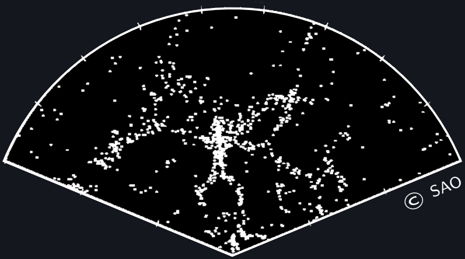
Galaxy evolution in the metric of the Cosmic web

Katarina Kraljic

Laboratoire d'Astrophysique de Marseille

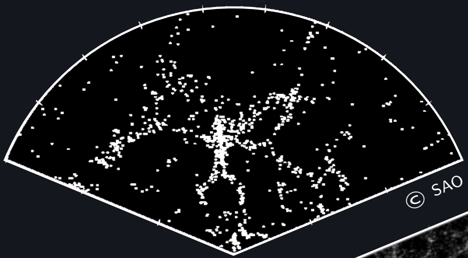
with

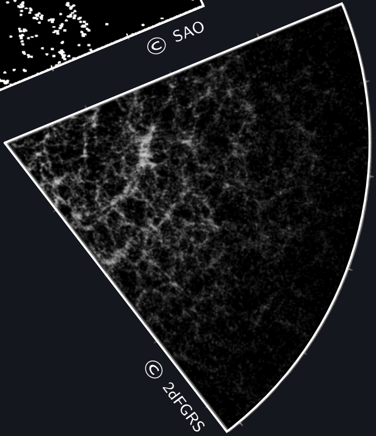
C. Pichon, Y. Dubois, S. Codis, C. Laigle (IAP)
S. Arnouts, M. Treyer, D. Vibert (LAM)
J. Devriendt (Oxford), M. Musso (ICTP), D. Pogosyan (Alberta)



de Lapparent et al. 1986

CW in a nutshell

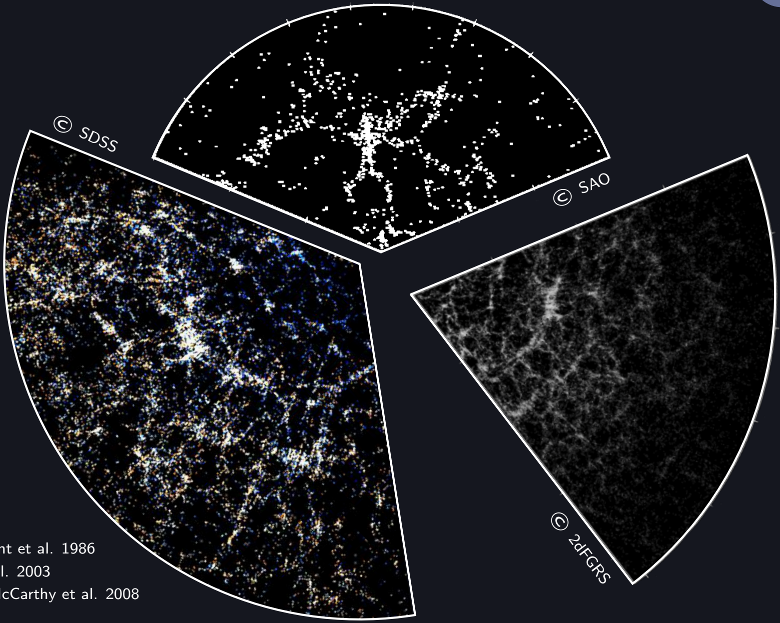




de Lapparent et al. 1986
Colless et al. 2003

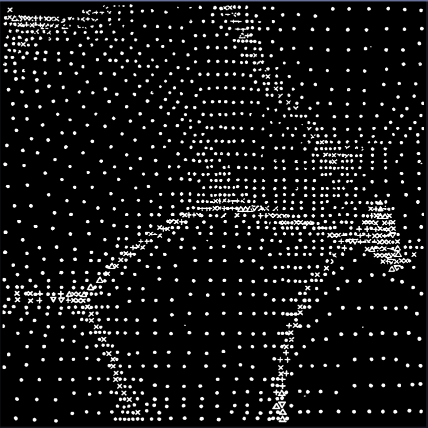
CW in a nutshell

from observations . . .



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

CW in a nutshell



Sergei Shandarin
Zel'dovich 1970

Cosmic web

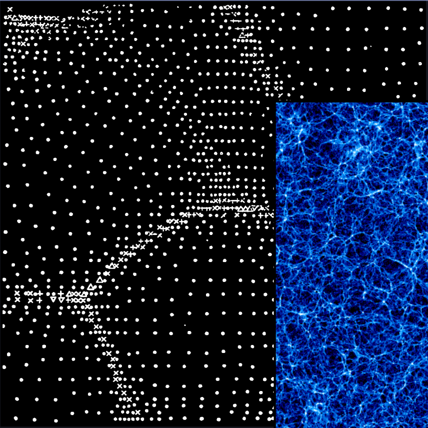
Klypin & Shandarin 1993
Bond, Kofman & Pogosyan 1996

CW in a nutshell

Cosmic web

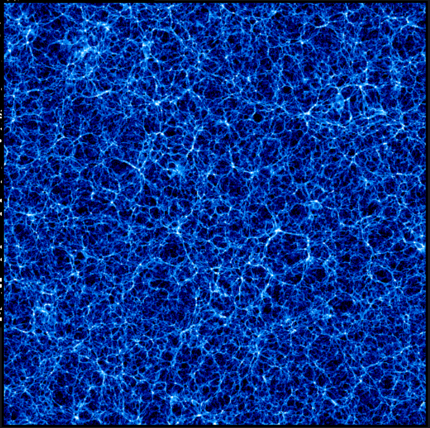
Klypin & Shandarin 1993

Bond, Kofman & Pogosyan 1996



Sergei Shandarin

Zel'dovich 1970



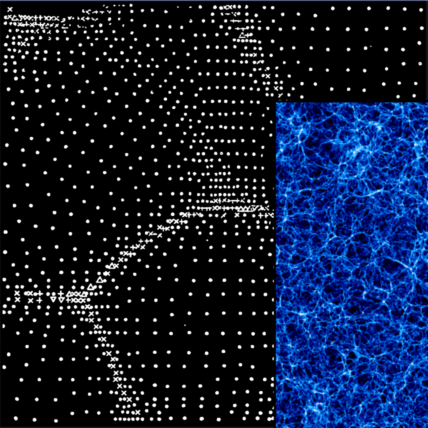
Marenostrum • Yepes et al. 2007

CW in a nutshell

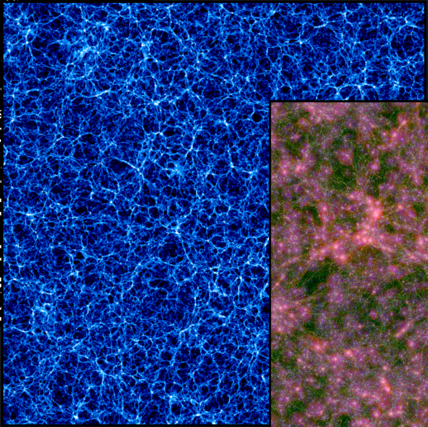
Cosmic web

Klypin & Shandarin 1993

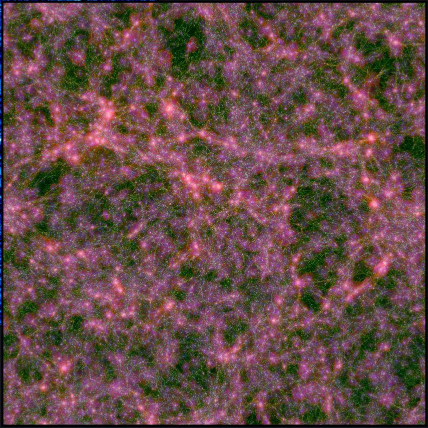
Bond, Kofman & Pogosyan 1996



Sergei Shandarin
Zel'dovich 1970



Marenostrum • Yepes et al. 2007



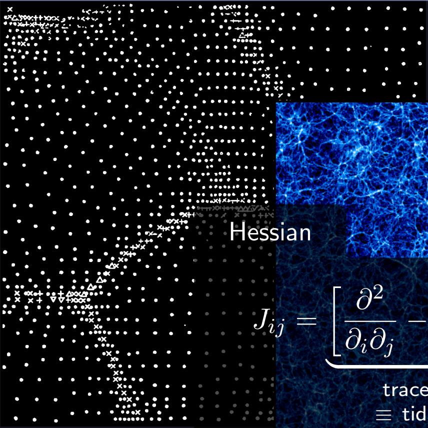
HORIZON-AGN • Dubois et al. 2014

CW in a nutshell

Cosmic web

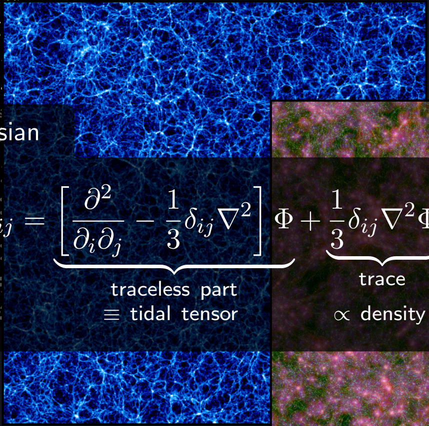
Klypin & Shandarin 1993

Bond, Kofman & Pogosyan 1996

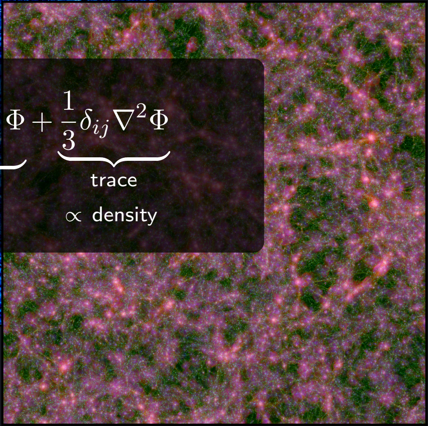


Sergei Shandarin

Zel'dovich 1970



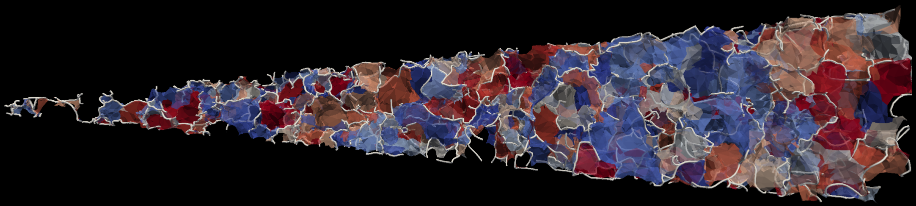
Marenostrum • Yepes et al. 2007



HORIZON-AGN • Dubois et al. 2014

Hessian

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

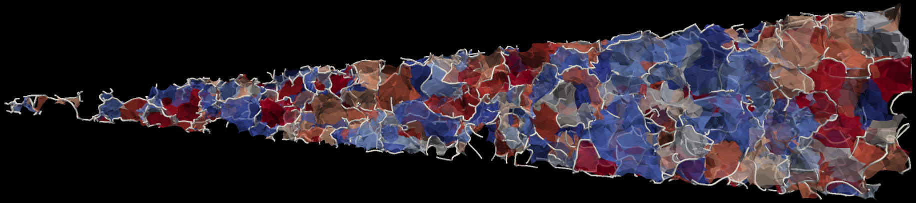


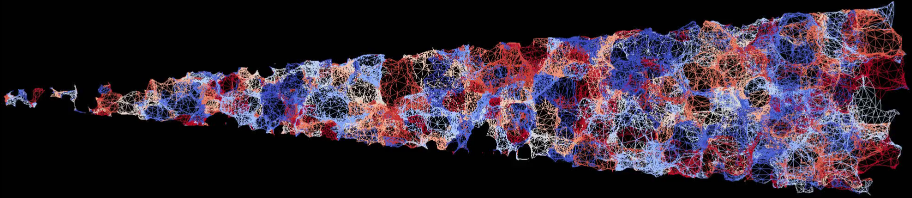
DisPerSE

- 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)

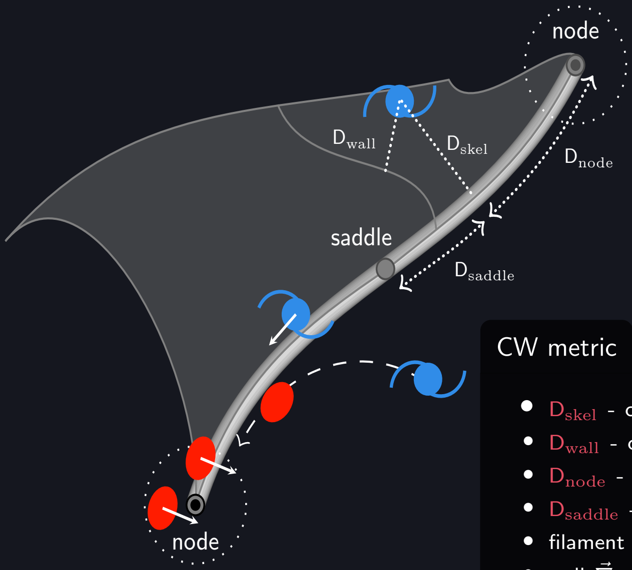
DisPerSE (Sousbie et al. 2011)





GAMA (Driver et al. 2009, 2011)

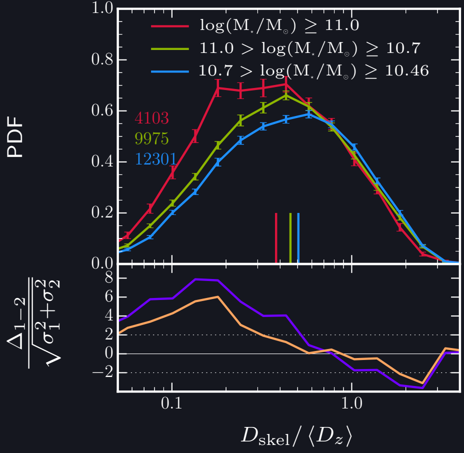
DisPerSE (Sousbie et al. 2011)



CW metric

- D_{skel} - closest filament
- D_{wall} - closest wall
- D_{node} - filament's node
- D_{saddle} - filament's saddle
- filament $\vec{\nabla}$: nodes removed
- wall $\vec{\nabla}$: nodes & filaments removed

Mass segregation

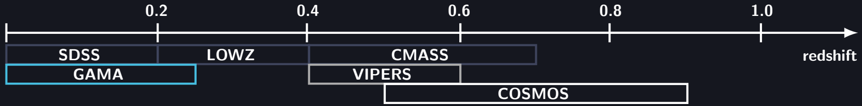


- more massive galaxies closer to filaments in observations $z < 0.9$

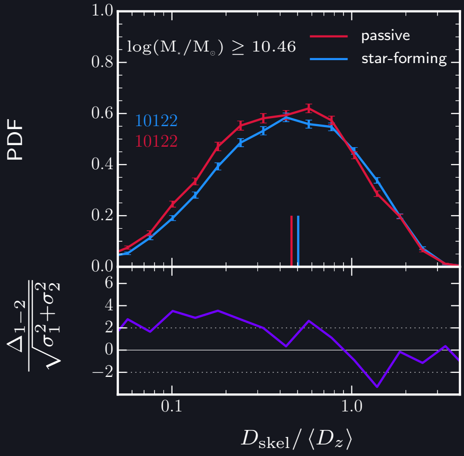
Poudel et al. 2016, Chen et al. 2017
Malavasi et al. 2017
Kraljic et al. 2018, Laigle et al. 2018
Winkel et al. 2021

consistent with simulations

Hz-AGN; **Kraljic et al. 2018**, Laigle et al. 2018



Mass-matched



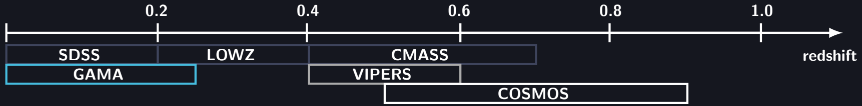
Color/Type segregation

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

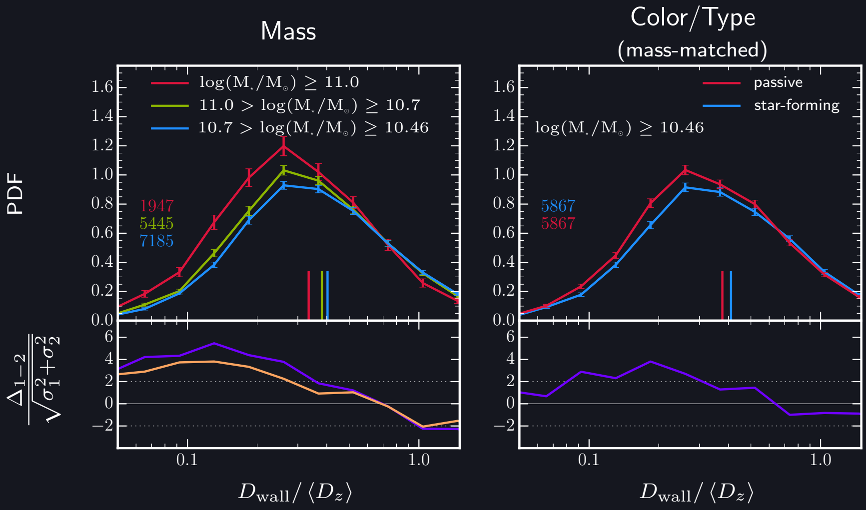
Chen et al. 2017, Kuutma et al. 2017
Poudel et al. 2017, Malavasi et al. 2017
Kraljic et al. 2018, Laigle et al. 2018
Winkel et al. 2021

consistent with simulations

Hz-AGN: **Kraljic et al. 2018**, Laigle et al. 2018



Transverse $\vec{\nabla}$



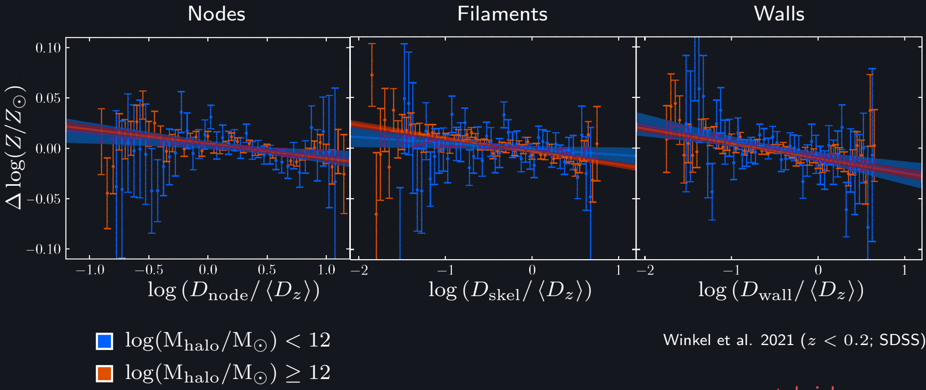
Kraljic et al. 2018 ($z < 0.25$; GAMA)

consistent with Hz-AGN

with SDSS ($z < 0.2$; Winkel et al. 2021)

Z/age/α elements segregation

Central galaxies



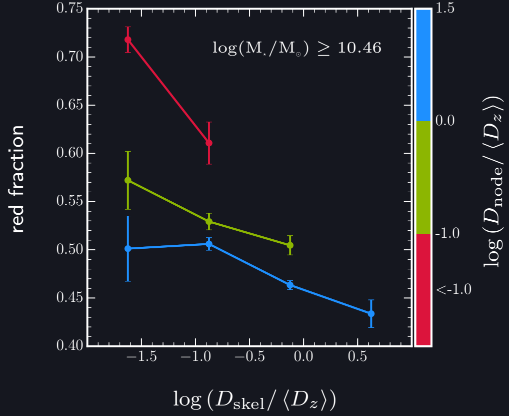
Winkel et al. 2021 ($z < 0.2$; SDSS)

- centrals at given ($M_\star$, M_{halo}) closer to CW components are

- more metal rich also
- older
- slightly α-enhanced

'Pre-processing'

All galaxies

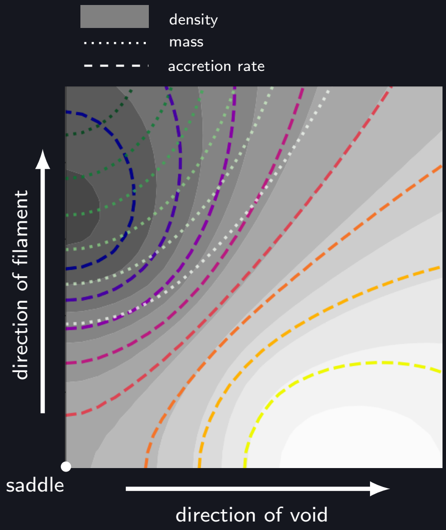


- red/passive fraction increases

  near the nodes (groups/clusters) at fixed $D_{\rm skel}$

  near the filaments at fixed $D_{\rm node}$

Kraljic et al. 2018 ($z < 0.25$; GAMA)



...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

Horizon-AGN / noAGN

- large-scale hydrodynamical cosmological simulation
- RAMSES (Teyssier et al. 2002)
- $\mathrm{L}_{box} = 100\ h^{-1}$ Mpc
- $\Delta x = 1$ kpc
- SF: Schmidt relation
- stellar feedback: winds, SN Ia, II
- AGN / no AGN feedback

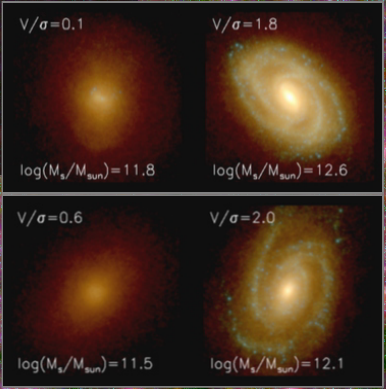
Dubois et al. 2014, 2016

Saddle frame

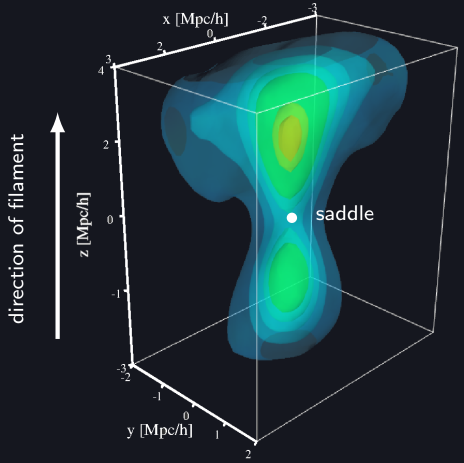
Horizon-AGN / noAGN

- large-scale hydrodynamical cosmological simulation
- RAMSES (Teyssier et al. 2002)
- $L_{box} = 100\ h^{-1}$ Mpc
- $\Delta x = 1$ kpc
- SF: Schmidt relation
- stellar feedback: winds, SN Ia, II
- AGN / no AGN feedback

Dubois et al. 2014, 2016

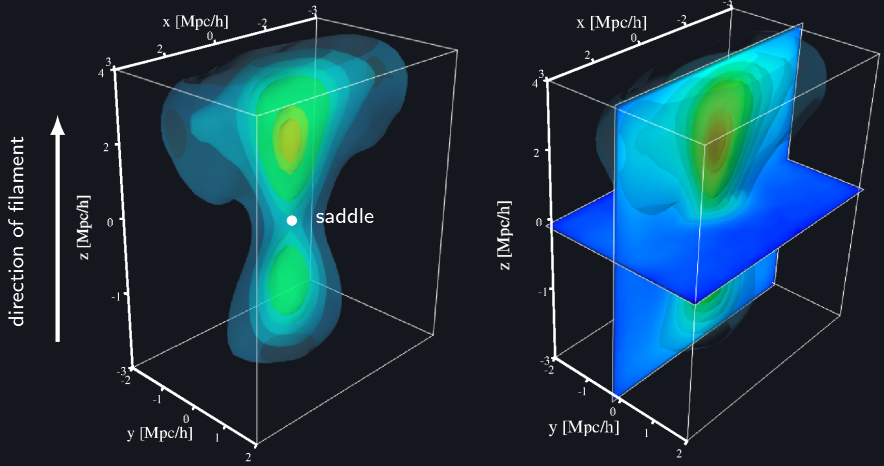


Saddle frame



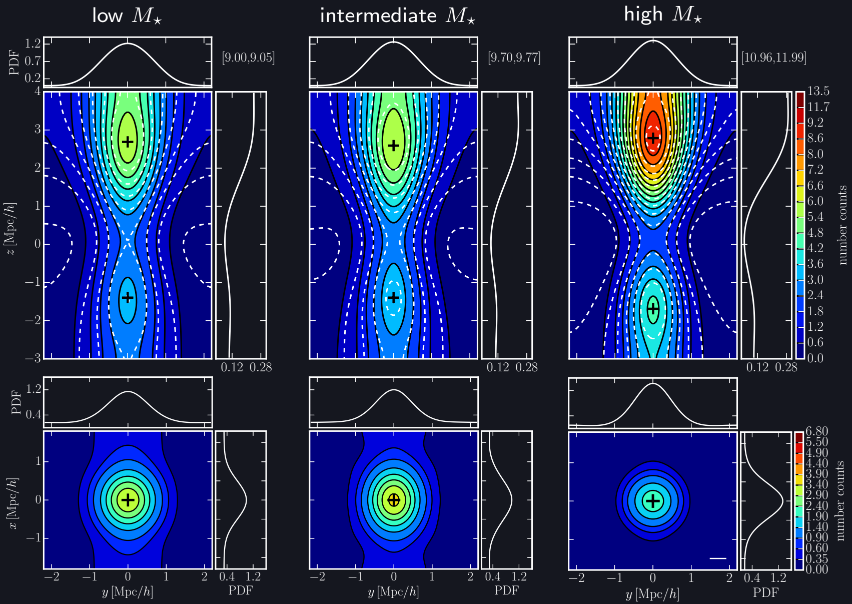
Kraljic et al. 2019

Saddle frame

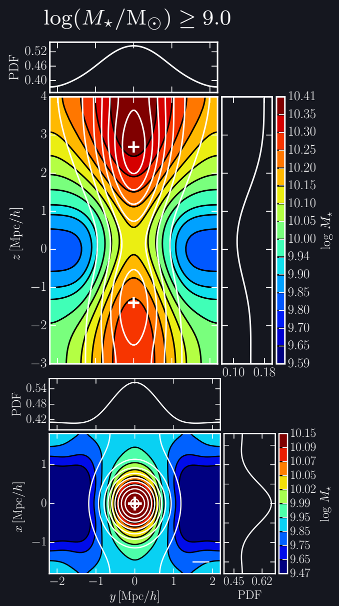


Kraljic et al. 2019

Saddle frame



Saddle frame

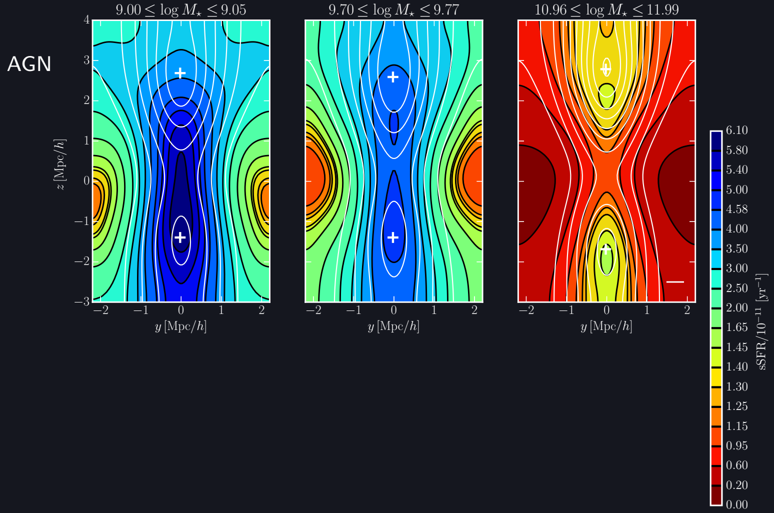


Iso-contours

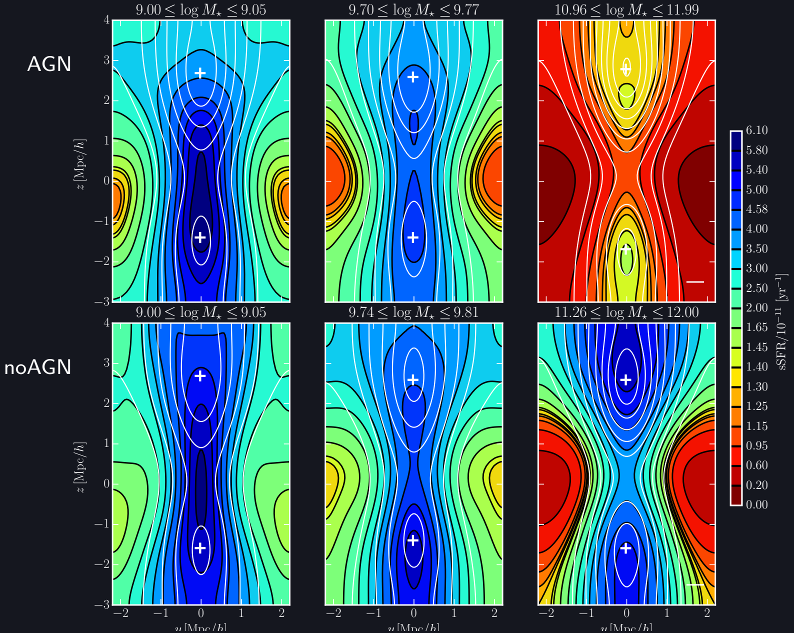
- radial & angular dependence
- saddles: min longitudinally
- saddles: max transversally
- higher $M_\star$ in fils vs voids
- higher $M_\star$ in nodes vs saddles

Kraljic et al. 2019

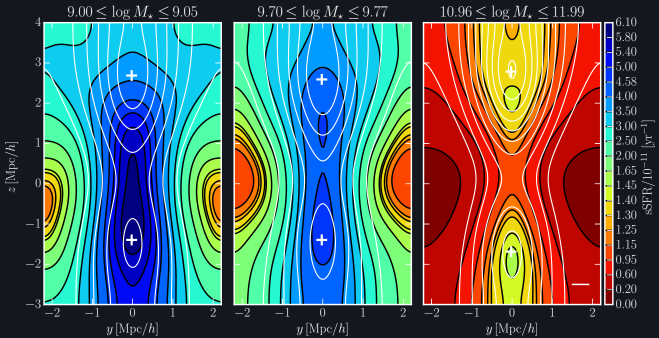
Saddle frame



Saddle frame

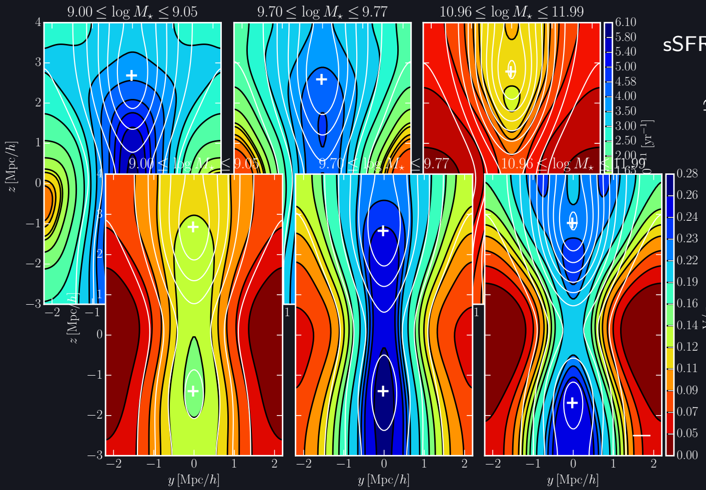


Saddle frame



sSFR

Saddle frame

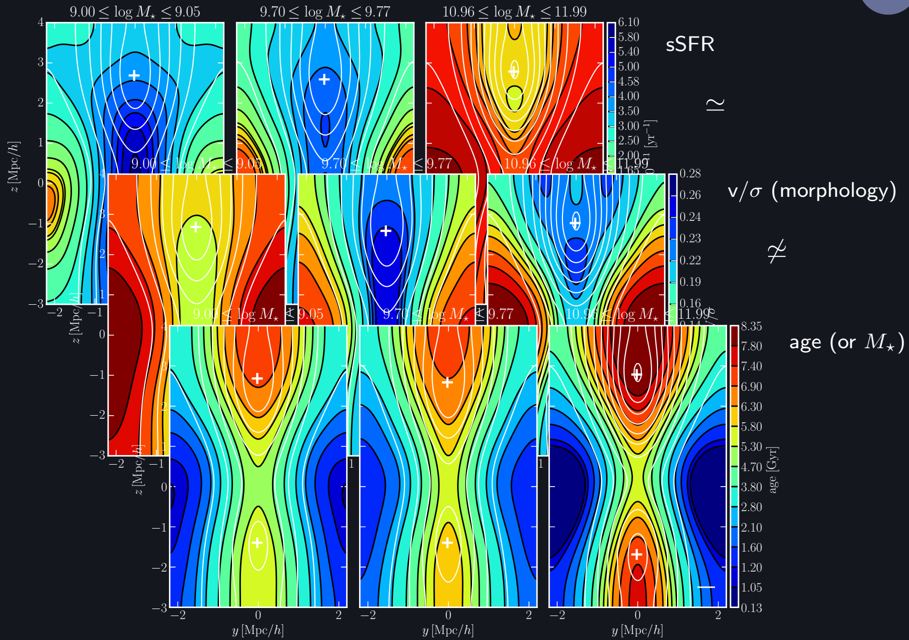


sSFR

$\simeq$

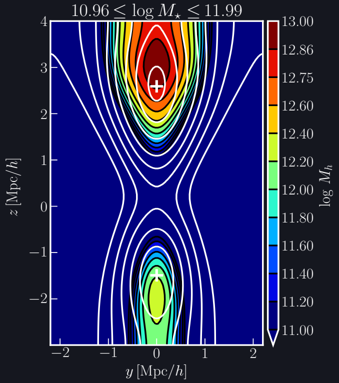
v/σ (morphology)

Saddle frame



Saddle frame

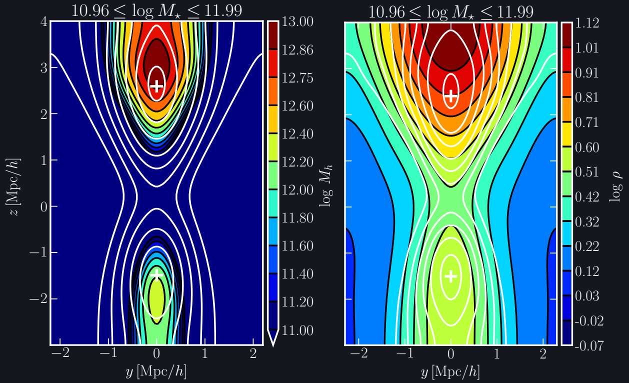
M_{halo}



Kraljic et al. 2019

Saddle frame

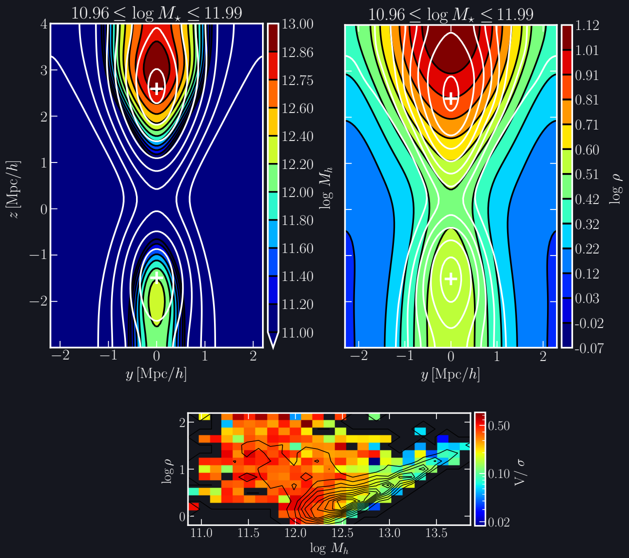
$M_{halo} + \rho$



Kraljic et al. 2019

Saddle frame

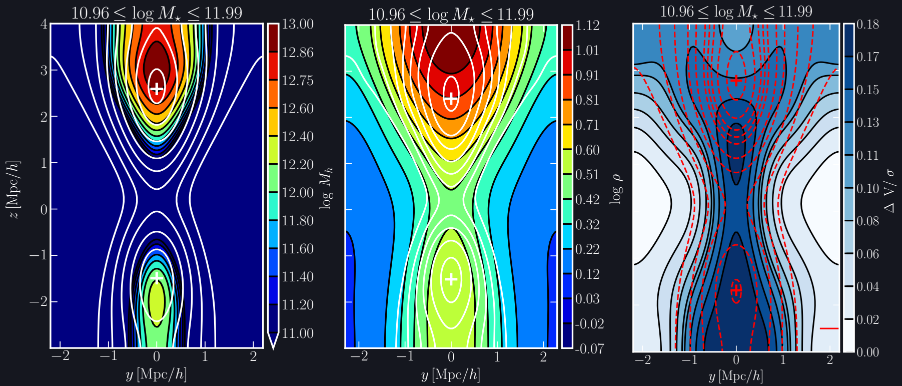
$$M_{halo} + \rho + f(M_{halo}, \rho)$$

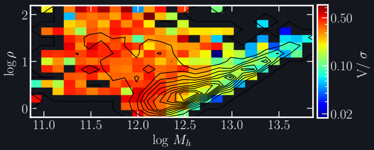


Kraljic et al. 2019

Saddle frame

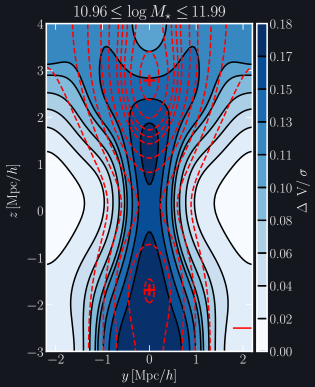
$M_{halo} + \rho + f(M_{halo}, \rho)$ ············► residuals





Kraljic et al. 2019

residuals

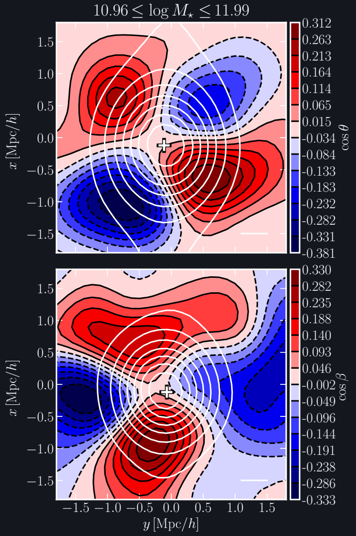


Kraljic et al. 2019

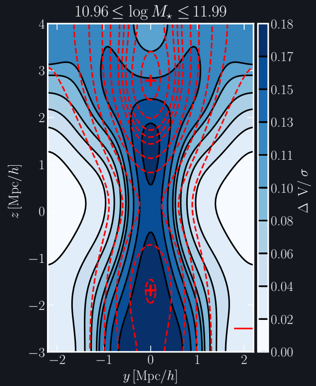
Saddle frame

spin

vorticity



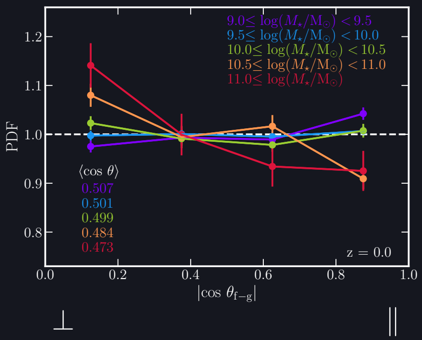
residuals

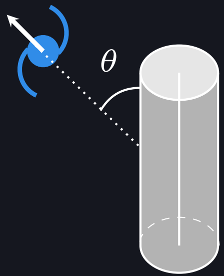


Kraljic et al. 2019

see also Codis et al. 2015
Laigle et al. 2015

Filaments

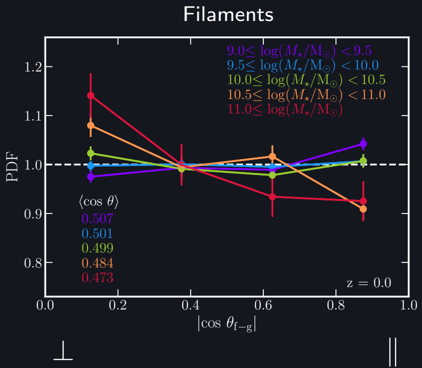


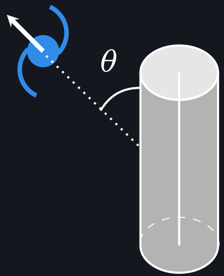


- massive galaxies tend to have spin ⊥
- low-mass galaxies tend to have spin ∥

Kraljic et al. 2020a SIMBA

see also Dubois et al. 2014 HORIZON-AGN
Codis et al. 2018
Wang et al. 2018 ILLUSTRIS





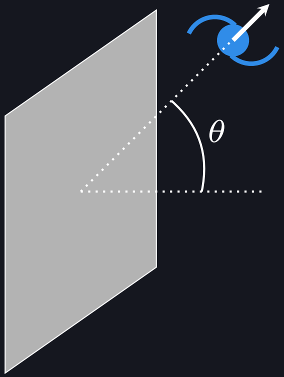
- massive galaxies tend to have spin $\perp$
- low-mass galaxies tend to have spin $\|$

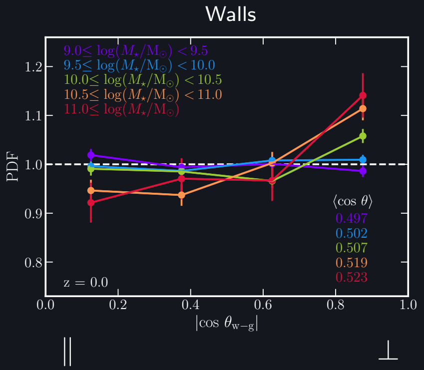
also
- massive halos tend to have spin $\perp$
- low-mass halos tend to have spin $\|$

Kraljic et al. 2020a SIMBA

see also Dubois et al. 2014 HORIZON-AGN
Codis et al. 2018
Wang et al. 2018 ILLUSTRIS

see also e.g. Hahn et al. 2007
Codis et al. 2012
Ganeshaiah Veena et al. 2018
Kraljic et al. 2020a

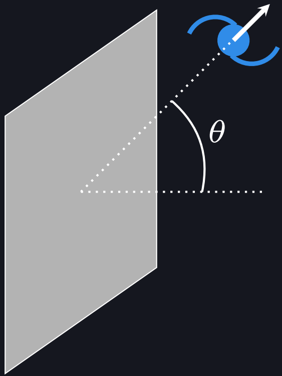




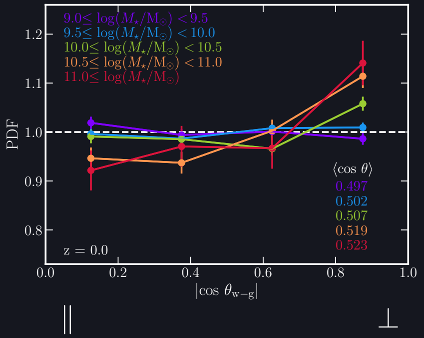
- massive galaxies tend to have spin ⊥
- low-mass galaxies tend to have spin ||

Kraljic et al. 2020a SIMBA

see also Codis et al. 2018 HORIZON-AGN



Walls



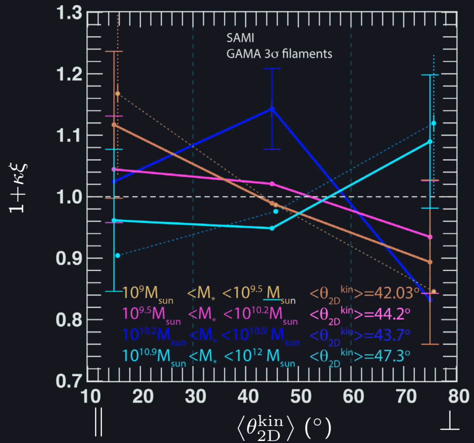
also
- massive halos tend to have spin ⊥
- low-mass halos tend to have spin ||

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

Kraljic et al. 2020a SIMBA

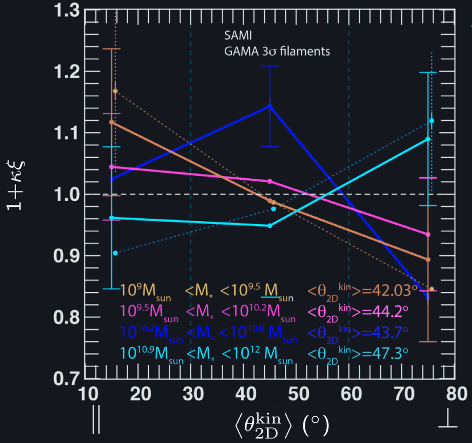
see Codis et al. 2015 (conditional TTT)

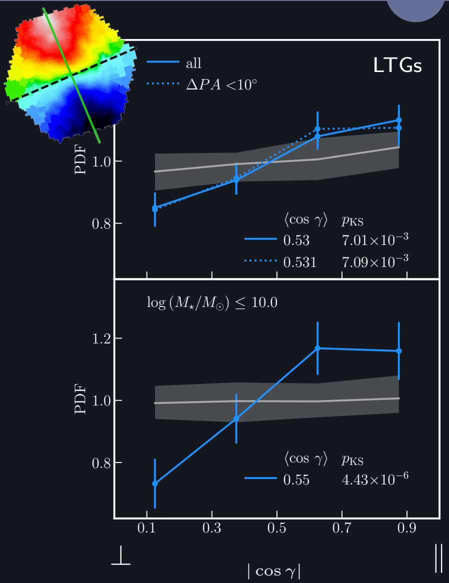
see also Codis et al. 2018 HORIZON-AGN



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

Welker et al. 2020 (SAMI)

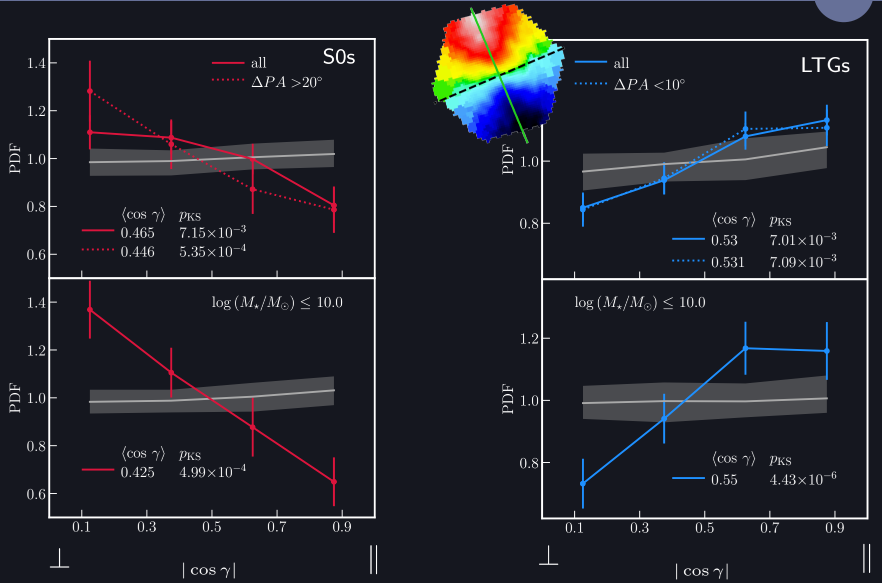




- massive galaxies tend to have spin ⊥
- low-mass galaxies tend to have spin ||

Welker et al. 2020 (SAMI)

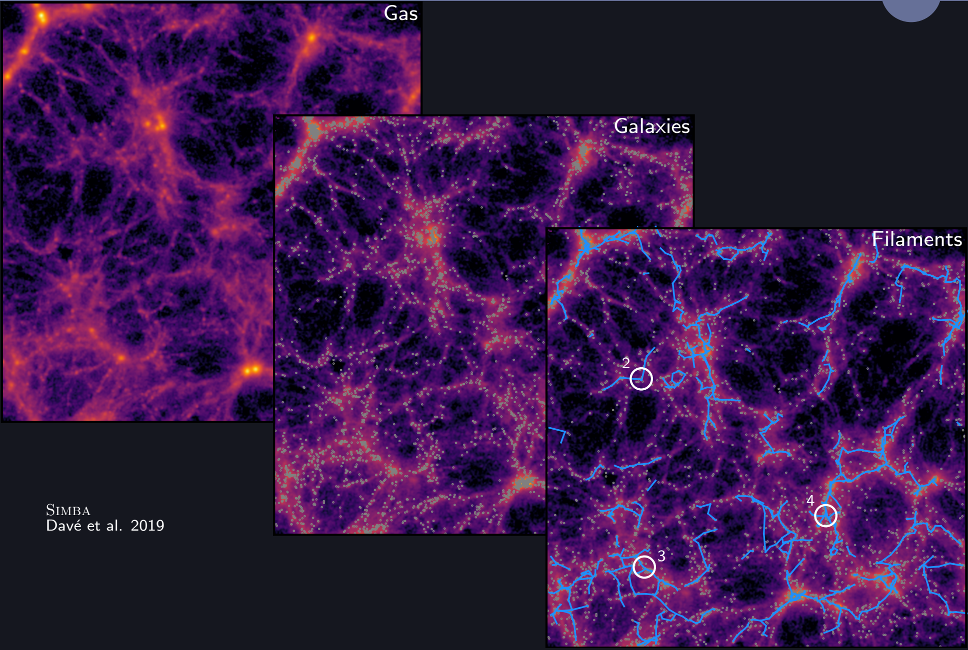
Kraljic et al. 2021 (MaNGA)



LTGs see e.g. Tempel et al. 2013 vs Lee & Erdogu 2007
S0s see e.g. Tempel et al. 2013, Pahwa et al. 2016

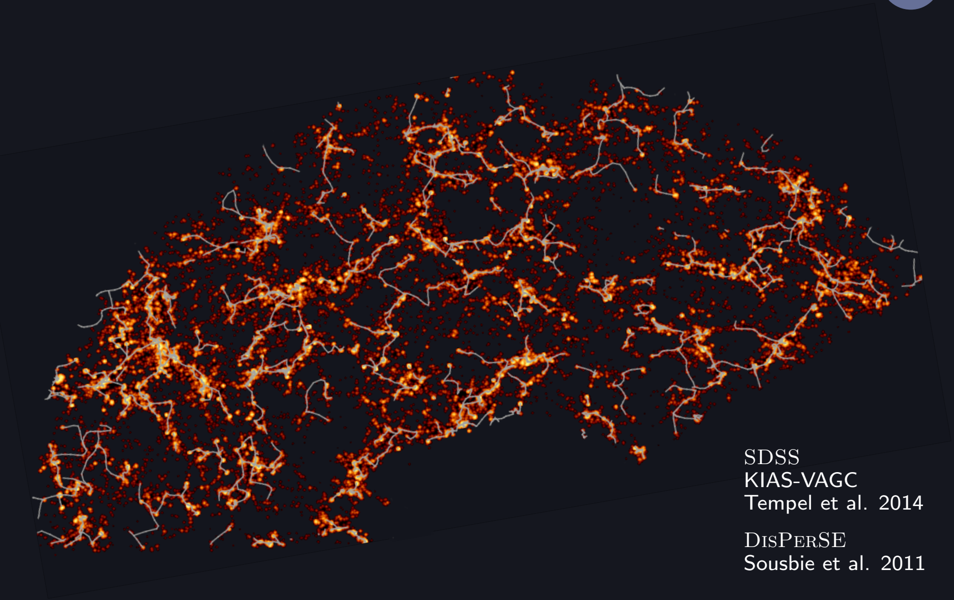
Kraljic et al. 2021 (MaNGA)

Nodes



SIMBA
Davé et al. 2019

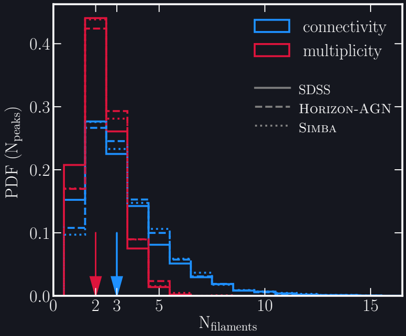
Nodes



SDSS
KIAS-VAGC
Tempel et al. 2014

DisPerSE
Sousbie et al. 2011

Nodes

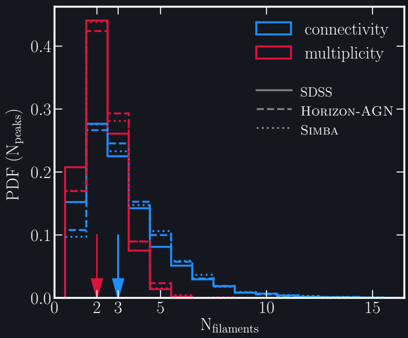


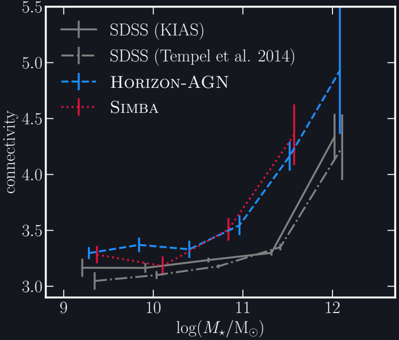
see Codis et al. 2018 for GRF

Kraljic et al. 2020b

see also Darragh-Ford et al. 2019 for BCGs

Nodes





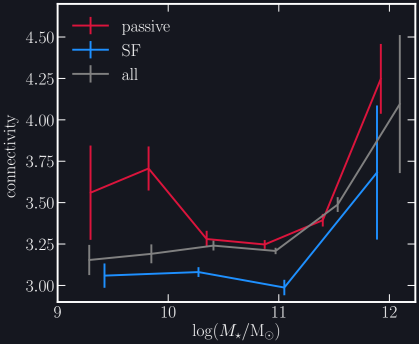
see Codis et al. 2018 for GRF

Kraljic et al. 2020b

see also Darragh-Ford et al. 2019 for BCGs

Star formation/SDSS

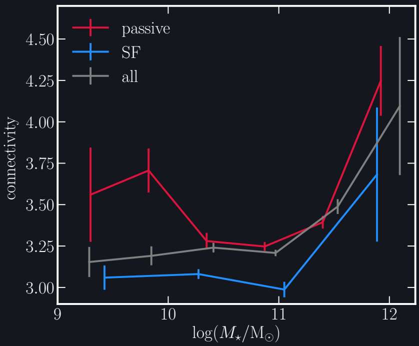
Stellar mass



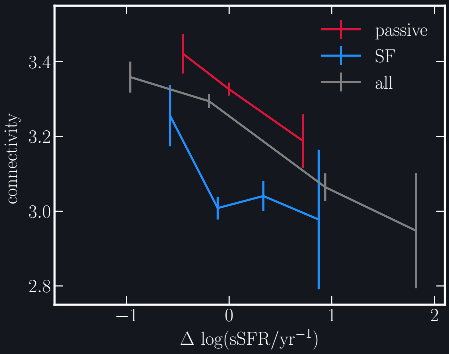
Kraljic et al. 2020b

Star formation/SDSS

Stellar mass



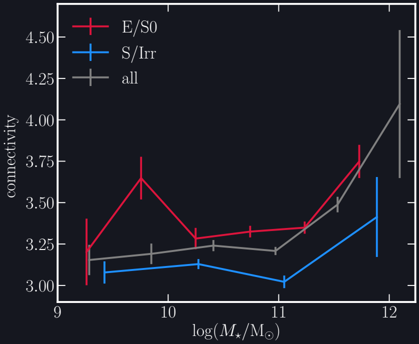
sSFR residuals



Kraljic et al. 2020b

Morphology/SDSS

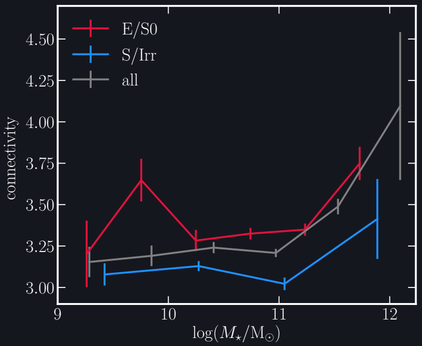
Stellar mass



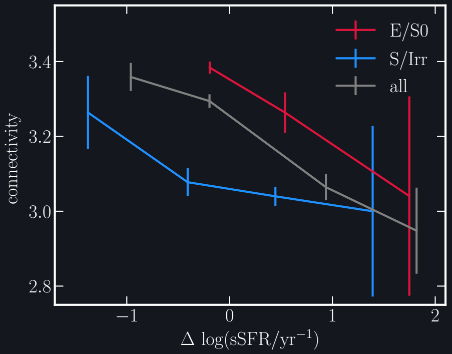
Kraljic et al. 2020b

Morphology/SDSS

Stellar mass

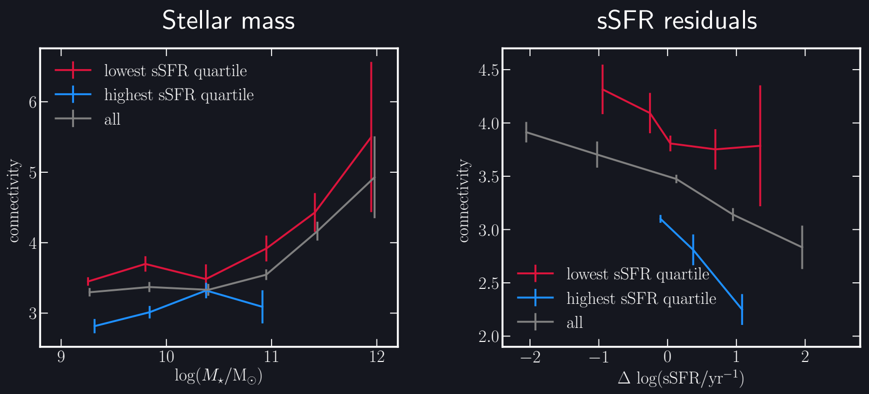


sSFR residuals

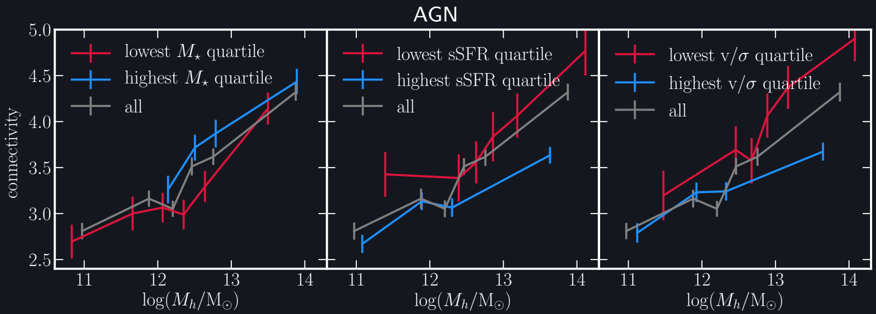


Kraljic et al. 2020b

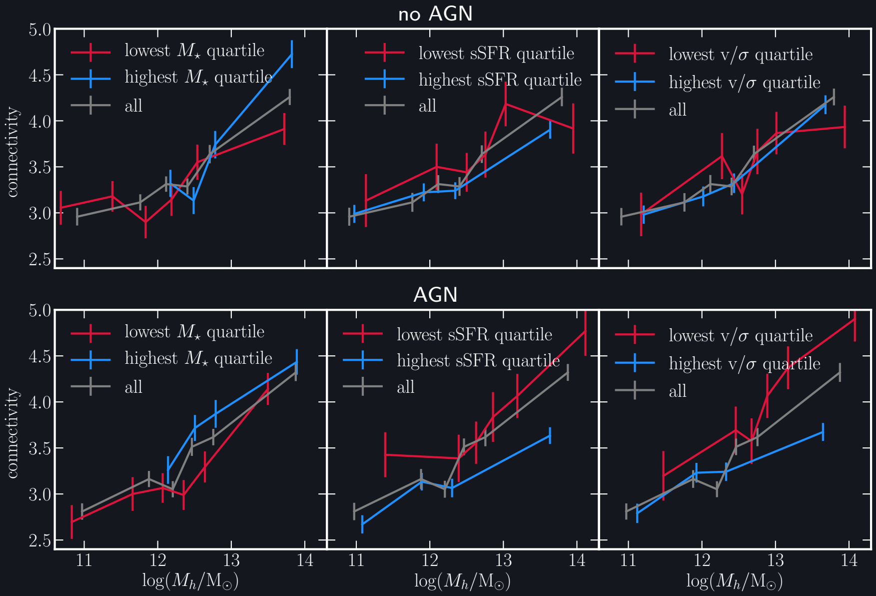
Star formation/HzAGN



Kraljic et al. 2020b



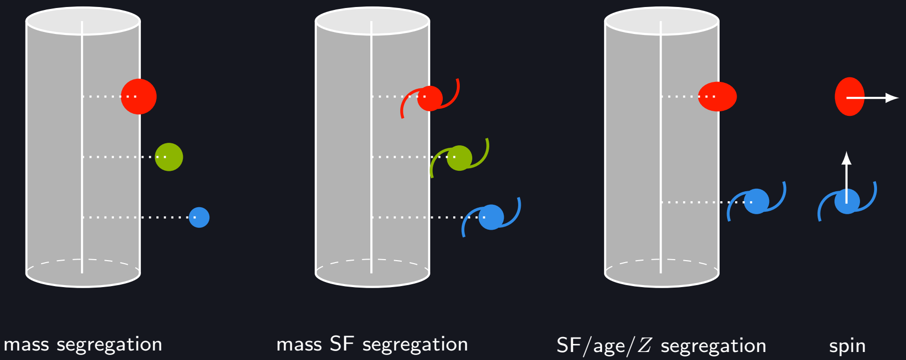
AGN
connectivity
5.0
4.5
4.0
3.5
3.0
2.5
lowest $M_\star$ quartile
highest $M_\star$ quartile
all
lowest sSFR quartile
highest sSFR quartile
all
lowest v/σ quartile
highest v/σ quartile
all
11
12
13
14
$\log(M_h/\mathrm{M}_\odot)$


no AGN
AGN
lowest $M_\star$ quartile
highest $M_\star$ quartile
all
lowest sSFR quartile
highest sSFR quartile
all
lowest v/σ quartile
highest v/σ quartile
all
connectivity
5.0
4.5
4.0
3.5
3.0
2.5
11
12
13
14
$\log(M_h/\mathrm{M}_\odot)$

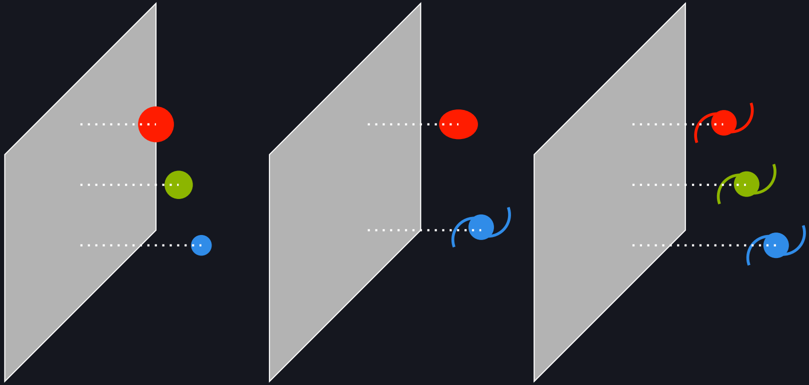
Conclusions

Mass & color & age & metallicity segregation

Alignment



Mass & color & age & metallicity segregation



mass segregation

SF/age/Z segregation

mass SF segregation

Kraljic et al. 2018 (GAMA; $z < 0.25$)

Winkel et al. 2021 (SDSS; $z < 0.2$)

Conclusions

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)