Lessons Learned from Making FIFI-LS a Reality

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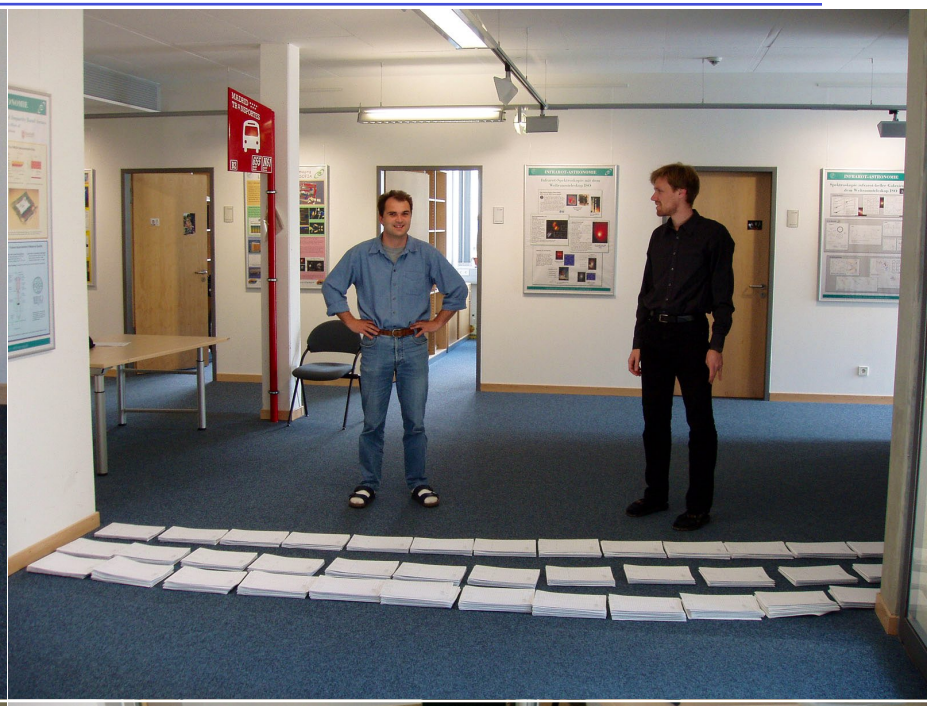
(Meta-)Lesson 1

- Criminal investigators know that witnesses' memories can become quite unreliable after ~20 years
- This applies to the speaker, too…
- Should have started exercise while memories were fresh…

- Three main areas:
  - Programmatics
  - Technical issues
  - Scientific/observational optimisation

Civil Passenger Airplane (FAA) / NASA Rules

- Most of the team spending/wasting siginifcant fraction of instrument development time on airworthiness certification
- Formal certification not even always allowing safest solution!
- Very high frustration level - task should have been outsourced to qualified/experienced firm, but no funding for that
- Team would have refused to take same approach, again




A Far-Infrared Field-
Line-Spectrometer for

Slipping Schedule

- FIFI-LS was developed with the expectation to fly before Herschel, with corresponing funding line
- Multiple issues with SOFIA program ruined the hope for pioneering/pilot observations during window of exclusive access to spectral range
- Financial “damage” was cushioned by important bridiging funding from DLR
- Slip of start of operation after (very successful) Herschel mission led to loss of support for commissioning/operation of FIFI-LS by MPE

"Failure is not an Option!"

- After the effort invested by many, and with demonstrable demand for post-Herschel access to FIR imaging spectroscopy by the community, a joint effort to save this (promised) capability on SOFIA seemed appropriate
- This view was shared by the Observatory Director
- A smooth transition of the (complex) instrument from MPE to IRS was achieved, with temporary presence of the "old" team at the new site and creative effort to secure funding for the commissioning and transfer to AFRS by IRS
- What looked like a crazy idea initially, became a reality thanks to determination of all involved parties

Slipping Schedule

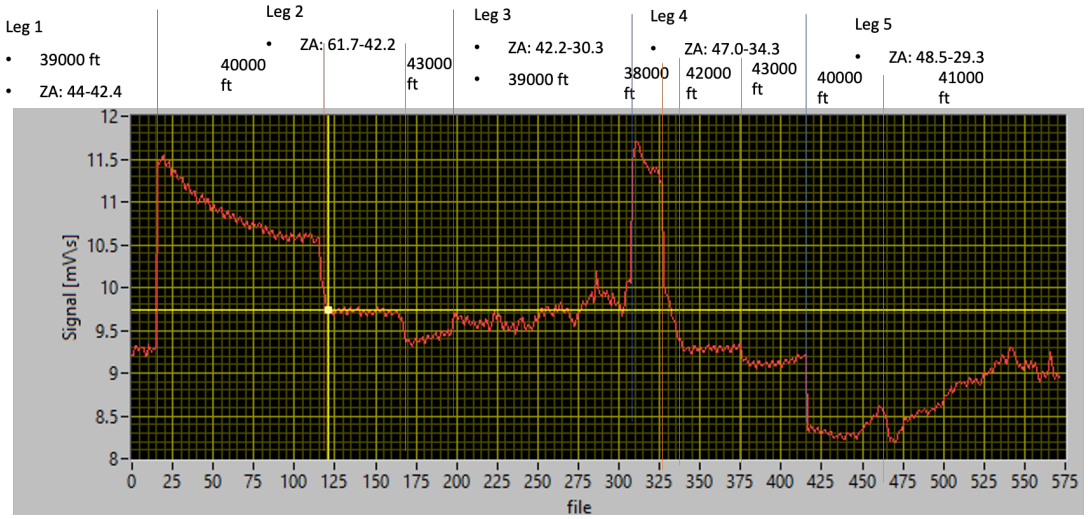
- Should one take this as a given with any (somewhat ambitious) observatory project?
- What is the best way to conceive a "time-invariant" instrument in an evolving environment (astronomy)?
  - Remember: the originally claimed strength of SOFIA over space missions was the rapid development/upgrade/ exchange of innovative instrumentation
  - In the end, we flew PACS before FIFI-LS
- How do we keep (good) people motivated to invest their time and effort into such developments?

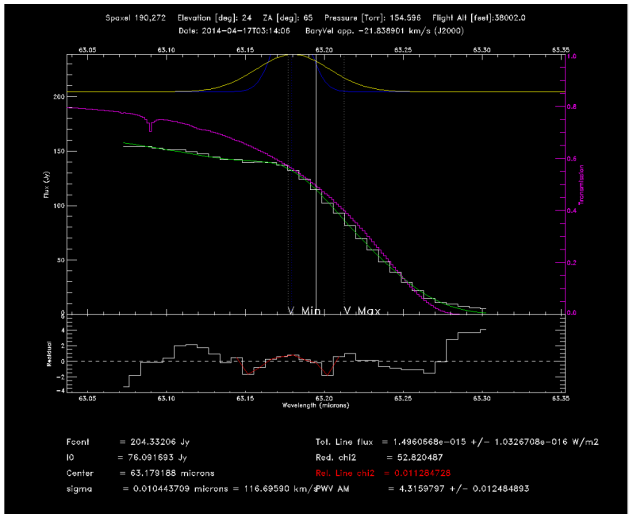
Synergies between FIFI-LS and PACS

- The parallel development of FIFI-LS and PACS with partly overlapping teams allowed a mutual exchange of ideas/solutions
  - The FIFI-LS team found a break-through solution for the large, stressed photoconductor arrays, where the PACS team had failed
  - The cryogenic readout electronics, developed by our Belgian PACS consortium partners, would have been way out of scope for the (institute-funded) FIFI-LS project, but was indispensible
  - The cryogenic operation of the arcsecond resolution angular encoder (Inductosyn) for the gratings was spearheaded by the FIFI-LS team and then also adopted by PACS
  - The triaxial cryo-cables were an ESA-funded Herschel/PACS development, which was inherited by FIFI-LS

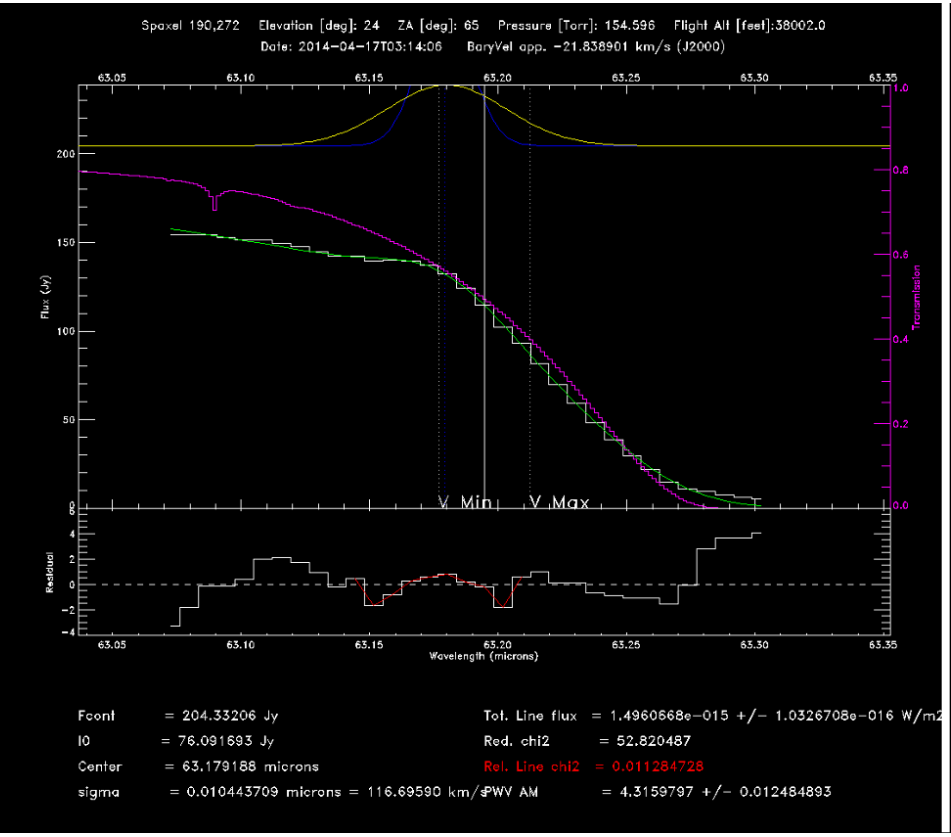
Missing Synergy: Data Pipeline Effort

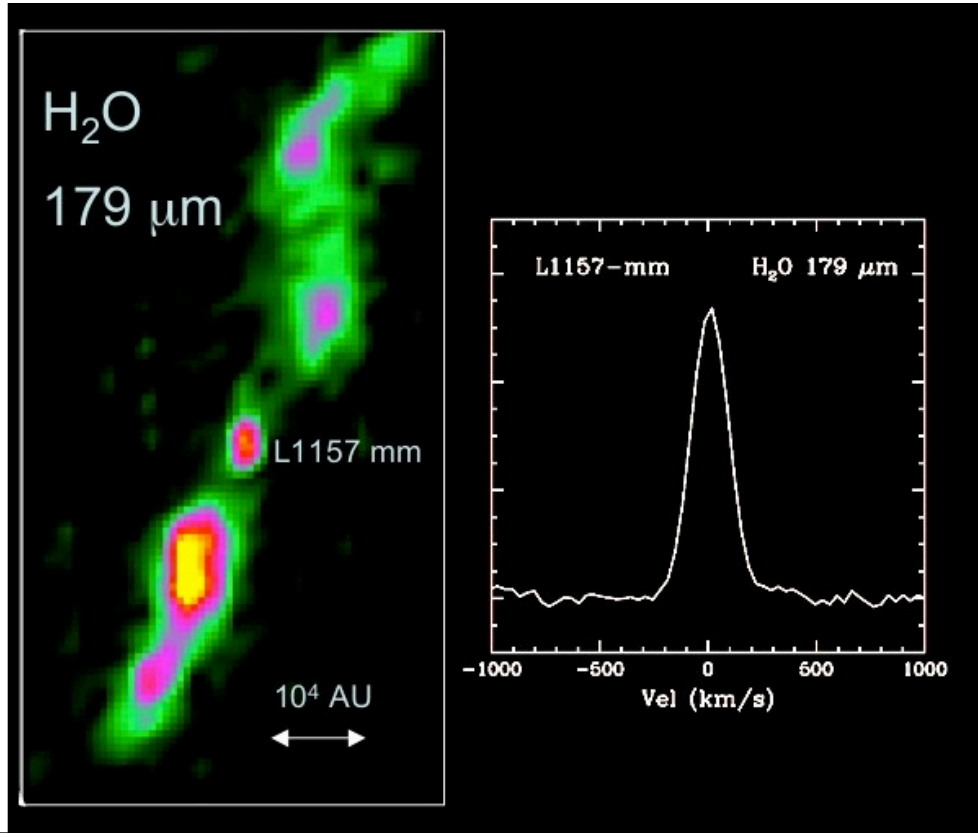
- PACS had a large spectrometer pipeline working group — with relatively easy observing conditions
  - very stable telescope background (also used for continuous calibration) and no atmosphere
- FIFI-LS had to rely on "heroic effort" by few individuals — with much more challenging observing conditions
  - variable atmospheric transmission
  - unresolved telluric lines close to observed wavelength





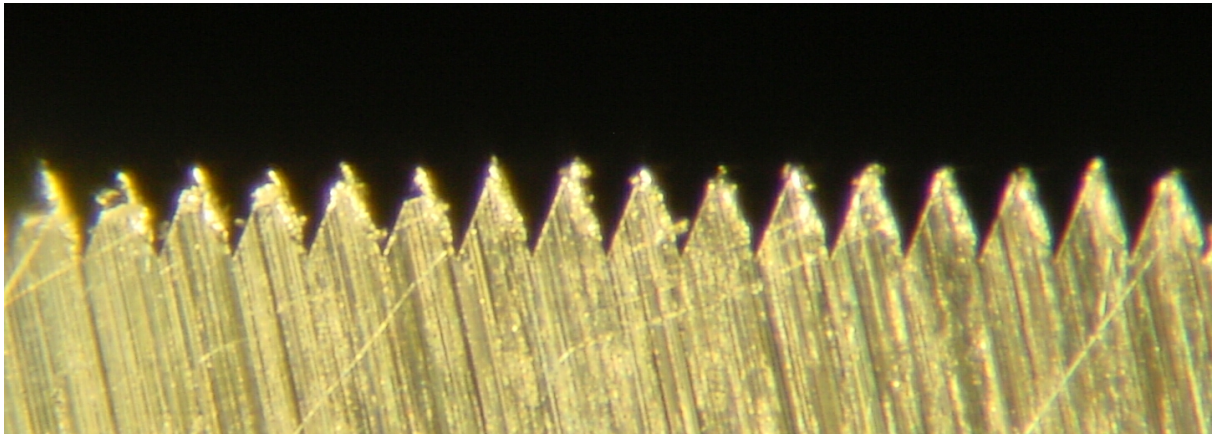
[O I] (SOFIA) vs. H_2O (Herschel)





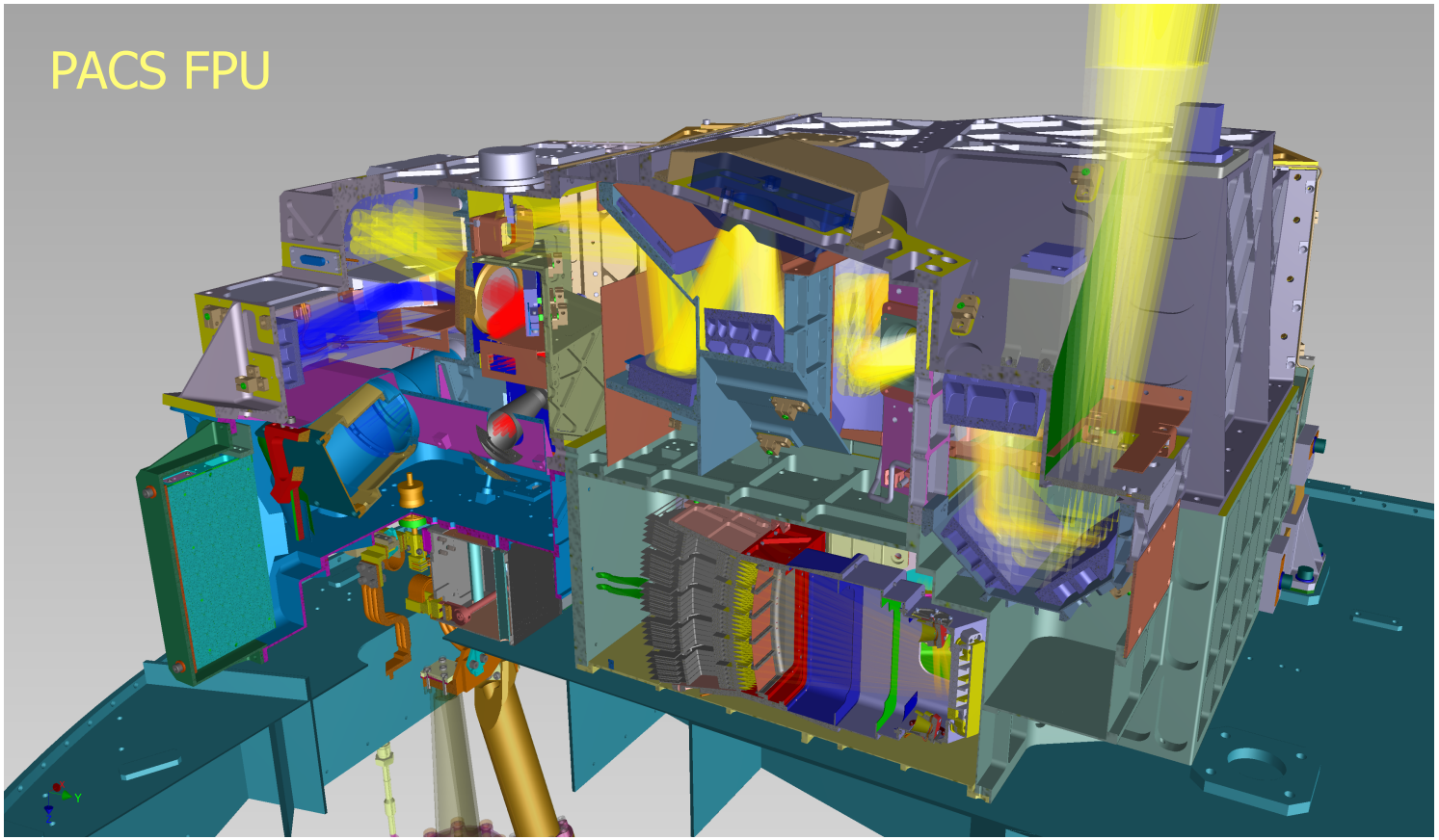
Grating: Less Straight-Forward than Expected

- To maximise optical transmission, single-grating spectrometer
  - no order sorter, has to operate in 1st (to 2nd) order
  - cannot be described by simple diffraction theory
  - full EM calculation dictates (no surprise) very deep profile for high efficiency in nominal order/direction
- First supplier failed
- Second supplier succeeded (after 3 machine-months), but called it "ruinous" job, never to be repeated
- Should explore new ways (periodic metamaterial pattern?)



Feasibility of Complex Optics

- Should be broken into subunits with clean interfaces (pupils, foci)
- Individual alignment of subunits reduces complexity of end-to-end alignment



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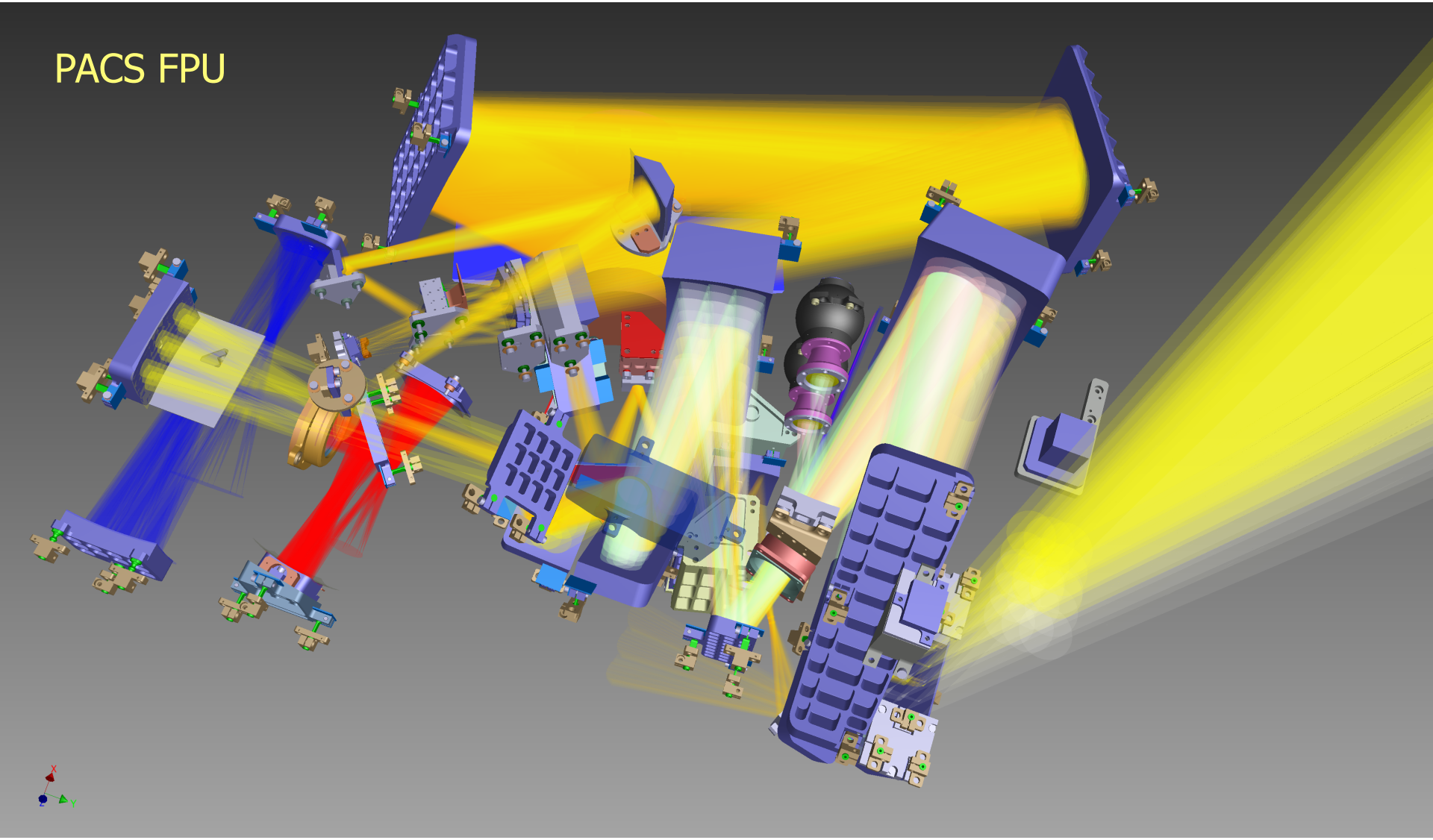
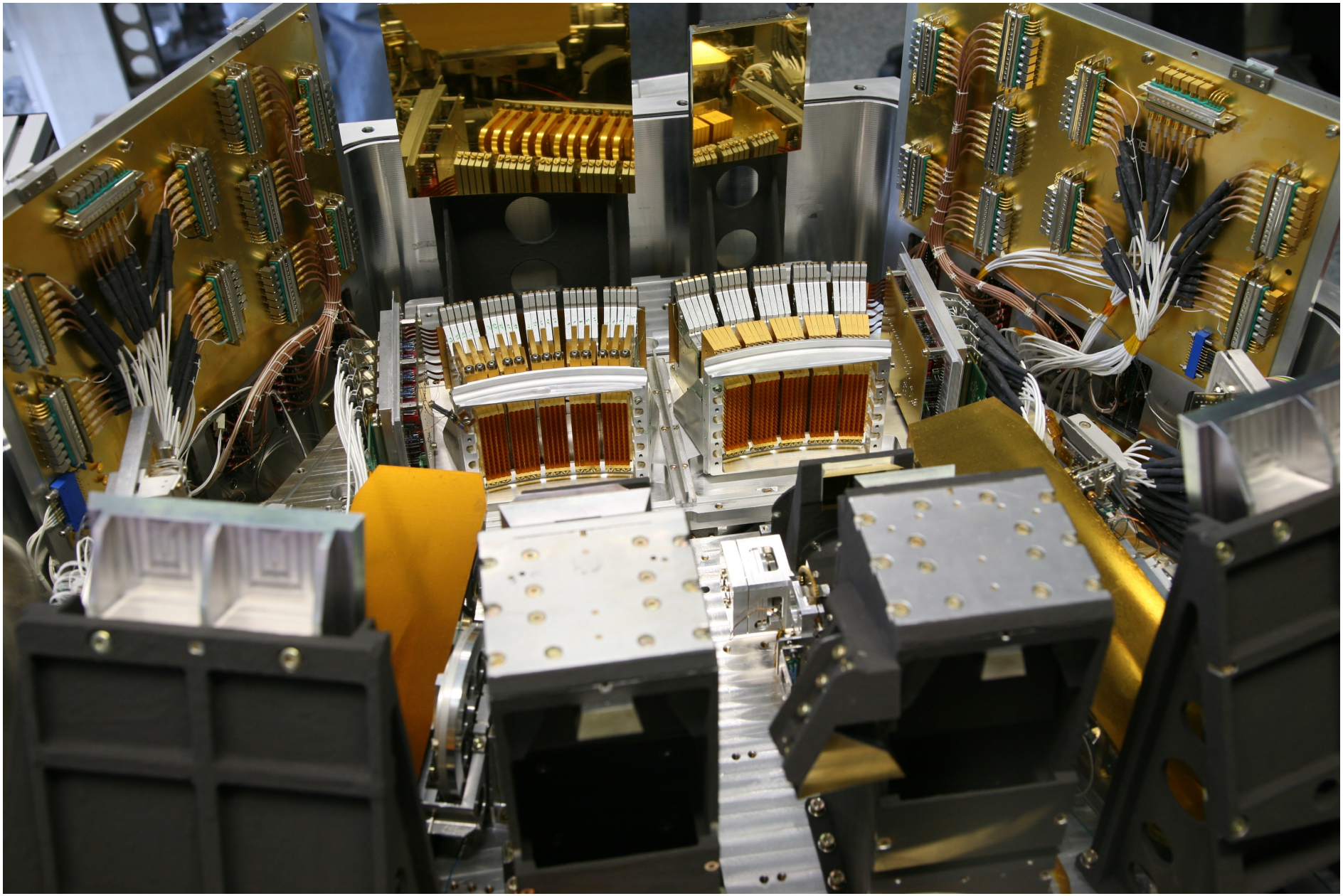
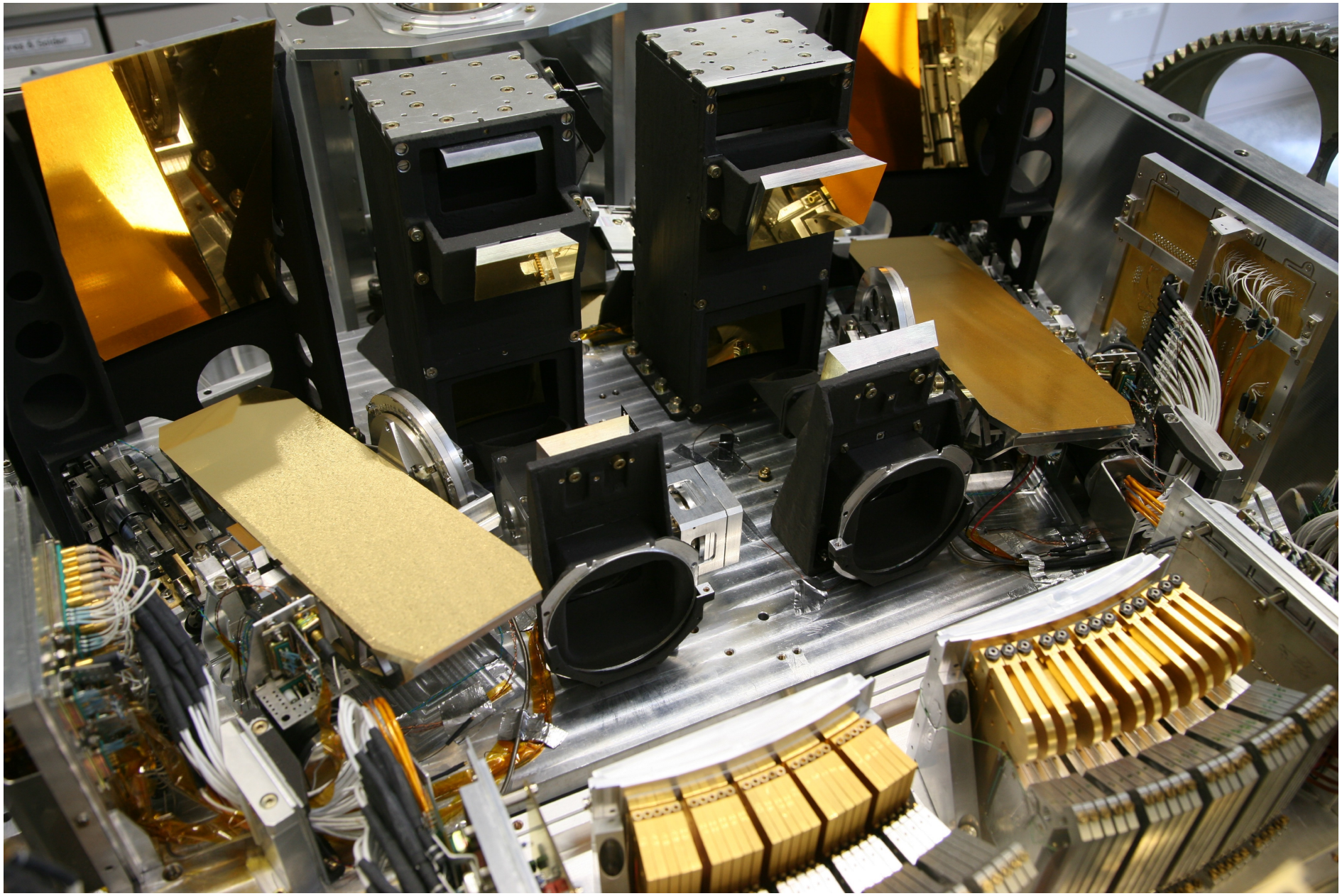
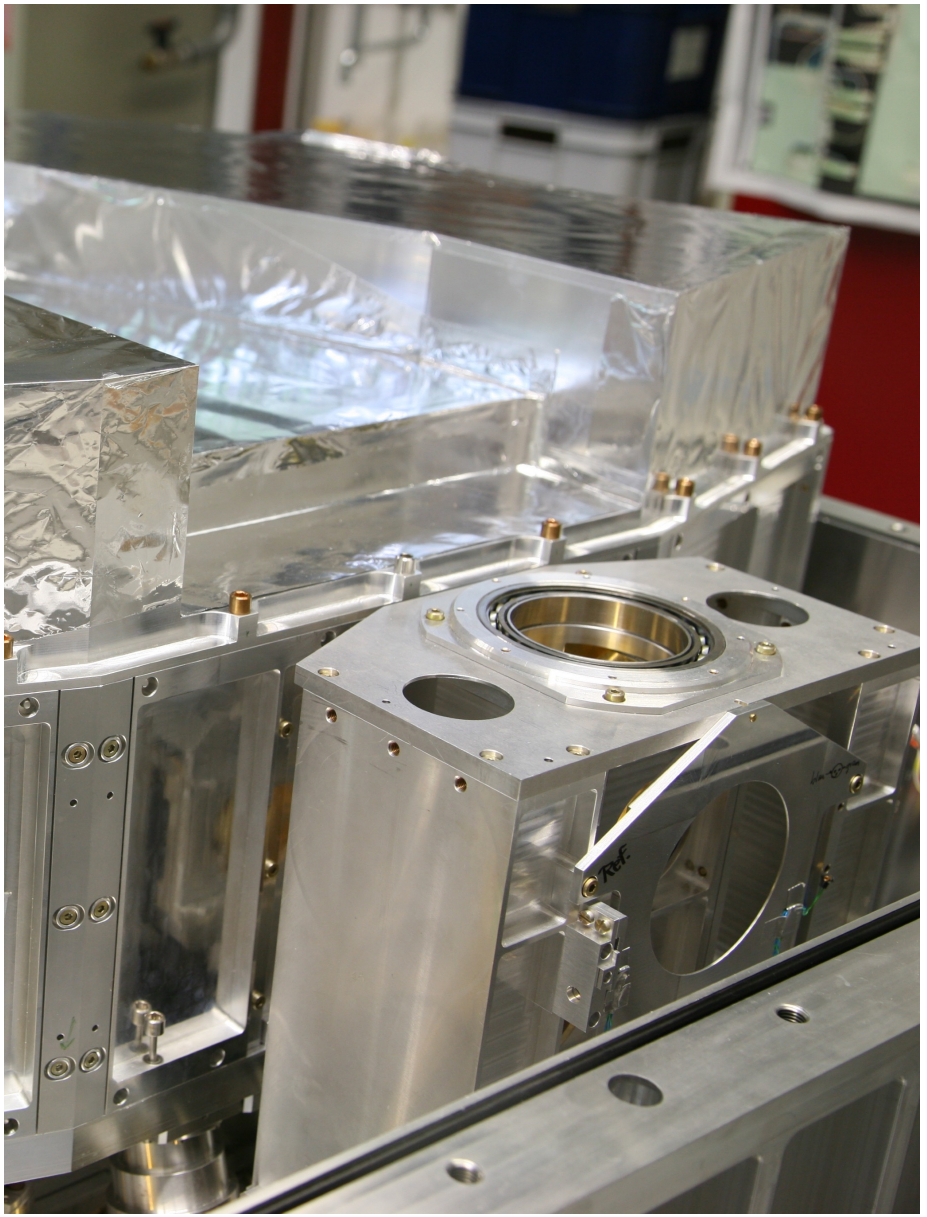




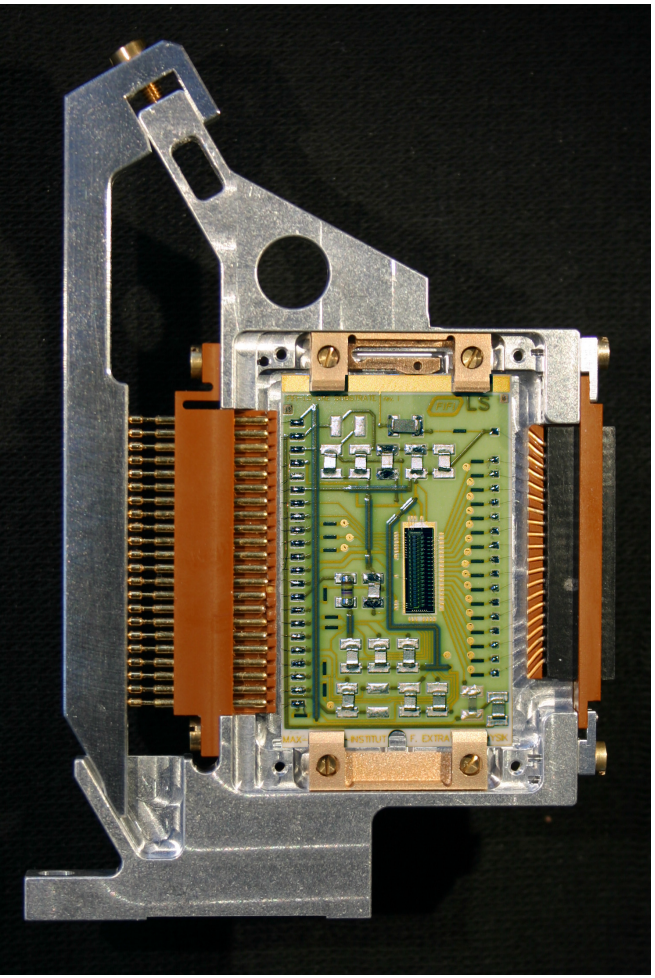




Structural Concepts for Optics

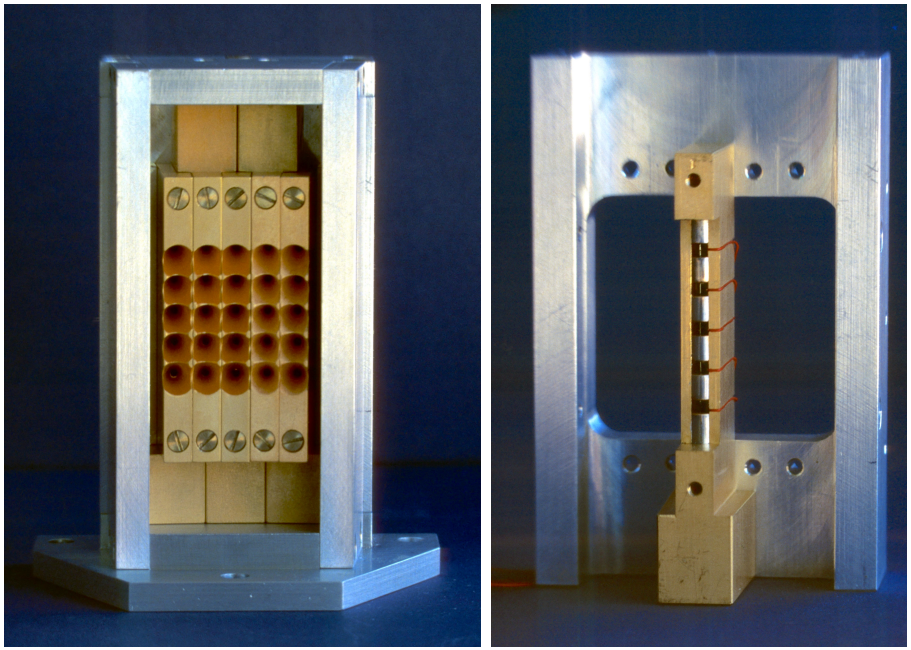
- For FIFI-LS, we adopted "classic" (optical bench) approach
  - arrange optical elements with their mounts on common plate
  - makes assembly and later access relatively easy
  - stiffness and immunity against distortion from temperature changes not optimal
- For PACS, we explored "automotive" (self-supporting body) design, which suppresses large-scale bending modes, compared to flat plate
  - innovative mirror mounts, which allowed (some) final alignment through closed box
  - complex, expensive manufacture
  - very high alignment stability

CREs, or: Is it possible to prepare a gourmet meal from inferior ingredients?



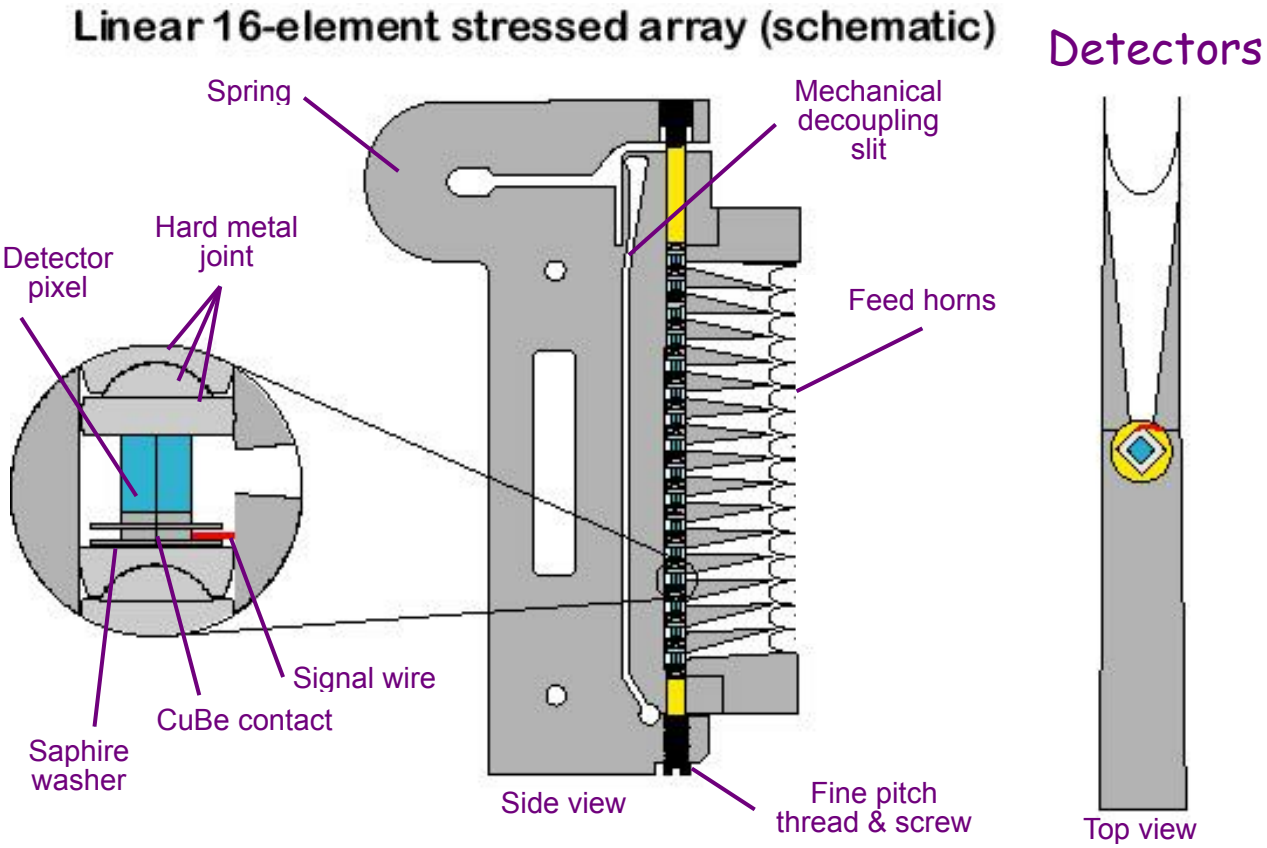
- Low telescope background and bandwidth of PACS spectrometer —> NEP of few 10^{-18}W/Hz$^{1/2}$
- Initial limiting factor was not the detectors but the cryogenic readout electronics
- We had been looking into solutions based on GaAs MESFET ICs, but no partner with that competence
- Si MOSFETs can work at (sub-)LHe temperature, but with significant performace drawbacks
- In the course of 7 chip generations, our KU Leuven /IMEC PACS consortium partners managed to
  - sufficiently understand the low-T physics of the MOSFETs
  - overcome their limitations by clever circuit design

Stressed Photoconductor Arrays: Scalability?

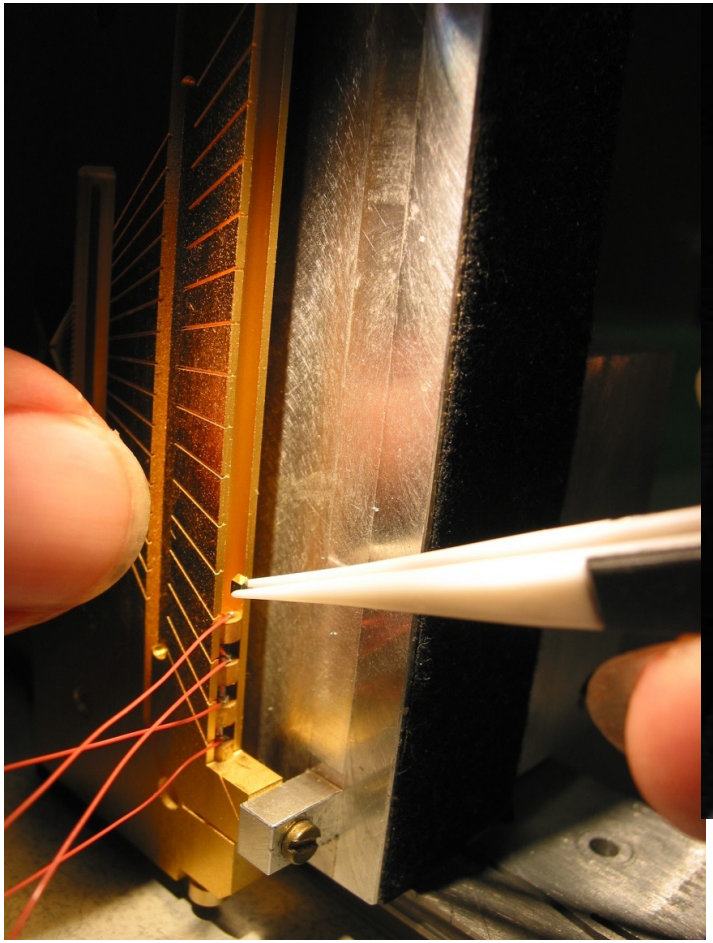


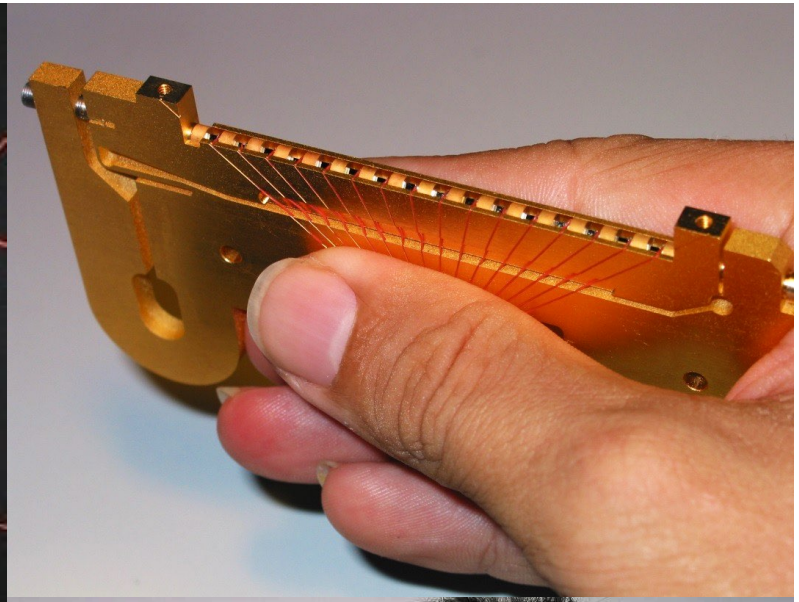
- Initial (naive) idea: more modules, longer modules
- Collapsed test modules as well as FEM anaysis demonstrated that uniform stress would require impossible tolerances on Ge crystals and WC pistons

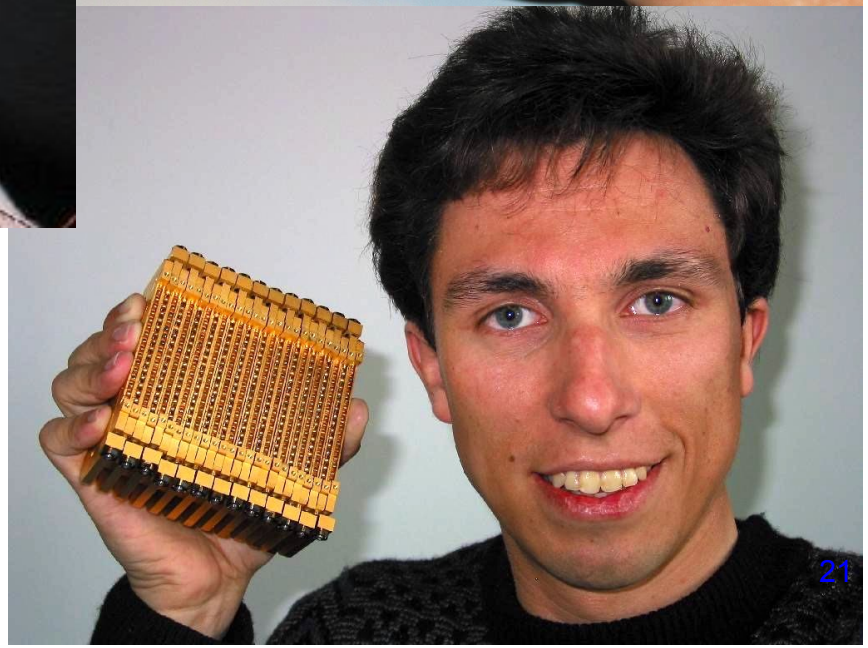
Bigger —> More Complex Design



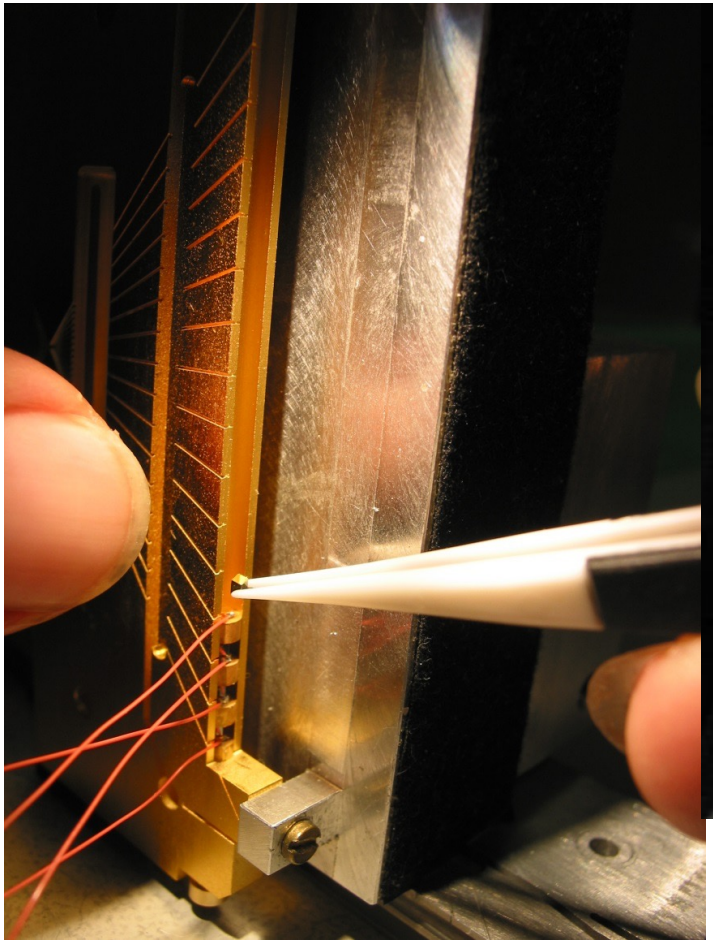
- Self-adjusting joints for homogeneous stress

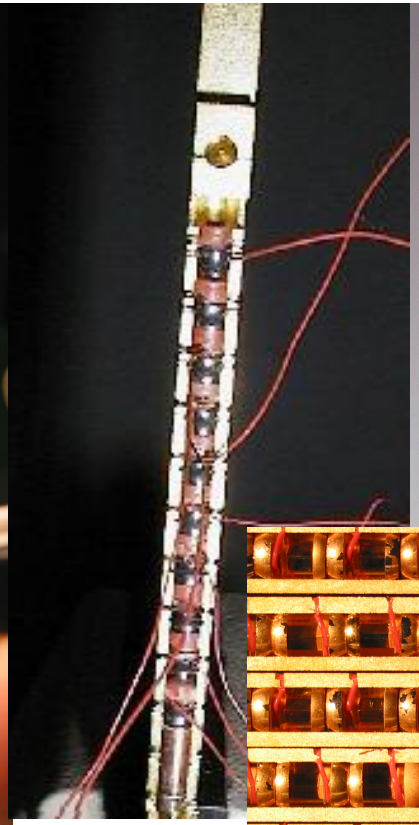


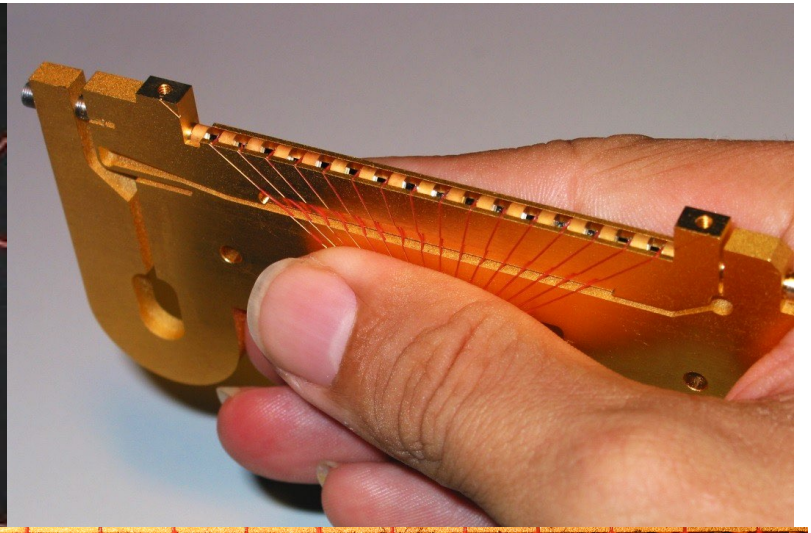


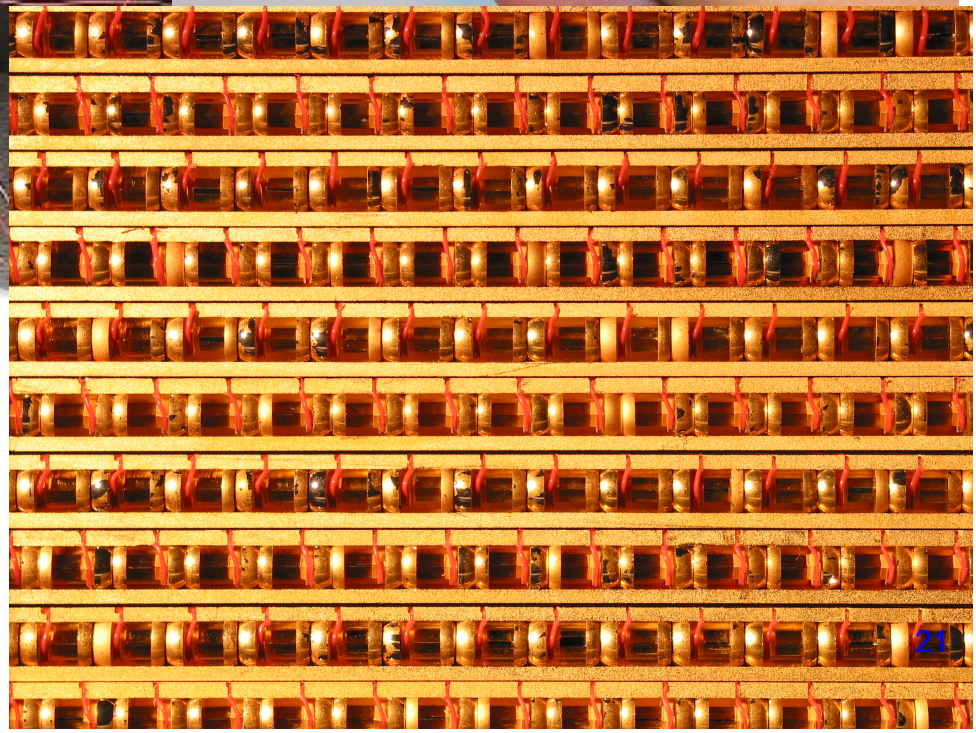


Assembling the detector array by hand:
800 individual pixels





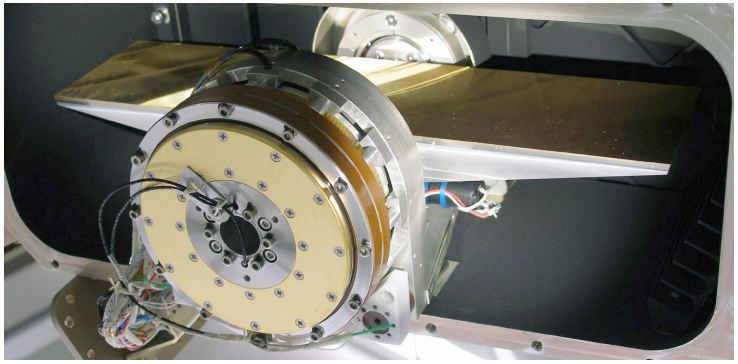


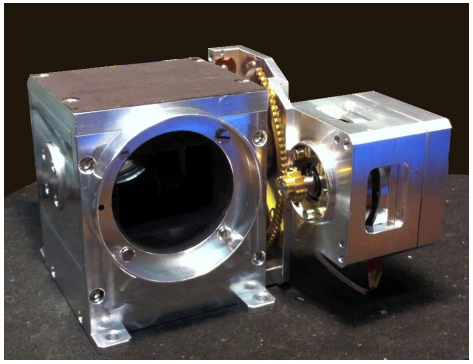


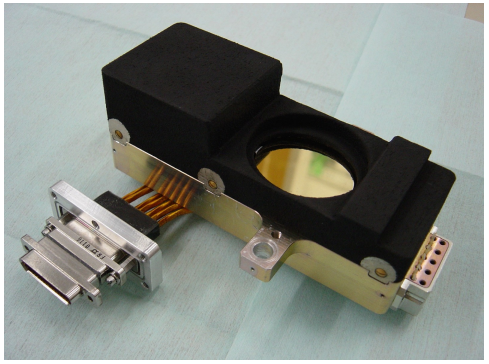
Assembling the detector array by hand:
800 individual pixels

Cryo-Mechanisms

- Used to have a bad reputation (in space missions)
- This is not a "natural law" - simple causes of failure
  - Poor design
  - Lubrication
- In FIFI-LS and PACS we have examples from relatively poor to excellent mechanical design — and zero failures
- We have successfully done away with conventioal (dry) lubricants
  - Good: proper coating of contact surfaces, or use of materials which need no treatment/lubrication
  - Even safer: flex-links (eliminates risk of contamination)
- Found good solutions for low-dissipation cryo-actuators/motors







Problem Zones

- Electrical contacts / connectors
  - had some drop-outs in the FIFI-LS detector environment toward the end of the SOFIA operation (spring contact?)
  - lost half of the "red" PACS photometer focal plane due to a disconnected line, either caused by loose indium bump or connector
- Instrument Control/Software
  - infinite loop in PACS SPU software (under very special conditions) stopped Herschel observations for two days
  - how much observing time was lost due to computer problems with FIFI-LS?
- Note: Electronics (hardware) worked flawlessly with both instruments, over all the years! (No "SEUs")

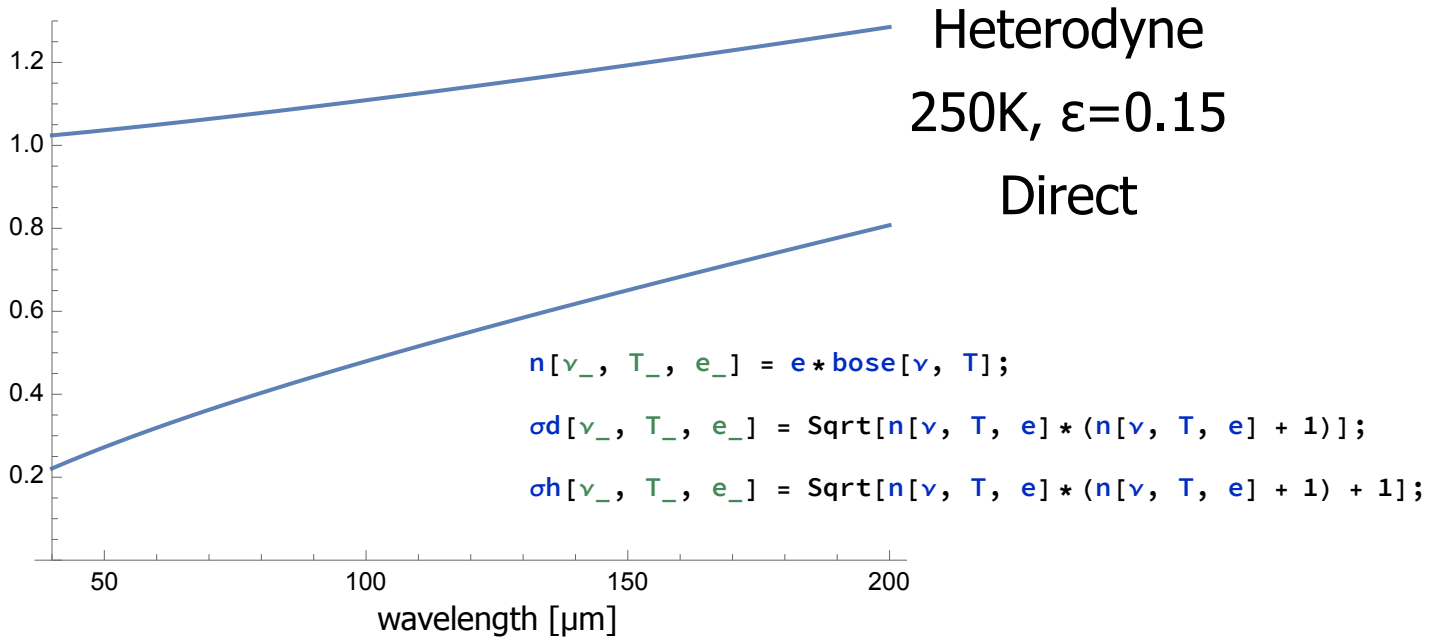
Competence and Experience

- Knowledge/competence resides in the heads of individuals, not with a company name, and not even in documented procedures
  - Companies are good at presenting themselves with an "acquisition team", but continued availability is never guaranteed
  - Nothing is more expensive, in the end, than trying to save money by giving a task to a cheaper, but not fully competent contractor
  - Some critical components of FIFI-LS/PACS would not be available today, as critical personnel has moved on to other fields

Optimum Instrument for the Job?

- FIFI-LS primarily seen as precursor instrument to PACS spectrometer, with main emphasis on extragalactic science
- Spectral resolution and balance between spectral and spatial multiplexing selected (within all kinds of constraint/envelopes) as best compromise (for both instruments)
- We underestimated the difficulty of removing telluric lines at the spectral resolution (R~1500) of the instruments — not an issue in space, of course!
- On the KAO (with Fabry-Pérot based FIFI) we were flexible with spectral resolution

Direct Detection vs. Heterodyne



- Fundamental advantage of direct detection not overwhelimg with warm telescope / atmosphere
- Achievable really only under “ideal” conditions
  - no other fluctuations (atmosphere)
  - resolution bandwidth matched to spectral line width

Conclusions for Next Round (Spectrometer)

- Trivial: Take advantage of bigger detectors (possible with alternative technologies)
  - On a stratospheric platform, don't expect much improvement per detector, though — photoconductors essentially BLIP
- Increase spectral resolution (on sub-orbital platform)
- If a space mission can be promoted / pushed through, I would prefer it any time over airborne
  - with direct detection, enormous gain in sensitivity
  - much higher observing efficiency (24/7)
  - similar development time scale
  - better defined boundary conditions / less hassle
- Can community (which?) agree on strategic plan, rather than being perceived as divided/undecided?

Thanks!

Questions?