Galaxy formation with large-scale hydrodynamical cosmological simulations

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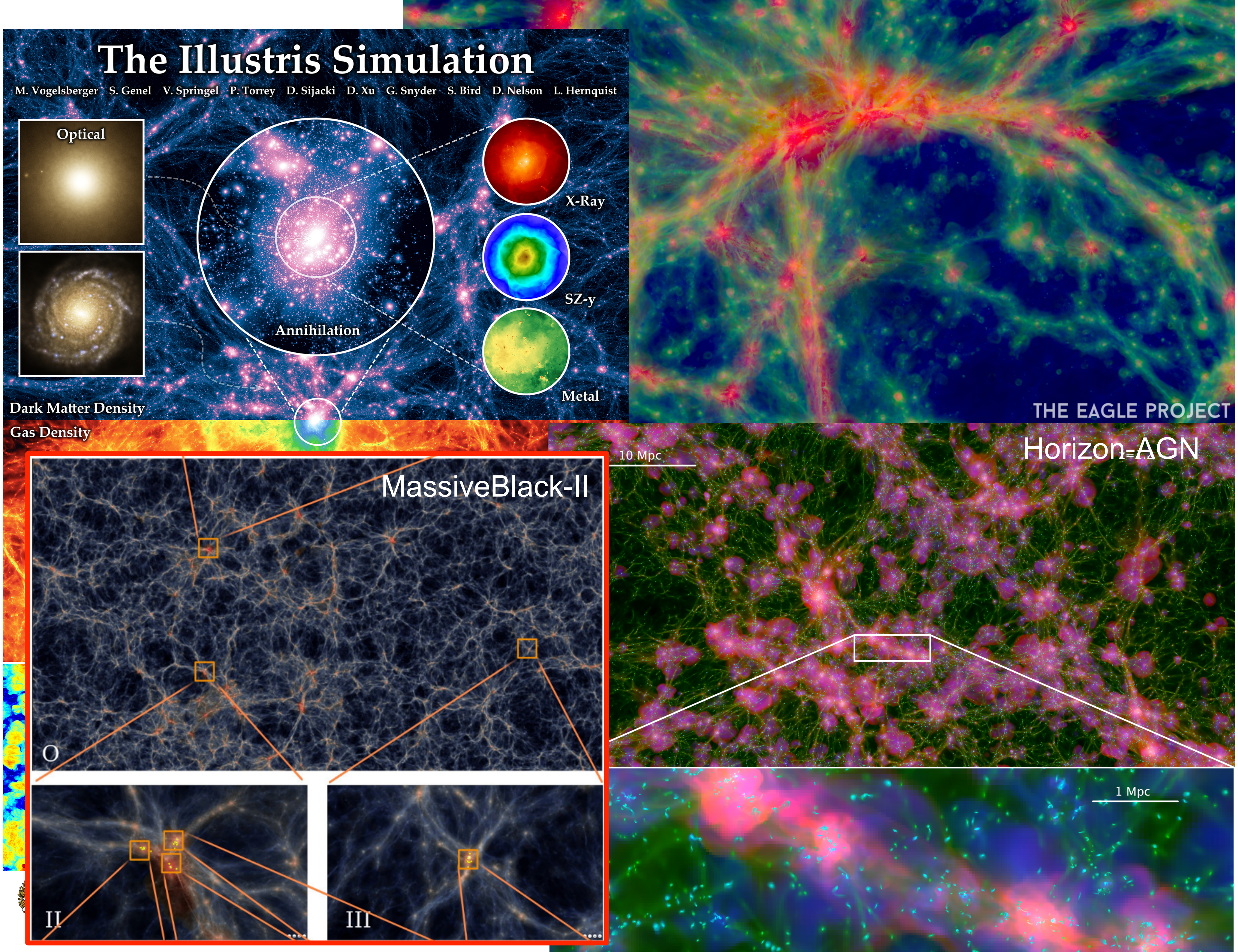
Ricarda Beckmann, Karim Benabed, Elisa Chisari, Hoseung Choi, Sandrine Codis, Julien Devriendt, Raphaël Gavazzi, Céline Gouin, Sugata Kaviraj, Taysun Kimm, Katarina Kraljic, Clotilde Laigle, Garreth Martin, Jongwon Park, Minjung Park, Sébastien Peirani, Christophe Pichon, Mark Richardson, Marta Volonteri, Charlotte Welker, Sukyoung Yi

Horizon-AGN simulation
http://horizon-simulation.org

25 Mpc/h

z=0


The Illustris Simulation
M. Vogelsberger 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
Dark Matter Density
Gas Density
THE EAGLE PROJECT
Horizon-AGN
10 Mpc
1 Mpc
MassiveBlack-II
O
II
III

The numerical challenge

Illustris : L_{box}=100 Mpc, 6.0x10^9 gas cells, dx~1 kpc, Moving Mesh (Arepo)
Vogelsberger et al (2014)

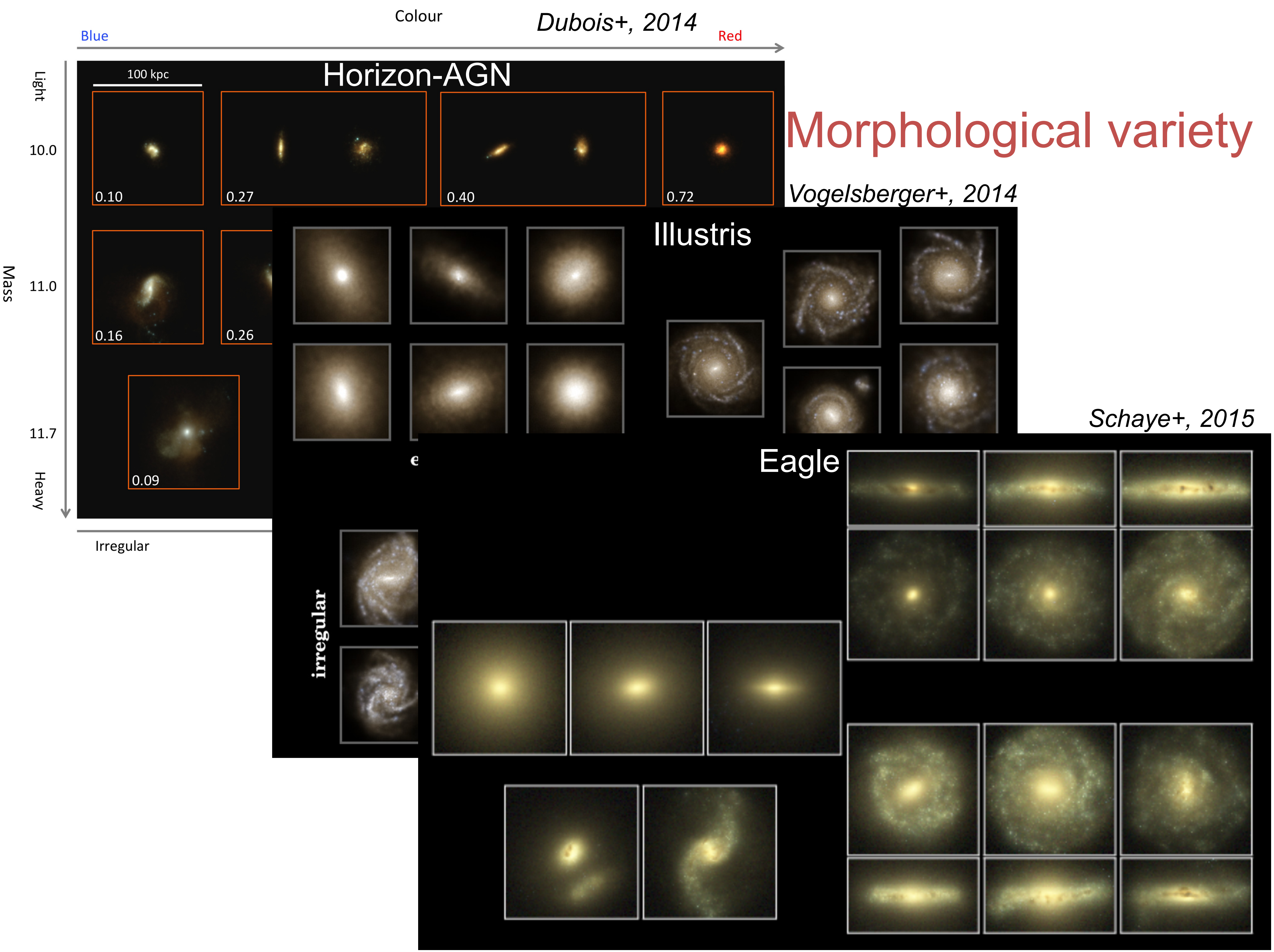
Eagle : L_{box}=100 Mpc, 3.5x10^9 gas particles, dx~1 kpc, SPH (Gadget)
Schaye et al (2015)

MassiveBlack-II: L_{box}=140 Mpc, 5.8x10^9 gas particles, dx~2 kpc, SPH (Gadget)
Tenneti et al (2014)

Horizon-AGN : L_{box}=140 Mpc, 7.0x10^9 gas cells, dx~1 kpc, AMR (Ramses)
Dubois et al (2014) (10 CPU Mh)

IllustrisTNG : L_{box}=100 Mpc, 6.0x10^9 gas cells, dx~1 kpc (18 CPU Mh)
L_{box}=300 Mpc, 1.5x10^10 gas cells, dx~1.5 kpc (35 CPU Mh)
Pillepich et al (2018)

Morphological variety

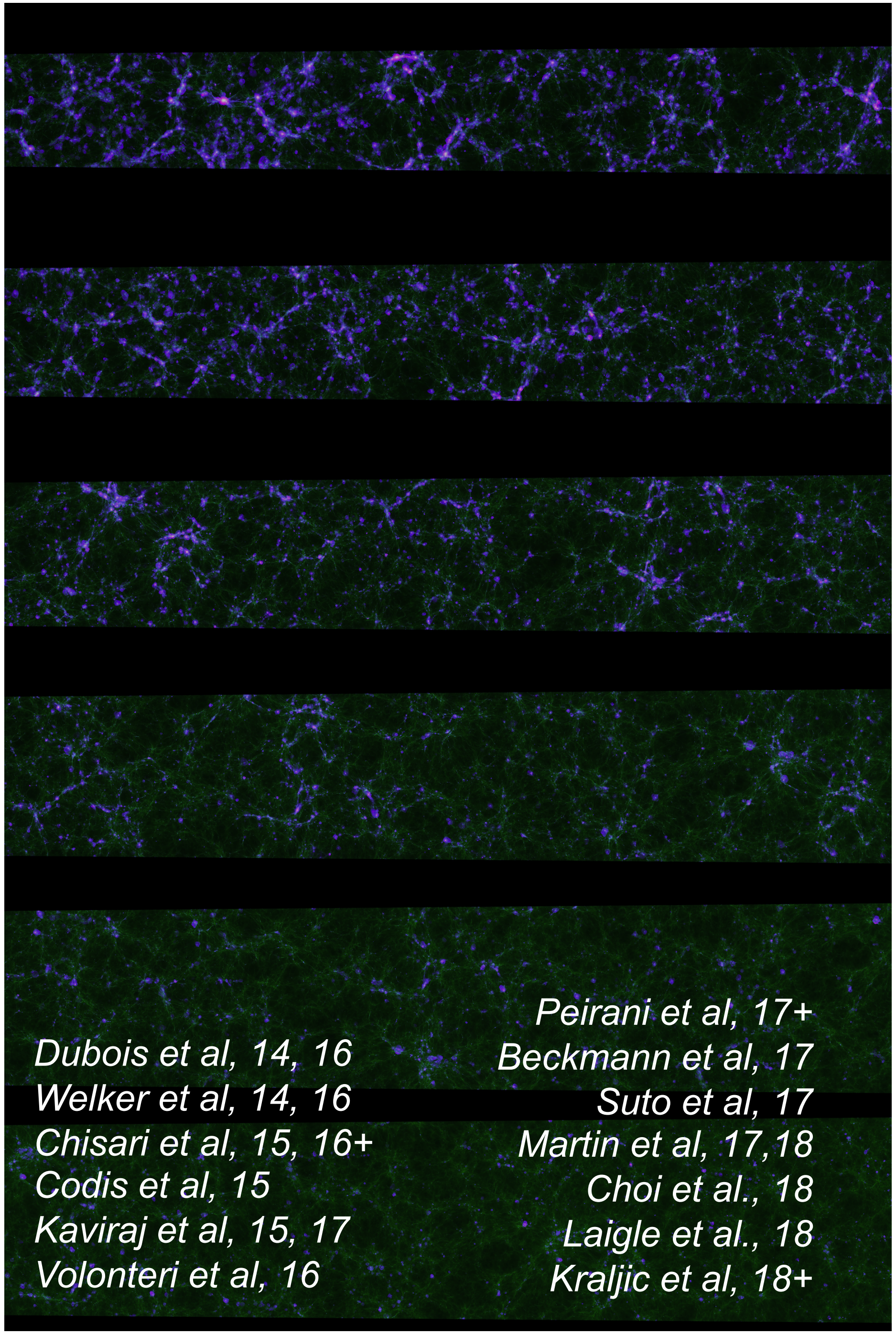



Without AGN: massive blue spirals are everywhere!

The Horizon-AGN simulation

- Simulation content
  - Run with Ramses (AMR) *Teyssier (02)*
  - L_{box}=100 Mpc/h
  - 1024^3 DM particles $M_{DM,res}=8x10^7\ M_{sun}$
  - Finest cell resolution dx=1 kpc
  - Gas cooling & UV background heating
  - Low efficiency star formation
  - Stellar winds + SNII + SNIa
  - O, Fe, C, N, Si, Mg, H
  - AGN feedback radio/quasar *(Dubois+, 12)*
- Outputs
  - Standard outputs ~200 Myrs (100 TB)
  - Star particles stored every 10-20 Myr (30TB)
  - Lightcones (1°x1°) performed on-the-fly (15TB)
    - Dark Matter (position, velocity)
    - Gas (position, density, velocity, pressure, chemistry)
    - Stars (position, mass, velocity, age, chemistry)
    - Black holes (position, mass, velocity, accretion rate)
- z=0 using 10 Mhours on 4096 cores at Occigen (CINES) on 2 GENCI grants (2013-2014)
- 150 000 galaxies per snapshot (> 50 part.)
- 7.10^9 leaf cells (more than Illustris or Eagle)

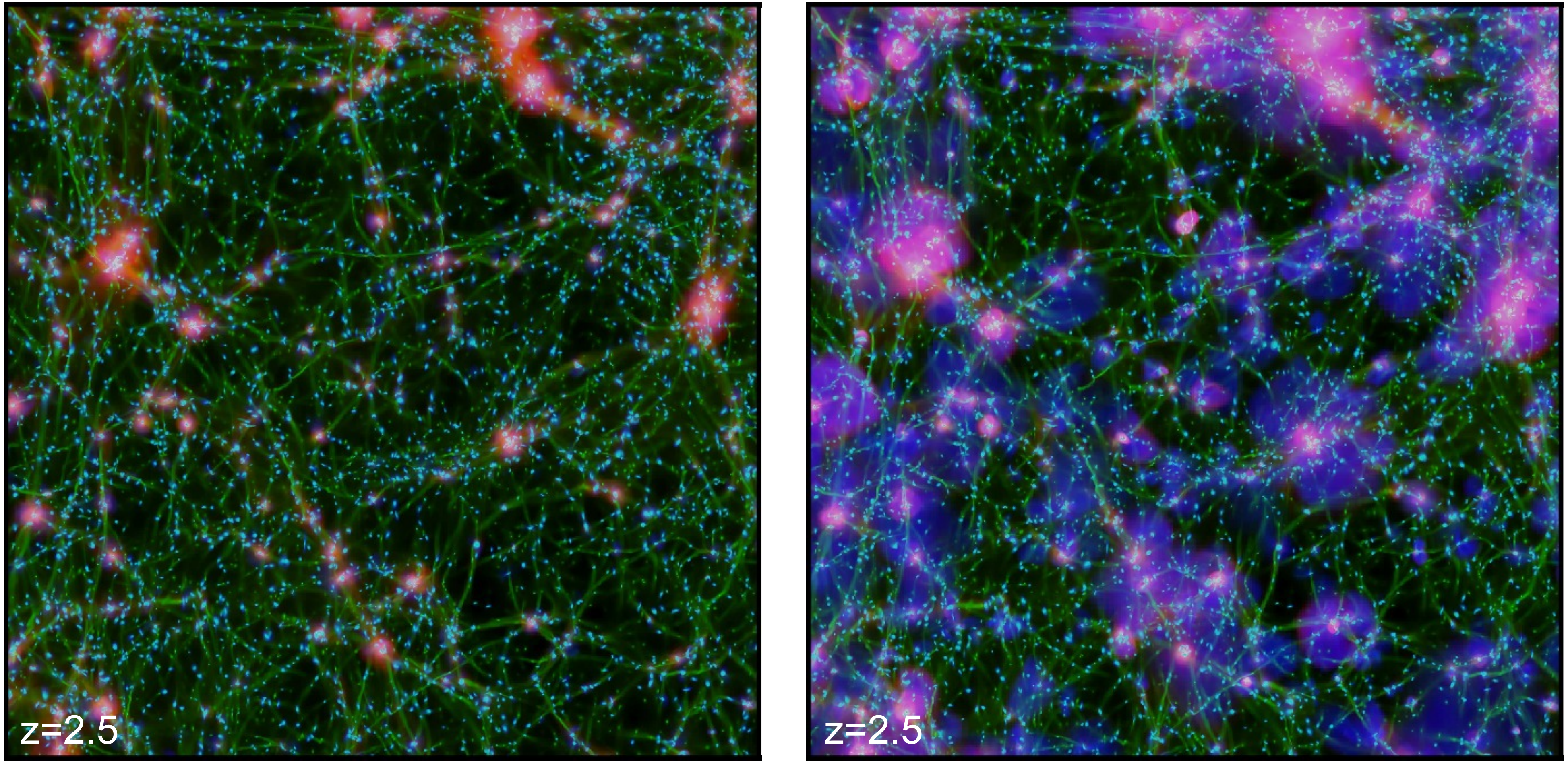
http://horizon-simulation.org/



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

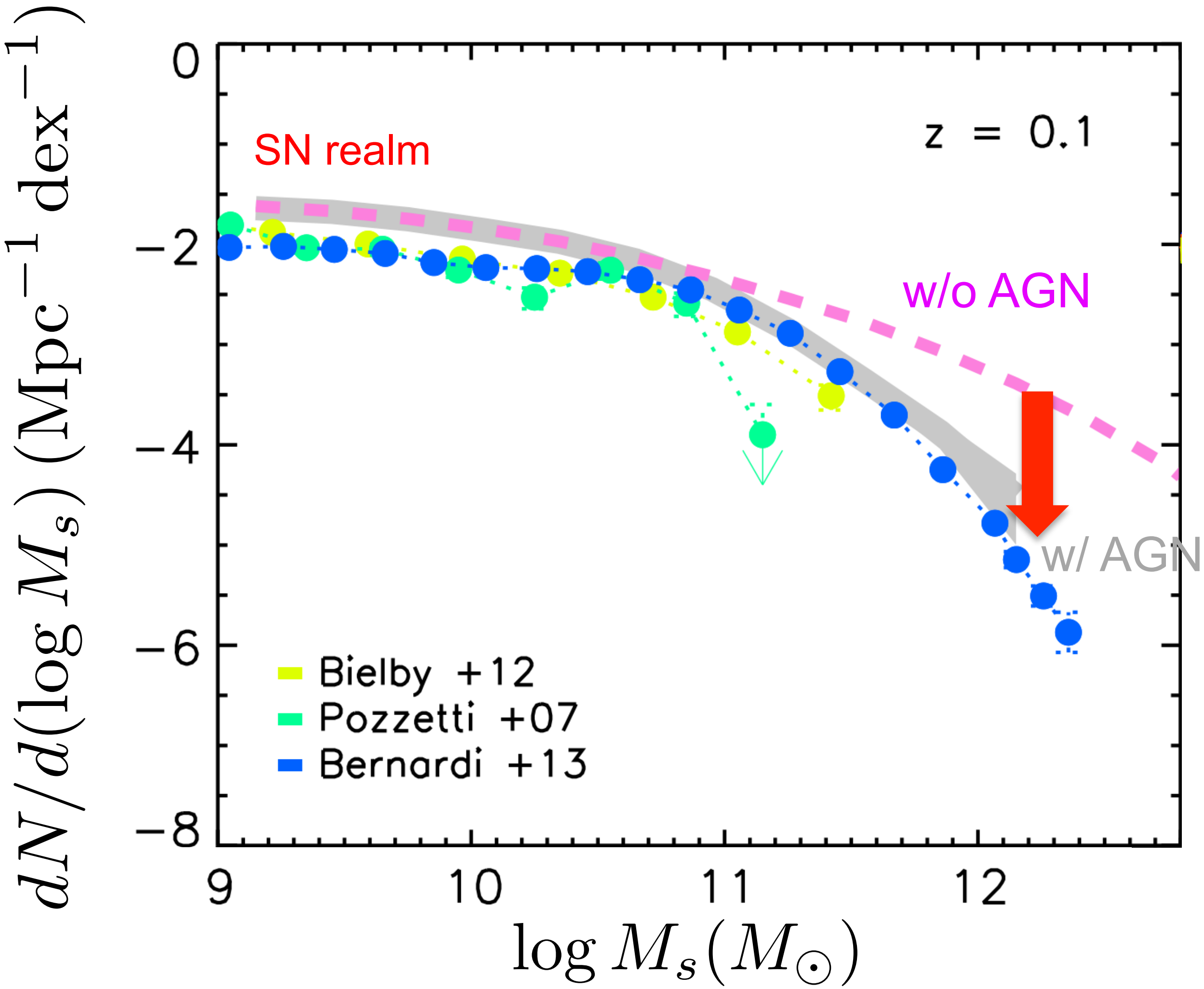
Green: gas density / Red: temperature / Blue: metallicity

Horizon-noAGN Horizon-AGN

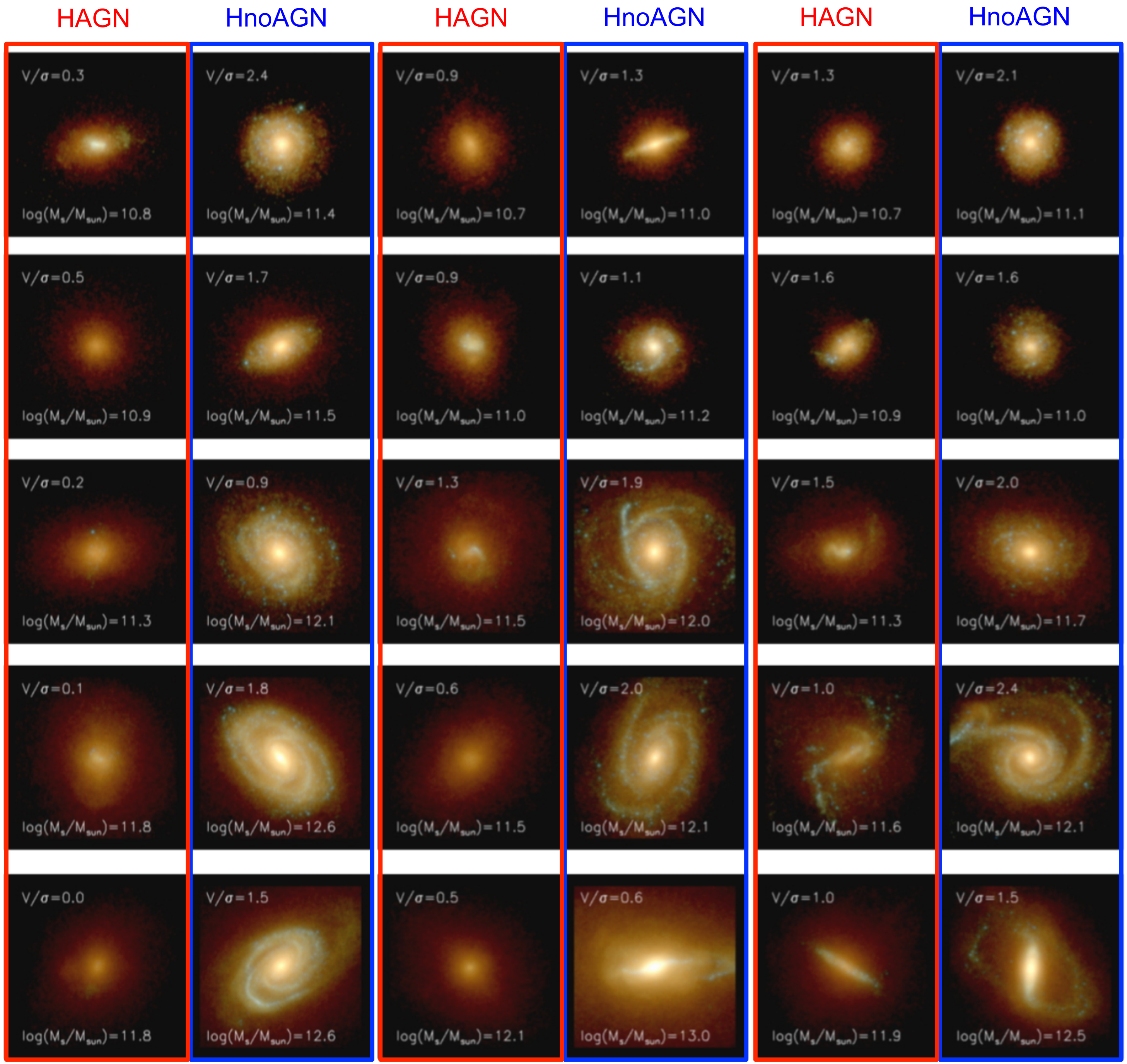


Motivation for AGN feedback

Galaxy mass functions in the Horizon-AGN project



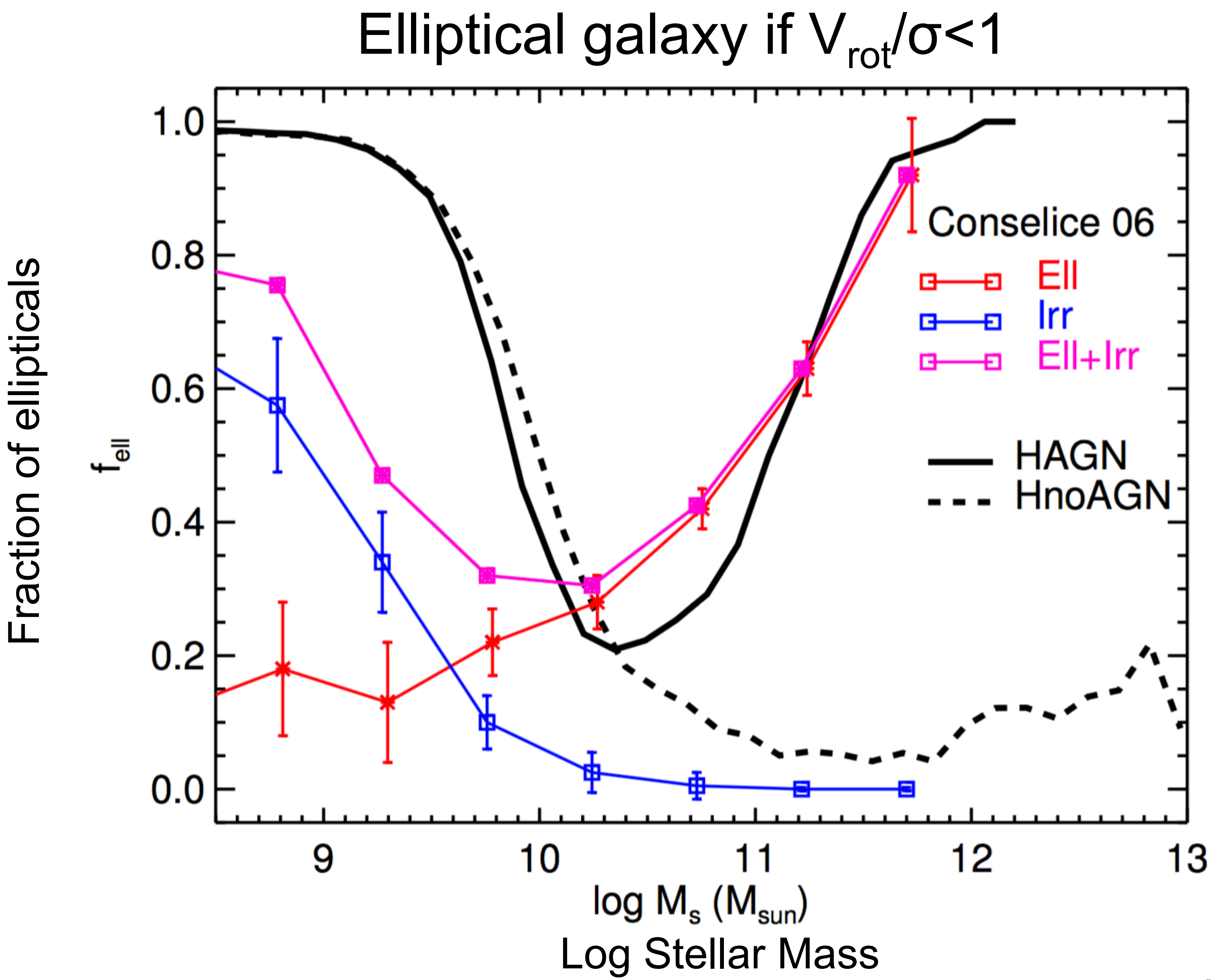
Kaviraj, Laigle et al, 2017



AGN feedback model:
- Bondi accretion rate
- Booth & Schaye 2009 boost
- Eddington limited
- Quasar (heating mode)
- Radio mode (biconical jet)

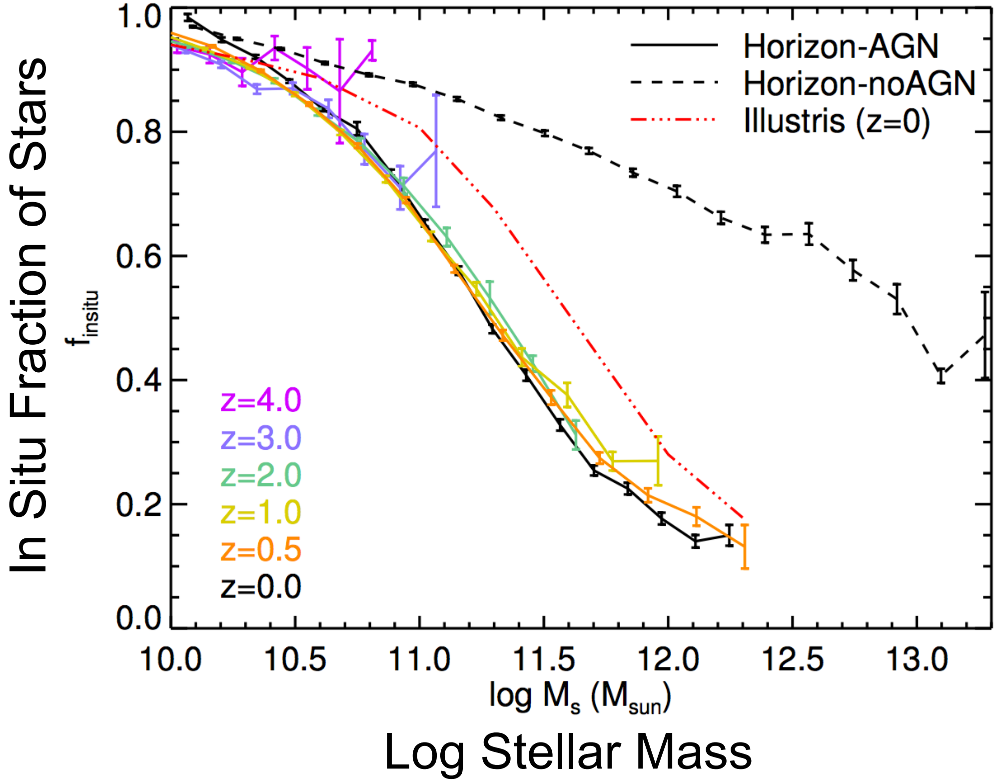
Dubois+ 2016

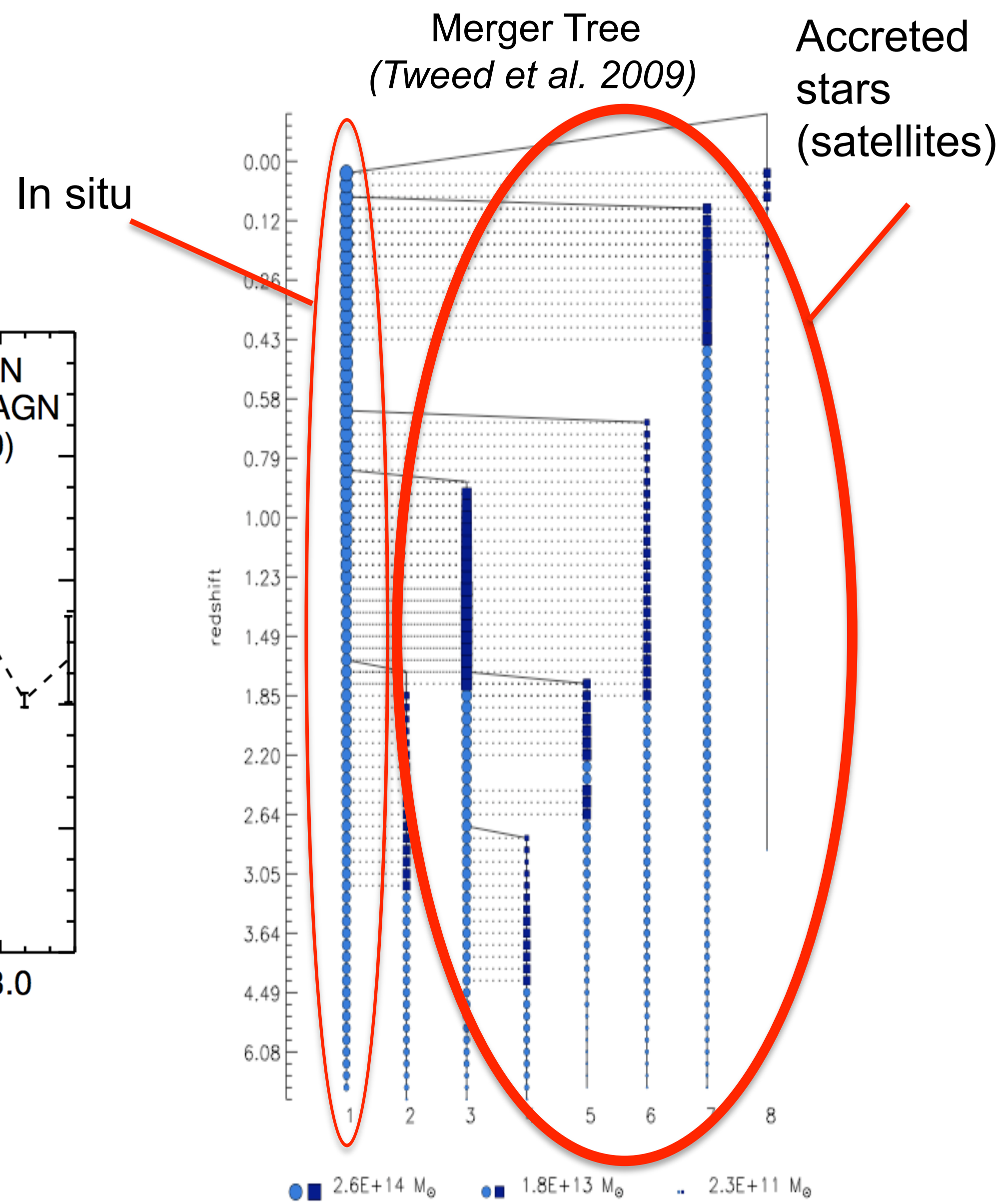
Fraction of Ellipticals



Dubois+ 2016

The origin of the stars

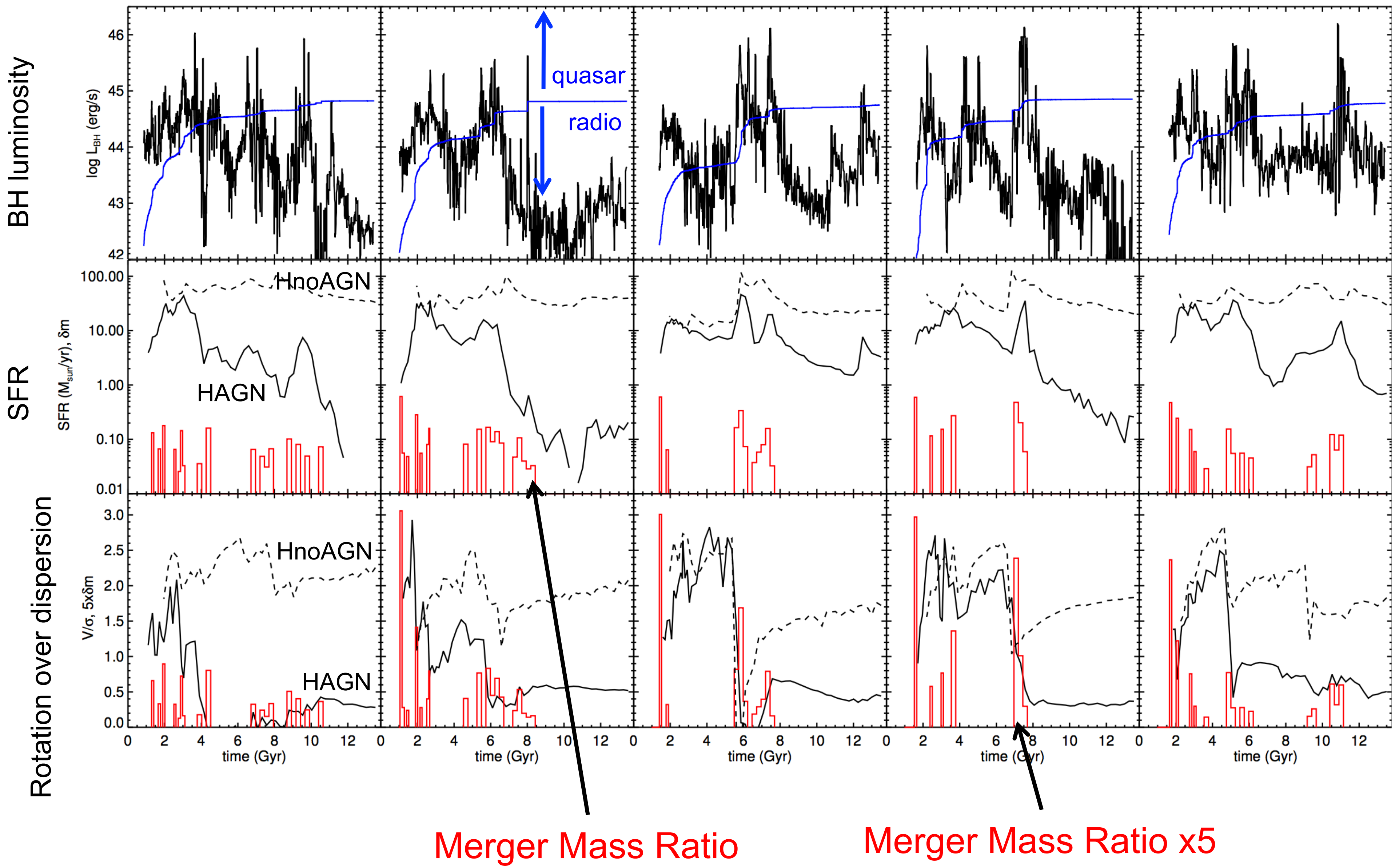




Dubois+ 2016
See also Oser+ 2010; Lackner+ 2012; Dubois+ 2013; Rodriguez-Gomez+ 2016
Lee & Yi, 2013 (SAM)

Dubois+ 2016

A few exemples of $2x10^{11}$ M_{sun} galaxies



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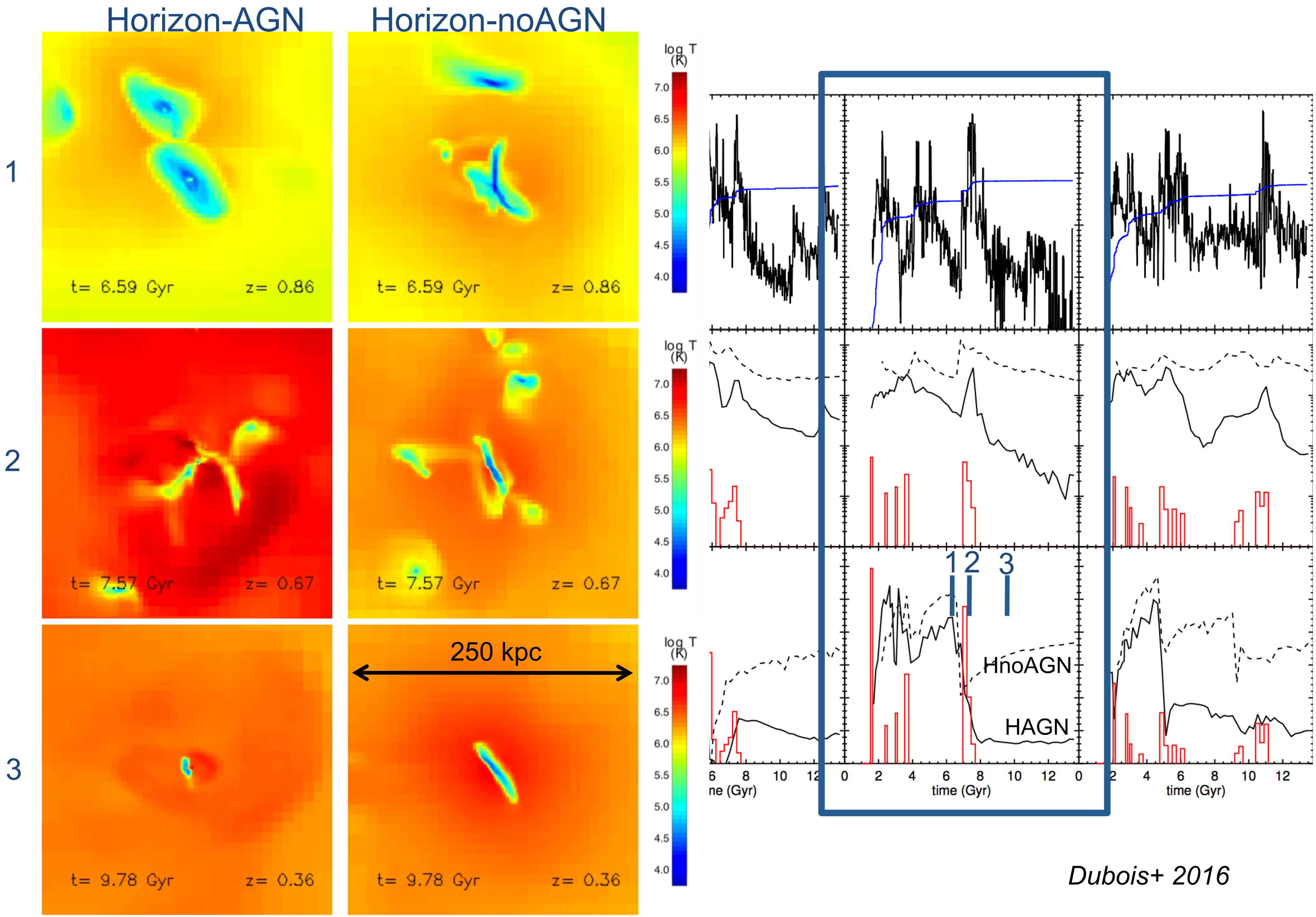
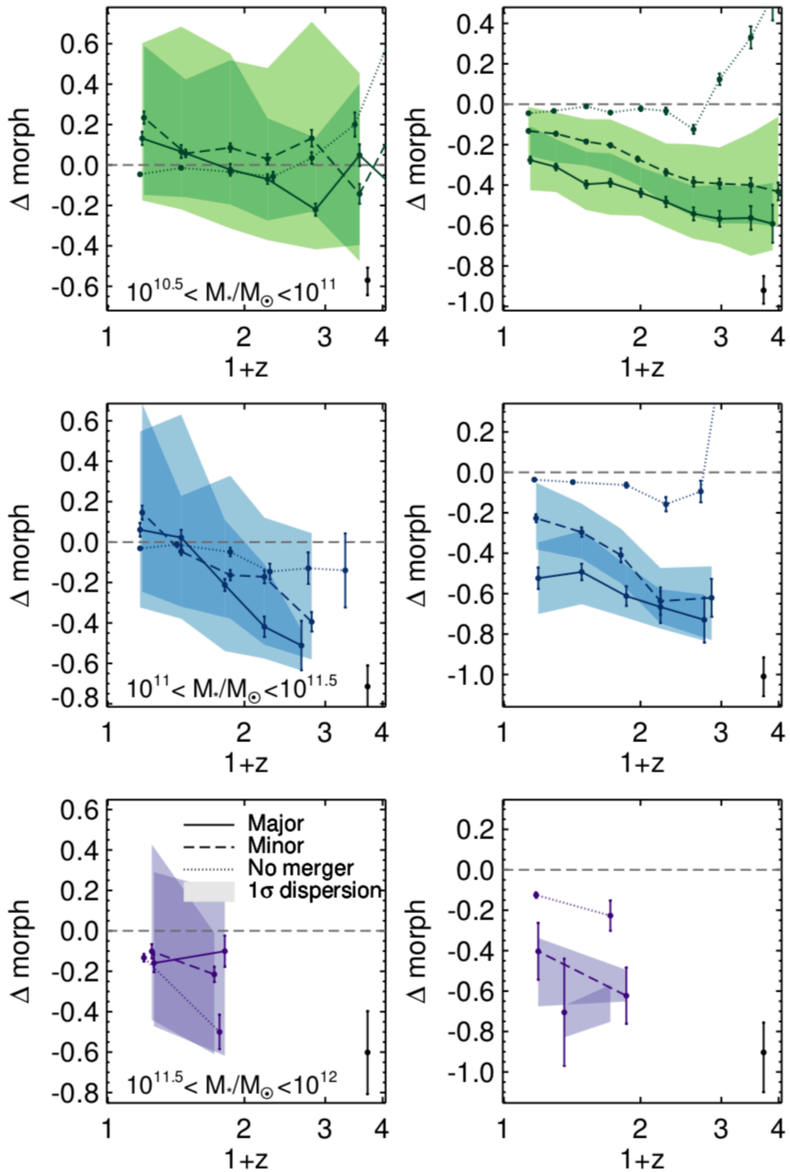


Dubois+ 2016

Galaxies are not equally affected by mergers

progenitor is: a spheroid a disc



Spheroid-like progenitors don't care much about mergers or smooth evolution. They tend to remain spheroids.

Disc-like progenitors enduring mergers more likely lead to spheroids

Martin+18

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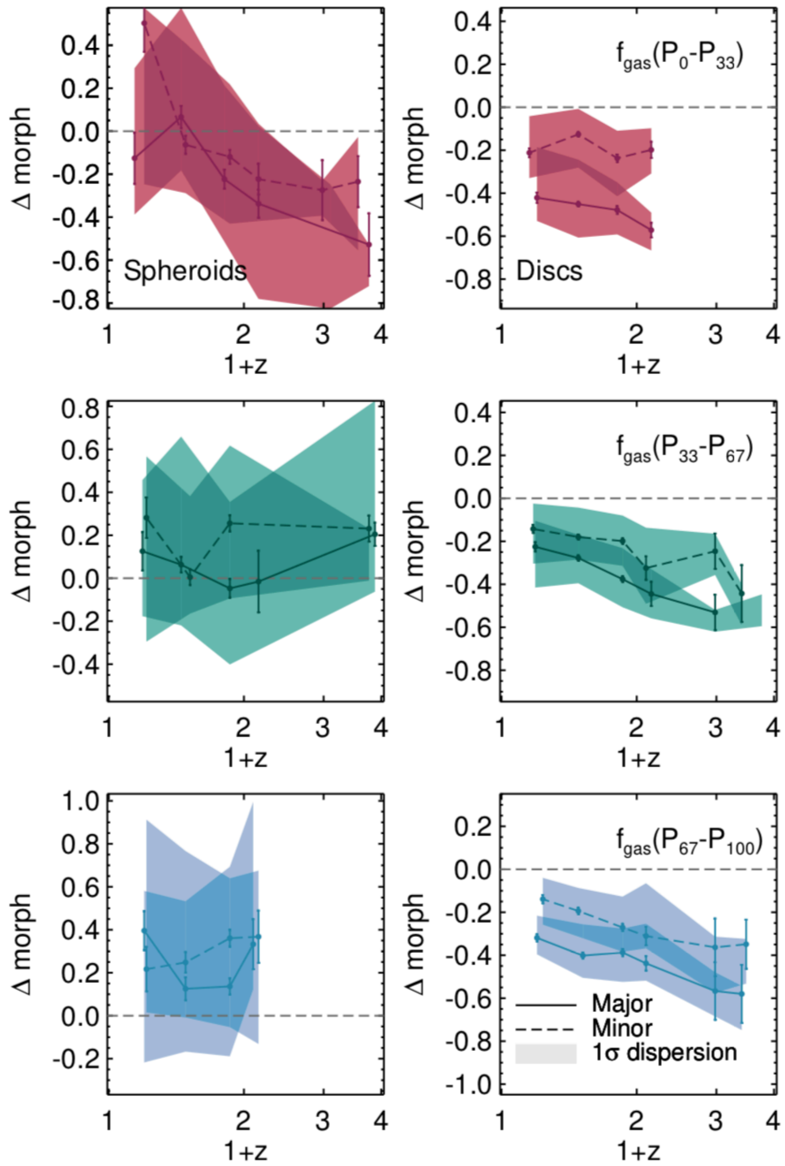


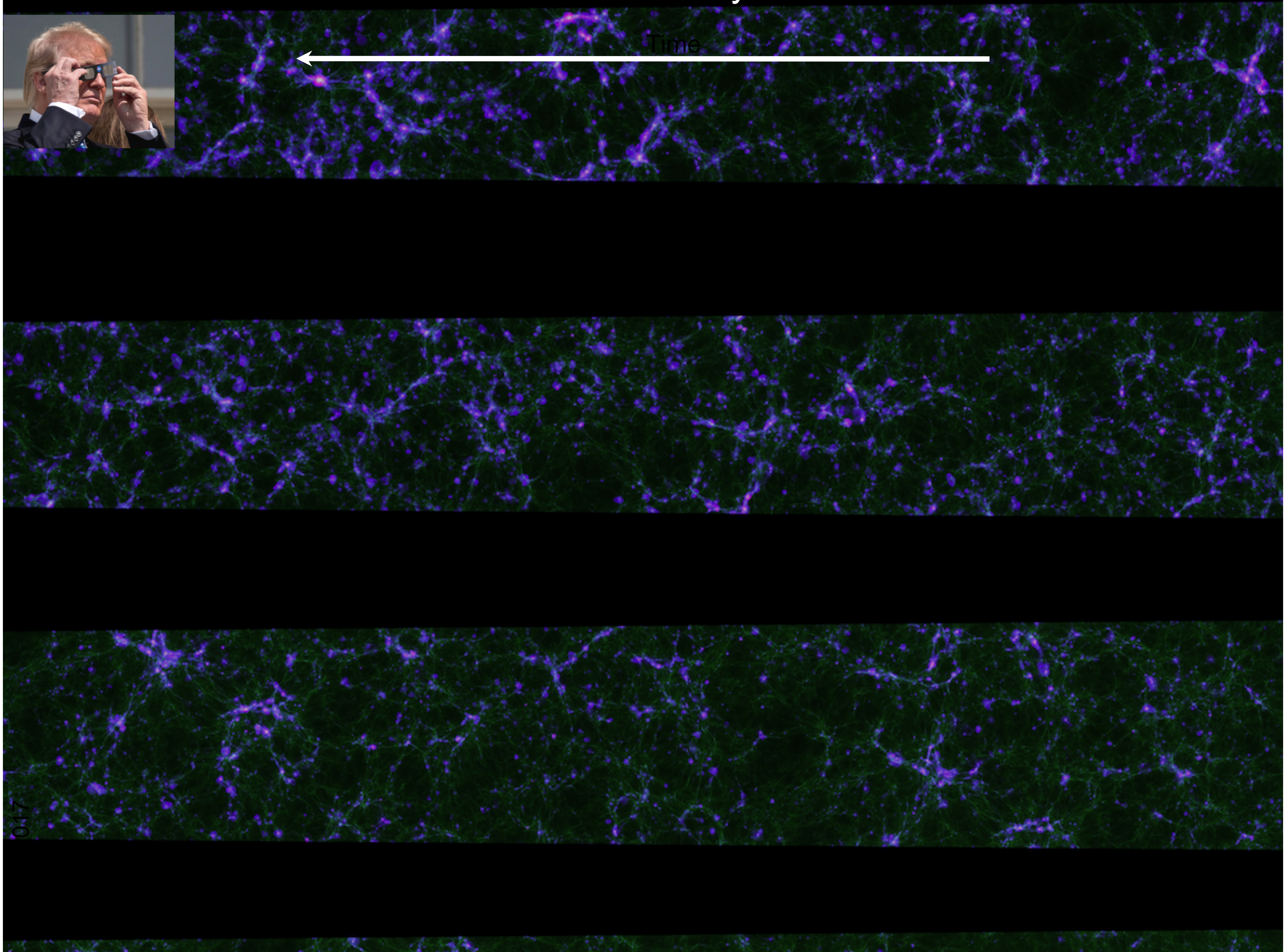
more gas rich

Spheroid-like progenitors stay spheroids for gas-poor mergers but rebuild their disc if gas-rich merger

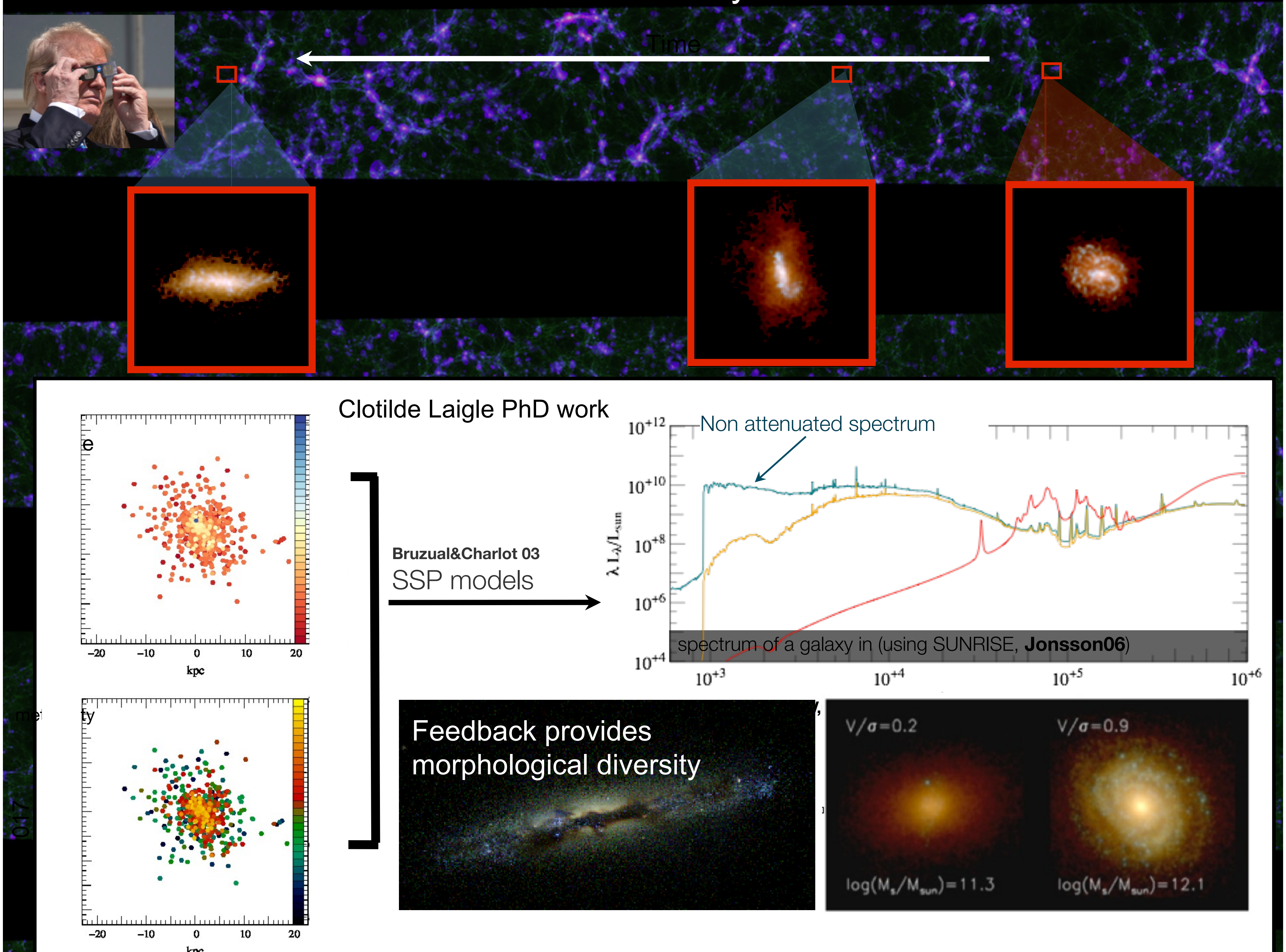
Disc-like progenitors turn more likely spheroids by mergers, whatever the gas richness

Martin+18

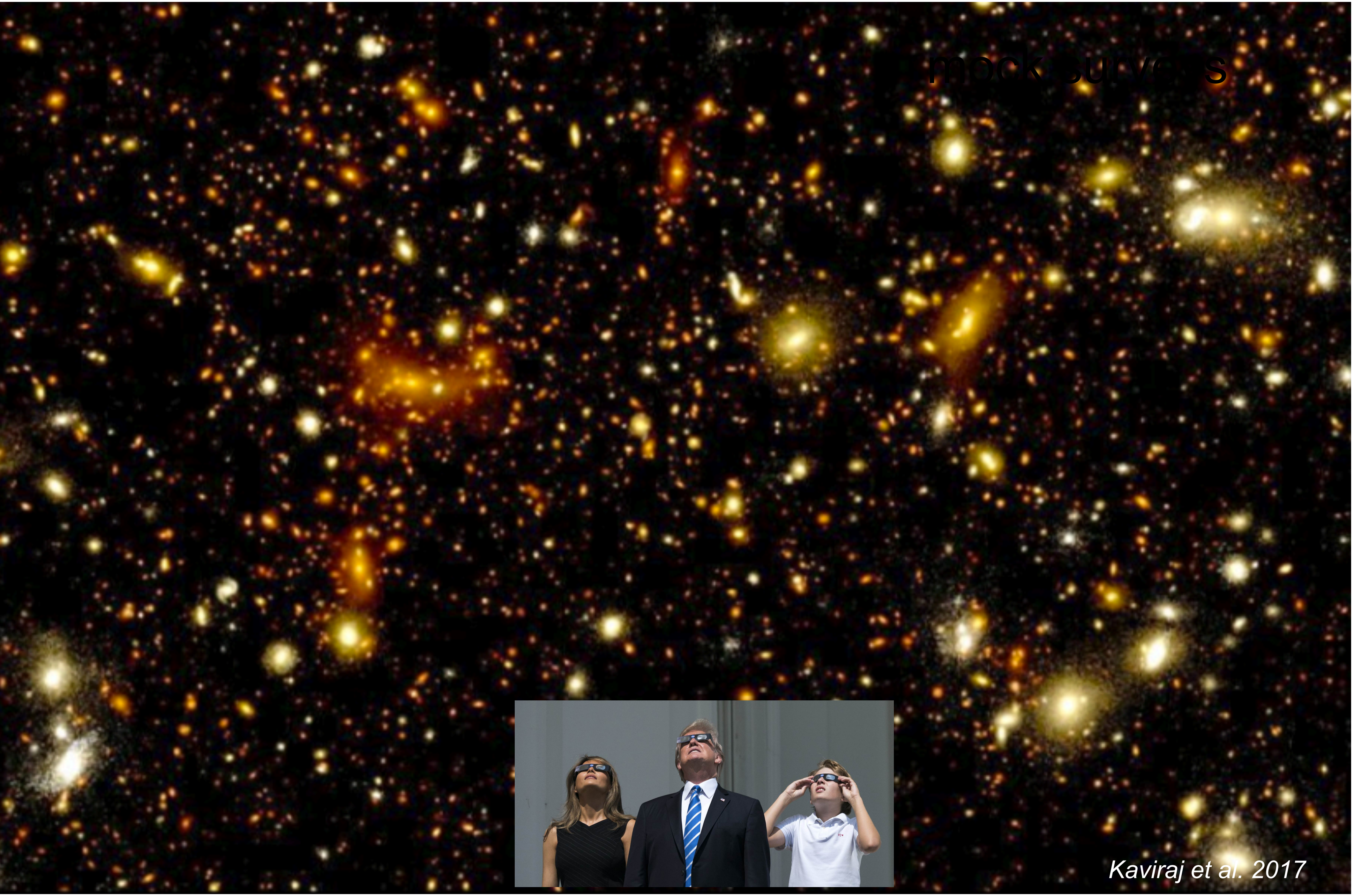
mock surveys



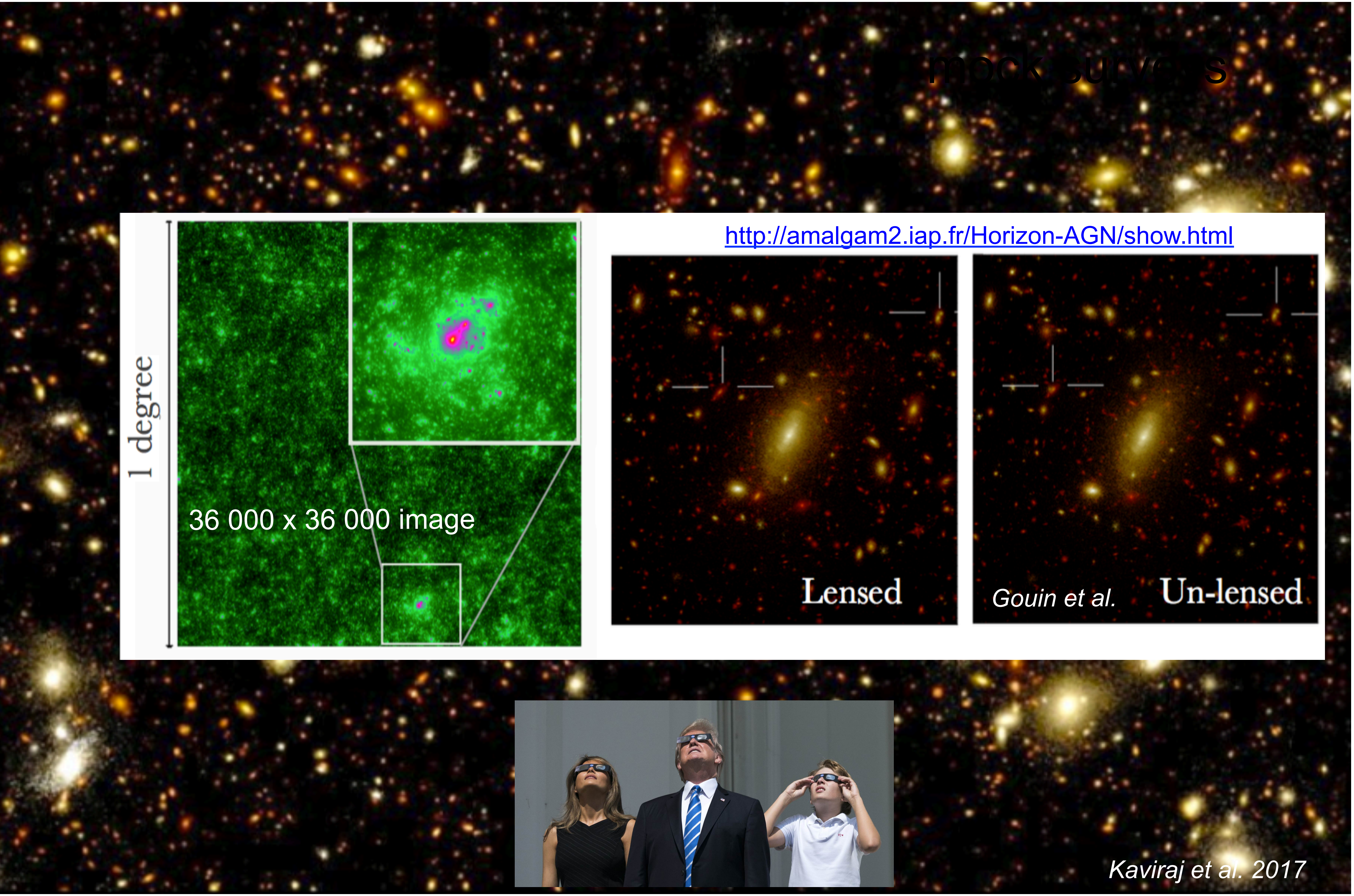
mock surveys



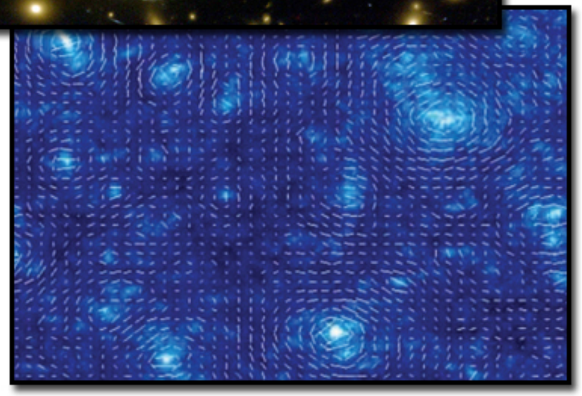
mock surveys



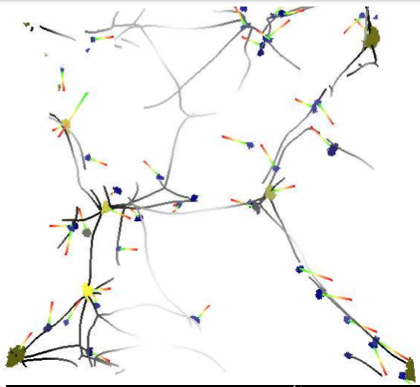
Kaviraj et al. 2017


mock surveys
http://amalgam2.iap.fr/Horizon-AGN/show.html
1 degree
36 000 x 36 000 image
Lensed
Gouin et al.
Un-lensed
Kaviraj et al. 2017

Why care about galaxy alignements?

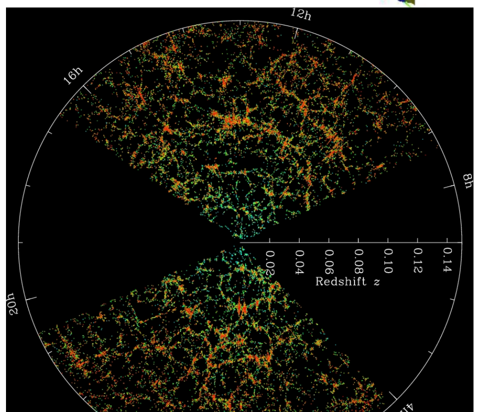


- Euclid and LSST will constrain the nature of the dark energy with the amount of deformation of galaxies by gravitational lensing
- Constraint through the measurement of the matter power spectrum and its derivatives (role of baryons?)
- Intrinsic alignment of galaxies is a spurious bias that must be quantified
- Need for large-scale simulations and direct observations

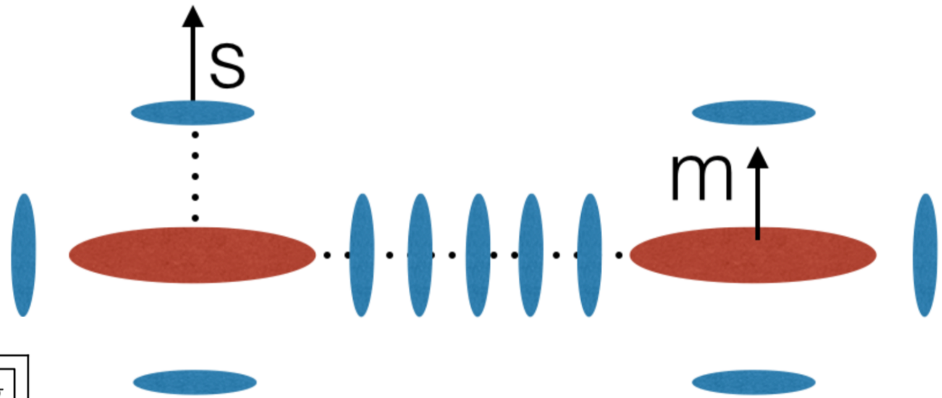


- Galaxies form at special locations of the cosmic web (sheets, filaments, nodes) & their angular momentum properties is inherited from large scales

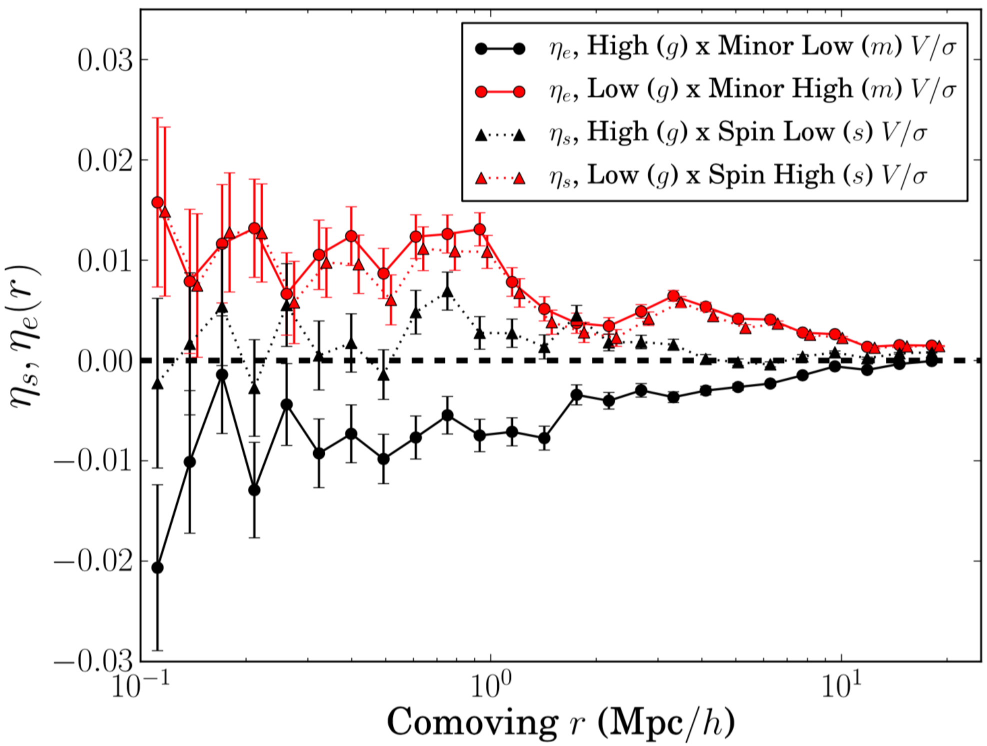
1. <u>Feedback changes the angular momentum content of galaxies</u>
2. <u>Evaluate the intrinsic alignment of structures</u>



Position-shape cross-correlations depend on morphology



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

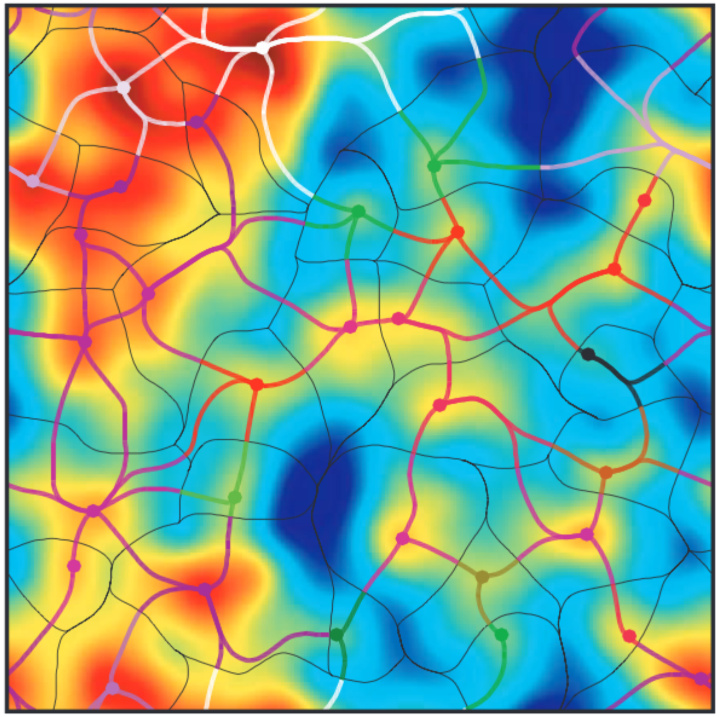


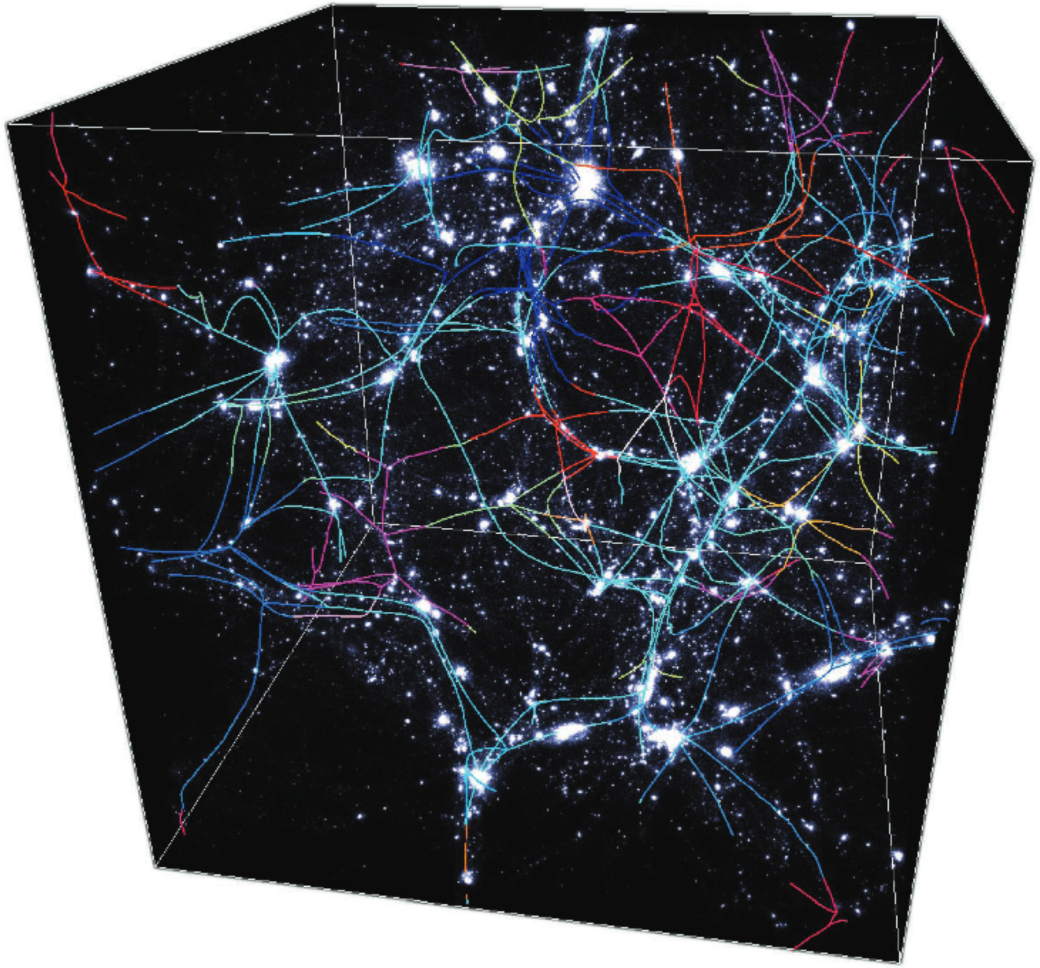
No evidence of tangential alignements of discs in Eagle (Velliscig+, 2015) and MBII & Illustris (Tenneti+, 2015)

Chisari et al, 2015, 2016
See also Codis et al, 2015

Extract the Skeleton of the cosmic web

Ridges of Marmot Basin

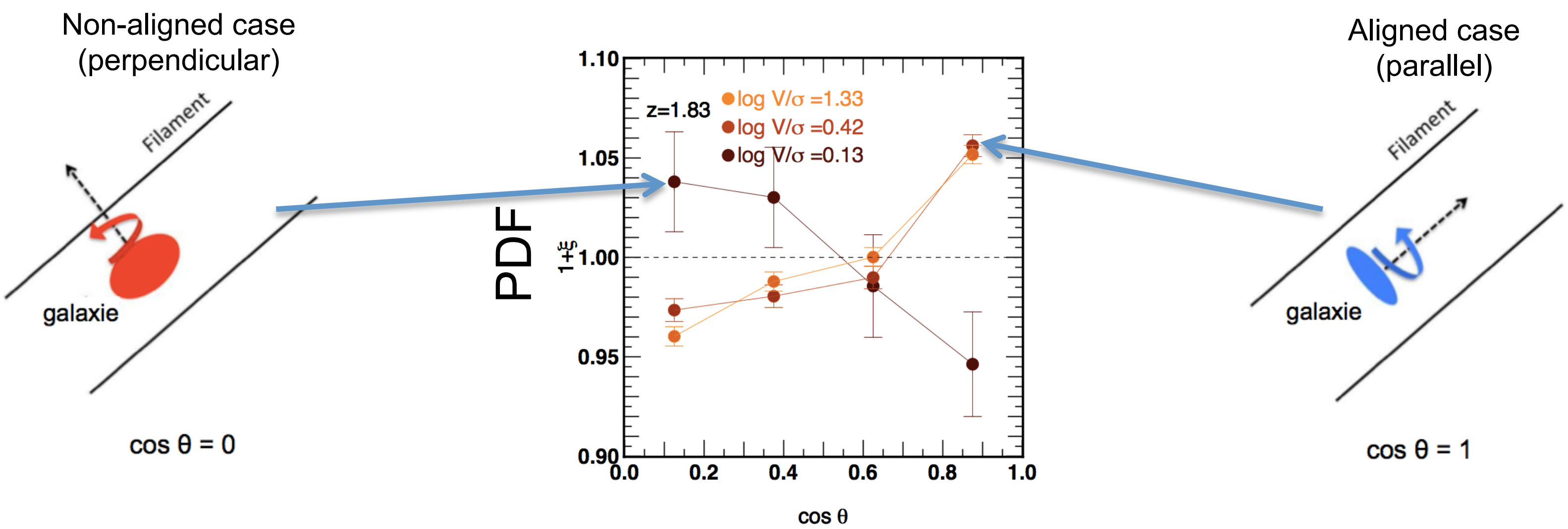




Skeleton of the LSS, *Sousbie et al (2009)*

Cosmic web and galaxies alignment

<u>Discs</u> : spin aligned with cosmic filaments
<u>Ellipticals</u> : spin perpendicular with cosmic filaments



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

Cosmic web and galaxies alignment

Discs : spin aligned with cosmic filaments
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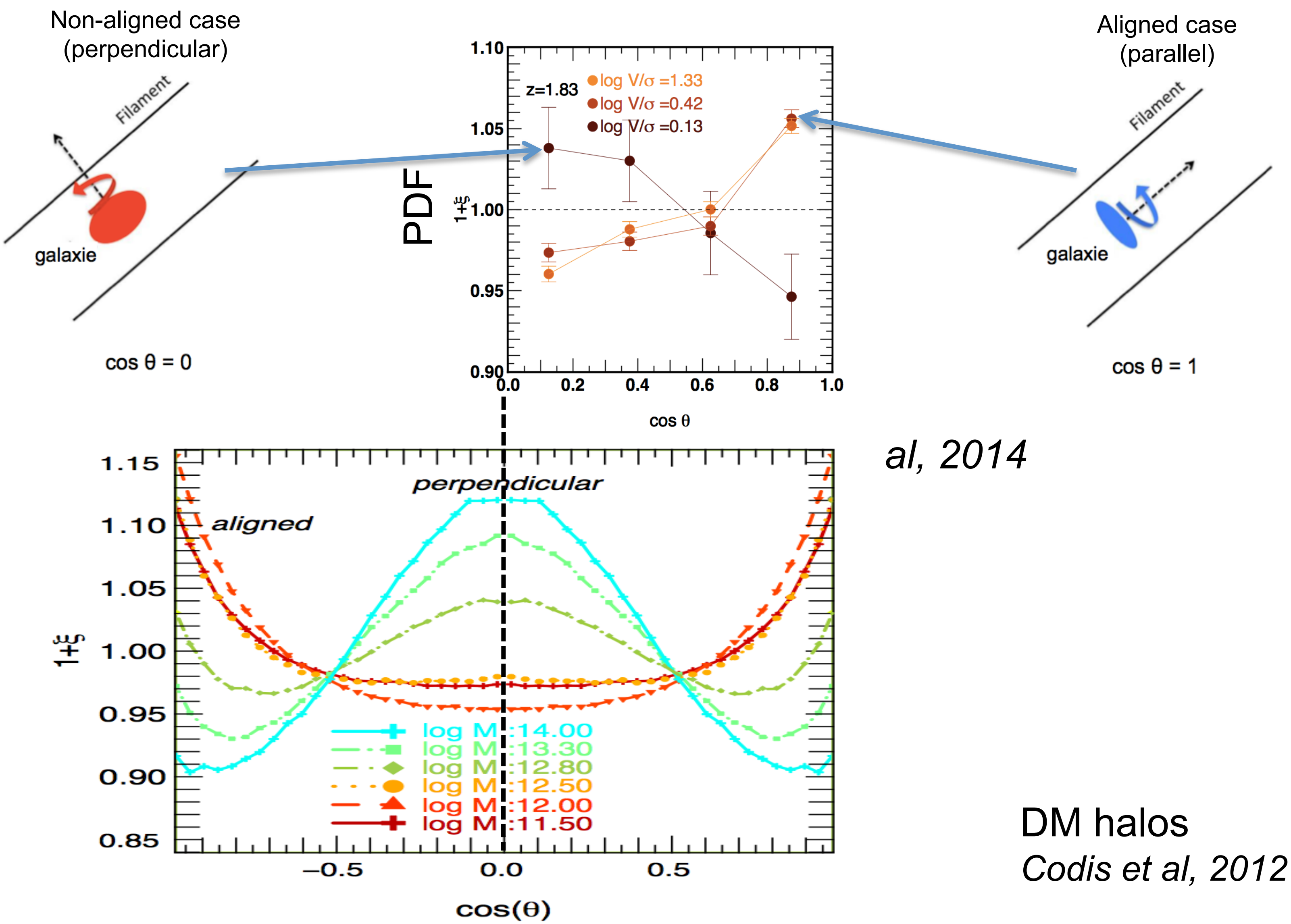
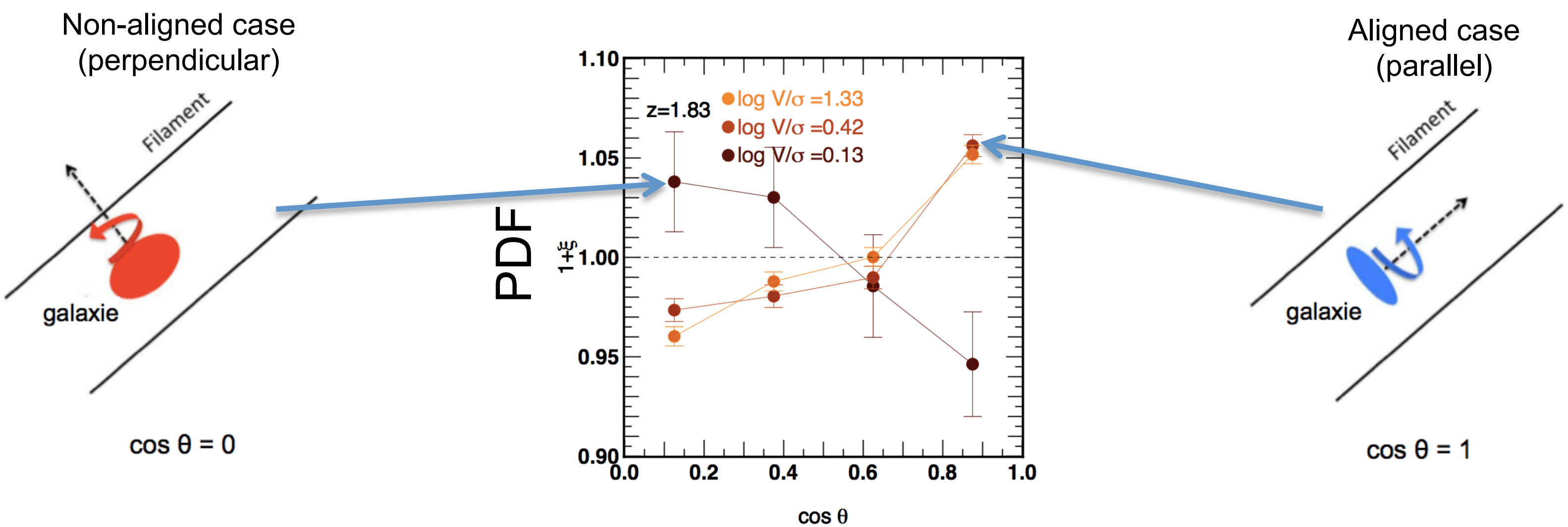


al, 2014

DM halos
Codis et al, 2012

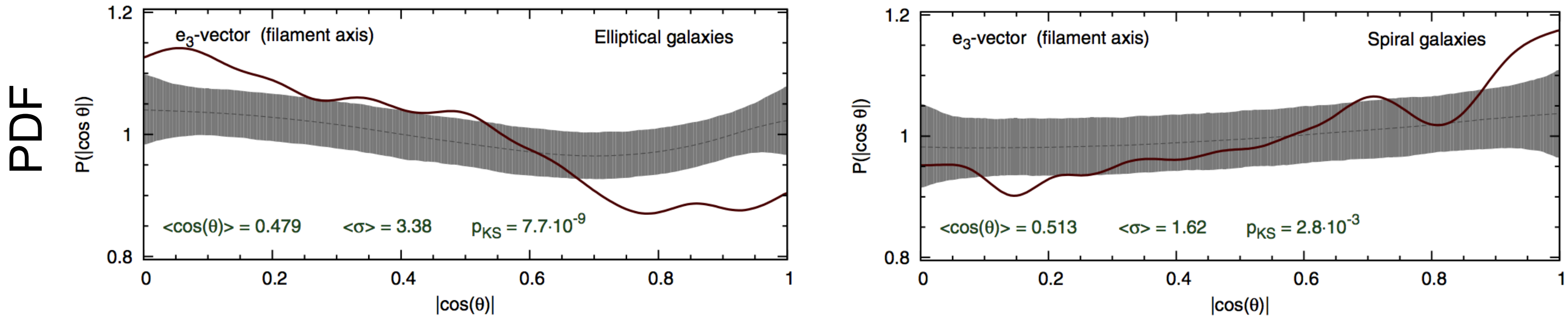
Cosmic web and galaxies alignment

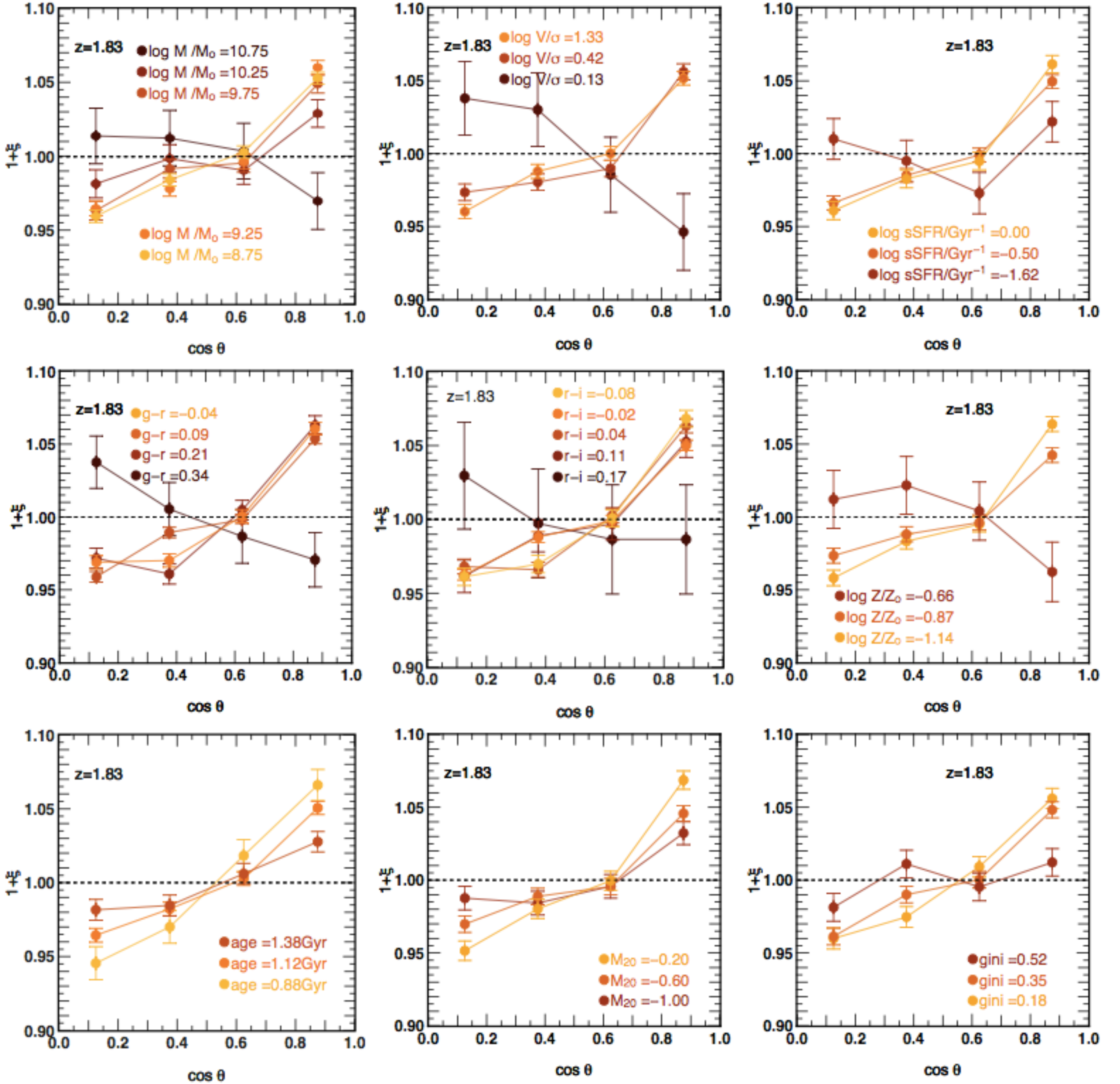
Discs : spin aligned with cosmic filaments
Ellipticals : spin perpendicular with cosmic filaments



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

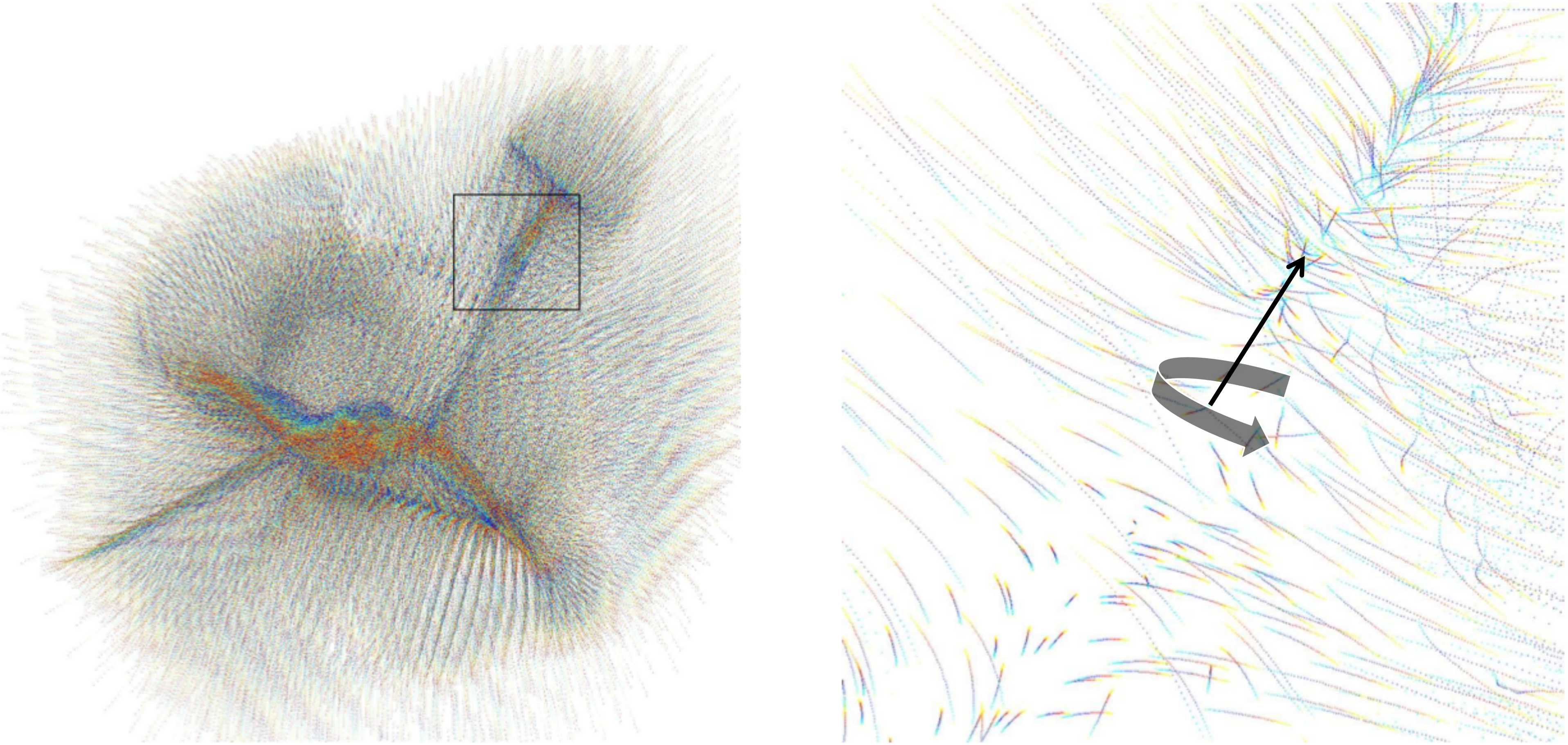
Observations (SDSS) / *Tempel & Libeskind, 2013*





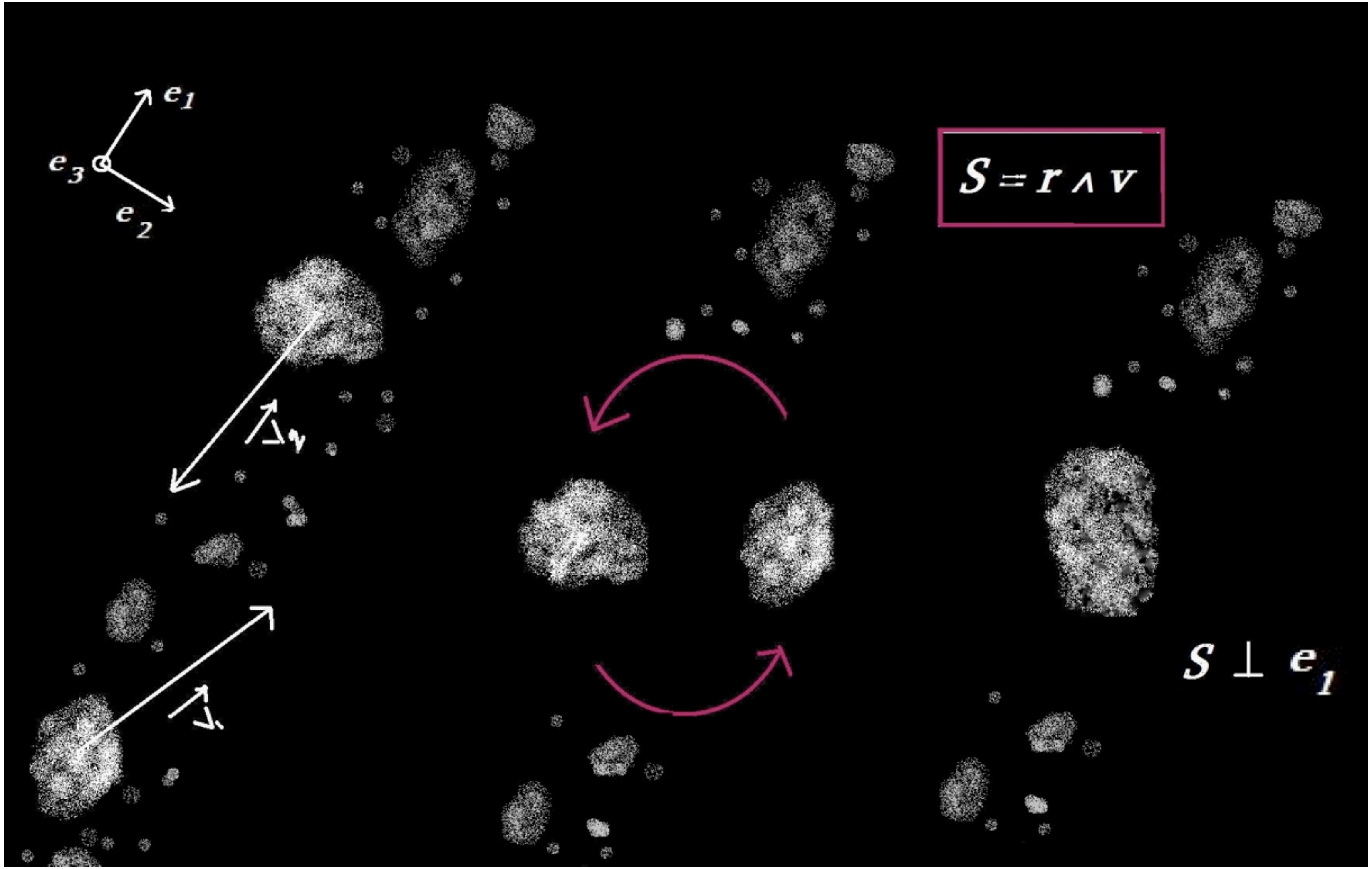
Dubois et al, 2014

Why do low-mass halos align with filaments?



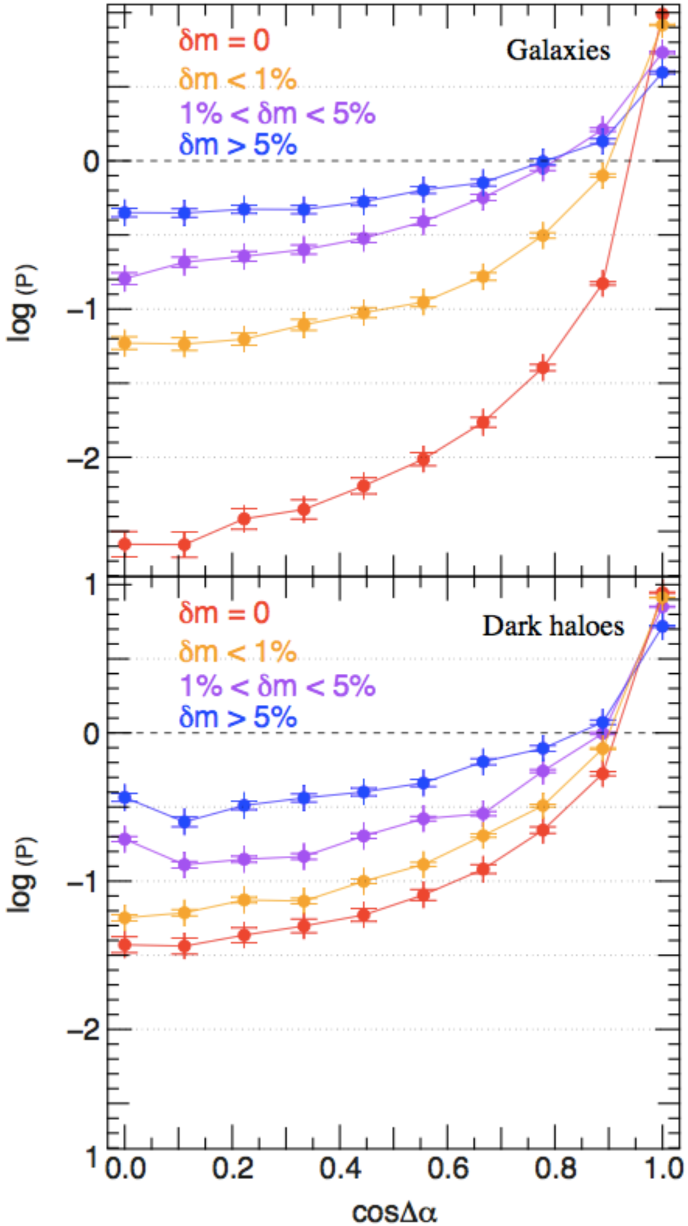
Pichon et al (2011)
See also Pichon & Bernardeau (1999)
Laigle et al (2015)
Codis, Pichon, Pogosyan (2015)

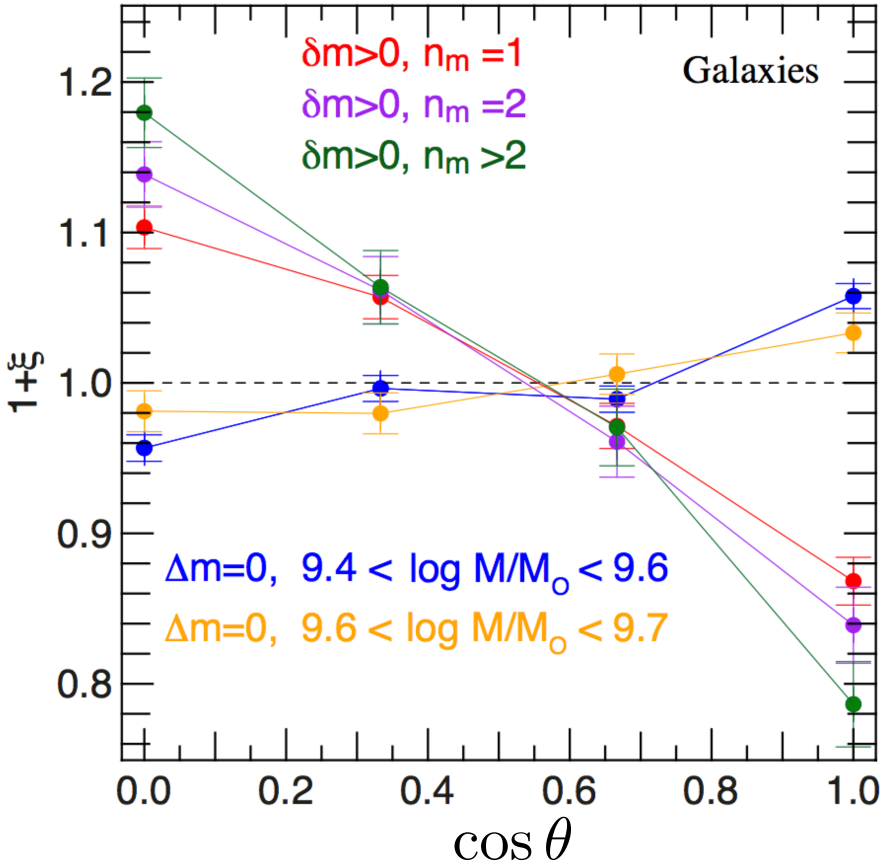
Why do high-mass halos are perpendicular to filaments?



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

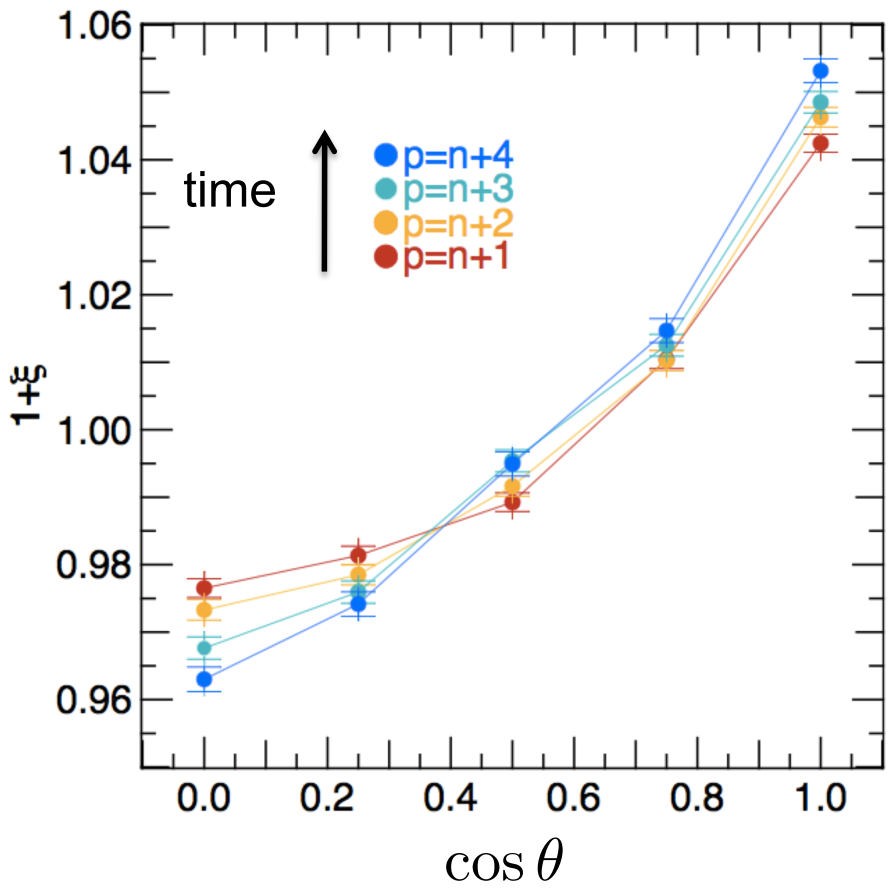




Welker et al, 2014

Re-alignment of galaxies

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

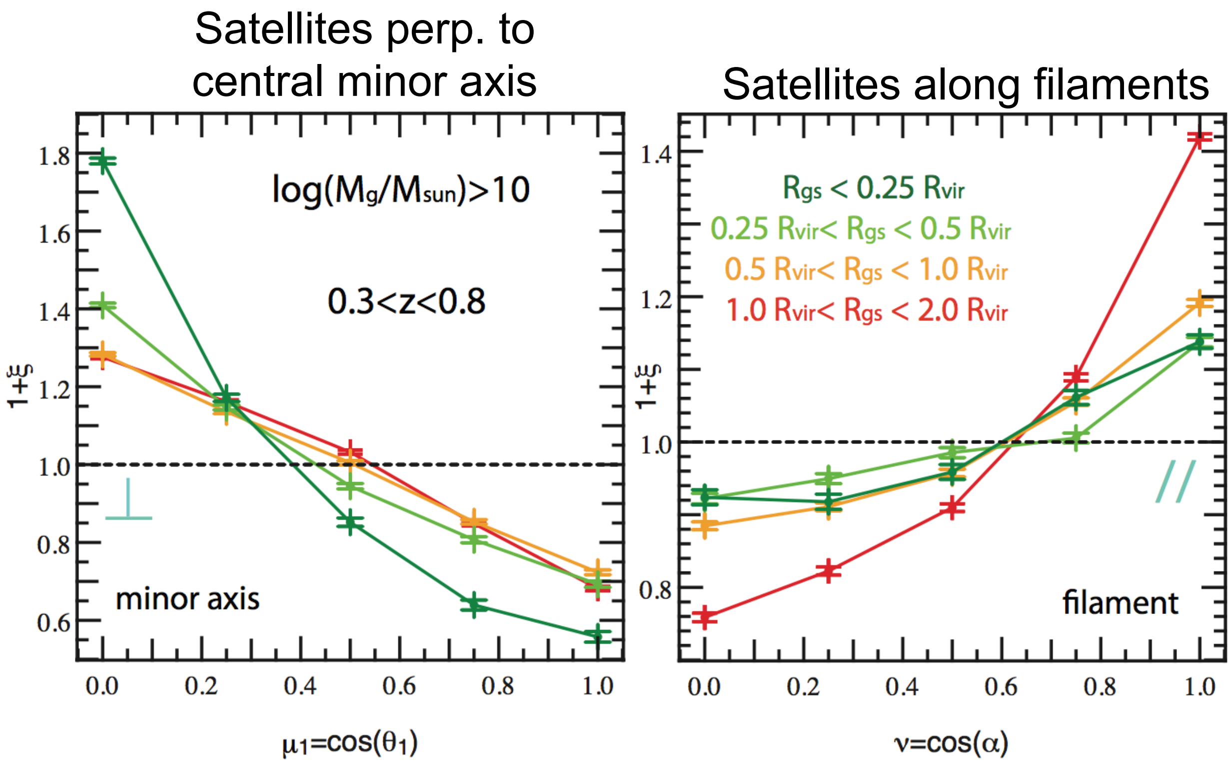


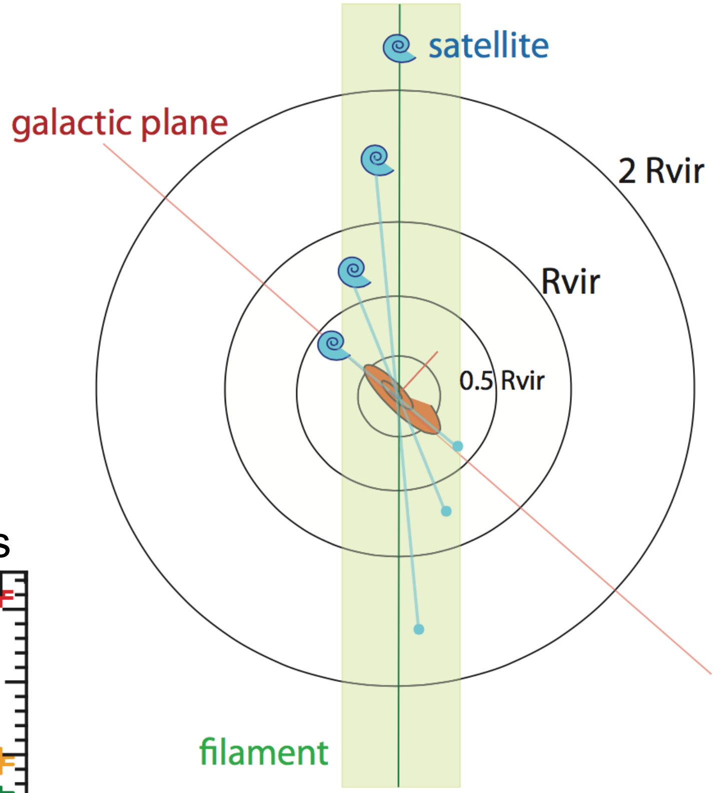
As AGN feedback prevents gas accretion in massive galaxies, it also prevents massive galaxies to realign with the cosmic filaments after a merger.

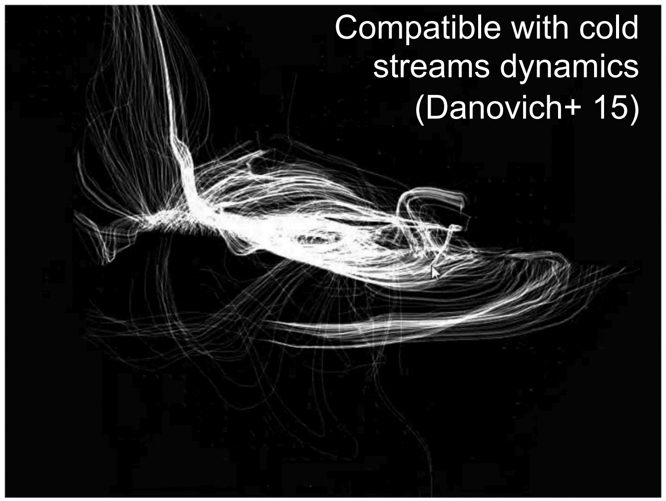
AGN feedback is mandatory to get galaxies perpendicular with cosmic filaments.

Welker et al, 2014

Satellites rotate in the galactic plane of the central as they get closer

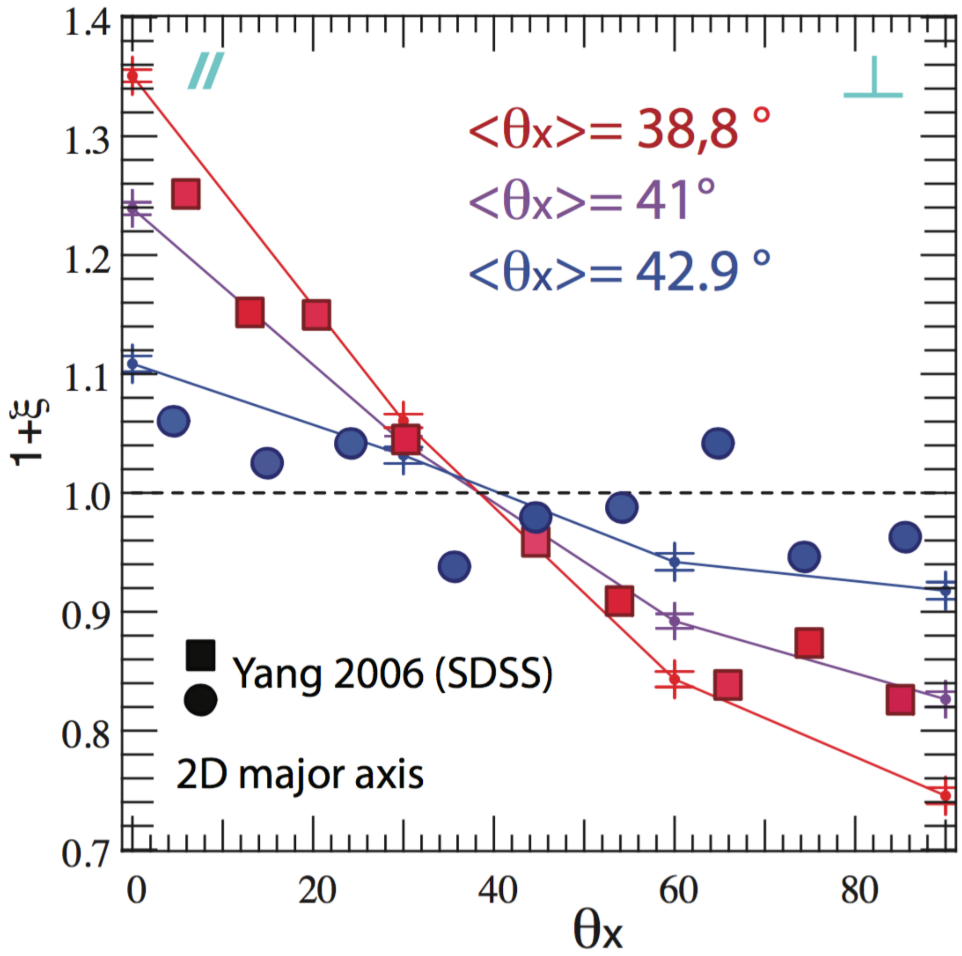


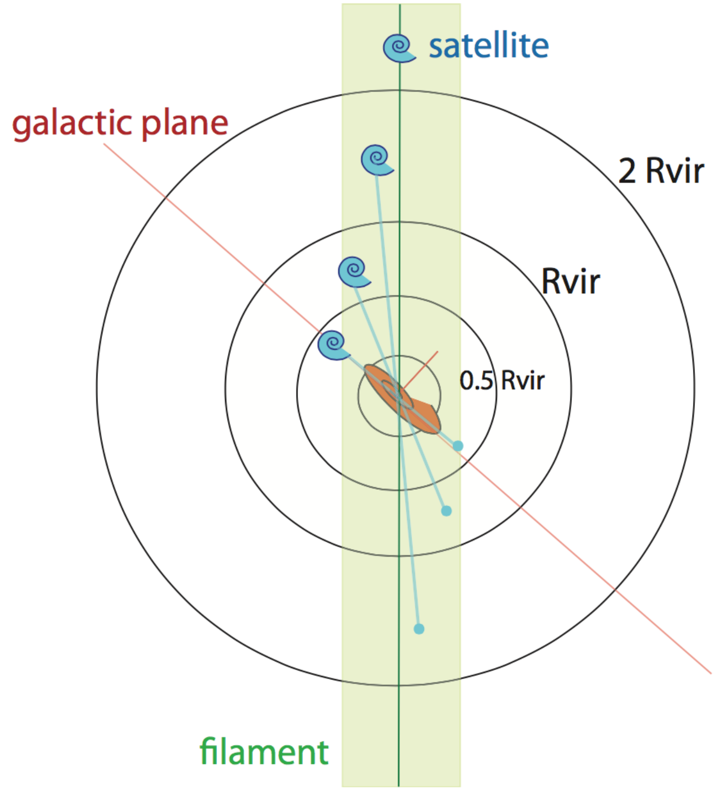




Welker, YD+ 18
See also Aubert, Pichon, Colombi 04 (DM only)

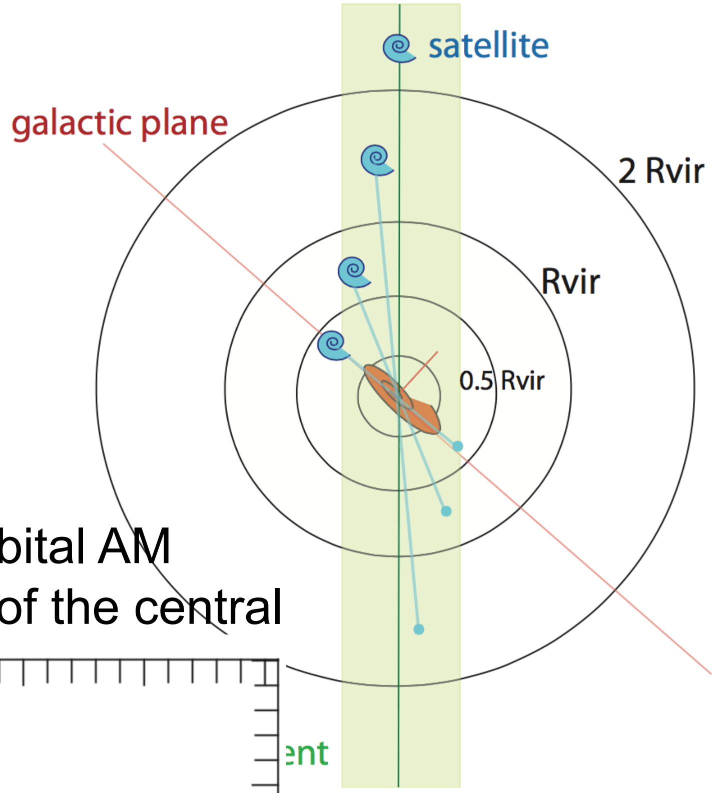
Plane of sattelites is a standard feature of a LCDM Universe

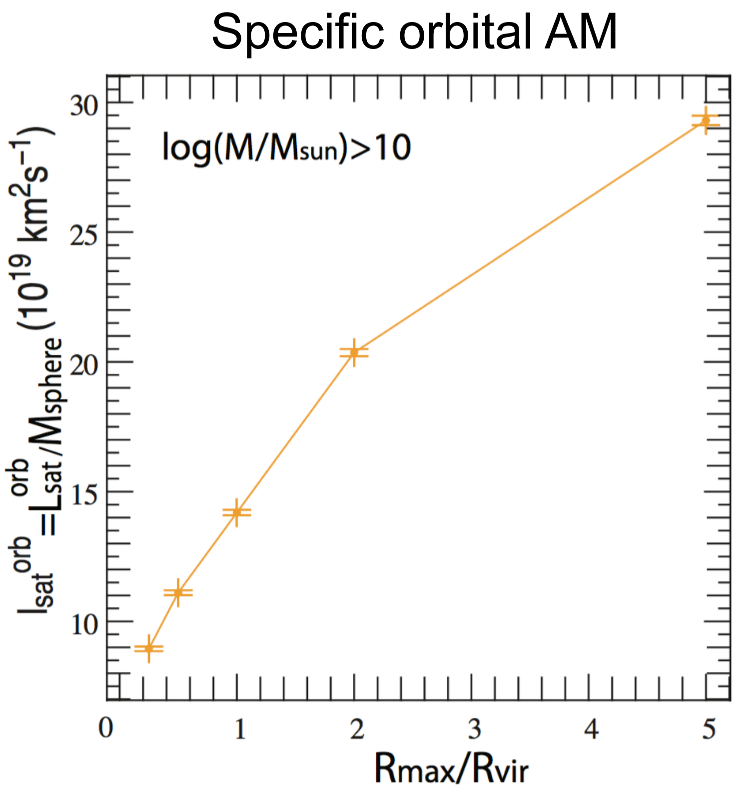


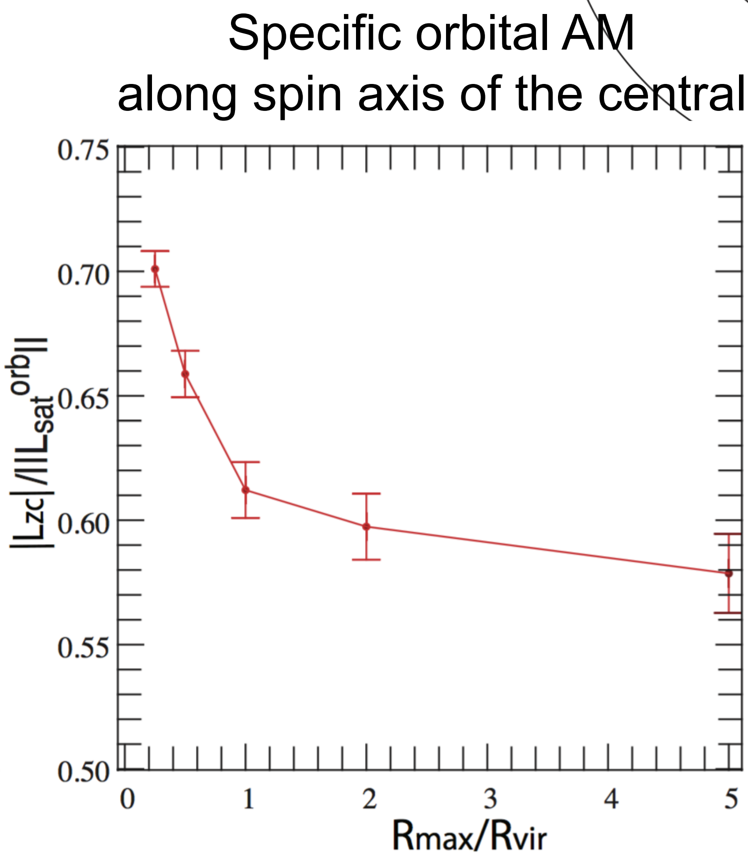


Welker, YD+ 18

And selectively cancel their orbital AM







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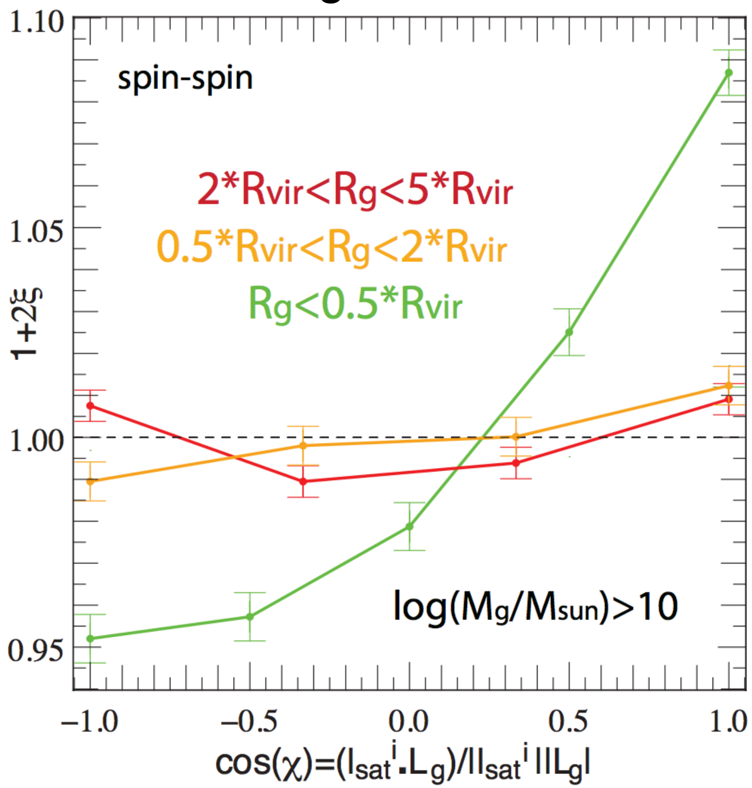
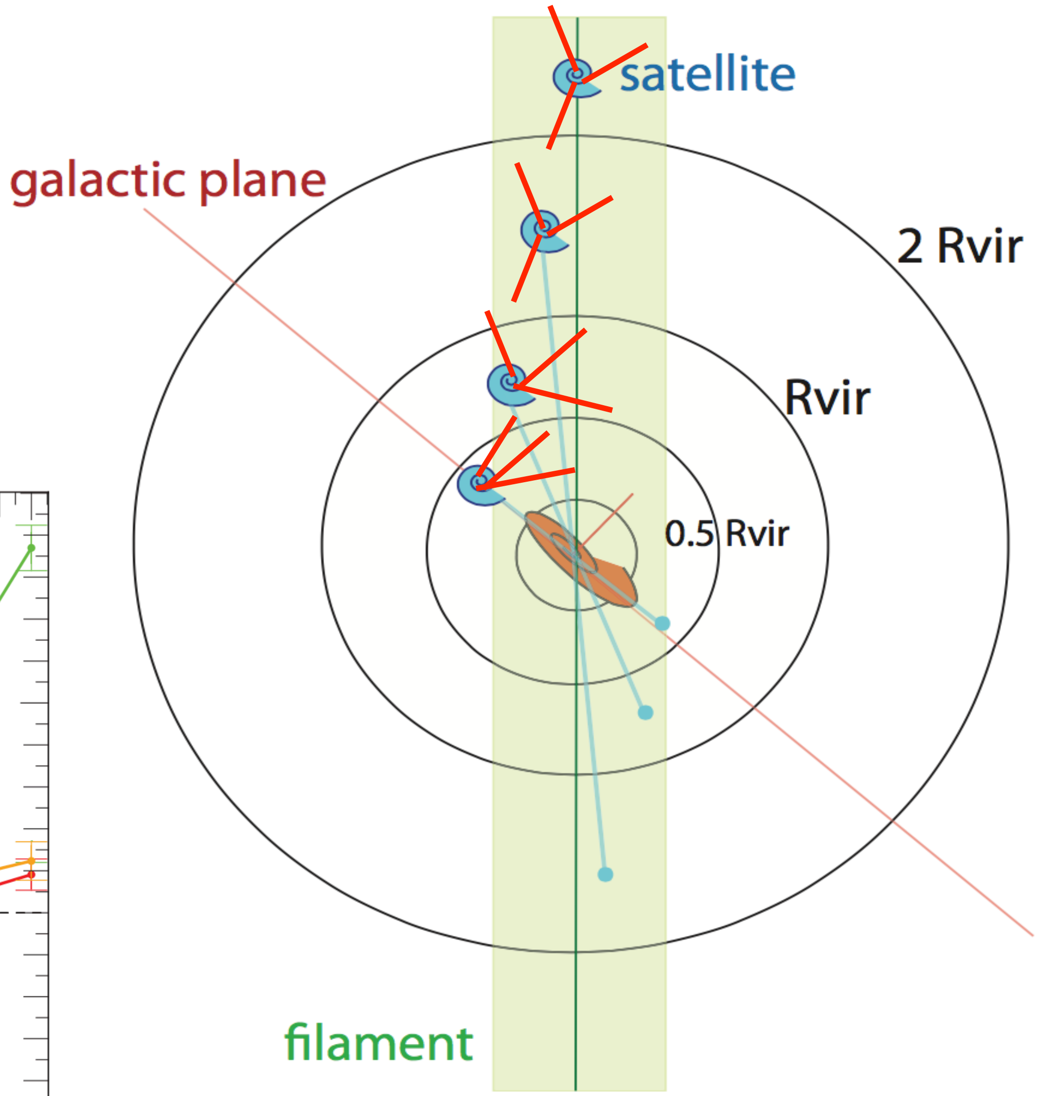
Spin-spin alignement

Central spin-satellite spin alignement

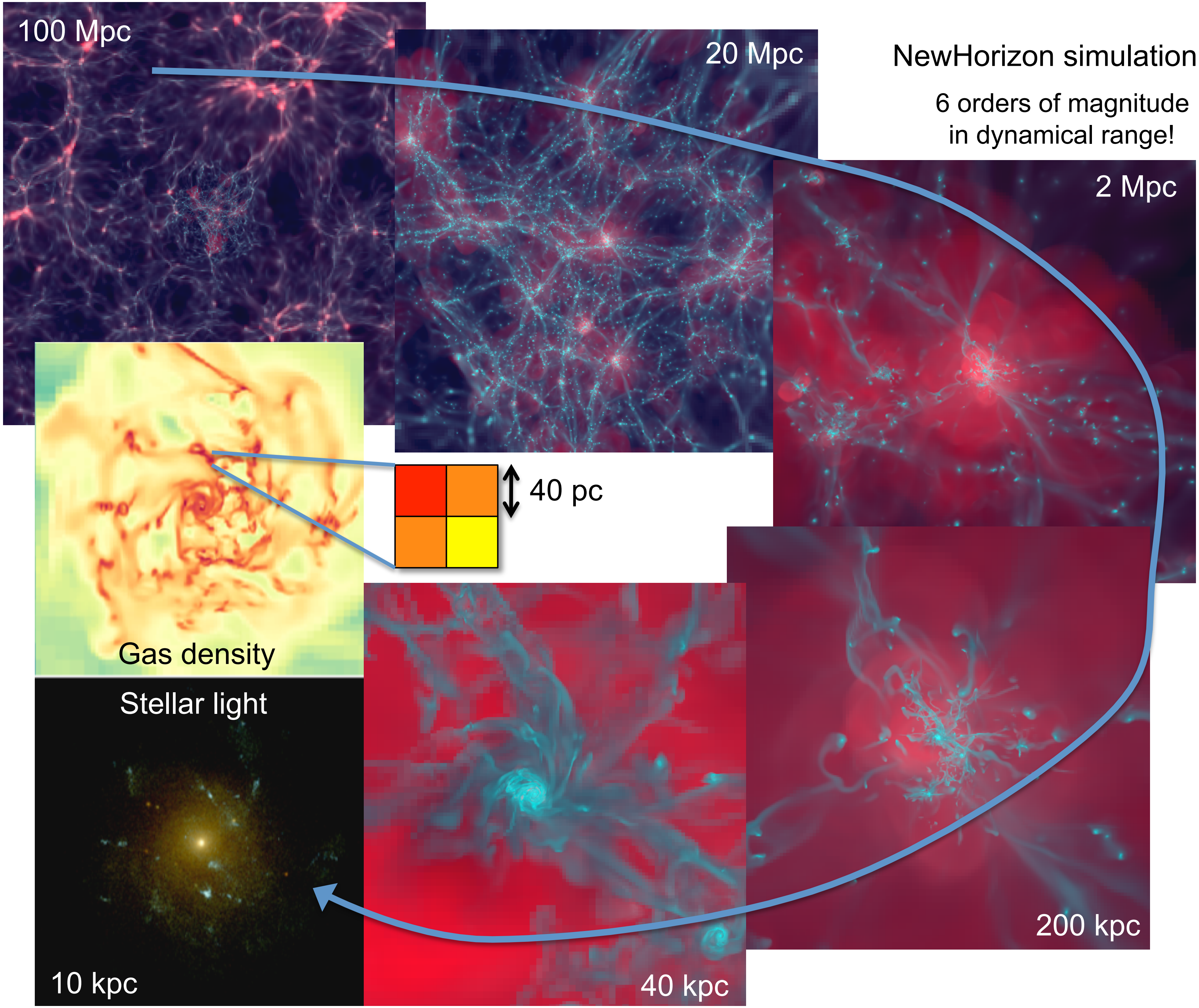




Welker, YD+ 18

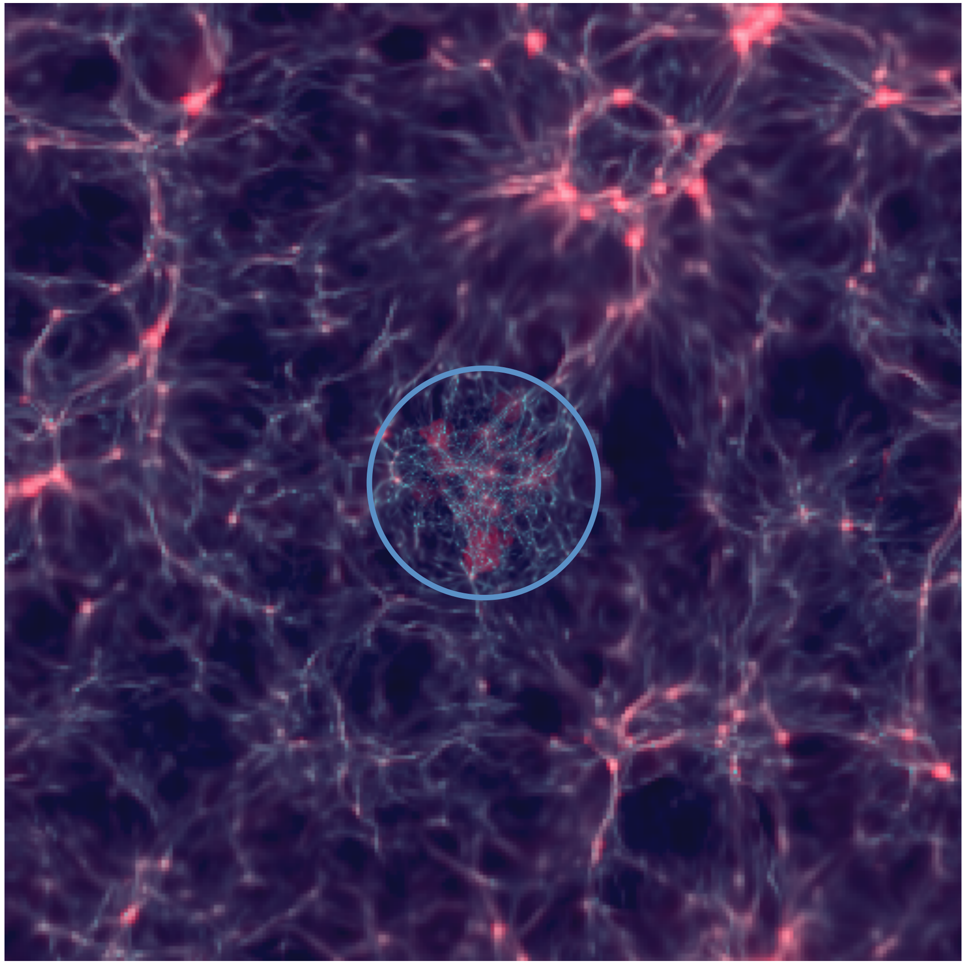
NewHorizon simulation

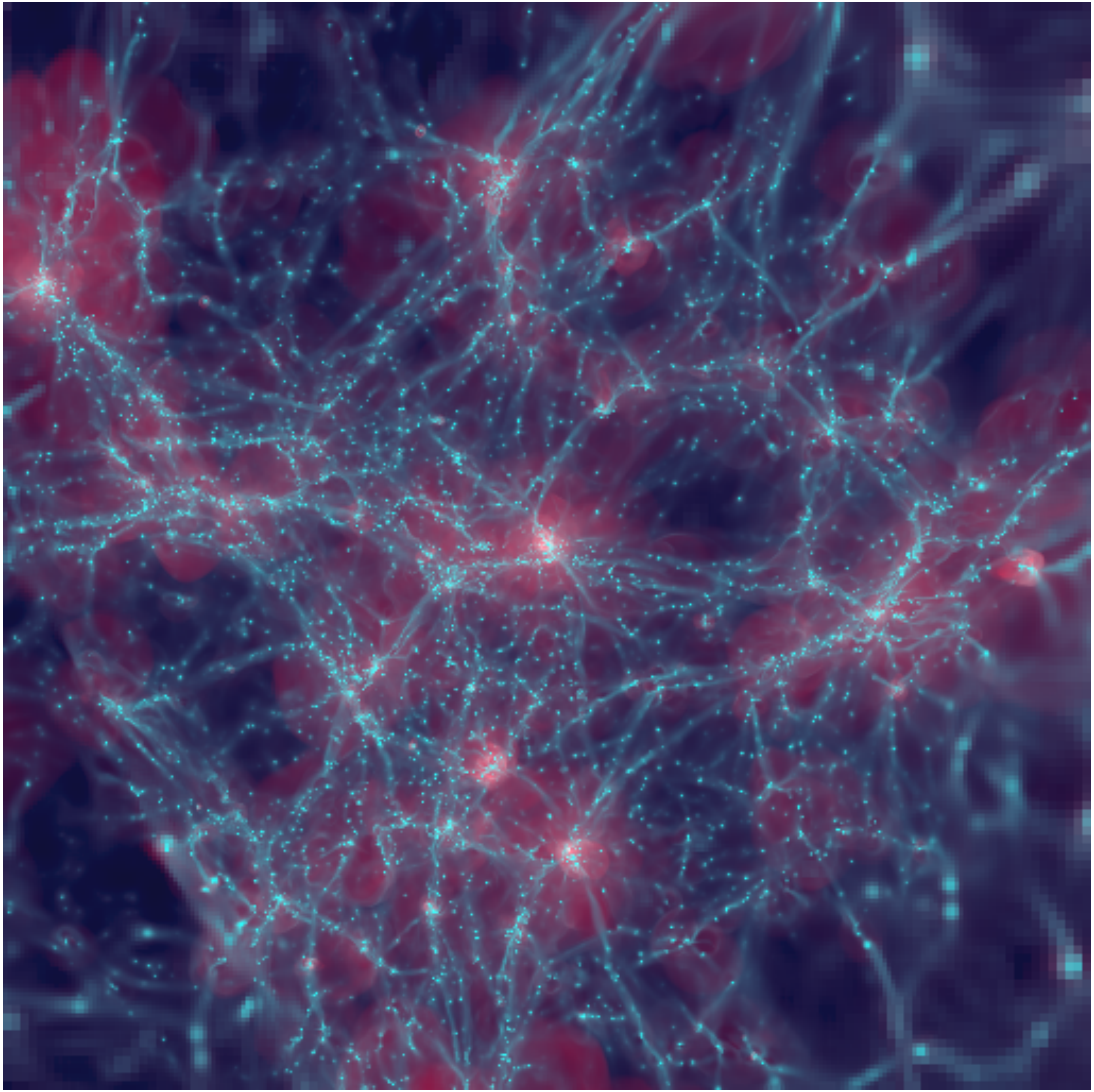
6 orders of magnitude
in dynamical range!

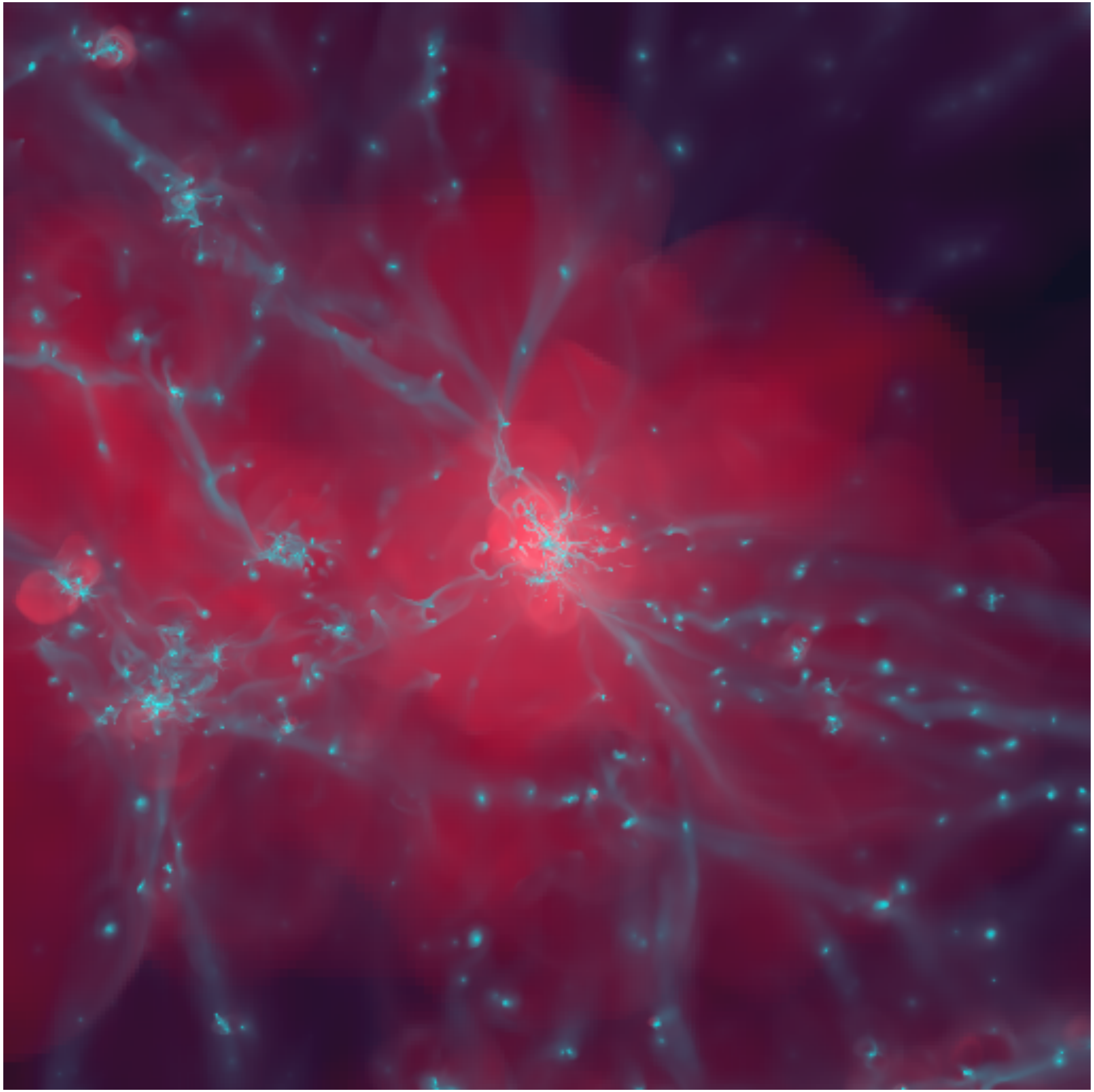


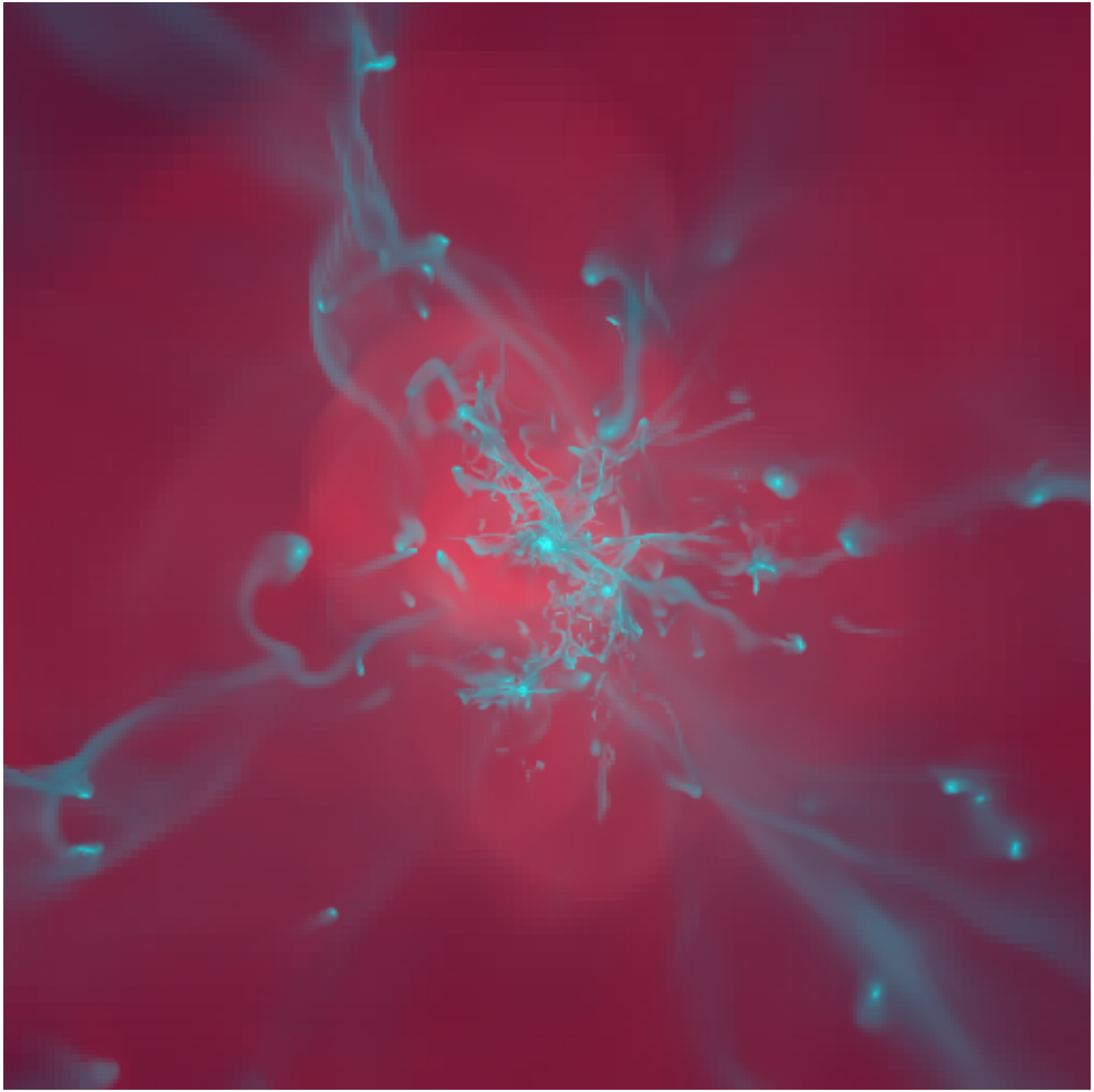
NewHorizon

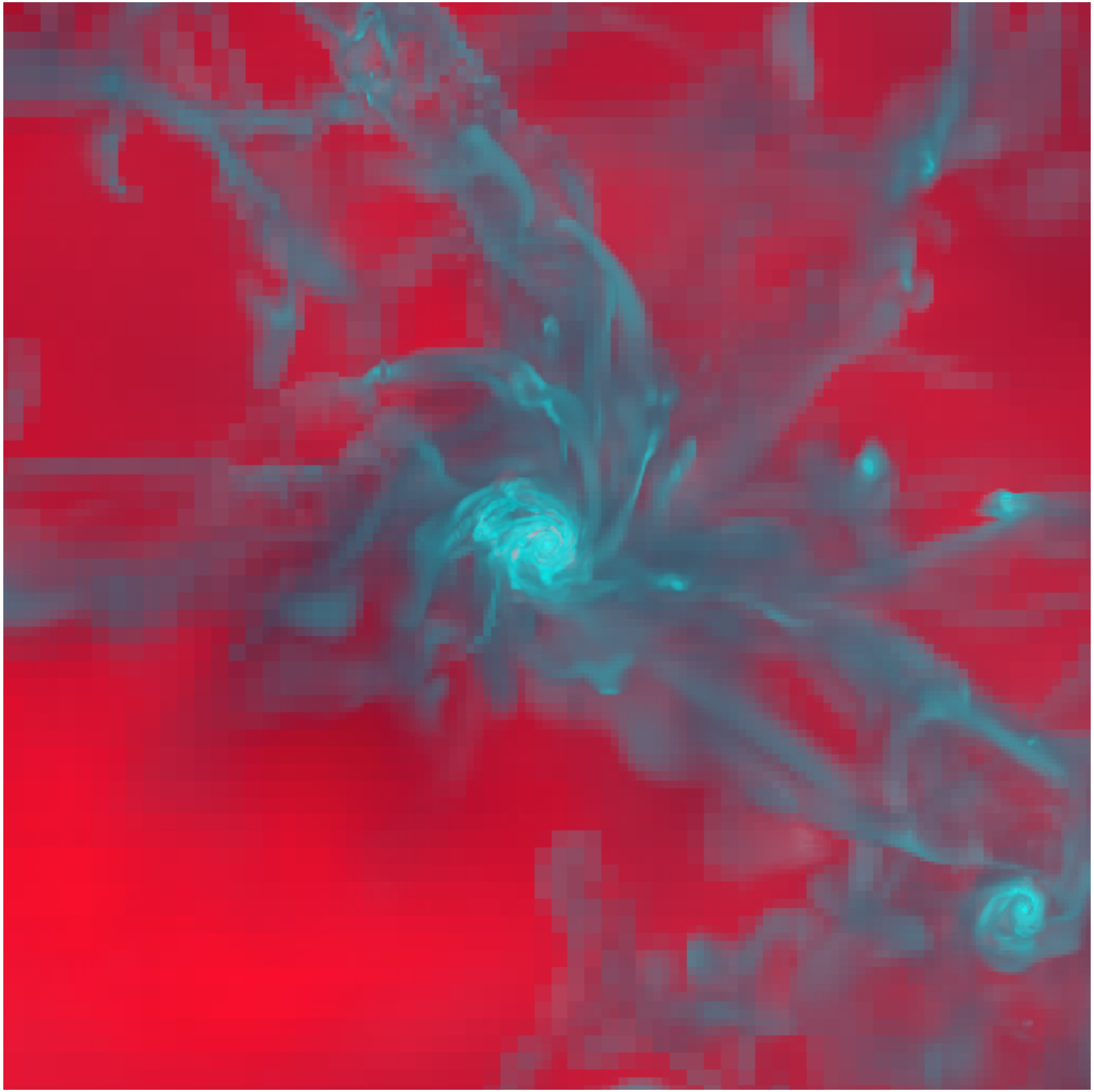
- Simulation content
  - Same IC phases than Horizon-AGN
  - High-res sphere of 10 Mpc radius (average density environment)
  - $M_{DM,hires}=10^6\ M_{sun}$ (vs $10^8\ M_{sun}$ in HAGN)
  - $M_{*,res}=10^4\ M_{sun}$ (vs $10^6\ M_{sun}$ in HAGN)
  - dx=0.04 kpc
  - Turbulent SF criterion *(Padoan & Nordlund, 11, Devriendt et al)*
  - Mechanical SNII feedback *(Kimm et al, 14,15)*
  - AGN feedback + BH spin-dependent model *(Dubois et al, 14)*
  - Gas tracer particles
- Outputs every 15 Myr (~150 GB each)
- z=0.7 so far with ~25 Mhours (French+Korean effort)











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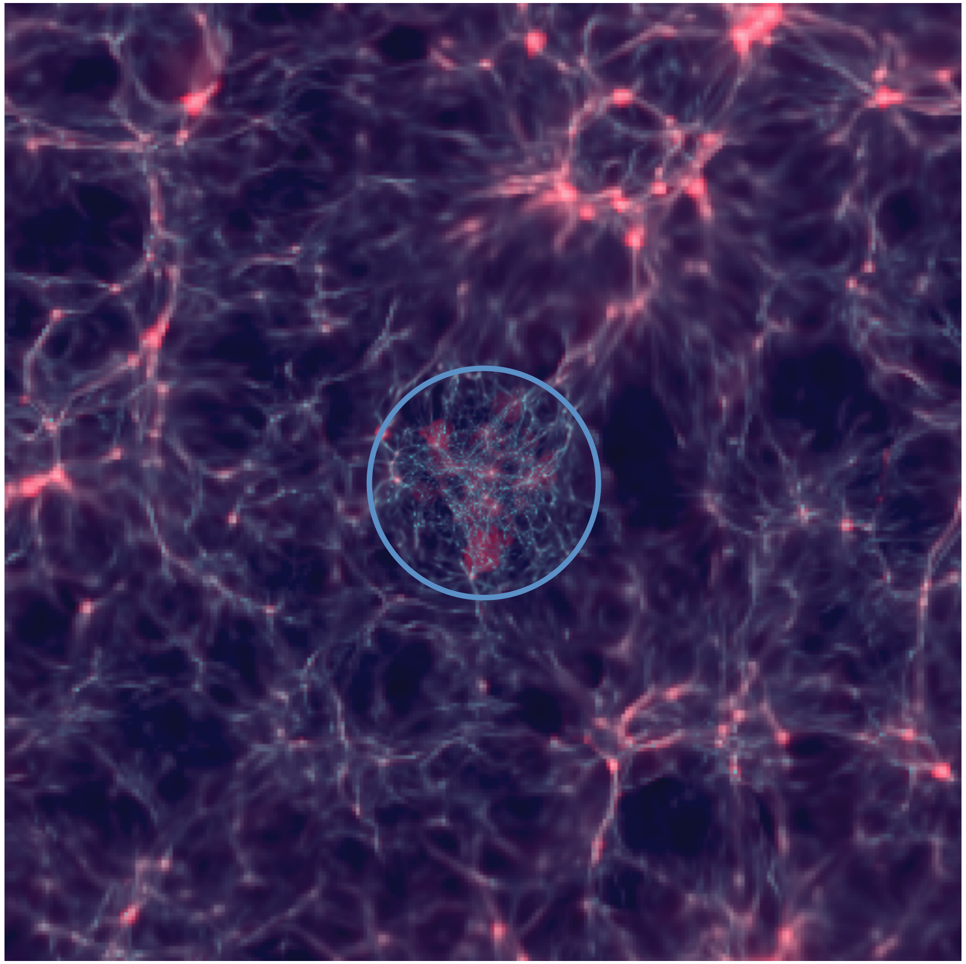


Turbulent star formation

$$\frac{d\rho_*}{dt} = \epsilon_* \frac{\rho_g}{t_{ff}}$$

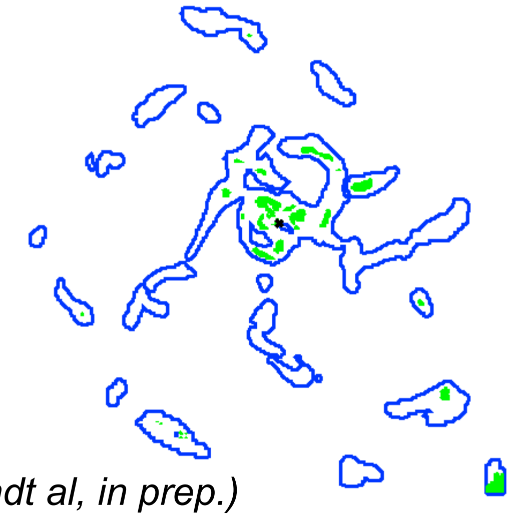
? ? ?

Star formation efficiency is no more an *ad hoc* user-defined parameter

a few % (e.g. 90% of the community) – 100 % (FIRE Hopkins+)

Efficiency is set up by the turbulent properties of the ISM

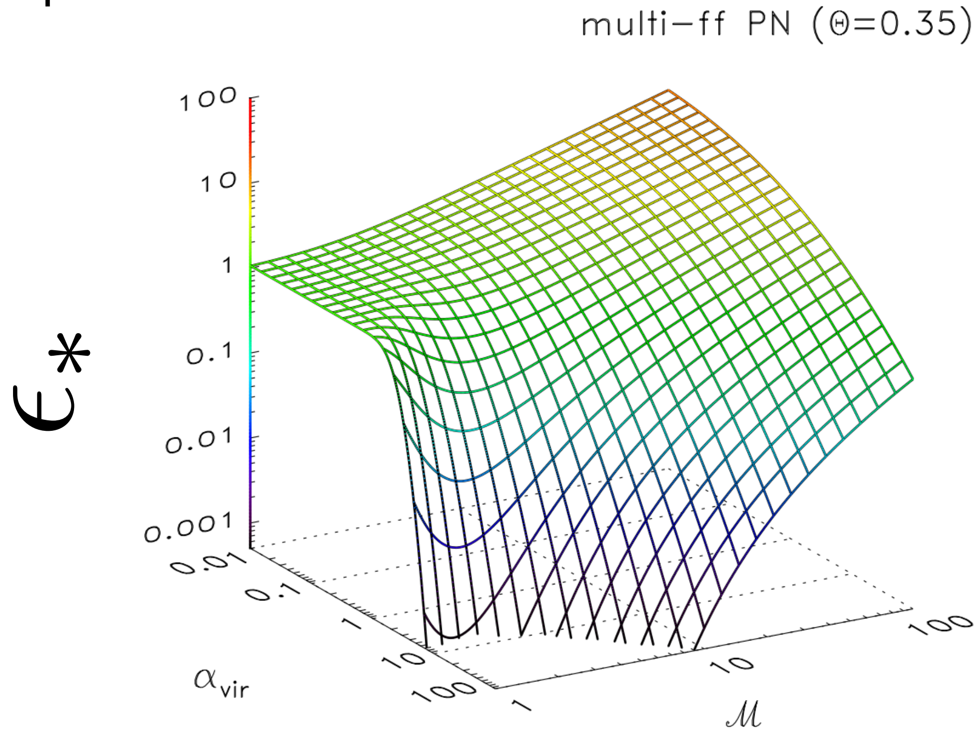
$$\epsilon_* = f(\mathcal{M}_{turb}, \alpha_{vir})$$



(Devriendt al, in prep.)

Blue contours: gas isodensity at 100 at/cm^3

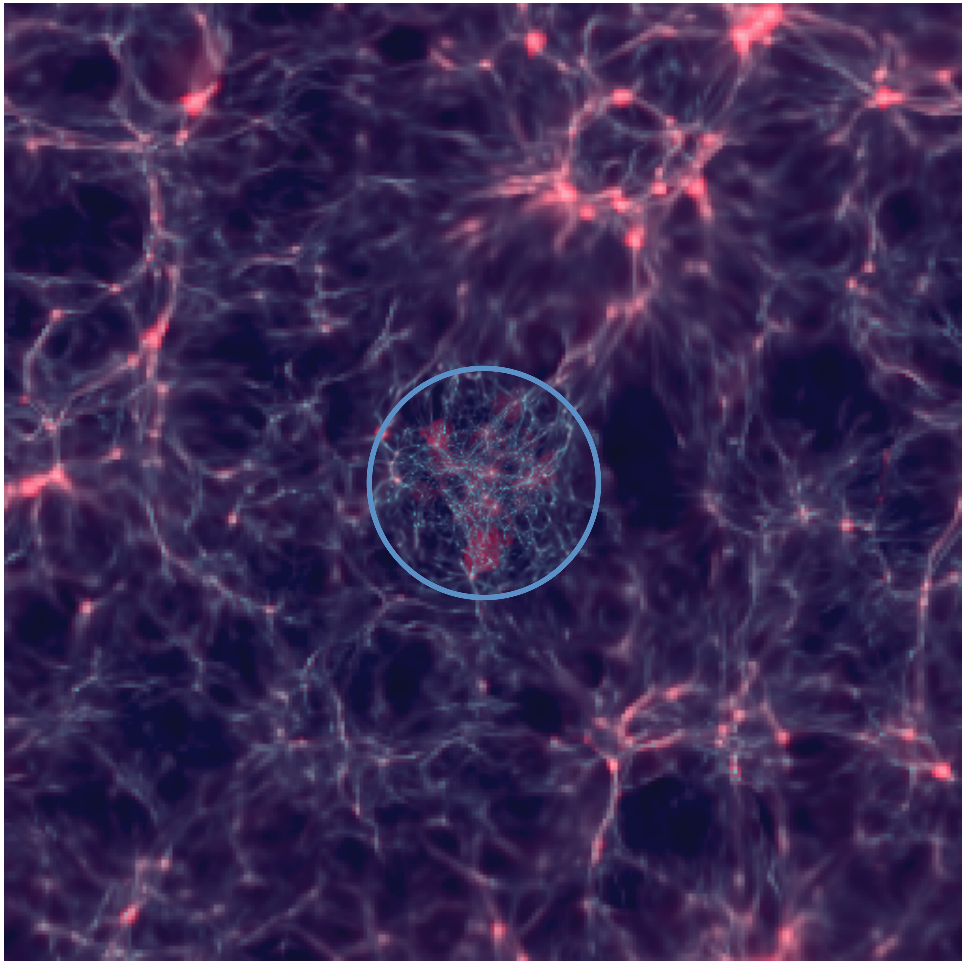
Green : gravitationally unstable regions



Federrath & Klessen, 2012

NewHorizon

- Simulation content
  - Same IC phases than Horizon-AGN
  - High-res sphere of 10 Mpc radius (average density environment)
  - $M_{DM,hires}=10^6\ M_{sun}$ (vs $10^8\ M_{sun}$ in HAGN)
  - $M_{*,res}=10^4\ M_{sun}$ (vs $10^6\ M_{sun}$ in HAGN)
  - dx=0.04 kpc
  - Turbulent SF criterion
    (Padoan & Nordlund, 11, Devriendt et al)
  - Mechanical SNII feedback
    (Kimm et al, 14,15)
  - AGN feedback + BH spin-dependent model
    (Dubois et al, 14)
  - Gas tracer particles
- Outputs every 15 Myr (~150 GB each)
- z=0.7 so far with ~25 Mhours (French+Korean effort)



Momentum-driven SN feedback

(Kimm & Cen, 2014)

A collection of SN explosions can be described by essentially 4 successive phases:

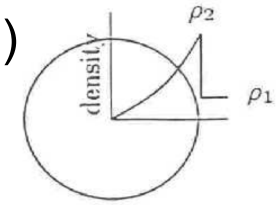
1) ~~The ejecta phase where ejecta mass is larger than that of the engulfed background gas.~~ (never applies in practice)

2) The energy-conserving phase (=Sedov solution): ejecta mass is negligible and the initial energy of SN is conserved.

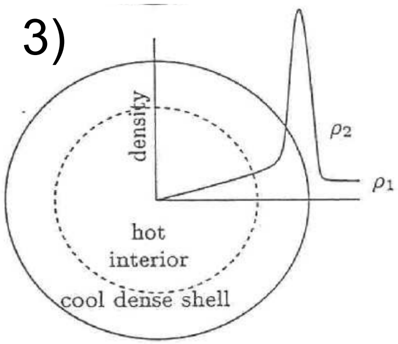
3) The momentum-driven phase: the internal energy of the shocked shell has been radiated away, momentum is kept conserved and is set up according to gas properties (density, metallicity) and energy of the explosion.

$$p_{\mathrm{SN,snow}} \approx 3 \times 10^5\,\mathrm{km\,s^{-1}\,M_\odot}\,E_{51}^{16/17} n_{\mathrm{H}}^{-2/17} Z'^{-0.14}$$

2)



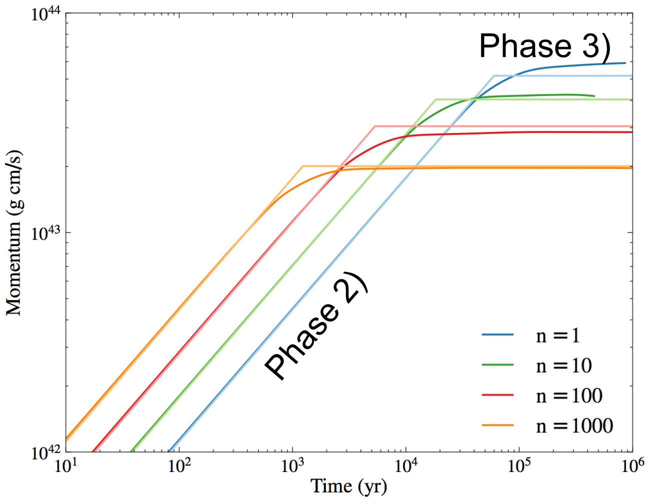
3)



Do the feedback according to 2) or 3) by either simply depositing internal energy or putting the right amount of momentum to the gas, respectively.

+

If phase 3), we double the amount of deposited momentum due to the pre-heating phase from OB stars (Geen et al, 2014)



Iffrig & Hennebelle, 2015

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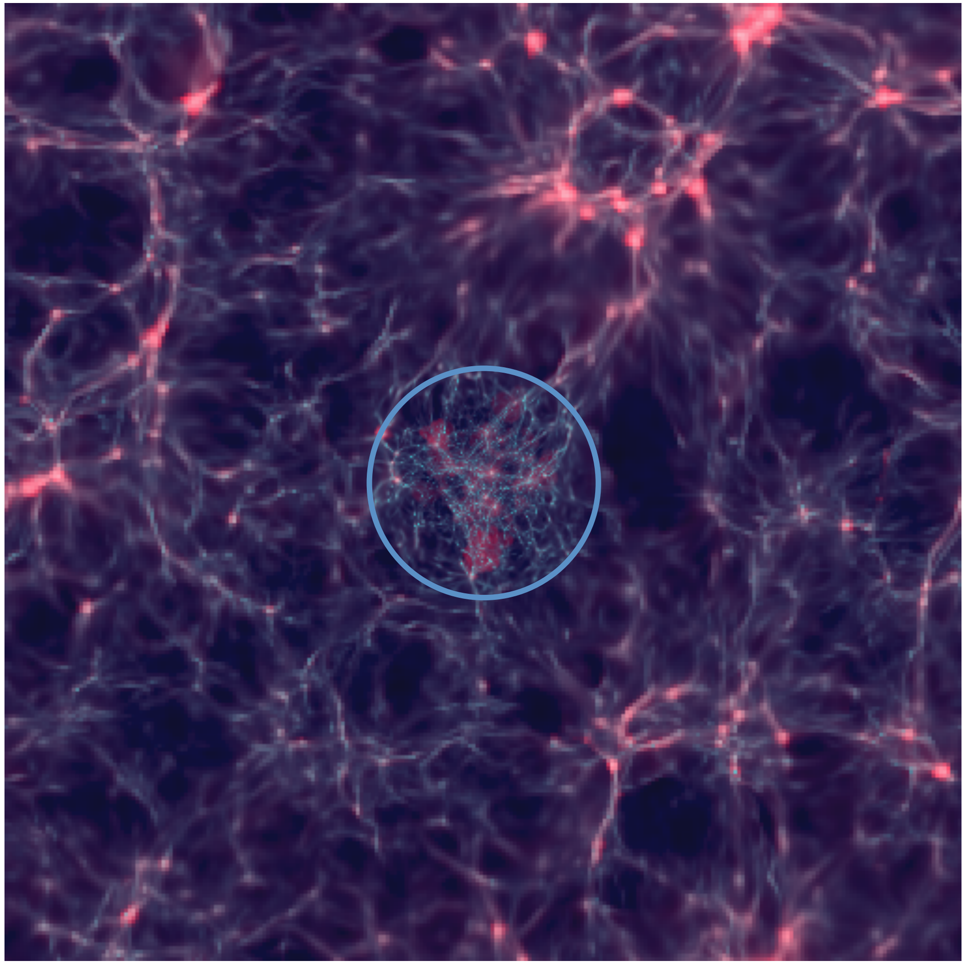


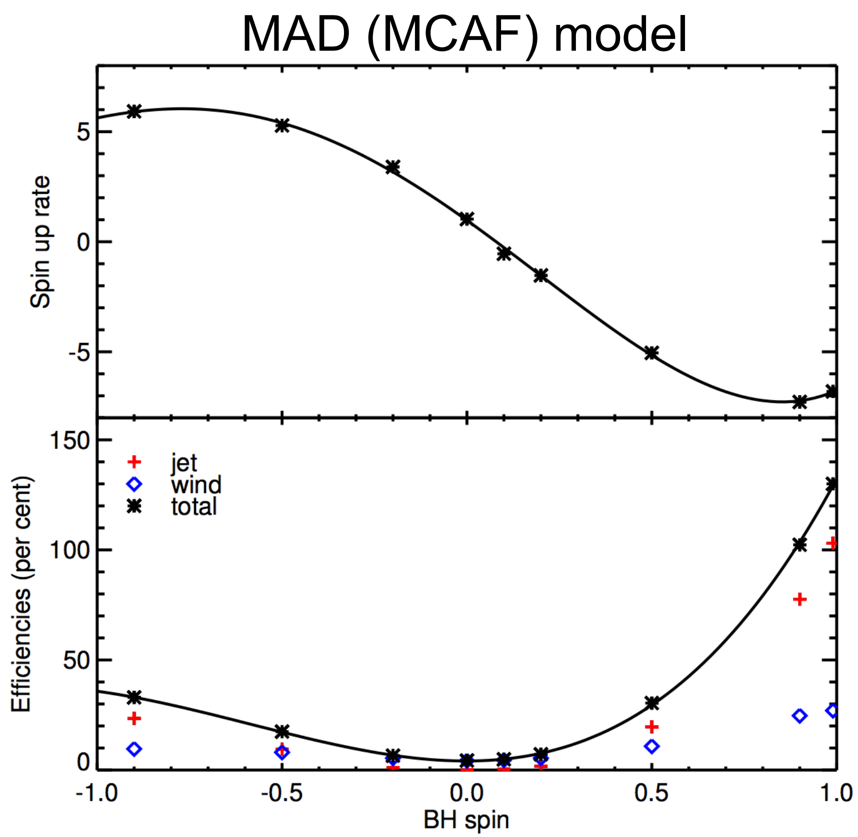
New BH/AGN model

BHs can be completely described by their mass, spin and ~~charge~~ (no hair theorem)

Why are BH spins of any interest for galaxy formation problems???

- **Spins** set the **radiative efficiency** of the accretion disc through the size of its innermost stable circular orbit (ISCO).
- **Radiative efficiency** sets the **Eddington rate** of accretion.
- **Spins** set the **jet mode efficiency** of AGN feedback through magnetically arrested disc (MAD) solutions (McKinney+, 2012; Tchekovskoy+, 2012).
- **Spins** set the AGN **jet orientation.**

Thus, spins change both the intrinsic BH accretion rates and the AGN feedback energy deposit



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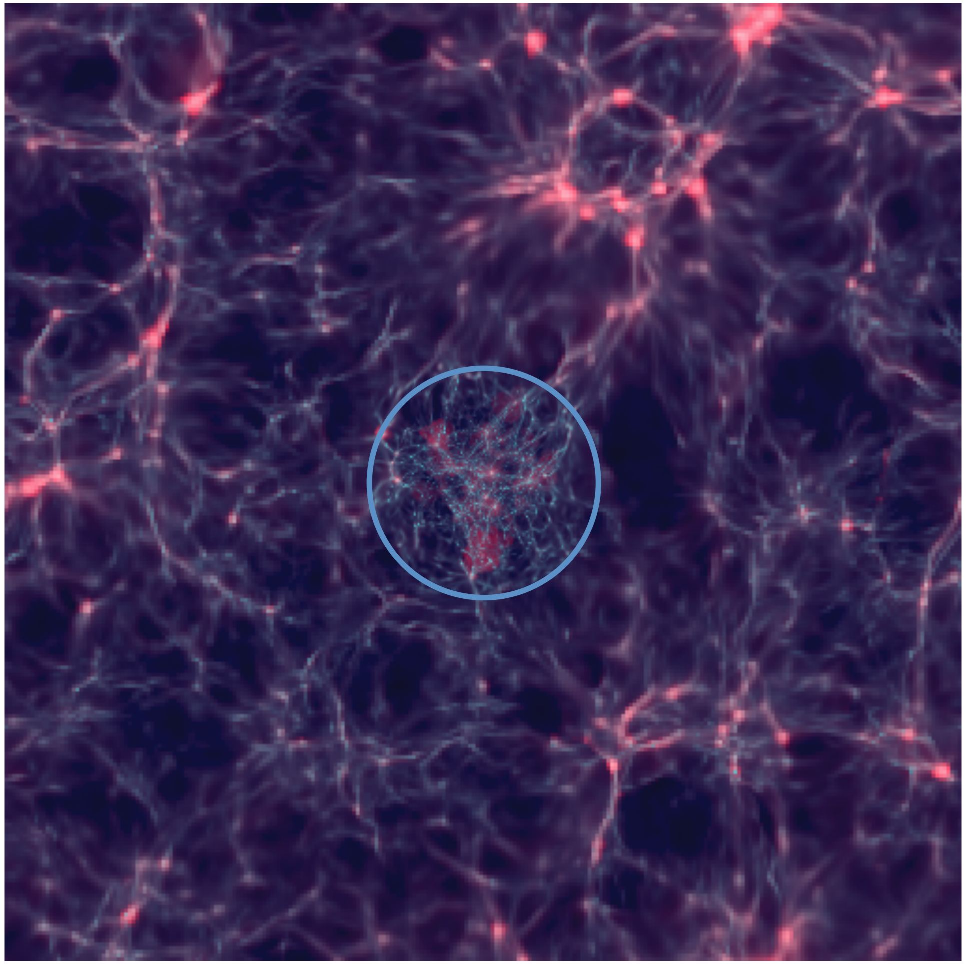
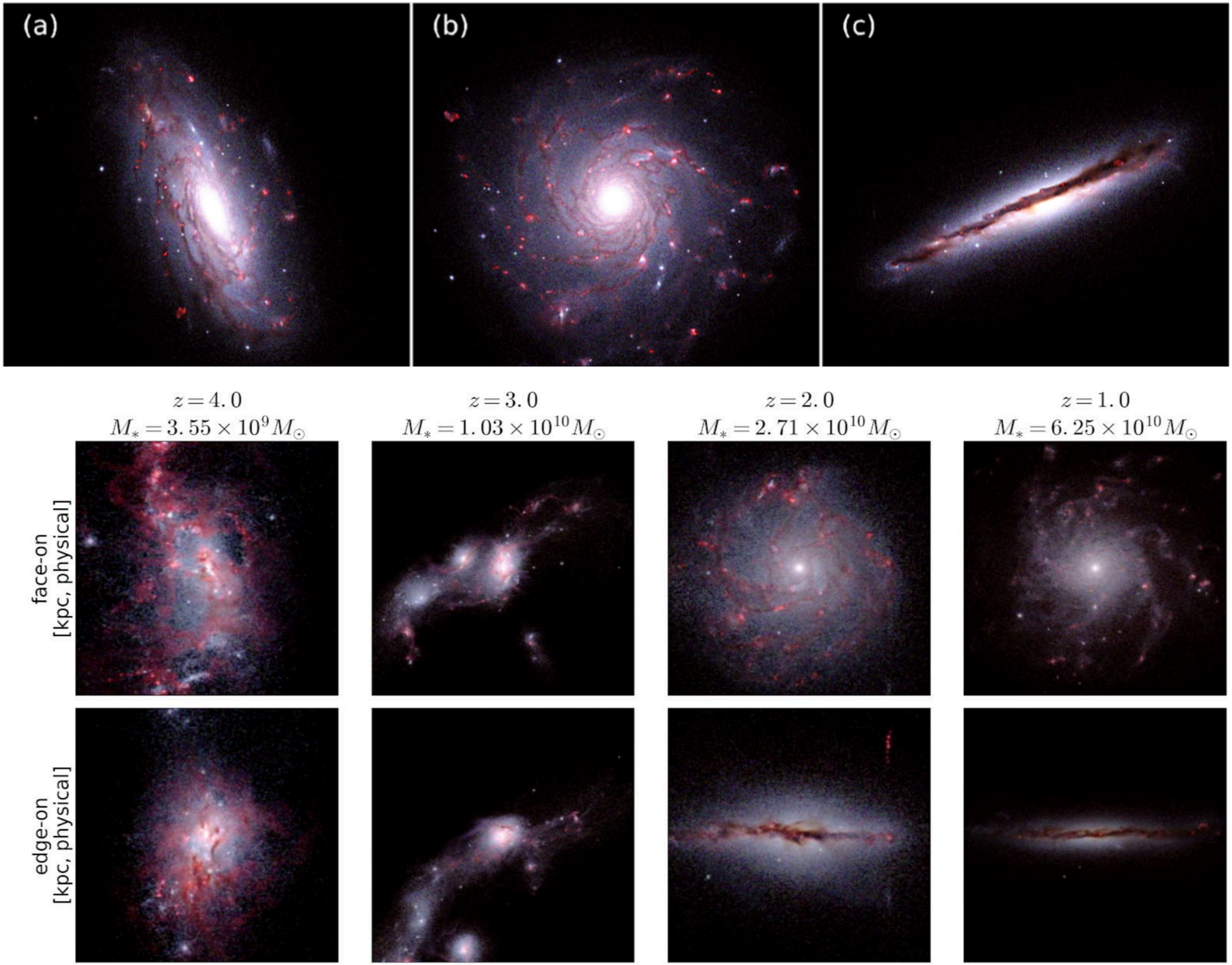
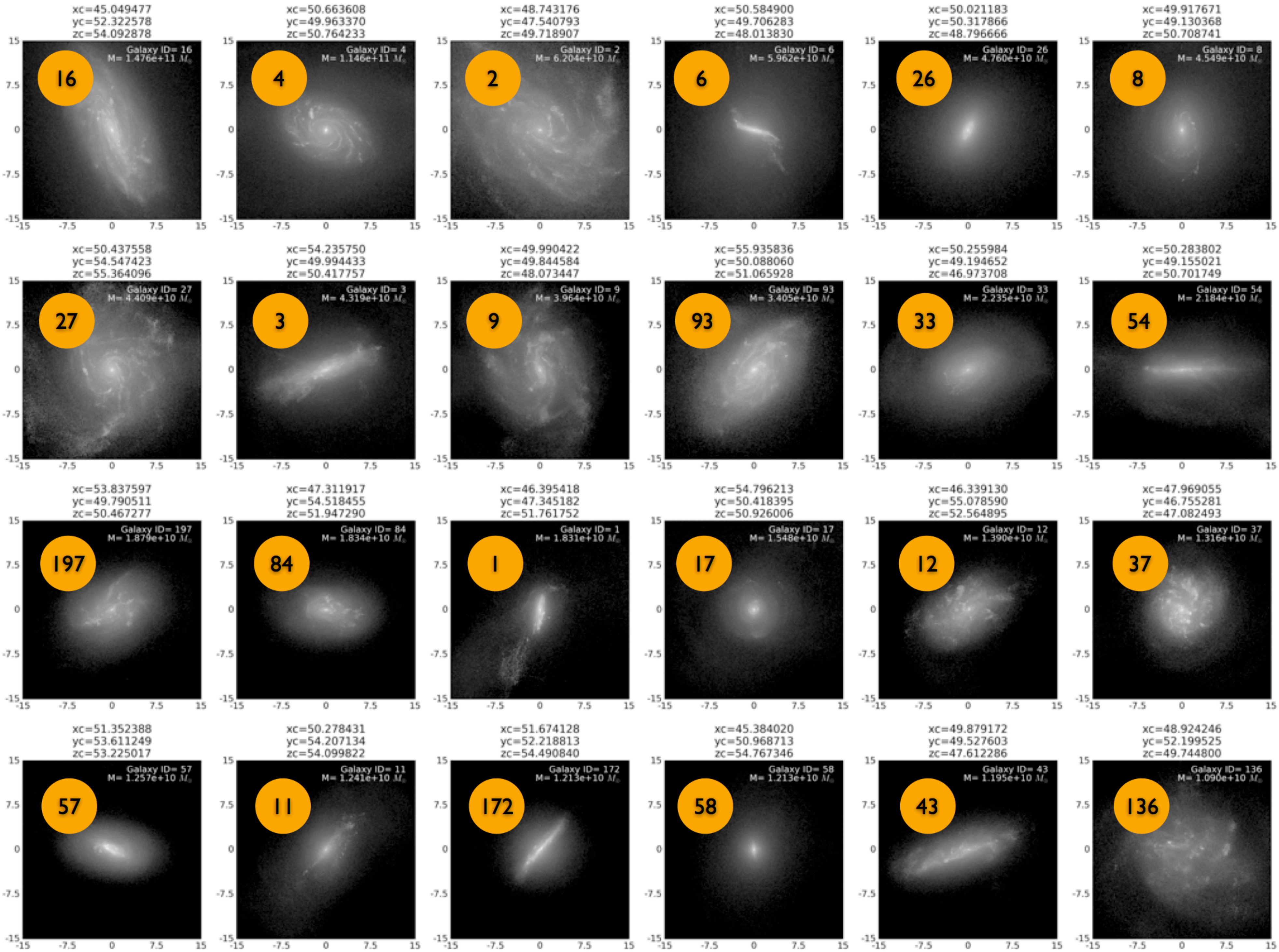
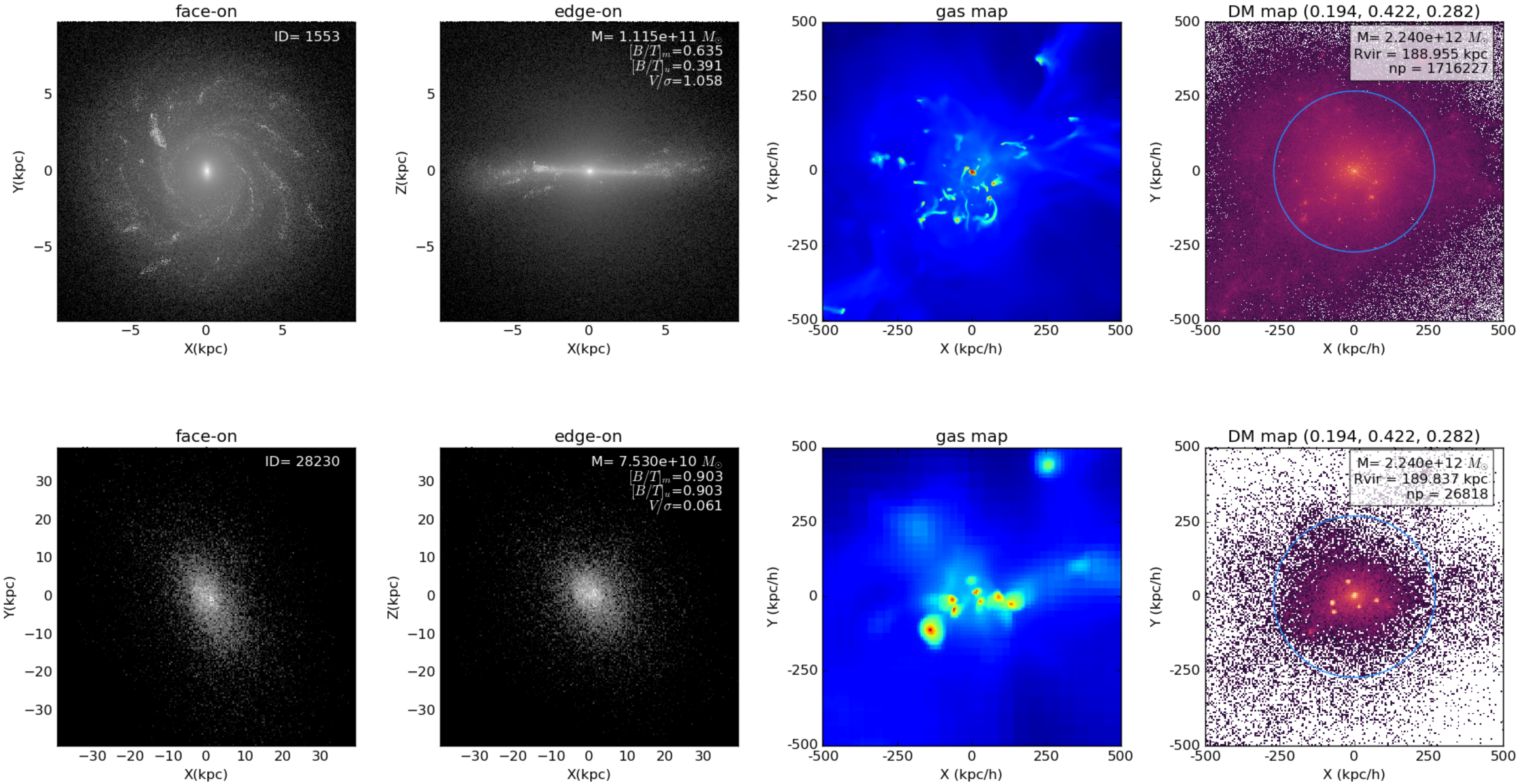


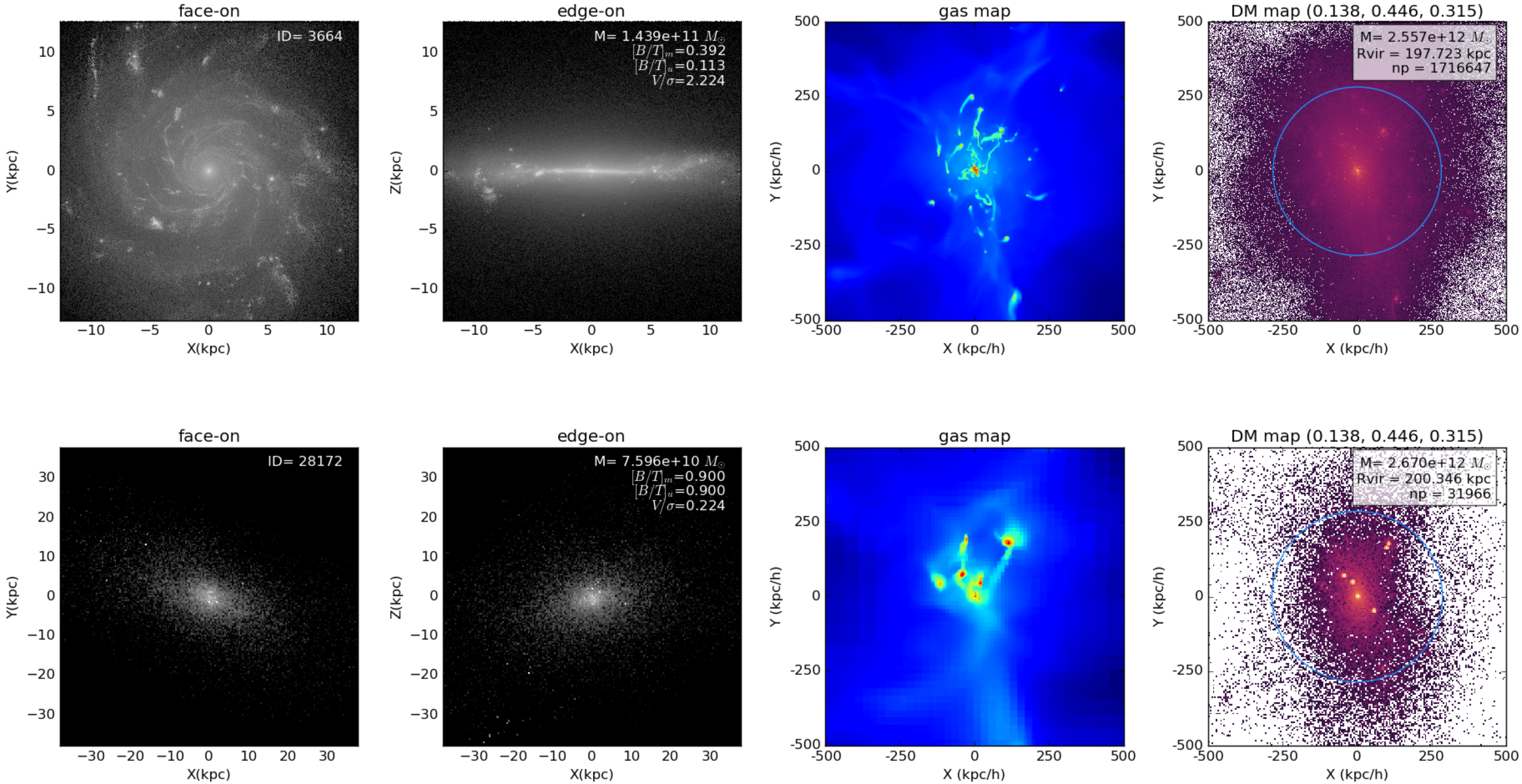

(a)
(b)
(c)
$z = 4.0$
$M_* = 3.55 \times 10^{9} M_\odot$
$z = 3.0$
$M_* = 1.03 \times 10^{10} M_\odot$
$z = 2.0$
$M_* = 2.71 \times 10^{10} M_\odot$
$z = 1.0$
$M_* = 6.25 \times 10^{10} M_\odot$
face-on
[kpc, physical]
edge-on
[kpc, physical]

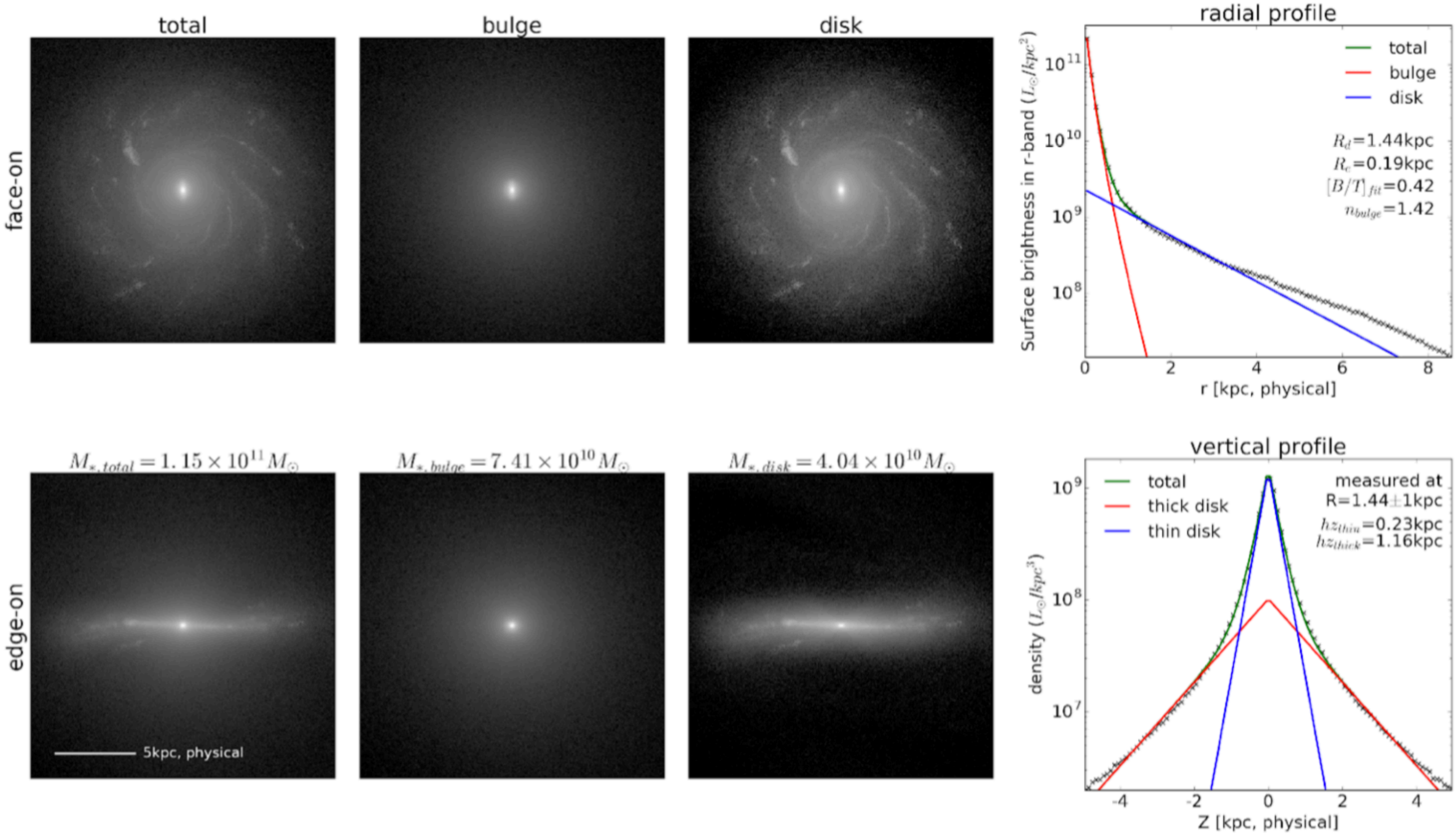

xc=45.049477
yc=52.322578
zc=54.092878
Galaxy ID= 16
M= 1.476e+11 $M_\odot$
16
xc=50.663608
yc=49.963370
zc=50.764233
Galaxy ID= 4
M= 1.146e+11 $M_\odot$
4
xc=48.743176
yc=47.540793
zc=49.718907
Galaxy ID= 2
M= 6.204e+10 $M_\odot$
2
xc=50.584900
yc=49.706283
zc=48.013830
Galaxy ID= 6
M= 5.962e+10 $M_\odot$
6
xc=50.021183
yc=50.317866
zc=48.796666
Galaxy ID= 26
M= 4.760e+10 $M_\odot$
26
xc=49.917671
yc=49.130368
zc=50.708741
Galaxy ID= 8
M= 4.549e+10 $M_\odot$
8
xc=50.437558
yc=54.547423
zc=55.364096
Galaxy ID= 27
M= 4.409e+10 $M_\odot$
27
xc=54.235750
yc=49.994433
zc=50.417757
Galaxy ID= 3
M= 4.319e+10 $M_\odot$
3
xc=49.990422
yc=49.844584
zc=48.073447
Galaxy ID= 9
M= 3.964e+10 $M_\odot$
9
xc=55.935836
yc=50.088060
zc=51.065928
Galaxy ID= 93
M= 3.405e+10 $M_\odot$
93
xc=50.255984
yc=49.194652
zc=46.973708
Galaxy ID= 33
M= 2.235e+10 $M_\odot$
33
xc=50.283802
yc=49.155021
zc=50.701749
Galaxy ID= 54
M= 2.184e+10 $M_\odot$
54
xc=53.837597
yc=49.790511
zc=50.467277
Galaxy ID= 197
M= 1.879e+10 $M_\odot$
197
xc=47.311917
yc=54.518455
zc=51.947290
Galaxy ID= 84
M= 1.834e+10 $M_\odot$
84
xc=46.395418
yc=47.345182
zc=51.761752
Galaxy ID= 1
M= 1.831e+10 $M_\odot$
1
xc=54.796213
yc=50.418395
zc=50.926006
Galaxy ID= 17
M= 1.548e+10 $M_\odot$
17
xc=46.339130
yc=55.078590
zc=52.564895
Galaxy ID= 12
M= 1.390e+10 $M_\odot$
12
xc=47.969055
yc=46.755281
zc=47.082493
Galaxy ID= 37
M= 1.316e+10 $M_\odot$
37
xc=51.352388
yc=53.611249
zc=53.225017
Galaxy ID= 57
M= 1.257e+10 $M_\odot$
57
xc=50.278431
yc=54.207134
zc=54.099822
Galaxy ID= 11
M= 1.241e+10 $M_\odot$
11
xc=51.674128
yc=52.218813
zc=54.490840
Galaxy ID= 172
M= 1.213e+10 $M_\odot$
172
xc=45.384020
yc=50.968713
zc=54.767346
Galaxy ID= 58
M= 1.213e+10 $M_\odot$
58
xc=49.879172
yc=49.527603
zc=47.612286
Galaxy ID= 43
M= 1.195e+10 $M_\odot$
43
xc=48.924246
yc=52.199525
zc=49.744800
Galaxy ID= 136
M= 1.090e+10 $M_\odot$
136
15
7.5
0
-7.5
-15
-15
-7.5
0
7.5
15

Qualitative improvement of galaxy description over Horizon-AGN

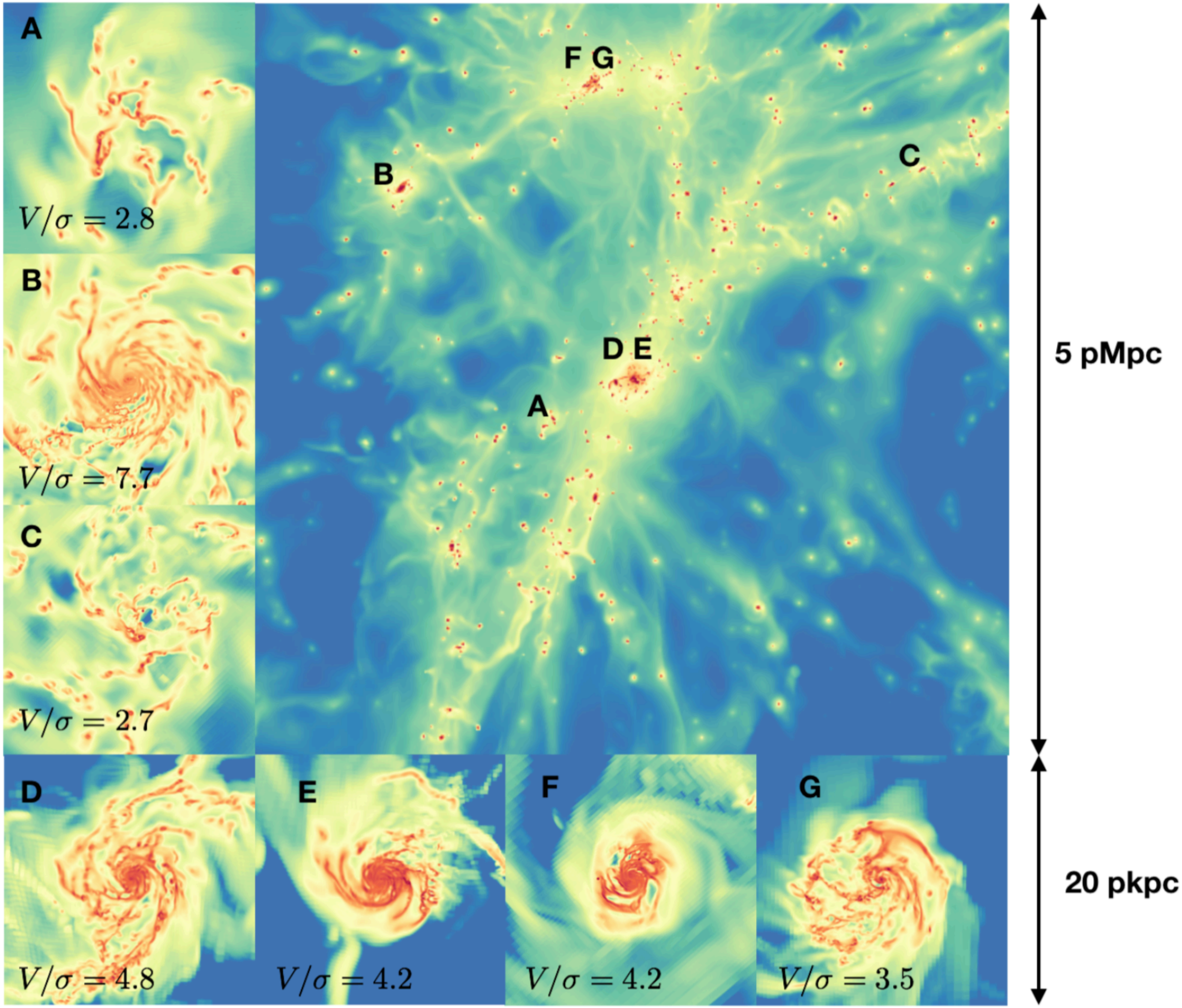


Qualitative improvement of galaxy description over Horizon-AGN



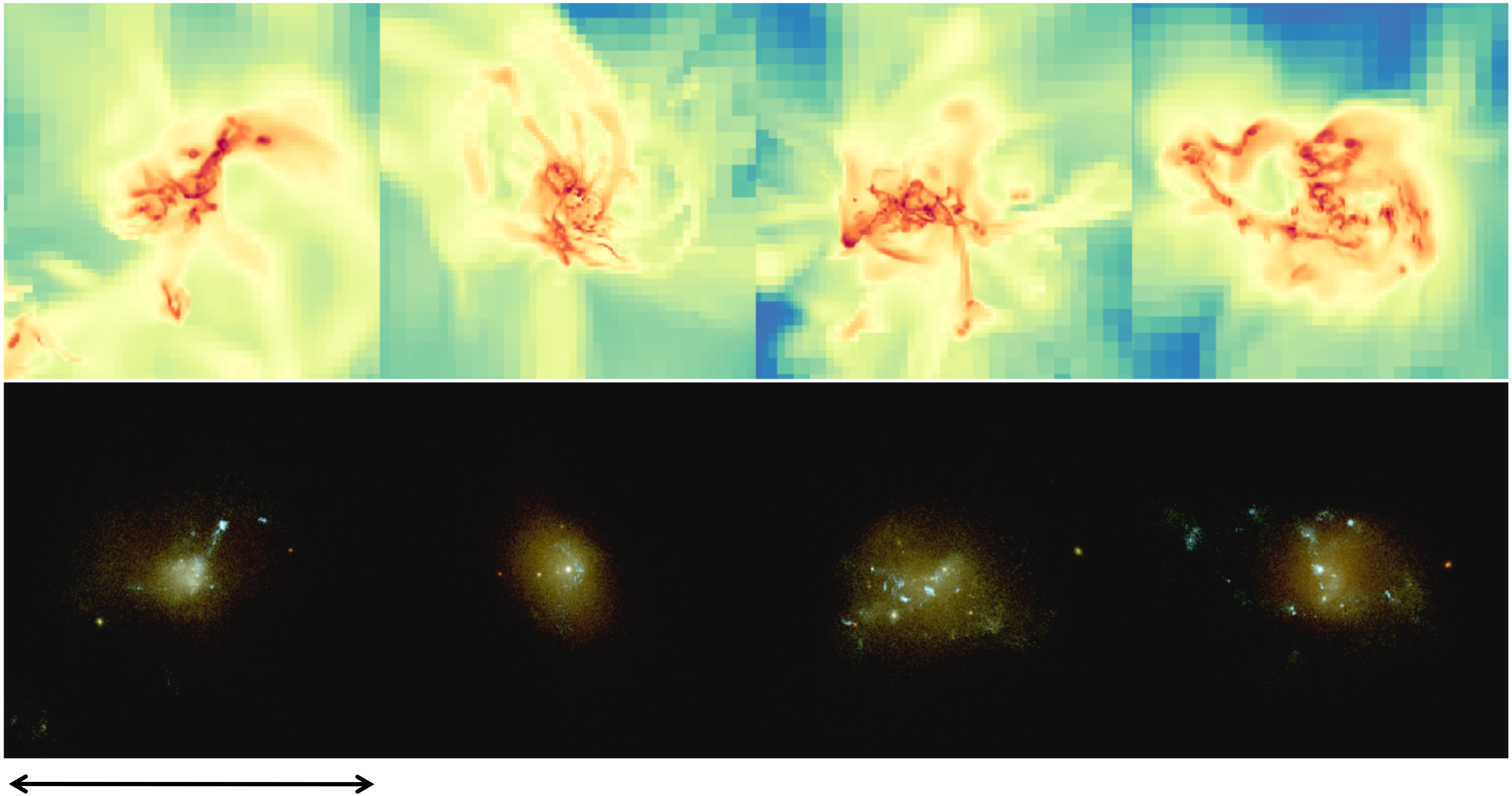


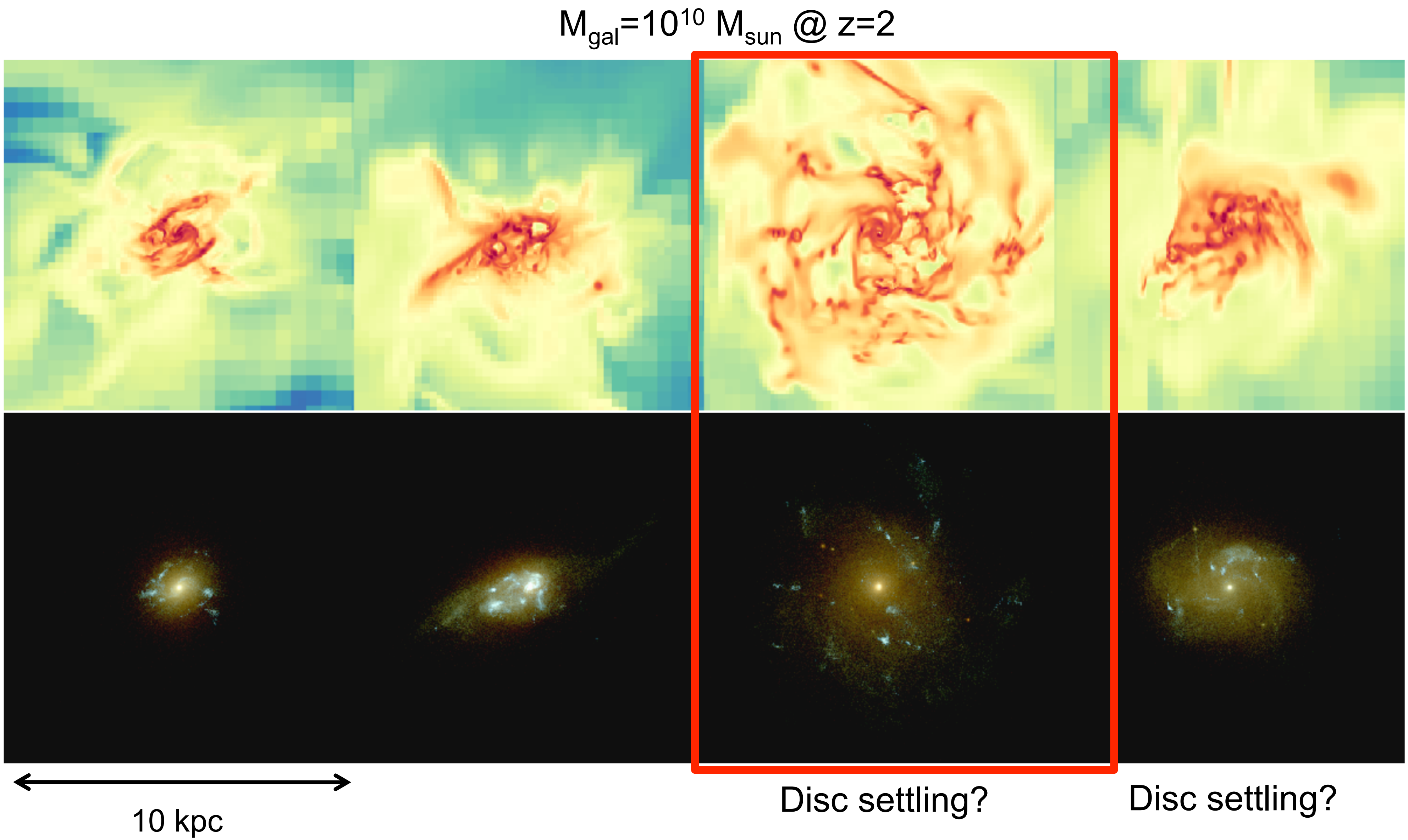
total
bulge
disk
face-on
edge-on
$M_{*,total} = 1.15 \times 10^{11} M_\odot$
$M_{*,bulge} = 7.41 \times 10^{10} M_\odot$
$M_{*,disk} = 4.04 \times 10^{10} M_\odot$
5kpc, physical
radial profile
total
bulge
disk
R_d=1.44kpc
R_e=0.19kpc
$[B/T]_{fit}$=0.42
n_{bulge}=1.42
Surface brightness in r-band ($L_\odot/kpc^2$)
r [kpc, physical]
vertical profile
total
thick disk
thin disk
measured at
R=1.44±1kpc
hz_{thin}=0.23kpc
hz_{thick}=1.16kpc
density ($L_\odot/kpc^3$)
Z [kpc, physical]



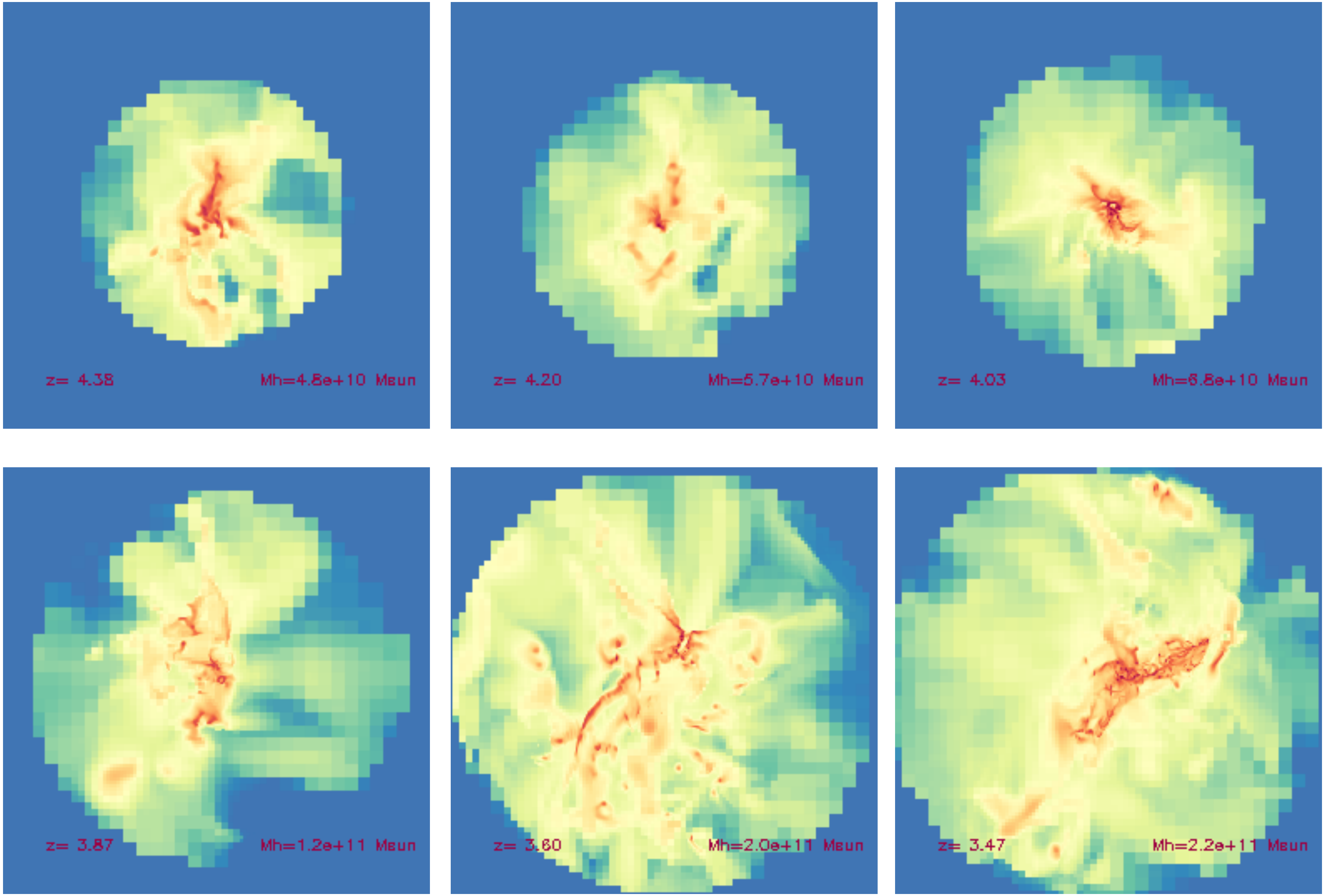
A
$V/\sigma = 2.8$
B
$V/\sigma = 7.7$
C
$V/\sigma = 2.7$
D
$V/\sigma = 4.8$
E
$V/\sigma = 4.2$
F
$V/\sigma = 4.2$
G
$V/\sigma = 3.5$
F G
D E
5 pMpc
20 pkpc

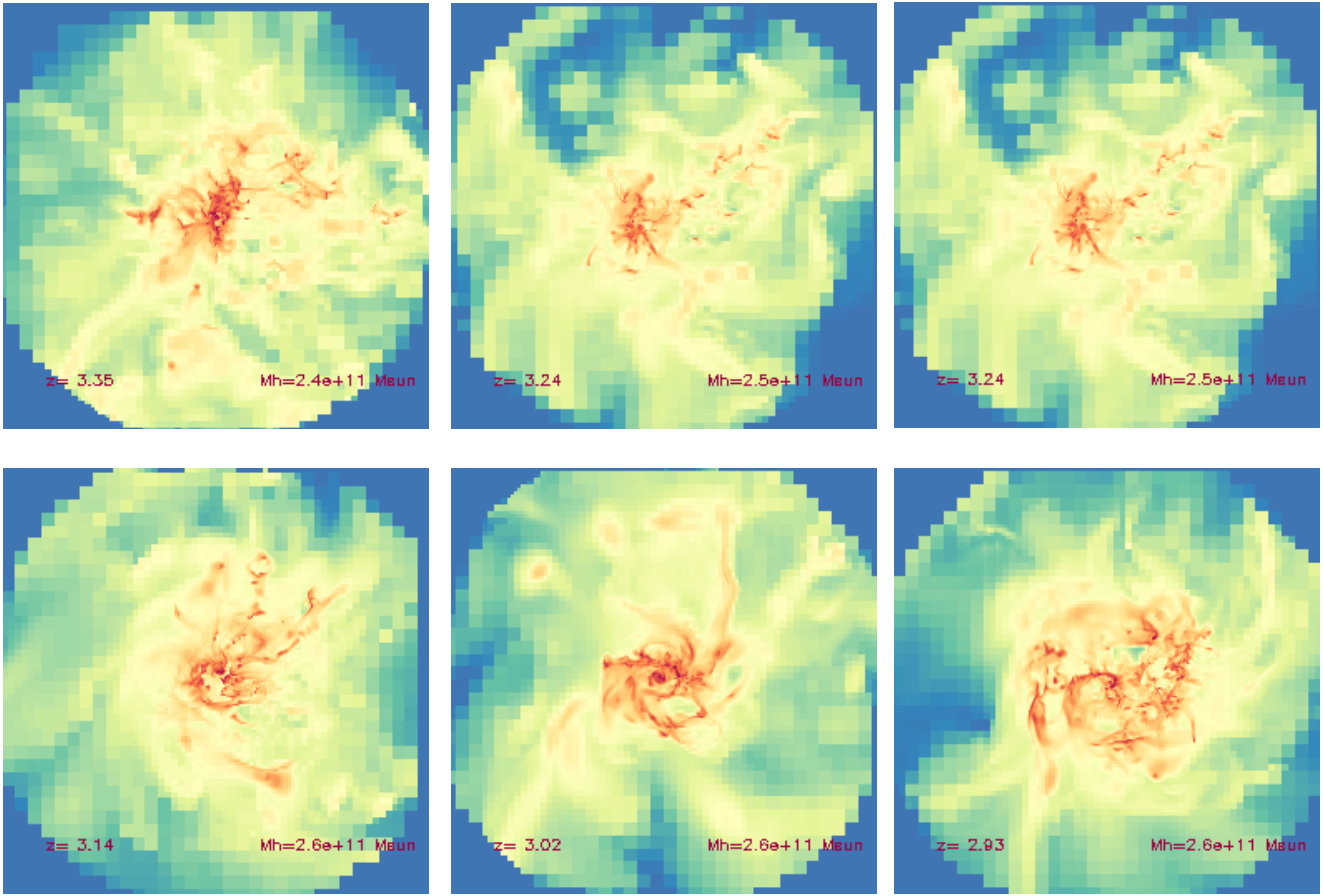
M_{gal}=5x10^{9} M_{sun} @ z=2

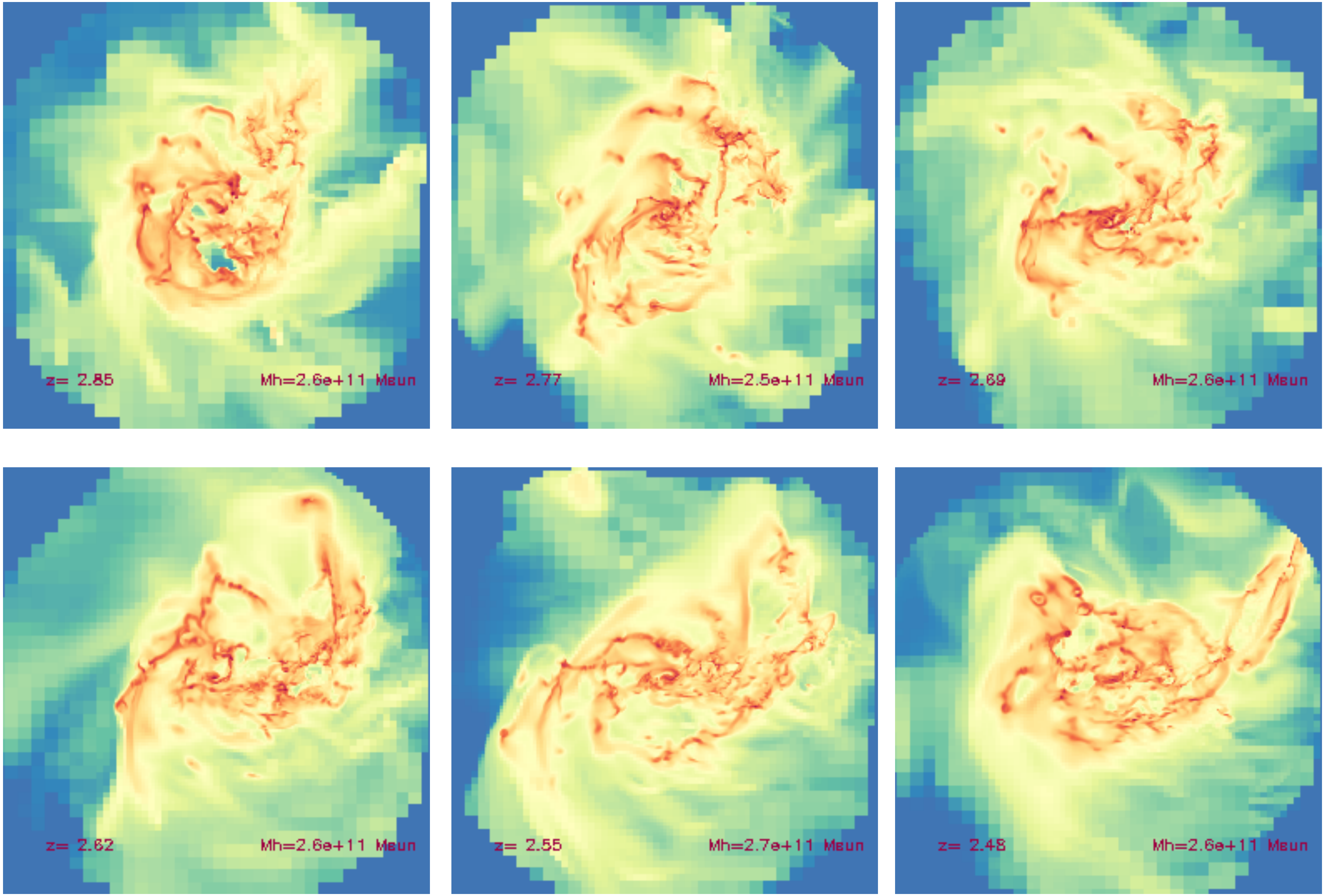


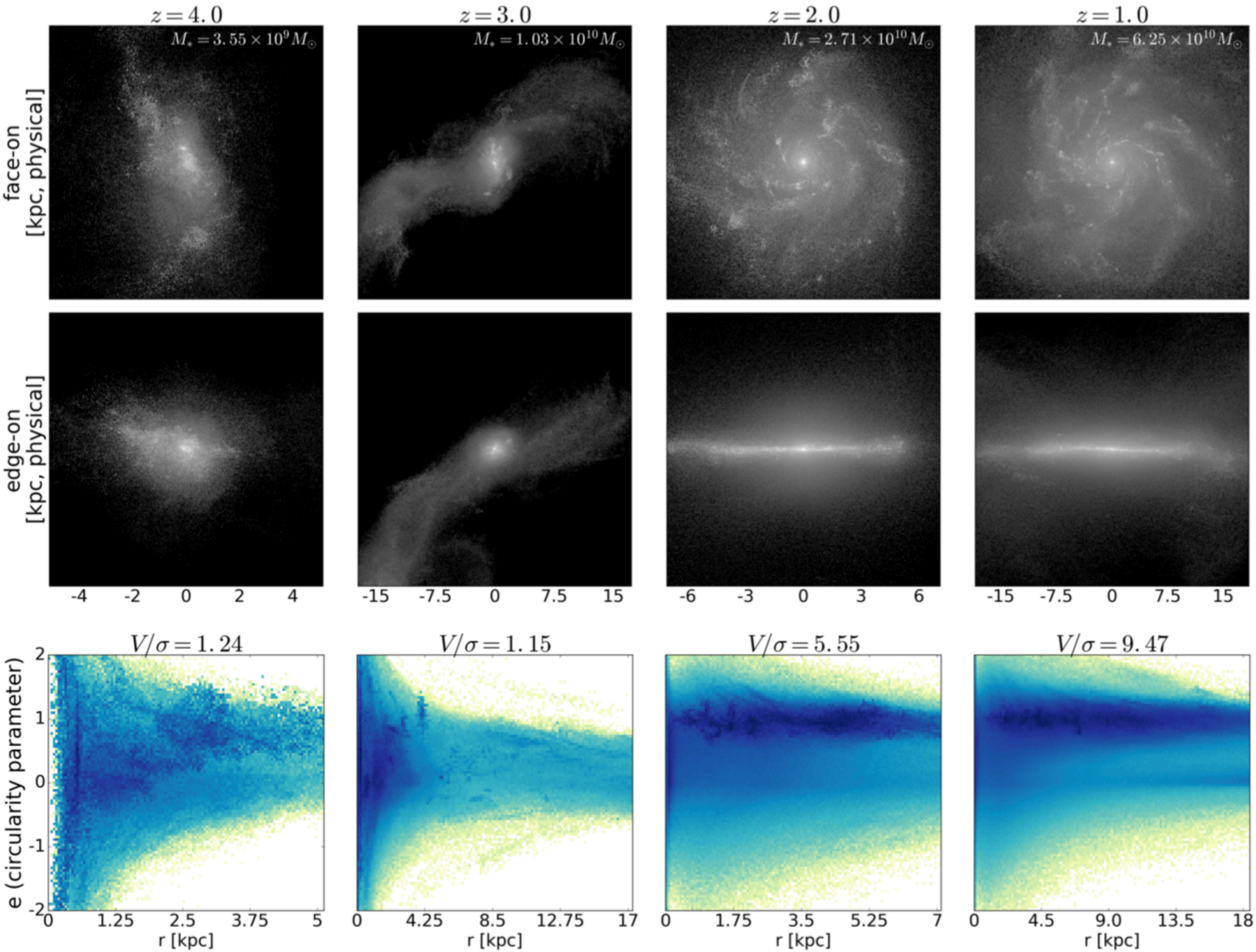


$M_{gal}=10^{10}\ M_{sun}$ @ z=2
10 kpc
Disc settling?
Disc settling?


z= 4.38
Mh=4.8e+10 Msun
z= 4.20
Mh=5.7e+10 Msun
z= 4.03
Mh=6.8e+10 Msun
z= 3.87
Mh=1.2e+11 Msun
z= 3.60
Mh=2.0e+11 Msun
z= 3.47
Mh=2.2e+11 Msun


z= 3.35
Mh=2.4e+11 Msun
z= 3.24
Mh=2.5e+11 Msun
z= 3.24
Mh=2.5e+11 Msun
z= 3.14
Mh=2.6e+11 Msun
z= 3.02
Mh=2.6e+11 Msun
z= 2.93
Mh=2.6e+11 Msun


z= 2.85
Mh=2.6e+11 Msun
z= 2.77
Mh=2.5e+11 Msun
z= 2.69
Mh=2.6e+11 Msun
z= 2.62
Mh=2.6e+11 Msun
z= 2.55
Mh=2.7e+11 Msun
z= 2.48
Mh=2.6e+11 Msun



$z = 4.0$
$z = 3.0$
$z = 2.0$
$z = 1.0$
$M_* = 3.55 \times 10^9 M_\odot$
$M_* = 1.03 \times 10^{10} M_\odot$
$M_* = 2.71 \times 10^{10} M_\odot$
$M_* = 6.25 \times 10^{10} M_\odot$
face-on [kpc, physical]
edge-on [kpc, physical]
-4 -2 0 2 4
-15 -7.5 0 7.5 15
-6 -3 0 3 6
-15 -7.5 0 7.5 15
$V/\sigma = 1.24$
$V/\sigma = 1.15$
$V/\sigma = 5.55$
$V/\sigma = 9.47$
e (circularity parameter)
2 1 0 -1 -2
0 1.25 2.5 3.75 5
0 4.25 8.5 12.75 17
0 1.75 3.5 5.25 7
0 4.5 9.0 13.5 18
r [kpc]

Selecting settled galaxies through their gas kinematics