The VLA-COSMOS 3GHz survey
Cosmic evolution of radio AGN and star forming galaxies since $z \sim 5$

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Galaxy Populations

- Bimodality in galaxy populations
  - **Red sequence**: early type/spheroidals, no/little star formation
  - **Blue cloud**: disk galaxies, abundant star formation

- Evolution of galaxies through cosmic time: **Blue ➔ red**
  - Via conversion of gas reservoir into stars
  - Via passive fading of stars & galaxy mergers
  - Aided by AGN feedback

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  Blue $\rightarrow$ red
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Questions:
1) Impact of dust onto cosmic star formation history?
2) Impact of AGN onto galaxy evolution?
Cosmic star formation history

- Lilly Madau plot
- Compilation based on different star formation estimators (UV, IR, radio, Hα..)
- Dust correction = major challenge

→ Dust-unbiased star formation rate tracers (at high-z) needed
Cosmic star formation history at high-z

- Lyman-Break Galaxy selection (HUDF +HUDF09, GOODS+ERS +CANDELS, CDF-S)
- UV-based star formation
- Dust extinction estimated based on UV-continuum slope
- Difficulty accounting for dusty starbursts (>100 $M_\odot$/yr)

Bouwens et al. (2015)
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Dust-unbiased star formation rate tracers (at high-z) needed
Radio-mode AGN feedback in cosmological models

- "maintenance" mode
- Once a static hot (X-ray) halo forms around galaxy
- Modest BH growth
- Radio outflows heat surrounding gas
  
  "truncation of further stellar mass growth"
Radio-mode AGN feedback in cosmological models

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- Radio outflows heat surrounding gas
- Truncation of further stellar mass growth

Allows good reproduction of observed galaxy properties

Radio-mode AGN feedback in cosmological models

Croton et al. (2006)
Radio-mode AGN feedback in cosmological models

Croton et al. (2006): Volume averaged kinetic heating rate over the full simulation as a function of redshift

Radio-AGN feedback: this curve can be inferred from observations
Radio-mode AGN feedback in cosmological models

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Impact of AGN onto galaxy evolution? radio

Radio-AGN feedback: this curve can be inferred from observations
VLA-COSMOS 3GHz Large Project
VLA-COSMOS 3 GHz Large Project + COSMOS

- **VLA-COSMOS 3GHz Large Project**
  - Smolčić et al. (2017a)
  - 384 hours (A+C configurations, 2012/13/14)
  - 3 GHz (2 GHz bandwidth)
  - 0.75” resolution
  - rms ~2.3 µJy/beam over 2°
  - 10,830 sources

- **COSMOS Project**
  - Scoville et al. (2007)
  - 2° equatorial field
  - X-ray to radio imaging (>30 bands)
    - Galaxy photo-z accuracy
      (Ilbert et al. 2009; Laigle et al., in prep.)
    - AGN photo-z accuracy
      (Salvato et al. 2009; Marchesi et al., subm.)
  - >100,000 spectra (VLT, Magellan, Keck)
Final mosaic
Final mosaic
Final mosaic
The star forming & AGN galaxy samples

VLA-COSMOS 3GHz LP (>11.5 µJy)
(Smolčić et al. 2017a)

+ COSMOS MIR sources
(Laigle et al. 2016)

~35% spec-z, else photo-z with
$\sigma_{\Delta z/(1+z)}<0.021$
The star forming & AGN galaxy samples

VLA-COSMOS 3GHz LP (\(>11.5 \, \mu\text{Jy}\))
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\[\text{Radio-excess} = \text{radio AGN} \quad (1814)\]
\[\text{No radio-excess} = \text{radio SFG} \quad (5915)\]

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Smolčić et al. (2017b), Delvecchio et al. (2017)
The star forming & AGN galaxy samples

VLA-COSMOS 3GHz LP (>11.5 µJy) (Smolčić et al. 2017a)

+ COSMOS MIR sources (Laigle et al. 2016)

- Radio-excess = radio AGN (1814)
- No radio-excess = radio SFG (5915)

- Radio luminosity functions at rest-frame 1.4 GHz out to z~5 ($V_{\text{max}}$)
- Local LF (Condon et al. 2002; Best et al. 2005; Mauch & Sadler 2007); fixed shape, fit to data assuming pure luminosity or luminosity + density ($\Phi + L$) evolution
- 1.4 GHz luminosity used as proxy for SFR & kinetic jet luminosity (Delhaize et al. 2017; Willott et al. 1999)

~35% spec-z, else photo-z with $\sigma_{\Delta z(1+z)}<0.021$

Smolčić et al. (2017b), Delvecchio et al. (2017)
Radio-based cosmic star formation history
Radio luminosity functions at rest-frame 1.4 GHz ($V_{\text{max}}$)

Local LF (fit to Condon et al. 2002, Best et al 2005, Mauch & Sadler 2007 data); fixed shape, fit to data assuming pure luminosity or luminosity + density ($\Phi+L$) evolution

Compared to IR-based derivations: Gruppioni et al. (2013), Magnelli et al. (2013)
- $L_{\text{IR}} \rightarrow L_{1.4\text{GHz}}$ using $q(z)$

Compared to UV-based derivations: Bouwens et al. (2015)
- $L_{\text{UV}} \rightarrow \text{SFR} \rightarrow L_{1.4\text{GHz}}$ using $q(z)$

$$\log \frac{L_{1.4\text{GHz}}}{\text{W Hz}^{-1}} = 16.556 - 0.4(M_{1600\alpha} - A_{\text{UV}}) - q_{\text{IR}}(z)$$

$$A_{\text{UV}} = 4.43 - 1.99\beta$$

(IRX–$\beta$ relation, function of UV mag; Bouwens et al. 2014; Meuerer et al. 1999)

Novak et al. (2017)
In fair agreement with dust-corrected UV-based results at $z>3$ (Bowens et al. 2015) slightly higher than Maudau & Dickinson (2014) compilation (but within error)
Radio-based cosmic star formation history

Combined dust-corrected UV and radio data

→ possible systematic 15-20% underestimation of highly obscured SFRD estimated from the rest-frame UV observations (Bouwens et al. 2015)
Radio-mode AGN feedback
Radio luminosity functions at rest-frame 1.4 GHz ($V_{\text{max}}$)

- Local LF (Mauch & Sadler 2007): fixed shape, fit to data assuming pure luminosity or luminosity + density ($\Phi+L$) evolution

- Fair agreement with previous results

Smolčić et al. (2017c)
Radio-mode feedback

- Agreement with SAGE model (Croton et al. 2016)
- Many assumptions & simplifications in both observational and semi-analytic models still to be tested

Smolčić et al. (2017c)
Summary

VLA-COSMOS 3 GHz Large Project
- Simultaneously the largest and deepest radio continuum survey at high angular resolution
- 10,830 radio sources (S/N>5, $\text{rms}=2.3 \text{ uJy/beam}$, resolution 0.75”, 2 square degree area)
- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts ($z<6$)
- Data products available through IPAC/IRSA: http://irsa.ipac.caltech.edu/Missions/cosmos.html

Dust unbiased cosmic star formation history since $z\sim 5$
- In fair agreement with previous results based on IR, and UV data
- Tight constraint on galaxies with SFR>$100 \, M_{\odot}/\text{year}$ → possible 15-20% underestimation of highly obscured SFR estimated from the rest-frame UV observations at $z=4$ and 5

Radio-mode AGN feedback since $z\sim 5$
- Key ingredient of cosmological models to reproduce number of massive galaxies
- In fair agreement with SAGE model
- Many assumptions and simplifications in both observational and semi-analytic models still to be tested