40 kpc

z = 1.8

IllustrisTNG/TNG50

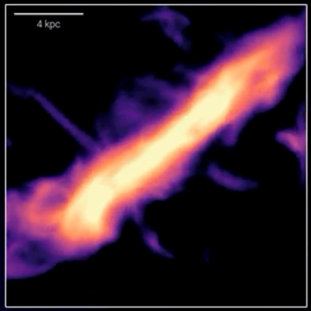
Galaxy assembly, outflows and the evolution of disks with cosmological simulations

ANNALISA PILLEPICH
MPIA, Heidelberg

log $M_\star$ = 9.91

SFR = 8.7 $M_\odot$ yr^{-1}

TNG50



(**)TNG = The Next Generation

Scope of this talk

1. To showcase what the most novel numerical calculations can do, with a focus on the **TNG50 simulation**, the last installment of the IllustrisTNG(**) project.

2. To discuss testable and quantitative model predictions re:
   - The evolution of the **structures and kinematics**
   - Galactic gas **outflows**

   of star-forming galaxies through cosmic time

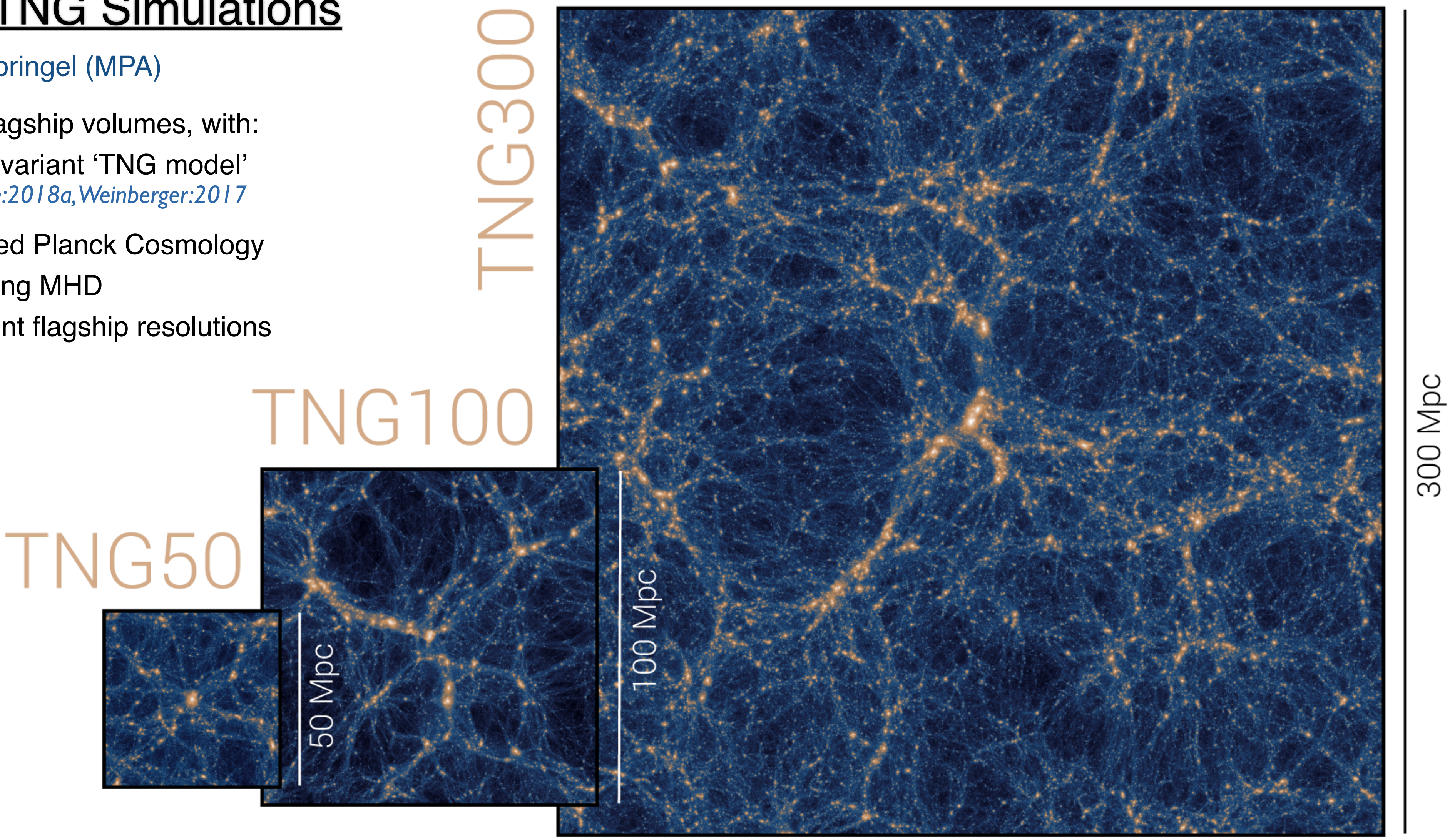
TNG50

The TNG Simulations

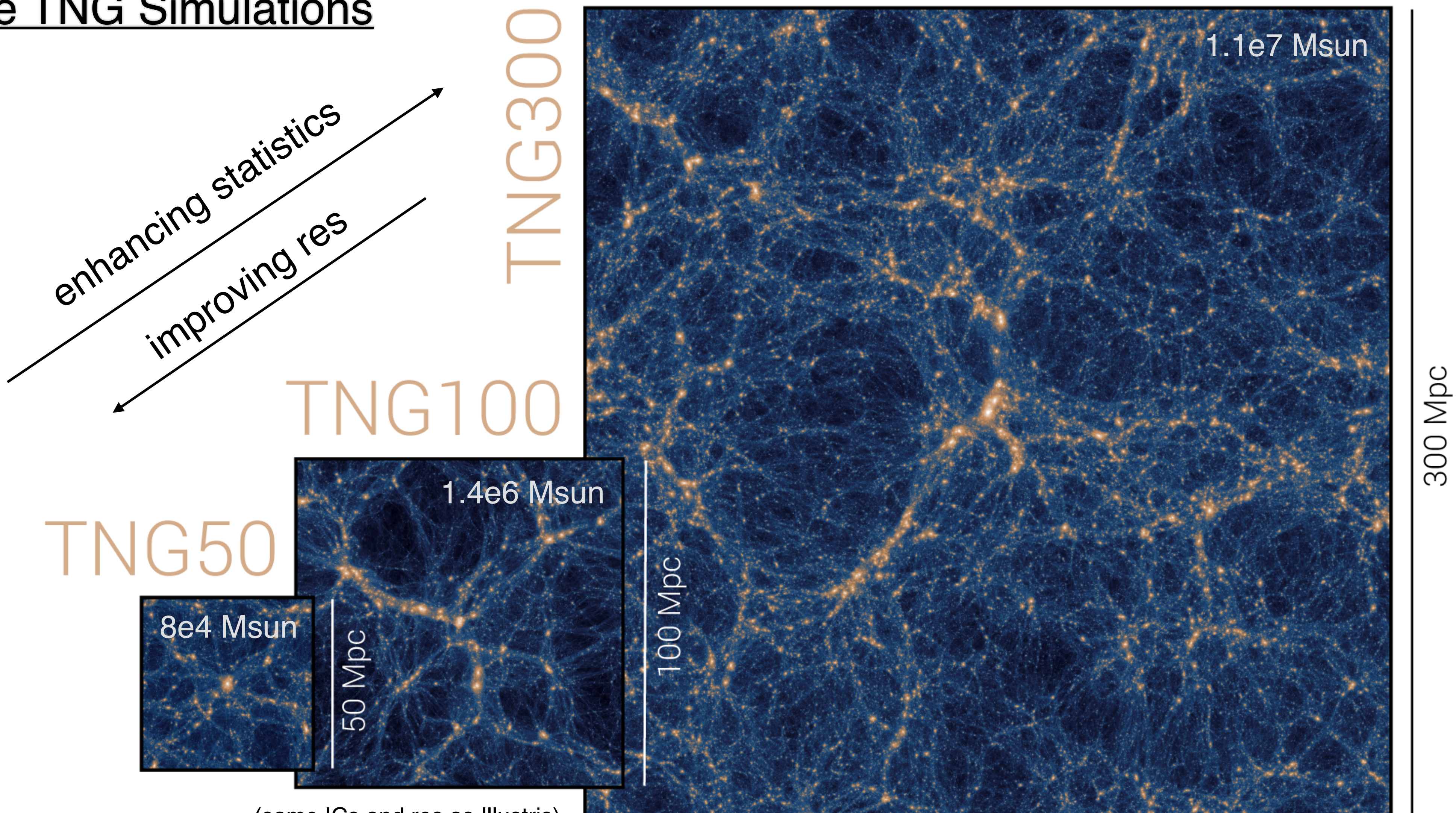
PI: V. Springel (MPA)

Three flagship volumes, with:

- new invariant ‘TNG model’
  Pillepich:2018a, Weinberger:2017
- Updated Planck Cosmology
- Including MHD
- Different flagship resolutions

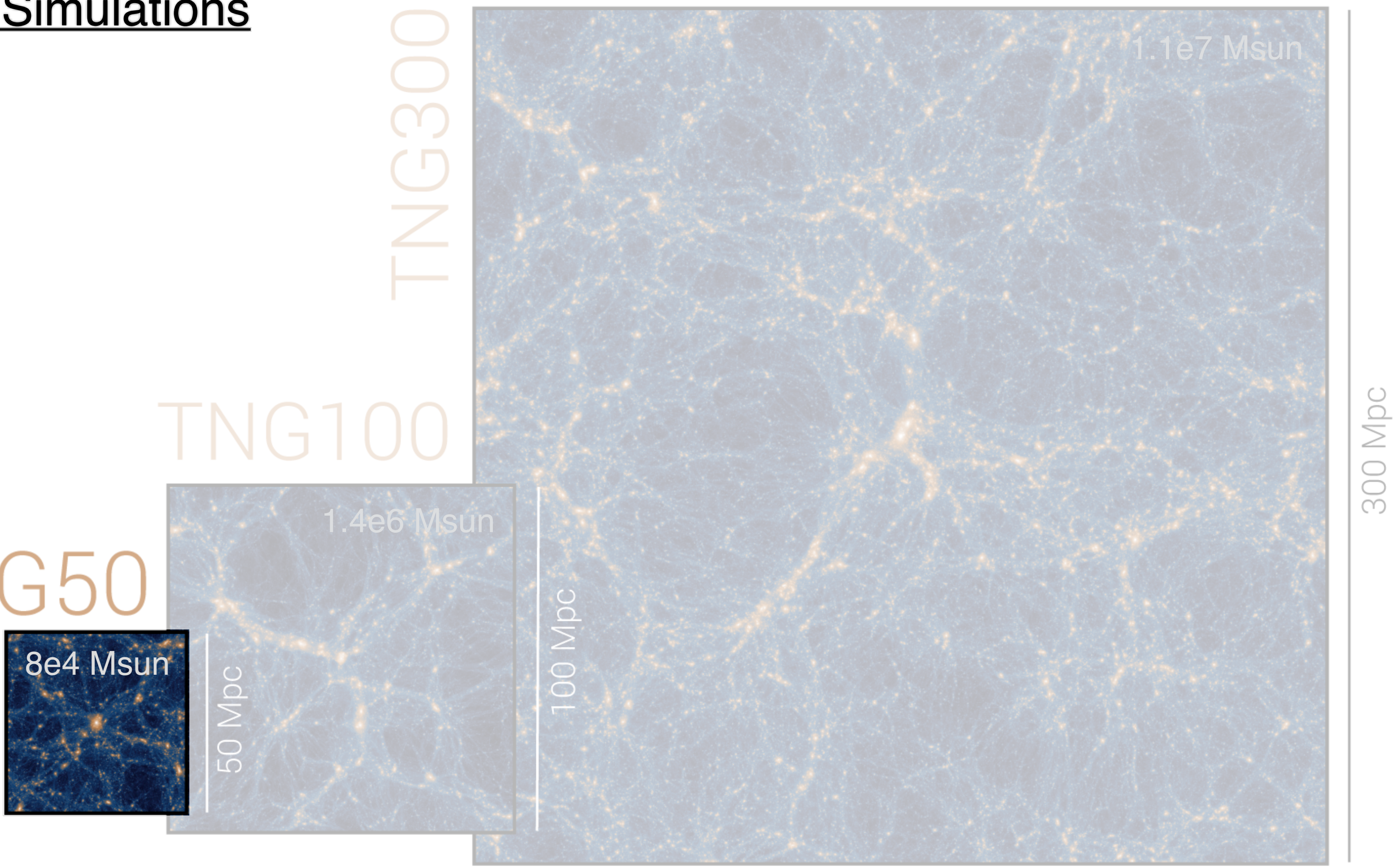


The TNG Simulations



(same ICs and res as Illustris)

The TNG Simulations

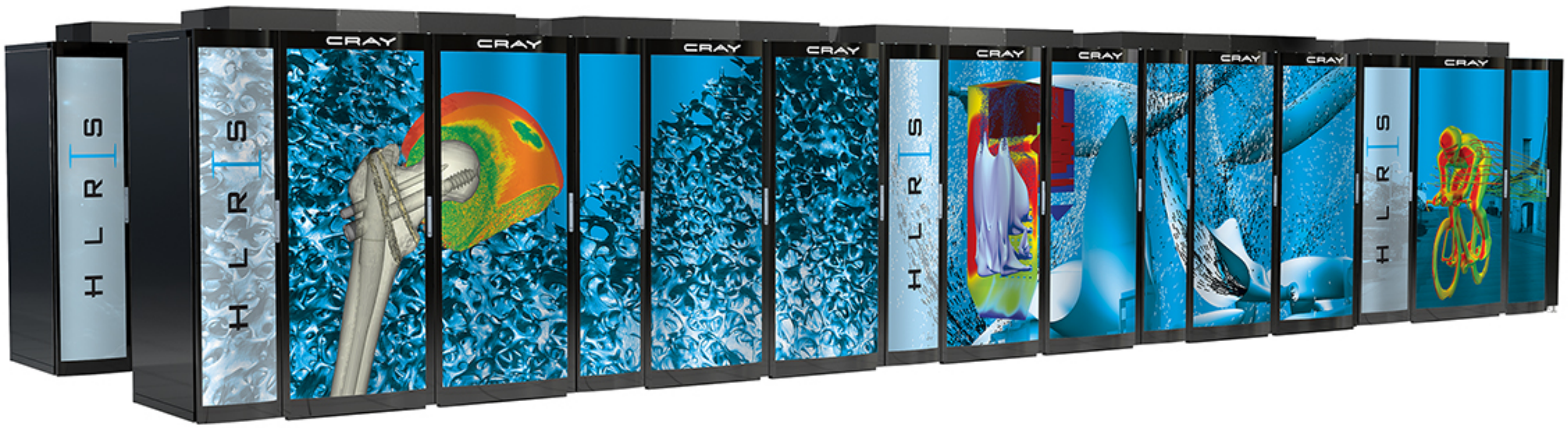


Cosmological volume at zoom resolution

The TNG50 simulation, a field-leading computational endeavour

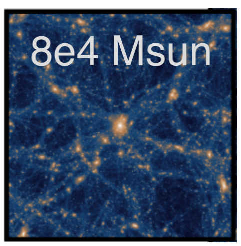
Co-PIs: D. Nelson (MPA), A. Pillepich (MPIA)

HazelHen (Stuttgart)
Cray Cluster
7712 nodes
with 24 cores/node
5.3GB of memory per core!



TNG50

Cosmological volume at zoom resolution



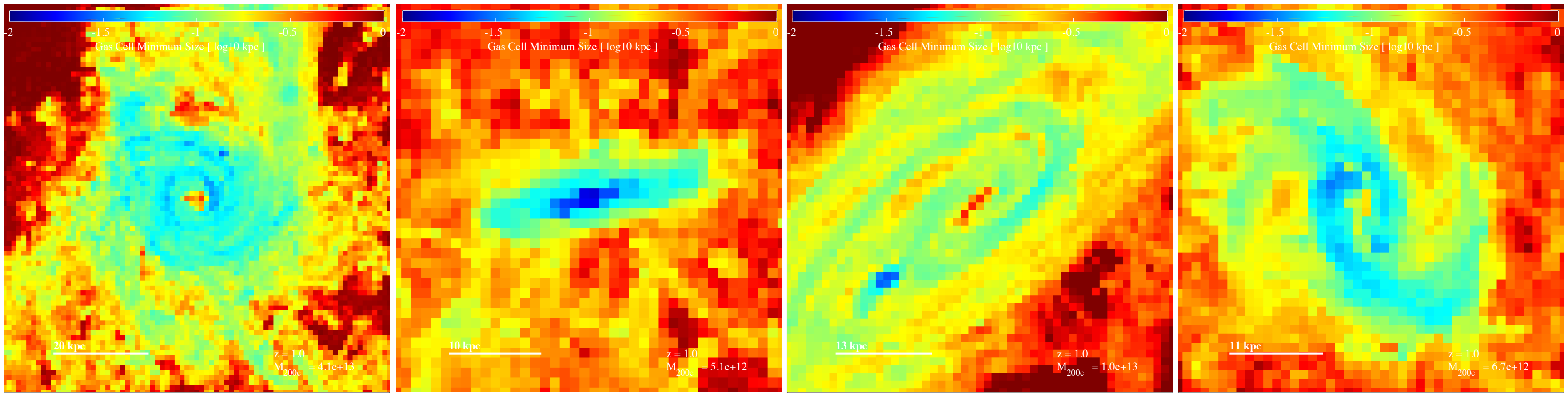
It has run for more than one year, 24/7 on 16k computing cores!

TNG50: Pillepich, Nelson et al. 2019
TNG50: Nelson, Pillepich et al. 2019

The TNG50 simulation: unprecedented resolution for unbiased statistics

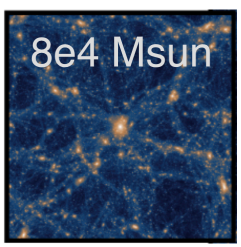
Co-PIs: D. Nelson (MPA), A. Pillepich (MPIA)

10 com pc ——— spatial resolution ——— 100 com pc ——— spatial resolution ——— 1 com kpc



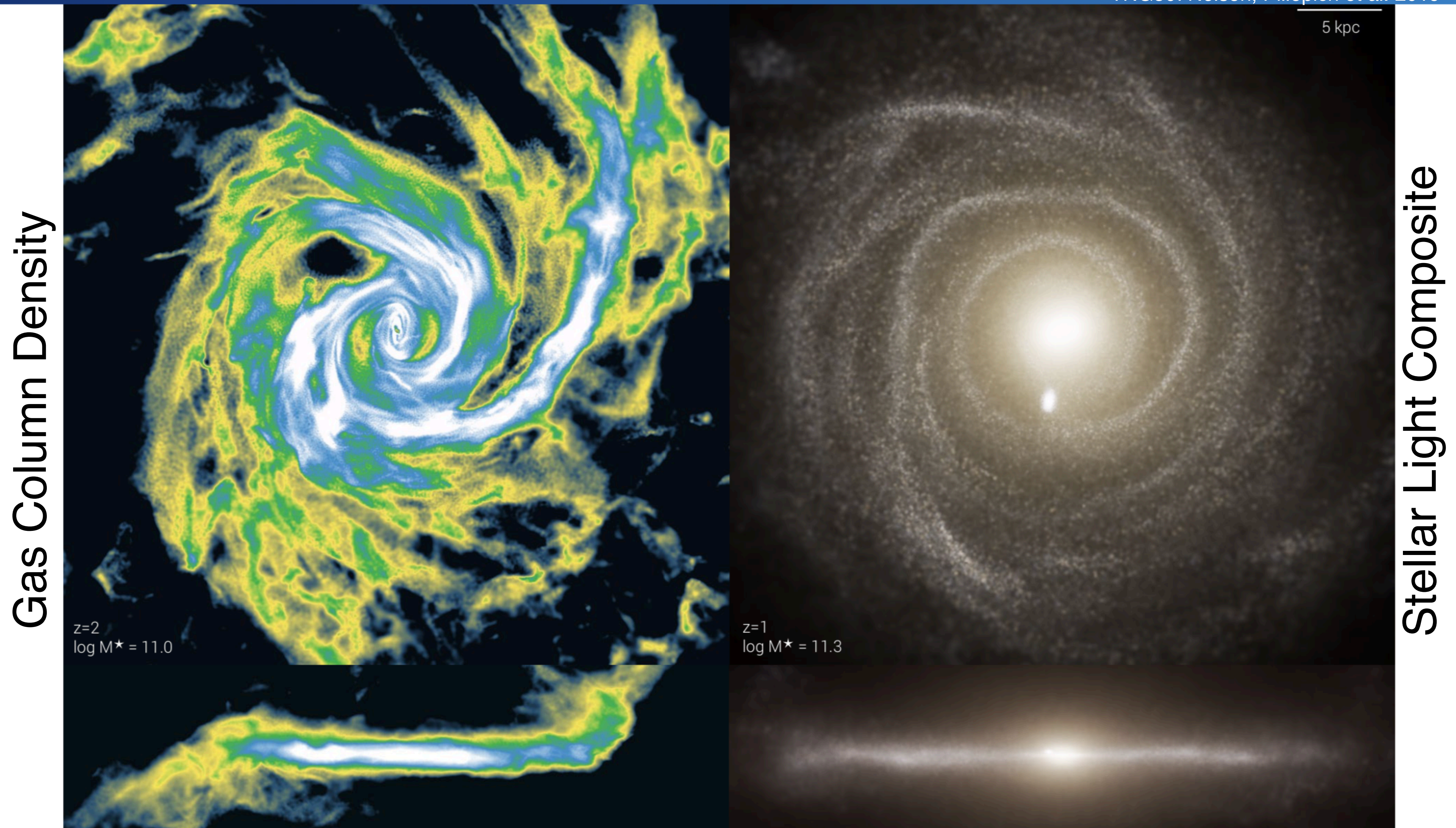
TNG50

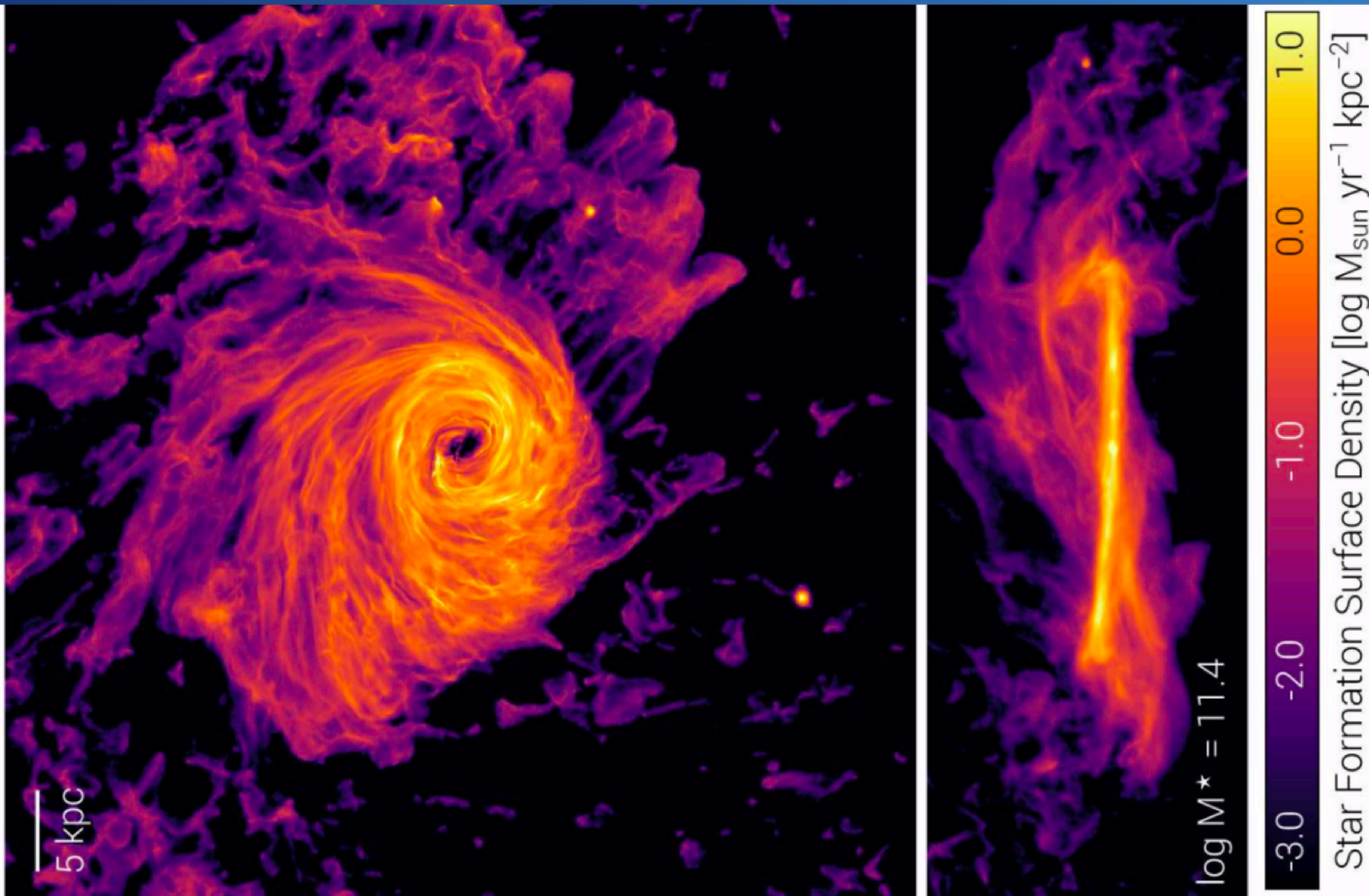
Cosmological volume at zoom resolution



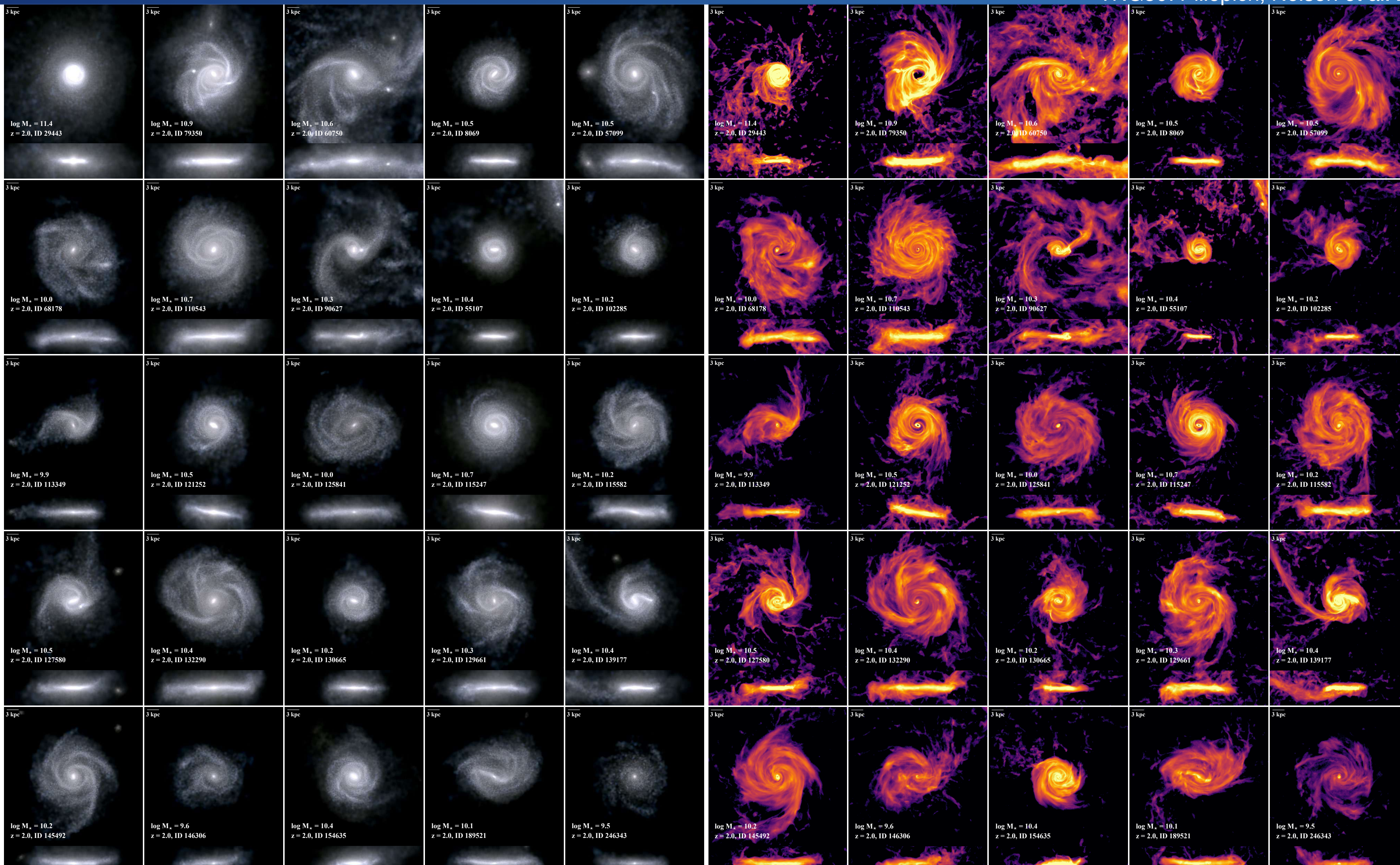
Star-formation and (stellar) feedback are sub grid below the 70-140pc scale

TNG50: Pillepich, Nelson et al. 2019
TNG50: Nelson, Pillepich et al. 2019

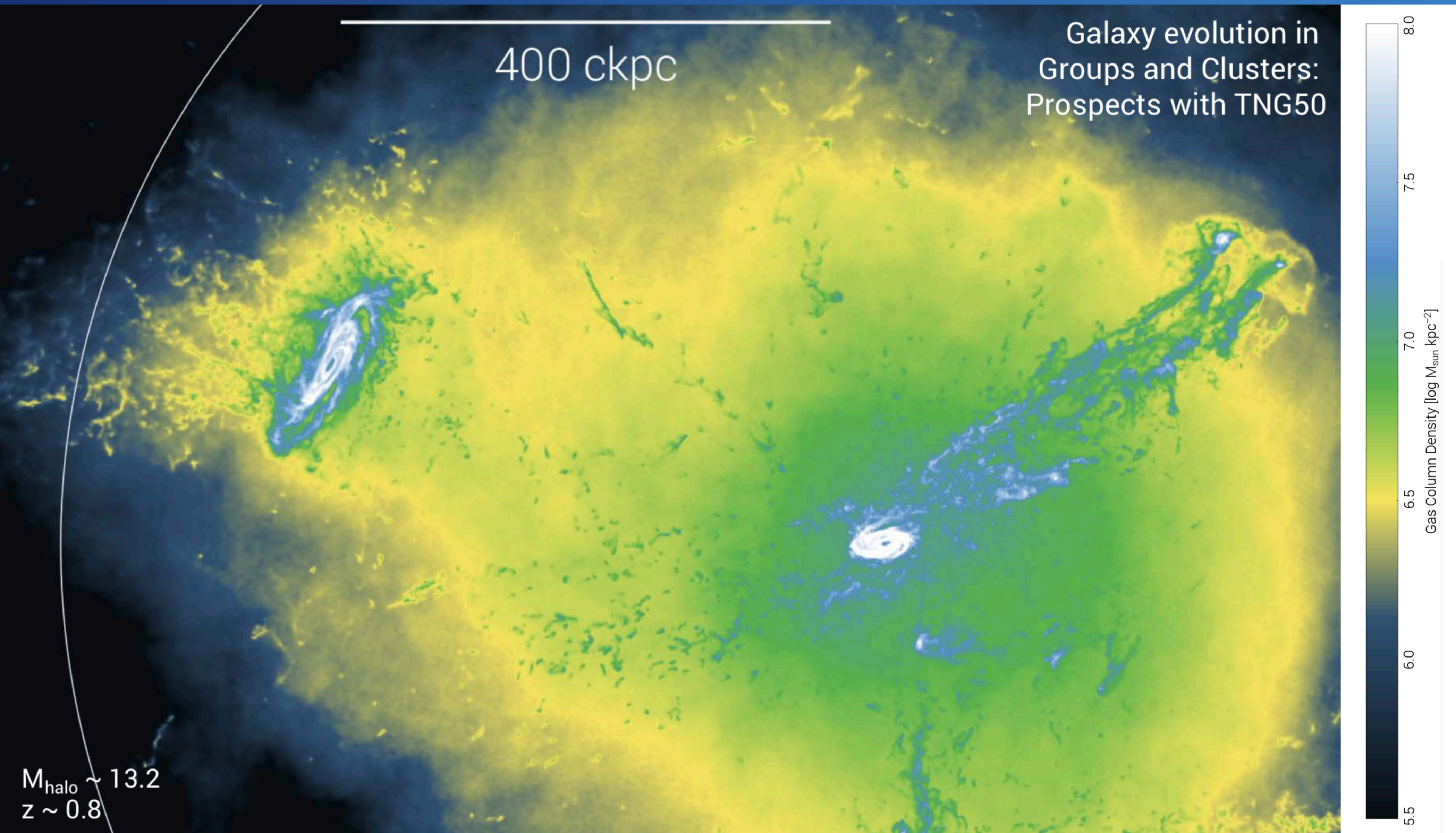

Gas Column Density
z=2
log M★ = 11.0
5 kpc
z=1
log M★ = 11.3
Stellar Light Composite

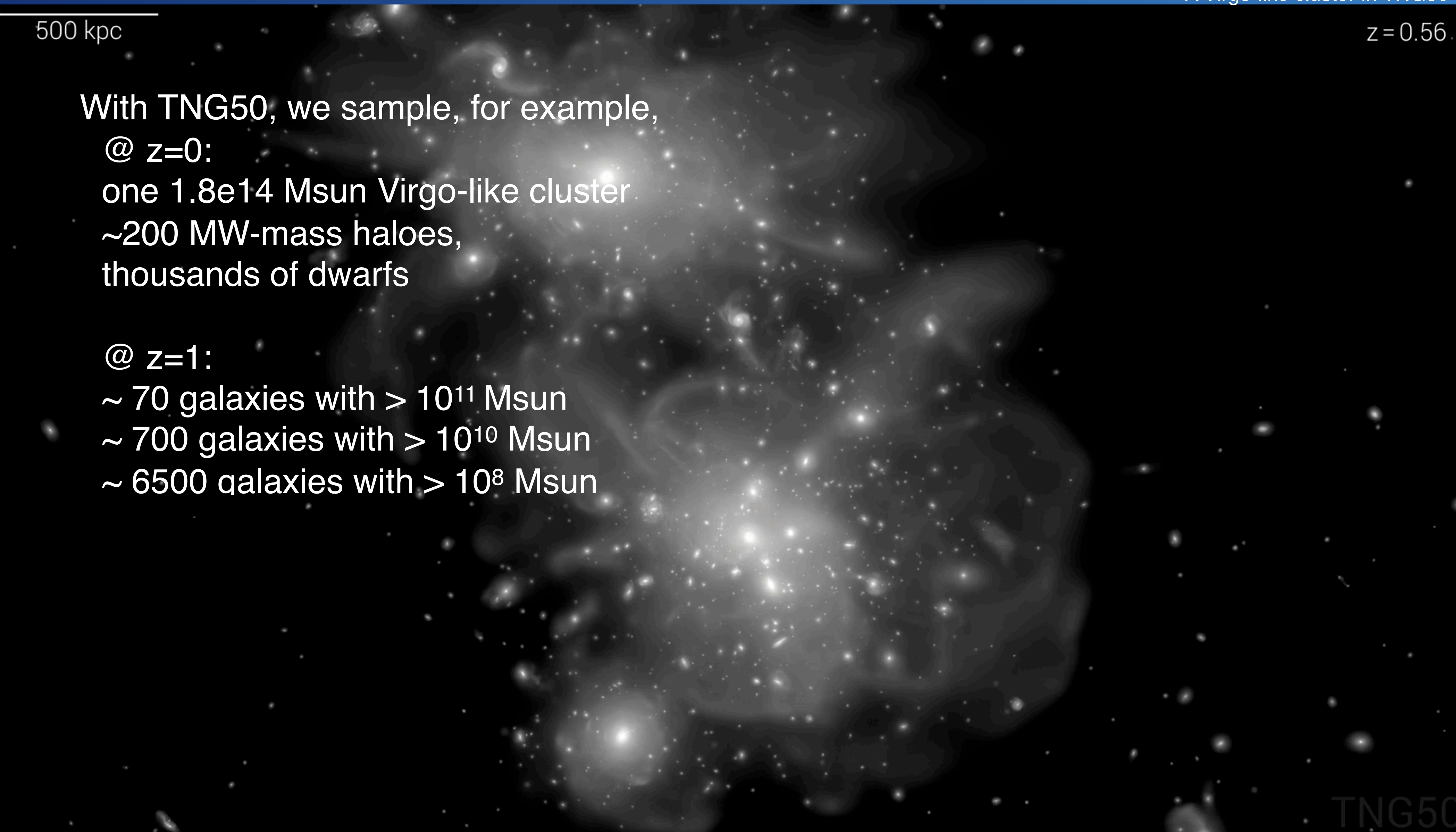

5 kpc
log M⋆ = 11.4
-3.0
-2.0
-1.0
0.0
1.0
Star Formation Surface Density [log M_{sun} yr^{-1} kpc^{-2}]

Stellar Light composite



Hα light


400 ckpc
Galaxy evolution in
Groups and Clusters:
Prospects with TNG50
8.0
7.5
7.0
6.5
6.0
5.5
Gas Column Density [log M_sun kpc^-2]
M_halo ~ 13.2
z ~ 0.8



With TNG50, we sample, for example,

@ z=0:

one 1.8e14 Msun Virgo-like cluster

~200 MW-mass haloes,

thousands of dwarfs

@ z=1:

~ 70 galaxies with > 10^{11} Msun

~ 700 galaxies with > 10^{10} Msun

~ 6500 galaxies with > 10^{8} Msun

The physical ingredients behind large-volume cosmological sims

Cosmological gas accretion (i.e. accretion rates), galaxy mergers and galaxy interactions, tidal and ram pressure stripping, dynamical friction, any form of gravitational "heating" are self-consistent

↑

COSMOLOGICAL ICs (LCDM)
GRAVITY+HYDRODYNAMICS

Gas Cooling/Heating ◣
■ Conversion of gas into stars (TNG: density threshold)
Stellar Evolution ◣
Metal Enrichment (TNG: H, He, Fe, C, Mg, …) ◣
■ Stellar Feedback (TNG: decoupled winds)
■ Black Hole Seed and Growth
■ Black Hole Feedback (TNG: high vs. low accret)

→ gas outflows and recycling

■ Subgrid recipes

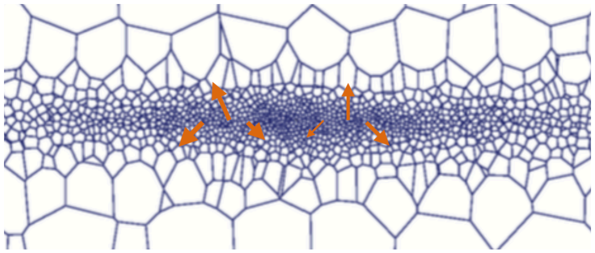
◣ Via "tables"

What sets apart the TNG model from previous calculations

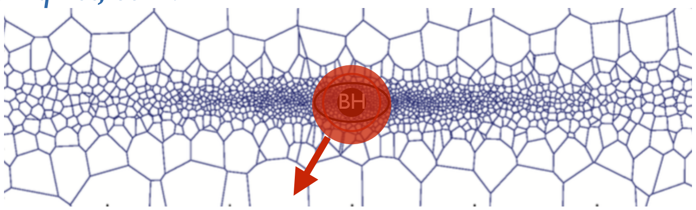
0. The moving-mesh code AREPO
Springel 2010

1. Magnetic fields (MHD follows the self-consistent amplification of a primordial field)
Pakmor et al. 2013, 2014, 2017

2. Updated galactic scale wind (stellar) feedback (compared to e.g. Illustris)
Pillepich, Springel, Nelson et al. 2018a



3. Novel two-mode scheme for SMBH feedback, particularly the new "kinetic" BH-driven pulsated wind
Weinberger, Springel, Hernquist, et al. 2017



4. Updated Yield tables, metal tracking + Neutron-star mergers sub grid recipes for production of Europium
Naiman, Pillepich et al. 2018
Pillepich, Springel, Nelson et al. 2018a

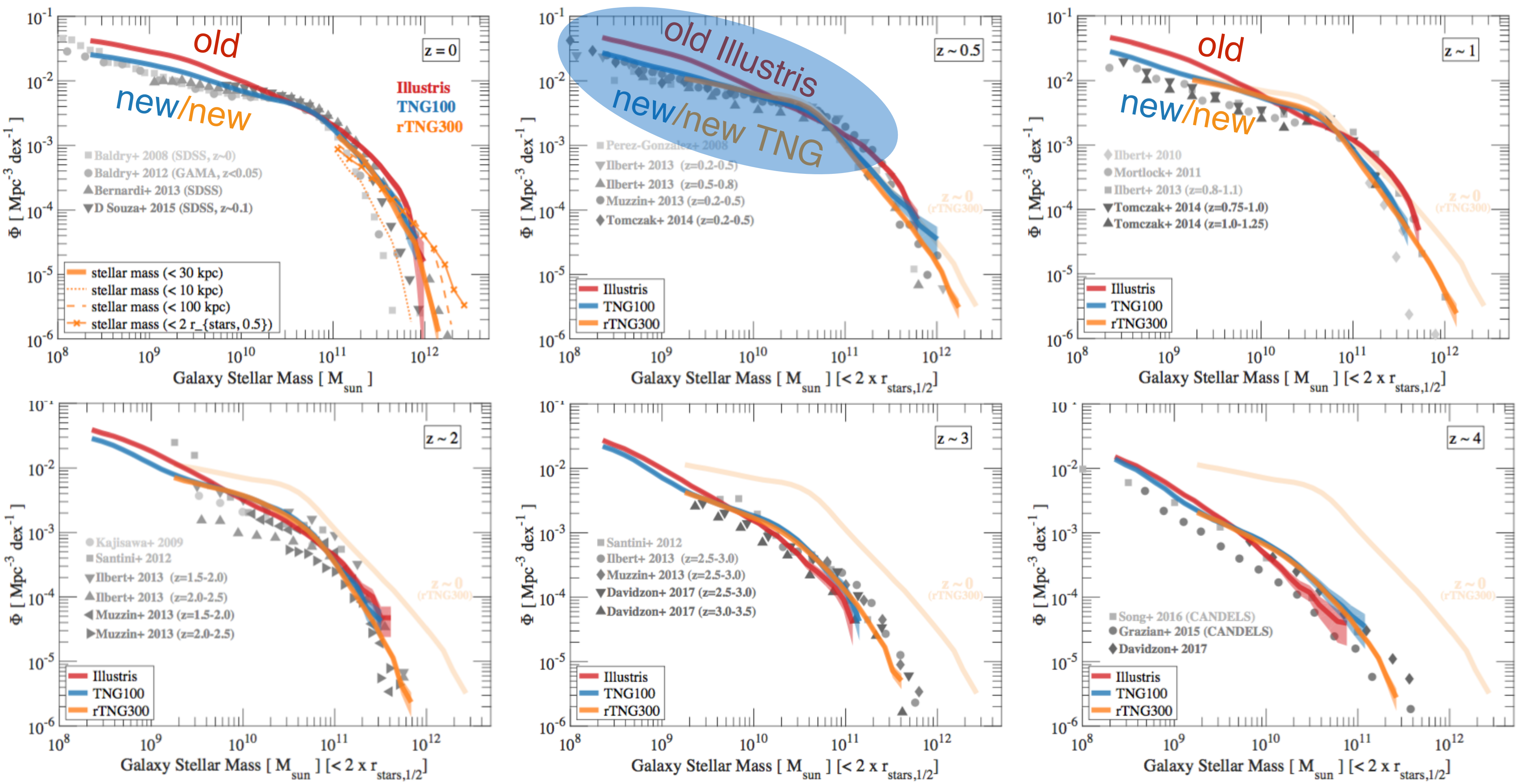
5. The augmented and unprecedented scope

Schaal & Springel 2015
\+ The Shock finder, new output strategy, ….

On reproducing observed galaxy statistics and integral properties

i.e. on model validations

The TNG galaxy mass functions have reasonable shapes (z = 0, 1, …4)

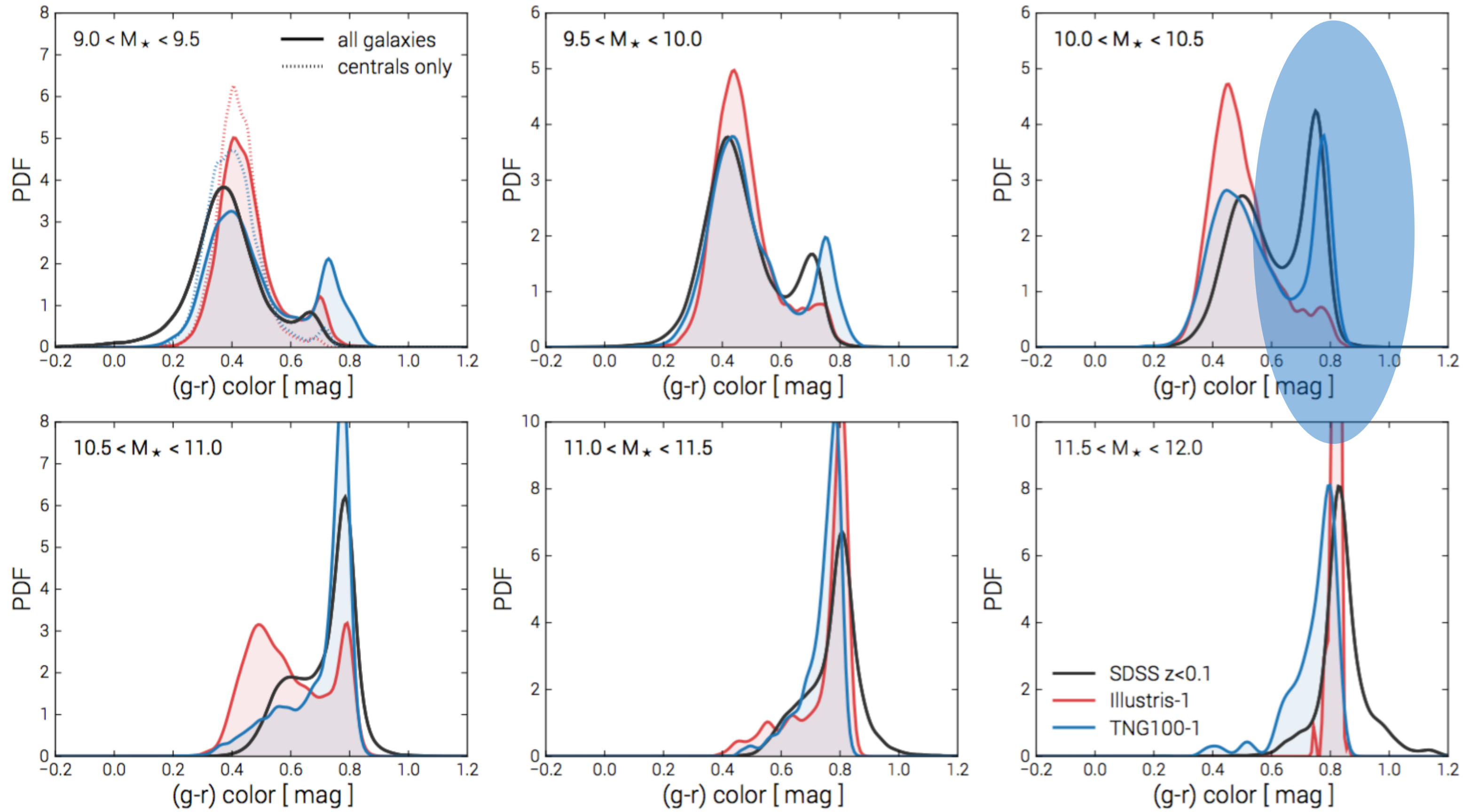


TNG100/TNG300: Pillepich, Nelson, Hernquist, et al. 2018b

The TNG color bimodality is in quantitative agreement with SDSS

SDSS
Illustris/TNG

Note: We obtain galaxy colors by accounting for the unresolved and resolved effects of dust

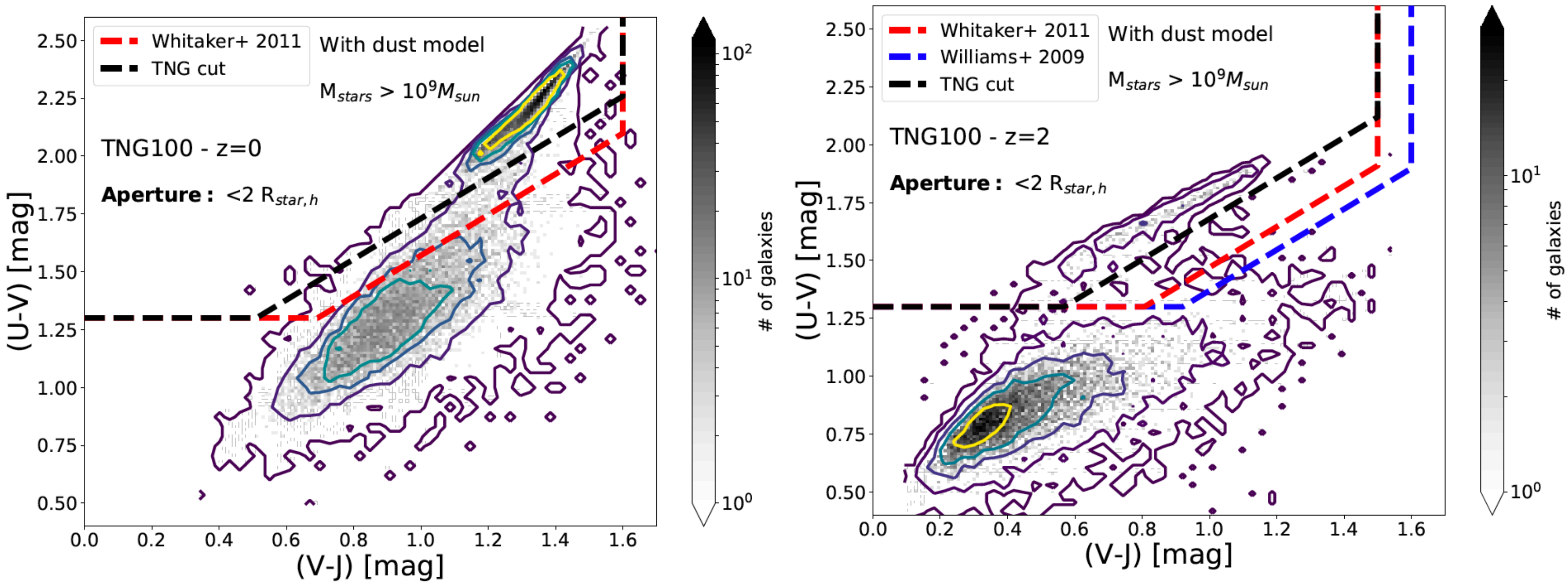


The blue/red balance shifts towards larger masses, and TNG recovers the abundance of red galaxies at the high mass end

Nelson, Pillepich, Springel, et al. 2018

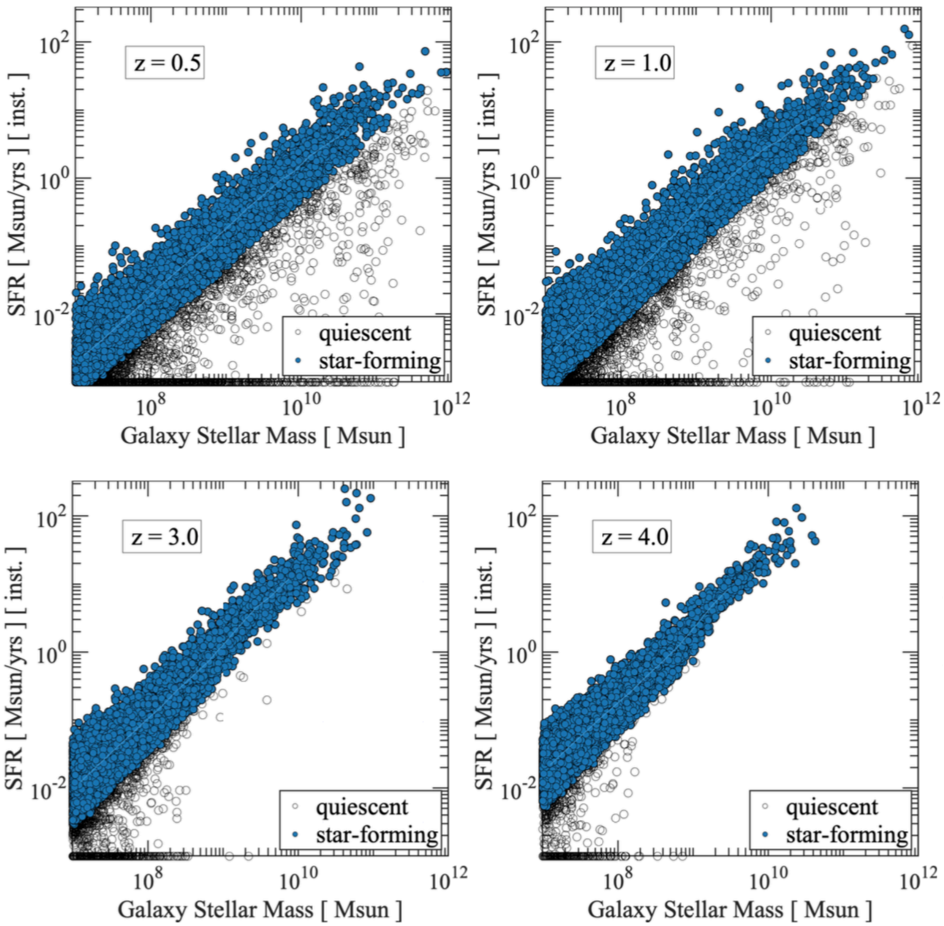
The z=0-2 UVJ diagram exhibit two clearly-separated classes of galaxies

Note: We obtain galaxy colors by accounting for the unresolved and resolved effects of dust



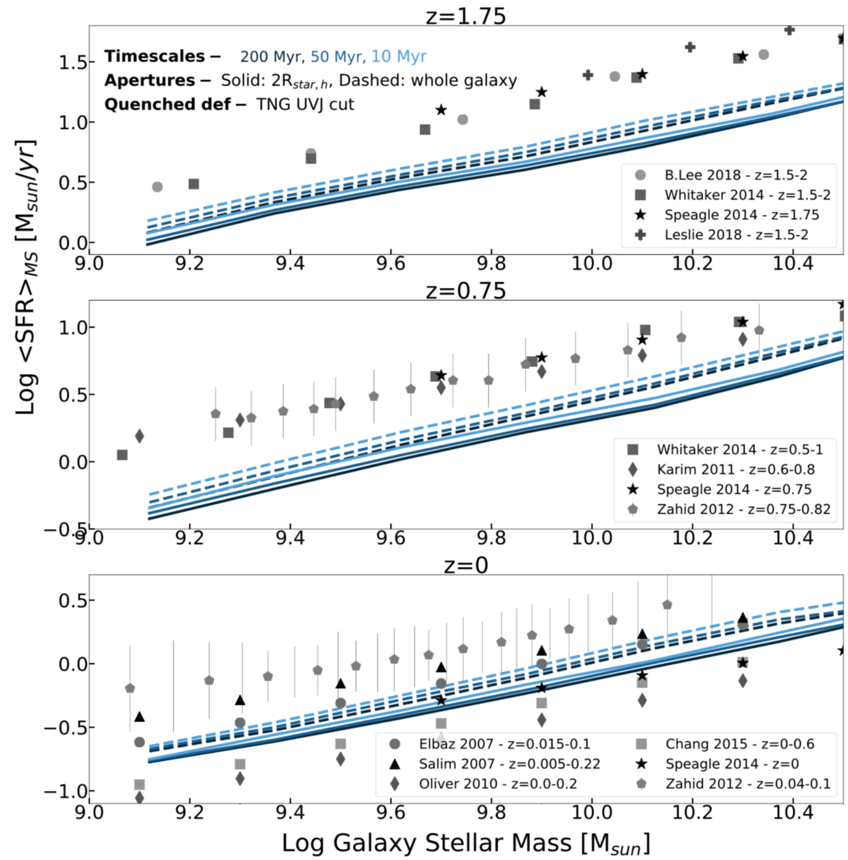
Donnari, Pillepich, Nelson et al. 2019

The TNG model returns a well-defined SFMS all the way to high redshifts



Pillepich, Nelson et al. 2019a

SFR is higher at higher redshifts, albeit with lingering inconsistencies between models and observations at z>1 on the locus of SFMS

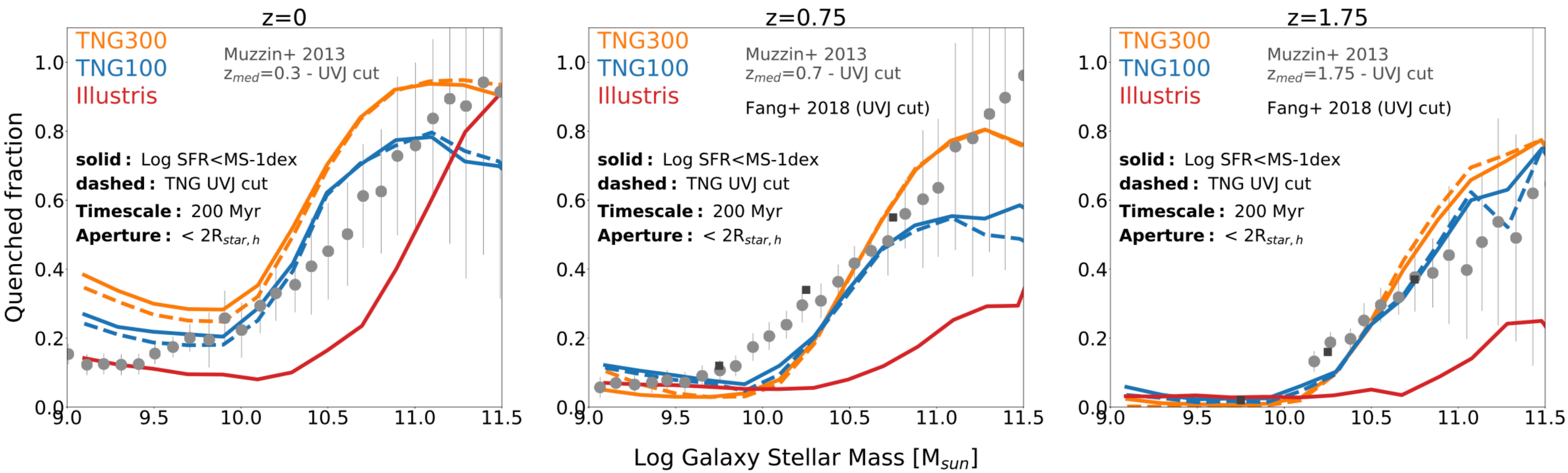


Donnari, Pillepich, Nelson et al. 2019

The quenched fractions are at last in better agreement with observations

Observations and simulations agree in that the fraction of quenched galaxies increases with galaxy mass and time

Note: here both centrals and satellites

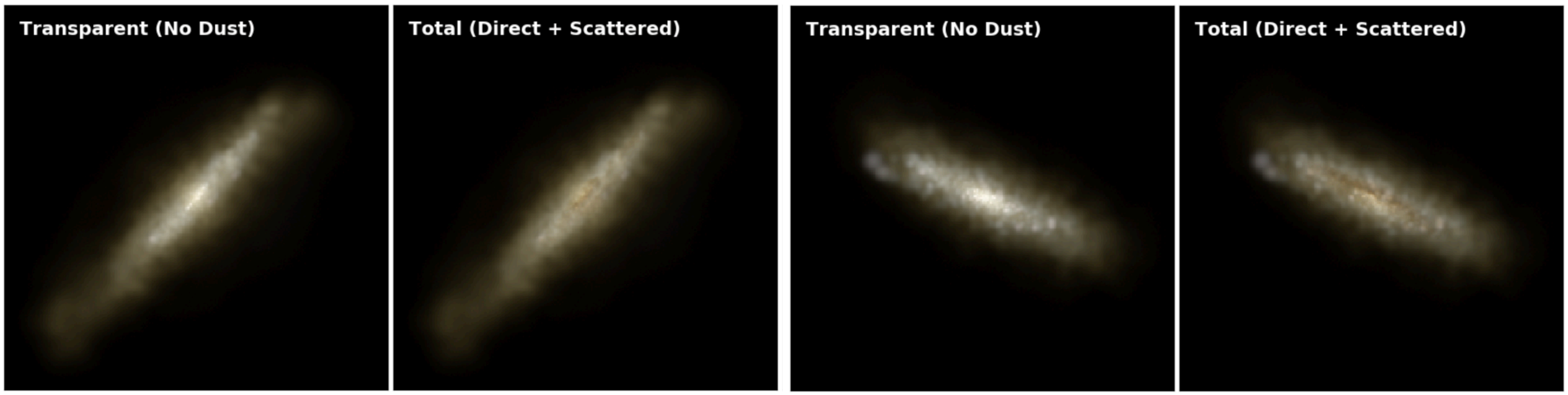


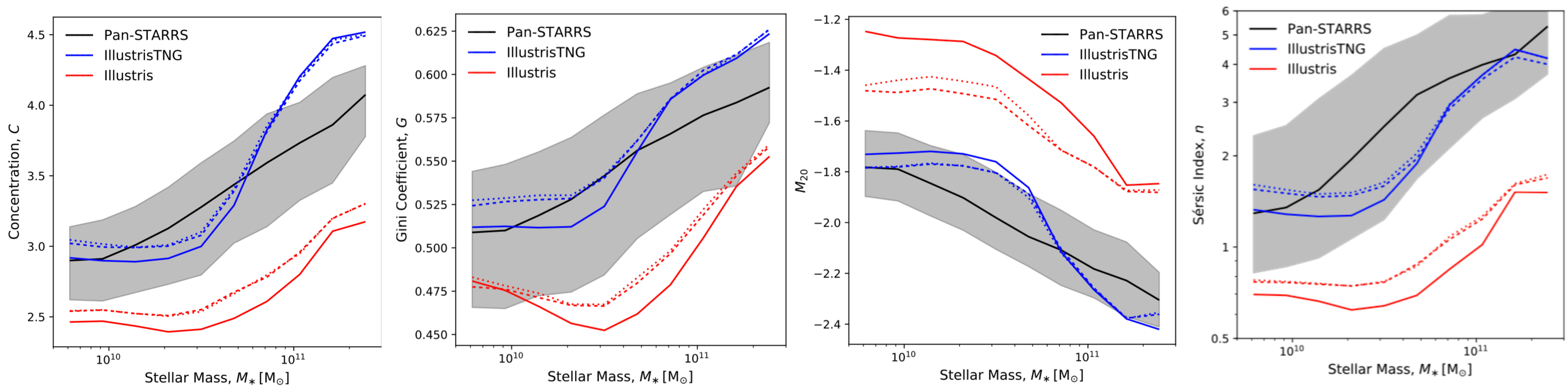
In TNG, this has been achieved thanks to the new BH-driven wind feedback

Donnari, Pillepich, Nelson et al. 2019

The z=0 optical morphologies are consistent with Pan-STARRS data

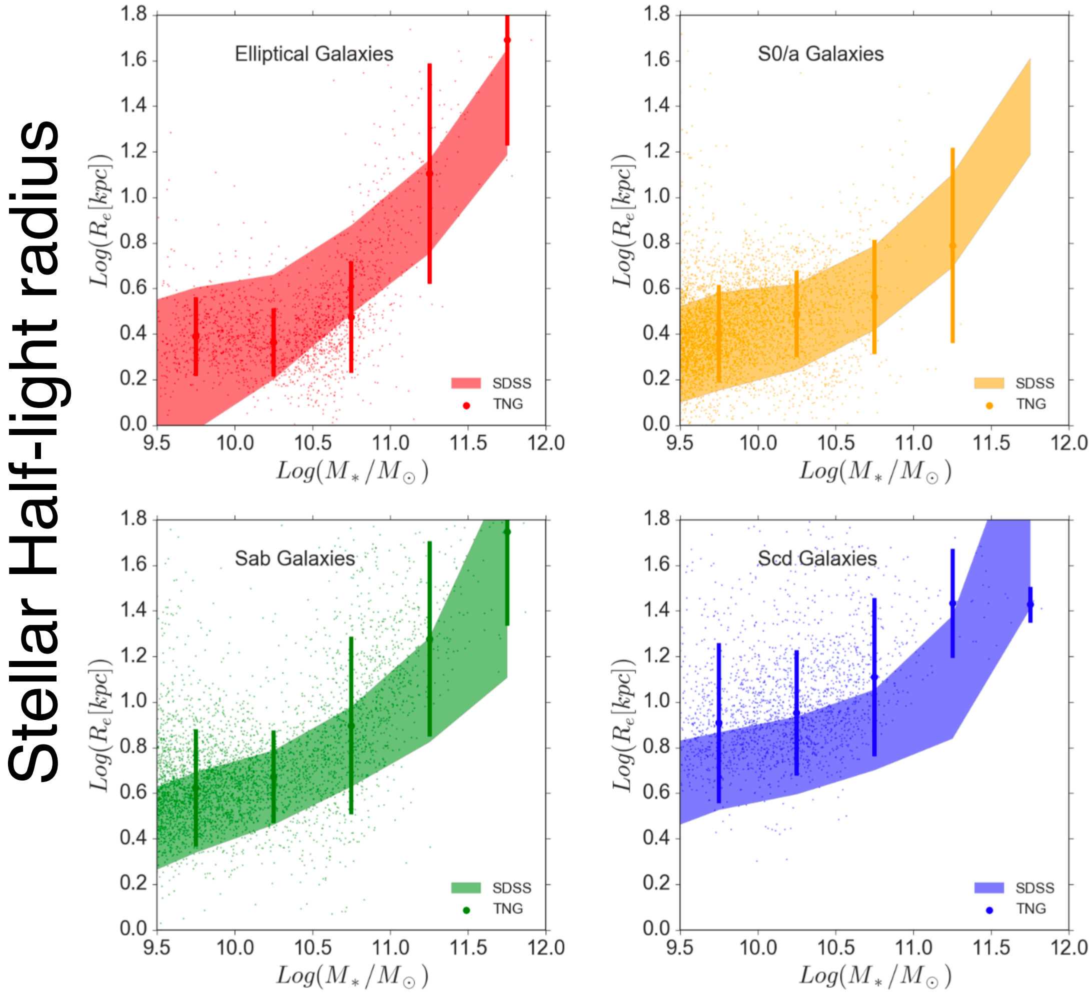
We have constructed synthetic images of TNG galaxies, including the effects of dust and the effects of the PSF and background noise typical of Pan-STARRS observations





Rodriguez-Gomez et al. 2018 (via SKIRT postprocessing)

The z=0 stellar sizes of TNG are compatible with SDSS also across galaxy types



We have generated SDSS mock images (r band) of 12000 TNG galaxies

We have trained a convolutional neural network on SDSS images classified by professional astronomers in various morphological classes and run the CNN on TNG galaxies

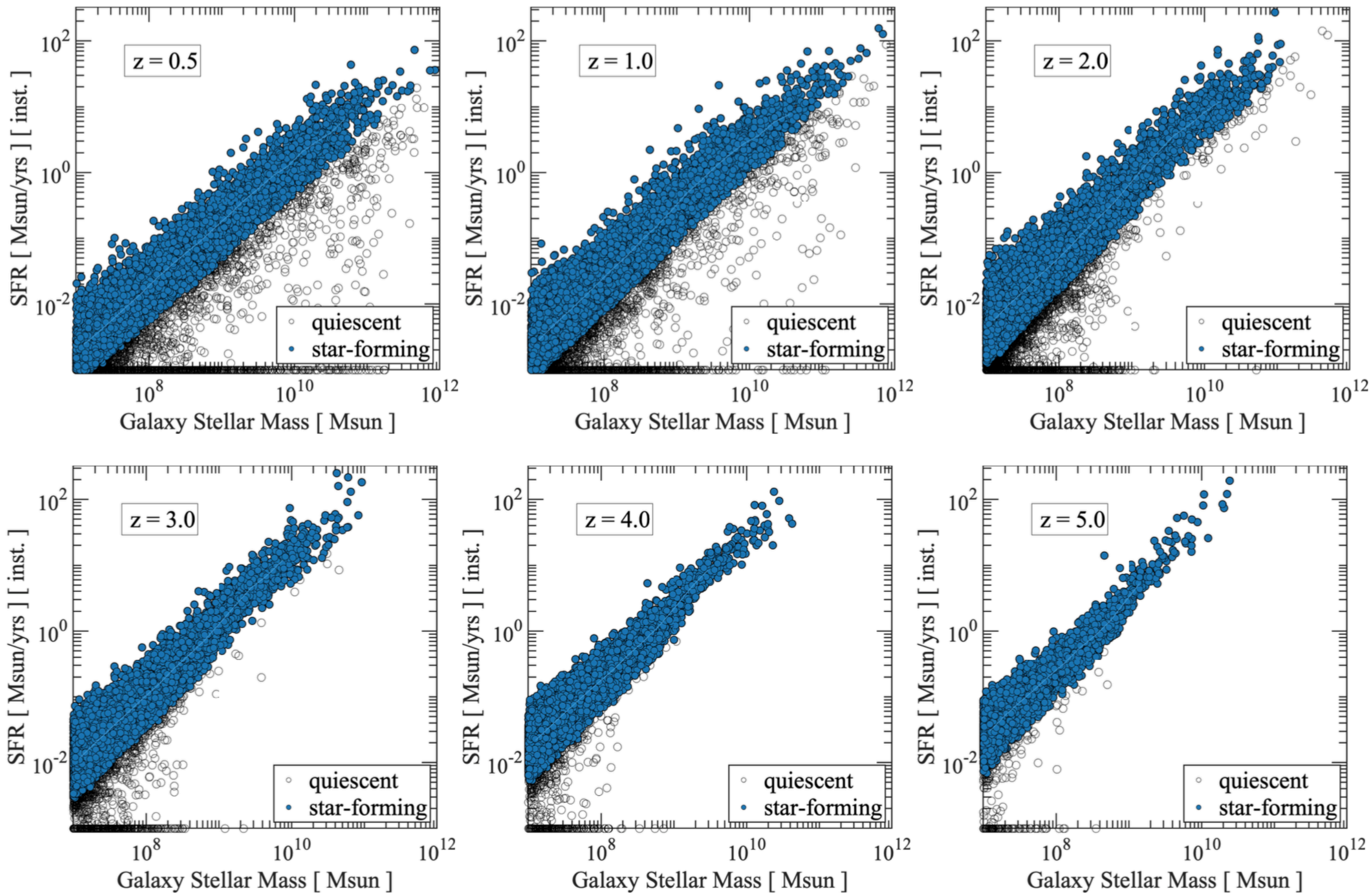
(BUT in TNG there seem to be too many massive disks!)

Huertas-Company et al. with AP 2019

See also Genel, Nelson, Pillepich, et al. 2018

On the evolution of
structures and kinematics
of star-forming galaxies,
across cosmic epochs

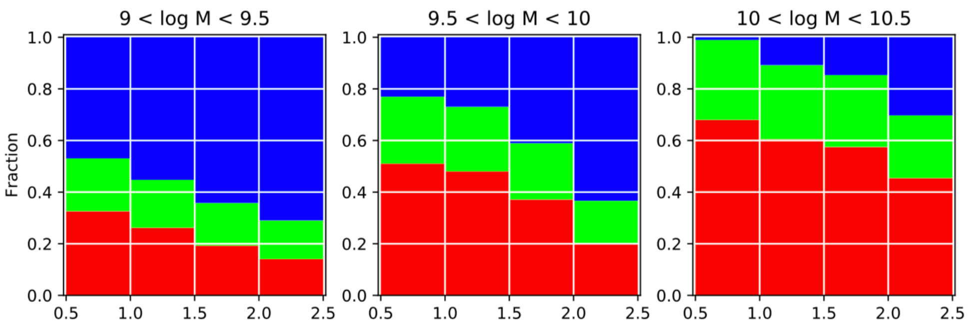
Let us focus on star-forming galaxies in TNG50



TNG50: Pillepich, Nelson, et al. 2019

An observational dichotomy is in place at intermediate and high redshifts

Morphologies/structures from stellar light



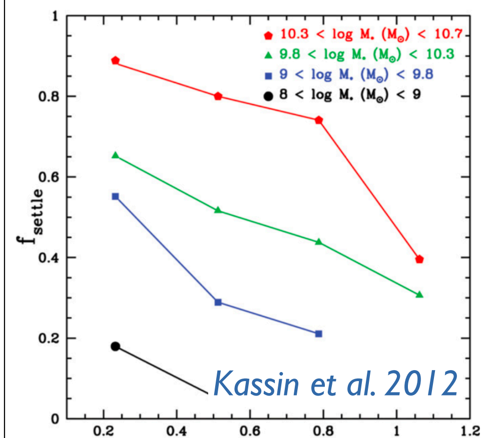
redshift

Zhang et al. 2018
Van der Wel et al. 2014

disks
spheroidal
elongated

According to CANDELS data in restframe optical: galaxies are disky in larger fractions at lower redshifts (and larger masses)

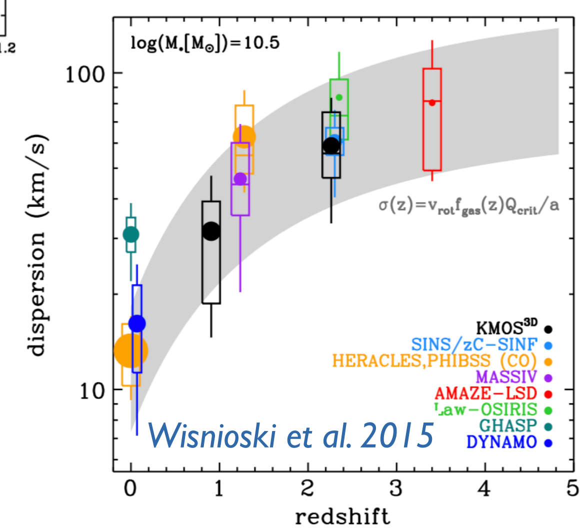
Kinematics from gas emission lines (mostly Hα)



redshift

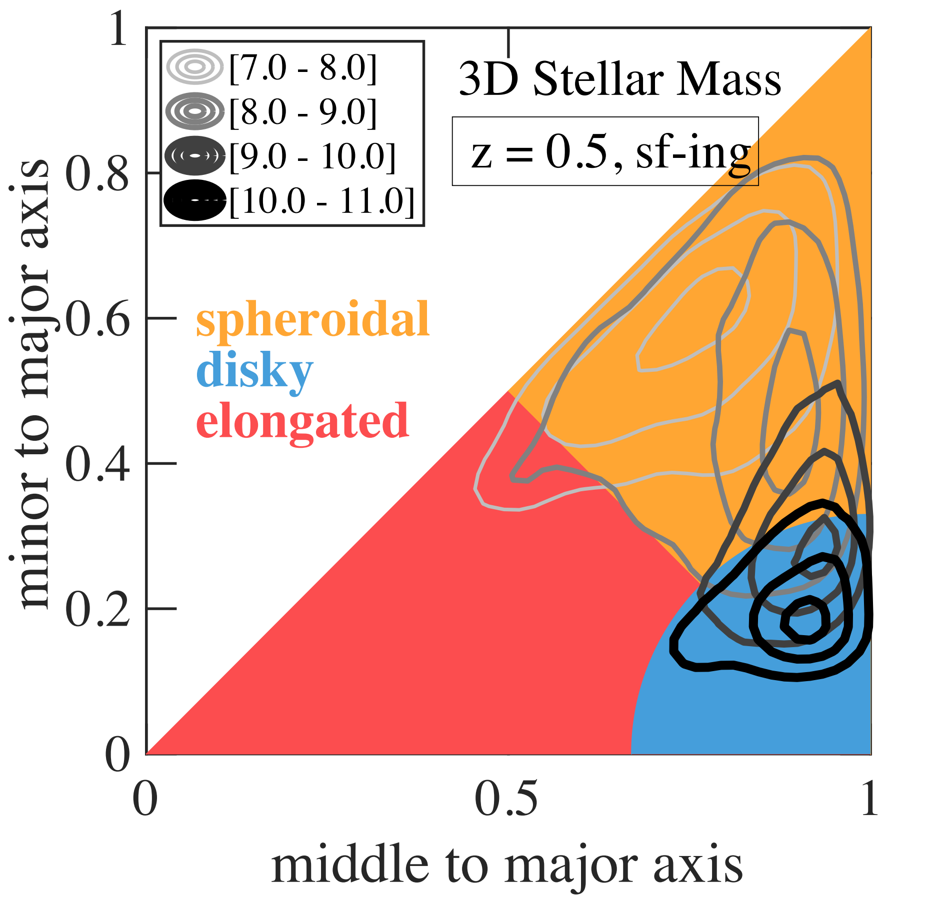
The fraction of star-forming galaxies with $V/\sigma > 3$ increases with time at fixed stellar mass

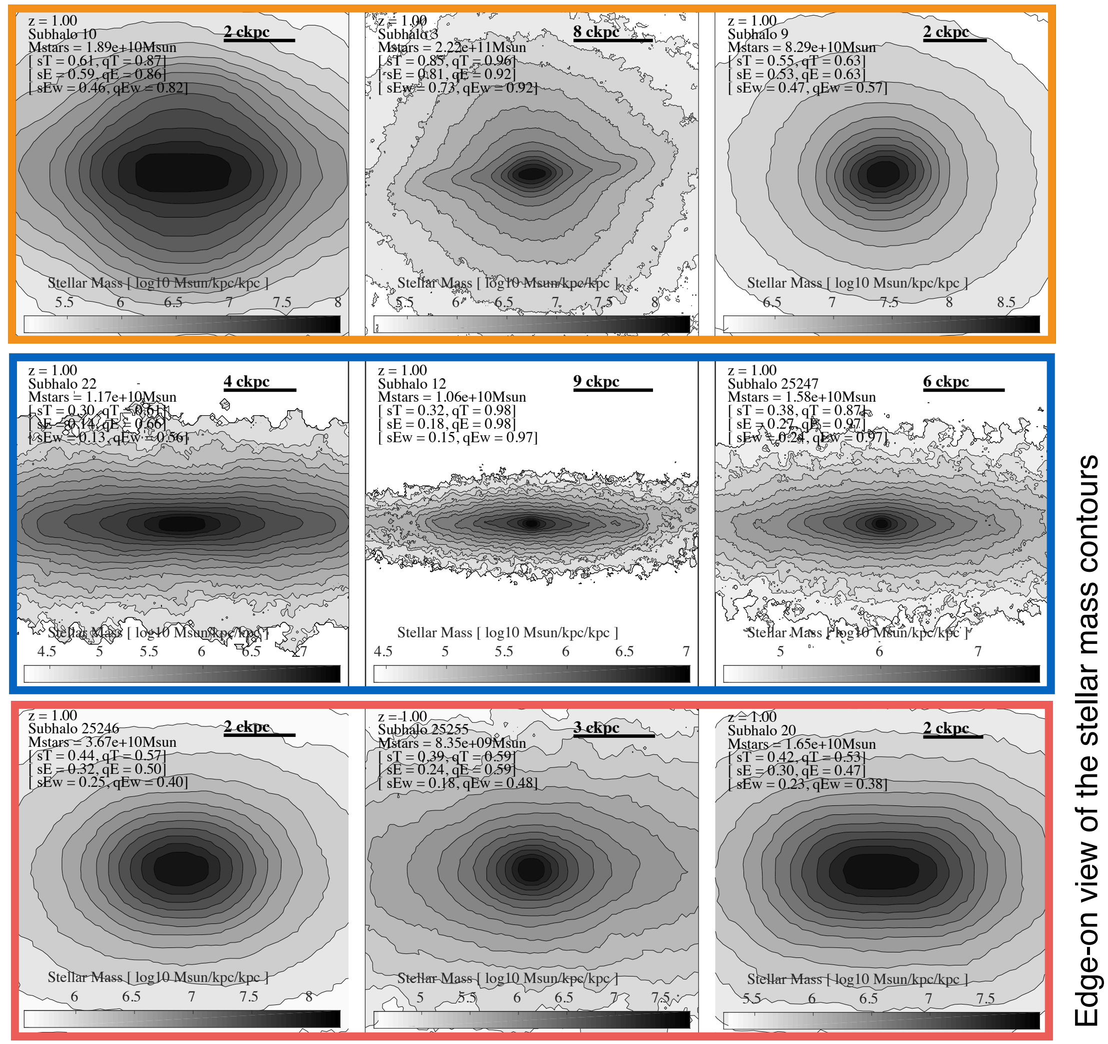
z>1 star-forming gaseous disks have a much larger contributions of random motions than low-redshift galaxies



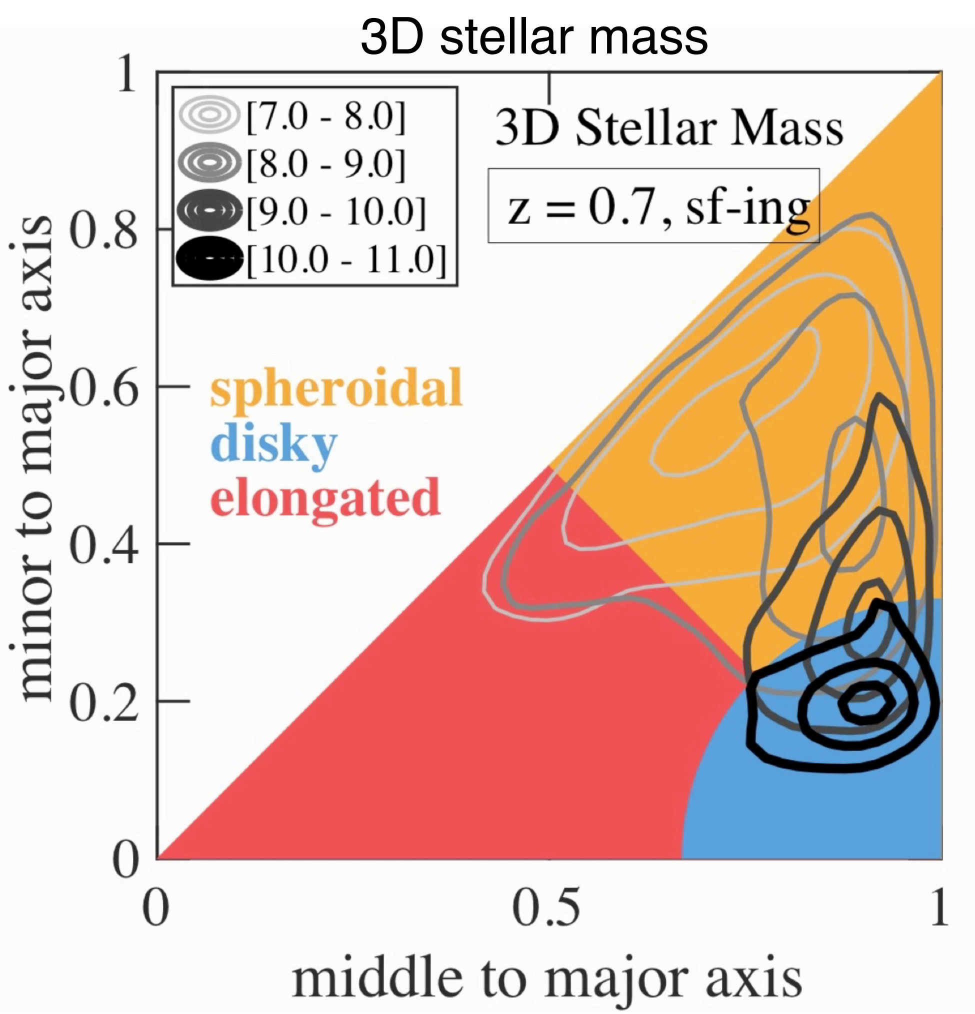
We can study the mix of morphologies or 3D shapes with TNG50

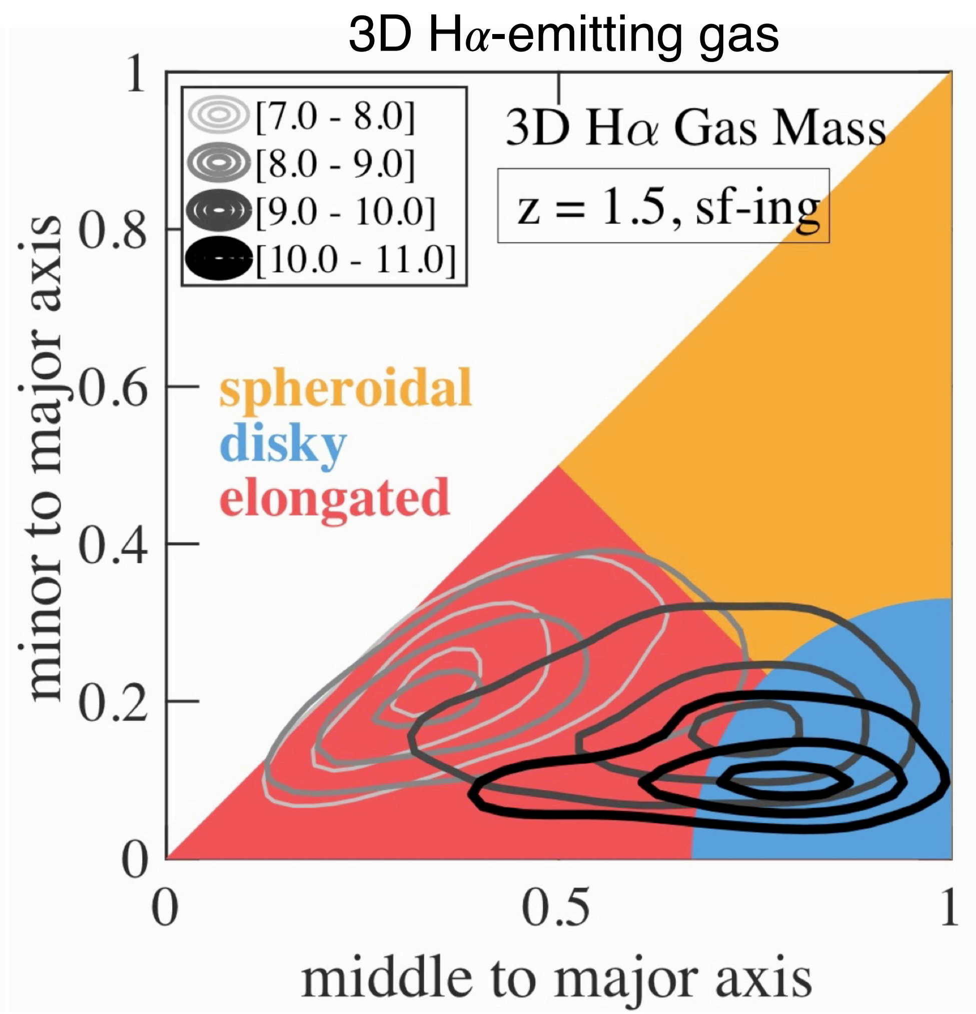
Note: here axis ratios are determined via diagonalization of the mass tensor at a certain radius (twice the stellar half-mass radius)





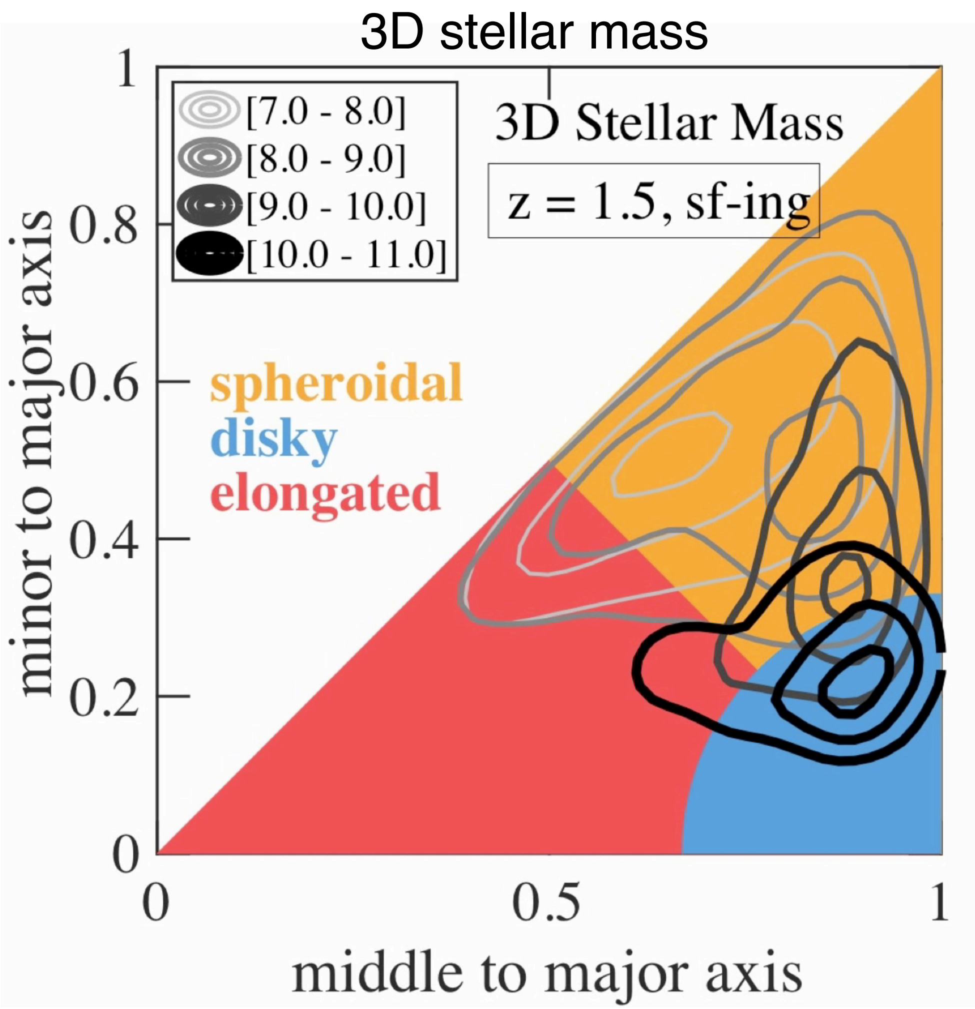
Gaseous structures are more disky or elongated than stellar bodies

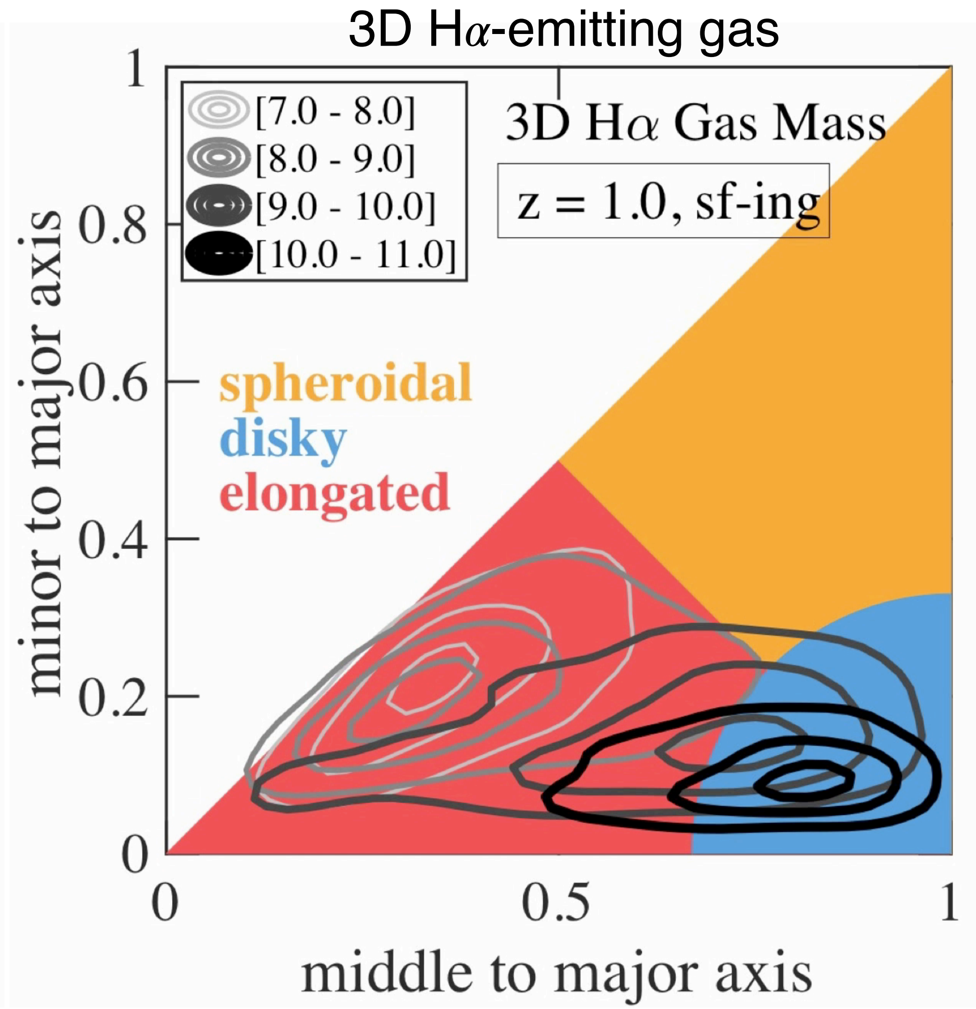




TNG50: Pillepich, Nelson, et al. 2019

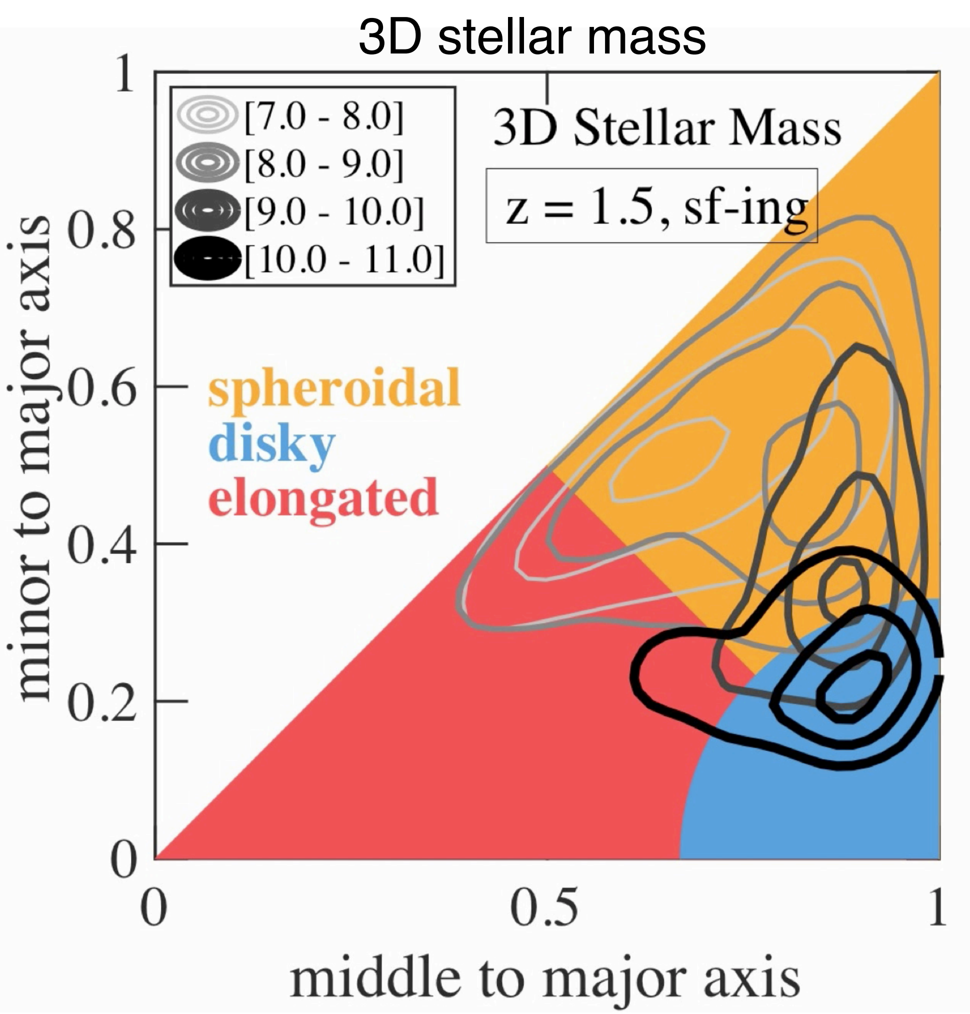
Both stellar and gaseous structures get “diskier” as the Universe evolves

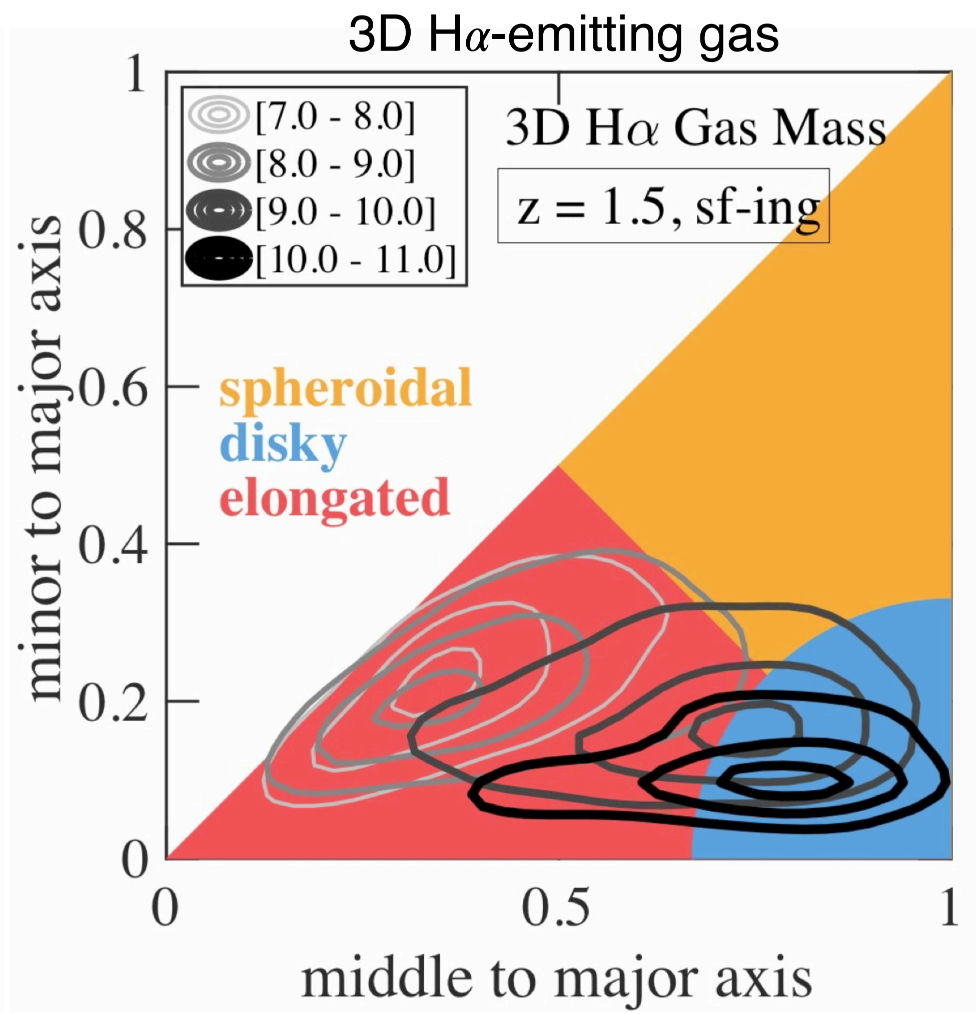




TNG50: Pillepich, Nelson, et al. 2019

<u>At any time, more massive galaxies are “diskier” than lower mass galaxies</u>

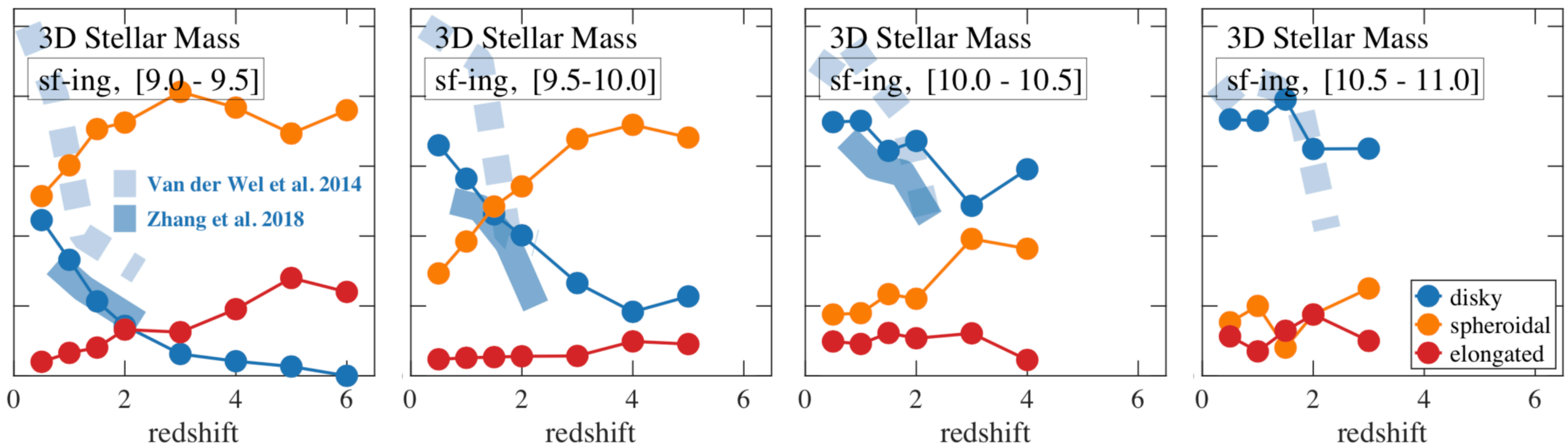




TNG50: Pillepich, Nelson, et al. 2019

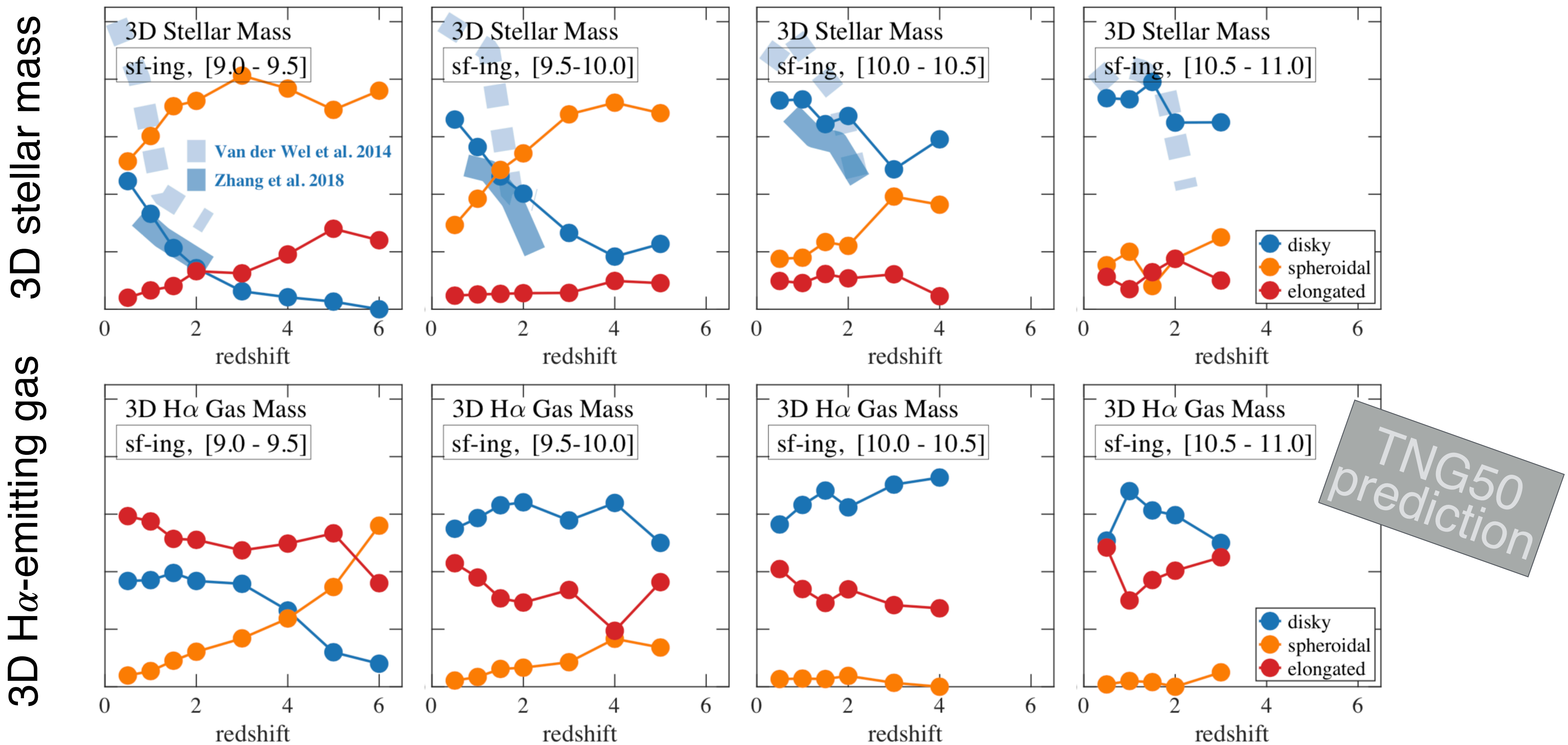
The fraction of disky galaxies always increases towards z = 0 (in the stars!)

3D stellar mass



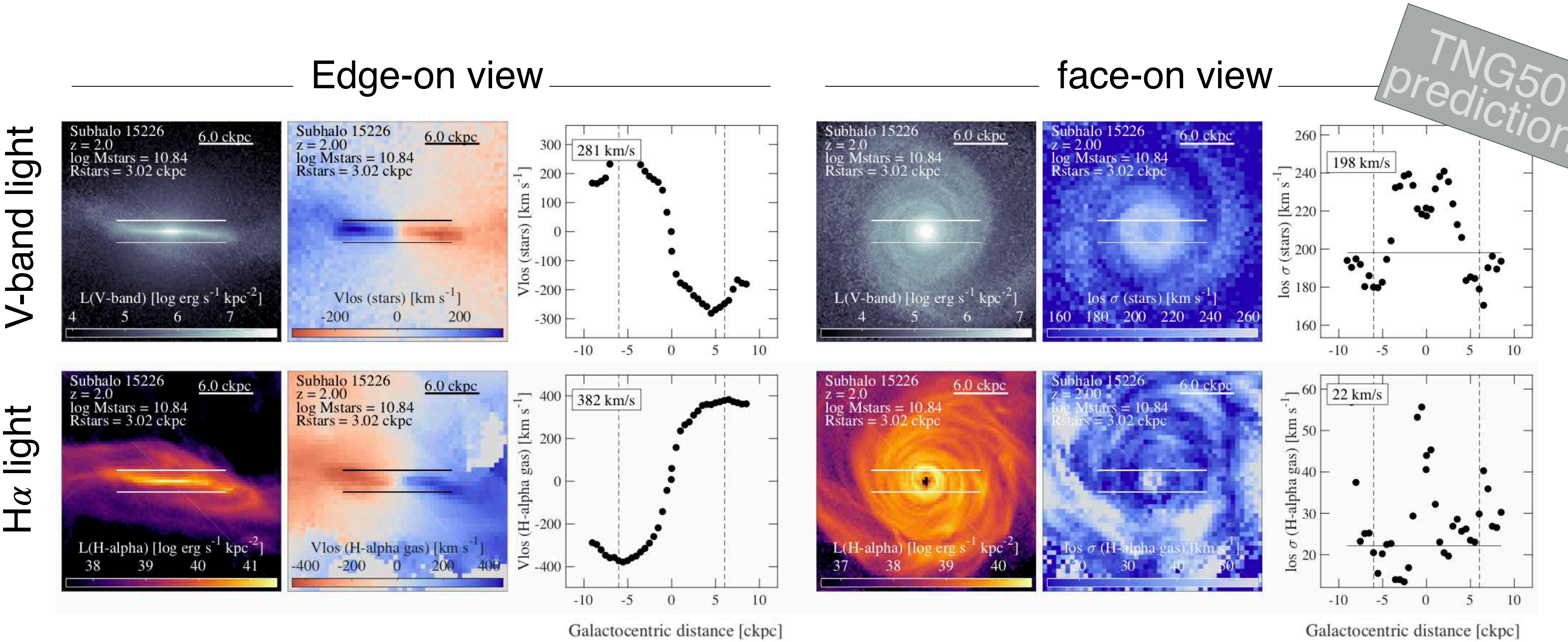
TNG50: Pillepich, Nelson, et al. 2019

Gas arranges in thin/disky configurations at most times and masses



TNG50: Pillepich, Nelson, et al. 2019

We can extract kinematics from TNG50 galaxies

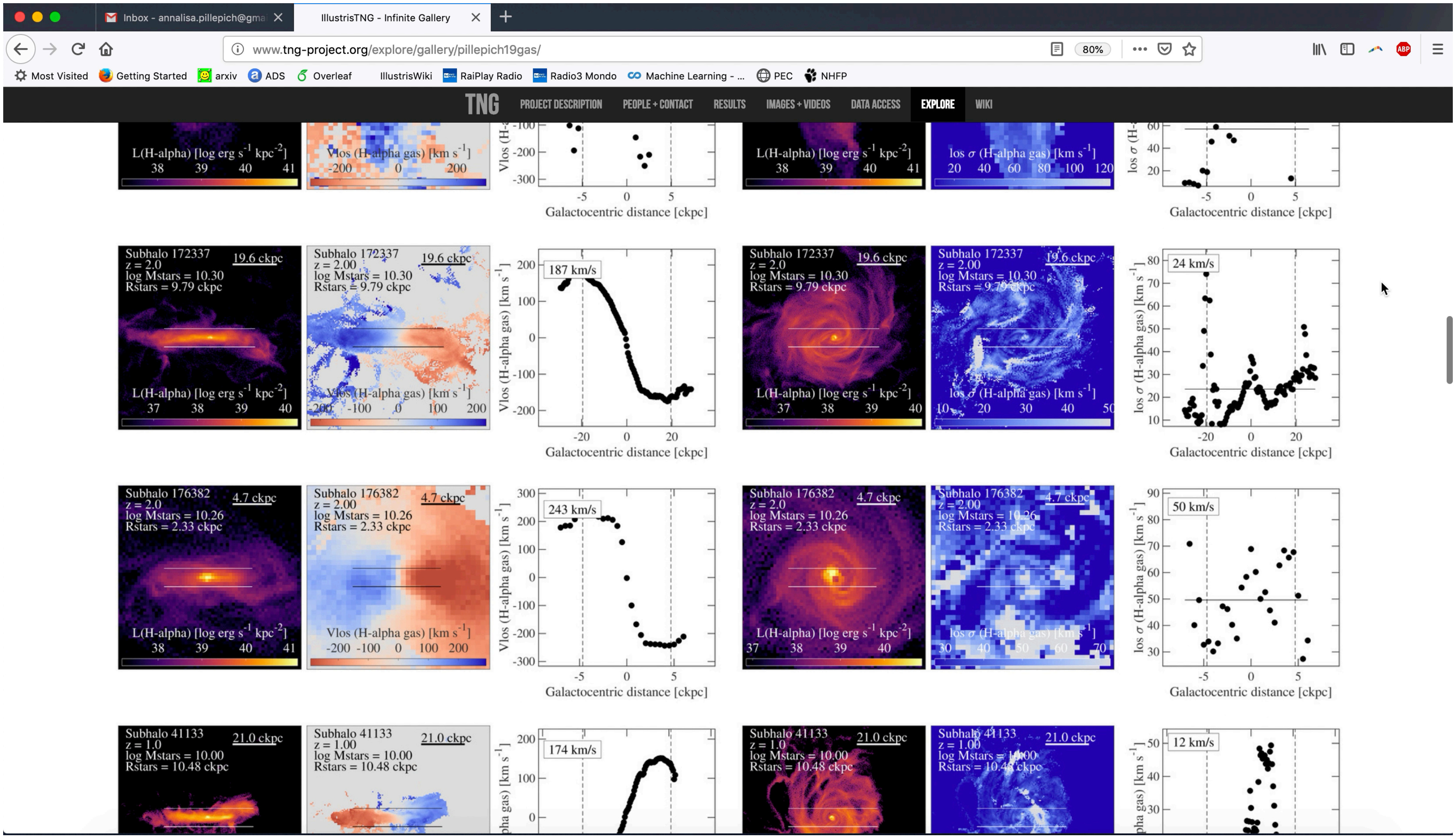


Vrot = max of rotation curves

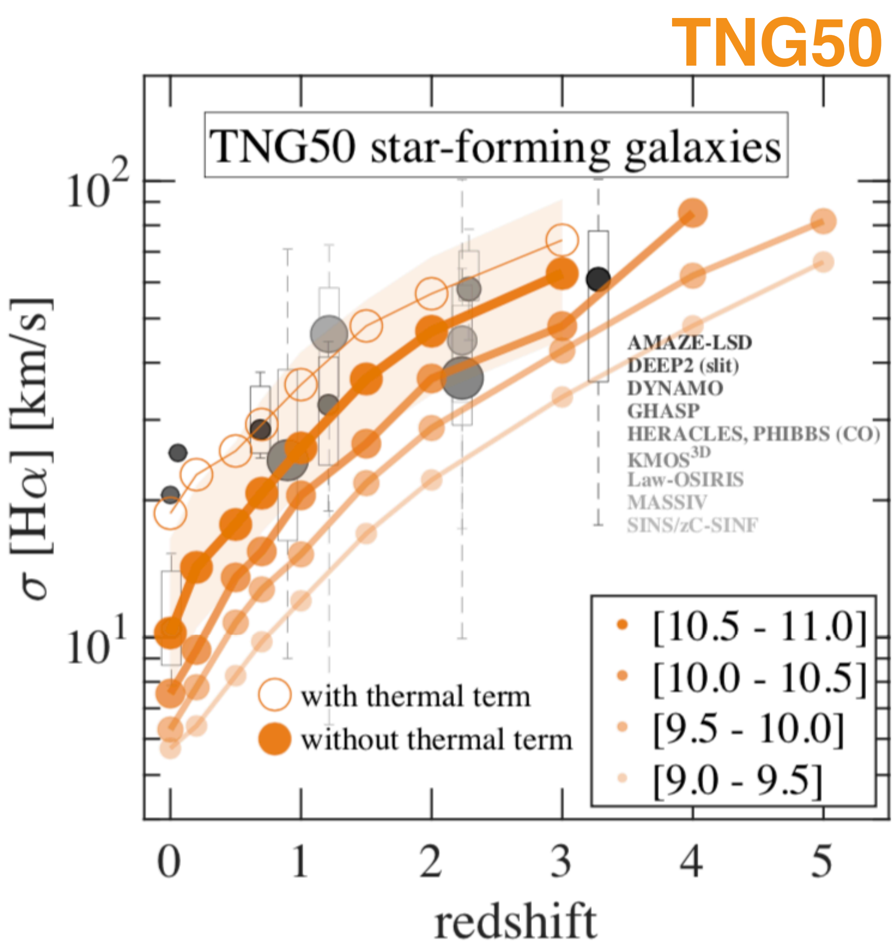
σ = average in pixels of 0.5kpc
(where V is max)

TNG50: Pillepich, Nelson, et al. 2019

We can extract kinematics from TNG50 galaxies from thousands of galaxies!



Star-forming galaxies have larger velocity dispersions at higher z (in the gas!)



In the simulations, we recover the redshift trends observed with Hα observations

This is a non-trivial confirmation of the bounty of the underlying physical ingredients

What processes can maintain star-forming and dense gas dynamically hot against cooling?

Galaxy mergers and interactions

Inflows of gas

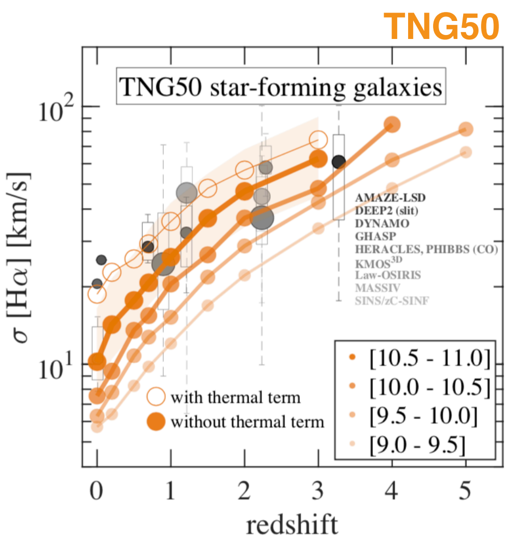
Outflows of gas (feedback)

Small-scale ISM turbulence

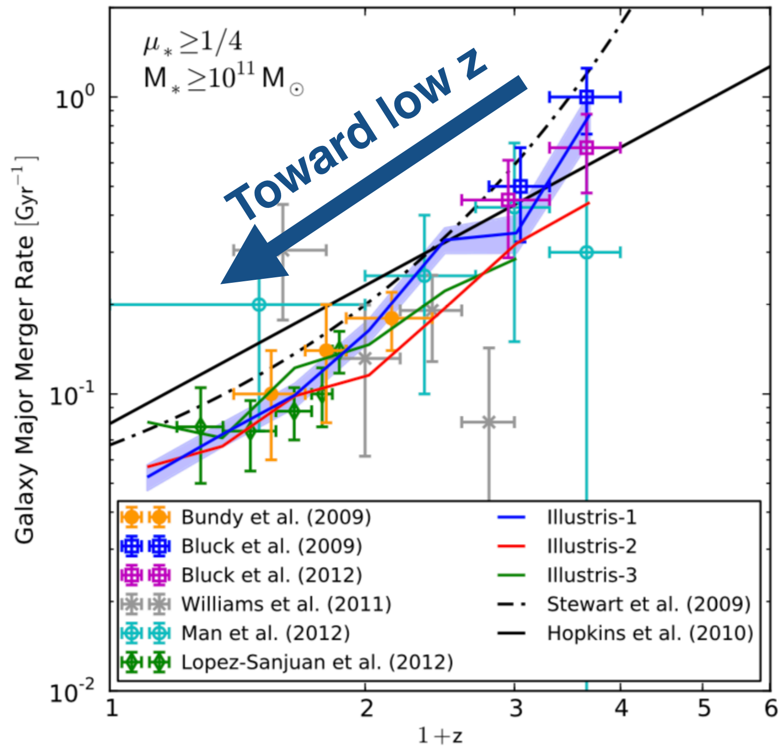
Note: please focus on the redshift trend, not the normalization necessarily

TNG50: Pillepich, Nelson, et al. 2019

Why lower gas velocity dispersions at later times?



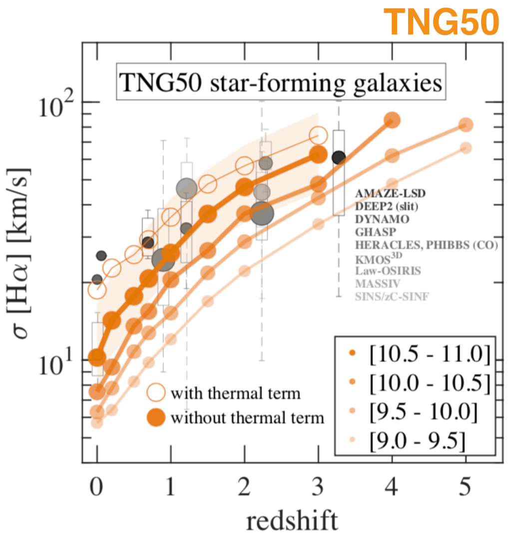
1. The rates at which galaxies merge decline as the Universe ages and the hierarchical growth progresses



Let us think about the processes that can maintain star-forming and dense gas dynamically hot against cooling

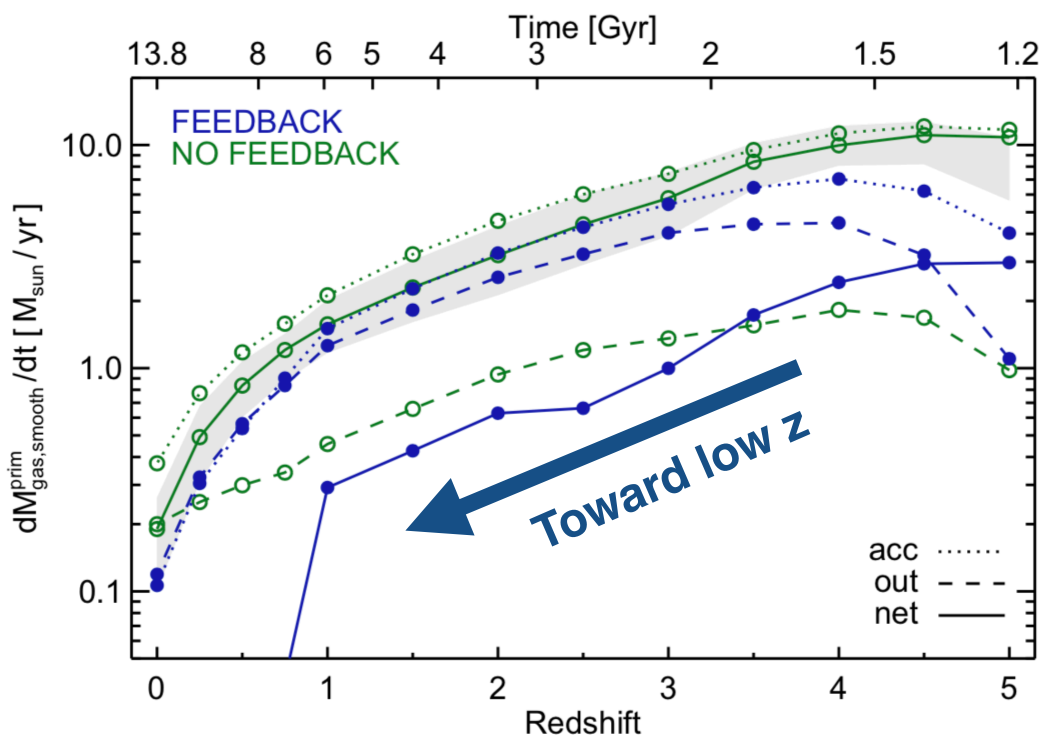
e.g. Illustris: Rodriguez-Gomez et al. with AP 2015

Why lower gas velocity dispersions at later times?



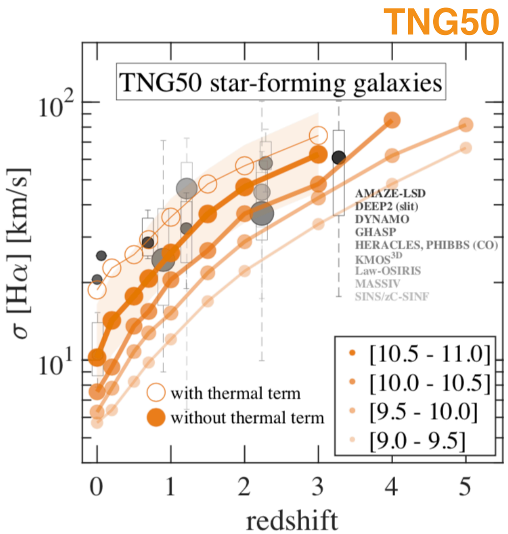
Let us think about the processes that can maintain star-forming and dense gas dynamically hot against cooling

2. The rates at which smooth gas inflows into galaxies decline as the time goes by



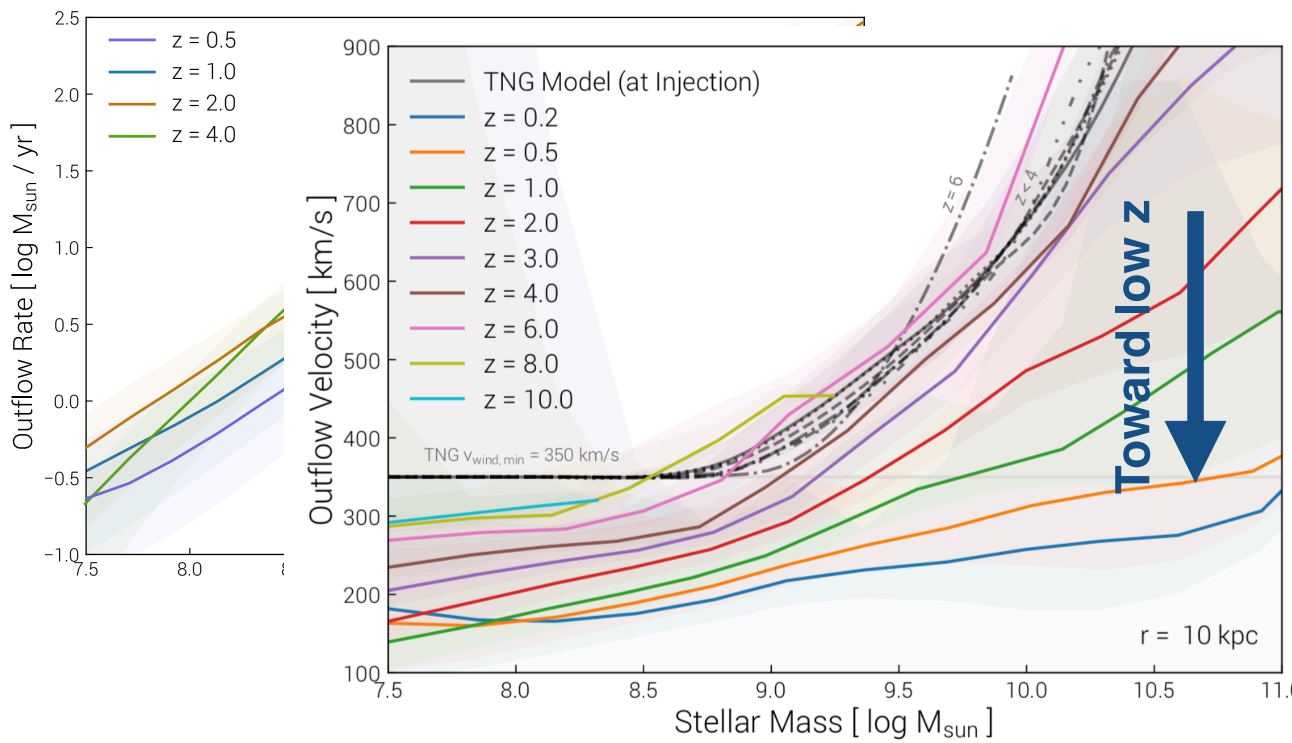
e.g. Illustris: model Nelson et al. 2015

Why lower gas velocity dispersions at later times?



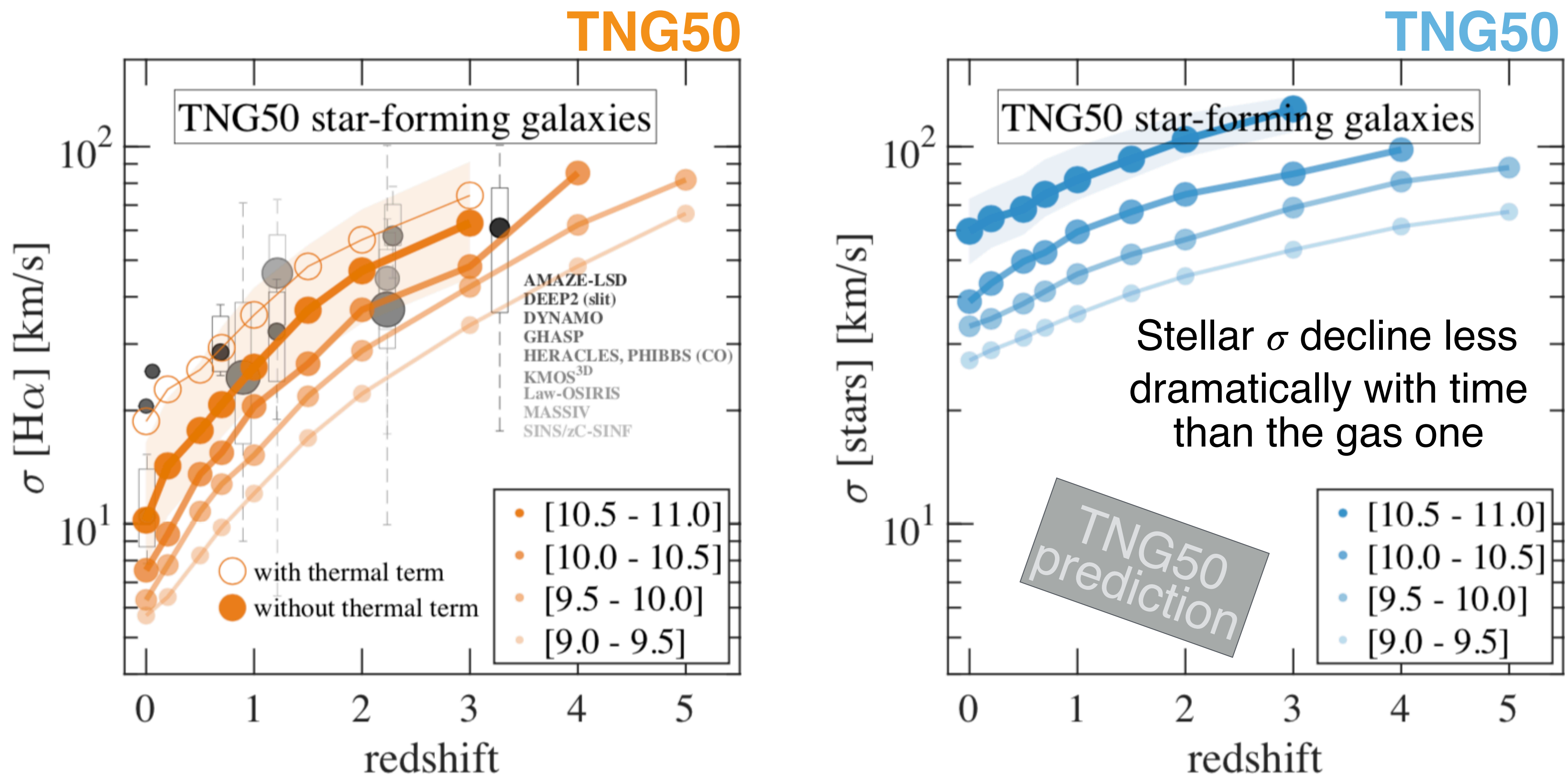
Let us think about the processes that can maintain star-forming and dense gas dynamically hot against cooling

3. Gas outflow rates and outflow velocities get smaller as galaxies lower their star formation rates at fixed mass, as the Universe evolves



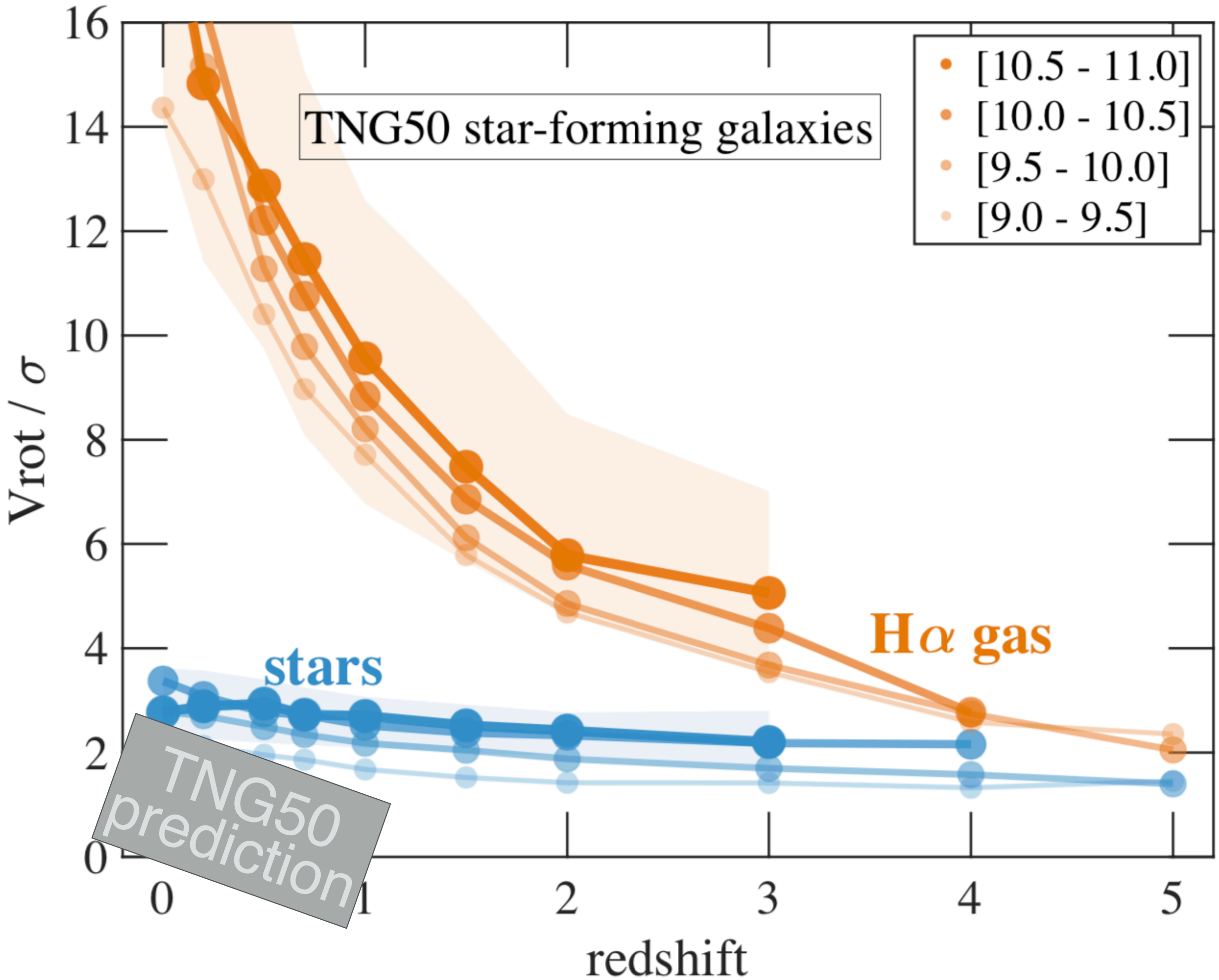
TNG50: Nelson, Pillepich et al. 2019

Stellar velocity dispersions are always larger than the star-forming gas'



TNG50: Pillepich, Nelson, et al. 2019

Star-forming galaxies have rotationally-supported gas disks since z~4-5



This is qualitative consistent with observational findings, depending on measurement choices.

The balance between ordered and chaotic motions increases with time, but much more so for gaseous than stellar structures

Vrot/σ grows in time with both Vrot and σ *declining* with time

TNG50: Pillepich, Nelson, et al. 2019

Galaxy shapes and kinematics are determined by a host of processes

Accretion of cosmic gas into galaxies

Star formation

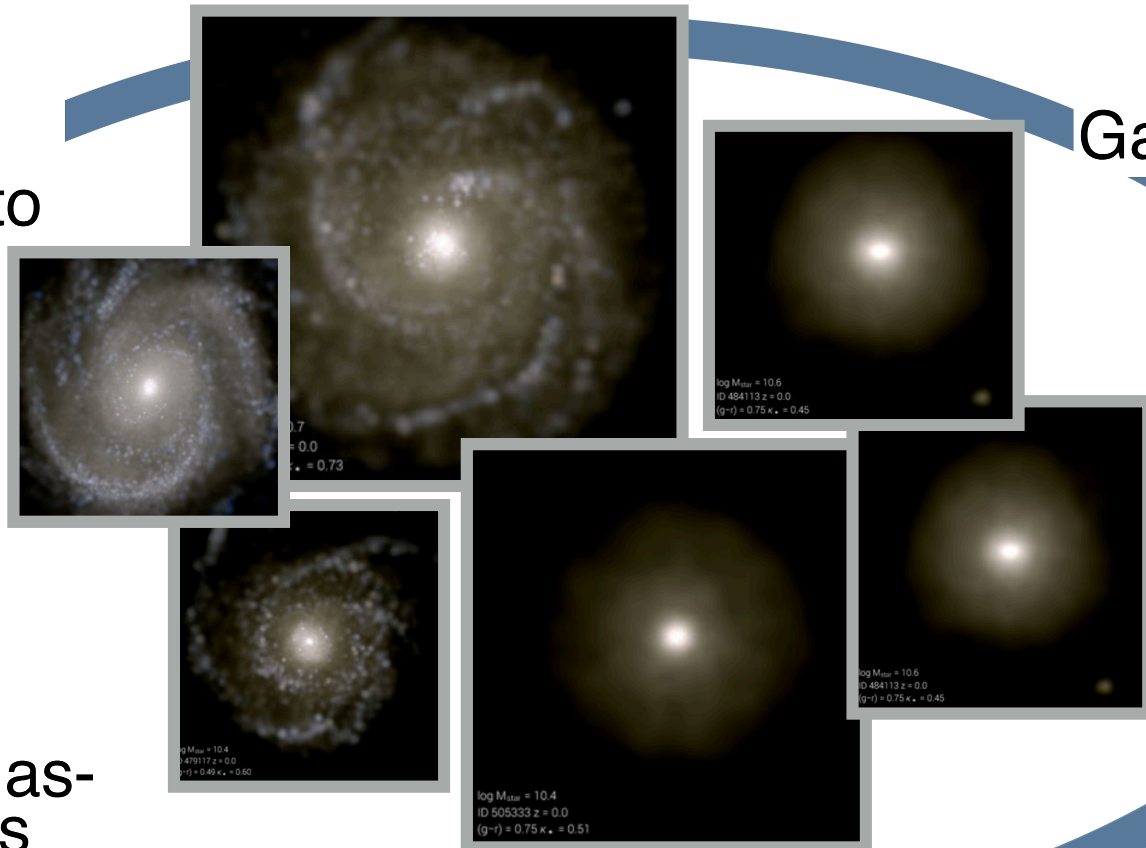
Gas-rich and gas-poor mergers

Galaxy interactions and stellar stripping

Feedback and outflows from stars

Feedback and outflows from SMBHs

Gas recycling

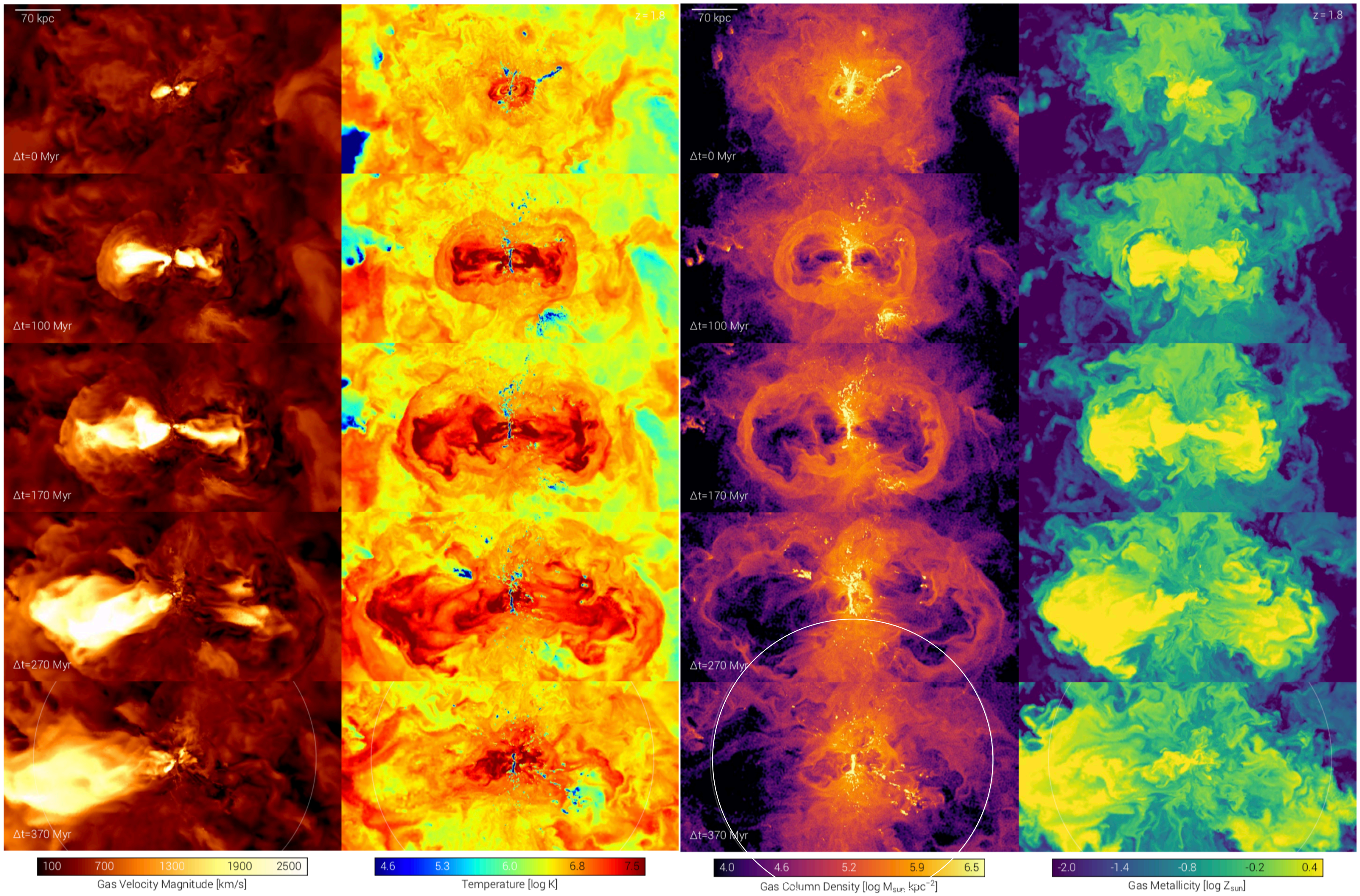


All intertwined, z and mass dependent

On Outflows

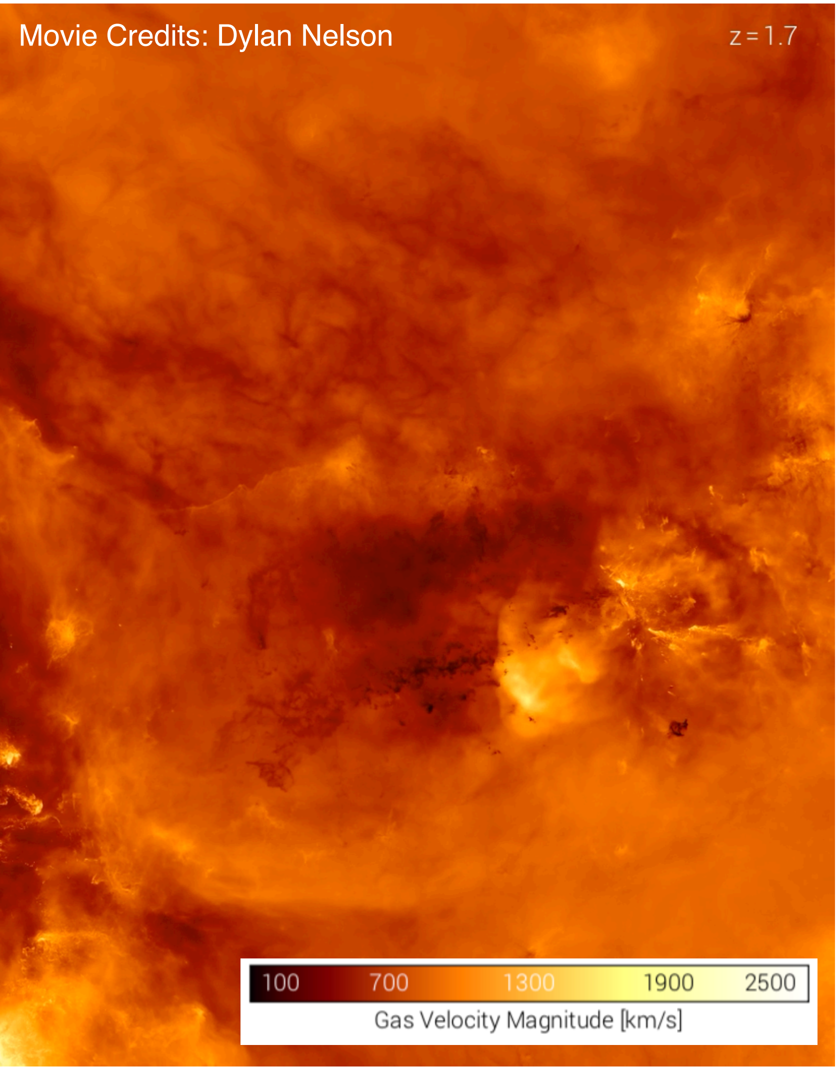
In the TNG model, we invoke pulsated kinetic BH-driven winds at low-accretion rates

Gas outflows from events of black-hole feedback.
The BH at the center of this massive galaxy exerts a kinetic, isotropic kick



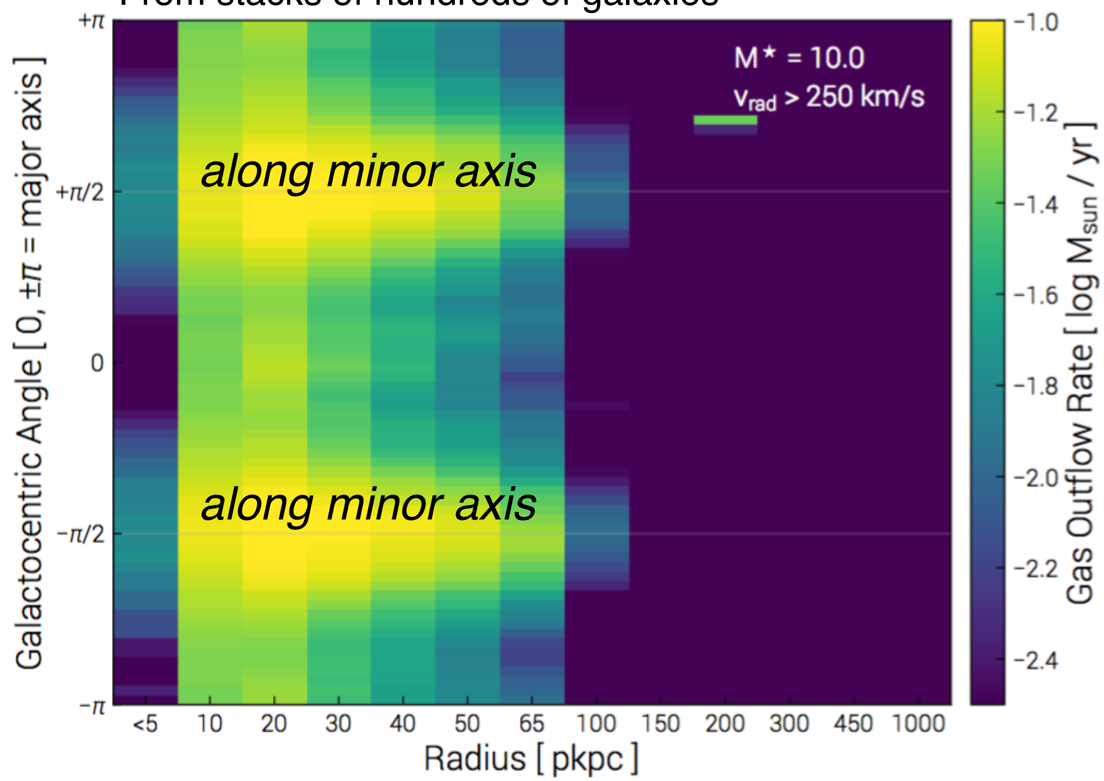
TNG50: Nelson, Pillepich et al. 2019

BH and stellar feedback superimpose and produce gas outflows



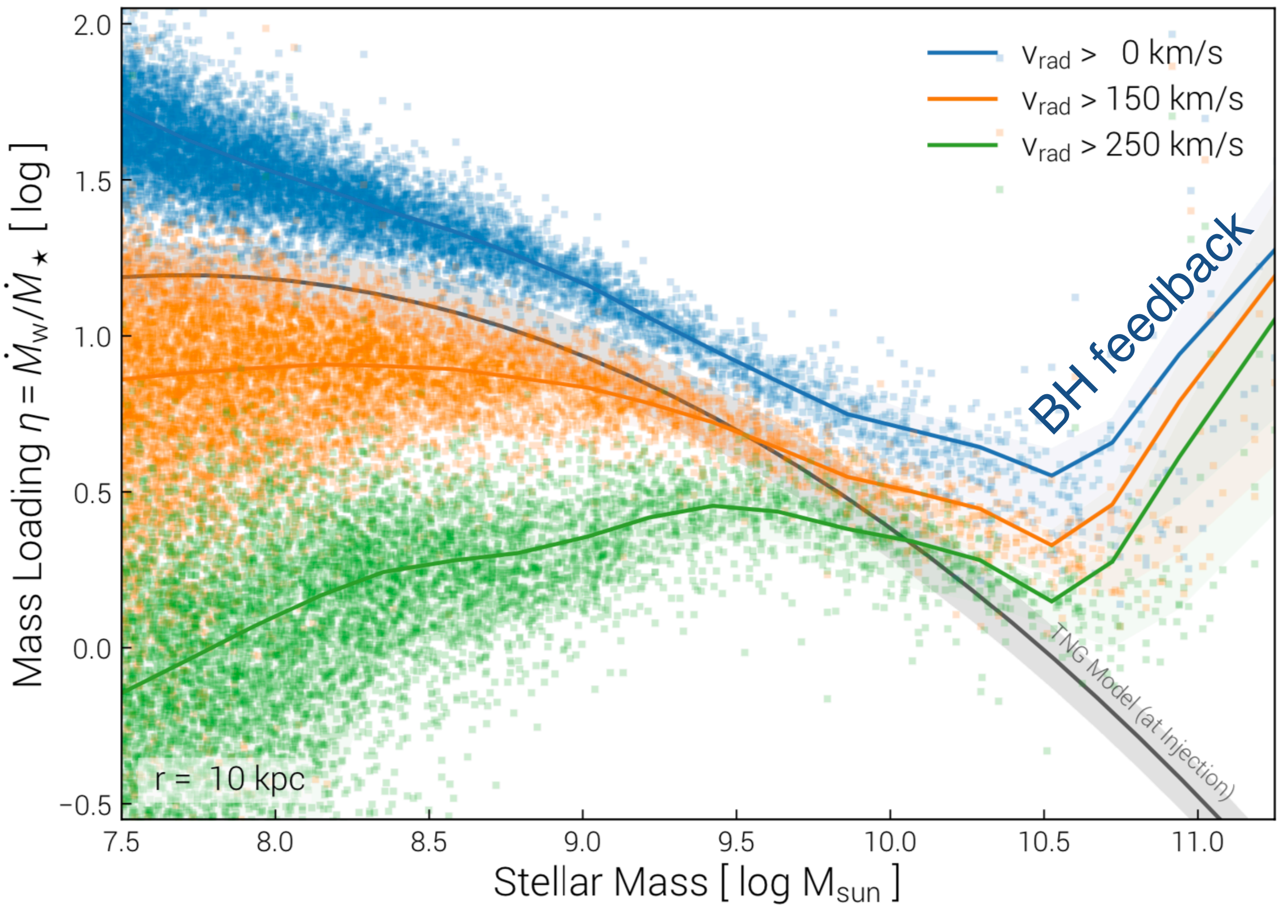
Gas outflows emerge bipolar/biconical!
(even though injected isotropically)

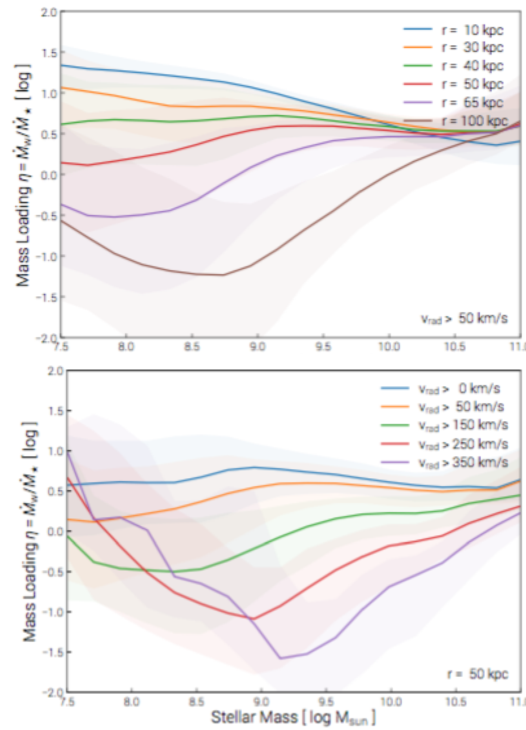
From stacks of hundreds of galaxies



TNG50: Nelson, Pillepich et al. 2019

The mass loading factor of outflows is *not* a monotonic function of mass





larger impact parameters

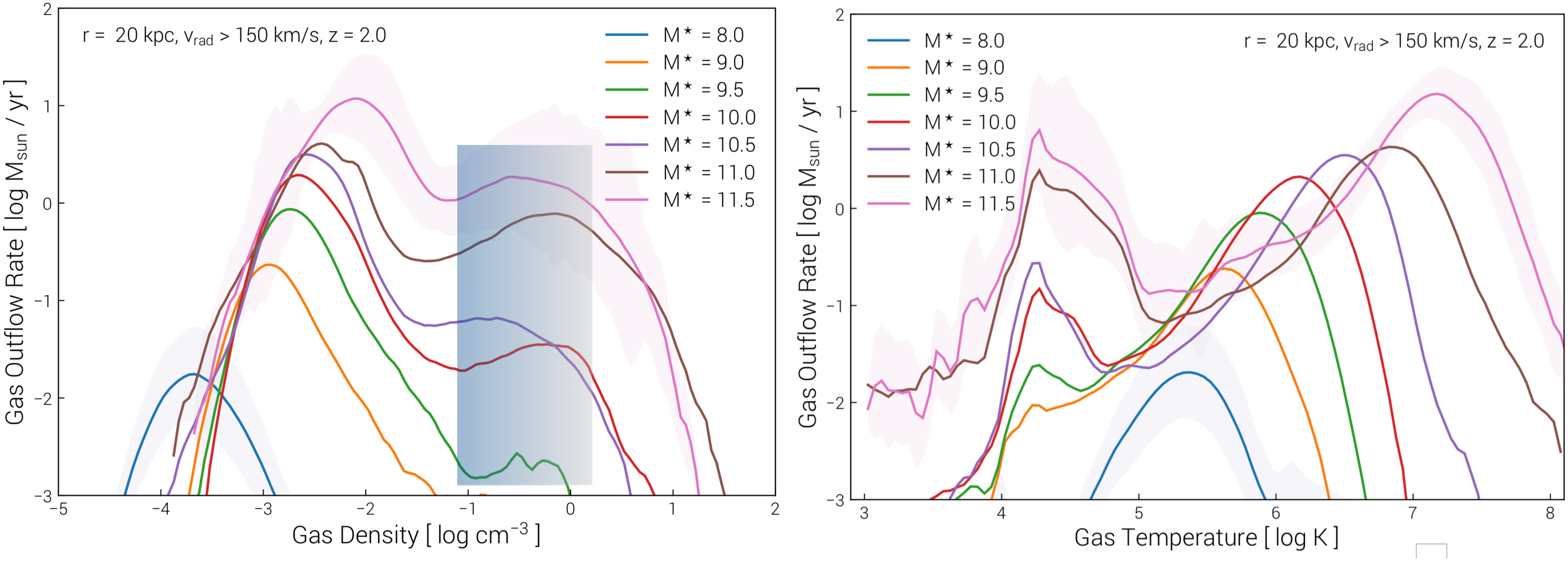
larger outflow speeds

i.e. eta is a function of (Mstars, z, r, v_cut, phase)

TNG50: Nelson, Pillepich et al. 2019

The quantitative characterization of outflows is truly a multi-dimensional problem

Because, even with feedback models as “simple” as in TNG, we naturally produce “multi-phase” outflows (in T, rho, v, and Z)



AGN Feedback

Looking ahead….

If we want to learn anything, galaxy formation and evolution must become a truly **quantitative effort**:

We need to go beyond the narrative of specific few cases and build understanding with **large**, **unbiased**, **self-consistent** populations of objects.

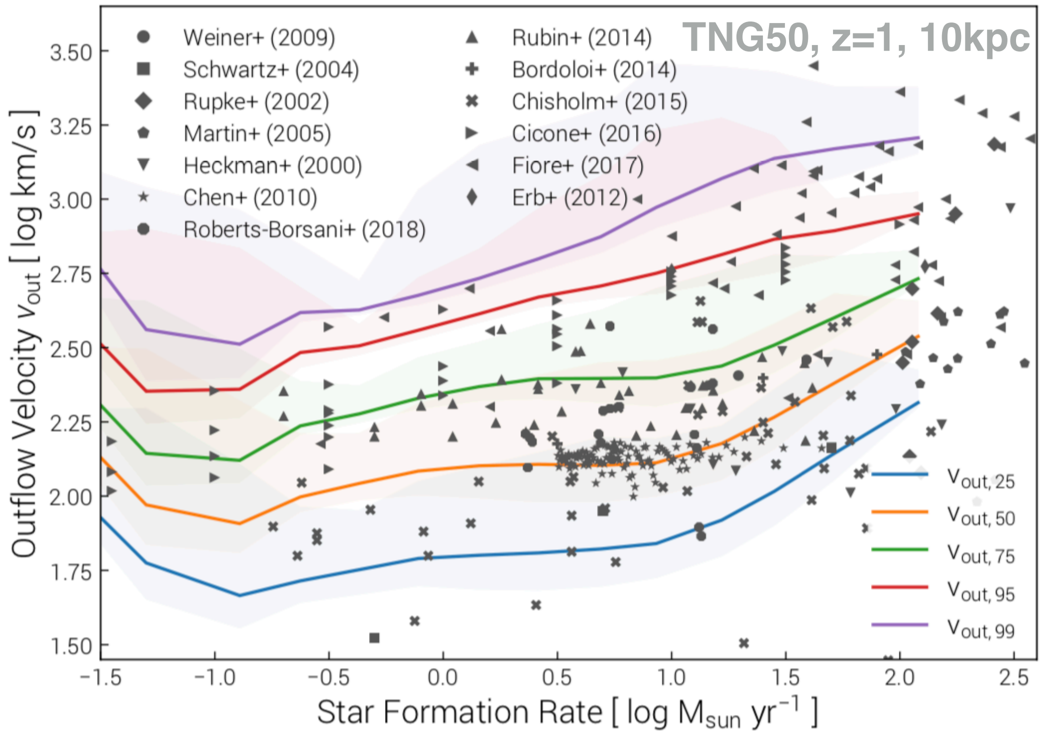
This is what we are trying to achieve with TNG and what will be possible also at high-z with the ELTs….

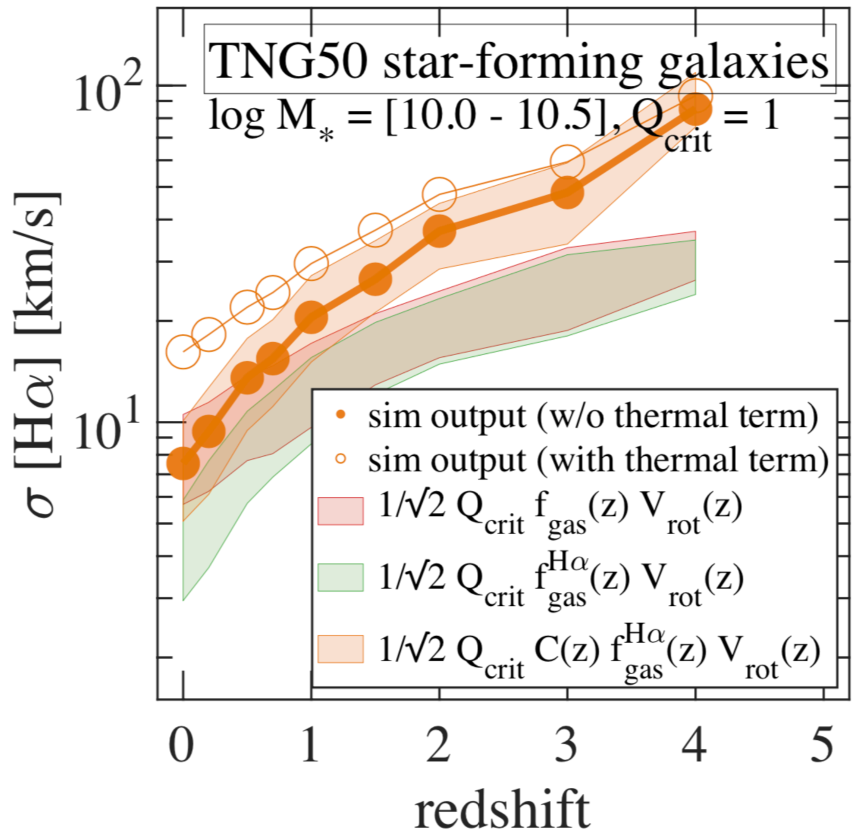
Discriminating among models and interpretation pathways by comparing to observations requires accuracies that the field is not used to, esp. in terms of

- Properly accounting for selection functions
- Properly mimicking the observational measurements on simulated data

Two examples on how delicate it can be….

The same galaxy formation model can manifest itself in a diverse number of ways in terms of gas outflows





Even with simulated data only, it is extremely hard to e.g. discern whether disk instability theory alone justifies the simulated output, depending on the particulars of the measurements

Thanks for your attention!