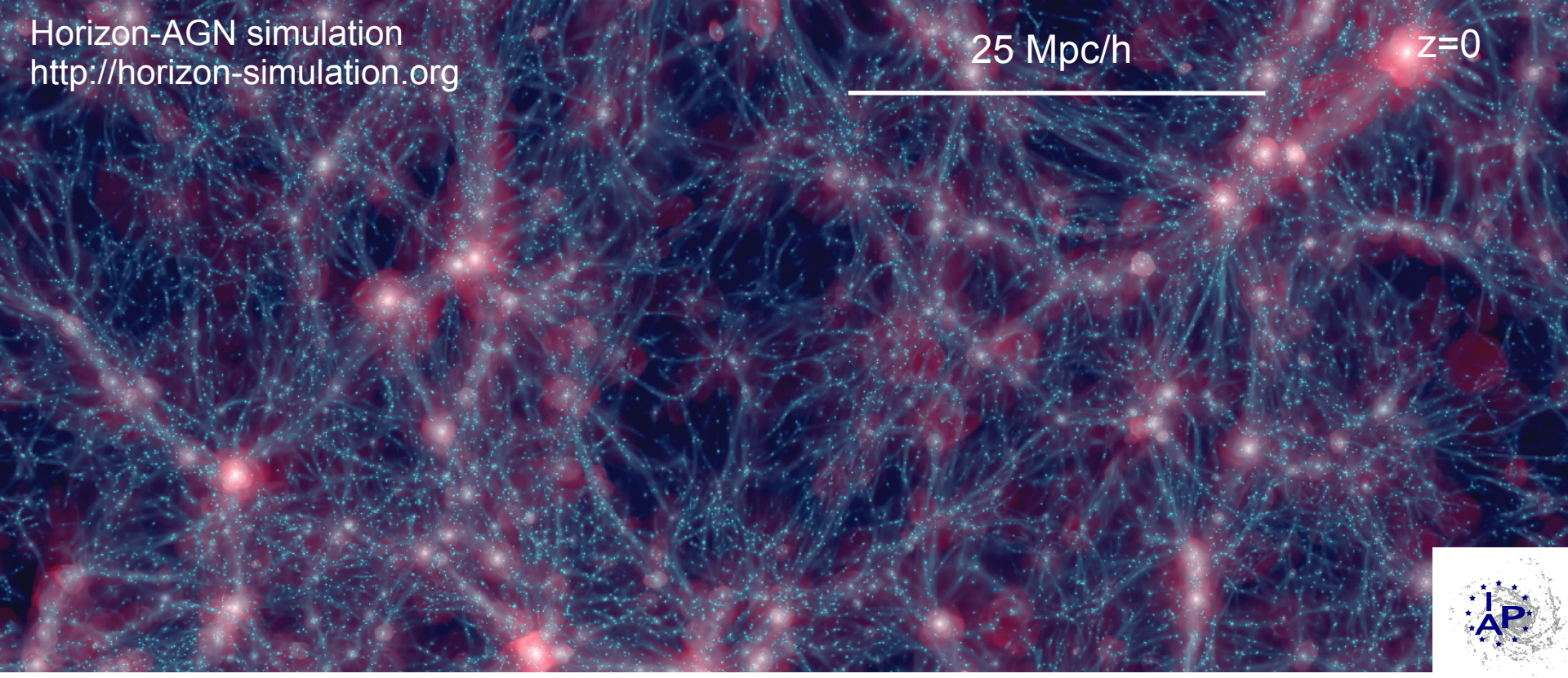
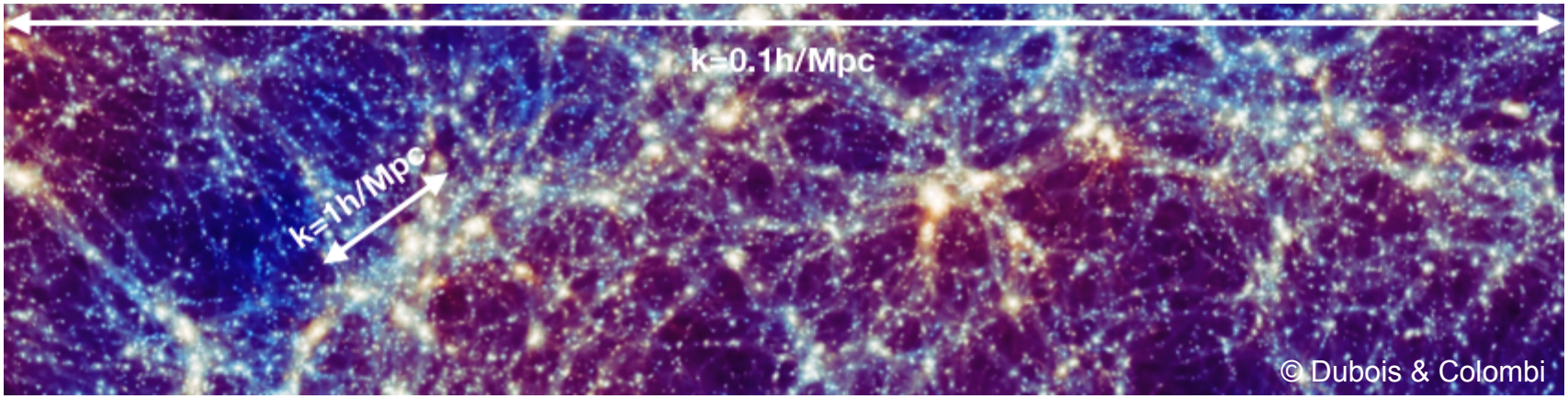
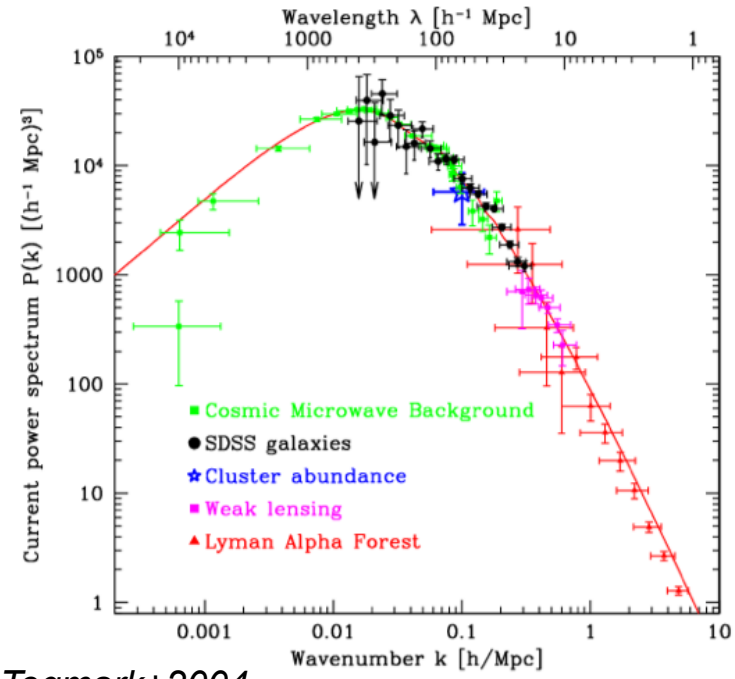


Effect of baryons and modification of gravity

Yohan Dubois
Institut d'Astrophysique de Paris

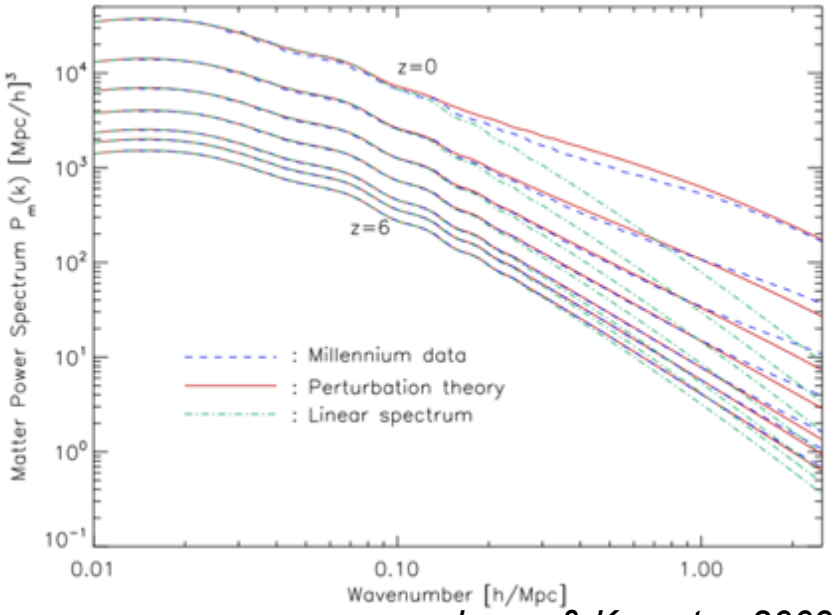
Clustering: a probe for cosmology





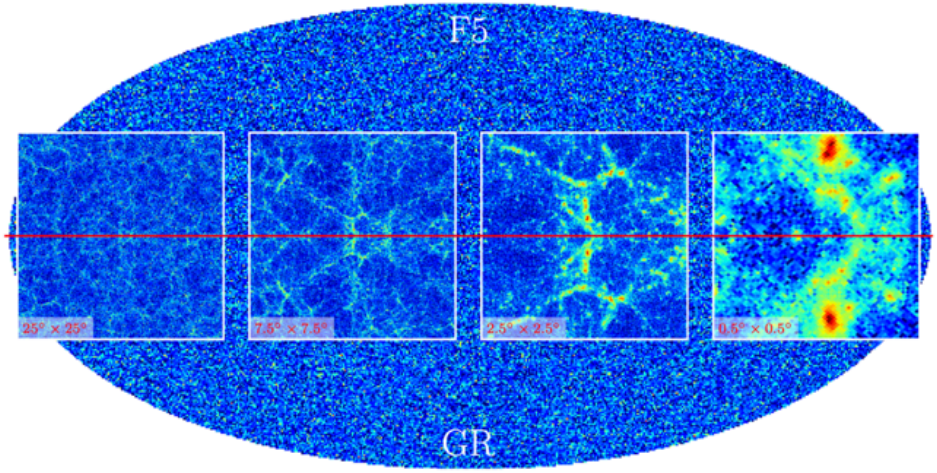
Tegmark+2004

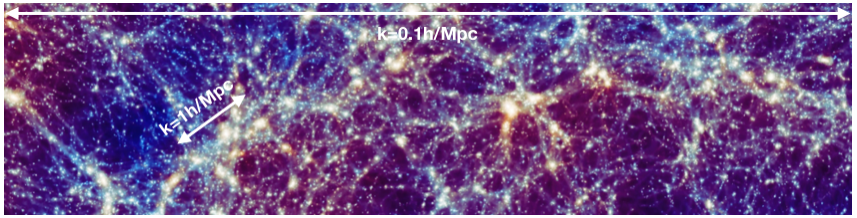
Need for accurate simulations



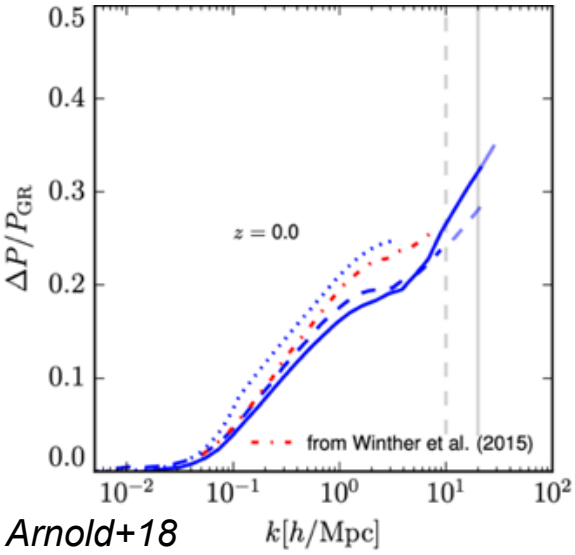
Jeong & Komatsu 2009

Clustering: a probe for cosmology
But deviations to non-standard ΛCDM are subtle (~1-10%)



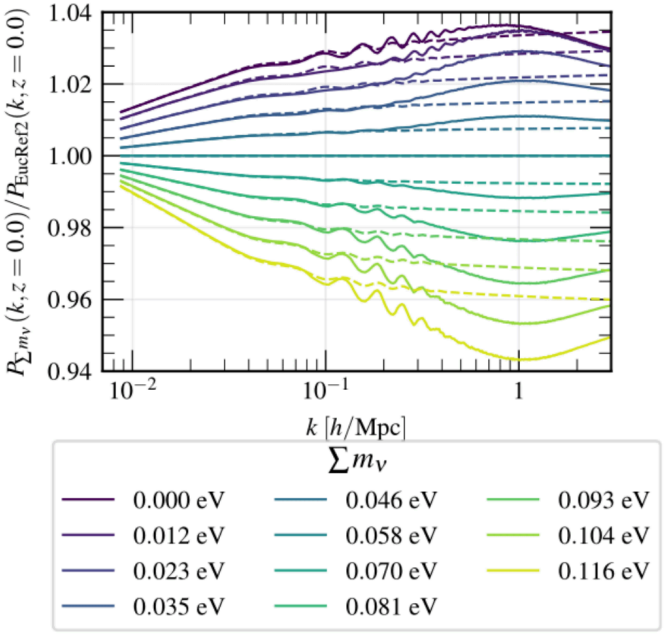


Modified gravity

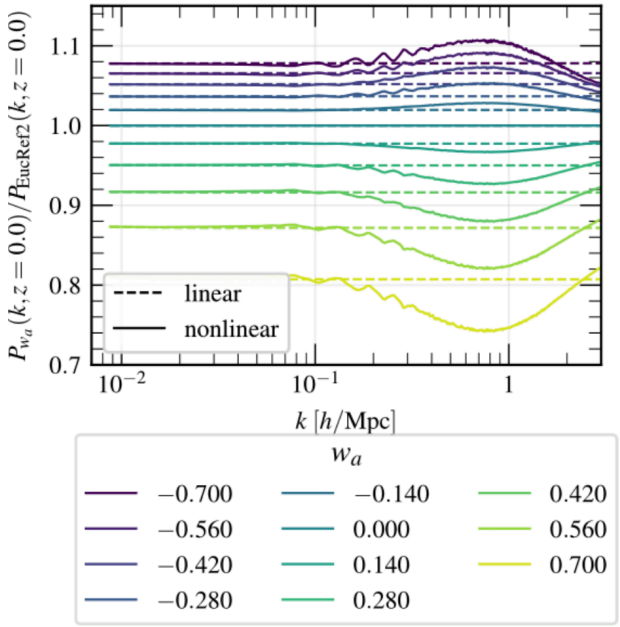


Arnold+18

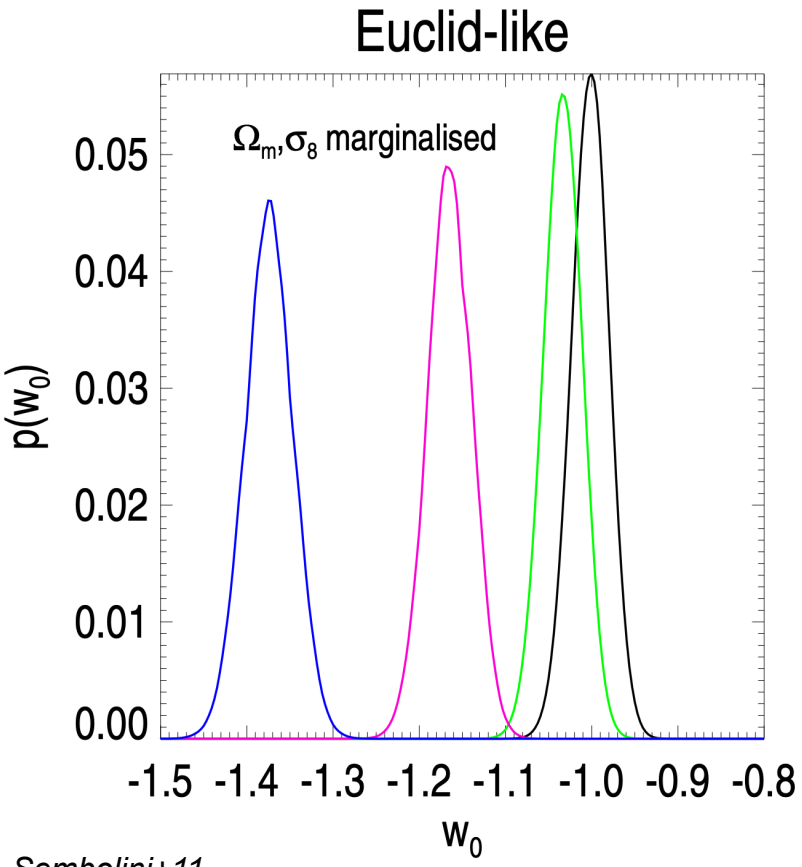
Neutrinos *Knabenhans+20*



Dynamical DE

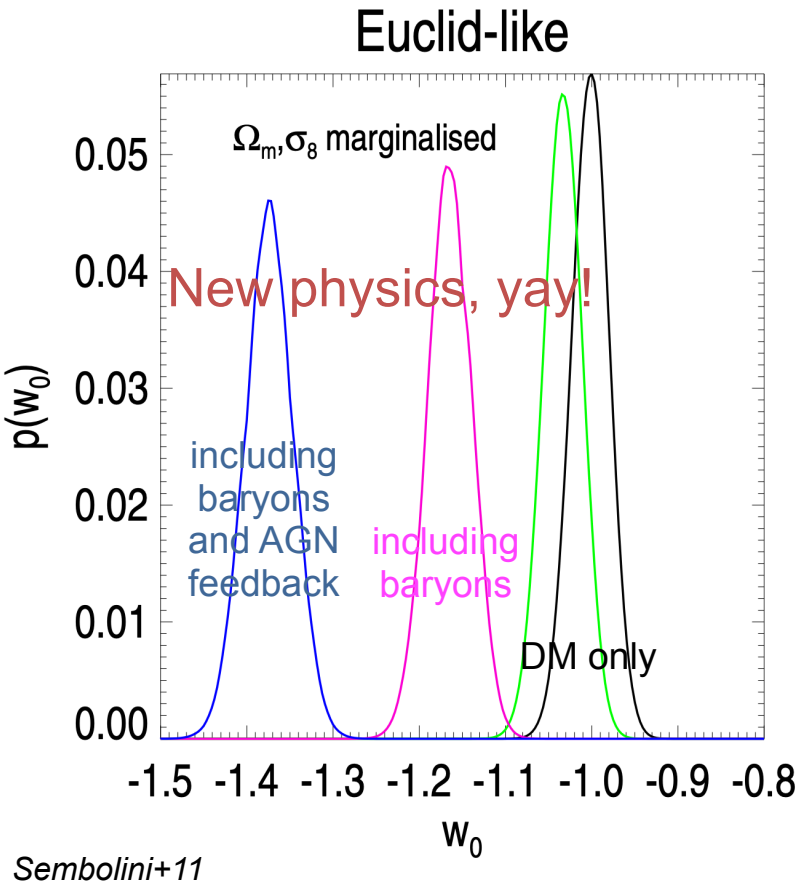


Clustering: a probe for cosmology



Sembolini+11

Clustering: a probe for cosmology
…And baryons are messing things up!

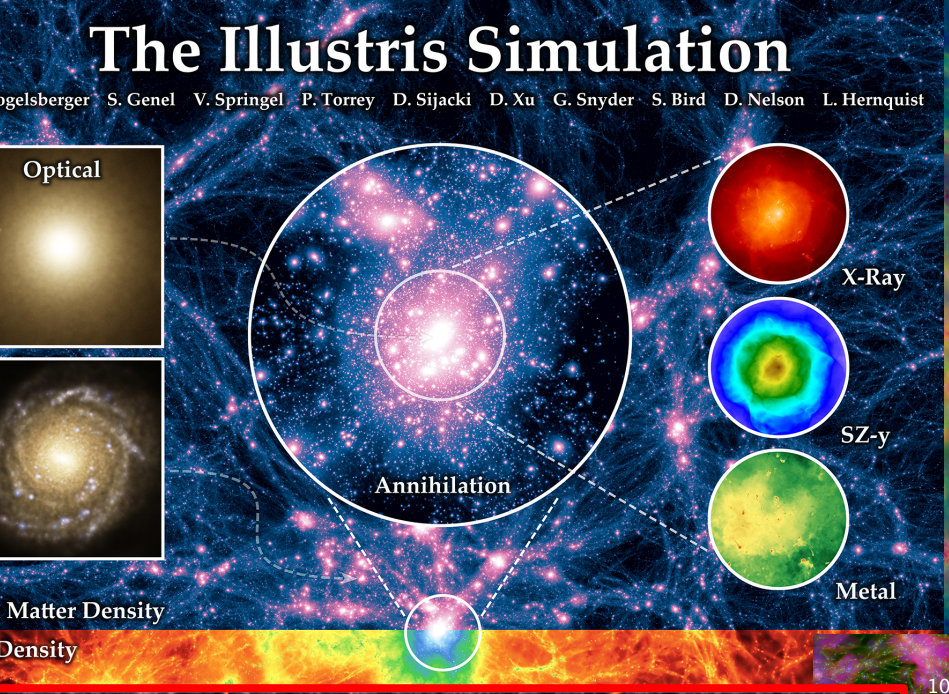


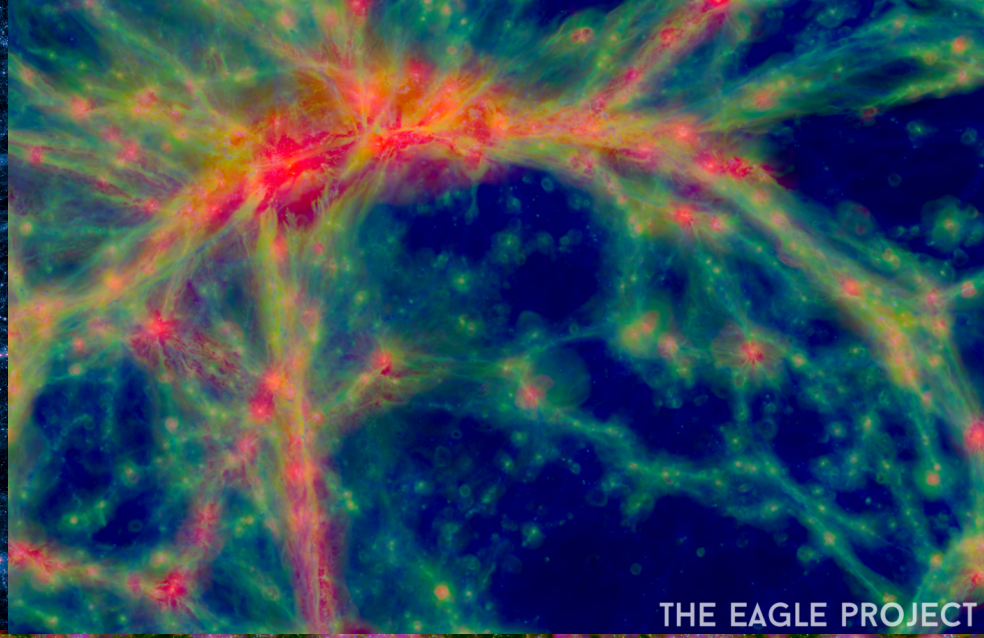
Sembolini+11

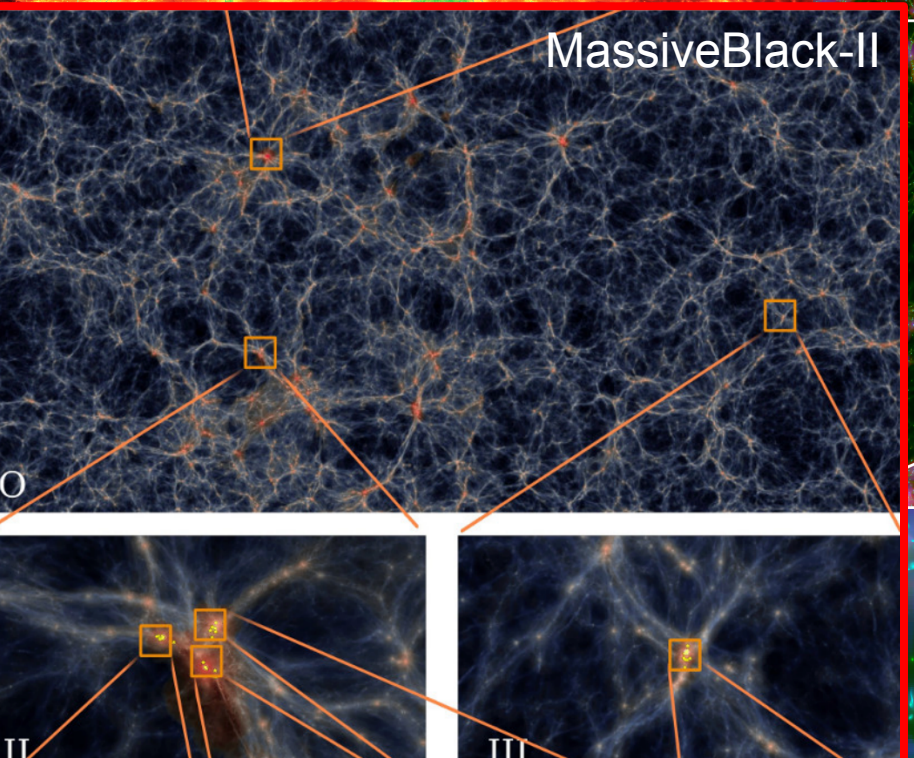
Cosmological simulations

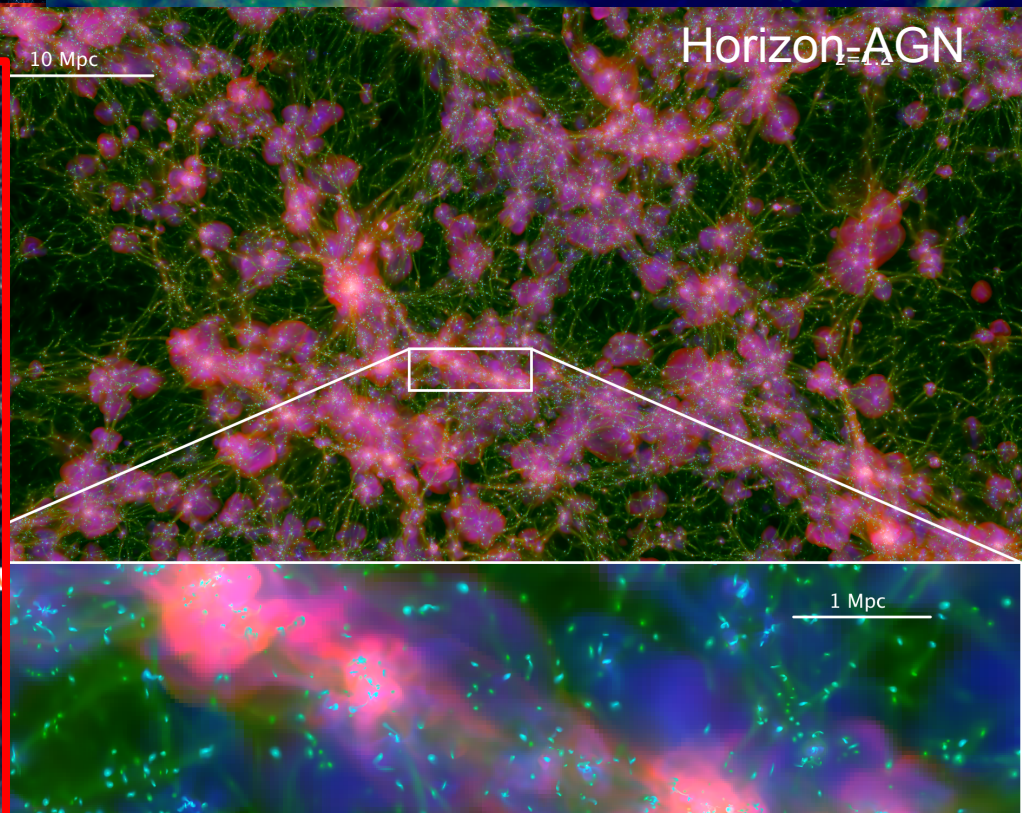
Tuning models for complicated feedback physics to match observations

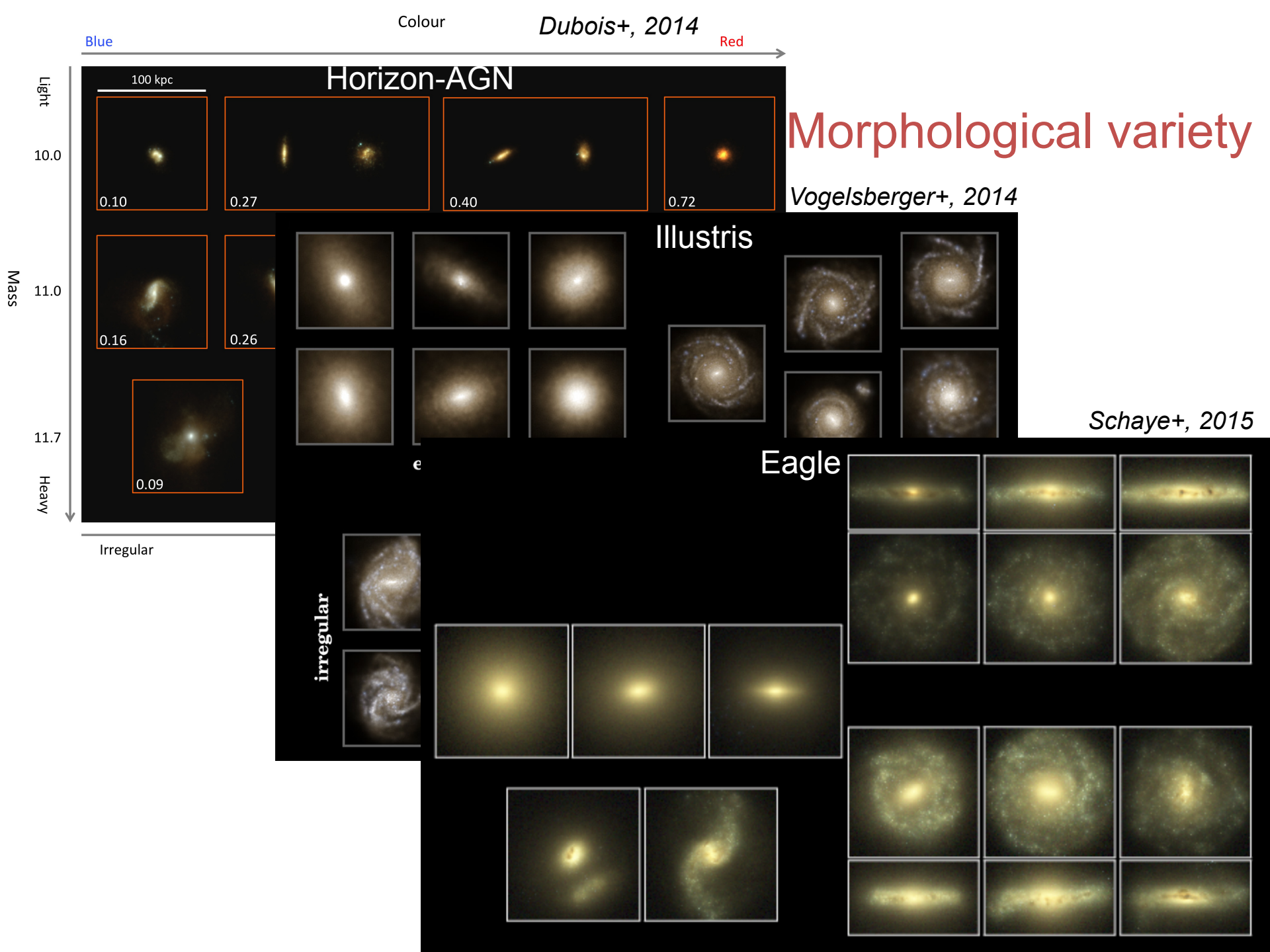
Tuning gravity to match observations


The Illustris Simulation
ogelsberger S. Genel V. Springel P. Torrey D. Sijacki D. Xu G. Snyder S. Bird D. Nelson L. Hernquist
Optical
Annihilation
X-Ray
SZ-y
Metal
Matter Density
Density


THE EAGLE PROJECT


MassiveBlack-II

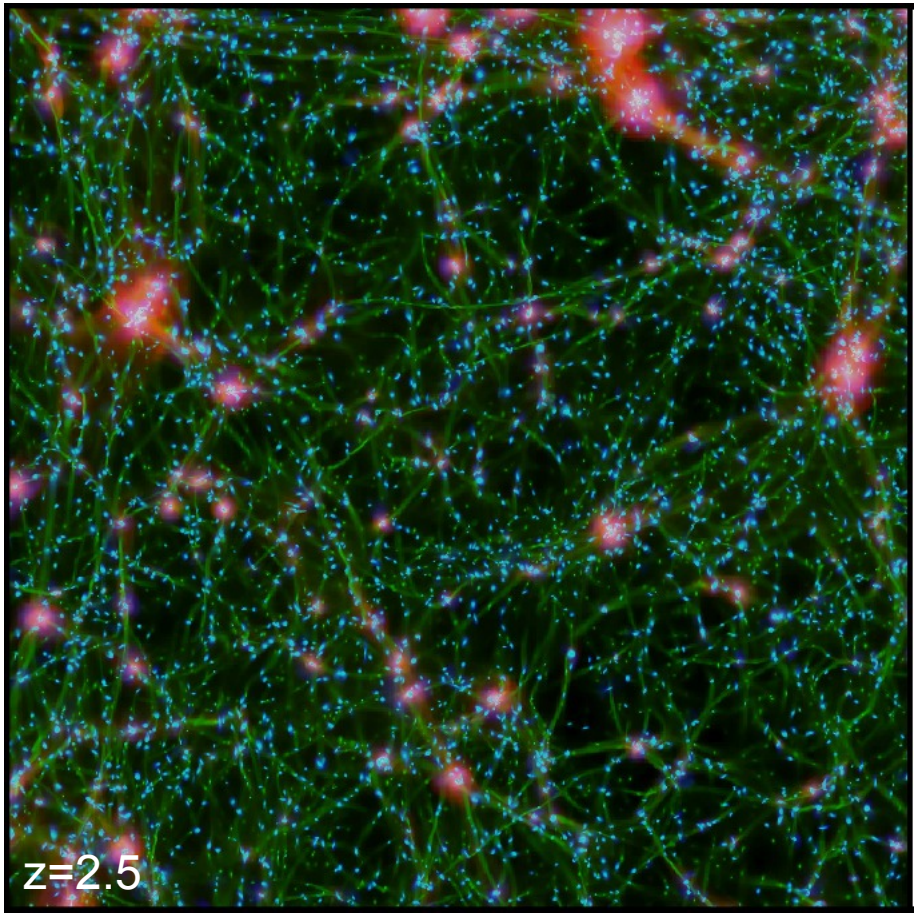

Horizon-AGN
10 Mpc
1 Mpc


Colour
Dubois+, 2014
Blue
Red
Light
Mass
Heavy
10.0
11.0
11.7
100 kpc
Horizon-AGN
0.10
0.27
0.40
0.72
0.16
0.26
0.09
Irregular
Morphological variety
Vogelsberger+, 2014
Illustris
irregular
Schaye+, 2015
Eagle

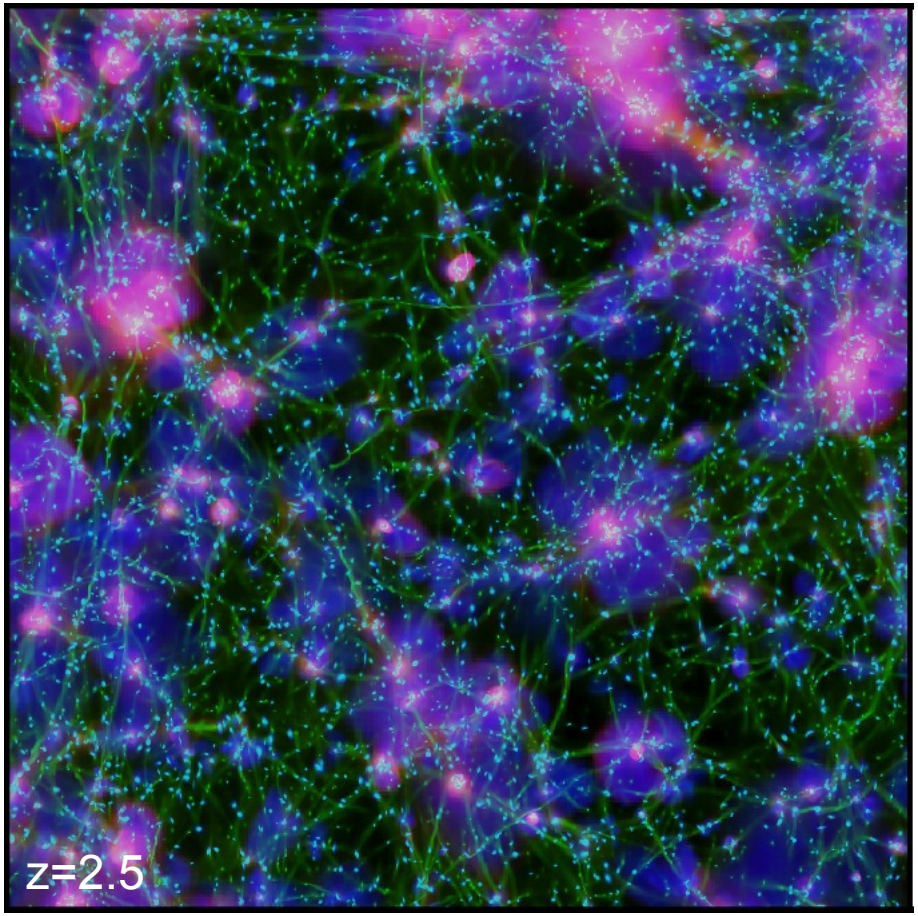
A visual inspection of the impact of AGN feedback on large-scale structures

Green: gas density / Red: temperature / Blue: metallicity

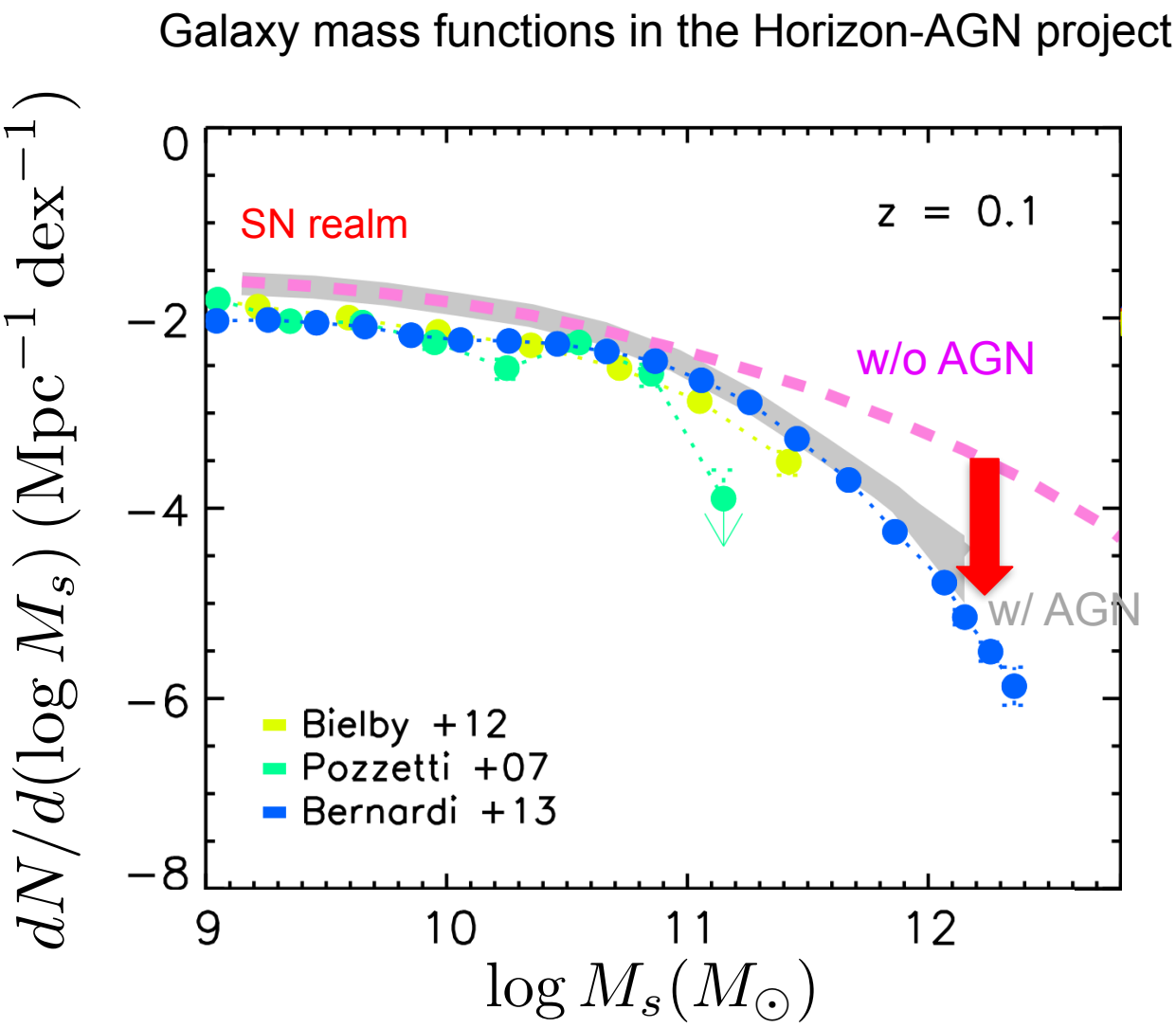
Horizon-noAGN



Horizon-AGN

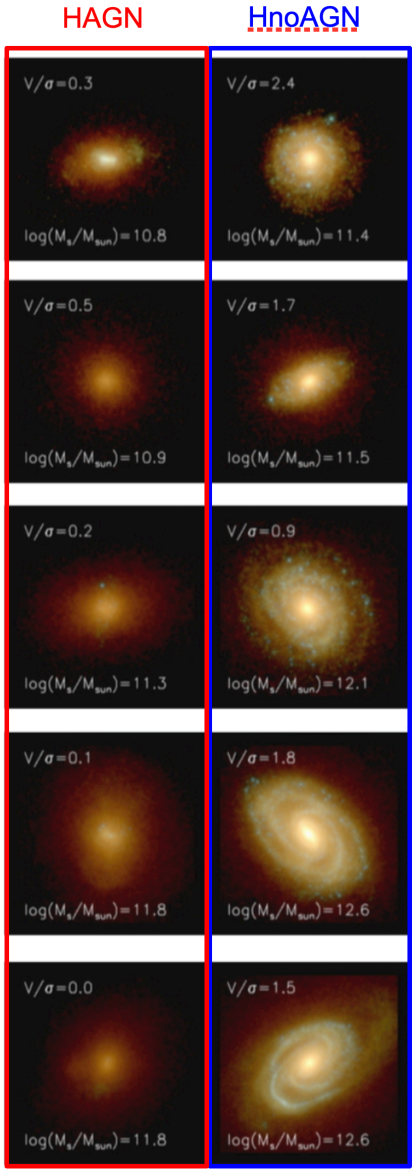


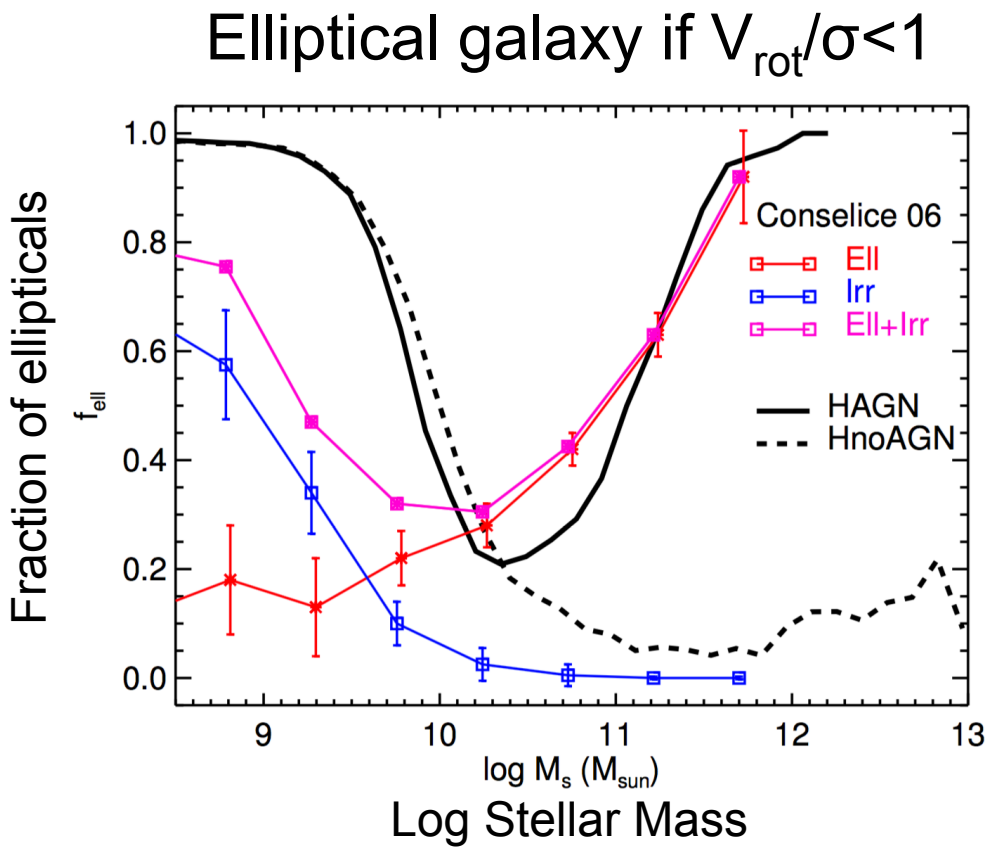
Motivation for AGN feedback



Kaviraj+17

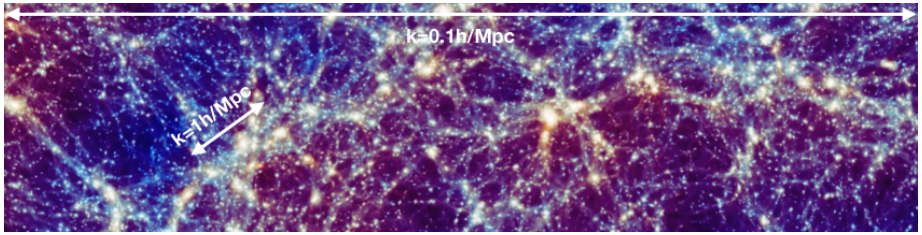
Better galactic physics produce more realistic galaxies



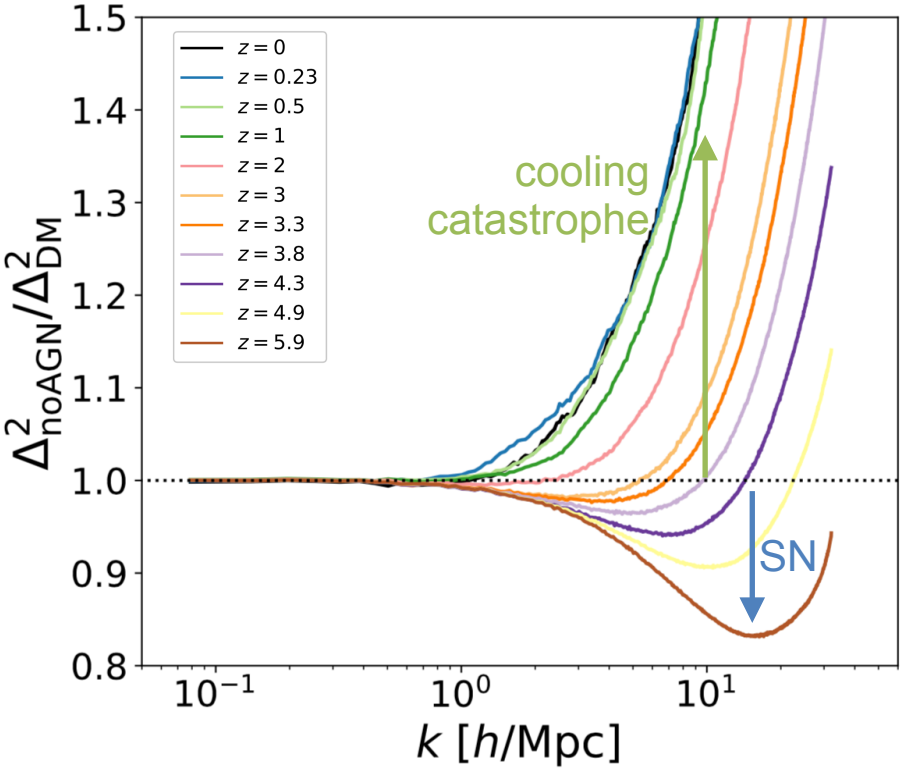


Dubois+16

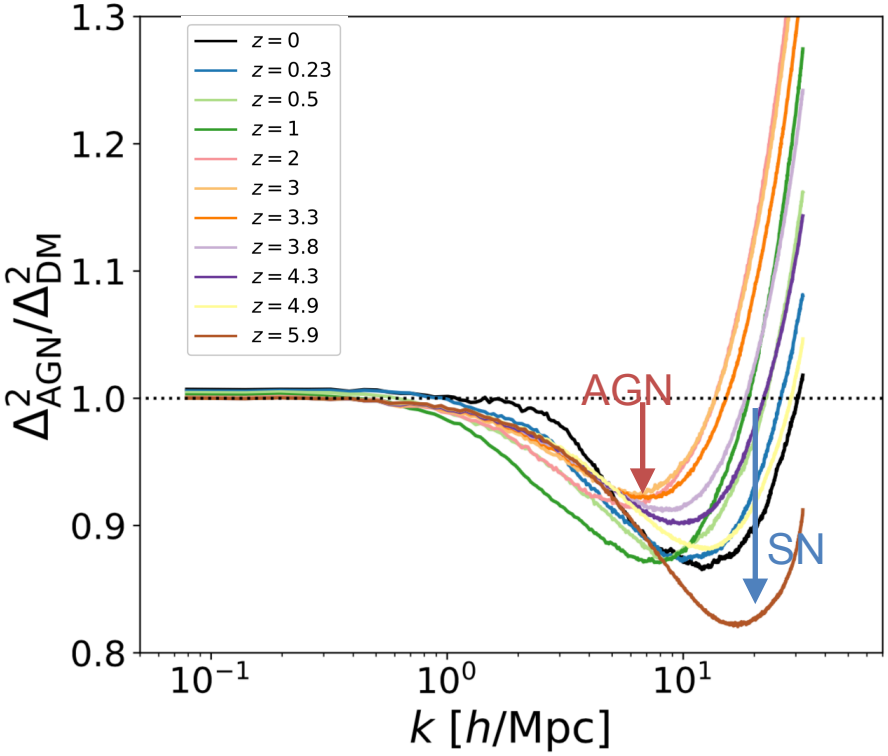
How is the matter Power Spectrum affected by baryons?



No AGN wrt DM-only



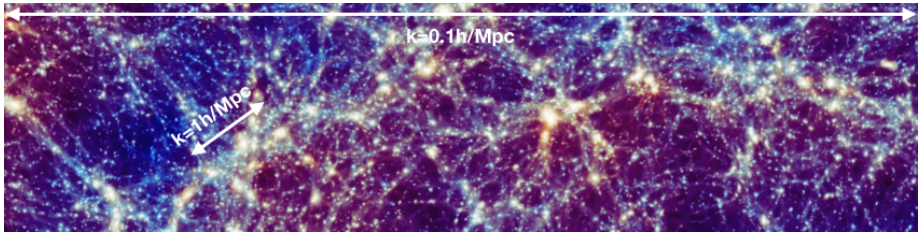
AGN wrt DM-only



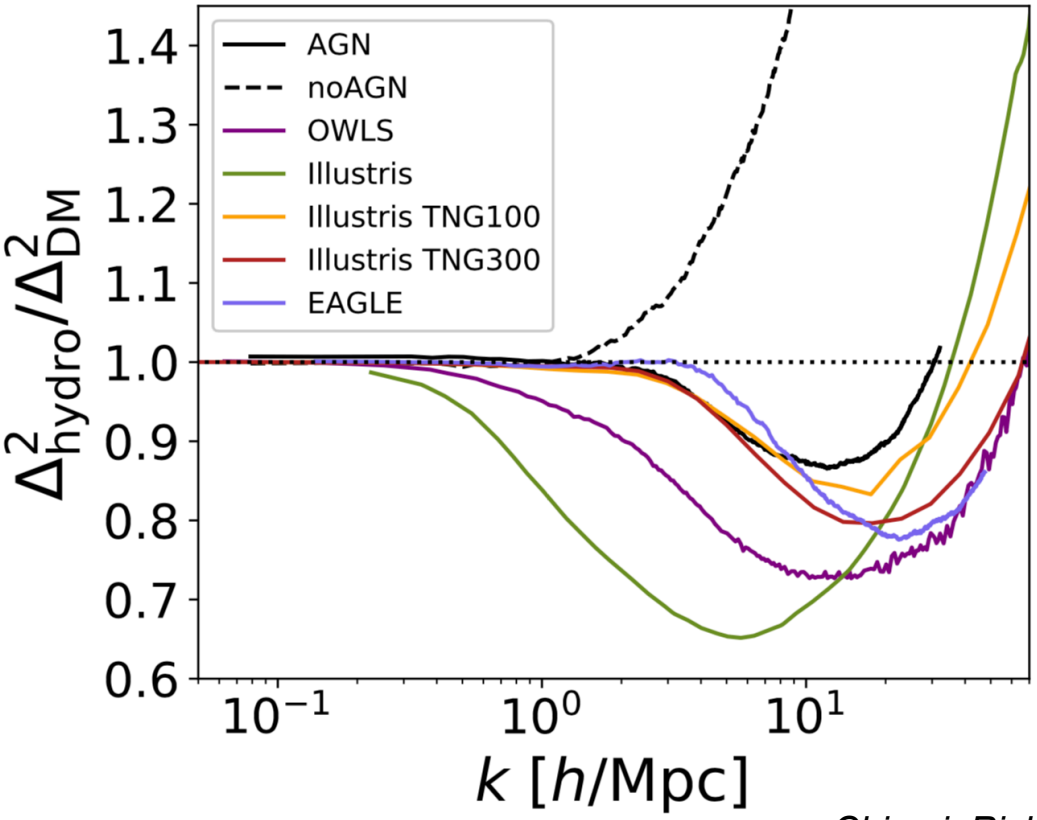
Chisari, Richardson, Devriendt, YD+ 18
See Van Daalen+ 11; Hellwing+ 16; Springel+ 18

Horizon-AGN simulation

How is the matter Power Spectrum affected by baryons?



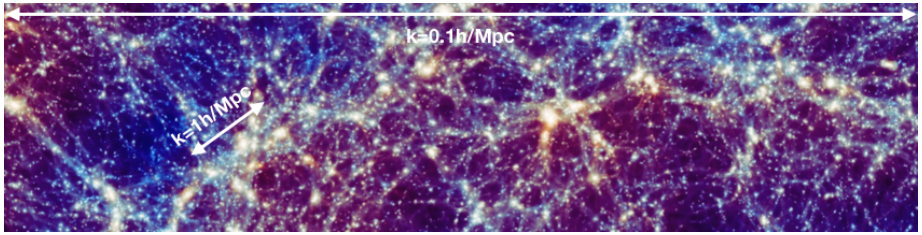
baryonic simulation PS over DM-only simulation PS



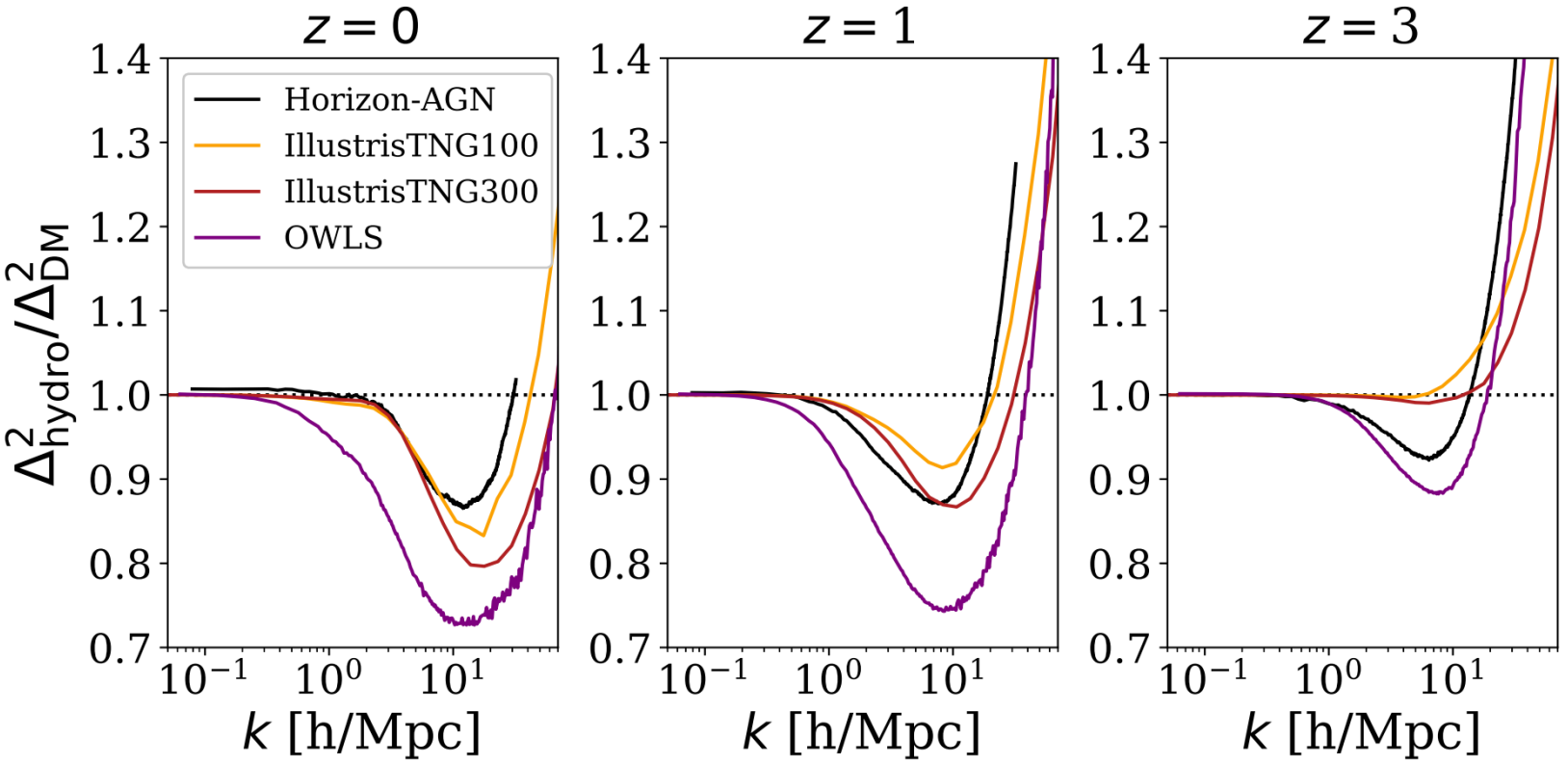
Chisari, Richardson, Devriendt, YD+ 18
See Van Daalen+ 11; Hellwing+ 16; Springel+ 18

Horizon-AGN simulation

How is the matter Power Spectrum affected by baryons?



baryonic simulation PS over DM-only simulation PS

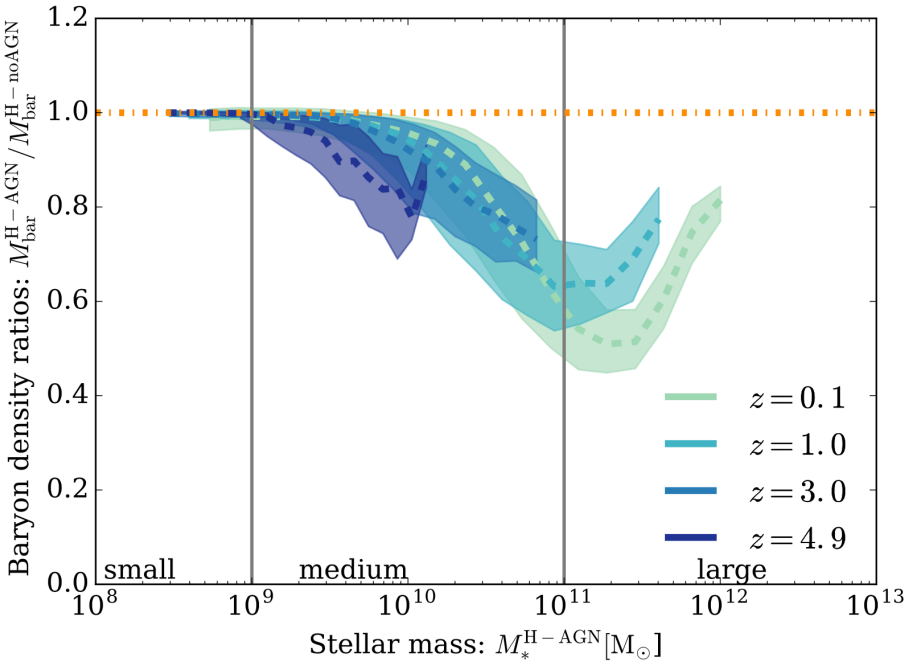


Chisari, Richardson, Devriendt, YD+ 18
See Van Daalen+ 11; Hellwing+ 16; Springel+ 18

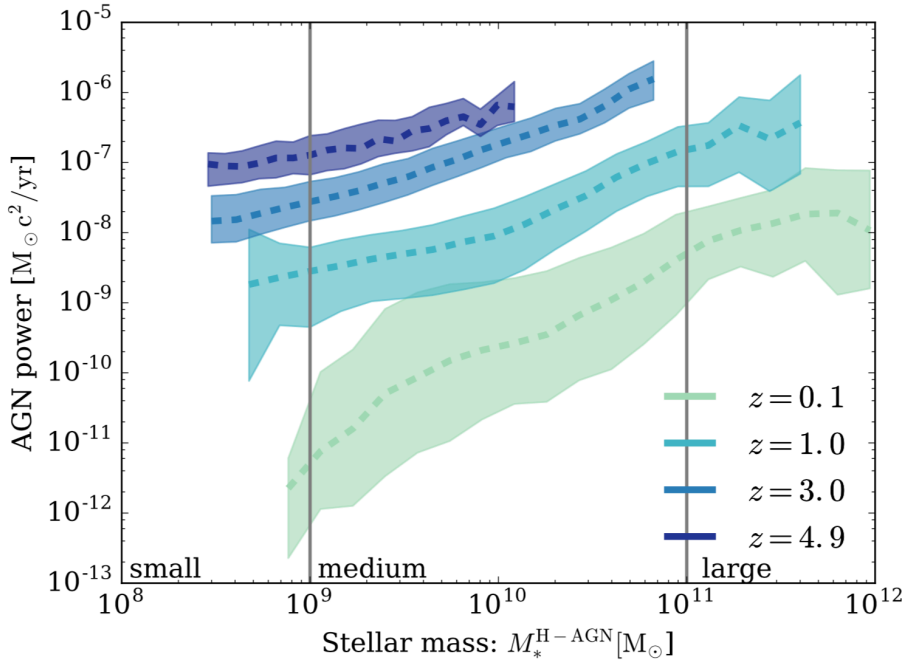
Horizon-AGN simulation

High redshift galaxies experience more AGN feedback which drives differential impact on baryon content in halos

Ratio of halo baryonic mass
AGN over no AGN in halos



AGN luminosity input

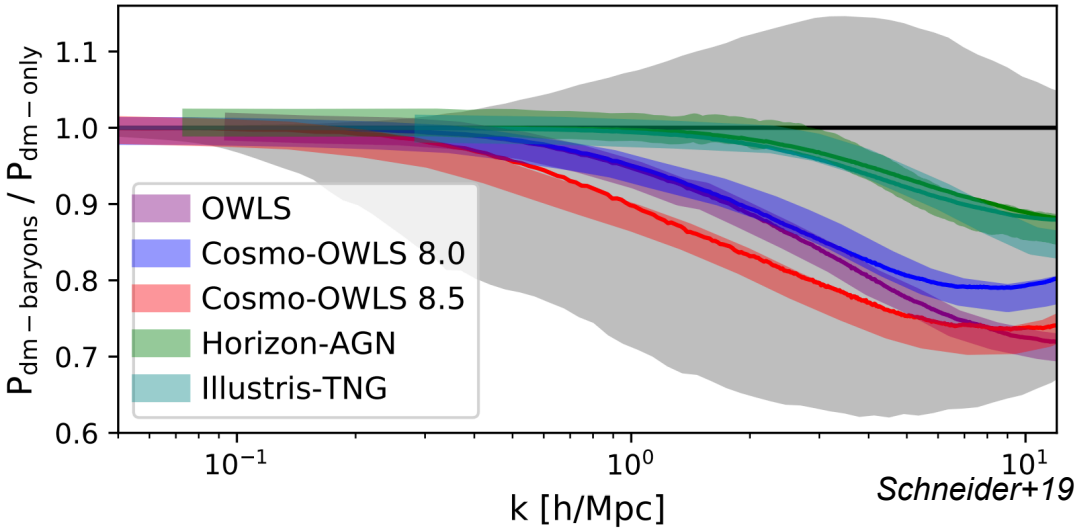


Horizon-AGN simulation

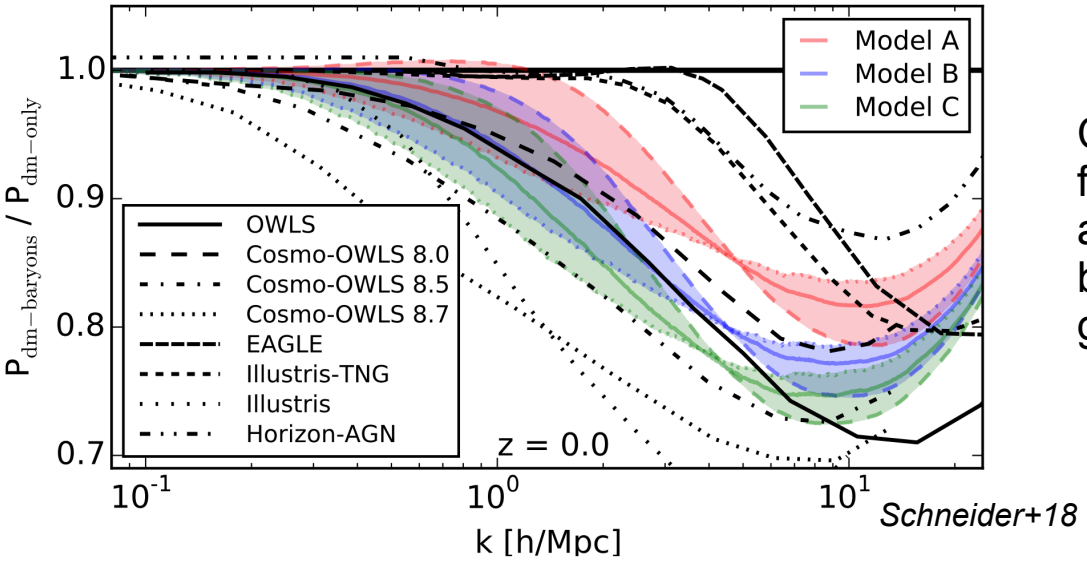
Beckmann+17

Analytical models to predict how baryons affect the matter PS

by considering how mass is distributed and ejected in groups/clusters

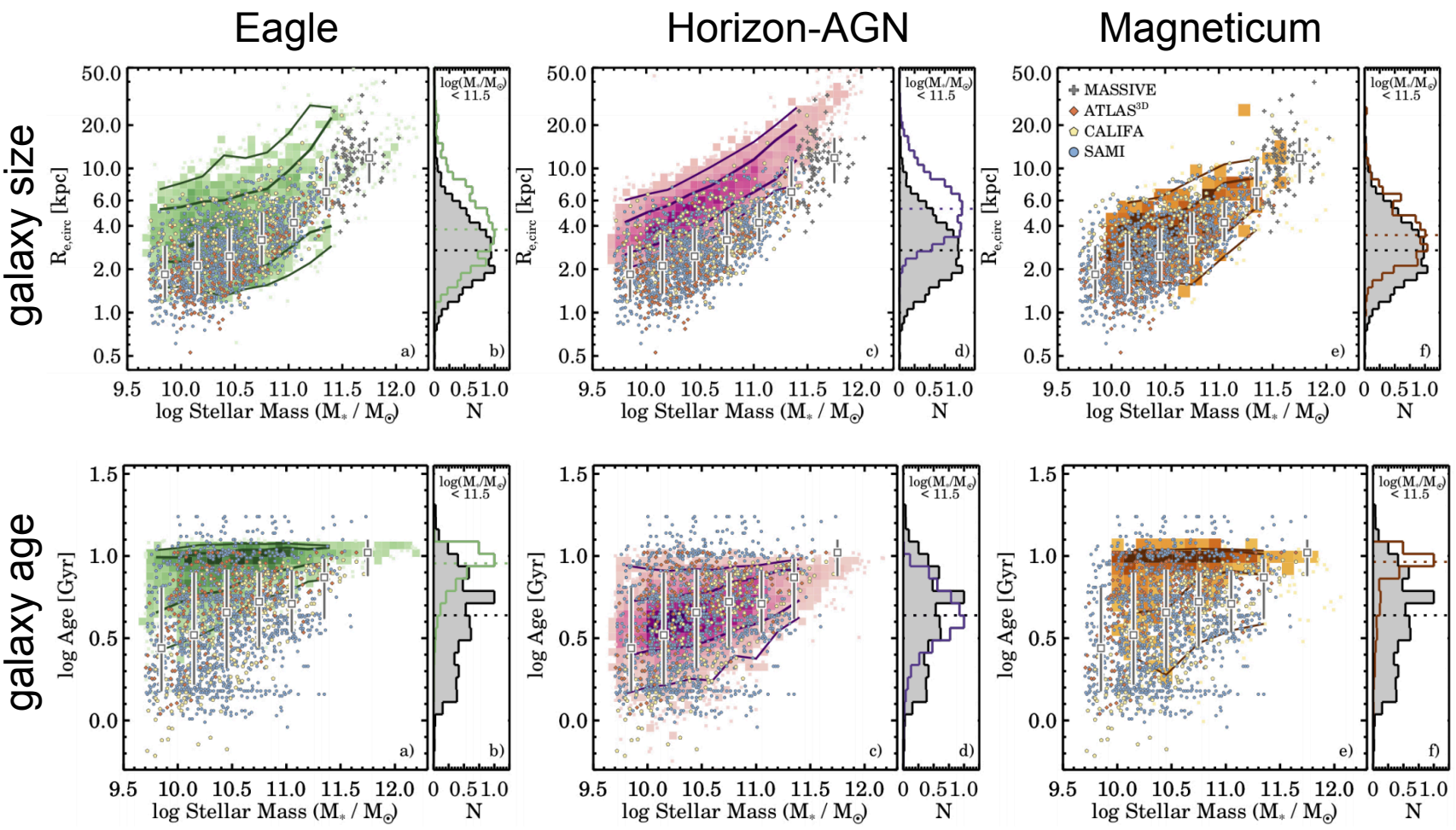


Solid lines are not a fit to the simulations (in shades)



Colours are using obs. data from groups/clusters + assumptions on hydrostatic bias (« Model ») and how gas is ejected

Simulated galaxy properties compared to data

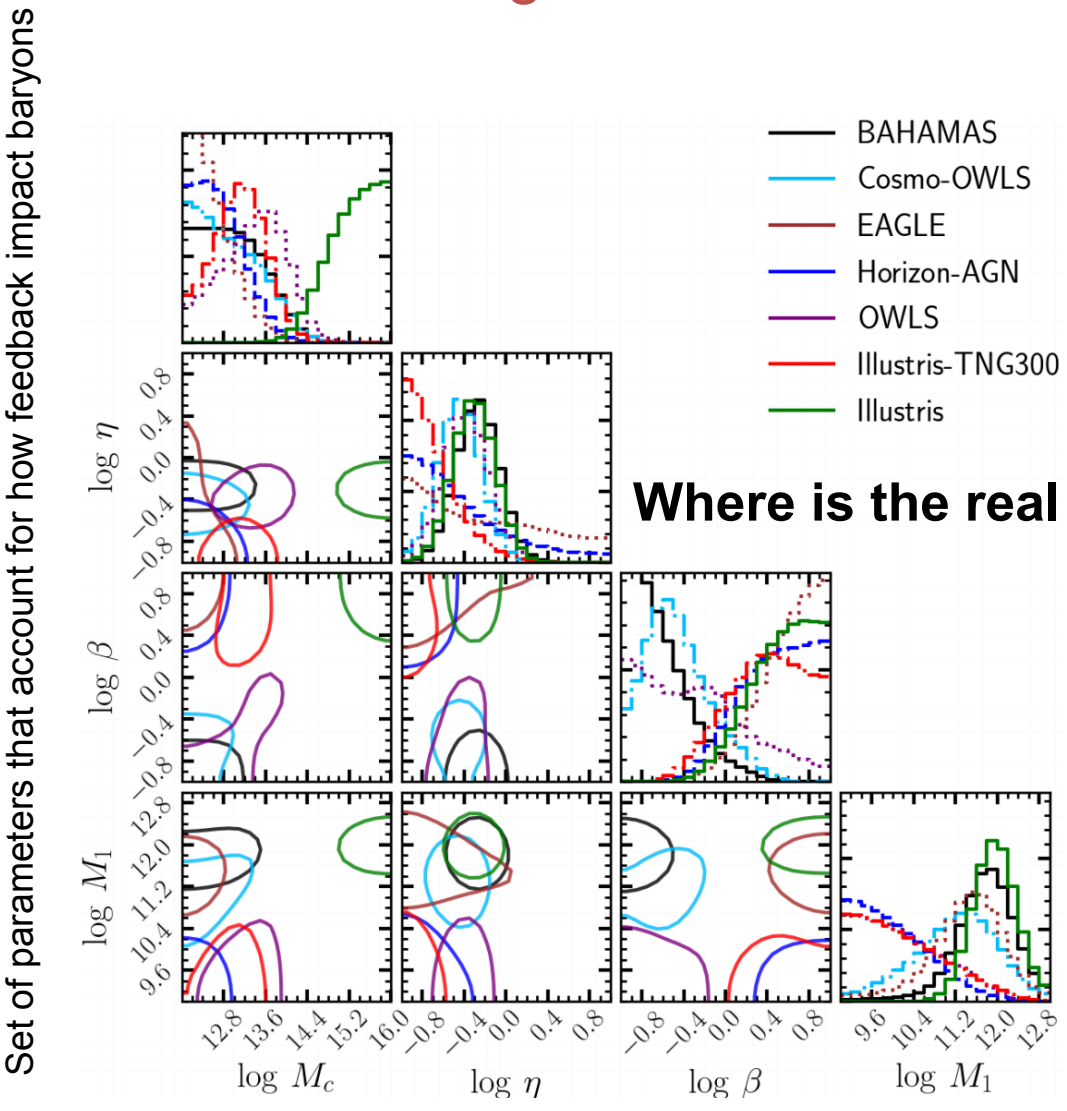


Van de Sande+19

If one can connect how CGM/IGM is affected as a function of galaxy properties (in a unique way?), there is hope to constrain baryonic effects **<u>at a few per cent</u>** on the PS.

(Eagle physics was calibrated on the size-mass relation, Schaye+15)

Parameter fit of the « baryonification » model to cosmological simulations

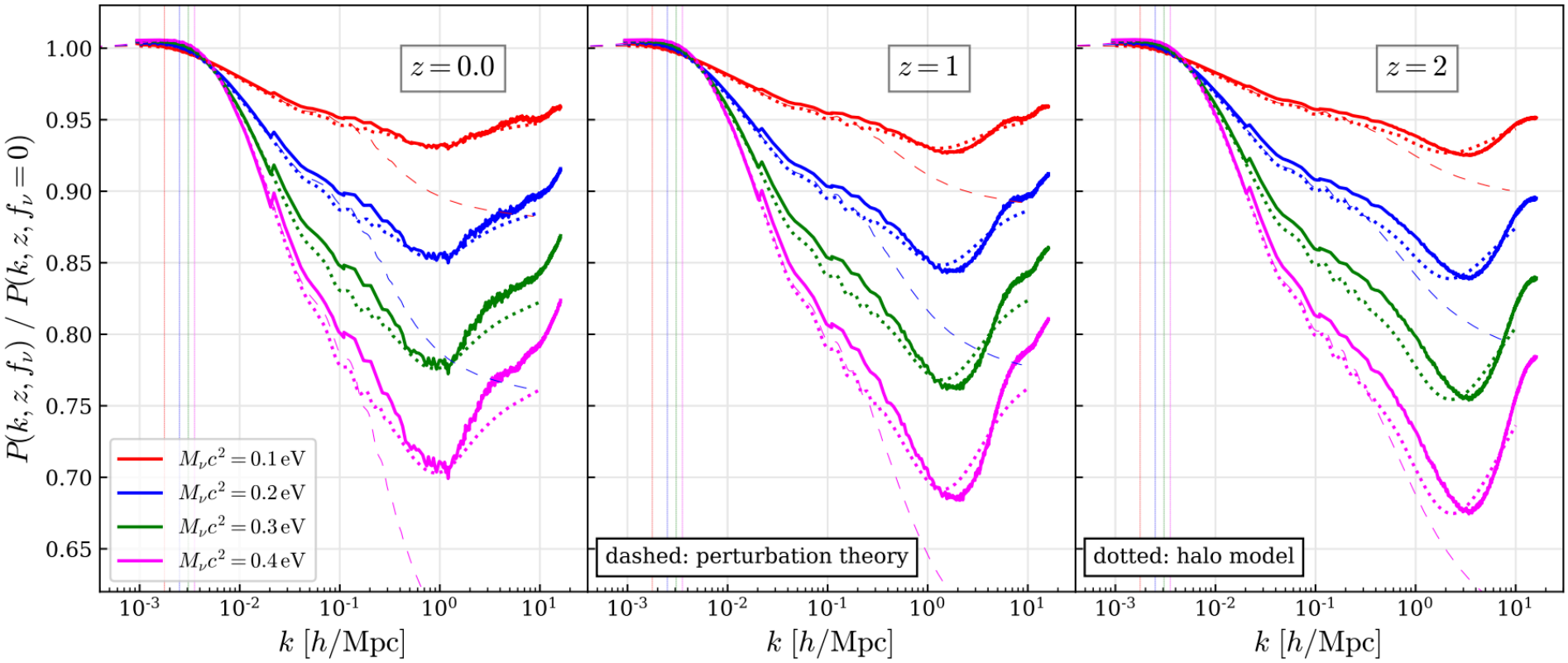


Where is the real Universe standing?

Aricco+20
(based on the Schneider model)

Effect of neutrinos on the power spectrum with N-body simulations

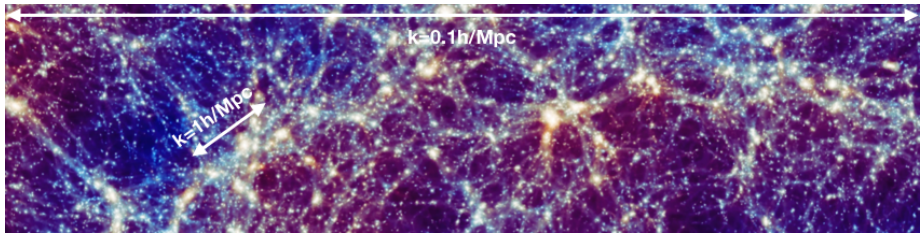
Ratio of PS w/ neutrino versus w/o neutrinos



Yoshikawa+20

See also Cataneo+20

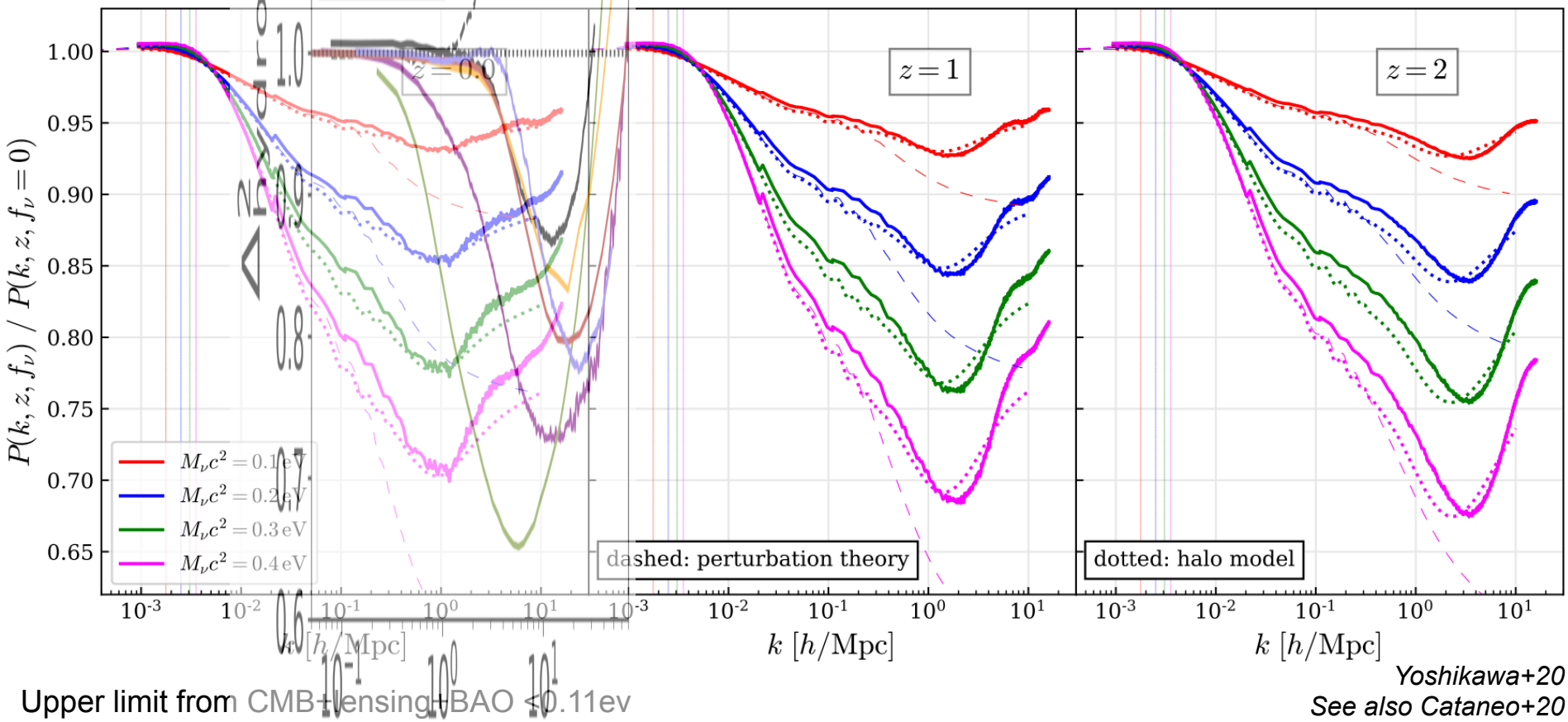
Upper limit from CMB+lensing+BAO <0.11ev (Palanque-Delabrouille+20)



BAHAMAS simulations (McCarthy+17) show that the effect of feedback and of neutrinos on the PS can be decoupled (1% accuracy, Mummery+20)

Effect of neutrinos on the power spectrum with N-body simulations

Ratio of PS w/ neutrino versus w/o neutrinos



Yoshikawa+20
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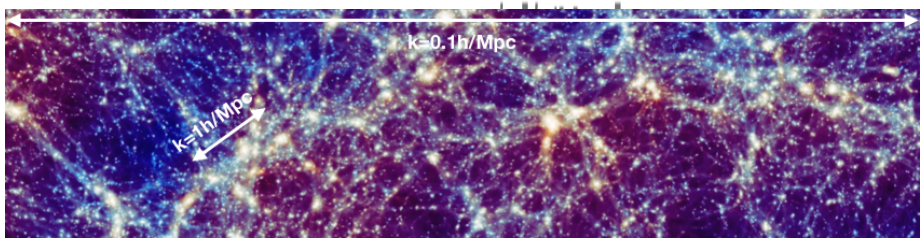
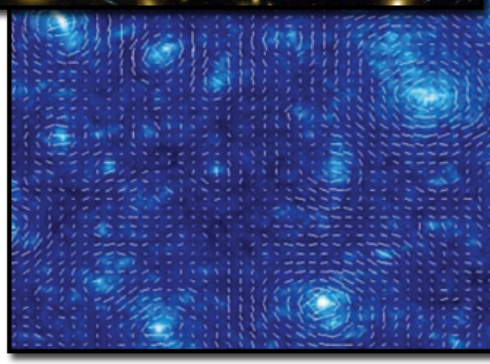
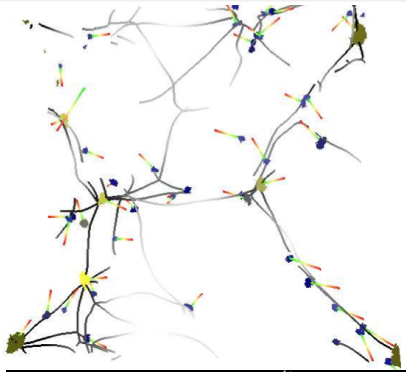


BAHAMAS simulations (McCarthy+17) show that the effect of feedback and of neutrinos on the PS can be decoupled (1% accuracy, Mummery+20)

And baryons are messing things up …even more: intrinsic alignements

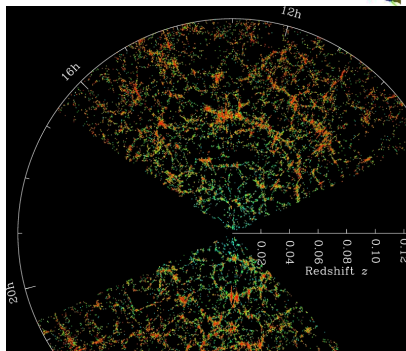


- Euclid and LSST will put more severe constraints on dark energy, neutrino mass, and modified gravity using cosmic shear
- Constraint through the measurement of the matter power spectrum (role of baryons?)
- Intrinsic alignment of galaxies is a spurious bias that must be quantified
- Need for large-scale simulations and direct observations

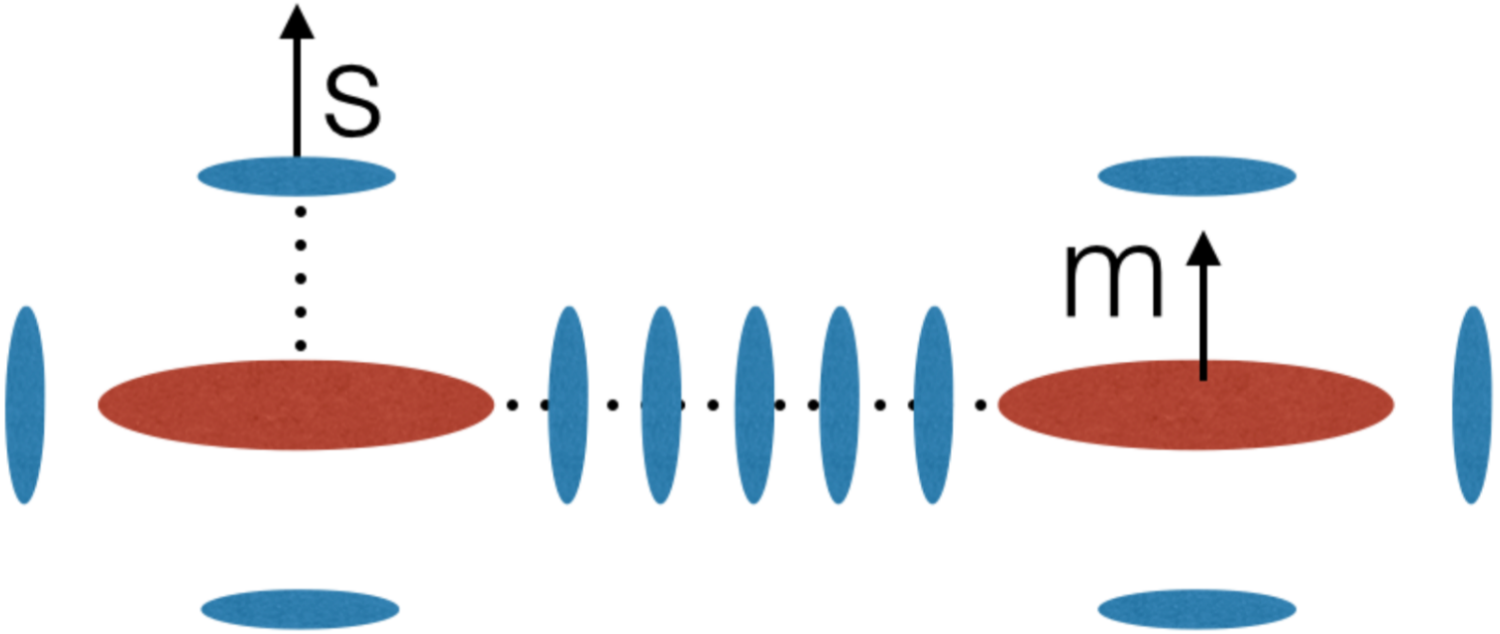


- Galaxies form at special locations of the cosmic web (sheets, filaments, nodes) & their angular momentum properties is inherited from large scales

1. Feedback changes the angular momentum content of galaxies
2. Evaluate the intrinsic alignment of structures

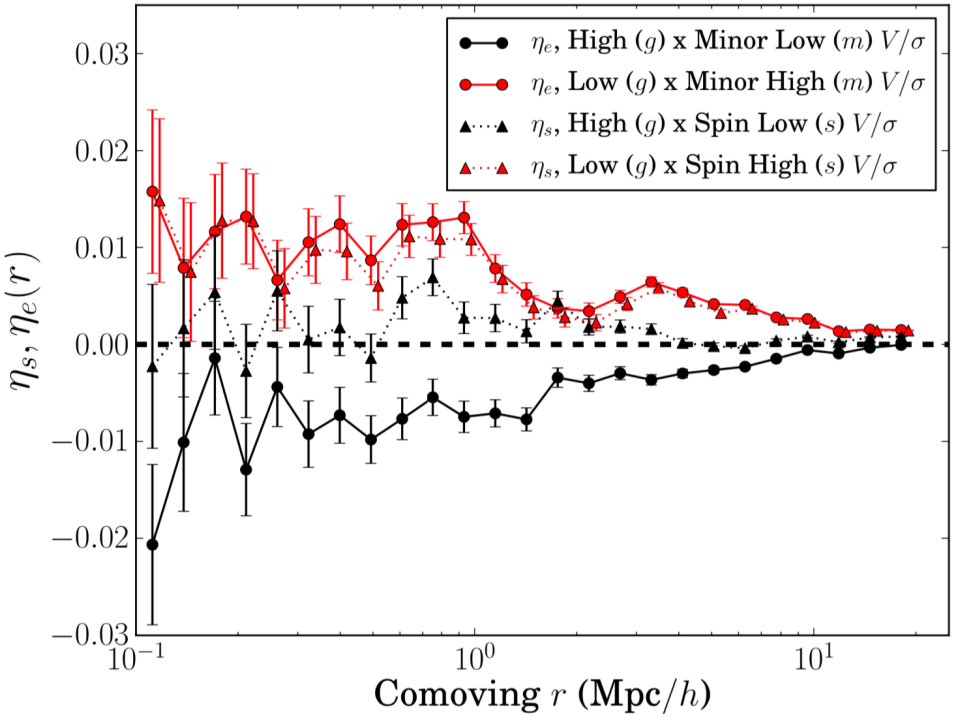


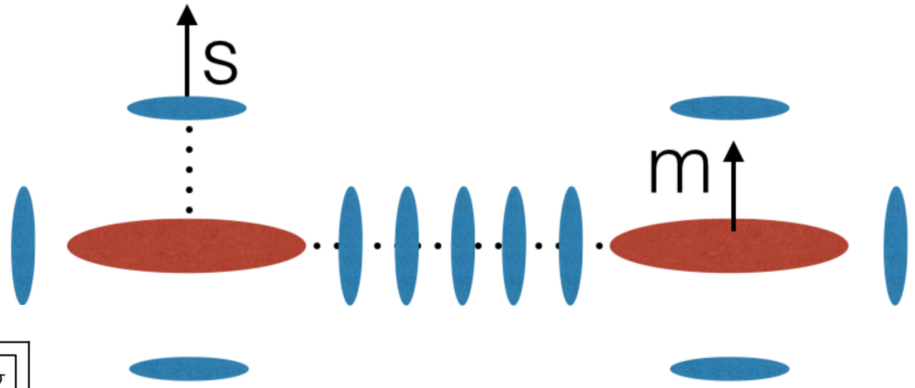
Do we understand intrinsic alignements?



Position-shape cross-correlations depend on morphology

$$\eta_e(r) = \langle |\hat{\mathbf{r}} \cdot \hat{\mathbf{e}}(\mathbf{x}+\mathbf{r})|^2 \rangle - 1/3$$

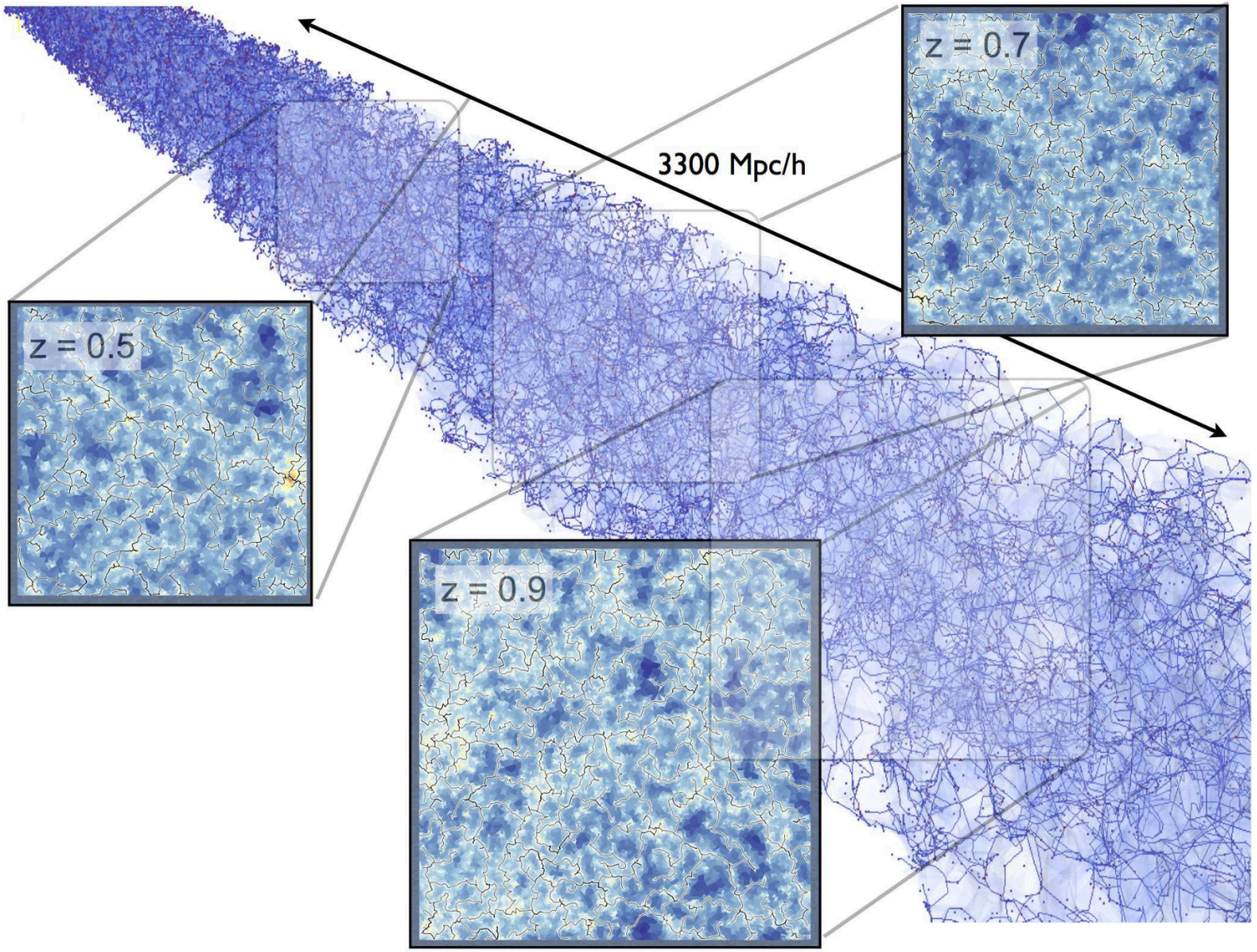




No evidence of tangential alignements of discs in Eagle (Velliscig+, 2015) and MBII & Illustris (Tenneti+, 2015)

Chisari et al, 2015, 2016
See also Codis et al, 2015; Soussana+

Horizon-AGN lightcone skeleton

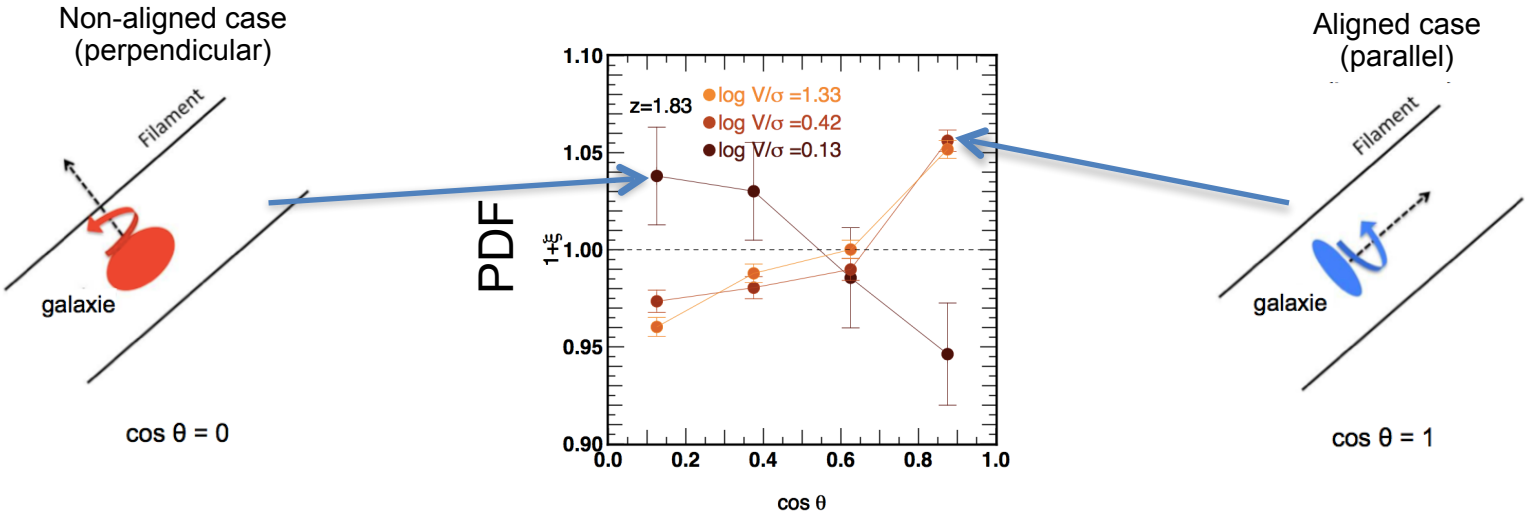


Skeleton of the LSS, *Sousbie+2009*

Laigle+2017

Cosmic web and galaxies alignment

Discs : spin aligned with cosmic filaments
Ellipticals : spin perpendicular with cosmic filaments



Horizon-AGN simulation / *Dubois et al, 2014*

Cosmic web and galaxies alignment

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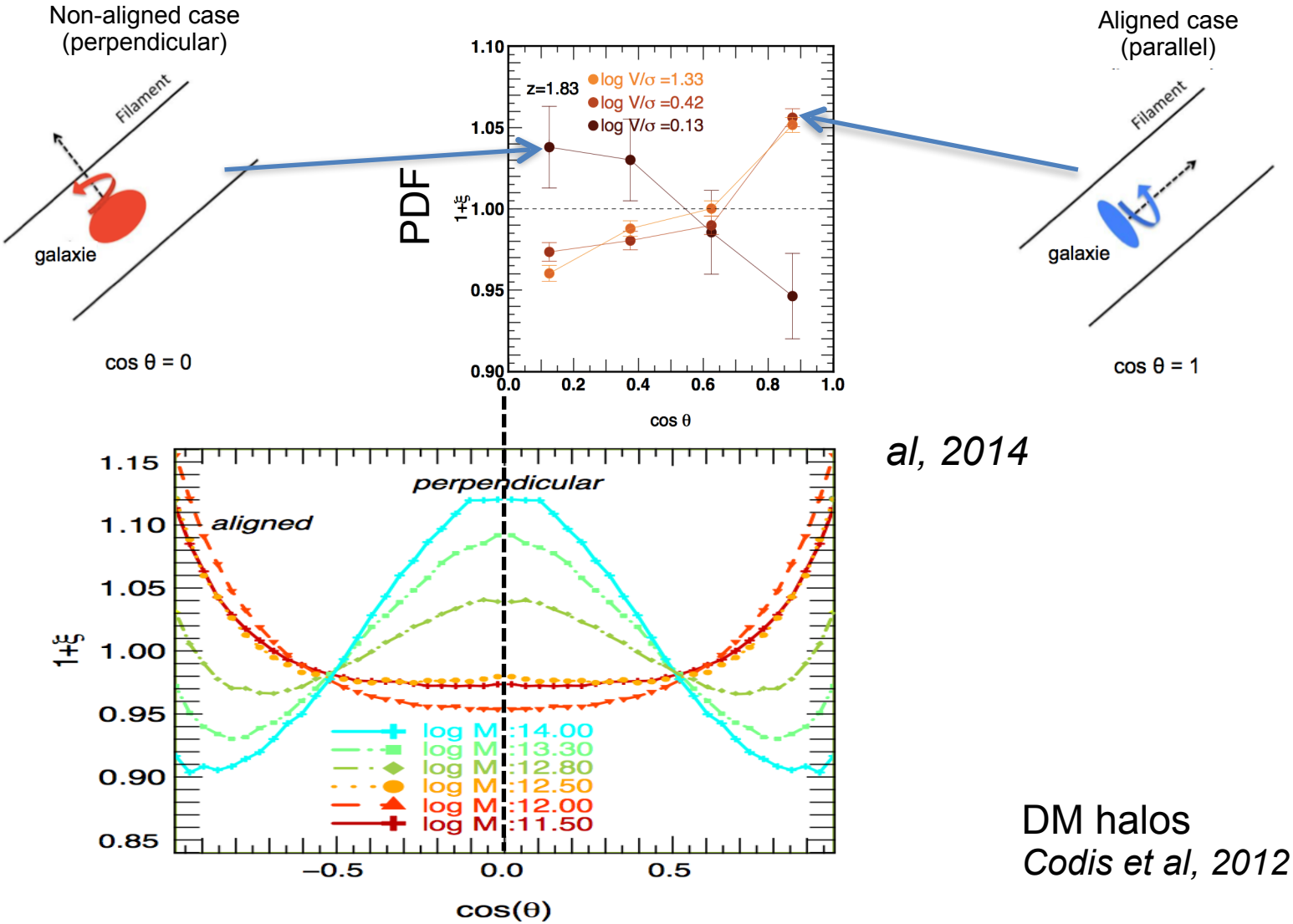

al, 2014

DM halos
Codis et al, 2012

Cosmic web and galaxies alignment

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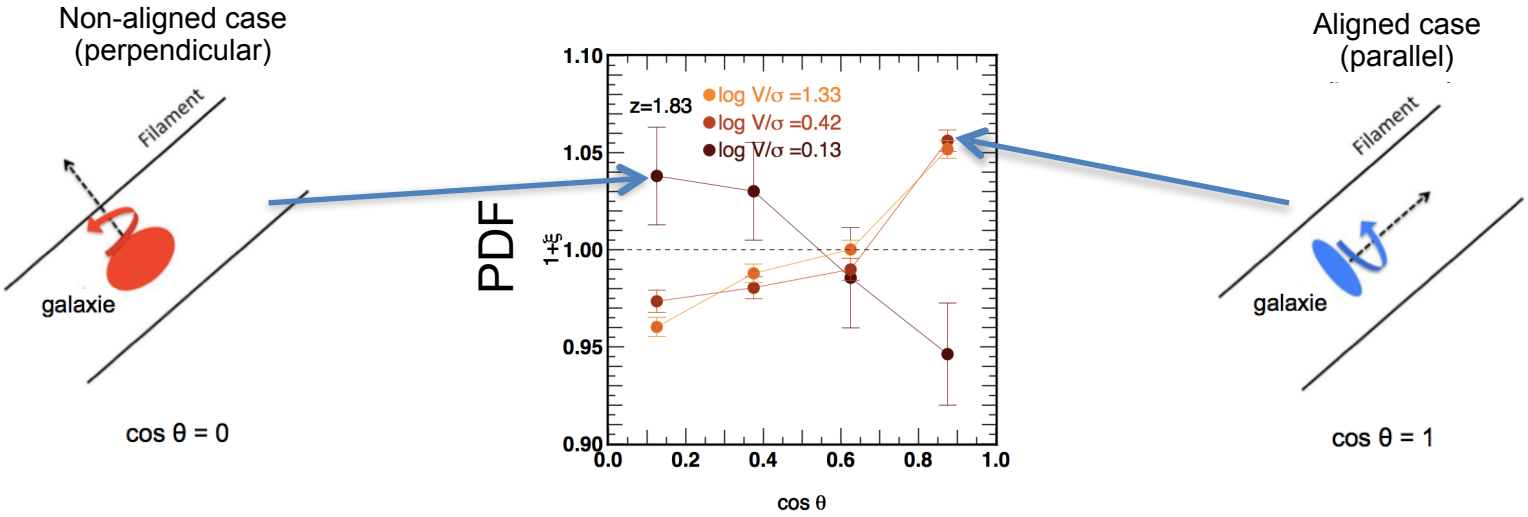
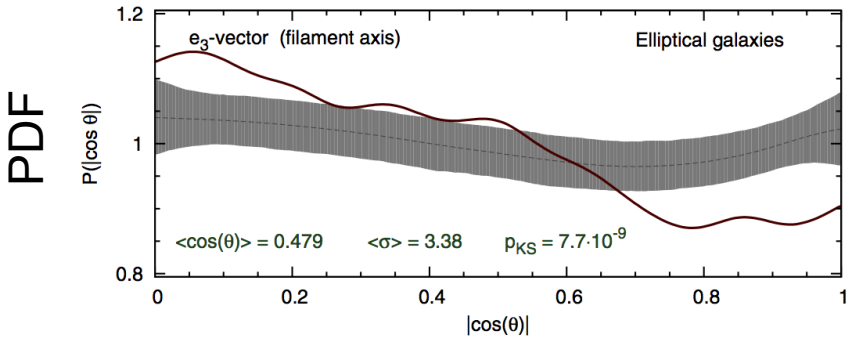
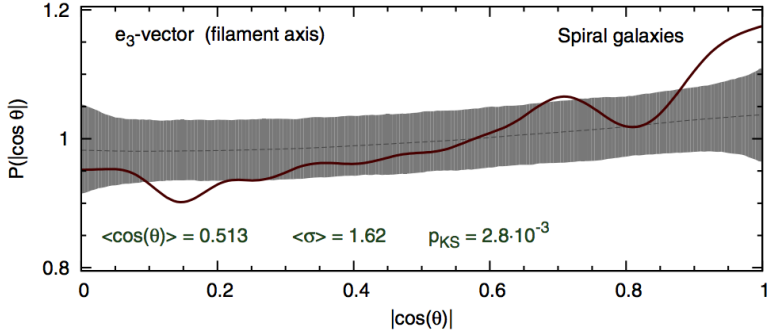


Horizon-AGN simulation / *Dubois et al, 2014*

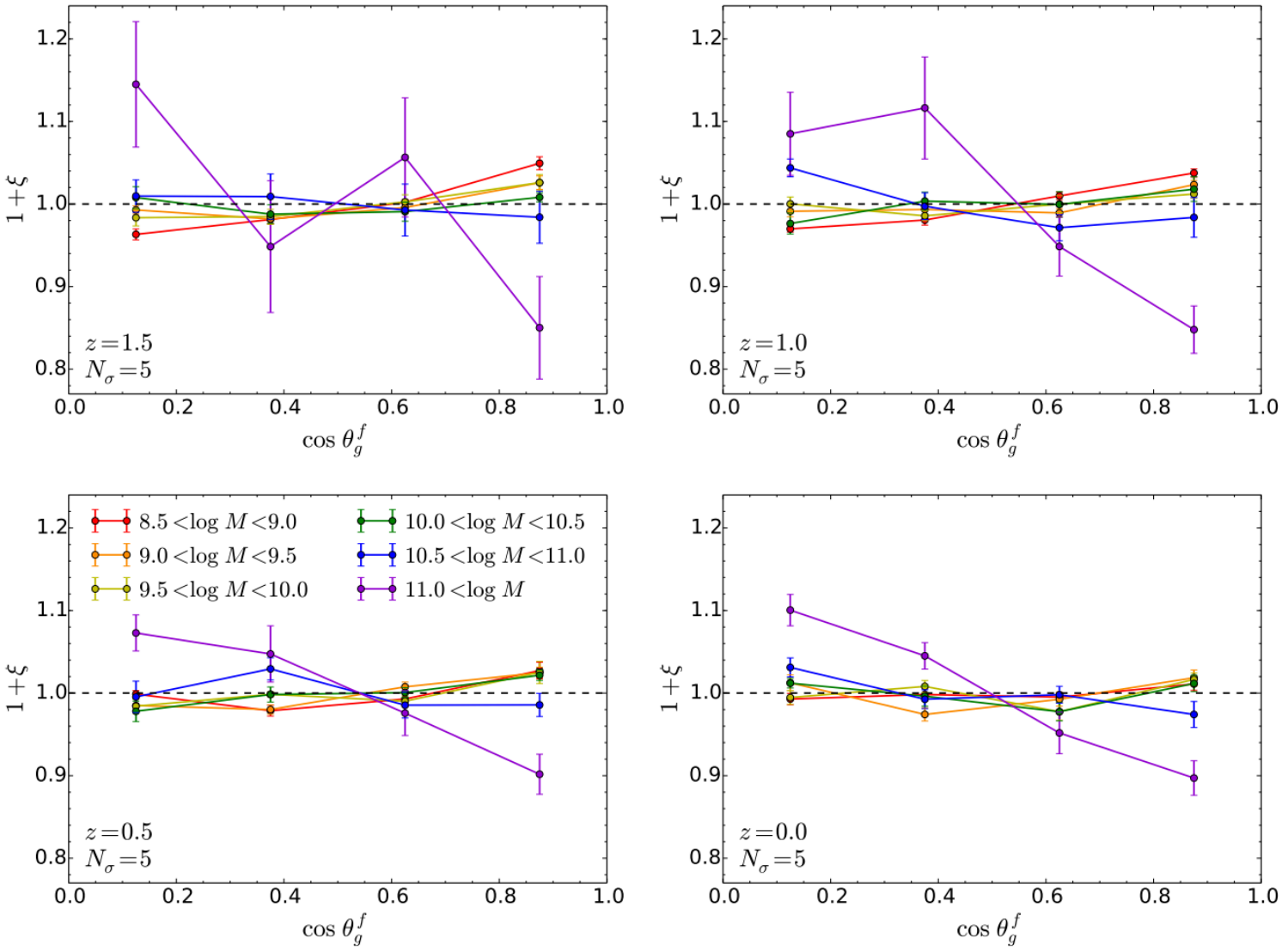
Observations (SDSS) / *Tempel & Libeskind, 2013*





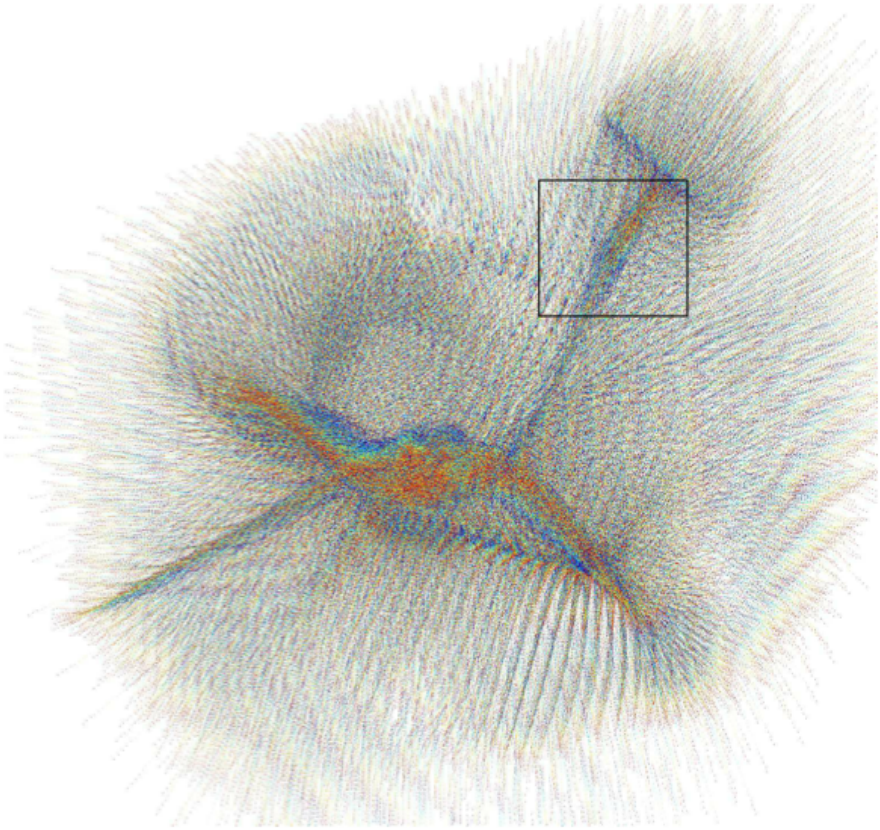
See also Welker+19 using SAMI and GAMA

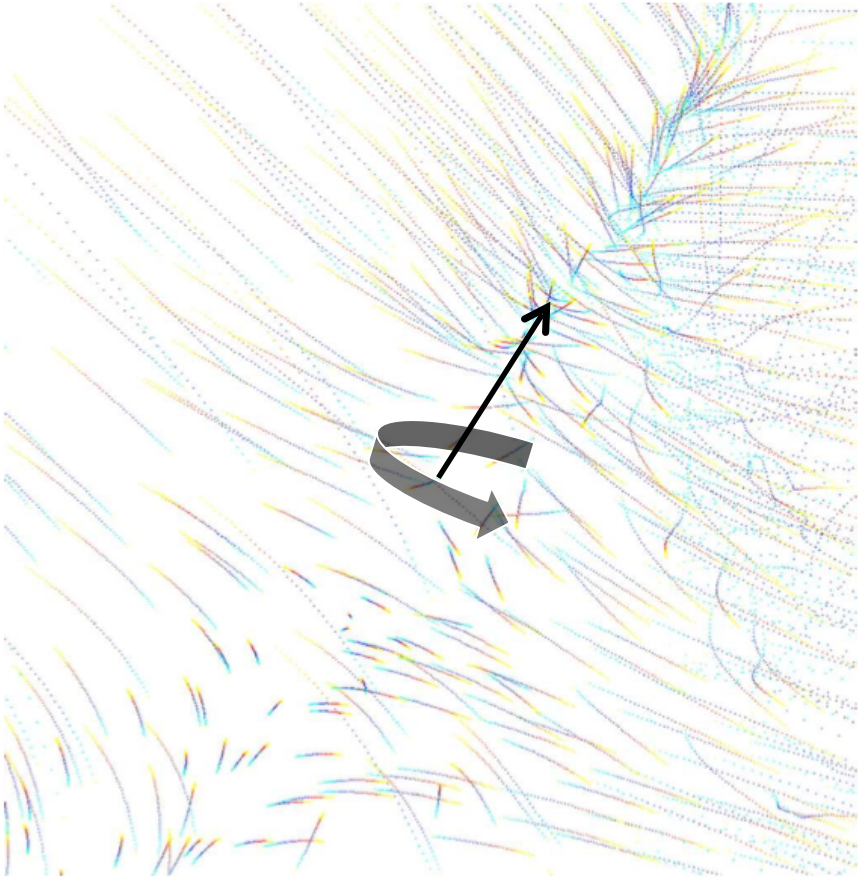
Alignments with filaments evolve with redshift



Codis, Jindal, … YD+18
See also Bate, Chisari+19

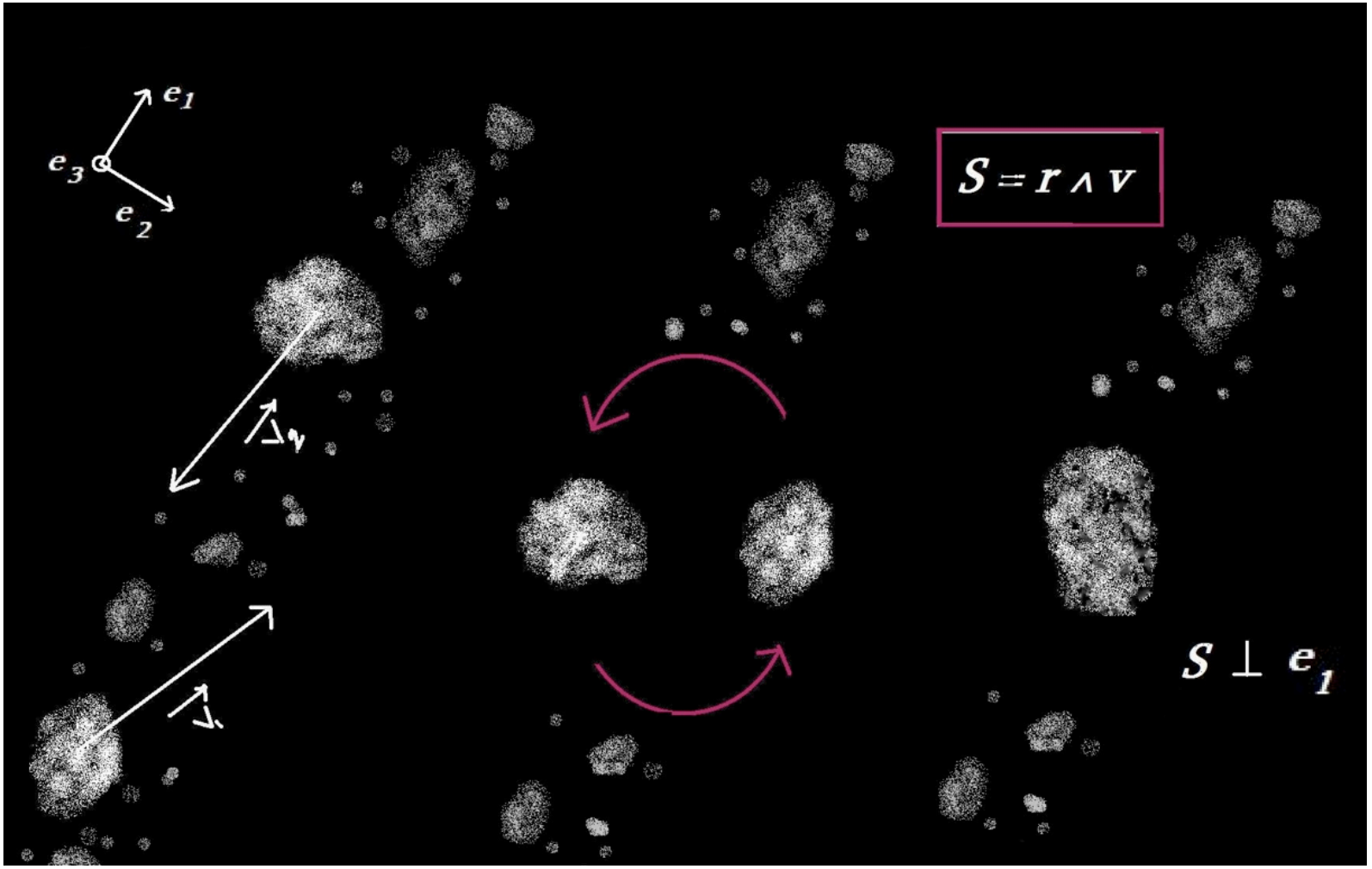
Why do low-mass halos align with filaments?





Pichon+11
See also Pichon & Bernardeau 99
Laigle+15
Codis, Pichon, Pogosyan 15

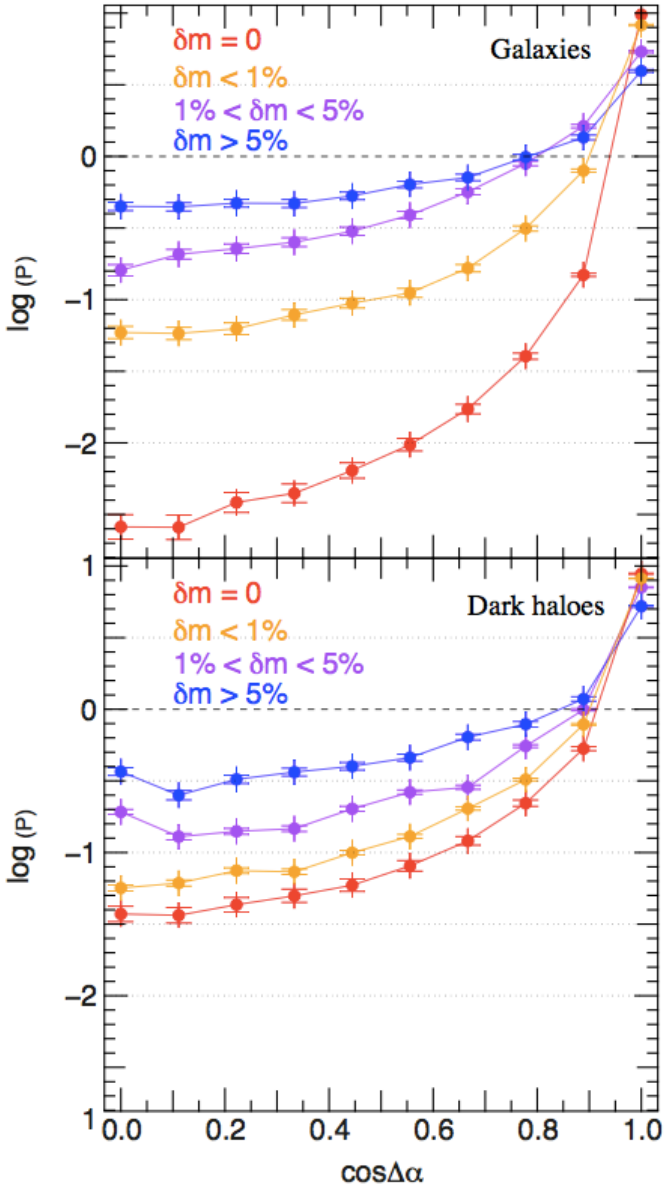
Why do high-mass halos are perpendicular to filaments?

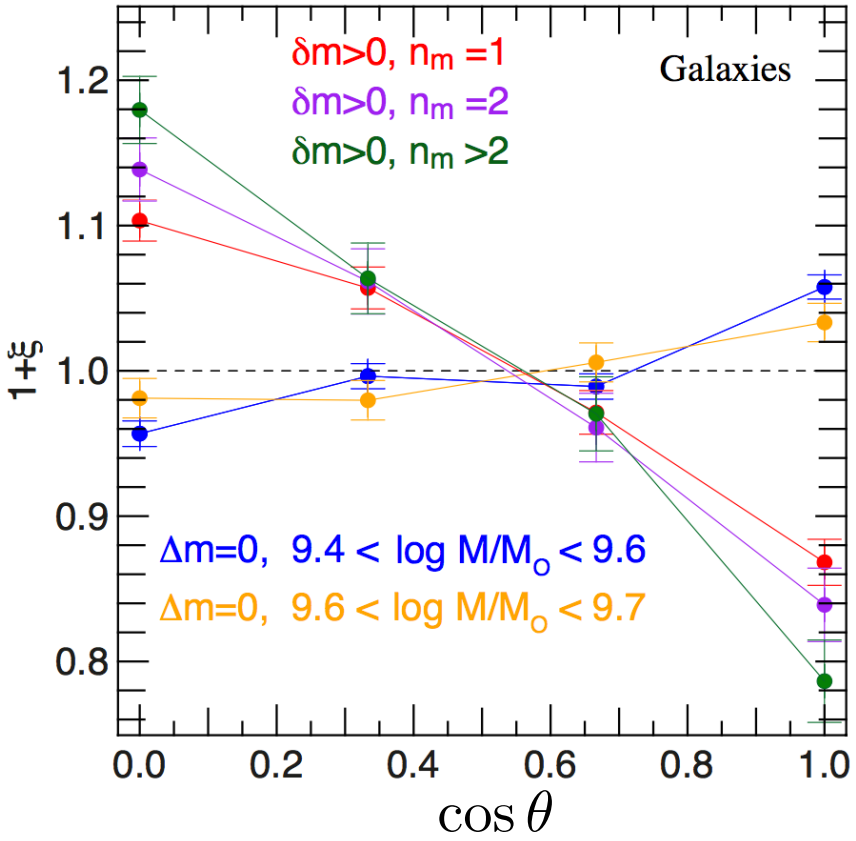


Courtesy of S. Codis

See Codis+15 for a prediction of spin acquisition in filaments using an anisotropic tidal torque theory

The origin of spin flips is mergers

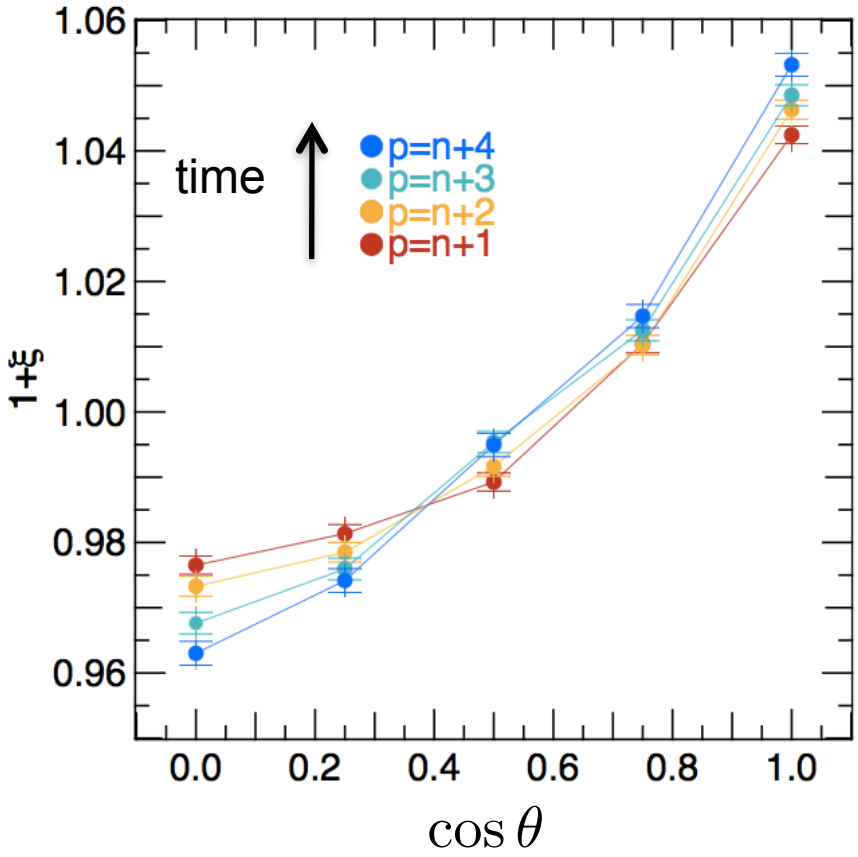




Welker+14

Re-alignment of galaxies

In absence of mergers, galaxies tend to realign with the cosmic web because of smooth gas accretion



As AGN feedback prevents gas accretion in massive galaxies, it also prevents massive galaxies to realign with the cosmic filaments after a merger.

AGN feedback is mandatory to get galaxies perpendicular with cosmic filaments.

Welker+14

« LCDM faces a series of small-scale ($k>1Mpc^{-1}$) challenges »

- cusp-core(1): simulated halos are too cuspy (NFW) w.r.t observed halos

- missing satellites(2): simulated subhalo mass functions over-predict low-mass halos w.r.t observed MW satellites

- too-big-to-fail(3): simulated MW-like satellites have too much DM w.r.t to observed satellites

(+ Baryonic Tully-Fisher & Thin plane of MW satellites)

(1) Flores & Primack 94, Moore 94
(2) Klypin+ 99, Moore+ 99
(3) Boylan-Kolchin+11

See Bullock+17 for a recent review

« LCDM faces a series of small-scale ($k>1 Mpc^{-1}$) challenges »

Possible solutions with alternative DM

- cusp-core[(1)]: simulated halos are too cuspy (NFW) w.r.t observed halos — SIDM
- missing satellites[(2)]: simulated subhalo mass functions over-predict low-mass halos w.r.t observed MW satellites — WDM
- too-big-to-fail[(3)]: simulated MW-like satellites have too much DM w.r.t to observed satellites — SIDM WDM

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Self-interacting Dark Matter (SIDM)
➡ efficient redistribution within the center of halos

Warm Dark Matter (WDM)
➡ introduce a cut-off scale in the power spectrum

+ MOND, coupled DE-DM, etc.
(add here your favorite exotic physics)

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WDM

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SIDM WDM

All these « issues » stemmed from (C)DM-only simulations

(+ Baryonic Tully-Fisher & Thin plane of MW satellites)

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Maschenchko+07; Governato+12; Pontzen&Governato+12; Teyssier+13; +++

(low mass)

Feedback from SNe and AGN

(high-mass)

Peirani+08,19; Duffy+10, Dubois+10; +++

Feedback from SNe + (reioni.)

Zolotov+12; Wetzel+16; Garrison-Kimmel+19

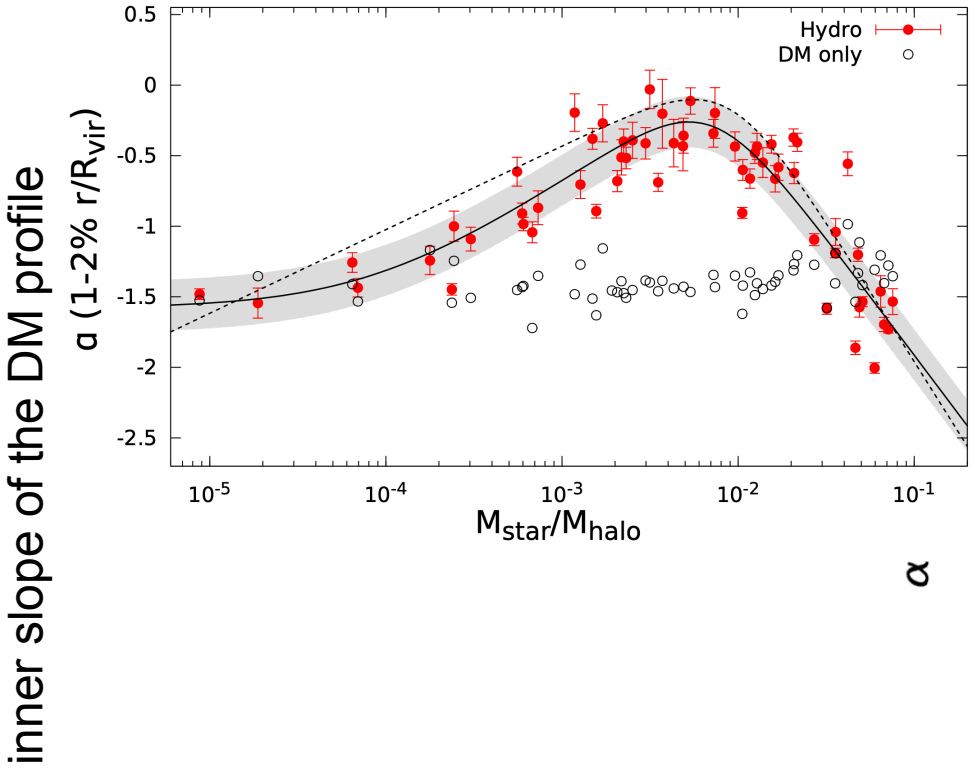
Feedback from SNe

Zolotov+12; Dutton+16; Wetzel+16; Garrison-Kimmel+19

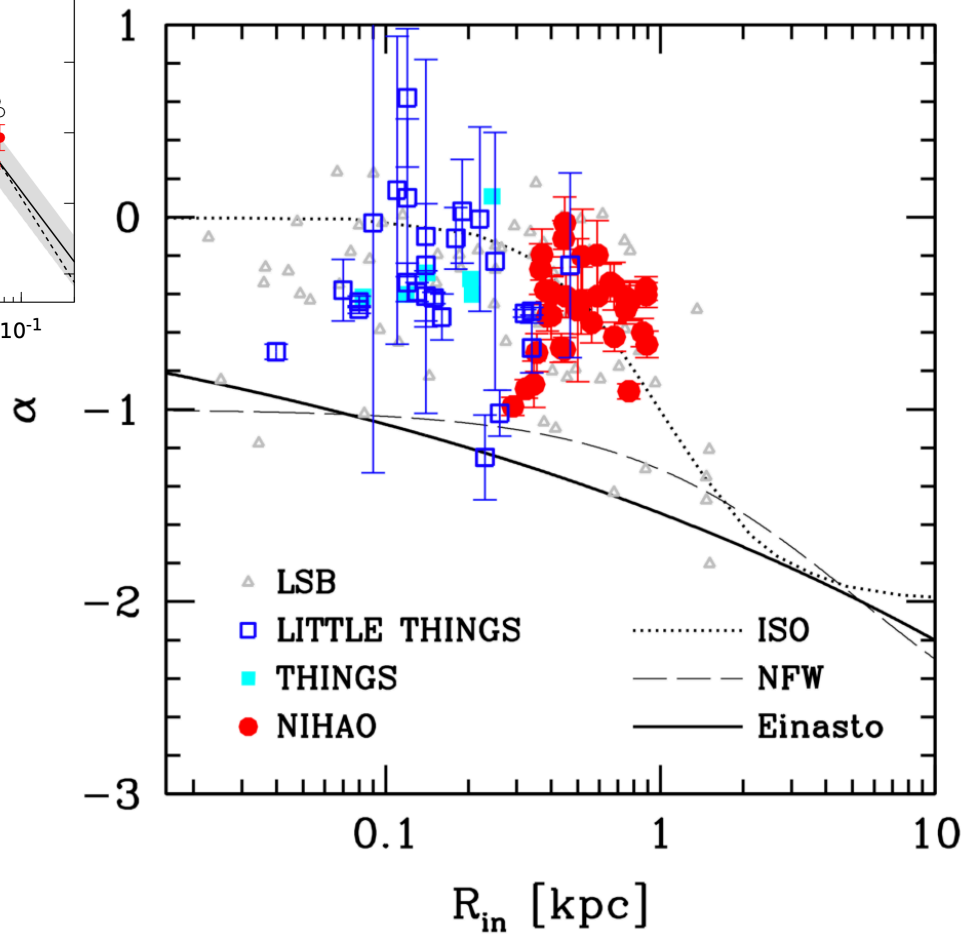
Feedback is first and foremost required to solve the « cooling catastrophe » + ample direct observational evidence of feedback: galactic winds, AGN jets and cavities, etc.

« Non-cold » dark matter does little to the cooling catastrophe issue: gas will still cool on time scales << Hubble time.

Baryons doing their baryonic stuff: The cusp-core (LCDM+Feedback)

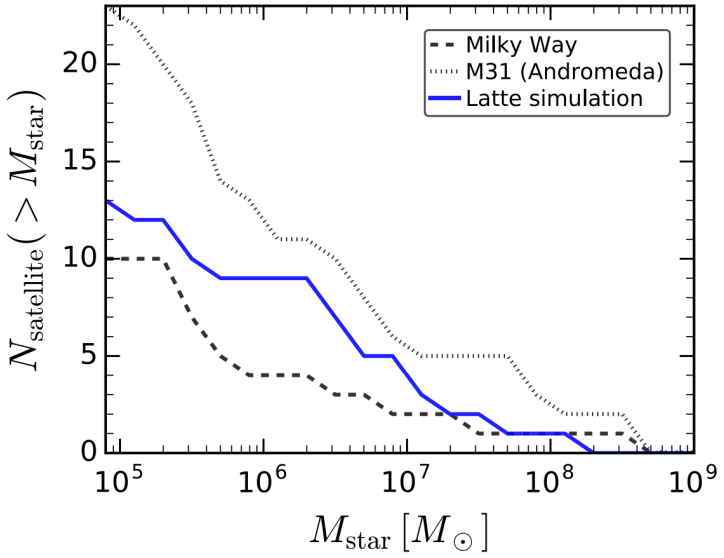


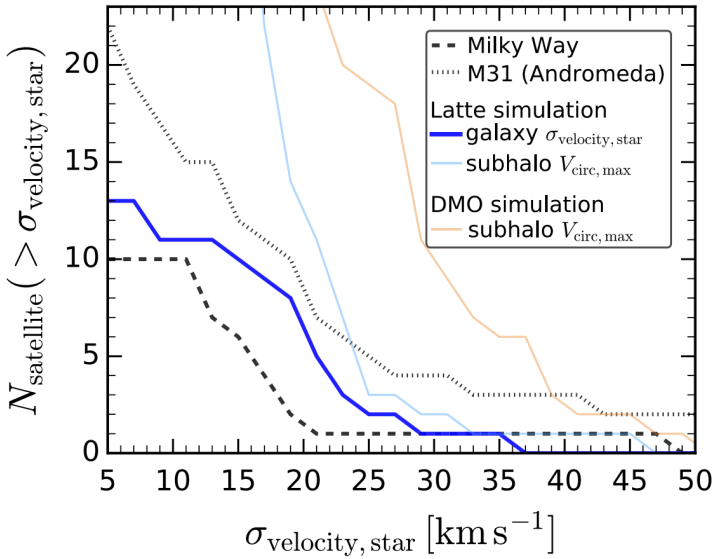
Tollet+16

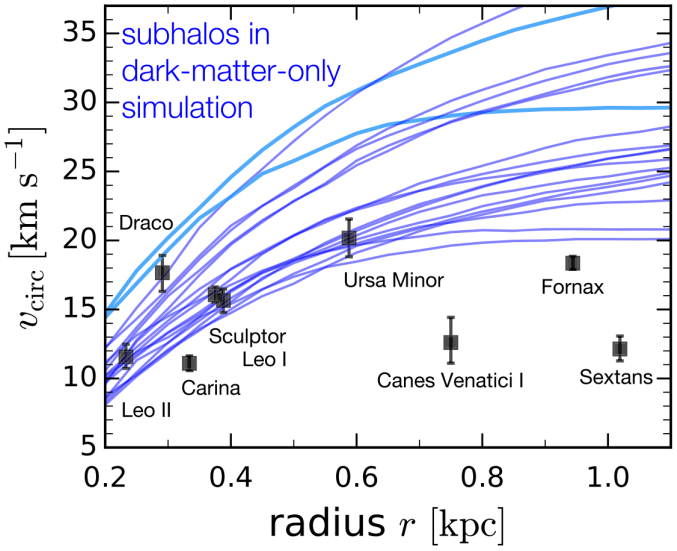


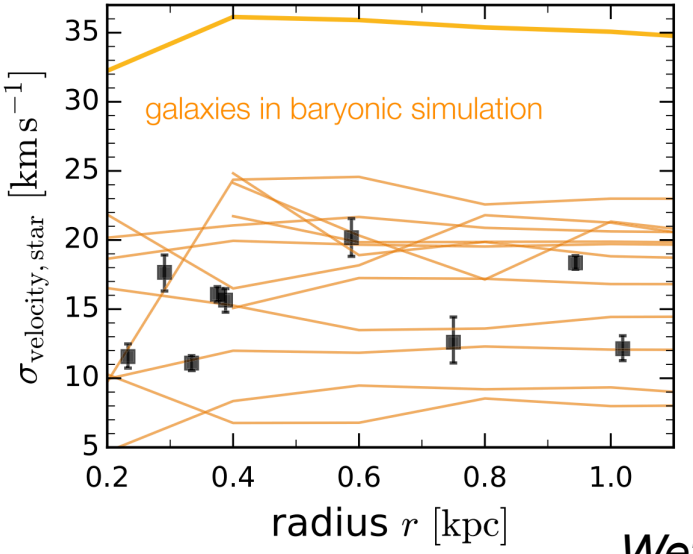
Baryons doing their baryonic stuff: Missing satellites & Too-big-to-fail

(LCDM+Feedback)



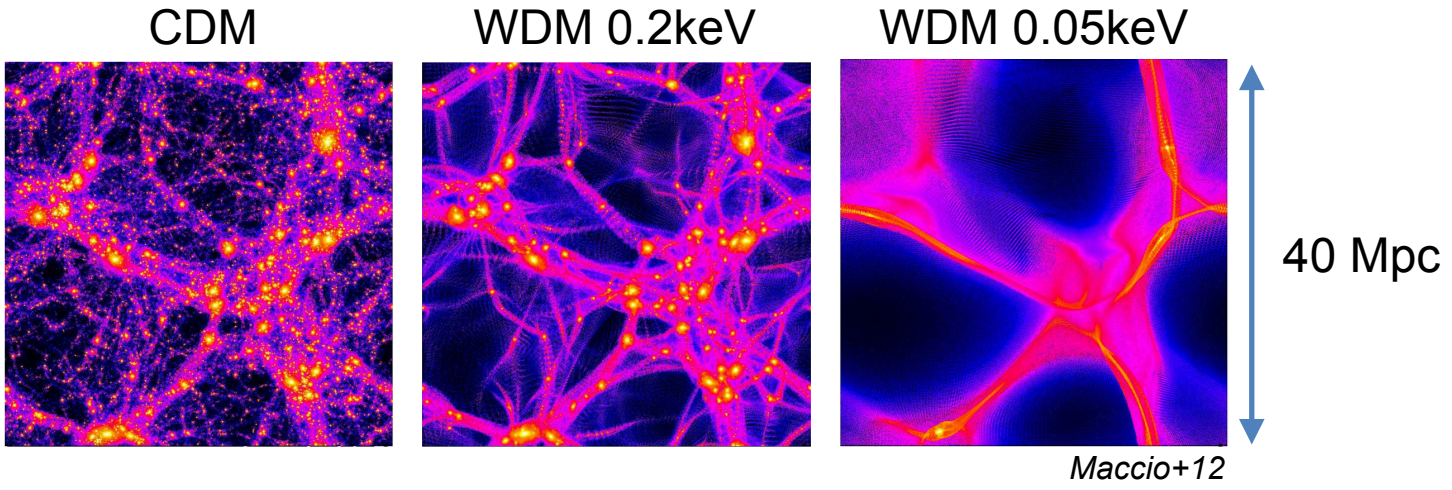




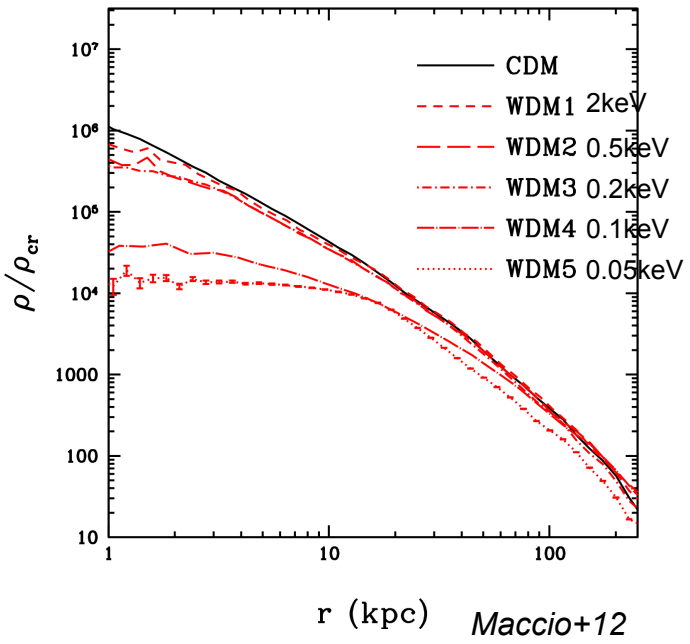


Wetzel+16

WDM DM-only



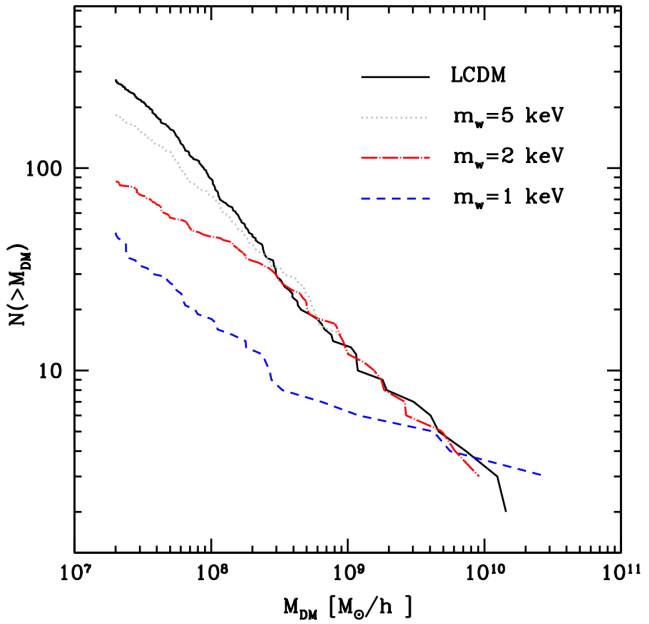
Maccio+12



Maccio+12

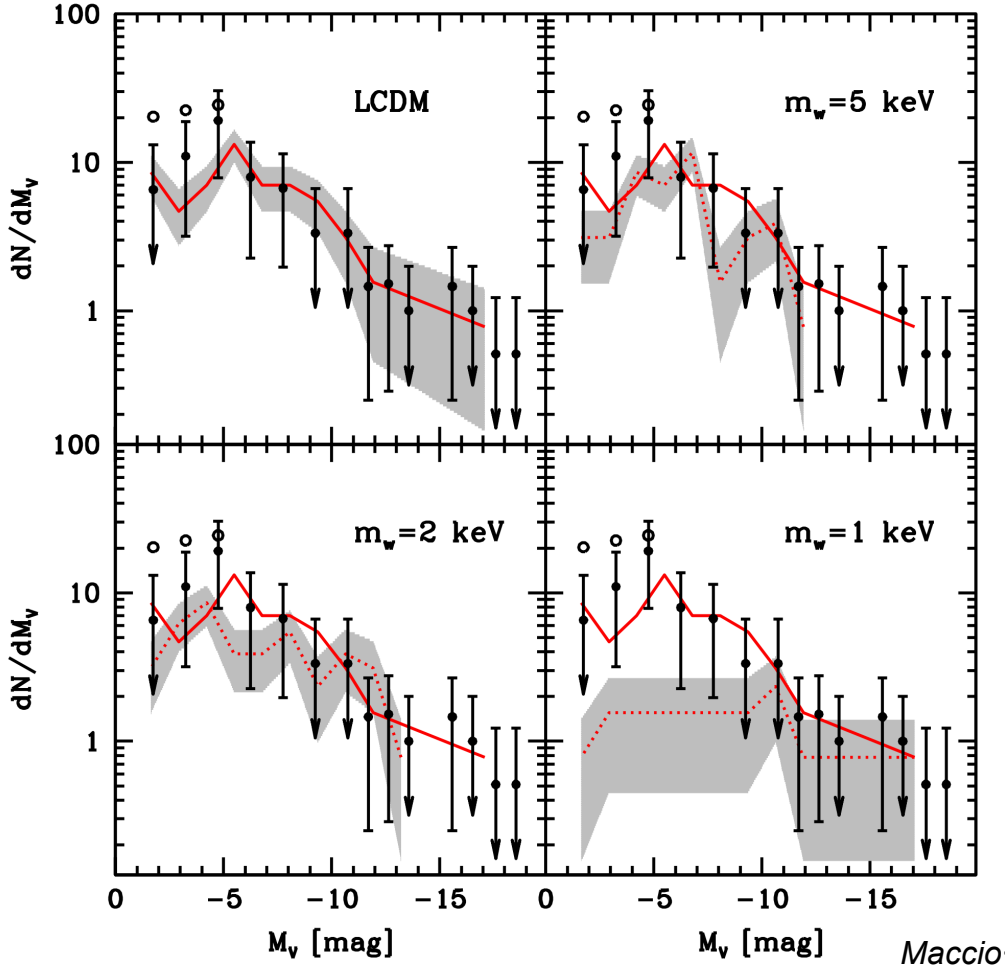
Ruled out by Ly-α forest and BAO obs. (Viel+08; Palanque-Delabrouille+20) m_W>1-5keV

Maccio+10



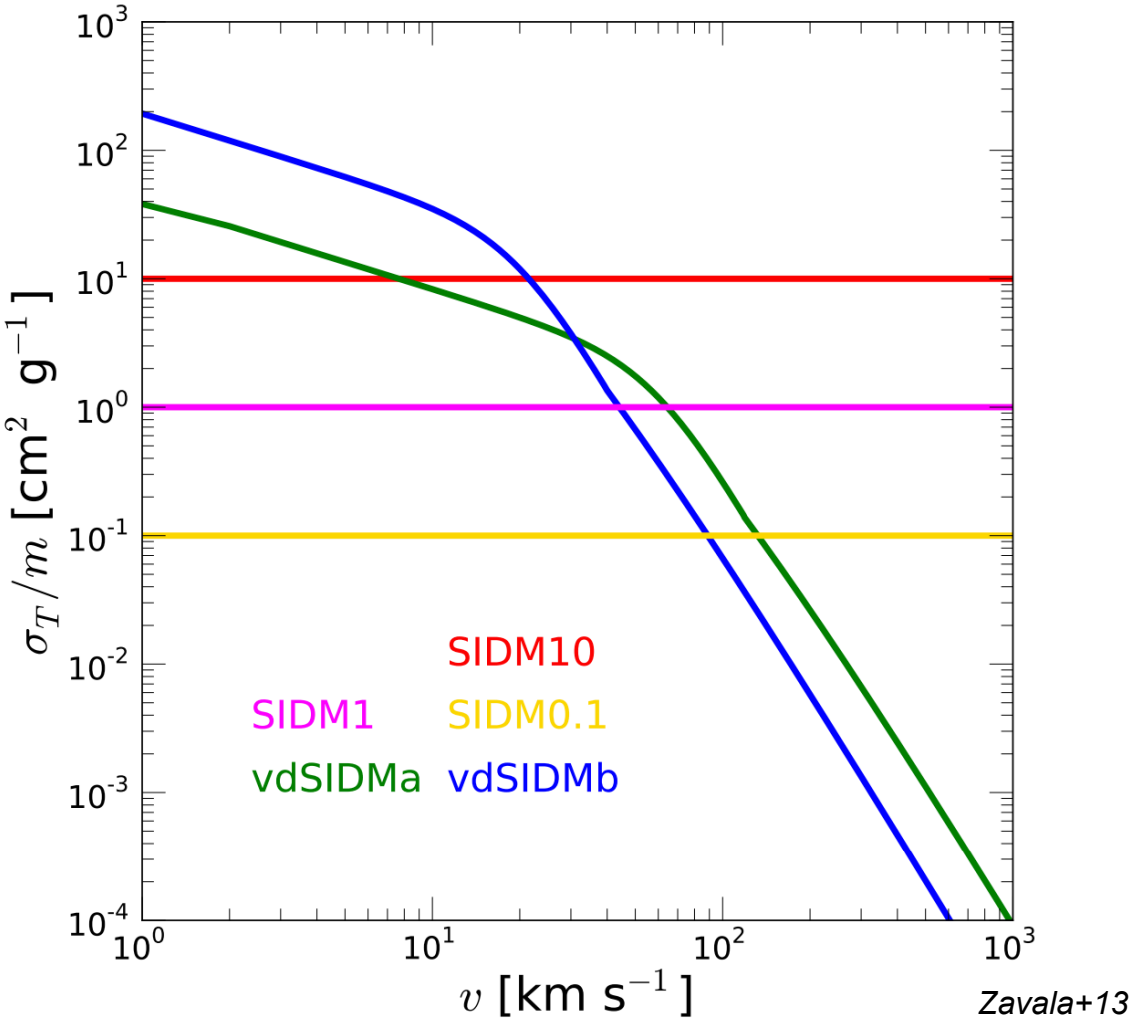
WDM DM-only

N-Body + semi-analytical model for galaxies (not hydro)



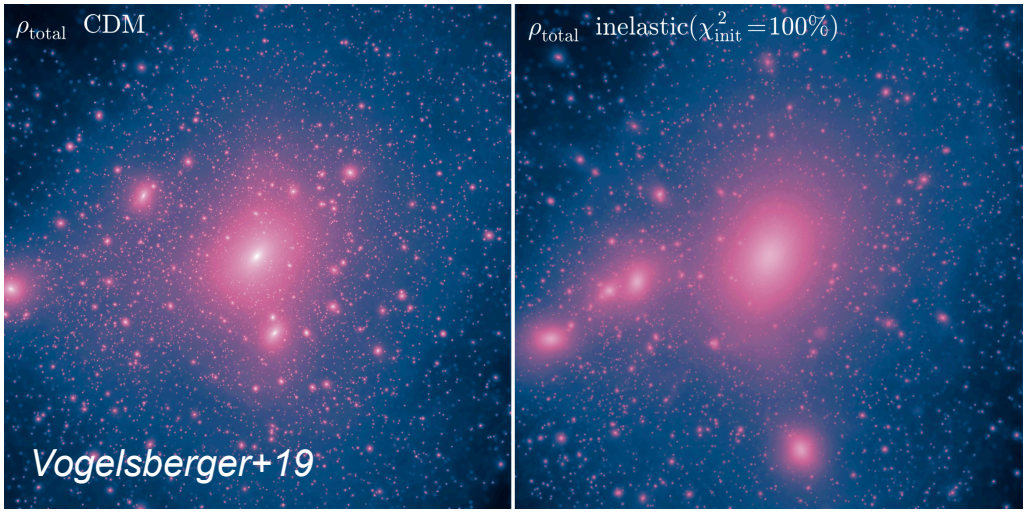
Maccio+10

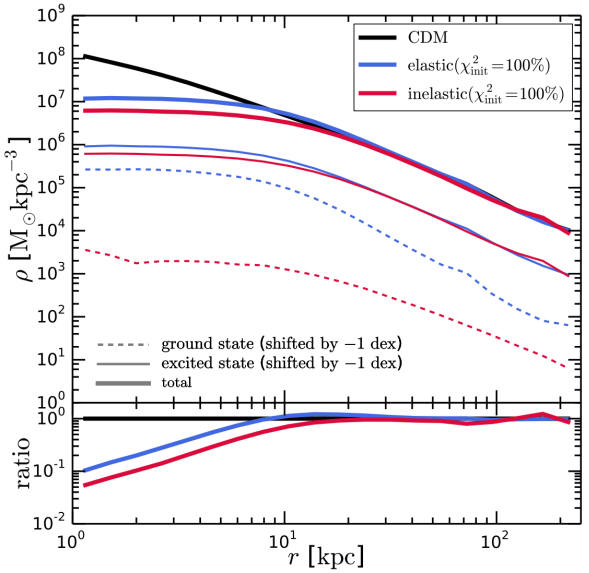
SIDM DM-only

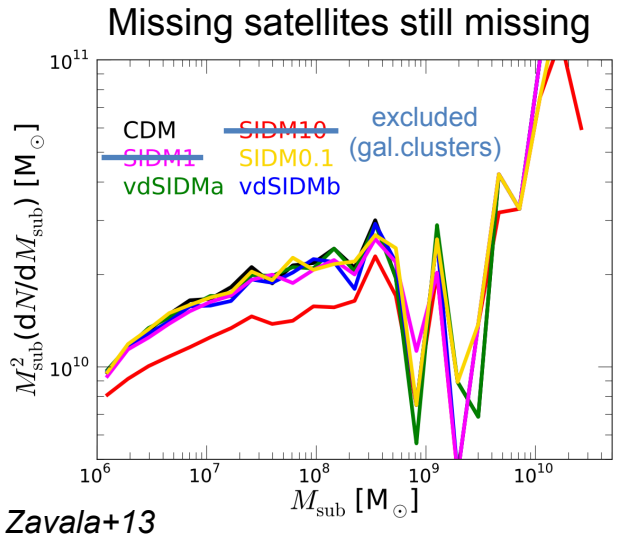


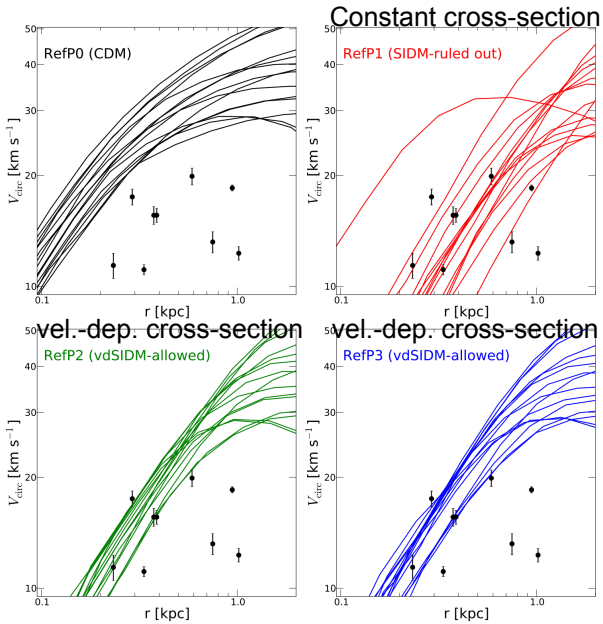
Zavala+13

SIDM DM-only


$\rho_{\rm total}$ CDM
$\rho_{\rm total}$ inelastic($\chi^2_{\rm init}$=100%)
Vogelsberger+19

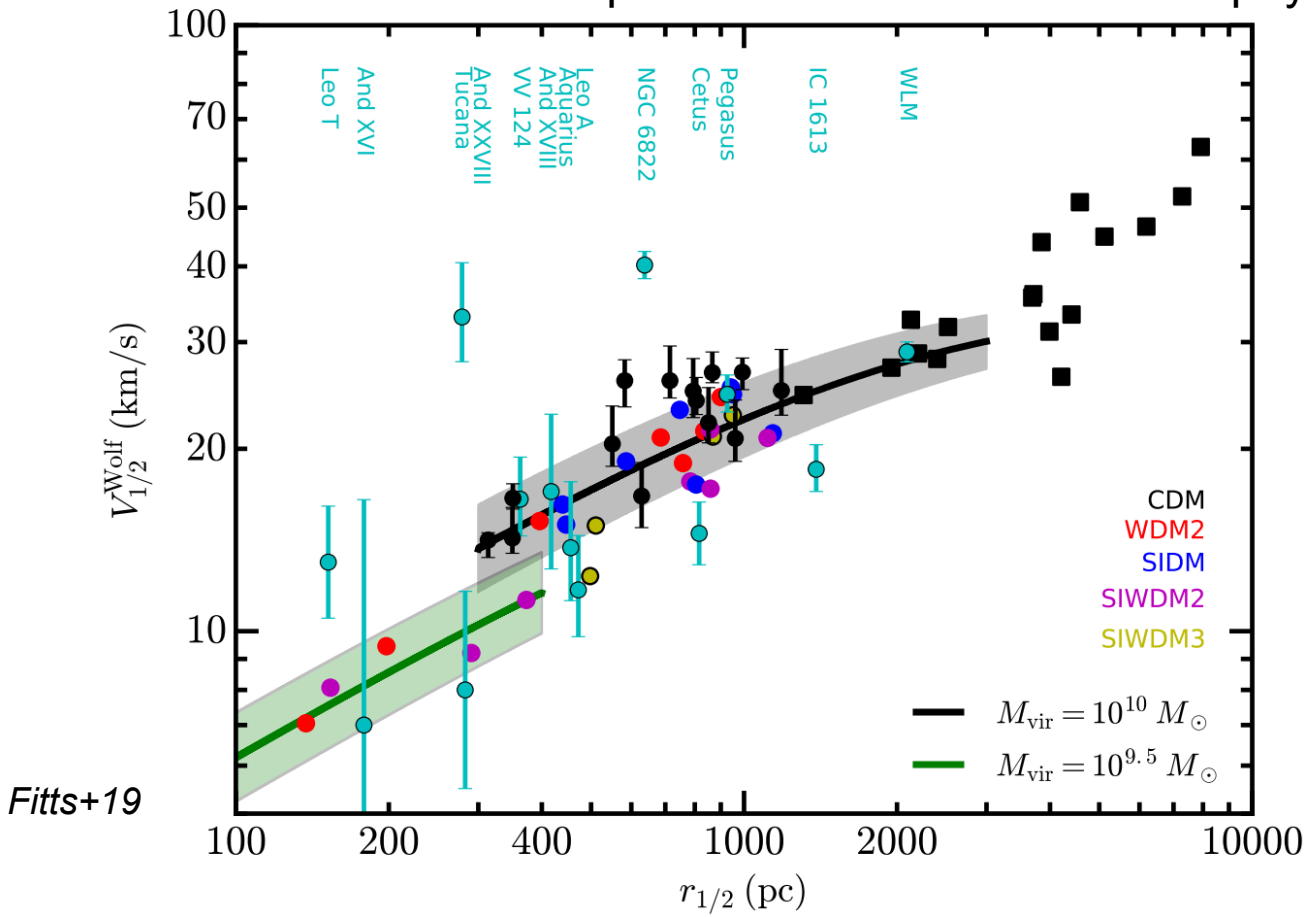

CDM
elastic($\chi^2_{\rm init}$=100%)
inelastic($\chi^2_{\rm init}$=100%)
ground state (shifted by −1 dex)
excited state (shifted by −1 dex)
total
ρ [M$_\odot$kpc^{-3}]
ratio
r [kpc]


Missing satellites still missing
CDM
SIDM10
SIDM1
SIDM0.1
excluded
(gal.clusters)
vdSIDMa
vdSIDMb
$M^2_{\rm sub}$(dN/d$M_{\rm sub}$) [M$_\odot$]
$M_{\rm sub}$ [M$_\odot$]
Zavala+13


Constant cross-section
RefP0 (CDM)
RefP1 (SIDM-ruled out)
vel.-dep. cross-section
vel.-dep. cross-section
RefP2 (vdSIDM-allowed)
RefP3 (vdSIDM-allowed)
$V_{\rm circ}$ [km s^{-1}]
r [kpc]
Vogelsberger+12

SIDM + Feedback

No clear signature of DM models:
Feedback is much more important than subtleties in DM physics?



Fitts+19

See also: Vogelsberger+14; Despali+19; Vargya+21; Shen+21

Summary

- Upcoming large-scale structure surveys probe both the cosmological nature of the Universe **and** the galactic baryonic physics
- Clustering properties of large-scale structures are affected by galactic outflows
- Outflows are a key but not-so-well constrained process of galaxy evolution
- Cosmic filaments have a significant footprint on galaxy alignements (and other galaxy properties), which again depends on the physics of feedback
- Other proxies/signatures of feedback should be used to constrain their effect on the main cosmological probes