Tracing the baryonic cosmic web: predictions from cosmological simulations

Davide Martizzi
Mark Vogelsberger
Maria Celeste Artale
Markus Haider
Paul Torrey
Federico Marinacci
& the rest of the IllustrisTNG Collaboration
My old love: baryon astrophysics

Simulations of Stellar Feedback
(Martizzi+ 2015, 2016, 2019 in prep.)

Cosmological simulations of galaxy clusters with AGN feedback
(Martizzi+ 2012a-b, 2013, 2014a-b, 2016)

Simulations of AGN Feedback
(Martizzi+ 2013, 2019)
My new love: the Baryonic Cosmic Web

Baryonic cosmic structure growth is a multi-physics process.

Multiple galaxy populations and gas phases influenced by:
- Hydrodynamics, e.g. expansion, shocks.
- Radiative processes, e.g. heating, cooling, ionization.
- Gravity and dynamics.
- Location in the Cosmic Web via environment-dependence of the processes above?
Phase 1
The Gaseous Cosmic Web
Studying the Gaseous Cosmic Beacons

Here comes the “simpleton theorist”. For the purpose of this talk:

- A Cosmic Beacon is a very luminous, distant object.
- Transient nature is not necessarily required.
- We need to be able to detect them efficiently in a wavelength range of our choice.
- We’d better be able to take their spectra.

Example: using quasar spectra to detect intervening HI absorbers.

I’m not picky. Candidates: Quasars, GRBs, SNe, TDEs…
Example 1:
Ly-α Forest and Tomography

Density field reconstructed using Ly-α absorbers in the spectra of 240 quasars and galaxies (Lee+ 2018, CLAMATO survey)

~2250 HI absorbers in HST/COS spectra at z<0.75 (Danforth+ 2016)
Example 2: Circumgalactic Medium

Credit: Tumlinson+

Werk+ 2014
Selfish Desires

• See these successes extended to other phases of gas in the Universe at small and large scales.

• See kinematic information added to our knowledge of all gas phases.

• Include topological information on the cosmic web added to the knowledge of all gas phases.

• Make simulation-informed predictions and feasibility studies for future observations of the properties mentioned above.
Cosmological Hydrodynamical Simulations

State-of-the-art cosmological simulations (Illustris, EAGLE, Horizon-AGN, MUFASA, etc.):

- Follow dark matter and gas (hydro)dynamics.
- Include radiative cooling.
- Include models for star formation.
- Include models for stellar and AGN feedback.
- Possibly more physics...
Simulations of choice: IllustrisTNG

This is a suite of cosmological hydrodynamical simulations ran with the moving-mesh code AREPO (Springel 2010).

Solver for collisionless dynamics largely derived from the previous code Gadget-3.

The code combines the advantages of Eulerian and Lagrangian hydrodynamic solvers.

Solutions are Galilean-invariant.

The famous KH instability example
Simulations of choice: IllustrisTNG

<table>
<thead>
<tr>
<th></th>
<th>Illustris</th>
<th>TNG100</th>
<th>TNG50</th>
<th>TNG300</th>
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<td>L75n1820TNG</td>
<td>L35n2160TNG</td>
<td>L205n2500TNG</td>
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<td>yes</td>
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<td>Planck 2015</td>
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<td>2 x 2160^3</td>
<td>2 x 2500^3</td>
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<td>1.39e6</td>
<td>8.47e4</td>
<td>1.1e7</td>
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<td>7.46e6</td>
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<tr>
<td>~EpsilonBaryons [kpc]</td>
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<td>0.7</td>
<td>0.3</td>
<td>1.5</td>
</tr>
</tbody>
</table>

Original Illustris galaxy formation model (Vogelsberger+ 2014)

IllustrisTNG galaxy formation model (Pillepich+ 2018)
Simulations of choice: IllustrisTNG

Notable physical ingredients (Pillepich+2018, Weinberger+2018):

- Ideal MHD included in all runs.

- Star formation assumes Chabrier 2003, IMF.

- Sub-grid model for galactic winds.

- Bi-modal AGN feedback model. Quasar mode = thermal injection. Jet mode = kinetic injection.

\[ v_w = \max \left[ \kappa_w \sigma_{\text{DM}} \left( \frac{H_0}{H(z)} \right)^{1/3}, v_{w,\text{min}} \right] \]

\[ \dot{E}_{\text{therm}} = 0.02 \dot{M} c^2 \]

\[ \dot{E}_{\text{kin}} = \epsilon_{f,\text{kin}} \dot{M} c^2 \]

- Metal advection. Metal yields from SNe type I and II, plus NS-NS mergers (r-process elements).
Simulations of choice: IllustrisTNG

Galaxy Morphologies in TNG100

Pillepich+2018
Simulations of choice: IllustrisTNG

CGM maps in TNG100

Nelson+2018
Baryons in the Cosmic Web of IllustrisTNG

Goals:

• Explore the connection between the state of baryons and the Large Scale Structure.

• Provide a significant update and generalization to previous theoretical prediction on the “Baryon Census”.

• Provide theoretical predictions for the detection of undetected phases.
Gas Phases in IllustrisTNG

Martizzi+ 2018

WHIM: UNDETECTED PHASE OF THE IGM

WHIM could be detected by X-ray absorption spectroscopy

“Old” Illustris  
- Where are these phases?
- Is topological information important if we want to find them with Cosmic Beacons?

IllustrisTNG

WHIM—UNDETECTED PHASE OF THE IGM

WHIM could be detected by X-ray absorption spectroscopy
Let’s add info on the Cosmic Web

Martizzi+ 2018

We need a Cosmic Web classification method:

\[ \delta(x,R) \]

Over-density smoothed on some scale \( R \)

<table>
<thead>
<tr>
<th>Cosmic Web Class</th>
<th>W = 0  -  Knot</th>
</tr>
</thead>
<tbody>
<tr>
<td>W = 1  -  Filament</td>
<td></td>
</tr>
<tr>
<td>W = 2  -  Sheet</td>
<td></td>
</tr>
<tr>
<td>W = 3  -  Void</td>
<td></td>
</tr>
</tbody>
</table>

I use a classic method developed by Forero-Romero+2009.
Let’s add info on the Cosmic Web
Martizzi+ 2018

Forero-Romero+2009 method. In the Zel’dovich approximation the deformation tensor determines whether a particular region will undergo gravitational collapse along a given axis.

Step 1: Measure the deformation tensor.
\[ \nabla^2 \phi = 4\pi G \bar{\rho} \delta \]
\[ \Psi_{ij}(x) = \partial_i \partial_j \phi(x) \]

Step 2: Diagonalize the deformation tensor.
\[ \text{det}(\Psi(x) - \lambda(x)I) = 0 \]

- 3 principal axes at each location.
- Measure N = number of axes along which the structure collapses (\( \lambda > \text{threshold} \)).
- Cosmic Web Class \( W = (3-N) \).
Cosmic Web Classification
Mass Fraction of Collapsed Structures

IllustrisTNG - TNG100
Martizzi+2018

Cosmic Web Classification performed on a density field smoothed on a scale $R = 4 \text{ Mpc/h.}$
Gas in Knots, Filaments, Sheets and Voids

Multiple gas phases are influenced by the location in the Cosmic Web.
Gas in Knots, Filaments, Sheets and Voids

Study the evolution of gas fractions in different phases.

- WHIM and Diffuse IGM dominate the budget.
- WHIM becomes dominant only at $z<1$.
- Diffuse IGM dominates voids and sheets.
- WHIM is prominent only in filaments and knots.
- Knots are the only regions with significant Hot Medium.
Gas Metallicities

Martizzi+2018

The WHIM is metal rich compared to the Diffuse IGM.
Ionization State

Artale+ (in prep.)
Gas in Knots, Filaments, Sheets and Voids

Diffuse IGM and WHIM populate different regions of the cosmic web. In fact the WHIM only occupies ~10% of the volume at z=0. The Diffuse IGM occupies ~89% of the volume at z=0.
Column Densities of “WHIM” Absorbers

WHIM OVII has been recently detected by Nicastro+ 2018. Is it WHIM?
Work so far

• Explore the connection between the state of baryons and the Large Scale Structure. DONE.

• Provide a significant update and generalization to previous theoretical prediction on the “Baryon Census”. DONE.

• Provide theoretical predictions for the detection of undetected phases. FOLLOW-UP WORK.
Athena X-ray Observatory

The X-IFU proposed for Athena will have:

- 2.5 eV spectral resolution.
- FoV 5 arcmins.
- 5” pixels.

Credit: Athena team

Kaastra+ 2013 proposed to observe 25 AGN and 40 GRB afterglows over 5 years.

Still feasible according to updated models and Athena specs?
Synergy Needed with Observers

- Are the specs of future X-ray telescopes sufficient?
- Can a “wide survey of Cosmic Beacons” be designed with these specs?
- Quasars are natural targets to study WHIM absorption...
- What about GRB afterglows? Any future telescope with fast pointing features?
- There is a lot of time before Athena is launched. There is enough time to make proof-of-concept studies and predictions.
Phase 2
Galaxies in the Cosmic Web
(Very Preliminary)
Galaxy Formation

- Hierarchical evolution determined by dark matter halo merger tree.
- Galaxy properties depend on processes internal to dark matter halos. E.g. feedback, secular processes.
- Galaxy properties can be influenced by external processes. E.g. ram-pressure stripping and galaxy harassment in galaxy clusters.
- Does the large scale Cosmic Web morphology leave an imprint on galaxy properties?
Galaxy-Filament Alignments

Krolewski+2019: measure alignment between galaxy spins and cosmic filaments using MaNGA galaxies.

Mass dependent spin alignment?
Galaxies vs. Cosmic Web

From Kraljic+2018
Analysis of GAMA galaxies
Stellar mass function vs. Environment

From Etherington+2017
Analysis of DES galaxies
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

- Dark Matter Halo Mass $= M_{dm}$
- Stellar Mass $= M_{star}$
- Galaxy sSFR
- Galaxy Colors
- Formation time $z_{form}$
- Large-scale over-density $\delta(R=8 \, \text{Mpc/h})$
- Cosmic Web Class $= W$

How do they correlate?
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

- Dark Matter Halo Mass = $M_{dm}$
- Stellar Mass = $M_{star}$
- Galaxy sSFR
- Galaxy Colors
- Formation time $z_{form}$
- Large-scale over-density $\delta(R=8 \text{ Mpc/h})$
- Cosmic Web Class = $W$
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

- Dark Matter Halo Mass = \( M_{\text{dm}} \)
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- Formation time \( z_{\text{form}} \)
- Large-scale over-density \( \delta(R=8 \, \text{Mpc}/h) \)
- Cosmic Web Class = \( W \)
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

Are the two parameters completely degenerate???
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

$\delta$ is just the over-density.

$W$ traces the shape of the over-density field.

The variables correlated, but with a large scatter.

They are not entirely degenerate.

More on this to be published in Martizzi+ (in prep.).
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).
Galaxies vs. Cosmic Web

Get predictions from cosmological hydro simulations (IllustrisTNG).

![Graph showing the relationship between quenched fraction and redshift for different mass bins.](image)

Increasing Stellar Mass

All Galaxies
Conclusions

• Current and future galaxy (redshift) surveys allow Cosmic Web reconstruction.

• Cosmological hydrodynamical simulations predict interesting effects that connect galaxy properties to the properties of the large scale Cosmic Web.

Suggestions:

Go to your survey, apply a Cosmic Web Classification method and measure new effects!