

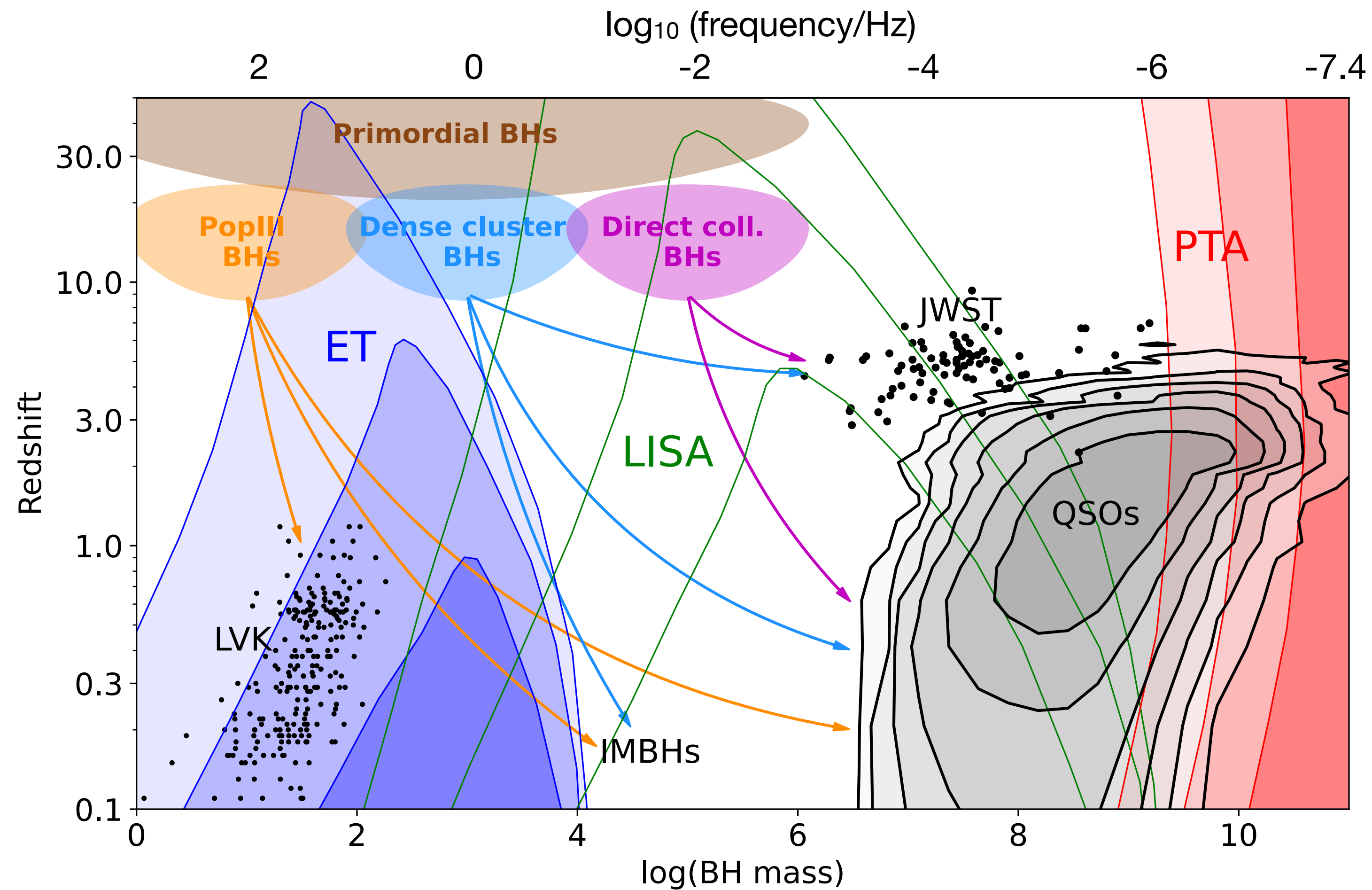
# Compact dual and lensed AGN with MAVIS, MORFEO/MICADO and ANDES



F. Mannucci

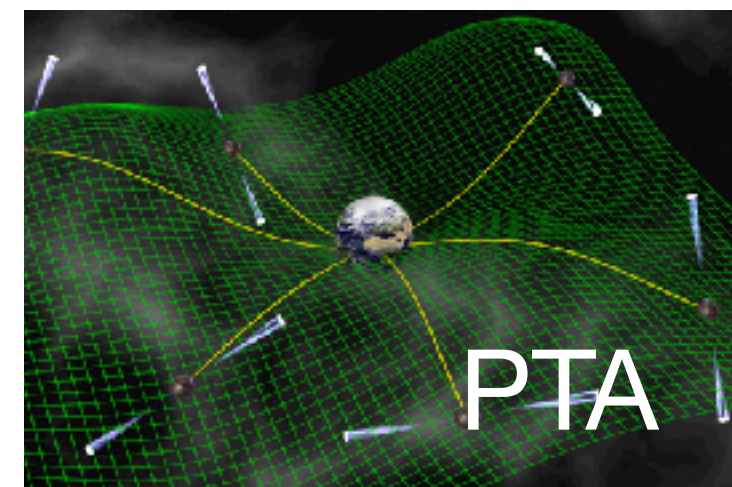
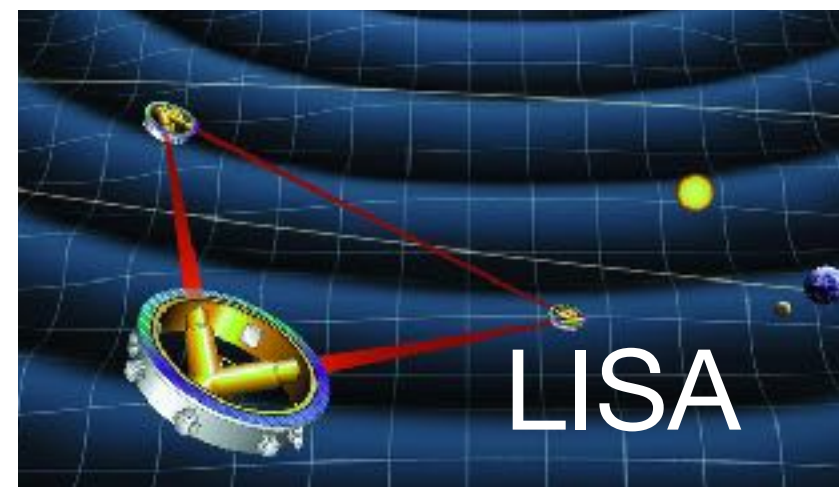
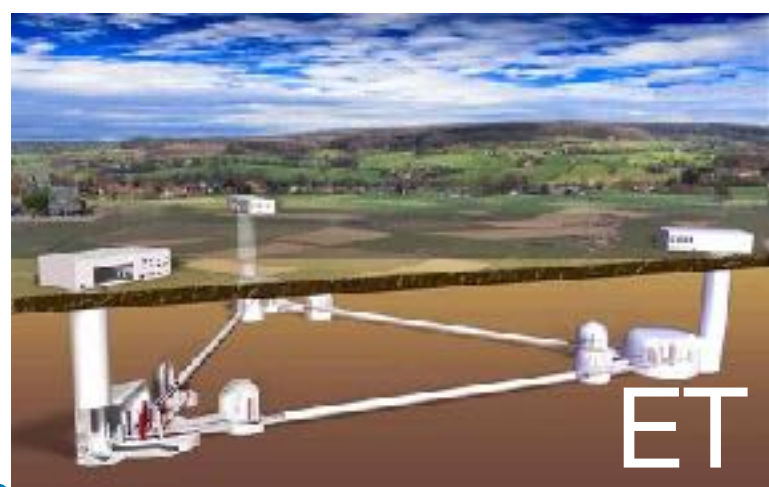
INAF - Osservatorio Astrofisico di Arcetri, Florence

# The cosmic journey of black holes



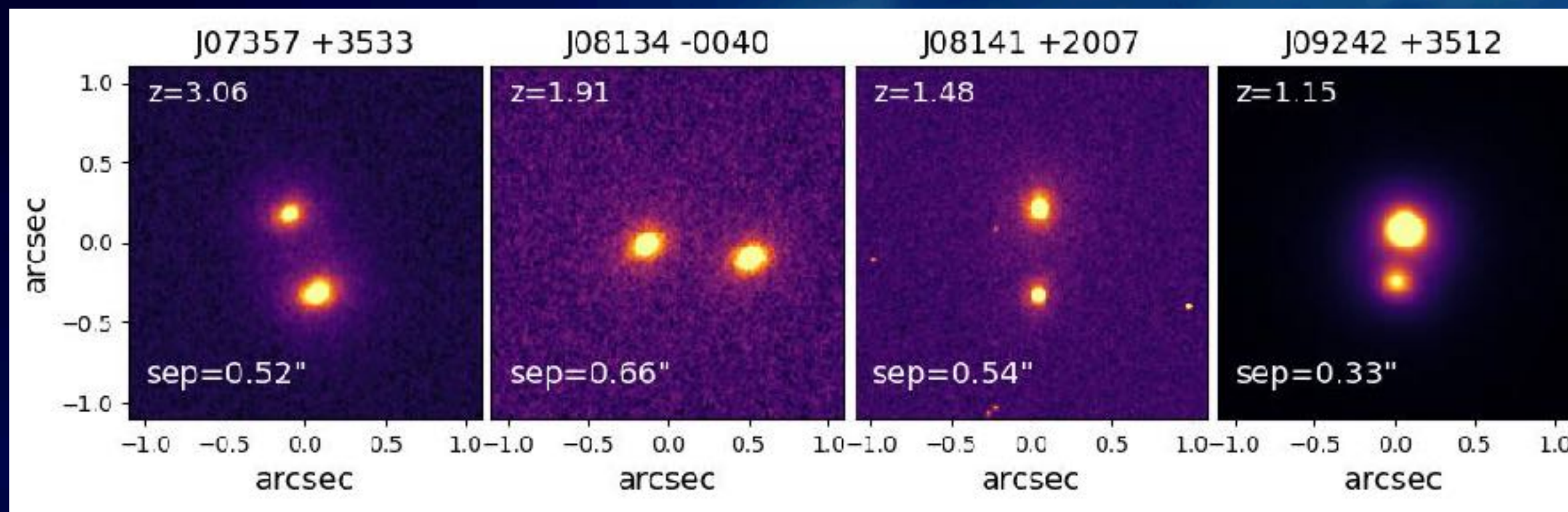
1. Gas accretion
2. Merging

Giersz+15, Miller+02, Lousto+10, Gerosa+19, Dubois+14, Kulier+15, Smith+18, Latif & Ferrara 16, Schneider+23, Di Matteo 23, Arca Sedda+21, Wu & Shen 22, Abbott+23, Juodžbalis+25, Zhuang+25



# Hierarchical merging

Tremmel et al, 2018

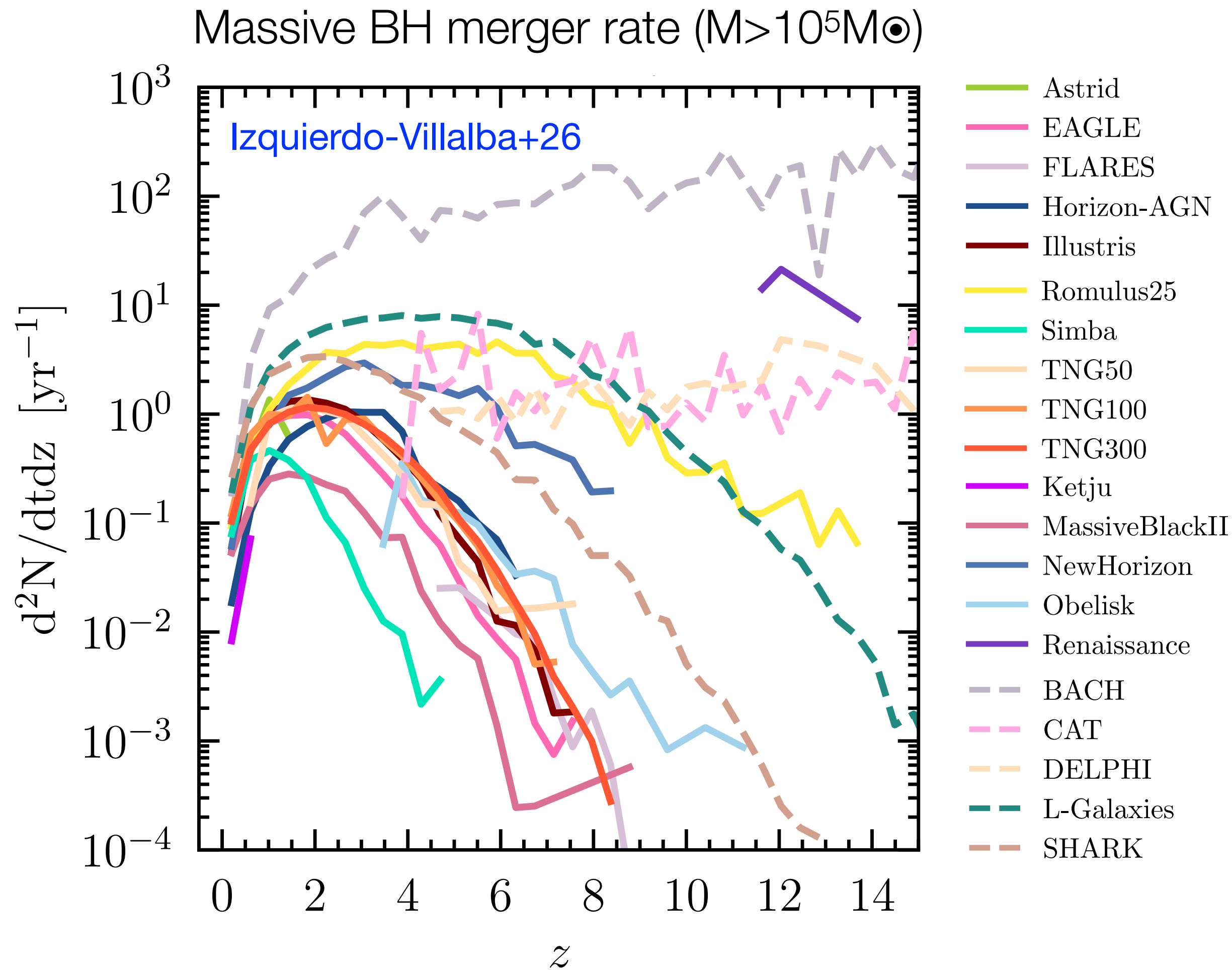


LBT, Mannuci+22, Nat.Astr.

- Long ( $10^8$ - $10^{10}$  yr) merging timescales →
1. large population of **dual AGN** in the same host galaxy (kpc separation)
  2. **binary SMBH** at sub-pc separations emitting continuous GWs

# Dual AGN and GW events

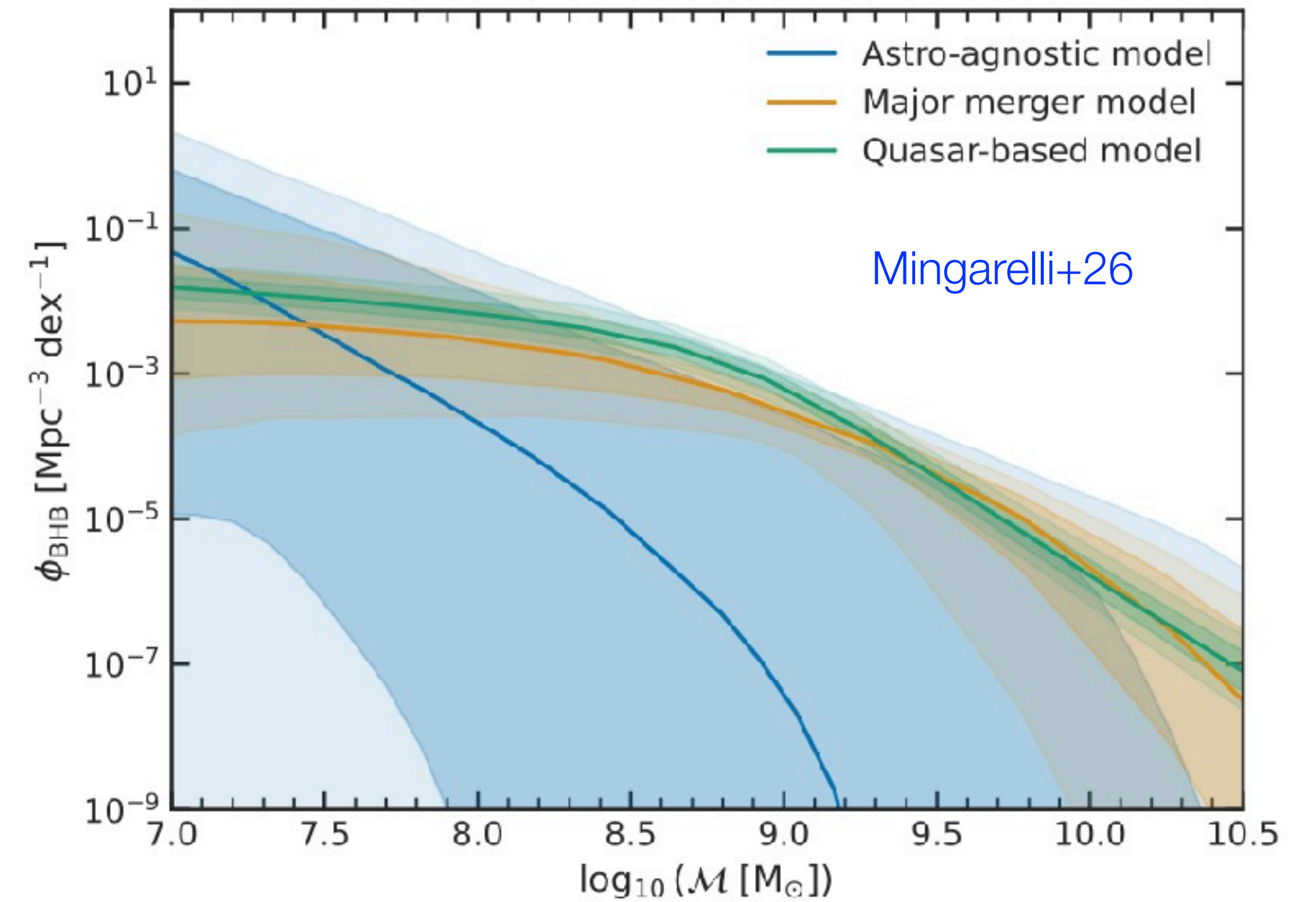
## Predictions



Colpi+14, Amaro-Seoane+17, Babak+17, Izquierdo-Villalba+22, Agazie+23

## Interpretations

Binary BH merger rate models compatible with PTA results



# Strategy and instruments

thanks to M. Scialpi, C. Marconcini, L. Ulivi, Q. D'Amato, M. Zanchettin, G. Tozzi, I. Lamperti, M. Ceci M. Ginolfi et al.



## Selection:

Multiple QSOs from large sky-coverage, high spatial resolution surveys

1. Gaia Multi peak (GMP)
2. Euclid
3. LOFAR

## Integrated spectroscopy:

- confirm the QSO
- measure redshift
- presence of a star

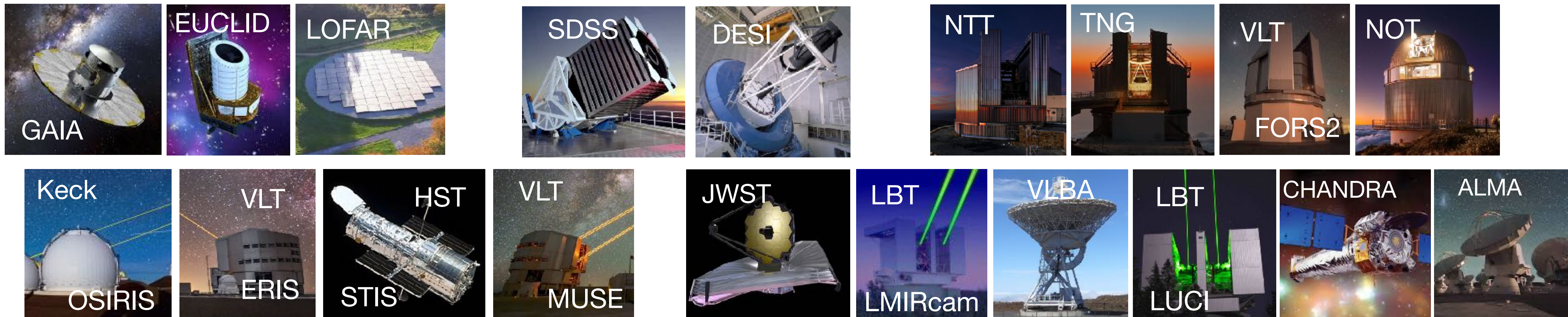
1. Archive: SDSS+DESI+...
2. New observation: VLT, NTT, TNG, .....

## Spatially-resolved spectroscopy

nature and properties

## Follow-ups:

X-ray, midIR, submm, Radio



# Strategy and instruments

multiple QSOs

redshift/contamination

classification/properties



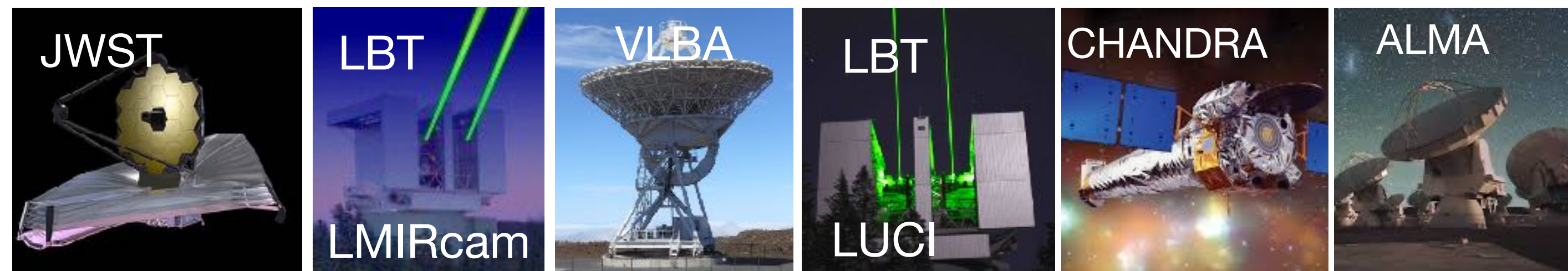
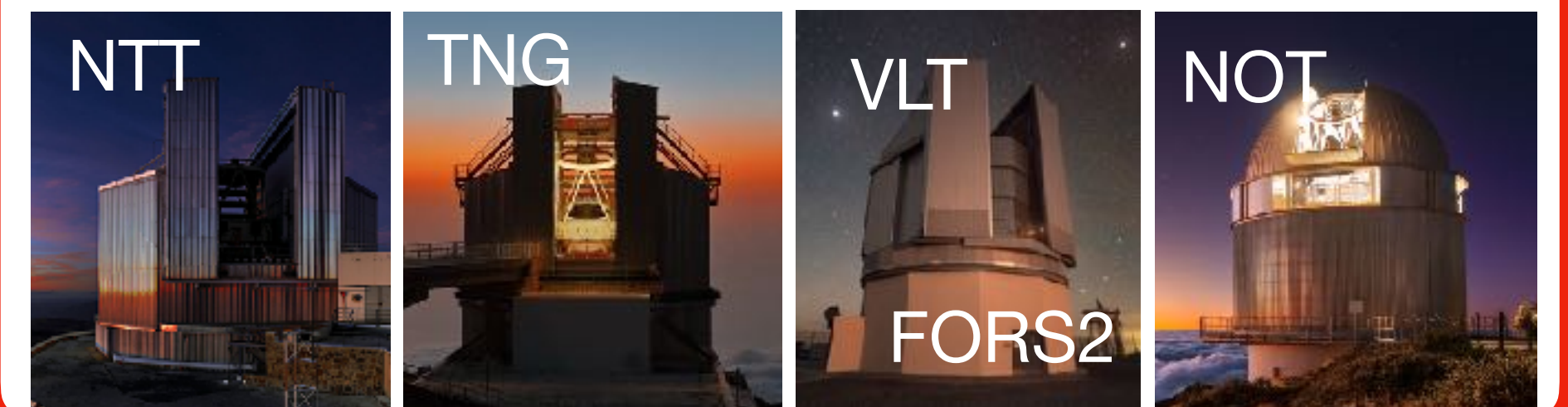
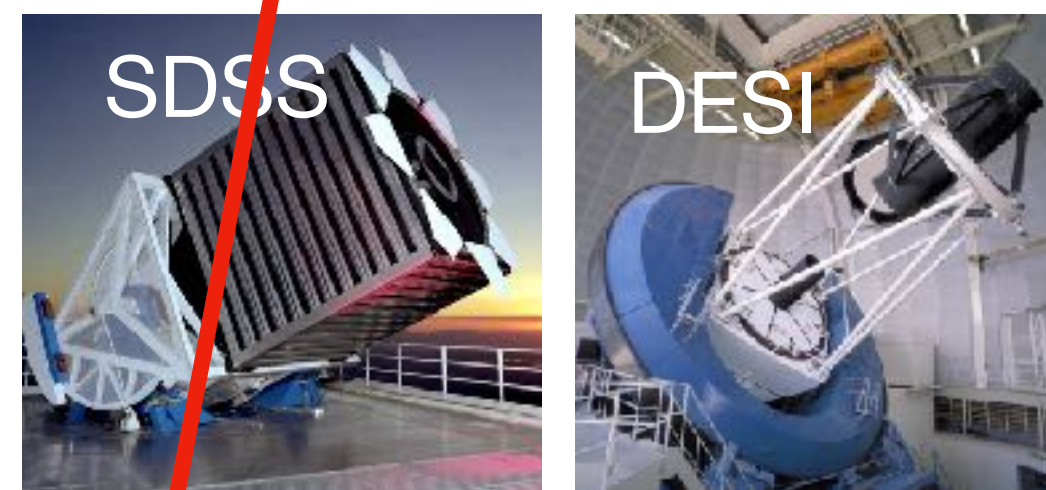
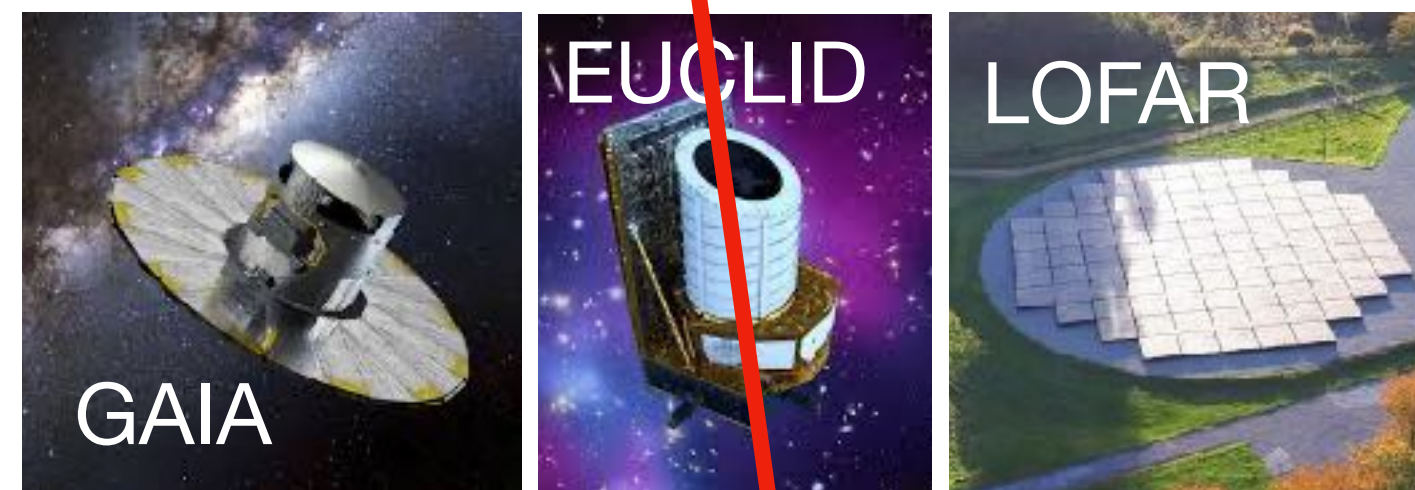
ESO GTO 115hr



COSMIC DUETS

ESO LP 138hr, PI: M. Scialpi

several tens of nights



# Status: first statistical sample ever

## GMP:

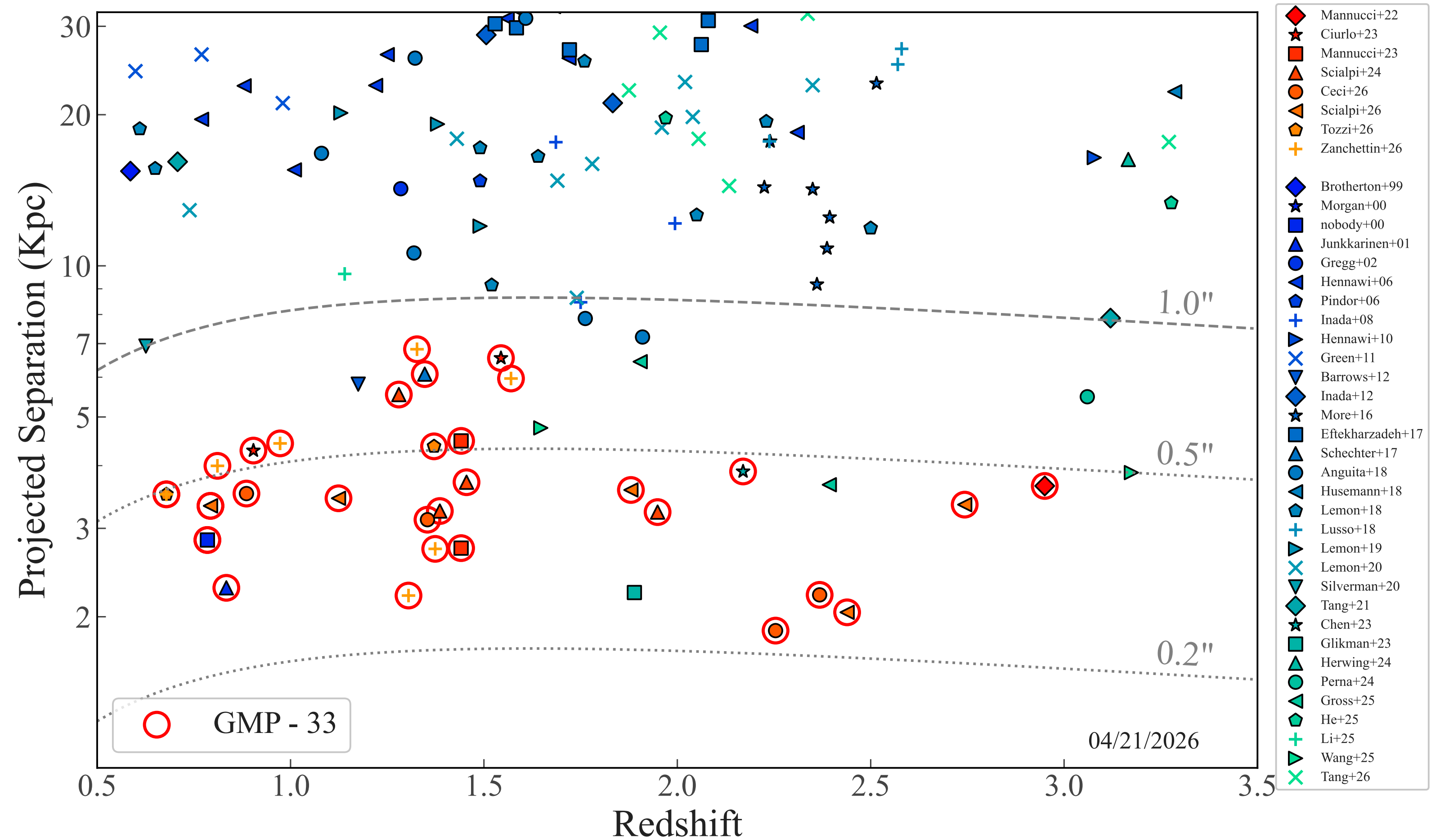
- ~60 confirmed QSO pairs
- 33 confirmed duets
- 22 Confirmed lensed QSO
- 5 "pairs"

## Physical quantities:

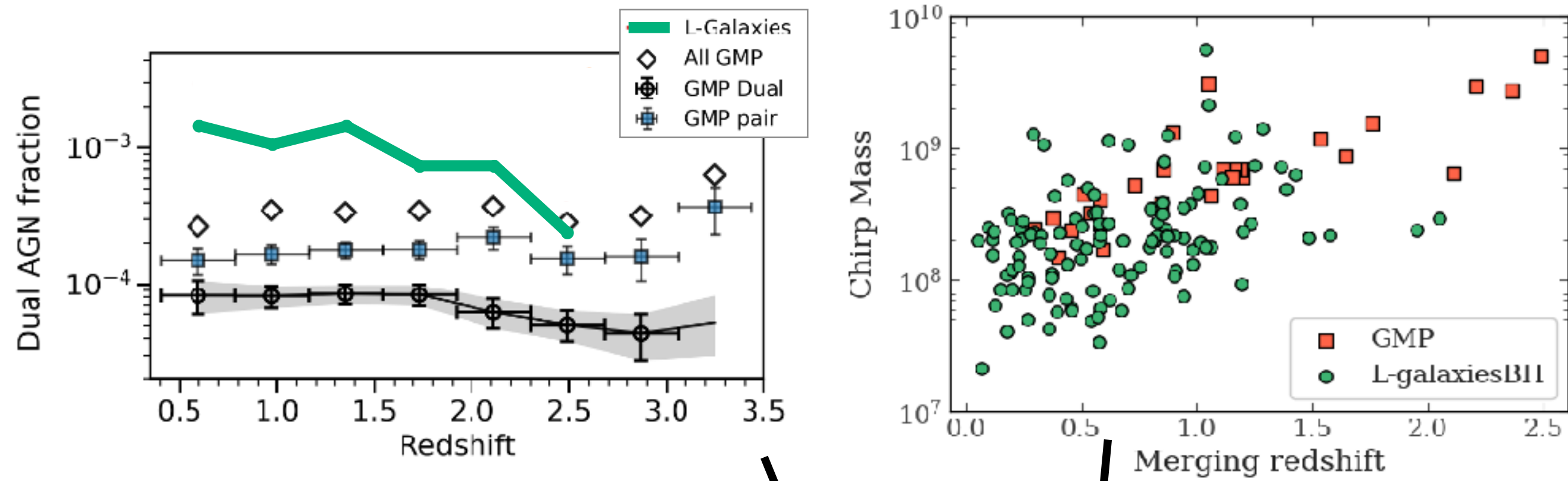
- BH masses
- Eddington ratios
- Separation distribution
- dual fraction
- redshift evolution
- .....

Comparison with model predictions → revision of the models

All Spectroscopically-confirmed dual AGN at  $\text{sep} < 20 \text{kpc}$

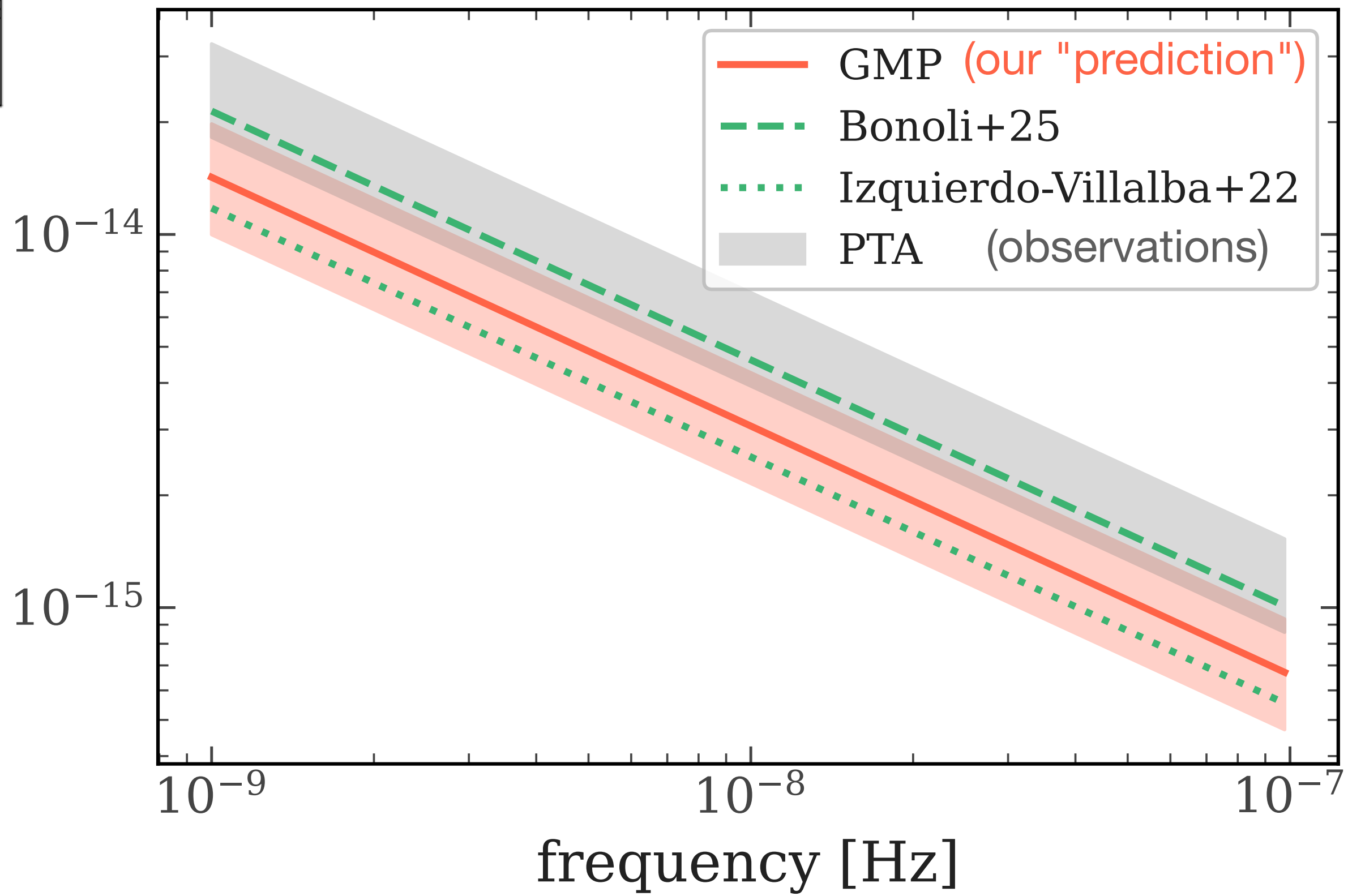
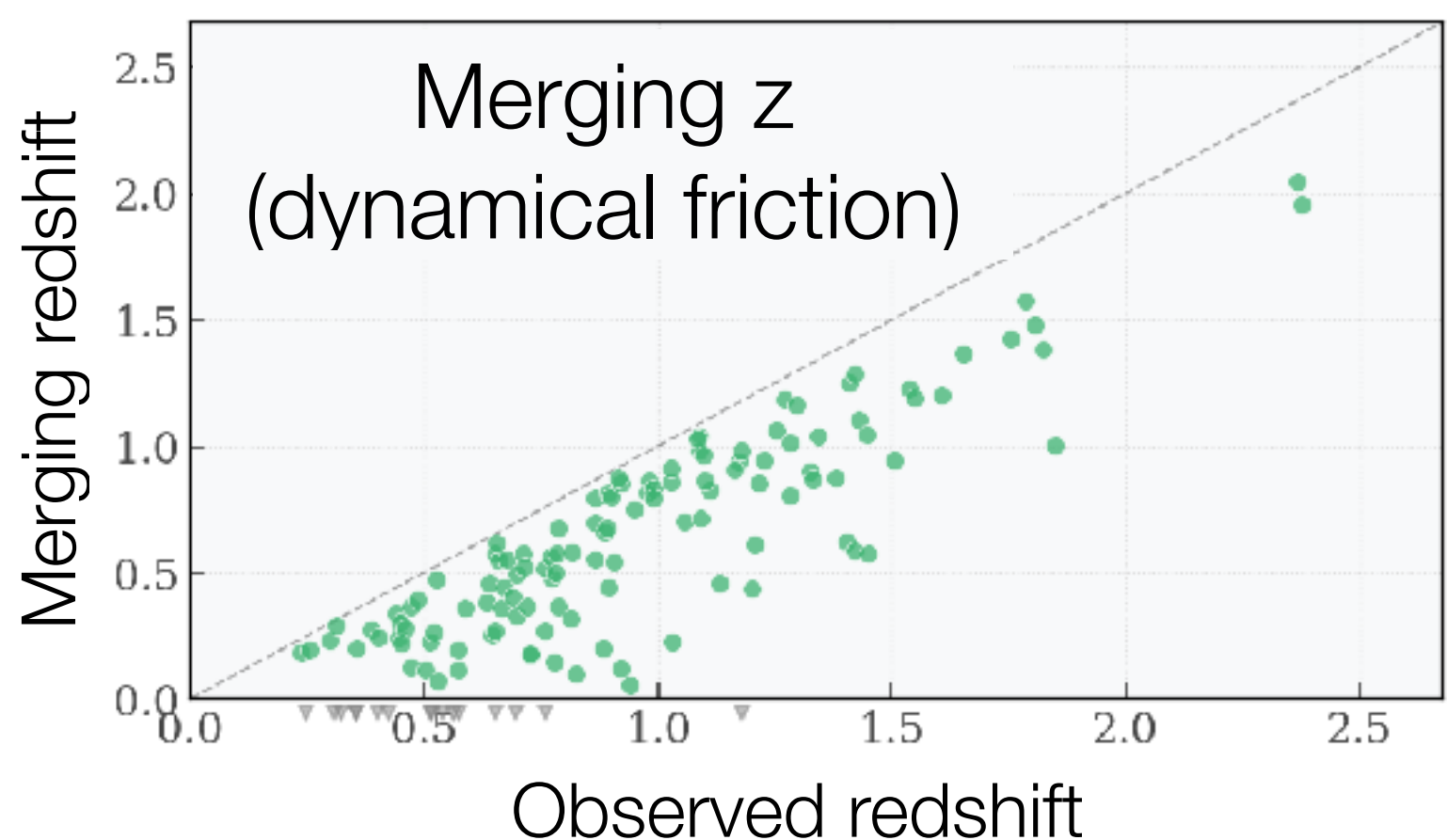


# Predictions on GW background at PTA frequencies



$$h_c^2(f) = \frac{4G^{5/3} f^{-4/3}}{3c^2 \pi^{1/3}} \int \int \rho(z, \mathcal{M}) \frac{\mathcal{M}^{5/3}}{(1+z)^{1/3}} dz d\mathcal{M} h_c(\nu)$$

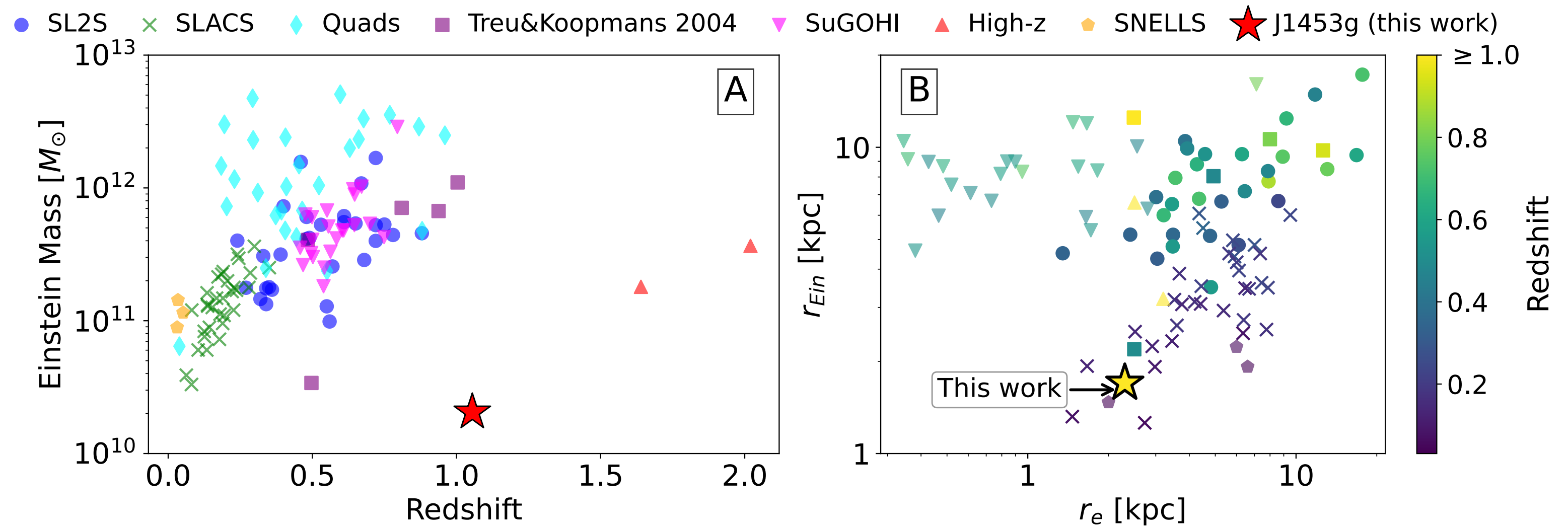
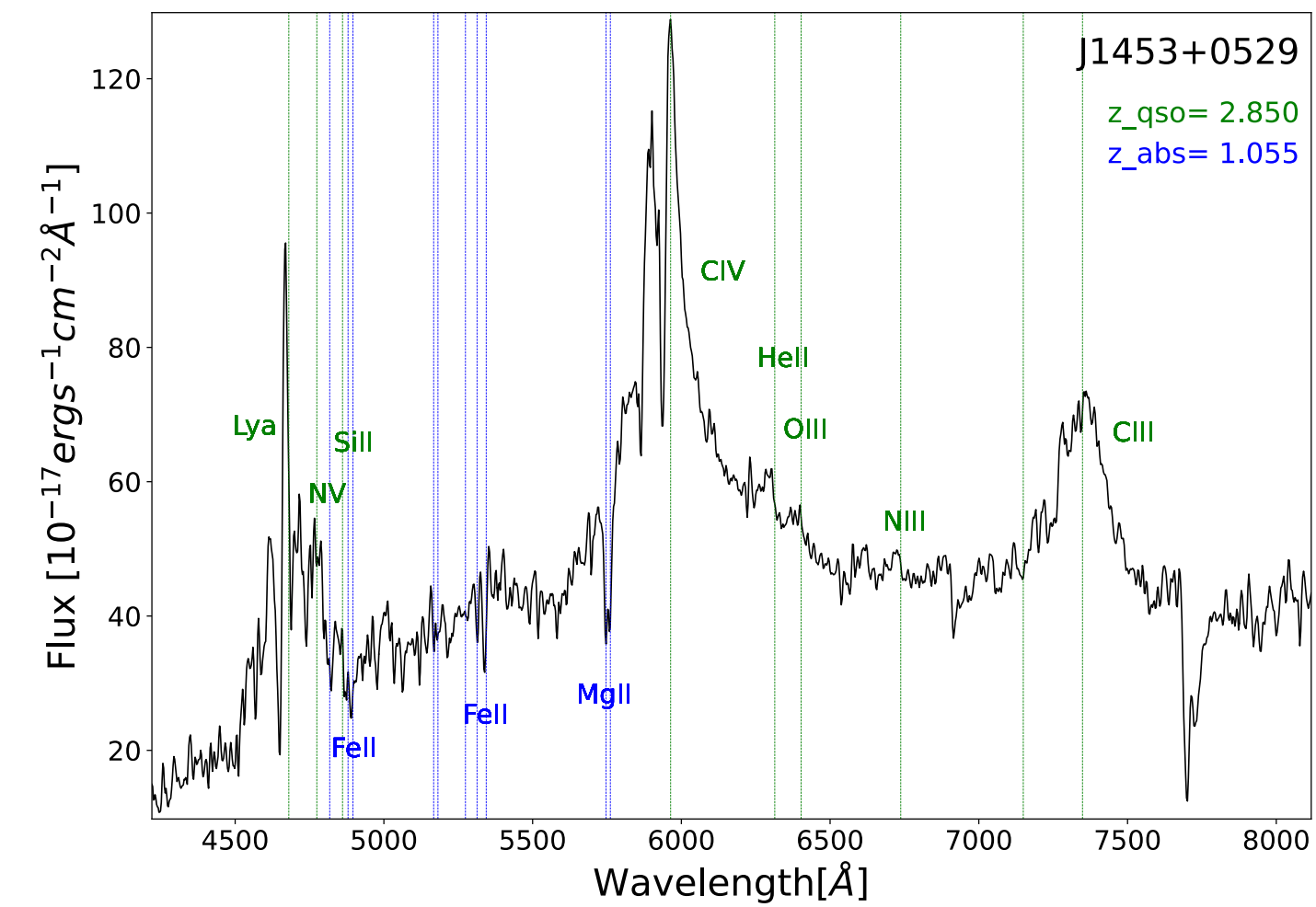
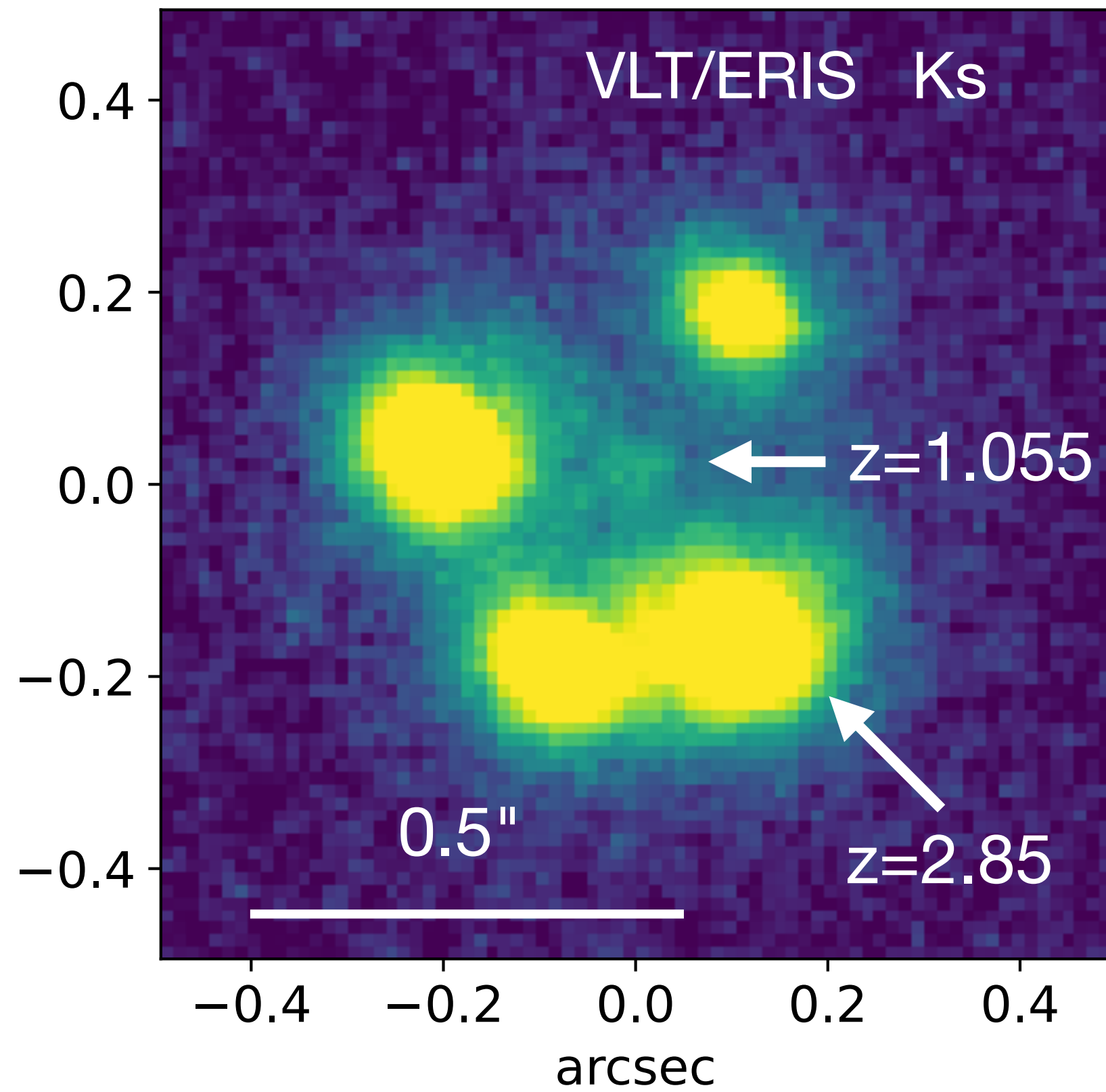
Bonoli+25, Mingarelli+26



# GMP: lensed QSO

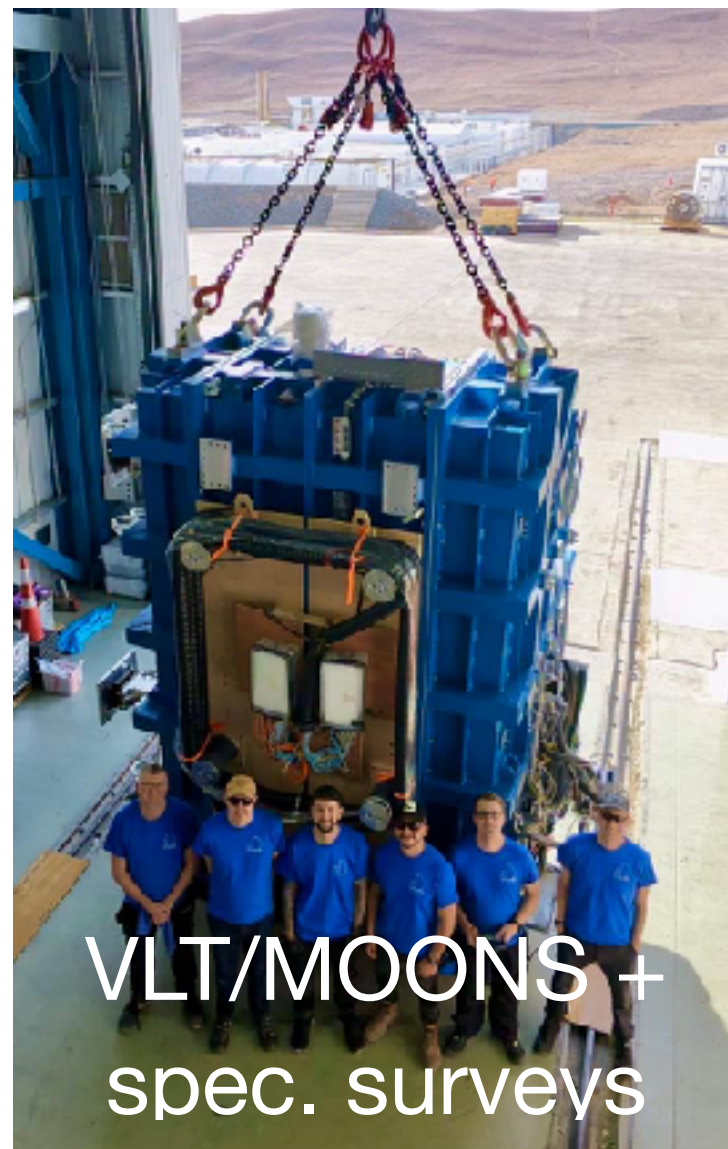
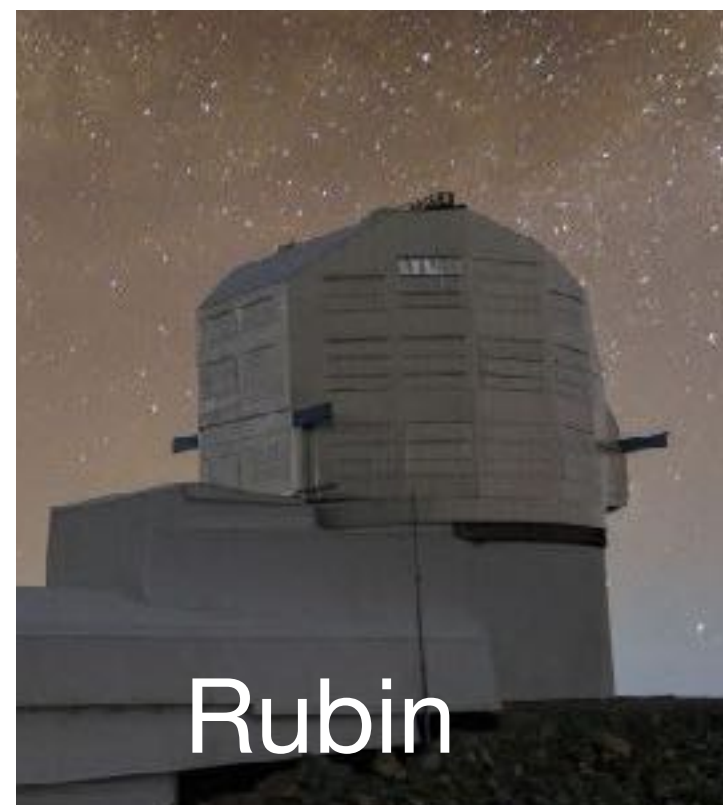
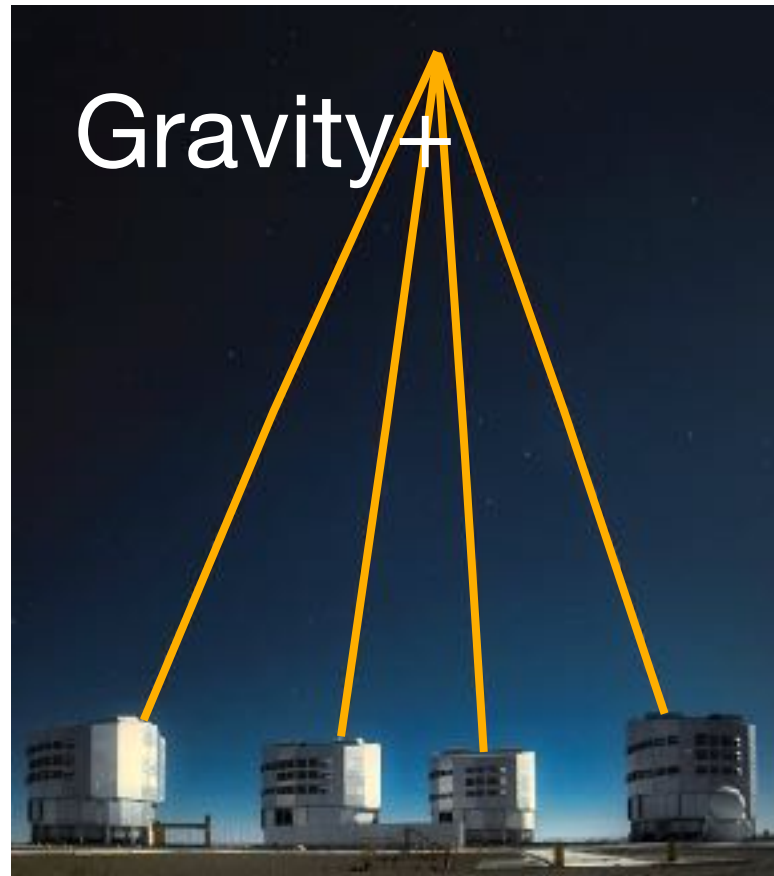
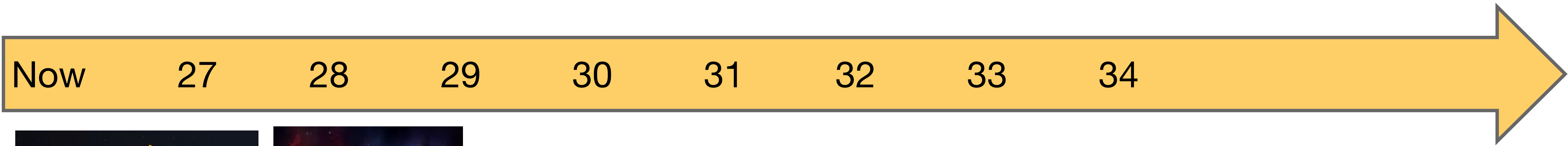
## Lensed QSOs

Most compact quad QSO known ( $R_{\text{Ein}} \sim 0.2''$ )

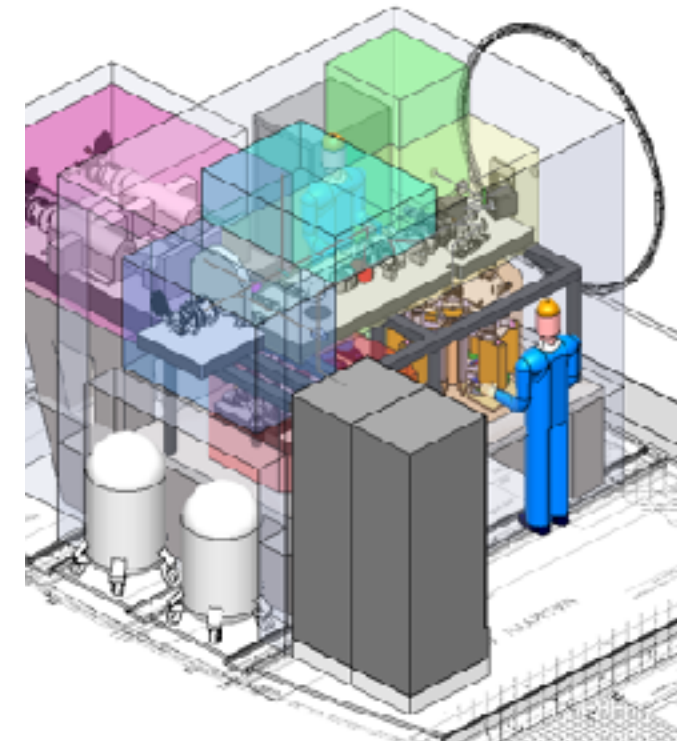


D'Amato+26, Nature Astr.

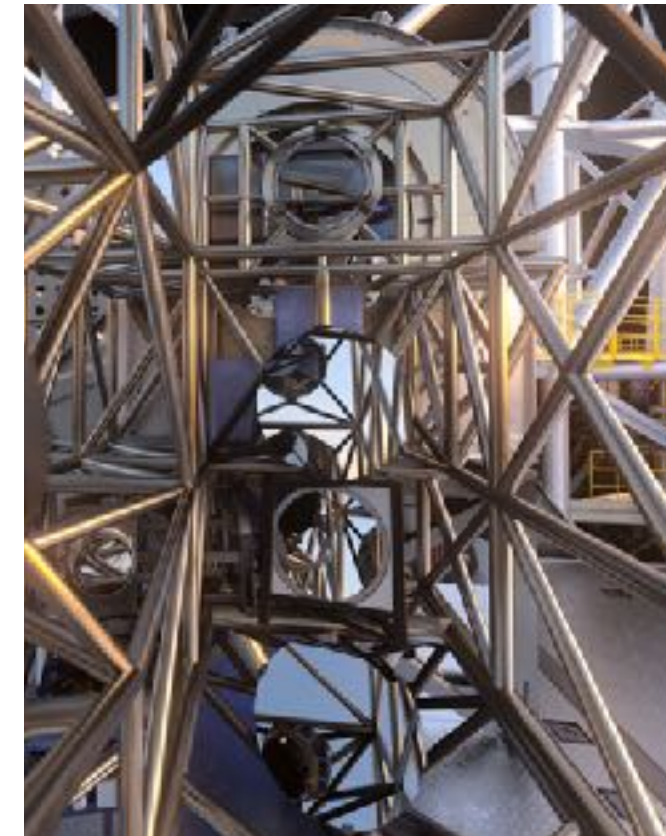
# The near future



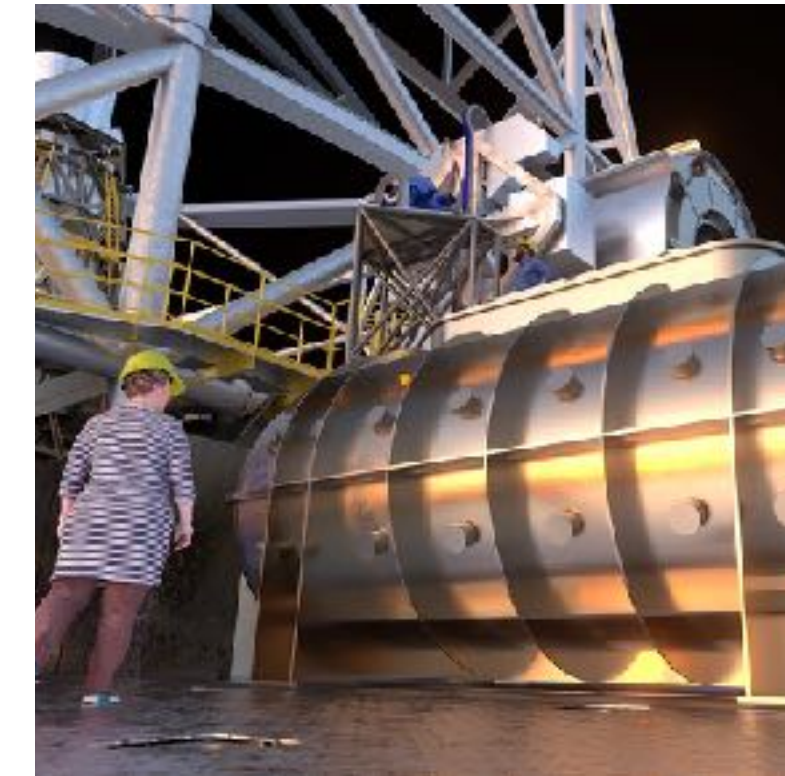
MAVIS



MORFEO/  
MICADO



ANDES



KBI





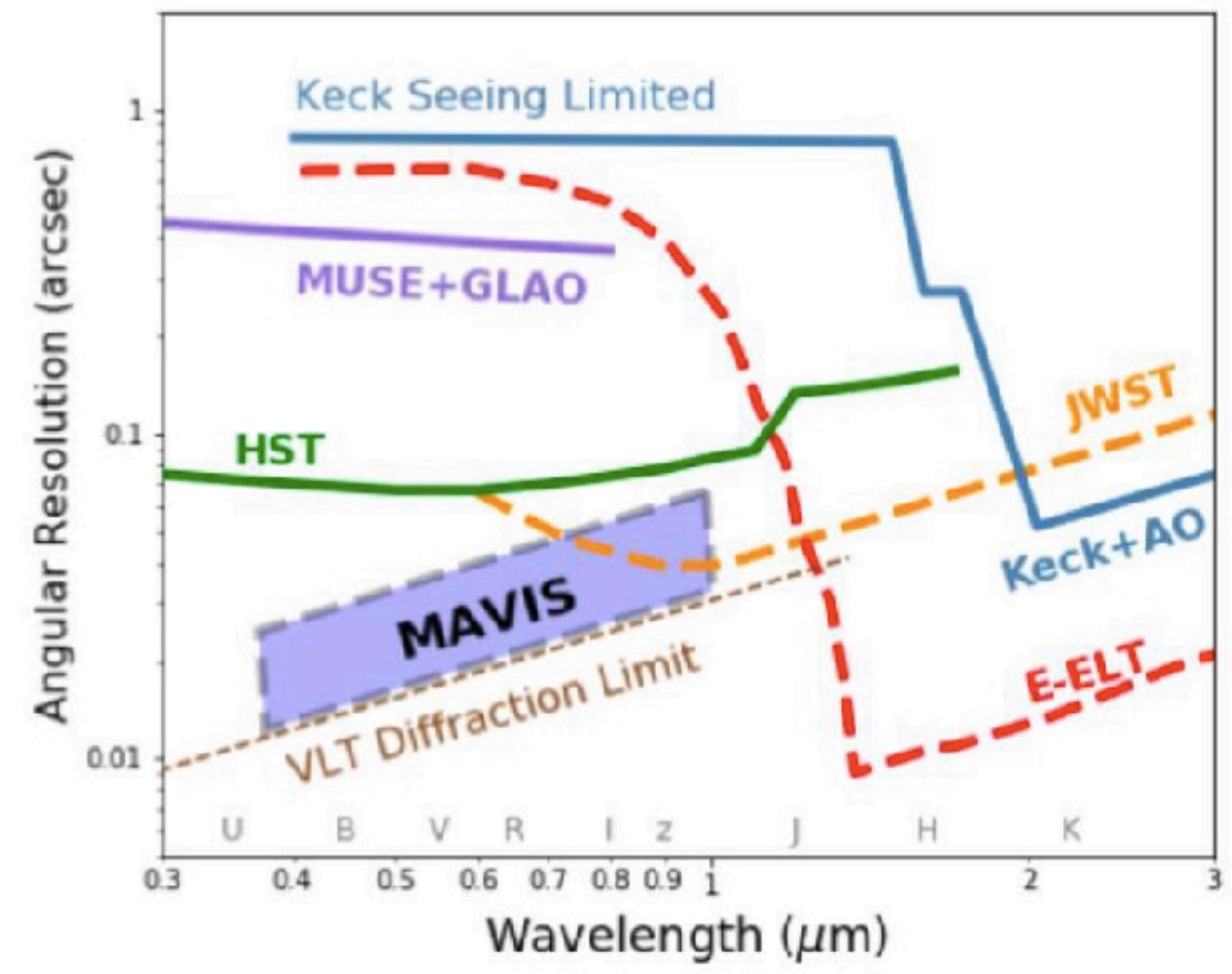
# MAVIS on VLT

Australia + INAF + France + ESO

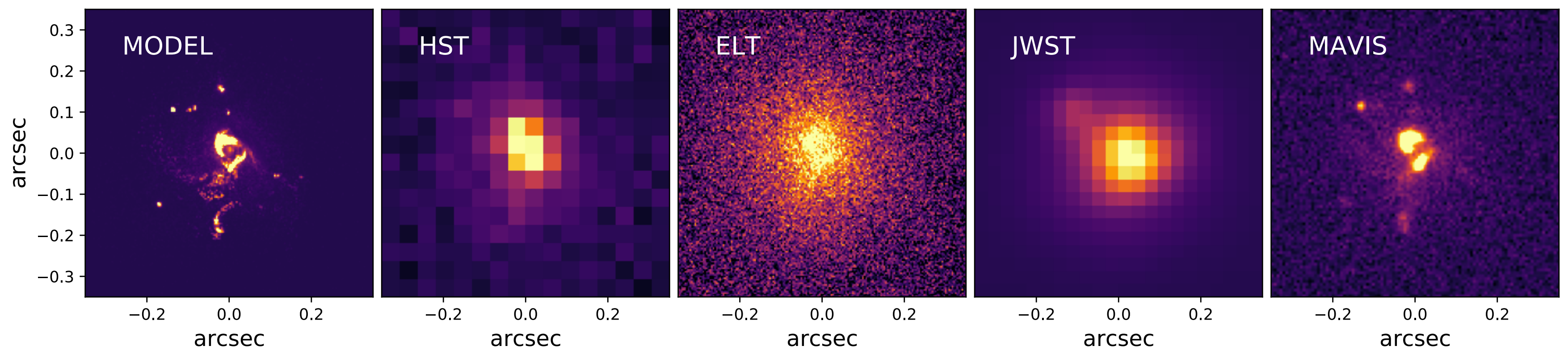
Optical MCAO



8 LGS + 3 NGS  
 SR ~ 15% (V band)  
 Sky coverage ~ 50% Gal.pol  
 Imager: 30"x30", 7mas pixel  
 20mas resolution (V band)  
 V=29.5 (point, 5σ, 1hr)



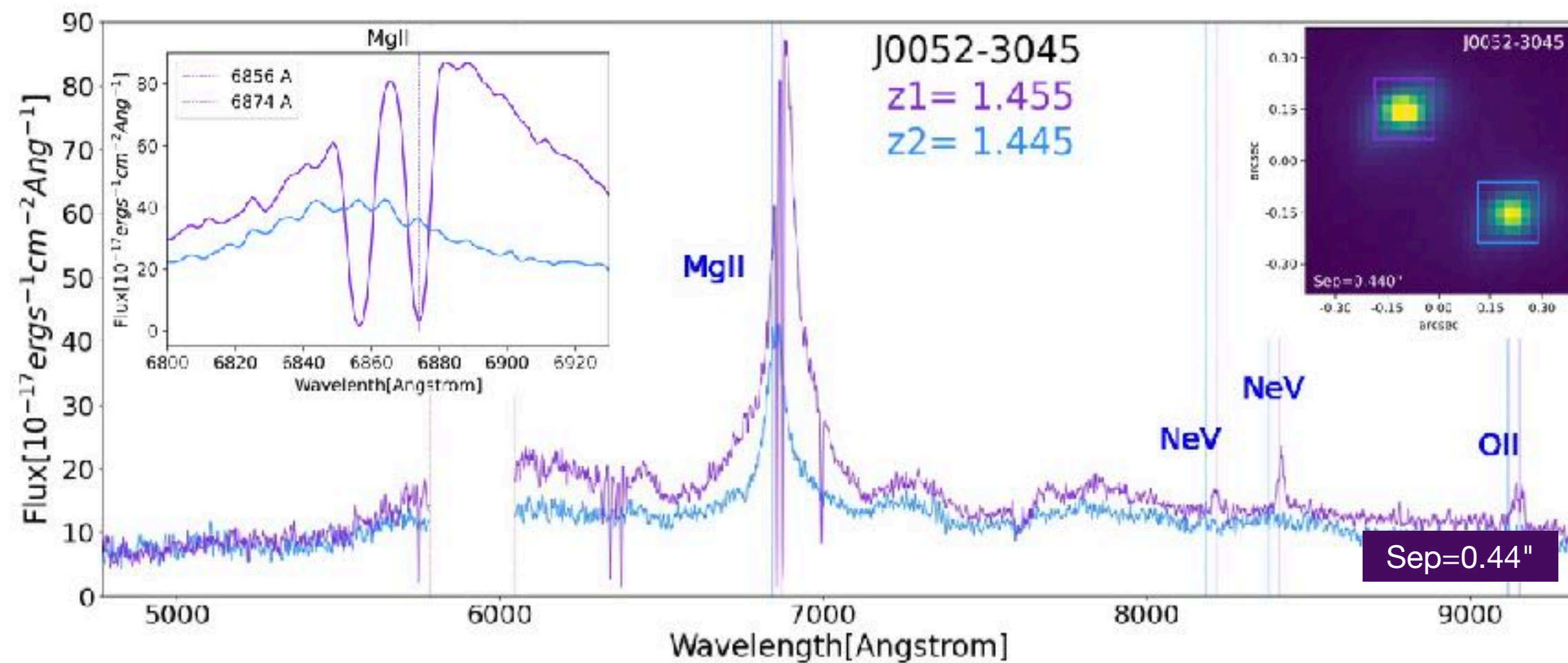
IFU, 370-1000nm  
 25mas and 50mas  
 R=5000 - 120000



# MAVIS vs. MUSE



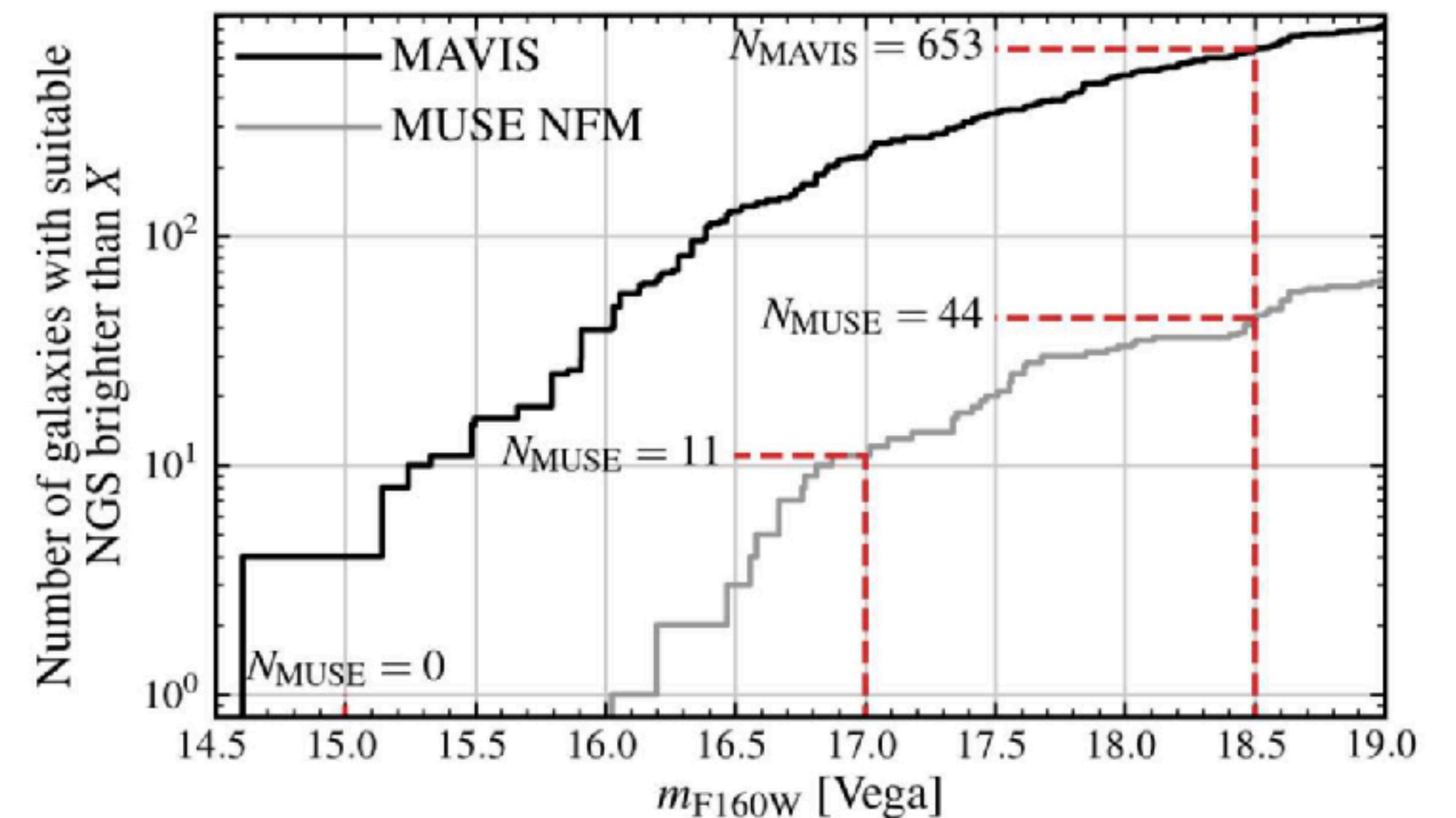
## Adaptive-optics IFUs



**MUSE-NFM:** limited to brightest objects ( $J < 17.5$ ):

1. ~30% of the Gaia-selected sample
2. 0% of the Euclid-selected sample

~20 times larger sky coverage  
unbiased luminosity coverage



# Binary/dual with MORFEO/MICADO

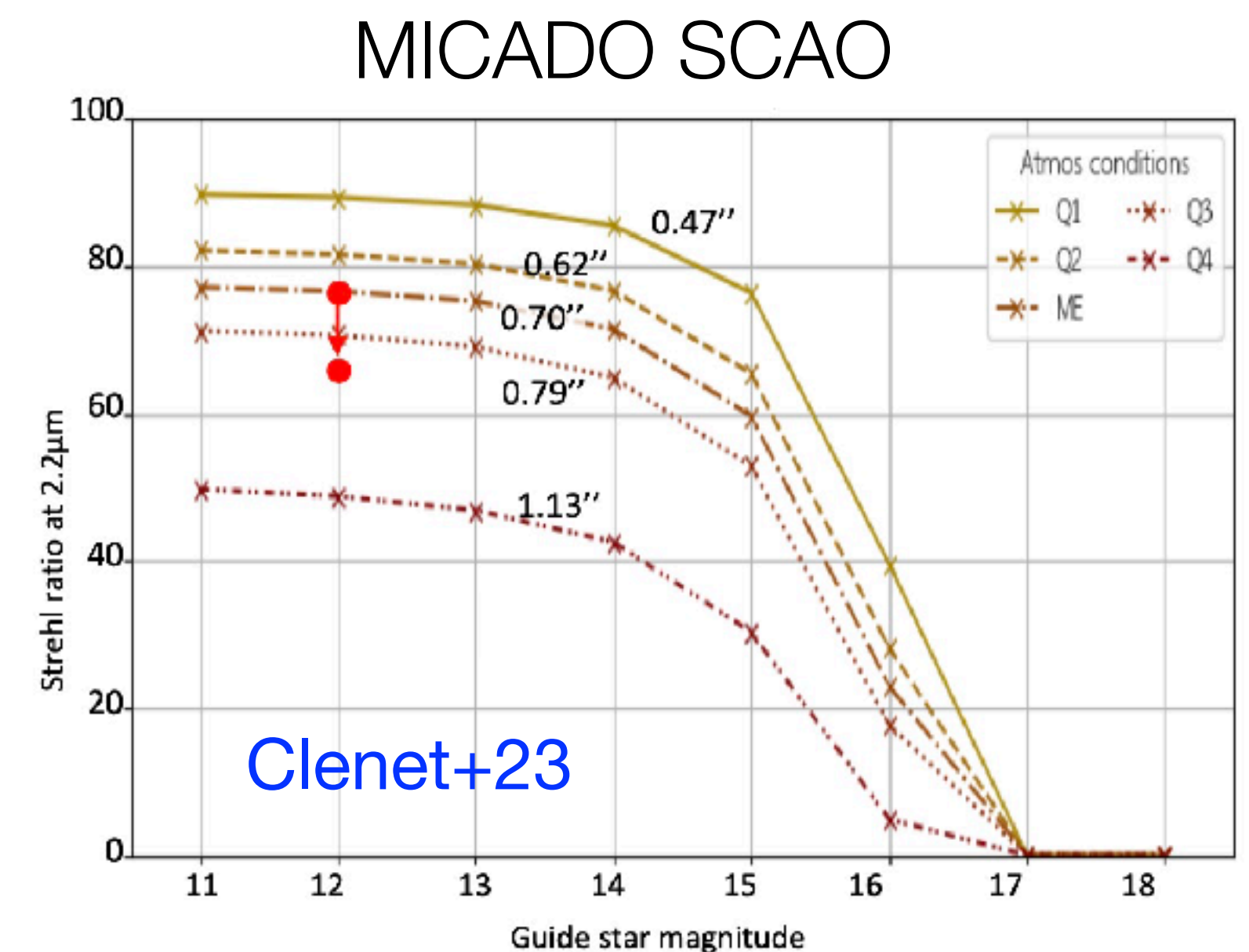


- High sensitivity for point sources
- High spatial resolution ( $\sim 10$  mas - 80 pc @  $z > 1$ )
- High astrometric precision ( $\sim 50$   $\mu$ as - 0.4 pc @  $z > 1$ )
- High spectro-astrometry resolution ( $\sim$ few  $\mu$ as)
- Spatially-resolved spectroscopy,  $\Delta v \sim 15$  km/sec:



MICADO/SCAO: mag < 15

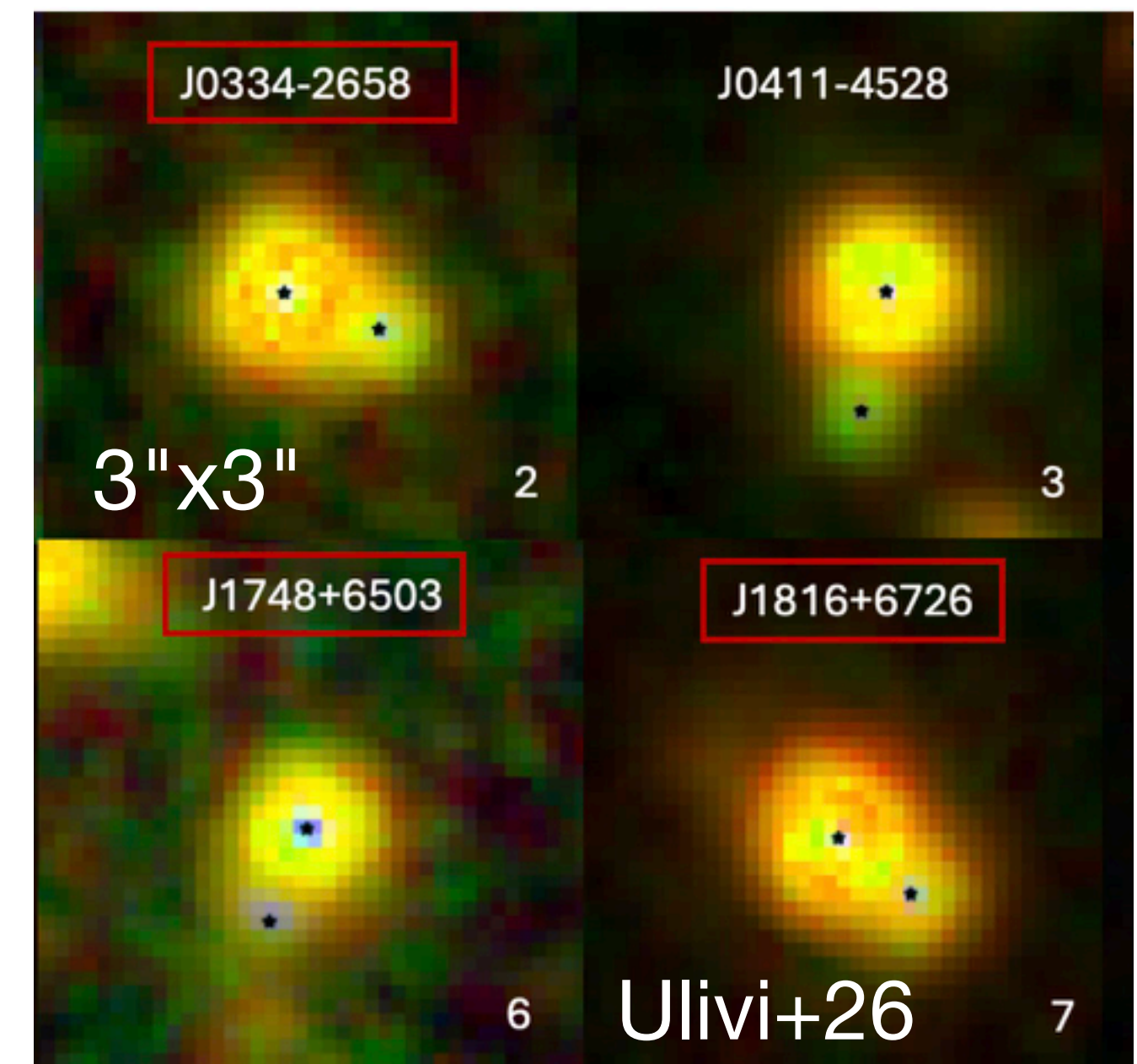
MCAO/MORFEO essential for sky coverage



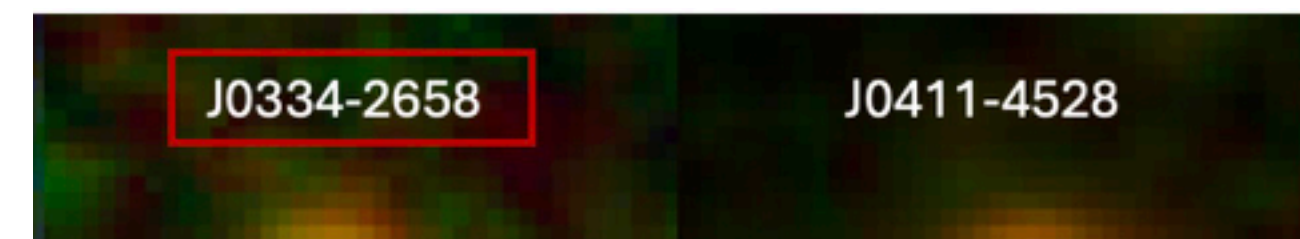
# Binary/dual with MORFEO/MICADO

How to pre-select candidates?

- blind?
- All-sky Euclid/Roman (sep > 0.15")

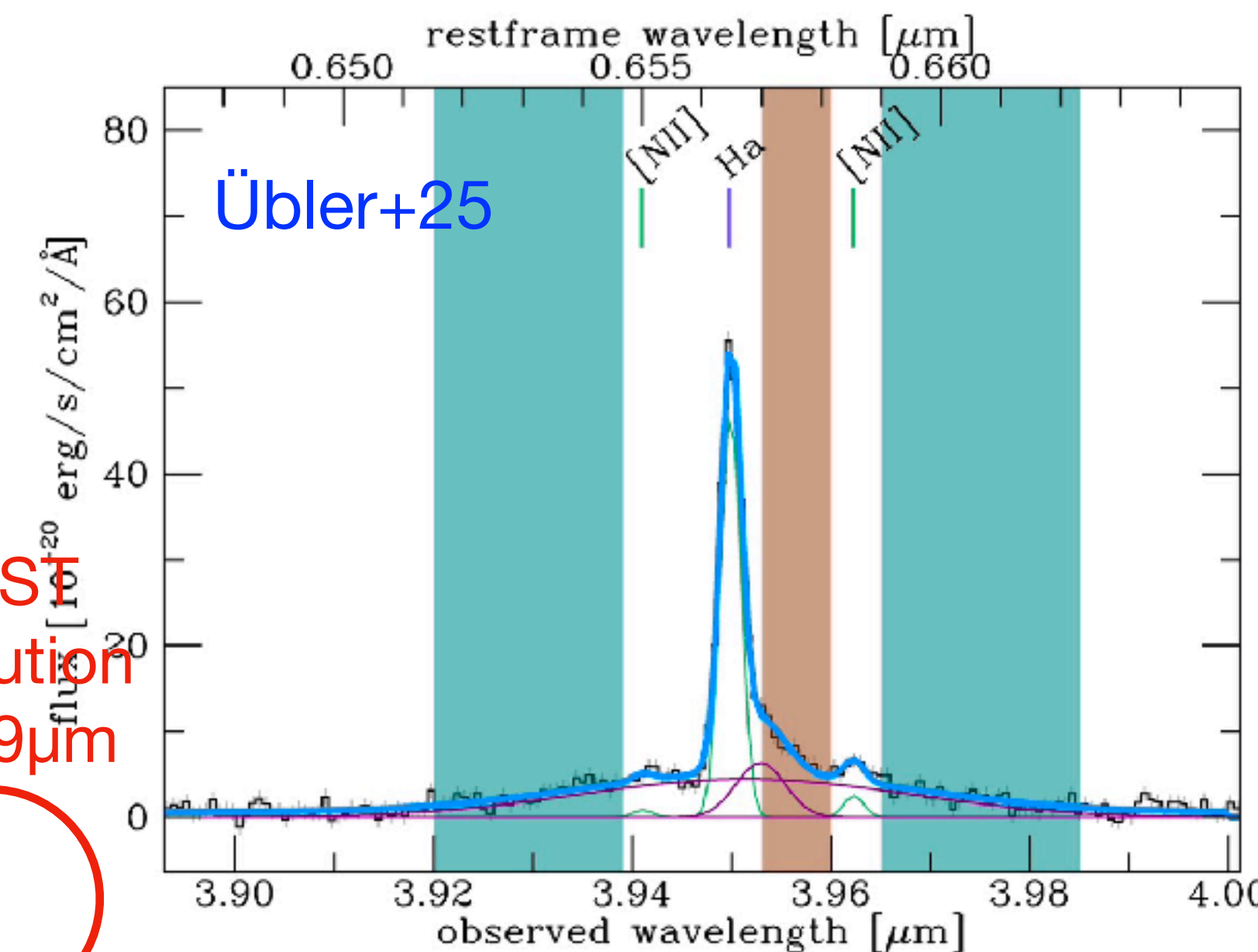
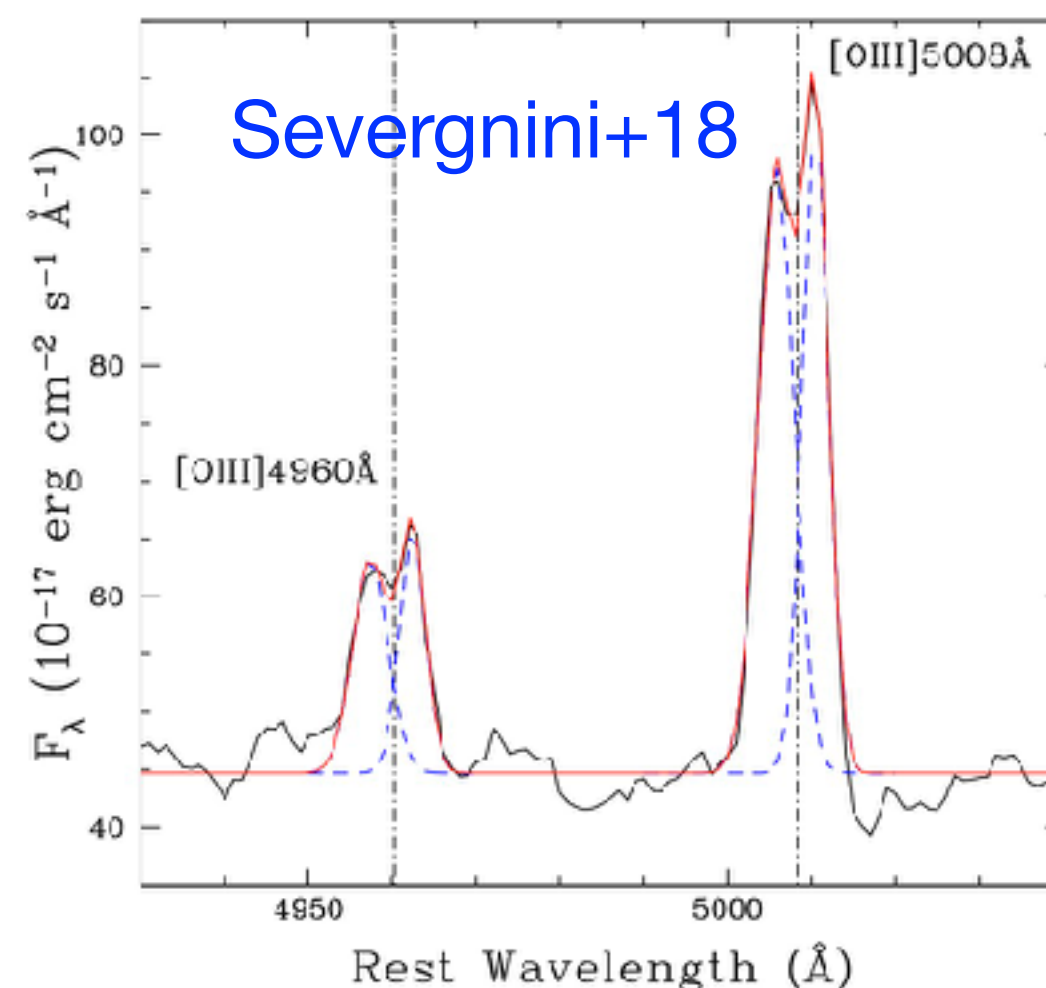


# Binary/dual with MORFEO/MICADO



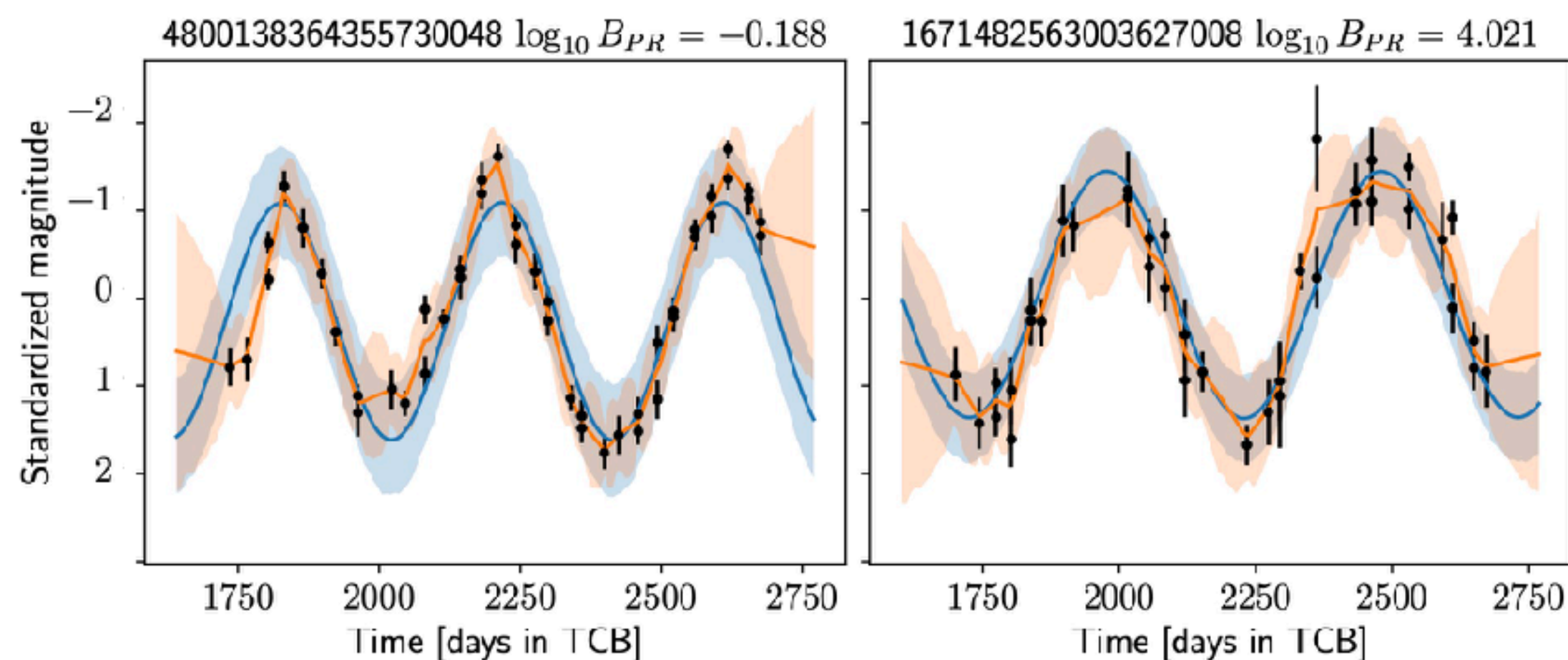
## How to pre-select candidates?

- blind?
- All-sky Euclid/Roman (sep > 0.15")
- Barely-resolved candidates with JWST
- Multi-peaked line profiles
- Variability (LSST)



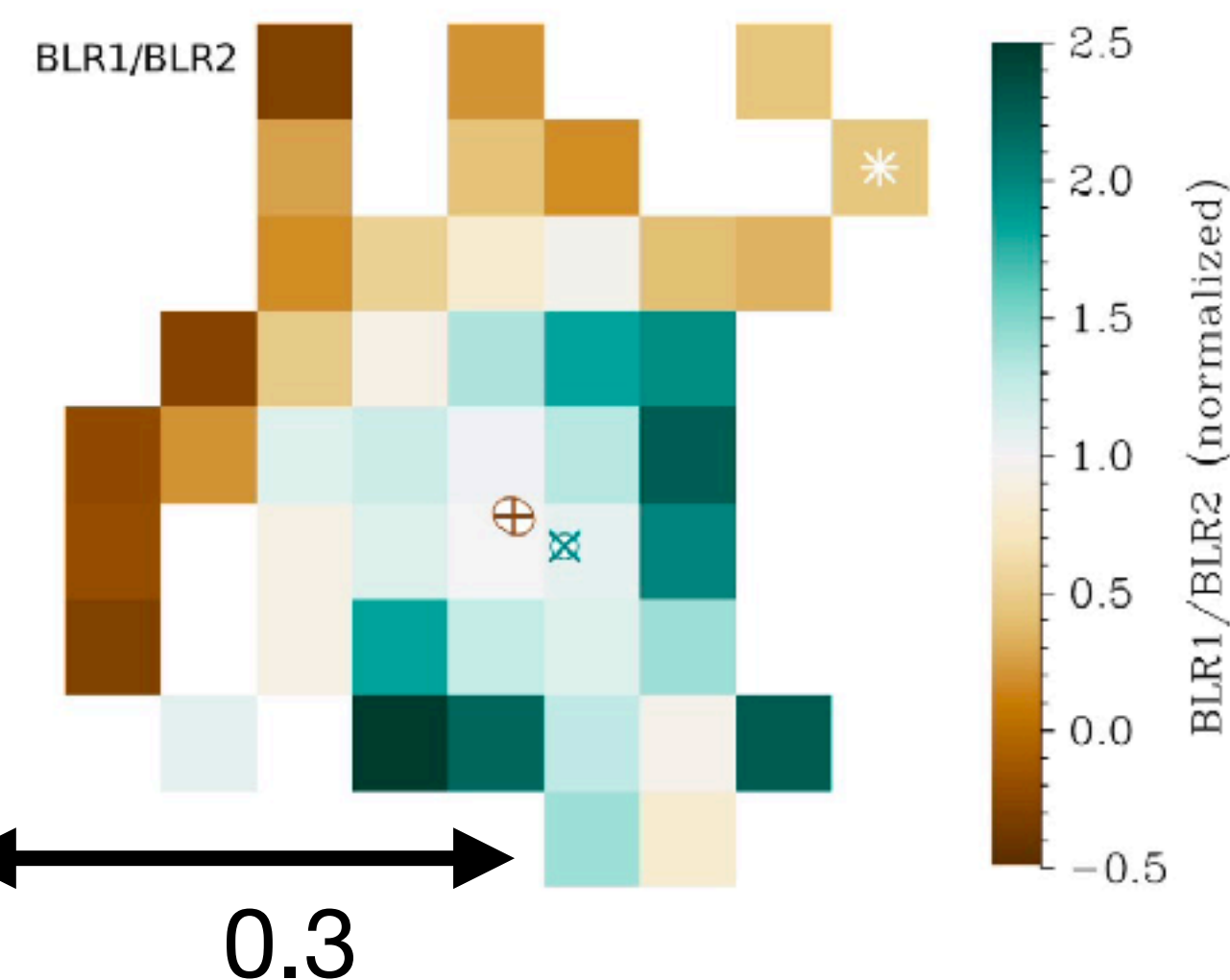
JWST  
resolution  
@ 3.9 micrometers

~125mas

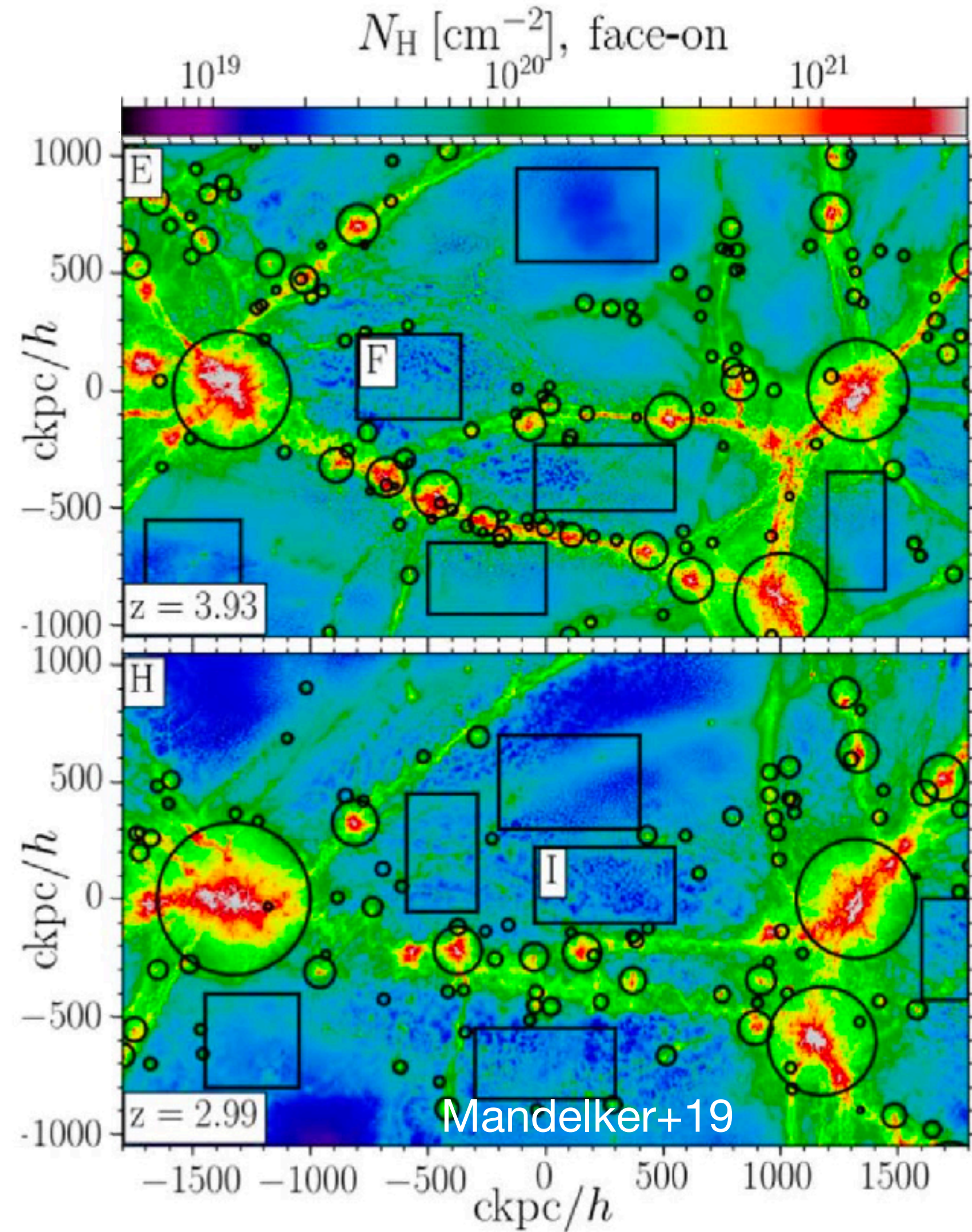


ELT  
resolution  
@ 1.6 micrometers

~8mas



# Small scale structure of CGM and IGM



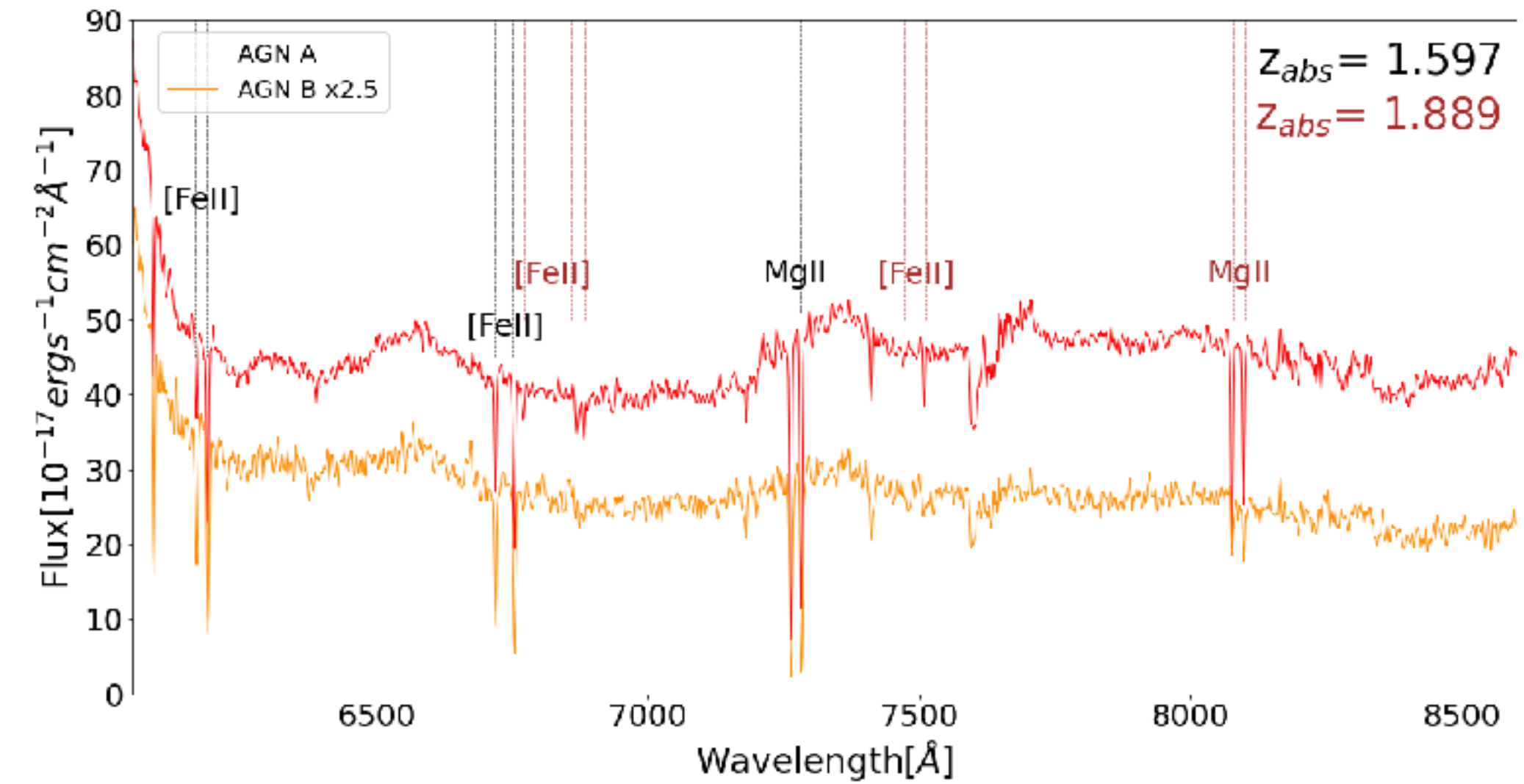
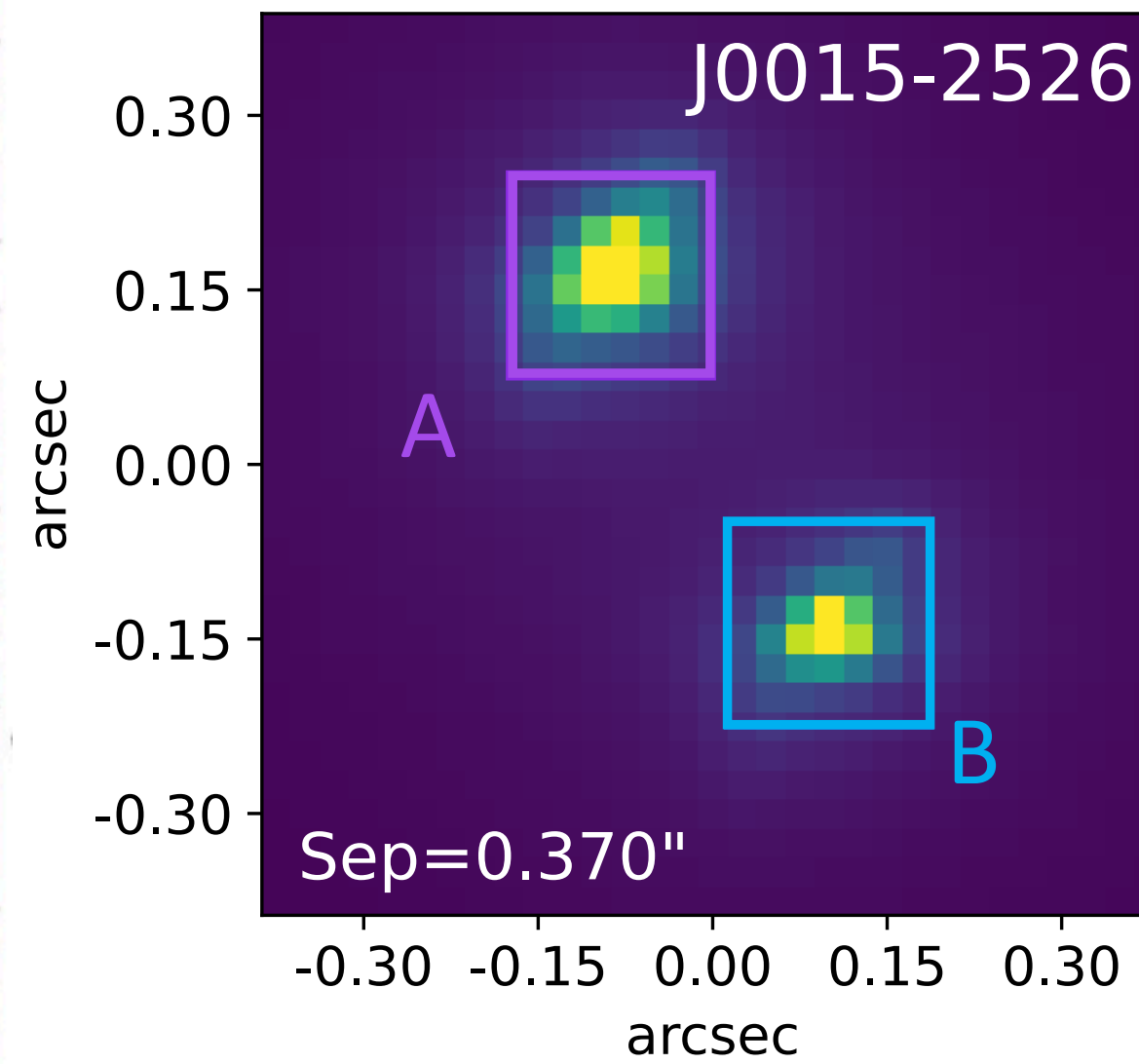
## IGM

Shocks  $\rightarrow$  thermal instabilities

$\rightarrow$  kiloparsec-scale clouds,  $T \sim 10^4 \text{K}$ ,  $n = 10^{-3} \text{cm}^{-3}$

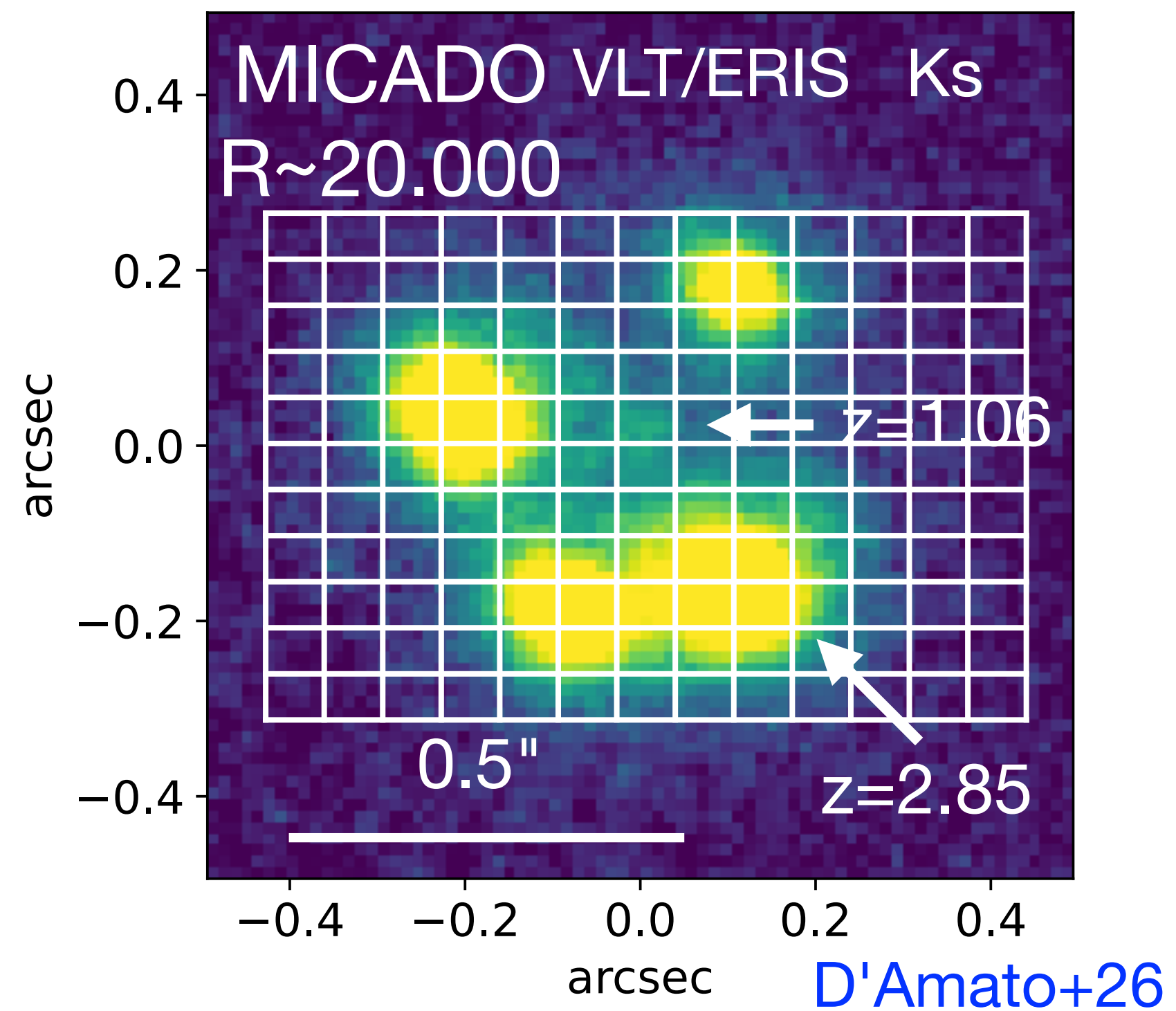
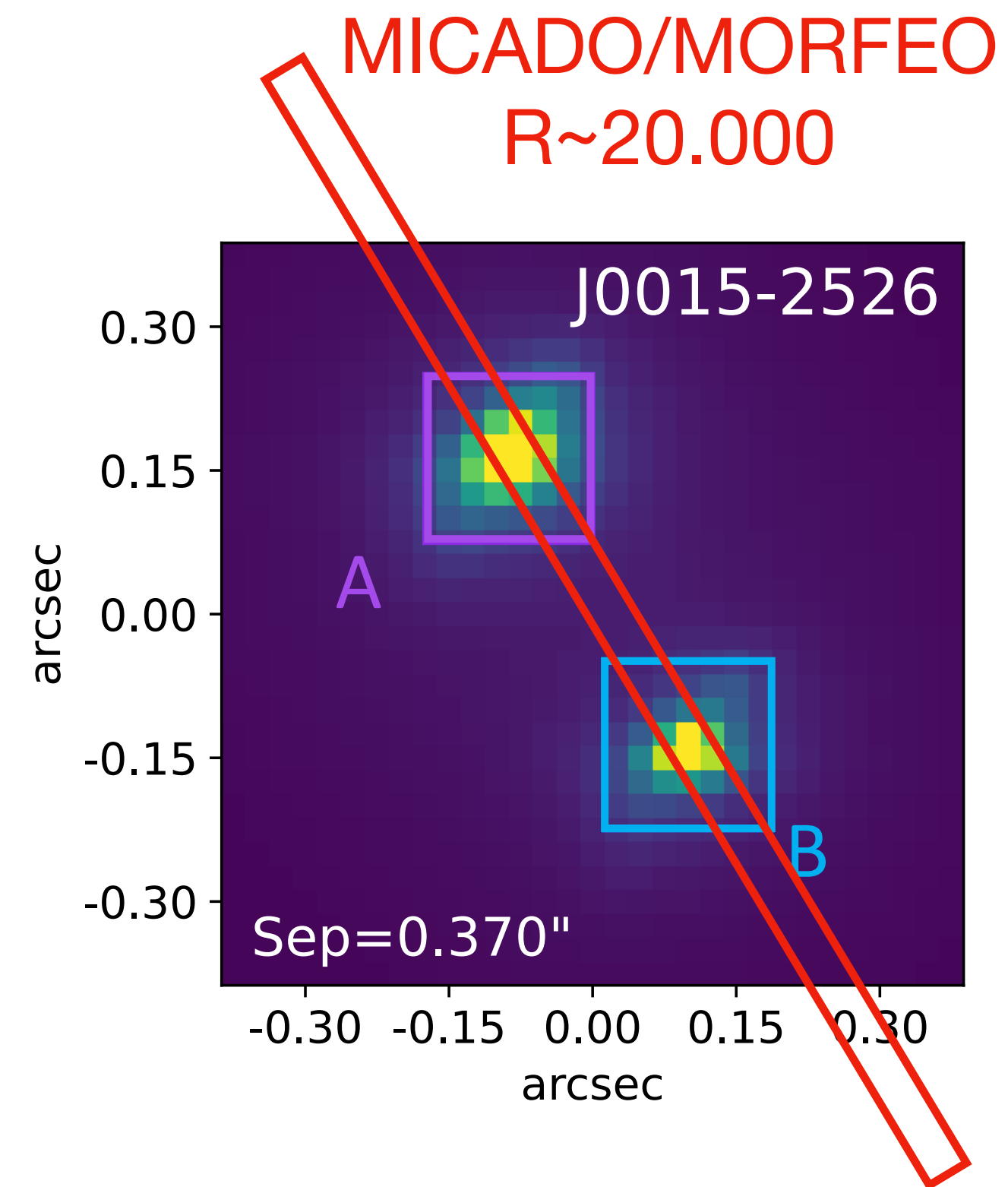
$\rightarrow$  hot medium

$T \sim 10^6 \text{K}$ ,  $n = 10^{-5} \text{cm}^{-3}$

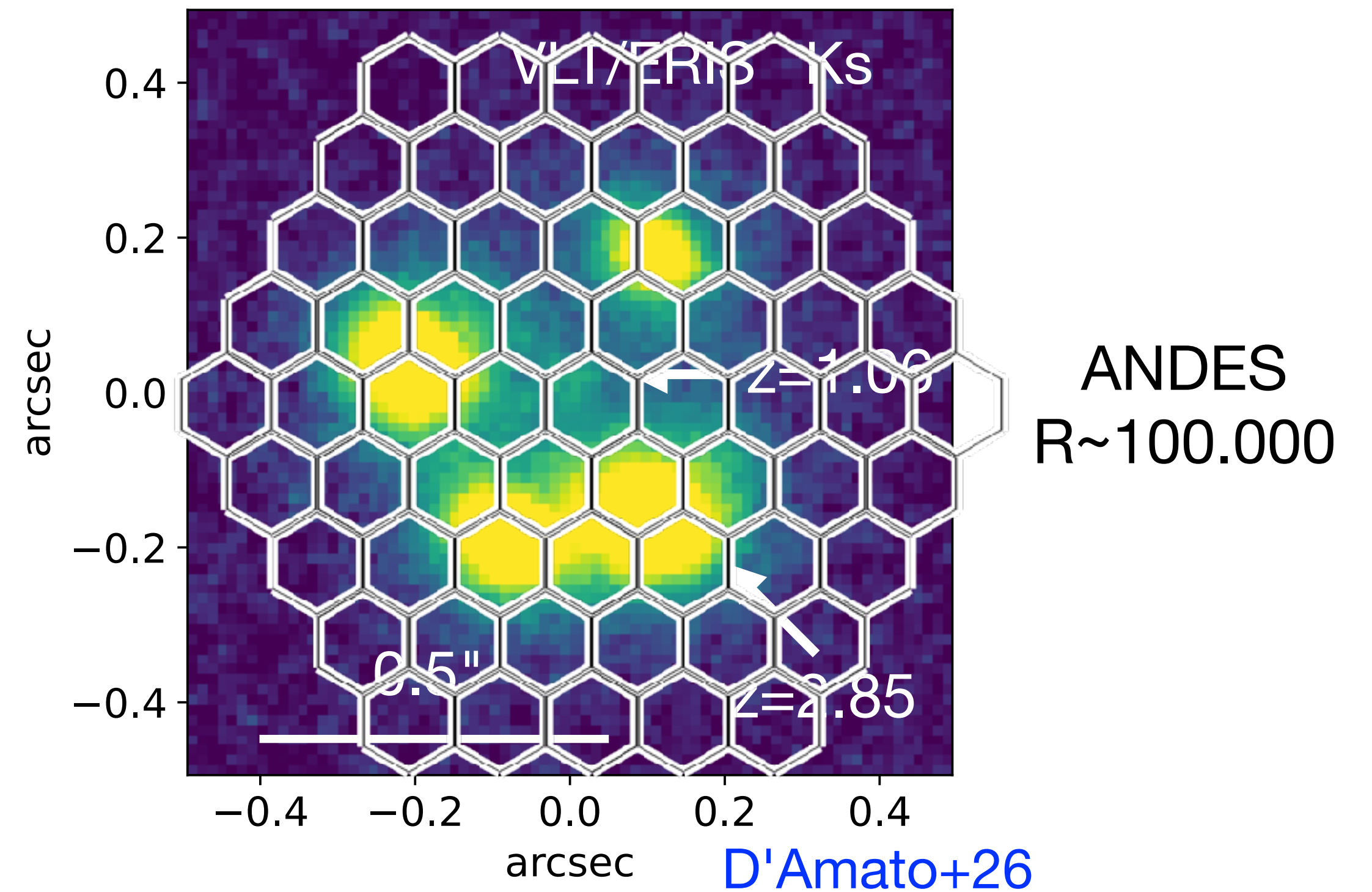
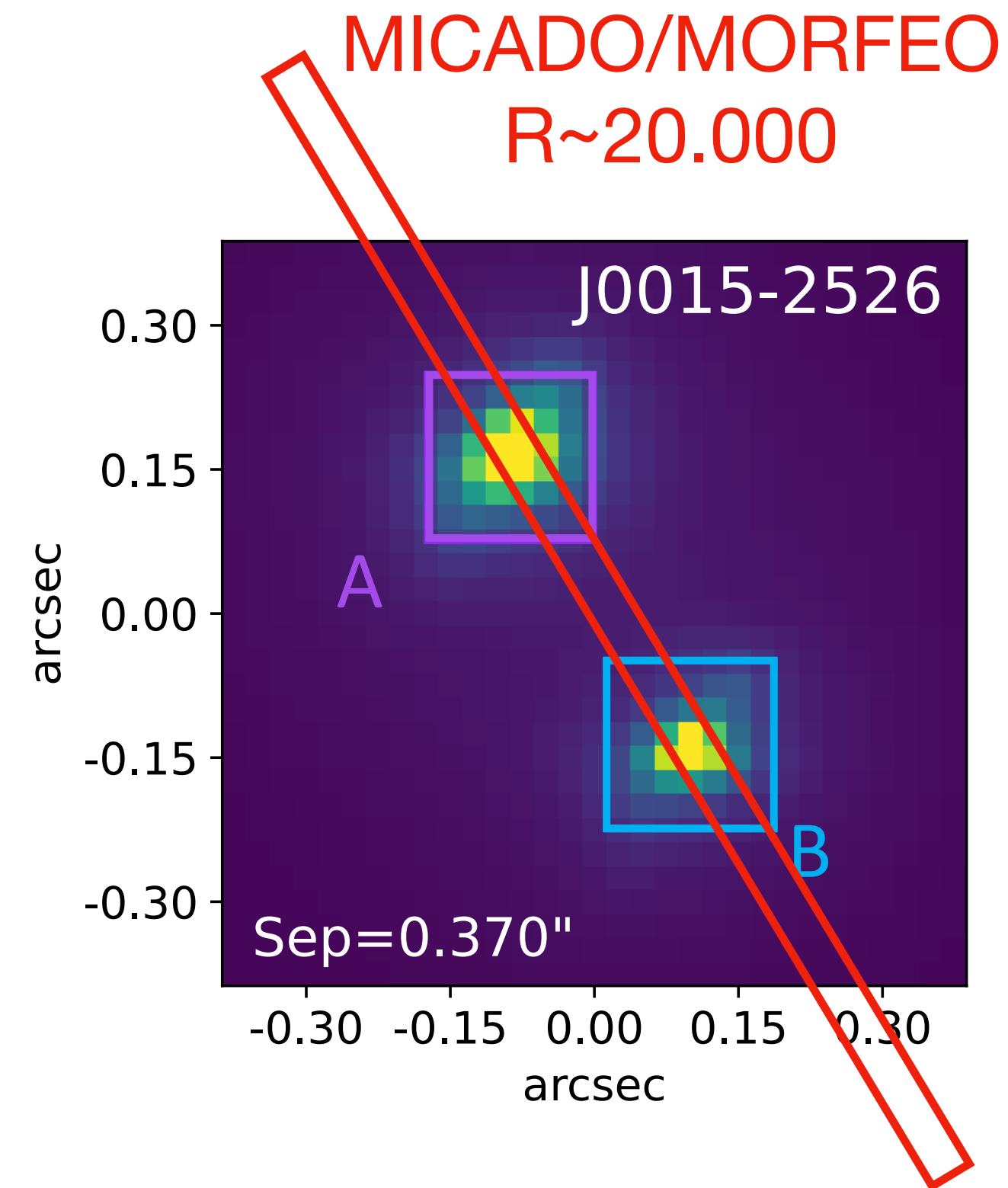


Rauch+01, Chen+14, Zahedy+16; Rubin+18, Kulkarni+19, Mandelker+19, Gronke+20,22 Augustin+21, Fumagalli+24, Dutta+24, Yao+25

# MICADO - ANDES



# MICADO - ANDES

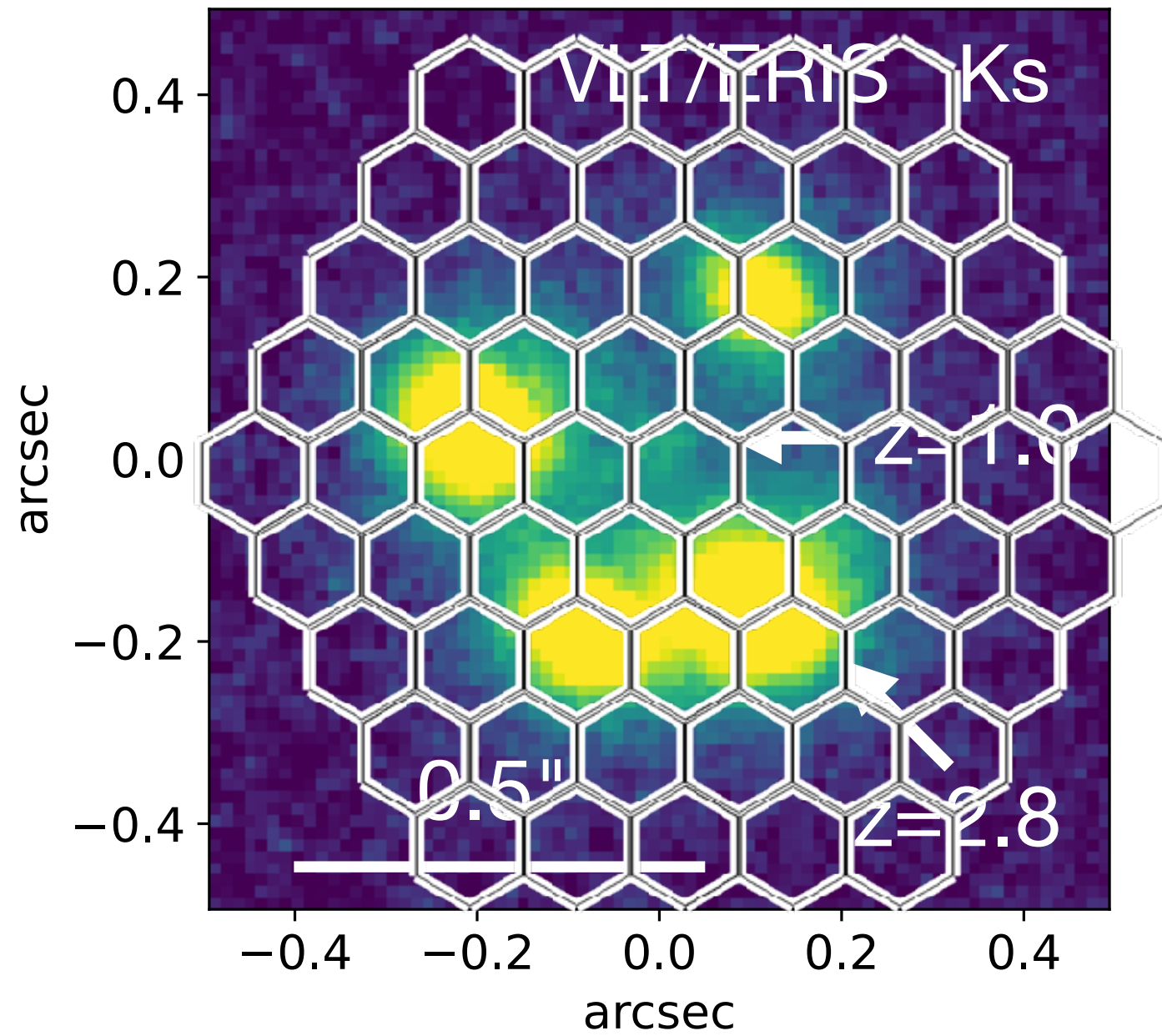


ANDES: only spectrograph with both high spatial and spectral resolution

# ANDES for resolved IGM properties

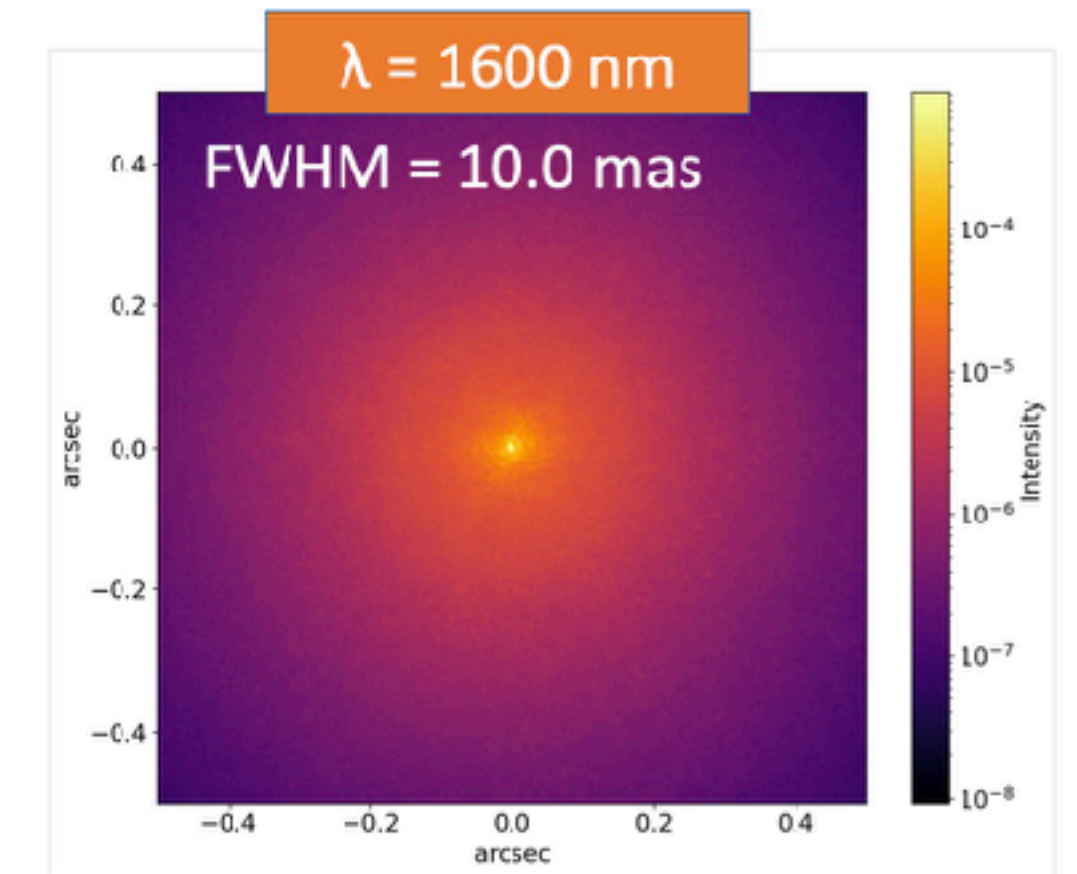
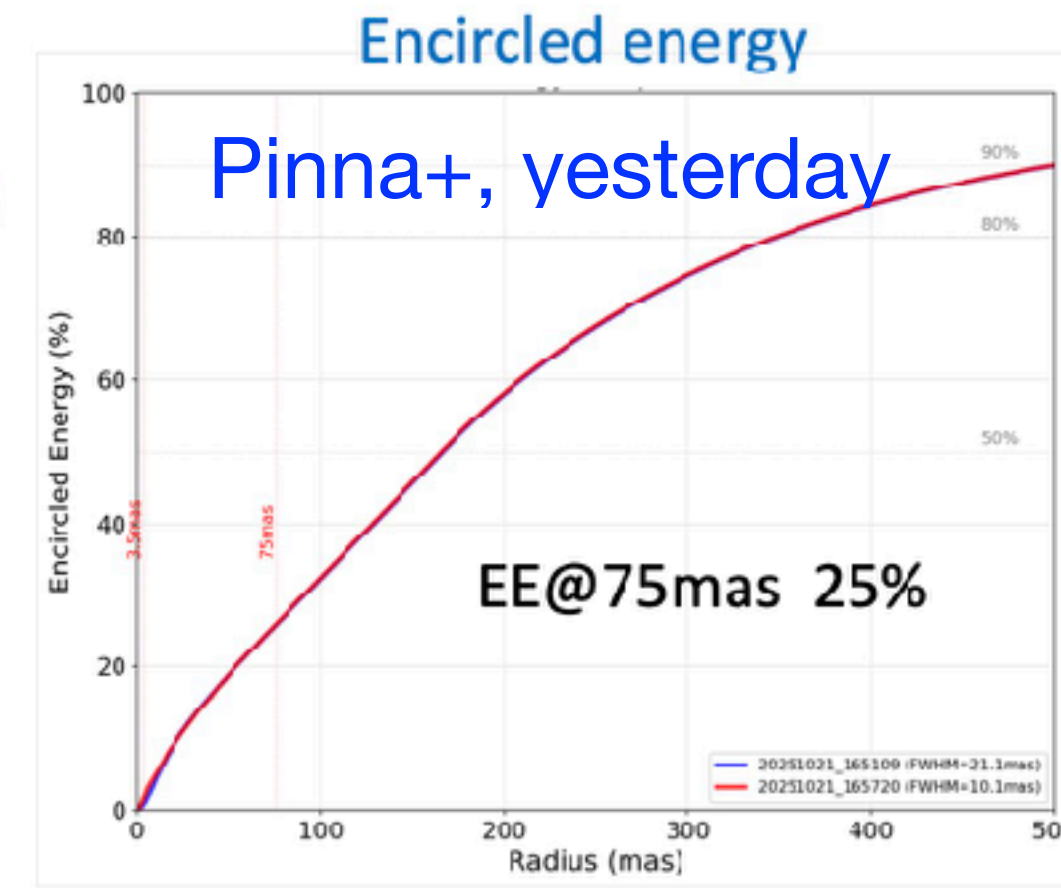
Requirements:

ANDES  
R~100.000

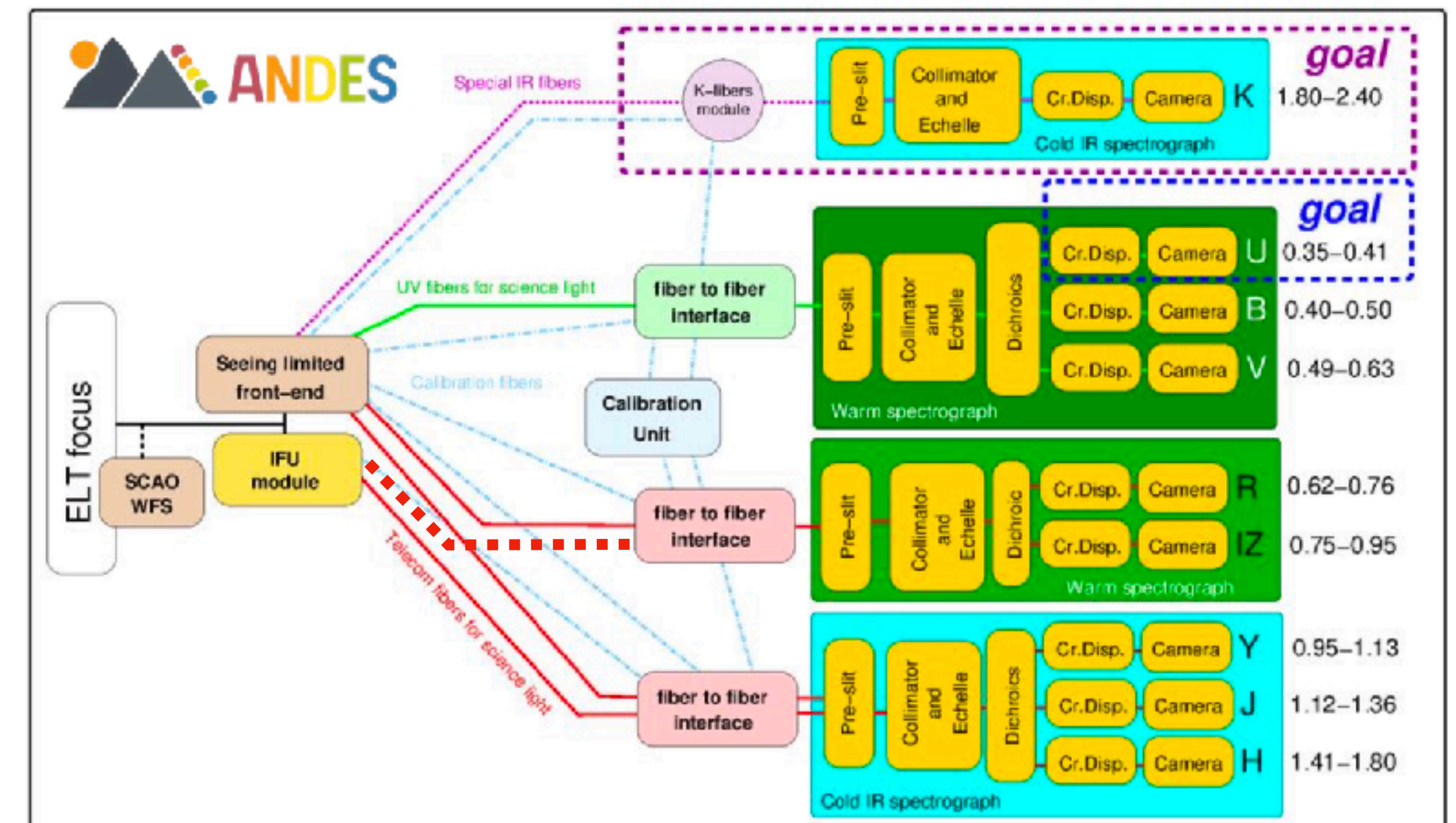


$I = 18$   
SR 3.5% (H)

1. Faint AO  
NGS



2. AO module for  
the RIZ arm?  
lower redshift,  
brighter QSOs



Mandelker+19, Gronke+20,22, Fumagalli+24, Dutta+24, Yao+25

# Conclusions

- Using ~20 telescopes/instruments to build a large sample of duets at sub-arcsec separations (common host galaxy) and  $z > 0.5$
- First statistical sample of duets with a well defined selection function for statistical studies and GW predictions
- Future:
  - MAVIS: large sky coverage
  - MICADO/MORFEO: fainter/closer systems
  - ANDES: IGM 3D structure

