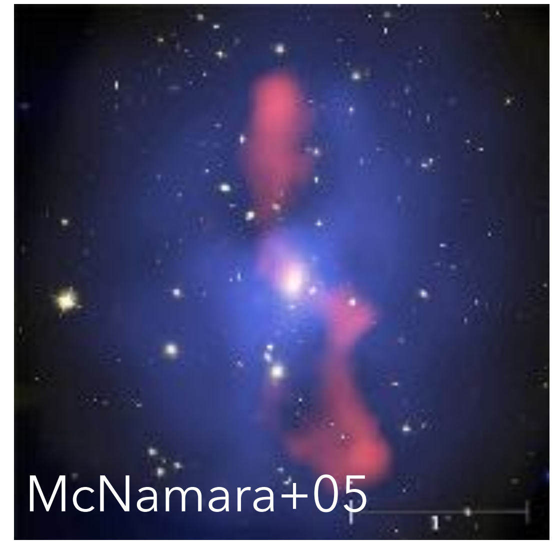
# High-z Radio Galaxy Survey with Subaru HSC

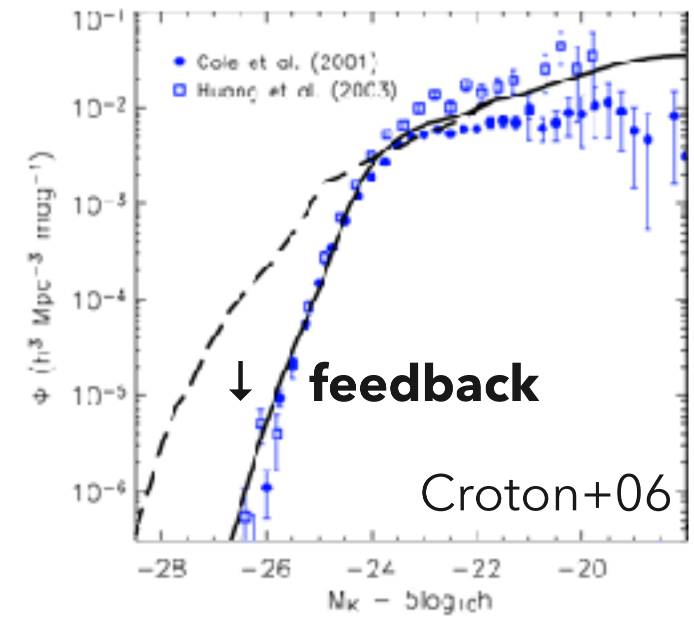
**Takuji Yamashita (NAOJ)**
**and the WERGS collaboration**

# High-z radio galaxies in early universe

## Negative feedback on SF

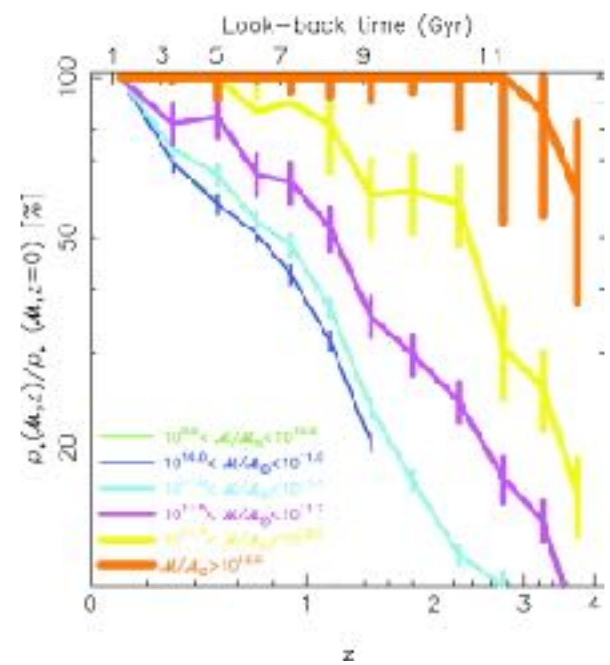
- SF Suppression
- Key effect to reproduce the massive end of MF




## Evolution of massive galaxies

- The most massive galaxies have been formed at z > 3
- A half of local stellar mass was assembled at 1 < z < 4




← log $M_*$/Msun> 12

Perez-Gonzalez+08

## Beacon for proto-clusters

- RGs are often associated with overdense regions

## Constrain theory on the black hole growth

- RGs tend to have massive stellar mass (>$10^{11}$ Msun).

# High-z Radio galaxies (HzRGs)

## Evolution of radio galaxies

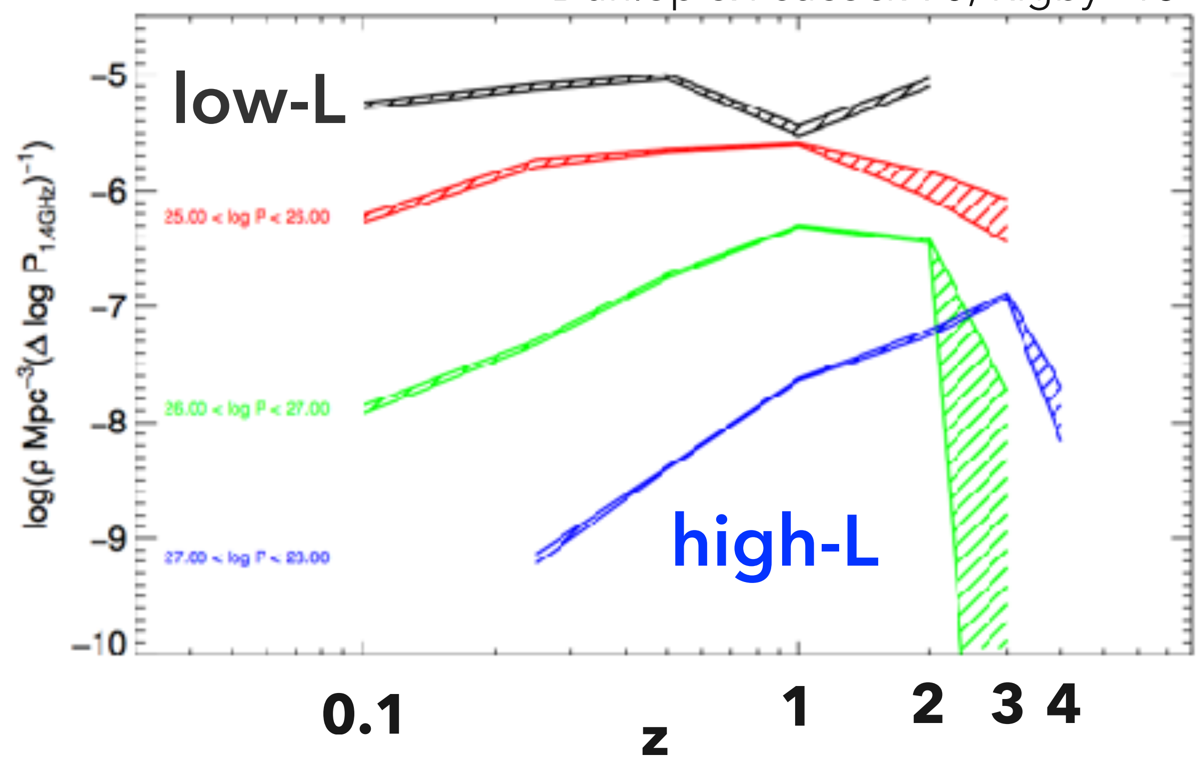
- Number density (ND) moderately increases up to z = 1 – 2
- Abruptly decline at z ~ 2 – 3
- ***At z > 3, ND is not well constrained due to a dearth of HzRG samples***

## z > 4 HzRGs

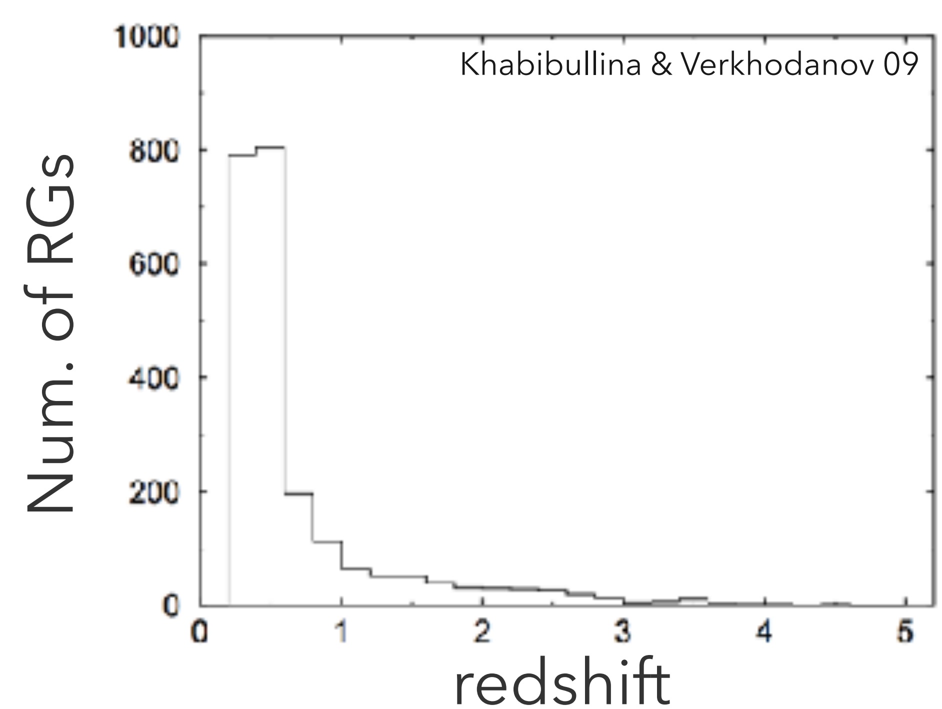
- **Only 13 HzRGs** have been discovered to date.
- All known z > 4 RGs were found with **an ultra-steep spectrum technique**, except for two HzRG(s).

Number density evolution of HzRGs

Dunlop & Peacock 90; Rigby+15




Redshifts of spectroscopically identified RGs



# HzRG Search with the ultra-steep spectral tech.

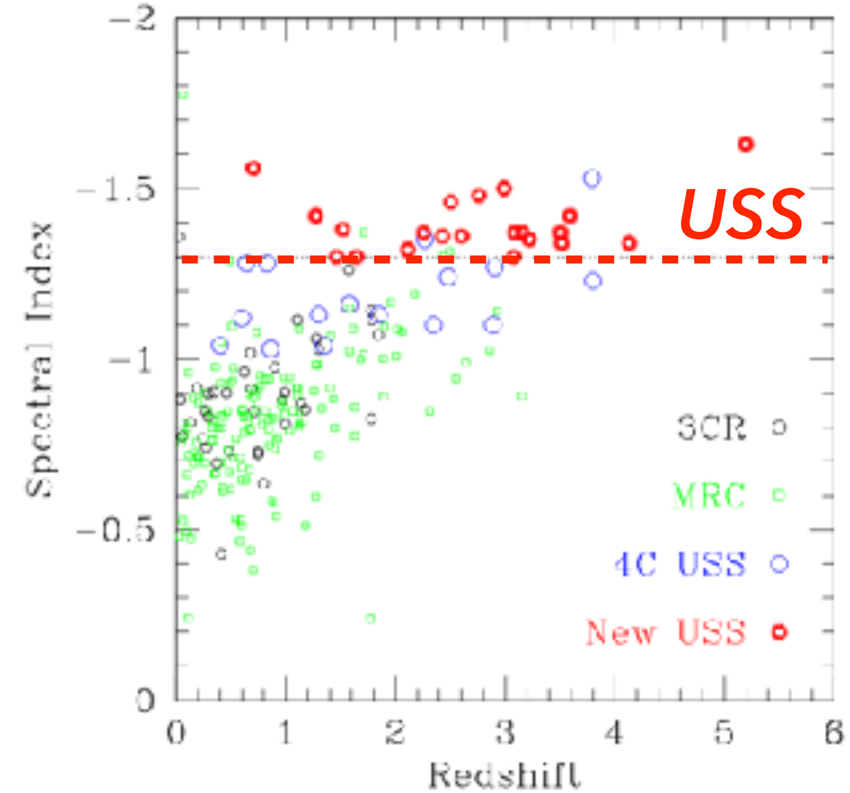
## Search for HzRGs

- It's not easy to find HzRGs because of
  - the low surface densities (<1/$z$/deg$^2$)
  - much more optical faintness than quasars

## Ultra-steep spectra (USS)

- Empirical relation: z - α (radio spectral index)
- HzRGs are believed to have an ***ultra-steep*** radio spectrum
  - $\alpha < -1.3 \quad (S_\nu \propto \nu^\alpha)$
- Based on an idea: ideal spectra steepen with frequency

**325MHz-1.4GHz spectral index vs. redshift**
(De Breuck et al. 2000)

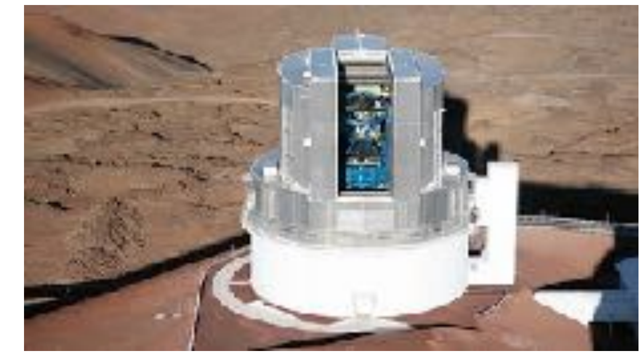



## Bias toward USS

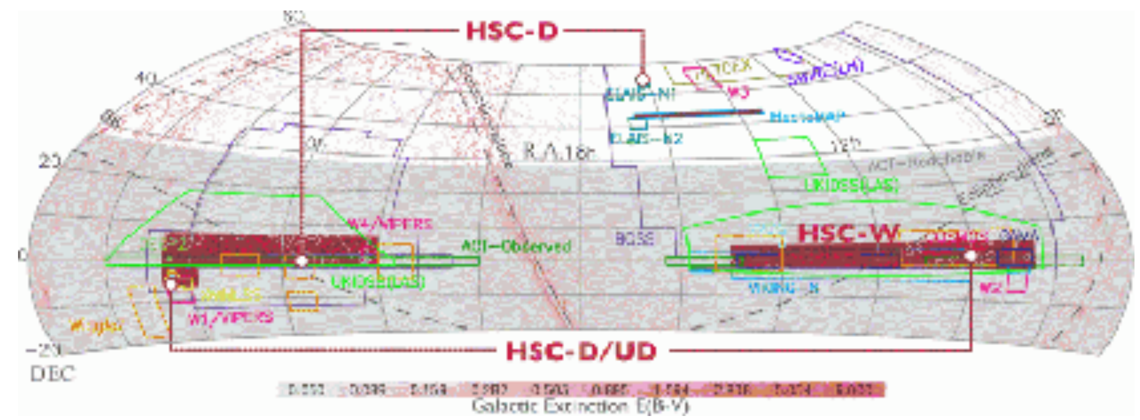
- A sample bias of HzRGs from USS could impact on the number density evolutions (Jarvis+01; Yuan+17)
- There are two objects (z~4-5) without USS (Jarvis+09; Waddington+99)
- Known z > 4 HzRGs must be the tip of the iceberg!

# Approach not relying on USS

## Subaru HSC-SSP: wide & deep optical imaging



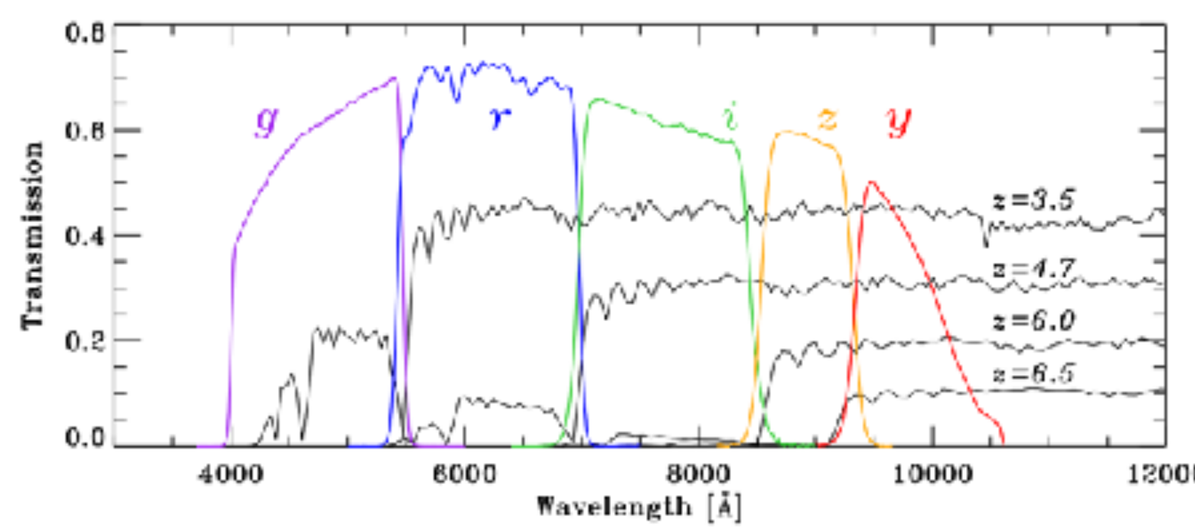
- Hyper-Suprime Cam (HSC)
- 5 BBs & 4 NBs
- 1400 deg2 & r~26 in the Wide layer
- On-going survey




## Apply "Lyman break technique" to HzRG search

- HSC-SSP enables us to use Lyman break technique for HzRGs
  - The best way for high-z surveys (e.g., Ono+18; Akiyama+18; Matsuoka+18)
  - **z = 3.5 - 7.0 HzRGs** will be found
- Not relying on USS
  - **no bias of radio SED**

Ono+18



# WERGS

## WERGS: Wide and Deep Exploration of Radio Galaxies with Subaru HSC

*Exploration of high-z or optically faint radio galaxies with Subaru HSC in order to tackle the issues on the galaxy/AGN evolution.*

- T. Nagao, Y. Matsuoka, M. Kajisawa, M Niida, A. Noboriguchi, A. Ishida, K. Matsuoka (Ehime U.), M. Akiyama, W. He, K. Ichikawa (Tohoku U.), Y. Toba, Y. Ueda (Kyoto U.), H. Ikeda, M. Tanaka, M. Schramm, I. Tanaka, T. Kawamuro, H. Uchiyama (NAOJ), T. Morokuma, Kianhong Lee (IoA, U. of Tokyo), T. Kawaguchi (Onomichi), C.-H. Lee (NOAO), Li-Ting Hsu (ASIAA), Y. Ono, Y. Harikane (ICRR, U. of Tokyo), M. Onoue (MPIA), K. Ogura (Bunkyo), N. Kawakatu (Kure), K. Inayoshi (KIAA)

- Optical spectroscopy (T. Yamashita)
- SED fitting (Y. Toba)
- IR counterparts (K. Ichikawa)
- X-ray (eROSITA, XMM) follow-up (K. Ichikawa, Y. Ueda, T. Kawamuro, L.T. Hsu)
- HzRGs (H. Uchiyama, K. Lee, T. Yamashita)

### HSC-SSP

- Early-release data (S16A)
- grizy

| | Wide | Ultra-Deep |
|---|---|---|
| Limiting mag i [mag] | 26.4 | 27.0 |
| Area [deg$^2$] | 154 | 2 |

X

### VLA FIRST 1.4GHz survey

- 1.4 GHz (20 cm) imaging
- Area = 10,575 deg$^2$; ~ SDSS
- Detection limit = 1 mJy
  (SF gals are not detected at z>0.5)
- Resolution = 5″ , Accuracy < 0.5″

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### 2 samples

- **Photo-z (z<2) Sample (Yamashita+18, Toba+2019)**
  - ~ 3600 RGs in the early-release HSC-SSP region (~150deg$^2$)
  - SED fitting (e.g., SFR, M*, $L_{AGN}$)
- **Dropout sample (Yamashita+ in prep.)**
  - g/r-dropouts with VLA FIRST detections

- grizy

| | Wide | Ultra-Deep |
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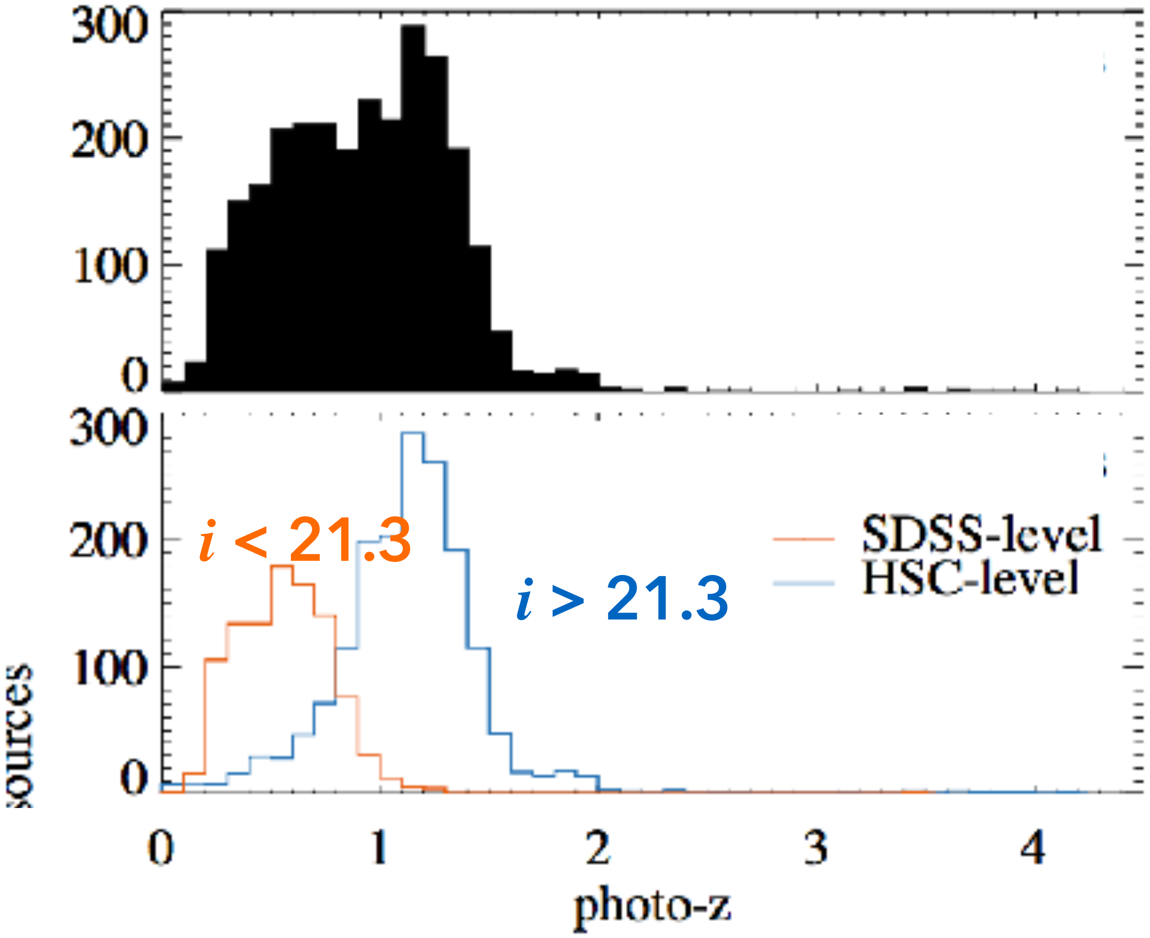
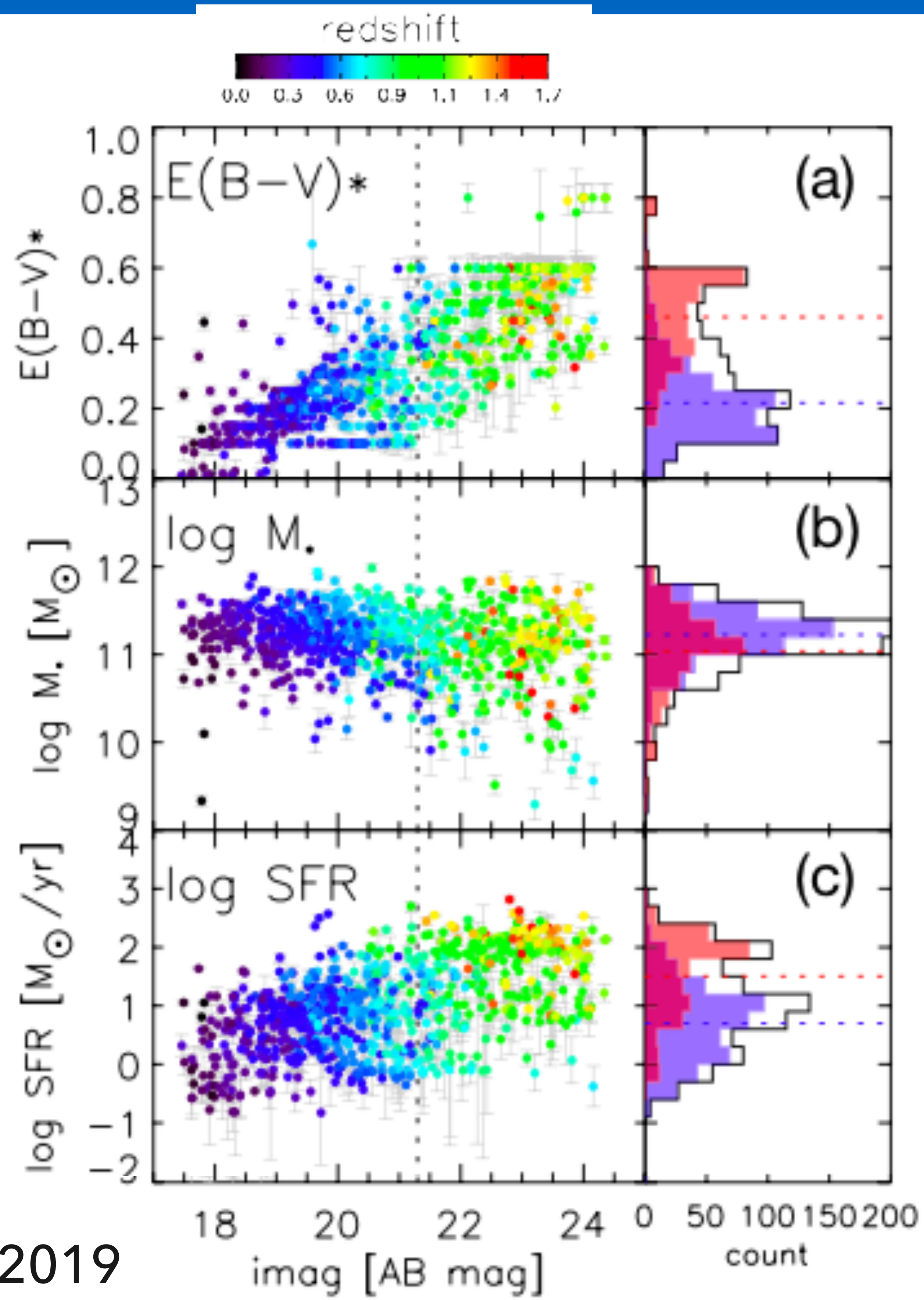
# Photo-z sample

P9: Toba et al.

- ~ 3600 RGs at z <~ 2 in 150deg$^2$
- SED fitting (u-band – radio)
  - z ~ 1 RGs have
    - higher SFR
    - larger extinction
    - less-massive stellar mass




Yamashita+2018

Toba, TY+ 2019

# z~5 HzRGs: Lyman break selection

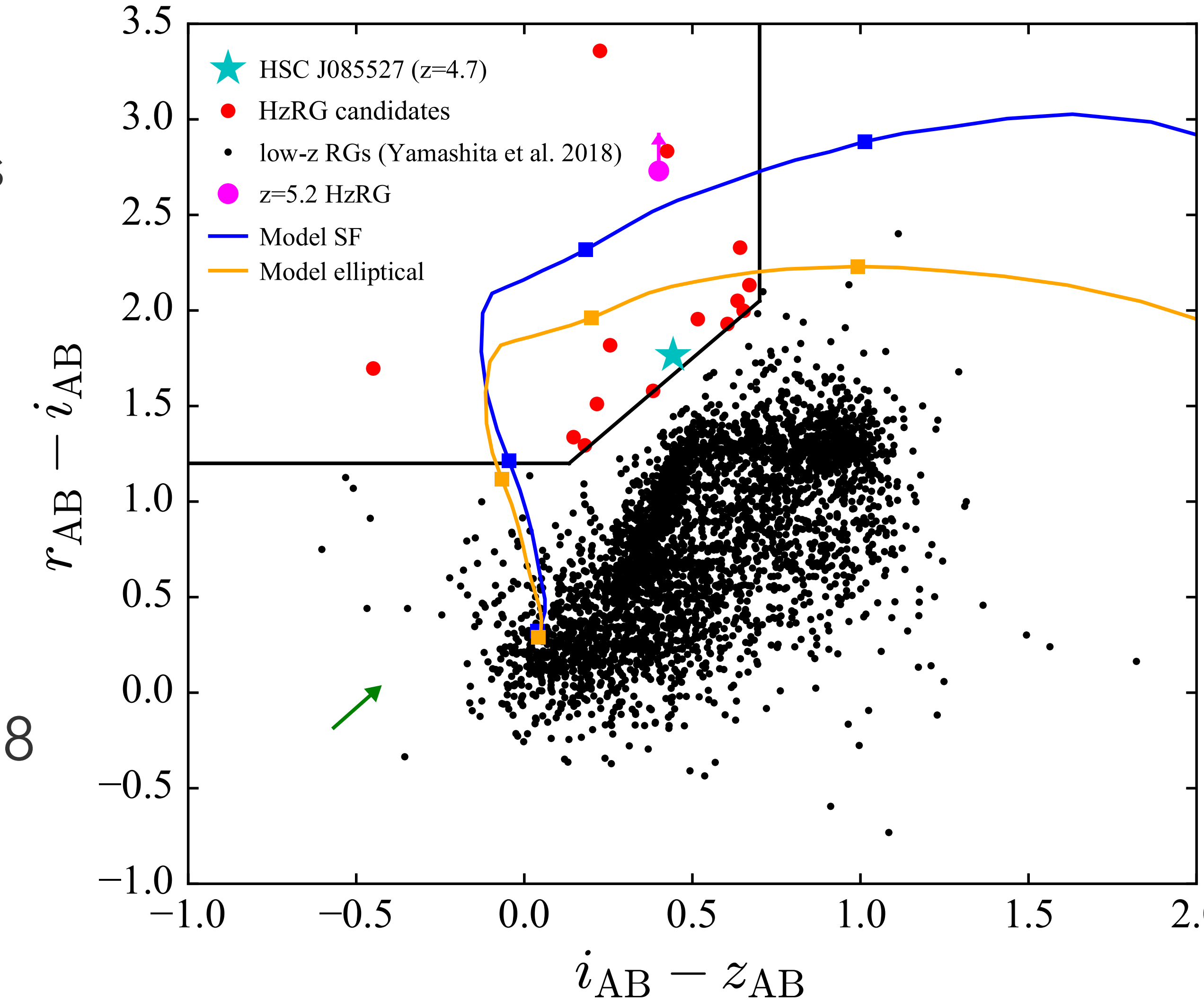
## 1. Dropouts

- Lyman break for FIRST radio sources
  - *riz* color selection for z ~ 5 radio sources (ref. the COLDRUSH project, Ono et al. 2018)
  - 16 *r*-band dropouts (z ~ 5 candidates) in the HSC-SSP region.

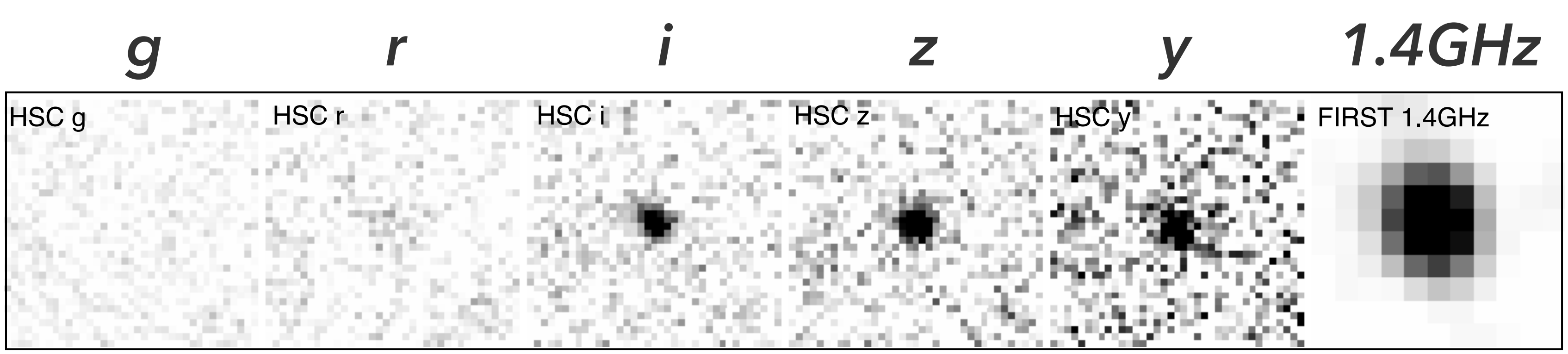
## 2. Follow-up spectroscopy

- Gemini-FT/GMOS spectroscopy in Feb 2018 for a z~5 candidate
  - z_AB = 23.5 mag
  - 2 hours exposures

***Color selection***




***r-dropout target***



# z = 4.7 HzRG: our first discovery

z=4.72 HSC HzRG

**Redshift**

- Asymmetric line profile & r-dropout → Lya line
- Lya emission line at 6959 A
- Redshift:  z = 4.72

# The host galaxy

- log $M_*/M_\odot$ = 11.4 at the cosmic age of 1.3 Gyr
  - The *Ks* magnitude is consistent with the *K* - *z* relation for RGs
  - As massive as other HzRGs
  - **The massive end** of MF of *z*~5 Lyman break galaxies (e.g., Yabe et al. 2009)
- E(B-V) = 0.4, large extinction → abundant gas/dust?

# Not Ultra-Steep Spectrum

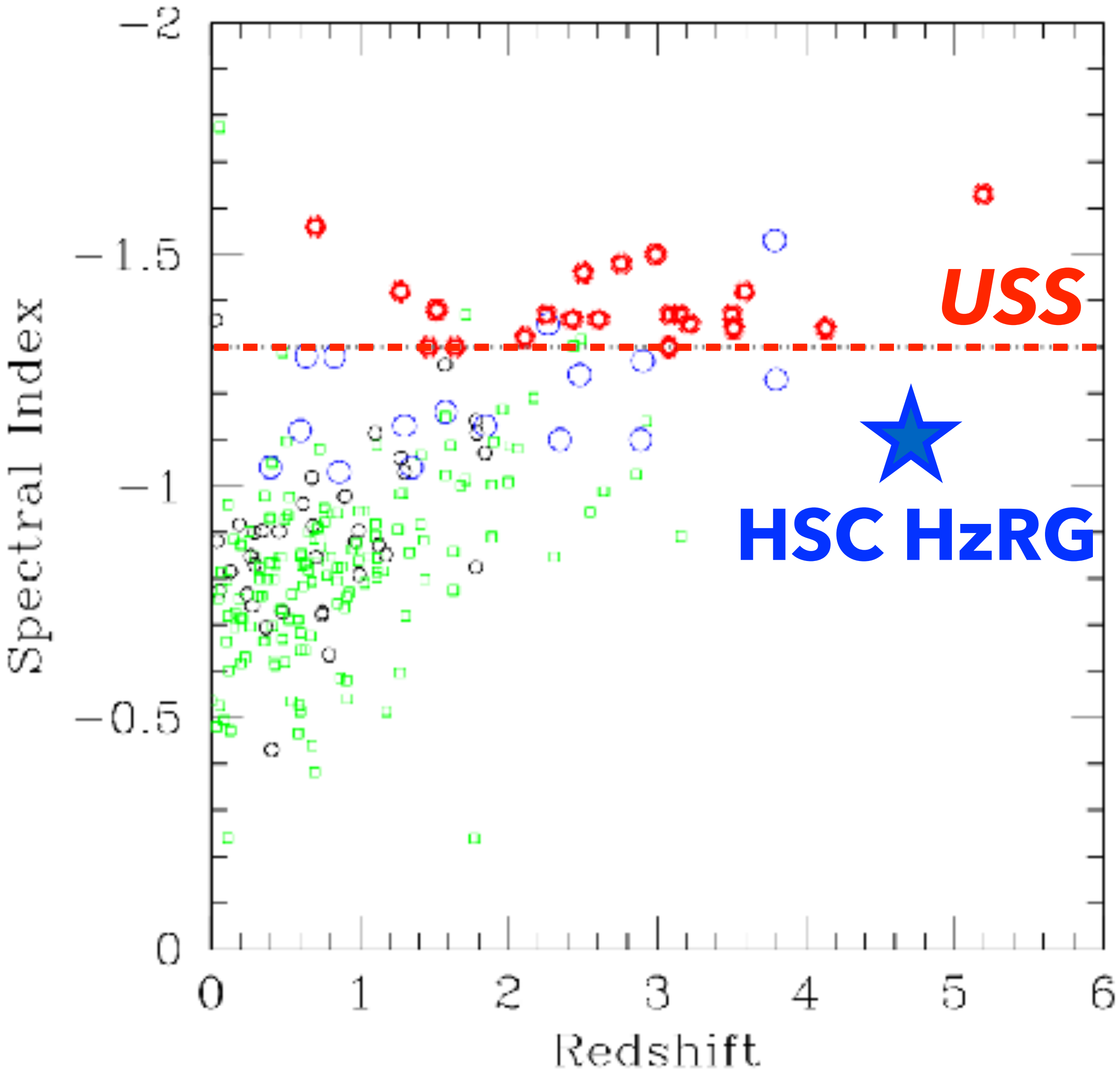
## Radio spectral index

- $\alpha_{(325\text{MHz-}1.4\text{GHz})} = -1.1$
- $\alpha_{(150\text{MHz-}1.4\text{GHz})} = -0.97$
  - **Non USS**

  ✳ USS definition: $\alpha < -1.3$
  (De Breuck et al. 2000, Saxena et al. 2018)

- This discovery show a variety of a at high-z universe
- It demonstrates the advantage of our survey over the USS technique!
- **Higher-z dropout radio galaxies!**

**325MHz-1.4GHz spectral index vs. redshift**
(De Breuck et al. 2000)



# PFS-SSP study

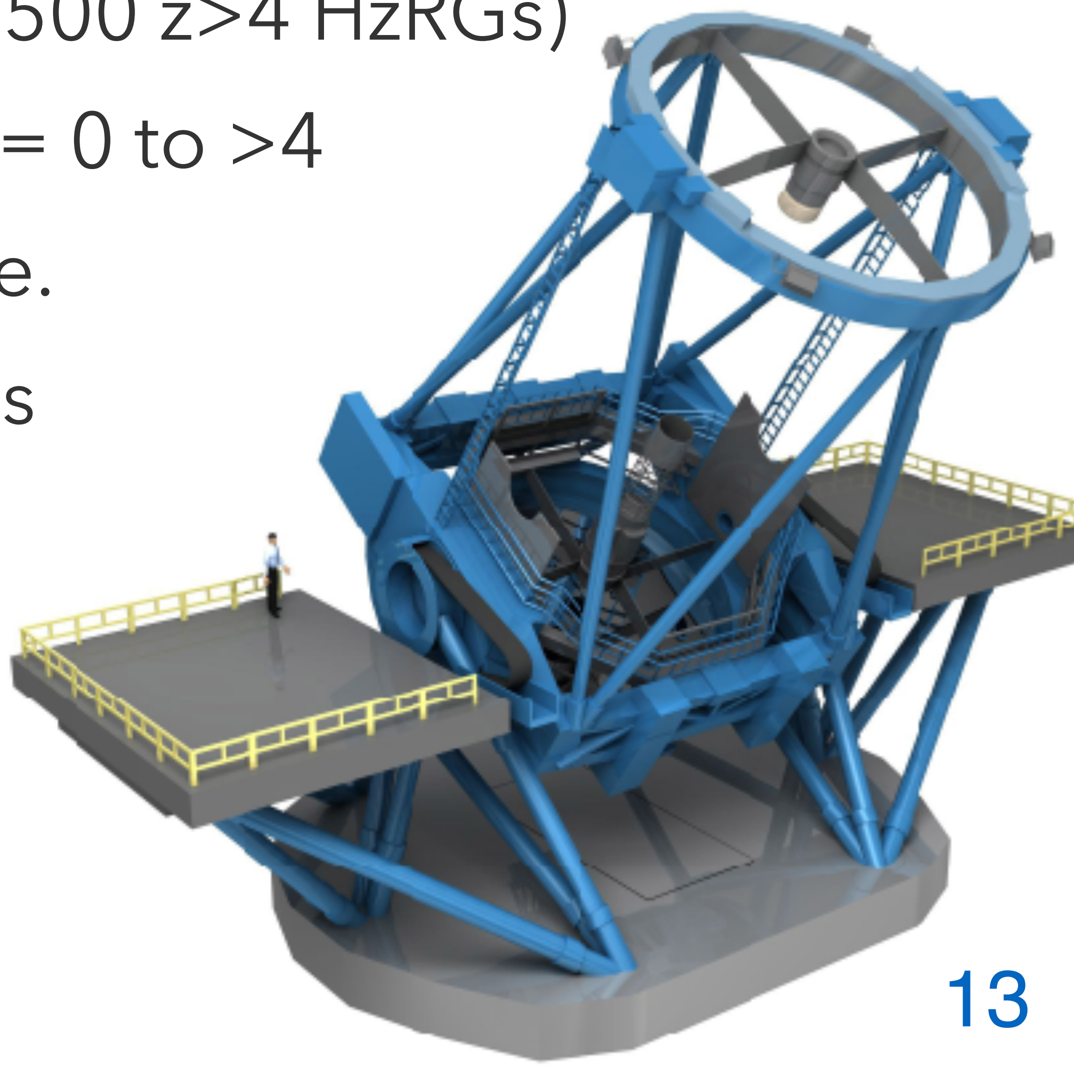
### The Large spectroscopic survey with Subaru/PFS

- 1400 deg$^2$ sky will be observed
- 380-1260 nm in optical & NIR is covered

### Radio galaxies census

200k RGs expected in the PFS-SSP field (~500 z>4 HzRGs)

- **Number density evolution** of RGs from z = 0 to >4 to examine the role of RGs in the Universe.
- **SF activity and stellar age** of host galaxies as functions of z and radio-AGN power to reveal the feedback effect
- **Environments** as a function of z and radio-AGN power



# Summary

- **Lyman break technique** is now applied to the HzRG survey by taking advantage of Subaru HSC-SSP
- **z = 4.7 HzRG** was found out of the pre-selected g-dropouts with radio detections
- The z = 4.7 HzRG are
  - **not USS** ($\alpha$ = –1.1)
  - **massive** ($\log M_*/M_\odot = 11.4$)
- This discovery demonstrates the feasibility of our HzRG search

- **Future**:
  - Large RG survey with PFS
    - Draw the number density evolution of RGs from local to high-z !
    - Reveal the effect and evolution of the radio-AGN feedback !