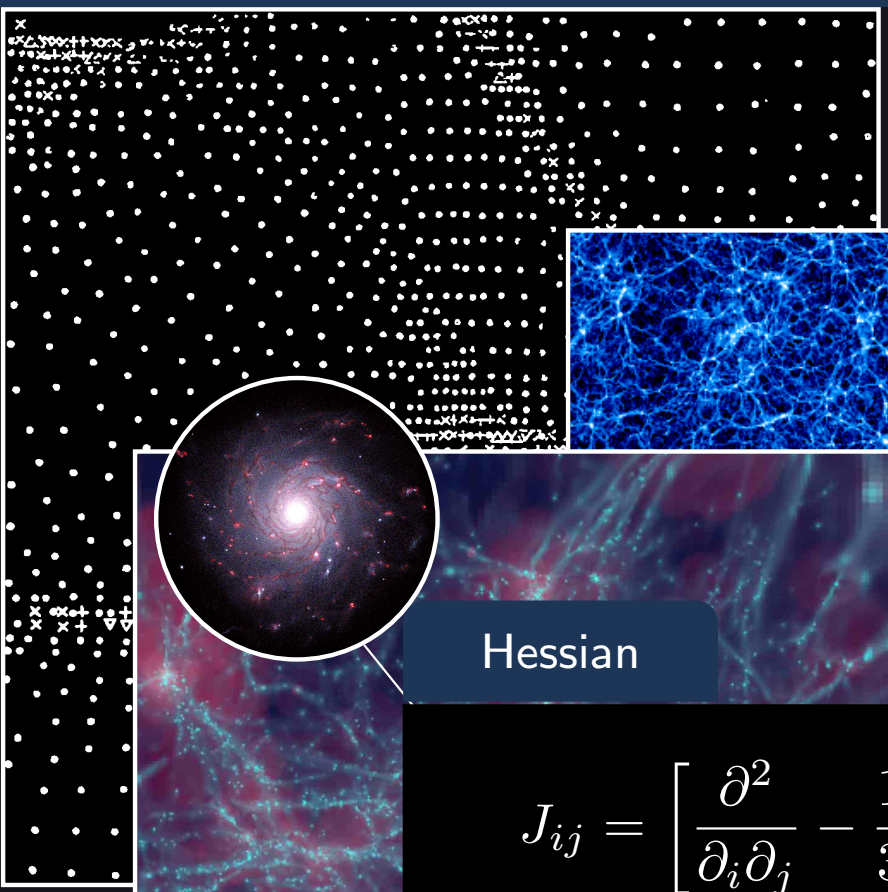

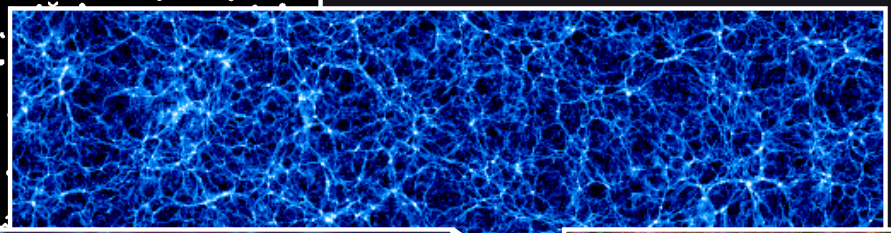

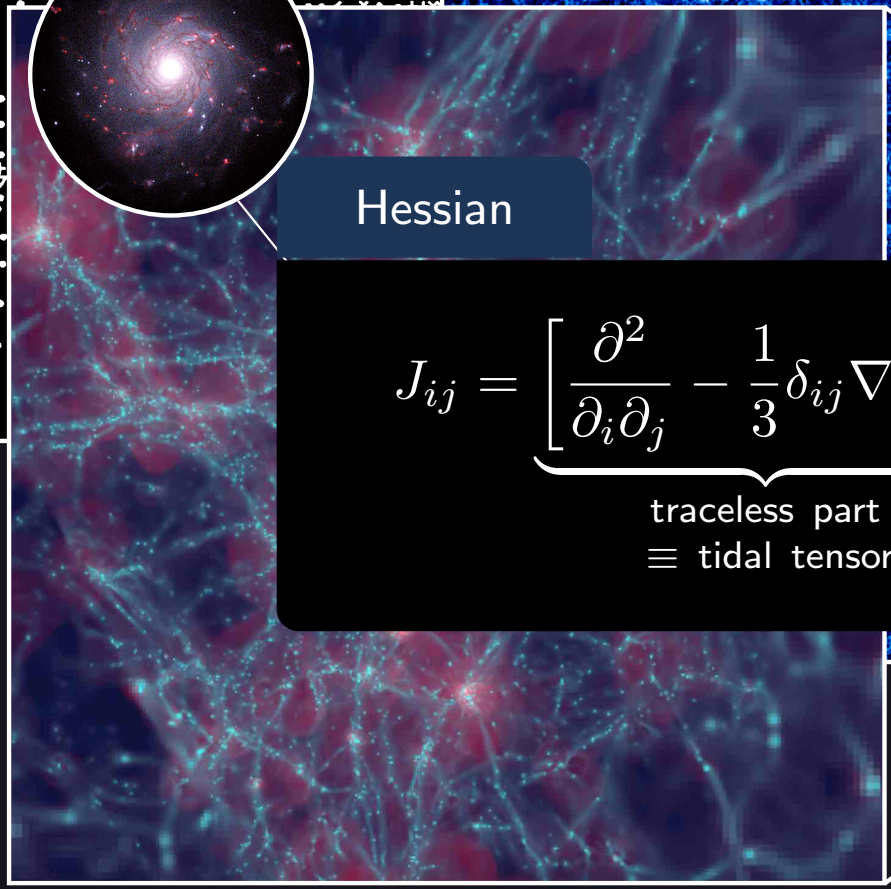

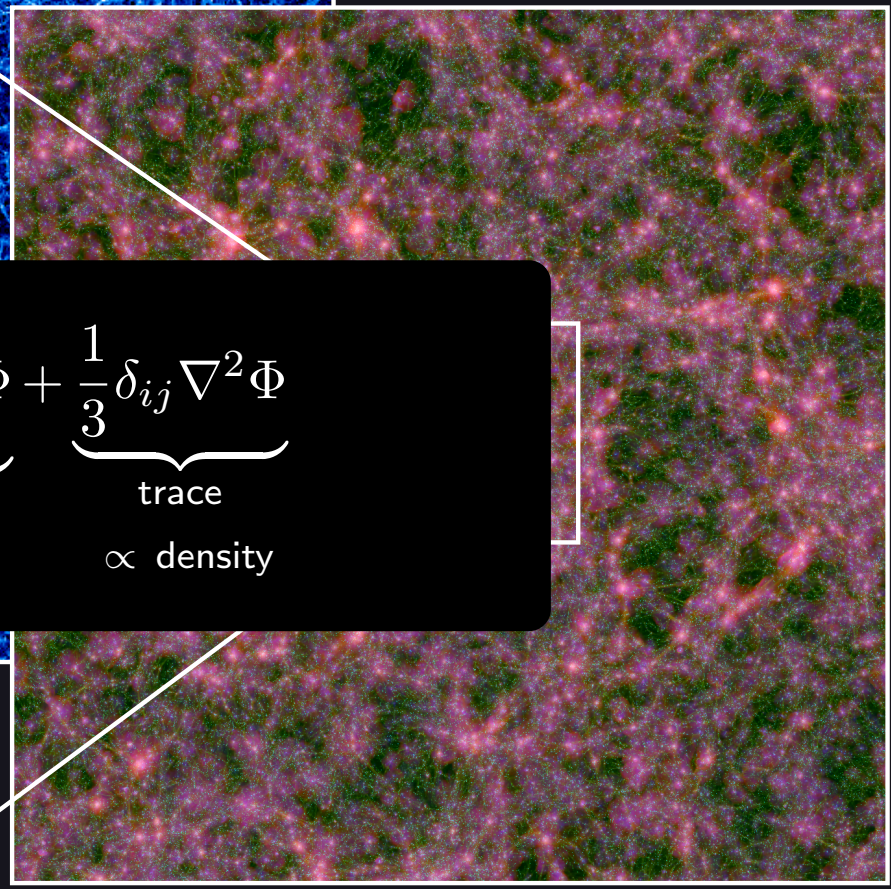

Hessian

$$J_{ij} = \underbrace{\left[\frac{\partial^2}{\partial_i \partial_j} - \frac{1}{3}\delta_{ij}\nabla^2\right]\Phi}_{\text{traceless part} \equiv \text{tidal tensor}} + \underbrace{\frac{1}{3}\delta_{ij}\nabla^2\Phi}_{\text{trace} \propto \text{density}}$$

NewHorizon • Dubois et al. 2021

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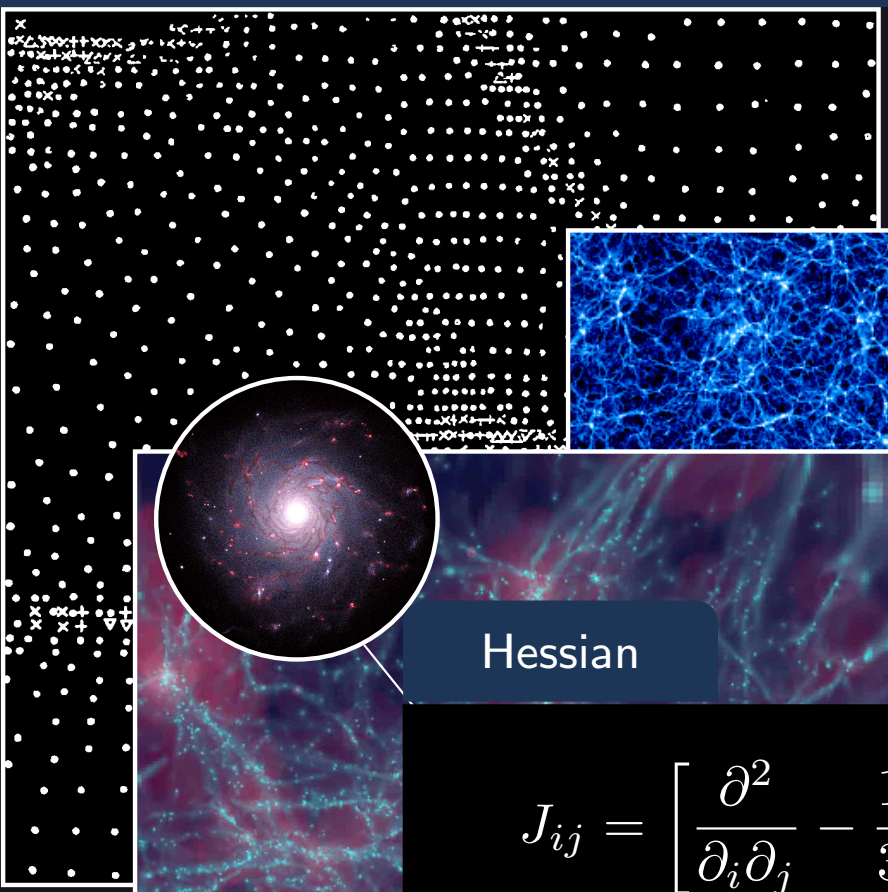

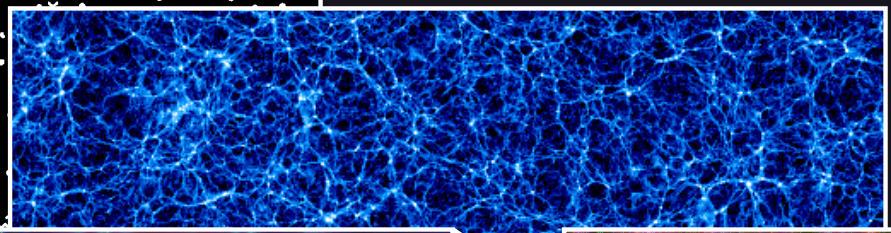

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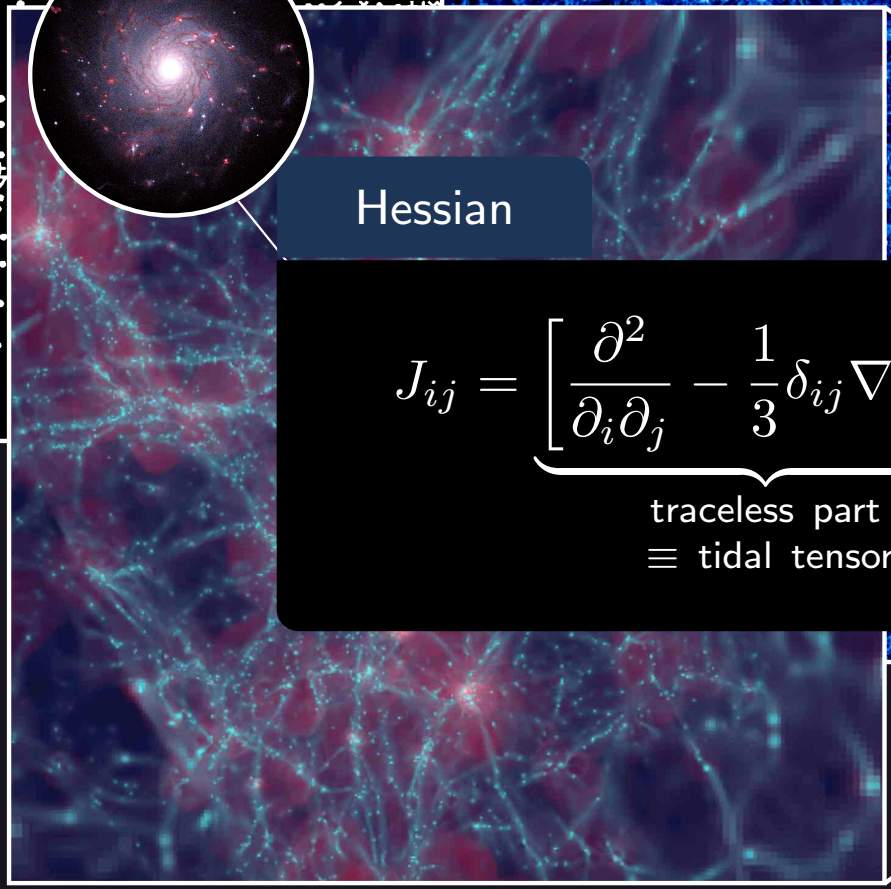
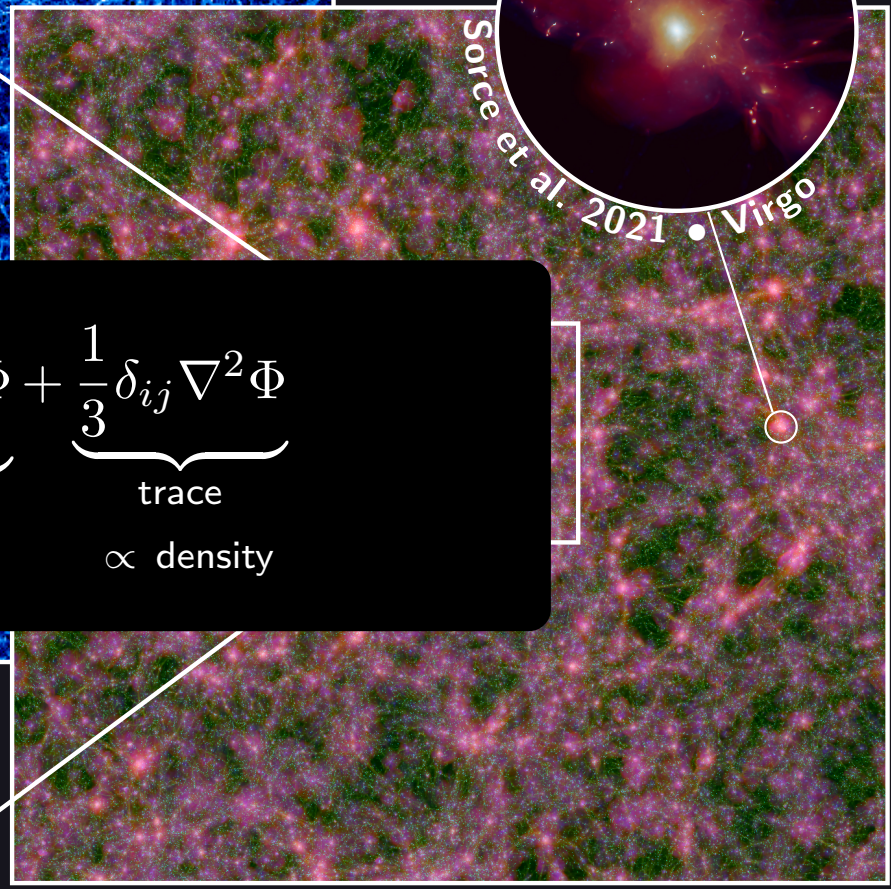
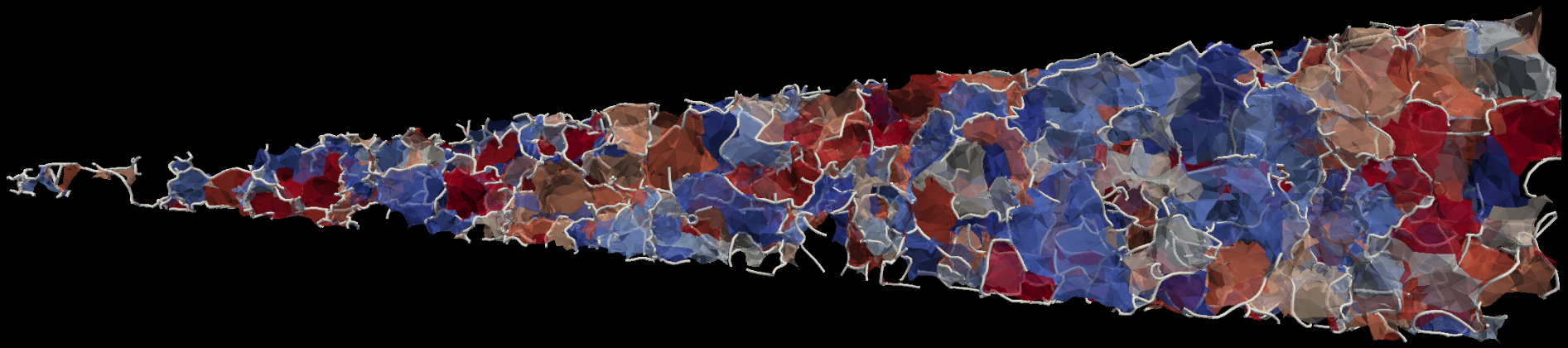


NewHorizon • Dubois et al. 2021



Horizon-AGN • Dubois et al. 2014

The Cosmic web identification



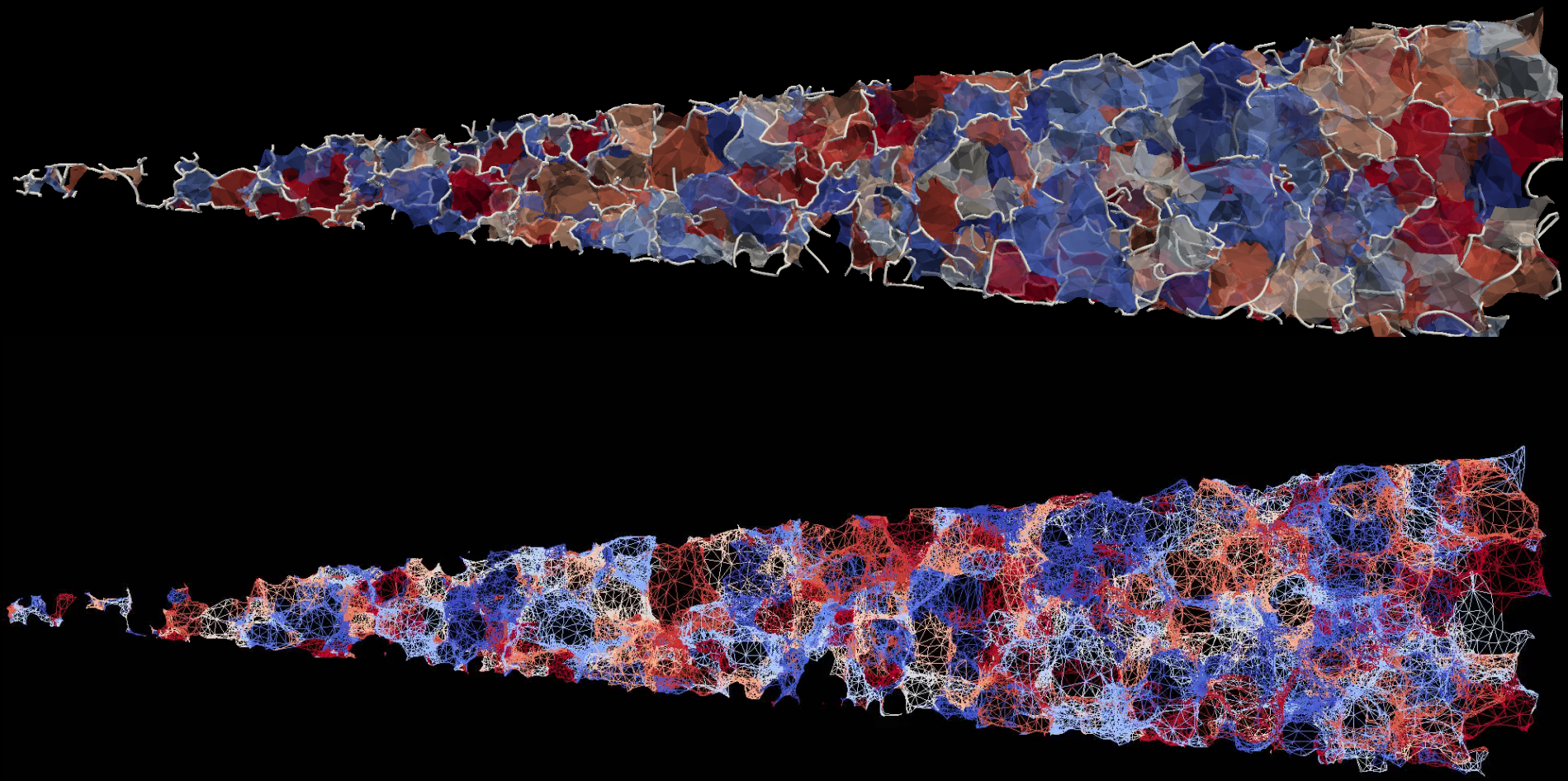
DisPerSE

- geometric 3D ridge extractor
- discrete data sets
- scale and parameter-free
- Delaunay complex & DTFE
- discrete Morse theory
- persistence theory

GAMA (Driver et al. 2009, 2011)

DisPerSE (Sousbie et al. 2011)

The Cosmic web identification



GAMA (Driver et al. 2009, 2011)

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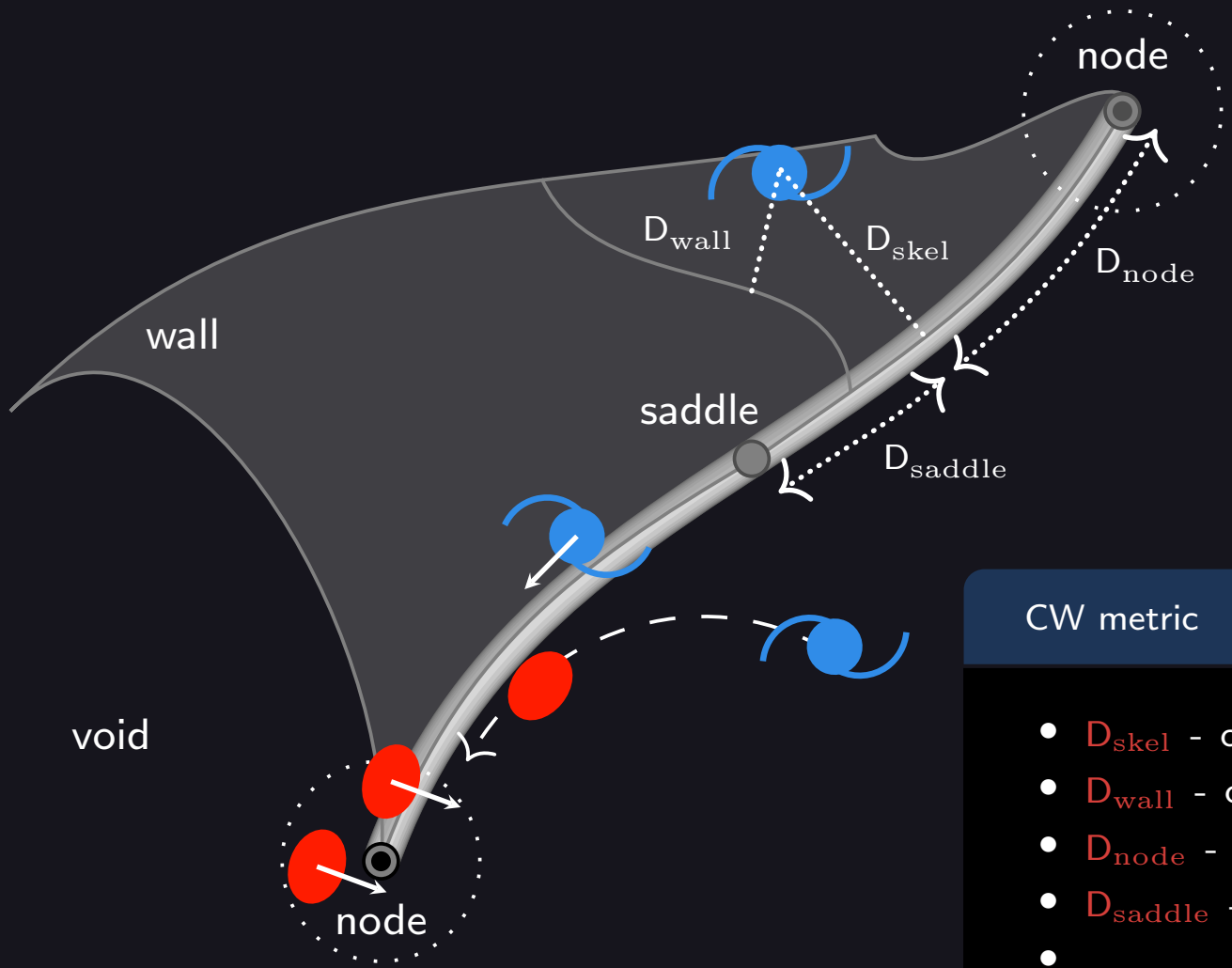
The Cosmic web metric

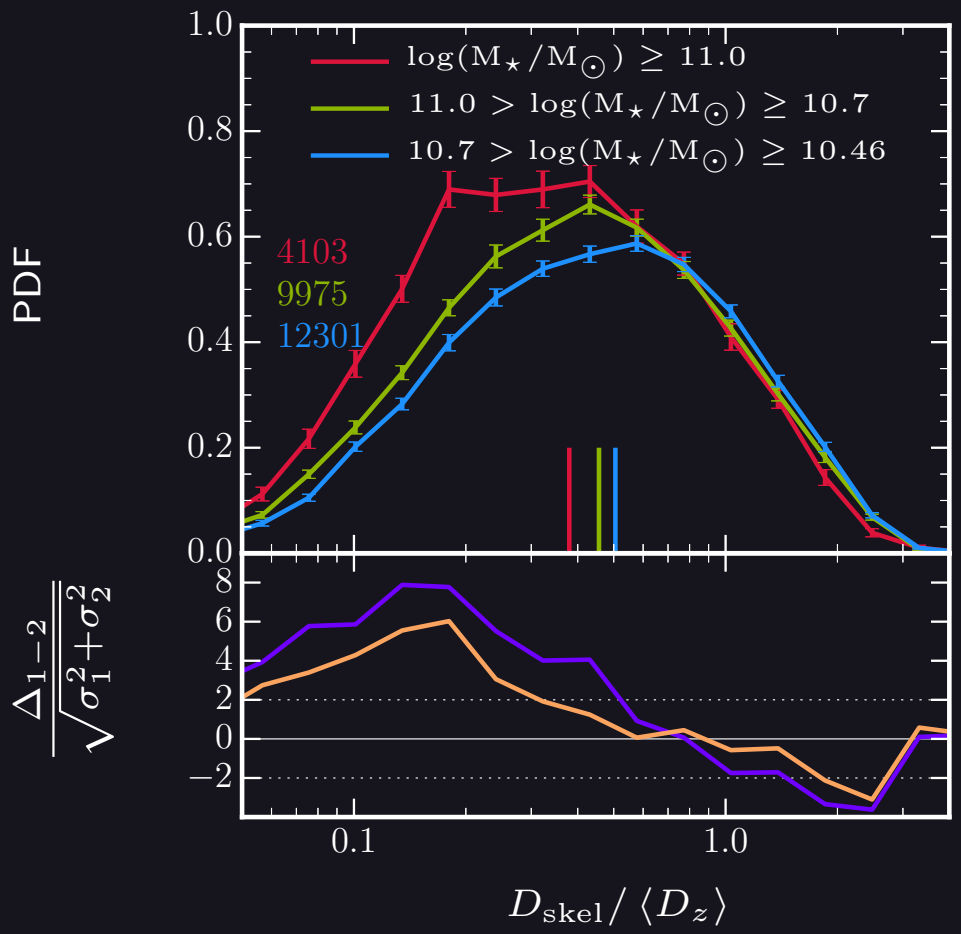


CW metric

- D_{skel} - closest filament
- D_{wall} - closest wall
- D_{node} - filament's node
- D_{saddle} - filament's saddle
- ...
- nodes - connectivity

Scalar properties

– Mass segregation –



- **more massive** galaxies **closer** to filaments in observations $z < 0.9$

Poudel et al. 2016, Chen et al. 2017

Malavasi et al. 2017

Kraljic et al. 2018, Laigle et al. 2018

Winkel et al. 2021

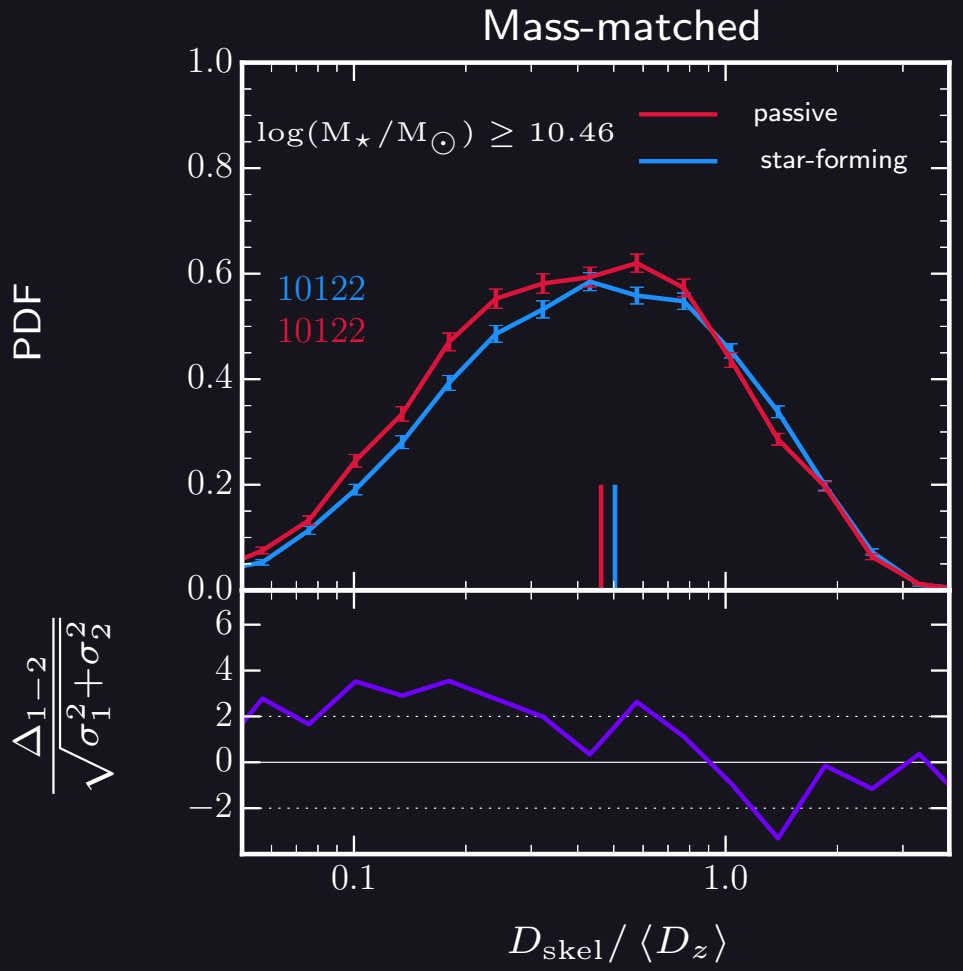
consistent with simulations

Horizon-AGN; Kraljic et al. 2018, Laigle et al. 2018

Simba: Bulichi, Davé & Kraljic 2023

Scalar properties

– sSFR/color segregation –

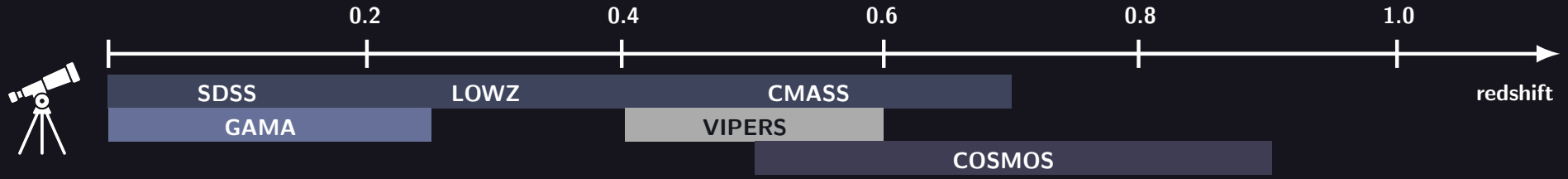


- **passive/red** galaxies **closer** to filaments in observations $z < 0.9$

Chen et al. 2017, Kuutma et al. 2017
Poudel et al. 2017, Malavasi et al. 2017
Kraljic et al. 2018, Laigle et al. 2018
Winkel et al. 2021

consistent with simulations

Horizon-AGN: Kraljic et al. 2018, Laigle et al. 2018
Simba, Eagle, IllustrisTNG: Bulichi, Davé & Kraljic 2023
IllustrisTNG: Hasan et al. 2023



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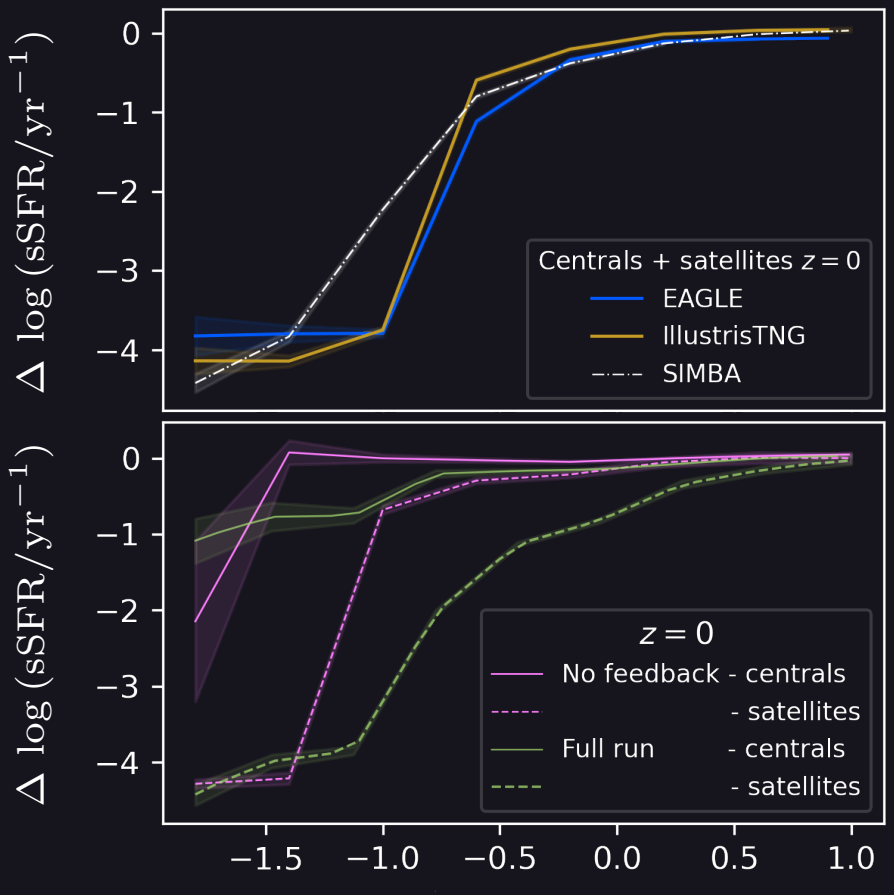

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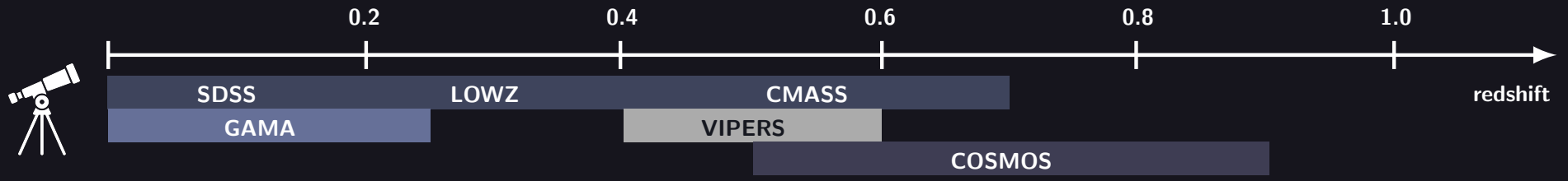
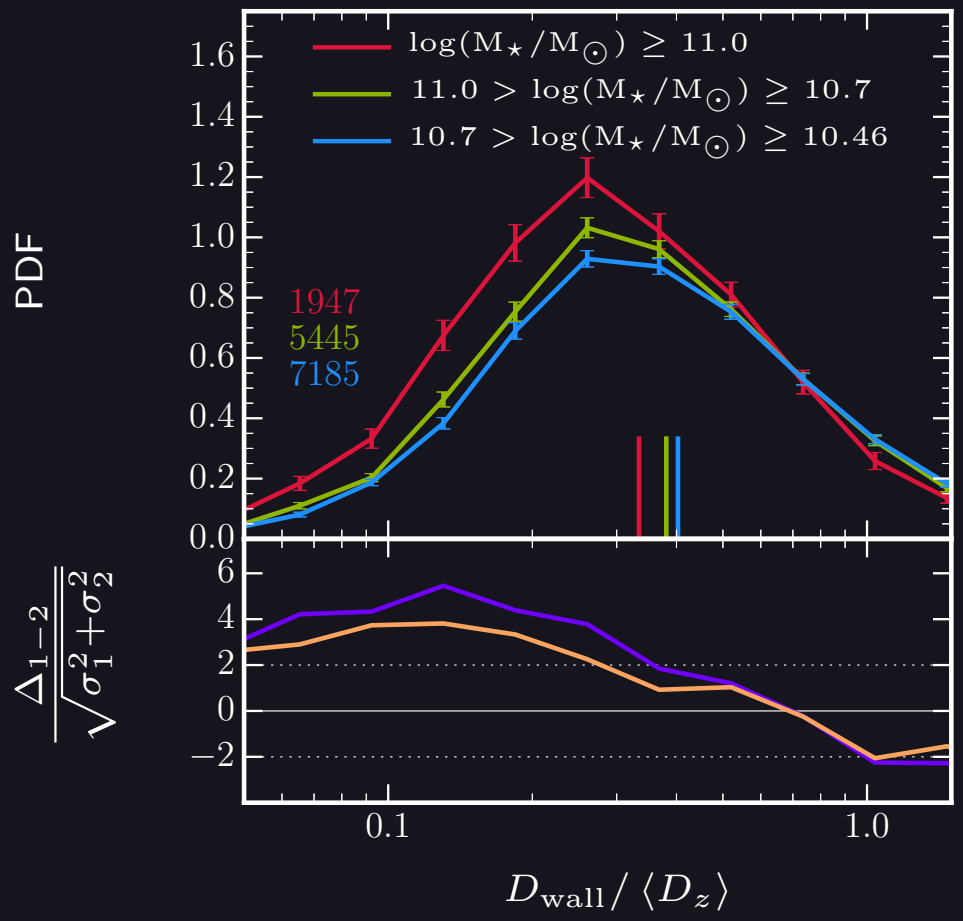
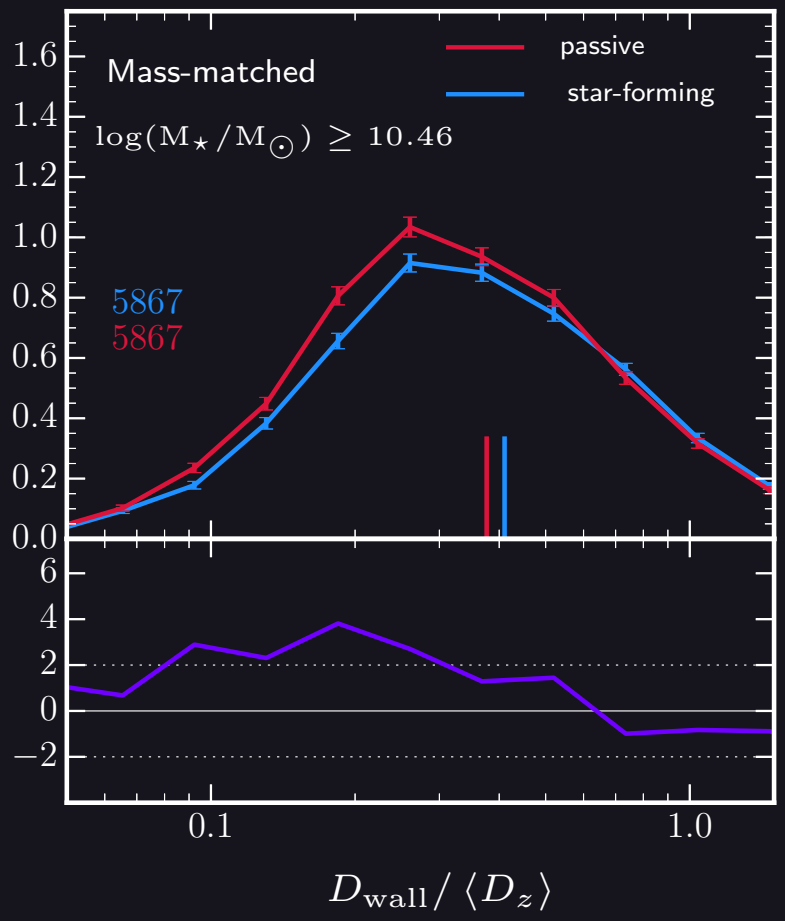
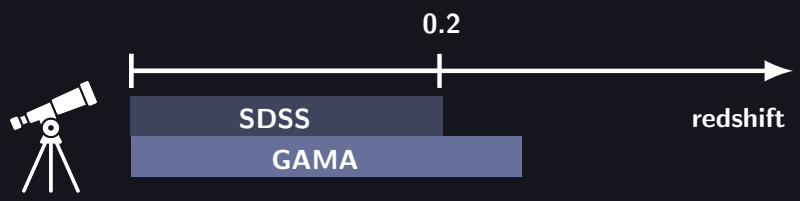


Scalar properties

– Mass and sSFR/color segregation –







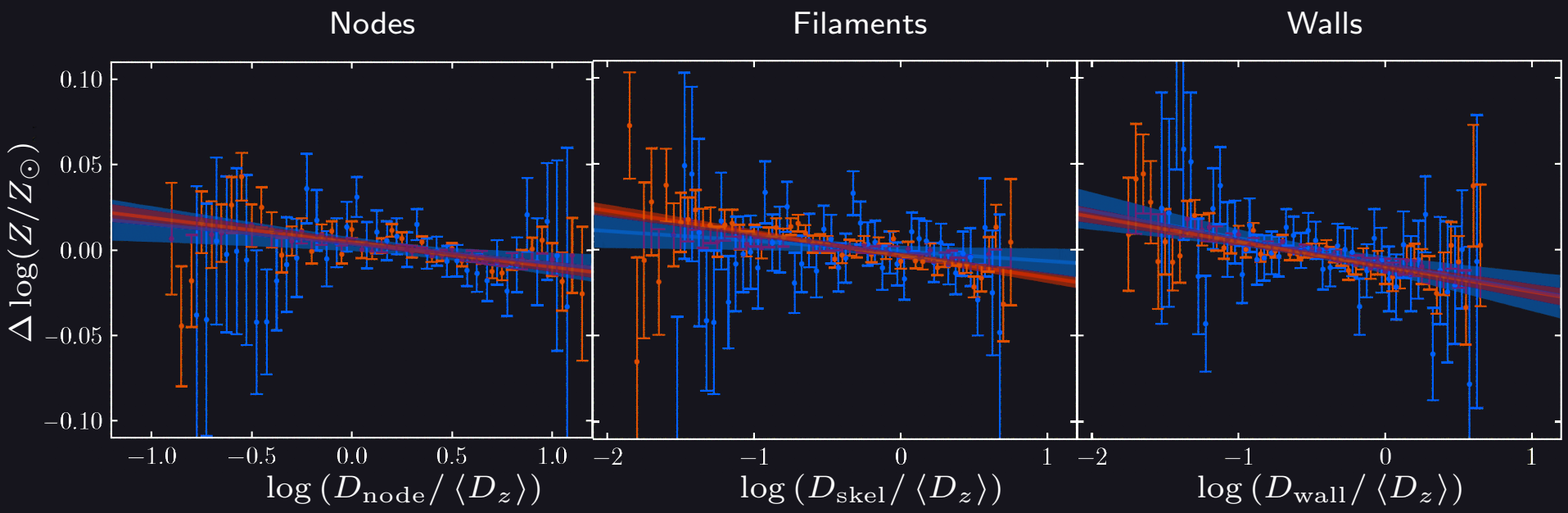
- **massive/passive** galaxies **closer** to walls

Kraljic et al. 2018, Winkel et al. 2021

consistent with simulations

Horizon-AGN: Kraljic et al. 2018

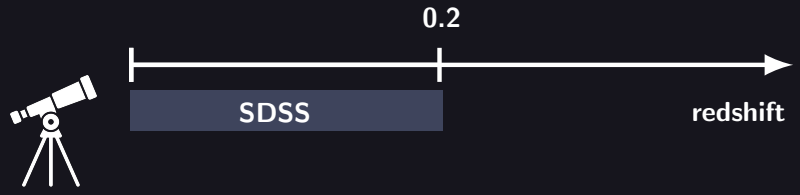
– Metallicity/age/α elements segregation –



- $\log(\mathrm{M_{halo}}/\mathrm{M_\odot}) < 12$
- $\log(\mathrm{M_{halo}}/\mathrm{M_\odot}) \geq 12$

- centrals at given ($\mathrm{M_\star}$, $\mathrm{M_{halo}}$) closer to CW are
  more **metal rich**
  older
  α-enhanced

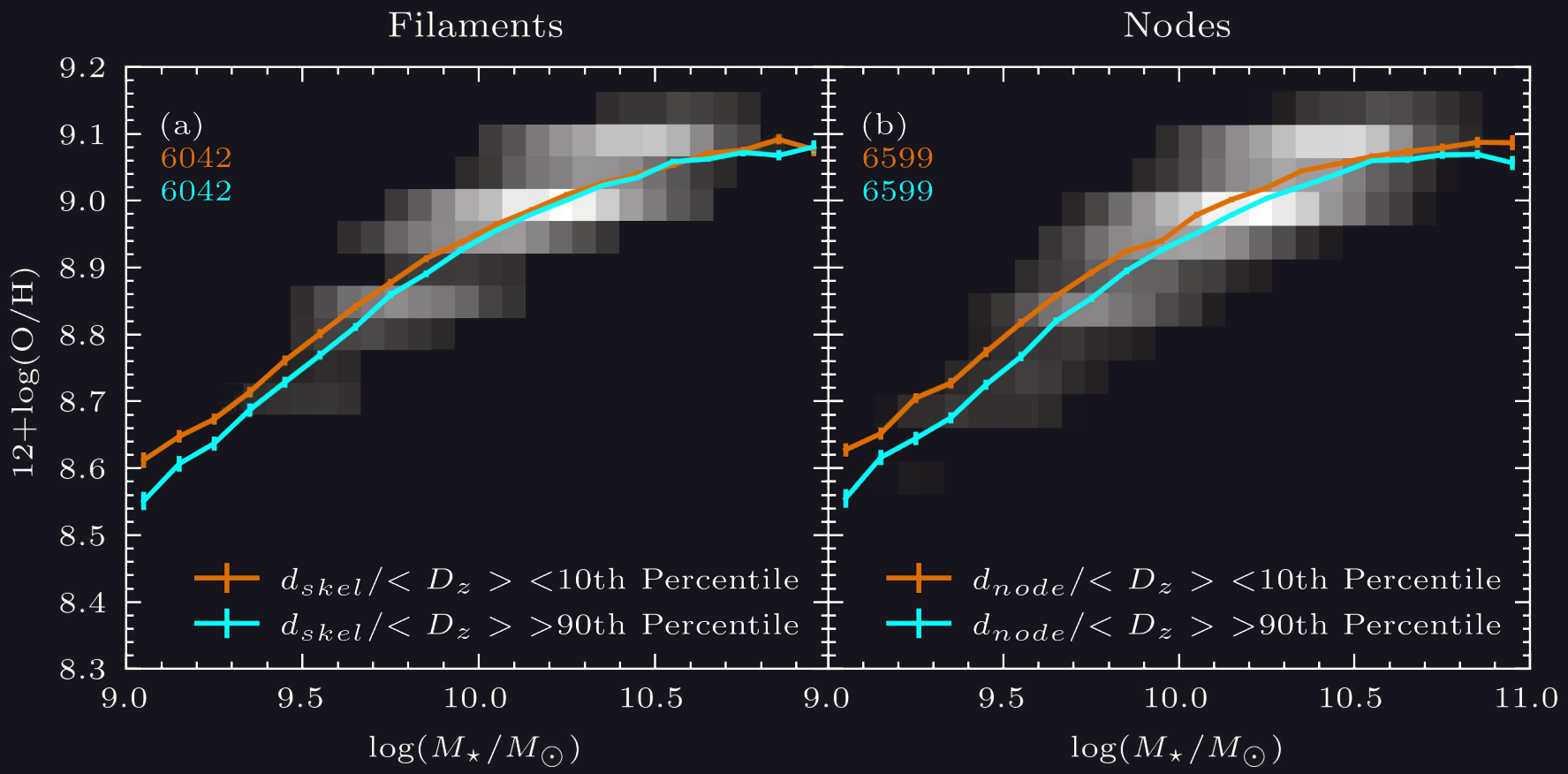
Winkel et al. 2021



consistent with simulations
/filaments

Simba, Eagle, IllustrisTNG: Bulichi, Davé & Kraljic 2023

– Gas-phase metallicity segregation –
$M_\star$- gas metallicity relation



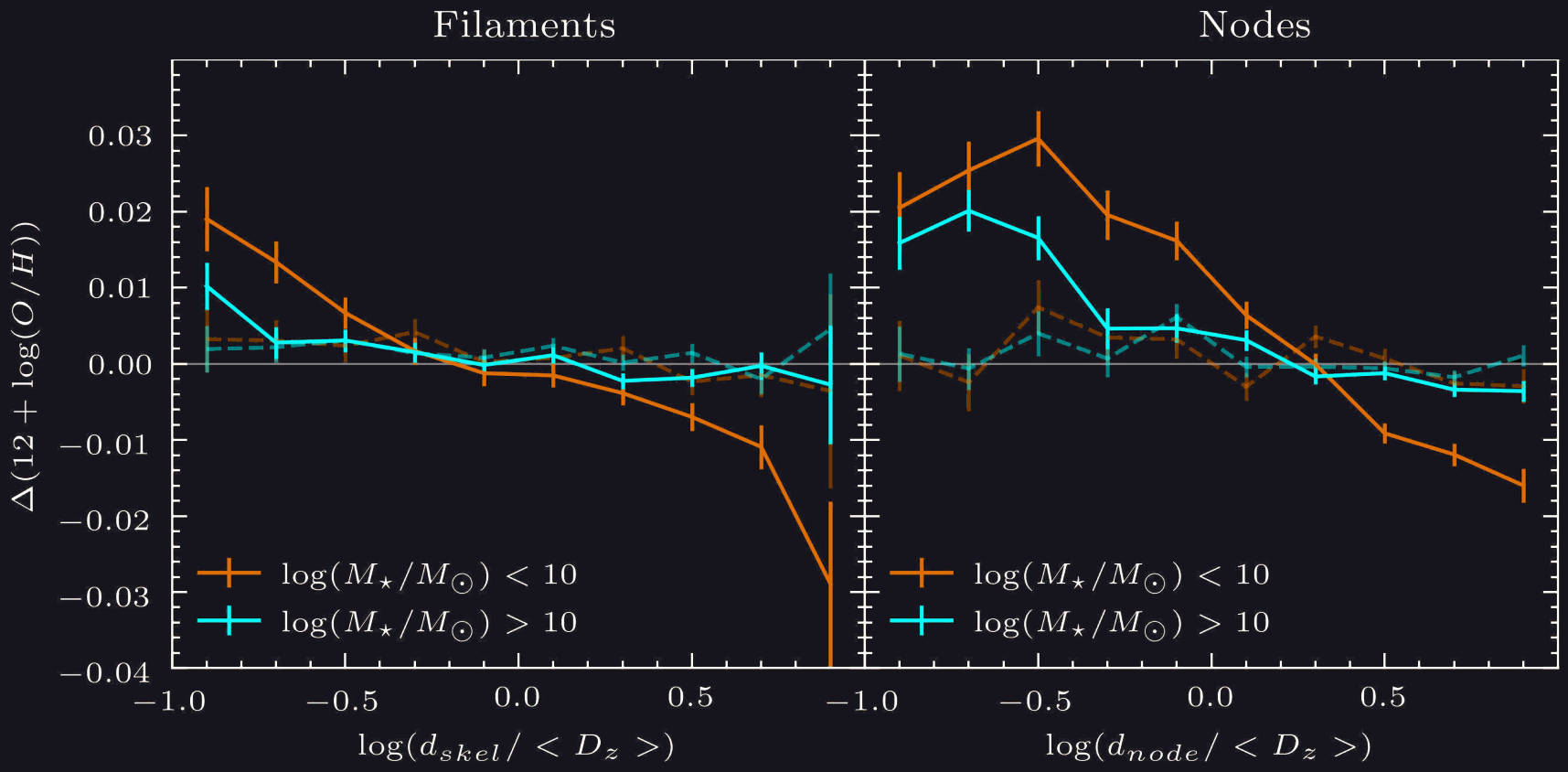
- **higher** gas-phase metallicity **closer** to the CW

Donnan, Tojeiro & Kraljic 2022

consistent with simulations

IllustrisTNG: Donnan, Tojeiro & Kraljic 2022

– Gas-phase metallicity segregation –
effect **beyond** $M_\star$ & density



- **higher** gas-phase metallicity **closer** to the CW

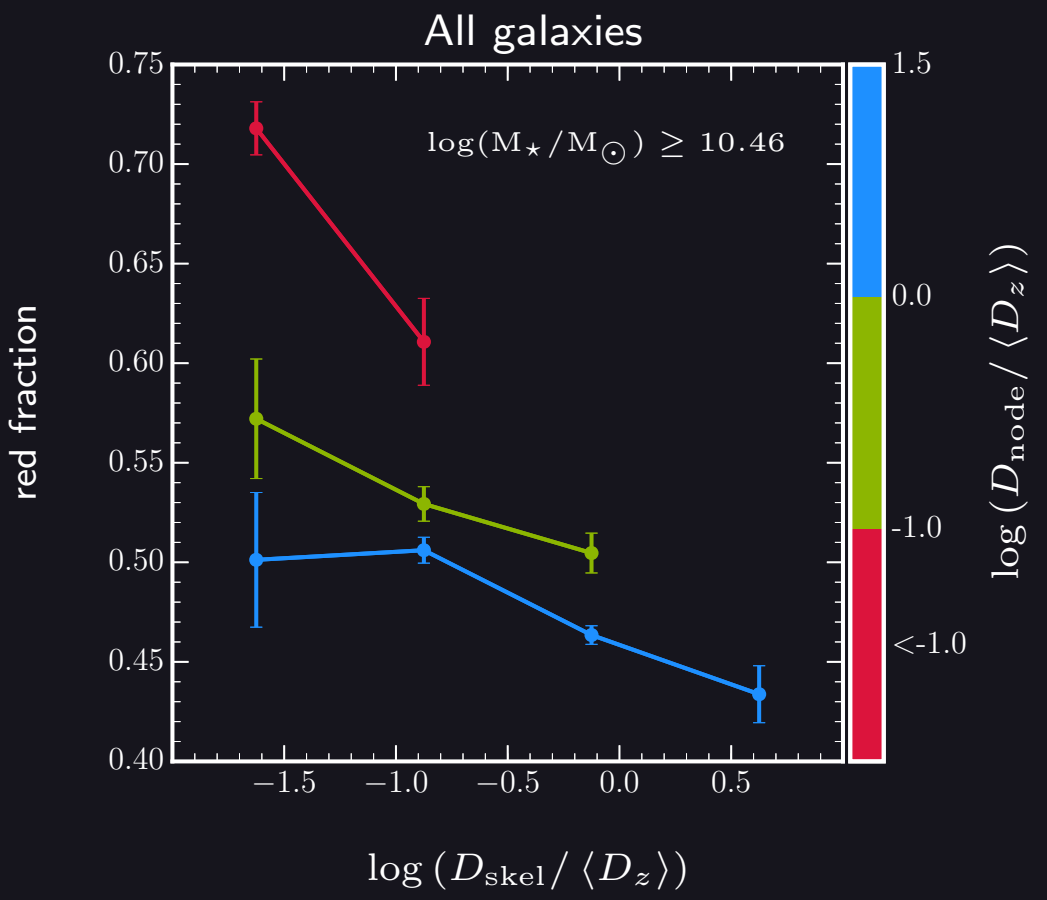
Donnan, Tojeiro & Kraljic 2022

consistent with simulations

IllustrisTNG: Donnan, Tojeiro & Kraljic 2022

Scalar properties

– 'Pre-processing' –



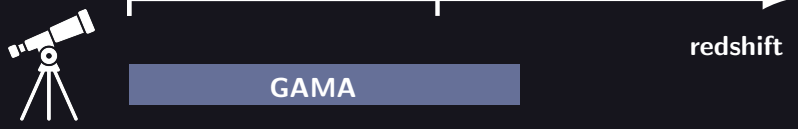
- **passive/red** galaxy fraction **increases**
near the nodes (groups/clusters)
at fixed D_{skel}
near the filaments
at fixed D_{node}

Kraljic et al. 2018

see also Sarron et al. 2019 for clusters ($0.15 < z < 0.7$)

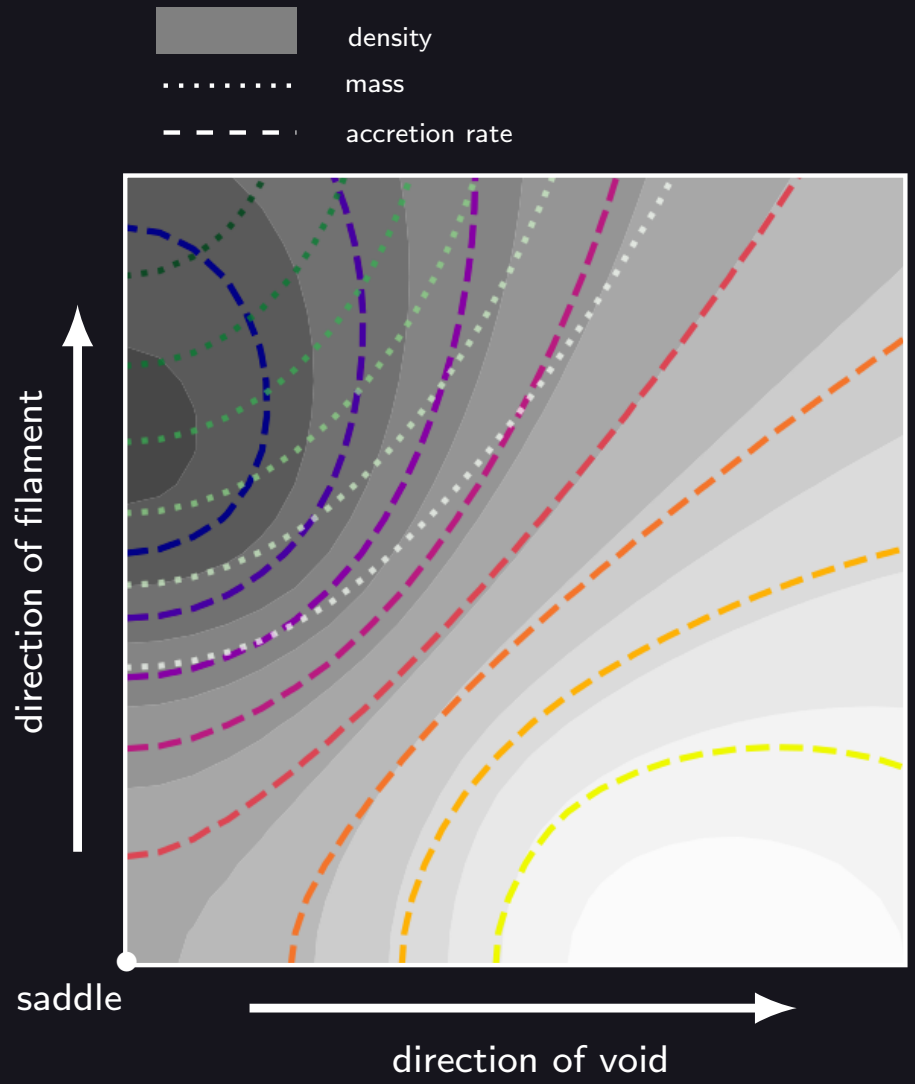
consistent with simulations

Simba: Bulichi, Davé & Kraljic 2023



– Interpretation –

. . . hints from the excursion set theory



Large-scale tides

- impact on the assembly history of halos

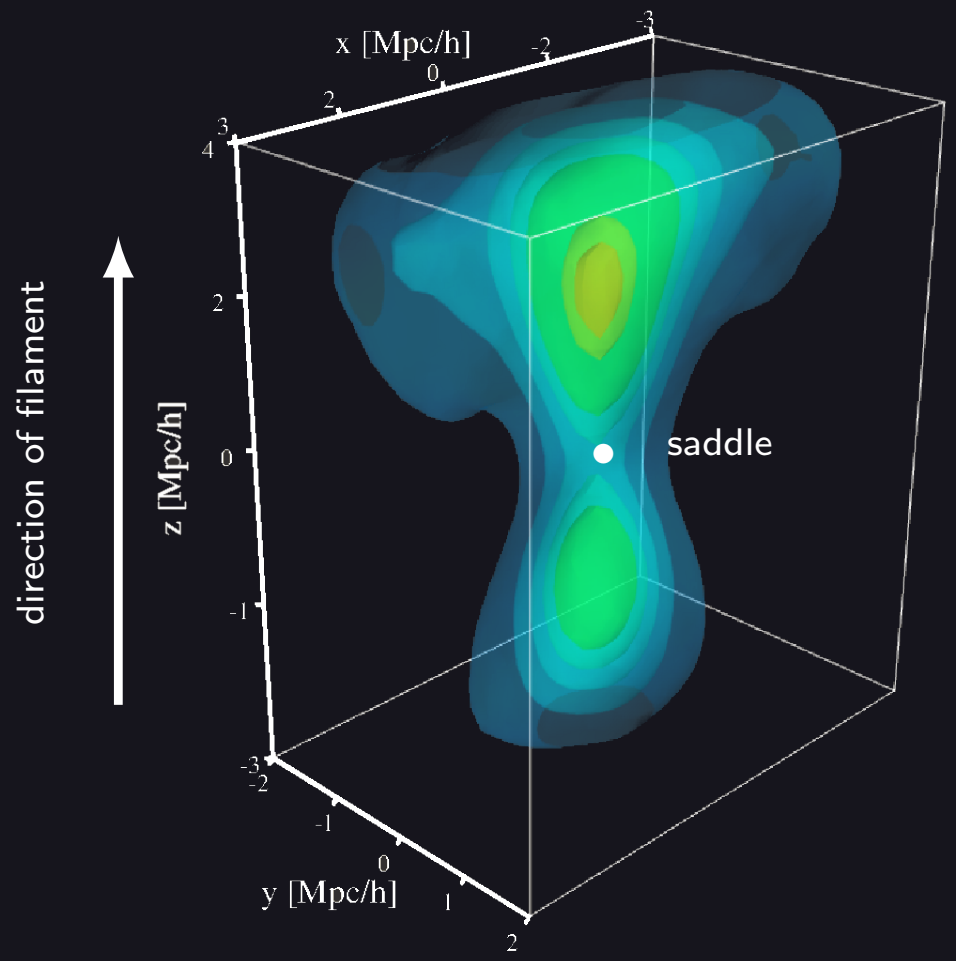
mass
accretion rate
formation time

depend on the **geometry of the saddle**

Musso et al. 2018

see also e.g. Dalal et al. 2008, Hahn et al. 2009
Ludlow et al. 2014
Borzyszkowski et al. 2017
Paranjape et al. 2018

– Stacking galaxies –

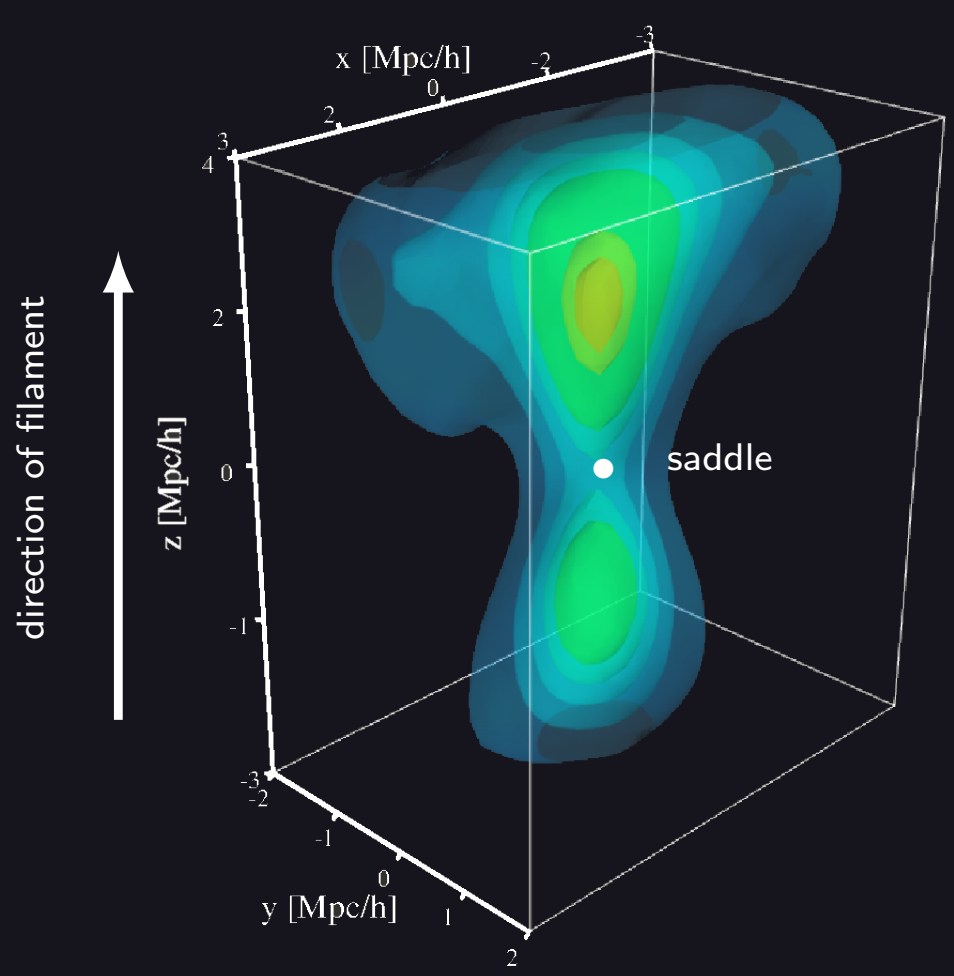


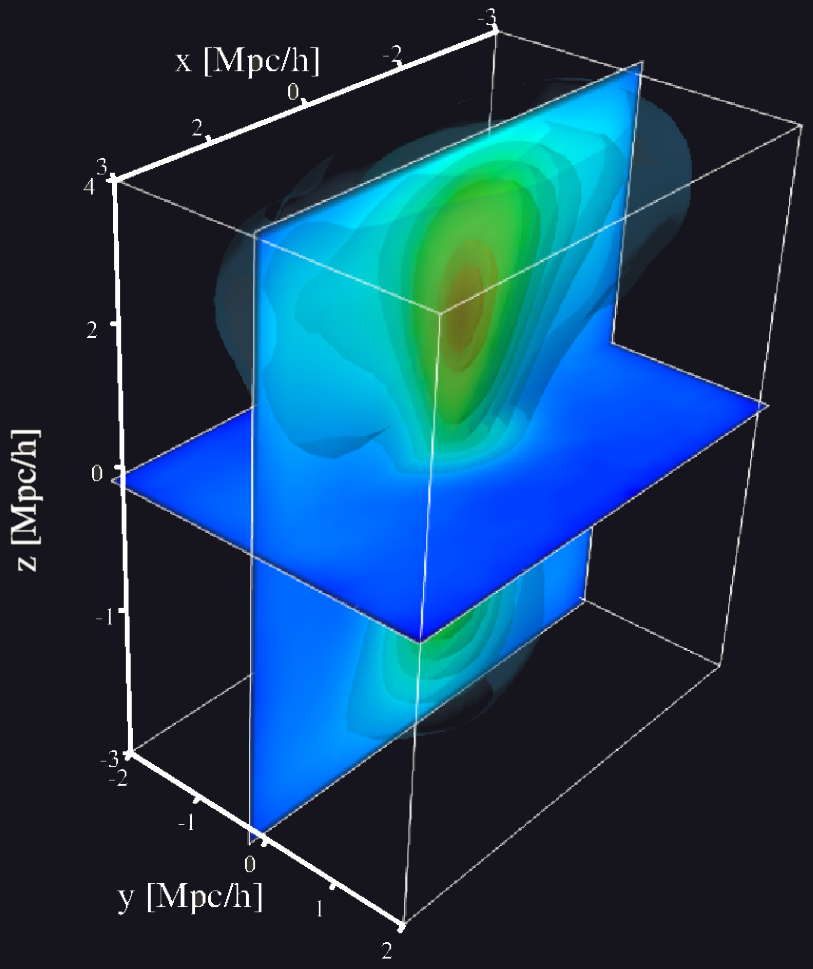
Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

Saddle frame

– Stacking galaxies –



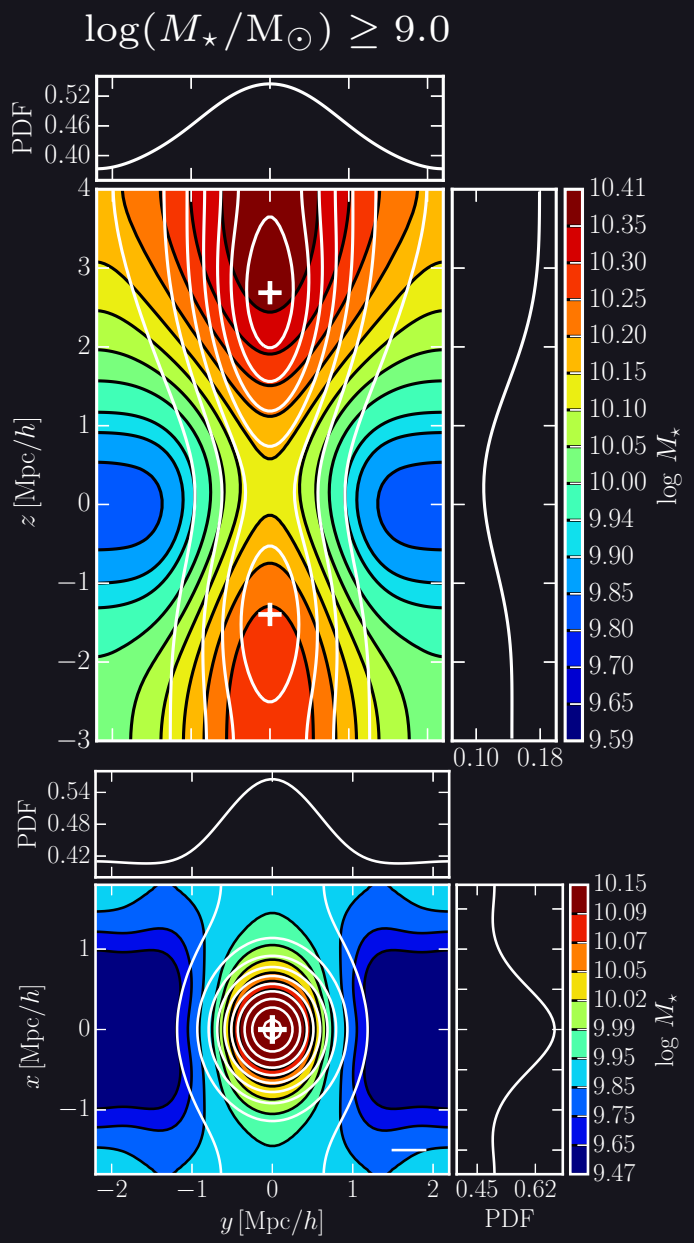


Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

Saddle frame

– Stacking galaxies –
Stellar mass



Iso-contours

- radial & angular dependence
- saddles: min longitudinally
- saddles: max transversally
- higher $M_\star$ in filaments vs voids
- higher $M_\star$ in nodes vs saddles

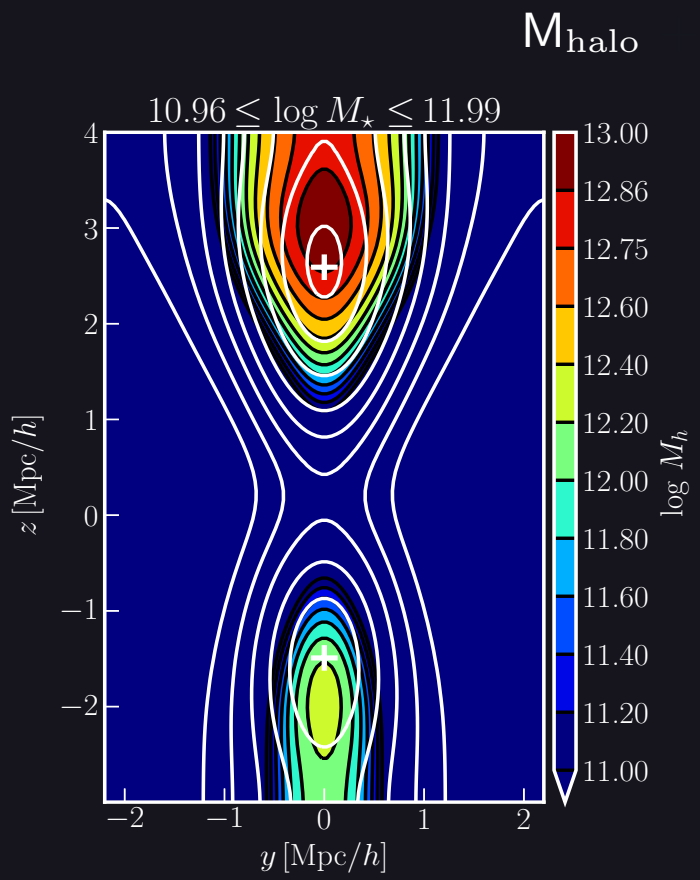
Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

Saddle frame

– Stacking galaxies –

Hidden variable: M_{halo} & ρ?



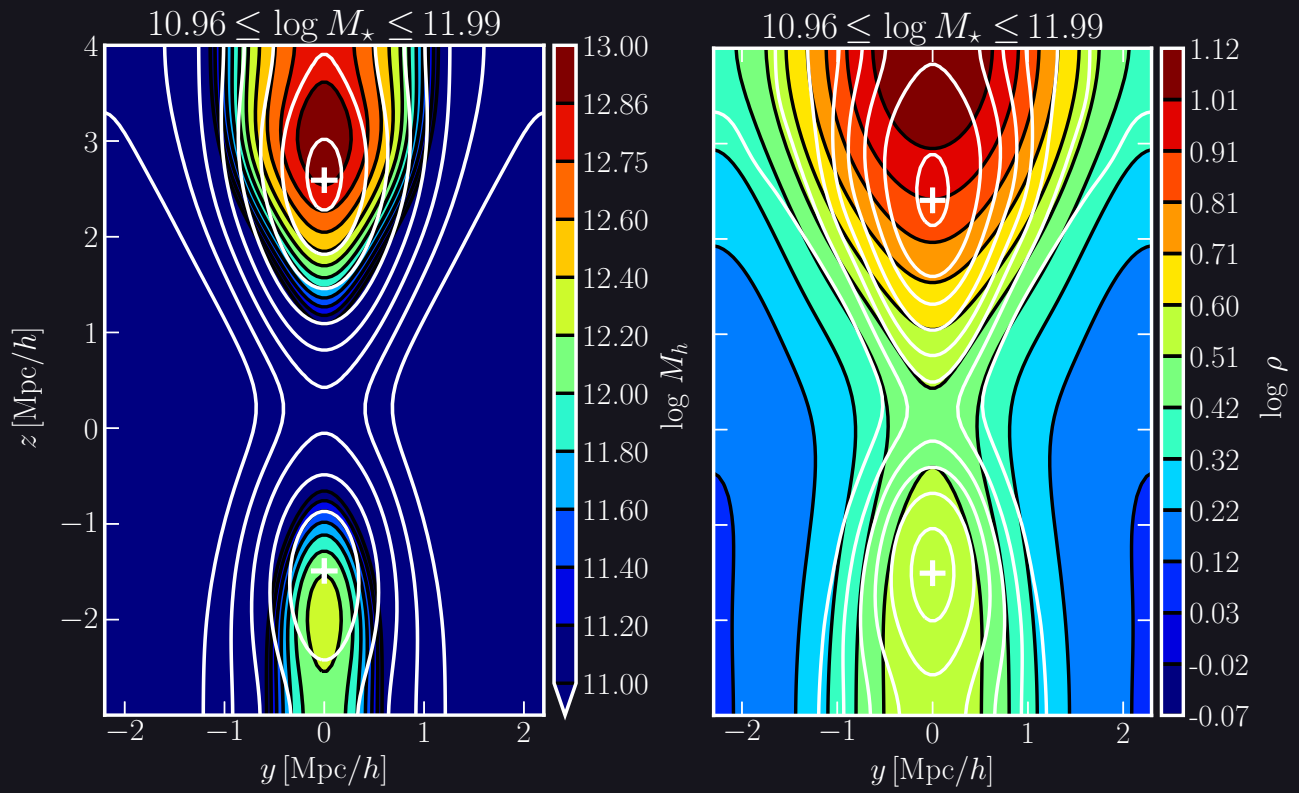
Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

– Stacking galaxies –

Hidden variable: M_{halo} & ρ?

$M_{halo} + \rho$



Kraljic et al. 2019

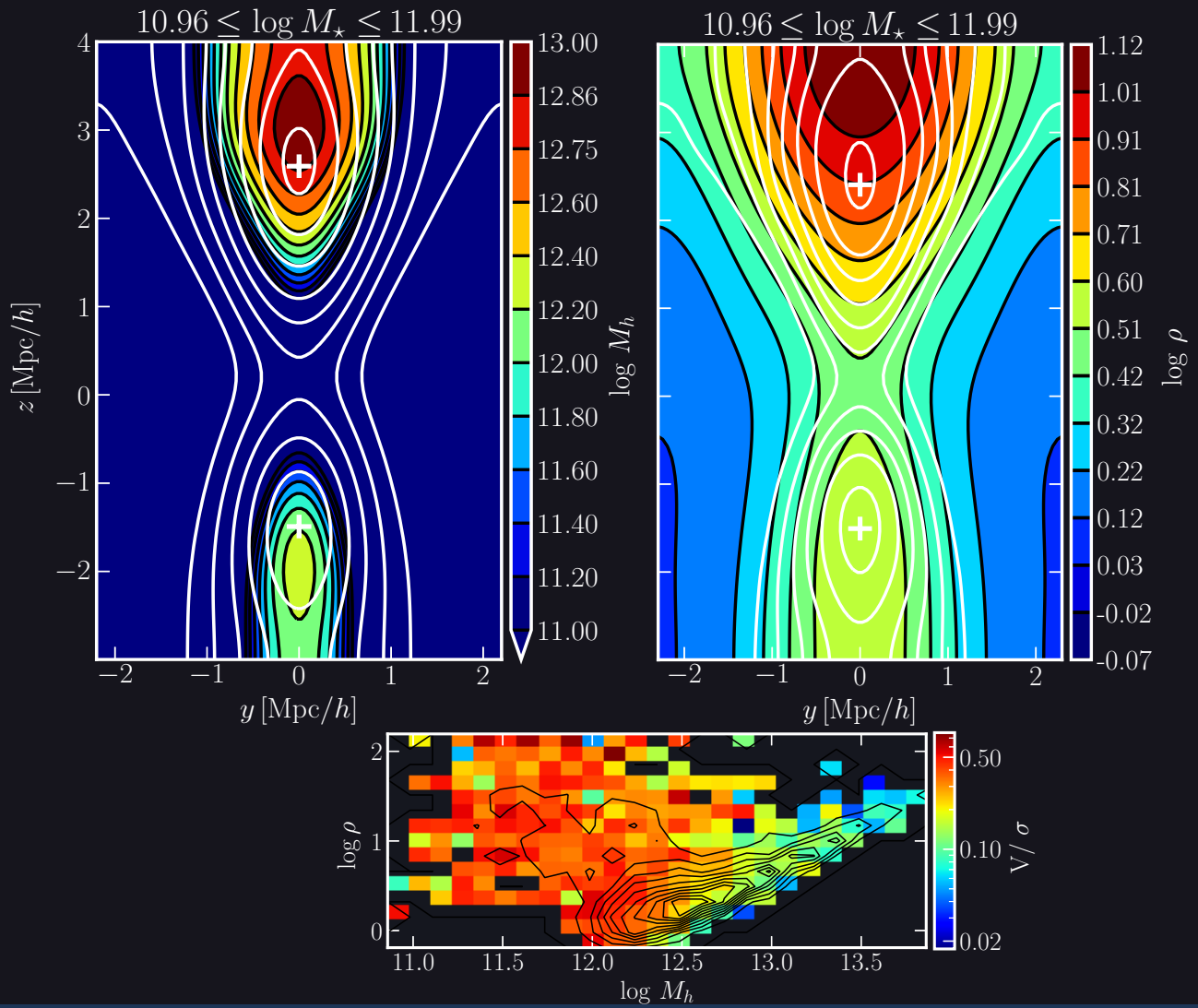
Horizon-AGN: Dubois et al. 2014

Saddle frame

– Stacking galaxies –

Hidden variable: M_{halo} & ρ?

$M_{halo} + \rho + f(M_{halo}, \rho)$



Kraljic et al. 2019

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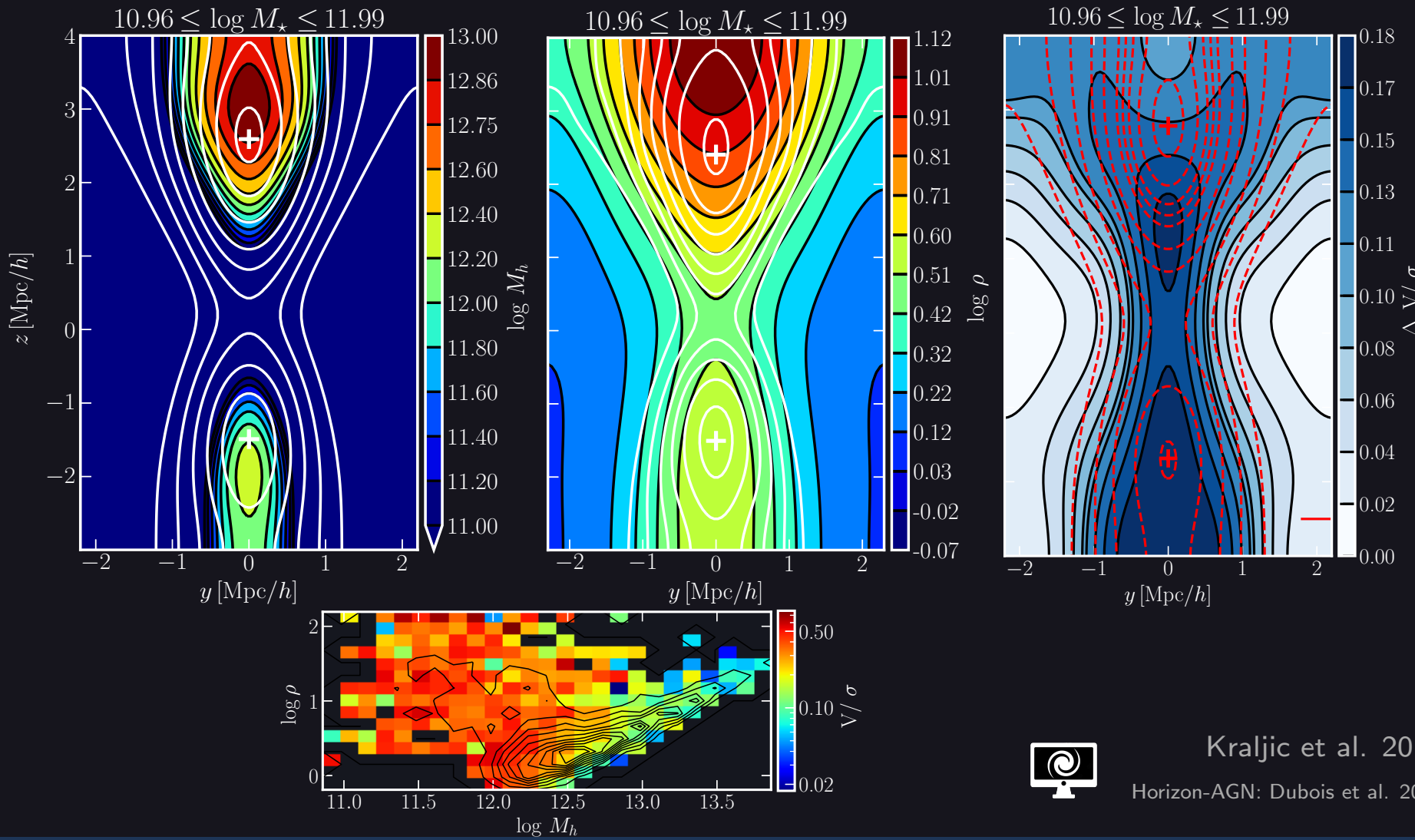
$M_{halo} + \rho + f(M_{halo}, \rho)$ ⋯⋯► residuals



Kraljic et al. 2019

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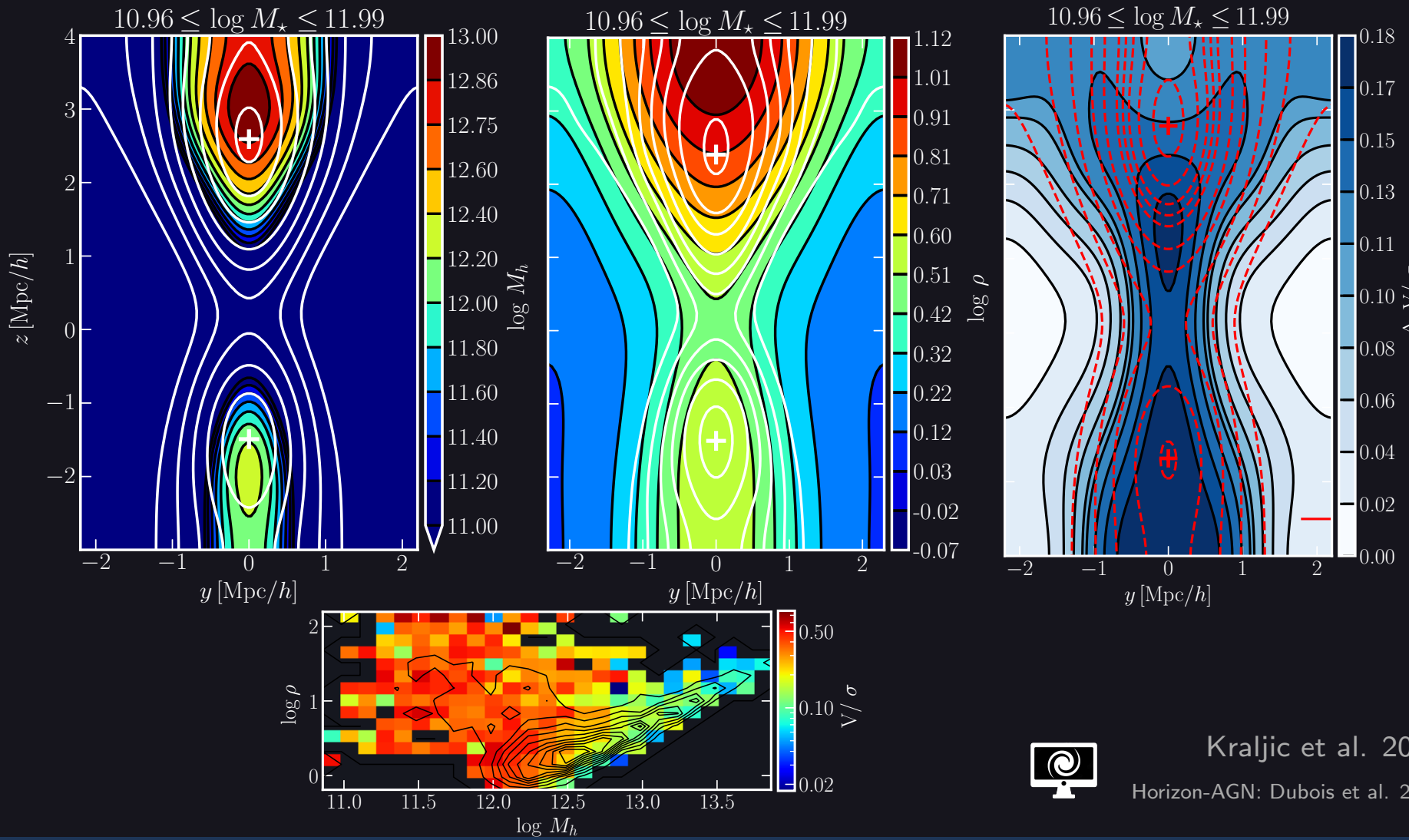

Kraljic et al. 2019

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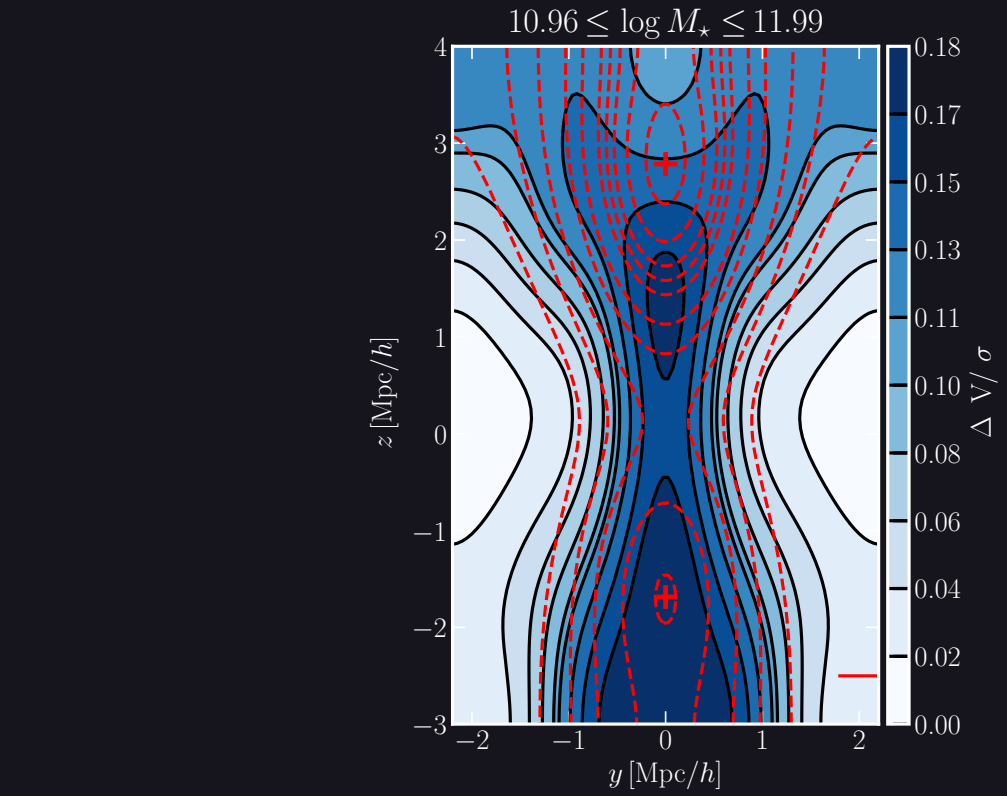
– Stacking galaxies –

Hidden variable: spin advection?

residuals



Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

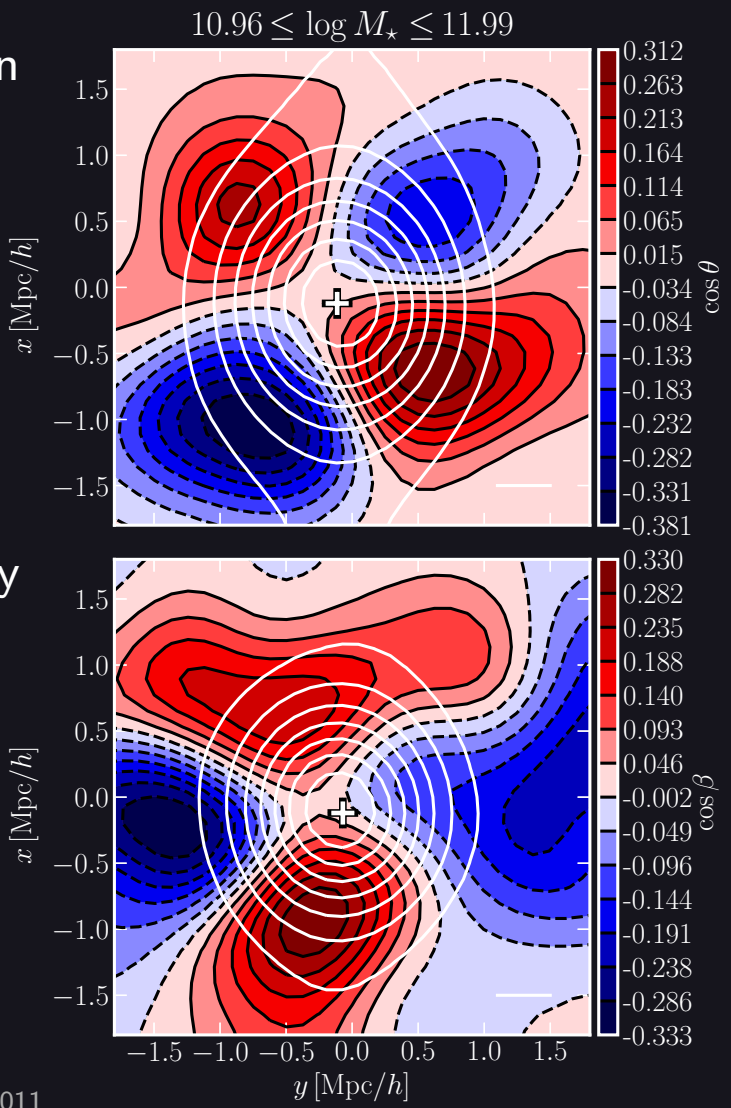
Saddle frame

– Stacking galaxies –

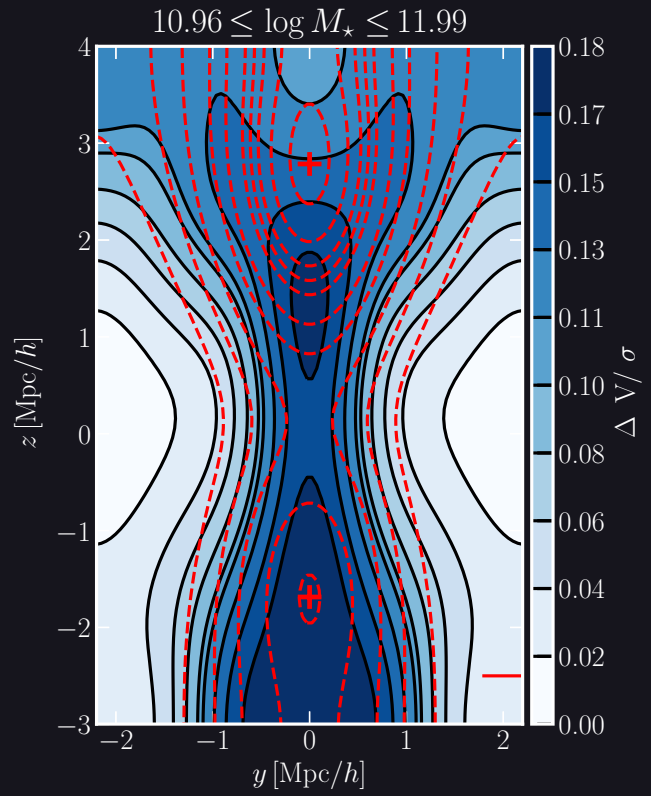
Hidden variable: spin advection?

spin

vorticity



residuals



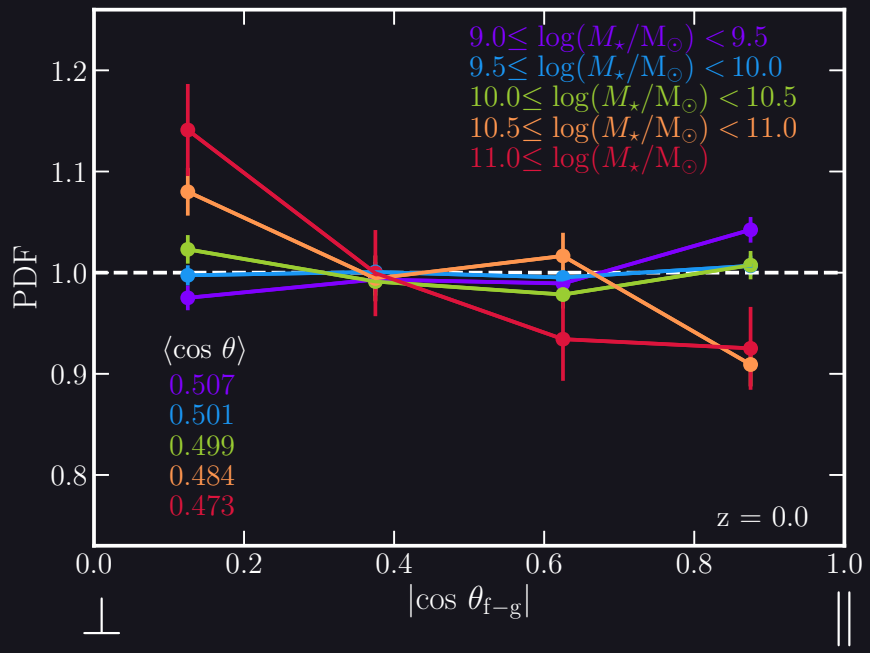
see also Pichon et al. 2011
Codis et al. 2015
Laigle et al. 2015
Song et al. 2021

Kraljic et al. 2019

Horizon-AGN: Dubois et al. 2014

Spin properties

Filaments



- **massive** galaxies tend to have spin ⊥
- **low-mass** galaxies tend to have spin ||

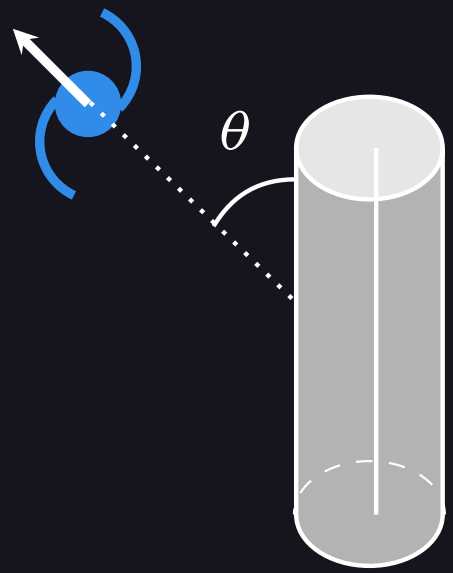
consistent across different simulations

Simba: Kraljic et al. 2020a

Horizon-AGN: Dubois et al. 2014, Codis et al. 2018

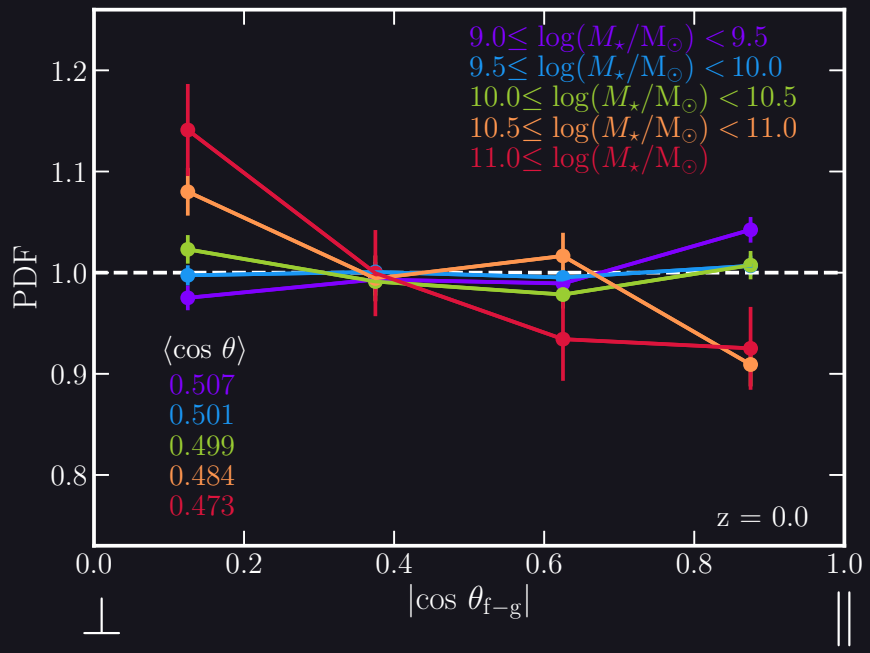
Illustris: Wang et al. 2018

– **Angular momentum vector** –



Spin properties

Filaments



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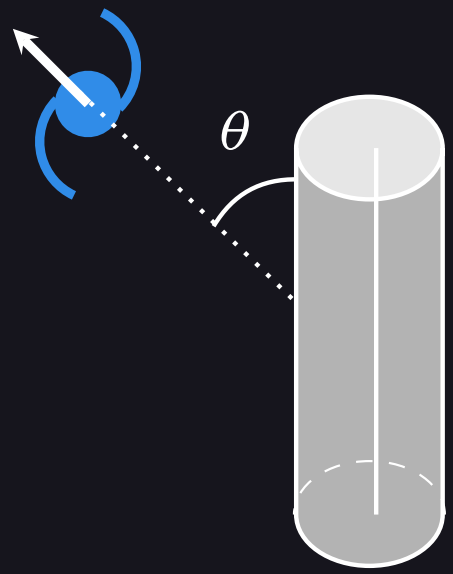


also

- **massive** halos tend to have spin ⊥
- **low-mass** halos tend to have spin ||

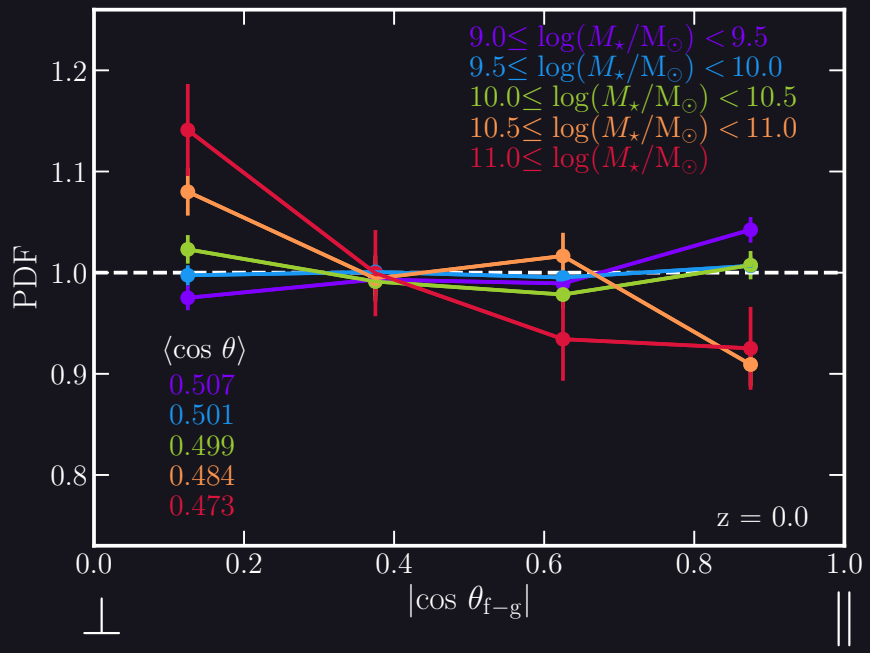
e.g. Hahn et al. 2007

Codis et al. 2012, Kraljic et al. 2020a

Ganeshaiah Veena et al. 2018

Spin properties

Filaments



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Horizon-AGN: Dubois et al. 2014, Codis et al. 2018
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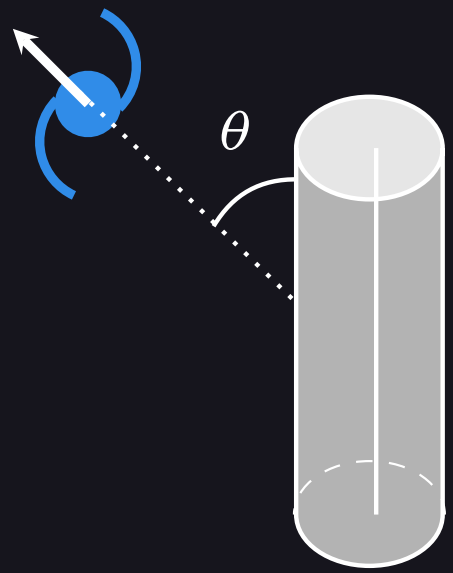

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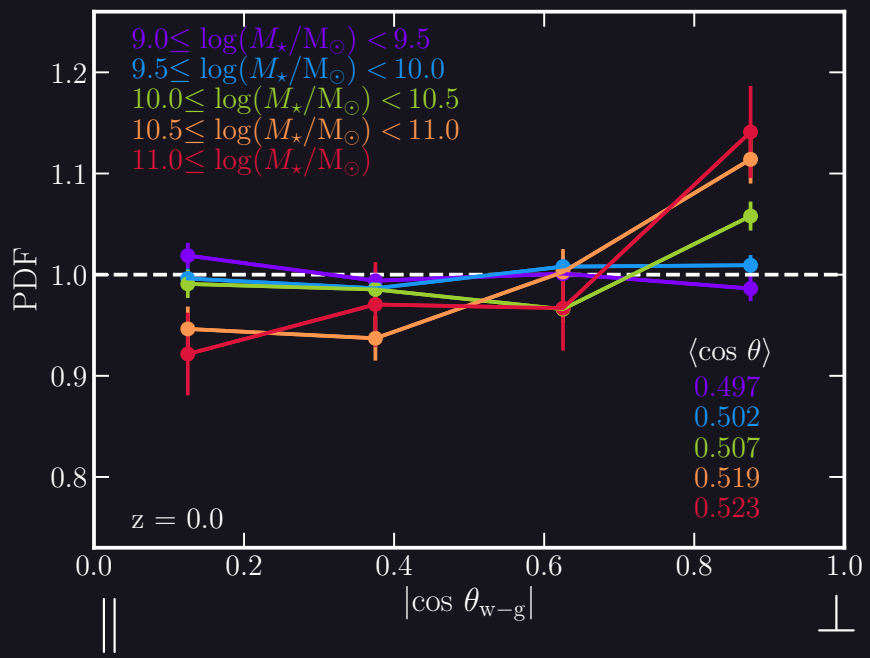
Codis et al. 2012, Kraljic et al. 2020a
Ganeshaiah Veena et al. 2018

LTGs	e.g. Tempel et al. 2013, Kraljic et al. 2021 **vs** Lee & Erdogu 2007	||
S0s	e.g. Tempel et al. 2013, Pahwa et al. 2016, Kraljic et al. 2021	⊥
Mass	Welker et al. 2020 (galaxy), Barsanti et al. 2022 (bulge)	transition

Spin properties

Walls



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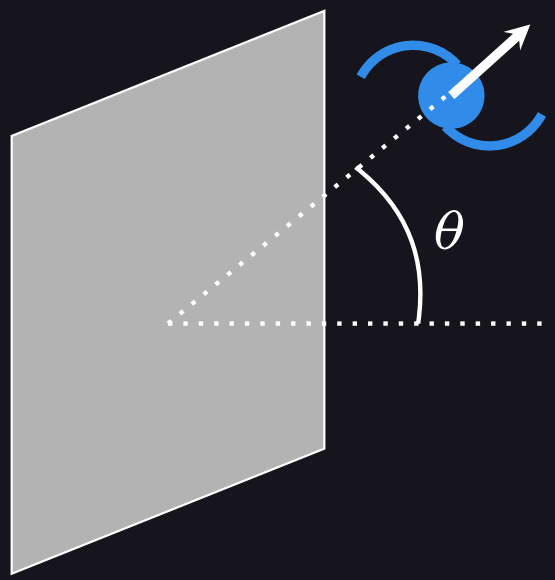
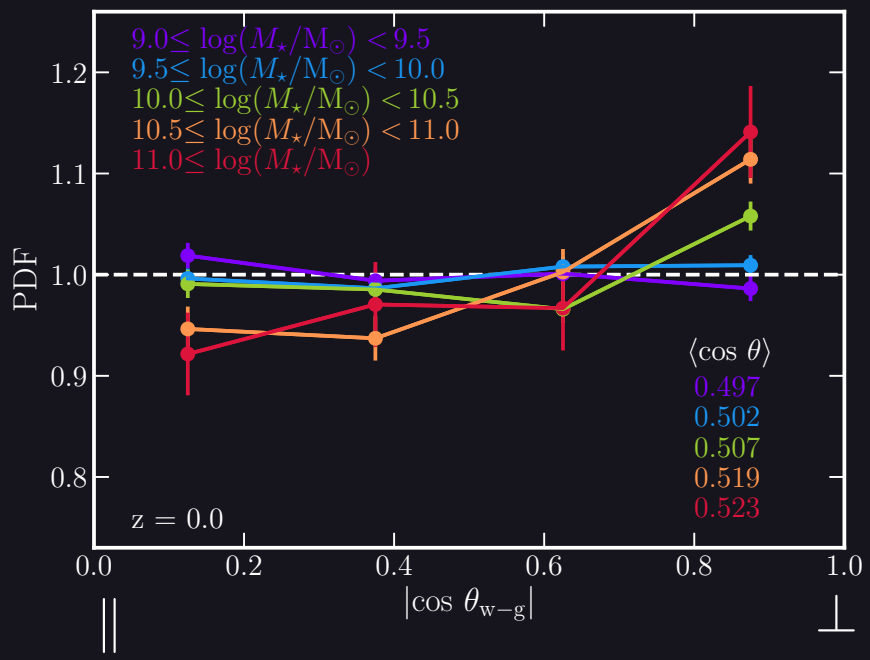


Spin properties

Walls



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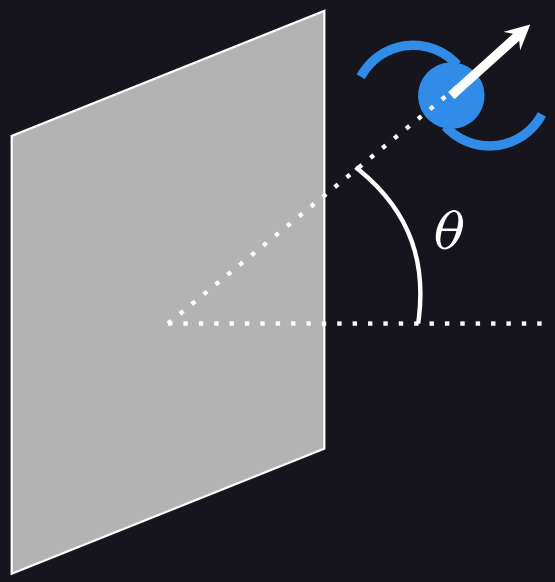

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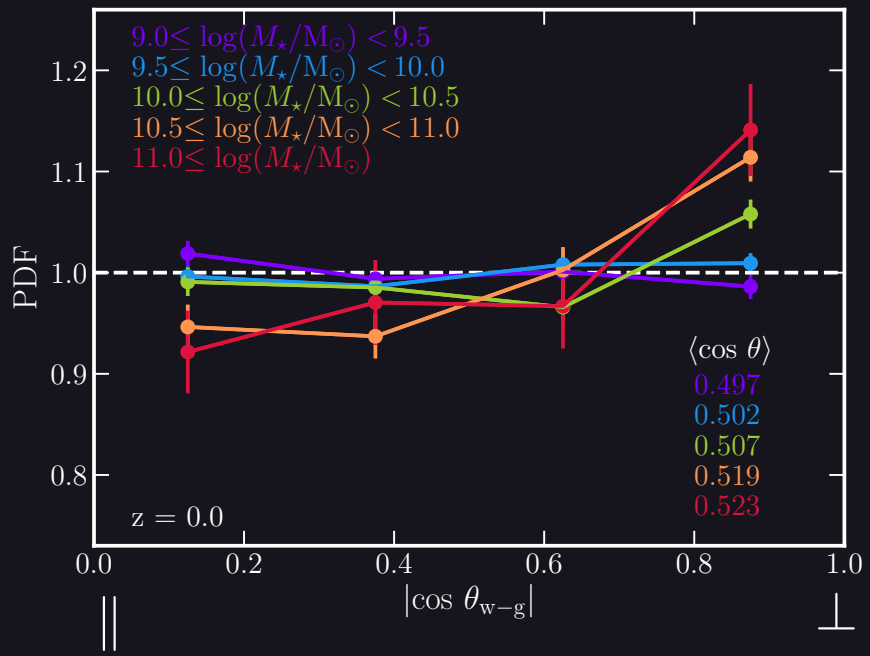
see Codis et al. 2015 (conditional Tidal Torque Theory)

Spin properties

Walls



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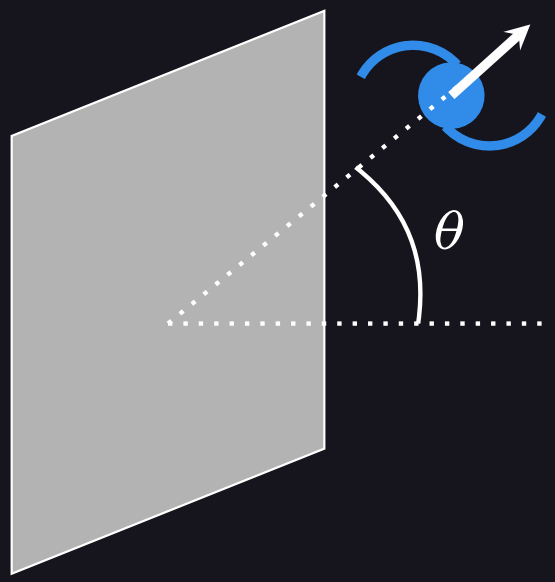

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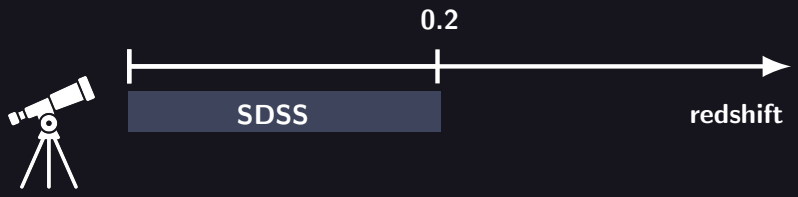
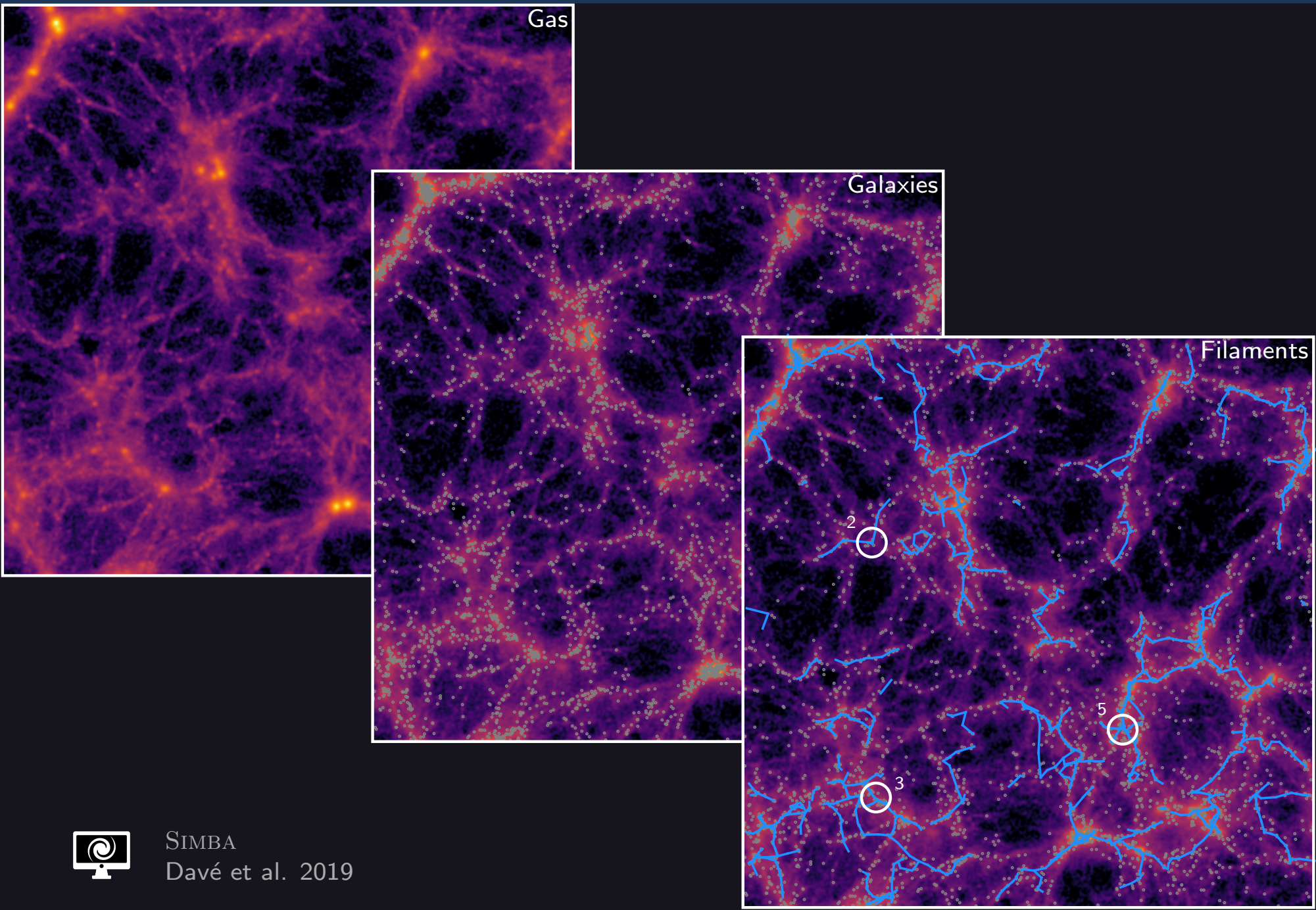


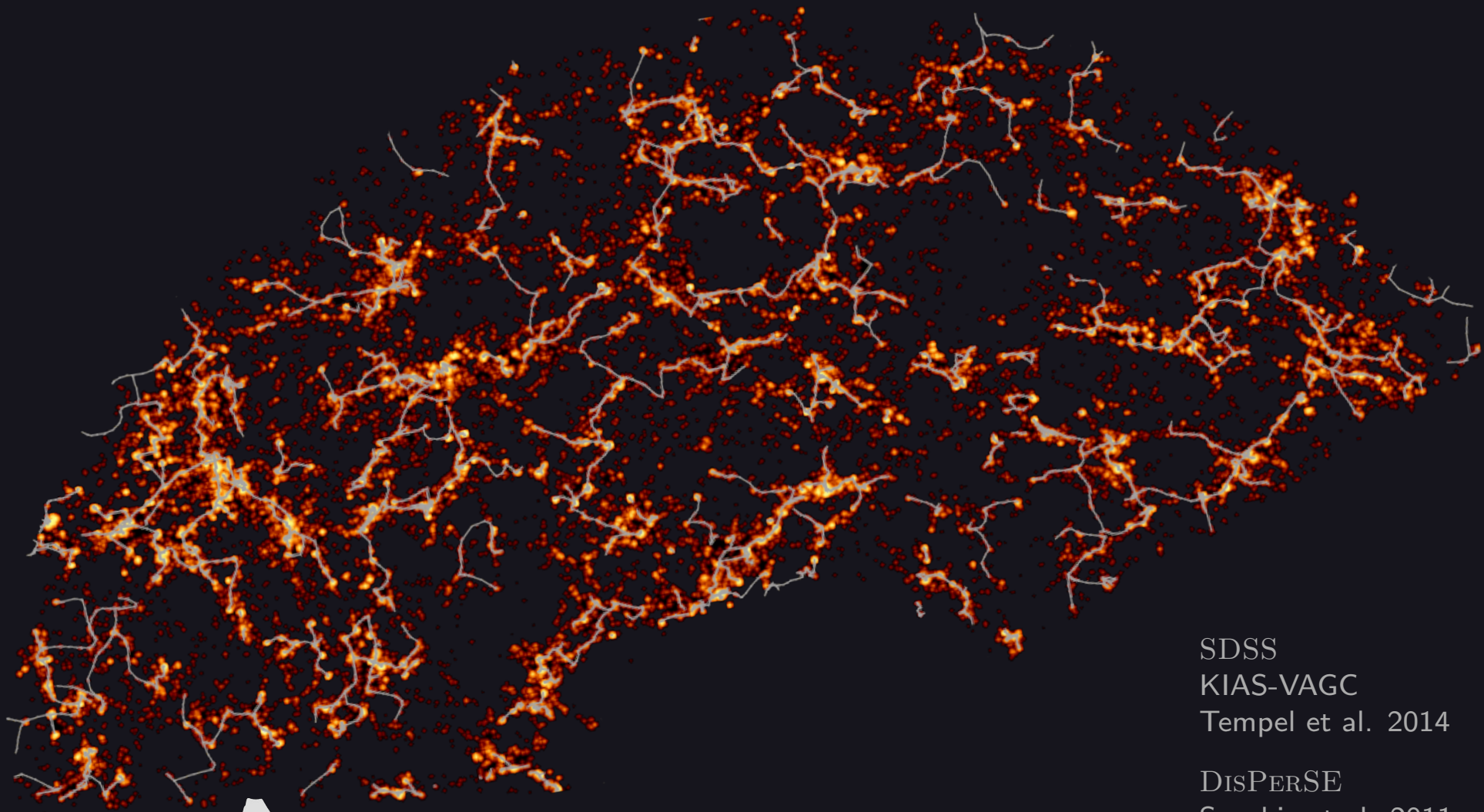
Mass Lee & Moon 2023 (spirals)

Connectivity of the Cosmic web



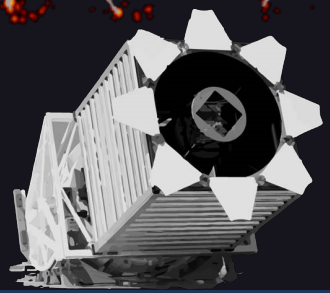
Simba
Davé et al. 2019

Connectivity of the Cosmic web



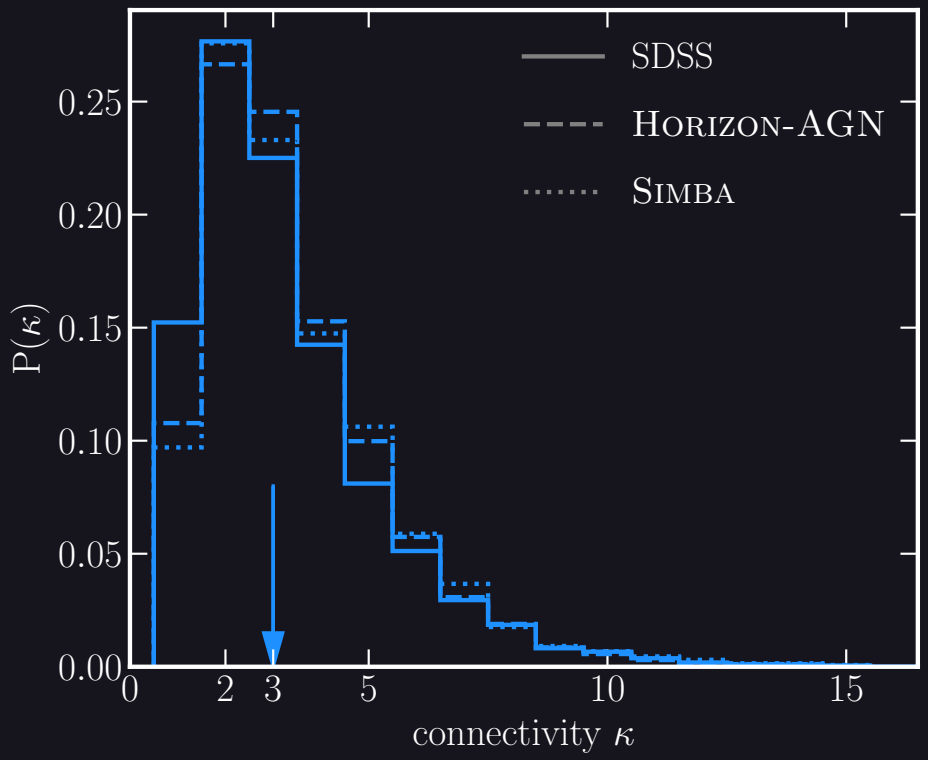
SDSS
KIAS-VAGC
Tempel et al. 2014

DisPerSE
Sousbie et al. 2011



SDSS

– Stellar mass –



see Codis et al. 2018 for GRF

Kraljic et al. 2020b

see also e.g. Darragh-Ford et al. 2019 for BCGs
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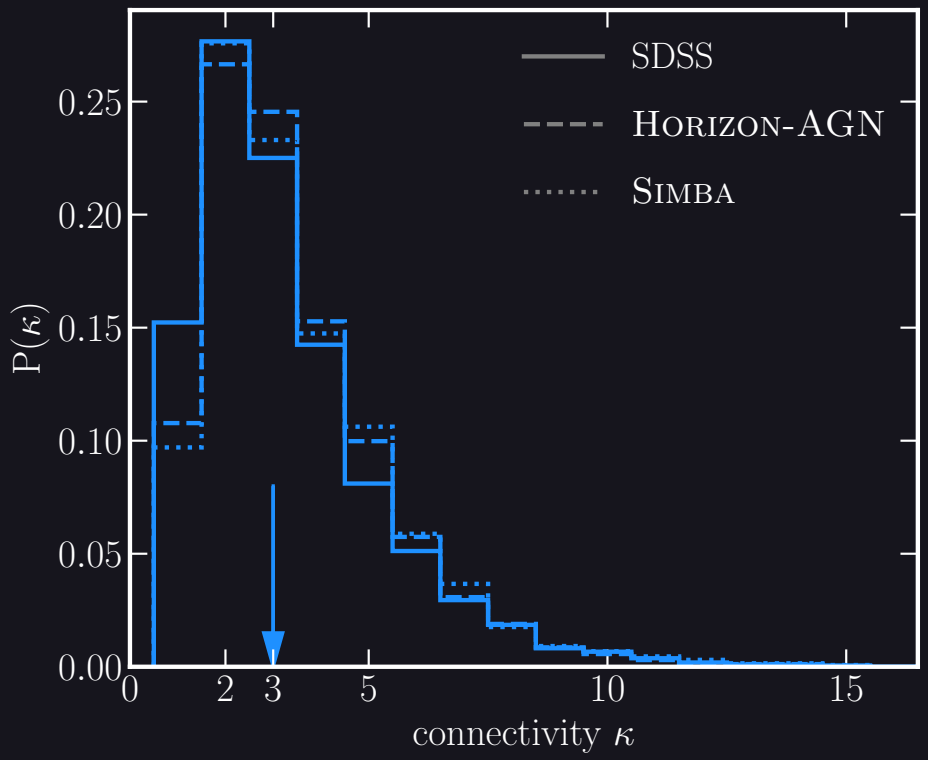

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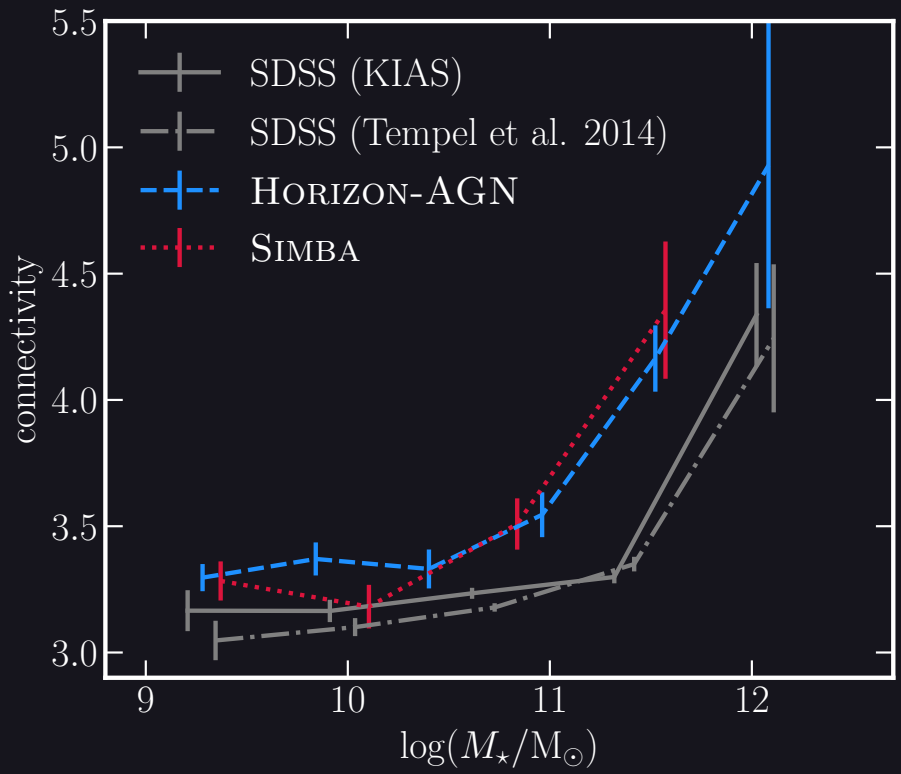

Kraljic et al. 2020b

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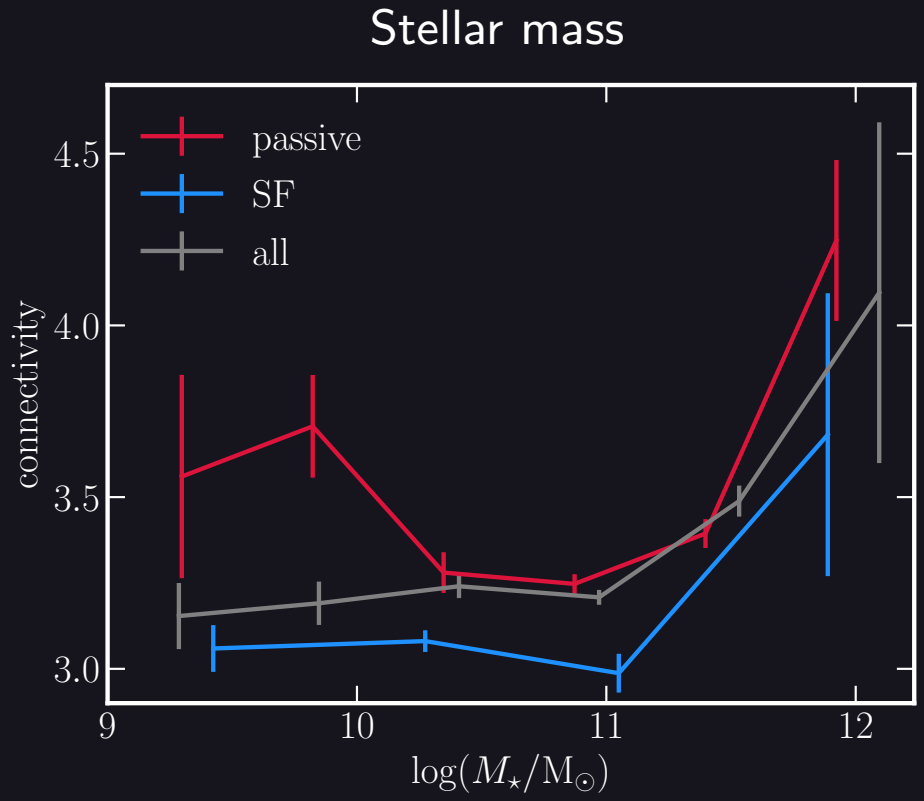
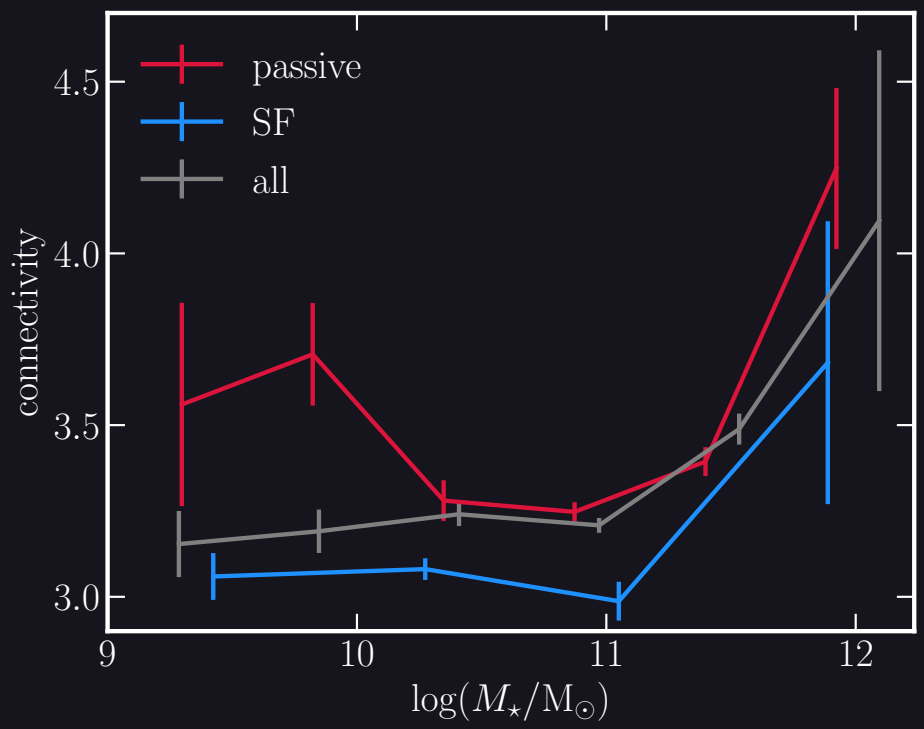
– Beyond stellar mass –



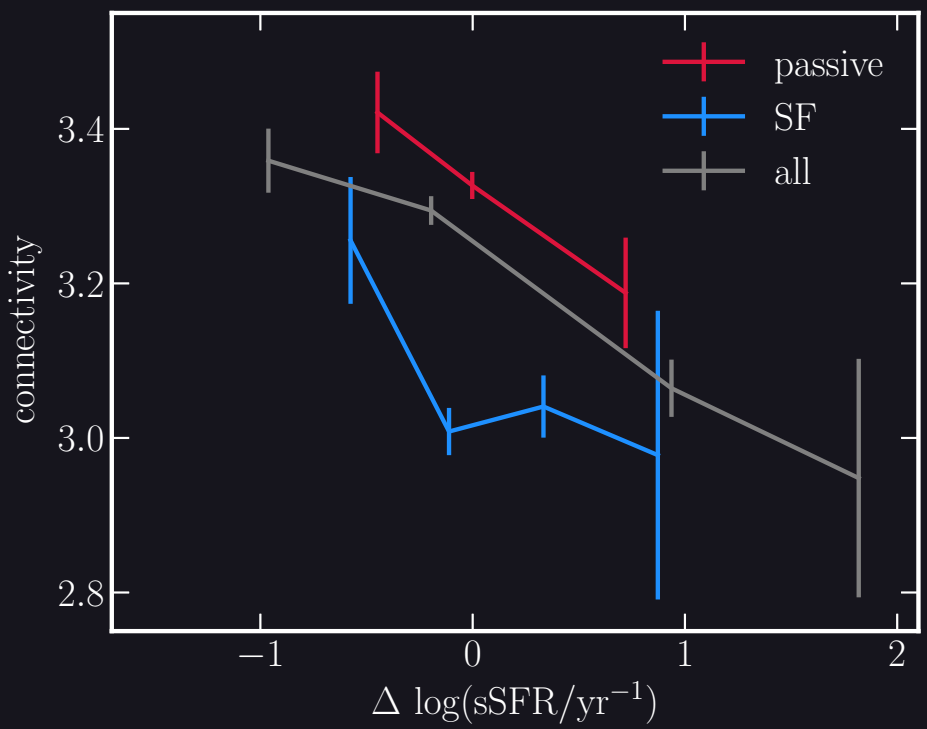

SDSS

– Beyond stellar mass –

Stellar mass



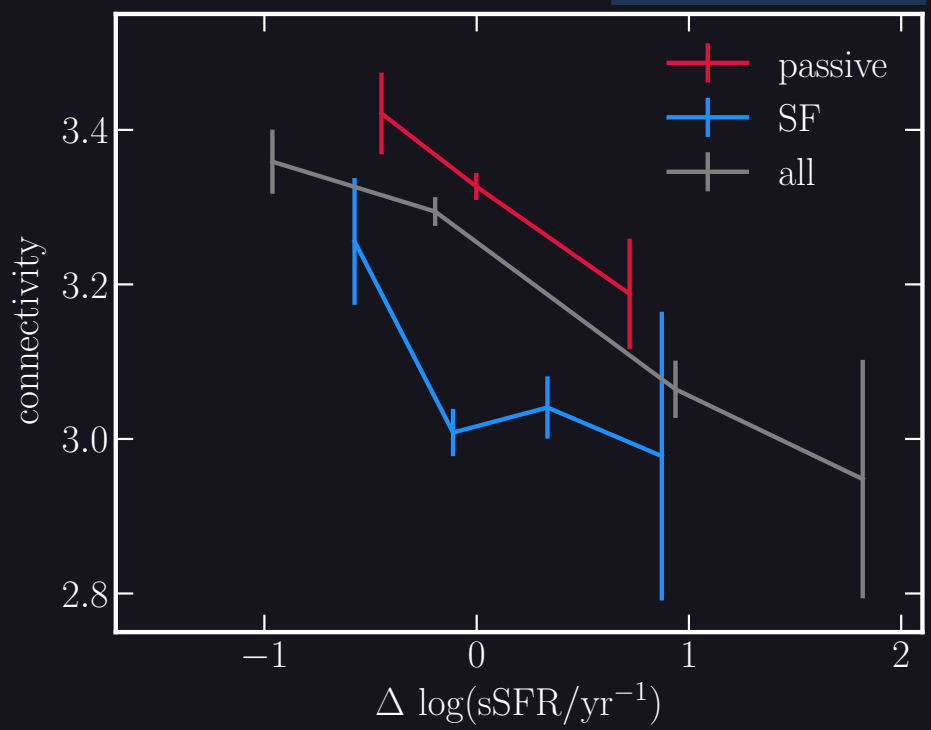
sSFR residuals




SDSS

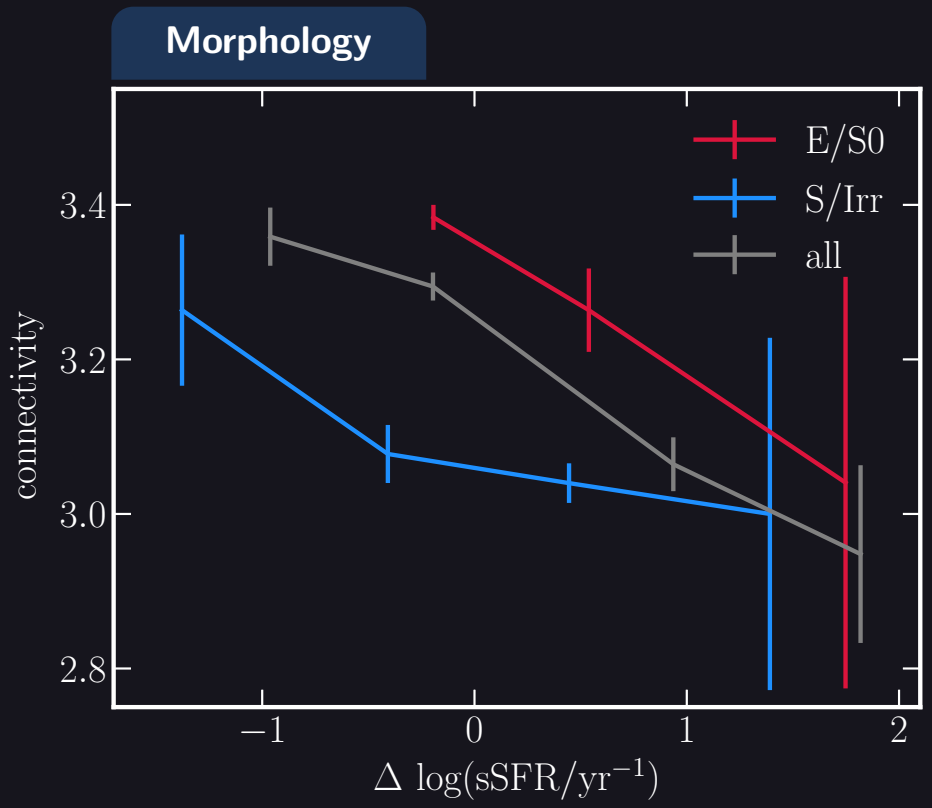
– Beyond stellar mass –

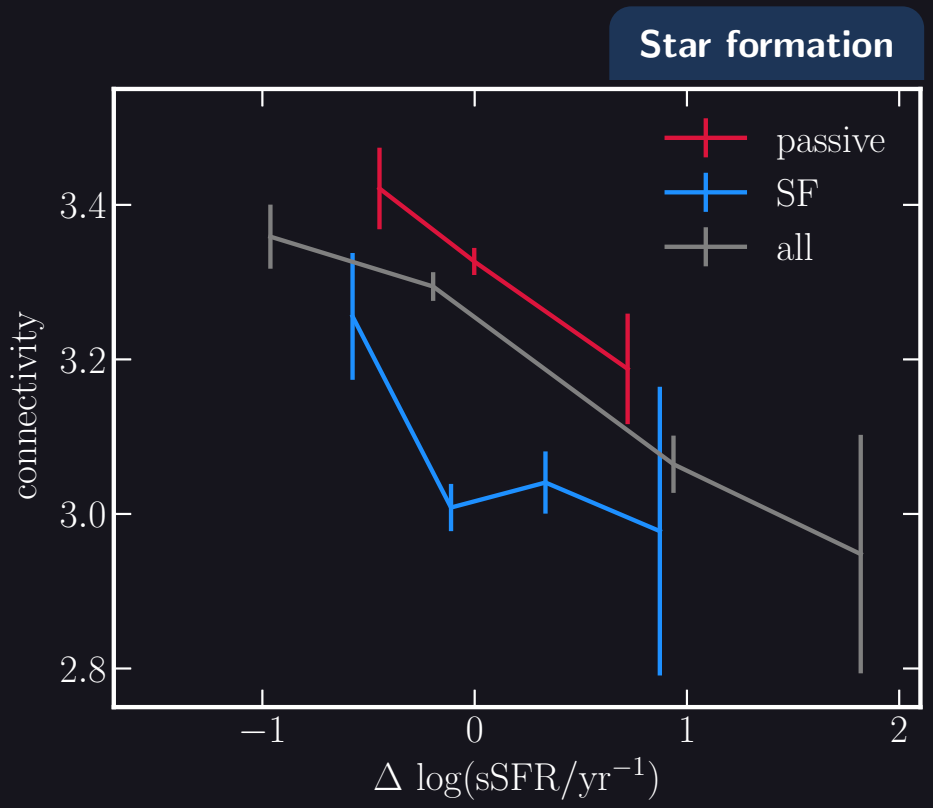
Star formation



SDSS

– Beyond stellar mass –





– Beyond stellar mass –

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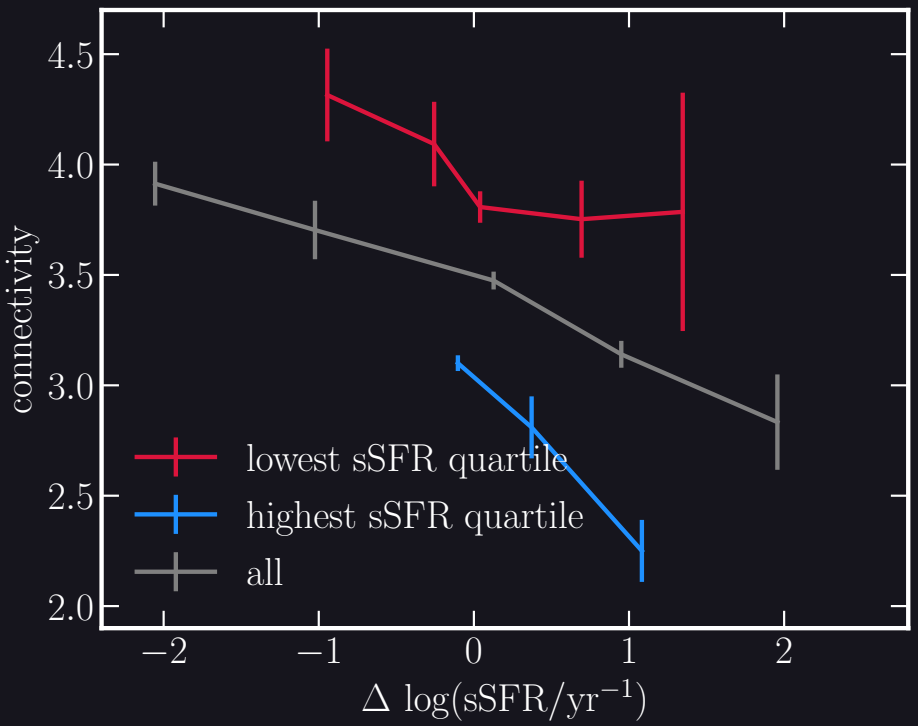
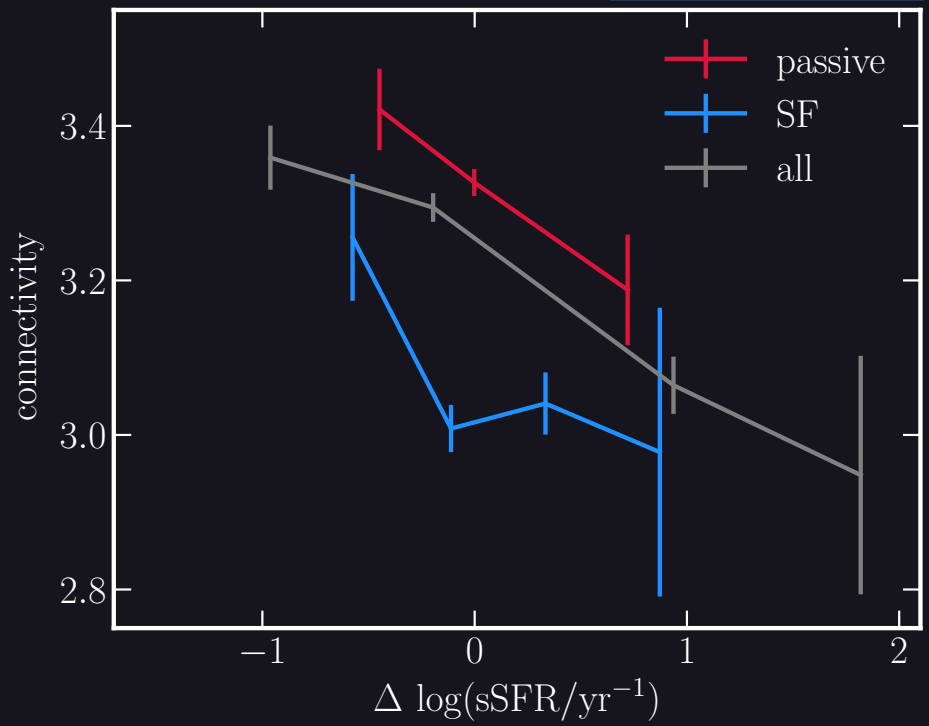
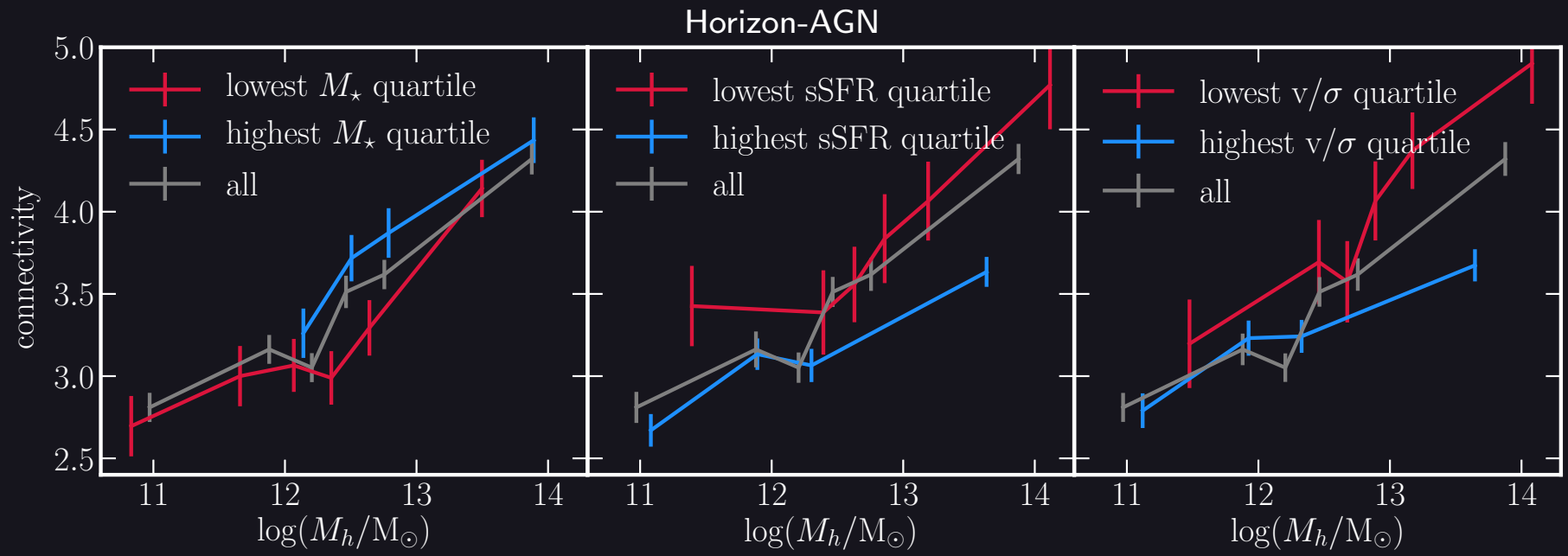




Horizon-AGN: Dubois et al. 2014
Simba: Davé et al. 2019

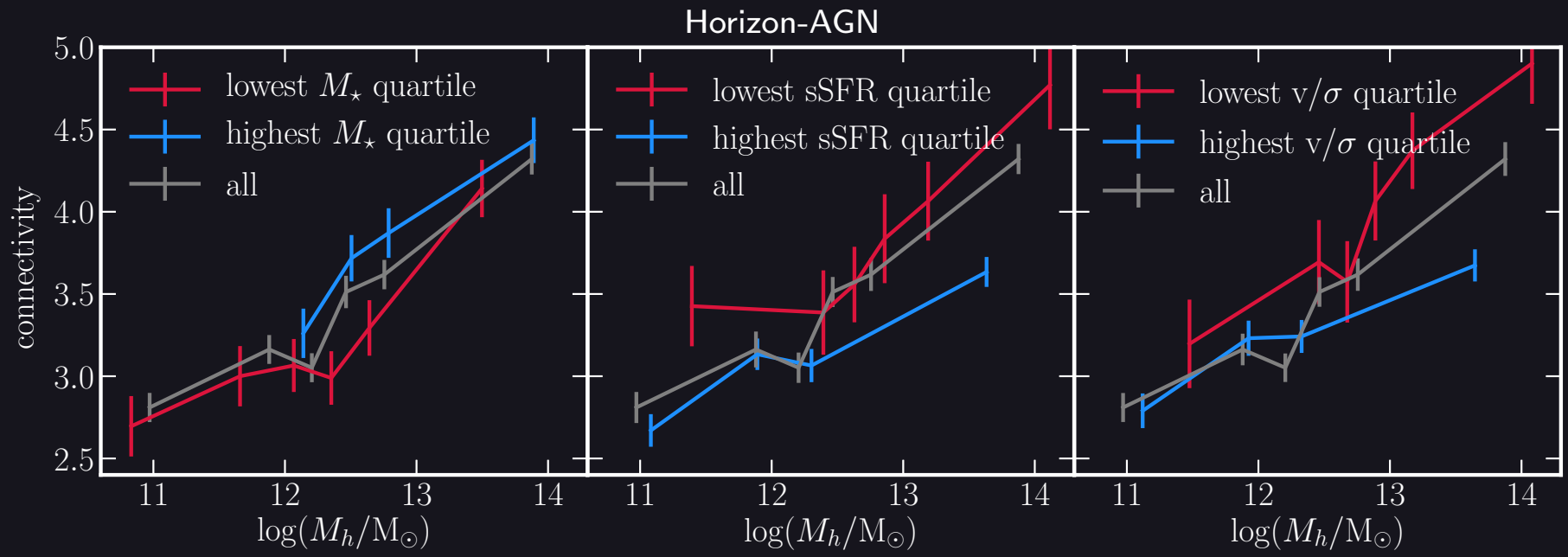
SDSS

– Halo mass –



Kraljic et al. 2020b

– Halo mass –



At fixed halo mass, centrals with higher connectivity tend to be

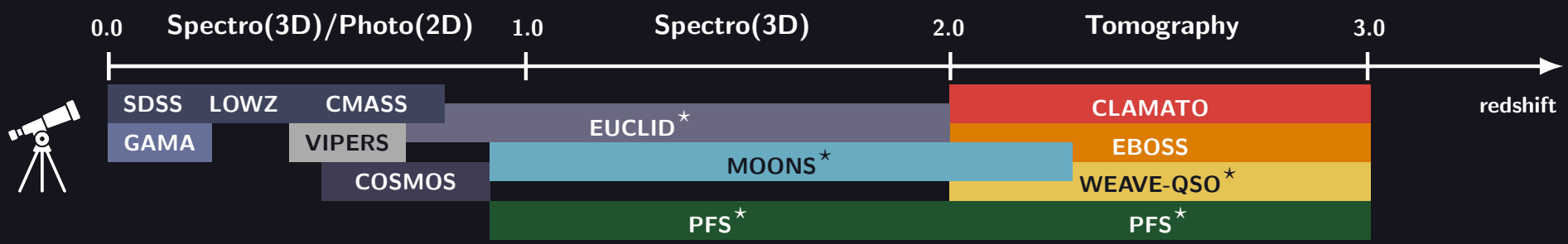
- more massive
- less star-forming
- more elliptical

Kraljic et al. 2020b

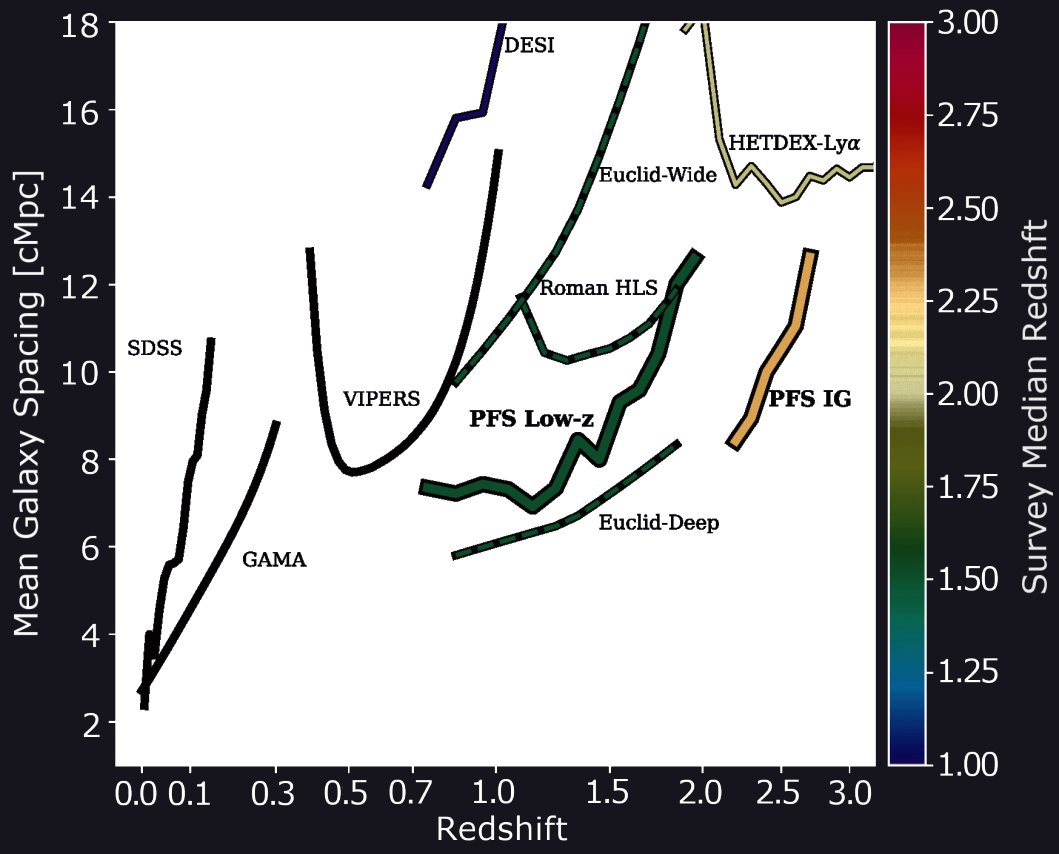
Mapping the cosmic web

Mapping the cosmic web

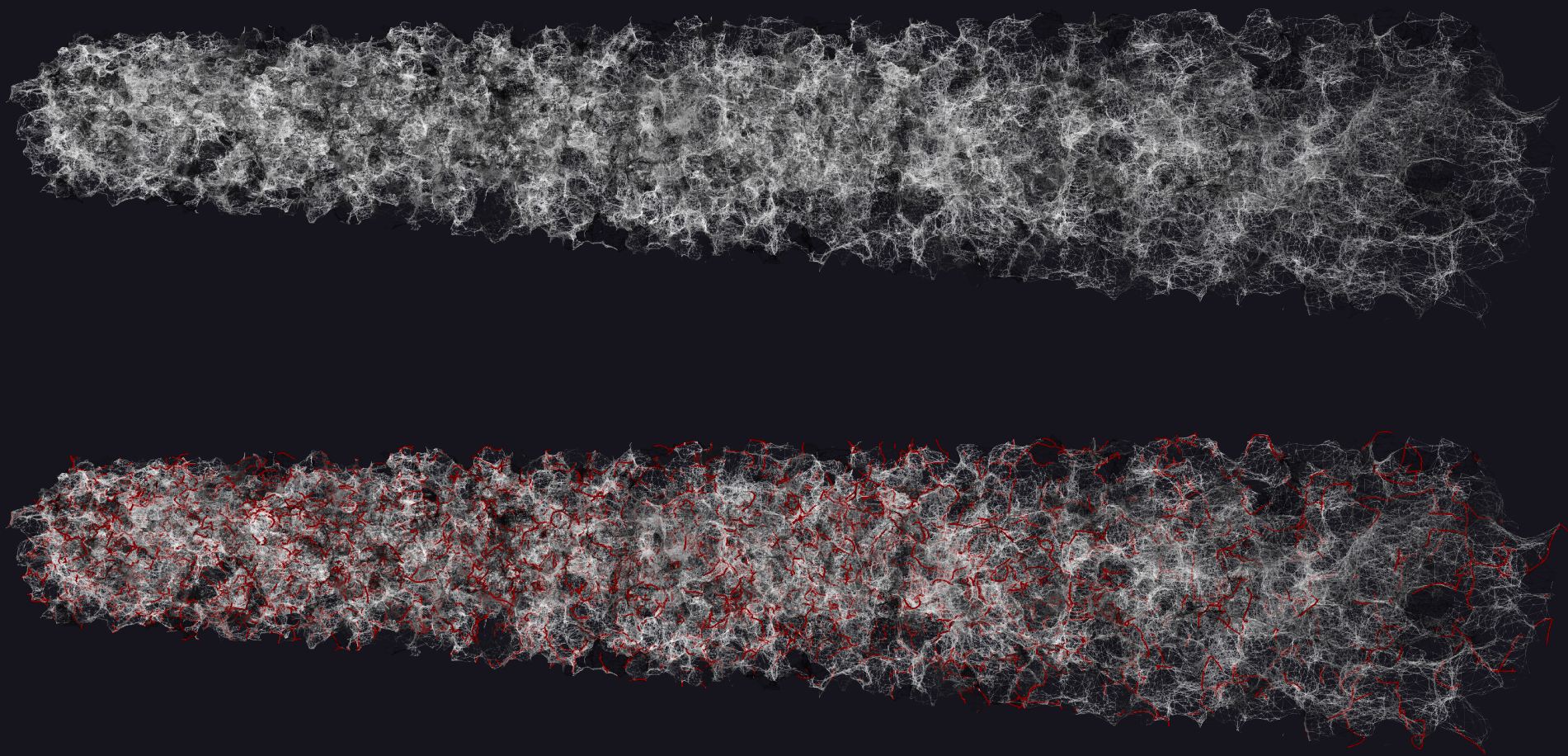
Mapping the cosmic web



Mapping the cosmic web



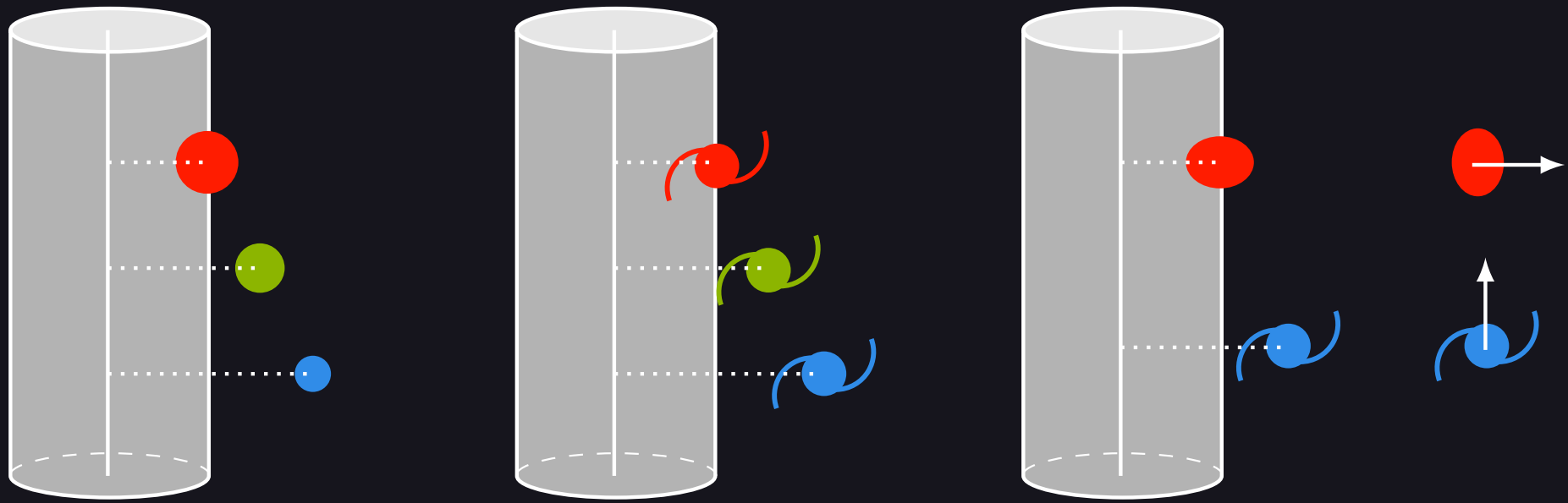
Greene & PFS Collaboration (2022)



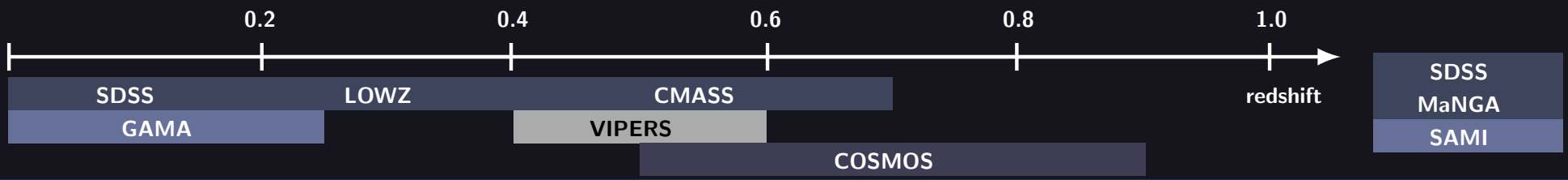

0.0
Spectro(3D)/Photo(2D)
1.0
Spectro(3D)
2.0
Tomography
3.0
redshift
SDSS
LOWZ
CMASS
GAMA
VIPERS
COSMOS
EUCLID*
MOONS*
PFS*
CLAMATO
EBOSS
WEAVE-QSO*
PFS*

Summary: Filaments

Mass & color & age & metallicity segregation **Alignment**



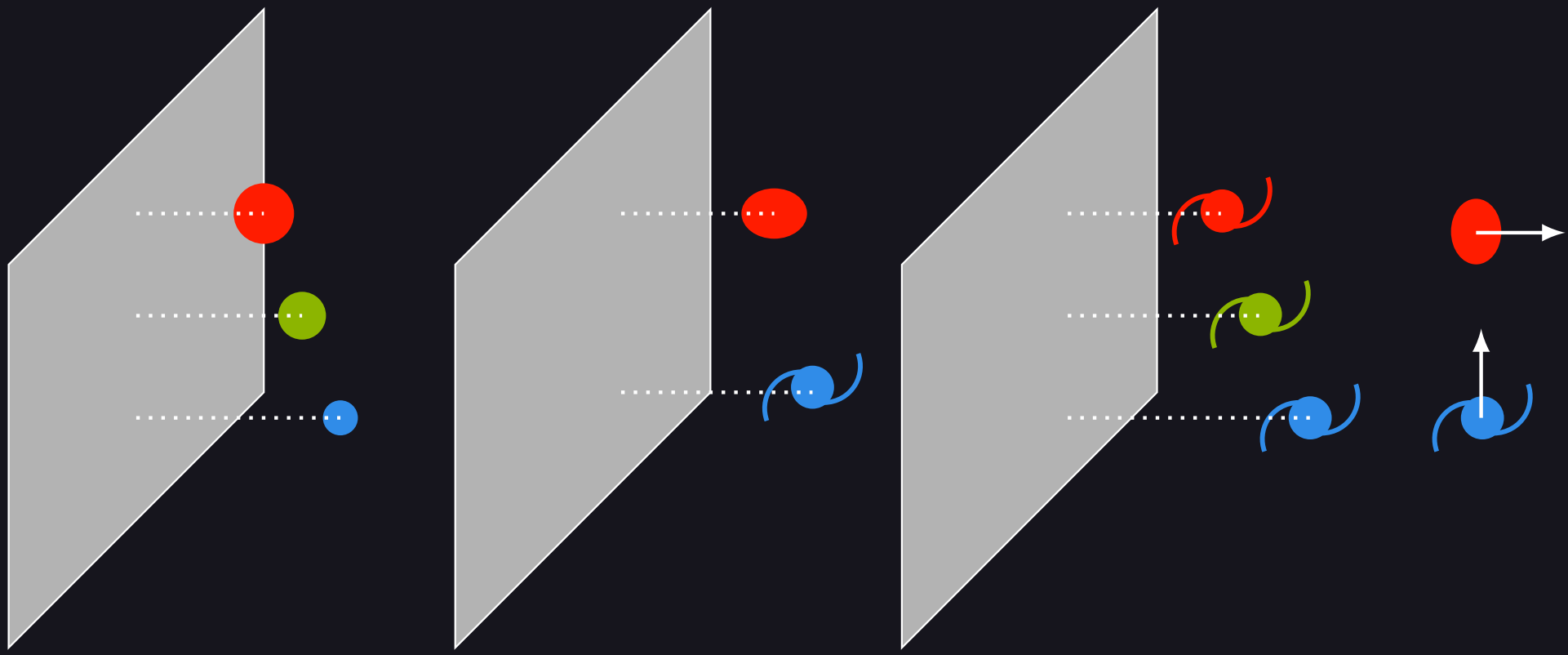
mass segregation SF segregation SF/age/Z segregation spin



Summary: Walls

Mass & color & age & metallicity segregation

Alignment



mass segregation

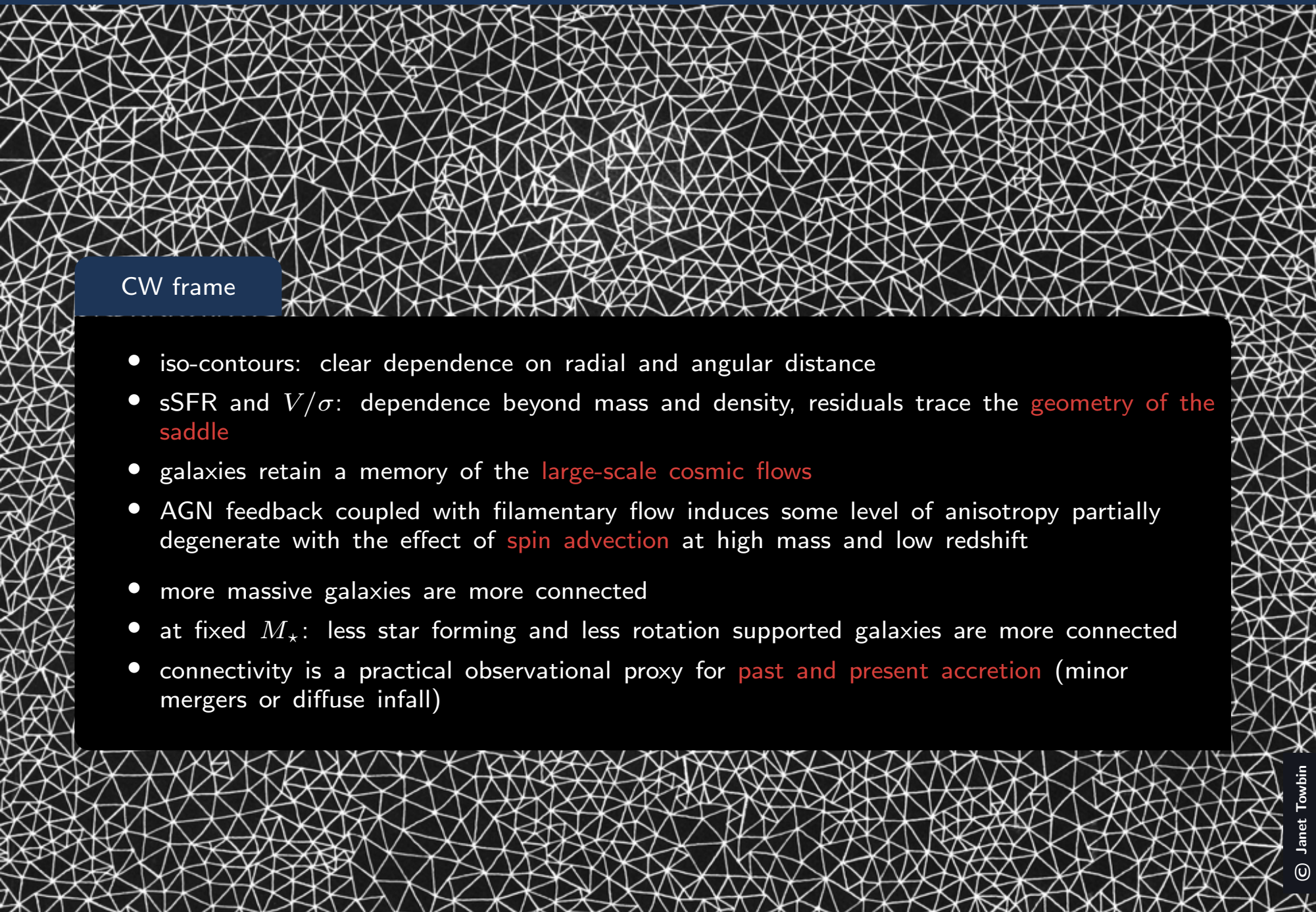
SF/age/Z segregation

mass SF segregation

spin

SDSS

Summary: Saddles/Nodes



CW frame

- iso-contours: clear dependence on radial and angular distance
- sSFR and V/σ: dependence beyond mass and density, residuals trace the geometry of the saddle
- galaxies retain a memory of the large-scale cosmic flows
- AGN feedback coupled with filamentary flow induces some level of anisotropy partially degenerate with the effect of spin advection at high mass and low redshift
- more massive galaxies are more connected
- at fixed $M_\star$: less star forming and less rotation supported galaxies are more connected
- connectivity is a practical observational proxy for past and present accretion (minor mergers or diffuse infall)