Elusive AGN
Fairfax, June 14th, 2017

The deepest view of radio AGN in COSMOS:
a two-fold population (arxiv:1703.09720)

Ivan Delvecchio (University of Zagreb, Croatia)
ivand@phy.hr

On behalf of:
V. Smolčić, G. Zamorani, C. Del P. Lagos, S. Berta, J. Delhaize, N. Baran, D. Alexander, D. Rosario, V. Gonzalez-Perez, O. Ilbert, C. Lacey, O. Le Fèvre, O. Miettinen, M. Bondi, C. Carilli, P. Ciliegi, K. Mooley, M. Novak, E. Schinnerer, M. Aravena, P. Capak, F. Civano, N. Fanidakis, N. Herrera-Ruiz, A. Karim, C. Laigle, S. Marchesi, H. McCracken, E. Middleberg, M. Salvato and L. Tasca

The VLA-COSMOS 3 GHz Large Project

(press release yesterday in A&A special issue)

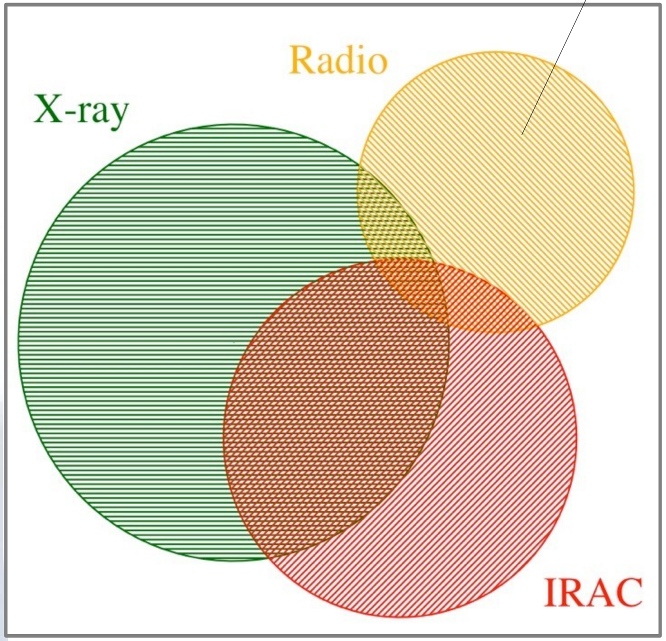
http://cosmos.astro.caltech.edu/news/52

- **1. Smolcic, ..., ID et al. (2017a):** *Source catalog and data release* **(arXiv:1703.09713)**
- **2. Smolcic, ID et al. (2017a):** *Multiwavelength counterpart catalog* **(arXiv:1703.09719)**
- **3. Delvecchio et al. (2017):** *AGN and host-galaxy properties out to z~5* **(arXiv:1703.09720)**
- **4. Delhaize, Smolcic, ID et al. (2017):** *The IRRC of star-forming galaxies out to z~5* **(arXiv:1703.09723)**
- **5. Novak, ..., ID et al. (2017):** *Cosmic star formation history since z~5* **(arXiv:1703.09724)**

THAT'S ALL PUBLIC!
(IPAC/IRSA database)

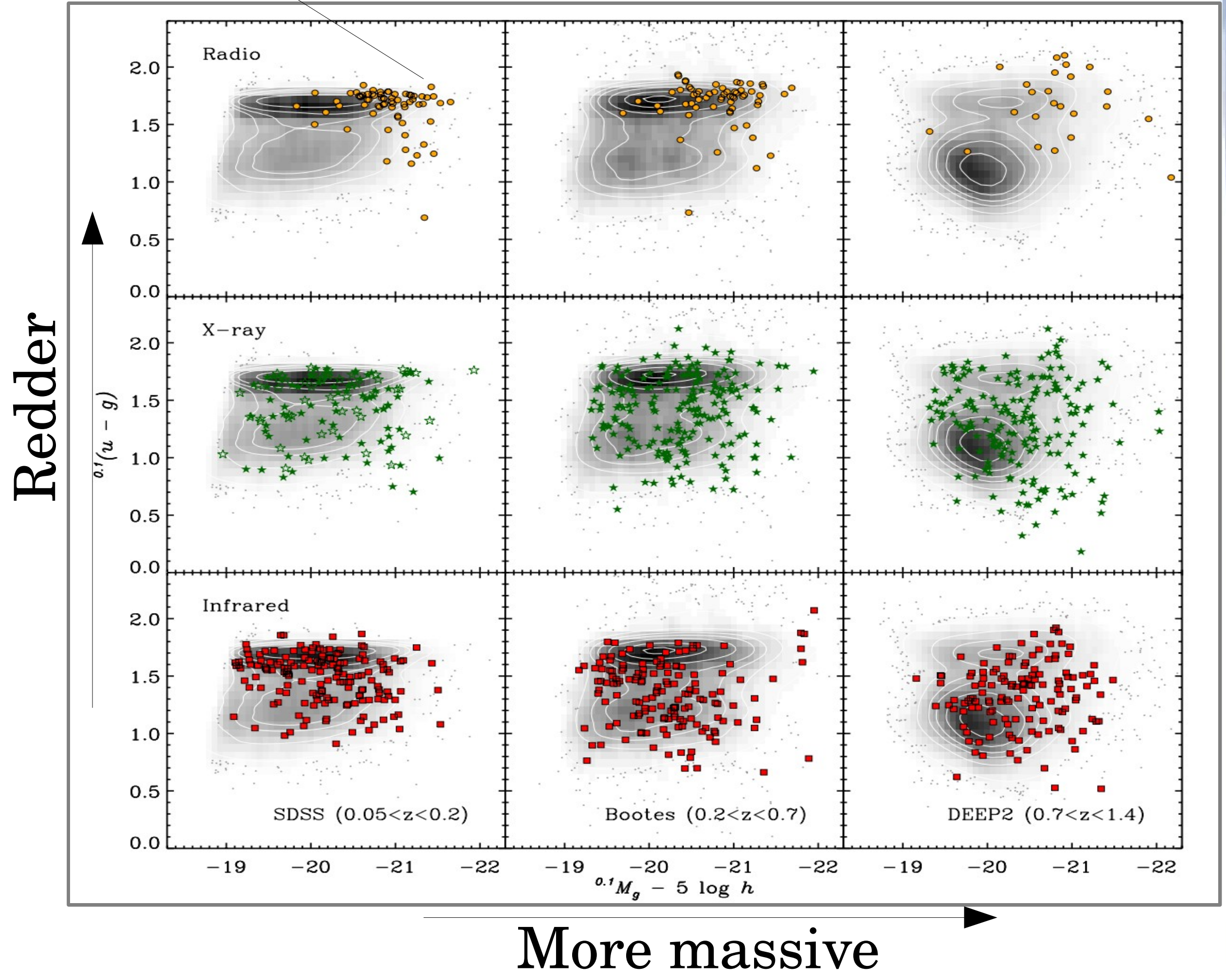
Radio (bright) AGN are special

$L_{1.4} > 10^{24.8}$ W/Hz

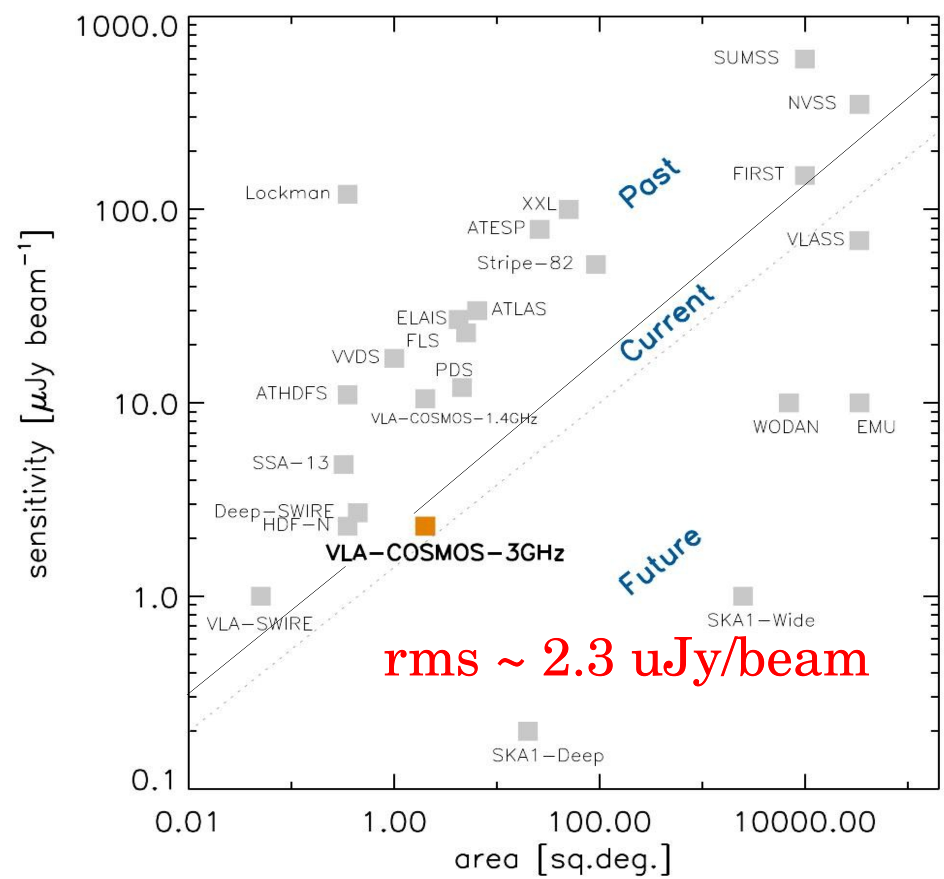


Hickox et al. (2009)

Goulding et al. (2014)



Going deeper and back in time: The 3 GHz VLA-COSMOS survey



PI: V. Smolčić

- 10,830 radio sources selected at 3 GHz (10 cm) down to an unprecedented sensitivity over 2.6 deg^2 of the COSMOS field (Smolčić et al. 2017a)
- ~90% have optical/NIR counterpart in the COSMOS2015 catalog (Smolčić, Delvecchio et al. 2017b).
- Accurate redshifts and opt-mm photometry (>30 bands) from the COSMOS2015 catalogue (Laigle et al., 2016)

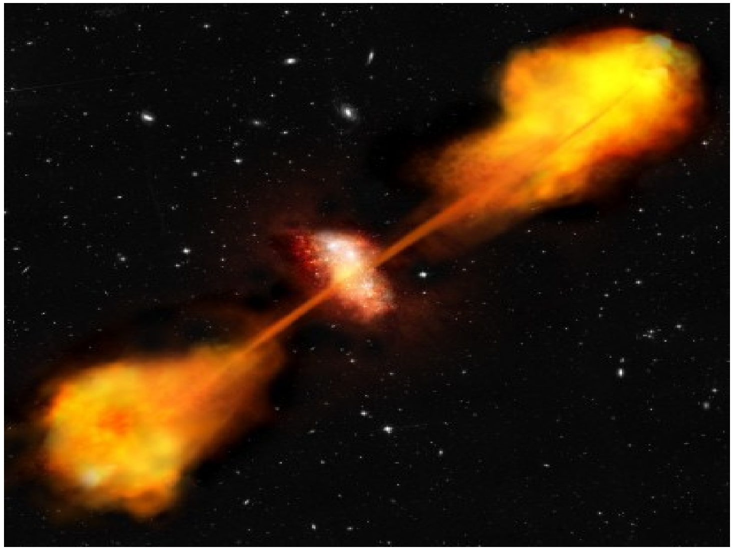
FINAL SAMPLE:
7,729
radio sources + multi-λ

Hunting for AGN

Radiative mode

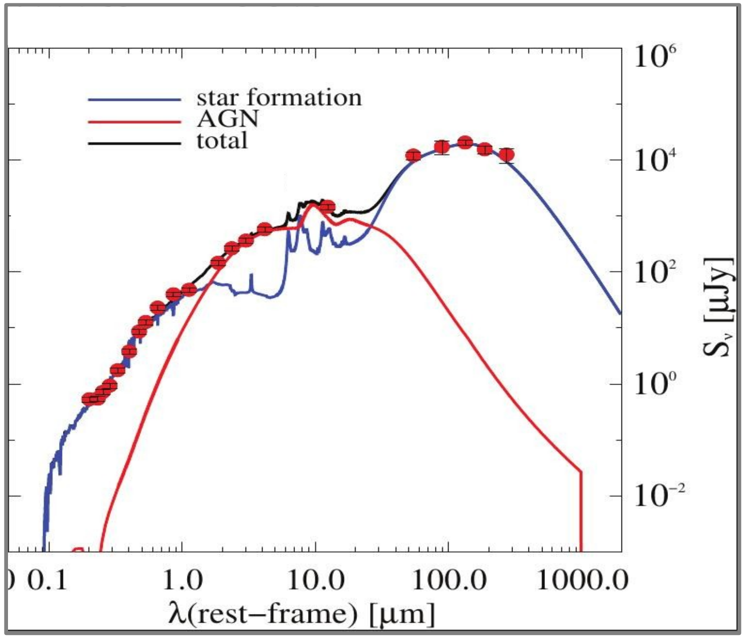
VS

Jet mode



Hunting for AGN

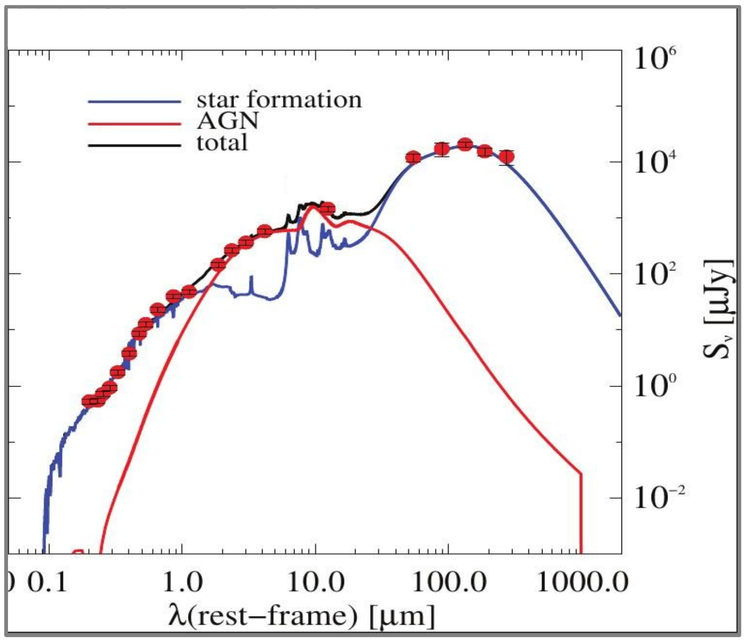
Moderate-to-high radiative luminosity AGN (**HLAGN**) ~ 21%



1) **$L_X > 10^{42}$ erg/s** (e.g. Szokoly et al. 2004)
2) **Mid-IR** colour-colour diagram (Donley et al. 2012)
3) **SED-fitting** decomposition
SED3fit (Berta et al. 2013)
http://cosmos.astro.caltech.edu/page/other-tools

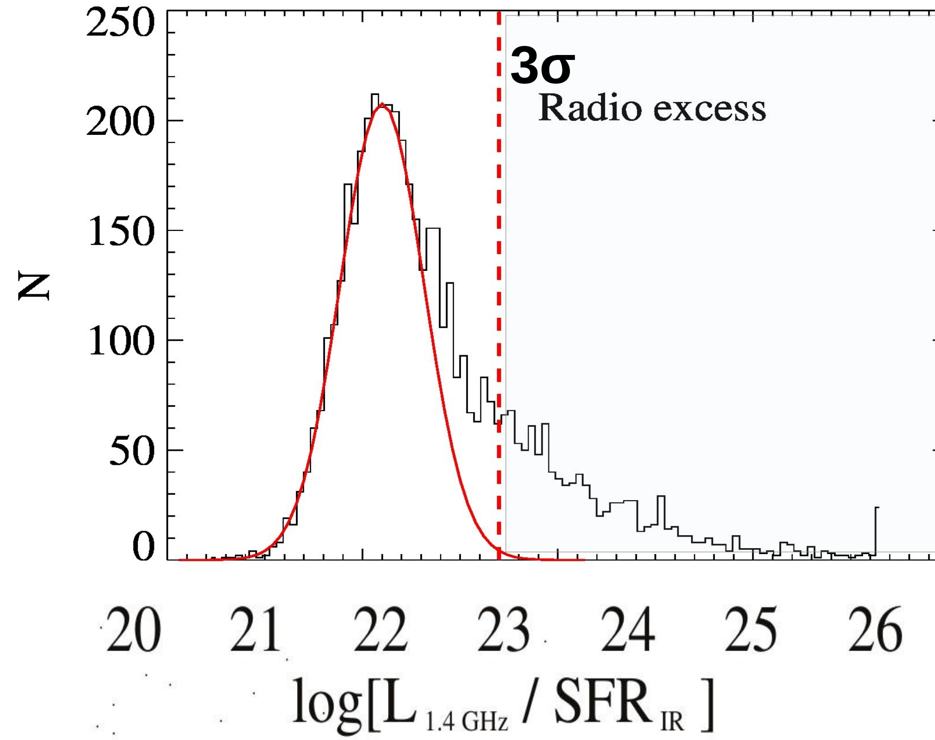
Hunting for AGN

Moderate-to-high radiative luminosity AGN (**HLAGN**) ~ 21%



1) **$L_x > 10^{42}$ erg/s** (e.g. Szokoly et al. 2004)
2) **Mid-IR** colour-colour diagram
   (Donley et al. 2012)
3) **SED-fitting** decomposition
   SED3fit (Berta et al. 2013)
   http://cosmos.astro.caltech.edu/page/other-tools

Low-to-moderate radiative luminosity AGN (**MLAGN**) ~ 17%



Not X-ray/MIR/SED AGN
AND **>3σ Radio-excess**

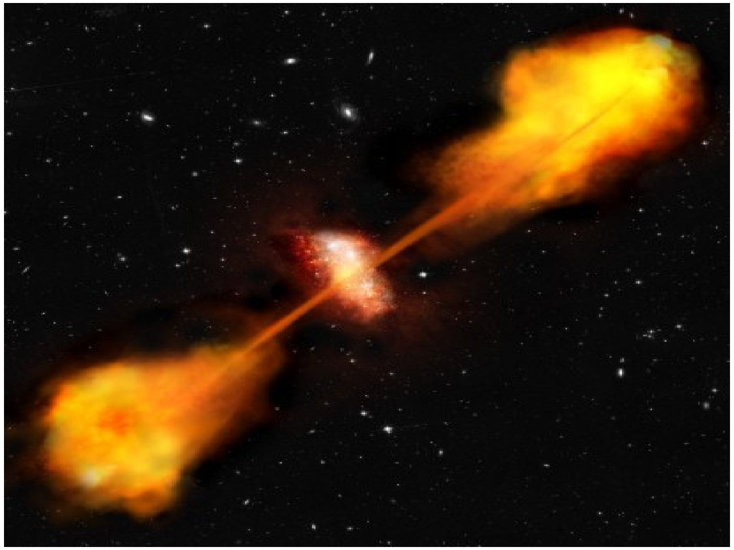
(Delvecchio et al. 2017, see also Del Moro et al. 2013)

Hunting for AGN

Moderate-to-high radiative luminosity AGN (**HLAGN**) ~ 21%

1) **Lx > 10^{42} erg/s** (e.g. Szokoly et al. 2004)
2) **Mid-IR** colour-colour diagram (Donley et al. 2012)
3) **SED-fitting** decomposition **SED3fit** (Berta et al. 2013) http://cosmos.astro.caltech.edu/page/other-tools

Low-to-moderate radiative luminosity AGN (**MLAGN**) ~ 17%

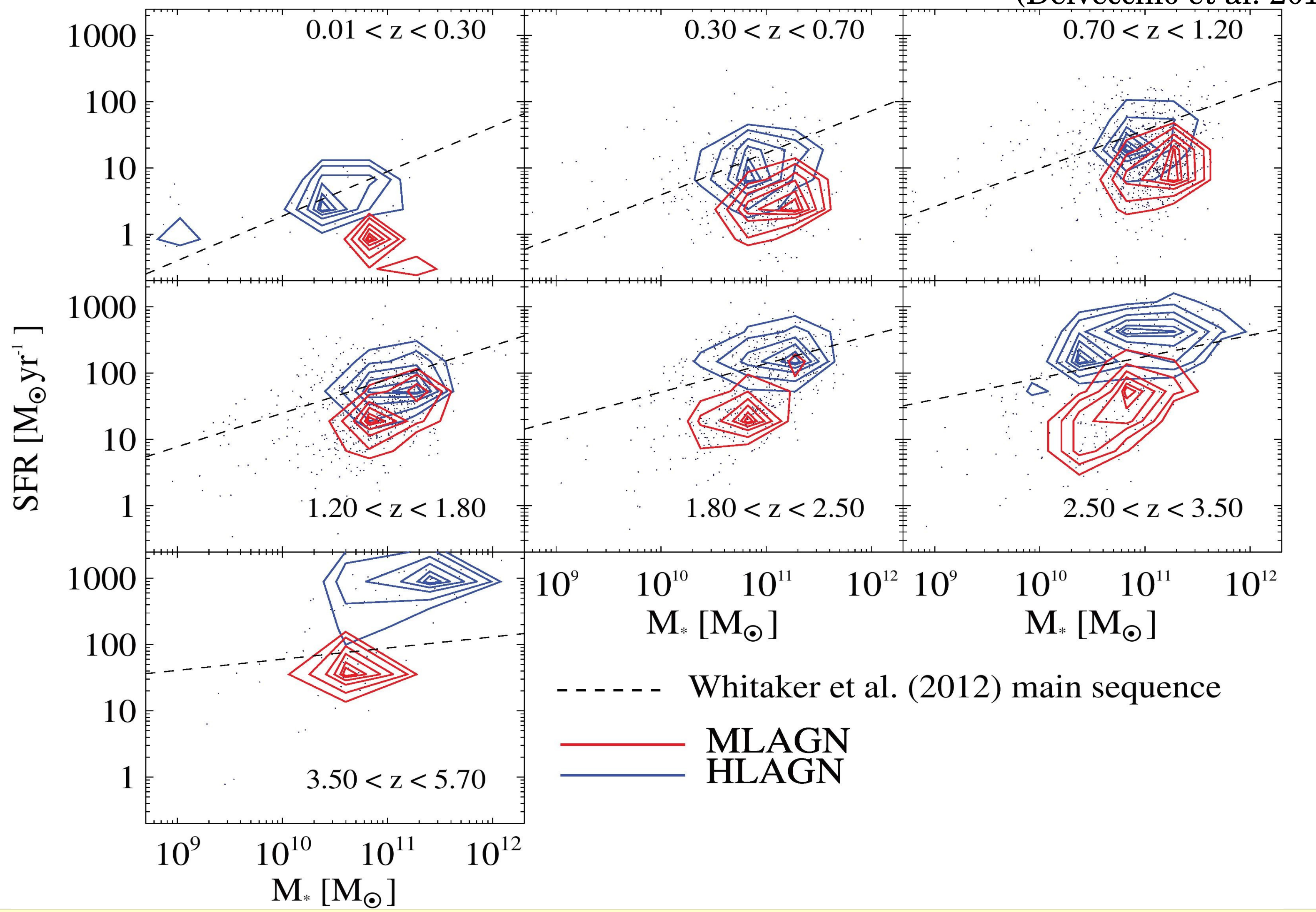


Not X-ray/MIR/SED AGN *AND* **>3σ Radio-excess**

(Delvecchio et al. 2017, see also Del Moro et al. 2013)

The SFR-M* plane of Radio AGN hosts

(Delvecchio et al. 2017)

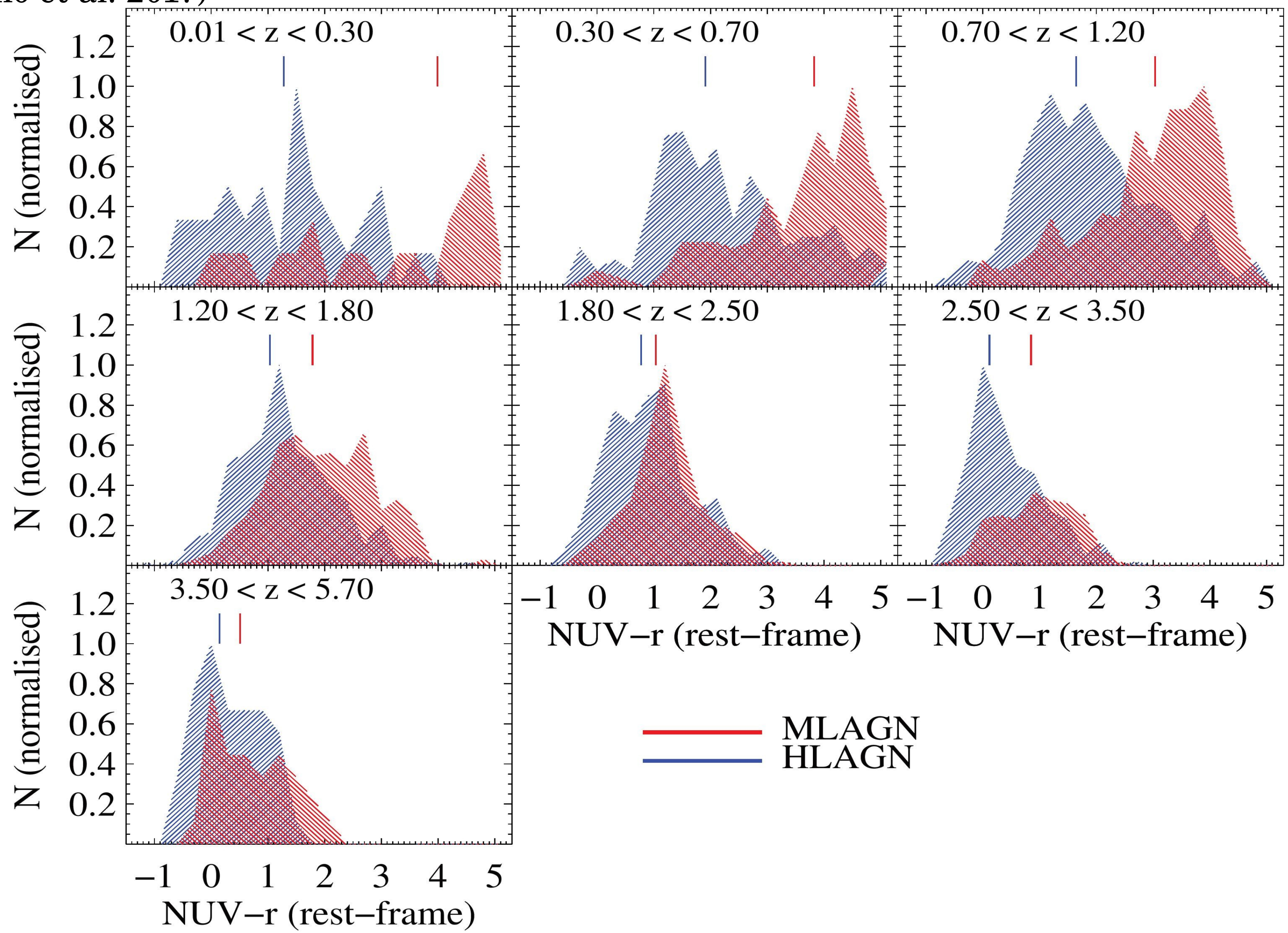


HLAGN lie around the main sequence (e.g. Hickox et al. 2009; Bonzini et al. 2013, 2015)

MLAGN reside systematically below the MS (Best & Heckman 2012; Heckman et al. 2014)

NUV-r galaxy colours

(Delvecchio et al. 2017)



HLAGN lie in blue/green galaxies, MLAGN lie in red/green galaxies.

Two-fold galaxies ⟷ AGN dichotomy?

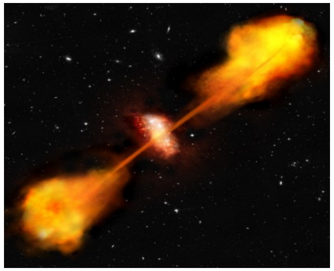
Two-fold galaxies ⟷ AGN dichotomy?

Lx / Lradio
radiative-to-mechanical AGN power

HLAGN?

Radiatively inefficient

MLAGN?



Radiatively efficient

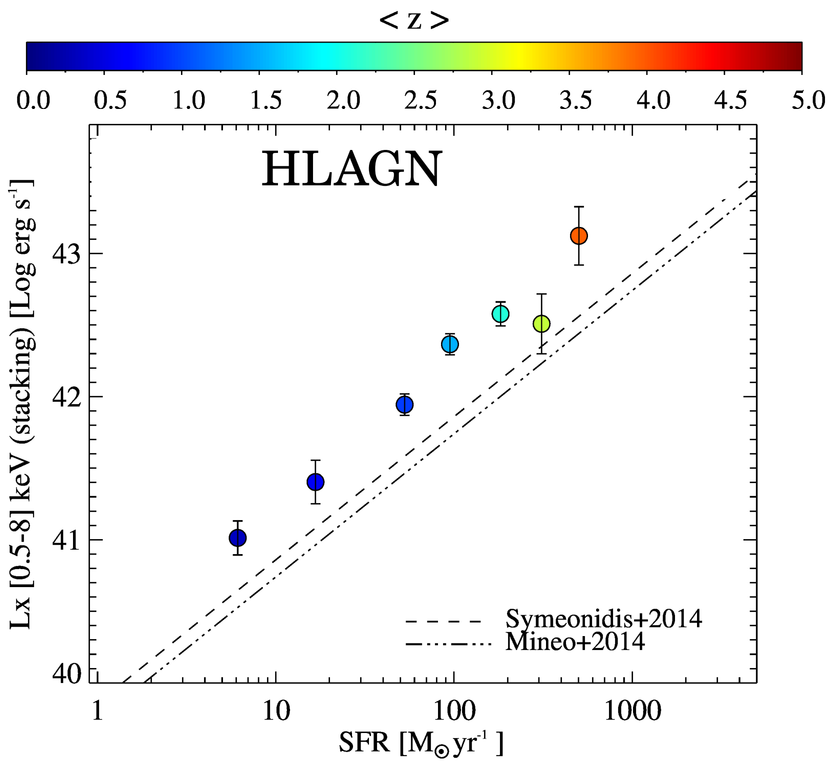
Lx / M* ~ *Specific BHAR* ~ *Eddington ratio*

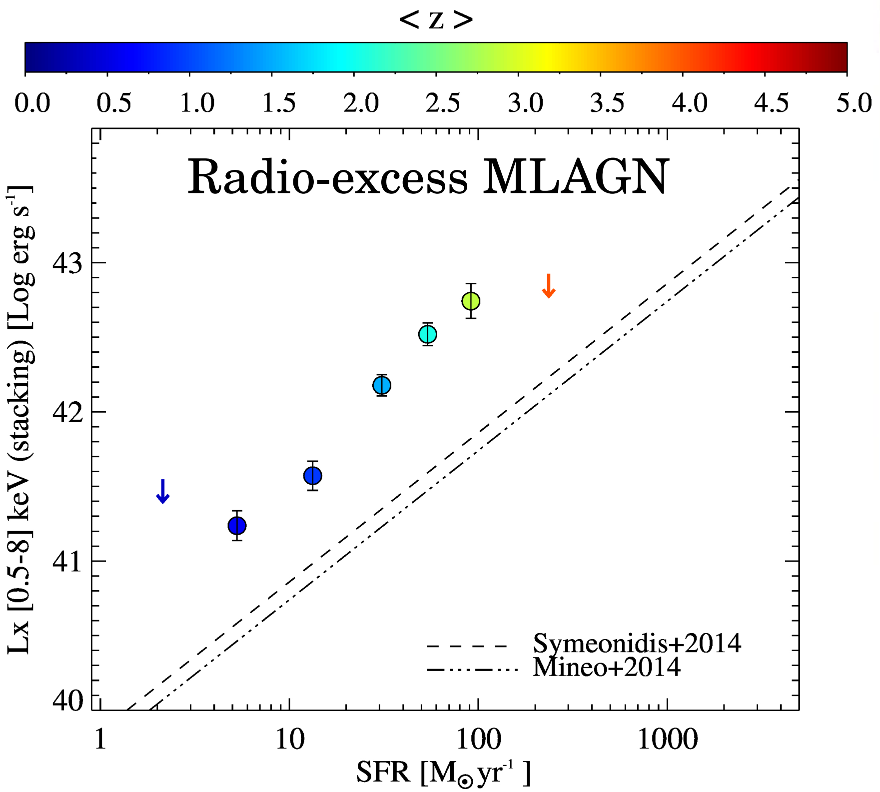
X-ray stacking of HLAGN vs MLAGN

- X-ray stacking tool CSTACK*
- Stacking Chandra images of X-ray undetected sources, binned in class and redshift

→

- >2σ detection at almost all redshifts
- Excess in X-ray emission due to AGN





* http://lambic.astrosen.unam.mx/cstack/ (developed by T. Miyaji)

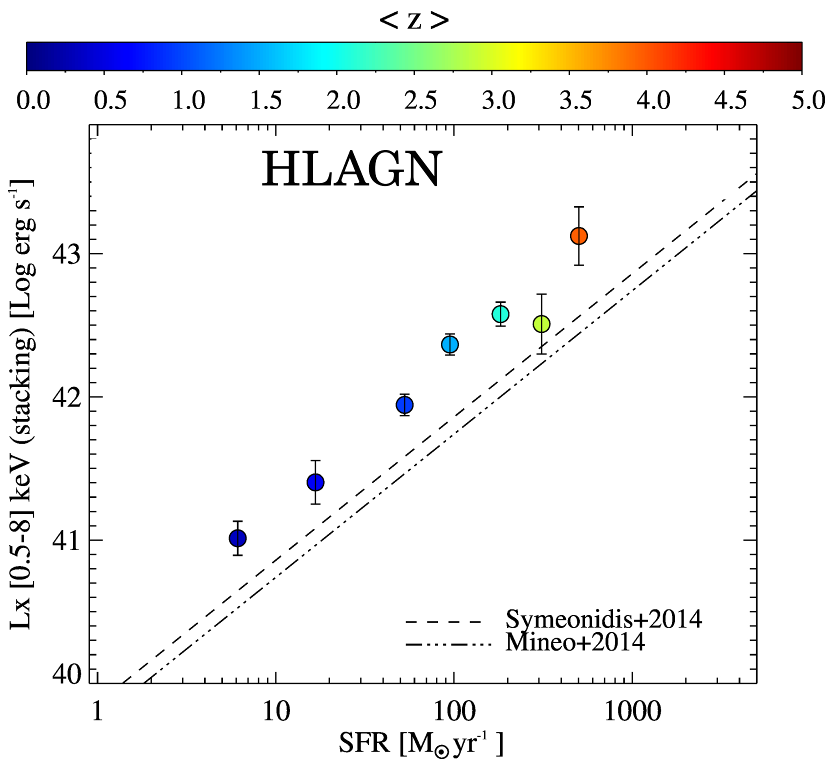
(Delvecchio et al., in prep.)

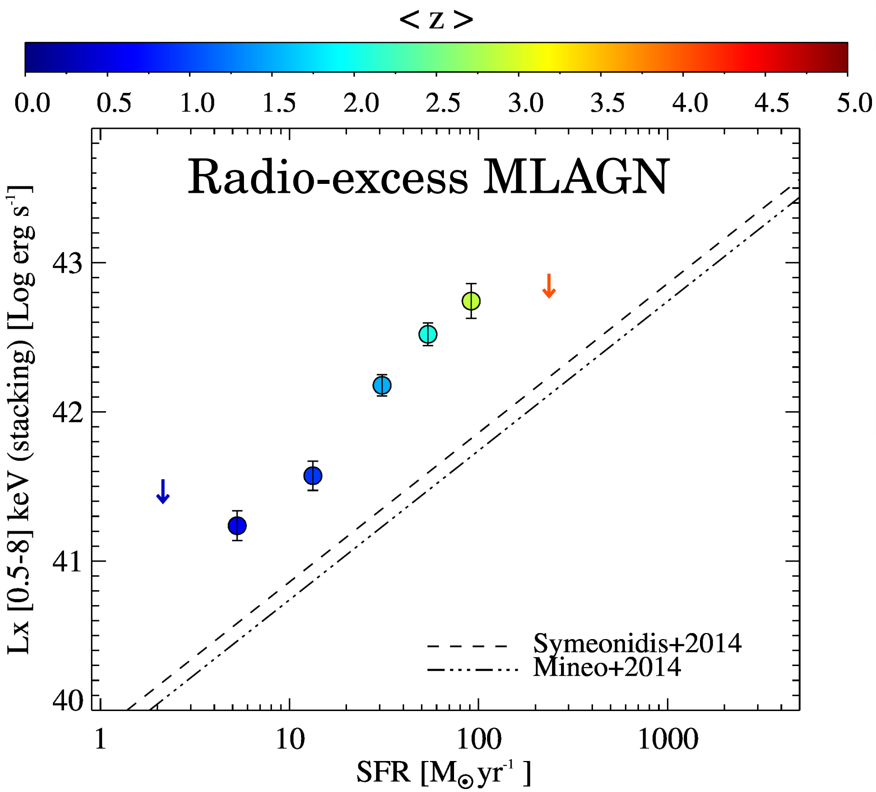
X-ray stacking of HLAGN vs MLAGN

- X-ray stacking tool CSTACK*
- Stacking Chandra images of X-ray undetected sources, binned in class and redshift

→

- >2σ detection at almost all redshifts
- Excess in X-ray emission due to AGN
- From $L_{X(AGN)}$ to $L_{bol(AGN)}$ (Lusso+2012)
- From $L_{bol(AGN)}$ to Eddington ratio via $M^*/M_{BH} = 500$ (Häring & Rix 2004)



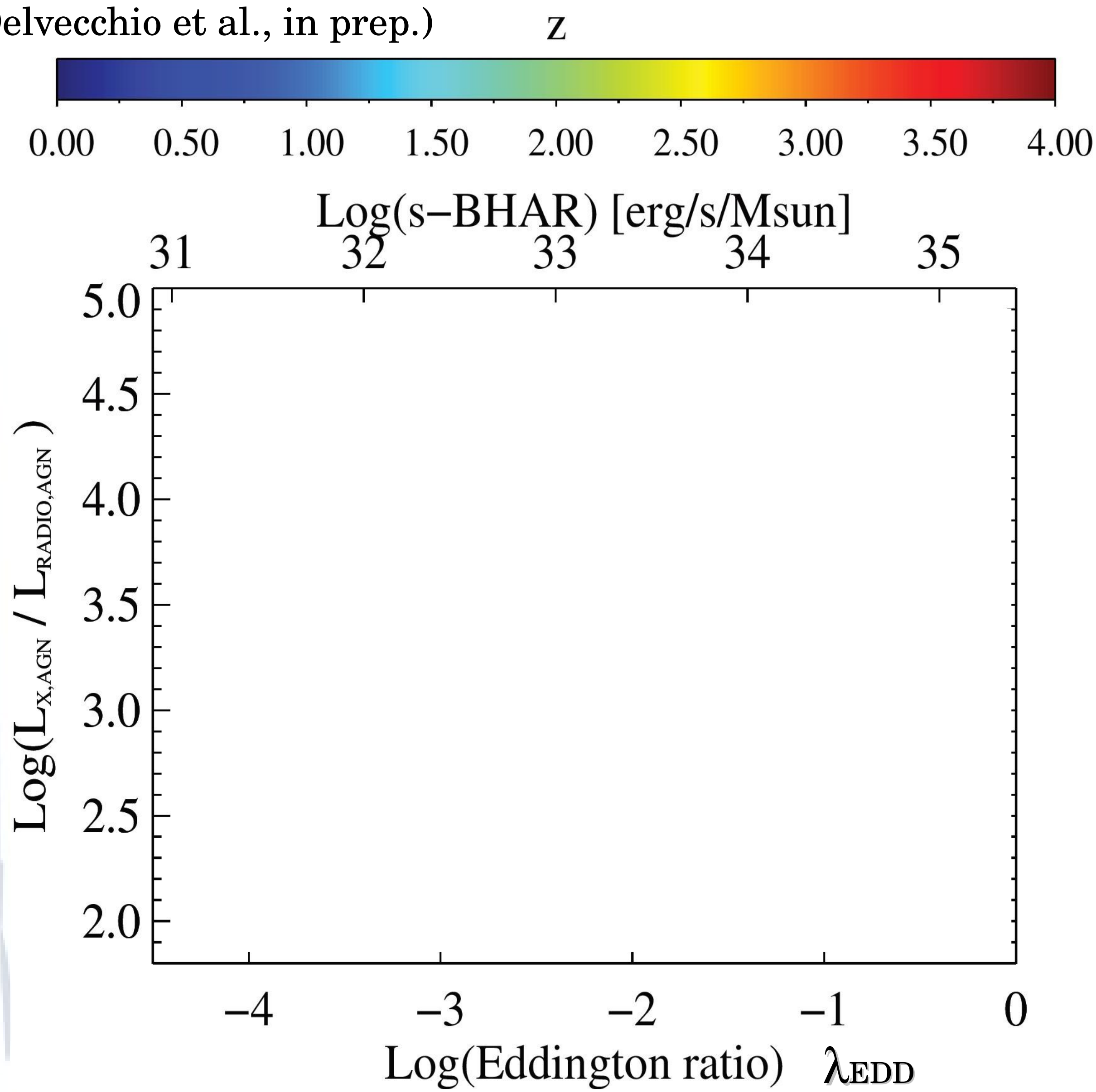


* http://lambic.astrosen.unam.mx/cstack/ (developed by T. Miyaji)

(Delvecchio et al., in prep.)

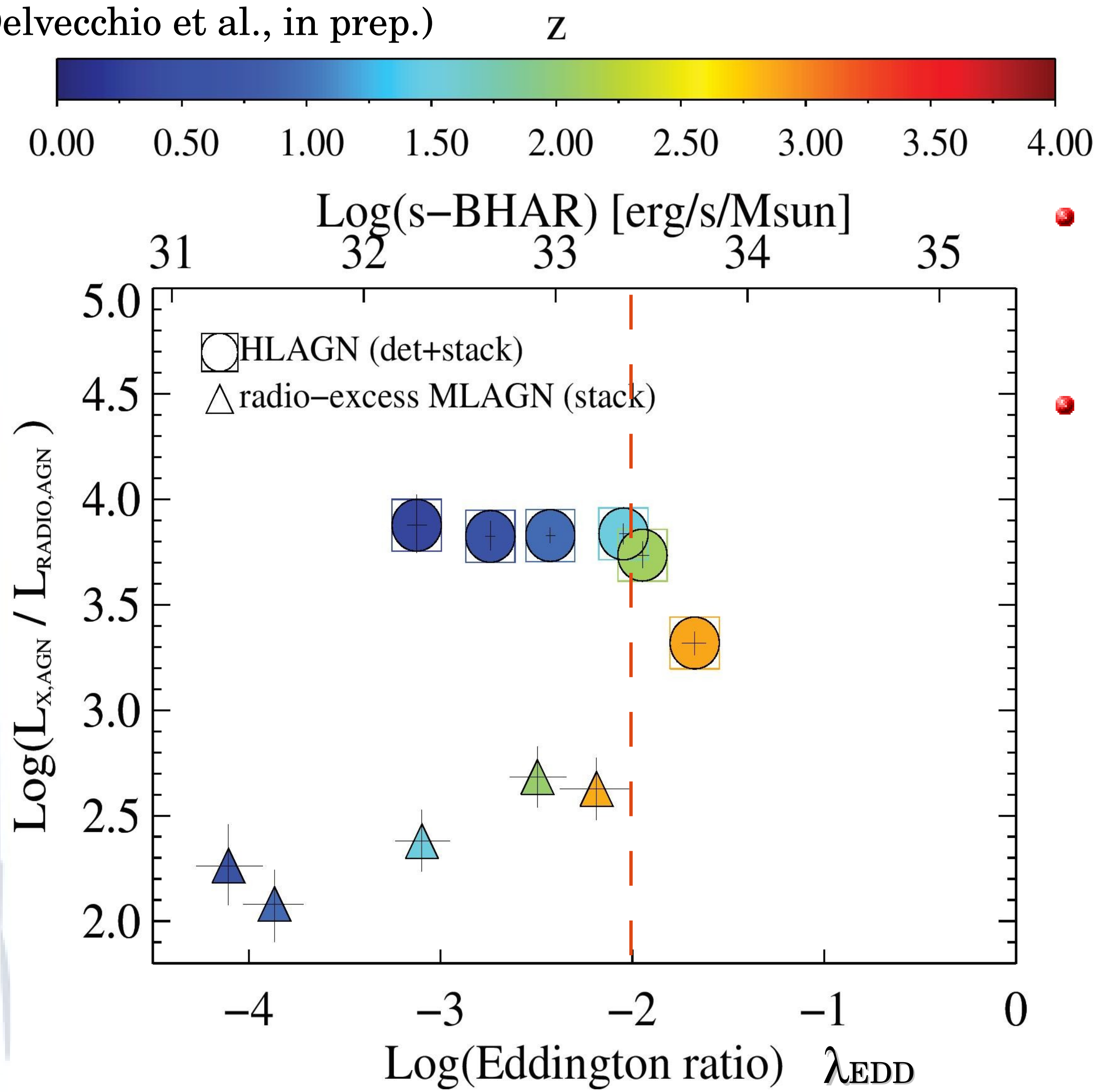
Eddington ratio – vs – *Lx / Lradio*

(Delvecchio et al., in prep.)



Eddington ratio – vs – *Lx / Lradio*

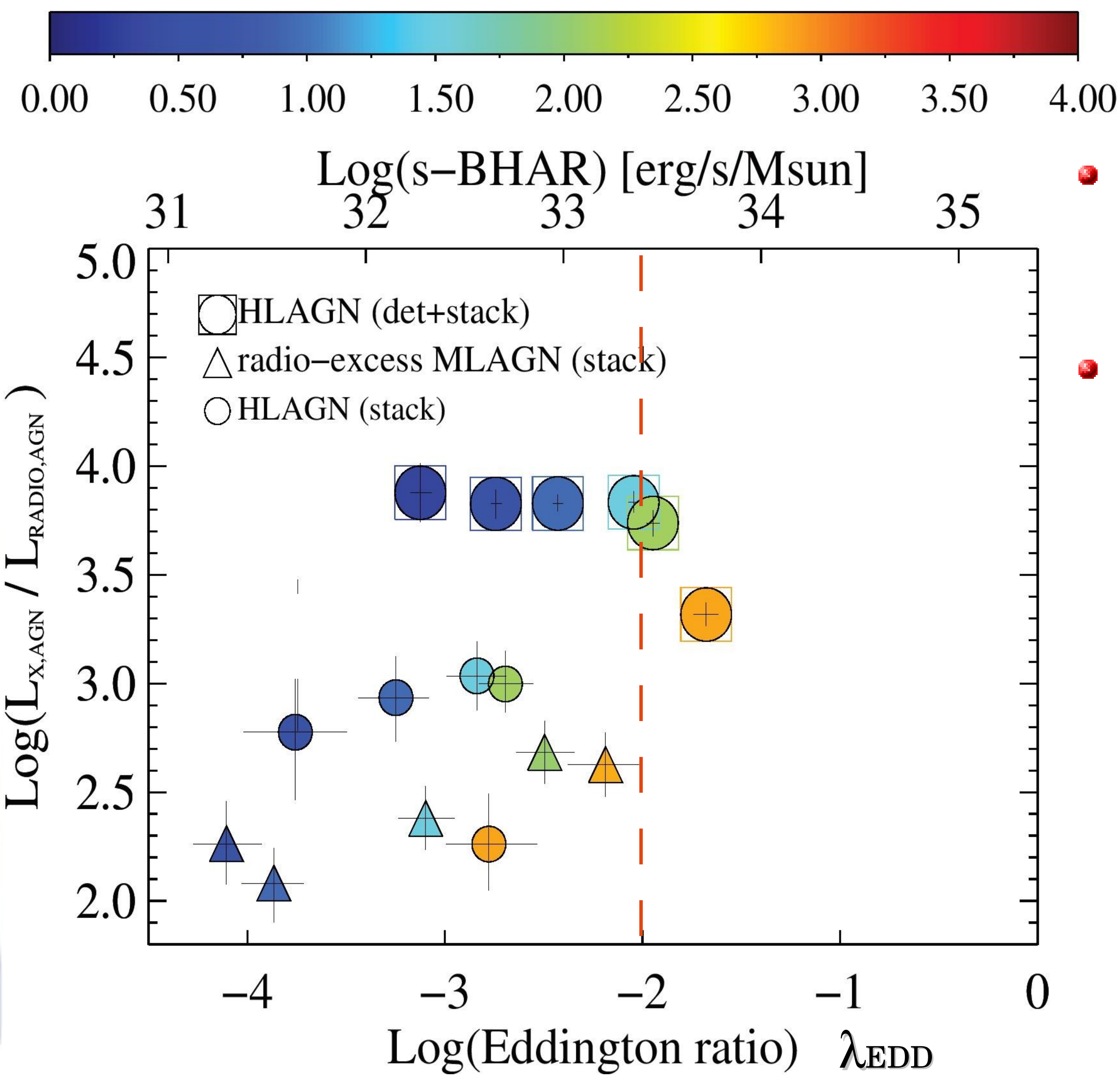
(Delvecchio et al., in prep.)



- The full HLAGN population displays higher λ_{EDD} than MLAGN (Padovani et al. 2015)
- Radio-excess MLAGN display *radiatively-inefficient* accretion (Best & Heckman 2012; Heckman et al. 2014)

Eddington ratio – vs – *Lx / Lradio*

(Delvecchio et al., in prep.)



- The full HLAGN population displays higher λ_{EDD} than MLAGN (Padovani et al. 2015)
- Radio-excess MLAGN display *radiatively-inefficient* accretion (Best & Heckman 2012; Heckman et al. 2014)

At moderate $L_{x,AGN}$ (from stacking) we observe:

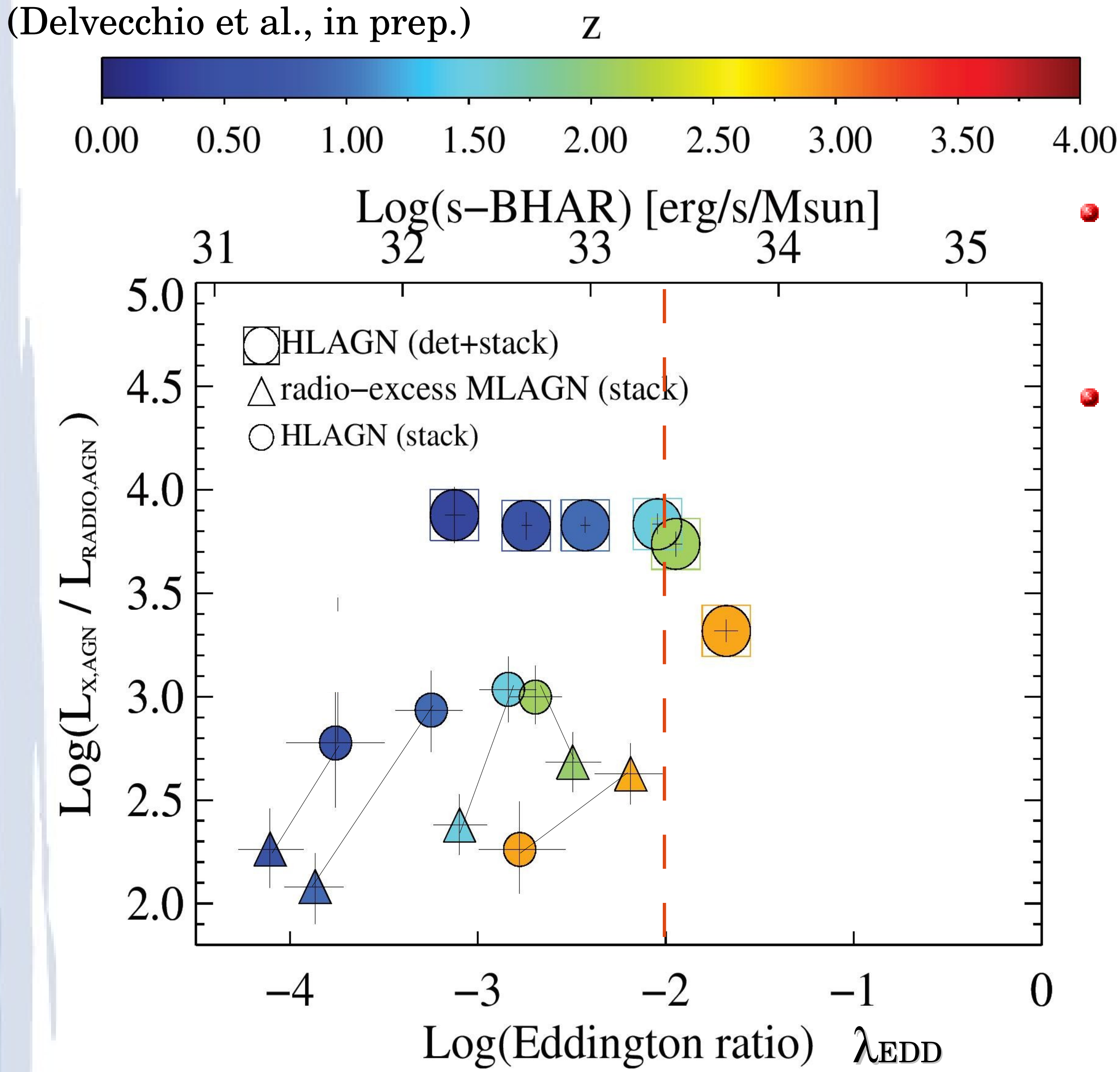
- (z<1)

λ_{EDD} (HLAGN) > λ_{EDD} (MLAGN)

- (z>1)

λ_{EDD} (HLAGN) ~ λ_{EDD} (MLAGN)

Eddington ratio – vs – *Lx / Lradio*



- The full HLAGN population displays higher λ_{EDD} than MLAGN (Padovani et al. 2015)
- Radio-excess MLAGN display *radiatively-inefficient* accretion (Best & Heckman 2012; Heckman et al. 2014)

At moderate $L_{x,AGN}$ (from stacking) we observe:

- (z<1)

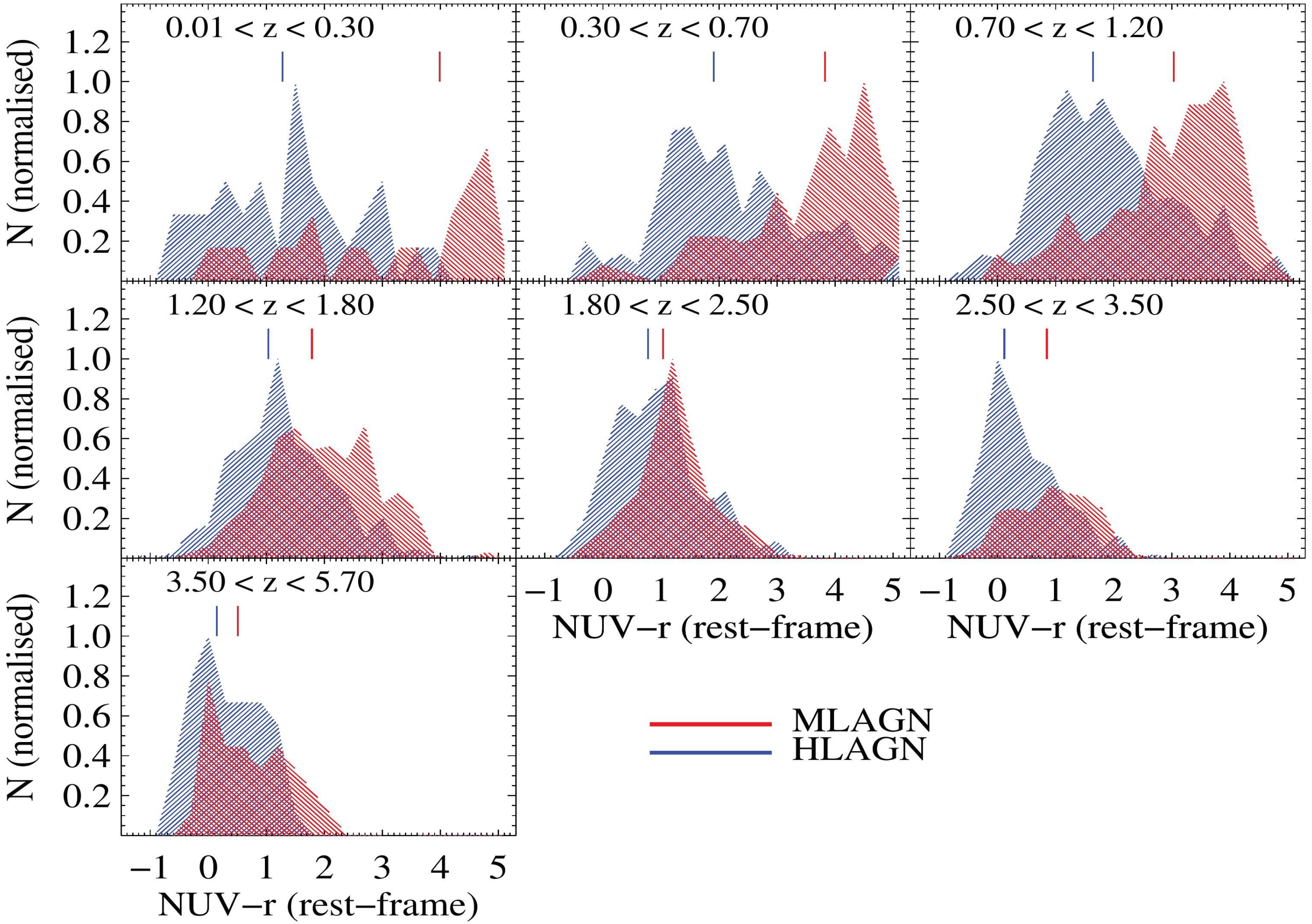
λ_{EDD} (HLAGN) > λ_{EDD} (MLAGN)

- (z>1)

λ_{EDD} (HLAGN) ~ λ_{EDD} (MLAGN)

Eddington ratio ↔ galaxy colour

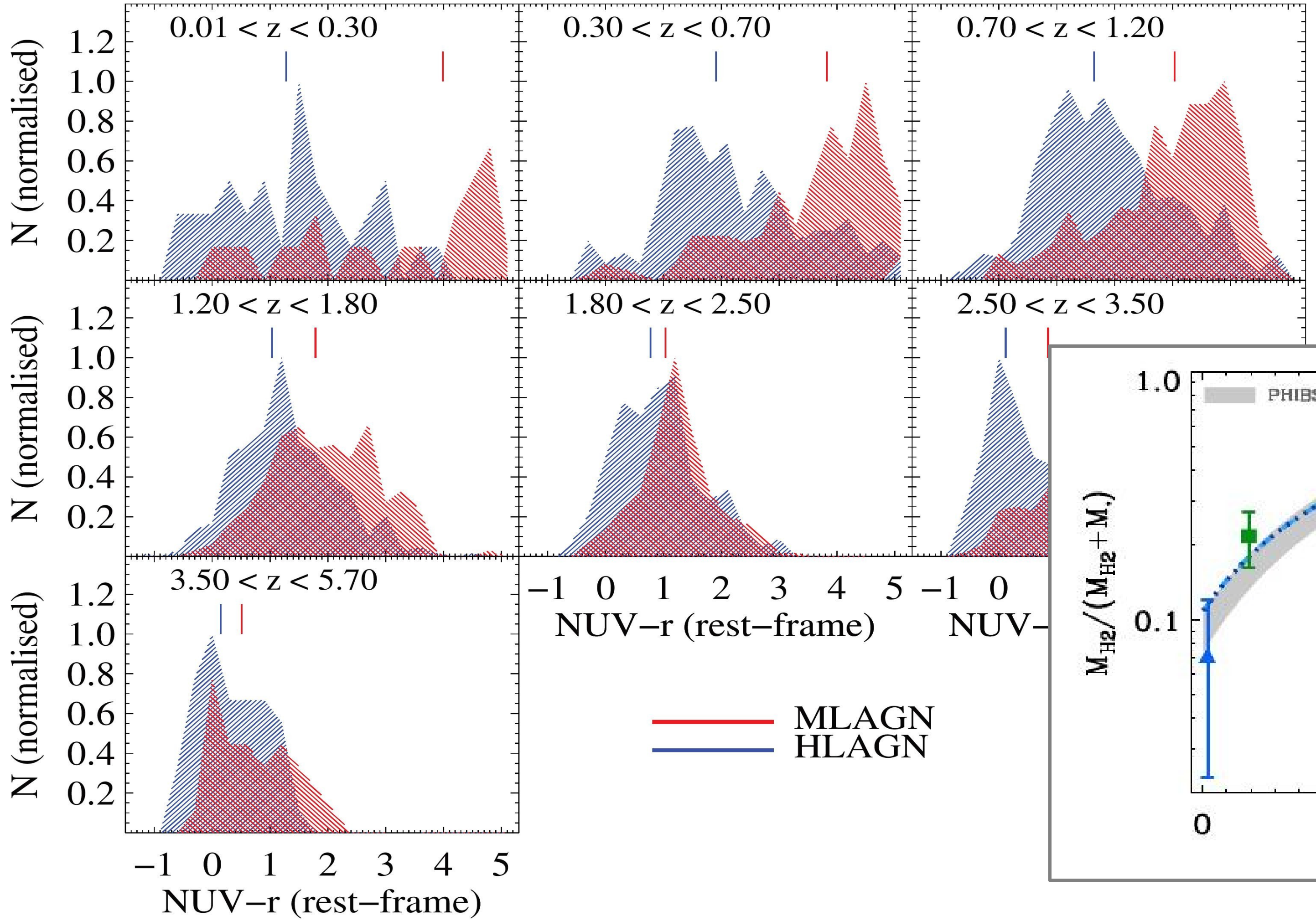
(Delvecchio et al. 2017)



HLAGN lie in blue/green galaxies, MLAGN lie in red/green galaxies.
Their overlap increases towards higher redshifts (i.e. less red galaxies)

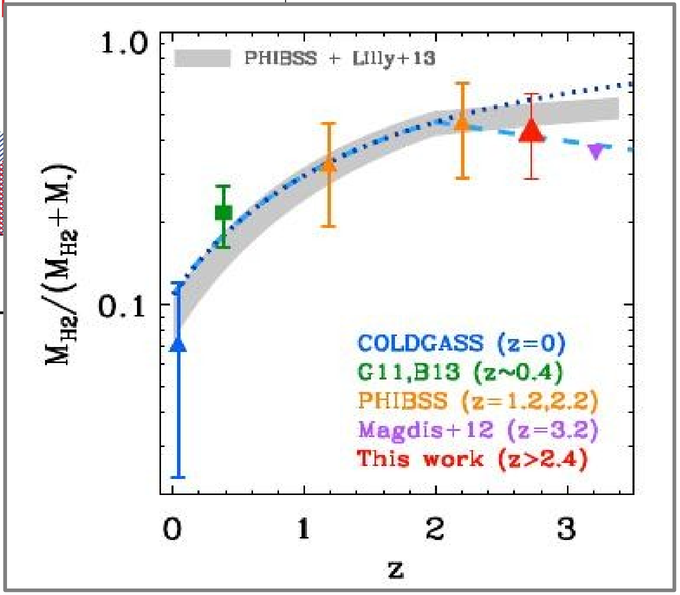
Eddington ratio ⟷ galaxy colour

(Delvecchio et al. 2017)



?

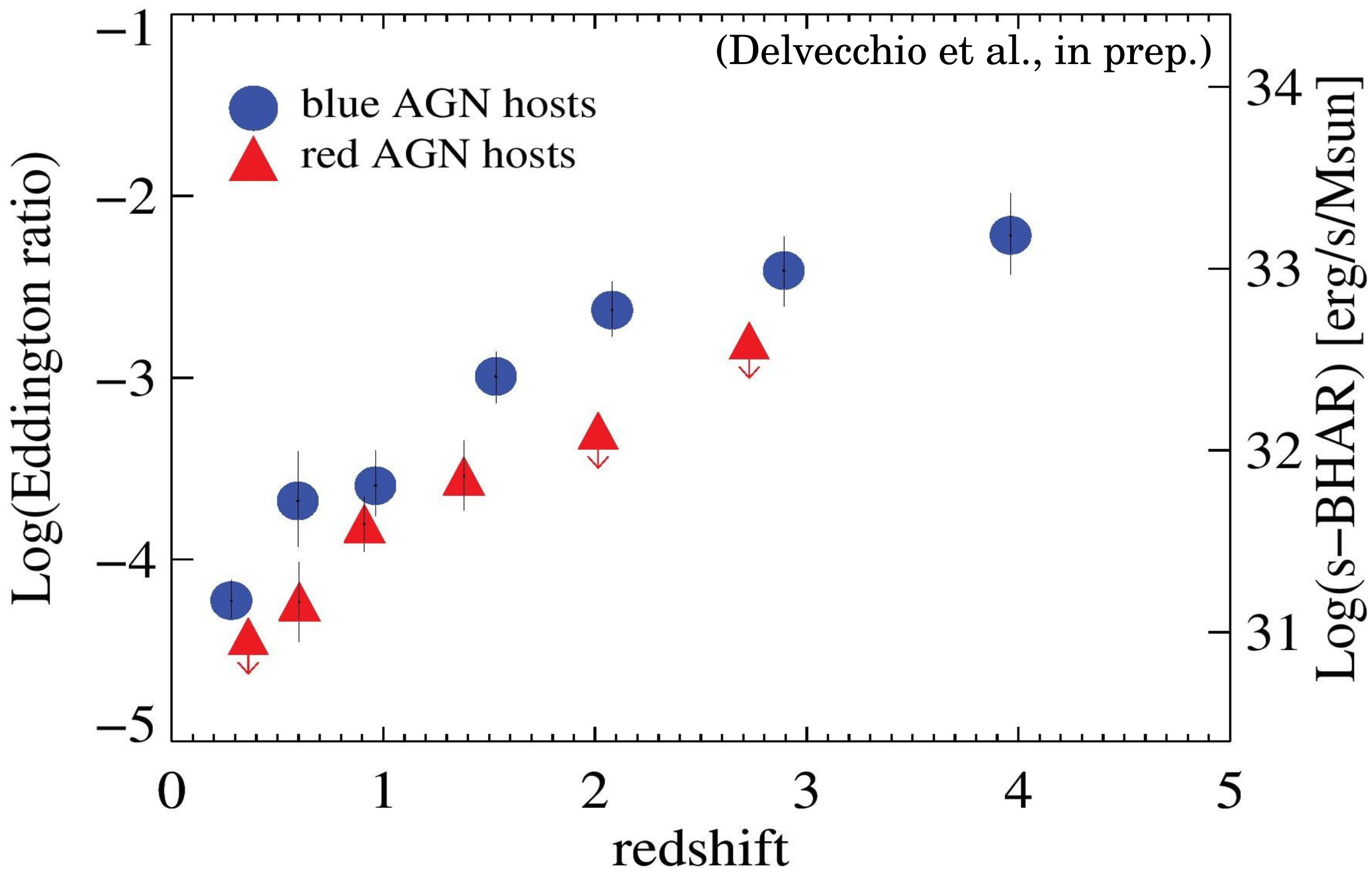
fgas



Saintonge et al. (2013)

Evolution of the gas fraction and optical colours in galaxies might be tied to the AGN Eddington ratio: common fuelling?

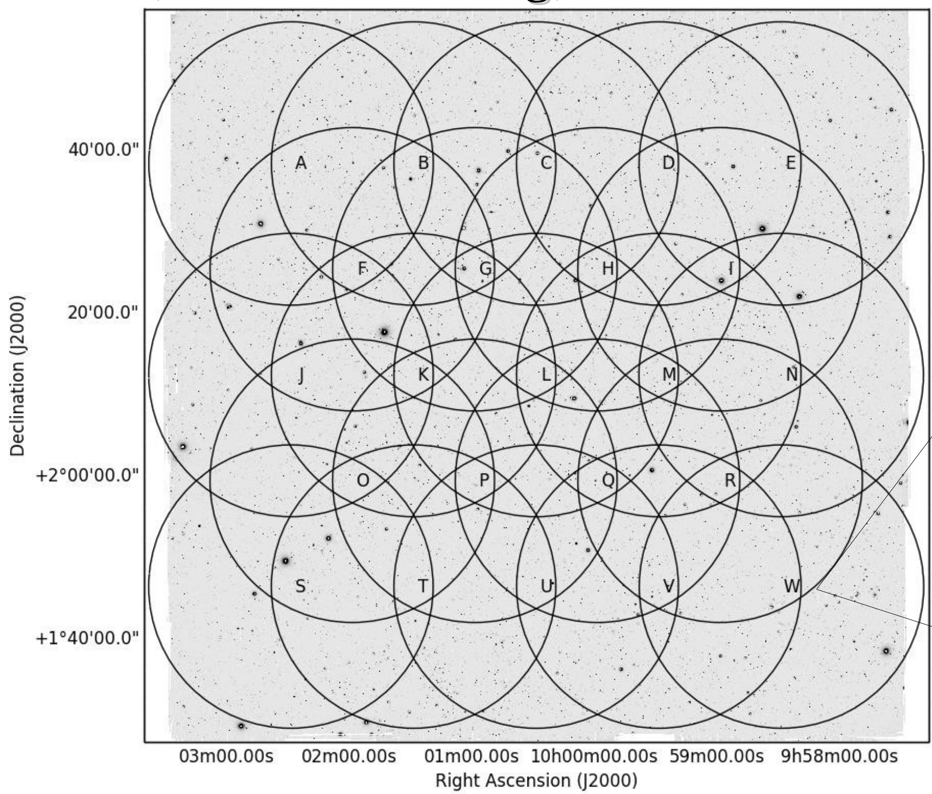
Stacking blue vs red AGN hosts



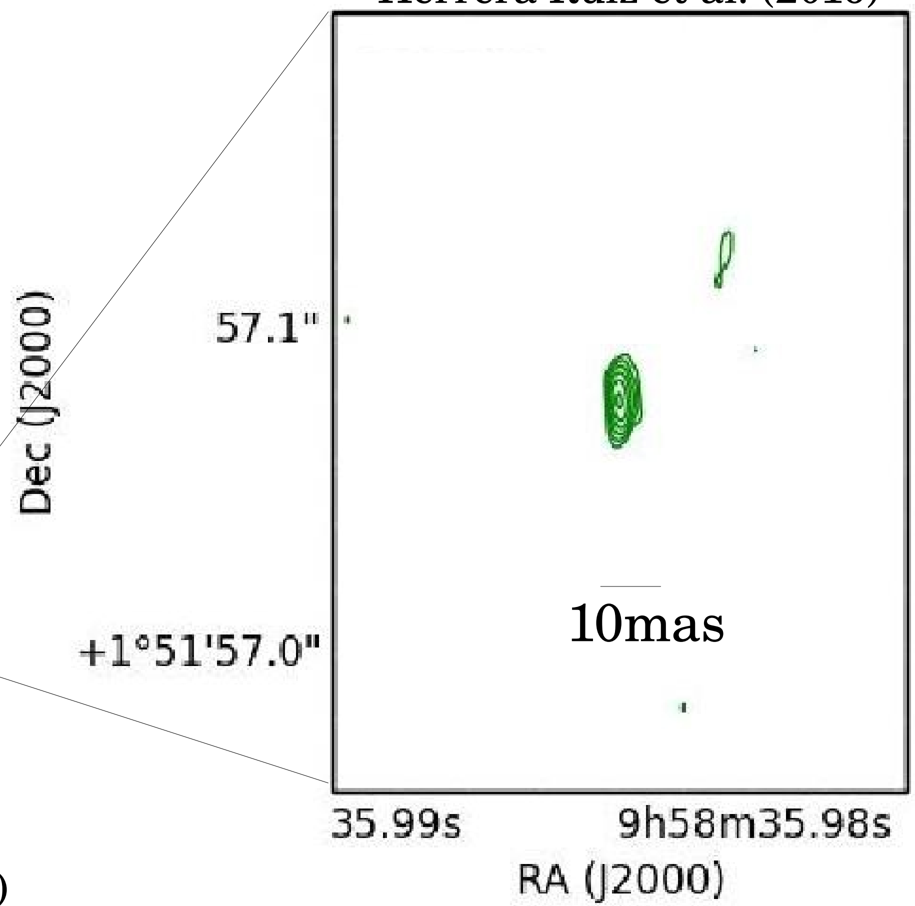
Blue AGN hosts display higher Eddington ratios than red AGN hosts at *all* redshifts (e.g. Bernhard et al. 2016; Aird et al. 2017)

Overcoming host-galaxy dilution: VLBI interferometry

(PI: E. Middleberg)

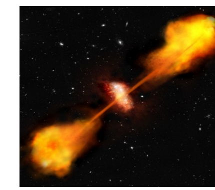


Herrera Ruiz et al. (2016)



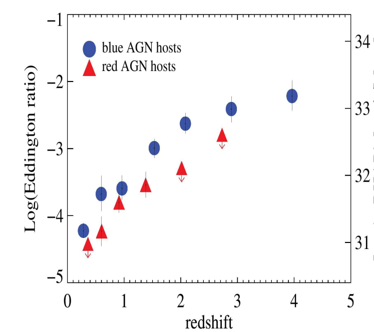
(Courtesy of E. Middleberg and N. Herrera Ruiz)

Take-home messages



Deepest radio observations in COSMOS reveal
a mixture of two AGN/host populations:
HLAGN (X-ray/MIR/SED) vs MLAGN (radio-excess)

The observed trends with Eddington ratio
might be tied to the evolution
of the cold gas content (common fuelling?)

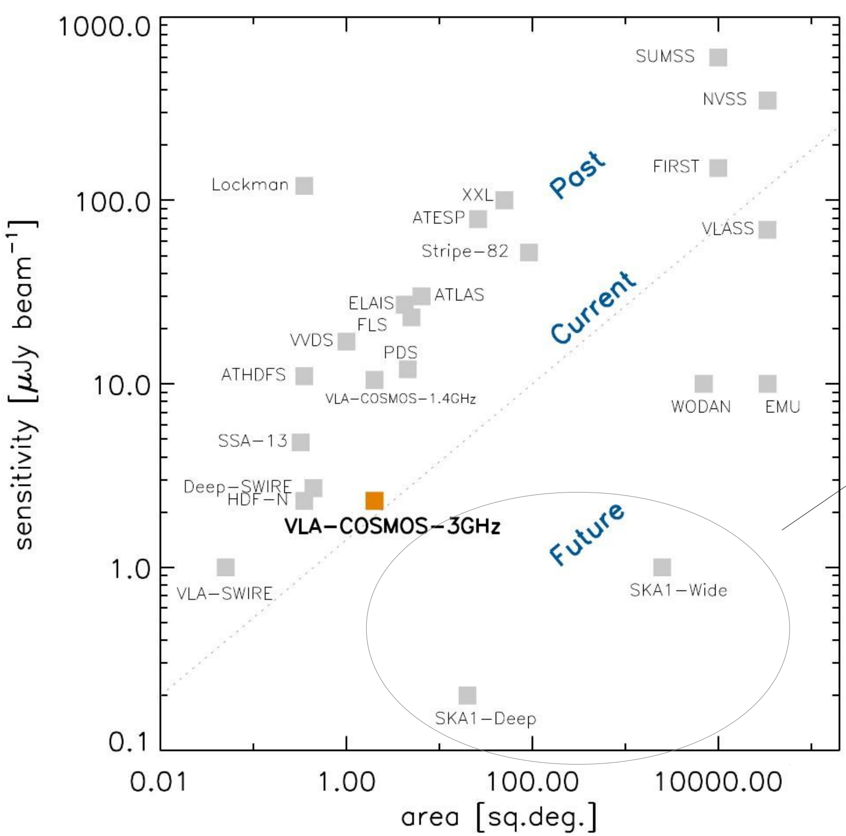


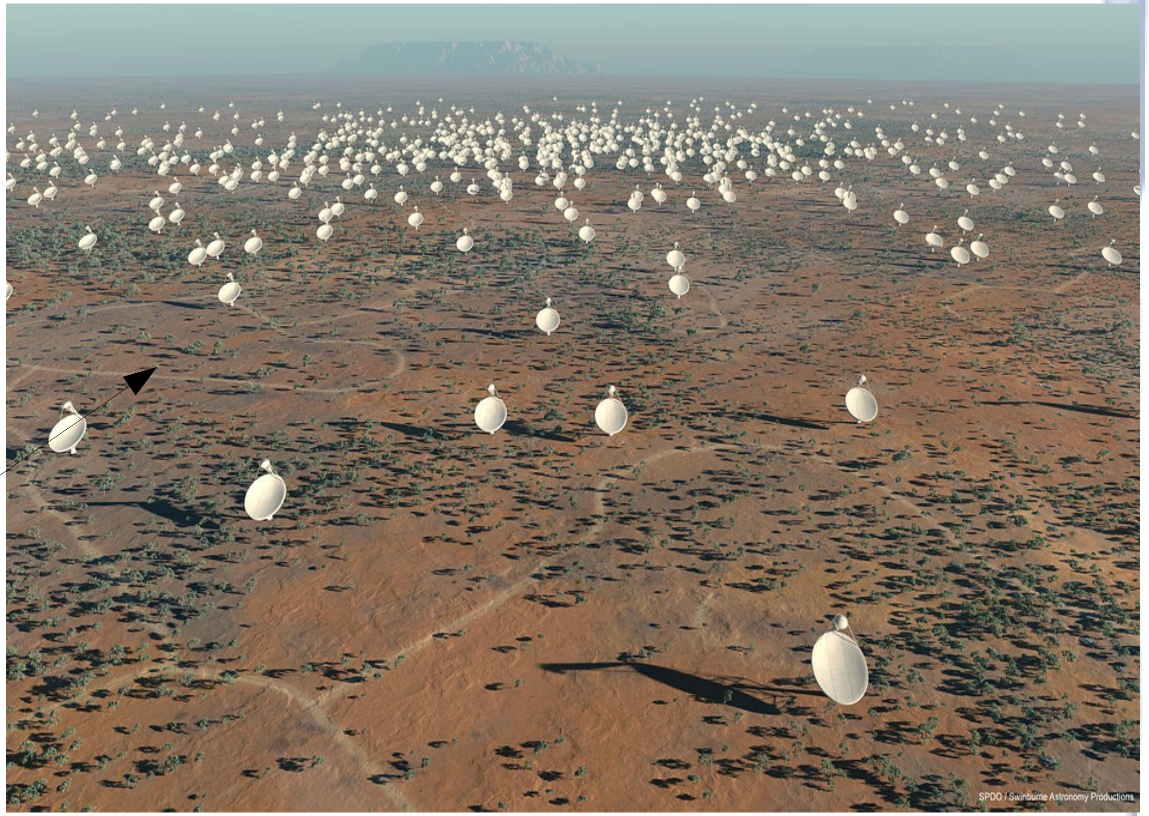
Check out our press release on A&A special issue!
http://cosmos.astro.caltech.edu/news/52

Supplementary slides

Elusive AGN in the next era:
The Square Kilometer Array (SKA)

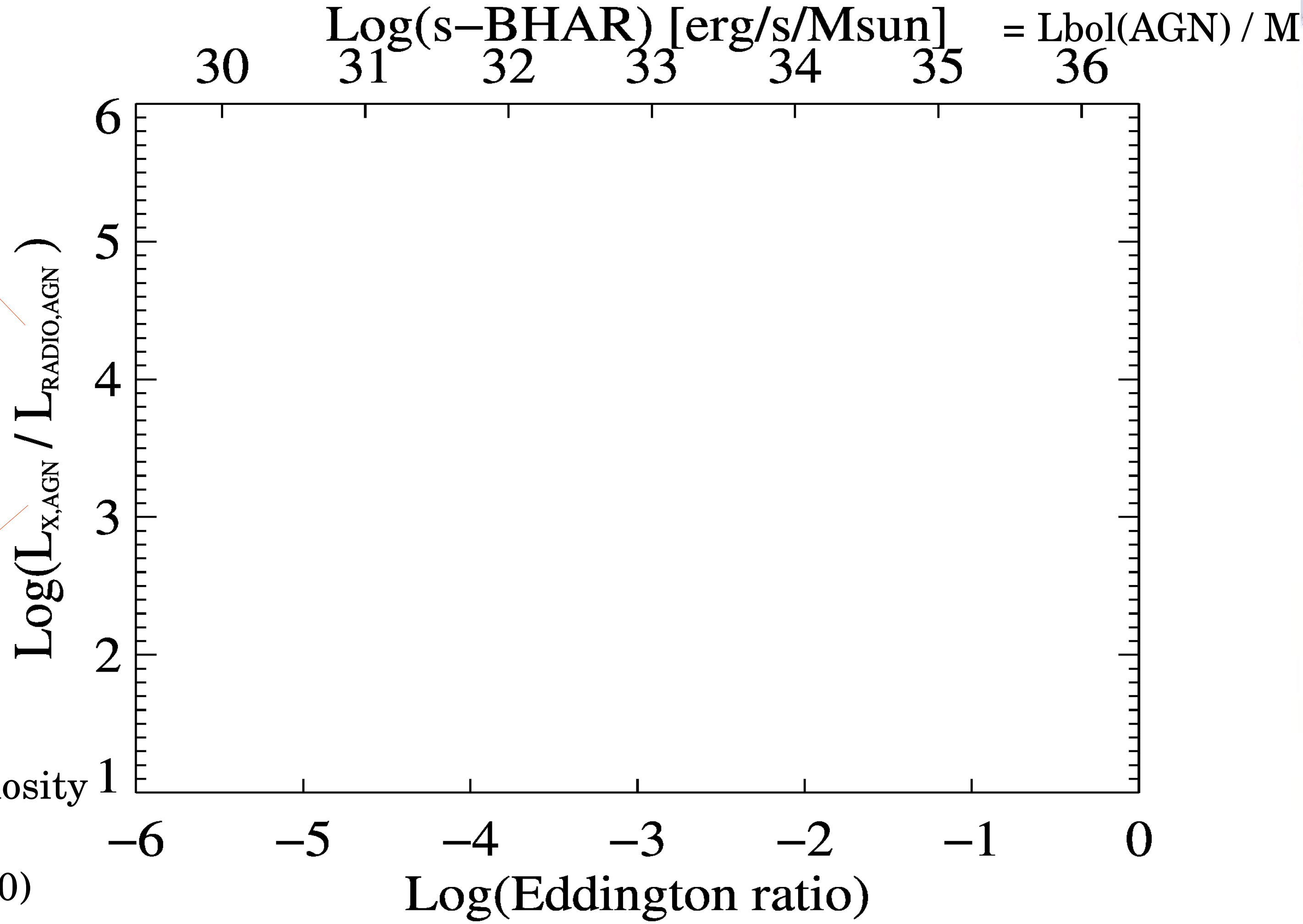
(Unprecedented sensitivity at ~mas resolution)





The *Eddington ratio* – vs – *Lx / Lradio* plot

Offset from IRRC

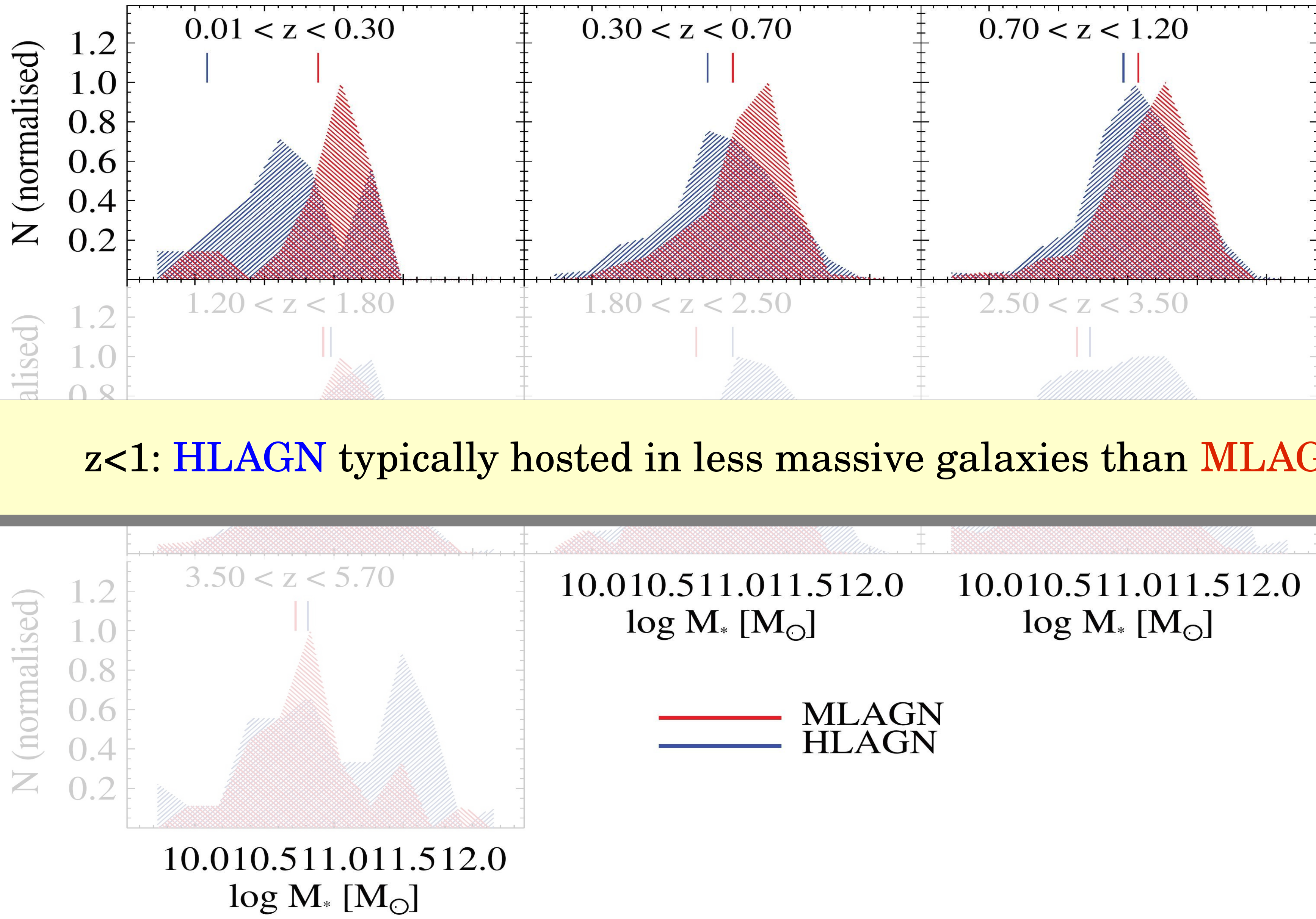


Intrinsic AGN X-ray luminosity via correction for nuclear obscuration (Xue et al. 2010)

- From Lx(AGN) to Lbol(AGN) via luminosity-dependent bolometric corrections (Lusso et al. 2012)
- From Lbol(AGN) to Eddington ratio by assuming M*/Mbh = 500 (Häring & Rix 2004)

Stellar mass distributions

(Delvecchio et al. 2017)

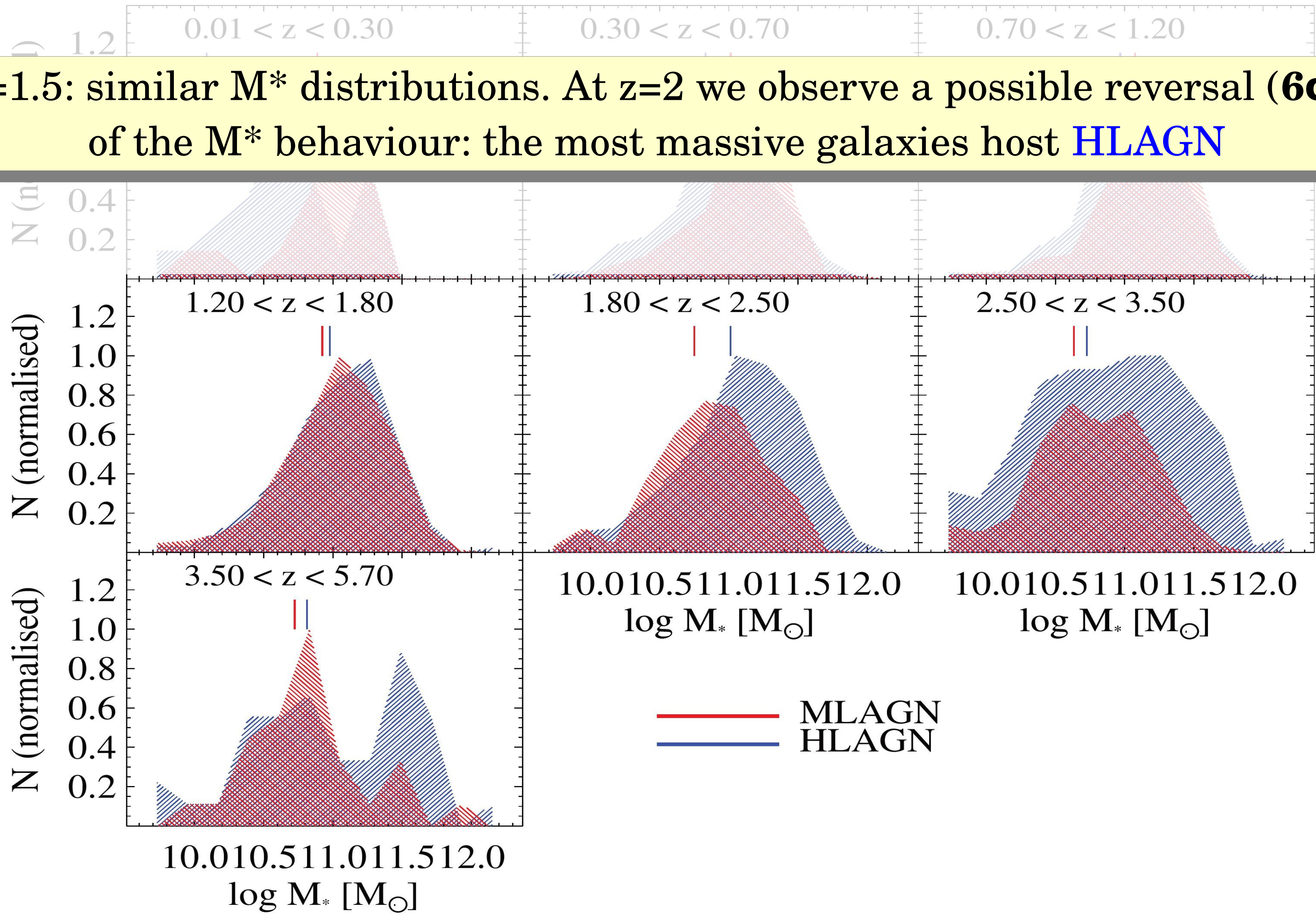


z<1: HLAGN typically hosted in less massive galaxies than MLAGN

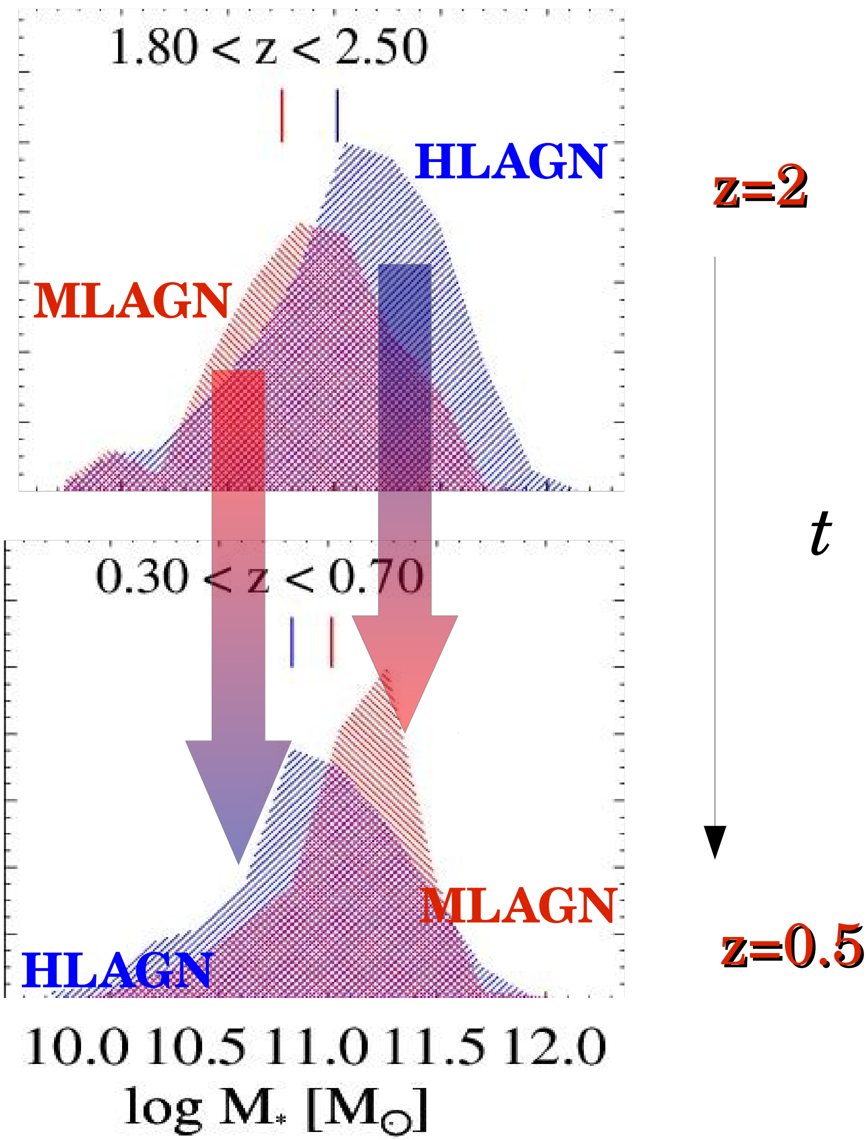
Stellar mass distributions

(Delvecchio et al. 2017)

z=1.5: similar M* distributions. At z=2 we observe a possible reversal (**6σ**) of the M* behaviour: the most massive galaxies host HLAGN

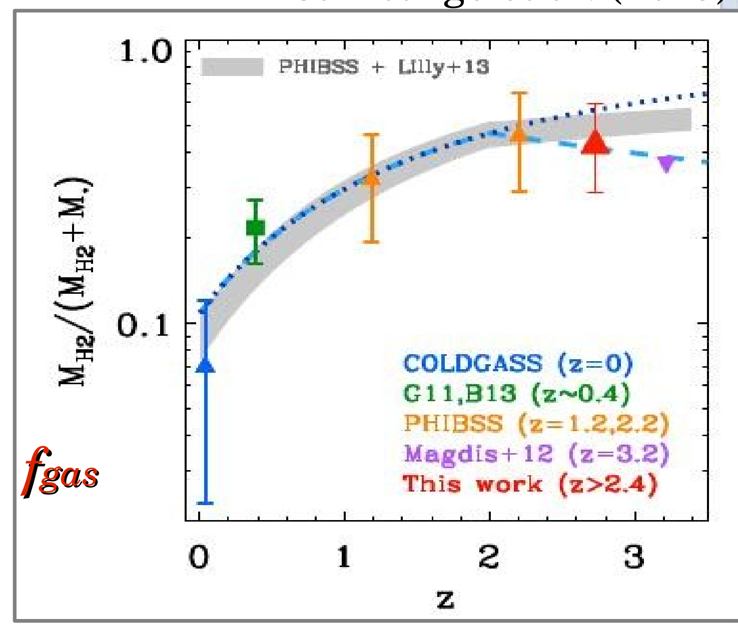


Hint of "downsizing"?



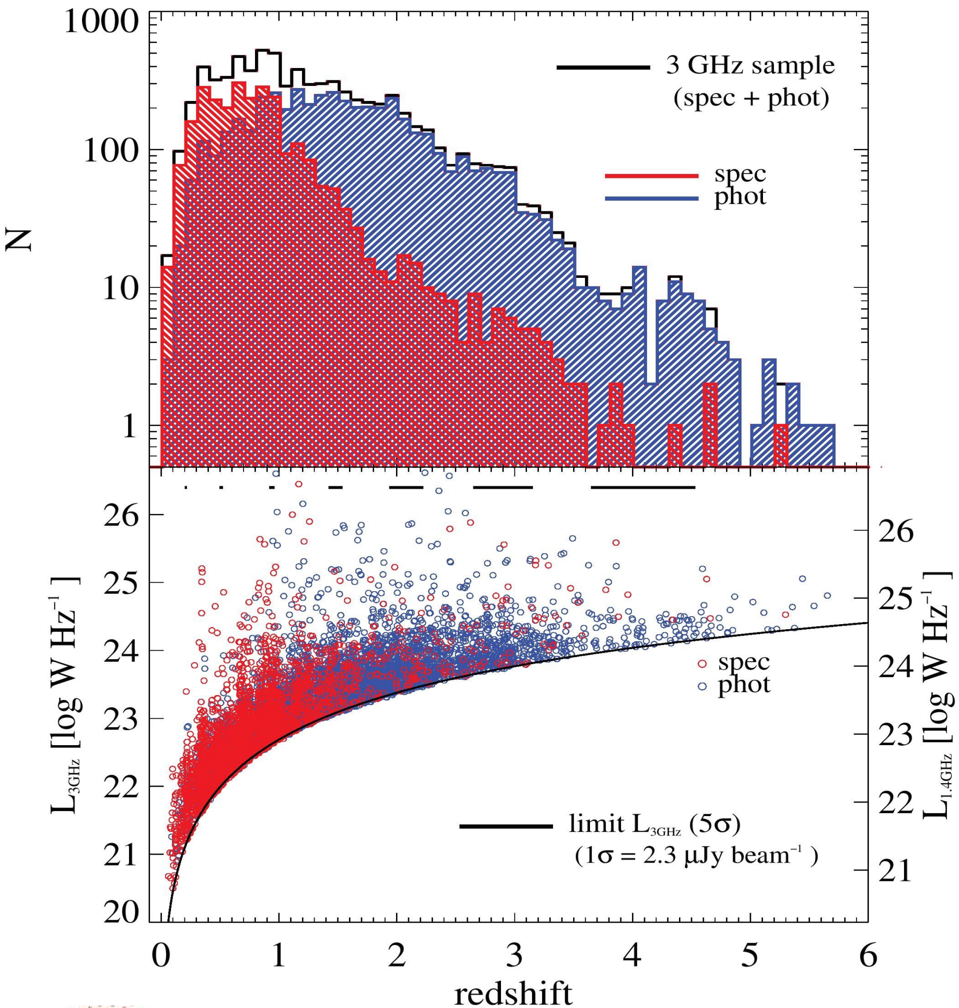
The most massive galaxies are very gas rich, and trigger radiative AGN activity (HLAGN)

Saintonge et al. (2013)



At later times, AGN activity fades: massive galaxies host MLAGN. HLAGN in less massive systems

Going deeper and back in time: The 3 GHz VLA-COSMOS survey

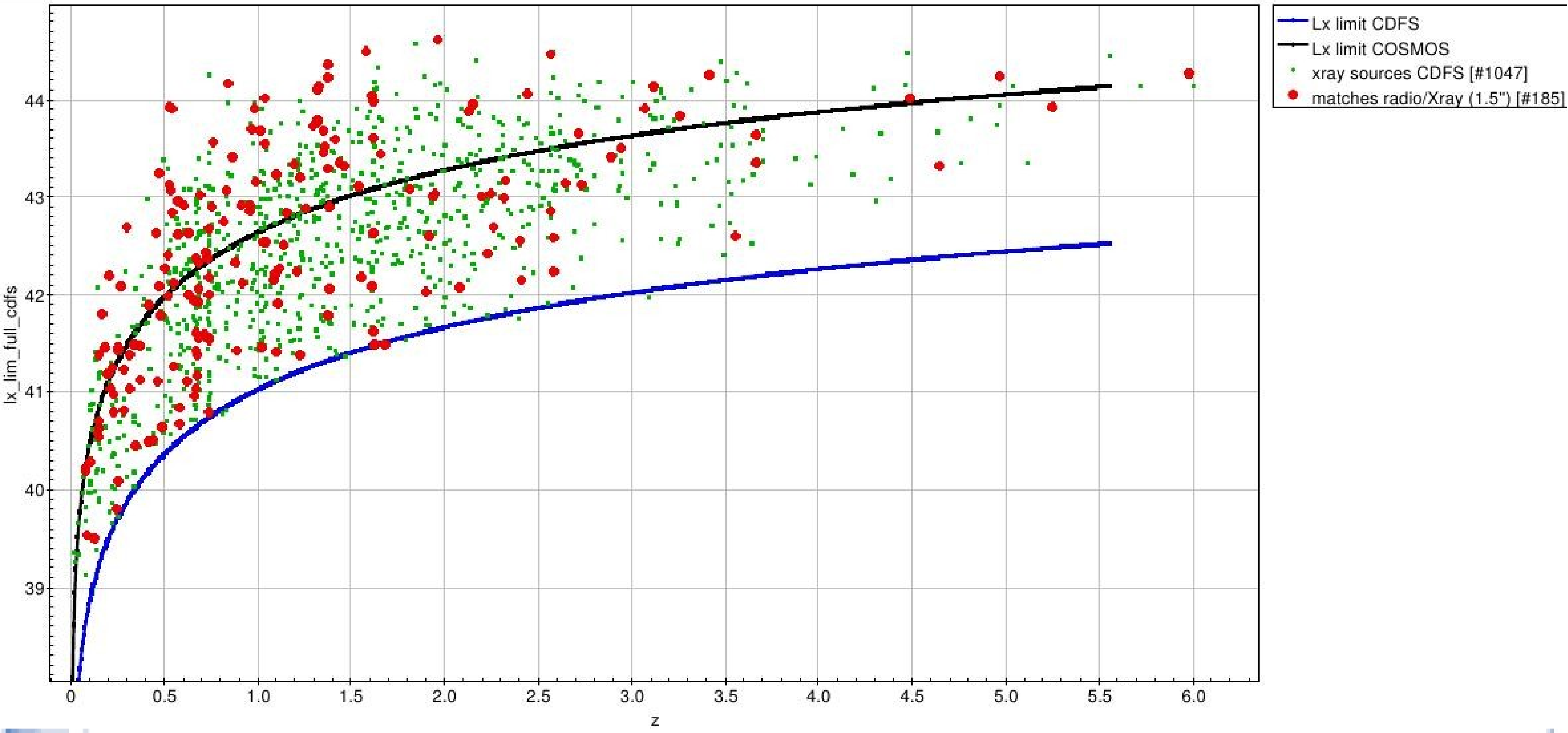


- 10,830 radio sources selected at 3 GHz (10 cm) down to an unprecedented sensitivity over 2.6 deg^2 of the COSMOS field (Smolčić et al. 2017a)
- ~90% have optical/NIR counterpart in the COSMOS2015 catalog (Smolčić, Delvecchio et al. 2017b).
- Accurate redshifts and opt-mm photometry (>30 bands) from the COSMOS2015 catalogue (Laigle et al., 2016)

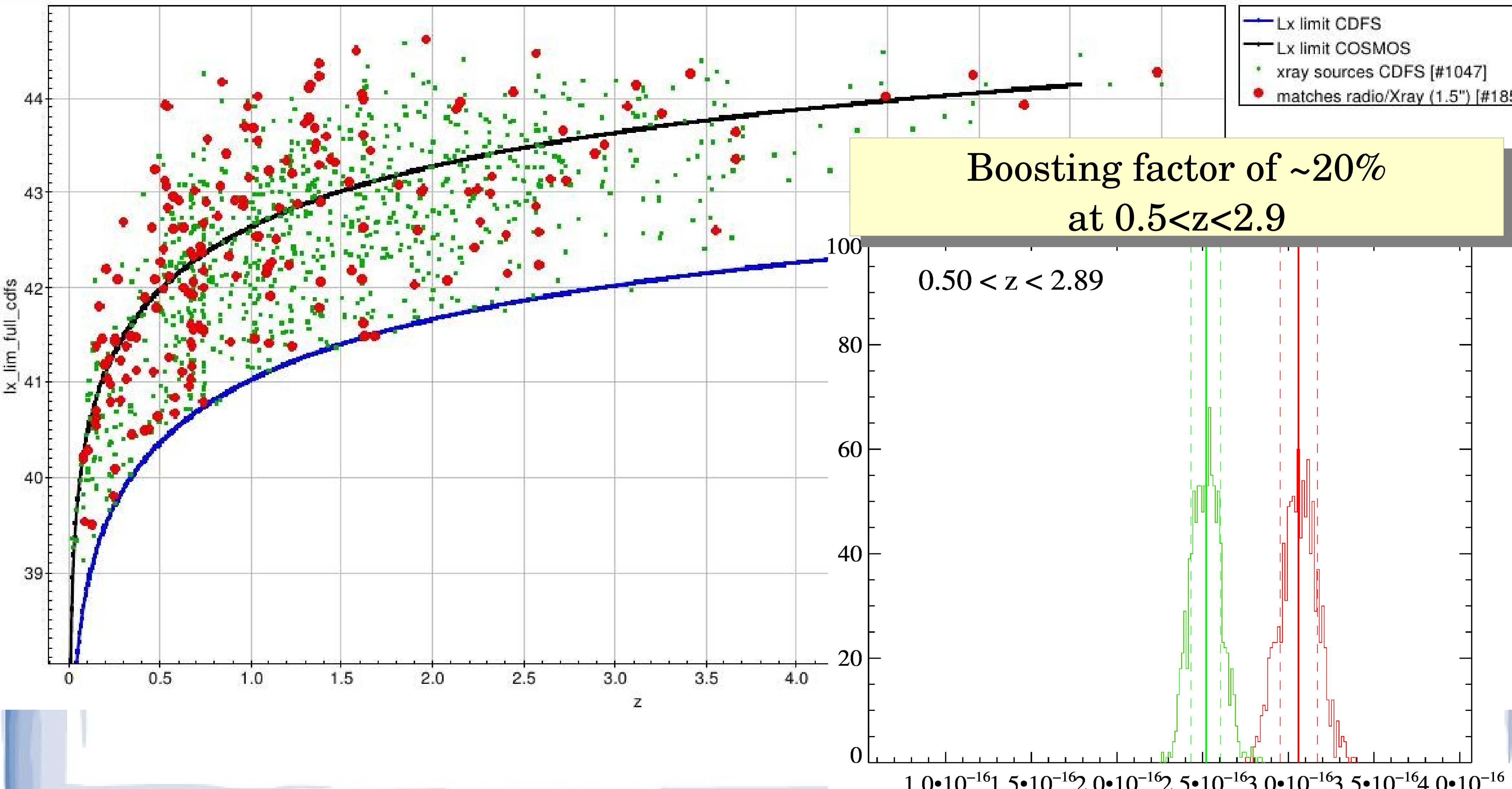
PI: V. Smolčić

FINAL SAMPLE:
7,729
radio sources + multi-λ

HLAGN vs MLAGN: expected cross-contamination



HLAGN vs MLAGN: expected cross-contamination



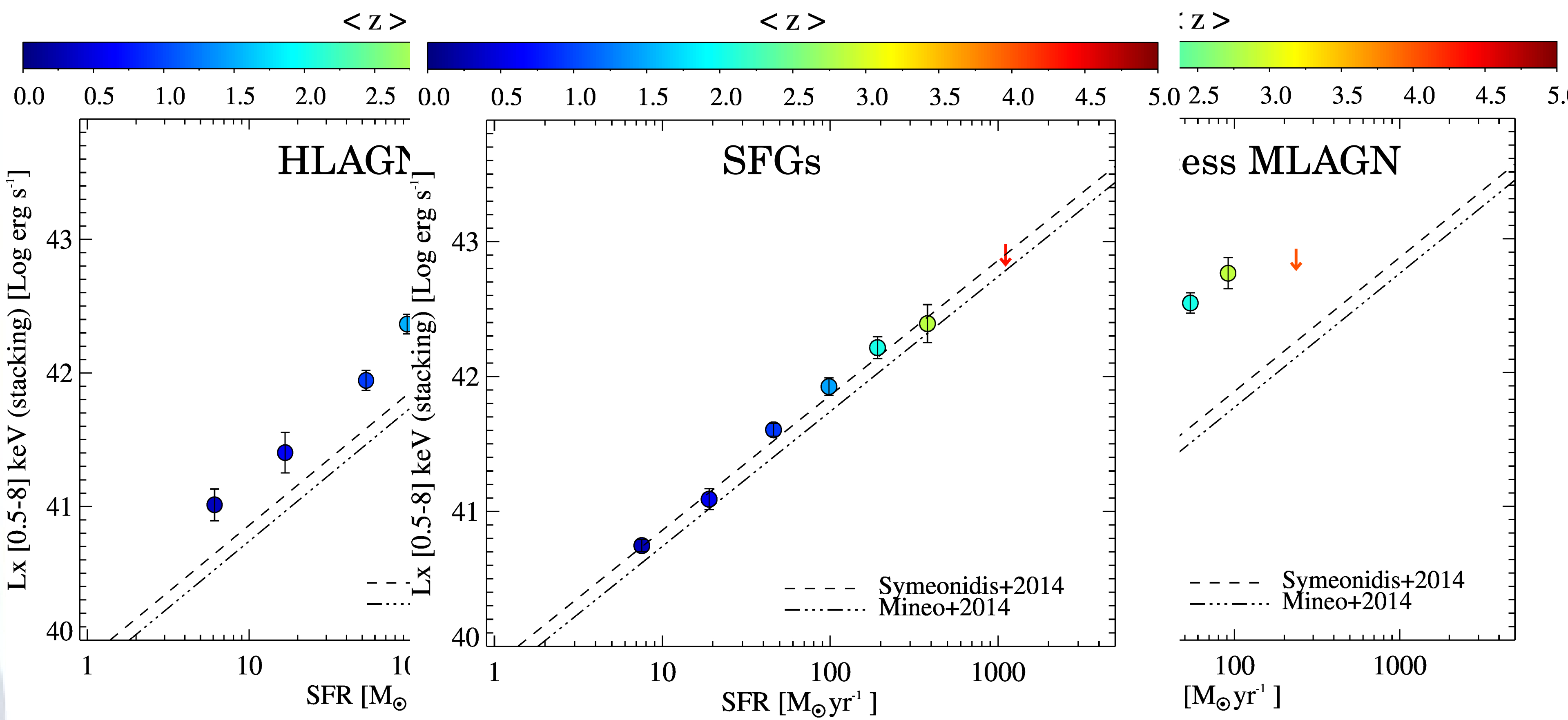
Boosting factor of ~20%
at 0.5<z<2.9

X-ray stacking of HLAGN vs MLAGN

- X-ray stacking tool CSTACK*
- Stacking Chandra images of X-ray undetected sources, binned in class and redshift

→

- >2σ detection at almost all redshifts
- Excess in X-ray emission due to AGN
- SFGs don't show any X-ray excess

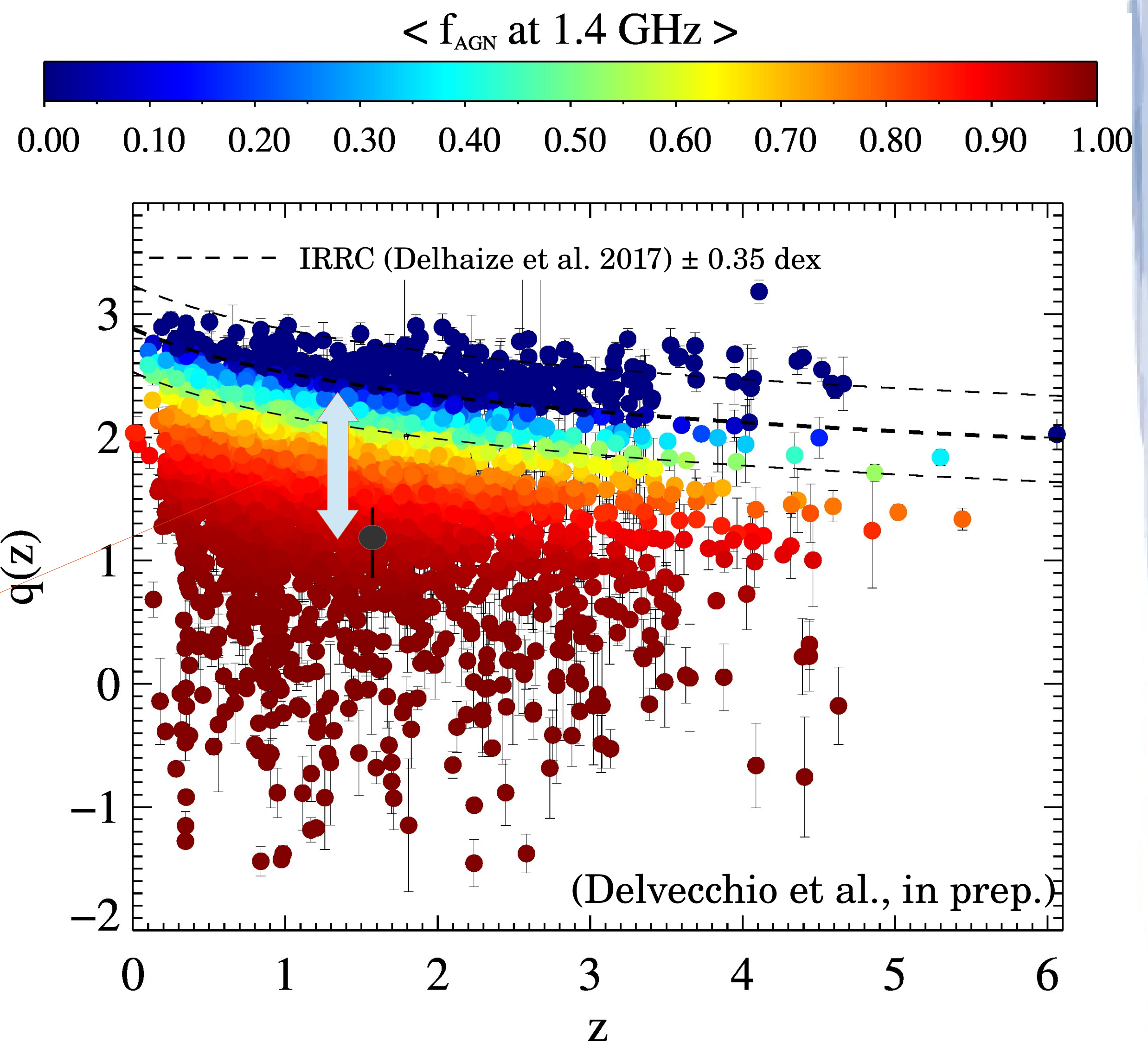


* http://lambic.astrosen.unam.mx/cstack/ (developed by T. Miyaji)

1. Subtracting SF contribution from radio

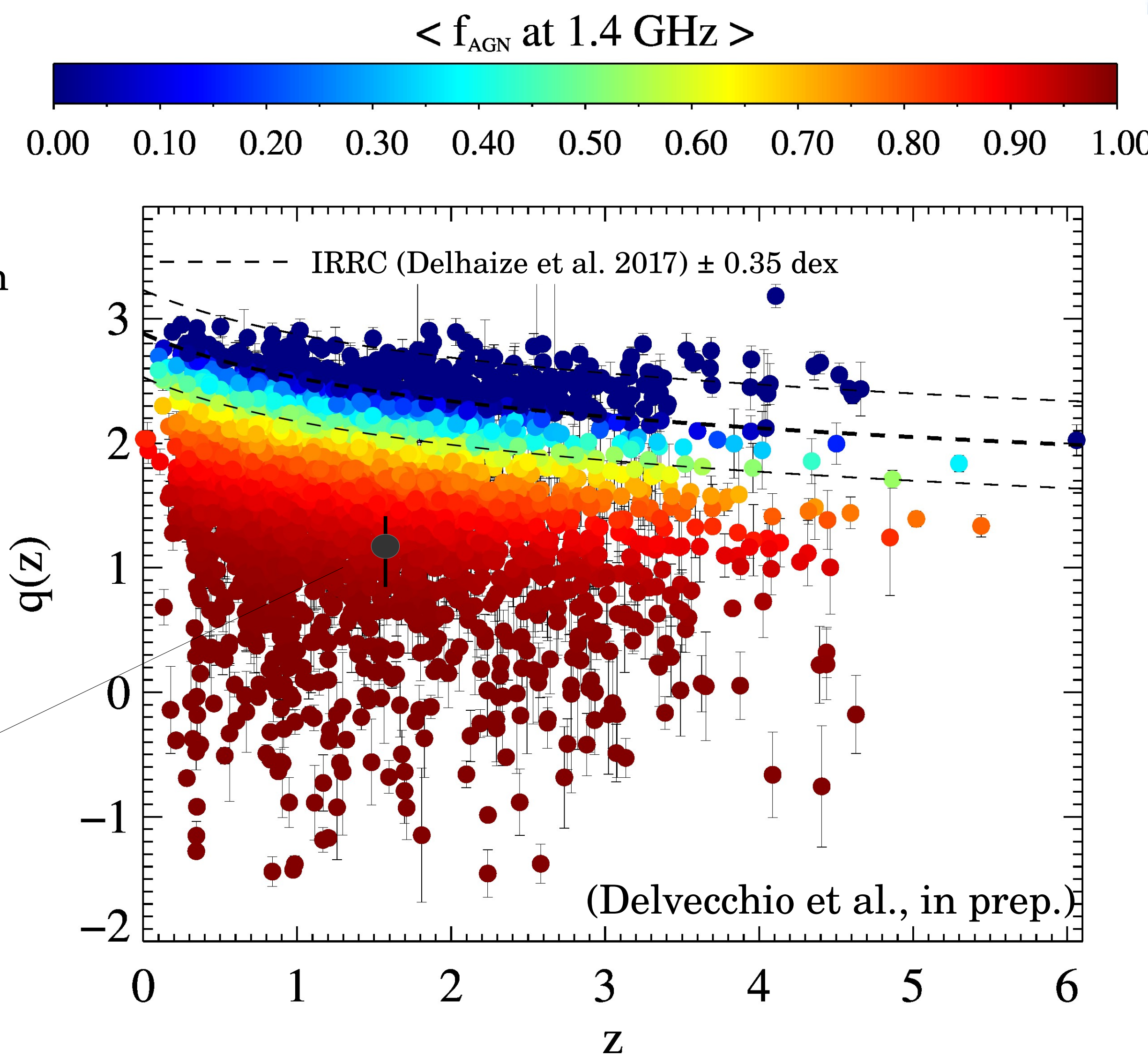
- We measure the q-offset of each source from the IRRC
- Monte Carlo: for each source, we looped over the uncertainty on both the observd q and the IRRC

$$f_{AGN} = 1 - 10^{(-\Delta q)}$$

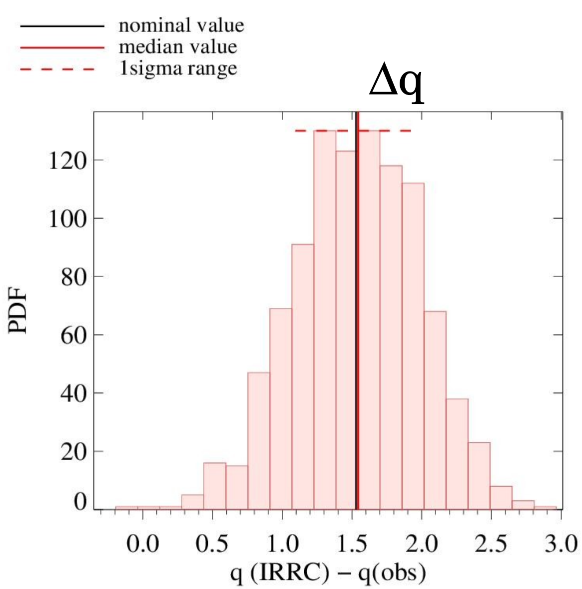


1. Subtracting SF contribution from radio

- We measure the q-offset of each source from the IRRC
- Monte Carlo: for each source, we looped over the uncertainty on both the source's q(z) and the IRRC

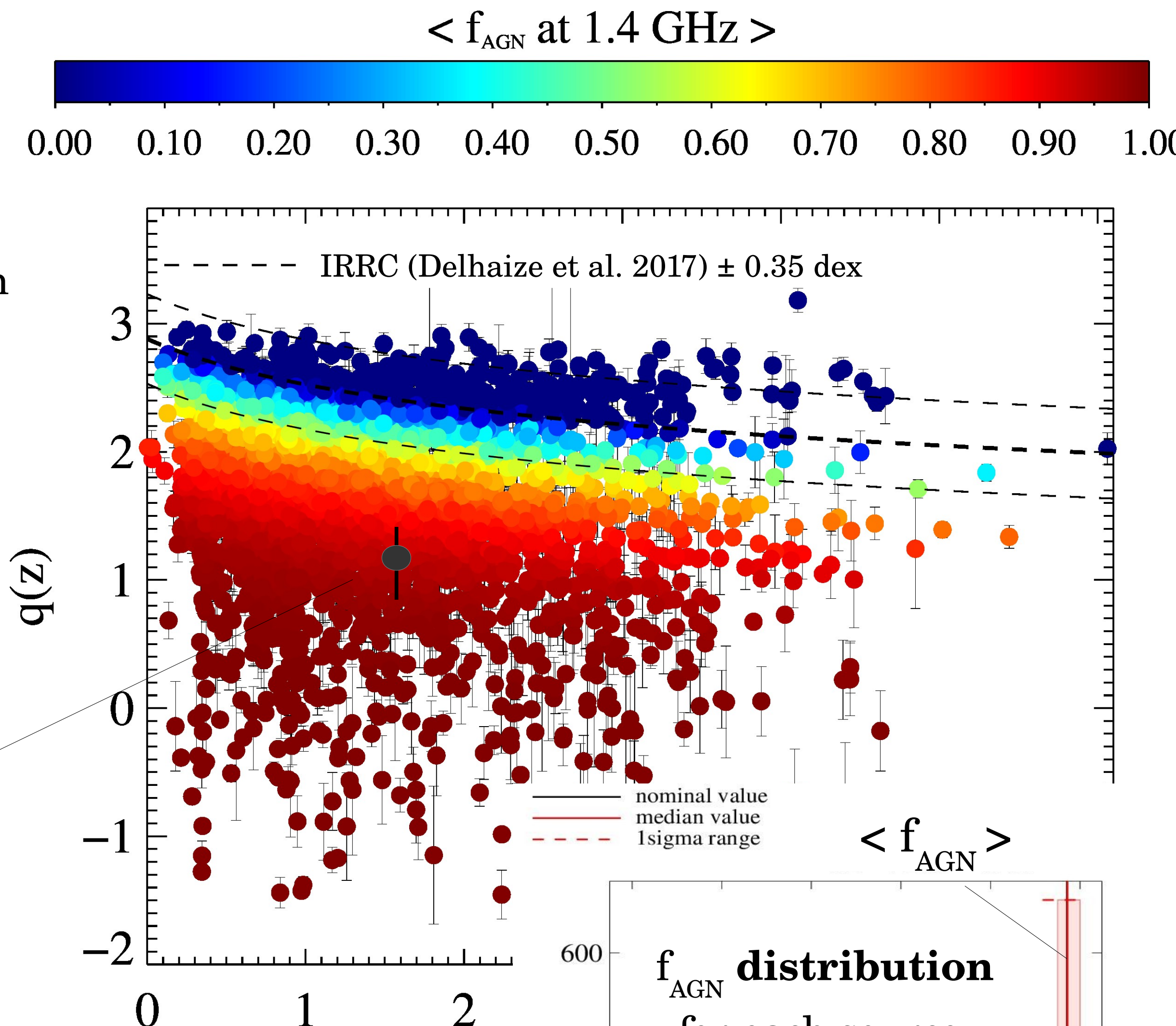


Δq distribution for each source

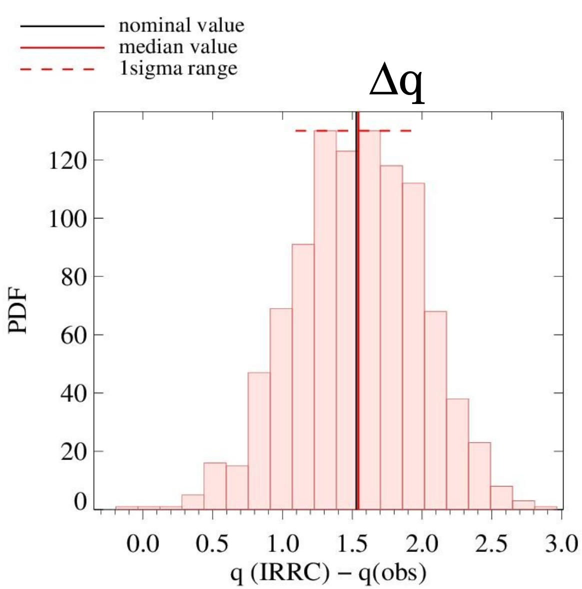


1. Subtracting SF contribution from radio

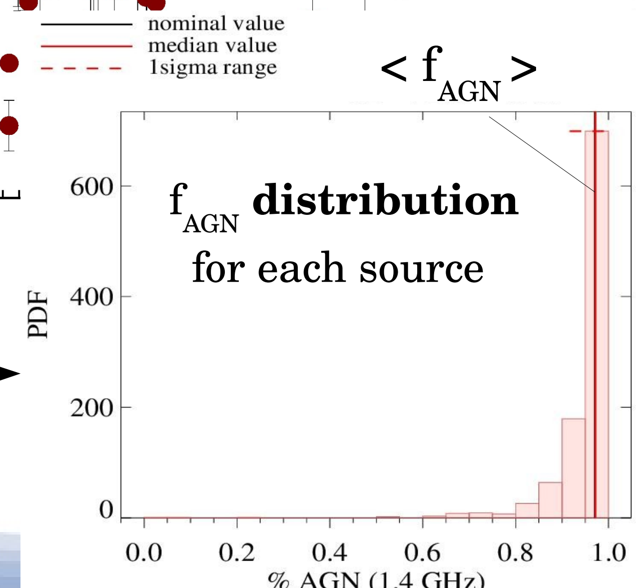
- We measure the q-offset of each source from the IRRC
- Monte Carlo: for each source, we looped over the uncertainty on both the source's q(z) and the IRRC



Δq distribution for each source



$$f_{AGN} = 1 - 10^{(-\Delta q)}$$



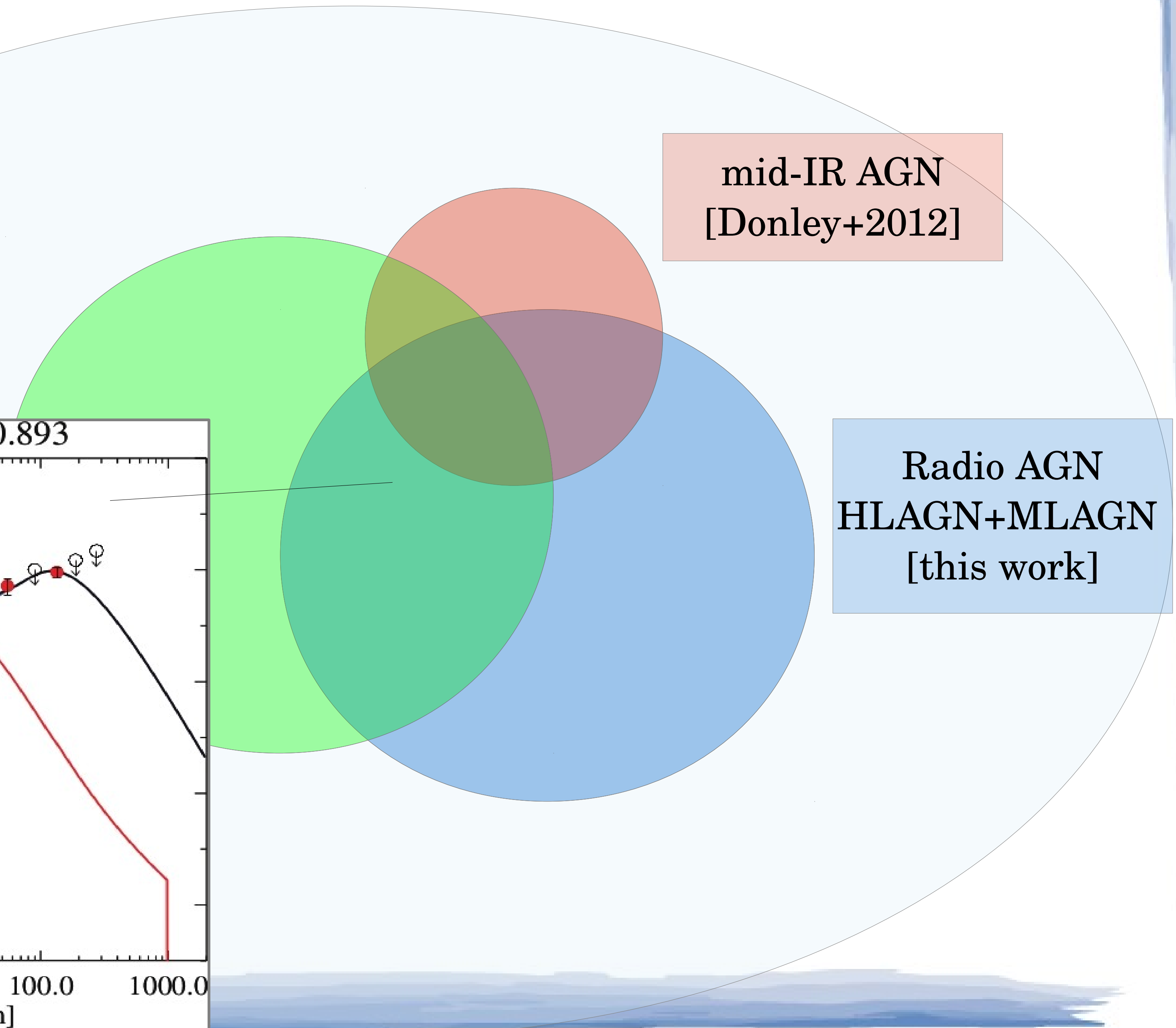
AGN populations in the COSMOS field

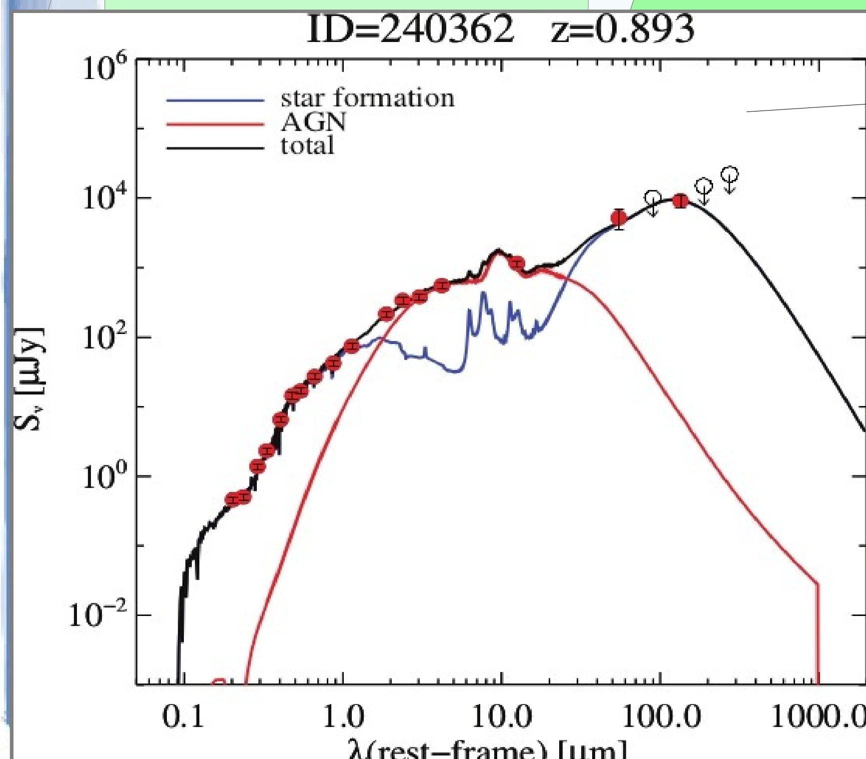
COSMOS2015 catalog

X-ray AGN
[Lx > 10^{42} erg/s]
Civano et al. (2016);
Marchesi et al. (2016)

mid-IR AGN
[Donley+2012]

Radio AGN
HLAGN+MLAGN
[this work]

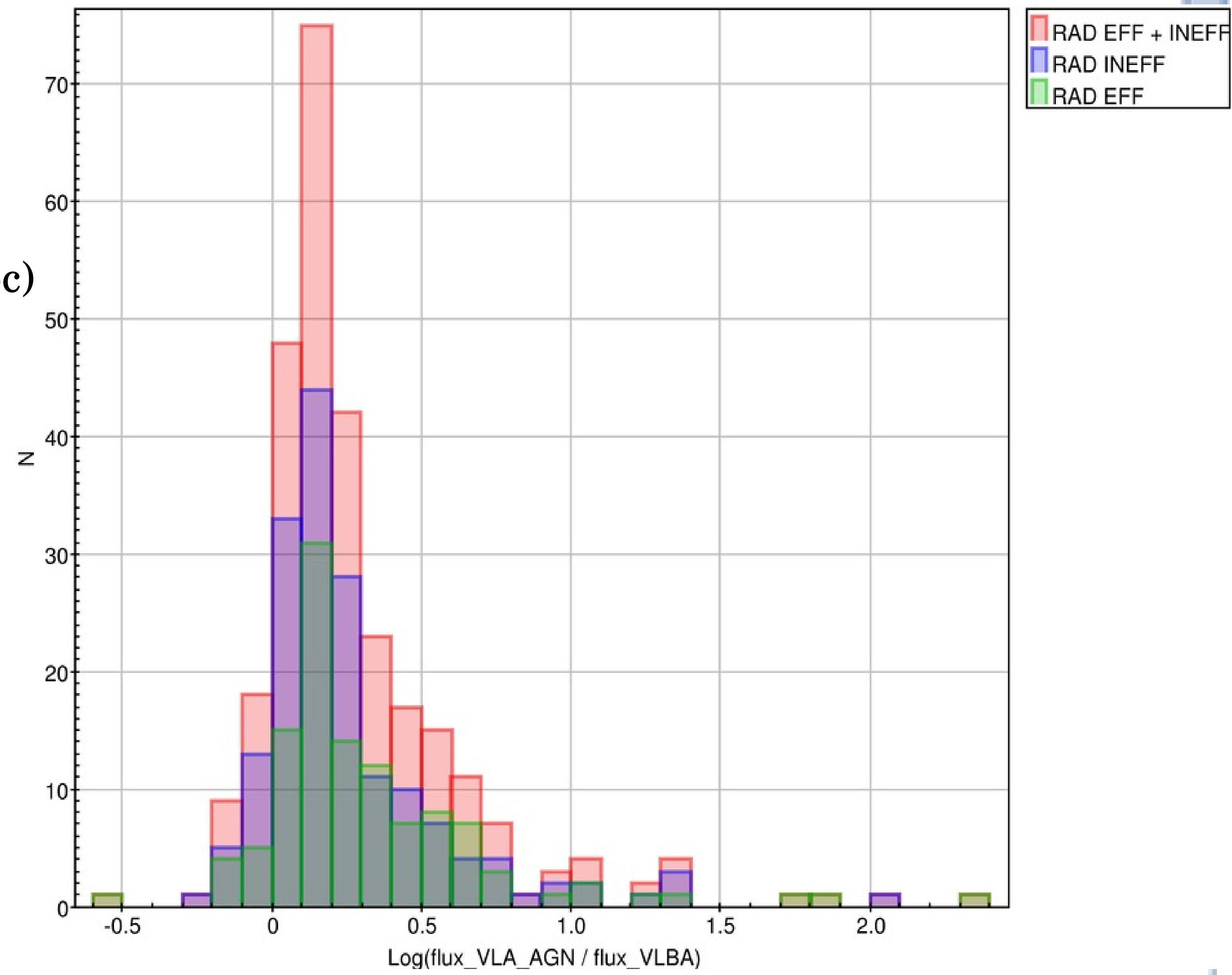




VLBA – vs – VLA emission

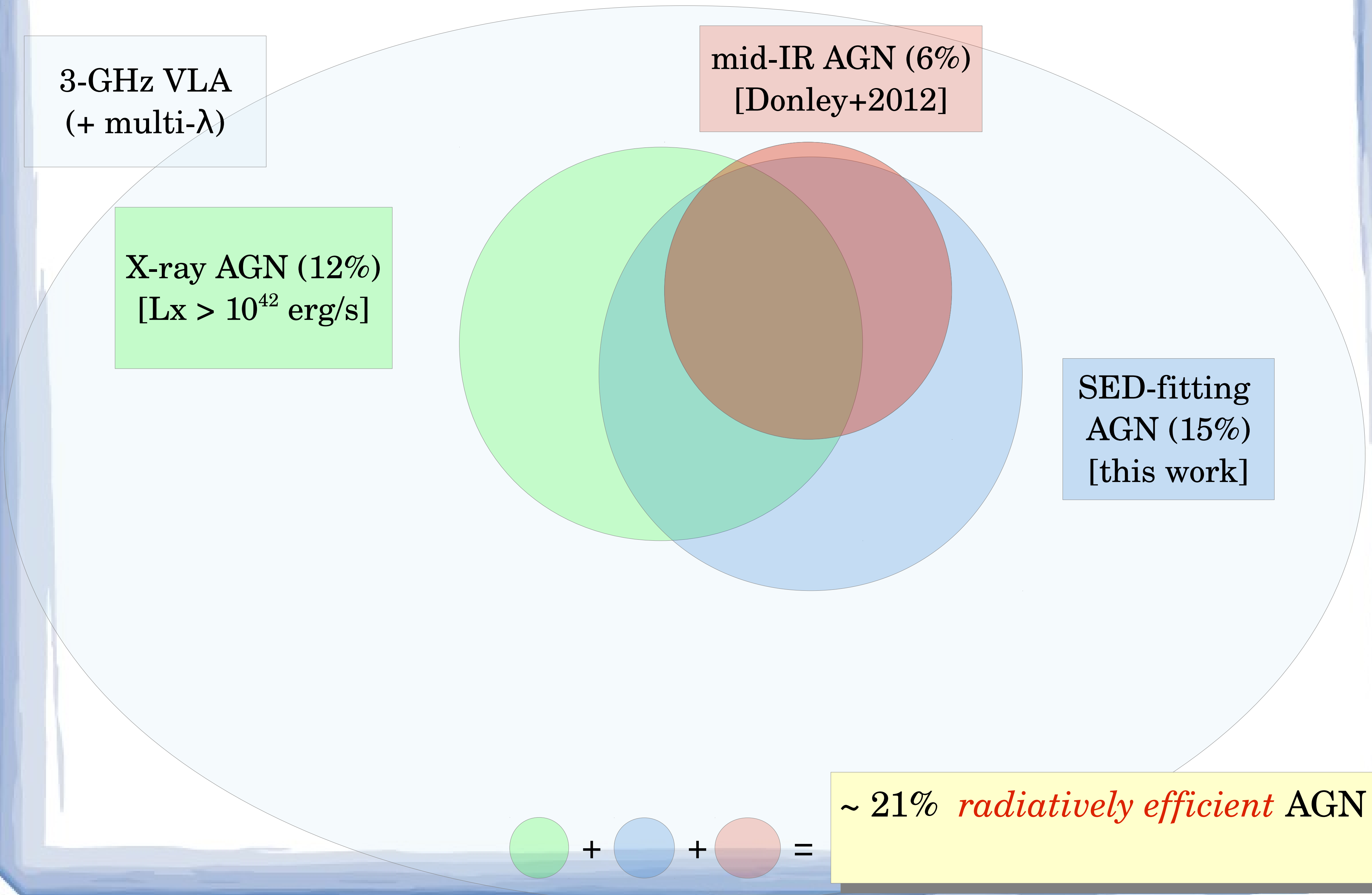
Radio emission
(345 sources):

~50% core (20-100pc)
~50% outer regions



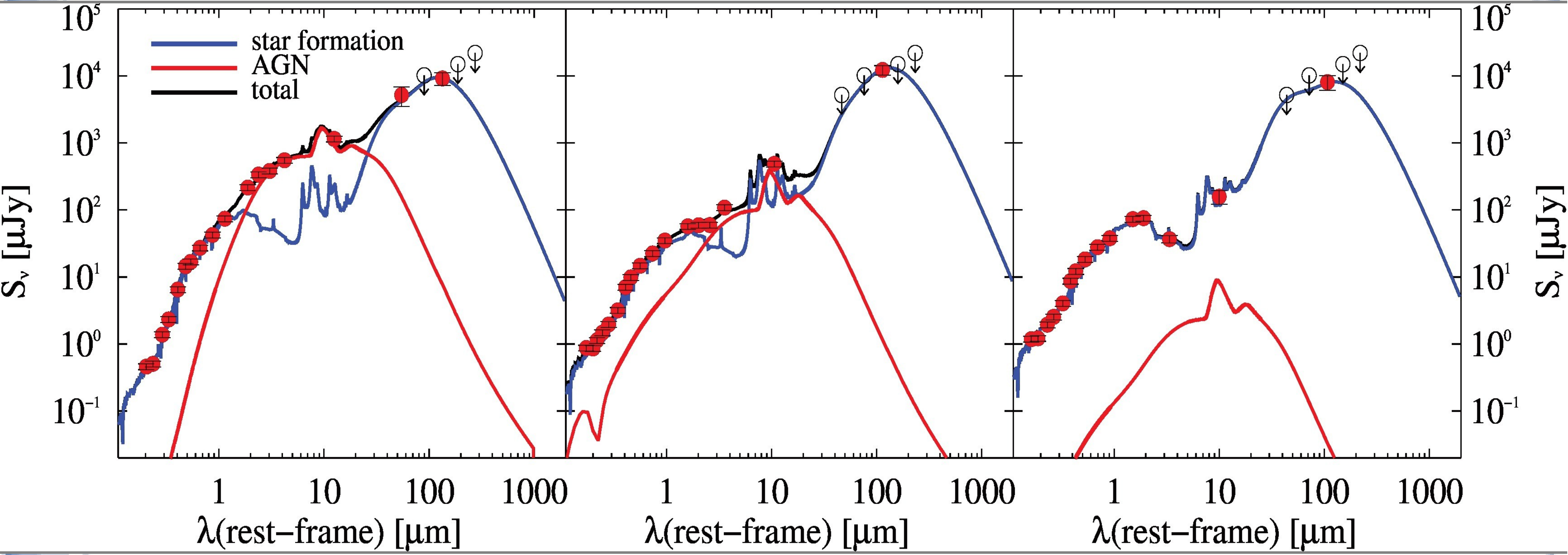
<TOTAL / CORE radio emission> ~ 0.25-0.3 dex

AGN populations in Radio



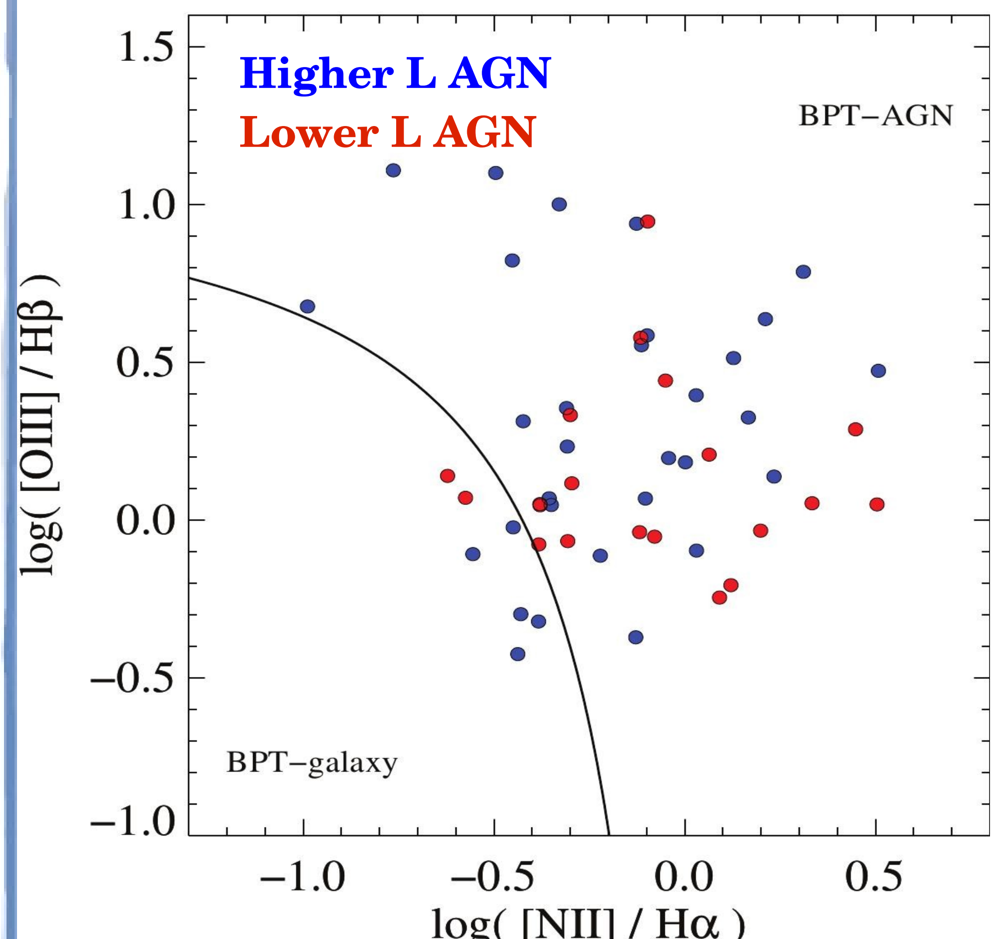
SED examples of Rad. Eff. AGN

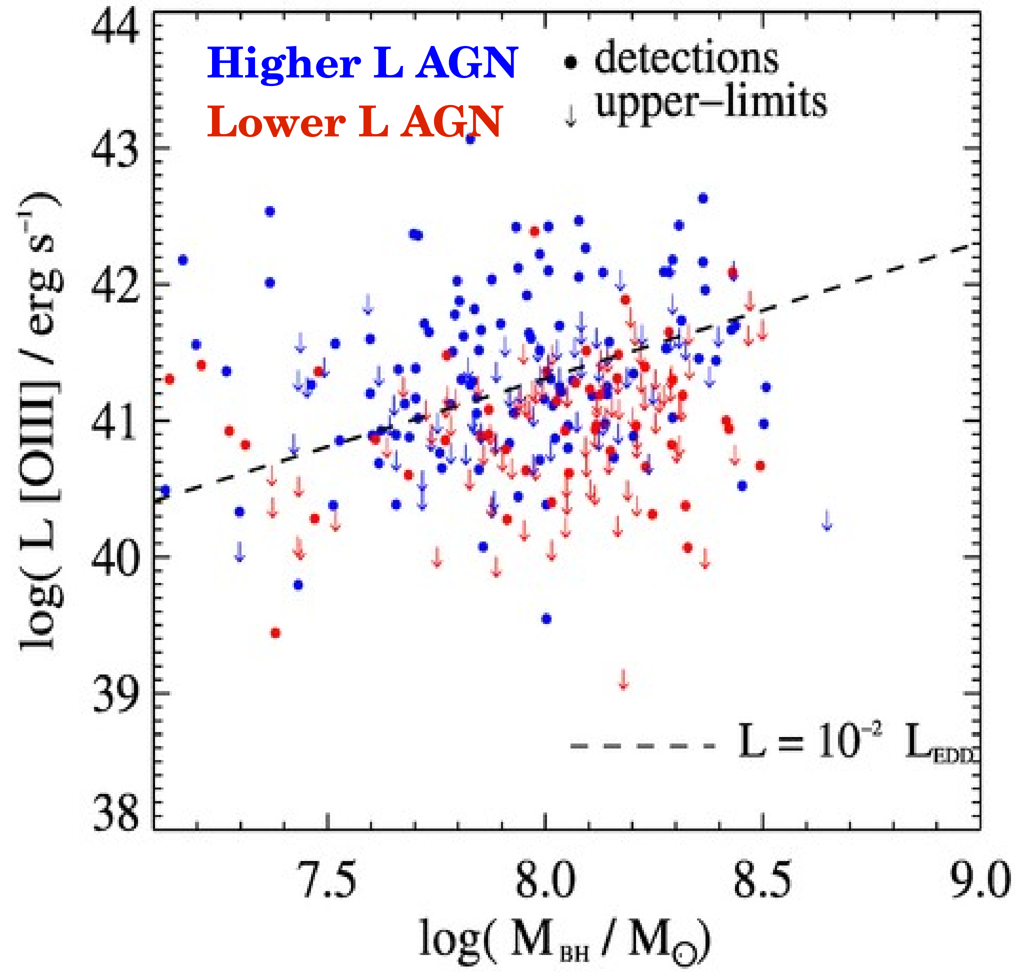
SED+MIR+Xray AGN **SED-only AGN** **Xray-only AGN**



Radio-selected AGN: optical spectroscopy

COSMOS field <z>=0.32





- 86% of radio-selected AGN in the BPT-AGN wedge
- Clear separation HLAGN-vs-MLAGN at Edd. Ratio ~ 1% (locally)

SED-selected AGN