Growing in Dual
A SCUBA-2 Survey on Quasars hosting Lyman Alpha Nebula at Cosmic Noon

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Development of Massive Elliptical Galaxies

TODAY
13.7 billion years

Local elliptical galaxy

5 billion years
Merging galaxies

3 billion years
Compact galaxy

2 billion years
Quasar

1.5 billion years
Dusty starburst galaxy

1 billion years
Merger

BIG BANG
Rate of stellar mass assembly
(Star Formation Rate)

\[ \geq 10^{11} \, M_\odot \]

\[ \geq 100 \, M_\odot/yr \]

Stellar mass
Rate of stellar mass assembly
(Star Formation Rate)

\[ \geq 100 \, M_\odot/yr \]

Stellar mass \[ \geq 10^{11} \, M_\odot \]

Active star formation with loads of gas and dust
- S2CLS,
- S2COSMOS,
- STUDIES,
- S2LXS,
- NEPSC2,
- AWESOME...

Development of Massive Elliptical Galaxies

NASA, ESA, S. Toft, and A. Feild
The rate of stellar mass assembly (Star Formation Rate) is $\gtrsim 100 \, M_\odot/yr$. Stellar mass is $\gtrsim 10^{11} \, M_\odot$. This work focuses on the key transition phase between SF and blackhole accretion. RAGERS - This work.
QSO-SMG coevolution

Evidence from cross correlation

Herschel 250/350/500 micron

<z=2.5> SDSS quasars

Wang et al. 2015
QSO-SMG coevolution
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Emissions from quasars

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QSO-SMG coevolution

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<z=2.5> SDSS quasars

Emissions from quasars

Coevolving SMGs at ~10 Mpc scales

Wang et al. 2015
Halos hosting QSOs / SMGs

Two-point auto-correlation functions

$$\xi_2(\Delta) = \frac{1}{V} \int d^3x \, \delta(x)\delta(x + \Delta).$$
Halos hosting QSOs / SMGs

Two-point auto-correlation functions

\[ \xi_2(\Delta) = \frac{1}{V} \int d^3x \, \delta(x) \delta(x + \Delta). \]
Halos hosting QSOs / SMGs

Two-point auto-correlation functions

\[ \xi_2(\Delta) = \frac{1}{V} \int d^3x \, \delta(x) \delta(x + \Delta). \]
Halos hosting QSOs / SMGs
Both hosted by halos with $\sim 10^{13}$ solar masses
and would evolve into present day galaxy clusters

Two-point auto-correlation functions

$$\xi_2(\Delta) = \frac{1}{V} \int d^3x \, \delta(x) \delta(x + \Delta).$$

Lim, CCC et al. 2020
Theoretical perspectives on proto-clusters

Chiang et al. 2017
Theoretical perspectives on proto-clusters

Much more extended in the early times

Chiang et al. 2017
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Chiang et al. 2017

ALMA

z~2-3

Protocluster \langle R_L \rangle
Protocluster Core \langle R_{200} \rangle

Procluster Membership Probability

r [comoving Mpc]
Theoretical perspectives on proto-clusters

Much more extended in the early times

Chiang et al. 2017

Theoretical perspectives on proto-clusters

Much more extended in the early times

Chiang et al. 2017
QSO sample [QSO-MUSEUM]

Quasars hosting Lyα Nebula uncovered by MUSE

FAB et al. 2018
**ELAN : Enormous Lyα Nebula**

- Discovered with narrow-band and VLT/MUSE
- $2 < z < 3.2$
- Only $\sim 5\%$ of relatively bright quasars ($M_i < 24$) show such nebulae
- Together with the brightness and the physical extend of Lyα, evidence suggest a large amount ($10^{10}-10^{11}$ solar masses) of cool ($T \sim 10^4 \text{K}$) and clumpy ($C \sim 100$) gas.

Cantalupo+2014, Hennawi+2015, Cai+2017, FAB+2018
Classes of Lyα Nebula

Ouchi+2020
SCUBA-2 850 micron observations

-1 mJy/beam r.m.s. at 850 micron
SCUBA-2 850 micron observations

-1 mJy/beam r.m.s. at 850 micron

FAB, CCC, et al. 2018;
Nowotka, CCC, FAB, et al. 2022
SCUBA-2 850 micron observations

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Number counts analyses

Methodology - making mock images with models to account for various effects

Casey et al. 2014
Number counts analyses

Methodology - making mock images with models to account for various effects

Construct noise/jackknife map

\[
\begin{align*}
\left( \frac{t_1}{t_2} \right) \times \frac{1}{\sqrt{t_1 + t_2}}
\end{align*}
\]

Respective exposure times of \( t_1 \) and \( t_2 \)

Casey et al. 2014
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\[
\left( \frac{t_1}{t_1 + t_2} \right) \times 1 / \sqrt{t_1 + t_2}
\]

Respective exposure times of \( t_1 \) and \( t_2 \)

Inject sources drawn from \( dN/dS \) into jackknife map, for example:

\[
\frac{dN}{dS} = \begin{cases} 
\frac{N_0}{S_0} \left( \frac{S}{S_0} \right)^{-\alpha} & : S \leq S_0 \\
\frac{N_0}{S_0} \left( \frac{S}{S_0} \right)^{-\beta} & : S > S_0 
\end{cases}
\]

Choose best-guess \( N_0, S_0, \alpha, \beta \)

Randomize source positions, convolve with beam.

Casey et al. 2014
Number counts analyses

Methodology - making mock images with models to account for various effects

Construct noise/jackknife map

\[
\left( \frac{1}{\sqrt{t_1 + t_2}} \right) \times \left( \begin{array}{c} t_1 \\ t_2 \end{array} \right) = \left( \begin{array}{c} \frac{1}{\sqrt{t_1 + t_2}} \end{array} \right)\left( \begin{array}{c} t_1 \\ t_2 \end{array} \right)
\]

Respective exposure times of \( t_1 \) and \( t_2 \)

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\end{cases}
\]

Choose best-guess \( N_0, S_0, \alpha, \beta \)

Randomize source positions, convolve with beam.

Measure \( dN/dS \), compare sims maps to real map \( dN/dS \)

Alter choice of \( N_0, S_0, \alpha, \beta \) until best agreement with real \( dN/dS \) is found (e.g. Markov Chain method)

Casey et al. 2014
Results - number counts
Results - number counts

![Graph showing number counts and Fabulous and Overdensity regions.]

Nowotka, CCC, FAB, et al. 2022
Results - number counts

Overdensity

Nowotka, CCC, FAB, et al. 2022
Results - number counts

Over-abundance in all four ELAN fields, by a factor of ~2-4
Integrated SFR density
Integrated SFR density

- Assuming all sources in excess of the field counts are associated with the central systems
Integrated SFR density

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- Apply a conversion between S850 and SFR
Integrated SFR density

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Integrated SFR density

~300 times the cosmic mean and comparable to what model predicts

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- Apply a conversion between S850 and SFR

Nowotka, CCC, FAB, et al. 2022
Expanding the survey
QSO with smaller nebula sizes
More counts

Ubiquitous overdensity, confirming intimate coevolution between SMGs and QSOs

FAB, CCC, Nowotka in prep.
ALMA spectral follow-up

Membership confirmation
ALMA spectral follow-up

Membership confirmation
ALMA spectral follow-up

Membership confirmation

Wang, CCC, FAB in prep.
ALMA spectral follow-up
Membership confirmation

Wang, CCC, FAB in prep.
ALMA spectral follow-up

No coherent structures found

Wang, CCC, FAB in prep.
ALMA spectral follow-up

Some bound and some unbound

Preliminary

Wang, CCC, FAB in prep.
Take away messages

• We have found ubiquitous over-densities of submillimeter sources around a sample of 10 quasars hosting Lyα nebula, confirming intimate co-evolution between dusty star-forming galaxies and quasars.

• Follow-up studies are ongoing in order to confirm membership and understand their physical properties such as phase space distributions and the interstellar medium.

• SCUBA-2 remains a world-leading instrument in mapping the dust-obscured star formation over large scales.