Synergies in Spectroscopy between SOFIA and the Ground:

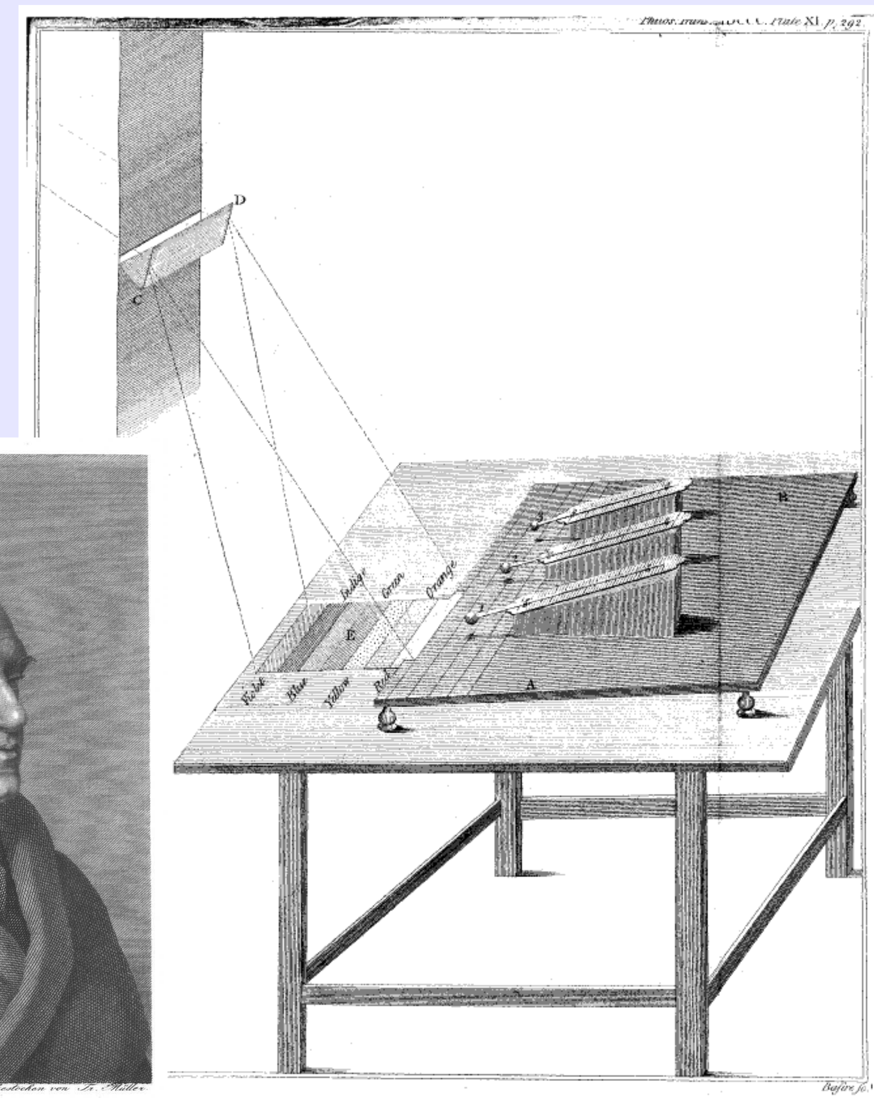
Ulli Käufl, Ringberg Workshop on Spectroscopy with SOFIA March 16, 2015

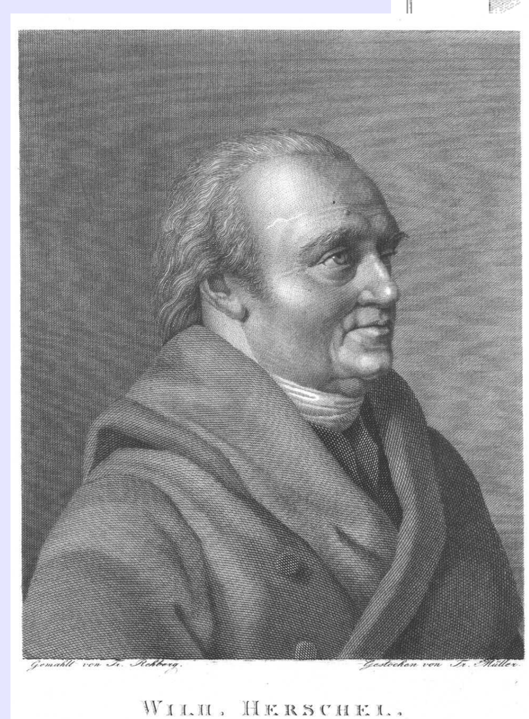
Background Noise Limit:

"*Observing at 10µm has been likened to observing visually through a telescope lined with luminescent panels and surrounded by flickering light as though the telescope were on fire*"
Low & Rieke, 1974

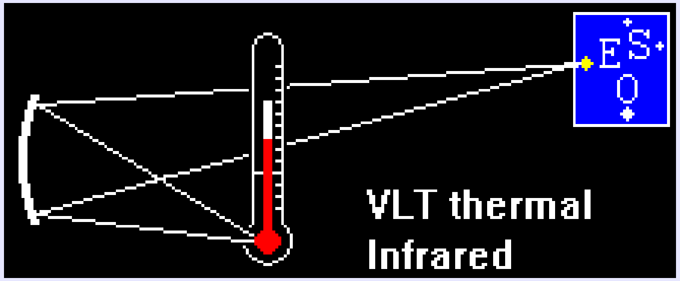
note:

2014: this should read:
“Observing > 2.3*µm ...*”



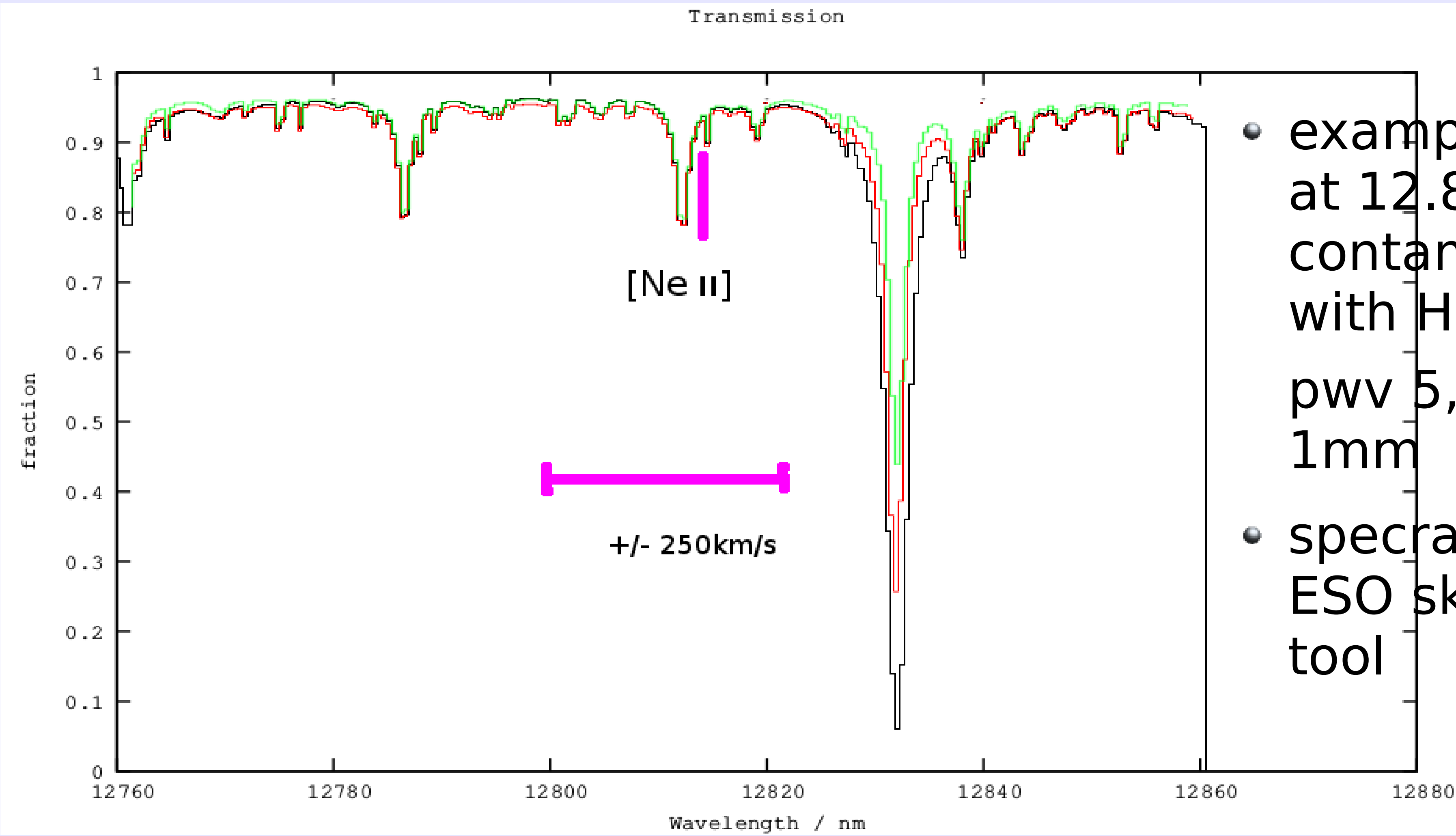


Outline



- wavelength range λ: 3-13.3μm
- mostly high resolution work: λ/Δλ > 30.000
    - no science case for ground based medium resolution spectroscopy
    - low resolution work still interesting in N-band for SEDs / dust
- focus on facility instrumentation, hence mostly about ESO VLT instrumentation
    - VLT-CRIRES λ/Δλ ≤ 100.000 λ: 3-5.5 μm encompasses Keck HIRES
    - VLT-VISIR λ/Δλ ~ 500 and 30.000
      only facility world wide but PI instruments exist
- spectro astrometry, a spatial super resolution technique

spectroscopy: enhancing what you want to see

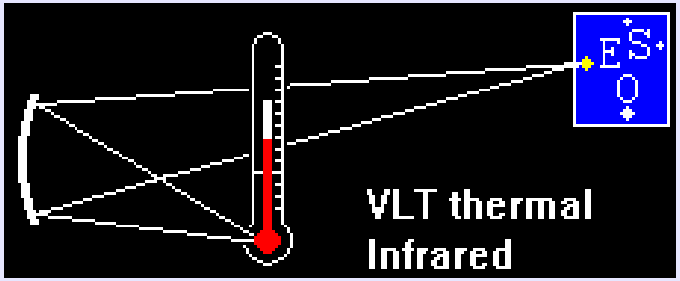


- example: [Neii] at 12.83 µm, contamination with H_2O

  pwv 5, 2.5 and 1mm
- specra from ESO skycalc tool

- message 1: only if you resolve **<u>telluric</u>** lines can one correct
- message 2: it may pay off to wait for pwv to fall

Monitoring of precipitable water vapour at observatory



- introduced at VLT in 2012 as part of the VISIR upgrade
- commercial fully automated radiometer with IR channel for sky brightness to monitor thin clouds (Kerber et al 2012)
- carefully cross-calibrated with radio sondes and Echelle spectroscopy from 500-5000 nm
- the ESO-VLT is operated in <1 hour time slices: the pwv-value is now a scheduling criterion, user specified, equivalent to the seeing

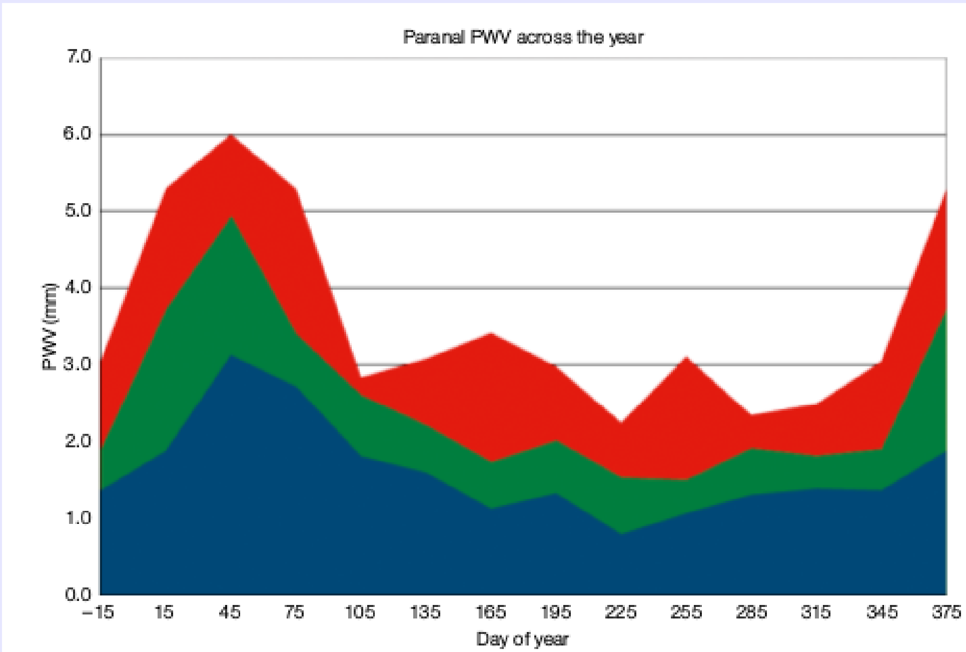
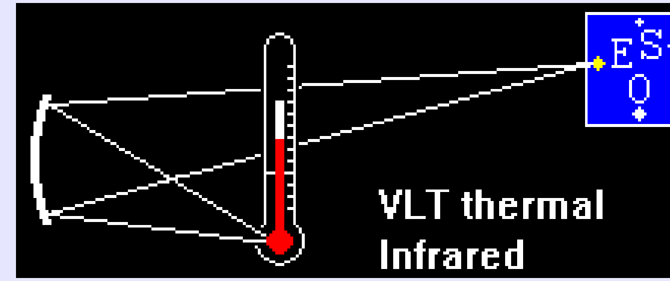


Figure 5. PWV conditions over Paranal based on the analysis of about a decade of UVES data (Kerber et al., 2010a). A pronounced seasonal variation is evident, but very low PWV (< 1.5 mm) conditions are available at the 25 % level for most of the year.

The right spectral resolution?



irrespective of width of spectral features in astronomical object, **what counts is rejecting telluric features**

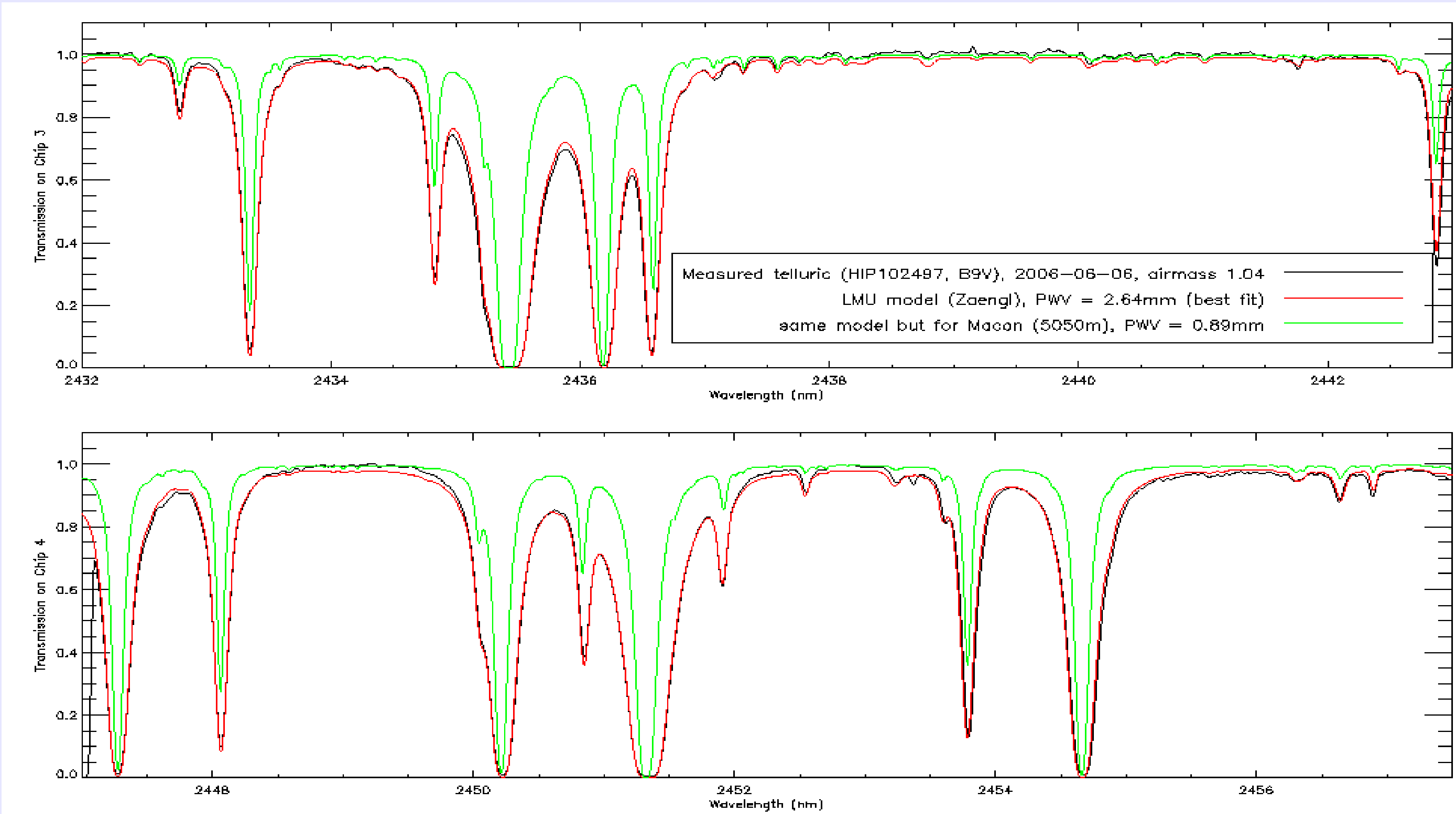
ESO offers sophisticated LBLRT atmospheric calculator

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

c.f Noll et al, A&A 2012 & Jones et al, A&A 2013

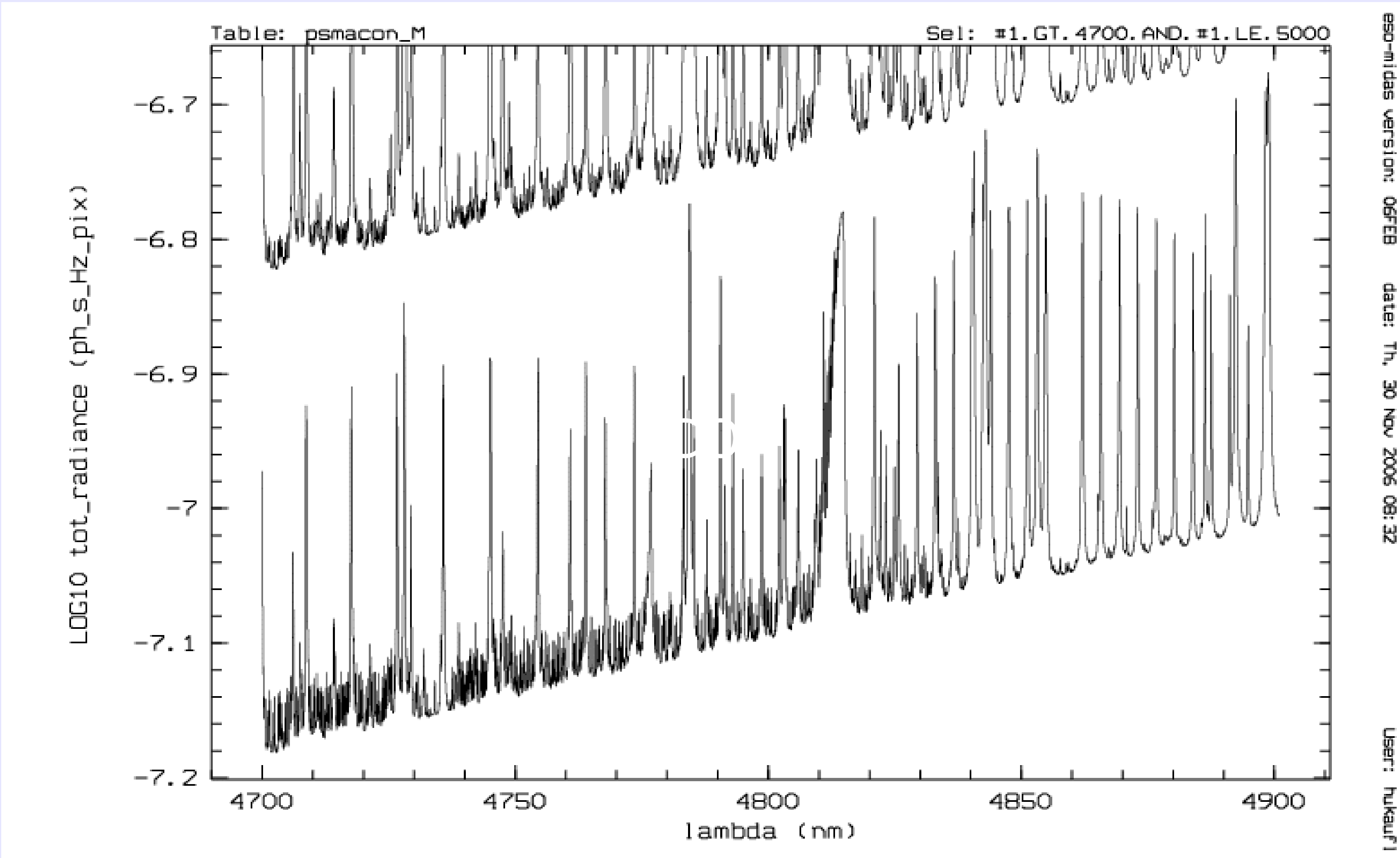
- explicitly calculating the annular Doppler shift modulation

LBLRT Quality Check



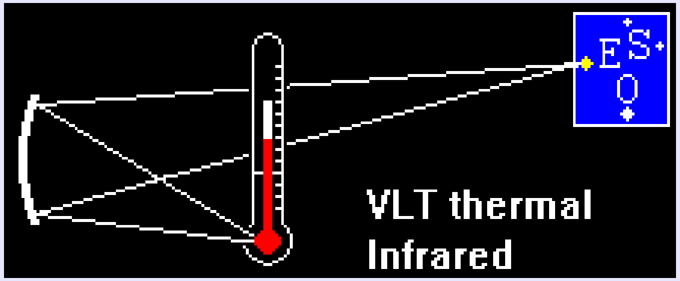
- measured vs. calculated K-band spectra
  c.f. Seyfahrt and Käufl, A&A 2008?

An Example from M-Band



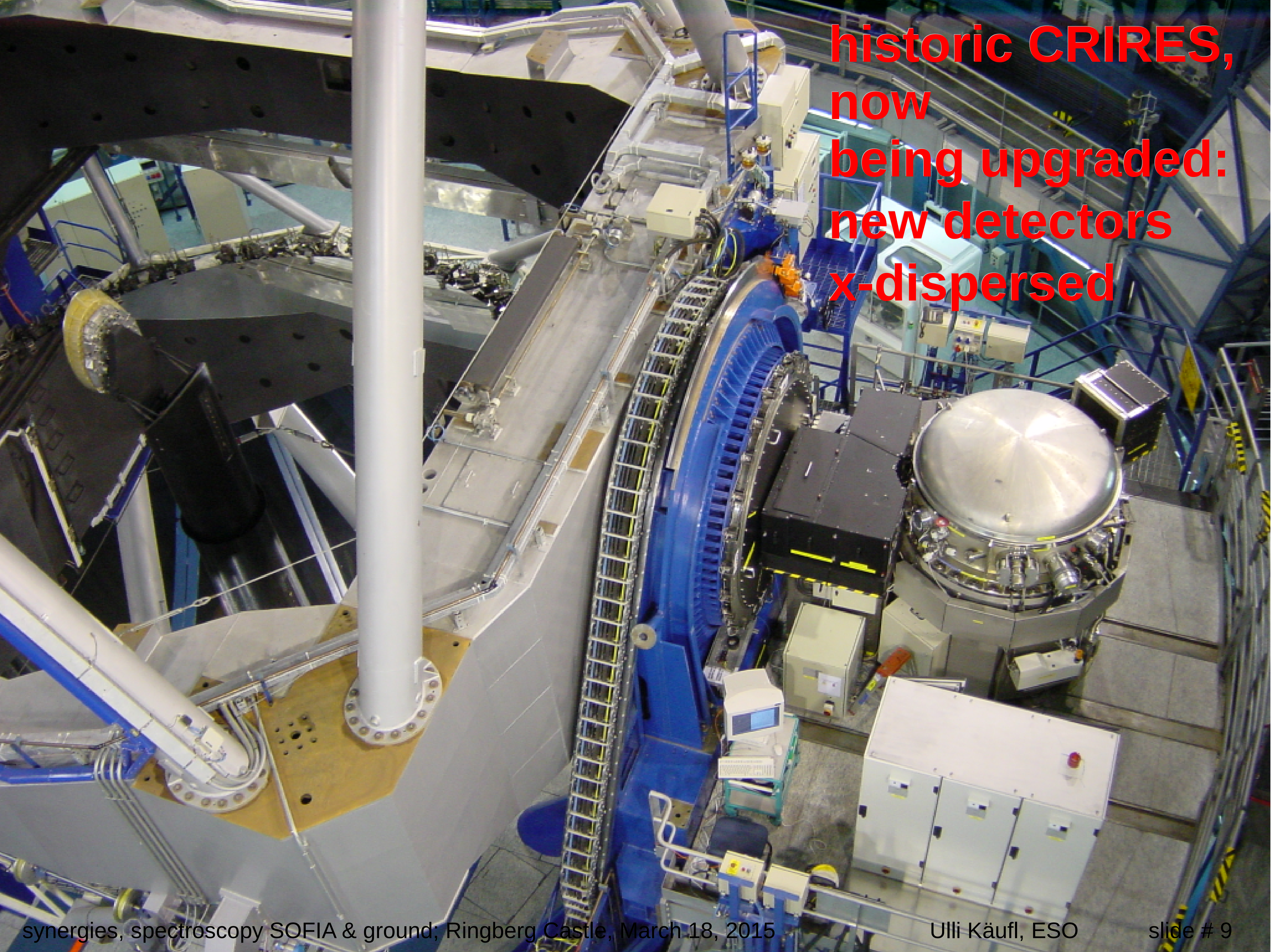
- an example or radiance in the region of the CO fundamental band, Paranal vs 5050m

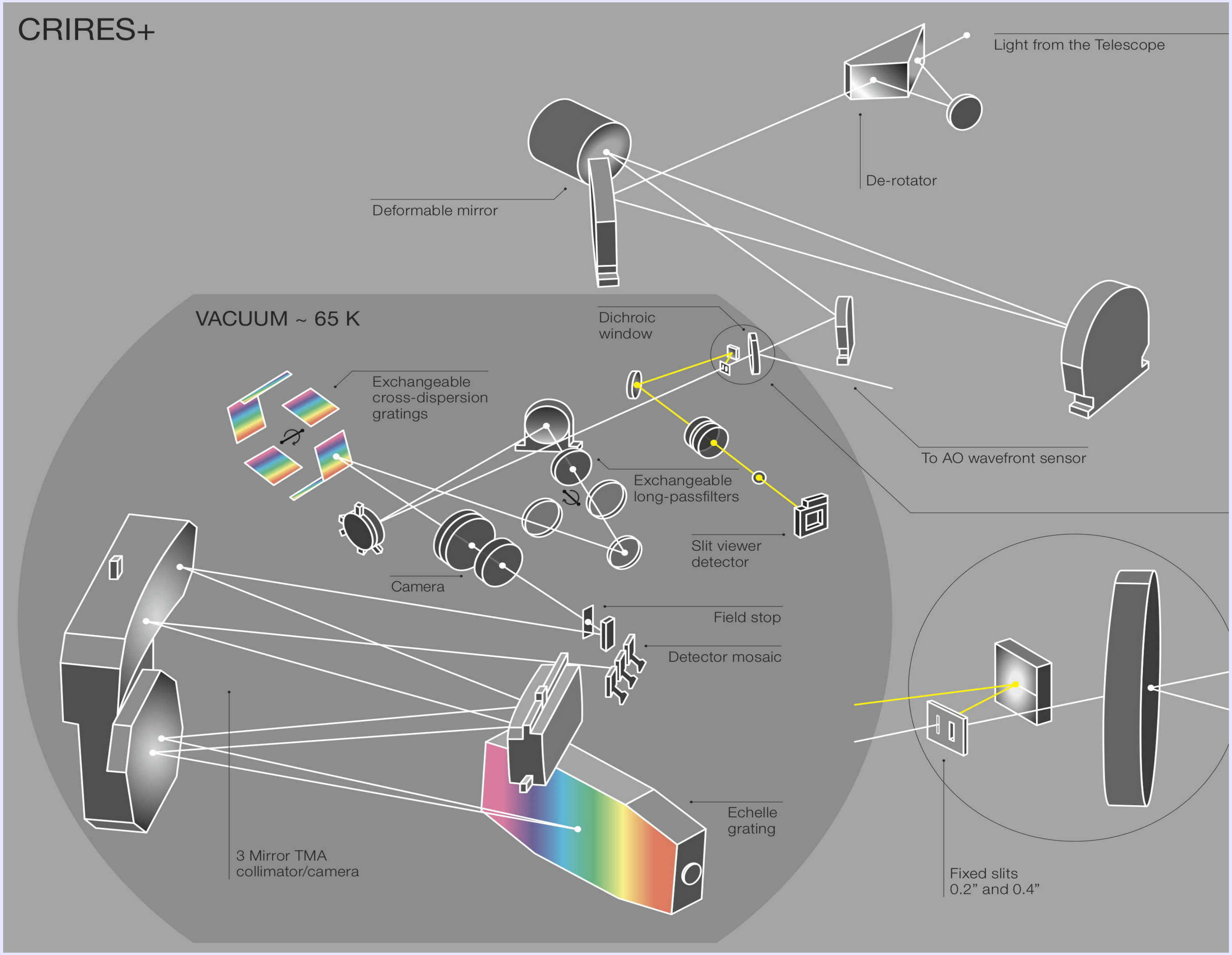
Don't forget shotnoise ...



- detector noise and dark current are basically negligible for modern HgCdTe detectors up to λ ≲ 5500 nm
- internal background and dark current also negligible:
  - VLT-CRIRES: DC < 1/20th e^-
  - VLT-VISIR: DC < 200 e^-
- dominant back-ground sources
  - thermal radiation of telescope and warm optics
  - line radiation of infrared active atmospheric trace species H_2O, CO, CO_2, CH_4, N_xO_y, OCS ....
  - shot noise of the source: high dispersion projects often require s/n ≳100 needs 10^4 e^- => noise ~100 e^-

historic CRIRES,
now
being upgraded:
new detectors
x-dispersed





Schematics of CRIRES

after the upgrade, 2017 the old pre-disperser will be replaced by a set of x-dispersion gratings

CRIRES
main characteristics

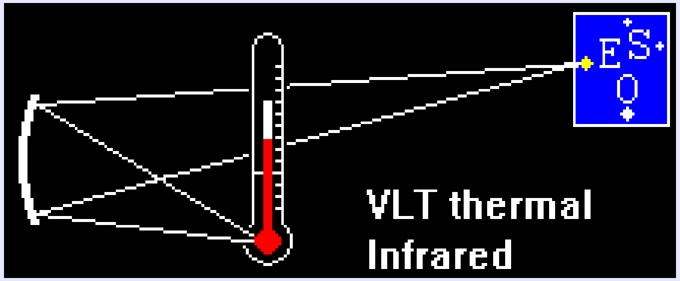
- **frequency coverage:** ν ~ 58.000 – 310.000 GHz
  (λ ~ 950 – 5200 nm)
- **spectral resolution:** ν / Δν (λ / Δλ) ≈10^5 or
  Δv ≈ 3km/s
  (2 pixel Nyquist sampling)
- **array detector mosaic:**
  4 x 1024 x 512 Aladdin III InSb mosaic
  ☞ instantaneous ν - coverage ~ 2.0 %
  pixel scale 0.1"/pix
- **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 5 mas tracking error
- **self-aligning spectrograph:** piezo vernier alignment

CRIRES
main characteristics (cont)

- spectrograph **intrinsic stability** << 75m/s
  preference in design was given to stability
  ☞ gas cells for high precision radial velocity work
  and <u>absolute frequency</u> calibration
- curvature sensing **Adaptive Optics**
  ☞ 0.05” spatial resolution per pixel in
  slit siewer camera
  right: composite JHK false color image
  the Jovian satellite Io (dia 1.1”)

- **spectro-polarimetry in lines:**
  - after upgrade
  - magnetic fields
  - exo-planet atmospheres
  - goal to measure all 4 Stokes parameter

M-band highlight spectro-astrometry



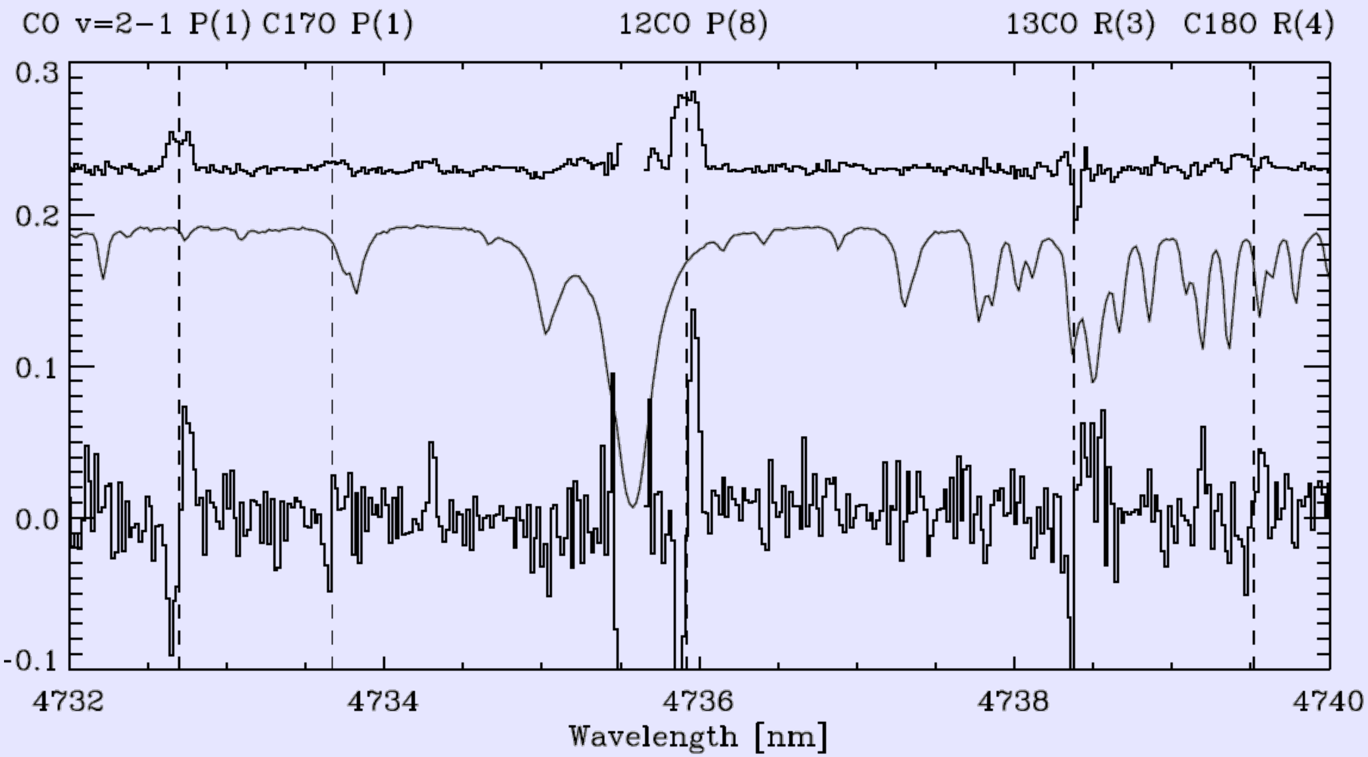
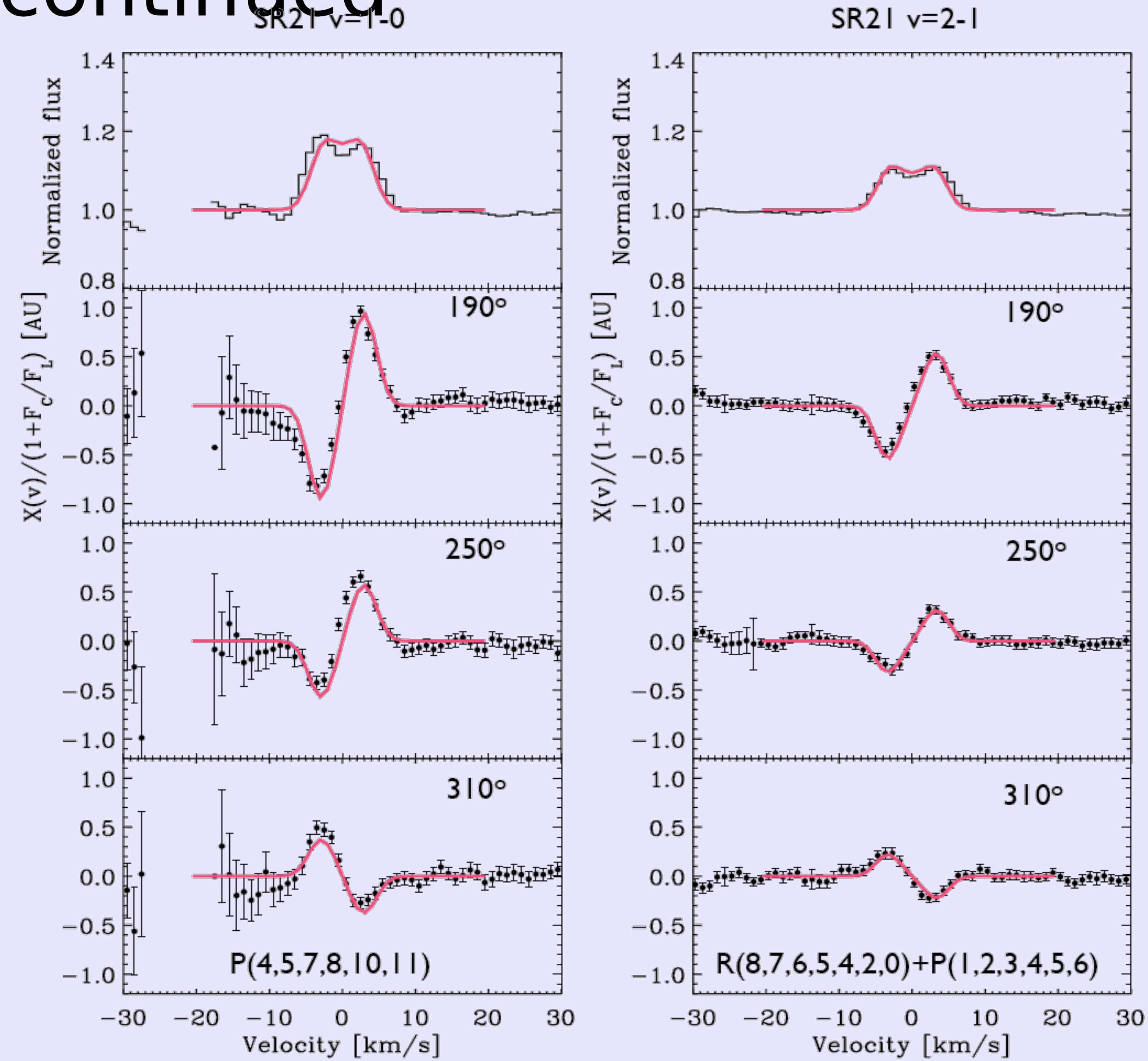


FIG. 1.— A small section of the spectral range covered for SR 21 showing the flux spectrum (*top*), the atmospheric transmission spectrum (*middle*) and the spectro-astrometric signal (*bottom*). The units on the vertical axis are in pixels, relevant for the spectro-astrometric signal; the other two curves are scaled for clarity. The emission lines in the $v = 1 - 0$ rovibrational band (unless otherwise indicated) intrinsic to the SR 21 disk are marked with vertical dashed lines.

^{12}CO / ^{13}CO profiles of a disk with known inner hole (SR 21)

(Pontoppidan et al. ApJ 2008)

Spectro-astrometry continued



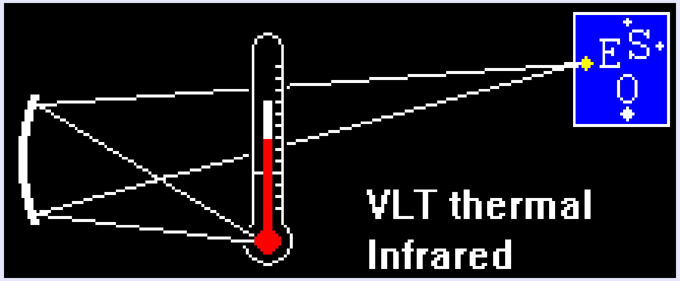
^{12}CO fundamental band, all rotational lines averaged

astrometric signature as a function of Doppler velocity for three slit position angles

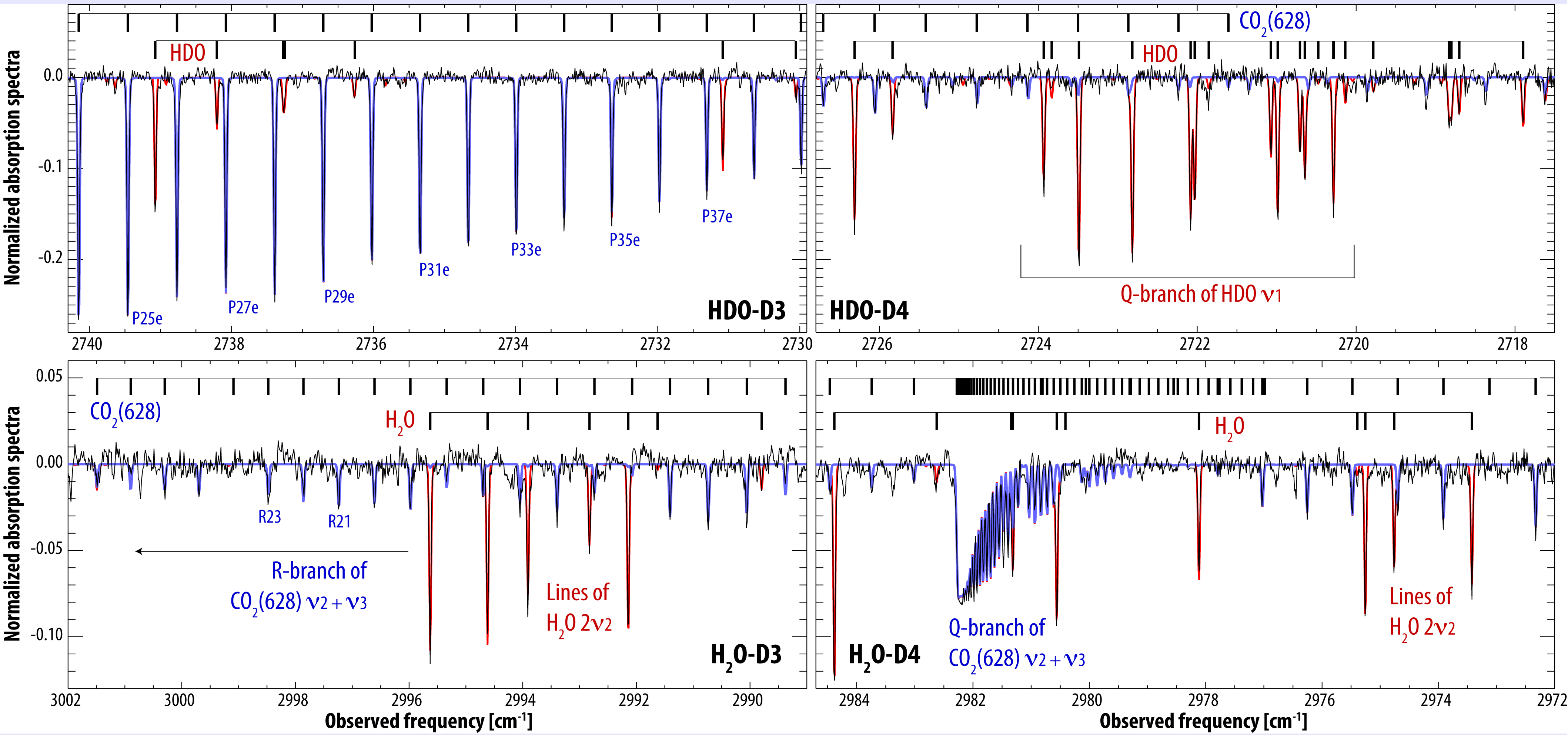
note:
spatial resolution ~ 0.1 AU
(< 1 mas) !!!!

(Pontoppidan et al. ApJ 2008)

D/H, another scientific highlight here Mars

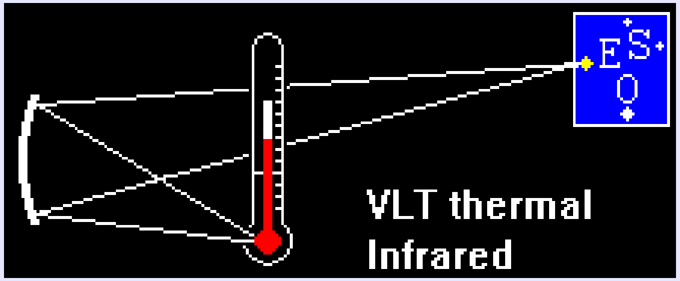


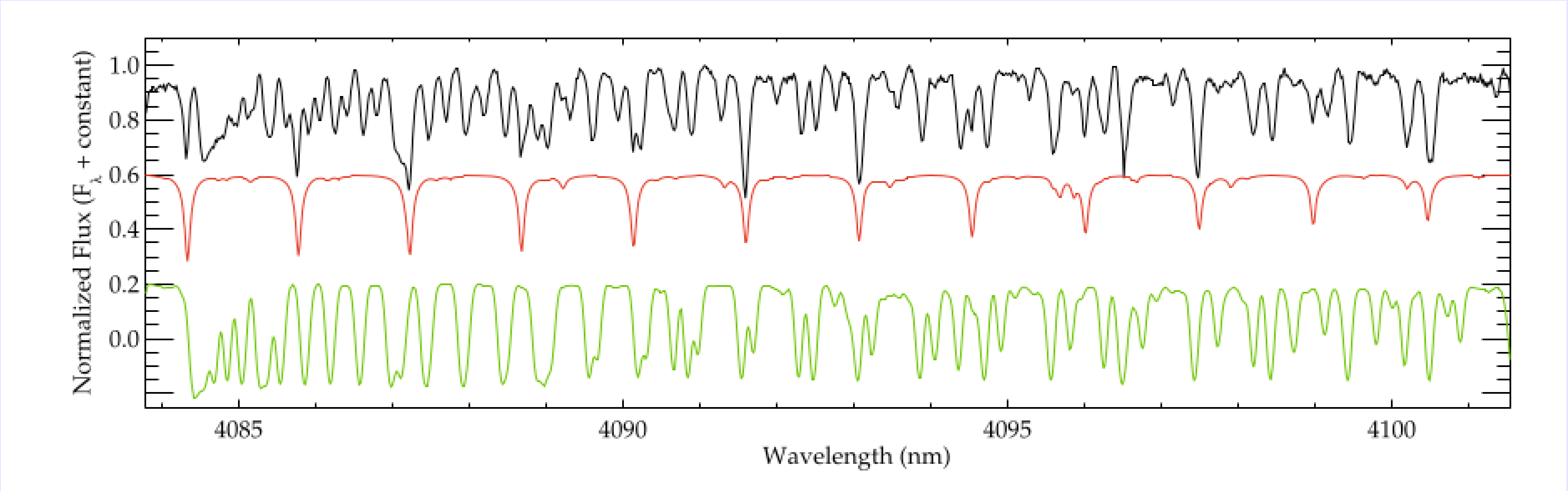
- typical spectrum, Mars VLT-CRIRES
- 6 years of data, Villanueava et al, Science 2015



- D/H enrichment up to 10 relative to VSMOW found
- suggests existence of ocean >1km on Mars

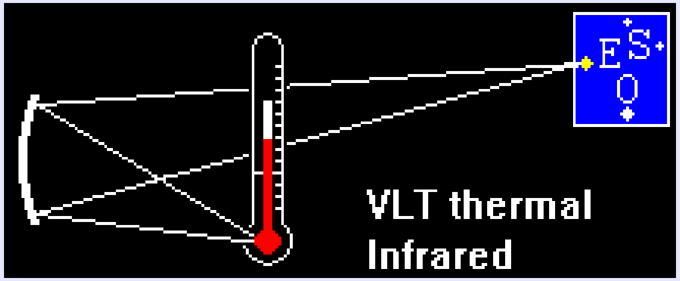
Frequency calibration with telluric lines: CRIRES





- SiO overtone in MS-Vel vs telluric N_2O allowed for a frequency calibration / stability of 20m/s (Seifahrt&Käufl A&A, 2008)
- using the ESO-UVES archive Figueroa et al, A&A, 2010 showed that telluric lines intrinsically allow for spectral calibrations to the 5-10m/s level

What about SEDs?



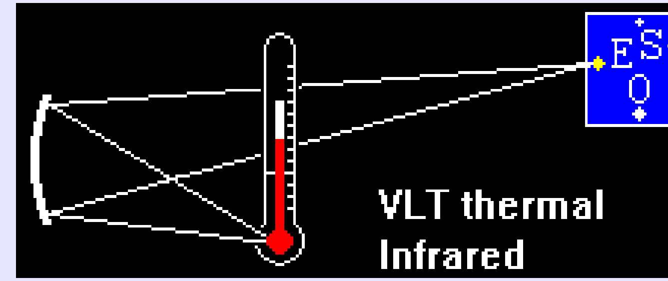
- 3-5.5μm:
  - after the CRIRES upgrade both the L and M-band can be covered with ~6 exposures at $\lambda/\Delta\lambda \sim 10^5$
  - as telluric features are adequately resolved, they can be fully accounted for
  - rebinning of data with statistic weights will yield data far superior to low resolution work

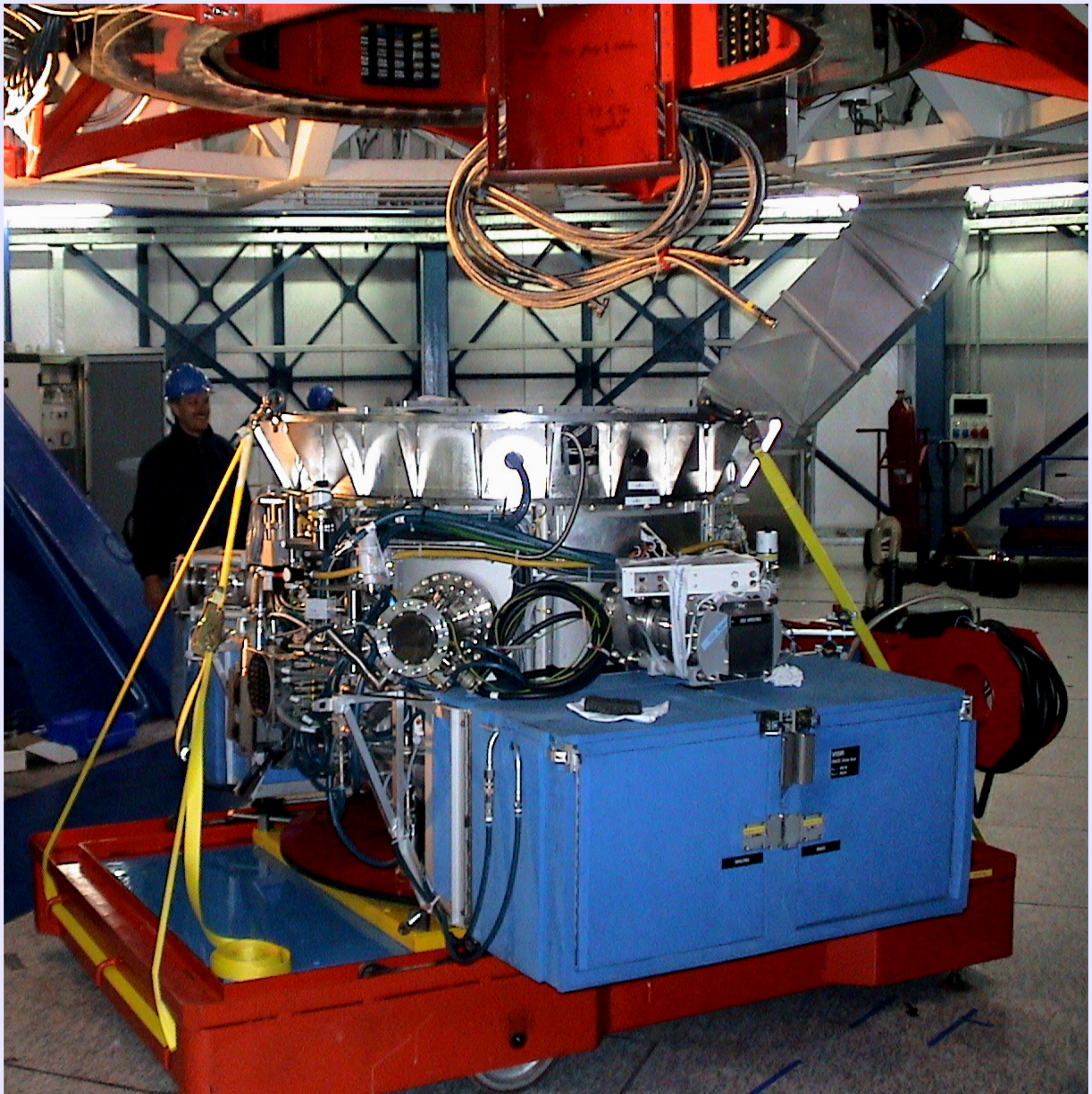
note (Dan Jaffe):

you cannot be too thin, you cannot be too rich
and you cannot have too much spectral resolution

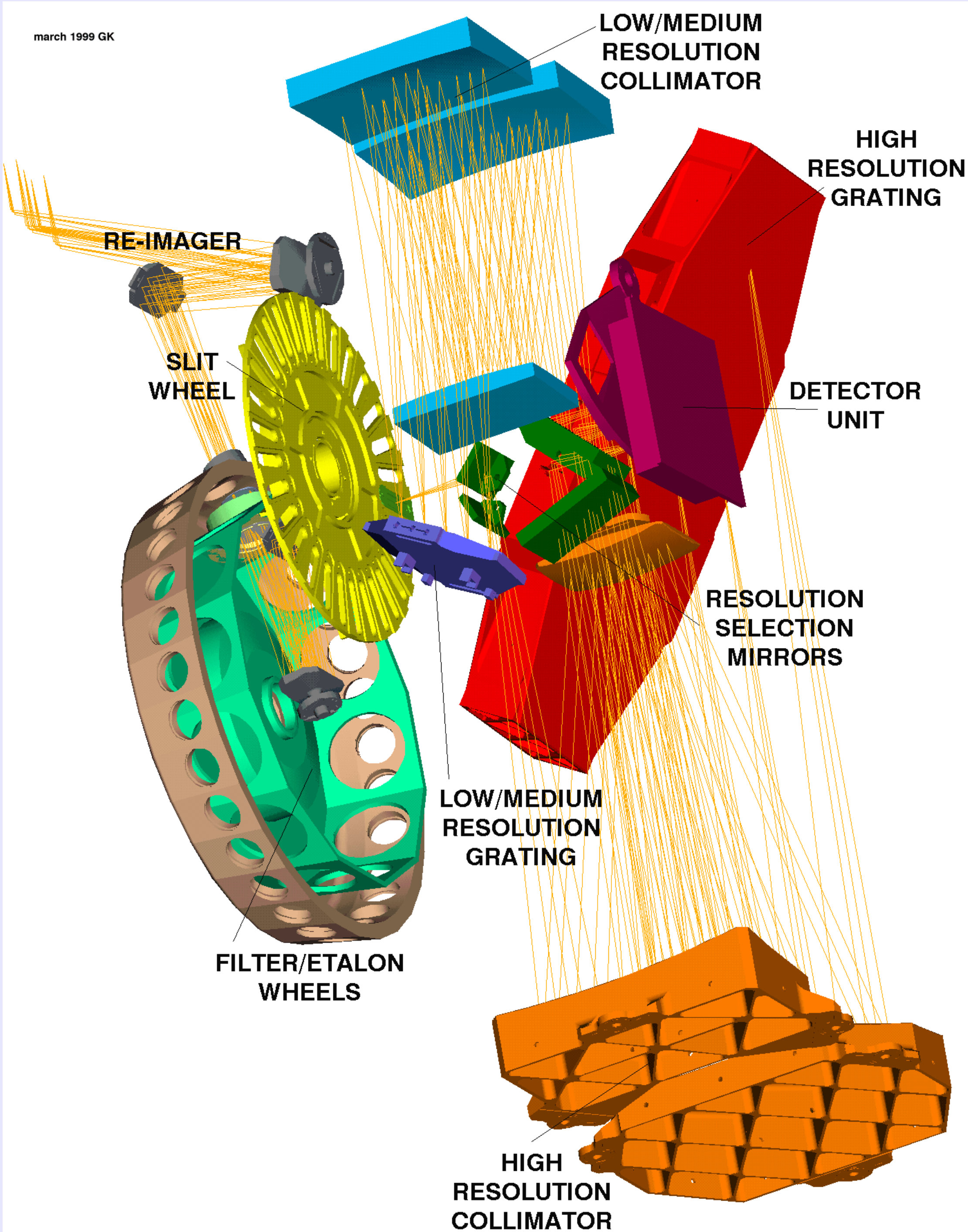
- 7.7-13.3μm to be continued with VISIR

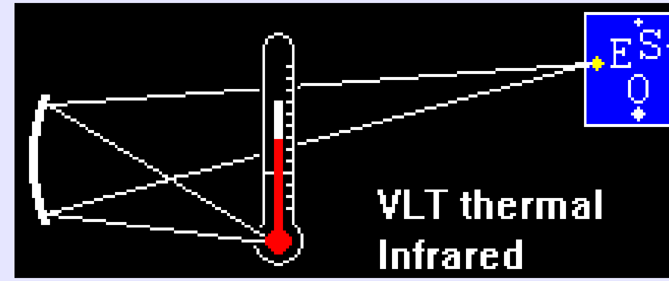
VISIR at the VLT: Overview





- built by CEA/Astron, upgraded by ESO
- 10/20 μm imager/ spectrometer (R ~ 500 – 30.000)
- sensitivity (BLIP) ~ 2mJy 10μm imaging ~ 40-1000mJy spectro
- diffraction limited (FWHM ~0.3“ sampling 0.045” / pix)
- as of Nov 2014 back @ VLT-UT3





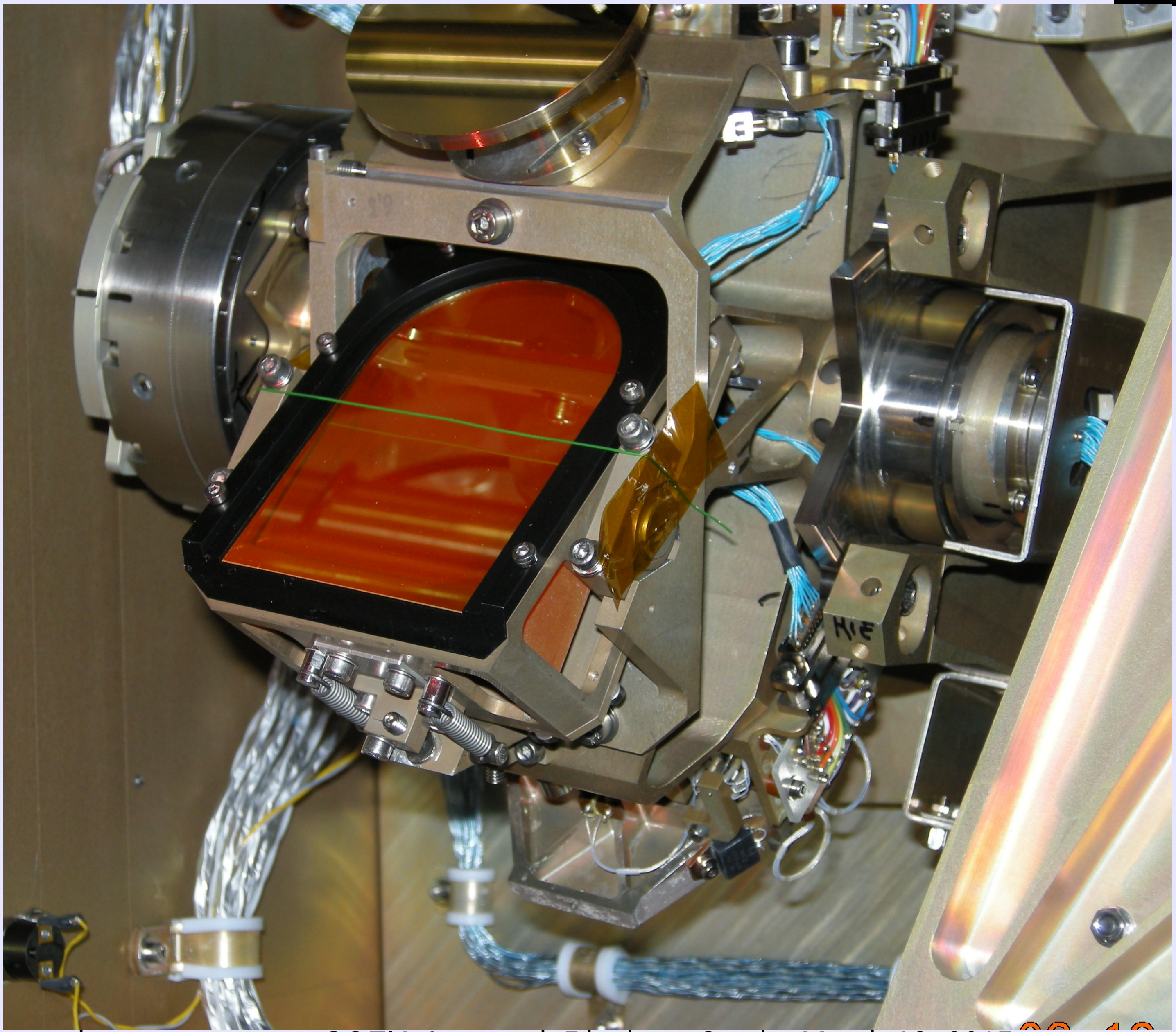
schematics of VISIR spectrograph

- two collimators
- low, medium and high resolution modes
- 8-13 µm in one exposure with prism (λ/Δλ~500)
- 7.7-13.3 µm Echelle mode (λ/Δλ~30.000)
  general: x-dispersed

  selected lines: long slit mode

close-up ZnSe prism on low-res caroussel

VLT thermal Infrared

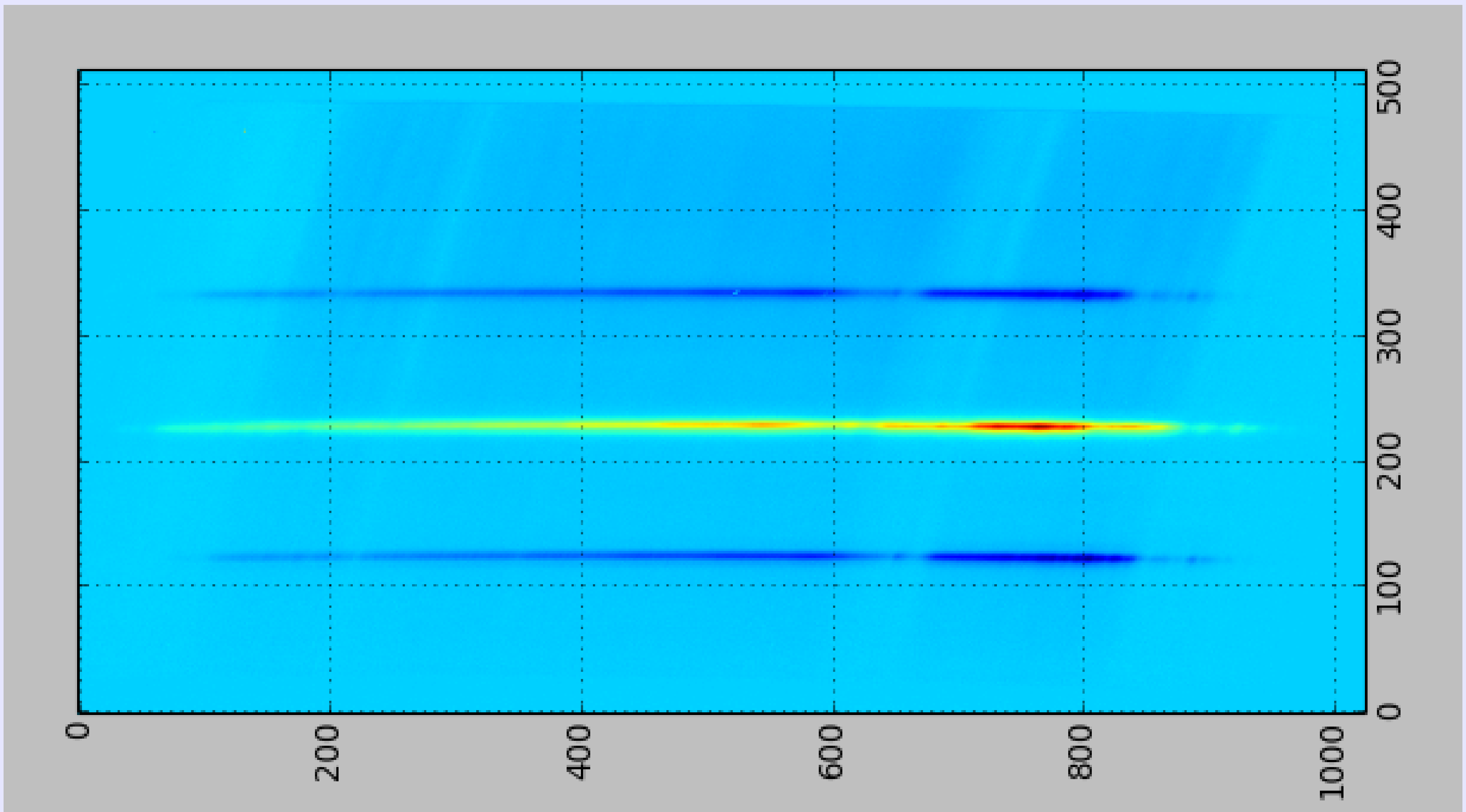


Why a prism?

ZnSe prism gives complete N-band in one exposure
=> 4 fold more efficient than “old” VISIR
λ/Δλ: 300-500
no filter etc => highest throughput
and
straylight by design minimized

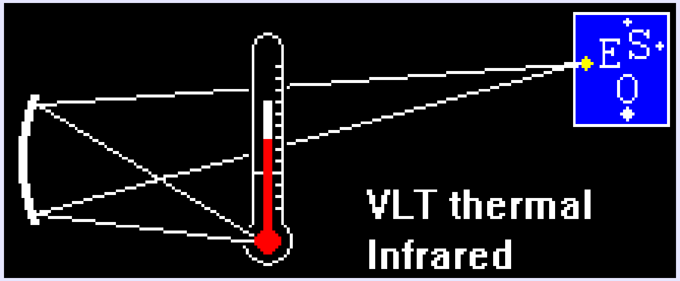
VISIR upgrade

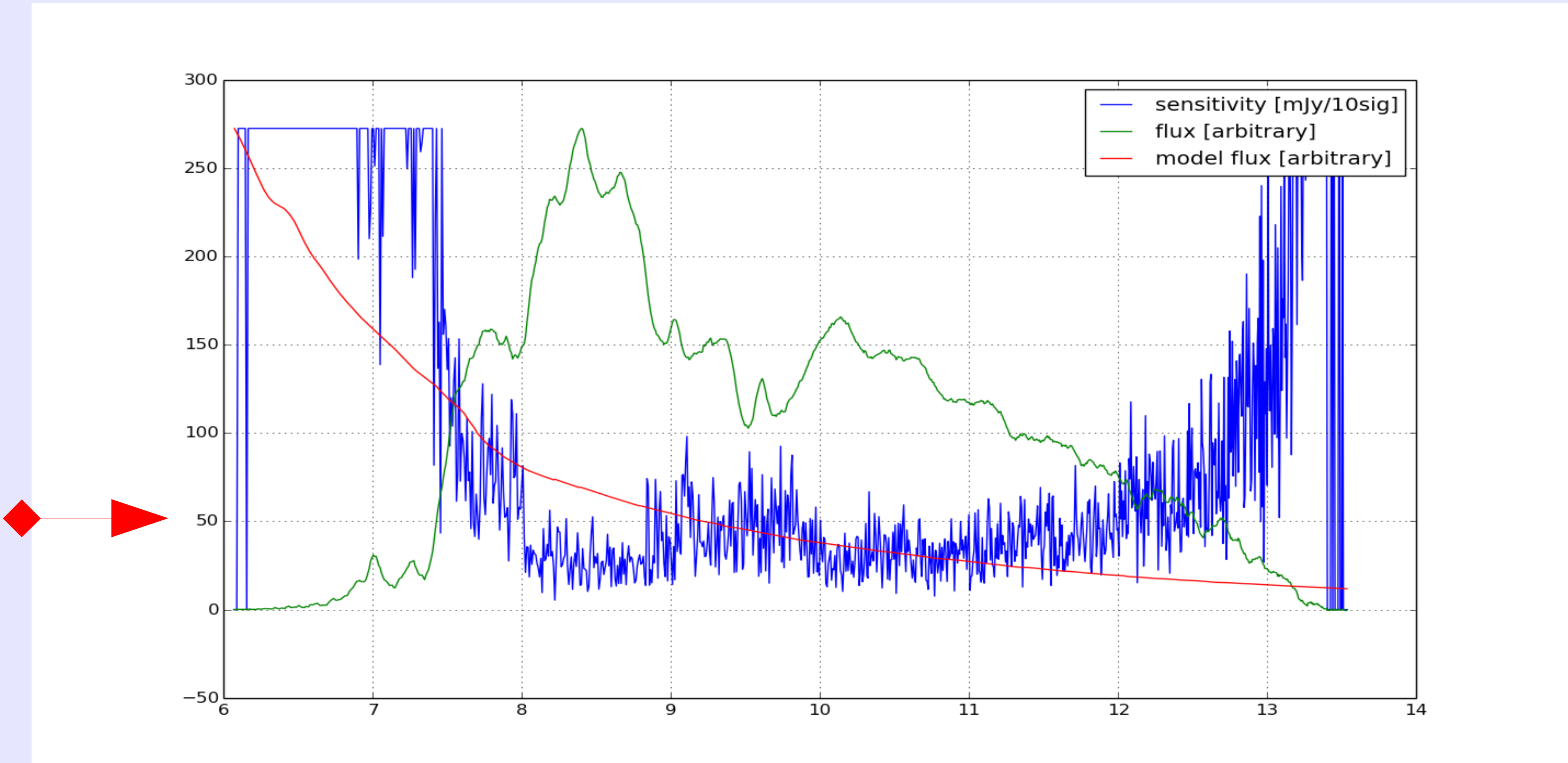
low resolution prism mode



- standard star spectrum spanning 23.000GHz to 39.000GHz (vulgo 7.7 to 13.3µm)

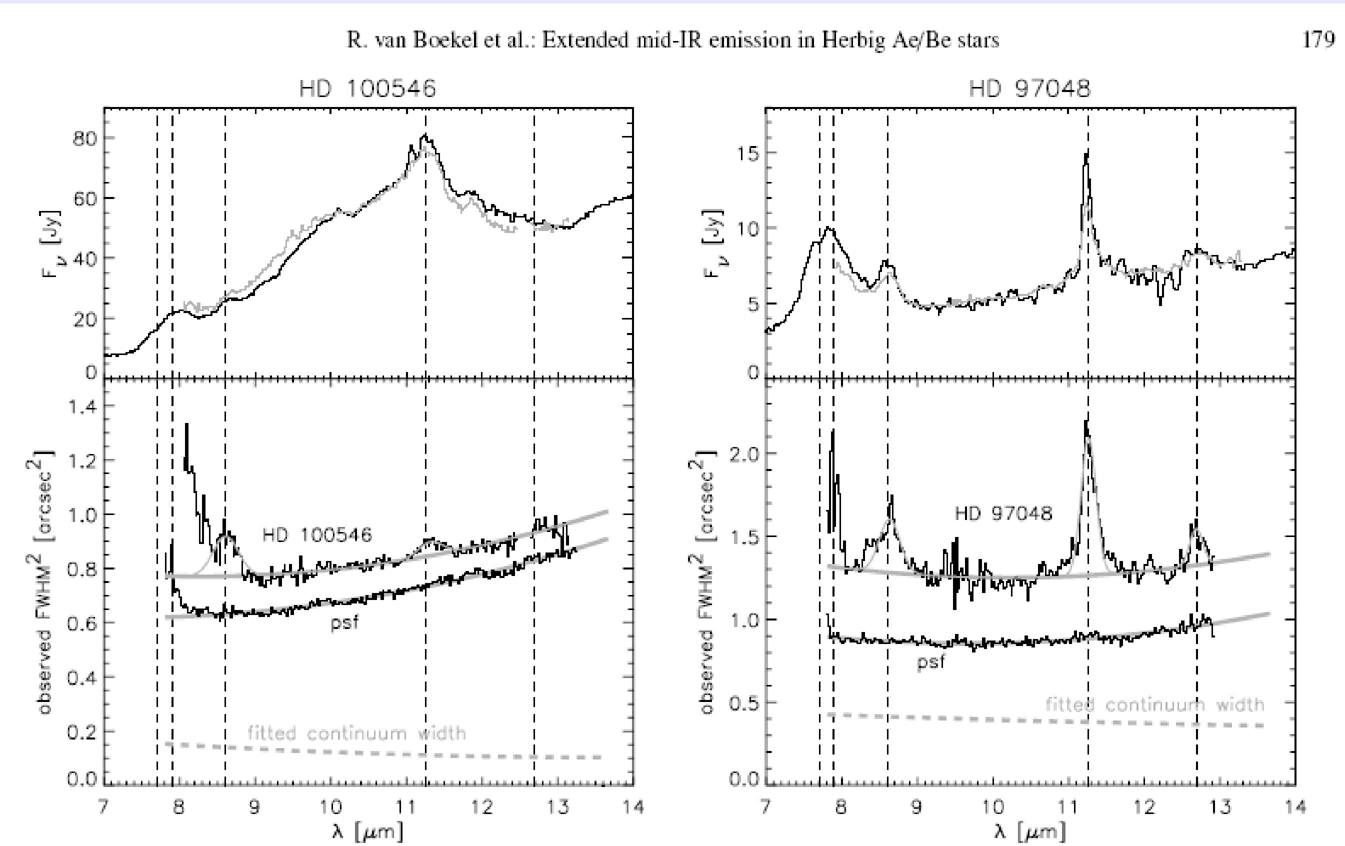
VISIR low resolution sensitivity





- i.e. a factor of 2 improvement to old VISIR, while 4 times faster!
- VISIR spectroscopy now as good as TIMMI2 imaging was

spectro-astrometry: the SED case

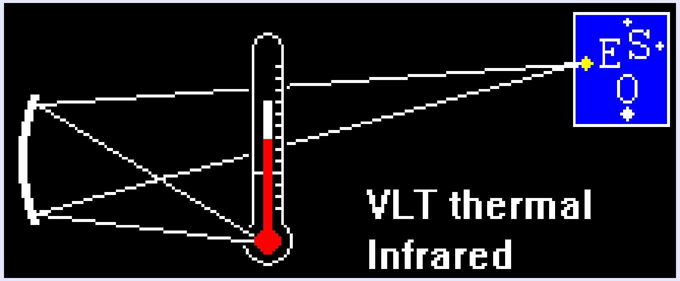


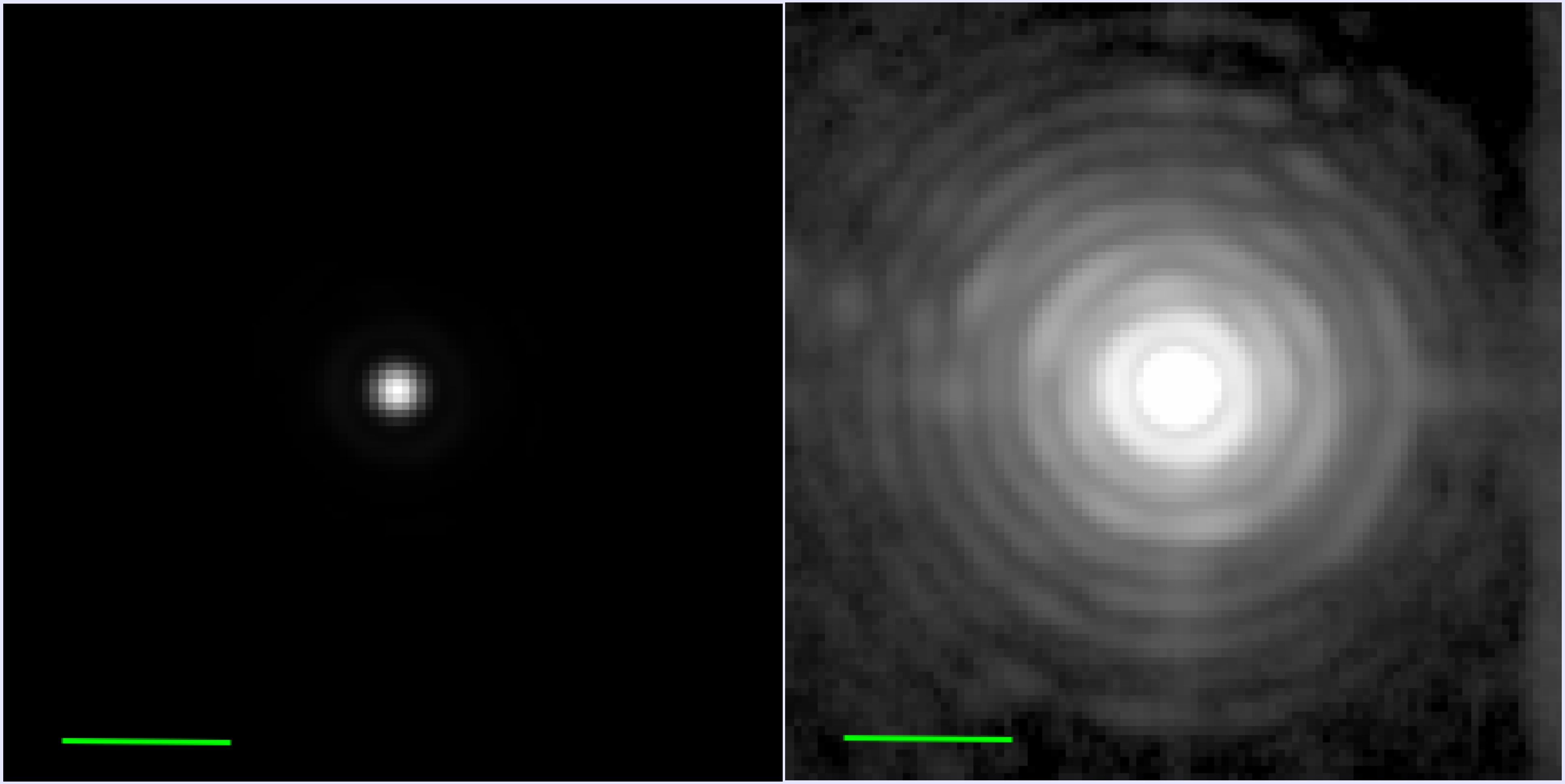
left:
circum-stellar material observed with the ESO 3.6m telescope around a Herbig AeBe star at a spatial scale of 1/5th of a pixel, here 0.1” **note:** this corresponds to a ~330m interferometric baseline (van Boekel et al. 2004, A&A **418**, 177)

How does it work?

differential method, using shape of the cross-dispersion profile as a PSF proxy to deconvolve the spectrum in spatial direction in an adjacent wavelength interval (similar to spectral differential imaging SDI)

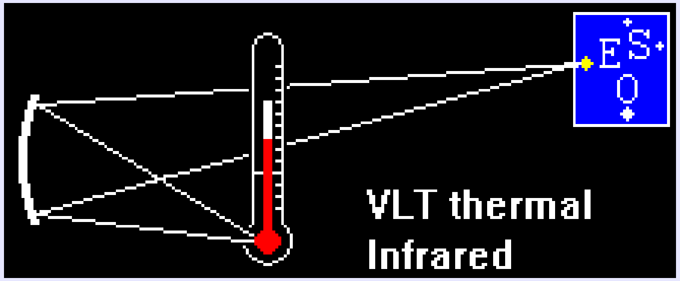
VISIR upgrade, small excursion to imaging



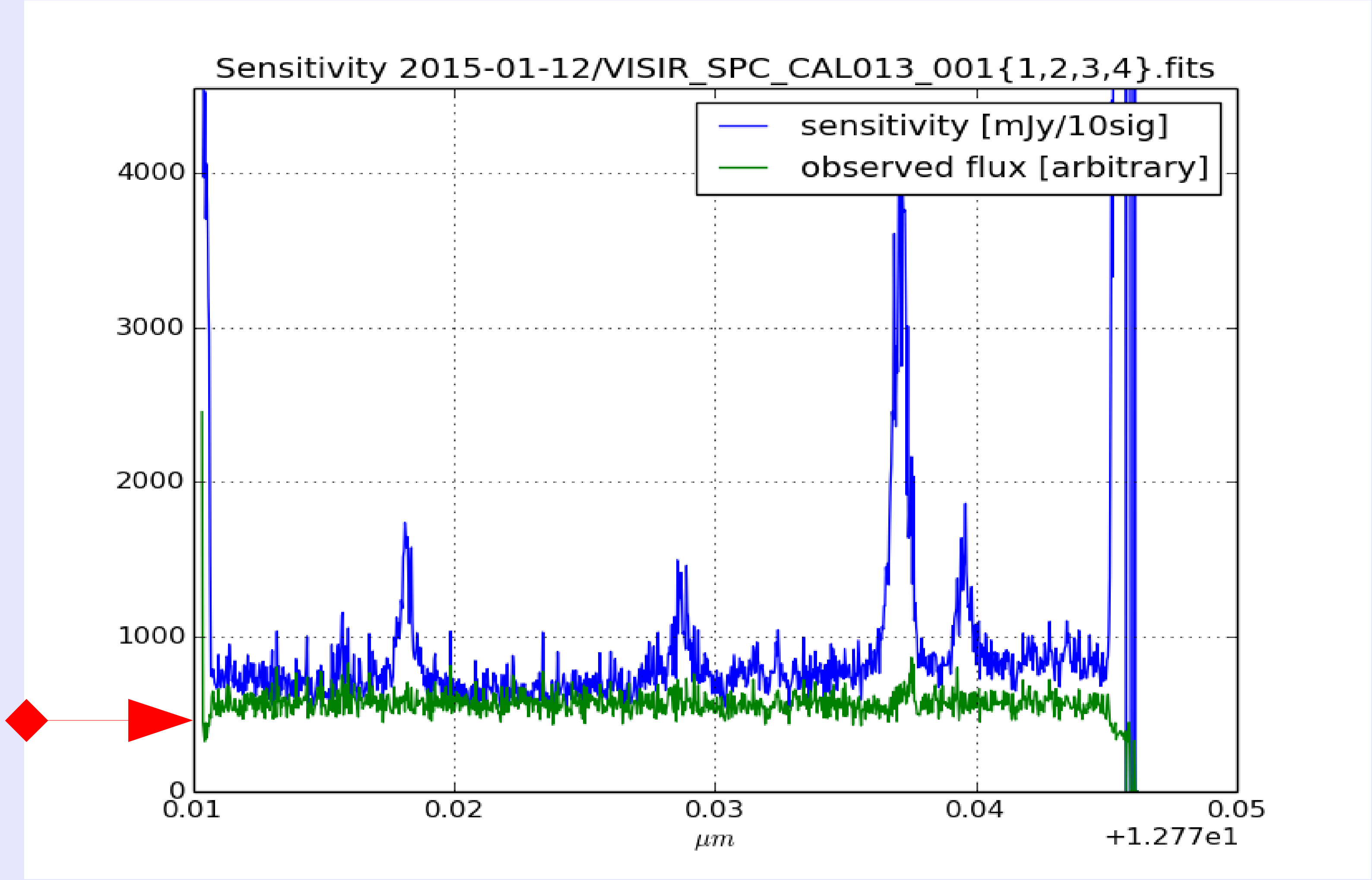


- left linear, right logarithmic (burst mode)
- green bar 1 arcsec

VISIR Echelle Sensitivity



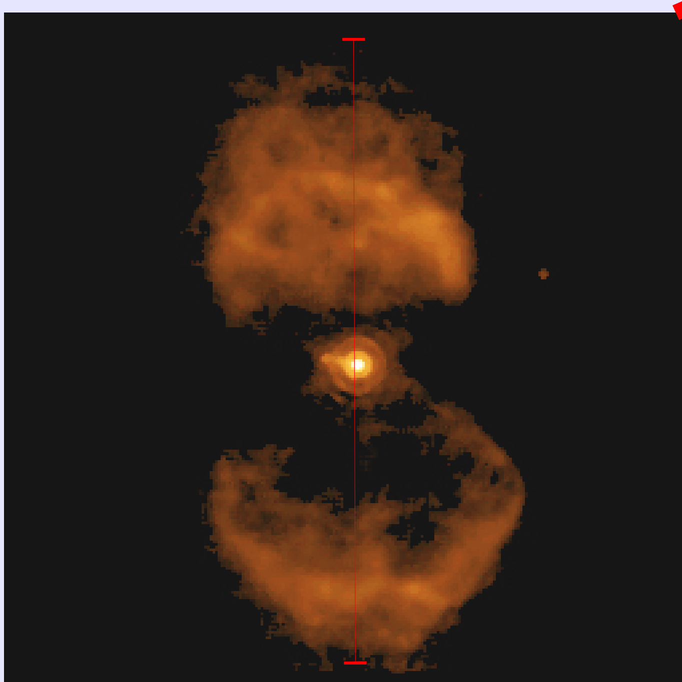
example at λ~ 12.8 µm

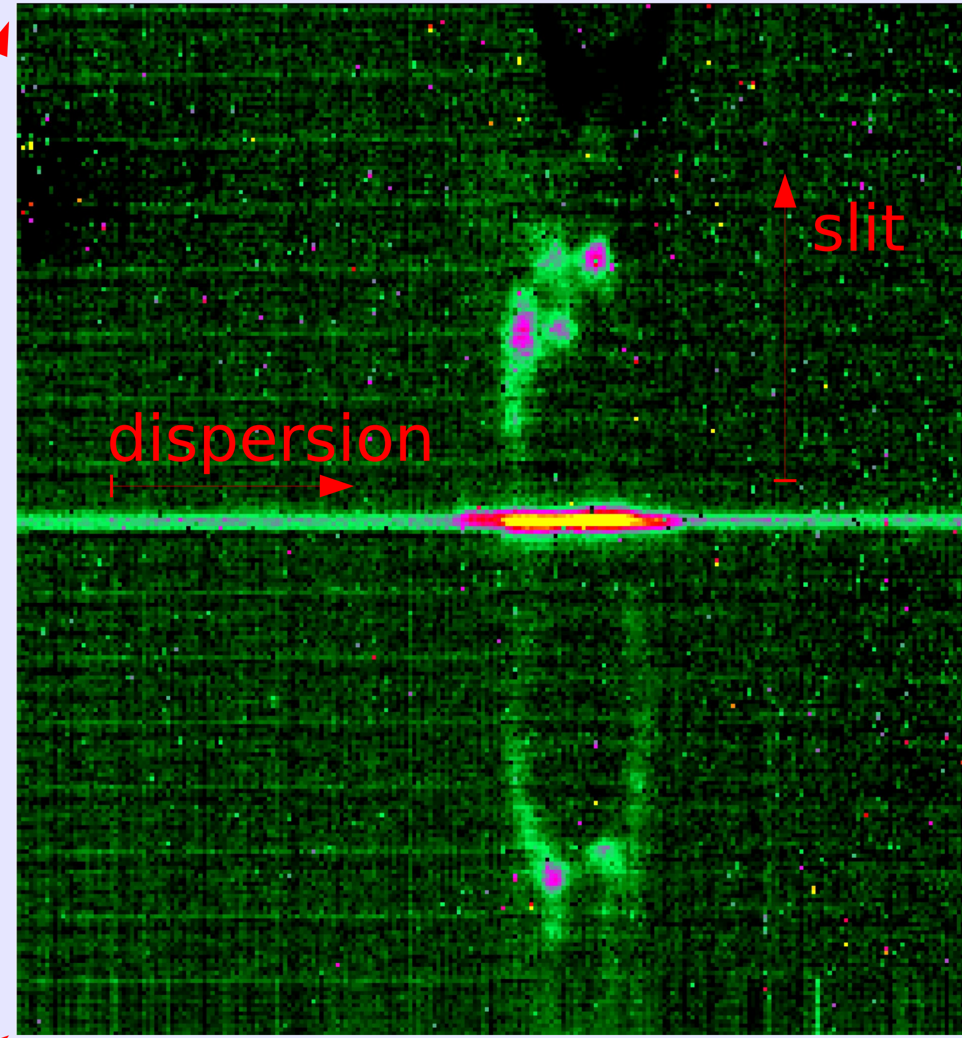


- at least a 40-60% improvement, while 2 times faster!
- preliminary, set-up and pipeline not tuned

VISIR Spectrograph 1st Light

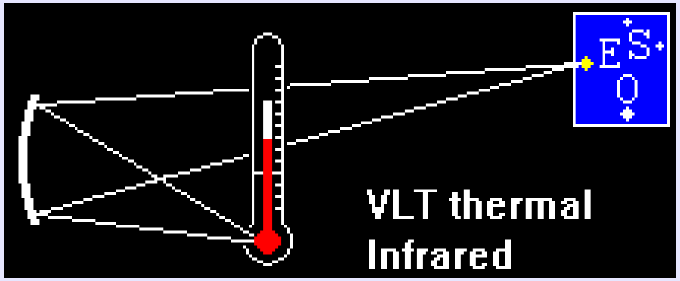
- more 1st light results
  Menzel 3 [Ne II], λ ~ 12.8μm
- long-slit spectroscopy
  R ~ 30000 (i.e. 10 km/s)



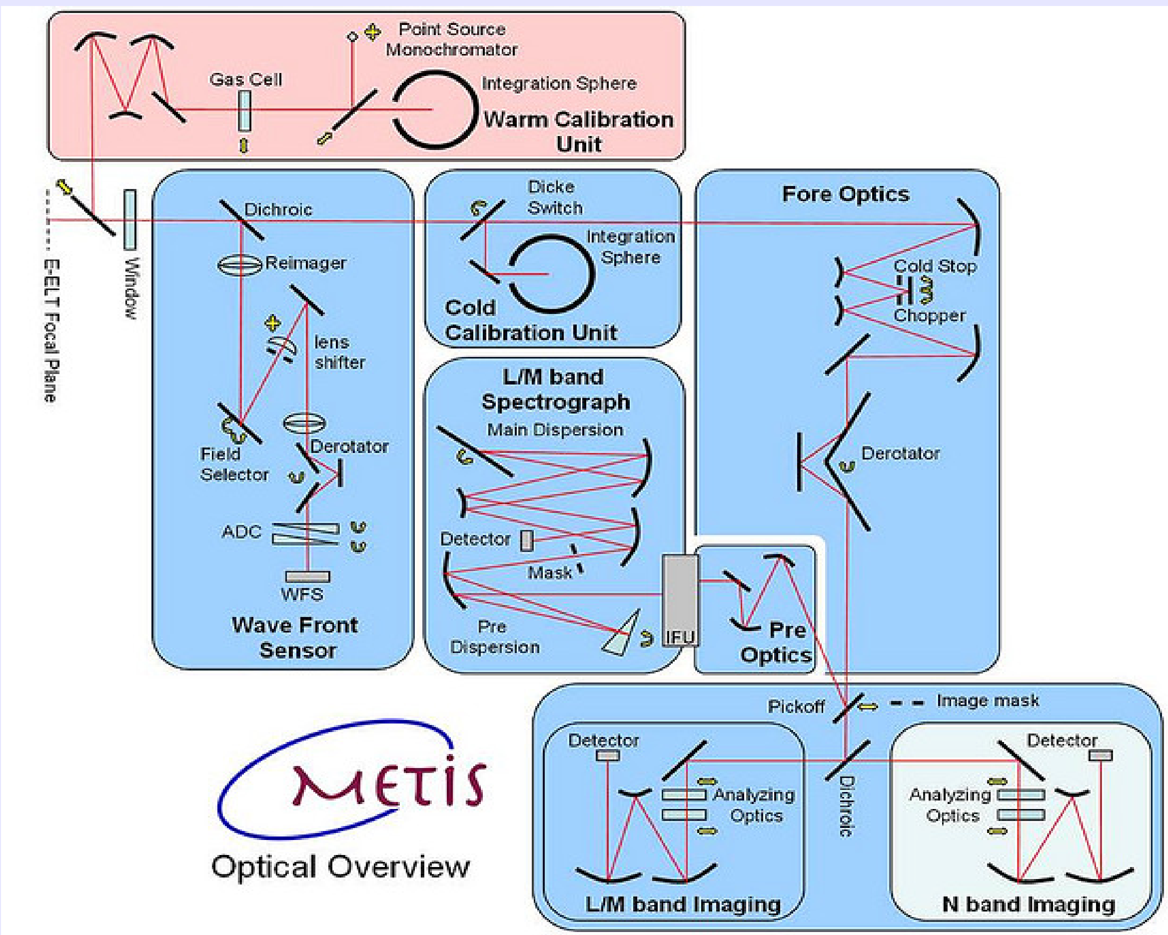


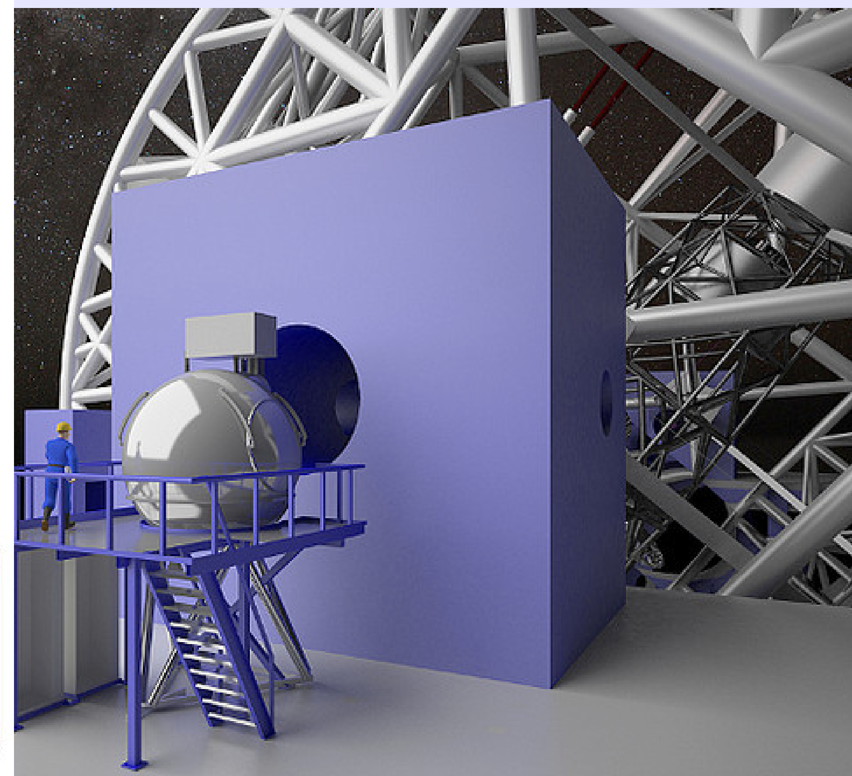
- note: in BLIP (back-ground noise limited performance) S/N α √ R

Outlook: E-ELT-METIS

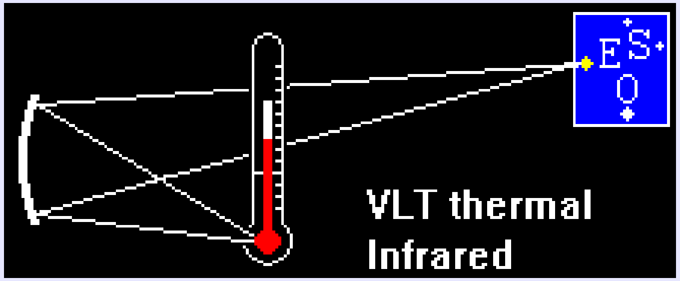


- E-ELT, 38m,
  Cerro Armazones 3064m vs 2634m
- METIS is CRIRES-red and VISIR-blue
  http://metis.strw.leidenuniv.nl/index.php





Conclusions



- many spectral lines only accessible for SOFIA
- Q-band on average much better from SOFIA
- global SEDs better from SOFIA
- specific lines in windows always better from the ground, even when only marginally possible
- spatial information from ground unsurpassed
  - 8m vs 2.5m
  - super-resolution techniques
- flexibility in scheduling and PWV monitoring allow for sensitive ground based synoptic observations
- SOFIA and ground based telescopes thus “orthogonal”
- SOFIA to prepare the Q-band science case for the E-ELTs


DON’T PANIC