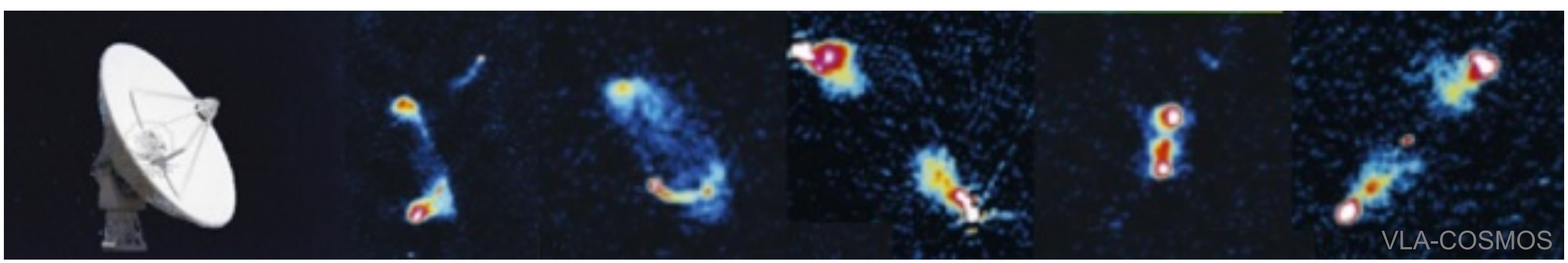
Black hole mass growth across cosmic time: Insights from the VLA-COSMOS survey

Vernesa Smolčić (University of Zagreb, Croatia)

Mladen Novak, Lana Ceraj, Ivan Delvecchio, Jacinta Delhaize, (Uni. Zagreb)
Eva Schinnerer (MPIA), Kunal Mooley (Caltech), Chris Carilli (NRAO),
Marco Bondi, Paolo Ciliegi, Gianni Zamorani (INAF)
& (VLA-) COSMOS collaboration



Outline

1. Radio AGN and their role in galaxy formation and evolution

2. VLA-COSMOS 3 GHz Large Project

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

Outline

1. Radio AGN and their role in galaxy formation and evolution

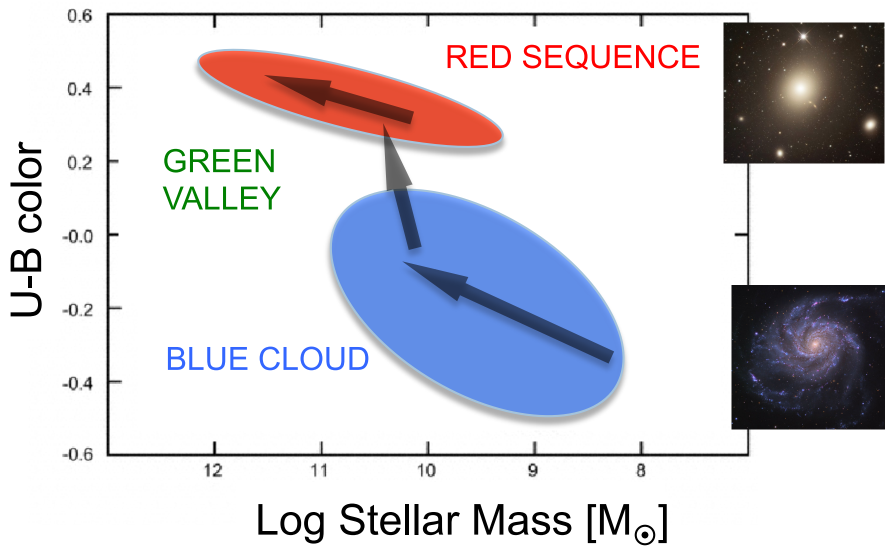
2. VLA-COSMOS 3 GHz Large Project

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

Galaxy evolution

- 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

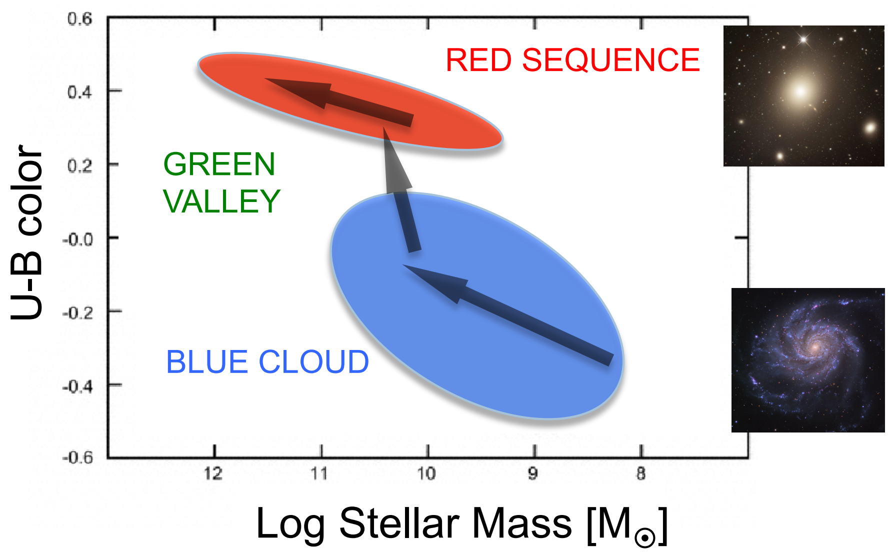


Sanders & Mirabel 1996, Bell et al. 2004, Borch et al. 2006, Faber et al. 2007, Hopkins et al. 2007, Peng et al. (2010, 2012, 2014) & many others

Galaxy evolution

- 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

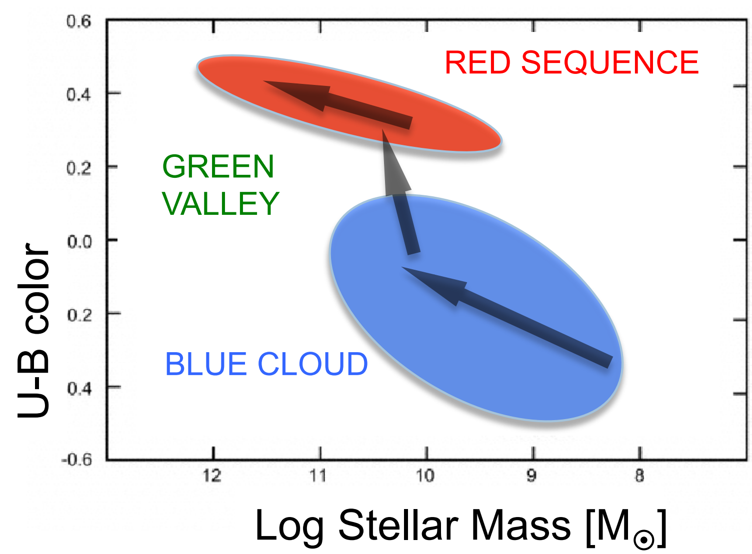


Sanders & Mirabel 1996, Bell et al. 2004, Borch et al. 2006, Faber et al. 2007, Hopkins et al. 2007, Peng et al. (2010, 2012, 2014) & many others

Impact of AGN onto galaxy evolution?

AGN feedback in cosmological models

QUASAR MODE



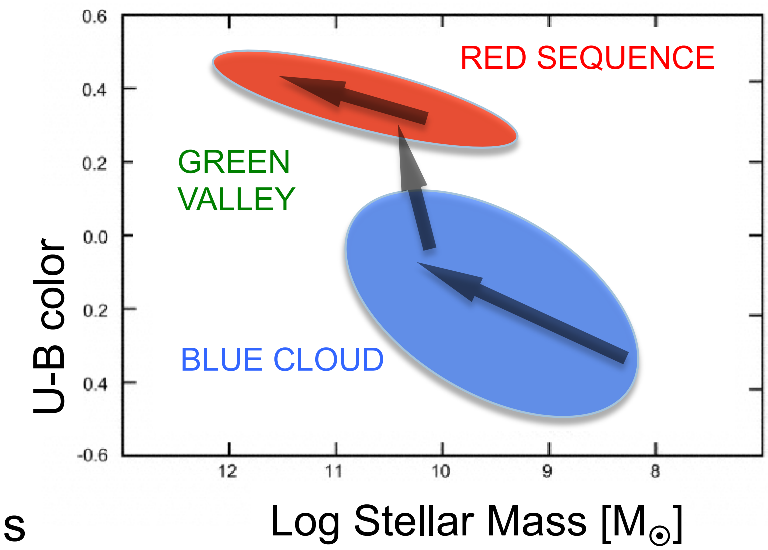
RADIO MODE

AGN feedback in cosmological models

RADIO MODE

QUASAR MODE

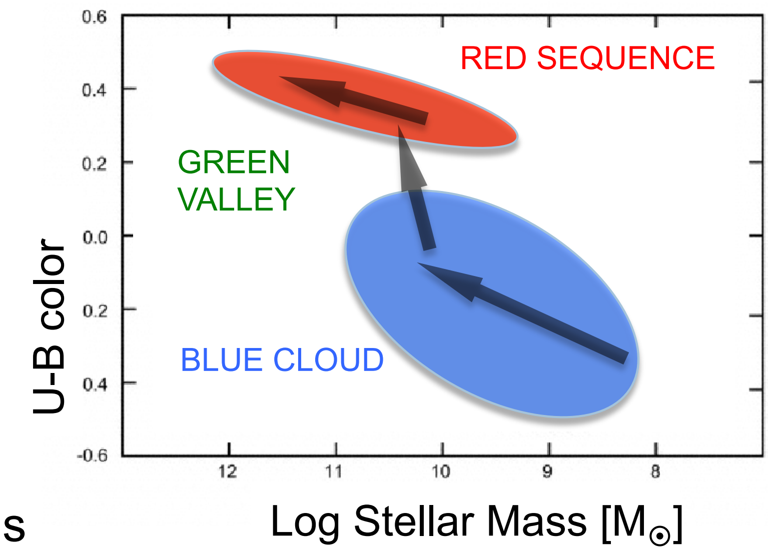
- “truncation” mode
- Merger driven
- Vigorous BH mass growth
- Quasar wind expels gas from galaxy’s center → termination of quasar & starburst phase
- Not necessarily linked to radio outflows



AGN feedback in cosmological models

QUASAR MODE

- "truncation" mode
- Merger driven
- Vigorous BH mass growth
- Quasar wind expels gas from galaxy's center → termination of quasar & starburst phase
- Not necessarily linked to radio outflows



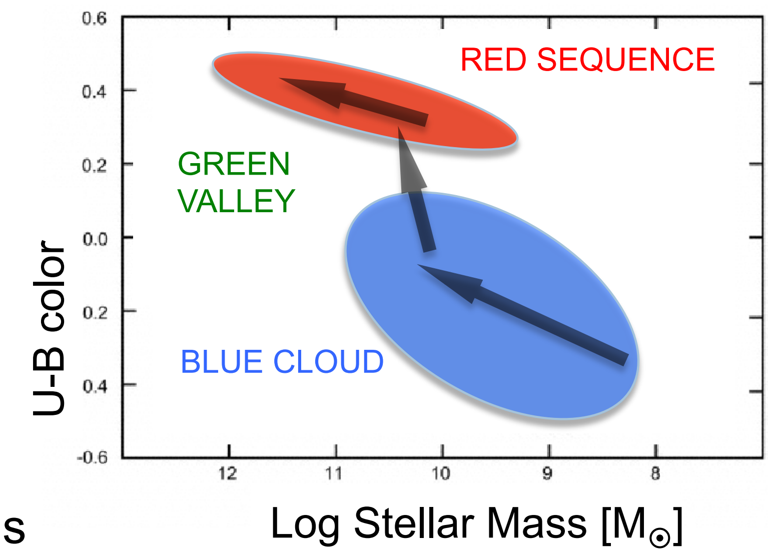
RADIO MODE

- "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

AGN feedback in cosmological models

QUASAR MODE

- "truncation" mode
- Merger driven
- Vigorous BH mass growth
- Quasar wind expels gas from galaxy's center → termination of quasar & starburst phase
- Not necessarily linked to radio outflows



Allows good reproduction of observed galaxy properties

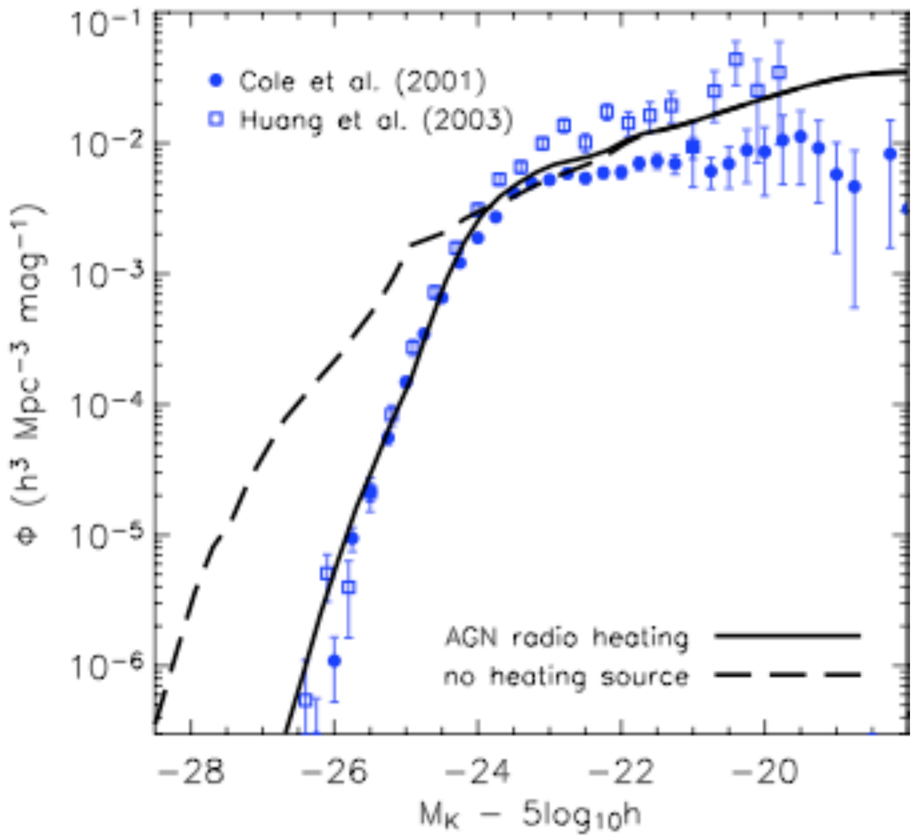
e.g., Croton et al. (2006); Bower et al. (2006); Sijacki et al. (2006), Hopkins et al. (2006), Fanidakis et al. (2012); Croton et al. (2016)

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

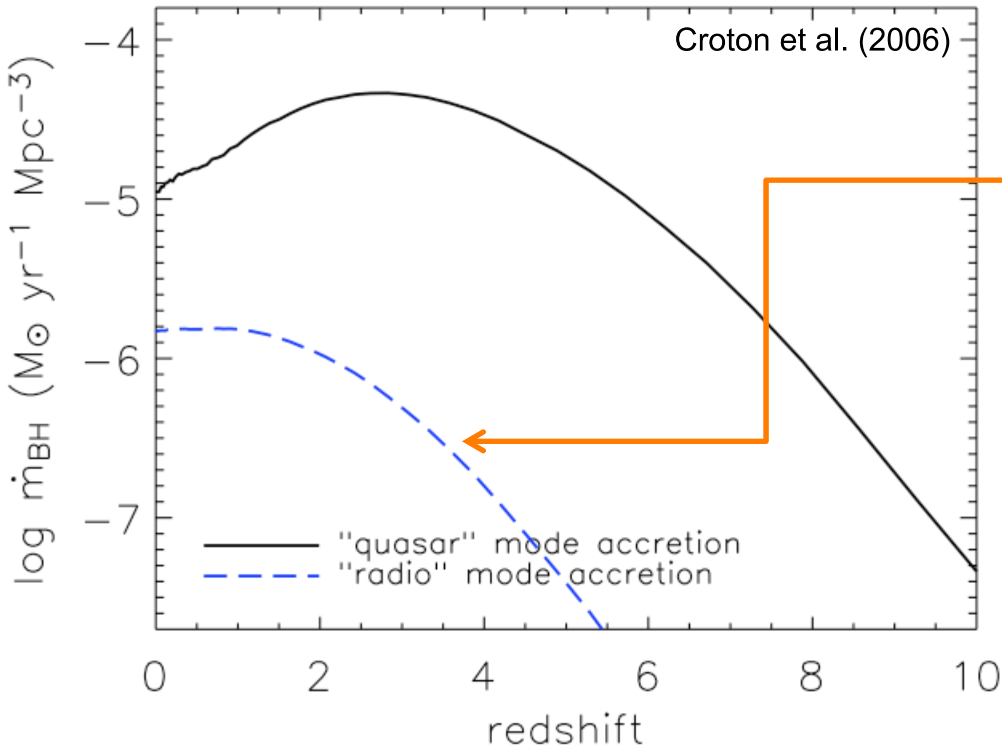
Radio-mode AGN feedback in cosmological models

Croton et al. (2006)



Radio-mode feedback in cosmological models

SMBH accretion rate density as a function of redshift from simulation



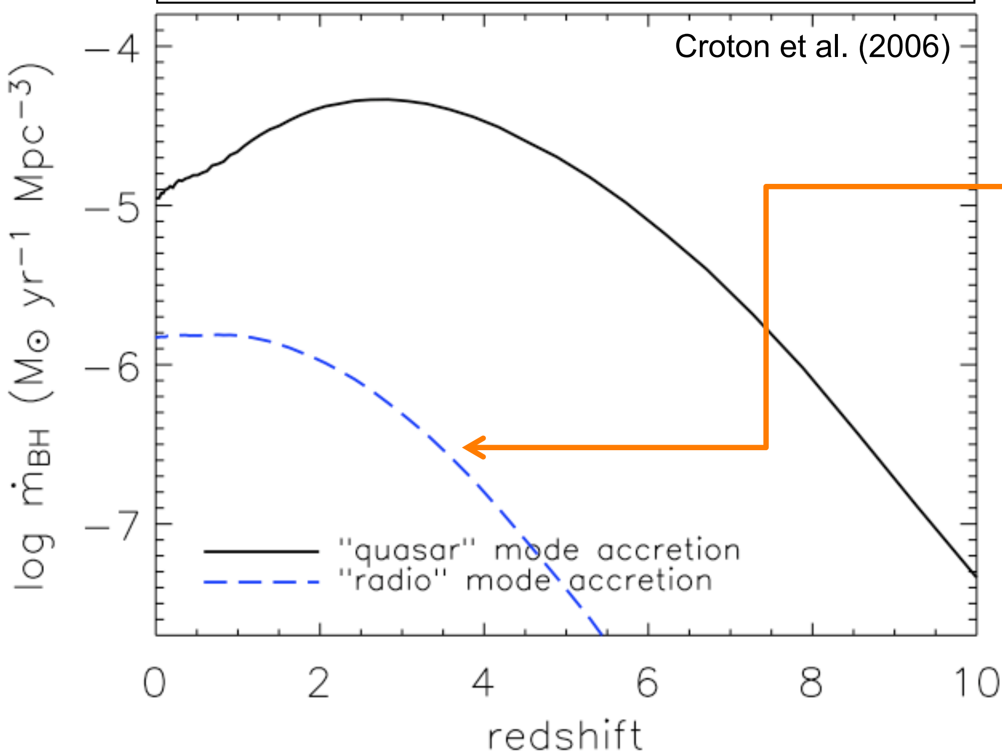
Radio-mode AGN feedback

SAGE semi-analytic model
(Croton et al. 2016)

- Bondi-Hoyle accretion of hot gas
- Luminosity of SMBH in radio mode, $L=0.1\dot{m}c^2$, taken as source of heating that offsets the energy losses of the cooling gas

Radio-mode feedback in cosmological models

SMBH accretion rate density as a function of redshift from simulation



can be inferred from observations

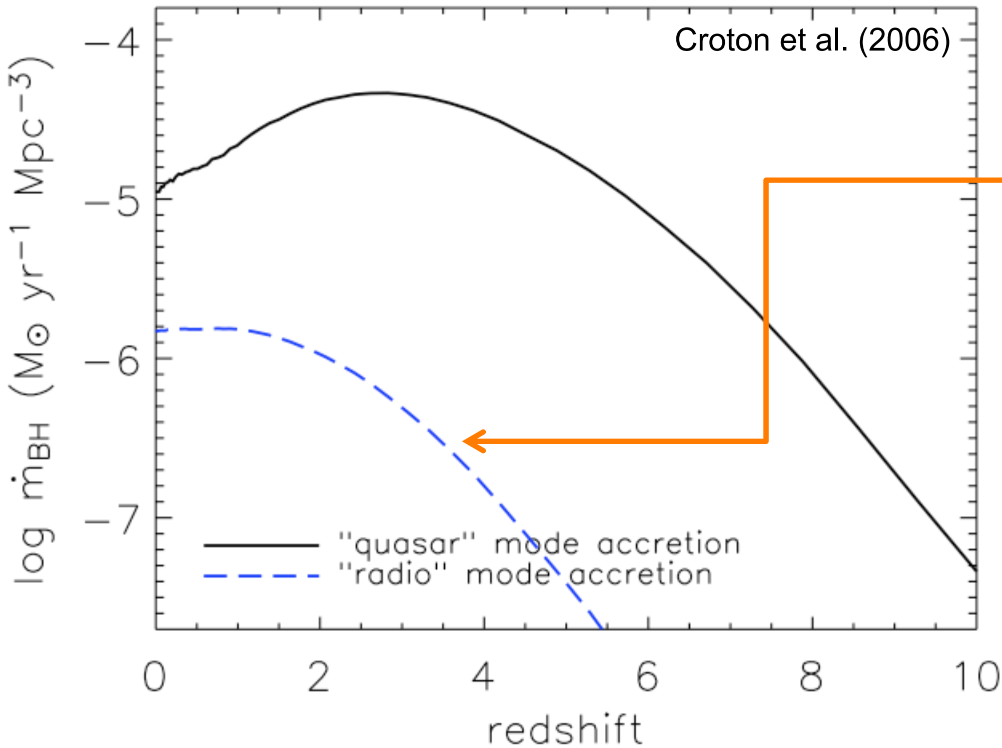
Radio-mode AGN feedback

SAGE semi-analytic model
(Croton et al. 2016)

- Bondi-Hoyle accretion of hot gas
- Luminosity of SMBH in radio mode, $L=0.1\dot{m}c^2$, taken as source of heating that offsets the energy losses of the cooling gas

Radio-mode feedback in cosmological models

SMBH accretion rate density as a function of redshift from simulation



can be inferred from observations

Radio-mode AGN feedback

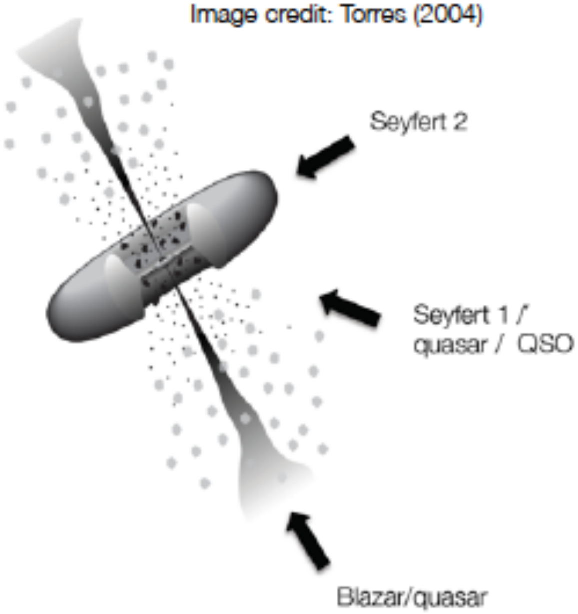
1) deep, large sky area radio observations
2) multi-λ coverage
   - ➔ precise redshifts
   - ➔ an efficient AGN identifier
3) "radio-mode" luminosity density (~SMBH accretion rate density; $L=0.1\dot{m}c^2$) as function of redshift

LE vs. HE radio AGN: Fundamental physical differences

High-excitation ~ thin disk ~ radiatively efficient accr. flow

- Strong emission lines in optical spectrum
- X-ray, MIR, optical AGN (Unified model for AGN)

Image credit: Torres (2004)



Low-excitation ~ thick disk ~ radiatively inefficient accr. flow

- Optical spectrum devoid of strong emission lines (usually LINER, absorption line AGN)
- Identified as AGN in the radio window

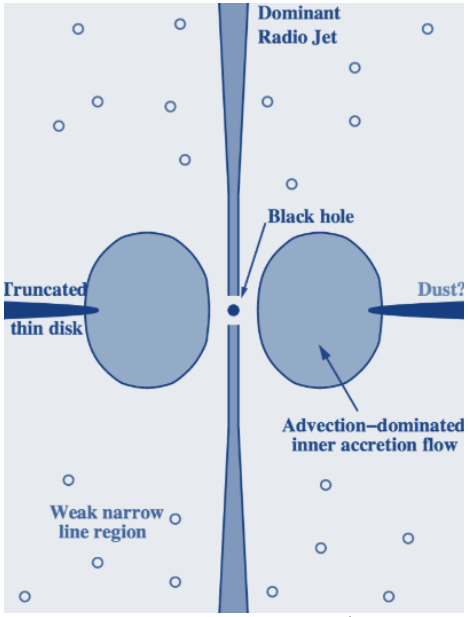


Image: Heckman & Best (2014)

HERAGN or HERG or
Cold-mode AGN or
Radiative-AGN or
Quasar-mode or
High SMBH accretors or
Thin-disk

Image credit: Torres (2004)

LERAGN or LERG or
Hot-mode AGN or
Jet-mode AGN or
Radio-mode or
Low SMBH accretors or
Thick-disk, ADAF, RIAF

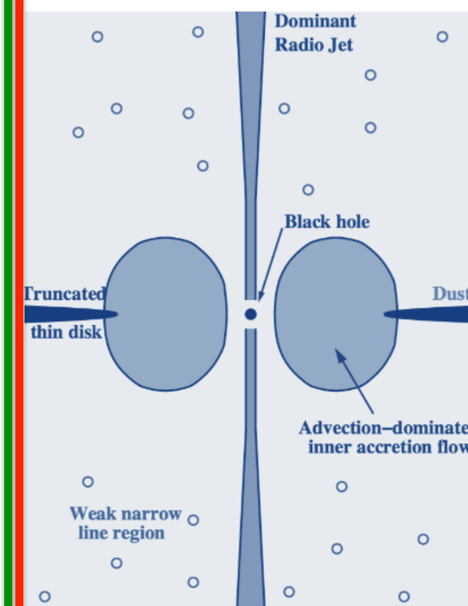


Image credit: Heckman & Best (2014)

	HERAGN	LERAGN	References
Other names	HERG Cold-mode AGN Radiative-AGN Quasar-mode High SMBH accretors Thin-disk	LERG Hot-mode AGN Jet-mode AGN Radio-mode Low SMBH accretors Thick-disk, ADAF, RIAF	
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \leq 10^{26}$W/Hz)	e.g., Kauffmann et al. 2008, Best & Heckman 2012
Optical color	Green	Red	e.g., Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5 \times 10^{10} M_\odot$)	e.g., Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3 \times 10^8 M_\odot$)	Low ($< 4.3 \times 10^7 M_\odot$)	e.g., Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim 10^9 M_\odot$)	e.g., Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	e.g., Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009
BH accretion mode	Radiatively efficient	Radiatively inefficient	e.g., Evans et al. 2006; Merloni & Heinz 2008; Fanidakis et al. 2012

HERAGN or HERG or
Cold-mode AGN or
Radiative-AGN or
Quasar-mode or
High SMBH accretors or
Thin-disk

Image credit: Torres (2004)

LERAGN or LERG or
Hot-mode AGN or
Jet-mode AGN or
Radio-mode or
Low SMBH accretors or
Thick-disk, ADAF, RIAF

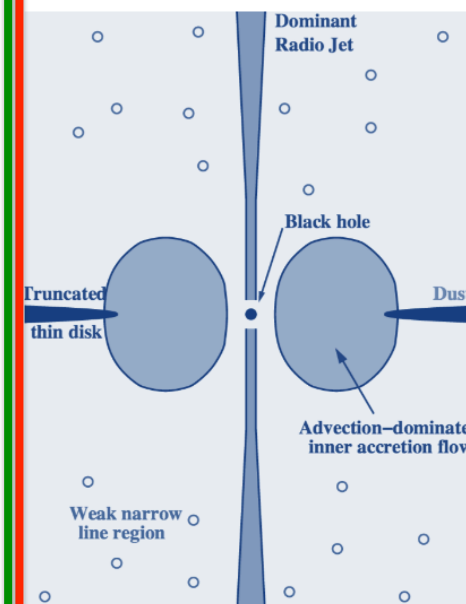
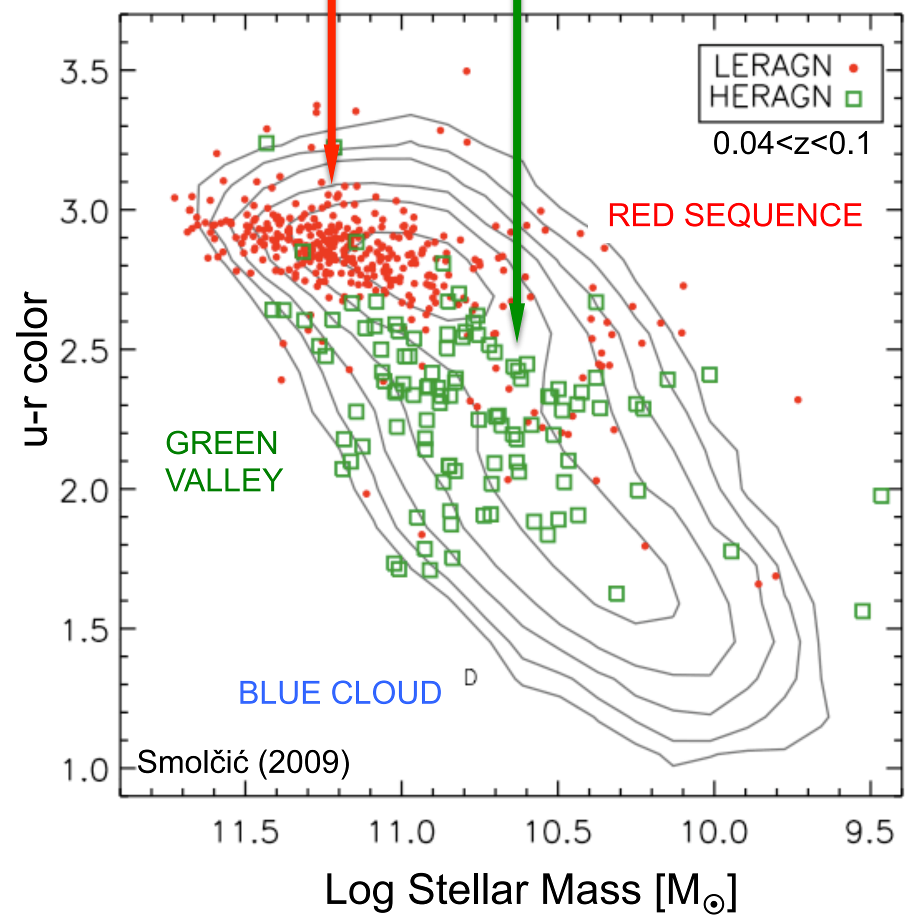


Image credit: Heckman & Best (2014)

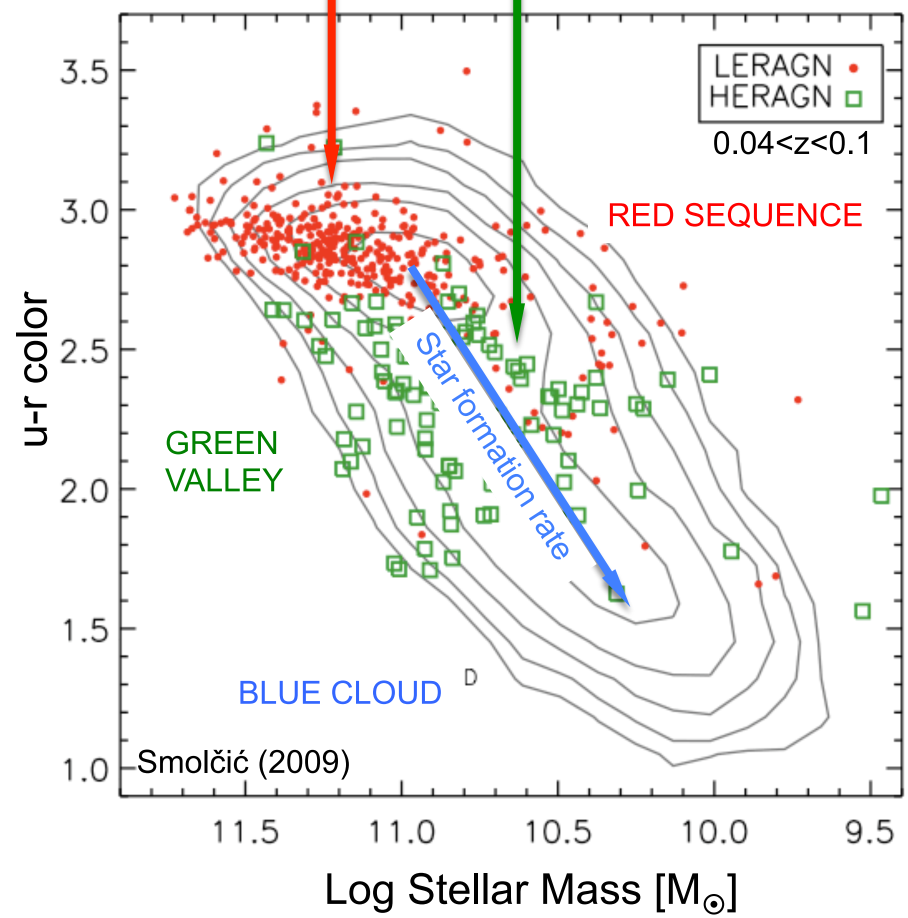
See Smolčić (2016)

	HERAGN	LERAGN	References
Other names	HERG Cold-mode AGN Radiative-AGN Quasar-mode High SMBH accretors Thin-disk	LERG Hot-mode AGN Jet-mode AGN Radio-mode Low SMBH accretors Thick-disk, ADAF, RIAF	
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \leq 10^{26}$W/Hz)	e.g., Kauffmann et al. 2008, Best & Heckman 2012
Optical color	Green	Red	e.g., Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10}M_{\odot}$)	e.g., Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3\times10^{8}M_{\odot}$)	Low ($<4.3\times10^{7}M_{\odot}$)	e.g., Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim10^{9}M_{\odot}$)	e.g., Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	e.g., Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009
BH accretion mode	Radiatively efficient	Radiatively inefficient	e.g., Evans et al. 2006; Merloni & Heinz 2008; Fanidakis et al. 2012



See Smolčić (2016)

	HERAGN	LERAGN	References
Other names	HERG Cold-mode AGN Radiative-AGN Quasar-mode High SMBH accretors Thin-disk	LERG Hot-mode AGN Jet-mode AGN Radio-mode Low SMBH accretors Thick-disk, ADAF, RIAF	
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \leq 10^{26}$W/Hz)	e.g., Kauffmann et al. 2008, Best & Heckman 2012
Optical color	Green	Red	e.g., Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10} M_\odot$)	e.g., Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3\times10^{8} M_\odot$)	Low ($<4.3\times10^{7} M_\odot$)	e.g., Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim10^{9} M_\odot$)	e.g., Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	e.g., Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009
BH accretion mode	Radiatively efficient	Radiatively inefficient	e.g., Evans et al. 2006; Merloni & Heinz 2008; Fanidakis et al. 2012



See Smolčić (2016)

1. **Radio AGN and their role in galaxy formation and evolution**

2. **VLA-COSMOS 3 GHz Large Project**

3. **VLA-COSMOS 3 GHz Large Project galaxy populations**

4. **Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5**

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8$ M_{SOL}; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9$ M_{SOL}; $L < 0.1$ L_{EDD})
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

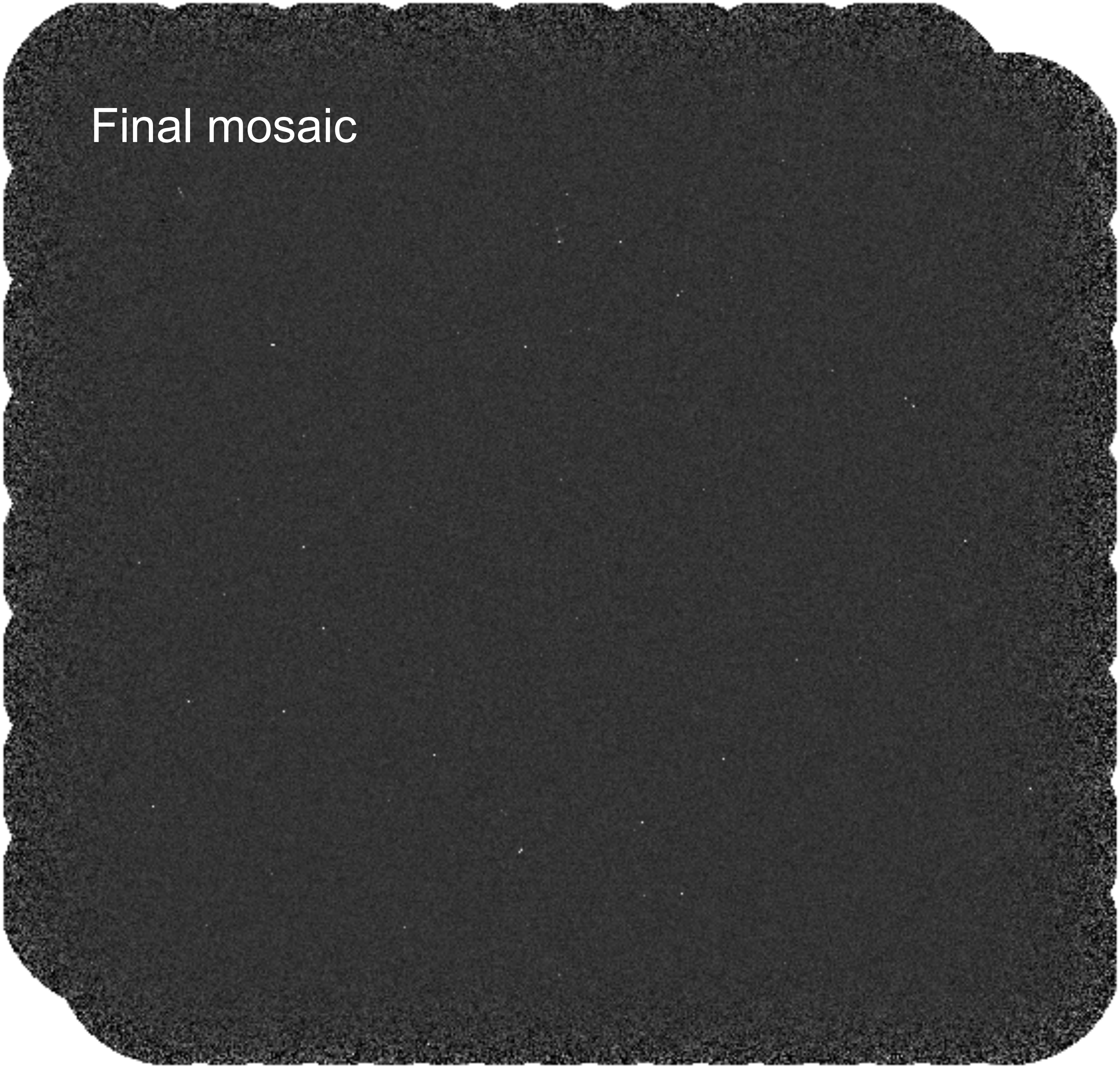
The VLA-COSMOS 3 GHz Large Project

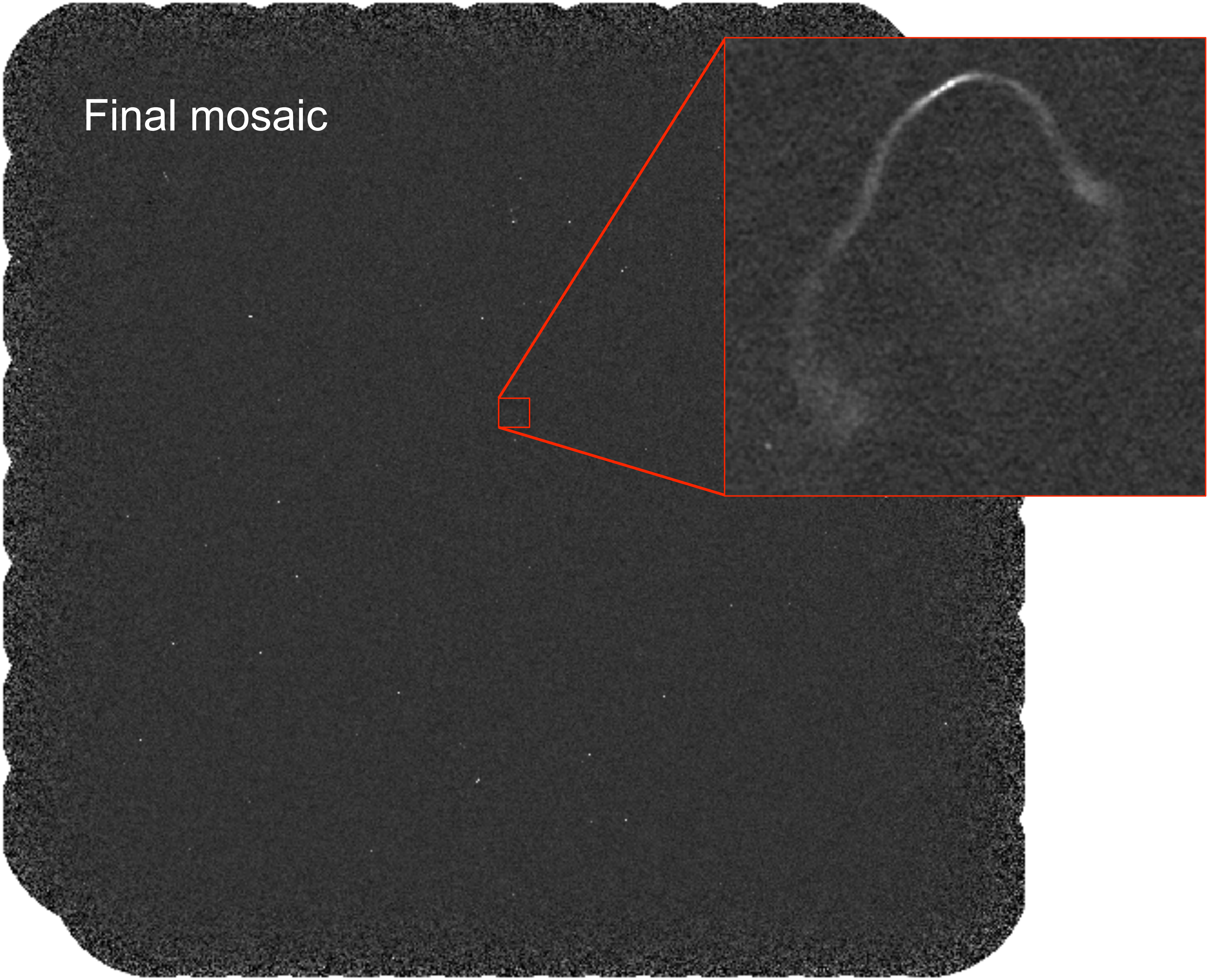
Data available from:
http://irsa.ipac.caltech.edu/data/COSMOS/images/vla/
http://irsa.ipac.caltech.edu/data/COSMOS/tables/vla/

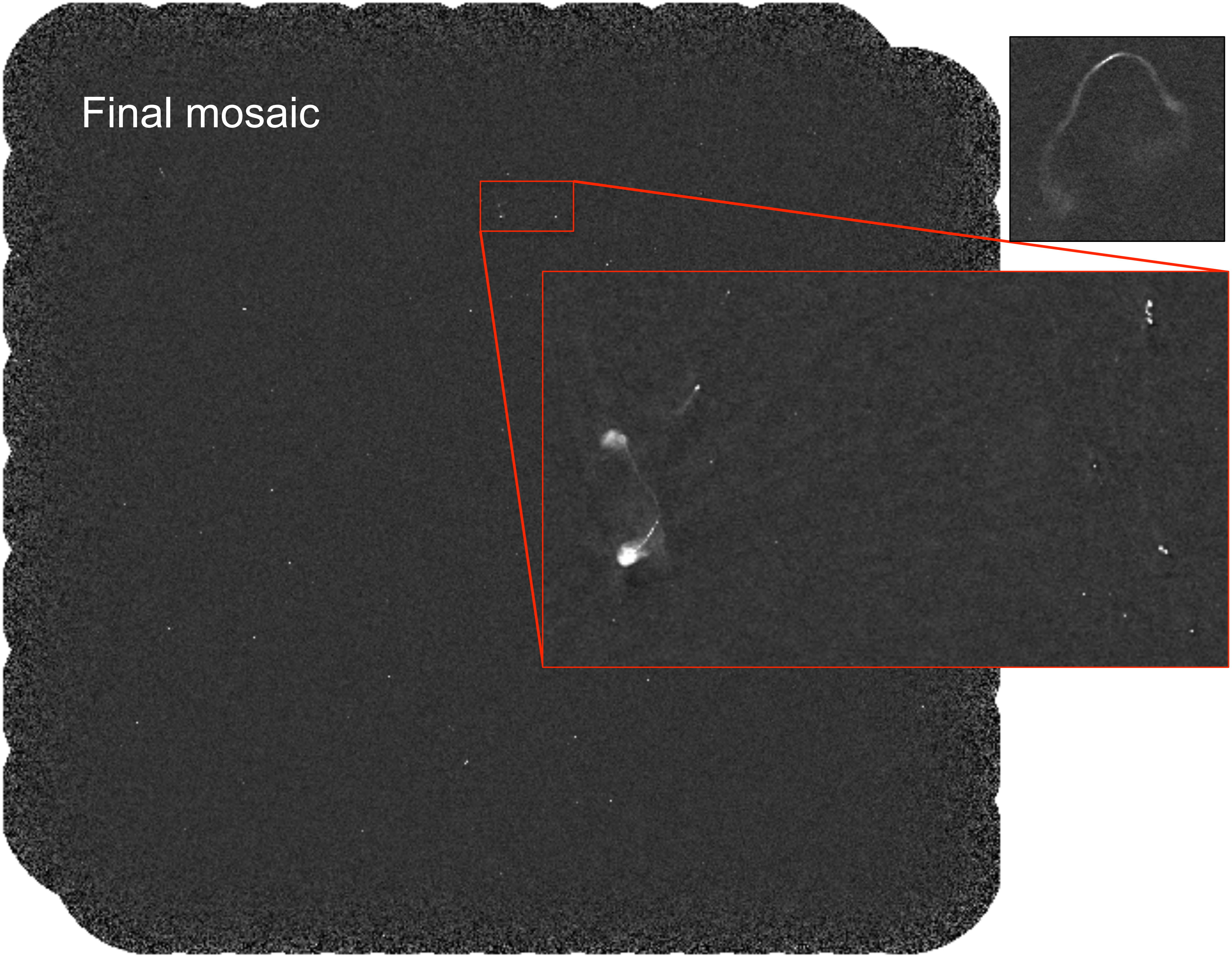
- 384 hours (A+C array)
- 3 GHz (2 GHz bandwidth)
- 0.75'' resolution
- rms ~2.3 μJy/beam
- 10,830 sources (67 multi-component)
- Rigorous quality assessment
  (flux, astrometry, resolution bias …)

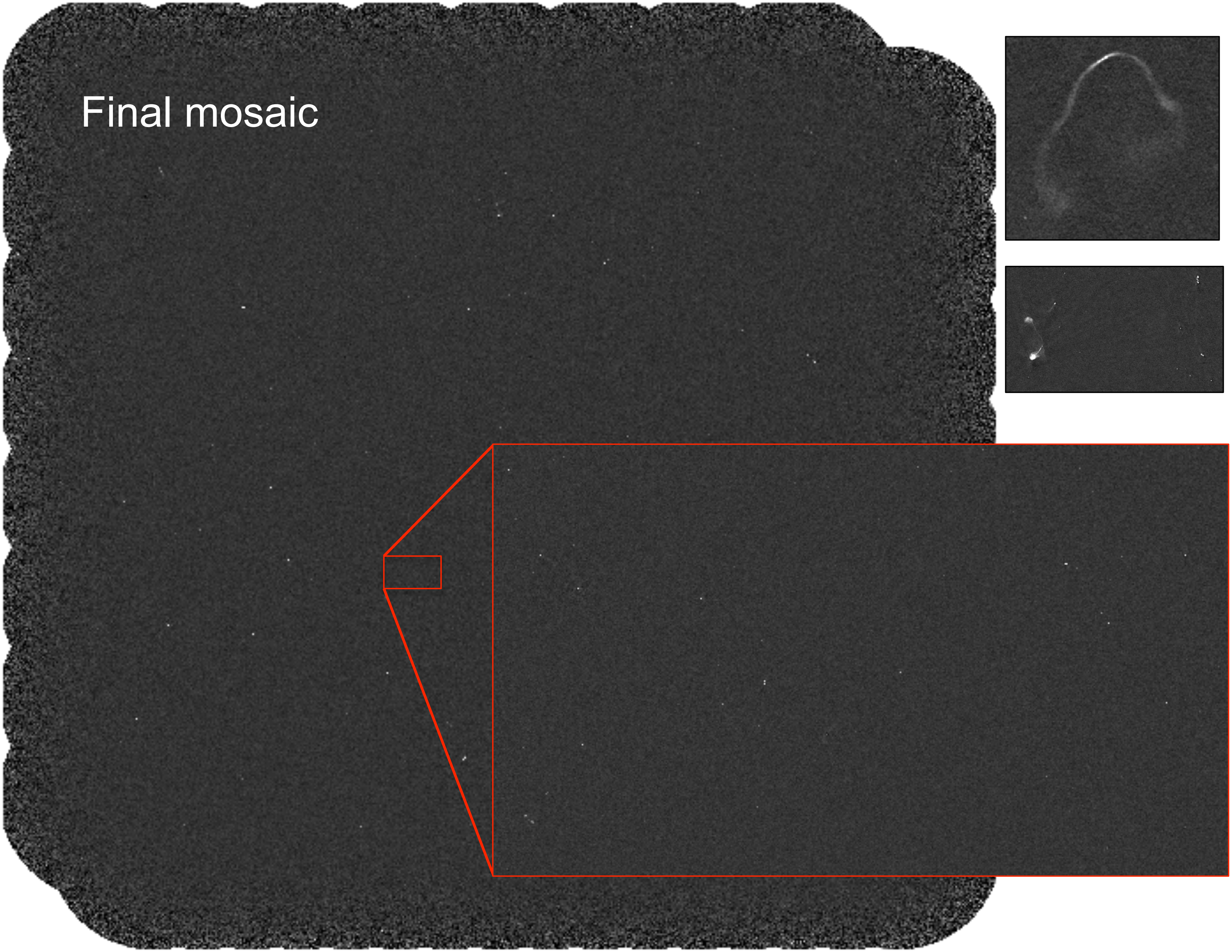
Simultaneously the largest and deepest cm radio continuum survey at high (0.75'') angular resolution to-date

Smolčić et al. (2017a)

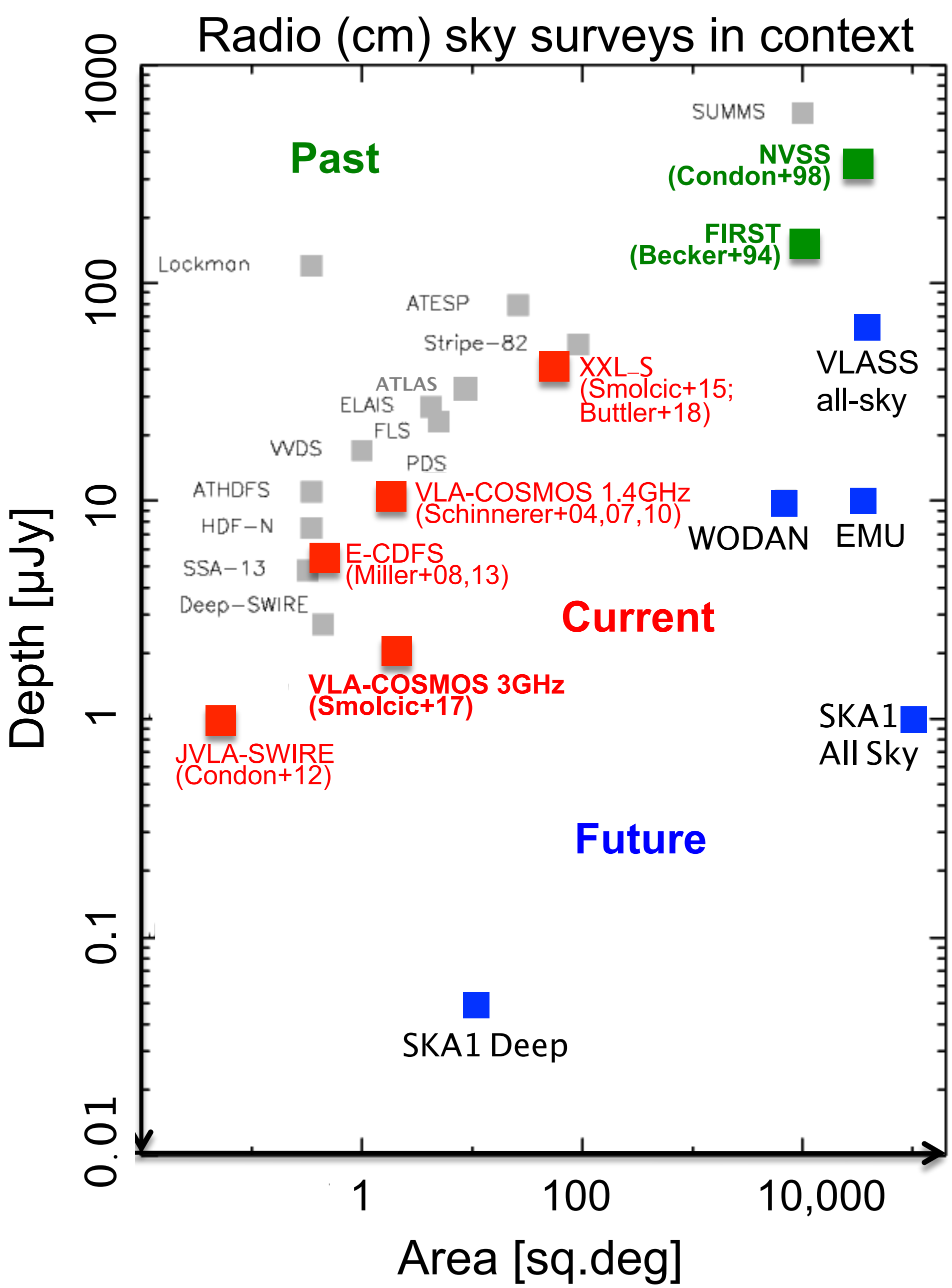

Final mosaic


Final mosaic

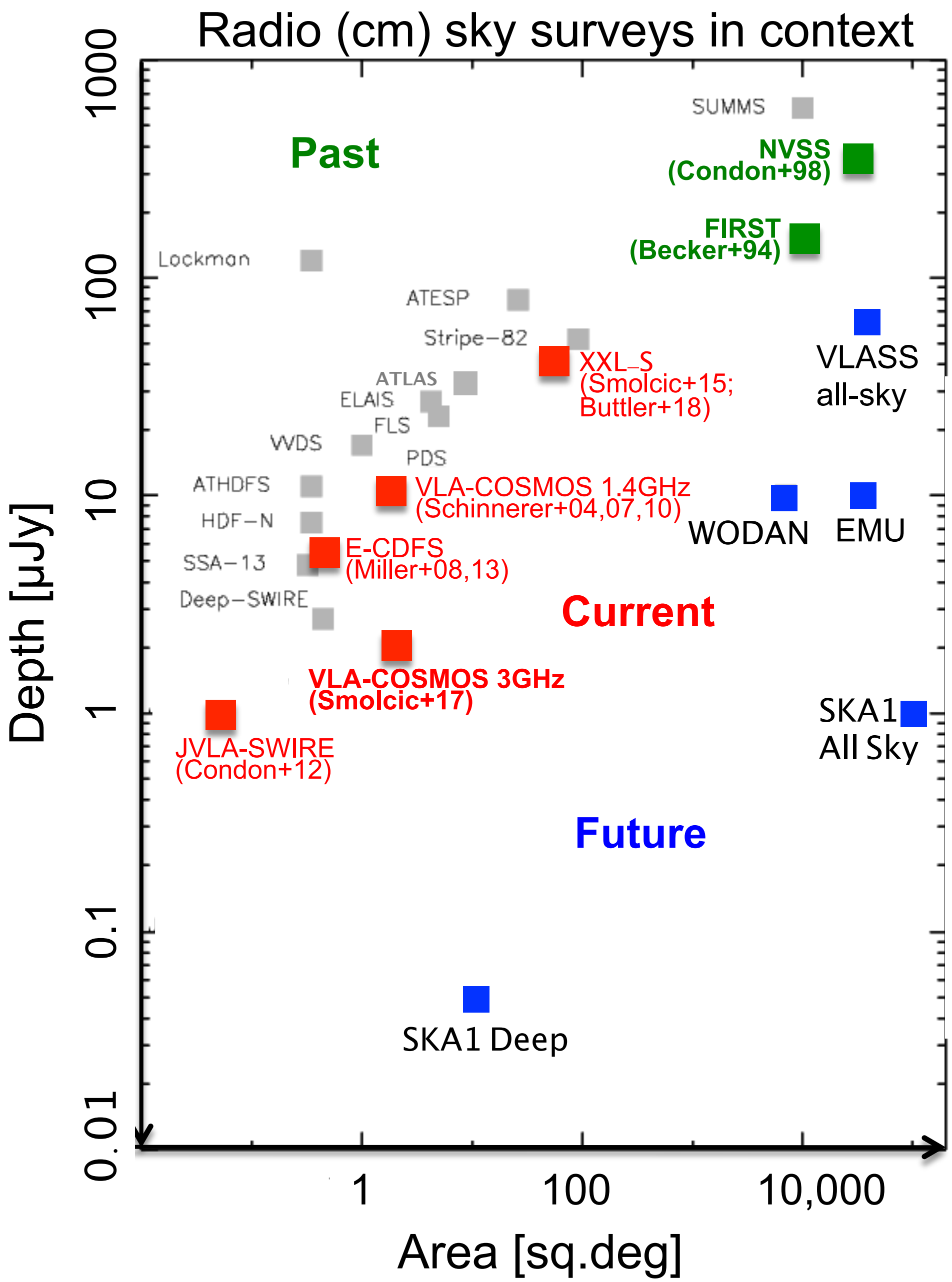

Final mosaic

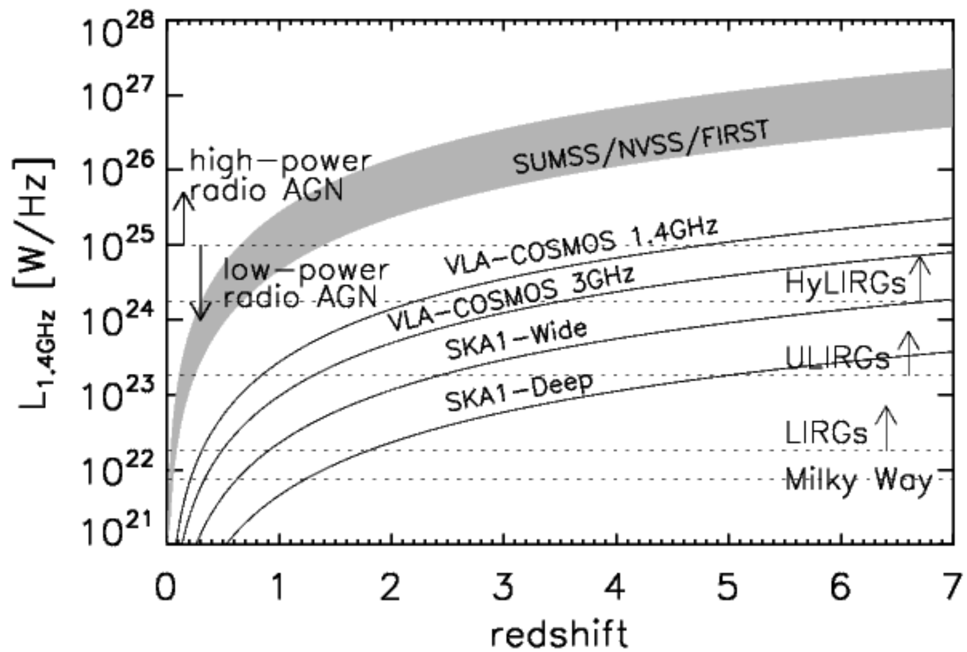

Final mosaic

VLA-COSMOS 3 GHz Large Project in context



VLA-COSMOS 3 GHz Large Project in context





1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of “radio-mode feedback”, controlling build-up of M_* in massive galaxies
- “Radio-mode AGN feedback” is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts’ star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 μJy/beam, resolution 0.75’’, 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

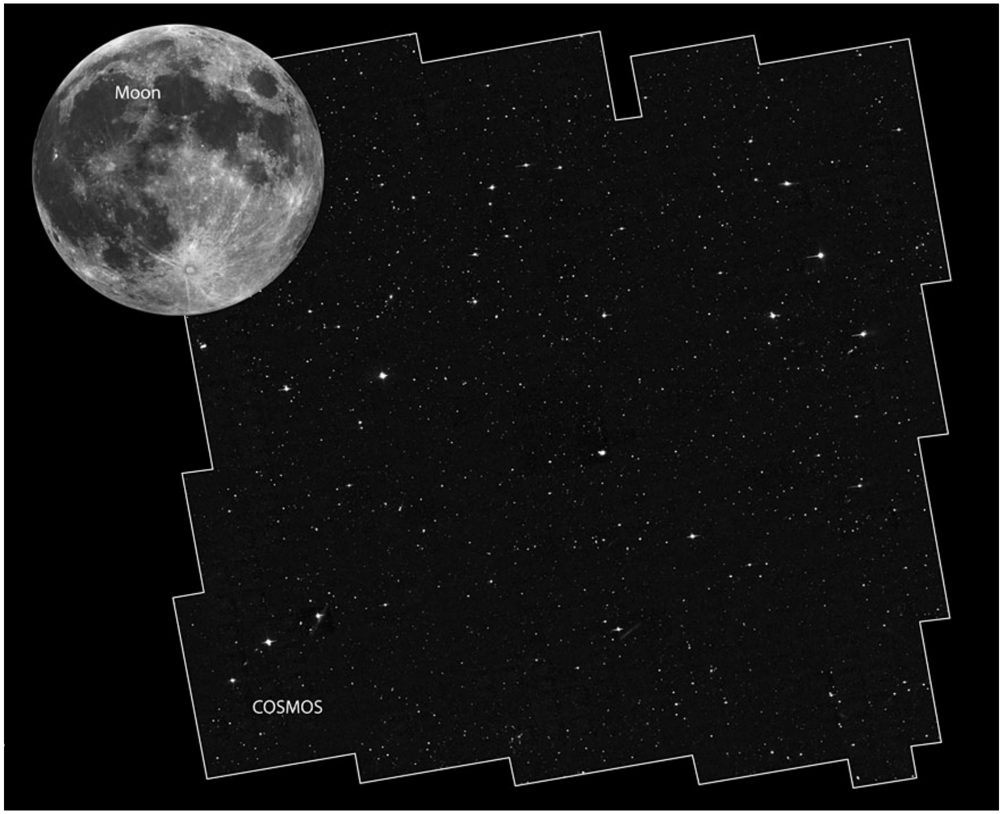
2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

VLA-COSMOS 3GHz Large Project
+
COSMOS multi-λ data

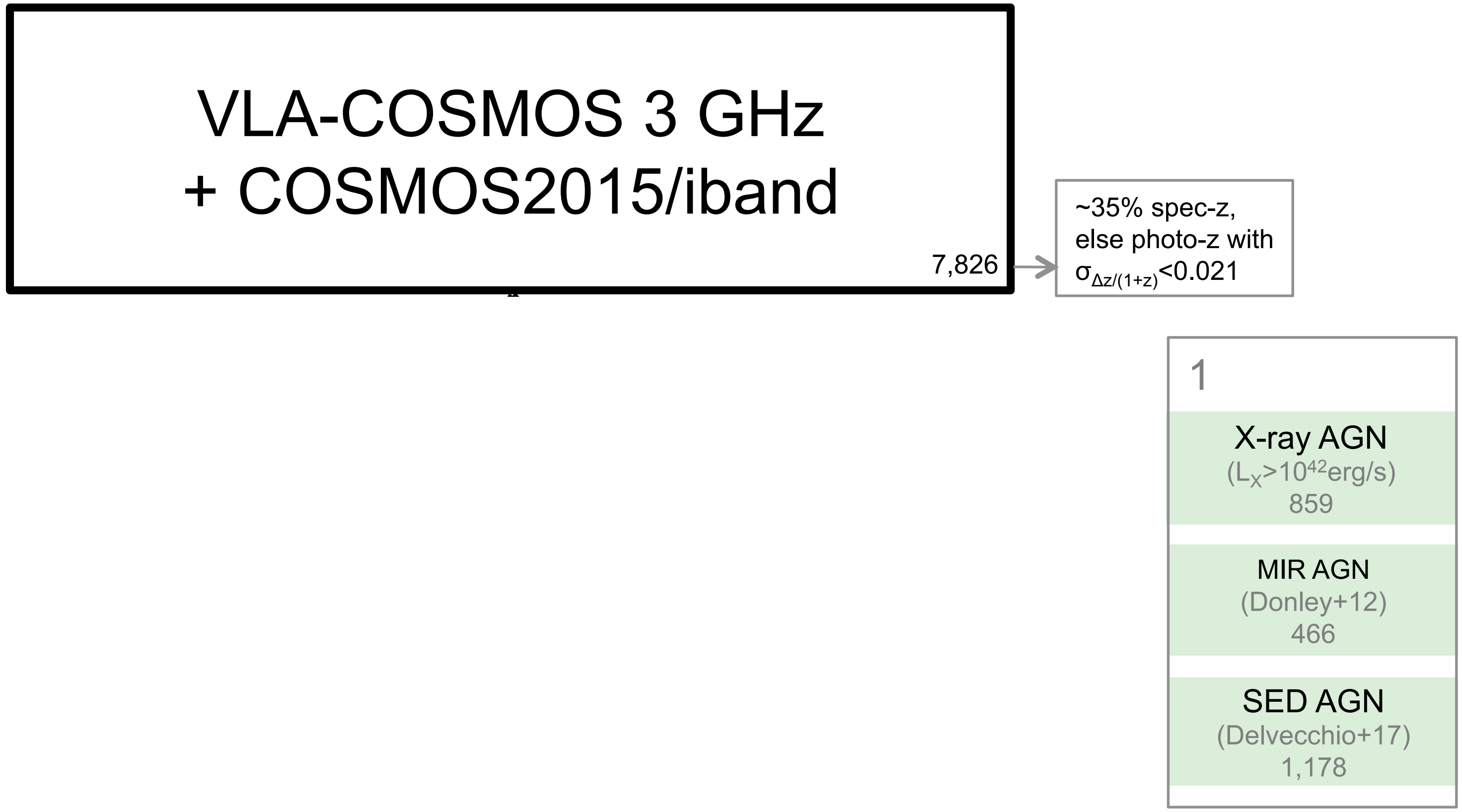


- VLA-COSMOS 3GHz Large Project
  - PI: Smolčić (Smolčić et al.,2017a)
  - 384 hours (A+C configurations, 2012/13)
  - 3 GHz (2 GHz bandwidth)
  - 0.75'' resolution
  - rms ~2.3 μJy/beam over 2□^{O}
  - 10,830 sources
- COSMOS Project
  - Scoville et al. (2007)
  - 2□^{O} equatorial field
  - X-ray to radio imaging (>30 bands)
    - Galaxy photo-z (Ilbert et al 2009; Laigle et al. 2016)
    - AGN photo-z (Salvato et al. 2009; Marchesi et al. 2016)
  - >100,000 spectra (VLT, Magellan, Keck)

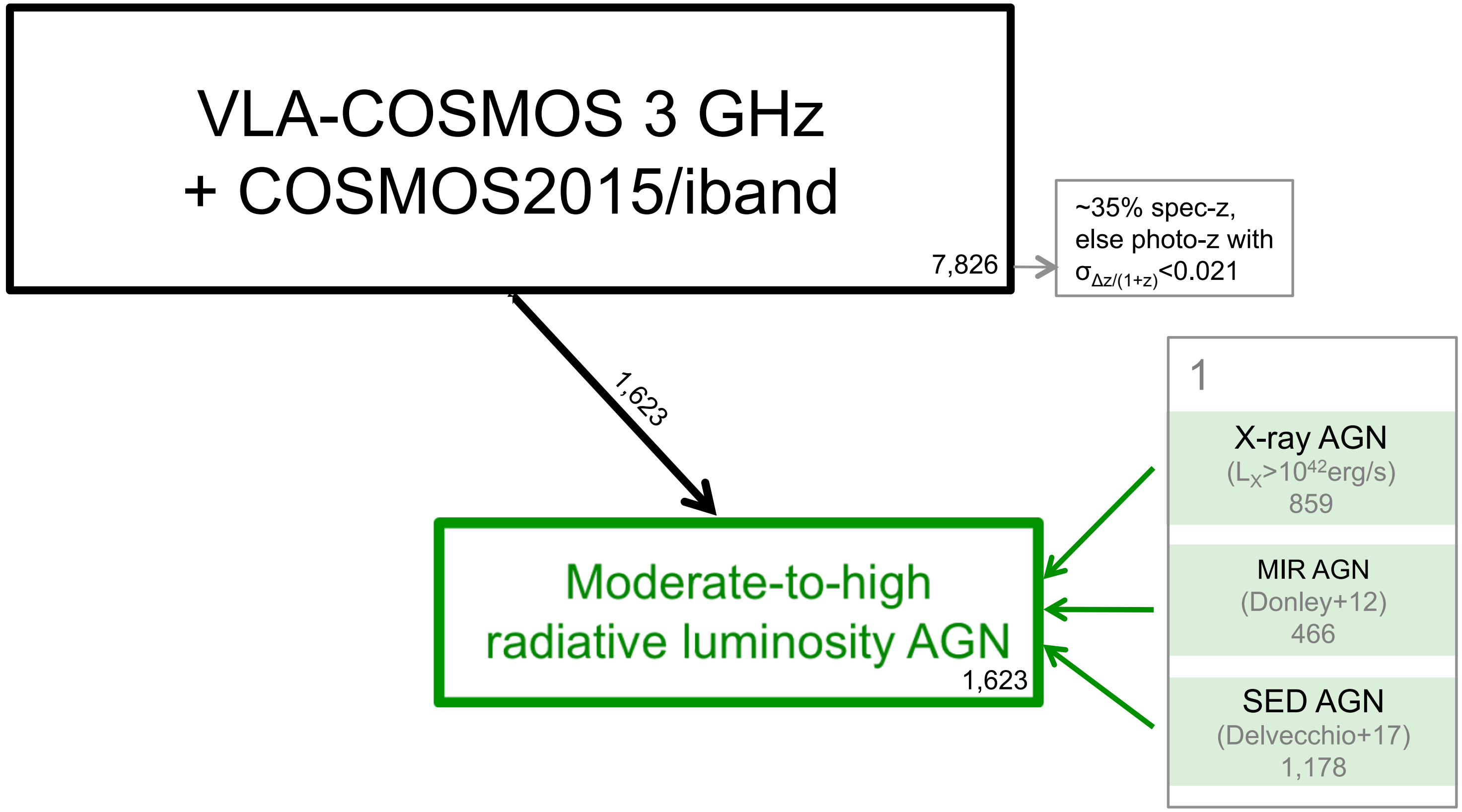
VLA-COSMOS 3 GHz
+ COSMOS2015/iband

7,826 → ~35% spec-z, else photo-z with $\sigma_{\Delta z/(1+z)}<0.021$

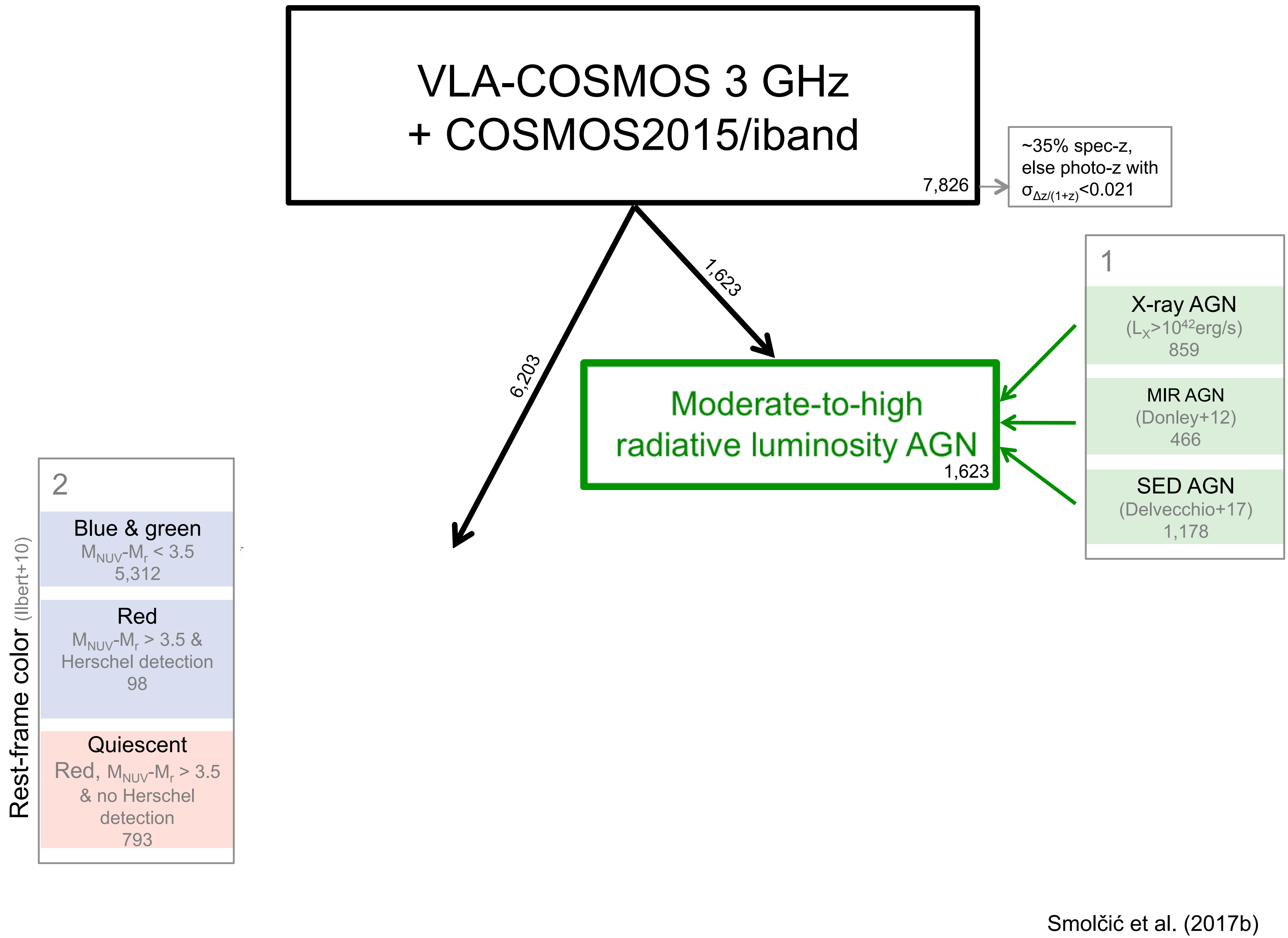
Smolčić et al. (2017b)

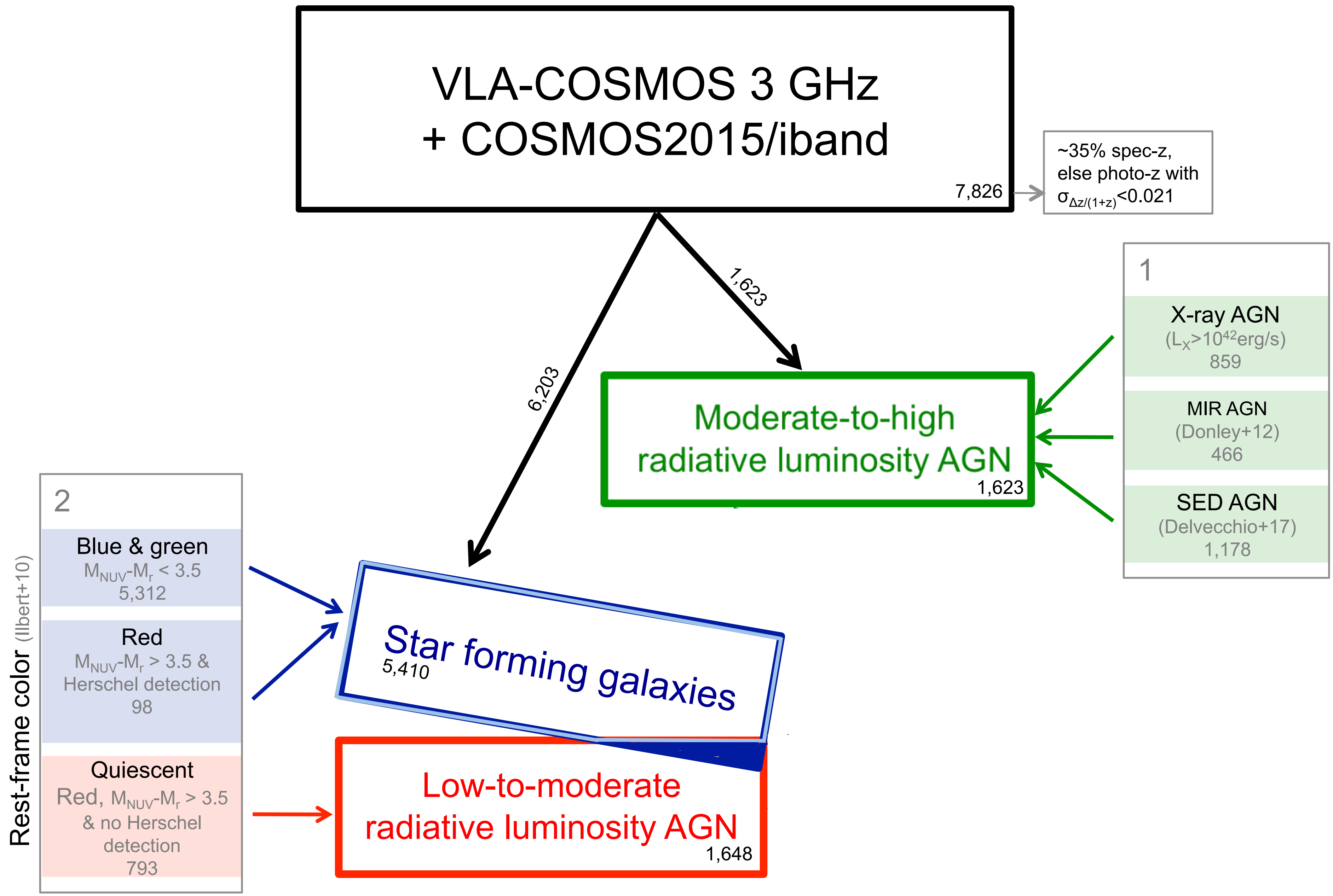


Smolčić et al. (2017b)

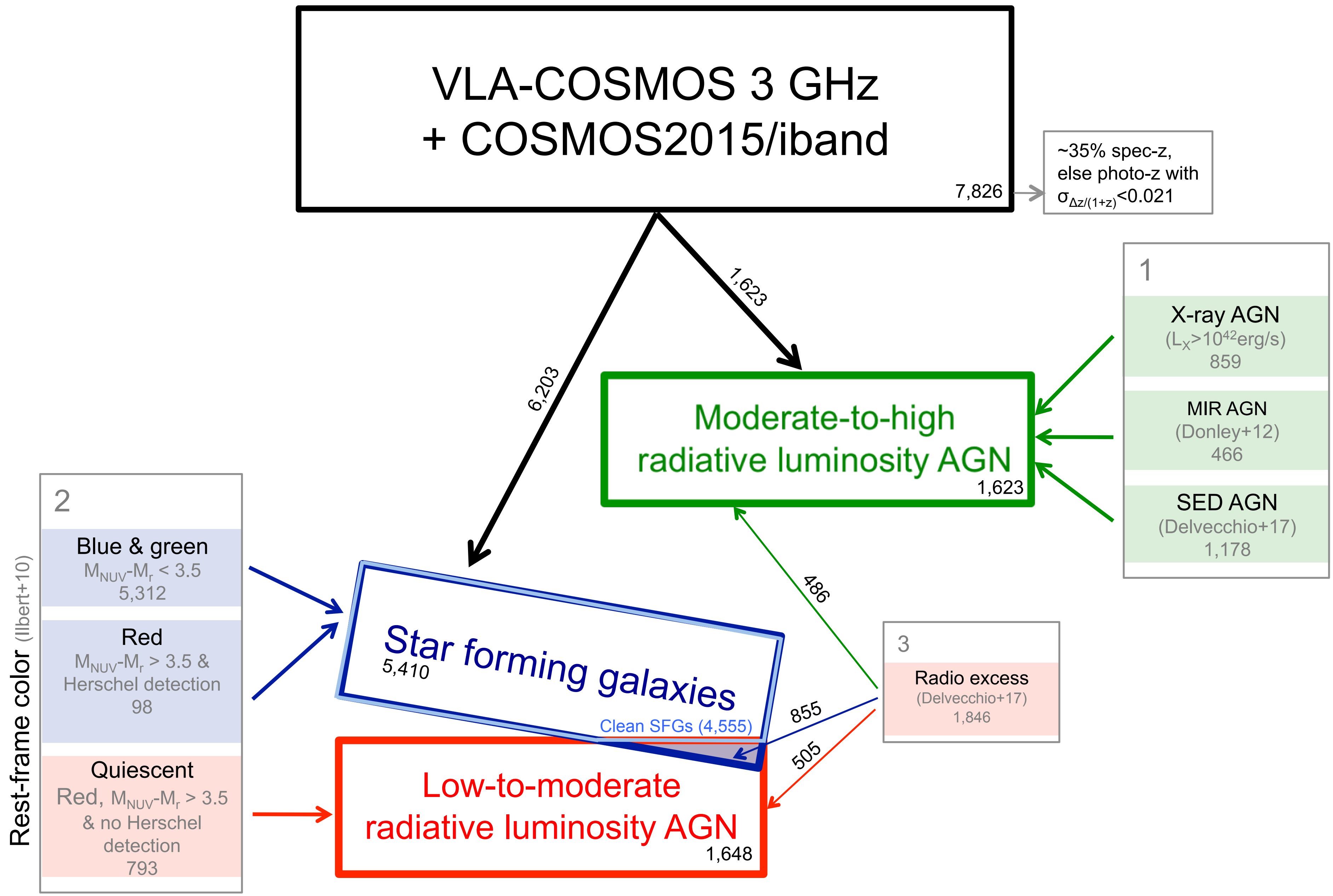


Smolčić et al. (2017b)


VLA-COSMOS 3 GHz
+ COSMOS2015/iband
7,826
~35% spec-z, else photo-z with $\sigma_{\Delta z/(1+z)}$<0.021
1,623
6,203
Moderate-to-high radiative luminosity AGN
1,623
1
X-ray AGN
($L_X > 10^{42}$ erg/s)
859
MIR AGN
(Donley+12)
466
SED AGN
(Delvecchio+17)
1,178
2
Rest-frame color (Ilbert+10)
Blue & green
$M_{NUV}-M_r < 3.5$
5,312
Red
$M_{NUV}-M_r > 3.5$ &
Herschel detection
98
Quiescent
Red, $M_{NUV}-M_r > 3.5$
& no Herschel detection
793
Smolčić et al. (2017b)



Smolčić et al. (2017b)



Smolčić et al. (2017b)

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH.

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH.

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts (z<6)
- Source classification based on various (X-ray, MIR, colors, radio excess) criteria, assessing composite nature

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH.

2. VLA-COSMOS 3 GHz Large Project

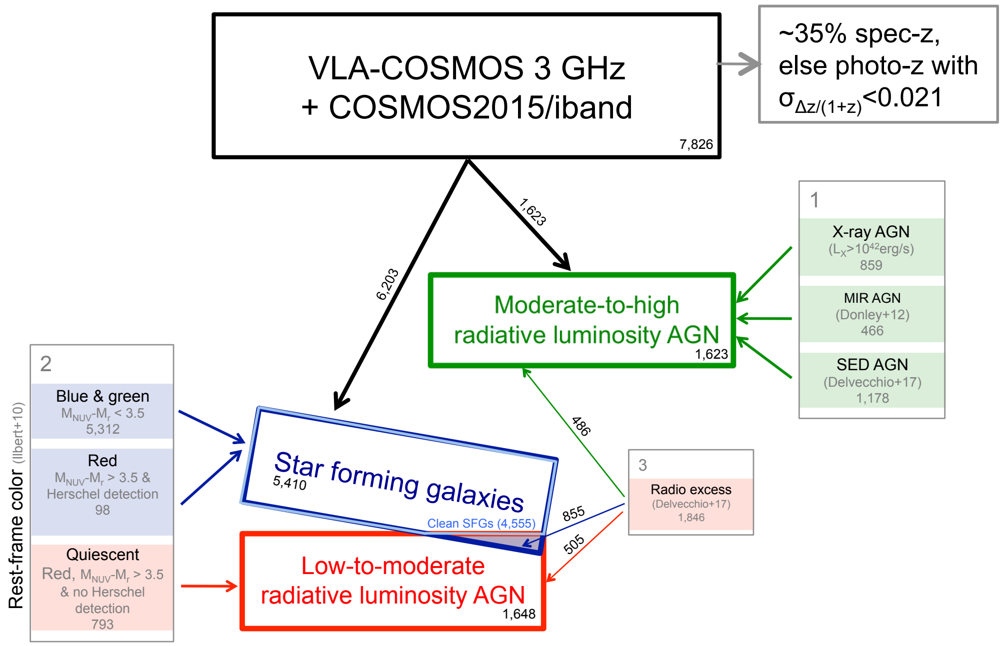
- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts (z<6)
- Source classification based on various (X-ray, MIR, colors, radio excess) criteria, assessing composite nature

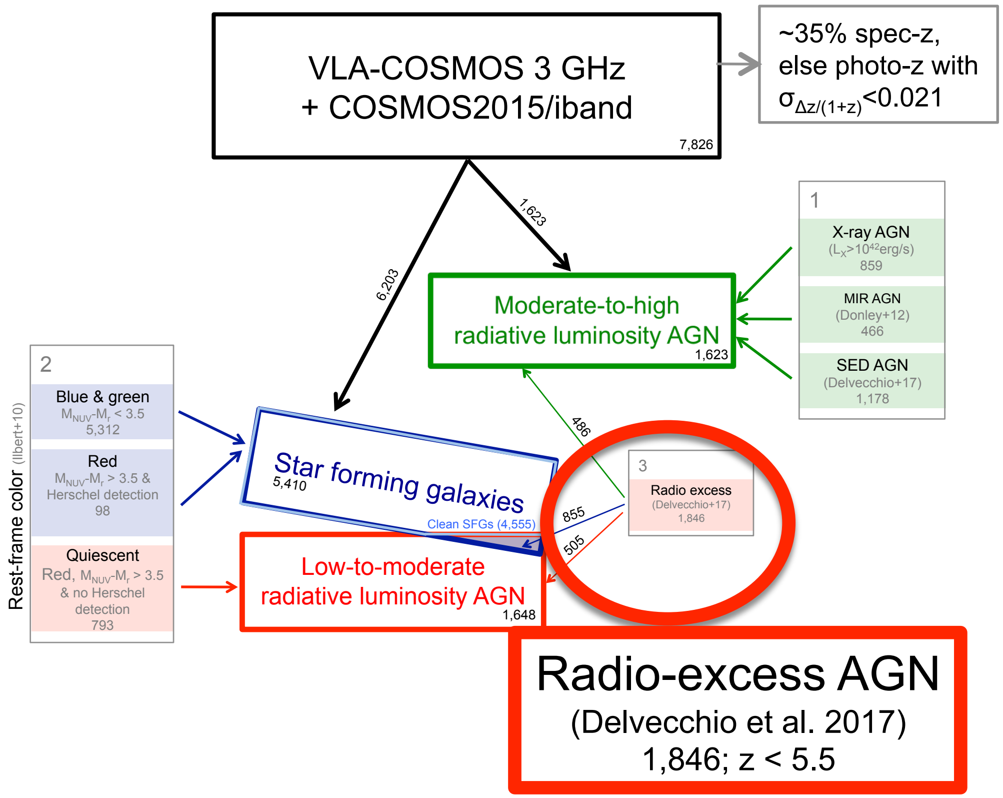
4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

The VLA-COSMOS 3 GHz Large Project radio source sample



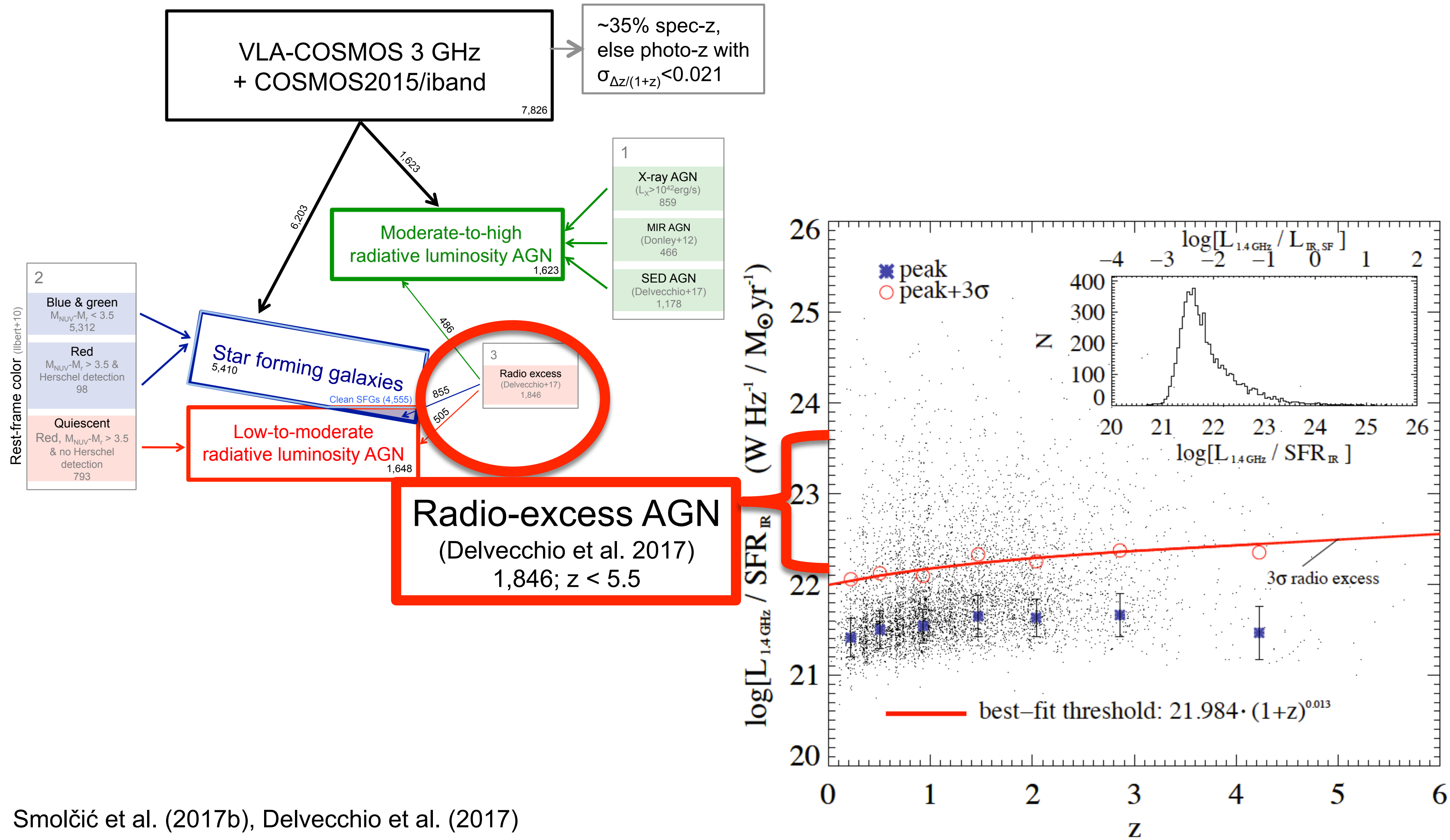
Smolčić et al. (2017b), Delvecchio et al. (2017)

The VLA-COSMOS 3 GHz Large Project radio source sample



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

The VLA-COSMOS 3 GHz Large Project radio source sample



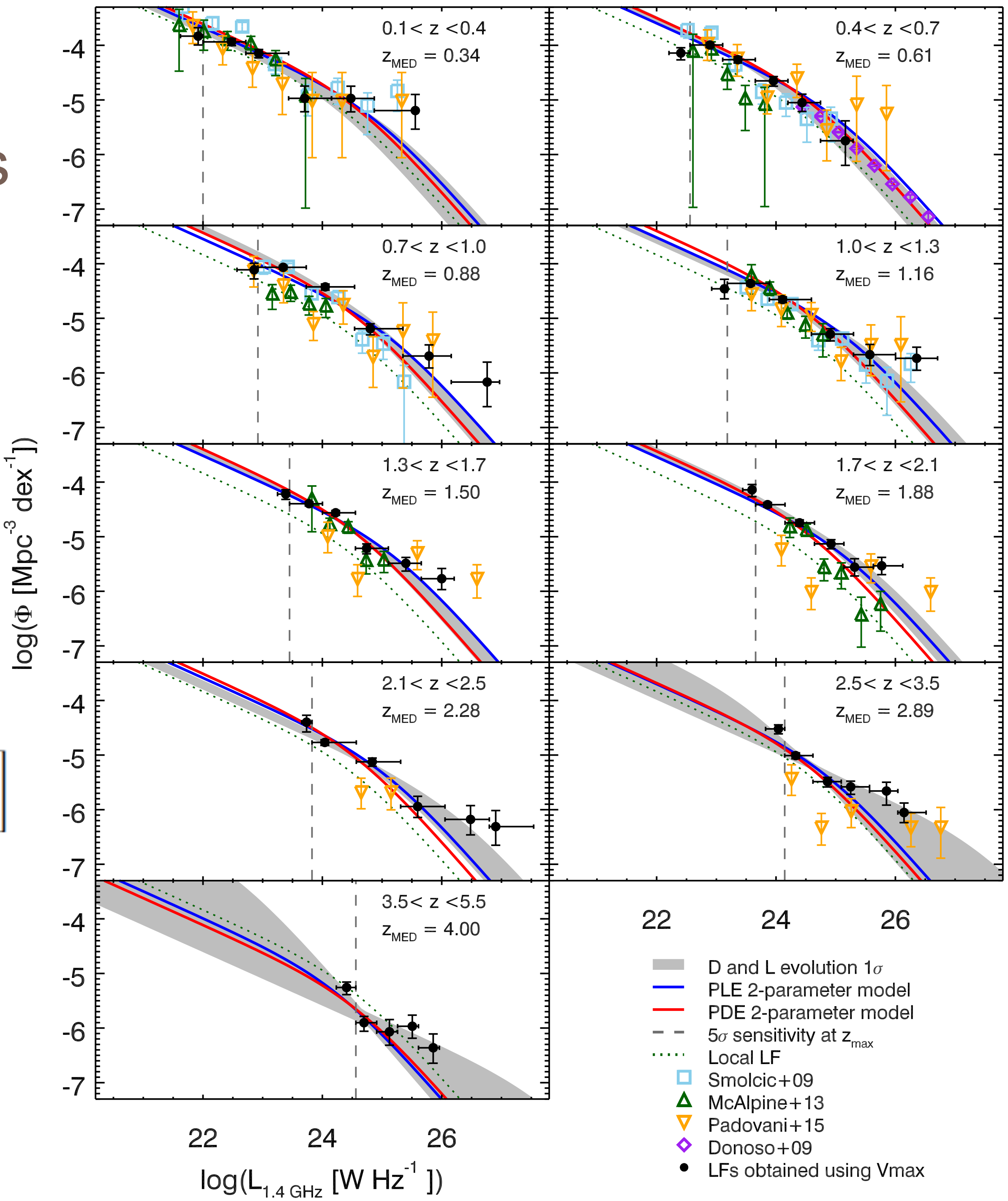
Smolčić et al. (2017b), Delvecchio et al. (2017)

Radio AGN luminosity functions

- 1,846 radio-excess AGN
- Good agreement with
  - local LF (Mauch & Sadler 2007)
  - LFs @ z~0.5 (Sadler et al. 2007; Donoso et al. 2009)
  - LFs from deep surveys (VIDEO-XMM3 field, McAlpine et al. 2013; ECDFS, Padovani et al. 2015)
- Evolution parametrization:

$$\Phi(L, z, \alpha_L, \beta_L, \alpha_D, \beta_D) =$$
$$= (1+z)^{\alpha_D + z \cdot \beta_D} \times \Phi_0 \left[\frac{L}{(1+z)^{\alpha_L + z \cdot \beta_L}} \right]$$

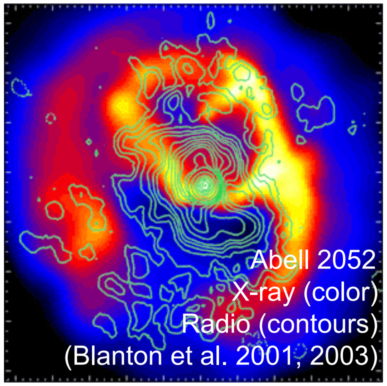
  - PLE ($\alpha_D = \beta_D = 0$):
    $\alpha_L = 2.88 \pm 0.17$
    $\beta_L = -0.84 \pm 0.07$
  - PDE ($\alpha_L = \beta_L = 0$):
    $\alpha_D = 2.00 \pm 0.01$
    $\beta_D = -0.60 \pm 0.02$



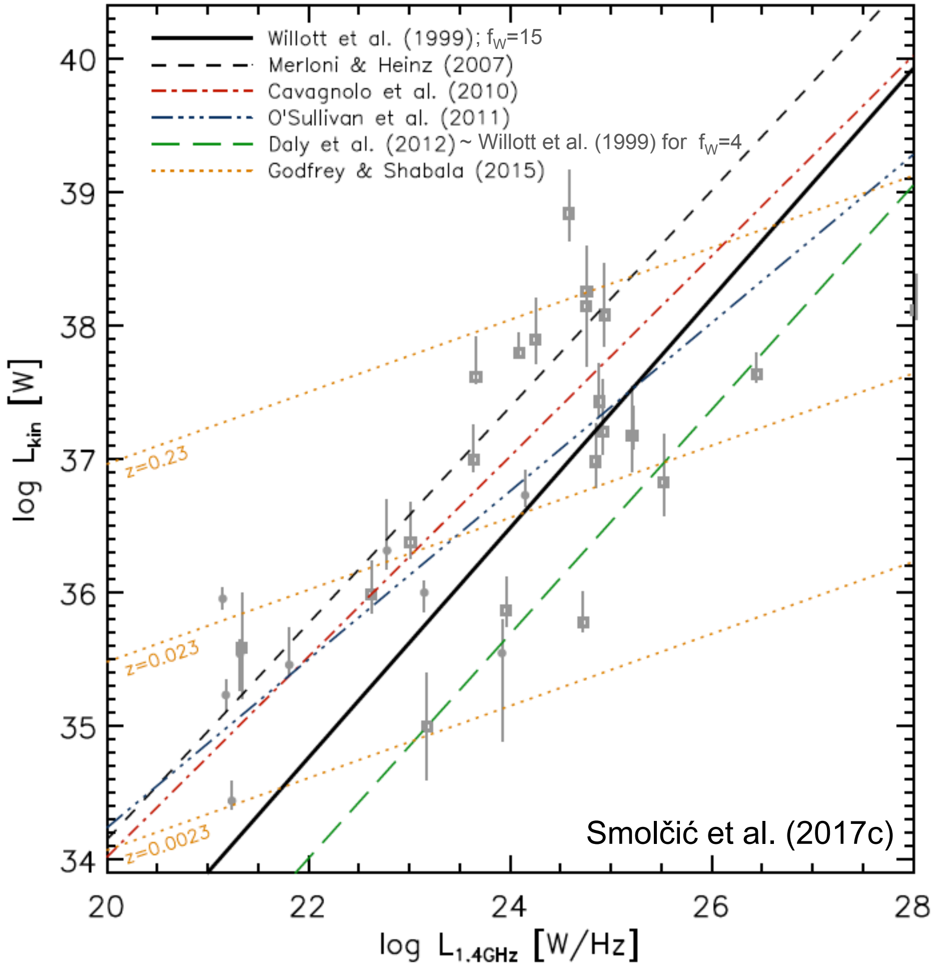
Smolčić et al. (2017c); Novak et al. (2018)

Radio luminosity ➡ kinetic luminosity

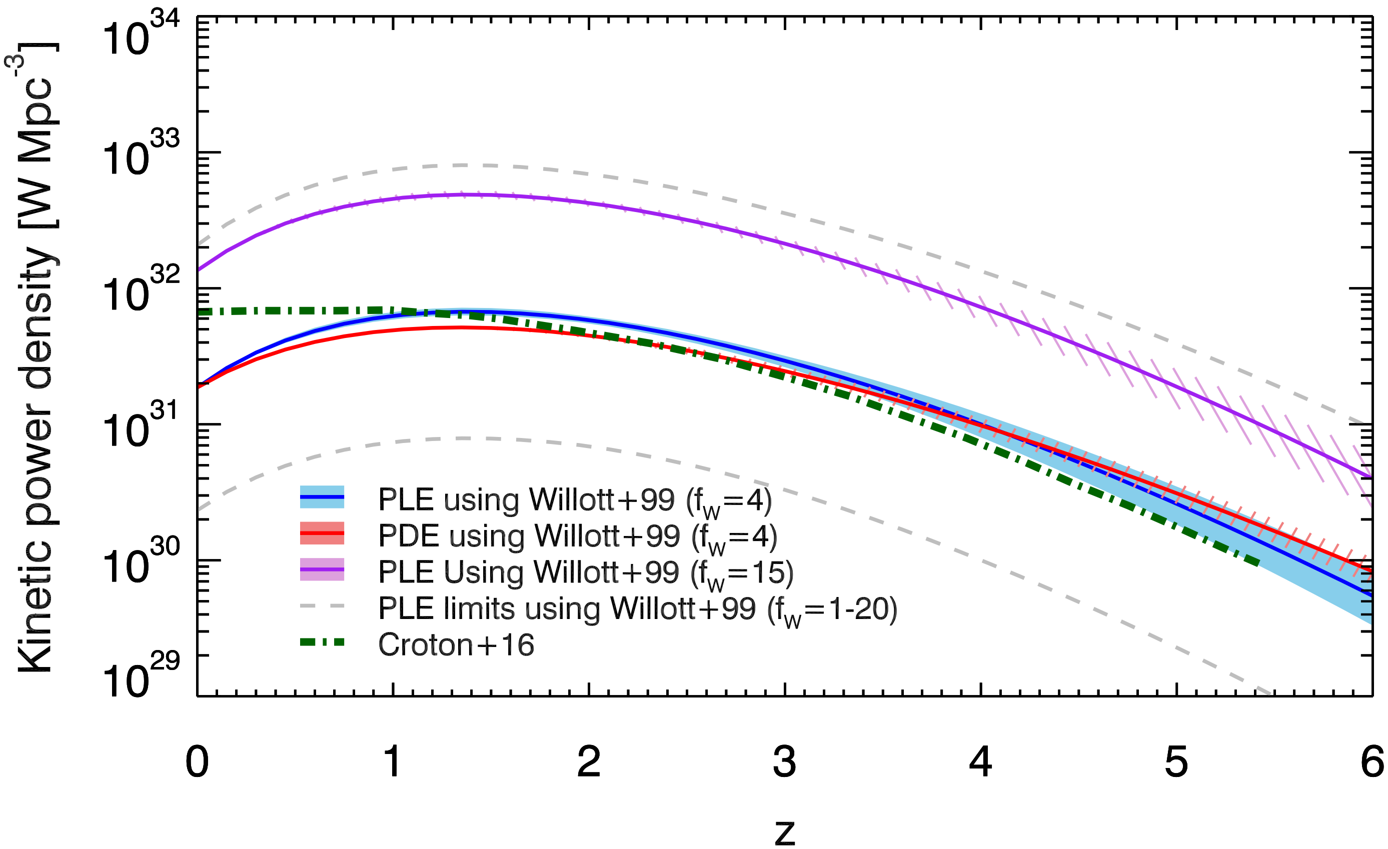
- Rate at which radio AGN transfer energy to their environments
- Scaling relations based on
  - radio galaxies in galaxy clusters: (e.g., Bîrzan et al. 2004, 2008) radio emission inflates buoyantly rising bubbles in X-ray plasma; large scatter
  - minimum energy arguments: (Willott et al. 1999) minimum energy stored in the lobes to produce the observed synchrotron luminosity; all uncertainties stored in parameter f_W ~ 1-20



Dunn & Fabian 2004
Bîrzan et al. 2004
Allen et al. 2006
Rafferty et al. 2006
O'Sullivan et al. 2011



Radio-AGN feedback models vs. observations



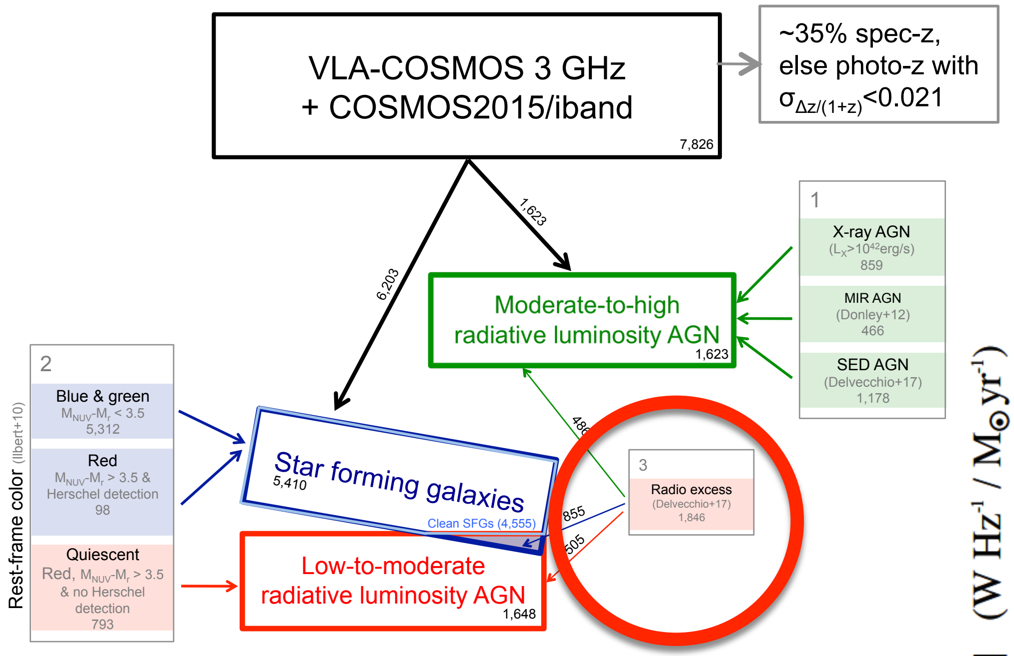
Agreement between semi-analytic model & observations encouraging for the idea of 'radio mode' feedback in the context of massive galaxy formation; still large systematic uncertainties remain

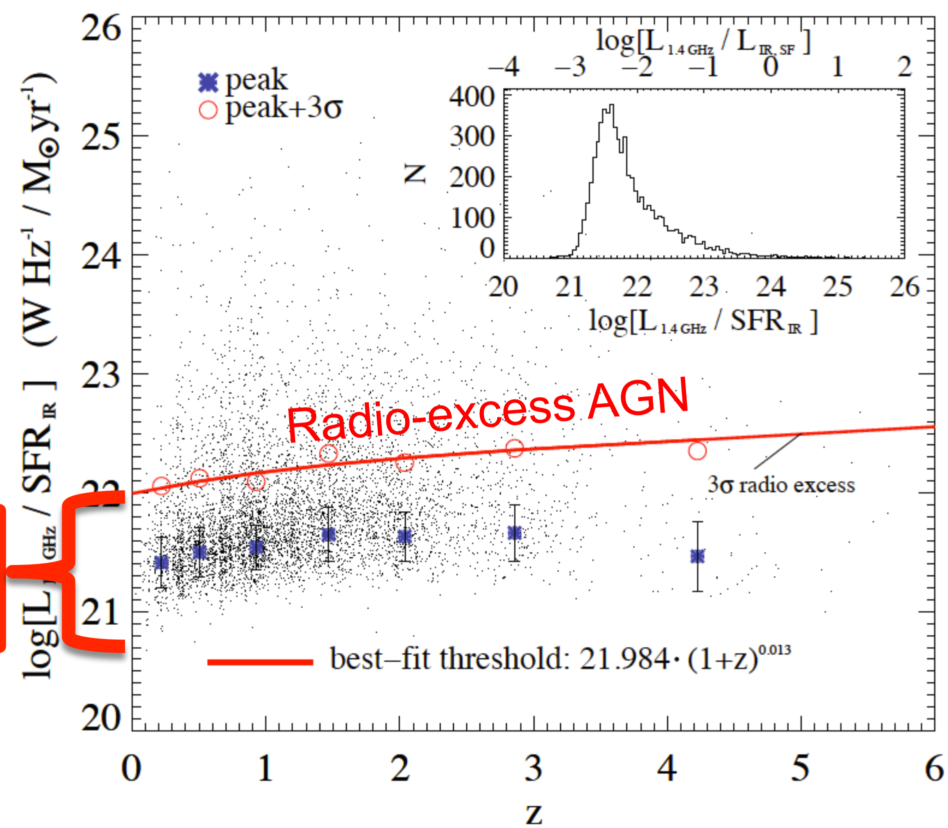
Kinetic luminosity density ← $L_{kin} = 0.1\dot{m}c^2$ → SMBH accretion rate density

Croton et al. (2006, 2016)

Smolčić et al. (2017c);
see also Smolčić et al. (2009)

The sample used: Radio-excess AGN

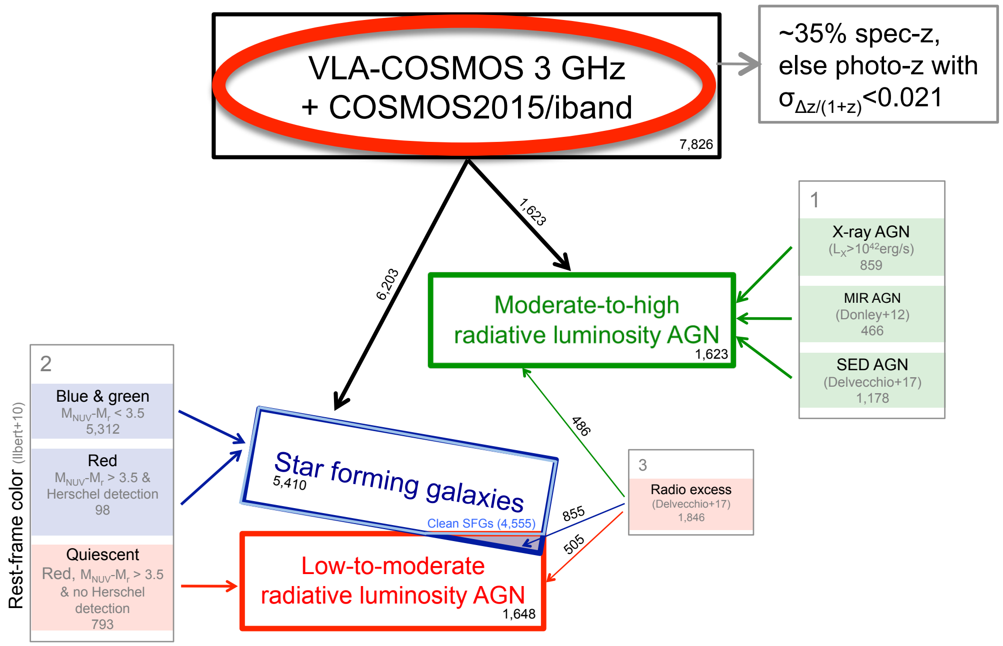




Jet emission missed?

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

Full sample + radio luminosity decomposition



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

Radio luminosity decomposition

$L_{radio} = L_{radio}(SF) + L_{radio}(AGN)$

$L_{IR} \rightarrow SFR \rightarrow L_{radio}(SF) \rightarrow L_{radio}(AGN)$

SED fitting
(Mahphys + AGN component; Delvecchio et al., 2017)

Using evolving q(z)
(see Delhaize et al., 2017)

Ceraj et al. (2018; subm.); Delvecchio et al. (in prep.)

Radio luminosity decomposition

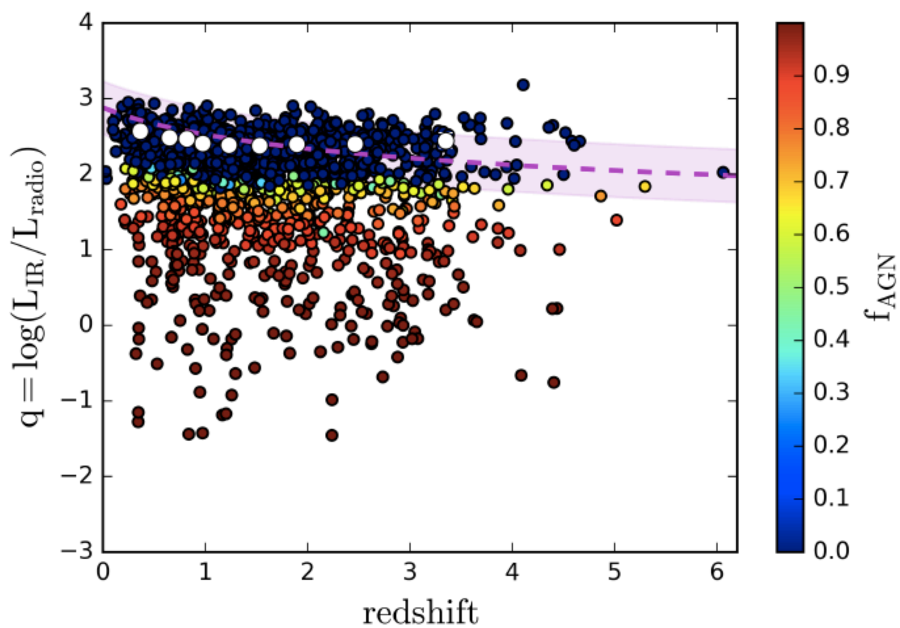
$L_{radio} = L_{radio}(SF) + L_{radio}(AGN)$

$L_{IR} \rightarrow SFR \rightarrow L_{radio}(SF) \rightarrow L_{radio}(AGN)$

SED fitting
(Mahphys + AGN component; Delvecchio et al., 2017)

Using evolving q(z)
(see Delhaize et al., 2017)

IR – radio correlation as a function of redshift, q(z)



$$q_{TIR} = \log\left(\frac{L_{TIR}}{3.75\times10^{12}\,Hz}\right) - \log\left(\frac{L_{1.4GHz}}{WHz^{-1}}\right)$$

$$f_{AGN} = 1 - 10^{q_{TIR} - \bar{q}_{TIR}}$$

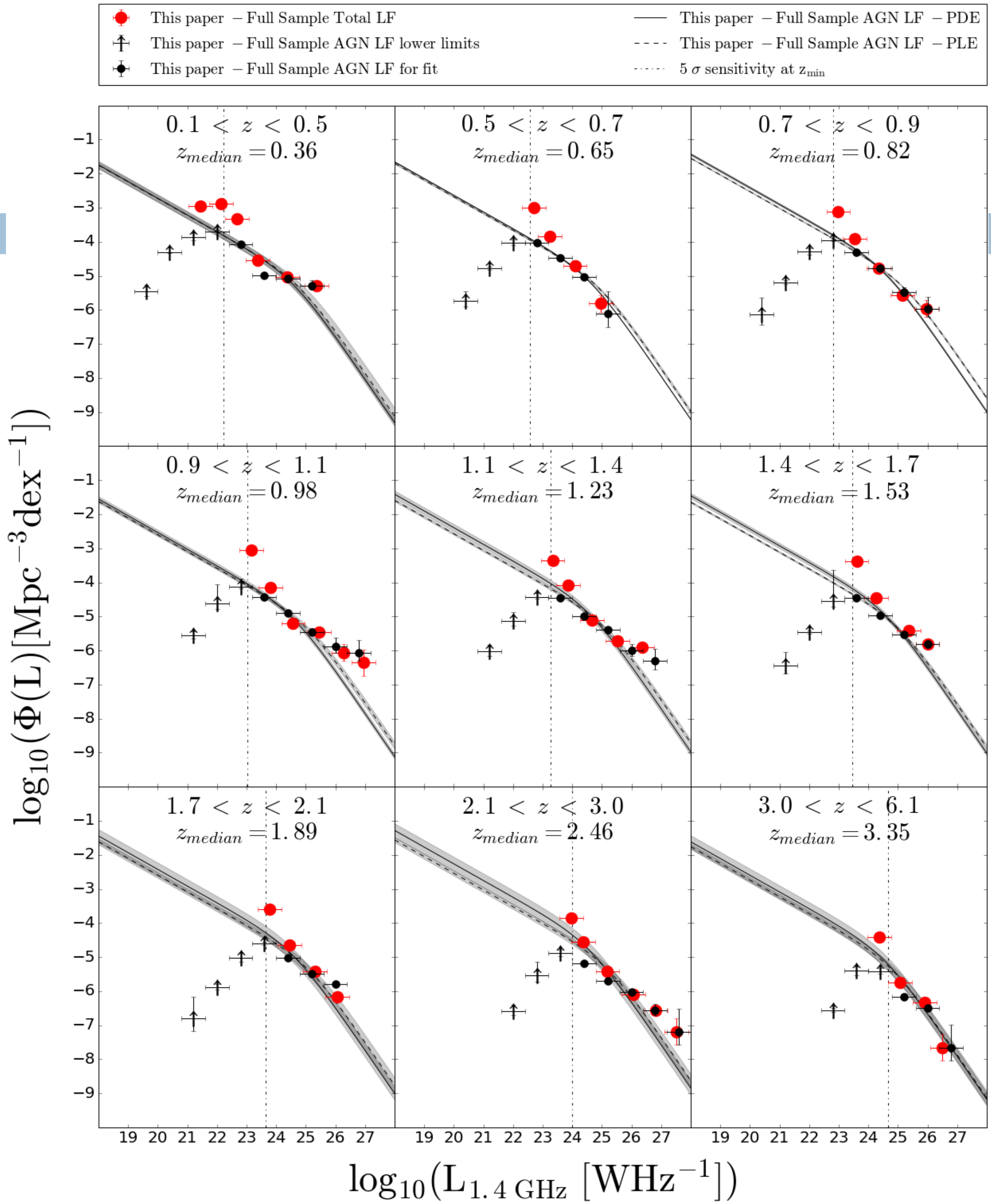
Ceraj et al. (2018; subm.); Delhaize et al. (2017)

Radio AGN luminosity functions

- Full sample + radio luminosity decomposition
- Good agreement with local AGN LF (Mauch & Sadler 2007)
- Evolution parametrization:

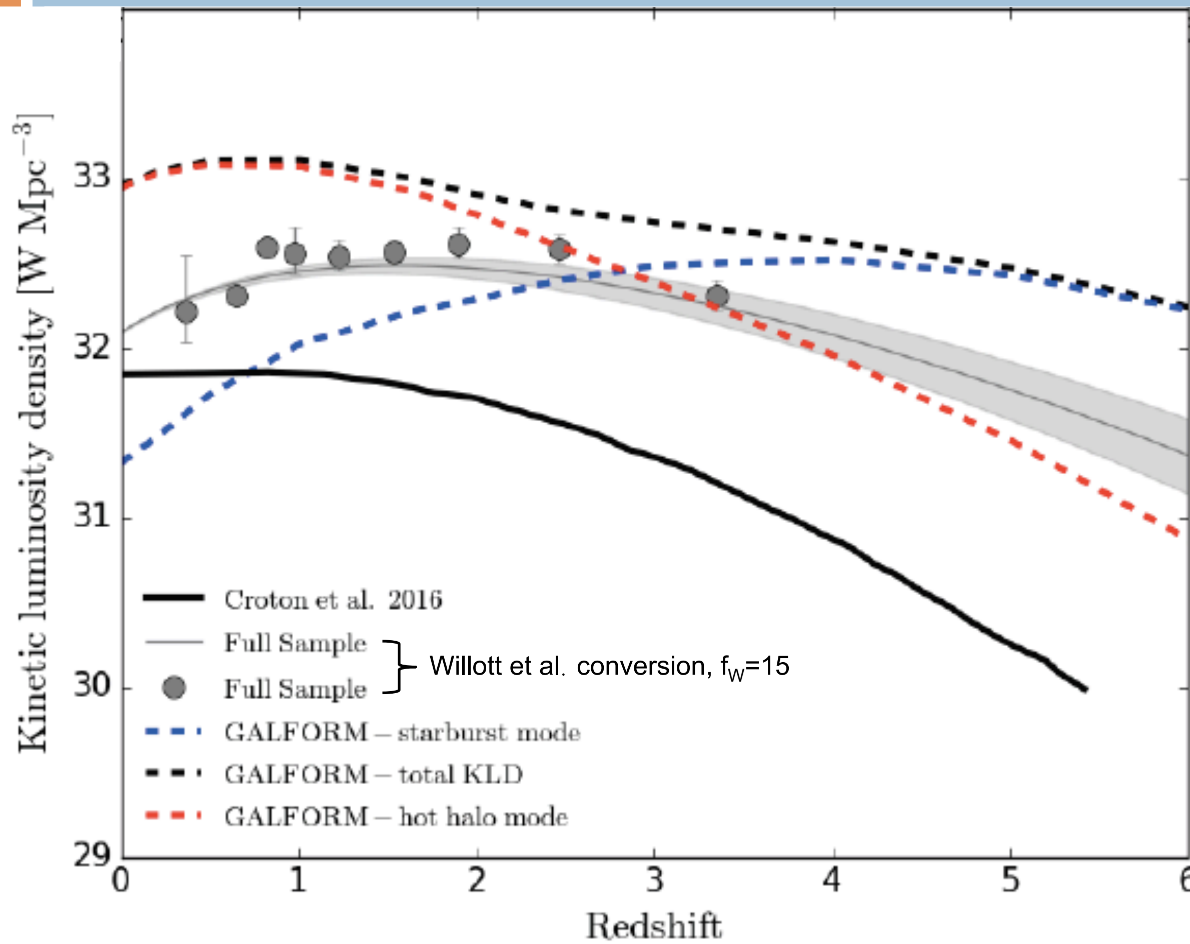
$$\Phi(L, z, \alpha_L, \beta_L, \alpha_D, \beta_D) =$$
$$= (1+z)^{\alpha_D + z\cdot\beta_D} \times \Phi_0 \left[\frac{L}{(1+z)^{\alpha_L + z\cdot\beta_L}} \right]$$

  - PLE ($\alpha_D = \beta_D = 0$):
    $\alpha_L = 2.19 \pm 0.07$
    $\beta_L = -0.67 \pm 0.04$
  - PDE ($\alpha_L = \beta_L = 0$):
    $\alpha_D = 1.47 \pm 0.05$
    $\beta_D = -0.43 \pm 0.03$



Ceraj et al. (2018; subm.)

Radio-AGN feedback models vs. observations



Many simplifications in both the observational and semi-analytic approaches

Ceraj et al. (2018; subm.)

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts (z<6)
- Source classification based on various (X-ray, MIR, colors, radio excess) criteria, assessing composite nature

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of "radio-mode feedback", controlling build-up of M_* in massive galaxies
- "Radio-mode AGN feedback" is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts' star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75'', 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts (z<6)
- Source classification based on various (X-ray, MIR, colors, radio excess) criteria, assessing composite nature

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

- Kinetic luminosity exterted by radio AGN may be high enough to balance radiative cooling of hot gas since z~5 (agreement with SAGE model)
- Many simplifications and unknowns still remain to be resolved (e.g., $L_{1.4GHz} \rightarrow L_{kin}$)

Summary

1. Radio AGN and their role in galaxy formation and evolution

- Radio AGN deemed drivers of “radio-mode feedback”, controlling build-up of M_* in massive galaxies
- “Radio-mode AGN feedback” is a regular ingredient in cosmological models, yet still rather poorly understood
- Two fundamentally different types of radio AGN:
  - Radiatively efficient (Seyfert, QSO; high-excitation; HERG; $M_{BH} \sim 10^8 M_{SOL}$; $L \sim L_{EDD}$)
  - Radiatively inefficient (LINER, absorption line; low-excitation; LERG; $M_{BH} \sim 10^9 M_{SOL}$; $L < 0.1 L_{EDD}$)
- All types of standard AGN can be detected in radio (given high enough sensitivity) BUT the source of radio emission may arise from hosts’ star formation rather than jets associated with the SMBH

2. VLA-COSMOS 3 GHz Large Project

- 10,830 radio sources (S/N>5, rms=2.3 uJy/beam, resolution 0.75’’, 2 square degree area)
- Simultaneously the largest and deepest radio continuum survey at such angular resolution

3. VLA-COSMOS 3 GHz Large Project galaxy populations

- Combined with COSMOS multi-λ dataset with highly accurate photometric (+spec.) redshifts (z<6)
- Source classification based on various (X-ray, MIR, colors, radio excess) criteria, assessing composite nature

4. Cosmic evolution of radio AGN and implications for radio-mode feedback since z ~ 5

- Kinetic luminosity exterted by radio AGN may be high enough to balance radiative cooling of hot gas since z~5 (agreement with SAGE model)
- Many simplifications and unknowns still remain to be resolved (e.g., $L_{1.4GHz} \rightarrow L_{kin}$)