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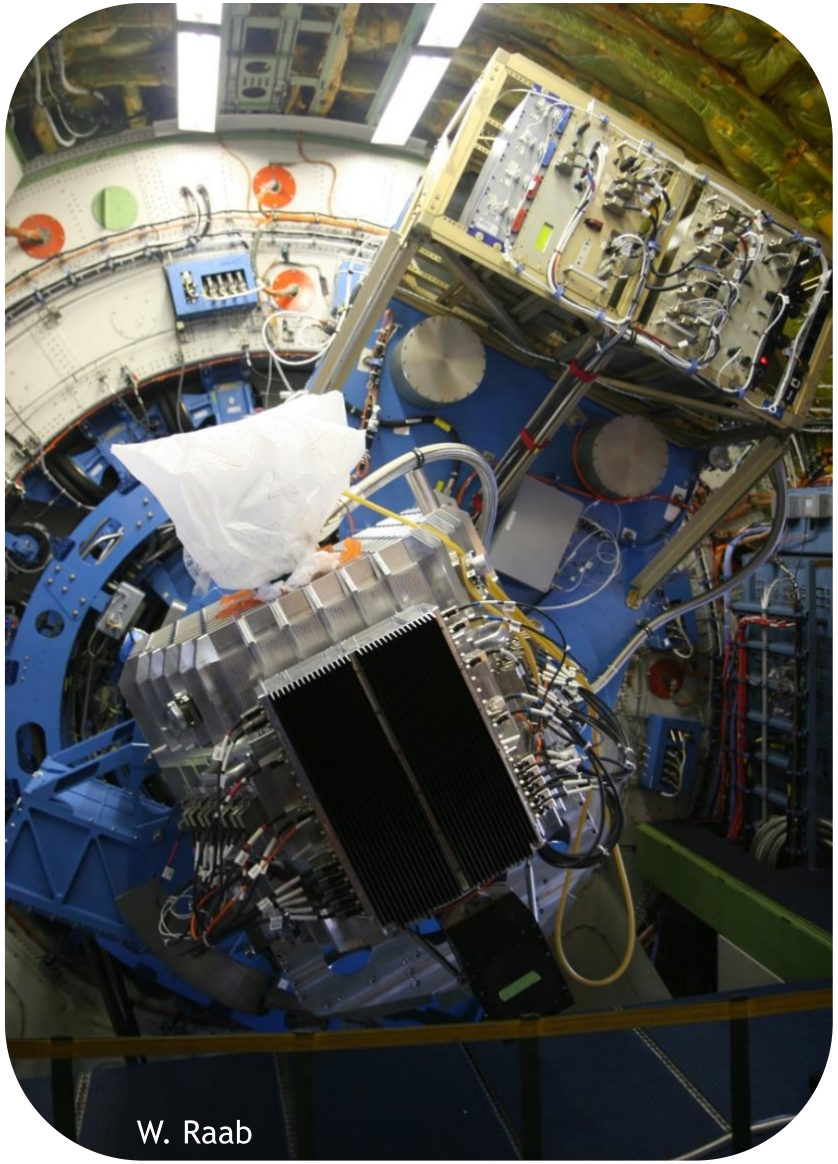

FIFI-LS
The Field-Imaging Far-Infrared Line Spectrometer

S. Colditz
C. Fischer
&
FIFI-LS Team

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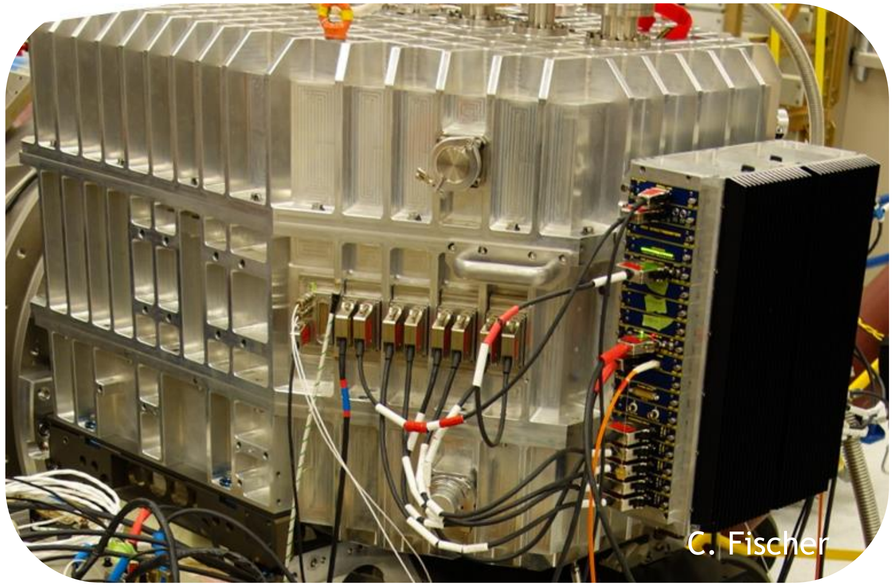
Outline

- Top Level Design Features
- Performance/Calibration
- Using FIFI-LS
- Science Examples



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- Field-Imaging Far-Infrared Line Spectrometer
- Two spectral channels: 51 – 120µm and 115 – 203 µm
- Simultaneous spatial imaging in the two channels:
  30"x30" and 60"x60" field of view respectively
- Each field of view resolved with 5 x 5 spatial pixels
- Medium spectral resolution: R ~ 500 – 2000 (~150 – 600 km/s)
- 16 Pixels in spectral direction in each spatial pixel
- Instantaneous spectral coverage: ~1500 km/s

  e.g. velocity distribution in galaxies including baseline on both sides

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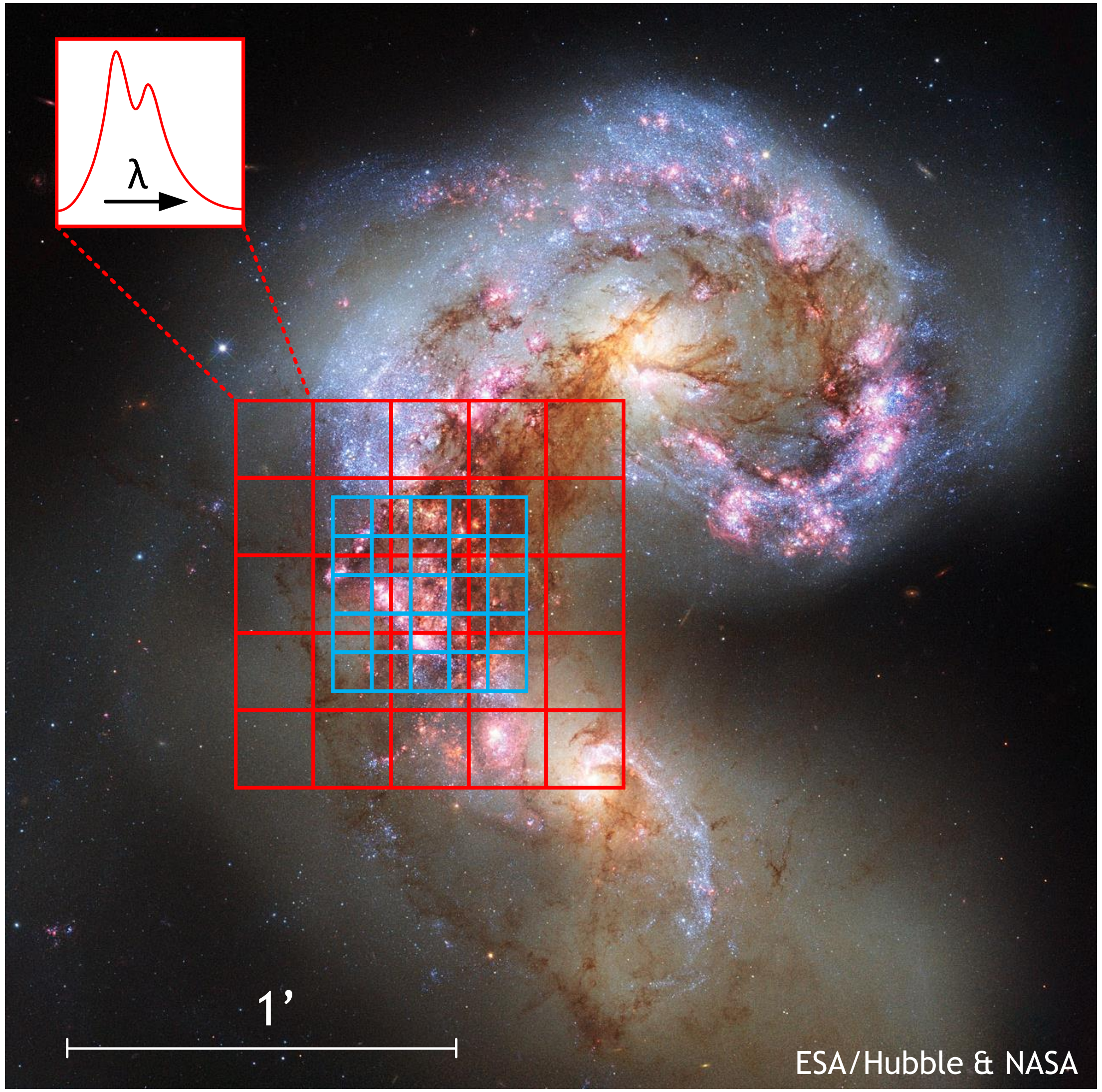
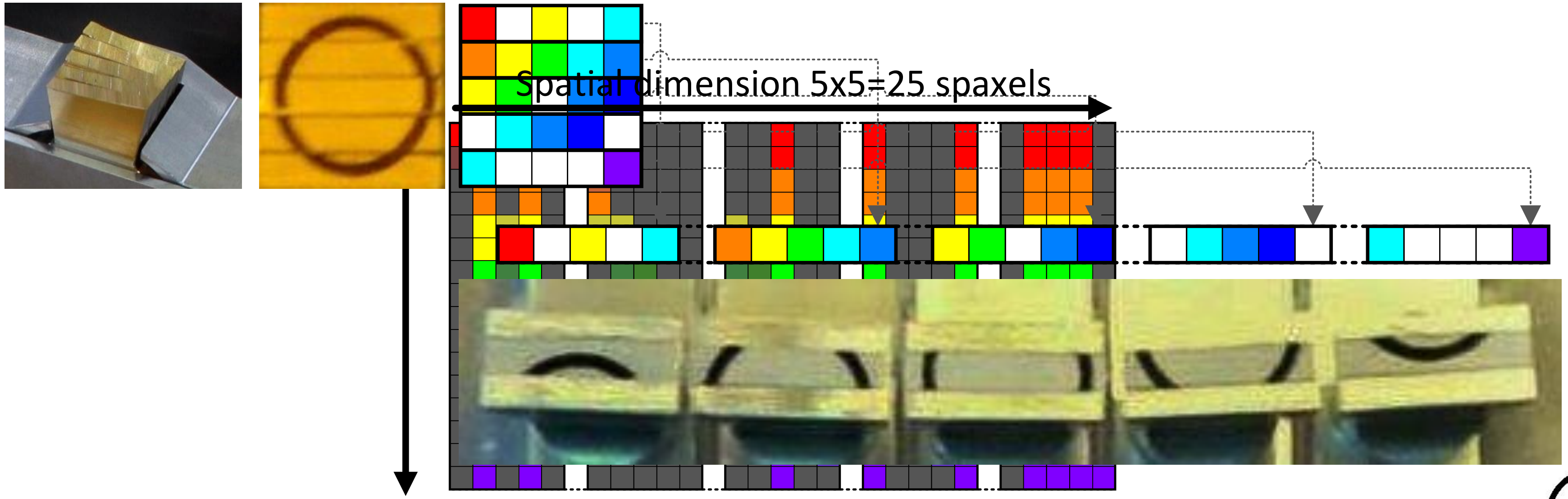
Field-Imaging Spectroscopy:

- 2-dimensional Field of View
  5x5 spatial pixels = ‘spaxels’
- 3^{rd} dimension spectral information
- 3D data but
  2D detector arrays



Top Level Design Field Imaging II

- Mirrors rearrange 5x5 spaxel FOV into 25x1 spaxel slit
- Slit enters grating spectrometer
- Spectrally dispersed light is imaged on 25x16 pixel detector array
  → 400 pixels



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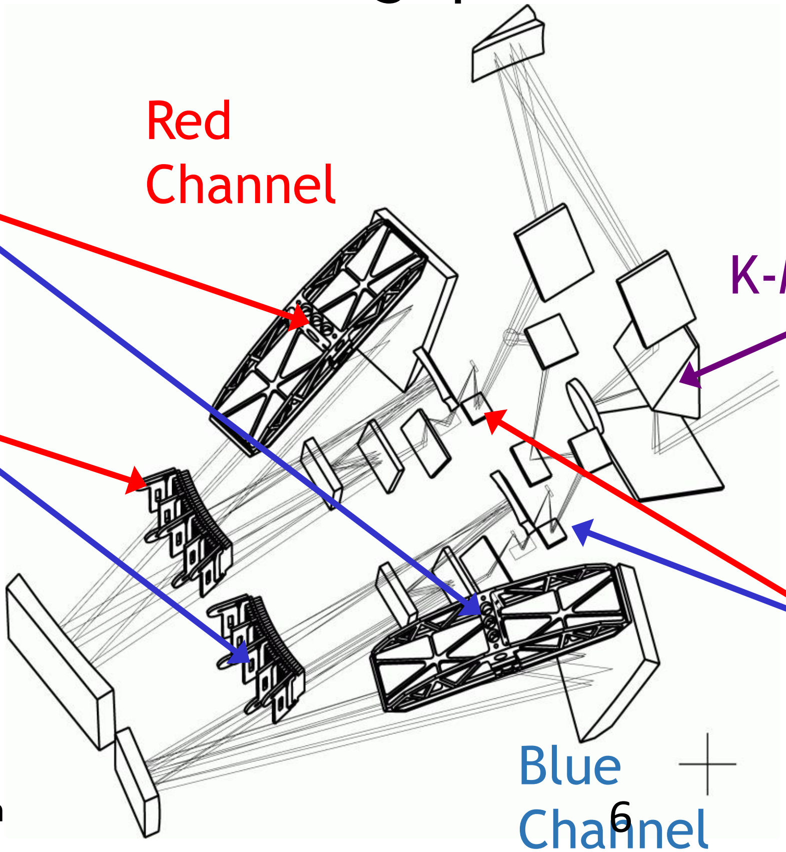
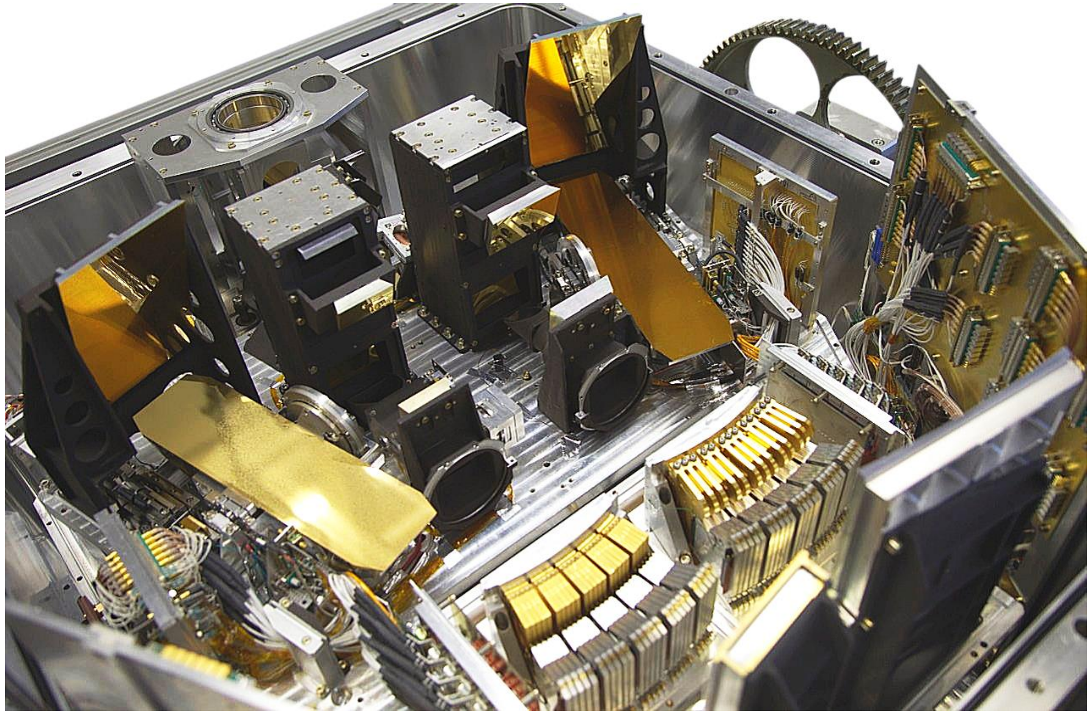
Top Level Design Layout

- Four layer bath cryostat (290K, 77K, 6K, 1.8K)
- Reflective image slicer as integral field unit
- Grating spectrometers in Littrow-Mounting





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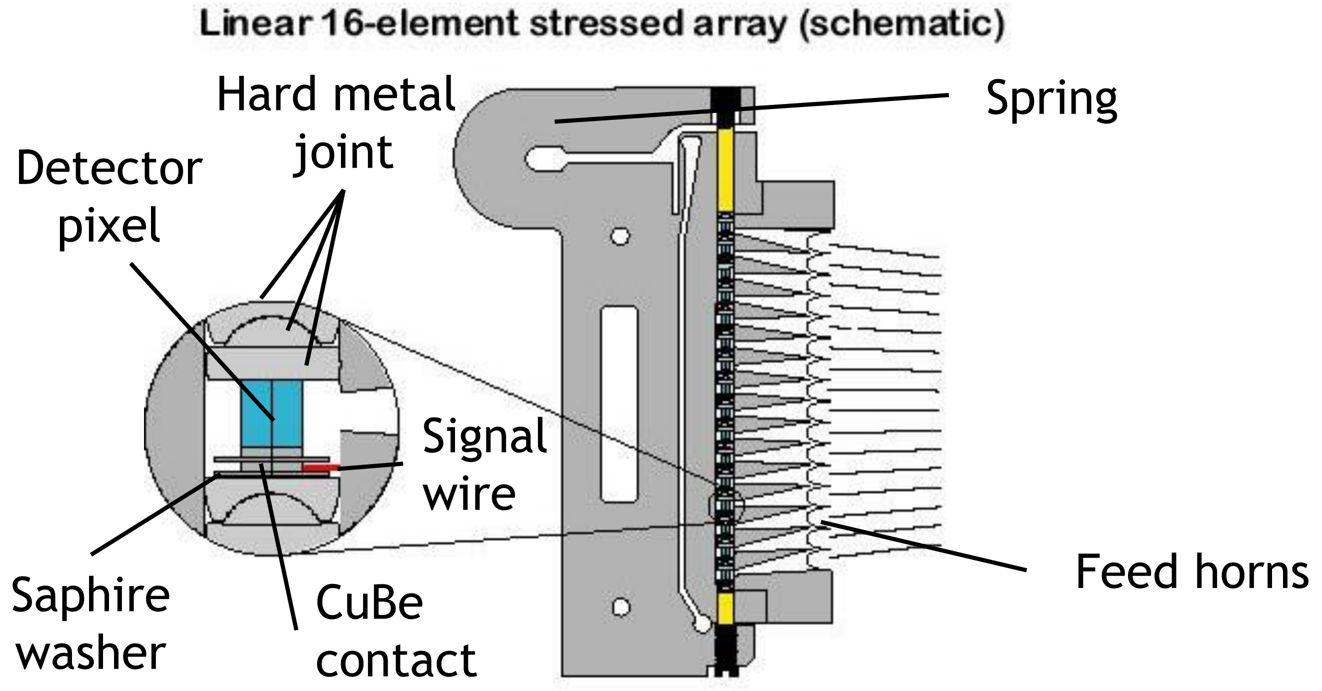
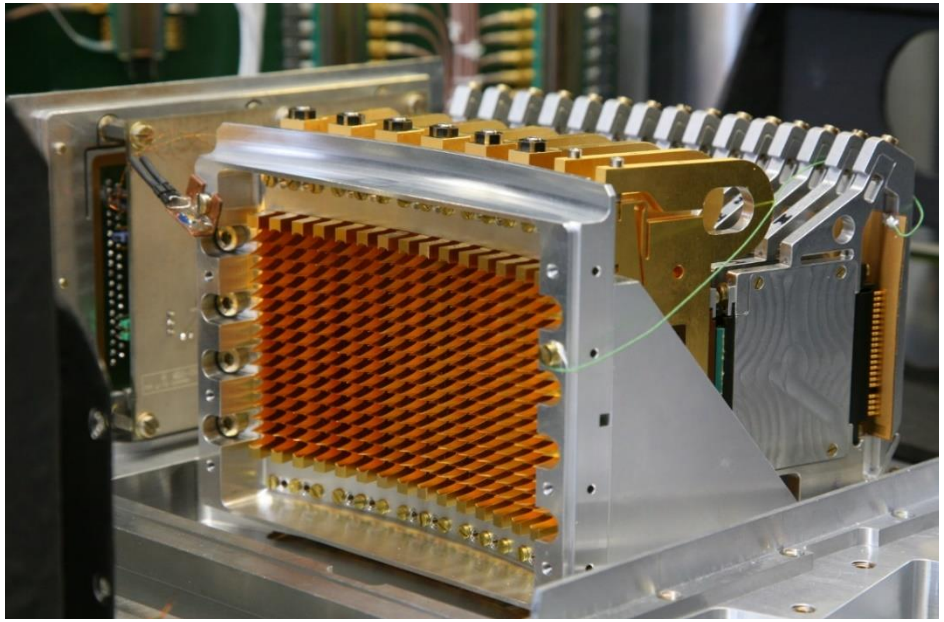
- 2 Ge:Ga photoconductor arrays
  25x16=400 pixels in each array
- Stressed (long λ) and unstressed (short λ)
- Quantum efficiency: 20-30%





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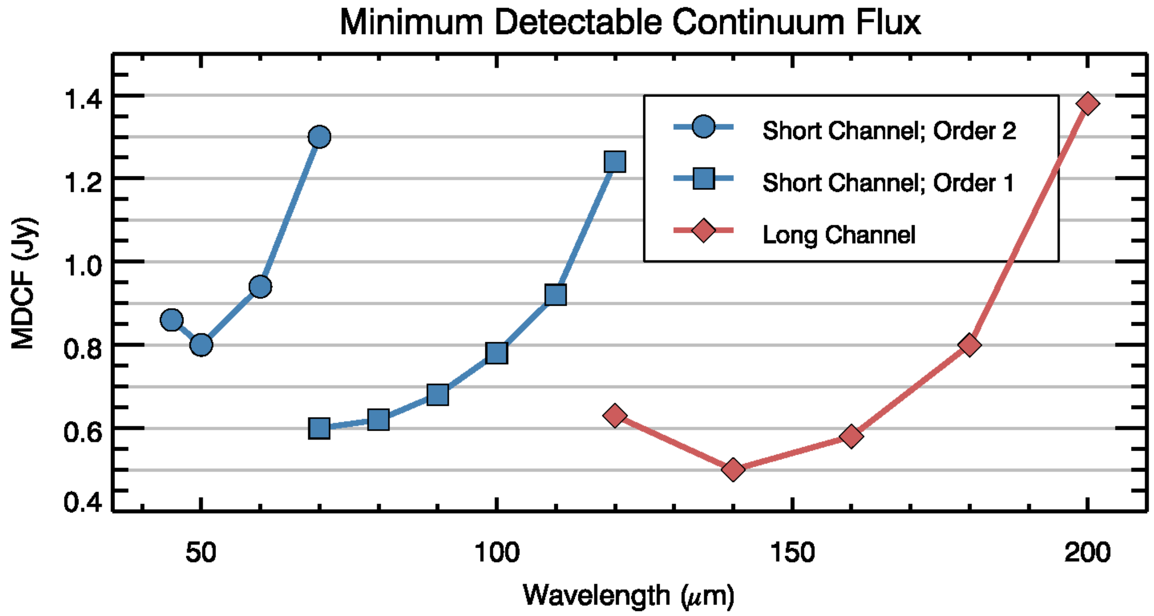
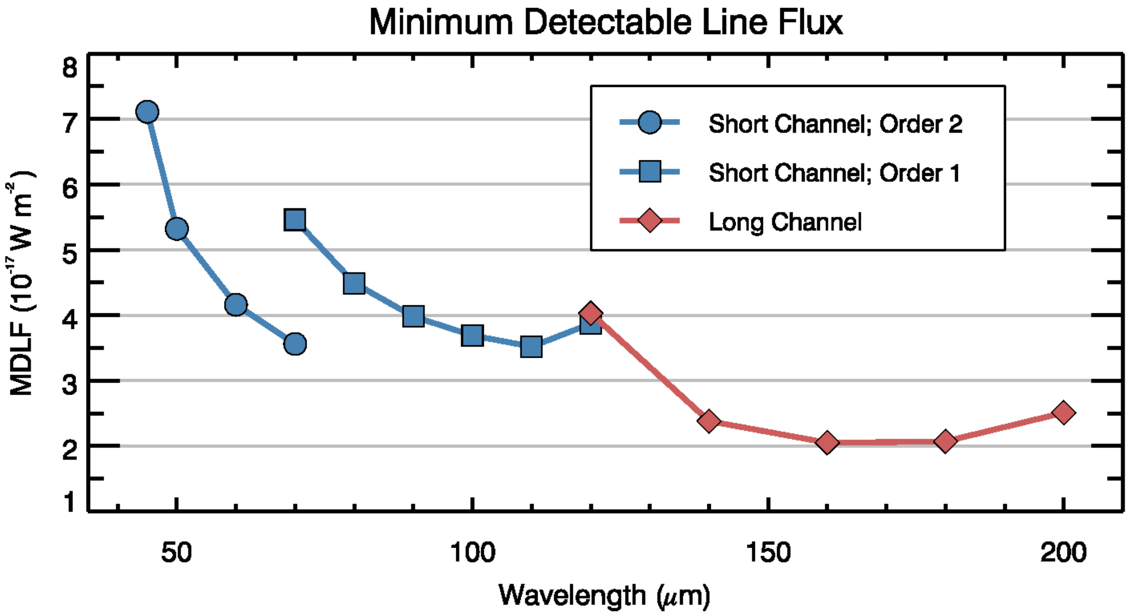
Performance I

Sensitivity

S/N 4 in 900s, Jy/Spaxel



S/N 4 in 900s, W/m² / Spaxel



Current values from Observers Handbook – will be updated (new improved entrance filter)

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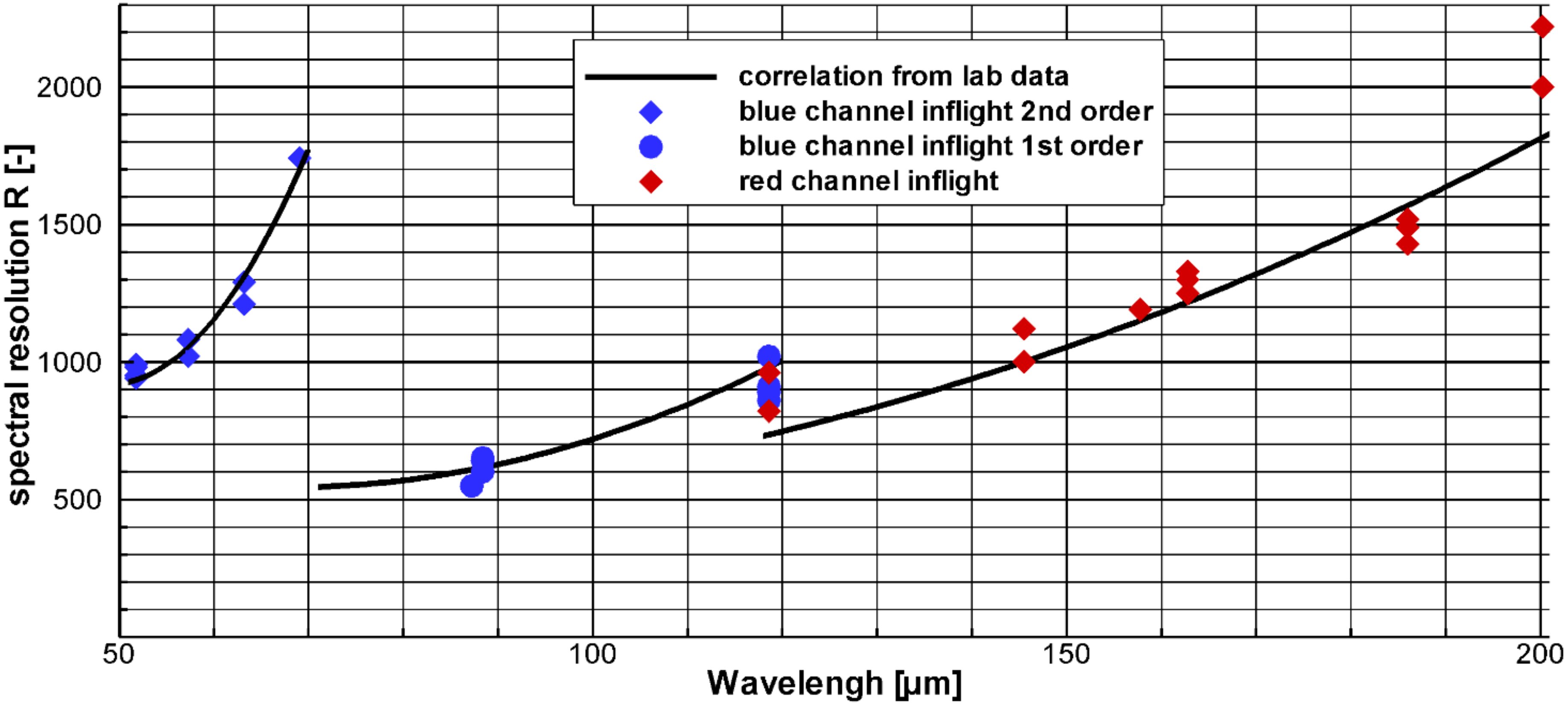
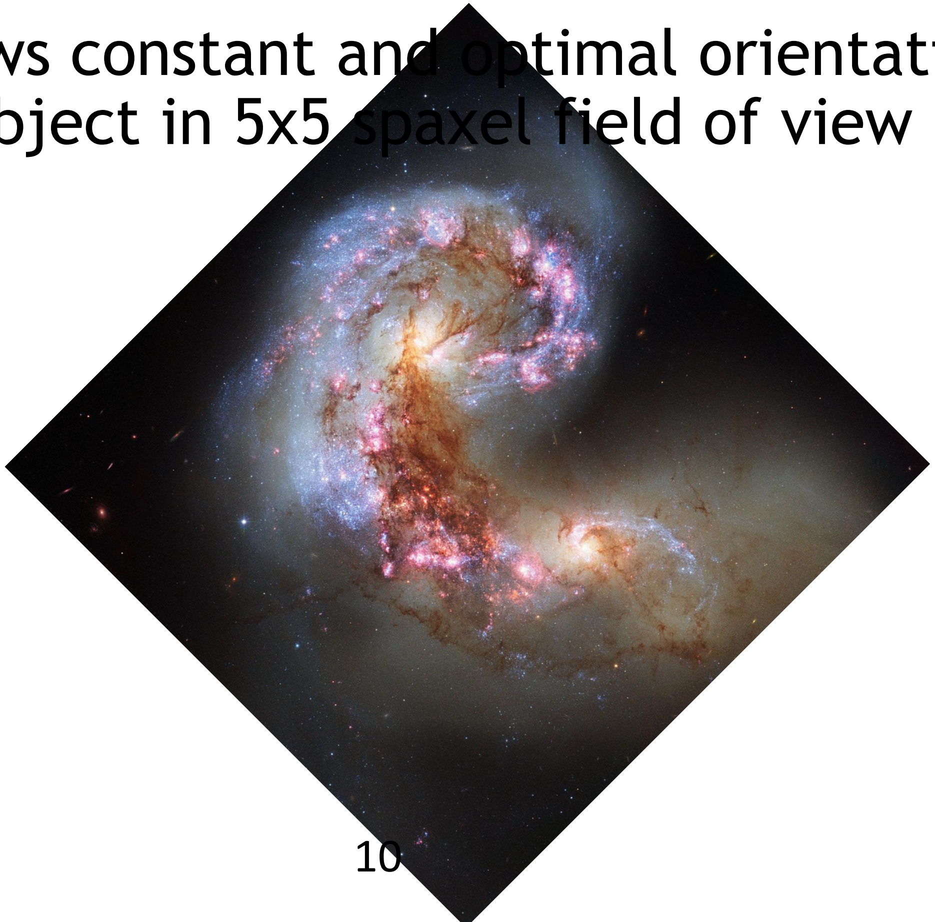
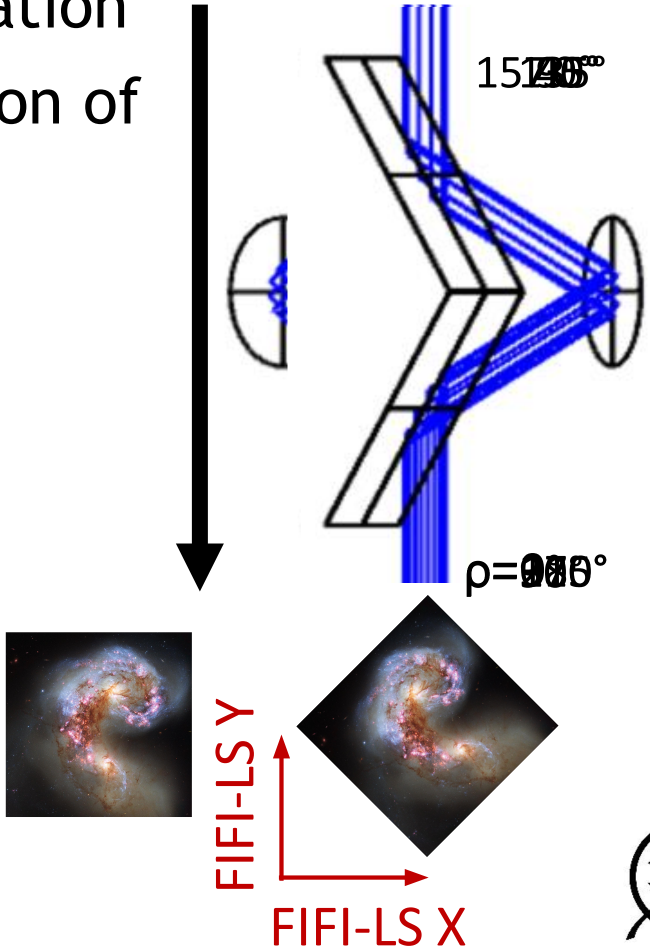
Spectral Resolution



Spatial Calibration I: Beam Rotation

- Image on sky may be rotated
- K-Mirror assembly used to change rotation
- Allows constant and optimal orientation of an object in 5x5 spaxel field of view





Spatial Calibration II

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- Relative Spaxel positions are measured in the laboratory
- Absolute position on the sky is recalibrated once per flight series
- PSF is dominated by the telescope
  - First order approximation is PSF diameter in seconds of arc is better than 1/10th of the observed wavelength in μm
  - e.g. 100μm approximately <10 seconds of arc

Wavelength Calibration I

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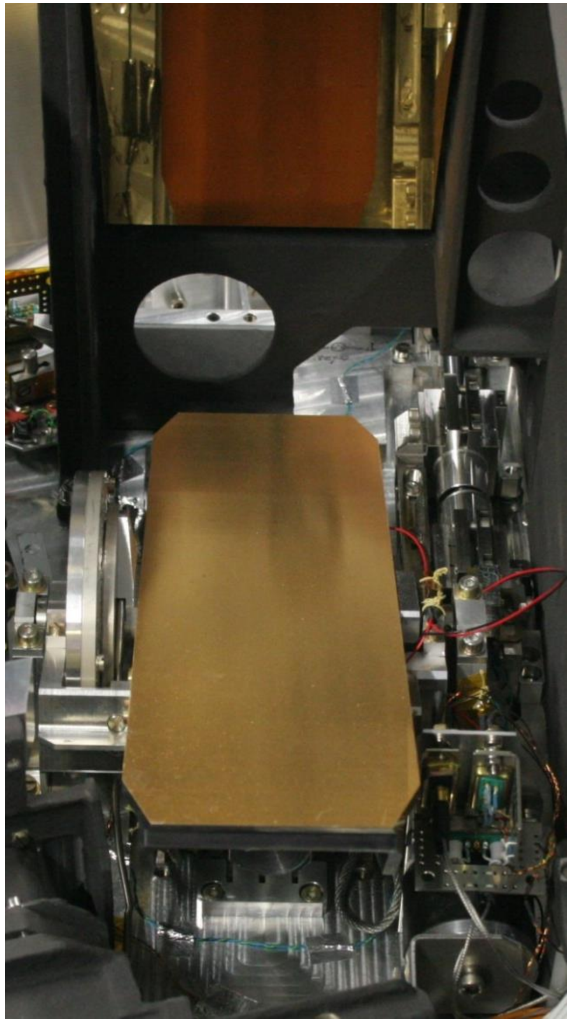
- Movable reflecting gratings
- Observed wavelength dependent grating angle
- Grating angle (φ) measured with Inductosyn® Transducer
- 0.077” = 1 ‘Inductosyn Unit’ [ISU] → 360° ≈ 16,777,000 ISU
- λ[μm] = f(GratingAngle[ISU]) ?



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- 10+ water lines measured in each spectral channel → more than 4000 data points per channel (25 Spaxels x 16 spectral Pixels x 10 Line Positions)
- Least squares approx. fits the 32 parameters of the calibration model

$$\lambda = \frac{g_0 \cos(\vartheta(Spaxel\#))}{\mathrm{m}} (\underbrace{\sin(\varphi - \gamma)}_{\text{Inbound}} + \underbrace{\sin(\varphi + \gamma + \delta(Pixel\#))}_{\text{Outbound}})$$

- 3 final calibration models provided (one in each spectral band):

  λ[µm] = f(GratingAngle) for all 400 pixels of each spectral band

- **Calibration accuracy ±10%** of a spectral resolution element in the laboratory (15-60km/s depending on λ)
- Accuracy comparable to PACS-Spectrometer on Herschel Satellite

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- Two spectral channels: 51 – 120µm and 115 – 203 µm

line	λ [µm]	line	λ [µm]	line	λ [µm]	line	λ [µm]
[OIII]	51.8	CH_4	80.1	CO	104.4	CO	162.8
OH	55.9	CO	84.4	CO	118.6	OH	163.3
[NIII]	57.3	OH	84.5	[NII]	122	HCN	169.4
[OI]	63.2	CO_2 (ice)	86	CO	124.2	CO	174
C_2H_2	68.6	CO	87.2	CO	130.4	CO	186
CO	69.1	CH_4	87.3	[OI]	145.5	CO	200.3
C_2H_2	69.7	[OIII]	88.4	CO_2 (ice)	146		
CO	70.9	OH	96.3	CO	153.3		
CO	77.1	CO	96.8	[CII]	157.7		

- [CII] has been detected up to z = 0.04

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Using FIFI-LS

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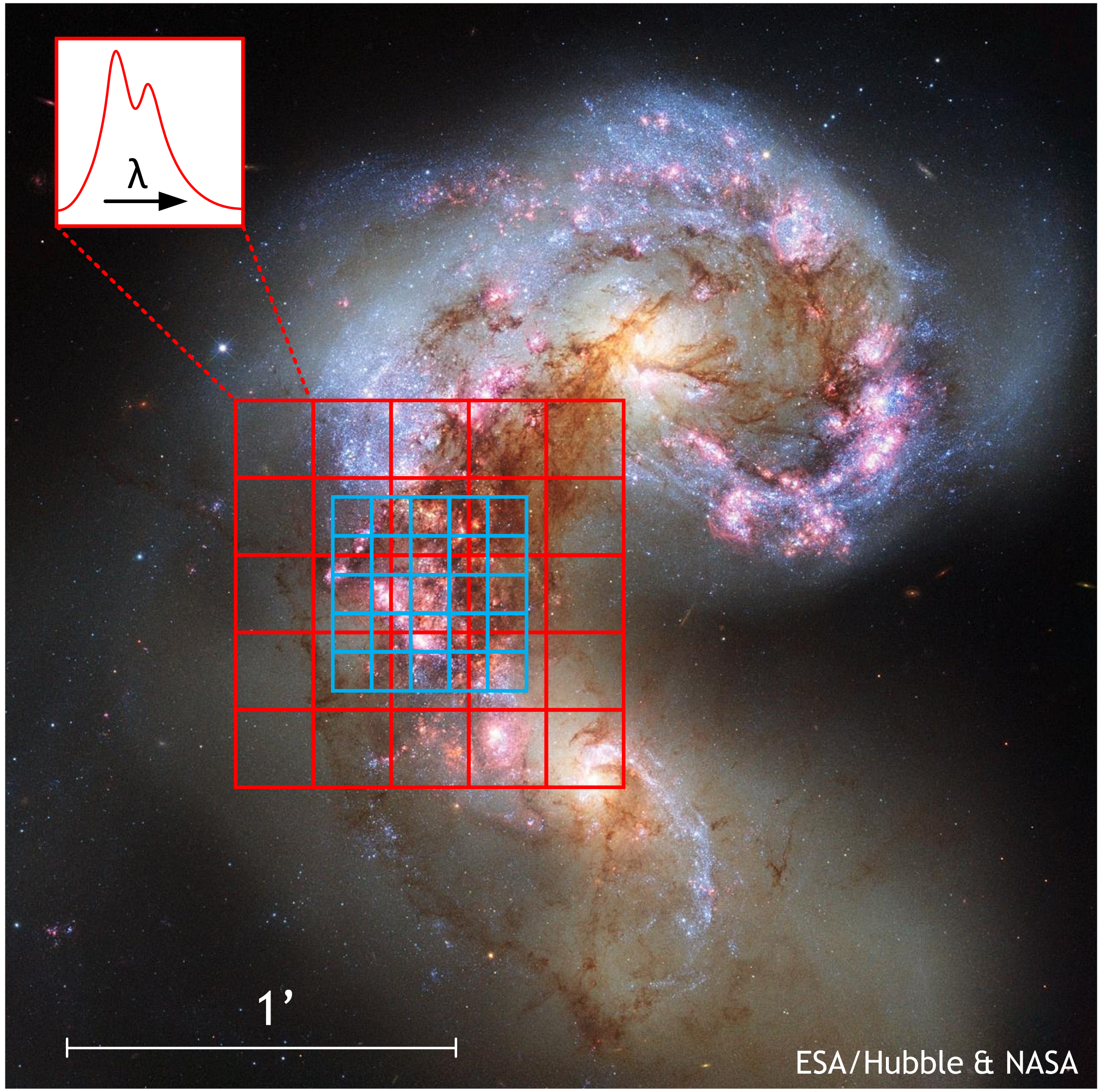
- Simultaneous spatial imaging:
  30"x30" and 60"x60" respectively in each channel

- Each field of view resolved with 5 x 5 spatial pixels



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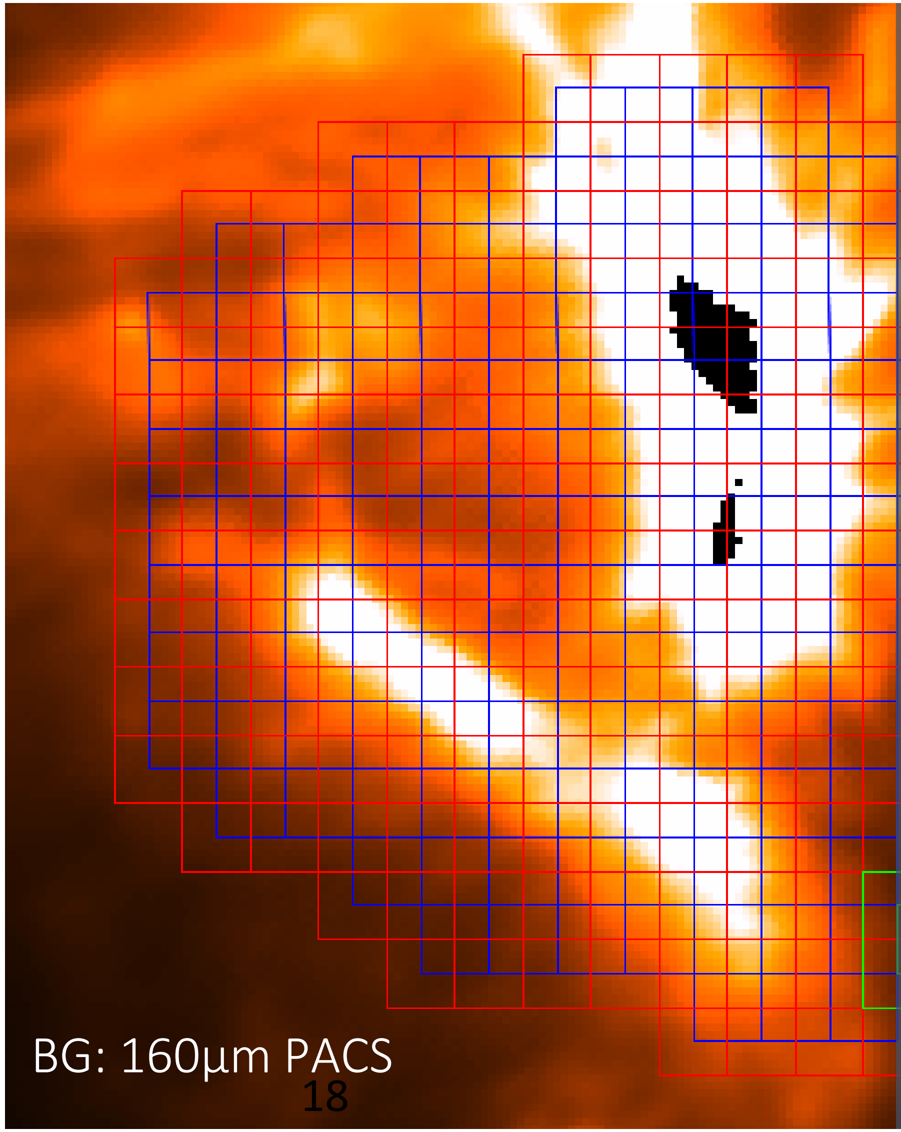
- Some mapping examples



- 30’’ raster
- 10s on source per field
- Will yield 40s on source for red channel
- 3e-17 W/m² noise level (line flux per spaxel) for [CII] 157.741µm
- 1.6e-16 W/m² noise level W(line flux per spaxel) for [OI] 63.184µm
- 76 min total time (130 fields)
- Half pixel sampling in red channel
- full pixel sampling in the blue channel
- Half pixel sampling for blue channel recommended but would double the integration time

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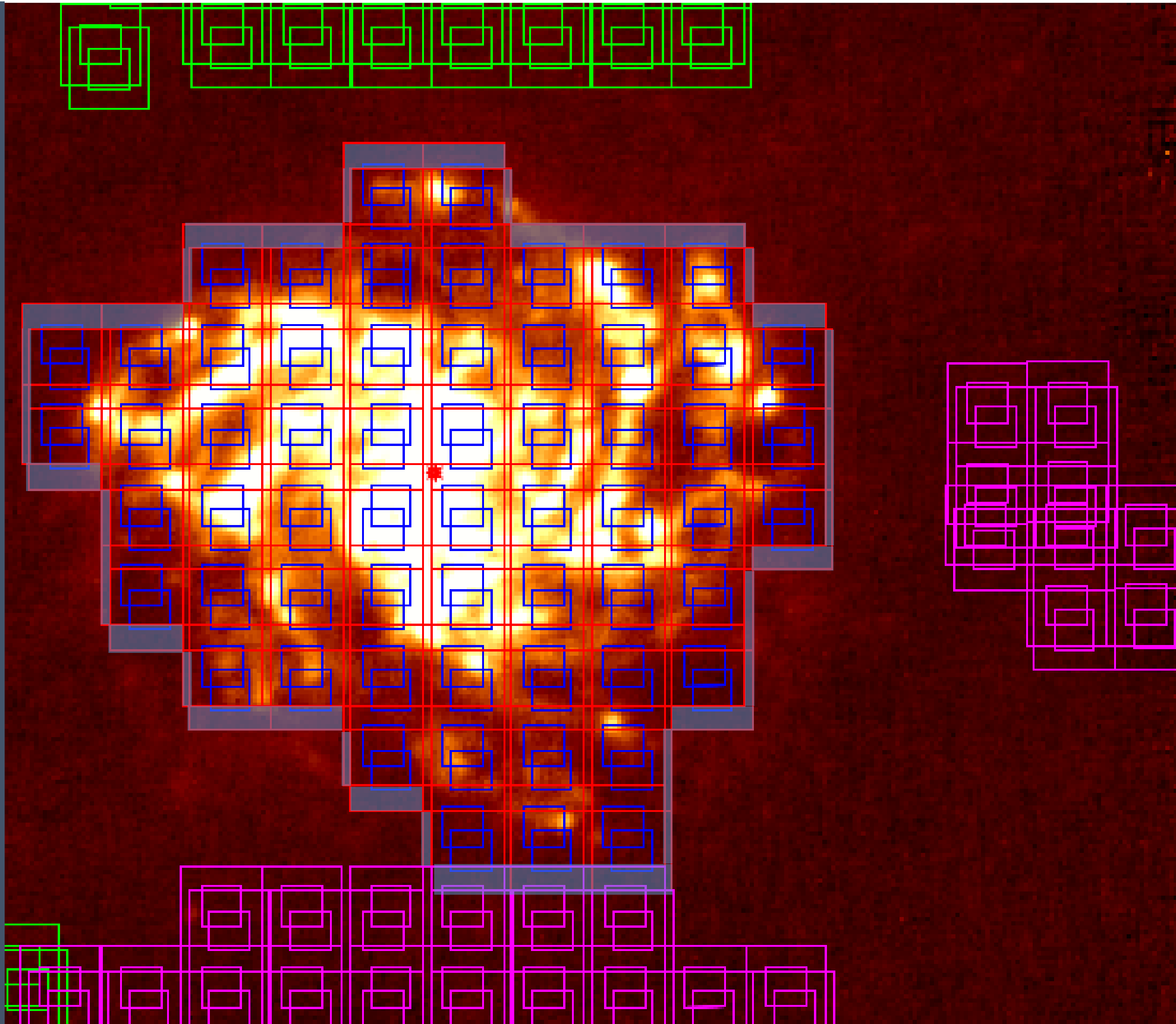
- Some mapping examples

- 2 x 60’’ raster
- Double coverage for the red map
- Incomplete coverage for the blue map
- Symmetric chop with 4 nod cycles per field (120s on source)
- 1.2e-17 W/m² noise level (line flux per spaxel) for [CII] 157.741µm
- 10h total time (120 fields)
- Half pixel sampling in red channel
- Be aware of outer area with half integration time and non ideal sampling
- Possible alternative:
- 30” raster -> 240 fields -> 90s on source -> 1e-17 W/m² noise -> 15h



Using FIFI-LS

- Some mapping examples

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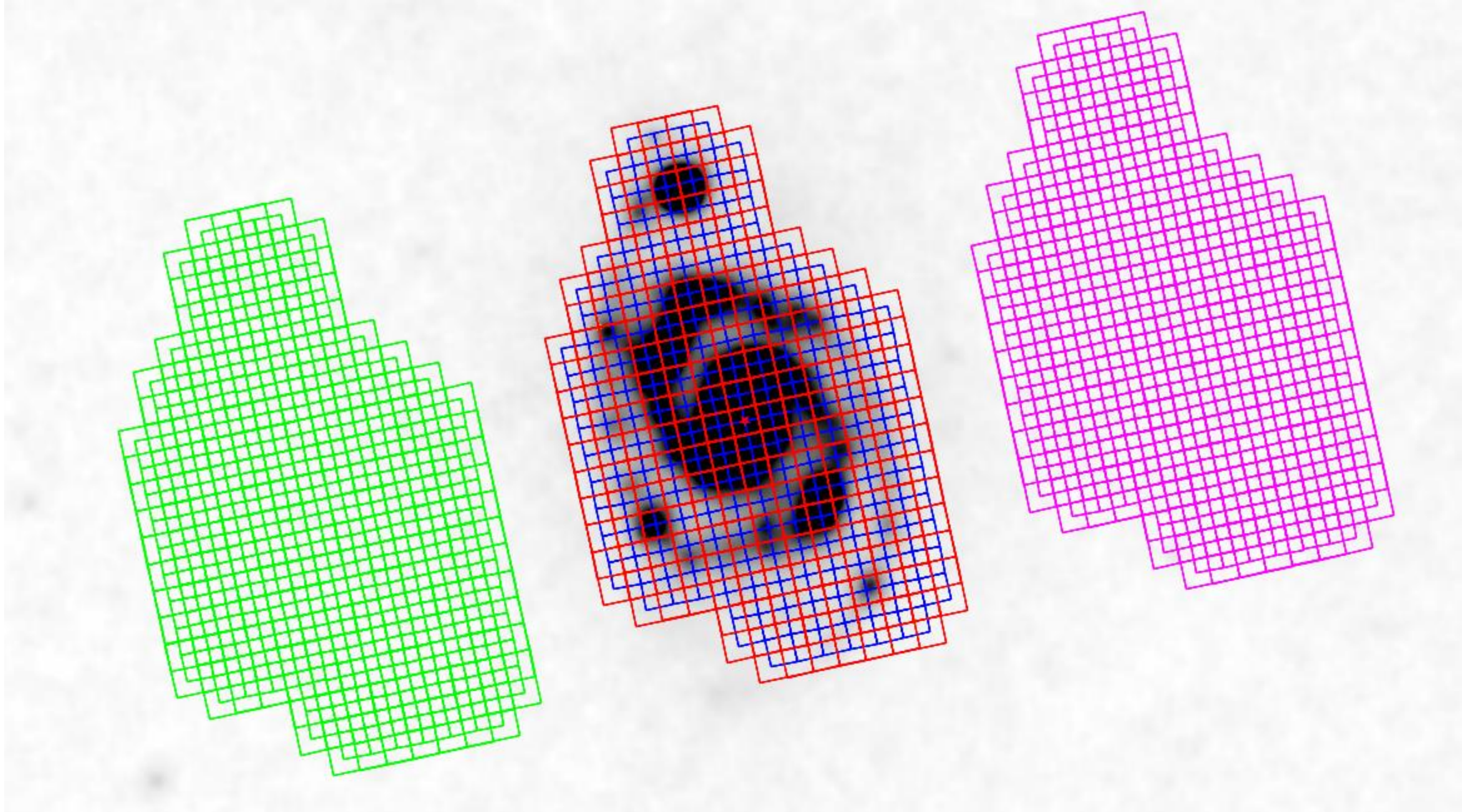
- Possible alternative:
- 30" raster -> 240 fields -> 90s on source -> 1e-17 W/m² noise -> 15h
- Spatial sampling / dithering
- Observing modes



Observing modes

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- **FIFI-LS does typically chop**
- **Matched chop/nod**
  - Up to 10 arcmin total throw
    - Some recommended limits at shorter wave length
    - Highest observing efficiency
- **Asymmetric chop**
  - Up to 10 arcmin total throw
  - Partial asymmetric chop possible (helps with certain telescope limitations on chop angle vs. throw)
  - Low observing efficiency
- **Bright object mode**
  - available when instantaneous spectral coverage is sufficient
  - ABA or AABAA nodding scheme
  - Medium efficiency but fastest mode available
- **Integration time is typically a multiple of:**
  - 30 s on source -> 76 s with overheads (Symmetric chop)
  - 15 s on source -> 57 s with overheads (ABA asymmetric chop)
  - 10 s on source -> 35 s with overheads (AABAA asymmetric chop)
- **Total power mode and OTF now available!**

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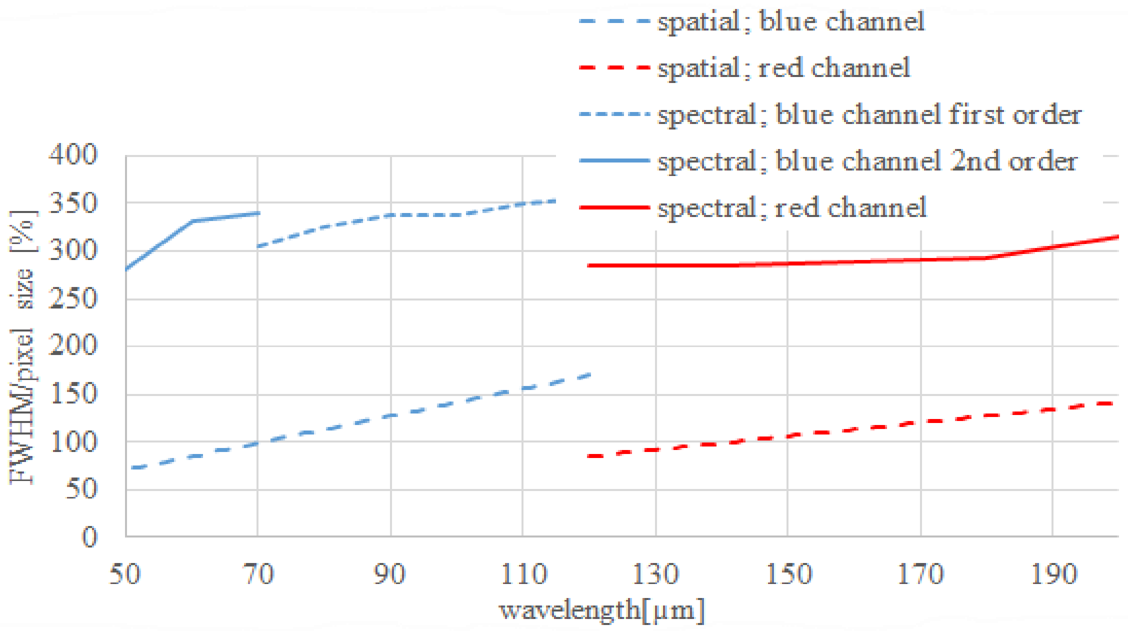
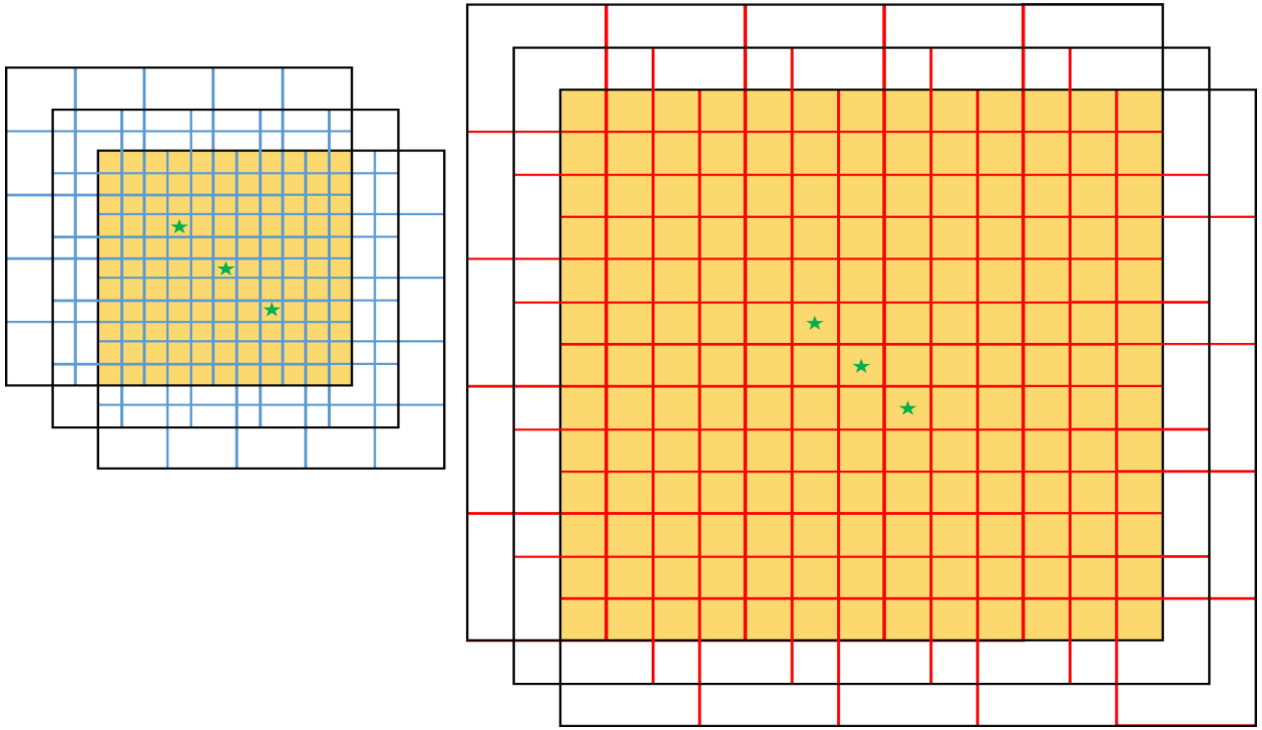
dithering

- Spatial dithering
  - Why do we need to care?
  - Things get easier for deeper integrations
    - More time to use nod cycles for new positions
    - Example: 4'',4'' ; 0'',0'' ; -4'',-4''
    - Will result in 2''/4'' sampling for blue/red channel





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- **Medium spectral resolution: R ~ 500 - 2000 (~150 - 600 km/s)**
- **16 Pixels in spectral direction in each spatial pixel**
- **Instantaneous spectral coverage: ~1500 km/s**
  e.g. velocity distribution in galaxies including baseline on both sides
- Velocity information is available
- Continuum information is available and can be used to help with telluric correction (see tutorial)
- How do I need to consider this for my observations?

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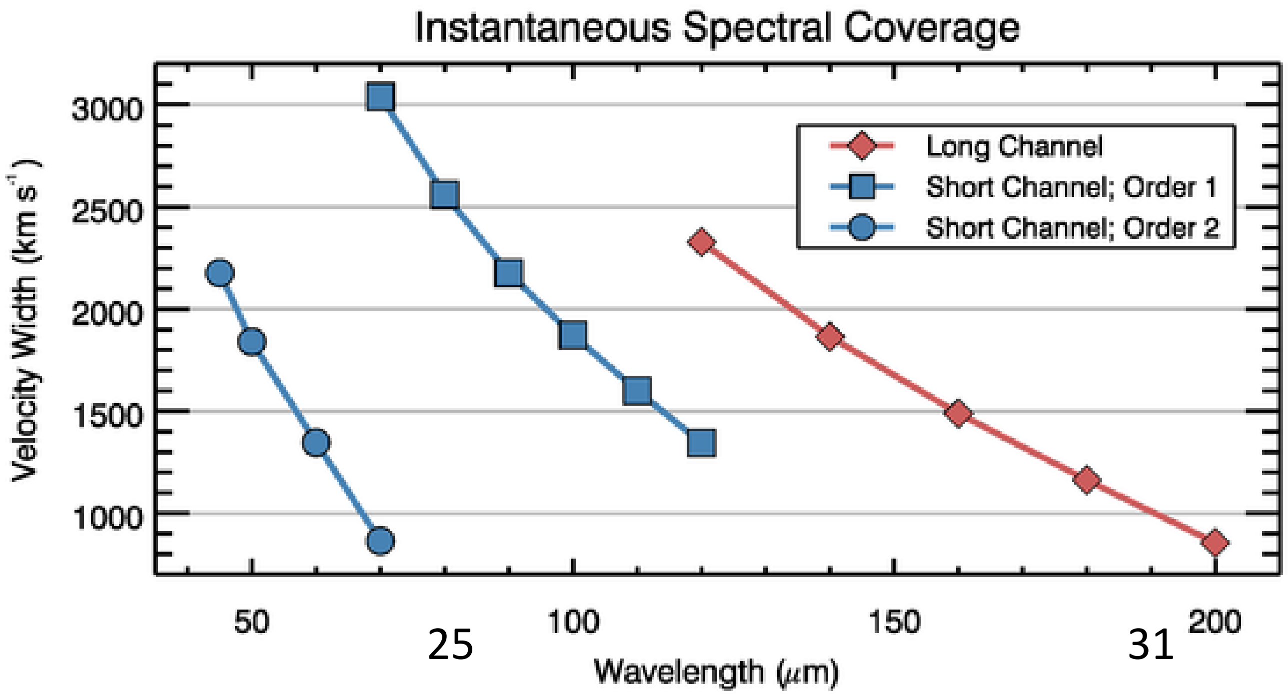
- How do I need to consider this for my observations?
- Does my line fit on the detector?
- How many detectors do I need spectrally?



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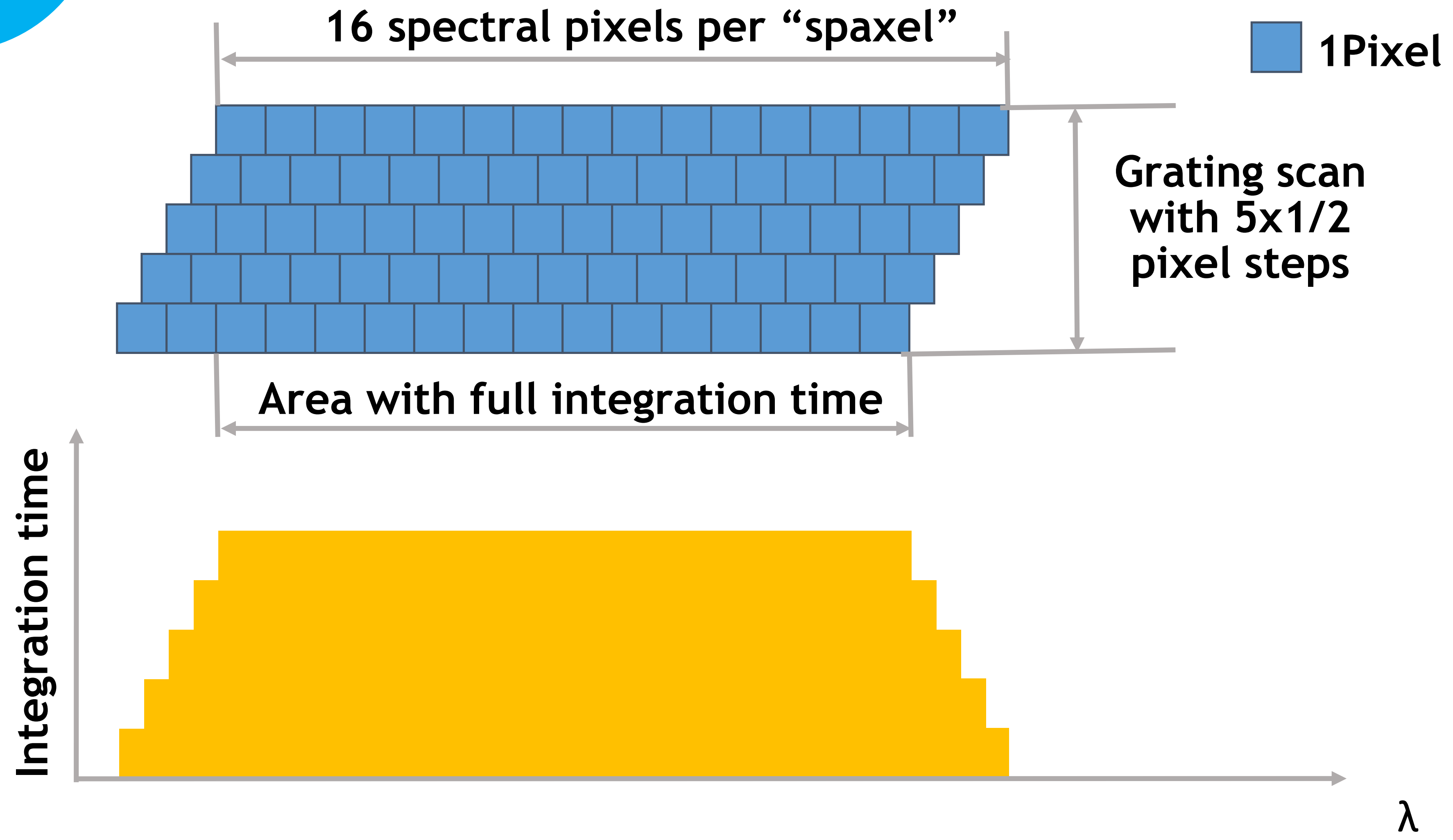
Be aware how FIFI-LS works spectrally



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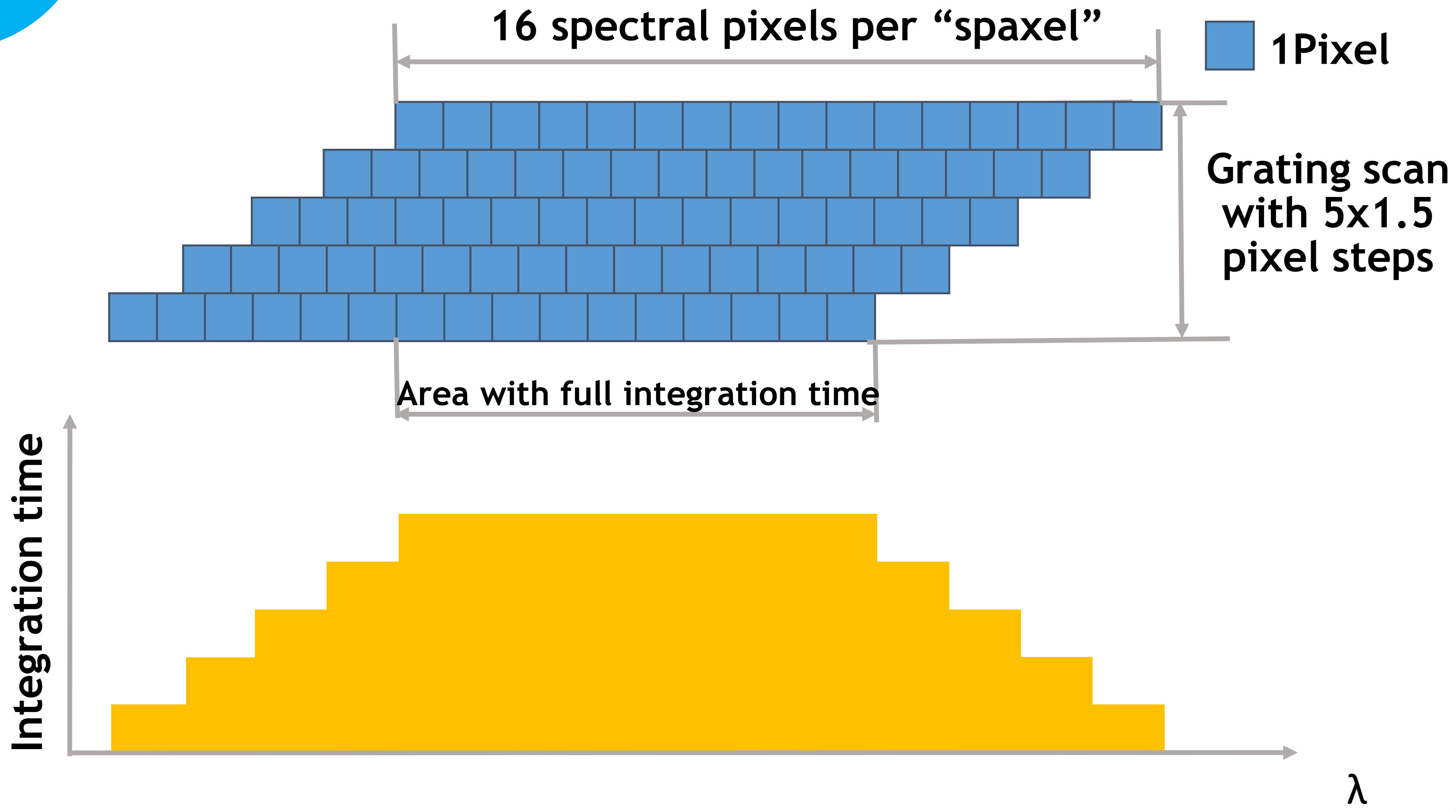
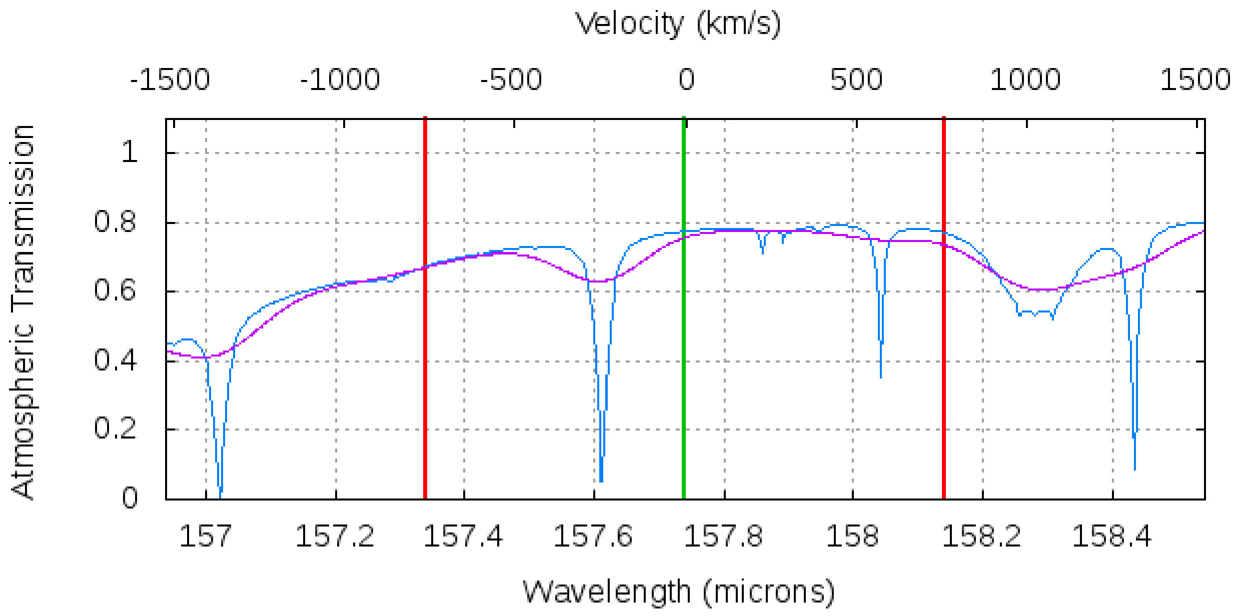
Be aware how FIFI-LS works spectrally



Using FIFI-LS

- How do I need to consider this for my observations?

- There is an residual atmosphere



FIFI-LS science examples

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Alignment with SOFIA Science Focus Areas:

- **Birth of Planets and Stars: Infall**
  - Molecular Clouds: IRDCs, “Dark” Molecular Gas, Molecular Gas in SF regions
  - Protostars, Disks, Accretion: YSOs (incl. S255, FU Oris), HHs and jets
  - Feedback: effects in SF regions
  - 37% of proposals
- **Path to Life: Dust through Cosmic Time**
  - Dust in outflows of stars and supernovae: Cas A and other young SN Remnants
  - Astrochemistry: Fullerenes in PNe, PAHs in PDRs
  - Planetary Atmospheres: Solid State features in Mars’ atmosphere, Titan
  - 20% of proposals
- **Extreme Environments: Unveiling Starbursts and AGN**
  - Dust surrounding BHs: GC
  - Imaging of local starbursts: 30 Dor, M82, NGC 1569
  - Local Analogs to high-z galaxies: numerous proposals and samples
  - Observations of AGN: several proposals
  - 43% of proposals

FIFI-LS science examples

Some open time proposals:

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FIFI-LS [OIII] Spectrosopy of Nearby Infrared Bright Galaxies: Tracing Stellar Populations, the O/N Abundance Ratio, and absolute abundances

Probing the large scale multiphase ISM in an extreme starforming low-metallicity environment: 30 Doradus in the LMC

Investigating the composition of Titan's stratosphere with SOFIA: time variability & intriguing unidentified signatures

Characterizing the Energetics of the Youngest Protostars: FIFI-LS Spectroscopy of Herschel-Identified Extreme Class 0 objects in Orion

Calibrating CII as a SFR Tracer Across the Entire Disk of the Star-forming Galaxy NGC 6946

Investigating the atomic jet component in a O-type YSO

Unveiling the Star Formation History of the Massive Galactic Center H II Region Sagittarius B1

Modeling the ionized gas in low-metallicity environments: the nearby dwarf galaxy IC10

Joint Impact Proposal: A complete velocity resolved 3-D [CII] map of the M51 grand-design spiral galaxy: Unraveling the impact of spiral density waves on the evolution of the ISM and star formation.

Neutral and Ionized Gas from the Most Energetic Extragalactic Nuclear Superbubble in NGC 3079

THz Observations of Interstellar Ices: Expanding the Power of FIFI to Explore Solid-State Astrophysics

The role of cold gas in the evolution of nearby giant elliptical galaxies

FIFI-LS Observations of Coolants in IRDCs

Probing the hidden atomic gas in Class I jets

Far-infrared OH Lines as a Proxy for Water Vapor Beyond the Snowline

Mapping extended [CII] emission in shock-dominated Seyfert galaxies with likely radio jet/ISM interactions

How accurate is [CII] tracing star formation in nearby luminous AGN?

Tracing Shocked gas in Stephan's Quintet and NGC 4258 with SOFIA

Understanding the Galactic center's ionizing sources

Exploring Far-IR Abundance Diagnostics in Nearby Galaxies

The structure of a PDR -M17-SW

Physical conditions in the dense molecular clumps of the Cas A supernova remnant

Deciphering Star Formation in Disk Galaxies: Relating ISM conditions to the Molecular Gas Fraction in NGC5055

Unraveling the Physical Processes of Molecular Gas Excitation in N159W with SOFIA FIFI-LS

Far-Infrared in the EDGE/CALIFA Sample of Galaxies

Tracing the heat wave of an accretion outburst from a high-mass young stellar object

Investigating atomic jets in high-mass YSOs

Revealing the formation of fullerenes in planetary nebulae.

End

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FIFI-LS/SOFIA vs. PACS/Herschel

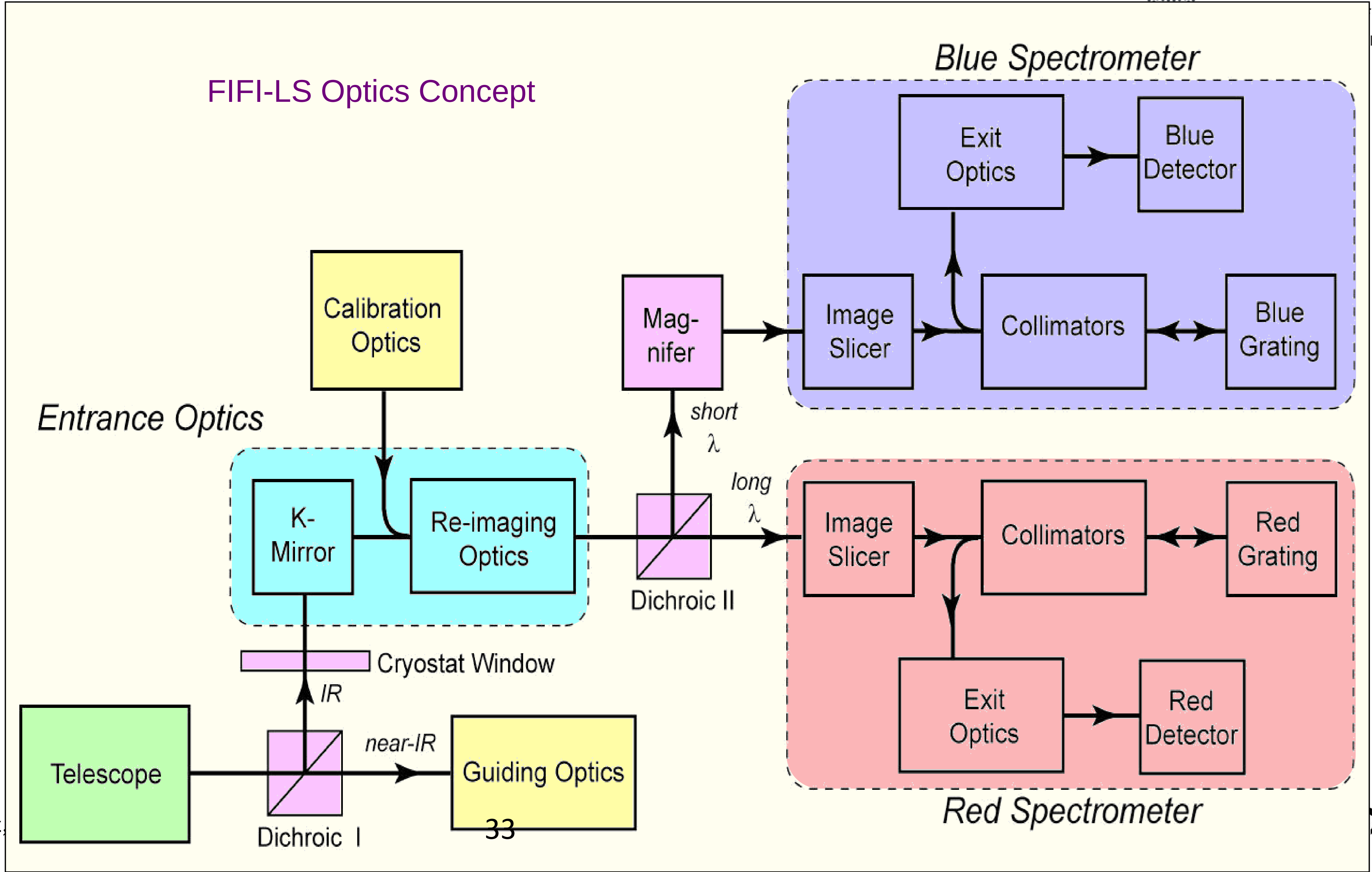
FIFI-LS/SOFIA:

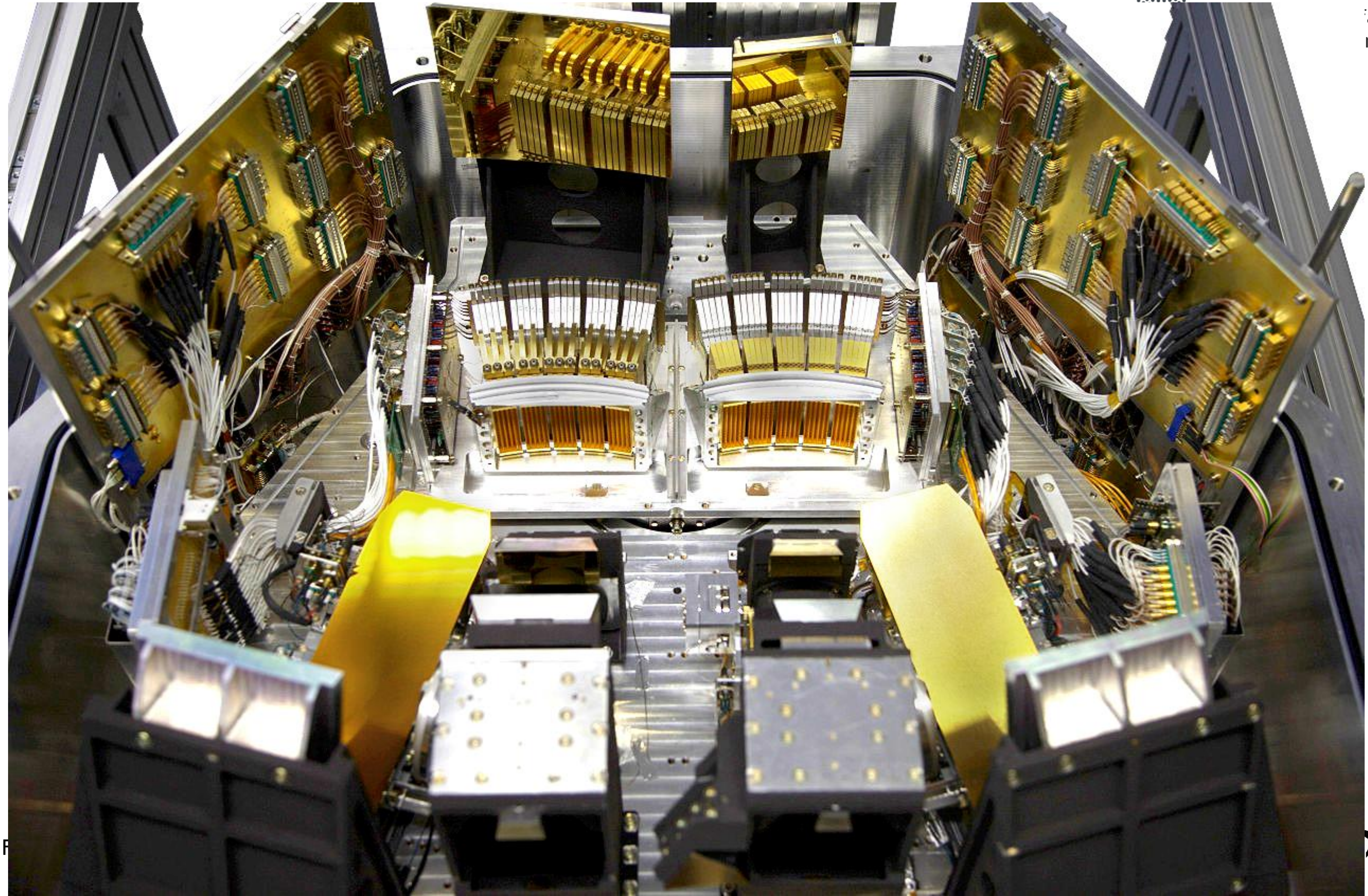
2.5m warm telescope
Atmospheric absorption
2 IFUs, image slicers, gratings
2 25x16 pixel Ge:Ga photoconductor arrays
5x5 spatial pixels; each 6"x6" & 12"x12"
FOV ~ 30"x30" and 60"x60"
16 spectral pixels
51 – 210 μm
R ~ 500 - 2000 (Δv ~ 150 - 600 km/s)
MDCF (5σ/1 hr) ~ 300 mJy
MDLF (5σ/1 hr) ~ 1.25×10^{-17} W/m^2
Blue & red channels, independent – flexible and efficient observing
Shortest integration time ~ few sec
Mapping is fairly fast and efficient
Upgradeable
Operating now!

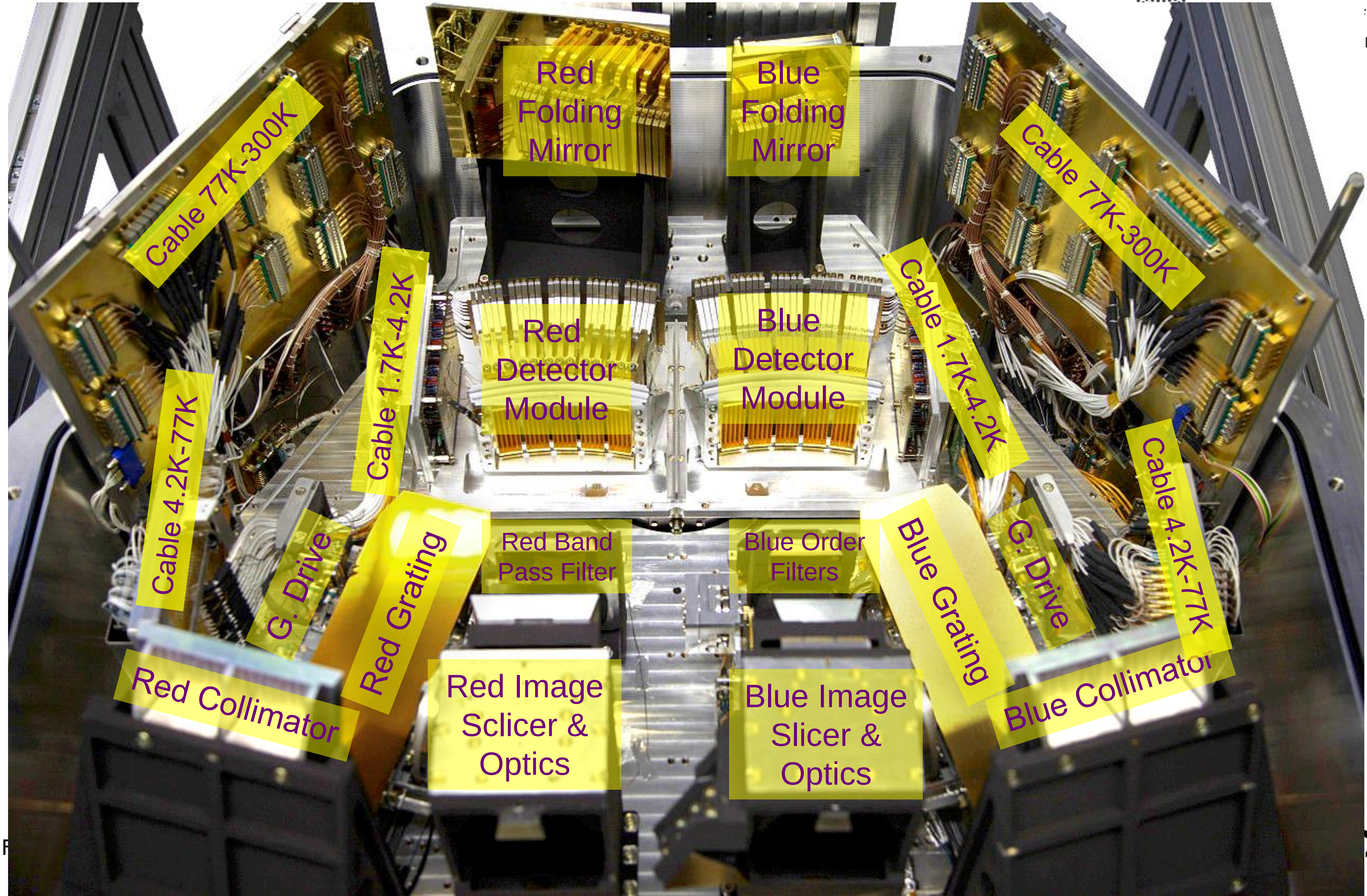
PACS/Herschel:

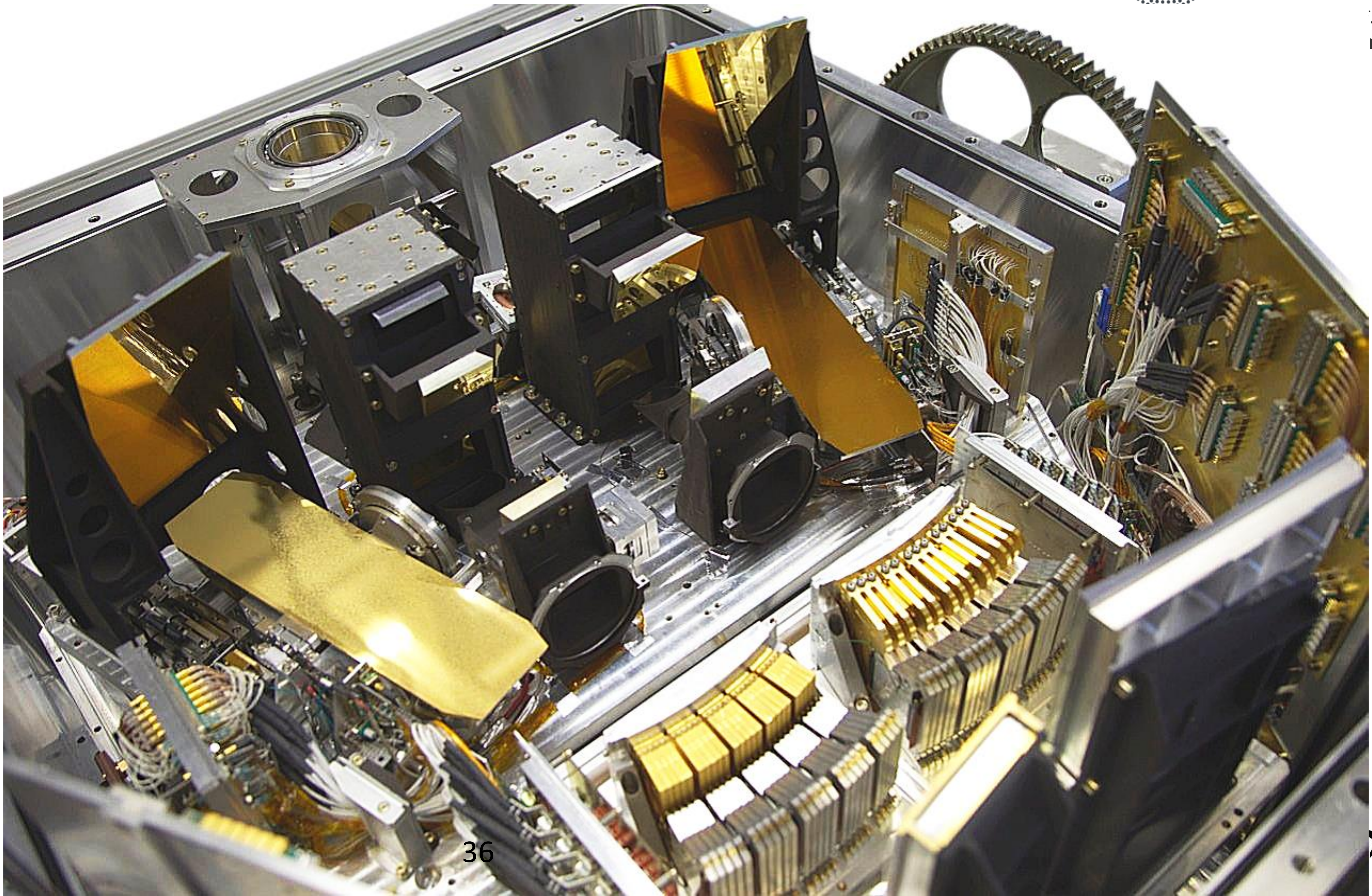
3.5m cold telescope
No atmosphere
1 IFU, image slicer, grating
2 25x16 pixel Ge:Ga photoconductor arrays
5x5 spatial pixels; each 9.4"x9.4"
FOV ~ 47"x47"
16 spectral pixels
55 - 210 μm
R ~ 1000-4000 (Δv ~ 75 - 300 km/s)
MDCF (5σ/1 hr) ~ 100 mJy
MDLF (5σ/1 hr) ~ 2×10^{-18} W/m^2
Blue & red channels, coupled

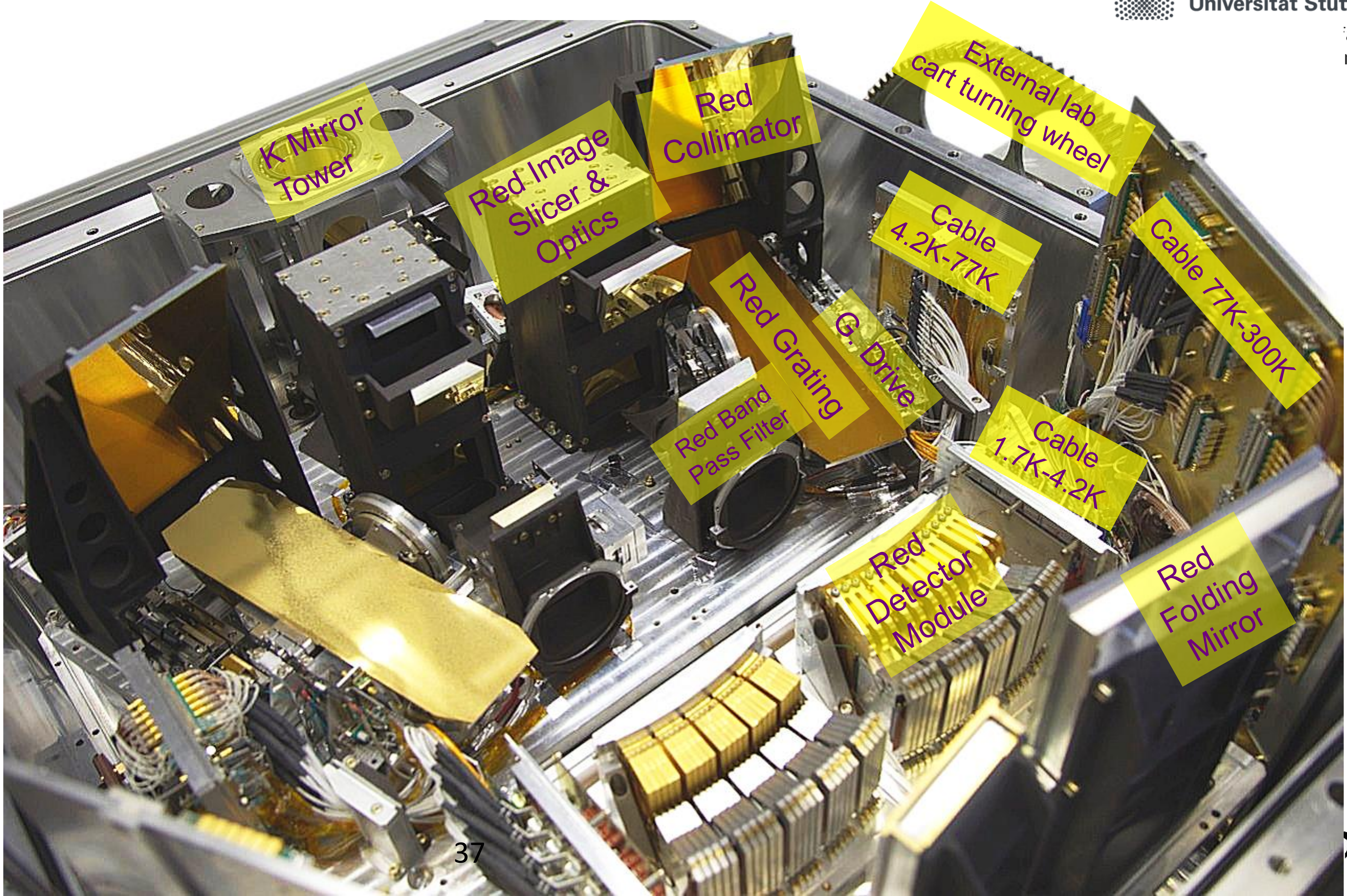
Shortest integration time ~ 7 min
Mapping speed relatively slow
Technology is frozen
No longer operational!

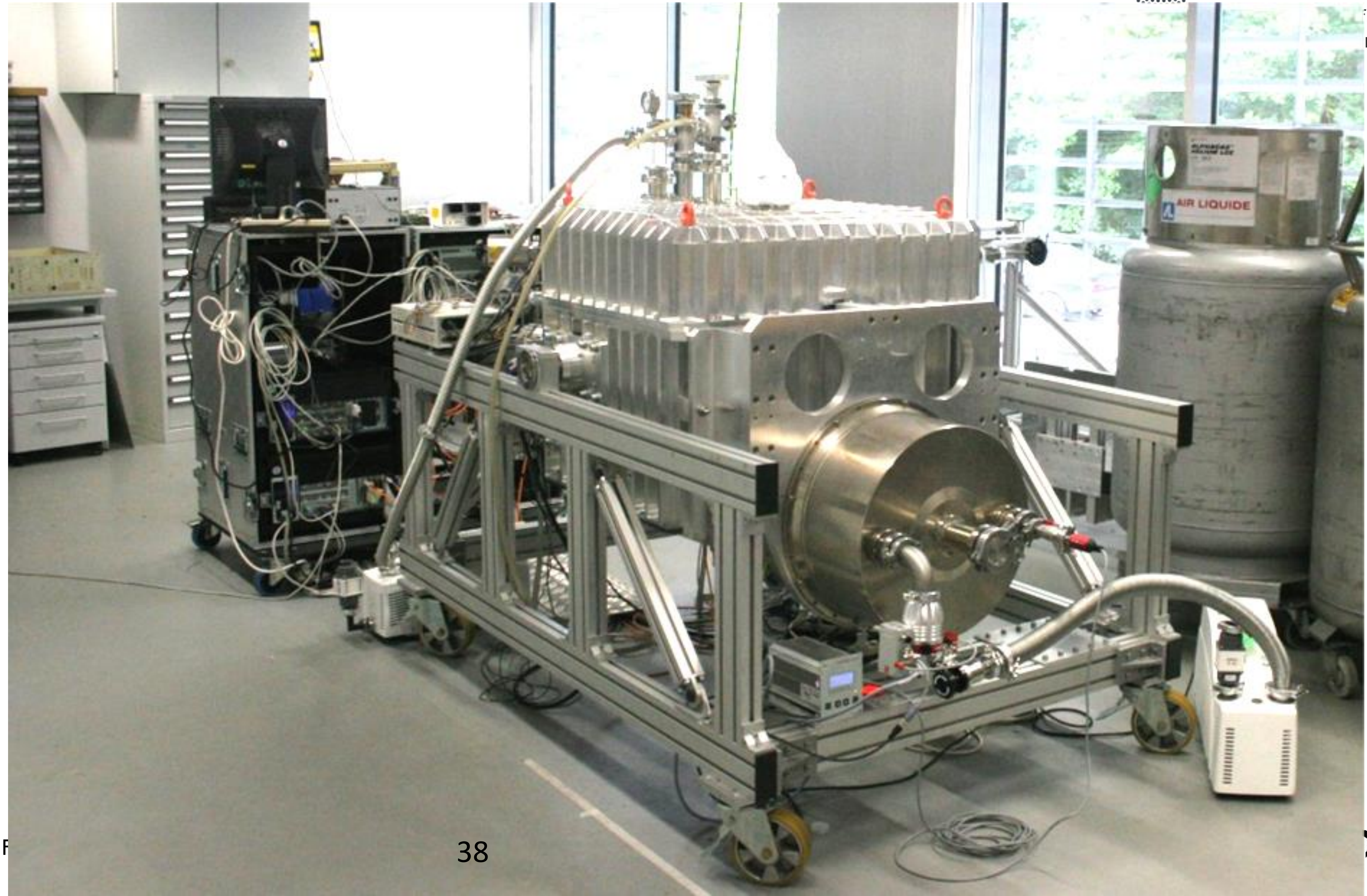

FIFI-LS Optics Concept
Blue Spectrometer
Exit Optics
Blue Detector
Image Slicer
Collimators
Blue Grating
Mag-nifer
Calibration Optics
Entrance Optics
short λ
long λ
K-Mirror
Re-imaging Optics
Dichroic II
Image Slicer
Collimators
Red Grating
Cryostat Window
IR
Exit Optics
Red Detector
Telescope
near-IR
Guiding Optics
Dichroic I
Red Spectrometer

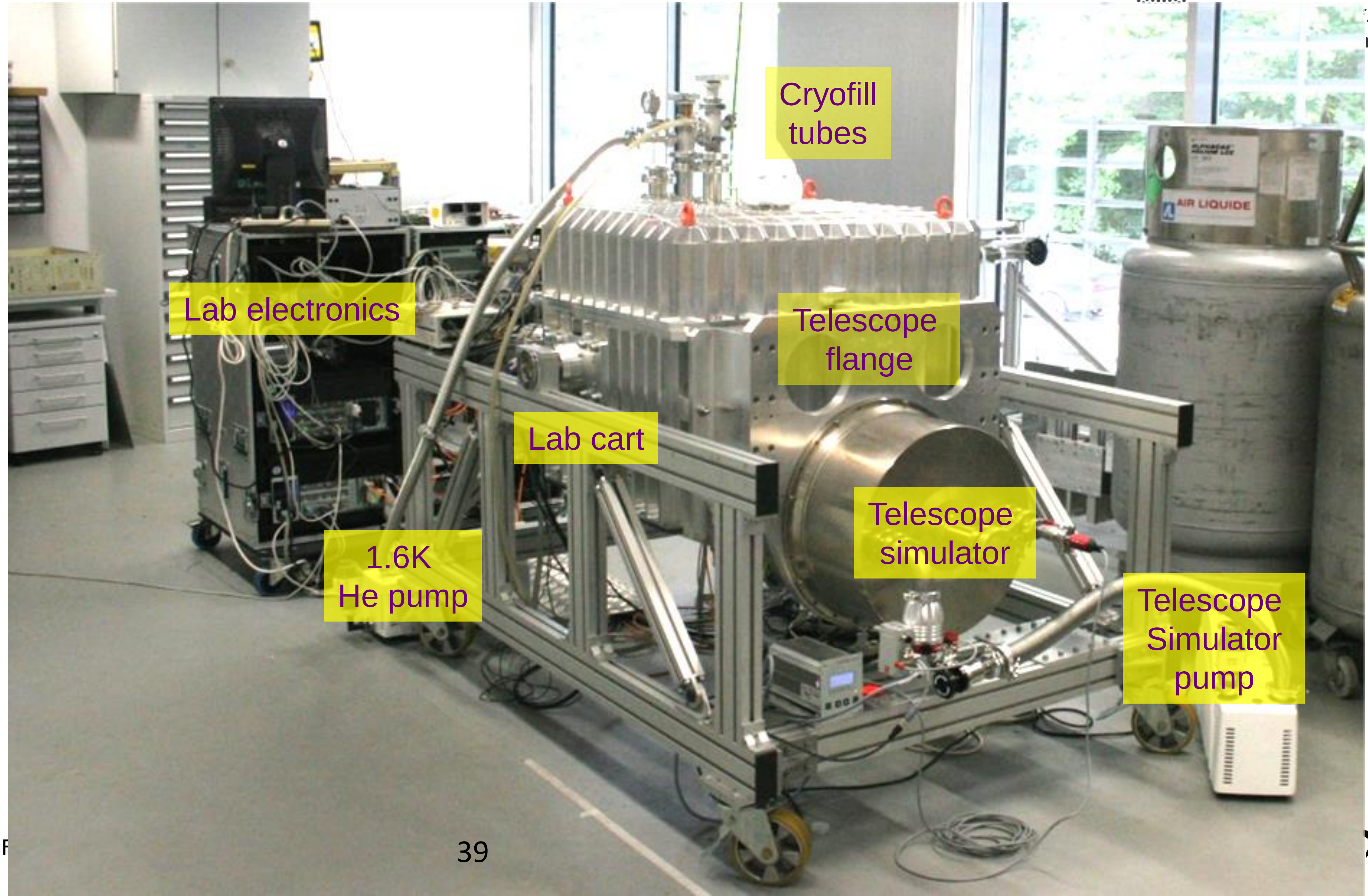



Red Folding Mirror
Blue Folding Mirror
Cable 77K-300K
Cable 77K-300K
Cable 1.7K-4.2K
Cable 1.7K-4.2K
Red Detector Module
Blue Detector Module
Cable 4.2K-77K
Cable 4.2K-77K
G. Drive
G. Drive
Red Grating
Blue Grating
Red Band Pass Filter
Blue Order Filters
Red Collimator
Blue Collimator
Red Image Sclicer & Optics
Blue Image Slicer & Optics




K Mirror Tower
Red Image Slicer & Optics
Red Collimator
External lab cart turning wheel
Cable 4.2K-77K
Cable 77K-300K
Red Grating
G. Drive
Red Band Pass Filter
Cable 1.7K-4.2K
Red Detector Module
Red Folding Mirror


AIR LIQUIDE


Cryofill tubes
Lab electronics
Telescope flange
Lab cart
Telescope simulator
1.6K He pump
Telescope Simulator pump
AIR LIQUIDE