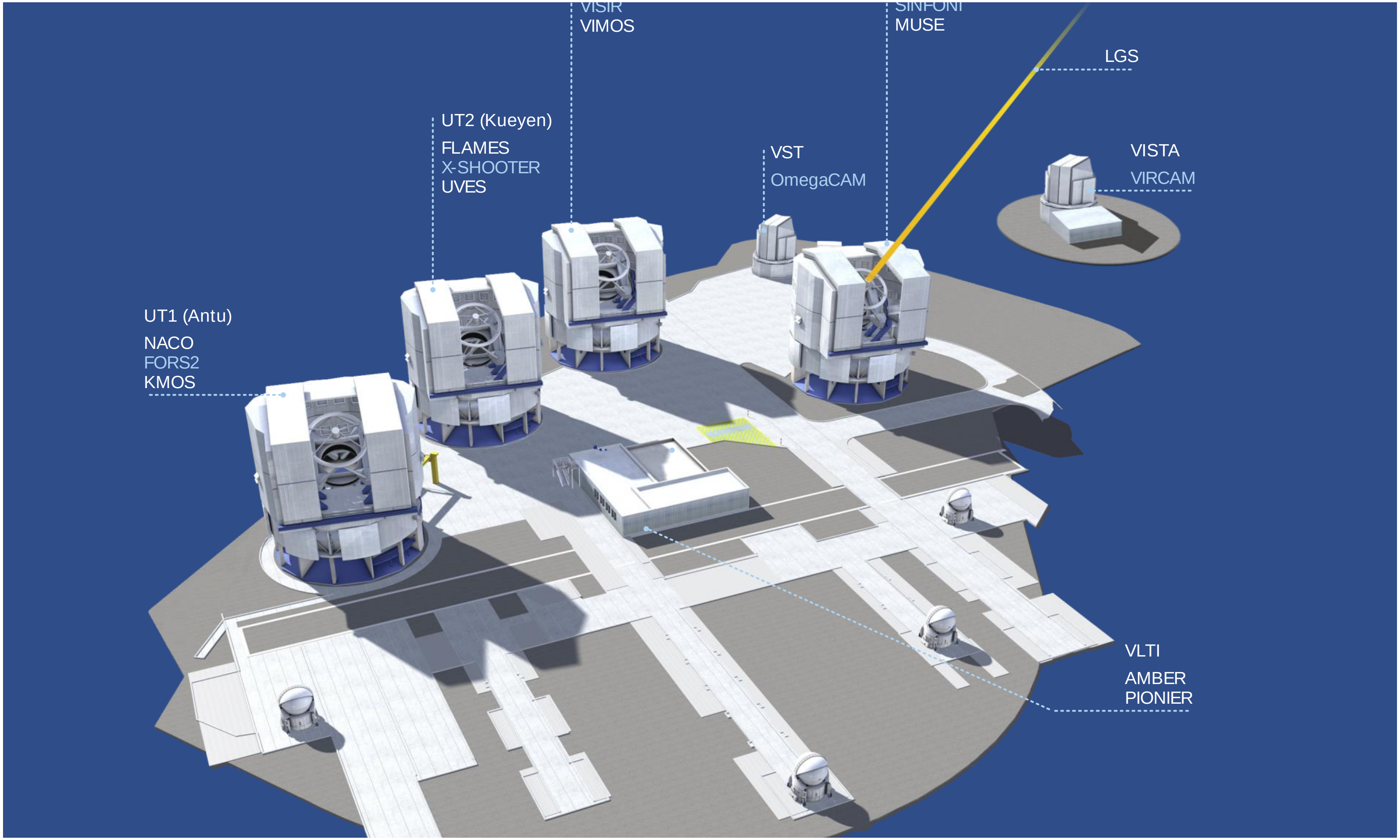
# Ground Based Instrumentation for Astronomy

L. Pasquini, ESO

# Talk Summary

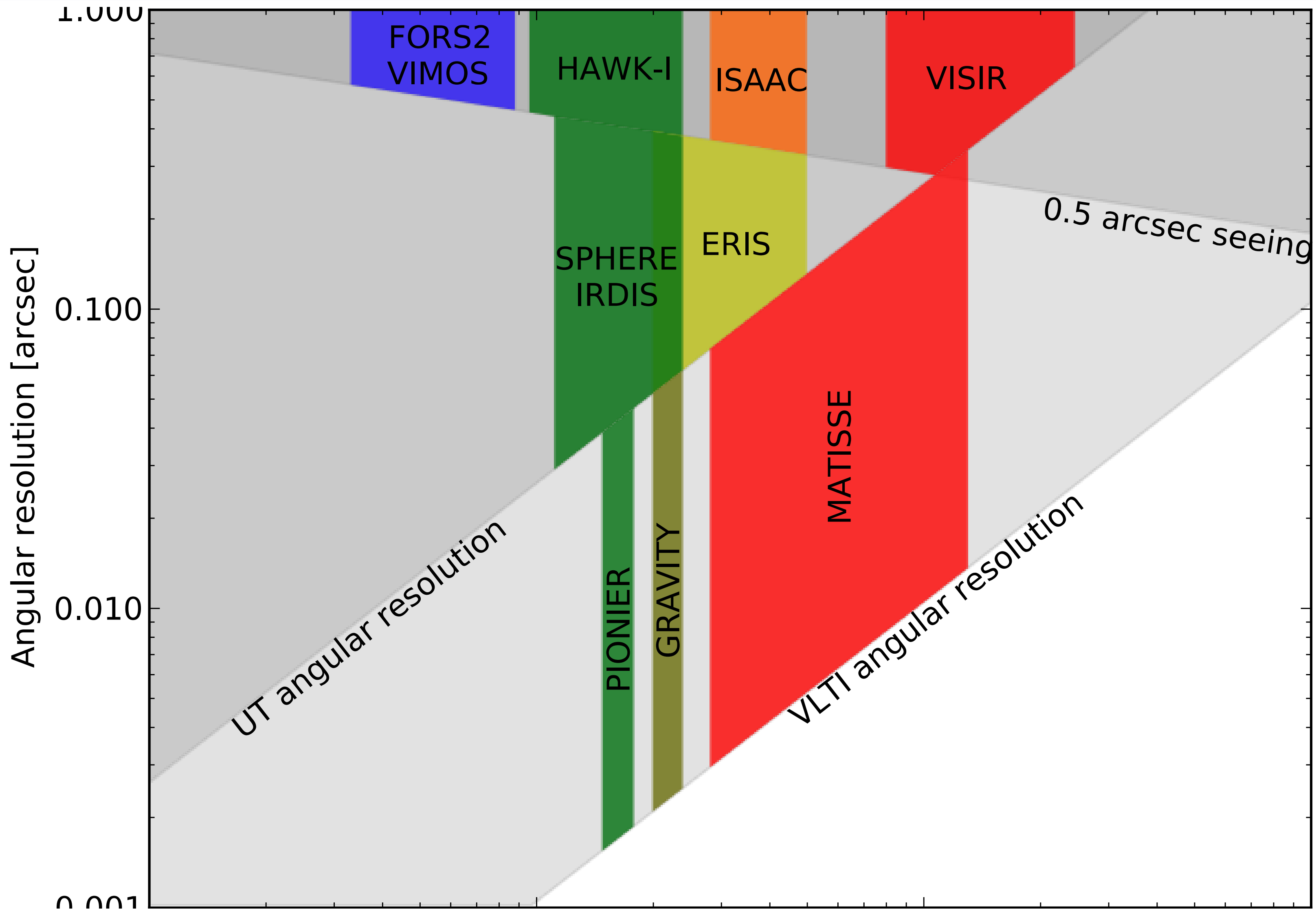
- Setting the Stage
- Couple of general points
- Recent examples

# The Paranal Instruments

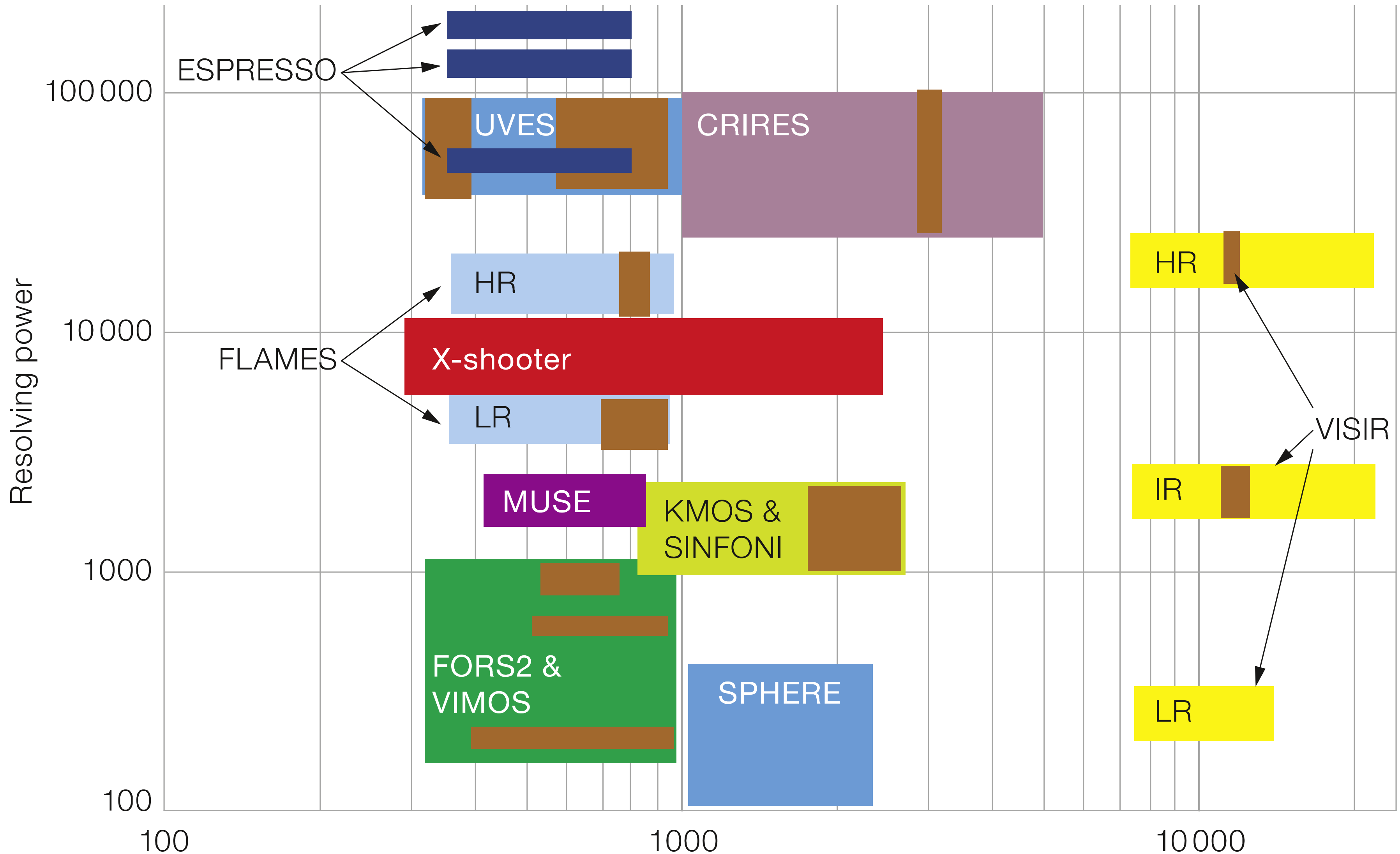


# Setting the stage

# Imaging


1.000
0.100
0.010
0.001
Angular resolution [arcsec]
FORS2
VIMOS
HAWK-I
ISAAC
VISIR
SPHERE
IRDIS
ERIS
0.5 arcsec seeing
MATISSE
PIONIER
GRAVITY
UT angular resolution
VLTI angular resolution

# Spectroscopy



# Some other basic facts

- Instruments are built ‘in house’ or in collaboration with community, in exchange of GTO. ESO remains an ‘intelligent costumer’.
- ESO is a community observatory: both ‘general use’ and ‘dedicated’ instruments
- Costs: from 3-4 ME (for 4m class telescopes) to 30-40 ME (HW and FTEs included: 2$^{nd}$Gen VLT instruments)
- Development time: 4-10+ years after approval
- Large variety of parameters and characteristics

# Signal To Noise

- It always enter into play.. Scientific requirements, pixel scale, resolution…

$$S/N = \frac{N_{ph}}{\sqrt{N_{ph} + N_{pix} * (RON^2 + DK) + N_{sky} + N_{oth}}}$$

Valid for on-chip un-binned pixels, slightly more complex for IR observations

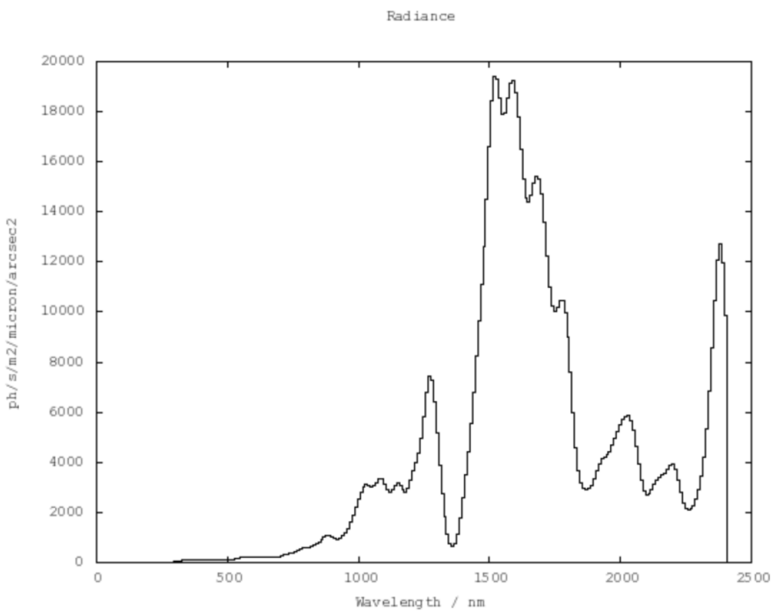
$N_{ph}$ = Photons from Source
$N_{sky}$ = Photons from sky
$N_{oth}$ = Any other source – shall be Zero (but it may cost A LOT to get it..)

# Signal

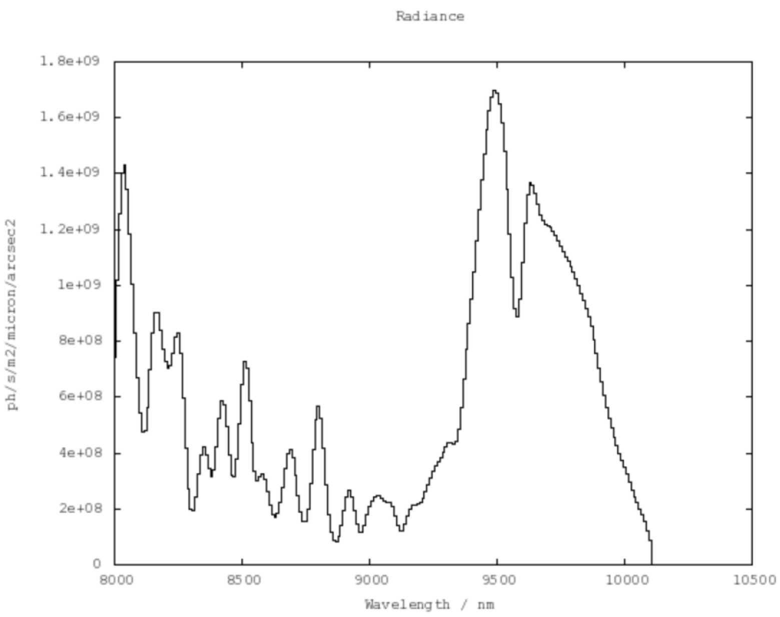
- Maximize Efficiency:
  - Design – minimize Optical Components
  - Coatings! (big improvements in past years)
  - Detectors QE (almost perfect in opt.- VG in IR)
  - Match pixel size..
  - $PDE_{max}$ ~ 35% (not for all instruments, Not much improvement possible)
- Bigger Telescopes ($D^2$) (?!) – Dedicated ones (?)

# Sky Noise

- Sky Varies a LOT with Wavelength




X label: Wavelength / nm, Y label: ph/s/m2/micron/arcsec2



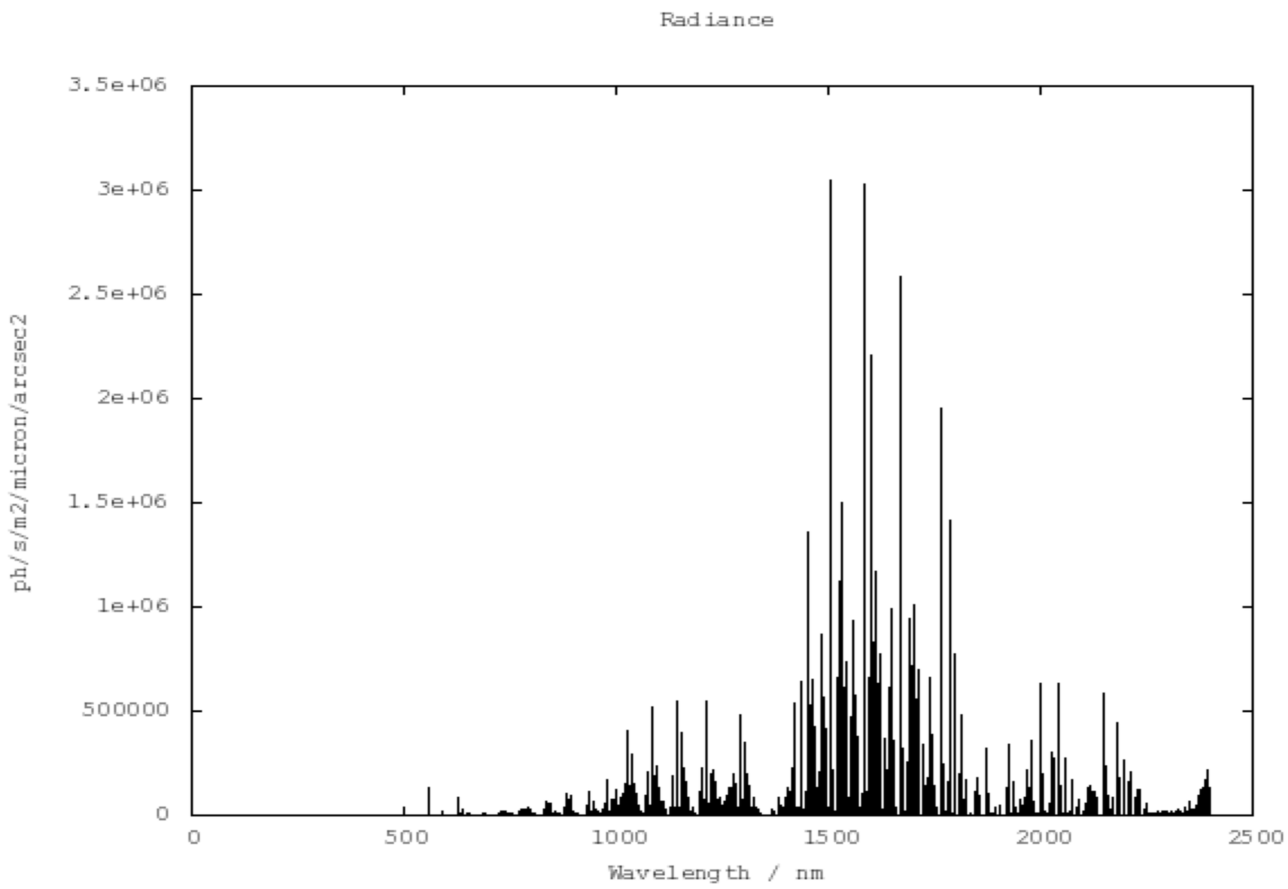

X label: Wavelength / nm, Y label: ph/s/m2/micron/arcsec2

Low res sky simulations

http://www.eso.org/observing/etc/bin/gen/form?INS.MODE=swspectr+INS.NAME=SKYCALC

# Sky Noise

- AND Spectral Resolution….. Lot of spectral range is basically dark…



# Detector Noise

- Detector Noise :

| Det / Type | RON (e-) | DK (e-/hour) | Note |
|---|---|---|---|
| CCD | 2 | Negl. | 300-1000 nm |
| Hawaii2RG | 3 | 10 | 1000-5000 nm |
| Aquarius | 250 | 4700 | >6000 nm |

Rather good performances, limiting mostly for High Res spectroscopy
Up to ~100 pixels/resolution elements can be used

# Scaling Laws

- The resolution observed is NOT the disperser resolution, but given by the width of the entrance ‘slit’ as mapped onto the spectrum formed in the focal plane of the camera

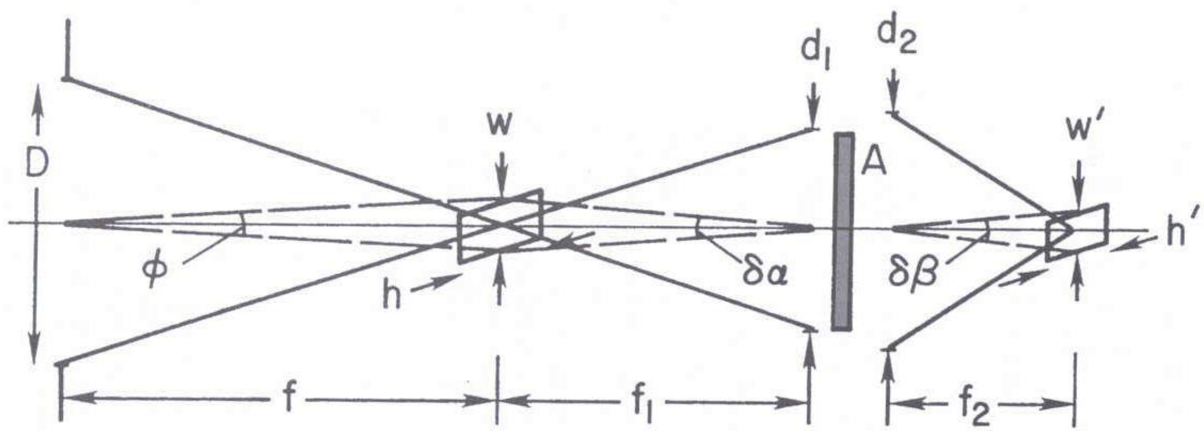



Fig. 12.4. Schematic layout of slit spectrometer with dispersing element of angular dispersion $A$. See text, Section 12.2, for definitions of parameters.

# Scaling laws

- Spectrograph' size:

$$R * a = \frac{2BTg(q)}{D}$$

R = Resolving Power
B = Spectrograph collimated beam
D = Telescope diameter
UVES at VLT R=40000, α=1 arcsec, Tg(θ)=4, B=20cm ➔ 80 cm grating..
4m for a 40M telescope…

To reduce α one can use Image Slicers …. Pupil Slicers ..all solutions that require re-formatting on the detector plane and use more pixels..

# Pixel Scale

The width of the slit projected on the detector
of the slit can be easily expressed as

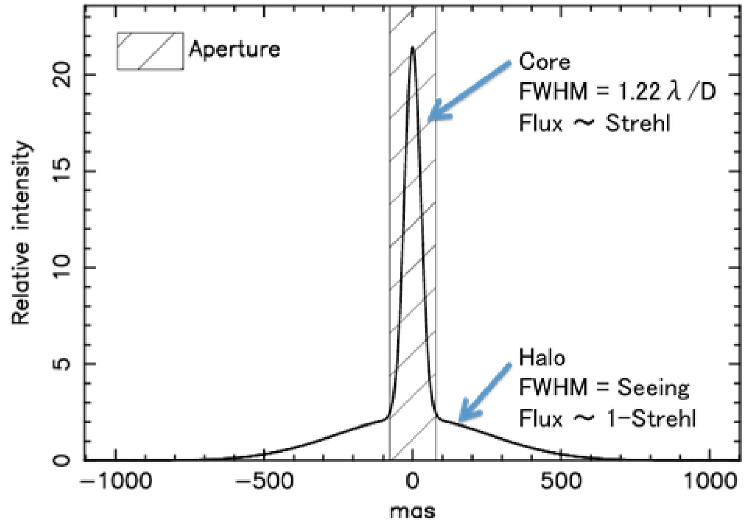
$$w' = \frac{\alpha f_{tel} f_{cam}}{f_{coll}} = \frac{\alpha D F_{tel} * F_{cam}}{F_{coll}}$$

α= aperture on the sky
D=Telescope diameter
F=Focal aperture

The bigger the telescope, the faster the camera aperture. For D=8m and α = 1 arcsec, w'= 30 μm (2 pixels) for $F_{cam}$=0.77

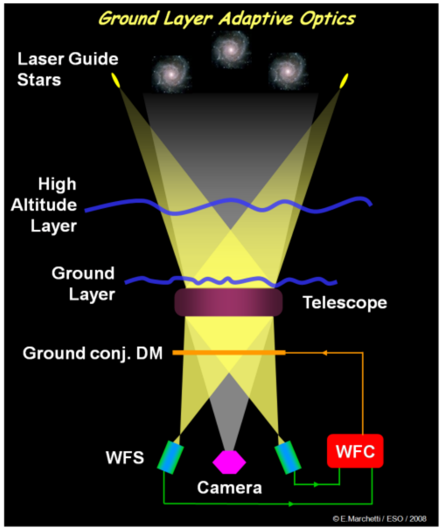
# Larger Telescopes

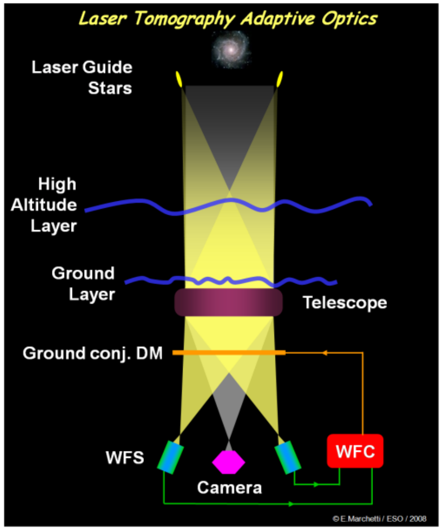
- Full advantage if close to diffraction limit:

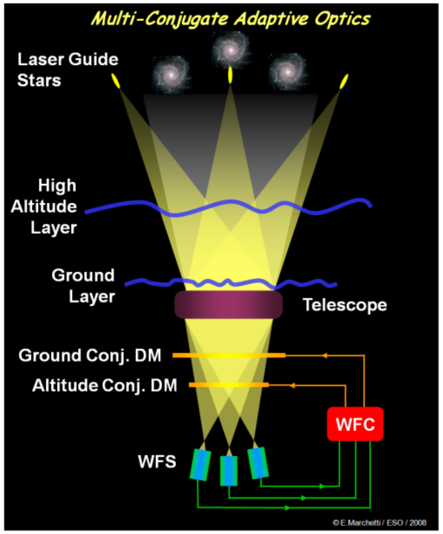


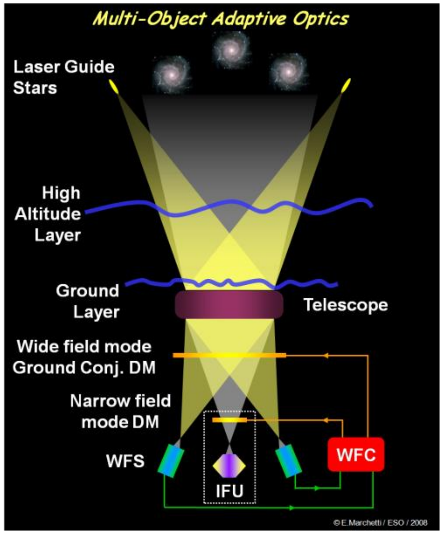

- Instrument size does not depend on D, sky contribution decreases, $N_{ph}$ increases…
- Atmosphere (seeing) makes: larger Instrument difficult matching, sky contribution not to decrease

# E-ELT AO Zoo

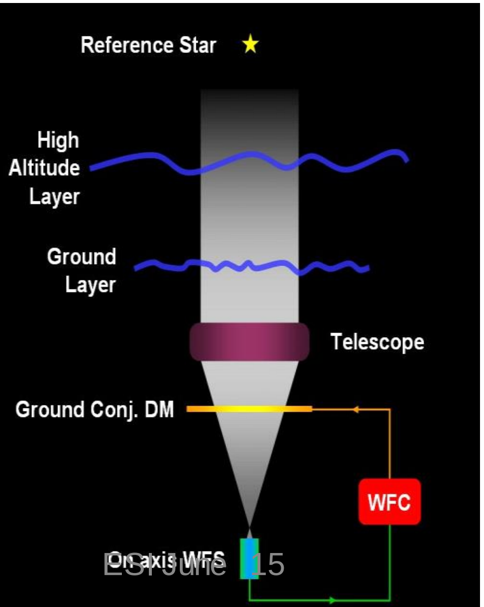


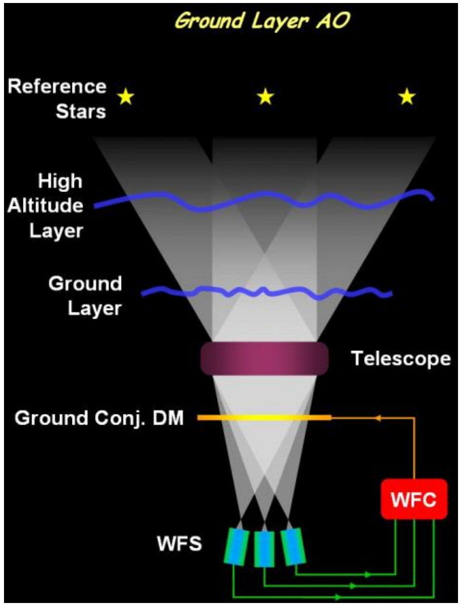




**SCAO & XAO: EPICS**

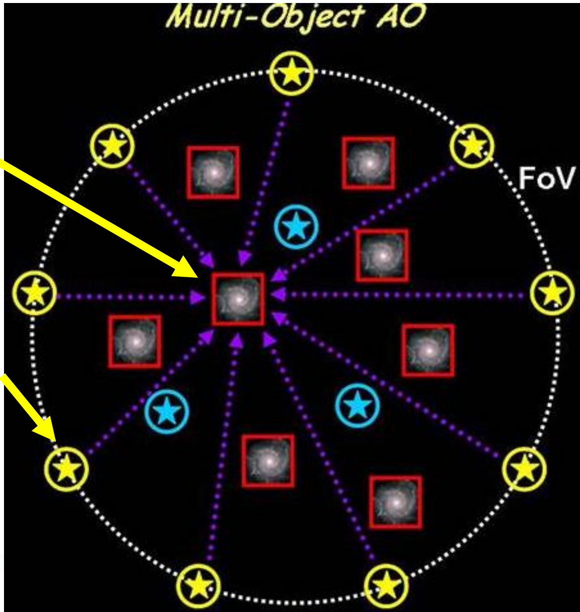



**GLAO-NGS**




**Few" IFU**

**6-8 LGSs in Ø 7.2'**



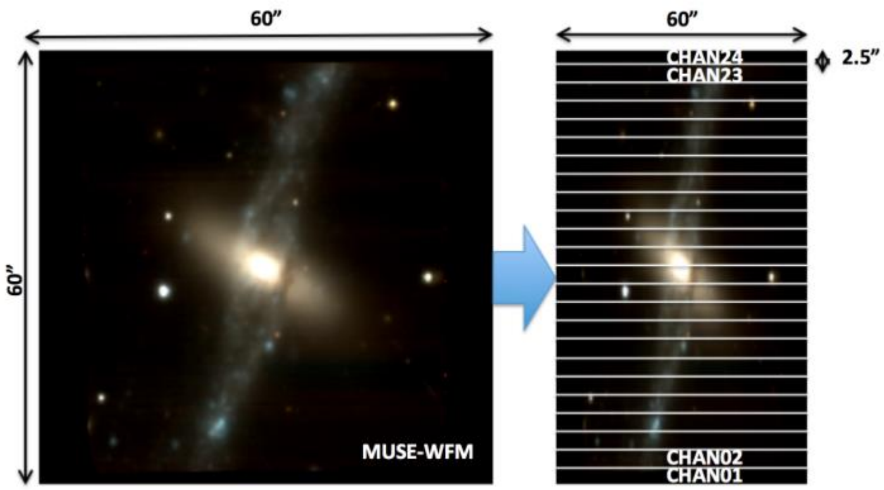
# Recent Examples

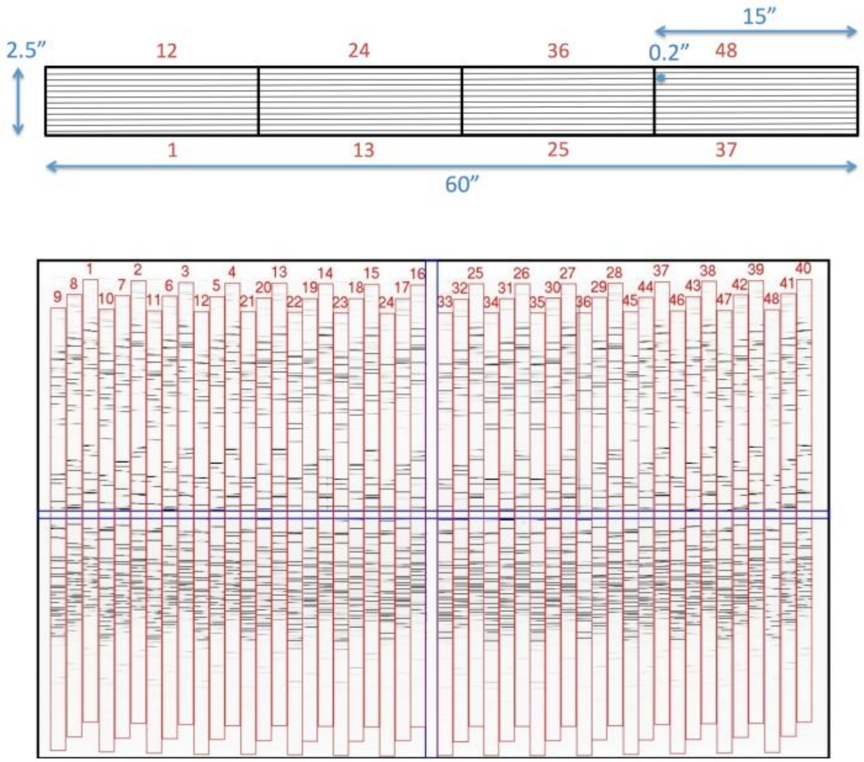
- Spectroscopy and imaging: MUSE, the most advanced IFU

- Precision Spectroscopy: ESPRESSO

# MUSE

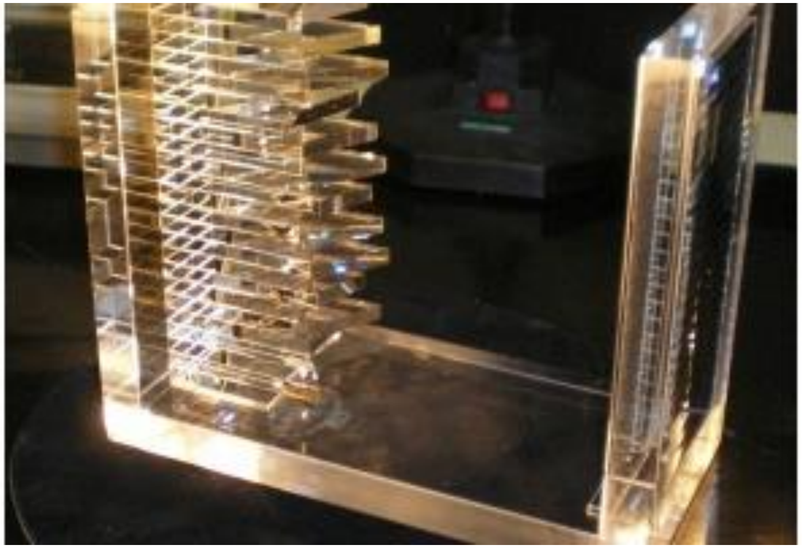
- Integral Field Unit (IFU): The first with excellent image quality. Get the spectrum of every point in a 1x1 arcmin field

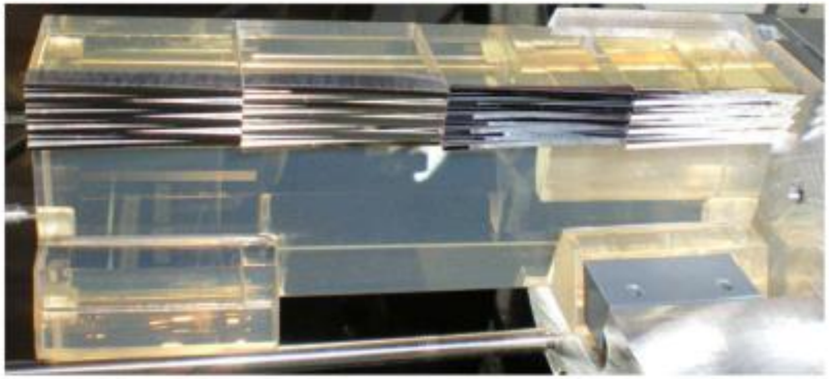


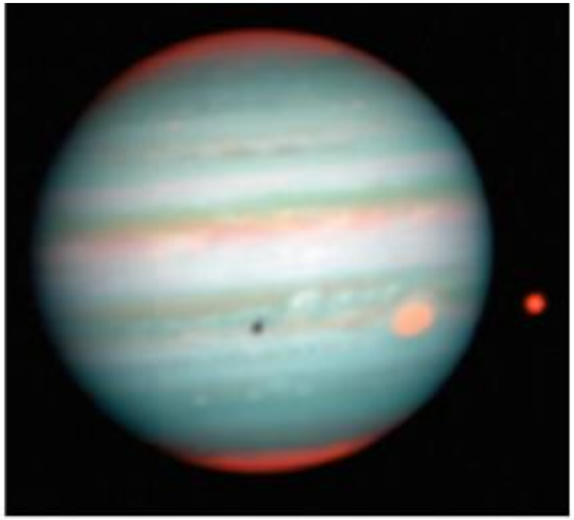
# MUSE (PI: R. Bacon, Lyon)

# MUSE in reality

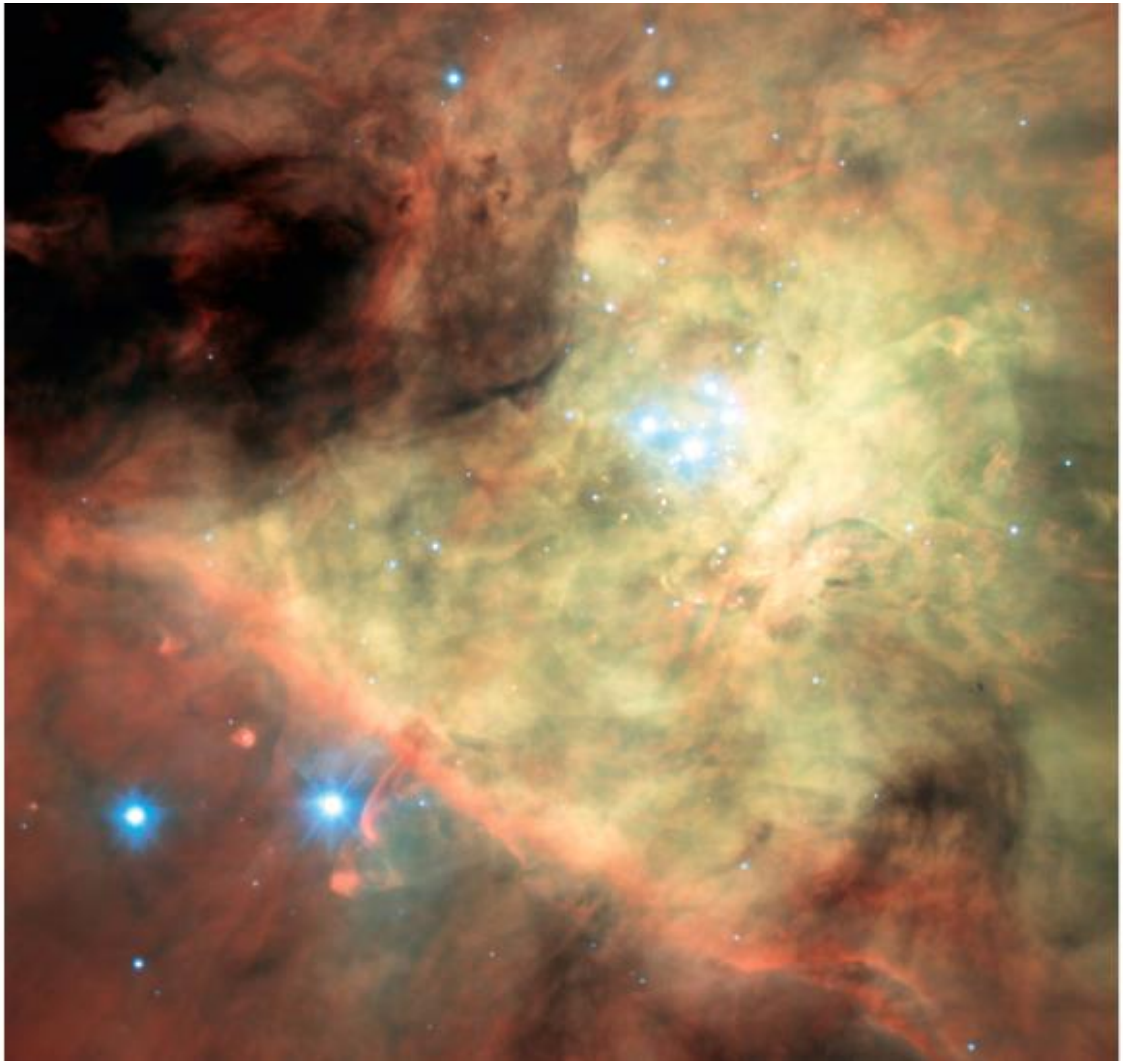




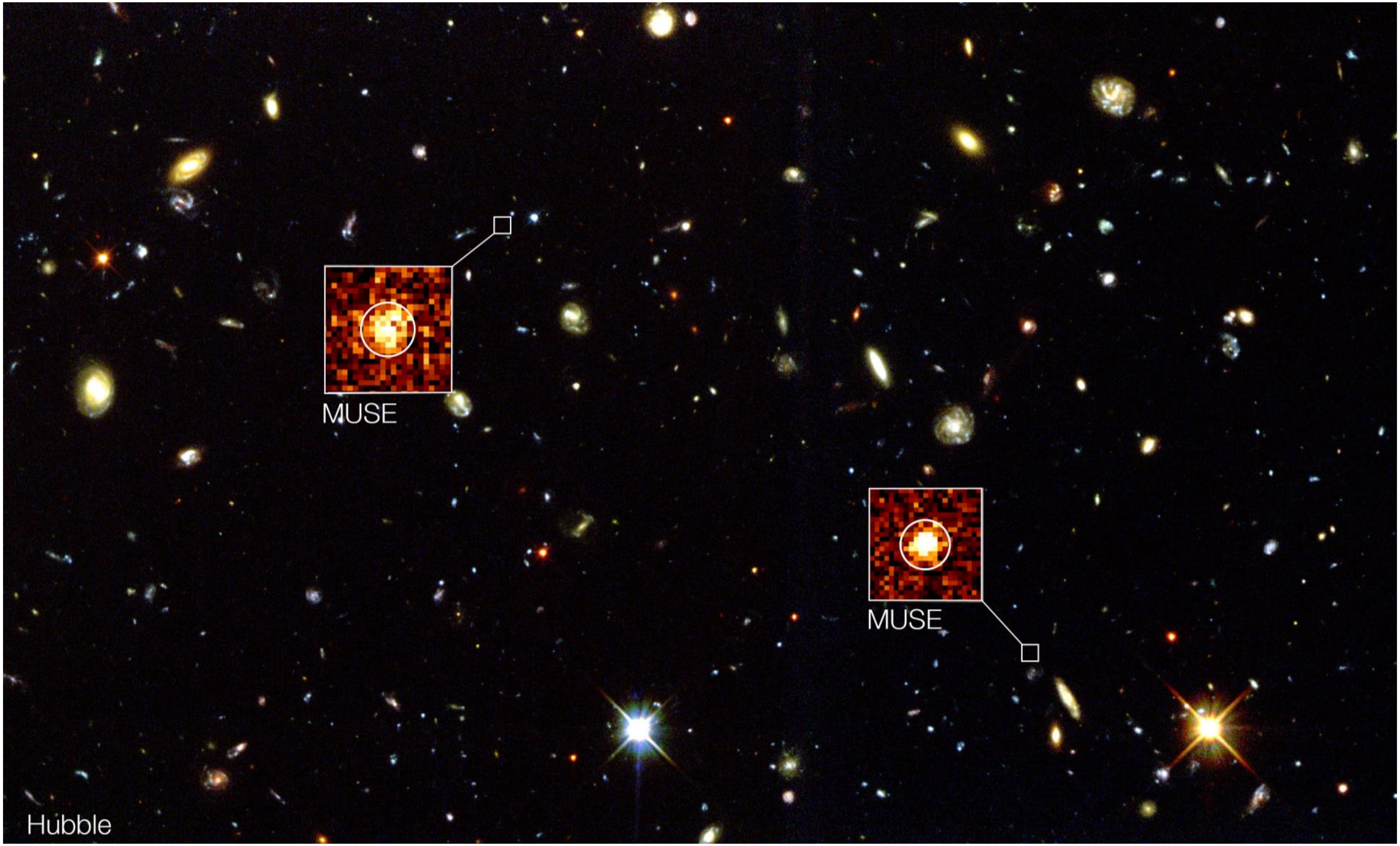
# Some examples



b)



# Power of Spectroscopy



# Precision Spectroscopy

- New Frontier: exoplanet search …

Doppler shifts induced by orbiting planet on stars varies from several m/sec for short period Jupiter masses to 8 cm/sec for Earth-type around a solar star.

- ESPRESSO is the new instrument for the VLT
- Rely on the success and experience of HARPS at the 3.6m at La Silla

- Observatoire de Genève
- Physikalisches Institut, Bern
- Observatoire Haute-Provence
- Service d’Aéronomie, Paris
- ESO

# HARPS: stability at 1 m/s

⊗RV =1 m/s

⇕

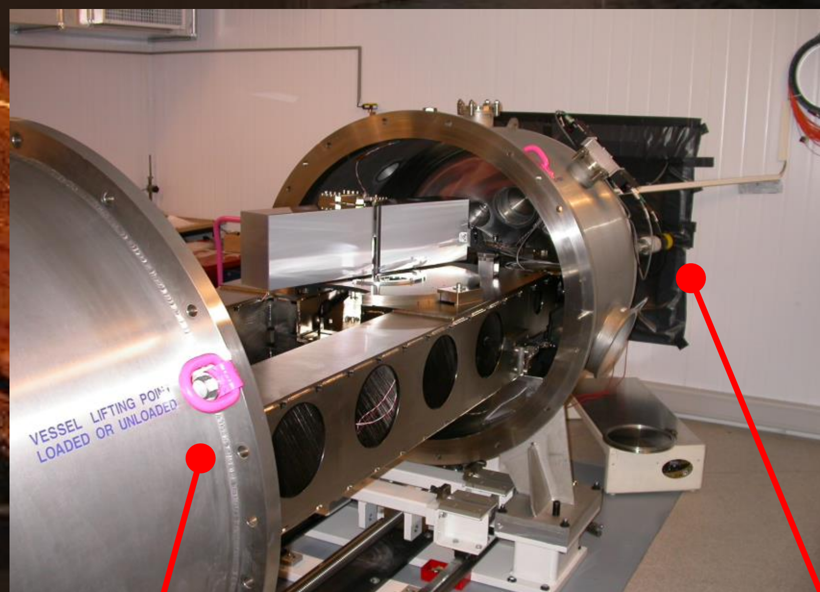
⊗L =0.00001 A

⇕

15 nm

⇕

1/1000 pixel




thorium calibration

2–fiber fed

⊗RV =1 m/s

⇕

⊗T =0.01 K

⇕

⊗p=0.01 mBar

Pressure controlled

Temperature controlled

# HARPS Errors

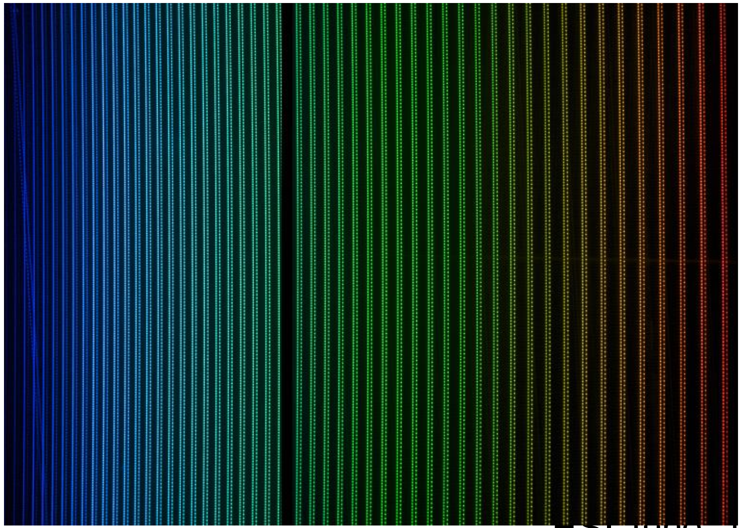
- Wavelength calibration ThAr: 30cm/s
- Guiding* : 30cm/s
- Photon noise
- Other sources (estimated) ≤ 15cm/s

* Faster and more accurate guiding system implemented, contribution to the RV error budget estimated in ≤ 15cm/s

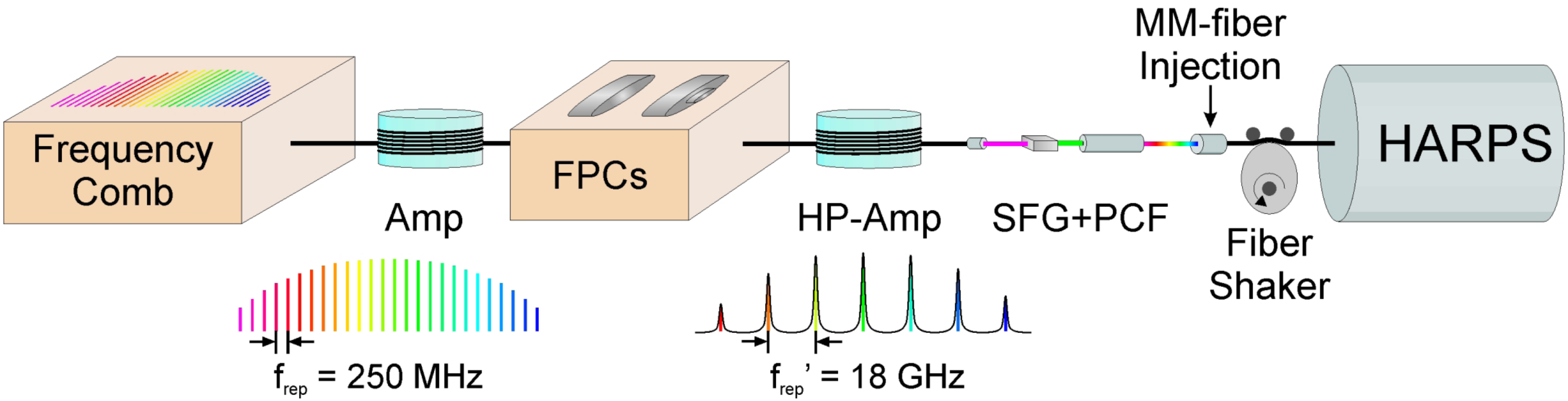
# LFC as calibrator

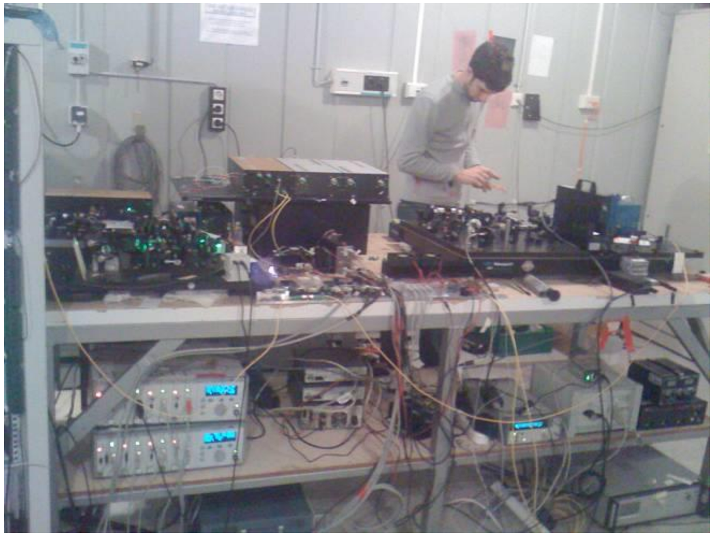
Laser Frequency Combs is the ideal spectrograph calibrator:

- Provides millions of perfectly equidistant lines (in frequency)
- Lines frequency is known a priori
- Covers a large wavelength domain
- Stabilized at the $10^{-11}$ to $10^{-16}$ level
- The absolute reference linked to an atomic clock



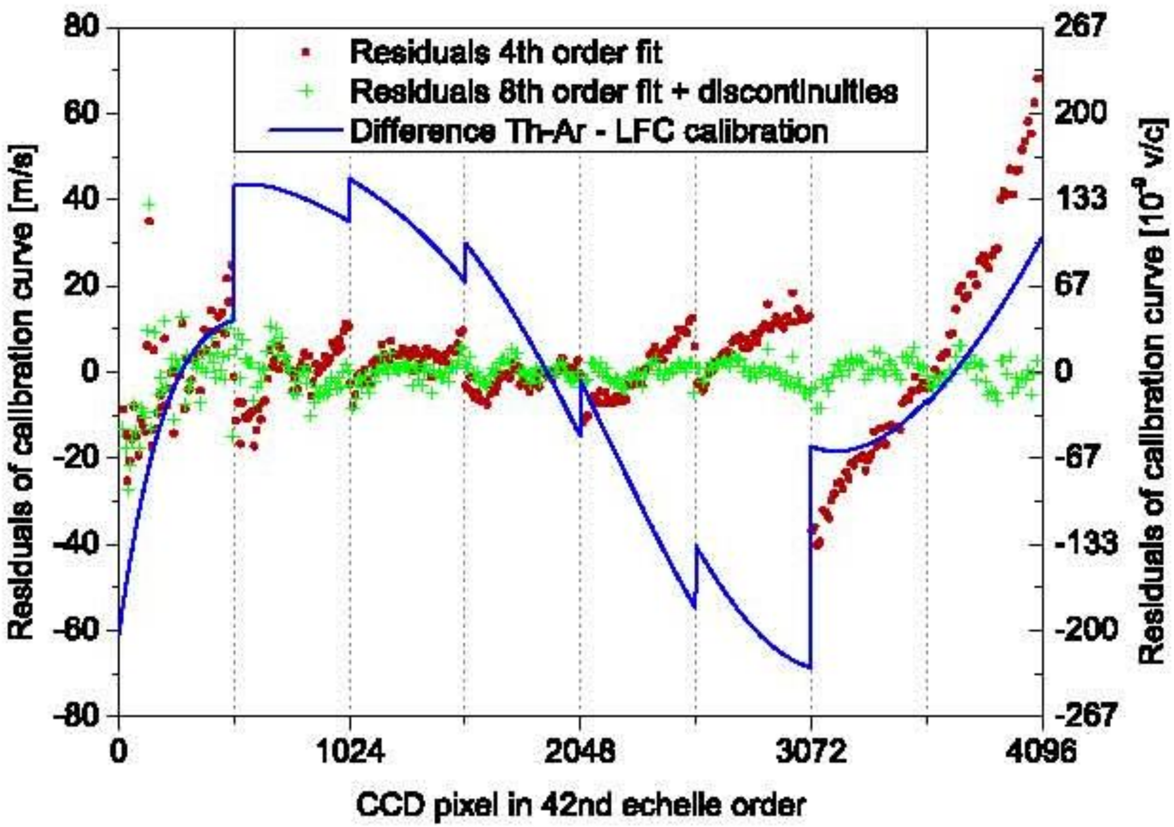
# LFC design & Engineering



# Wavelength calibration

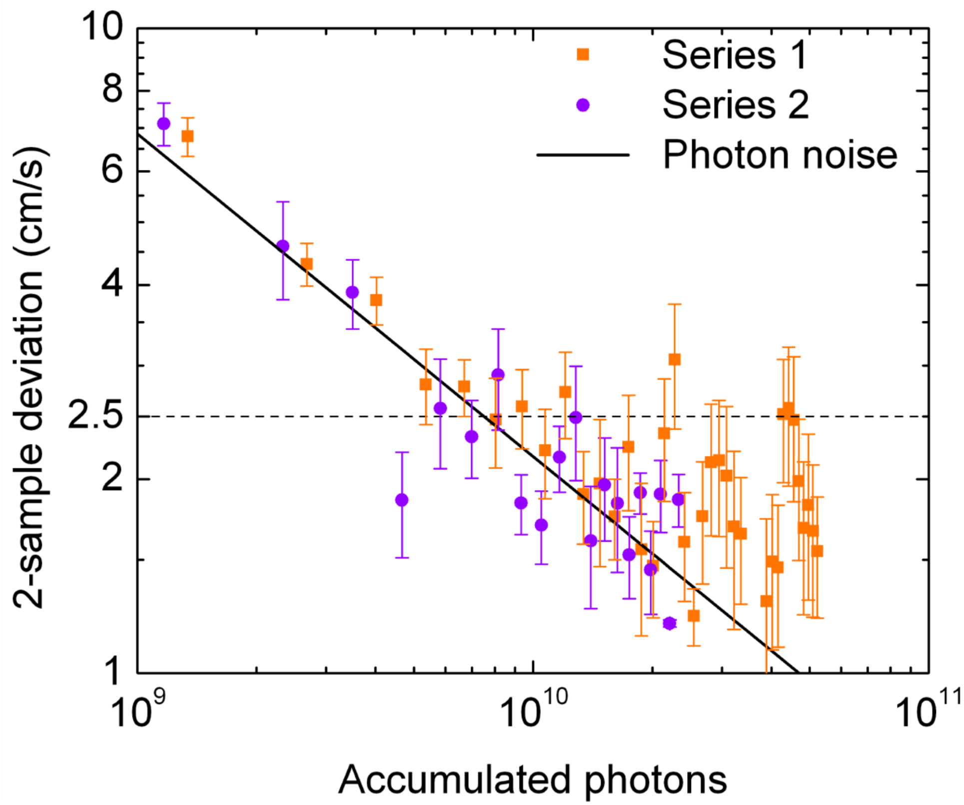
Detect the systematics introduced by the stitching pattern of the CCD




**Wilken et al. MNRAS 405, L16–L20 (2010)**

# Precision

Achieved photon noise limited repeatability down to 2.5cm/s




**Turn-key system has been delivered , in commissioning**

Wilken et al. 2012, Nature

# What is ESPRESSO?

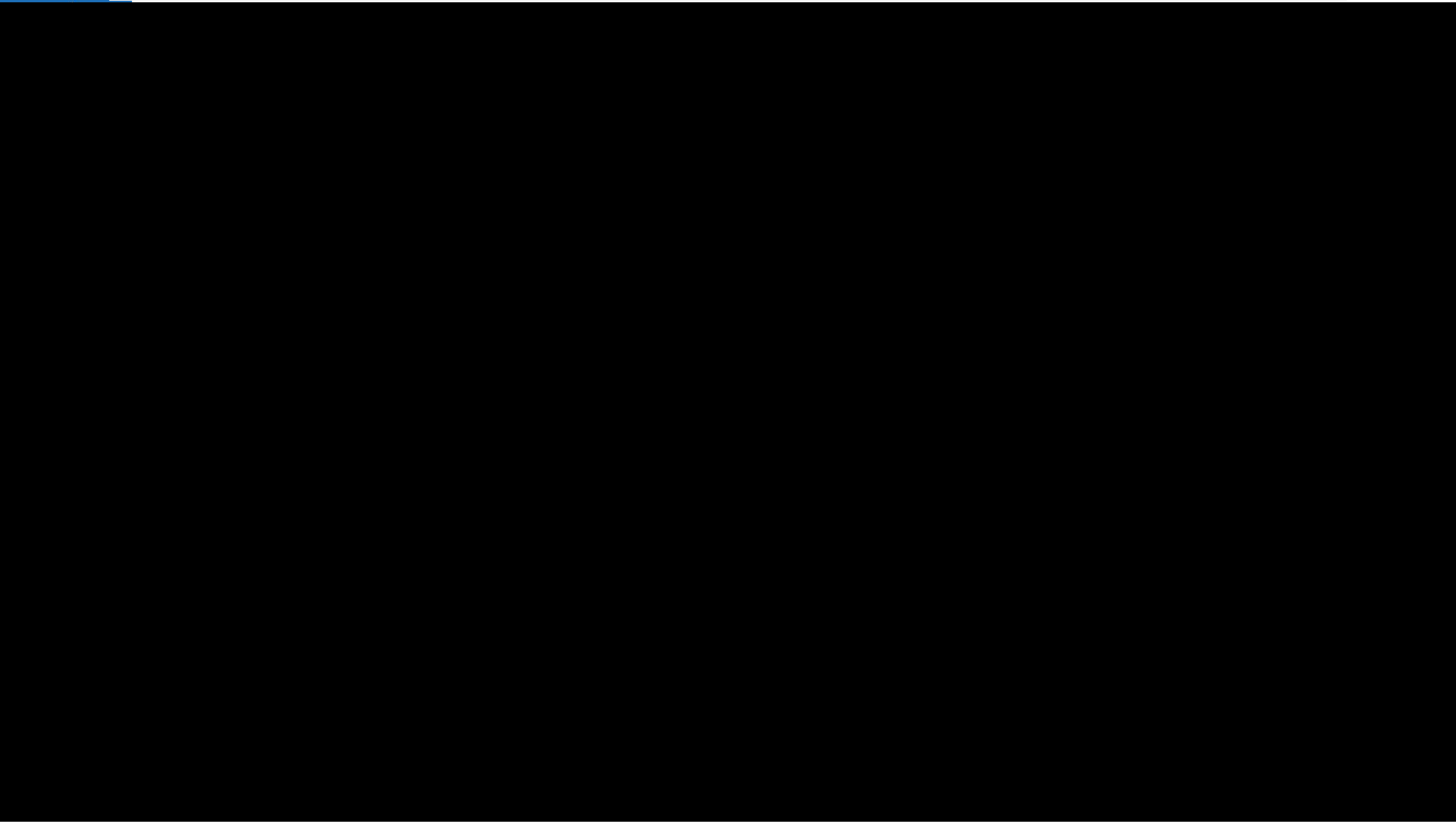
- ESO asked for an instrument with specific science cases and clear characteristics

- Rocky Planets
- Variability of physical Constants
- Chemical composition of stars in nearby galaxies

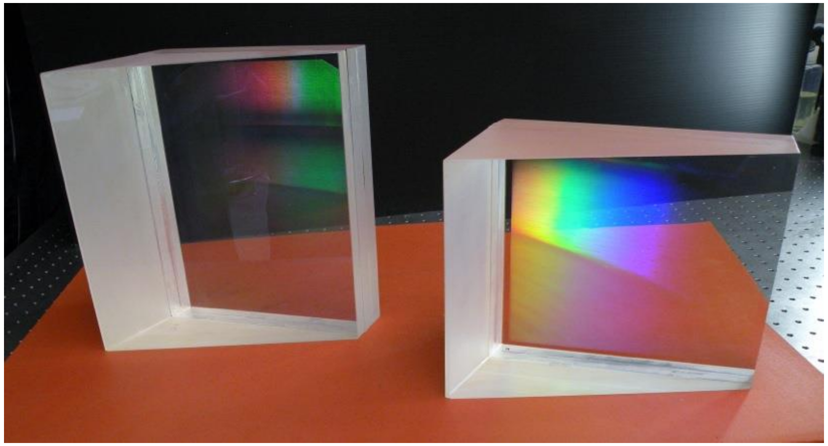
Observatoire de Geneva and University of Bern, Switzerland
INAF-Trieste and Brera, Italy
Instituto de Astrofisca de Canarias, Spain
Universidade do Porto and Lisboa, Portugal
ESO

PI: F. Pepe (Geneve)

# ESPRESSO Development



# ESPRESSO in Construction…



# The end

- Thank you for your attention
- Any question?

# Quantum Jump?

- Efficient AO in Optical
- Noisless detectors – with high QE
- 3D detectors

# Some Requirements

| Requirement | Standard 1-UT | 4-UT | Very-High Res 1-UT |
|---|---|---|---|
| Wavelength Range | 380-686 nm | 380-686 nm | 380-686 nm |
| Resolving Power | 120.000 | 30.000 | 220.000 |
| Aperture on Sky | 1.0 arcsec | 4x1.0 arcsec | 0.5 arcsec |
| Sampling (average) | 3.3 pixels | 4.0 pixels (binned x2) | 2.1 pixels |
| Spatial Sampling | 6.9 pixels | 4.0 pixels (binned x2) | 3.5 pixels |
| Simultaneous reference | Yes (no sky) | Yes (no sky) | Yes (no sky) |
| Sky subtraction | Yes (no sim. ref.) | Yes (no sim. ref.) | Yes (no sim. ref.) |
| Total Efficiency | >10% at peak | >10% at peak | > 7% at peak |
| Instrumental RV precision (requirement) | <10 cm/sec | <=5 m/sec | <=5 m/sec |