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

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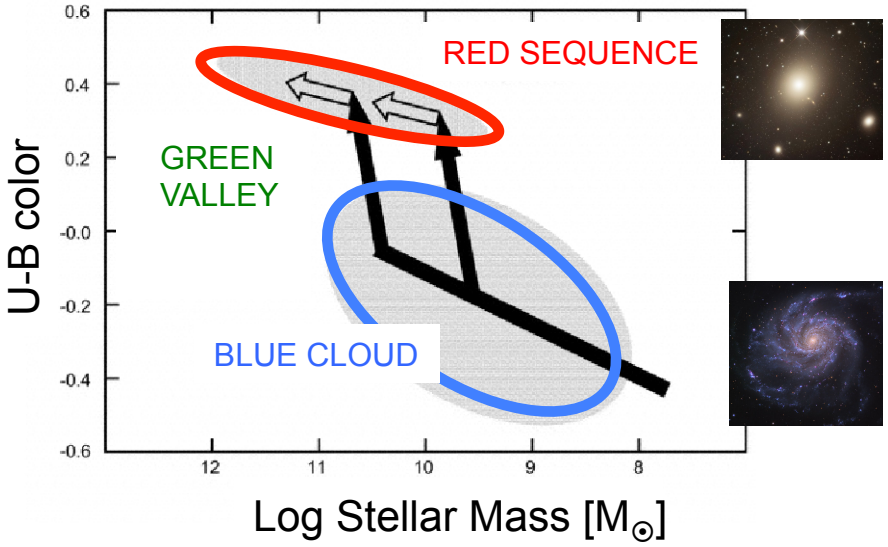
& (VLA-) COSMOS collaboration

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



Sanders & Mirabel 1996, Bell et al. 2004, Borch et al. 2006, Faber et al. 2007, Hopkins et al. 2007, Peng et al. (2010, 2012, 2014) & many others

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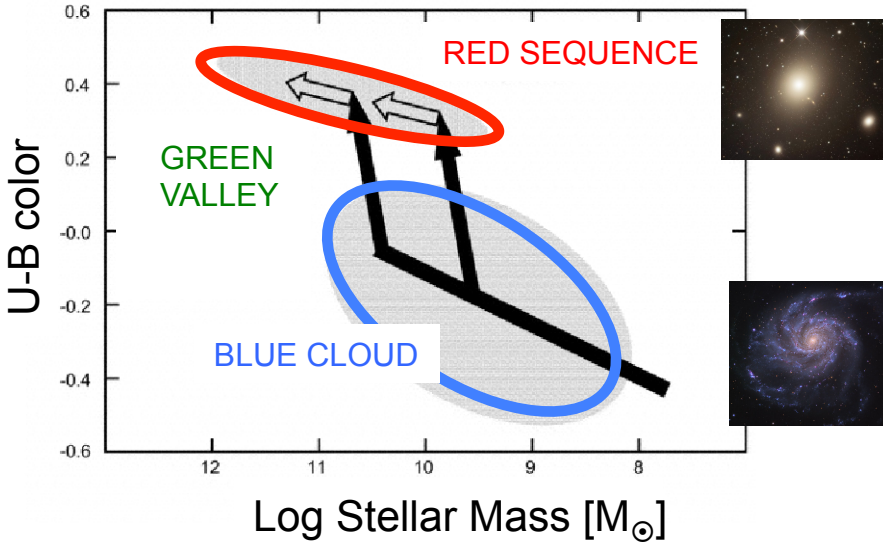

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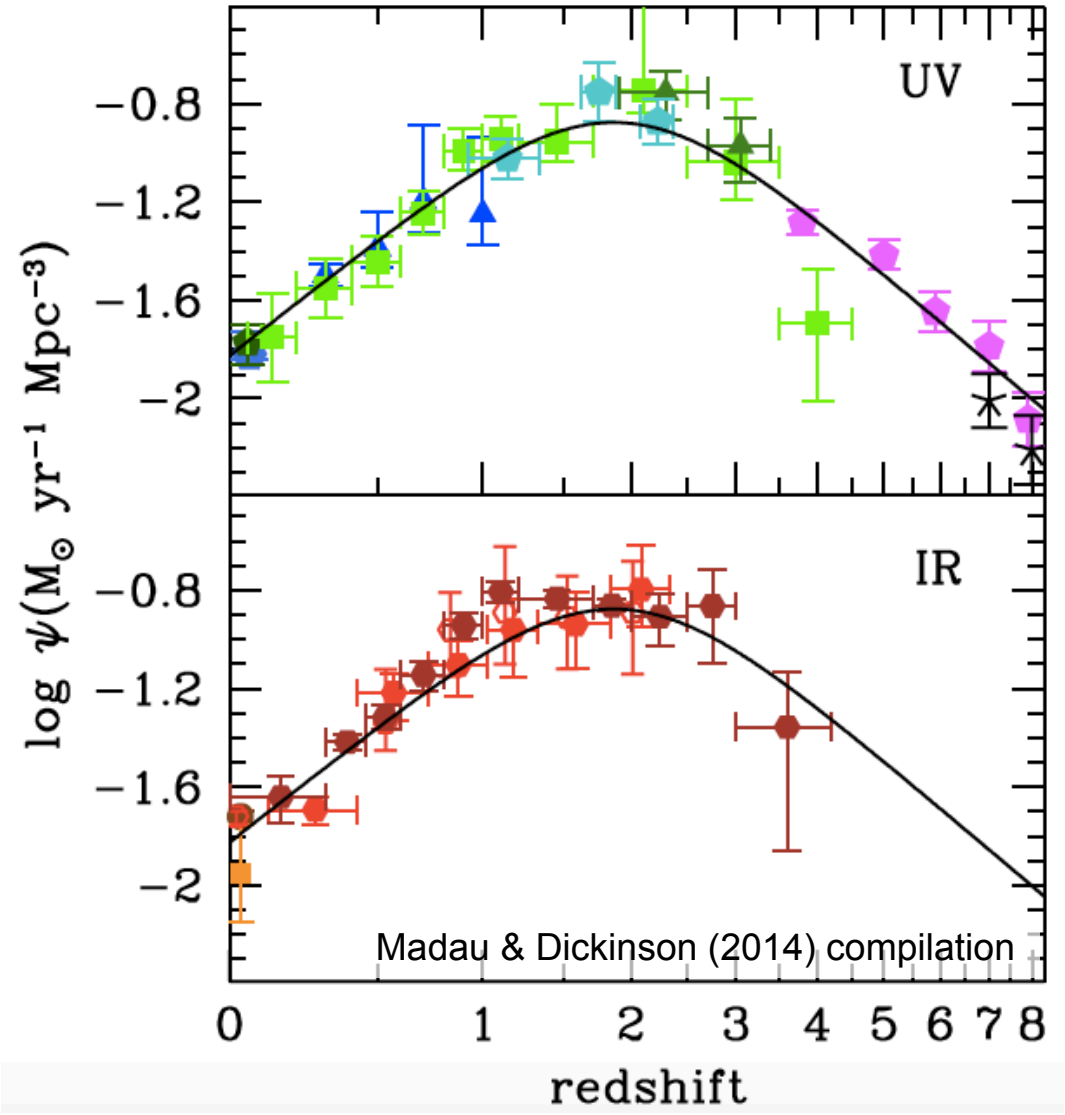
Questions:
1) Impact of dust onto cosmic star formation history?
2) Impact of AGN onto galaxy evolution?

Cosmic star formation history

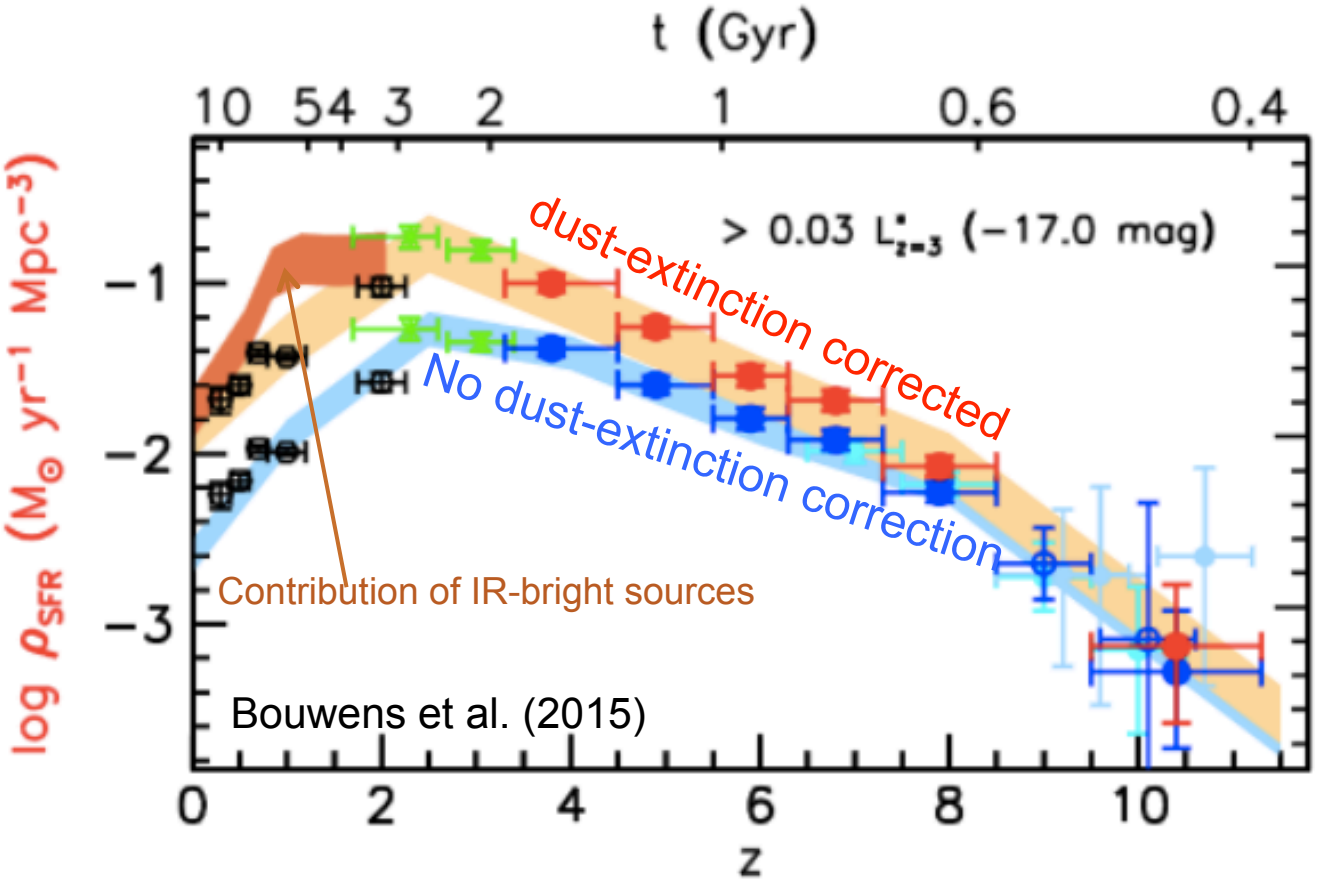
- Lilly Madau plot
- Compilation based on different star formation estimators
  (UV, IR, radio, Hα..)
- Dust correction = major challenge

→ 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)



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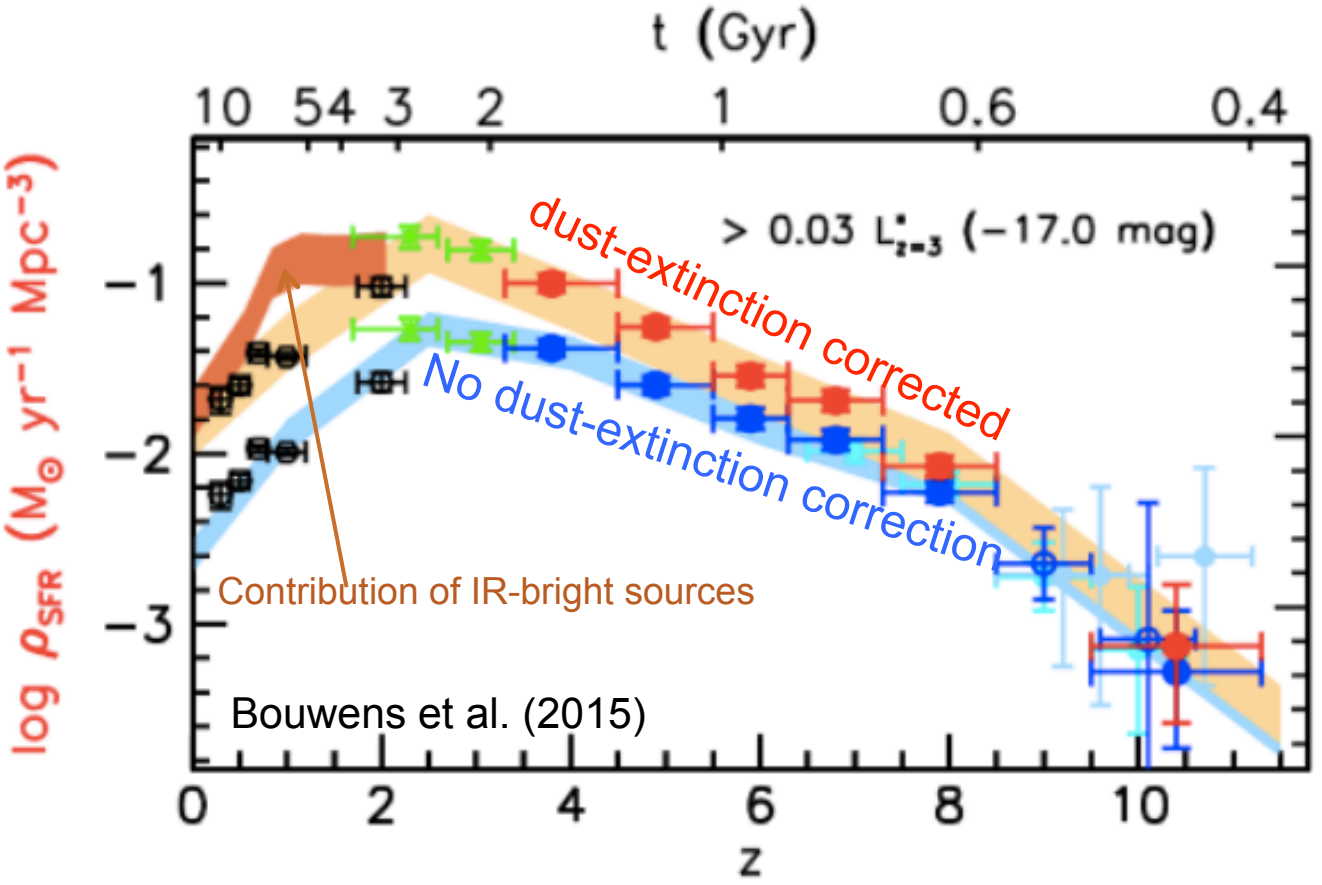
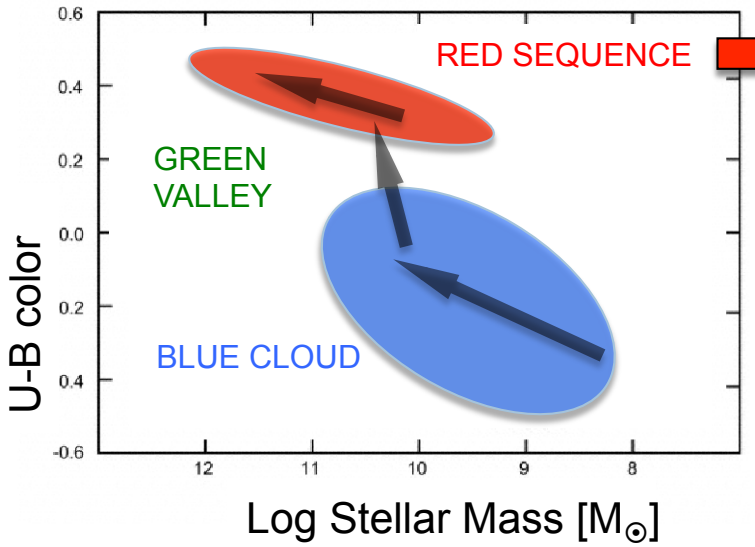


➔ Dust-unbiased star formation rate tracers (at high-z) needed

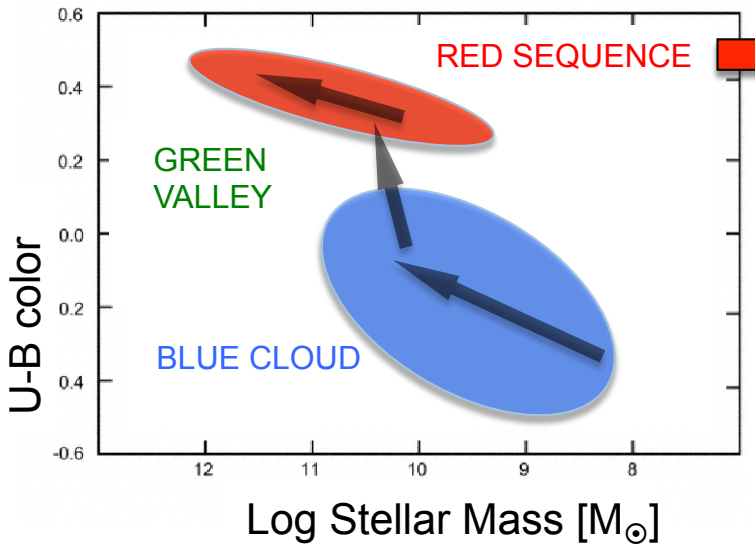
Radio-mode AGN feedback in cosmological models



RADIO MODE

- "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



RADIO MODE

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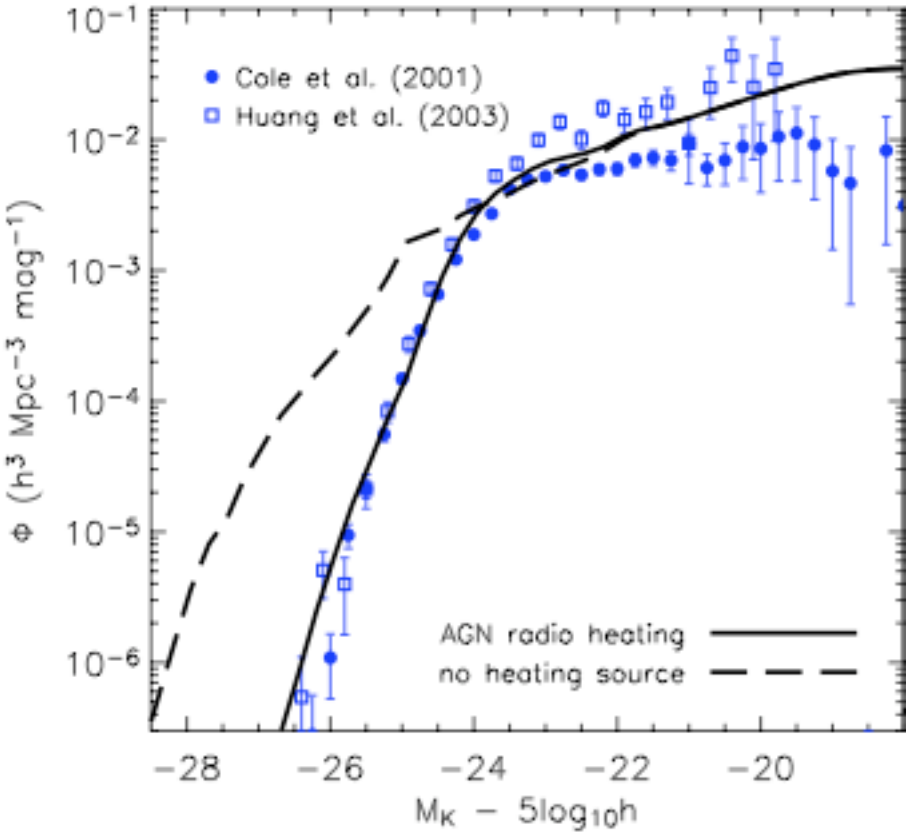
- Once a static hot (X-ray) halo forms around galaxy
- Modest BH growth
- Radio outflows heat surrounding gas → truncation of further stellar mass growth

Allows good reproduction of observed galaxy properties

Croton et al. 2006, 2016; Bower et al. 2006; Sijacki et al. 2006, Hopkins et al. 2006, Fanidakis et al. 2012…

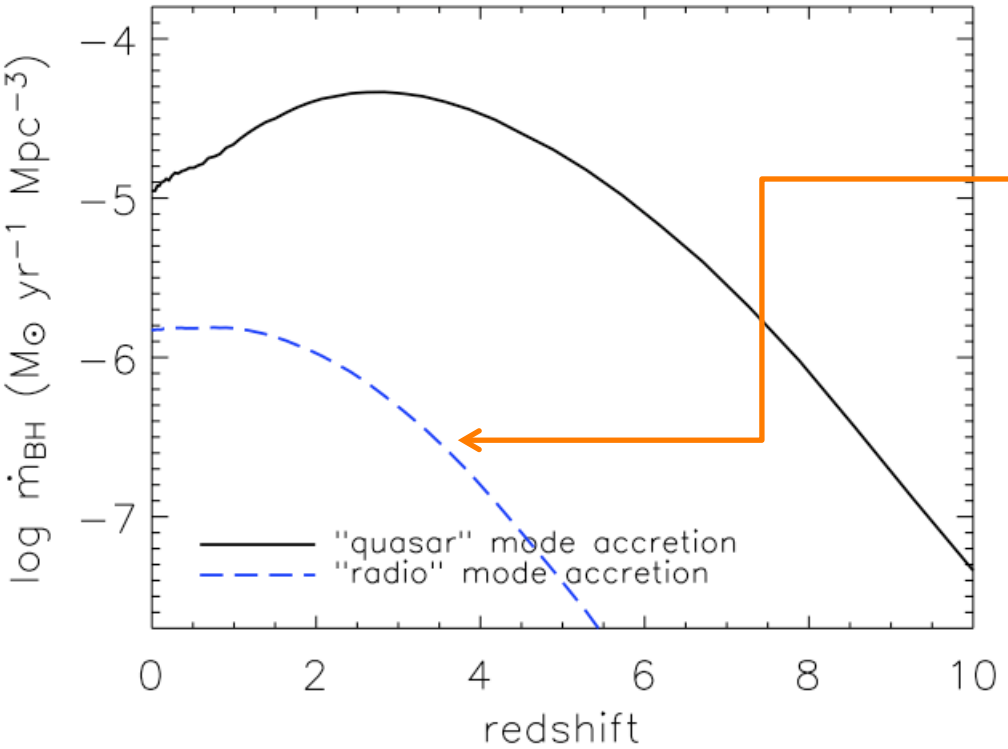
Radio-mode AGN feedback in cosmological models

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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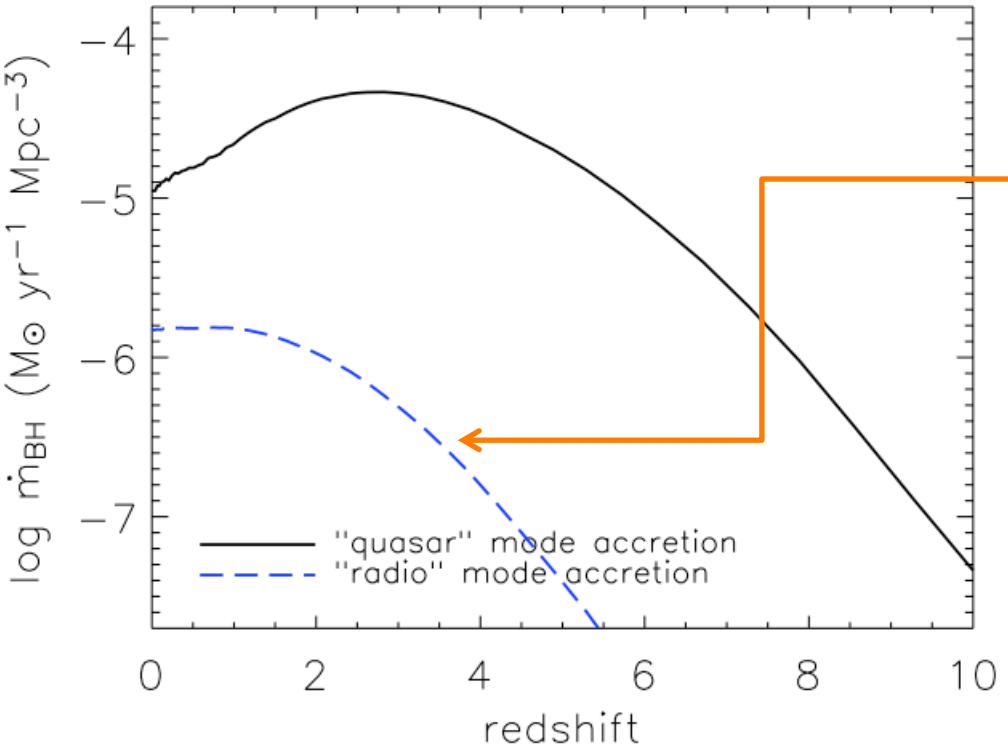


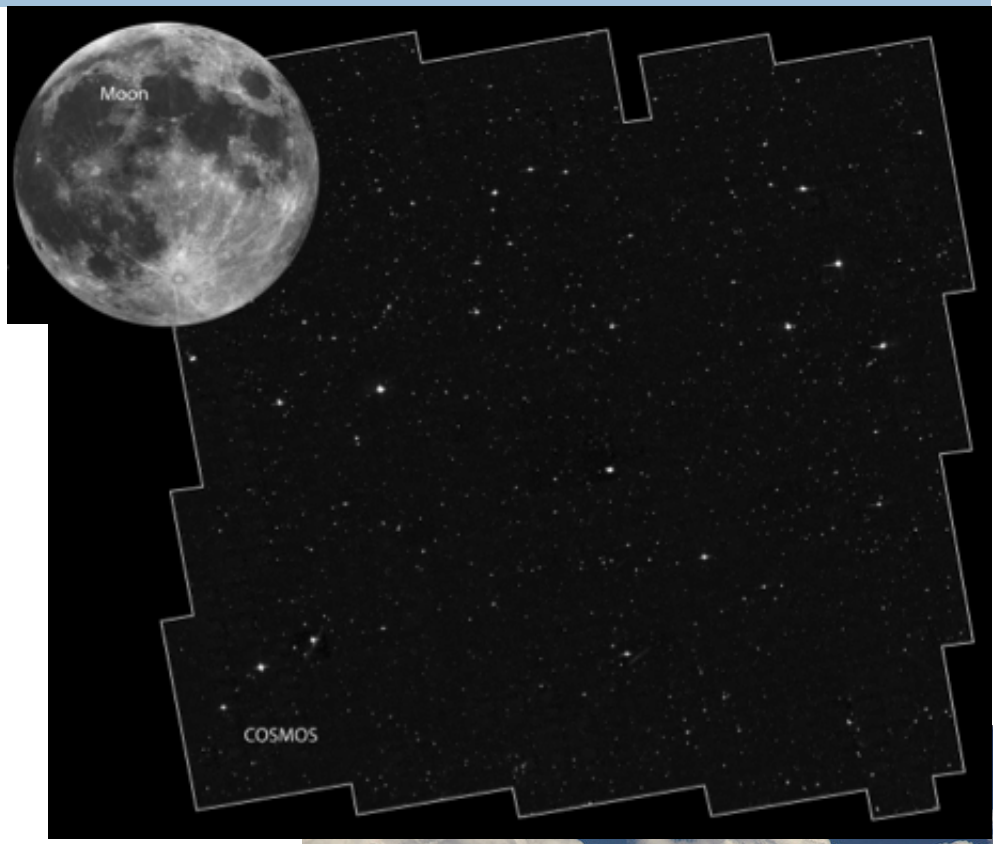
Radio-AGN feedback: this curve can be inferred from observations

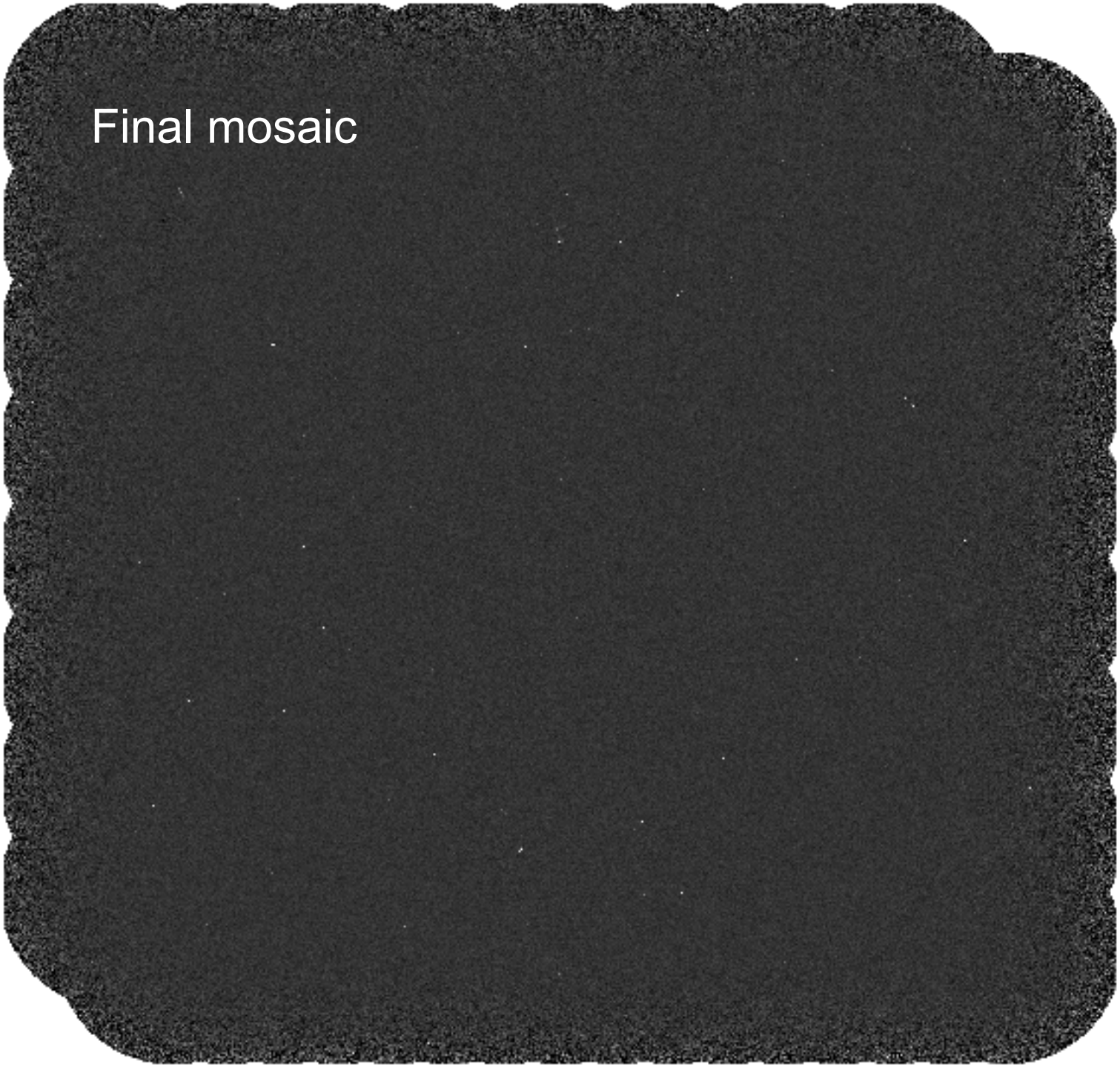
➔ Impact of AGN onto galaxy evolution? ➔ radio

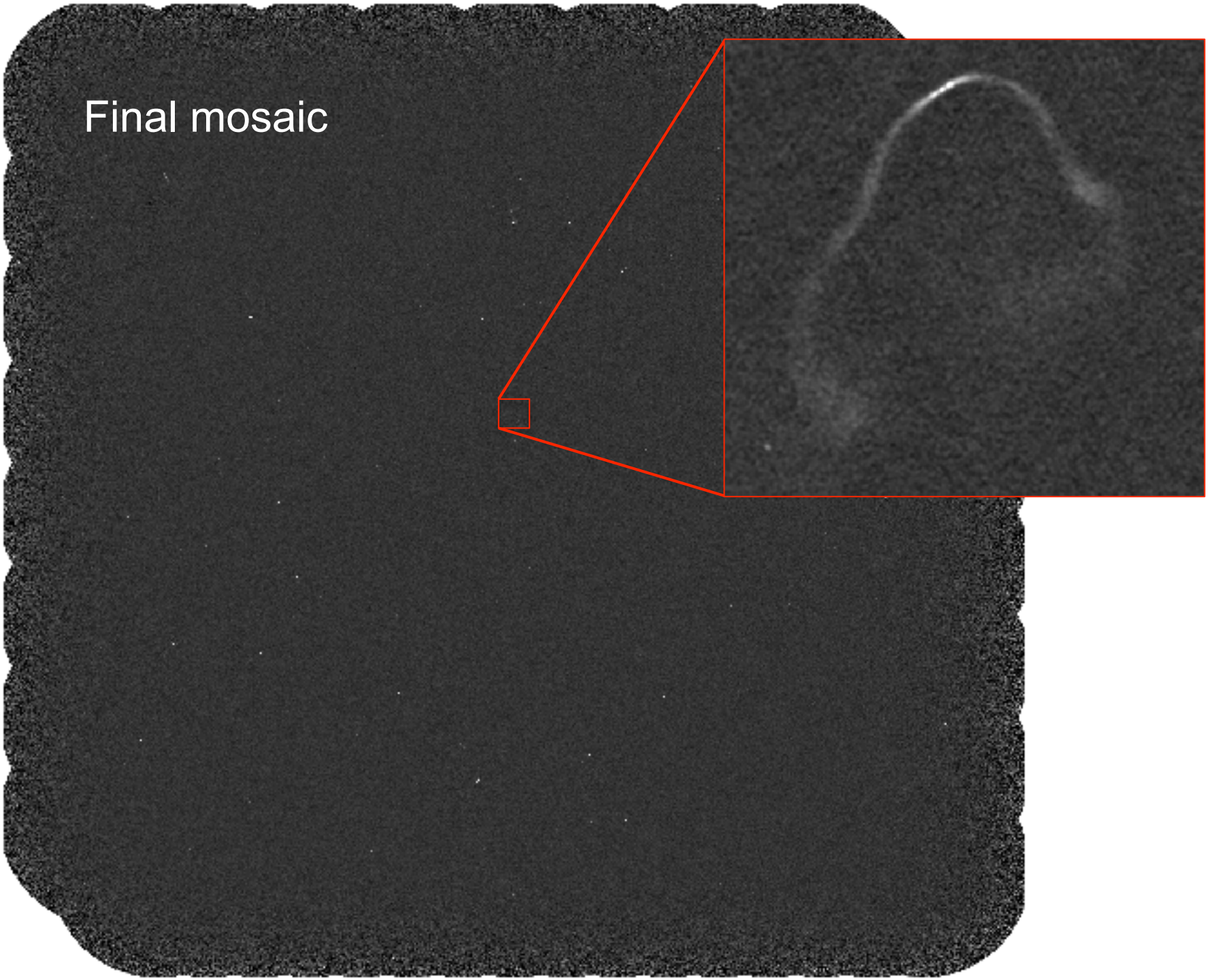
VLA-COSMOS 3GHz Large Project

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 band
    - 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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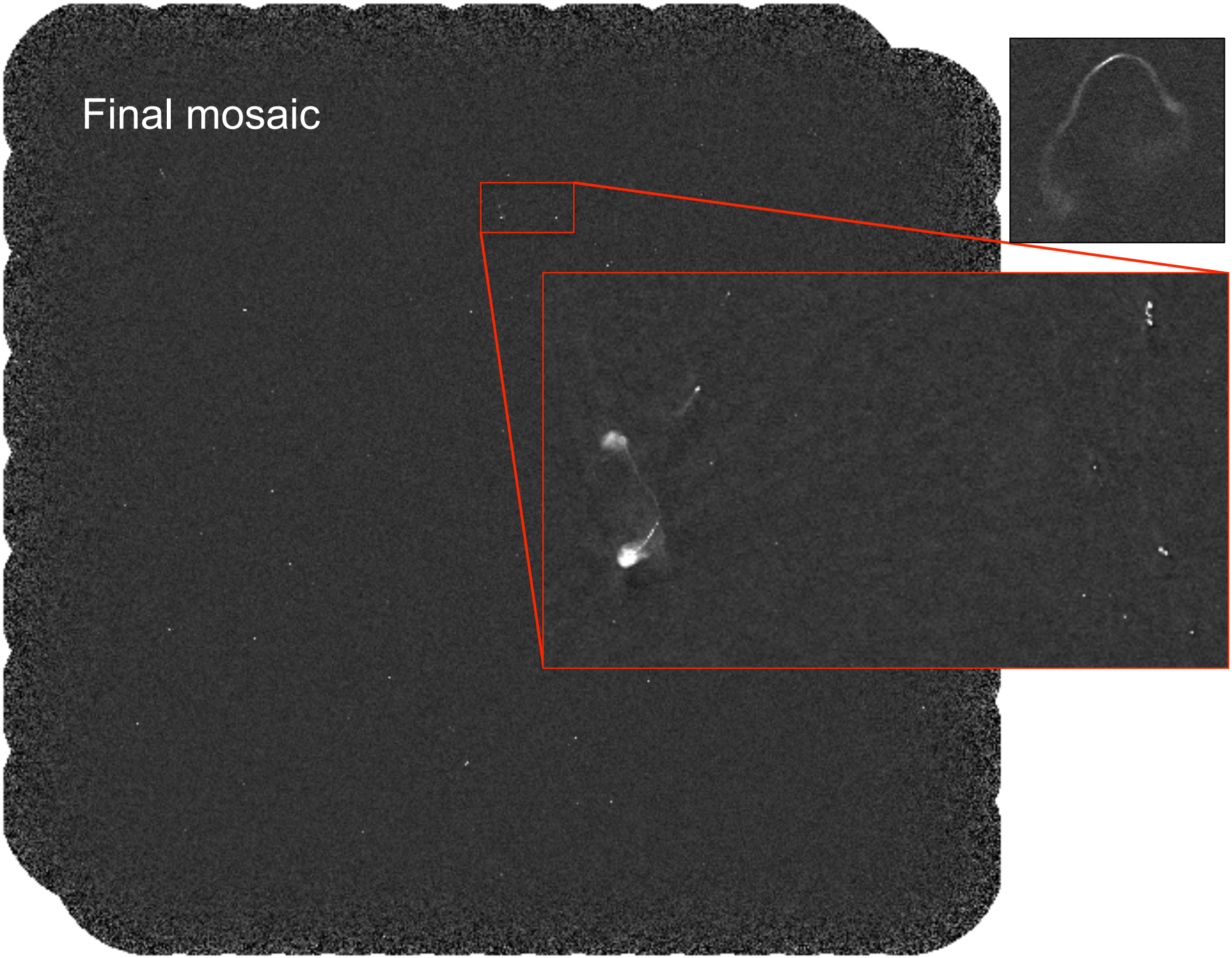
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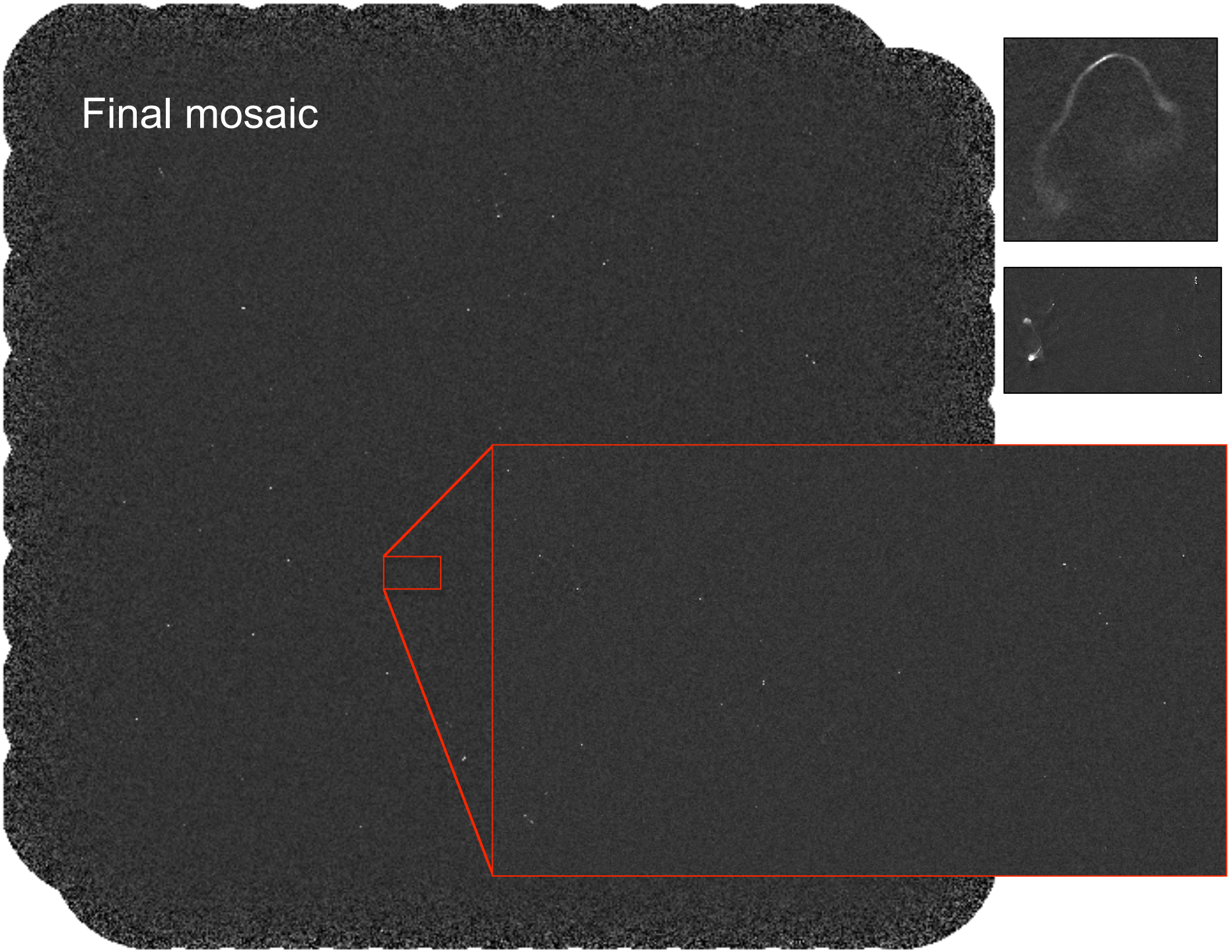

Final mosaic

The star forming & AGN galaxy samples

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

+

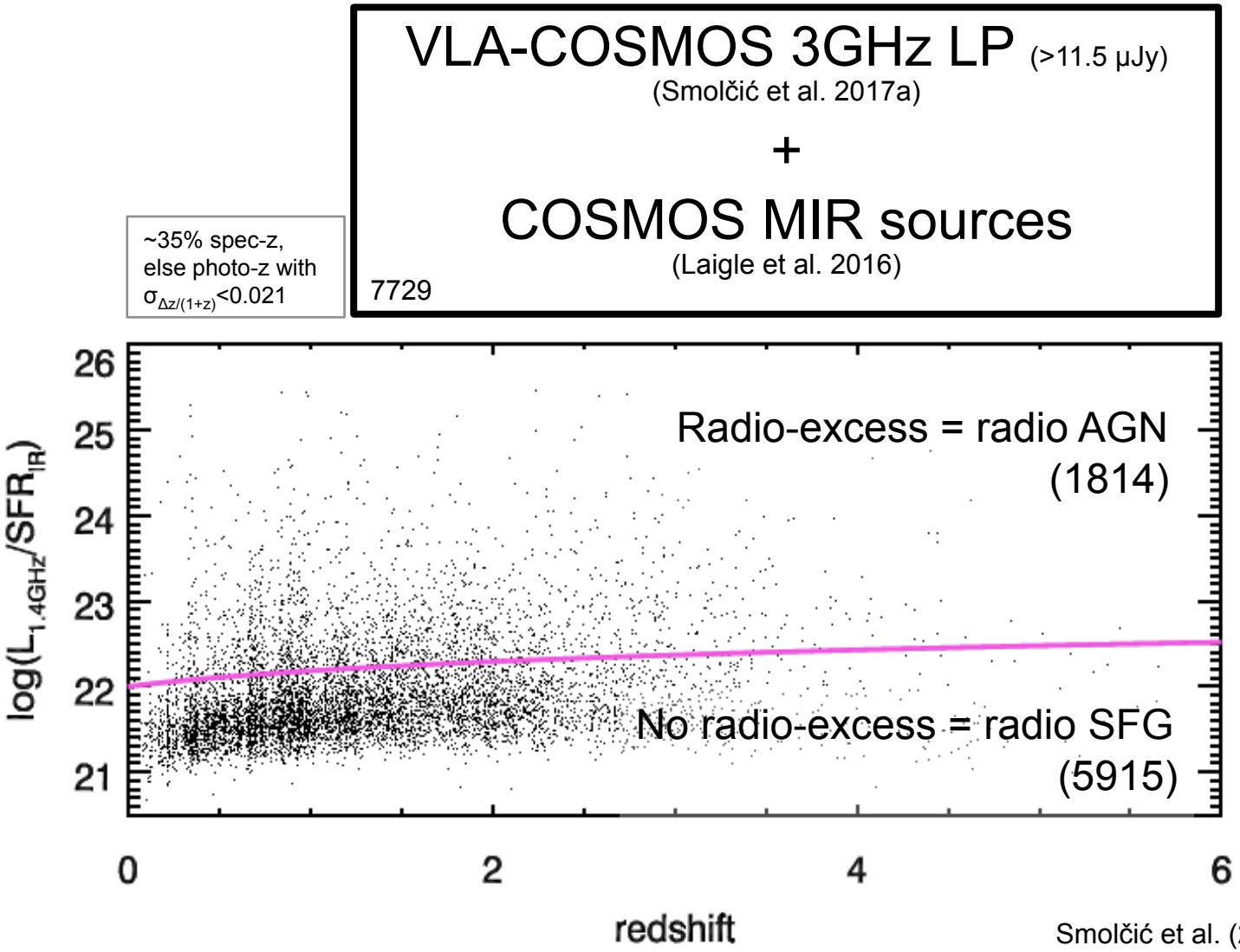
COSMOS MIR sources
(Laigle et al. 2016)

7729

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

Smolčić et al. (2017b), Delvecchio et al. (2017)

The star forming & AGN galaxy samples



Smolčić et al. (2017b), Delvecchio et al. (2017)

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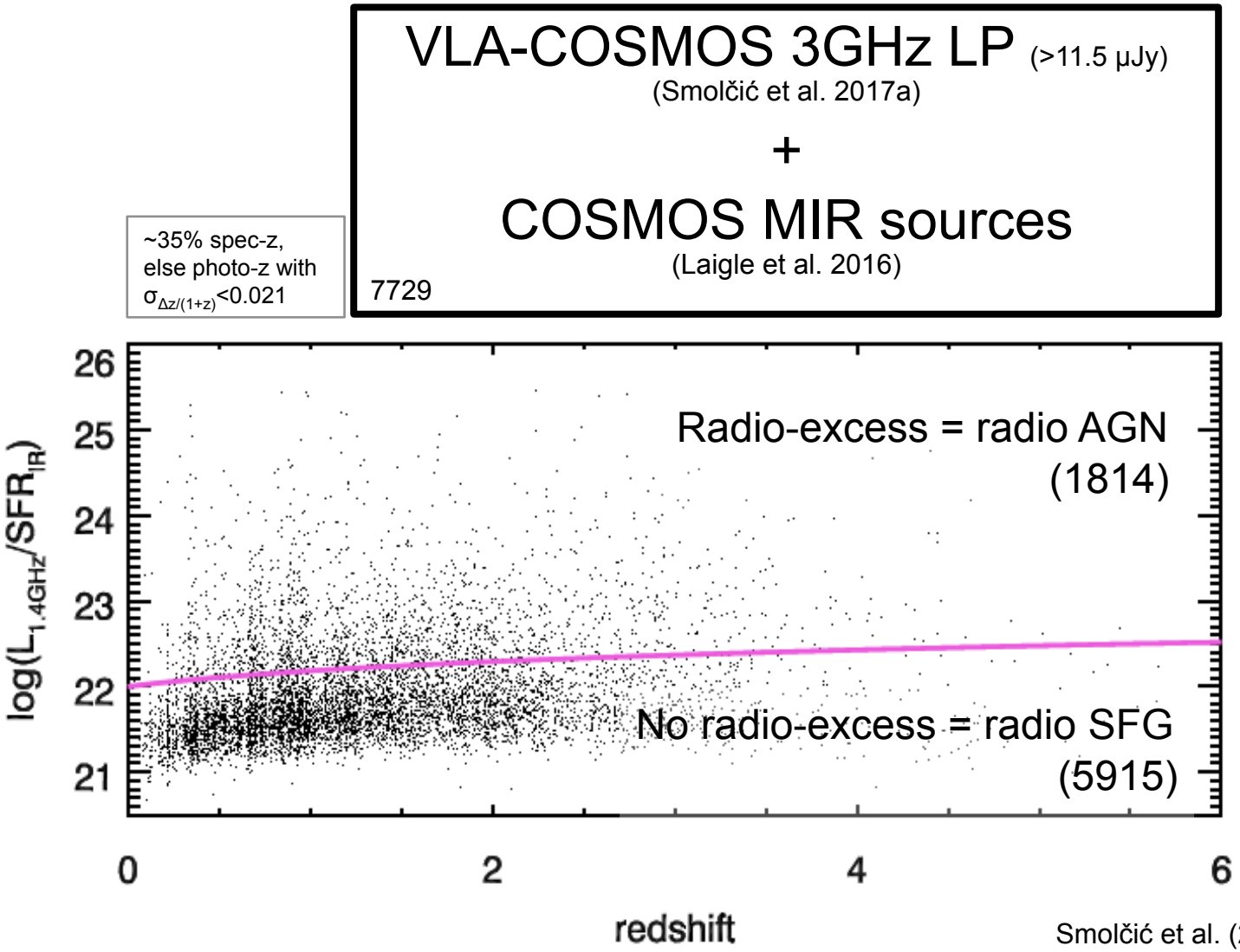


- Radio luminosity functions at rest-frame 1.4 GHz out to z~5 (V_{max})
- Local LF (Condon et al. 2002; Best et al. 2005; Mauch & Sadler 2007); fixed shape, fit to data assuming pure luminosity or luminosity + density (Φ+L) evolution
- 1.4 GHz luminosity used as proxy for SFR & kinetic jet luminosity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

Smolčić et al. (2017b), Delvecchio et al. (2017)

Radio-based cosmic star formation history

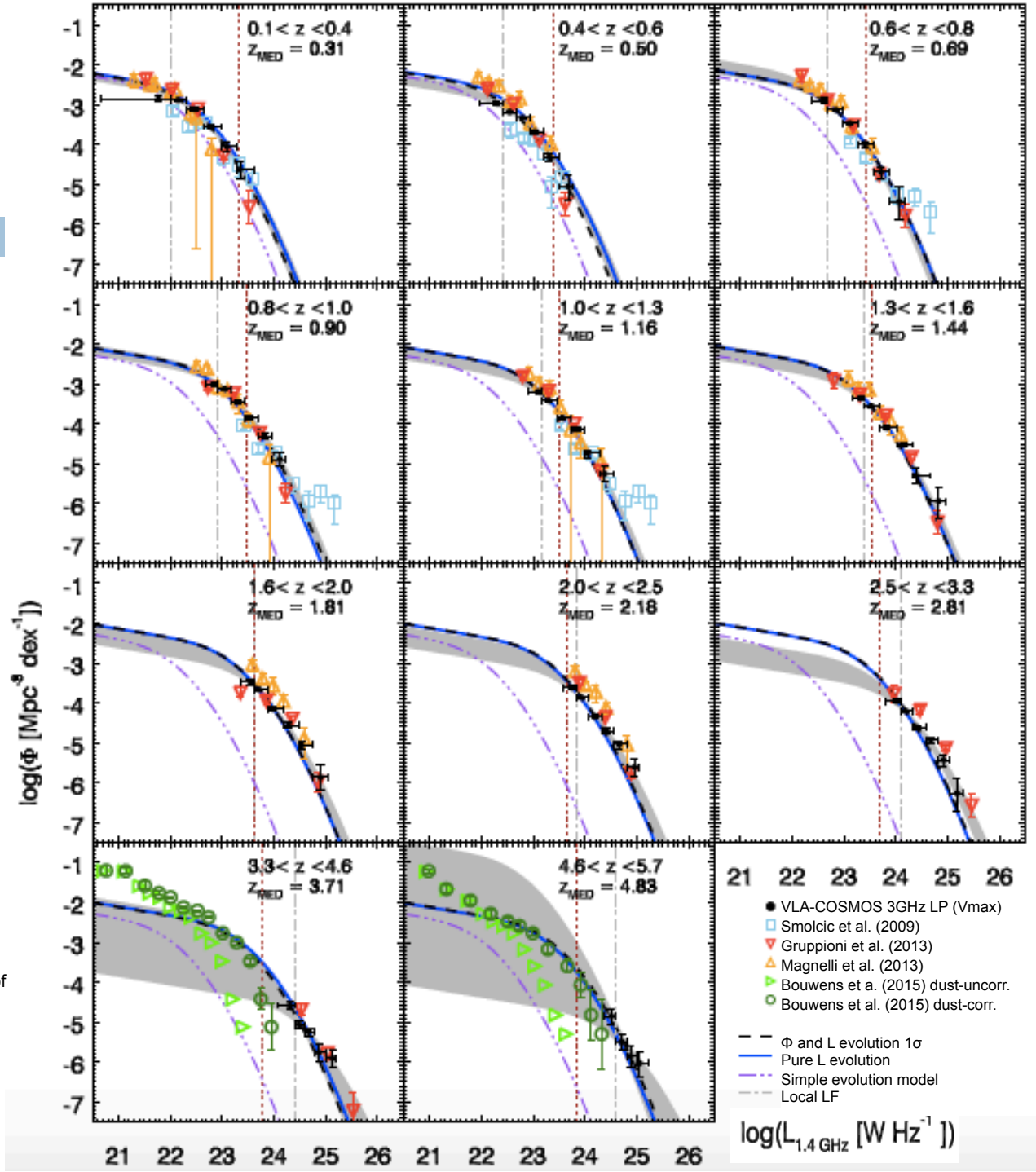
Radio-based cosmic star formation history

- Radio luminosity functions at rest-frame 1.4 GHz (V_{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 (Φ+L) evolution
- Compared to IR-based derivations: Gruppioni et al. (2013), Magnelli et al. (2013)
  - L_{IR} → $L_{1.4GHz}$ using q(z)
- Compared to UV-based derivations: Bouwens et al. (2015)
  - L_{UV} → SFR → $L_{1.4GHz}$ using q(z)

$$\log \frac{L_{1.4\ \mathrm{GHz}}}{\mathrm{W\ Hz^{-1}}} = 16.556 - 0.4(M_{1600,AB} - A_{UV}) - q_{\mathrm{TIR}}(z)$$

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

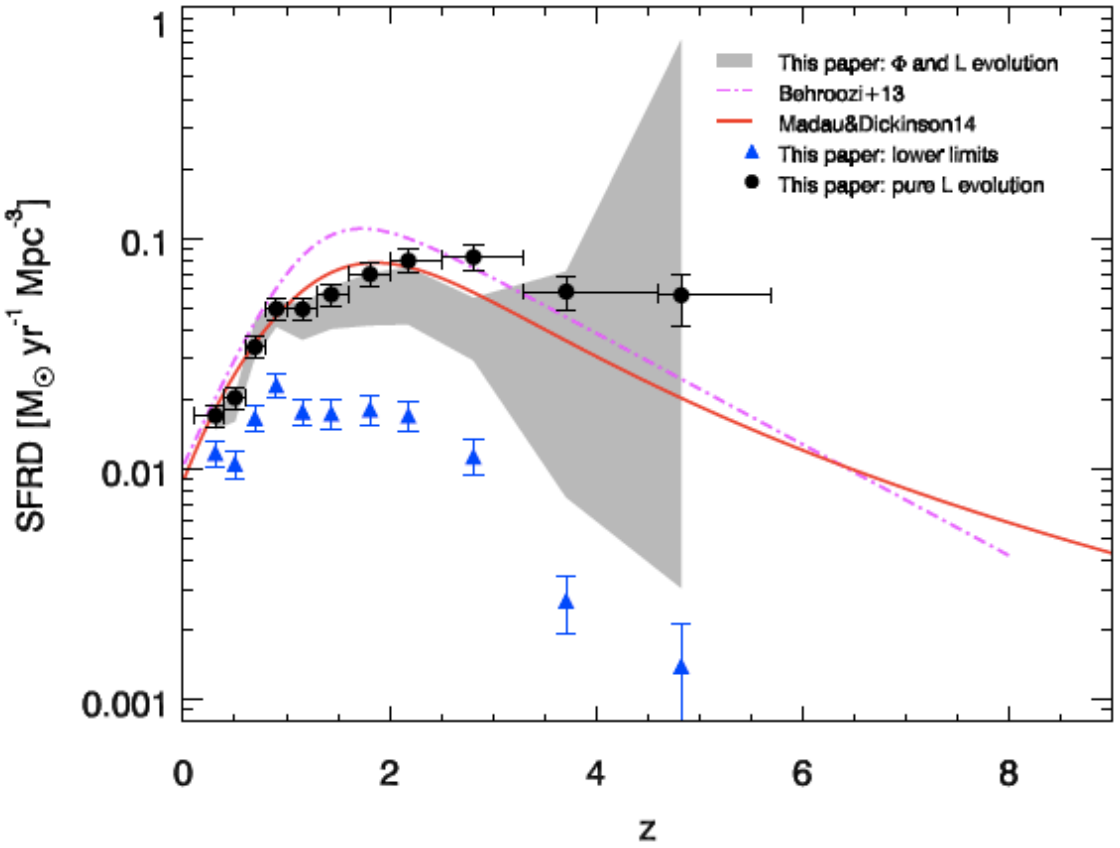
(IRX – β relation, function of UV mag; Bouwens et al. 2014; Meuerer et al. 1999)



Novak et al. (2017)

Radio-based cosmic star formation history

- 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)

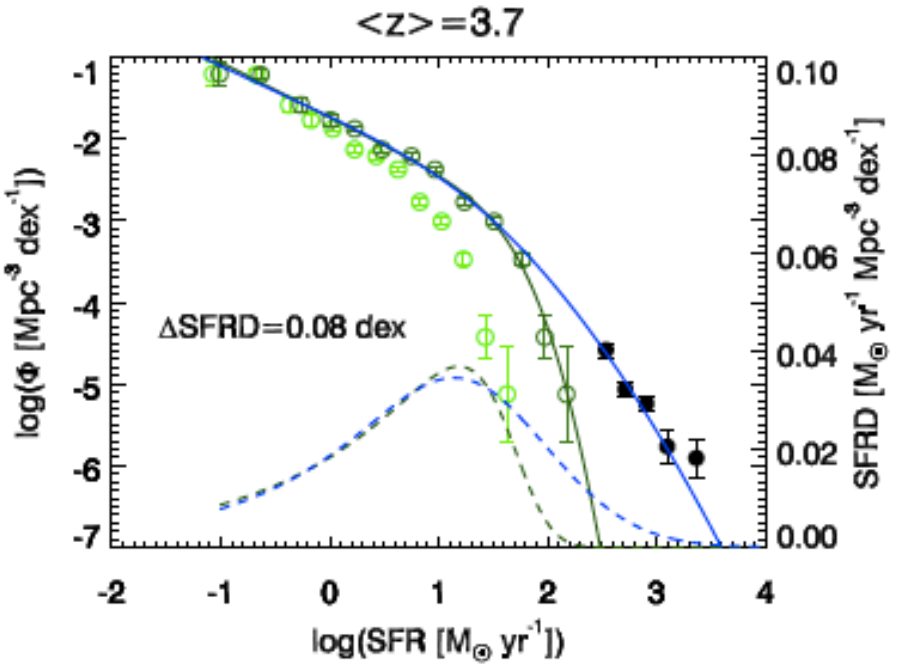


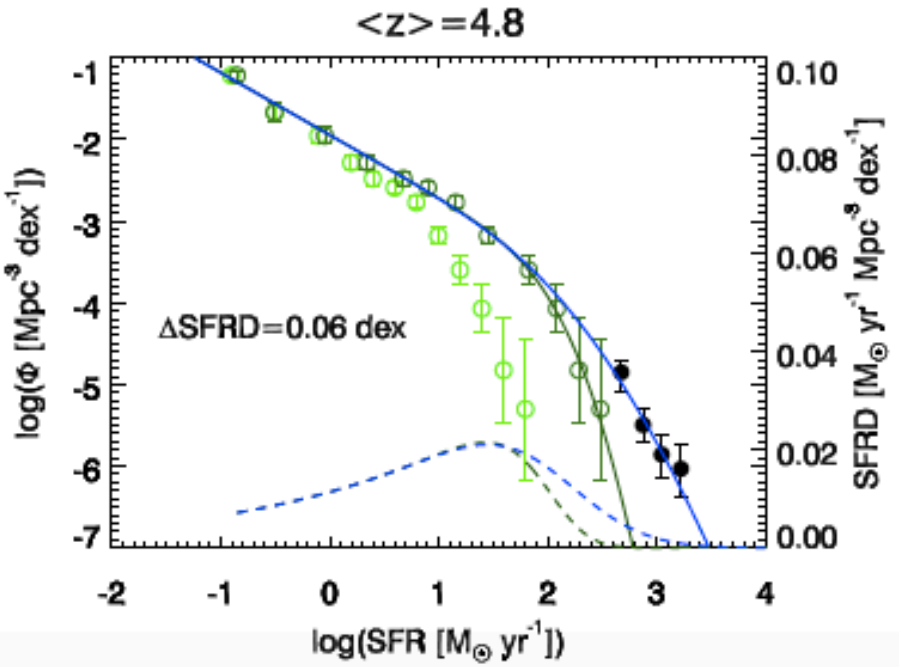
Novak et al. (2017)

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)



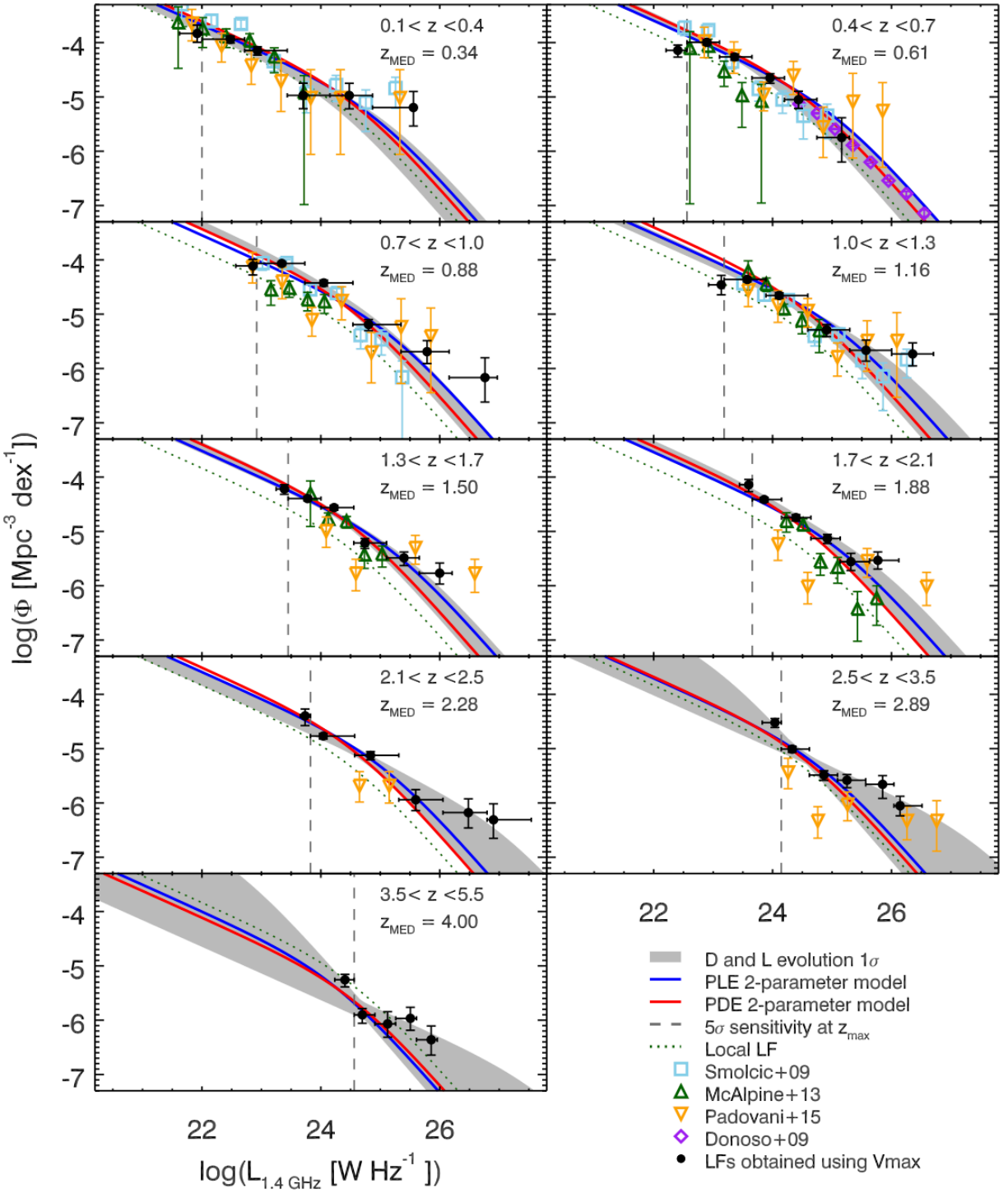


Novak et al. (2017)

Radio-mode AGN feedback

Radio-mode feeback

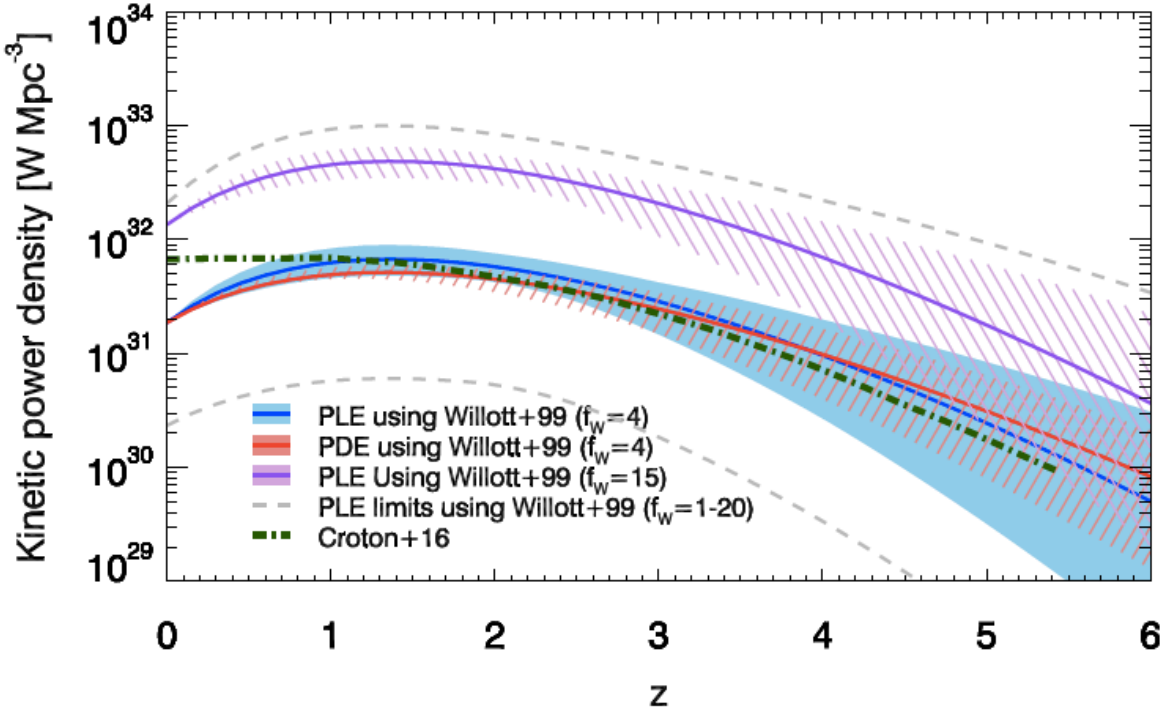
- Radio luminosity functions at rest-frame 1.4 GHz (V_{max})
- Local LF (Mauch & Sadler 2007): fixed shape, fit to data assuming pure luminosity or luminosity + density (Φ+L) evolution
- Fair agreement with previous results



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, rms=2.3 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~5

- In fair agreement with previous results based on IR, and UV data
- Tight constraint on galaxies with SFR>100 M_{Sun}/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~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