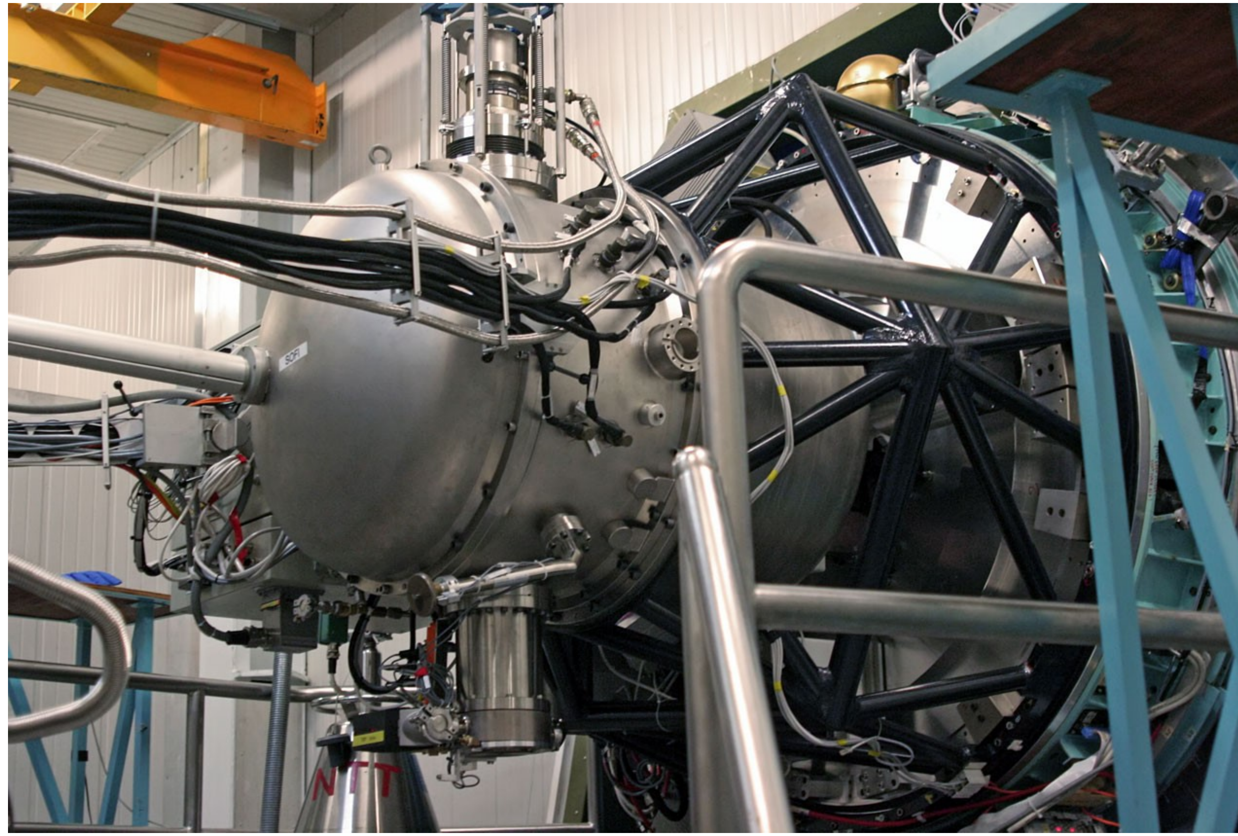
Observing with SOFI

Fernando Comerón (ESO)

What is SOFI?



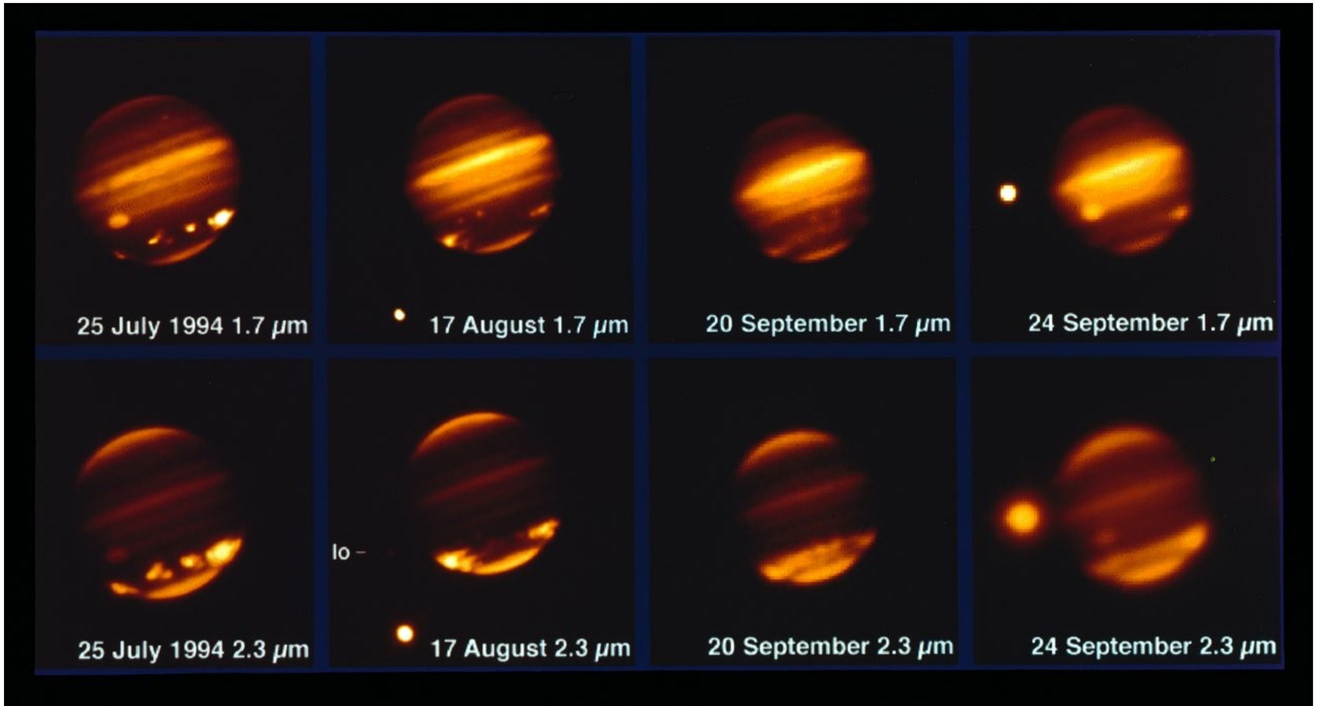
- An infrared array camera (1K x 1K) and low-resolution spectrograph at the New Technology Telescope
- 0.9-2.5 micron coverage (J, H, K bands)
- 5’ x 5’ field of view
- Polarimetric capabilities

A workhorse instrument: wide range of science cases.

How SOFI came to be

ESO's near-infrared capabilities in the mid-1990s:

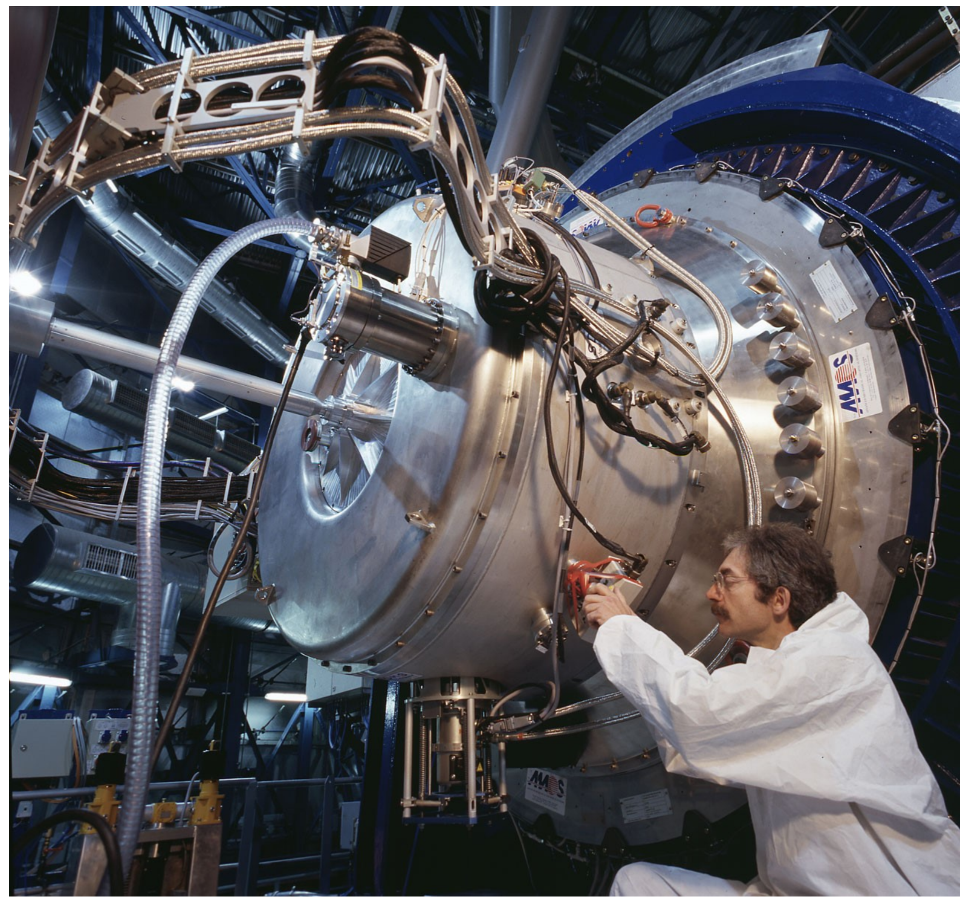
- IRAC-1: 64x64 imager, 1-5 microns
- IRAC-2b: 256x256 imager and Fabry-Perot at 2.2m telescope, 1-2.5 microns
- IRSPEC: facility spectrograph at the NTT, 1-5 microns
- ADONIS: Adaptive optics system at the 3.6m, 1-5 microns, 128x128
- SHARP: Adaptive optics visitor instrument at the NTT



How SOFI came to be

NTT upgrade in the late 1990s to make it a testbed for the VLT:

- SOFI planned to take advantage of new, larger format, more sensitive, cosmetically better detectors
- Designed to remain competitive at the NTT in the VLT era
- Reusing concepts, technology, software… used for ISAAC, being developed for the VLT
- Hence the name: SOFI=Son OF Isaac
- Built in record time: less than two years from detailed design to commissioning
- Operations started in 1998 (before ISAAC)
- Still in operation (but ISAAC was decommissioned in 2013)
- Still in high demand!



My own story with SOFI

- My first run with SOFI in 1999
- My last (for the time being!) run with SOFI in 2018
- Many runs in between, imaging and spectroscopy

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 465, 760–783 (2017) doi:10.1093/mnras/stw2760
Advance Access publication 2016 October 26

Physical parameters of late M-type members of Chamaeleon I and TW Hydrae Association: dust settling, age dispersion and activity

A. Bayo,[1,2]★ D. Barrado,[3] F. Allard,[4] T. Henning,[2] F. Comerón,[5]
M. Morales-Calderón,[3] A. S. Rajpurohit,[6] K. Peña Ramírez[7,8] and J. C. Beamín[1,8]

Astron. Astrophys. 359, 269–288 (2000)
ASTRONOMY AND ASTROPHYSICS

Probing the brown dwarf population of the Chamaeleon I star forming region★

F. Comerón[1], R. Neuhäuser[2], and A.A. Kaas[3]

A&A 433, 955–977 (2005)
DOI: 10.1051/0004-6361:20041586

Astronomy & Astrophysics

A&A 425, 489–508 (2004)
DOI: 10.1051/0004-6361:20040312

Astronomy & Astrophysics

Star formation in RCW 108: Triggered or spontaneous?★

F. Comerón[1], N. Schneider[2,3], and D. Russeil[4]

A&A 406, 1001–1017 (2003)
DOI: 10.1051/0004-6361:20030848

Astronomy & Astrophysics

A search for late-type supergiants in the inner regions of the Milky Way★,★★

F. Comerón[1], J. Torra[2], C. Chiappini[3], F. Figueras[2], V. D. Ivanov[4], and S. J. Ribas[2]

A Massive Star Odyssey, from Main Sequence to Supernova
Proceedings IAU Symposium No. 212, © 2003 IAU
K.A. van der Hucht, A. Herrero & C. Esteban, eds.

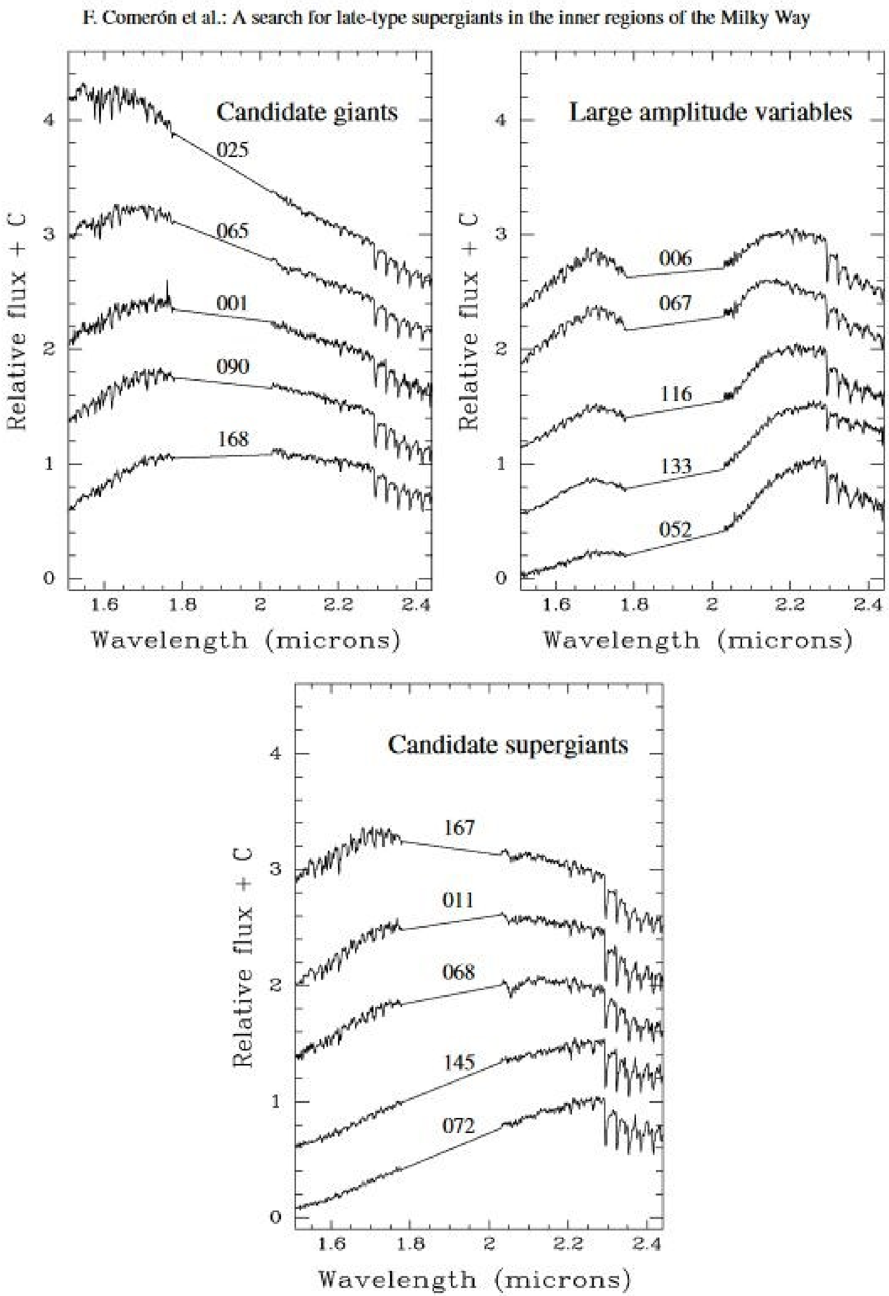
New low-mass members of the Lupus 3 dark cloud: Further indications of pre-main-sequence evolution strongly affected by accretion★

F. Comerón[1], M. Fernández[2], I. Baraffe[3], R. Neuhäuser[4,5], and A. A. Kaas[6]

The stellar content of obscured compact H II regions

Margaret M. Hanson[1], Lex Kaper[2], Arjan Bik[2], Fernando Comerón[3], Joachim Puls[4], Alexander Jokuthy[4], and Rolf-Peter Kudritzki[5]

My story with SOFI



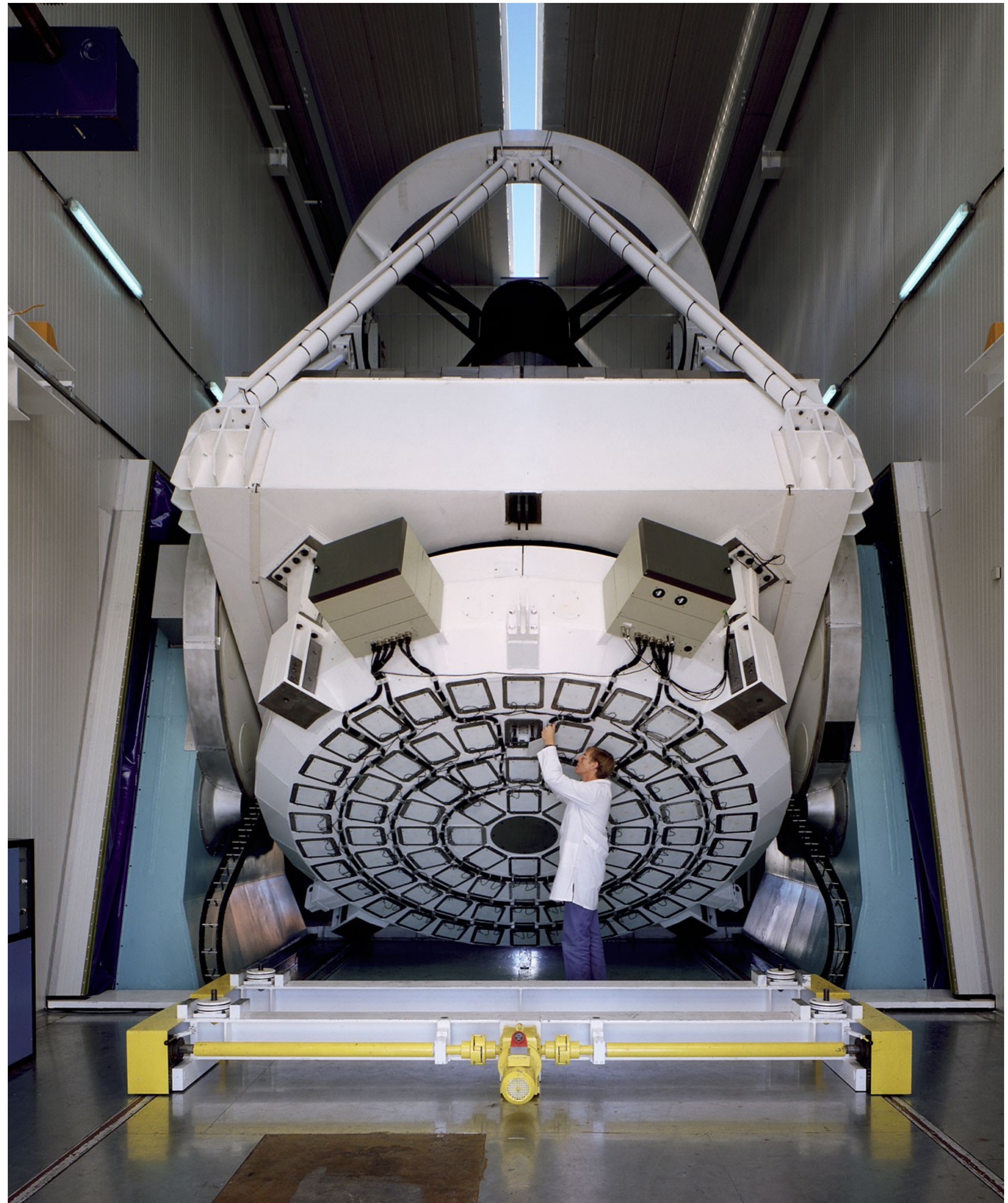
SOFI today among ESO infrared instruments

Other near-infrared instruments at ESO today…

- VIRCAM at VISTA (4m telescope, 1.4 x 1.4 degrees field)
- HAWK-I at the VLT (8.2m telescope, 7.5 x 7.5 arcmin field)
- SPHERE at the VLT (imaging, integral field spectroscopy and polarimetry with extreme adaptive optics)
- KMOS at the VLT (multi-IFU spectroscopy)
- X-Shooter at the VLT (broad wavelength coverage at intermediate resolution)
- CRIRES (high-resolution spectroscopy in 1-5 microns)
- MATISSE (interferometry > 3 microns)
- GRAVITY (interferometry 2.0-2.4 microns)
- PIONIER (interferometry H-band)

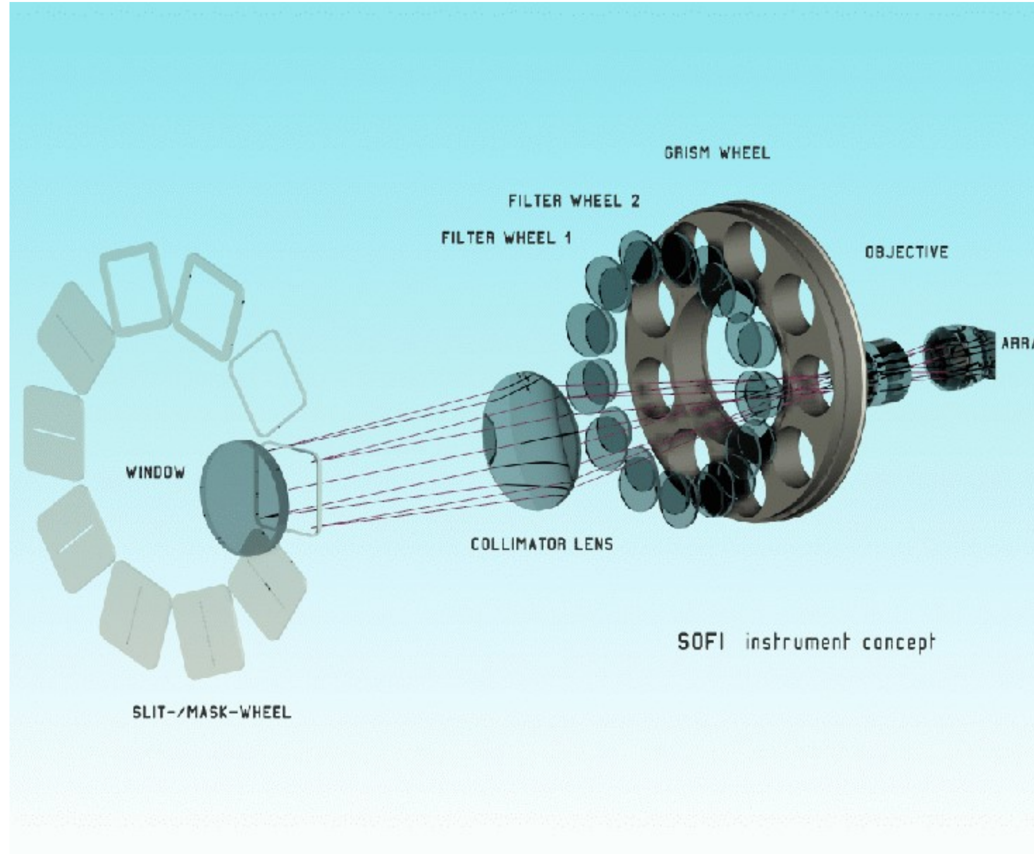
SOFI at the NTT

- Located at one of the two Nasmyth platforms of the NTT
- First instrument designed from the beginning to be VLT-compliant to enter operation
- Imaging with 0"288 pixel scale, 4'92 x 4'92
- Spectroscopy with grisms at 0"273 pixel scale:
  - Low resolution: $\lambda / \Delta\lambda = 930$ (z to H bands), $\lambda / \Delta\lambda = 980$ (H to K bands)
  - Medium resolution: several grisms with $\lambda / \Delta\lambda = 1400\text{-}2200$ (more restricted wavelength coverage)
- Polarimetry with Wollaston prism



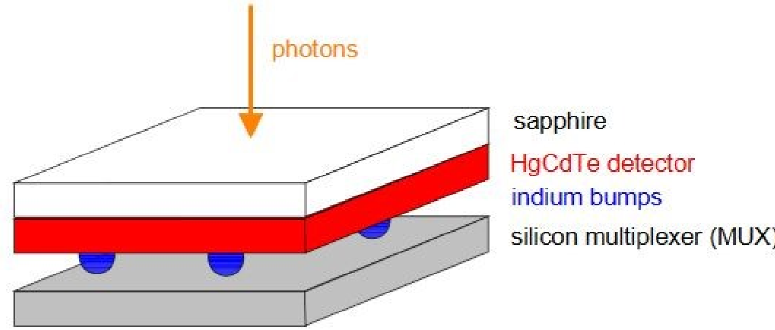
Optical layout

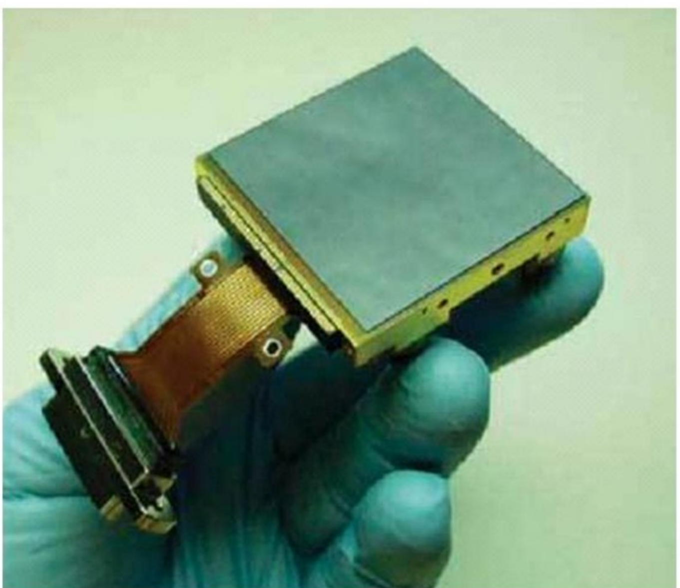
- SOFI is a cryogenic instrument (like all instruments having capabilities beyond H-band)
- Instrument contained in a vacuum vessel
  - Not only the detector, but all the interior of the instrument is cooled down to 77K
- Minimal number of optical surfaces and moving parts: keep interventions to a minimum!
- Window seals the interior
- Telescope focus at slit and mask wheel
- Large assortment of broad- and narrow-band filters
- Low- and medium-resolution grisms in a separate wheel
- Objectives can be exchanged for different pixel scales, optimized for imaging or spectroscopy

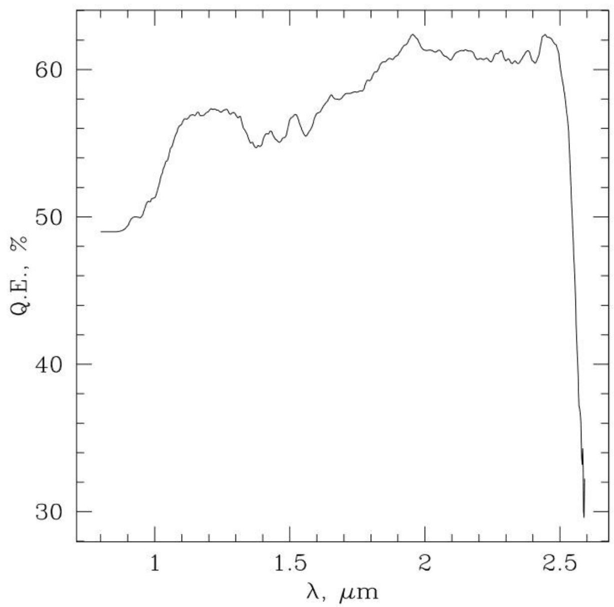


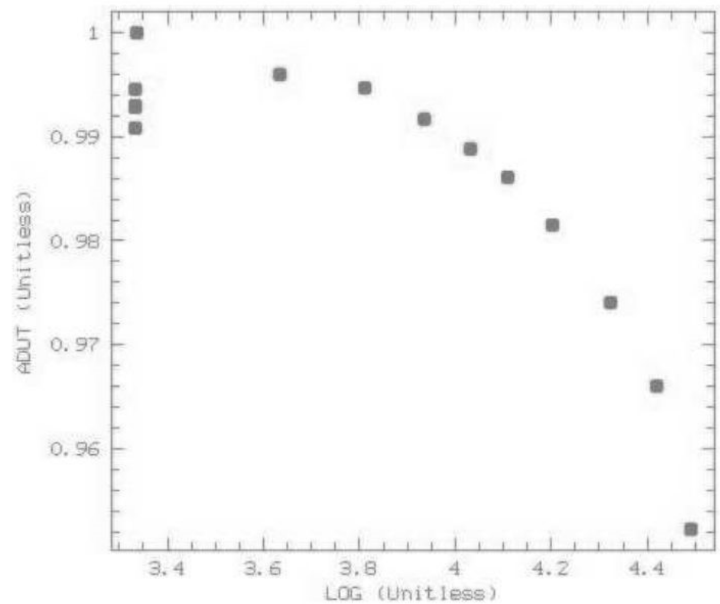
Detector

- Hawaii-1 Hg:Cd:Te 1024x1024 array
- ~65% quantum efficiency
- Good linearity characteristics up to ~20,000 ADU
- Well Depth ~32,000 ADU
- Low dark current (20 e-/hour, <4 ADU/hour)
- Low readout noise (12 electrons, <3 ADU)
- Good cosmetic quality (very few bad pixels)
- Minimum integration time 1.182 s

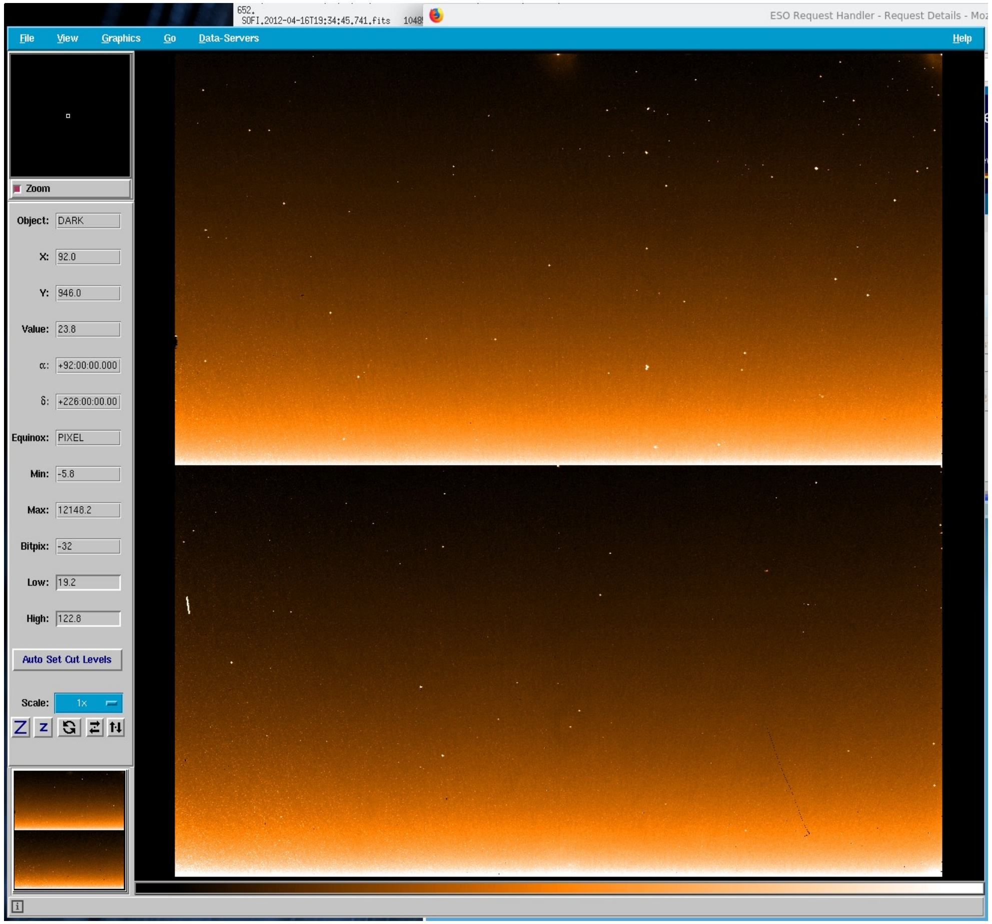


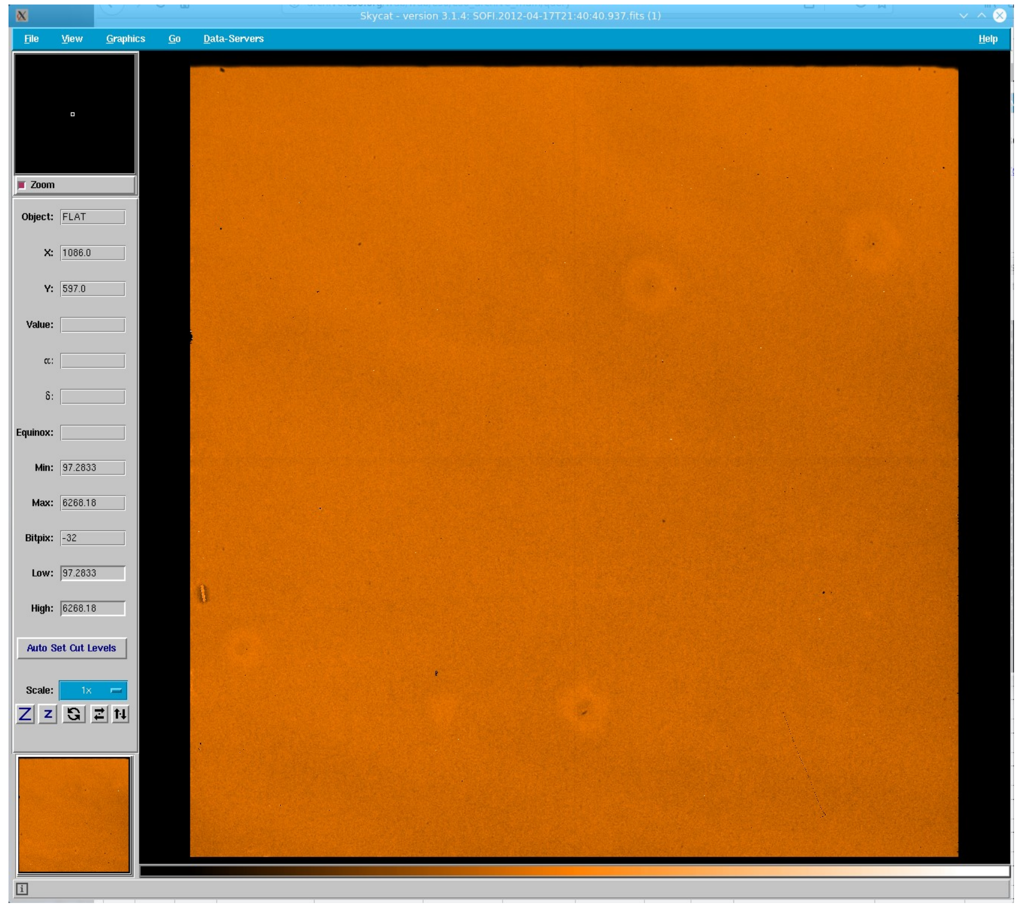




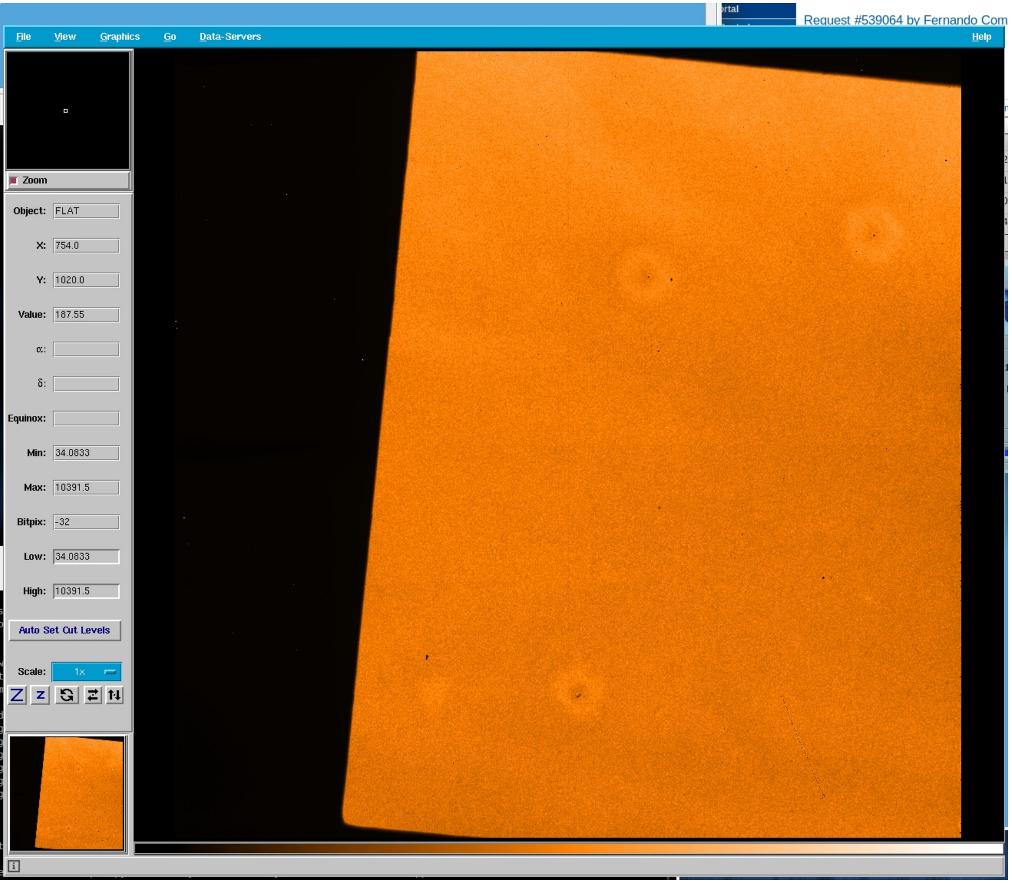


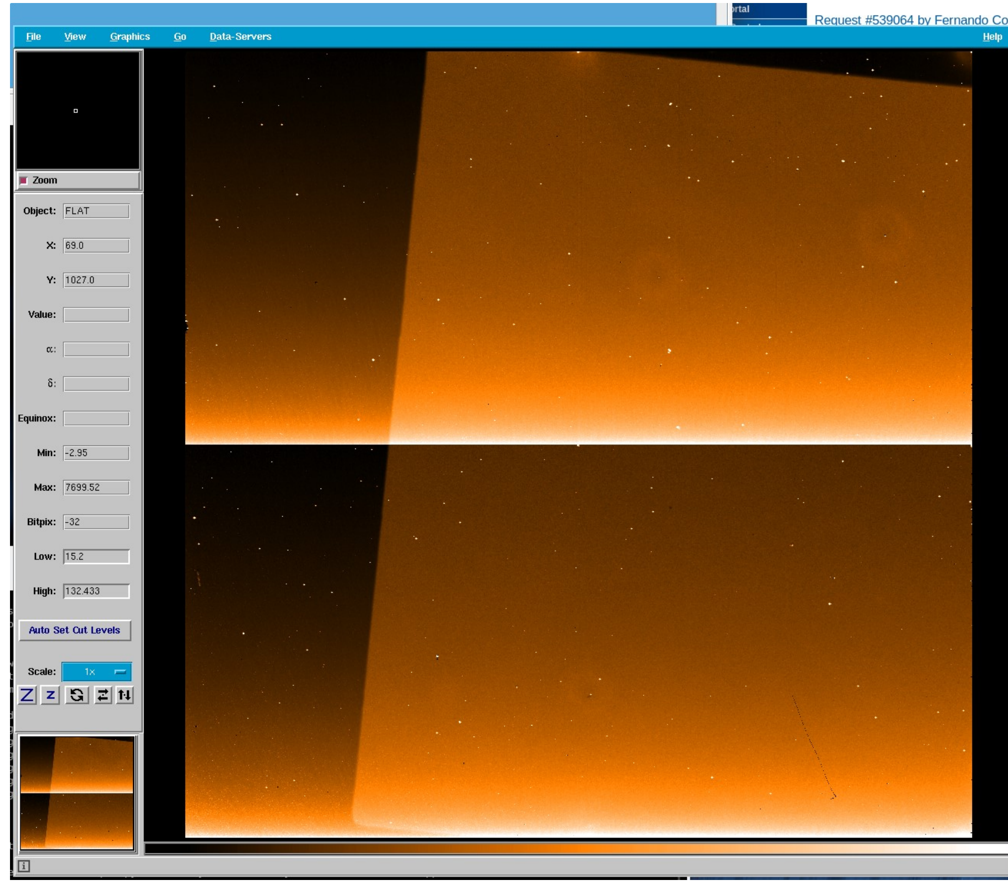
Dark and flat field





Some subtleties…

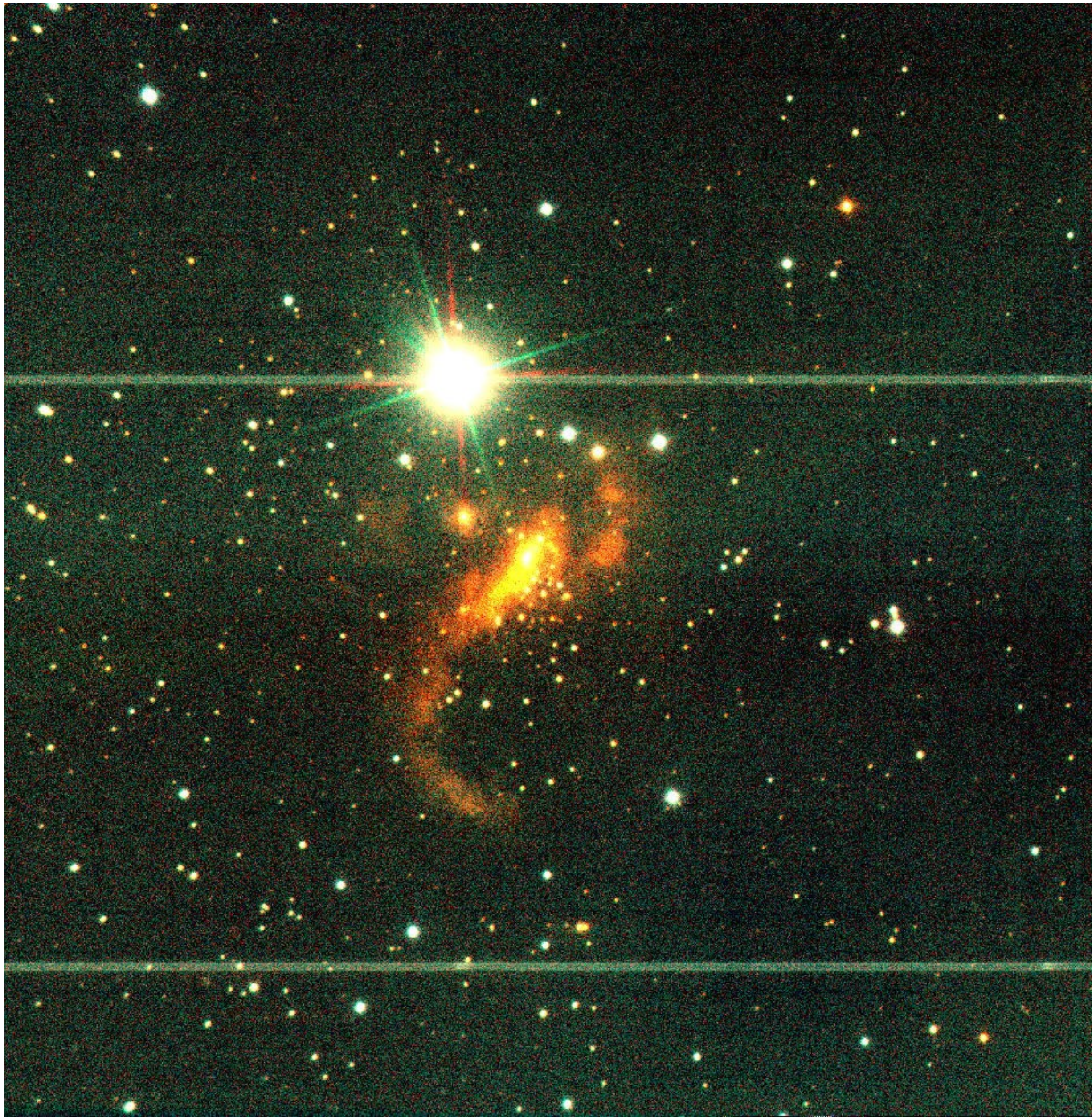




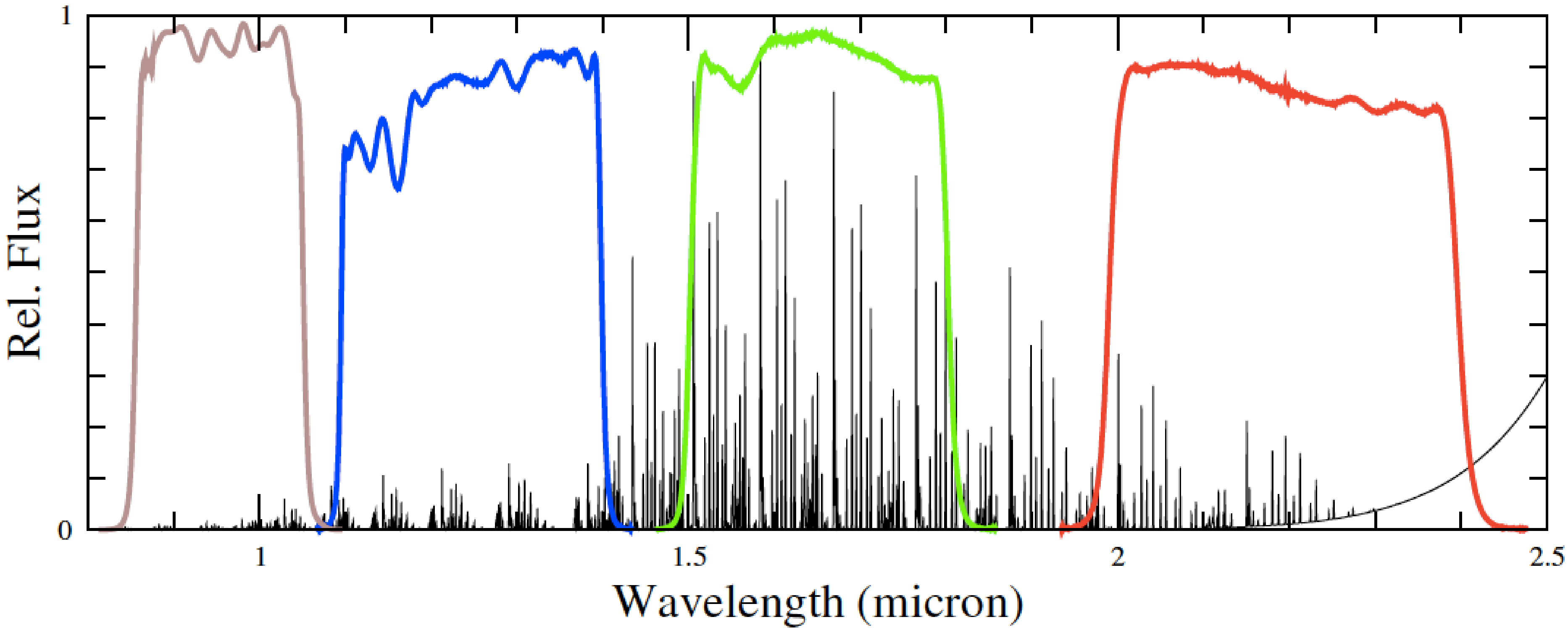
- Zero level depends (weakly) on the exposure level: special, partly masked flats make the problem (mostly) go away

Some subtleties…

- Electronic ghosts in rows of saturated targets
- Interquadrant row cross-talk



Background



Sky background and variability is a major factor in infrared observations

- Short exposures to avoid saturation (by the sky!) and sky variations
- Limiting factor in high-accuracy photometry in the infrared
- Observing with SOFI requires specific techniques to allow sky removal

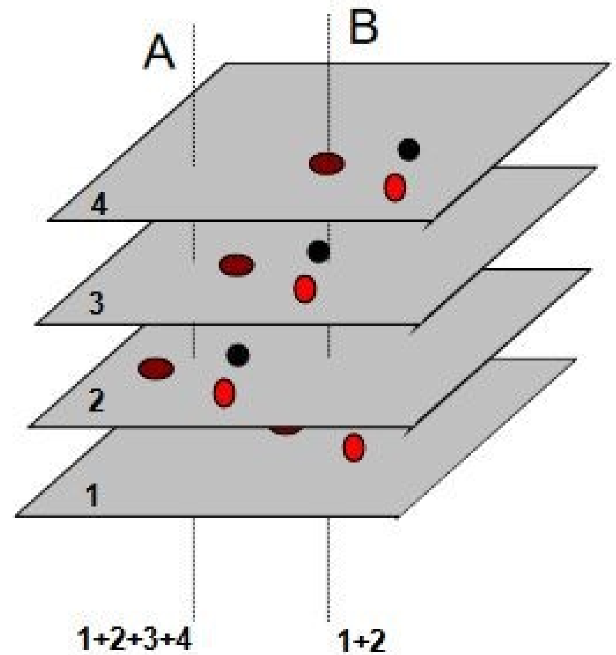
Exposure parameters

Two fundamental parameters common to (almost) all infrared instruments:

- DIT: Detector integration Time, duration of one single exposure
- NDIT: Number of individual integrations to be stacked at the detector

All near-infrared observations are obtained with *dithering* or *jittering* of the telescope around the position of the object

- Make a small offset of the telescope often enough so that sky variability is (almost) negligible
  - Subtraction of consecutive frames leads to (near) cancellation of the sky (positive and negative images)
- NEXPO (or NOBS, or NJIT…): number of dithered positions on the sky

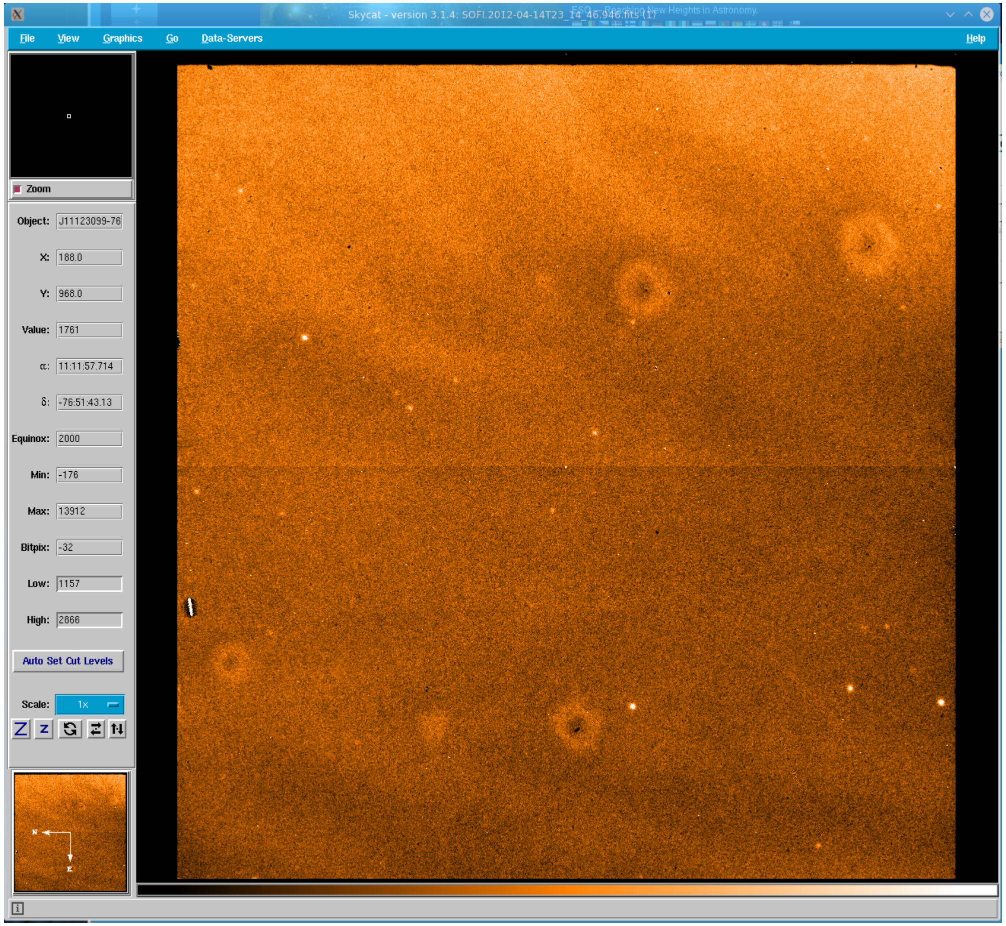


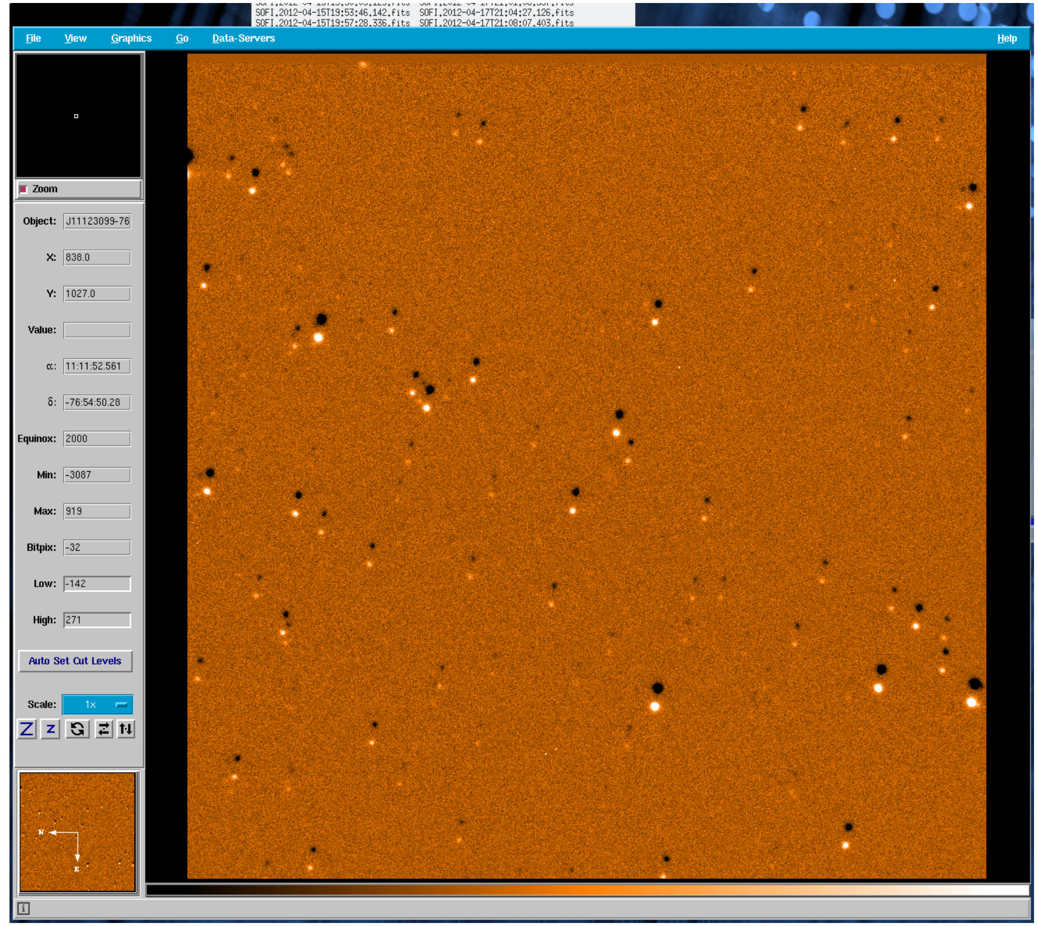
How to choose exposure parameters?

Choosing the best combination of DIT/NDIT/number of jitter points is a trade-off of several factors. Exposure time is ultimately decided by the S/N needed on the target, but…

- DIT long enough to be sky-limited (as opposed to readout noise-limited)
- DIT short enough to avoid saturation (sky+object)
- DIT x NDIT short enough to keep sky variability small (no more tan ~5 min)
- Each readout comes with an overhead in time (and some readout noise)
- Each telescope offset comes with an even bigger overhead in time
  - For a given total exposure time (DIT x NDIT x number of jitter points), the higher the NDIT and number of jitter points the higher the overhead
- In very crowded fields, sky subtraction may be posible only

Sky subtraction

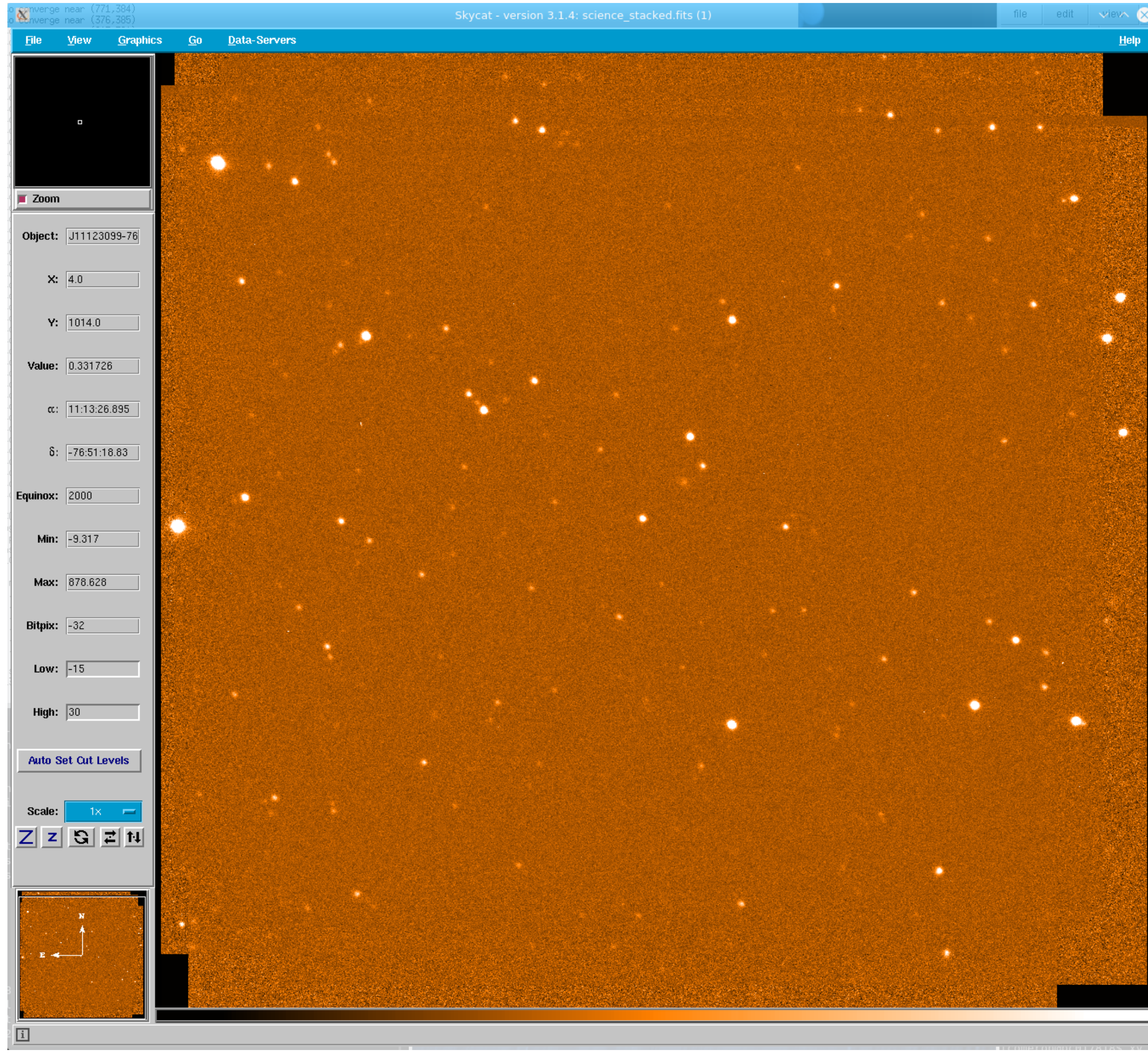




…Beware: sky-subtracted frames look good, but flat-fielding is still needed to correct for pixel-to-pixel response.

Stacking: final image

Final frame obtained by stacking the sky-subtracted, flat-flelded images after correcting for the telescope motions (shift-and-add).



Photometric calibration

Instrumental photometry must be transformed to a standard system (see Bessell 2005, Ann. Rev. A&A 43, 293)

- Some reference standards: e.g., Persson et al. (1998 AJ, 116, 2475; designed for NICMOS at HST)
- But almost every field contains stars from 2MASS (Skrutskie et al. 2006, AJ, 131, 1163; https://irsa.ipac.caltech.edu/Missions/2mass.html)
- SOFI broad-band filter set closely matches 2MASS filter set, but color corrections may be needed
  - When high accuracy photometry is needed
  - When broad range of reddenings is present in the field

$$J = j + C_j + 0.0693(J - H) - 0.0177(J - H)^2$$

$$H = h + C_h + 0.0086(H - K_s) - 0.0313(H - K_s)^2$$

$$K_s = k_s + C_k + 0.0078(H - K_s) - 0.0076(H - K_s)^2$$

Example transformation equations (for a different instrument; numerical values of the coefficients not aplicable to SOFI!)

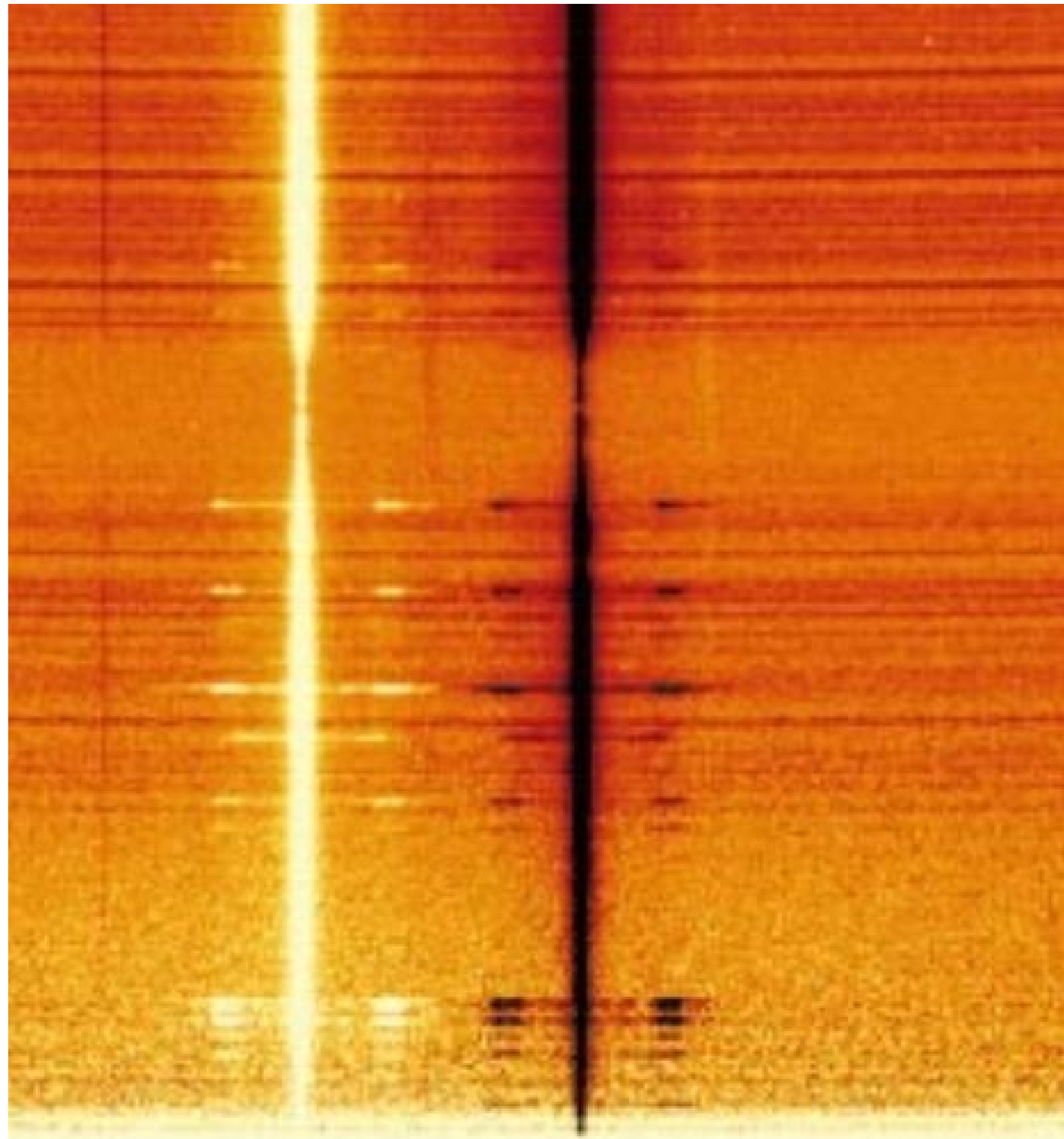
Astrophysics of narrow-band filters

SOFI has a wide range of narrow-band filters available, suitable for specific studies:

- NB 1.083: HeI in the J-band; ionized nebulae, emission-line stars
- NB 1.257: [FeII] in the J-band: shock tracer, emission in diffuse regions, supernova remnants
- NB 1.282: Paschen-beta
- NB 1.644: [FeII] in the H-band: shock tracer, emission in diffuse regions
- NB 2.059: HeI in the K-band: ionized nebulae, emission-line stars
- NB 2.124: H_2, tracer of shocks in molecular gas, photodissociation regions
- NB 2.170: Brackett-gamma
- NB 2.248: H2, tracer of shocks in molecular gas, photodissociation regions
- NB 2.336: CO, cool stars, circumstellar envelopes
- Plus some designed for continuum sampling and for isolating low-background regions (no OH lines)

Spectroscopy

Similarly for spectroscopy: apertures are extracted from pairwise-subtracted spectra (effect of sky variability more visible because of regions with/without lines, varying termal background)

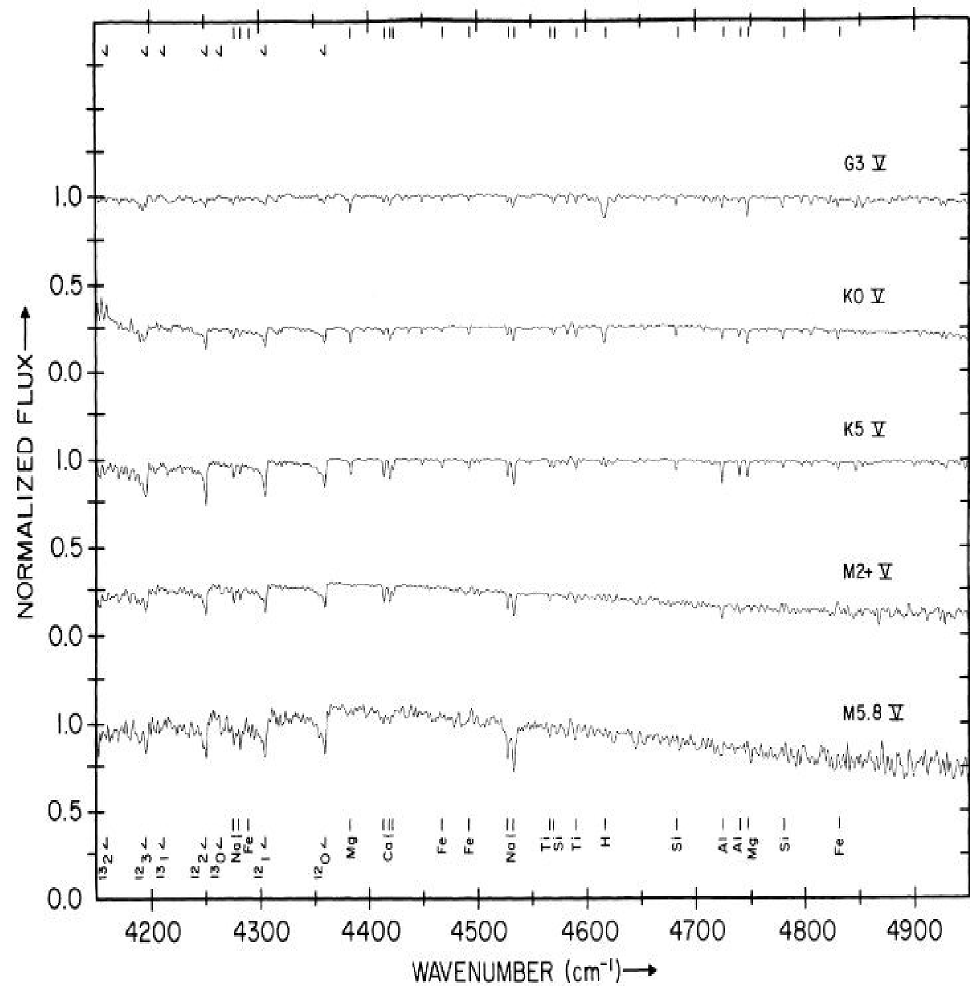


Calibrating spectroscopic observations

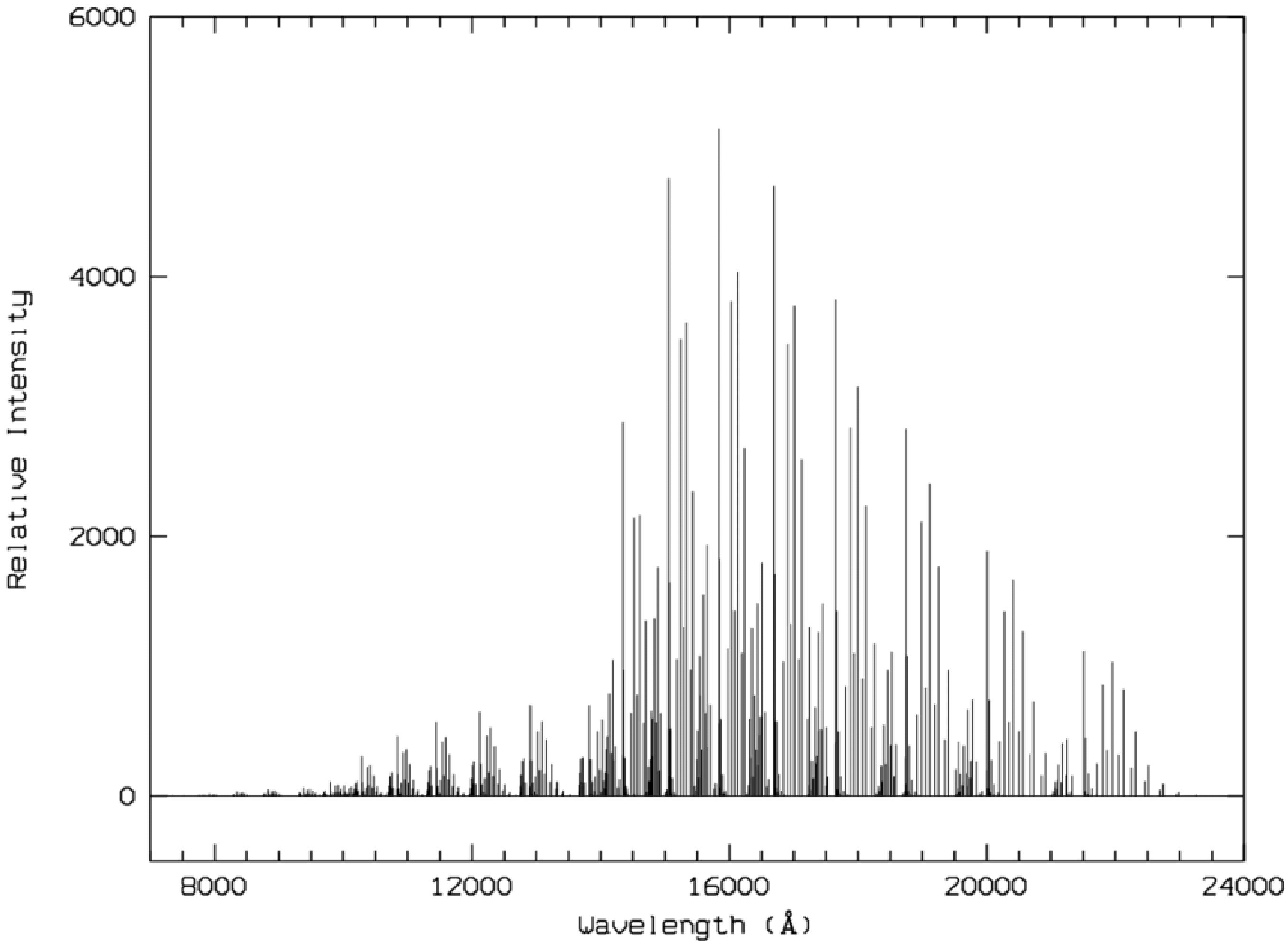
- Telluric calibration stars (not "telluric standards"!!)
  - Low resolution: Early-type stars generally OK (unless you are calibrating… early-type stars!): few features in the near-infrared.
  - Solar analogs (G0V-G5V) a good solution:
    - Divide target star by analog
    - Multiply result by library spectrum of the Sun

    Only telluric features removed in this way

Important rule: always observe telluric calibration close in time and airmass!



Calibrating spectroscopic observations



- Usual procedure in visible and infrared: arc lamps (emission-line calibration source in the instrument)
- In the infrared, OH lines are most often used for wavelength calibration

Some great resources to plan your observations:

- SOFI webpages: https://www.eso.org/sci/facilities/lasilla/instruments/sofi.html
- SOFI User Manual: https://www.eso.org/sci/facilities/lasilla/instruments/sofi/doc/manual.html
- SOFI Exposure Time Calculator: http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=SOFI+INS.MODE=swimaging, http://www.eso.org/observing/etc/bin/gen/form?INS.NAME=SOFI+INS.MODE=swspectr
- ESO Science Archive: http://archive.eso.org