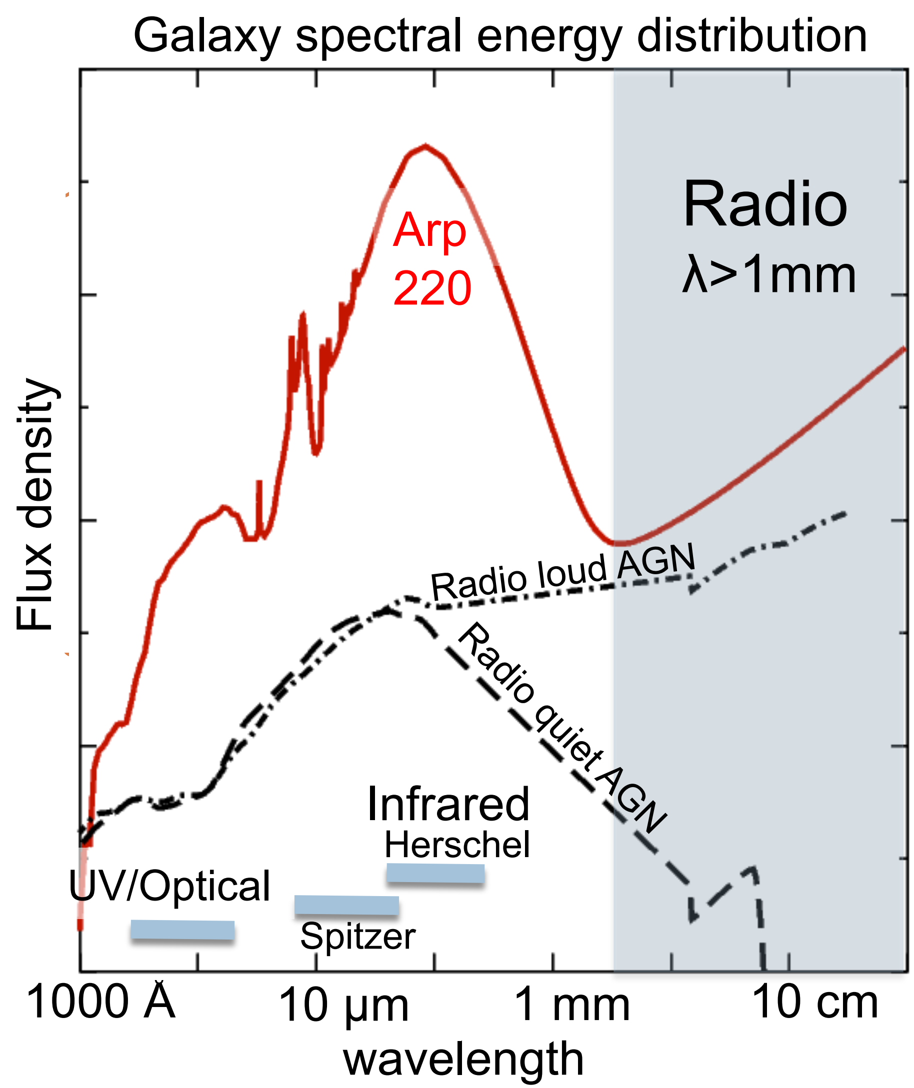
Long wavelengths and the Square Kilometre Array
(in the context of radio continuum surveys)

Vernesa Smolčić (University of Zagreb, Croatia)

Why radio?



“Quantum leap” in instrumentation:

Jansky VLA, ATCA, ALMA, LOFAR, SKA & precursors

Major upgrade of existing radio facilities

VLA (Very Large Array, USA)

GMRT (Giant Metrewave Radio Telescope, India)

ATCA (Australia Telescope Compact Array)

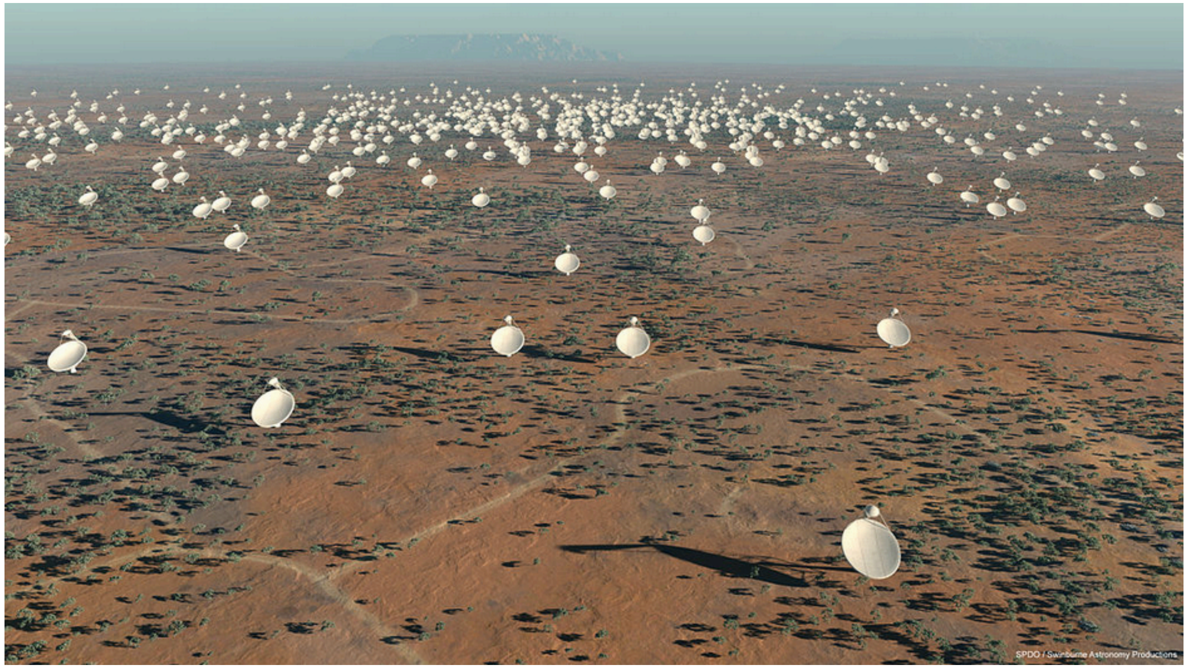
LOFAR

Low Frequency Array (10-240 MHz)

- no movable parts; the whole observable sky at the same time; pointing is preformed electronically - multi beam observations; large collecting area and high sensitivity

SKA: The Square Kilometre Array

- Locations:
  South Africa, Australia
- Phase 1 (2018-2023):
  10% of total collecting area
- Phase 2 (2023-2030):
  full capability (1 sq. km collecting area)
- First light: 2020
- Precursor Facilities:
  - Australian SKA Pathfinder (ASKAP)
  - MeerKAT (South Africa)
  - Murchinson Widefield Array (MWA)
- Pathfinders:
  Apertif, VLBI, e-MERLIN, JVLA, **LOFAR, ...**



SKA key science applications

- **Advancing Astrophysics with the Square Kilometre Array**

https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215

The Cradle of Life & Astrobiology Hoare, M. et al. 2015 PoS(AASKA14)115	**Cosmology & Dark Energy** Maartens, R. et al. 2015 PoS(AASKA14)016
Strong-field Tests of Gravity with Pulsars and Black Holes Kramer, M. & Stappers, B. 2015 PoS(AASKA14)036	**Cosmic Dawn and the Epoch of Reionization** Koopmans, L. et al. 2015 PoS(AASKA14)001
The Origin and Evolution of Cosmic Magnetism Johnston-Hollitt, M. et al. 2015 PoS(AASKA14)092	**The Transient Radio Sky** Fender, R. et al. 2015 PoS(AASKA14)051
Galaxy Evolution probed by Neutral Hydrogen Staveley-Smith, L. & Oosterloo, T. 2015, PoS(AASKA14)167	**Galaxy Evolution probed in the Radio Continuum** Prandoni, I. & Seymour, N. 2015 PoS(AASKA14)067

Braun et al. (2015)

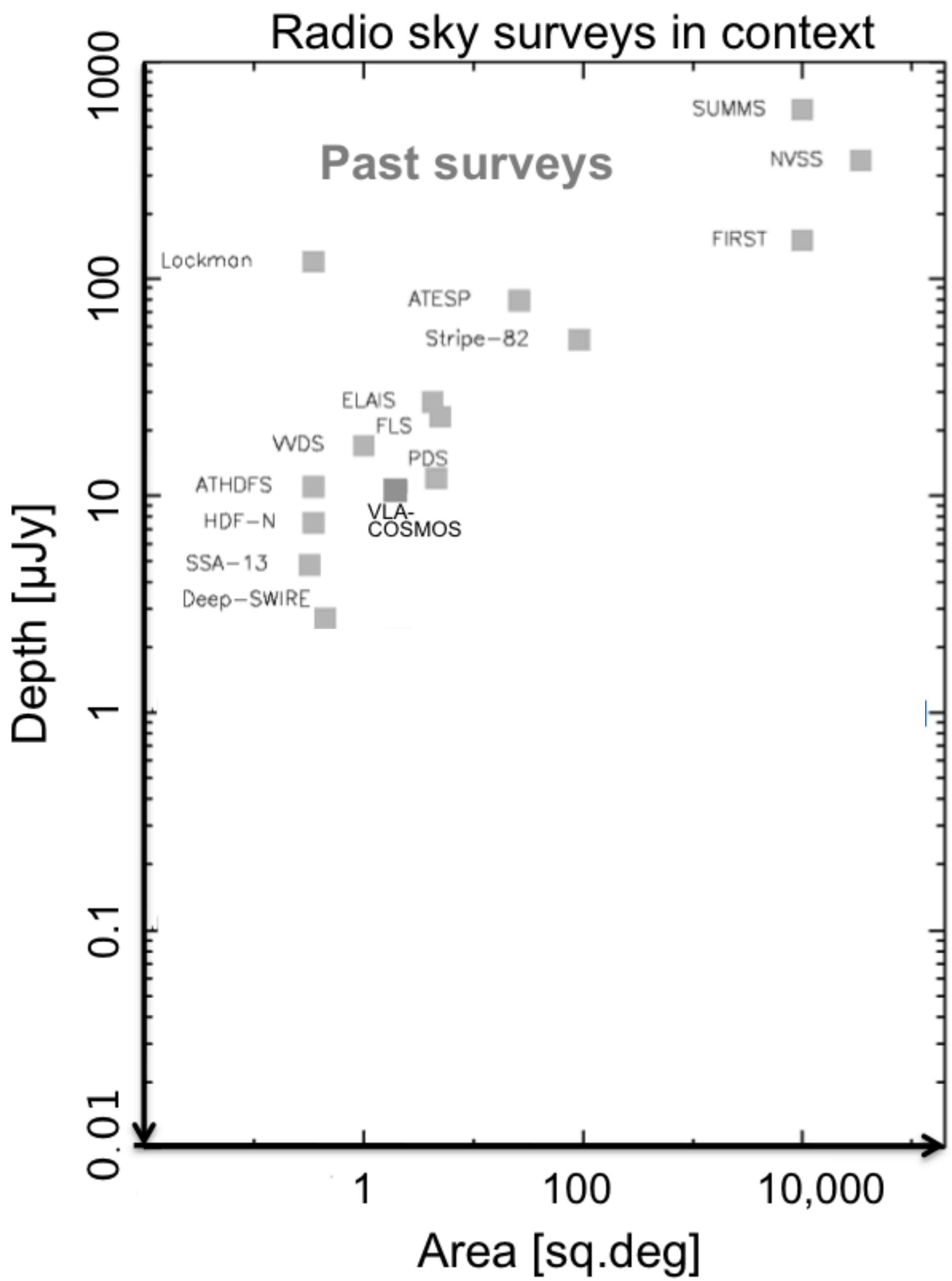
SKA key science applications

- **Advancing Astrophysics with the Square Kilometre Array**

https://pos.sissa.it/cgi-bin/reader/conf.cgi?confid=215

The Cradle of Life & Astrobiology Hoare, M. et al. 2015 PoS(AASKA14)115	**Cosmology & Dark Energy** Maartens, R. et al. 2015 PoS(AASKA14)016
Strong-field Tests of Gravity with Pulsars and Black Holes Kramer, M. & Stappers, B. 2015 PoS(AASKA14)036	**Cosmic Dawn and the Epoch of Reionization** Koopmans, L. et al. 2015 PoS(AASKA14)001
The Origin and Evolution of Cosmic Magnetism Johnston-Hollitt, M. et al. 2015 PoS(AASKA14)092	**The Transient Radio Sky** Fender, R. et al. 2015 PoS(AASKA14)051
Galaxy Evolution probed by Neutral Hydrogen Staveley-Smith, L. & Oosterloo, T. 2015, PoS(AASKA14)167	**Galaxy Evolution probed in the Radio Continuum** Prandoni, I. & Seymour, N. 2015 PoS(AASKA14)067

Braun et al. (2014)


Radio sky surveys in context
Past surveys
SUMMS
NVSS
FIRST
Lockman
ATESP
Stripe−82
ELAIS
FLS
VVDS
PDS
ATHDFS
HDF−N
VLA-COSMOS
SSA−13
Deep−SWIRE
Depth [μJy]
1000
100
10
1
0.1
0.01
1
100
10,000
Area [sq.deg]

ATLAS

(Norris et al. 2006, Middelberg et al. 2008, Hales et al. 2013, Frazen et al. 2014, Banfield et al. 2014)

2GHz, 7 sq.deg, rms~15μJy

JVLA-SWIRE

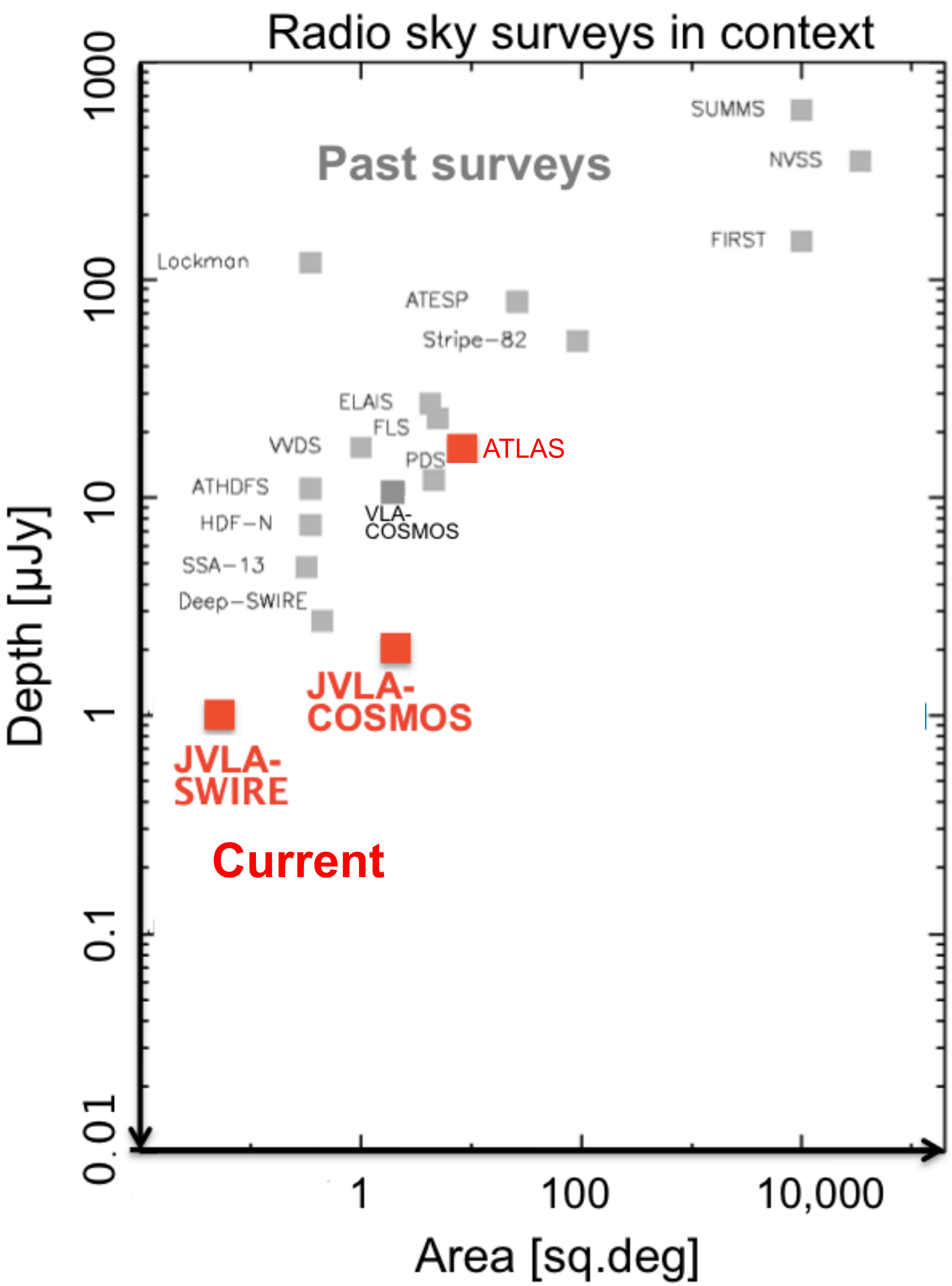
(Condon et al. 2012)

3GHz,~225amin^2, rms~1μJy

JVLA-COSMOS

(Smolcic et al. 2017)

3GHz, 2 sq.deg, rms~2.3μJy



VLASS

tier 1-3, >2015

Westerbork-WODAN

(PI: Rottgering)

northern sky, rms~10μJy/b
1000sq.deg, rms~5μJy/b

ASKAP-EMU

(PI: Norris)

1.1-1.4GHz, southern hemisphere, rms~10μJy/b, 10'' resolution, >2015

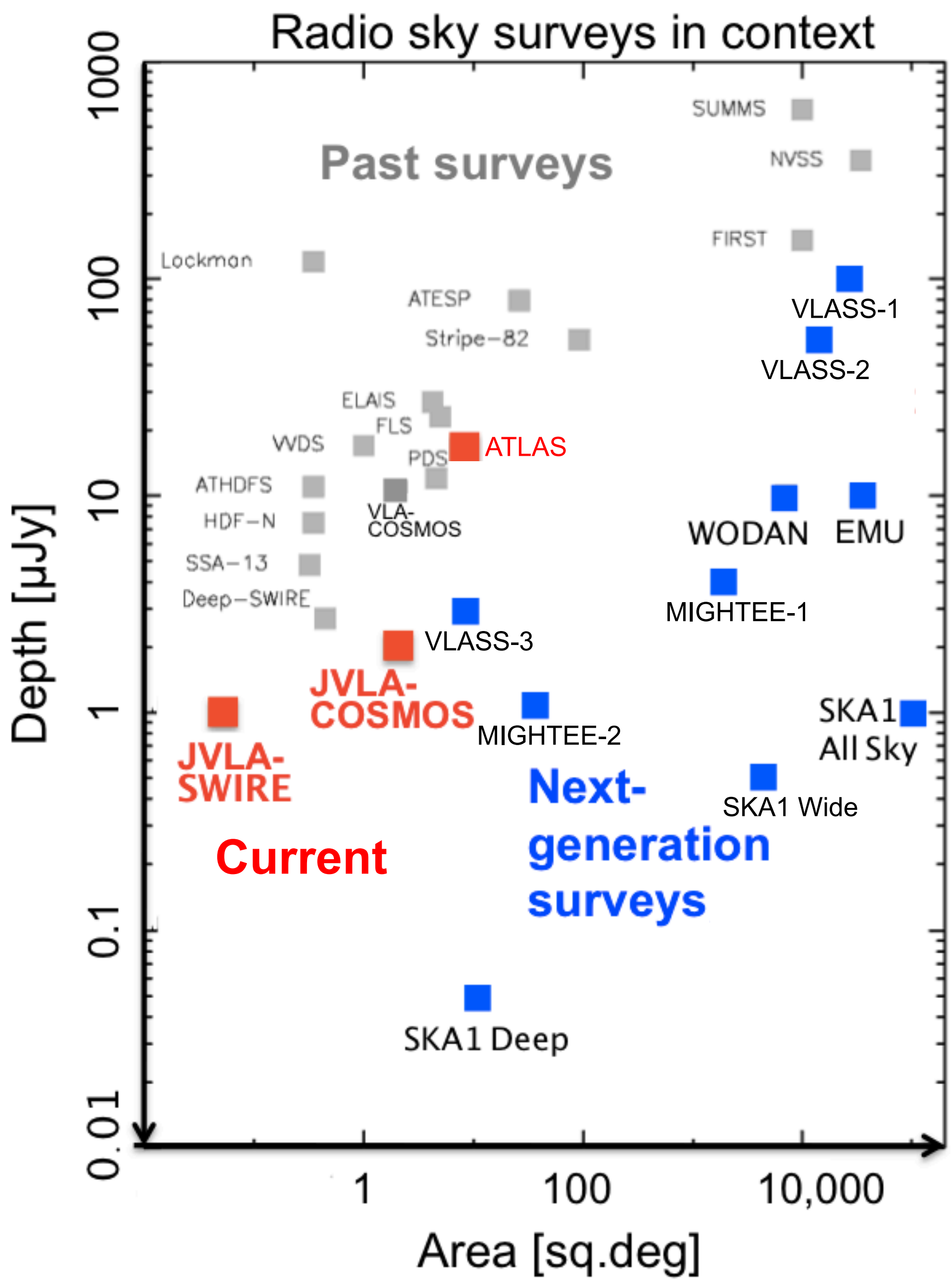
Meerkat-MIGHTEE

(PI: Van der Heyden & Jarvis)

tier 1-3

SKA

All sky: ~1μJy/b
Wide: 5000sq.deg., 0.5μJy/beam
Deep: 10 sq.deg., 50 nJy/beam



Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 μJy
~6000 galaxies

Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 μJy
~6000 galaxies

JVLA - COSMOS
(2013-2017)
27 antennas

2 sq deg
Rms=2 μJy
~11,000 galaxies

Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 µJy
~6000 galaxies

JVLA - COSMOS
(2013-2017)
27 antennas

2 sq deg
Rms=2 µJy
~11,000 galaxies

VLA Sky Survey
(2018-)
27 antennas

34,000 sq deg
Rms=69 µJy
~10 million galaxies

Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 μJy
~6000 galaxies

JVLA - COSMOS
(2013-2017)
27 antennas

2 sq deg
Rms=2 μJy
~11,000 galaxies

VLA Sky Survey
(2018-)
27 antennas

34,000 sq deg
Rms=69 μJy
~10 million galaxies

ASKAP – EMU early
(2016-2018)
12 antennas

1000 sq deg
Rms=30 μJy
0.5 million galaxies

Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 μJy
~6000 galaxies

JVLA - COSMOS
(2013-2017)
27 antennas

2 sq deg
Rms=2 μJy
~11,000 galaxies

VLA Sky Survey
(2018-)
27 antennas

34,000 sq deg
Rms=69 μJy
~10 million galaxies

ASKAP – EMU early
(2016-2018)
12 antennas

1000 sq deg
Rms=30 μJy
0.5 million galaxies

ASKAP – EMU
(>2018)
30-36 antennas

3π sr
Rms=10 μJy
70 million galaxies

Pathfinders

ATCA – ATLAS
(2006-2014)
6 antennas

7 sq deg
Rms=15 μJy
~6000 galaxies

JVLA - COSMOS
(2013-2017)
27 antennas

2 sq deg
Rms=2 μJy
~11,000 galaxies

VLA Sky Survey
(2018-)
27 antennas

34,000 sq deg
Rms=69 μJy
~10 million galaxies

ASKAP – EMU early
(2016-2018)
12 antennas

1000 sq deg
Rms=30 μJy
0.5 million galaxies

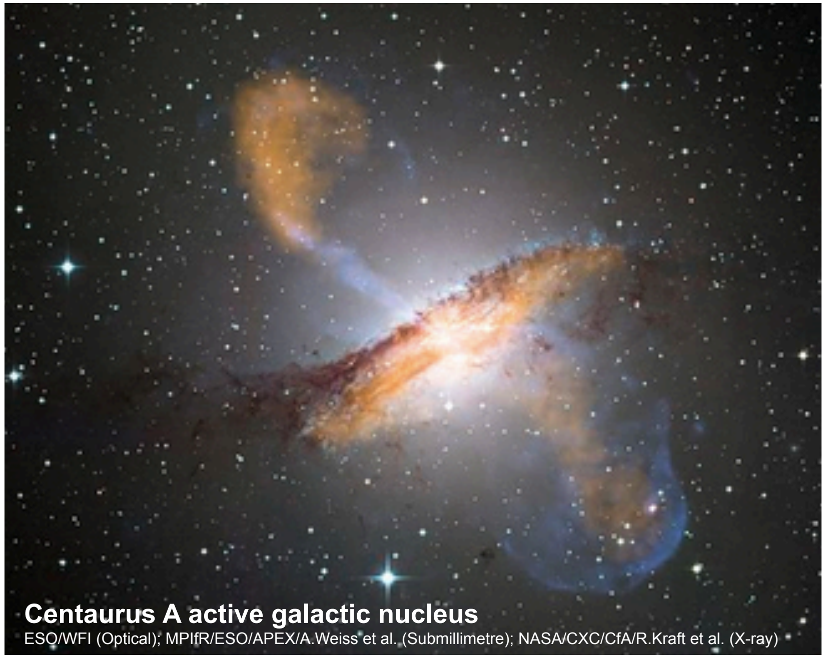
ASKAP – EMU
(>2018)
30-36 antennas

3π sr
Rms=10 μJy
70 million galaxies

SKA1-SURVEY
(>2020)
96 antennas

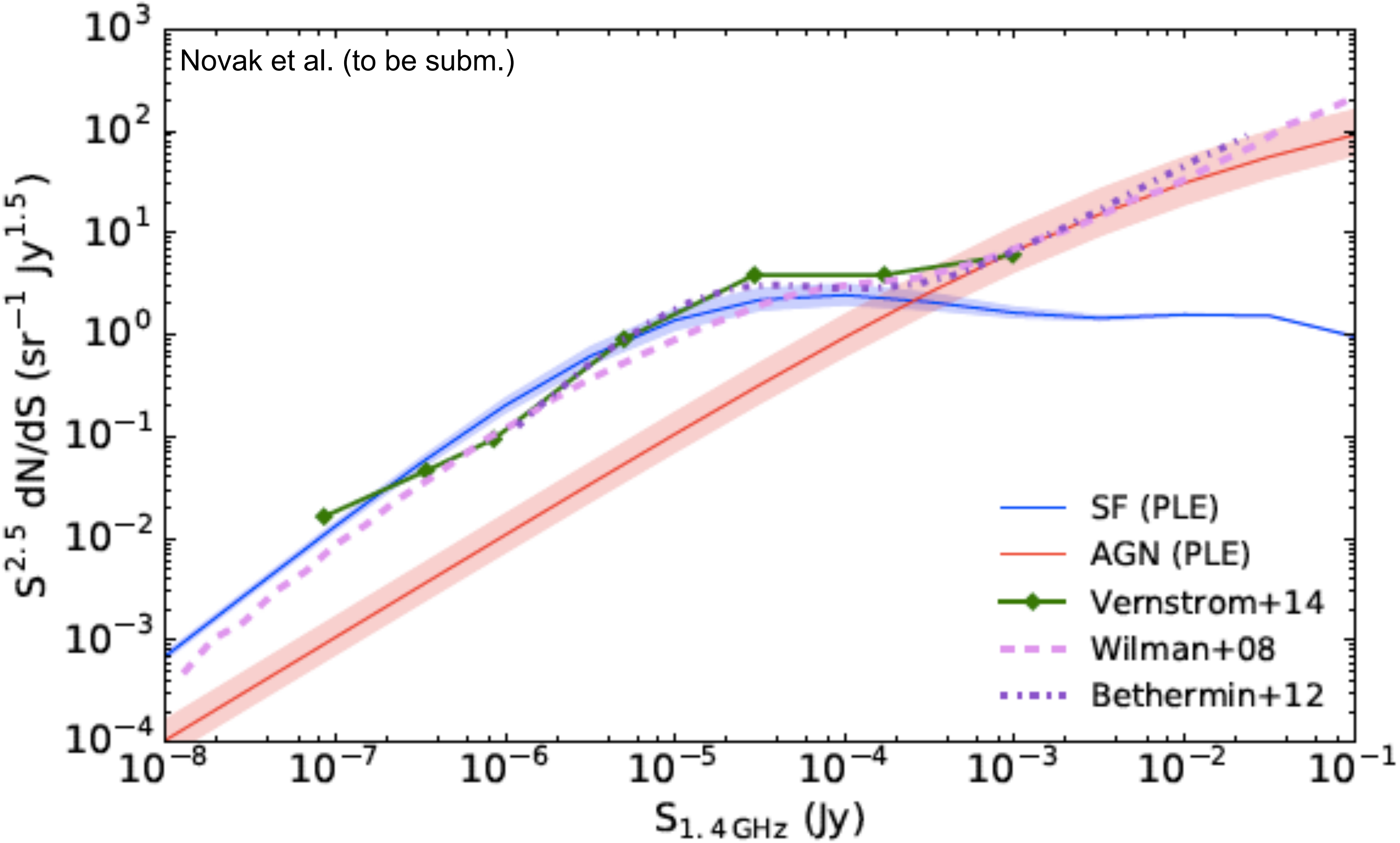
3π sr
Rms=2 μJy
500? million galaxies

Radio populations



1. Star forming galaxies: supernovae remnants
2. Active galactic nuclei: jets
3. Synchrotron emission

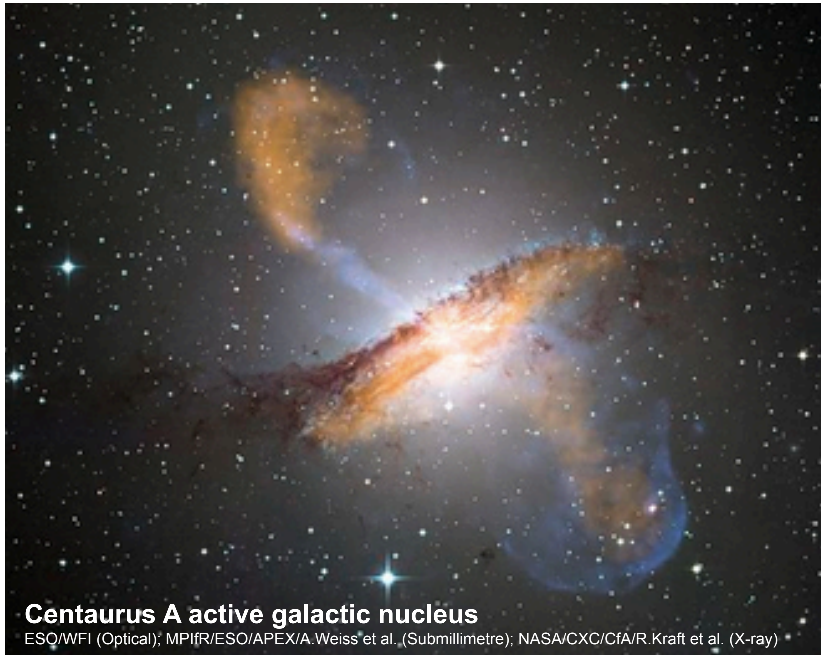
Radio source counts



- Based on VLA-COSMOS 3 GHz Large Project (Smolcic et al. 2017)
- ~8,000 radio sources out to z~5

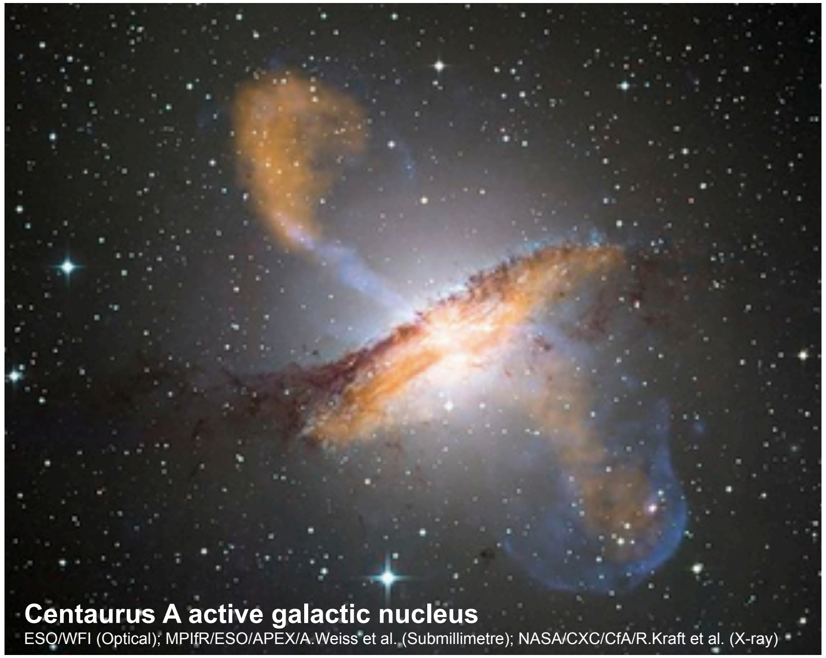
The power of radio

M82 star forming galaxy
Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI), and P. Puxley (National Science Foundation)



Centaurus A active galactic nucleus
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

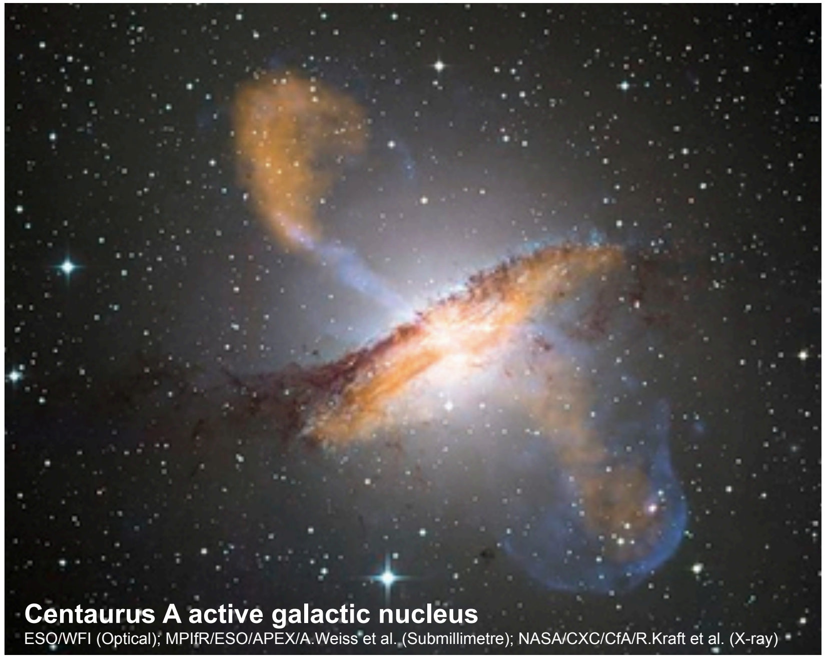
The power of radio



1. Dust-unbiased SF tracer at *high* angular resolution

The power of radio

M82 star forming galaxy
Credit: NASA, ESA, and The Hubble Heritage Team (STScI/AURA); Acknowledgment: J. Gallagher (University of Wisconsin), M. Mountain (STScI), and P. Puxley (National Science Foundation)



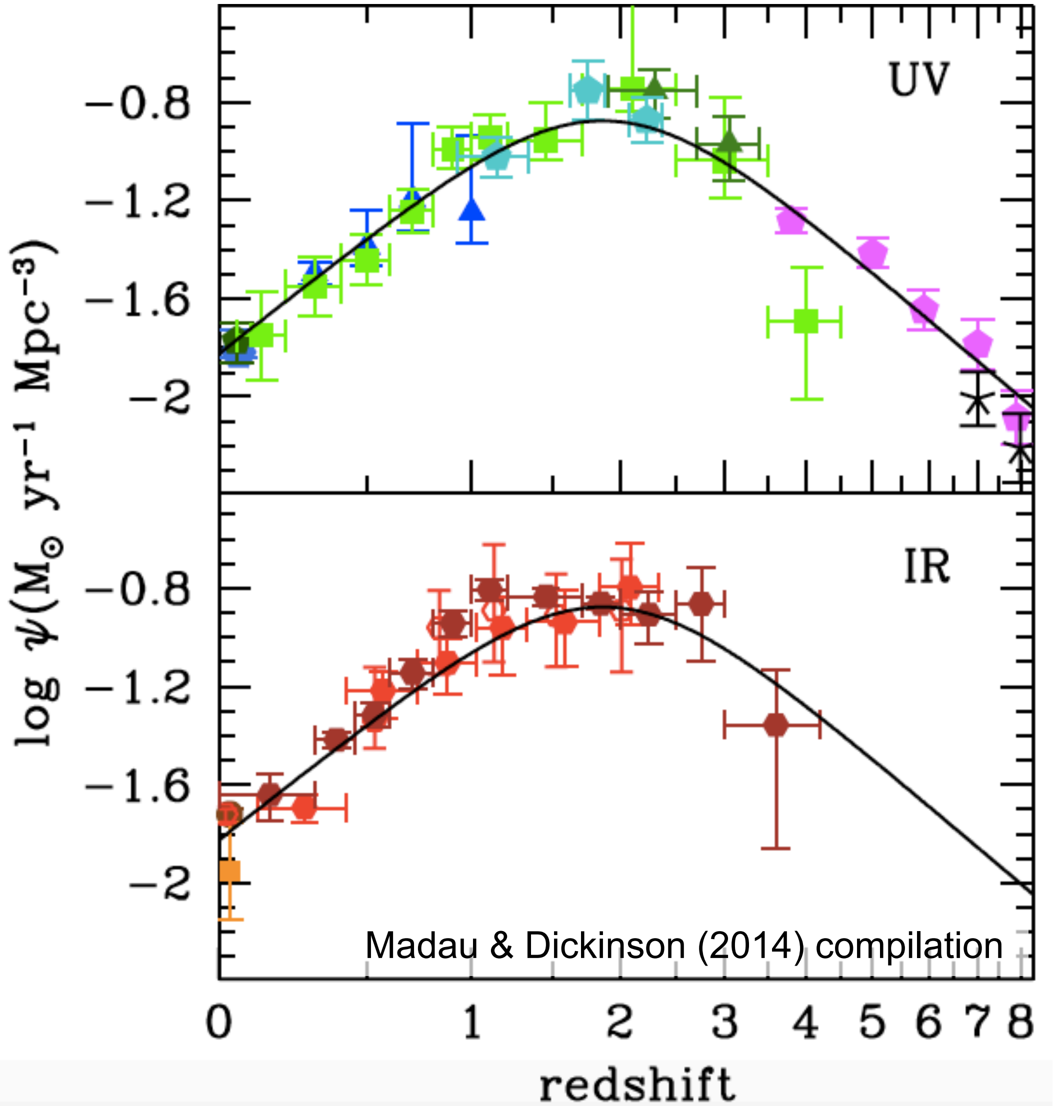
Centaurus A active galactic nucleus
ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

1. Dust-unbiased SF tracer at *high* angular resolution
2. Unique AGN

Cosmic star formation history

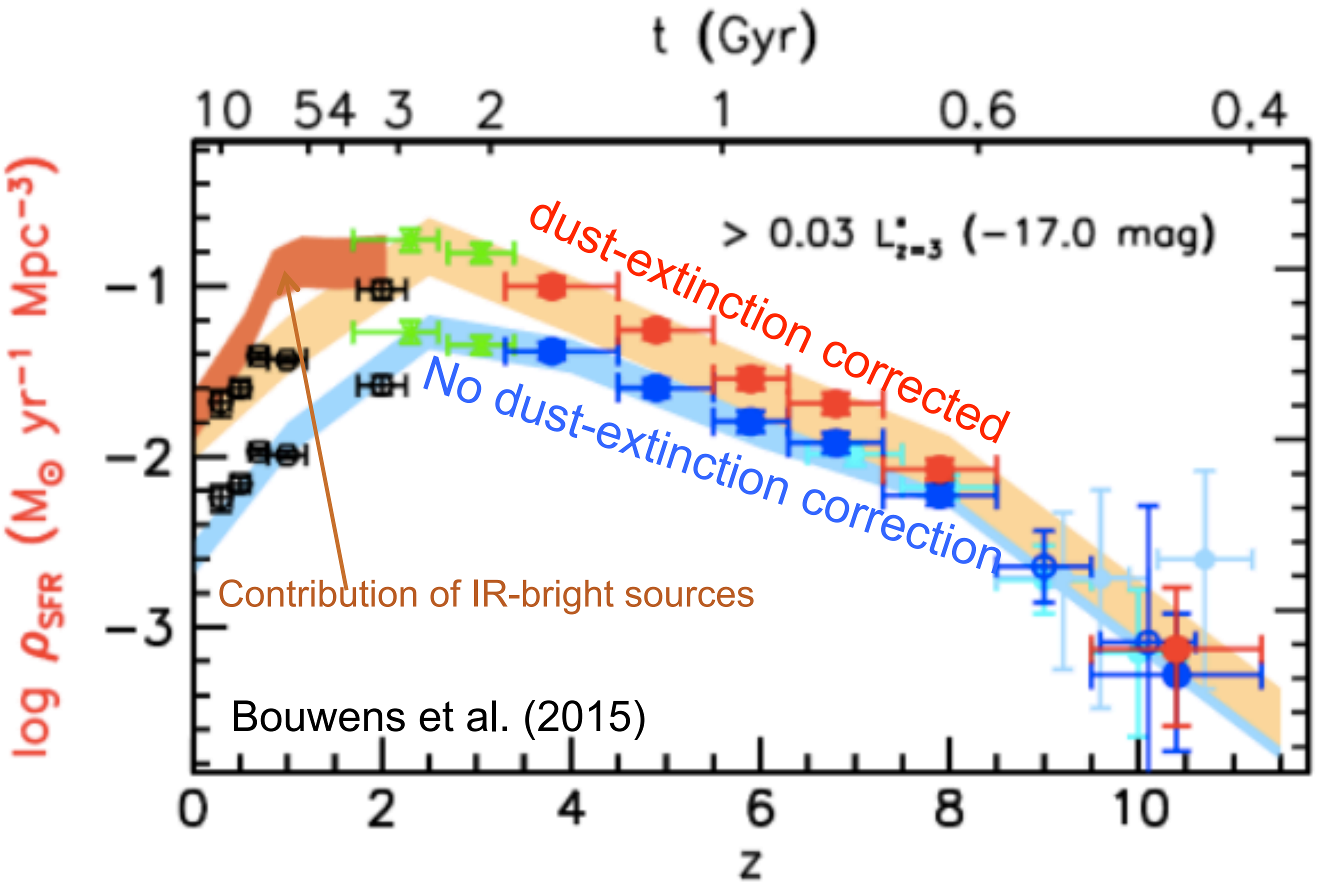
- Lilly Madau plot
- Compilation based on different star formation estimators
  (UV, IR, radio, Hα..)
- Dust correction = major challenge

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



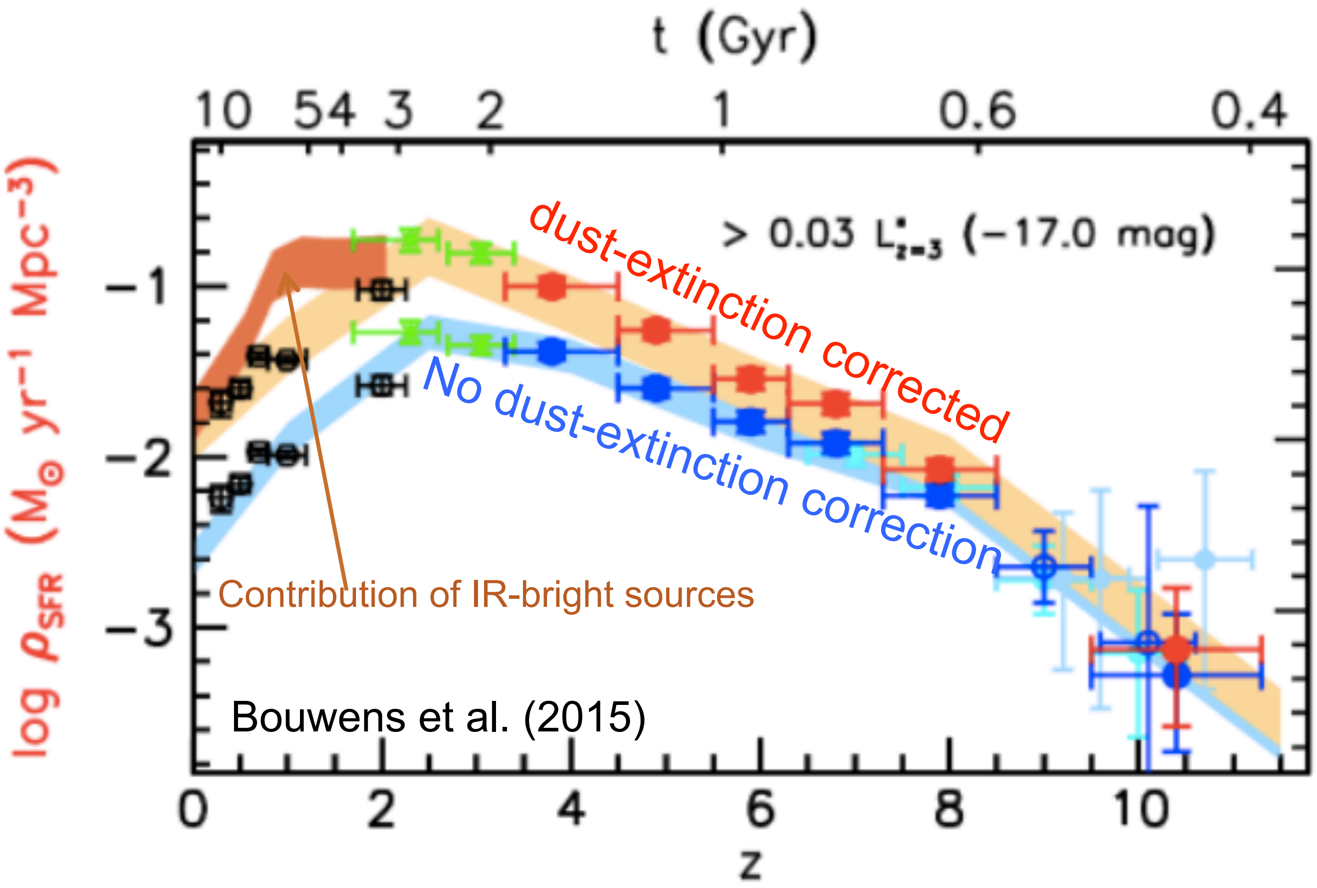
Cosmic star formation history at high-z

- 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)



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)



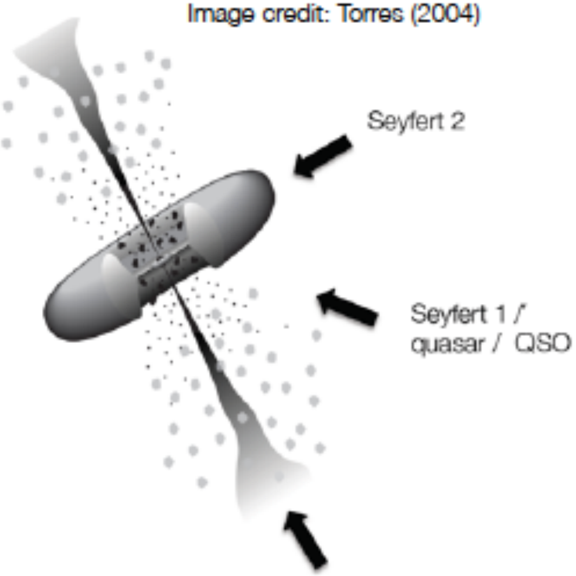
➔ Dust-unbiased star formation rate tracers (at high-z) → radio

AGN in the radio regime: low-excitation (LE) vs. high excitation (HE)

High-excitation = cold mode = radiatively efficient

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

Image credit: Torres (2004)



Low-excitation = hot mode = radiatively inefficient

- Optical spectrum devoid of strong emission lines
- Identified as AGN in the radio window
- Usually LINER, absorption line AGN, FR I type
- $L_{1.4GHz} < 10^{26}$ W/Hz

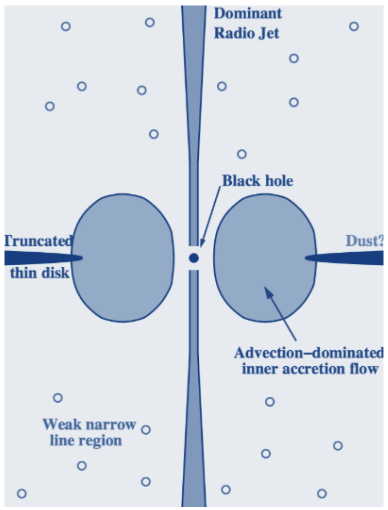
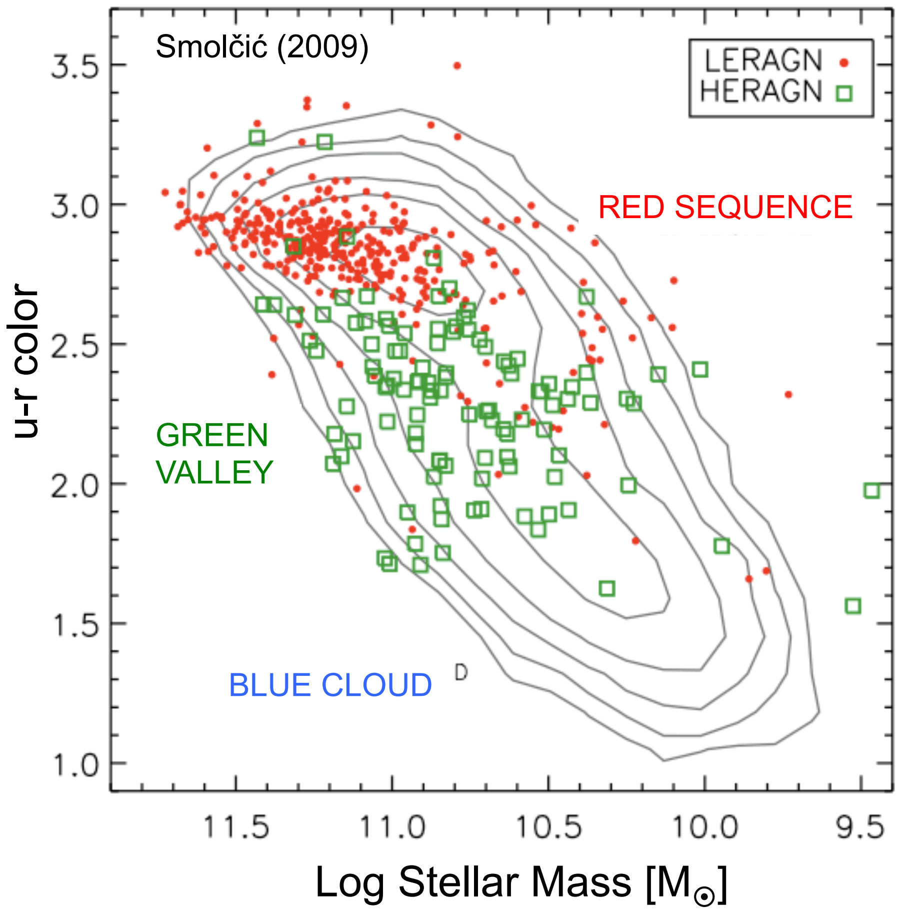


Image: Heckman & Best (2014)

LERG vs HERG: fundamental physical differences

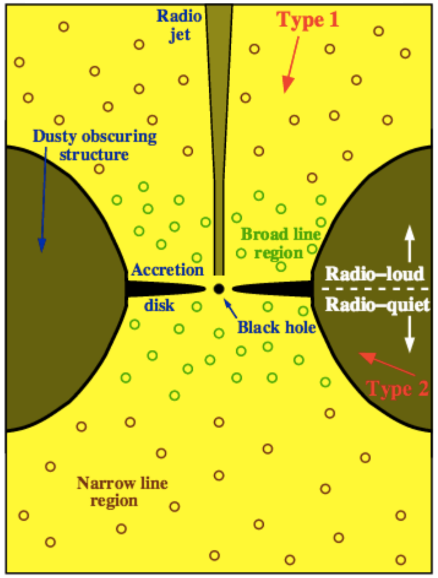
	HERAGN	LERAGN	References
Other names	HERG Cold-mode AGN Radiative-AGN Quasar-mode High SMBH accretors Thin-disk	LERG Hot-mode AGN Jet-mode AGN Radio-mode Low SMBH accretors Thick-disk, ADAF	
Radio luminosity	High ($L_{20cm} \gtrsim 10^{26}$W/Hz)	Lower ($L_{20cm} \lesssim 10^{26}$W/Hz)	e.g., Kauffmann et al. 2008, Best & Heckman 2012
Source of radio emission	SF+AGN	AGN	e.g., Moric et al. 2010; Hardcastle et al. 2013; Gurkan et al. 2015
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
Environment	Low-density	Wider range of densities	e.g., Gendre et al. 2013
Cosmic evolution	Steep	Mild	e.g., Sadler et al. 2007, Donoso et al. 2009; Best et al. 2014; Smolčić et al. 2009, 2015; Padovani et al. 2011, 2015



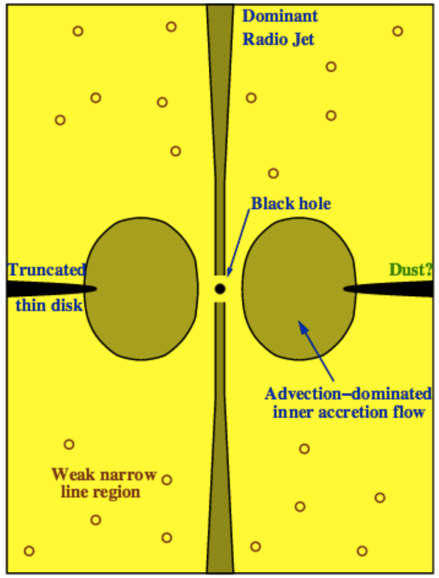
LERG vs HERG: fundamental physical differences

	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	
Radio luminosity	High ($L_{20cm} \gtrsim 10^{26}$W/Hz)	Lower ($L_{20cm} \lesssim 10^{26}$W/Hz)	e.g., Kauffmann et al. 2008, Best & Heckman 2012
Source of radio emission	SF+AGN	AGN	e.g., Moric et al. 2010; Hardcastle et al. 2013; Gurkan et al. 2015
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
Environment	Low-density	Wider range of densities	e.g., Gendre et al. 2013
Cosmic evolution	Steep	Mild	e.g., Sadler et al. 2007, Donoso et al. 2009; Best et al. 2014; Smolčić et al. 2009, 2015; Padovani et al. 2011, 2015

HERAGN or HERG or
Cold mode AGN or
Radiative mode AGN

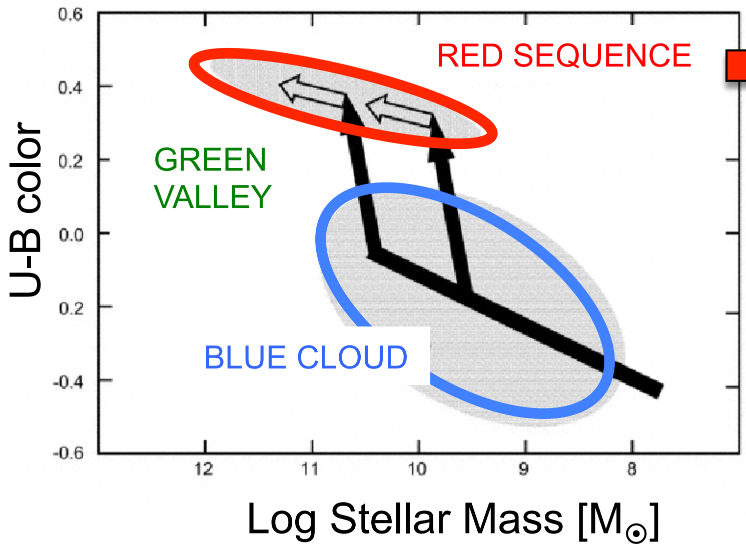


LERAGN or LERG or
Hot mode AGN or
Jet mode AGN



Heckman & Best (2014)

Radio-mode AGN feedback in cosmological models



RADIO MODE

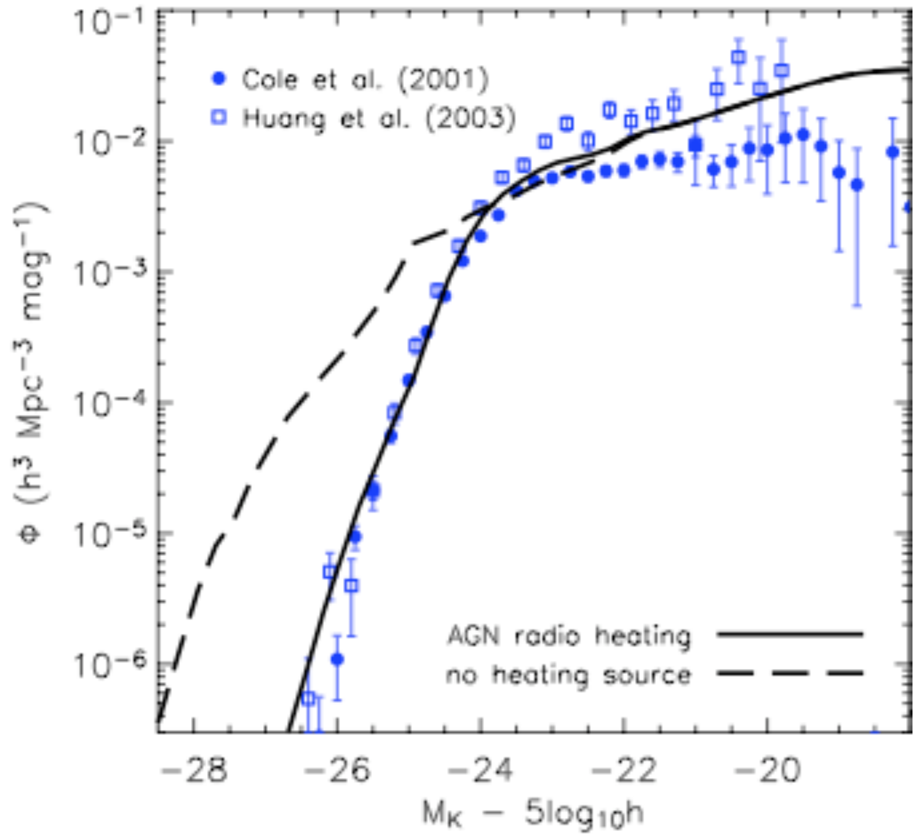
- "maintenance" mode
- Once a static hot (X-ray) halo forms around galaxy
- Modest BH growth
- Radio outflows heat surrounding gas → truncation of further stellar mass growth

Allows good reproduction of observed galaxy properties

Croton et al. 2006; Bower et al. 2006; Sijacki et al. 2006, Hopkins et al. 2006…

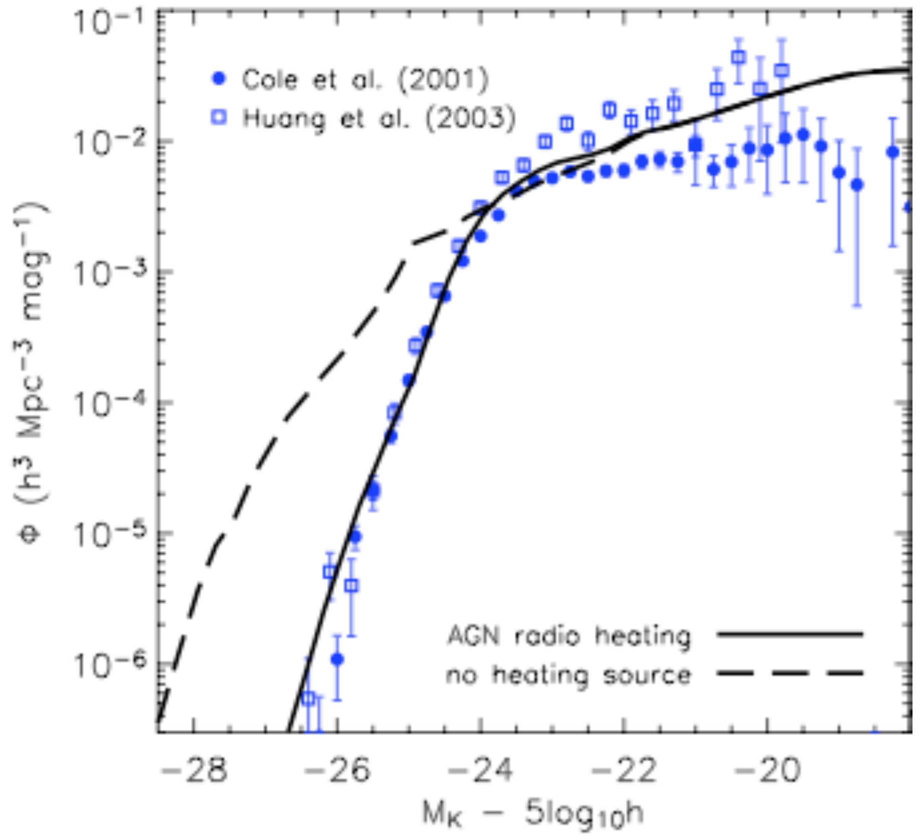
Radio-mode AGN feedback in cosmological models

Croton et al. 2006



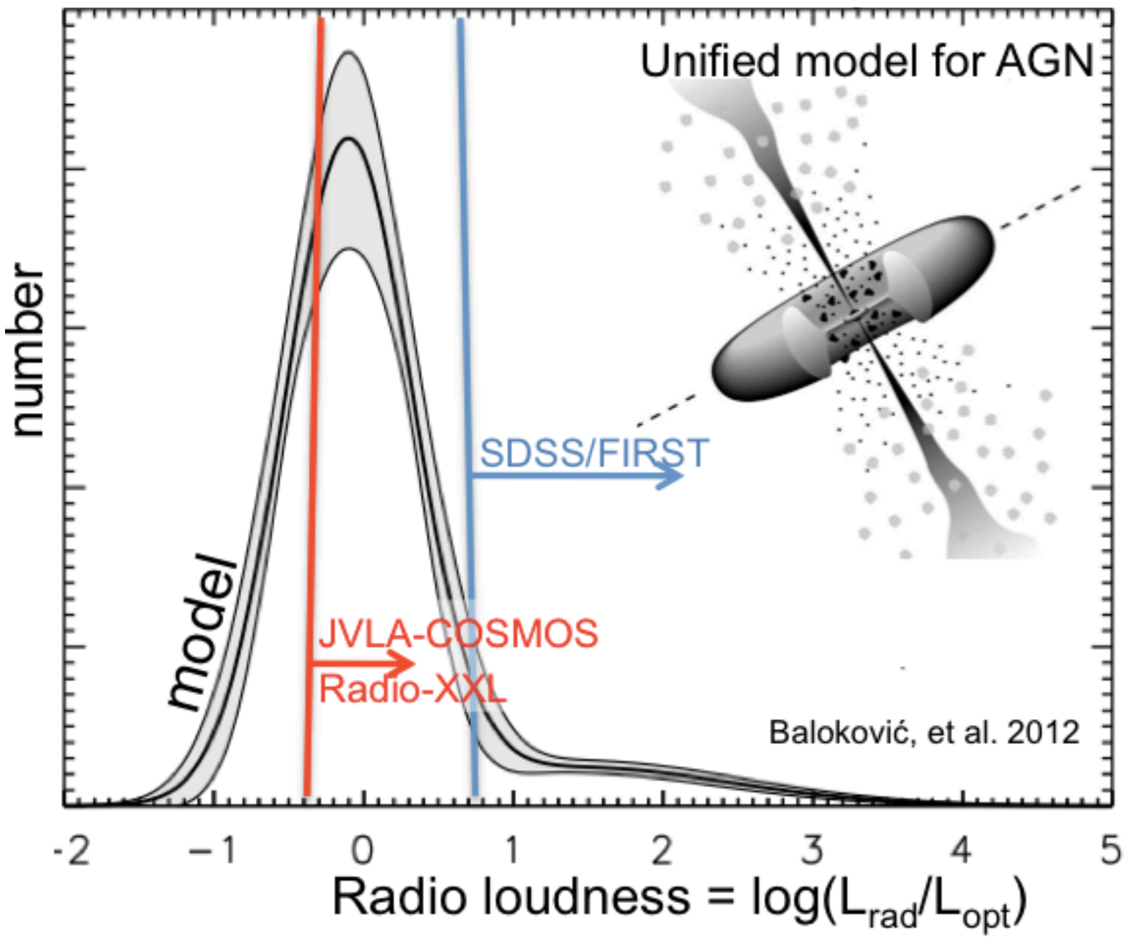
Radio-mode AGN feedback in cosmological models

Croton et al. 2006



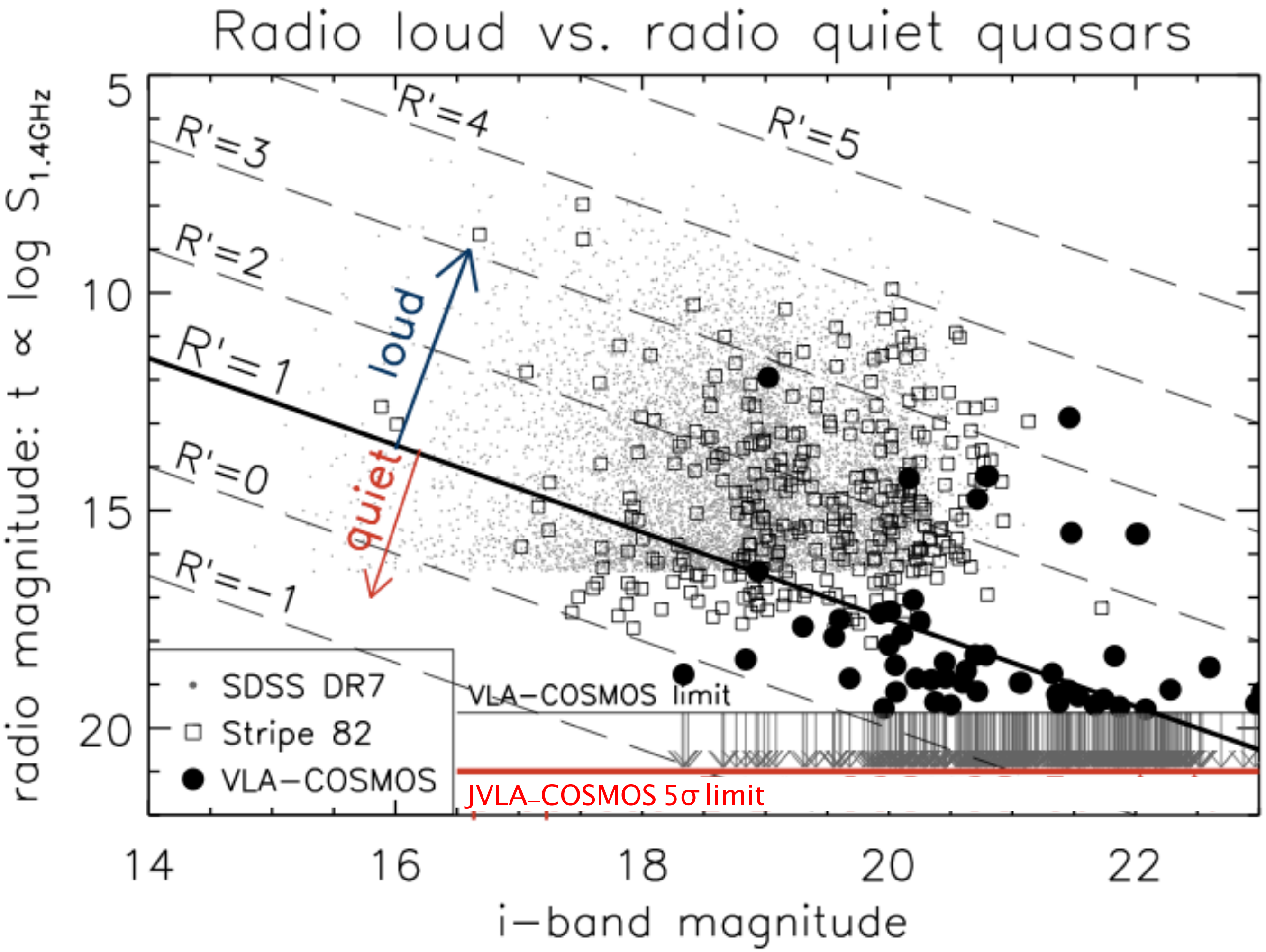
➔ Impact of AGN onto galaxy evolution? ➔ radio

Quasar radio loudness dichotomy

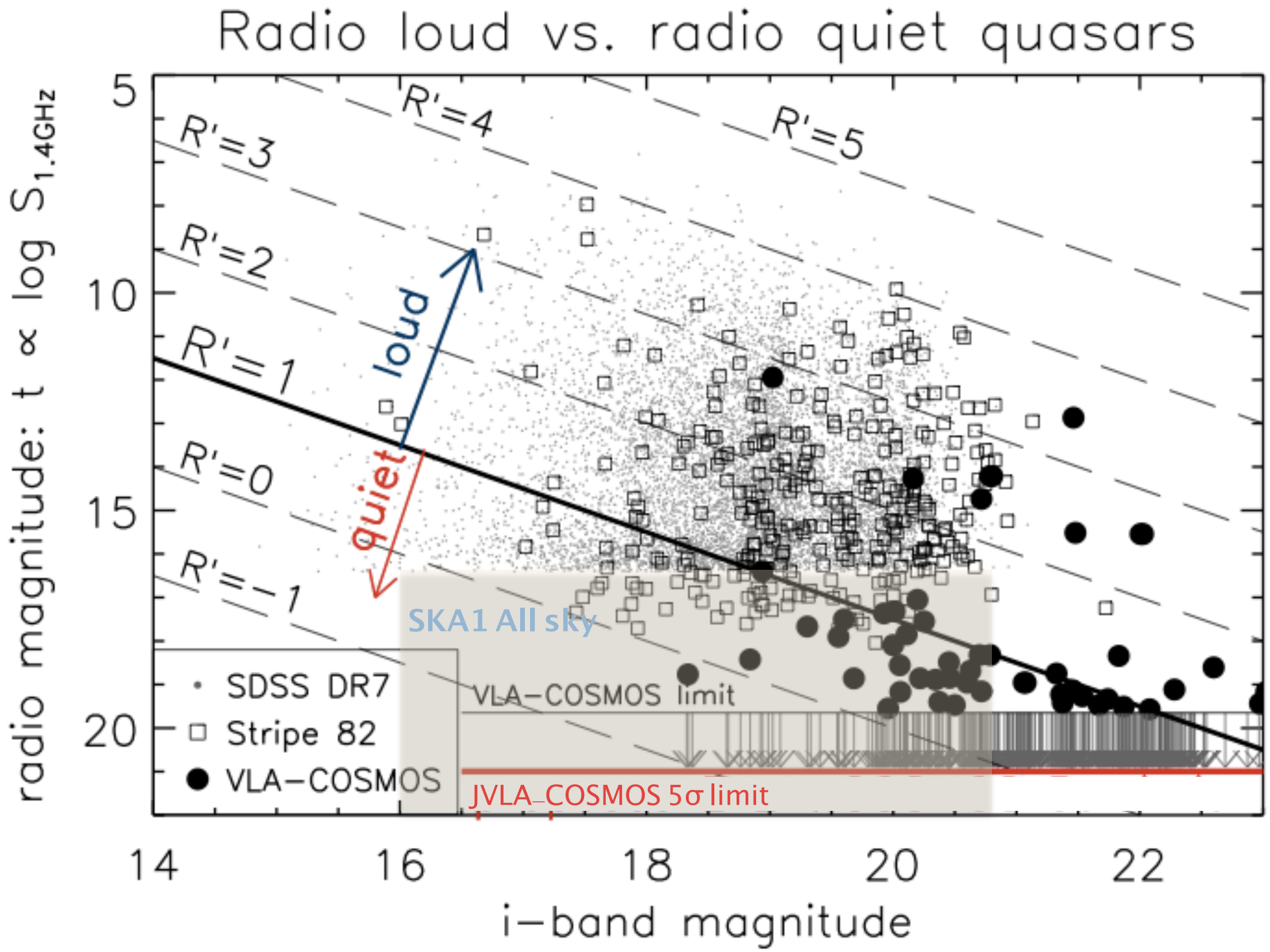


- One of the longest standing issues in observational astronomy
- Fundamental physical differences between radio loud and radio quiet quasars?

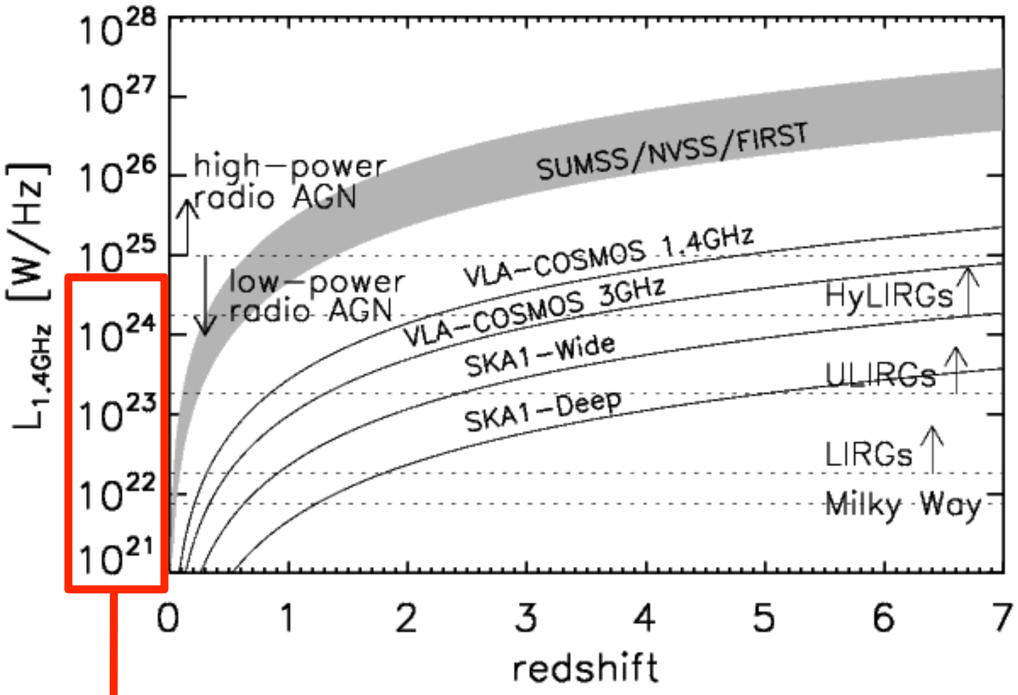
Quasar radio loudness dichotomy



Quasar radio loudness dichotomy



The power of radio



Star forming galaxies & radio AGN responsible for radio-mode feedback

SKA & pathfinders

1. Dust-unbiased SF tracer at *high* angular resolution

   → Impact of dust onto the cosmic star formation history?

2. Unique AGN

   → Impact of AGN onto galaxy evolution?

3. "Quantum leap" in instrumentation: Jansky VLA, ATCA, ALMA → SKA and precursors