Joint Survey Processing and *High-Redshift* Galaxies*

* z > 6

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+ the IPAC JSP team
(Ben, George, Nathaniel, Ranga, Roberta, Sergio…)

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Artist's impression of a quasar

Motivation

Our goal is to study large samples of galaxies in the Epoch of Reionization ($z > 6$) to:

- understand better the processes that ionized the early Universe
- understand the formation and growth of early galaxies via their physical properties and clustering environments

Multi-wavelength data over wide area are crucial:

- Selection of high-z galaxies requires data in the blue (and red)
- Characterization of physical properties requires data in the red

Requirements for JSP

To achieve high-redshift science, we need highly consistent pixel photometry across multiple wavelengths (data sets) at the survey limits.

Individual Data Products

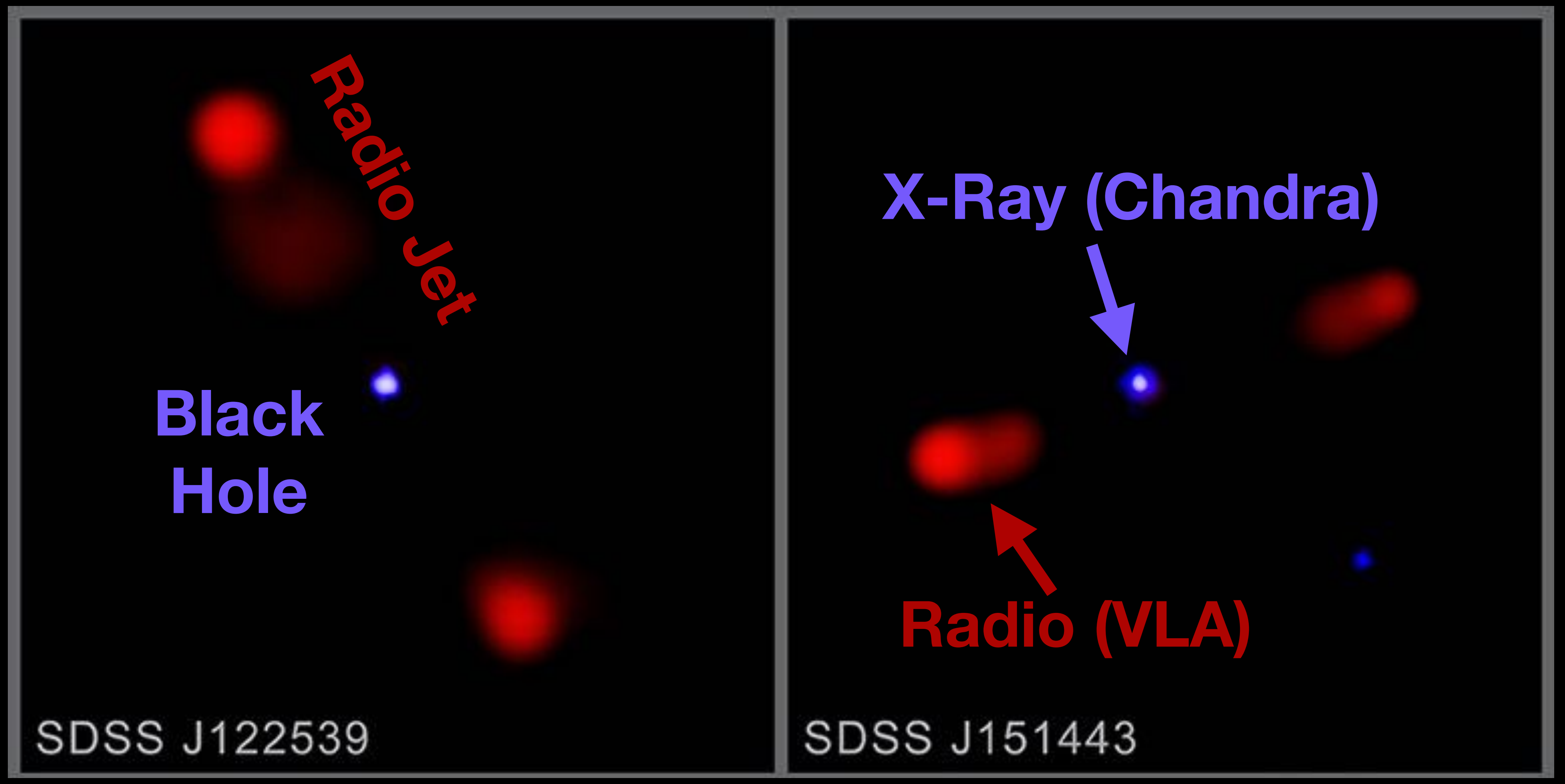
- Co-adds **and** single exposures
- Accurate magnitude- and position-dependent PSF across data set
- Precise photometric calibration

Across Data Products

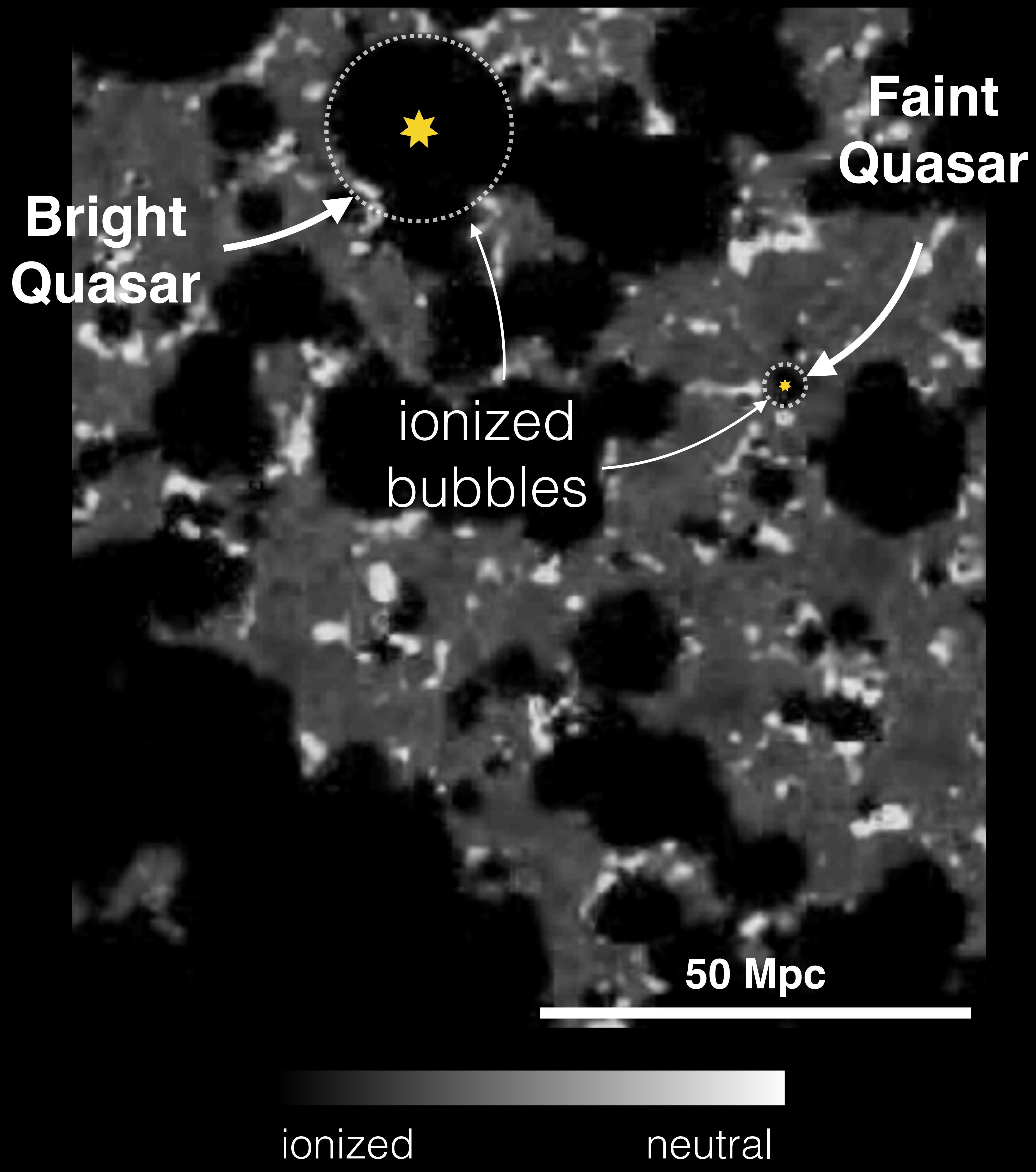
- Standardization of photometry, calibrations/corrections, flagging, masking
- Astrometric alignment
- Consistent photometric extraction at pixel level at survey limits (including limits!)
- Quality checks (photometry, PSF, etc)

Example Application: Finding Quasars in the EoR

- Quasars are powered by massive black holes and ionize the surrounding hydrogen
- They are tracers of black hole growth and reionization.



Zhu et al. (2020)

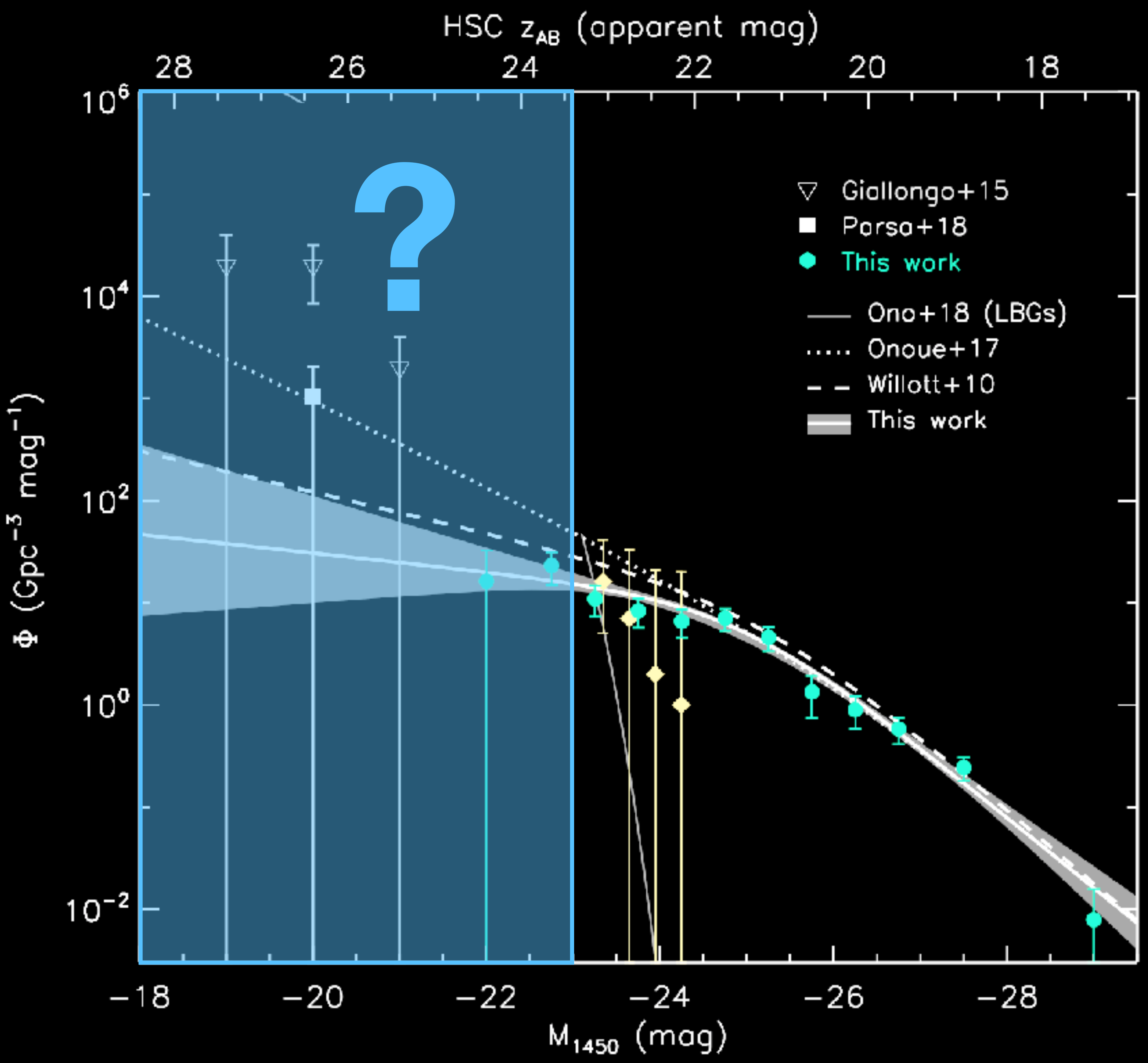


Example Application: Finding Quasars in the EoR

Faint Quasars are hard to catch:

- ➡ They are faint and missed in shallow wide-field surveys
- ➡ Point sources with similar brightness and color as cool dwarf stars (types M, L, T, …)

No consensus on the number of faint quasars at z > 6!

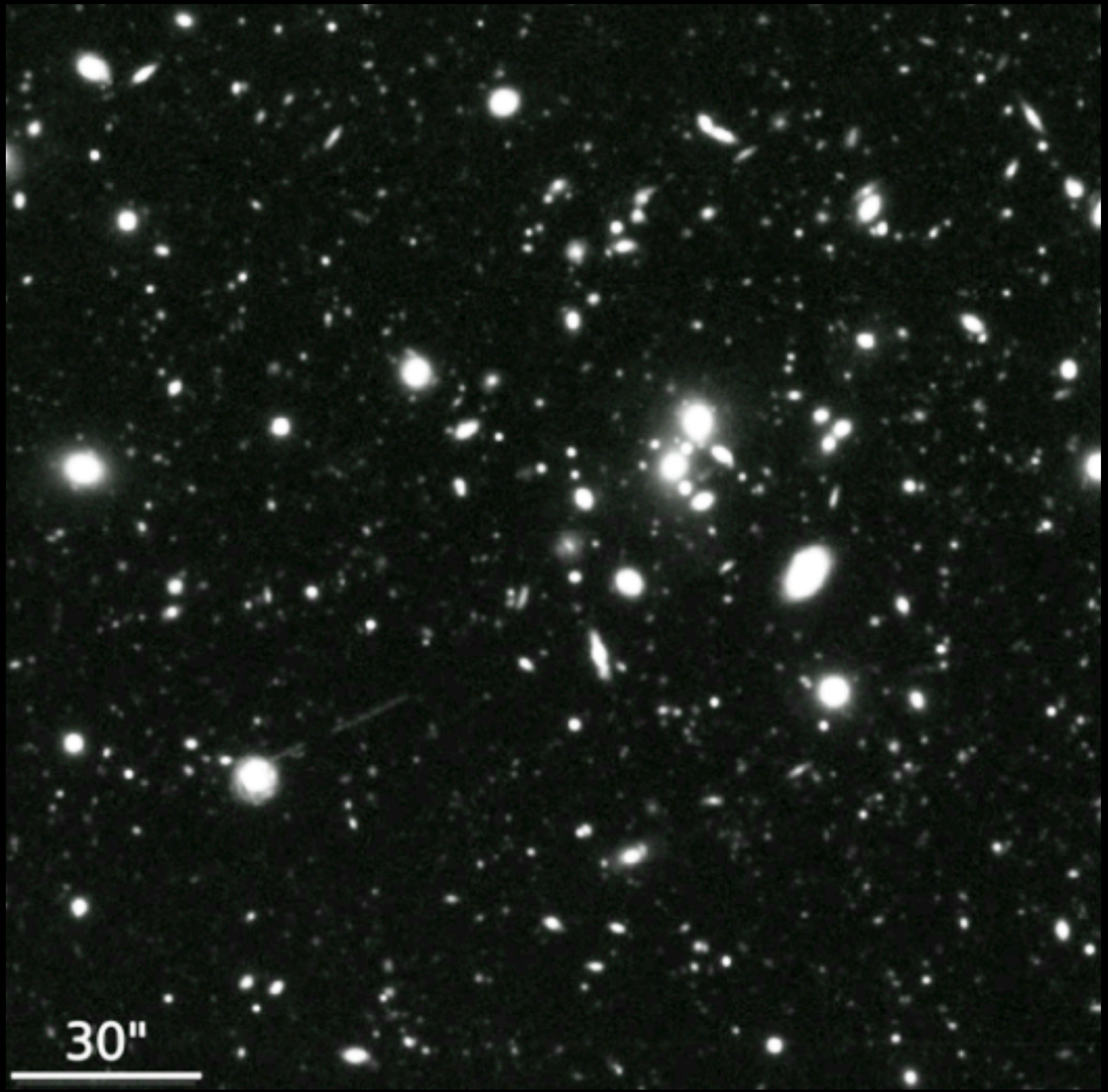


Matsuoka et al. (2018)
(combining SDSS, CFHQS, SHELLSQ)

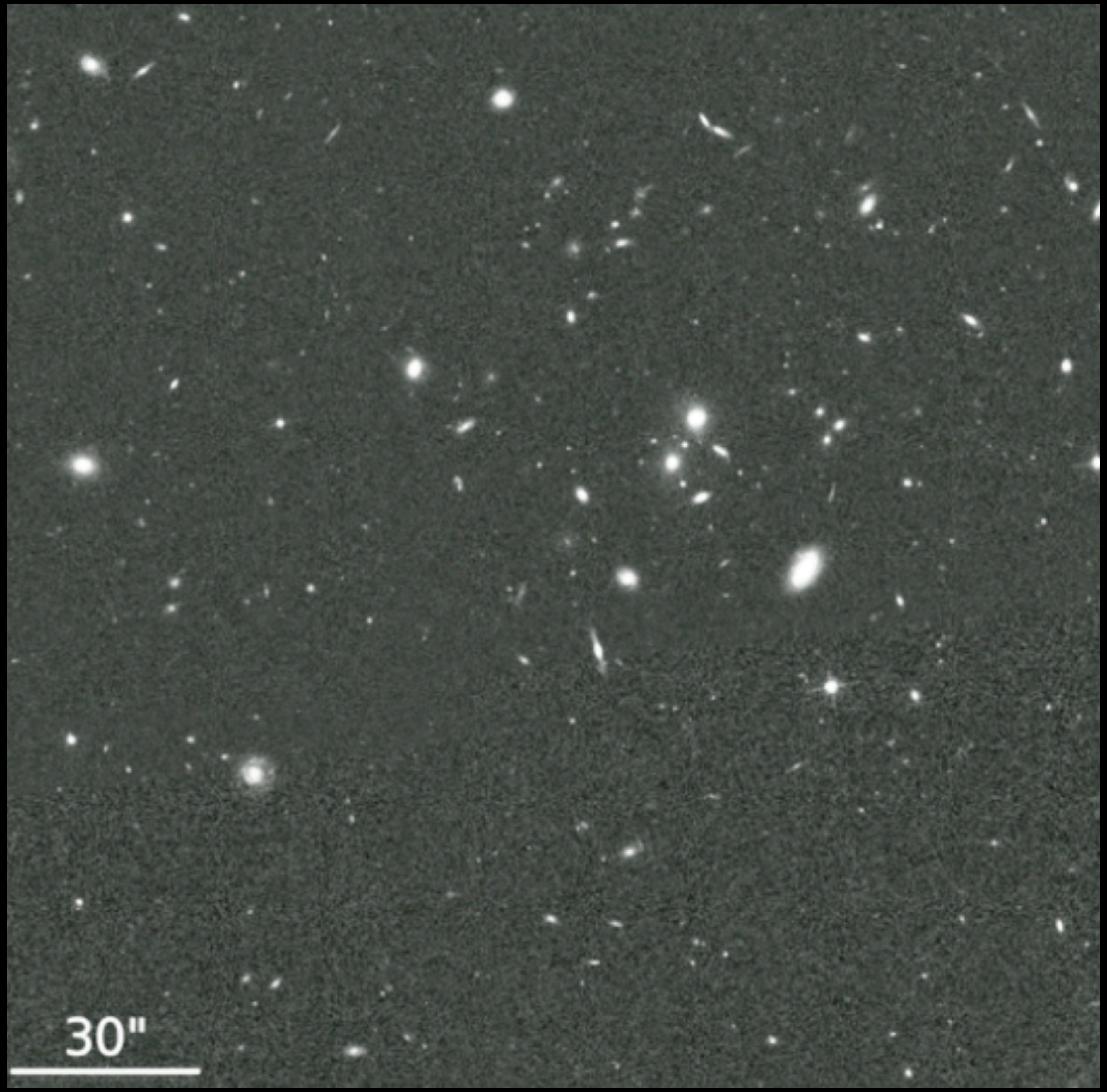
Example Application: Finding Quasars in the EoR

Two datasets similar to future *Rubin* and *Euclid/Roman* surveys:

Subaru HyperSupreme-Cam *i*-band



Hubble ACS/F814W



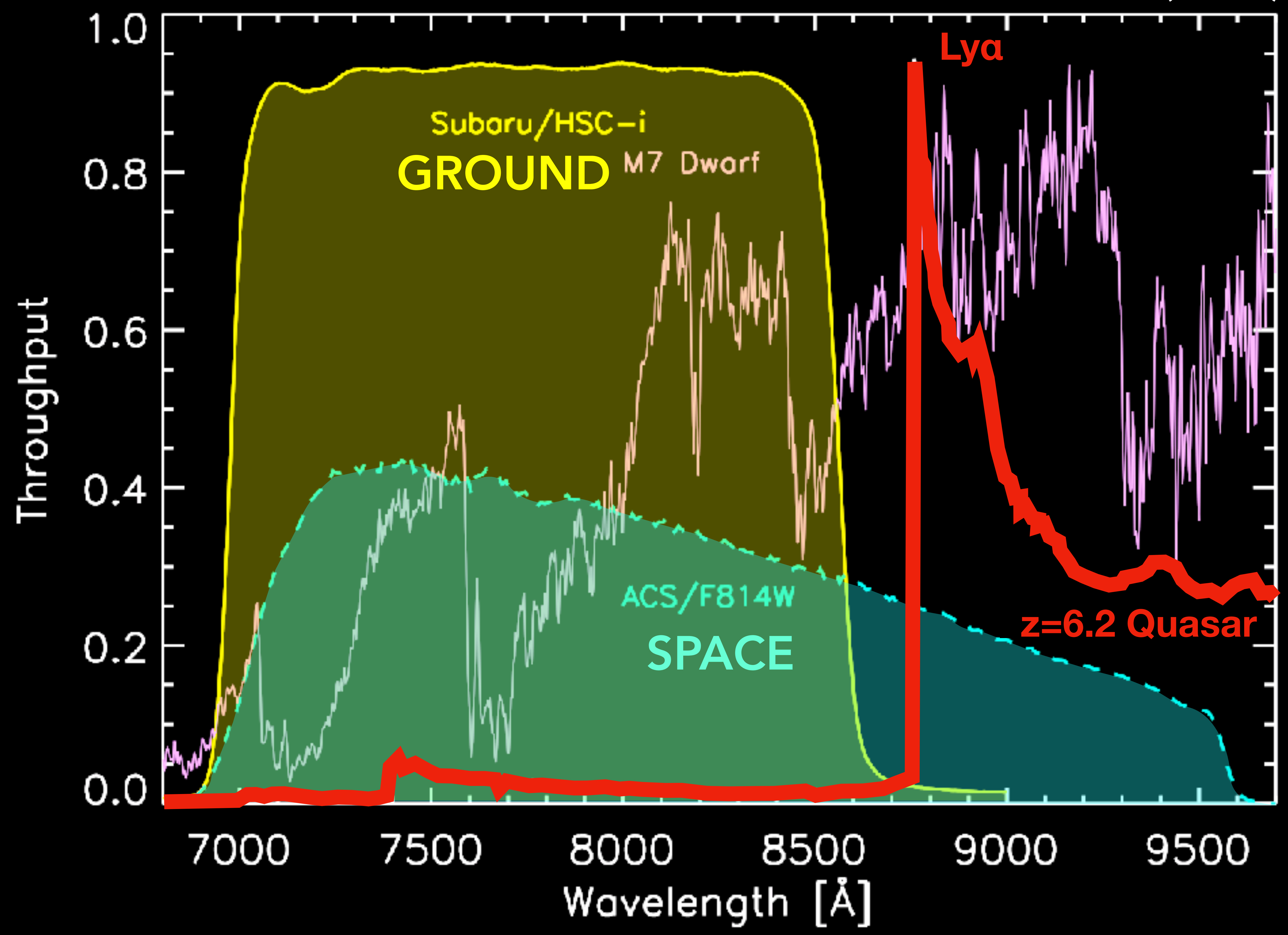
Finding Quasars with Joint Survey Processing

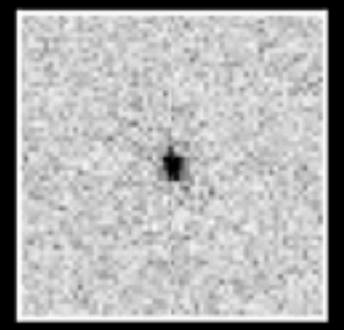
Quasars can be selected by

- Red color across the Lyman Break (+ IGM absorption)
- Compactness (point source) in space-based imaging

Search for z > 6 low-luminosity* Quasars in the COSMOS field by combining **Subaru/HSC i-band and HST F814W** observations

Faisst + JSP-team et al. (2021)





∧ [■ - ■ = Red Color]

* M_{UV} > -22 AB

COSMOS: Scoville et al. (2007), Koekemoer et al. (2007)

HSC: Aihara et al. (2008)

Pixel-Level Joint Photometry

Need accurate photometry of space- and ground-based datasets

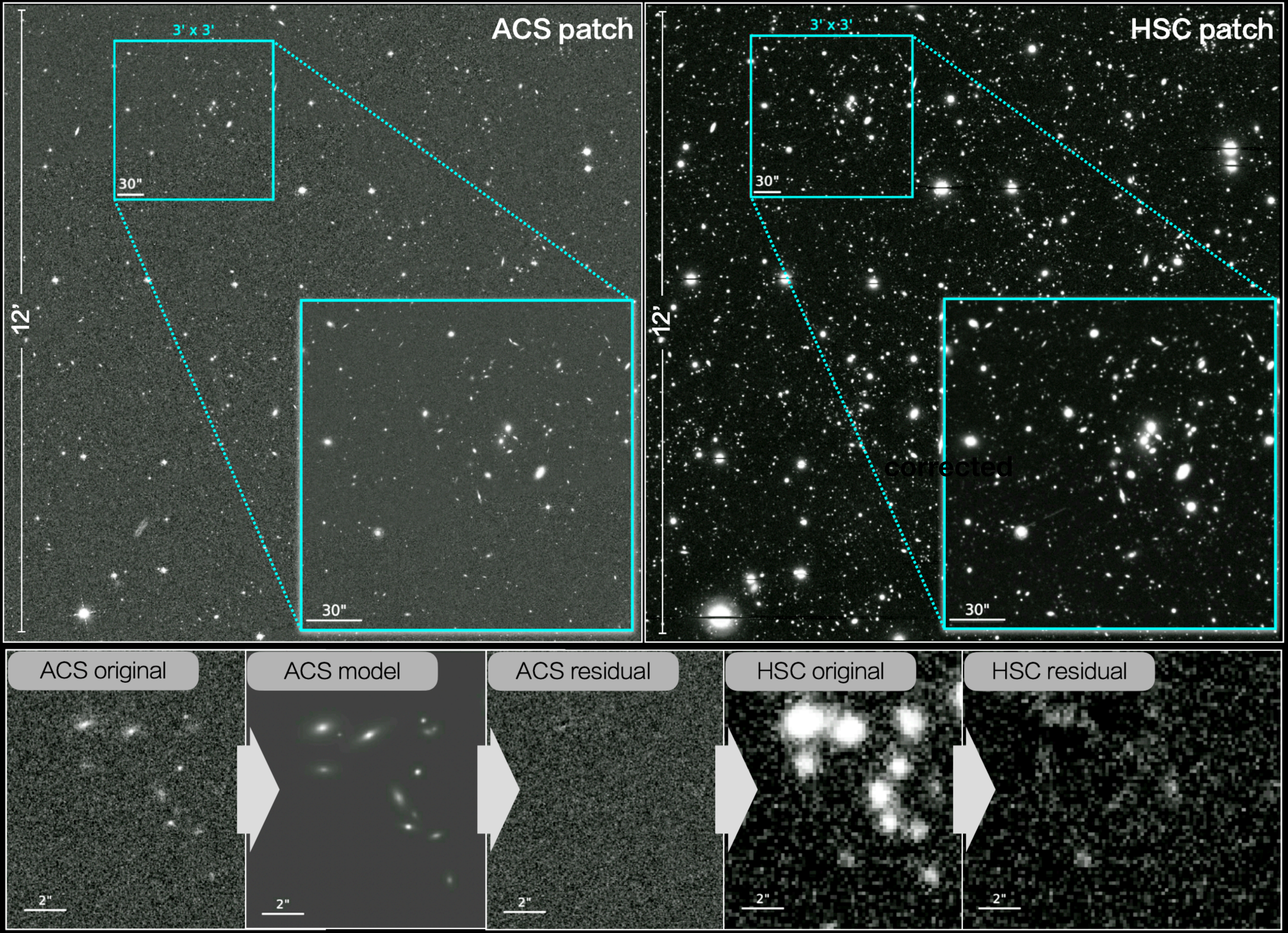
Challenges:

- Different seeing/PSF, pixel scale, sensitivity, and astrometric alignment
- Confusion/blending! (>30% of sources at > 25 mag AB, ground based)
- Expect mostly non-detections in HSC (blue) images for z > 6 Quasars

Solution: Prior-based forced photometry (e.g., *Tractor* (Lang et al. 2016))

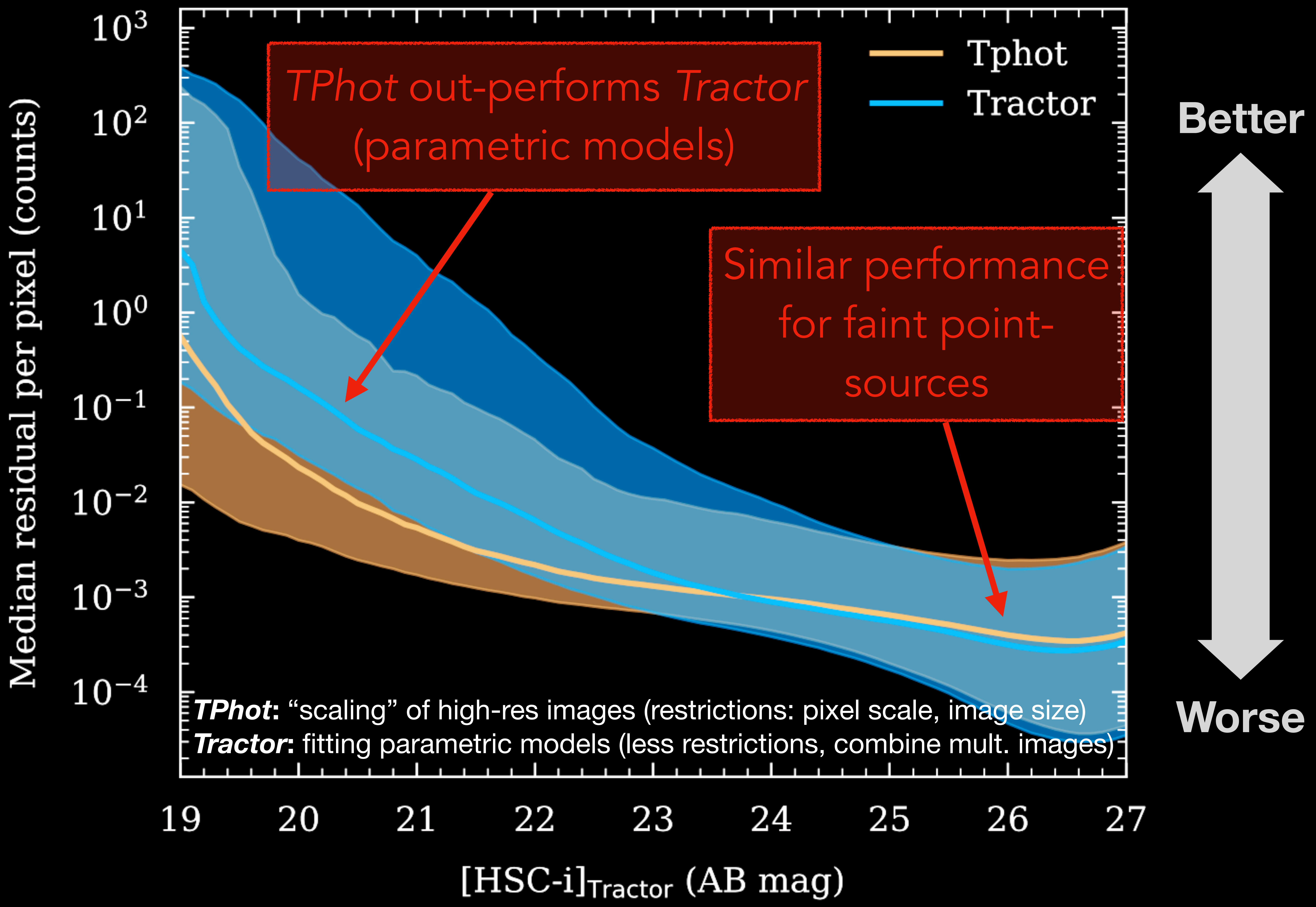
Prior-based forced photometry fitting. Use high-resolution HST/ACS images to measure photometry on low-resolution HSC images

Pixel-Level Joint Photometry



Faist + JSP-team et al. (2021)

The Ideal Photometry Tool: A **Hybrid** approach?

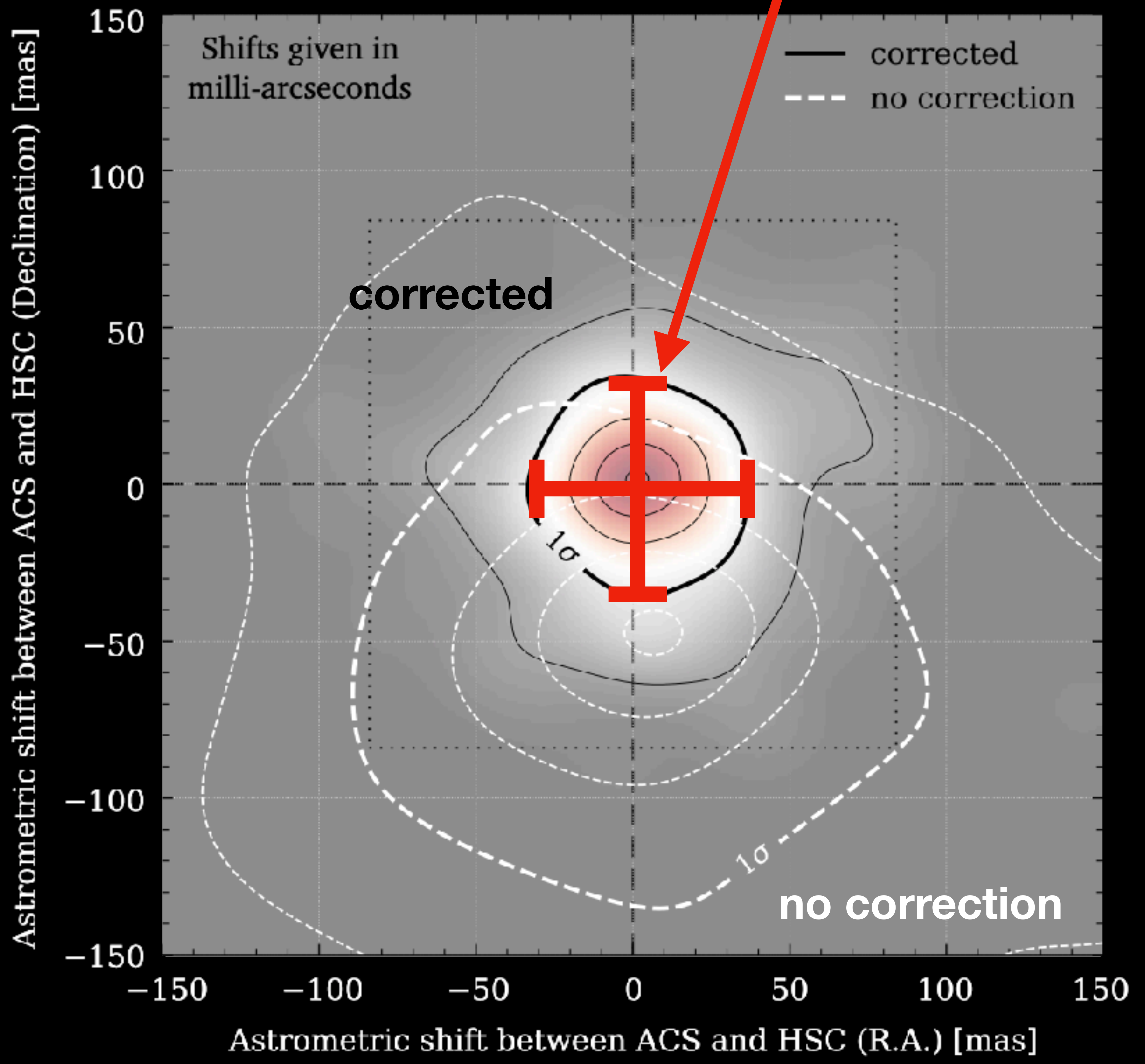


Pixel-Level Joint Photometry

Necessary preparation:

1. Astrometric alignment of HST/ACS and HSC images using Gaia stars and compact extragalactic sources

Achieve accuracy of **~30 mas** with no significant bias



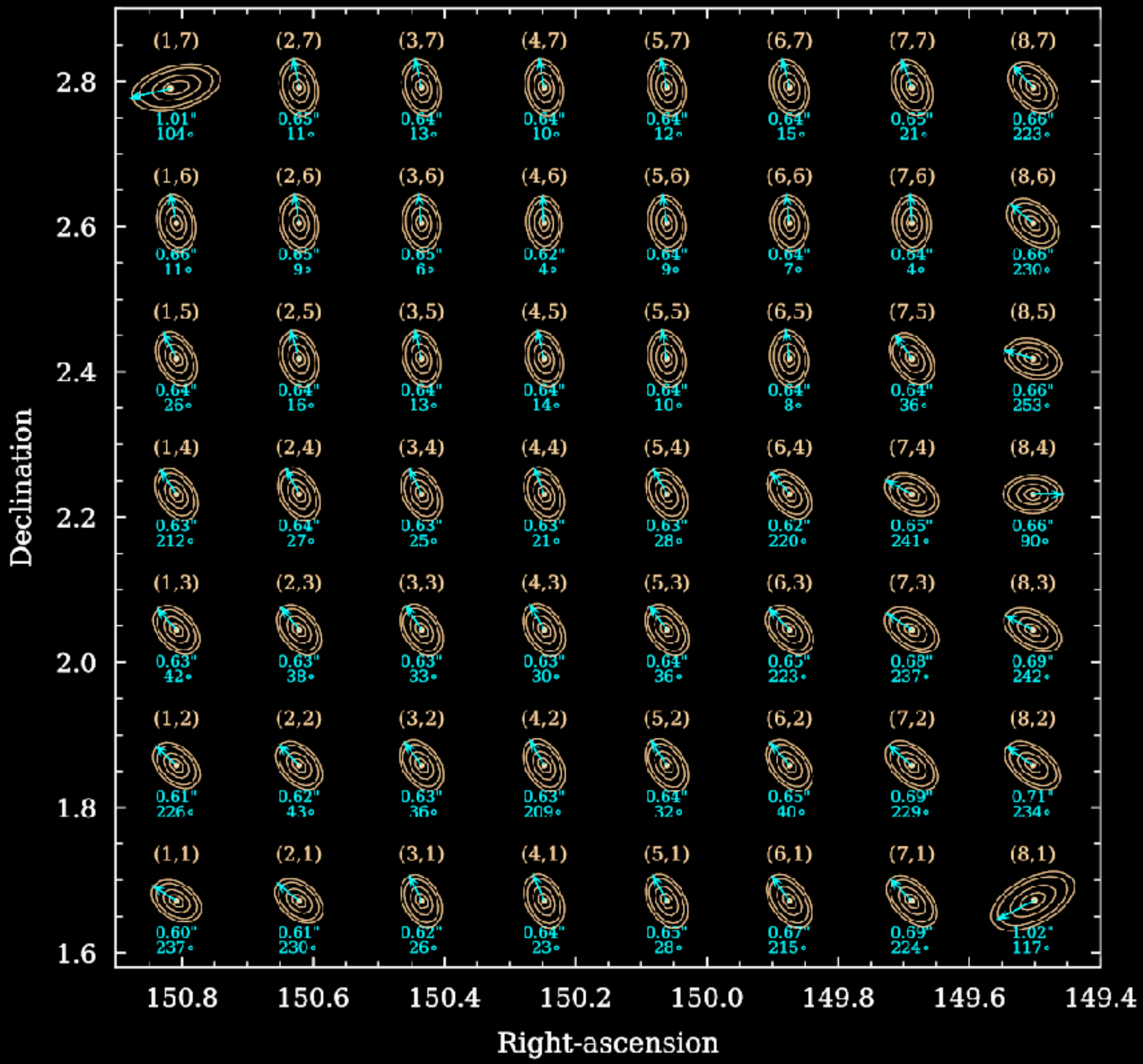
Faisst + JSP-team et al. (2021)

Pixel-Level Joint Photometry

Necessary preparation:

1. Astrometric alignment of HST/ACS and HSC images using Gaia stars and compact extragalactic sources

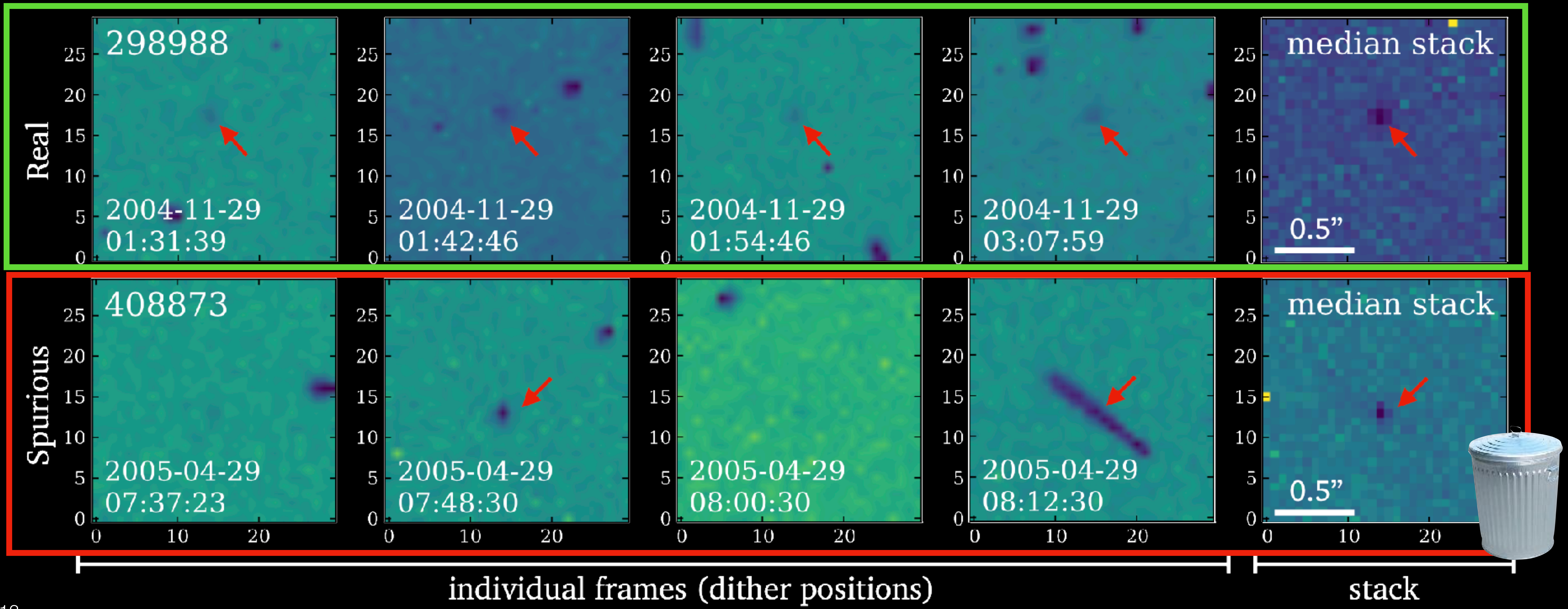
2. Measure position-dependent PSF (to convolve prior models)



Faisst + JSP-team et al. (2021)

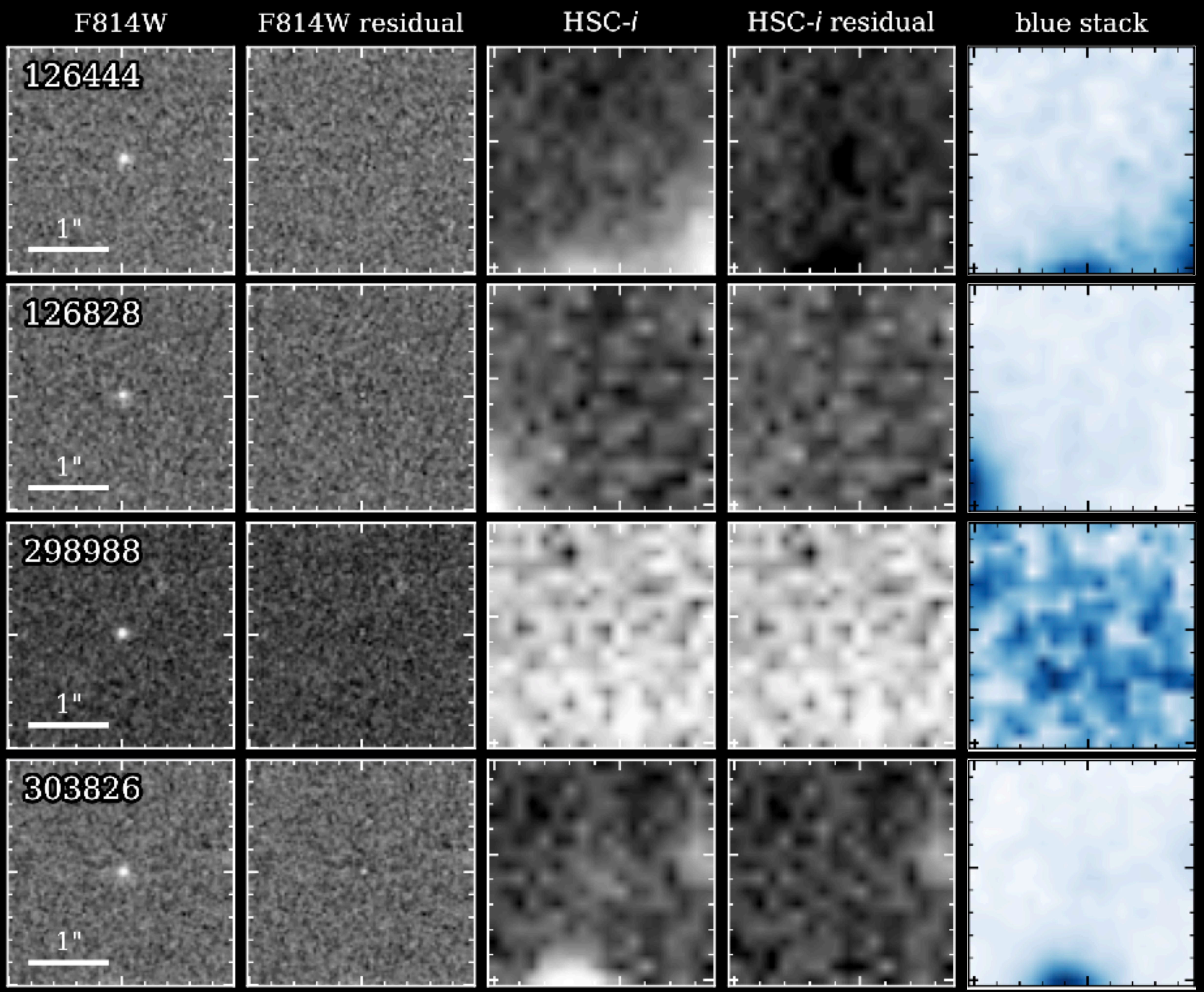
Removal of Spurious Detections in Multi-Frame Data

A lot of spurious detections in sample (poor cosmic ray rejection because only 4 dither frames for HST/ACS observations)



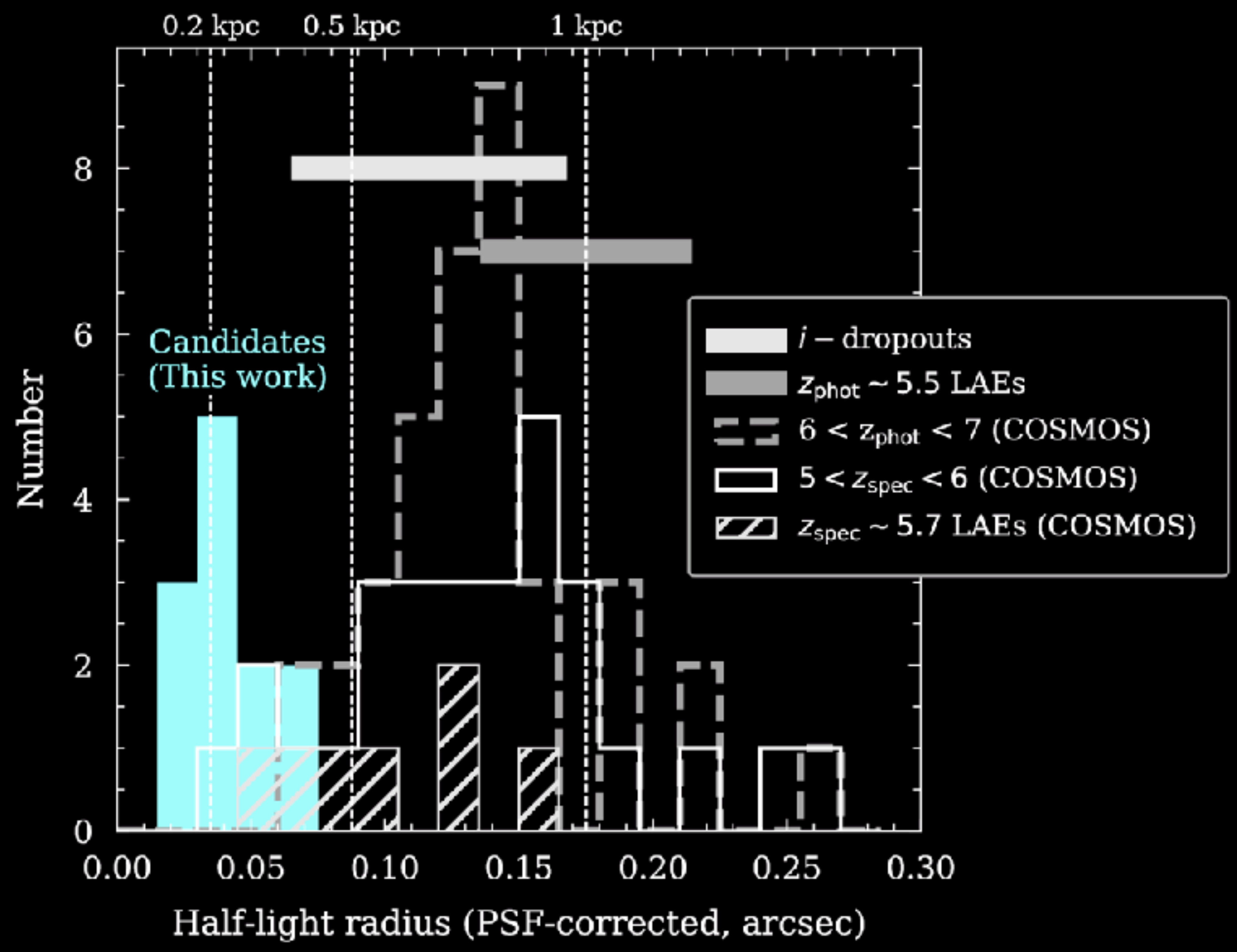
The Final Sample of Low-Luminosity z > 6 Quasars

4 examples of our 12 candidates



Much more compact than galaxies at similar z

(average 200pc)



The Final Sample of Low-Luminosity z > 6 Quasars

What about cool dwarf stars?

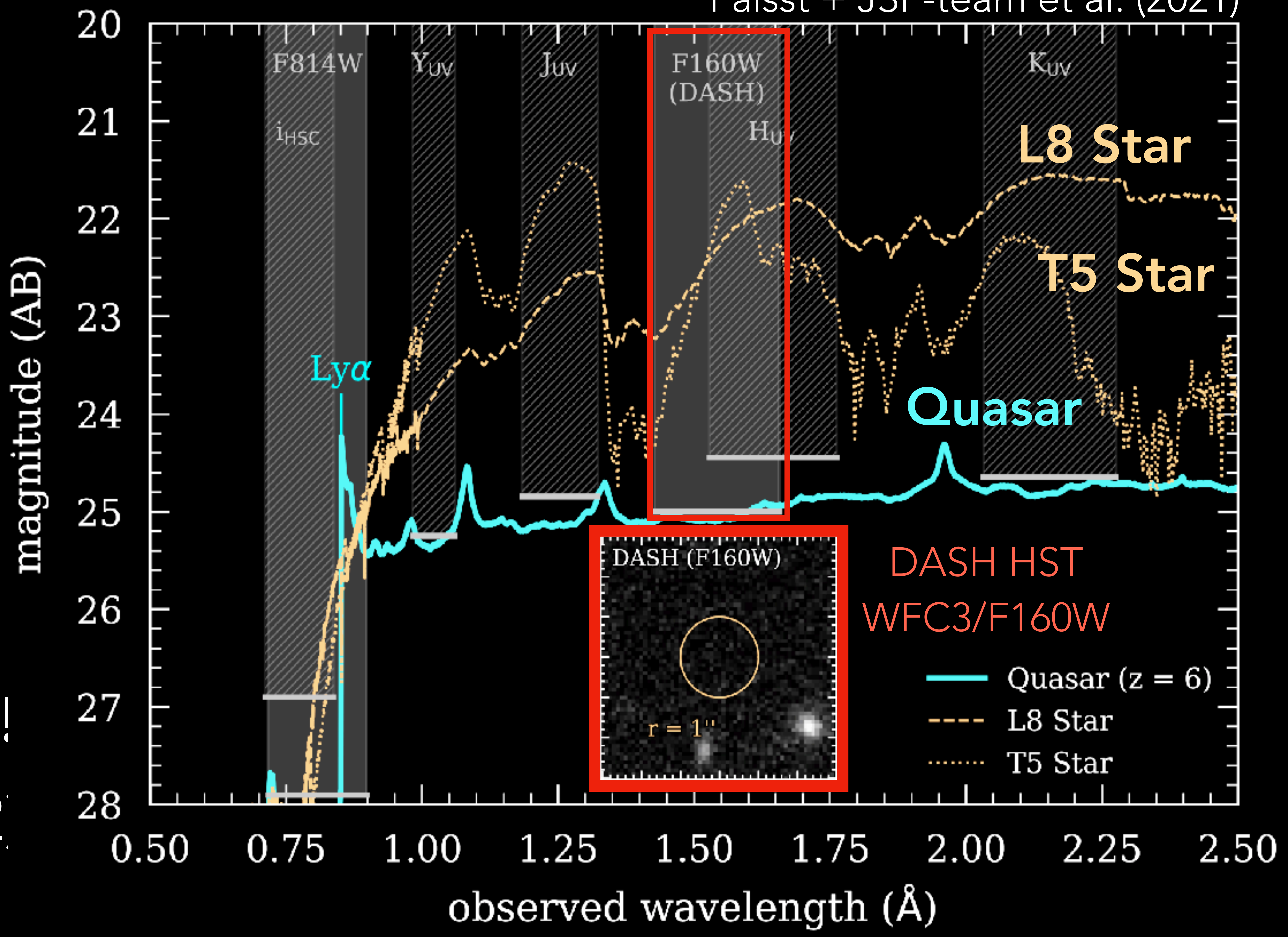
Similar number of L and T stars expected over survey area (1.64 deg²) in direction to COSMOS field.

… but…

No detection in HST *H*-band!

Rule out stars (for 7 out of 12)

Faisst + JSP-team et al. (2021)



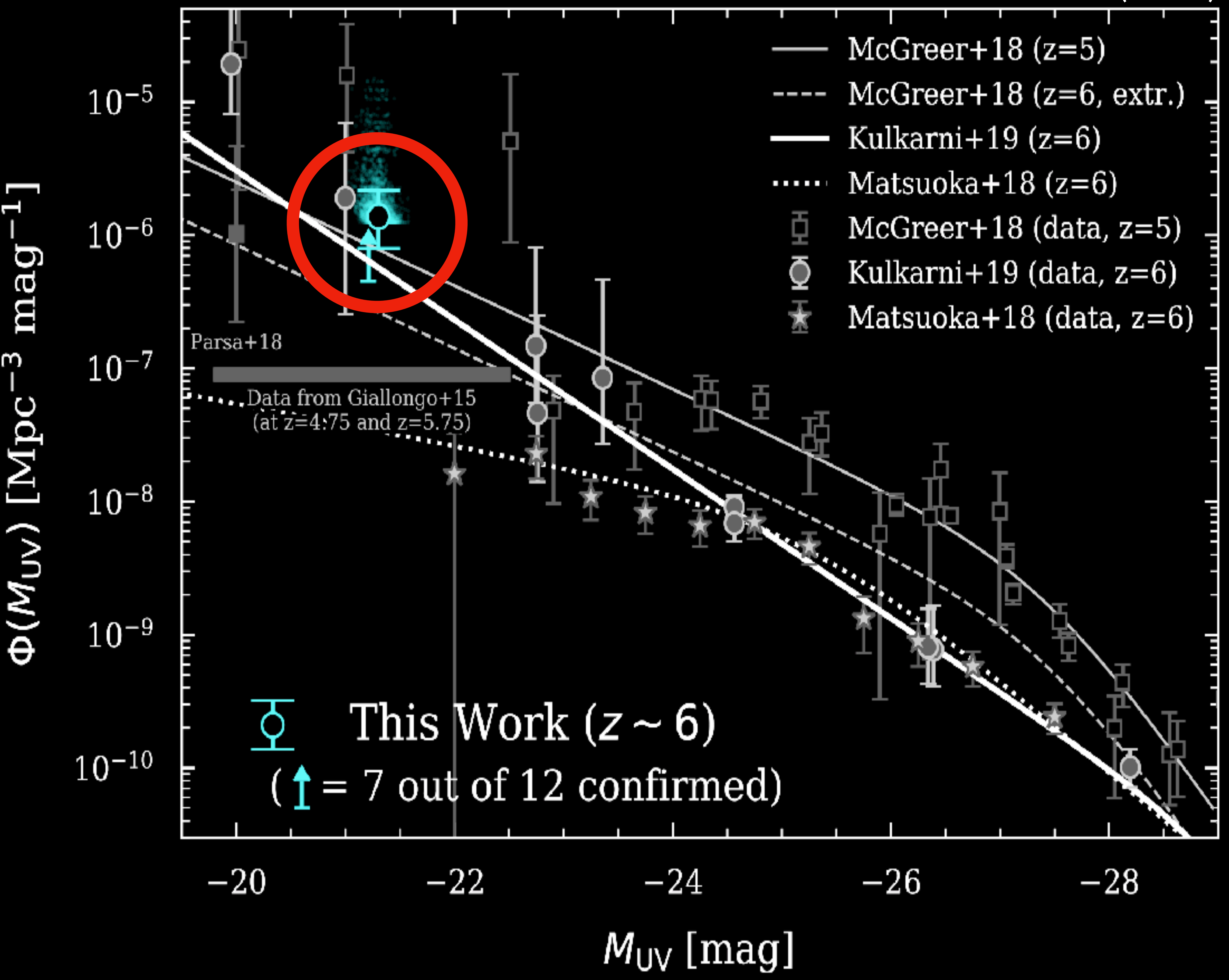
The Faint End of the Quasar Luminosity Function at z > 6

Assuming our candidates are low-luminosity quasars, we find a space density of

~10^{-6} Mpc^{-3} at M_{UV} = -21AB

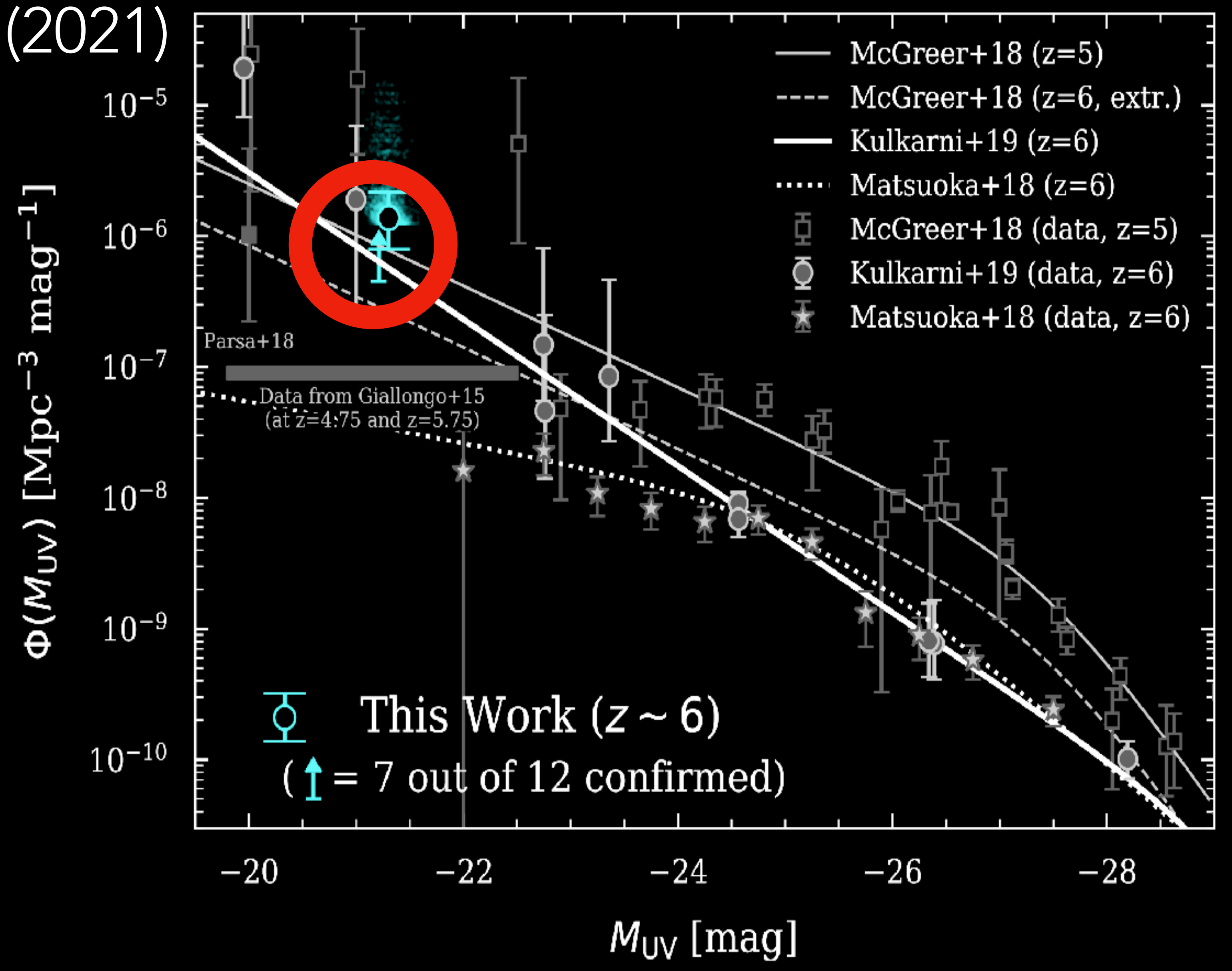
Consistent with photometric sources, but 1-2 magnitudes higher than spectroscopic survey *(Matsuoka et al. 2018)*

Faisst + JSP-team et al. (2021)



Conclusions

Faisst + JSP-team et al. (2021)



Science

- Quasar luminosity function at z > 6 keeps rising
- Still, low-luminosity Quasars only contribute ~10% to reioinzation but they can accelerate ionization of IGM

Joint Survey Processing

- Joint analysis of space and ground-based data to obtain multi-wavelength data is crucial for high-redshift science
- Pixel-level forced photometry is a basic and crucial need for analyzing future survey data with different properties such as from *Roman*, *Rubin*, and *Euclid*.
- Crucial steps: consistent prior-based photometric extraction, astrometric alignment, PSFs calculation

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