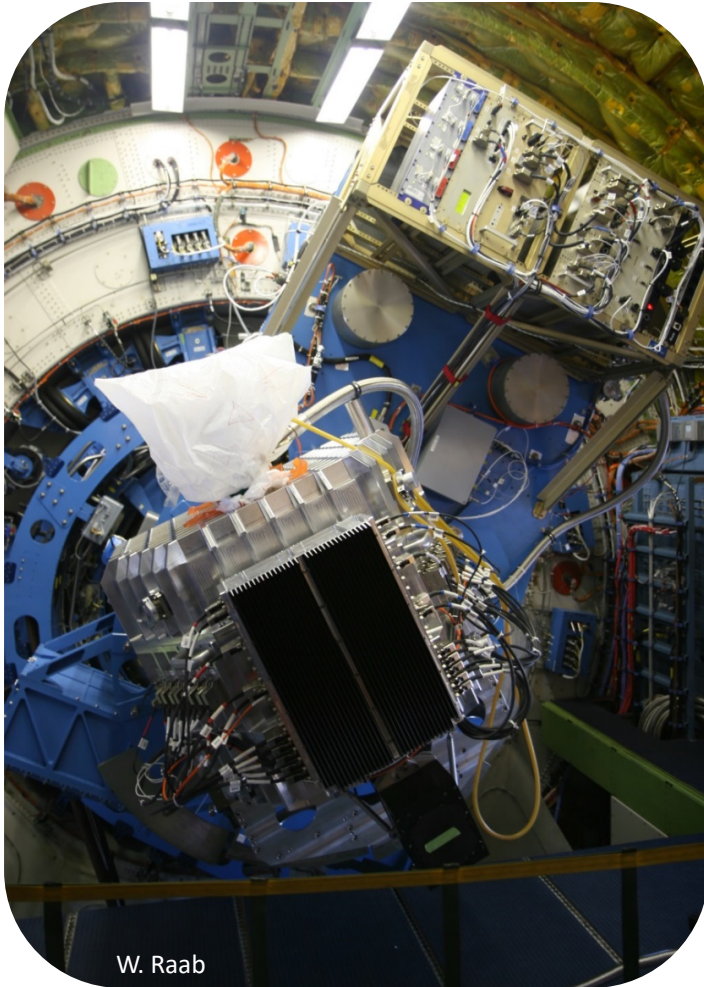




W. Raab

03.05.2018 S. Colditz, C. Fischer



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FIFI-LS

The Field-Imaging Far-Infrared Line Spectrometer

S. Colditz
C. Fischer
&
FIFI-LS Team



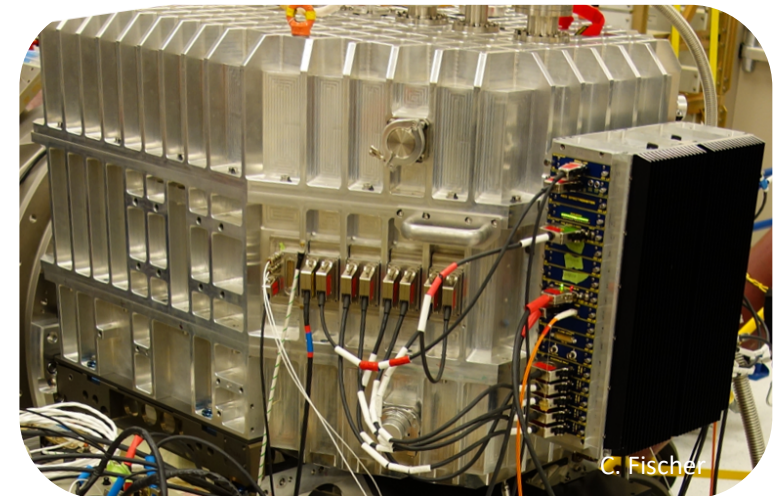
Outline

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



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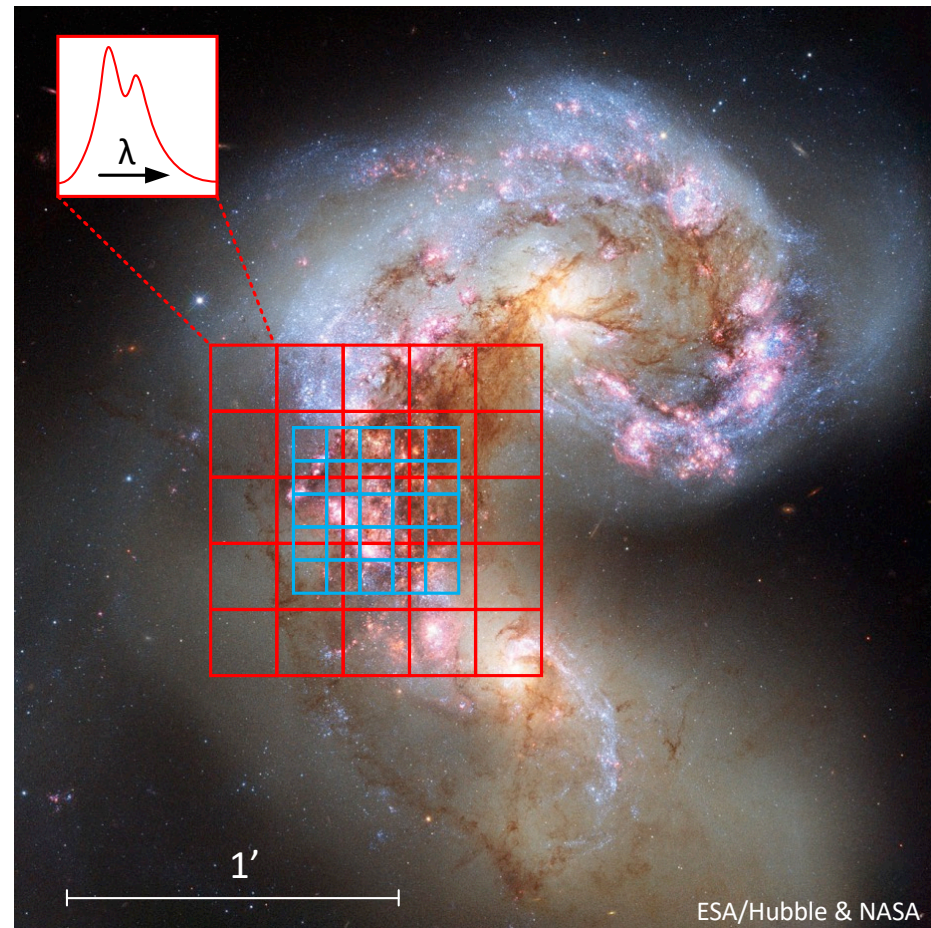




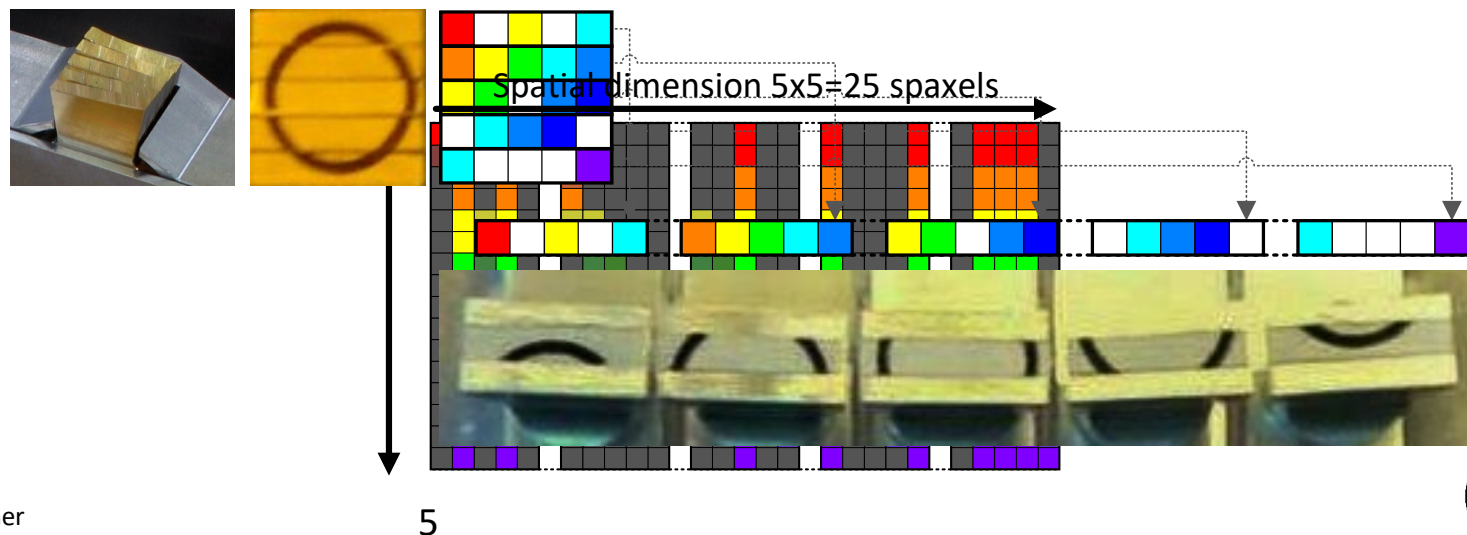
- Field-Imaging Far-Infrared Line Spectrometer
- Two spectral channels: 51 – 120 μ m and 115 – 203 μ m
- Simultaneous spatial imaging in the two channels:
30"x30" and 60"x60" field of view respectively
- Each field of view resolved with 5 x 5 spatial pixels
- Medium spectral resolution: $R \sim 500 - 2000$ ($\sim 150 - 600$ 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

Field-Imaging Spectroscopy:

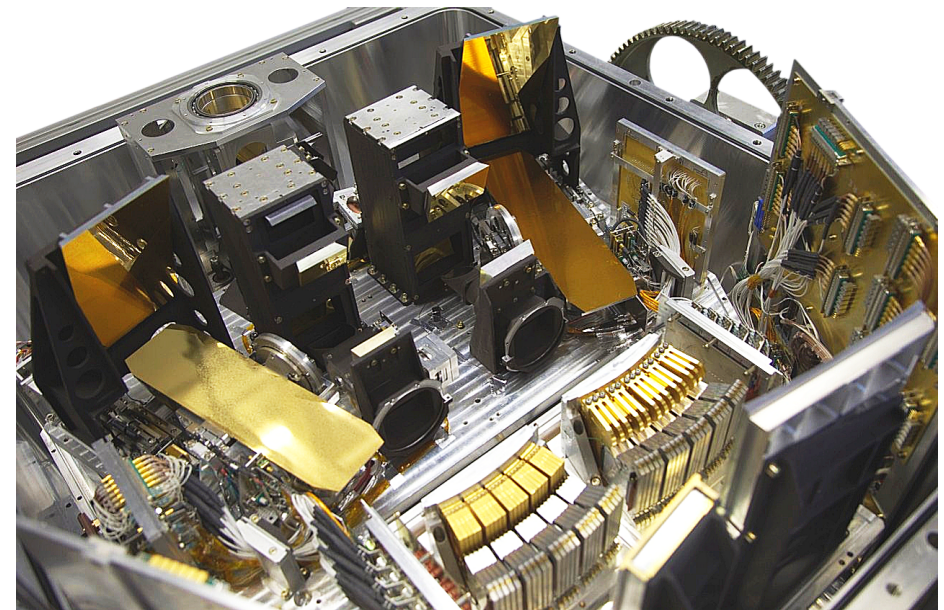
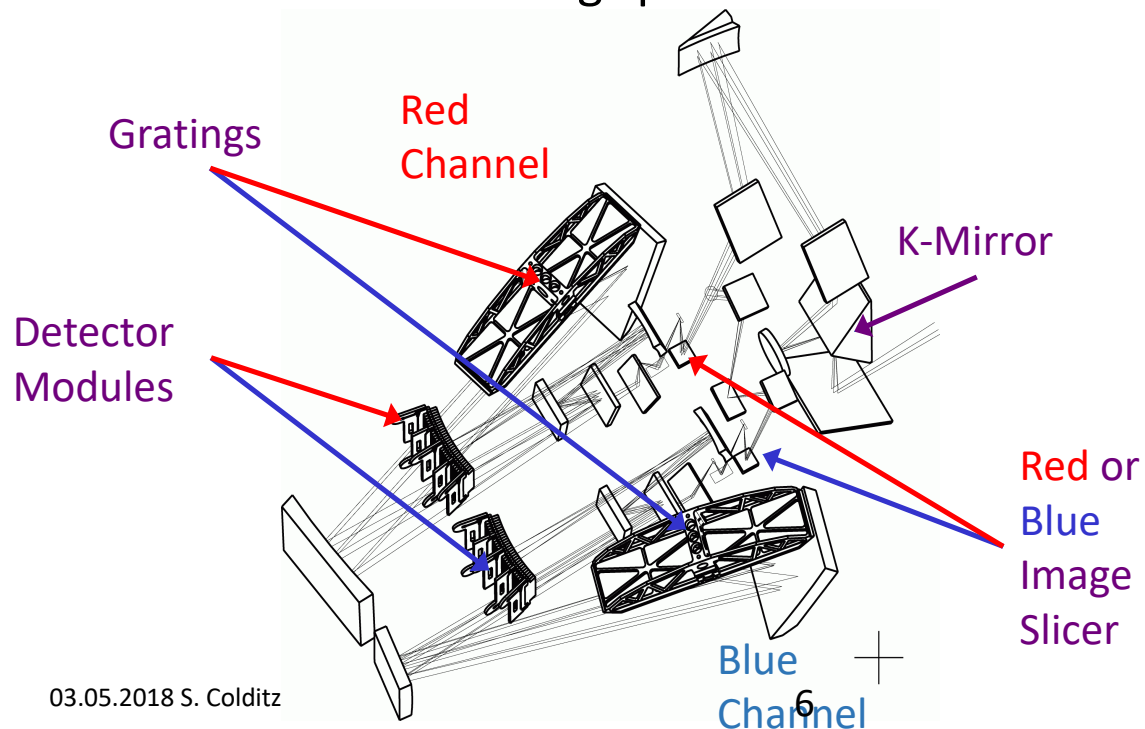
- 2-dimensional Field of View 5x5 spatial pixels = 'spaxels'
- 3rd dimension spectral information
- 3D data but 2D detector arrays



- 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

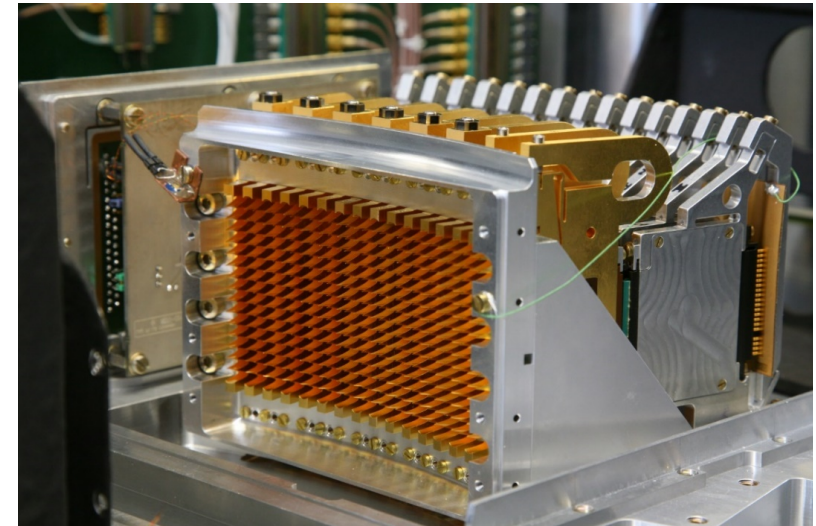
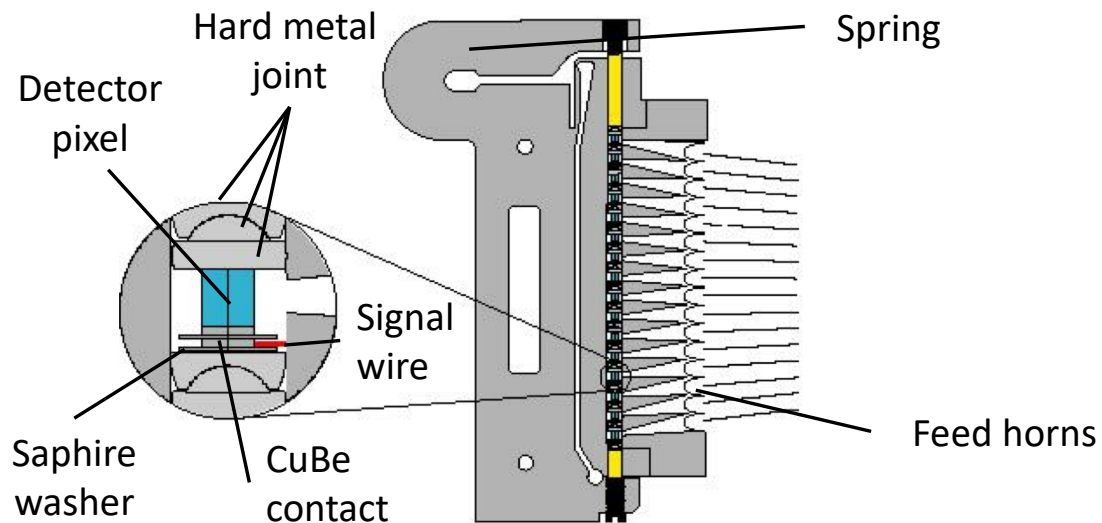


- Four layer bath cryostat (290K, 77K, 6K, 1.8K)
- Reflective image slicer as integral field unit
- Grating spectrometers in Littrow-Mounting



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

Linear 16-element stressed array (schematic)



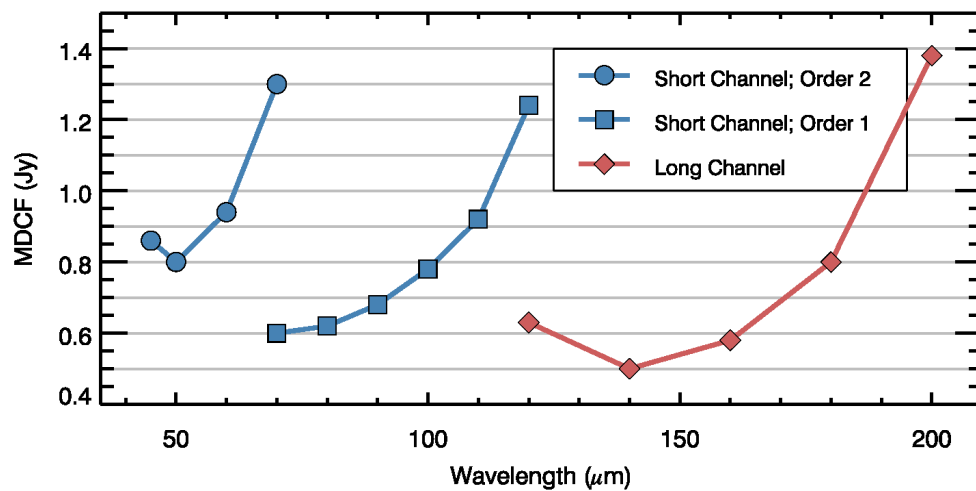


Performance I

Sensitivity

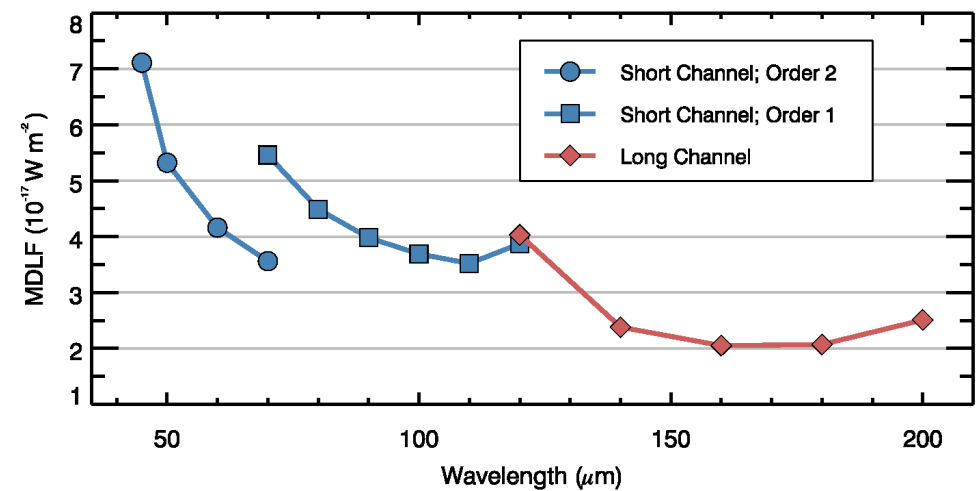
S/N 4 in 900s, Jy/Spaxel

Minimum Detectable Continuum Flux



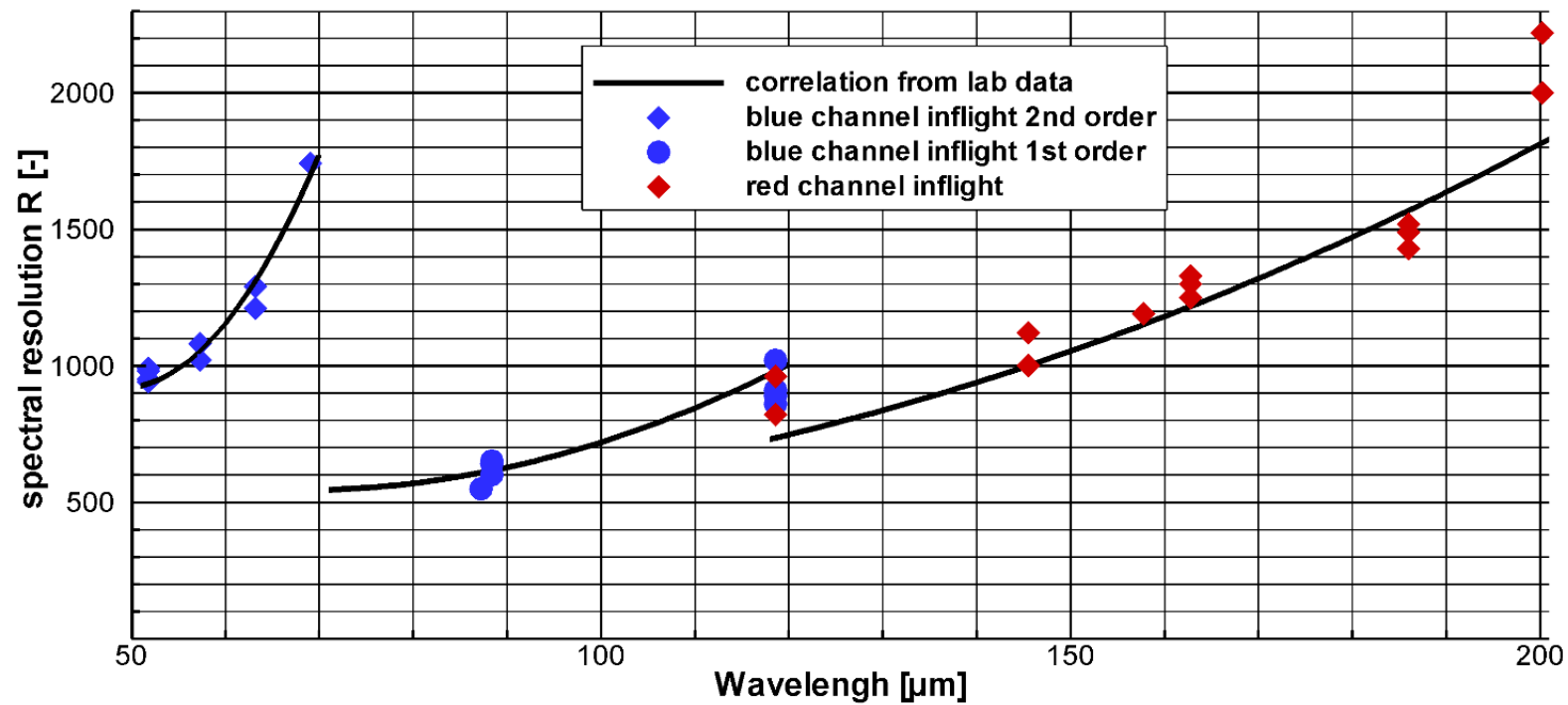
S/N 4 in 900s, W/m^2 / Spaxel

Minimum Detectable Line Flux



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

Spectral Resolution

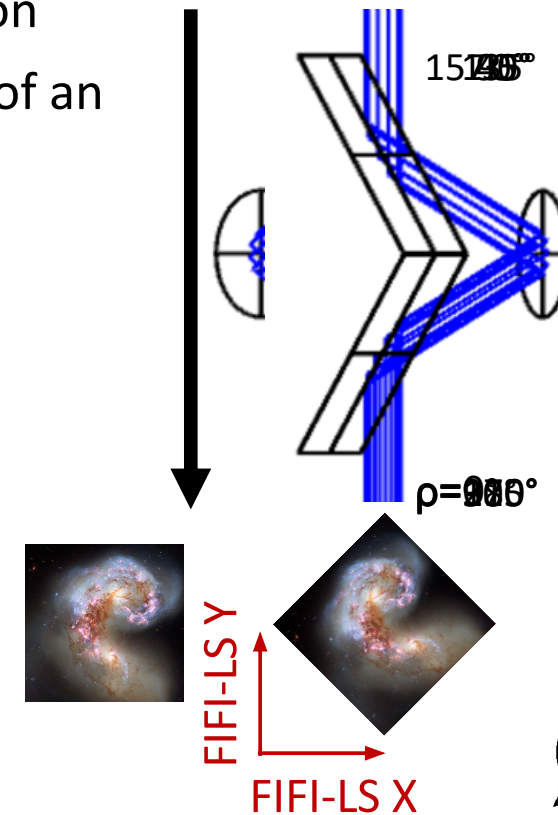
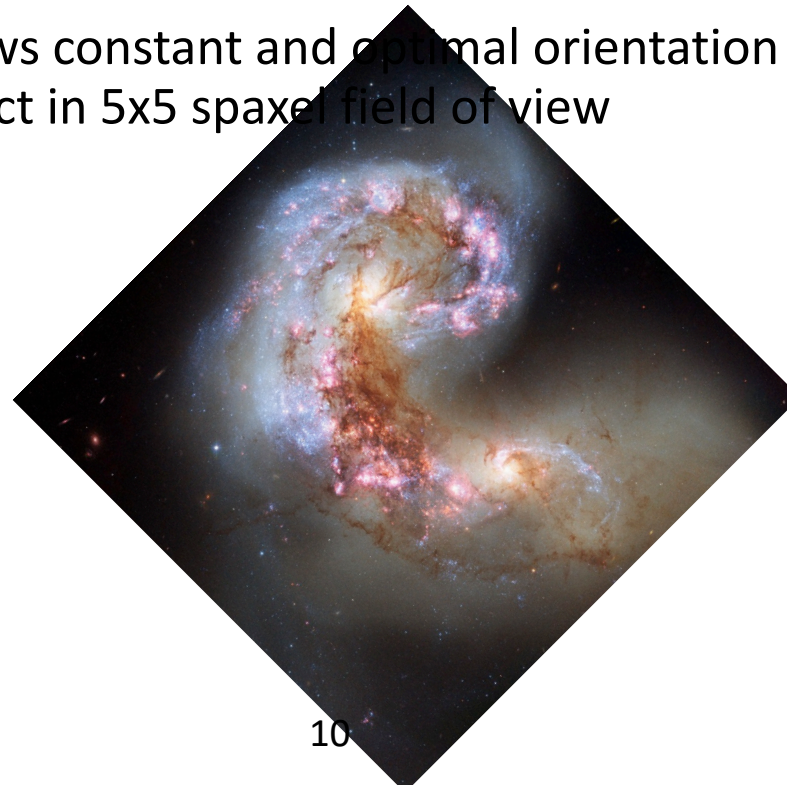


Spatial
Calibration I:
Beam Rotation



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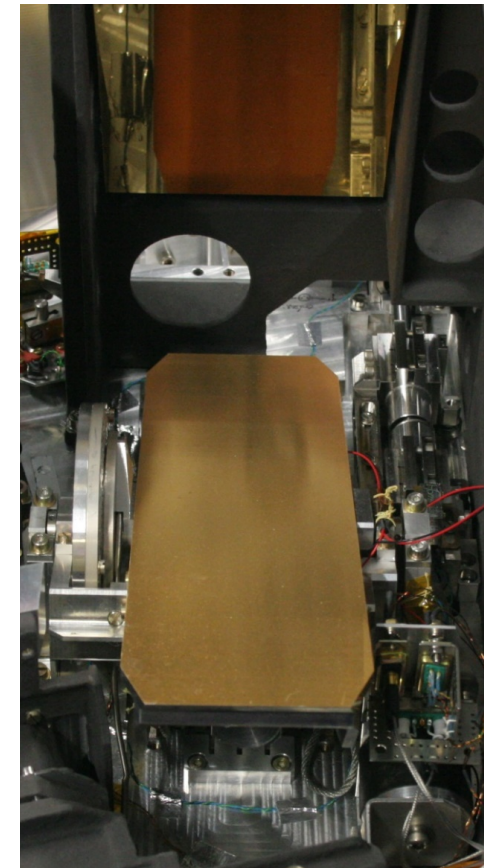
- Image on sky may be rotated
- K-Mirror assembly used to change rotation
- Allows constant and optimal orientation of an object in 5x5 spaxel field of view





- 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 $1/10^{\text{th}}$ of the observed wavelength in μm
 - e.g. $100\mu\text{m}$ approximately <10 seconds of arc

- Movable reflecting gratings
- Observed wavelength dependent grating angle
- Grating angle (φ) measured with Inductosyn[®] Transducer
- $0.077'' = 1$ 'Inductosyn Unit' [ISU]
 $\rightarrow 360^\circ \approx 16,777,000$ ISU
- $\lambda[\mu\text{m}] = f(\text{GratingAngle}[\text{ISU}])$?



- 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

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

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

$$\lambda[\mu\text{m}] = f(\text{GratingAngle}) \text{ for all 400 pixels of each spectral band}$$

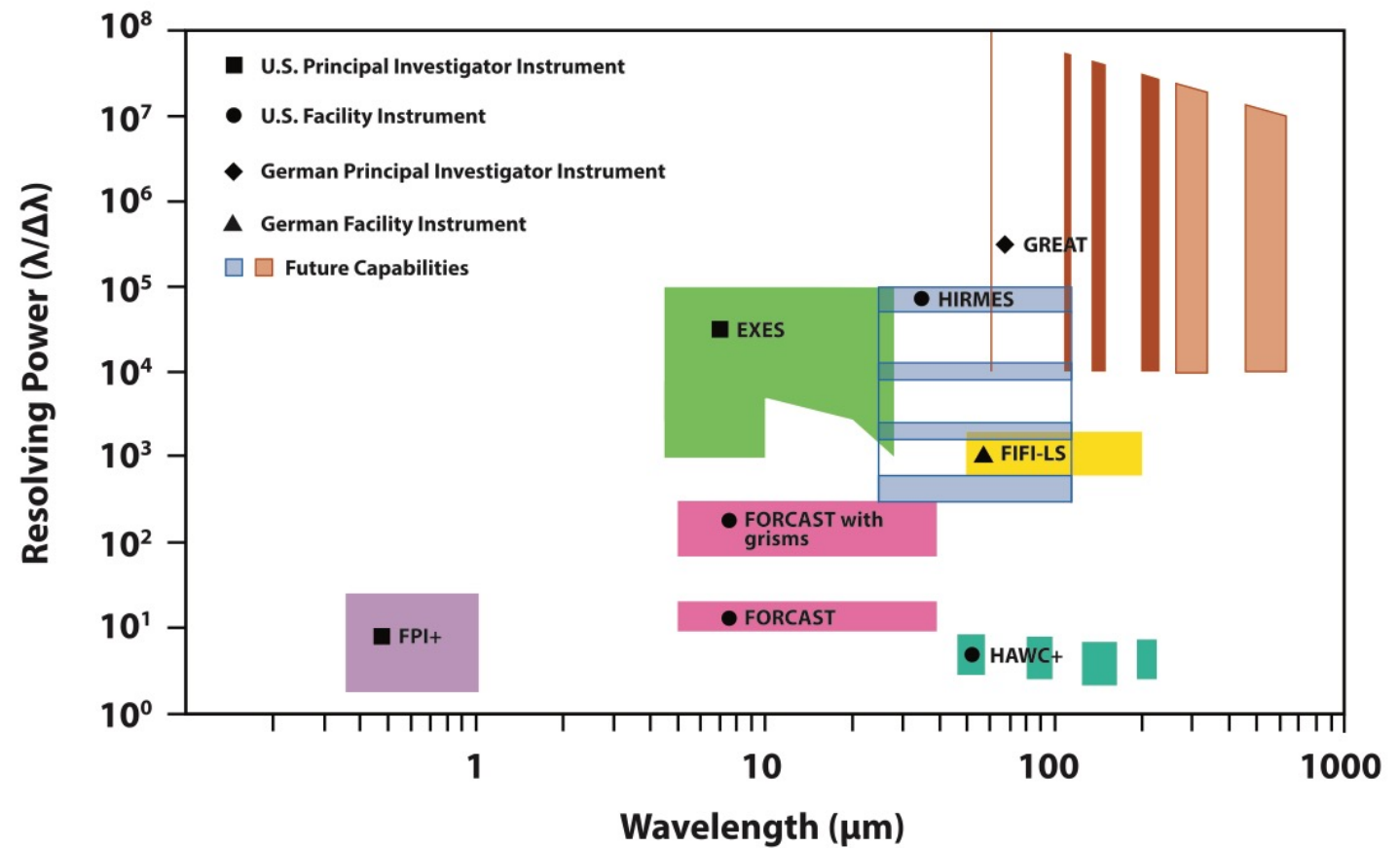
- **Calibration accuracy ±10%** of a spectral resolution element in the laboratory (15-60km/s depending on λ)
- Accuracy comparable to PACS-Spectrometer on Herschel Satellite

Using FIFI-LS



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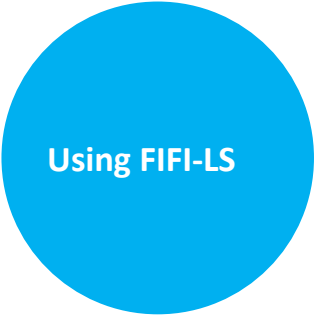


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e.g. velocity distribution in galaxies including baseline on both sides

- Two spectral channels: 51 – 120 μm 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 ₂ H 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 ₂ H 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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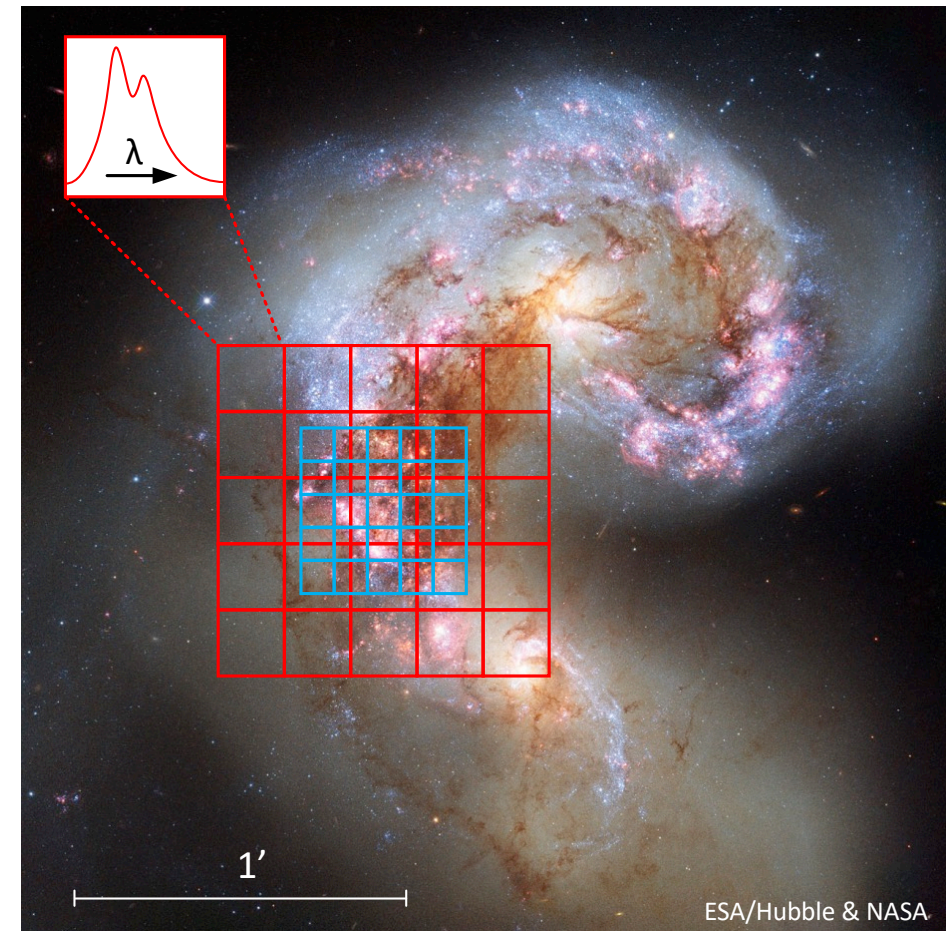
Using FIFI-LS

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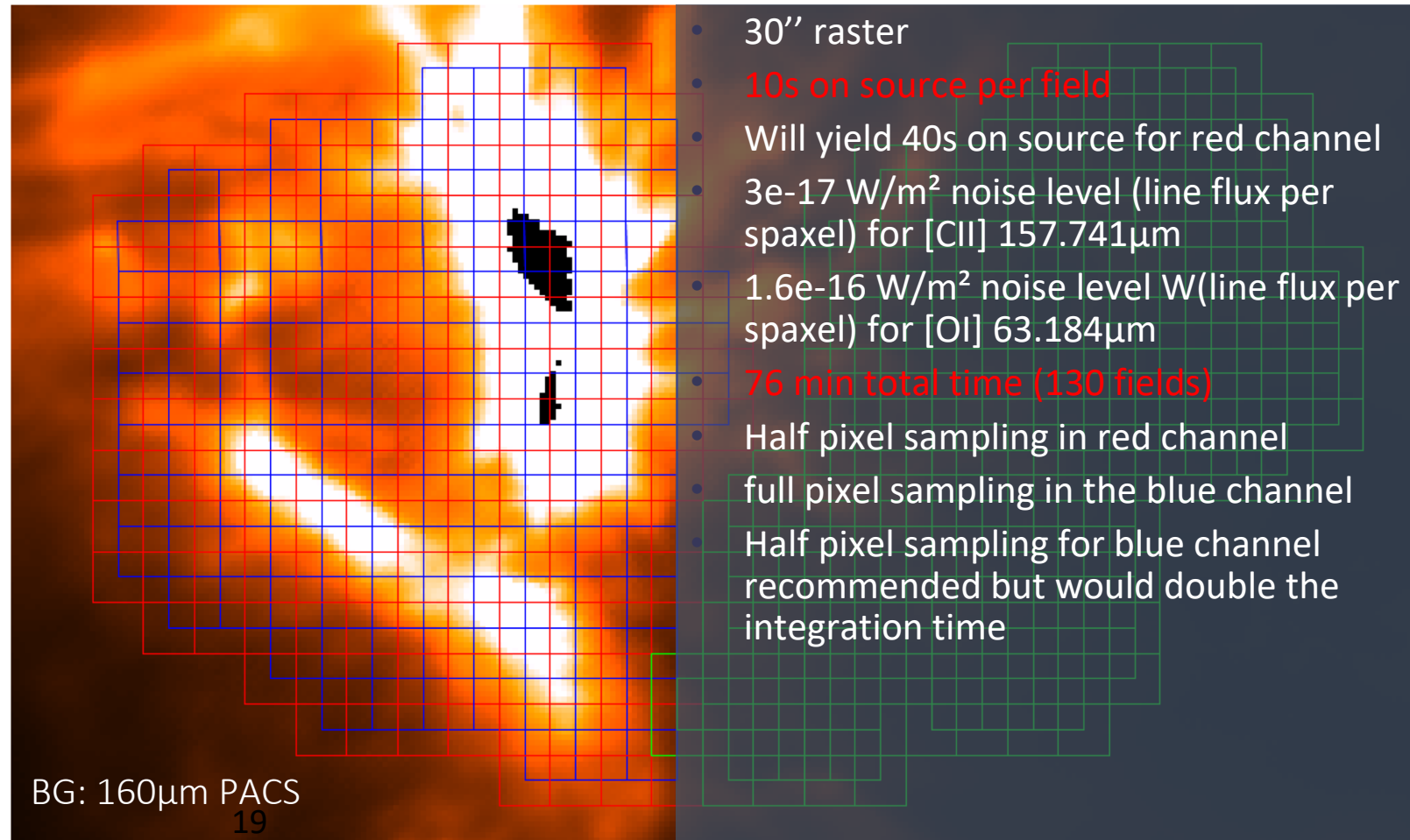
Using FIFI-LS

- Some mapping examples



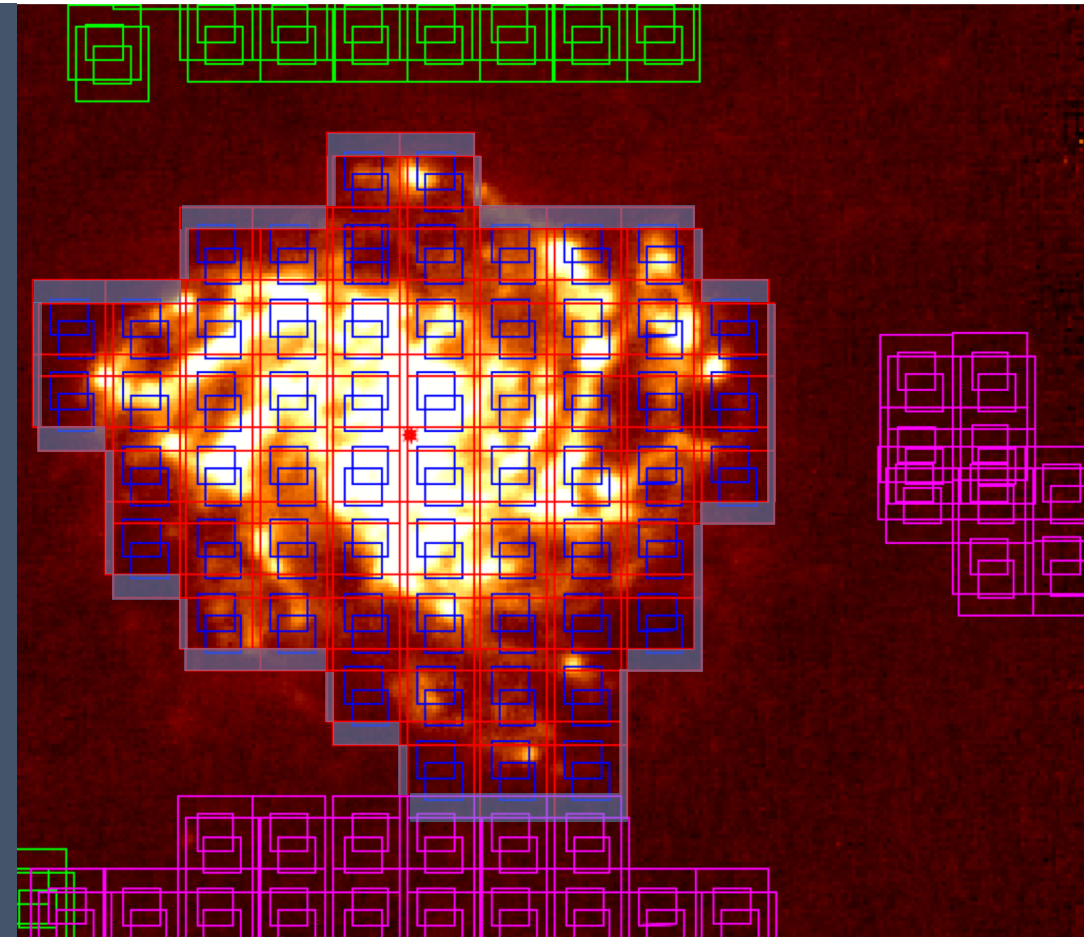
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- Some mapping examples

- 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)
- $1.2 \times 10^{-17} \text{ W/m}^2$ noise level (line flux per spaxel) for [CII] $157.741 \mu\text{m}$
- **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 -> $1 \times 10^{-17} \text{ W/m}^2$ noise -> 15h



Using FIFI-LS

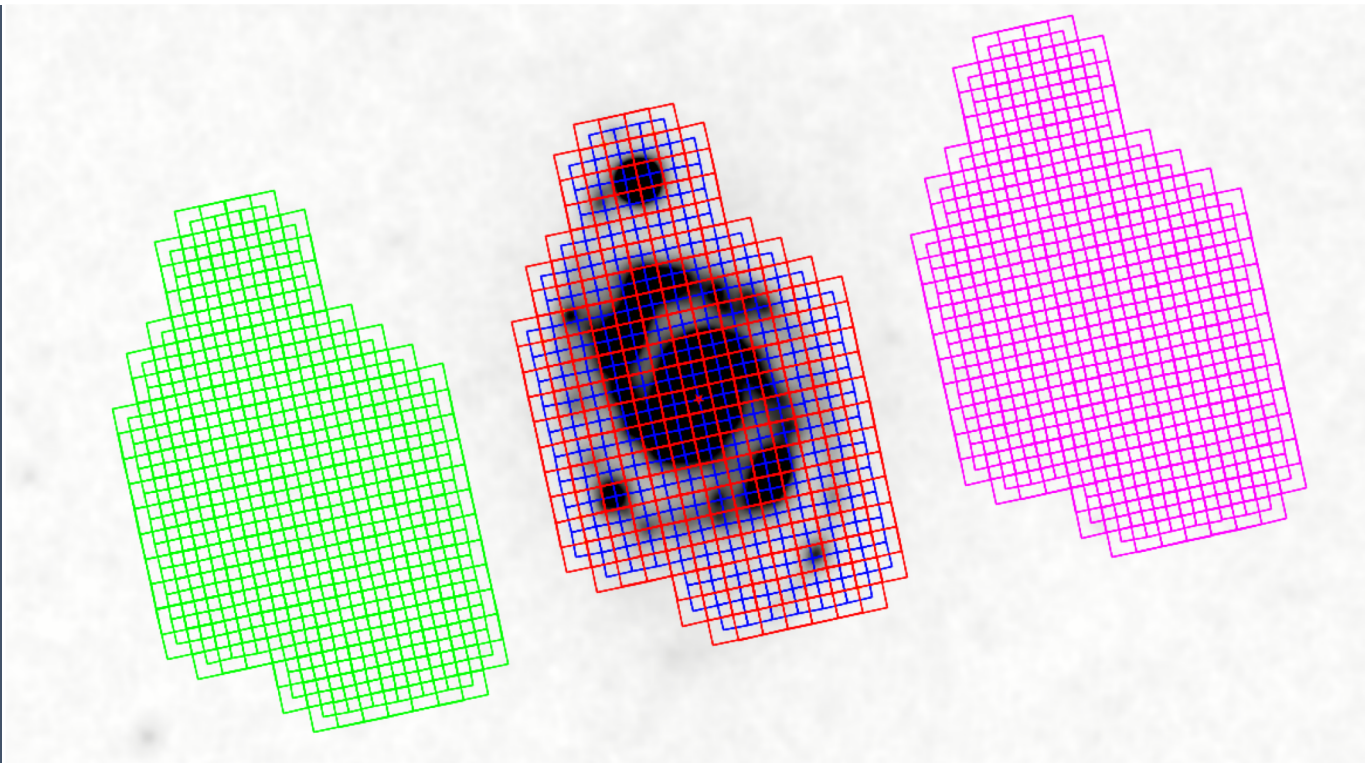
- Some mapping examples

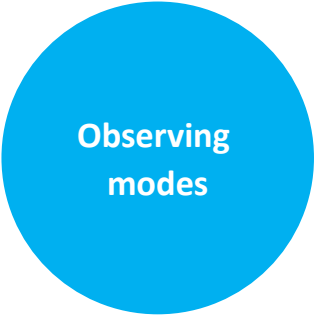


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- Possible alternative:
- 30" raster -> 240 fields -> 90s on source -> $1e-17$ W/m² noise -> 15h
- Spatial sampling / dithering
- Observing modes





Observing modes

- **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 modes available on request, recommended on source time 10-15 s**

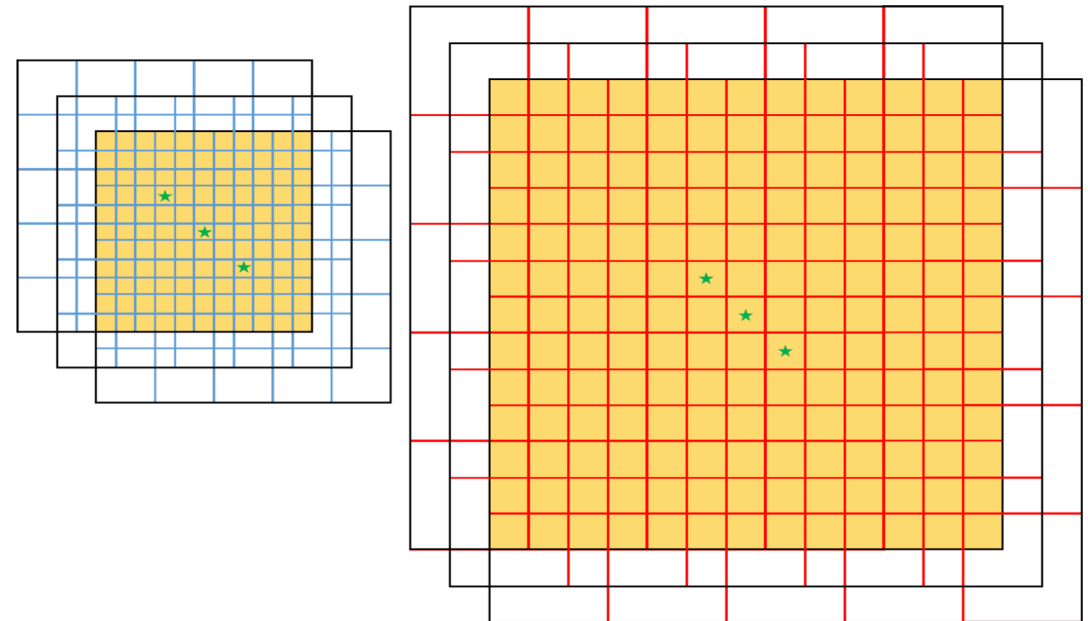
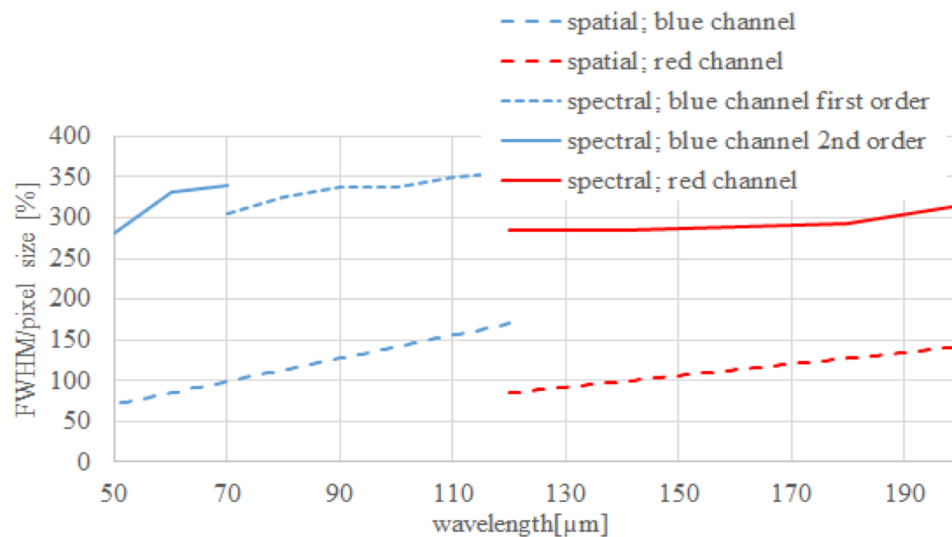


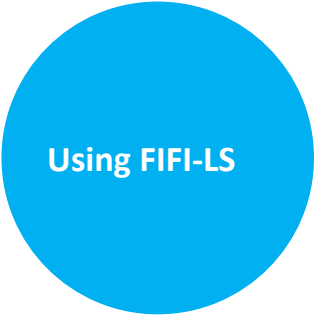
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- Spatial dithering
 - Why do we need to care?
 - Things get easier for deeper integrations
 - More time to use nod cycles for new positions
 - Example: 4'', 4'' ; 0'', 0'' ; -4'', -4''
 - Will result in 2''/4'' sampling for blue/red channel





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

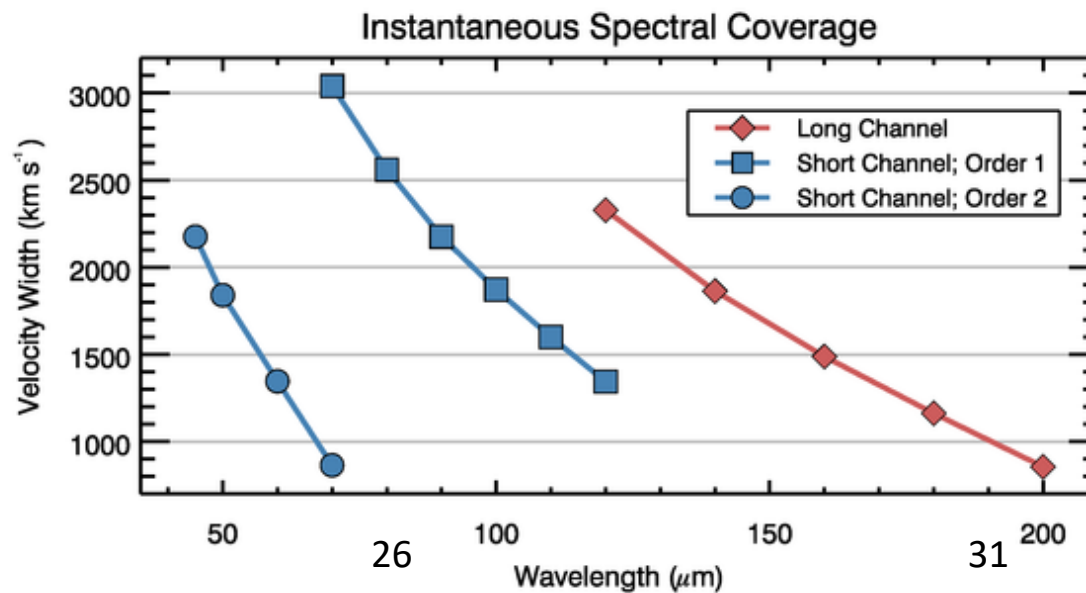
- **Medium spectral resolution: $R \sim 500 - 2000$ ($\sim 150 - 600$ km/s)**
- **16 Pixels in spectral direction in each spatial pixel**
- **Instantaneous spectral coverage: ~ 1500 km/s**
e.g. velocity distribution in galaxies including baseline on both sides
- Velocity information is available
- Continuum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

Using FIFI-LS



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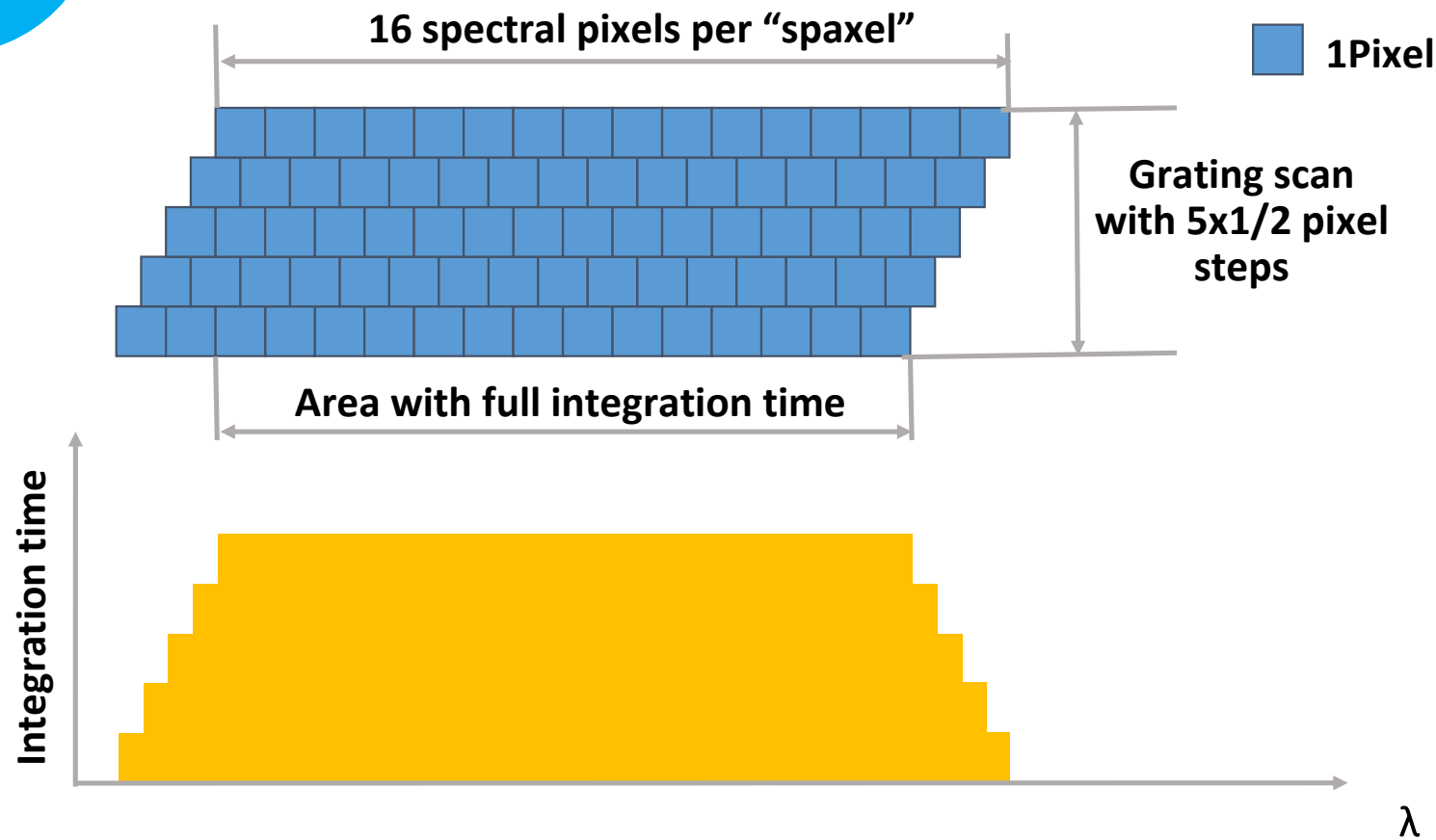
- How do I need to consider this for my observations?
- Does my line fit on the detector?
- How many detectors do I need spectrally?





Using FIFI-LS

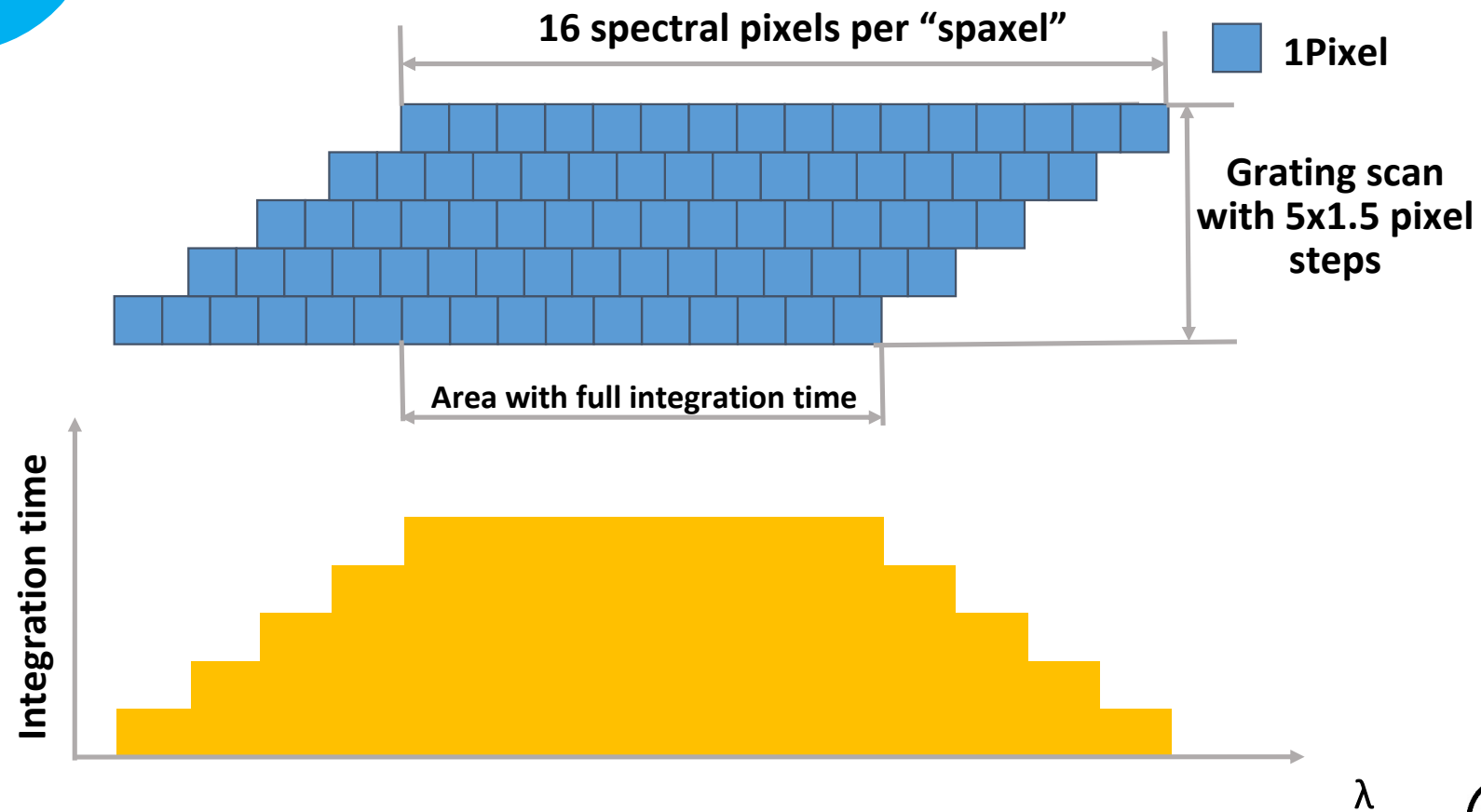
Be aware how FIFI-LS works spectrally





Using FIFI-LS

Be aware how FIFI-LS works spectrally



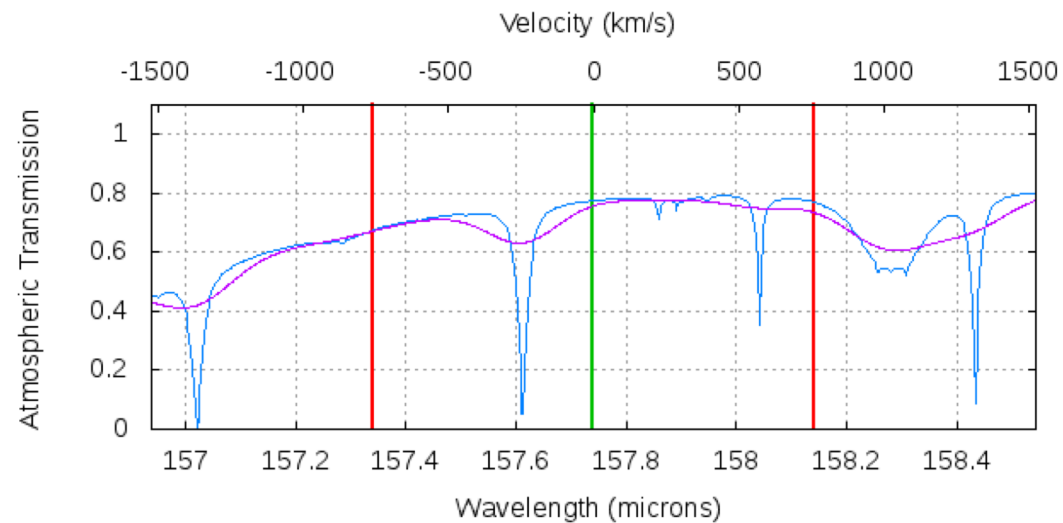
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- How do I need to consider this for my observations?
- There is an residual atmosphere



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:

FIFI-LS [OIII] Spectroscopy 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



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

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

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

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

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

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

31

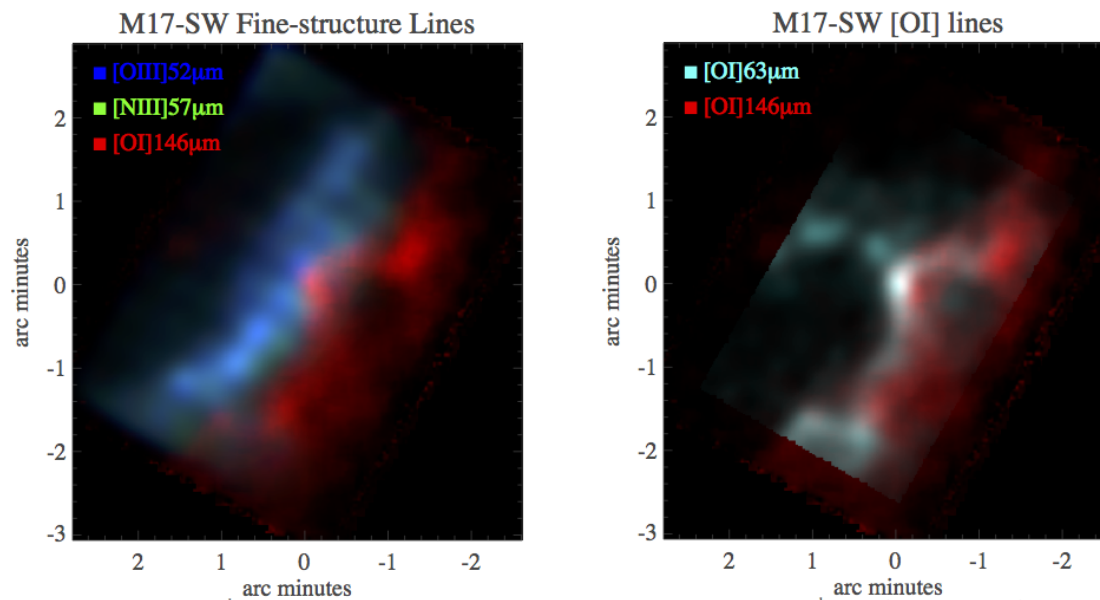
Revealing the formation of fullerenes in planetary nebulae.



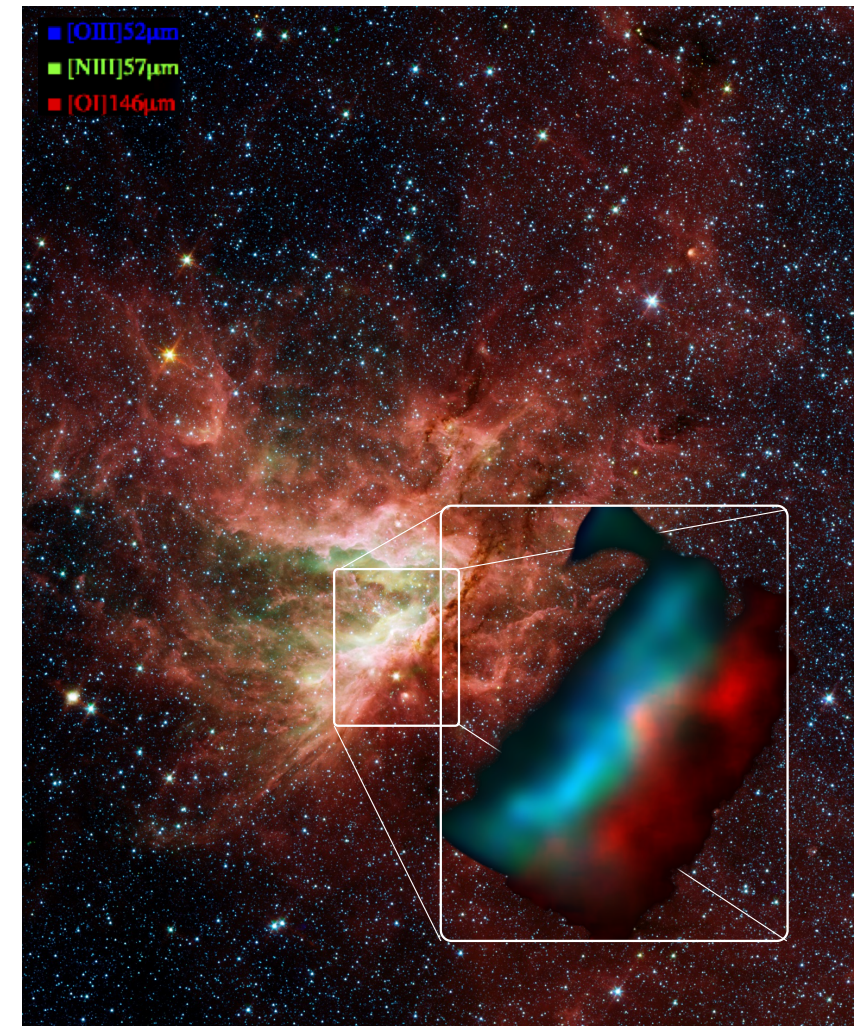
FIFI-LS science
examples

M17-SW

40 min wall clock time per line pair

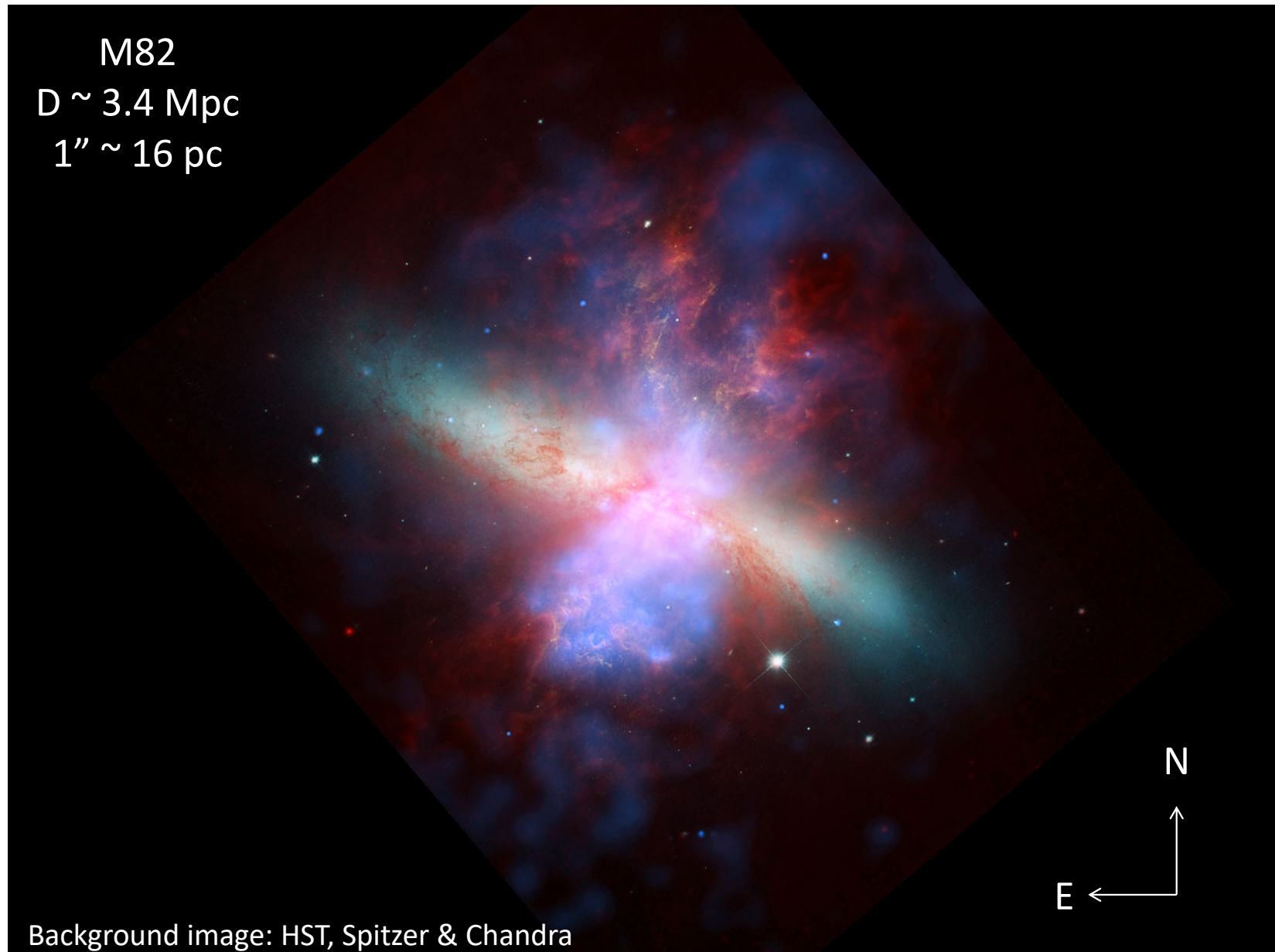


- Clear separation of high ionization lines from low ones, revealing HII/PDR structure, which can be compared to models
- [O I] lines provide density/temperature diagnostic in PDR
- [O III] lines give the density in the H II region



FIFI-LS science
examples

M82
 $D \sim 3.4 \text{ Mpc}$
 $1'' \sim 16 \text{ pc}$



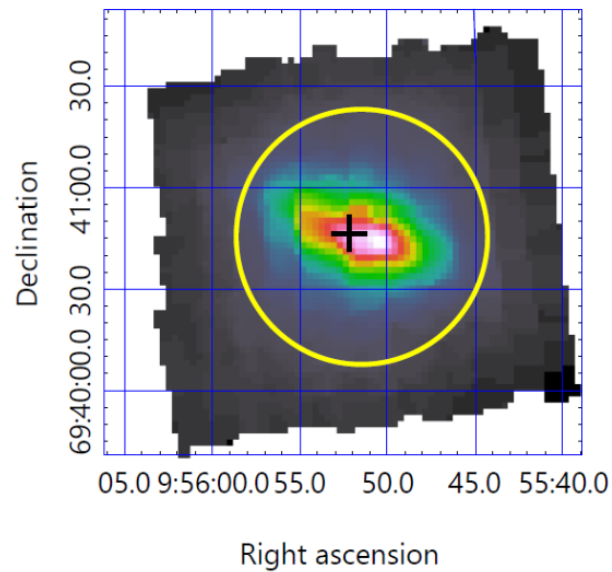
FIFI-LS science
examples

Mapping M82

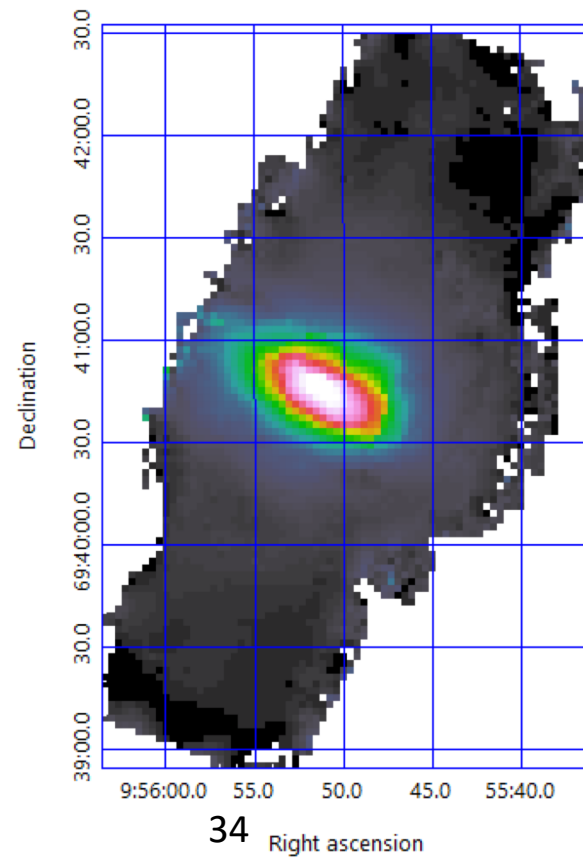


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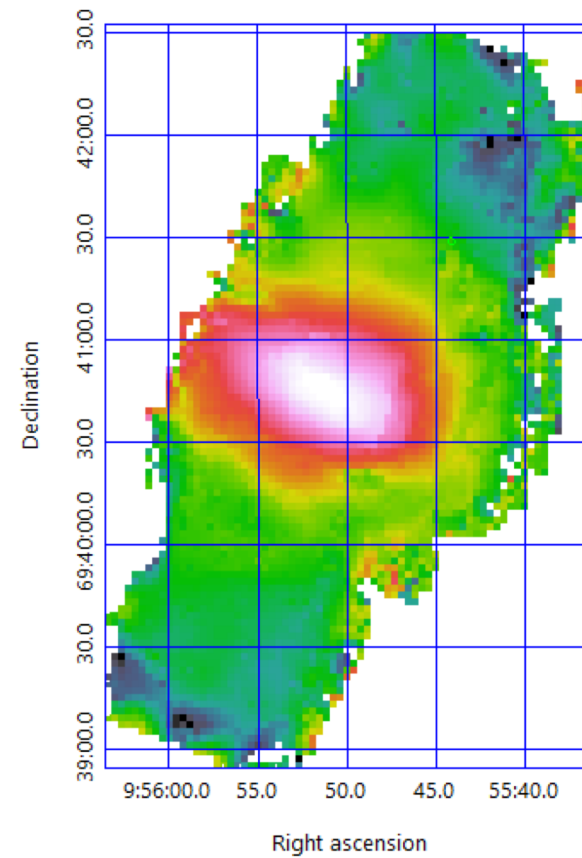
PACS [C II] 158 μm map



FIFI-LS [C II] 158 μm map



Log scale



Emission at 1-2%
peak level

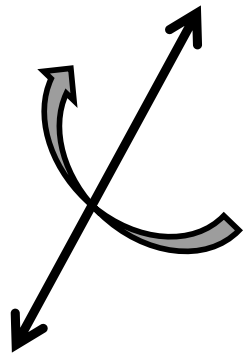


Mapping M82

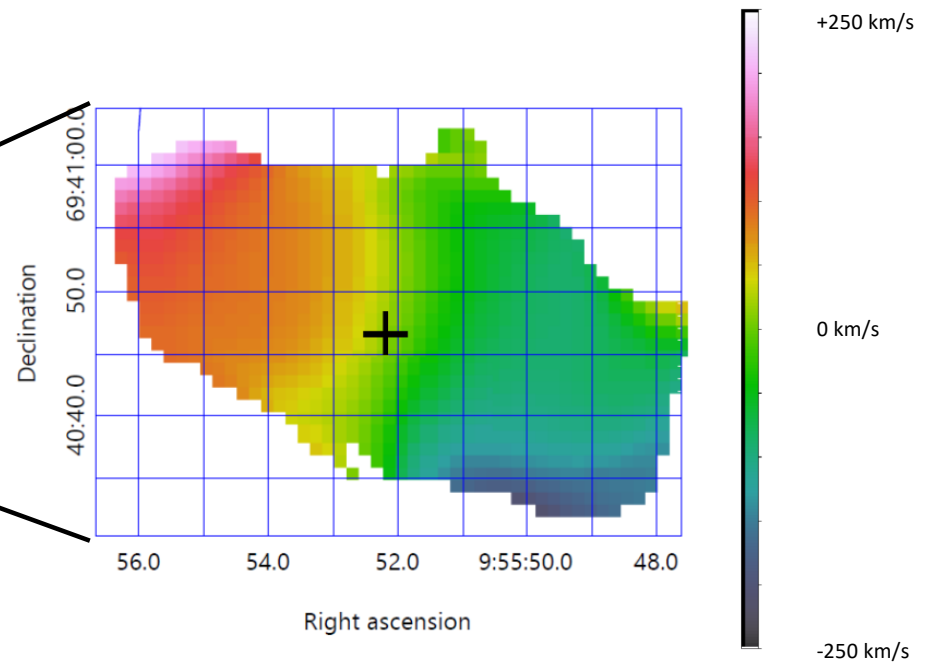
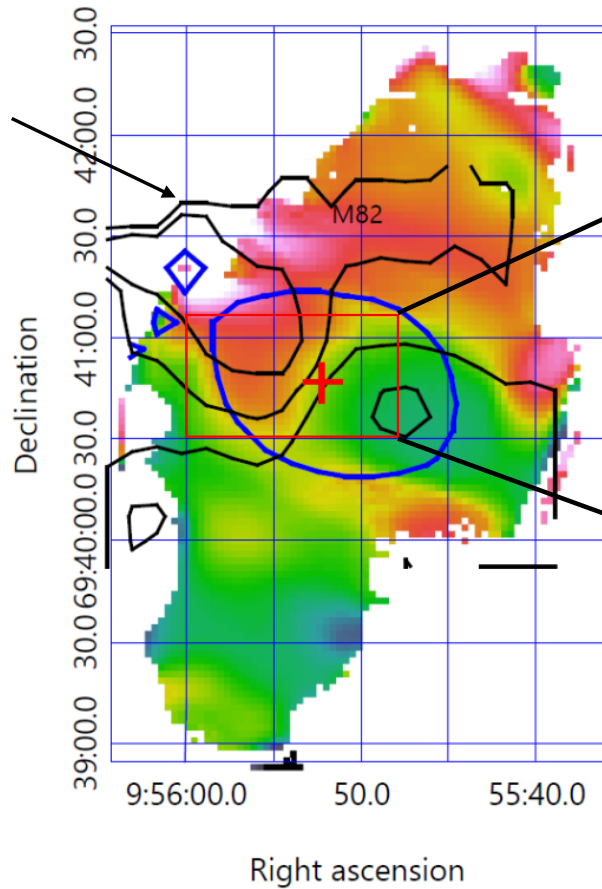
FIFI-LS [C II] 158 μm velocity map

FIFI-LS [O III] 52 μm velocity map

PACS velocity contours



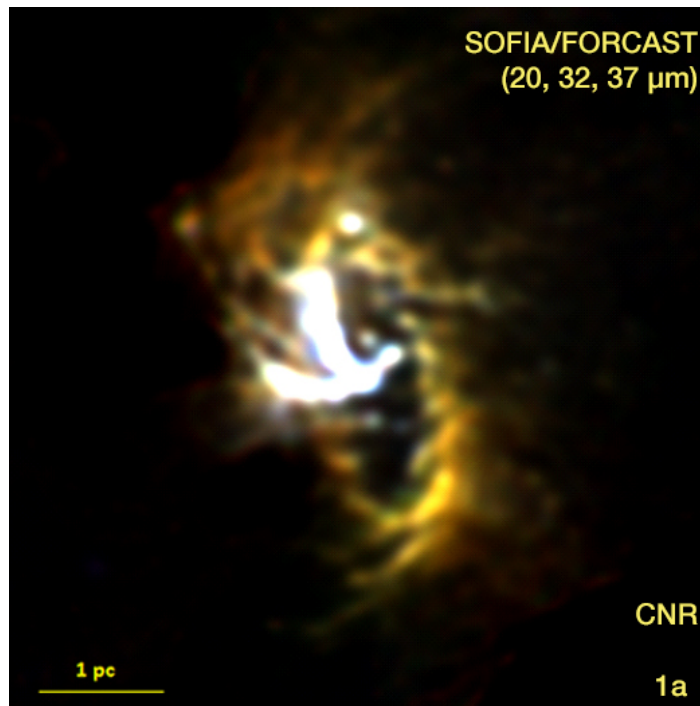
Rotation +
Outflow



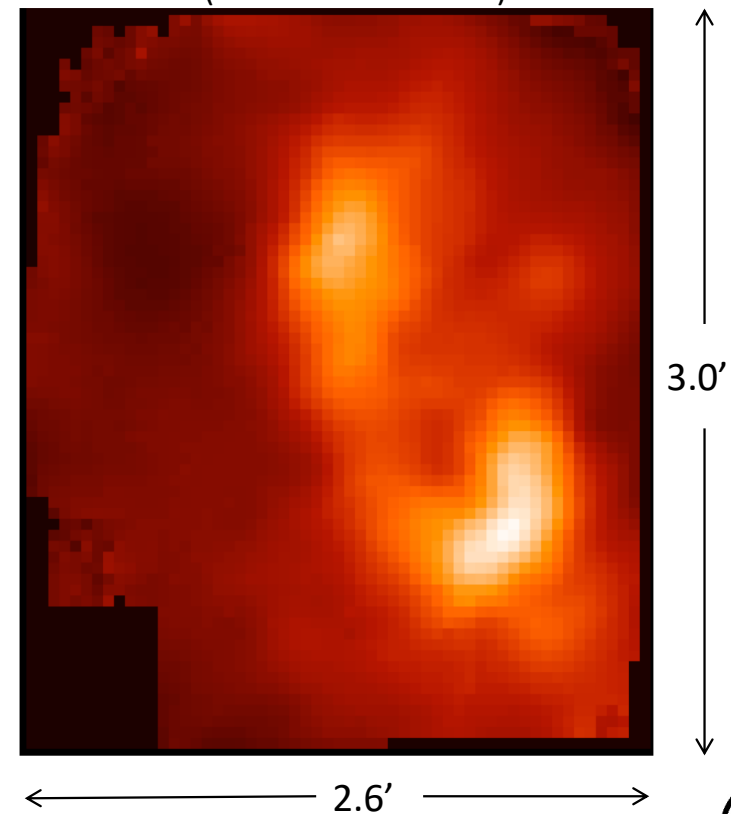
Mapping the CNR in the GC



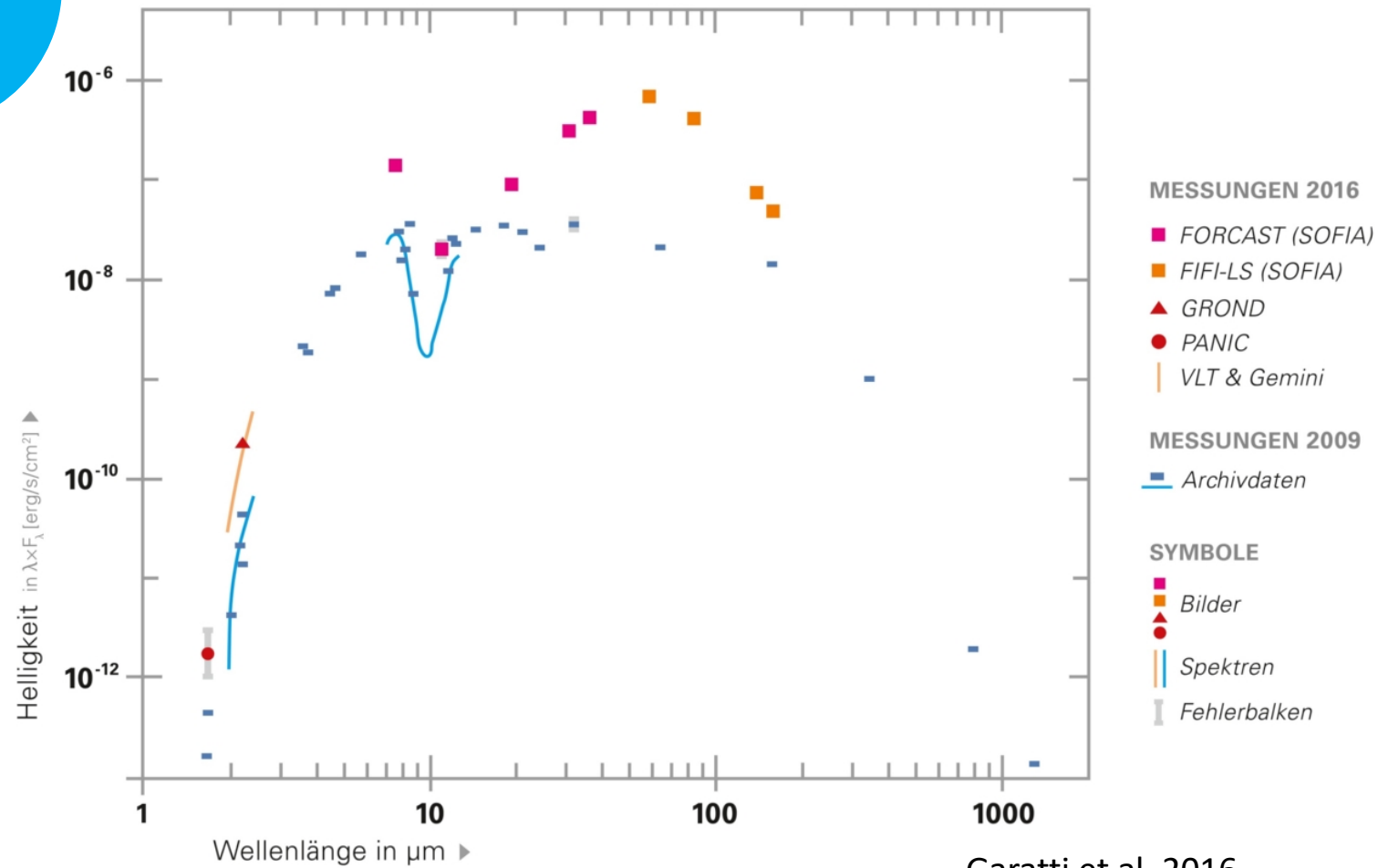
FORCAST Observations of the CNR
(Lau et al. 2013)



FIFI-LS Observations of the CNR at 145 μm
(Iserlohe et al. 2018)



S255IR NIRS 3



Garatti et al. 2016



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End

**Sebastian
Colditz**

