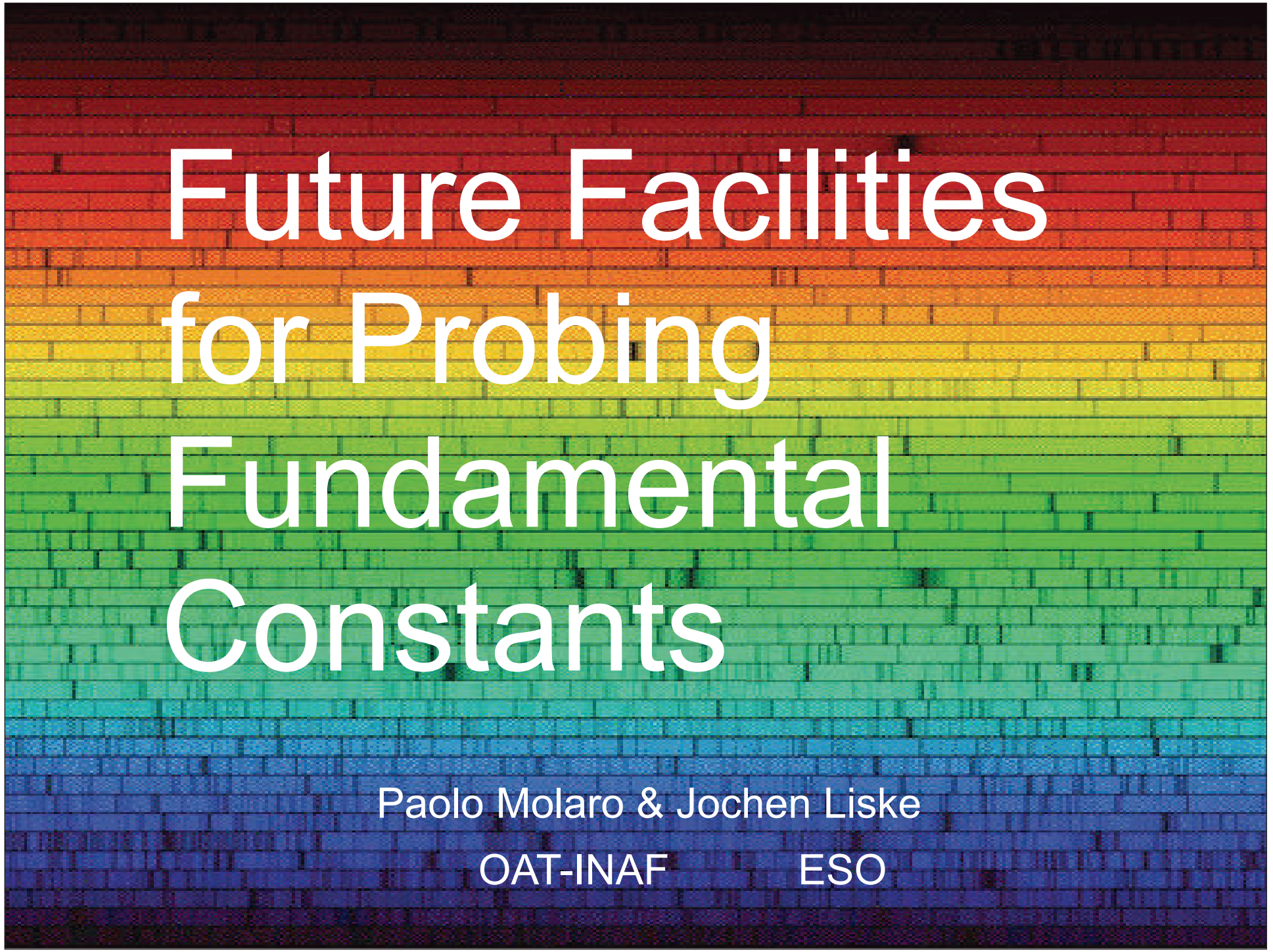
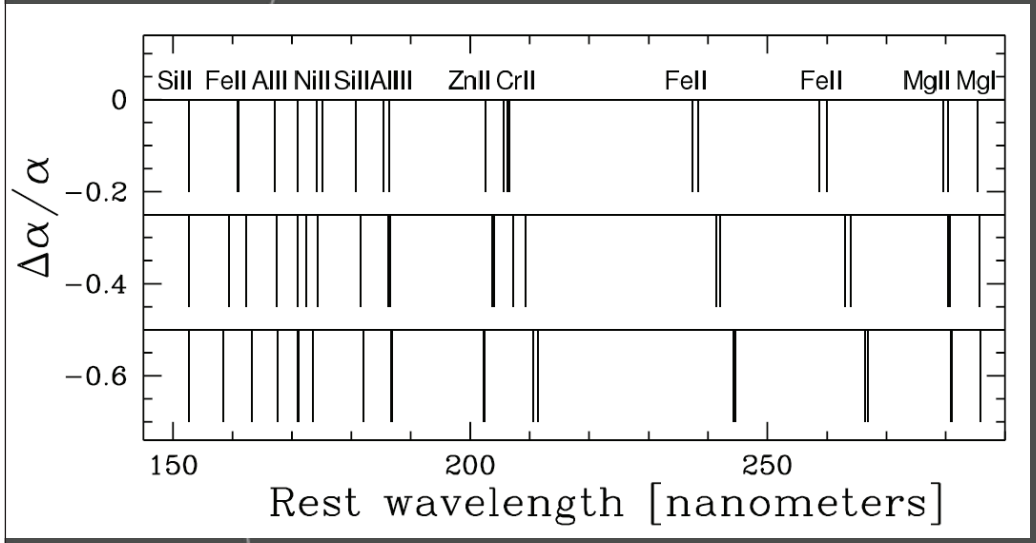
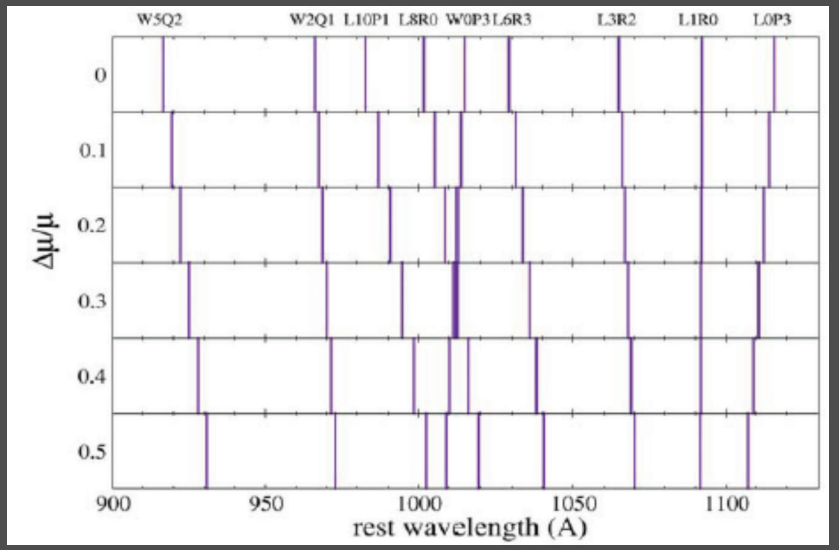

Future Facilities
for Probing
Fundamental
Constants
Paolo Molaro & Jochen Liske
OAT-INAF
ESO

What shifts?

All atomic transitions depend on α



Lyman Werner transitions of H2

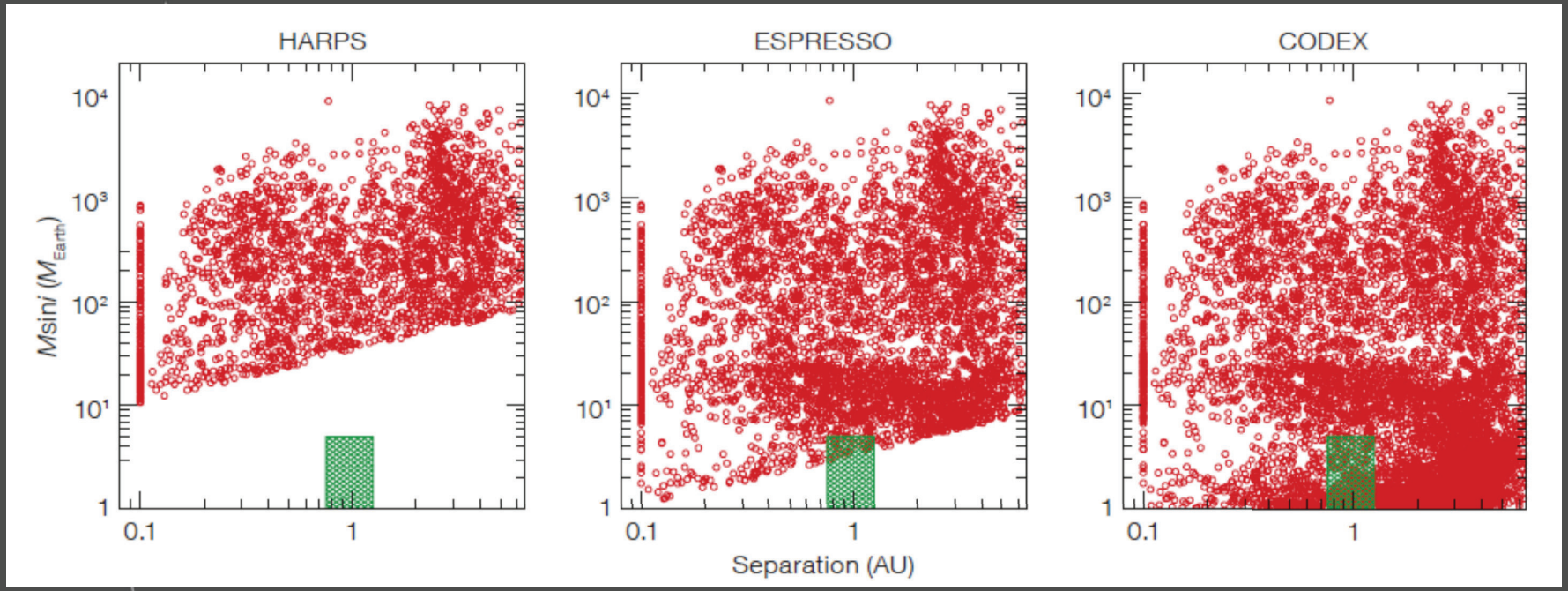


$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(\mathcal{Q}_1 - \mathcal{Q}_2)} = \frac{\Delta v}{2\,c\,\Delta\mathcal{Q}}$$

$\Delta\mu/\mu = \Delta v/c\Delta K$

Shifts 15-20 m/s for 10^{-6}

ESO Roadmap



1 m/s 0.10 m/s 0.01 m/s

reduction of systematics + photon collection

HARPS Legacy

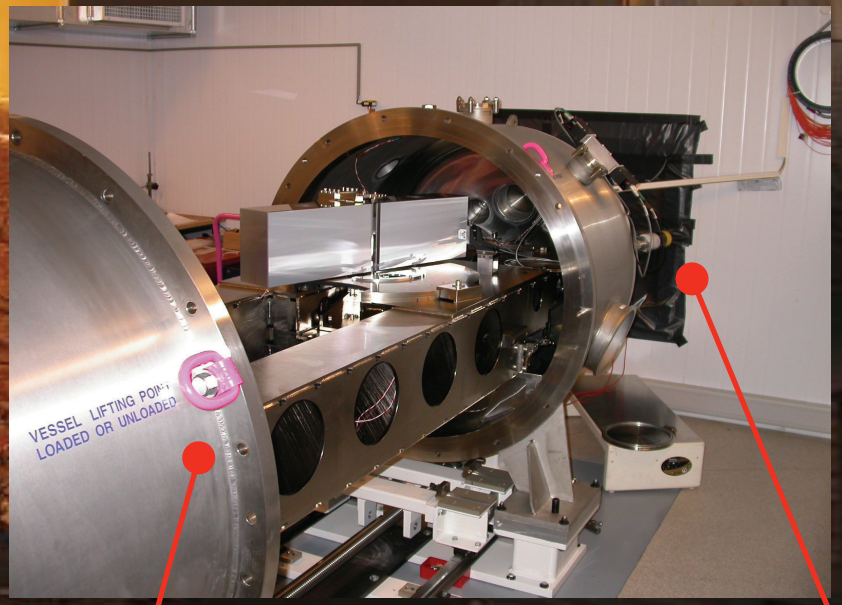
ΔRV =1 m/s

ΔRV =1 m/s

Δλ=0.00001 A

15 nm

1/1000 pixel



2–fiber fed

ΔRV =1 m/s

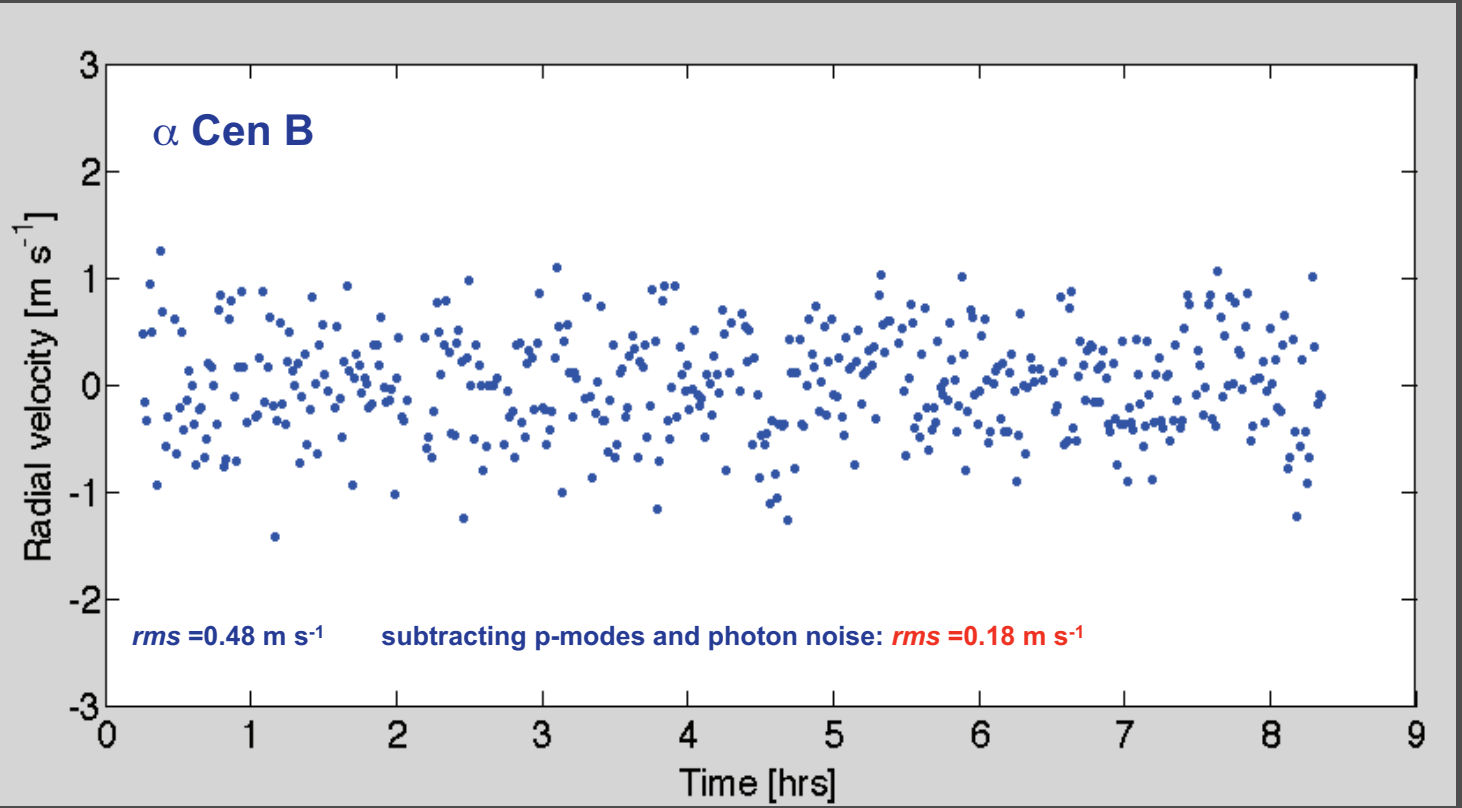
ΔT =0.01 K

Δp=0.01 mBar

Pressure controlled

Temperature controlled

HARPS limits?

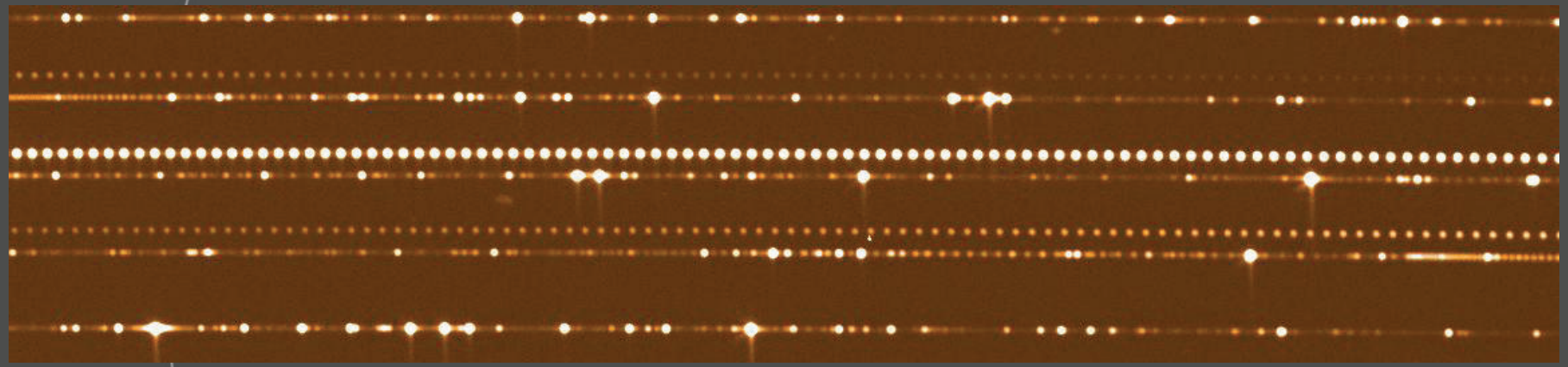


Residual noise. From where it comes from?

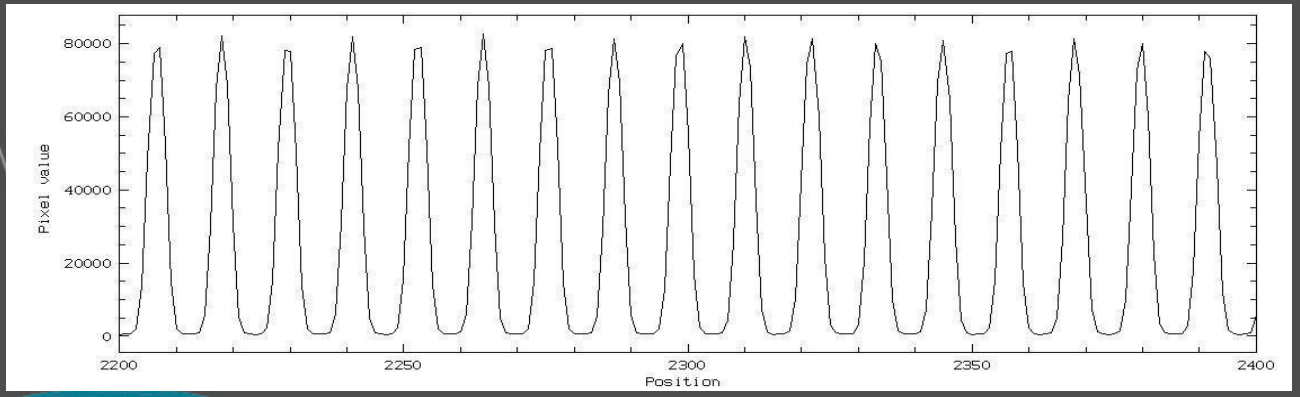
From global to local

Are spectrographs reliable?

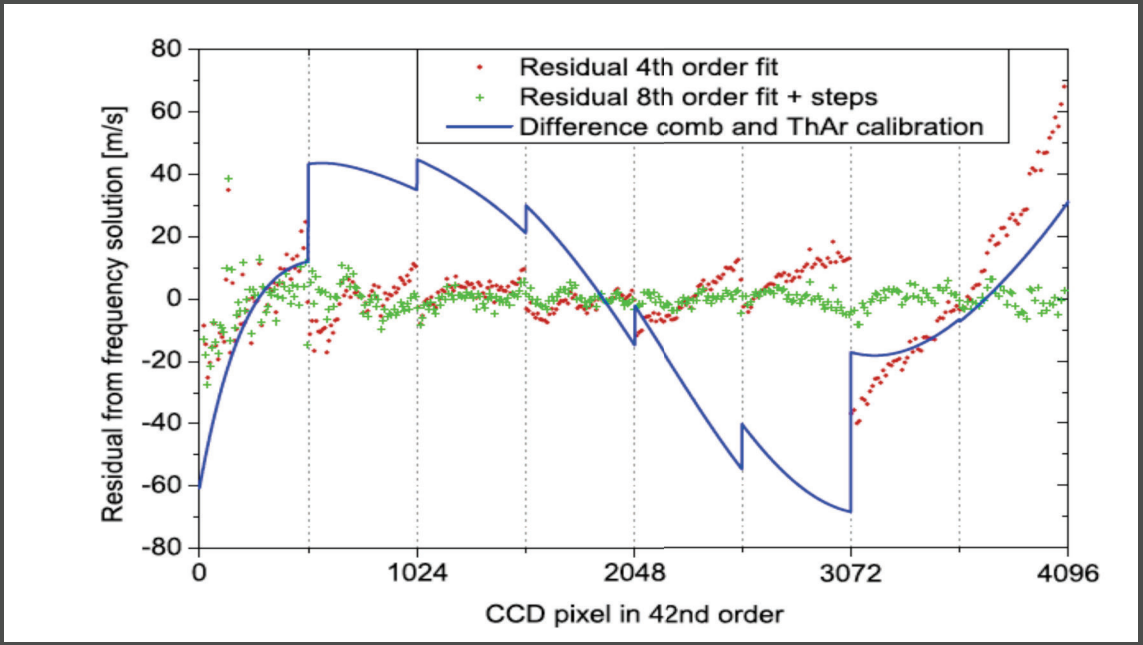
HARPS experience : laser comb 2009



5120 A



Laser Comb - ThAr



Wilken et al 2010

512 pixel pattern

Deviations up to ~100 m/s (but ~ 0 in the mean)

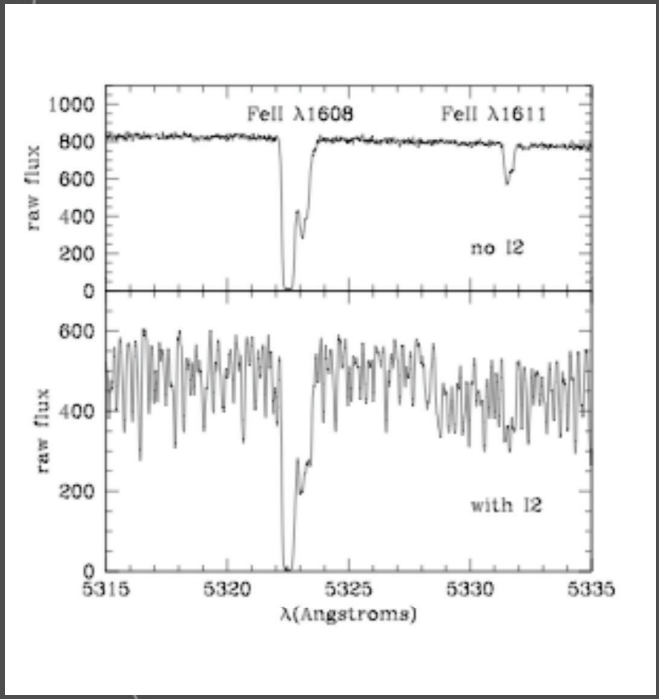
➡ $d\alpha/\alpha \sim 5 \times 10^{-6}$

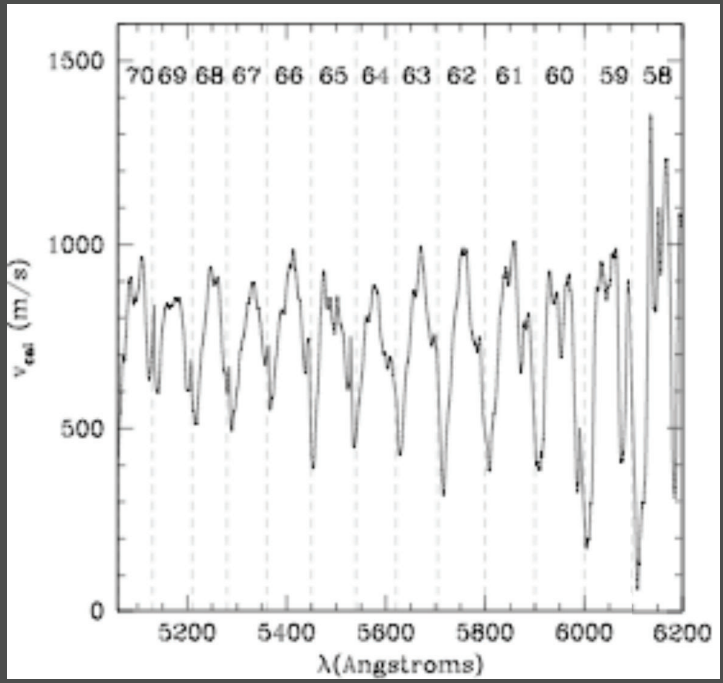
- and UVES? HIRES?

Keck-HIRES

- I2
- I2 Th-Ar comparison

PHL 952



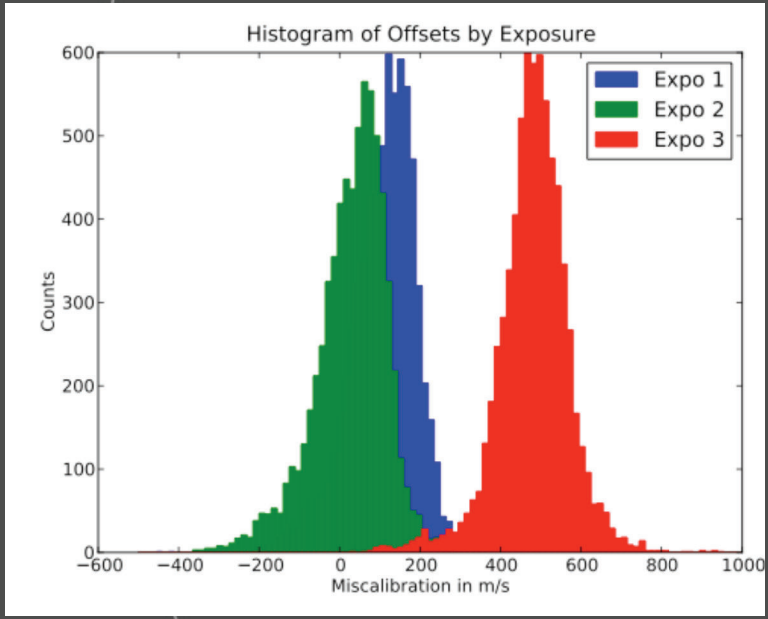


Griest et al 2010

VLT-UVES

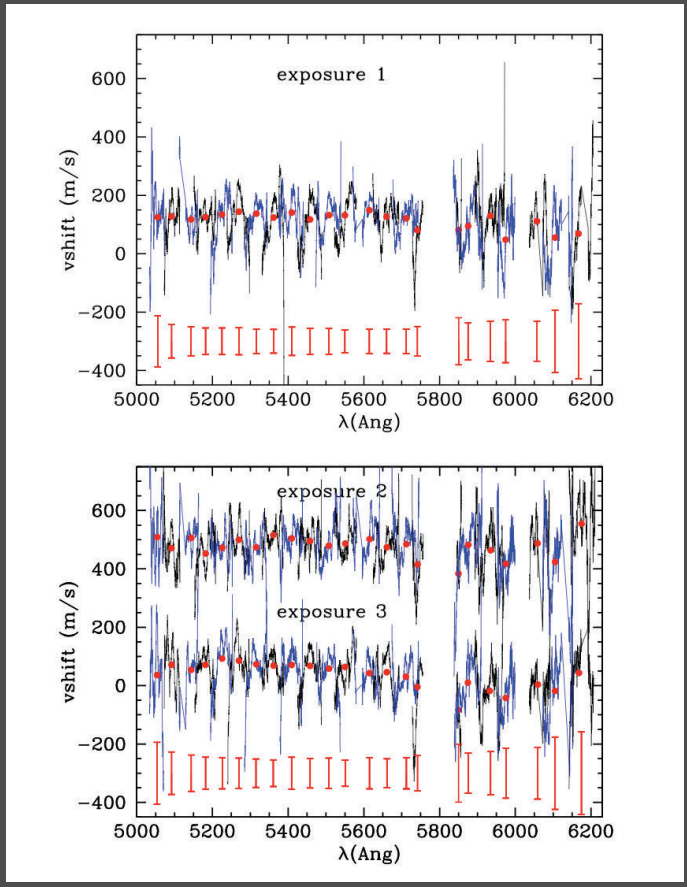
- I2 Th-Ar comparison

Whitmore et al 2010 astro-ph 1004.3325



Global offsets up to 1 km/s

Slit-effects!

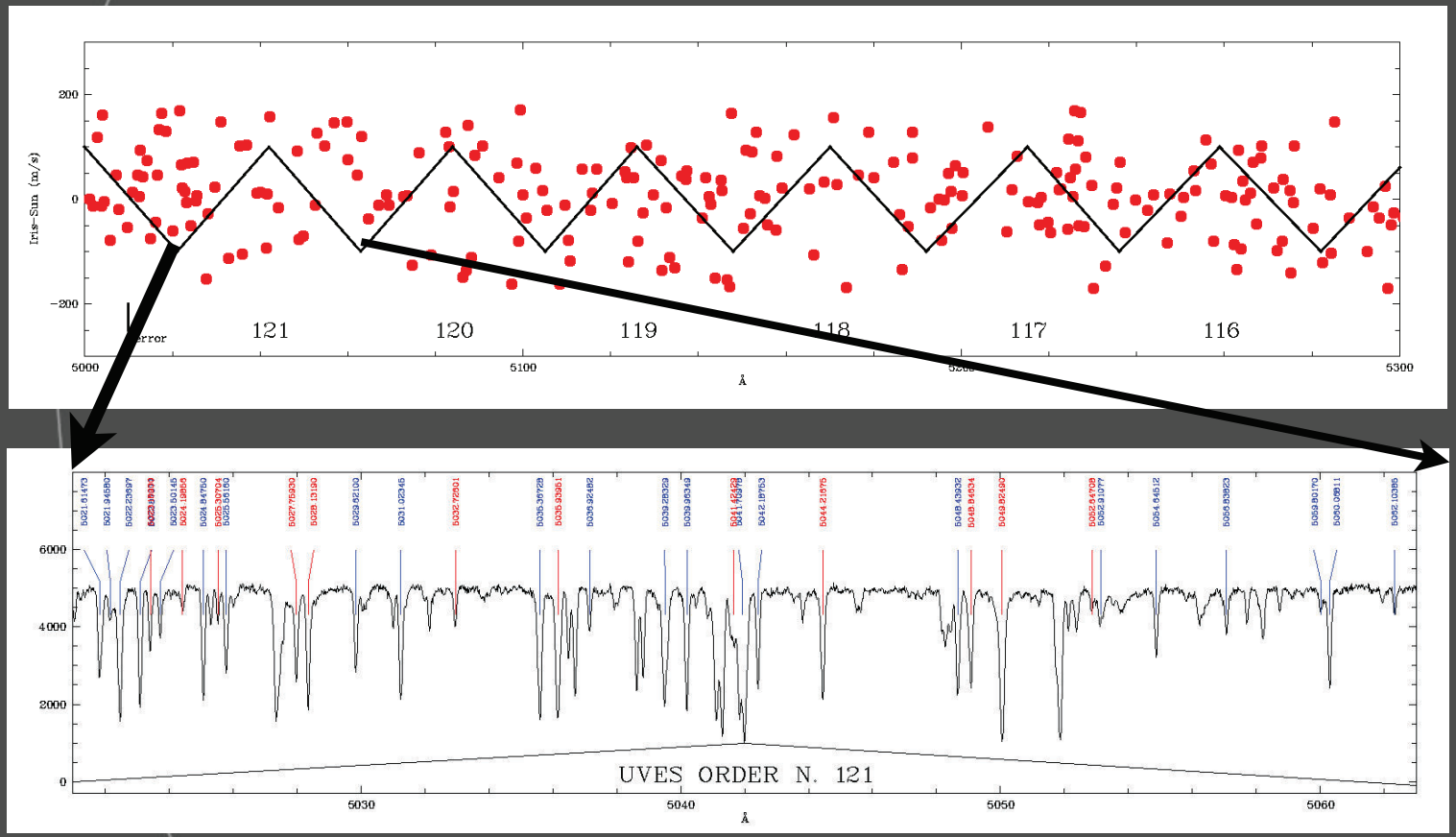


Order saw-tooth modulation

Amplitude σ_V ~ 100 m/s

with asteroids

UVES observations of Iris



see Poster

$\sigma_v \sim 80$ m/s

espresso

PRO (F)

PROJECT

- ✓ **Started 2007**
- ✓ **Presently in post-Phase A**
- ✓ **Endorsed by June 2010 ESO Council**
- ✓ **Commissioning by 2015**

The Echelle SPectrograph for Rocky Exoplanets and Stable Spectroscopic Observations

CONSORTIUM

- ✓ Geneva Observatory, Bern University (Switzerland)
- ✓ CAUP, Porto and Universidade de Lisboa (Portugal)
- ✓ IAC (Spain)
- ✓ Milan and Trieste Observatories (INAF, Italy)
- ✓ ESO

Team

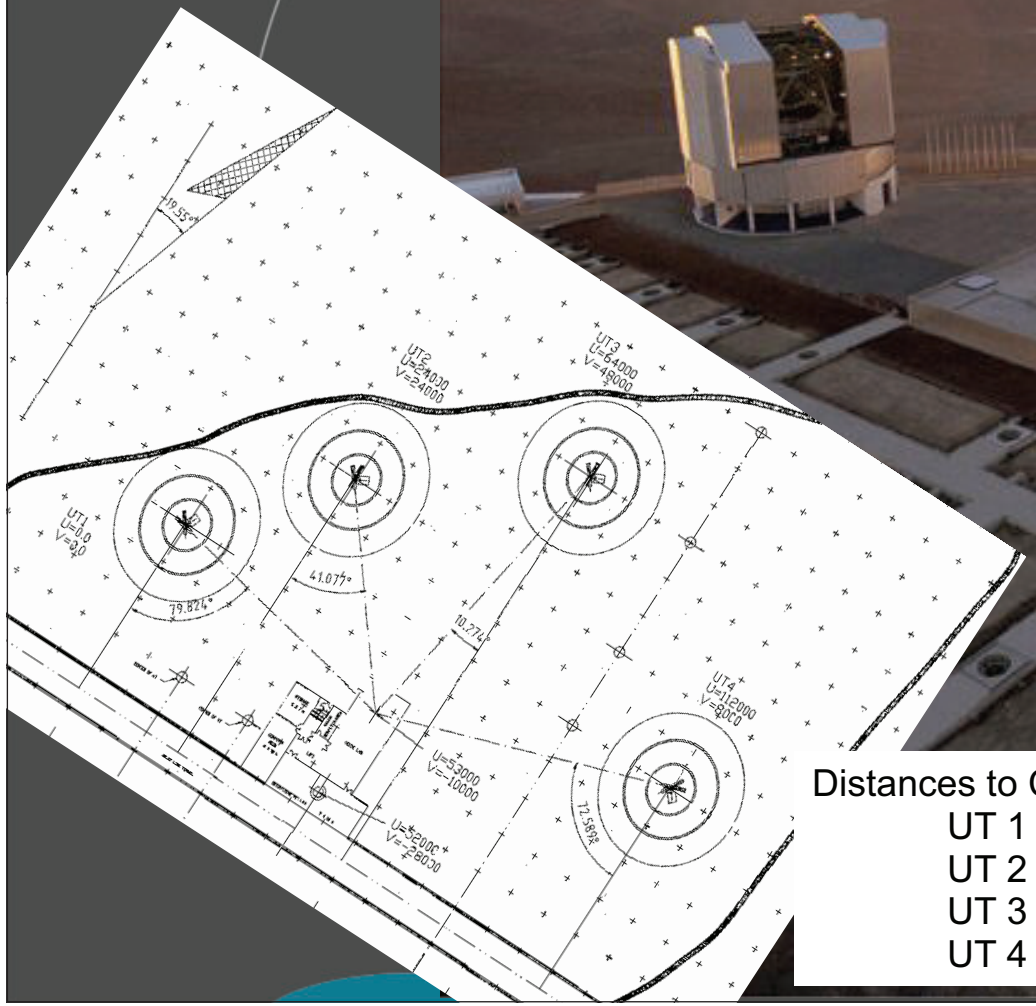
Francesco A. Pepe, Stefano Cristiani, Rafael Rebolo Lopez, Nuno C. Santos, Antonio Amorim, Gerardo Avila, Willy Benz, Piercarlo Bonifacio, Alexandre Cabral, Pedro Carvas, Roberto Cirami, João Coelho, Maurizio Comari, Igor Coretti, Vincenzo De Caprio, Hans Dekker, Bernard Delabre, Paolo Di Marcantonio, Valentina D'Odorico, Michel Fleury, Ramòn Garcia Lòpez,

José Miguel Herreros Linares, Ian Hughes, Olaf Iwert, Jorge Lima, Iocken Liske, Jean-Louis Lizon, Gaspare Lo Curto, Christophe Lovis, Antonio Manescau, Carlos Martins, Denis Mégevand, André Moitinho, Paolo Molaro, Mario Monteiro, Manuel Monteiro, Christoph Mordasini, Luca Pasquini, Didier Queloz, José Luis Rasilla, Jose Manuel Rebordão, Samuel Santana Tschudi, Paolo Santin, Danuta Sosnowska, Paolo Spanò, Fabio Tenegi, Stéphane Udry, Eros Vanzella, Matteo Viel, Maria Rosa Zapatero Osorio, Filippo Zerbi

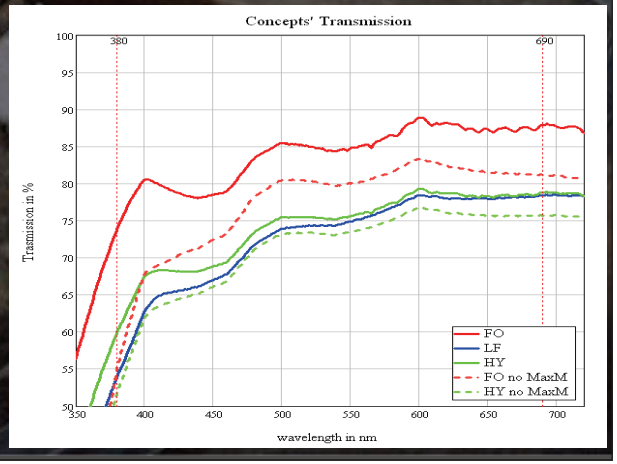
espresso
PROJECT

Foreseen since 1977....

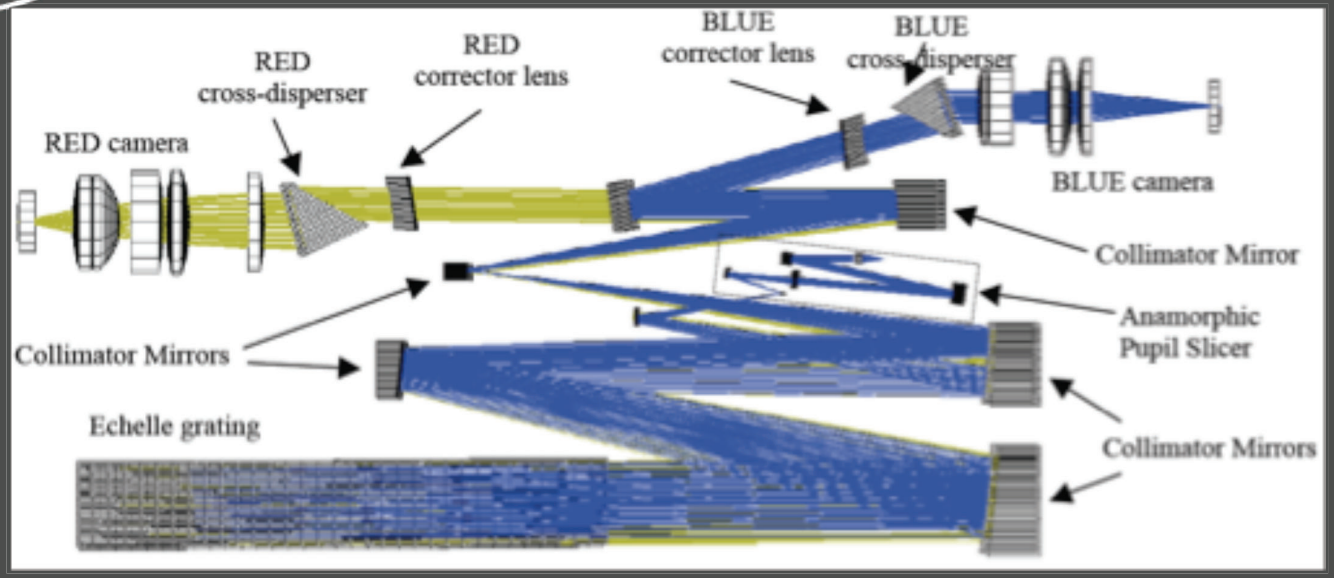
- ✓ A spectrograph on a 16 m telescope,
- ✓ the largest visible photon-collector until ELTs will be available



Distances to Combined Lab
UT 1 – 69 m
UT 2 – 48 m
UT 3 – 63 m
UT 4 – 63 m



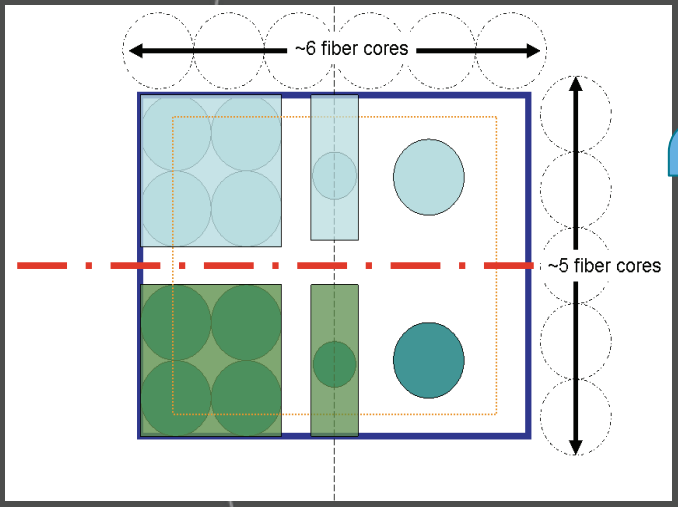
Optical Design

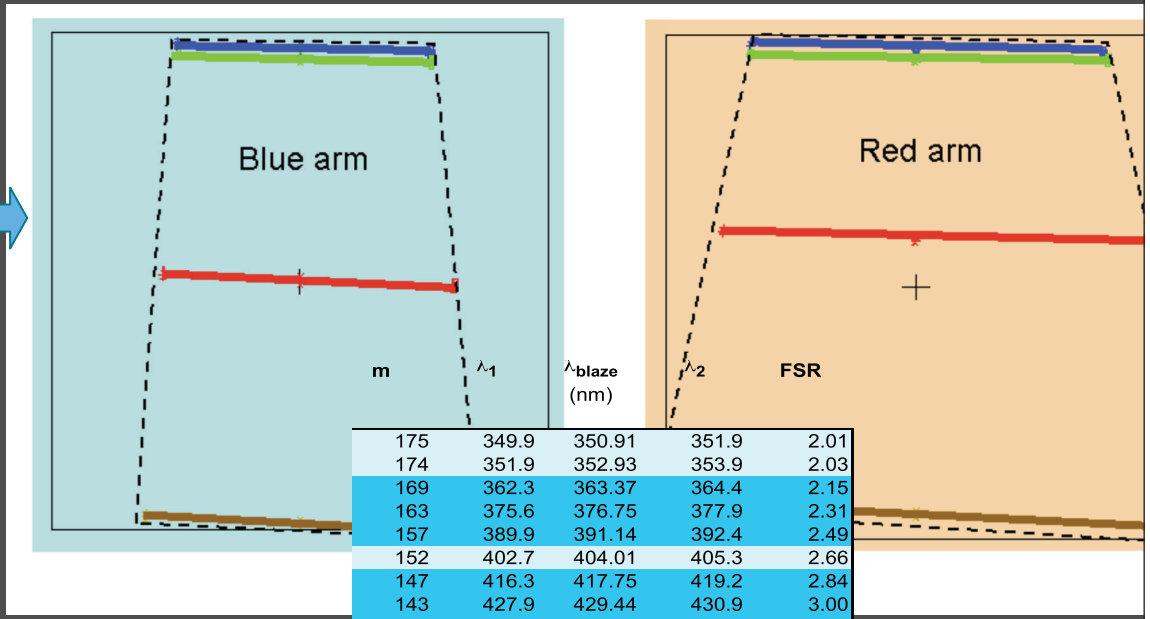


- ✓ Fiber-fed, cross-dispersed Echelle spectrograph with pupil slicing
- ✓ High stability spectrograph (vacuum, thermal, mechanical)
- ✓ FOV = 1.0 arcsec
- ✓ R = 70’000 (4 UT), 140’000 (1 UT) or 225’000 (1UT, high-resolution)
- ✓ Sampling = 3.5 pixels/RE @ R=140‘000

- ✓ Wavelength range: 380 – 813 nm (divided in two arms)
- ✓ CCDs: Two 9 cm x 9 cm chips

Entrance slit





175	349.9	350.91	351.9	2.01
174	351.9	352.93	353.9	2.03
169	362.3	363.37	364.4	2.15
163	375.6	376.75	377.9	2.31
157	389.9	391.14	392.4	2.49
152	402.7	404.01	405.3	2.66
147	416.3	417.75	419.2	2.84
143	427.9	429.44	430.9	3.00
136	449.9	451.54	453.2	3.32
130	470.6	472.38	474.2	3.63
129	474.2	476.04	477.9	3.69
128	477.9	479.76	481.6	3.75
123	497.2	499.27	501.3	4.06
118	518.2	520.42	522.6	4.41
112	545.9	548.30	550.7	4.90
107	571.2	573.92	576.6	5.36
103	593.3	596.21	599.1	5.79
99	617.2	620.30	623.4	6.27
92	663.9	667.50	671.1	7.26
86	709.9	714.07	718.2	8.30

combination of the light of the 4 telescopes at the detector!

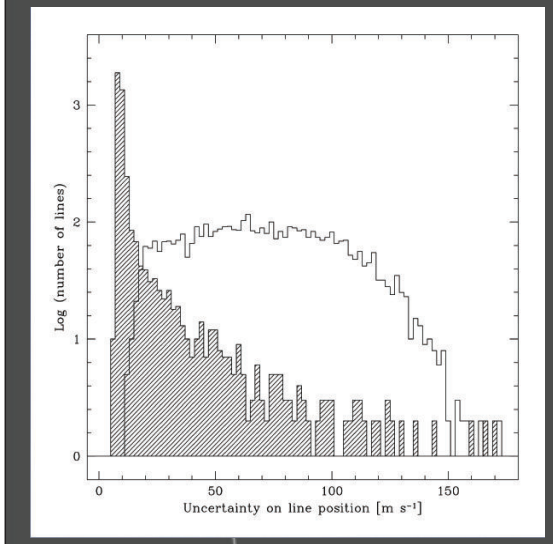
ESPRESSO is

- A super-HARPS on a 10 m-class telescope
- The highest-resolution instrument on a 10 m-class telescope (R~225,000)
- An instrument producing cleanest, best-quality spectra, both at high and low SNR
- A spectrograph on a 16 m telescope, the largest visible photon-collector available

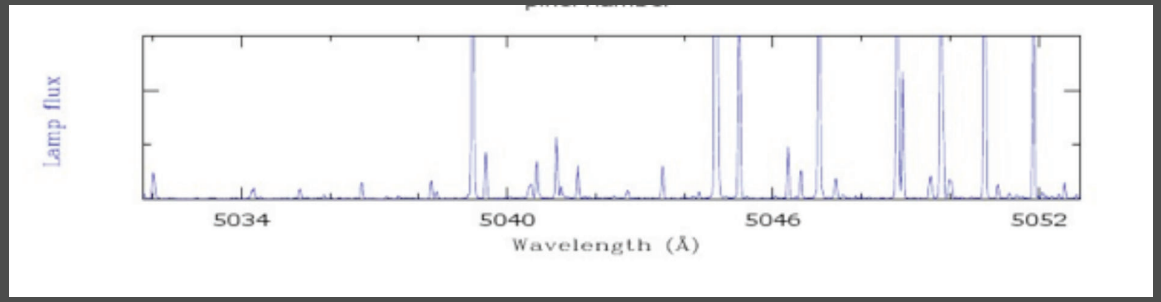
Keep on moving: R & D

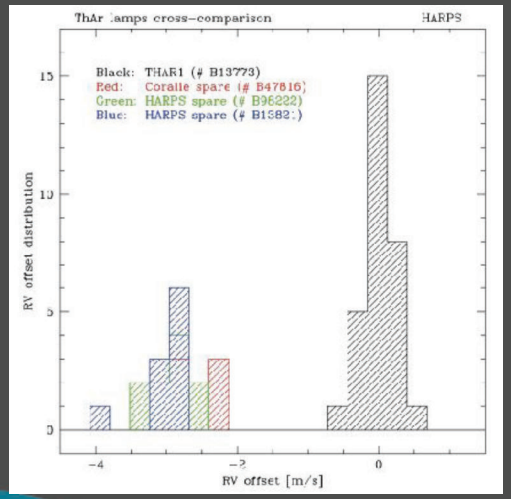
- ✓ **Wavelength Calibration**
- ✓ **Telescope Guiding and fiber scrambling**
- ✓ **Detector Stability**

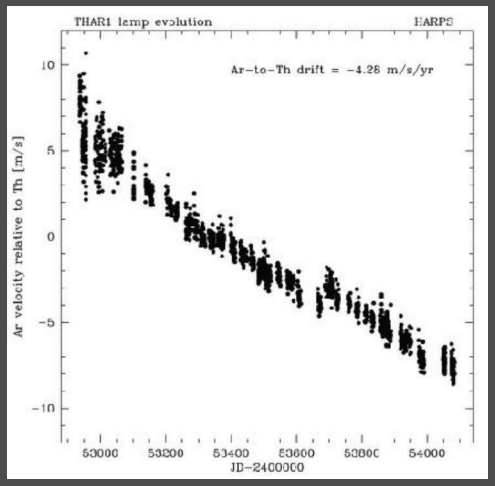
The wavelength calibration Bottle-neck



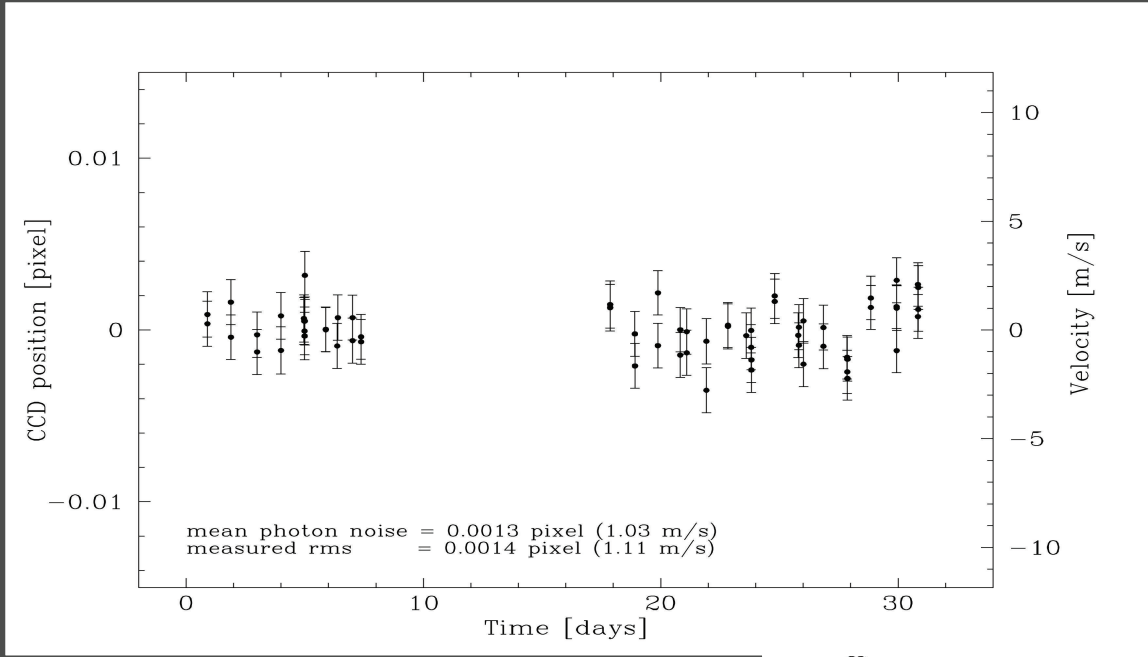
4000 ThAr lines, precision 15-150 m/s



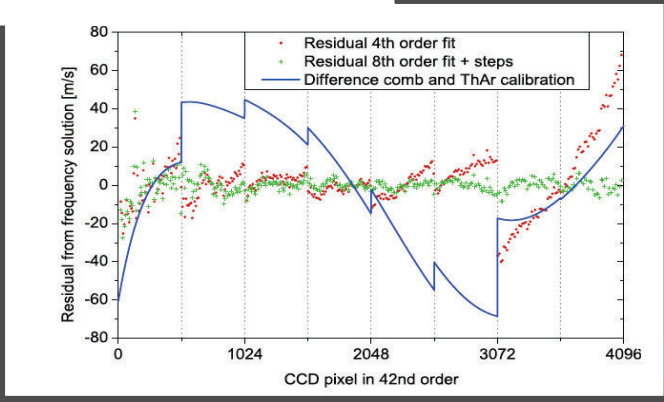




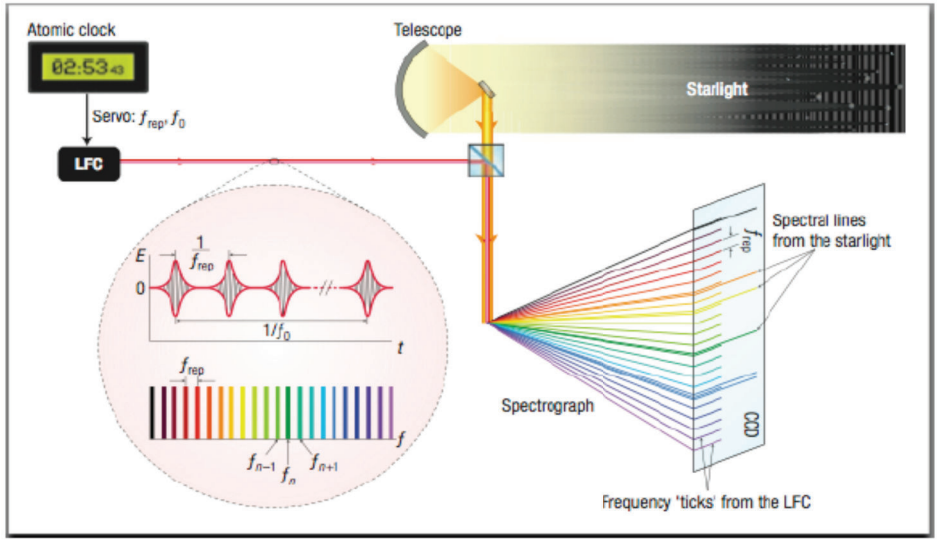
Absolute position of a Th line on the CCD over one month

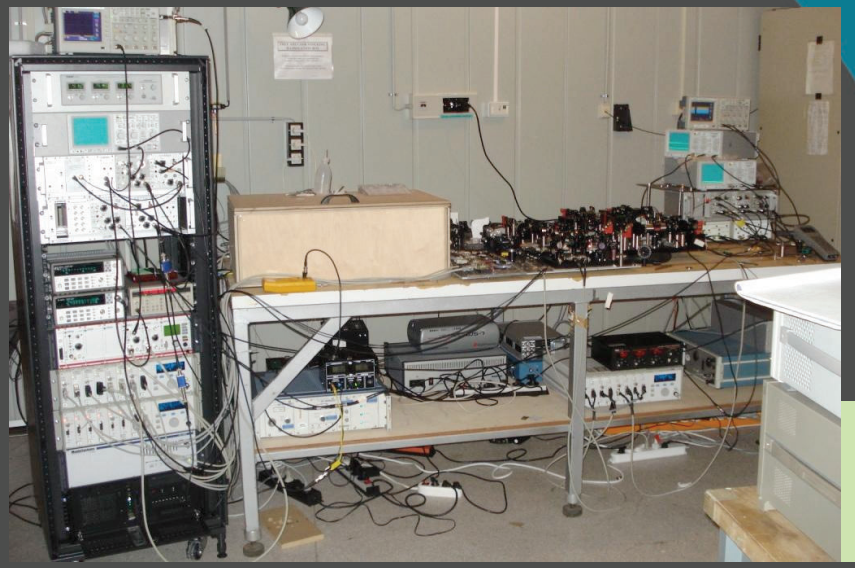


Single line < 1 m/s (1/1000 px)
the problem is the wavelength calibration

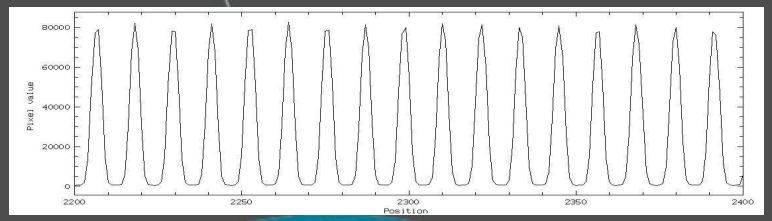


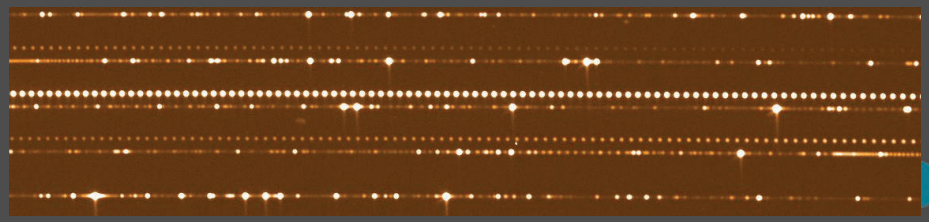
Laser Comb



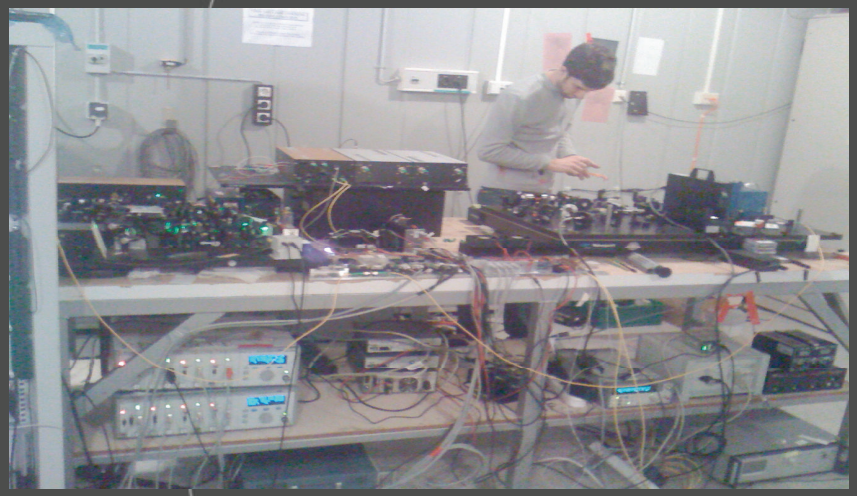


- Optical or NIR laser producing a train of femptoseconds pulses (controlled by an atomic clock)
- Produces a spectrum of evenly spaces delta-functions whose positions are known very precisely
- Prototype tested at HARPS Jan 2009





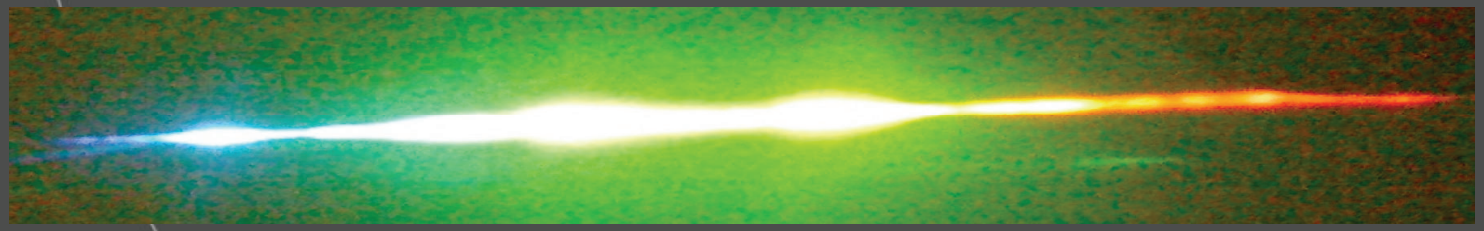
LFC mission on HARPS, March 2010

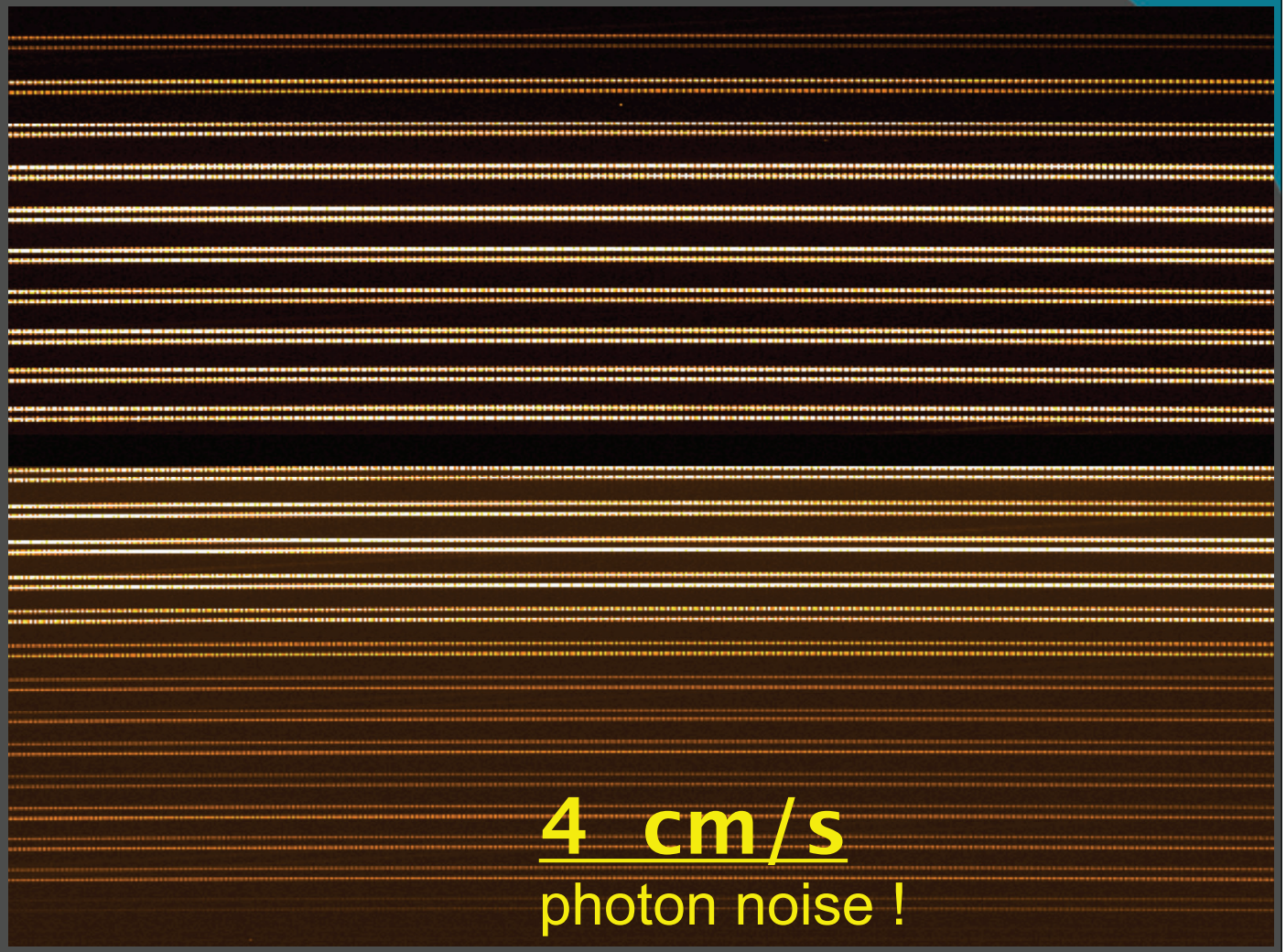


- Covers from 470nm to 580nm
- 23 orders with 11000 lines

with the Th we use ~ 1000 lines!!

The comb after broadening





11k lines
23 orders,
110 nm
~450 lines/ord.

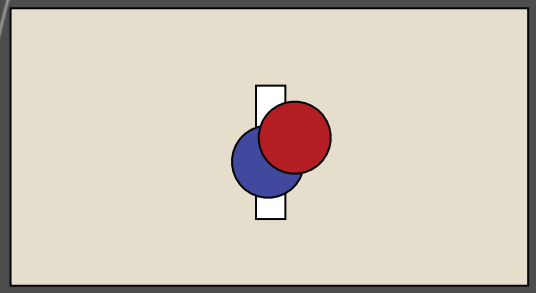
6 times more
flux than ThAr

4 cm/s
photon noise !

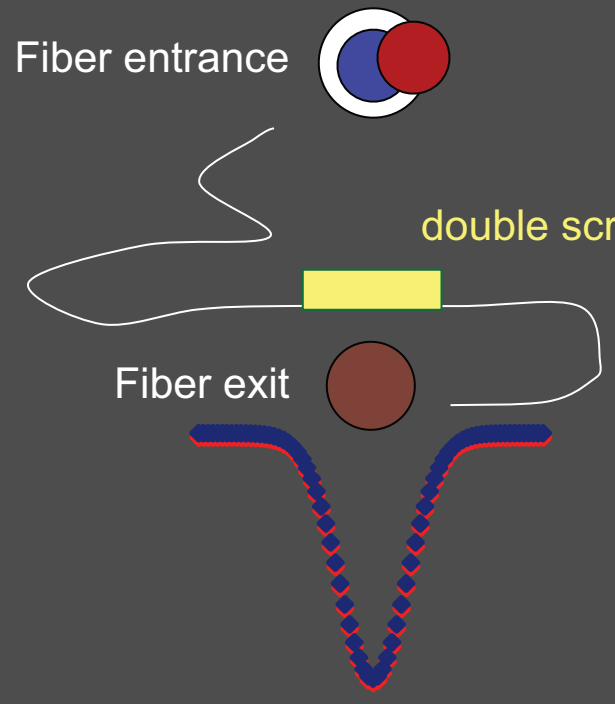
Laser comb will change High Resolution spectroscopy

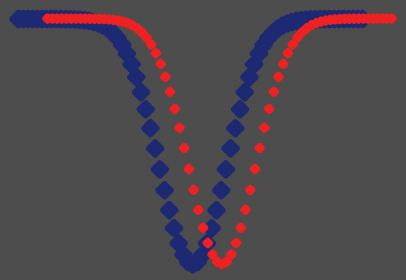
Improving the spectrograph feeding

Slit spectrograph



Fiber-fed spectrograph



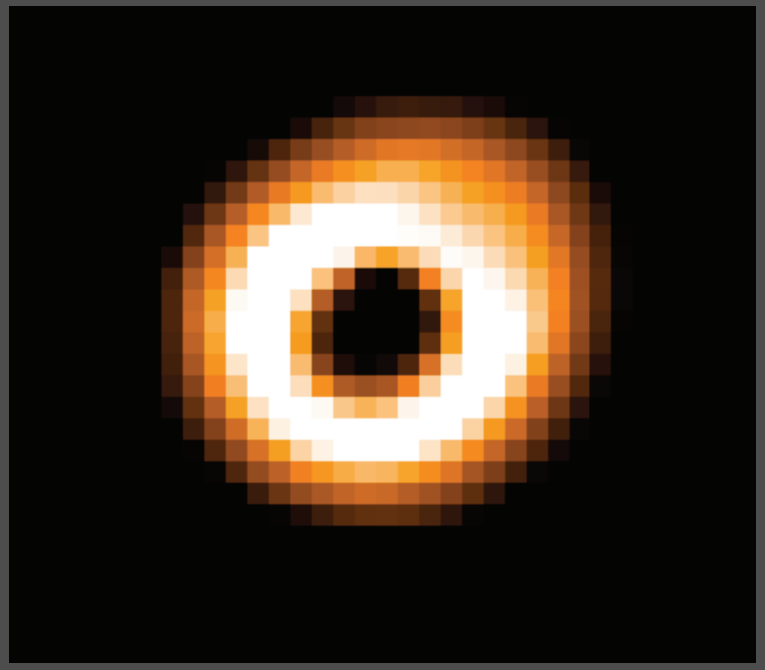


Δ RV

Light injection, guiding

"Bad" guiding, 0.5" decentering,
~3 m/s contribution to RV

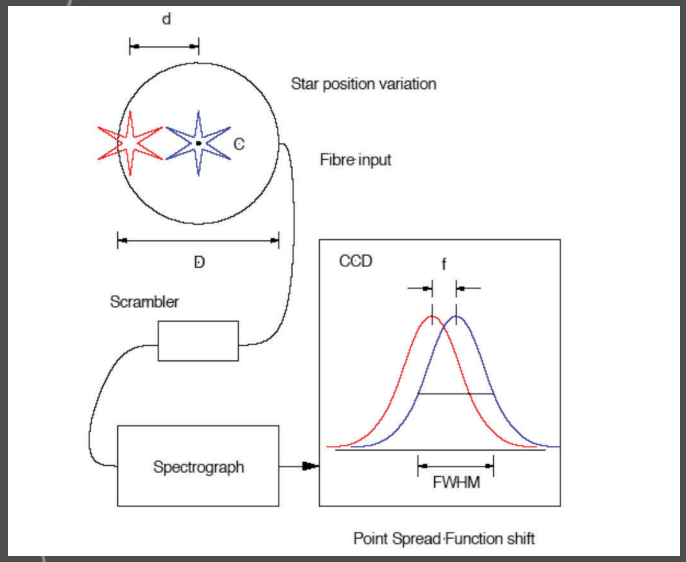
"Good" guiding, 0.1" RMS,
~30 cm/s contribution to RV

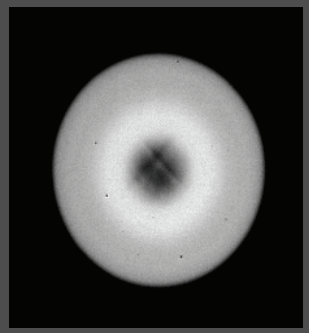


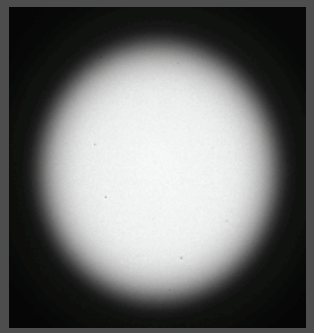
- **New guiding system with high frequency in operation at 3.6 m telescope starting 2011**

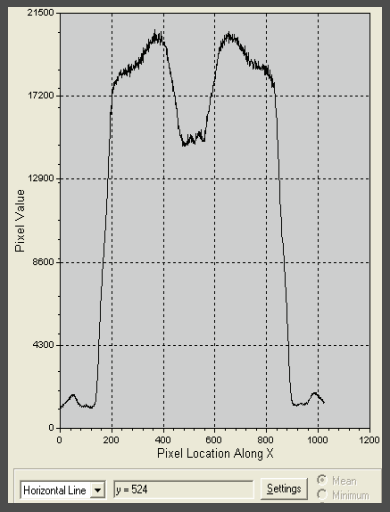
Fibres & Scrambling

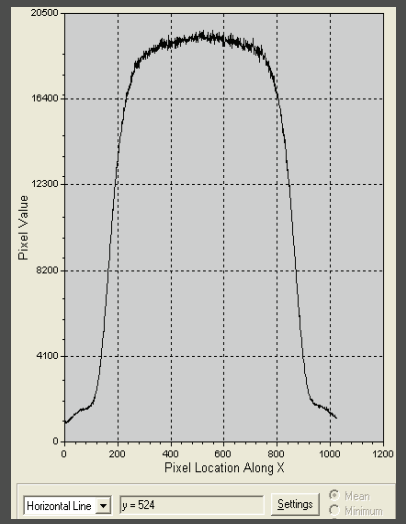
Square 200 um fibre. Centre +50 μm











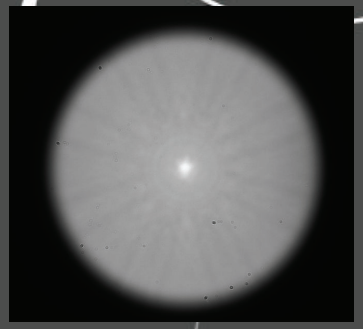
Scrambling Gain = (d/D)/(f/FWHM)

1 cms^{-1} means Gain=2500
for 0.01 arcsec guiding error

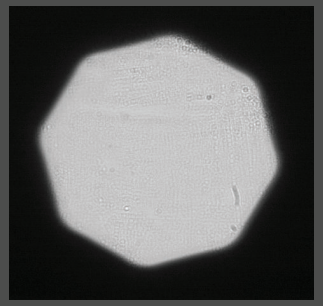
Free

Squeezed

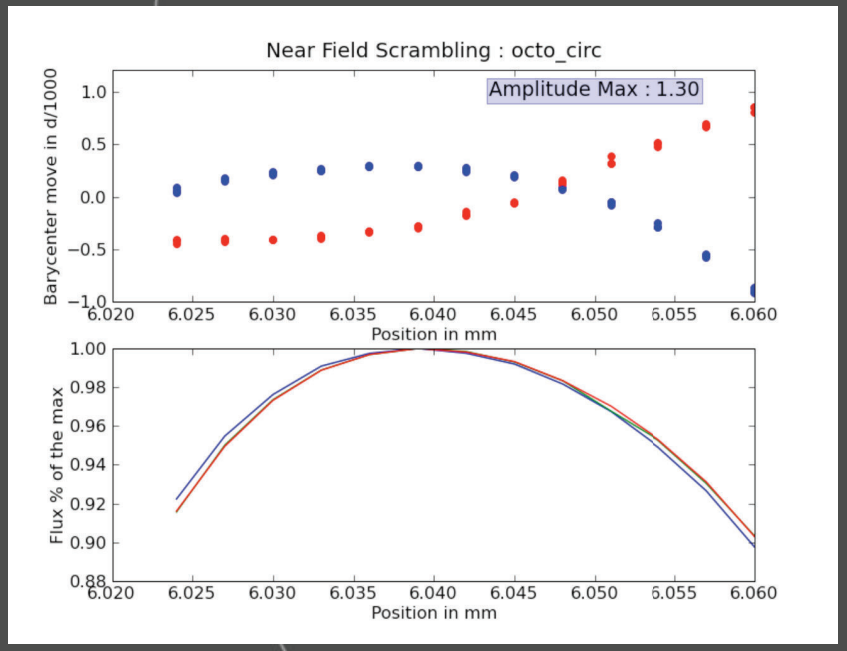
Scrambling fibers



Diameter : 70 microns
Star size : 35 microns

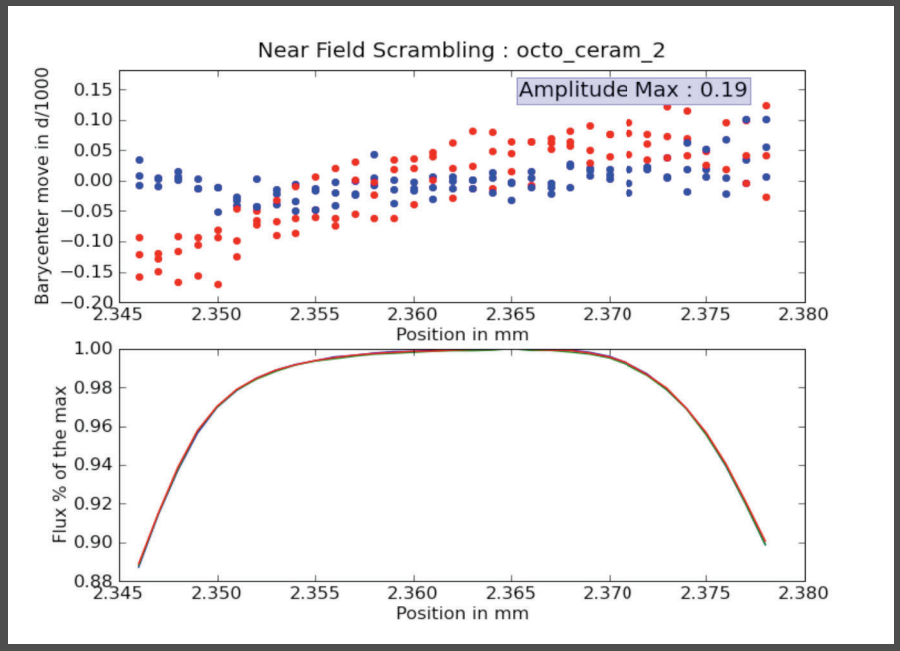


Circular fiber :



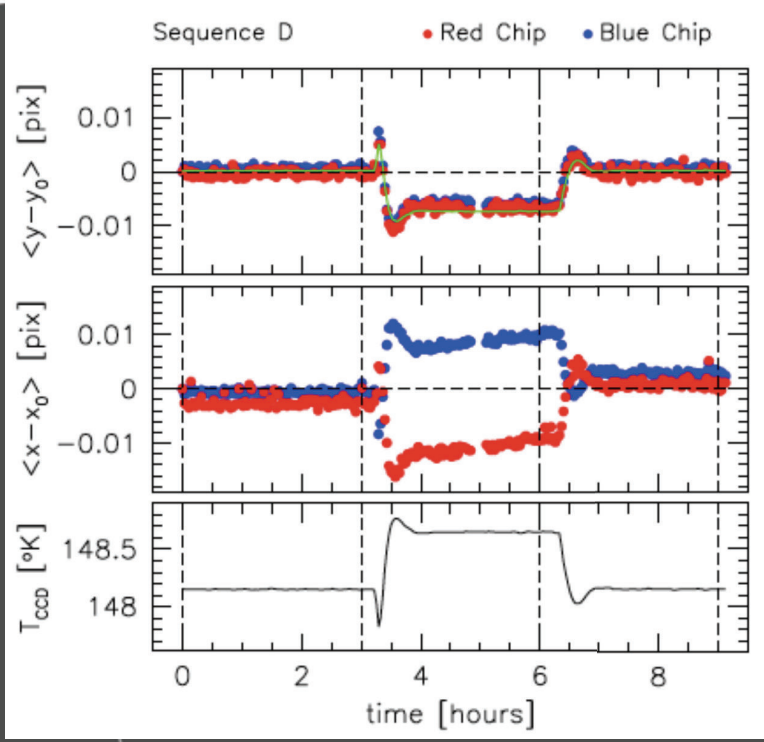
1d/1000

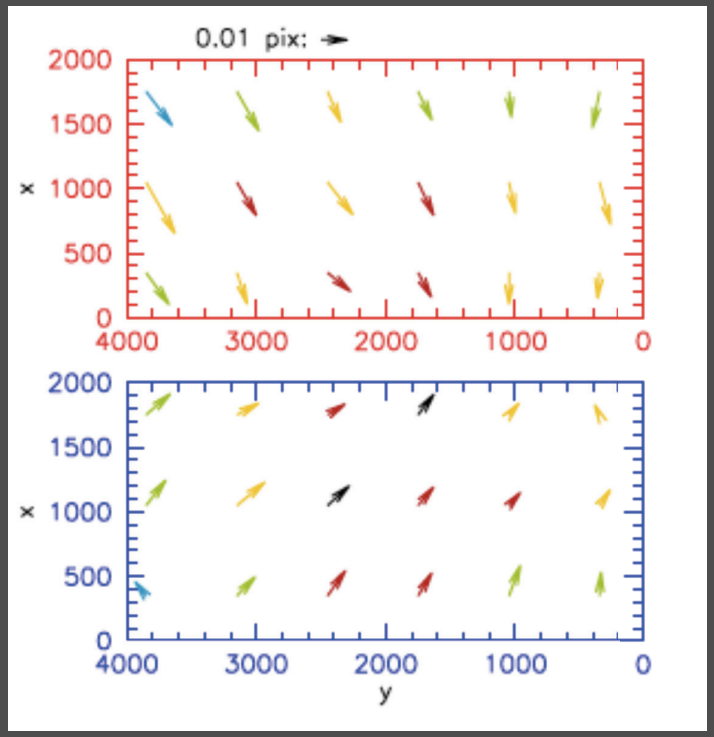
Octagonal fiber :



1D/10000 ==> < 30 cm/s

Surprise: Detector is alive



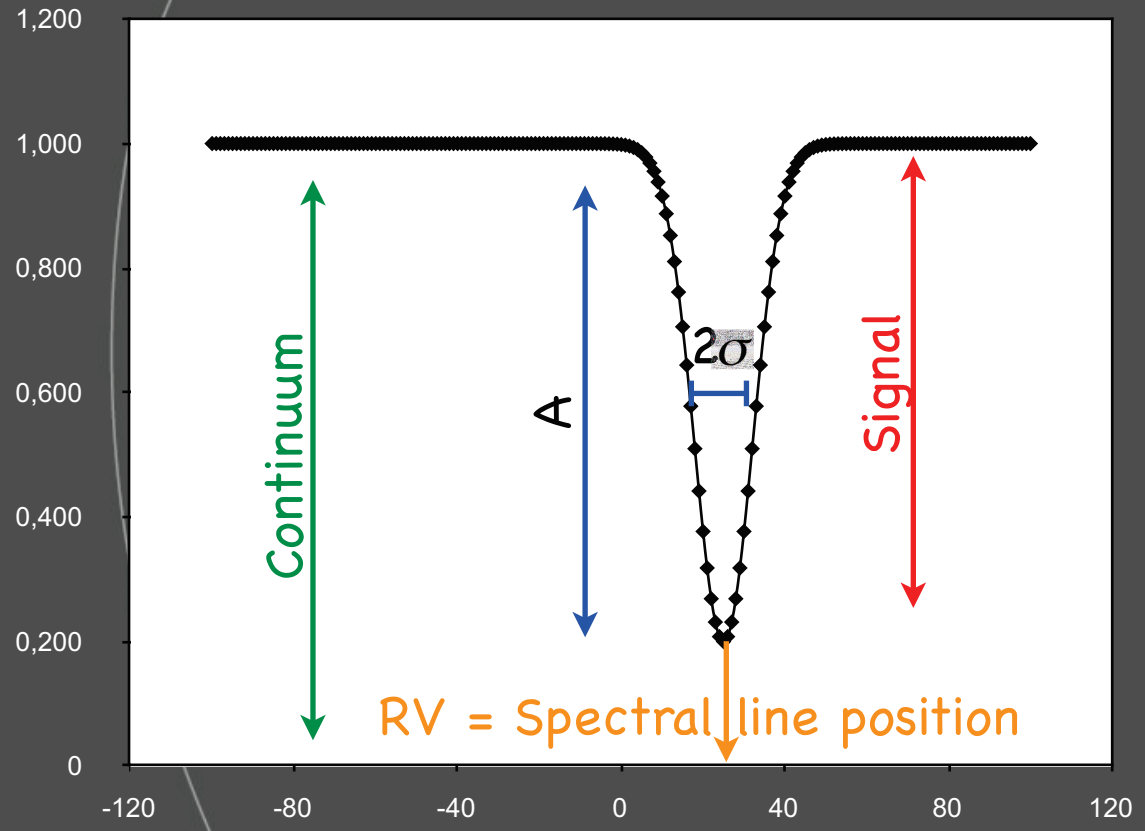


Differential movements of Th-A lines in the CCD: ~0.01/2 pixel/K (1 cm/s mK)
CCD expands around the attachments of the mosaic to the support

Development of super stable cryostat (FP7)

PHOTON NOISE

ESPRESSO a photon noise limited instrument



For exact formulae see:

Butler et al. 1996

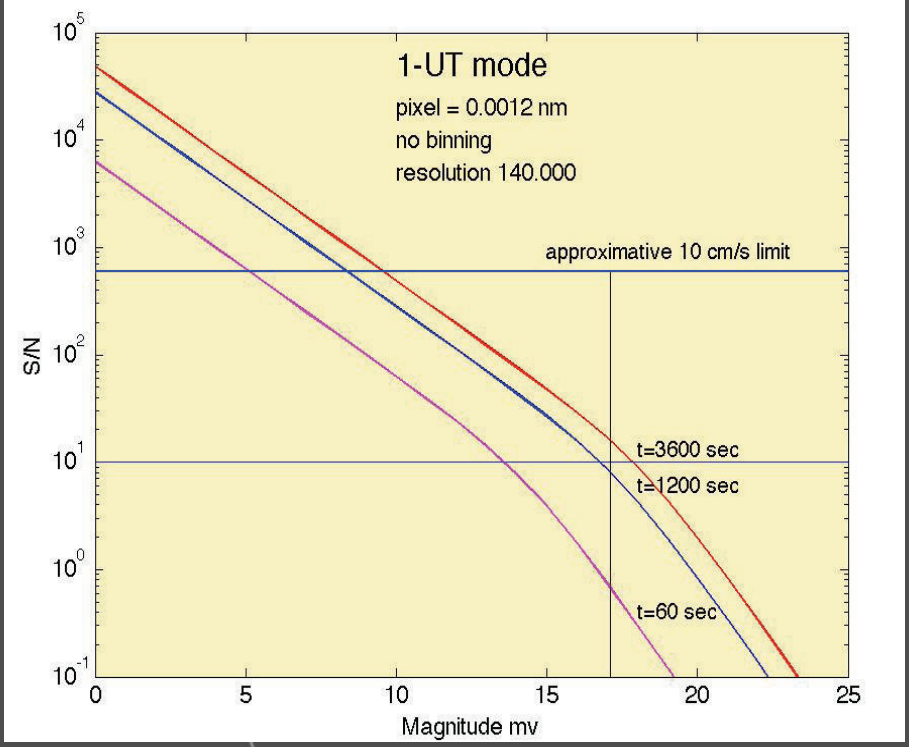
Bouchy et al. 2001

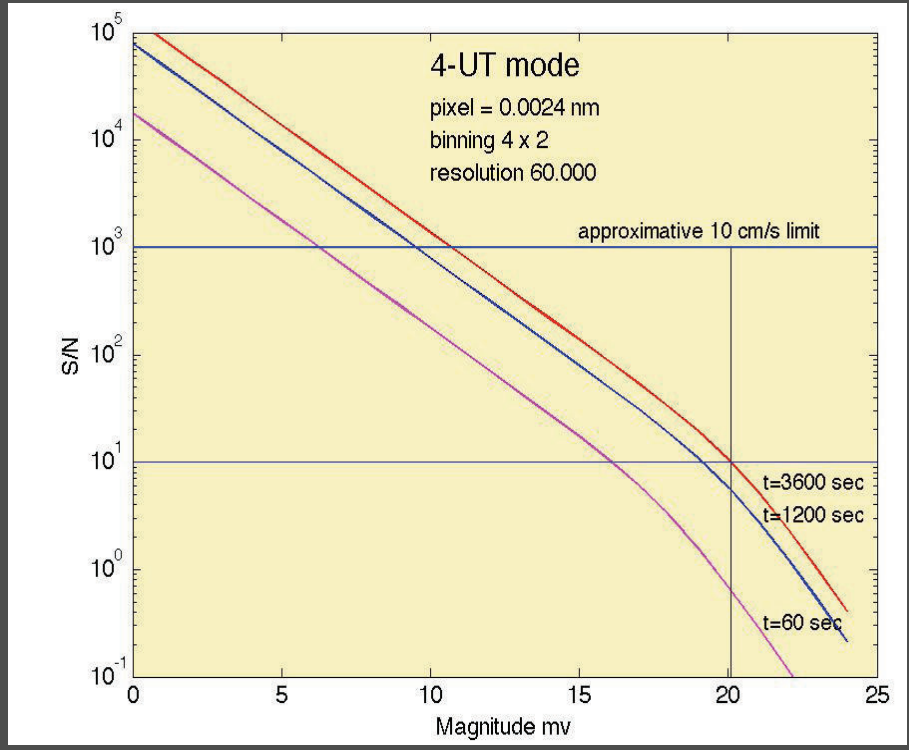
Approximation:

$$\varepsilon_{\text{single line}} = \frac{\sqrt{2 - A}}{2} \cdot \frac{\sqrt{\sigma}}{A} \cdot \frac{1}{SNR}$$

S/N ~ 100=> RV ~ 10 m/s

Performances





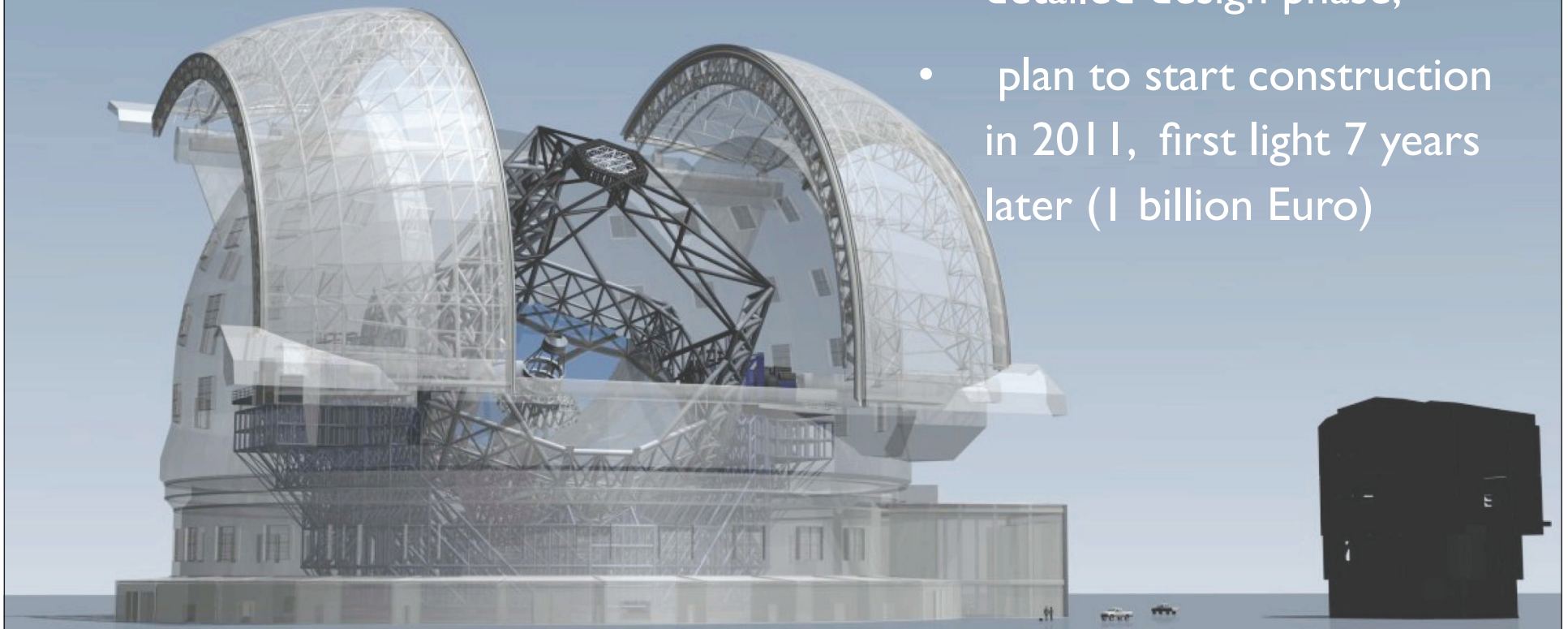
1 UT S/N=10 1 h for V= 17 like UVES without systematics
4 UT S/N=10 1 h for V= 20 break of the 1 ppm barrier

CCD ron 2e/px
dc 3e/h

ESO
European Organisation for Astronomical Research in the Southern Hemisphere

The World's Biggest Eye on the Sky

- The project is in the detailed design phase,
- plan to start construction in 2011, first light 7 years later (1 billion Euro)

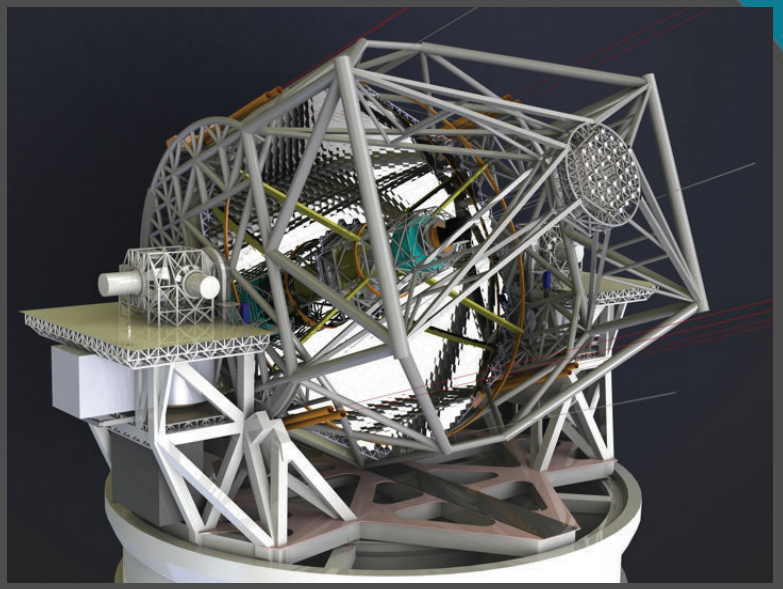


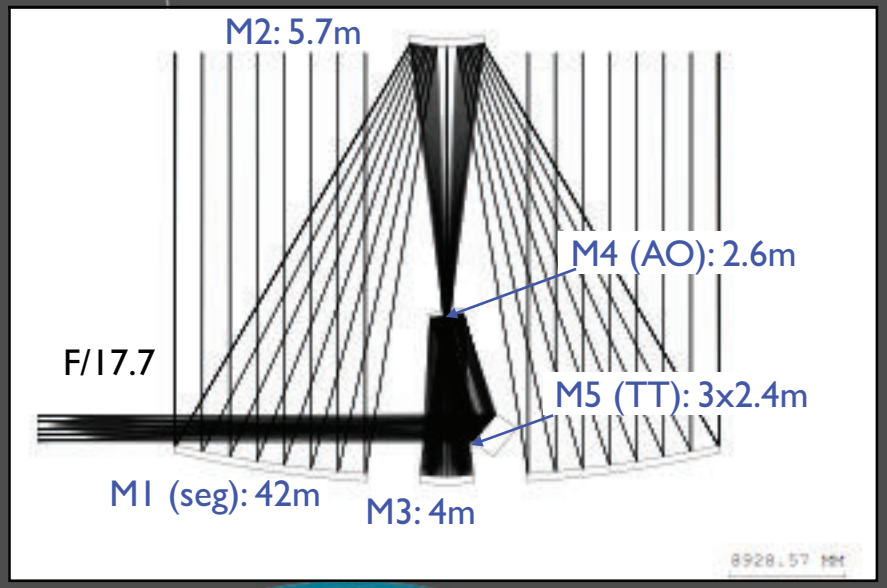
E-ELT

VLT

The Telescope

- Nasmyth telescope with a segmented primary mirror of 42 m diameter
- Nearly 5000 tons of structure
- Two instrument platforms of the size of tennis courts

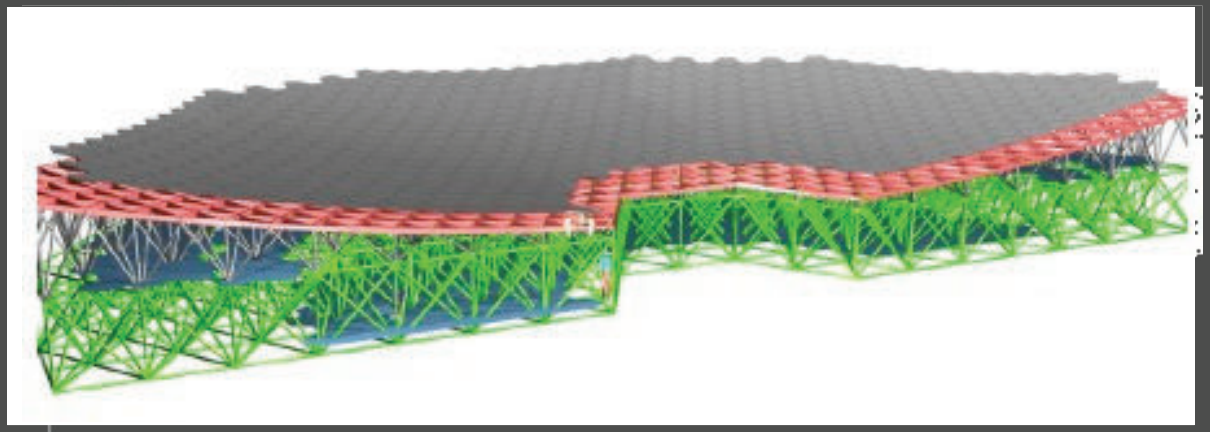


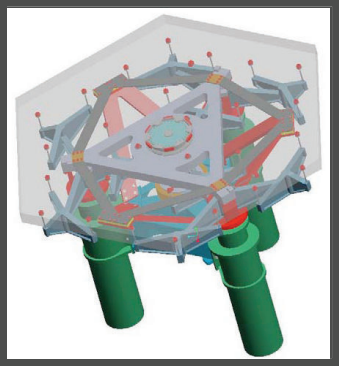


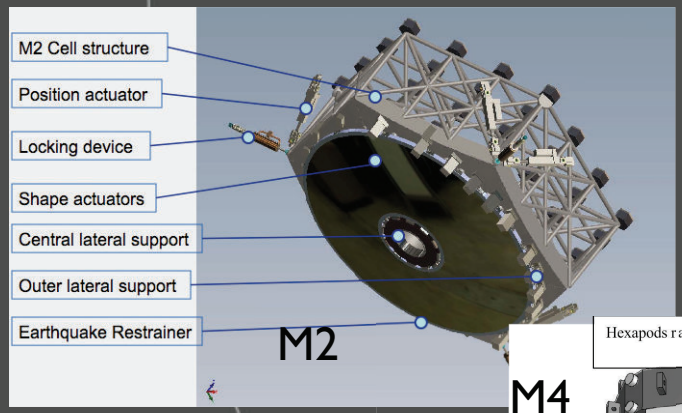
- Novel 5 mirror design to include adaptive optics in the telescope
- Classical 3-mirror anastigmat + 2 flat fold mirrors [M4,M5]
- Outstanding image quality

The Mirrors

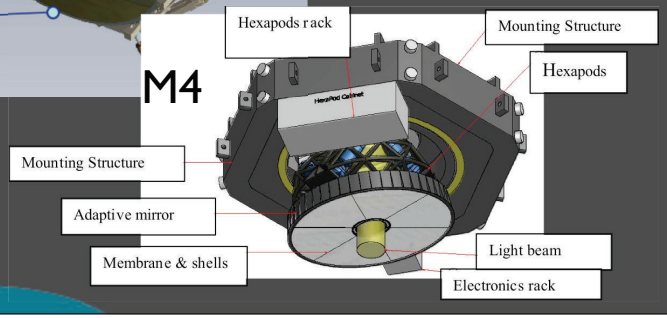
- Primary mirror: 42m ∅, 984 segments of 1.4m, 1200 m^2







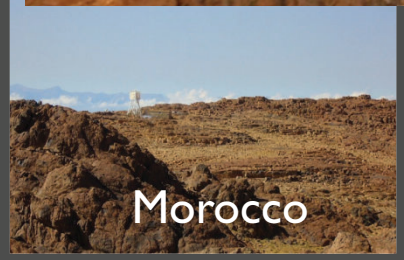
- Secondary: 5.6m ∅, 156 axial supports
- Tertiary: 4m ∅, controls f-ratio



- M4: 2.6m ∅ flat, adaptive with 6000-8000 actuators
- M5: 3x2.4m, flat, tip-tilt

The Site

- Several sites in Chile, Morocco, the Canary Islands, Argentina, Mexico, ... are being intensively tested



ESO
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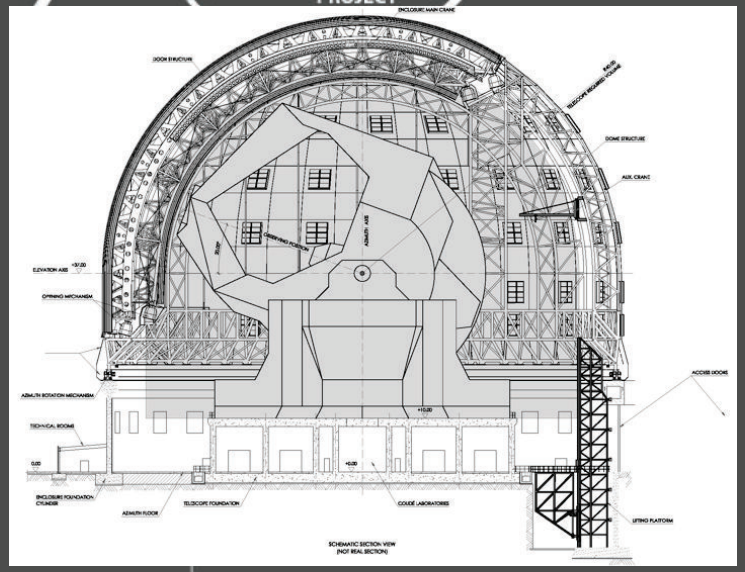
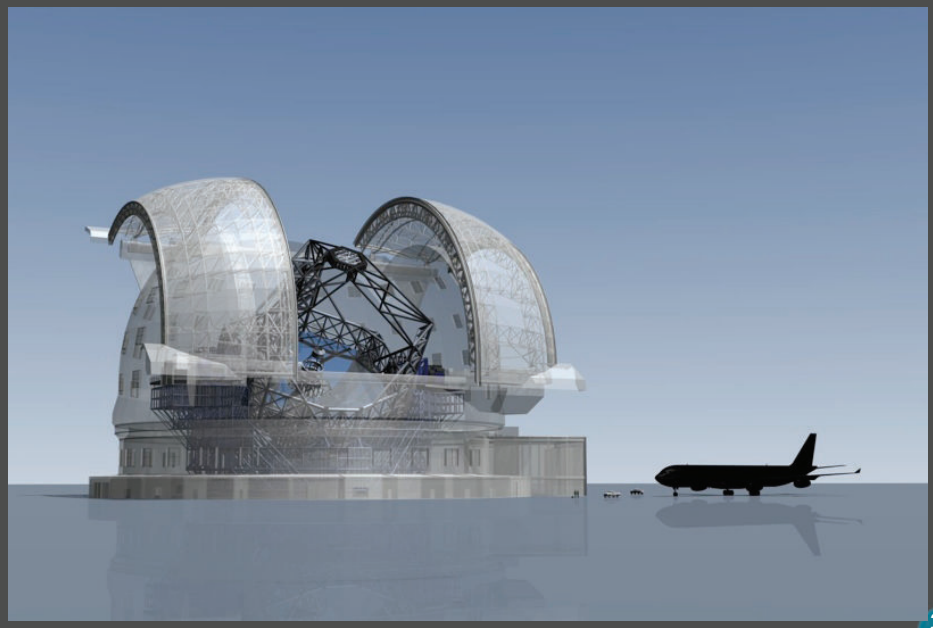
espresso PROJECT

The Dome



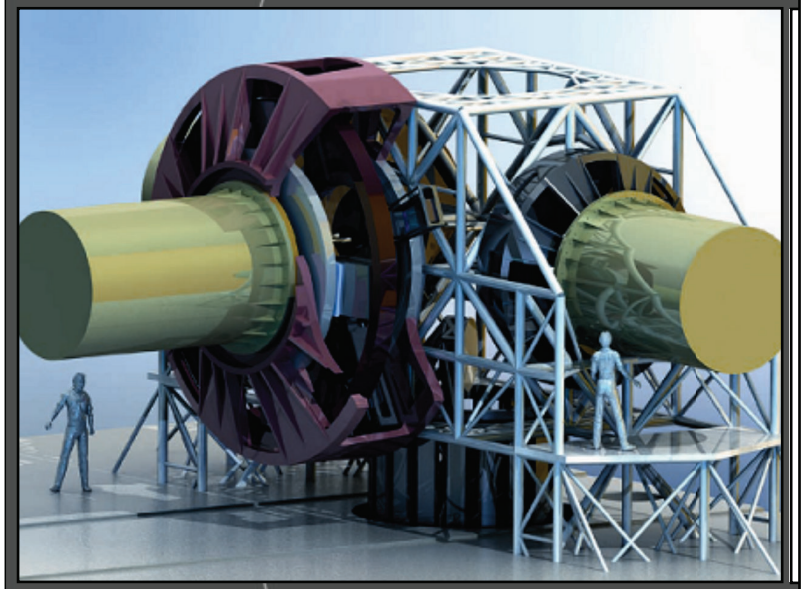
- The E-ELT dome: base of 100m diameter, and 80m high
- The size of a football stadium

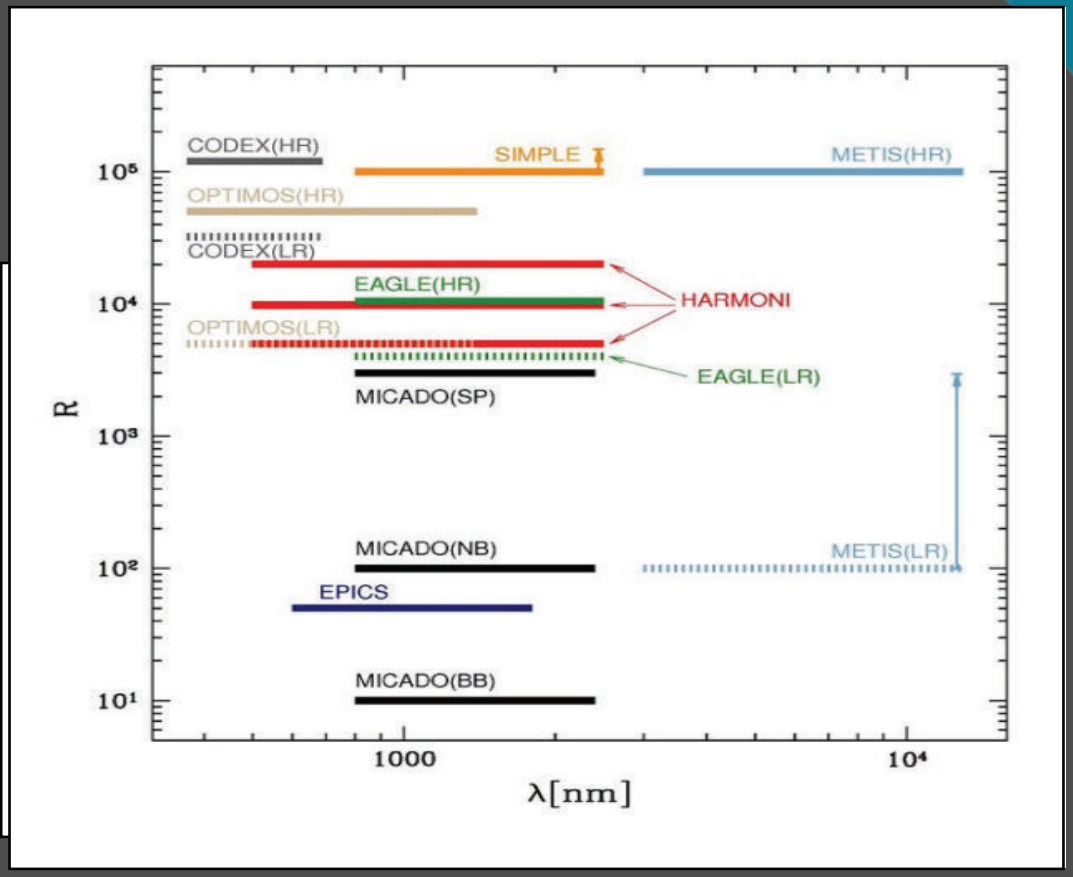
- Close to 4000 tons of steel
- Fully air-conditioned and wind shielded
- Equipped with several heavy duty cranes and a lifting platform for instruments



The Instruments

- Telescope can host up to 10 instruments





- Eight instrument concepts & two post-focal adaptive optics modules are running until end of 2009
- CODEX (COsmic Dynamical EXperiment) unlikely first light instrument

CODEX Consortium

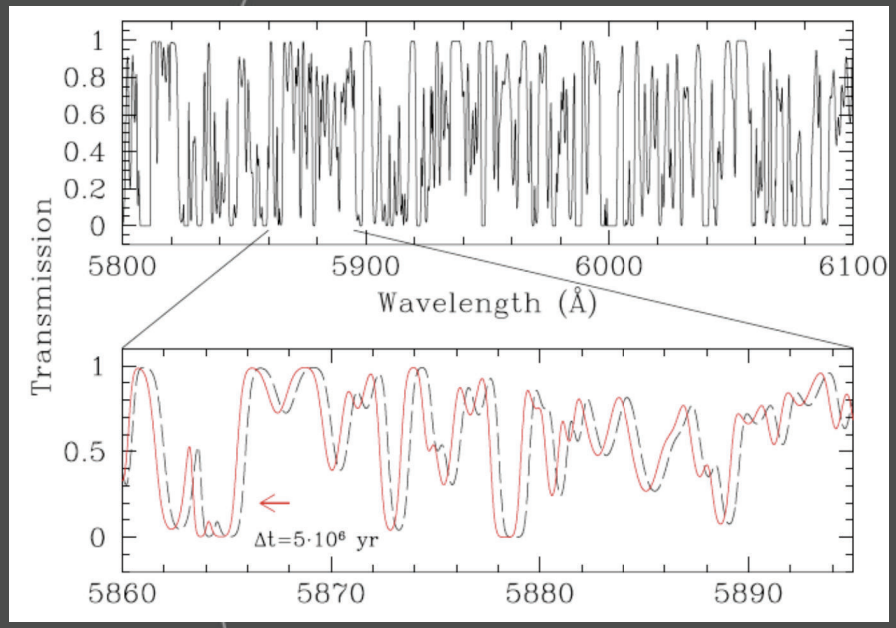
CODEX Team

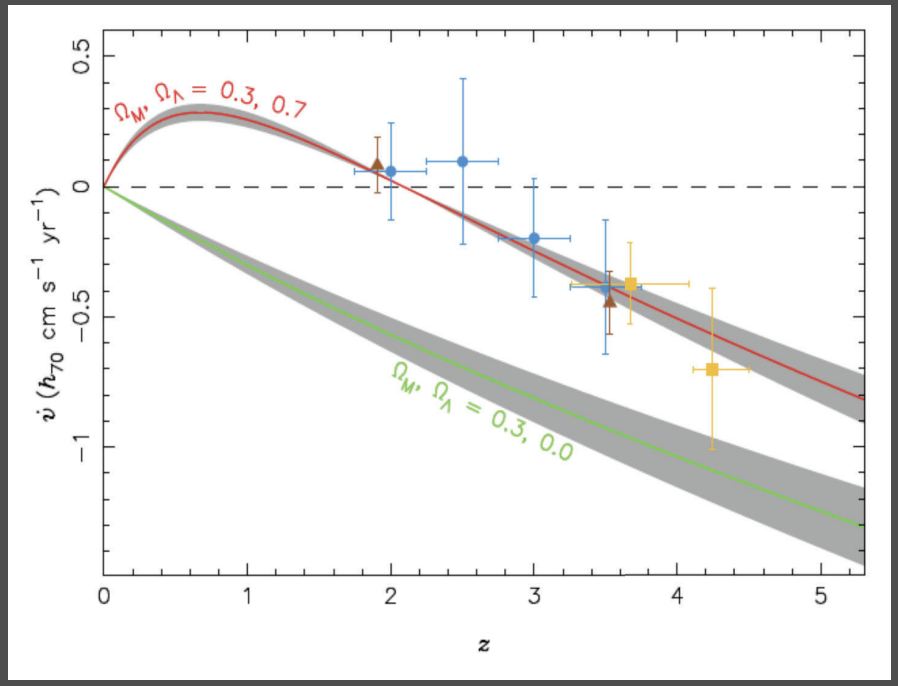
Luca Pasquini, Stefano Cristiani, Ramón Garcia-Lopez, Martin Haehnelt , Michel Mayor, Gerardo Ávila, George Becker , Piercarlo Bonifacio, Bob Carswell, Roberto Cirami, Maurizio Comari Igor Coretti, Gaspare Lo Curto, Hans Dekker, Bernard Delabre, Miroslava Dessauges, Paolo di Marcantonio, Valentina D'Odorico, Artemio Herrero, Garik Israelian, Olaf Iwert, Jochen Liske, Christophe Lovis, Antonio Manescau, Denis Mégevand, Paolo Molaro, Dominique Naef, María Rosa Zapatero Osorio, Francesco Pepe, Rafael Rebolo, Marco Riva, Paolo Santin, Paolo Spanò, Fabio Tenegi, Stéphane Udry, Eros Vanzella, Matteo Viel, Filippo Maria Zerbi.

universal expansion

Liske et al 2008

$$\dot{z} = (1+z)H_0 - H(z)$$





precision & accuracy of few cm/s
400 nights of the E-ELT over 10 years

Codex Requirements

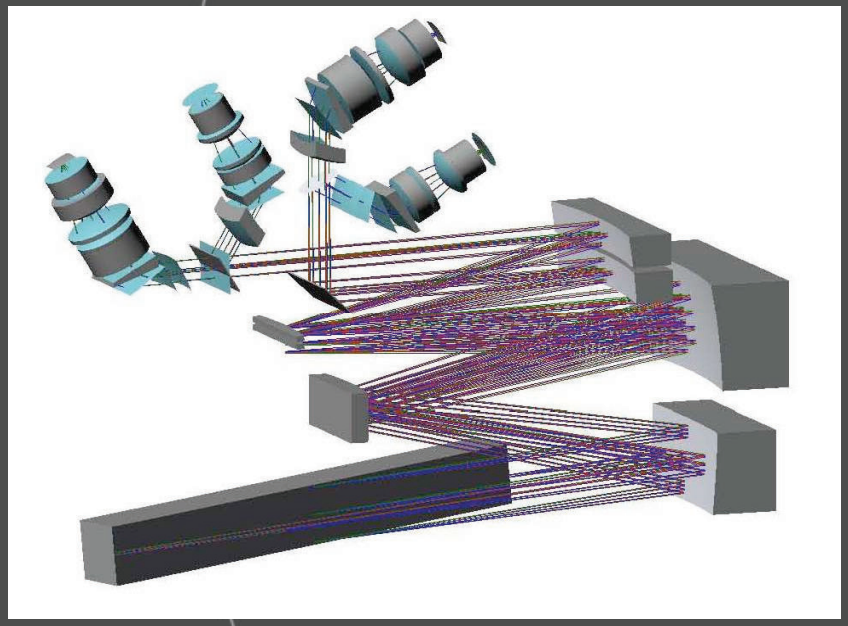
	Espresso (1UT)	CODEX
Telescope	VLT (8m)	E-ELT (42m)
Scope	Rocky Planets	Earth-Like
Sky Aperture	1 arcsec	0.80 arcsec
R	150000	150000
λ Coverage	350-730 nm	380-680 nm
λ Precision	5 m/sec	1 m/sec
RV Stability	< 10 cm/sec (1/5000 pixel)	< 2 cm/sec

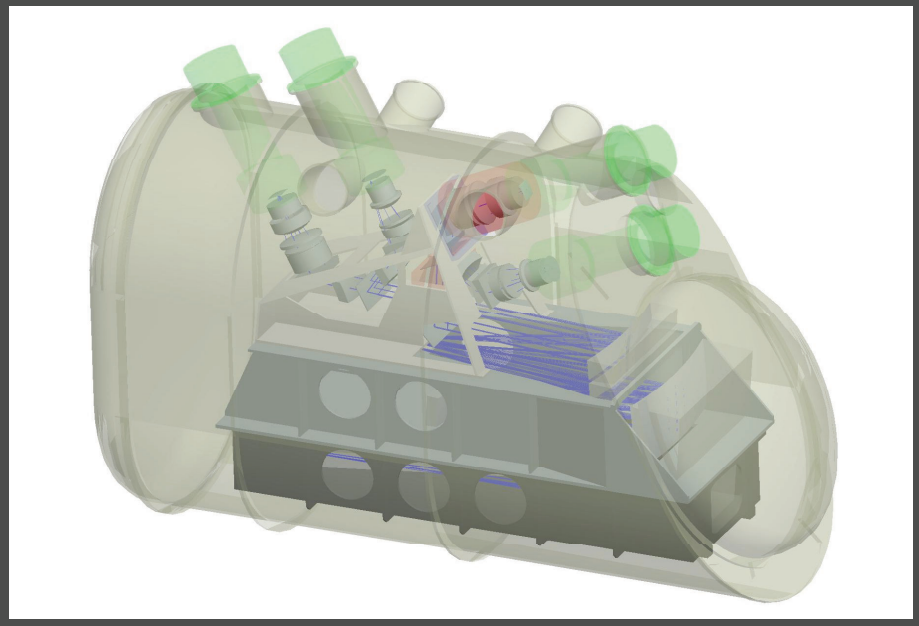
similar technical solutions

Optical Design

High Resolution at Large telescopes very challenging

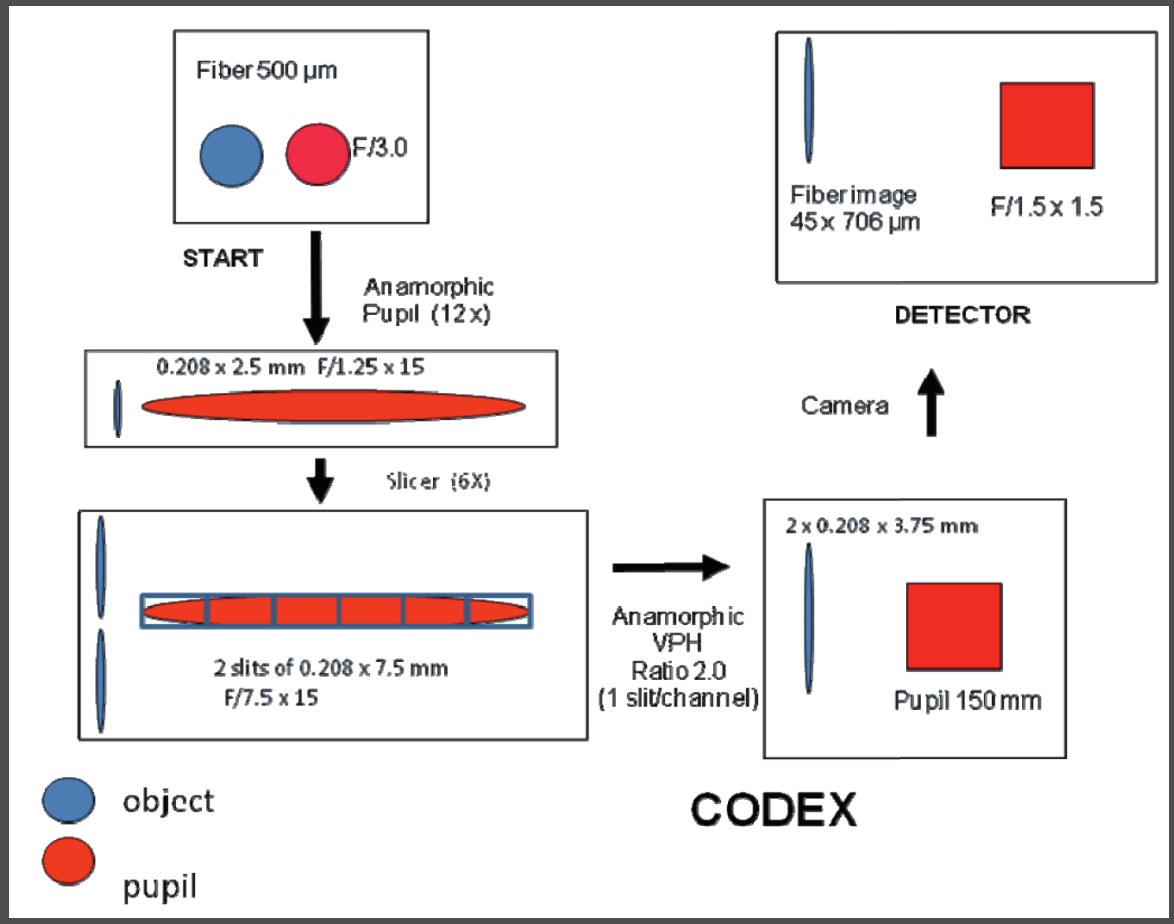
Dimensions vacuum vessel:
3x2.4x4.2 (m) [height x width x length]





Anamorphism (12X) plus Pupil Slicer (8X) → 1 echelle (1.6 x 0.2m)
Dychroic → 4 Spectra (2 Red + 2 Blue)
Slanted VPHG compress each of the spectra to 45x706 microns on 2 blue and 2 red cameras
Object + sky (or simultaneous calibration) recorded simultaneously

Pupil and Image evolution



Two spectra (obj + sim cal or sky) recorded simultaneously in each camera (2 blue and 2 red cameras)

Performances

E-ELT D=42 m

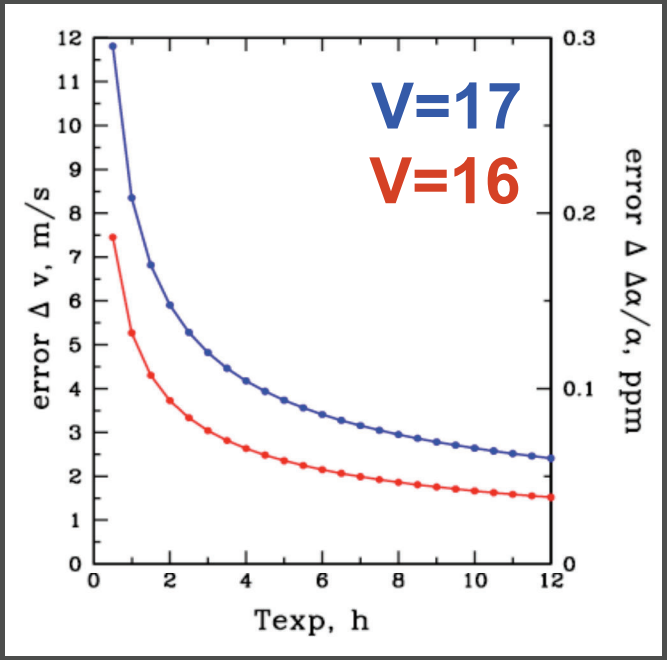
R=150K

EW=50 mA

b=2 km/s

λ=5000 A

E=15%



σ_v ~ 1-2 m s^{-1} (for a pair)

→ $\sigma_{\Delta\alpha/\alpha}$ ~ 1 x10^{-7} (FeII-MgII)

→ 5 x10^{-8} (FeII-FeII)

(order of the NH3 signal in the MW)

Further improvement from averaging lines

But possible stops from astronomical sources

CONCLUSIONS

- ESPRESSO (in 4-5 years!) will enable tests of the stability of fundamental constants to greatly improved new limits and breaking the wall of 1 ppm

- New wavelength calibration mandatory. Several technical issues considerably improved (probably limitation from astronomical source)

- CODEX similar technical solutions adopted for ESPRESSO but research is going on. (the case of FC is much easier than the expansion). Another order of magnitude improvement 0.1 ppm

- Fundamental constants should be found varying within two order of mag from present limits: i.e at level of 10^{-8} or never revealed by this techniques!


Thank you