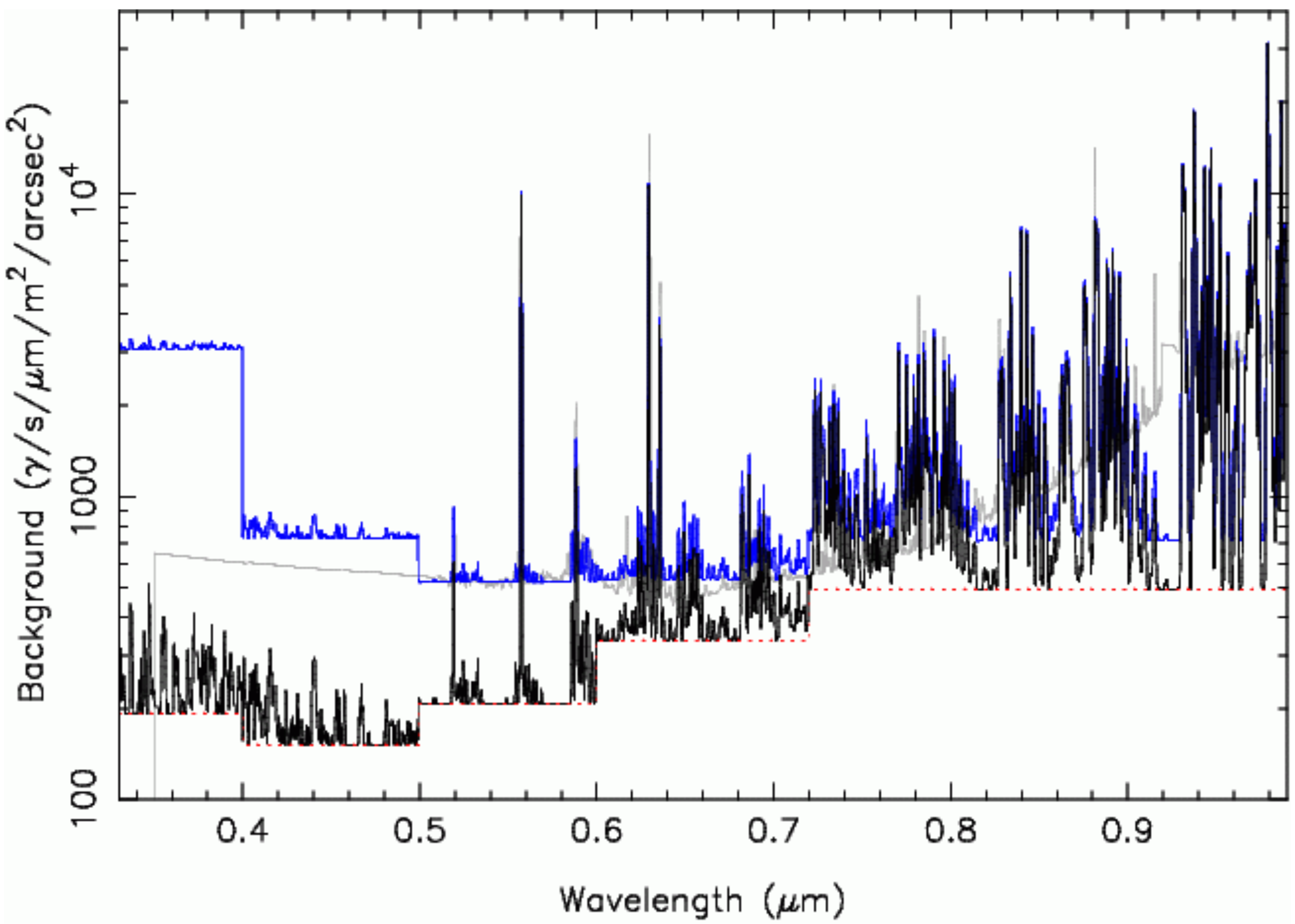
GEPI - Observatoire de Paris

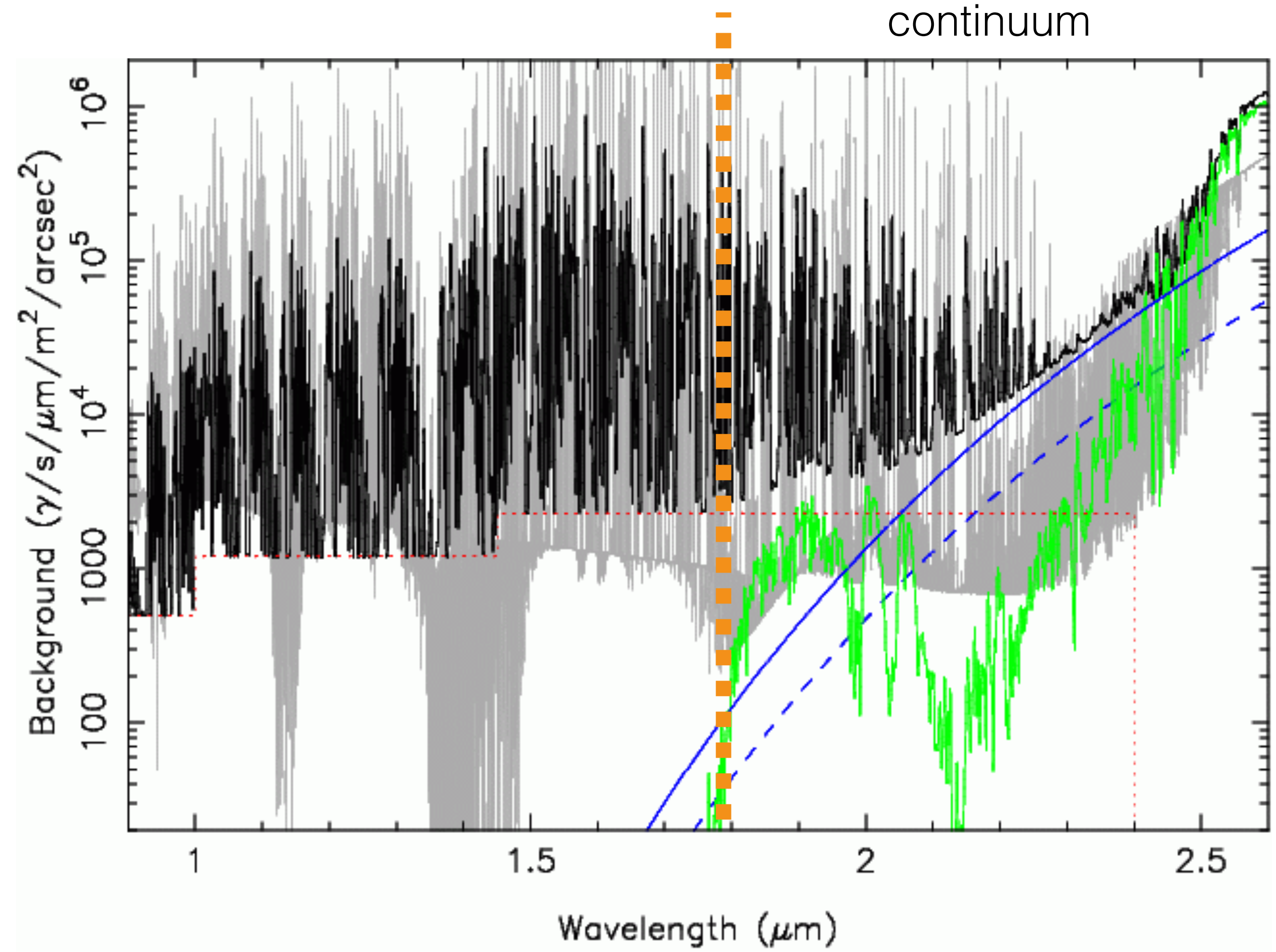
Sky subtraction with fiber-fed spectrograph

Myriam Rodrigues

Know your enemy: the sky spectrum up to H-band



Dominated by the thermal continuum



from https://www.eso.org/sci/facilities/eelt/science/drm/tech_data/background/

Fiber-fed spectrograph and the observations of faint targets

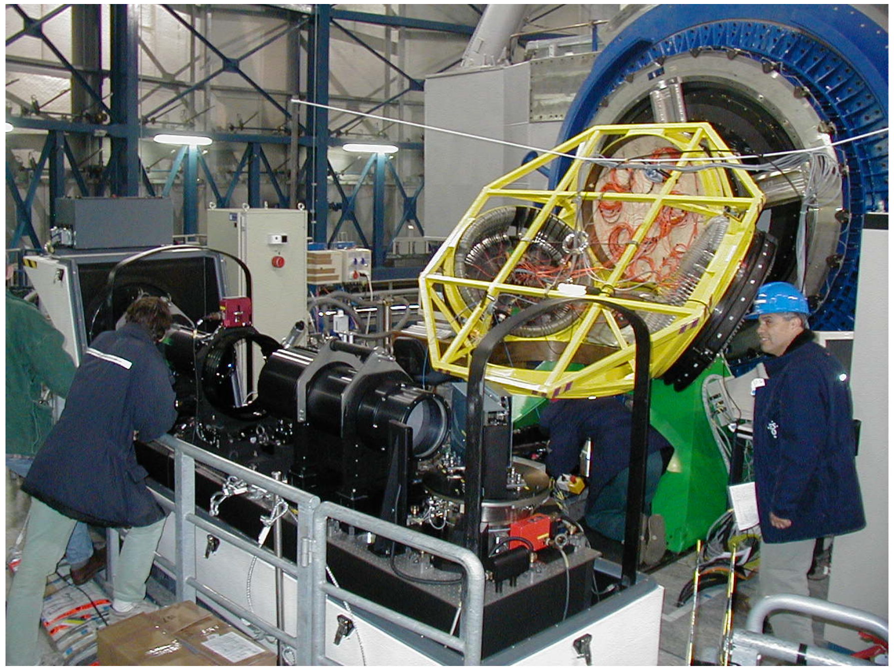
- Instrumental - Significant loss of light compared to slit spectrographs (e.g. Fibre cross-talk on the detector, Focal Ratio Degradation)

- Sky subtraction - the sky cannot be observed both simultaneously and in the same position of the science target.

Fiber-fed spectrographs are versatile instruments:

- High multiplex
- Large field of view
- Multiple modes : apertures, IFUs
- Homogenous wavelength coverage

Current and futur fiber-fed spectrograph at ESO



FLAMES/GIRAFFE

Fov: 25 arcmin in diameter

Multiplex: 130 apertures; 8 IFU

R: 5500-65100

Coverage: 370-950 nm

MOONS

Fov: 25 arcmin in diameter

Multiplex: 1000 apertures

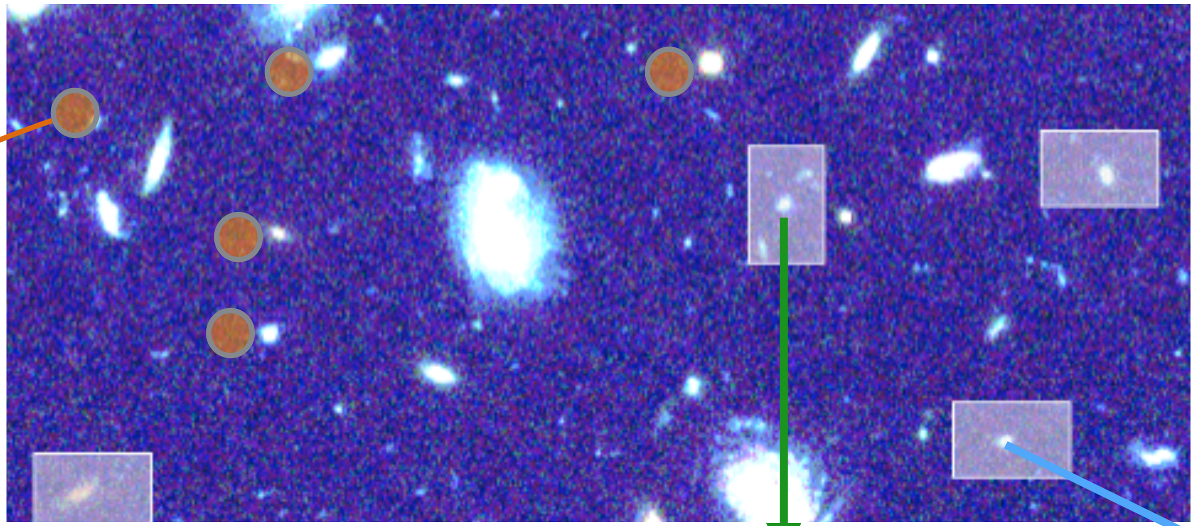
R: 4000-20000

Coverage: 800-1630 nm

Current and futur fiber-fed spectrograph at ESO

MOSAIC @ E-ELT

Field of view: *7 arcmin ⌀ at the 40m E-ELT*



High Multiplex Mode (HMM)

On Sky aperture	0.9″
Multiplex	200
Spectral Resolution	5000 & 15000
λ coverage	0.4 - 1.8 μm

High Definition Mode (HDM)

IFU field of view	2.0 x 2.0″
Multiplex	10 IFUs
Spatial pixel size	75 mas
Ensquared Energy	> 25% EE
R	5000
λ coverage	0.8 - 1.8 μm

InterGalatic Medium (IGM)

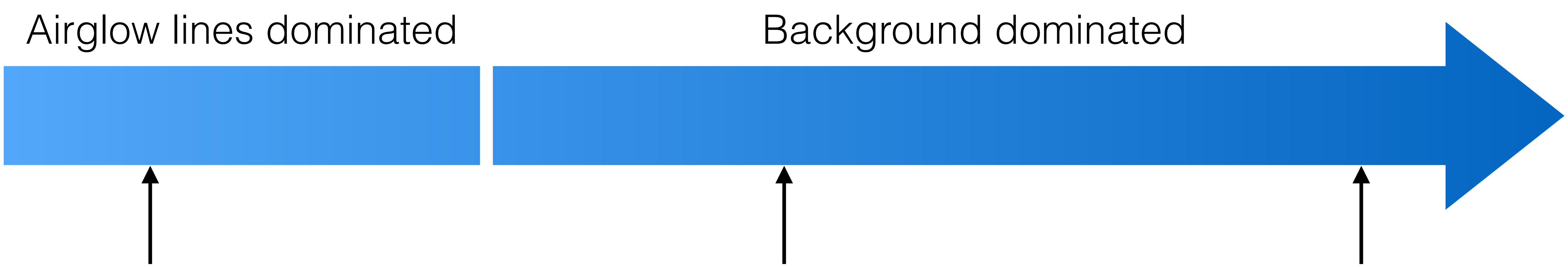
IFU field of view	2.0″ x 2.0″
Multiplex	10 IFUs
Spatial pixel size	0.3 arcsec
R	5000
λ coverage	0.4 - 1.0 μm

Sky subtraction regime

Sky background mag/arcsec^2

V	R	i	z	J	H	K
21.9	21.85	21.5	21.04	18	16.5	15.7

from X-shooter obs. R=5000



FLAMES/GIRAFFE

Resolved stellar population
r = 17-19
I=19

(GAIA-ESO survey)

MOONS

Resolved stellar population and faint galaxies
H_{AB} = 25 mag (16h)

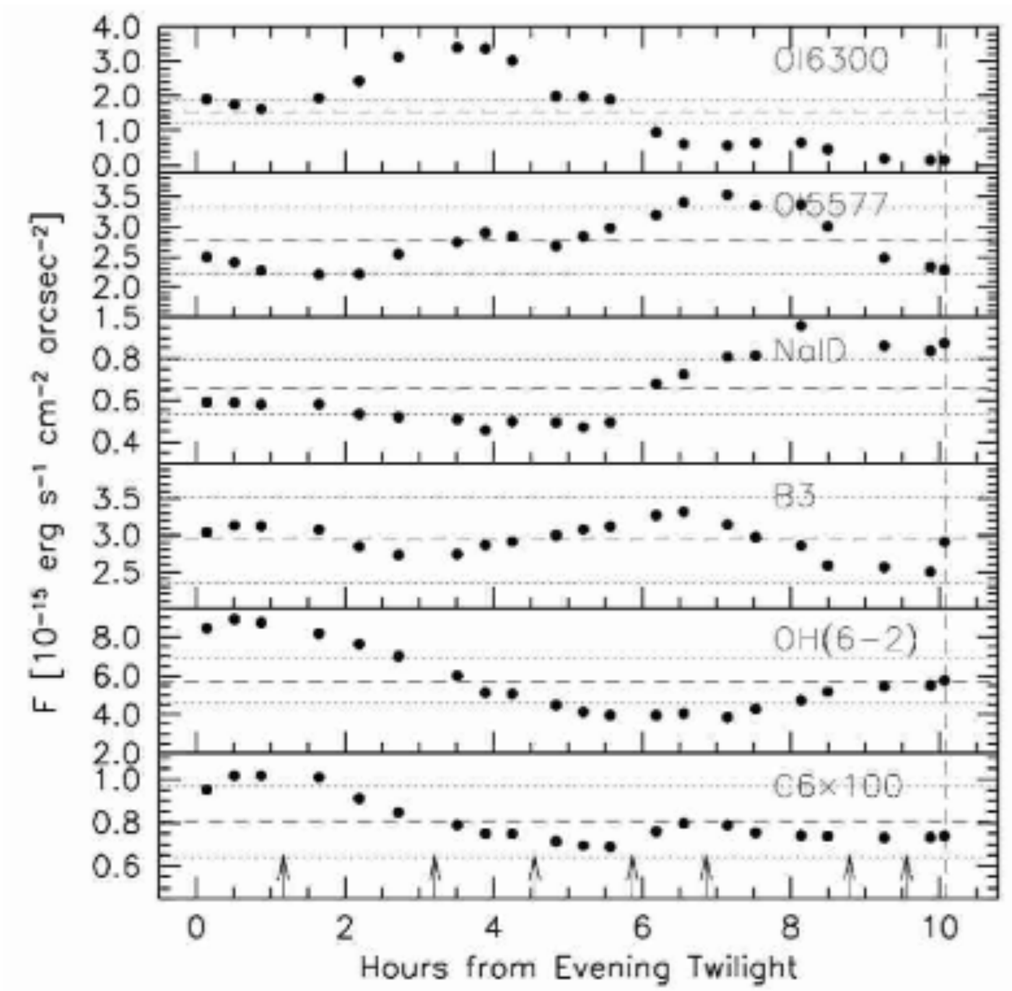
MOSAIC@E-ELT

Resolved stellar population and first galaxies
H_{AB} = 29 mag in emission
H_{AB} = 27-2 mag v in continuum

Airglow-lines dominated regime

Properties of the airglow lines

Chemiluminescence from a thin layer of the upper atmosphere (OH, O2)



Sequence of spectral measurements for some sky features measure in FORS1 spectra by Patat et al. 2008.

Variability of their fluxes ~20% in time scales from minutes to decades

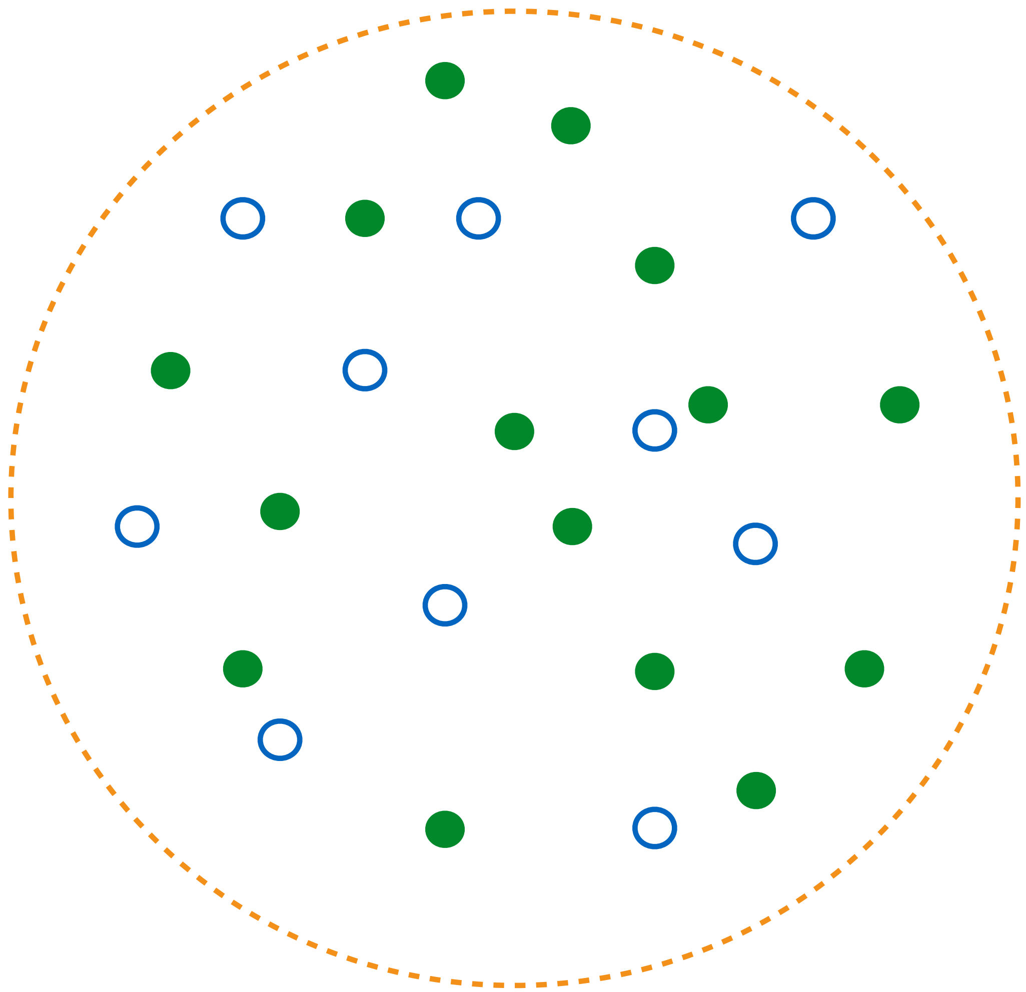
Ramsay et al. 1992, Khomich et al. 2008; Patat 2008; Noll et al. 2012

Fluctuations:

- Diurnal and seasonal variations
- Gravity waves propagating in the upper atmosphere

but also **spatial variability**

Observational strategies



○ dedicated sky fibres
● science fibers

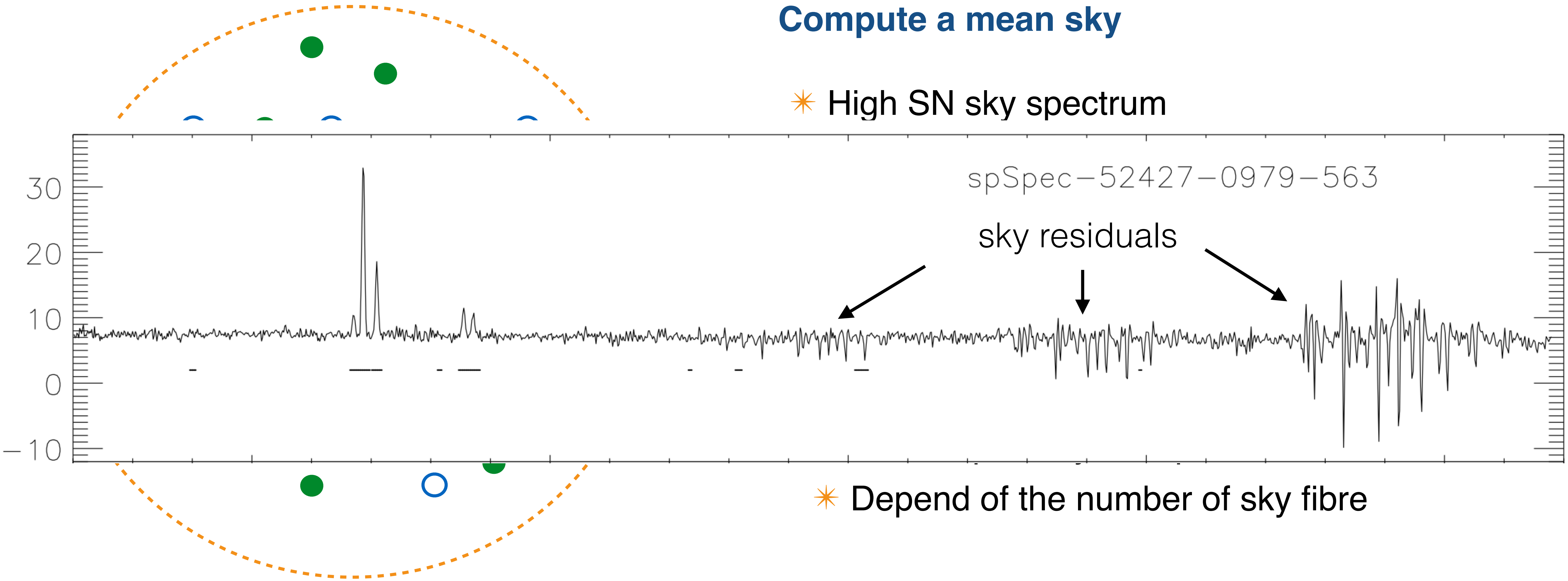
Compute a mean sky

- High SN sky spectrum
- Sky and science are probed simultaneously
- Not account for the spatial variation in the field

Compute a closest sky

- Noisy spectra
- Correct partially the spatial variation
- Depend of the number of sky fibre

Observational strategies



Compute a mean sky

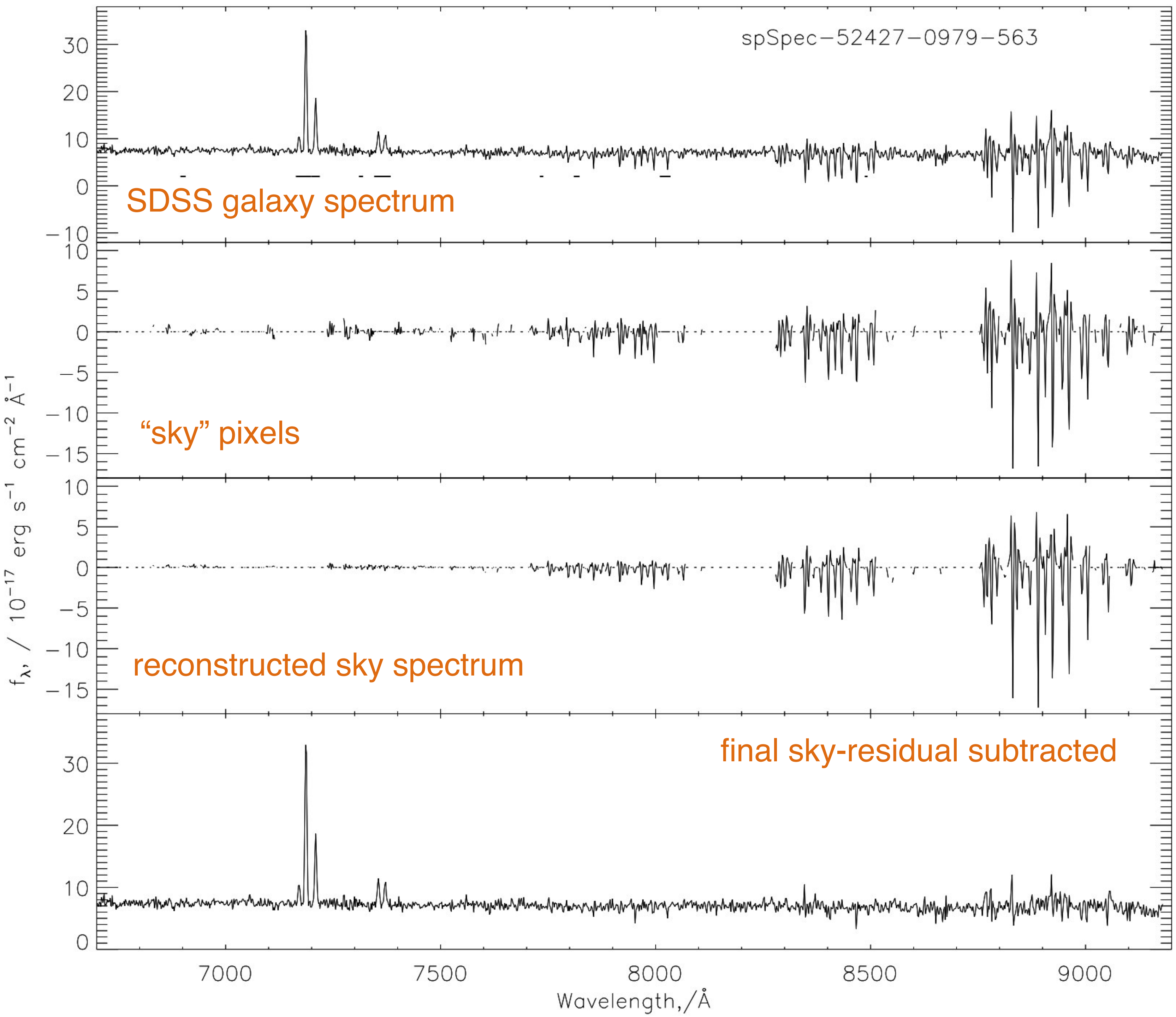
- ✳ High SN sky spectrum
- ✳ Depend of the number of sky fibre

○ dedicated sky fibres

● science fibers

Data reduction

Remove residuals using principal component analysis



Wild & Hewett 2005

Sharp et al. 2010

Also : Negative matrix factorisation with sparsity (Zhang, Zhang, Ye 2016)

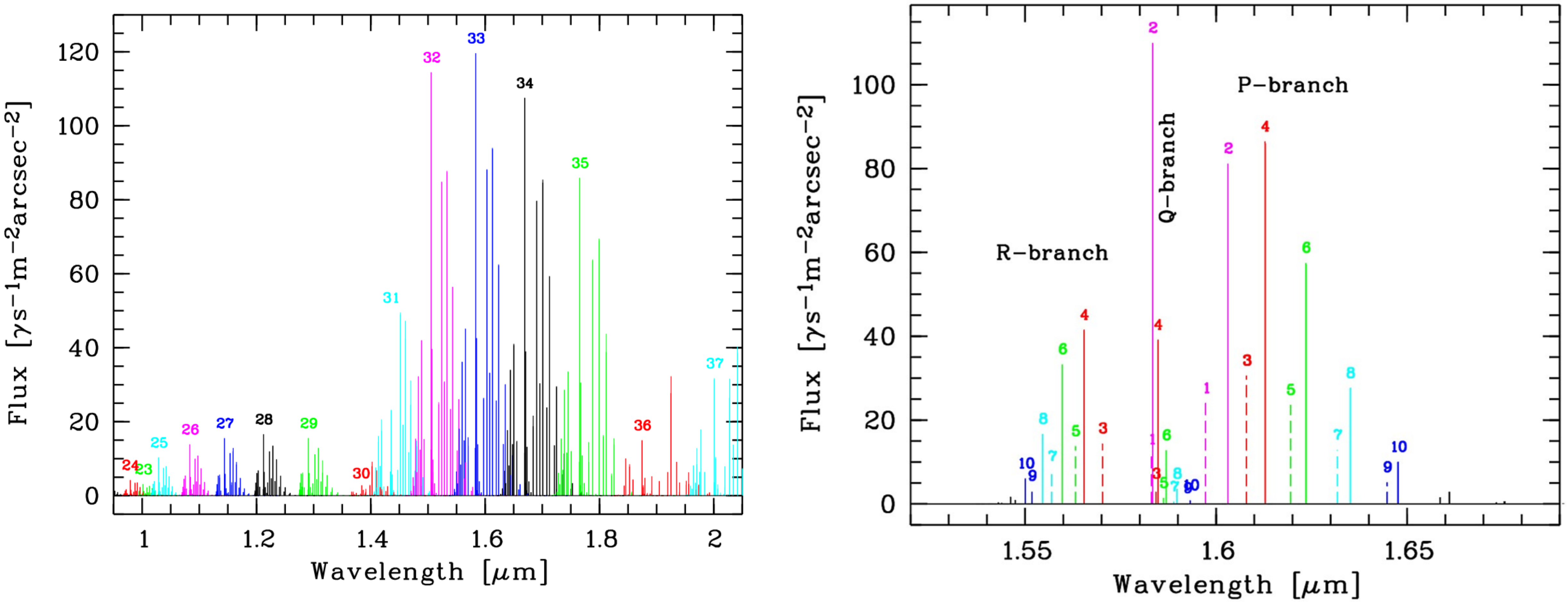
Data reduction

Physical modelling of OH temporal variation

Ric Davies et al. 2007 for SINFONI data

Skycorr (Noll+2014)

Vibrational and rotational OH groups in the near-IR (from Noll +2014)



The fluctuations are the same for lines within a group

Data reduction

Surface recomposition method

Rodrigues et al. 2008

1) Sky continuum is interpolated in the position of the science fibre by reconstructing of the surface in each lambda segment

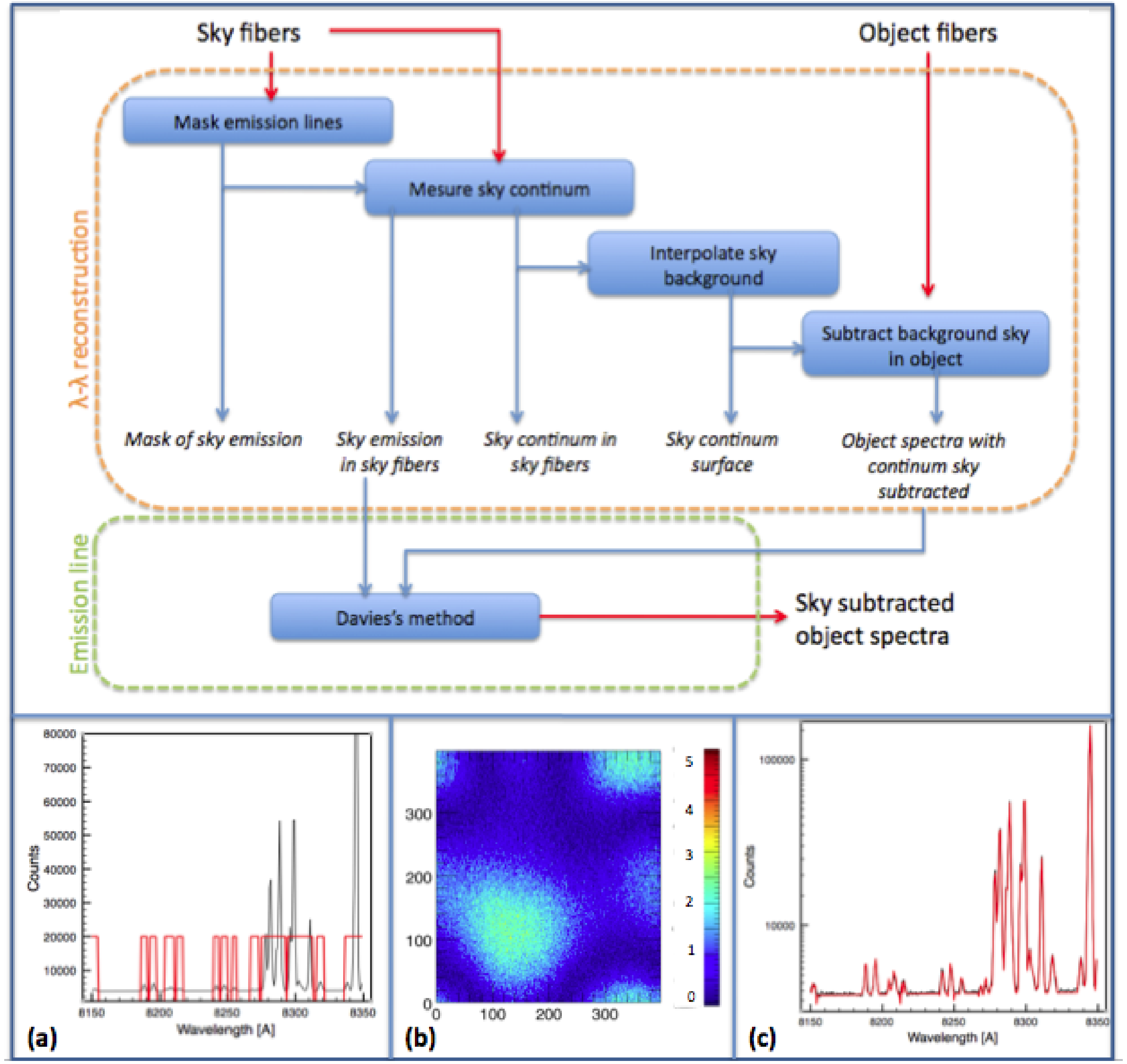
2) Emission lines are subtracted using OH modelling

Optimal subtraction

Li Causi et al. 2005

Mitigate the LSF variation

Match the OH lines in extracted sky and target spectra by means of ILS adaptation.

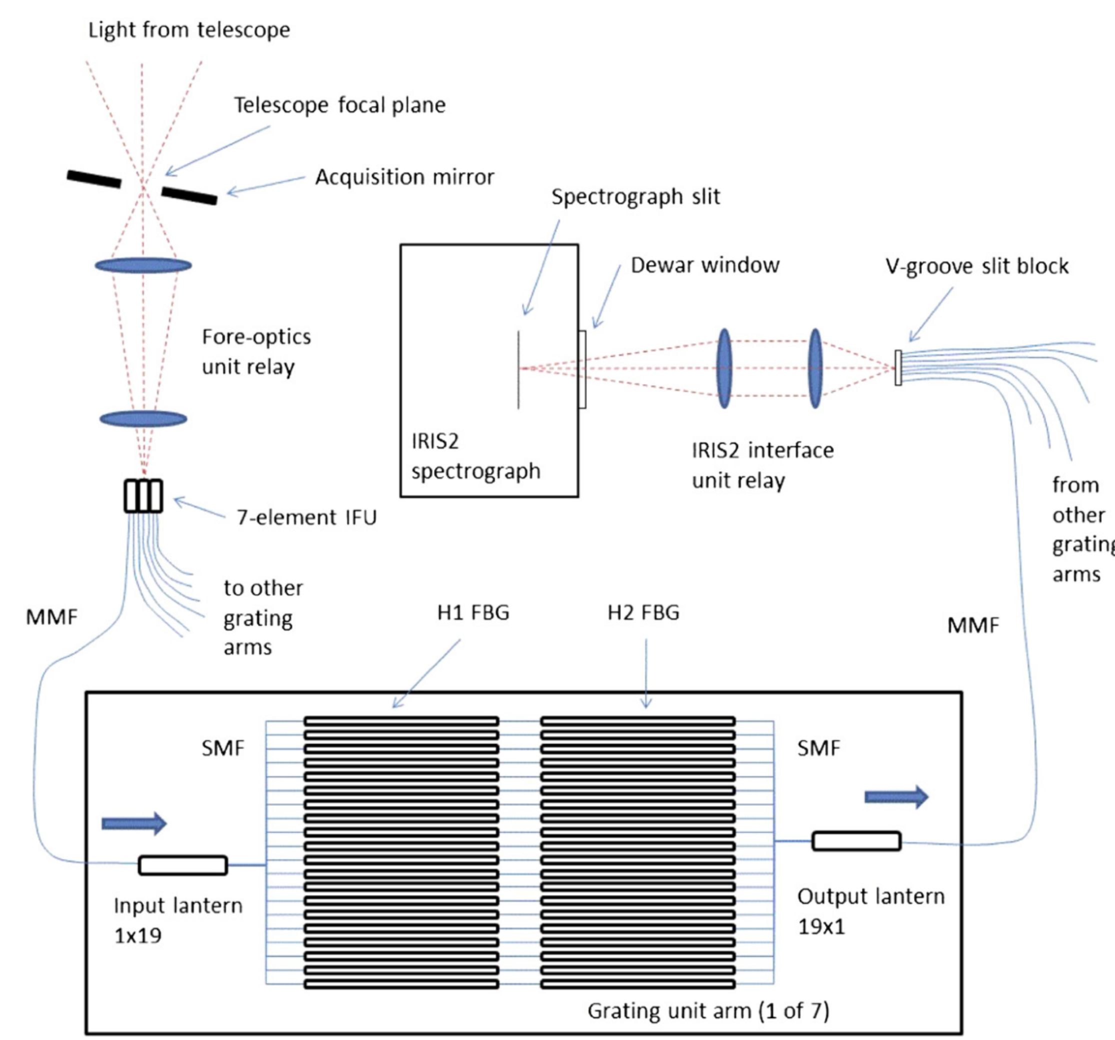


Instrumental concept

- ✳ Fibre Bragg gratings (Bland-Hawthorn et al 2009): removal before dispersion
- ✳ High dispersion OH masking (Maihara et al. 1993): intermediate HR spectrum
- ✳ Rugate ion beam sputtering filters (Gunster et al. 2011): removal before dispersion

GNOSIS/ IRIS2 at 3.9 m Anglo-Australian Telescope

Fibre Bragg gratings and photonics lanterns to suppress the 103 brightest atmospheric emission doublets between 1.47 and 1.7μm.

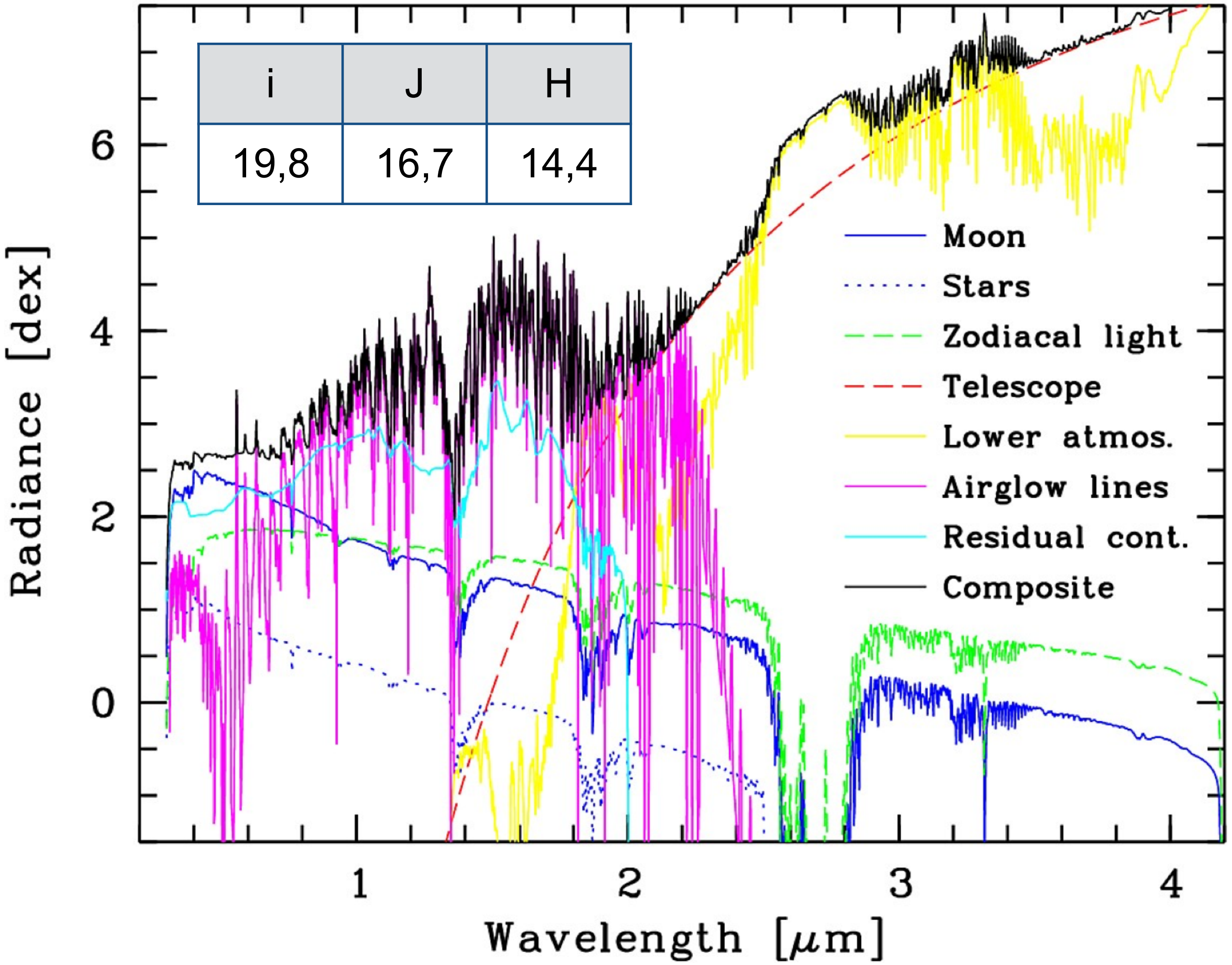


Trinh et al. 2013

Continuum dominated regime

Properties of the continuum

Noll et al 2012



Sky sources

- ✳ Moon (still present in J band)
- ✳ Zodiacal light
- ✳ Unresolved star background
- ✳ Airglow continuum:
  - Chemical reaction involving nitric oxide (Khomich+2008, Noll+2012)
  - Wings of Lorentzian of multiple OH line (Sullivan & Simcoe 2012)

Instrumental residuals

scattered light, fiber-to-fiber response, residuals from pixel-to-pixel variations, etc..

Properties of the airglow background

At 900nm

Narrow-band imaging data and spectroscopy obtained with ESO-VLT/FORS2

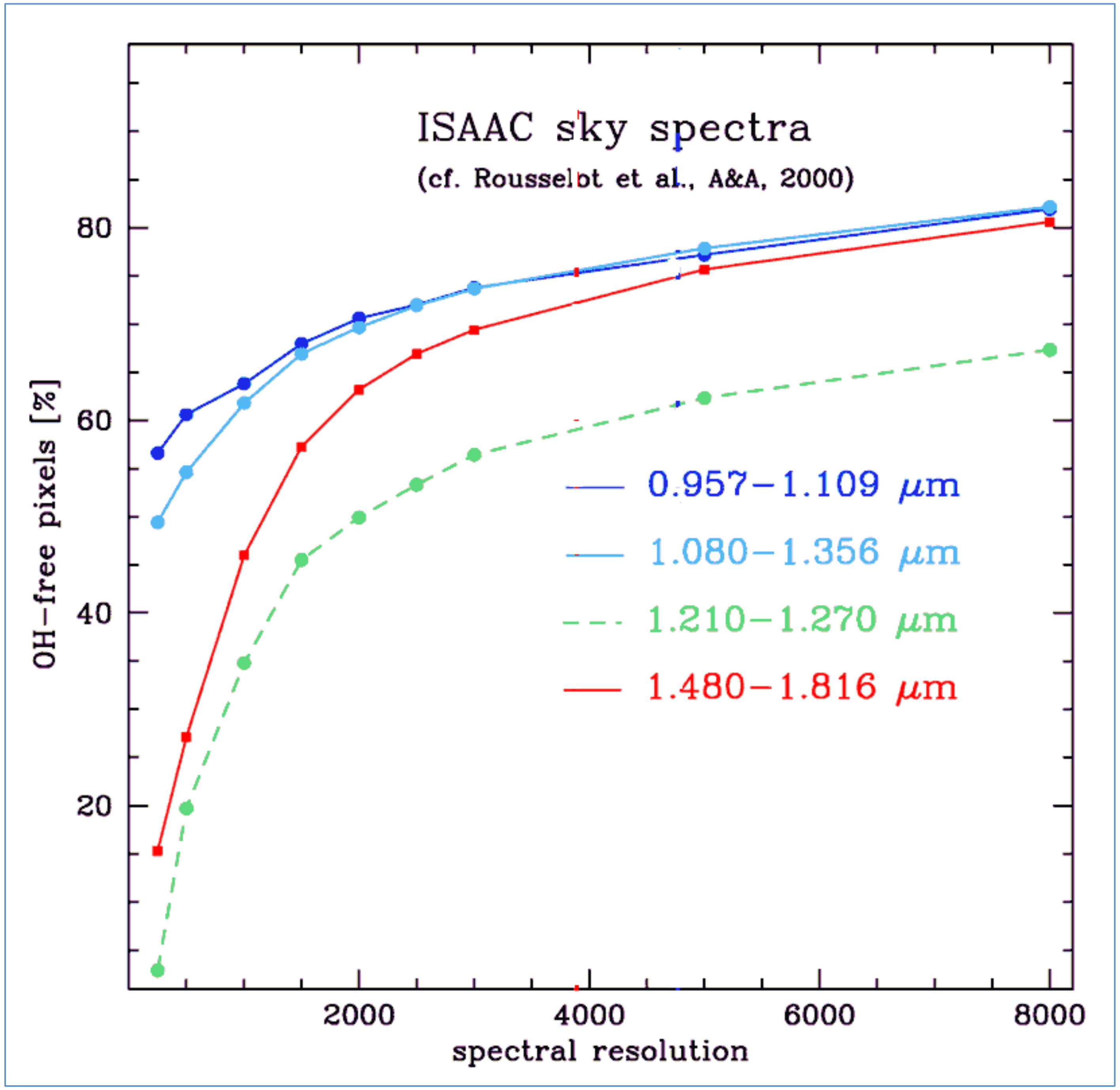
(Puech et al. 2012, Yang et al. 2012)

- Spatial variations over scales of ~1′′, 30” up to ~150′′, with total amplitudes below 0.5% of the mean sky background
- Need to sample the sky on spatial scales significantly below 30 arcsec and timescales significantly below 30 min

In the near-IR

In progress with HAWKI narrow band imaging

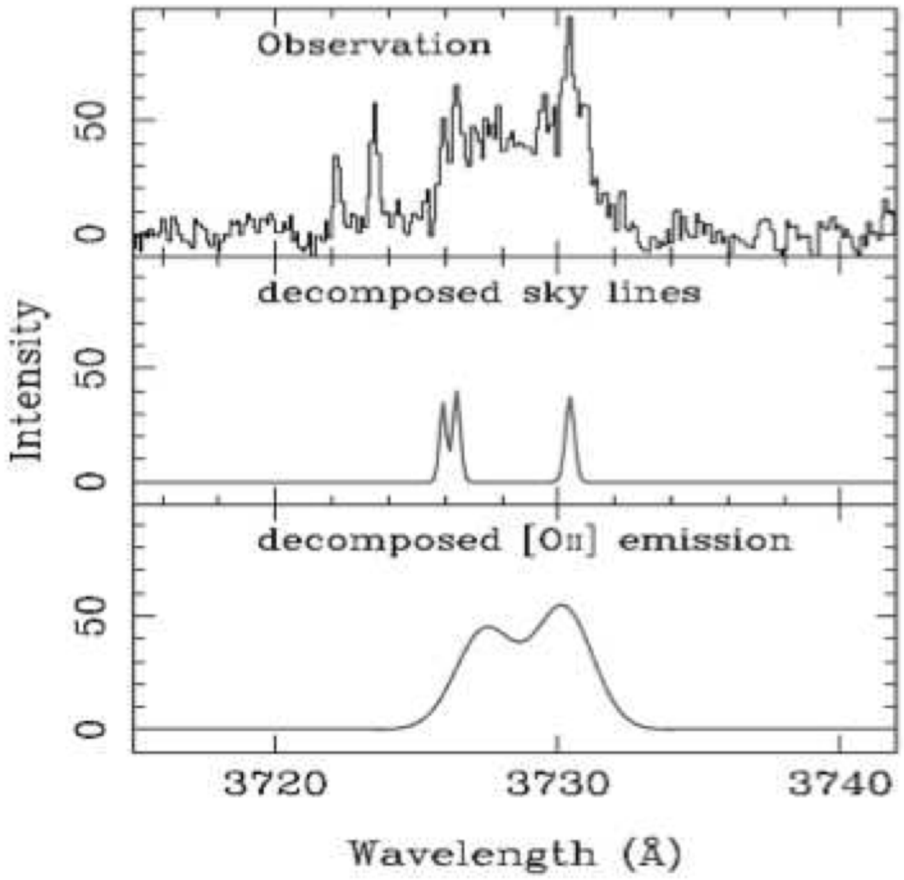
Sky subtraction strategies NIR



Spectral resolution

Observe between the OH lines
R > 3000 in NIR

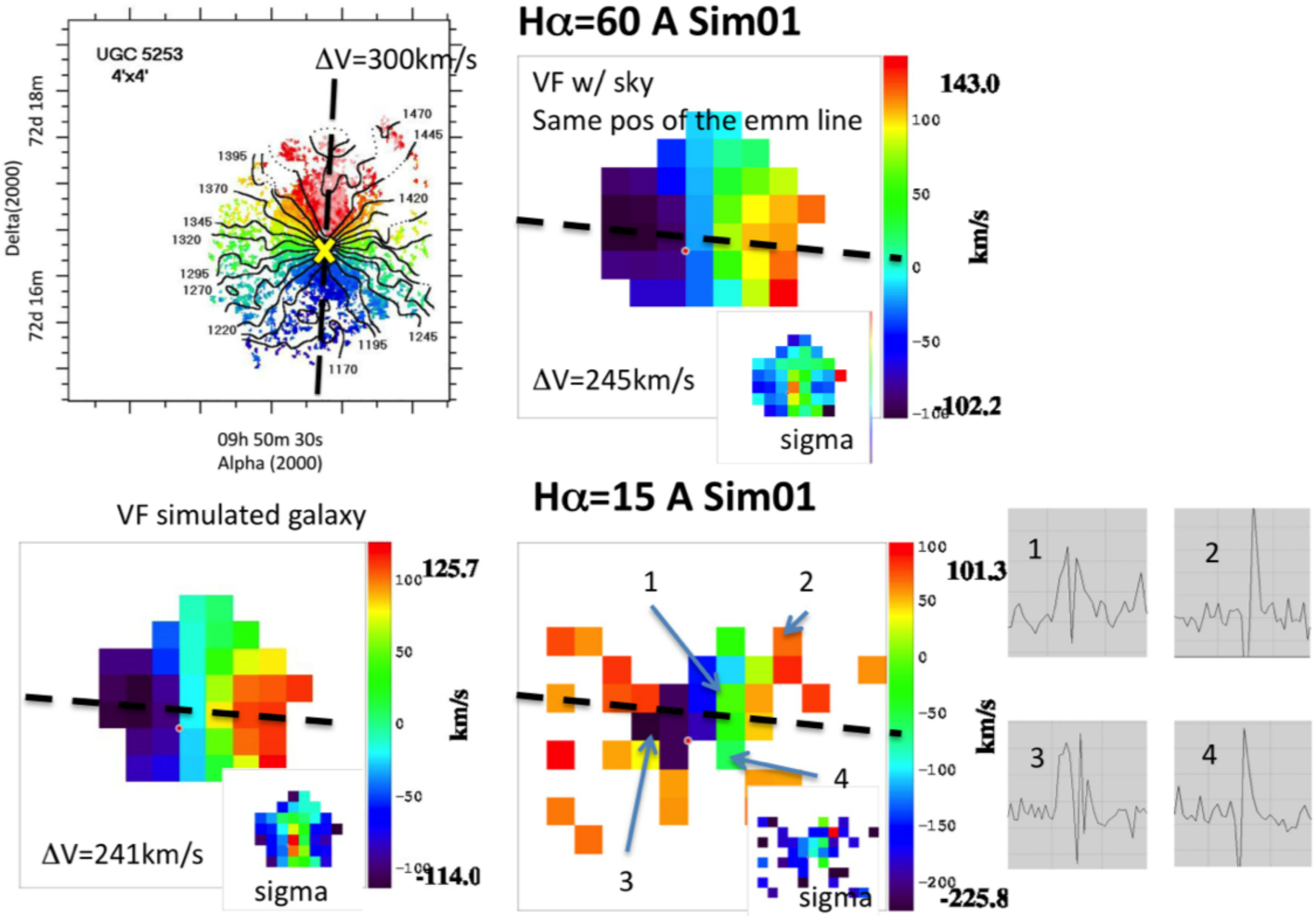
Separate the object line from faint OH lines



Observe at moderate resolution

Simulation of KMOS observations of a distant galaxies

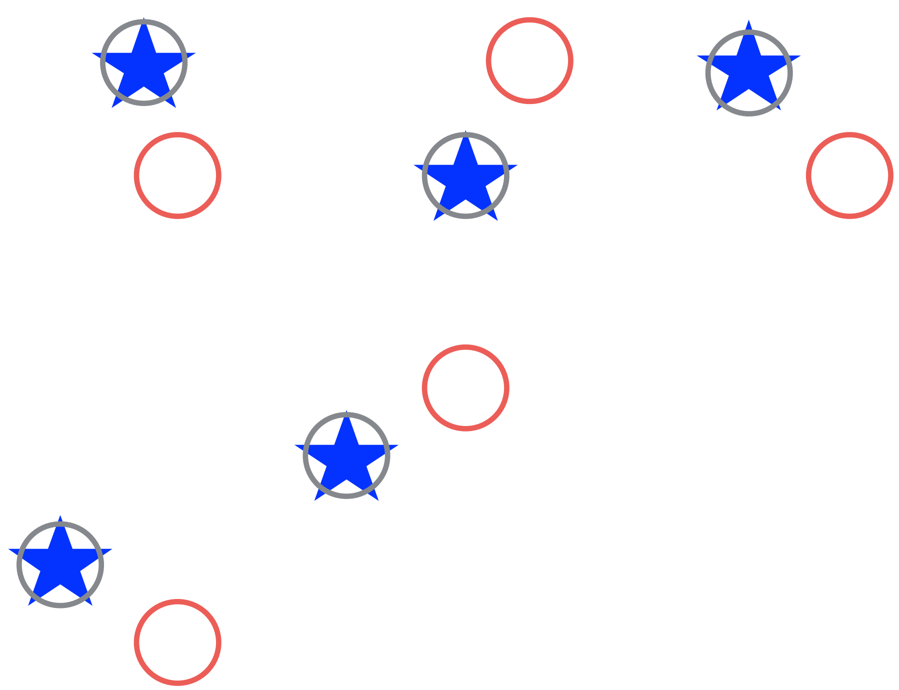
YJ band R= 3600



Sky subtraction strategies

Dual fiber stare

Two fibres (one sky and one object) separated by < 20” ⇒ Pseudo slit



Advantage

✳ The sky is sampled simultaneously that the science target. Correct the temporal variations of the sky

✳ The science target is observed 100% of the time

Disadvantage

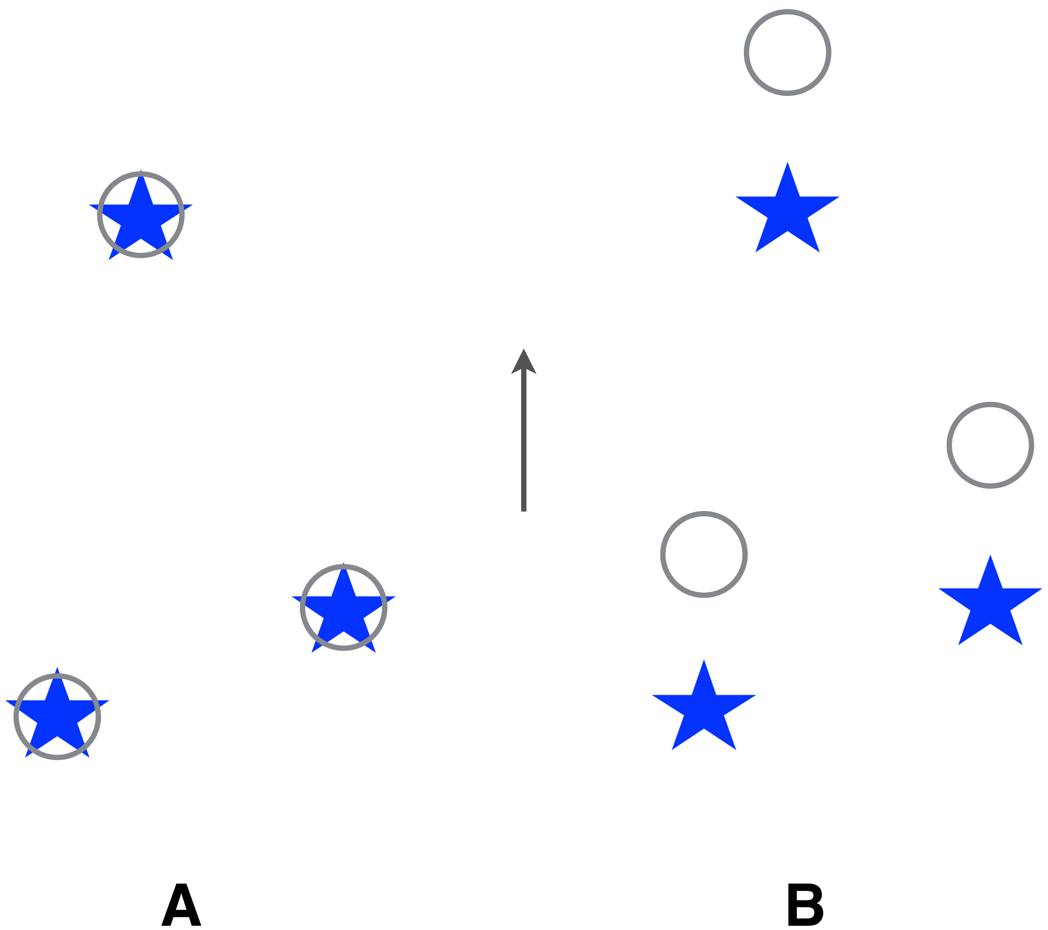
✳ Instrumental response is not corrected

✳ Decreases the multiplex capabilities

Continuum dominated regime

Beam switching

- Typical offset of <20” between the two positions
- ABBA cycle or ABA
- Exposure of ~15min (limit the temporal variation)



Advantage

- The instrumental response is corrected by the nodding (since observing the object and sky with the same fibre)

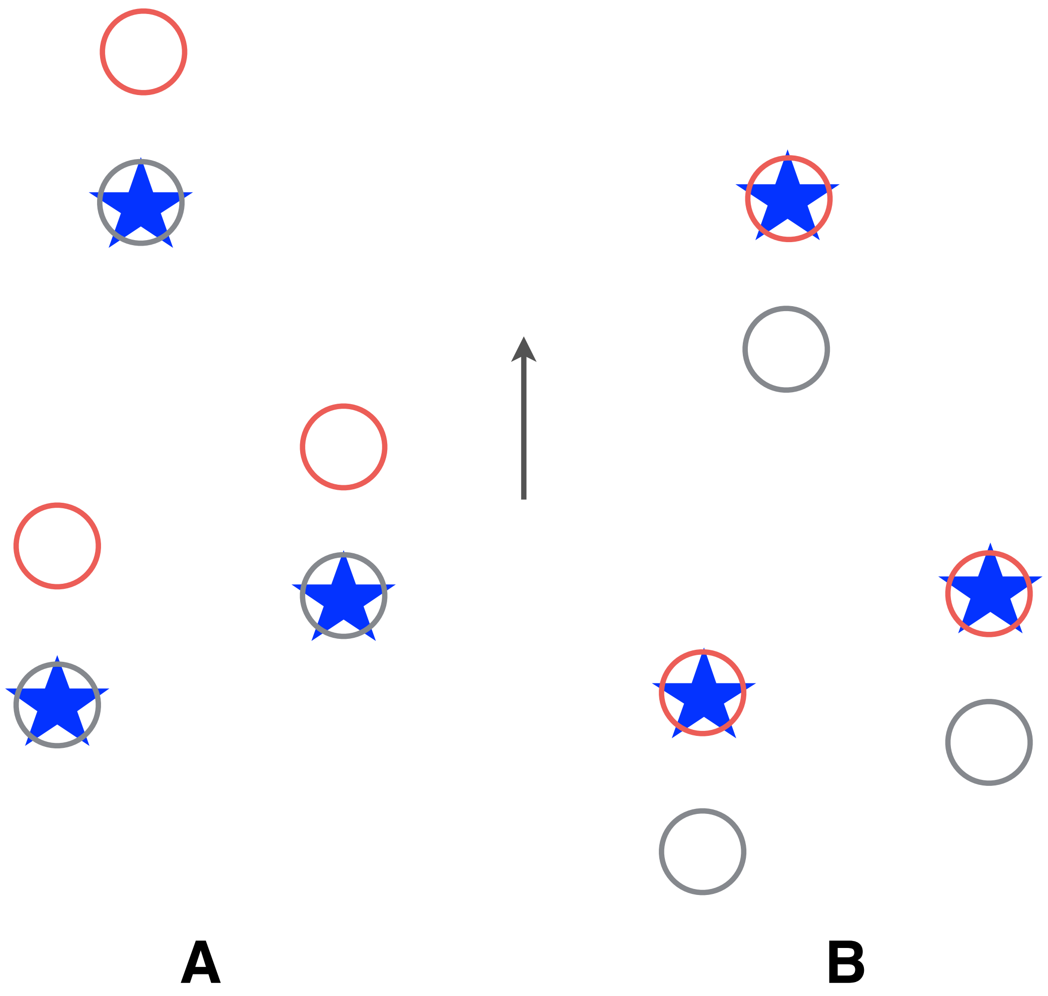
Disadvantage

- The science target is observed 50% or 2/3 of the time
- Crowded fields

Continuum dominated regime

Cross Beam switching

The offset during the beam-switching has to be equal to the distance between the two fibres (sky/obj)



Advantage

- The instrumental response is corrected by the nodding
- The science target is observed 100% of the time

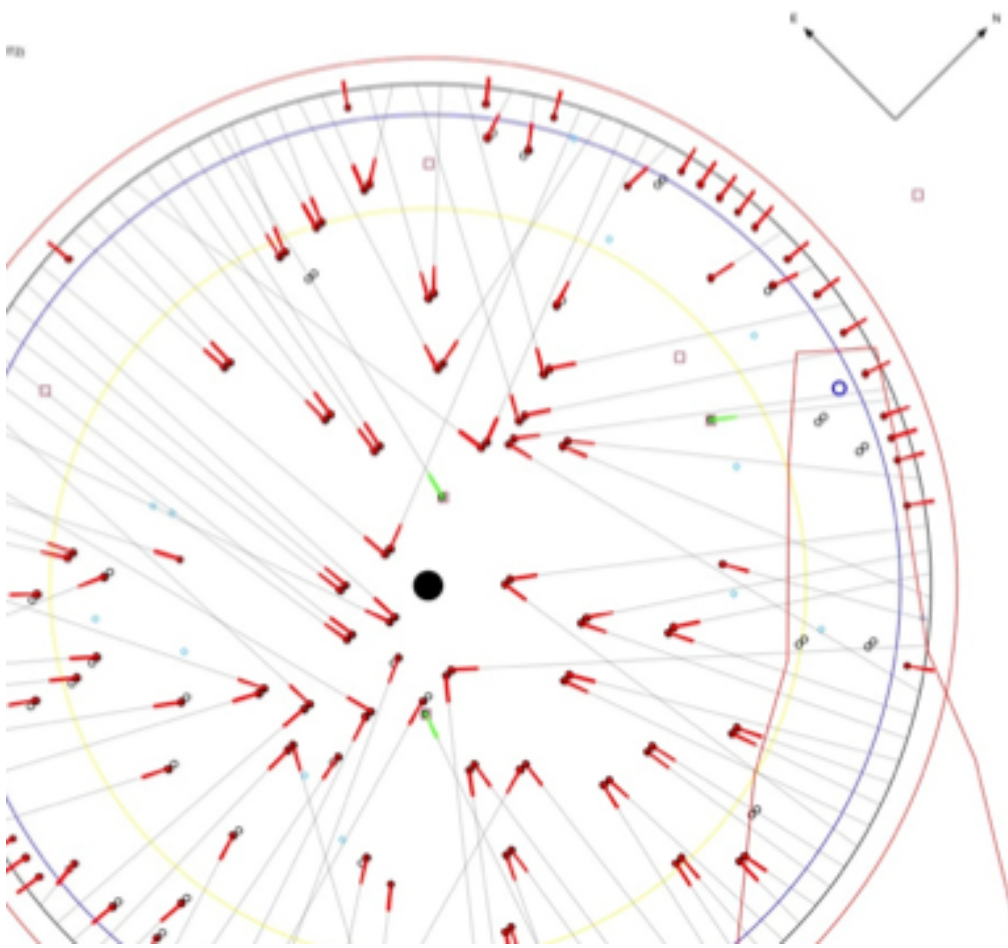
Disadvantage

- Decreases the multiplex
- Crowded fields
- Positioner

On-sky test

Observational setup

Rodrigues et al. 2012 SPIE

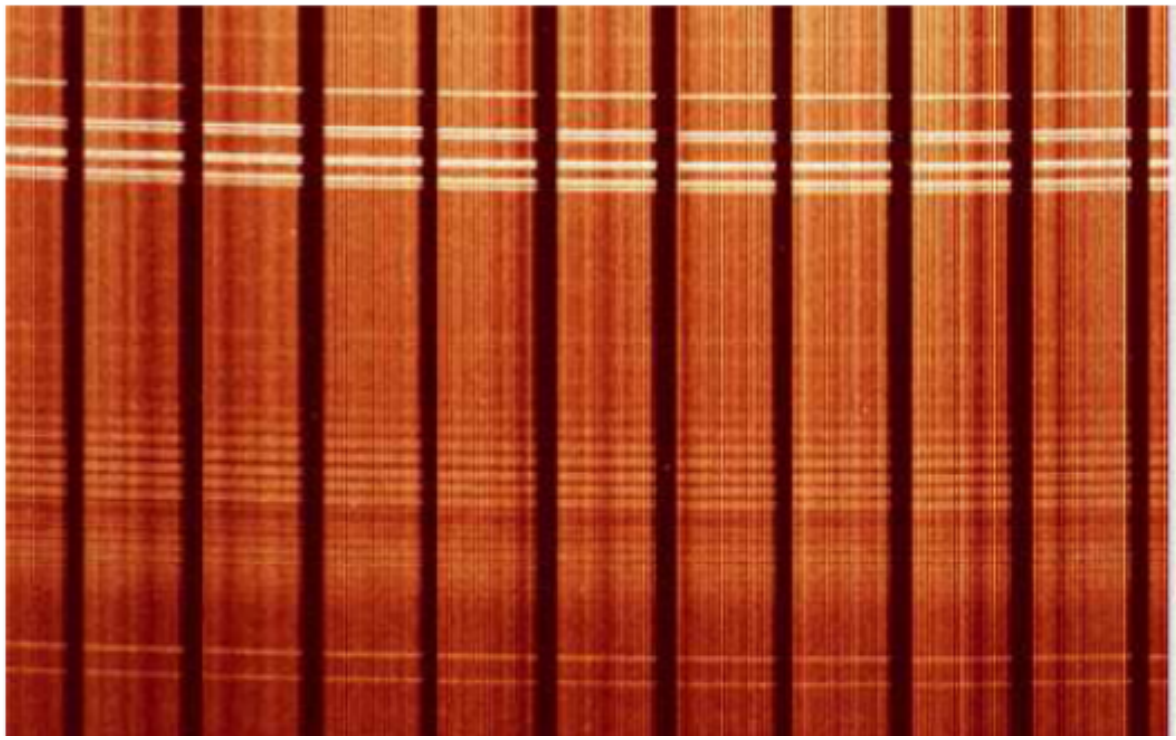


- FLAMES/VLT, in the reddest setting: 820–940 nm with a spectral resolution of *R* = 6500
- 3 cycles A B , exposures of 600s each exposure
- Attached flat-field exposures
- Nodding NS axis (Obj in the southern fibre at position A)
- 28 degrees from bright moon
- 15 pairs with object I_{AB}-band magnitudes fainter than 21.
- 3 pure sky pairs

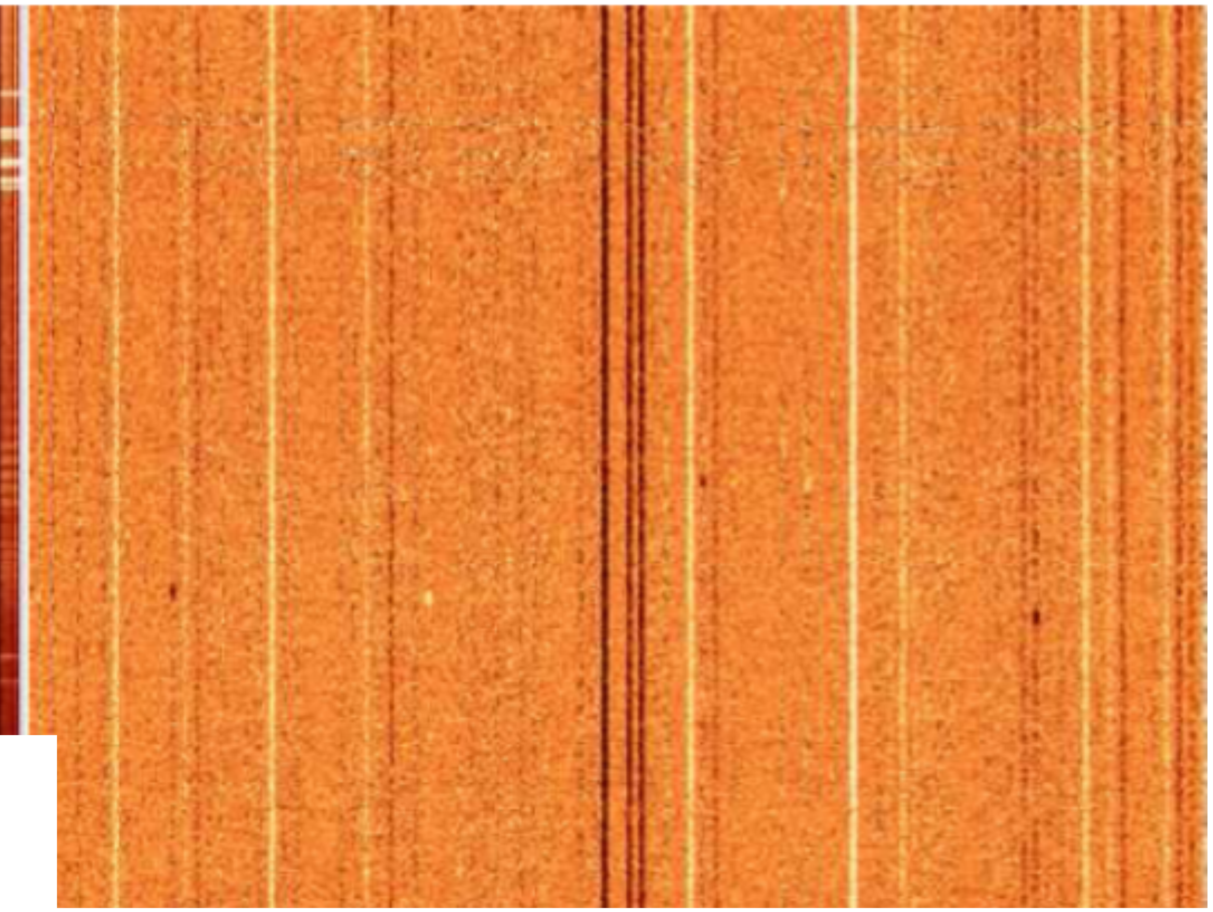
Targets are ~7 times fainter than the contribution from the sky continuum

On-sky test

A Frame



A -B Frame



Xswitch

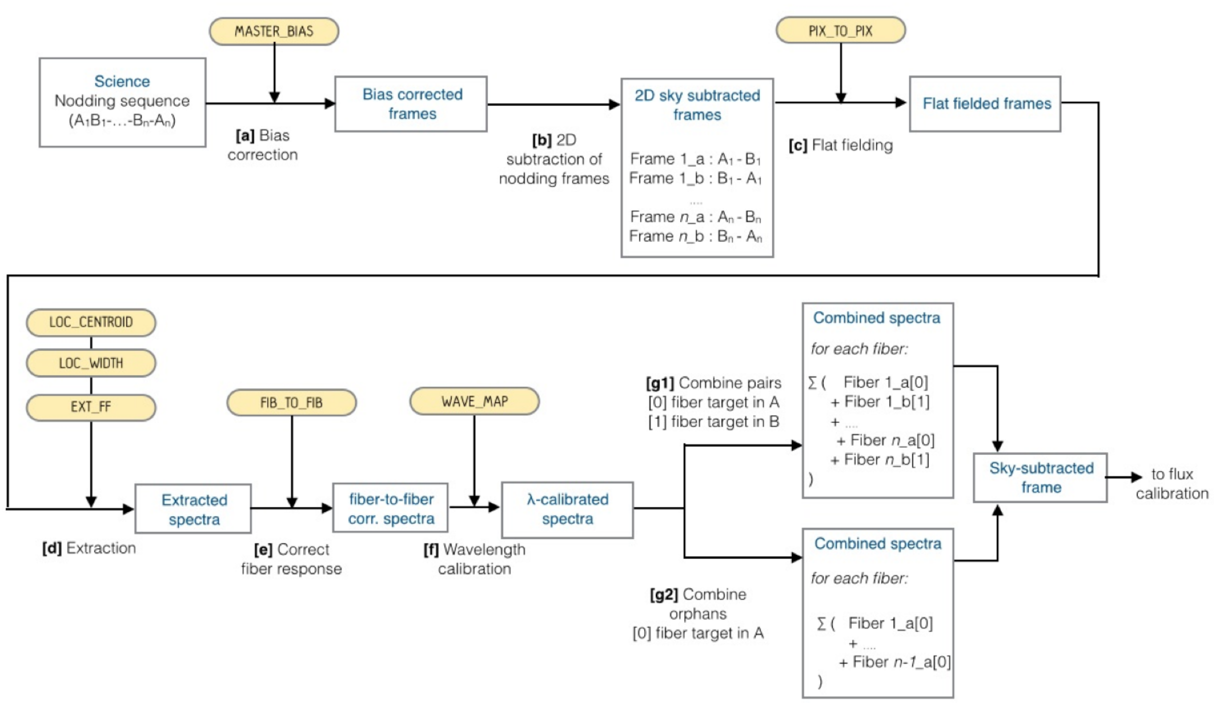


Figure 7-1 Data flow of the Xswitch mode.

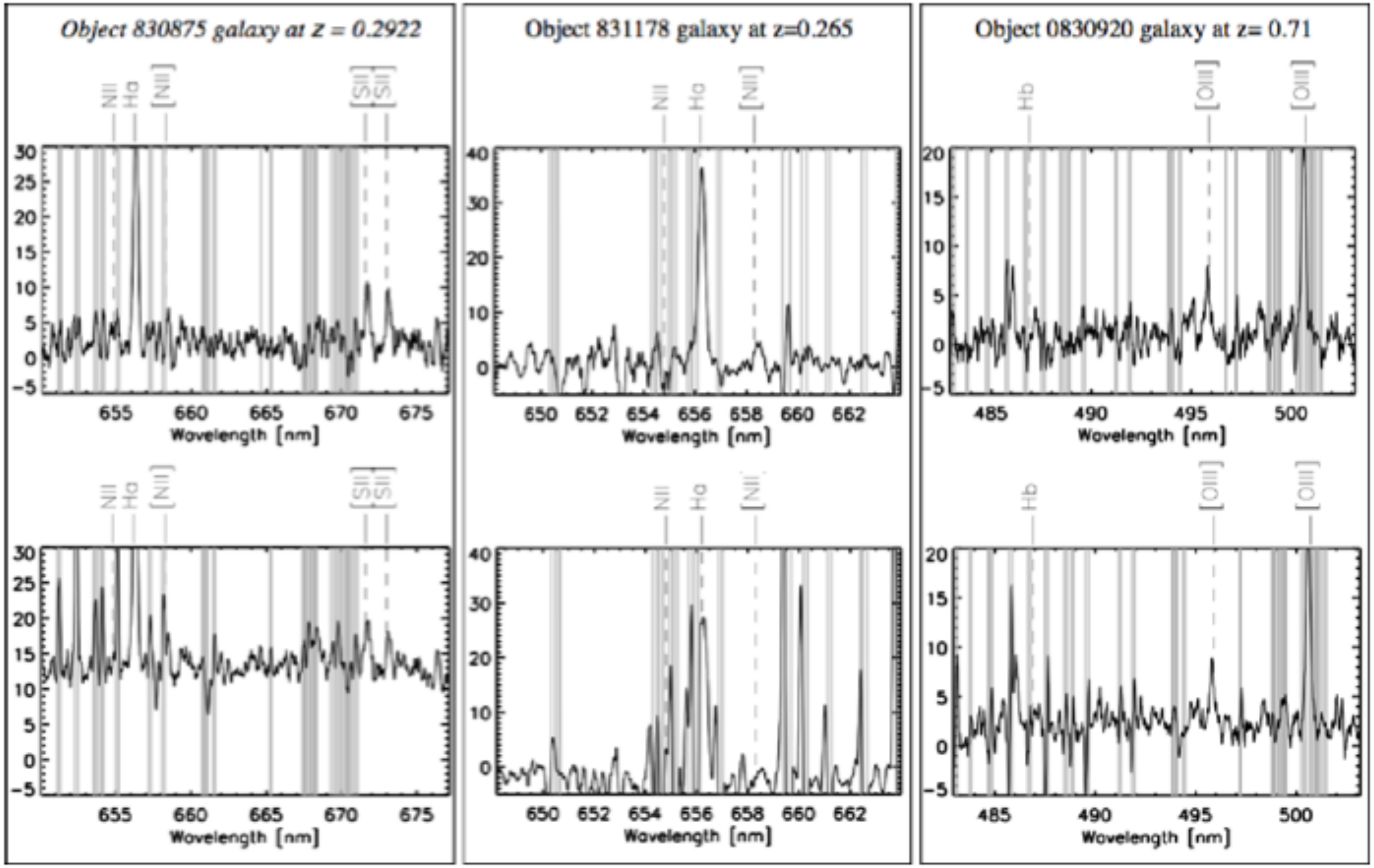
On-Sky test

Results on faint lines

Lines as faint as 3.67 × 10–17 erg/s/cm2/Hz are detected after 1 hour of exposure with cross beam switching

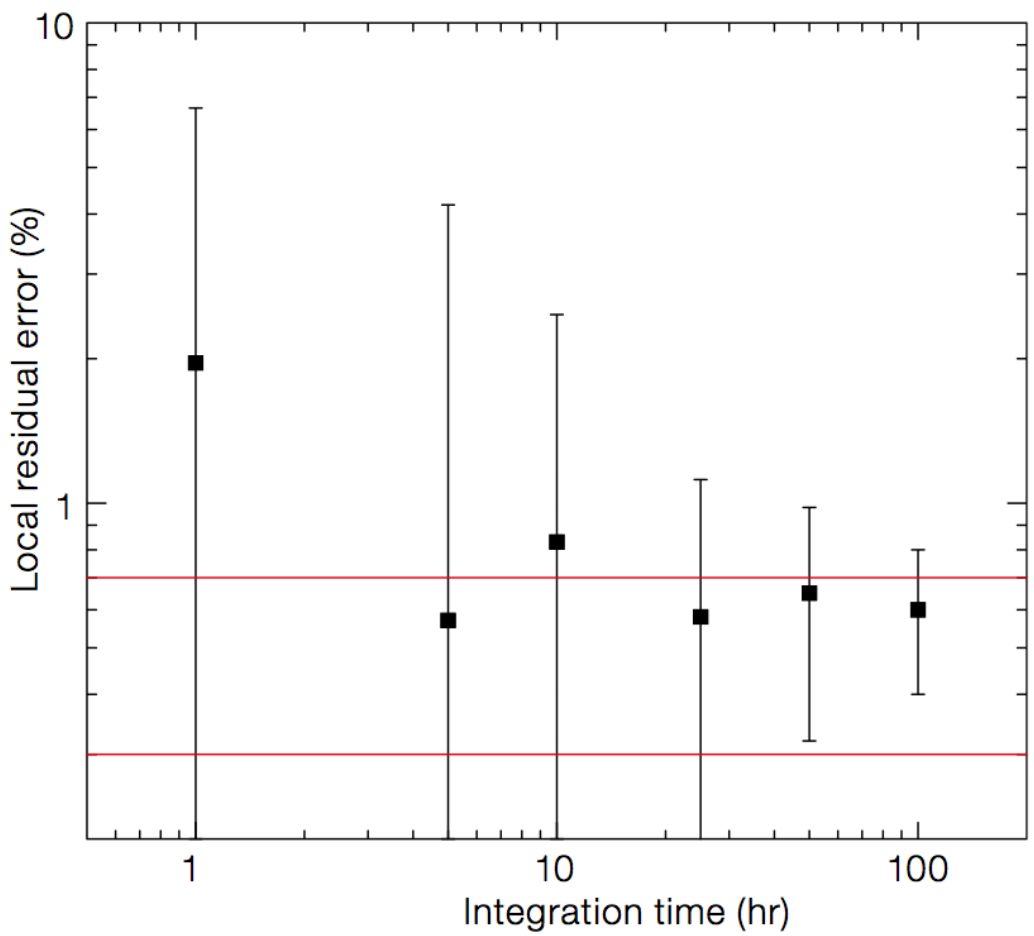
Cross-beam switching

Mean sky



Continuum dominated regime

Accuracy on the background subtraction



- Cross beam-switching methods give accuracy and precision of the sky subtraction under 0.6 %
- Gain on accuracy ~10x compared to the other sky subtraction methods

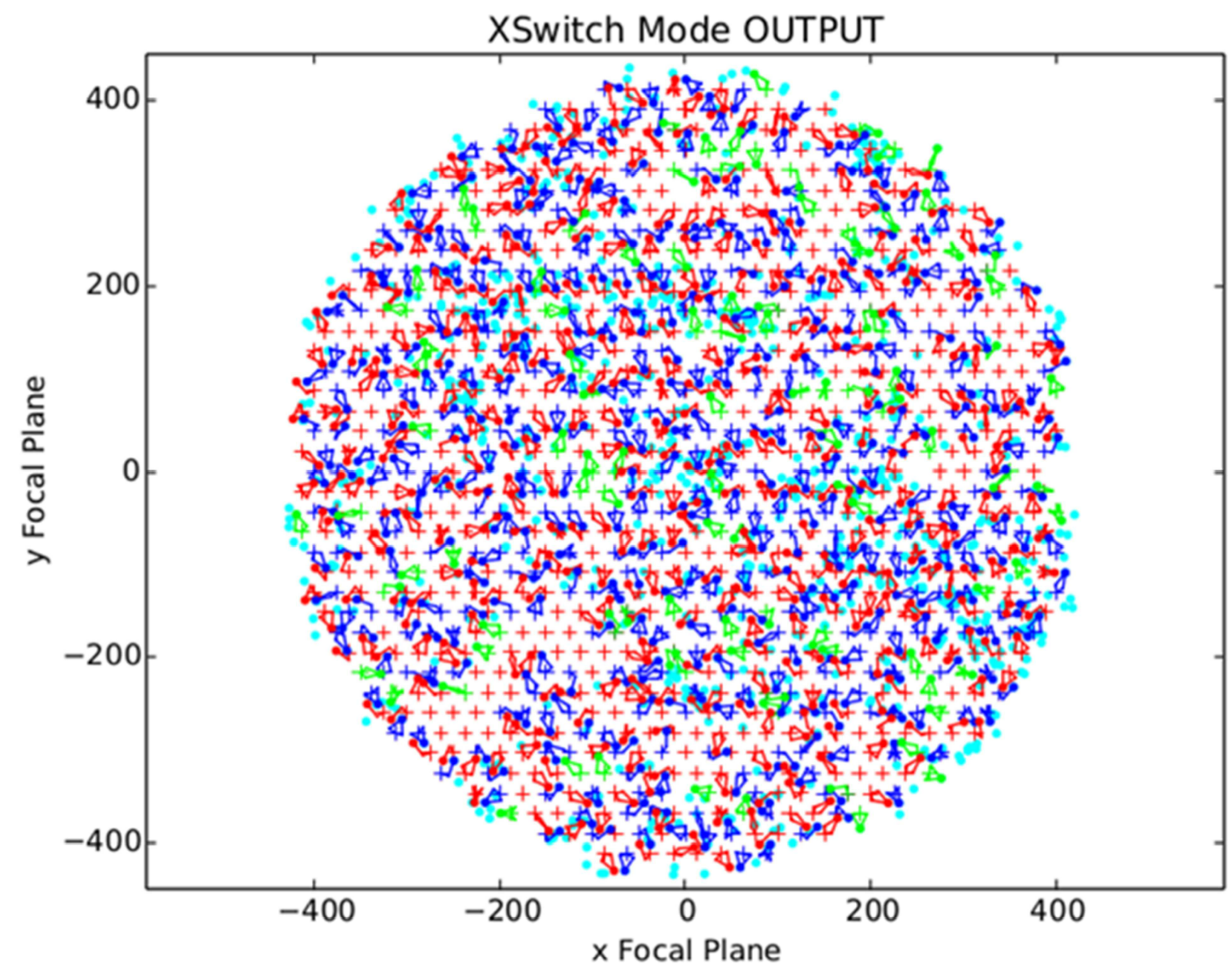
➡ test on-sky the accuracy of the cross beam-switching in the near IR

Impact for the MOONS design and operation

Positionner

- pairs of fibres with a fixed distance between the two fibres
- all the pairs have to be aligned onto the same axis

→ The fibre should reach the center of the adjacent patrol area



Preparation tool

- maximise pairs of object/sky
- Input catalogue with all the sources in the field

Testing the cross-beam switching in simulated data

Virtual MOONS

- Optical model of the instrument (line spread function, distorsion, scatter light)
- Detector (dust, surface, pixel-to-pixel variations, RON, hot and dead pixels)

Extragalatic case : SDSS-like survey

sources: galaxies $20<H_{AB}<23.5$ z=[0.8,1.8]
+ 4 check stars 16-19

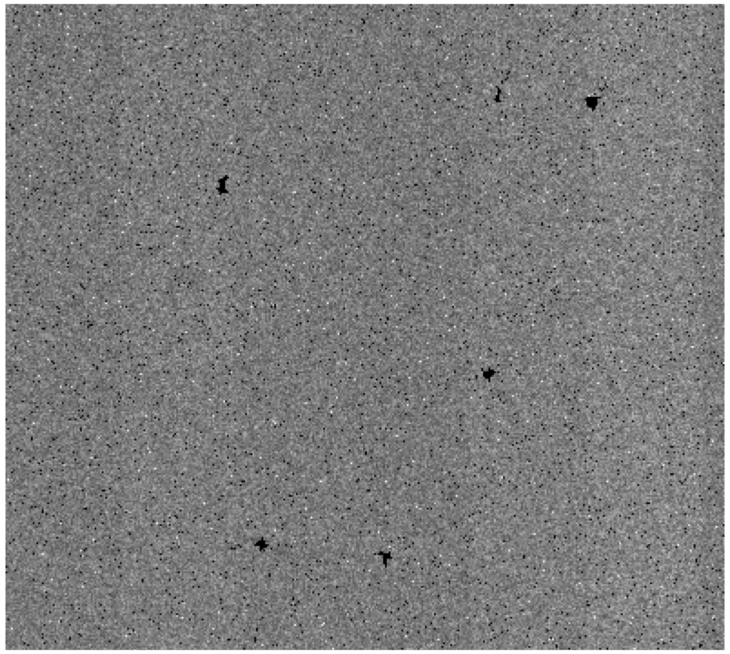
- Moderate resolution : R=6000
- 1h observations split in 4 exposures of 15min
- Xswitch: A - B - A - B
- Configuration from the preparation software

Sky model

- Advanced sky model from ESO *(Noll et al. 2014)*
- Spatial and temporal variation of the sky continuum :
0.4% at 30” scale and 0.4% at <0.8”

Simulated frames

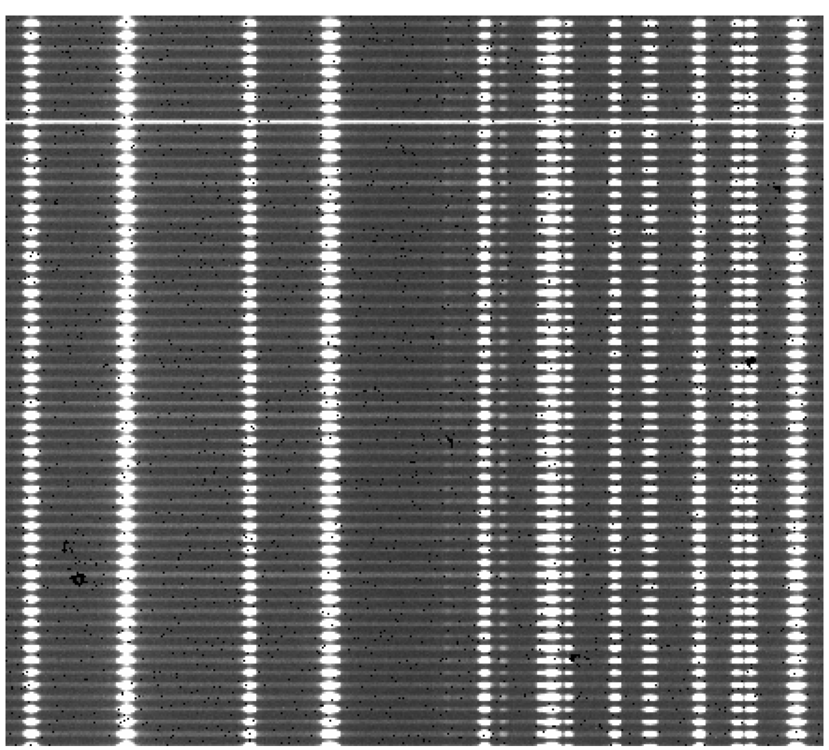
Dark



Flat

Information on the pairs inherited from the preparation software

Science



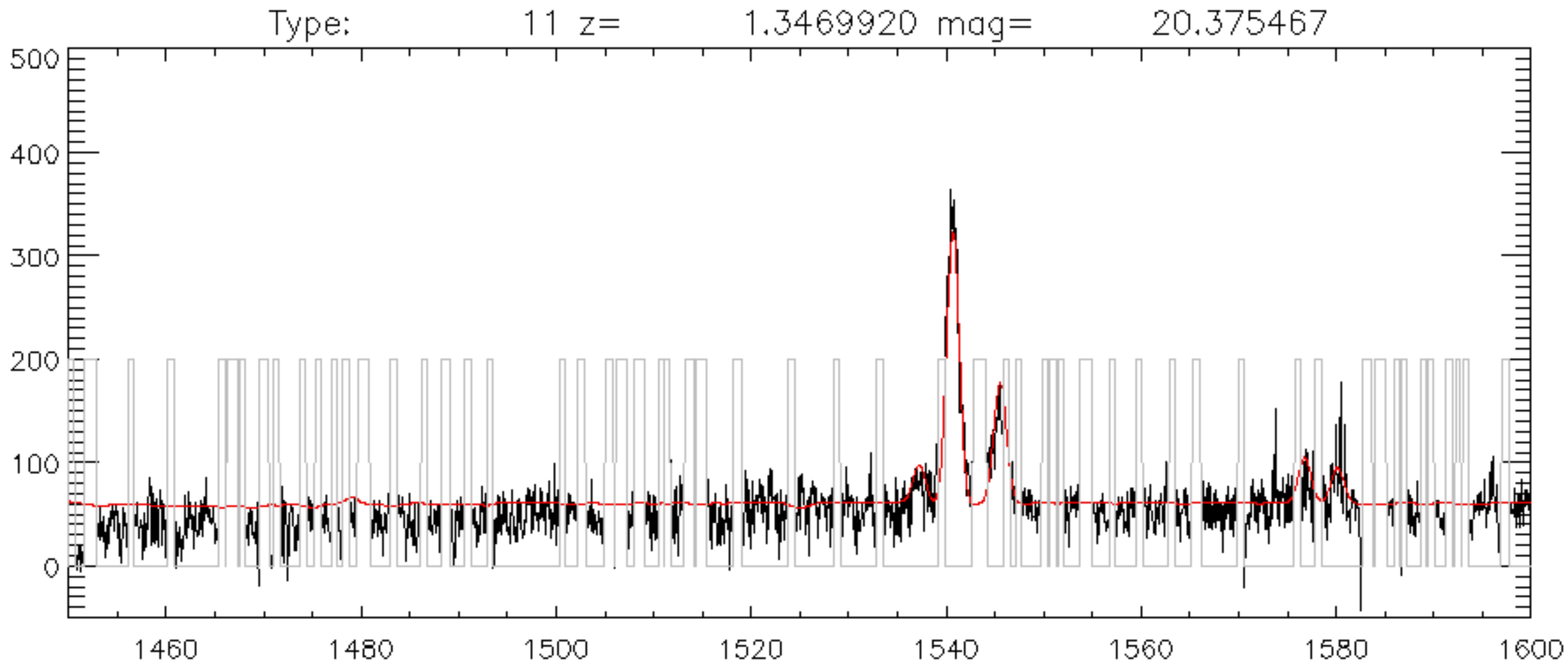
Fiber allocation

Select	ROW I10	COL I10	RA_OBJECT D23.17	DEC_OBJECT D23.17	FLAG I10	OBJECT I10
All Invert	Modify	Modify	Modify	Modify	Modify	Modify
20	32	4	-0.02992266406249660	-0.17666996842956501	11	7319
21	32	2	-0.01448066406248930	-0.17095796842956501	11	6590
22	32	0	-0.00021366406249967	-0.16495196842956500	11	5831
23	30	18	-0.10887166406249101	-0.16136996842956600	14	28362
24	30	16	-0.09407066406251370	-0.16942196842956500	-11	30107
25	30	14	-0.08473166406250240	-0.16852296842956499	-11	29986
26	30	12	-0.07153366406251389	-0.16541996842956500	-11	29522
27	30	10	-0.06034866406250220	-0.16831696842956501	-11	29893
28	30	8	-0.04484566406250680	-0.16655796842956500	-11	28688
29	30	6	-0.03591966406250440	-0.17231896842956601	-11	28691
30	30	4	-0.02374266406249600	-0.17149196842956499	-11	7319
31	30	2	-0.00830066406248875	-0.16577996842956599	-11	6590
32	30	0	0.00595133593751029	-0.15977396842956501	-11	5831
33	28	22	-0.13957166406248700	-0.15493396842956600	11	27404
34	28	20	-0.12638866406248900	-0.15268996842956600	11	26630
35	28	18	-0.11326566406251000	-0.15816996842956499	11	27753

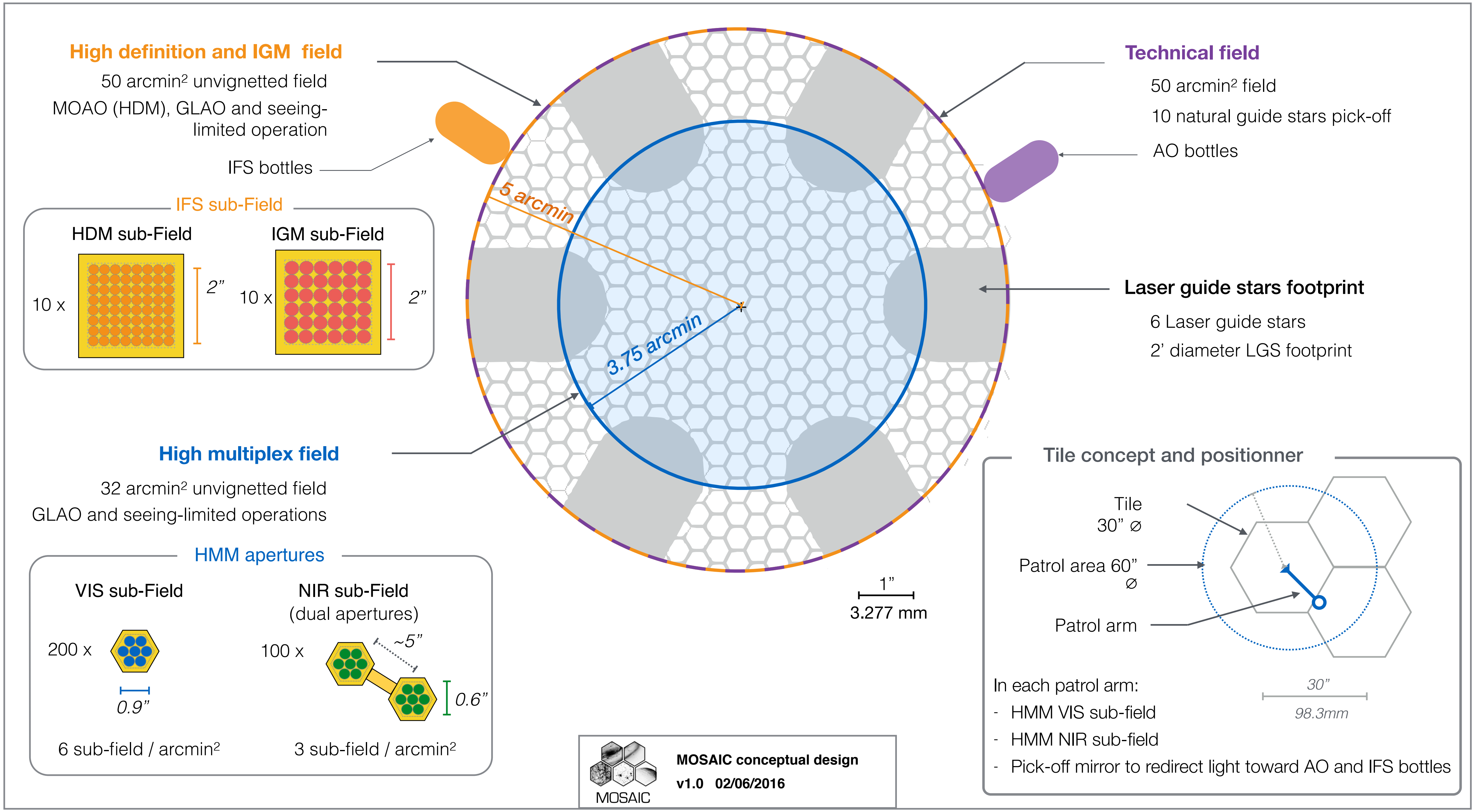
Results from the Xswitch: simulations

- The simulations mimic 1h of observation in H-band, split into 4 exposures of 15 min in a nodding sequence (A-B-A-B)

- Reduced with the MOONS DRS



Impact for the MOSAIC design and operation



Nodding will be made from the positionner (cannot nod the E-ELT and open AO-loop each 15min!)

Lesson learn from KMOS: Faint sky lines variations

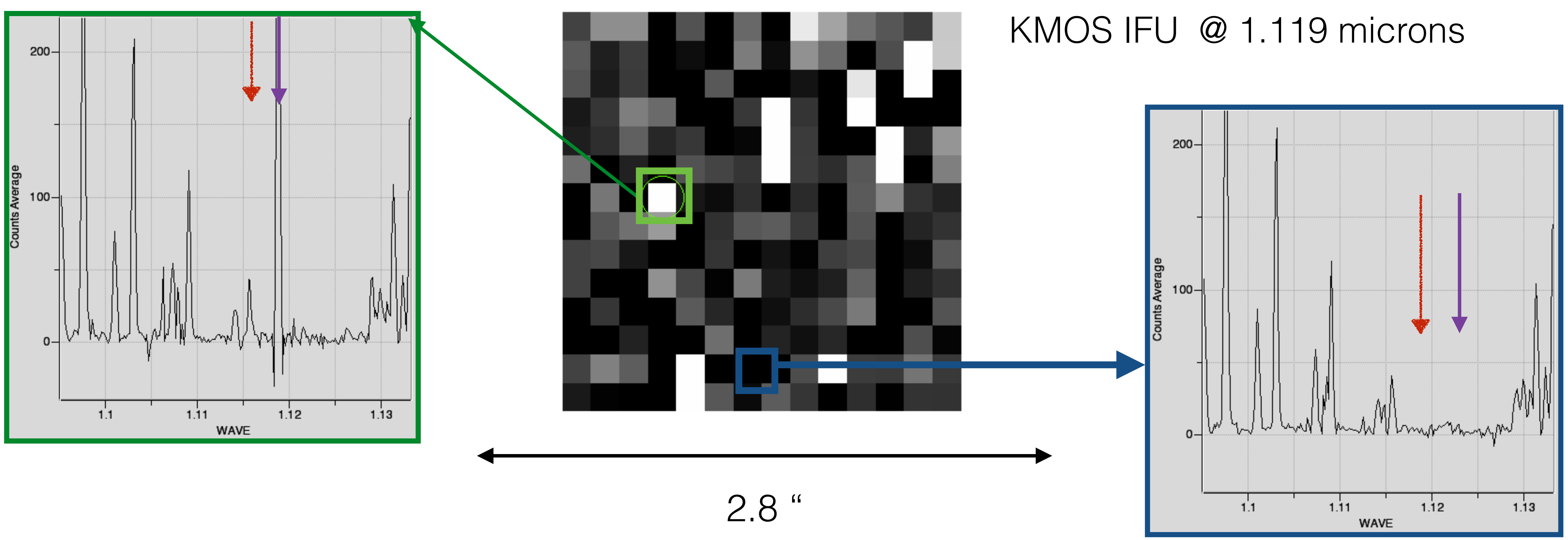
Spatial and temporal variation in 9 consecutive exposures of 10 min (Flores+16)

Brighter skylines

Changes spatially and temporally (10 min), 5 to 10% and up to 15%

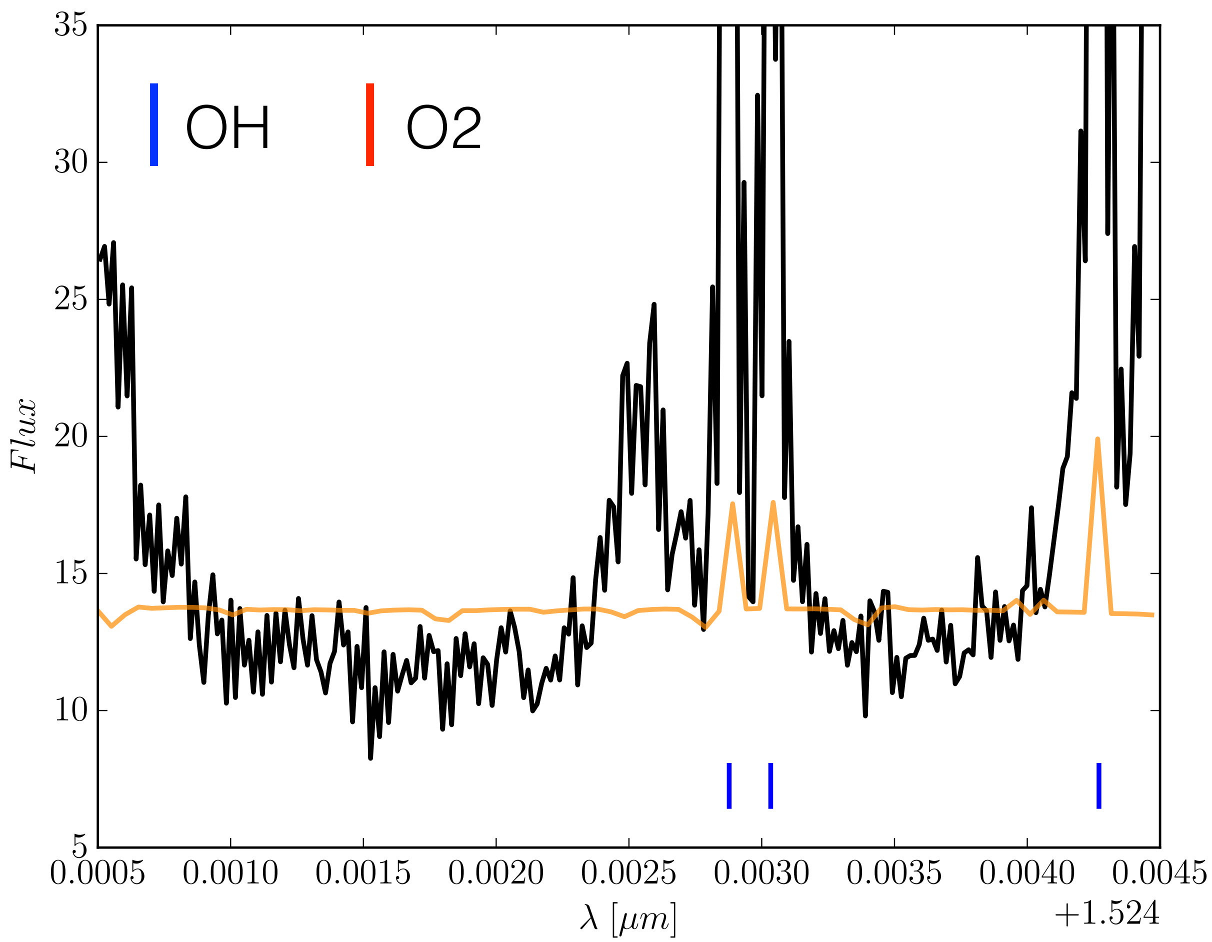
Faint skylines

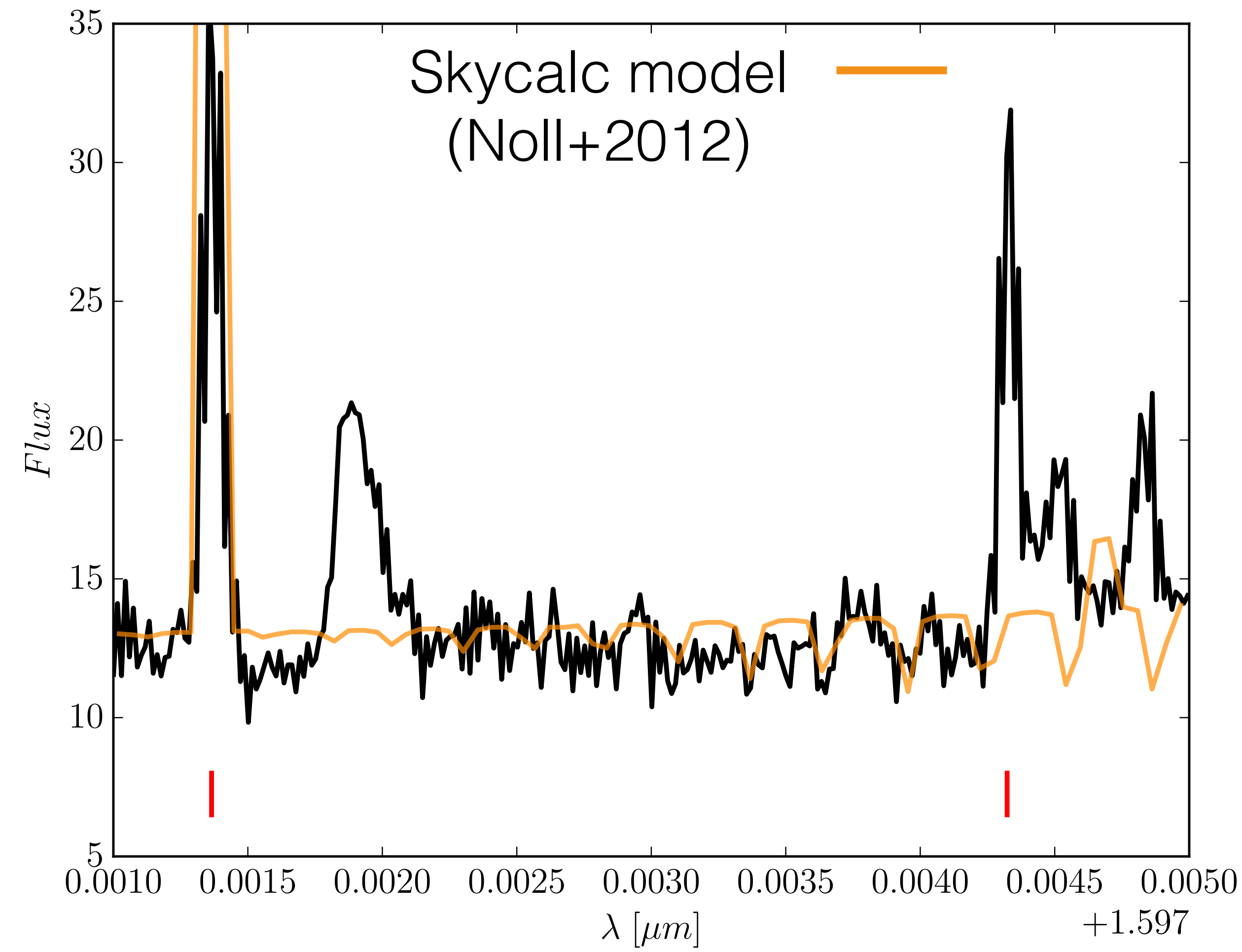
- 10 to 80 times fainter than the strong skyline in the spectral window
- spatial and temporal amplitude of up to 100%.



Faint sky lines catalogue

- H-band - free from intense sky lines $F_{line} < 19.6$ mag/arcsec^2 according to Oliva et al. (2015) based on high resolution GIANO NIR spectra
- APOGEE spectra at R=22 500 18 sky fibres combined





Catalogue of faint lines in H-band (Sanchez-Janssen in prep)

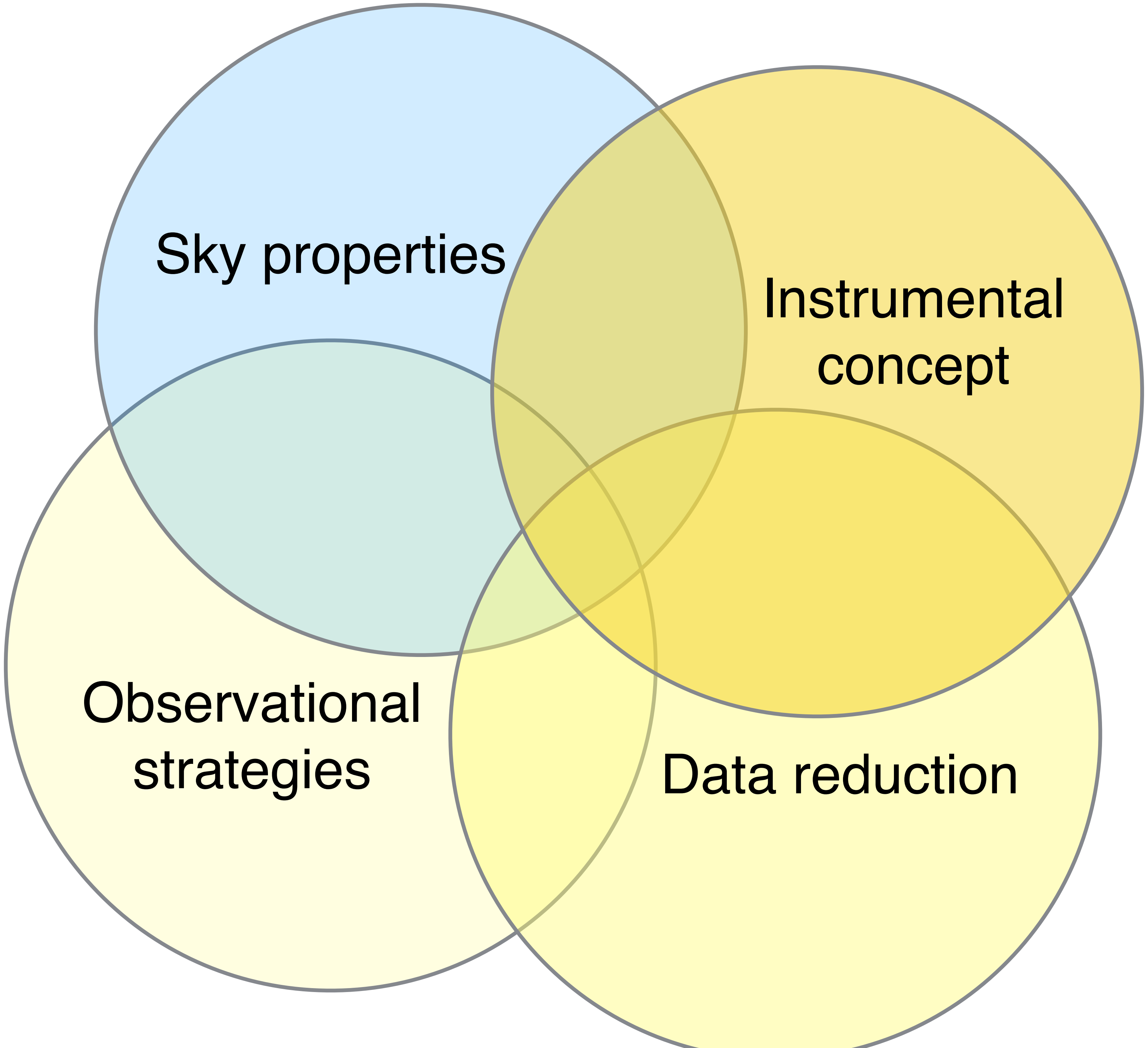
Conclusion

- Set of methods to achieve good of sky subtraction in the Airglow lines dominated regime
- Possible to reach < 1% accuracy on sky-subtraction of the background using cross-beam switching
- This mode is being integrated to the design of next fiber-fed spectrograph (MOONS@VLT, MOSAIC@E-ELT)

- Progress on the characterisation of the sky in the NIR
  - Spatial and temporal variation of the sky background
  - Complete the line catalogues: faint lines

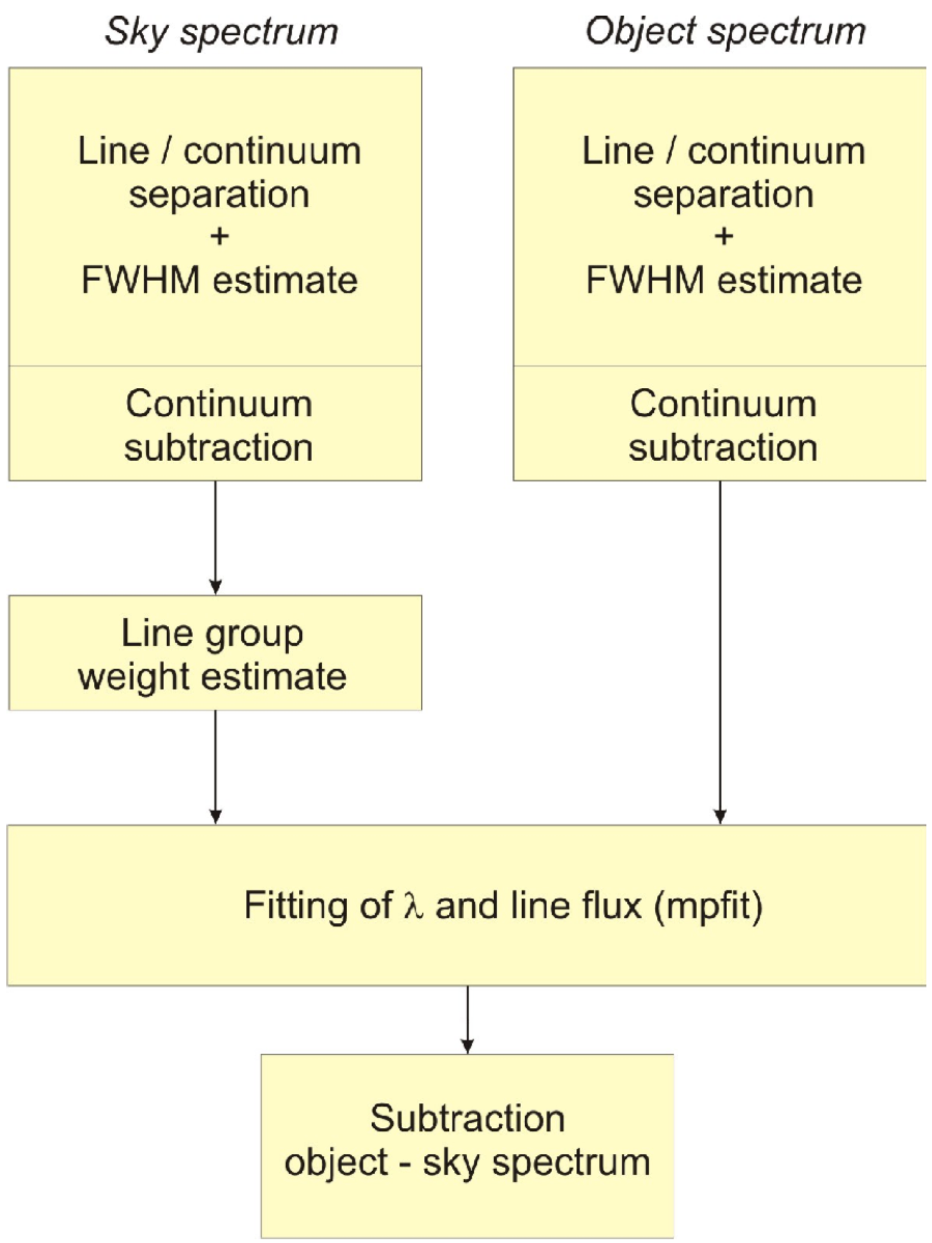
- Instrumental residuals
  - NIR detectors
  - Fiber responses
  - Scatter light

Sky subtraction in the different regimes



Data reduction

Physical modelling of OH temporal variation



http://www.eso.org/sci/software/pipelines/skytools/skycorr

Skycorr (Noll+2014)

1- Line and continuum are separated

2- Continuum is evaluated in the sky spectrum and subtracted to both sky and object spectrum

3- Weight mask for the different airglow line groups in the reference sky spectrum using a extended sky model

4- Reference sky line spectrum is fitted to the emission lines in the science spectrum (flux and wavelength fitting)

5- Best-fit sky spectrum is subtracted to the object spectrum