Insights from the MW/M31-like galaxies of the TNG50 simulation

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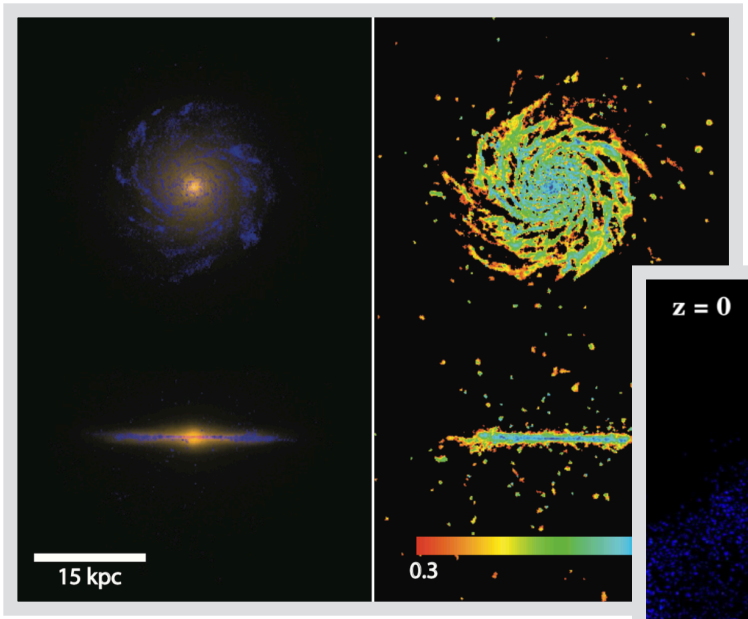
About 10 years ago, people simulated the first “realistic” disk-like galaxies in the full cosmological context

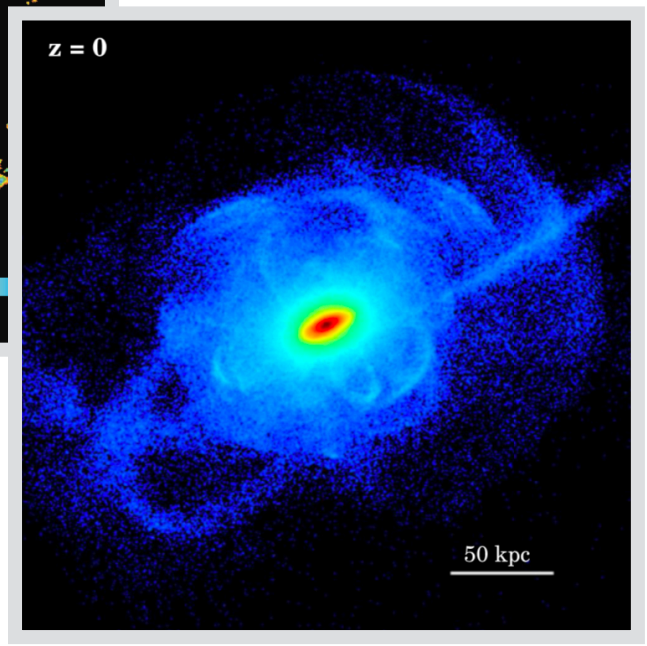
E.g. **Eris**
Gasoline code
zoom-in cosmological technique
N-body + SPH

DM, GAS, STAR particle mass =
$1x10^5$, $2x10^4$, $6x10^3$ $M\odot$
~120pc spatial resolution

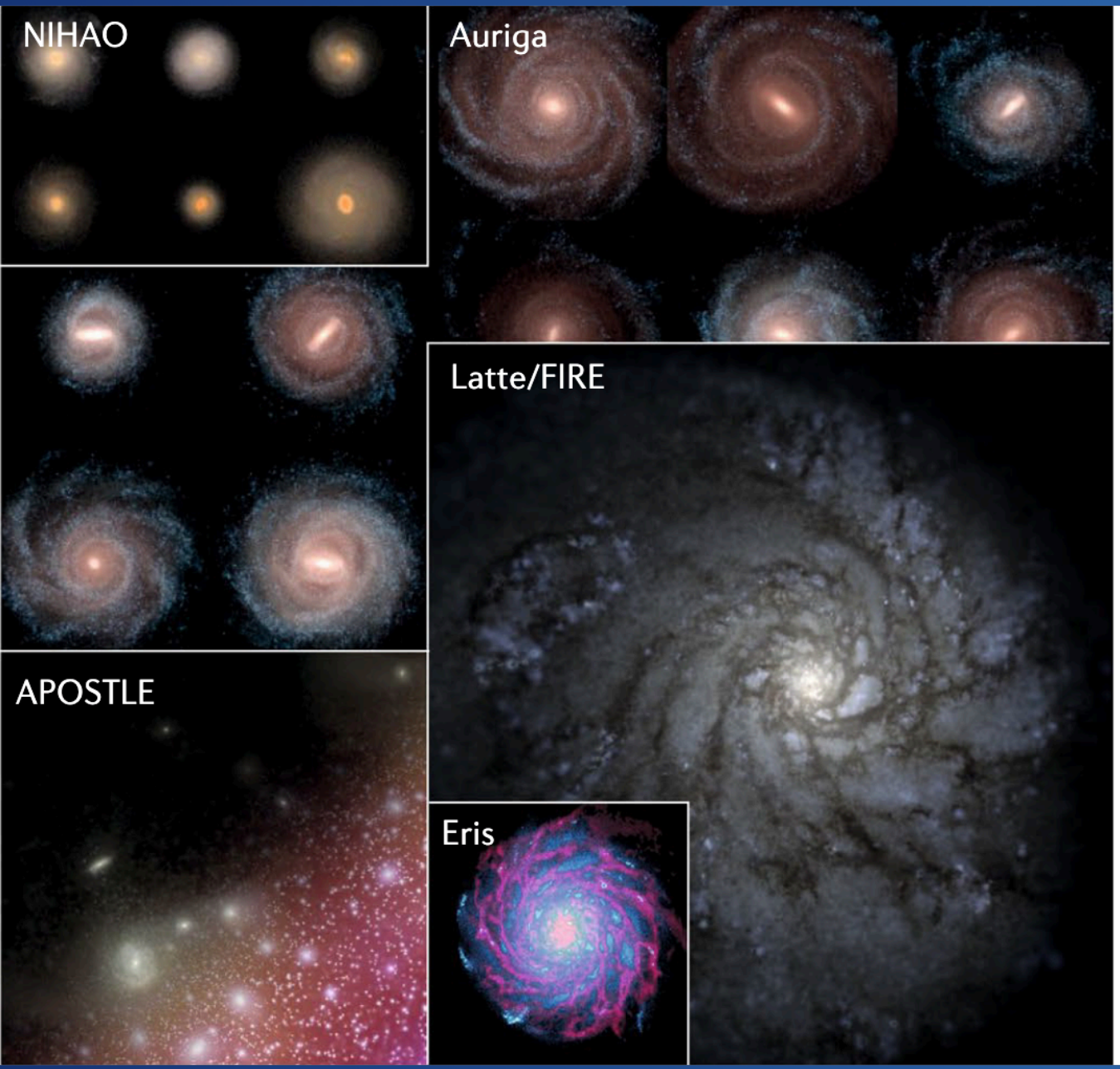
1 disk galaxy:
Mtot = $8x10^{11}$ $M\odot$; Mstars = $4x10^{10}$ $M\odot$

Guedes+ 2011





Rashkov, Pillepich+ 2013



Additional cosmological simulations of individual MW-like galaxies followed…

(so-called zoom-in simulations)

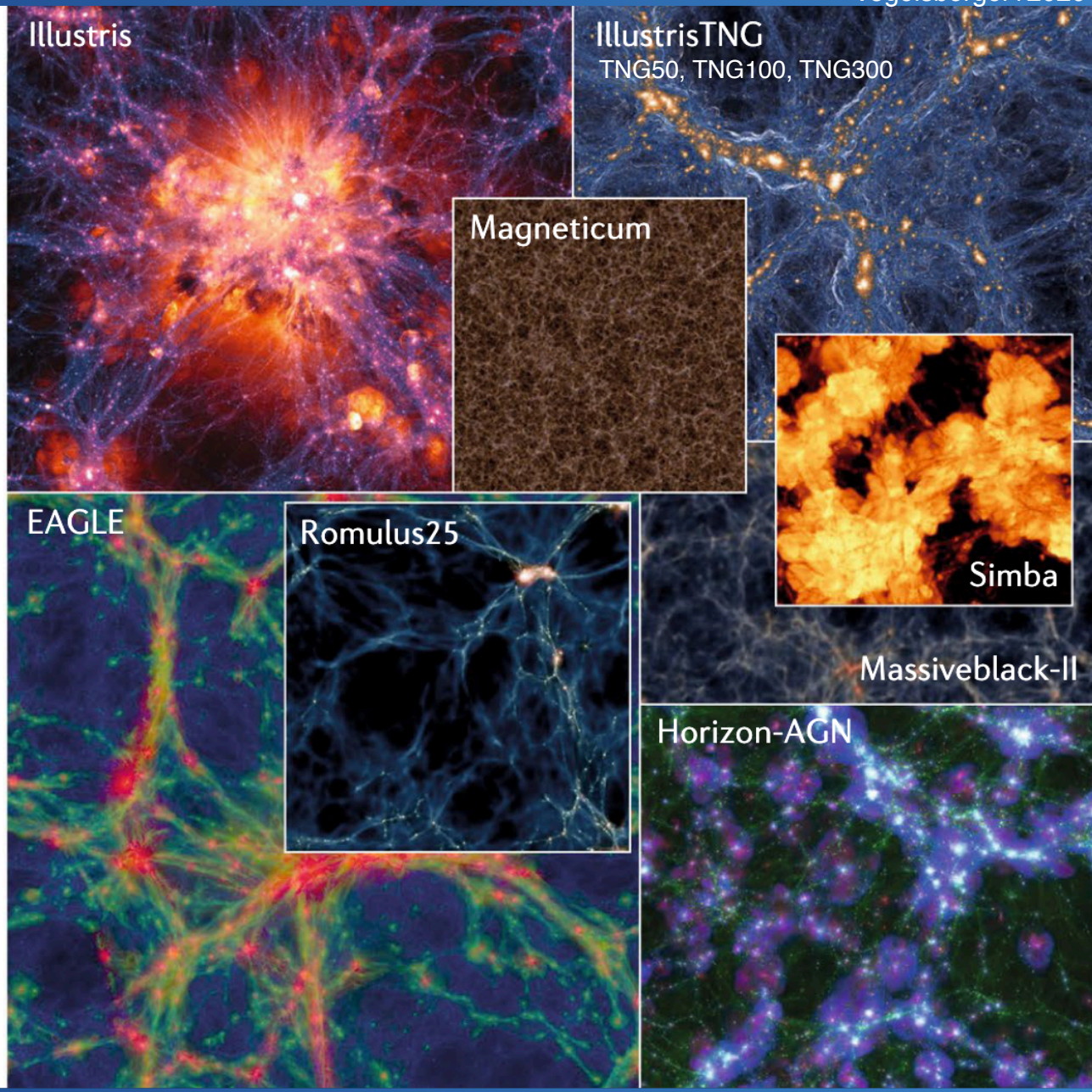
Vogelsberger+2020

Since 2014-2015, cosmological large-volume M(HD) simulations started to reproduce the observed *diversity* of galaxies

All with different codes, numerical resolution, and details of the galaxy-formation models:

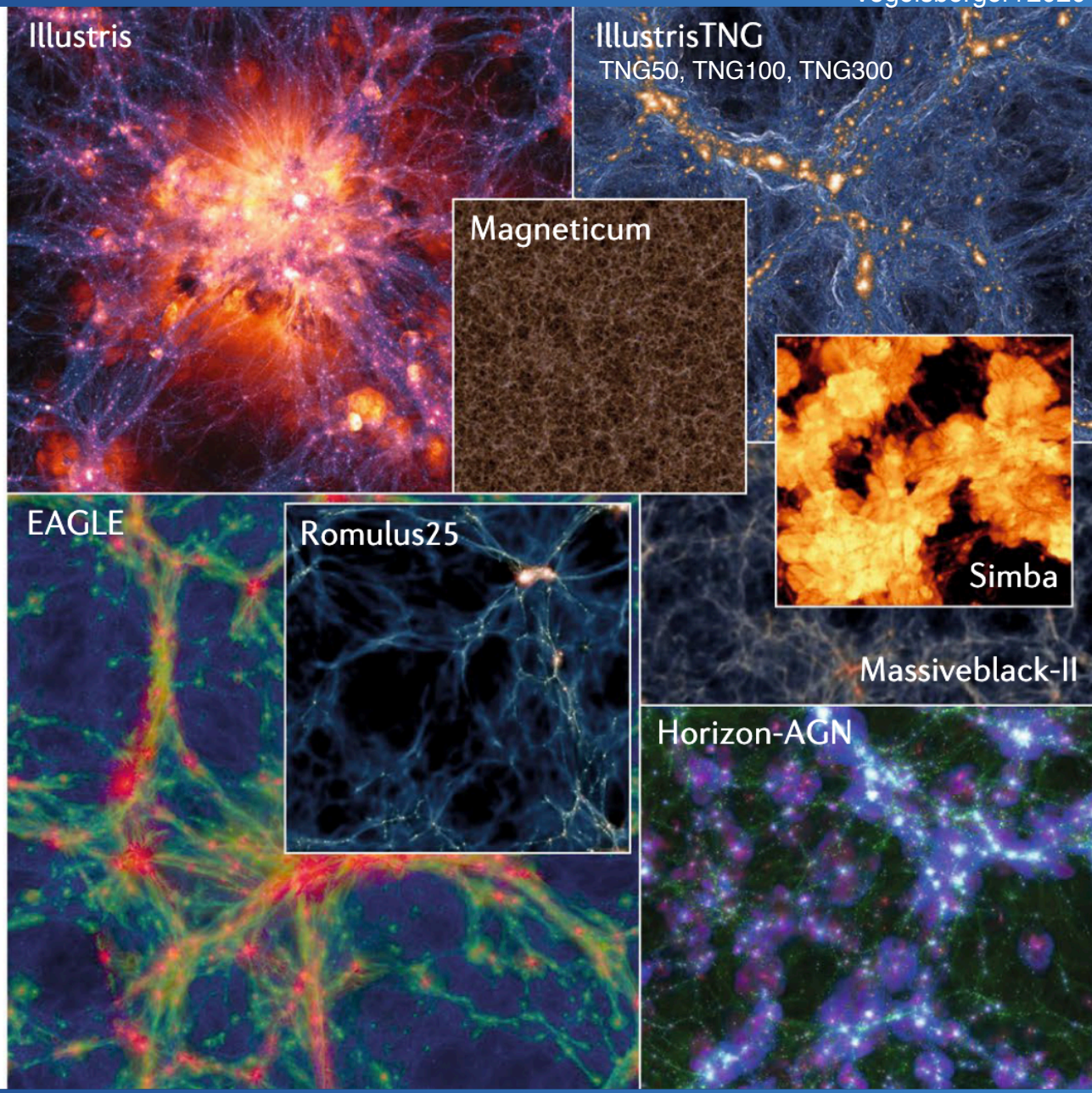
star formation,
gas cooling/heating,
chemical enrichment,
stellar feedback,
SMBH seeding, growth, and feedback

But no: $<10^4$ K gas, radiative transfer, resolved SN explosions, cosmic rays, collimated jets, …

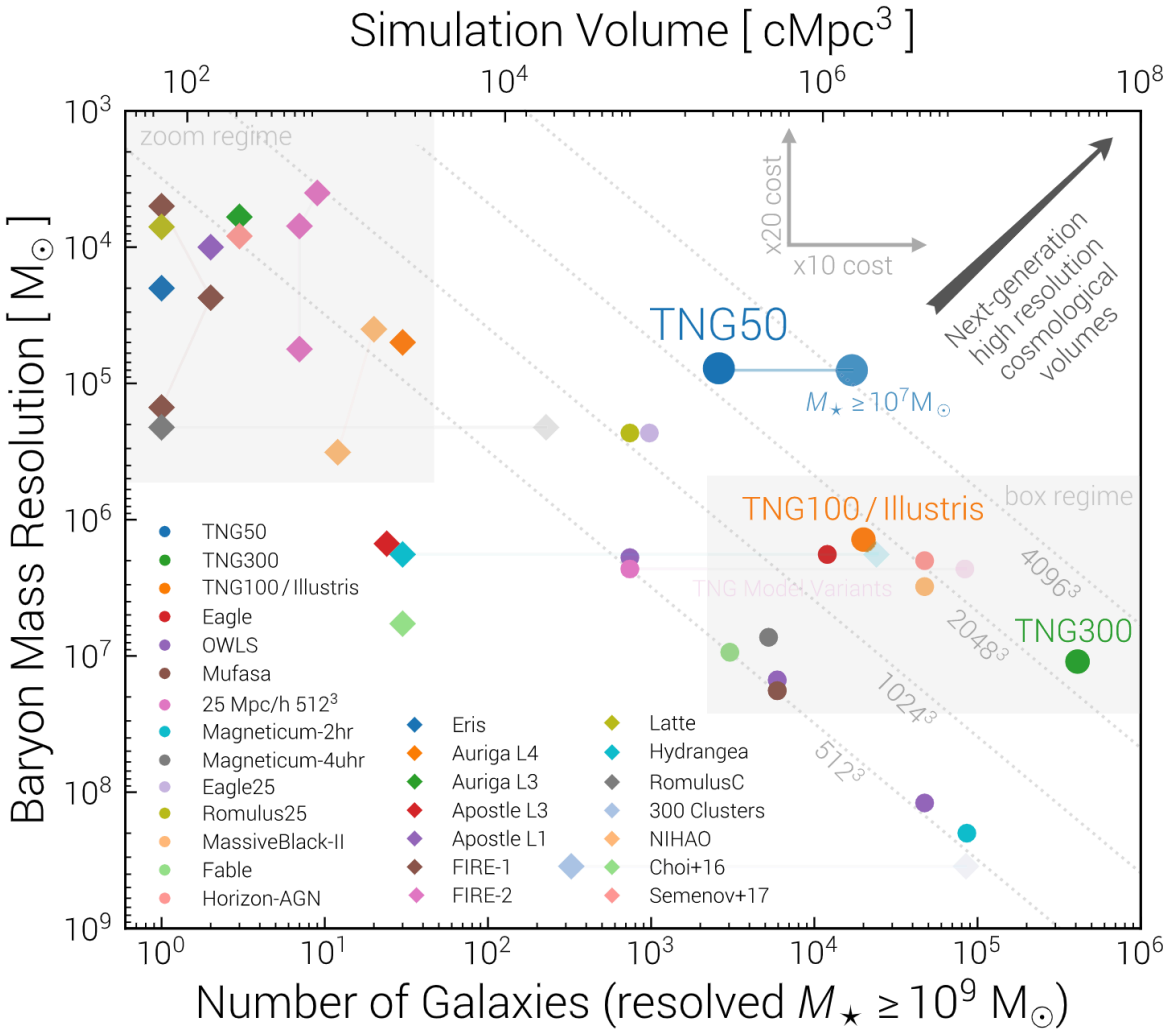


Since 2014-2015, cosmological large-volume M(HD) simulations started to reproduce the observed *diversity* of galaxies

=> 100s-1000s MW/M31-like galaxies!!!



TNG50 returns an exceptional statistics at zoom-like resolution



TNG50:

~5 pc smallest cell size

100-200 pc average cell size in sf-ing regions

290 pc softening of stars/DM particles

8×10^4 M⊙ stellar particles

$< 50 \times 10^3$ years smallest time steps

Including:

SMBH feedback

Magnetic fields

Shock finder

SNIa, SNII, AGB enrichment

10 elements + Eu

…

Nelson, Pillepich, Springel + 2019
Pillepich, Nelson, Springel + 2019

The TNG50 is an unprecedented laboratory also for MW-related science:

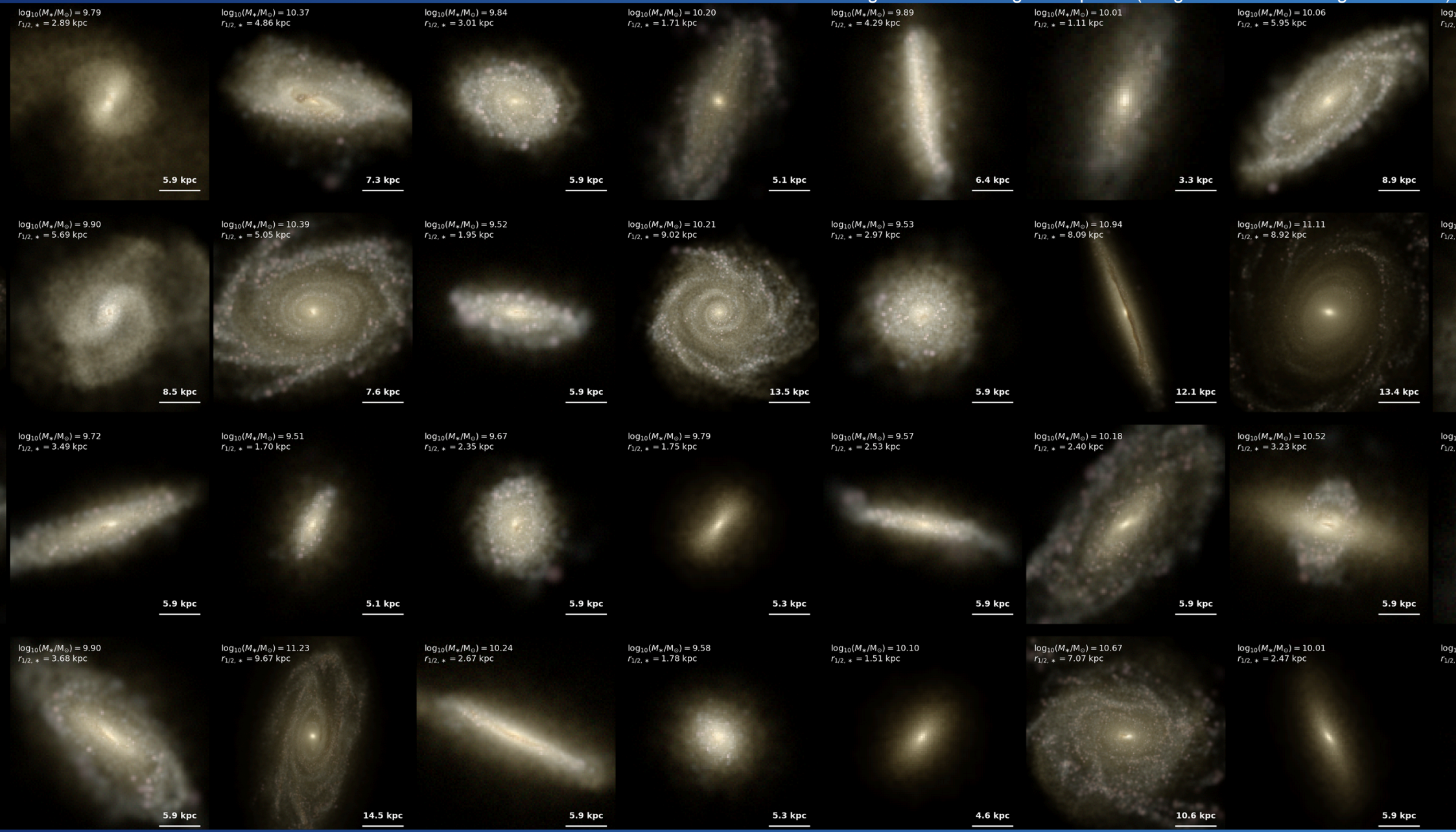
it returns at z=0
~200 well-resolved and diverse MW/M31-like galaxies

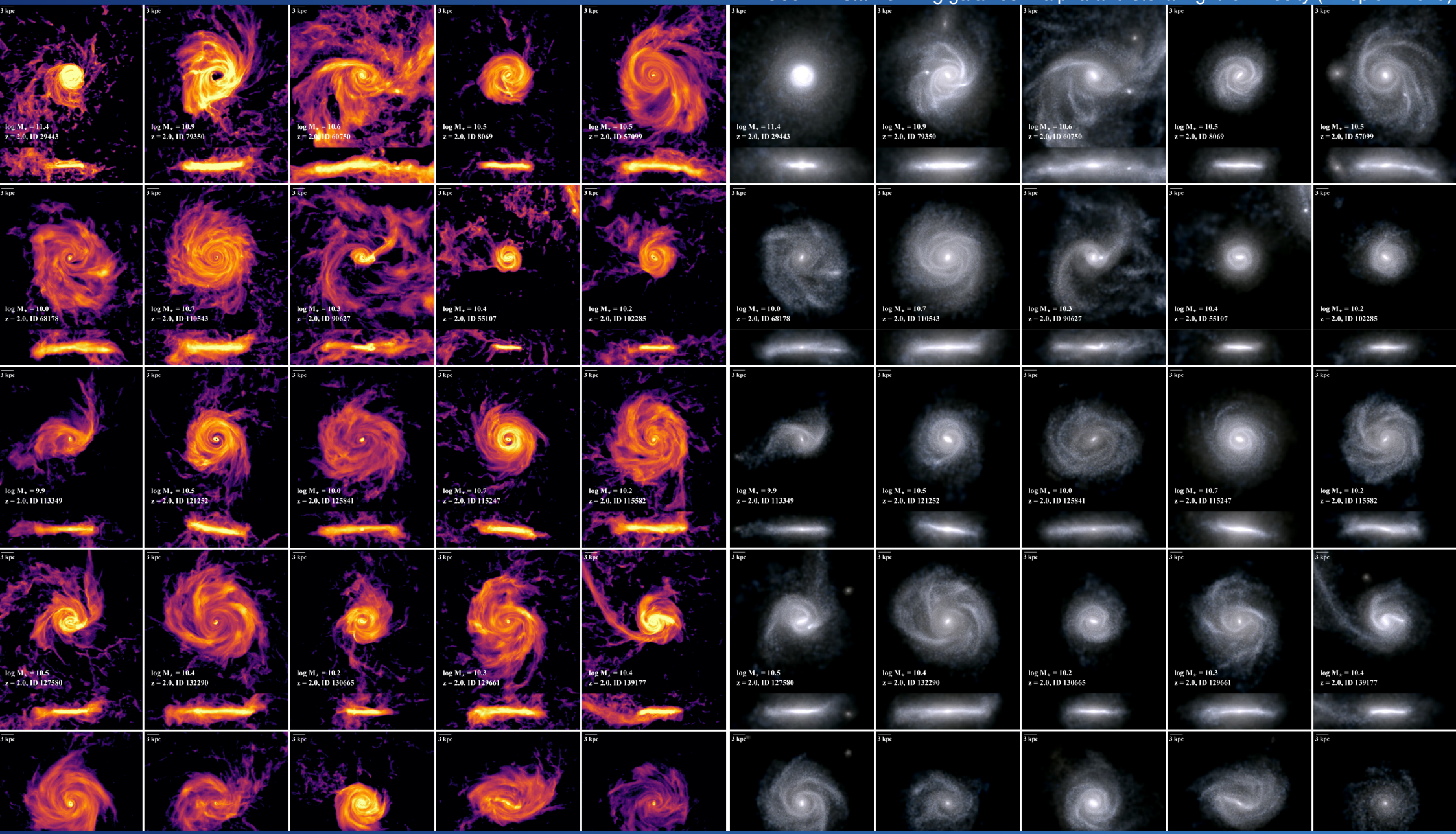
TNG50 data is fully public +

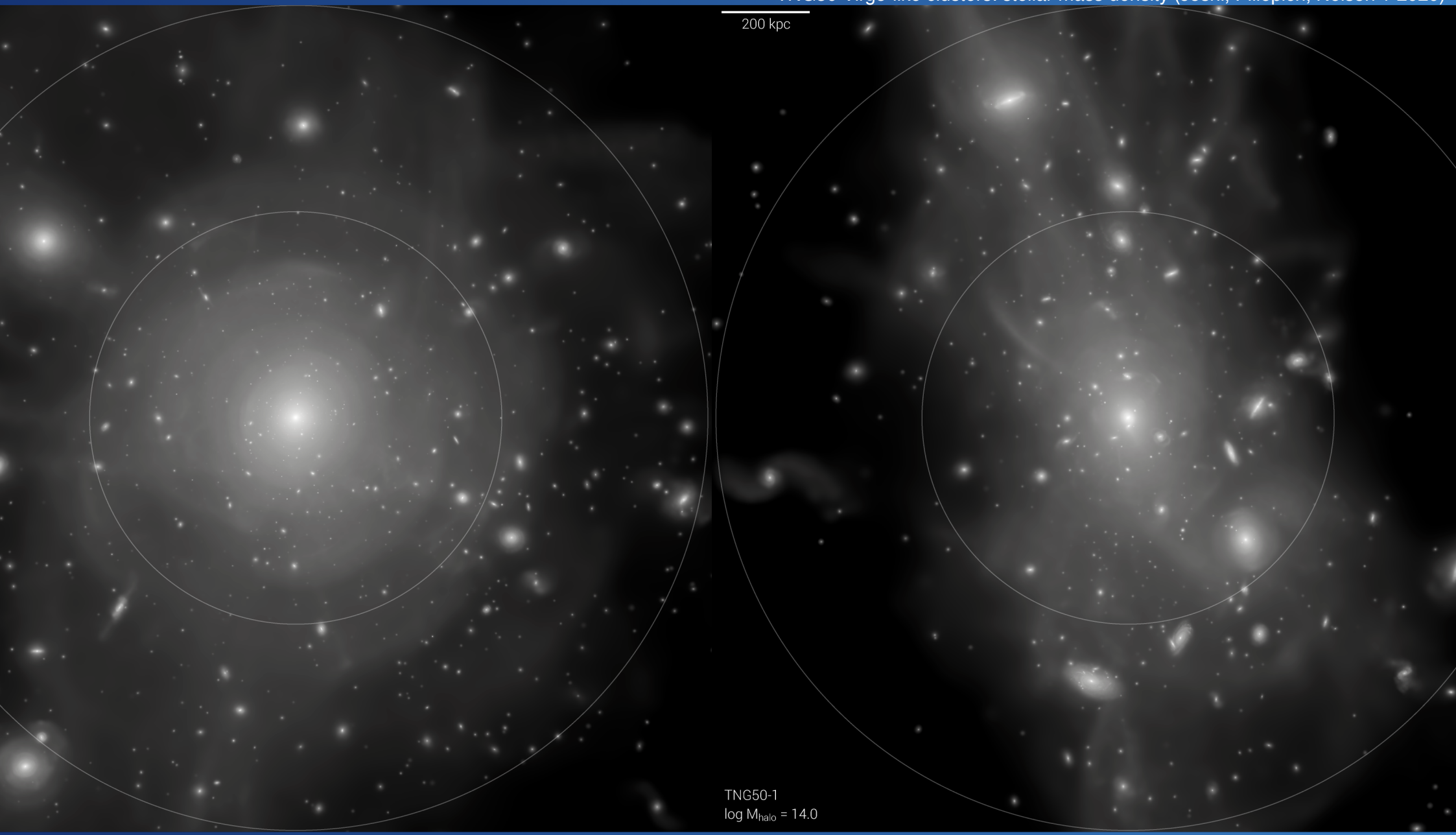
coming soon: release of even richer and easier-to-use data products of the TNG50 MW/M31-like galaxies

Pillepich+2022 in prep

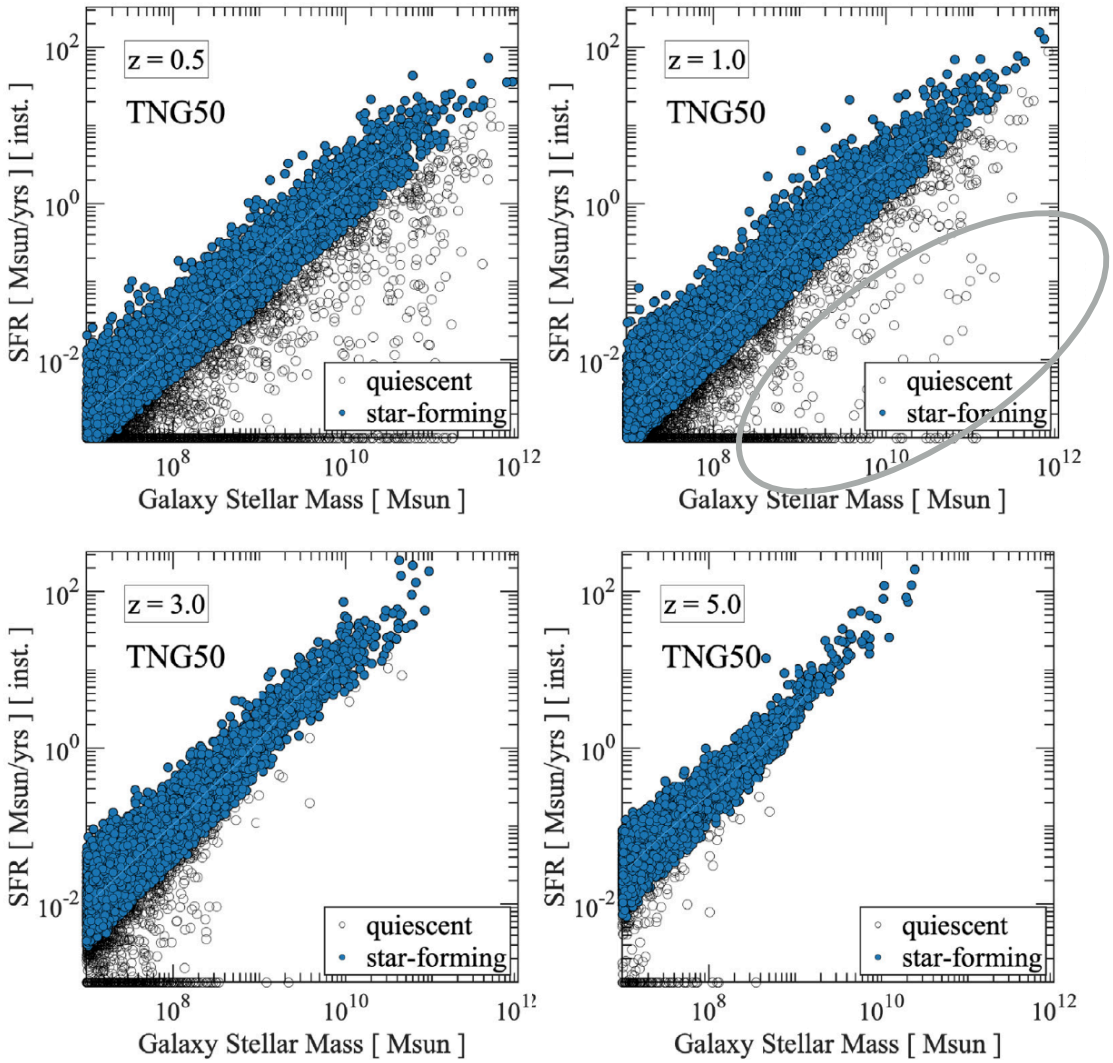
Why TNG50?


log10(M*/M⊙) = 9.79
r1/2, * = 2.89 kpc
5.9 kpc
log10(M*/M⊙) = 10.37
r1/2, * = 4.86 kpc
7.3 kpc
log10(M*/M⊙) = 9.84
r1/2, * = 3.01 kpc
5.9 kpc
log10(M*/M⊙) = 10.20
r1/2, * = 1.71 kpc
5.1 kpc
log10(M*/M⊙) = 9.89
r1/2, * = 4.29 kpc
6.4 kpc
log10(M*/M⊙) = 10.01
r1/2, * = 1.11 kpc
3.3 kpc
log10(M*/M⊙) = 10.06
r1/2, * = 5.95 kpc
8.9 kpc
log10(M*/M⊙) = 9.90
r1/2, * = 5.69 kpc
8.5 kpc
log10(M*/M⊙) = 10.39
r1/2, * = 5.05 kpc
7.6 kpc
log10(M*/M⊙) = 9.52
r1/2, * = 1.95 kpc
5.9 kpc
log10(M*/M⊙) = 10.21
r1/2, * = 9.02 kpc
13.5 kpc
log10(M*/M⊙) = 9.53
r1/2, * = 2.97 kpc
5.9 kpc
log10(M*/M⊙) = 10.94
r1/2, * = 8.09 kpc
12.1 kpc
log10(M*/M⊙) = 11.11
r1/2, * = 8.92 kpc
13.4 kpc
log10(M*/M⊙) = 9.72
r1/2, * = 3.49 kpc
5.9 kpc
log10(M*/M⊙) = 9.51
r1/2, * = 1.70 kpc
5.1 kpc
log10(M*/M⊙) = 9.67
r1/2, * = 2.35 kpc
5.9 kpc
log10(M*/M⊙) = 9.79
r1/2, * = 1.75 kpc
5.3 kpc
log10(M*/M⊙) = 9.57
r1/2, * = 2.53 kpc
5.9 kpc
log10(M*/M⊙) = 10.18
r1/2, * = 2.40 kpc
5.9 kpc
log10(M*/M⊙) = 10.52
r1/2, * = 3.23 kpc
5.9 kpc
log10(M*/M⊙) = 9.90
r1/2, * = 3.68 kpc
5.9 kpc
log10(M*/M⊙) = 11.23
r1/2, * = 9.67 kpc
14.5 kpc
log10(M*/M⊙) = 10.24
r1/2, * = 2.67 kpc
5.9 kpc
log10(M*/M⊙) = 9.58
r1/2, * = 1.78 kpc
5.3 kpc
log10(M*/M⊙) = 10.10
r1/2, * = 1.51 kpc
4.6 kpc
log10(M*/M⊙) = 10.67
r1/2, * = 7.07 kpc
10.6 kpc
log10(M*/M⊙) = 10.01
r1/2, * = 2.47 kpc
5.9 kpc


3 kpc
log M* = 11.4
z = 2.0, ID 29443
log M* = 10.9
z = 2.0, ID 79350
log M* = 10.6
z = 2.0, ID 60750
log M* = 10.5
z = 2.0, ID 8069
log M* = 10.5
z = 2.0, ID 57099
log M* = 10.0
z = 2.0, ID 68178
log M* = 10.7
z = 2.0, ID 110543
log M* = 10.3
z = 2.0, ID 90627
log M* = 10.4
z = 2.0, ID 55107
log M* = 10.2
z = 2.0, ID 102285
log M* = 9.9
z = 2.0, ID 113349
log M* = 10.5
z = 2.0, ID 121252
log M* = 10.0
z = 2.0, ID 125841
log M* = 10.7
z = 2.0, ID 115247
log M* = 10.2
z = 2.0, ID 115582
log M* = 10.5
z = 2.0, ID 127580
log M* = 10.4
z = 2.0, ID 132290
log M* = 10.2
z = 2.0, ID 130665
log M* = 10.3
z = 2.0, ID 129661
log M* = 10.4
z = 2.0, ID 139177


200 kpc
TNG50-1
log M_{halo} = 14.0

TNG50 returns both a SFMS as well as quenched galaxies



Pillepich, Nelson, Springel + 2019

Star forming main sequence

galaxy mass ↗ SFR values ↗

redshift ↗ locus of SFMS ↗

+ agreement with observations

Donnari, Pillepich + 2019
Erica Nelson + 2021

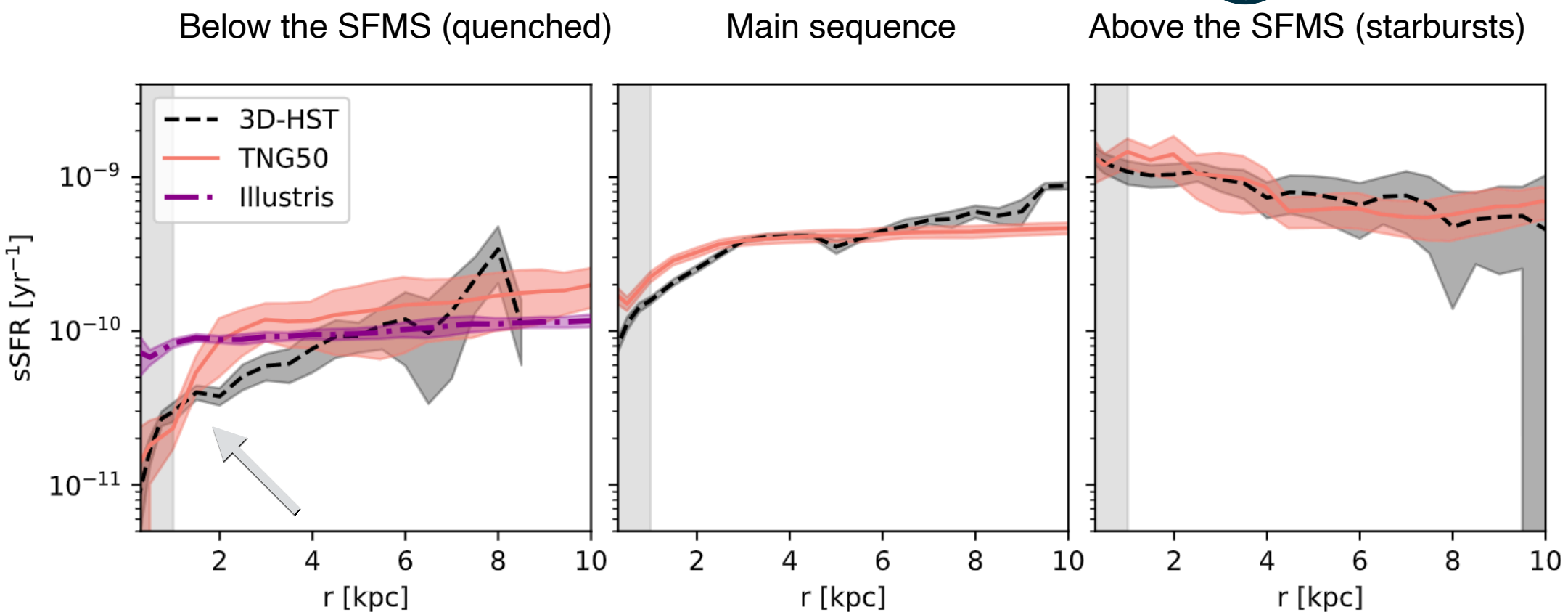
Quenched galaxies:

At the low-mass end: environment
At the high-mass end: SMBH feedback

e.g.
Weinberger+2018
Zinger, Pillepich+2020
Donnari, Pillepich + 2021a
Joshi, Pillepich+2021

TNG50's inside-out quenching is consistent with 3D-HST data

$M_* \sim 10^{10.5\text{-}11}\ M_\odot$, z ~1
Hα-based SFRs

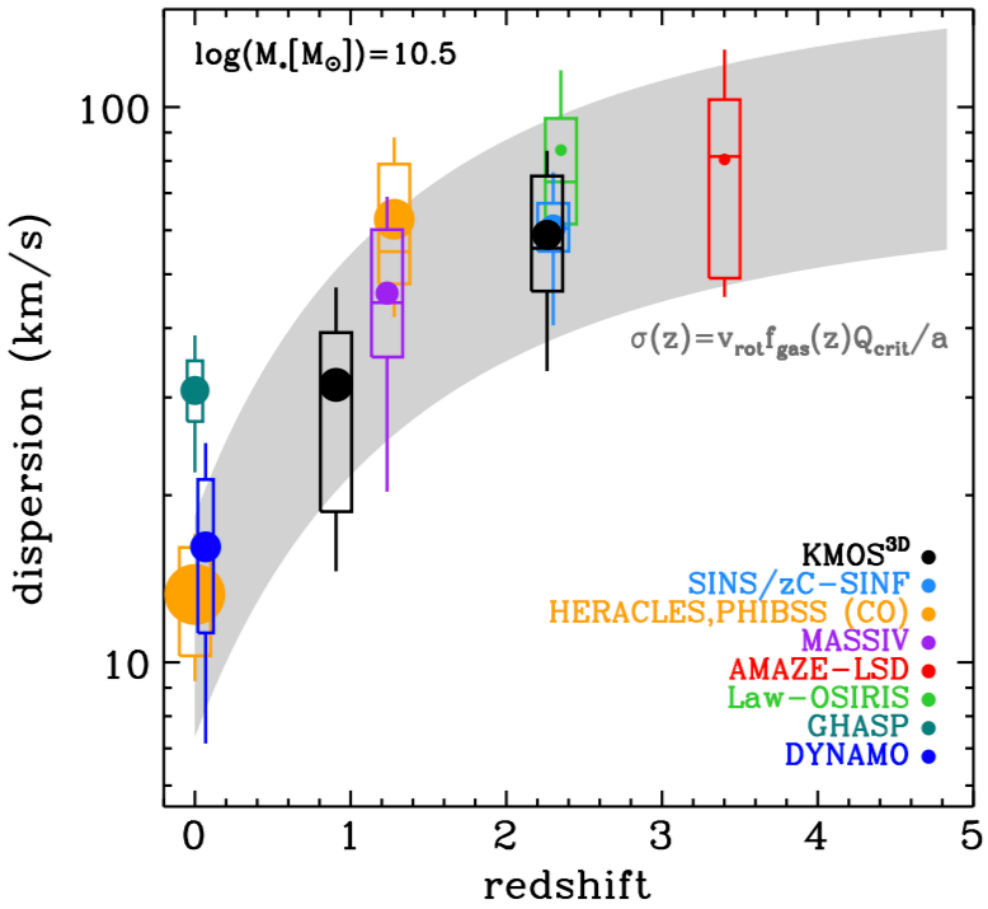


SMBH feedback in TNG => physical state/abundance of the ISM altered

Nelson Erica, Tacchella, Diemer+ /w Pillepich 2021

TNG50 returns more “turbulent/chaotic” star-forming galaxies at earlier times

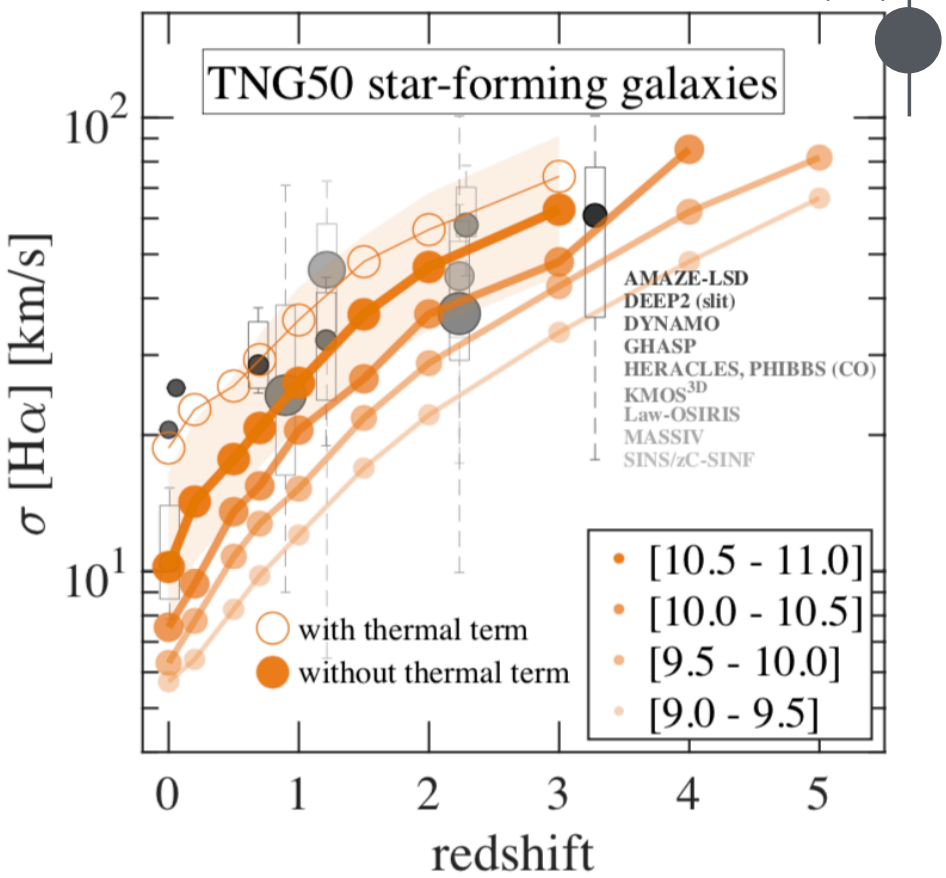
Observed



e.g. Wisnioski + 2015

Simulated

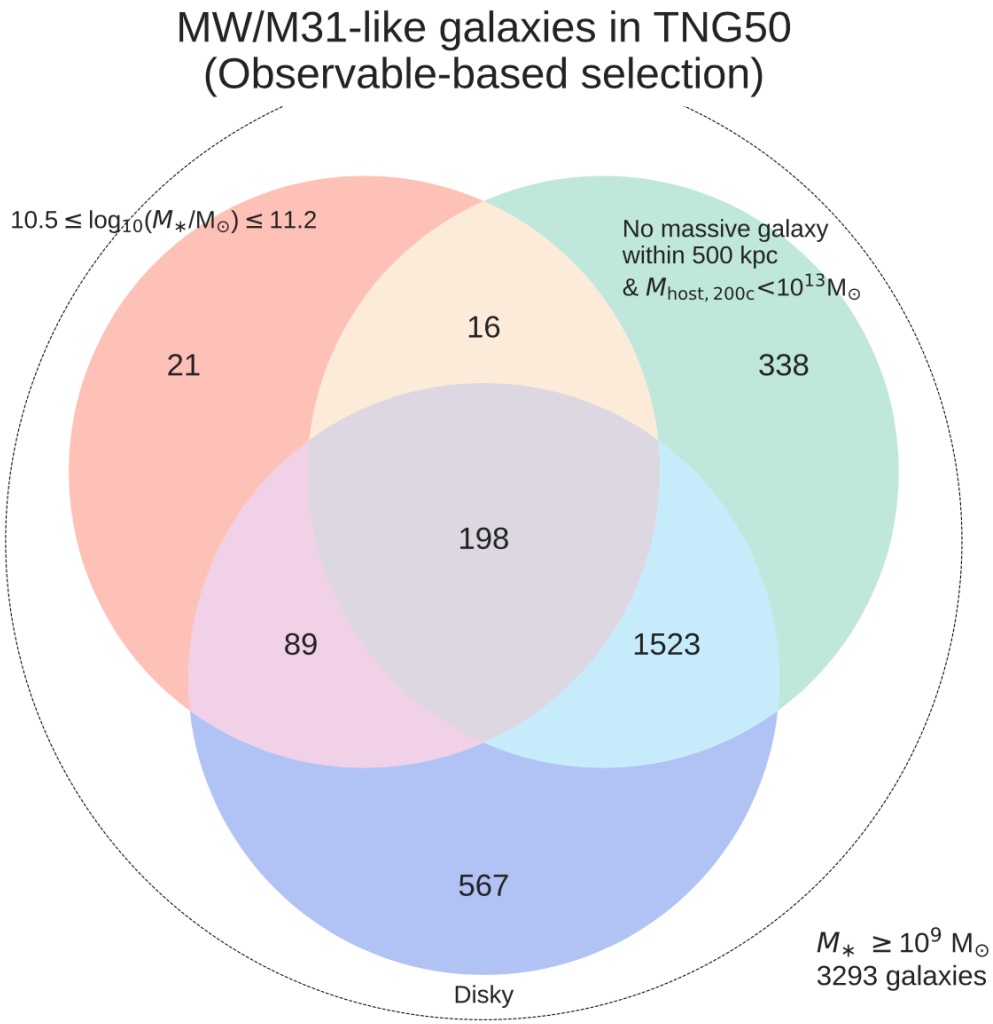
Neeleman+ 2019 with ALMA (CII)



TNG50: Pillepich, Nelson,Springel+ 2019

MW/M31-like galaxies from TNG50

We select MW/M31-like galaxies based on global observable properties

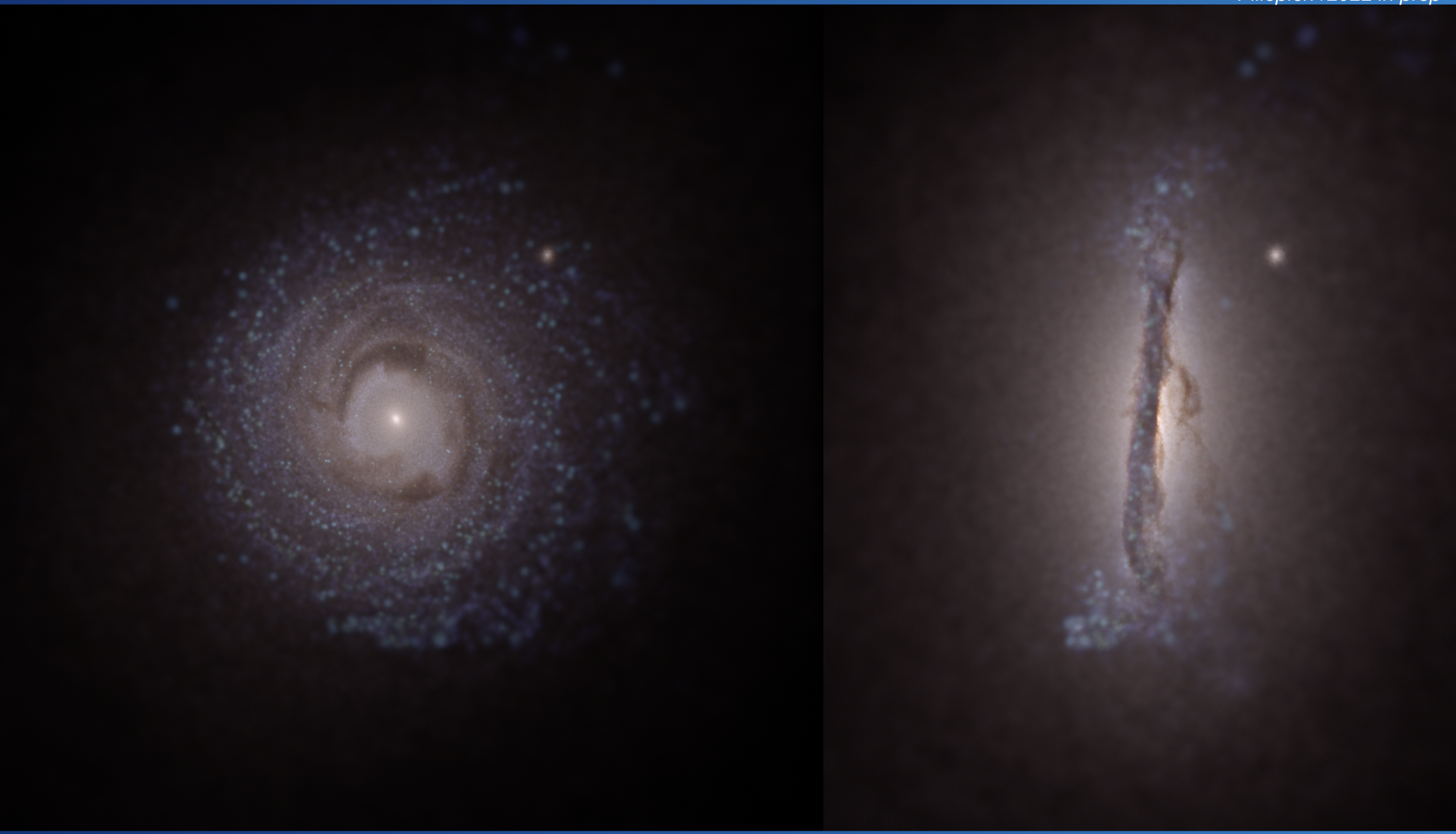


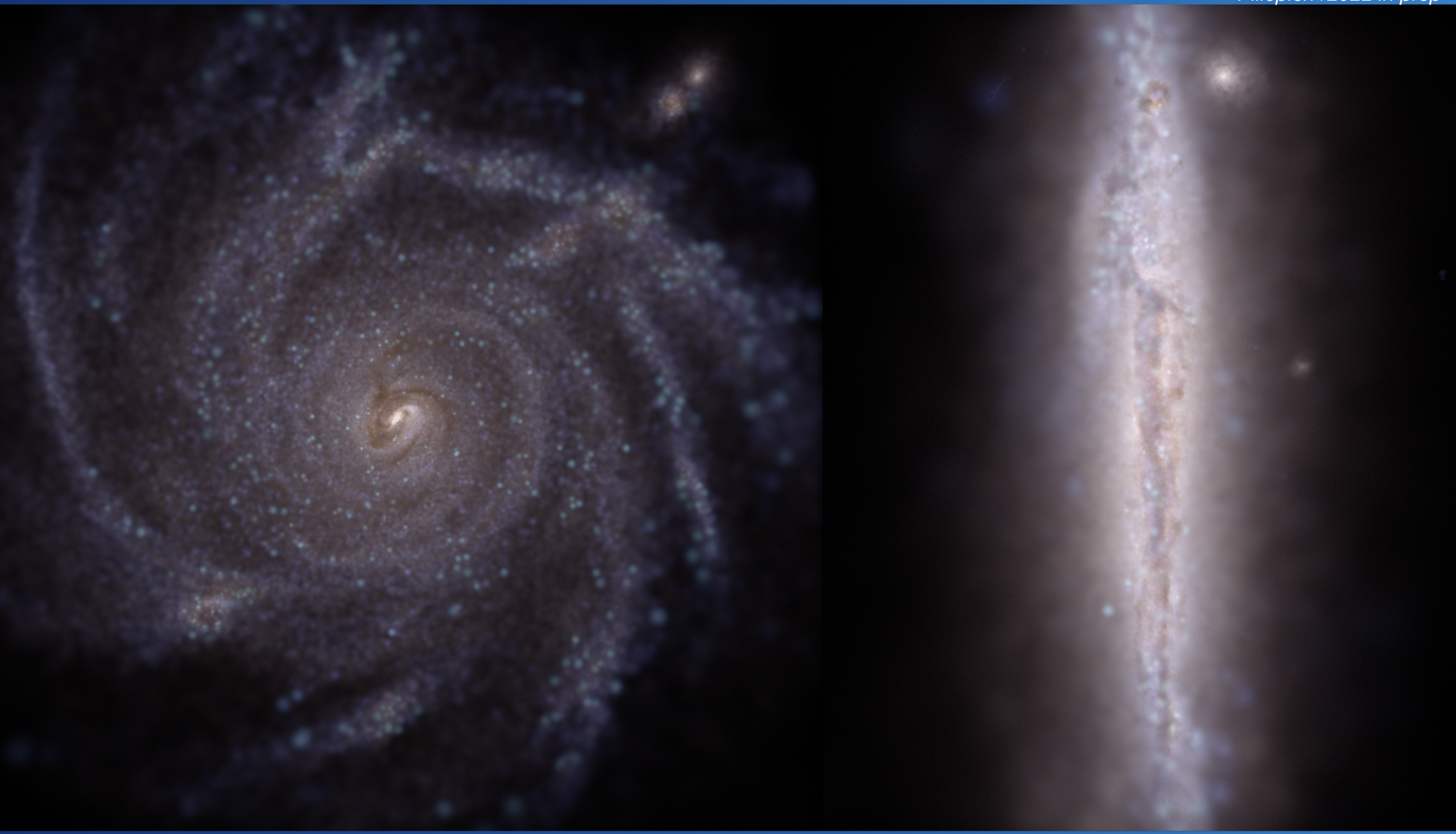
Selection agnostic wrt total halo mass, recent merger history, …

By design, both MW and M31-mass galaxies

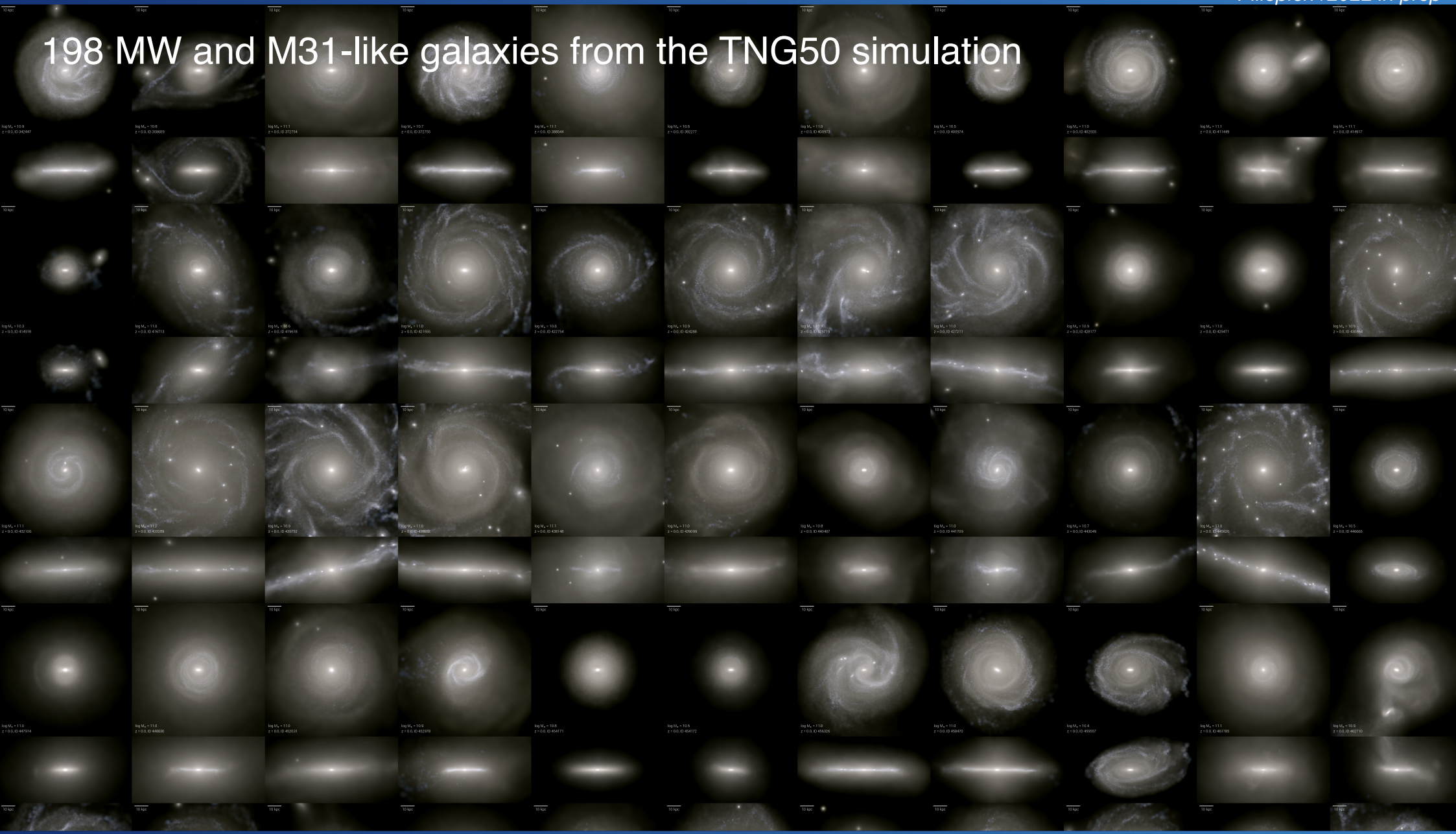
No constraints a priori on detailed structural properties

Pillepich+2022 in prep
Venn diagram credits: D. Sotillo-Ramos

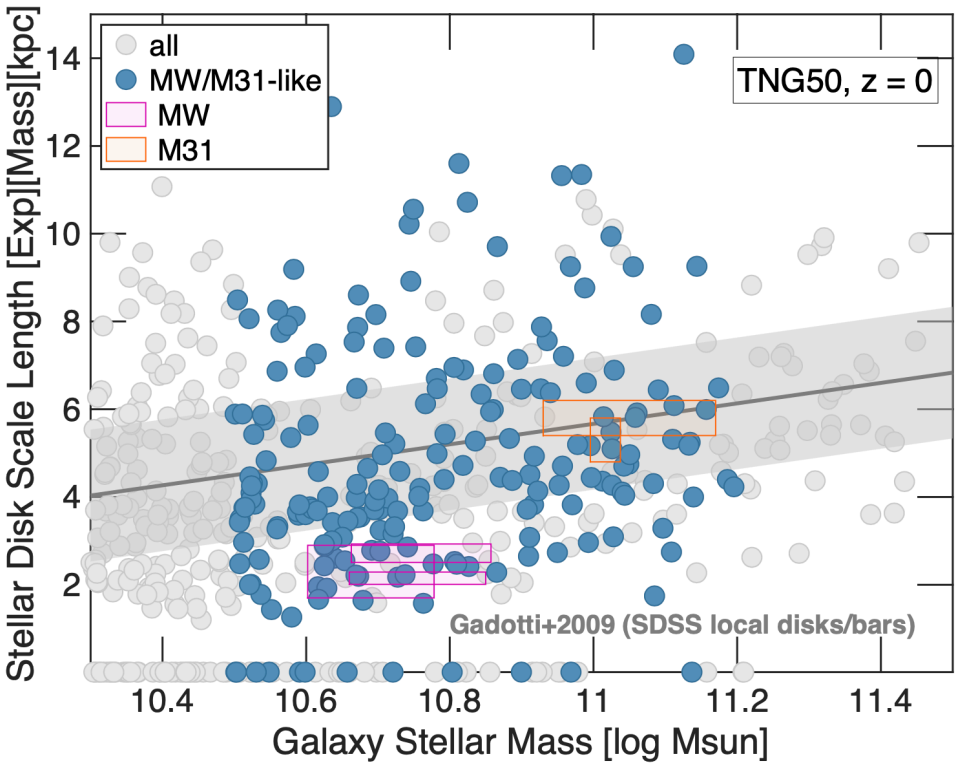


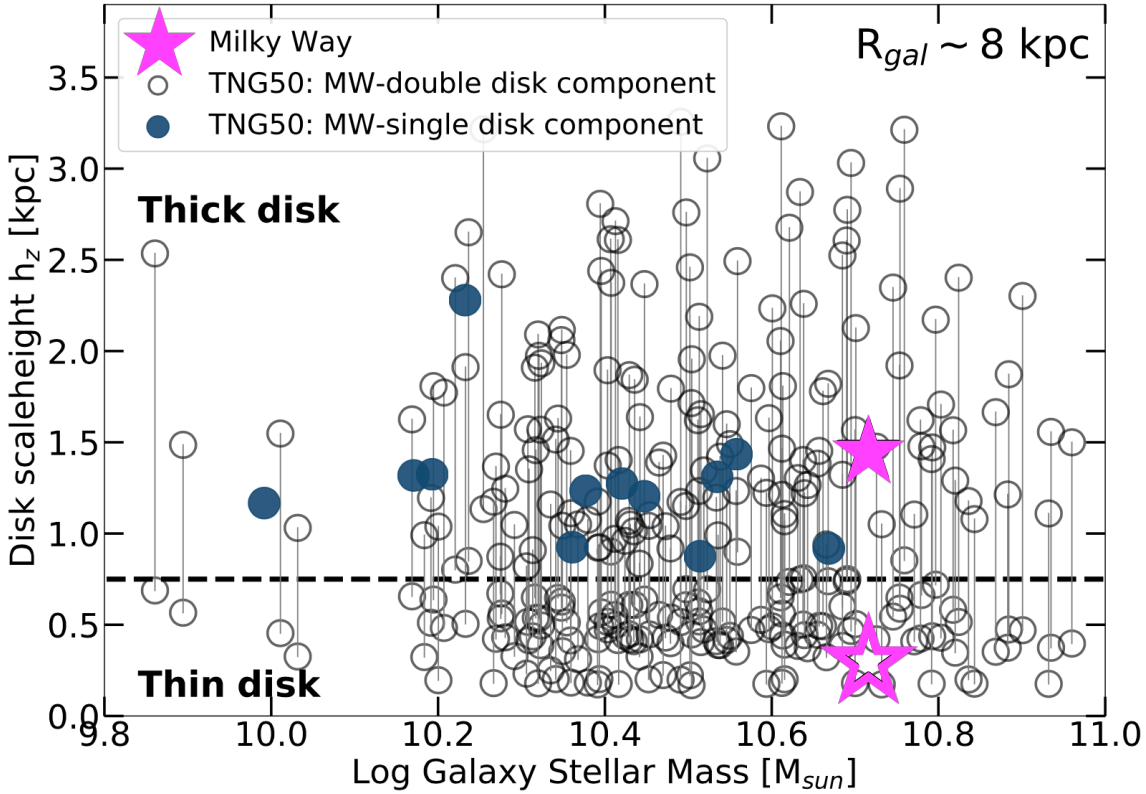


198 MW and M31-like galaxies from the TNG50 simulation



The TNG50 MW/M31-like galaxies span a diversity of stellar disk structures

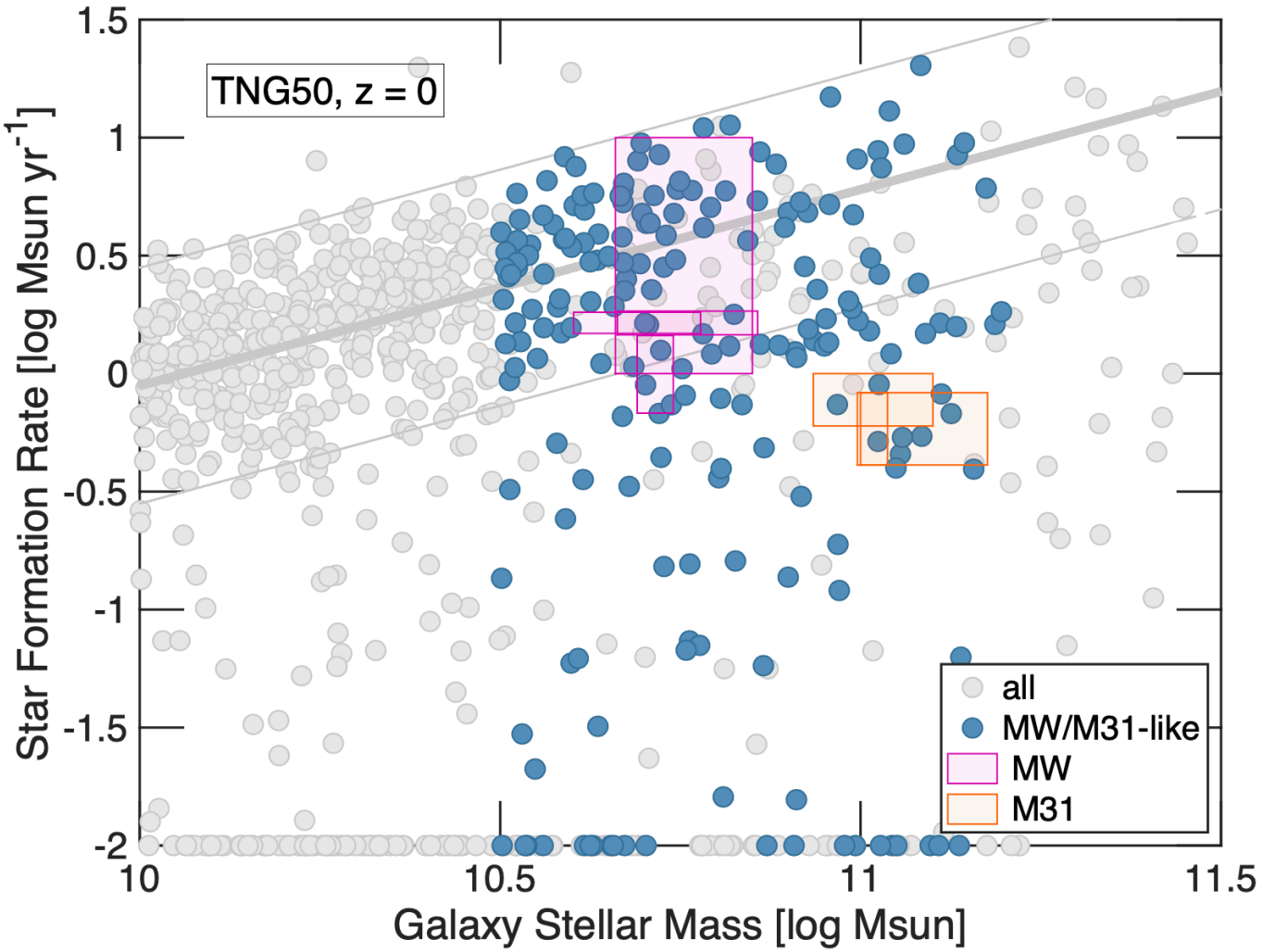




Including ~2-kpc small stellar disks and
stellar disk heights of ~100s parsecs

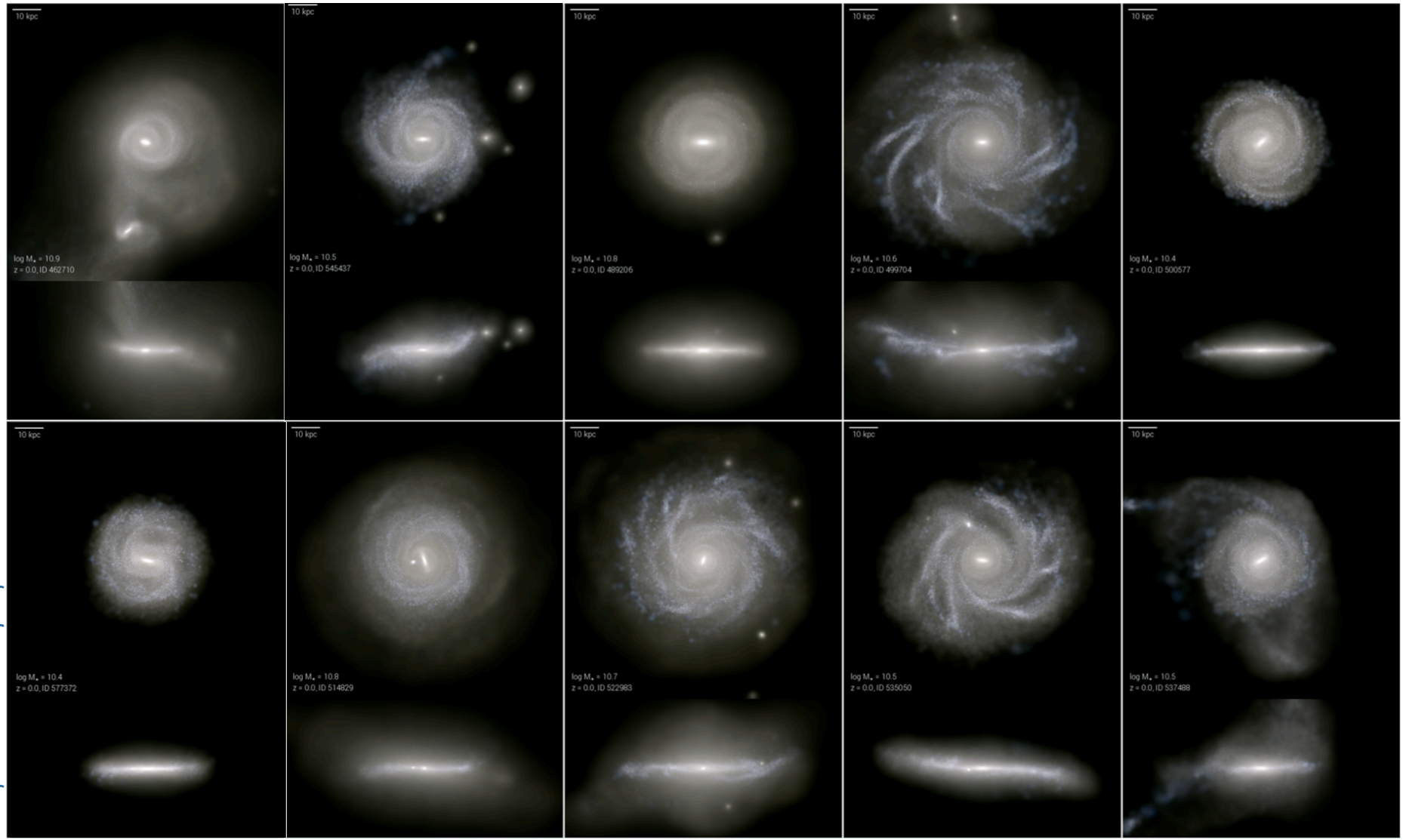
Pillepich+2022 in prep
See also Sotillo-Ramos+2022ab

The TNG50 MW/M31-like galaxies span a diversity of current SFRs



Pillepich+2022 in prep

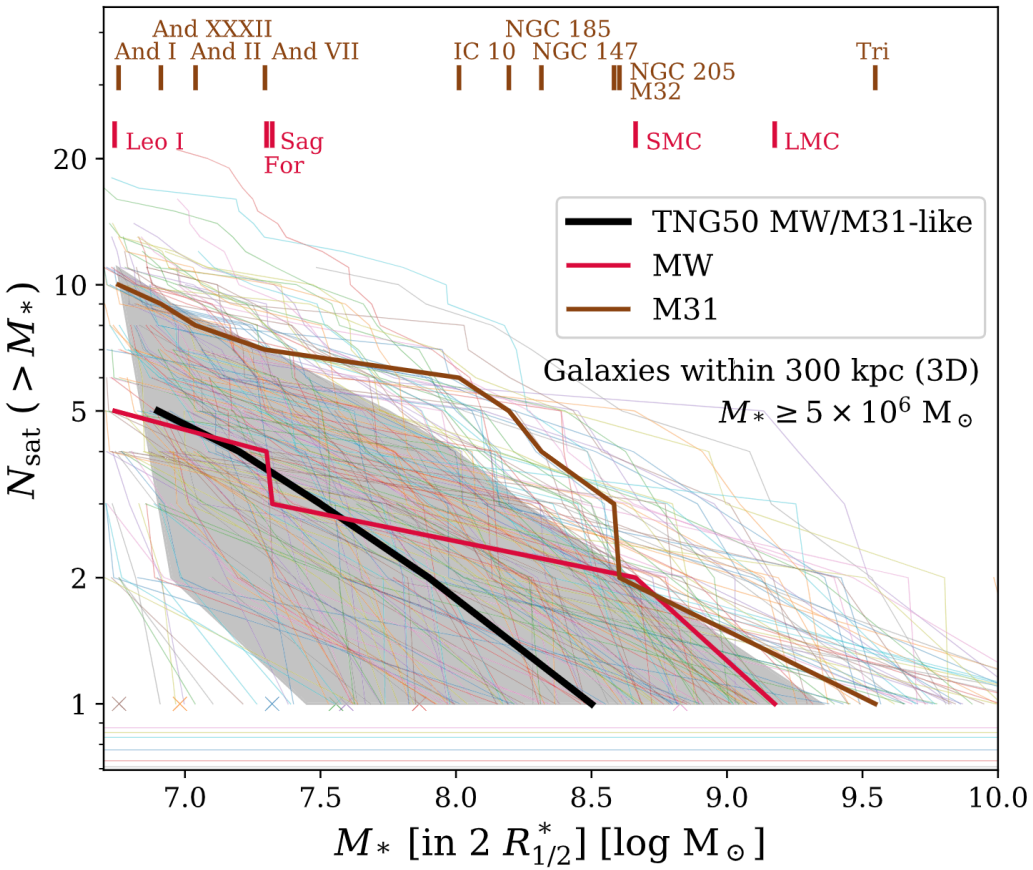
>1/2 TNG50 MW/M31-like galaxies have a stellar bar, of diverse properties

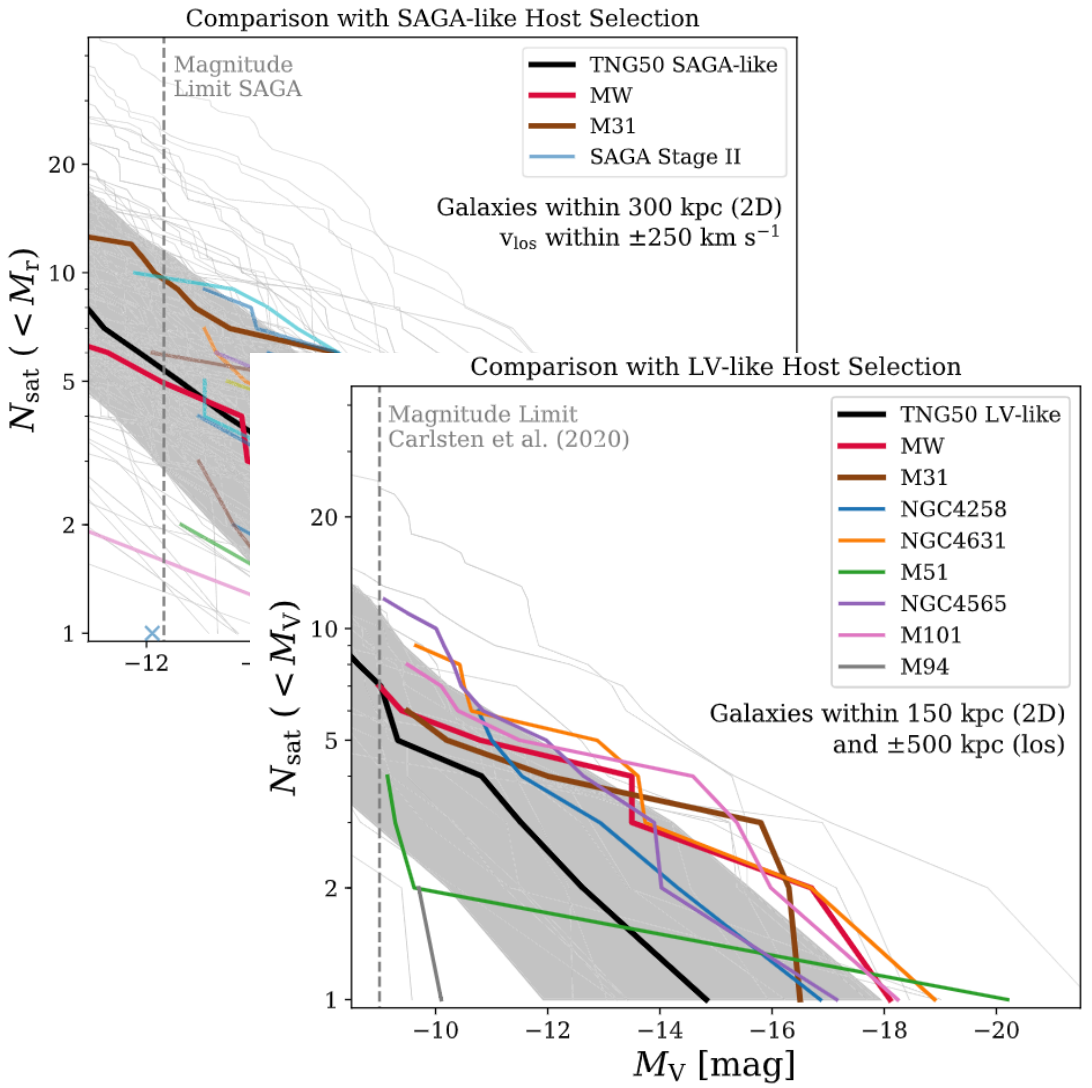


Pillepich+2022 in prep

Insights from TNG50 MW/M31-like galaxies

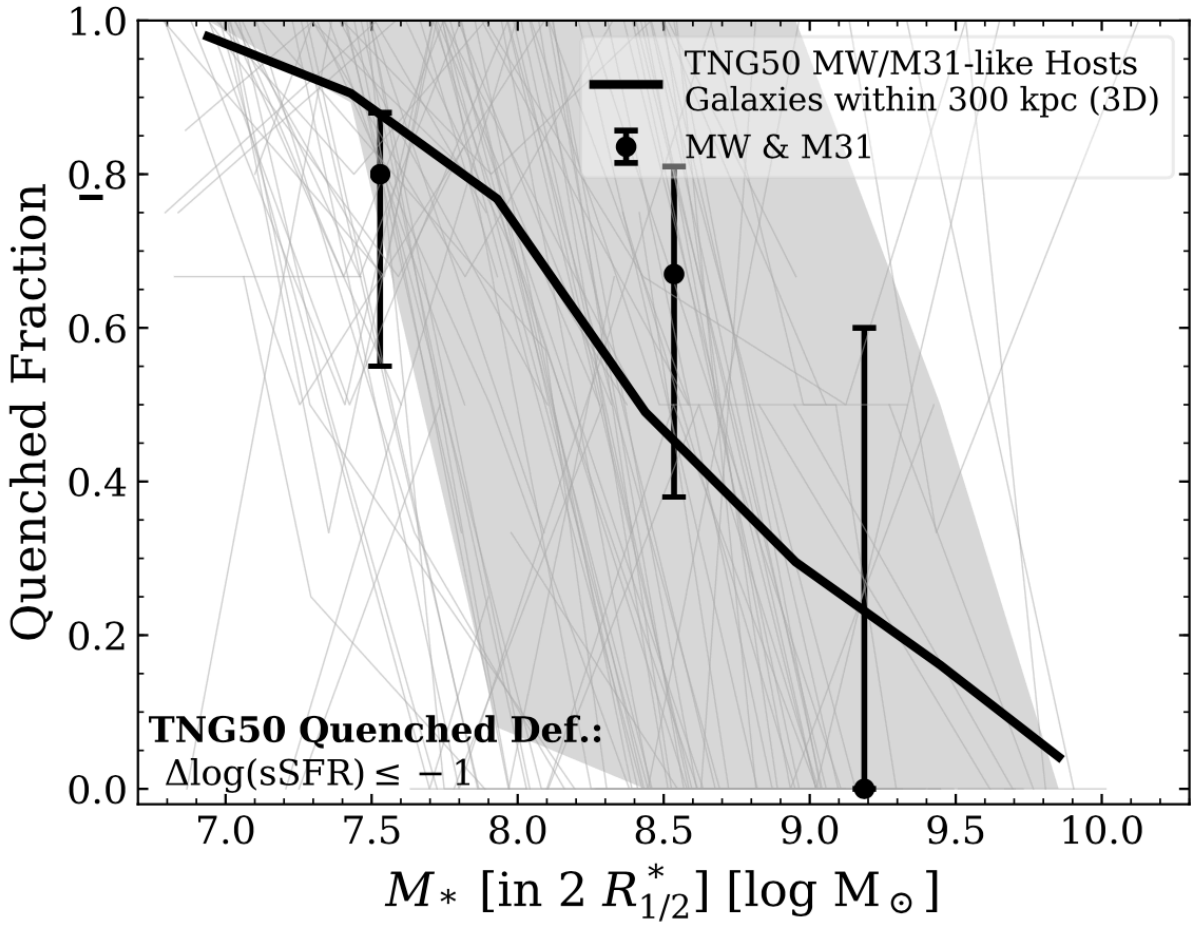
#1 There is no missing satellites problem (at least in the classical sense)





Engler, Pillepich, Pasquali+2021

#2 The satellite quenched fractions vary enormously from host to host

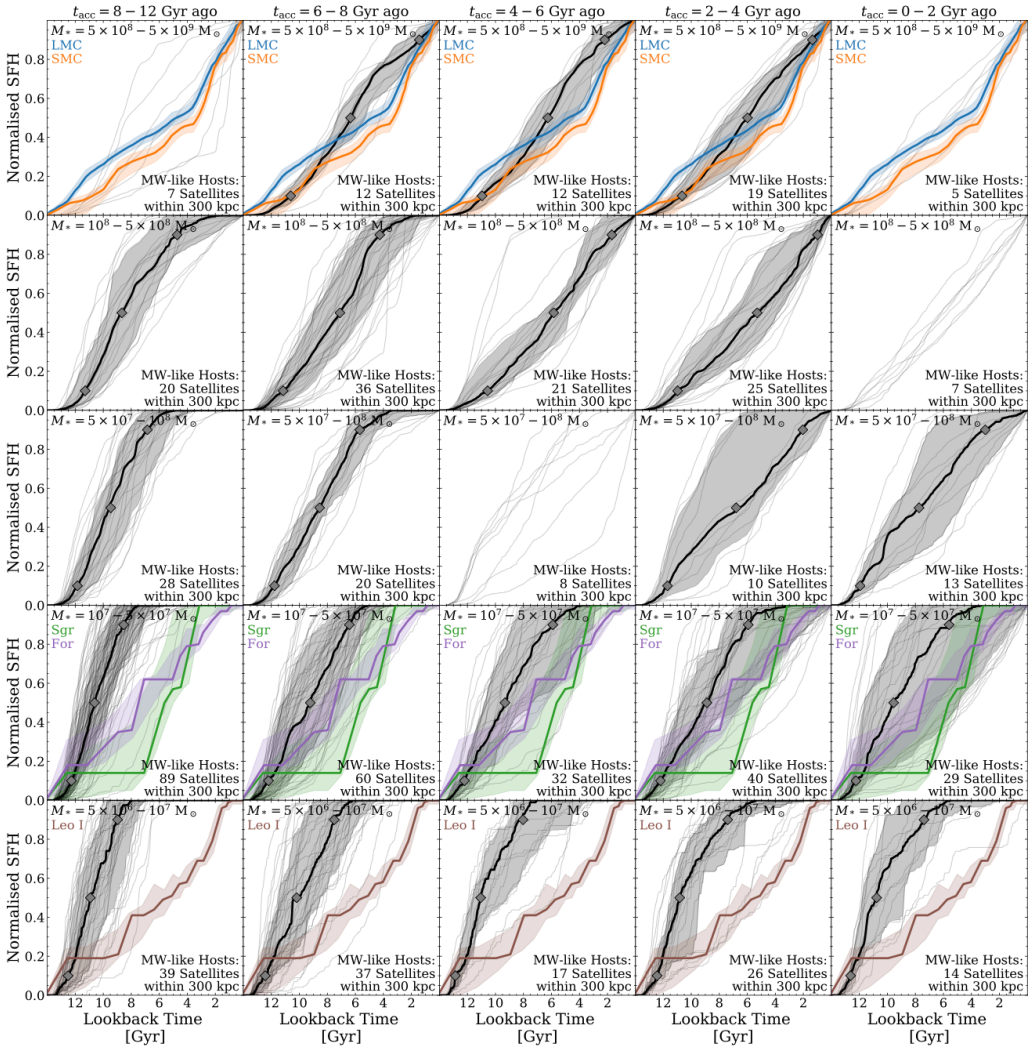


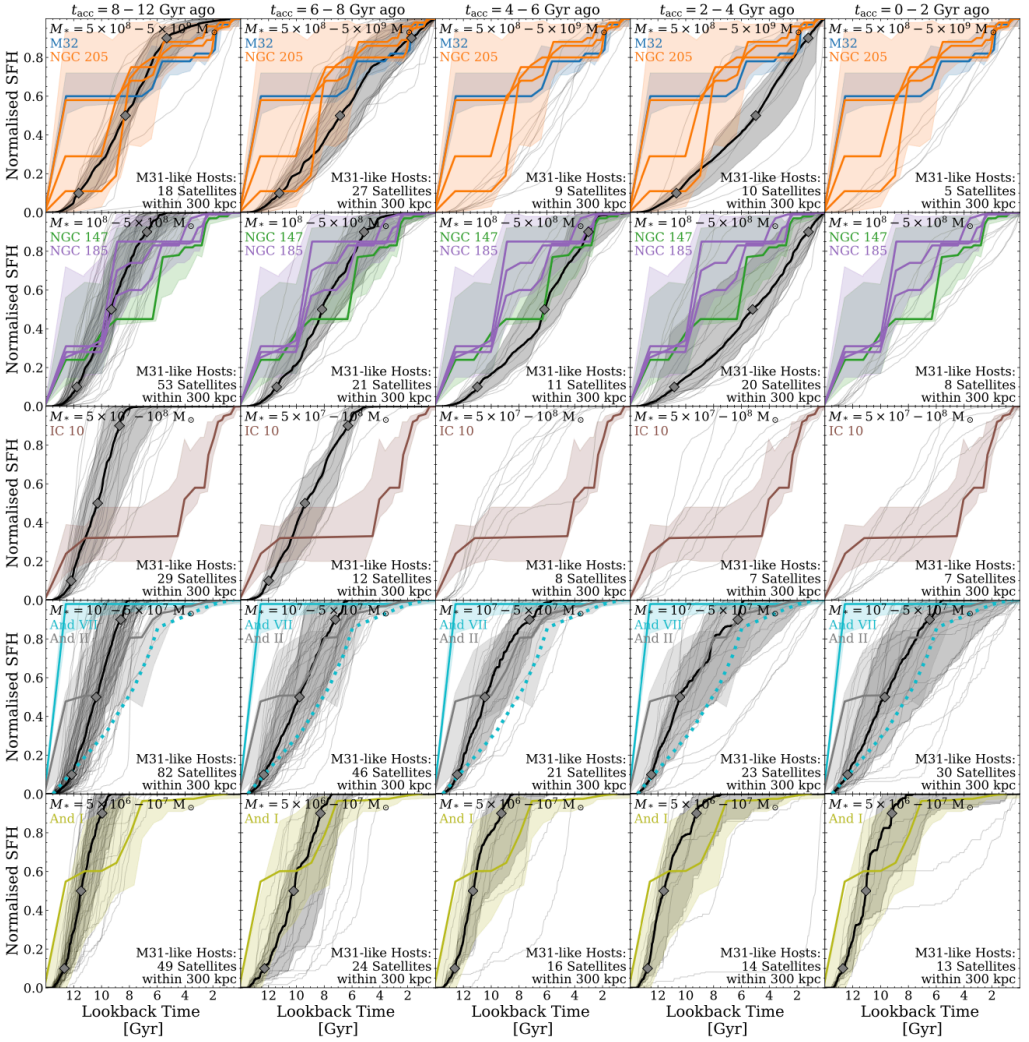
Individual TNG50 MW/M31-like hosts

Mean across 198 TNG50 MW/M31-like hosts

Engler, Pillepich, Joshi+2022, submitted (on astro-ph soon)

#3 The SF/SFH properties of MW/M31-like satellites are diverse



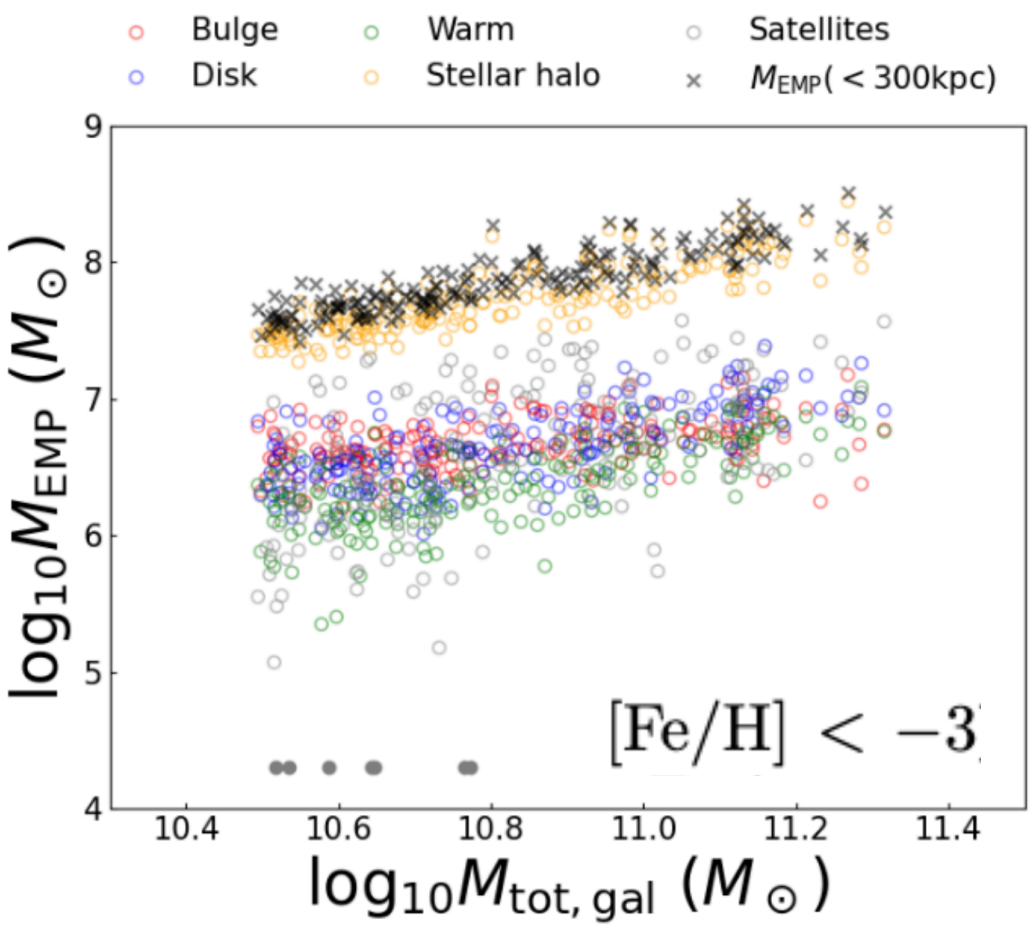


TNG50 MW-like hosts

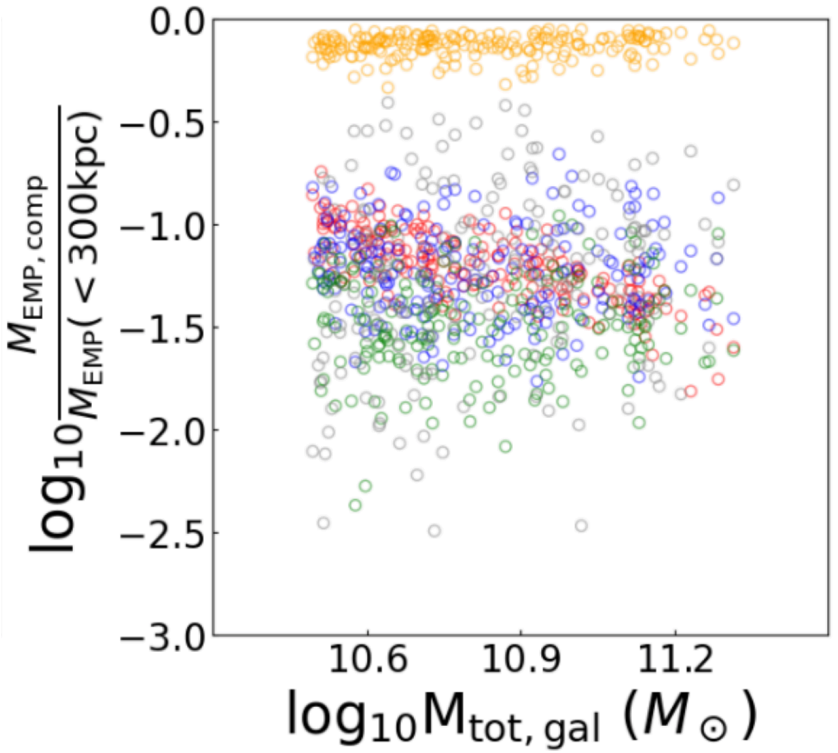
Engler, Pillepich, Joshi+2022, submitted (on astro-ph soon)

TNG50 M31-like hosts

#4 The majority of extremely metal-poor stars are typically in the stellar halo

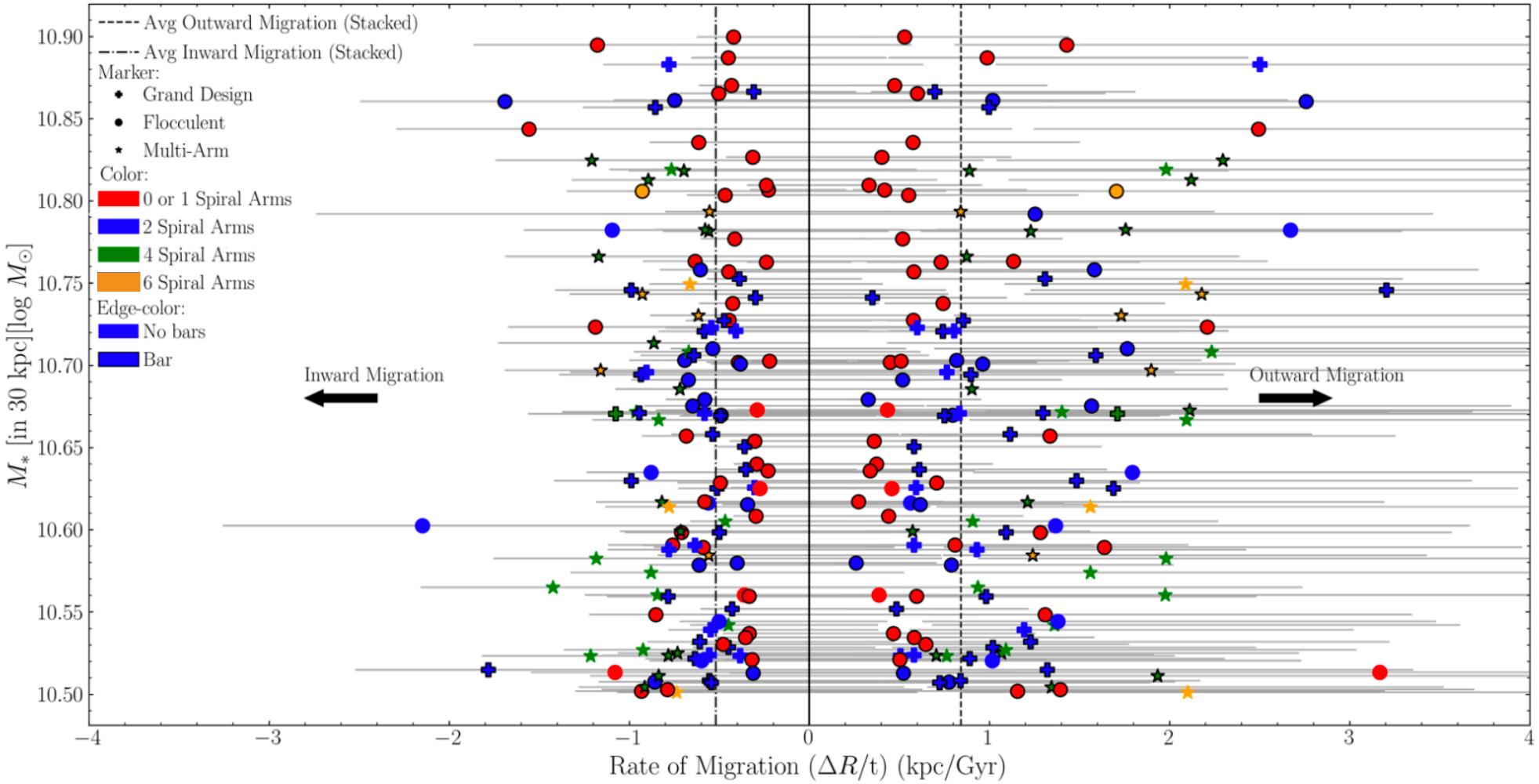


But a few tens TNG50 MW/M31-like galaxies exhibit non-negligible contributions of EMPs in cold disk-like orbits



Chen, Pillepich, Glover, Klesse+2022, submitted (on astro-ph soon)

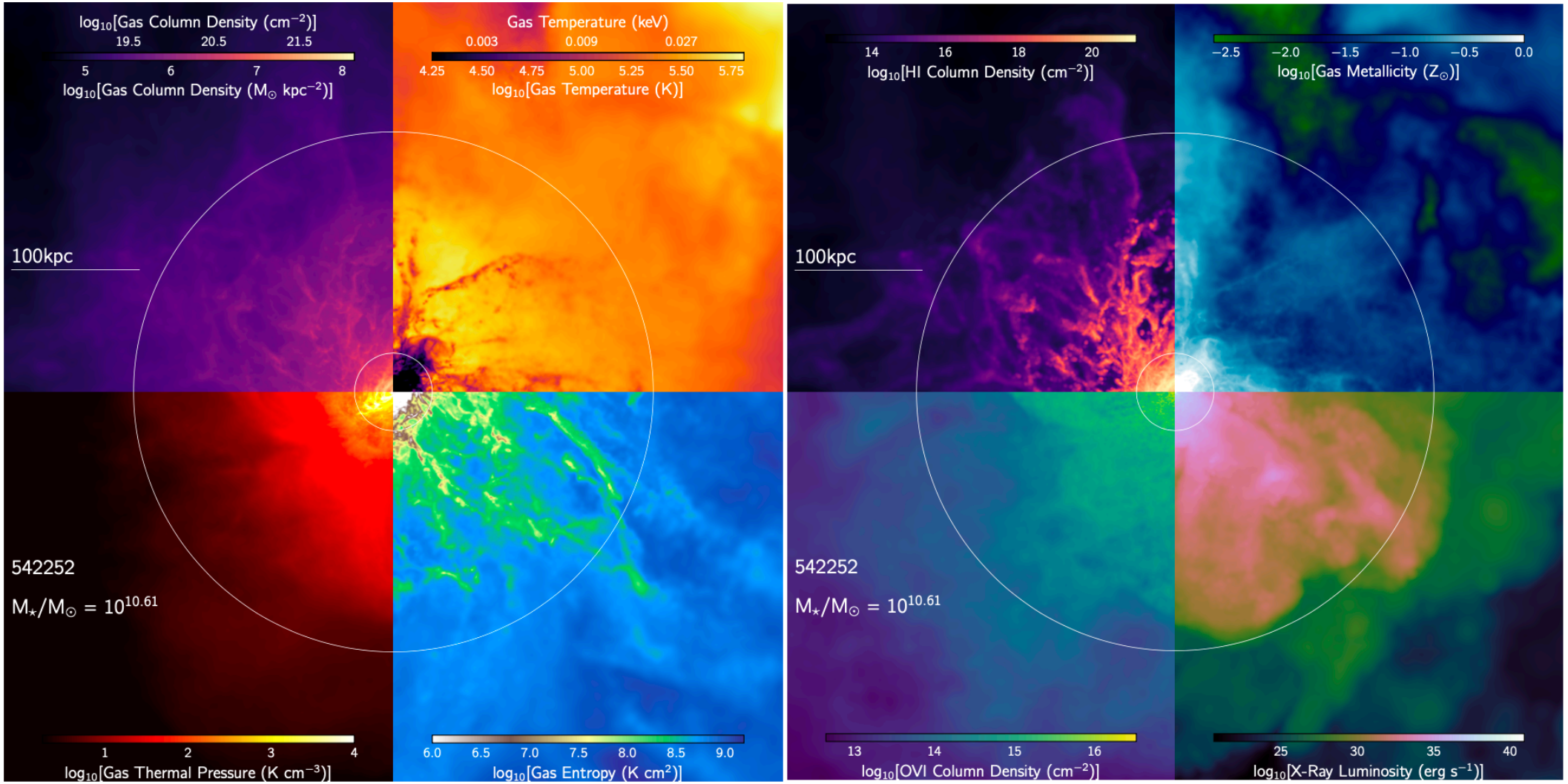
#5 Galaxies with more numerous spiral arms exhibits “more” stellar migration



Bisht, Pillepich+2022, in prep

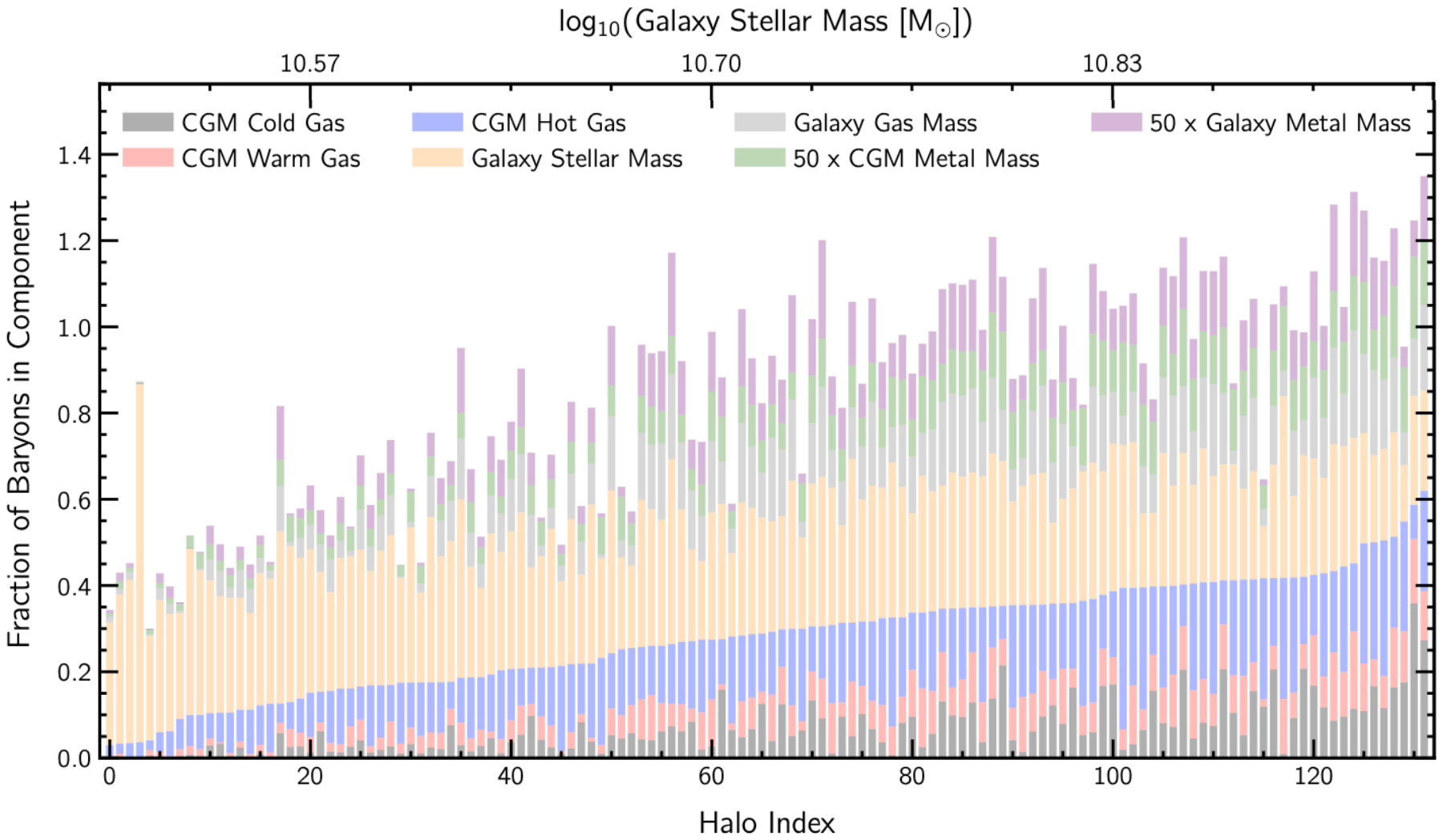
Insights from TNG50 MW/M31-like galaxies on the gaseous haloes

a) The gaseous haloes of TNG50 MW/M31-like galaxies are beautifully complex



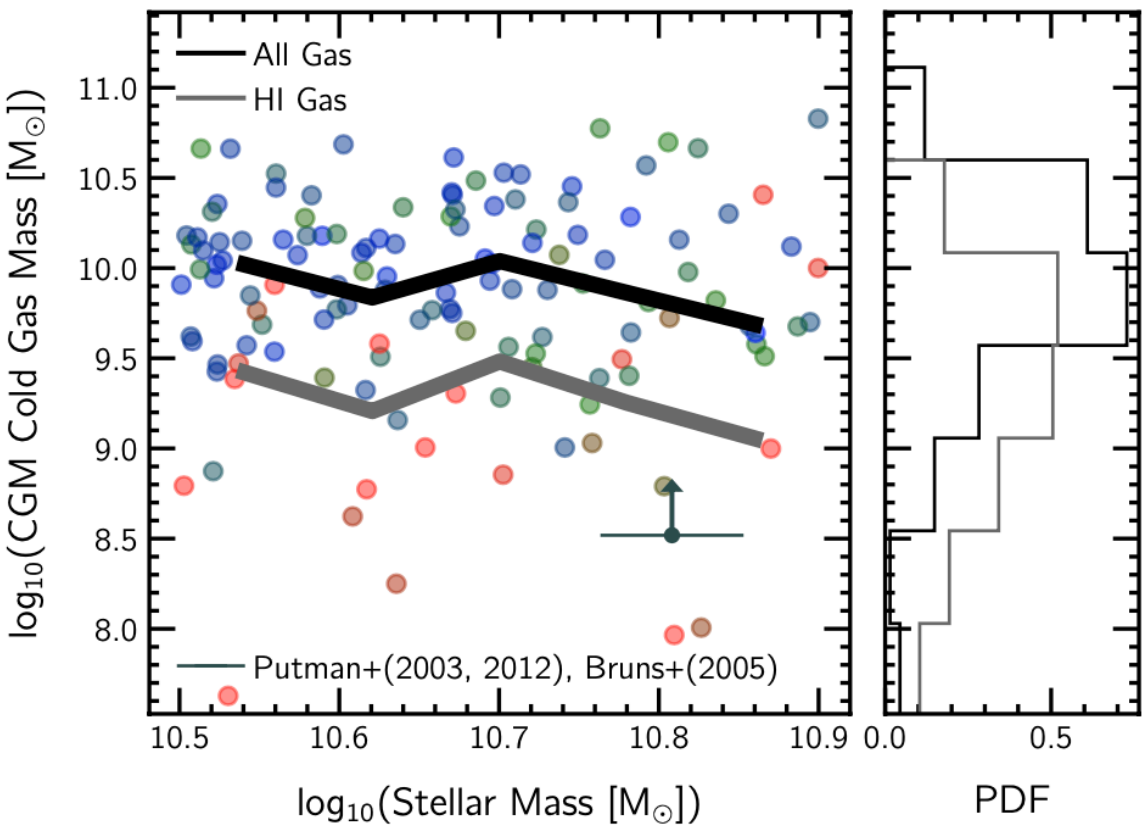
Ramesh, Nelson & Pillepich+2022, to be submitted

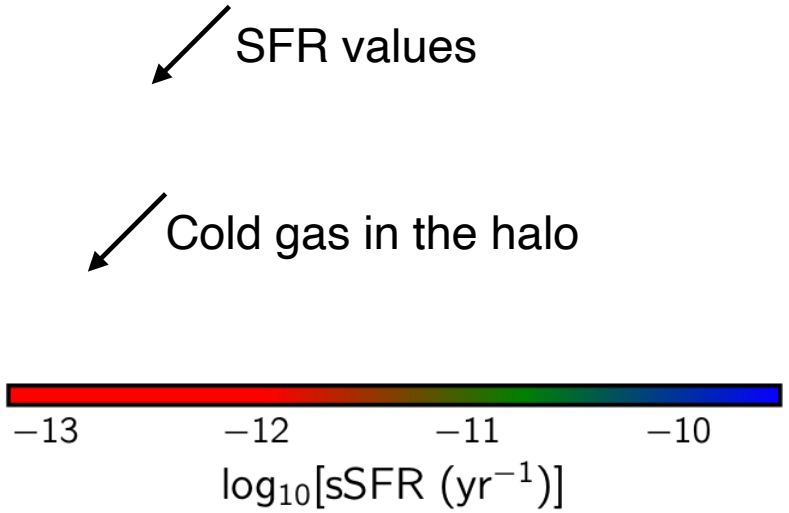
b) The gaseous haloes of TNG50 MW-like galaxies are -again- diverse



Ramesh, Nelson & Pillepich+2022, to be submitted

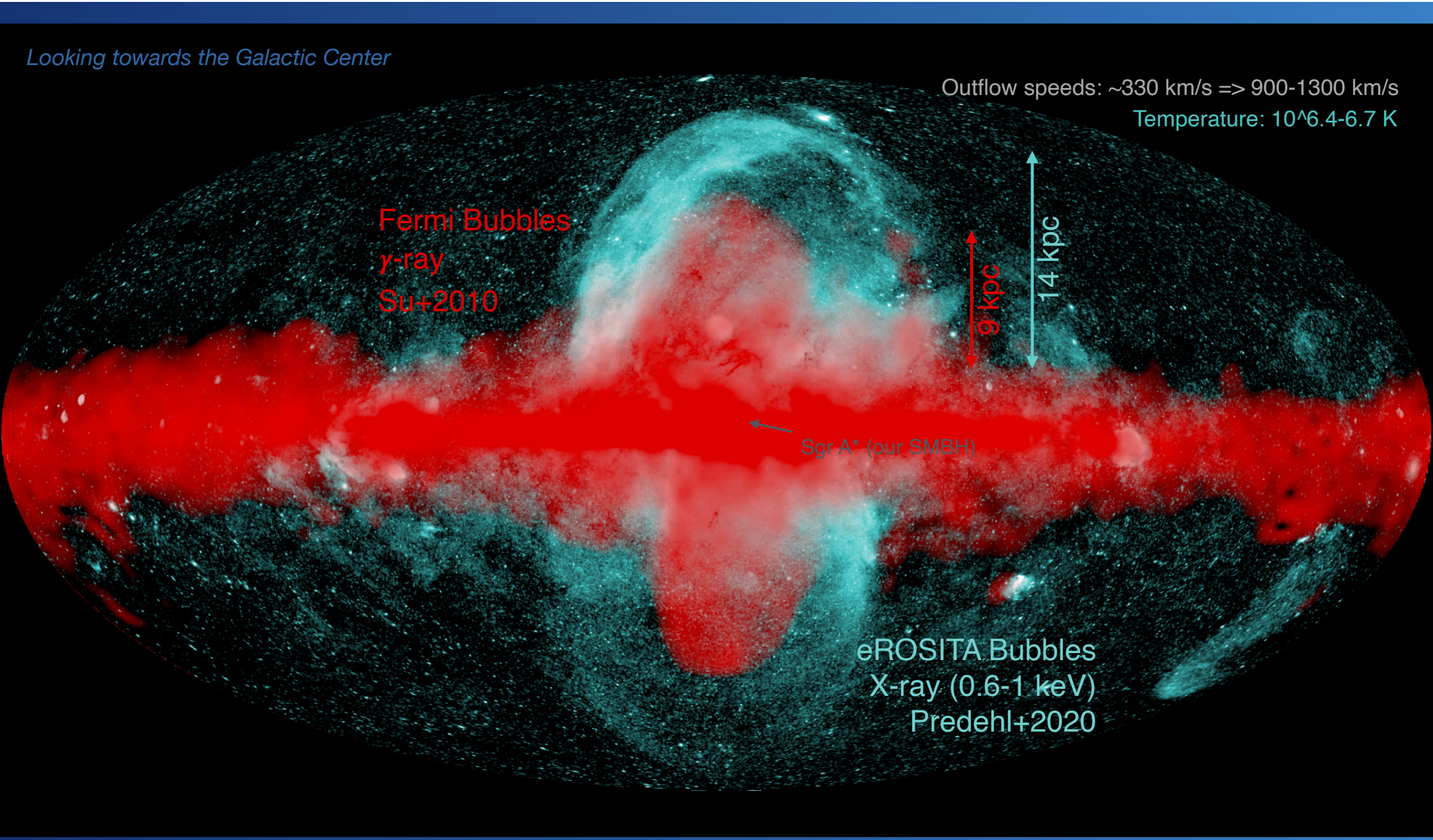
c) This diversity gaseous halo diversity is related to energy injections from SMBHs

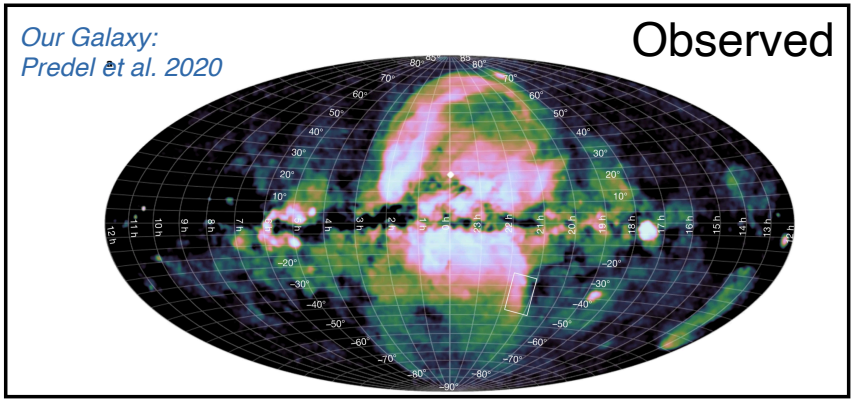




Ramesh, Nelson & Pillepich+2022, to be submitted

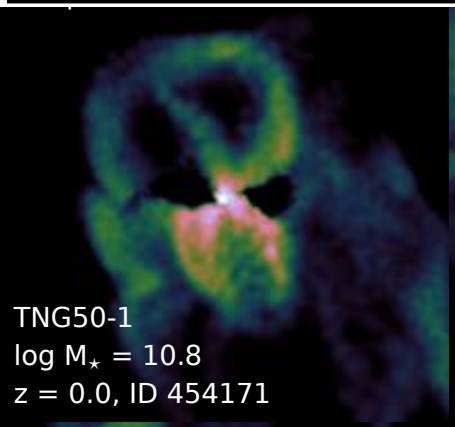
TNG50 and eROSITA-like bubbles

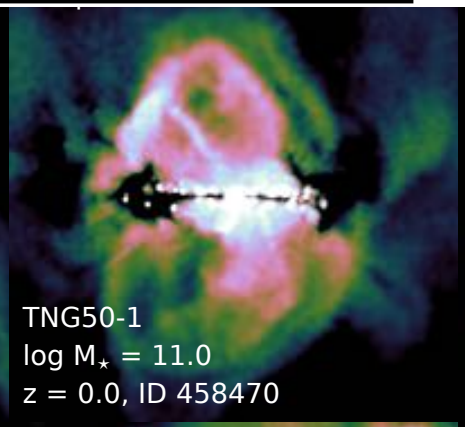

Looking towards the Galactic Center
Outflow speeds: ~330 km/s => 900-1300 km/s
Temperature: 10^6.4-6.7 K
Fermi Bubbles
γ-ray
Su+2010
9 kpc
14 kpc
Sgr A* (our SMBH)
eROSITA Bubbles
X-ray (0.6-1 keV)
Predehl+2020

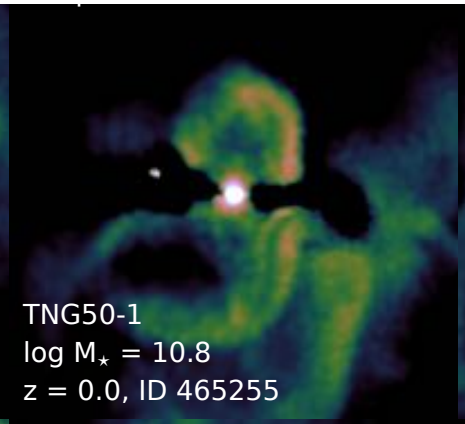


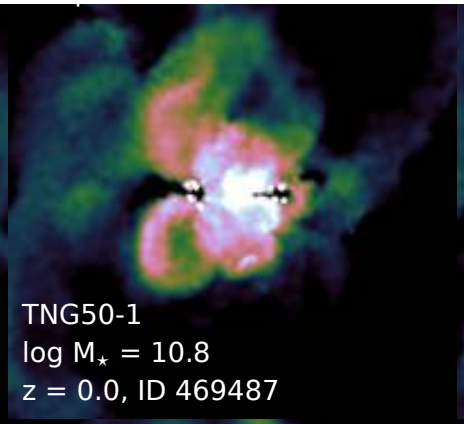
TNG50 returns eROSITA-like bubbles in MW/M31-like galaxies

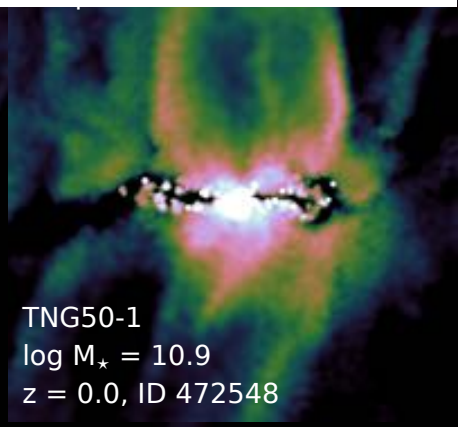
Simulated

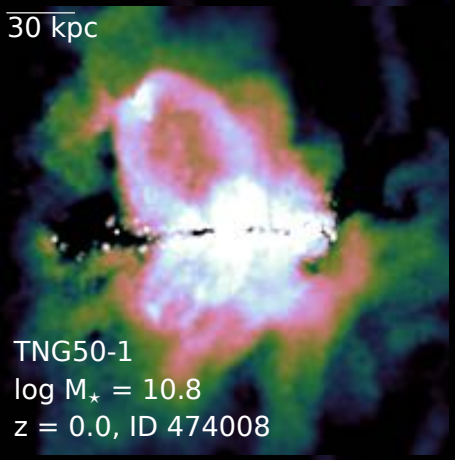


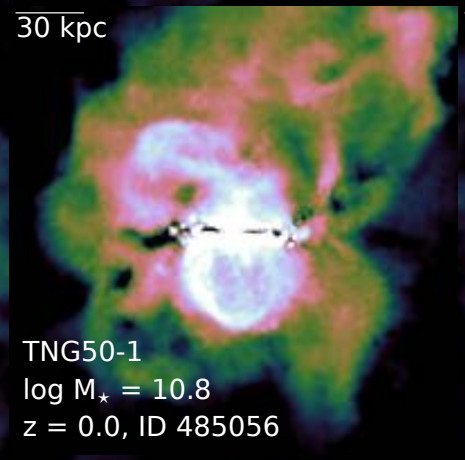


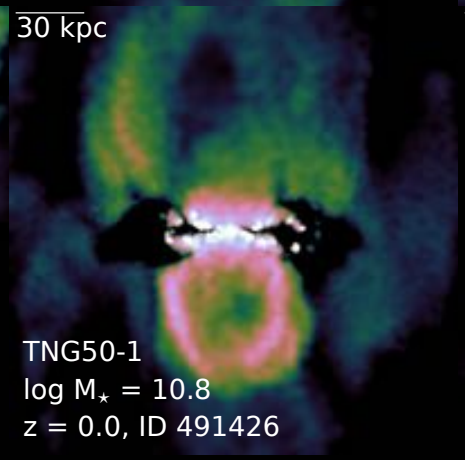


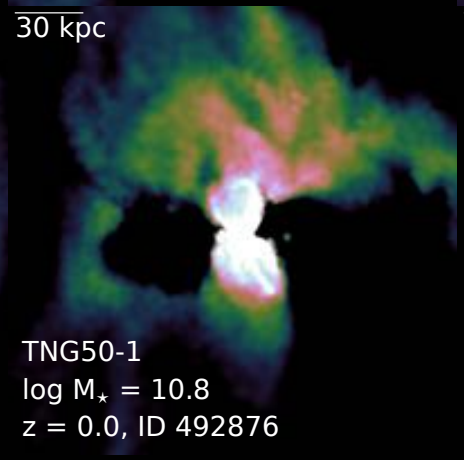


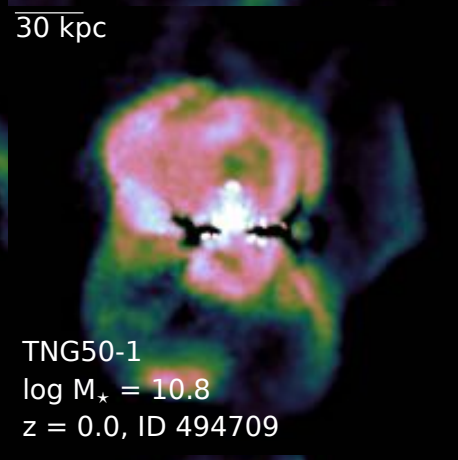












In TNG50, eROSITA-like bubbles are inflated by energy injections from the SMBH

Pillepich, Nelson, Truong, et al. 2021

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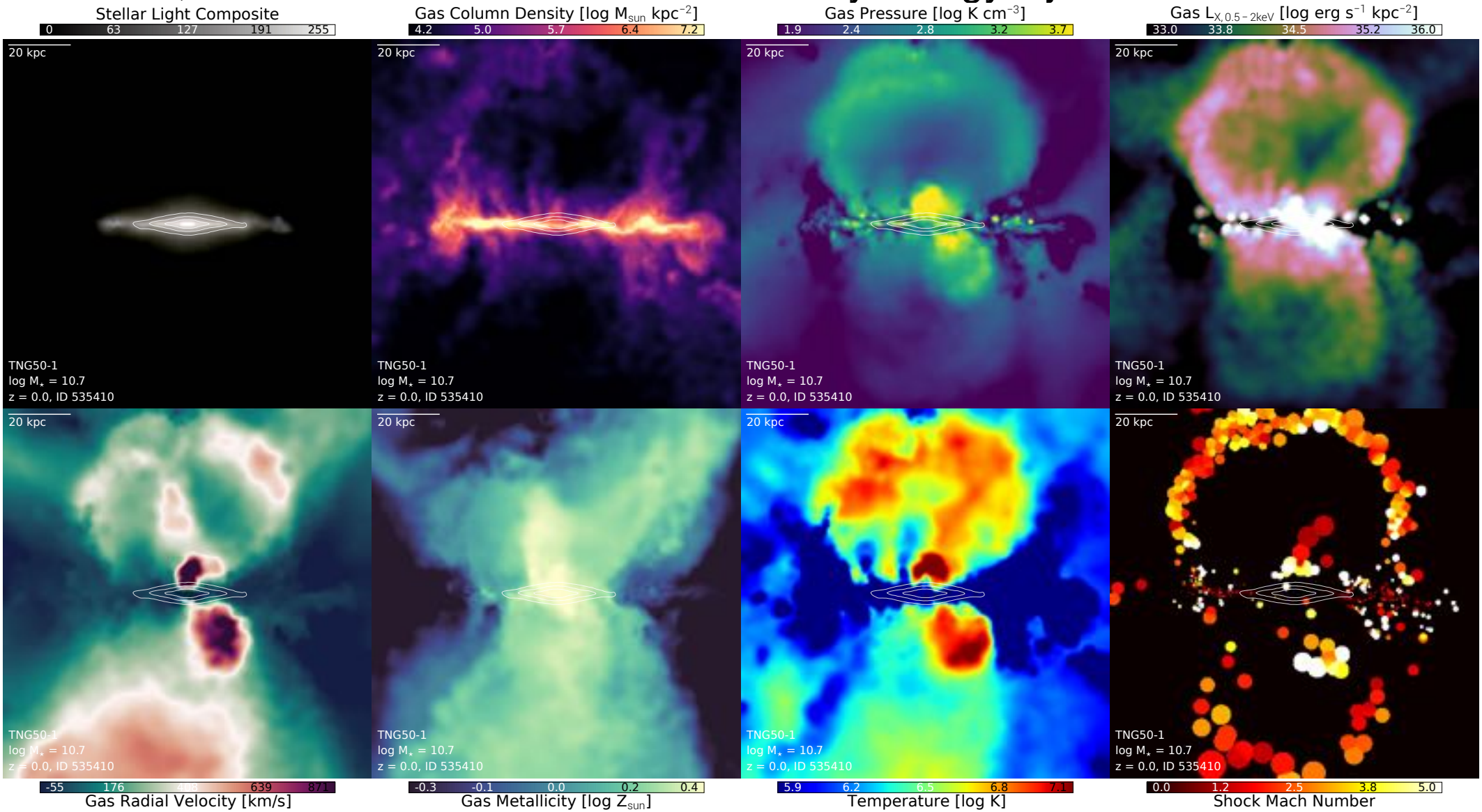
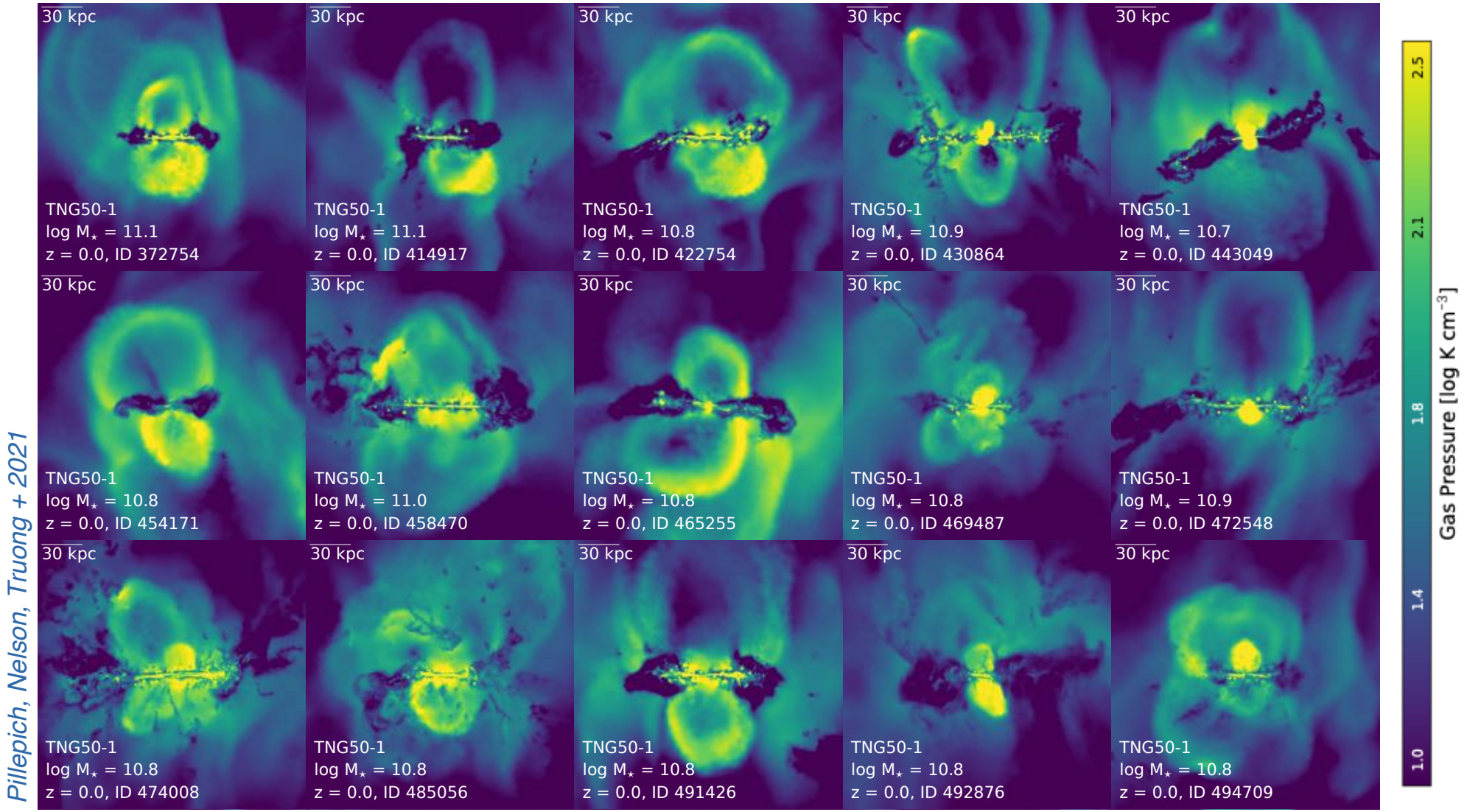


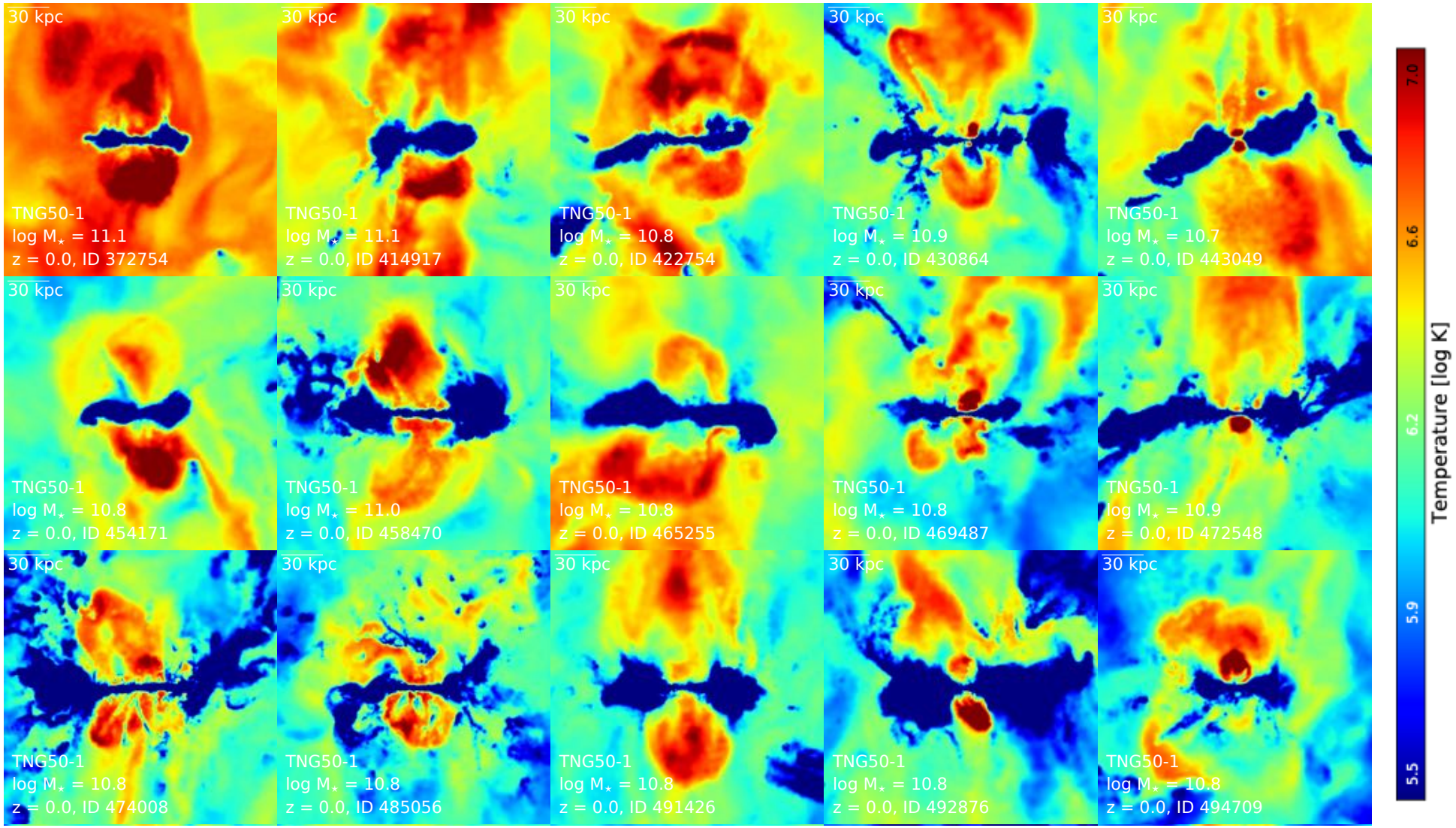
Pillepich, Nelson, Truong + 2021

TNG50 bubbles are manifest as over-pressurized cocoons



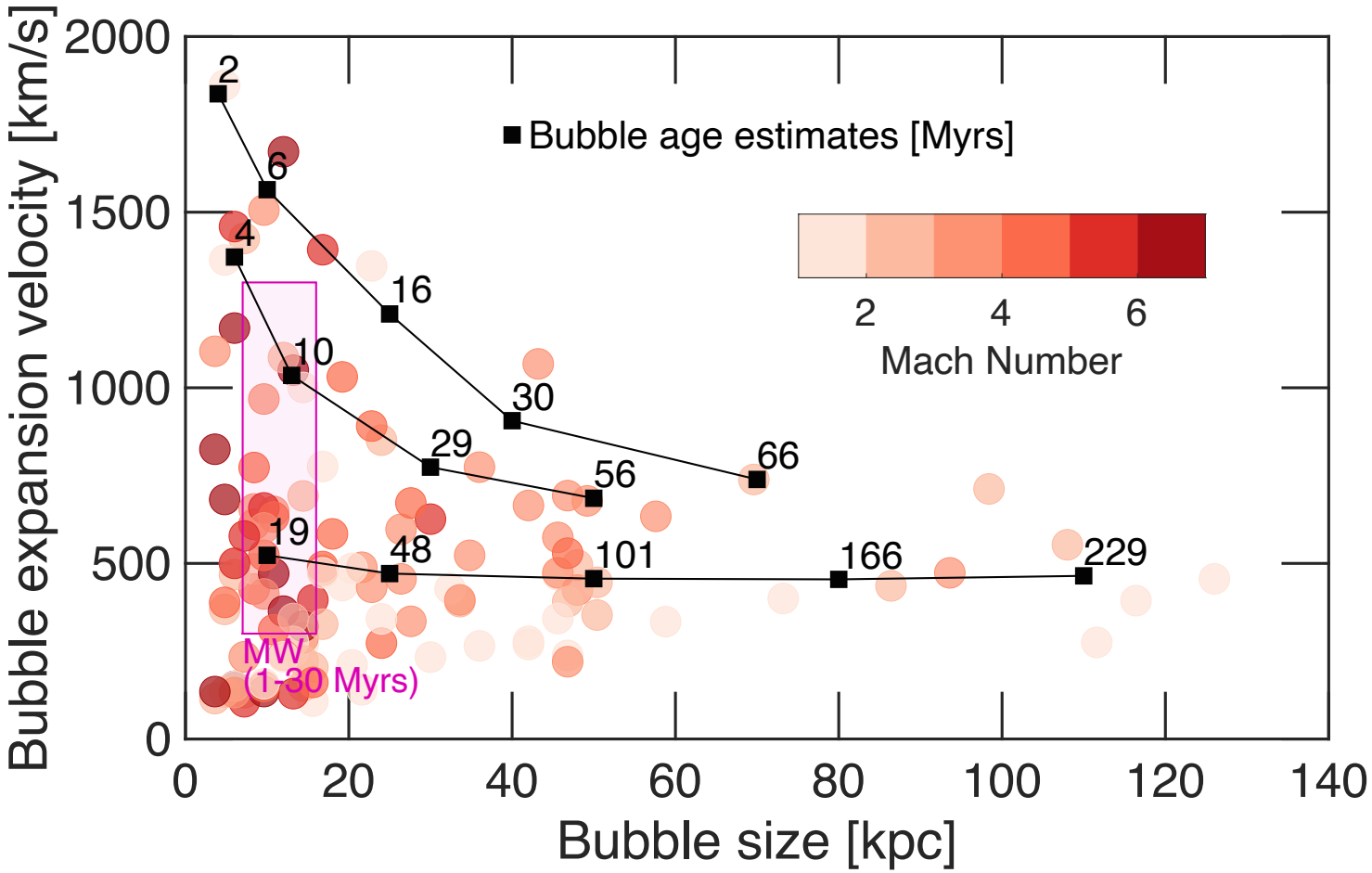
Pillepich, Nelson, Truong + 2021

TNG50 bubbles are manifest as over-pressurized cocoons, of hot gas



Pillepich, Nelson, Truong + 2021

2/3 of the TNG50 MW/M31-like galaxies at z=0 exhibit bubbles



Same feedback model (SMBH-driven outflows) => diverse sizes and expansion velocities

Pillepich, Nelson, Truong + 2021

2/3 of the TNG50 MW/M31-like galaxies at z=0 exhibit bubbles

=> 2 actual predictions:

- Other features of piled up gas in coherent fronts may be present in the CGM of the Galaxy, at larger galactocentric distances.

- A large number MW/M31-like galaxies prior to, or on the verge of, being quenched should exhibit eROSITA-like bubbles

Pillepich, Nelson, Truong + 2021

The TNG50 is an unprecedented laboratory also for MW-related science:

it returns at z=0
~200 well-resolved and diverse MW/M31-like galaxies

TNG50 data is fully public +

coming soon: release of even richer and easier-to-use data products of the TNG50 MW/M31-like galaxies

Pillepich+2022 in prep