Simulating Galaxy Clusters (and their galaxies!) with IllustrisTNG

ANNALISA PILLEPICH
MPIA, Heidelberg
Simulations of Clusters of Galaxies with IllustrisTNG

Annalisa Pillepich, MPIA, 2018/03/18

Image Credits: Dylan Nelson
Scope of this talk

1. To introduce the IllustrisTNG simulations
   (TNG = The Next Generation)

2. To showcase the many scientific insights and applications these simulations allow

.... for galaxy clusters
**Take-home messages**

- Keywords to associate to the IllustrisTNG simulations: cosmological simulations, large volumes, gravity, MHD, star formation, chemical enrichment, gas cooling, feedback from stars and feedback from super massive black holes.

- They are a laboratory to study - with one common set of ingredients - galaxy clusters as massive as $10^{15} \text{ Msun}$ as well as to resolve galaxies like the Classical Dwarfs of the Milky Way.

- In fact, the IllustrisTNG simulations were developed with the goal of reproducing realistic galaxy populations.

- $z=0$ basic galaxy statistics provide important constraints on some of the physical ingredients governing the ICM: chiefly, the AGN feedback.

- Our new effective AGN feedback implementation appears to return reasonable star forming/quenching galaxies & reasonable ICM scaling relations.
The IllustrisTNG Project
Simulations of Clusters of Galaxies with IllustrisTNG

The TNG Team

Volker Springel
Heidelberg Institute for Theoretical Studies
PI: Overall TNG Project

Lars Hernquist
Harvard University

Annalisa Pillepich
Max Planck Institute for Astronomy, Heidelberg
Co-PI: TNG50 Project

Rüdiger Pakmor
Heidelberg Institute for Theoretical Studies

Dylan Nelson
Max Planck Institute for Astrophysics, Garching
Co-PI: TNG50 Project

Rainer Weinberger
Heidelberg Institute for Theoretical Studies

Federico Marinacci
Massachusetts Institute of Technology

Jill Naiman
Harvard University

Mark Vogelsberger
Massachusetts Institute of Technology

Shy Genel
Center for Computational Astrophysics, Flatiron Institute

Paul Torrey
Massachusetts Institute of Technology

Original Illustris Team + Debora Sijacki et al.
The TNG Simulations

Three flagship volumes, with:

- new invariant ‘TNG model’
- Updated Planck Cosmology
- Including MHD
- Different flagship resolutions

\[Pillepich:2018a,\text{Weinberger:2017}\]
The TNG Simulations

Springel et al. 2018
Pillepich et al. 2018b
Naiman et al. 2018
Marinacci et al. 2018
Nelson et al. 2018
+
Genel et al. 2018
Vogelsberger et al. 2018
Torrey et al. 2018
Weinberger et al. 2018
...

Simulations of Clusters of Galaxies with IllustrisTNG

Annalisa Pillepich, MPIA, 2018/03/18
The TNG Simulations

- Enhancing statistics
- Improving resolution

TNG Simulations
- TNG50: 8e4 Msun, x(2x3) realizations
- TNG100: 1.4e6 Msun, x(2x3) realizations
- TNG300: 1.1e7 Msun, x(2x3) realizations

(same ICs and res as Illustris)
The TNG Model

**AREPO code**

*Springel:2010*

+ **Illustris Framework**

*Vogelsberger+ 2013, Torrey+ 2014, Genel +2014a; Vogelsberger 2014a,b, Genel+ 2014b, Sijacki+2015*

---

**COSMOLOGICAL ICs (LCDM)**

**GRAVITY+HYDRODYNAMICS**

- Gas Cooling/Heating
- Threshold-based star formation
- Stellar Evolution
- Metal Enrichment (H, He, C, Mg, …)
- Galactic Winds Feedback
- Black Hole Seed and Growth
- Black Hole Feedback

---

**Underlying objectives:**

1. expand Illustris scope
2. include new physics
3. improve upon the previous issues identified in Illustris galaxies and haloes

---

**Numerical improvements**

*Pakmor et al. 2016, Springel et al.*

**New physics and sub grid models:**

- **MHD**
  * Pakmor et al. 2011, Pakmor & Springel 2013
- New pulsed kinetic **BH-driven winds**
- **Refined galactic wind feedback**
- Revised stellar evolution choices
- New/different yield tables

**Novel diagnostic tools:**

* Schoal & Springel 2015, Schoal et al. 2016*

- Cosmological shock finder
- Metal tracking
- Subgrid for neutron-star mergers

---

*e.g. Too low halo gas fractions within R500 in haloes > 10^{13.5} Msun*
Magnetic Fields
**TNG finding: Magnetic Fields in/around galaxies “know” their type**

Magnetic Field Topology:

- **Disk galaxies:** well ordered in the disk place
- **Elliptical Galaxies:** field orientation not well defined

### Disk

- $M_* = 1.7 \times 10^{10} M_\odot$

### Elliptical

- $M_* = 26.1 \times 10^{10} M_\odot$
TNG finding: Magnetic Fields in/around galaxies “know” their color

Magnetic Field Strength:

Blue galaxies: 10-30 microGauss
Red Galaxies: < 1 microGauss

(not a causation!)
New Diagnostic Tools
Simulations of Clusters of Galaxies with IllustrisTNG

Annalisa Pillepich, MPIA, 2018/03/18

Pillepich, Springel, Nelson et al. 2018a

DM Density

Gas Density

~37 Mpc
Simulations of Clusters of Galaxies with IllustrisTNG

Annalisa Pillepich, MPIA, 2018/03/18

Mach Numbers

Energy dissipated via Shocks

Pillepich, Springel, Nelson et al. 2018a
The complex ICM structure is revealed in the gas discontinuities
New AGN Feedback: BH-driven winds
BH Feedback: Subgrid Implementation

Our AGN feedback is an *effective* model

Goal: to exchange energy and/or momentum from the central BH to the surrounding medium
(in order to regulate star formation!)

Possibly, with outcomes that resemble what we think we see in reality

BHs are usually placed by hand as “sink particles”:
they can grow in mass by ‘accreting’ material from the surroundings
**BH Feedback: Subgrid Implementation**

**Thermal Dump (near the BH)**
- Continuous?
  - yes e.g. Illustris, HorizonAGN
  - no e.g. Eagle, Magneticum(?)
- Only at high accretion rates?
  - yes e.g. Illustris
  - no e.g. Eagle (all the time)

**Thermal Dump (bubbles)**
- Very sporadic, energetic bubbles: Illustris
- More frequent, “smaller bubbles”: Auriga
- Only at low accretion rates?
  - yes e.g. Illustris
  - no e.g. Auriga (all the time)

**Isotropic?**
- no e.g. TNG, each time in different dirs
- no: bipolar e.g. HorizonAGN

**Continuous?**
- ~ e.g. TNG, each time in different dirs

**Kinetic Kick**
- yes e.g. TNG, HorizonAGN

- Affecting only non-self shielded gas
  - e.g. Mufasa, NIHAO variations

---

*See also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012; Weinberger et al. 2017*
**Simulations of Clusters of Galaxies with IllustrisTNG**

---

**BH Feedback: Subgrid Implementation**

**Thermal Dump (near the BH)**
- Continuous?
  - yes e.g. Illustris, HorizonAGN
  - no e.g. Eagle
- Only at high accretion rates?
  - yes e.g. Illustris
  - no e.g. Eagle (all the time)

**Thermal Dump (bubbles)**
- Very sporadic, energetic bubbles: Illustris
- More frequent, “smaller bubbles”: Auriga
- Only at low accretion rates?
  - yes e.g. Illustris
  - no e.g. Auriga (all the time)

**Isotropic?**
- no e.g. TNG, each time in different dirs
- no: bipolar e.g. HorizonAGN

**Continuous?**
- ~ e.g. TNG, each time in different dirs

**Only at low accretion rates?**
- yes e.g. TNG, HorizonAGN

**Kinetic Kick**

**see also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012; Weinberger et al 2017**

---

**Illustris Feedback**

**“By Hand” heating of the gaseous halo**

Affecting only non-self shielded gas
- e.g. Mufasa, NIHAO variations

---

*Annalisa Pillepich, MPIA, 2018/03/18*
BH Feedback: Subgrid Implementation

Thermal Dump (near the BH)
Continuous?
- yes e.g. Illustris, HorizonAGN
- no e.g. Eagle

Only at high accretion rates?
- yes e.g. Illustris
- no e.g. Eagle (all the time)

Isotropic?
- no e.g. TNG, each time in different dirs
- no: bipolar e.g. HorizonAGN

Continuous?
- ~ e.g. TNG, each time in different dirs

Only at low accretion rates?
- yes e.g. TNG, HorizonAGN

Kinetic Kick

There are free parameters, of course. These were chosen in order to reproduce some observed z=0 galaxy statistics (chiefly, the galaxy stellar mass function, galaxy sizes, and the gas content of massive haloes)

The BH-driven wind quenches galaxies at the right mass scale:

See also Choi et al. 2012, 2014, 2015; Dubois et al. 2010, 2012; Weinberger et al. 2017
The TNG cluster sample
Thousands of clusters at unprecedented resolution

**TNG300**
- mb ~ 1.1e7 Msun
- <gas cell>_sf ~ 700 pc

**TNG100**
- mb ~ 1.4e6 Msun
- <gas cell>_sf ~ 355 pc

**TNG50**
- mb ~ 8.5e4 Msun
- <gas cell>_sf ~ 140 pc

- 2300 haloes > 10^{13} Msun
- 280 haloes > 10^{14} Msun
- 3 haloes > 10^{15} Msun

- 182 haloes > 10^{13} Msun
- 10 haloes > 10^{14} Msun

- ~ 10 haloes > 10^{13} Msun
- 1 halo > 10^{14} Msun
TNG Results and Insights: on clusters
With TNG100+TNG300, we have three thousands massive galaxies

... with their central galaxy, satellite systems, diffuse stellar light, low-surface brightness features like shells and streams,... the latter are testimony of the accretion nature of these massive galaxies

$z = 0.0\quad M_{200c} = 1.7\times10^{14}$

Pillepich, Nelson, Hernquist et al. 2018b
The stellar mass of BCGs is by more than 70% accreted!

Massive galaxies (> $10^{11}$ Msun) have assembled more than half of their stars by accreting satellites and merging rather than making stars themselves.

Accreted stars dominate also within the innermost regions of the BCGs.

90% of the accreted stellar mass (< 30 kpc) in galaxies that sit in haloes > $10^{14}$ Msun has been brought in by galaxies at least as massive as a few $10^{10}$ Msun!

To properly model galaxies (and their AGN feedback!) across the mass spectrum is of the essence.
At any given time, 6-12% of satellites in groups and clusters are jellyfishes.
At any given time, 6-12% of satellites in groups and clusters are jellyfishes.
At any given time, 6-12% of satellites in groups and clusters are jellyfishes

Yun, Pillepich, et al. in prep
The gas-phase $Z$ of cluster galaxies is enhanced wrt to field galaxies …

Even before they fell into a cluster!

Images Credits: Annalisa Pillepich
... possibly (also) because they accrete pre-enriched gas!

The AGN feedback spreads the metals ....
The ICM metallicity profiles exhibit a central dichotomy for CC and NCC

CC = central entropy of less than 30 keV cm$^{-2}$.

CC groups have higher central gas-phase metallicities than NCCs.

Caveat: only ~20 objects with $M_{500,crit} > 10^{13.75} M_\odot$.

Vogelsberger, Marinacci, Torrey, et al. w/ AP 2018
TNG returns continuous gradients in the CC/NCC criteria

(see also Barnes’ talk!)

Barnes et al. w/AP 2018
... and reasonable consistency with observational findings, at intermediate $z$

Filled symbols:
- TNG300:
  - High-mass
    - $M_{500} \geq 2.0 \times 10^{14} M_{\odot}$
    - $N = 49$ ($z=0$)
    - $N = 2$ ($z=1$)

Open symbols:
- observations
  - $M_{500}$ median $\sim 4-6 \times 10^{14} M_{\odot}$

**Caveat:** here comparison is not mass matched

Barnes et al. w/AP 2018 (see also Barnes’ talk)
The TNG AGN feedback “naturally” produces different-entropy atmospheres

Quenched galaxies (with higher BH-driven energetics) have systematically higher CGM entropies, at fixed mass

Zinger, Pillepich et al., in prep
See also Zinger’s POSTER
The AGN feedback controls the thermodynamical properties of groups

The X-ray luminosity-mass scaling relations in TNG are in excellent agreement with observations (without selection biases).

TNG strongly improves upon the original Illustris model

Illustris’ groups and clusters were devoided of gas because of the too violent AGN “bubble” mode

Credits: D. Nelson.
See also Pop et al. in prep (and POSTER!)
The AGN feedback controls the thermodynamical properties of groups

The SZ-Mass scaling relation also appears strongly dependent on the AGN feedback scheme (especially at the group scale!).

In TNG much improvement!

Credits: Roxana Pop
See also Pop et al. in prep (and POSTER!)
We can model OVI, OVII, OVIII in our gaseous atmospheres

At any redshift and at any point in space, the simulation predicts gas **density**, gas **temperature** and gas **metallicity** (Oxygen mass fraction).

\[ [n_H, Z, T, z] \xrightarrow{\text{CLOUDY}} \text{Oxygen ion mass fractions} \]

\[ T \sim 10^5-10^6 \text{ K} \]
\[ n_H \sim 10^{-6} \text{ cm}^{-3} \] *increasing ionisation*
\[ T \sim 10^6-10^7 \text{ K} \]
\[ n_H \ll 10^{-6} \text{ cm}^{-3} \]

*Nelson, Kauffmann, Pillepich et al. 2018*
The OVI-OVIII content peaks at increasingly higher halo scales

The OVI ion is not necessary the most abundant of the high O ions

According to TNG, for OVI, OVII, and OVIII, the largest projected column densities are reached in halos of $10^{12}$, $10^{12.5}$, $10^{13}$ solar masses, respectively.
TNG provides expectations for future X-ray/OVII-OVIII campaigns

OVII and OVIII can be seen in absorption in the X-ray
(it has been done in the Milky Way CGM with Chandra and XMM-Newton)

Future X-ray absorption spectroscopy campaigns (e.g. with Lynx) will provide constraints on the highest state Oxygen ions

Nelson, Kauffmann, Pillepich et al. 2018
Looking ahead....

The TNG100 and TNG300 simulations will be fully publicly available by the end of this year.

IMPORTANT LIMITATIONS
In these types of simulations, we do not have:
• radiative transfer
• effects of radiation pressure
• chemistry (no complex molecules)
• dust formation/disruption
• in fact, we do not distinguish between HI and H2

• (anisotropic) termal conduction
• not-ideal MHD
• cosmic rays
• actual BH jets
• ....

ongoing developments in the AREPO community...