Milky-Way Analogues with Cosmological Simulations: *Illustris/TNG and other numerical projects*

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Rationale of this talk

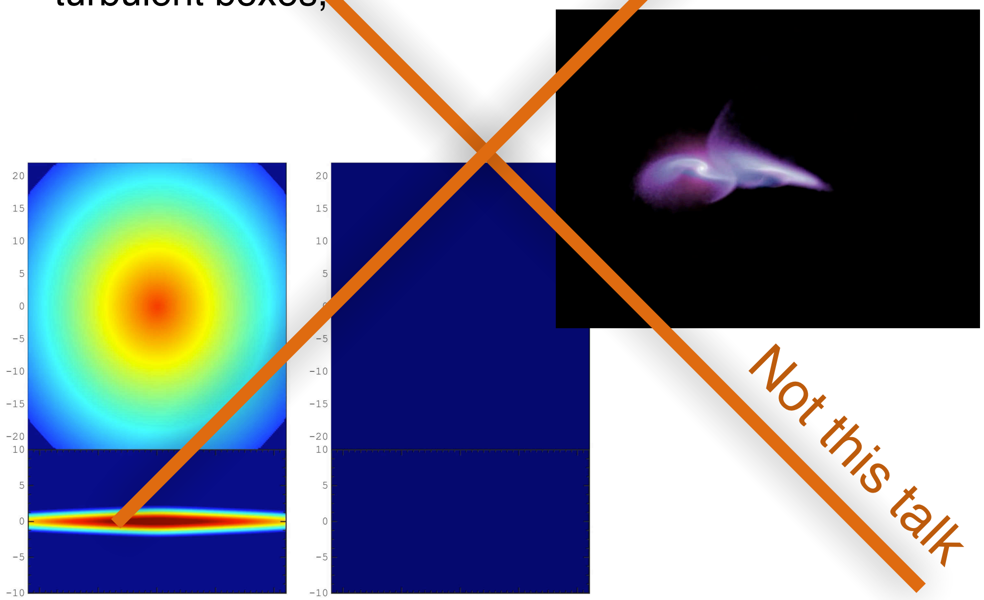
1. How do we make MW analogues at supercomputers?
2. How good do these analogues need to be?
3. What can we learn from them i.e. from such numerical experiments?

How do we make MW analogues
at supercomputers?

The foundations of *cosmological* simulations: the cosmological setup

Isolated/Idealized Experiments

Diverse Initial Conditions according to the application:
E.g. isolated disks, galaxy mergers, controlled LMC or Sagittarious bombardments of collision less disks, turbulent boxes, …



Credits/Refs: D'Onghia, Hernquist, Hopkins, Agertz, Laporte, Khoperskov…

Cosmological Simulations

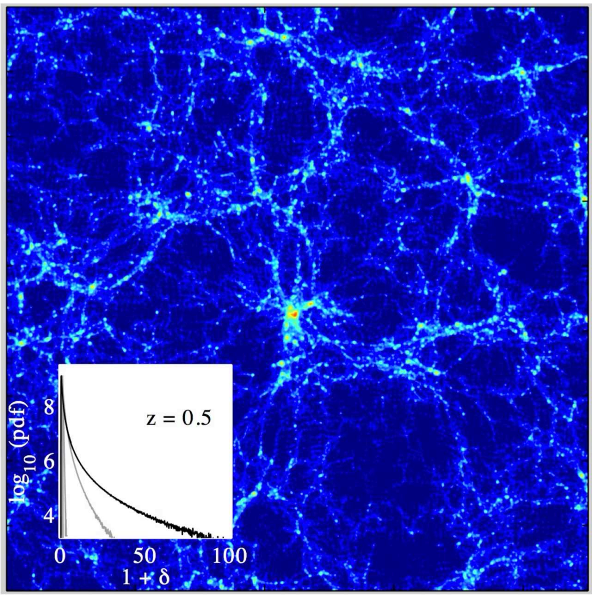
This talk

Cosmological Model => Initial Conditions
ICs = quasi-homogeneous and isotropic distribution of matter

This talk:
LCDM paradigm

For MWs:
Not just the main body, but also its satellites and surrounding haloes

~250 comoving Mpc (matter density projection)



Pillepich et al. 2008

ViaLactea + the Aquarius Project (2008): mature realizations of MW-like *haloes*

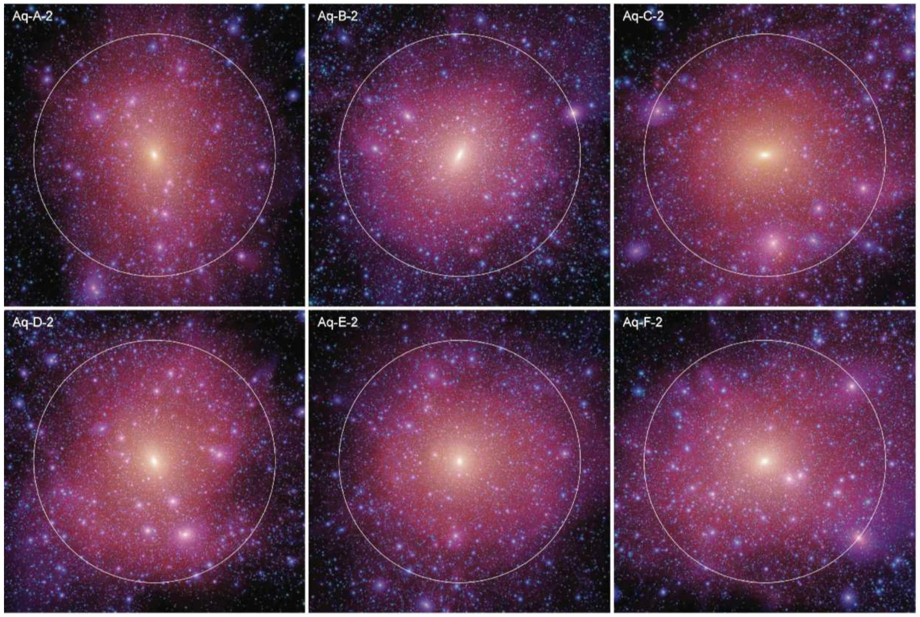
Around 2008, **dark-matter only** or N-body only or gravity-only simulations of haloes like the one of the MW already reached great levels of numerical sophistication, realized in the full cosmological context

Via Lactea (VL2, Diemand et al. 2008)
Code = PKDGRAV2; zoom-in cosmological technique
1 MW-mass halo (Mhalo = 10^12 Msun)
DM particle mass = 4e3 Msun

DM DENSITY

The Aquarius Project (Springel et al. 2008)
Code = Gadget-3; zoom-in cosmological technique
1+ 6 MW-mass haloes (Mhalo ~ 10^12 Msun)
DM particle mass~ 1e3-4 Msun

DM DENSITY



Eris (2011): the first realistic late-type simulation similar to the MW, with DM, stars, and gas

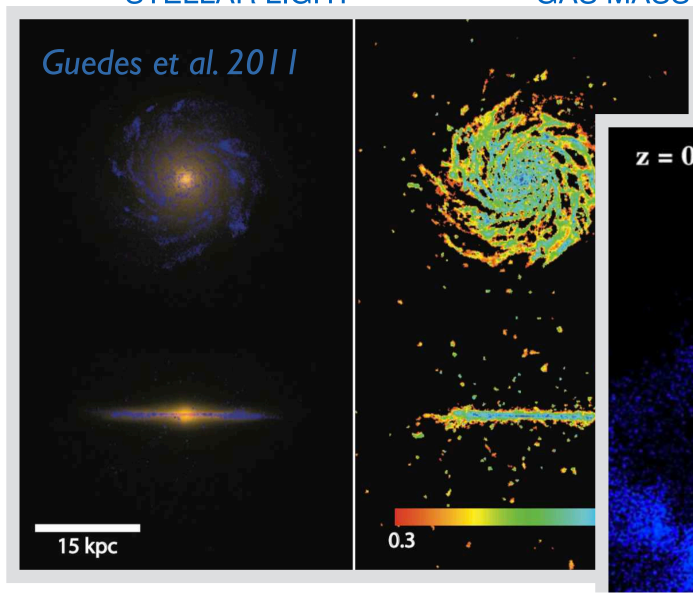
Eris (Guedes et al. 2011)
Code = Gasoline;
zoom-in cosmological technique
N-body + SPH
DM, GAS, STAR particle mass =
1e5, 2e4, 6e3 Msun
~120pc spatial resolution

1 disk galaxy:
MTot = 8e11 Msun; Mstars = 4e10 Msun

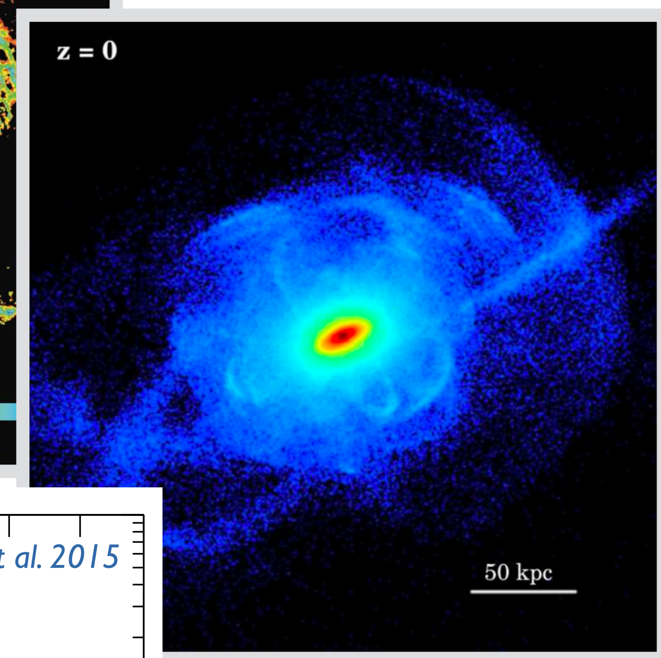
Galaxy Formation Model:

- radiative cooling of the gas
  (Compton, atomic, low-T Z-dependent)
- heating from cosmic UV Background
- Supernova feedback, a' la Stinson:2006
  i.e. thermal feedback from SNIa and SNII
- Star Formation a' la Governato 2010:
  - threshold n_{SF} = 5 atoms/cm3
  - efficiency ε_{SF} = 0.1
  - IMF: Kroupa et al. 1993
- NO AGN feedback

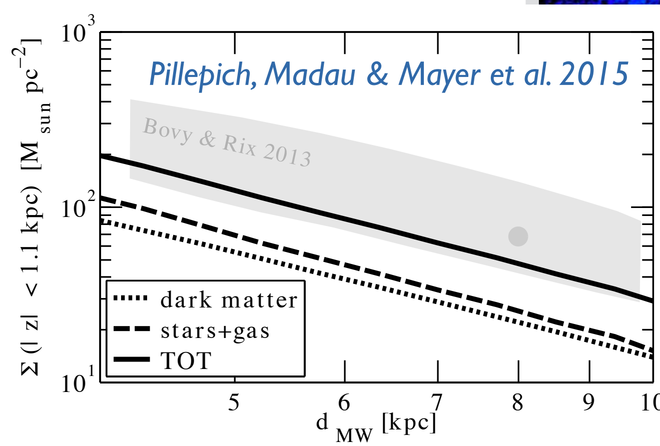
STELLAR LIGHT GAS MASS



STELLAR DENSITY



Rashkov, Pillepich et al. 2013

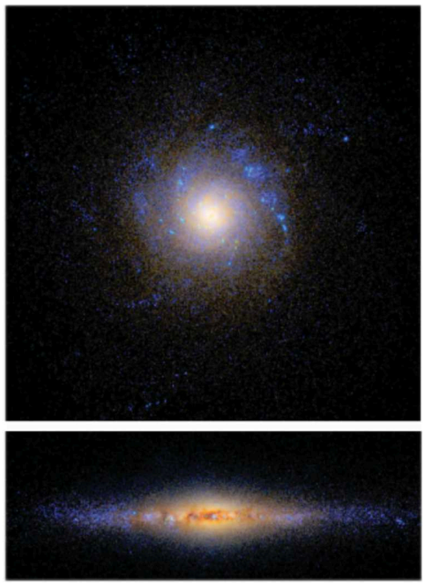


2013-2015: towards larger samples of L* galaxies with more complete physics

Projects with 1 to a few disk galaxies at 10^12 Msun haloes, with DM+GAS+STARS become “state of the art”

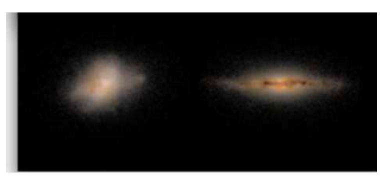
STELLAR LIGHT

Magicc* halo(s)
(Stinson et al. 2013)
Code = Gasoline;
zoom-in
1 MW-mass halo
(Mhalo = 8e11 Msun)



With “early” stellar feedback

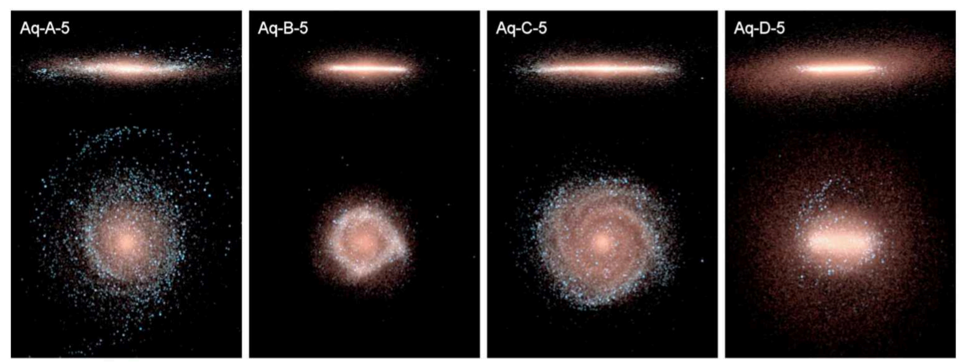
NIHAO sample
(Wang et al. 2015)
Code = GASOLINE
~15 MW-mass galaxies



The Hydro Aquarius Galaxies
(Marinacci et al. 2014)
Code = AREPO;
zoom-in
6 (+2) MW-like galaxies (Mhalo ~ 8e11-1.8e12Msun)

With “moving-mesh” hydro solver, metal line cooling, and black hole feedback!

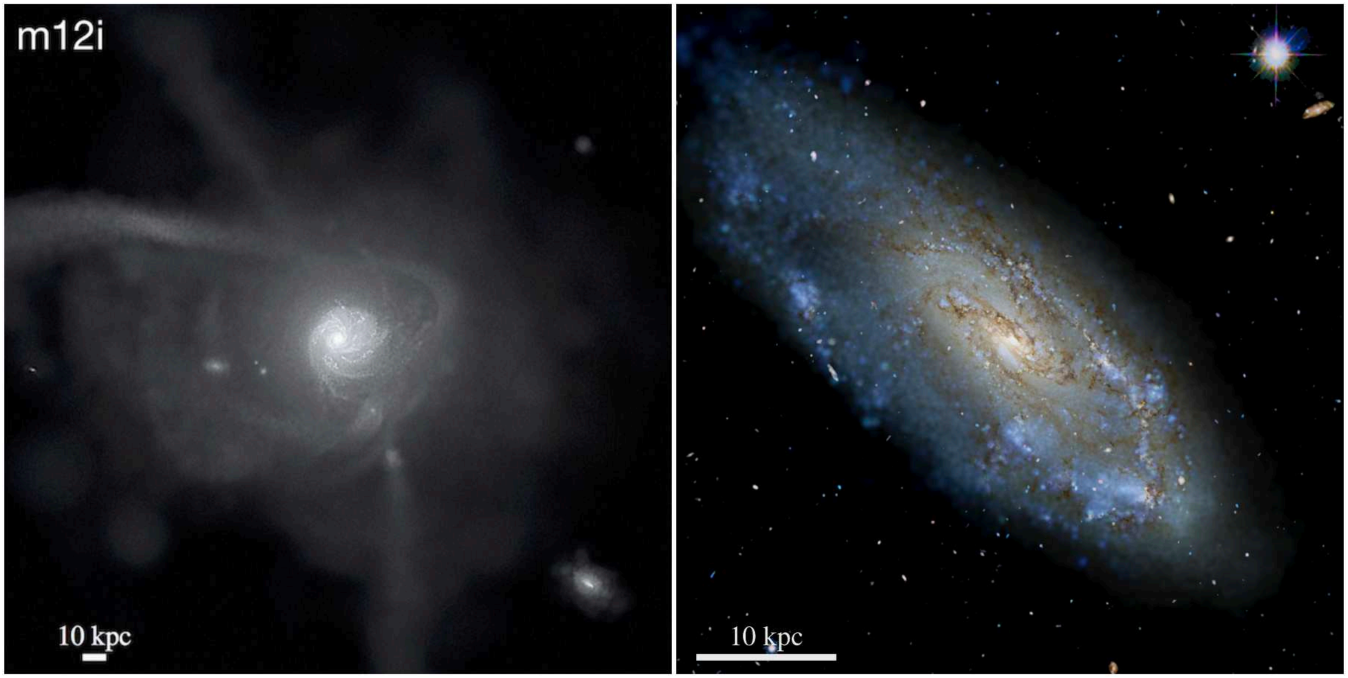
STELLAR LIGHT



The Latte Simulations (2016): more realistic treatments of SF and its feedback

STELLAR LIGHT (with DUST in post processing)

FIRE-2 generation of a handful of MW-like galaxies. (Wetzel et al. 2014)
Code = GIZMO (mesh-free); zoom-in
1-4 simulations (Mhalo ~1-2e12Msun)



Exquisite resolution:

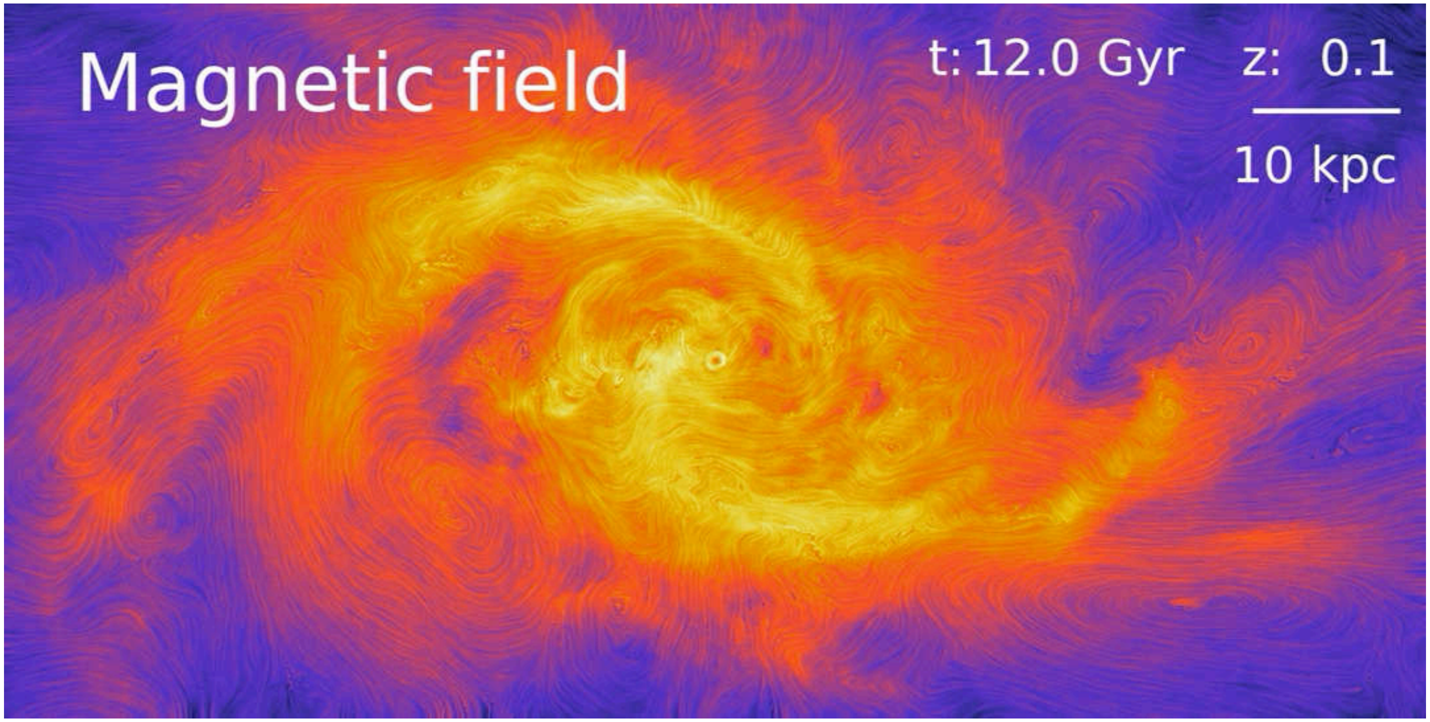
- 35,000 Msun for dark-matter
- 7070 Msun for gas
- 7070 Msun *initially* for stars (

With
•SF recipes beyond the density threshold
•explicit stellar feedback
•multi-phase ISM modeling
•(no BH feedback)

See also other grid-code disk galaxy simulations by e.g.
Agertz et al. 2016
Semenov et al. 2017

The Auriga Simulations (2017): BH feedback and magnetic field realizations

AURIGA SIMULATIONS
(Grand et al. 2017)
Code = AREPO
zoom-in
30+ galaxies (Mhalo ~1-2e12Msun)
GAS/STARS mass = ~5e4 Msun



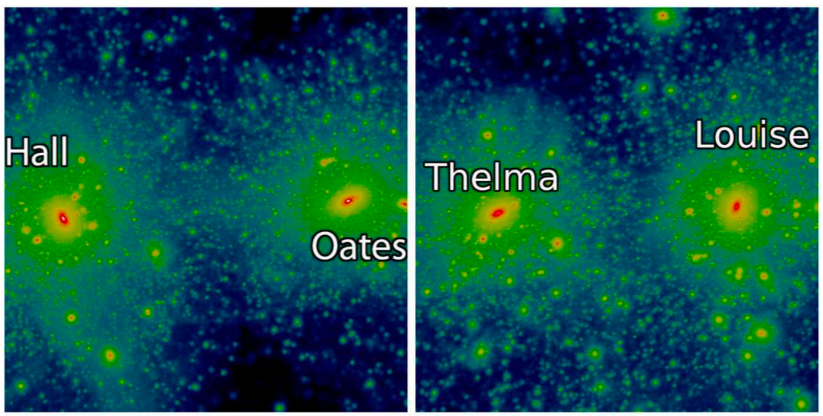
Pakmor et al. 2013, 2014, 2017

With black hole feedback and magnetic fields!
Chemical enrichment (SNIa, SNII, AGB; 11 elements)

Elvis and Apostle (2015): towards rendering the MW+M31 Local Group

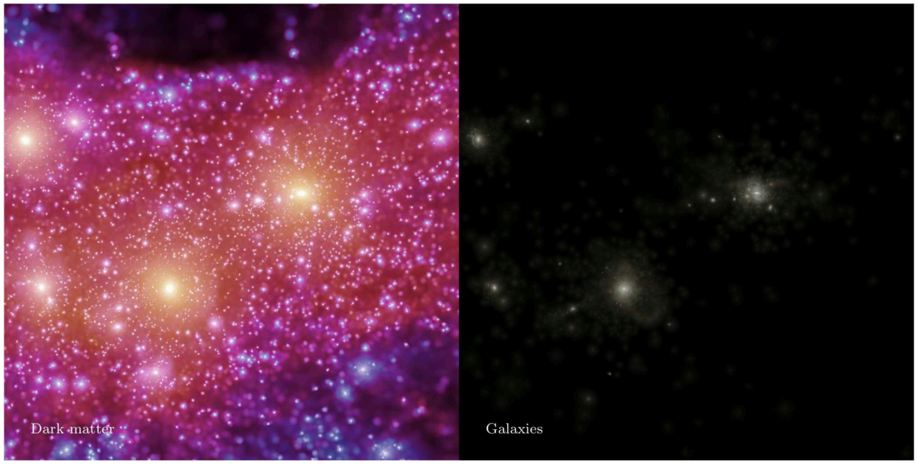
ELVIS DARK-MATTER ONLY
(Garrison-Kimmer et al. 2014)
Code = Gadget;
zoom-in
24 MW+M31 systems

DM DENSITY



See also **ELVIS on FIRE** (Garrison-Kimmer et al. in prep) with Gizmo

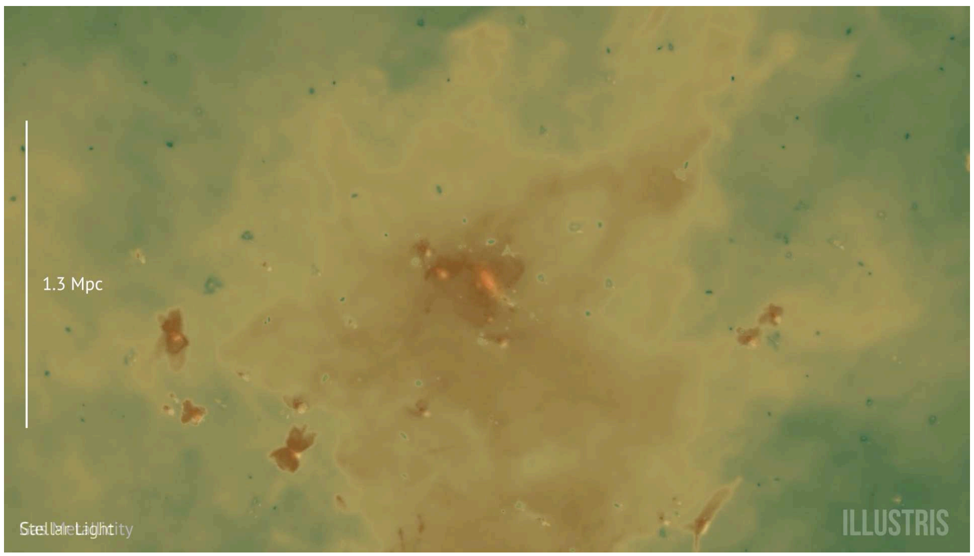
The APOSTLE (Sawala et al. 2015)
Code = Gadget;
zoom-in cosmological technique
EAGLE model, i.e. DM+STARS+GAS+BHs
12 MW+M31 systems



2014 onwards: the advent of large cosmological volumes for galaxy physics

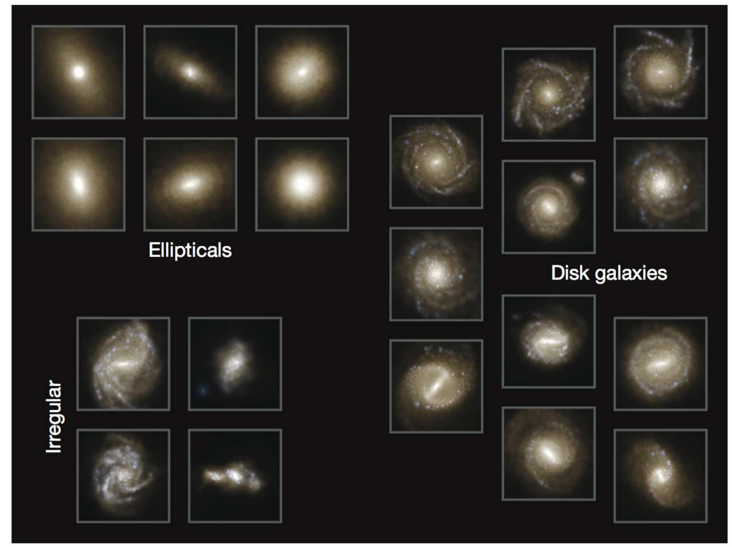
In 2014, Illustris was one of the first large cosmological volume simulation that followed the co-evolution of thousands of galaxies and was capable of reproducing the observed diversity of galaxies

AREPO Code
106.5 Mpc Cosmological Box
Halo Mass Range: < 2×10^{14} Msun; Res: ~ kpc, ~ 10^6 Msun



Credits: Dylan Nelson

Vogelsberger et al. 2014a,b, Genel et al. 2014, Sijiacki et al. 2015



Credits: Paul Torrey

Illustris, Eagle, Horizon-AGN, Massive-Black, Magneticum, Mufasa,

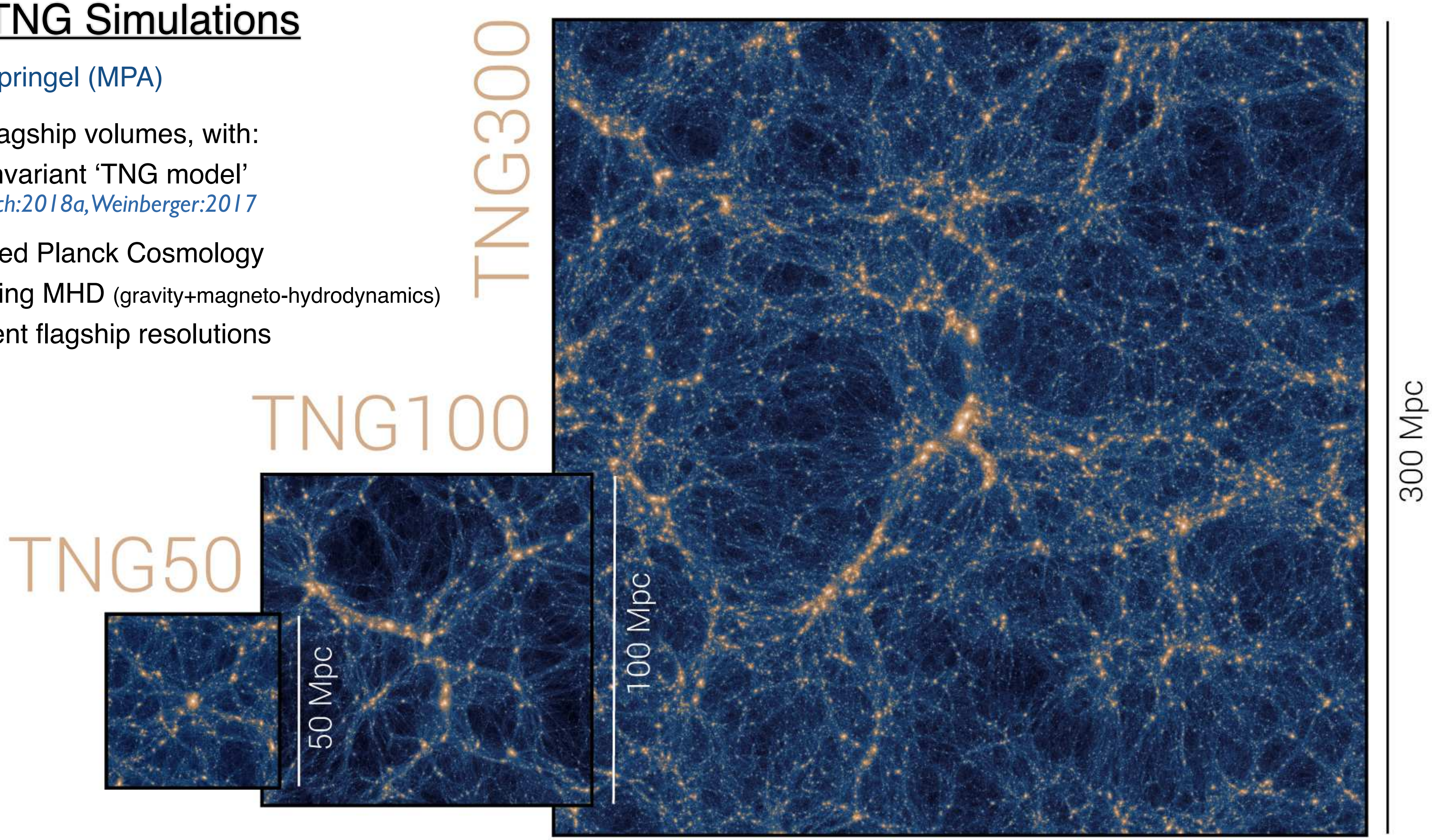
A few tens - 100 Mpc boxes
~1 kpc resolution
Tens of housands of well resolved galaxies,
including ~1e3 MW-mass central galaxies

The TNG Simulations

PI: V. Springel (MPA)

Three flagship volumes, with:

- new invariant 'TNG model'
  Pillepich:2018a,Weinberger:2017
- Updated Planck Cosmology
- Including MHD (gravity+magneto-hydrodynamics)
- Different flagship resolutions



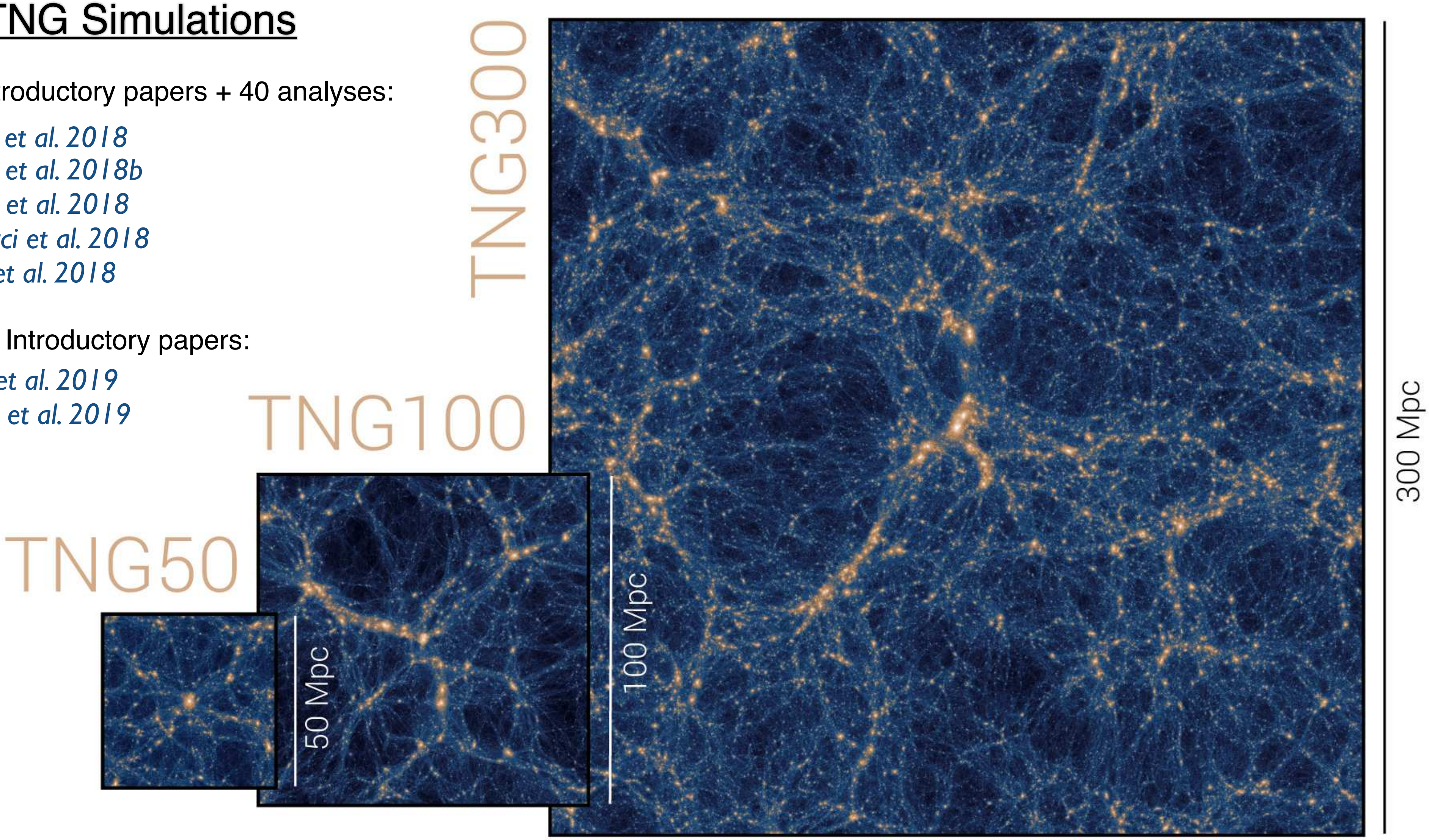
The TNG Simulations

TNG Introductory papers + 40 analyses:

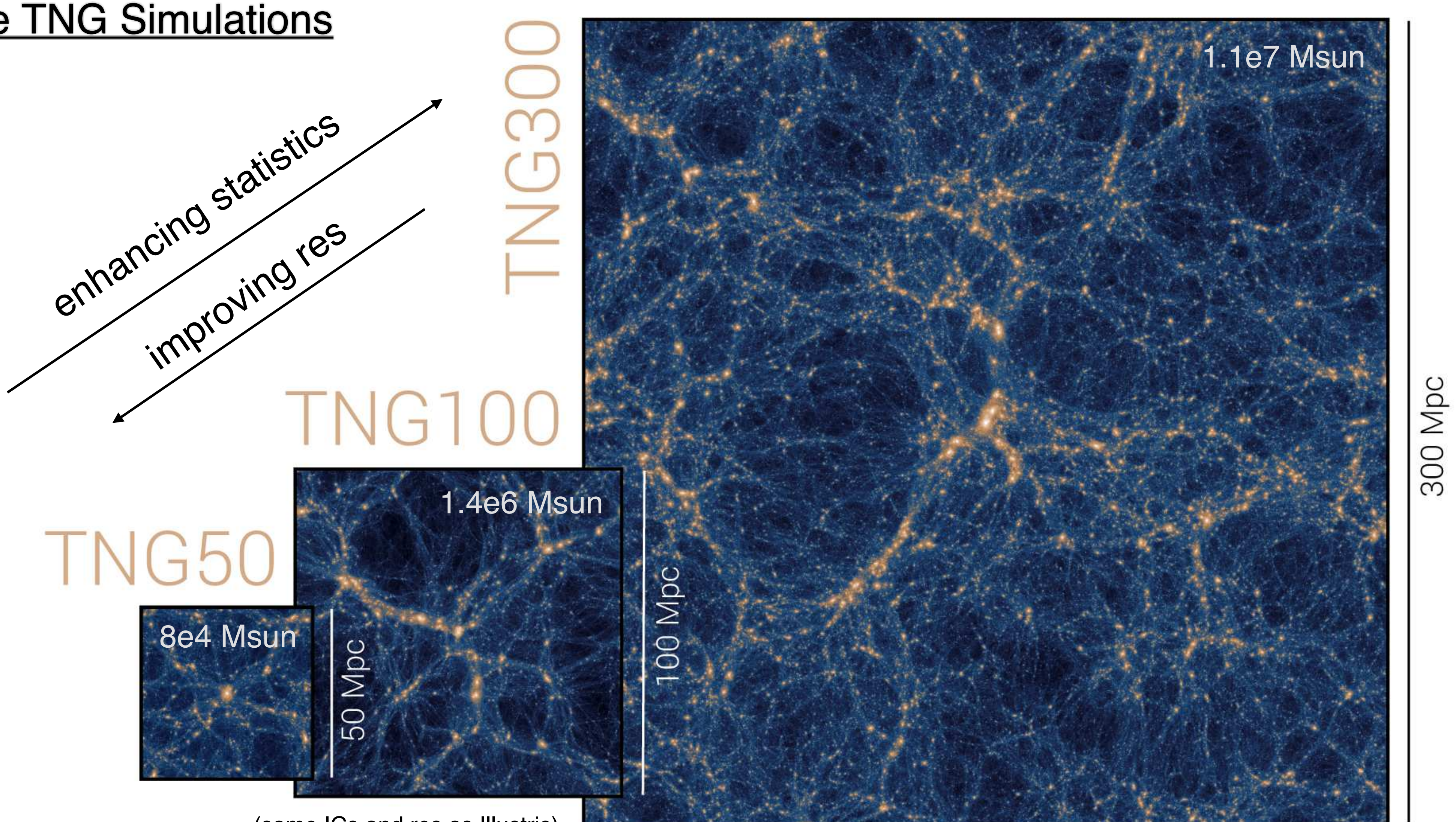
Springel et al. 2018
Pillepich et al. 2018b
Naiman et al. 2018
Marinacci et al. 2018
Nelson et al. 2018

TNG50 Introductory papers:

Nelson et al. 2019
Pillepich et al. 2019

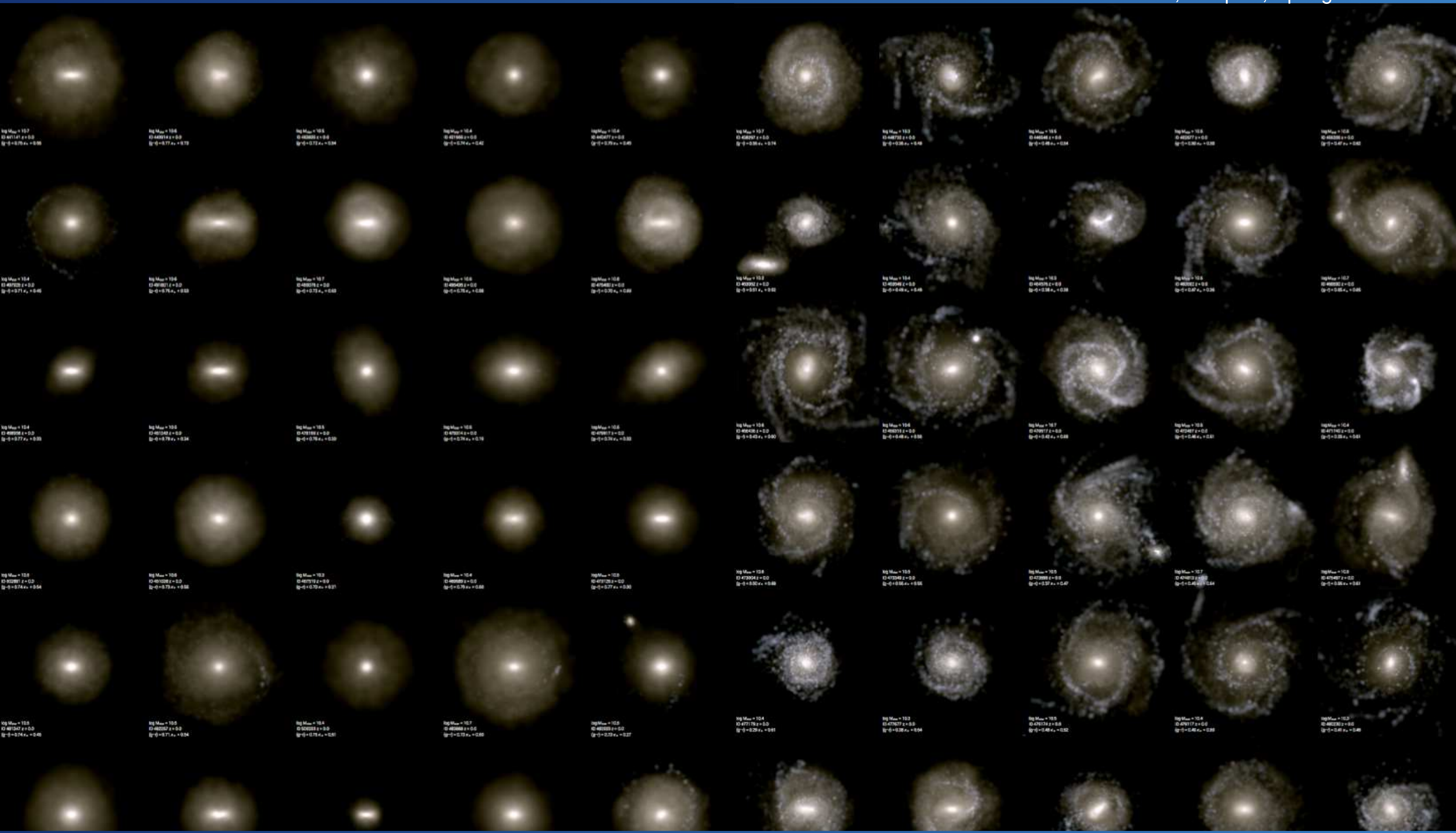


The TNG Simulations



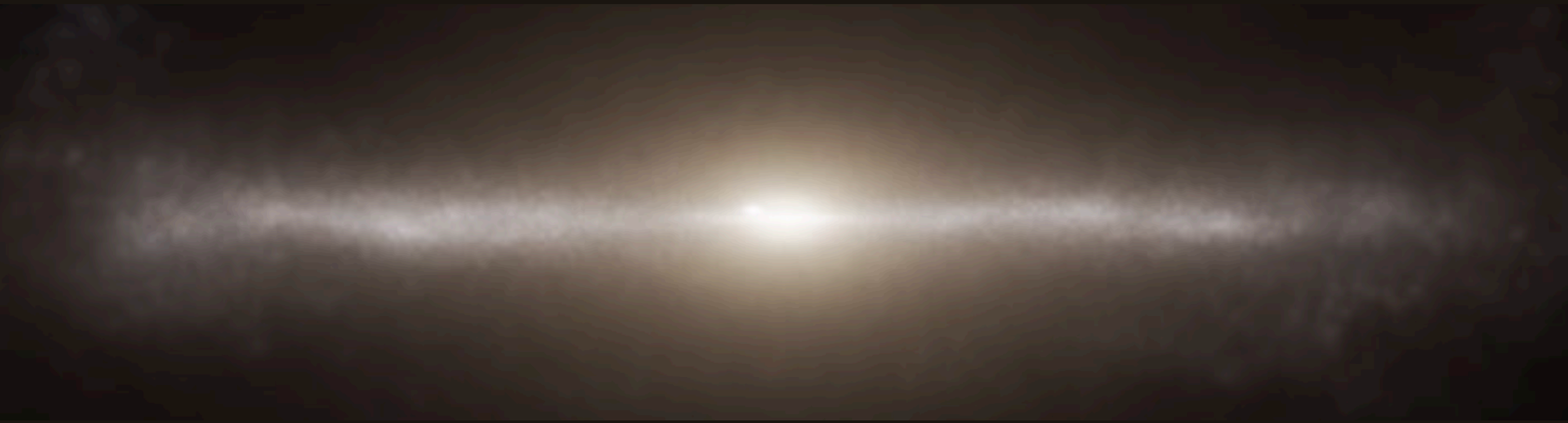
(same ICs and res as Illustris)

TNG100: Nelson, Pillepich, Springel et al. 2018



TNG50

z=1
log M★ = 11.3



[jwst f200w, f115w, f070w]

The TNG model: The physical ingredients behind large-volume simulations

Non-linear gravitational collapse, galaxy mergers and galaxy interactions, hierarchical growth of structure, cosmological gas accretion (i.e. accretion rates), shocks, tidal and ram pressure stripping, dynamical friction, any form of gravitational "heating" are all self-consistent and emerging features

↑

COSMOLOGICAL ICs (LCDM)
GRAVITY+(MAGNETO)HYDRODYNAMICS

(TNG: collisional excitation, collisional ionization, recombination, free–free emission + UV background + metal line cooling)

Gas Cooling/Heating ◣

■ Conversion of gas into stars (TNG: density threshold)

Stellar Evolution ◣

Metal Enrichment (TNG: SNIa, SNII, AGB: H, He, Fe, C, Mg, …) ◣

■ Stellar Feedback (TNG: decoupled winds)

■ Black Hole Seed and Growth → gas outflows and recycling

■ Black Hole Feedback (TNG: high vs. low accret)

■ Subgrid recipes

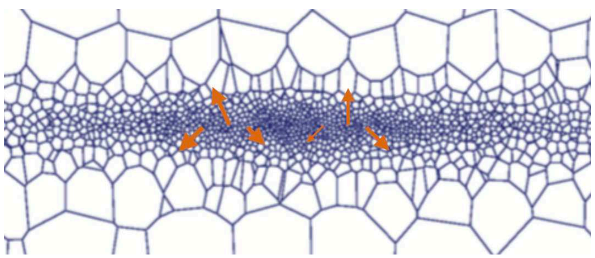
◣ Via "tables"

What sets apart the TNG model from previous calculations of similar scope

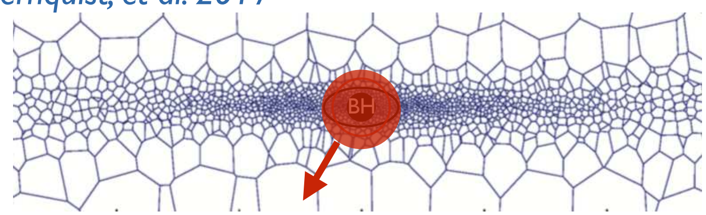
0. The moving-mesh code AREPO
Springel 2010

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



5. The augmented and unprecedented scope

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

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

Zoom-in runs vs. Cosmological volumes

Zoom-In simulations

Typically i.e. so far, very good numerical resolution
(state of the art: 100pc, 1e4-5Msun)

Typically, i.e. so far, more sophisticated and realistic galaxy physics models

Limited sampling: N_gal = 1-50

Biased Selections

Interpretation/model degeneracy:
Realization or physical ingredients?

Uniform-volume simulations

Typically i.e. so far, poorer numerical resolution
(state of the art: 700pc, 1e6Msun)

Typically, i.e. so far, coarser galaxy physics models (esp. treatment of the ISM)

Very good sampling: N_gal = 10k-100k

No Biased Galaxy Distributions, i.e. the "right" mass distribution and encompassing all possible assembly histories and environments

TNG50: bridging the gap between zoom-ins and large volumes

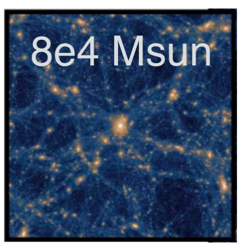
Co-PIs: A. Pillepich (MPIA), D. Nelson (MPA)

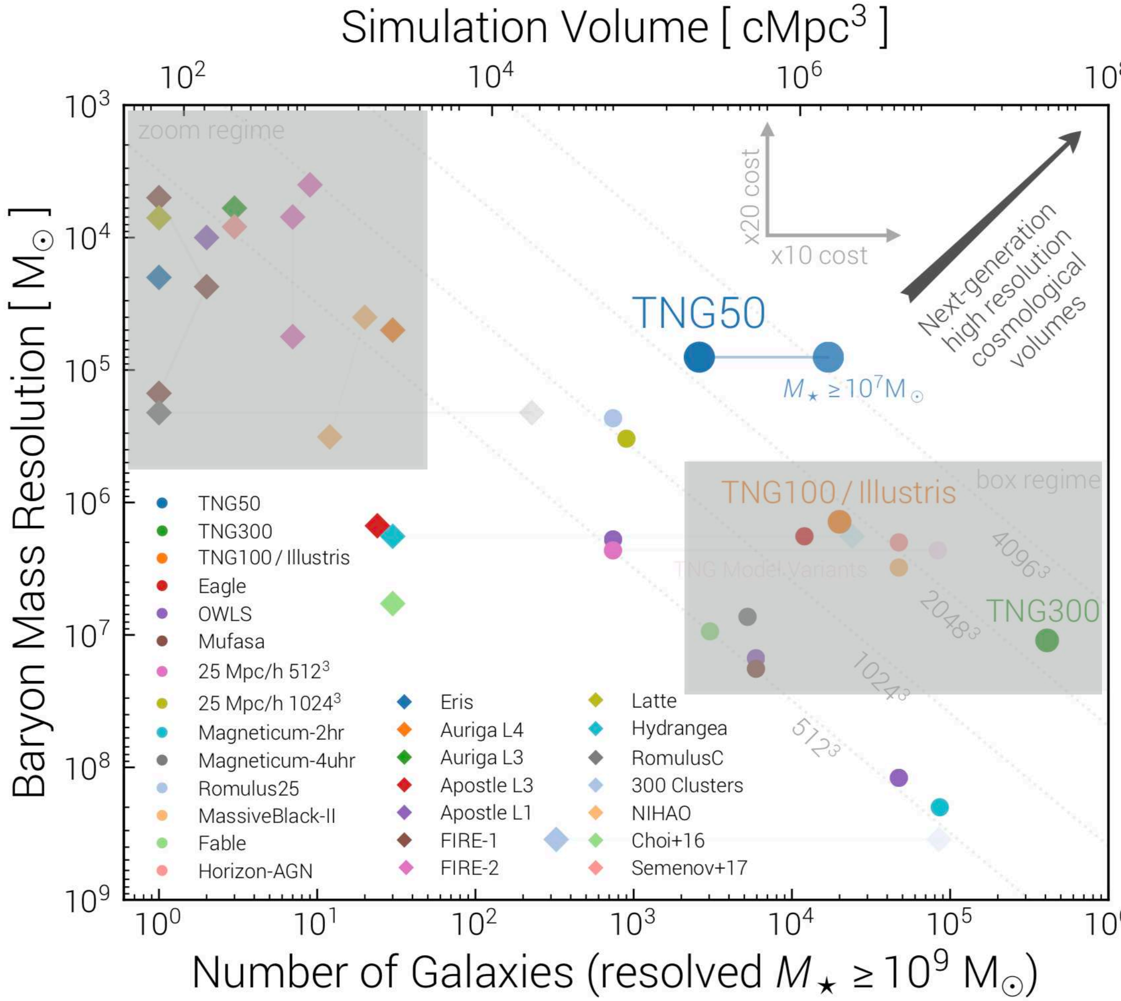
TNG50: Pillepich, Nelson et al. 2019
TNG50: Nelson, Pillepich et al. 2019

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

TNG50

Cosmological volume at zoom resolution



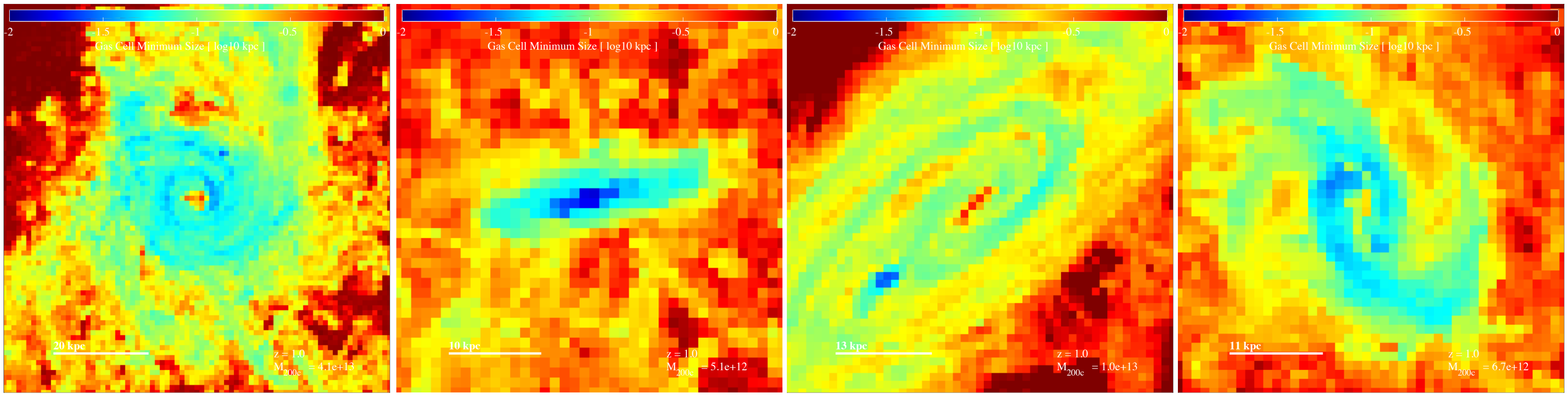


TNG50: Nelson, Pillepich et al. 2019

TNG50: bridging the gap between zoom-ins and large volumes

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

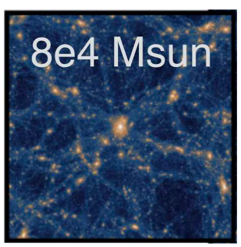
10 com pc ——spatial resolution—— 100 com pc ——spatial resolution—— 1 com kpc



TNG50: Nelson, Pillepich et al. 2019

TNG50

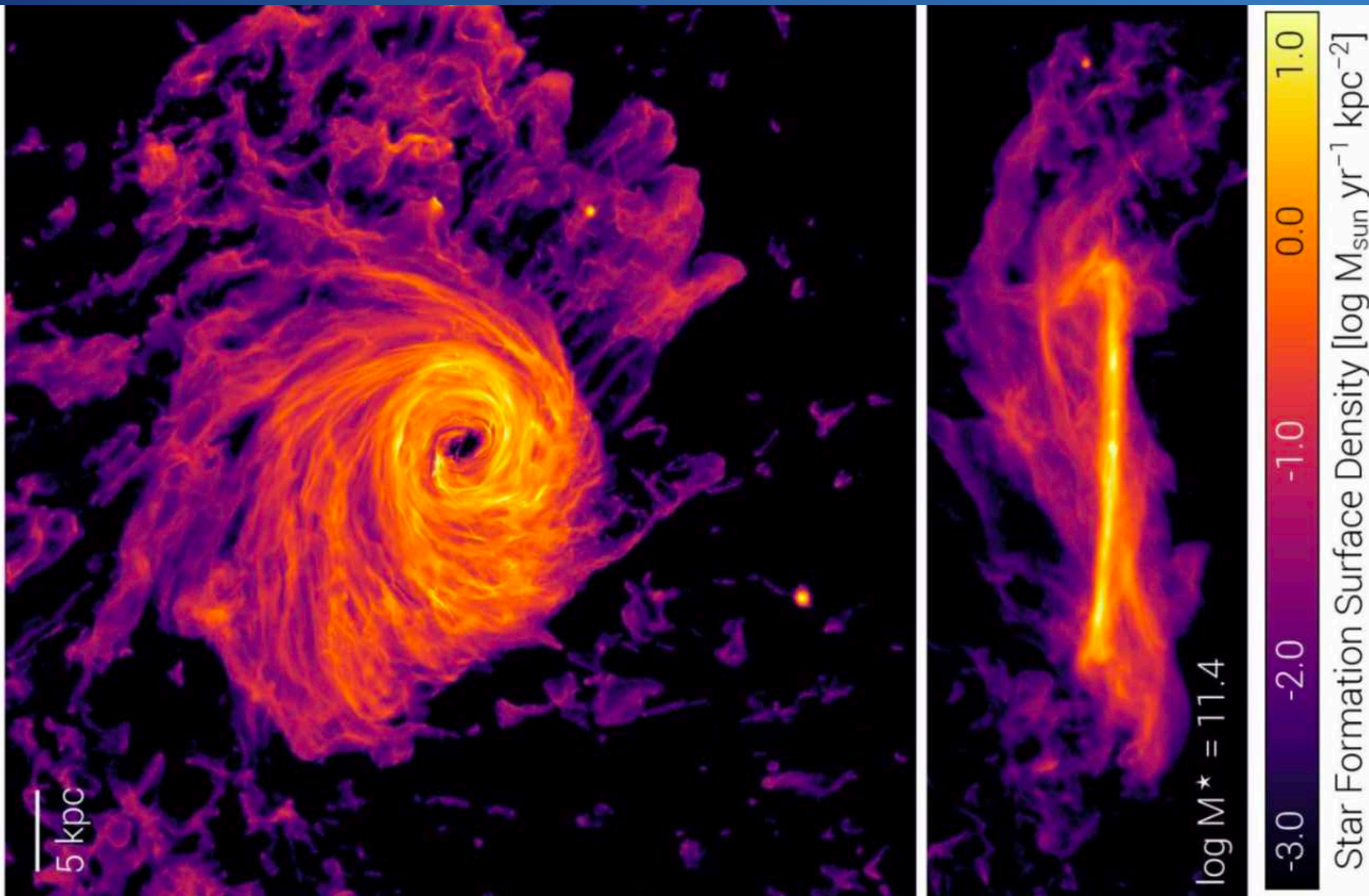
Cosmological volume at zoom resolution

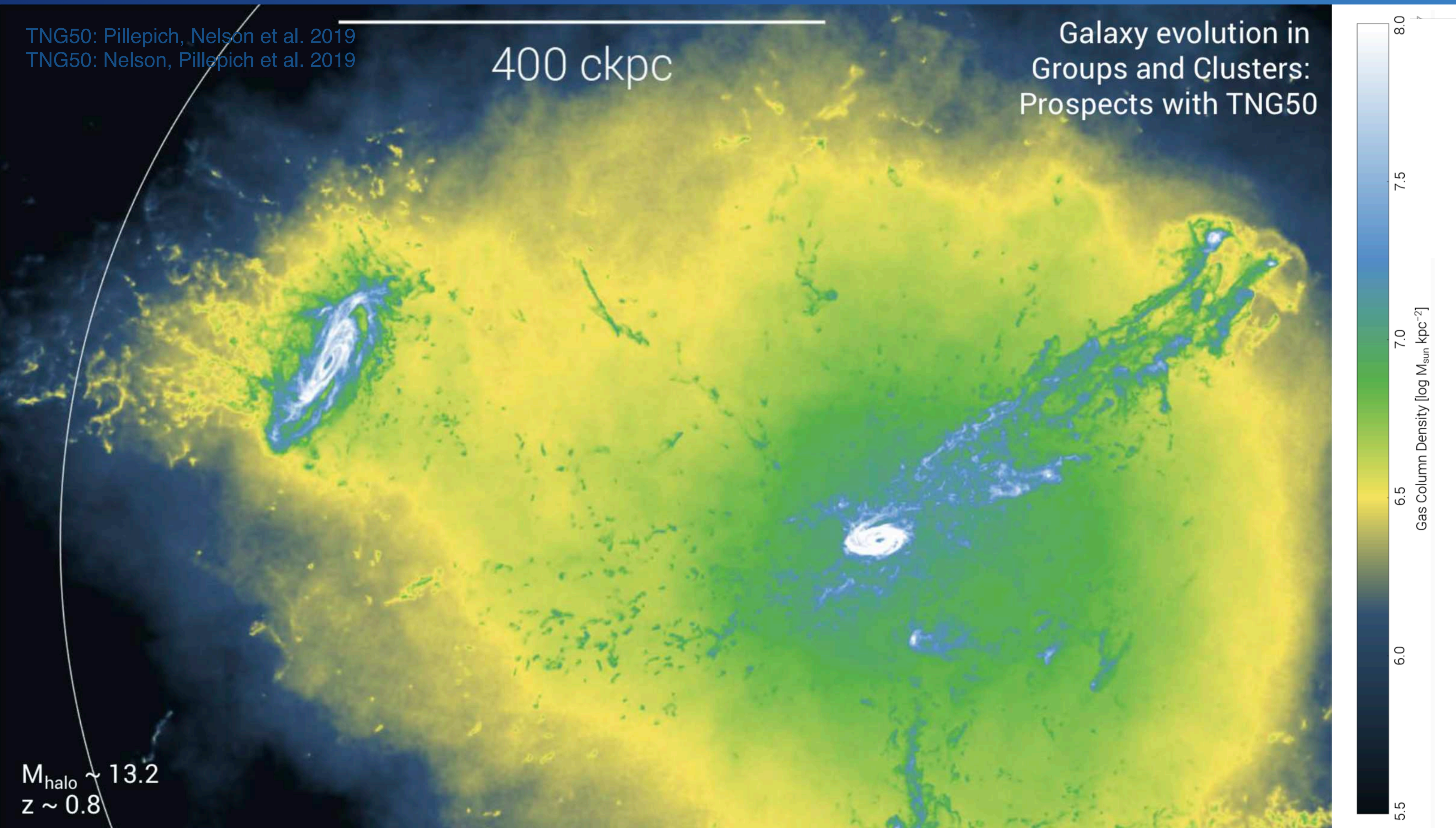


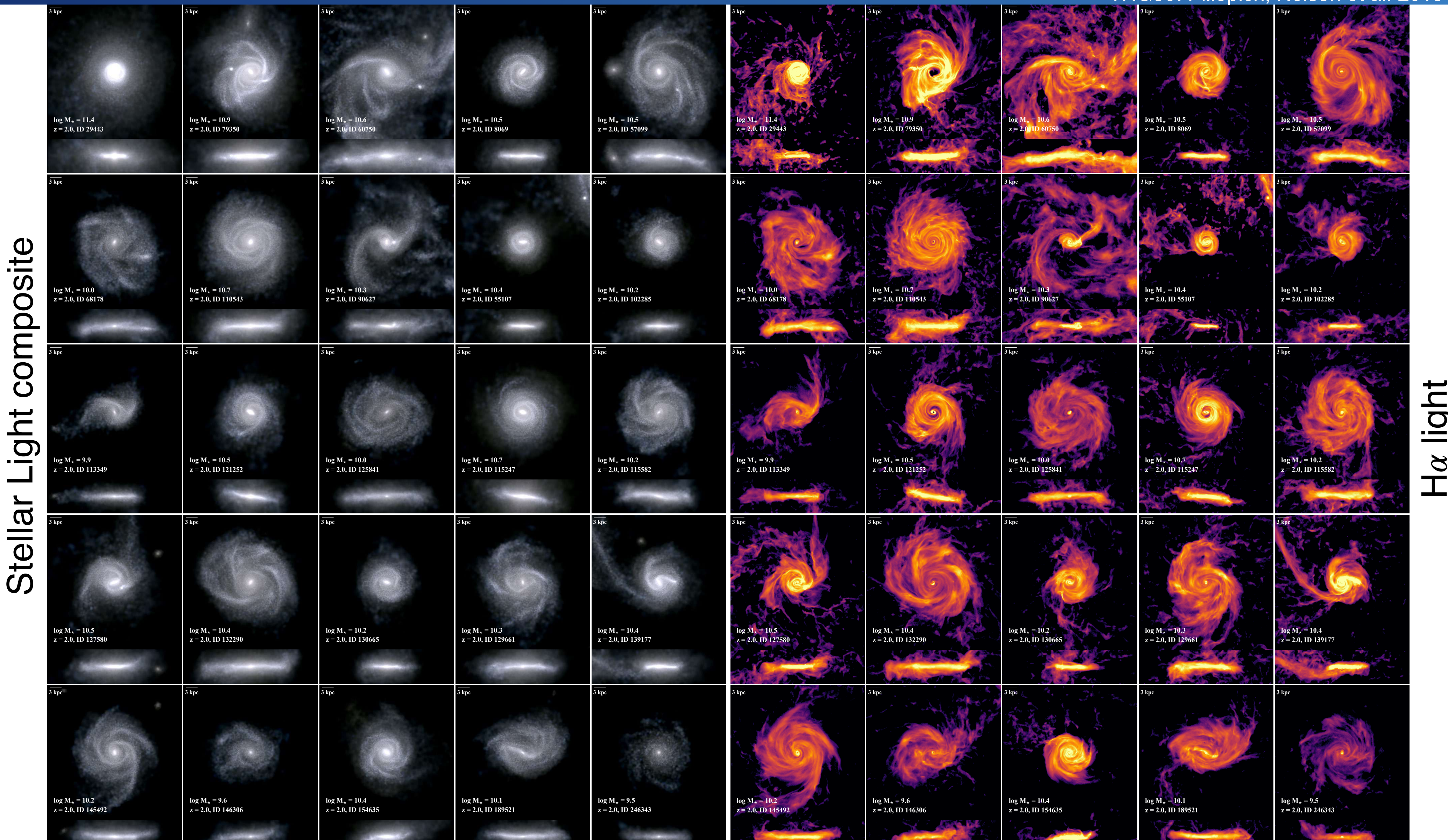
Star-formation and (stellar) feedback are sub grid below the 70-140pc scale

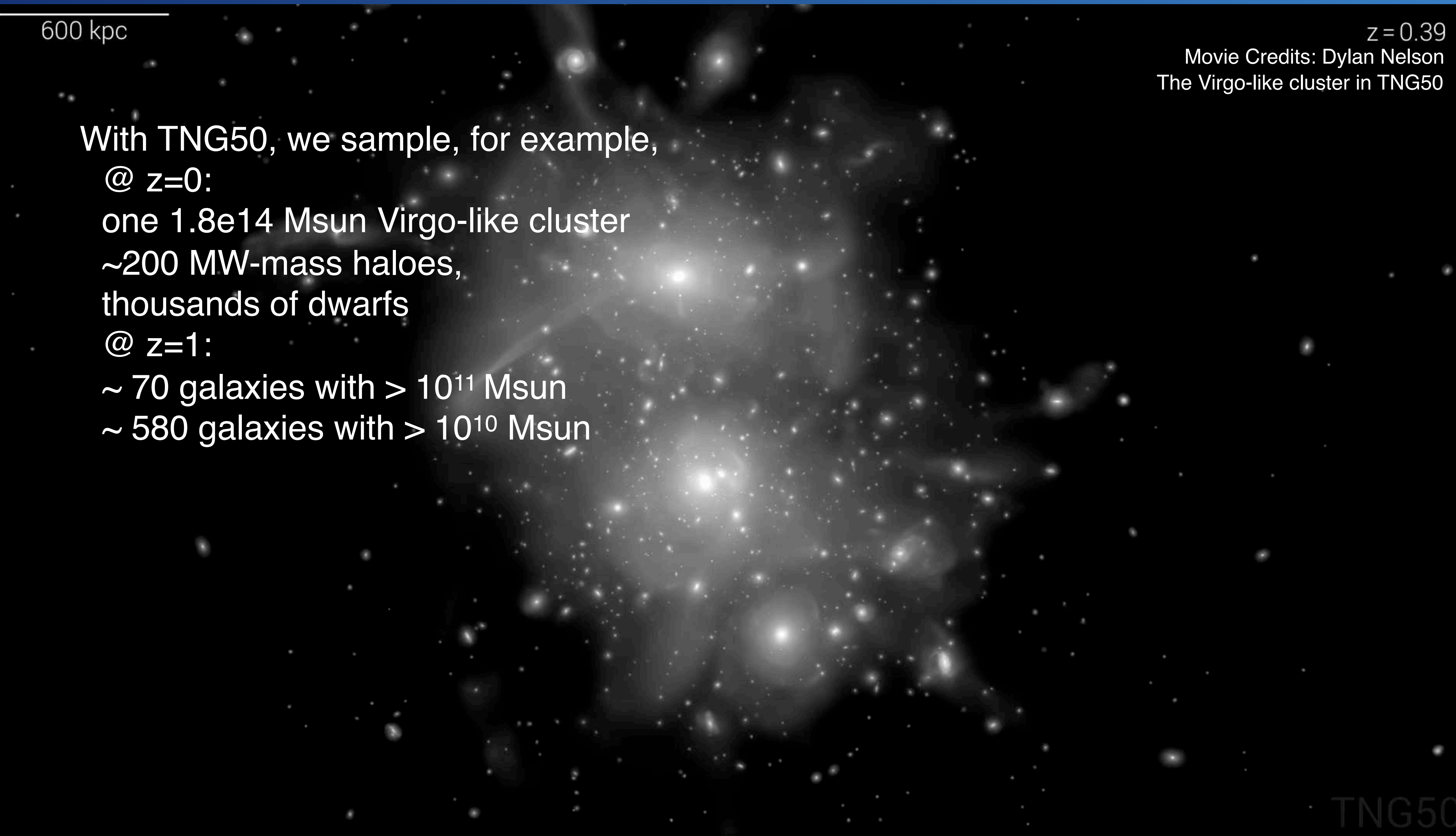
TNG50: Pillepich, Nelson et al. 2019
TNG50: Nelson, Pillepich et al. 2019

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




TNG50: Pillepich, Nelson et al. 2019
TNG50: Nelson, Pillepich et al. 2019
400 ckpc
Galaxy evolution in
Groups and Clusters:
Prospects with TNG50
M_{halo} ~ 13.2
z ~ 0.8
8.0
7.5
7.0
6.5
6.0
5.5
Gas Column Density [log M_{sun} kpc^{-2}]


Stellar Light composite
Hα light



With TNG50, we sample, for example,

@ z=0:

one 1.8e14 Msun Virgo-like cluster

~200 MW-mass haloes,

thousands of dwarfs

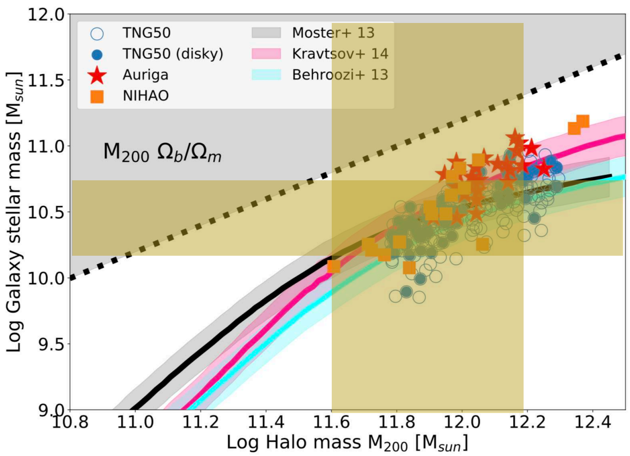
@ z=1:

~ 70 galaxies with > 10^{11} Msun

~ 580 galaxies with > 10^{10} Msun

How good do these MW analogues need to be?

Simulating L* galaxies vs. simulating *the* Milky Way



TNG50: Donnari, Pillepich et al. in prep

The relevant/possible/typically-adopted properties to define “analogues”:

- Halo/Stellar Mass in the 1e12/5e10 Msun range
- Disk Morphology
- Quiet recent merger history

(imposed in some zoom-in projects)

Milky Way VS Andromeda

- Bulge/Disk ratio?
- Thin vs. Thick morphological disks?
- Alpha-enhanced vs. Alpha-low disks?
- With the LMC and SMC?
- With a Sagittarius-like stream?
- With the Galaxy satellite luminosity function?
- Does it have a bar?
- ?

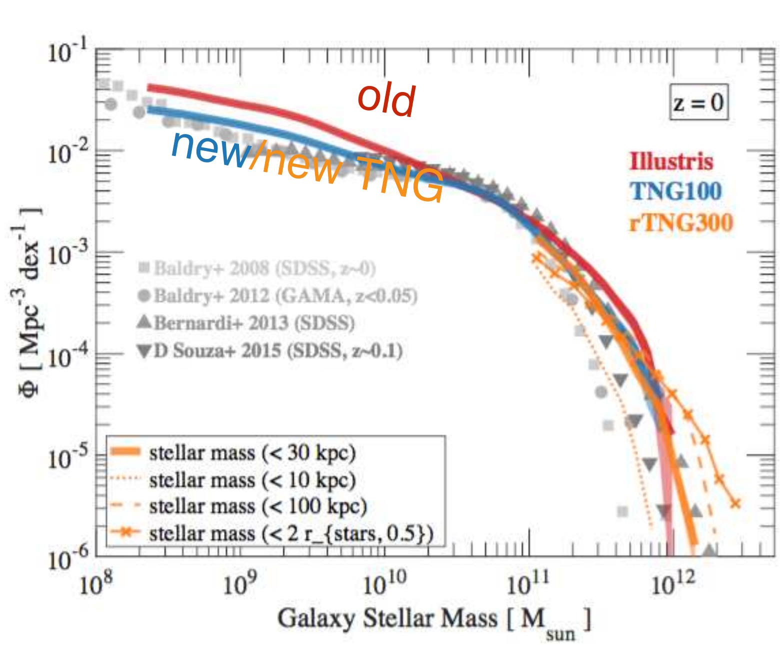
Constrained simulations?

The approach within large-volume cosmological simulations i.e. TNG

We develop models for the formation+evolution of galaxies that:

a. Function across masses, spatial scales, evolutionary stages and environments
b. Return the observed statistical properties of the ***galaxy populations***
c. Reproduce the ***structural, internal properties*** of individual galaxies

Against the most diverse sets of observational data and samples



Pillepich, Nelson, Hernquist, et al. 2018b

We search a posteriori for disk-like galaxies in ~10^12 Msun haloes among the many hundreds/thousands and:

a. See whether a "perfect" MW analog is returned and why (or why not)
b. Provide physical understanding, quantitative benchmarks, or insights for the formation of L* galaxies in general and thus of the Milky Way

What can we learn from such cosmological experiments?

Discussion Points

Choose your talk!
What topic?

1. On the diversity of galaxy disks at a given mass scale
2. On the interplay between baryons and dark matter
3. On the signatures of the hierarchical growth
4. On chemical enrichment
5. On the flaring of disks
6. On the “(un)settling” of the disks

On the diversity of galaxies at a given mass scale

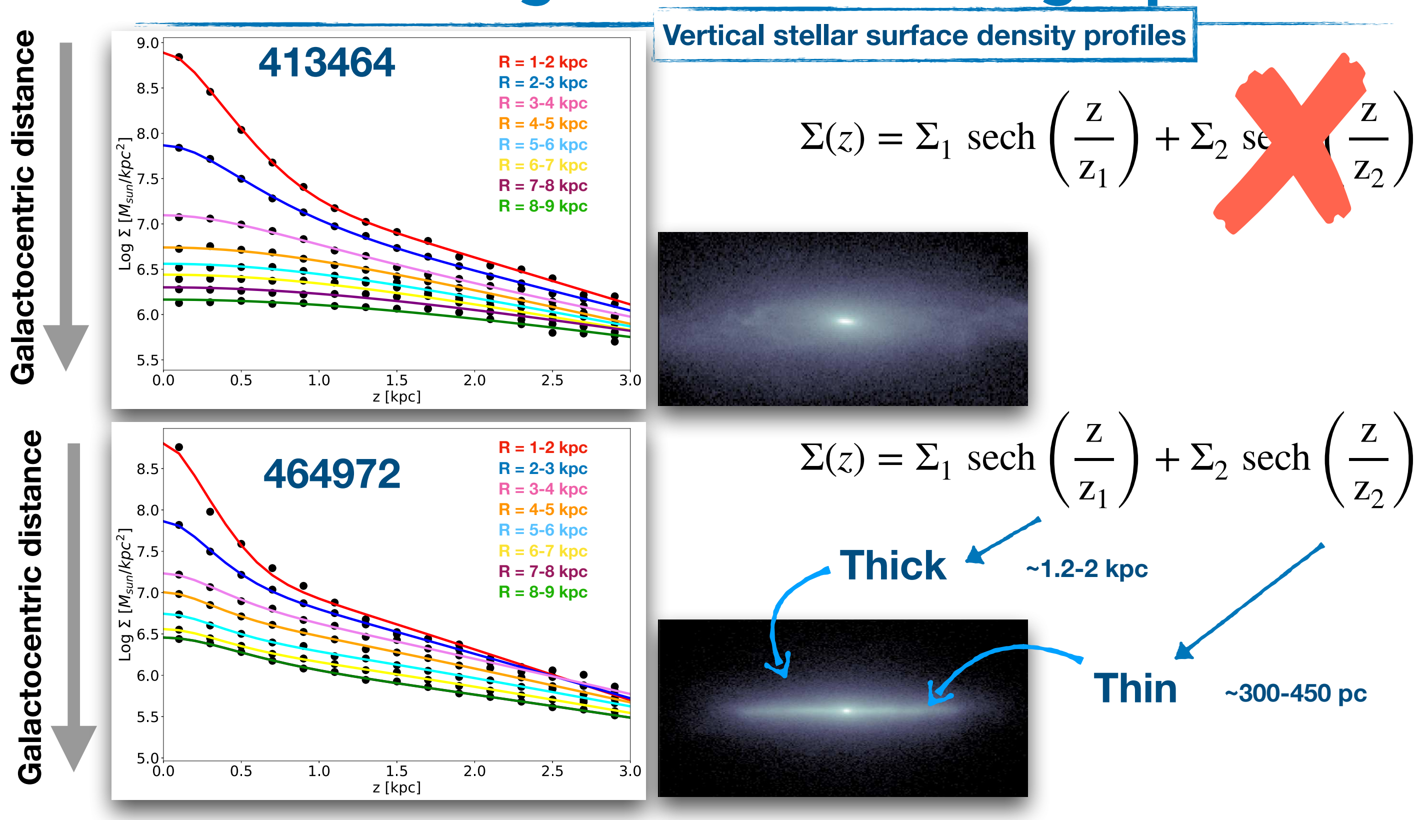
TNG50: Donnari, Pillepich et al. in prep

TNG50: Disk structures can be diverse, at fixed galaxy physics model

At the MW-mass scale, only a fraction of galaxies exhibit disk-like morphologies (of stellar mass or light).

Not all disk galaxies exhibit two morphological disk components (thin+thick) at ~8kpc.

Disk scale heights: double or single profiles?



Slides Credit: M. Donnari

TNG50: Disk structures can be diverse

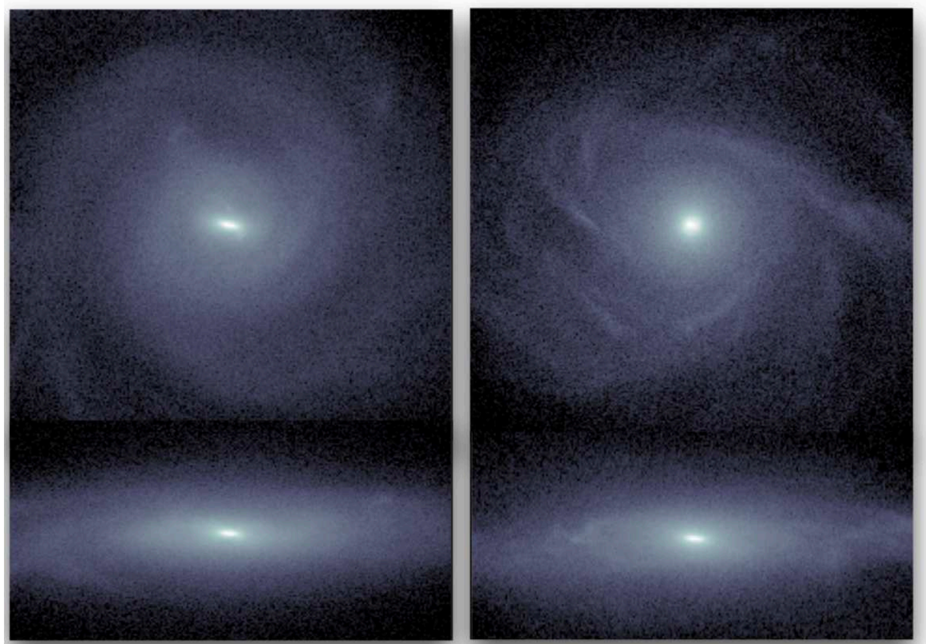
TNG50: Donnari, Pillepich et al. in prep

At the MW-mass scale, only a fraction of galaxies exhibit disk-like morphologies (of stellar mass or light).

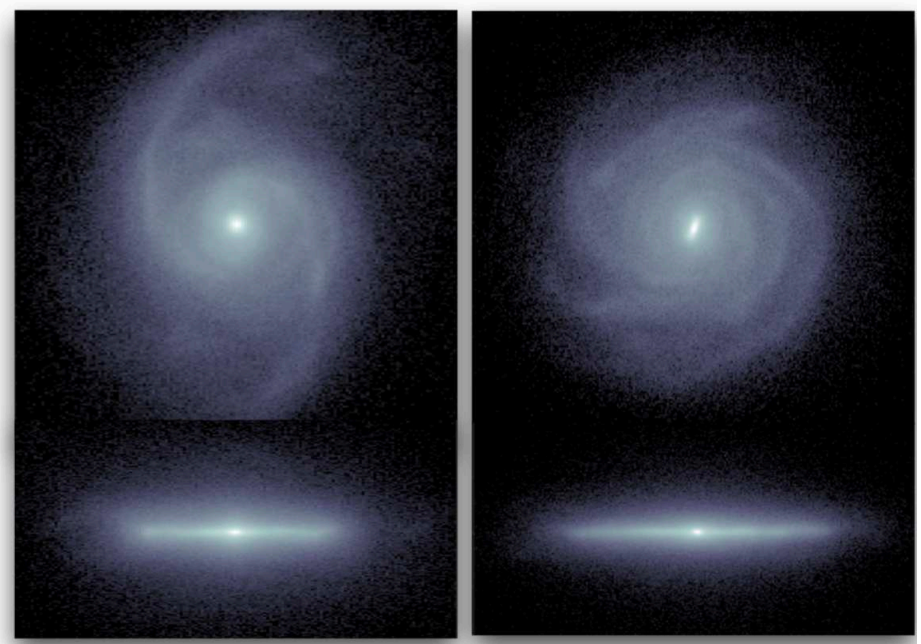
Not all disk galaxies exhibit two morphological disk components (thin+thick) at ~8kpc.

It depends on galaxy to galaxy!

Single disk component



Double disk components: thin and thick

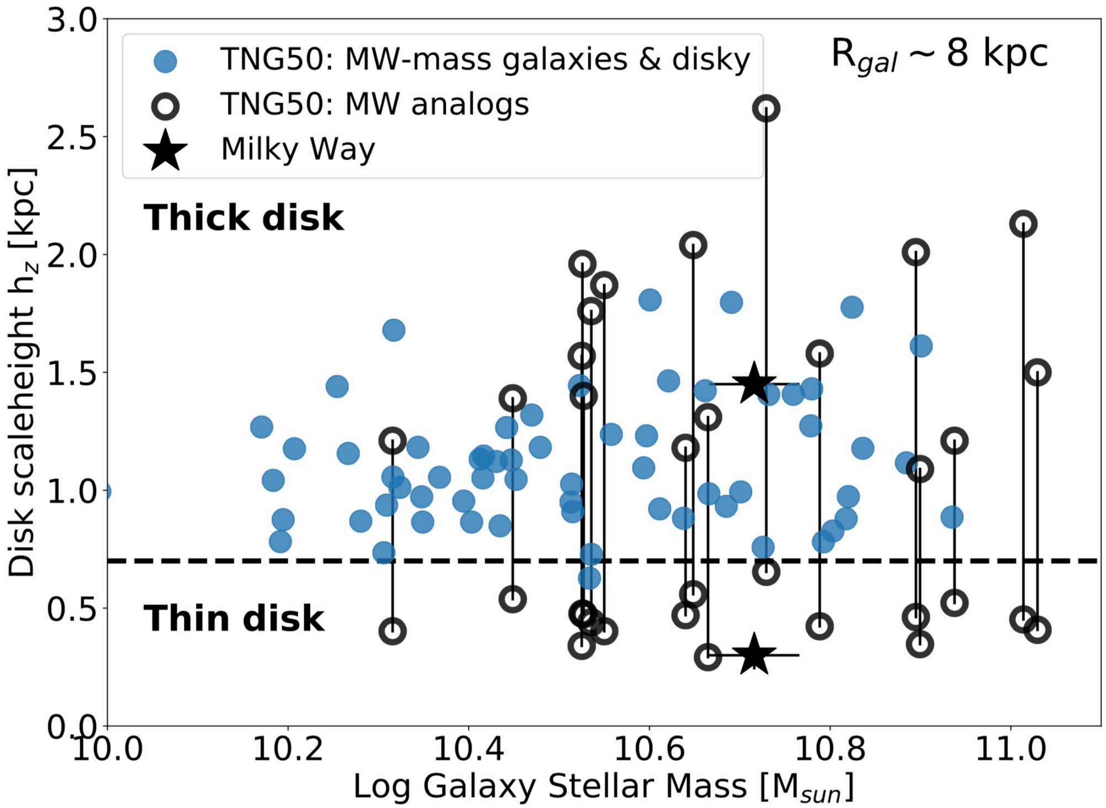


Slides Credit: M. Donnari

TNG50: Disk structures can be diverse

At the MW-mass scale, only a fraction of galaxies exhibit disk-like morphologies (of stellar mass or light).

Not all disk galaxies exhibit two *morphological* disk components (thin+thick) at ~8kpc.



Note: with TNG50 we can resolve disk heights down to ~300 pc

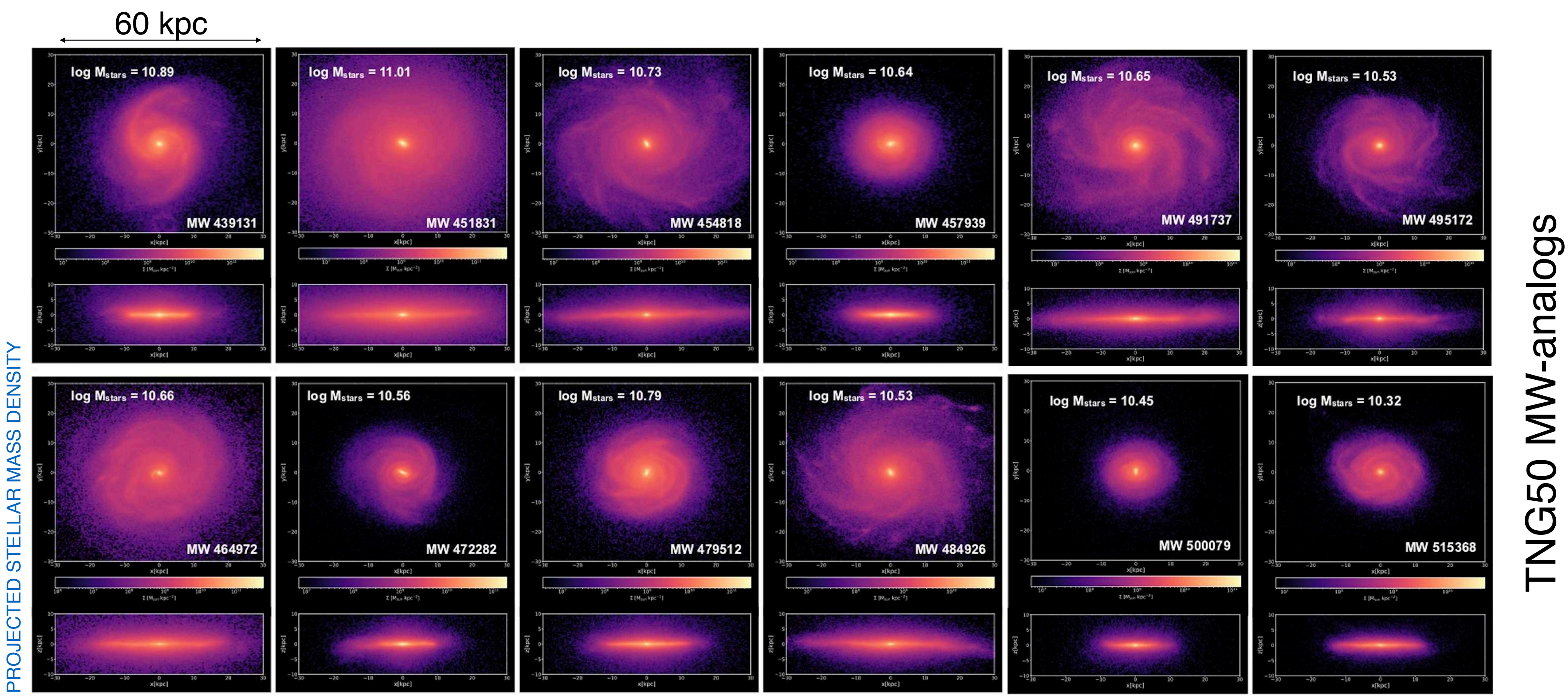
TNG50: Donnari, Pillepich et al. in prep

TNG50: Disk structures can be diverse

TNG50: Donnari, Pillepich et al. in prep

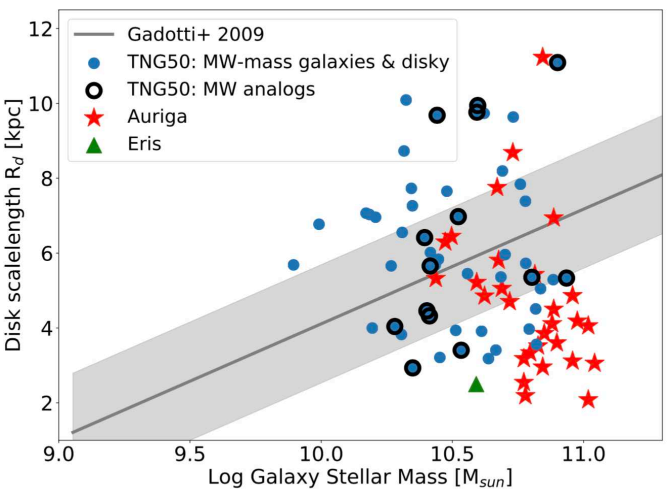
At the MW-mass scale, only a fraction of galaxies exhibit disk-like morphologies (of stellar mass or light).

Not all disk galaxies exhibit two morphological disk components (thin+thick) at ~8kpc.

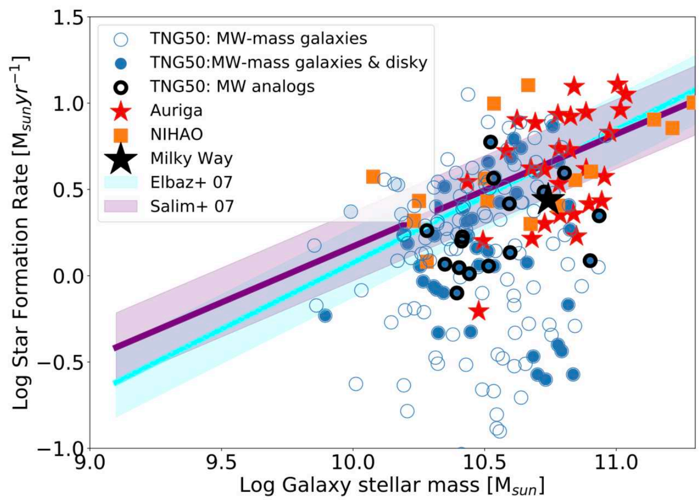


TNG(50): The general properties of L* galaxies can span large ranges

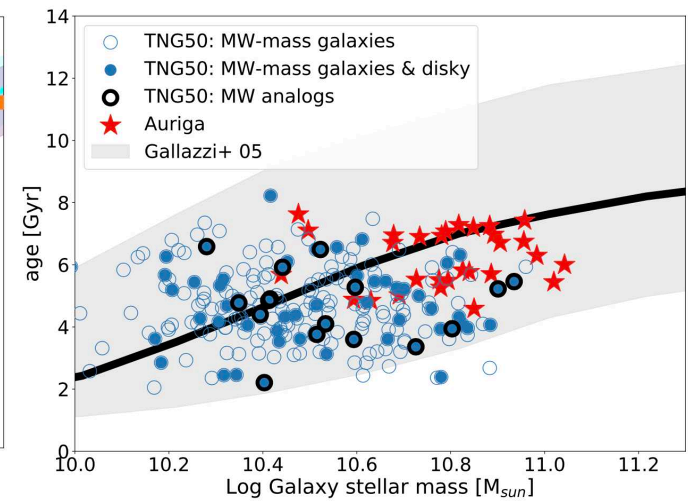
Disk scale lengths



Star Formation Rates



Stellar Ages

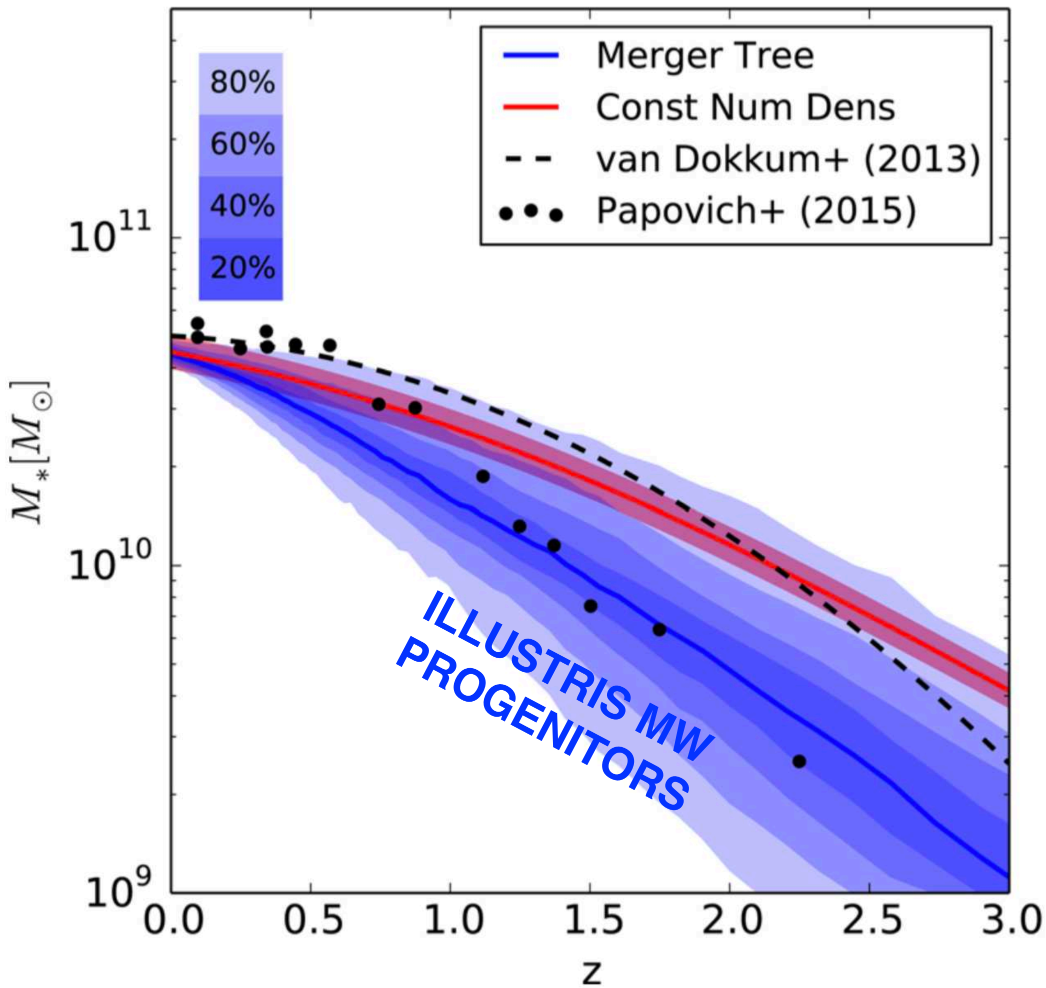


Within 0.3dex in stellar mass,

- Disk scale lengths can vary by a factor of 3
- SFRs can vary by more than an order of magnitude
- Mass-Weighted averaged stellar ages can vary by 3-4 Gyrs

TNG50: Donnari, Pillepich et al. in prep

Illustris: The stellar mass assembly histories of MW-mass galaxies can vary…



… a lot!

at z~2, MW-progenitors can span anything between 10e9 and 2e10 Msun

Disclaimer: here, no selection in morphology nor SFR is applied.

ILLUSTRIS: Torrey et al. incl. AP 2015

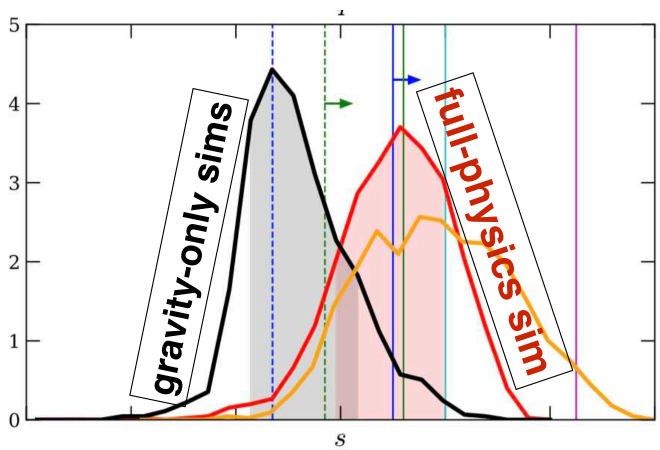
On the interplay between baryons and DM

Illustris: Baryonic physics “alters” the shapes of the underlying DM haloes

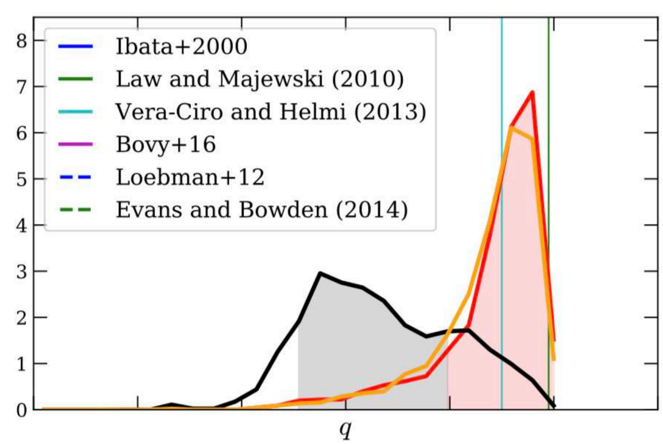
Case: many MW-like objects (10^12Msun and risky) from the ILLUSTRIS simulation

Distributions of shape parameters at 0.15Rvir for MW analogs:

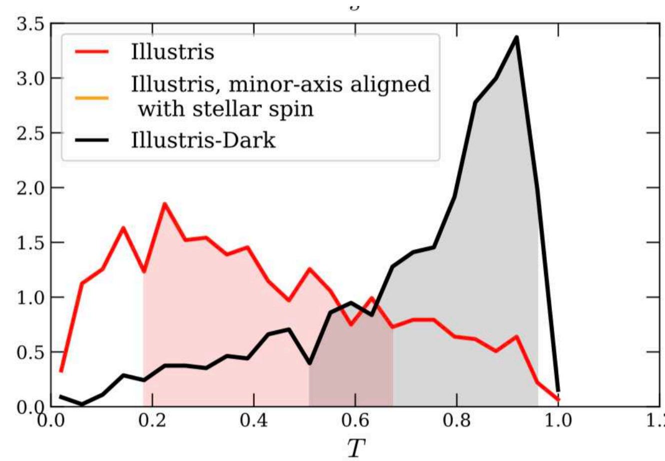
Minor-to-major axis ratios



Middle-to-major axis ratios



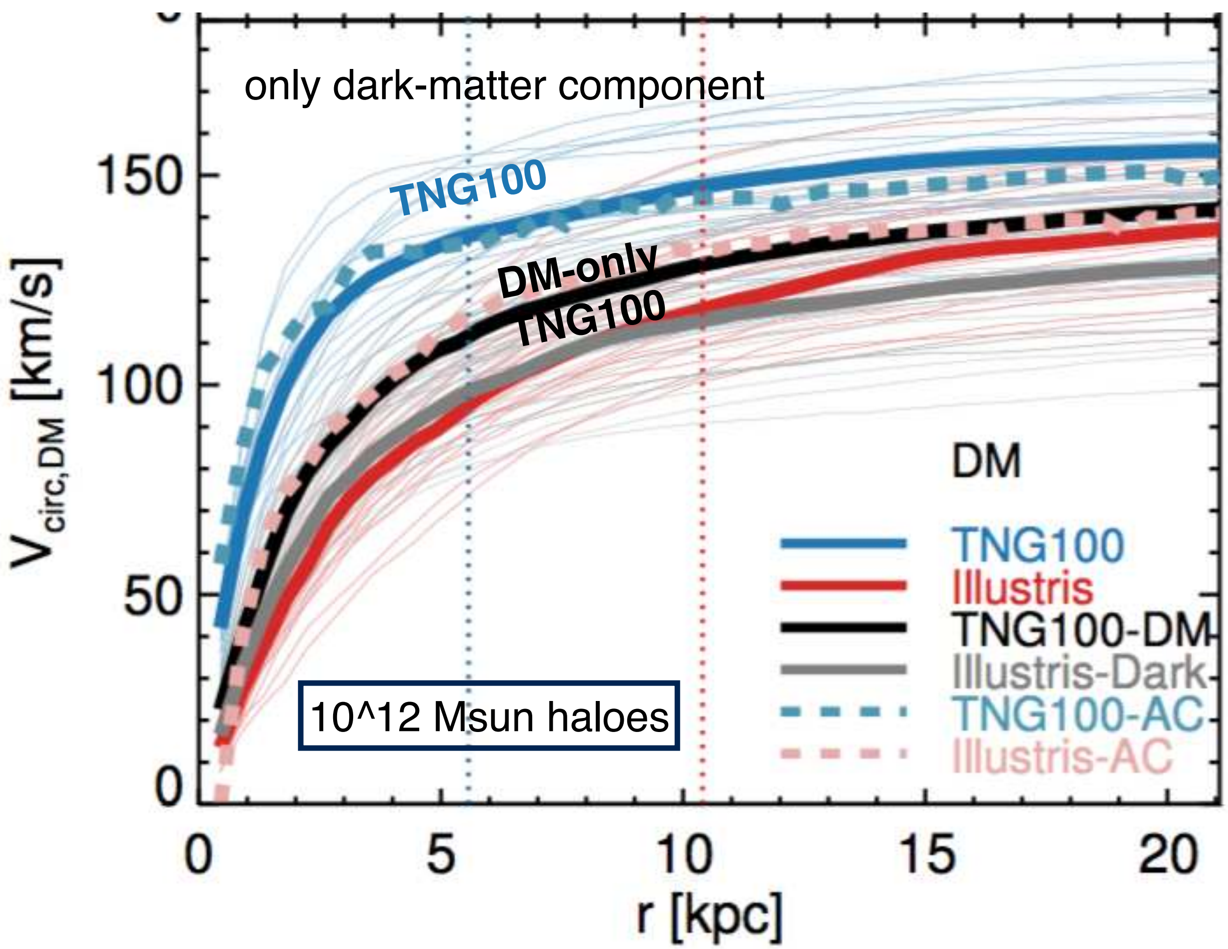
Triaxiality



With the full galaxy-physics implementation, baryons result in significantly rounder and more oblate haloes

ILLUSTRIS: Chua, Pillepich et al. 2019

Illustris/TNG: Baryonic physics "alters" the DM profiles



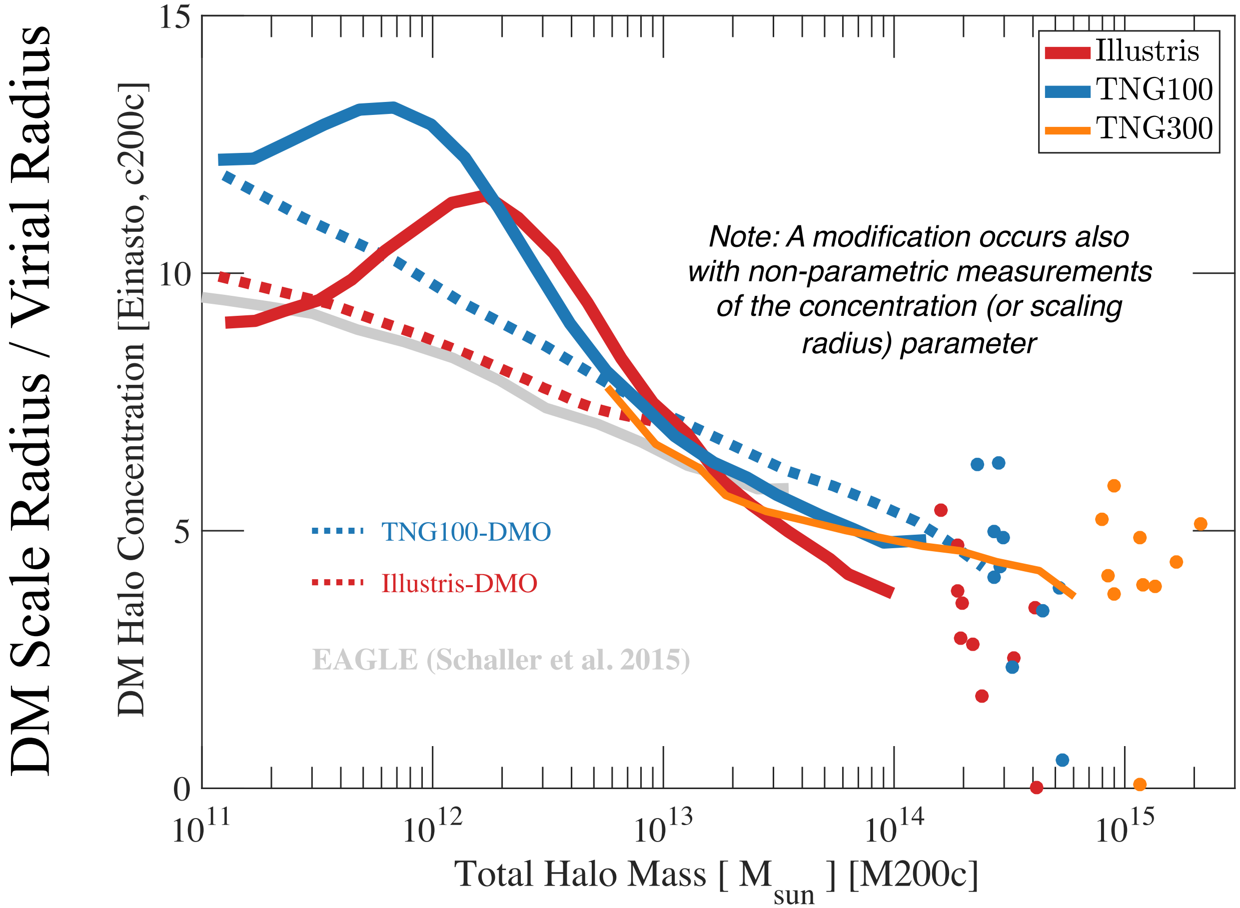
TNG MW-galaxies have enhanced DM mass within their central regions

Blue vs. Black =>
DM enhancement

In TNG, the DM contraction can be modelled with a Blumenthal-like adiabatic contraction (dashed blues)

TNG100: Lovell, Pillepich et al. in 2018

Illustris/TNG: Baryonic physics “alters” the DM concentration-mass relation



We have known since many years that more massive haloes are less concentrated than low mass ones

Baryonic physics affects the distribution of dark matter within haloes

In both Illustris and TNG, the DM concentration-mass relation gets modified by baryonic physics, in a not-monotonic way wrt DMO predictions.

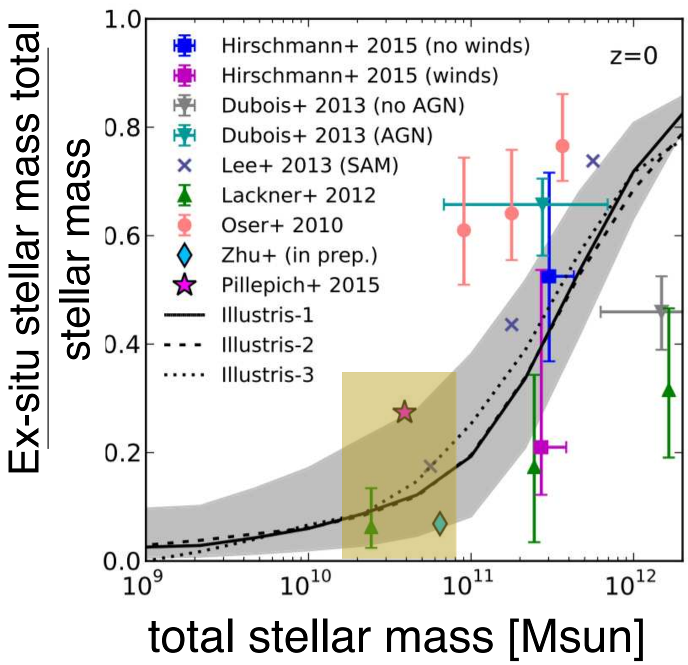
Yet, the effects of galaxy physics can be qualitatively and quantitatively different from model to model

[TNG50/100/300: Pillepich: preliminary]

sLovell, Pillepich et al. in 2018, Chua, Pillepich et al. 2017

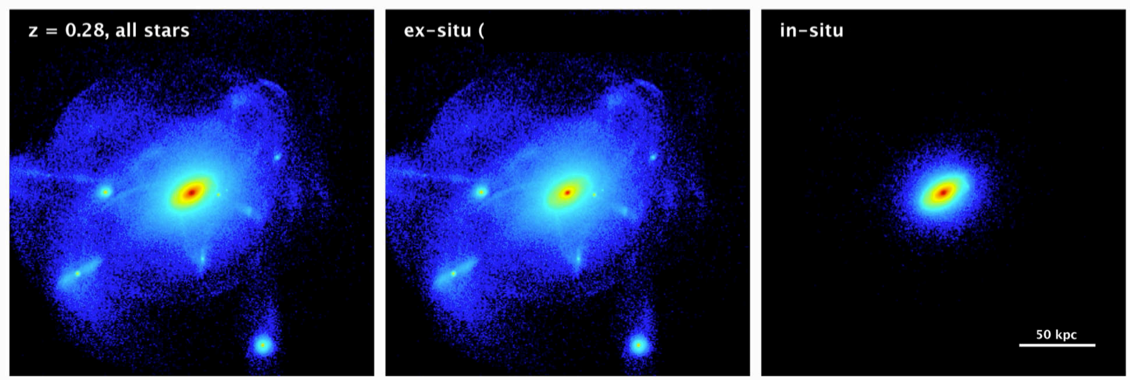
On the signatures of the hierarchical growth

Galaxies assemble their stars also via merging and tidal stripping, not just SF



Eris: Pillepich, Madau & Mayer 2015
Illustris: Rodriguez-Gomez, Pillepich, et al. 2016
TNG100/TNG300: Pillepich et al. 2018b

Pillepich, Madau, Mayer 2015: Evolution of Eris, a MW-like galaxy, in stellar density projection

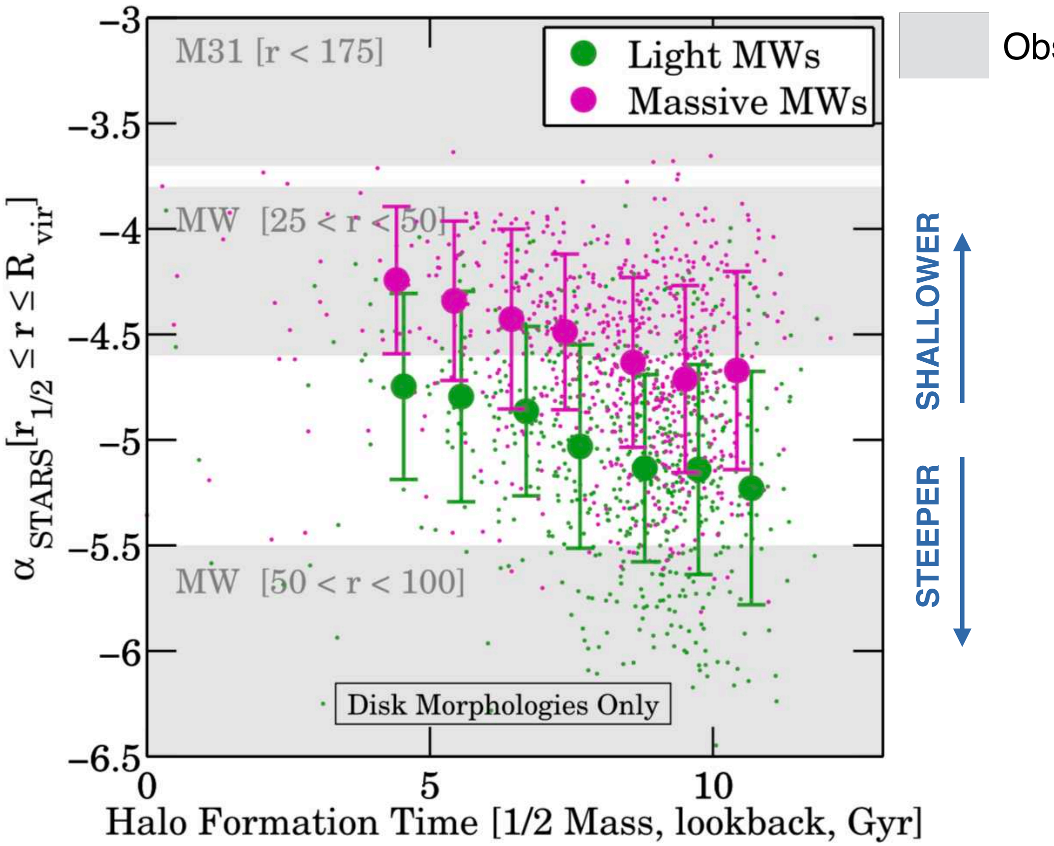


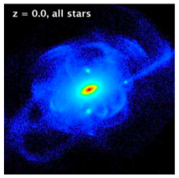
In situ - via gas inflow and star formation,
ex situ - via accretion: mergers and tidal stripping

1. MW-mass galaxies can have accreted between a few to ~30 per cent of their stars

2. Ex-situ stars dominate the mass budget towards large galactocentric distances: they make the stellar haloes

The 3D Power-Law Slopes of the Stellar Haloes know their host halo's history!





DM haloes which formed more recently exhibit shallower stellar haloes, at fixed halo mass

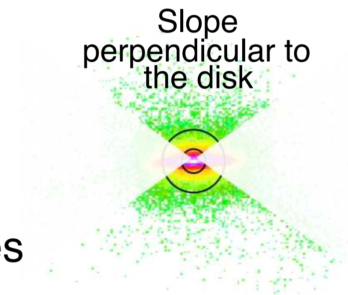
Caveat: large scatter

Illustris/TNG return differentiated stellar halo profiles for the Milky Way and Andromeda: Andromeda must have had a lively recent merger history…

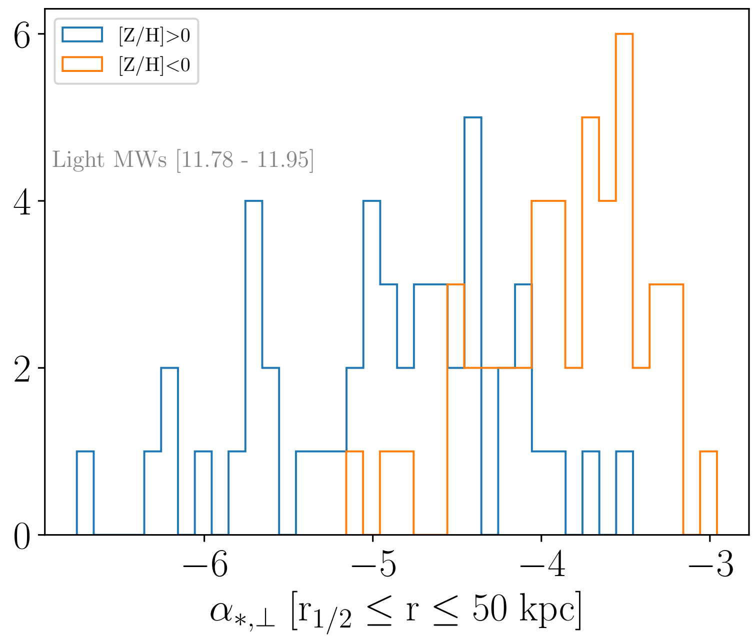
ILLUSTRIS: Pillepich, Vogelsberger, Deason, et al. 2014

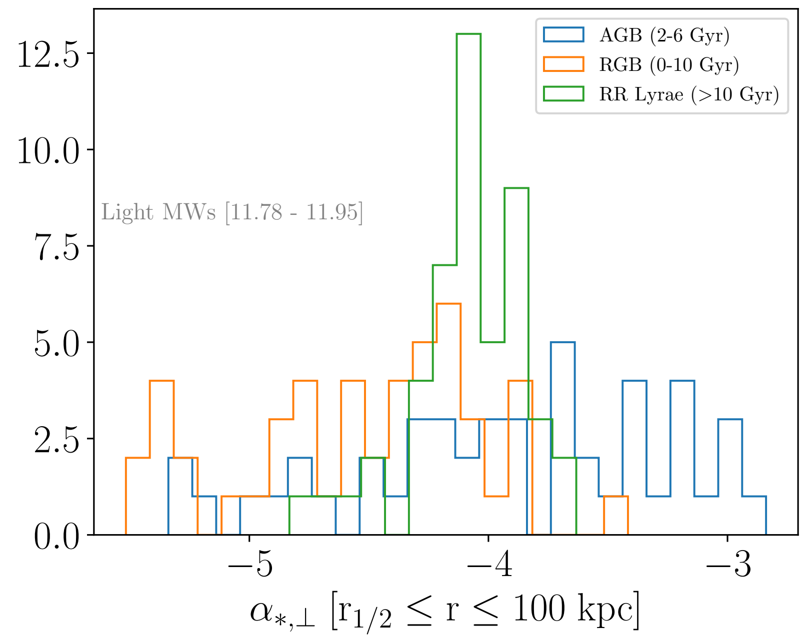
Note: in fact, observational constraints on the MW stellar halo profiles are highly uncertain!

The power-law slope of the MW stellar halo may depend on tracers



Metal-rich stars “trace” a steeper stellar halo than metal-poor stars
AGB, RGB, and RRLyrae stars can return quite different stellar halo slopes





Metal-poor stars

Metal-rich stars

RGB stars

RRLyrae

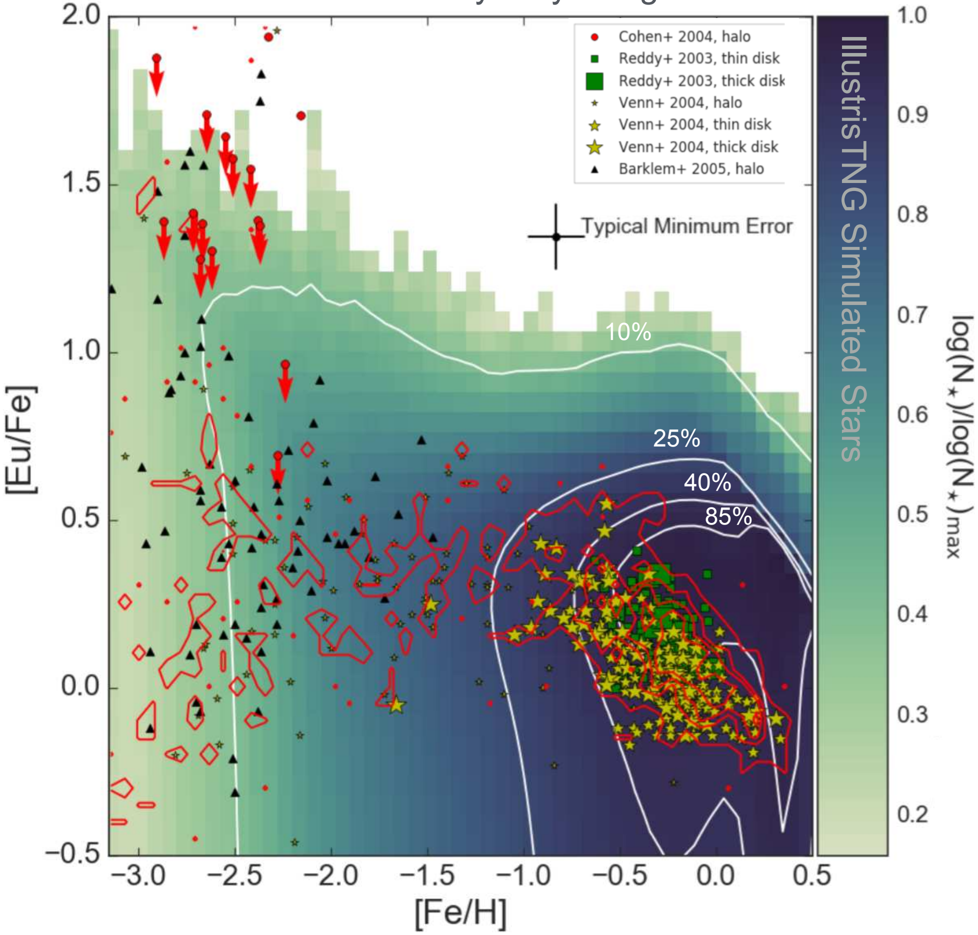
AGB stars

TNG50: Ondratschek, Pillepich et al. in prep.

On chemical enrichment

TNG100: A large spread in Europium abundances emerges in MW simulations

Europium distribution of stars stacked from ~800 simulated Milky Way-like galaxies



NOTE: The ansatz is that Europium is produced in neutron-star neutron-star mergers, modeled with a DTD and with yields re-scaled from the SNIa tables.

Here, MW analogues = 10^12 Msun haloes and disky

Europium abundances show **no** correlation with merger history, present day galactic properties, and average galactic stellar population age.

The Eu/Fe spread at low metallicities is sensitive to gas properties during redshifts z=2-4:

Highly Eu enhanced stars originate from older periods of star formation than those without strong enhancements, in period when the cosmic gas phase distribution of [Eu/Fe] was less homogeneous than it is presently.

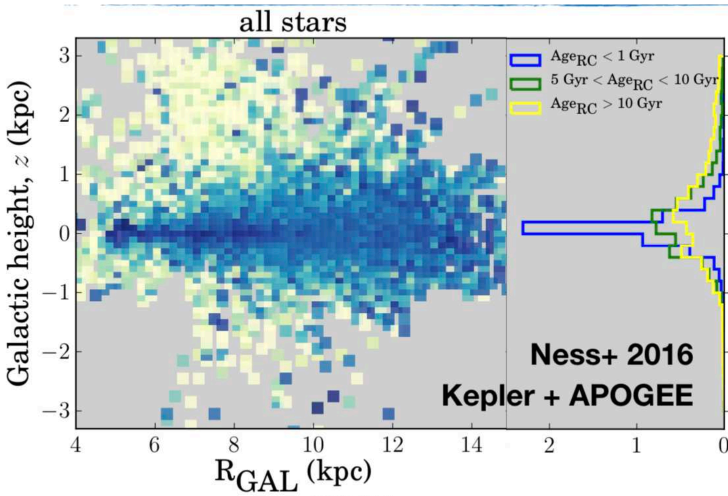
TNG100: Naiman, Pillepich et al. 2018

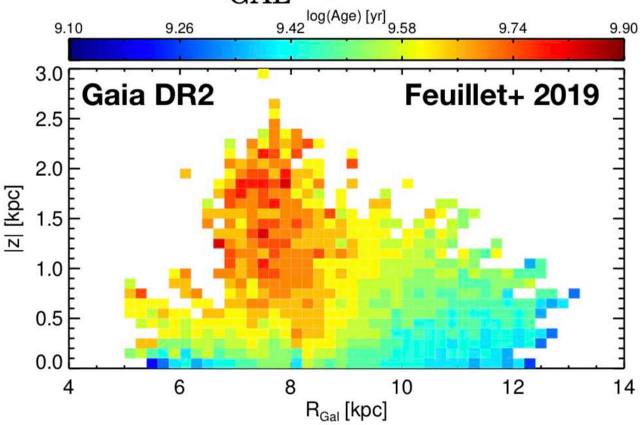
On the flaring of disks

The Galaxy’s disk flares… and so those of some zoom simulations

Observations suggest that in the Galaxy at high vertical distances from the midplane, disks are not composed only of old stars: at larger distances from the galactic centre, young stars dominate

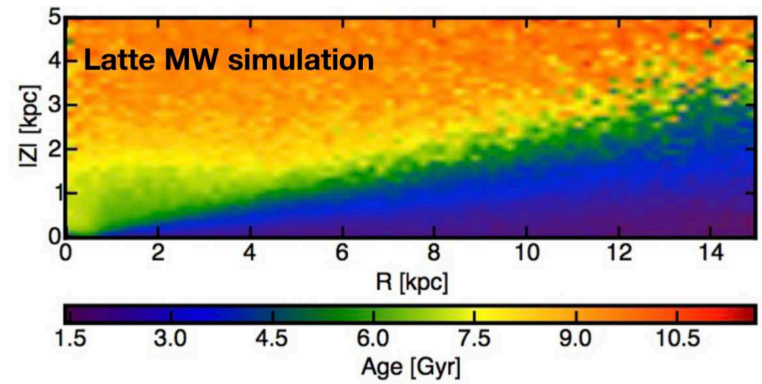
OBSERVATIONS



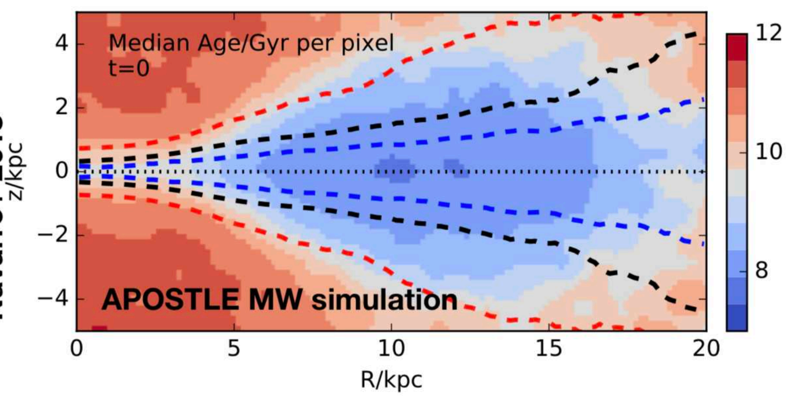


SIMULATIONS

Ma+ 2017



Navarro+ 2018

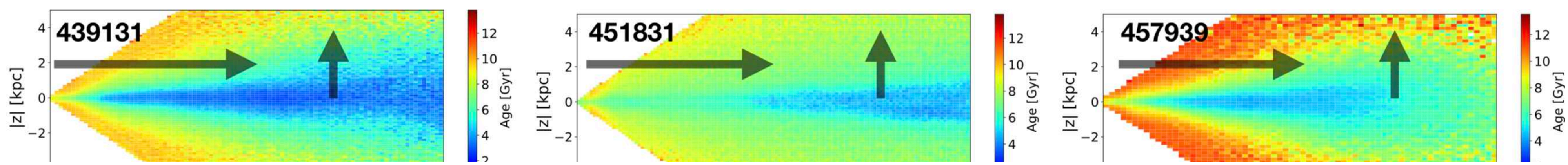


Slides Credit: M. Donnari

TNG50: Disk flaring is a very frequent phenomenon

Flaring emerges in all TNG50 MW analogues

lzl vs. galactocentric distances , color coded by stellar age [Gyr], in 3 random TNG50 MW analogues



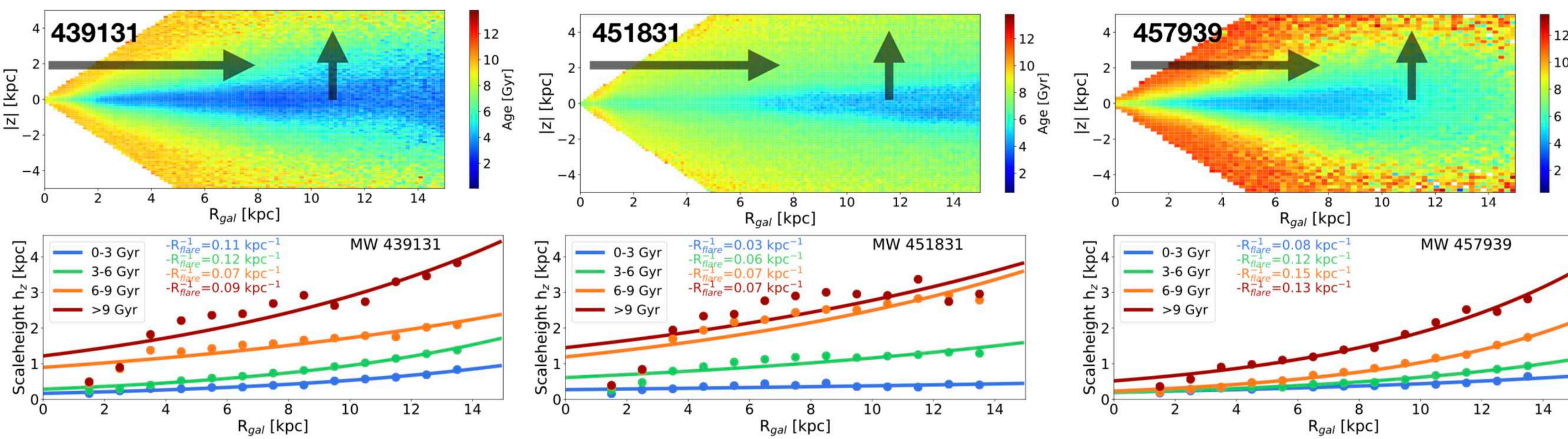
- In the mid-plane, typically the average age *decreases* for larger R, at least up to a certain distance
- At fixed R, the ages of star particles *increases* for larger lzl

TNG50: Donnari, Pillepich et al. in prep

TNG50: Disk flaring is a very frequent phenomenon

Flaring emerges in all TNG50 MW analogues

IzI vs. galactocentric distances , color coded by stellar age [Gyr], in 3 random TNG50 MW analogues



Scale height vs. galactocentric distances , in bins of stellar ages, in 3 random TNG50 MW analogues

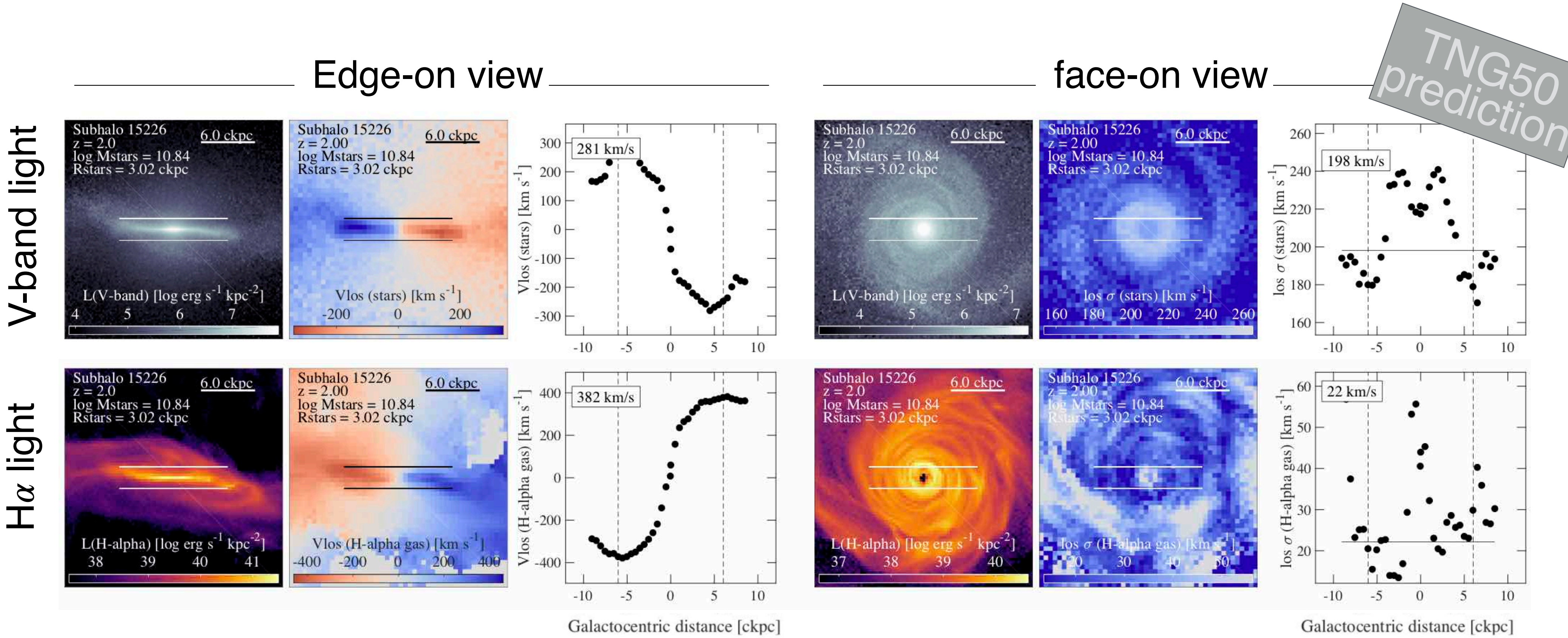
The scale heights of stars of fixed ages 'flares' outwards

TNG50: Donnari, Pillepich et al. in prep

On the (un?)settling of disks

We can extract kinematics from TNG50 galaxies, also at high z

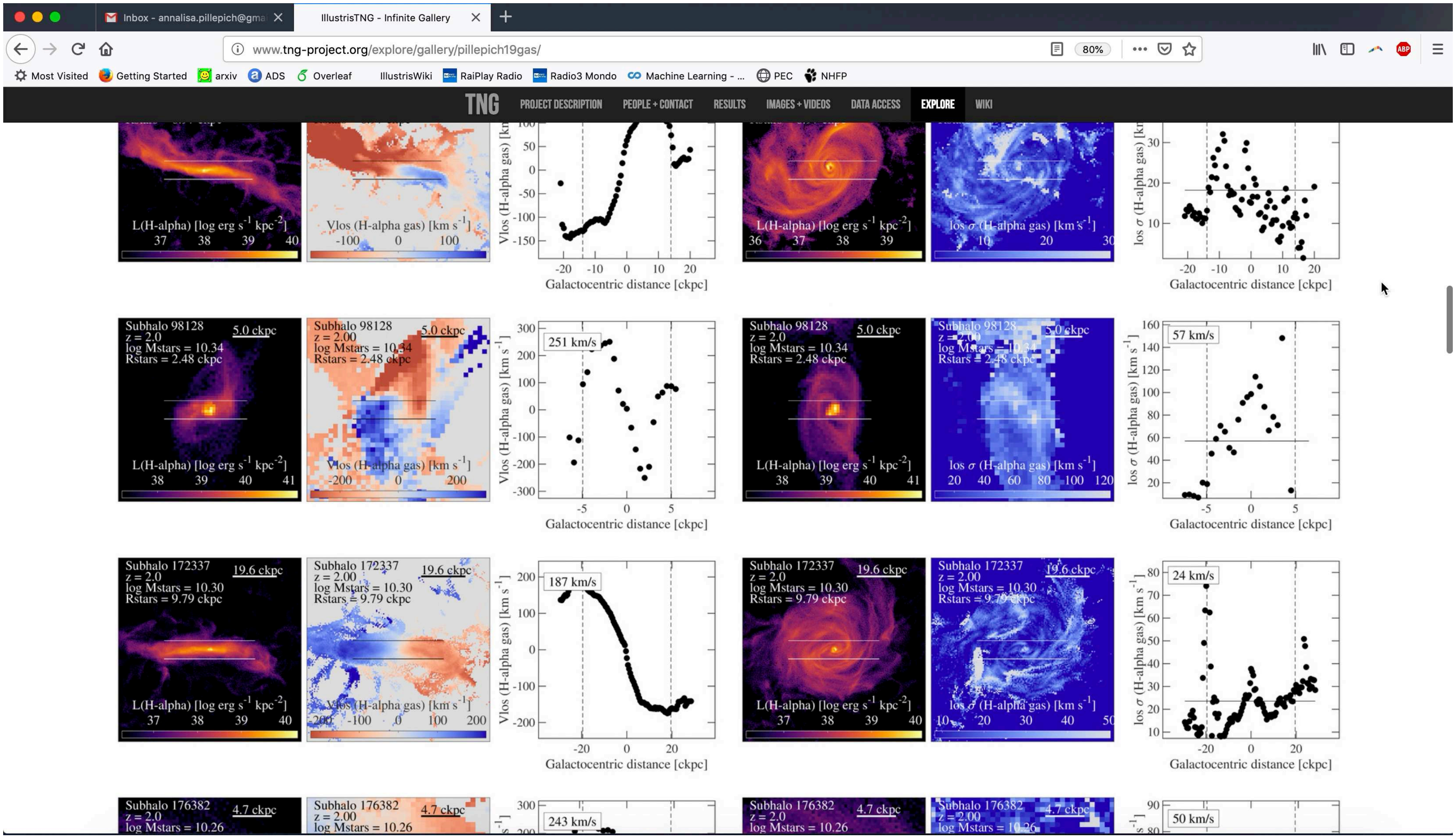
TNG50: Pillepich, Nelson, et al. 2019



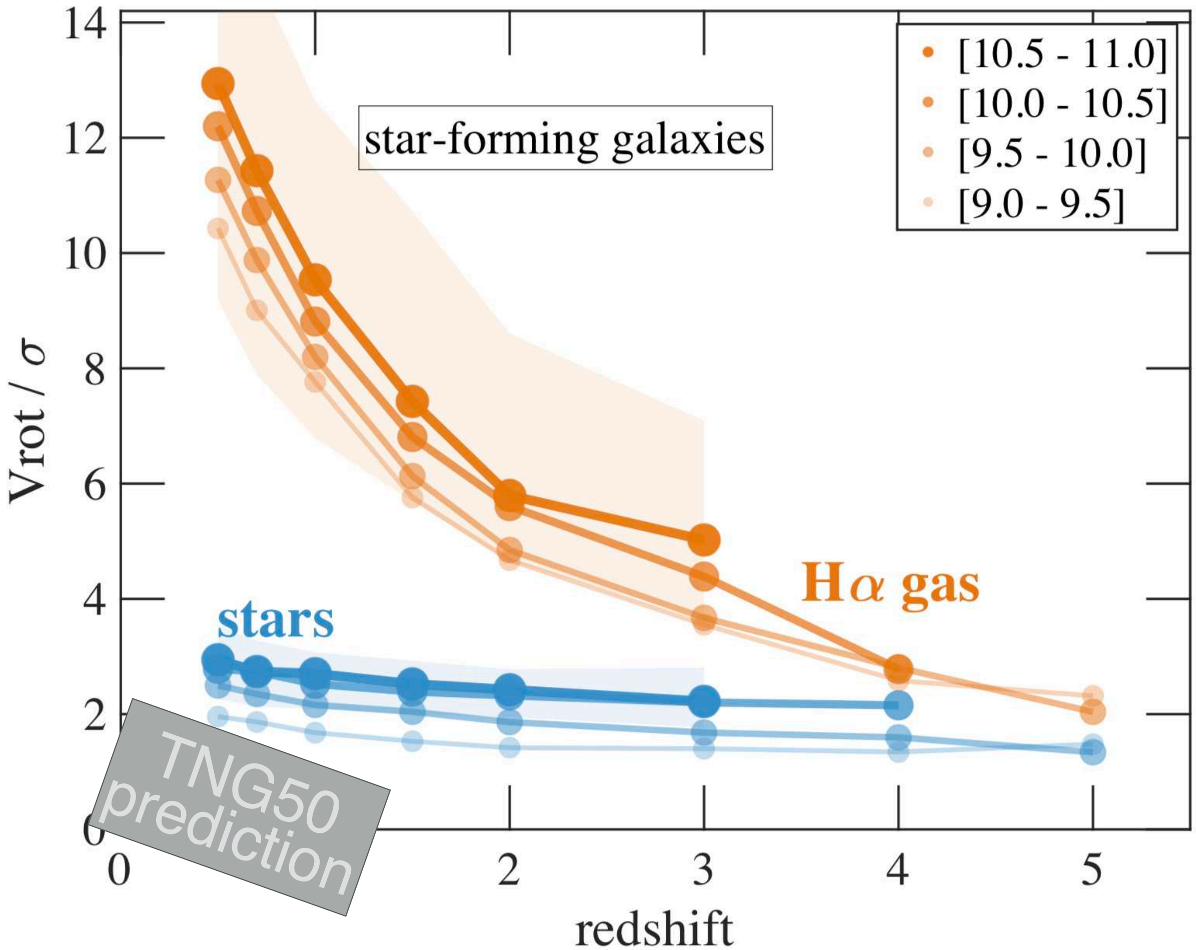
Vrot = max of rotation curves

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

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



TNG50: Star-forming galaxies have rotationally-supported gas disks since z~3-4



This is consistent with observational findings:

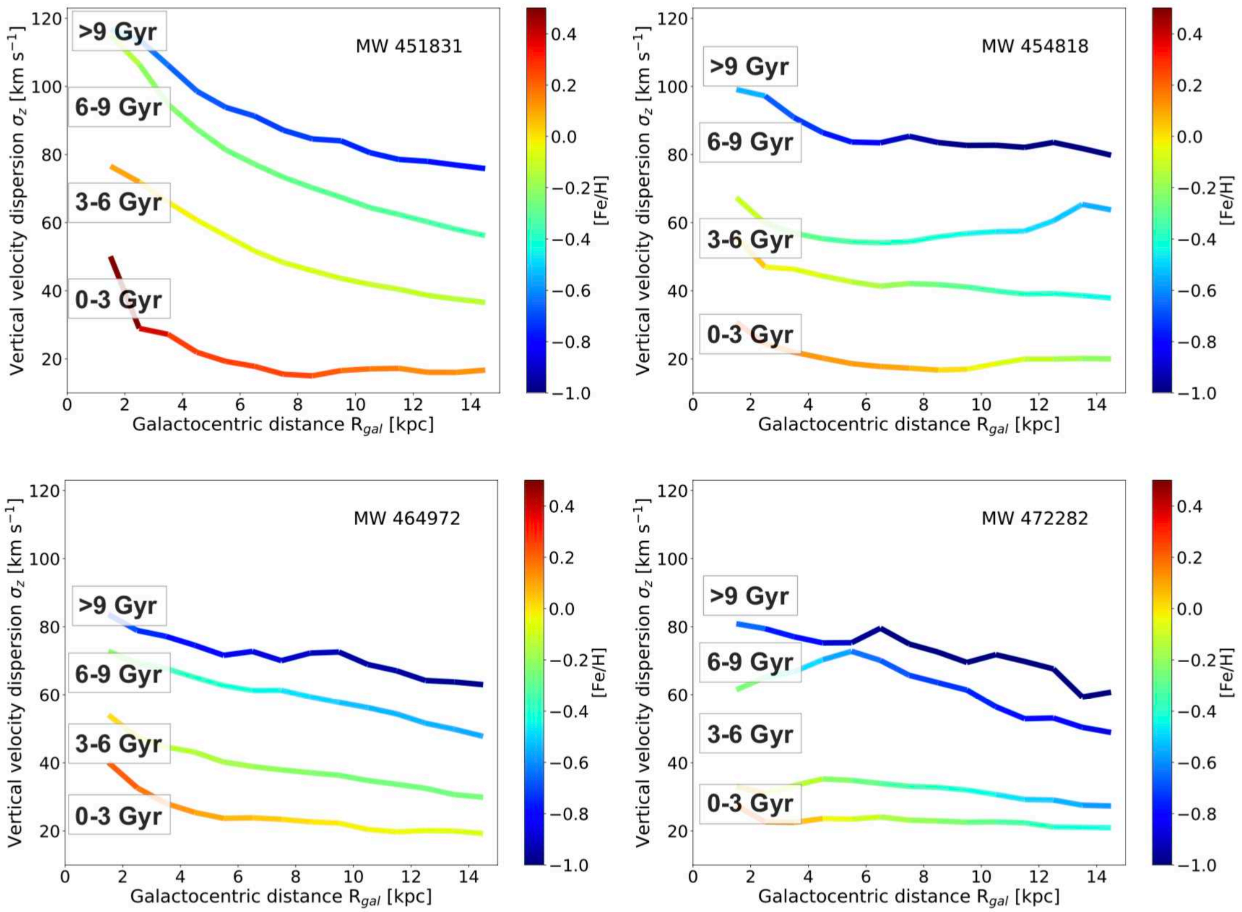
The balance between ordered and chaotic motions increases with time.

BUT!
Stars are always hotter than the star-forming gas

TNG50: Pillepich, Nelson, et al. 2019

TNG50: Older stars exhibit systematically larger velocity dispersions

Vertical stellar velocity dispersion



Are stars born with the kinematics of their parent gas and do they get heated up after birth (i.e. un-settled)?

Or are older stars born at higher velocity dispersions?

Credits: M. Donnari (MPIA)

Illustris, TNG100 and TNG300 are fully publicly available!

Illustris: Nelson, Pillepich, Genel et al. 2015
TNG: Nelson, Springel, Pillepich et al. 2019

TNG50
(for better spatially-resolved science and MW and low-mass galaxies)
will be released in early 2020

Acknowledgements: The TNG Team (the developers)

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Center for Computational Astrophysics, Flatiron Institute

Paul Torrey ■
Massachusetts Institute of Technology

HITS · CfA · Max-Planck-Institut für Astrophysik · Max-Planck-Institut für Astronomie Heidelberg · MIT

MPCDF Max Planck Computing & Data Facility – Rechenzentrum Garching der Max-Planck-Gesellschaft

FAS RC – FAS Research Computing, Harvard University, Faculty of Arts & Sciences

HLRS – High-Performance Computing Center | Stuttgart

GCS – Gauss Centre for Supercomputing

■ Original Illustris Team
+ Debora Sijacki et al.

Acknowledgements: The GC-theory MPIA team (the miners)

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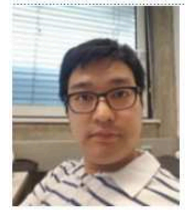
PhD Students



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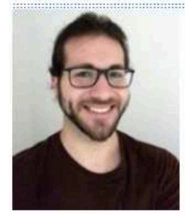

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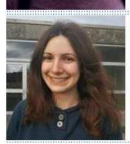

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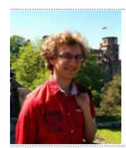

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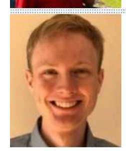

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