GLOWSKA 2016 - KIT - June 3rd 2016

A radio view on cosmic evolution: The 3GHz JVLA-COSMOS survey

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Cosmic Evolution Survey
cosmos

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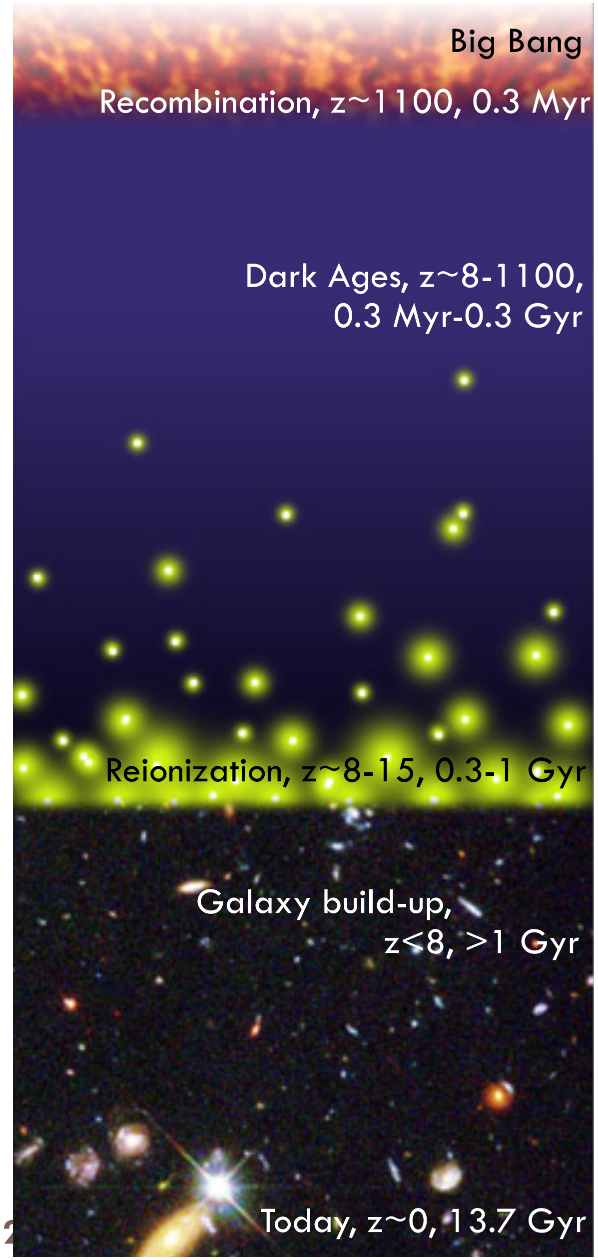
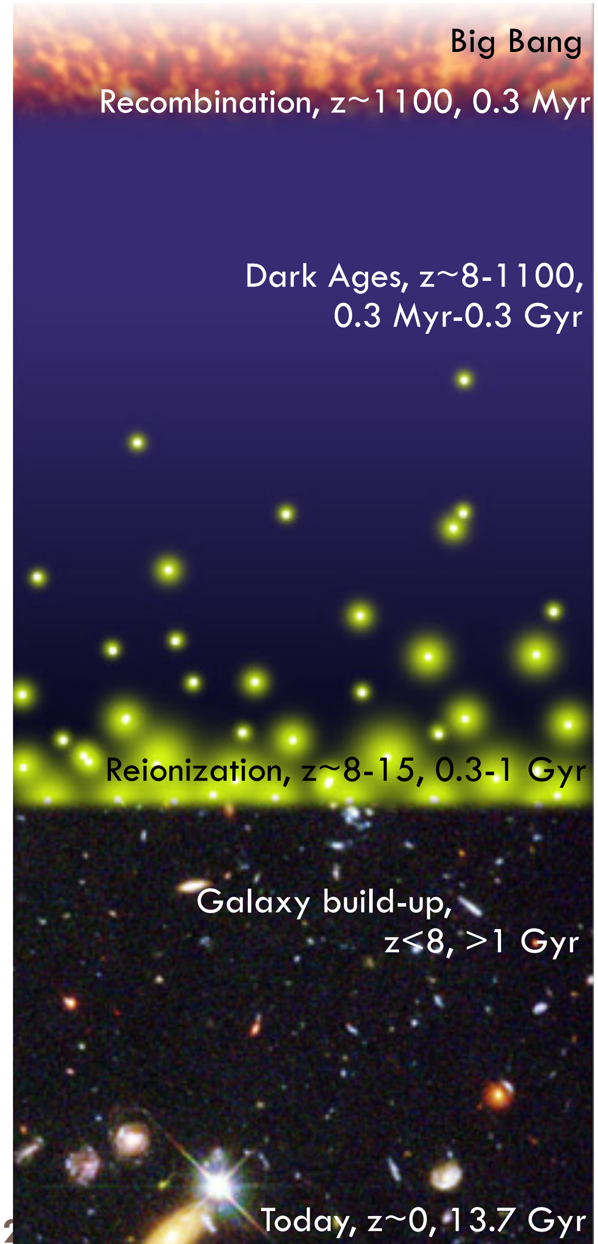
Cosmic history

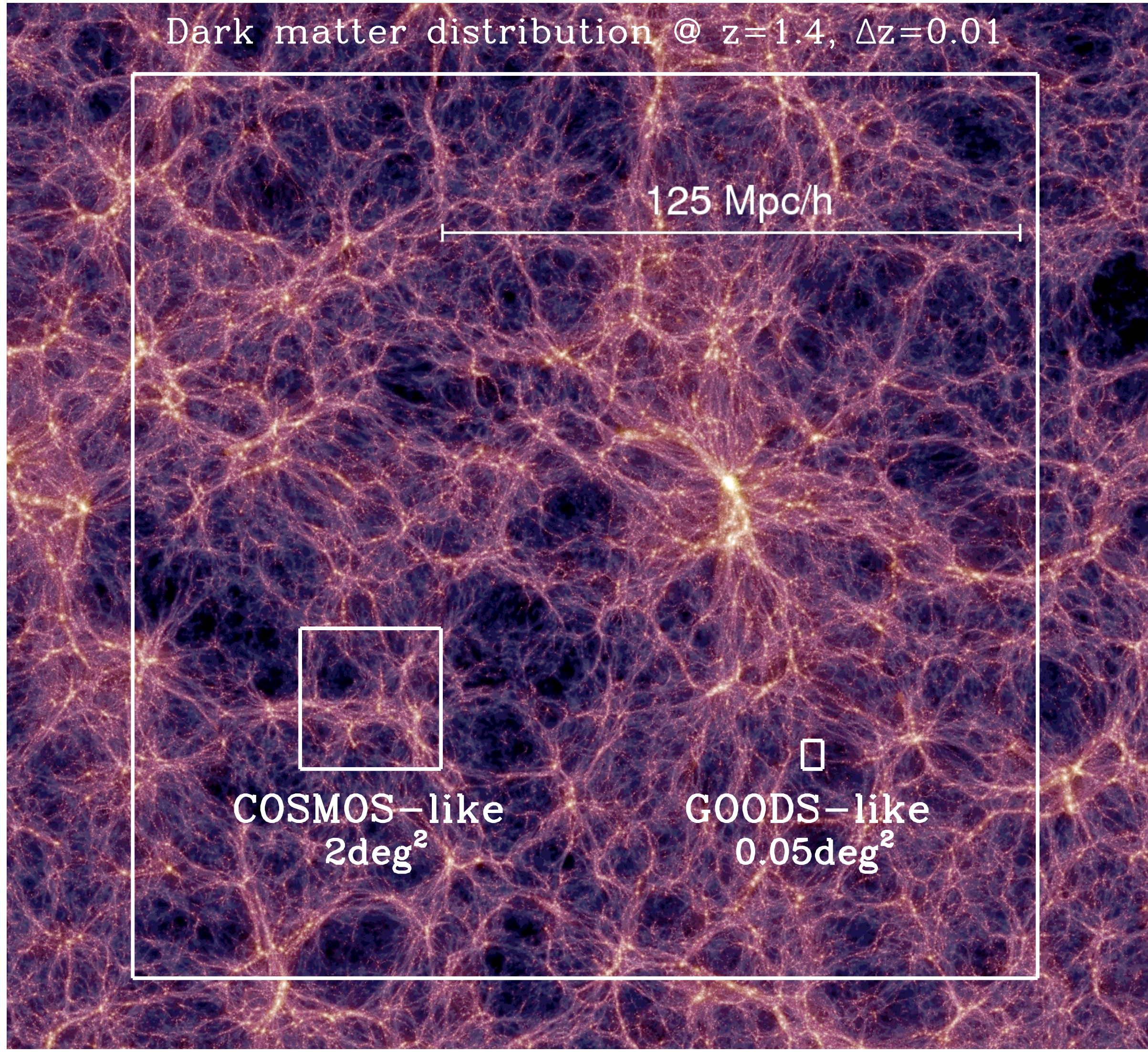


Understanding galaxy formation and evolution

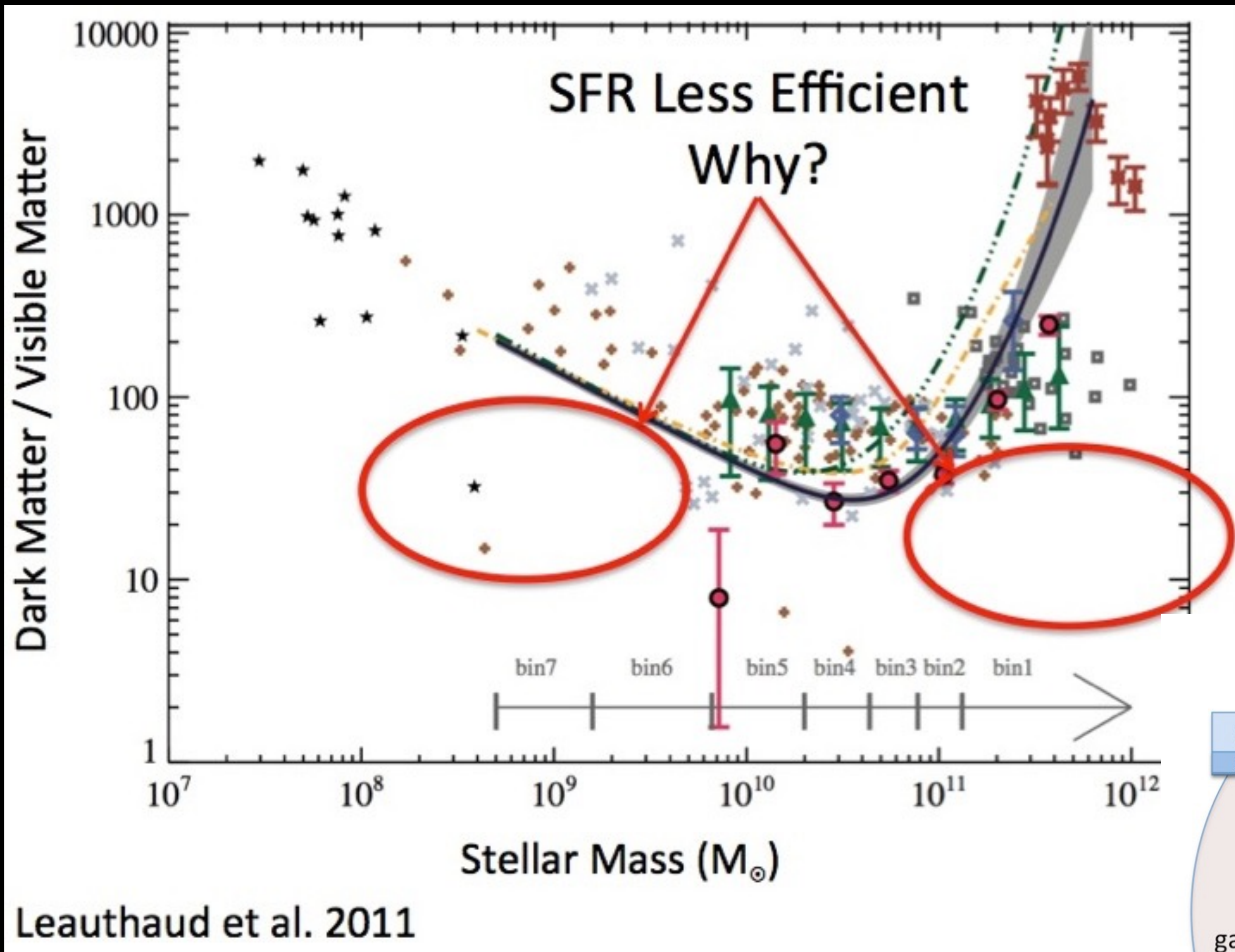
→ build-up of *stellar* and *central SMBH masses* over cosmic time and within their respective (cosmic) environments

Cosmic history

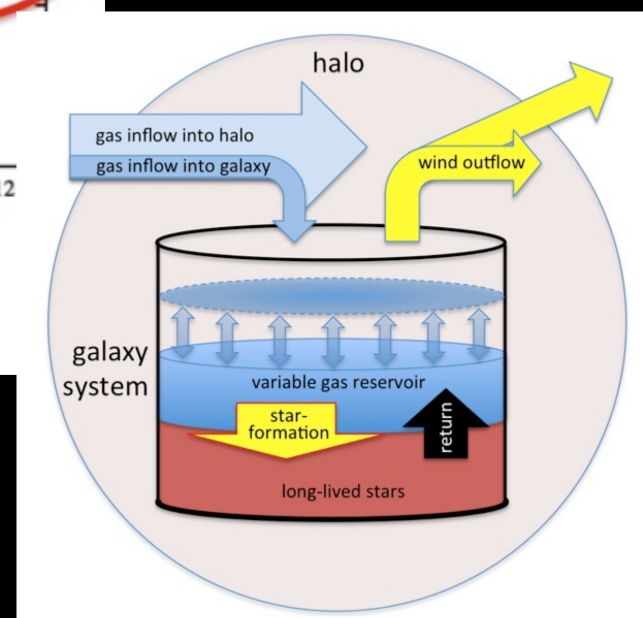




Understanding Galaxy Assembly



Lilly et al. (2013)

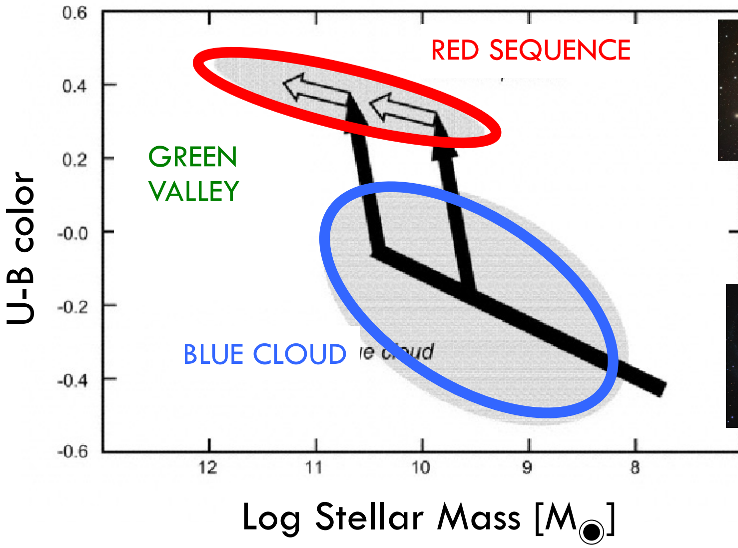


Goal: Observe the stellar matter as it is growing up and constrain what stops matter assembly in galaxies

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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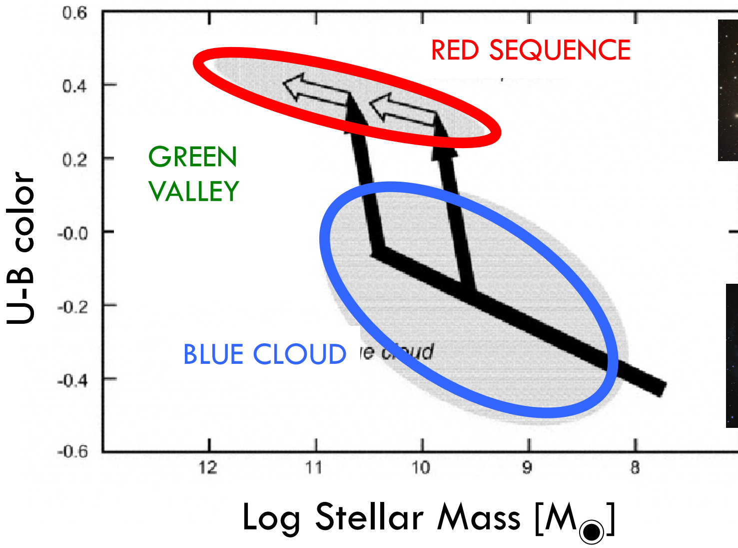

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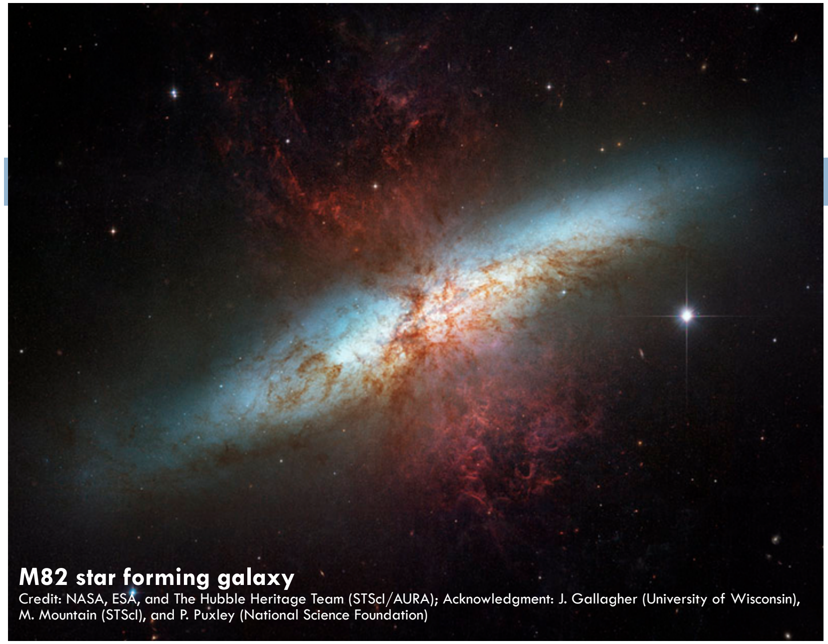
1) Impact of dust onto cosmic star formation history?
2) Impact of AGN onto galaxy evolution?

The power of radio



1. Dust-unbiased SF tracer at *high* angular resolution
2. Unique AGN, violating “Unified model for AGN”
3. “Quantum leap” in instrumentation: Jansky VLA, ATCA, ALMA → SKA and precursors

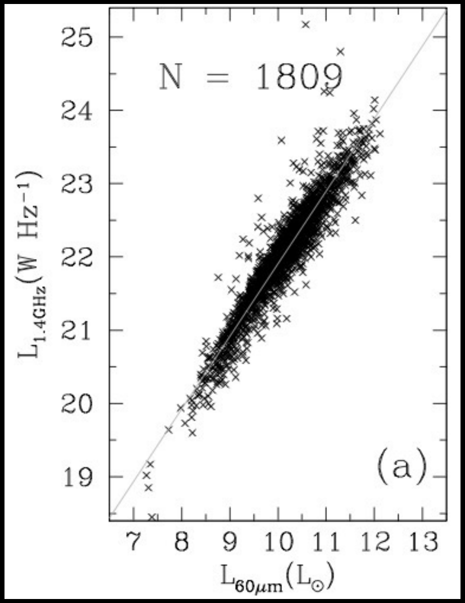
Why radio emission?

(I) **Tracing star formation:**

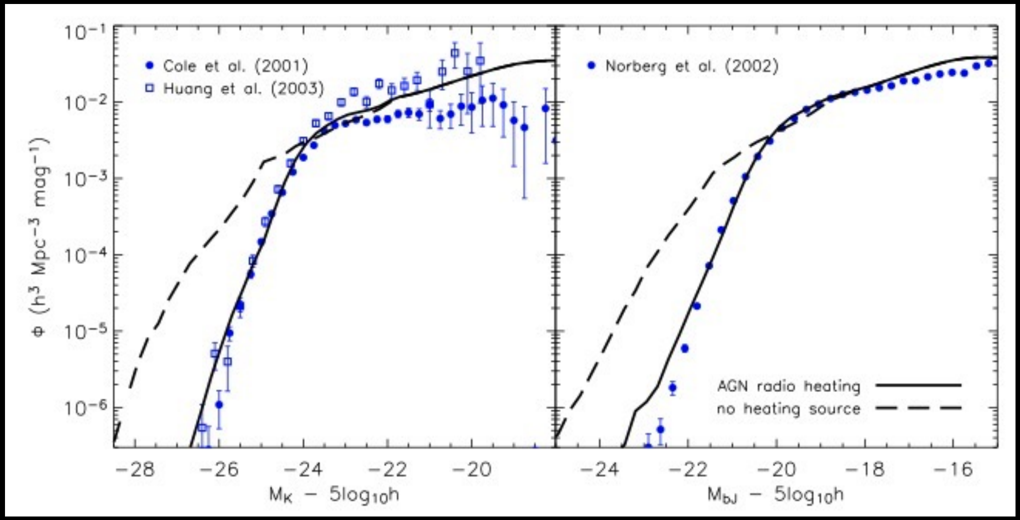
Empirically established correlation of galaxy-integrated radio and infrared emission bears the potential to monochromatically determine recent star formation

(II)**Quenching star formation:**

` Radio mode feedback' deemed essential to explain observed under-abundance of massive galaxies (radio outflows during phase of quiescent black hole accretion supposed to balance radiative hot gas cooling around massive elliptical galaxies)

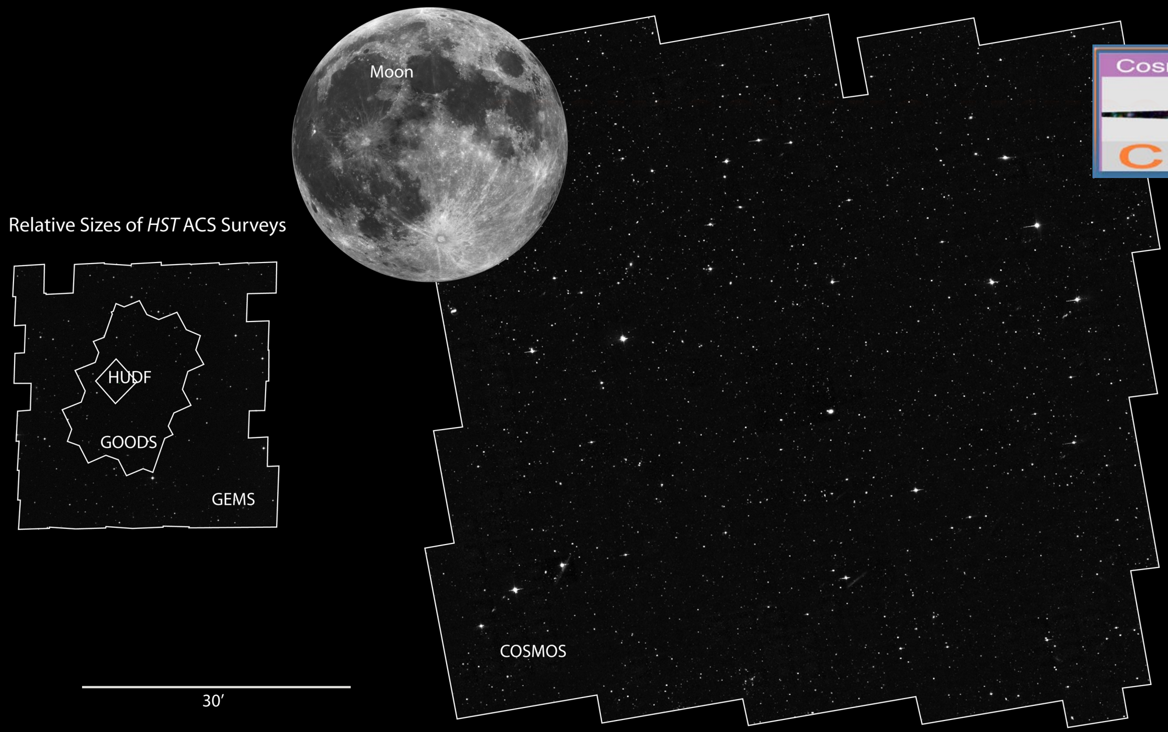


Yun et al. (2001)



Croton et al. (2005)

COSMOS: The richest pathfinder survey



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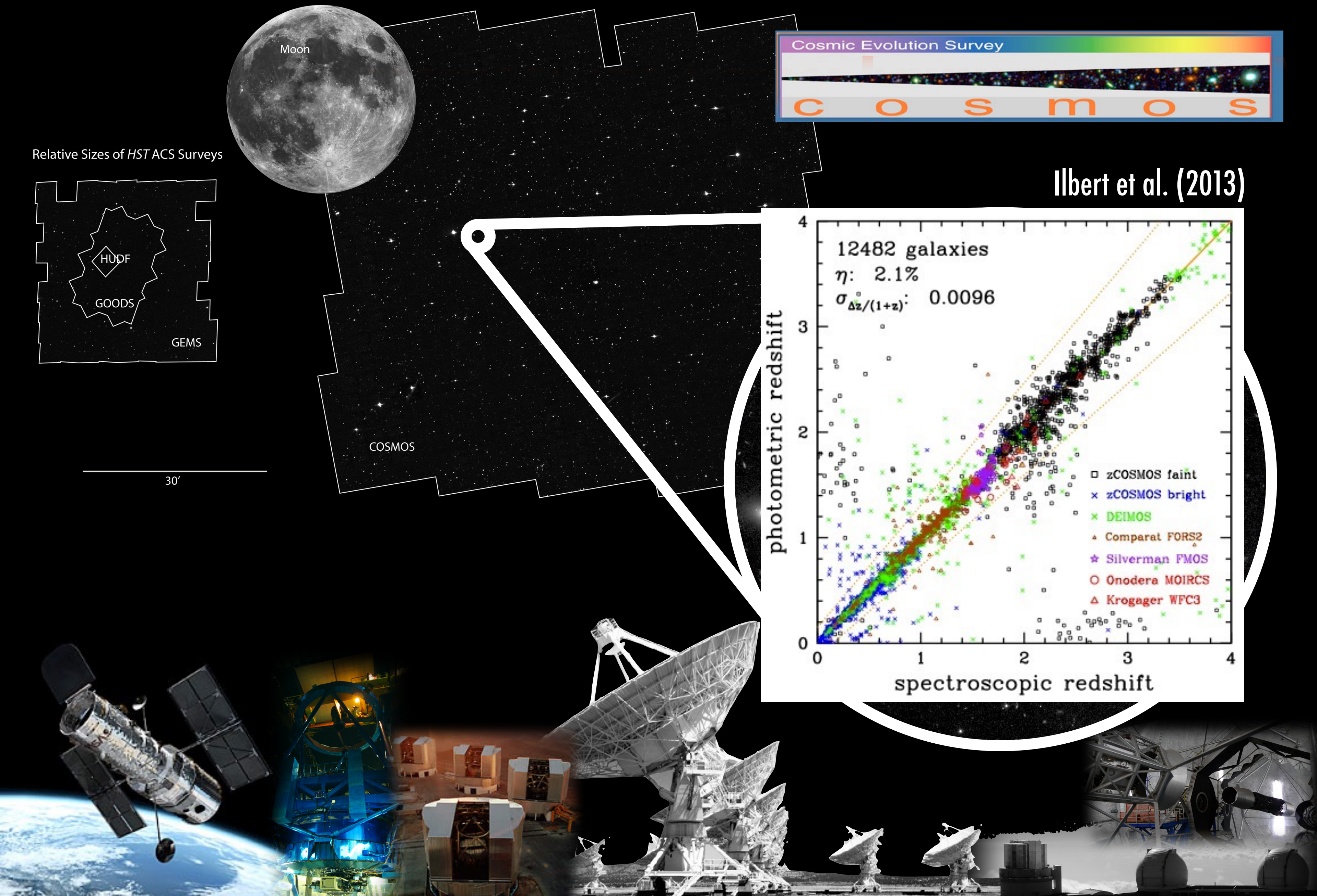
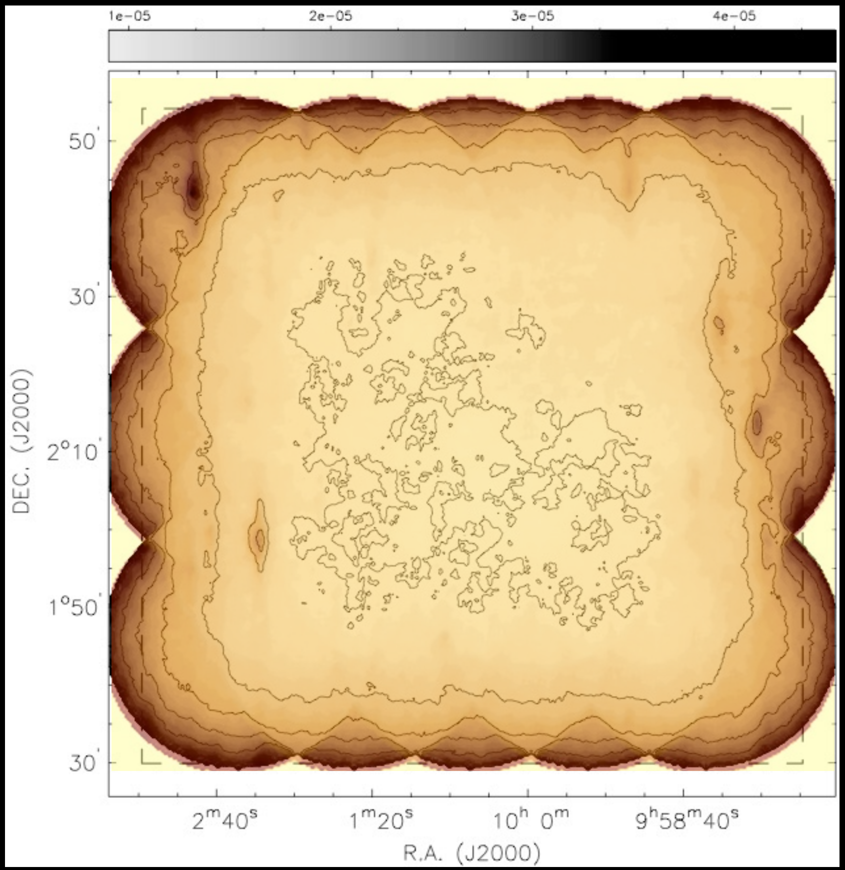


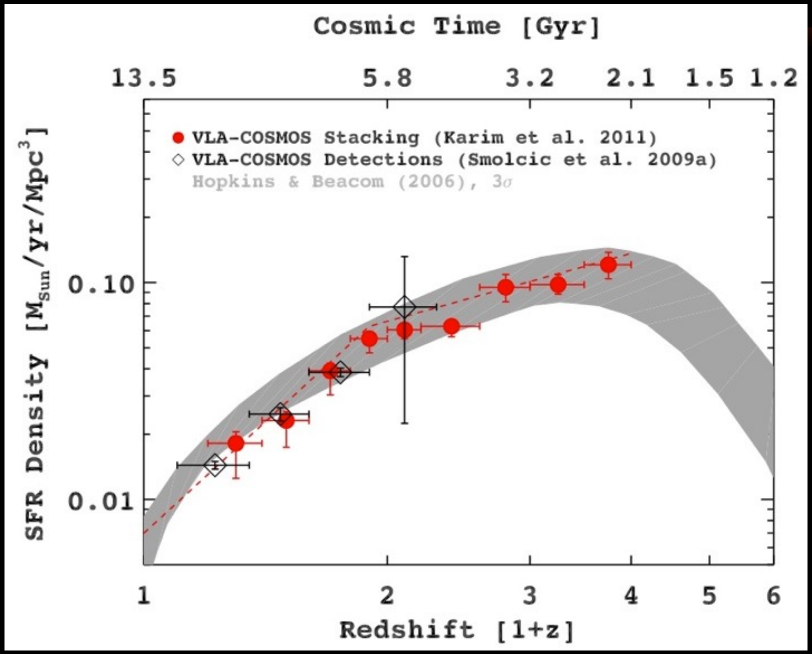
The VLA-COSMOS Project

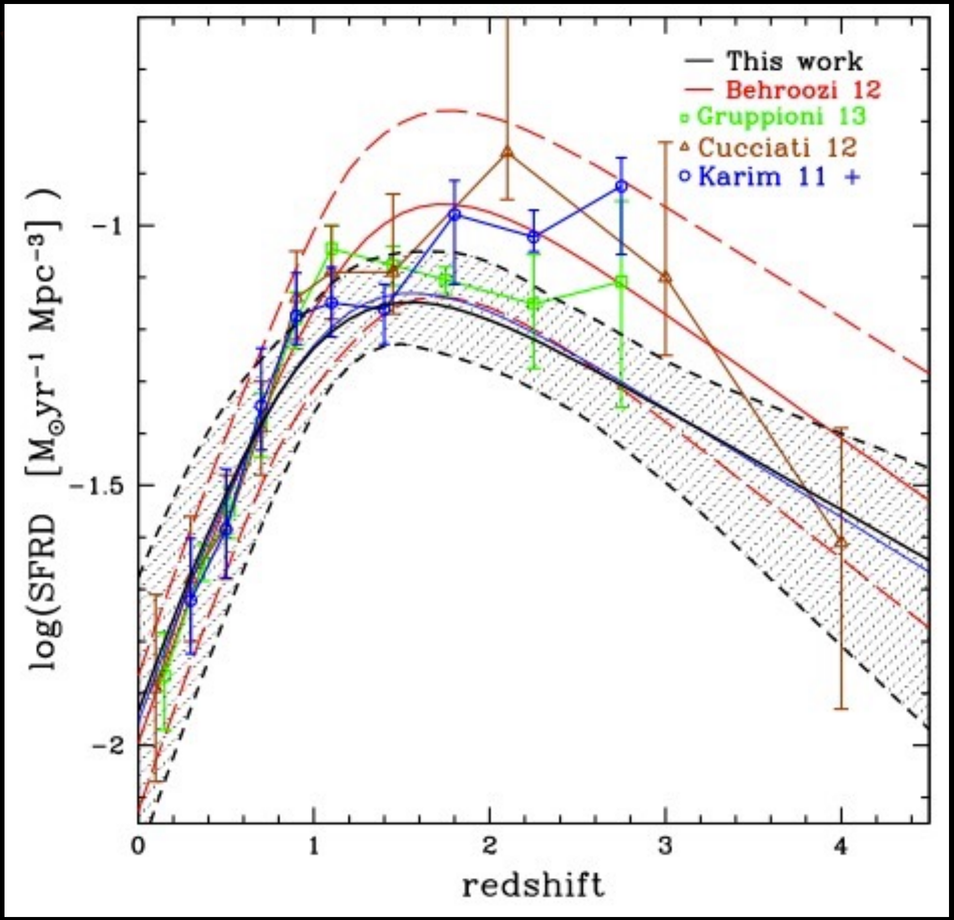
- 1.4GHz VLA imaging of COSMOS (2 deg^2, A+A+C config.)
- Resolution: 1.4" x 1.5"
- Sensitivity: ~12 (8) uJy
- 2,865 radio sources

Schinnerer et al. 2007 & 2010



The cosmic star formation history

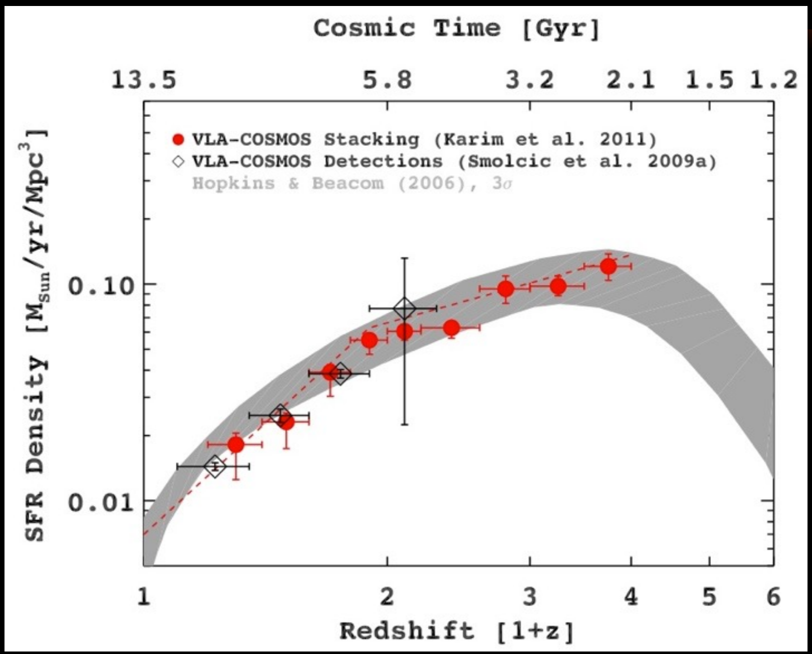


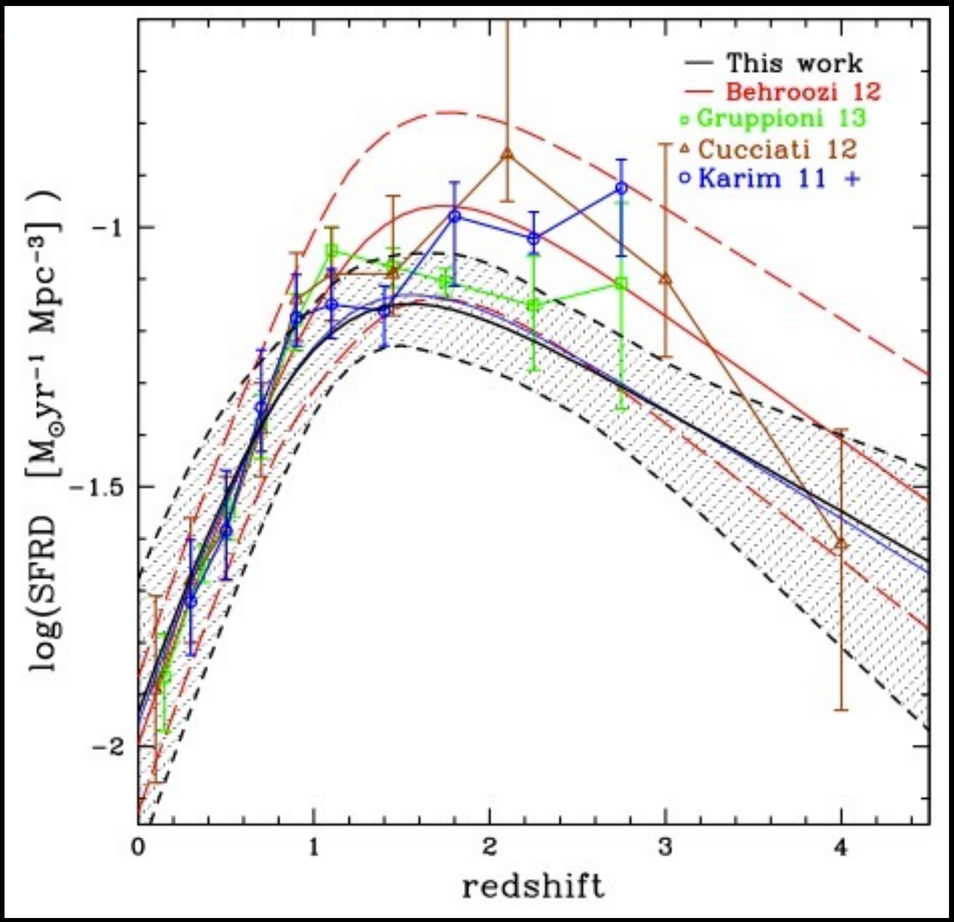


- Radio continuum as consistent probe of cosmic star formation over 11Gyr

Ilbert et al. (2013)

The cosmic star formation history

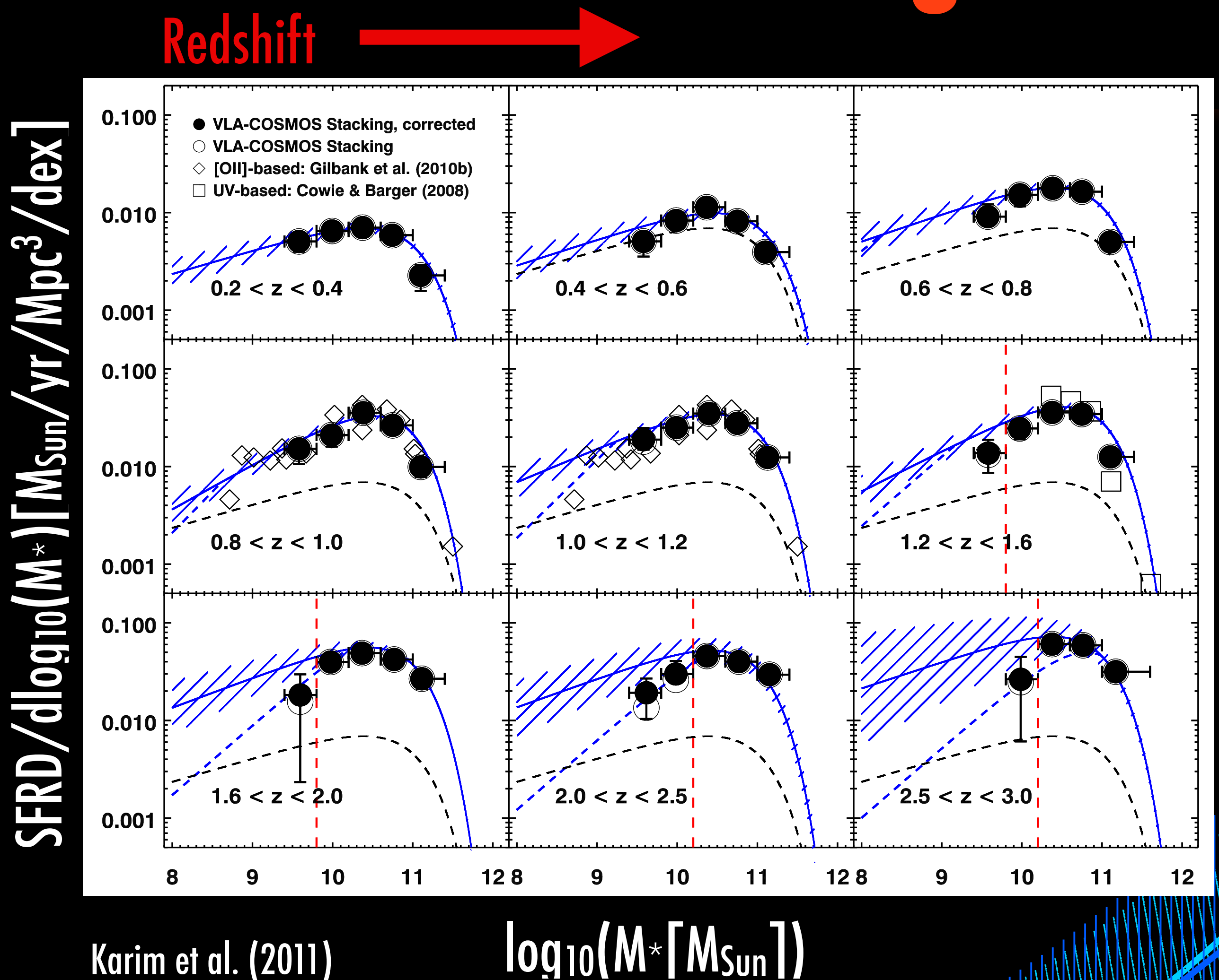




Ilbert et al. (2013)

- Radio continuum as consistent probe of cosmic star formation over 11Gyr
- Open questions: How diverse is the star forming galaxy population at intermediate redshift? how well are different SFRs calibrated against each other at higher z? How good are our radio K-corrections?

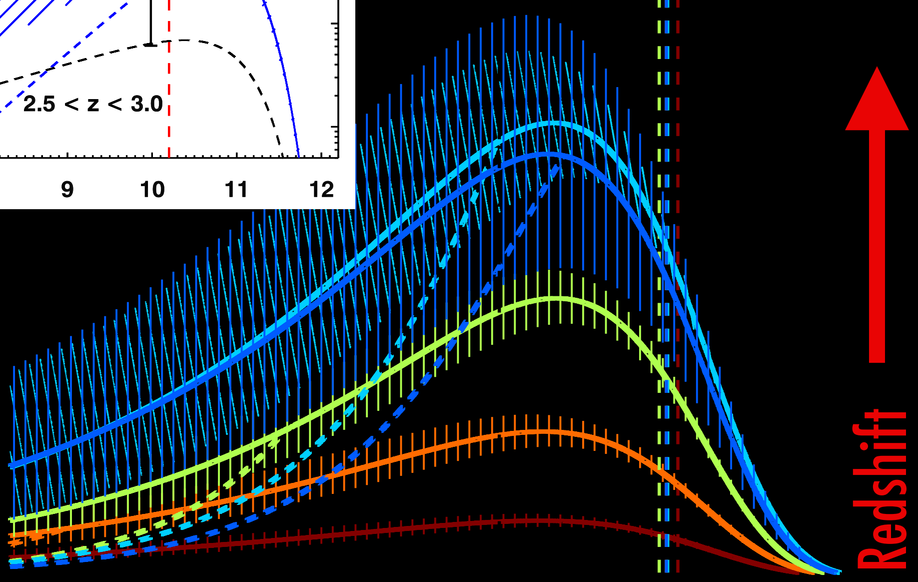
Pushing the radio horizon



Karim et al. (2011)

VLA-COSMOS

- Other science highlights include dissection of SF/AGN radio sources (Smolcic+08); evolutionary probe of radio-AG luminosity function (Smolcic +09, Smolcic, AK+in prep.); (non-)evolution of IR/radio relation (Sargent+10a,b)



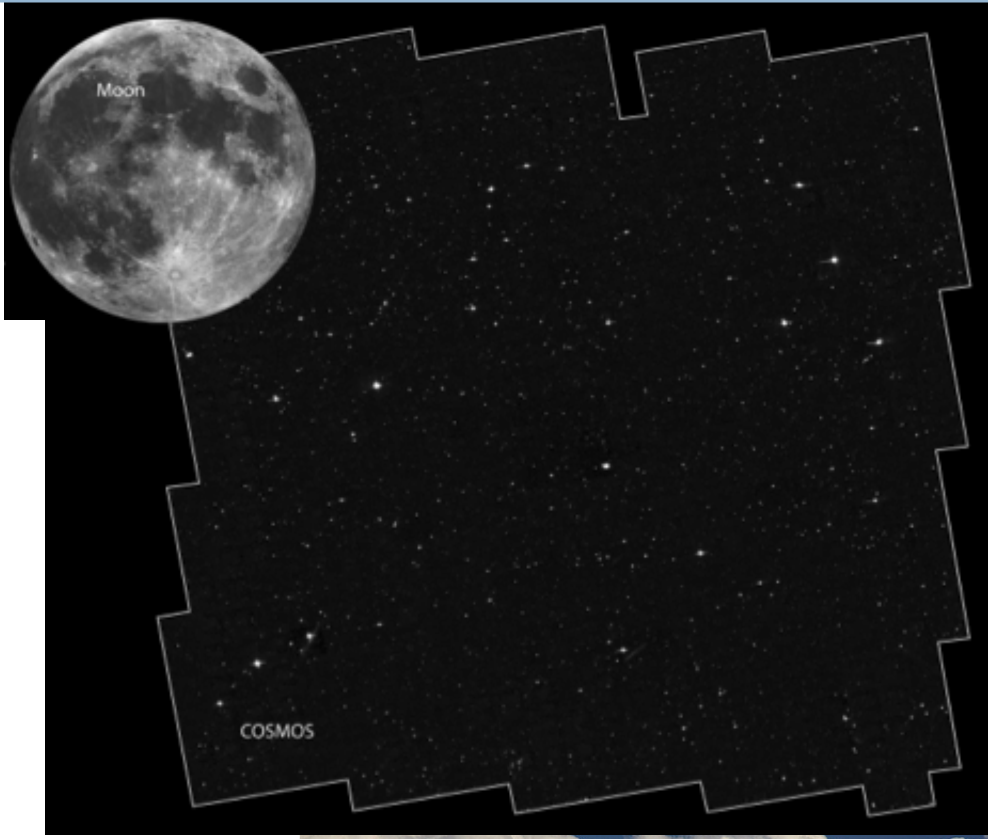
VLA-COSMOS 3GHz Large Project

or: Let’s make it a tradition…

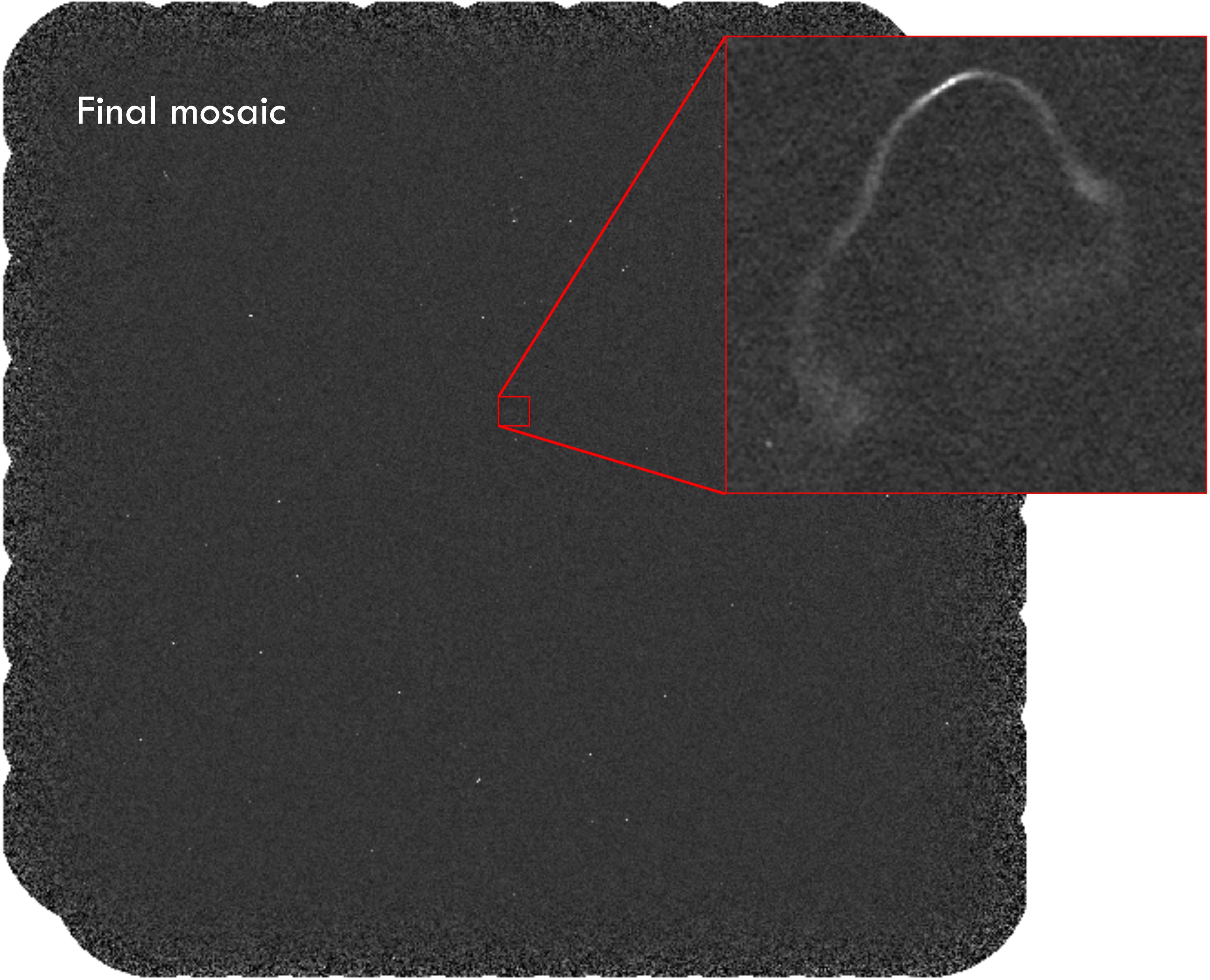
VLA-COSMOS 3 GHz Large Project + COSMOS

- VLA-COSMOS 3GHz Large Project
  - PI: Smolčić
  - 384 hours (A+C configurations, 2012/13)
  - 3 GHz (2 GHz bandwidth)
  - 0.75" resolution
  - rms ~2.3 μJy/beam over 2□°
  - ~11,000 source components

- 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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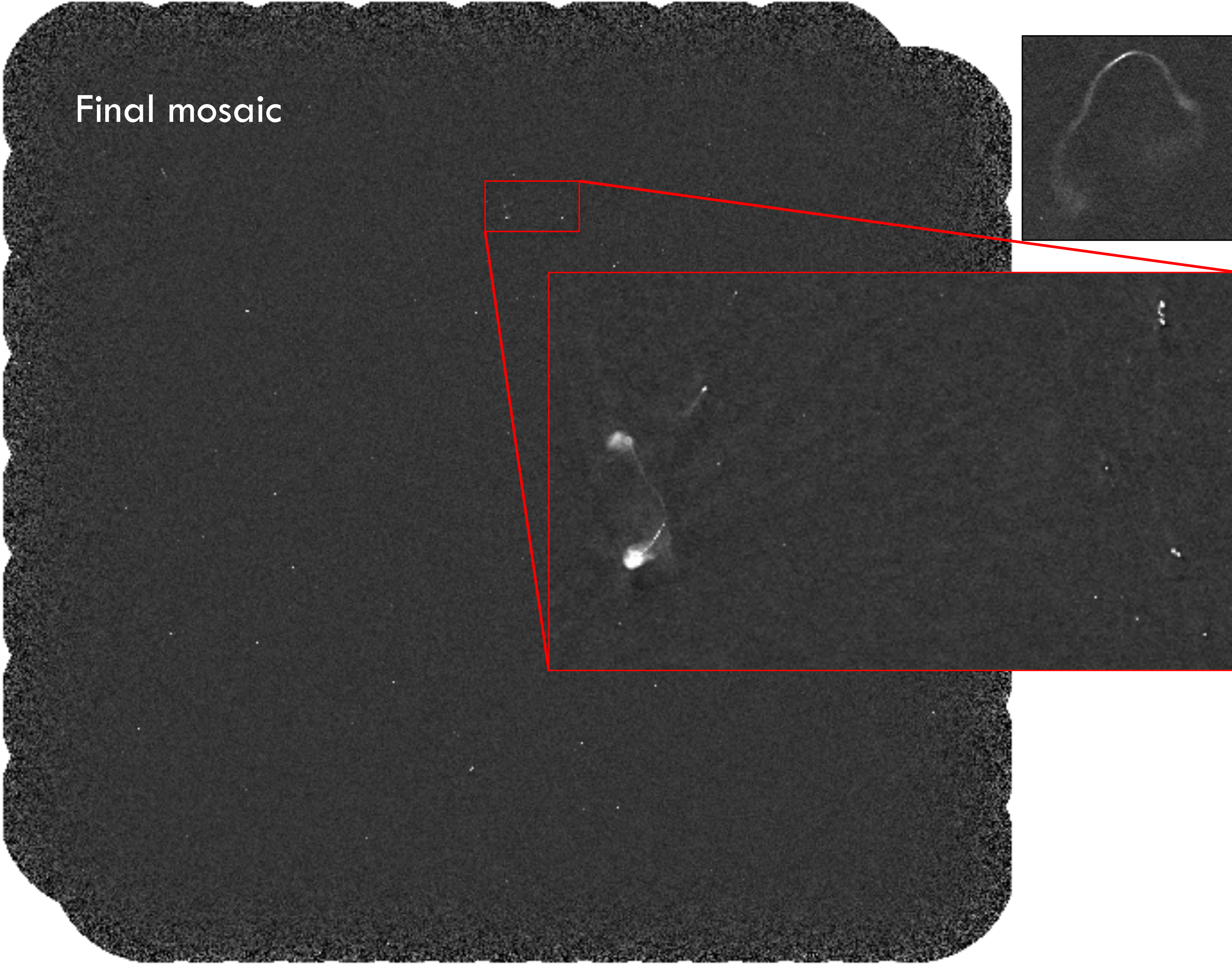
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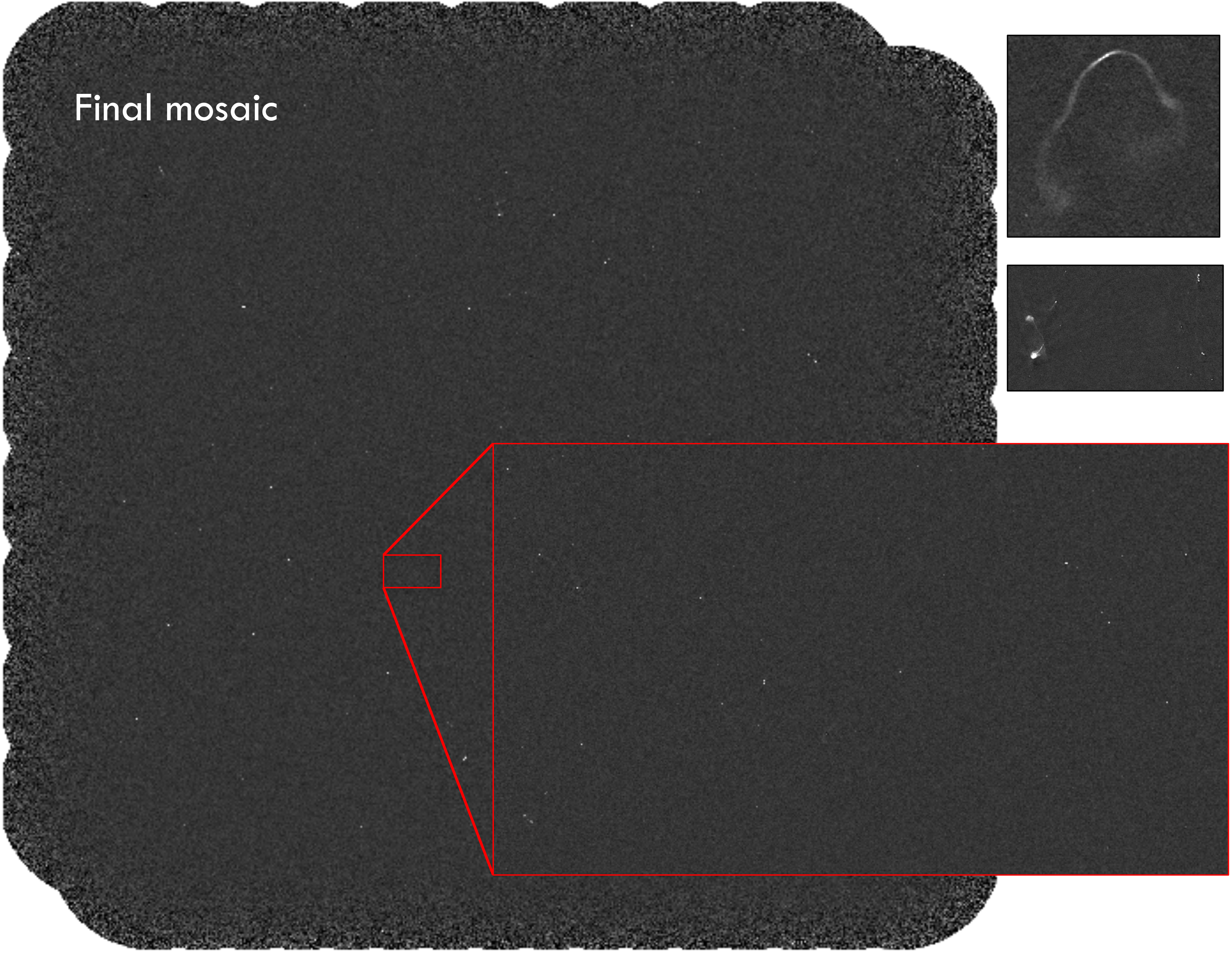
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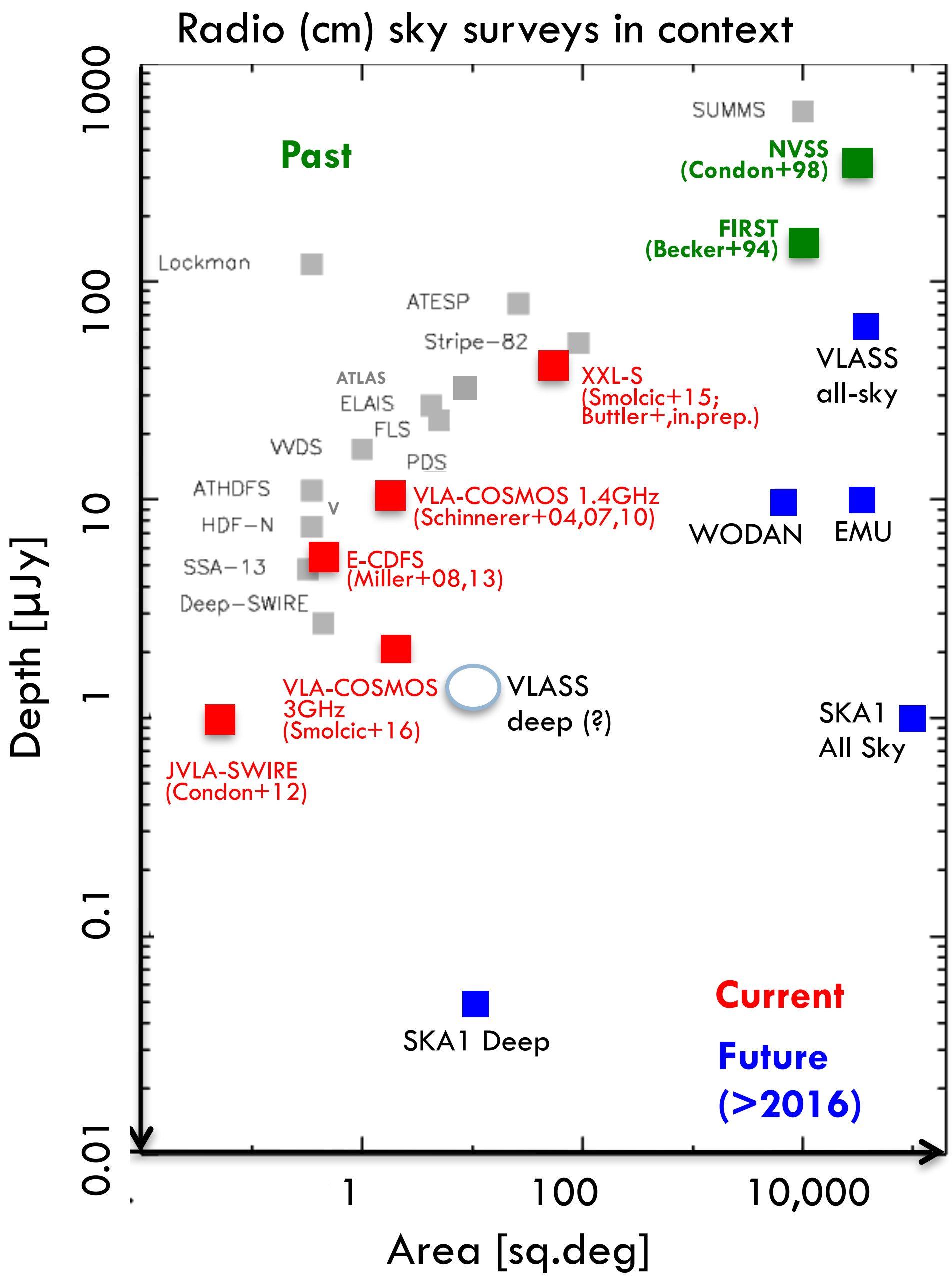

VLA-COSMOS 3GHz Large Project as an SKA pathfinder

- VLA-COSMOS 3GHz Large Project
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  - 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.)
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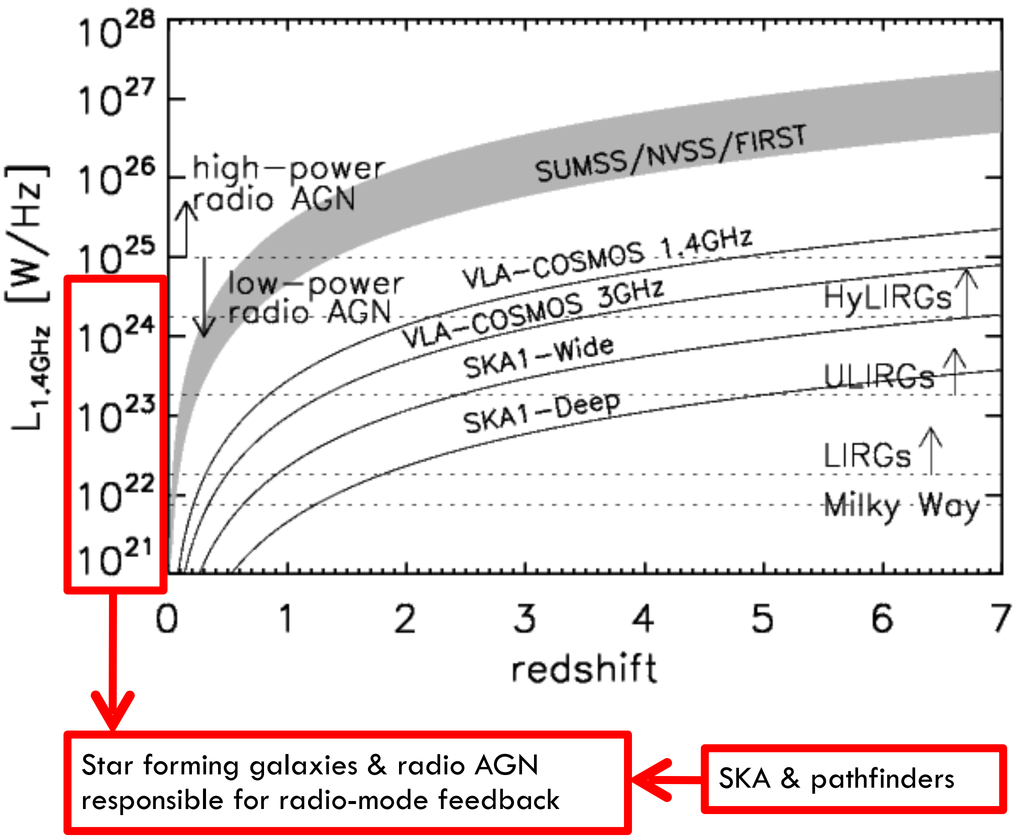
The power of radio



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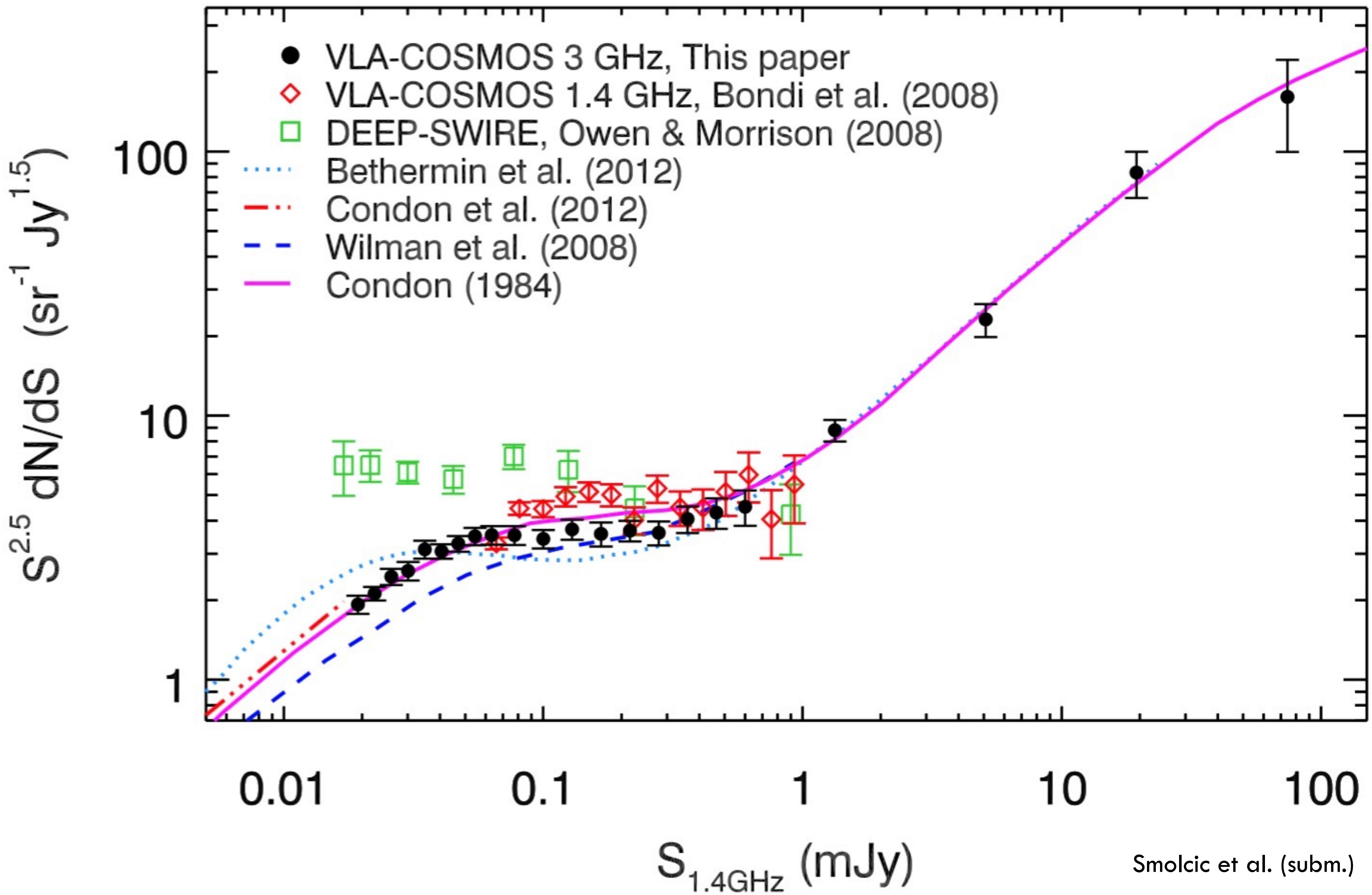
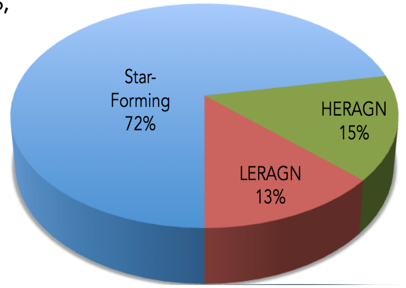
Source counts



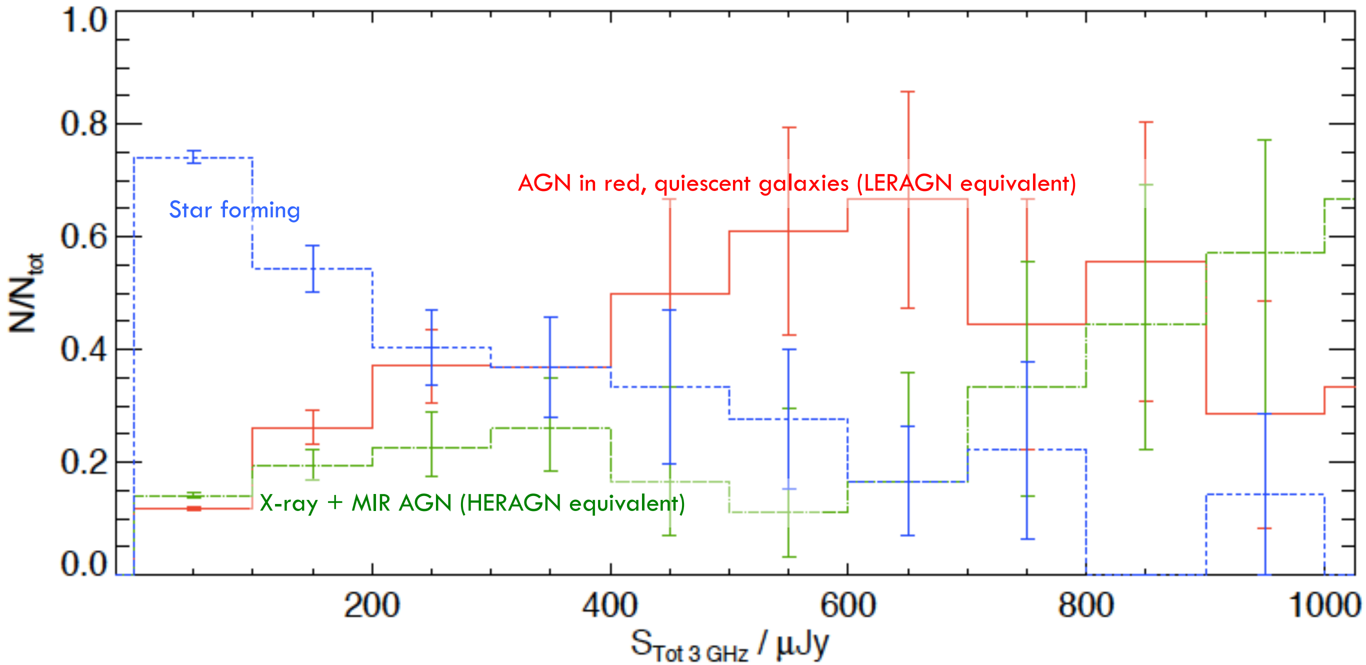
Smolcic et al. (subm.)

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 (& in prep.), 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)



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



Baran et al. (2016)

Radio as a dust-unbiased star formation tracer

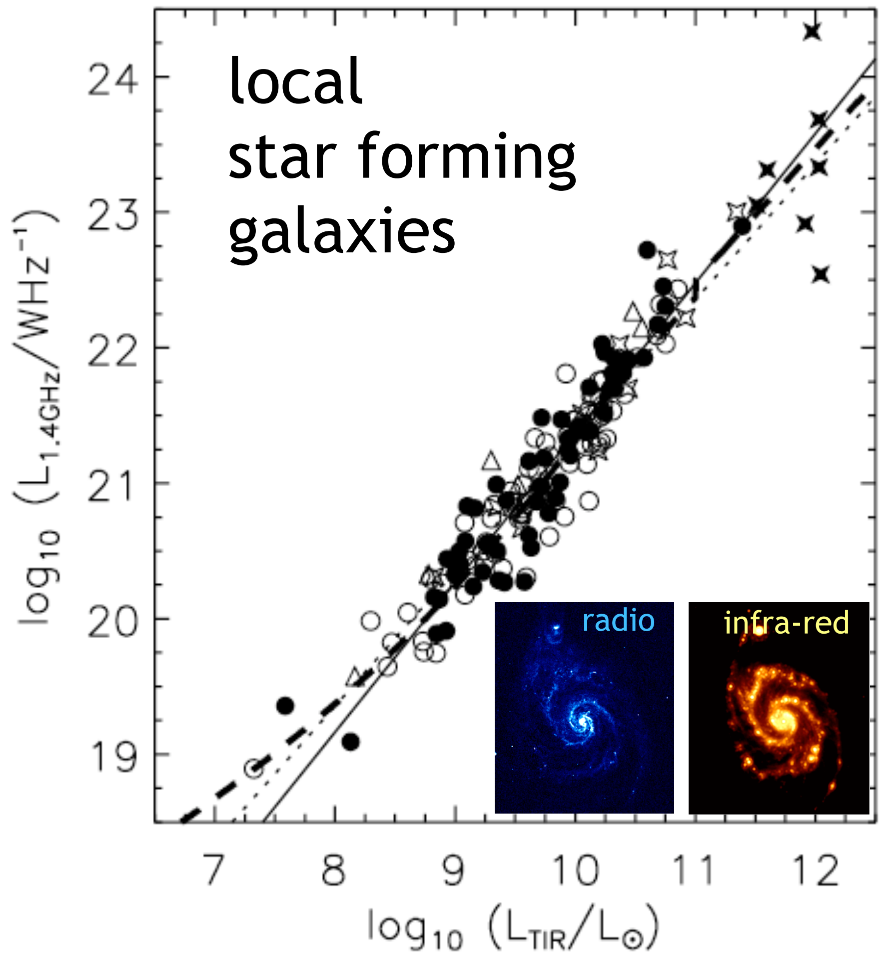
IR-radio correlation:

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

→ 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

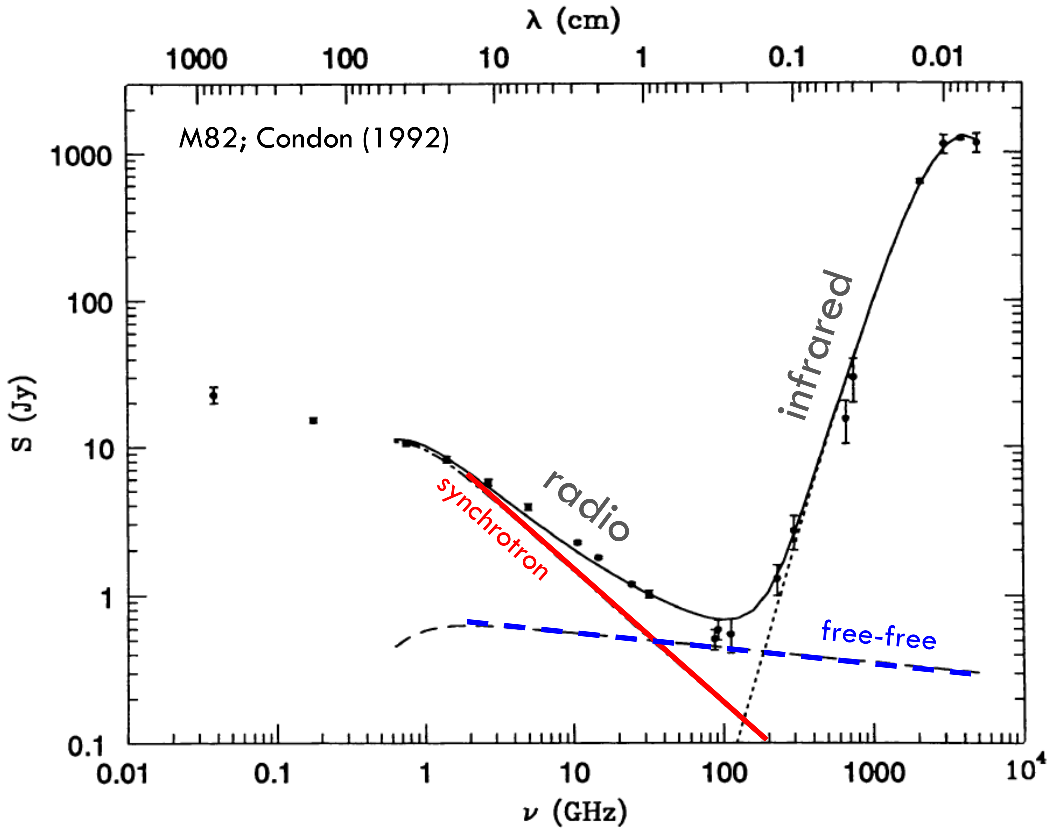


Radio as a dust-unbiased star formation tracer

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

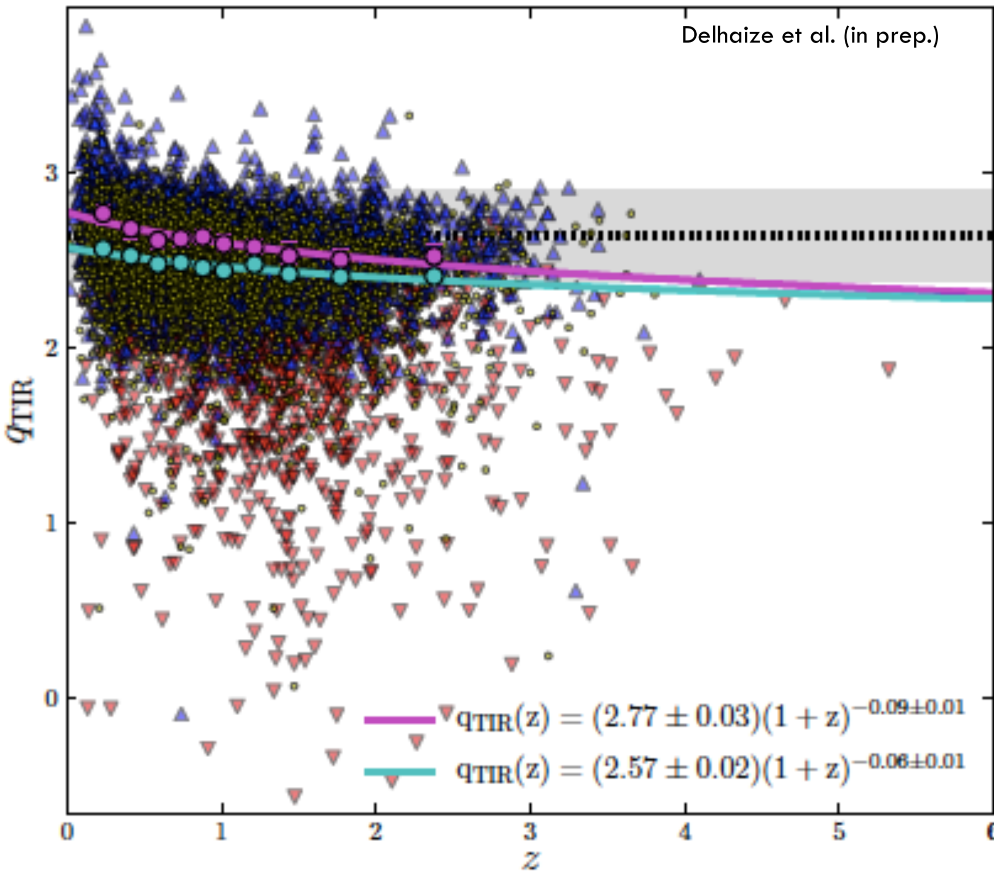
→ evolution of $q_{(F)IR}$ with cosmic time?

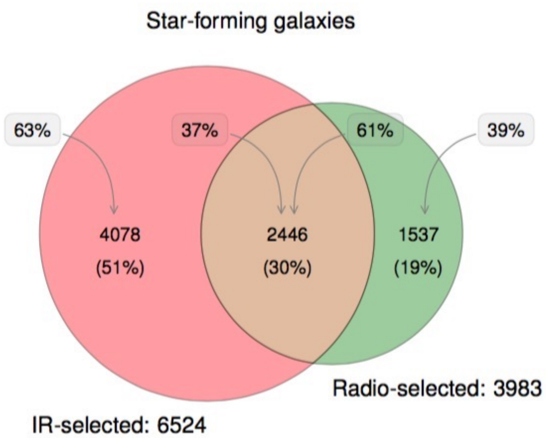


M82-type radio SED: Typically assumed radio spectral energy distribution (SED) for star forming galaxies

Radio as a dust-unbiased star formation tracer

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



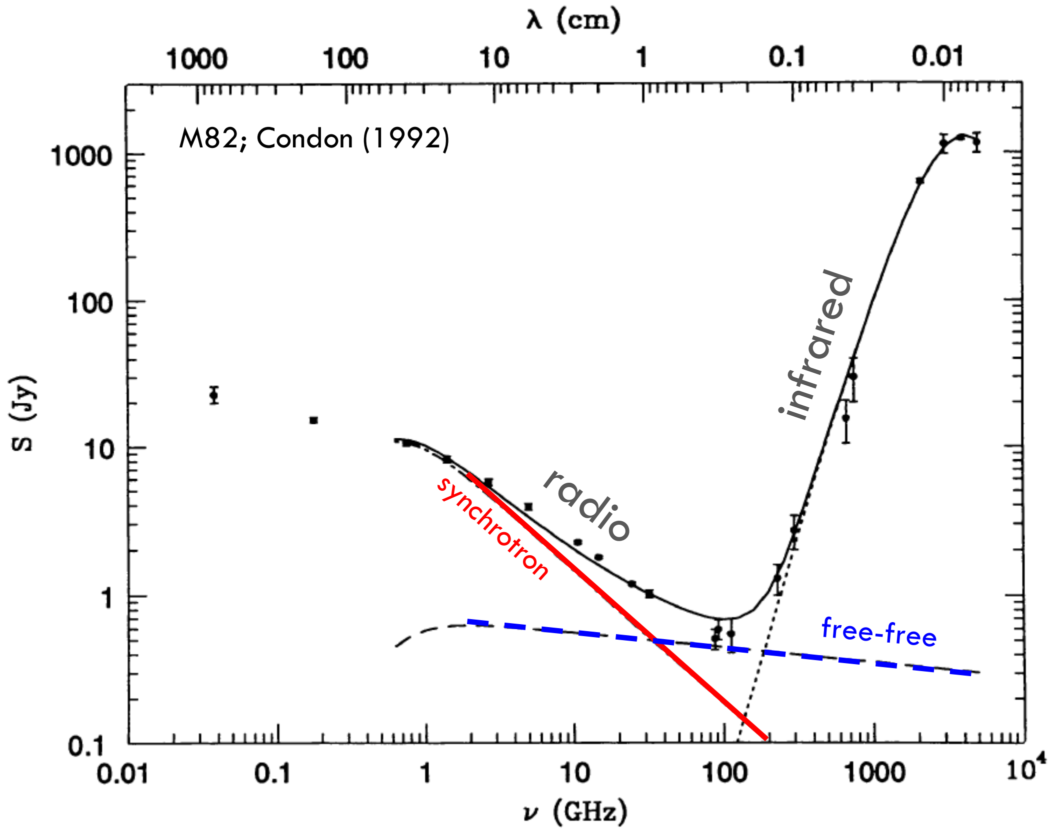


Observational results:

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

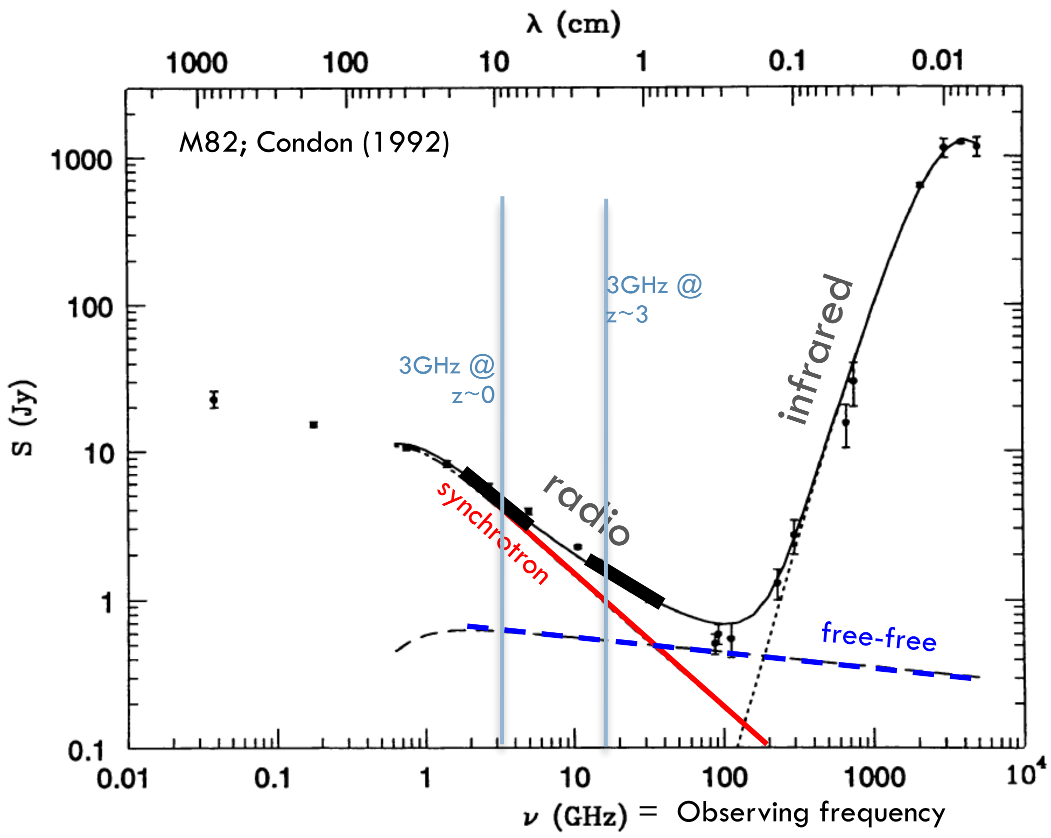
Delhaize et al. (in prep.); consistent with Sargent et al. (2010), Magnelli et al. (2015)

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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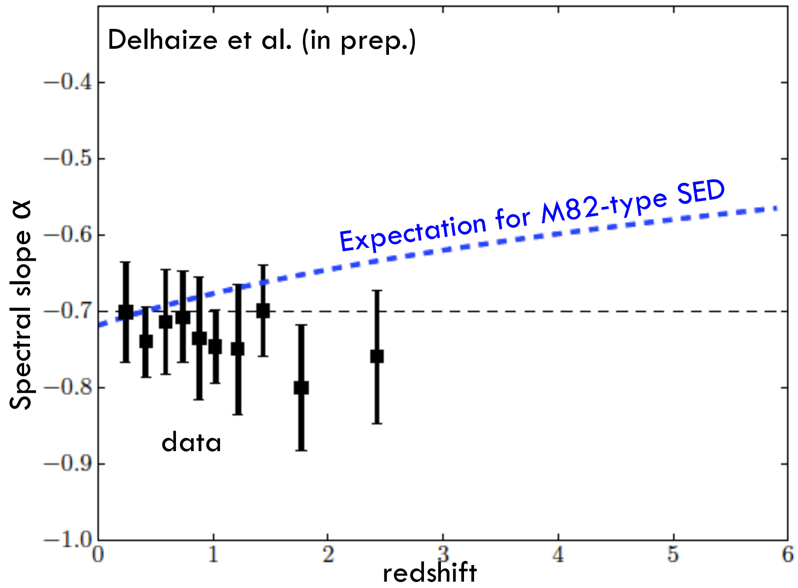

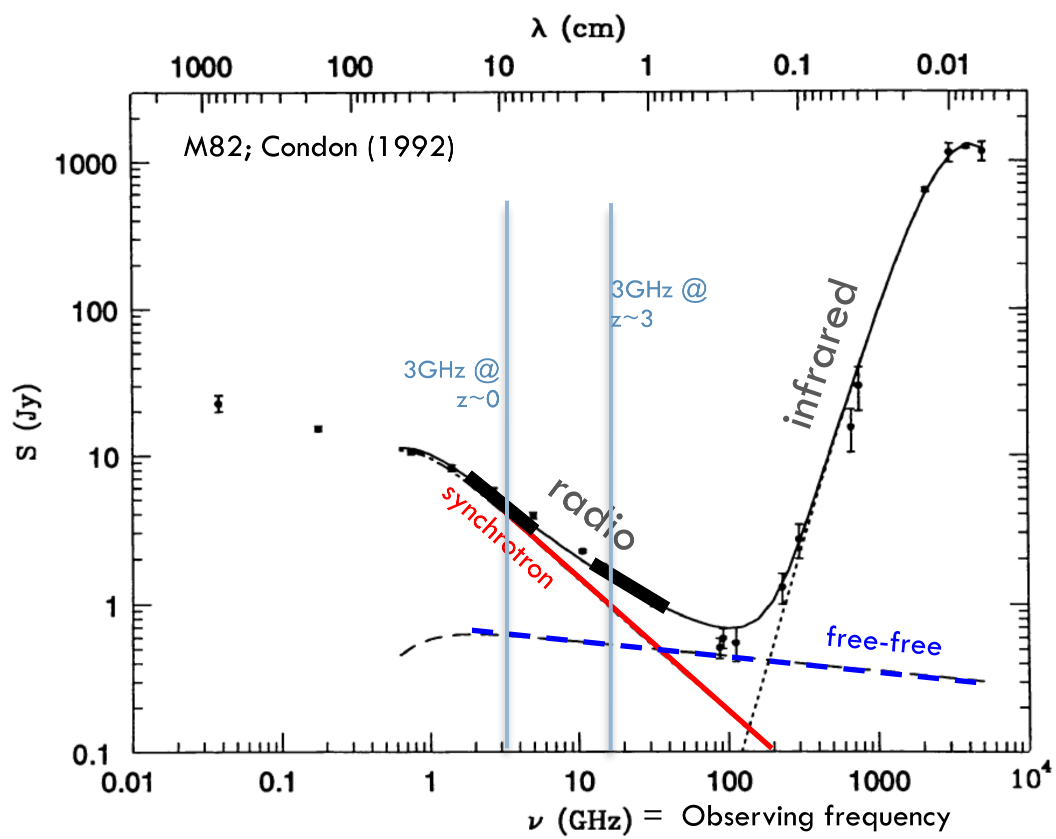

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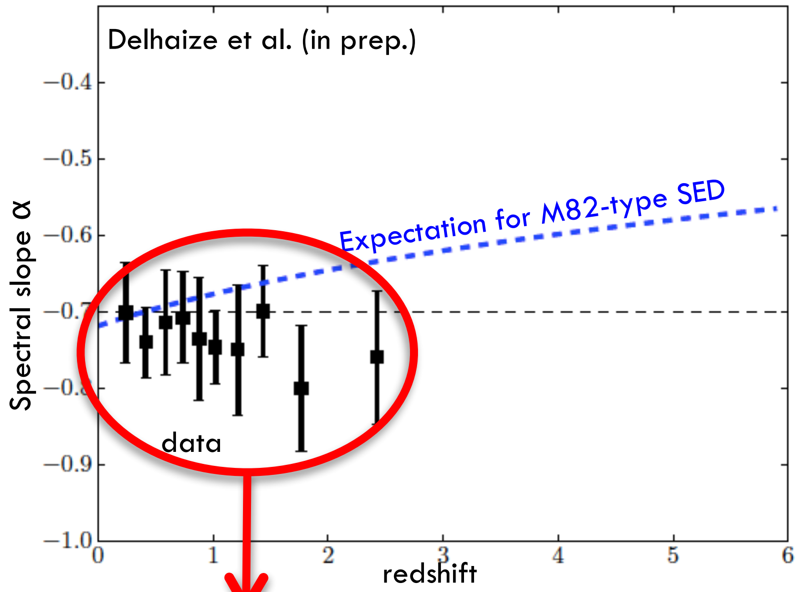
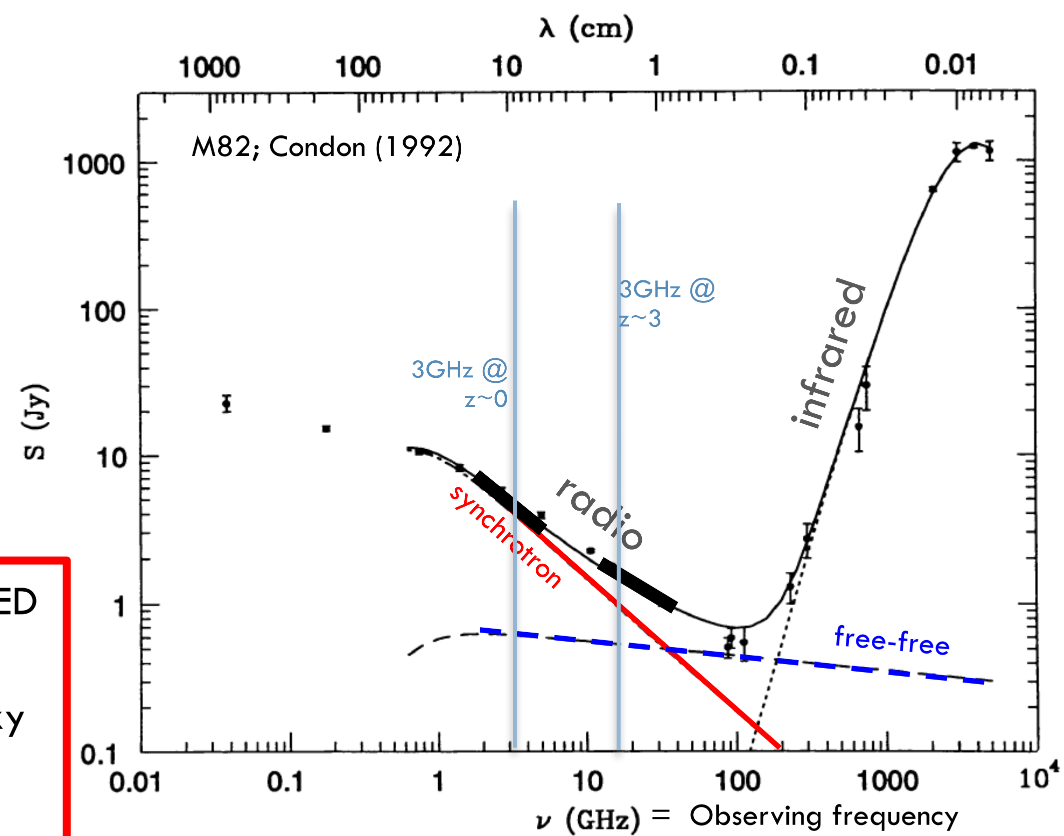
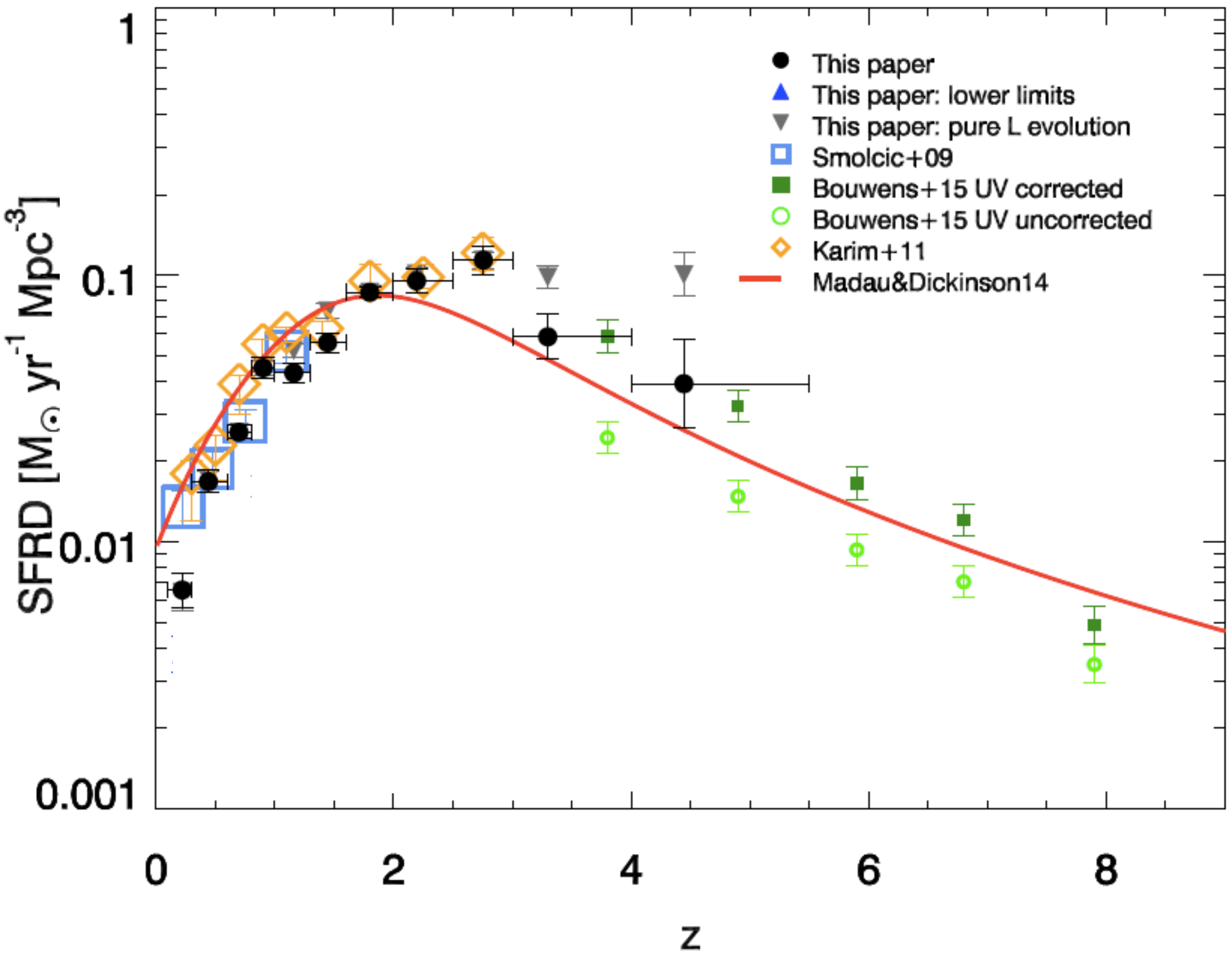




- Data *not* consistent with M82-type radio-SED shape across cosmic times
- Better understanding of star forming galaxy radio spectral energy distribution needed

The dust-unbiased cosmic star formation history revisited

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



Novak et al. (in prep)

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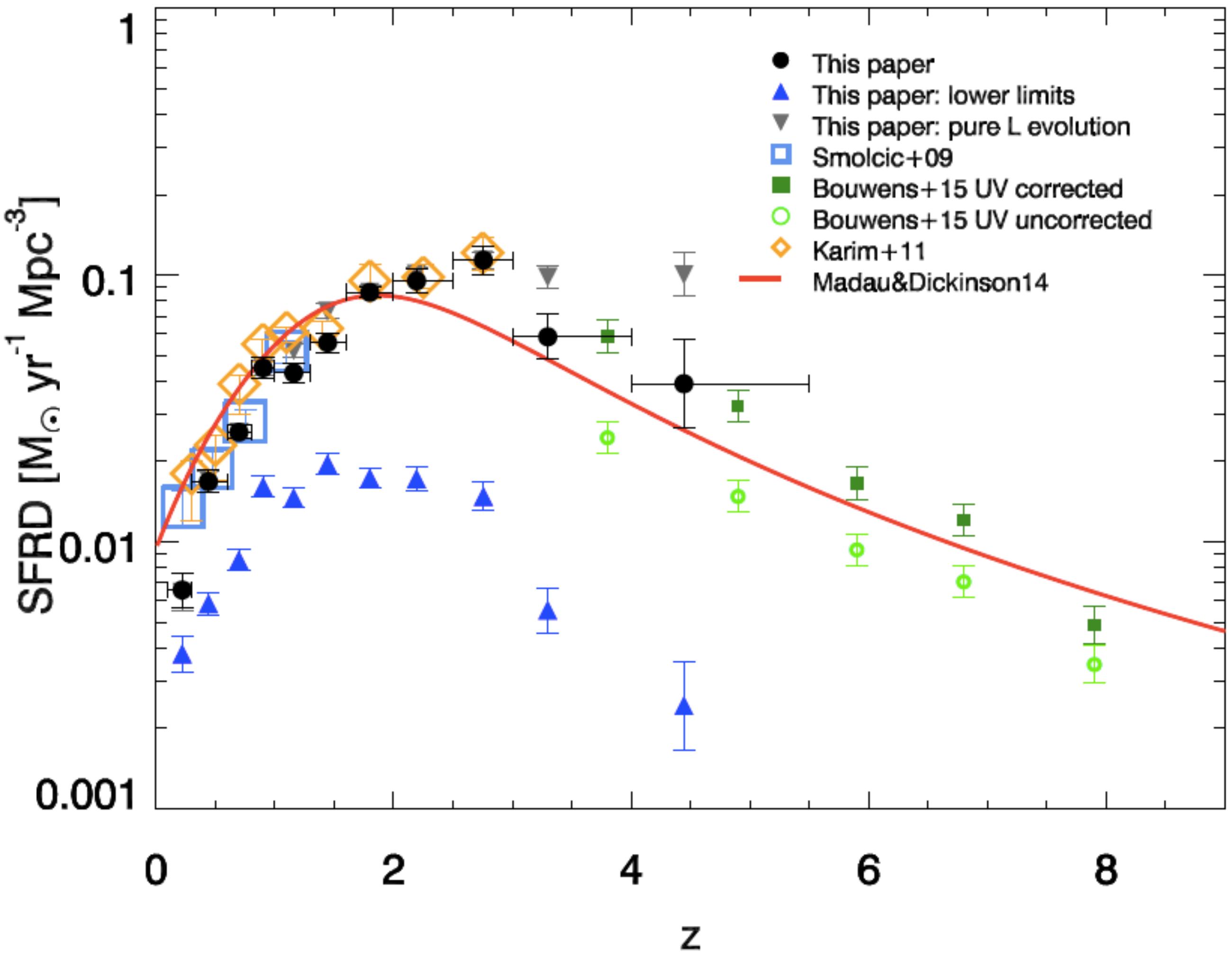
- Large extrapolation needed in radio → SKA to the rescue



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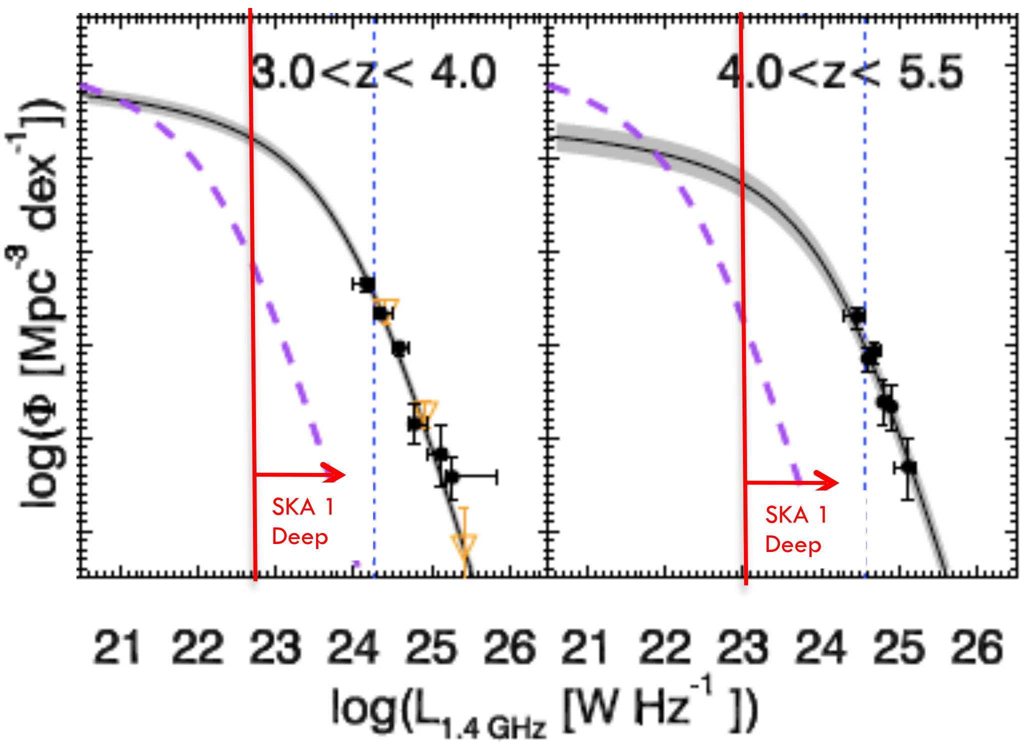
Star forming galaxy radio luminosity function



Novak et al. (in prep)

Summary

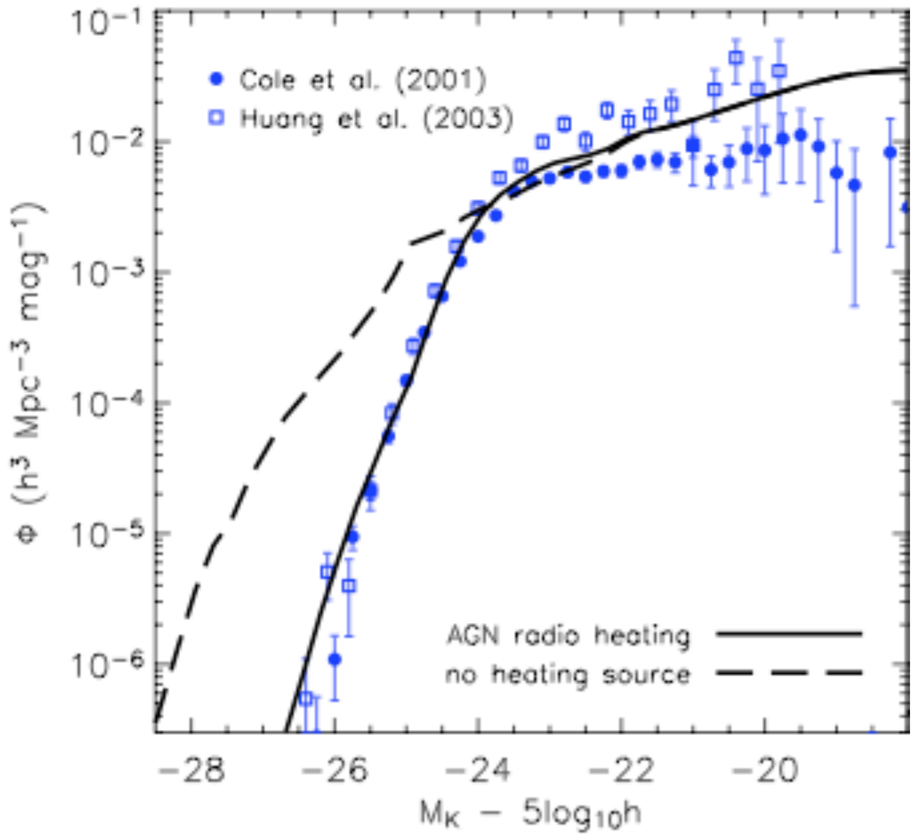
- (deep) Radio surveys - Key to understand cosmic evolution:
  - Efficient and unique star formation tracer: dust-unbiased & high angular resolution
  - Traces unique AGN → radio-mode feedback
  - Essential large-area diagnostic in upcoming survey landscape
  - Key German involvement
- JVLA-COSMOS (an important SKA survey pathfinder):
  - Providing stringent constraints to source populations SKA will see
  - Allowing for constraints on structural evolution of galaxies over cosmic time
  - Pushing persisting limits demands SKA
  - Motivating era of multi-wavelength radio surveys
- "Golden age" of radio astronomy → significant advance with current & next-generation radio facilities

VLA-COSMOS 3GHz Large Project

Additional material: First constraints on radio-mode feedback (work in progress)

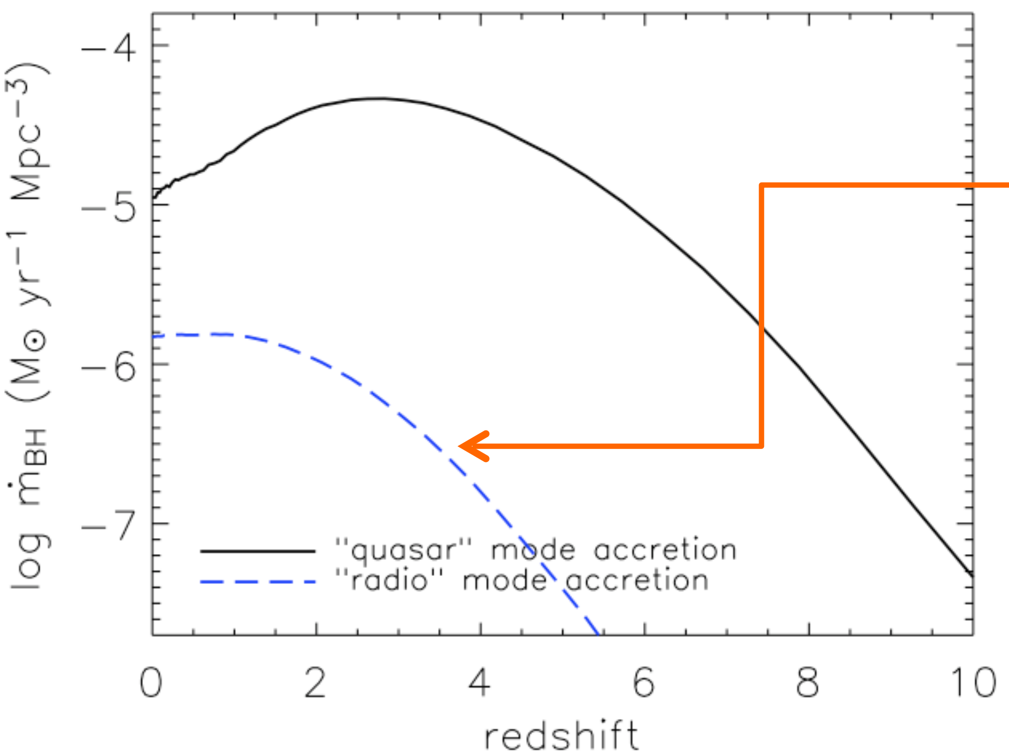
Radio-mode feedback in cosmological models

Croton et al. 2006



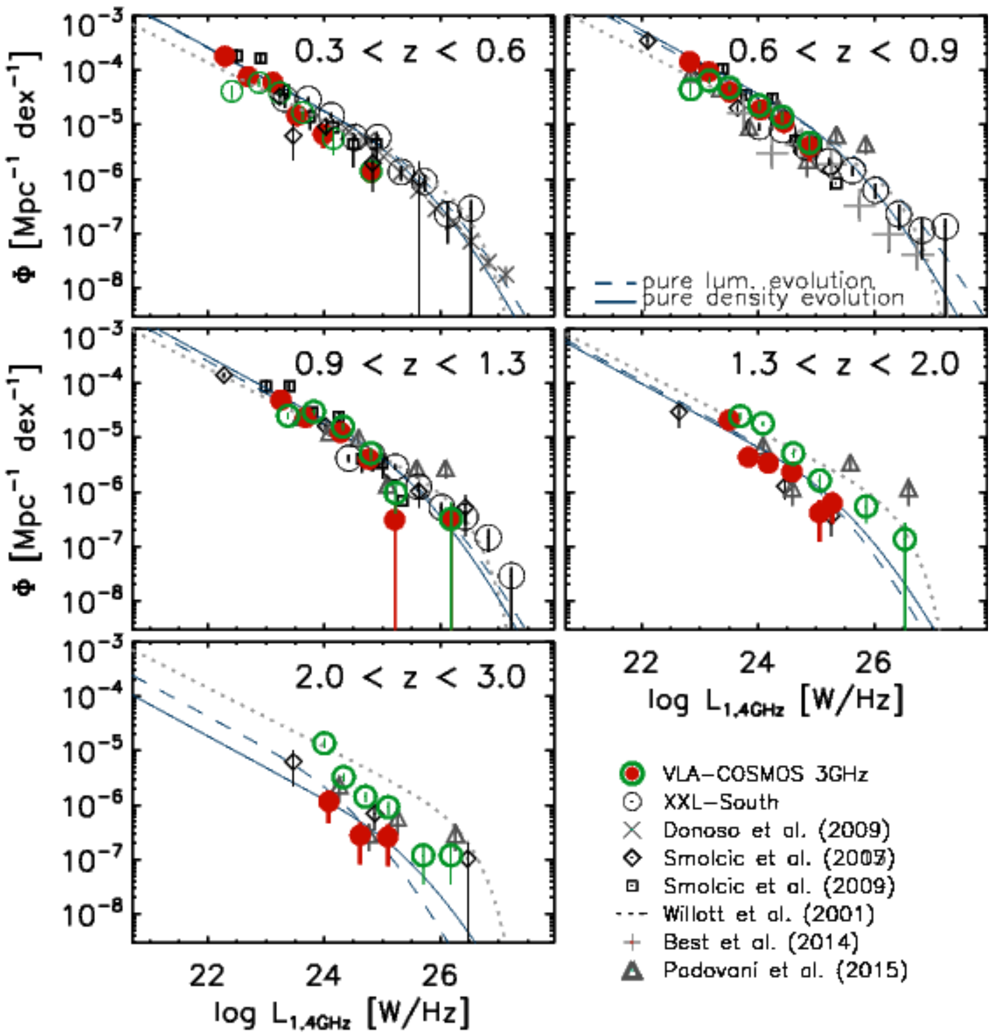
Radio-mode feedback in cosmological models

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

Cosmic evolution of LERAGN

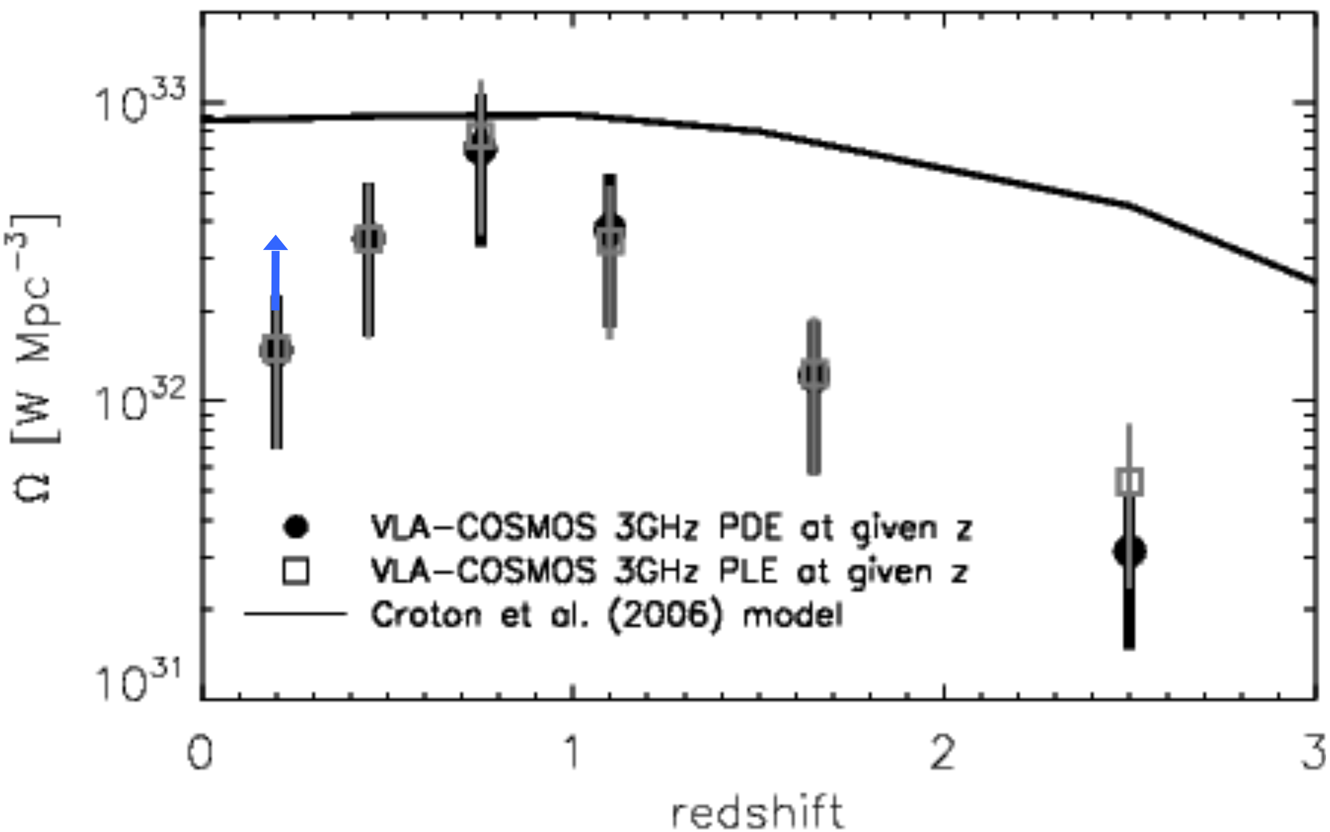


- LERAGN selection
  - Red, quiescent galaxies (M_{NUV}-M_{r*} > 3.5); Baran et al. (in prep.)
  - Radio luminosity excess: log (SFR_{RADIO} / SFR_{IR}) > 0.7; Delvecchio et al. (in prep.)
- Good agreement with previous studies:
  - E-CDFS (Padovani et al. 2015)
  - VLA-COSMOS 1.4GHz Large Project (Smolcic et al. 2015)
- z>1 volume density of radio lum. excess AGN > red, quiescent galaxies

Smolcic et al. (in prep.); Butler et al. (in prep)

Volume averaged mechanical heating rate through cosmic time

Red passive galaxies (X-ray, mid-IR, AGN excluded)

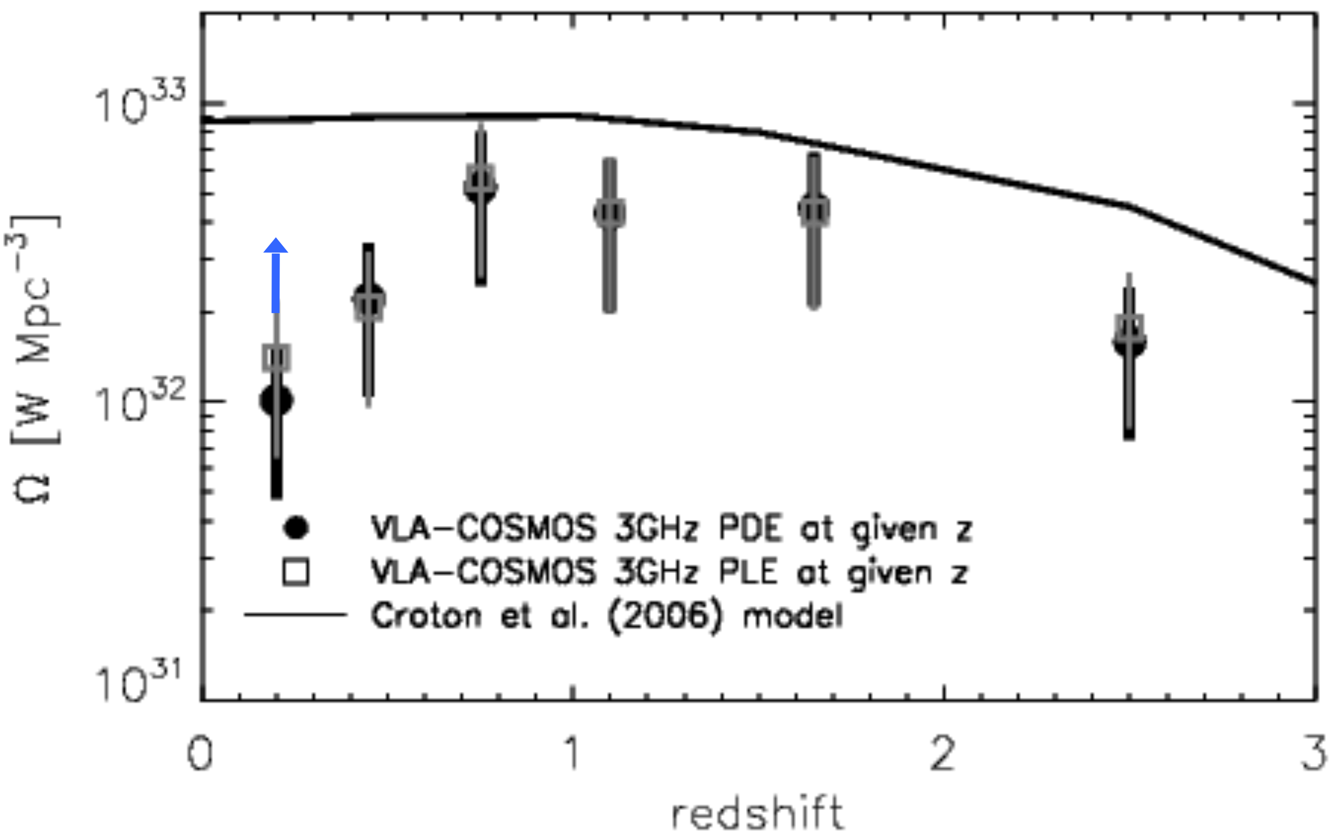


- Ω = Volume averaged mechanical heating rate
- O'Sullivan et al. (2011) conversion

Smolcic et al. (in prep.)

Volume averaged mechanical heating rate through cosmic time

Radio excess galaxies (X-ray, mid-IR, SED-AGN excluded)



- Ω = Volume averaged mechanical heating rate
- O'Sullivan et al. (2011) conversion

Smolcic et al. (in prep.)