Direct Detection Instruments for SOFIA: FIFI LS and Beyond

A. Poglitsch (MPE)

on behalf of
A. Krabbe (Univ. of Stuttgart) & the FIFI LS Team

Far Infrared Field Imaging Line Spectrometer (FIFI-LS): Key Characteristics

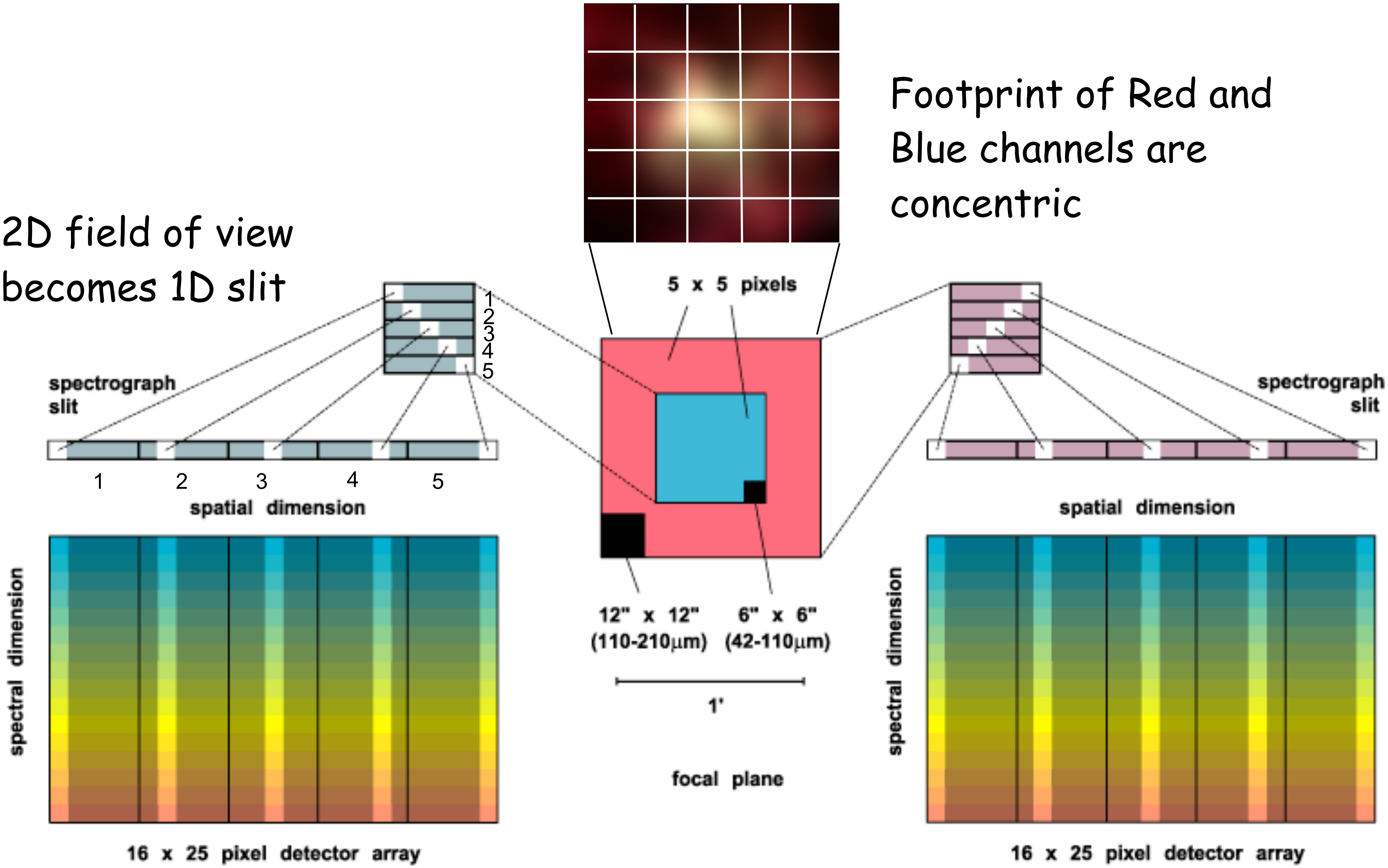
- Far-infrared grating spectrometer with two parallel channels:
  - Blue 42-105/130 μm (6" pixels)
  - Red 105/130-210 μm (12" pixels)

  (presently limited to >50μm by filters)
- Integral field concept: instantaneously imaging FIR line over 2-D field
  - for each channel, 5x5 spatial pixels ("spaxels"), each having 16 spectral pixels
- Moderate resolving power (for extragalactic science)
  - 1000-2000 depending on wavelength
- Sensitivity ~3…10×10^{-17} W/m^2 (4σ, 15min)

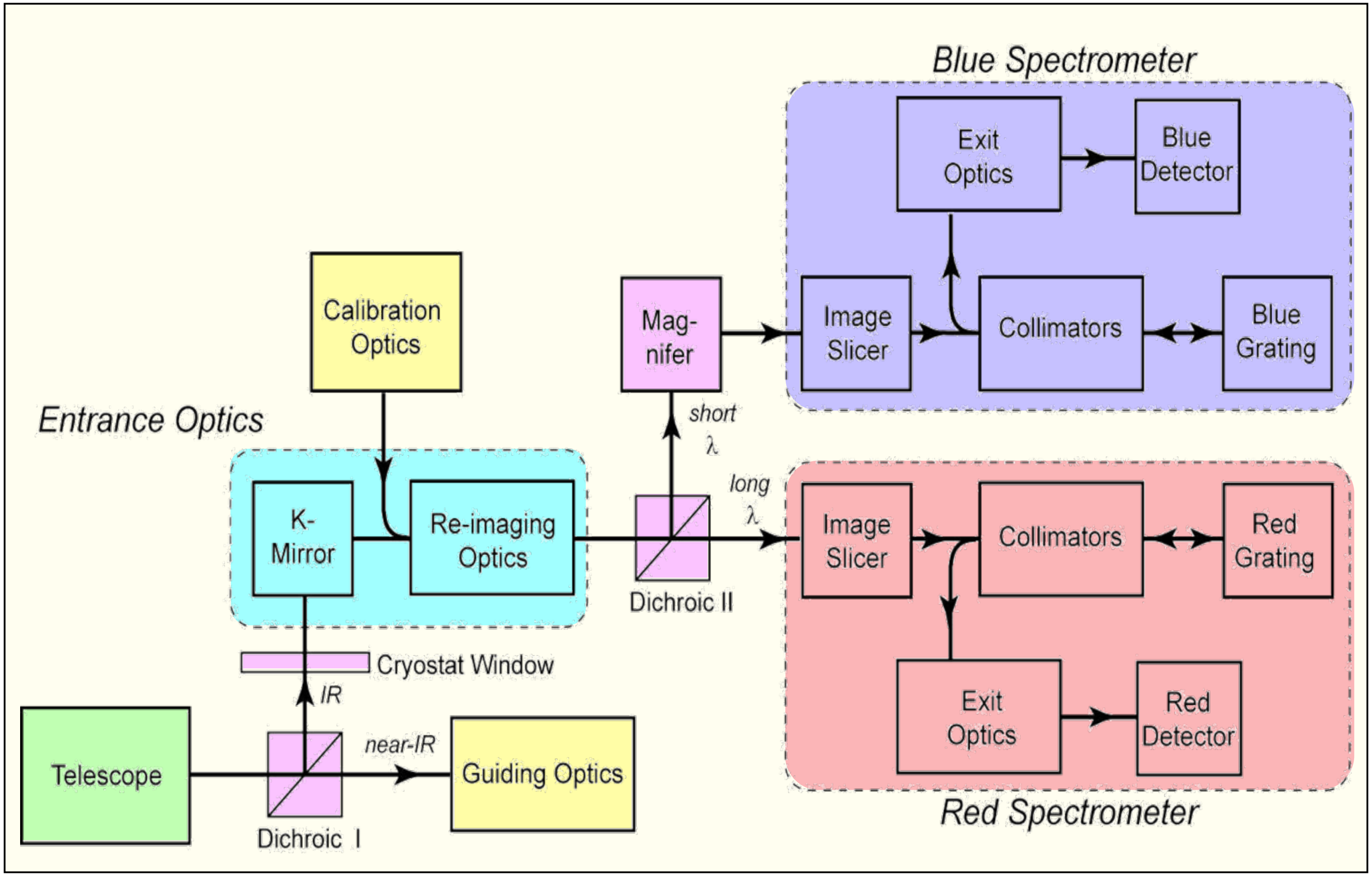
FIFI-LS: Focal Plane Footprint

Footprint of Red and Blue channels are concentric

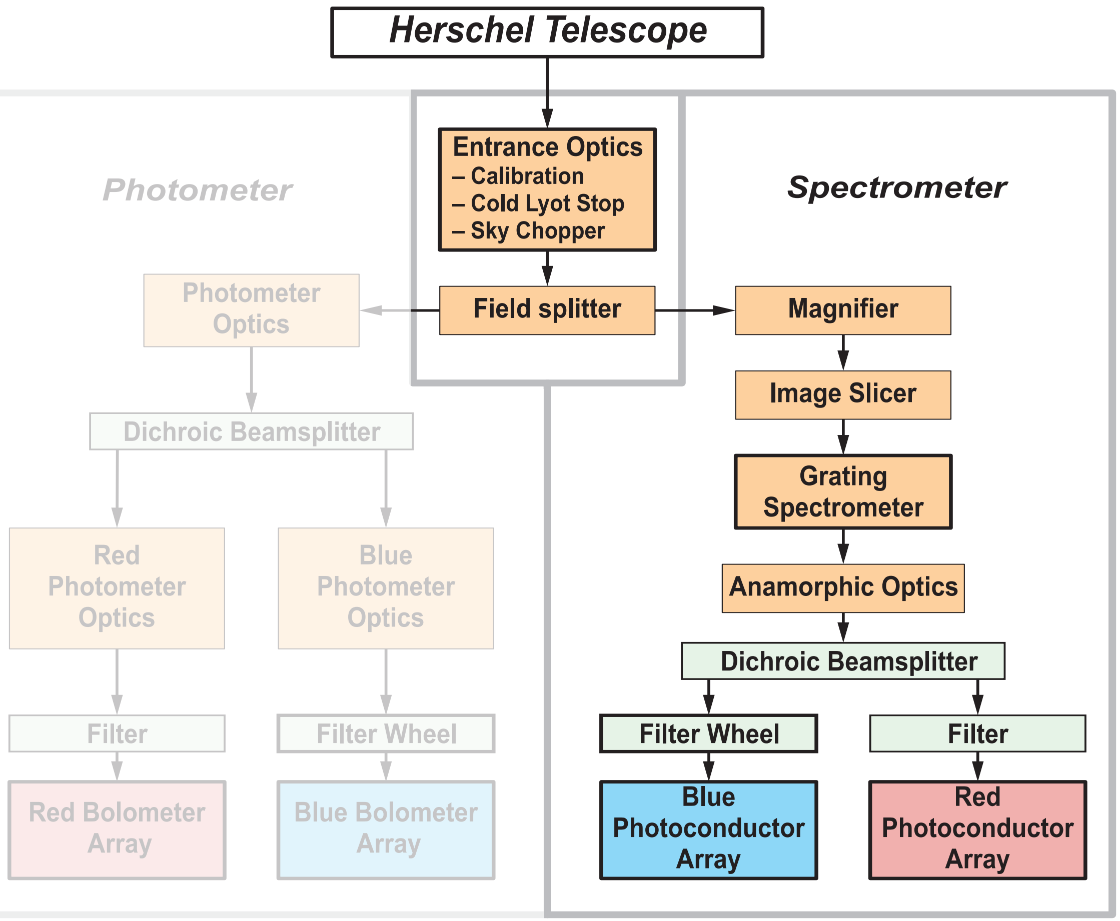
2D field of view becomes 1D slit

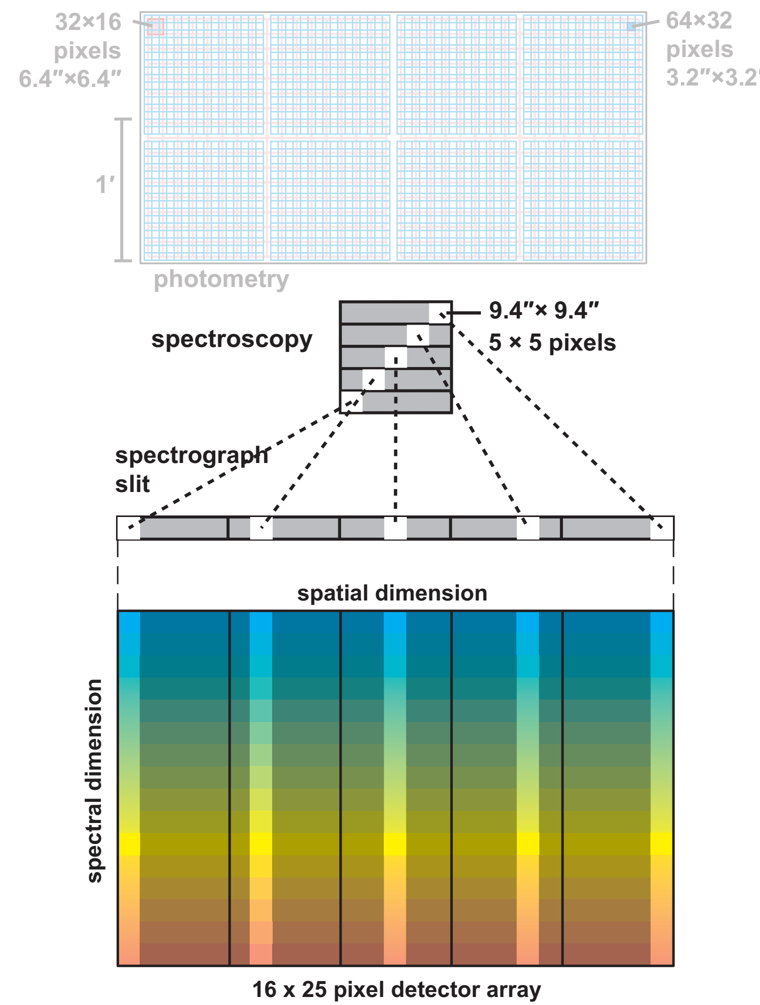


FIFI LS: Optics Train (Schematic)

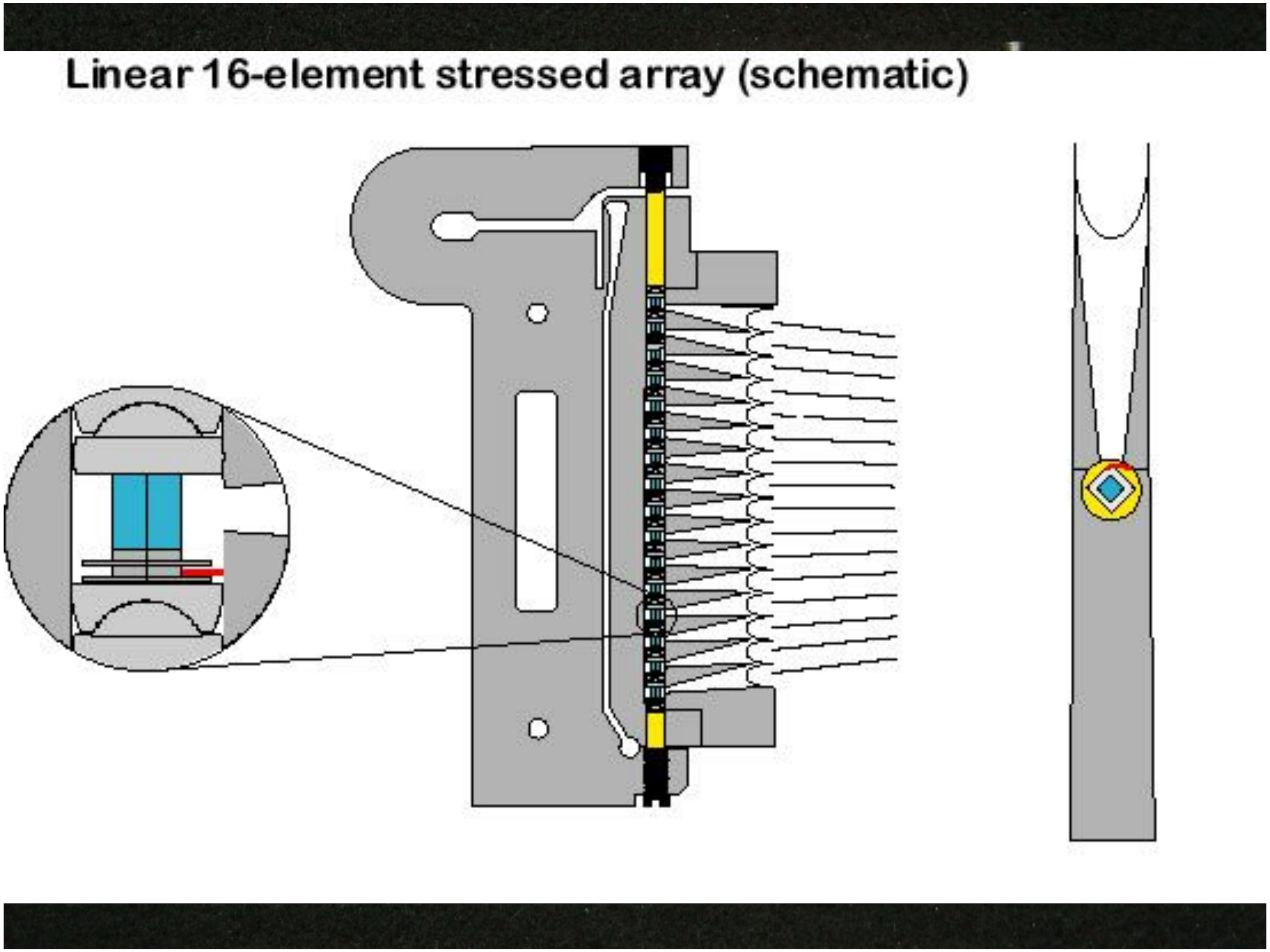


For Comparison: Herschel-PACS

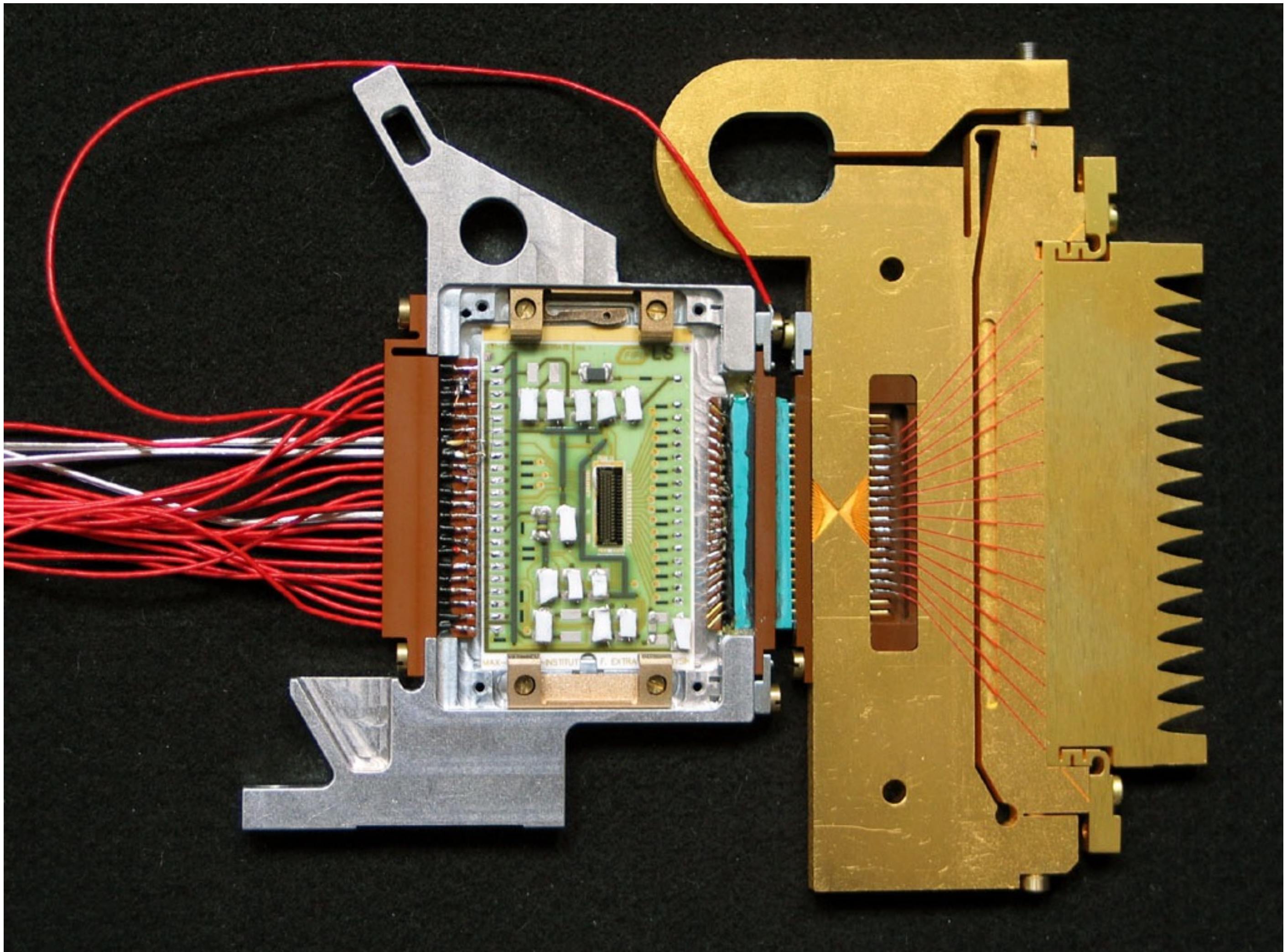




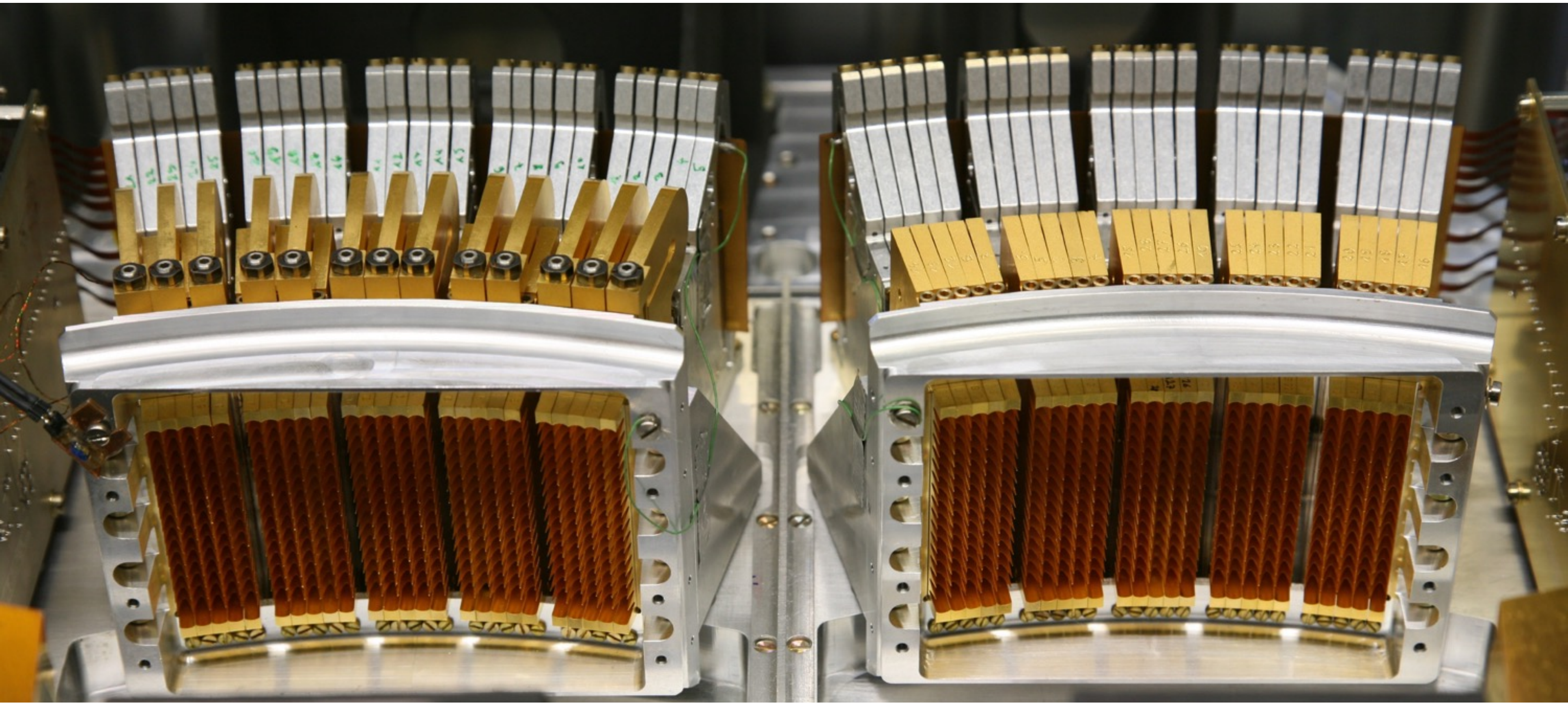
FIFI LS: Photoconductor Arrays



FIFI LS: Photoconductor Arrays

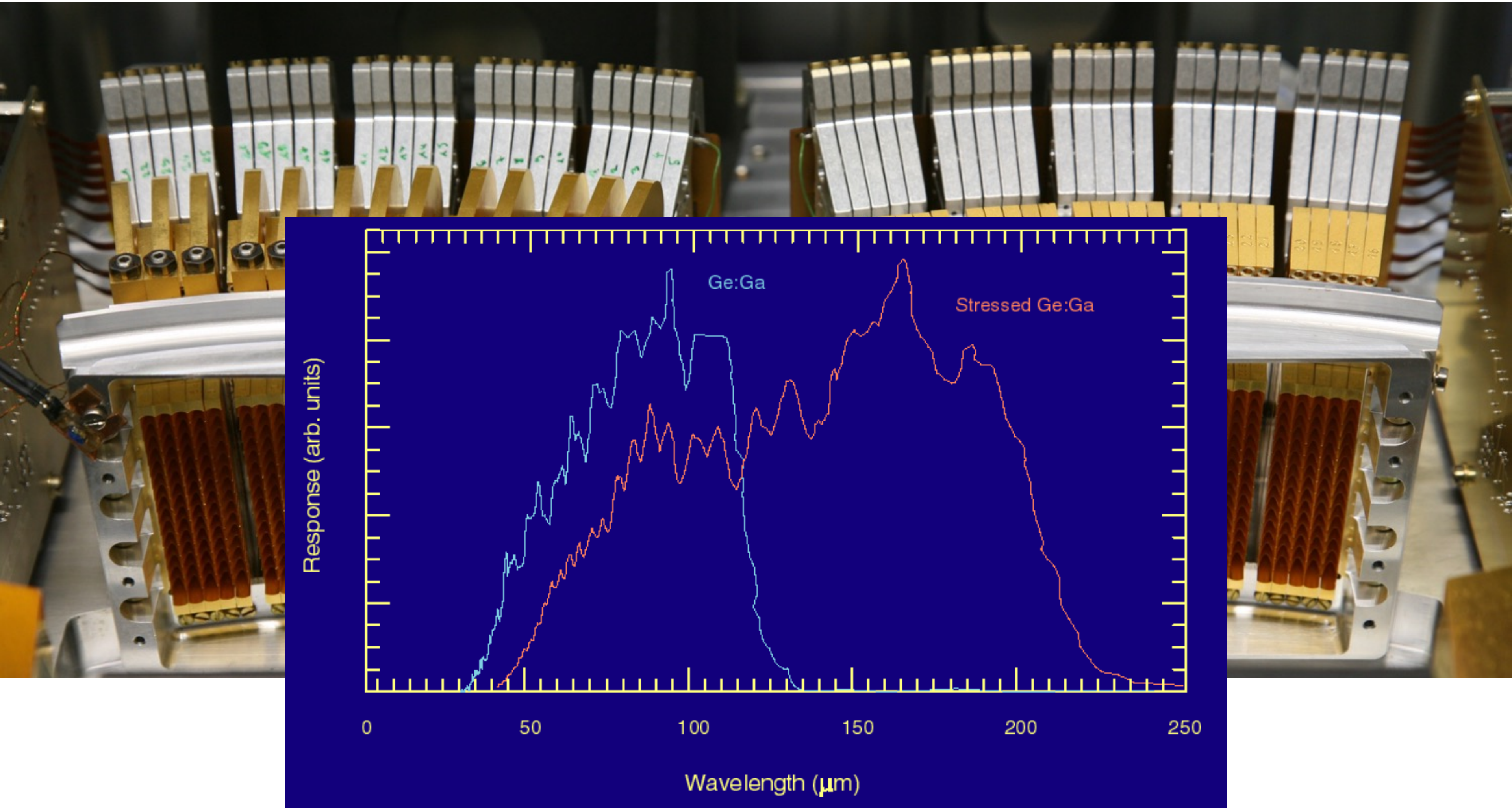


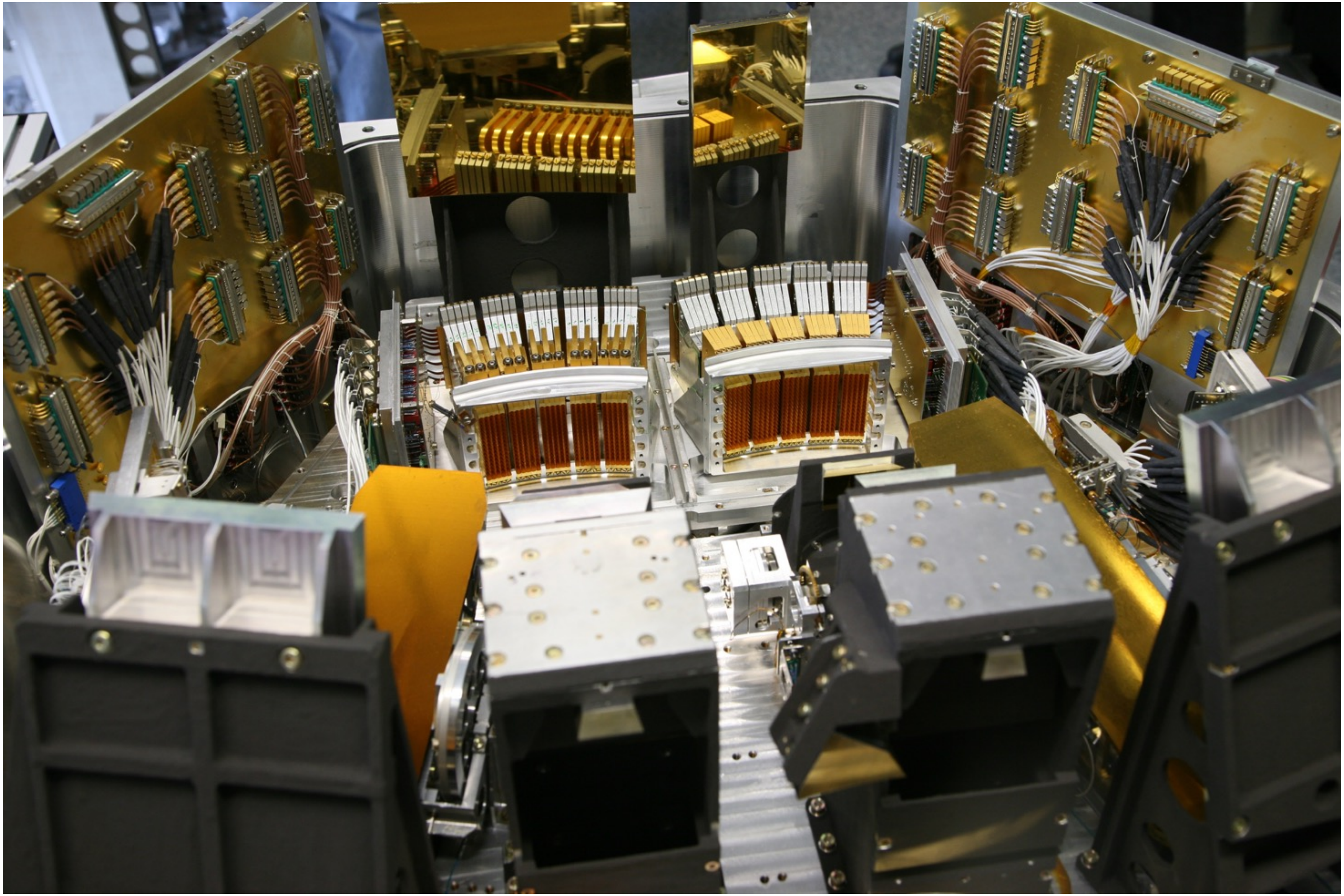
FIFI LS: Photoconductor Arrays

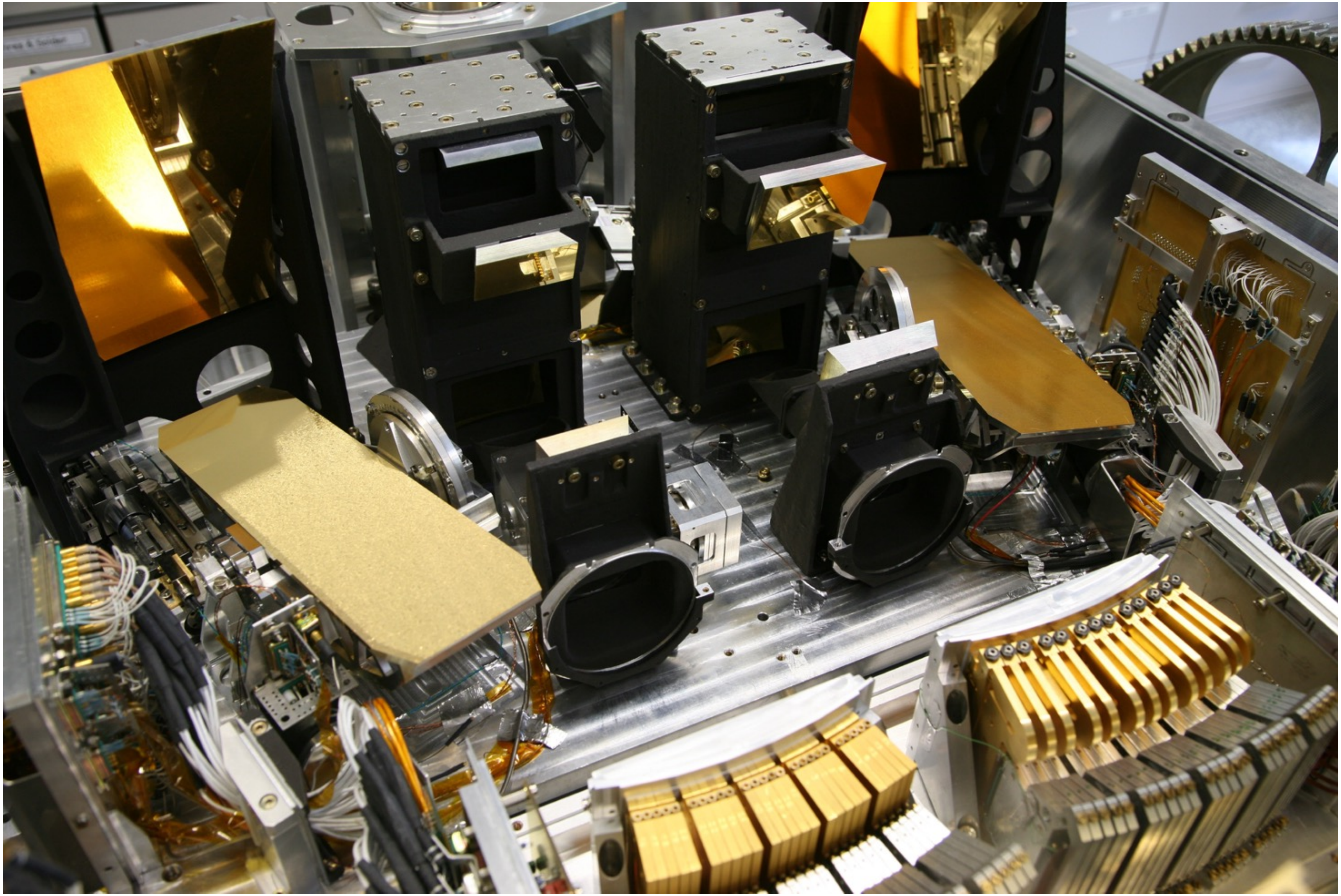


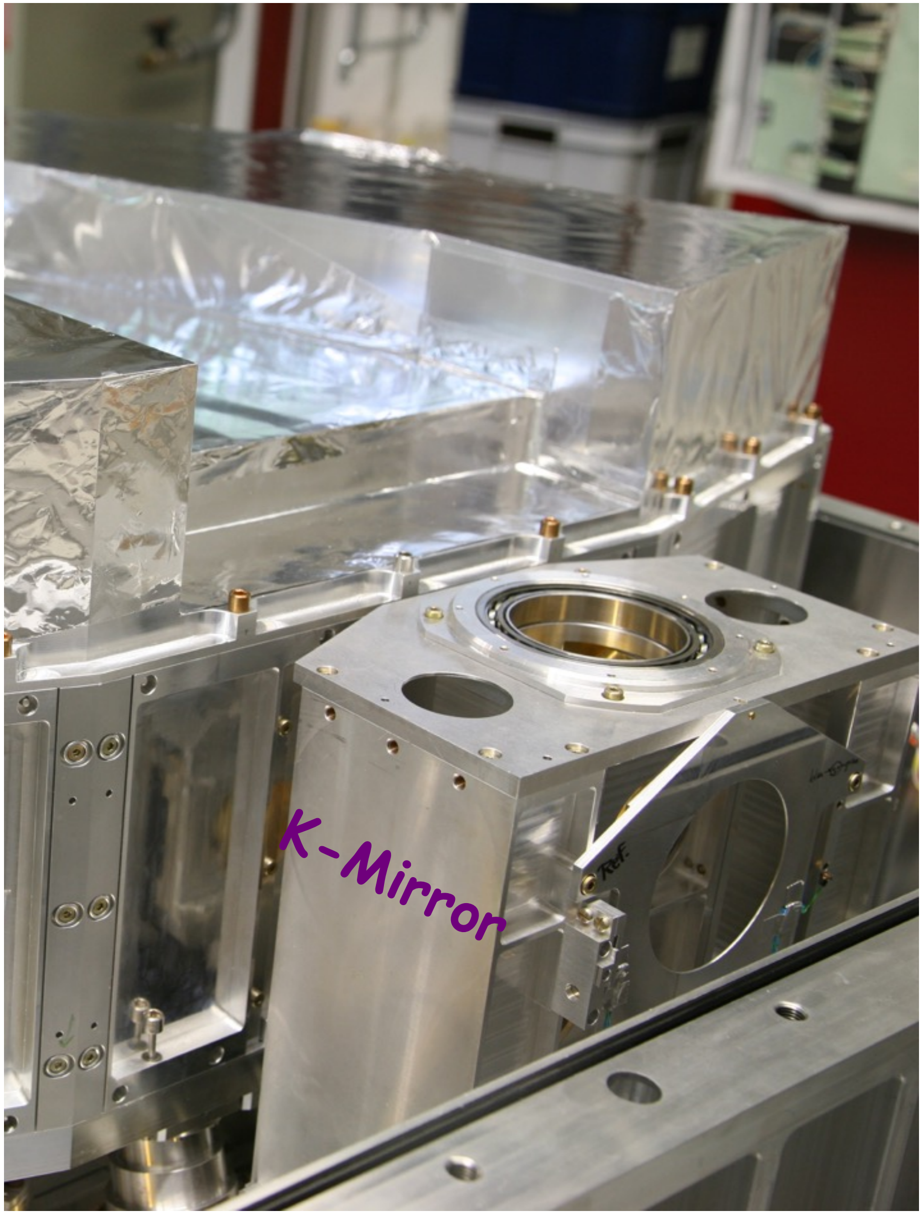
(stressed) (unstressed)

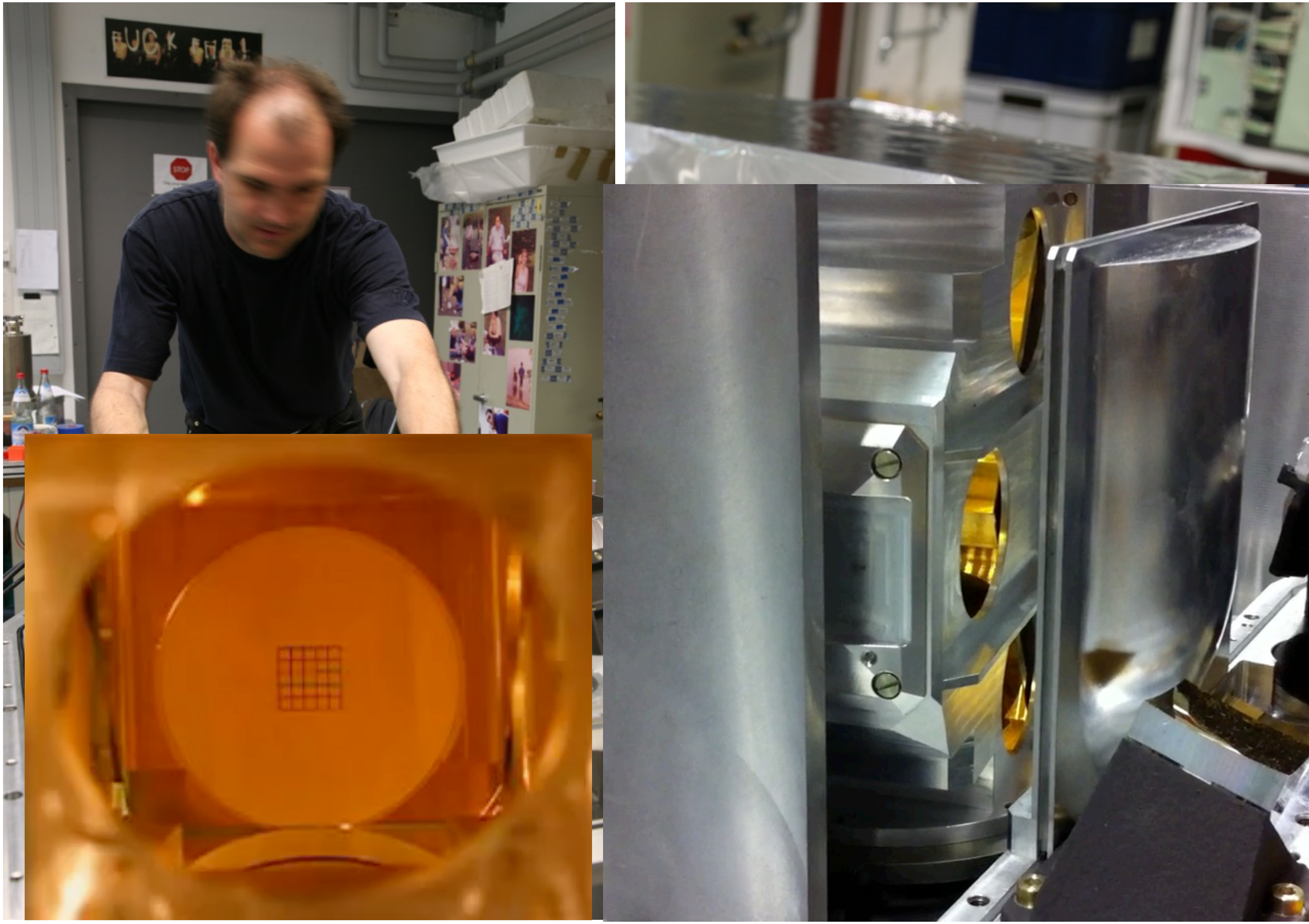
FIFI LS: Photoconductor Arrays



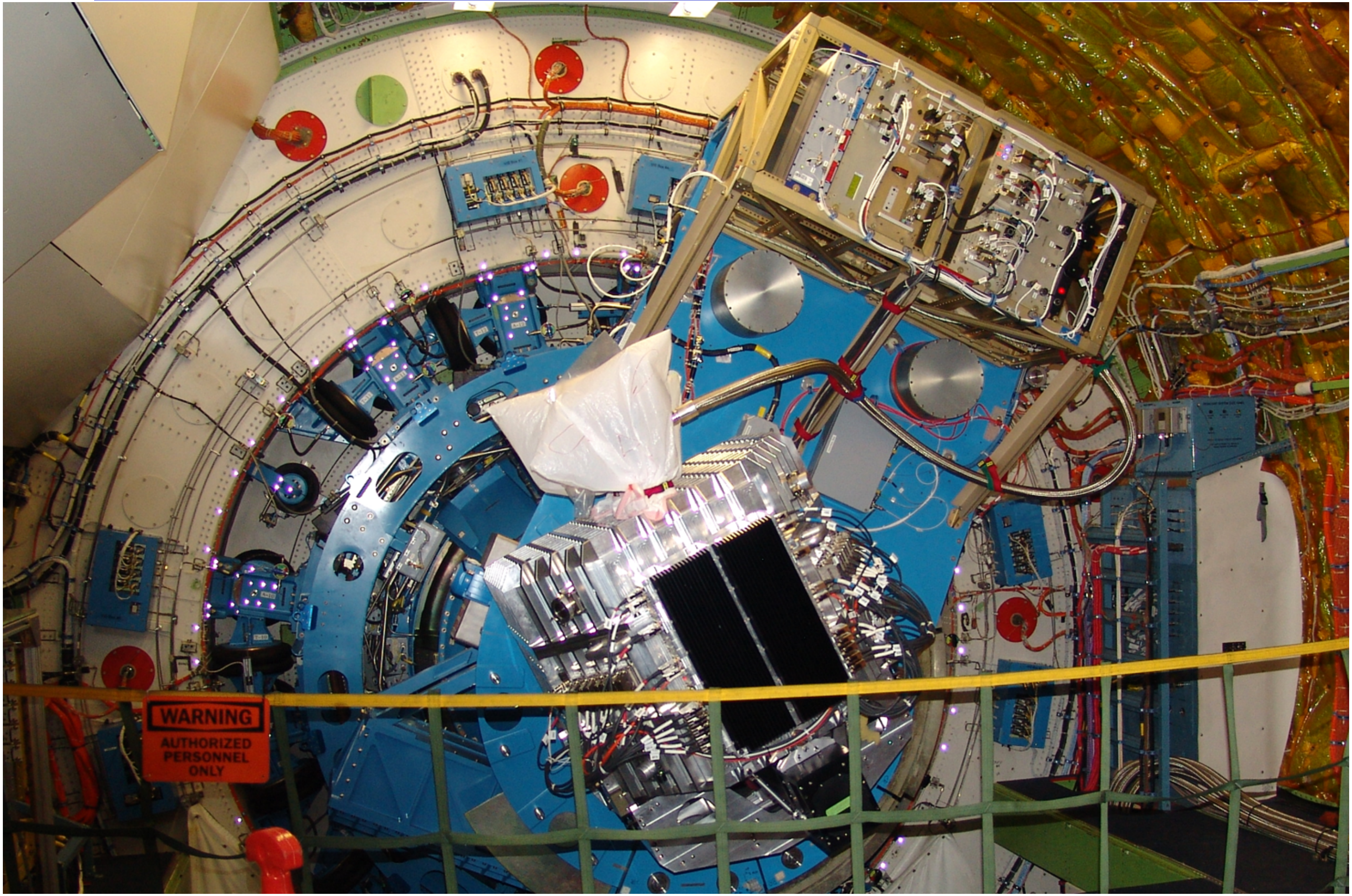


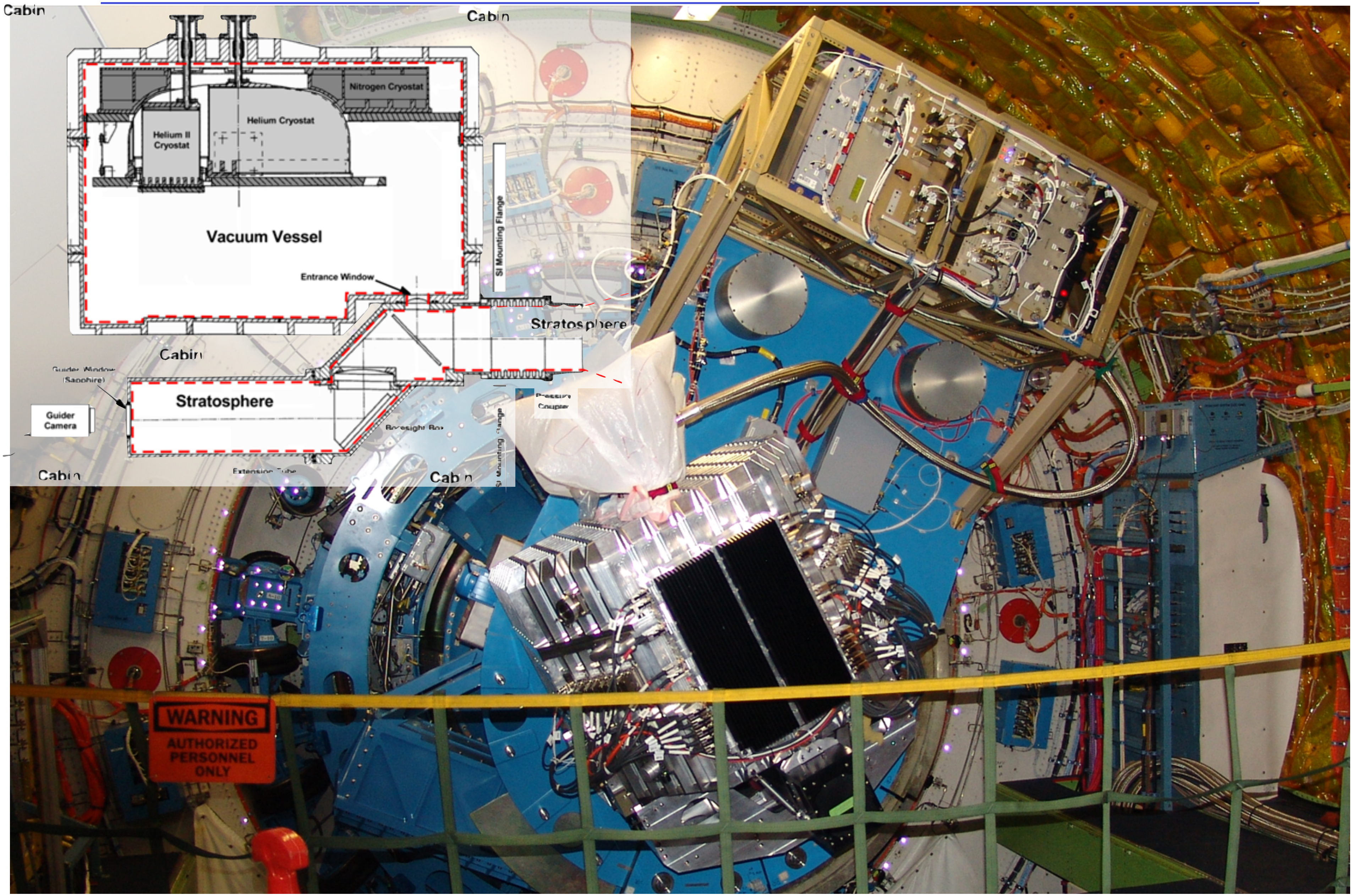



K-Mirror

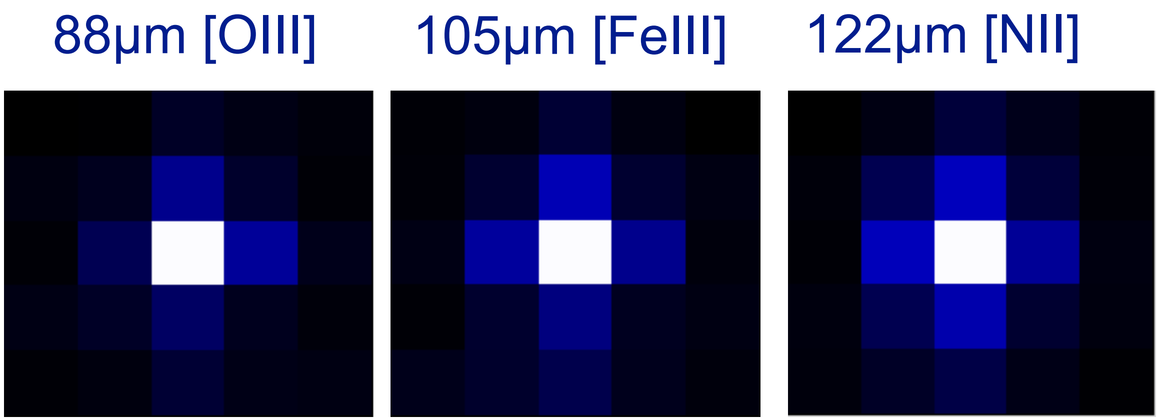


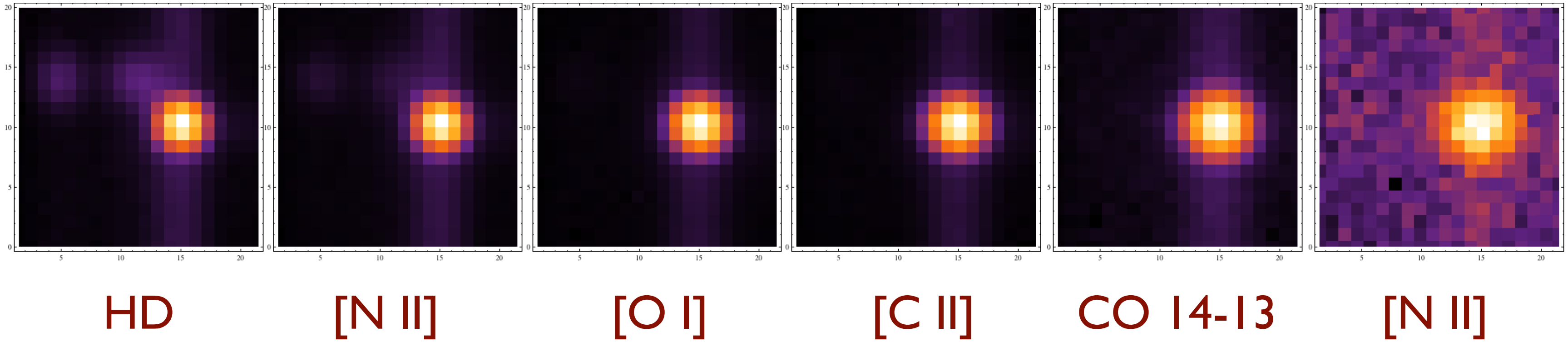
Direct Detection Instruments


WARNING
AUTHORIZED
PERSONNEL
ONLY

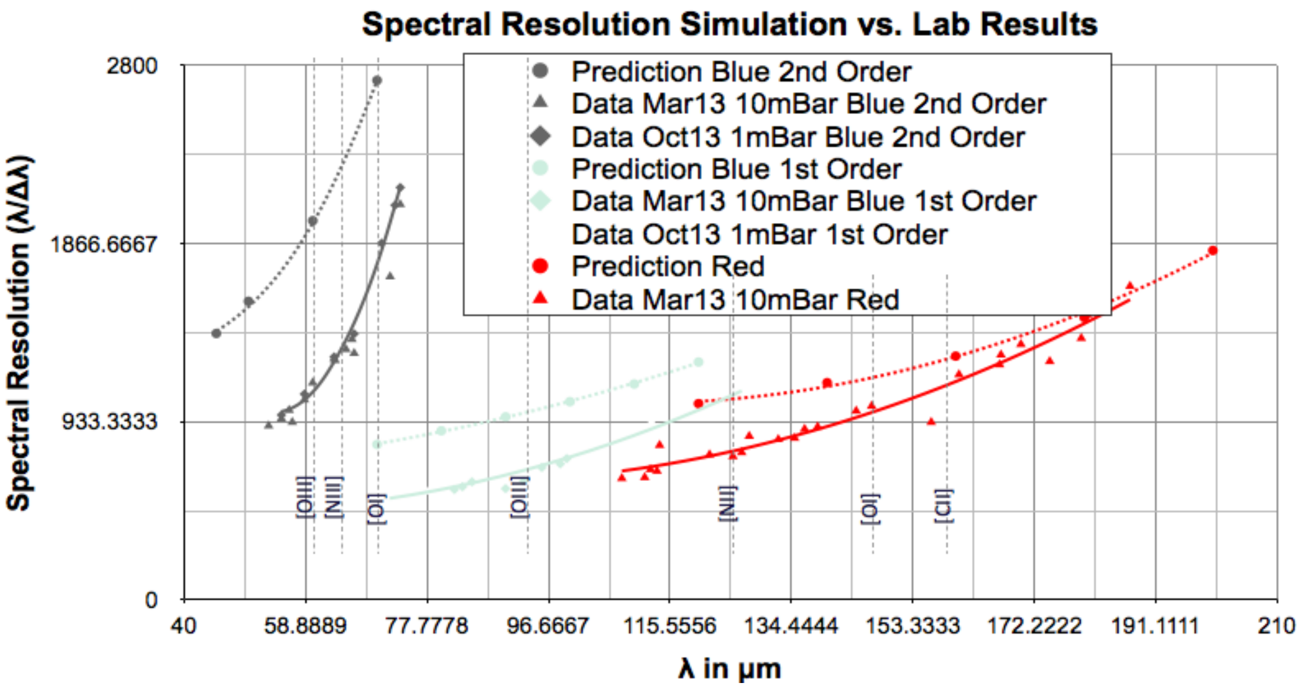

Cabin
Cabin
Nitrogen Cryostat
Helium Cryostat
Helium II Cryostat
Vacuum Vessel
Entrance Window
SI Mounting Flange
Stratosphere
Cabin
Stratosphere
Guider Camera
Cabin
Cabin
WARNING
AUTHORIZED PERSONNEL ONLY

FIFI LS: PSFs across the Wavelengths

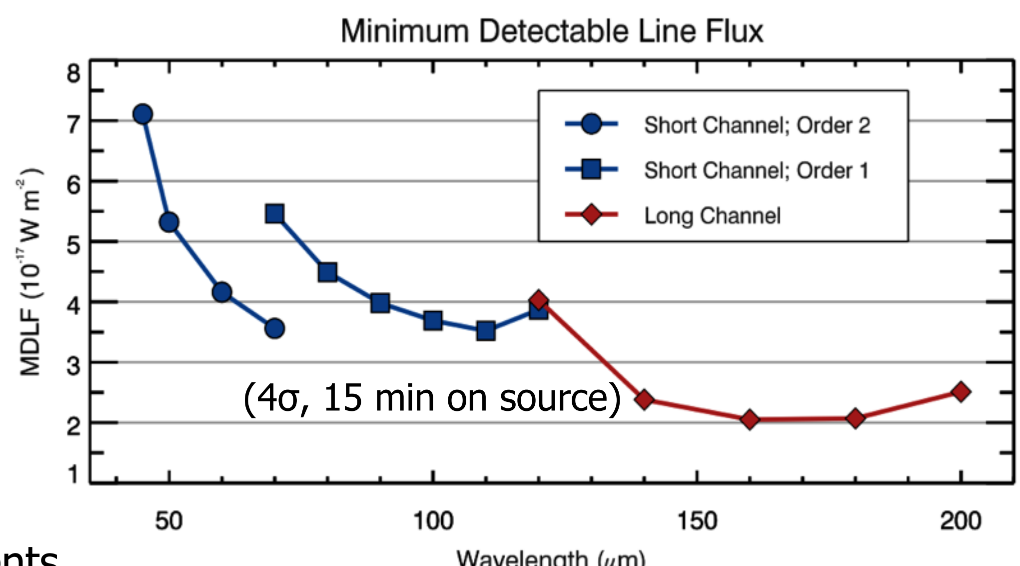




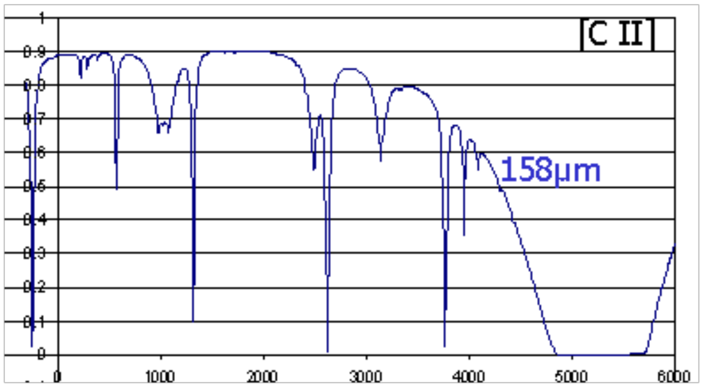
- PSFs fully understood in terms of diffraction and pixel sampling

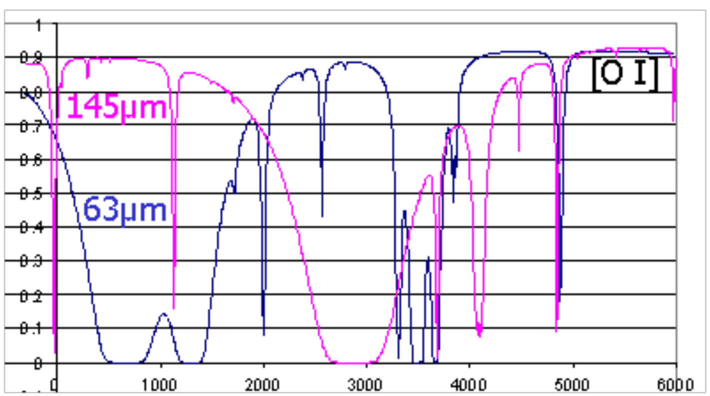


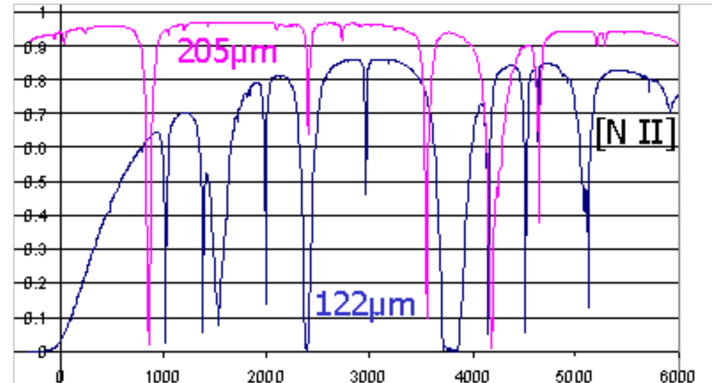
FIFI LS Performance: Modeling/Lab

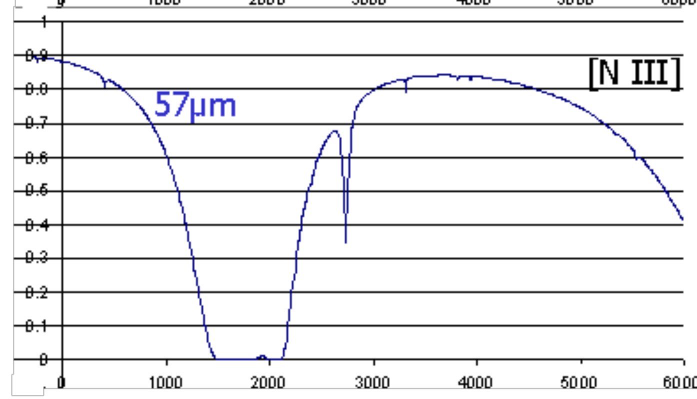


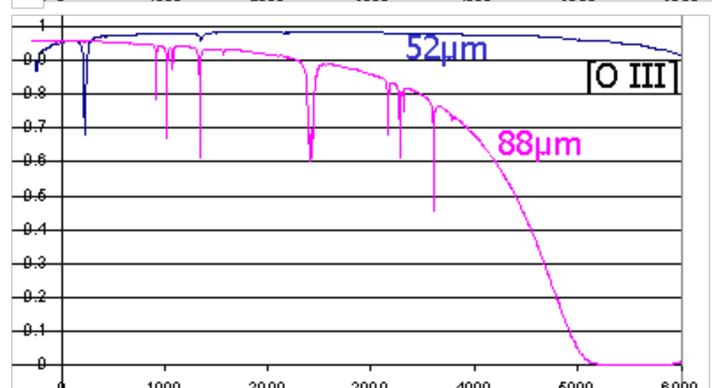
Atmospheric Constraints









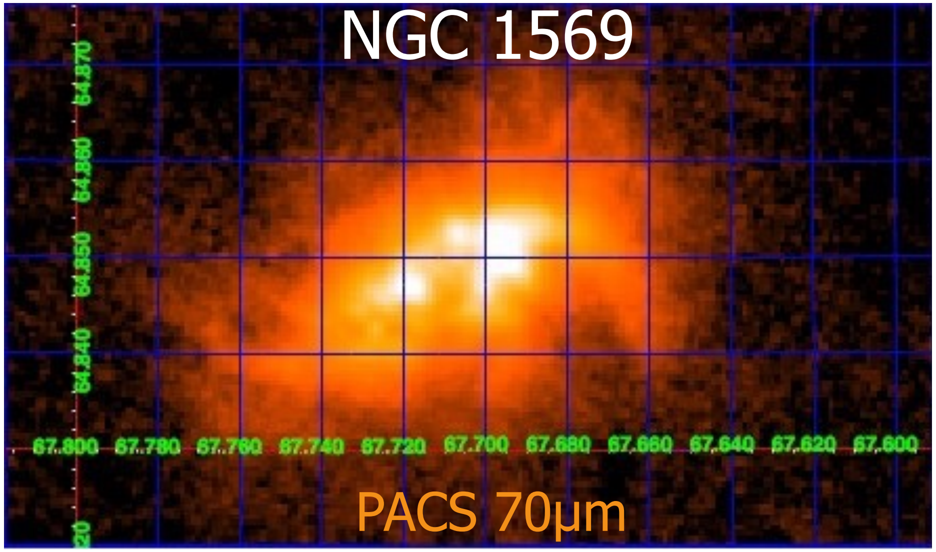


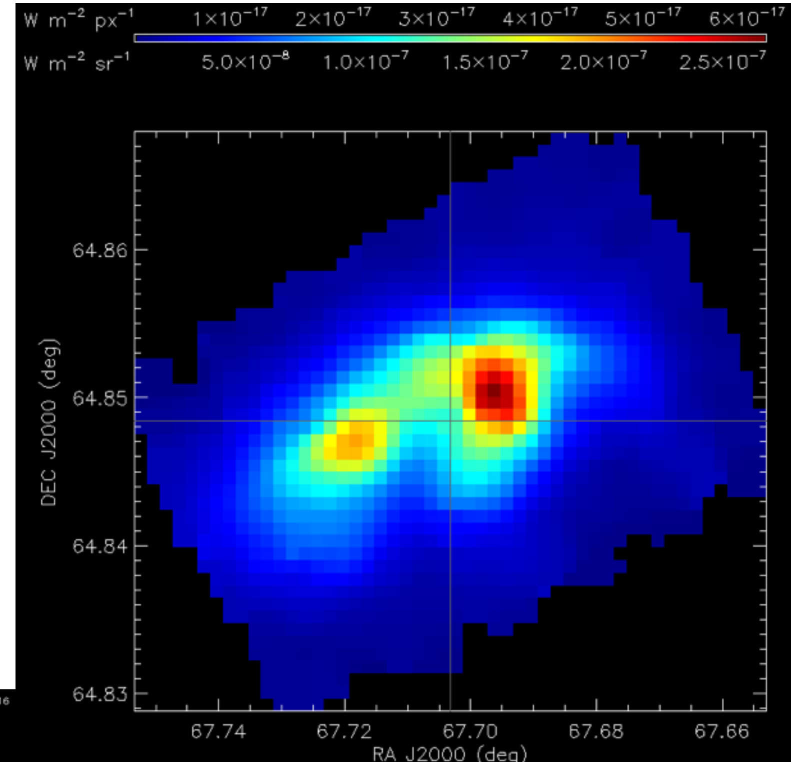
Standard Atmosphere
45deg Z.A. / FL 410

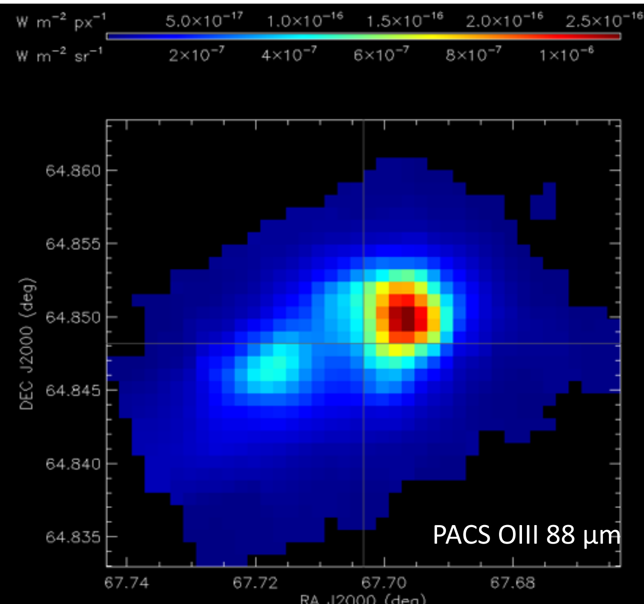
Unique Features of FIFI-LS in the Post-Herschel Era

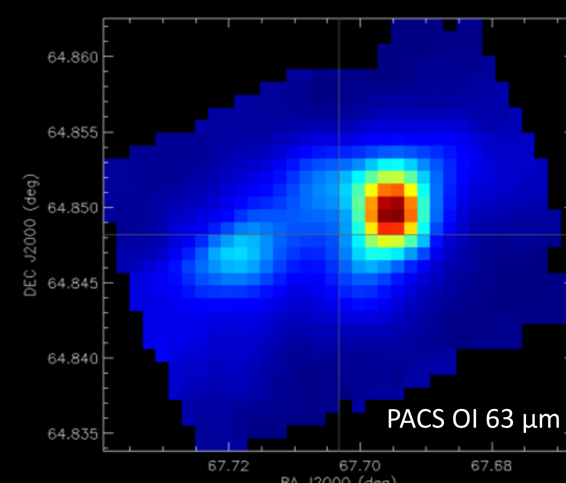
- FIFI-LS enables **reaction to major science discoveries** of Herschel, Planck and WISE, which are presently largely unknown, and none of these satellites is around for follow-up.
- FIFI-LS will be the **Galactic and extragalactic spectroscopic workhorse** with SOFIA. FIFI-LS has enough sensitivity to observe a substantial sample of nearby galaxies.
- FIFI-LS has the right combination of wavelength range and spatial resolution to **carry out unique new observations** beyond those possible with Herschel, Spitzer, ISO, and IRAS.
- On extended targets the **mapping efficiency** of FIFI-LS is much higher than with PACS, shifting the sensitivity ratio between PACS and FIFI-LS for such targets from 8 to 3-5.

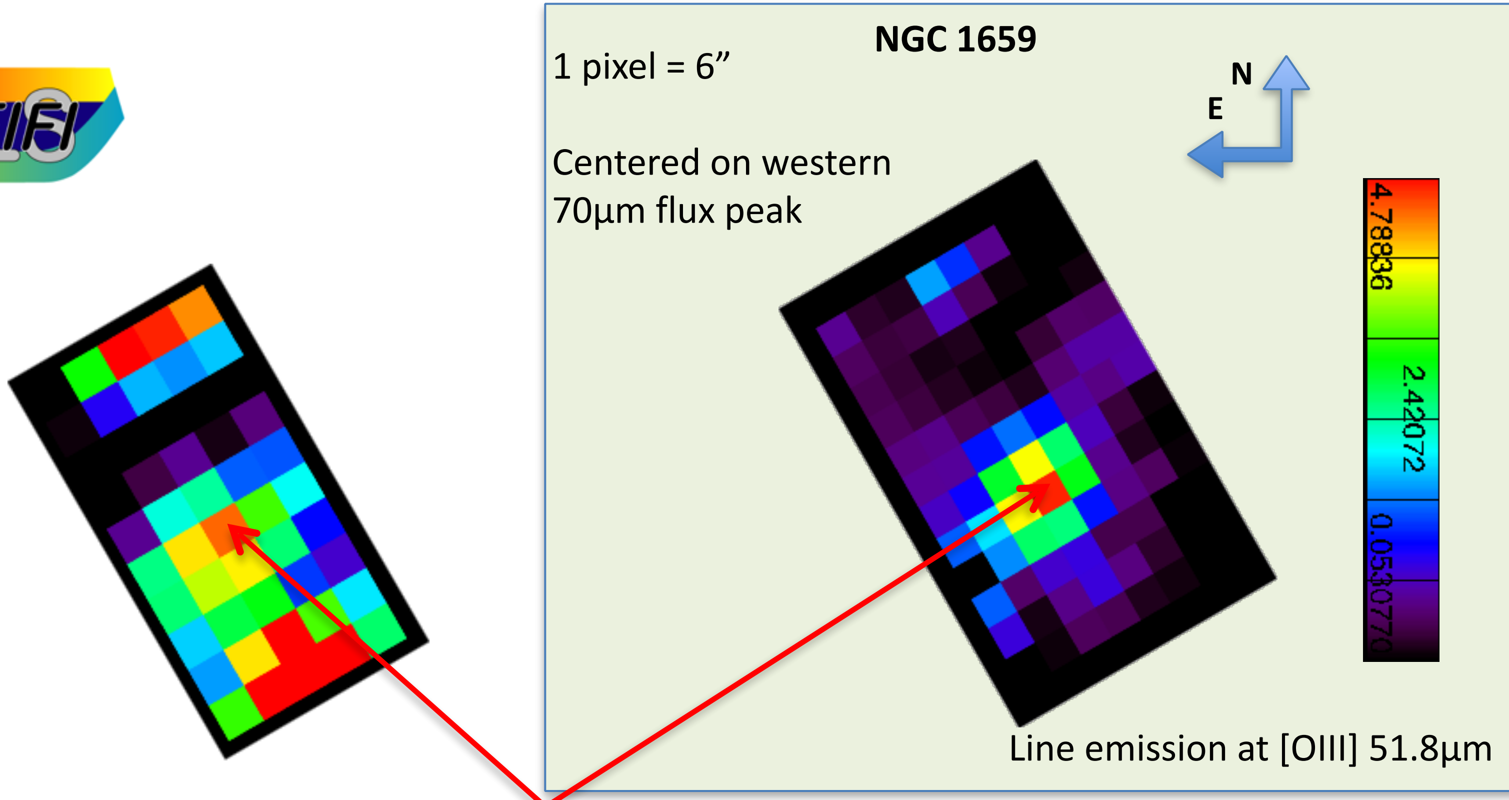
Extragalactic Science Teaser: NGC 1569







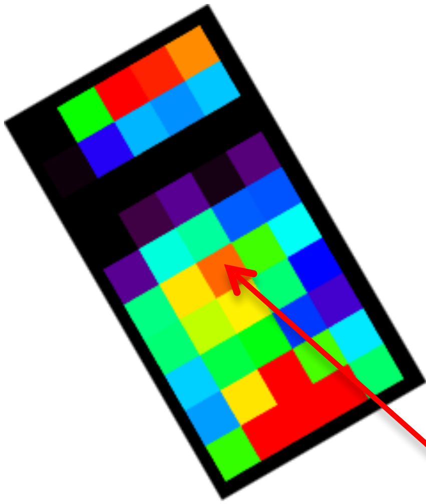


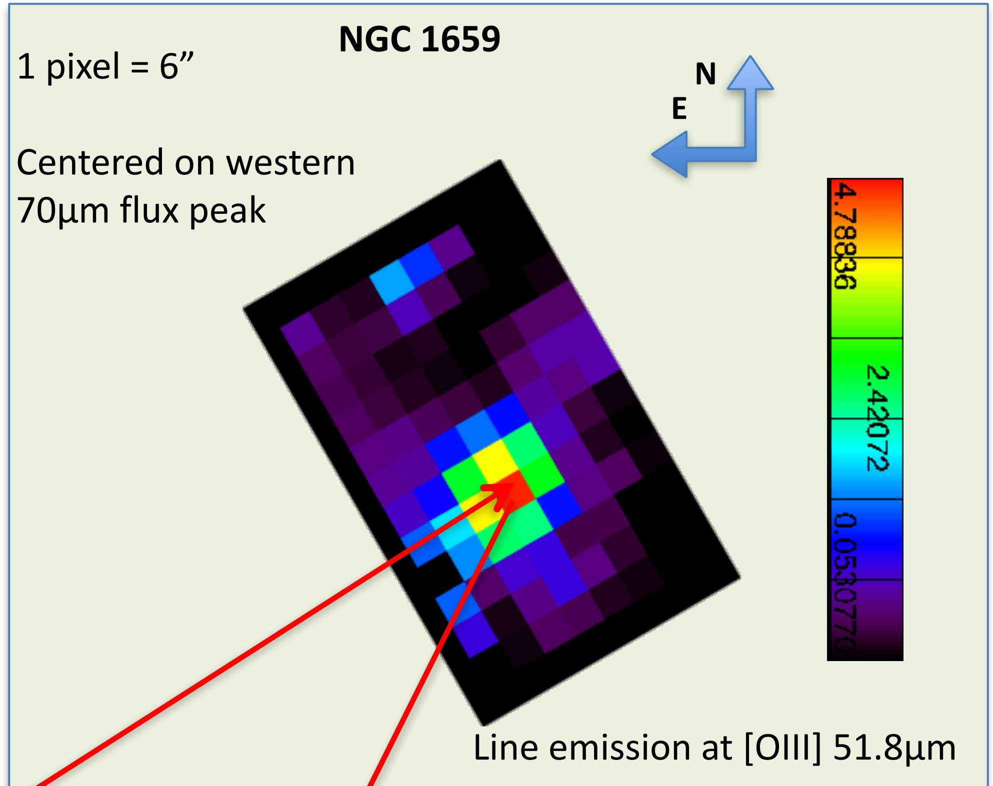


Reference Pixel

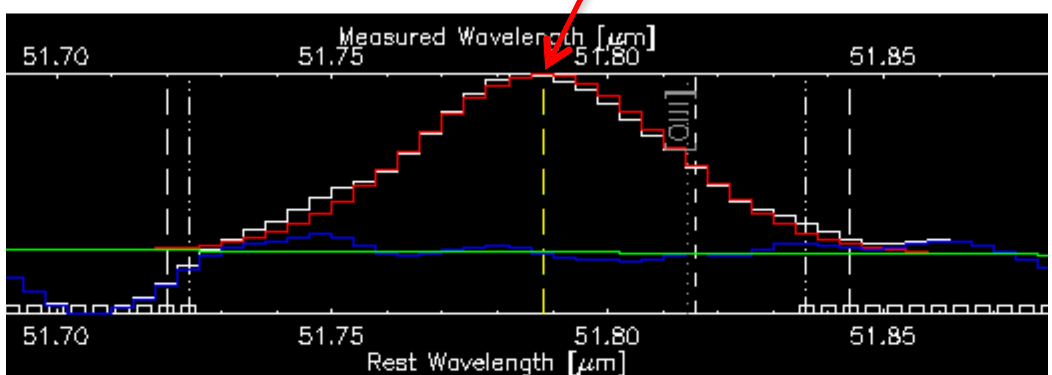
Partial dataset 2014
Initial Quick-look as of 2014

Full dataset 2014
Reduction as of March 2015

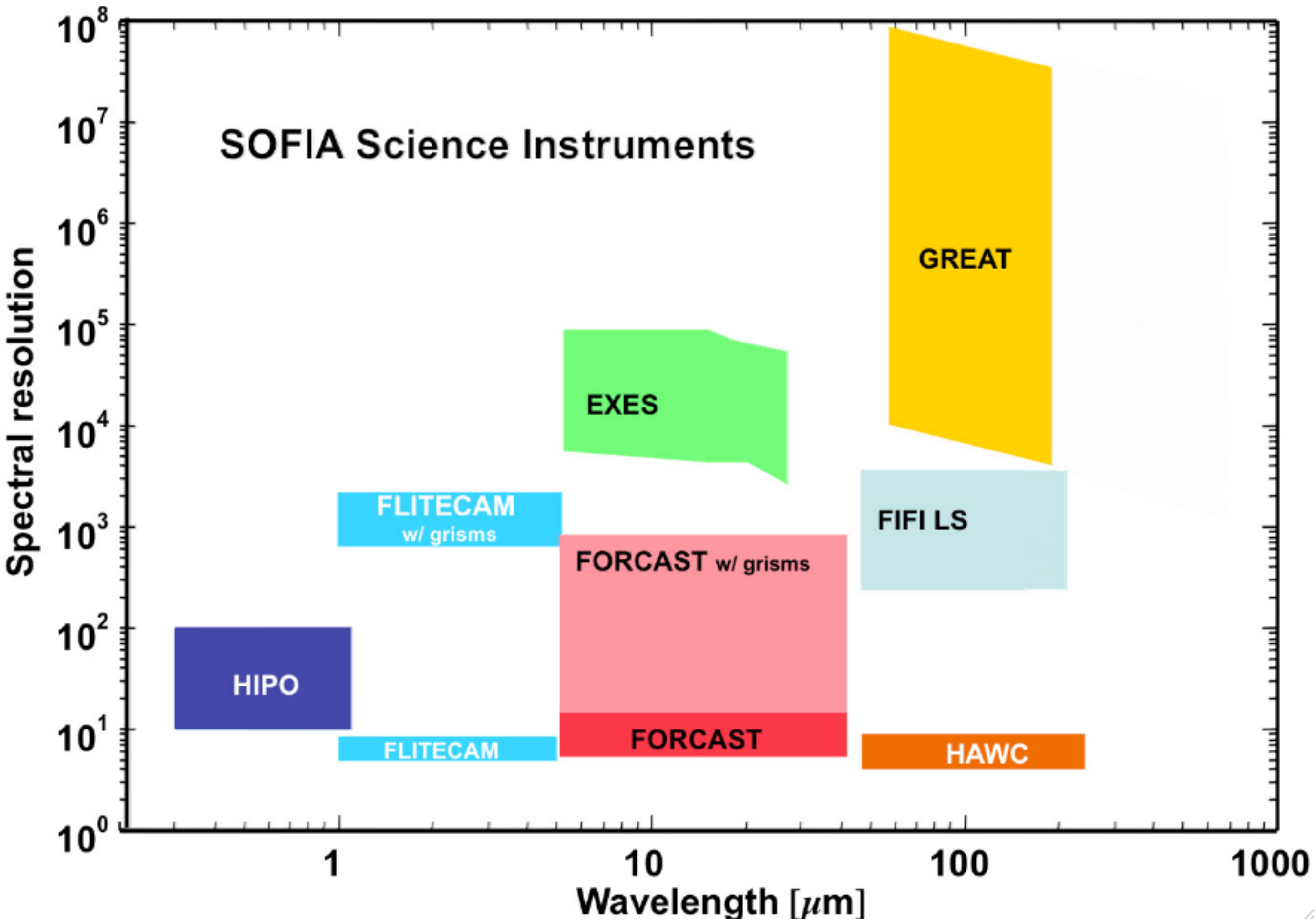




Reference Pixel



Where to Go Next?



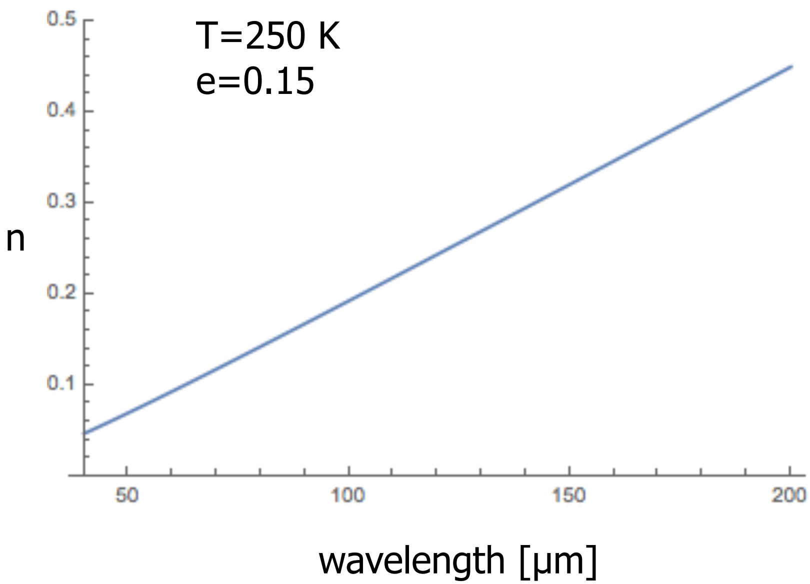
Fundamental Noise Limits for Direct vs. Heterodyne Detection

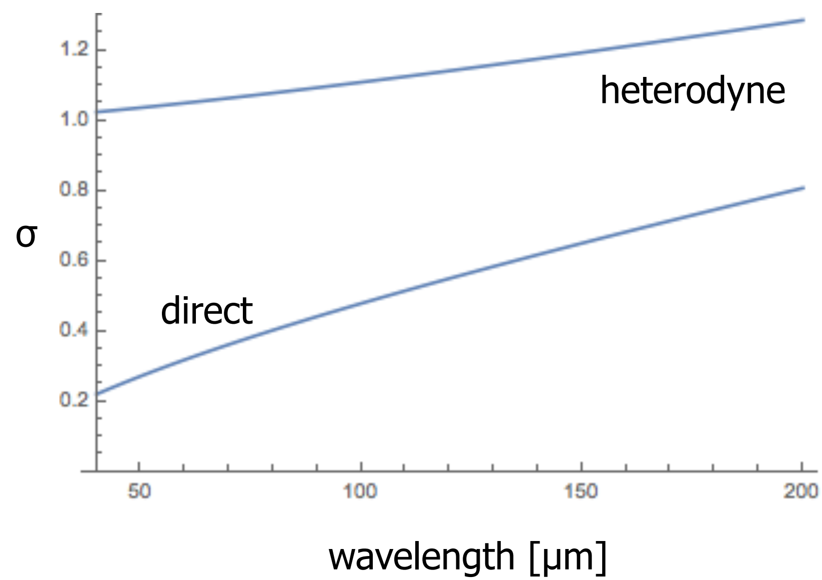
$$\mathrm{bose}(\nu\_, \mathrm{T}\_) = \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

$$n(\nu\_, \mathrm{T}\_, \mathrm{e}\_) = e\,\mathrm{bose}(\nu, T)$$

$$\sigma\mathrm{d}(\nu\_, \mathrm{T}\_, \mathrm{e}\_) = \sqrt{n(\nu, T, e)\,(n(\nu, T, e) + 1)}$$

$$\sigma\mathrm{h}(\nu\_, \mathrm{T}\_, \mathrm{e}\_) = \sqrt{n(\nu, T, e)\,(n(\nu, T, e) + 1) + 1}$$





“FIFI LS +”

- Options for upgrading the existing FIFI-LS
- Possible successor of FIFI-LS

"FIFI LS +"

- Options for upgrading the existing FIFI-LS

  Simple
  - Implement the dichroic at the boresight box.
  - Upgrade the cold dichroic to allow for using 42 – 50 μm wavelength range

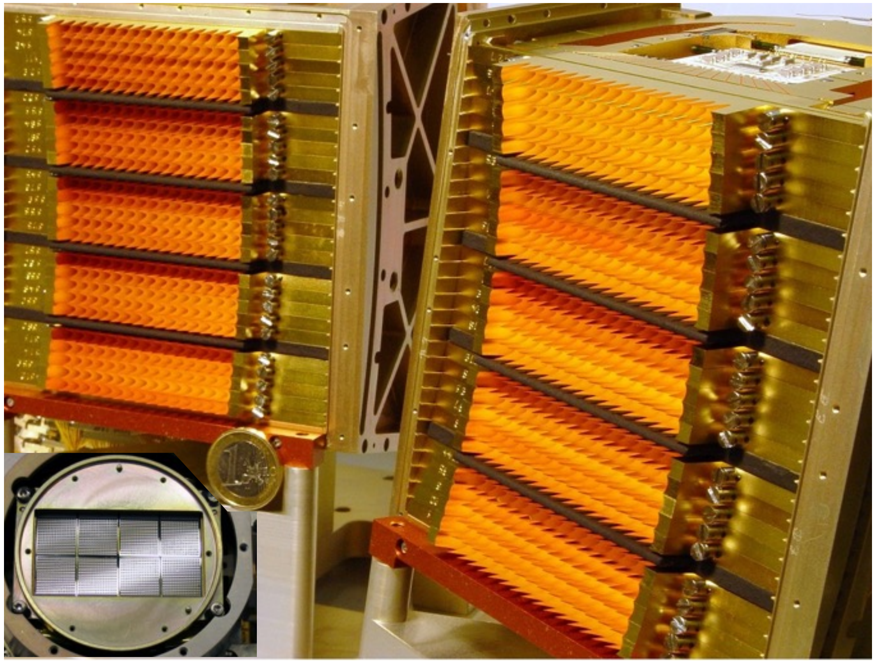
  Major impact
  - Match between the FOV of the red and the blue channel
  - Quadruple the # of spaxels in the blue channel
    - need to use new array technology

FIFI LS Successor Instrument

- The number of spaxels and spexels compared to FIFI-LS can be greatly increased
  - FIFI-LS not Nyquist sampled: Factor of 2 in pixel # (2-dim) per channel
  - FIFI-LS blue channel FOV match red channel: Factor of 4 in pixel #
  - Increase spectral coverage to 64 pixel:
    Get more baseline and improve spectral chopping and spectral scanning
  - Blue channel new array format: 25 x 16 → 200 x 64 (Factor of 32):
    FOV 1′x1′
  - Red channel new array format: 50 x 64 (or 200 x 64)
- Background limit case allows one to increase R to ~5000 without loss of sensitivity
  - Spectral coverage 64 pixel or 128 pixel
- # of pixel per array can grow to 200x128 or ~25,000 pixel
  > 50 times compared to what we have right now

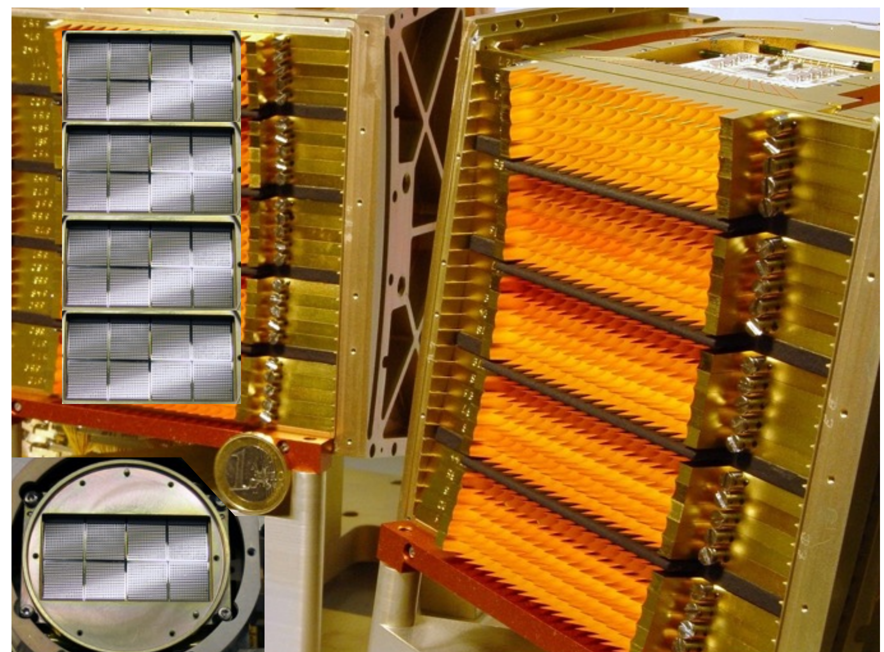
FIFI LS Successor Instrument

- Consequences
  - Using FIFI-LS technology will grow the instrument to a size & complexity which cannot be handled.
  - New detector technology required to handle ~25 000 pixels
  - Individual detector pixel need to shrink in size by a factor of ~10. Current feed horn size of FIFI-LS is ~4mm
  - Maybe a case for a D/US/+ collaboration



FIFI LS Successor Instrument

- Consequences
  - Using FIFI-LS technology will grow the instrument to a size & complexity which cannot be handled.
  - New detector technology required to handle ~25 000 pixels
  - Individual detector pixel need to shrink in size by a factor of ~10. Current feed horn size of FIFI-LS is ~4mm
  - Maybe a case for a D/US/+ collaboration



FIFI LS Successor Instrument

- Further Thoughts
  - Use bolometer or kinetic inductance detector (KID) arrays, which meanwhile have grown to maturity
  - Improve the sensitivity of the detector pixels over FIFI-LS
  - Extend wavelength range down to 28 µm to also cover the ground state transition of H_2, which will eventually be missed by JWST
  - Increase the turning range of the gratings to capture higher grating orders
  - Watch the development of the bandwidth and # pixels of heterodyne instruments

NIR Spectroscopy of Transiting Exoplanets with SOFIA

- Some History (A. K.)

2005 Idea: transiting exoplanets may be a good case for NIR imaging spectroscopy.
Simulation: demonstrated feasibility

2006. Keck OT proposal on HD189733b declined for formal reasons
Keck DDT proposal on HD204958b with OSIRIS: granted
VLT proposal onHD189733b & HD209458b with SINFONI: granted

2007. Basic Observing strategy reworked

2008. DDT Keck proposal on HD189733b with OSIRIS: granted

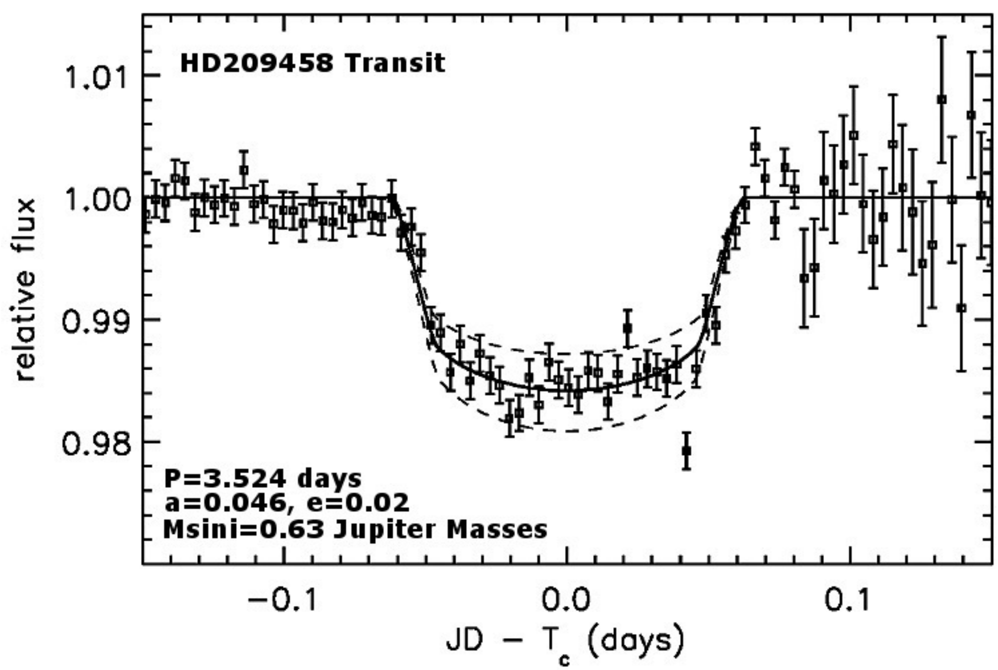
2009. Refinement of observing strategy and data reduction
Optimized strategy, nocturnal variations of atmospheric trace molecules

Conclusion that ground based transit spectroscopy will be very! difficult due to dominant systematic effects. Needs a satellite or SOFIA.

5 refereed publications and >14 oral conference contributions & papers

Lessons learned I

- Ground based transit spectroscopy of typical hot Jupiters requires typically ~5-6 hours observing time per transit
  - S/N ≥5000 (Planet signal ~1% of star; @NIR & R~2000 L/C ~0.1)
  - sophisticated observing strategy



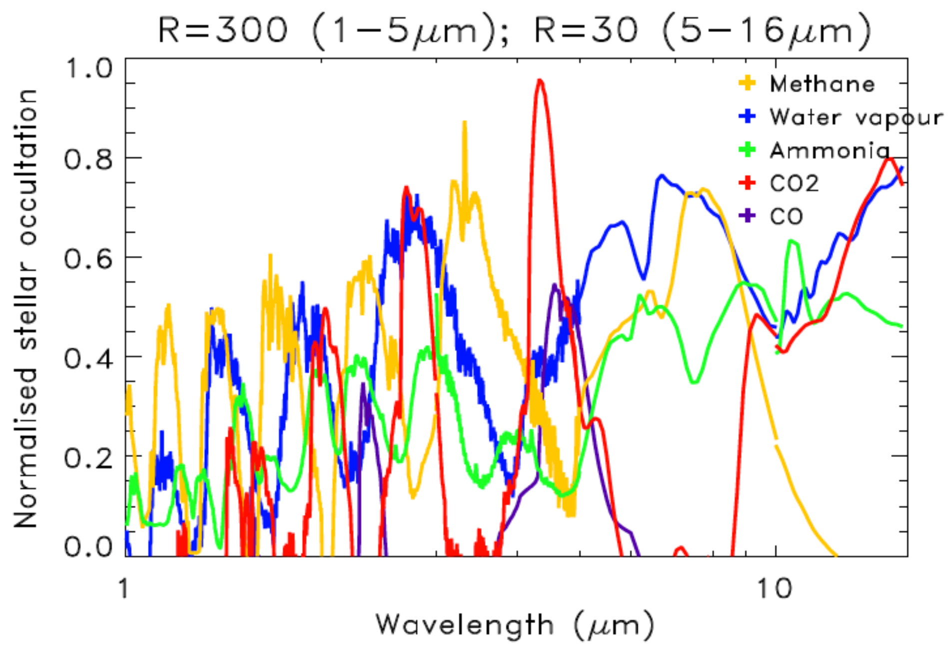
Lessons learned II

- Except for satellites, SOFIA is the 2nd best observatory (after HST) for observing exoplanetary transits.
  - The atmospheric transmission is much more stable
  - Much higher overall NIR spectral transmission
  - Characteristic atmospheric turbulence frequencies much higher compared with ground observations. The seeing disk is large but stable (high frequency seeing).
  - Partial pressure of atmospheric trace gases much lower
  - Flying west SOFIA can counteract the rotation of the earth
  - More observing opportunities per target per year

Ideas for a SOFIA Instrument I

- 1 - 5μm spectrometer
- for stars (small FOV)
- spectral resolution ≤ ~300

First guess:
- Small grating -> grism
- Lens optics
- LHe cooled or CCC
- Detectors available
-> proven technology

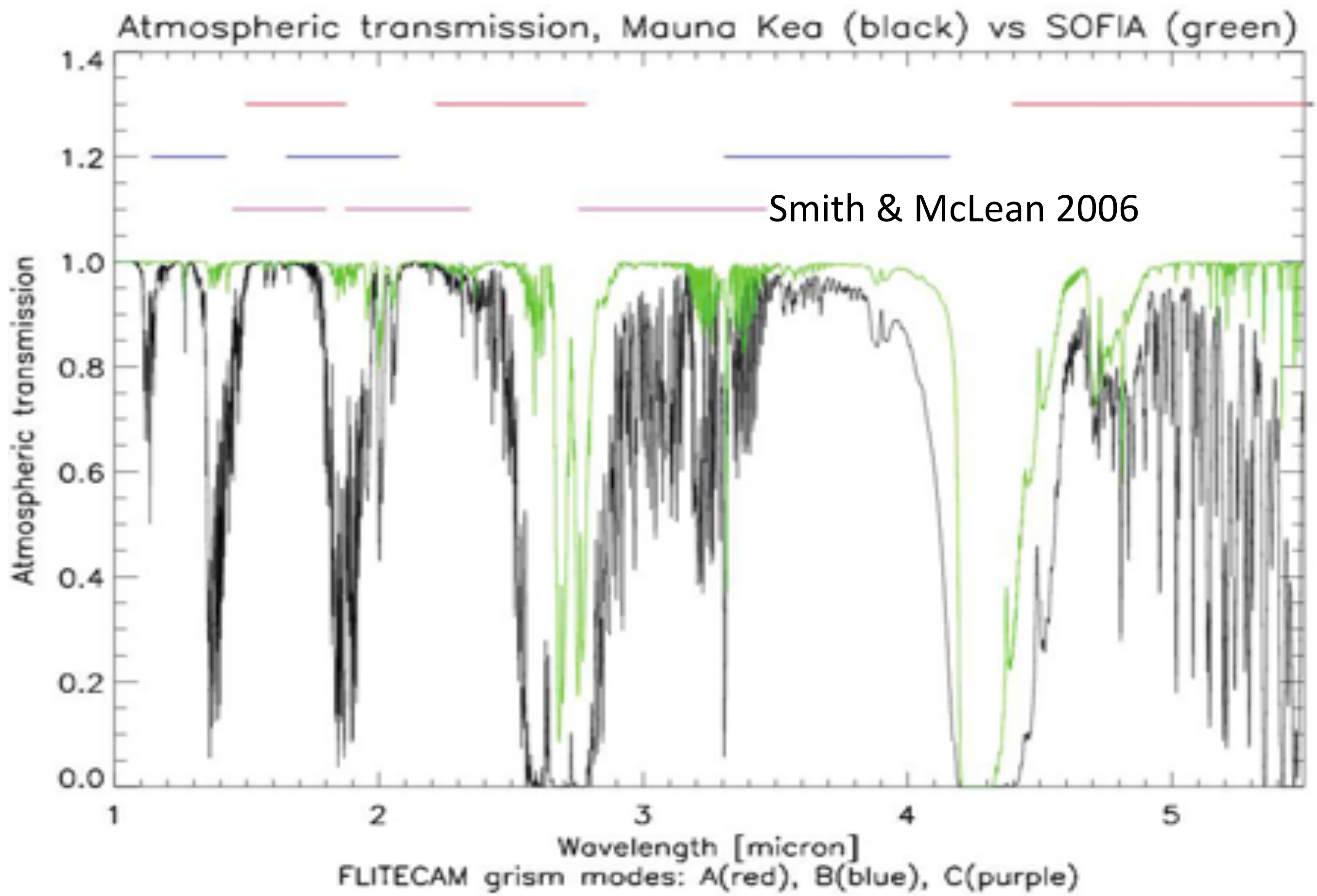


Looks easy ….., however …

Simulated transmission spectra of a gaseous exoplanet at 800 K (Hollis et al., 2013)

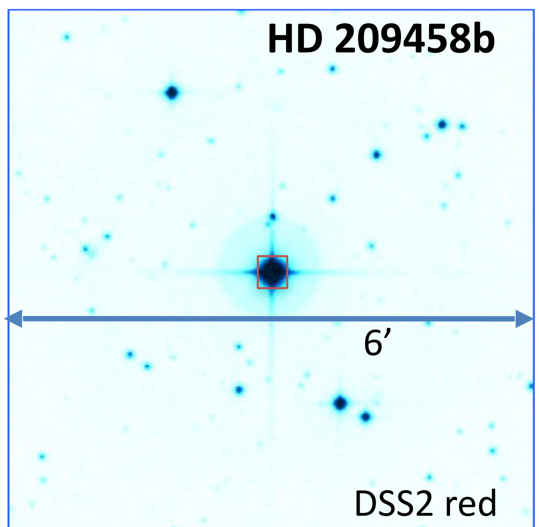
Ideas for a SOFIA Instrument II

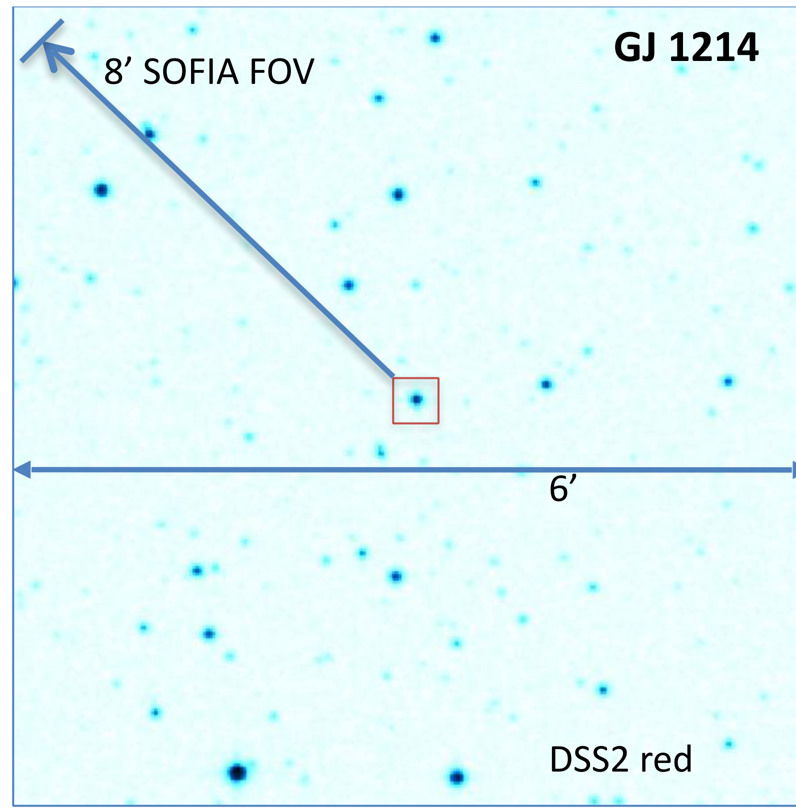
- Still need to beat the remaining atmosphere



Ideas for a SOFIA Instrument III

- Still need to calibrate, e.g., airmass
  - need field stars for comparison
  - sum of flux of field stars ≥ flux of exoplanet parent star.
  - monitor spectrum, flux not enough
  - not all field stars my be suited
  - enough field stars may not be available





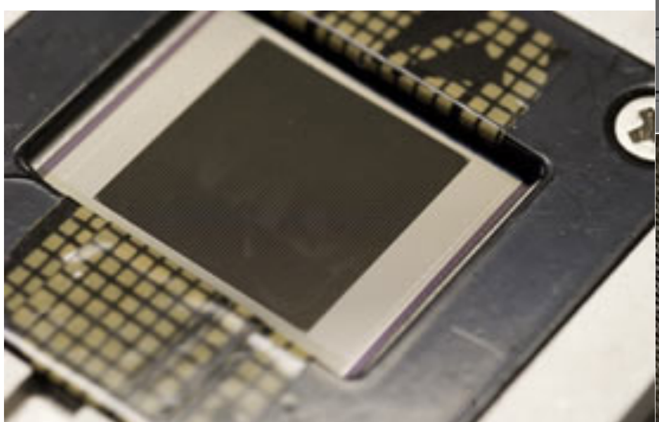
Ideas for a SOFIA Instrument IV

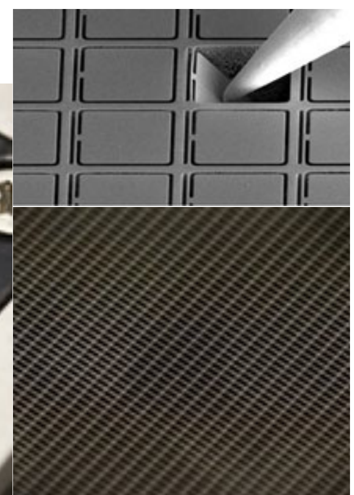
- Need to keep the instrument stable
  - simple mechanics
  - robust layout
  - no moving parts, if possible
  - pixel scale
    . coarse pixel scale: get all the flux on one spaxel
      - quadratic spectometer entrance aperture (or)
    . fine pixel scale: beat on the sensitivity profile of a single spaxel
      - imaging spectroscopy on small FOVs
  - other ideas?

Ideas for a SOFIA Instrument V

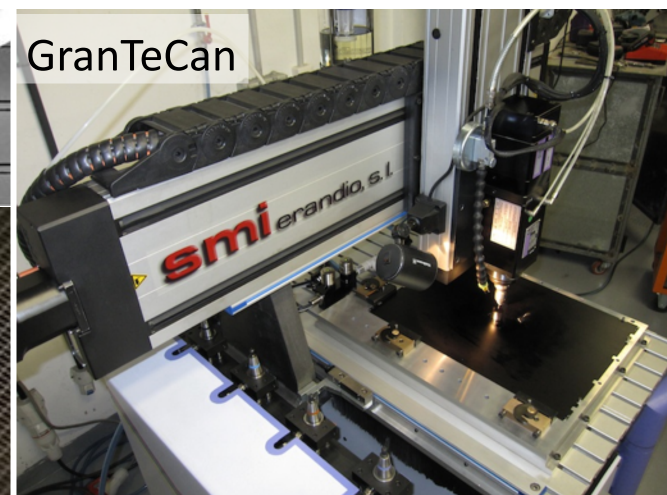
- Challenge: monitor spectra of random field stars
  - more than one field star necessary
  - Freely addressable micro-shutter array
    JWST proven technology
    They are tiny cells that measure 100 by 200 μm
  - Exchangeable stop with custom drilled holes
    ESO VMOS proven technology
    GranTECan OSIRIS proven technology
  - Probably expensive technology!
  - This requirement significantly increases the size of the instrument

JWST





GranTeCan



Things that also Play a Role

- SOFIA needs to prove that S/N ≥ 5000 can be achieved
  Maybe a task for FLITECAM
- There was probably already one proposal for such instrument in the last US call for next generation instruments
- Probability influenced by CfP ESA M3 Mission CfP
  - Decision on Plato, EChO, … this month
- Strategic decision between
  - smaller, modular more flexible instrument to be completed on shorter time scales that can be touched for upgrades, but would only provide limited # of features.
  - bigger, more complete instrument to be completed on longer timescales that will not easily be upgradable, but will provide more features.