Radio continuum surveys and galaxy evolution: The AGN view

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& the (VLA-)COSMOS collaboration

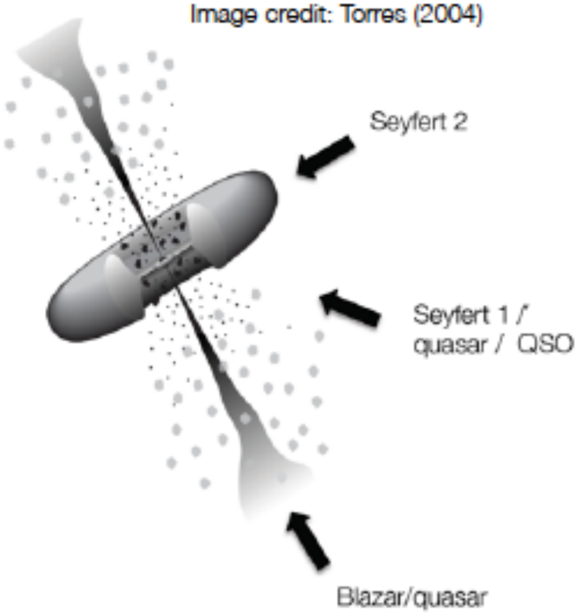
Radio AGN at low-z

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

High-excitation = cold mode = radiative mode

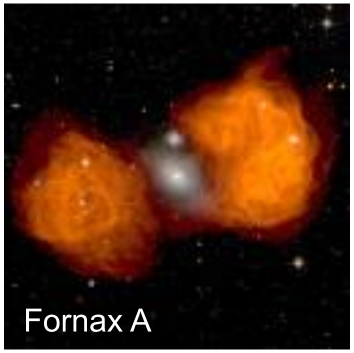
- Strong emission lines in optical spectrum
- X-ray, MIR, optical AGN (Unified model for AGN)

Image credit: Torres (2004)

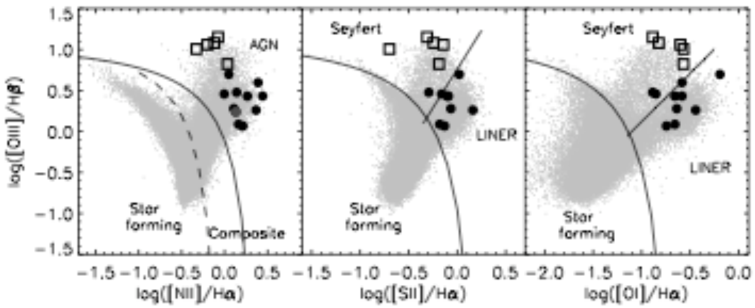


Low-excitation = hot mode = jet mode

- 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



LE vs. HE radio AGN: Fundamental physical differences



SDSS/NVSS (0.04<z<0.1) “main” spectroscopic sample (~7000 radio sources from Kimball & Ivezić 2008 catalog; ~500 radio AGN selected following Kewley et al. 2006)

Smolčić 2009

HERAGN		LERAGN
Green	vs.	Red
Low	vs.	high stellar mass
Low	vs.	high BH mass
High	vs.	low BH accr. rate

see also Best & Heckman 2012

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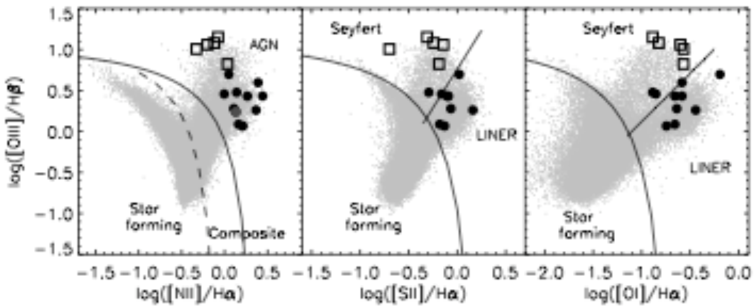

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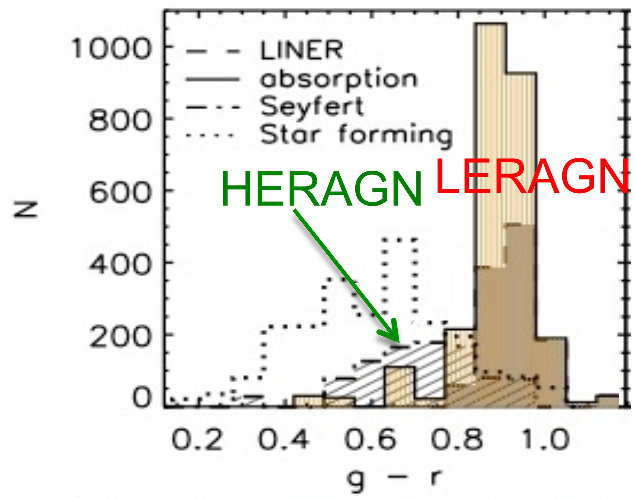

HERAGN LERAGN

Green vs. Red

Low vs. high stellar mass

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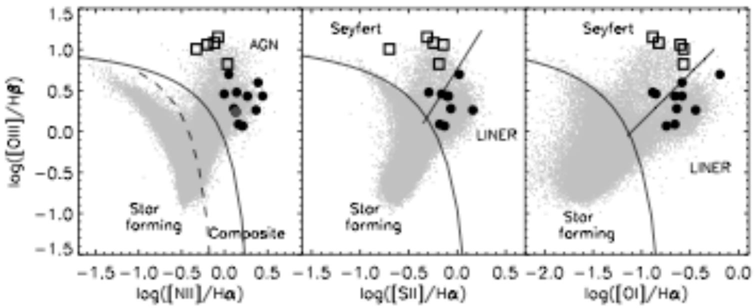

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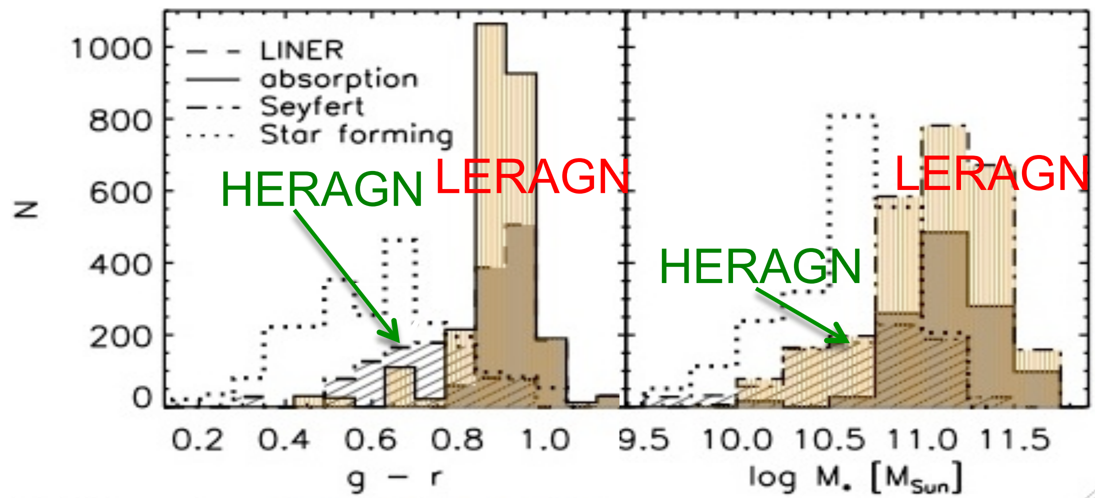

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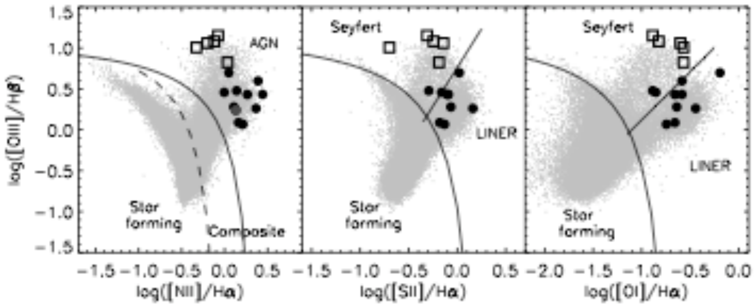

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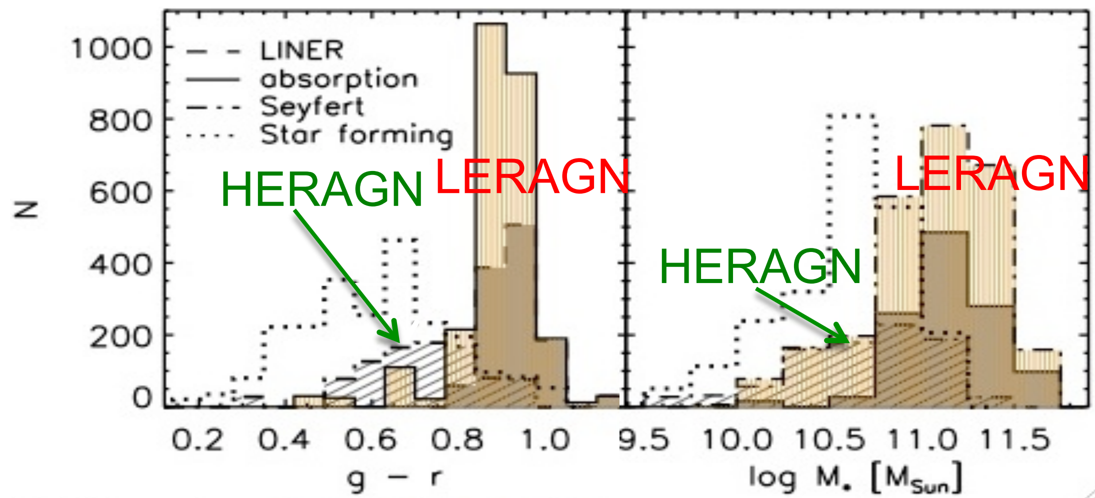

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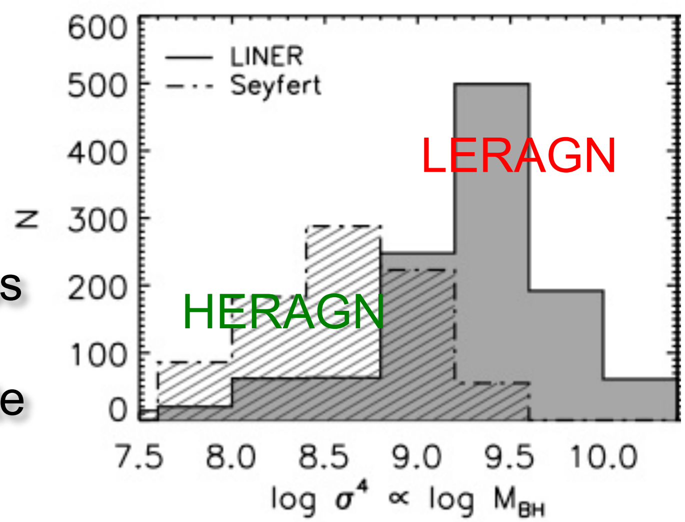

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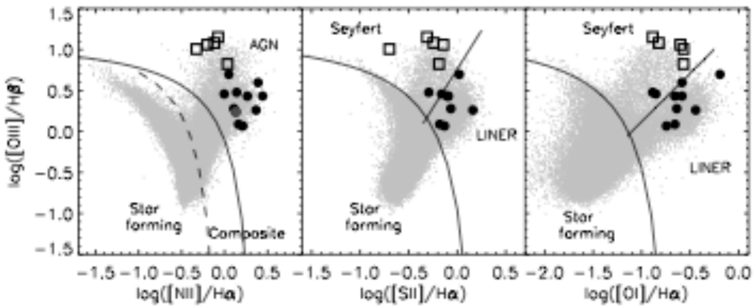

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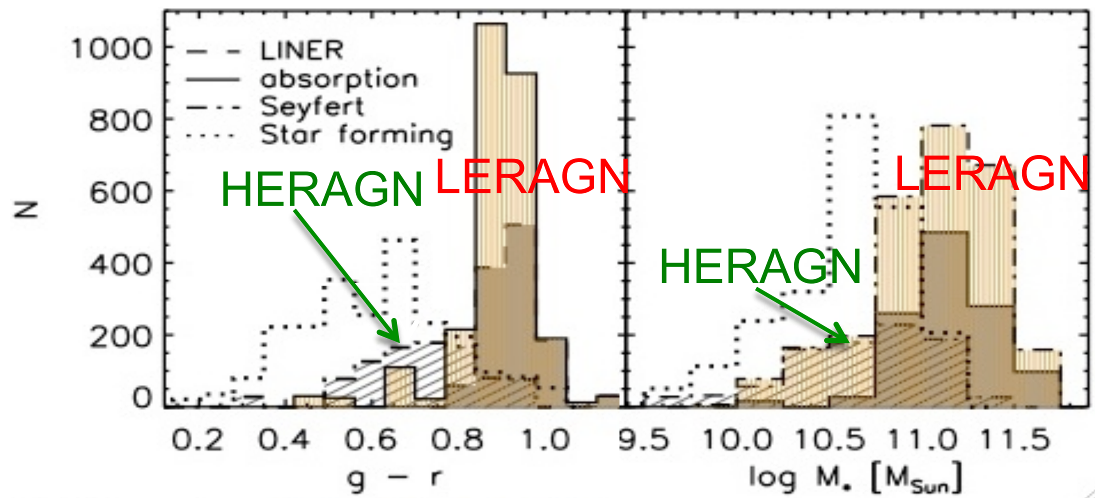

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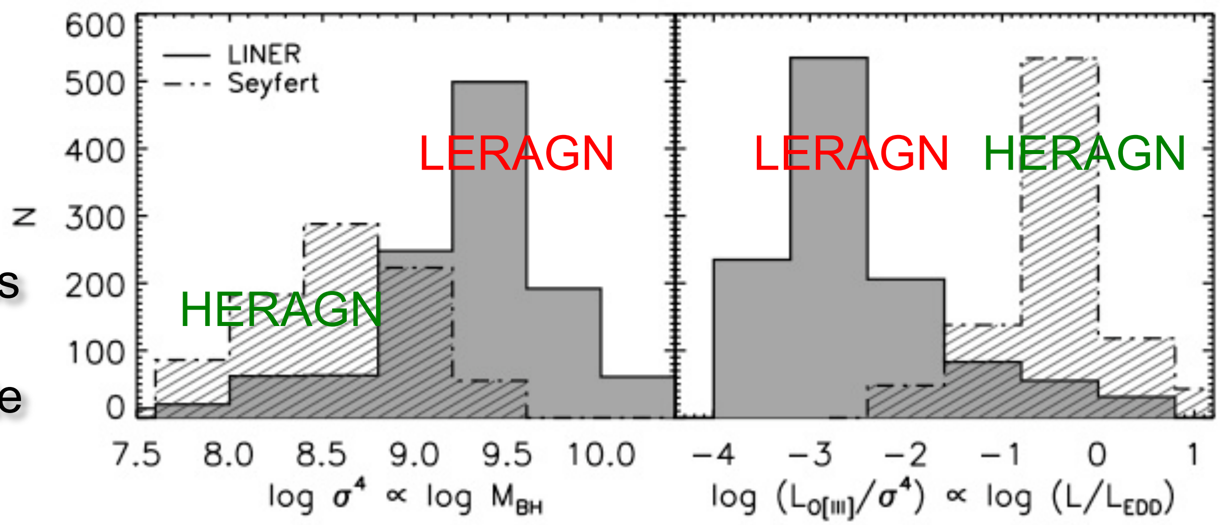

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Green vs. Red

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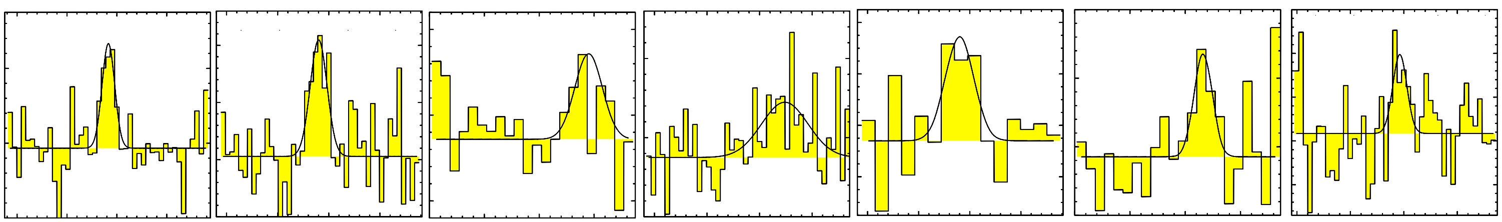
LE vs. HE radio AGN: Fundamental physical differences

- 21 radio AGN ($z<0.1$) drawn from the flux-limited 3CRR radio sample
  - High-resolution X-ray data ➔ BH accretion mode (Evans et al. 2006)
  - Optical spectroscopy ➔ LERAGN/HERAGN classification
- CO(1-0) observations toward 13/21 radio AGN: 140 hours with CARMA at 3mm
- 7/13 detections (2 with S/N>5 & 5 with S/N ~3); $M_{gas} = \alpha L'_{CO}$; α=1.5 (intermediate between Milky Way & ULIRG type galaxies)



Smolčić & Riechers (2009)

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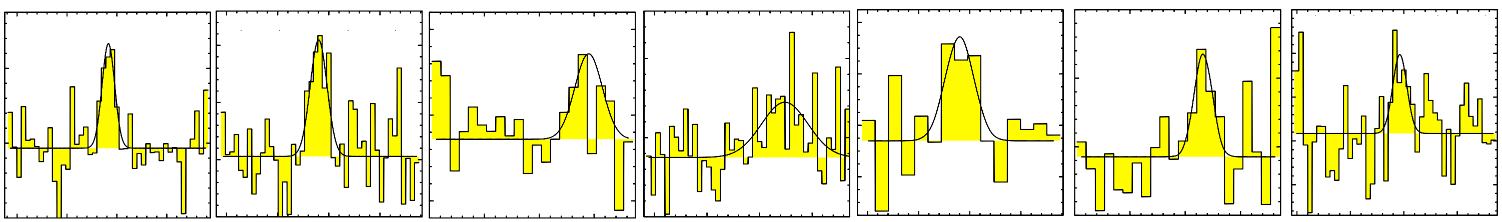
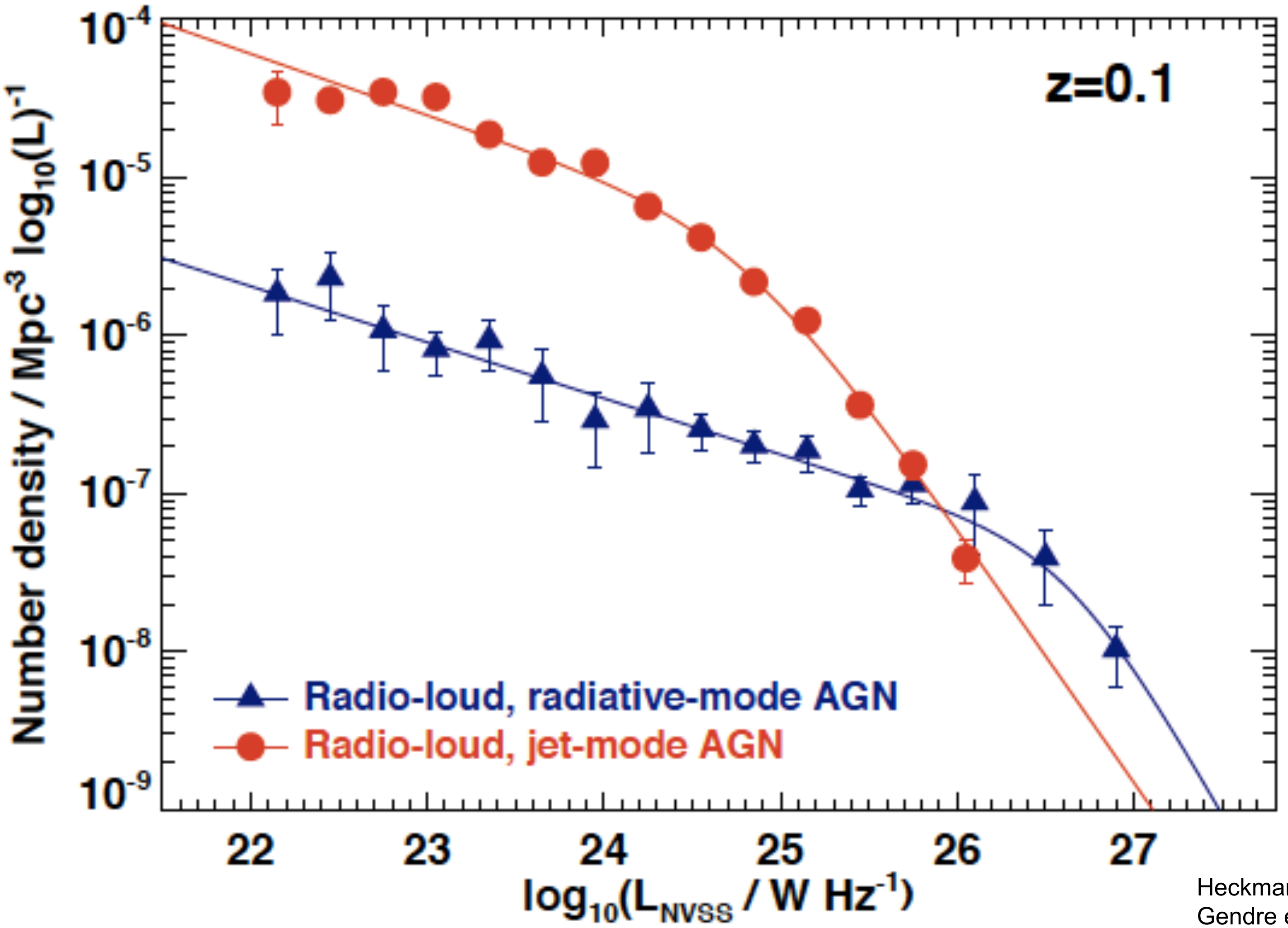


HERAGN: $\langle M_{gas} \rangle \sim 3\times10^{8}\ M_{\odot}$ >> LERAGN: $\langle M_{gas} \rangle \leq 4.3\times10^{7}\ M_{\odot}$

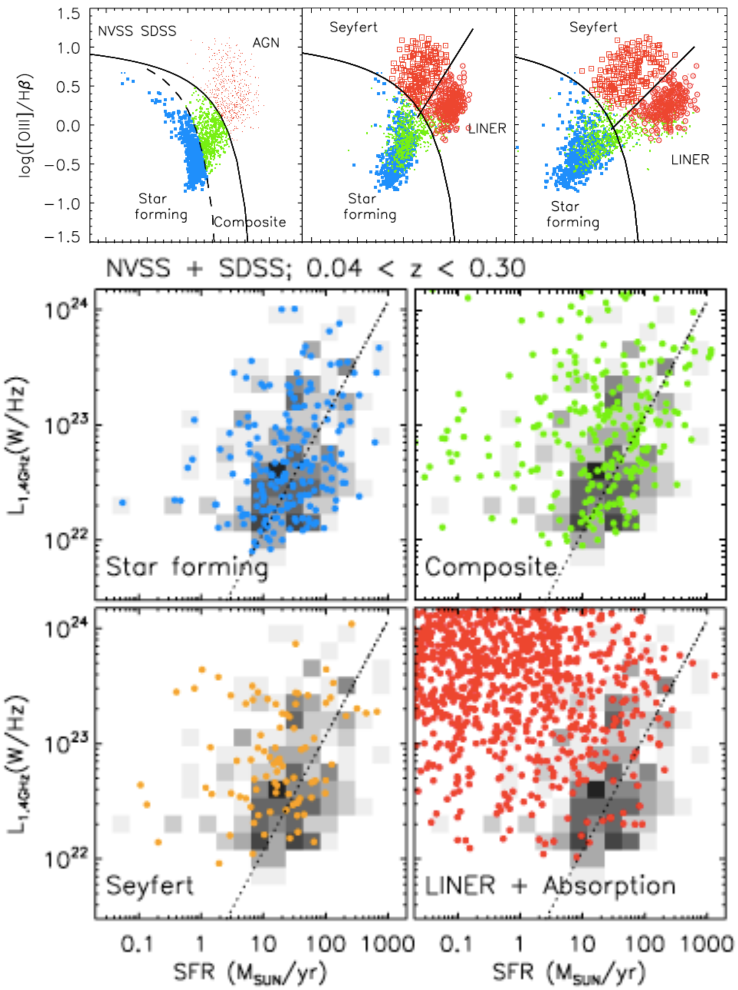
Smolčić & Riechers (2011)

Local LF of HE- & LERAGN



Heckman & Best (2014)
Gendre et al. (2013)
Best & Heckman (2012)

Source of radio emission in HE- & LERAGN



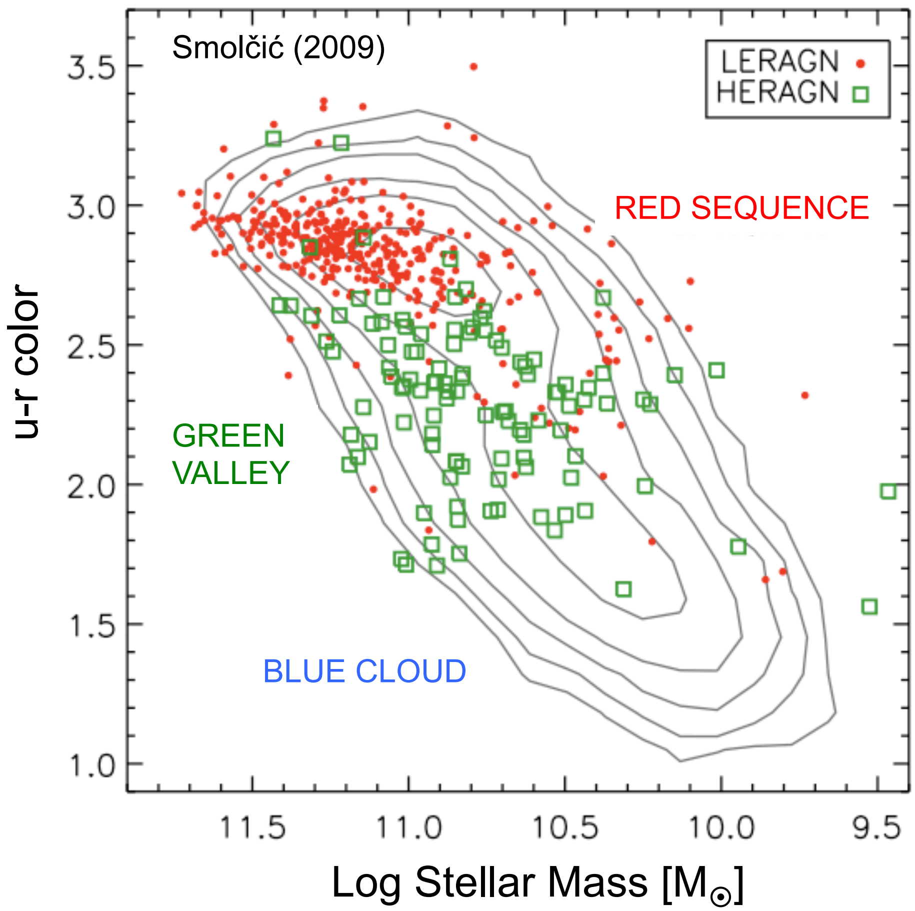
Galaxy Types	Radio SF	Radio AGN
SF	100%	0%
Composite	81.3%	18.7%
HERAGN Seyfert	56.8%	43.2%
LERAGN Abso+LINER	11.3%	88.7%

Moric et al. (2010)

- Higher SFR/sSFR in HERAGN vs. LERAGN (Gurkan et al. 2015; Herschel-ATLAS fields; see also Hardacastle et al. 2013)
- QSOs (see Condon et al. 2013, Kimball et al 2011 & White et al. 2015)

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

	HERAGN (cold mode)	LERAGN (hot mode)	References
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \lesssim 10^{26}$W/Hz)	Kauffmann et al. 2008, Heckman & Best 2012
Source of radio emission	SF+AGN	AGN	Moric et al. 2010; Hardcastle et al. 2013; Gurkan et al. 2015
Optical color	Green	Red	Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10} M_\odot$)	Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3 \cdot 10^8 M_\odot$)	Low ($< 4.3 \cdot 10^7 M_\odot$)	Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim 10^9 M_\odot$)	Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	Barthel 1989; Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009



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	HERAGN (cold mode)	LERAGN (hot mode)	References
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \leq 10^{26}$W/Hz)	Kauffmann et al. 2008, Heckman & Best 2012
Source of radio emission	SF+AGN	AGN	Moric et al. 2010; Hardcastle et al. 2013; Gurkan et al. 2015
Optical color	Green	Red	Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
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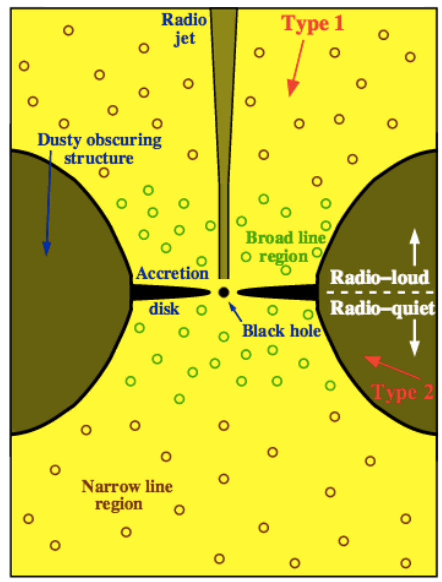
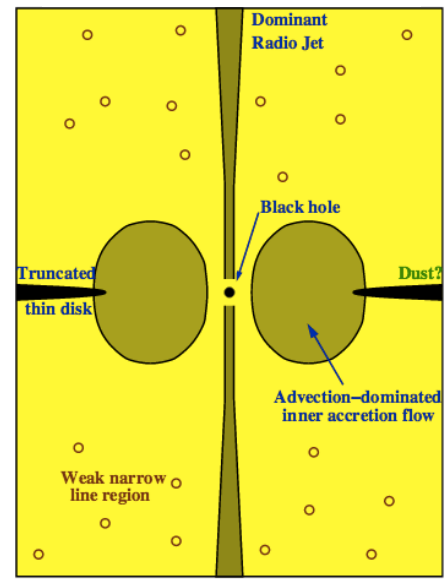
HERAGN or HERG or
Cold mode AGN or
Radiative mode AGN



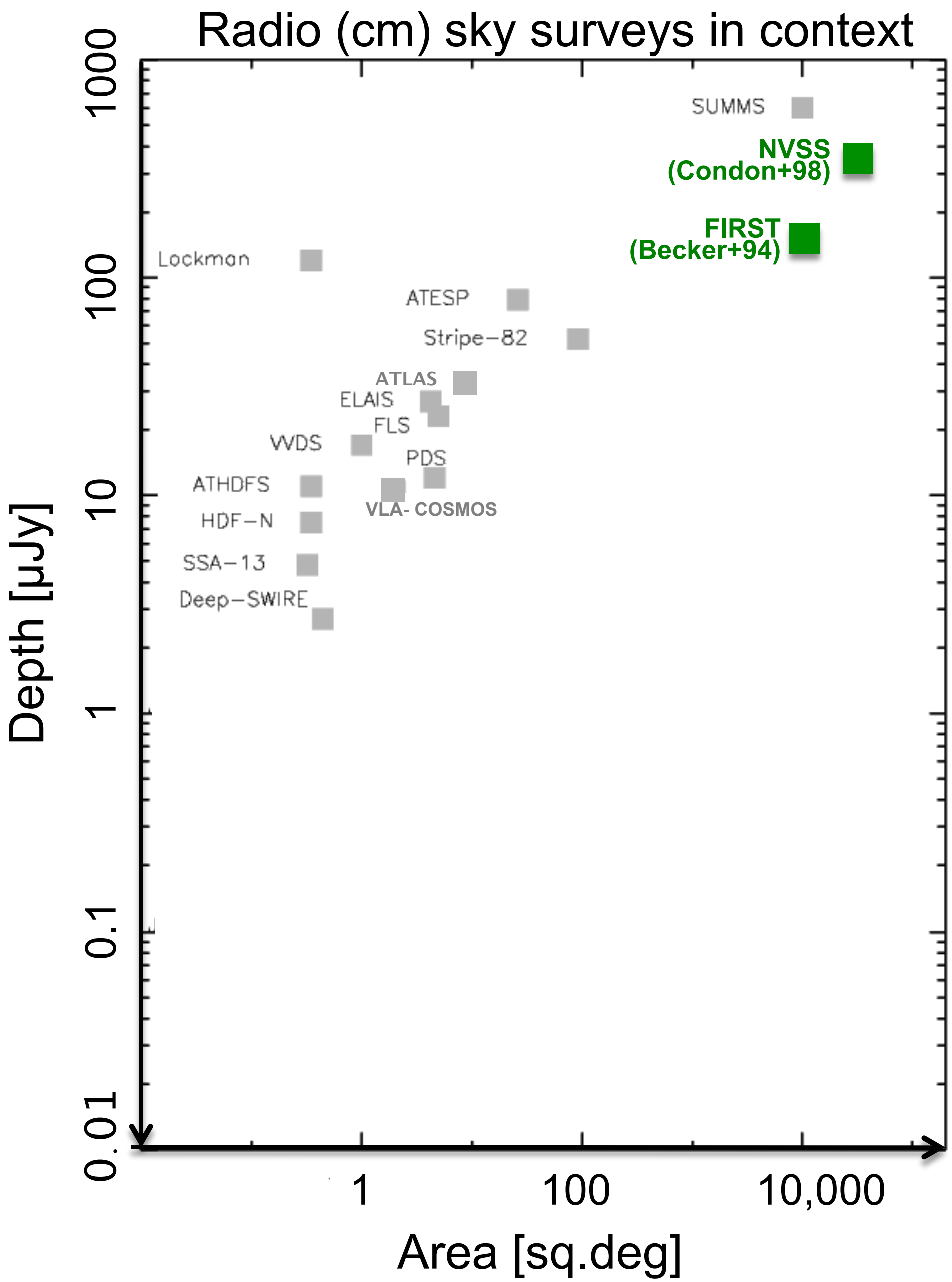
LERAGN or LERG or
Hot mode AGN or
Jet mode AGN

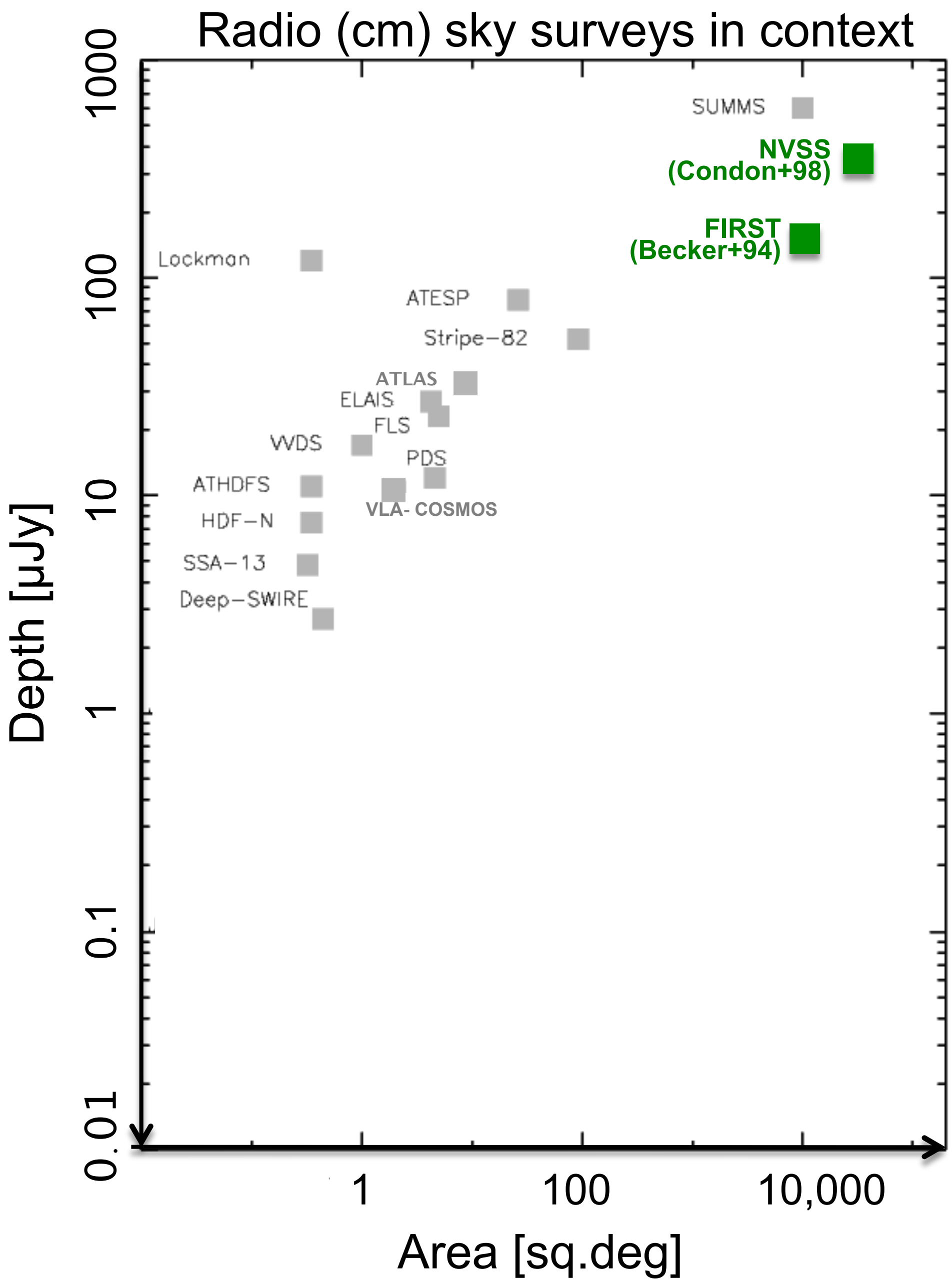


Heckman & Best (2014)

Radio AGN at high-z
(and their cosmic evolution)

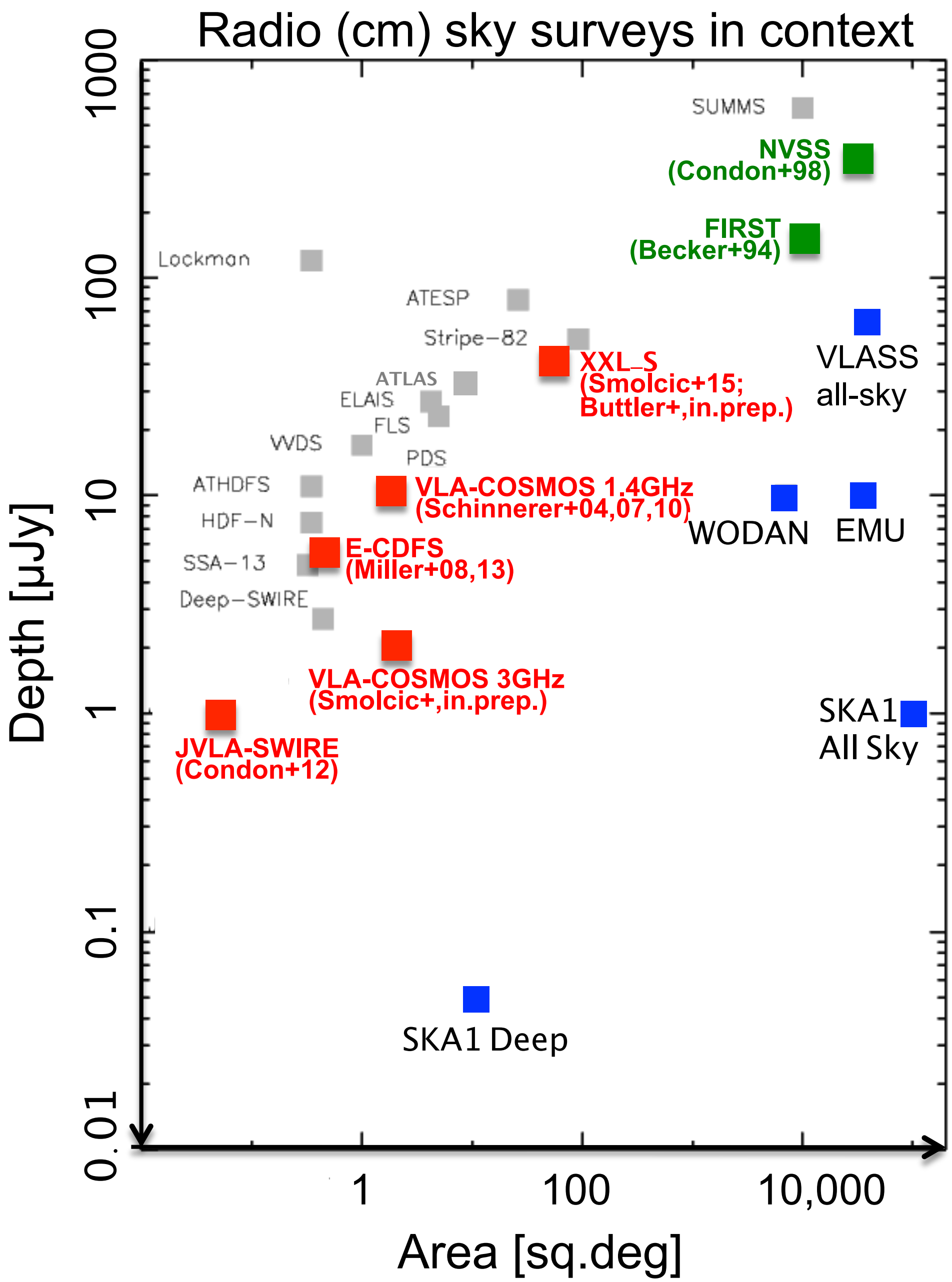
Probing high-z & evolution





Probing high-z & evolution

Challenges:
I) deep radio observations of
II) a large area on the sky
III) an efficient AGN identifier



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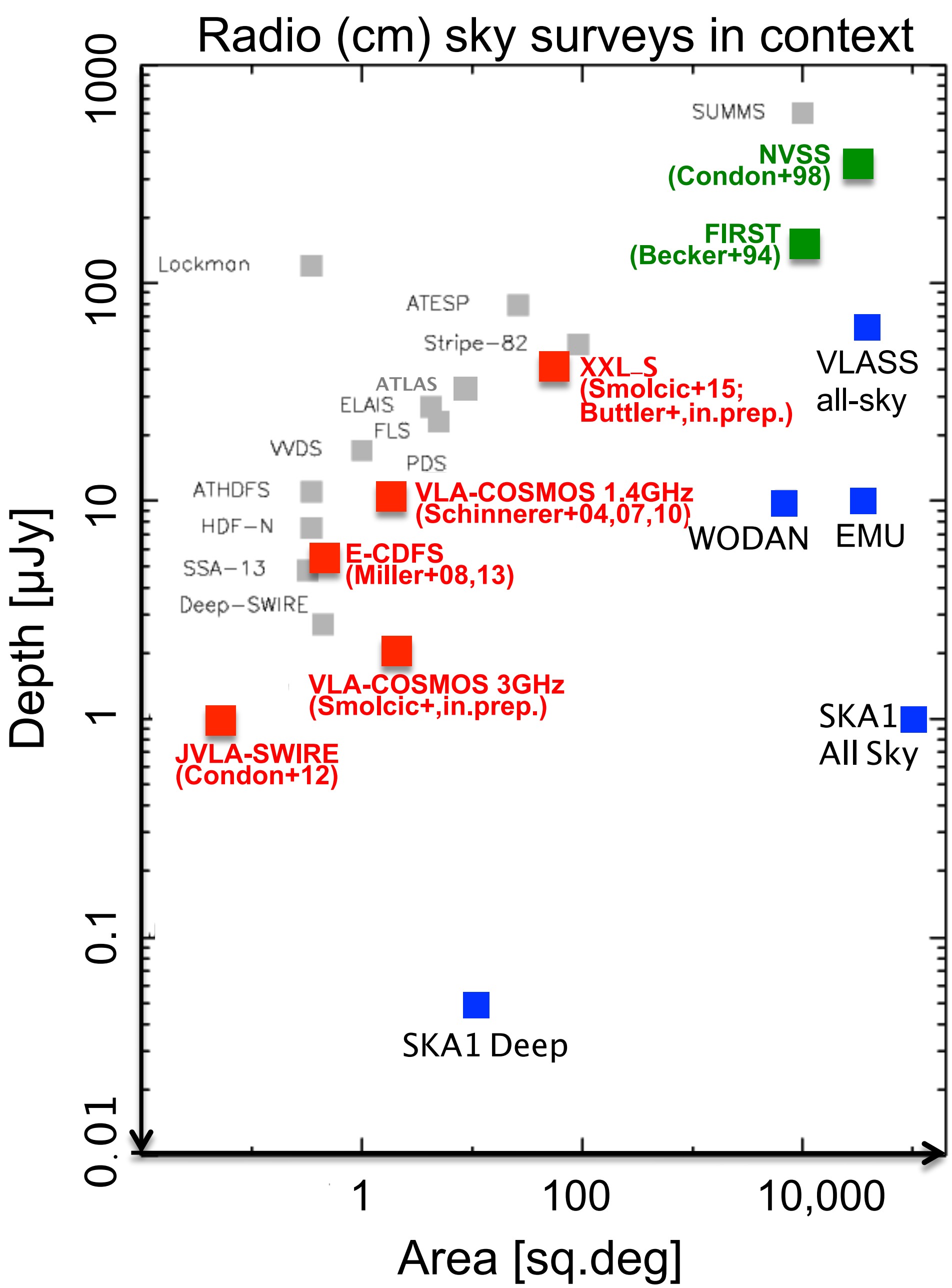

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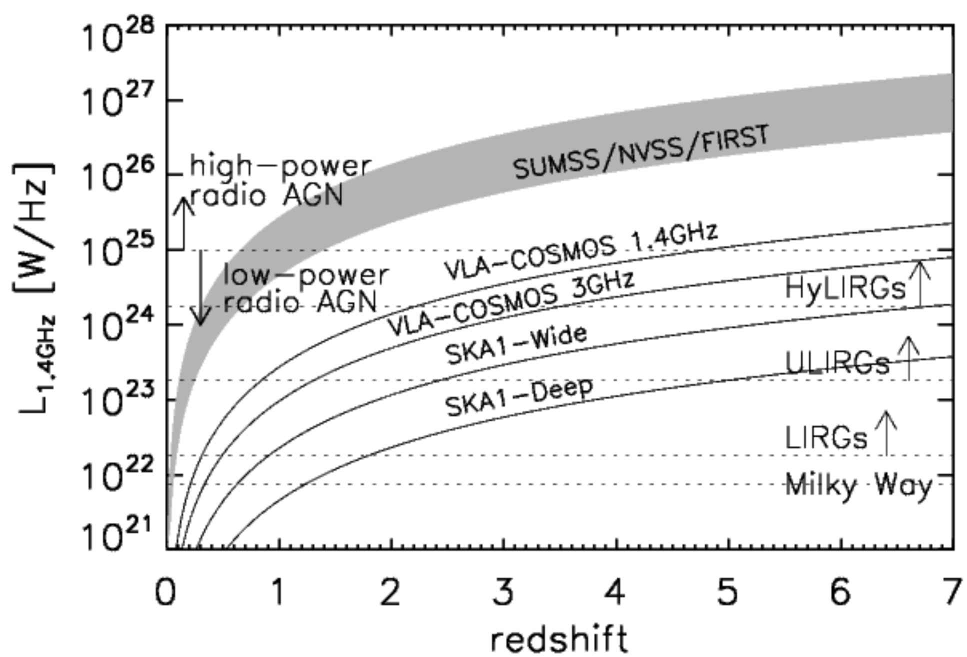


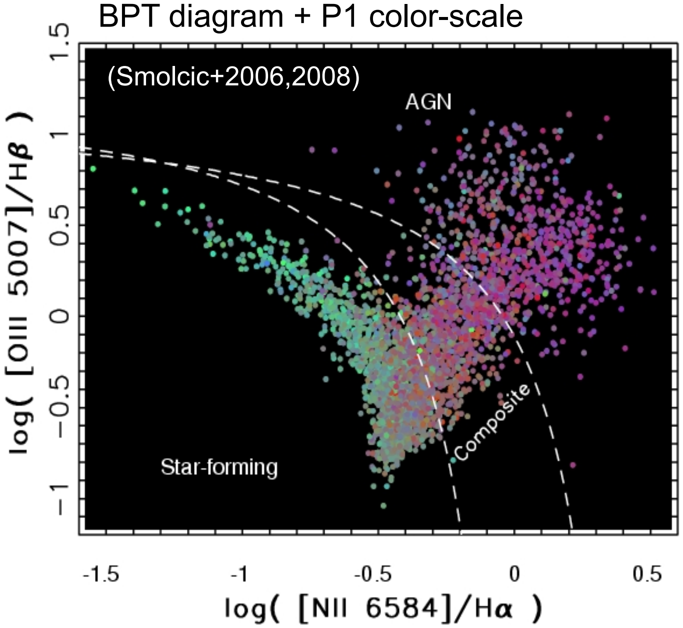
Separating star forming from AGN galaxies

- Optimal: spectroscopic diagnostic tools; z<0.3 (Baldwin, Phillips, Terlevich 1981, Kauffmann et al. 2003, Kewley et al. 2001, 2006)

- Deep radio surveys:
  - z>>0.3; i_{AB}≤26; spectroscopy not available for full sample

- Solution: proxies
  - X-ray + IR-selected AGN (e.g. Brusa et al. 2007; Donley et al. 2013; Padovani et al. 2011; Bonzini et al. 2013)
  - Rest-frame optical-NIR colors (e.g. Smolčić et al. 2006, 2008, Ilbert et al. 2010, 2012)
  - IR-radio correlation (e.g. Padovani et al. 2011, Bonzini et al. 2013)
  - SED fitting - SF+AGN (e.g. Delvecchio et al. 2014)
  - Nikola Baran's talk → separation of VLA-COSMOS 3GHz Large Project sources

BPT diagram + P1 color-scale



Host galaxy properties of HE- and LERAGN

- VLA-COSMOS 3GHz Large Project:
  - Smolčić et al. (in prep.)
  - 384 hours, 3 GHz (10cm); 2sq.deg.,resolution ~0.75”
  - depth ~2.3 μJy/beam
- Source separation
  - Delvecchio et al. (in prep.)
  - LERAGN selection:
    - Radio luminosity excess: log (SFR_{RADIO} / SFR_{IR}) > 0.7
  - HERAGN selection:
    - X-ray: $L_{2\text{-}10keV}$>10^{42} erg/s
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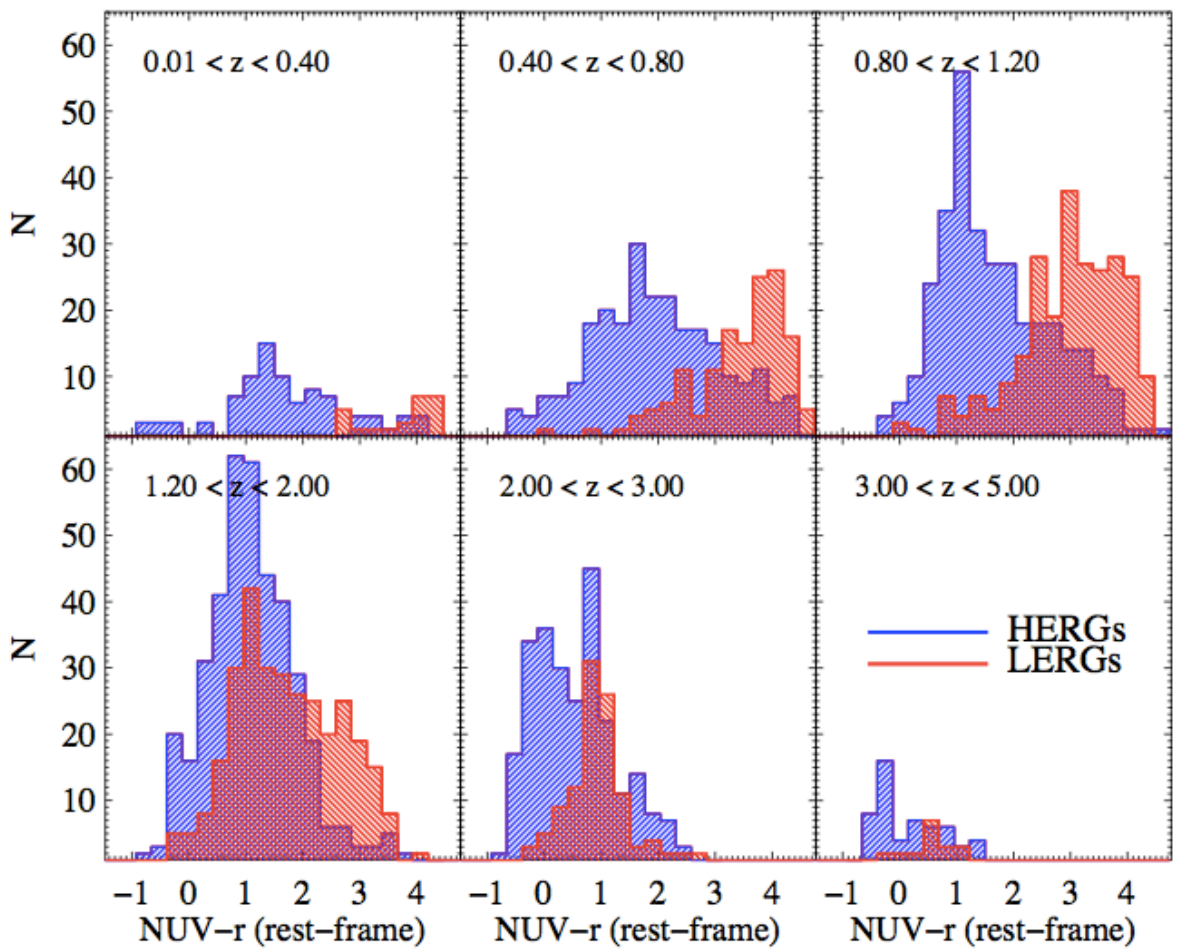

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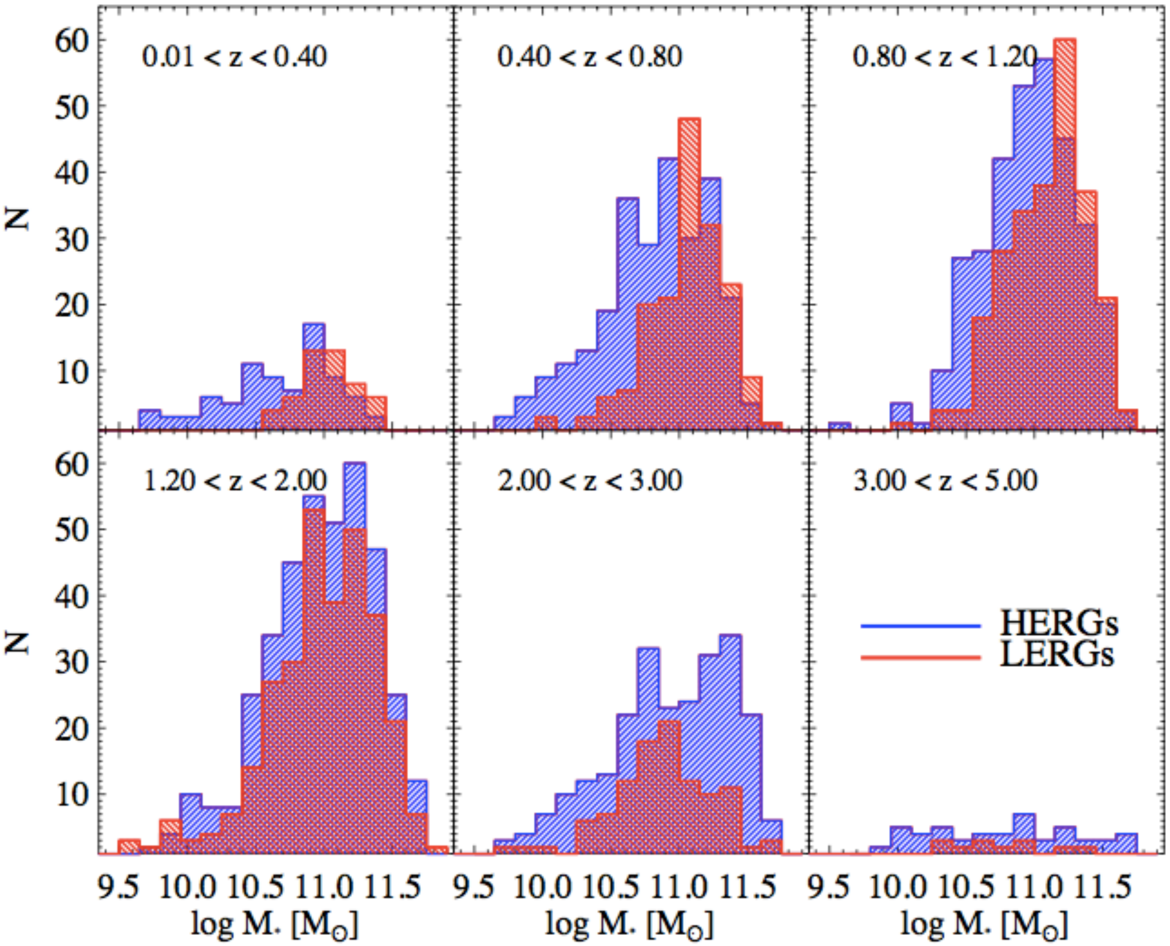

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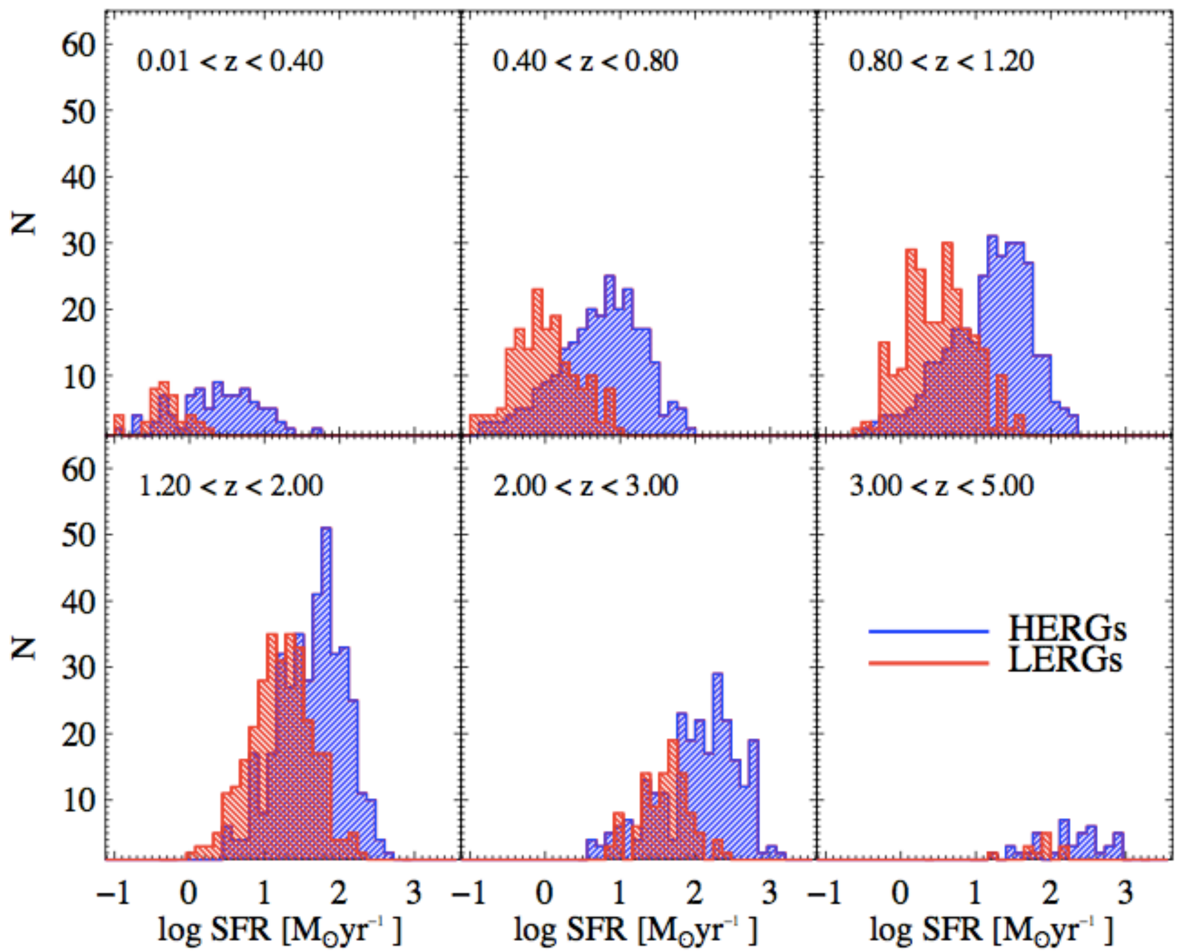

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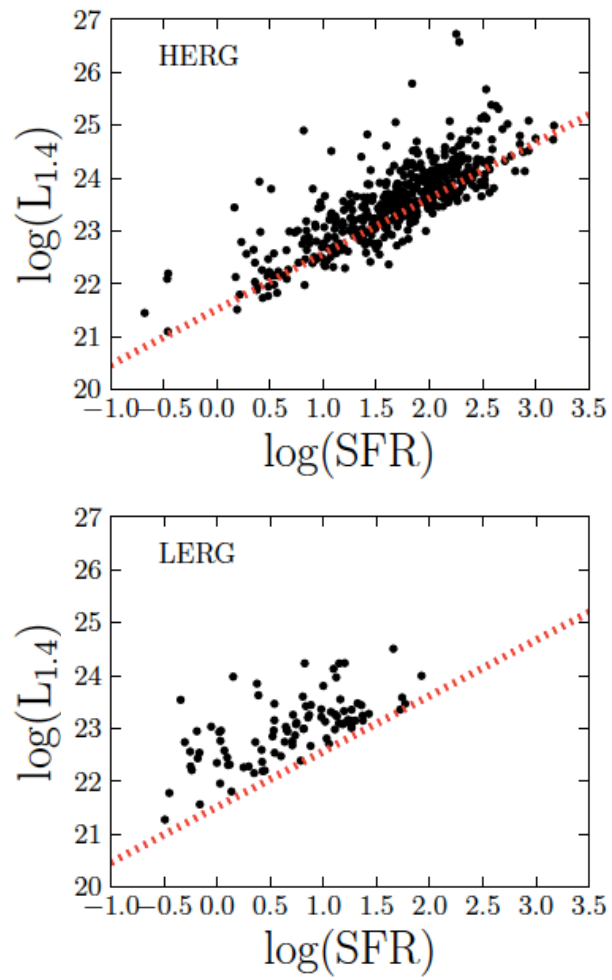

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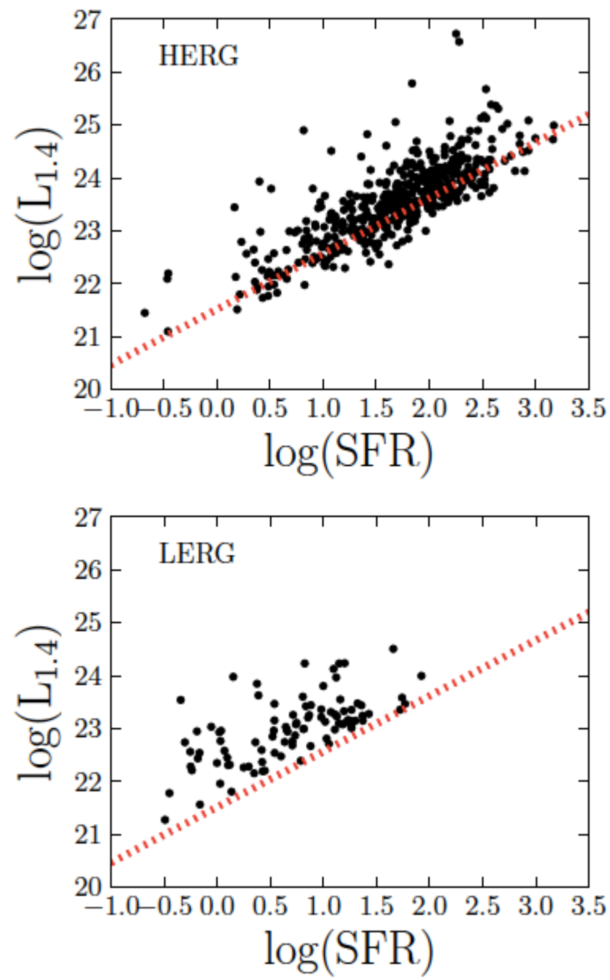
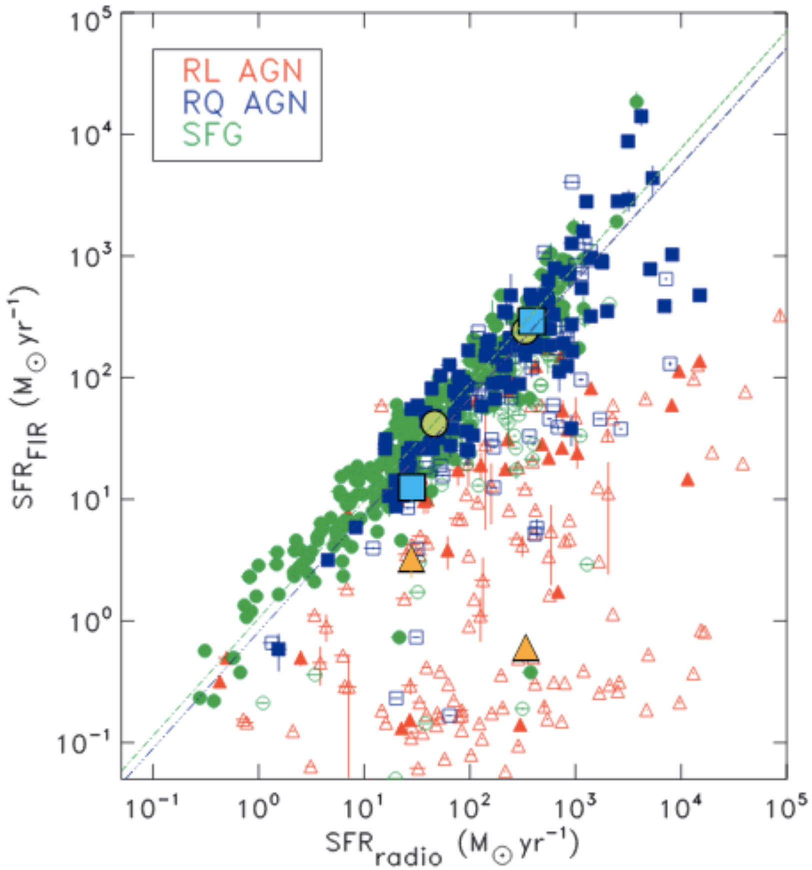
SF contribution to radio emission:
HERAGN: ~65-80% & LERAGN: <~20%



Delhaize et al. (in prep)

Source of radio emission

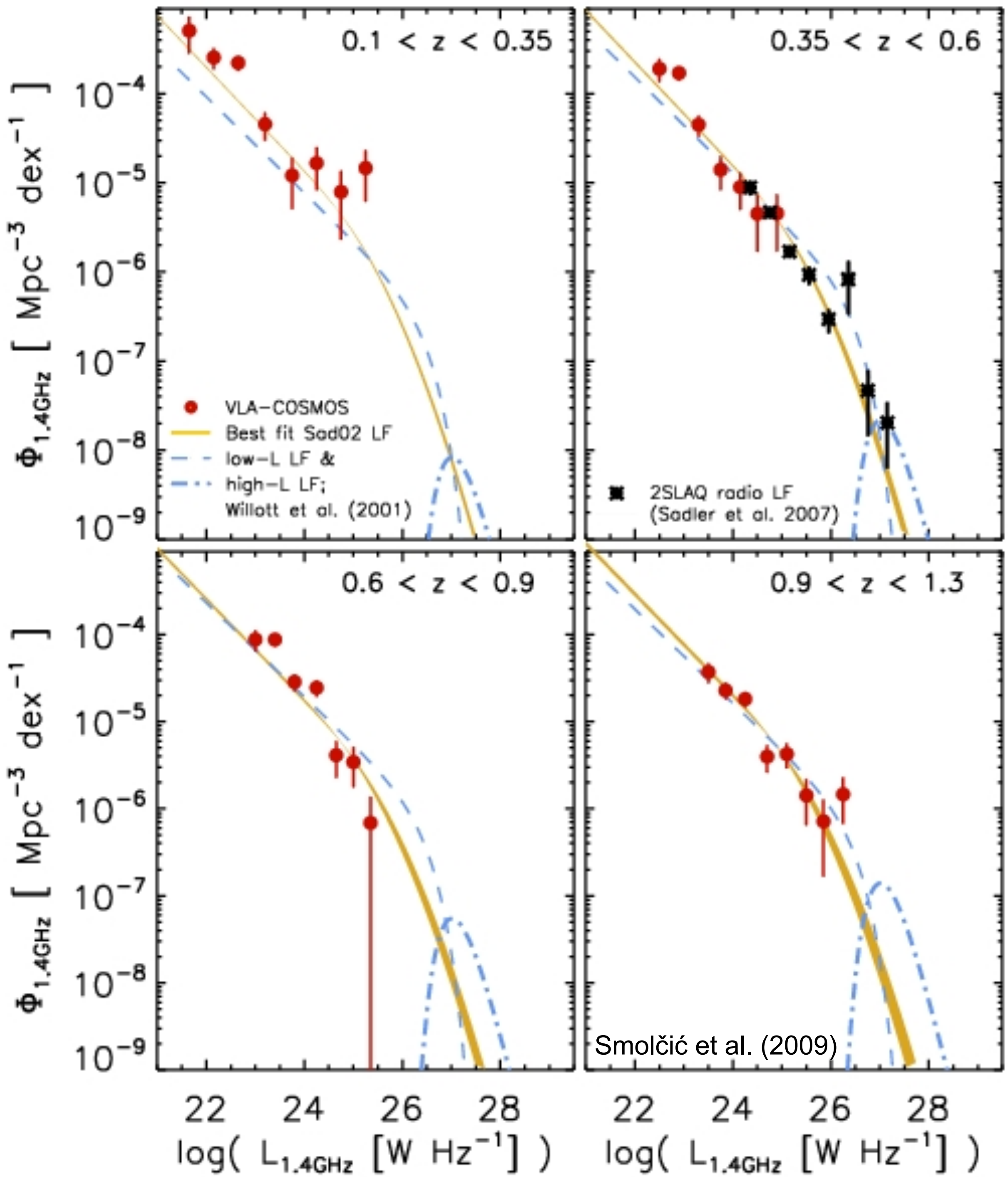
- E-CDFS:
  - Bonzini et al. (2015)
  - 1.4GHz, 0.3 deg^2
  - flux density limit 32.5μJy at field center
- Source separation
  - Bonzini et al. (2013), Padovani et al. (2011)
  - LERAGN (RQ) selection:
    - q_{24} radio excess
  - HERAGN (RL) selection:
    - X-ray: $L_{2\text{-}10keV} > 10^{42}$ erg/s
    - MIR (Donley et al. 2013)



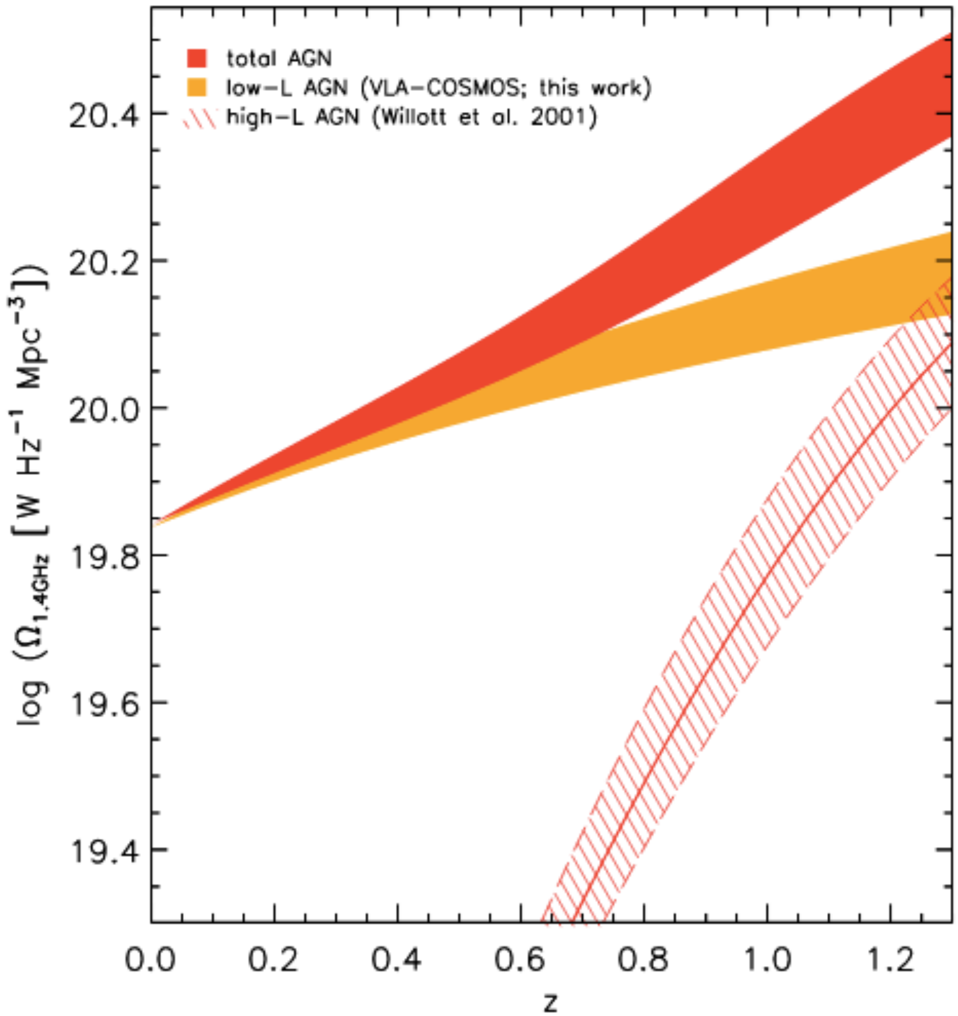
SF contribution dominates RQ (~HERAGN) radio emission
(Bonzini et al. 2015)

Radio AGN luminosity function

- P1 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)
- Modest evolution (consistent with with Clewley & Jarvis 2004, Sadler et al. 2007, Donoso et al. 2008):
  - $\alpha_D = 0$ & $\alpha_L = 0.8 \pm 0.1$
  - $\alpha_D = 1.1 \pm 0.1$ & $\alpha_L = 0$
- High-power radio AGN LF (Willott et al. 2001; 3CRR, 6CE, 7CRS), different evolution than low-power radio AGN



Cosmic evolution of radio AGN out to z~1.3

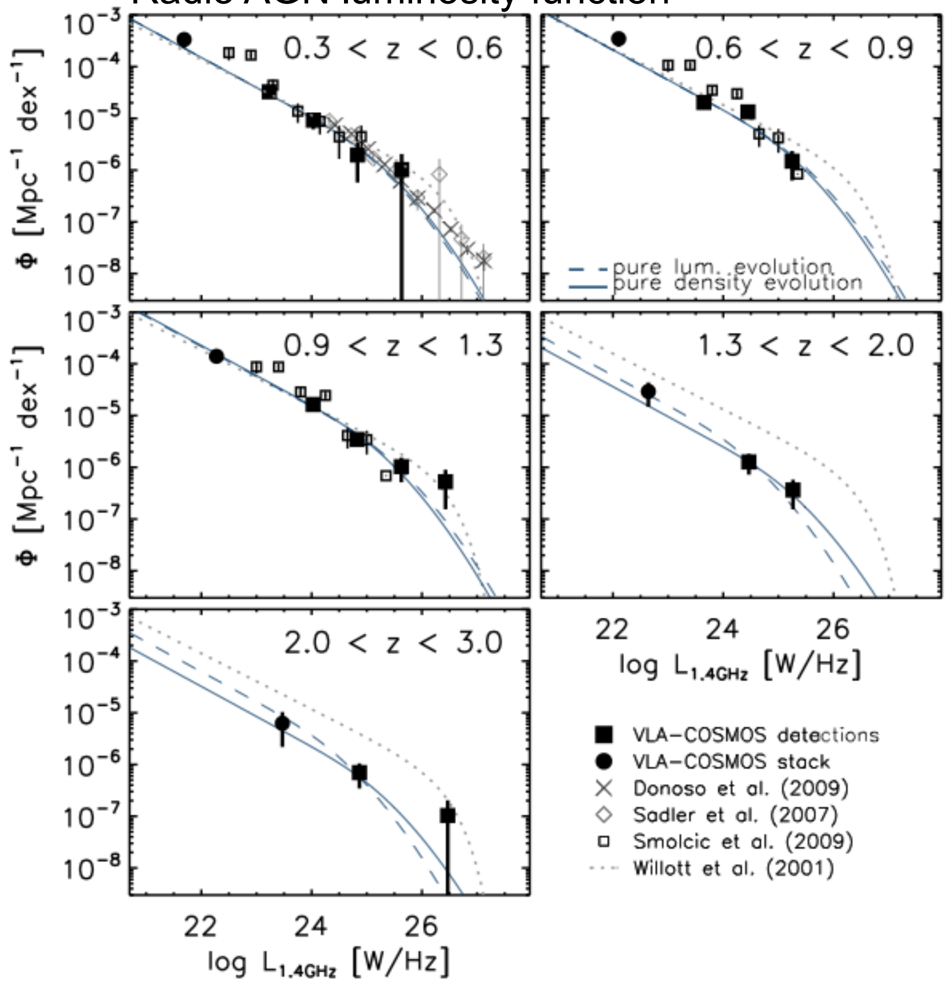


Smolčić et al. (2009)

LERAGN luminosity function at z<5

- VLA-COSMOS 1.4GHz
- Red, quiescent host galaxies
  - M_{NUV}-M_{r*} > 3.5, X-ray detected AGN excluded
  - Luminosity limited radio sample
  - Stack in radio map for those undetected in radio
- 0.1<z<0.3 LF agrees very well with previous determinations

Radio AGN luminosity function



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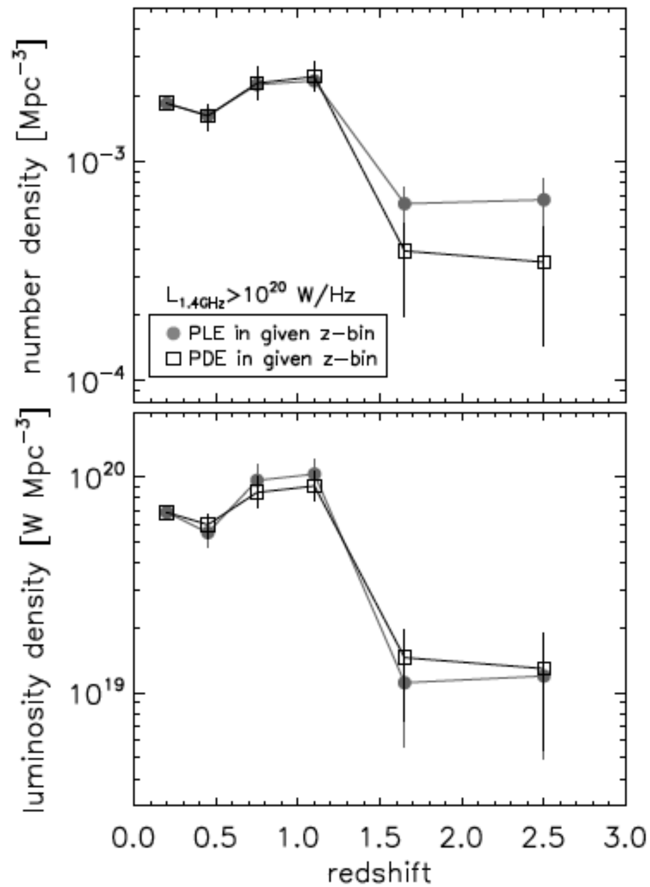
- 0.1<z<0.3 LF agrees very well with previous determinations

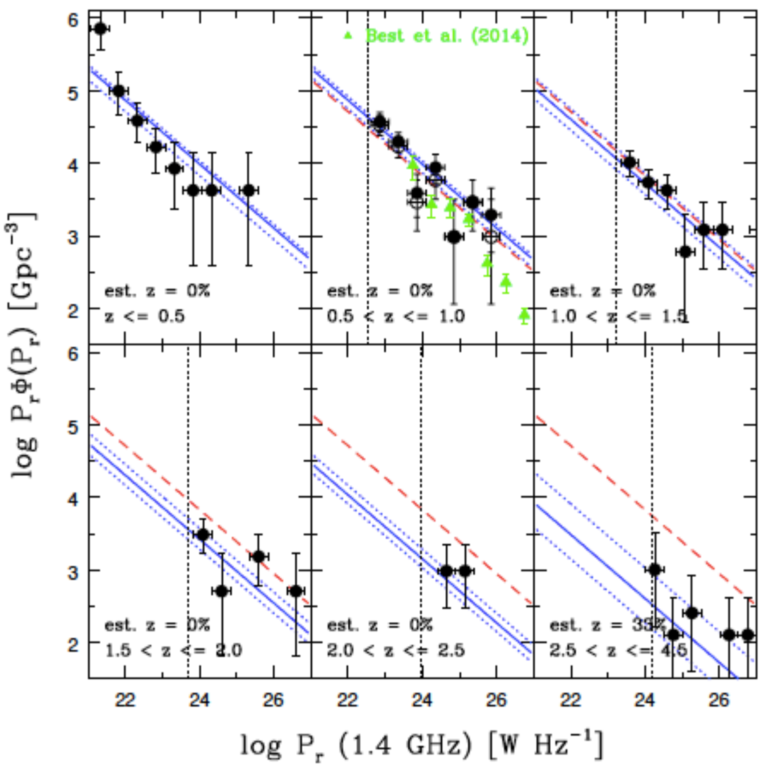
Radio AGN luminosity & number density evolution



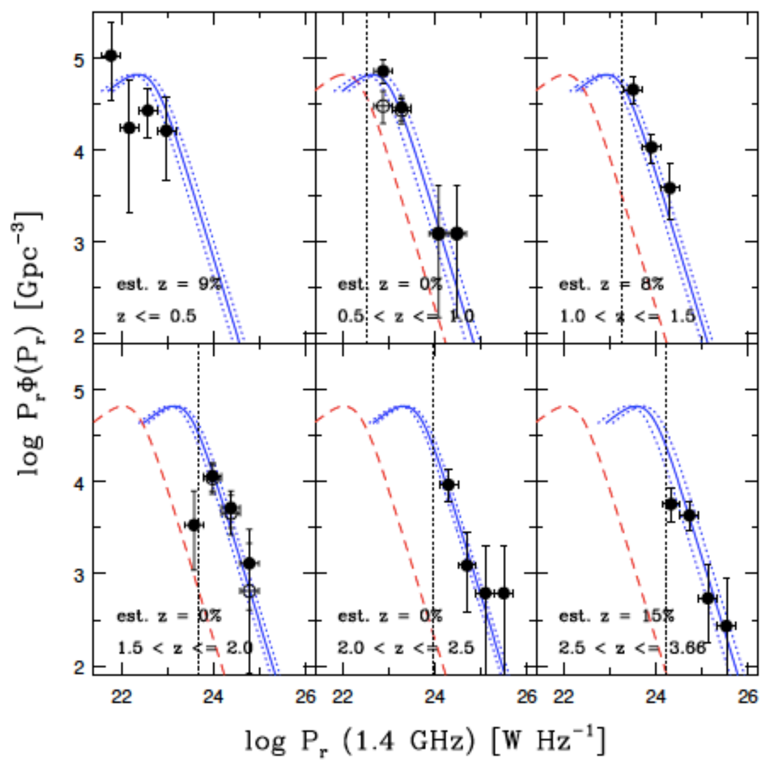
Smolcic et al. (2015)

Cosmic evolution of LE- and HERAGN

Radio loud AGN ~ LERAGN



Radio quiet AGN ~ LERAGN



E-CDFS, 1.4GHz, area 0.3 $deg^{2,}$ flux density limit 32.5 uJy at field center

Padovani et al. (2015)

Summary

	HERAGN (cold mode)	LERAGN (hot mode)	References
Radio luminosity	High ($L_{20cm} \geq 10^{26}$W/Hz)	Lower ($L_{20cm} \lesssim 10^{26}$W/Hz)	Kauffmann et al. 2008, Heckman & Best 2012
Source of radio emission	SF+AGN	AGN	Moric et al. 2010; Hardcastle et al. 2013; Gurkan et al. 2015
Optical color	Green	Red	Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10}M_{\odot}$)	Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3\bullet10^{8}M_{\odot}$)	Low ($<4.3\bullet10^{7}M_{\odot}$)	Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim10^{9}M_{\odot}$)	Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	Barthel 1989; Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009
Cosmic evolution	Steep	Flat + drop-off	Smolcic et al. 2009, 2015; Padovani et al. 2011, 2015

- Fundamental differences between low- and high- excitation radio AGN:
  stellar/BH mass, accretion rate/mode, evolution, gas/dust properties, source of radio emission
- Difference in cosmic evolution of LERAGN & HERAGN
- Open questions:
  - Physical properties through cosmic time
  - Source of radio emission
  - Tracing stellar and SMBH mass build-up through cosmic time
  - Role in galaxy formation/evolution

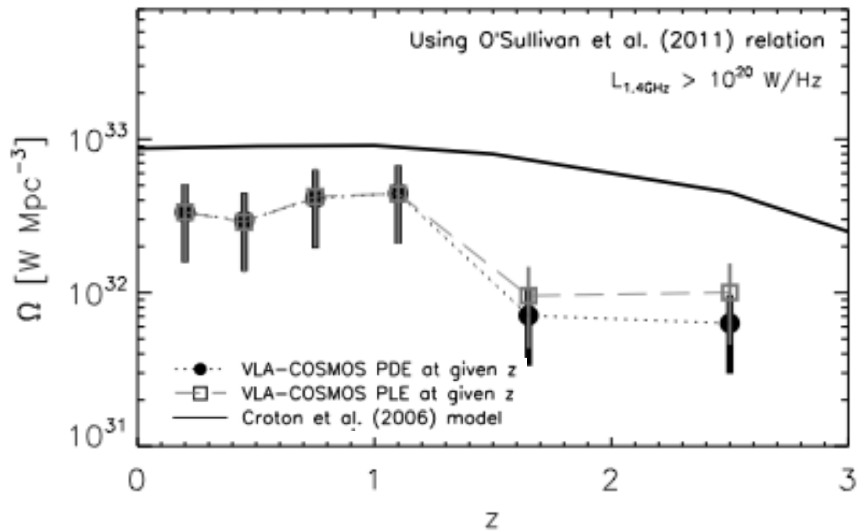
→ Deep, intermediate/large area radio surveys with exquisite multi-λ coverage

Probing out to z~3: radio-mode AGN feedback

- Systematics due to:
  - Unconstrained faint end of LF
  - conversion relation between 20cm and mechanical power
    - based on radio galaxies in galaxy clusters (Bîrzan et al. 2004, 2008, O'Sullivan et al. 2011): radio emission inflates buoyantly rising bubbles in X-ray plasma (i.e. cavities)
    - 0.85 dex scatter when 20cm radio power used

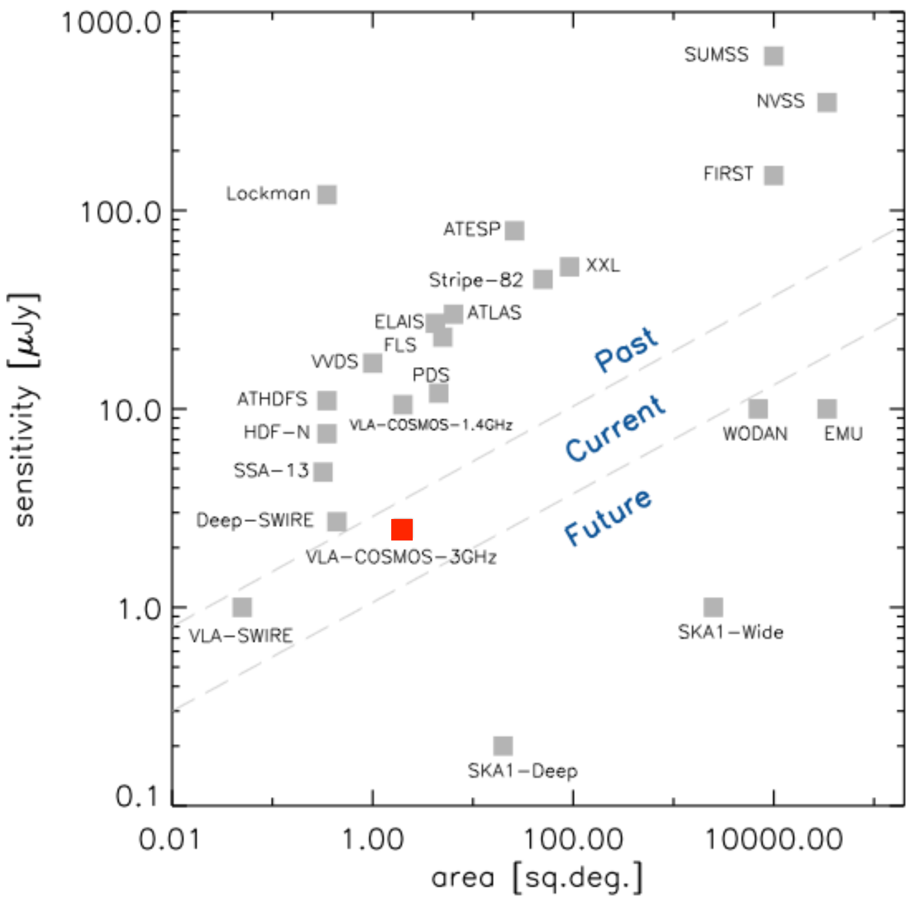
- Agreement between models & observations encouraging

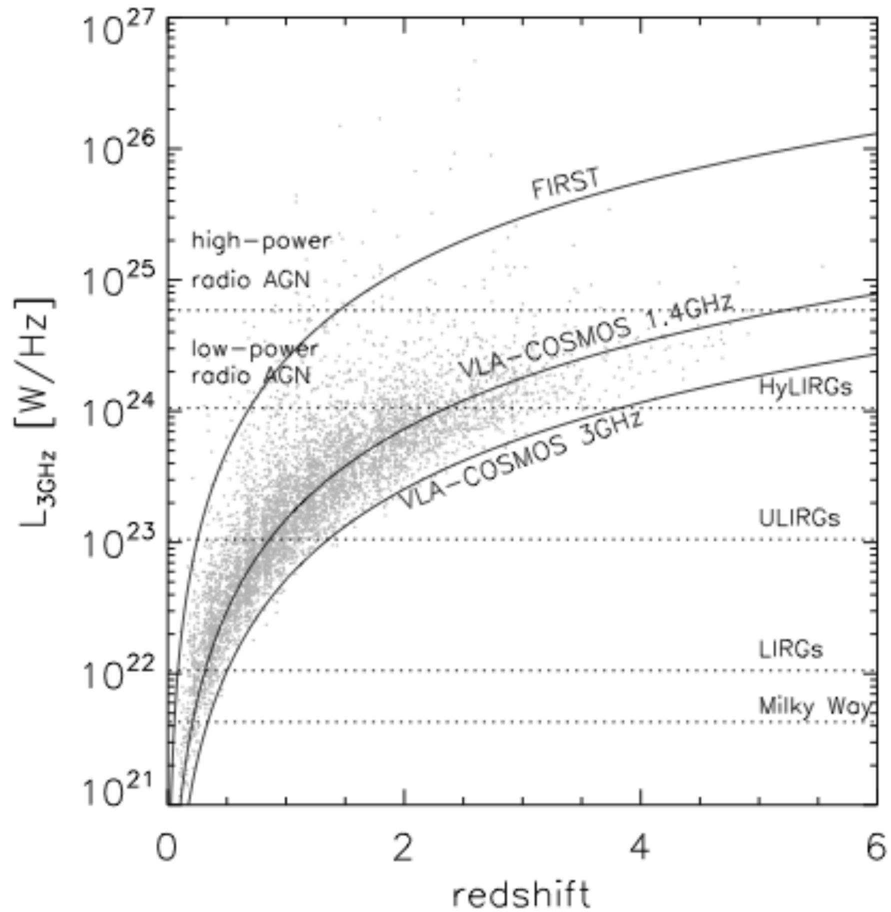
Radio-mode AGN feedback:
volume averaged mechanical heating rate vs. z



Smolcic et al. (2015), see also Smolcic et al. (2009)

VLA-COSMOS 3GHz Large Project

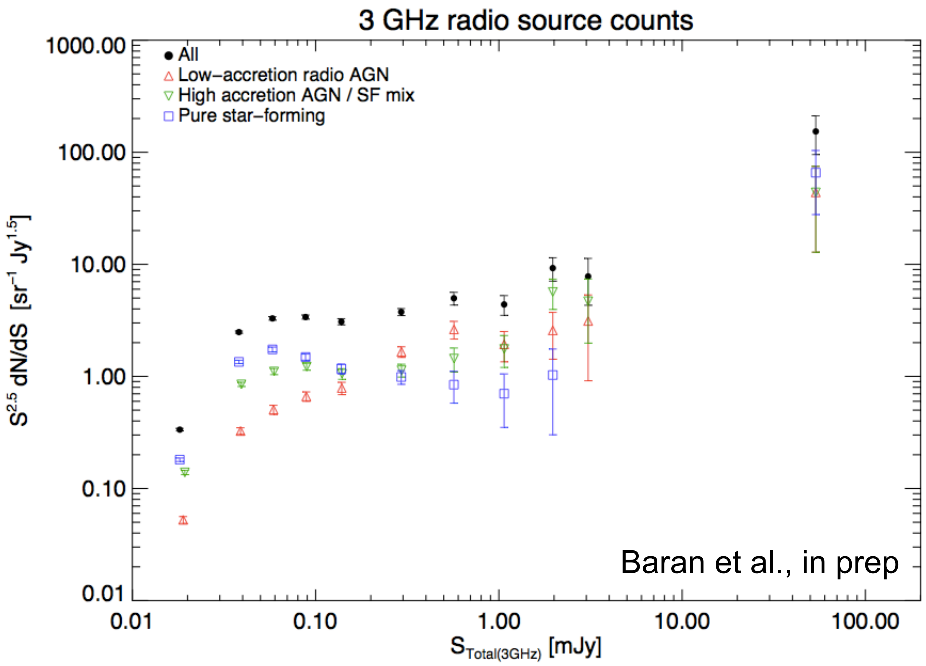




Smolcic et al., in prep

VLA-COSMOS 3GHz Large Project: First results

- VLA-COSMOS 3GHz Large Project:
  - Smolčić et al., in prep
  - 384 hours, 3 GHz (10cm); 2sq.deg.,resolution ~0.7-1”
  - depth ~2.45 μJy
  - 8765 source components
  - 2516 SF, 835 passive (LERAGN), 1676 intermediate (HERAGN/ composites); i*<25.5, X-ray AGN excluded
  - Outlook:
    - LFs and their evolution for subpopulations out to z>3 with direct detections, and further via stacking in radio map
    - predictions for the SKA, and its precursors



Summary & conclusions

- Fundamental differences between low- and high- excitation radio AGN (SDSS/NVSS): stellar/BH mass, accretion rate/mode, evolution, gas/dust properties

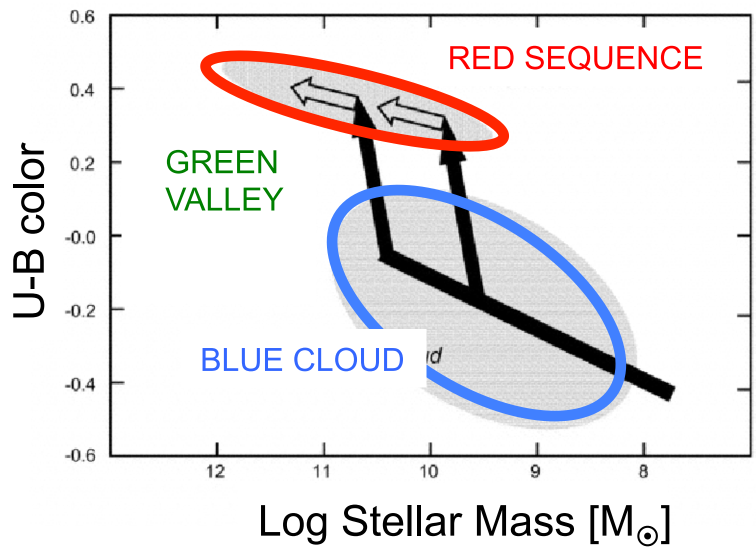
- LERAGN & HERAGN reflect different stages of massive galaxy formation in context of blue-to-red galaxy evolution

- LERAGN ($L_{1.4GHz} \leq 10^{25}$W/Hz) are likely prime generators of 'radio-mode' feedback

- First observational constraint (based on VLA-COSMOS) of importance of 'radio-mode' feedback in massive galaxy formation ($z \leq 3$): Fairly good agreement between radio-AGN feedback in model & observations

- Outlook: Constrain the faint end of radio AGN LF (JVLA-COSMOS @rms~2uJy)

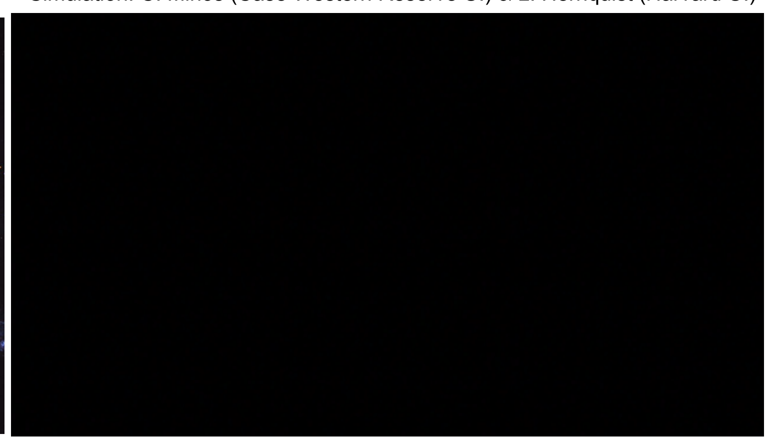
Massive galaxy formation: observations



- Blue-to-red galaxy formation
  - Sanders & Mirabel 1996, Bell et al. 2004, Borch et al. 2006, Faber et al. 2007, Hopkins et al. 2007 & many others

M101; The Pinwheel Galaxy; Copyright: A. Block, U. Arizona

Visualization: F. Summers (Space Telescope Science Institute).
Simulation: C. Mihos (Case Western Reserve U.) & L. Hernquist (Harvard U.)



M87; Virgo cluster; Copyright: R. Gendler

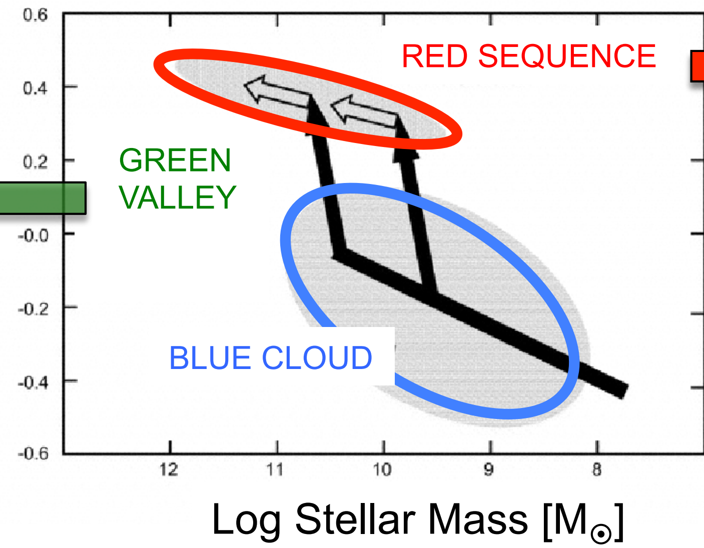
Massive galaxy formation: models

Problem: more massive galaxies predicted than observed

Solution: suppression of gas cooling in massive galaxies (e.g. Kauffmann et al. 1999, Somerville & Primack 1999, Cole et al. 2000)

Physics: Radio AGN are energetic enough to suppress cooling, if coupling to ICM/IGM efficient (e.g. Benson et al. 2003, Croton et al. 2006, Bower et al. 2006, Scannapieco et a. 2006)

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

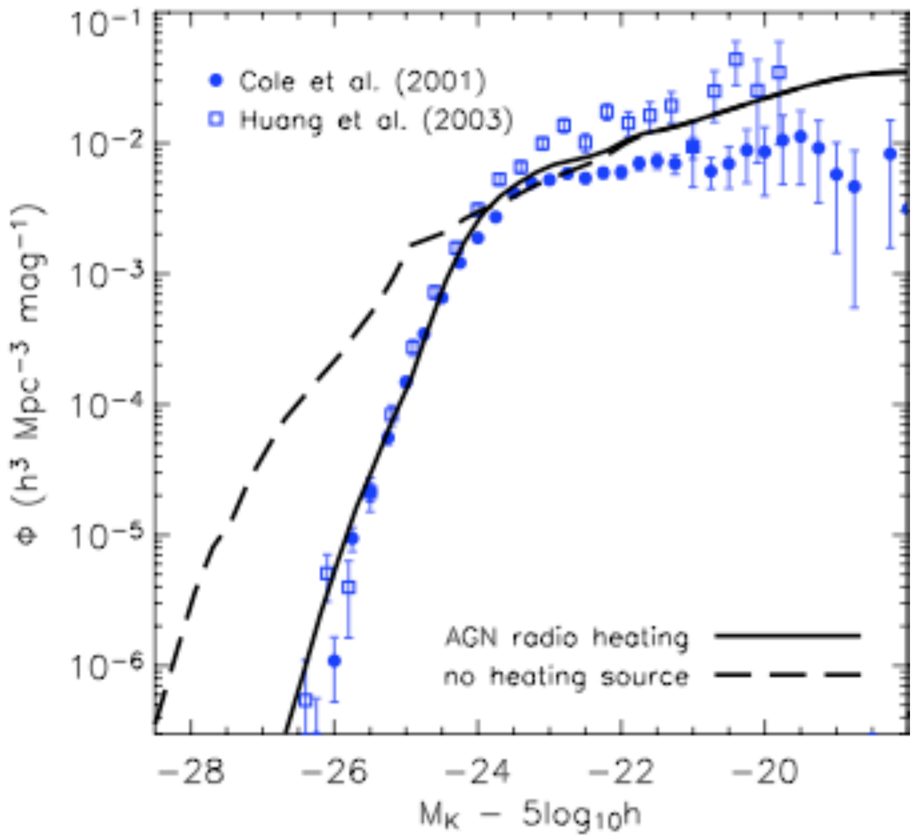
- "maintenance" mode
- Once a static hot (X-ray) halo forms around galaxy
- Modes BH growth
- Radio outflows heat surrounding gas → truncation of further stellar mass growth

Allows good reproduction of observed galaxy properties

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

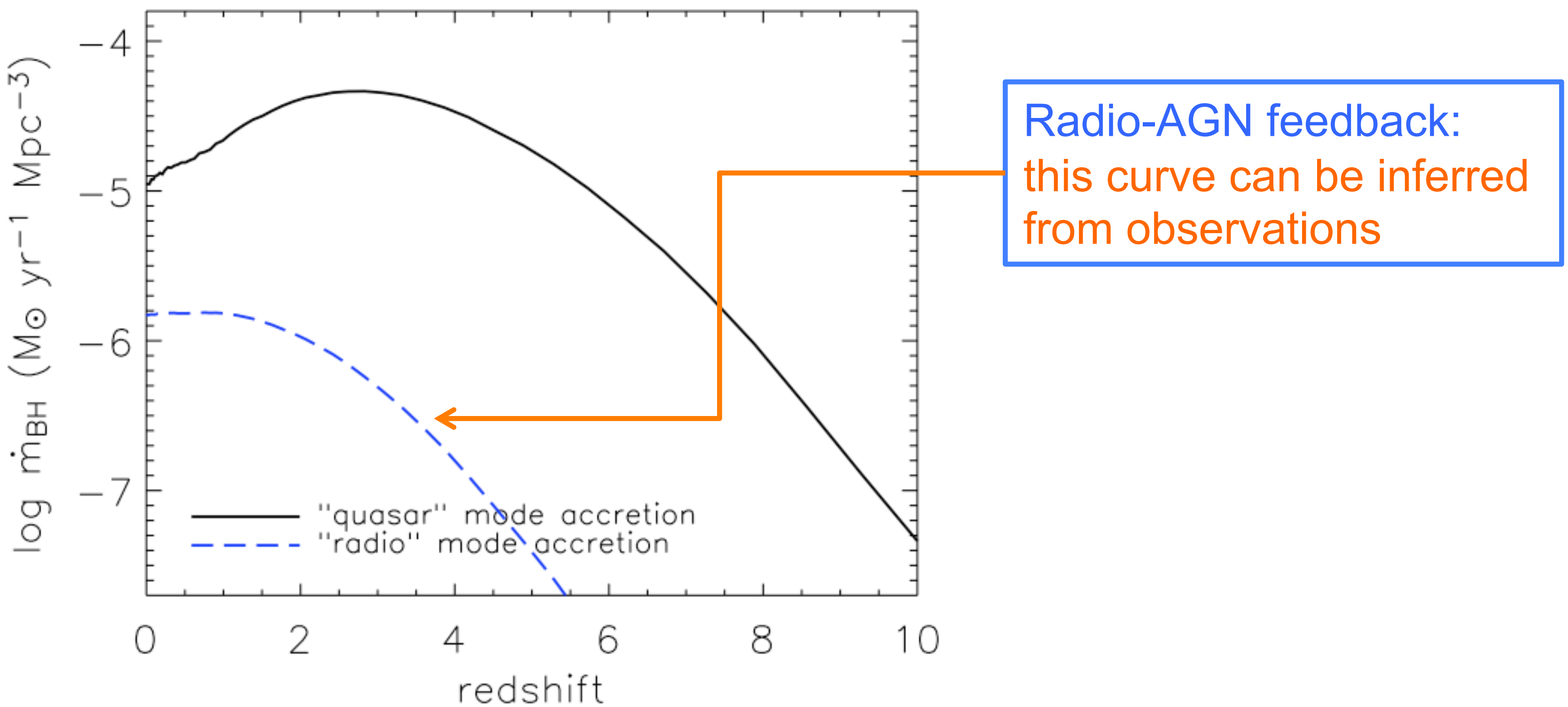
Radio-mode feedback in cosmological models

Croton et al. 2006

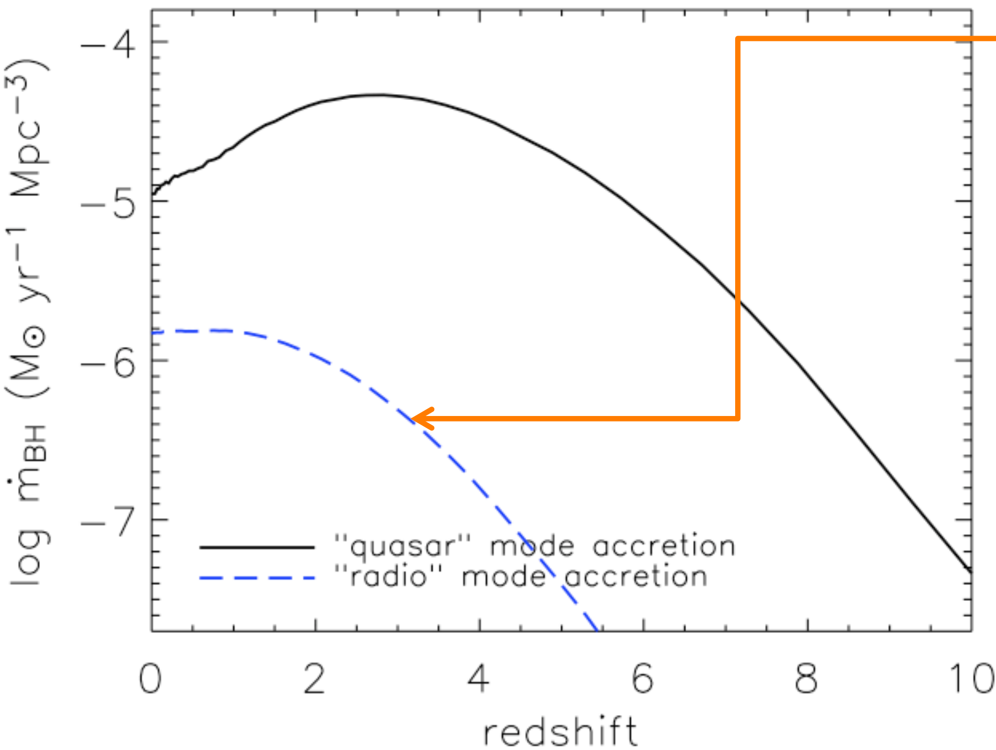


Radio-mode feedback in cosmological models

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



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

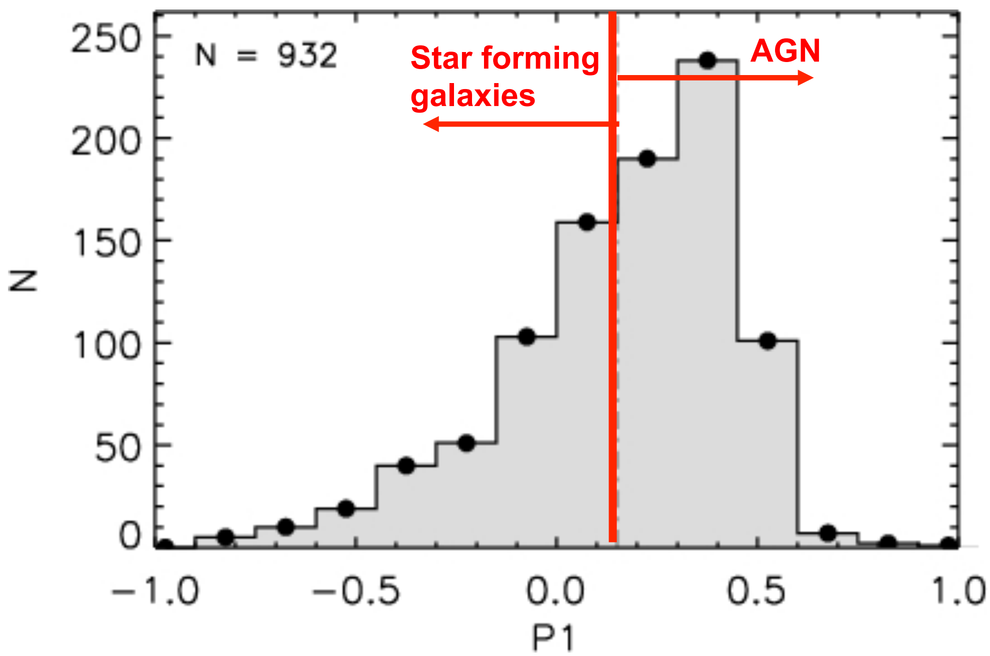
Low-luminosity radio AGN are prime generators of 'radio-mode' feedback ➡

I) deep radio observations of
II) a large area on the sky
III) an efficient AGN identifier

Rest-frame color based selection method applied to VLA-COSMOS sources

- Rest-frame color (P1) synthetized using Bruzual & Charlot (2003) stellar population synthesis models

  ➔P1 error ~ 0.1
- ~45% have spec- z
  ~55% have photo-z, δz~0.03(1+z)
- Applied to VLA-COSMOS galaxies at redshift ≤ 1.3
- Synthetized distribution similar to the local one (SDSS/NVSS)
- Rest-frame colors of radio selected galaxies seem not to evolve with redshift ➔ radio emission triggered in similar host galaxies at different redshifts (consistent Barger et al. 2007, Huynh et al. 2009)



Smolčić et al. (2008)

Composition of VLA-COSMOS radio AGN

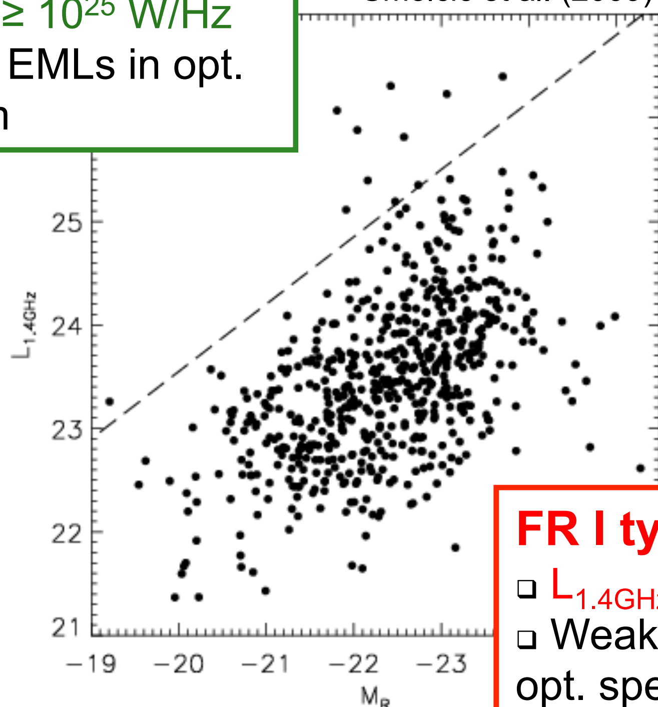
~600 radio AGN

($L_{1.4GHz} \leq 10^{25}$ W/Hz; $z \leq 1.3$)

FR II type:

- $L_{1.4GHz} \geq 10^{25}$ W/Hz
- Strong EMLs in opt. spectrum

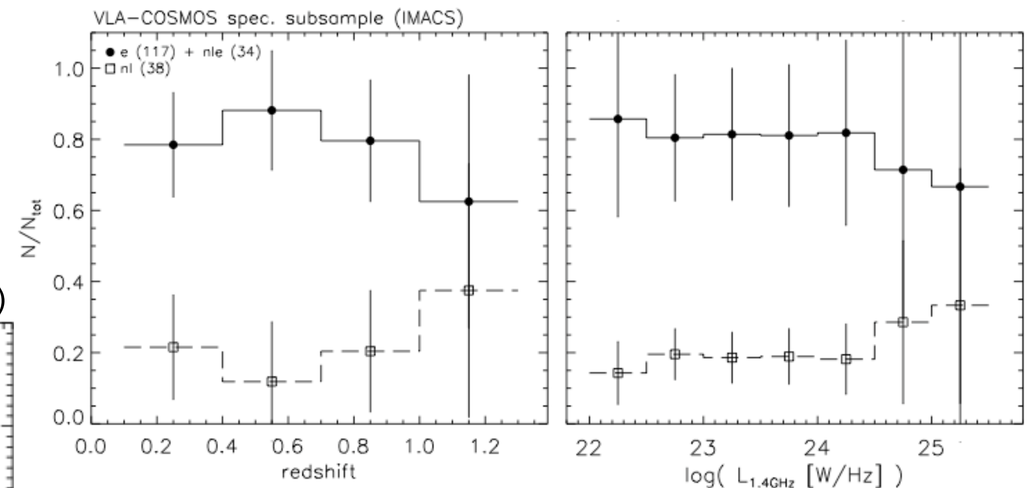
Smolčić et al. (2009)



Ledlow & Owen 1996

FR I type:

- $L_{1.4GHz} \leq 10^{25}$ W/Hz
- Weak or no EMLs in opt. spectrum



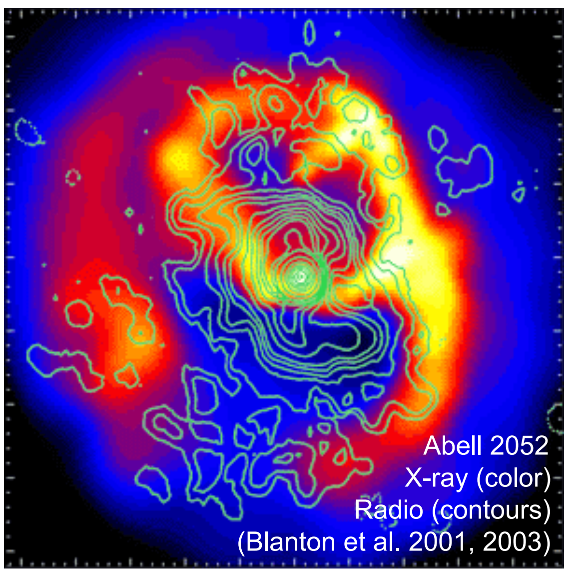
Spectroscopic subsample (IMACS, Trump et al. 2007; ~30% of total sample) suggests that 60-90% of VLA-COSMOS AGN are LERAGN

20cm power ➡ mechanical power output

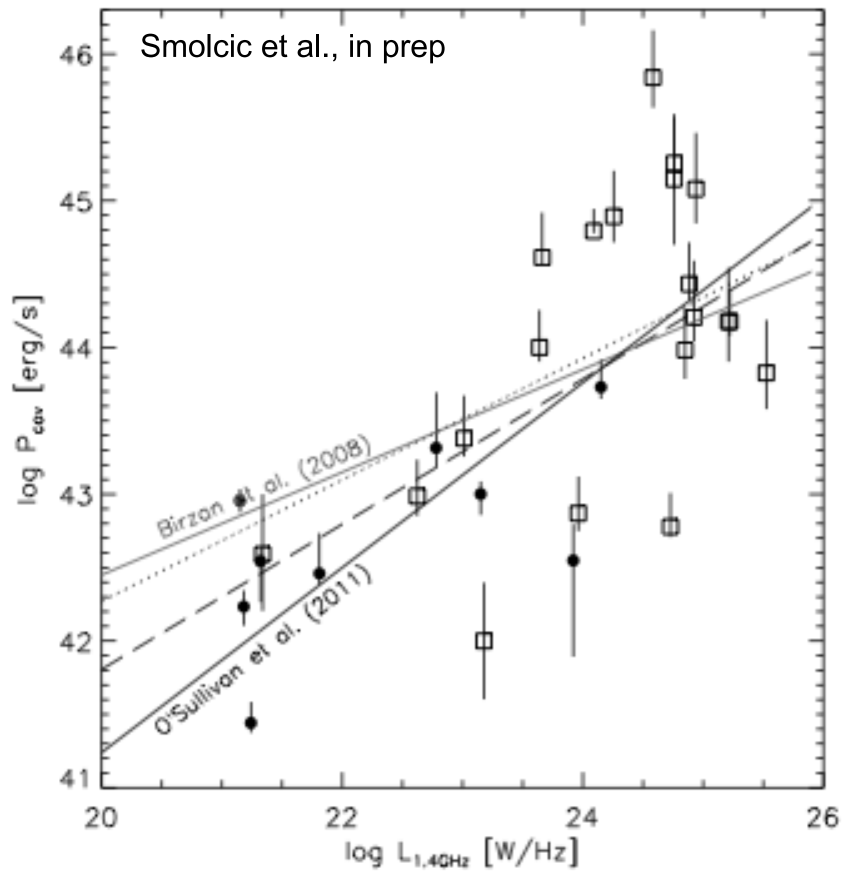
- Scaling relation based on radio galaxies in galaxy clusters (Bîrzan et al. 2004, 2008): radio emission inflates buoyantly rising bubbles in X-ray plasma (i.e. cavities)
- 0.85 dex scatter when 20cm radio power used

$$\log P_{\rm cav} = (0.35 \pm 0.07) \log P_{1400} + (1.85 \pm 0.10)$$

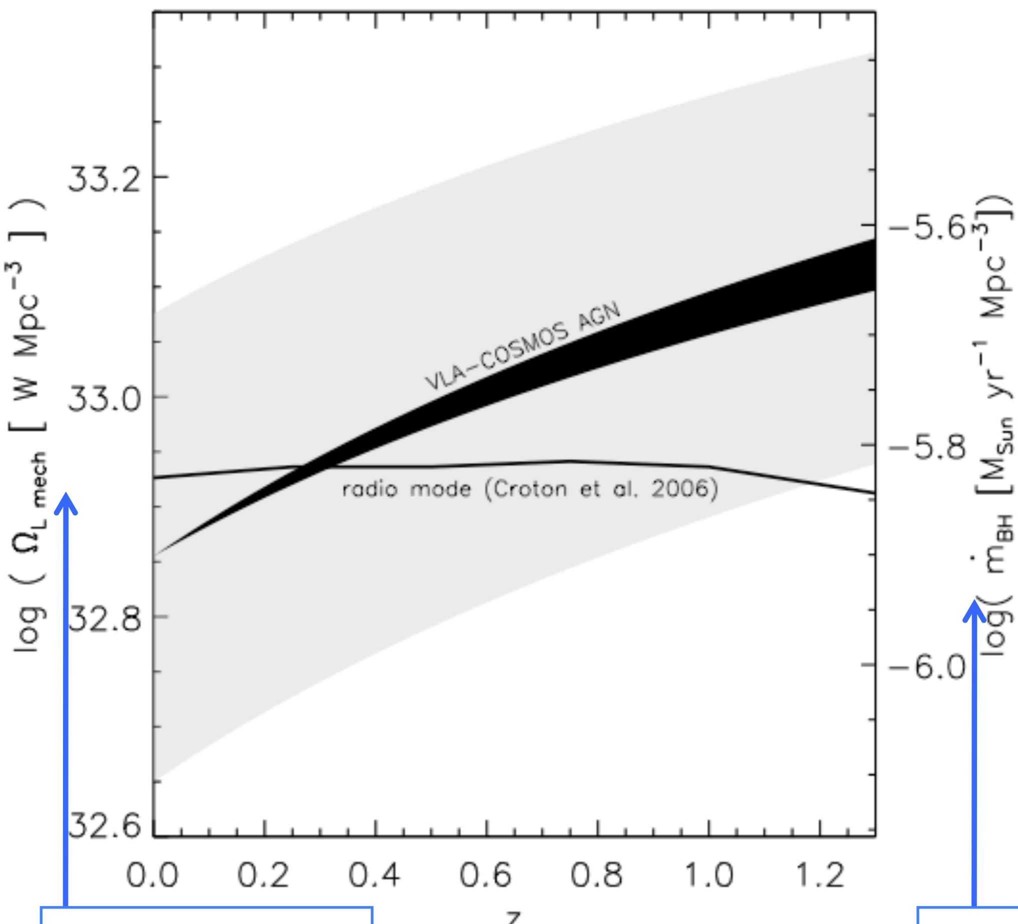
Birzan et al. 2008



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



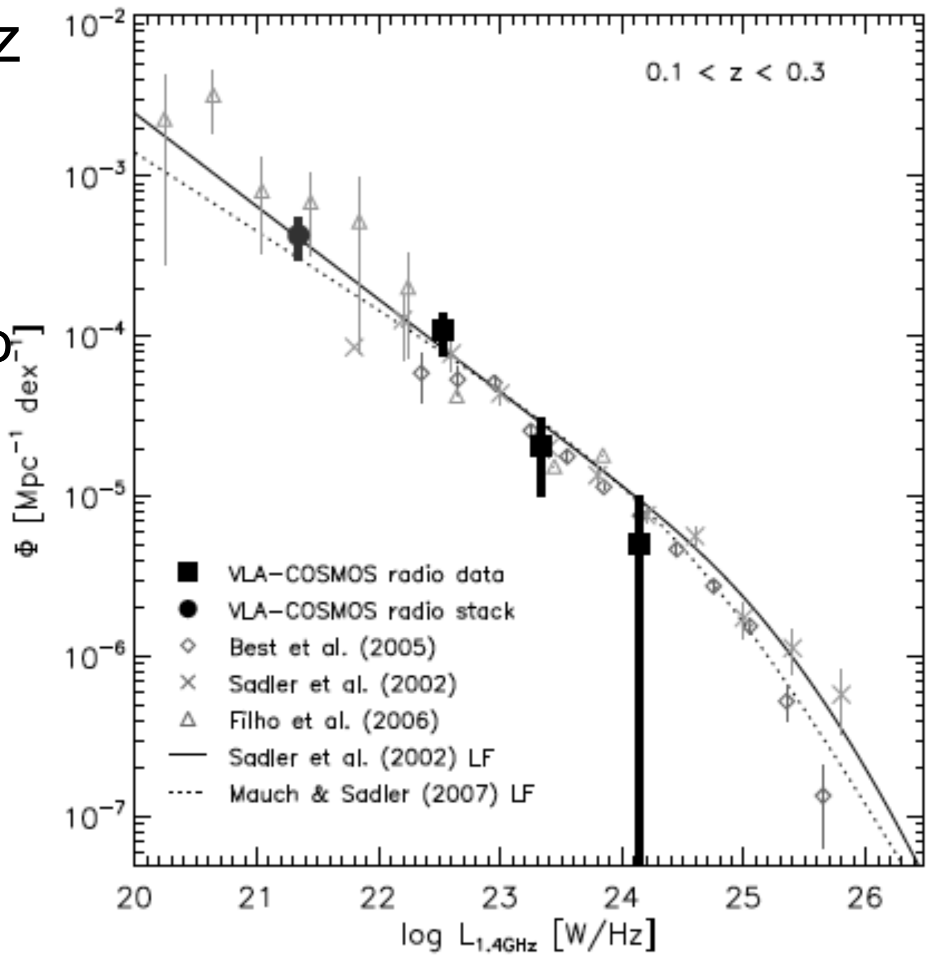
Agreement between cosmological model and observations is encouraging for the idea of 'radio mode' feedback in the context of massive galaxy formation

Smolčić et al. (2009)

Volume averaged mechanical heating rate ← $\Omega_{L\ mech} = 0.1\dot{m}c^2$ → Comoving BH accretion rate density

Radio (LER)AGN luminosity function

- VLA-COSMOS 1.4GHz
- Red, quiescent host galaxies: M_{NUV}-M_{r^*} > 3.5
  - Luminosity limited radio sample
  - Stack in radio map for those undetected in radio
- 0.1<z<0.3
- LF agrees very well with previous determinations

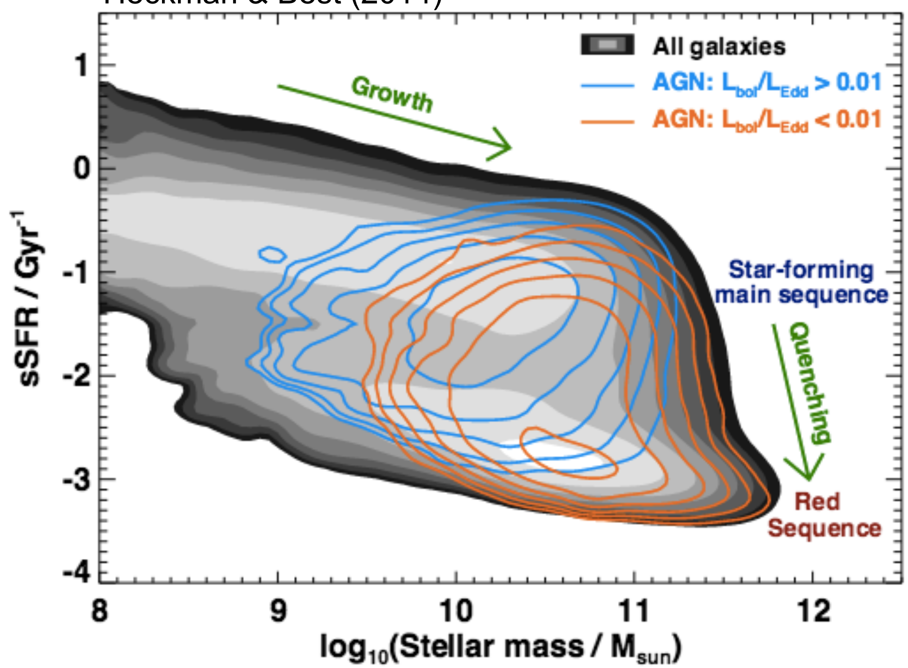


Smolčić et al. (2015, in prep)

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

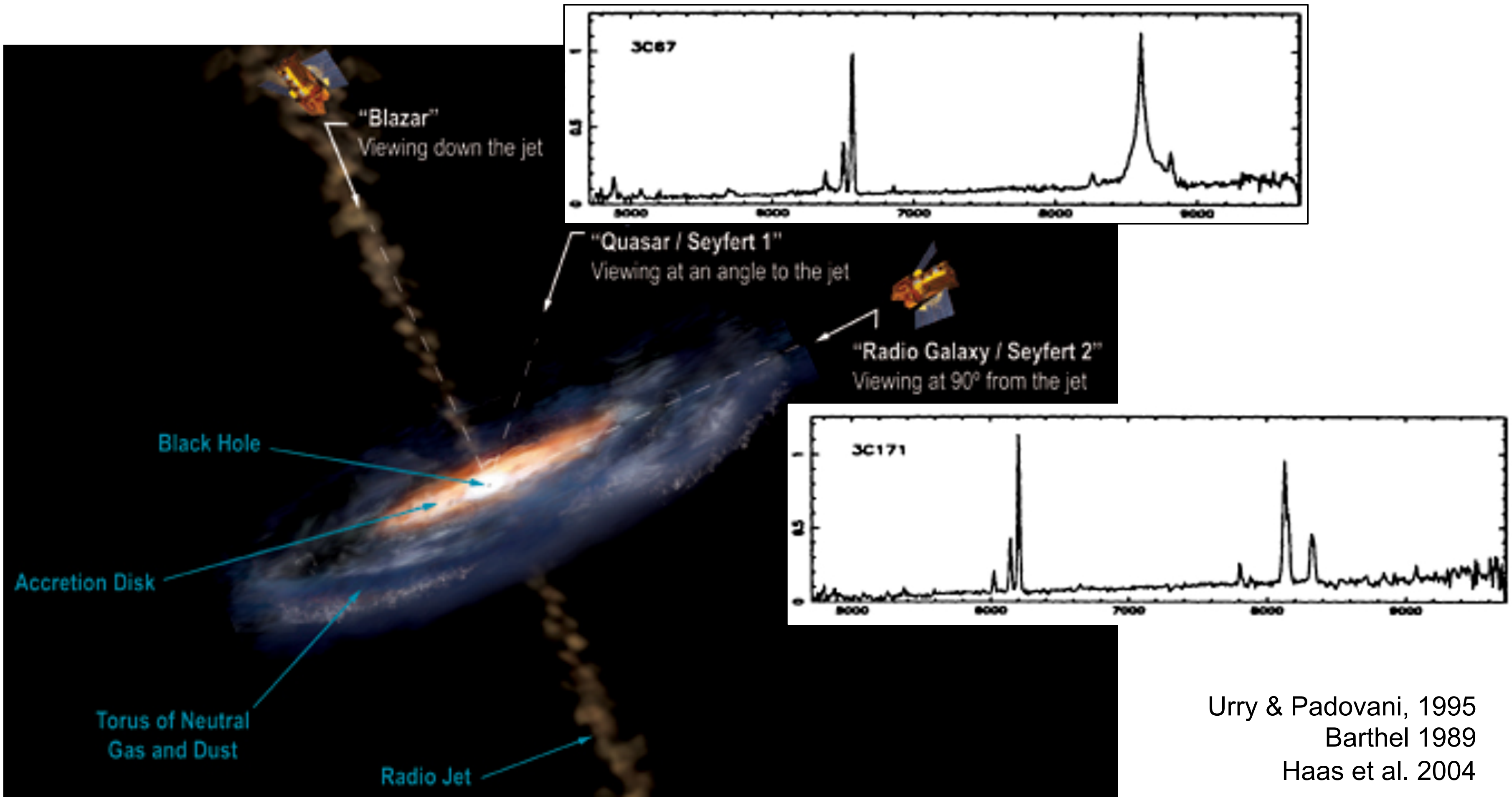
	HERAGN (cold mode)	LERAGN (hot mode)	References
Radio luminosity	High ($L_{20cm} \geq 10^{25}$ W/Hz)	Lower ($L_{20cm} \leq 10^{25}$ W/Hz)	Kauffmann et al. 2008, Heckman & Best 2012
Optical color	Green	Red	Baum et al. 1992; Baldi & Capetti 2008; Smolčić et al. 2008; Smolčić 2009
Stellar mass	Lower than LERAGN	Highest ($\geq 5\times10^{10} M_\odot$)	Kauffmann et al. 2008; Smolčić et al. 2008; Tasse et al. 2008; Smolčić 2009
Gas mass	Higher ($3\bullet10^{8} M_\odot$)	Low ($<4.3\bullet10^{7} M_\odot$)	Smolčić & Riechers 2011
BH mass	Lower than LERAGN	Highest ($\sim10^{9} M_\odot$)	Baum et al. 1992; Chiaberge et al. 2005; Kauffmann et al. 2008; Smolčić et al. 2008; Smolčić 2009
BH accretion rate	~Eddington	sub-Eddington	Barthel 1989; Haas 2004; Evans et al. 2006; Hardcastle et al. 2006, 2007; Smolčić 2009
Evolution ($z \leq 1.3$)	Steep	Flat	Smolčić et al. 2009, 2015; Padovani et al. 2011

Heckman & Best (2014)



Unified model for AGN

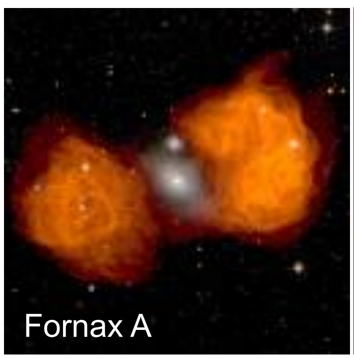
- High excitation radio AGN: HERAGN (or cold mode)

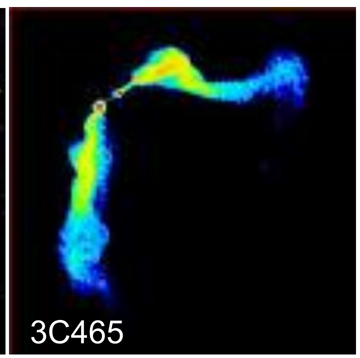


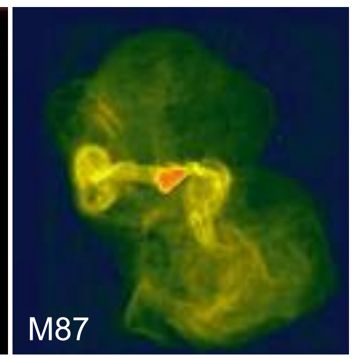
Urry & Padovani, 1995
Barthel 1989
Haas et al. 2004

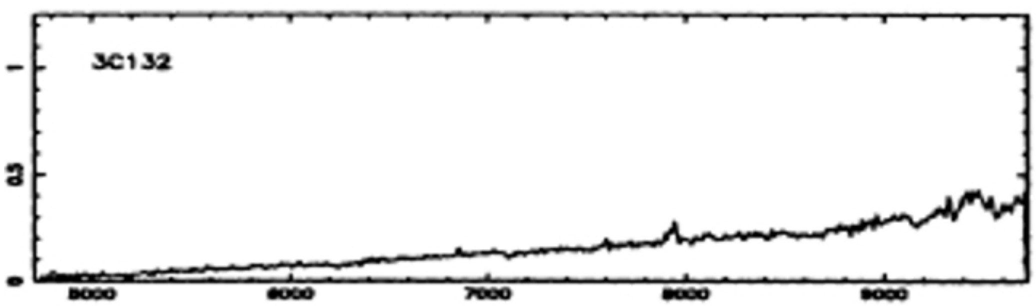
Low Excitation Radio AGN (LERAGN or hot mode): A challenge for the Unified Model

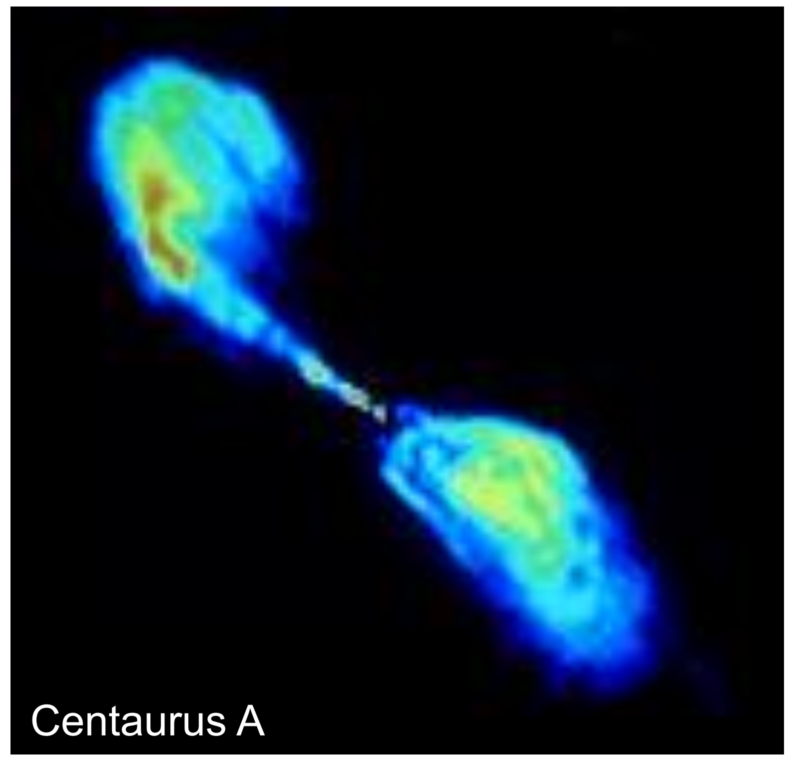
- Optical spectrum devoid of strong emission lines
- Identified as AGN in the radio window
  - Usually LINER, absorption line AGN & FR I type
  - $L_{1.4GHz} \lesssim 10^{25}$ W/Hz



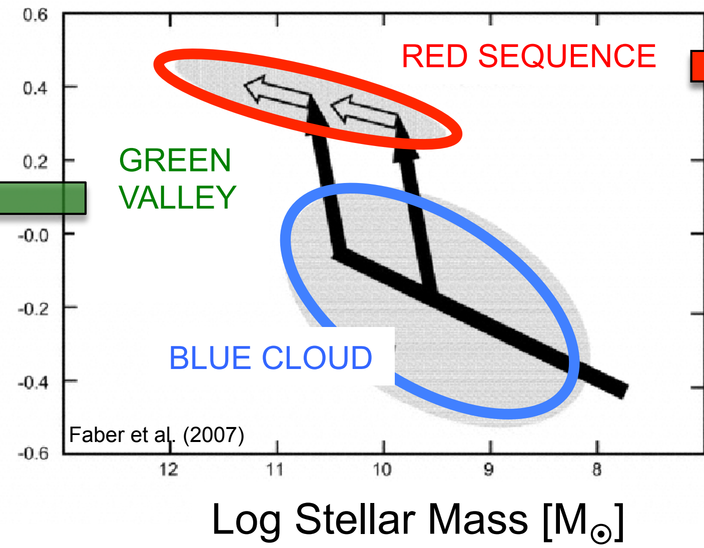








AGN feedback in cosmological models



QUASAR MODE

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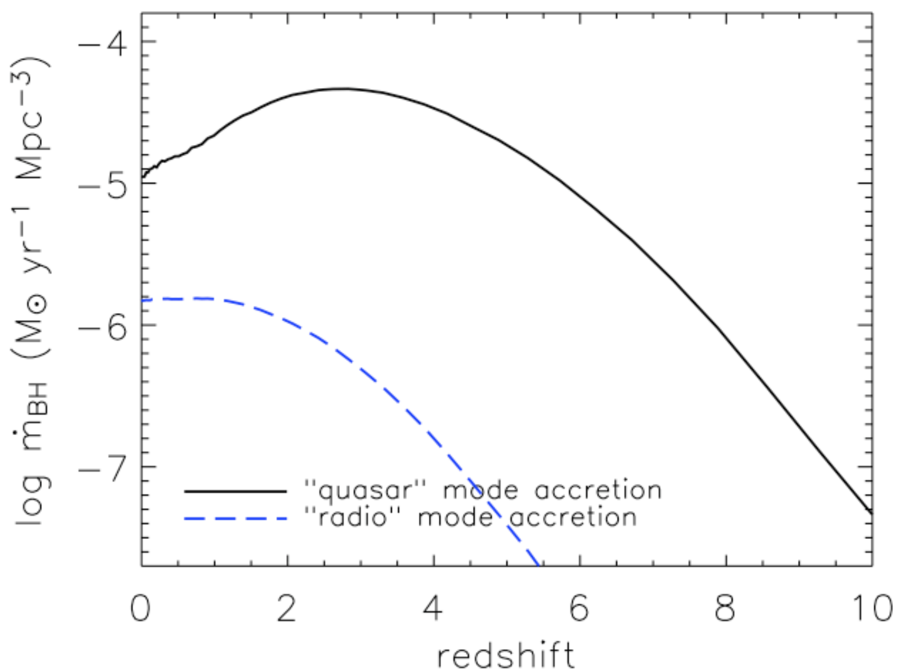
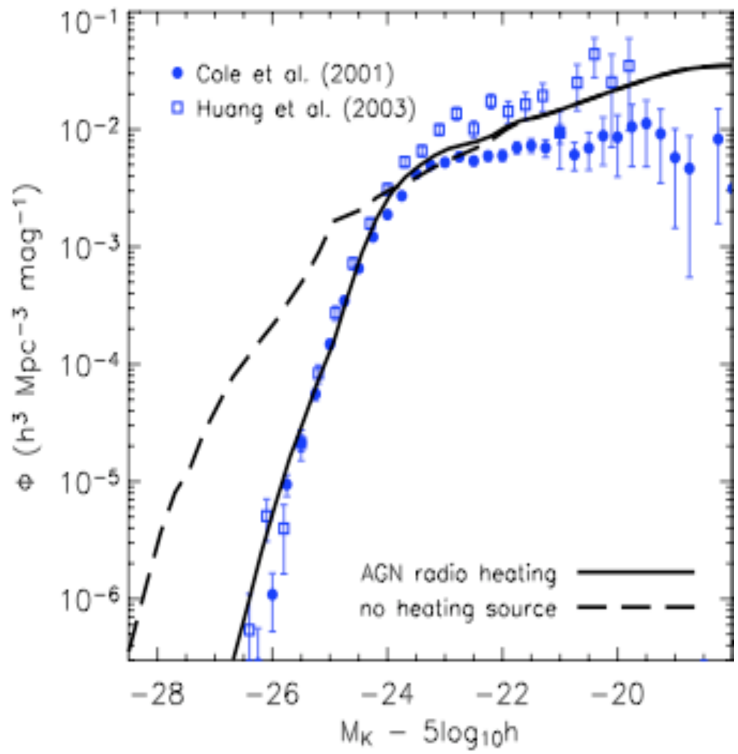
Allows good reproduction of observed galaxy properties

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

Radio-mode feedback in cosmological models

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





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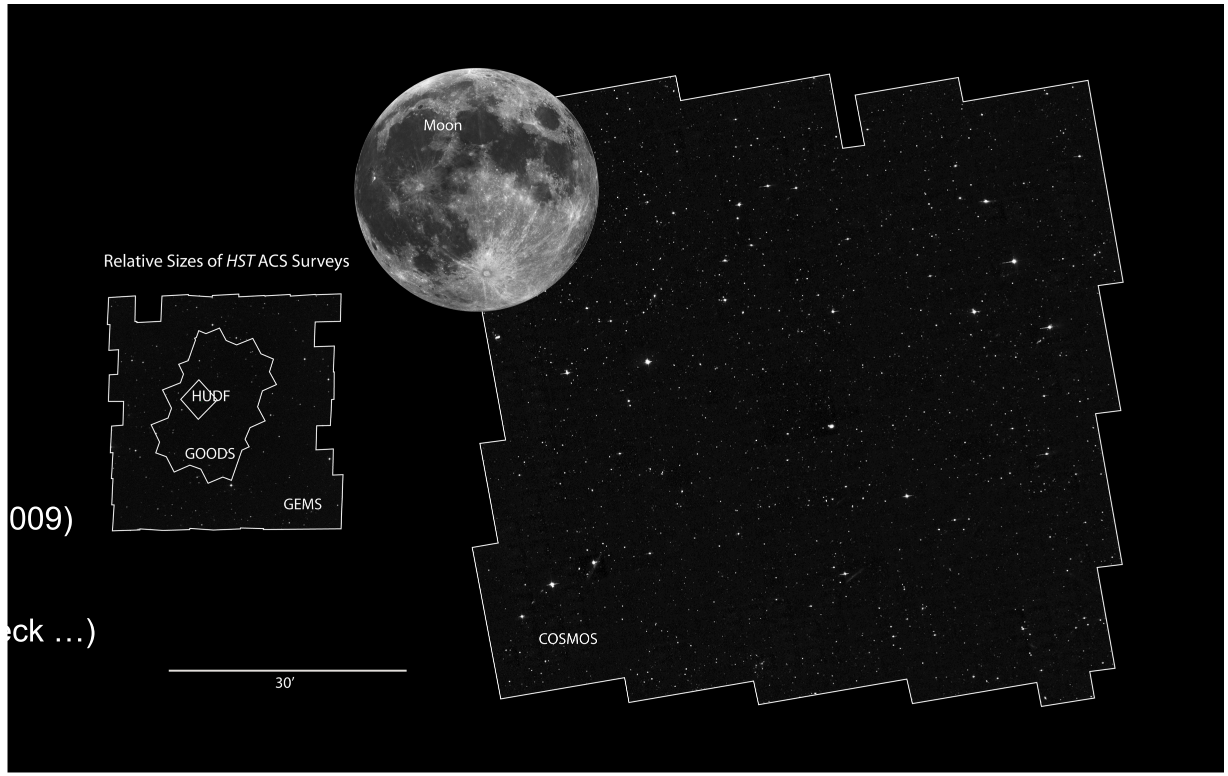

Relative Sizes of *HST* ACS Surveys
Moon
HUDF
GOODS
GEMS
COSMOS
30′

(Jansky) VLA-COSMOS:

core team: Schinnerer, Smolčić, Carilli, Sargent, Karim, Bondi, Ciliegi, Novak

1.4 GHz Large+Deep projects:

Schinnerer et al. (2004, 2007,2010)
337hrs, rms~10 μJy/b, 1.5” res.
~ 2,900 sources (S/N≥5; public)

324 MHz project:

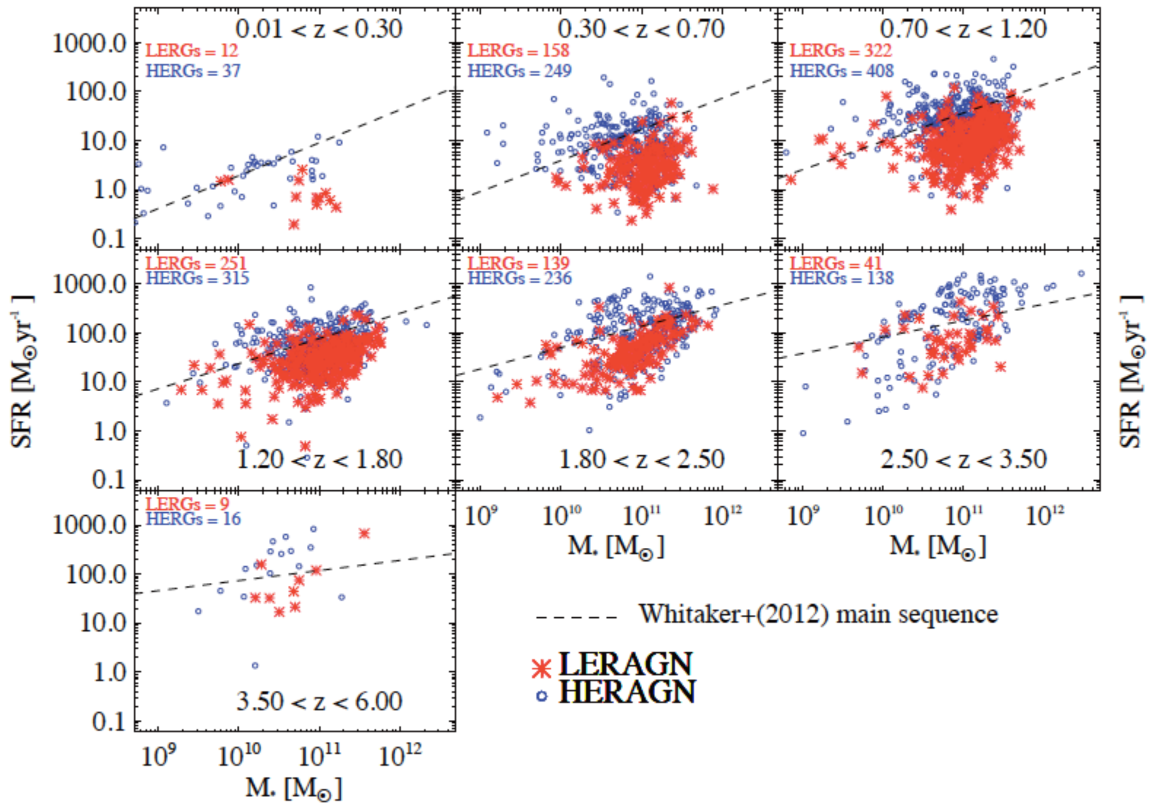
Smolčić **et al. 2014)**
24hrs, rms~0.5 mJy/b
~ 182 sources (S/N≥5; public)

3 GHz Large project:

Smolčić et al. (in prep)
384hrs, rms~2.45 μJy/b, 0.7’’-1’’ res.
8,765 source components, S/N≥5.5

Host galaxy properties of HE- and LERAGN

- VLA-COSMOS 3GHz Large Project:
  - Smolčić et al. (in prep.)
  - 384 hours, 3 GHz (10cm); 2sq.deg.,resolution ~0.75"
  - depth ~2.3 μJy/beam
- LERG selection:
  - Radio luminosity excess relative to SFR in host galaxy
- HERG selection:
  - X-ray: LX>1e42 erg/s
  - MIR (Donley et al. 2013)
  - SED fitting (Magphys +AGN; Delvecchio et al. 2014)



Delvecchio et al. (in prep)