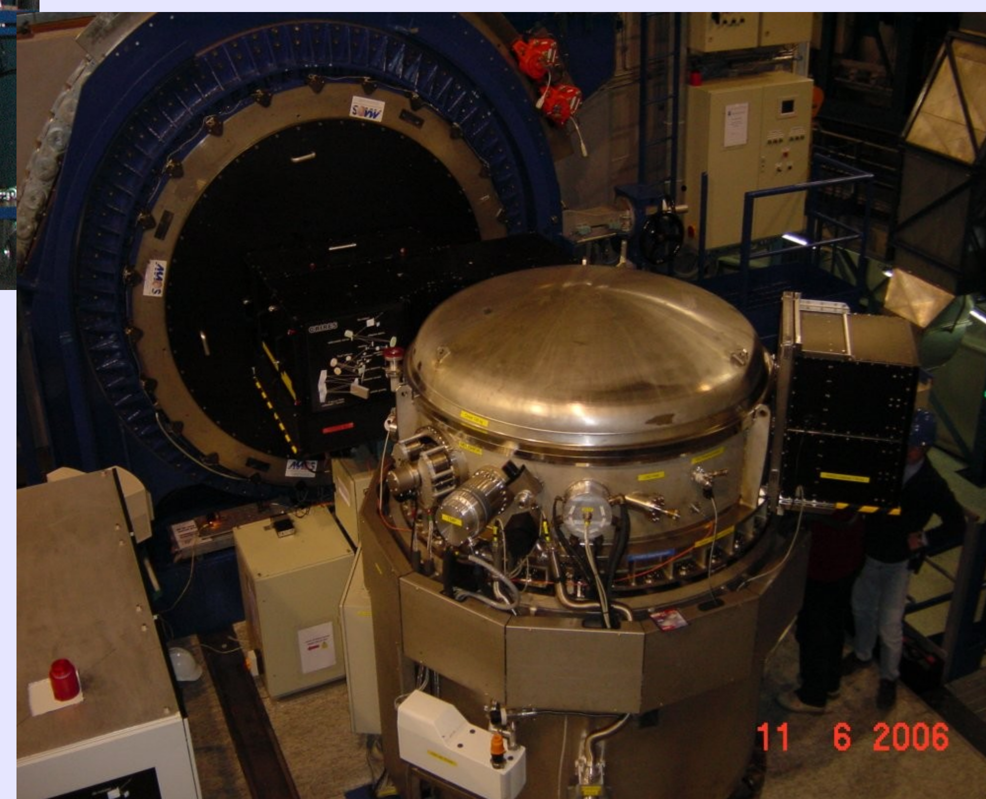
Commissioning of CRIRES, the High Resolution Infrared Spectrograph for ESO's VLT

Hans Ulrich Käufl, European Southern Observatory

3rd Nahual Workshop, Tautenburg, June 2006

▼ UT1 Nasmyth-A with CRIRES in commissioning and awaiting science verification

▲ CRIRES in the Paranal Integration Laboratory May '06



CRIRES:

Cryogenic Infrared Echelle Spectrograph

The team standing behind CRIRES:

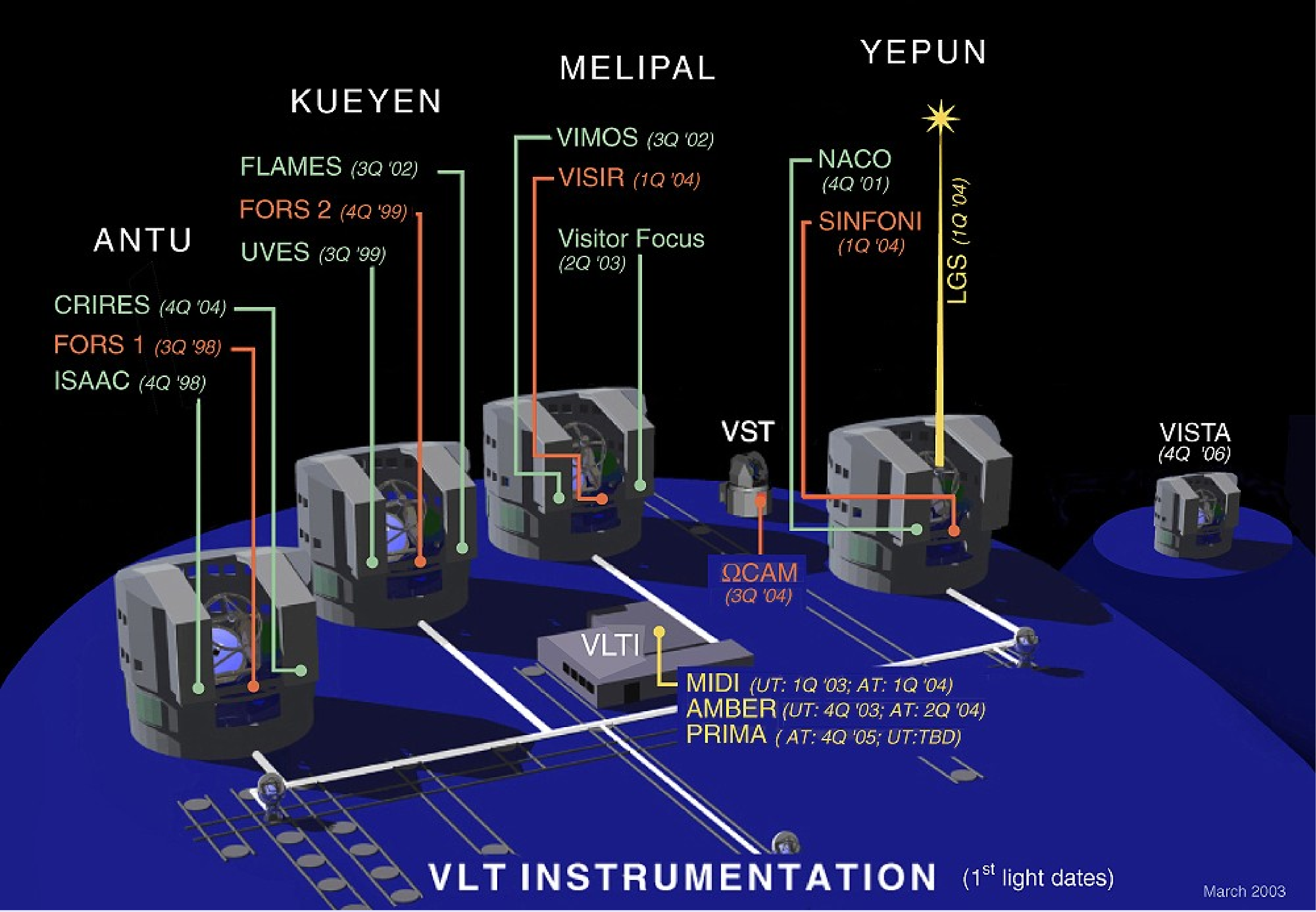
Pascal Ballester, Peter Biereichel, Paul Bristow (1), Mark Casali, Bernhard Delabre, Reinhold Dorn, Siegfried Eschbaumer, Raul Esteves, Enrico Fedrigo, Gert Finger, Gerhard Fischer, Domingo Gojak, Gotthard Huster, Yves Jung, Florian Kerber (2,3), Jean-Paul Kirchbaumer, Jean-Louis Lizon, Lars Lundin, Enrico Marchetti, Leander Mehrgan, Manfred Meyer, Alan Moorwood, Sylvain Oberti, Jean-Francois Pirard, Jerome Paufique (4), Eszter Pozna, Andreas Seifahrt, Ralf Siebenmorgen, Armin Silber, Barbara Sokar, Jörg Stegmeier, Sebastien Tordo, Stefan Uttenthaler

and many more in Garching and now also on Paranal and in Vitacura
many thanks to all of them!

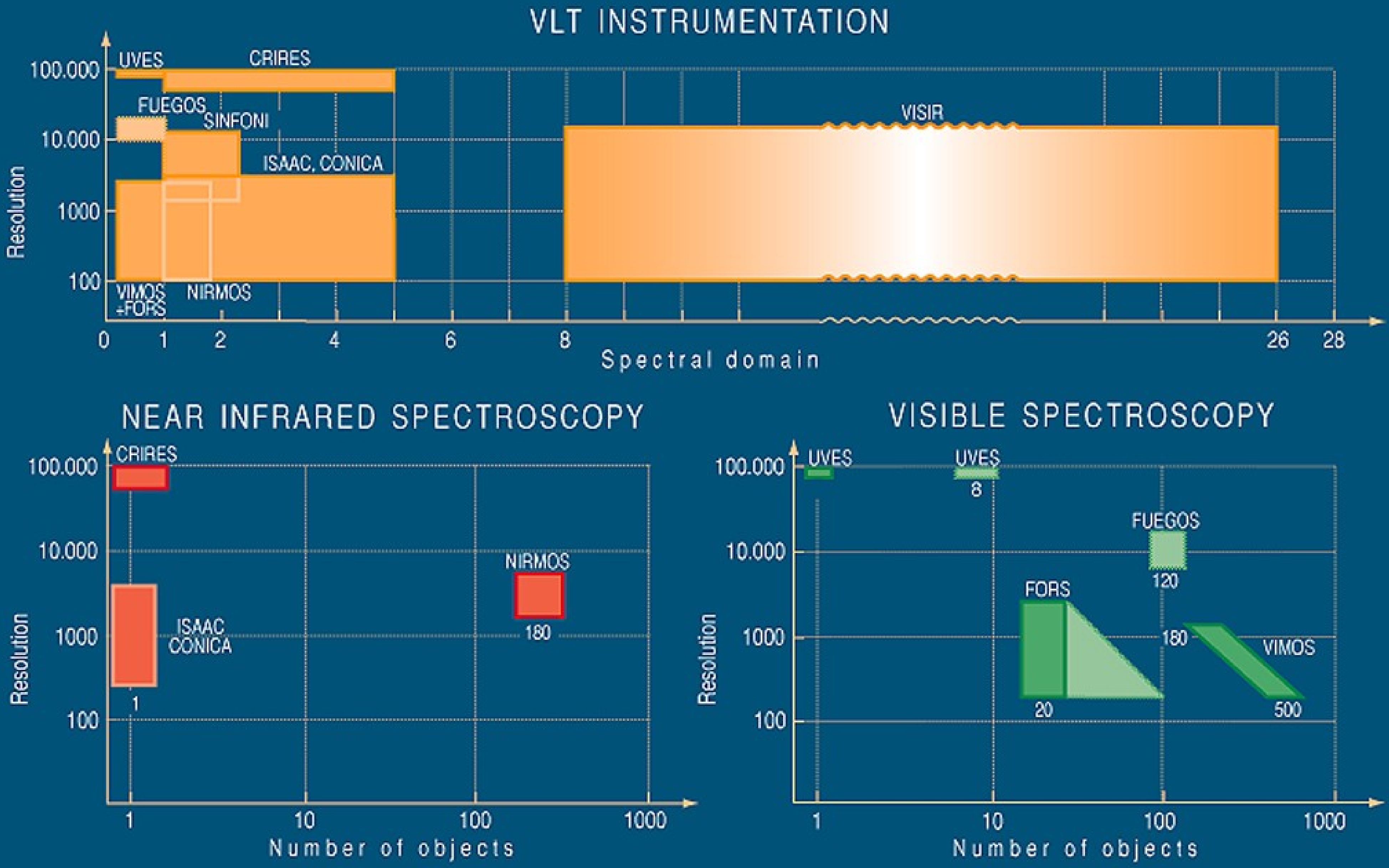
other papers: (1) 6270-67, (2) 6269-98, (3) 6269-149, (4) 6227-40

CRIRES is a 95% ESO built instrument

CRIRES is last of the 1st Generation VLT instrumentation Plan

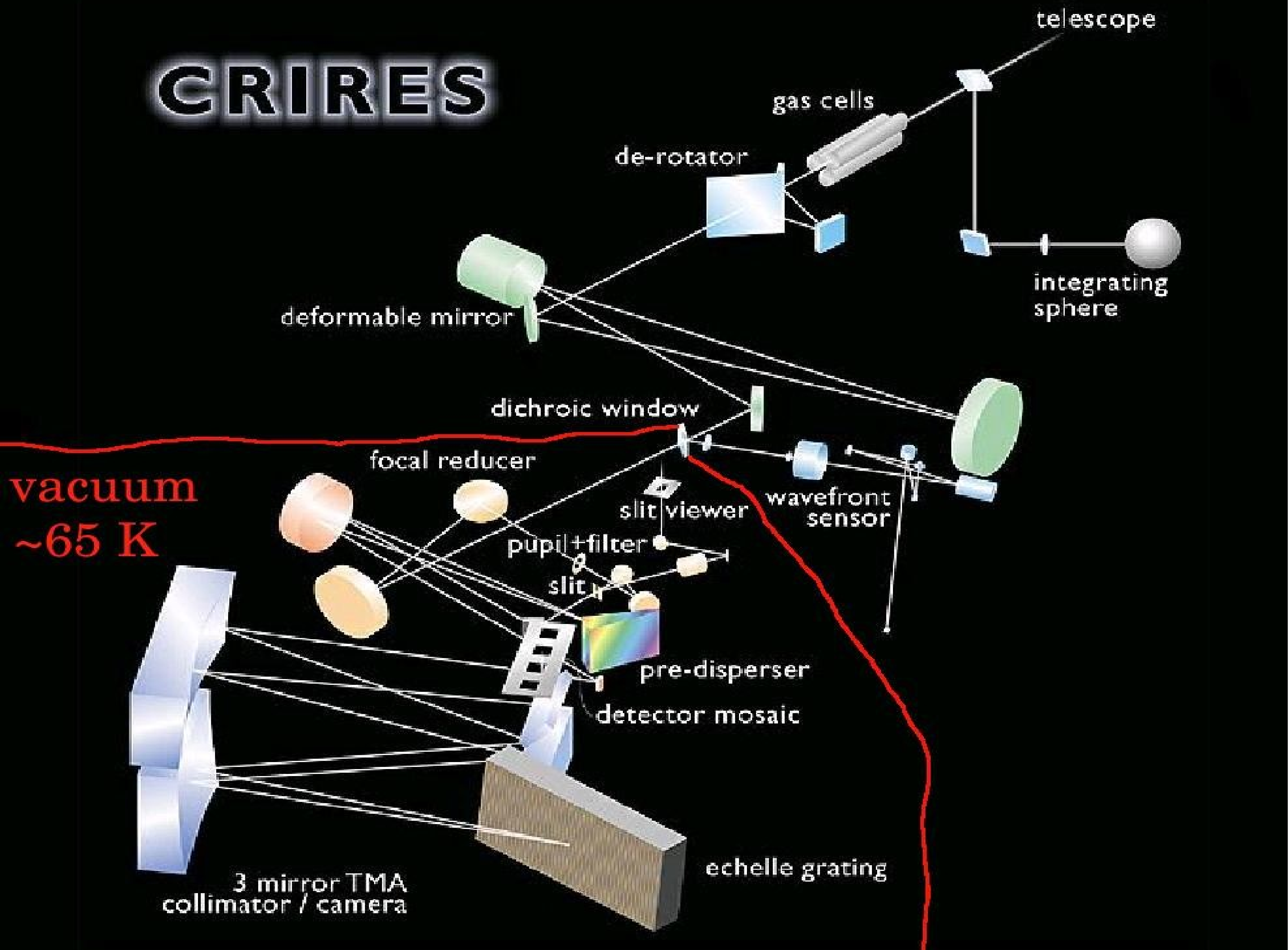

ANTU
KUEYEN
MELIPAL
YEPUN
CRIRES (4Q '04)
FORS 1 (3Q '98)
ISAAC (4Q '98)
FLAMES (3Q '02)
FORS 2 (4Q '99)
UVES (3Q '99)
VIMOS (3Q '02)
VISIR (1Q '04)
Visitor Focus (2Q '03)
NACO (4Q '01)
SINFONI (1Q '04)
LGS (1Q '04)
VST
ΩCAM (3Q '04)
VISTA (4Q '06)
VLTI
MIDI (UT: 1Q '03; AT: 1Q '04)
AMBER (UT: 4Q '03; AT: 2Q '04)
PRIMA (AT: 4Q '05; UT:TBD)
VLT INSTRUMENTATION (1st light dates)
March 2003

1ST GENERATION VLT INSTRUMENTS



ESO VLT VG21

CRIRES



telescope
gas cells
de-rotator
integrating
sphere
deformable mirror
dichroic window
focal reducer
vacuum
~65 K
slit viewer
wavefront
sensor
pupil+filter
slit
pre-disperser
detector mosaic
echelle grating
3 mirror TMA
collimator / camera

CRIRES main characteristics

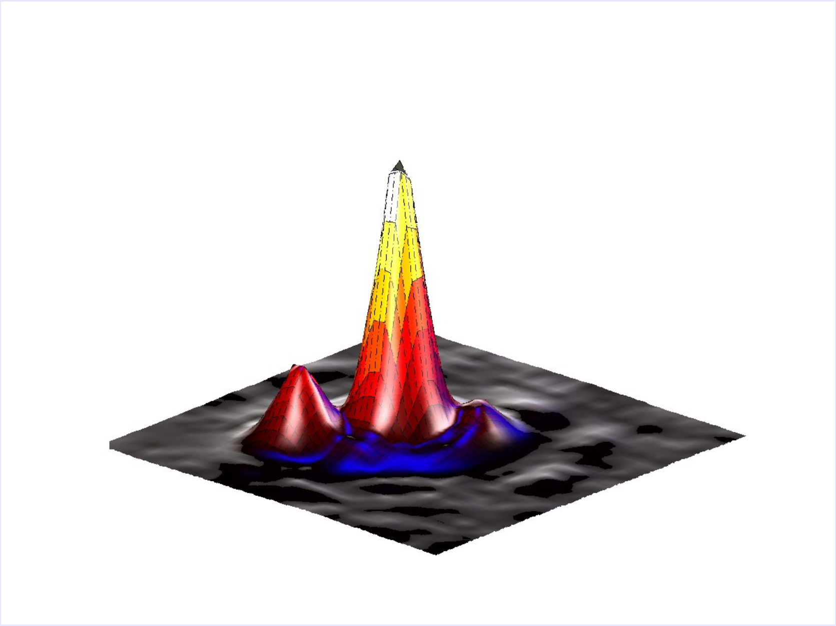
- **wavelength coverage:** λ ~ 0.95 – 5.2µm
- **spectral resolution:** $\lambda / \Delta\lambda \approx 10^5$ or $\Delta v \approx 3$km/s
  (2 pixel Nyquist sampling)
- **array detector mosaic:**
  4 x 1024 x 512 Aladdin III InSb mosaic
  ☞ instantaneous λ - coverage > 2.0 %
  pixel scale 0.1"/pix
- **infrared slit viewer** (Aladdin III) with J,H & K-filters
- **precision** for calibration and stability ~ 75m/s
  i.e. 1/20th of a pixel or 5mas tracking error
- Piezo-electric actuator in pre-disperser collimator for vernier adjustment of spectrum on detector
  (using sky-lines as reference)

CRIRES main characteristics (cont)

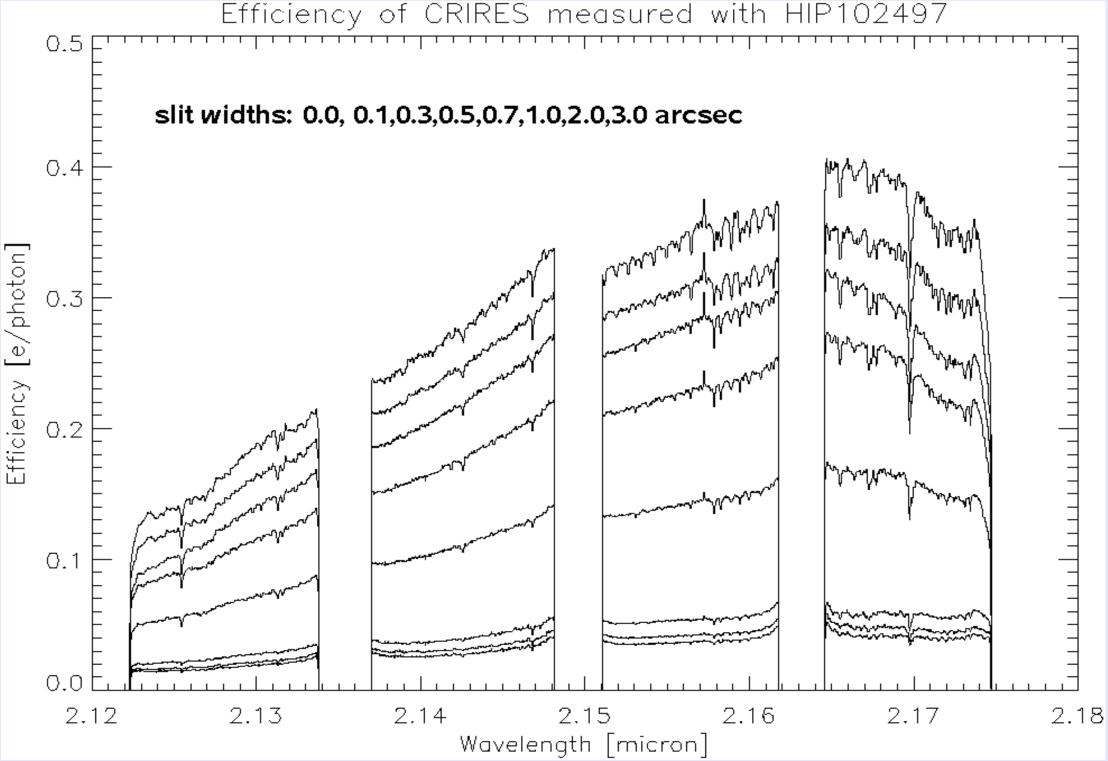
- spectrograph **intrinsic stability** <<< 75m/s
  preference in design was given to stability
  ☞ gas cells for high precision radial velocity work
- curvature sensing **Adaptive Optics**
  ☞ 0.2” spatial resolution for 40” slit
  right: composite JHK false color image of
  the Jovian Satellite Io (dia 1.1”)
  (c.f. Jerome Paufique et al. SPIE 2006, 6272-40)

- **spectro-polarimetry in lines:** magnetic fields
  - goal to measure all 4 Stokes parameter
  - λ / 4 Fresnel rhomb and λ / 2 plate
    in rotary mounts at the gas-cell slide
  - cold kinematic MgF_2 Wollaston prism in fore-optics

CRIRES Adaptive Optics Notes

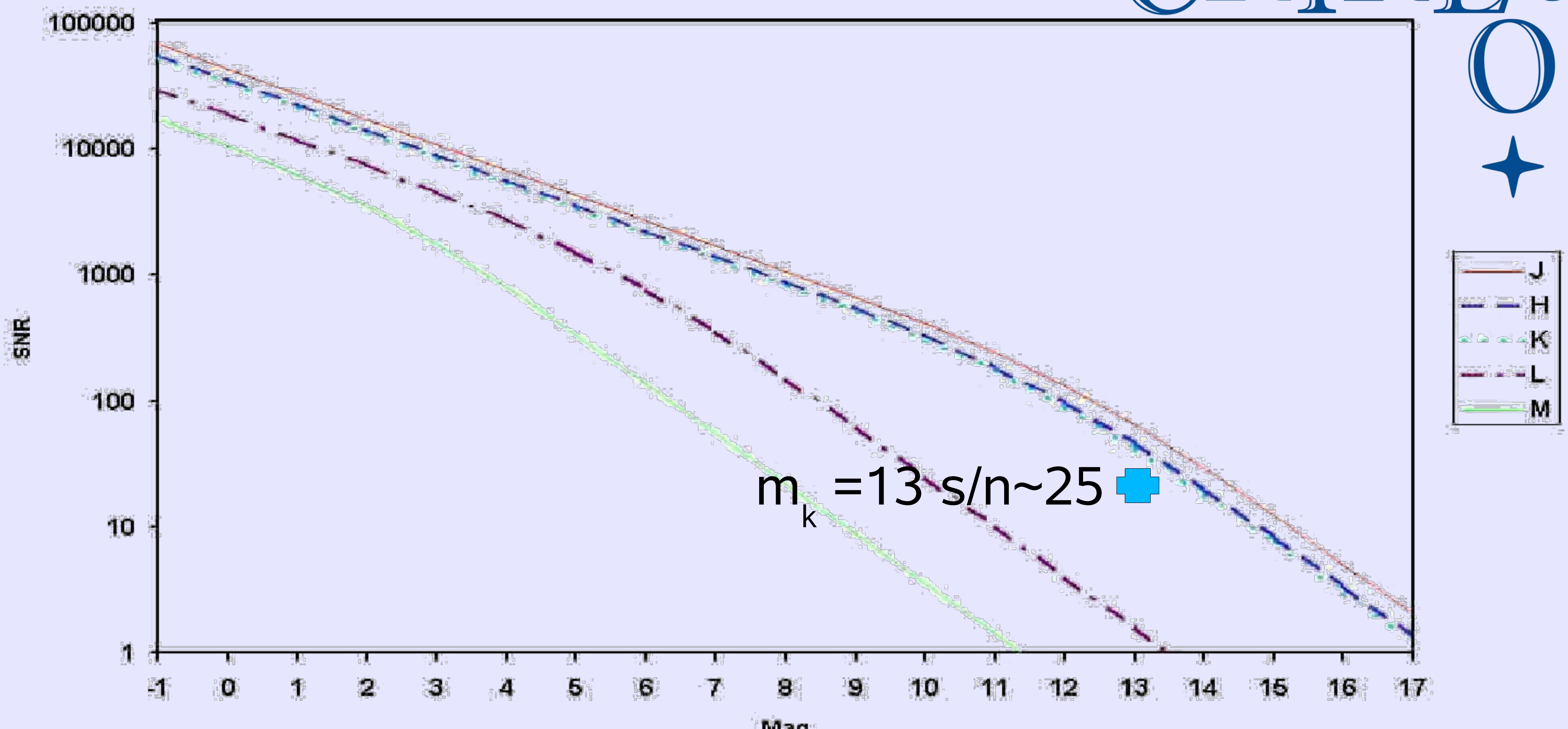


curvature sensing **Adaptive Optics**
☞ it really works:
left: 3D-image, K-band
HD105196 m_V=8.3, Δm_K=1.3
separation of 85mas



- spectrograph slit losses:
  ☞ external seeing 1.2-1.5"
  substantial slit losses
  i.e. AO / 0.2" slits only in reasonably good seeing

CRIRES sensitivity, 1 hour



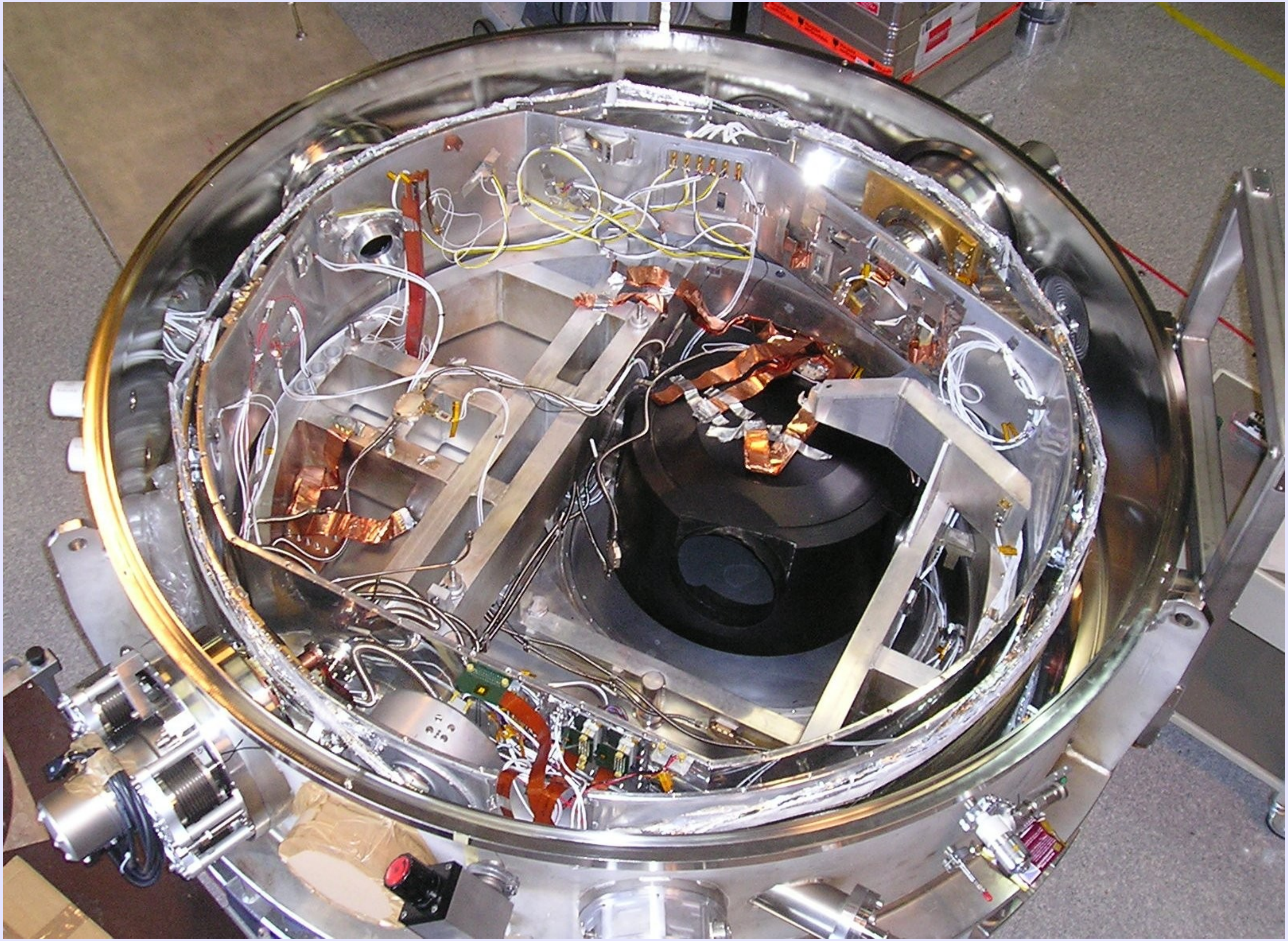
- **J & H – band:** detector & photon noise limited
- **K – band:** intermediate
- **L & M – band:** BLIP
- **=> e.g. the tip of the RGB and AGB in the LMC observable**
- **AO works in median seeing for stars $m_{V,R}$ < 15-17**

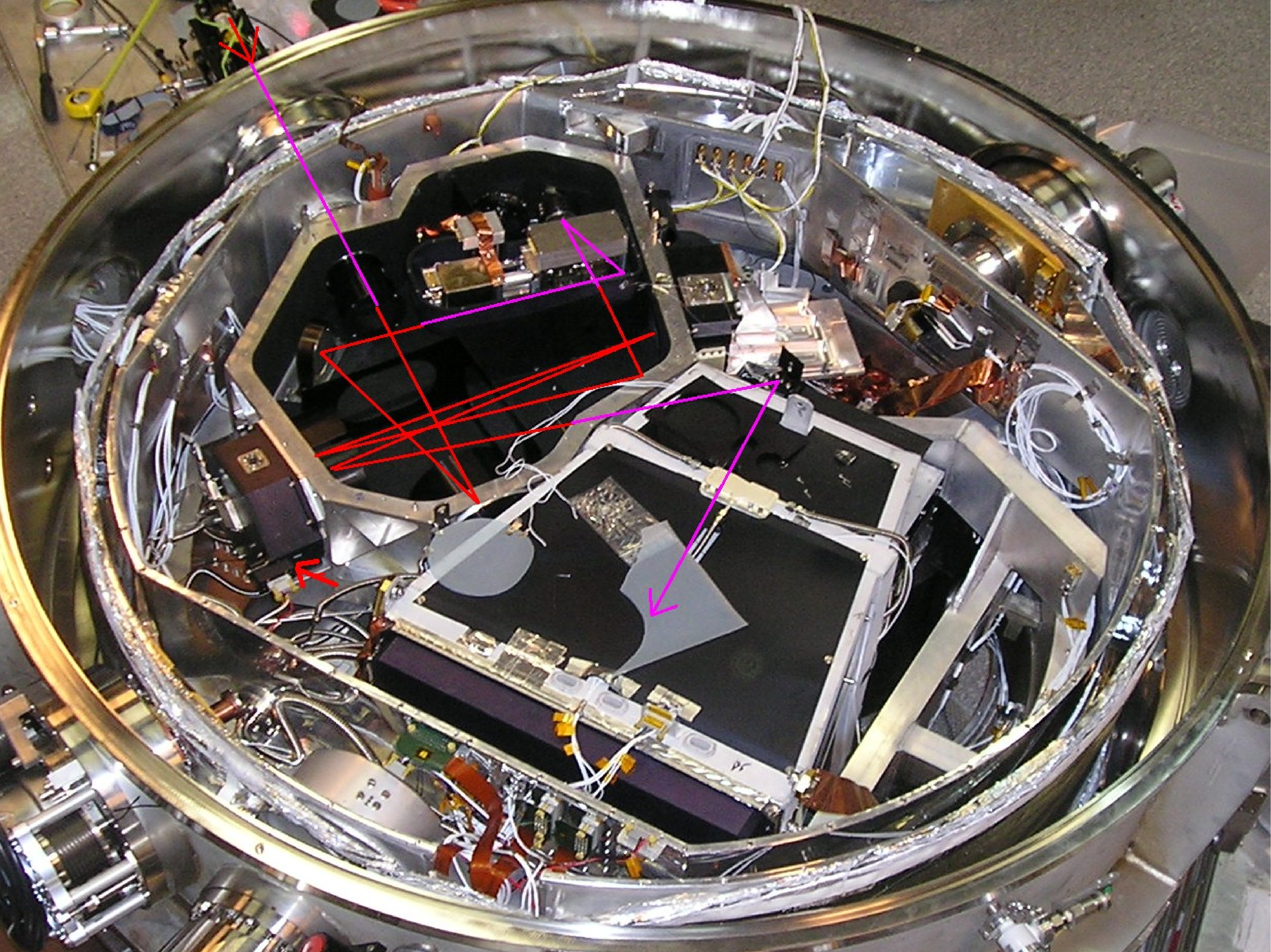
CRIRES

- Garching: April 28

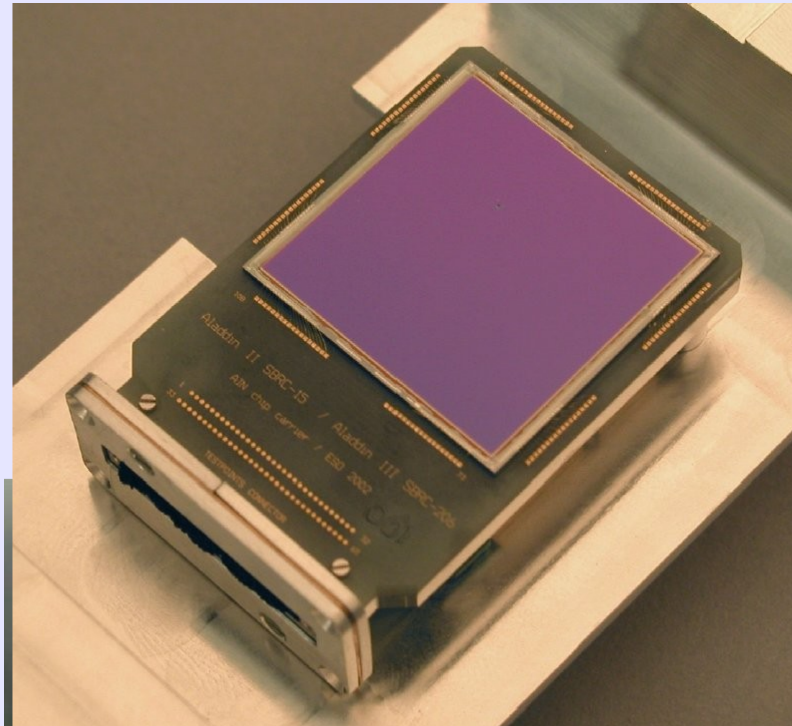
- **9 days later and 12000km further** on May 7
- **Paranal Ctrl-building parking lot** on May 8, 2006

`CRIRES without CRIRES'





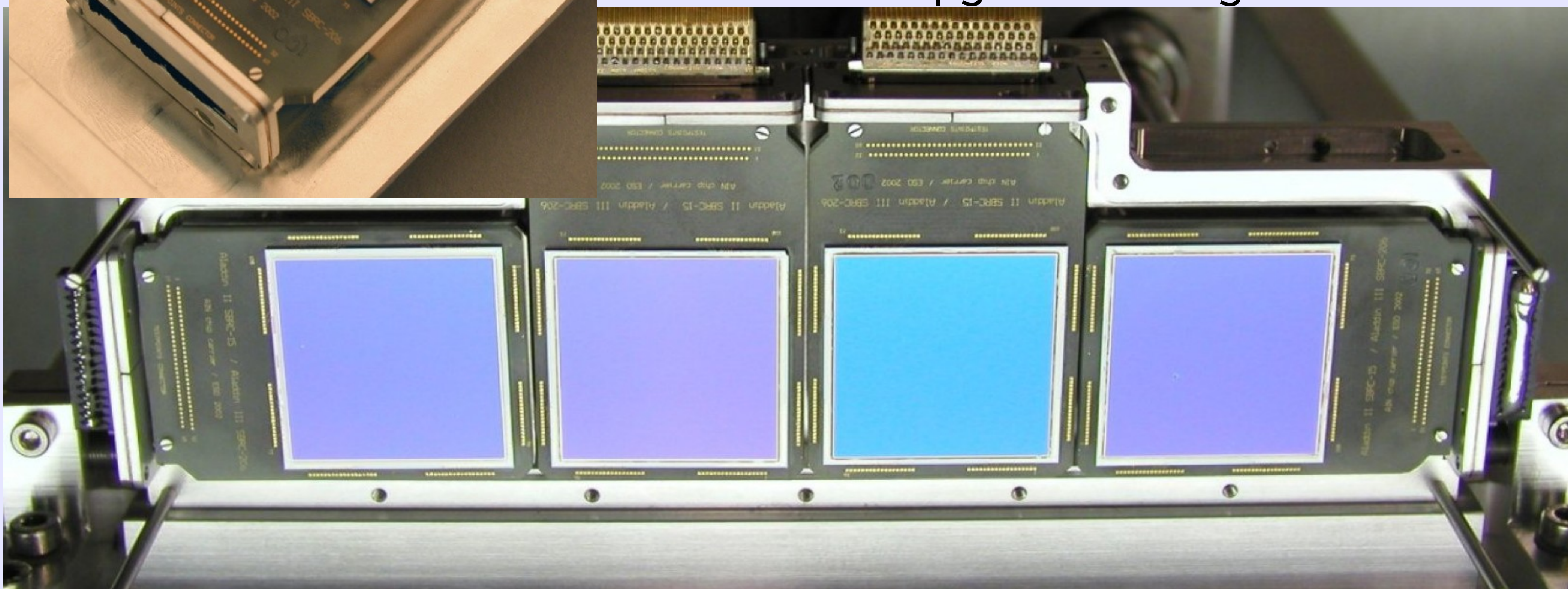
spectrograph focal plane assembly



◄ left: one of the four hybrids

▼complete assembly of mosaic

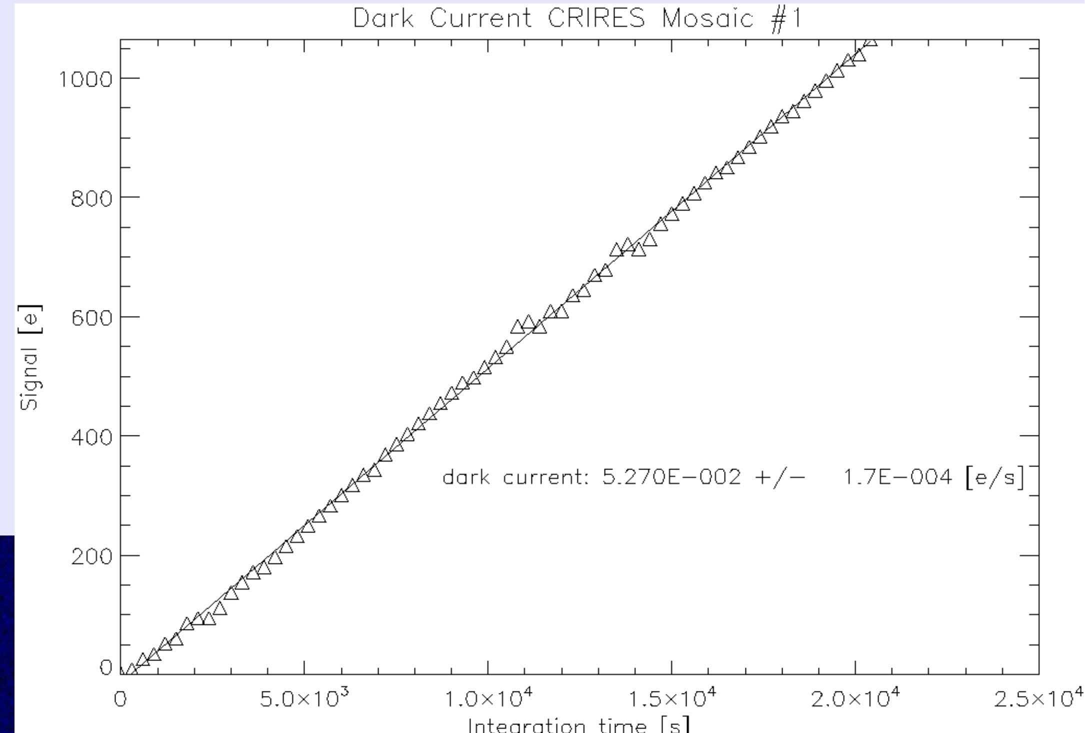
- 4 Aladdin III arrays, hybridized
- gap reduced to 286 pixel
- use band of 8 512x512 arrays
- detector upgrade invisaged

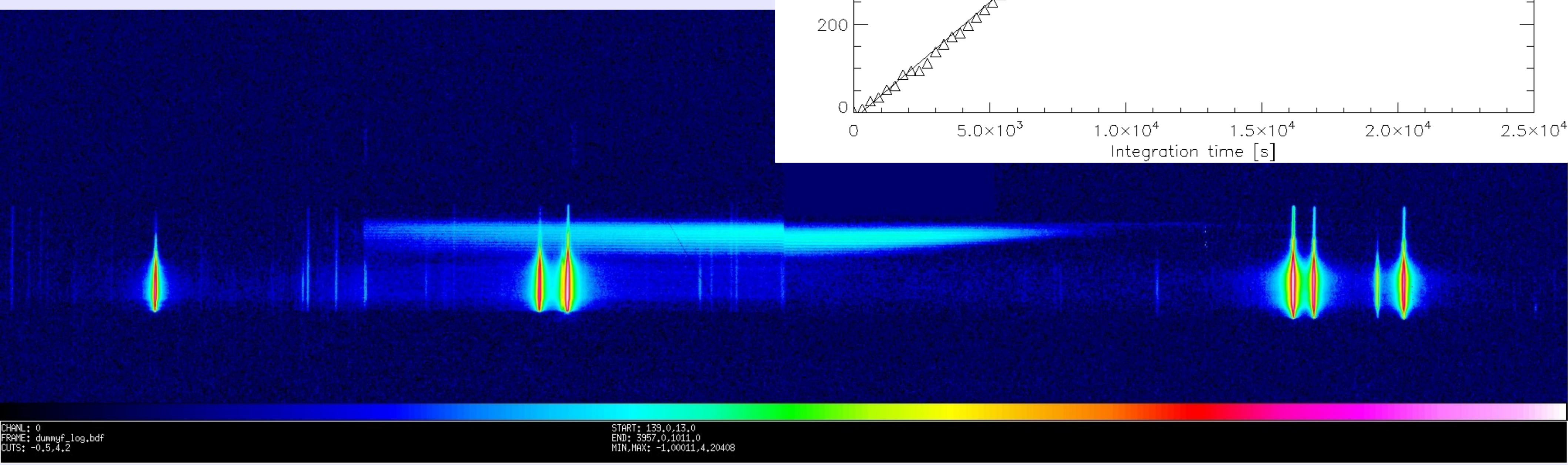


performance of instrument

- right: dark current measurements:
  0.05-0.2 e⁻/s in 12000 seconds
  @ 65 K (~30 W cooling reserve)

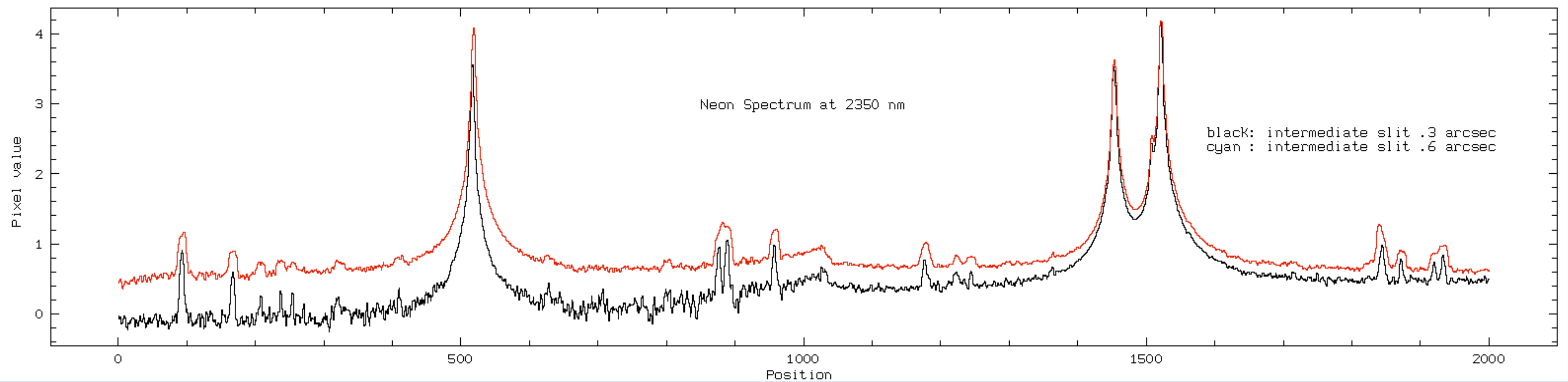
- ▼full spectrum, logarithmic
  K – band, Neon lamp
  (after 1st cooldown Paranal)





spectral purity (nitty gritty part)

- CRIRES K-band spectrum; **logarithmic**
  black: intermediate slit 0.3 arcsec
  red: intermediate slit 0.6 arcsec
  - evidence for ghosting at the 5 * 10^{-4} level (originating in pre-disperser; room for improvement)
  - some in-dispersion stray-light; grating ?
  - quasi-white light ghost (displaced out of order) impact to be assessed, can be eliminated, under evaluation



Why a spectral resolution of 10^5?

one possible answer:

You can't be too thin ... or too rich ...
and you can't have too much spectral resolution!
Dan Jaffe, 2003

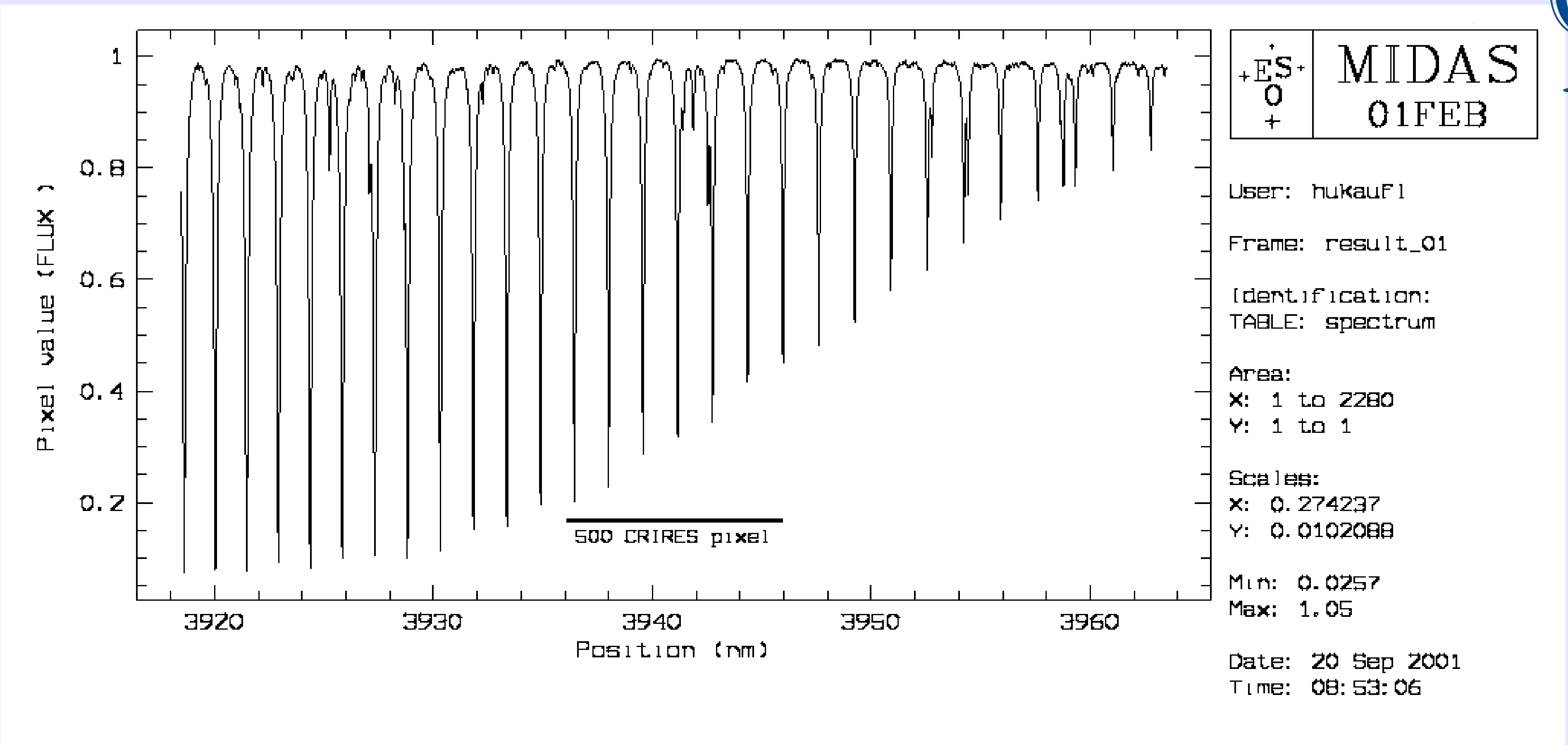
alternatively:

- astrophysical reasons ....

but

- spectral resolution considerations must also take into account, that it helps to reject interference by telluric lines

spectrum stability ~ 75 m/s ?

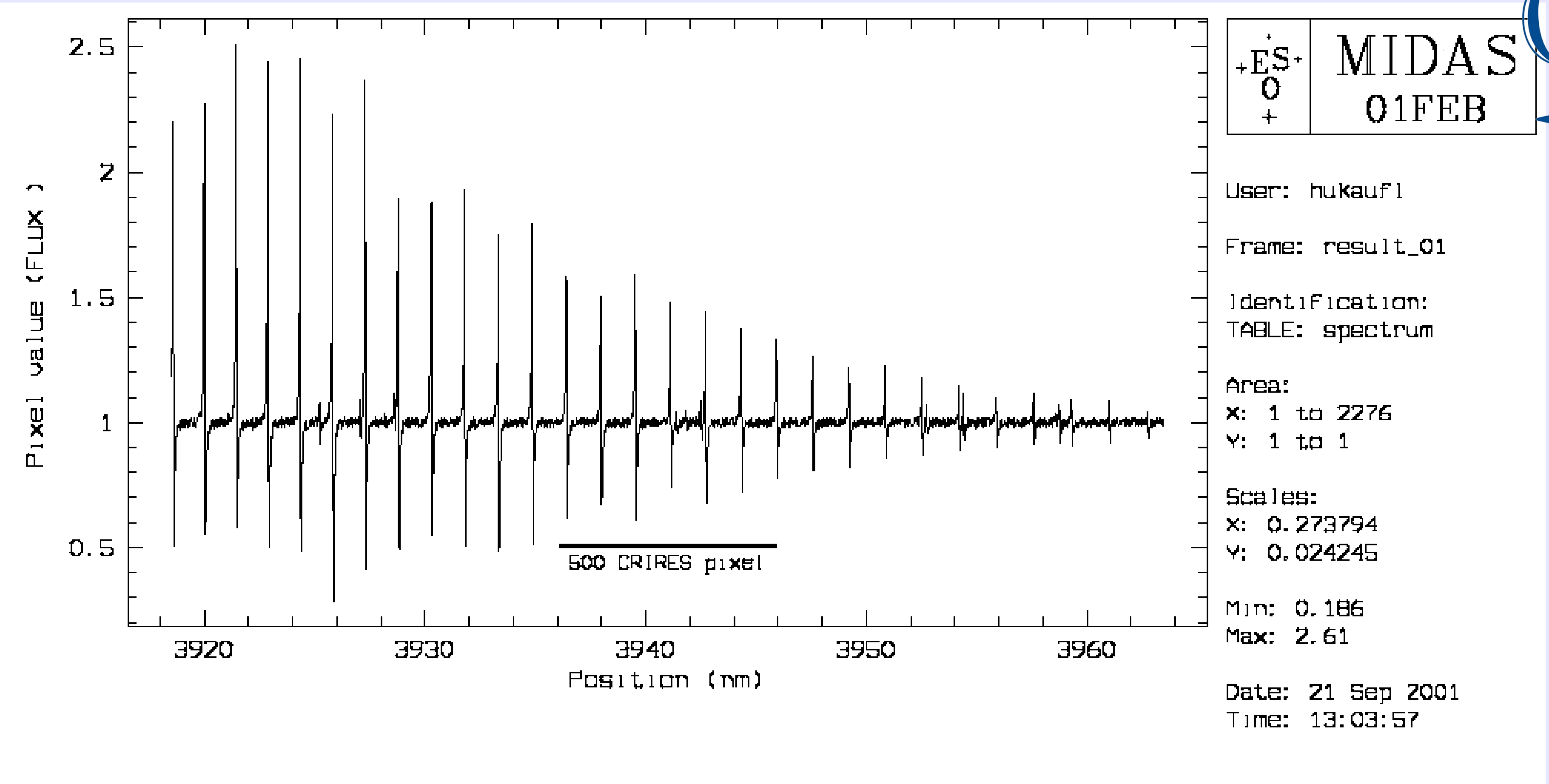


rebinned telluric FTS-spectra (McMath data) around 4µm:

- astrophysically relevant region: overtones of SiO & Brackett α
- spectral resolution and stability requirements for CRIRES set by science and by the need to reject telluric lines

spectrum stability ~ 75 m/s ?

CRIRES



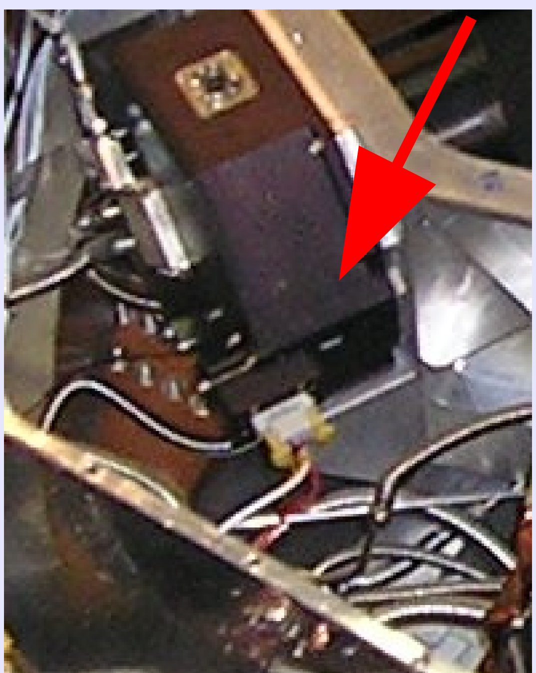
- simulated result spectrum in case of 0.5 pixel "flexure" between science exposure and calibration exposure
- => effect is only tolerable, if differential effects ≤ 0.05 pix (minimizes the need for "fudging" in the pipeline software)

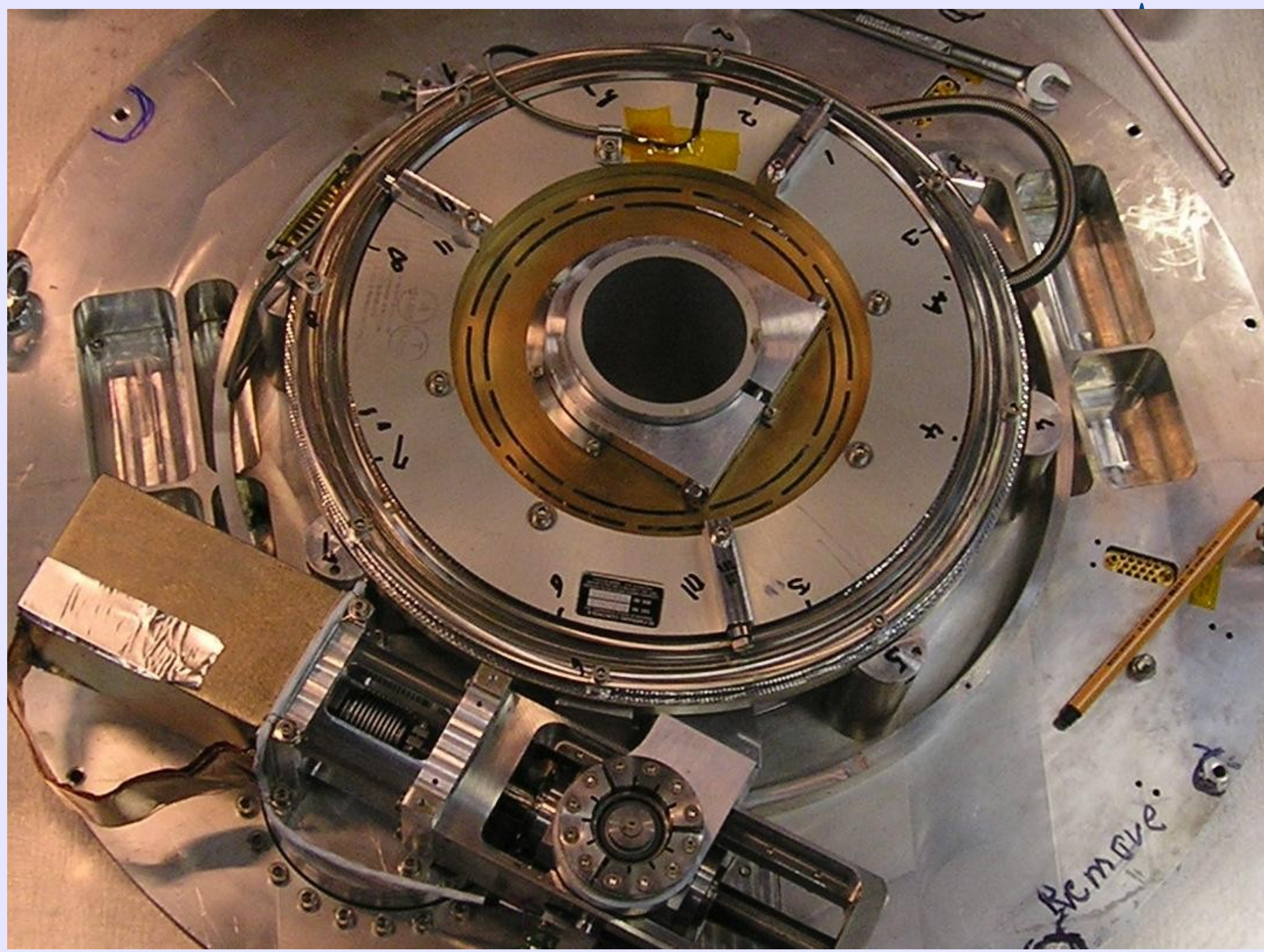
stability and reproducibility: tools

CRIRES

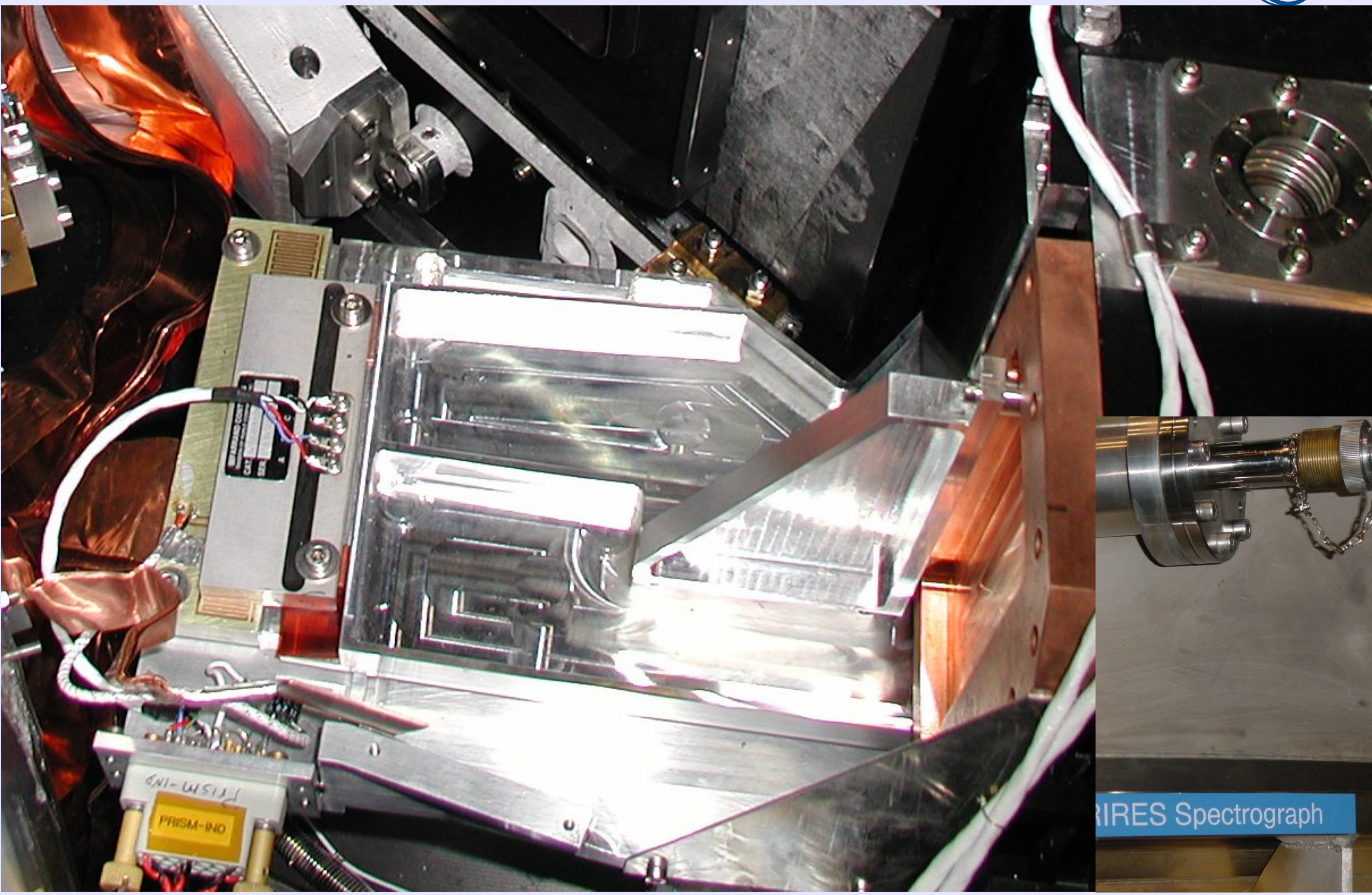
grating drive ►
with 1arcsec resolution
cryogenic encoder **but**
still not good enough

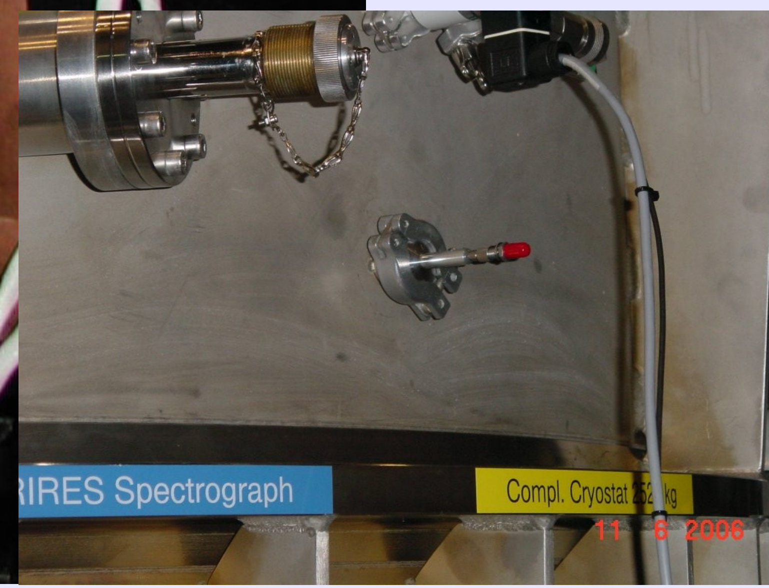
Piezo in pre-disperser collimator compensates stick slip effects ▼





stability and reproducibility: tools





prism drive encoder plus temperature stabilisation plus precise measurement of dn/dt (with NASA/GSFC) plus physical model of spectrograph plus ThAr for the infrared (with NIST), Kerber & Bristow

Calibration Plan

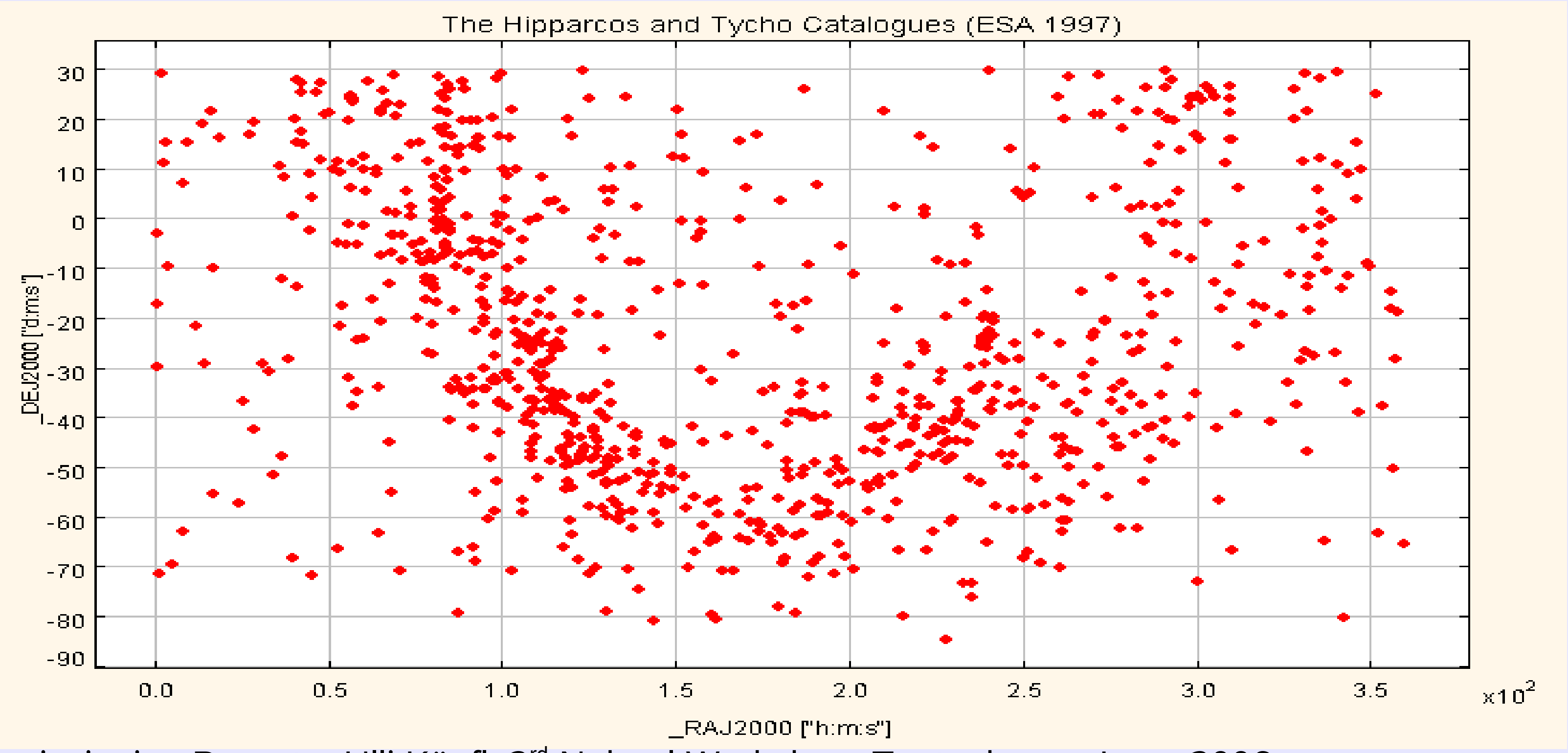
- based on simplified physical model for CRIRES optics
  - based on output of optical design calculation
  - goal here is, to have the minimum number of free parameters and to use a “physical”-parametrisation
  - collaboration with ST/ECF group to recycle the UVES & STIS experiences
- internal calibration unit (arc-lamps, continuum sources) to establish first model (also for the control software) for spectral calibration
- ThAr-spectrum extended into IR up to 4µm
- final spectral calibration and extraction using the
  OH-airglow and telluric absorption lines

example: night-sky + UC H II region λ:1.7->2.5µ

Calibration Plan (cont.)

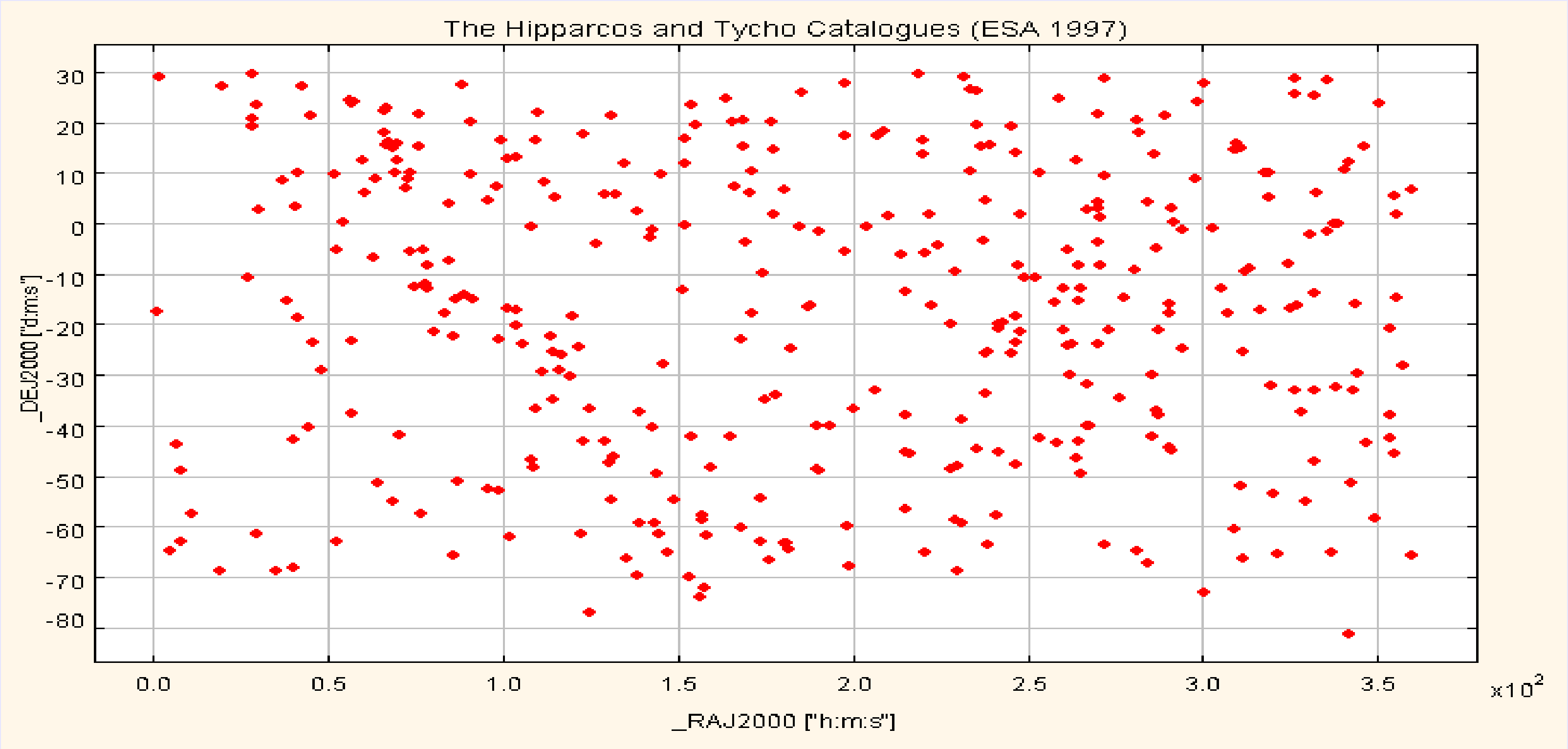
- flat-fielding 0-th order in-dispersion and along slit with internal calibration source
- refinement of flatfield with sky + calibration stars
  => development of a system of spectroscopic standards
  based on Hipparcos/Tycho catalogs and stellar models:
  - for **1-4µm** : A1 or earlier, $v_{mag} < 6.0$, $\delta < +30^{o}$

  => 900 stars ; model atmospheres in preparation (ESO with P. Coelho)



Calibration Plan (cont.)

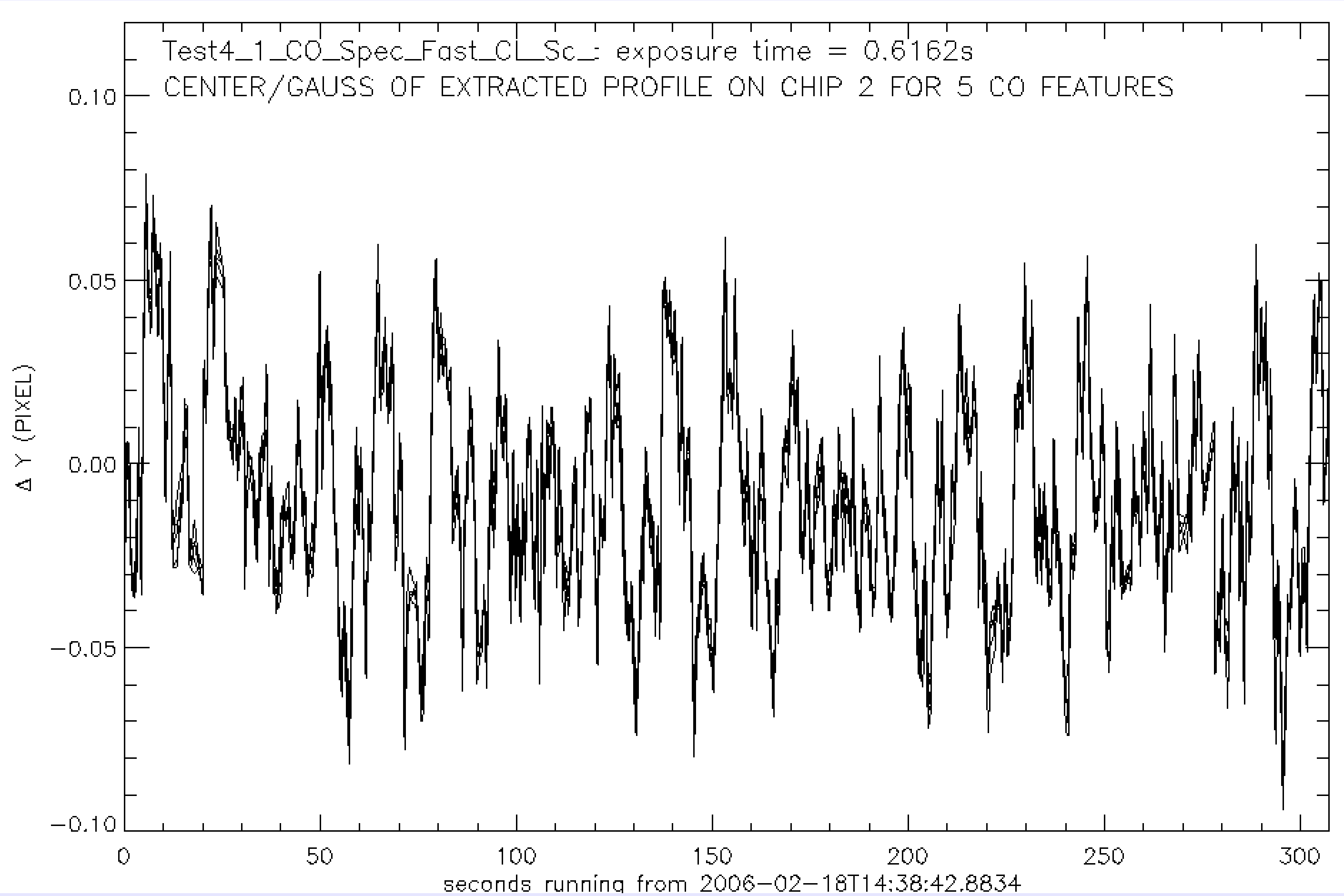
- for **4-5.2µm** : B8 or earlier, v_{mag} < 4.0, B8-G0, v_{mag} < 4.0
  => 466 stars, model atmospheres in preparation (ESO with P. Coelho)



- **polarimetry:**
  - simplified Mueller matrix description of CRIRES in progress
  - specialized calibration lamps in dome

end to end laboratory test (1)

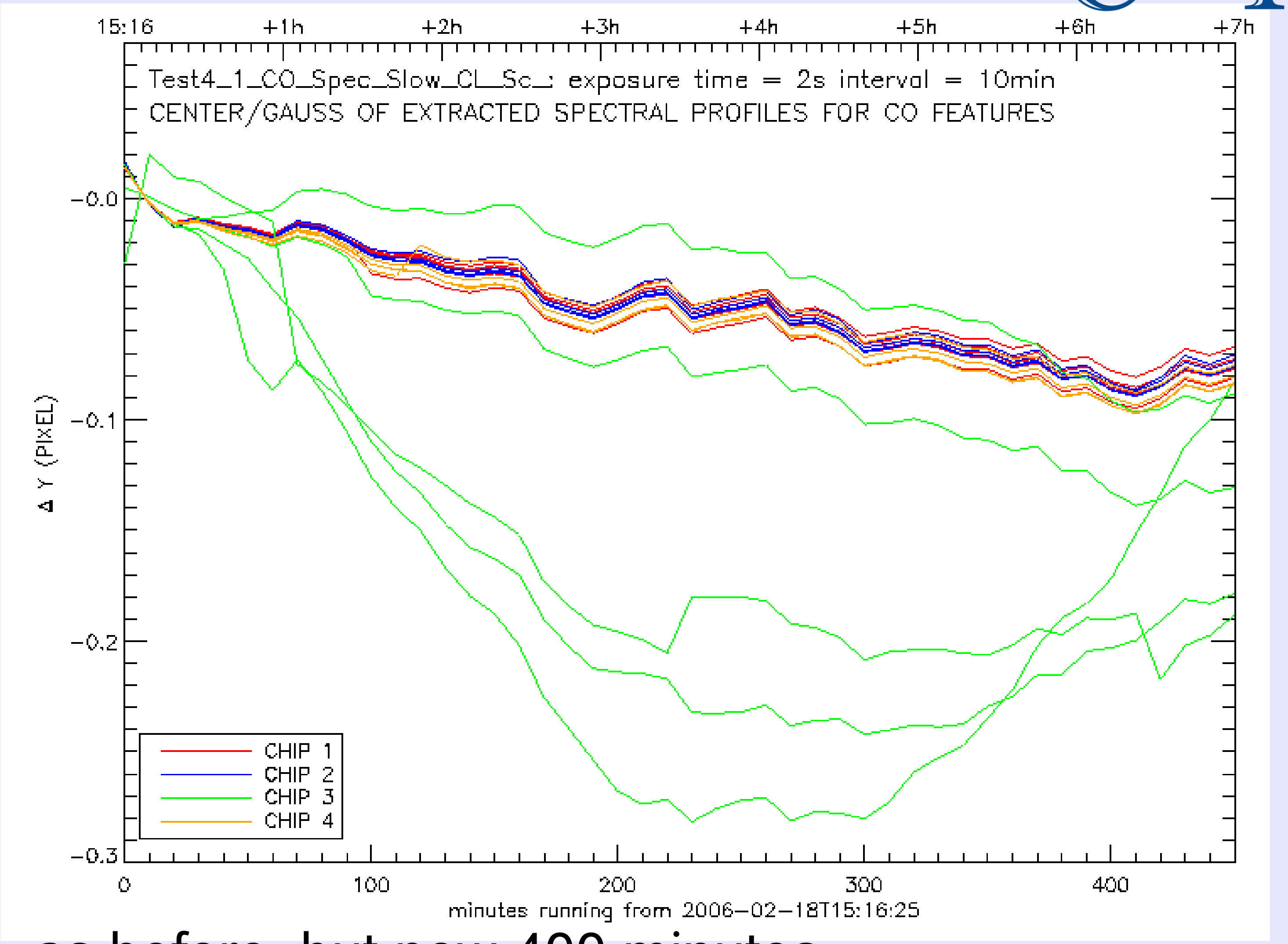
CRIRES



set-up: K-band, black-body with CO-gascell, fibre-feed to turbulence generator, adaptive optics loop closed, CRIRES nominal

note: data analysis very basic => some numeric noise as well

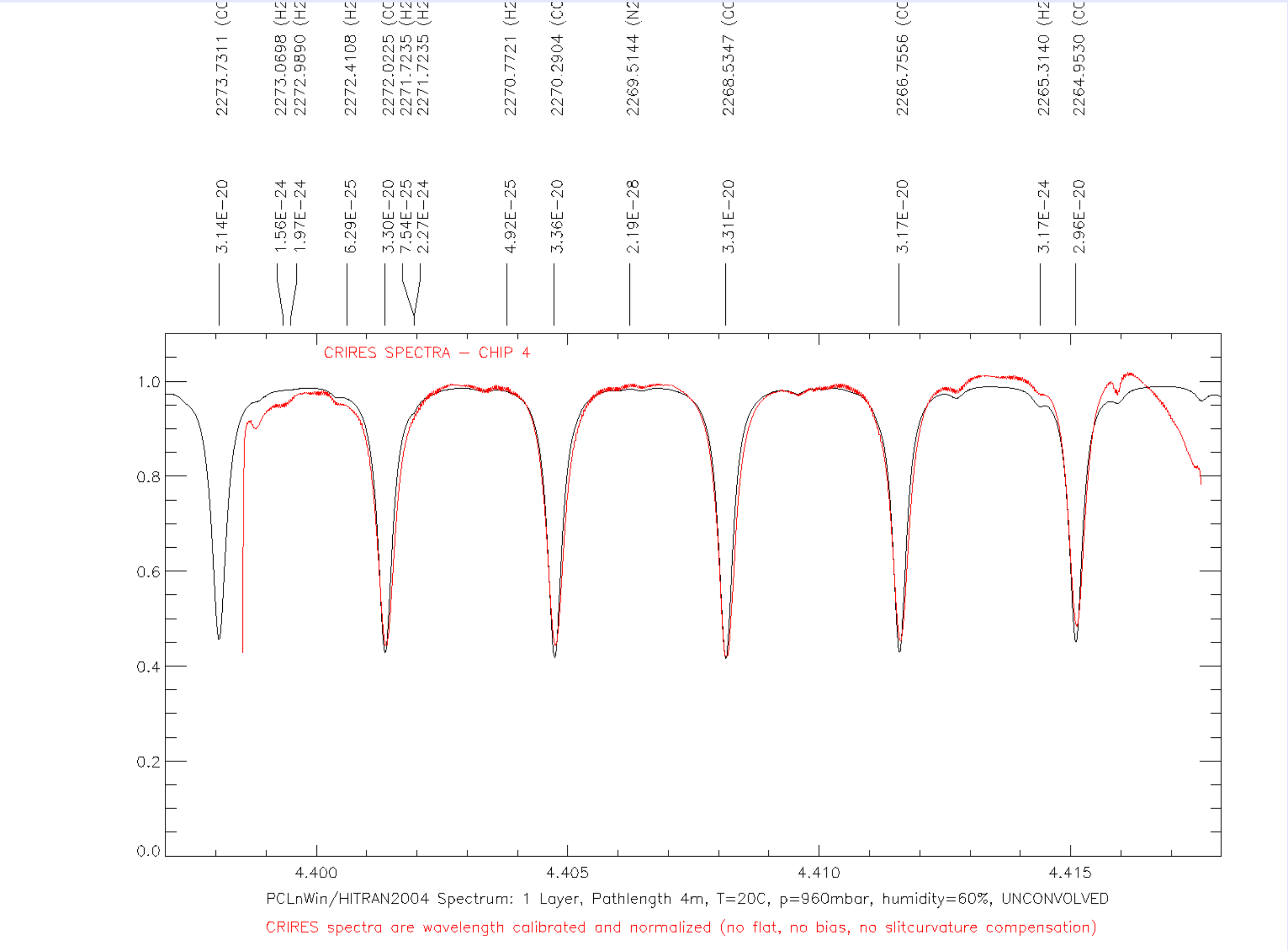
end to end laboratory test (2)



set-up: as before, but now 400 minutes
line positions color coded as to the respective mosaic detector

note: detector #3 erratic; thermal gradients across mosaic mount during testing

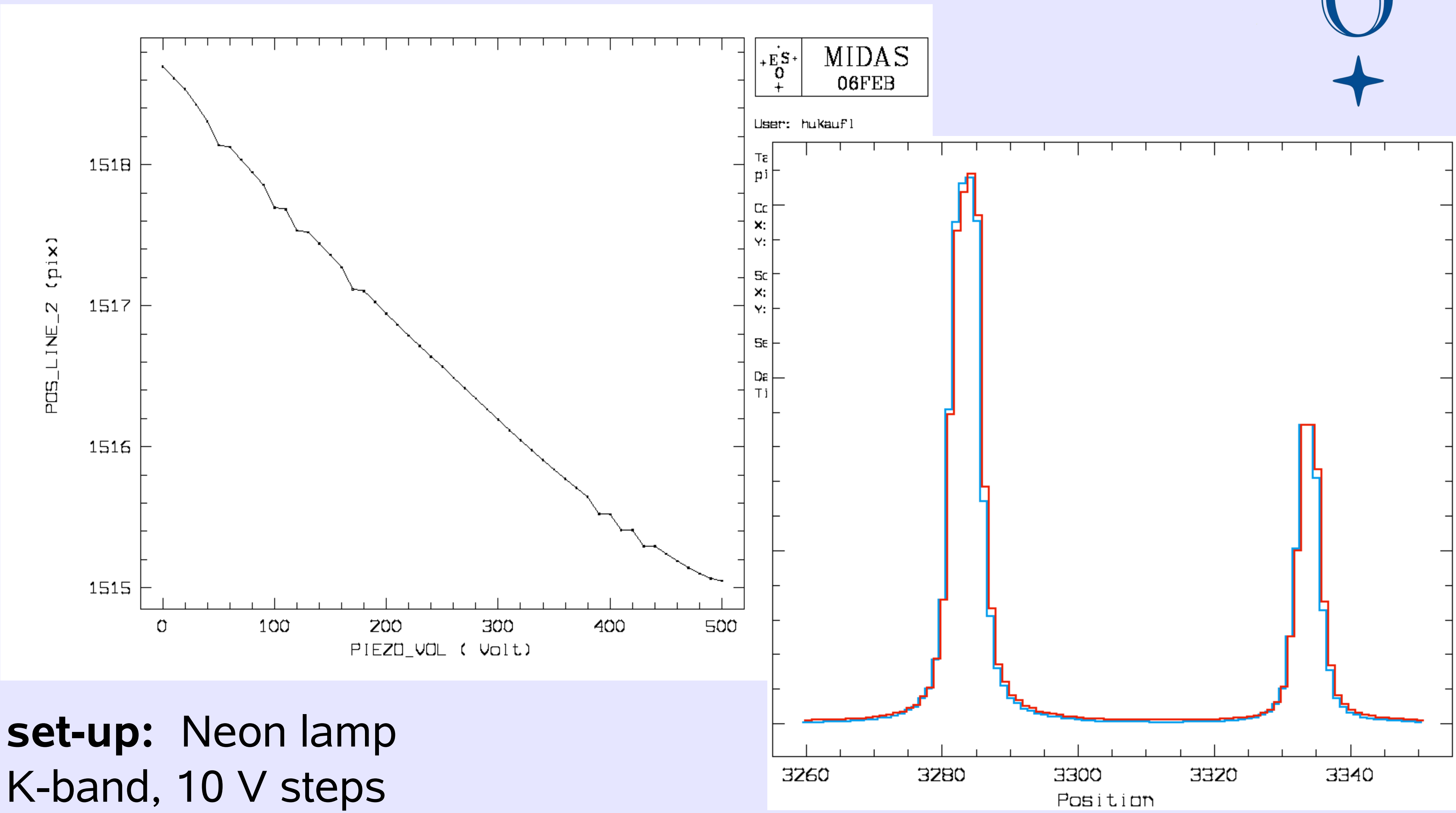
end to end laboratory test (3)



set-up: 4µm samplespectrum: black-body with CO-gascell

test of cryogenic Piezo

CRIRES



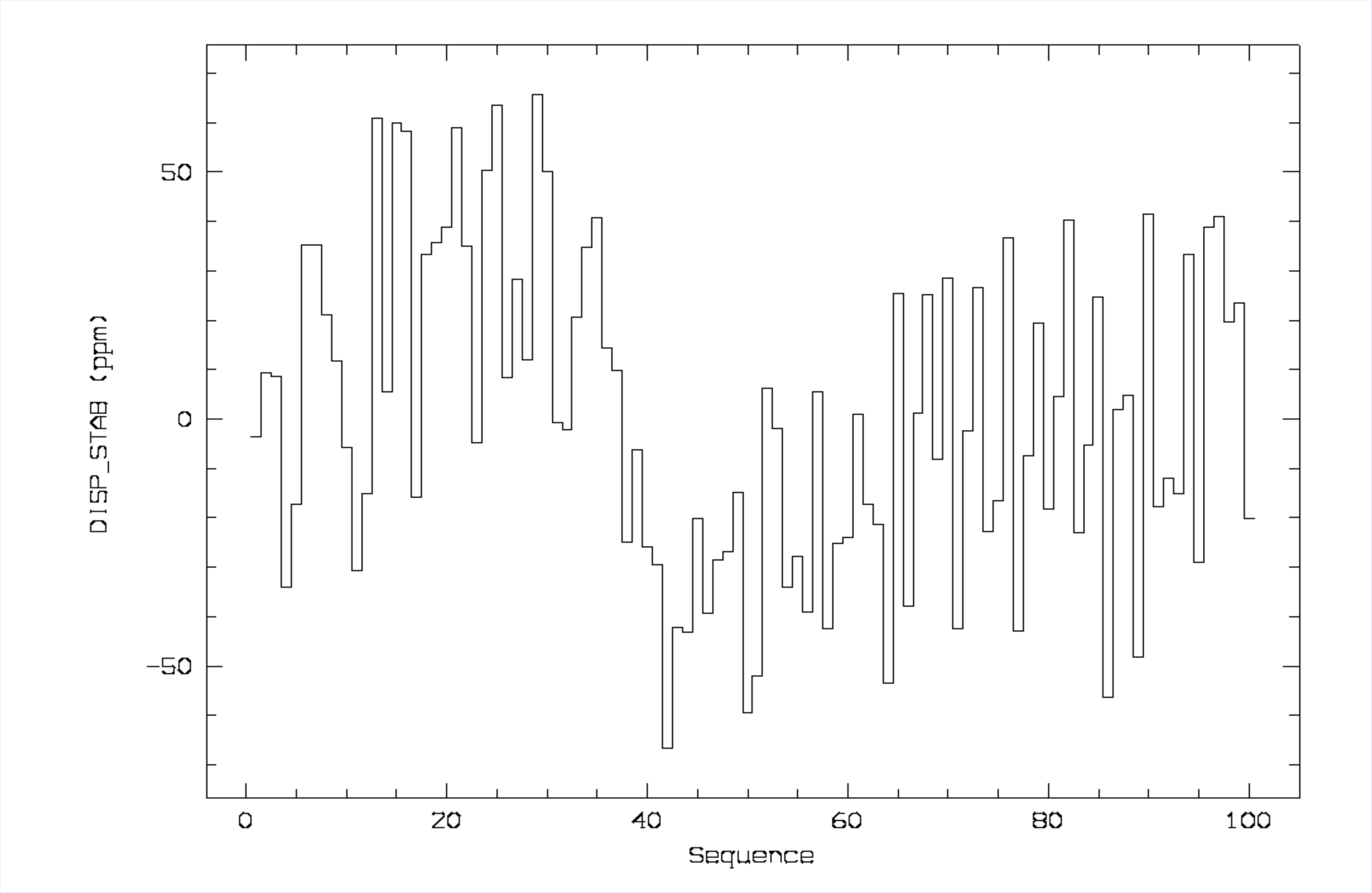
set-up: Neon lamp

K-band, 10 V steps

comparison of 2 consecutive spectra

constancy of dispersion

CRIRES



set-up: Ne-lamp, J-band, scatter of dispersion vs. grating repositioning stability peak to peak 100ppm (σ 32 ppm) goal 50ppm RMS

note: suffers some “numeric” noise, i.e. reality might be better

commissioning general

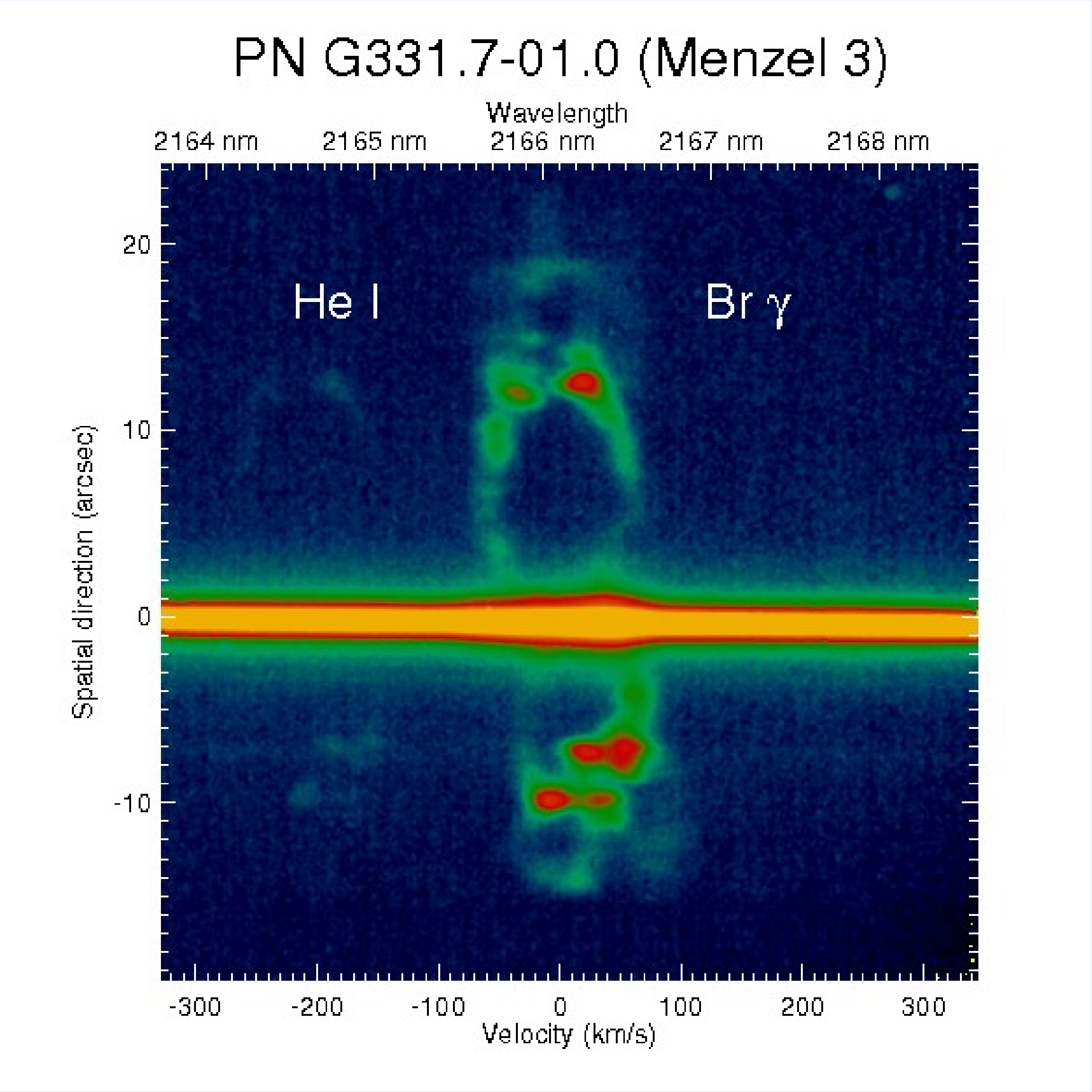
good:

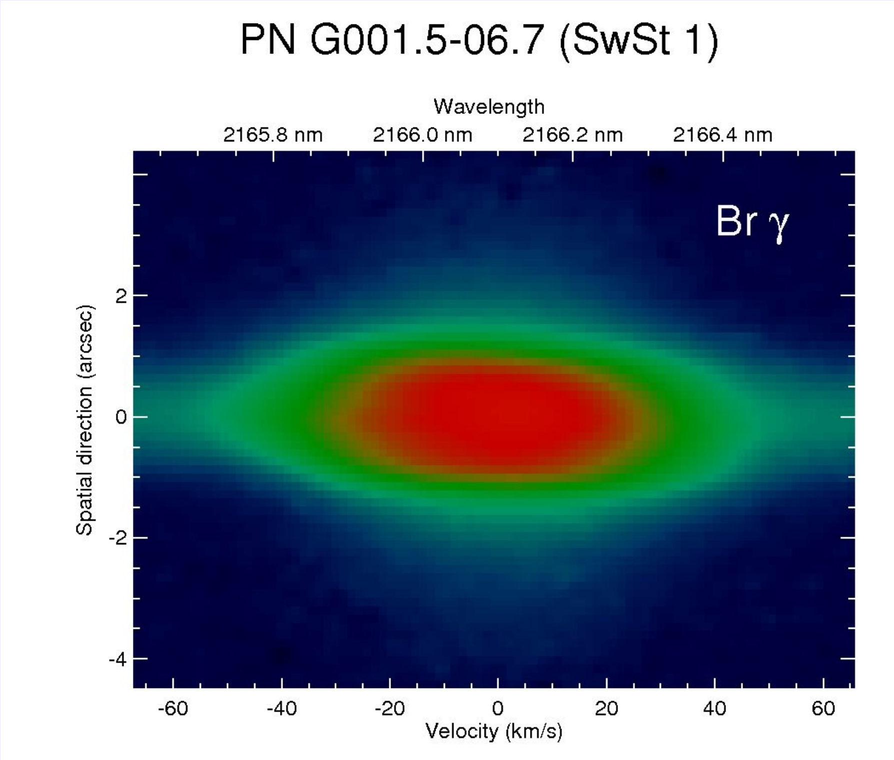
- CRIRES first light one day ahead of time
- resolution and image quality of spectrograph within spec (2.0 x 2.5 pixel)
- sensitivity approaching specs
- very low internal back-ground
- operational software ok
  i.e. chain from P2PP -> BOB -> archive fully operational
- pipe-line in progress

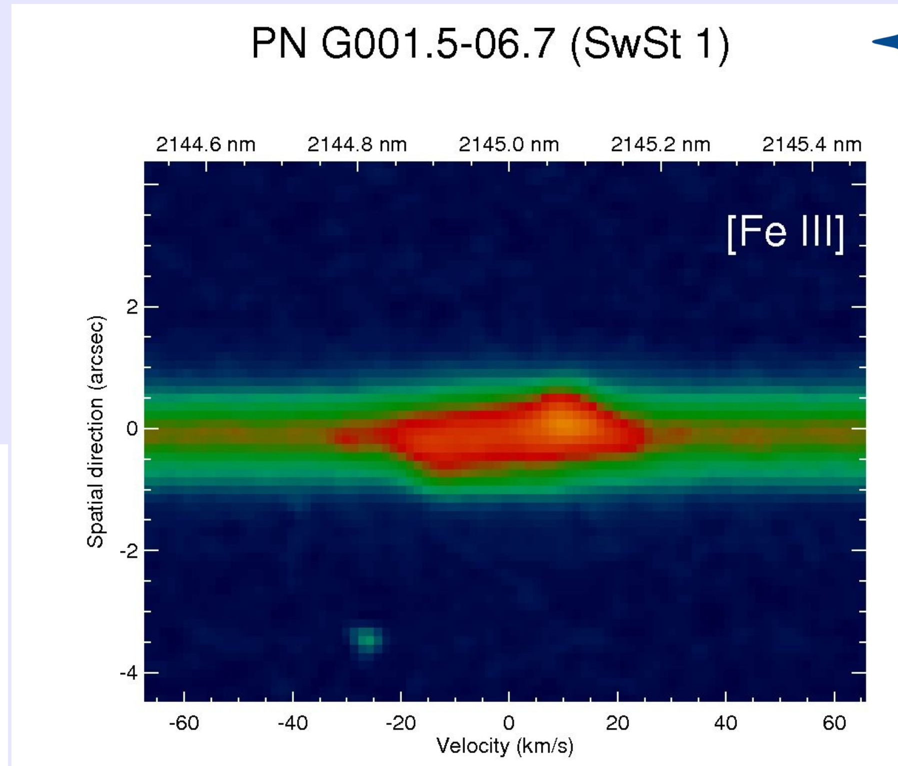
not so good:

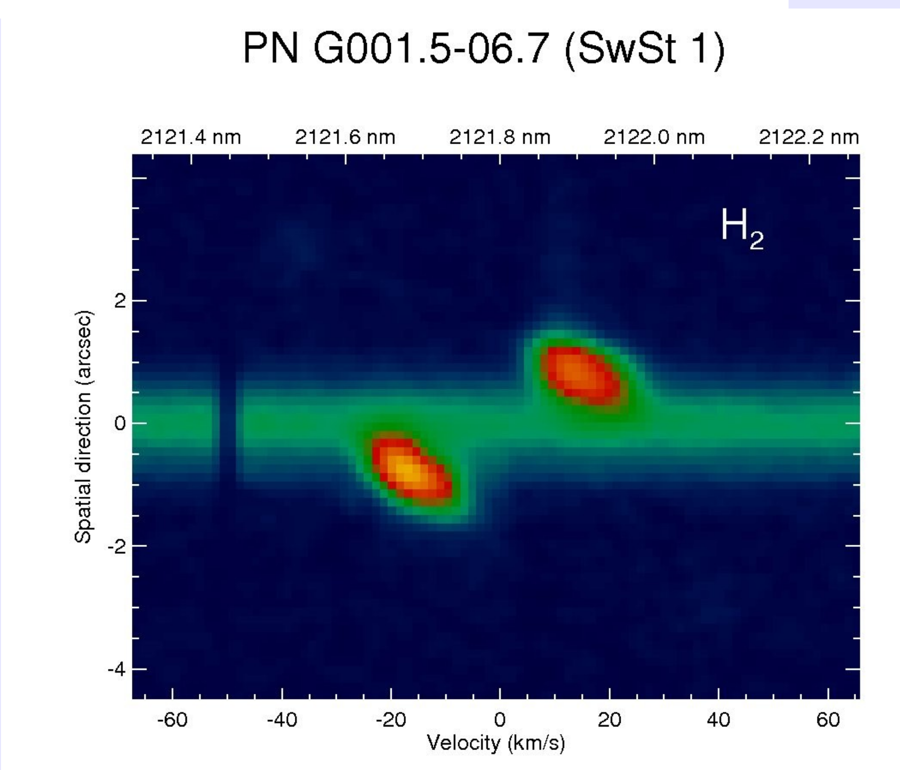
- mechanical problems with slit; will be re-built
- cosmetic quality of detectors: upgrade
- slit-viewer out of focus
- grating and prism movements: room for improvement
- thermal stability 200mK “breathing” every day
- spectro-polarimetry late

Menzel 3 aka the Ant Nebula

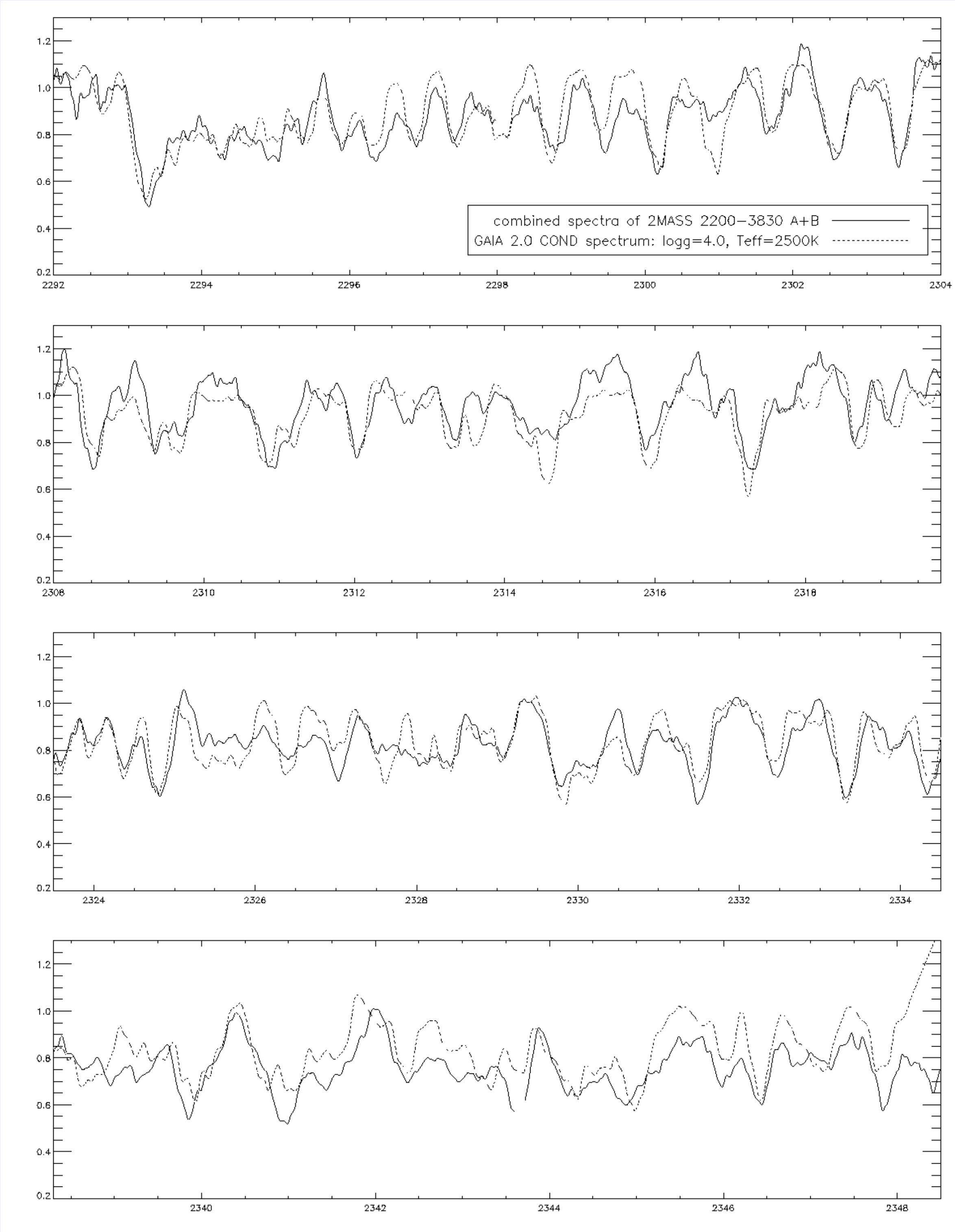



PN G001.5-06.7 (SwSt 1)
Wavelength
2165.8 nm
2166.0 nm
2166.2 nm
2166.4 nm
Br γ
Spatial direction (arcsec)
2
0
-2
-4
-60
-40
-20
0
20
40
60
Velocity (km/s)


PN G001.5-06.7 (SwSt 1)
2144.6 nm
2144.8 nm
2145.0 nm
2145.2 nm
2145.4 nm
[Fe III]
Spatial direction (arcsec)
2
0
-2
-4
-60
-40
-20
0
20
40
60
Velocity (km/s)


PN G001.5-06.7 (SwSt 1)
2121.4 nm
2121.6 nm
2121.8 nm
2122.0 nm
2122.2 nm
H2
Spatial direction (arcsec)
2
0
-2
-4
-60
-40
-20
0
20
40
60
Velocity (km/s)

HD 167362



spectrum of unknown to us binary BD

details:

- Denis J220002.05-303832.9 AB
- m_K 12.8 / 13 ; 1 arcsec separation (45' observing time) details: Burgasser & McElwein, APJ 2006
- measured (solid) vs. model atmosphere (courtesy P. Hausschild, dashed) A. Seifahrt, thesis

the coming months

scheduled:

- CRIRES first light June 4/5, 2006 ✔
- COMM 1 ends June 10/11 ✔
  thereafter issue of 1st call for proposals for science verification / science demonstration with restricted settings ***ongoing***
- ***new:*** mid July: re-alignment / modifications / lab-testing
- COMM 2 and ~4-5 nights of SV / SD Aug. 4-13,2006

planned:

- August: 2nd call for proposals for SV / SD
- inclusion in call for proposal for P79 (starts Apr. 2007)
- October 2006 4 nights COMM3 and ~ 5 nights SV / SD
- December 2006 4 nights COMM4 and ~ 5 nights SV / SD
- Jan/Feb 2007 handover CRIRES from ESO-INS to Paranal

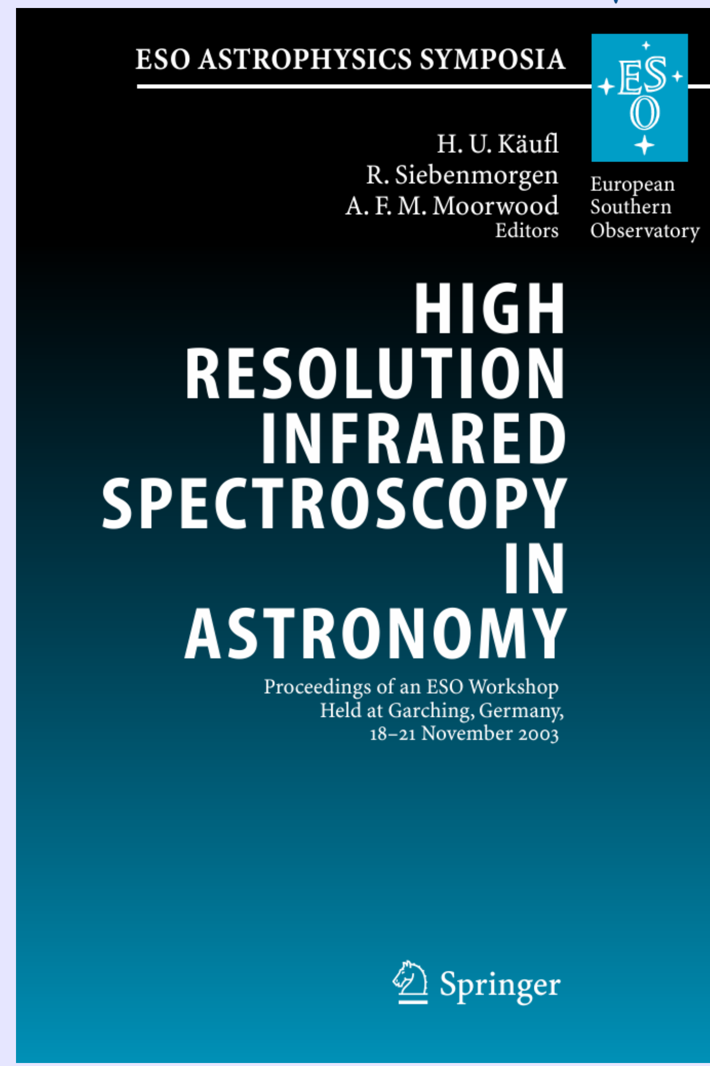
lessons learned

- pre- versus cross-dipersed
  - rather cross-dispersed ?!?!? for reasons of
    - stability
    - through-put
    - gas-cell could be put in arbitrary order

    but
  - **ZnSe-**prism not enough dispersion
  - really advantageous, a small IFU or image scrambler
- 0.2 arcsec slit is “an adventure”
- ***ghosts:*** white-light ghost was overlooked
- stability: “simple” regulation not sufficient
  Closed Cycle Coolers to be regulated as well
- optical metrology and active optics must part of design
- InSb can be destroyed with HeNe-lasers
- AO – interface and optical de-rotation very complex

Conclusions

- CRIRES is an unique facility instrument for the VLT
- 1st call for SV in few days
- unique science:
  - detection of planets around obscured pre-main sequence stars
  - detection/study of hot Jupiters
  - stellar oscillations
  - s-process nucleo-synthesis
  - http:www.eso.org/ekstasy2003
- due to extensive prototyping, off-line testing and the VLT standards and procedures no major “surprises” to be expected
- test bed for ELT science and site characterisation
- upgrades: detector & slit mechanics



More Questions