Rare Galaxies in the Early Universe
Subaru 20th Anniversary Meeting, Waikoloa, HI — 19 November 2019

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Large Scale Structure revealed in the COSMOS field.

Subaru: A revolutionary wide field of view.
$\Lambda$-CDM dictates that early Universe star-formation is highly clustered; “protoclusters” occupy large volumes.

Chaing et al. (2017)

Muldrew et al. (2015)
Percentage of ALL star formation embedded within progenitors of $>10^{14}\,M_\odot$ clusters:

- 15% at $z\sim 2$
- 30% at $z\sim 4$
- 40% at $z\sim 6$

Chaing et al. (2017)
SSA22: An exquisite example of intense star-formation in a “protocluster” environment at $z=3.1$
From Postage Stamps to Environmental Characterization ($z \sim 2-3$)

SSA22 survey from VIRUS on HET
(4200 LAEs btw 1.9<z<3.5)
Matsuda et al. (2005)

COSMOS $z \sim 2.5$ structure, Figure from Cucciati et al. 2018,
also Chiang et al. 2015, Casey et al. 2015, Casey 2016, Lee et al. 2017

Data from VIRUS on the HET at McDonald Observatory:
wide-field (12’) blue IFU used for HETDEX
Protocluster Imaging from HSC on degree scales based on drop-out selection techniques

PFS will be revolutionary in following up and confirming candidate structures: mapping their 3D distribution.
Pushing toward z>5-7: Reionization is patchy.

Rare galaxies act as beacons of Reionization Bubbles. i.e. Quasars, Radio-loud AGN, dusty star-forming galaxies, and UV-luminous galaxies.
dusty star-forming galaxies (DSFGs) as beacons of overdense environments in the first Gyr

- longer duty cycle than QSOs,
- more common than QSOs and equally massive,
- directly tied to stars in massive galaxies at lower-z.

SPT0311 at z=6.9; Strandet et al. 2017, Marrone et al. 2018
Why/how are dusty galaxies so fundamentally different than ‘normal’ galaxies?

Obscuration scales with mass — galaxies with high stellar mass and SFR are highly obscured.
dusty star-forming galaxies (DSFGs) are the most massive systems to be found at high-z

how did they mature so quickly post-Big Bang?
Where did the dust come from? (AGB stars? SNe?)

AGB Stars:
source of 50% of dust in ISM locally, but production rate not sufficient to explain all, need > 400 Myr post-SF to form Gehrz 1989, others, Matsuura et al. 2009, 2013

SNe:
destroy more dust than they produce. yield from 20M\textsubscript{sun} progenitor is \sim 0.15M\textsubscript{sun} of dust Nozawa et al. 2010, Cherchneff & Dwek 2010

ISM Grain Growth:
critically dependent on metallicity, with short-duration bursts requiring more metals Asano et al. 2013
Nuances in identification — redshifts are hard.

Very bright submm/mm flux densities used to select these sources is \( \sim \) constant with redshift.

e.g. Blain et al. 2002, Casey, Narayanan & Cooray 2014

Low resolution (single dish) obfuscates counterparts.

The rest-frame UV fluxes and colors used to find Lyman-break Galaxies map directly to redshift.

e.g. Steidel et al. 1996, Reddy & Steidel 2009.

They have good phot-z’s by definition.
Look to longer wavelengths over wide areas: 2mm, 3mm over 0.1-1deg\(^2\) to filter out low-redshift interlopers.
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2mm, 3mm over 0.1-1deg²
to filter out low-redshift interlopers

ALMA Cycle 6 Program (15 hours)
2mm, 0.08mJy RMS, 155arcmin²

In collaboration with: **Jorge Zavala**, Dave Sanders, Alex Karim, Jackie Champagne, Allison Man, Sune Toft, **Sinclaire Manning**, Karina Caputi, Anton Koekemoer, Elisabete da Cunha, Justin Spilker, Min Yun, Manuel Aravena, Joaquin Vieira, Kirsten Knudsen, Margherita Talia, Georgios Magdis, Chris Hayward, Johannes Staguhn, Marcella Brusa, Nick Scoville, Jean-Baptiste Jolly, Vernesa Smolcic, Matthieu Bethermin, Patrick Drew, Steve Finkelstein, Kartik Sheth, Peter Capak, Yoshi Taniguchi, Olivier Ilbert, Meg Urry, Jackie Hodge, Dave Clements, Seiji Fujimoto, Gabe Brammer, Ezequiel Treister, Jeyhan Kartaltepe (COSMOS Team)
ALMA Cycle 6 DDT for redshift confirmation
8 hours (!!) needed

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MAMBO-9: the most distant unlensed DSFG at z=5.85
Analysis of the 2mm map & sources: coming soon!

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<th>F814W</th>
<th>F125W</th>
<th>F160W</th>
<th>Ks</th>
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<th>4.5um</th>
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12 robust sources identified $>5\sigma$. 

Jiminez-Andrade et al. (2019)

"HST-dark" Casey et al. (2019)
Best-constrained obscured SFRD constraints from 3mm

Benefits from many CO programs at \( z \sim 1-2 \)

New constraints on SFRD from 3mm

ALMA Archival search:
found \( \sim 15 \) sources in 200arcmin\(^2\)

Jorge Zavala et al. 2018
Summary: Rare galaxies in the early Universe

Early Universe star-formation is highly clustered: expect it to sit in protoclusters on half degree scales.

Characterizing the patchiness of the Reionization Era will require a significant investment of existing facilities (HST, HSC) on degree scales.

There’s a fruitful population of rare galaxies between quasars and LBGs/LAEs: dusty starbursts.

We are just beginning to measure DSFG volume densities at z>3 using 2mm & 3mm wide-area surveys: synergy with large area imaging and long wavelength facilities crucial.