Universe(s) in a box: galaxy assembly, outflows and the evolution of disks with IllustrisTNG/TNG50

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$\log M_\star = 9.88$
SFR = $8.4 \, M_\odot \, yr^{-1}$
Historically, galaxy simulations have proceeded on two parallel tracks

Individual, isolated disks
i.e. galaxies

Large cosmological volumes where elements represent DM haloes only subject to gravity

Galaxy simulations have progressed enormously :)
Also cosmological simulations come in two main flavours

Zoom-ins: cosmological galaxies
[Erí, Auriga, Fire, Nihao, Vela, Naab sims …]

Uniform Volumes Cosmological Hydro Simulations
[Illustris, Eagle, Horizon-AGN, Massive-Black, Magneticum, Mufasa, …]

Gravity-Only Uniform Volumes
[M-XXL, Bolshoi, Las Damas, NewHorizon, Dark Sky, Trillion-particle simulation]

<table>
<thead>
<tr>
<th>1 - a few Mpc</th>
<th>20 - 100 Mpc</th>
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<tbody>
<tr>
<td>N\textsubscript{gal} \approx 1-30</td>
<td>N\textsubscript{gal} \approx 10k-100k</td>
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<tr>
<td>N\textsubscript{gal} \approx 0 (unless you do a SAM)</td>
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The gap between the two main flavors is getting smaller

Zoom-ins: cosmological galaxies [Eris, Auriga, Fire, Nihao, Vela, Naab sims …]

SAM = semi-analytical model
Zoom-ins: cosmological galaxies [Eris, Auriga, Fire, Nihao, Vela, Naab sims …]


TNG50: galaxy assembly, outflows, and the evolution of disks

(**)TNG = The Next Generation
Scope of this talk

1. The IllustrisTNG runs, and particularly TNG50, are state-of-the-art Universes in a box

2. Galactic structures shape galactic fountains, and vice versa:
   - testable and quantitative predictions re galactic-scale gas outflows
   - when and how galaxy disks become thinner with time
IllustrisTNG/TNG50:
The latest and most ambitious installment of the IllustrisTNG project
The IllustrisTNG Simulations (2016-2019)

3 flagship cosmological magneto-hydrodynamical simulations, from 50 to 300 Mpc per side, with a fixed ‘TNG model’ where we follow the co-evolution of:

- dark matter
- cosmic gas (H, He, …)
- super massive black holes
- stars
- magnetic fields
The IllustrisTNG Simulations (2016-2019)

- Annalisa Pillepich (MPIA, Co-PI: TNG50)
- Dylan Nelson (MPA, Co-PI: TNG50)
- Federico Marinacci
- Jill Naiman
- Lars Hernquist
- Mark Vogelsberger
- Ruediger Pakmor
- Paul Torrey
- Shy Genel
- Volker Springel (PI)
The IllustrisTNG Simulations
(2016-2019)

TNG50: galaxy assembly, outflows, and the evolution of disks

- TNG50: 8e4 Msun
- TNG100: 1.4e6 Msun
- TNG300: 1.1e7 Msun

Increasing volume
Improving resolution

2D matter distribution
(same ICs and res as original Illustris)
The TNG50 Simulation (2017-2019)

- Co-PI: Annalisa Pillepich (MPIA)
- Co-PI: Dylan Nelson (MPA)
The TNG50 Simulation: unprecedented resolution (in the hydro)

10 pc  spatial resolution  100 pc  spatial resolution  1 kpc

Galaxy disk thickness
≥ giant molecular clouds scales

In the star-forming regions of galaxies, 70-140 parsecs

galaxy internal structures and kinematics
subgrid star-formation and (stellar) feedback below such scales
The TNG50 Simulation: unbiased galaxy statistics, across environments

@ z=0: one Virgo-like cluster
~10 Fornax-like groups

@ z=0: ~200 MW-mass haloes

@ z=0: thousands of dwarfs

@ z=1:
~70 galaxies with $> 10^{11}$ Msun
~700 galaxies with $> 10^{10}$ Msun

one volume with
one unique set
of ingredients!
The TNG50 Simulation: a field-leading computational endeavour

It has run for more than one year, 24/7 on 16k computing cores!
TNG50: galaxy assembly, outflows, and the evolution of disks

Gas Column Density

JWST/NIRCam Stellar Light Composite

TNG50: Nelson, Pillepich et al. 2019
TNG50: galaxy assembly, outflows, and the evolution of disks
Validations: IllustrisTNG produces a reasonable, realistic galaxy population

- **Stellar mass functions at z=0, 1, 2, 3, 4.**

- **Mass dependent z=0 distribution of galaxy optical colors (g-r) vs. SDSS.**

- **Large-scale spatial clustering of galaxies, split by color, vs SDSS.**
Validations: IllustrisTNG produces a reasonable, realistic galaxy population

The quenched fraction of galaxies (their sSFRs) at $z=0$, $z=1$, $z=2$.

The gas-phase mass-metallicity relation at $z=0$, $z=1$, $z=2$.

Light-weighted stellar ages of galaxies vs SDSS at $z\sim0$. 
Validations: IllustrisTNG produces a reasonable, realistic galaxy population

Rodriguez-Gomez et al. 2019

Sersic index scaling and non-parametric morphological measurements vs. PanSTARRS imaging

Genel et al. 2018

Optical sizes (half-light radii) of galaxies, both star-forming and quiescent, at z=0 through z=2, vs SDSS and CANDELS.

Lovell, Pillepich et al. 2018

Non-baryonic components: dark matter fraction vs. mass at low-z

TNG50: galaxy assembly, outflows, and the evolution of disks
Annalisa Pillepich, Subaru 20th Anniversary, 2019/11/21
Validations: IllustrisTNG produces a reasonable, realistic galaxy population

Pop; Nelson et al. in prep

Truong, Pillepich et al. In prep

Halo x-ray luminosity scaling relation with stellar mass vs. SDSS/ROSAT.

X-ray properties ($T_X$, $L_X$) of ellipticals vs. ATLAS$^{3D}$ and MASSIVE.

…. 
The physical ingredients behind large-volume cosmological sims are many

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 [metal] cooling + heating/UVB
Conversion of gas into stars (TNG: density threshold)
ISM model (TNG: two-phase)
Stellar Evolution (TNG: SNIa, SNII, AGB)
Metal Enrichment (TNG: H, He, C, N, O, Ne, Mg, Si, Fe)
Stellar Feedback (TNG: decoupled kinetic winds)
Black Hole formation, growth, and merging
Black Hole Feedback (TNG: high vs. low accretion)

Essentially all these astrophysical phenomena are unresolved and require some level of ‘subgrid’ modeling

Subgrid recipes
“Calibration” vs observations:
• SFRD(z), z=0 SMF, z=0 SMHM,
• z=0 halo fgas, z=0 BH-M*, z=0 Re-M*

Via “tables”

gas outflows and recycling
What sets apart the TNG(50) model from previous calculations

0. The moving-mesh code AREPO
   *Springel 2010*
   Now public!!! Weinberger et al. 2019

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, ....

TNG50: galaxy assembly, outflows, and the evolution of disks

Annalisa Pillepich, Subaru 20th Anniversary, 2019/11/21
Modern cosmological hydro sims
= Open-ended laboratories for studying galaxy evolution
A community resource (data is public!)
Galactic structures shape galactic fountains, and vice versa
On Galactic-Scale Outflows
In the TNG model, black-hole and stellar feedback superimpose

- BH winds
- 1000km/s outflows
- Cocoon-like morphology
- Over-pressurized
- Metal-enriched
- Bubbles

TNG50: galaxy assembly, outflows, and the evolution of disks

TNG50: Nelson, Pillepich et al. 2019

TNG50: Subaru 20th Anniversary, 2019/11/21
Despite model simplicity at the **injection scale**, TNG50 reveals outflows complexity

“multi-phase” (in $T$, $\rho$, $v$, and $Z$)

$\Rightarrow$ different observational signatures for cold, cool, warm, & hot flows.

$\Rightarrow$ “multi-speed” $f(z, r, M, \ldots)$

*TNG50: Nelson, Pillepich et al. 2019*
Despite model simplicity at the injection scale, TNG50 reveals outflows complexity.

\[ \eta = \frac{\dot{M}_{\text{out}}}{\dot{M}_*} = f(M_{\text{stars}}, z, r, v_{\text{cut}}, \text{phase}) \]

Mass loading factor inversion as BH feedback kicks in.
Despite model simplicity at the **injection scale**, galactic fountains emerge in TNG50

Natural bipolar collimation despite initial isotropy (both SN- and BH-driven winds).

From stacks of hundreds of galaxies

**TNG50: Nelson, Pillepich et al. 2019**
TNG50: Gas outflow properties depend on galaxy type!

From thousands of galaxies

Higher specific star formation rates => faster outflows…
up to a certain mass!

Consistent trends with KMOS$^{3D}$ observations —
A non-trivial validation of the model

TNG50: Nelson, Pillepich et al. 2019
How galaxy disks become thinner with time

(of star-forming galaxies)
Observations: stellar bodies become more disk like, gas disks colder to lower z

Structures from stellar light imaging

Kinematics from gas/ISM emission lines (mostly Hα)

CANDELS restframe optical:
lower z (and larger mass)
⇒
more common galaxies with disk-like stellar structures

Ionized- and molecular gas observations
⇒
Lower turbulent/random velocity support in the gas phase at lower-z
The relative ‘thinness’ of disks (h/r) increases with time

Disks want to be thin
(~100-200pc scale heights are resolved in TNG50!)

TNG50: galaxy assembly, outflows, and the evolution of disks

TNG50: Pillepich, Nelson, et al. 2019
In the stars, galaxies become more ‘disky’ towards $z=0$

Note: Classification of galaxies based on 3D axis ratios

Fractions of disk galaxies

TNG50: galaxy assembly, outflows, and the evolution of disks

TNG50: Pillepich, Nelson, et al. 2019
We can extract kinematics from TNG50 galaxies!

\[ V_{\text{rot}} = \text{max of rotation curves} \]

\[ \sigma = \text{second-order moment of the los velocity of star-forming gas elements in pixels of 0.5kpc (along the structural major axis, where } V \text{ is max)} \]
We can extract kinematics from TNG50 galaxies from thousands of galaxies!
Star-forming galaxies have larger velocity dispersions at higher z (in the gas!)

From thousands of galaxies

Higher-z => more “chaotic” galaxies at fixed mass

In TNG50, recovery of trends seen with H\(\alpha\) observations:

Not a trivial confirmation of the bounty of the underlying physical ingredients

>100s massive modeled galaxies at high z required for the trend and the data comparison

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

TNG50: Pillepich, Nelson, et al. 2019

TNG50: galaxy assembly, outflows, and the evolution of disks

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Why lower gas velocity dispersions at later times? Or why higher ones at early times?

Q: What physical processes can maintain a disturbed (dynamically hot) star-forming gas reservoir at high redshift?

- Cosmic gas inflows
- Fountain inflow / halo recycling
- Outflows (feedback)
- Galaxy mergers / interactions
- (Small-scale ISM turbulence processes)

From thousands of galaxies

TNG50 star-forming galaxies

Neelman et al. 2019 @MPIA with ALMA (CII)

TNG50: Pillepich, Nelson, et al. 2019
Why lower gas velocity dispersions at later times? (at fixed galaxy mass!)

1. Lower redshift => lower galaxy merger rates

TNG50: galaxy assembly, outflows, and the evolution of disks

Mergers!
Why lower gas velocity dispersions at later times? (at fixed galaxy mass!)

2. Lower redshift =>
lower rates of smooth gas accretion into galaxies

Inflows!

TNG50: galaxy assembly, outflows, and the evolution of disks

Annalisa Pillepich, Subaru 20th Anniversary, 2019/11/21
Why lower gas velocity dispersions at later times? (at fixed galaxy mass!)

3. Lower redshift => lower rates of gas outflows

Outflows!

TNG50: galaxy assembly, outflows, and the evolution of disks
Why lower gas velocity dispersions at later times? (at fixed galaxy mass!)

4. Lower redshift => smaller velocities of gas outflows

Outflows!
Star-forming galaxies have rotationally-supported gas disks since $z \sim 2-3$

Lower redshift, larger ratio between ordered and chaotic motions

Qualitative consistency with observational findings: yeah!

TNG50: galaxy assembly, outflows, and the evolution of disks

TNG50: Pillepich, Nelson, et al. 2019
TNG50 insight: Galactic structure shapes galactic fountains, and vice versa

Lower redshift $\downarrow$
- smaller velocities and rates of gas outflows $\uparrow$
- lower rates of gas inflows $\downarrow$
- Stalling and fall back of gas outflows $\downarrow$
- More prominent galactic fountains of recycled gas $\downarrow$

Outflow collimation $\uparrow$
- redistribution of gas angular momentum $\uparrow$
- Enhancement disk formation $\uparrow$

TNG50: Pillepich, Nelson, et al. 2019
TNG50 provides testable (JWST, ELTs) predictions also for stellar kinematics

- **TNG50 predictions:**
  - \(\sigma_{\text{stars}} > \sigma_{\text{gas}}\), always
  - \(d\sigma_{\text{stars}}/dz < d\sigma_{\text{gas}}/dz\)

- Stellar velocity dispersions always larger than the gas’

- Different dynamics for stars (collisionless) and gas (collisional and dissipative)

- TNG50 predictions for galaxy assembly, outflows, and the evolution of disks

Concluding…

We are developing and exploiting state-of-the art model Universe(s) for the physics of galaxies: e.g. TNG50

Modern numerical experiments like TNG(50):
• are progressively more sophisticated and “realistic”
• produce many, diverse, and quantitative observationally testable predictions
• are a community resource (public!)
Looking ahead…

Community actions are needed on two fronts:

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<tr>
<th>Better models of the ISM and of the gas-radiation interaction</th>
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<td>E.g. In TNG, we do not have:</td>
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<tr>
<td>• radiative transfer</td>
</tr>
<tr>
<td>• effects of radiation pressure</td>
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<tr>
<td>• chemistry (no complex molecules)</td>
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<tr>
<td>• dust formation/disruption</td>
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<tr>
<td>• in fact, we do not distinguish between HI and H2</td>
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<tr>
<td>• …</td>
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<th>More careful, detailed, and sophisticated observations-simulations comparisons</th>
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<td>• application of “identical” operational definitions</td>
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<tr>
<td>• Accounting for “identical” selections (of observed galaxies)</td>
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<td>• Apply sophisticated post-processing methods to the simulations</td>
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Illustris, TNG100, and TNG300 are already completely publicly available:
Have fun!

The IllustrisTNG Project
The next generation of cosmological hydrodynamical simulations.
www.tng-project.org