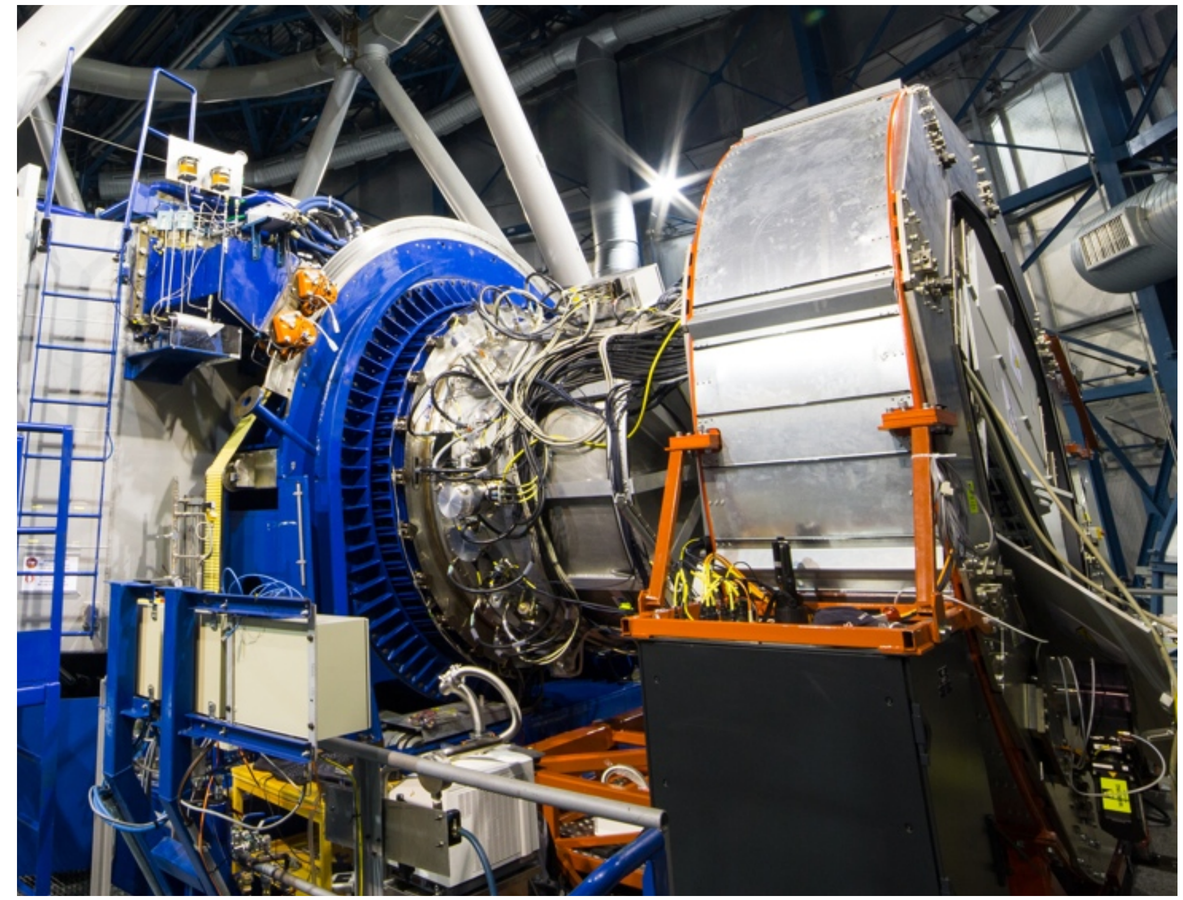
Trevor Mendel, MPE Garching

KMOS calibration and data reduction

Collaborators: Ralf Bender, Roberto Saglia, Alessandra Beifiori, Gabe Brammer, Jeffrey Chan, Ric Davies, Natascha Förster Schreiber, Matteo Fossati, Audrey Galametz, Ivelina Momcheva, Erica Nelson, Pieter van Dokkum, Dave Wilman, Emily Wisnioski, Stijn Wuyts

KMOS primary science drivers

- Resolved maps of local star-forming regions
- nearby stars and stellar populations
- kinematics of star-forming galaxies at $1<z<3$
- first star-forming objects at $z > 7$
- galaxy clusters at $z > 1$
- galaxy stellar populations at $z > 1$



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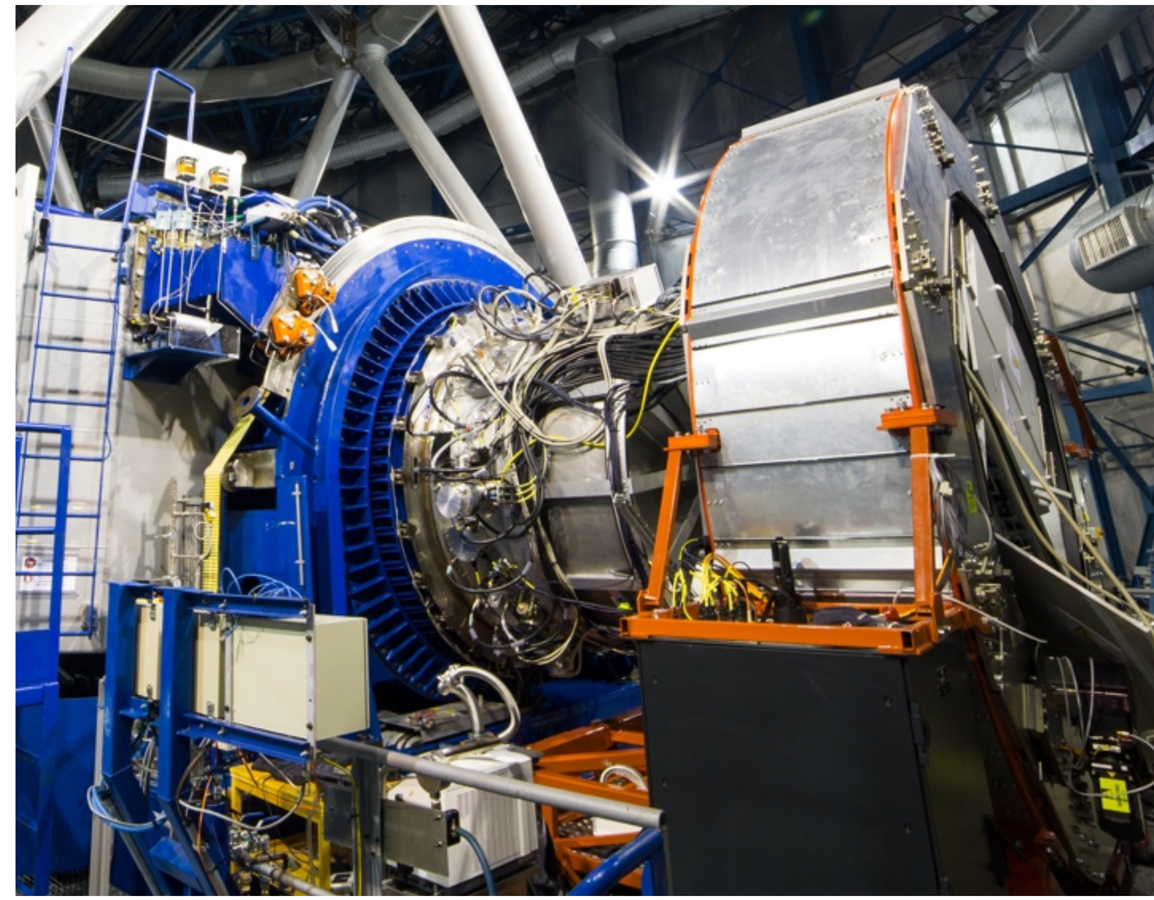

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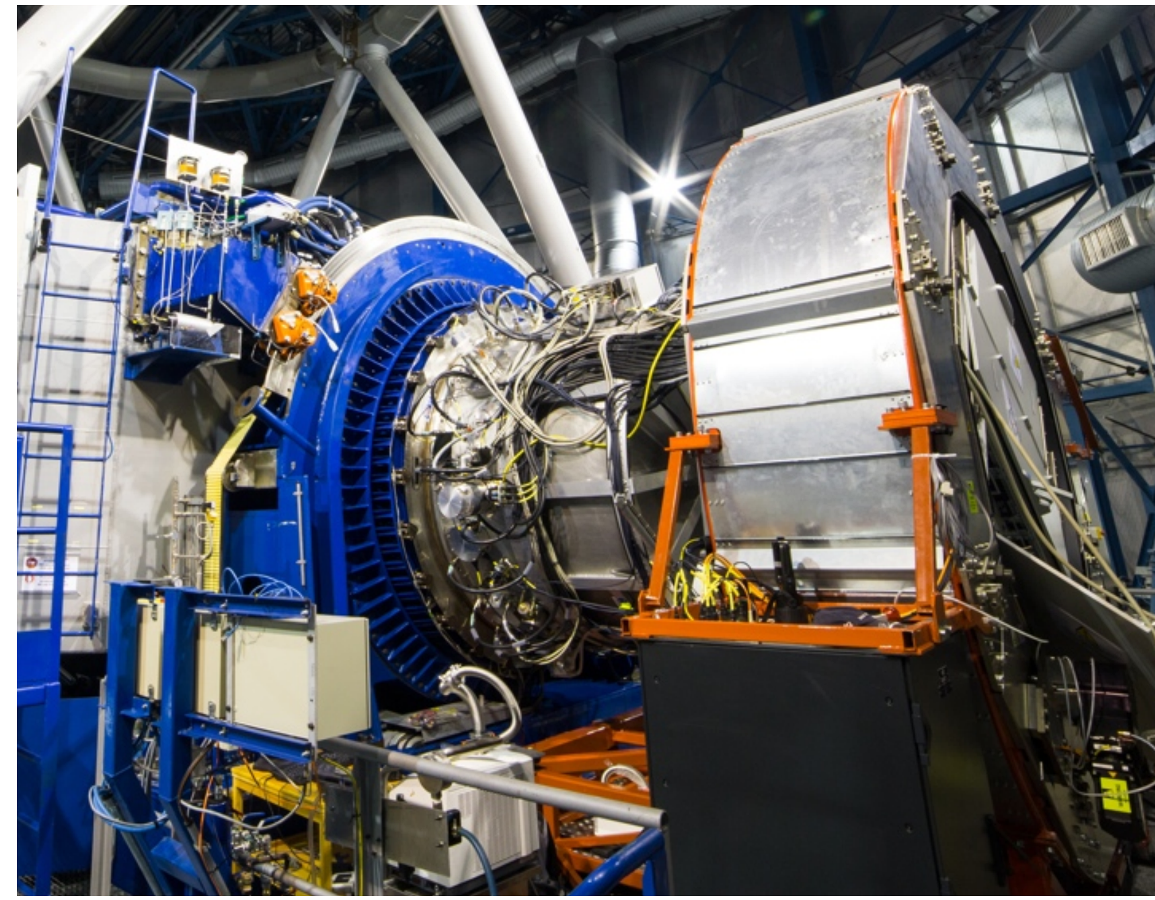

With monolithic IFUs (SINFONI/OSIRIS/NIRSpec/NIFS etc.), ~300 high-z galaxies measured in 300 nights of observing. KMOS offers a factor of 20 increase in survey speed => statistical studies of kinematics at high redshift

German KMOS GTO science program

KMOS^{3D}

- PIs: Förster Schreiber/Wilman
- spatially-resolved ionized gas kinematics for emission line galaxies in extragalactic deep fields at $1 < z < 3$ in the *YJ*, *H*, and *K* bands

KMOS Cluster Survey and VIRIAL surveys

- PIs: Bender/Davies and Mendel/Saglia
- stellar kinematics and rest-frame optical spectra for passive galaxies at $z > 1.5$ using very long integrations (20+ hours)

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KMOS Cluster Survey and VIRIAL surveys

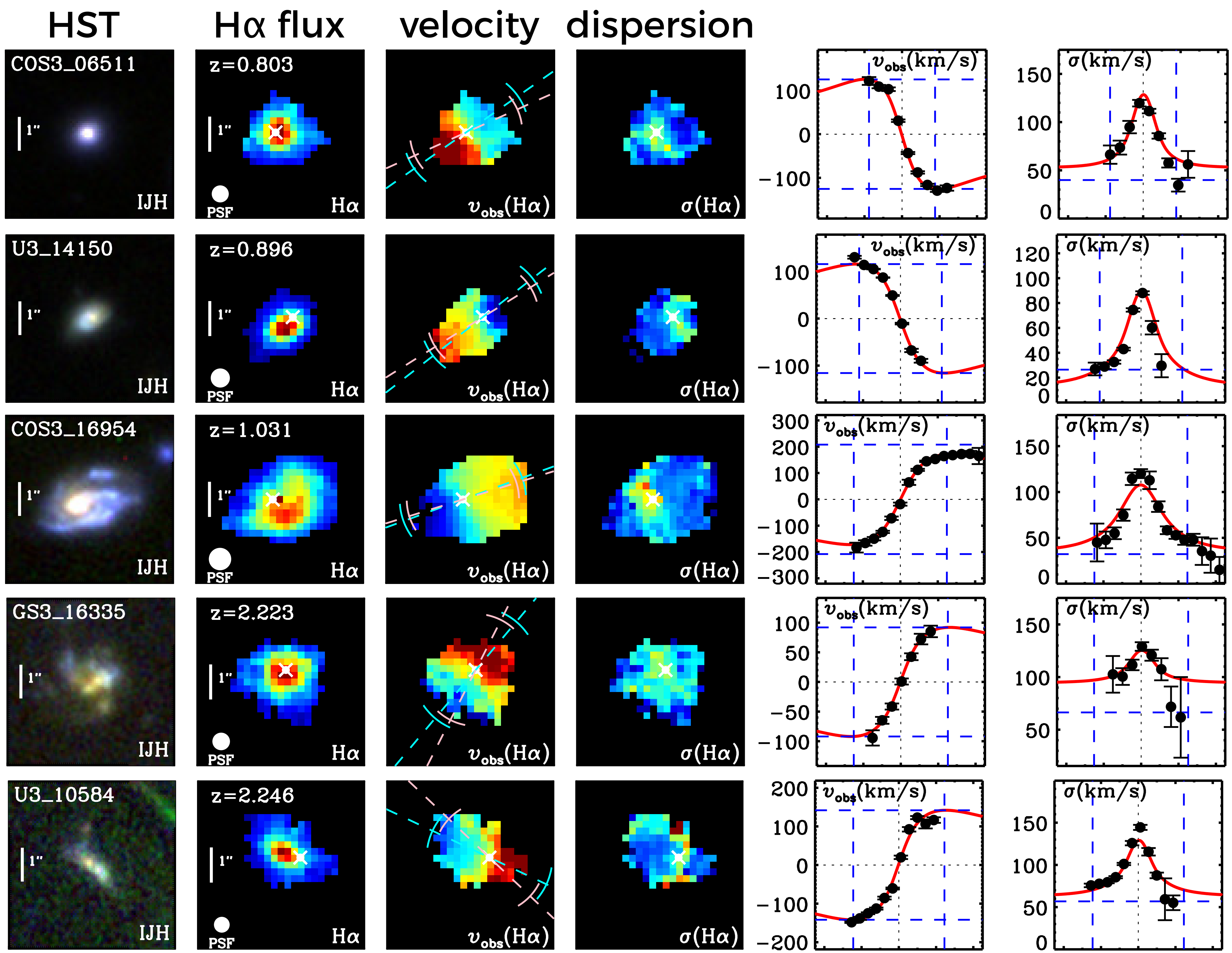
- PIs: Bender/Davies and Mendel/Saglia
- stellar kinematics and rest-frame optical spectra for passive galaxies at $z > 1.5$ using very long integrations (20+ hours)

1) Reliable registration of individual exposures / nights / runs to preserve spatial information in kinematic maps

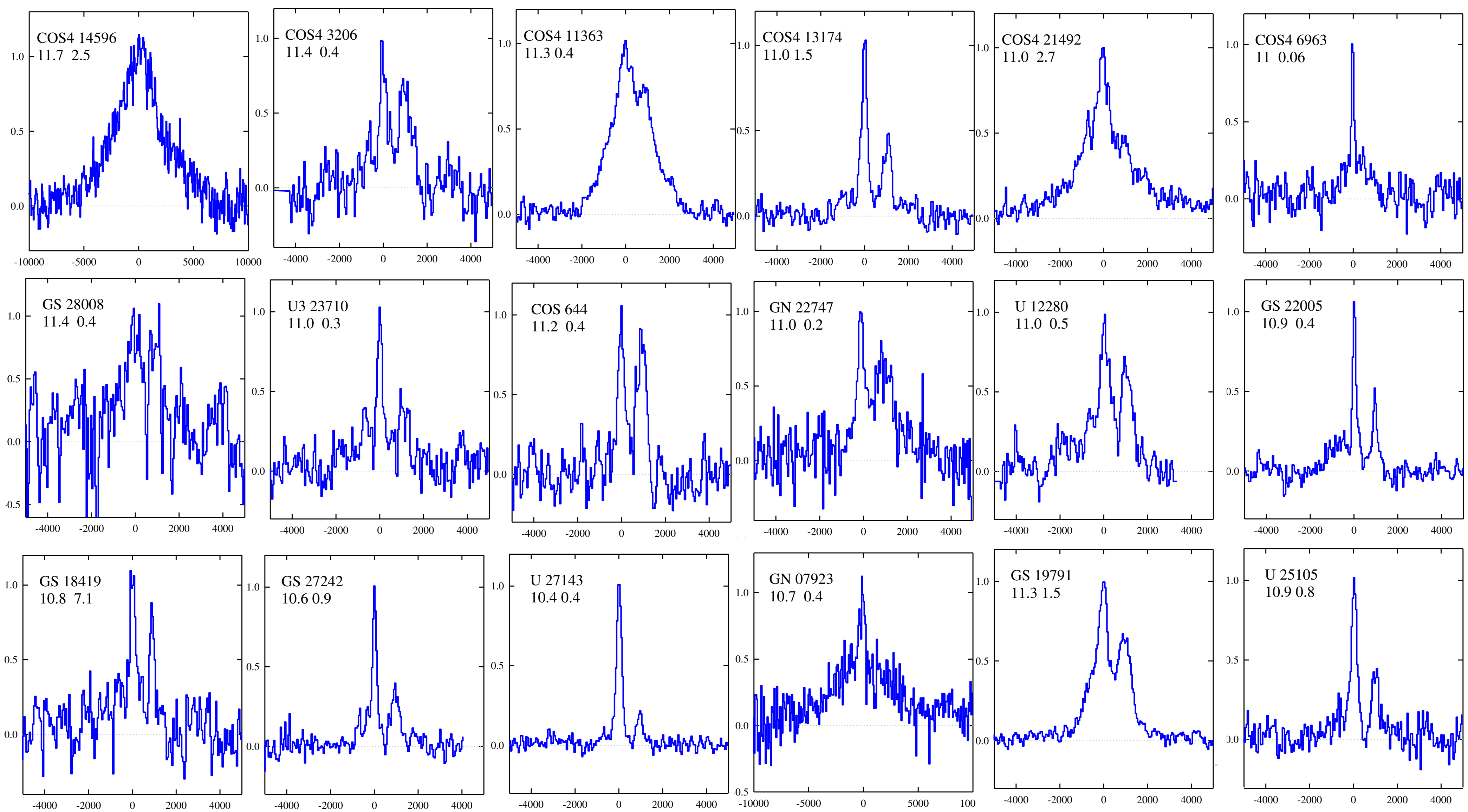
2) Reliable sky subtraction and telluric correction

3) Minimize systematic effects for long exposures

Flux and Kinematic maps from KMOS^{3D}

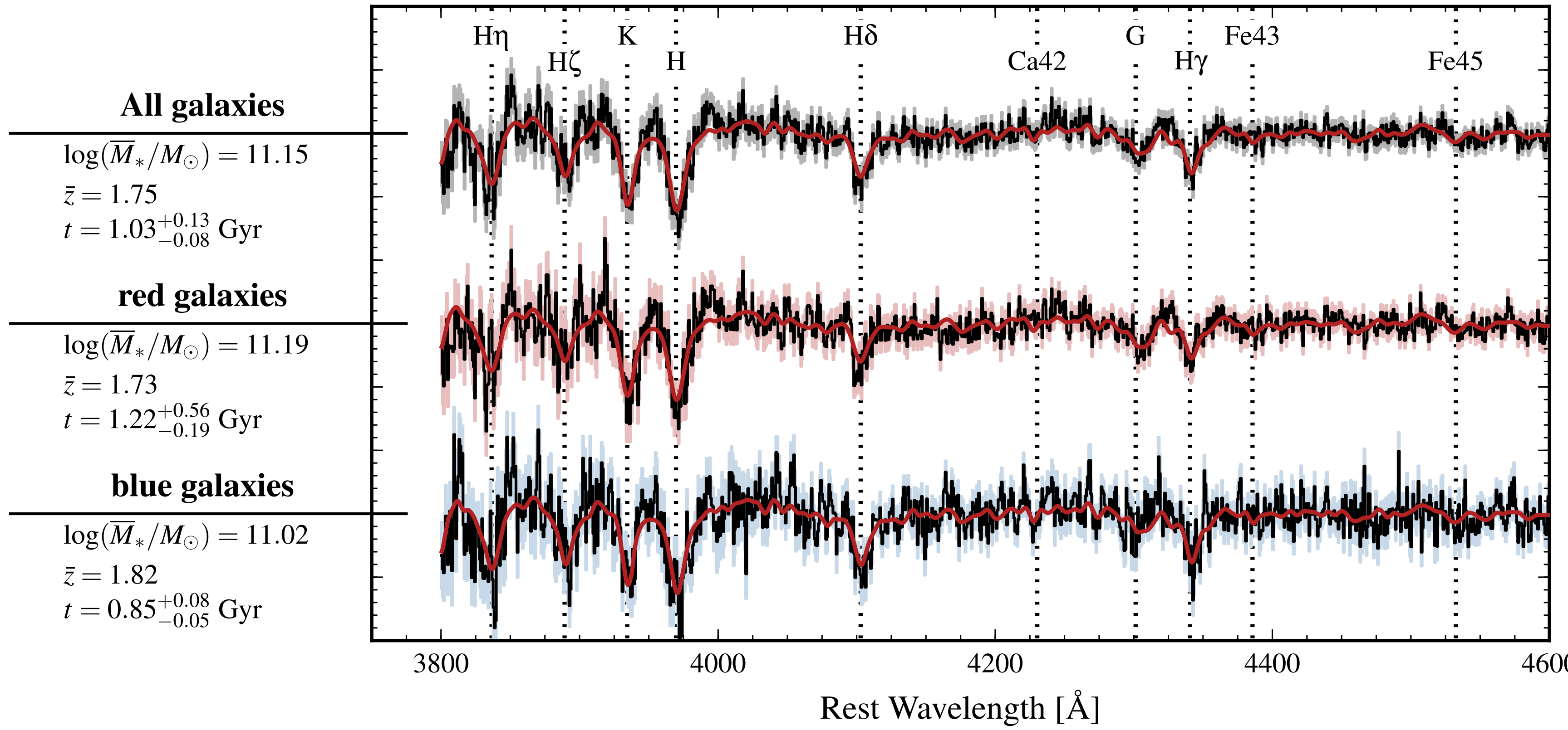


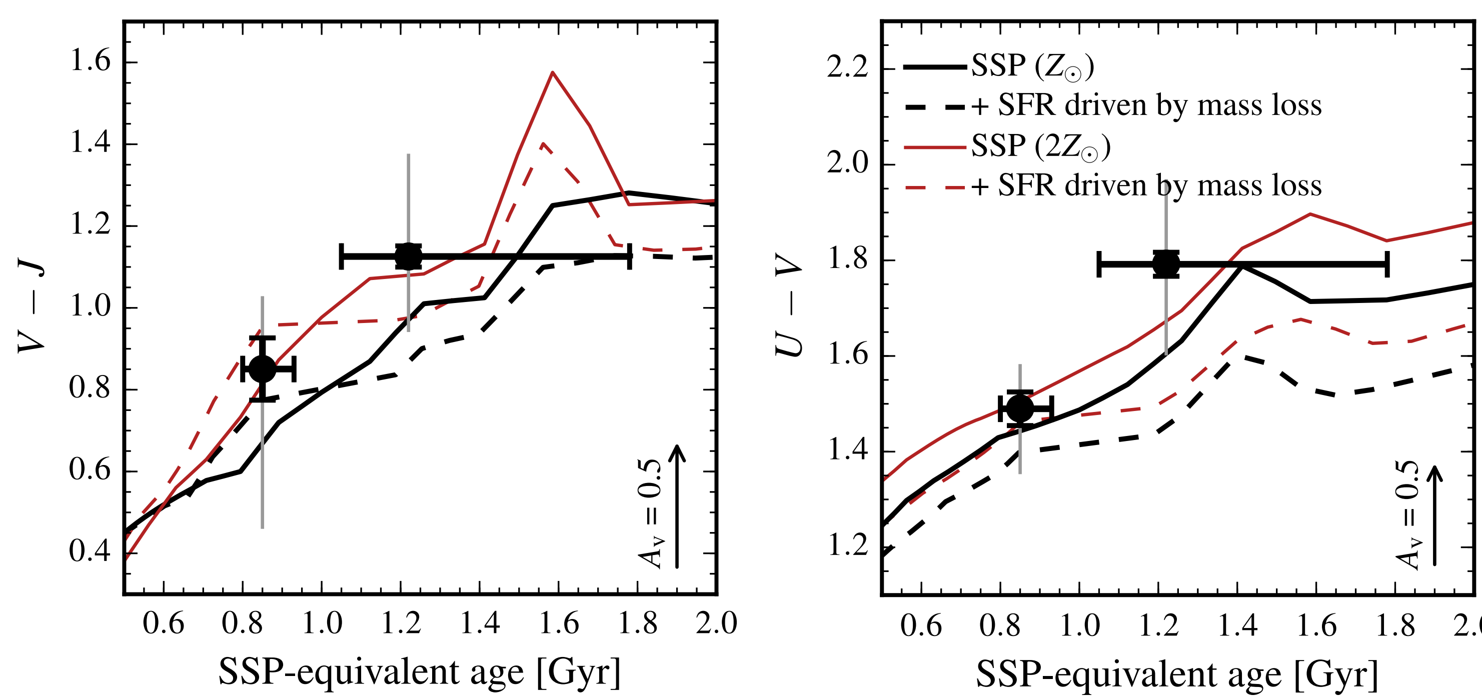
Detection of broad outflow components



 Genzel et al. 2015

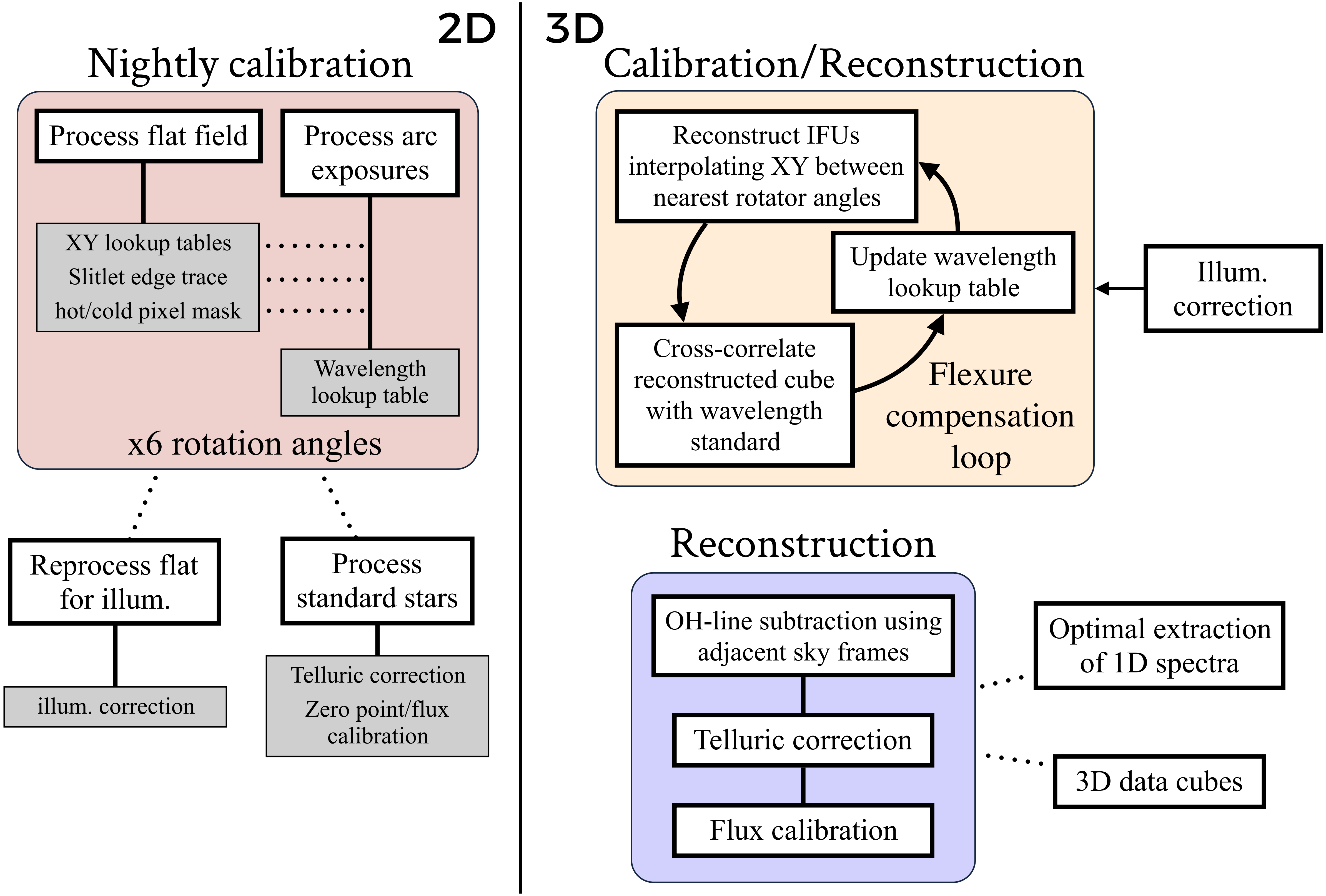
Stellar populations of passive galaxies at z~1.75





Mendel et al. 2015

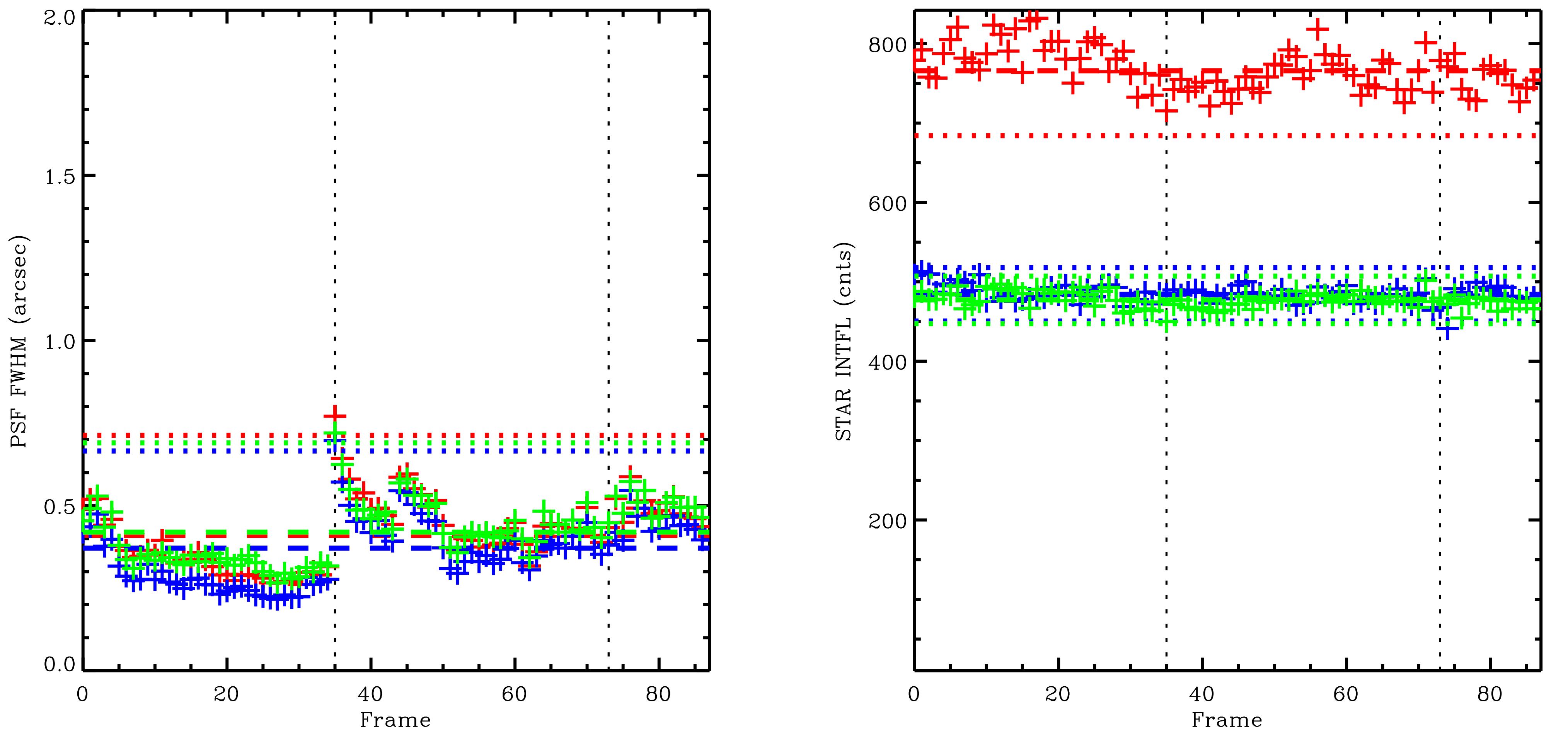
Standard KMOS data processing



On-sky monitoring

Include contemporaneous observation of stars in arm configuration

- 3 arms dedicated to stars (1 per detector)
- Used to monitor telescope tracking, dither pattern, PSF, throughput, telluric



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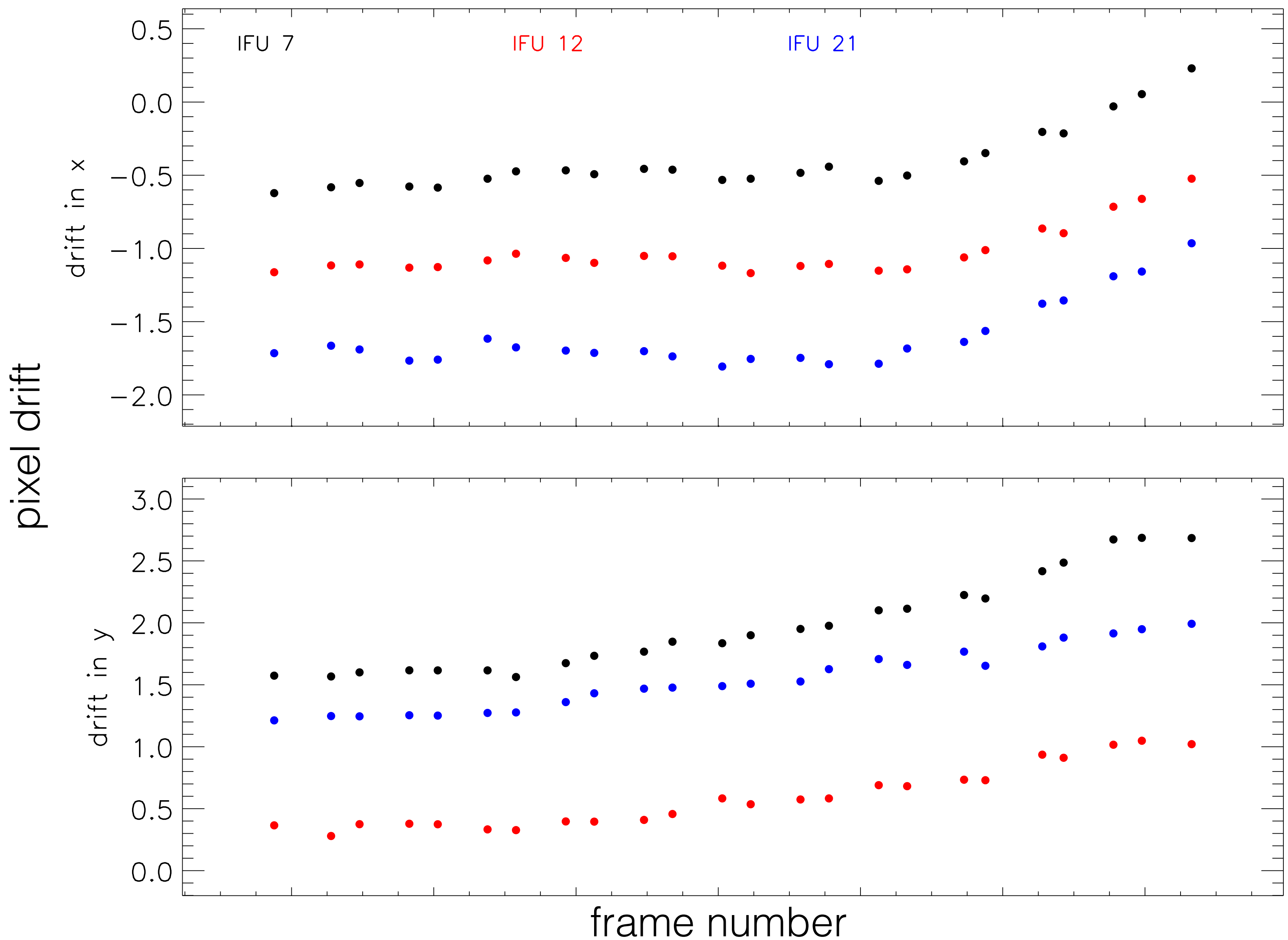
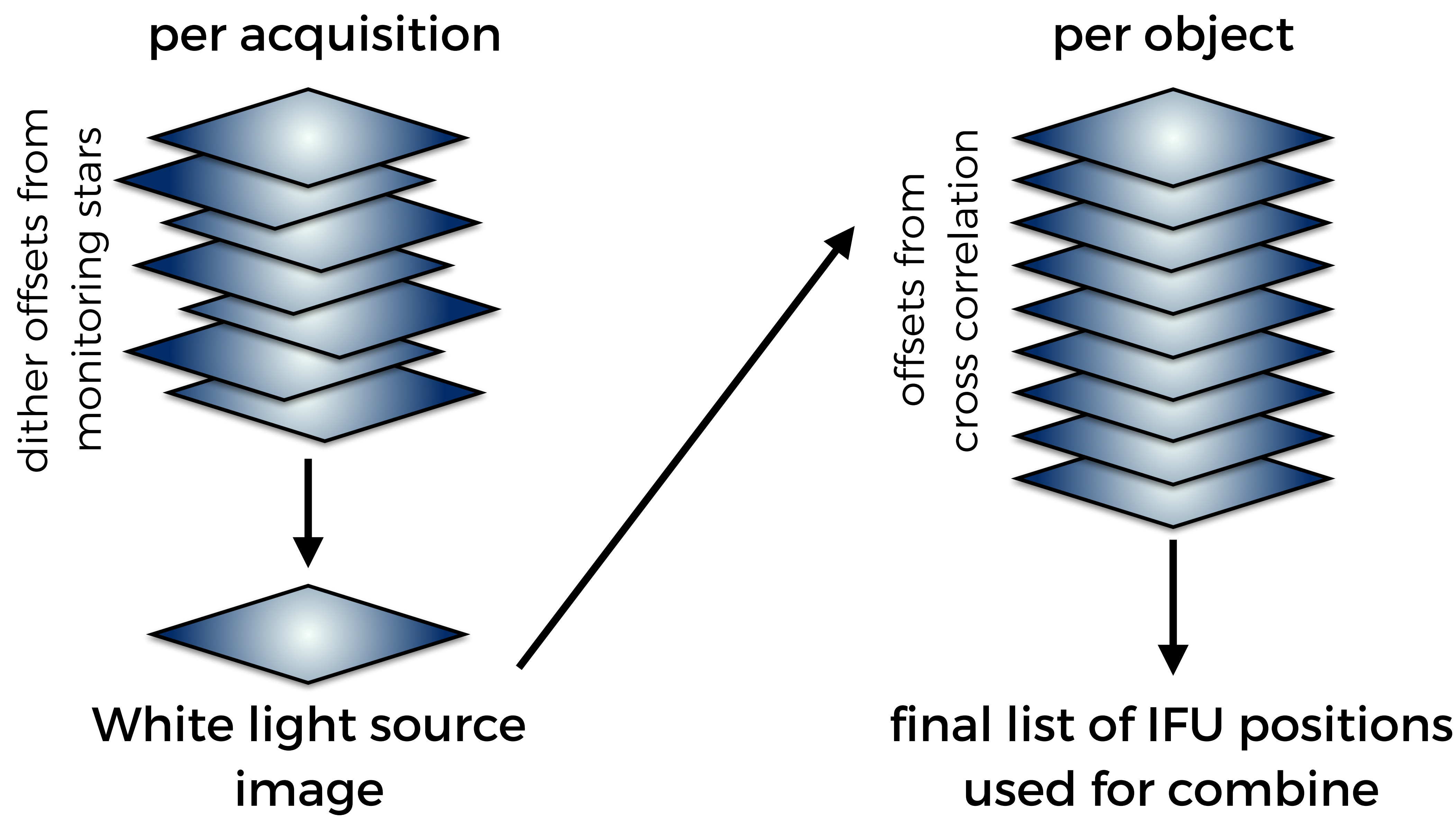


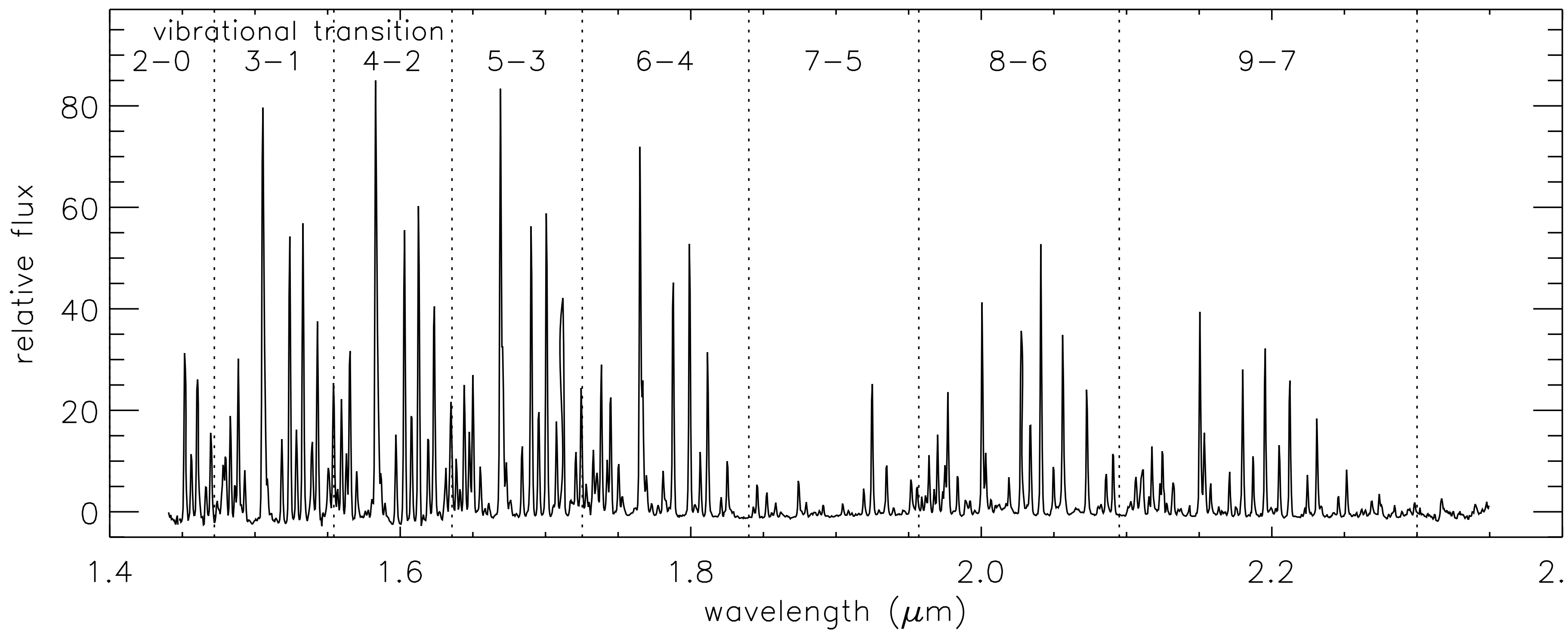
IFU registration and shifts

Relative arm positions change with re-configurations/rotation

- use monitoring stars to track the telescope dither pattern for each acquisition
- cross-correlate white-light images from each acquisition to derive final shifts on an object-by-object basis



Sky subtraction



Small IFU size (2.8”x2.8”) means we always use offset sky frames

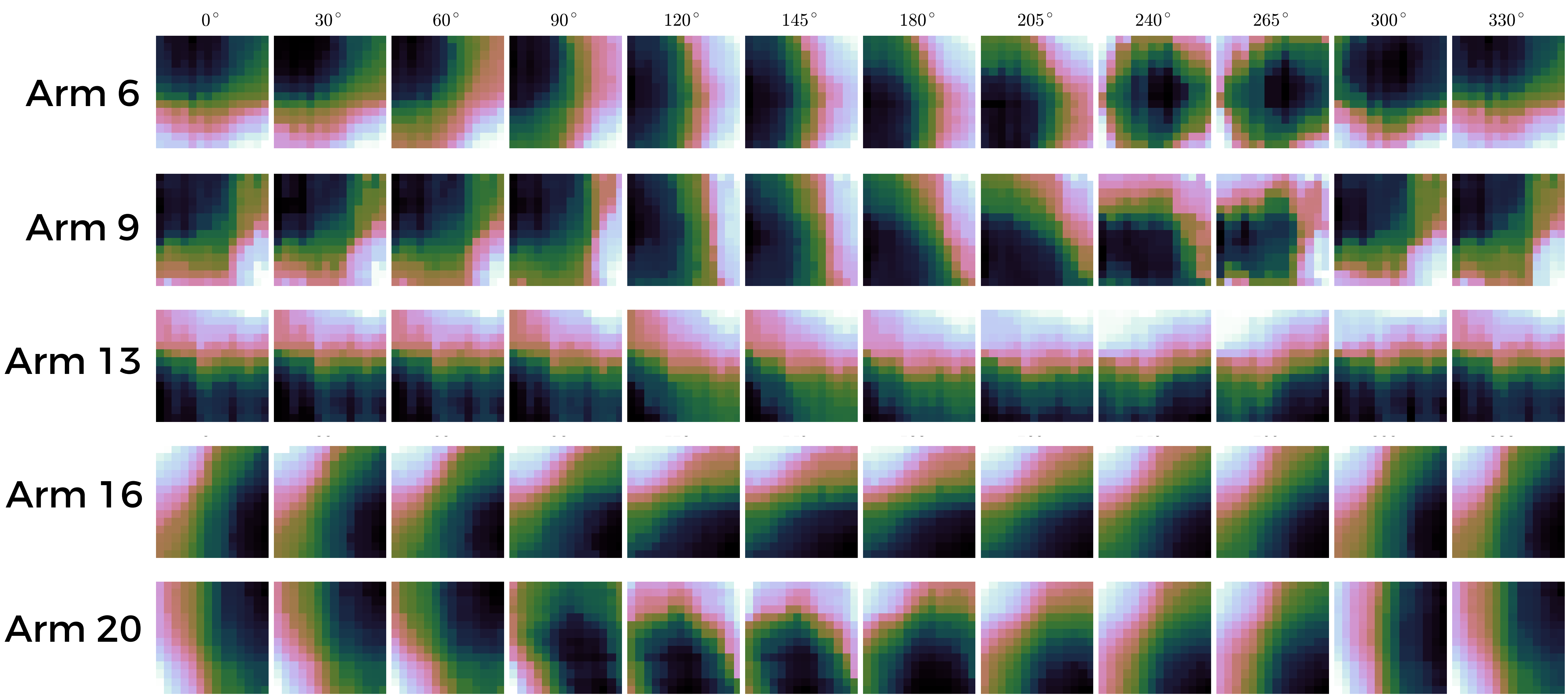
- Sky rescaled by dividing the spectrum into different transitions and fitting for variability of the OH line flux
- Modified to include an adaptive shift-and-stretch of the relative wavelength solutions (also now implemented in the ESO pipeline)

 Davies et al. 2007

Correcting for IFU illumination

Variation in the IFU illumination as a function instrument rotation

- changes of up to 2-5% across individual IFUS, 10-20% between IFUs
- in some cases jumps between calibration angles make it difficult to predict



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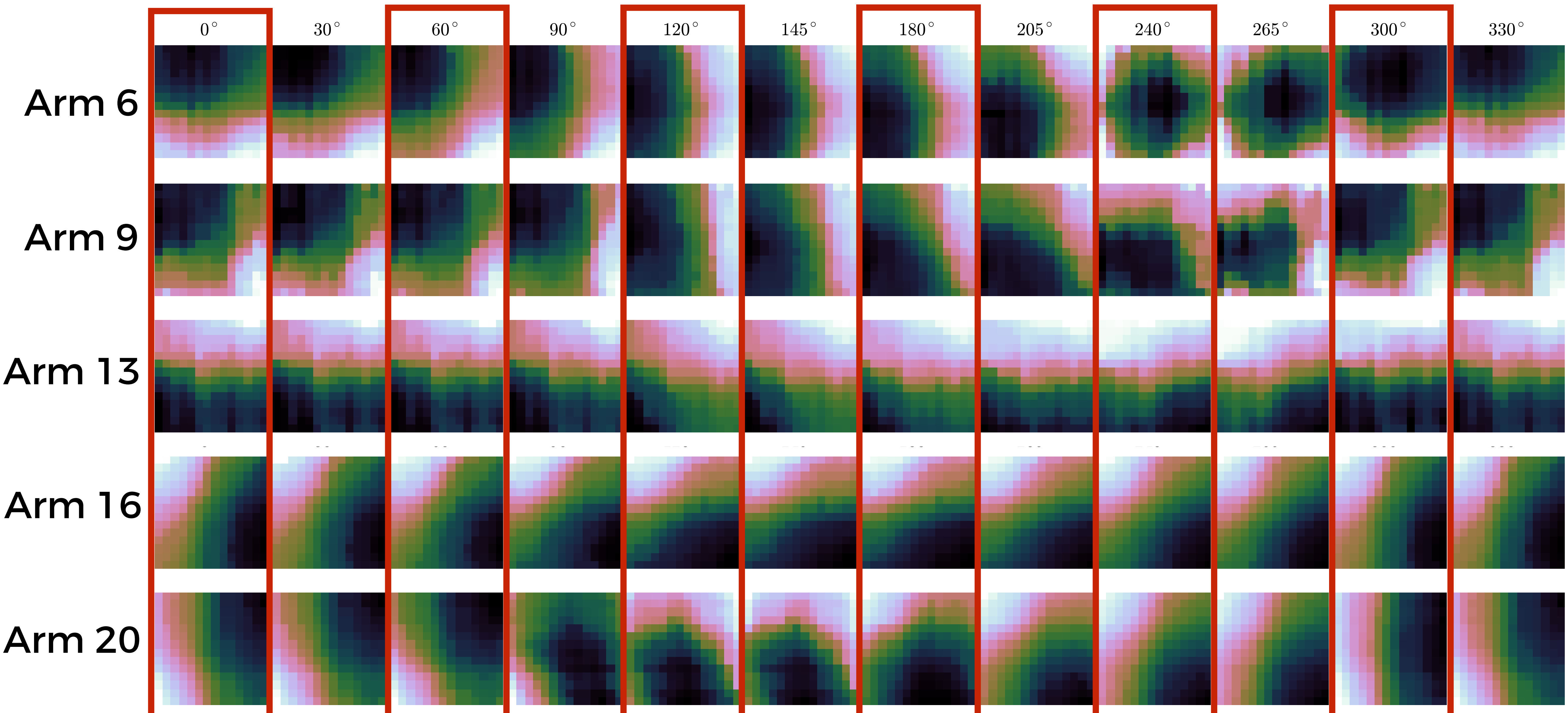
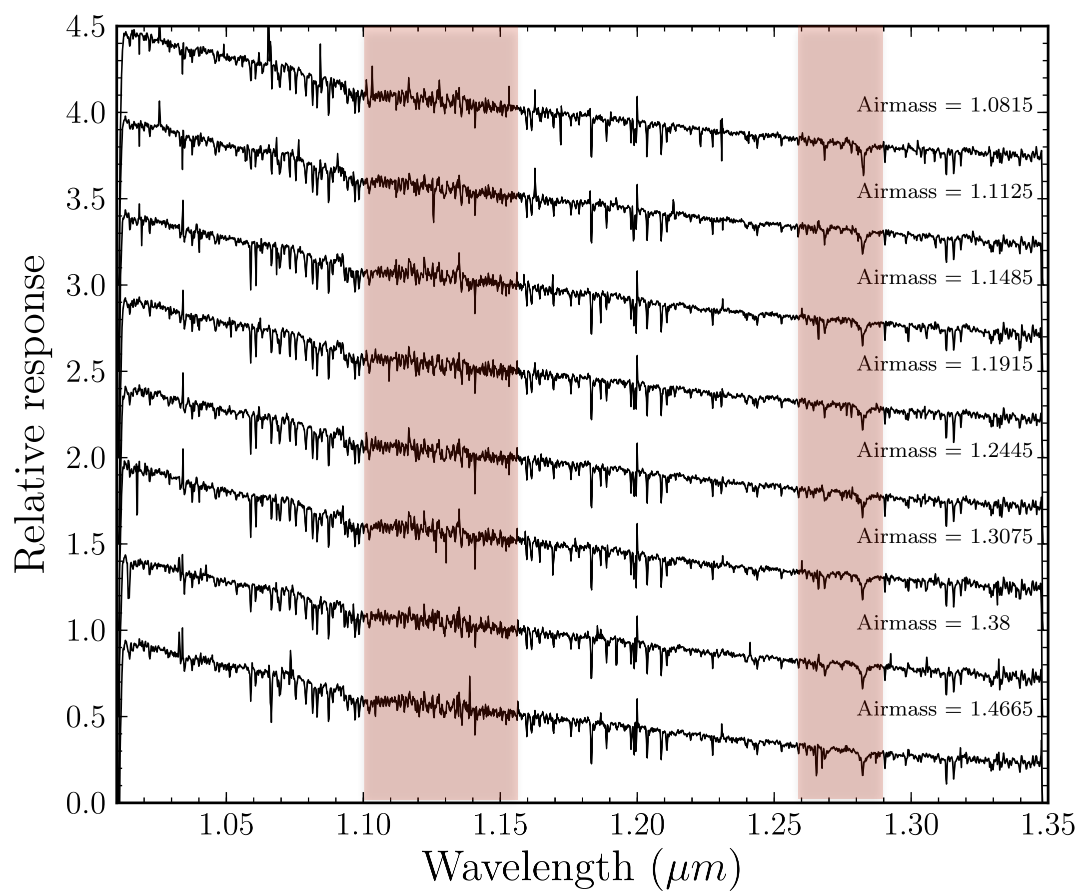


Telluric correction

Telluric calibration scheme based on adapting radiative transfer model from LBLRTM/Molecfit to match standard star observations

- Observe 2-3 telluric standards per night to calibrate PWV relative to atmospheric model for Paranal
- Once calibrated, we fix the rescaling of PWV (optionally as a function of time) and use the (time-dependent) atmospheric parameters to predict the atmospheric correction for every frame



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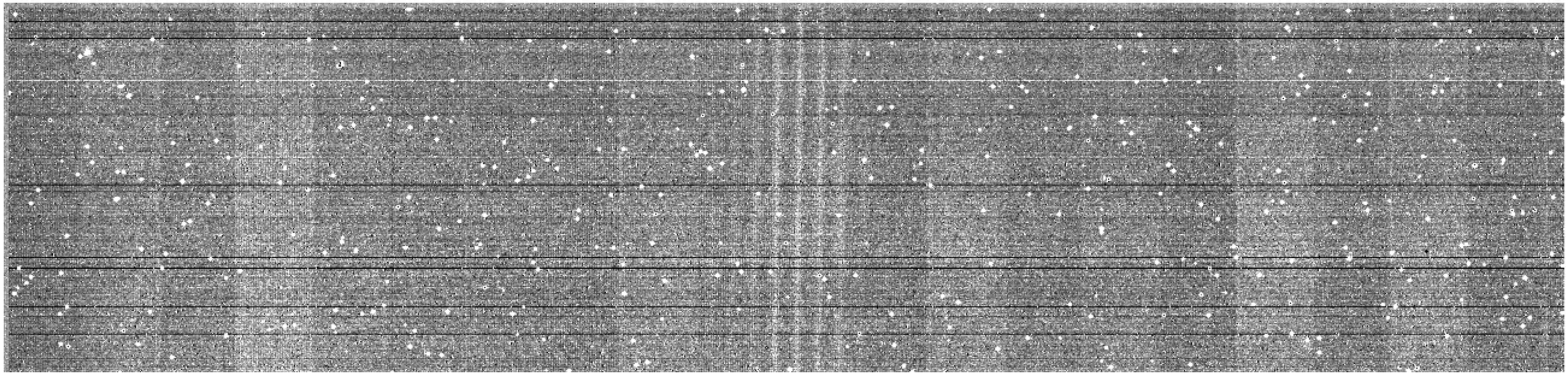
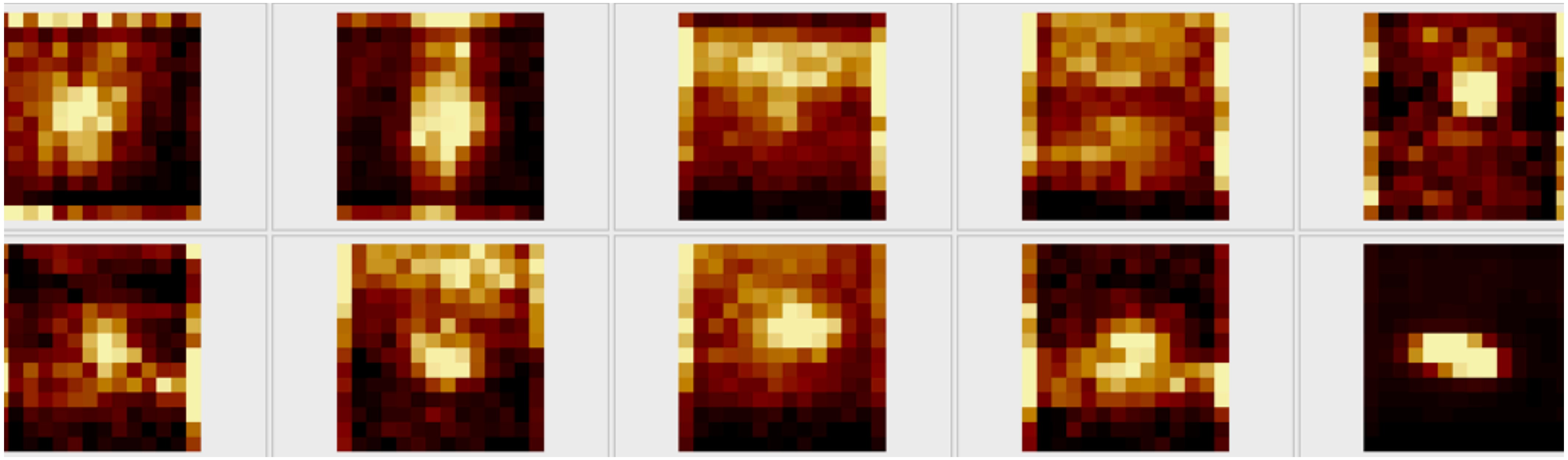
Still some challenges for a consistently good telluric correction

- Need a good model for the PSF
- Requires validation with bright enough monitoring stars to assess correction, but not so bright as to cause additional detector-level problems
- Still need to figure out how best to monitor arm-to-arm variation in instrument response

Output channel drift

Bias level drift on each of the 32 output channels leads to striping in reconstructed data





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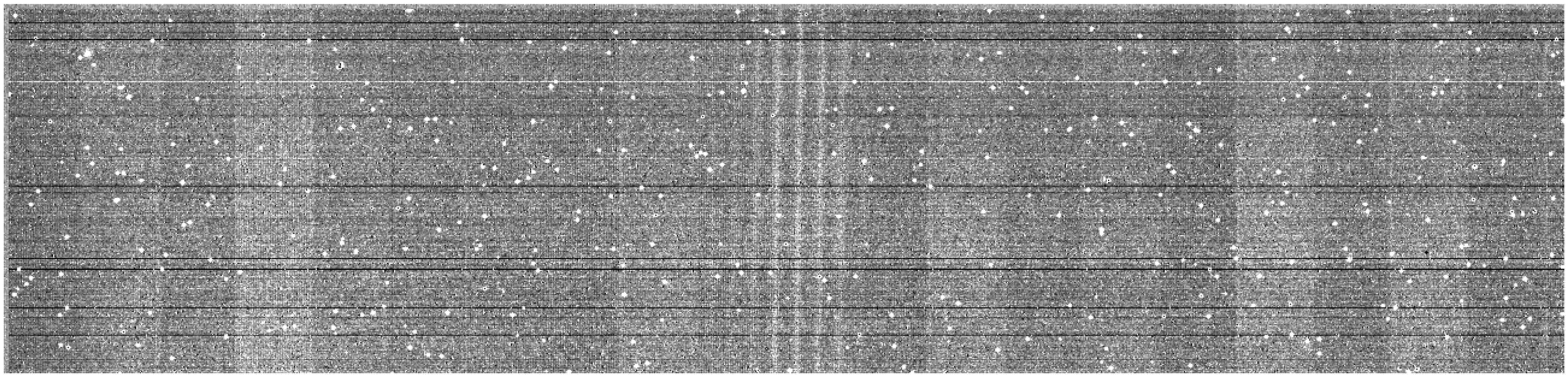
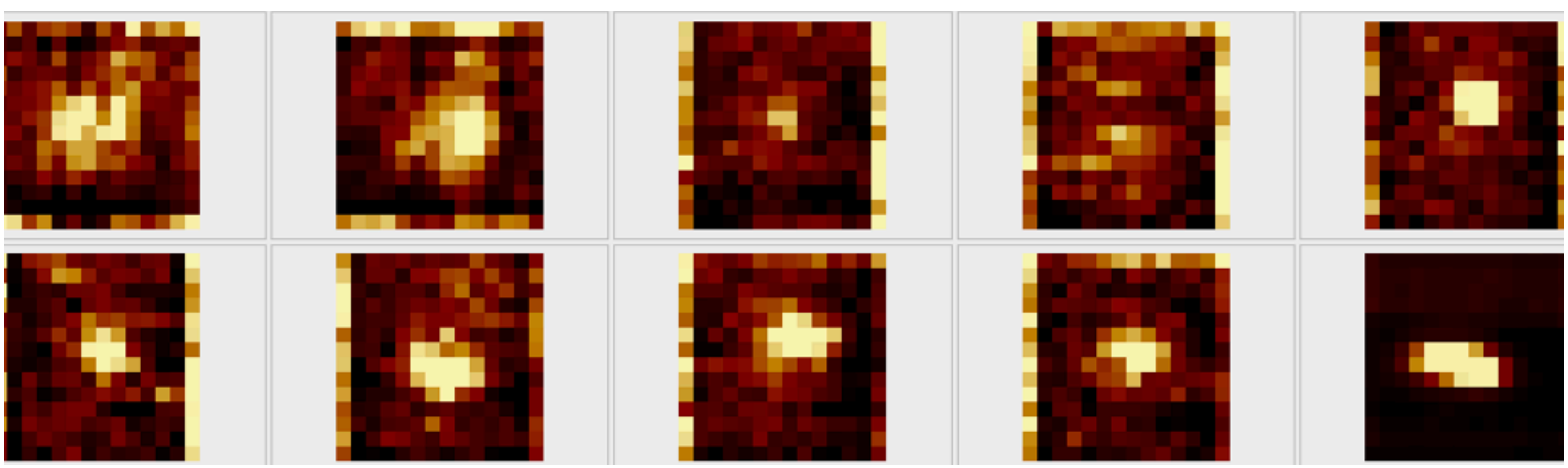
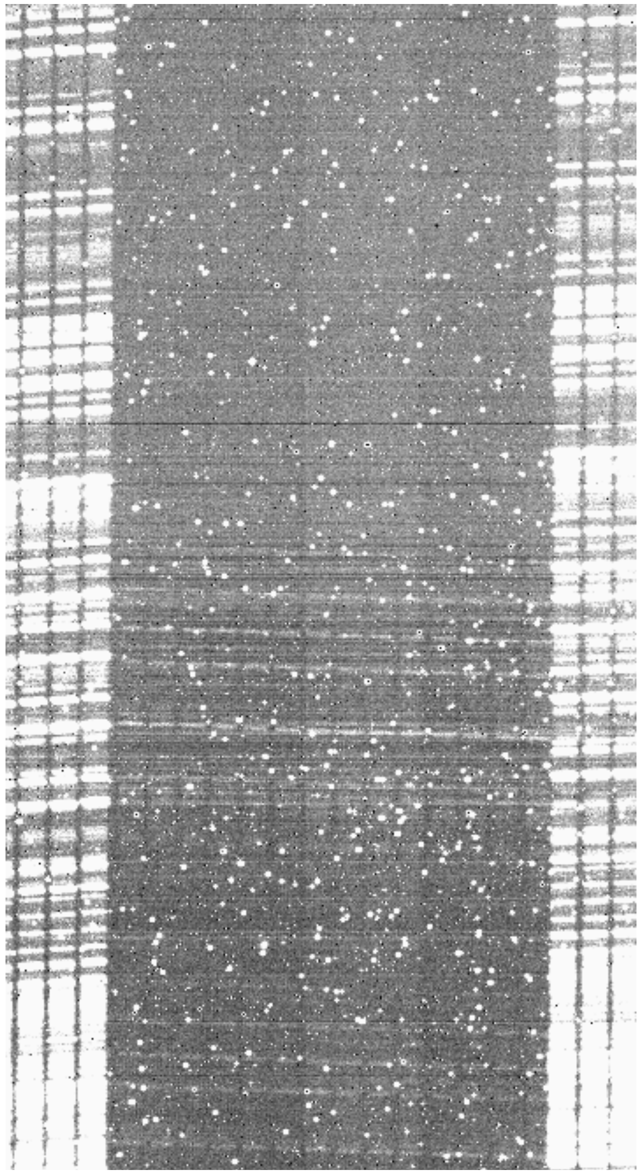




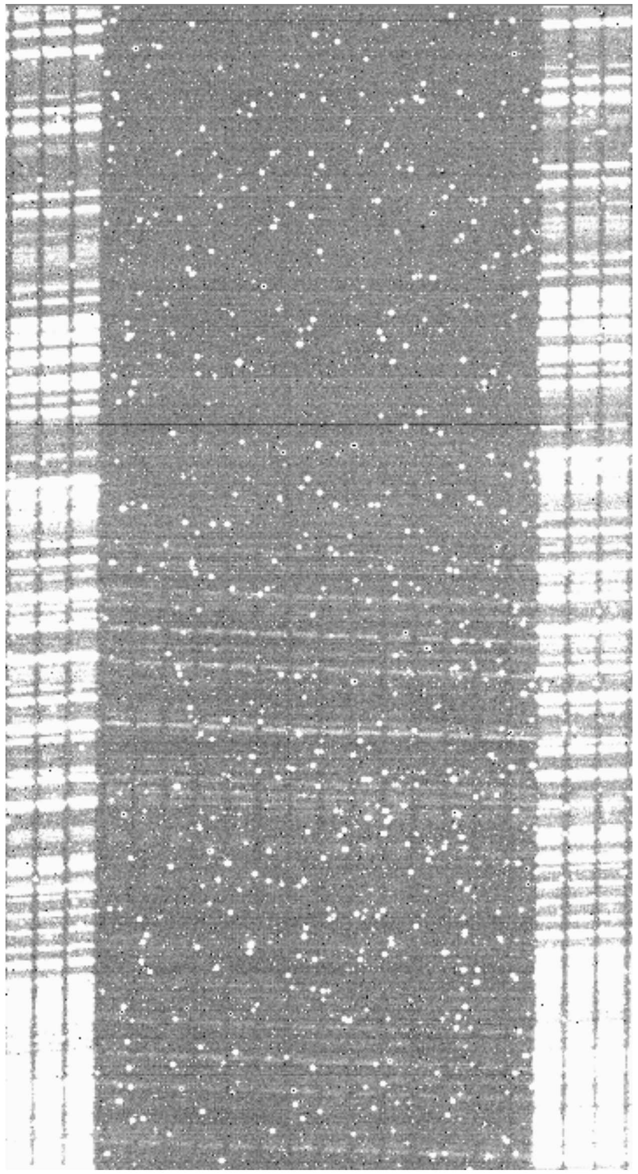
Output channel drift

Unknown but correctable(-ish) vertical structure in detector 1, possibly related to processing by the read/control electronics on detectors with “bad” reference pixels

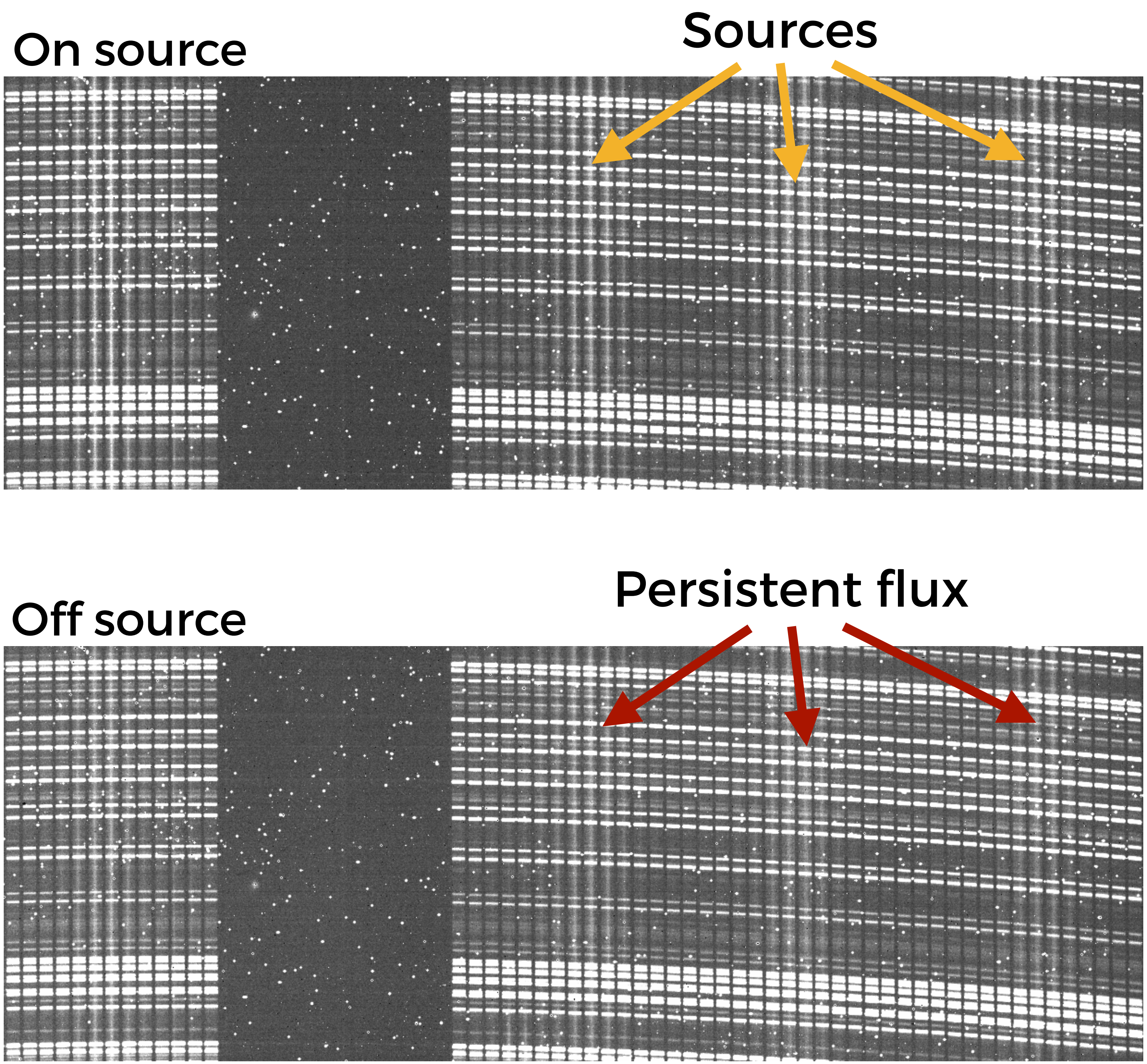
before correction



after correction

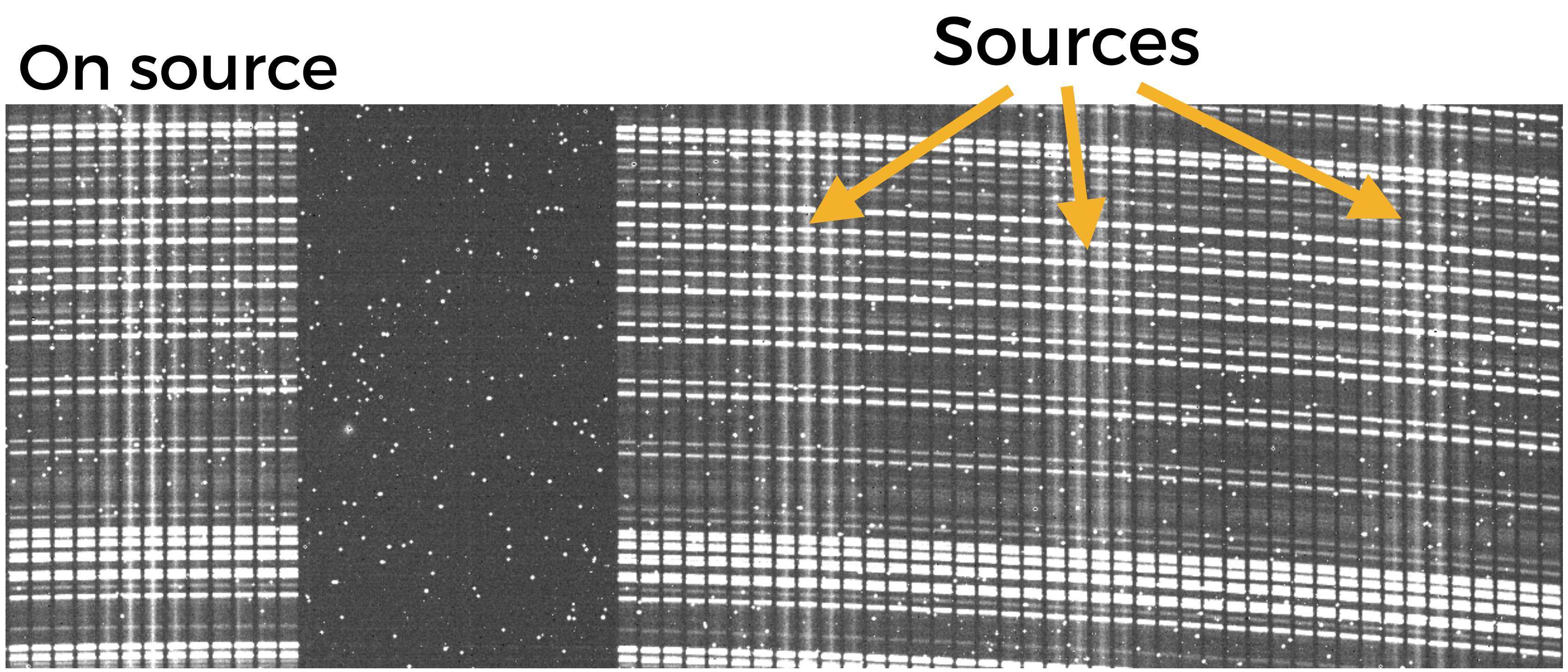


Persistence (again)

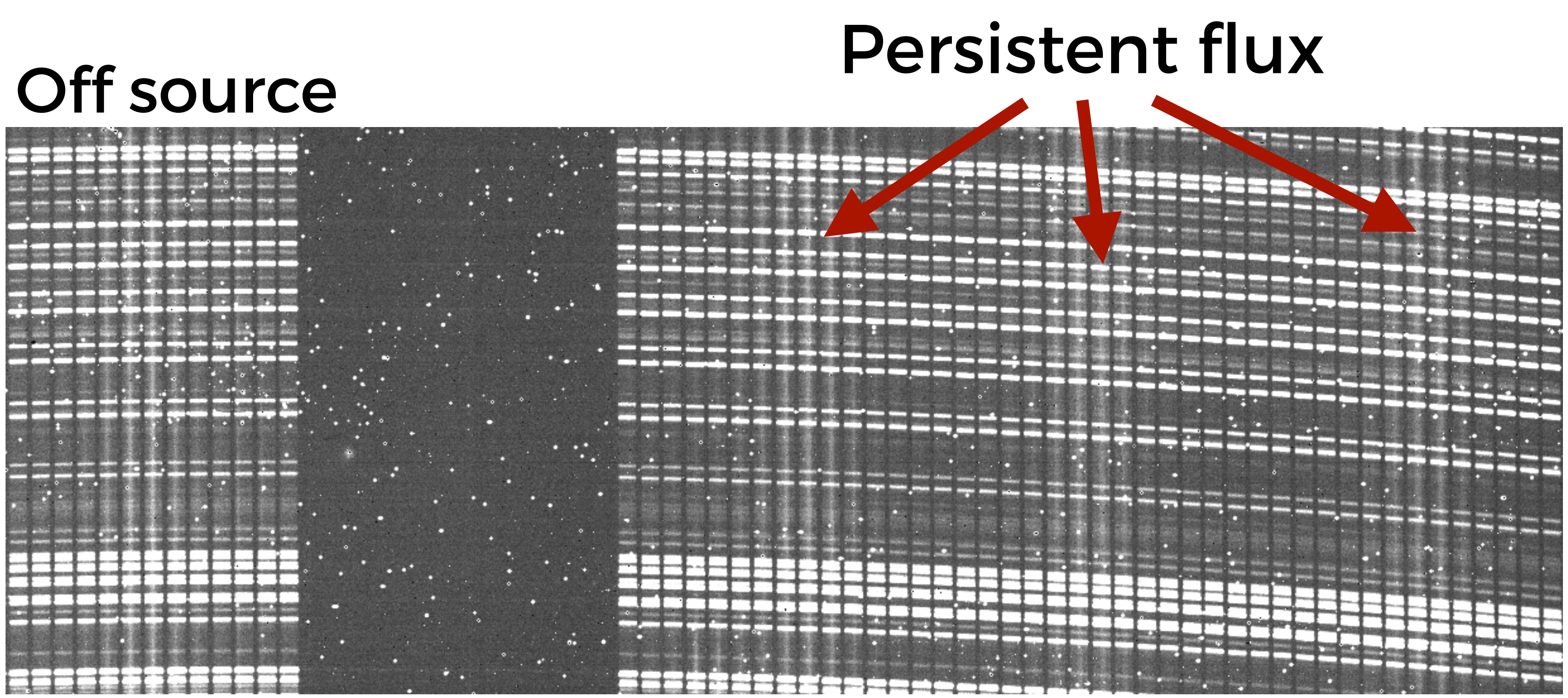


Persistence (again)

On source



Off source



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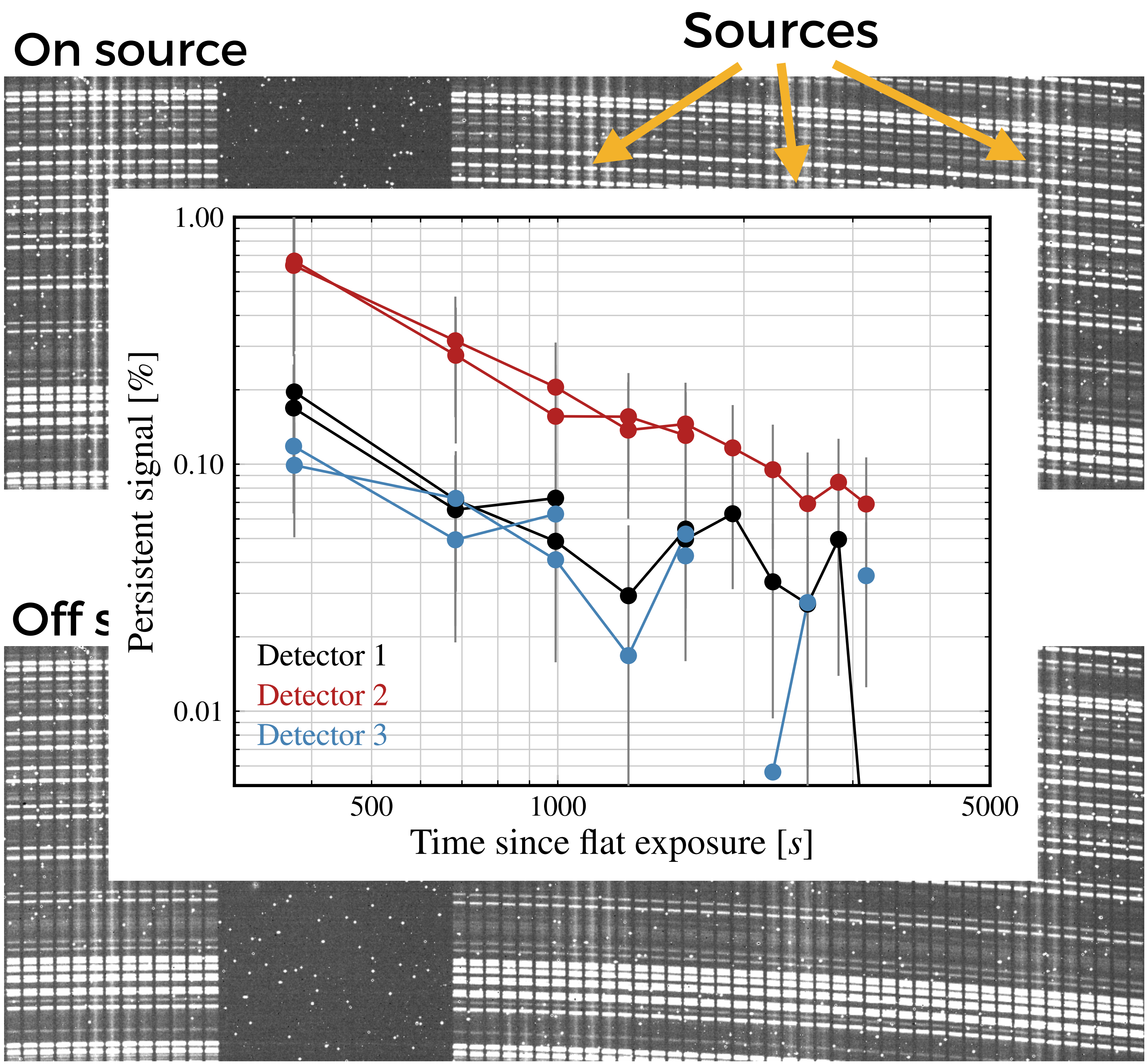
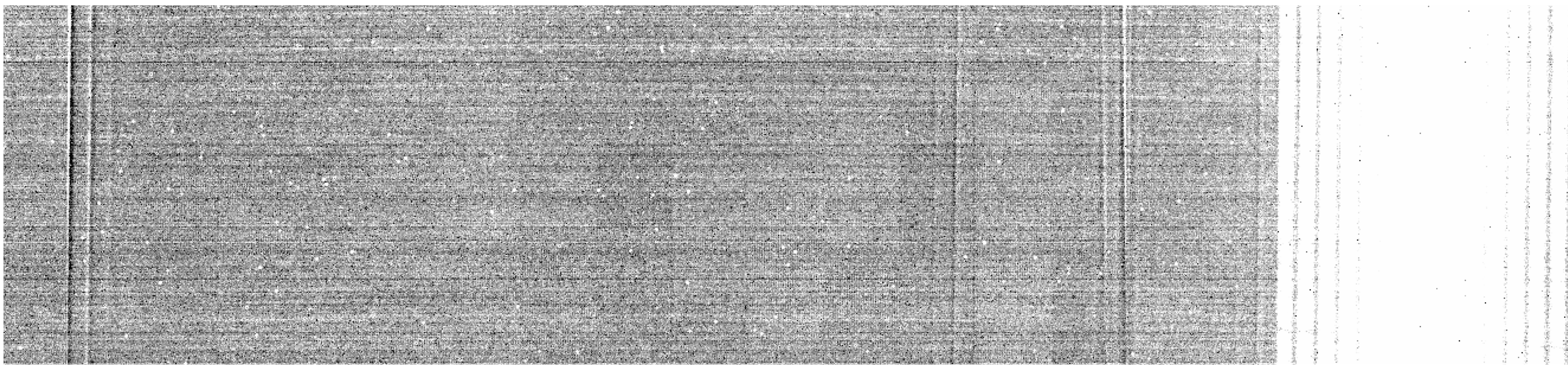


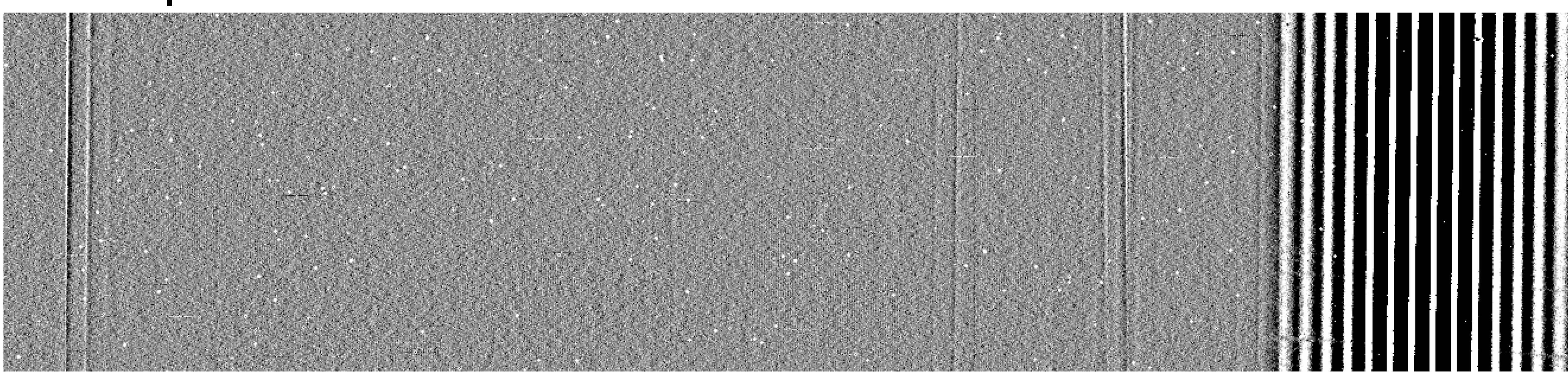
Inter-channel crosstalk

Capacitive coupling between different read channels at the ~sub percent level, but nevertheless important when dynamic range is large

Raw frame



Unsharp masked



Can these effects be calibrated out?

Row and column corrections

- Reference pixel correction now implemented in ESO KMOS pipeline.
- Useful to understand cause of detector 1 row offsets to ensure that the correction is not unnecessarily boosting noise.

Persistence corrections

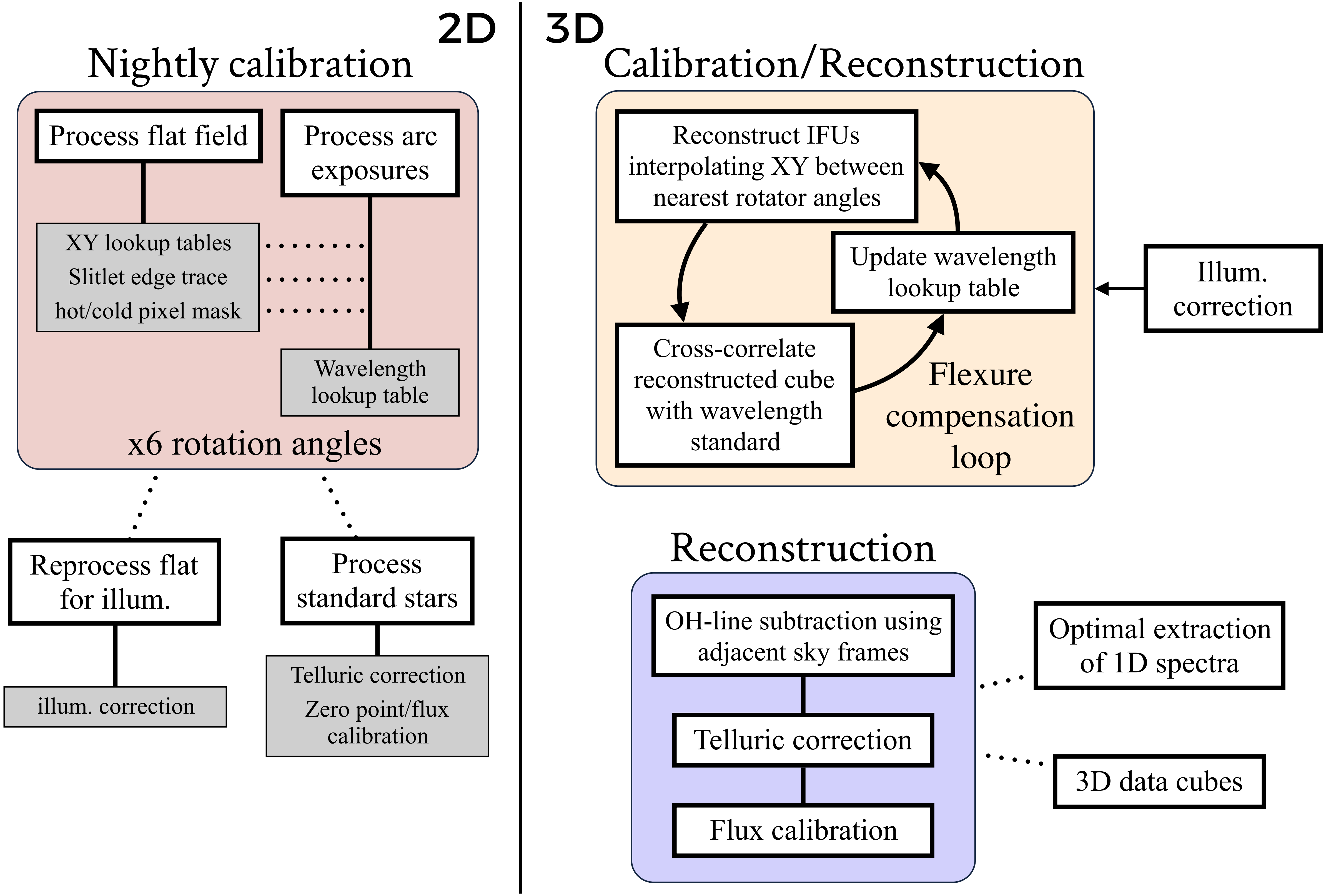
- Can be characterized using long flat + dark sequence to measure decay rate.
- Requires a better model for the dependence of persistent flux on source flux
- Can be somewhat mitigated by exposure tracking or global reset de-trapping?

Crosstalk calibration

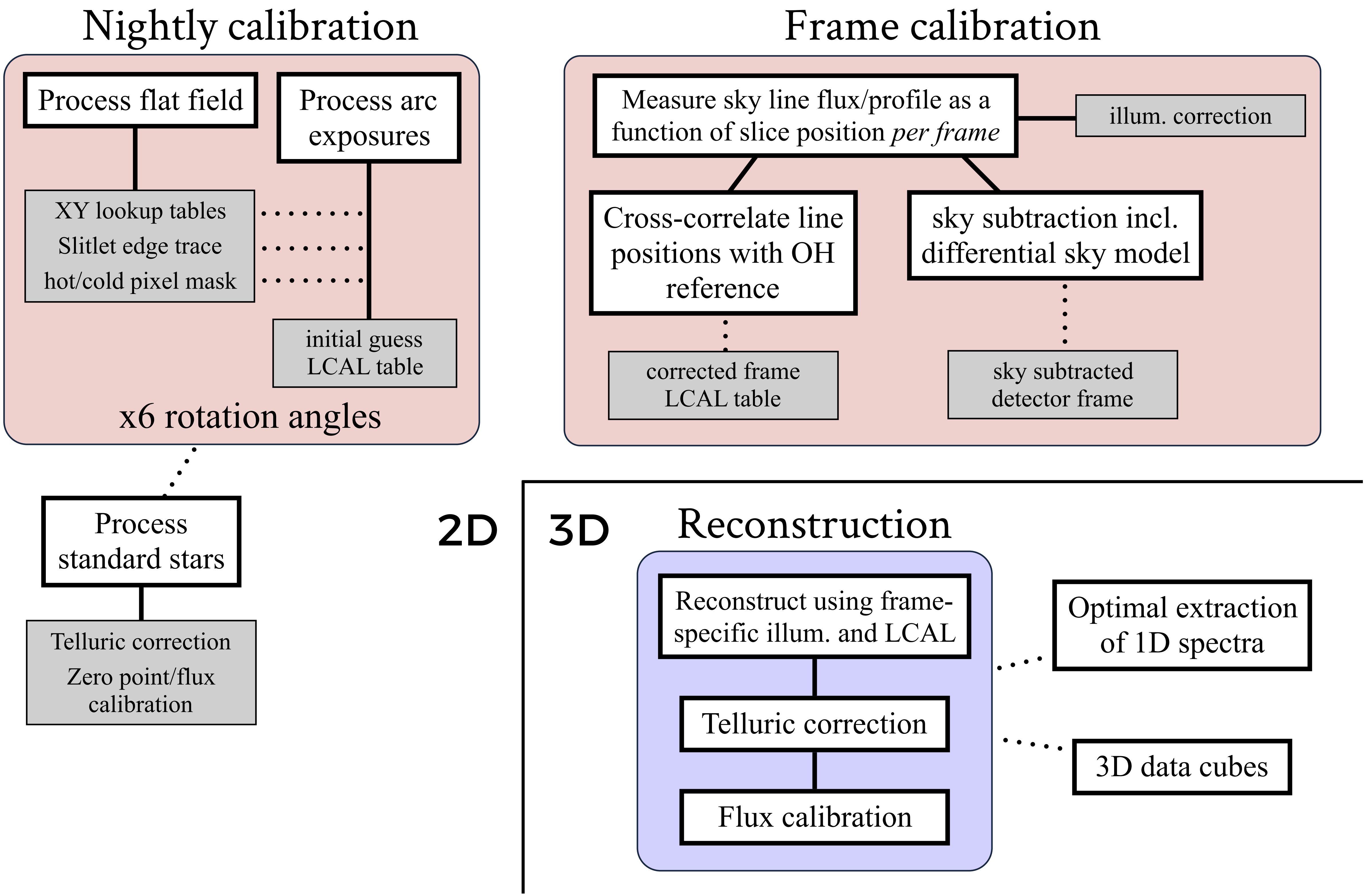
- Coupling coefficients can be measured from standard star frames, but requires nodding to cover all output channels.
- Non-trivial to implement correction without a good source model, but likely worthwhile for exposures with large dynamic range (or extremely faint objects).

Extensions/adaptations of the existing pipeline

Moving from cube- to detector-based processing



Moving from cube- to detector-based processing



Moving from cube- to detector-based processing

Motivation

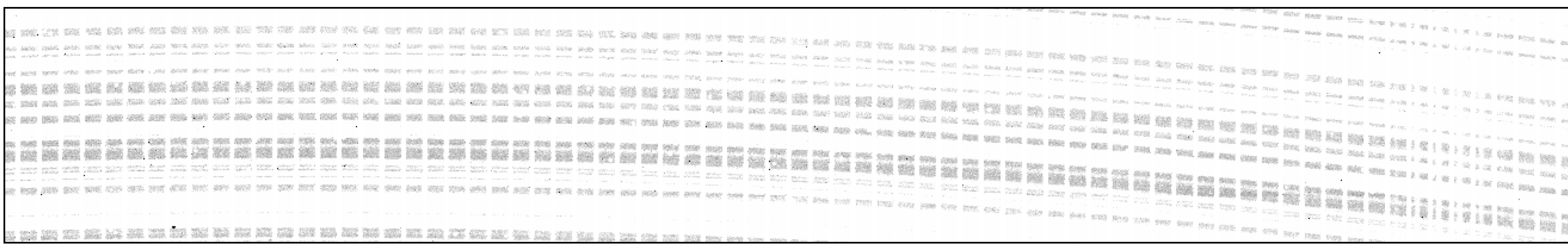
- Fewer operations on reconstructed data, more straightforward error handling and propagation
- better handling of detector-level effects (e.g. row/column drift, reflections)
- build frame-specific illumination and wavelength corrections which deal with mismatched calibration angles
- theoretically enables simultaneous reconstruction of all data for a given object, as opposed to reconstructing each exposure separately, then interpolating (again) to make a final cube.

Modified sky subtraction on the detector

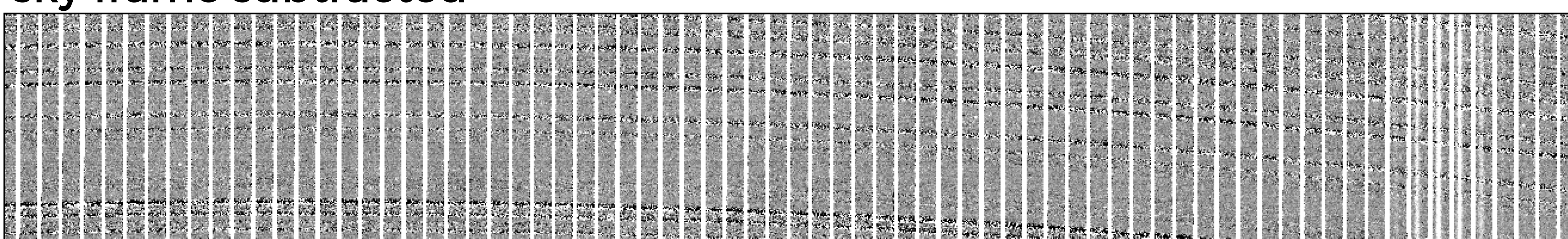
Similar concept to the Kelson et al. approach (also discussed by Igor)

- Significant slice-to-slice changes in resolution, as well as variability within each slice, make it difficult to construct a well-behaved polynomial model
- too few “clean” detector pixels per IFU to build a robust model IFU-per-IFU
- use a hybrid approach where we first subtract the sky frame, then model residuals as a function of wavelength and spectral resolution

raw detector



sky frame subtracted



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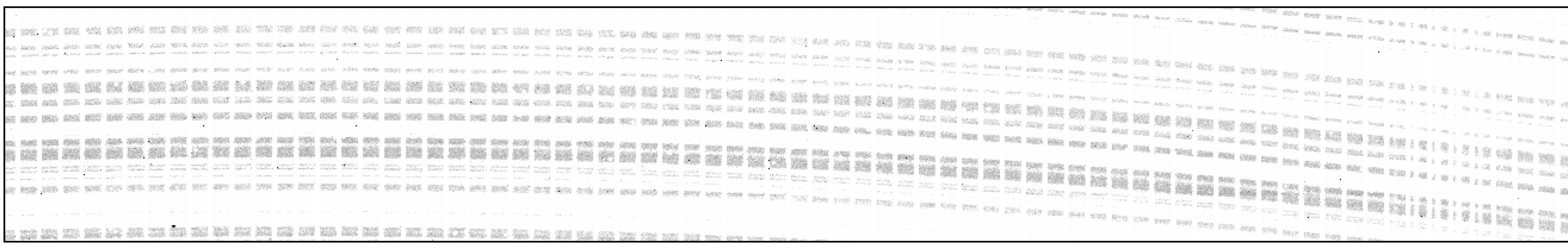
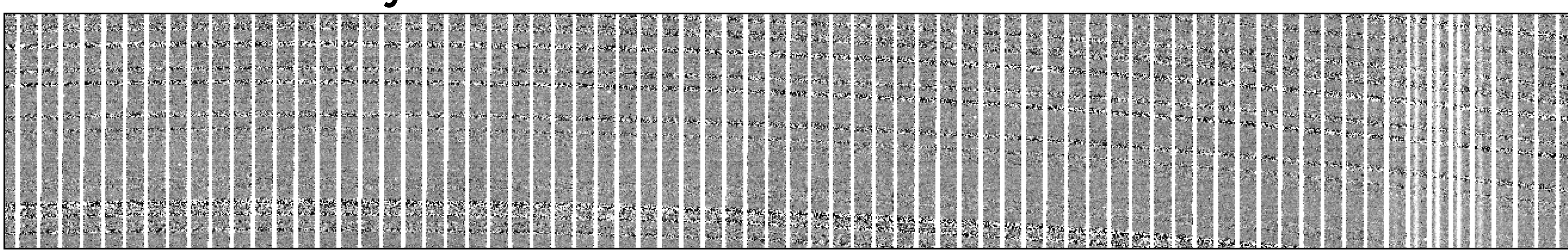


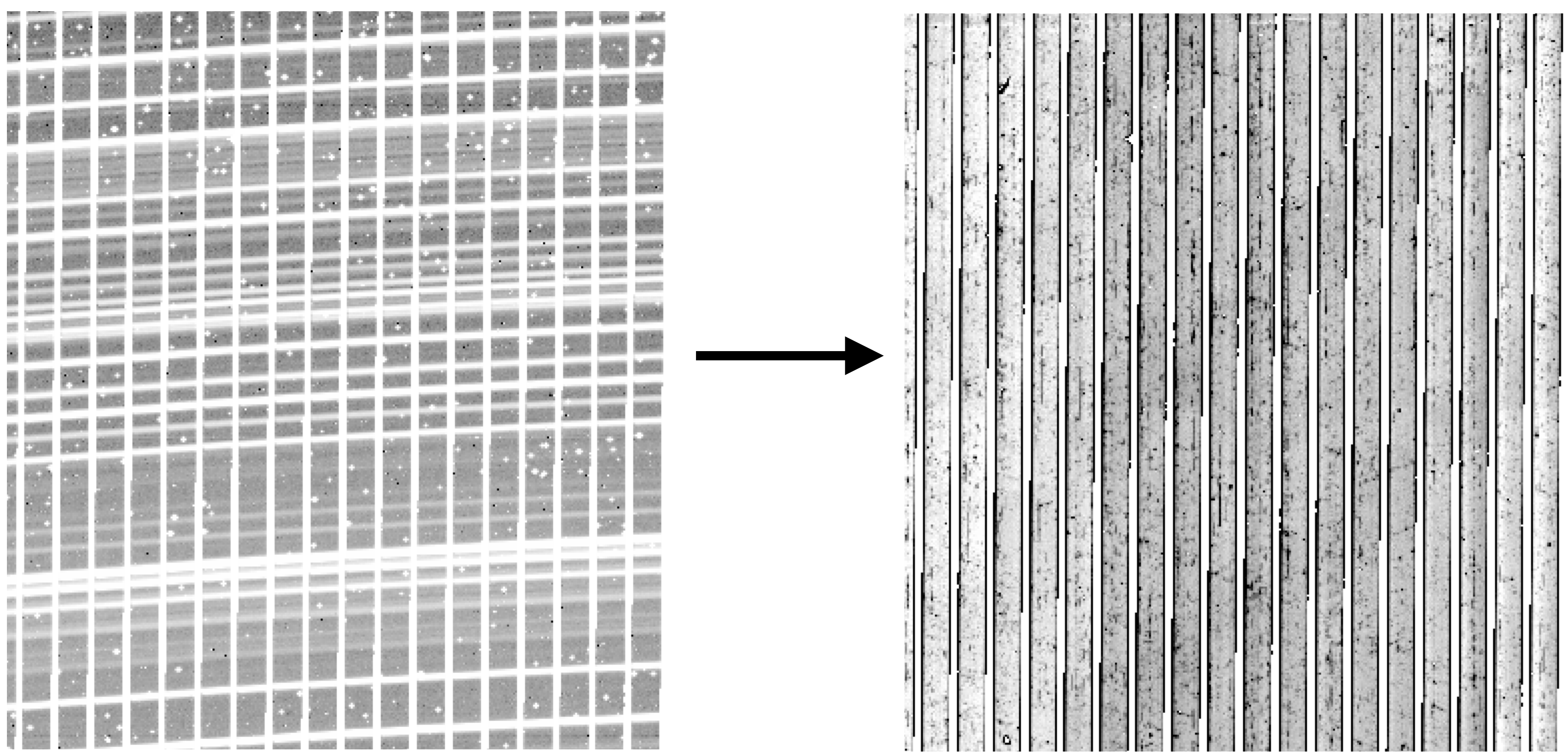
corrected with sky model



Frame-dependent illumination correction

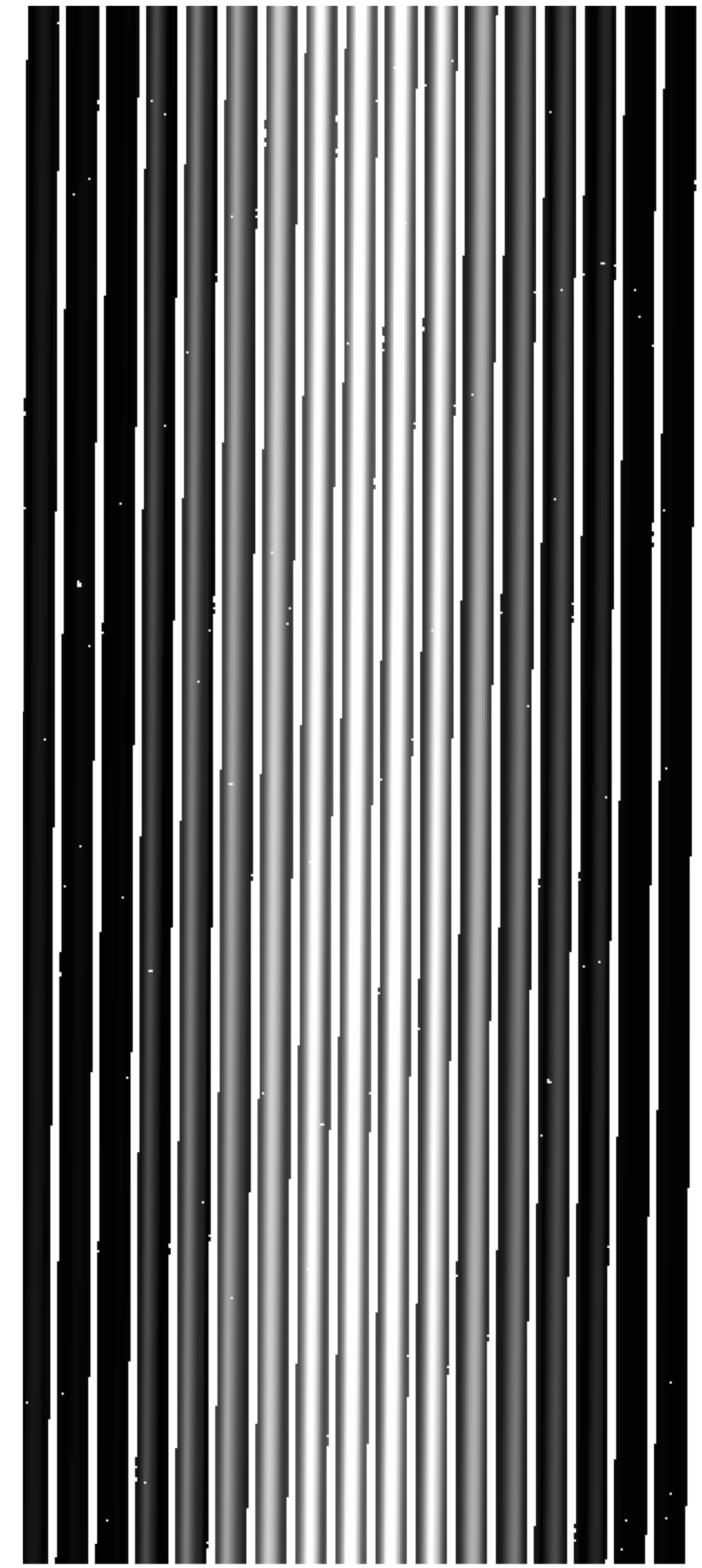
Construct frame-specific illumination correction using sky lines

- identify 30-50 bright sky lines in a moving 400mas window across each slice, which are fit with a Gaussian to measure flux, wavelength and resolution
- use wavelength relative to reference to modify LCAL table
- use flux ratios to measure illumination changes across each slice as well as slice-to-slice variability



Optimized 1D extraction

- Multiple reconstructions are sub-optimal for very faint sources => better to extract 1D spectra straight from the uncombined frames
- Use HST images as a prior for source positions during the frame registration, and use these to model source back to the detector plane
- Extract 1D spectrum in a single go!

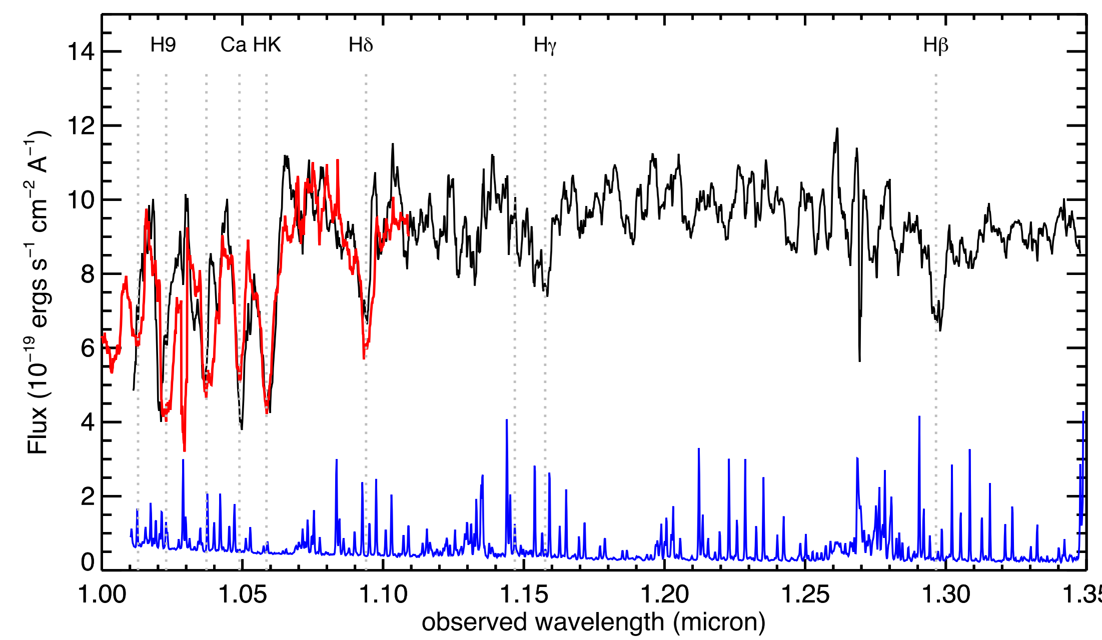


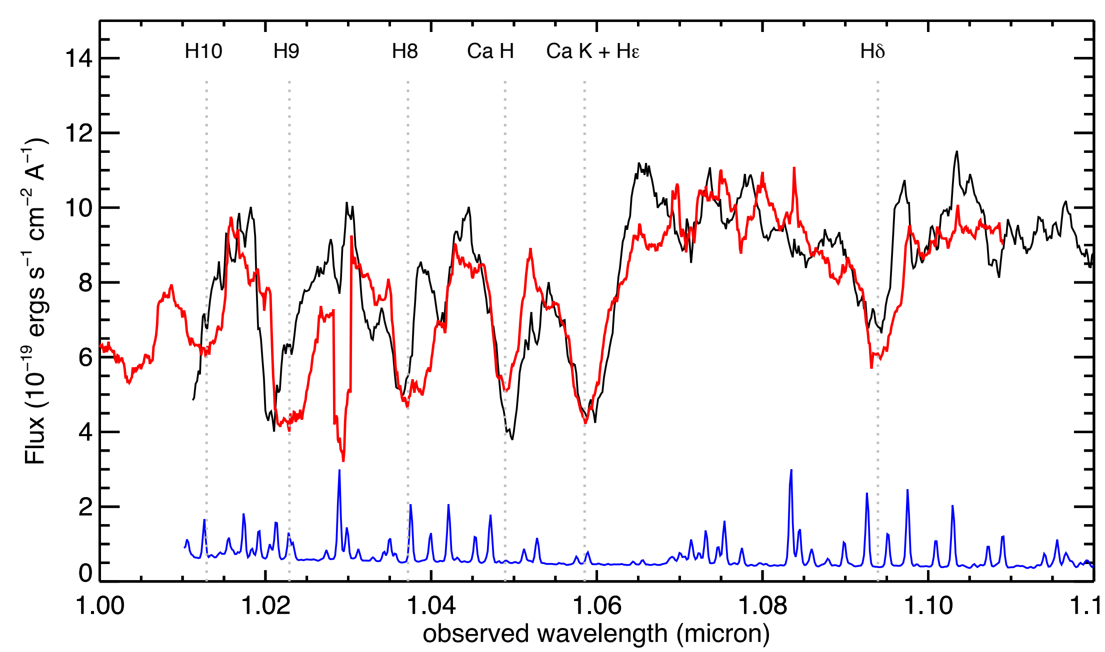
Advantages

- better handling of bad pixels/data
- trivial to generate bootstrap realizations of the output data (which is now out standard procedure)
- In the extreme case we can construct a complete forward model and perform spectral fits on simultaneous on the uncombined detector frames

Comparison to MOSFIRE data

- Passive galaxy at z = 1.66 observed with both KMOS and MOSFIRE@Keck (thanks to Sirio Belli for the comparison)
- Similar on-source exposure time after correcting for aperture size difference between Keck and VLT
- Sky subtraction with KMOS seems to be working remarkably well given difficulties with IFUs vs slits.
- Flux calibration agrees to within about 20% (but still trying to understand differences in extraction)





Final thoughts

KMOS has been operating smoothly since the last major intervention in Feb. 2015 to address arm failures.

Data reduction

- The default reduction pipeline now works well for emission-line data taken with relatively standard observing plan (OSO, short exposures…)
- There are still some outstanding detector-level effects to address systematics
- We're still exploring adaptations of the pipeline to shift processing from reconstructed cubes to detectors

Question:

- Should sky exposures be treated as part of the calibration plan for NIR instruments (i.e., should OOSOOOO even be an option)?