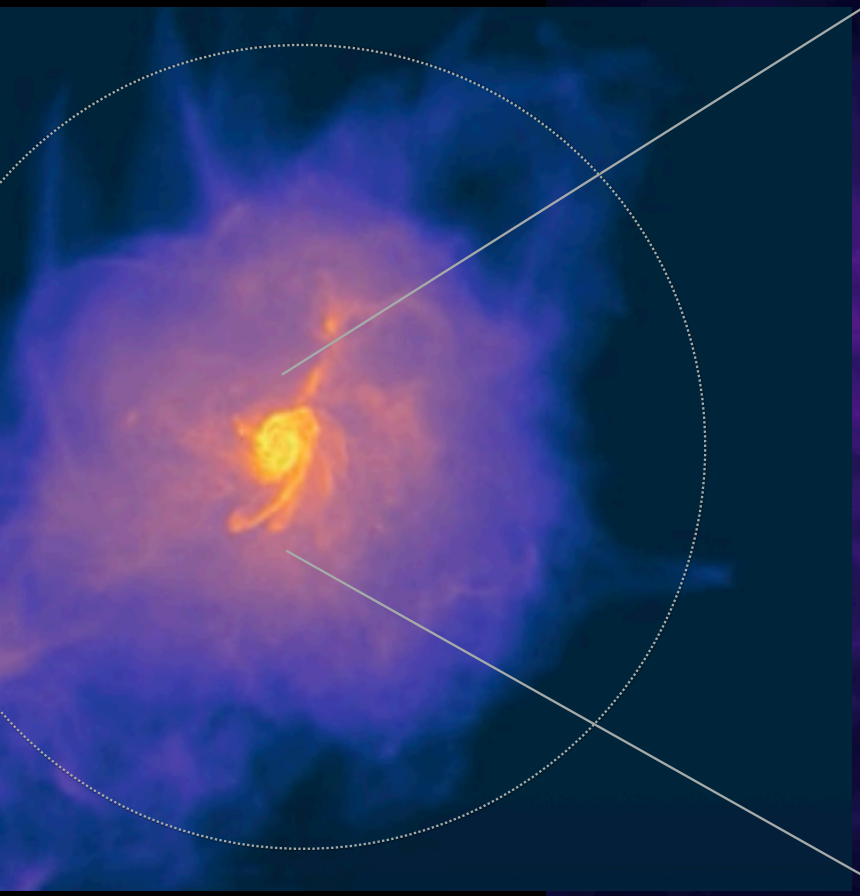
(Towards) cosmological galaxy formation and evolution at sub-parsec resolution

ANNALISA PILLEPICH
MPIA, Heidelberg

100 pc

A main theme of this meeting: “Bridging scales”



Halo scales (and beyond)

Galaxy scales

ISM (<100pc) scales

Bridging scales and connecting phenomena… in the hot gas phase (intermezzo)

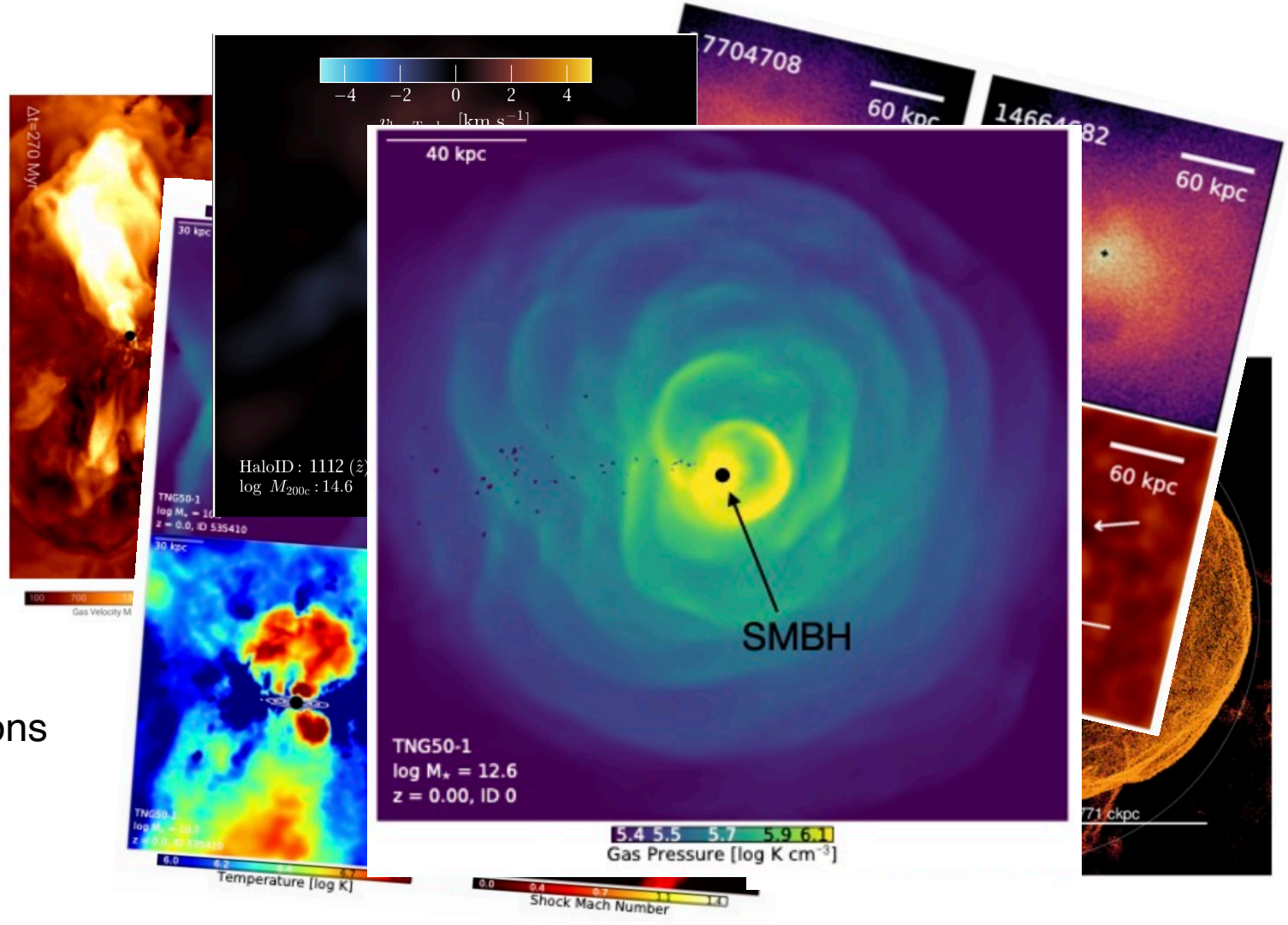
Reminder!
The hot volume-filling gas is believed to be the dominant component by mass of the CGM/IGrM/ICM

And a “classical” testbed for (AGN) feedback

If you are interested in

SMBH feedback
TNG and TNG-Cluster predictions
X-ray observations,

find me later!



Credits: Pillepich and Nelson+2019, Pillepich+2021, Prunier+2025, Prunier+ in prep, Chatzigiannakis+2025, Saha+in prep

Models for cosmological galaxies across physical assumptions

XXX = Notable examples of cosmological galaxy simulations, possibly incomplete, omitting idealized setups

Large “uniform-resolution” volume sims

e.g. IllustrisTNG
Eagle, HorizonAGN, …

NewHorizon
FIREbox

No $<10^4$ K gas Unresolved ISM	Multi-phase ISM/gas down to 10 K	Single stars $m_{baryons}$~1-100 Msun
e.g. Auriga, NIHAO,…	FIRE-2,3, EDGE, SERRA MEGATRON, THESAN-ZOOM (with RHD)	LYRA, EDGE-INFERNO

Cosmological zoom-in sims … of individual dwarfs

More accurate modelling of small-scale physics, better spatial/mass resolution →

Our current target

Resolved-ISM, sub-parsec, single-star cosmological simulations

Nelson+2025 in prep

Aka (for now): MCST sims (Matthew C. Smith and STRUCTURES sims)

Matthew C. Smith
(Now at MPA)

Dylan R. Nelson
(ITA, Heidelberg)

Annalisa Pillepich (MPIA, Heidelberg)
Ralf Klessen (ITA, Heidelberg)
Simon Glover (ITA, Heidelberg)

+ Chris Byrohl (ITA)
+ Eric Rohr (MPIA+ITA and now MPA)
+ Anirudh Ravishankar (MPIA)
  Shalini Kurinchi-Vendhan (MPIA)
  …

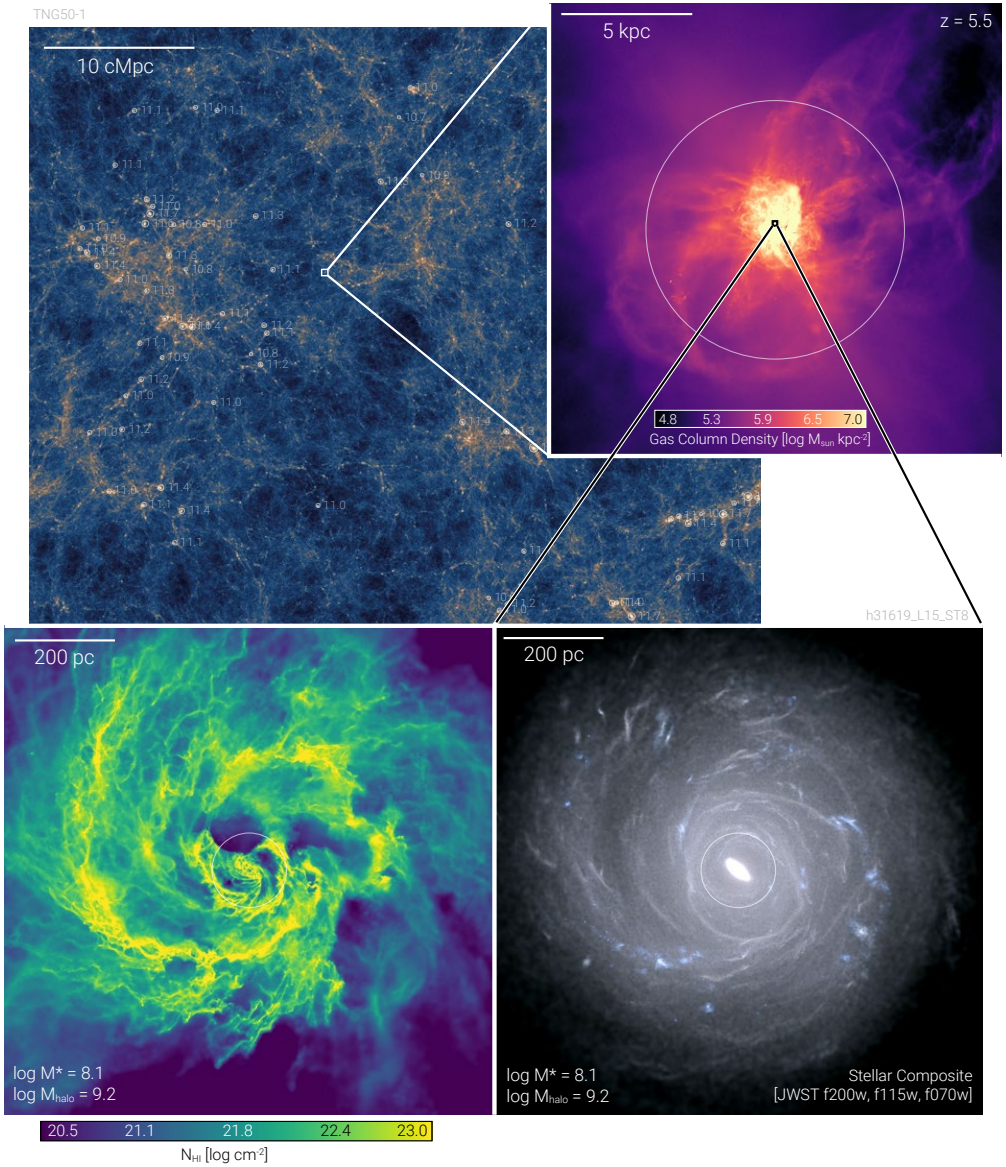
O(10) cosmological
zoom-in simulations
at high redshift (z>3-5)

Halo masses (z=5.5) =
$10^{8\text{-}10}$ Msun

With baryonic/cell target
mass resolution of
3, **24**, 200 Msun (!)
vs. $8\text{x}10^4$ Msun in TNG50

AREPO code
(gravity+hydro)

Multi-phase ISM model
down to 10k
Imladris model,
Smith 2025 in prep
+
SMBH seed, growth and
feedback



Resolved-ISM, sub-parsec, **single-star** cosmological simulations

Nelson+2025 in prep

Multi-phase ISM model down to 10k (Imladris model, Smith 2025)

Cooling and chemistry from ~10 K to ~10^8 K (largely via modified GRACKLE):

- Non-equilibrium primordial (H, He) chemistry
- Molecular hydrogen chemistry and cooling
- Heating from photodissociation of H_2 by LW photons, UV H_2 pumping
- Metal cooling (collisional and photoionization, based on CLOUDY)(*)
- Effects of dust via local dust-to-gas ratio
- Metalliciy floor at the initial conditions (*)
- All this accounting for interstellar-radiation field from a spatially-uniform UV+Xray background (FG+2020(*)) and local sources (stars)

Star formation, stellar evolution and enrichment with single-star treatment:

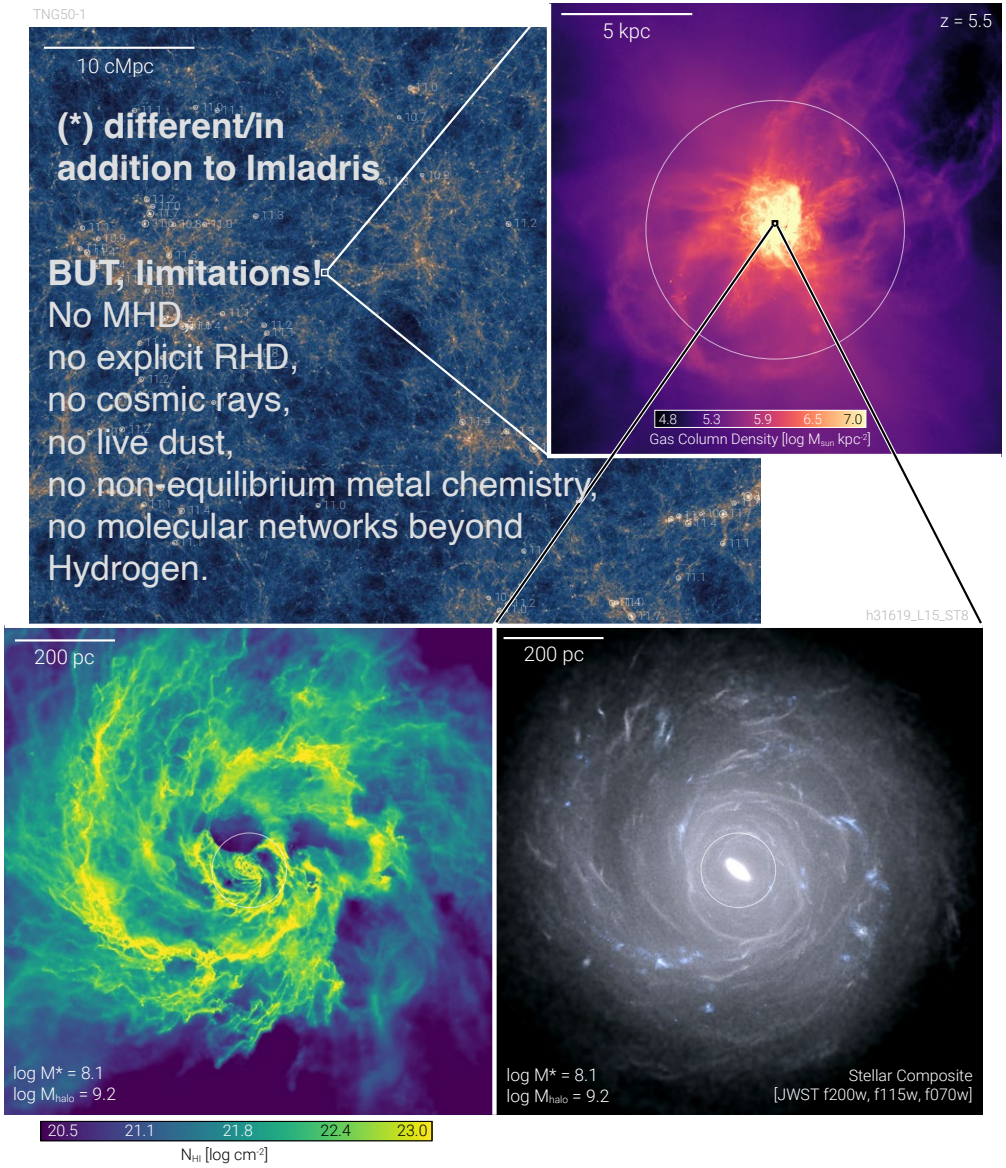
- Formation of stars for gravitationally-unstable gas (Jeans Mass threshold)
- Constant maximal SF efficiency per free-fall time
- Kroupa IMF
- **Individual star-sampling of the IMF (0.8-150 Msun) and "solo" star, i.e. single star treatment for stars above 3 or 5 Msun (depending on res)**
- Resolved mass, chemical, and radiative output of stars (including Q_HI and L_FUV)
- Tracking of production, evolution and return of 29 species: H, He, Li, Be, C, N, O, F, Ne, Na, Mg, Al, Si, P, S, Cl, Ar, K, Ca, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn

Stellar feedback:

- Photoionization feedback: ionization and heating of HII regions from ionizing radiation of stars, with a local, Healpix-based Stroemgren approximation
- Non-ionizing radiation feedback: photoelectric heating from LW and FUV
- Individual and time-resolved Type II supernovae feedback (mass, metals and energy): thermal dump if Sedov-Taylor phase resolved, else momentum injection + SNIa and stellar winds

Supermassive black holes physics (*)

- 1000 Msun seeds, in all haloes exceeding FoF mass of 10^8 Msun
- Bondi-Hoyle-Lyttleton gas accretion rate, capped at 10xEddington limit
- No needed spatial repositioning (dynamical friction naturally captured)
- Pure thermal, quasar-mode feedback (as in TNG)



See future papers!

:)

Conclusions/Summary

- Thanks to Matthew Smith and Dylan Nelson, we will have a new suite of ultra-high resolution cosmological simulations of galaxies, at high redshift

- It is going to be great fun to
  1) actually connect to high-z observations and
  2) to understand the interplay of
  feedback, ***chemistry and cooling****, star formation (and resolution)*
  and their effects on
  star formation histories*, outflows, stellar/gaseous structures, …*
  Especially in the very high-redshift, strongly-collapsing haloes