SMBH accretion properties of radio-selected AGN out to z~4

Ivan Delvecchio

PMF - University of Zagreb
CEA-Saclay (now as Marie Curie fellow)
ivan.delvecchio@cea.fr

On behalf of:
SMBH accretion properties of radio-selected AGN out to z~4

Are all radio AGN weakly accreting SMBHs? If not, does SMBH accretion change with radio power and/or cosmic time?
Radio (bright) AGN at $z<1$ are special

$L_{1.4} > 10^{24.8}$ W/Hz

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Radio (bright) AGN at $z<1$ are mostly weakly accreting SMBHs hosted within massive and passive galaxies.
Going deeper and further back in time:

The VLA-COSMOS 3 GHz Large Project

rms ~ 2.3 uJy/beam

PI: V. Smolčić
Going deeper and further back in time:
The VLA-COSMOS 3 GHz Large Project

- 7729 radio sources selected at 3 GHz (10 cm) with optical/NIR counterpart in the COSMOS2015 catalogue (Smolčić et al. 2017b).

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> 1800 radio AGN: identified via a significant (>2σ) excess in radio emission, relative to the IRRC of star-forming galaxies (Delhaize et al. 2017)
Radio-excess AGN out to z~4

- Selecting a L_{1.4}-complete subset of >1200 radio-excess AGN out to z~4
Radio-excess AGN out to z~4

- Selecting a L_{1.4}\text{GJ}\text{cgs}\text{-complete subset of more than 1200 radio-excess AGN out to z~4}
- About 12% (906/7729) of them is detected with deep Chandra imaging (Civano et al. 2016; Marchesi et al. 2016)
Radio-excess AGN out to $z \sim 4$

- Selecting a $L_{1.4\text{GHz}}$-complete subset of >1200 radio-excess AGN out to $z \sim 4$

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- Chandra stacking of X-ray detected & undetected radio-excess AGN (CSTACK)*

* http://lambic.astrosen.unam.mx/cstack/
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- $L_x$ → specific BH accretion rate ($s$-BHAR $\sim L_x/M^*$)
- $s$-BHAR $\longleftrightarrow$ Edd. Ratio (if fixed $M^*/M_{BH}$)

* http://lambic.astrosen.unam.mx/cstack/
Average s-BHAR as a function of $L_{1.4}$ and $z$
The average s-BHAR increases by a factor of 10 from $z \sim 0.7$ to $z \sim 3.5$

Radio and X-ray emission are not strongly correlated

The Edd ratio exceeds 1% (=\textit{radiatively efficient} BH accretion) at $z > 2$. The high-$z$ Universe seems to facilitate radiative AGN activity: \textit{cold gas} $\leftrightarrow$ \textit{SMBH accretion} (Aird et al. 2018)
How do radio AGN hosts evolve?

\[(NUV-r) / (r-J)\] locus to identify blue (=star forming) radio AGN hosts
(Ilbert et al. 2013; Davidzon et al. 2017)
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Radio AGN hosts were predominantly *star forming* at $z > 1.5$.
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- Does it imply that "jet-mode" feedback is less efficient at higher redshift?
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A control sample of non-AGN galaxies (matched in $M^*-z$) shows similar %SF hosts and similar redshift evolution.
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Radio AGN hosts were predominantly star forming at z>1.5
Does it imply that "jet-mode" feedback is less efficient at higher redshift?
A control sample of non-AGN galaxies (matched in M*-z) shows similar %SF hosts and similar redshift evolution.

The overall galaxy population becomes more SF with z, while the possible presence of a radio AGN does not seem to influence its evolution.
Take-home message

\[ z \ll 1 \quad \text{and} \quad \lambda_{\text{EDD}} \ll 1\% \]

\[ z > 1.5 \quad \text{(independently of } L_{1.4}^{\text{AGN}}) \]

- \text{Red and passive galaxy}
- \text{Weakly accreting SMBH (} \lambda_{\text{EDD}} \ll 1\% \text{)}
- \text{Radio (and non) AGN host}
- \text{Radio AGN}
- \text{Blue and highly star-forming galaxy}
- \text{Highly accreting SMBH (} \lambda_{\text{EDD}} > 1\% \text{)}
Supplementary slides
Average Lx of radio-excess AGN

X-ray stacking of radio-excess AGN within each \( L_{1.4} \)-z bin (CSTACK, T.Miyaji)

Comparison with X-ray emission expected from star formation (Symeonidis et al. 2014; Mineo et al. 2014)

The mean Lx derived from stacking is systematically higher than that expected from star formation
The average s-BHAR is significantly higher in **blue** radio AGN hosts, at fixed $L_{1.4}$ and $z$. 
Best & Heckman (2012) used multi-wavelength information to distinguish radio loud AGN between HERGs & LERGs.

Padovani et al. (2015) used deep VLA 1.4 GHz data in the E-CDFS to identify radio AGN down to the "radio quiet" regime.

SMBHs accretion rates are mostly limits (shaded areas) due to the large fraction of non-detections.
Take-home messages

- All galaxies become typically bluer with redshift, including radio AGN hosts.

- The qualitatively similar trends between s-BHAR and % SF hosts are plausible if cold gas drives radio AGN activity.

- No correlation between X-ray and radio emission processes might explain the non-trend between s-BHAR and $L_{1.4}$.

- Radio jet emission at $z>1.5$ traces also radiative AGN activity (High-Kinetic mode?)

Merloni & Heinz (2008)
The high-z Universe facilitates (radiative) AGN activity (*)

Typical Edd. Ratio increases with $z$,

(*) especially in star-forming galaxies
The high-z Universe facilitates (radiative) AGN activity

(*) especially in star-forming galaxies

Aird et al. (2018)

Typical Edd. Ratio increases with z, (*) especially in star-forming galaxies

The cold gas fraction $f_{\text{gas}}$ increases in main-sequence galaxies out to $z \sim 2-3$

SMBH accretion ↔ cold gas supply
Average Lx of radio-excess AGN

Investigating the simultaneous dependence of Lx on both L_{1.4} and redshift

The average Lx does not show a significant trend with L_{1.4} at fixed z, while it increases with redshift, at fixed L_{1.4}

- X-ray stacking of radio-excess AGN within each L_{1.4}-z bin (CSTACK, T. Miyaji)
- Combining X-ray detections and non-detections together
- Boostrapping to mitigate the effect of bright outliers
- Comparison with X-ray emission expected from star formation (Symeonidis et al. 2014; Mineo et al. 2014)
How do radio AGN hosts evolve?

- The average fraction of SF hosts increases with redshift, at fixed $L_{1.4}$, but does not depend on $L_{1.4}$.

- Radio AGN hosts were predominantly star forming at higher redshifts.

$(NUV-r) / (r-J)$ locus to identify blue (=star forming) radio AGN hosts (Ilbert et al. 2013; Davidzon et al. 2017)
Radio-excess AGN of a given \( L_{1.4} \) show increasing 3 GHz sizes with redshift.

- Rad. inefficient AGN accretion is associated with a compact radio core.
- Larger sizes might hint at a switch in the SMBH accretion mechanism.

(Bondi et al., 2018.)
The infrared-to-radio correlation

- Delhaize et al. (2017)

- Delhaize et al. (2017) removing 3σ outliers

- Delhaize et al. (2017) removing 2σ outliers
  (flatter than that published in D17, but largely consistent with literature)

Used in this work for consistency with our definition of radio-excess AGN

(Courtesy of J. Delhaize)
Overcoming host-galaxy dilution: **VLBI** interferometry

(Courtesy of E. Middleberg and N. Herrera Ruiz)
AGN feedback: two flavours

- **"Radiative mode"**
  - Cleaning mode
  - Moves the galaxy from "blue" to "red"
  - Radiatively efficient (L / L_{edd} > 1%)

- **"Jet mode"**
  - Maintenance mode
  - Keeps the galaxy "red"
  - Radiatively inefficient (L / L_{edd} << 1%)

Alexander & Hickox 2012
AGN feedback: two flavours

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- Cleaning mode
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''Jet mode''

- Maintenance mode
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Radio samples of AGN are crucial to probe the "Jet mode" phase of AGN feedback