Developing an instrument simulator for HARMONI

E-ELT Data Simulation Workshop

Munich, 14th April 2016

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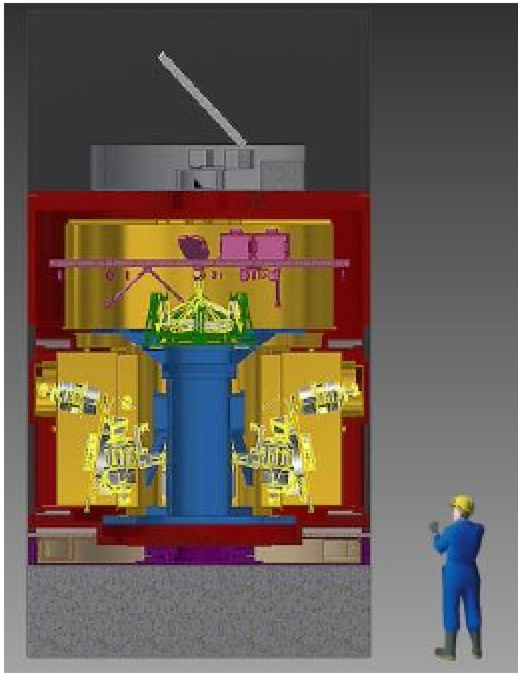
E-ELT/HARMONI



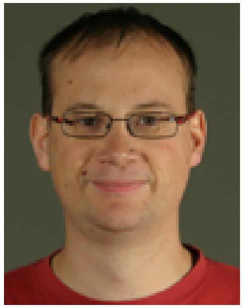
- First light Integral Field Spectrograph
- Large spectral band 0.47 – 2.45 µm
- FoV 152 x 214 = 32 528 spaxels
- 4 FoV scales:
  - 6.42’’x9.12’’, 3.04’’x4.28’’, 1.52’x2.14’’, 0.61’’x0.86’’
- 4 spectral resolutions:
  - R=400, R=3500, R=8000, R=20000

HARMONI Science Software

- CRAL is responsible for the HARMONI Science Software
  - Data Reduction System (Pipeline)
  - Instrument Numerical Model

Arlette Pécontal

Laure Piqueras



Aurélien Jarno

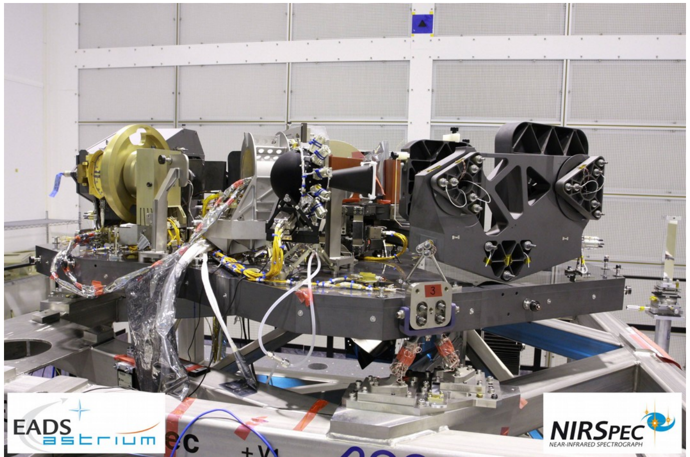
Why an instrument simulator for HARMONI?

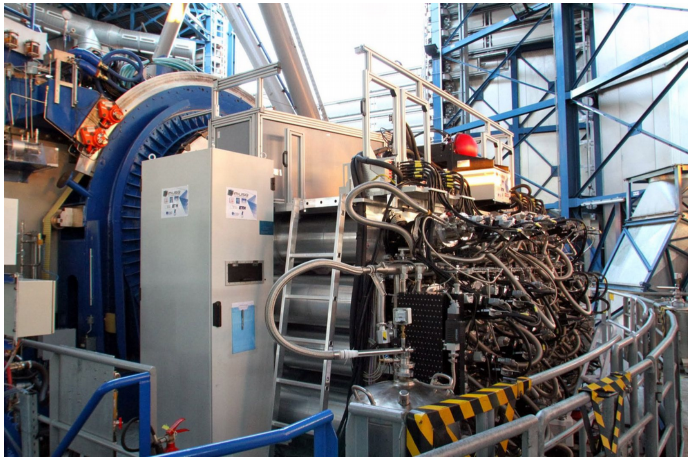
- Used to develop the data reduction pipeline
- Also a tool to understand the instrument
  - Inputs for performance-related trade-offs
  - Early verification of the instruments performances
  - Preparation of test and calibration campaigns
  - Validation or pre-validation of specifications before the on-sky commissioning
  - Providing synthetic detector readouts for
    - the development of various software (AIV, data analysis)
    - the science preparation

The instrument simulators developed at CRAL

- **JWST/NIRSpec**
  - Space based instrument
  - Imager / Long slit spectroscopy / MOS / IFS
  - NIR range: 0.6-5µm
  - Industrial context (ESA, EADS Astrium)

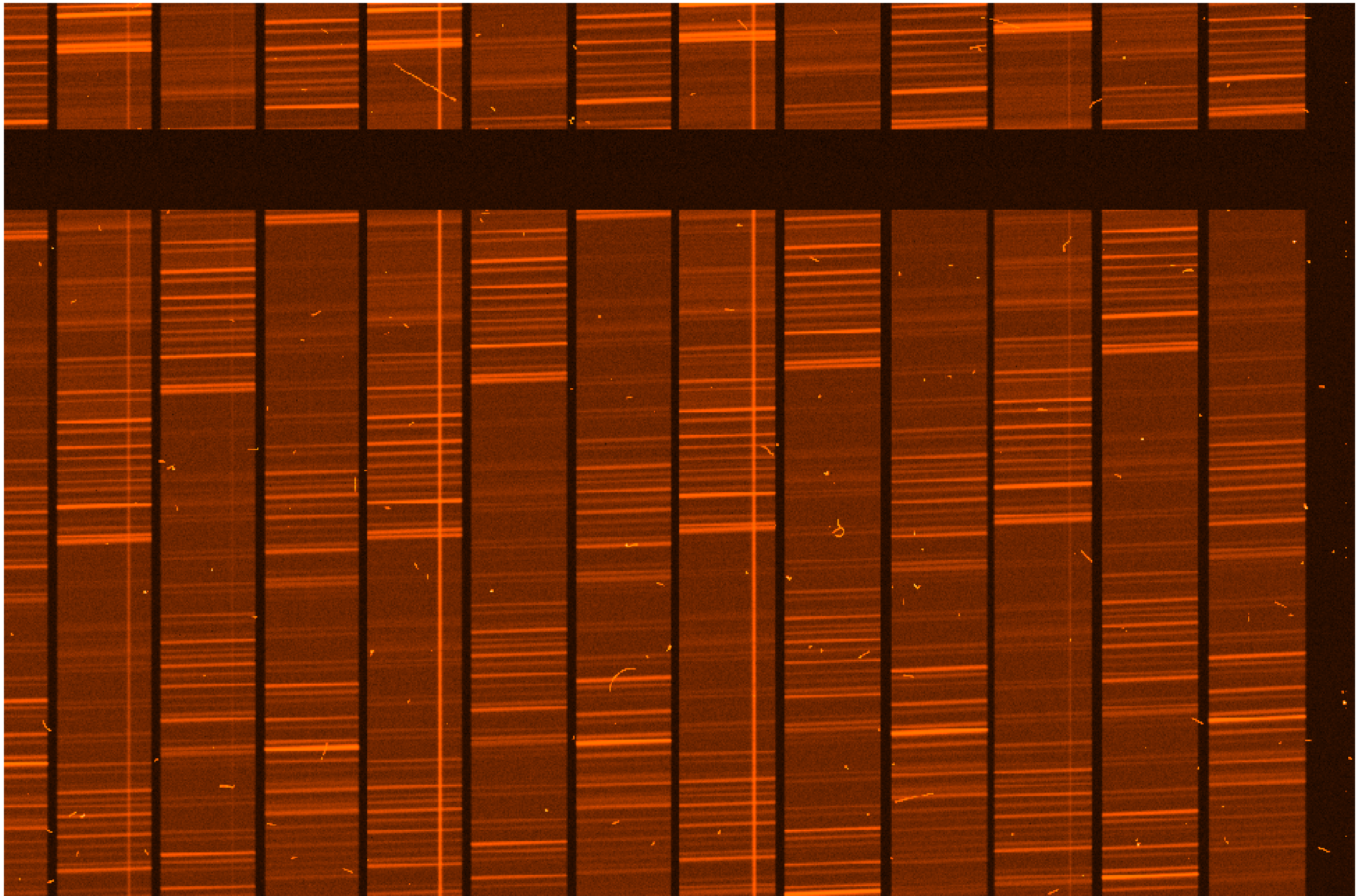
- **VLT/MUSE**
  - Ground based instrument
  - IFS
  - Visible range : 465-930 nm
  - Developed internally in the consortium





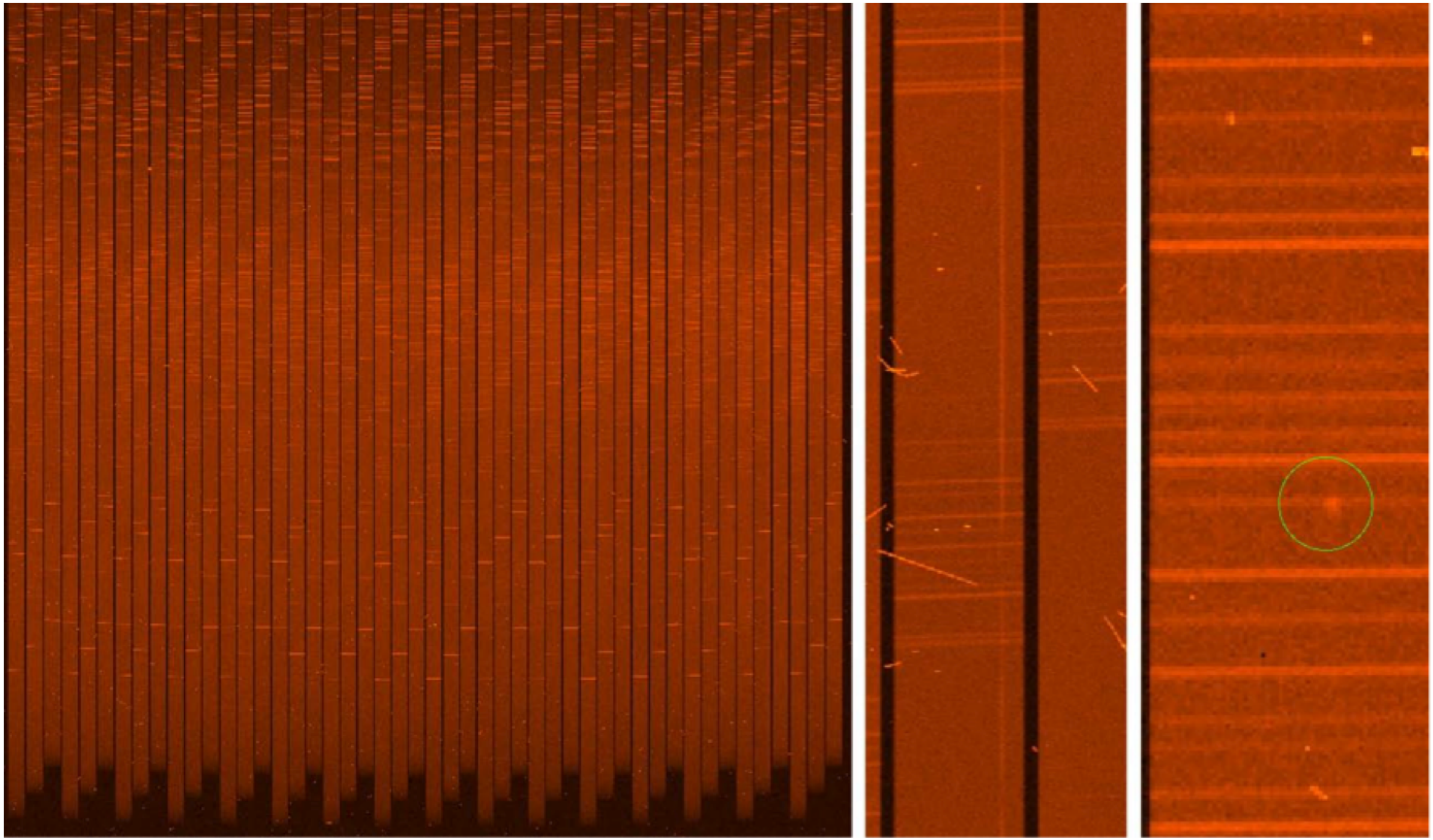
Example of MUSE (1)

- Single star



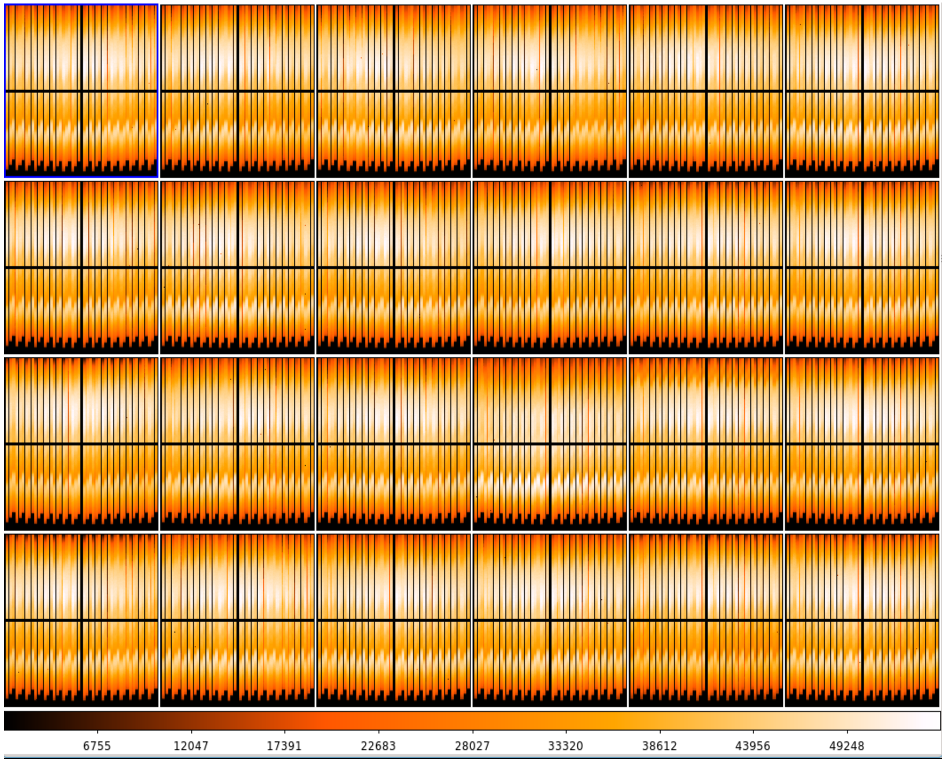
Example of MUSE (2)

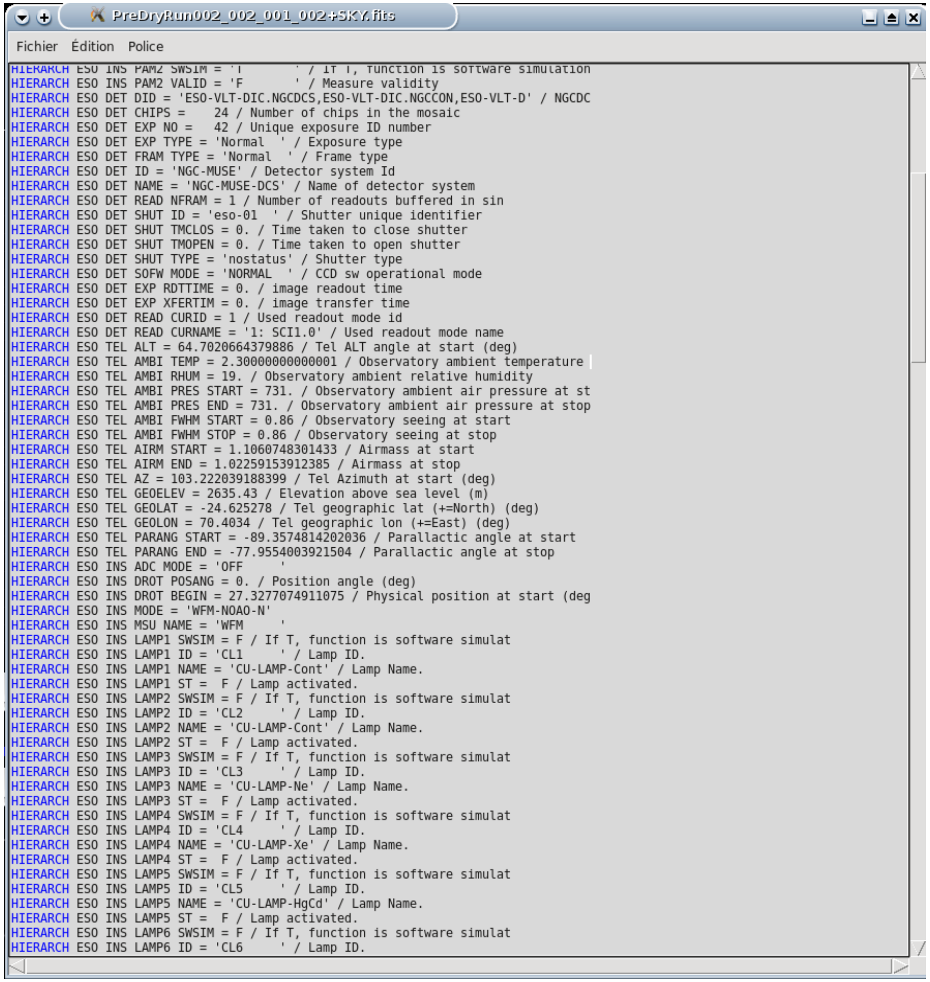
- Lyman-alpha emitter



Example of MUSE (3)

- Calibration exposures
- FITS headers

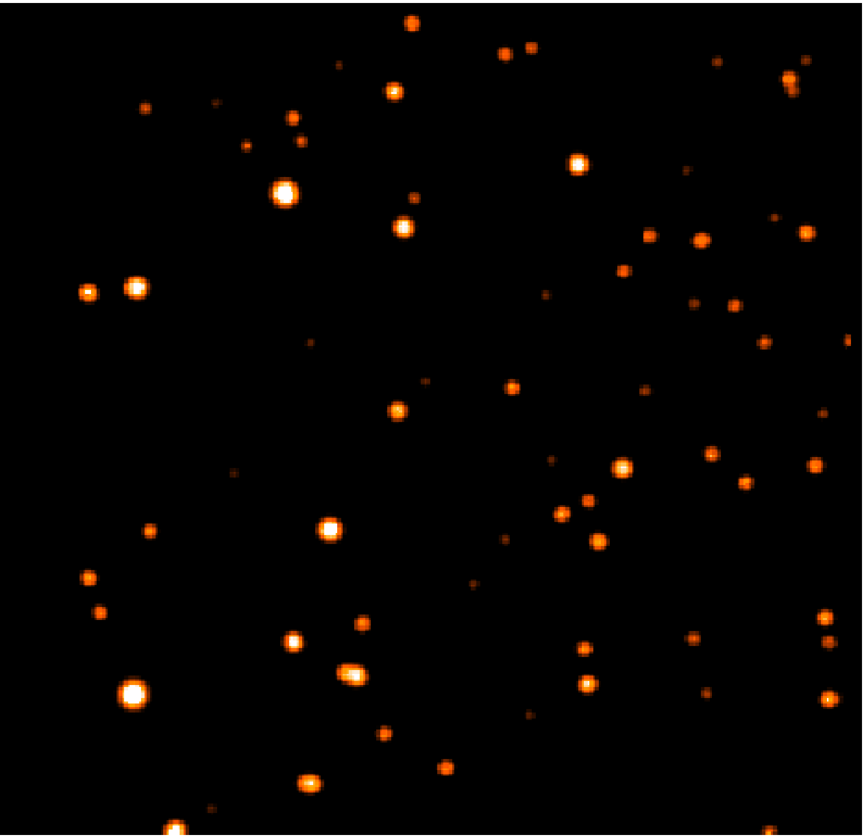


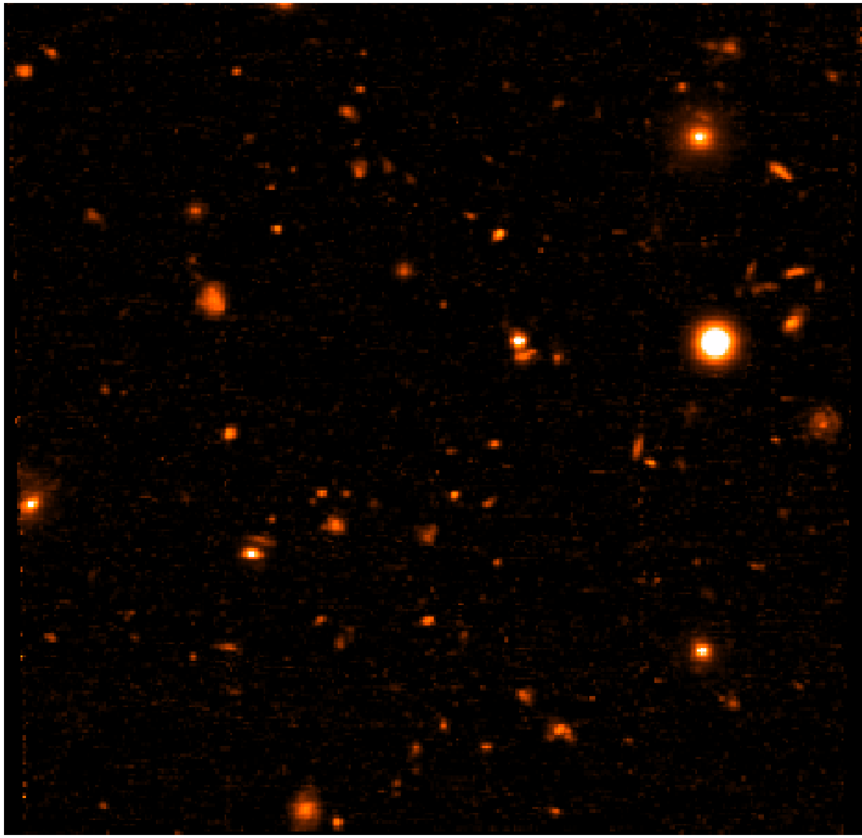


```
HIERARCH ESO INS PAM2 SWSIM = 'T      ' / If T, function is software simulation
HIERARCH ESO INS PAM2 VALID = 'F      ' / Measure validity
HIERARCH ESO DET DID = 'ESO-VLT-DIC.NGCDCS,ESO-VLT-DIC.NGCCON,ESO-VLT-D' / NGCDC
HIERARCH ESO DET CHIPS =    24 / Number of chips in the mosaic
HIERARCH ESO DET EXP NO =   42 / Unique exposure ID number
HIERARCH ESO DET EXP TYPE = 'Normal  ' / Exposure type
HIERARCH ESO DET FRAM TYPE = 'Normal  ' / Frame type
HIERARCH ESO DET ID = 'NGC-MUSE' / Detector system Id
HIERARCH ESO DET NAME = 'NGC-MUSE-DCS' / Name of detector system
HIERARCH ESO DET READ NFRAM = 1 / Number of readouts buffered in sin
HIERARCH ESO DET SHUT ID = 'eso-01  ' / Shutter unique identifier
HIERARCH ESO DET SHUT TMCLOS = 0. / Time taken to close shutter
HIERARCH ESO DET SHUT TMOPEN = 0. / Time taken to open shutter
HIERARCH ESO DET SHUT TYPE = 'nostatus' / Shutter type
HIERARCH ESO DET SOFW MODE = 'NORMAL  ' / CCD sw operational mode
HIERARCH ESO DET EXP RDTTIME = 0. / image readout time
HIERARCH ESO DET EXP XFERTIM = 0. / image transfer time
HIERARCH ESO DET READ CURID = 1 / Used readout mode id
HIERARCH ESO DET READ CURNAME = '1: SCI1.0' / Used readout mode name
HIERARCH ESO TEL ALT = 64.7020664379886 / Tel ALT angle at start (deg)
HIERARCH ESO TEL AMBI TEMP = 2.30000000000001 / Observatory ambient temperature
HIERARCH ESO TEL AMBI RHUM = 19. / Observatory ambient relative humidity
HIERARCH ESO TEL AMBI PRES START = 731. / Observatory ambient air pressure at st
HIERARCH ESO TEL AMBI PRES END = 731. / Observatory ambient air pressure at stop
HIERARCH ESO TEL AMBI FWHM START = 0.86 / Observatory seeing at start
HIERARCH ESO TEL AMBI FWHM STOP = 0.86 / Observatory seeing at stop
HIERARCH ESO TEL AIRM START = 1.1060748301433 / Airmass at start
HIERARCH ESO TEL AIRM END = 1.02259153912385 / Airmass at stop
HIERARCH ESO TEL AZ = 103.222039188399 / Tel Azimuth at start (deg)
HIERARCH ESO TEL GEOELEV = 2635.43 / Elevation above sea level (m)
HIERARCH ESO TEL GEOLAT = -24.625278 / Tel geographic lat (+=North) (deg)
HIERARCH ESO TEL GEOLON = 70.4034 / Tel geographic lon (+=East) (deg)
HIERARCH ESO TEL PARANG START = -89.3574814202036 / Parallactic angle at start
HIERARCH ESO TEL PARANG END = -77.9554003921504 / Parallactic angle at stop
HIERARCH ESO INS ADC MODE = 'OFF     '
HIERARCH ESO INS DROT POSANG = 0. / Position angle (deg)
HIERARCH ESO INS DROT BEGIN = 27.3277074911075 / Physical position at start (deg
HIERARCH ESO INS MODE = 'WFM-NOAO-N'
HIERARCH ESO INS MSU NAME = 'WFM     '
HIERARCH ESO INS LAMP1 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP1 ID = 'CL1     ' / Lamp ID.
HIERARCH ESO INS LAMP1 NAME = 'CU-LAMP-Cont' / Lamp Name.
HIERARCH ESO INS LAMP1 ST =  F / Lamp activated.
HIERARCH ESO INS LAMP2 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP2 ID = 'CL2     ' / Lamp ID.
HIERARCH ESO INS LAMP2 NAME = 'CU-LAMP-Cont' / Lamp Name.
HIERARCH ESO INS LAMP2 ST =  F / Lamp activated.
HIERARCH ESO INS LAMP3 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP3 ID = 'CL3     ' / Lamp ID.
HIERARCH ESO INS LAMP3 NAME = 'CU-LAMP-Ne' / Lamp Name.
HIERARCH ESO INS LAMP3 ST =  F / Lamp activated.
HIERARCH ESO INS LAMP4 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP4 ID = 'CL4     ' / Lamp ID.
HIERARCH ESO INS LAMP4 NAME = 'CU-LAMP-Xe' / Lamp Name.
HIERARCH ESO INS LAMP4 ST =  F / Lamp activated.
HIERARCH ESO INS LAMP5 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP5 ID = 'CL5     ' / Lamp ID.
HIERARCH ESO INS LAMP5 NAME = 'CU-LAMP-HgCd' / Lamp Name.
HIERARCH ESO INS LAMP5 ST =  F / Lamp activated.
HIERARCH ESO INS LAMP6 SWSIM = F / If T, function is software simulat
HIERARCH ESO INS LAMP6 ID = 'CL6     ' / Lamp ID.
```

Example of MUSE (4)

- Typical simulated scenes


Star field


Deep field

Principle of the simulator

- From incident photons to electrons

How is light spread on the detectors?

- Fourier optics propagation and PSF convolution
- Taking into account optical aberrations, wavefront errors, diffraction effects

Where does it go?

- Taking into account realistic coordinate transforms
- Modeling the dispersers

How many photons make it into electrons?

- Include information about the transmission/efficiency of the instrument
- Taking into account slit/diffraction losses
- Detector radiometric response

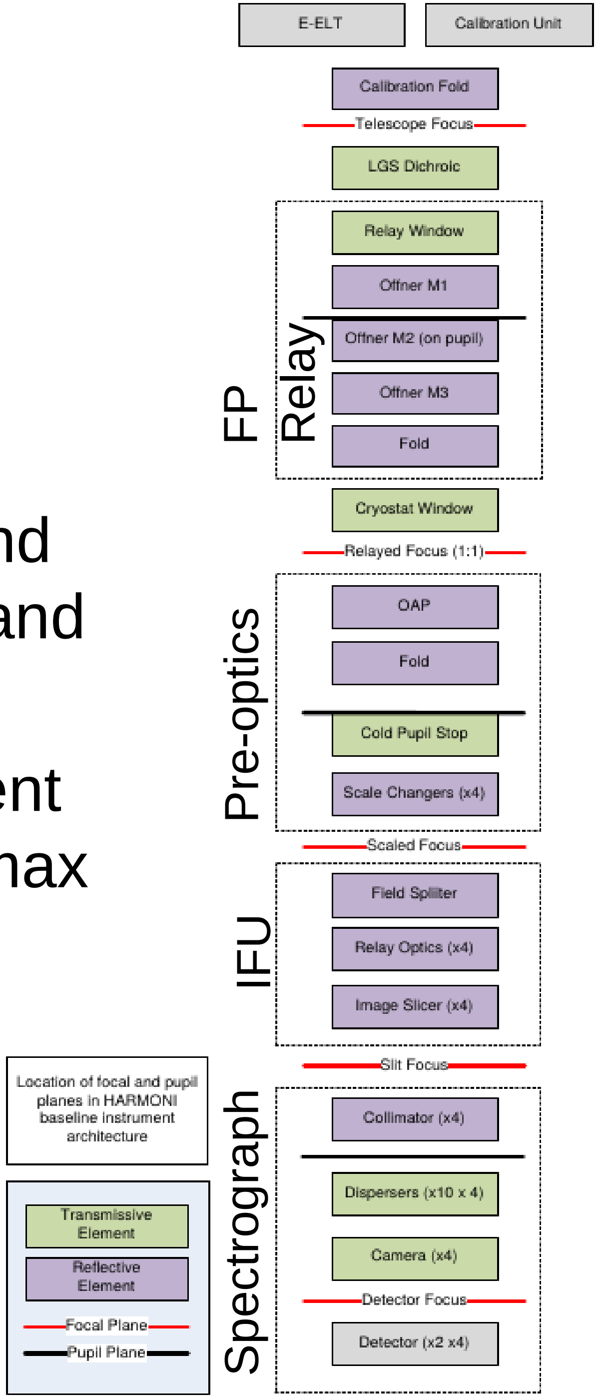
- From electrons to ADU

How electrons are counted?

- Detectors effects
- Read-out process and effects

Fourier optics

- Instrument divided into optical modules
- Wave-front propagation between pupil and image planes using Fourier transforms (and vice versa)
- Aberrations introduced using an equivalent wavefront error mask extracted from Zemax
    - Variable within the FoV
    - Variable with the wavelength
- PSFs can be computed on the fly for each optical module at multiple positions and wavelengths



E-ELT
Calibration Unit
Calibration Fold
Telescope Focus
LGS Dichroic

FP Relay
Relay Window
Offner M1
Offner M2 (on pupil)
Offner M3
Fold

Cryostat Window
Relayed Focus (1:1)

Pre-optics
OAP
Fold
Cold Pupil Stop
Scale Changers (x4)

Scaled Focus

IFU
Field Splitter
Relay Optics (x4)
Image Slicer (x4)

Slit Focus

Spectrograph
Collimator (x4)
Dispersers (x10 x 4)
Camera (x4)
Detector Focus
Detector (x2 x4)

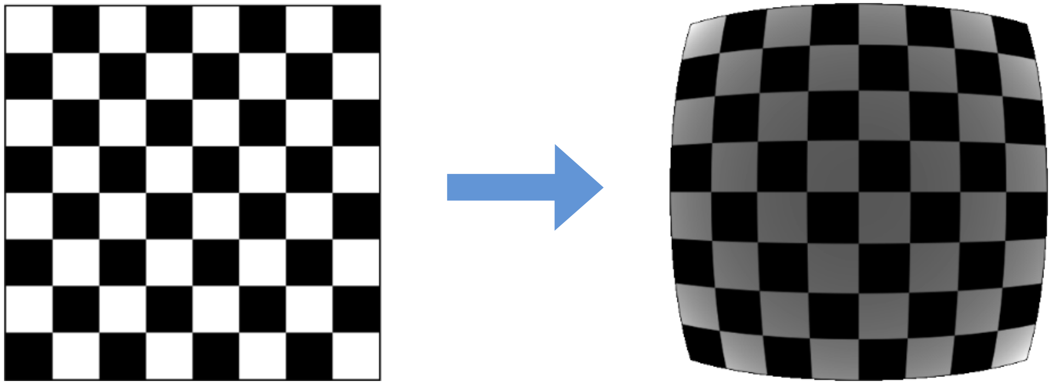
Location of focal and pupil planes in HARMONI baseline instrument architecture

Transmissive Element
Reflective Element
Focal Plane
Pupil Plane

Coordinate transforms

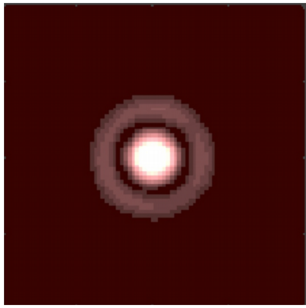
- Design coordinate transforms maps produced by ZEMAX
- Possibility to use measured maps
- Maps are used to produce a parametric model of the coordinates transform (3D polynomial)
- Dispersers modeled analytically
- Dilution function computed as $|\det(J_P(x,y,\lambda))|$

```
# Create a barrel coordinate transforms map
px = np.array([[ 0.0,  0.0,  0.0,  0.0],
               [ 1.0,  0.0, -0.1,  0.0],
               [ 0.0,  0.0,  0.0,  0.0],
               [-0.1,  0.0,  0.0,  0.0]])
py = np.array([[ 0.0,  1.0,  0.0, -0.1],
               [ 0.0,  0.0,  0.0,  0.0],
               [ 0.0, -0.1,  0.0,  0.0],
               [ 0.0,  0.0,  0.0,  0.0]])
```

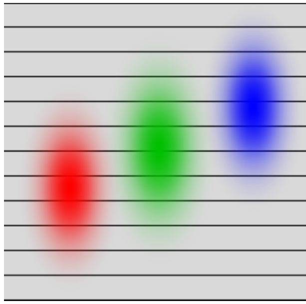


Atmosphere simulation

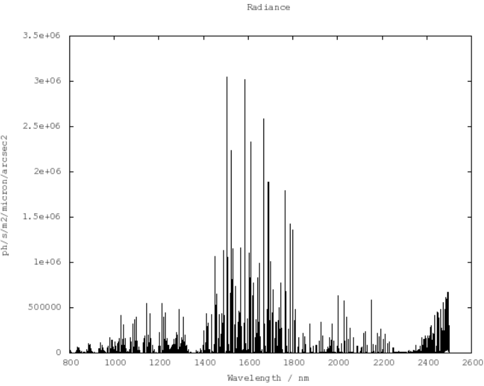
- Seeing
  - Modeled as a PSF variable over FoV and wavelength
  - Simulations done by AO team (LAM)
  - Also includes other telescope effects (pointing, wind shake, etc.)



- Atmospheric refraction
  - Depends on temperature, humidity, pressure
  - Depends on the parallactic angle, which varies during the exposure. We apply the integrated effect
    - for visible detectors during the whole exposure
    - for IR detectors between two readouts

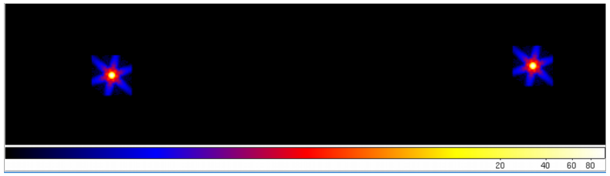


- Sky background and absorption lines
  - Modeled using ESO SKYCALC Sky Model Calcula

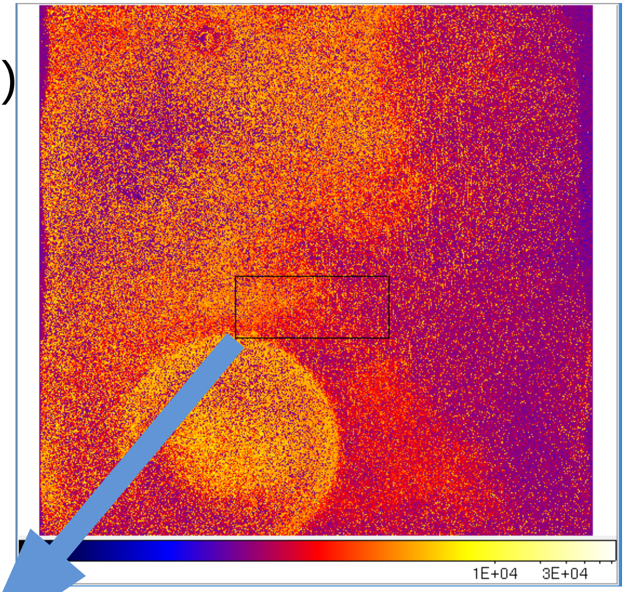


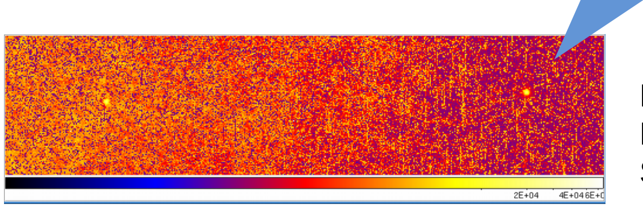
Detector modeling

- Reproduce the conversion from photons to electrons and to ADU
- Chromatic part
  - Sampling
  - Quantum efficiency
  - Inter and intra-pixel sensitivity
- Non chromatic part
  - Cosmetics (hot/dark pixels/columns/clusters, traps)
  - Dark current
  - Shot noise
  - Non linearity
  - Charge transfer efficiency
  - Read-out noise
  - Conversion into ADU
  - Cosmic rays



Zoom on pinholes in the electron rate map



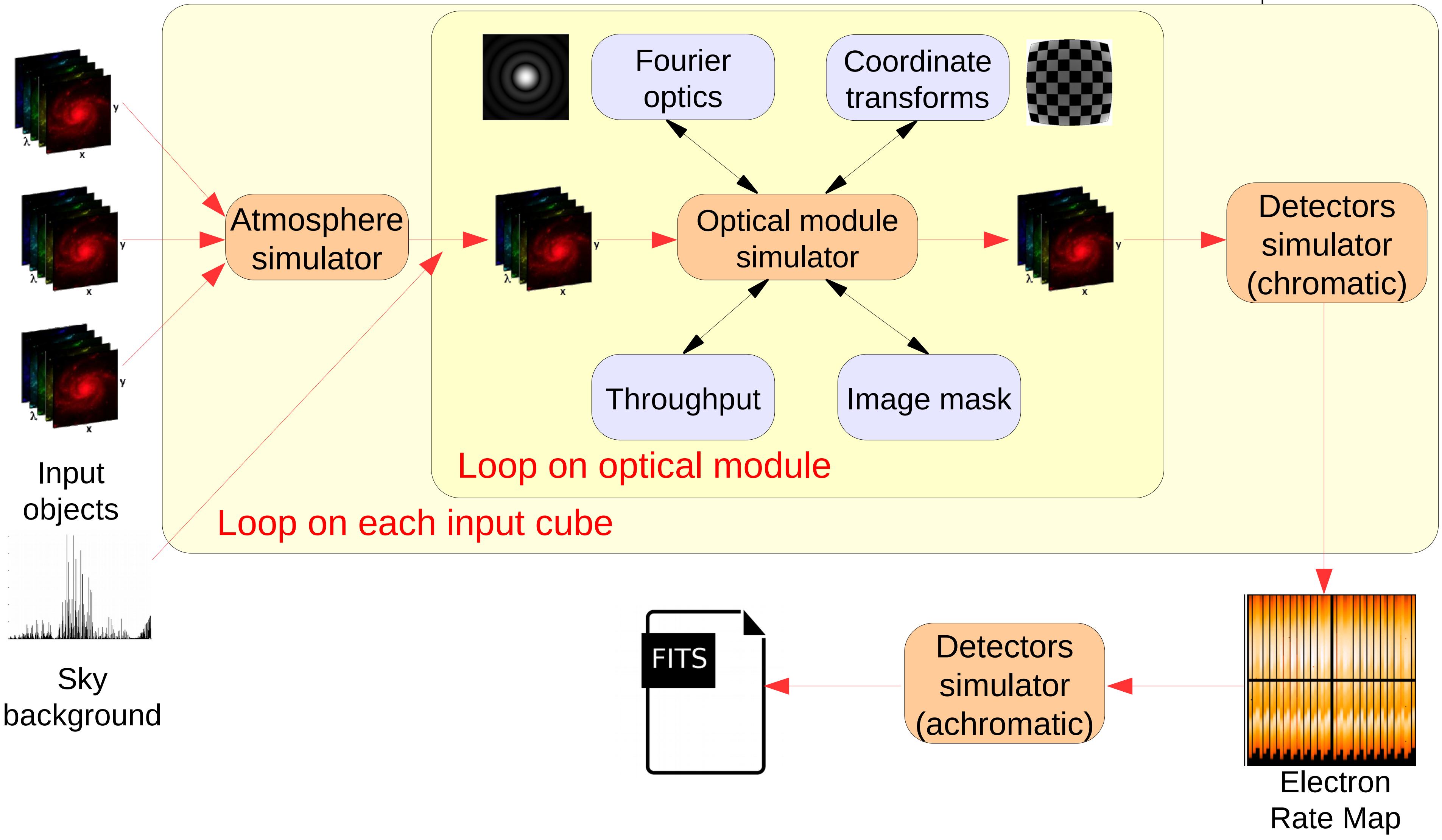


Exposure simulation with NIRSpec DM detector (zoom on pinholes and SCA491)

Exposure simulator (1)

- Glue between the previous software components to produce synthetic exposures
- Input data for on sky exposures
  - Astrophysical scene: set of "objects" (small cube) with their location
  - Sky coordinates
  - Date and time of observation
  - Atmospheric conditions (seeing, temperature, humidity, pressure, etc.)
- Input data for calibration exposures
  - Calibration unit setup (lamps, masks, …)
  - Date and time of observation

Exposure simulator (2)



Input objects

Sky background

Atmosphere simulator

Fourier optics

Coordinate transforms

Optical module simulator

Throughput

Image mask

Loop on optical module

Loop on each input cube

Detectors simulator (chromatic)

Electron Rate Map

Detectors simulator (achromatic)

FITS

Lessons learned: schedule and development methods

- A good phasing with the project is essential to make an instrument simulator useful
  - Needs a lot of data/information from the project
  - Living software which evolves as the instrument is being built
  - Can help developing data reduction and data analysis software
  - Can help doing strategic choices
- → Therefore:
  - → Flexible development methods
  - → Most demanded feature: exposure simulator
  - → Consider releasing exposures instead of software (at least during the development)

Lessons learned: track assumptions and limitations

- Usual initial goal: make the simulator as generic as possible
- Then comes the optimization time: adding assumptions and limitations
- It is essential to track the assumptions and limitations
  - In case of design changes (both simulator and instrument)
  - For future developers of the software
  - For the users (both of the software and simulated exposures)

Lessons learned: interfaces

- An instrument simulator manipulates a lot of data from various sources
  - Instrument model: optical design, wavefront maps, throughput, etc.
  - Astrophysical scenes: cubes, images, spectra, etc.
- → Use an interface control document
  - Should evolve with the developments if needed
  - Should be discussed with the users
- → Define a common vocabulary between all people
- Difficulties to get measured data from suppliers in a given format, sometimes even in a numerical format

Lessons learned: building instrument models

- Garbage in, garbage out principle: the main limitation comes from
  - the instrument knowledge
  - the availability and the quality of the characterization data
- → Participation to the AIV phase proved to be useful
- Building instrument models requires
  - A good knowledge of the instrument
  - A good knowledge of the simulator
  - A good knowledge of the science that will be done
- → Models should be created with the help of a scientist with strong instrumentation background

Lessons learned: programming language

- Instrument simulators are CPU and memory intensive
  - Fined-grain memory control
  - Multithreaded code
- Both MUSE and NIRSpec instrument simulators were fully developed in C++
- HARMONI instrument simulator will be developed
  - Mostly in Python
  - C/C++ for the computation intensive parts

NumPy SciPy astropy

A Community Python Library for Astronomy

Conclusion

- The HARMONI is project now in phase B
- The optical design is still changing a lot
- Currently in the early design phase of the instrument simulator
  - Mostly prototyping things
  - Testing new ideas