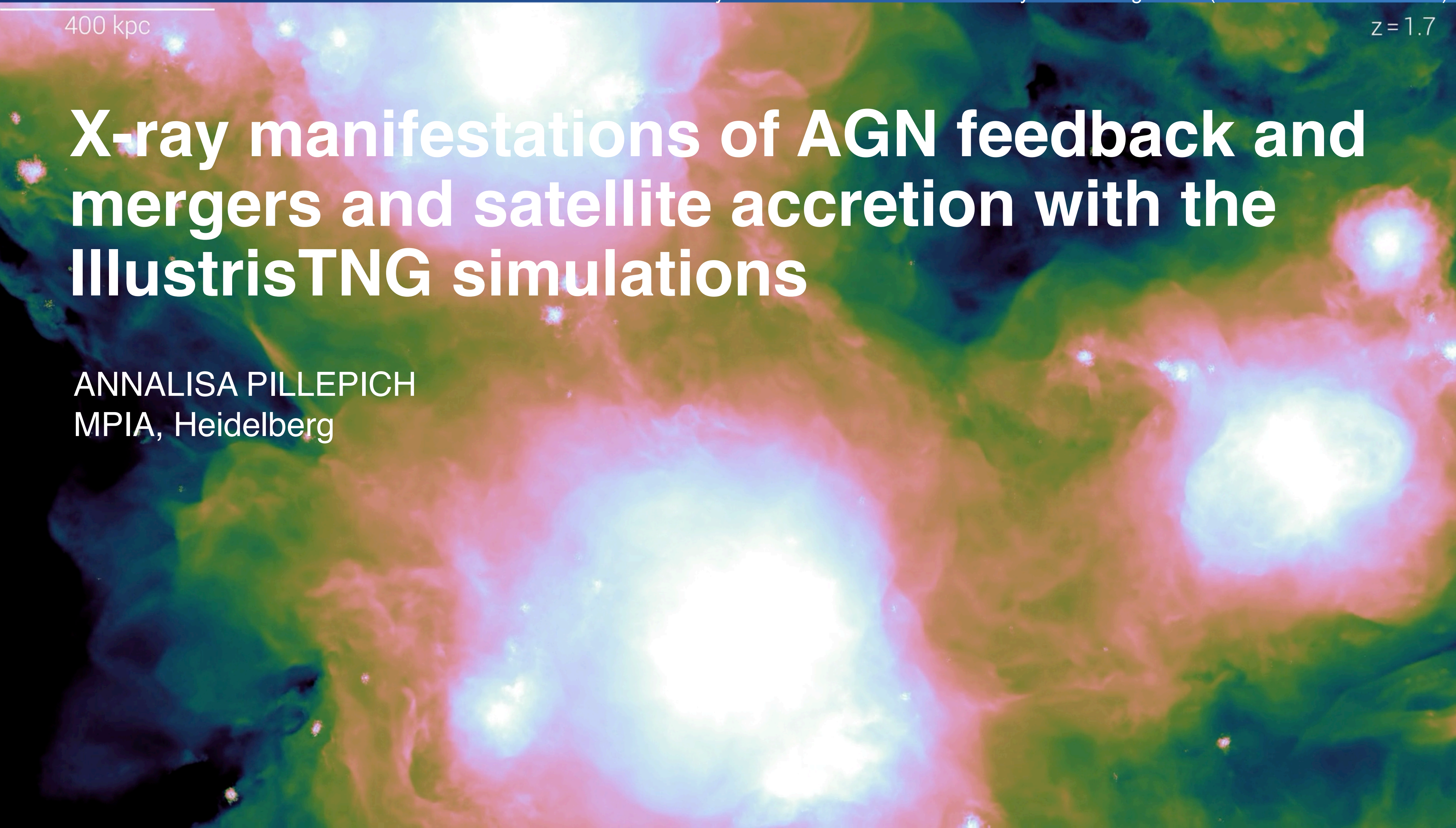


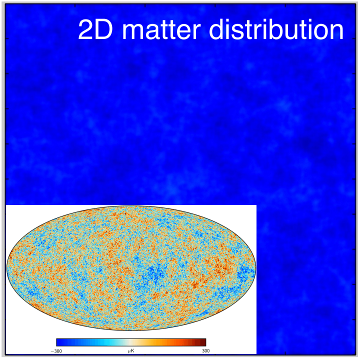
X-ray manifestations of AGN feedback and mergers and satellite accretion with the IllustrisTNG simulations

ANNALISA PILLEPICH
MPIA, Heidelberg

The current cosmological simulations for clusters and *their galaxies*

Characteristics of current cosmological large-volume (M)HD simulations of galaxies

Cosmological initial conditions…



≳ 100 Mpc

evolved through z=0

Coupled equations of Gravity
+
(Magneto)Hydrodynamics

in expanding and representative large portions of the ΛCDM Universe

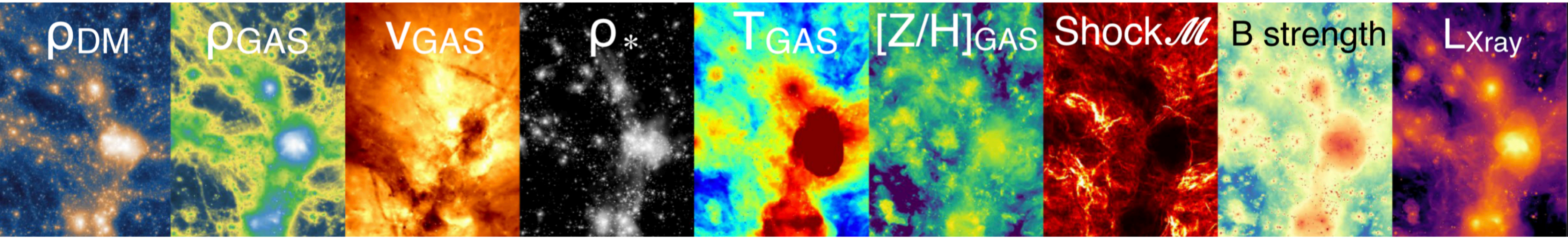
Physics of galaxy formation and evolution:

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

Spatial and mass resolution

much smaller than the scales of galaxies

Nelson, Springel, Pillepich + 2019 (TNG)



Coevolution of (cold)DM + gas + stars + SMBHs (+ B fields, …)

Vogelsberger+2020

Current cosmological (M)HD simulations of large volumes

No <10^4 K gas

No radiative transfer
i.e. no photons and no explicit effects of radiation pressure

No chemistry i.e. no molecules

No dust formation and disruption

No globular clusters

No individual molecular clouds and below

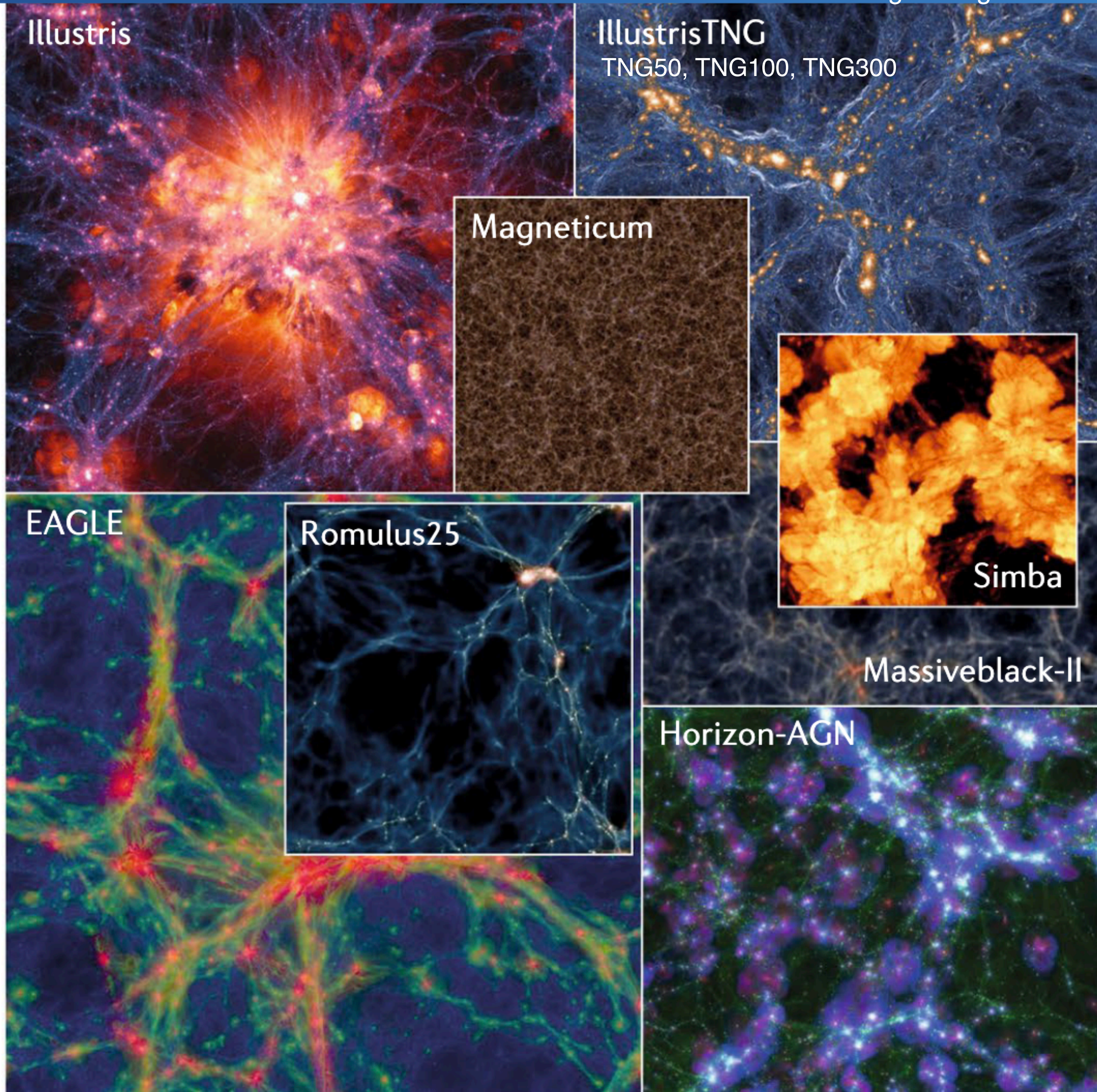
No cosmic rays

No (anisotropic) thermal conduction

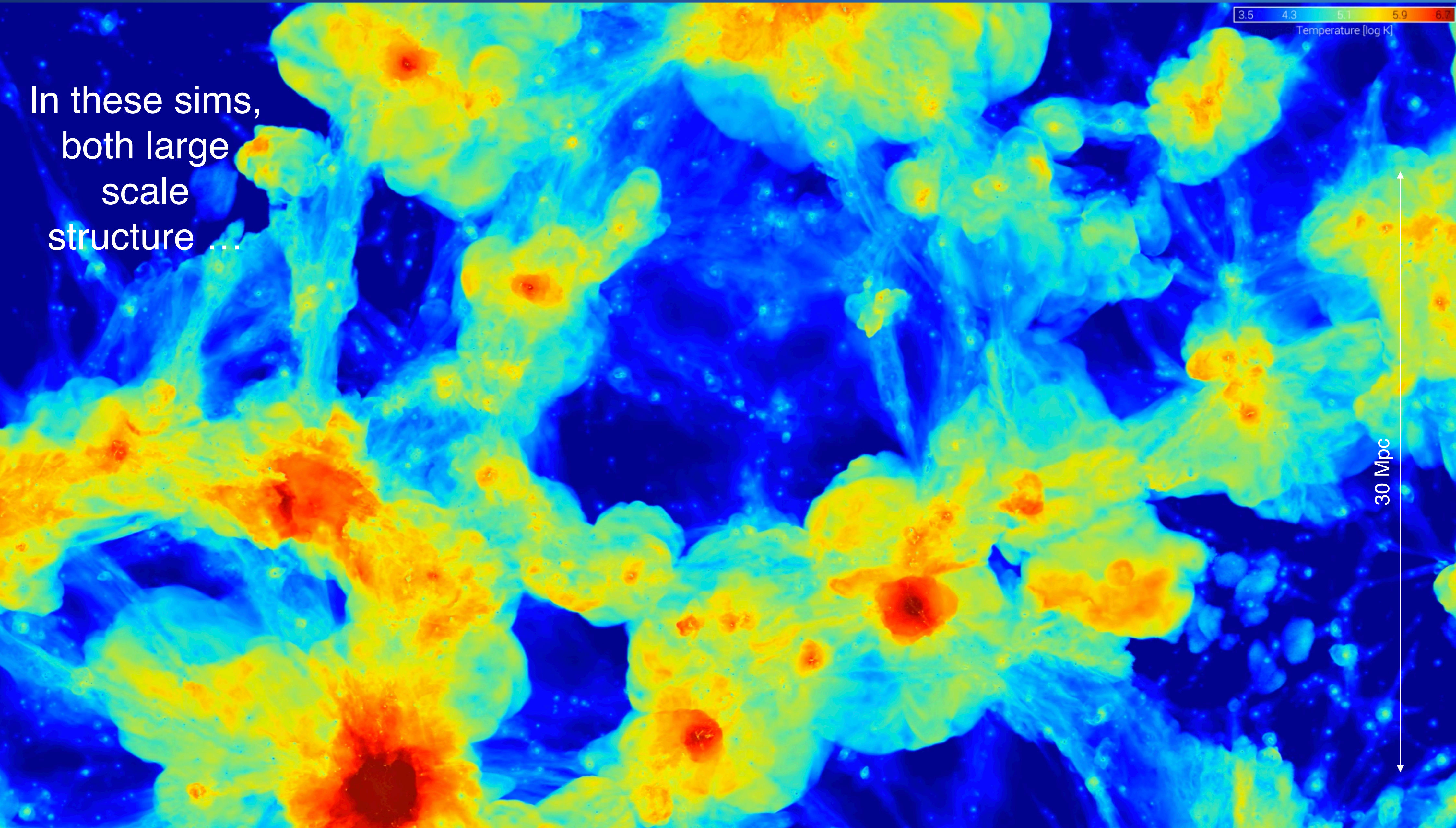
Typically, no collimated jets

Typically, no magnetic fields

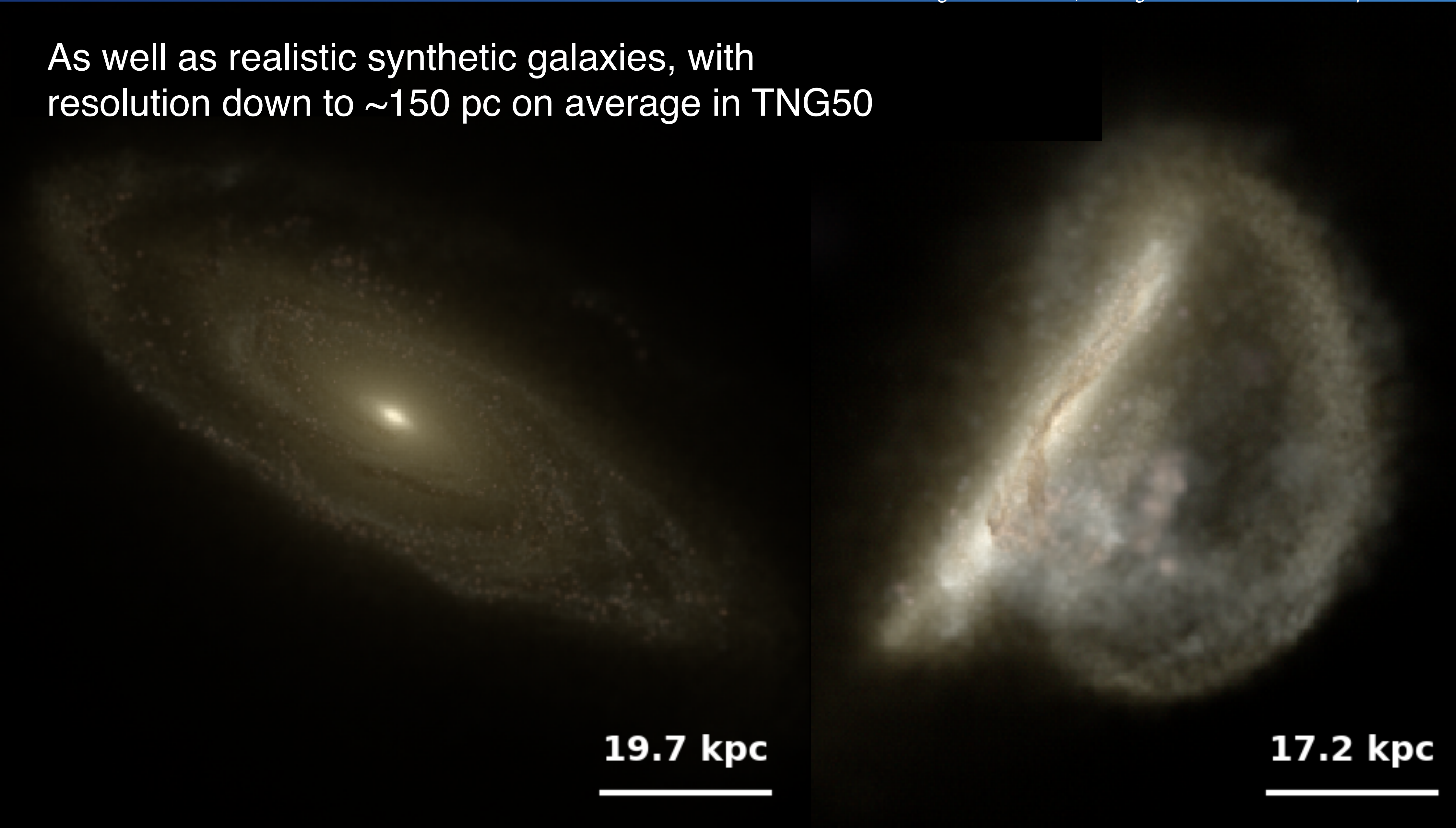
…



In these sims, both large scale structure …



As well as realistic synthetic galaxies, with resolution down to ~150 pc on average in TNG50



Current cosmological **large-volume** simulations of clusters and their galaxies

Simulation name	Year	Code	Box Size [cMpc]	Baryonic mass resolution [Msun]	# clusters (M200c>1e14)	# clusters (M200c>1e15)	References
Illustris	2014	AREPO	107	1.30E+06	10	0	Vogelsberger+14 Genel+14 Sijacki+15
Magneticum 4uhr	2014	GADGET-3	68.2	1.40E+07	A few	0	Hirschmann+14
Eagle	2015	GADGET-3	100	1.80E+06	~10	0	Schaye+15, Crain+2015
MassiveBlack-II	2015	GADGET-3	143	3.10E+06	~10	0	Khandai+15
HorizonAGN	2015	RAMSES	142	-	~10	0	Dubois+14
MUFASA	2016	GIZMO	74	1.80E+07	A few	0	Dave'+16
TNG100	2017	AREPO	111	1.40E+06	14	0	Springel+18, Pillepich+18, Nelson+18, Marinacci+18, Naiman+18
TNG300	2017	AREPO	303	1.10E+07	280	3	As TNG100
FABLE	2018	AREPO	59	9.40E+06	2	0	Henden+18
Simba 100	2019	GIZMO	147	1.80E+07	~10	0	Dave'+19
TNG50	2019	AREPO	52	8.50E+04	2	0	Nelson+19, Pillepich+19

All with different details in the implementation of the galaxy-formation models, e.g. feedback

Current cosmological **zoom** simulations of clusters and their galaxies

stellar/gas mass resolution better (i.e. smaller) than **a few 10^8 $M_\odot$**

i.e. all computing power in one single object at the time, chosen out of (very) large-volume, low-res simulations

Simulation name	Year	Code	(Parent) Box Size [cMpc]	Baryonic mass resolution [Msun]	# clusters (M200c>1e14)	# clusters (M200c>1e15)	Reference(s)
Dianoga	2015	GADGET-3	1388	2.10E+08	29	24	Rasia+2015, Planelles+2017
C-Eagle	2017	GADGET-3	3200	1.80E+06	30	7	Barnes+2017
Hydrangea	2017	GADGET-3	3200	1.80E+06	24	5	Bahe+2017
RHAPSODY-G	2017	RAMSES	1500	2.50E+08	10	10	Hahn+2017
Yonsei YZiCS	2017	RAMSES	284	5E+06	~13	~2	Choi&Yi 2017
FABLE Zoom	2018	AREPO	4300	1.50E+07	19	4	Henden+20
Three Hundred Project	2018	GADGET-X	1475	3.50E+08	324	~300	Cui+2018
Romulus-C	2019	ChaNGa	50	2.10E+05	1	0	Tremmel+2019
Dianoga High-res	2020	GADGET-3	1388	2.20E+07	12	7	Bassini+2020

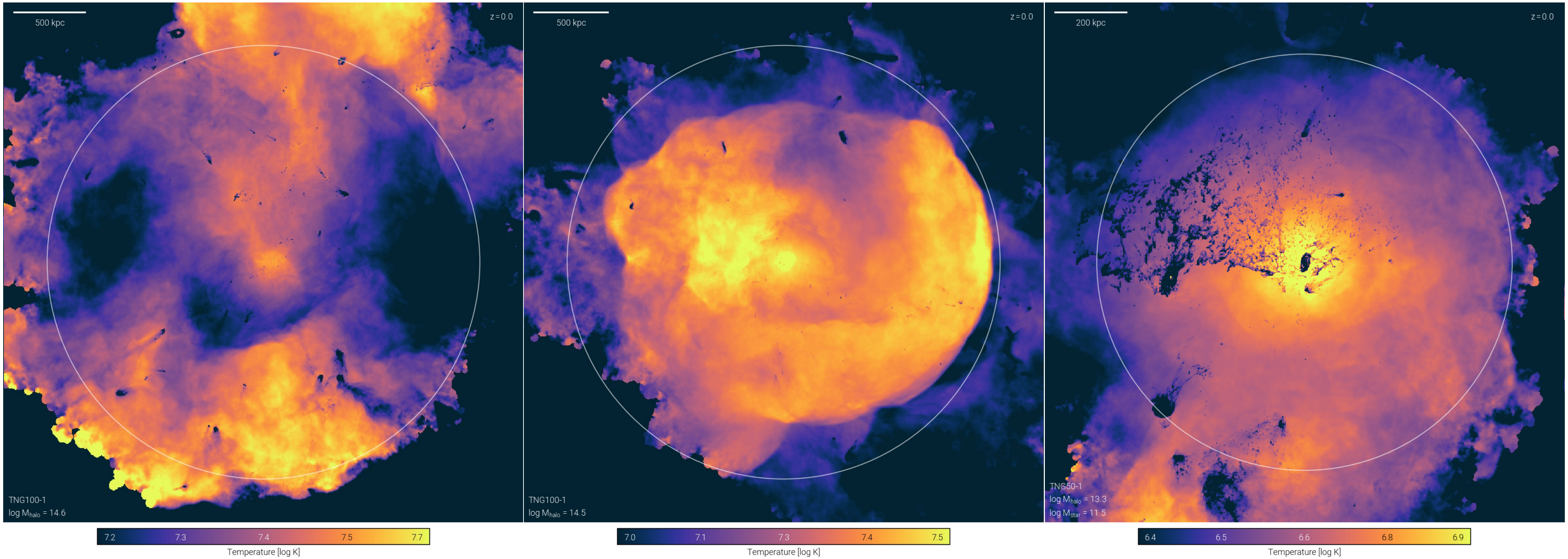
The groups and clusters in IllustrisTNG

TNG50,TNG100,TNG300: maximal combination of res and statistics, with B fields

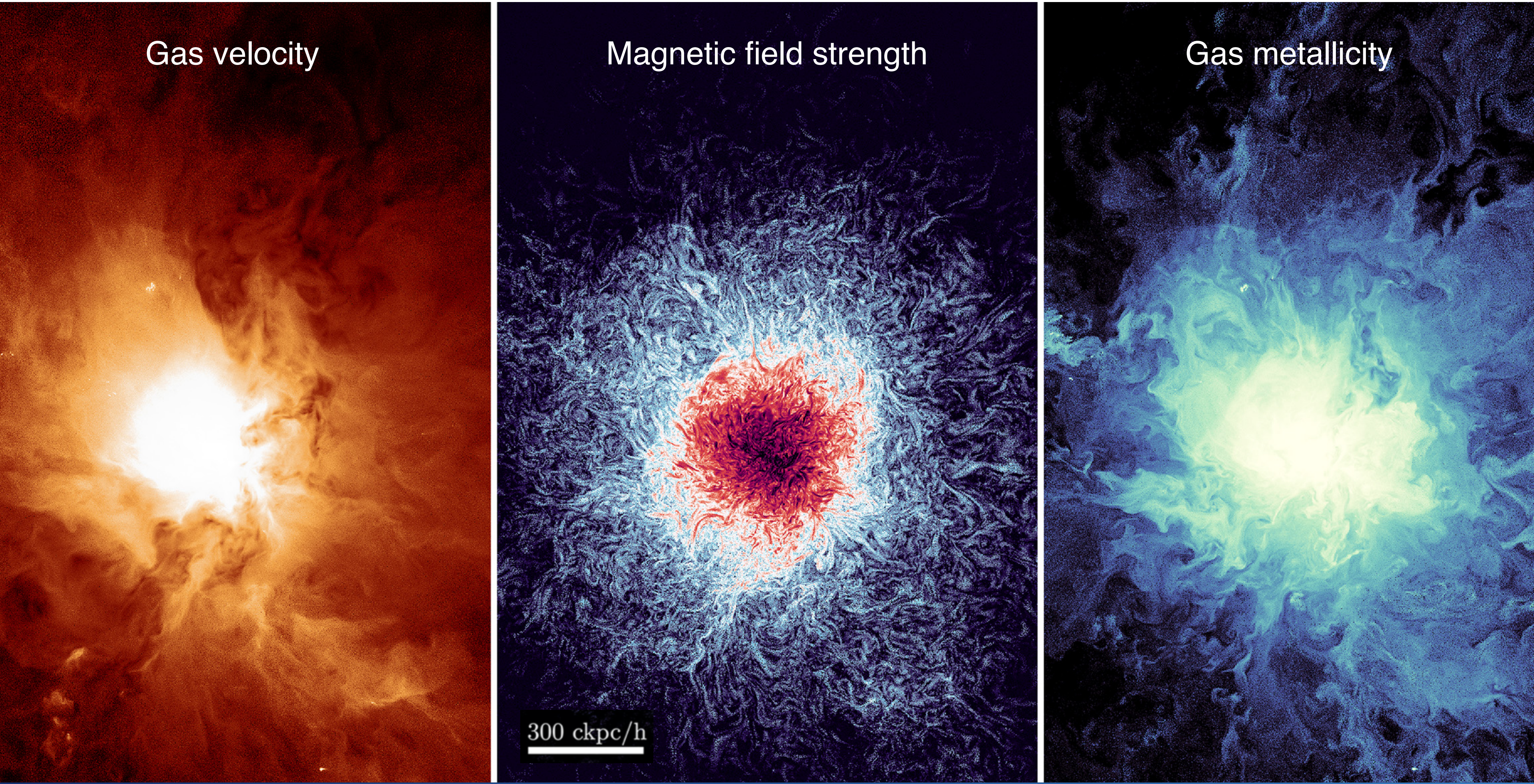
~300 haloes > 10^{14} M$_\odot$ at ≲10^7 M$_\odot$ and ≲ kpc resolution

Including MHD, Shock finder, SNIa, SNII, AGB enrichment across 10 elements

Mass-weighted gas temperature (Credits: Pillepich)



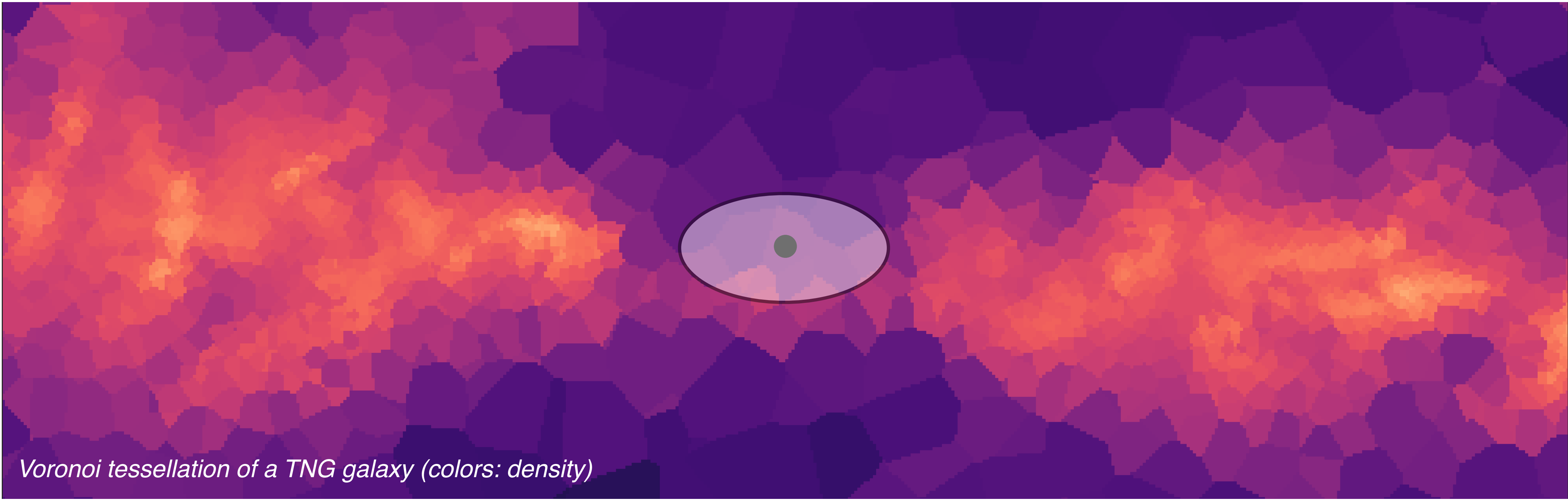
TNG50: two ~10^{14} $M_\odot$ clusters with ≲10^5 $M_\odot$ resolution



In TNG, SMBH feedback via three channels

Weinberger, Springel + w/ Pillepich 2017
Pillepich, Springel, Nelson + 2018

1) Thermal mode
At high accretion rates — continuous thermal dump



Voronoi tessellation of a TNG galaxy (colors: density)

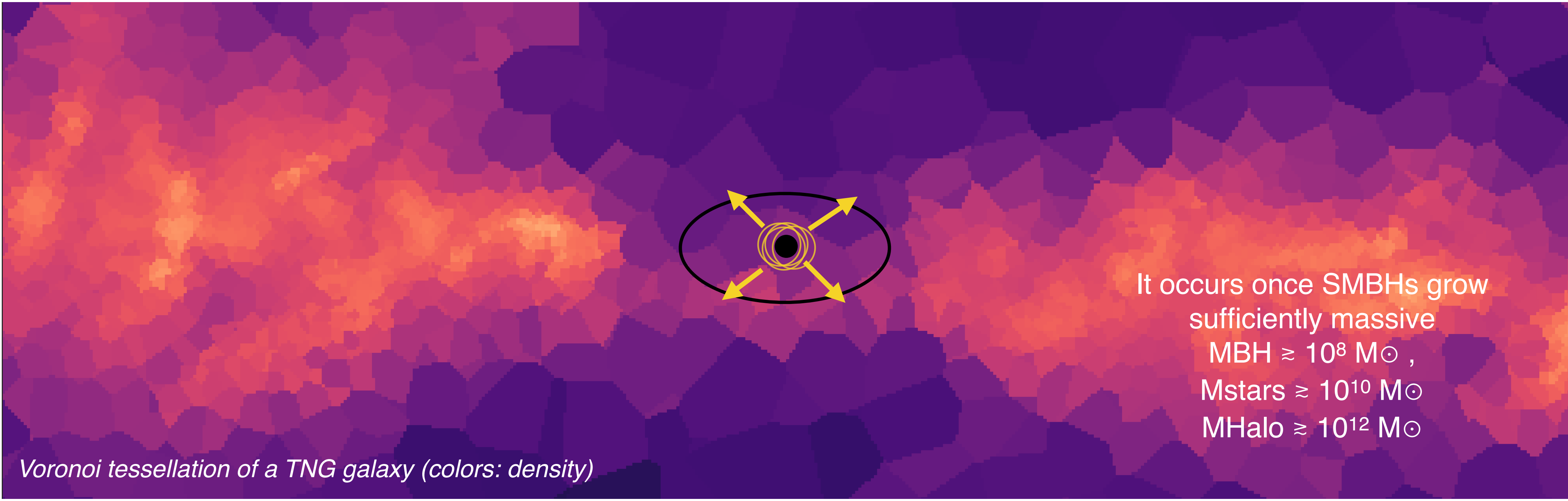
Subgrid model for “quasar-like feedback”

In TNG, SMBH feedback via three channels

Weinberger, Springel + w/ Pillepich 2017
Pillepich, Springel, Nelson + 2018

2) Kinetic mode
At low accretion rates —
intermittent, over-time isotropic kick of the surrounding gas

See also similar implementations:
Choi et al. 2012, 2014, 2015
Dubois et al. 2010, 2012



Voronoi tessellation of a TNG galaxy (colors: density)

Phenomenologically inspired by red geysers or ‘FR0’ galaxies
Cheung+2016 (Nature)
Baldi, Capetti & Giovannini 2016; Baldi+2019

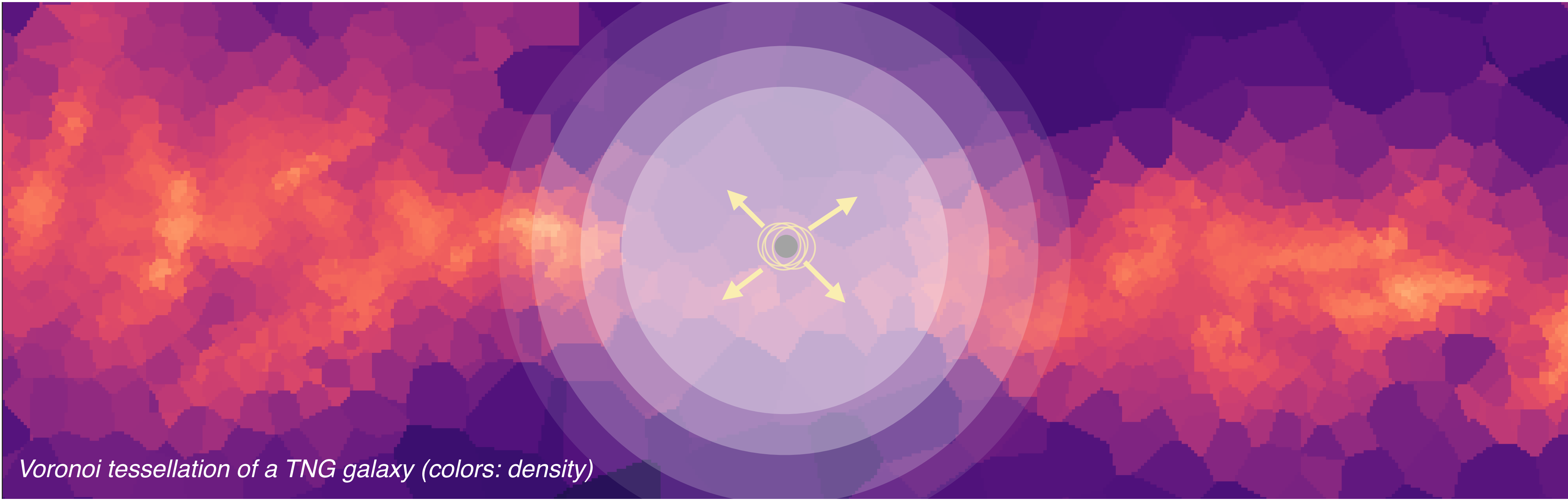
Physically, subgrid model for high-velocity accretion-disk winds or small-scale jets from low-luminosity SMBHs
ADIOS; advection-dominated inflow-outflow solution;
Blandford & Begelman 1999, Yuan & Narayan 2014

In TNG, SMBH feedback via three channels

Weinberger, Springel + w/ Pillepich 2017
Pillepich, Springel, Nelson + 2018

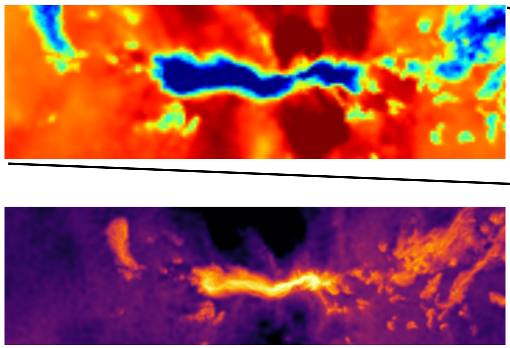
3) "Radiative" AGN feedback
At all times —
Additional modulation of the cooling due to AGN radiation

As implemented by Vogelsberger+2013

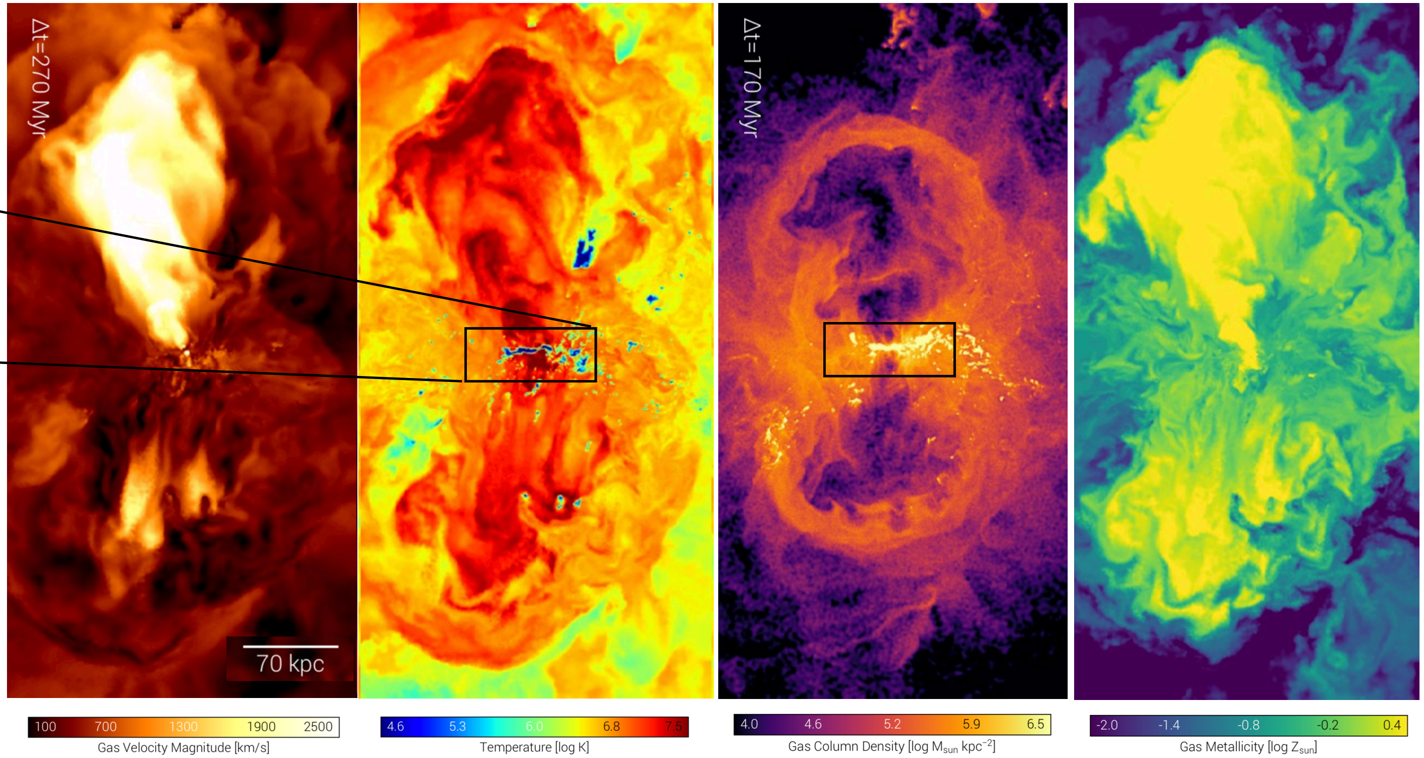

Voronoi tessellation of a TNG galaxy (colors: density)

In TNG massive galaxies, SMBH kinetic mode dominates and quenches SF ($M_{Halo} \gtrsim 10^{12}$ $M_\odot$)

TNG50, SMBH feedback in action (Nelson, Pillepich, Springel + 2019)



Cold SF-ing galaxy disk



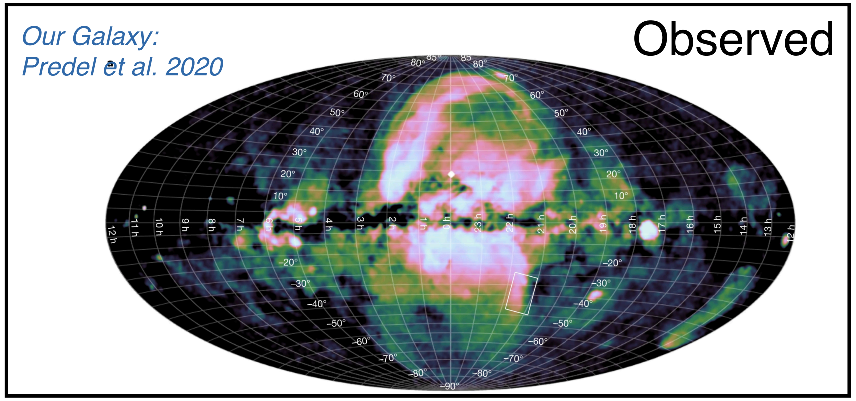
For TNG, see also
Terrazas, Bell, Pillepich + 2020
Zinger, Pillepich + 2020

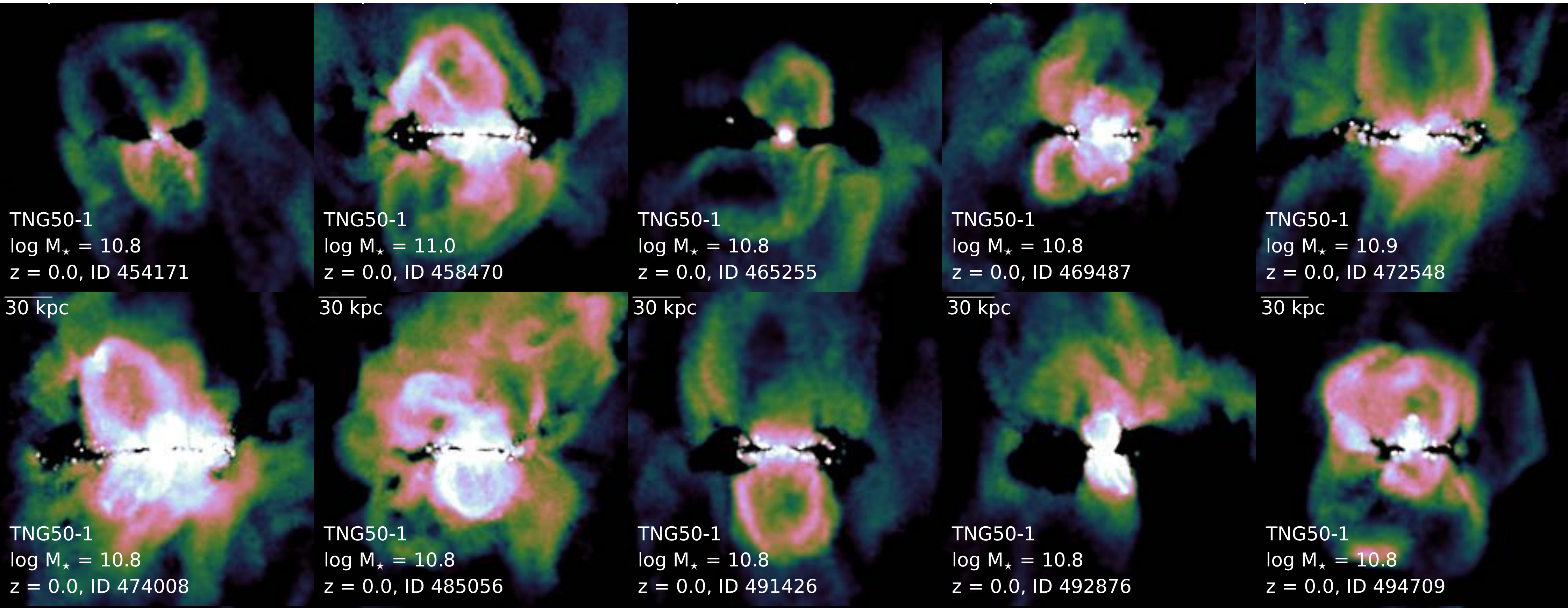
For EAGLE, see also
Davies + 2020
Oppenheimer + 2020

- Initiate galaxy quenching (ejective)
- Offset the cooling times of the halo gas (preventative)
- Effects to distances >> sites of the energy injections
- SMBH-driven outflows and effects: *not* isotropic

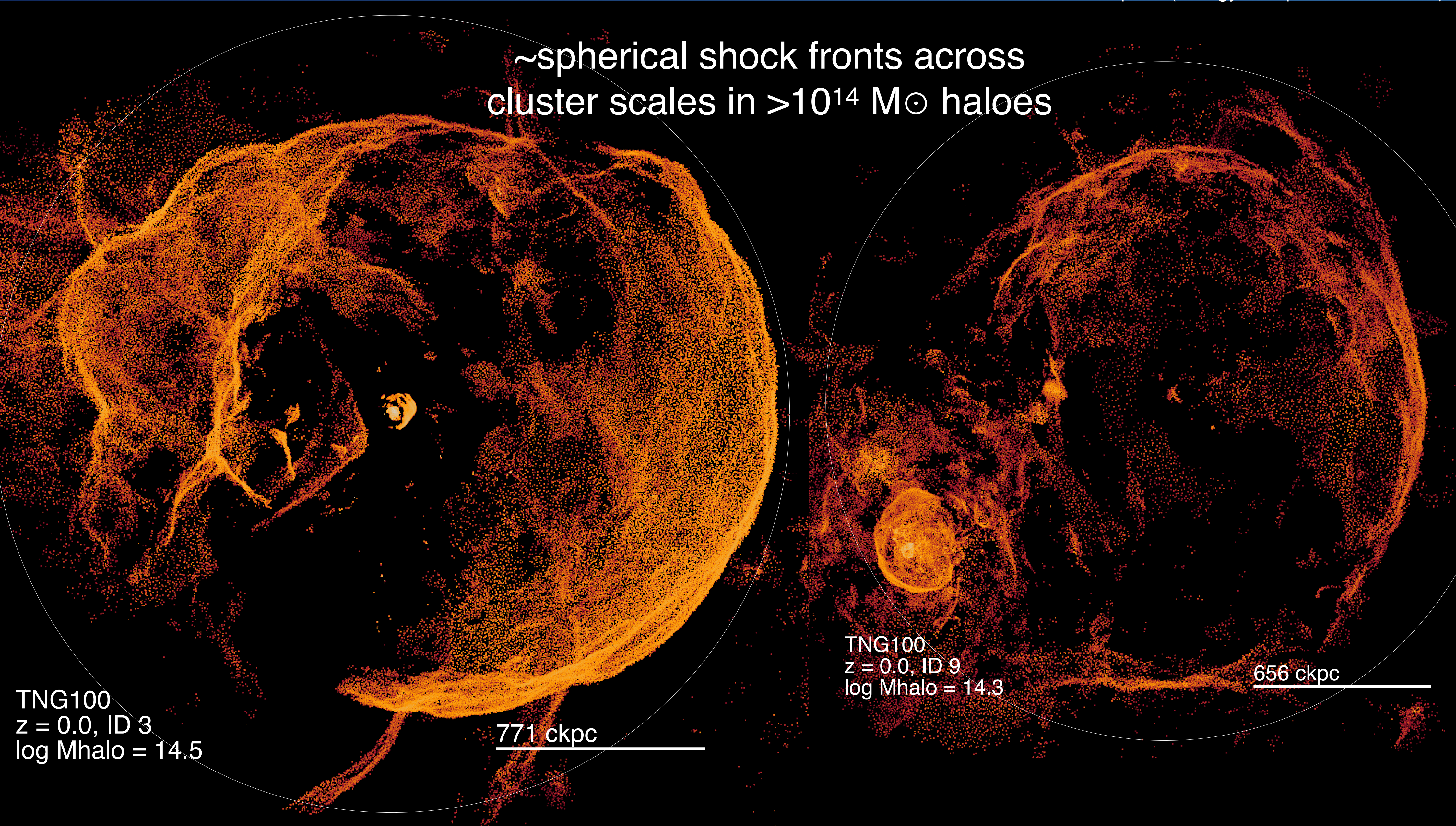
In TNG, the same model
for SMBH feedback
produces diverse manifestations in
the gas distribution, thermodynamics
and kinematics
in massive haloes

eROSITA-like bubbles in MW/M31-like galaxies (10^{12} M⊙ haloes)

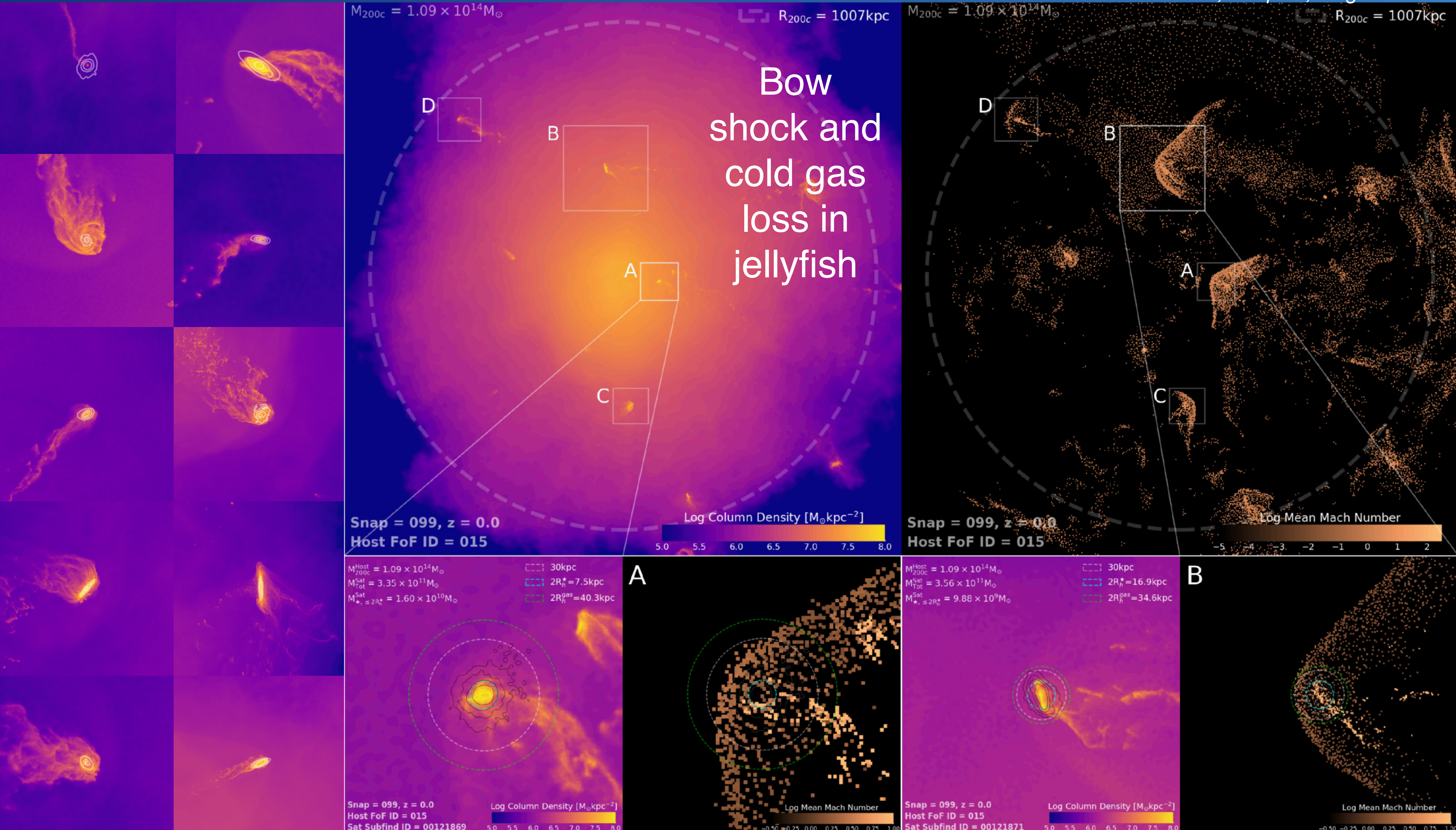


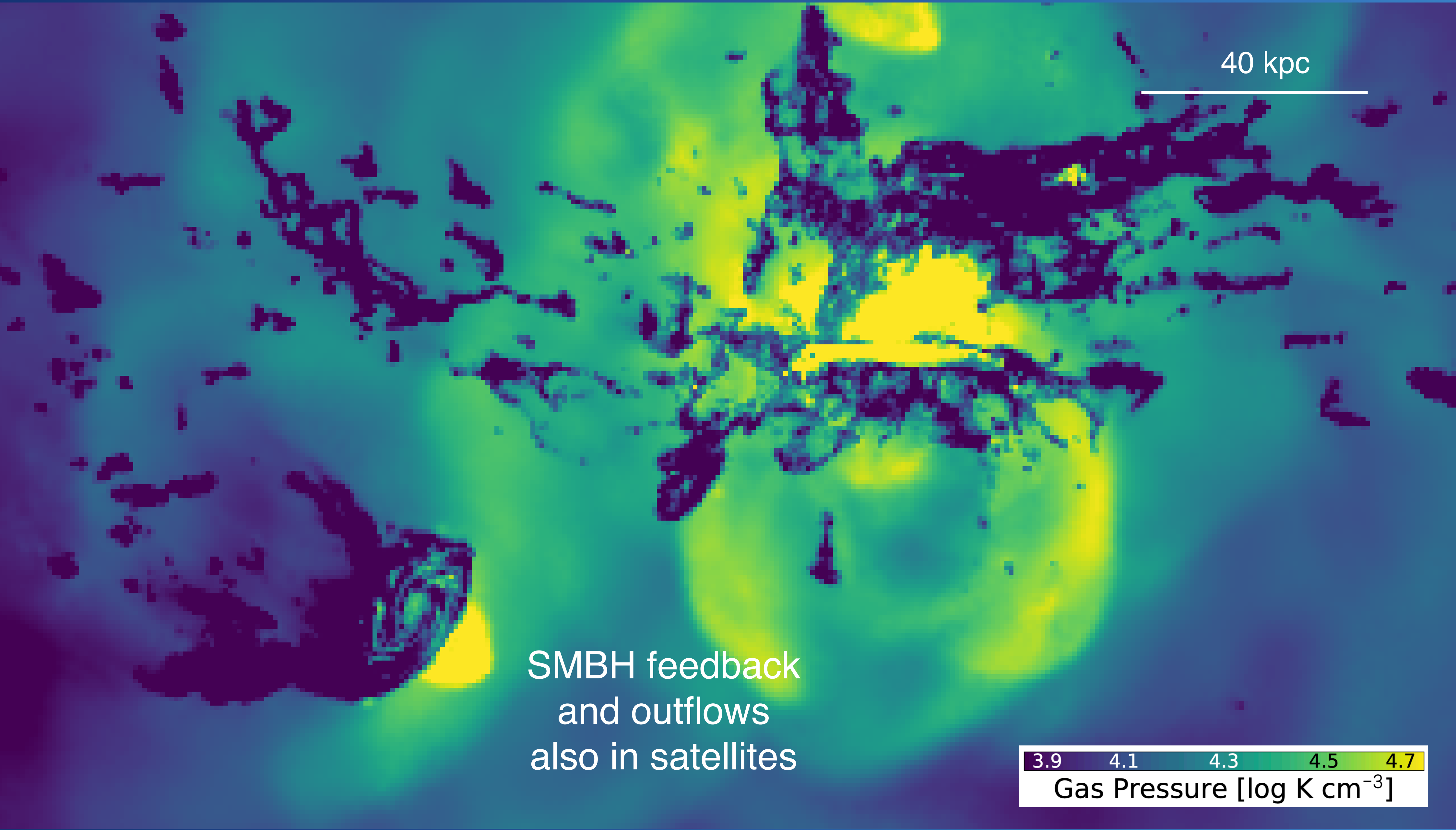


~spherical shock fronts across cluster scales in >10^{14} M⊙ haloes

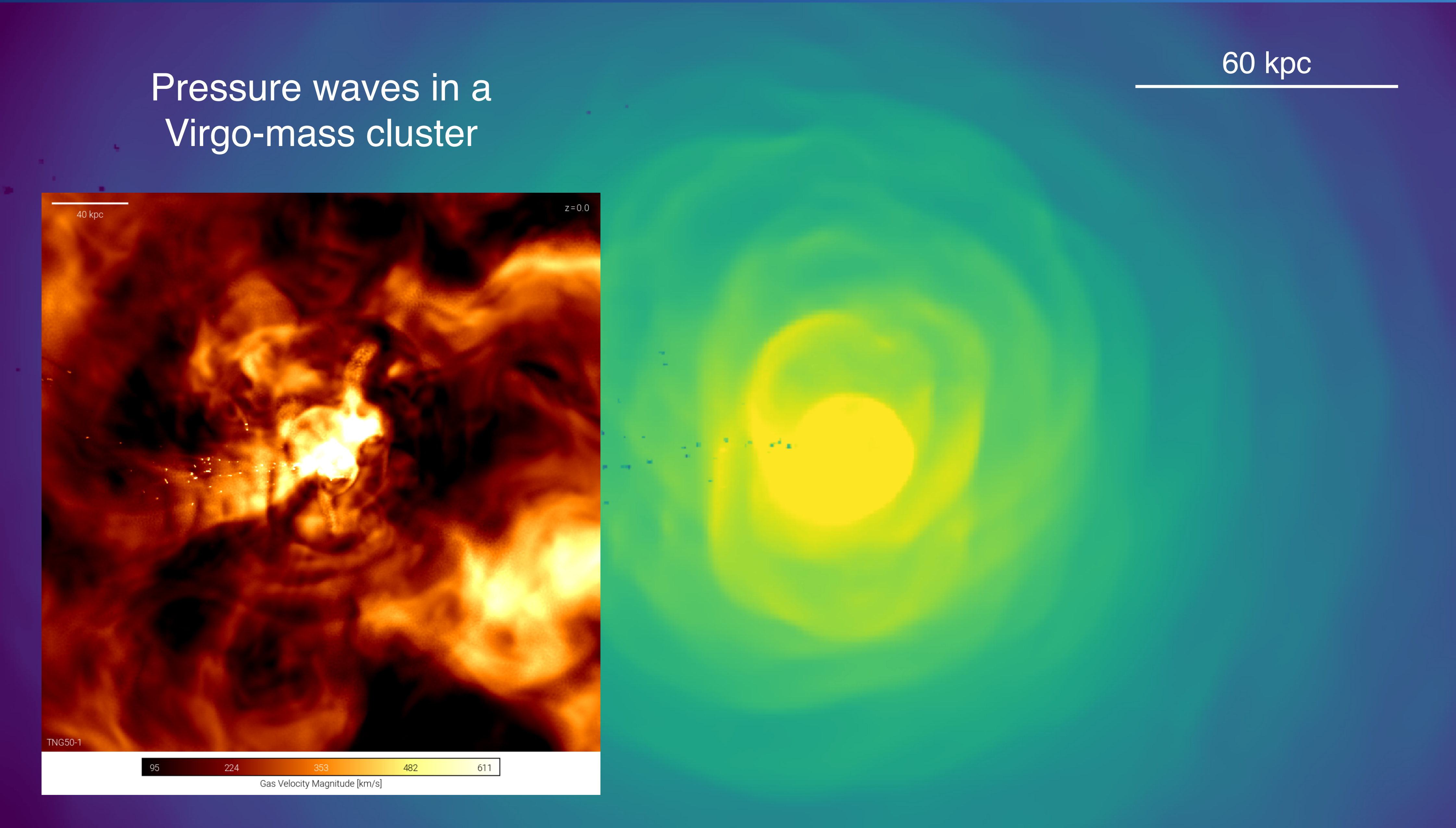


Bow shock and cold gas loss in jellyfish

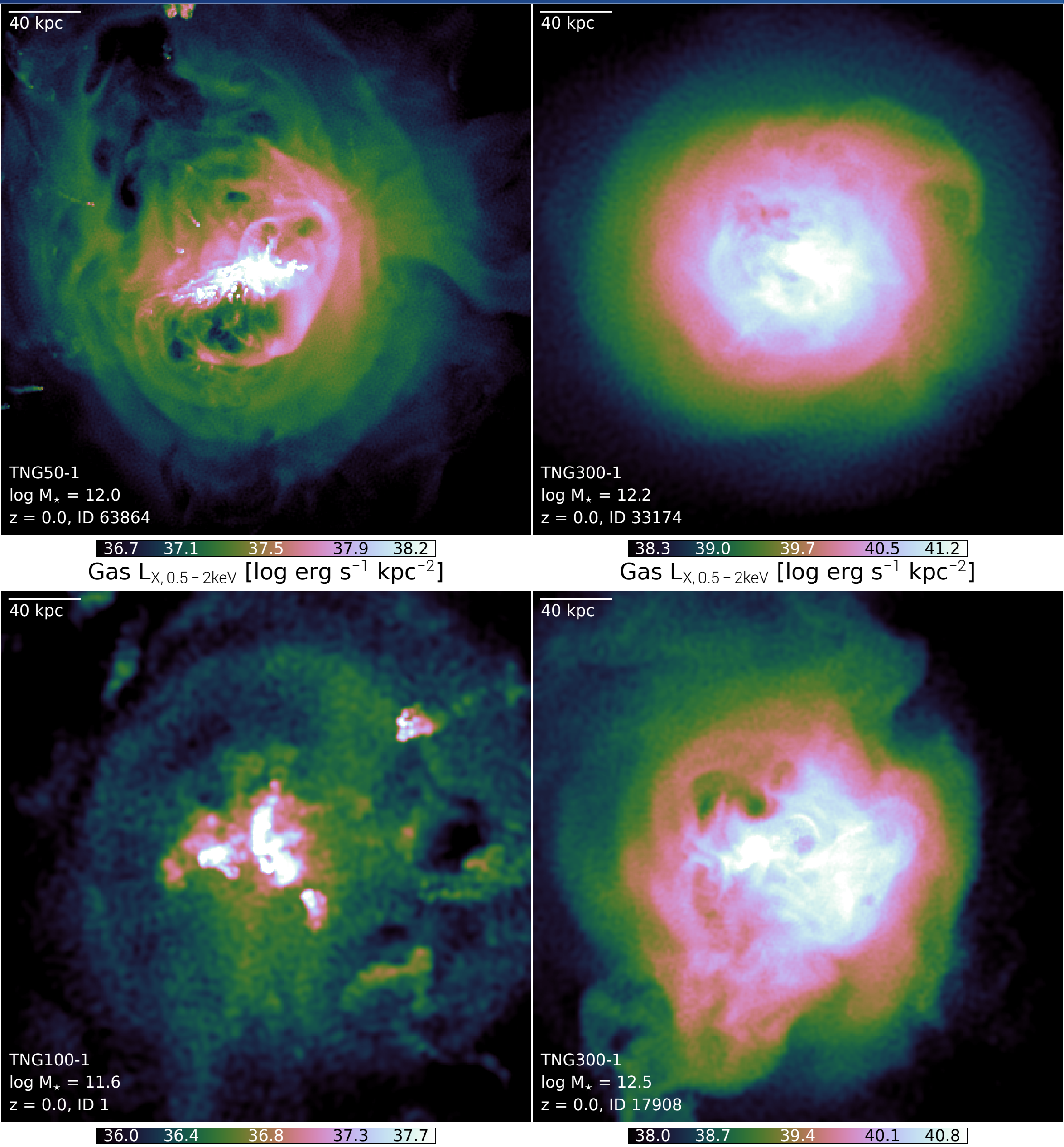


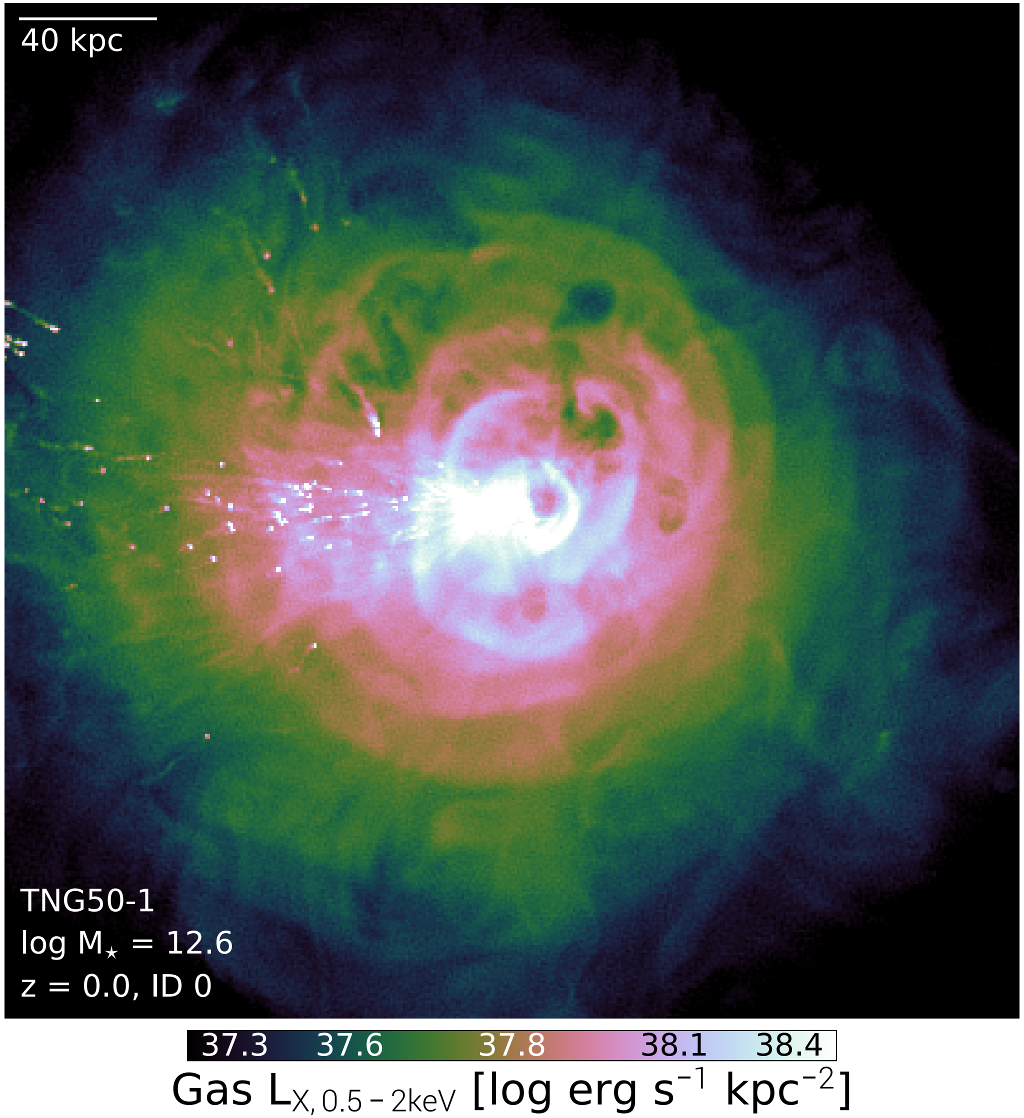

40 kpc
SMBH feedback
and outflows
also in satellites
3.9
4.1
4.3
4.5
4.7
Gas Pressure [log K cm^{-3}]

Pressure waves in a Virgo-mass cluster



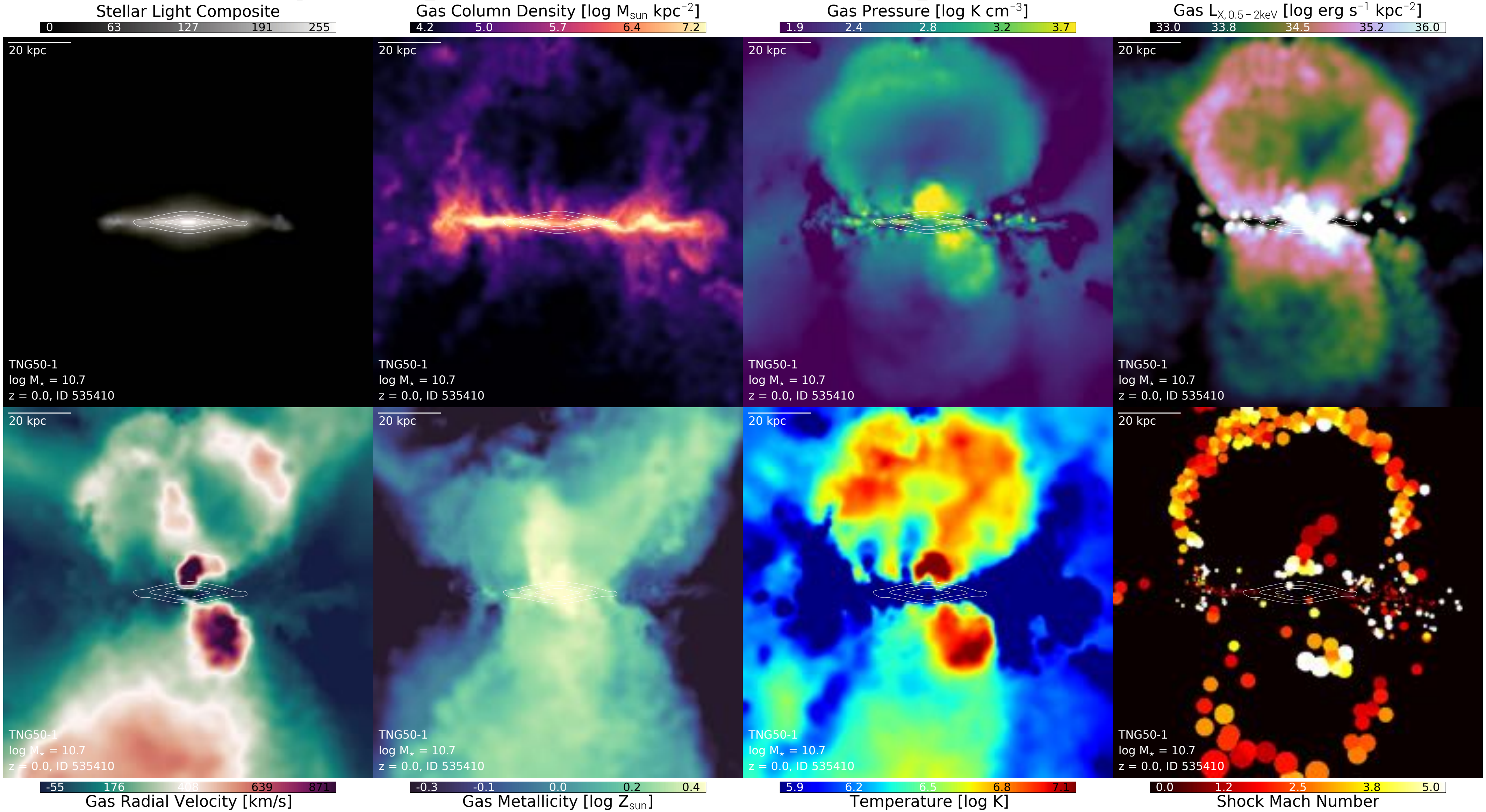
~ X-ray cavities





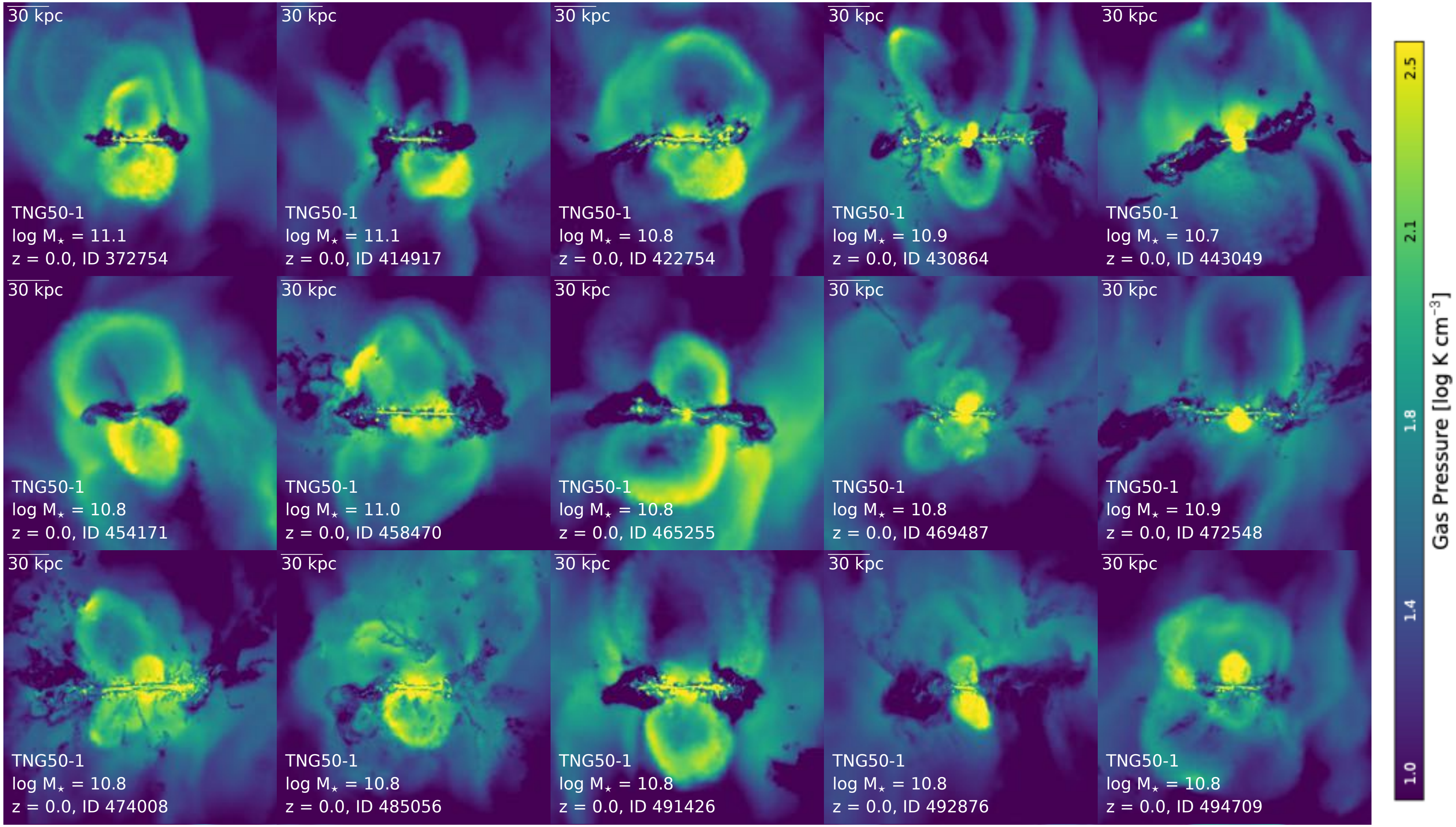
Insights from MW/M31-like galaxies

Bubbles naturally emerge in TNG50 MW/M31-like galaxies



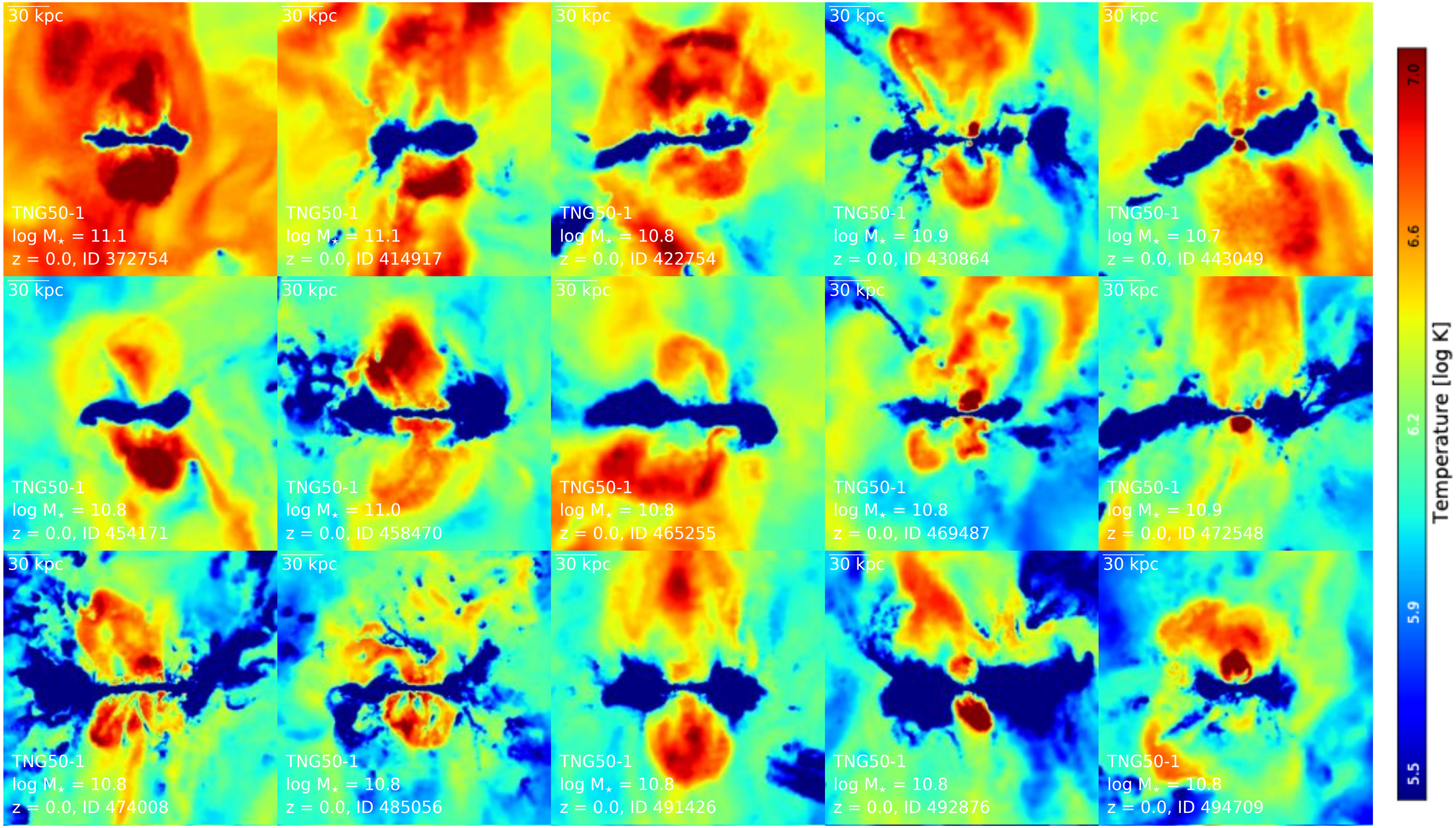
Pillepich, Nelson, Truong + 2021

TNG50 bubbles are manifest as over-pressurized cocoons



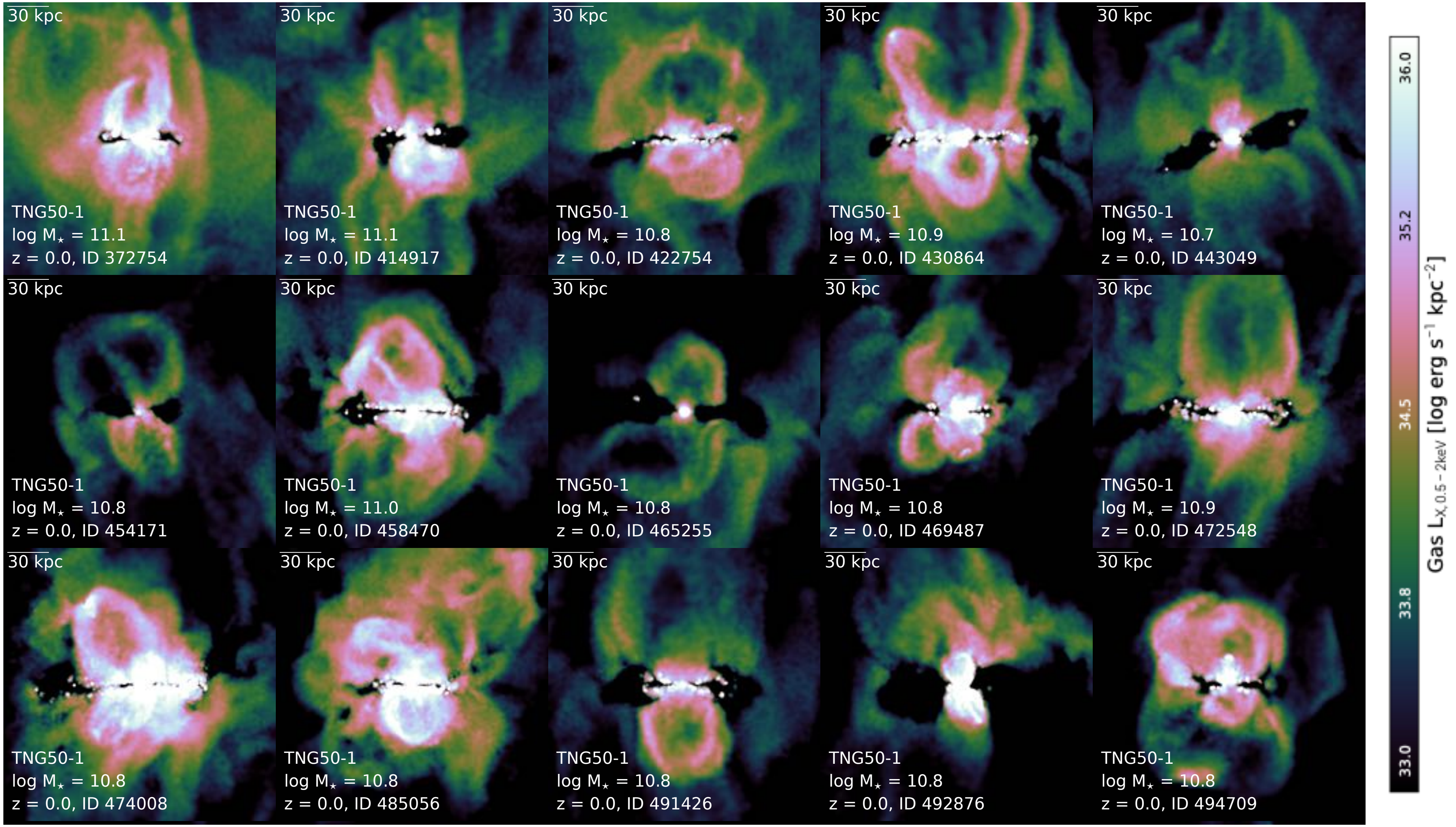
Pillepich, Nelson, Truong + 2021

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



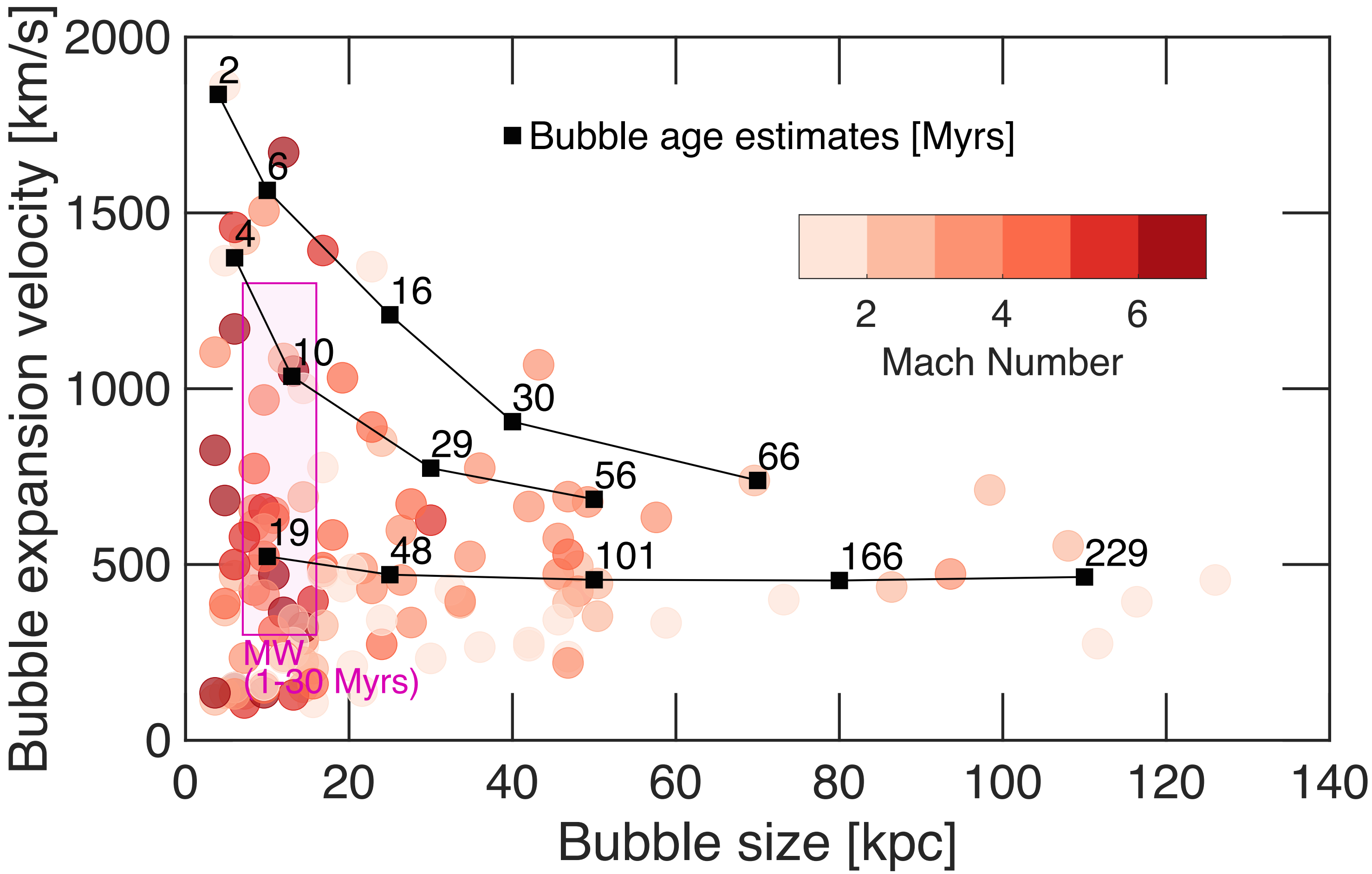
Pillepich, Nelson, Truong + 2021

TNG50 bubbles are manifest as X-ray emitting shells, cavities, … and are frequent!



Pillepich, Nelson, Truong + 2021

TNG50 predicts bubbles with *diverse* expansion velocities, sizes, and ages

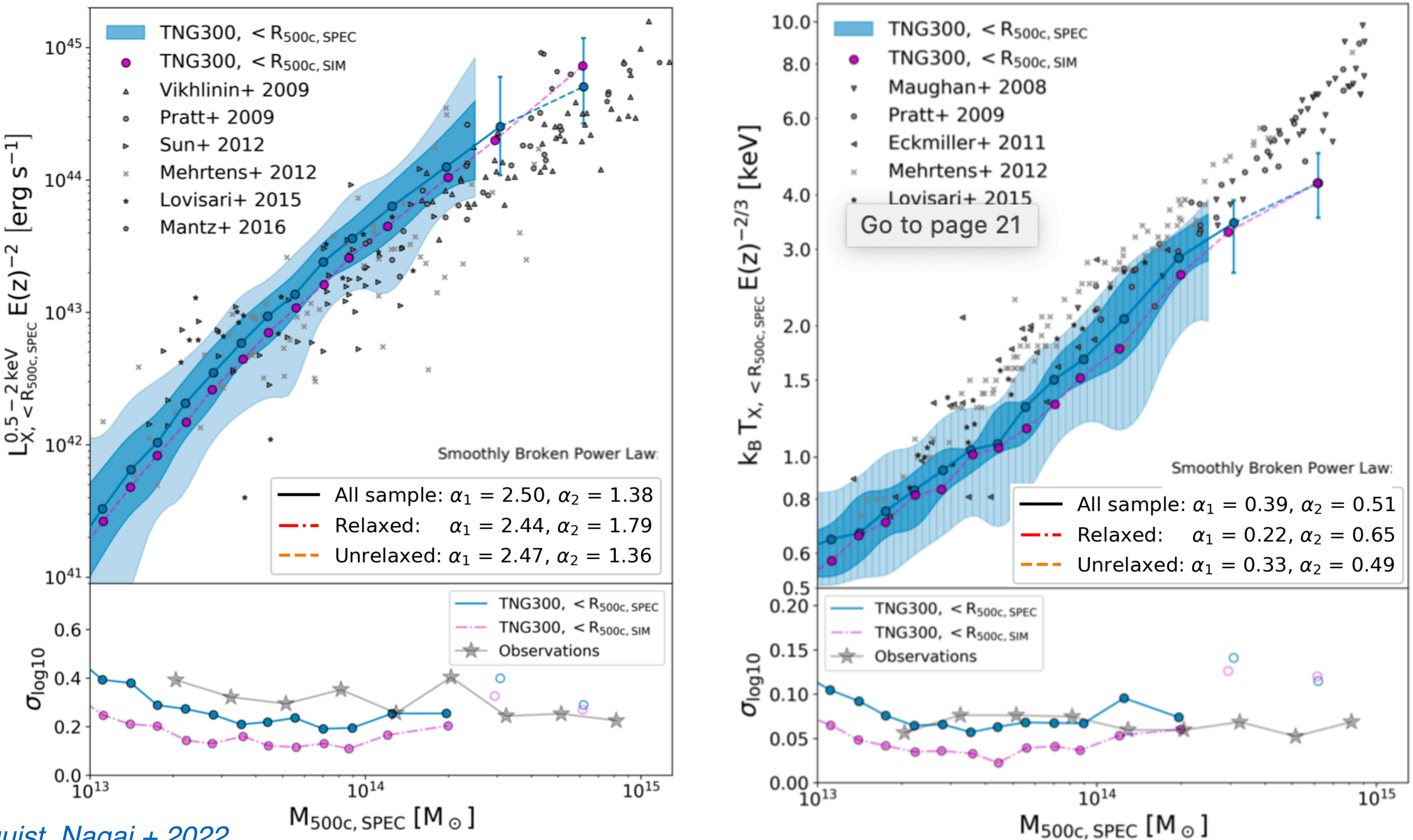


Their origin? Activity and energy injections from the SMBH

Pillepich, Nelson, Truong + 2021

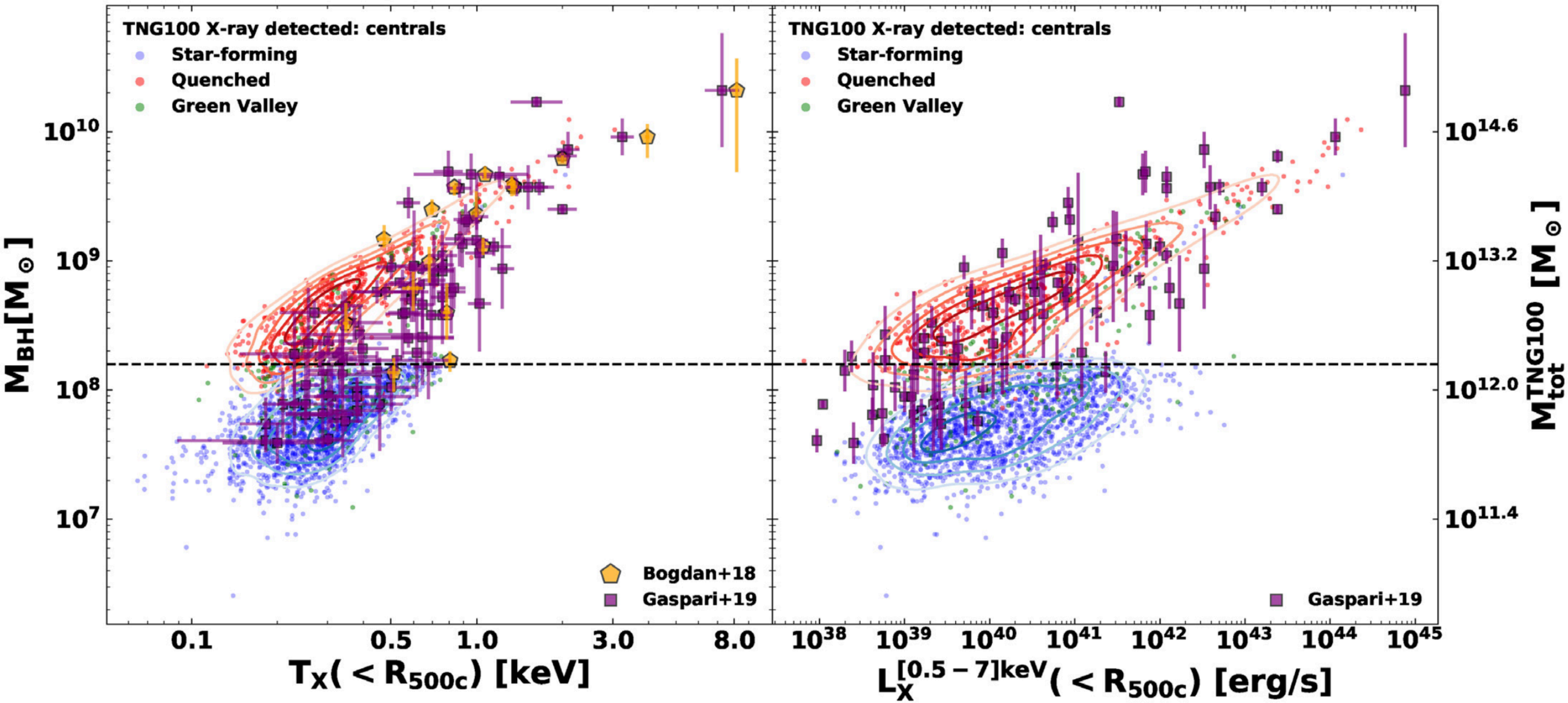
Back to groups and clusters

According to TNG, the X-ray scaling relations bend at the group-mass scale



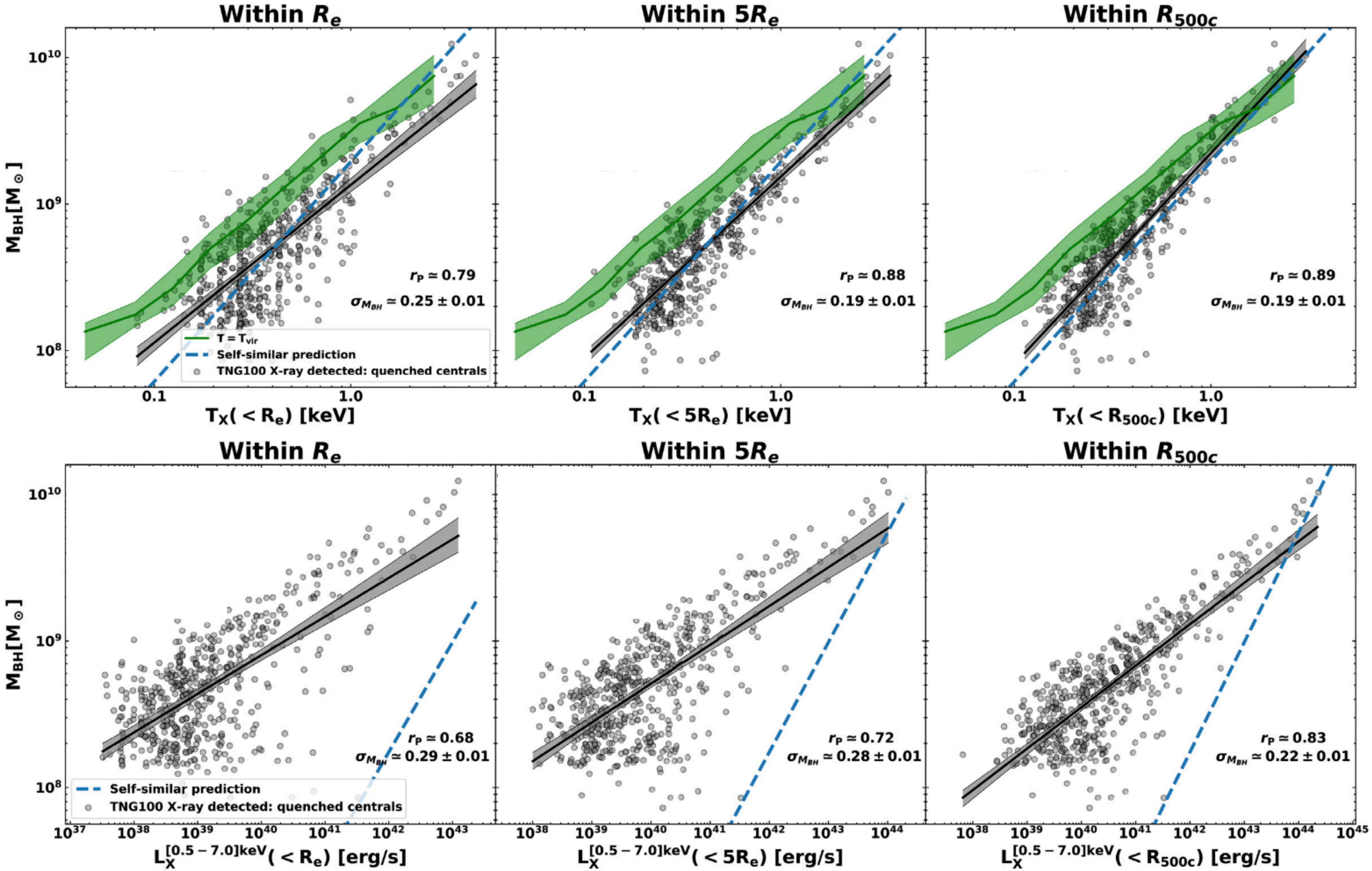
Pop, Hernquist, Nagai + 2022

According to TNG, the X-ray halo properties correlate with the central SMBH mass



Truong, Pillepich, Werner 2021

… also within small apertures



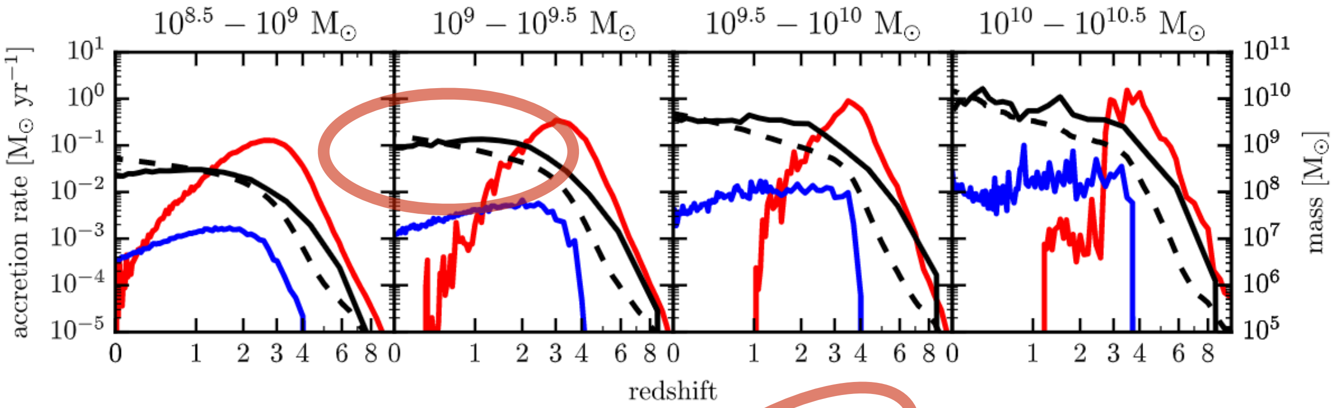
Truong, Pillepich, Werner 2021

The *existence* of such relationship is not due to SMBH feedback! It's indirect…

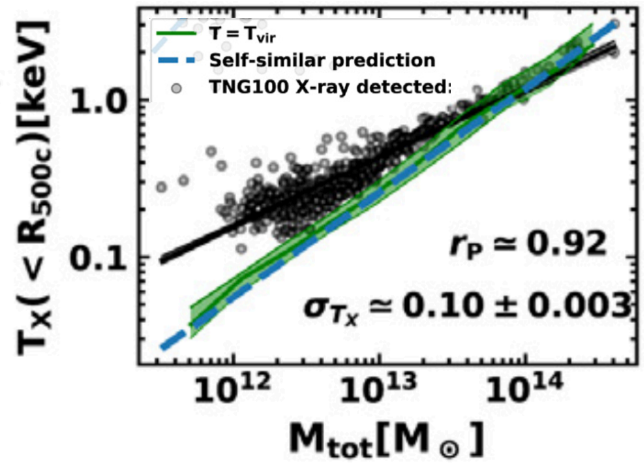
1. The SMBHs at the center of clusters have mostly grown via BH-BH mergers

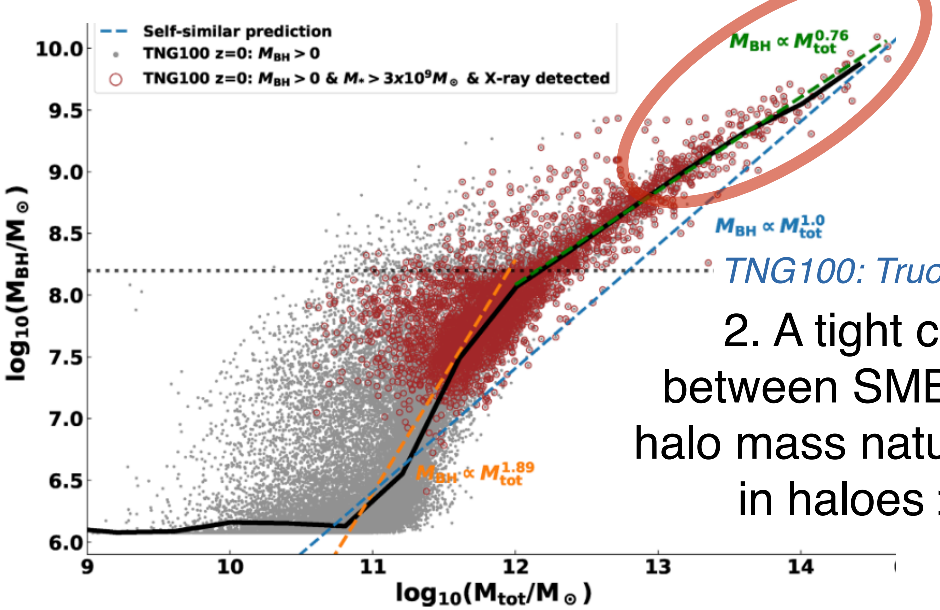
SMBH mass at z=0

TNG100/TNG300: Weinberger+2018



3. Halo mass and X-ray halo properties are correlated because of gravitational collapse



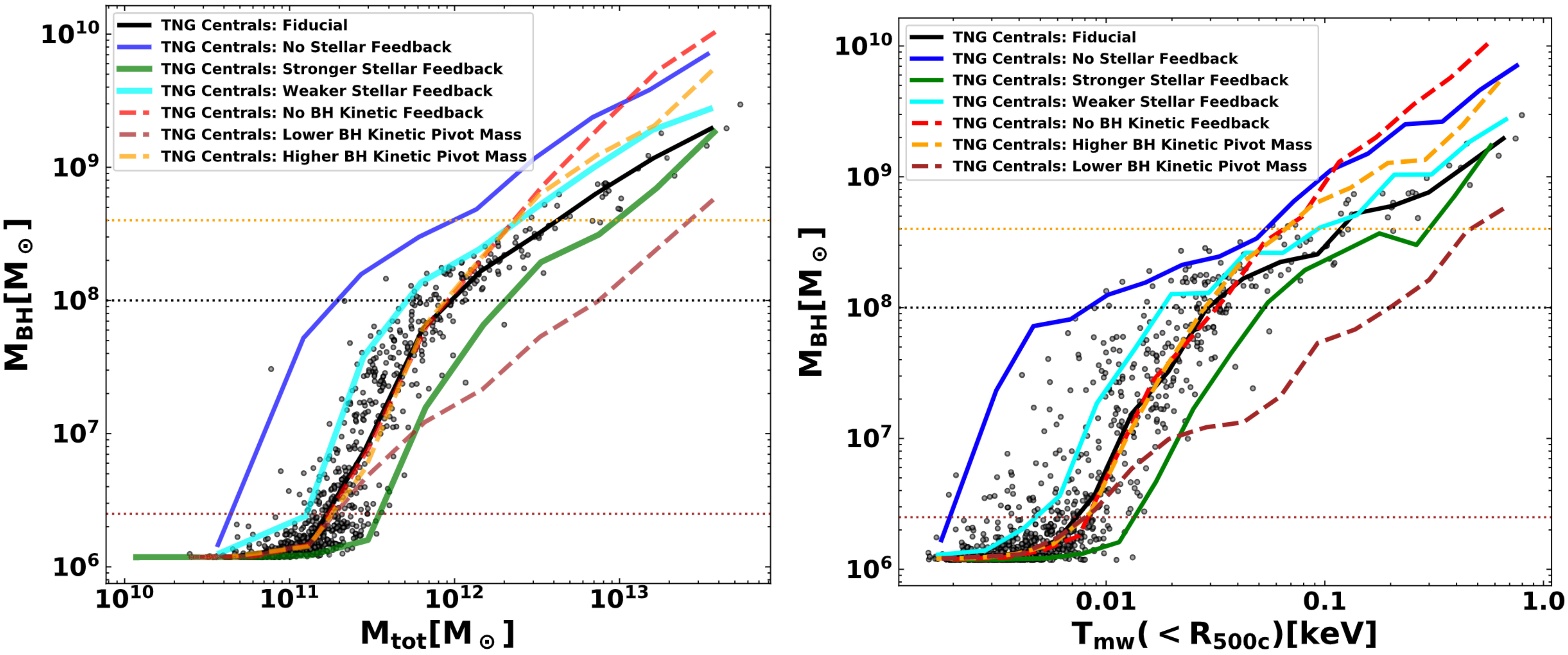


TNG100: Truong, Pillepich, Werner 2021

2. A tight connection between SMBH mass and halo mass naturally emerges in haloes >10^{13} M$_\odot$

=> tight relations between SMBH mass and ICM L_X and T_X are primarily a manifestation of the underlying relation with halo mass

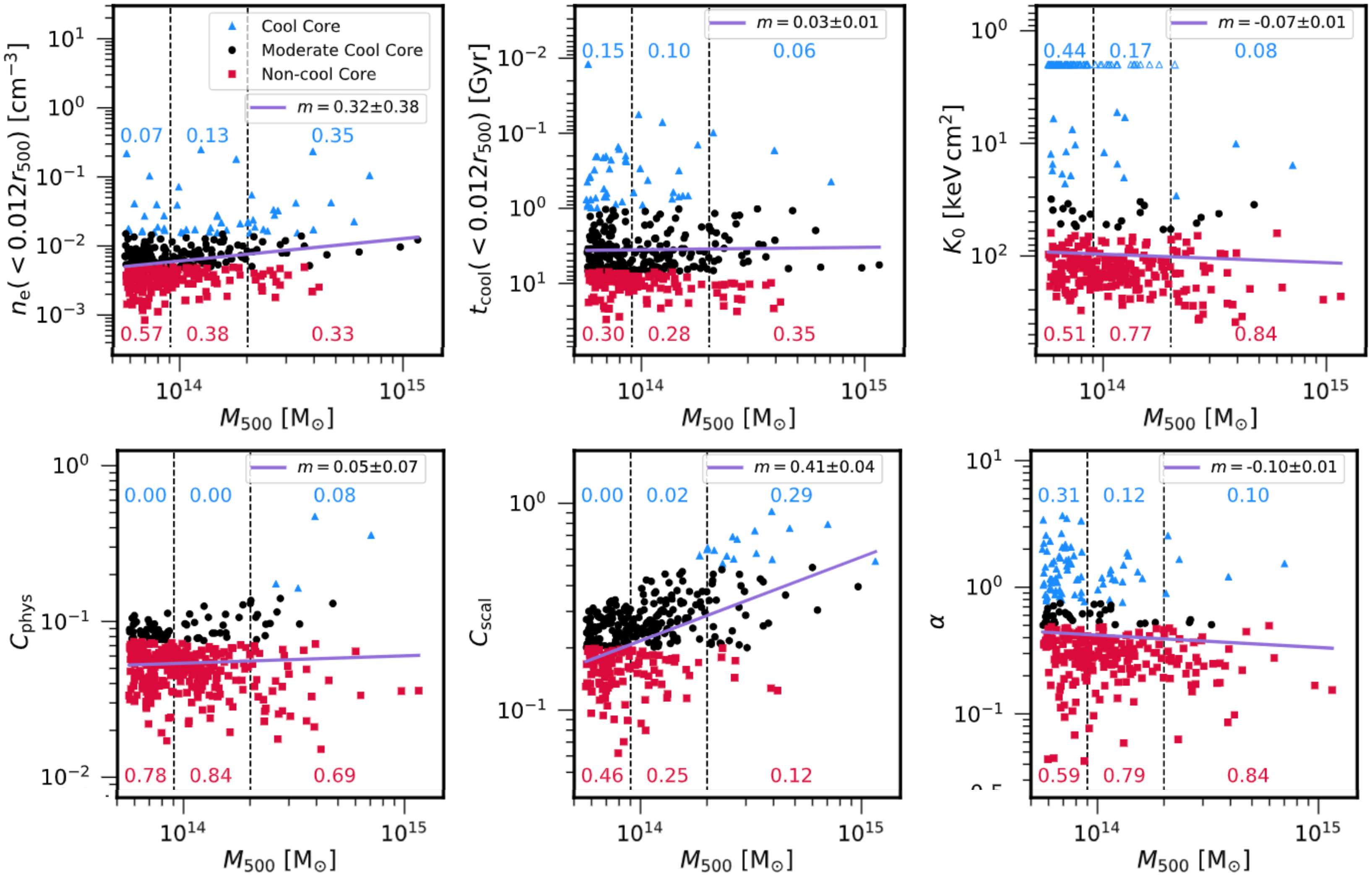
The shape and locus of such relationships are, yes!, modulated by SMBH feedback



And in fact more so at smaller clustercentric distances

Truong, Pillepich, Werner 2021

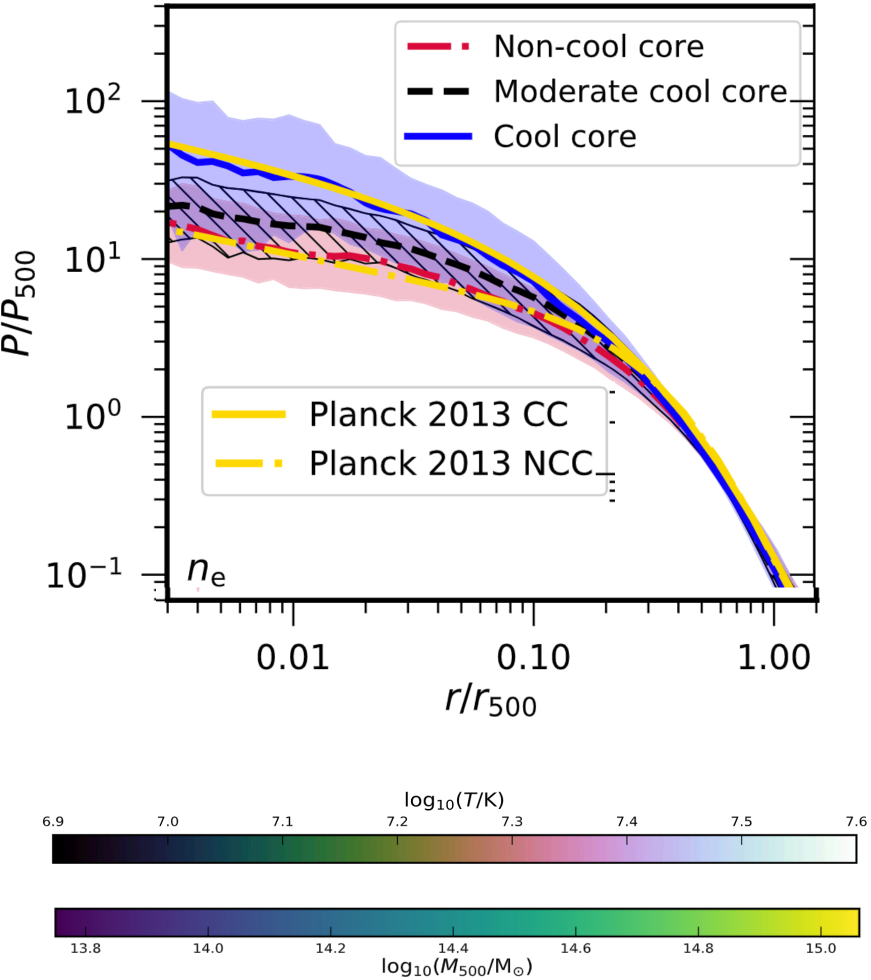
TNG returns an unprecedented diversity of CC/NCC-criteria properties

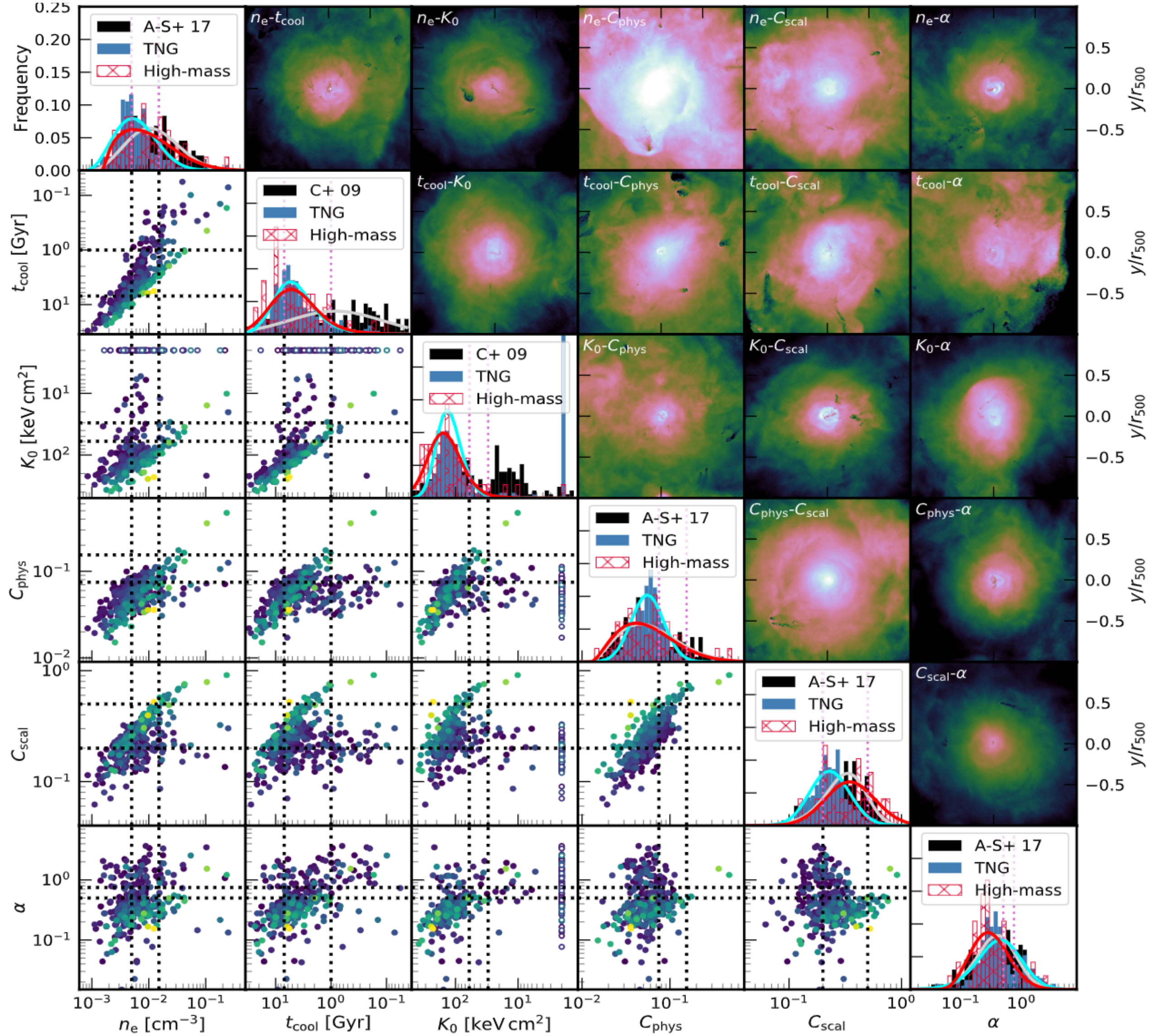


Criterion	Notation	Aperture	CC limit
Central electron number density	n_e	$0.012\, r_{500}$	$> 1.5 \times 10^{-2}$ cm^{-3}
Central cooling time	t_{cool}	$0.012\, r_{500}$	< 1 Gyr
Central entropy excess	K_0	–	< 30 keV cm^{-2}
Concentration parameter (physical)	C_{phys}	40.0, 400.0 kpc	>0.155
Concentration parameter (scaled)	C_{scal}	0.15, 1.0 r_{500}	>0.5
Cuspiness parameter	α	$0.04\, r_{500}$	>0.75

Barnes + \w Pillepich 2018

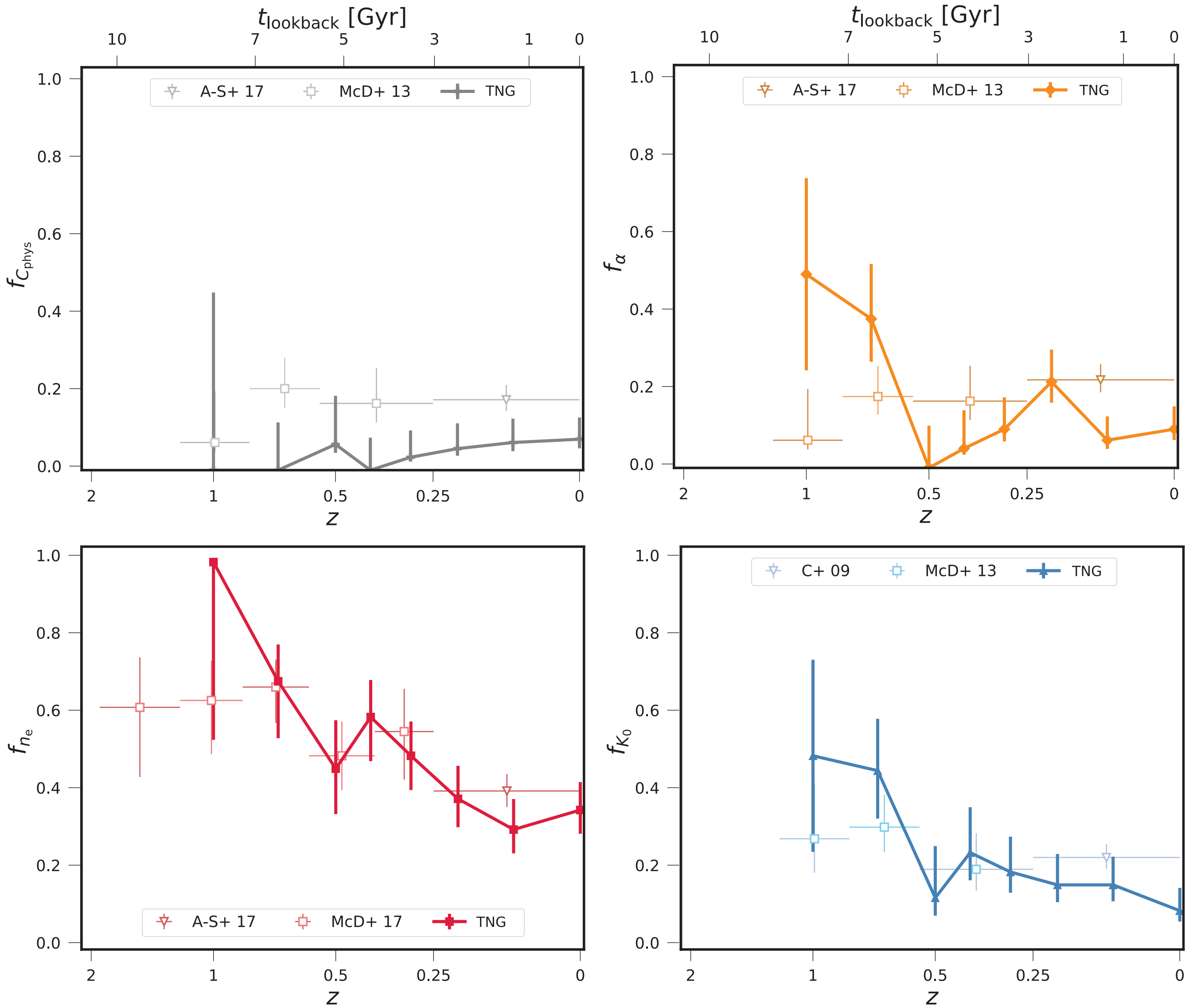
TNG returns continuous CC/NCC-criteria properties





Barnes + \w Pillepich 2018

TNG returns overall a reasonable agreement with observations!

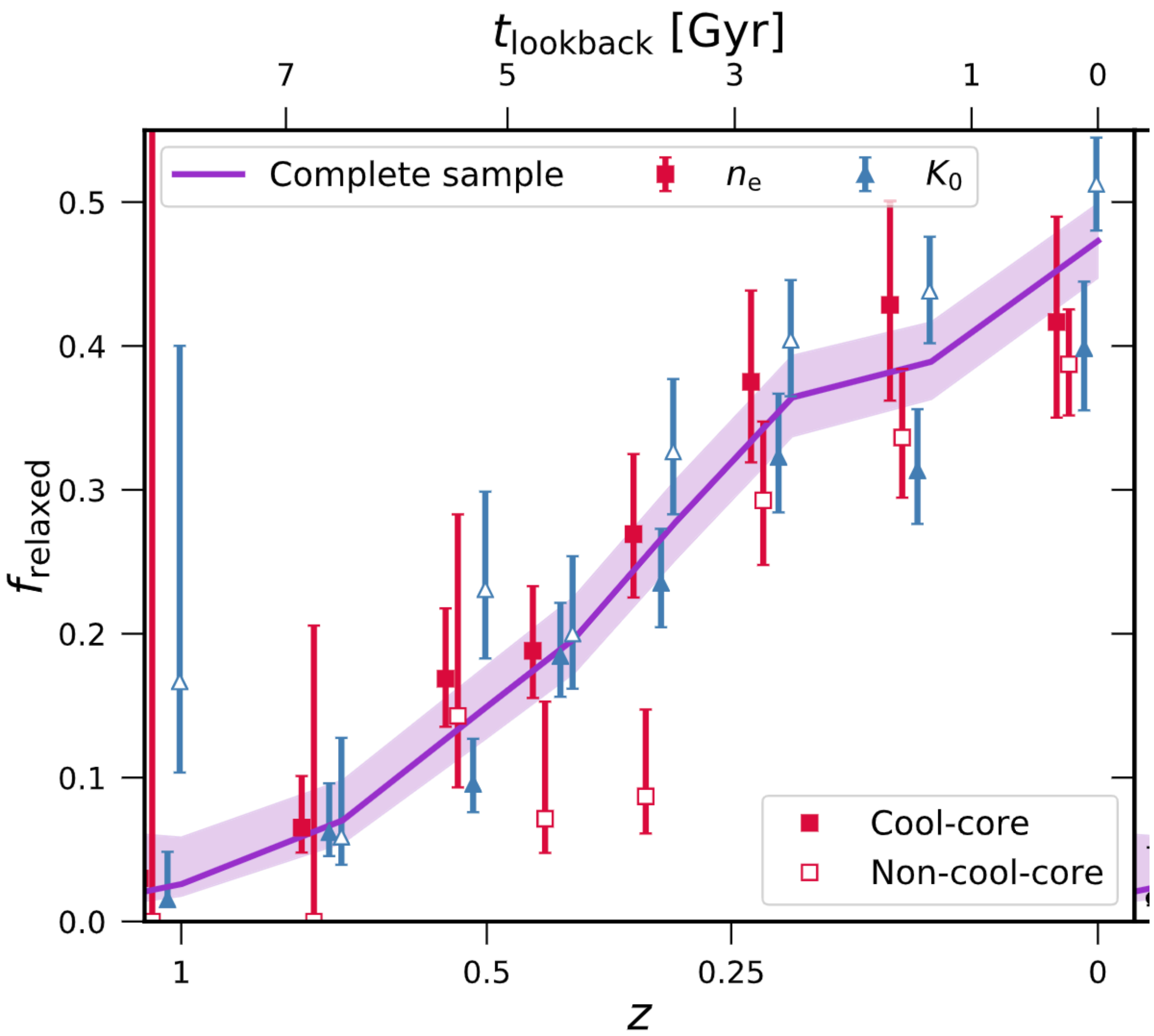


Caveat! here comparison not mass matched!!!

Esp. at high z, not enough massive clusters in TNG as in the selected observed samples

Barnes + \w Pillepich 2018

Mergers are probably not the sole drivers of the CC/NCC diversity



In TNG, no evidence that (NCCs) CCs have greater (un) relaxed fractions

i.e. no indication that mergers may disrupt CCs

Barnes + \w Pillepich 2018

In TNG, the same model for SMBH feedback produces diverse, highly spatially-resolved and ~realistic manifestations of gas properties in massive haloes

More with Nhut's talk!

But not so many really massive clusters…see Dylan's talk!

In TNG, the same model for SMBH feedback produces also realistic massive galaxies

(in terms of SFRs, quenched fractions, stellar morphologies and kinematics, …)

Simultaneous modeling of gaseous haloes and galaxies is important