Galaxy Formation and Dark Matter

Thiago S. Gonçalves
Karín Menéndez-Delmestre
Observatório do Valongo
Universidade Federal do Rio de Janeiro
Valongo Observatory
Astronomy Department of the Federal University of Rio de Janeiro
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• 60 years forming undergraduate Astronomy students
  – the only one in Brazil until very recently
• >10 years of Master Program, ~5 years of PhD program
• Demographics:
  – 14 professors
  – ~5 postdocs
  – 12 master students
  – 10 PhD students
  – 20 new undergrads/semester
Astronomy in Brazil

80 institutes in total
(based on the Brazilian Astronomical Society 2011 census)

- UFRN  +3
- UESC  +1
- LNA
- UFMG  +5
- Valongo/UFRJ
- National Observatory  +9
- CBPF
- IAG/U. São Paulo  +17
- INPE
- UFSC  +3
- UFRGS  +7

+22 other institutes, including SOAR!
Astronomy in Brazil

- Gemini North/South (8m)
  - 4.4% (250hrs/year)
- CFHT (3.6m)
  - 10-20 nights/year
- SOAR (4.2m)
  - 100 nights/year
- Pico dos Dias (1.6m)
- ESO/ALMA

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Galaxy formation: The classical view
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Formation of the large-scale structure

Planck collaboration

Illustris
Galaxy formation: The classical view

The interstellar medium (ISM): gas and stars

Non-linear processes: mechanical & radiative feedback, turbulence, magnetic fields

Gastrophysics
Galaxy formation: The classical view

Cosmologists

73% DARK ENERGY
23% DARK MATTER
3.6% INTERGALACTIC GAS
0.4% STARS, ETC.

NASA
Galaxy formation: The classical view

**Extragalactic Astrophysicists**

- 73% Dark Energy
- 23% Dark Matter
- 3.6% Intergalactic Gas
- 0.4% Stars, etc.

NASA
Galaxy formation: The classical view

But dark matter is a fundamental ingredient.
Galaxy formation: The classical view

Classical view: gas collapse and disk formation

Baugh (2006)
High redshift: A different paradigm
High-redshift: a different paradigm

The universe was forming stars more rapidly in the past

Madau & Dickinson 14
Protoclusters and the Establishment of the Galaxy-Environment Relation

Karín Menéndez-Delmestre
Valongo Observatory
Federal University of Rio de Janeiro, Brazil
Galaxy properties are connected to the environment

- **Morphological segregation**

The diagram shows the fraction of different galaxy types (Spirals + Irregulars, Lenticulars, Ellipticals) as a function of the logarithm of the projected density. The density is measured in Mpc$^{-2}$.

Dressler+80

ACS/HST: Abell 1689
Galaxy properties are connected to the environment

- **Morphological segregation**

![Diagram showing the relationship between galaxy morphology and log (projected density) [Mpc$^{-2}$].](image)

Dressler+80

ACS/HST: Abell 1689

**Denser environments**

Fraction

- Spirals + Irregulars
- Lenticulars
- Ellipticals
Galaxy properties are connected to the environment

- **Morphological segregation**

![Diagram showing morphological segregation](image)

Fraction of spirals (star-forming galaxies) decreases with increasing galaxy number density

- **Denser environments**

   - Ellipticals
   - Lenticulars
   - Spirals
   - Irregulars

- **Dressler+80**
What’s the origin of the galaxy-environment relation? Nature or Nurture? (that is the question...)

Nature?
• The environment establishes different initial conditions for different galaxies
• Galaxies are intrinsically different from the beginning
• The formation of ellipticals occurs at high-z in the densest regions
What’s the origin of the galaxy-environment relation? Nature or Nurture? (that is the question...)

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Nurture?
- Galaxies follow different evolutionary paths, depending on their local environment.
- Dense environments transform actively star-forming galaxies into more quiescent galaxies via interactions and removal of gas.

Kenney et al. 2003
What’s the origin of the galaxy-environment relation? Nature or Nurture? *(that is the question...)*

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BOTH?

• There are isolated galaxies with low star formation rates à the environment is not the only determinant!
What’s the origin of the galaxy-environment relation?

- Need to look back at the peak epoch of galaxy formation, where initial conditions likely set the stage for the establishment of the galaxy-environment relation.

Outstanding challenges remain to identify and characterize overdense regions in the distant universe.

Madau & Dickinson 2014
How to identify galaxy-overdense regions?

At low redshift:

1. **Galaxies**
   - Optical/near-IR/mid-IR: look for the **red sequence** in already-established clusters

(Gladders & Yee 2000)
How to identify galaxy-overdense regions?

At low redshift:

1. Galaxies
2. Gas
   - X-ray: trace the hot intracluster gas (e.g., Chandra, XMM)

Chandra images
Credit: NASA/CXC/MSFC/M.Bonamente et al.
How to identify galaxy-overdense regions?

At low redshift:

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2. Gas
   - X-ray
   - Sunyaev-Zeldovich effect using CMB experiments (SPT, ACT, Planck)

Abell 2319 Planck/ESA
How to identify galaxy-overdense regions?

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3. Gravitational lensing
   - Currently expensive, but, e.g., ESA’s Euclid mission, ~2020
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No perfect approach... out to \( z \sim 1-2 \)
(though extending further with follow-up of SZ-detections)

By the nature of these techniques, (most of) of these clusters are already "formed"
Protocluster tracers at higher redshifts

- Radio galaxies and quasars have been used to map the large scale structure at $z \sim 2.5$ (e.g., Venemans+02, Kurk+04, Overzier+05)

Largest black holes (and biggest galaxies) at high redshift, so likely progenitors of BCGs!
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Protocluster at $z \sim 2.2$ around radio galaxies with Subaru Telescope (Shimakawa+14)
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Approach:
Look for “more normal” galaxies in the vicinity of these tracers

$\lambda(\text{H}\alpha) = 6563\text{Å}$

Traces galaxy continuum dominated by line emission

Narrow-band

H$\alpha$ emitting galaxies
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- Protocluster galaxies are already more evolved than those in the field $\rightarrow$ accelerated formation in dense regions

Already evidence for enhanced evolution

Steidel et al. 2005
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Quite successful approach

- Ly-\( \alpha \) emitters
  - Around radio galaxy TN J1338-1942
  - Kurk+04

- H\( \alpha \) emitters
  - Around radio galaxy PKS 1138-262
  - Venemans+02

- H\( \alpha \) emitters at \( z \sim 2.2 \)

- Ly-\( \alpha \) emitters
  - \( z \sim 4.2 \)
Protocluster tracers at higher redshifts

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**HOWEVER:**

1. These tracers represent a short stage in the life of a galaxy ($\sim 10^7$ years)
2. Radio fluxes drop with redshift
   - strong observational bias towards more evolved structures

Many additional forming clusters... We need more abundant (somewhat less extreme) tracers!
High-Redshift Ultra-luminous Galaxies – untapped tracers of large-scale structure

- More abundant than QSOs by a factor of ~5-10 (Chapman+03+05, Coppin+06)
  - Submillimeter-selected ULIRGs

\[ \log_{10} F_{\nu} \left( W m^{-2} \right) \]

\[ \lambda (\mu m) \]

\[ 850 \mu m \]

\[ @ z \sim 2 \]

Kennicutt+03
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Why is the submm selection so special?
- "Normally", the further a galaxy is, the fainter it appears

![Graph showing flux density vs. redshift with various wavelength bands like optical, near-IR, radio, and mid-IR.](image)
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Why is the submm selection so special?
• “Normally”, the further a galaxy is, the fainter it appears
• (negative) K-correction in the submm/mm beats the odds!
  – As we search for galaxies further and further away, the submm/mm flux stays approximately the same!

SMGs are just as submm-bright at z~1 as they are at z~5 → key to inspect the very distant universe!
Submm Galaxies: Signposts of Protoclusters
(an on-going investigation...)

Co-Is: Peter Capak (Caltech, EUA), Andrew Blain (Leicester, UK), Kartik Sheth (NRAO, EUA), Thiago S. Gonçalves (Valongo/UFRJ), Claudia Scarlata (U. Minnesota, EUA), Aldée Charbonnier (Valongo/UFRJ), Harry Teplitz (Caltech, EUA), Paulo A. Lopes (Valongo/UFRJ)

Keck LRIS

Palomar LFC

Magellan IMACS
Submm Galaxies: Signposts of Protoclusters
(an on-going investigation…)

- We target candidate overdensities at $z \sim 1-5$
  - $> 4$ Gyr during which a protocluster slowly approaches virialization

**Steps**

1. **Identification** of overdensity members

Narrow-band selection of Ly$\alpha$ emitters

[Graphs and plots showing Ly$\alpha$ emission and redshift distributions]
Submm Galaxies: Signposts of Protoclusters
(an on-going investigation…)

• We target candidate overdensities at z~1-5
  > 4 Gyr during which a protocluster slowly approaches virialization

Steps
① Identification of overdensity members

![Redshift peaks around SMGs](image_url)
We target candidate overdensities at $z\sim1-5$

- $>4$ Gyr during which a protocluster slowly approaches virialization

Steps

1. Identification of overdensity members
2. Characterization of overall significance of the overdensity

- use studies of Ly$\alpha$ emitters in the field (i.e., outside of overdensity) at similar redshifts as a control comparison

(e.g., Large Lyman Alpha Survey; Rhoads et al. 2000)
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Tracers of halos with more modest masses, caught in an active period

→ SMGs appear to trace a wider range of environments!

HDF-North at z=1.99

SMGs
SFRGs
UV-selected

Chapman+09
Submm Galaxies: Signposts of Protoclusters
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Steps

① Identification of overdensity members
② Characterization of overall significance of the overdensity
③ Follow-up study of overdensity members to extract individual/stacked galaxy properties (e.g., mass, activity), probing for trends in the spatial distribution.

IMACS

Spitzer IRAC: 3.6, 4.5um
Submm Galaxies: Signposts of Protoclusters
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  > 4 Gyr during which a protocluster slowly approaches virialization

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① Identification of overdensity members
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③ Follow-up study of overdensity members to extract individual/stacked galaxy properties (e.g., mass, activity), probing for trends in the spatial distribution
④ Assessment of distribution in galaxy properties according to protocluster maturity (e.g., overdensity mass, gaussianity of the relative velocity of overdensity members)
Take Away Points

- Most massive structures formed over a wide redshift range
  - They are forming their stars/galaxies at z>2
  - Need to probe higher redshifts to trace the origin (and evolution) of the galaxy-environment relation
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• Most massive structures formed over a wide redshift range
  – They are forming their stars/galaxies at z>2
  – Need to probe higher redshifts to trace the origin (and evolution) of the galaxy-environment relation
• Radio galaxies have been successfully used as tracers of protoclusters, but need more abundant tracers at high redshift!
• SMGs appear to be good tracers of overdense regions at z>1
  – tracers of structures with modest masses caught in highly active periods
  → SMGs may be tracers of a wider range of environments beyond the progenitors of todays very rich clusters
Take Away Points

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• With our program we aim to probe for changes in the distribution of galaxy properties and explore the way galaxy and local environment relate to each other within the broader picture of a cosmologically-evolving overdensity.
The Nebular Gas in star-forming galaxies at high redshift
Star formation in galaxies
Star formation in galaxies

Local universe
Star formation in galaxies

Local universe

High redshift
Cold flows

Dekel & Birnboim 2006
Interactions and mergers?
IFU studies at z~2

Förster-Schreiber+09

Law+09
IFU studies at $z \sim 2$

Förster-Schreiber+09

Law+09
**High velocity dispersion**

**Stellar mass dependence of observables**

Virial mass: $2K+U = 0$

What is the main dynamical component?
Analogs at low redshift

- $z \approx 0.2$
- Selected by ultraviolet luminosity and surface brightness
Analogs at low redshift

Overzier+11

Santos-de-Oliveira+ in prep


- Local relation: more massive objects have greater metallicities.
- One explanation for this relationship is the stellar winds – produced by supernovae.
- Low-mass galaxies → small potential well → enriched material ejected from the galaxy → lower metallicities.

Our sample of compact and supercompact UVLGs are found below the local relation.

Overzier+11

Santos-de-Oliveira+ in prep

Low extinction

Low metallicities

Lyman break analogs (LBAs)
• Compact objects, high SFR, strong line emission – great case!
• Resolution down to 200pc with AO, very close to diffraction limit in a 10m telescope
• Observed line: Pa-α in the K-band
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Data at high $z$?

Real data

Artificially redshifted to $z=2.2$

Gonçalves+10

Law et al. 2007
More massive objects show stronger velocity shears with similar values to high-z
 Stellar mass dependence

More massive objects show stronger velocity shears with similar values to high-z

Gonçalves+10
Reddy & Steidel, 2009

The diagram shows the number density of galaxies as a function of their stellar mass. The x-axis represents the logarithm of the ratio of the galaxy's stellar mass to the solar mass ($\log[M_*/M_\odot]$), while the y-axis shows the number density per cubic megaparsec per decade. The data points and curves are used to compare different models or observations.
Reddy & Steidel, 2009
• Asymmetry measurement
• Distinction between mergers and rotating disks
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- Distinction between mergers and rotating disks
High-redshift data underestimates the asymmetry levels
Can we detect mergers at high redshift?

Overzier et al. 2010
Can we detect mergers at high redshift?

Overzier et al. 2010
Robertson & Bullock (2008)
Robertson & Bullock (2008)

This is a merger.

Kinematic properties depend on gas fraction of the interacting galaxies.
Kinematic properties depend on gas fraction of the interacting galaxies.
Dynamical mass ($\sigma$)

The impact of star formation

Gonçalves+10
Environment of LBAs

What is the environment of LBAs?
Luidhy Santana da Silva, PhD student

The ELBA/DECam survey:
• 3 sq. degrees at a time
• 4 bands \((u,g,r,i)\)
• equatorial fields
• detection limits \((10-\sigma\ AB, \text{ estimated})\):
  25.0 \((u)\), 26.0 \((g)\), 25.5 \((r)\), 24.5 \((i)\)
  (complete at \(z\sim 0.2\) down to \(10^9\ M_{\text{sun}}\))
• 27 sq. degrees completed thus far
ra 14:34:46.23
dec +02:02:56
equinox J2000
scale 0.676 arcsec/pix
width 6.76 arcmin
height 6.76 arcmin
ra: 14:34:46.23
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DECam
• Dark matter is taken for granted when it comes to galaxy formation studies, but it is fundamentally important.

• The formation of structures across cosmic time is heavily influenced by the dark matter content. How can we measure this?

• The same is true for galaxy formation within dark matter haloes.
Summary

• Dark matter is taken for granted when it comes to galaxy formation studies, but it is fundamentally important.

• The formation of structures across cosmic time is heavily influenced by the dark matter content. How can we measure this?

• The same is true for galaxy formation within dark matter haloes.