The final frontier of galaxy formation with galaxy clusters as cosmic telescopes

MARUŠA BRADAČ
And now for something completely different....

- When did reionization occur and how?

- What are the sources of first light? Can they sustain reionization?

- What are the properties of first galaxies?

...to see the first light in the Universe...
Some big open questions….

• When did reionization occur?

• What are the sources of first light? Can they sustain reionization?
  • Galaxies: steep LF ?, older stellar population ?, large $\xi_{\text{ion}}$ ?, $f_{\text{esc}}=0.2$ ?
  • Quasars: $f_{\text{esc}}=1.0$ ?, faint-end LF ✗

• What are the properties of first galaxies? 👀
Old stellar population

Detect + young stellar population

Topology of reionization, z confirmation

Gas reservoir, z confirmation
A LF extending to 0.001L∗?
Luminosity function → lensed version

Livermore et al. 2016
Some big open questions....

• When did reionization occur and how? 👏

• What are the sources of first light? Can they sustain reionization?

  • Galaxies: steep LF 👏, older stellar population ?, large ξ_{ion} ?, f_{esc}=0.2 ?

  • Quasars: f_{esc}=1.0 ?, faint-end LF ?

• What are the properties of first galaxies? 👀
Old stellar population

“90,000 dollars for every single target”
G. Tremblay
Galaxy clusters are fantastic!

MACS1149

Finney et al. 2018

\[ f^* = 0.012 \pm 0.004 \]
Galaxy clusters are fantastic!

MACS0416
$f^* = 0.009 \pm 0.003$
(Hoag et al. 2016)

A370
$f^* = 0.008 \pm 0.003$
Strait et al. 2018 in prep.
SURFS UP: Spitzer UltRa Faint SUrvey Program

- Sources responsible for reionization ($z \gtrsim 7$):
  - Star formation rates and stellar masses of a large number of galaxies (50 at $z \sim 7$ and 10 at $z \sim 8$)
  - Reconstructing the cosmic SFR and EOR


Old (~300Myr) stellar population in MACS1149–zD

The age of the universe at $z \sim 9.5$ is $\sim 520$Myr.

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• What are the properties of first galaxies? 👀
A spectrum is worth 10,000 pictures...
LAEs as a probe of reionization

Number evolution: $\varepsilon = 0.5$

Dimming: $\varepsilon = 0.5$

$z=6$

$z=7$

Tilvi et al.
LAEs behind MACS2129 with KECK

Huang et al. (incl MB) 2016

KECK follow up: PI Bradač
LAEs as a probe of reionization

MACS2129:1412

Huang et al. (incl MB) 2016

$z = 6.846 \pm 0.001$

$M^* = 2 \times 10^7 M_\odot$

$L = 0.14 L^*$
LAE behind MACS1423

Hoag, MB et al. 2017
WHAT ABOUT DUST?
GAS RESERVOIR, Z CONFIRMATION
Dust and \([\text{CII}]\) at \(z \sim 7\) with ALMA

CII detected at \(z \sim 7\)

Low \(\Delta v\) indicates possible Lyman continuum escaping

Bradač et al. 2016
Some big open questions....

• When did reionization occur?👏

• What are the sources of first light? Can they sustain reionization?
  • Galaxies: steep LF 👏, older stellar population 👏, large $\xi_{ion}$ 👏, $f_{esc}=0.2$ 👏

• What are the properties of first galaxies? 👏
Future is bright, magnified by lensing

41 clusters with HST imaging to study $z=7-11$ universe

190 orbits with HST in Cycle 23

550 hours with Spitzer

3(+6) nights with Keck

PI Coe, Spitzer PI Bradač

HST > 0.4 microns
- WFC3/IR
- NICMOS
- ACS / UVIS
- WFPC2
- no HST
- Frontier Fields
- CLASH
- RELICS

120” × 120” HST Image
Abell 2537

400” × 300” Spitzer Image
RXC J0600.1–2007
Future is bright, magnified by lensing

Salmon et al (incl MB) 2018
The future is JWST

- Study nebular emission lines at $z \sim 10$
- Detailed studies of sSFR, SFR, ages, metallicity of galaxies that are responsible for reionization.
- LAE fraction characterized to $<10\%$ precision
- Study velocity offsets between Ly$\alpha$ and systemic (study LyC escaping) for sub–L$^*$ galaxies.
- And SO MUCH MORE!!!! CLUSTER STUDIES!!!

...to see the first light in the Universe...
### Table 2: Target List.

<table>
<thead>
<tr>
<th>Cluster</th>
<th>RA</th>
<th>DEC</th>
<th>Redshift</th>
<th>Survey</th>
<th>JWST Visibility Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abell 370</td>
<td>02:39:52.8</td>
<td>-01:34:36</td>
<td>0.375</td>
<td>HFF</td>
<td>24 Jul-16 Sep + 12 Dec-02 Feb</td>
</tr>
<tr>
<td>M0416.1-2403</td>
<td>04:16:09.4</td>
<td>-24:04:04</td>
<td>0.395</td>
<td>HFF</td>
<td>12 Aug-09 Nov + 27 Nov-22 Feb</td>
</tr>
<tr>
<td>M0417.5-1154</td>
<td>04:17:34.7</td>
<td>-11:54:32</td>
<td>0.443</td>
<td>RELICS</td>
<td>17 Aug-20 Oct + 26 Dec-24 Feb</td>
</tr>
<tr>
<td>M1149.6+2223</td>
<td>11:49:35.9</td>
<td>+22:23:55</td>
<td>0.543</td>
<td>HFF</td>
<td>19 Apr-15 Jun + 05 Dec-27 Jan</td>
</tr>
<tr>
<td>M1423.8+2404</td>
<td>14:23:47.8</td>
<td>+24:04:40</td>
<td>0.545</td>
<td>CLASH</td>
<td>13 May-24 Jul + 08 Jan-15 Mar</td>
</tr>
</tbody>
</table>

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**JWST ERS A2744**

Through the looking GLASS: a JWST exploration of galaxy formation and evolution from cosmic dawn to present day (PI Treu)