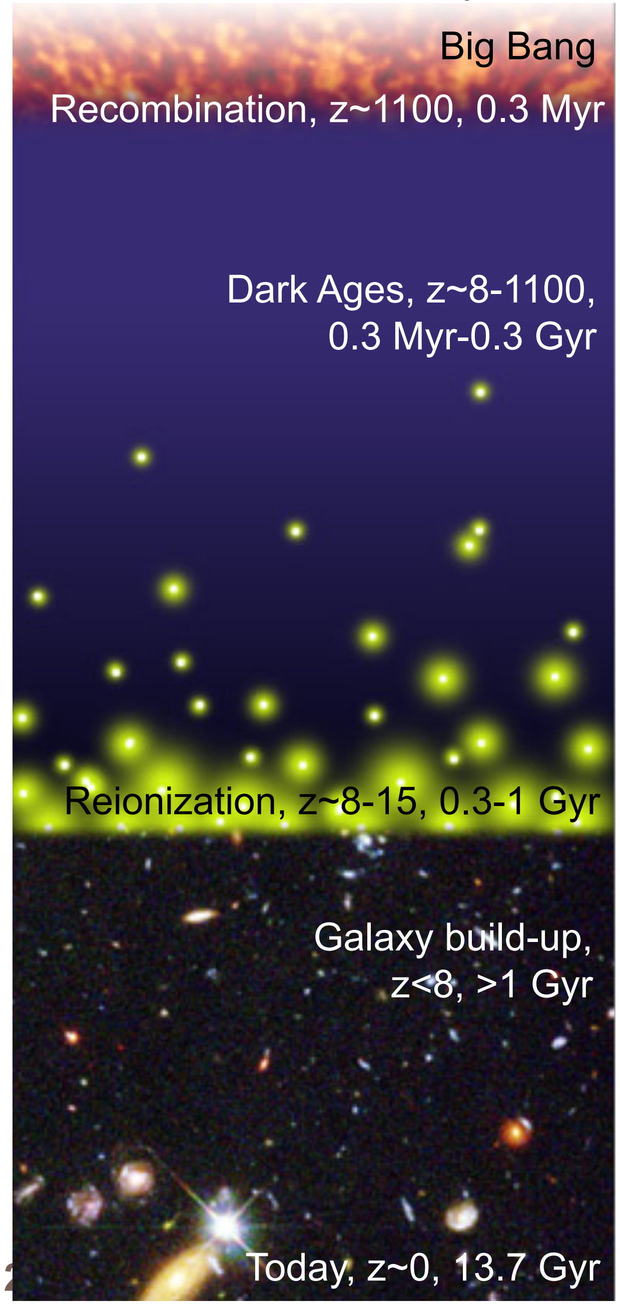
Radio sources and their cosmic evolution: Predictions for the SKA

Vernesa Smolčić (University of Zagreb, Croatia)

Cosmic history

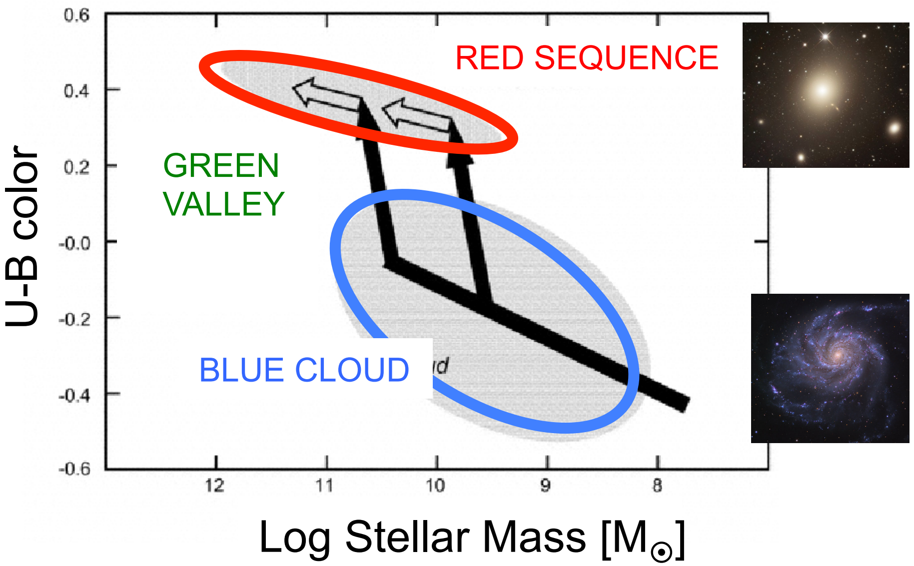


Understanding galaxy formation and evolution

→ build-up of *stellar* and *central SMBH masses* over cosmic time

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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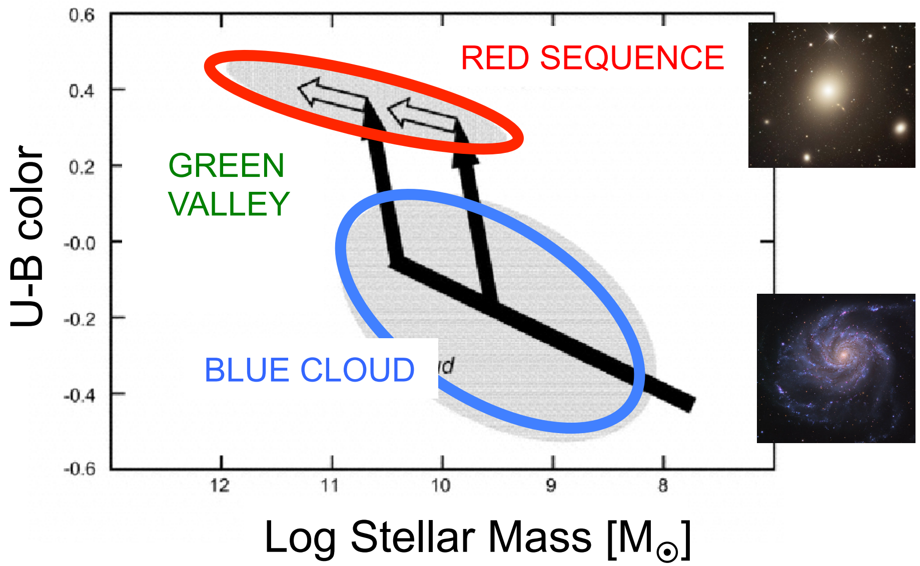

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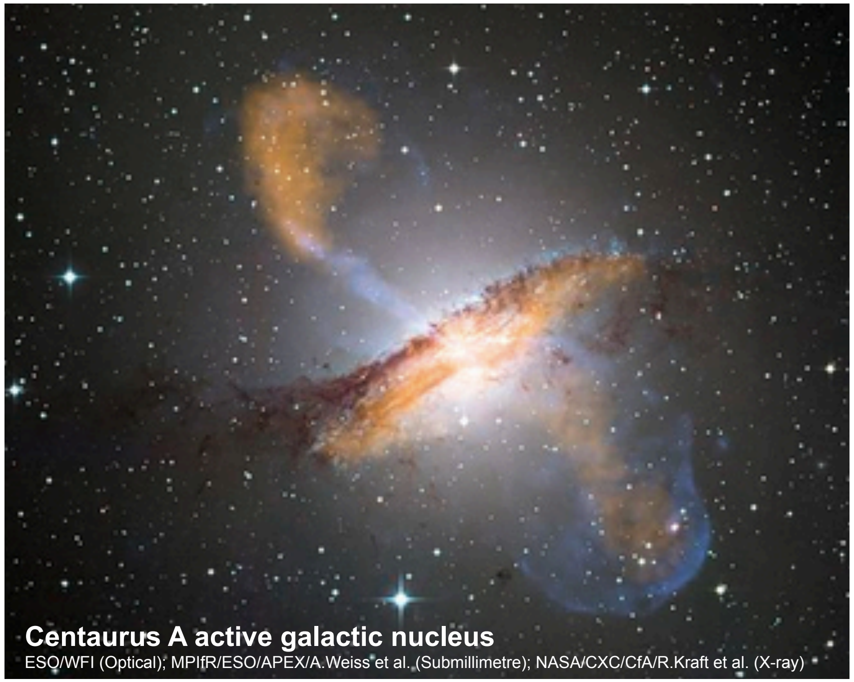
1) Impact of dust onto cosmic star formation history?
2) Impact of AGN onto galaxy evolution?

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)

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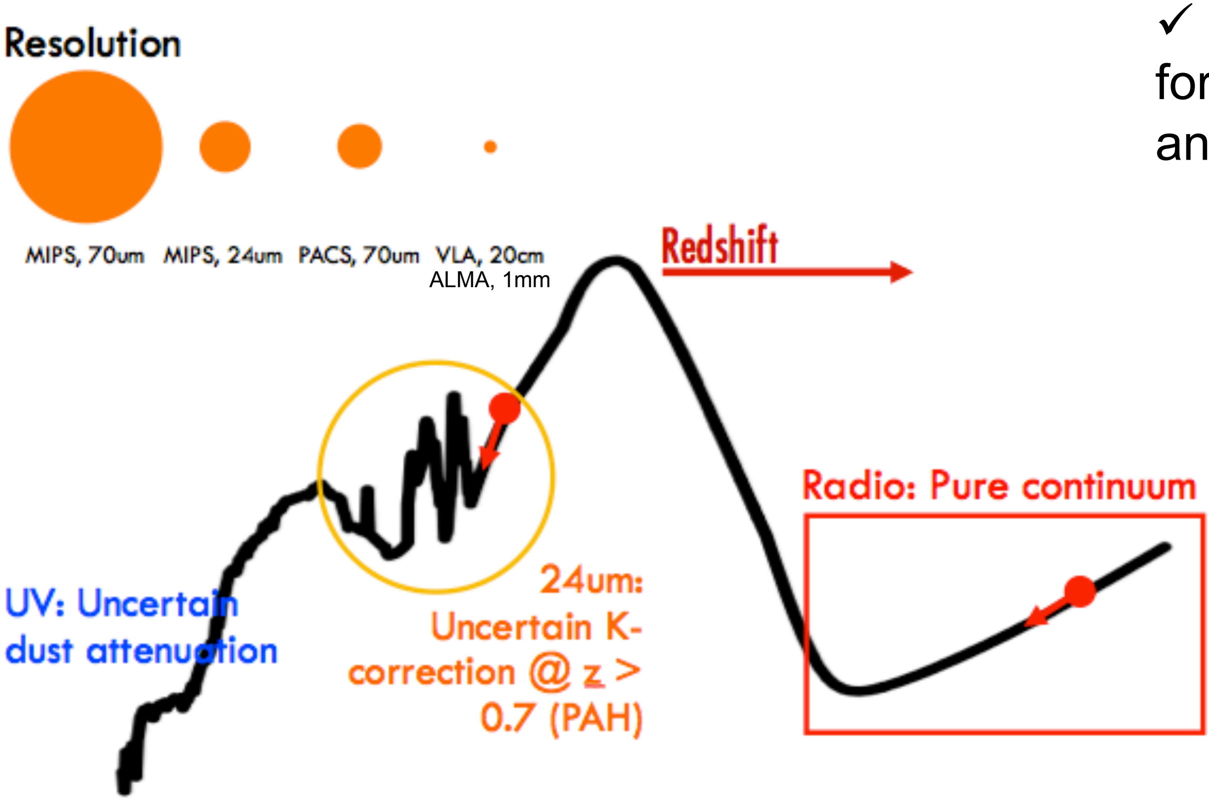

Advantage

✓ Dust-unbiased star formation tracer at high angular resolution

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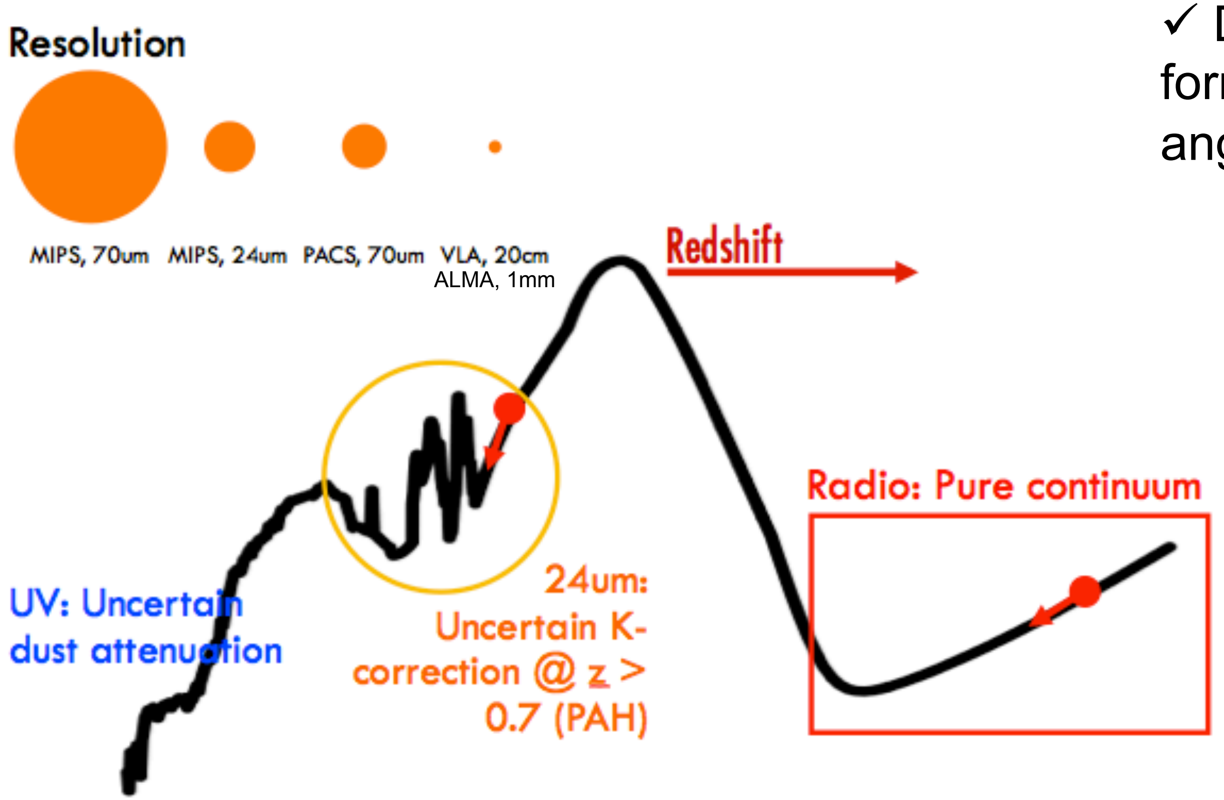


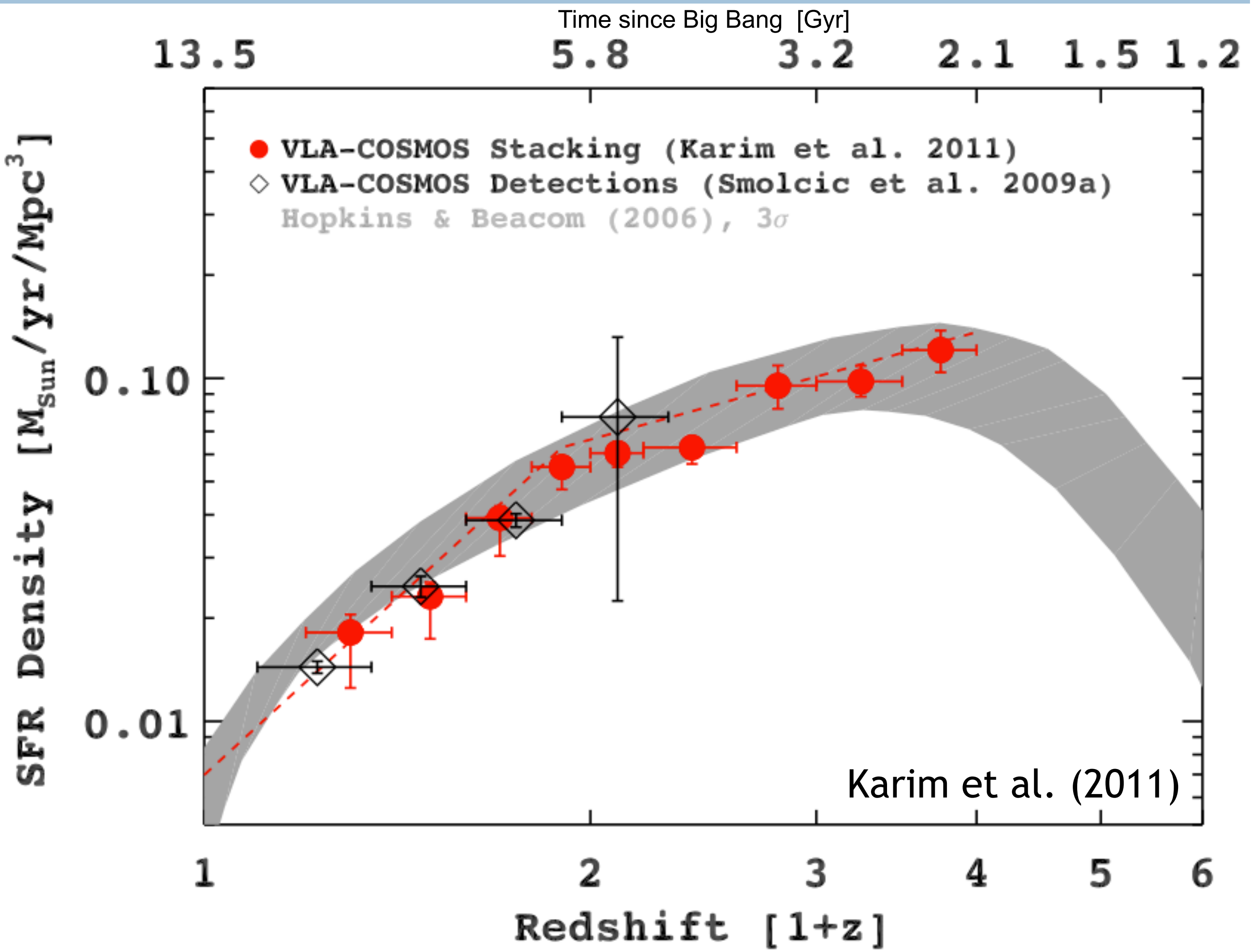
Advantage

✓ Dust-unbiased star formation tracer at high angular resolution

→ build-up of *stellar mass in galaxies* over cosmic time

Dust-unbiased cosmic star formation history

- Radio: good agreement with other studies
- To-date radio reaches z~3-4
(Haarsma+01; Seymour+08; Smolcic+09; Dunne+09; Karim+11)



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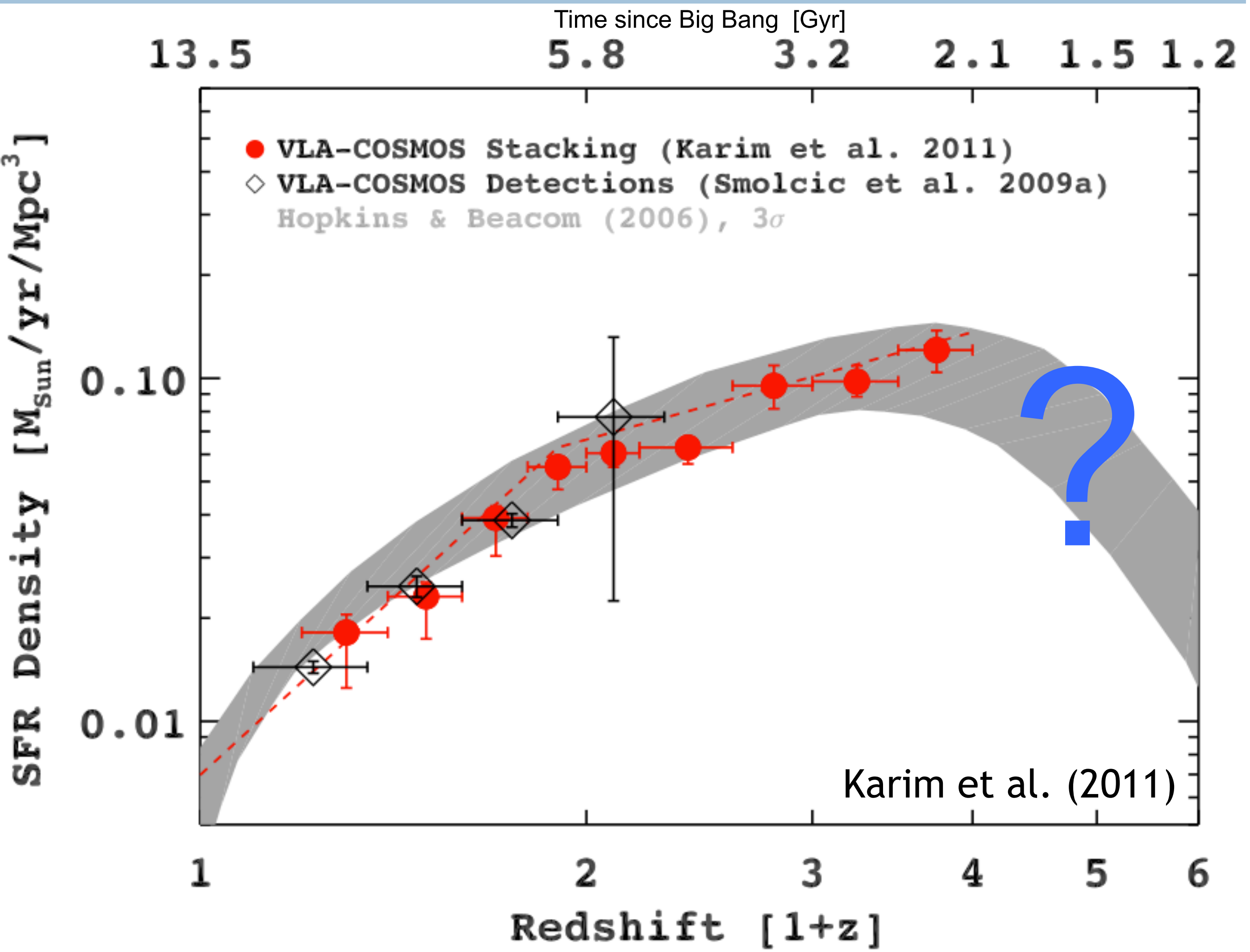
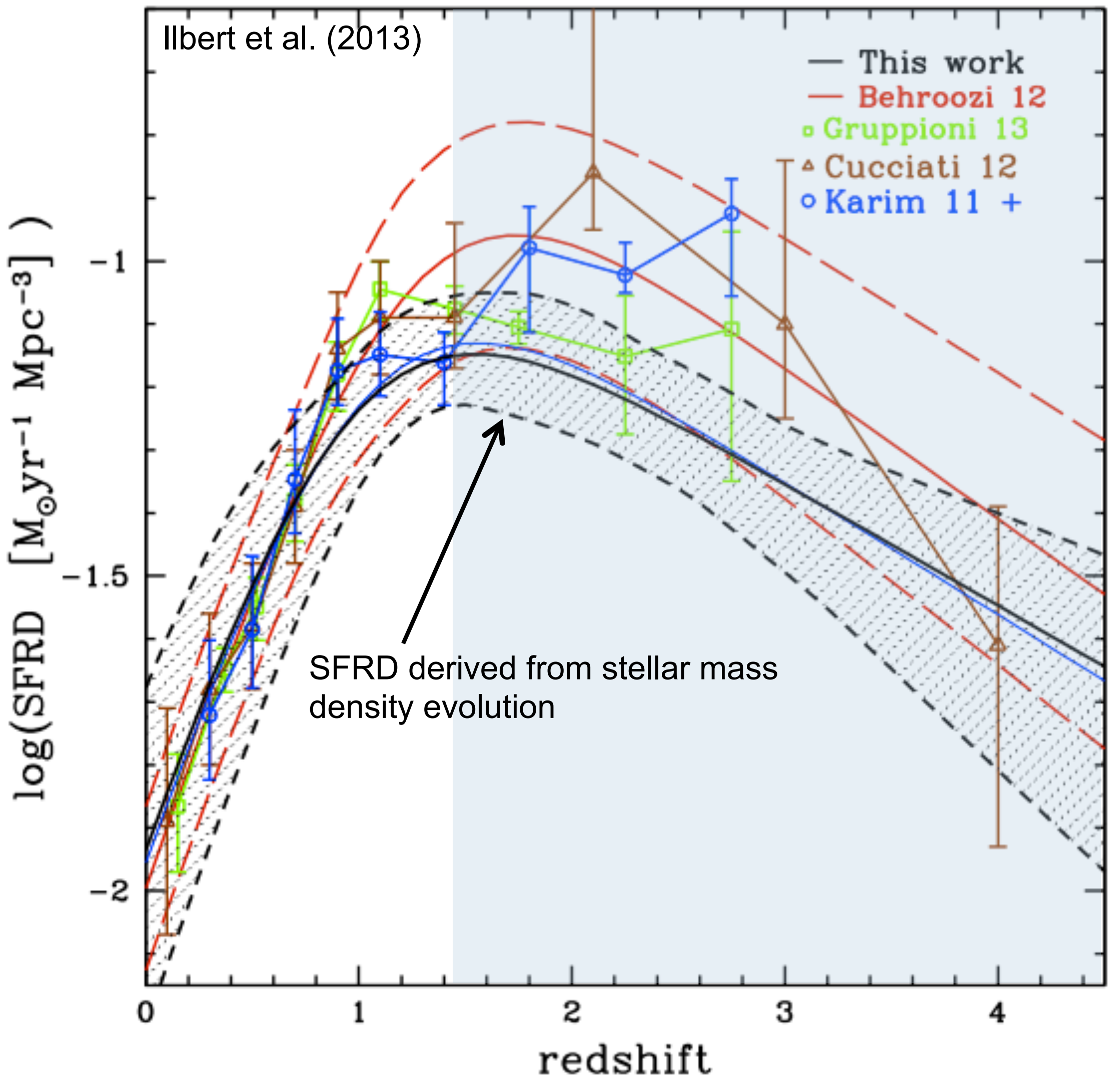


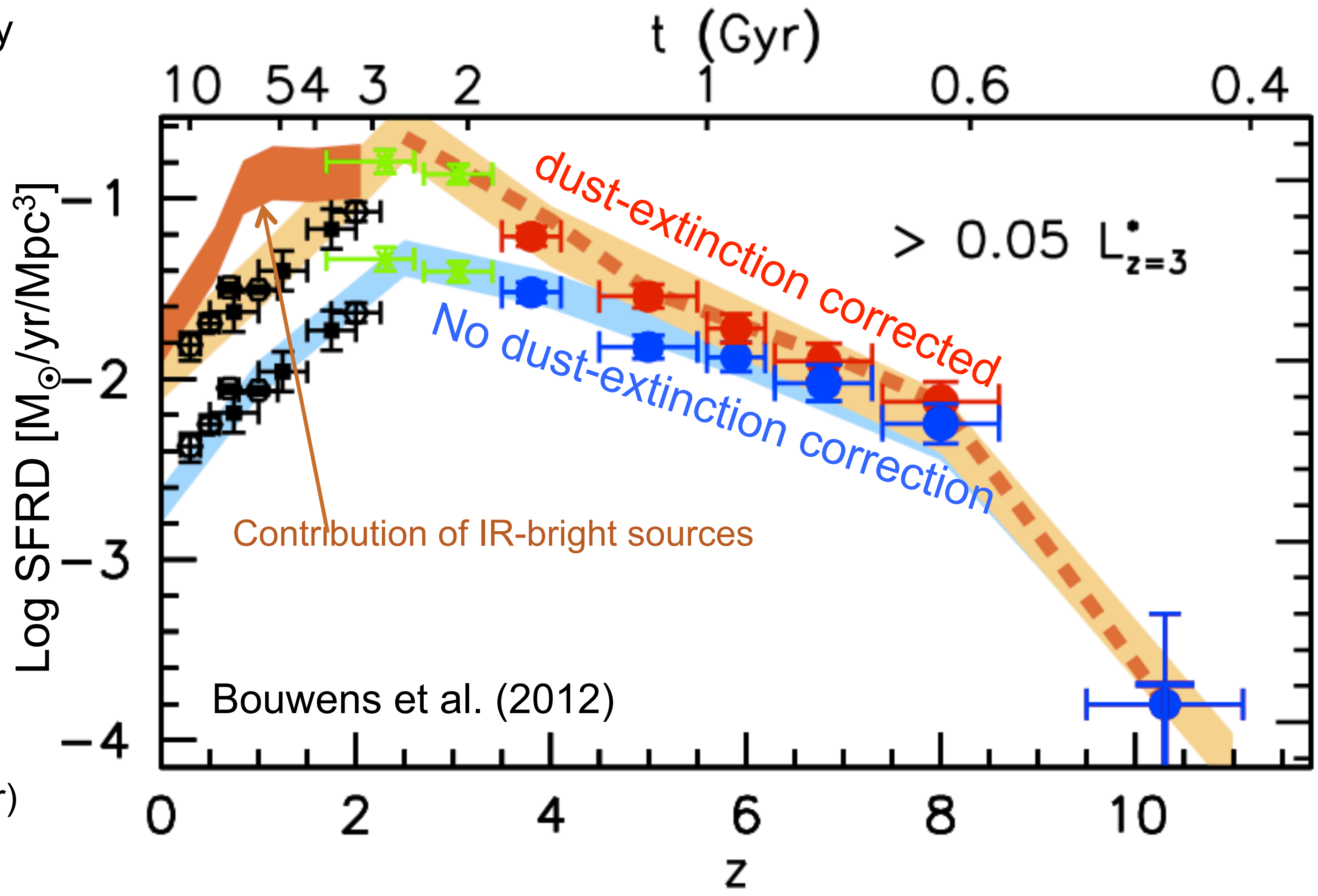
Cosmic star formation history at high-z

Good agreement between various tracers at z<1.5, *large spread at z>2*



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
- Method cannot account for dusty starbursts (>100$M_\odot$/yr)



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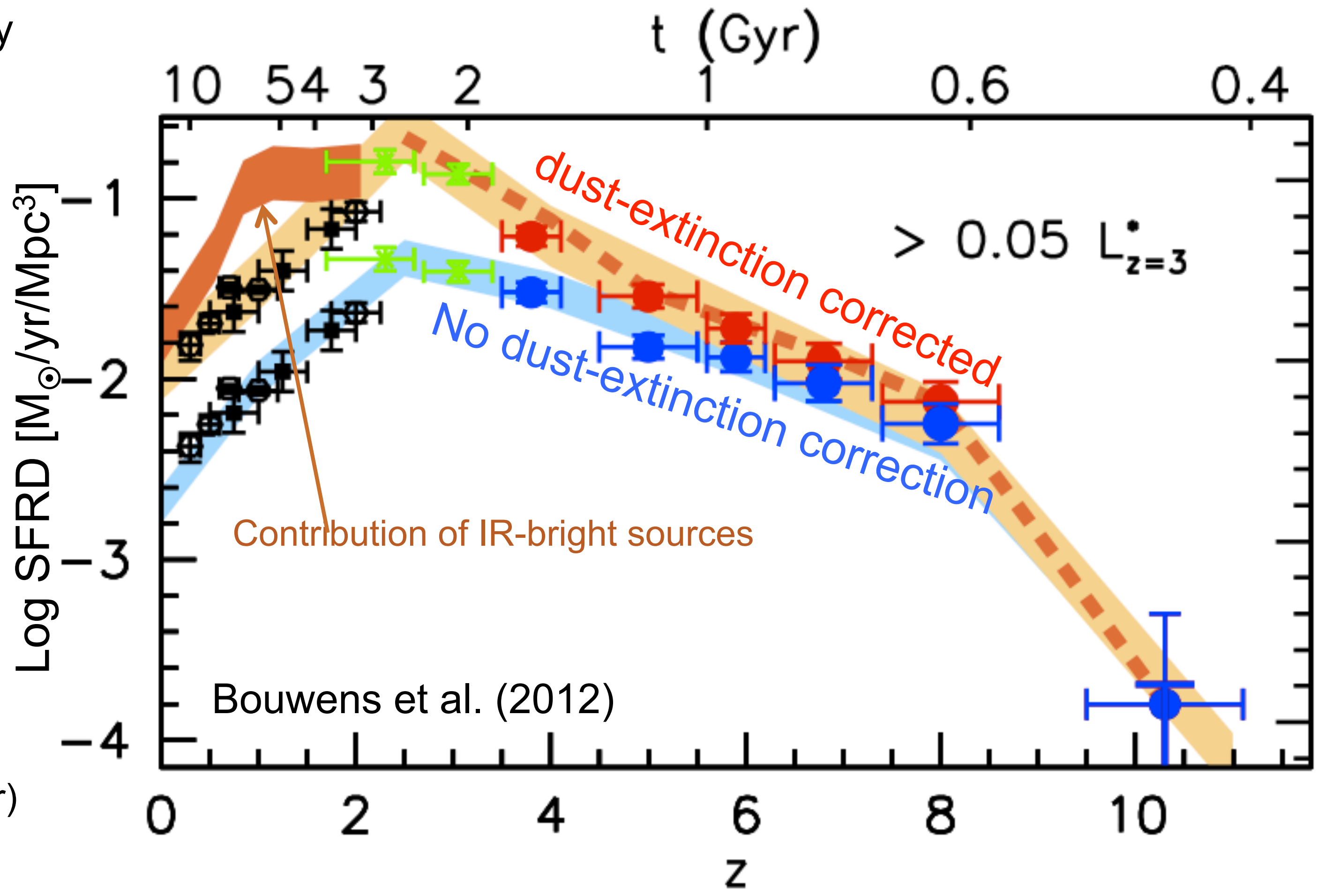


➔ Impact of dust onto cosmic star formation history ? ➔ radio

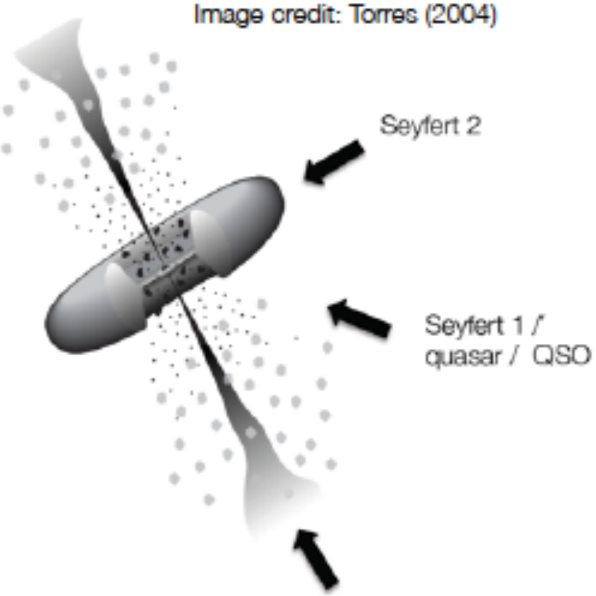
2 - Unique AGN, violating “Unified model for AGN”

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

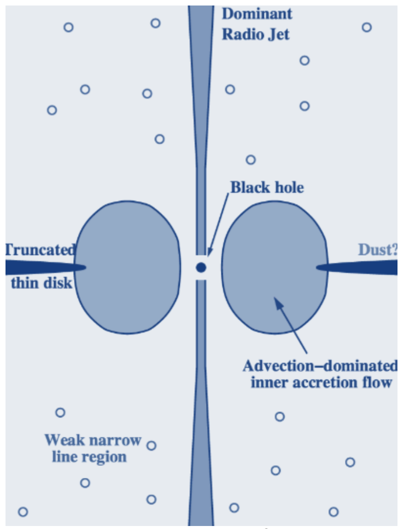
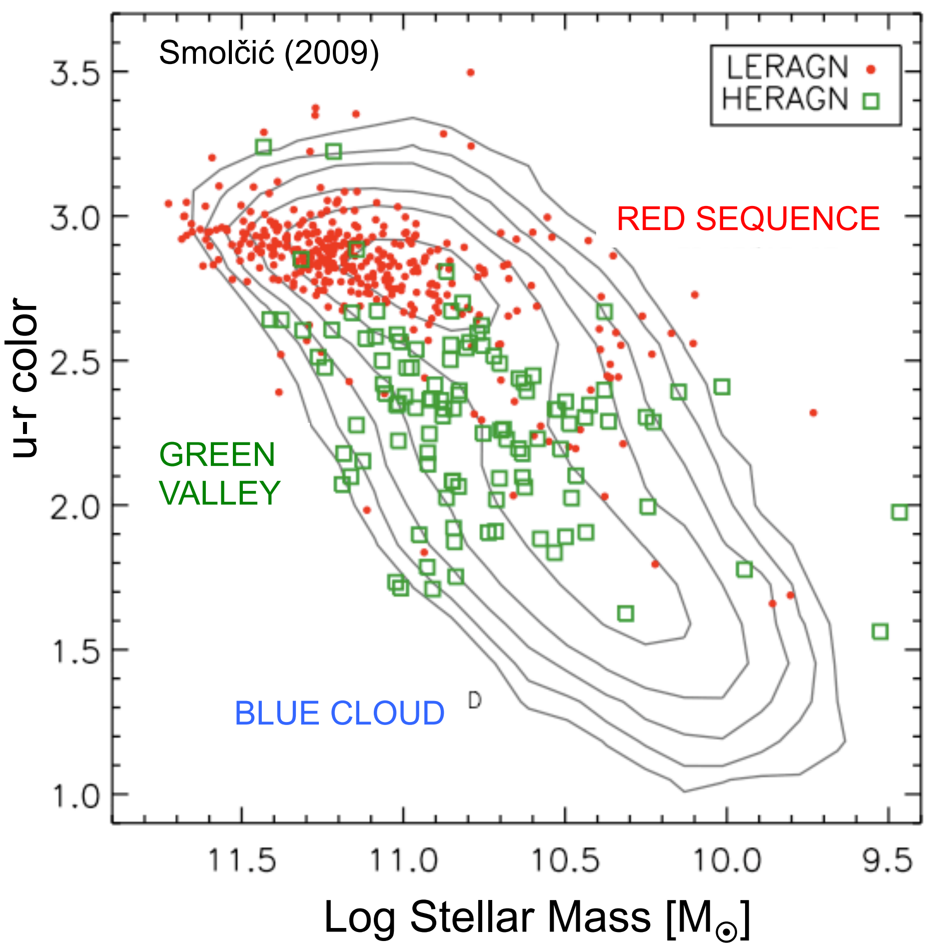


Image: Heckman & Best (2014)

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 ($L_{20cm} \geq 10^{26}$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



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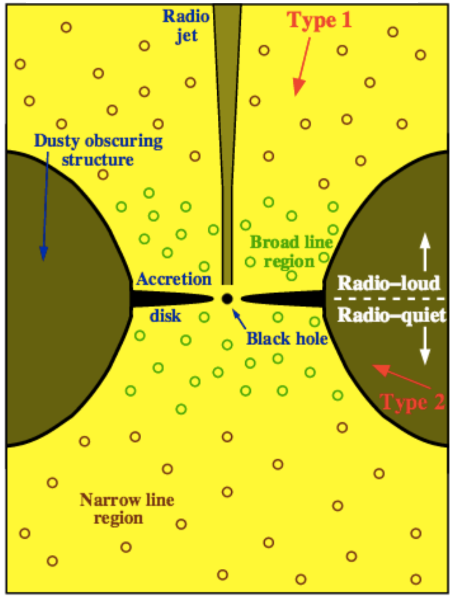
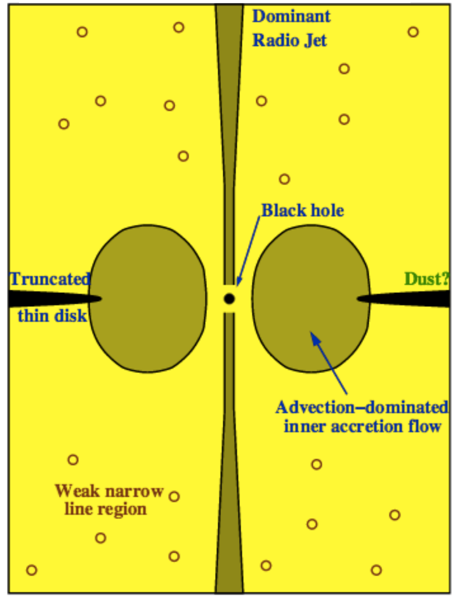
HERAGN or HERG or
Cold mode AGN or
Radiative mode AGN

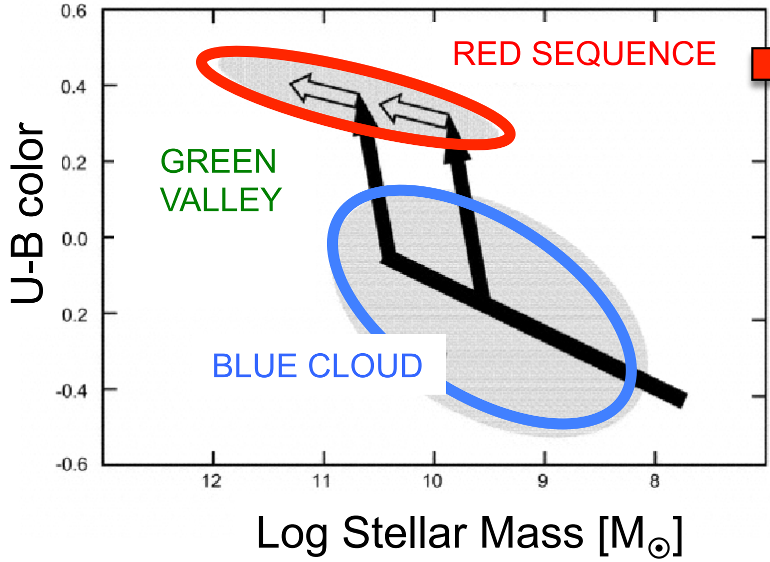


LERAGN or LERG or
Hot mode AGN or
Jet mode AGN



Heckman & Best (2014)

Radio-mode AGN feedback in cosmological models



RADIO MODE

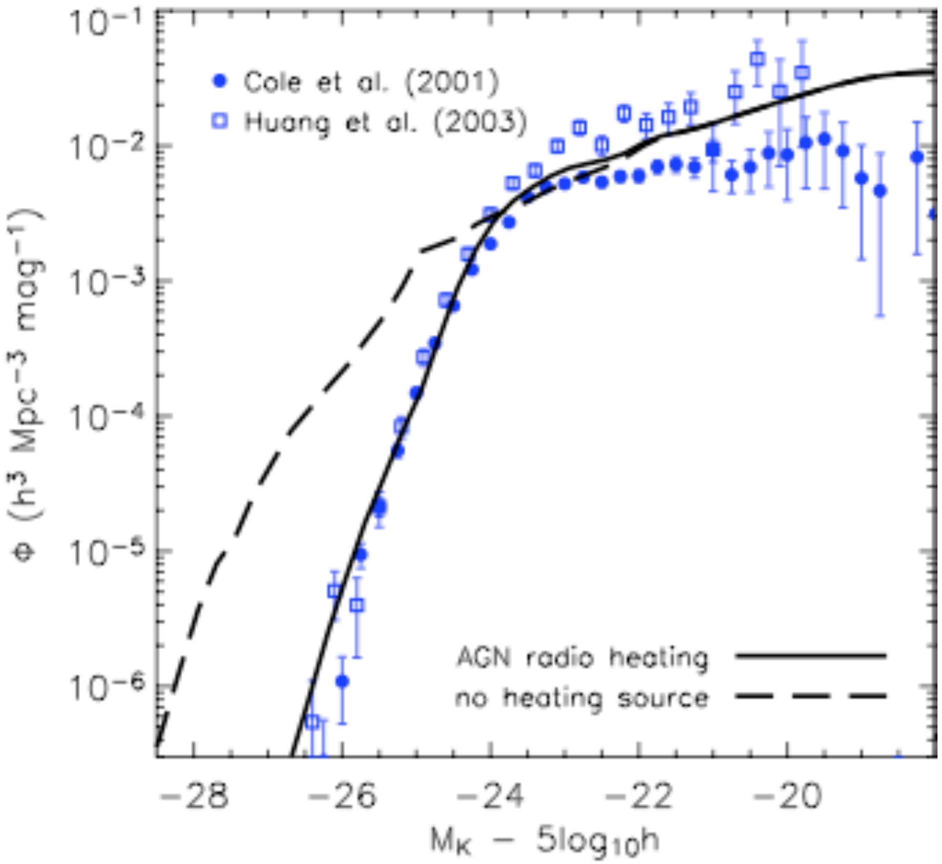
- "maintenance" mode
- Once a static hot (X-ray) halo forms around galaxy
- Modes BH growth
- Radio outflows heat surrounding gas → truncation of further stellar mass growth

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

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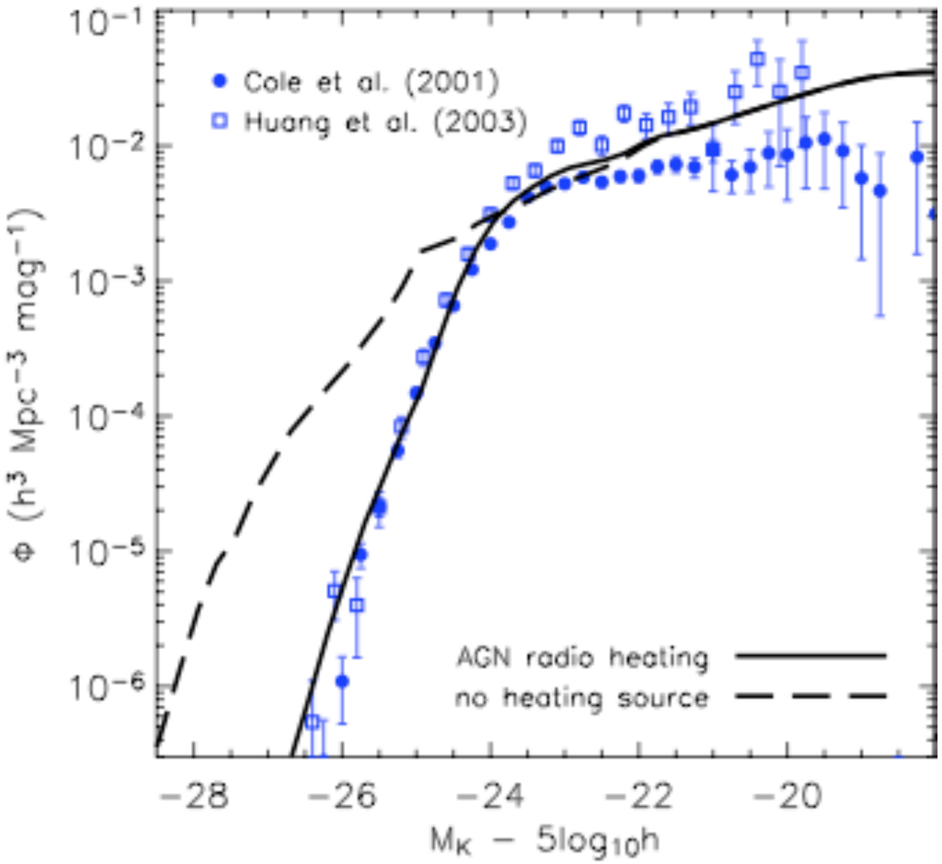


➔ Impact of AGN onto galaxy evolution? ➔ radio

3 – Quantum leap in instrumentation

Major upgrade of existing radio facilities

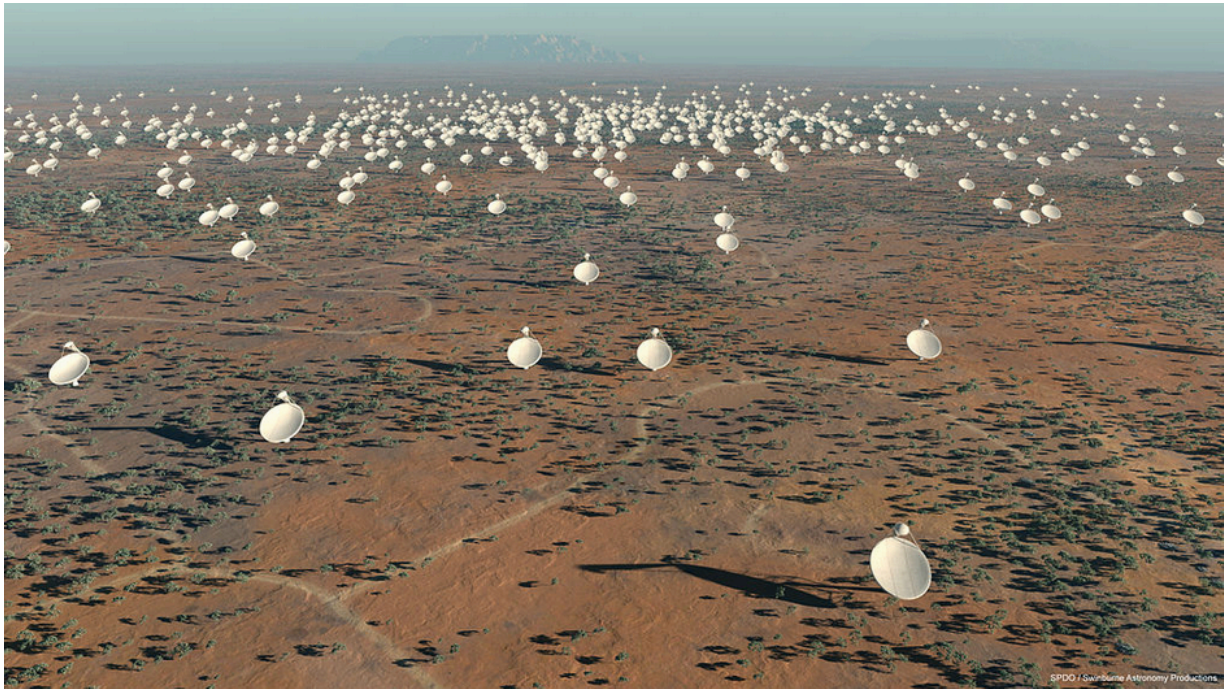
VLA (Very Large Array, USA)

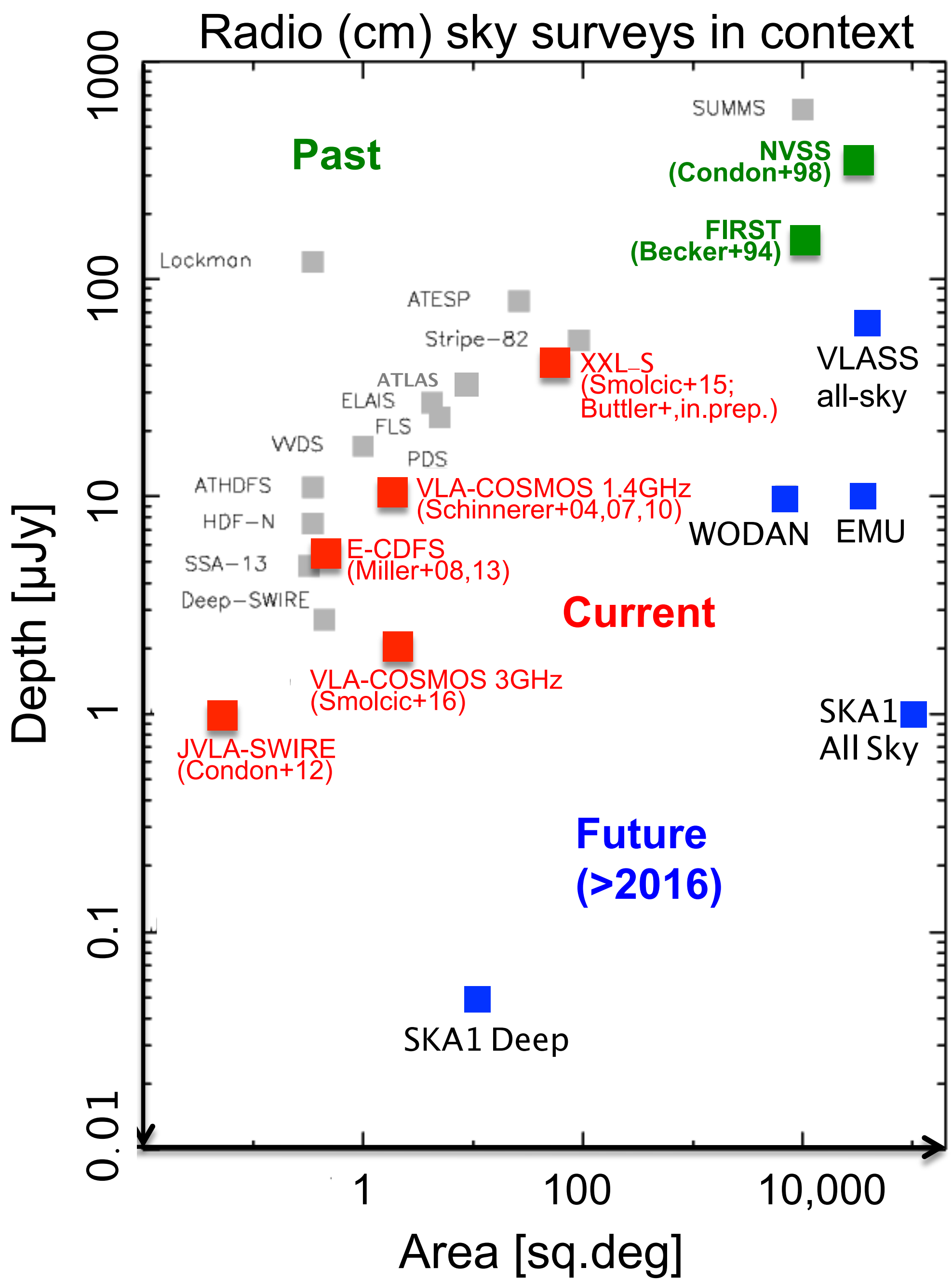
GMRT (Giant Metrewave Radio Telescope, India)

ATCA (Australia Telescope Compact Array)

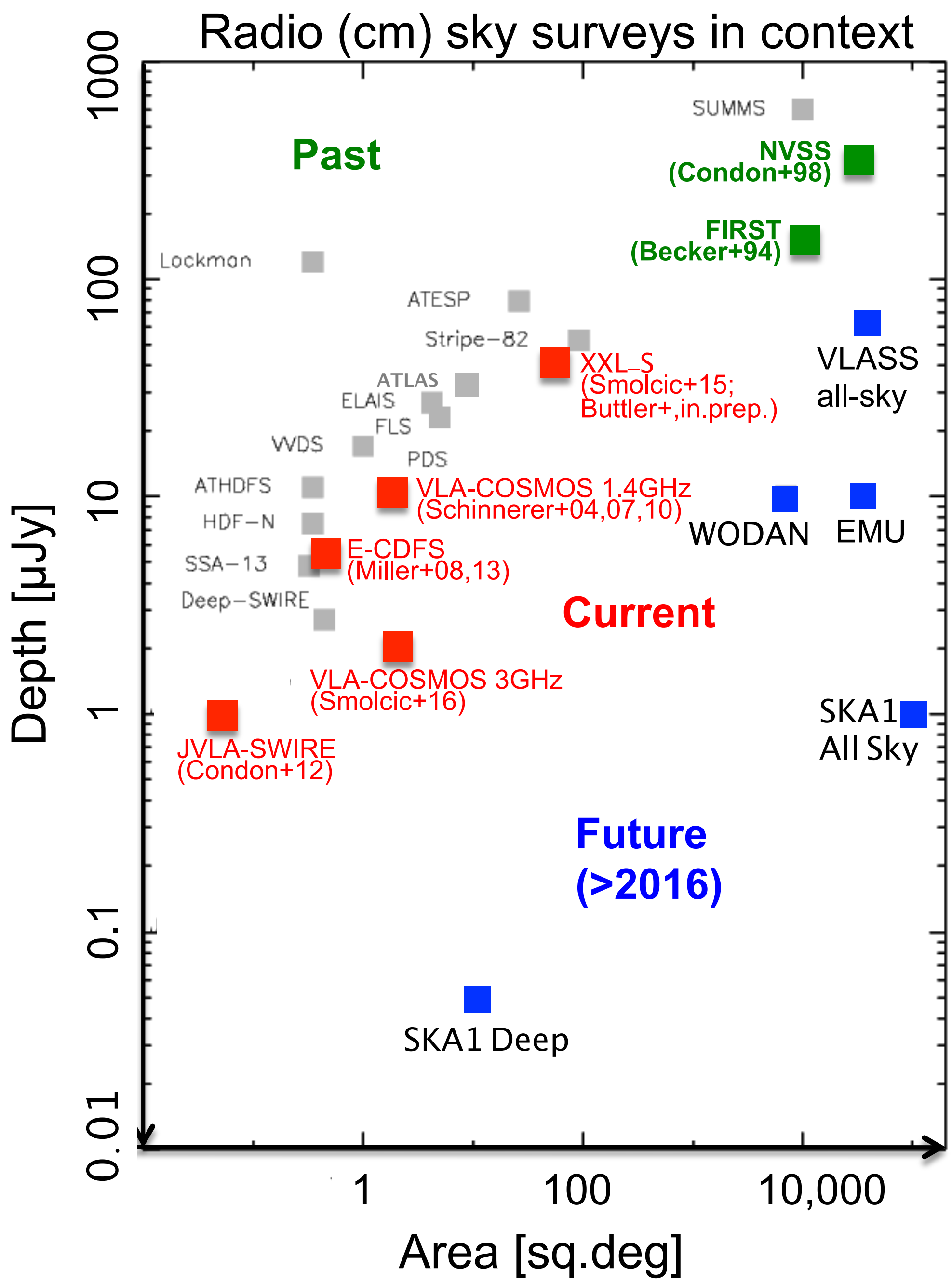
SKA: The Square Kilometre Array

- 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, …**





Radio (cm) sky surveys in context
Past
Current
Future (>2016)
SUMMS
NVSS (Condon+98)
FIRST (Becker+94)
Lockman
ATESP
Stripe−82
XXL-S (Smolcic+15; Buttler+,in.prep.)
ATLAS
ELAIS
FLS
VVDS
PDS
ATHDFS
HDF−N
SSA−13
Deep−SWIRE
VLA-COSMOS 1.4GHz (Schinnerer+04,07,10)
E-CDFS (Miller+08,13)
VLA-COSMOS 3GHz (Smolcic+16)
JVLA-SWIRE (Condon+12)
VLASS all-sky
WODAN
EMU
SKA1 All Sky
SKA1 Deep
Depth [μJy]
1000
100
10
1
0.1
0.01
Area [sq.deg]
1
100
10,000



The power of radio

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

   → Impact of dust onto the cosmic star formation history?

2. Unique AGN, violating "Unified model for "AGN"

   → Impact of AGN onto galaxy evolution?

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

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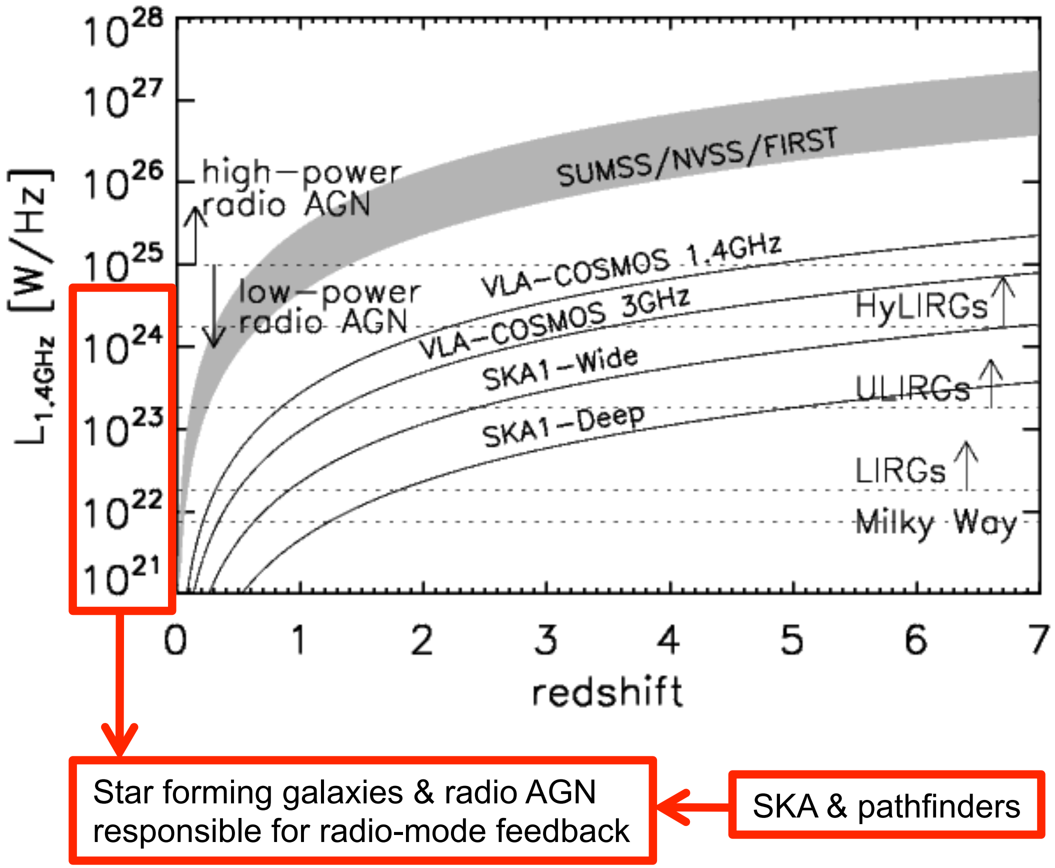

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Current understanding & open questions → SKA

MicroJansky radio sources: What will the SKA see?

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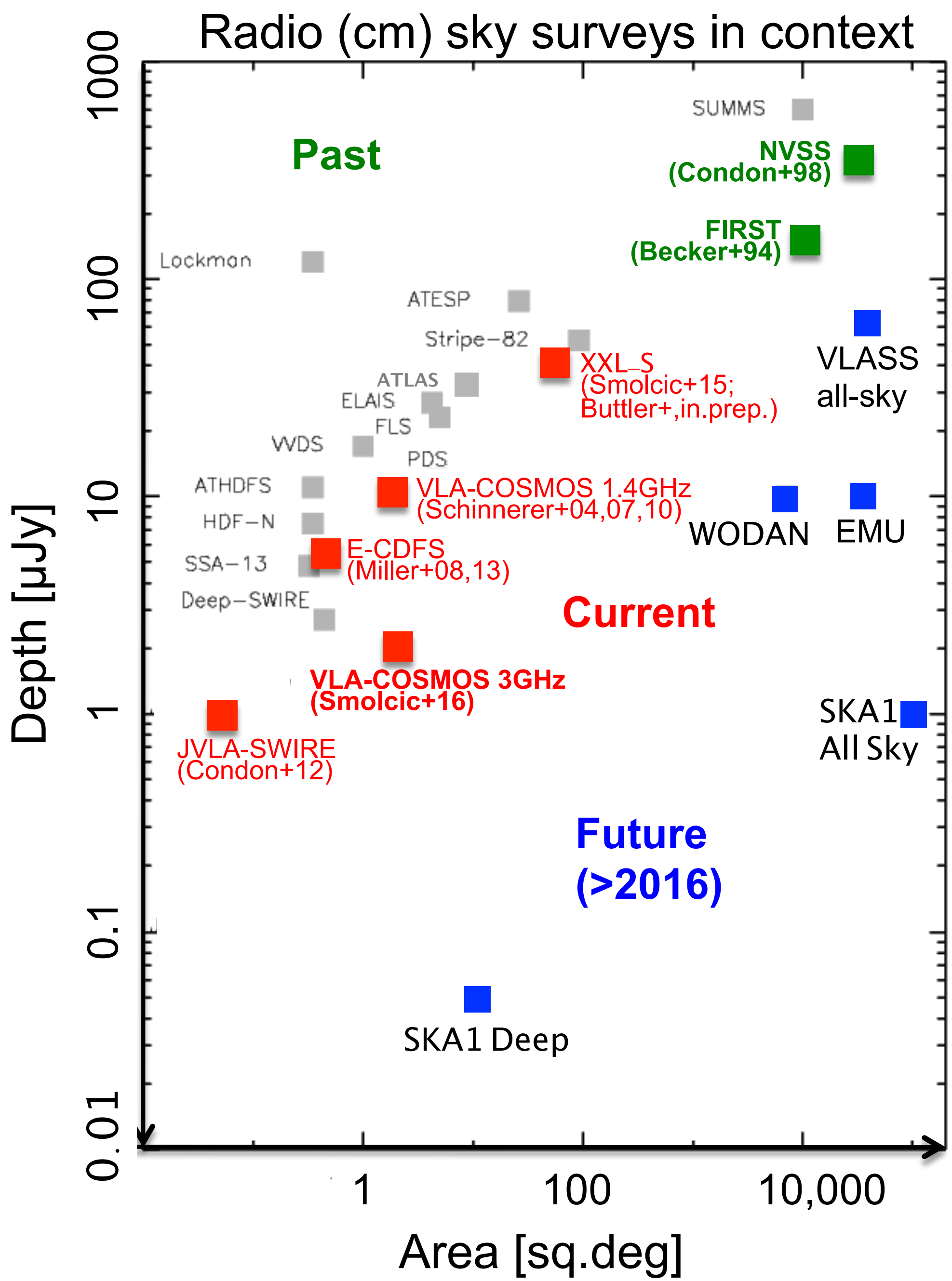
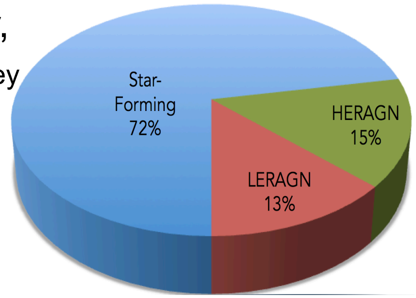


VLA-COSMOS 3GHz Large Project as an SKA pathfinder

- VLA-COSMOS 3GHz Large Project
  - PI: Smolčić (Smolčić et al., subm.)
  - 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 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)

Radio source populations in VLA-COSMOS 3GHz Large Project: What will the SKA see?

- VLA-COSMOS 3GHz Large Project
  - 6,214 radio sources with NIR counterparts over 1.8 square degrees
  - Source -- AGN and star forming galaxy -- separation: Combination of X-ray, MIR, rest-frame color (see Baran et al., in prep, Delvecchio et al., 2014, Brusa et al. 2007; Donley et al. 2013; Padovani et al. 2011; Bonzini et al. 2013, Smolčić et al. 2006, 2008, Ilbert et al. 2010, 2012)



Baran et al. (2016)

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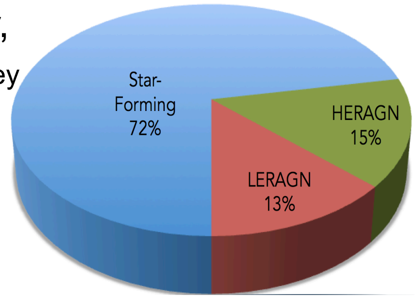
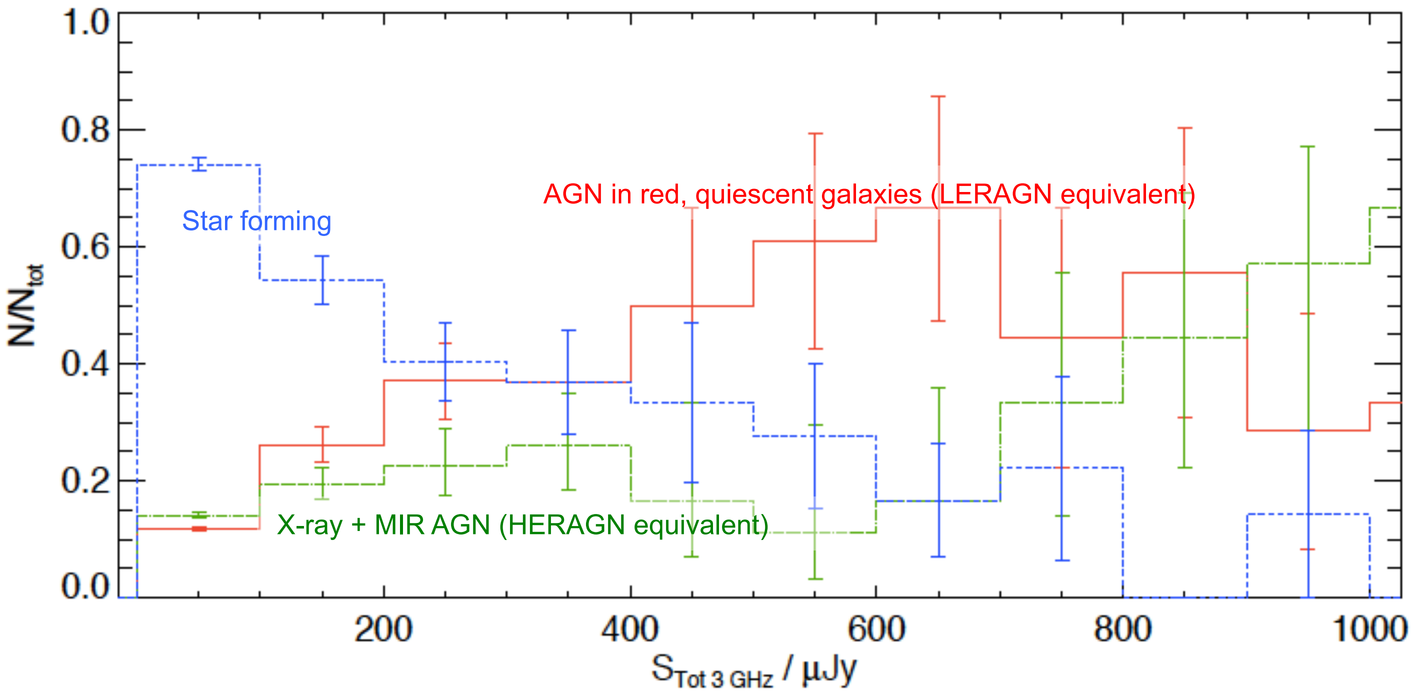


- Star forming galaxies start dominating the counts at <200μJy
(Consistent with Bonzini et al. 2013, Padovani et al. 2015; ECDFS)



Baran et al. (2016)

Current understanding & open questions → SKA

MicroJansky radio sources: What will the SKA see?

Below ~200 μJy star forming galaxies start dominating the radio source counts

Impact of dust onto cosmic star formation history?

Impact of AGN onto galaxy evolution?

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Radio as a dust-unbiased star formation tracer

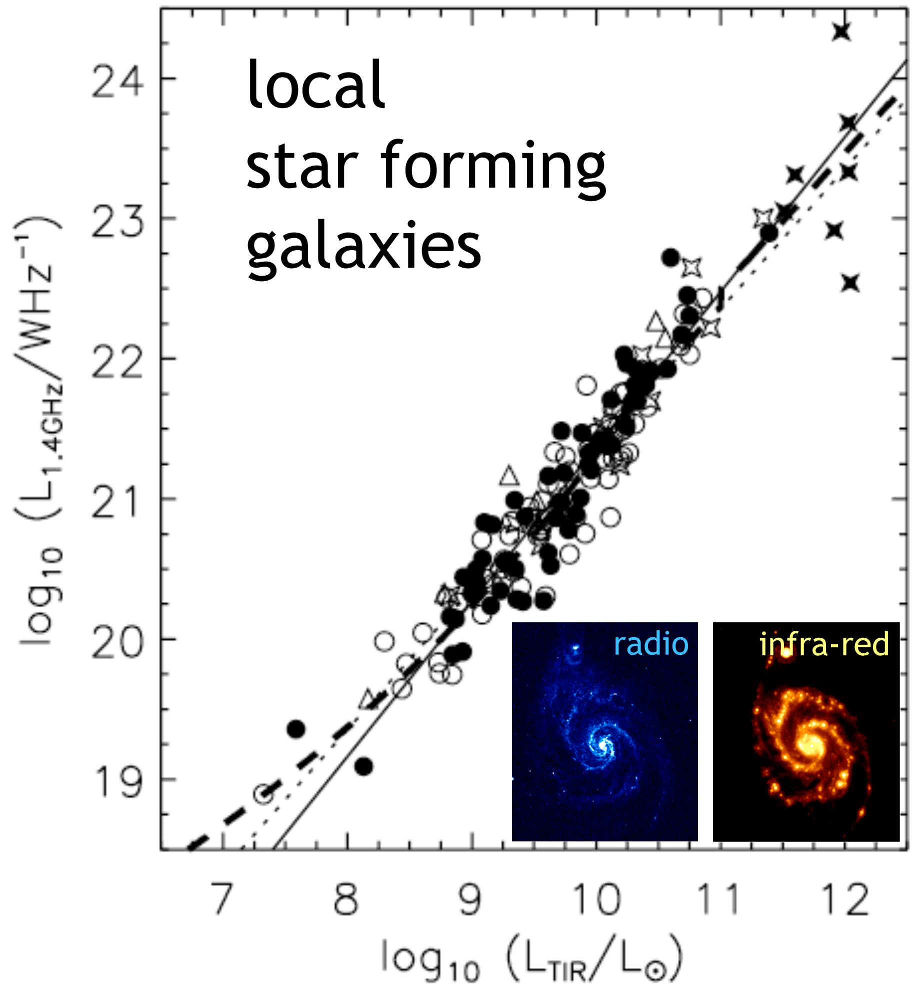
IR-radio correlation:

$$q_{(F)IR} = \log \frac{L_{(F)IR}}{L_{1.4GHz}} + \text{const.}$$

➔ radio continuum traces very well (high-mass) star formation

de Jong et al. (1985), Helou et al. (1985), Condon (1992) , Bell (2003), Yun, Reddy, Condon (2001)

IR-radio correlation

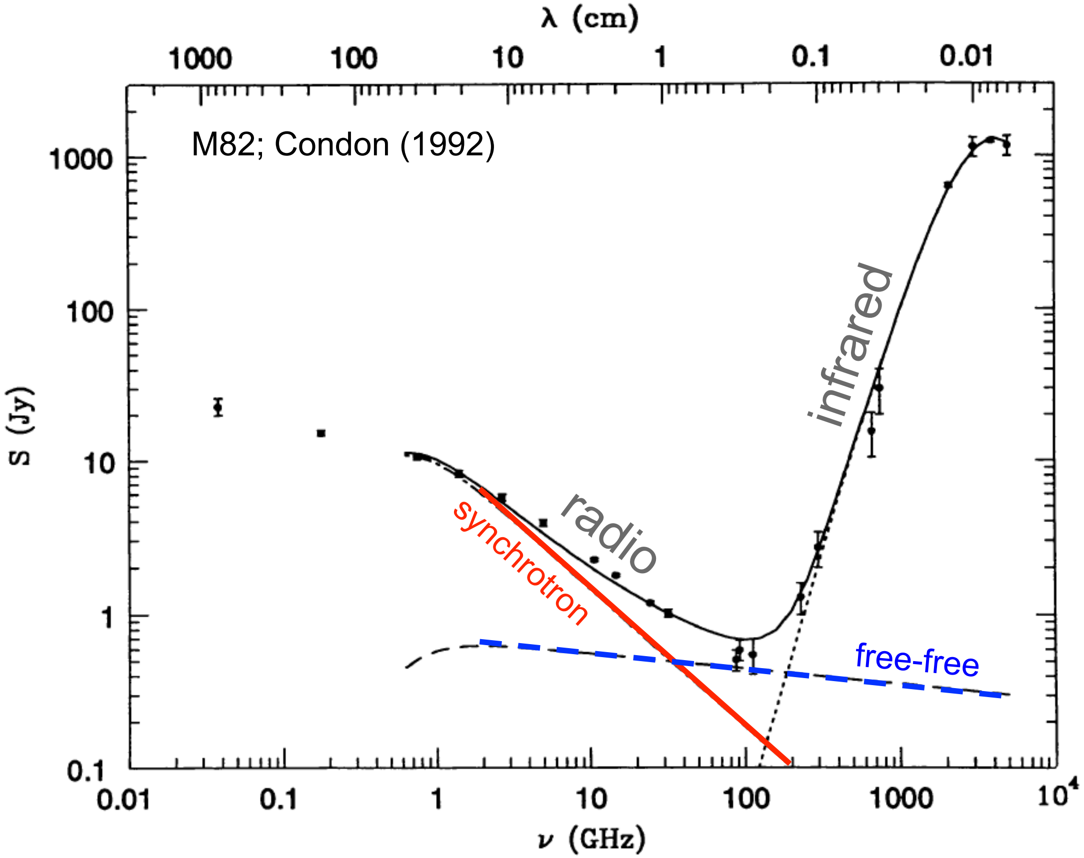


Radio as a dust-unbiased star formation tracer

Local star forming galaxies

- Radio observed @cm λ = synchrotron (+ free-free) emission
- Power-law spectrum ($S_\nu \sim \nu^\alpha$) characterized by spectral index α
  - Synchrotron (supernovae remnants): α = -0.8
  - Free-free (thermal bremsstrahlung within HII regions): α = -0.1
- At typical obs. freq. (1-3 GHz) non-thermal synchrotron dominates → anchoring $L_{1.4GHz}$ to SFR via $q_{(F)IR}$ needed

→ evolution of $q_{(F)IR}$ with cosmic time?



M82-type radio SED: Typically assumed radio spectral energy distribution (SED) for star forming galaxies

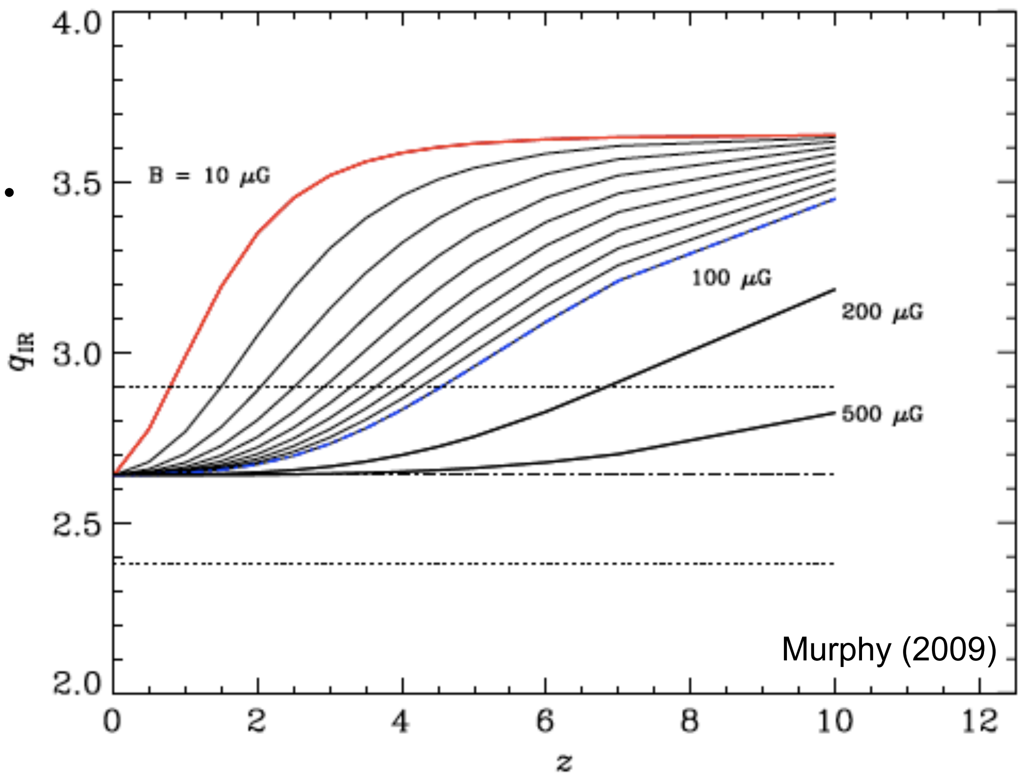
Radio as a dust-unbiased star formation tracer

$$q_{(F)IR} = \log \frac{L_{(F)IR}}{L_{1.4GHz}} + \text{const.}$$

➔ **analytic expectation: q increases with increasing redshift**

Mostly because of decrease in $L_{1.4GHz}$ due to inverse Compton scattering of CMB photons at high redshift, as energy density of CMB photons rises with redshift as $(1+z)^4$

Cosmic evolution of the IR-radio correlation



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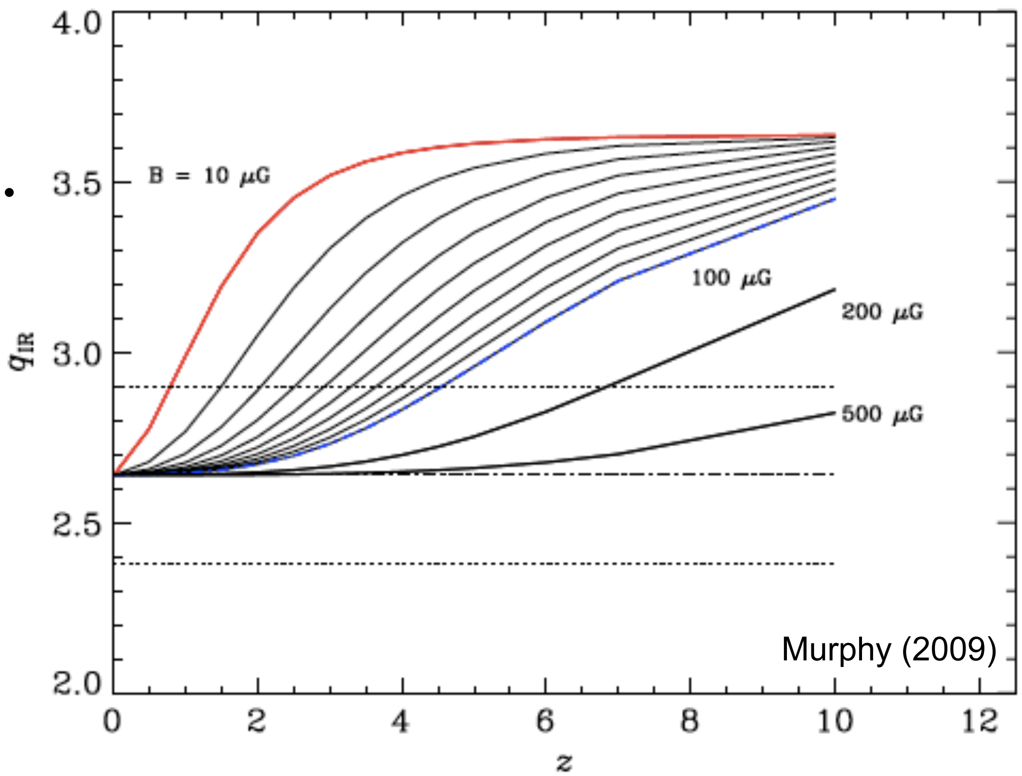
Mostly because of decrease in $L_{1.4GHz}$ due to inverse Compton scattering of CMB photons at high redshift, as energy density of CMB photons rises with redshift as $(1+z)^4$

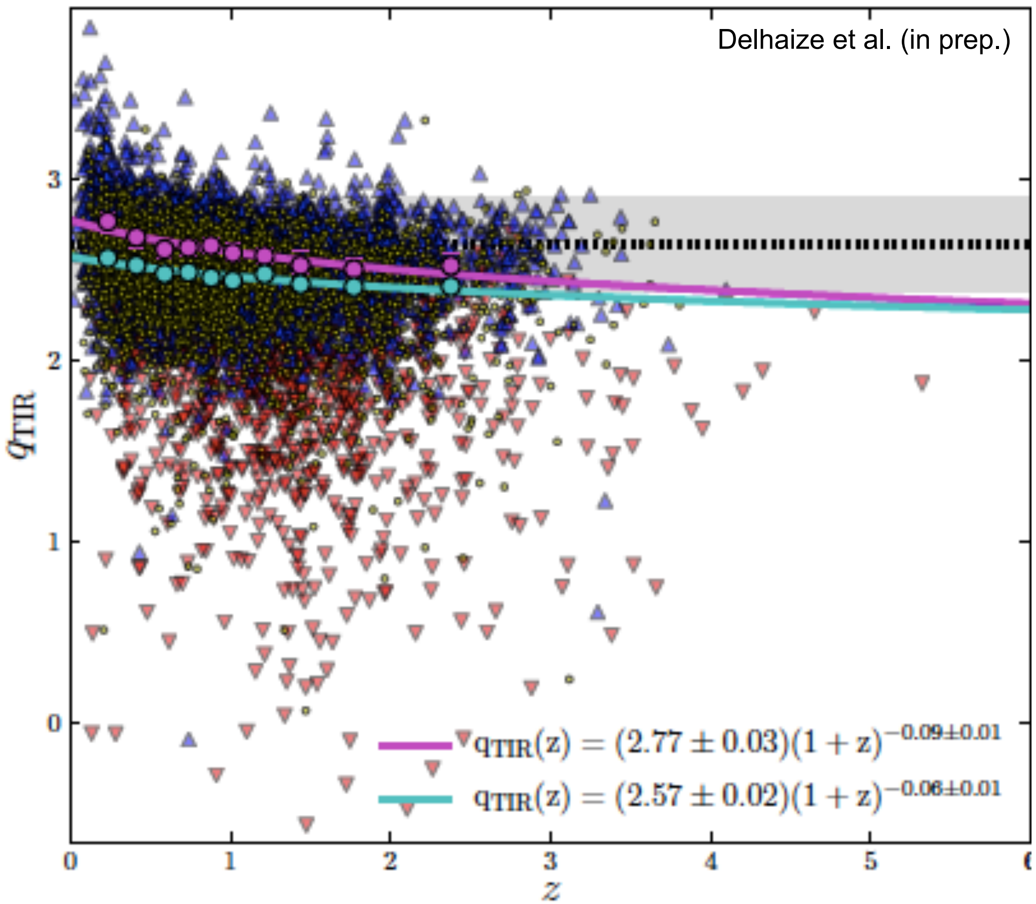
Cosmic evolution of the IR-radio correlation

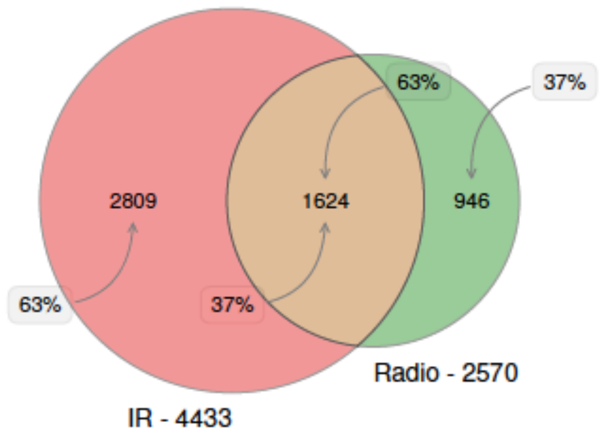


→ Do observations support this?

Radio as a dust-unbiased star formation tracer

- VLA-COSMOS 3GHz Large Project + Spitzer + Herschel
- Only star forming galaxies
- $q = \log L_{IR} - \log L_{1.4GHz} + \text{constant}$



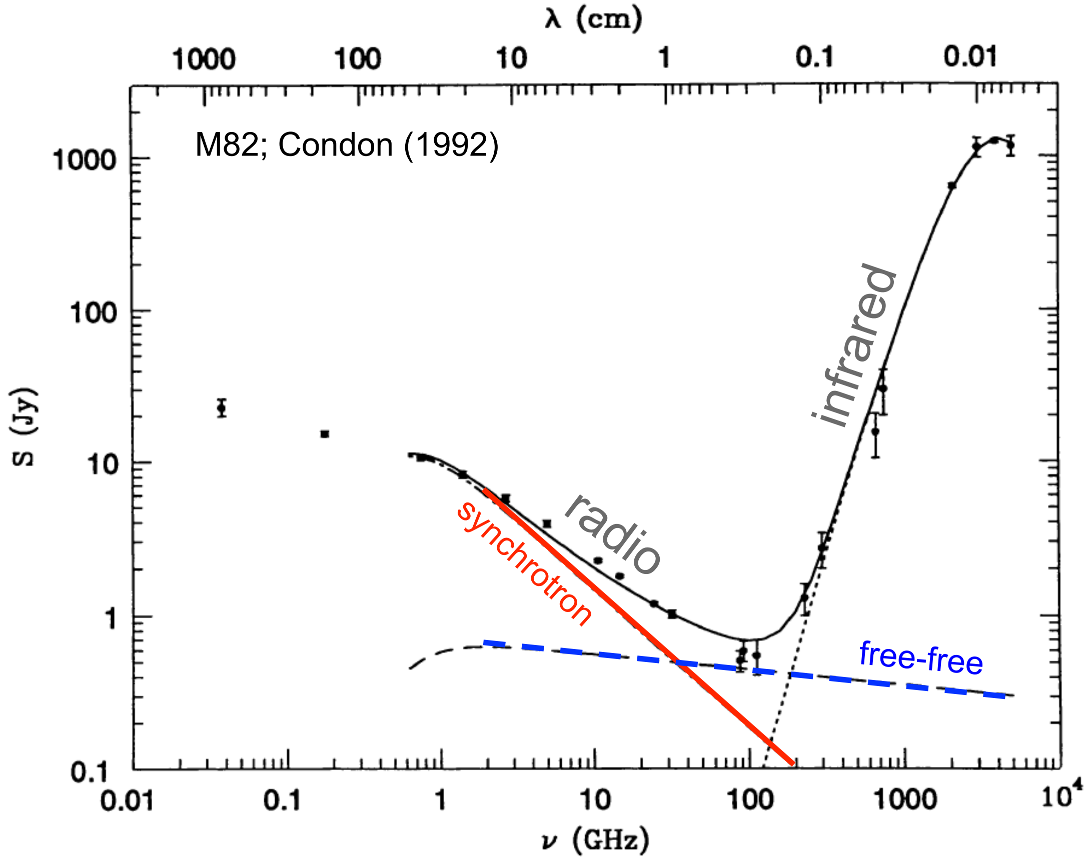


Observational results:

- q_{IR} decreases with increasing redshift
- Contrary to analytic predictions of cosmic evolution of q_{IR}

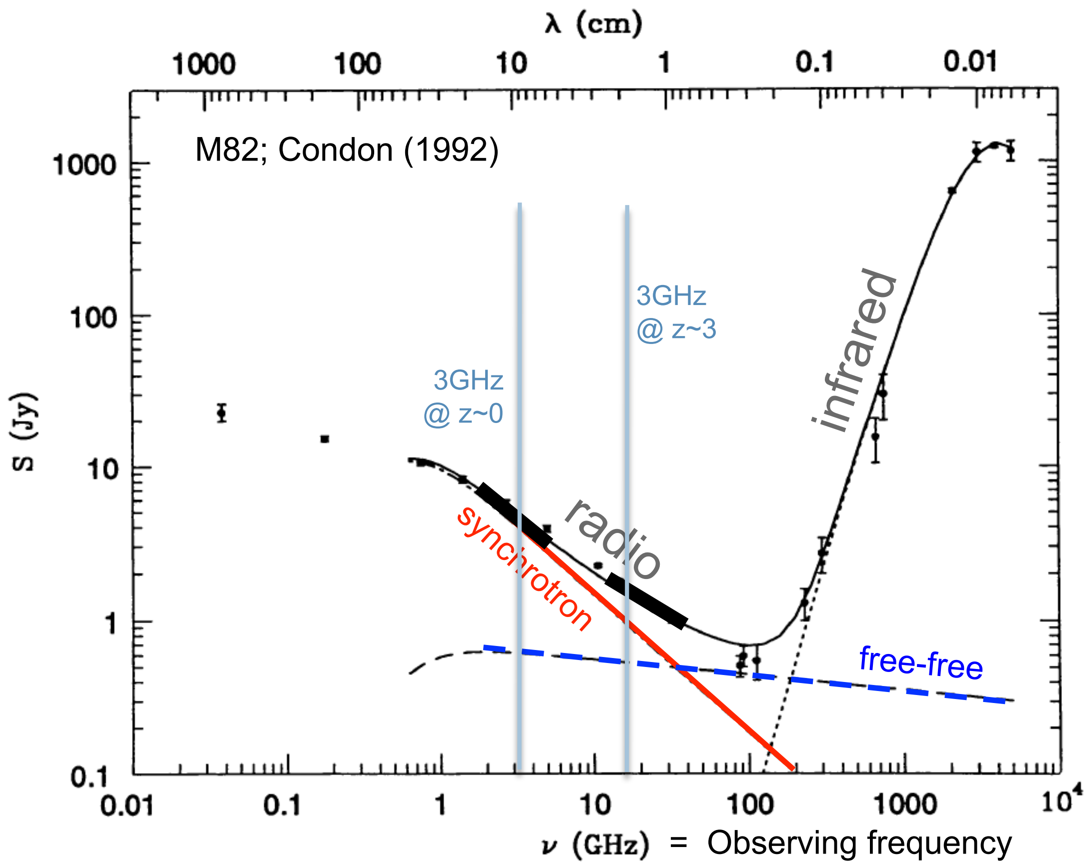
Delhaize et al. (in prep.); consistent with Sargent et al. (2010), Magnelli et al. (2012)

Testing the star forming galaxy SED across cosmic time



Testing the star forming galaxy SED across cosmic time

- M82-type SED correct across z → total spectral slope flattens with z



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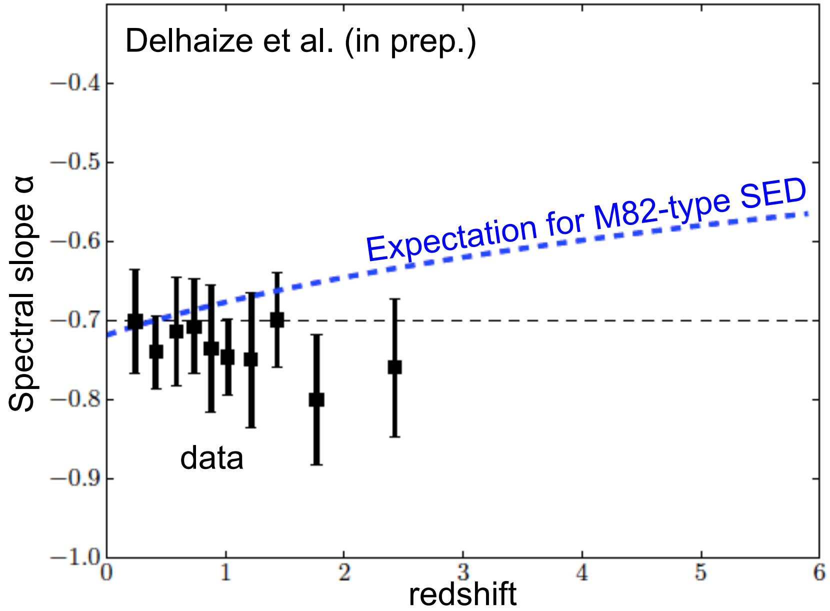

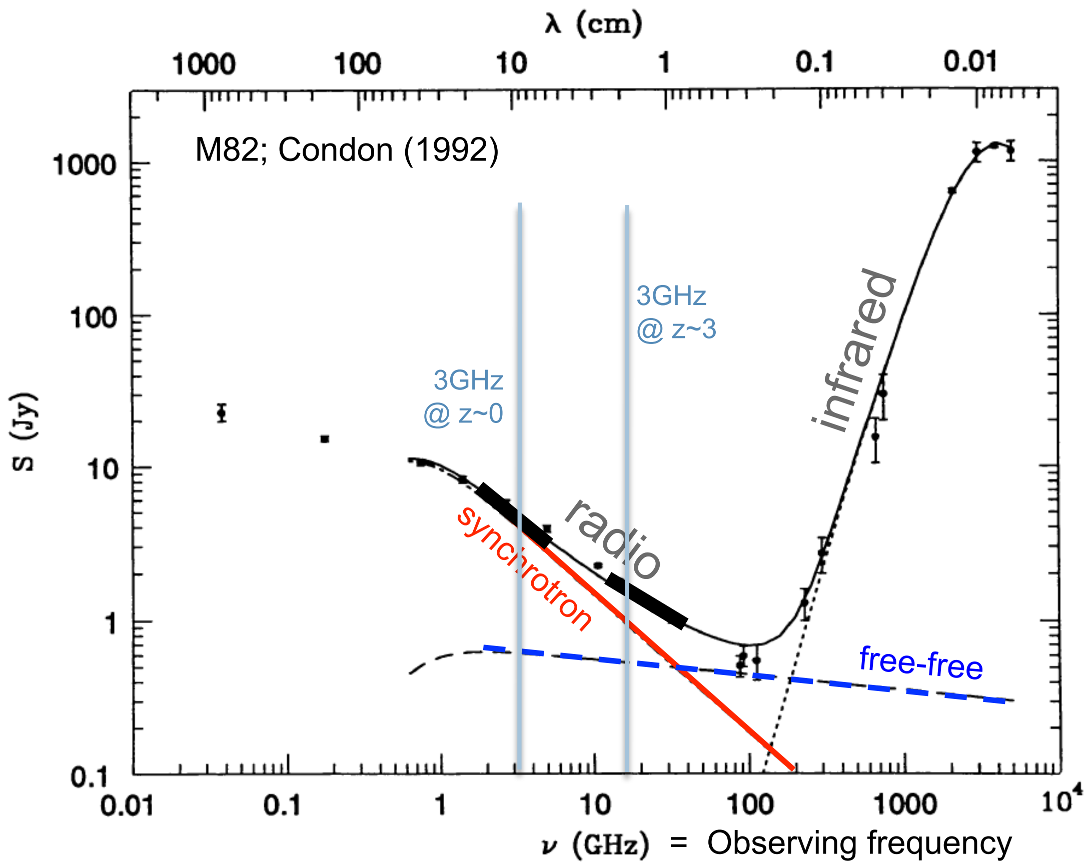

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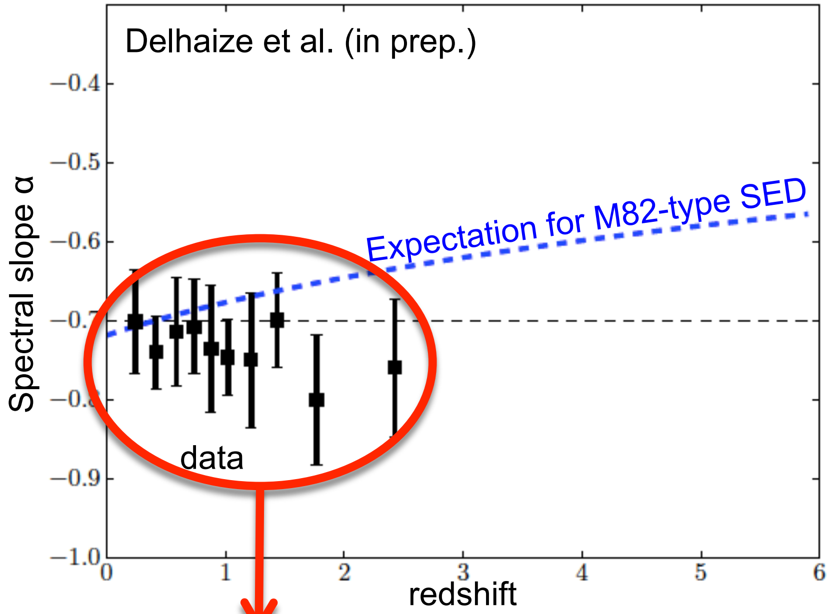
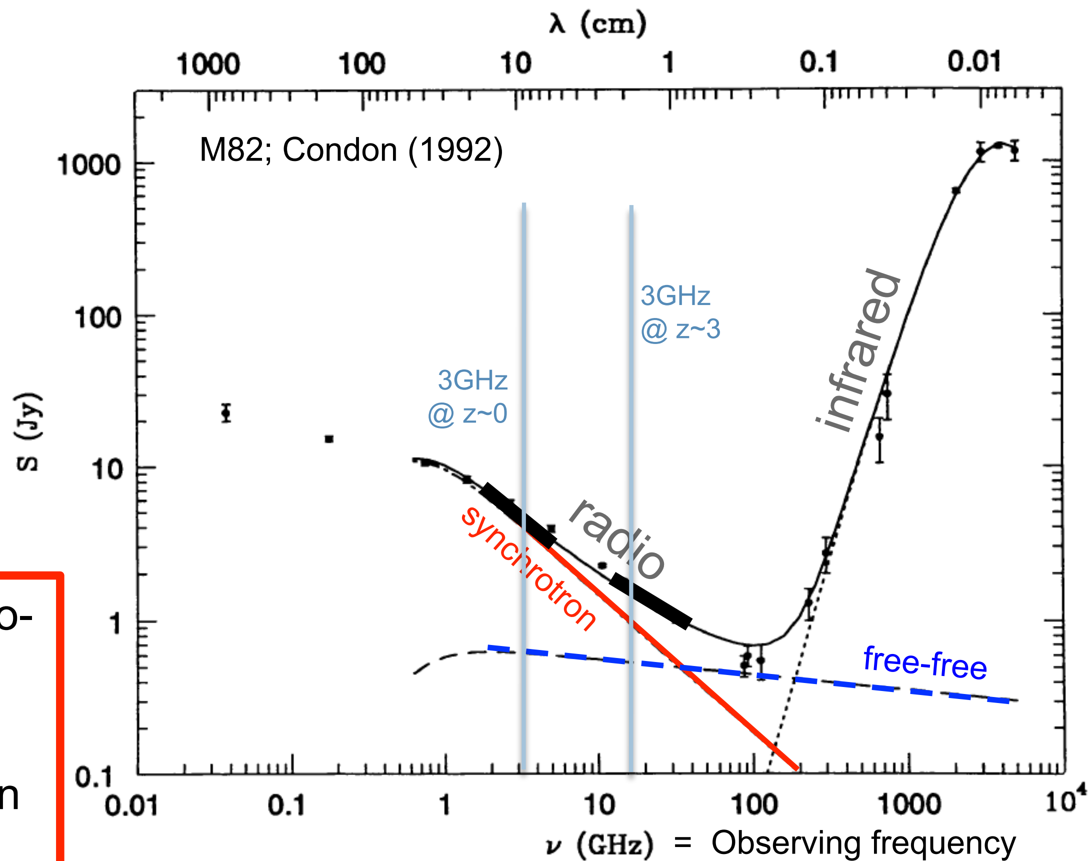
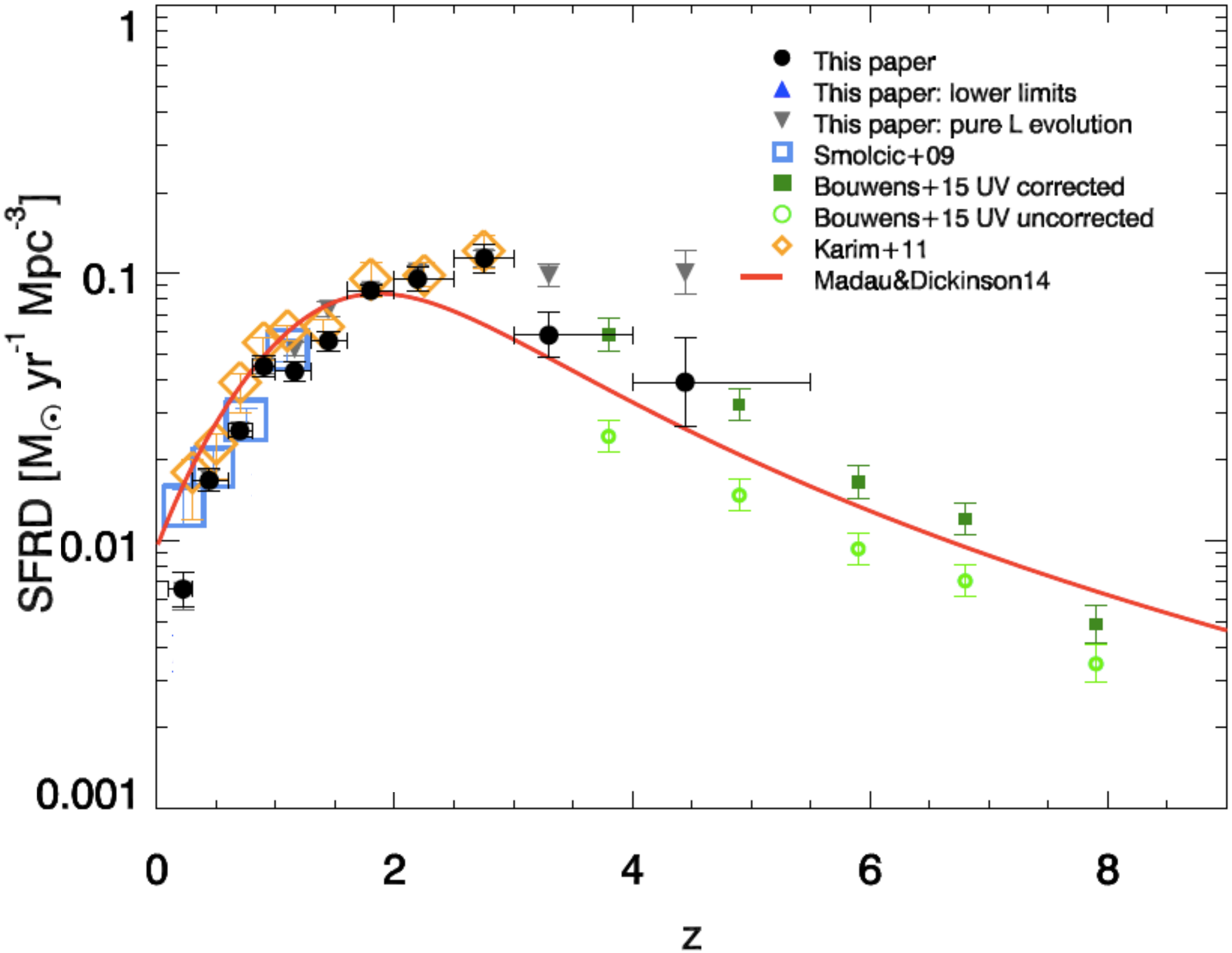


- Data *not* consistent with M82-type radio-SED shape across cosmic times
- Better understanding of star forming galaxy radio spectral energy distribution needed



Impact of dust onto cosmic star formation history?

- Radio-based cosmic star formation history
  - VLA-COSMOS 3GHz Large Project star forming galaxies
- In agreement with dust-corrected LBG results (Bowens et al. 2015) at z>3



Novak et al. (in prep)

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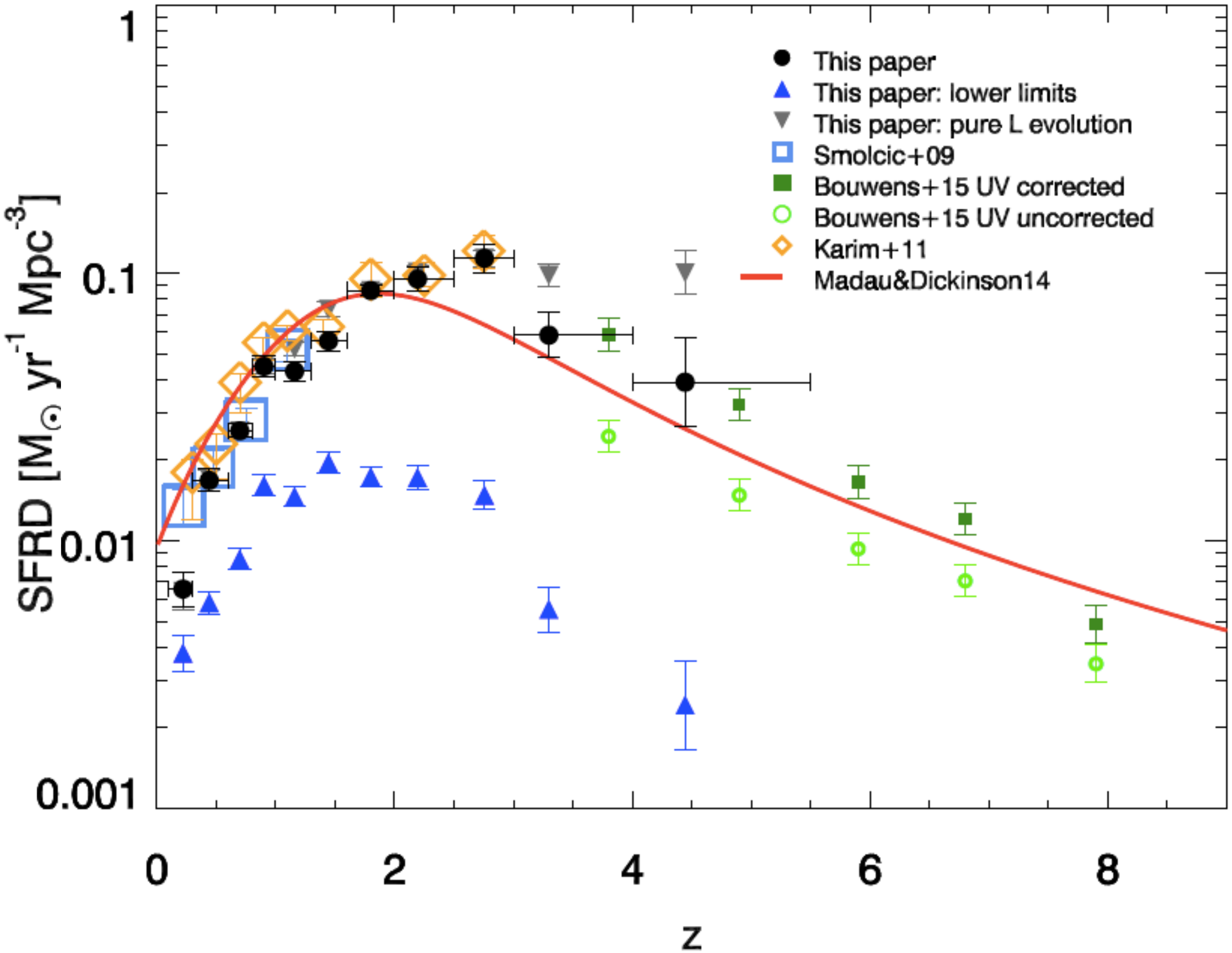

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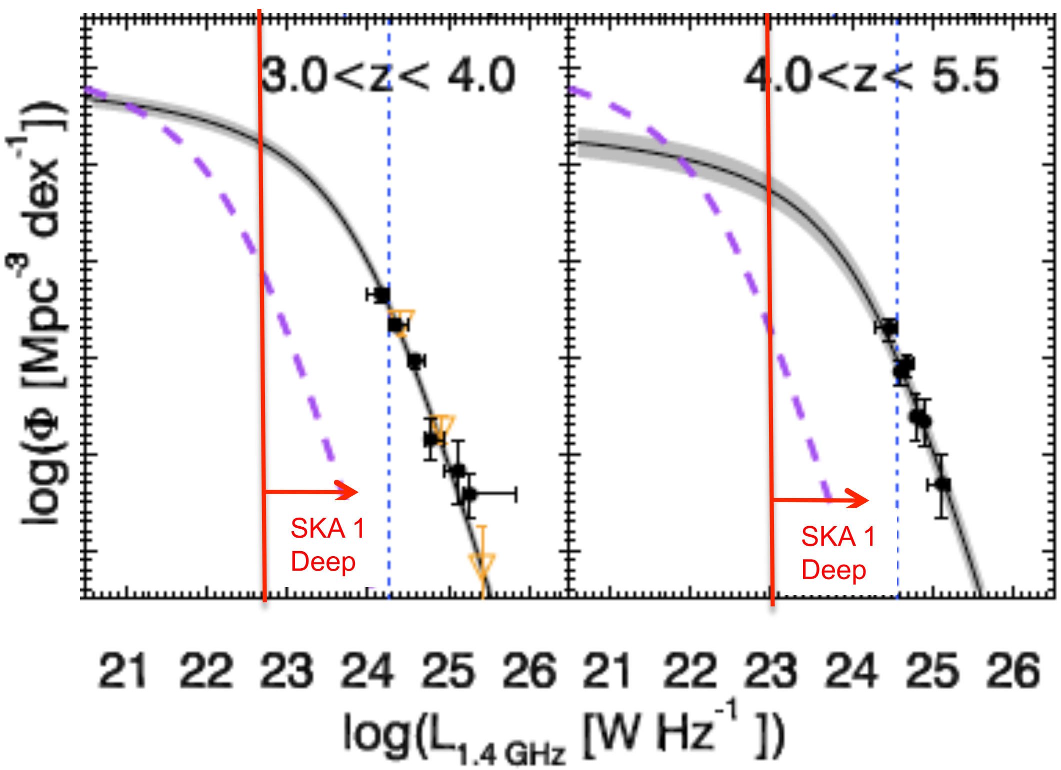
Star forming galaxy radio luminosity function



Novak et al. (in prep)

Current understanding & open questions → SKA

MicroJansky radio sources: What will the SKA see?

- Below ~200 μJy star forming galaxies start dominating the radio source counts

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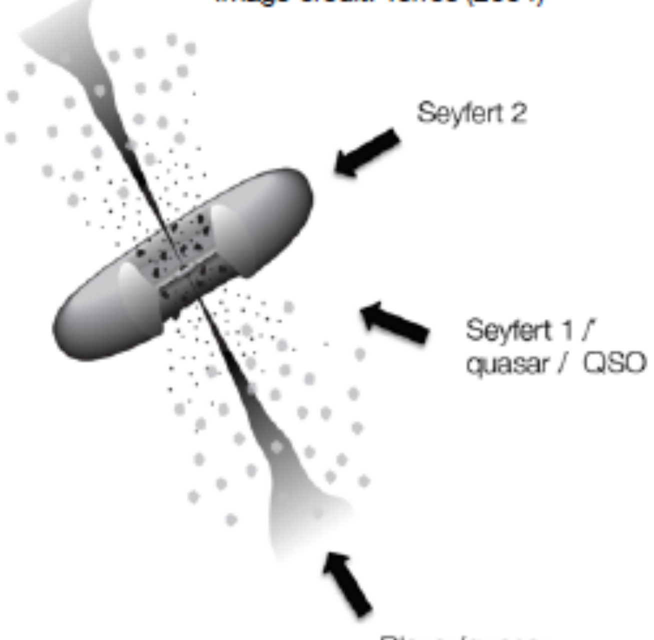
Impact of AGN onto galaxy evolution?

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

High-excitation = cold mode = radiatively efficient

- Unified model for AGN

Image credit: Torres (2004)



Low-excitation = hot mode = radiatively inefficient

- $L_{1.4GHz} < 10^{26}$ W/Hz

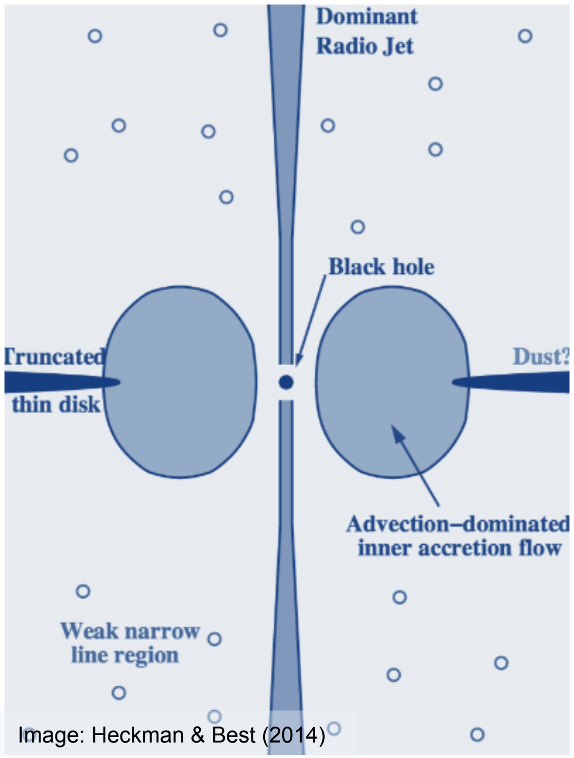


Image: Heckman & Best (2014)

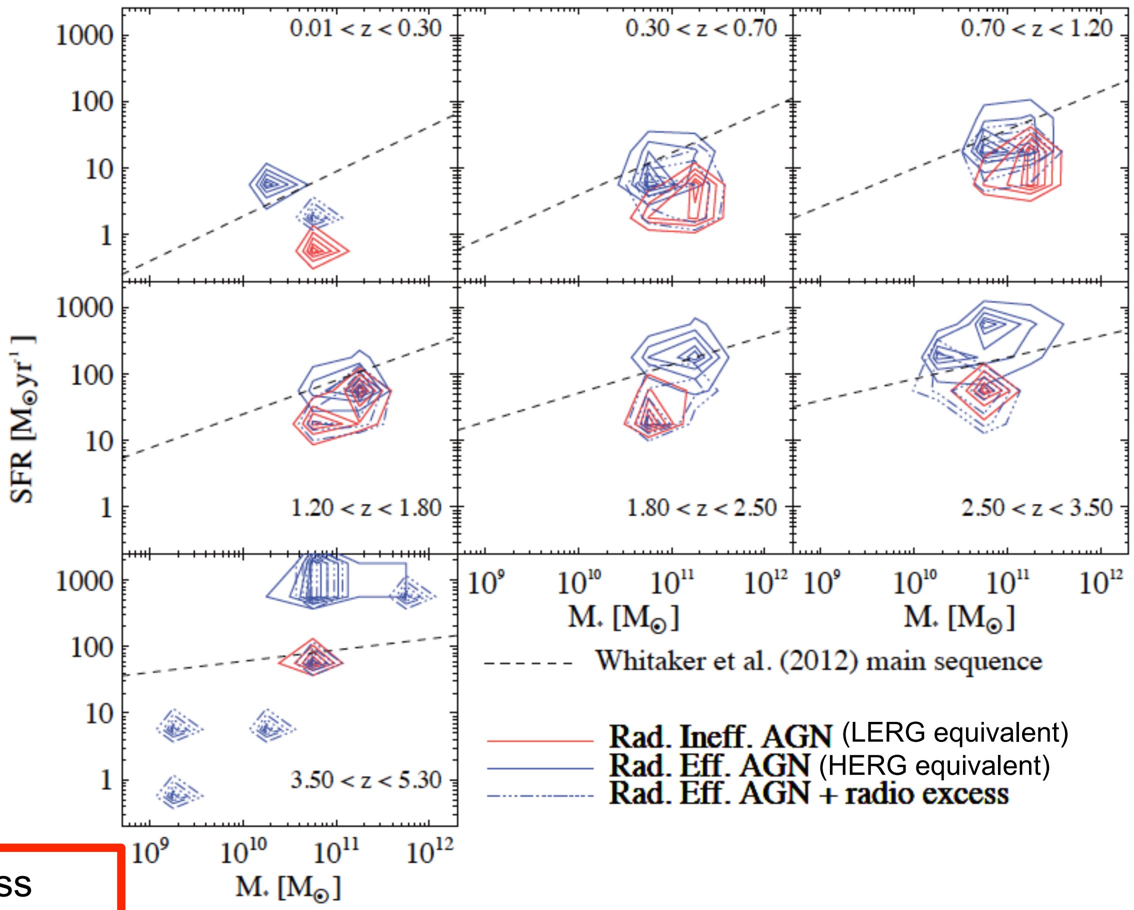
HERG/LERG dichotomy across cosmic time?

HERG/LERG dichotomy across cosmic time?

VLA-COSMOS 3 GHz Large Project

AGN selection

- Baran et al. (in prep.), Delvecchio et al. (in prep.)
- LERAGN selection:
  - Radio-loud AGN: Radio excess relative to that expected from SFRs in hosts
- HERAGN selection:
  - X-ray: $L_{2\text{-}10keV}$>10^{42} erg/s
  - MIR (Donley et al. 2013)
  - SED fitting (Magphys+AGN)



- First sample to test dichotomy across cosmic time
- Higher LERG (than HERG) stellar masses at z<1, while opposite at high-z

Delvecchio et al. (in prep.)

Source of radio emission in HE- & LERAGN ?

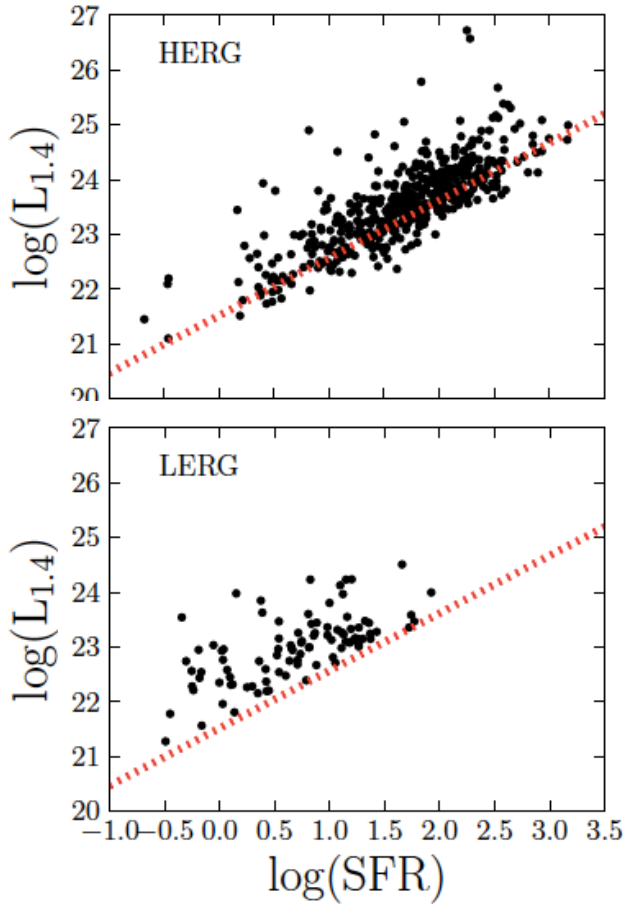
Source of radio emission in HE- & LERAGN ?

- Higher SFR/sSFR in HERAGN vs. LERAGN (Moric et al. 2010; Gurkan et al. 2015; Hardacastle et al. 2013; Bonzini et al. 2015; Delhaize et al., in prep, Delvechio et al., in prep)

- Source of radio emission in AGN:
  - HERGs: SF+AGN (how much? Function of ?)
  - LERGs: AGN
  - QSOs: SF? and/or AGN? (e.g., Kimball et al. 2011; Condon et al. 2013; White et al. 2015)

- Impact on galaxy evolution?

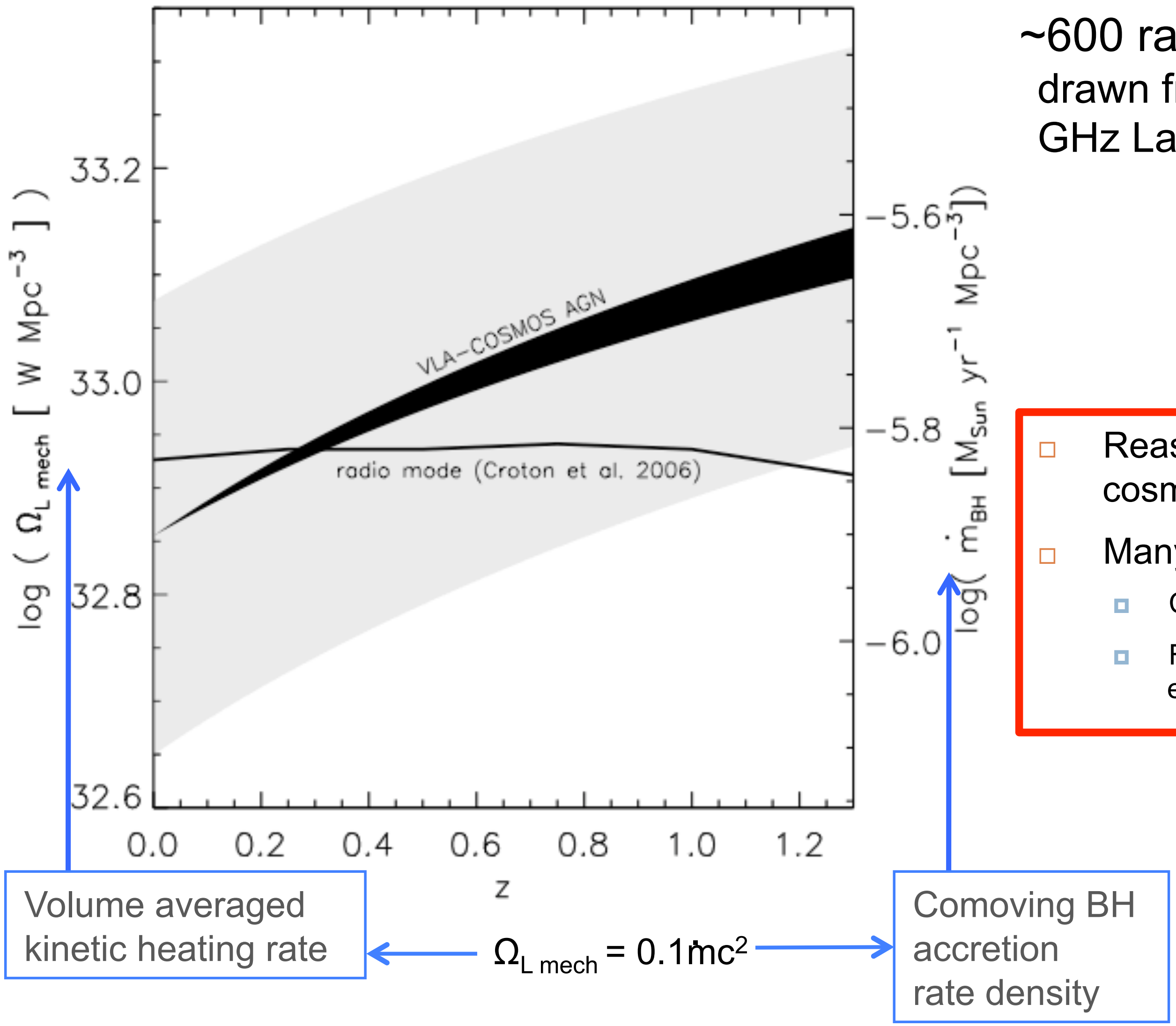
- SKA perspective:
  - high-resolution radio imaging of large samples of radio AGN → direct separation of SF + AGN (jet) components



VLA-COSMOS 3GHz Large Project: SF contribution to radio emission: HERAGN: ~65-80%; LERAGN: <~20% (Delhaize et al., in prep)

Testing radio-mode feedback

Testing radio-mode feedback



~600 radio AGN ($L_{1.4GHz} \leq 10^{25}$ W/Hz; z≤1.3) drawn from the VLA-COSMOS 1.4 GHz Large Project (Smolcic et al. 2008)

- Reasonable agreement between cosmological model and observations
- Many open questions remain:
  - Conversion between $L_{1.4GHz}$ & L_{kin}
  - Fraction of L_{kin} deposited & dissipated into environment

Smolcic et al. (2009)

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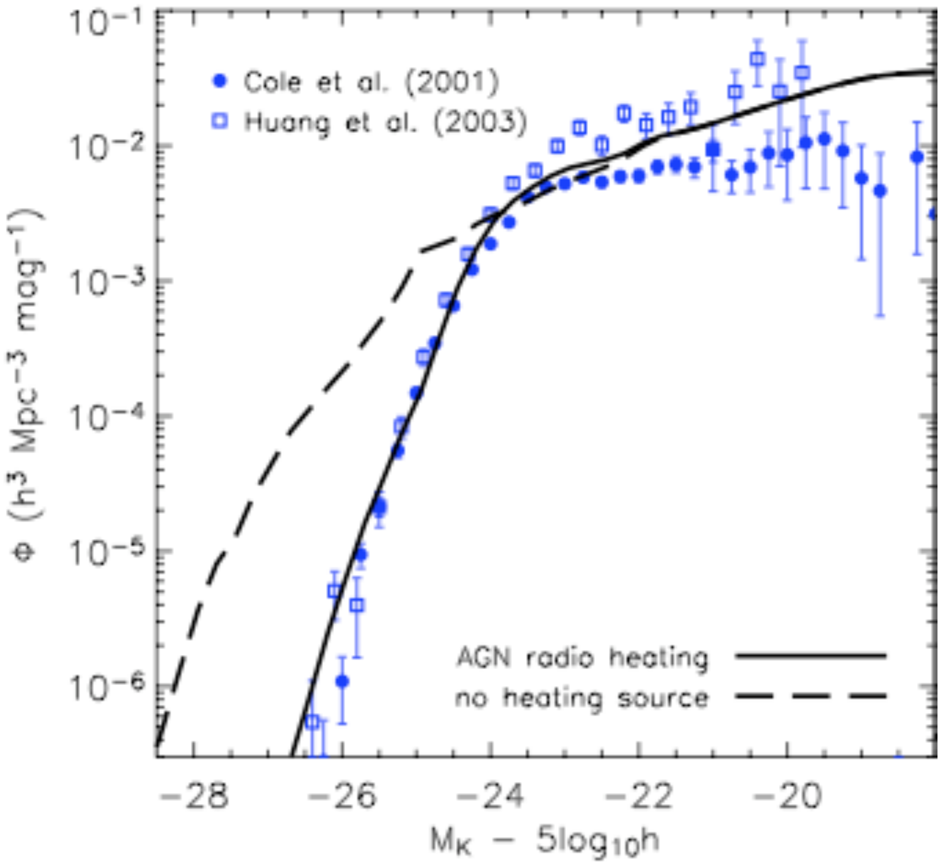
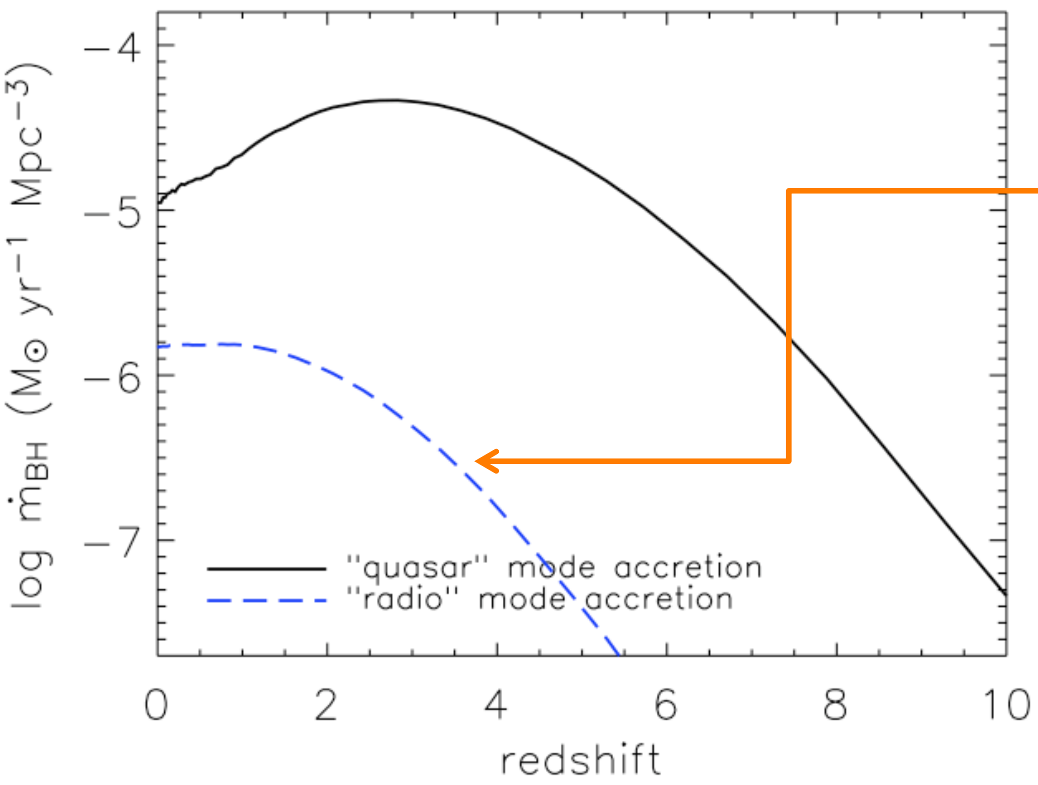
Radio-mode feedback in cosmological models

Croton et al. 2006



Radio-mode feedback in cosmological models

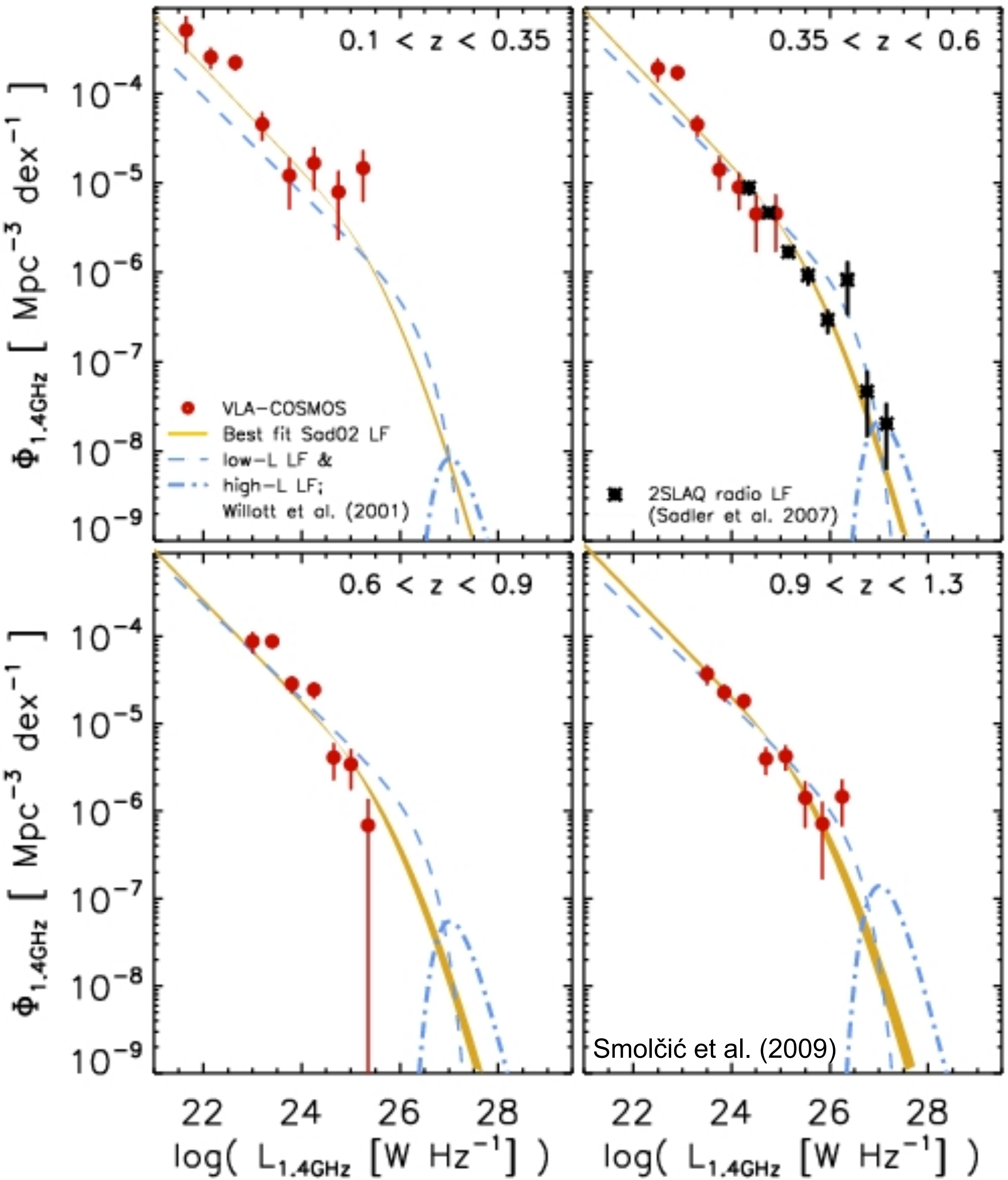
Croton et al. 2006: Volume averaged mechanical heating rate over the full simulation as a function of redshift



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

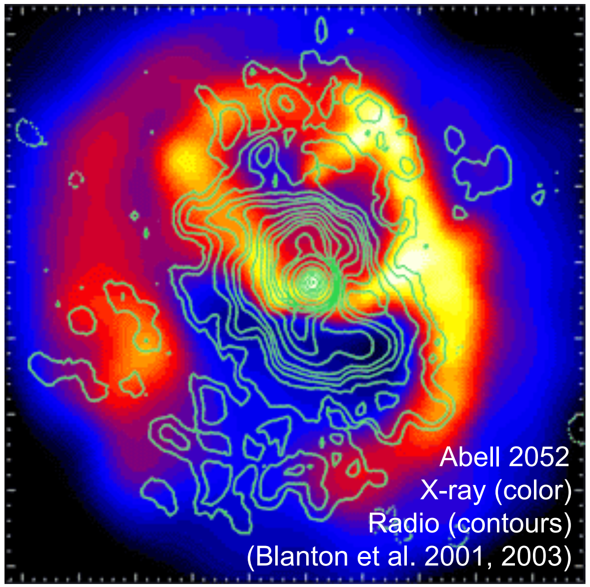
Testing radio-mode feedback

- Radio AGN luminosity functions
- Rest-frame color selection of red galaxies, ~600 radio AGN (Smolcic et al. 2009)
- Good agreement with local LF (Sadler et al. 2002) & LF @ z~0.5 (Sadler et al. 2007)
- High-power radio AGN LF (Willott et al. 2001; 3CRR, 6CE, 7CRS), different evolution than low-power radio AGN



20cm luminosity ➡ kinetic jet luminosity

- Scaling relation based on radio galaxies in galaxy clusters (Bîrzan et al. 2004, 2008): radio emission inflates buoyantly rising bubbles in X-ray plasma (i.e. cavities)
- 0.85 dex scatter when 20cm radio luminosity used



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