FIFI+LS: a timely upgrade to FIFI-LS

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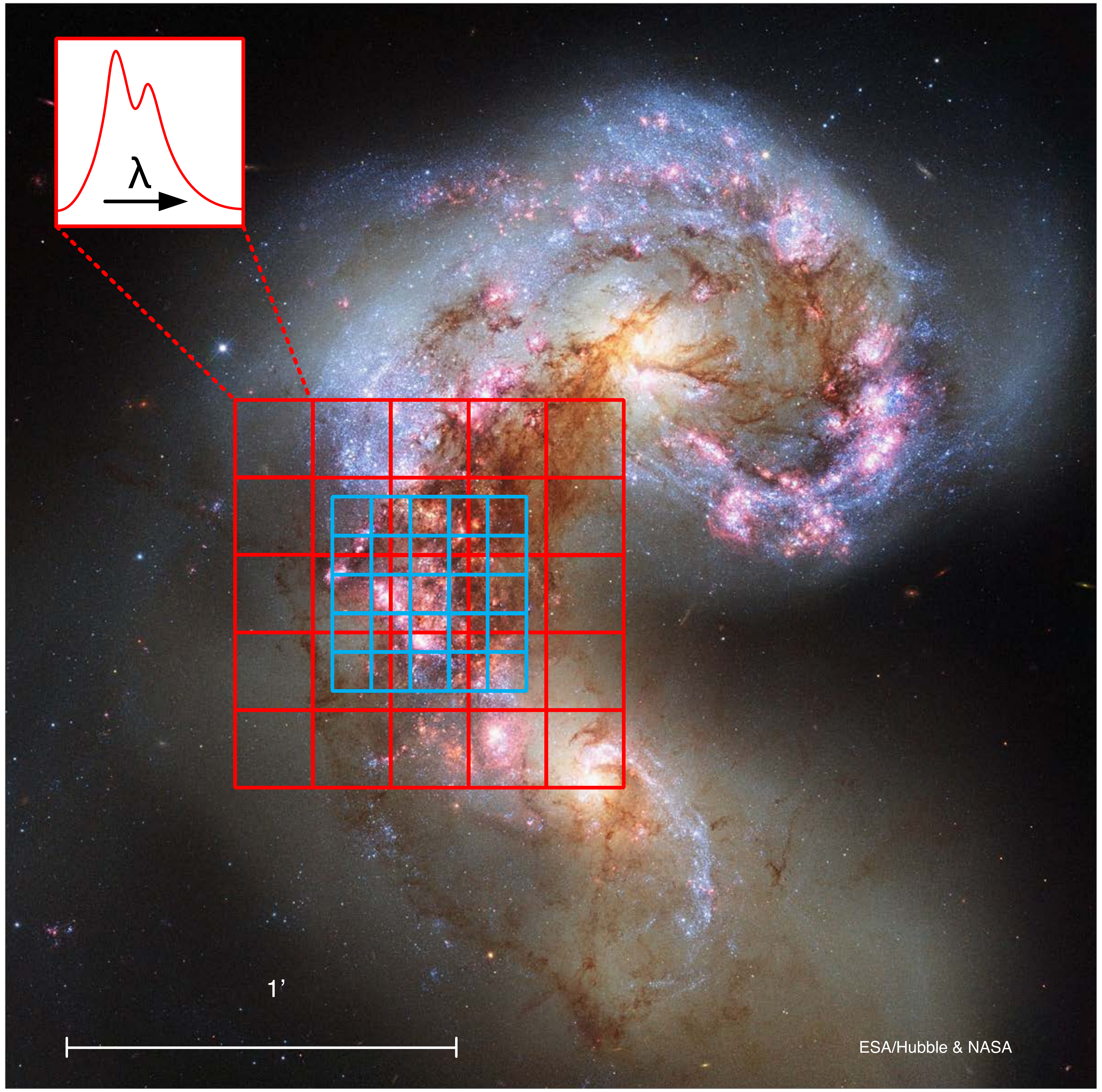
FIFI-LS

- Two independent spectrometers in one cryostat: **Blue (51-125 µm)** and **Red (115-203 µm)**.
- Each spectrometer has 5x5 spaxels (16 pixels in velocity), scaled for telescope diffraction—**6" pixels in Blue** and **12" pixels in Red**.
- Detectors are 20+ years old gallium-doped germanium photometer technology, dependent on the PACS cold read out electronics development.
- Designed to observe two FIR lines with moderate resolution (R~500-2000 depending on wavelength) in galaxies. This is a trade-off on the need to observe wide line widths (from galaxy-wide emission), especially rotating line widths, and sensitivity to measure, for example, galaxy inter-arm regions.

FIFI-LS Image Slicing Design

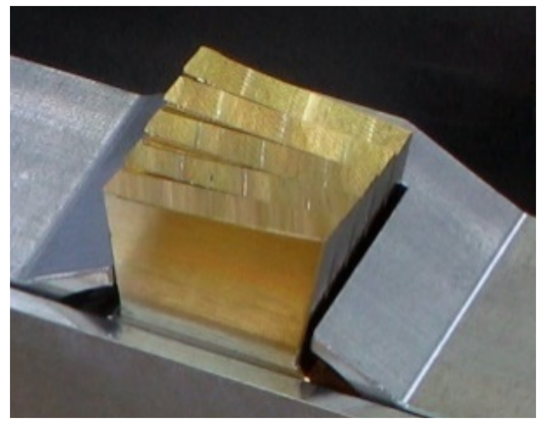
Field-Imaging Line Spectrometer:

- 2-dimensional Field of View 5x5 spatial pixels = ‘spaxels’
- 3rd dimension spectral information = 16 pixels
- 3D data but 2D detector arrays



FIFI-LS Image Slicing

- Mirrors rearrange 5x5 spaxel FOV into 25x1 spaxel slit



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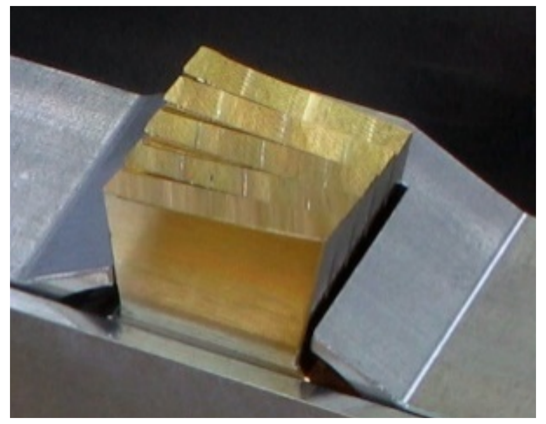

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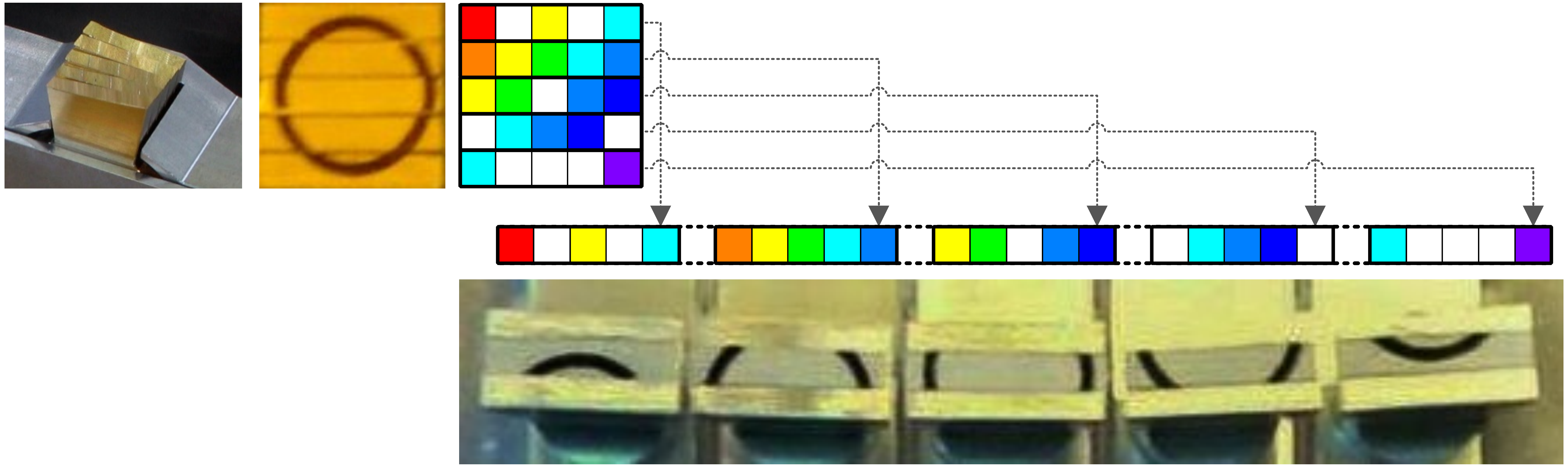
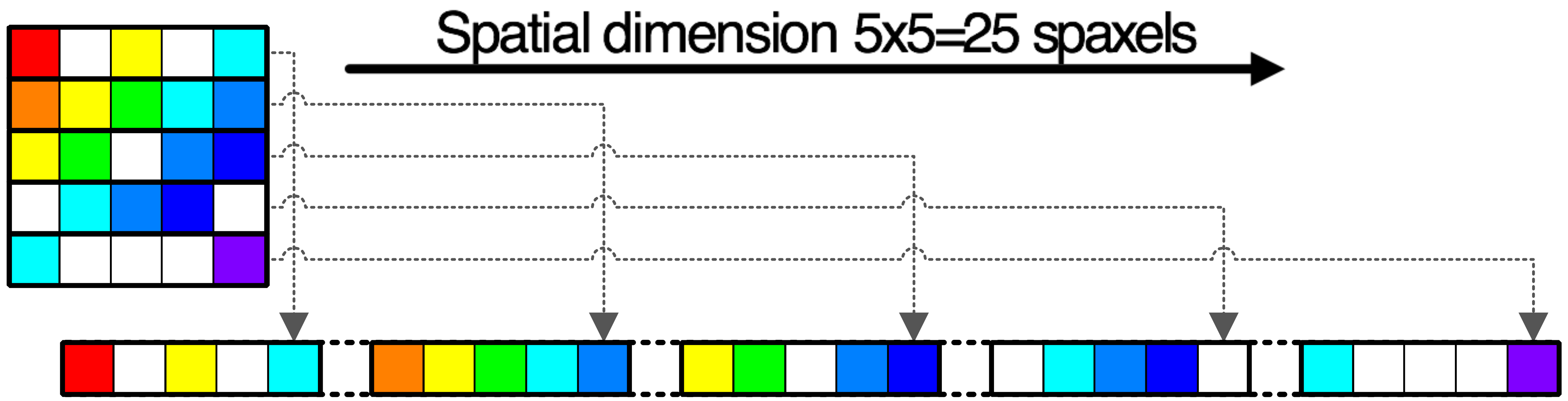


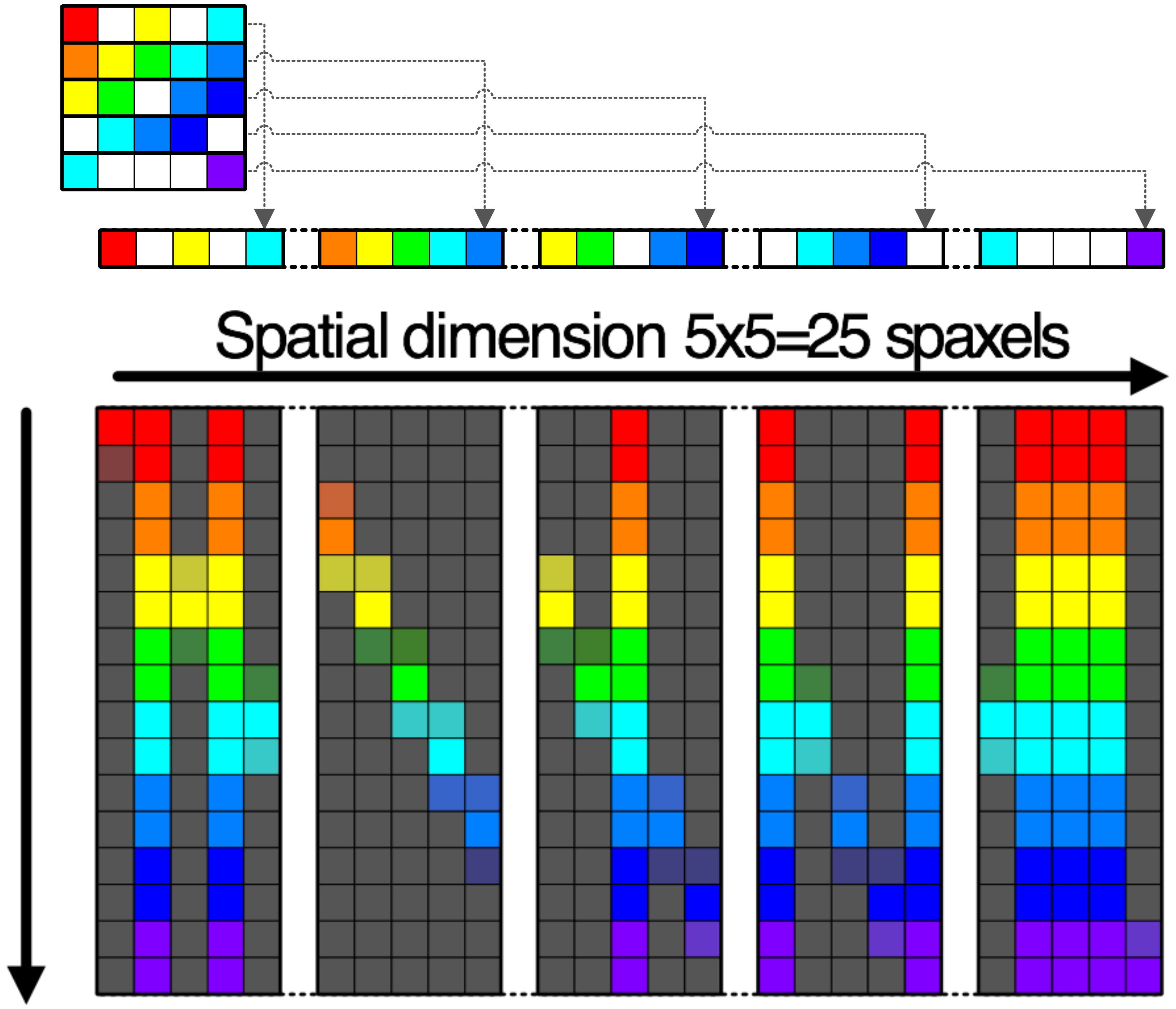
FIFI-LS Image Slicing

- Mirrors rearrange 5x5 spaxel FOV into 25x1 spaxel slit
- Slit enters grating spectrometer



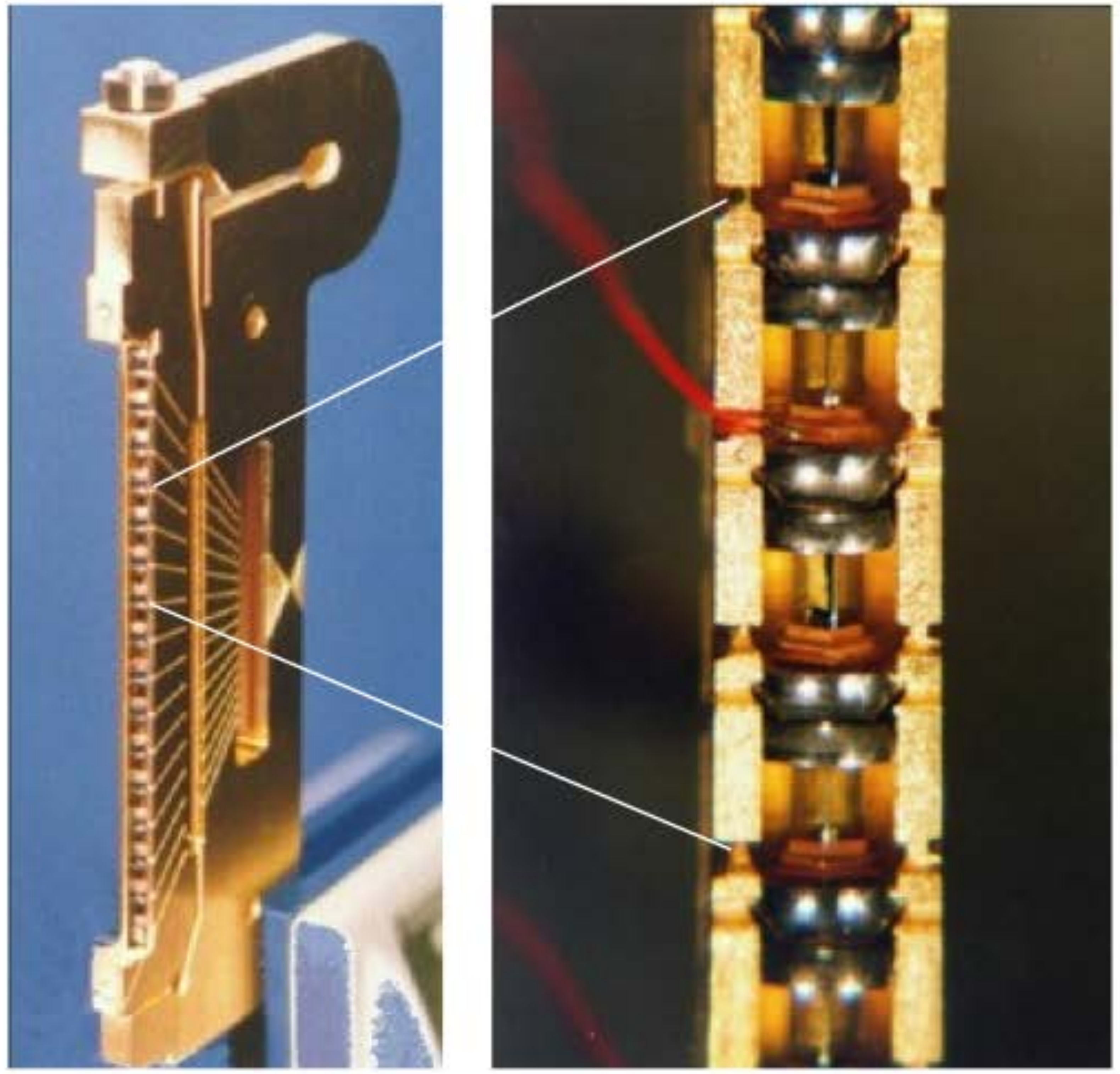
FIFI-LS Image Slicing

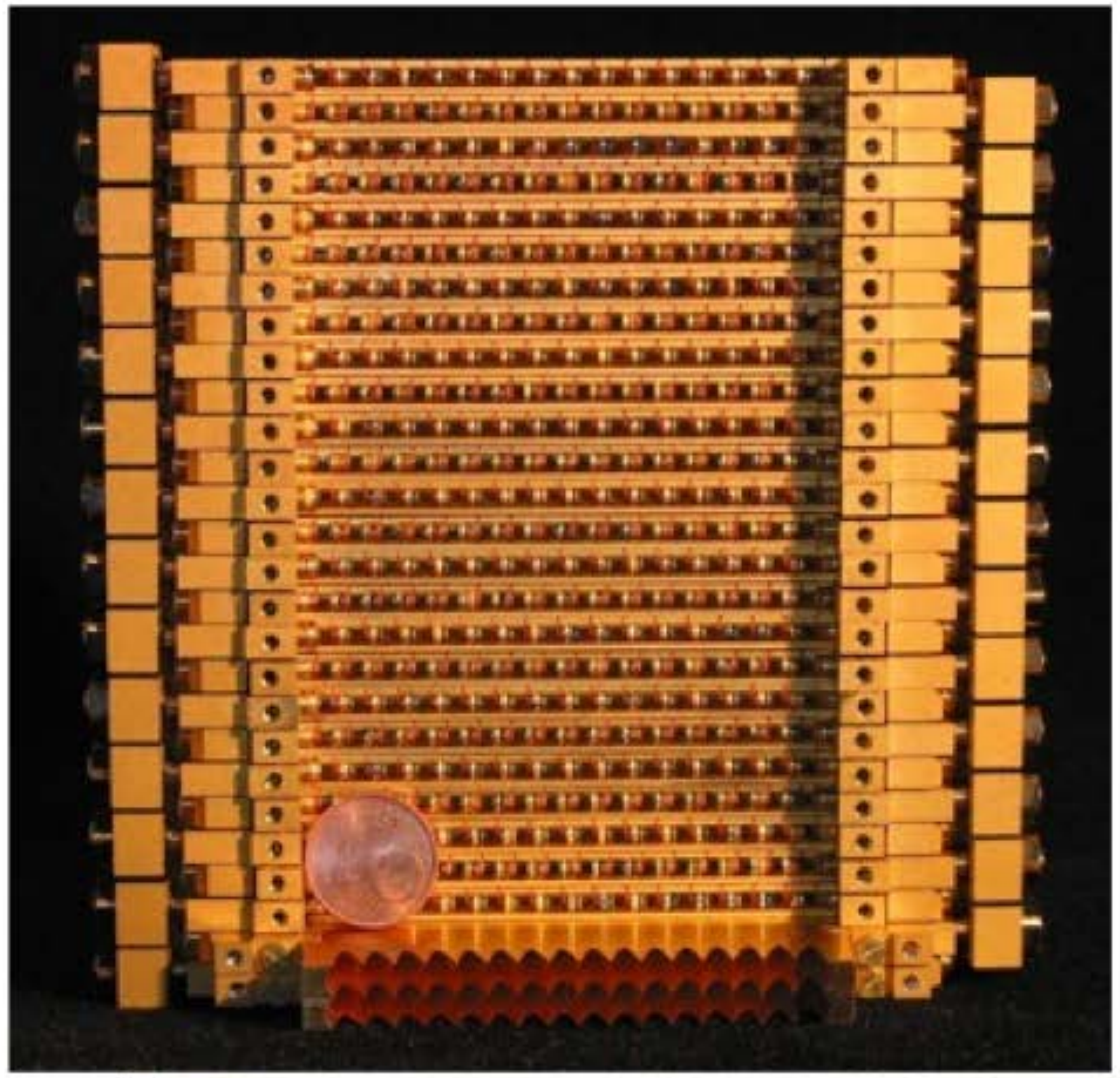
- Mirrors rearrange 5x5 spaxel FOV into 25x1 spaxel slit
- Slit enters grating spectrometer
- Spectrally dispersed light is imaged on 25x16 pixel detector array
  → 400 pixels



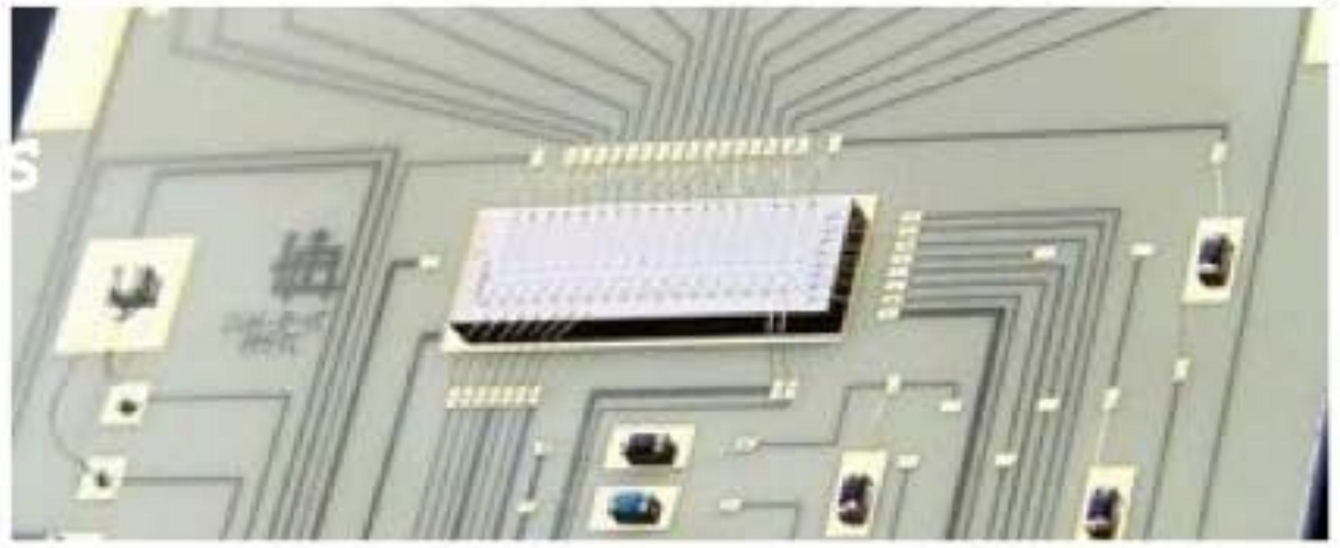
Current Detectors

1 spaxel = 16 pixels

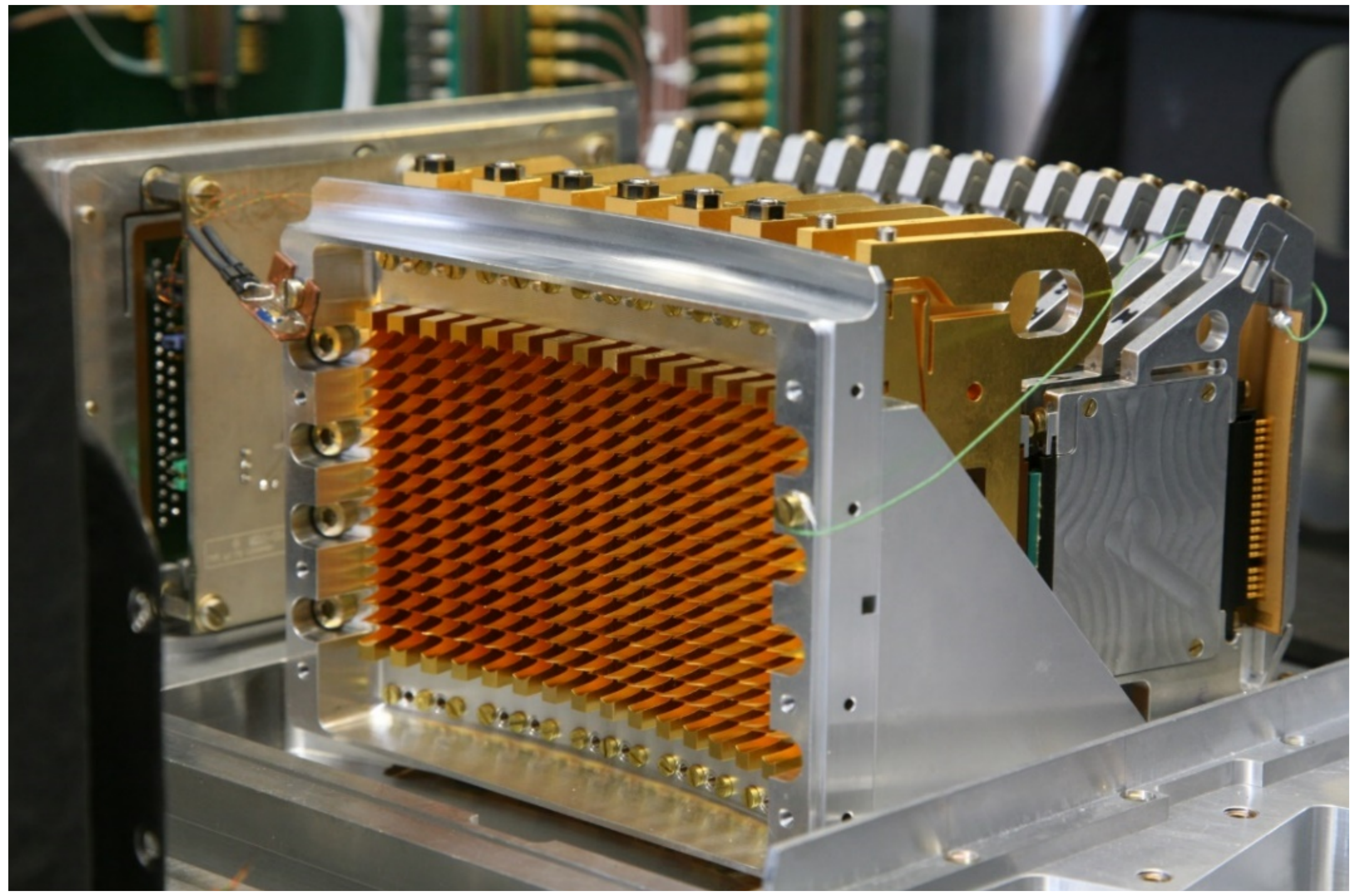




25 spaxels



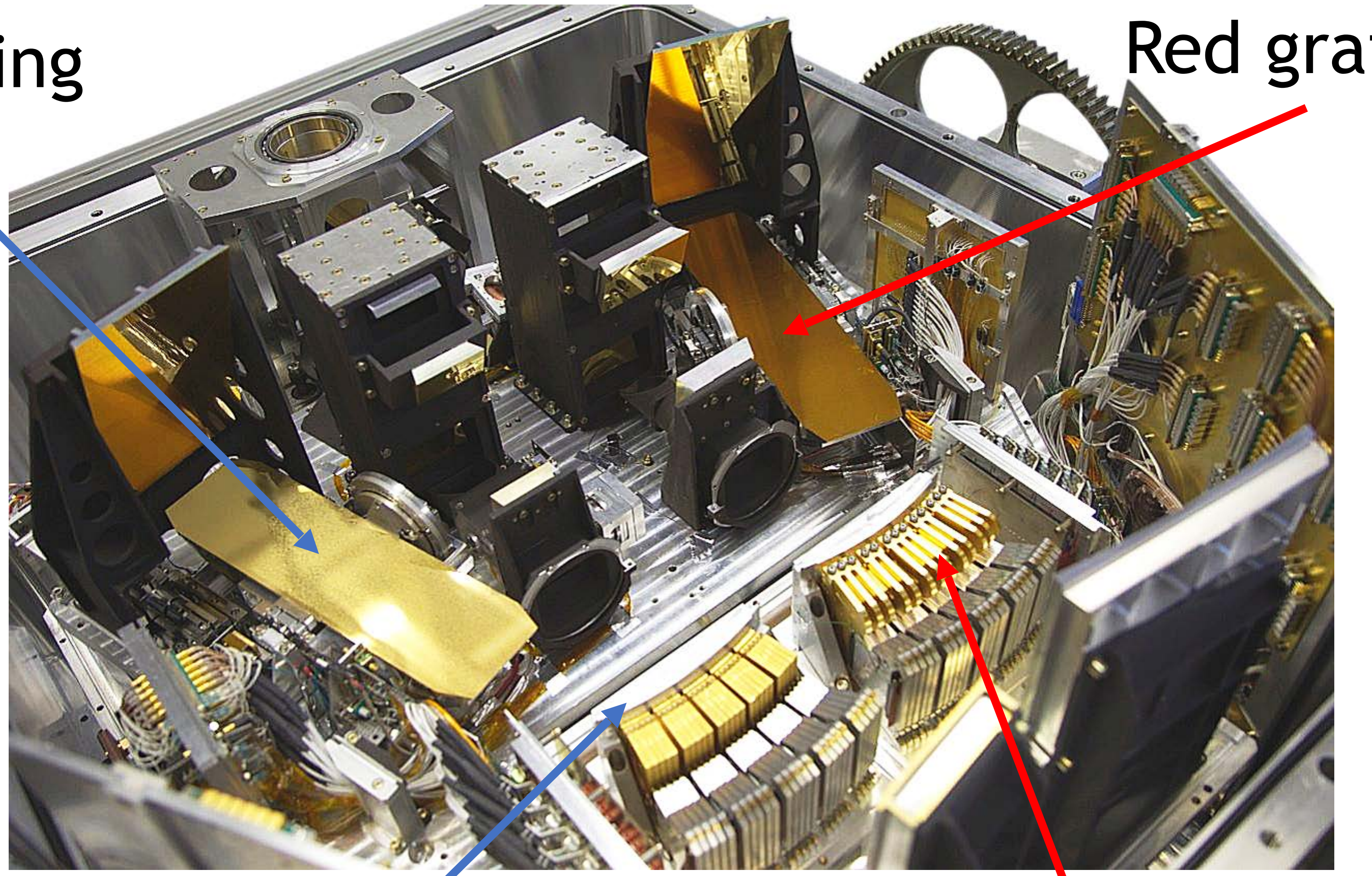
25 spaxels x 16 = 400 pixels

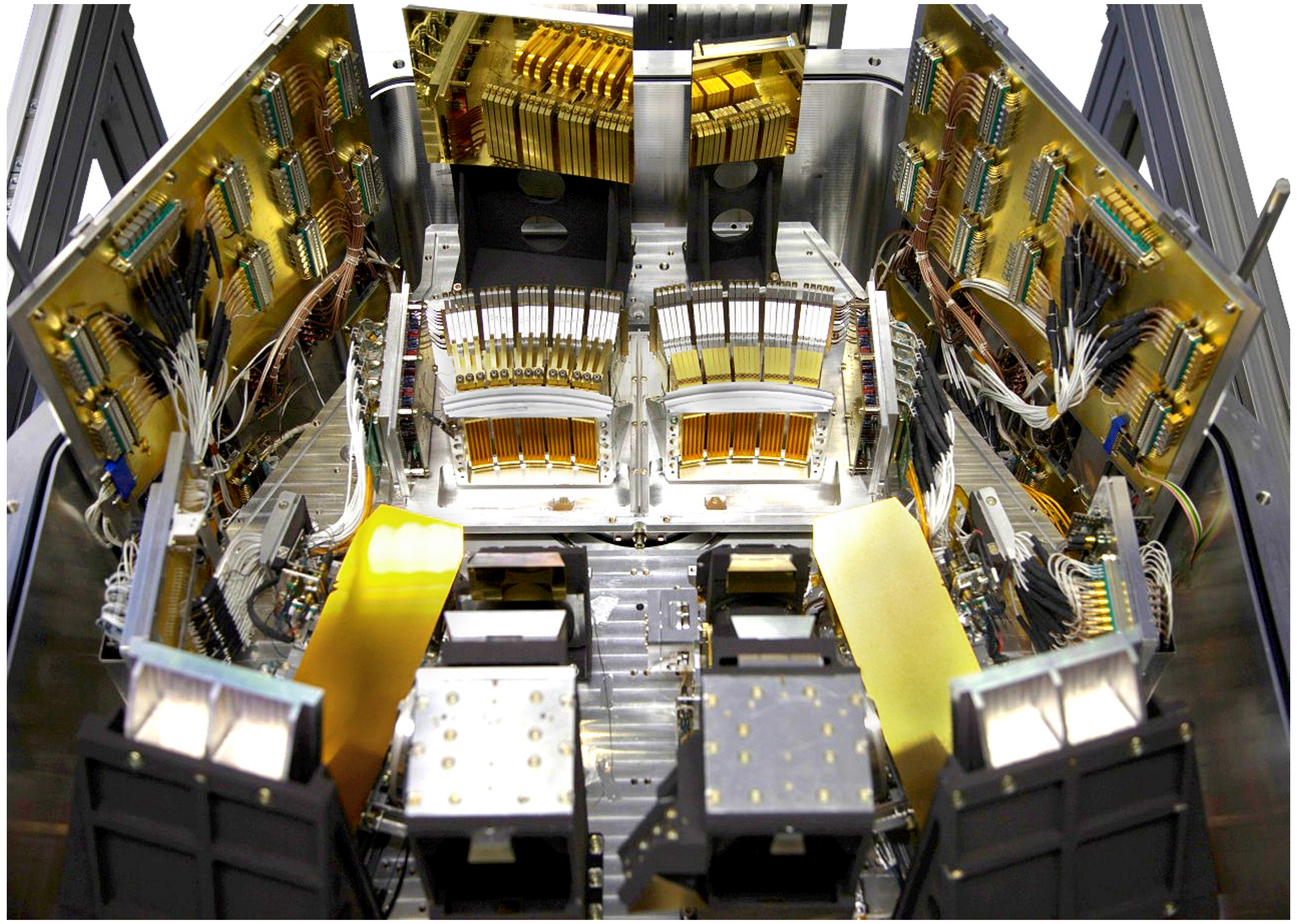


FIFI-LS Resolution

- Littrow spectrometer with movable grating provides wavelength selection and resolving power.

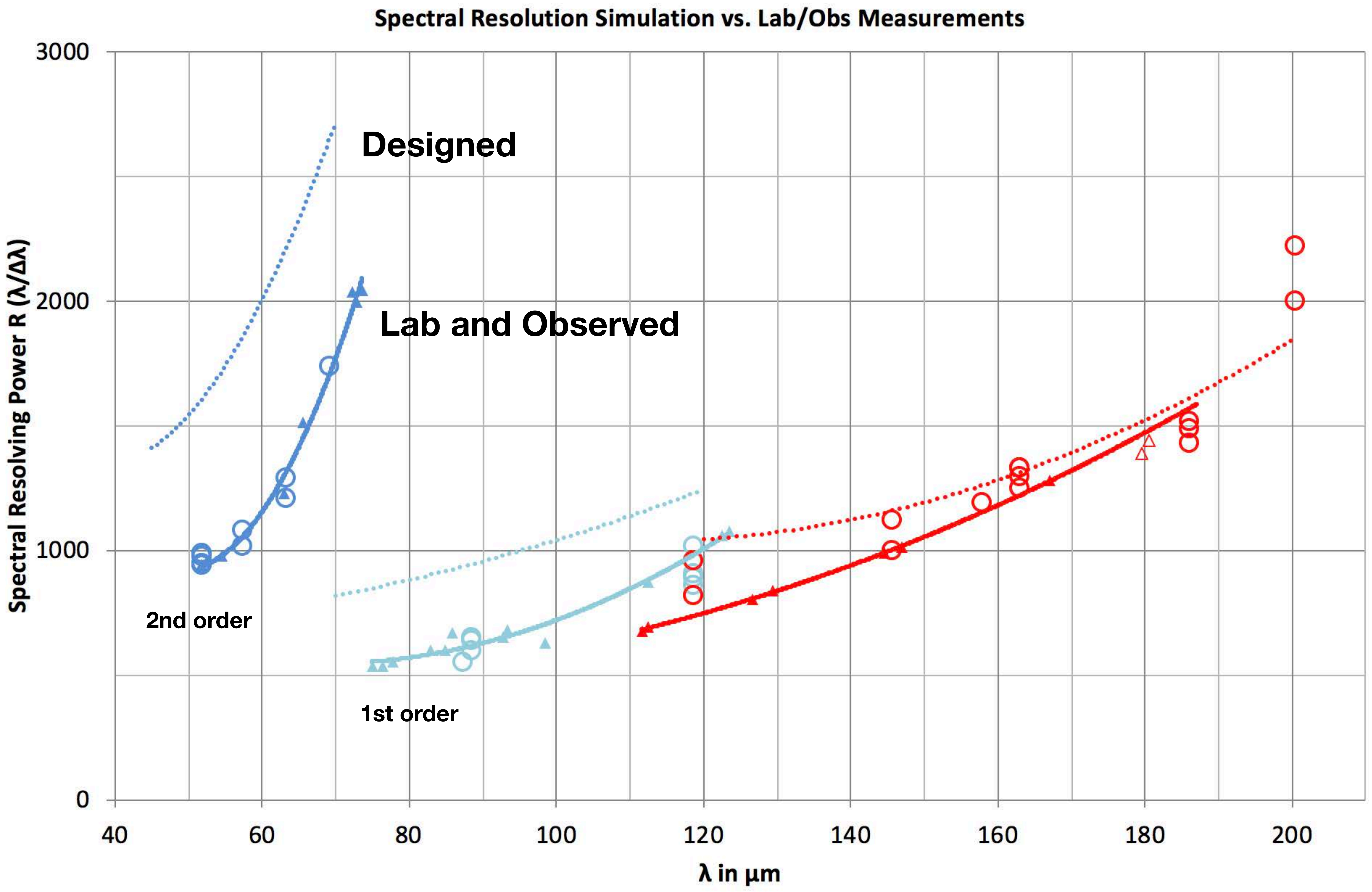
- Resolution is primarily determined by grating length.





Resolution on the Sky

- Resolution in Blue channel is lower than expected.
- Likely a mirror alignment or mirror manufacturer issue in Blue channel. But, not resolved due to required downtime to investigate and resources.



Colditz et al. 2017
Fischer et al. 2017

FIFI-LS Science

- Far-IR range accessible to FIFI-LS hosts a wealth of diagnostic emission lines:

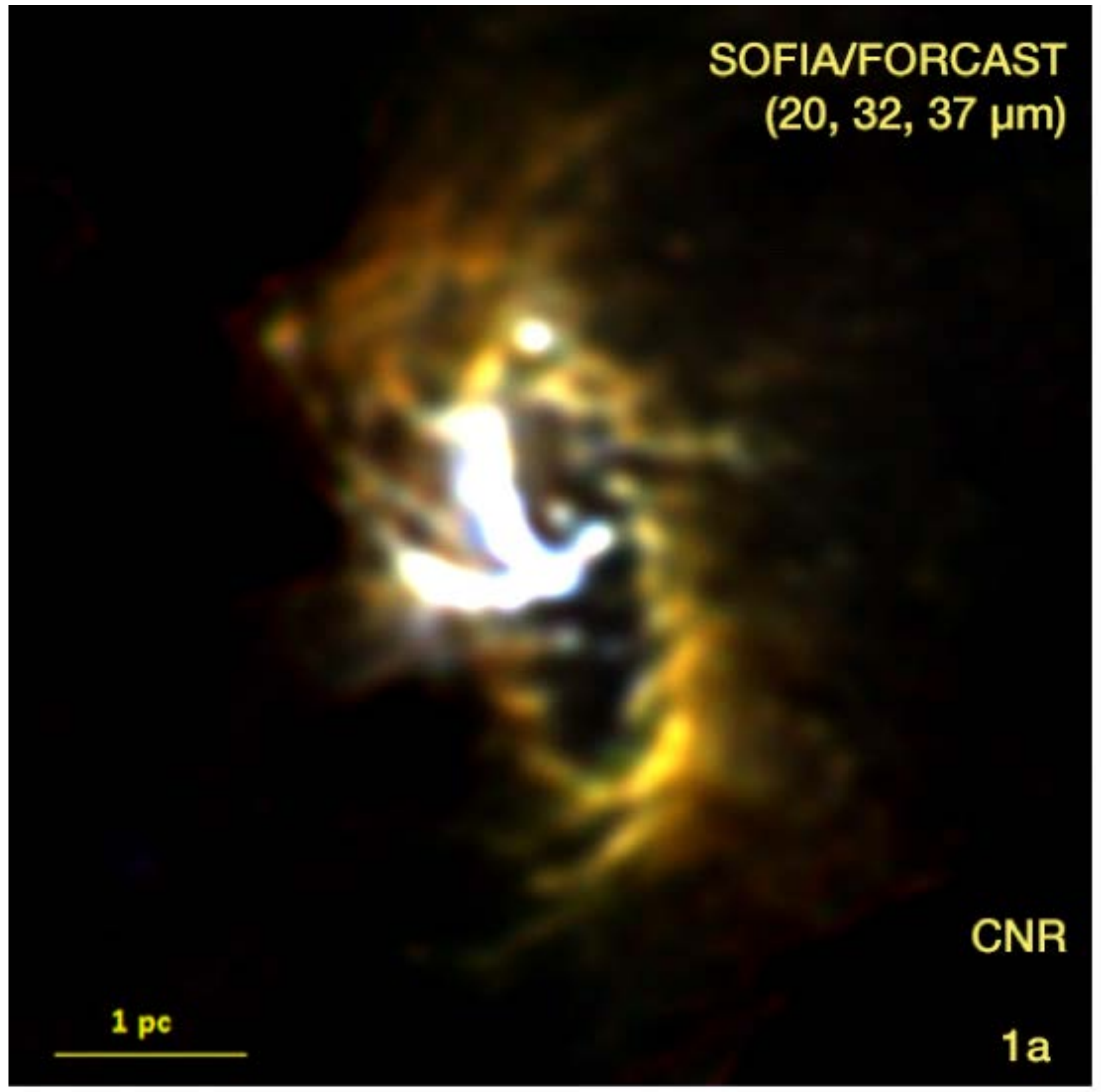
line	$\lambda[\mu m]$	line	$\lambda[\mu m]$	line	$\lambda[\mu m]$	line	$\lambda[\mu m]$	line	$\lambda[\mu m]$
[OIII]	51.8	CO	70.9	CH_4	87.3	CO	124.2	OH	163.3
OH	55.9	CO	77.1	[OIII]	88.4	CO	130.4	HCN	169.4
[NIII]	57.3	CH_4	80.1	OH	96.3	[OI]	145.5	CO	174
[OI]	63.2	CO	84.4	CO	96.8	CO_2 (ice)	146	CO	186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

- Fine Structure lines are particularly important:
  - Transitions between collisionally-excited levels within the ground state
  - Easily excited at temps and densities typical of ISM, PDRs, HII regions
  - Generally optically thin
  - Relatively unaffected by extinction
  - Major gas coolants
  - [C II] 158 is typically ~1% of total FIR flux

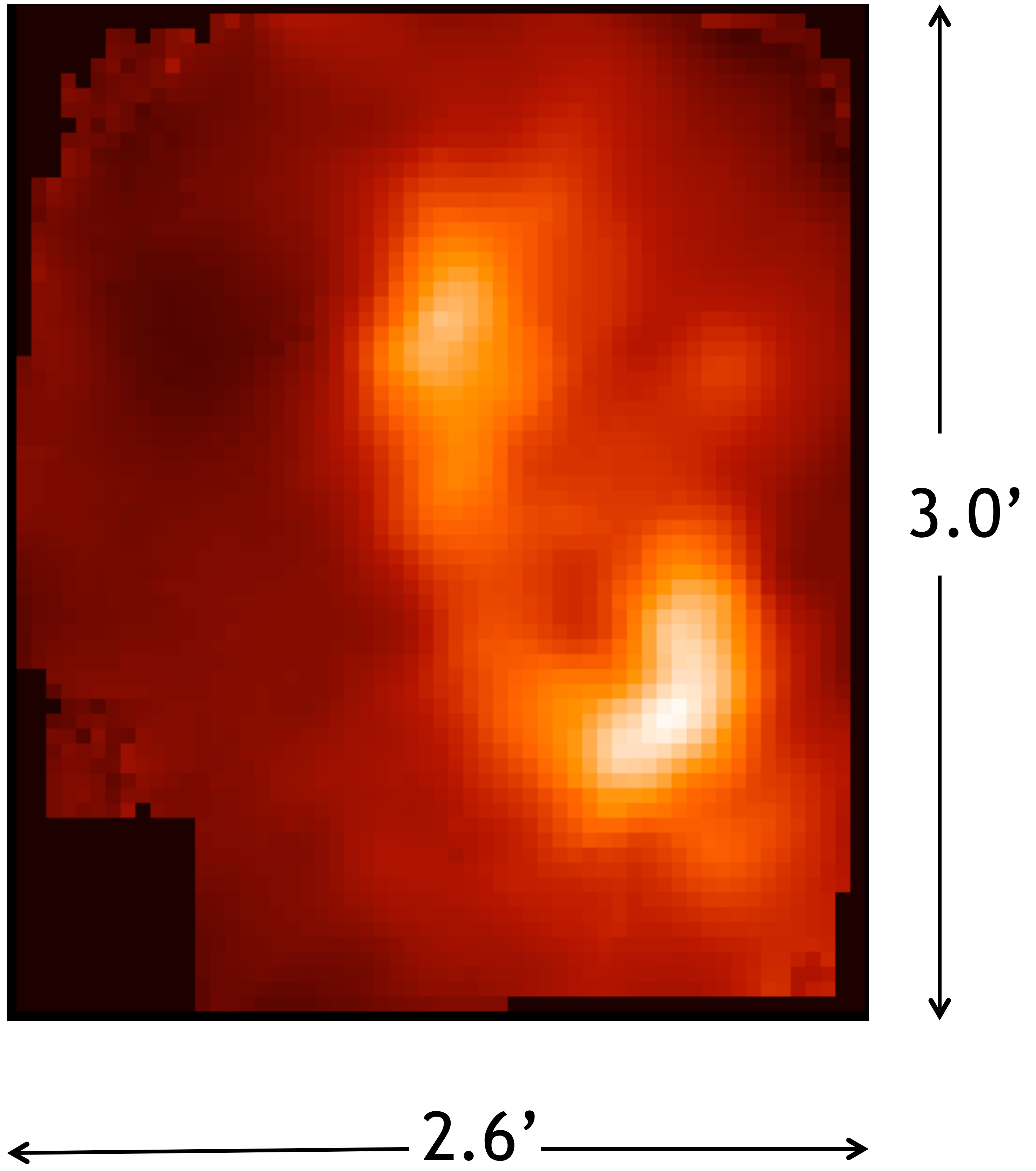
- Line pairs provide extinction-free probes of physical conditions in the neutral and ionized gas in the dust-obscured star forming regions of galaxies
  - temperatures (T), densities (n), abundances (Z), UV intensity (G_0), SFR

Examples of FIFI-LS Science programs: Mapping the CNR in the GC (Iserlohe et al. 2019)

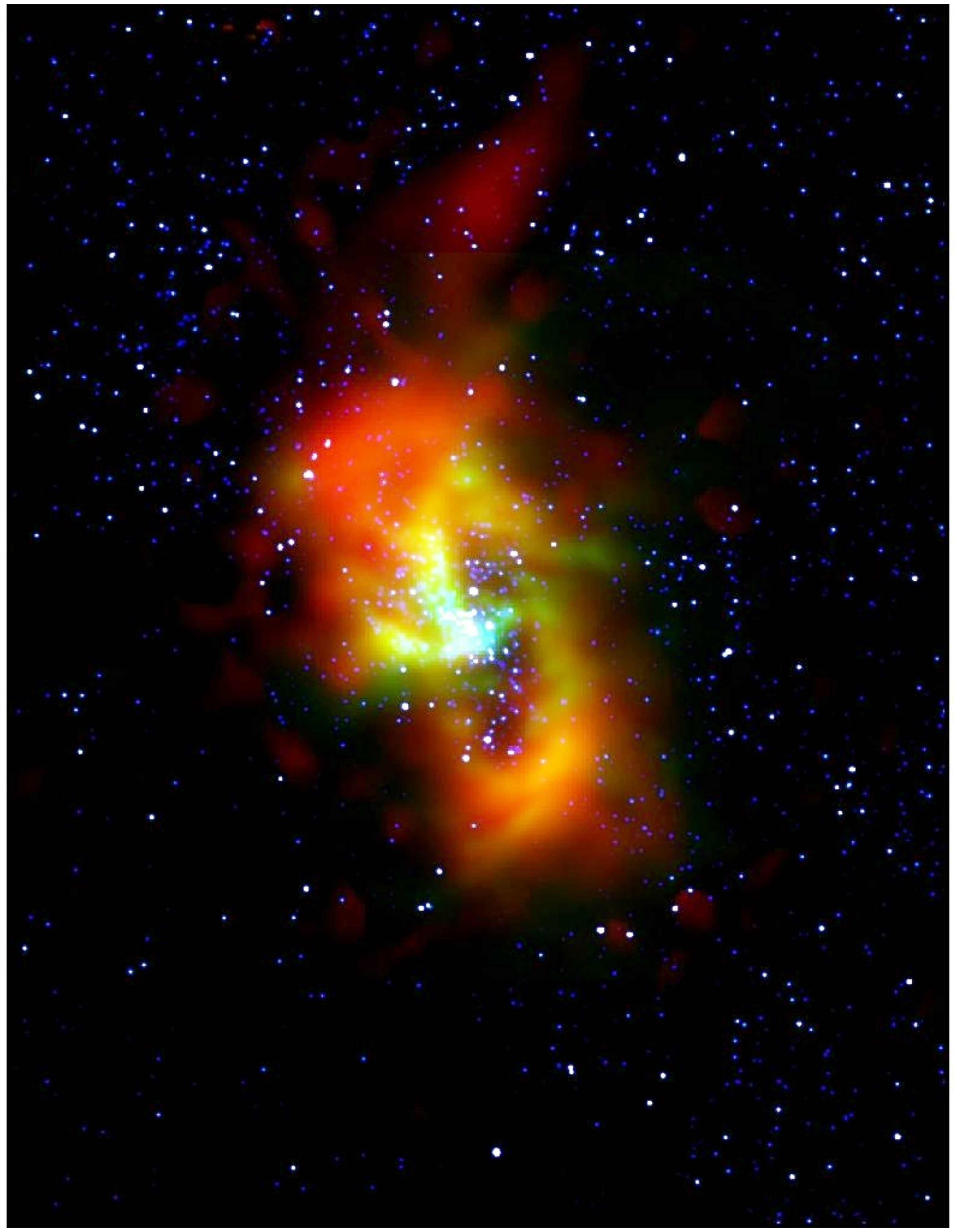
FORCAST Observations of the CNR
(Lau et al. 2013)



FIFI-LS Observations of the CNR at [OI] 145 μm
(Iserlohe et al. 2019)



Blue: HST NICMOS
Green: FORCAST 31 μm
Red: FIFI-LS [OI] 63 μm



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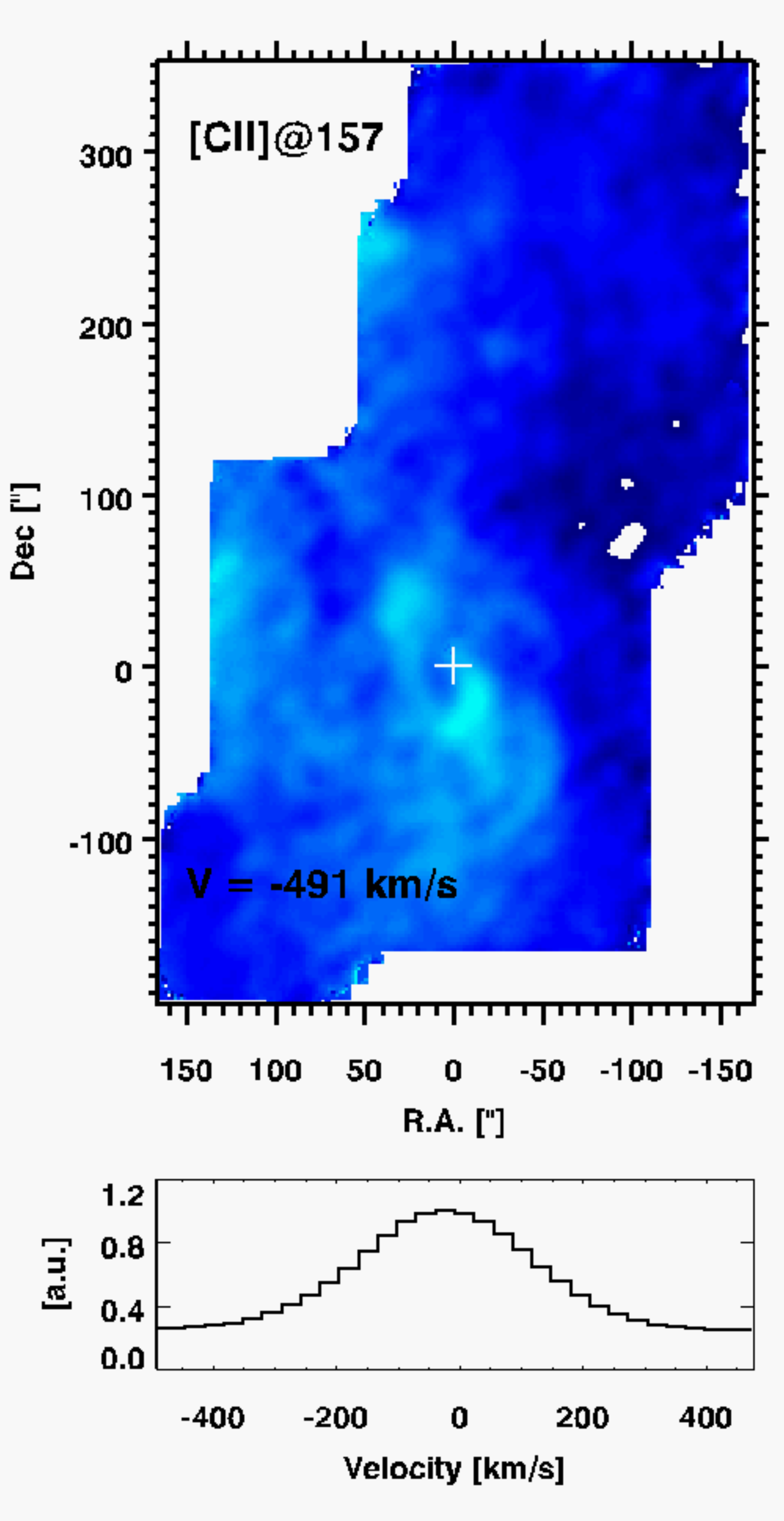

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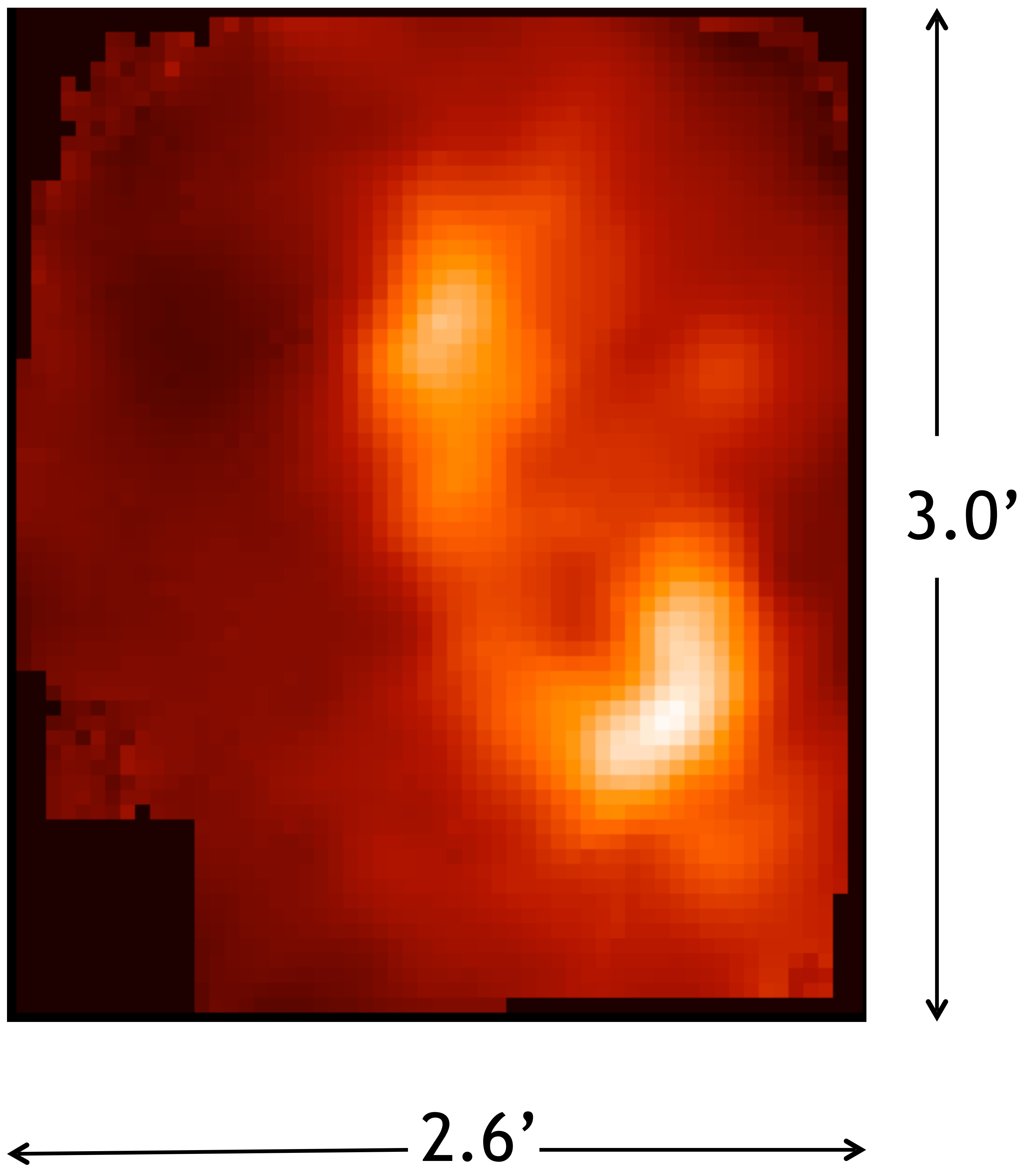

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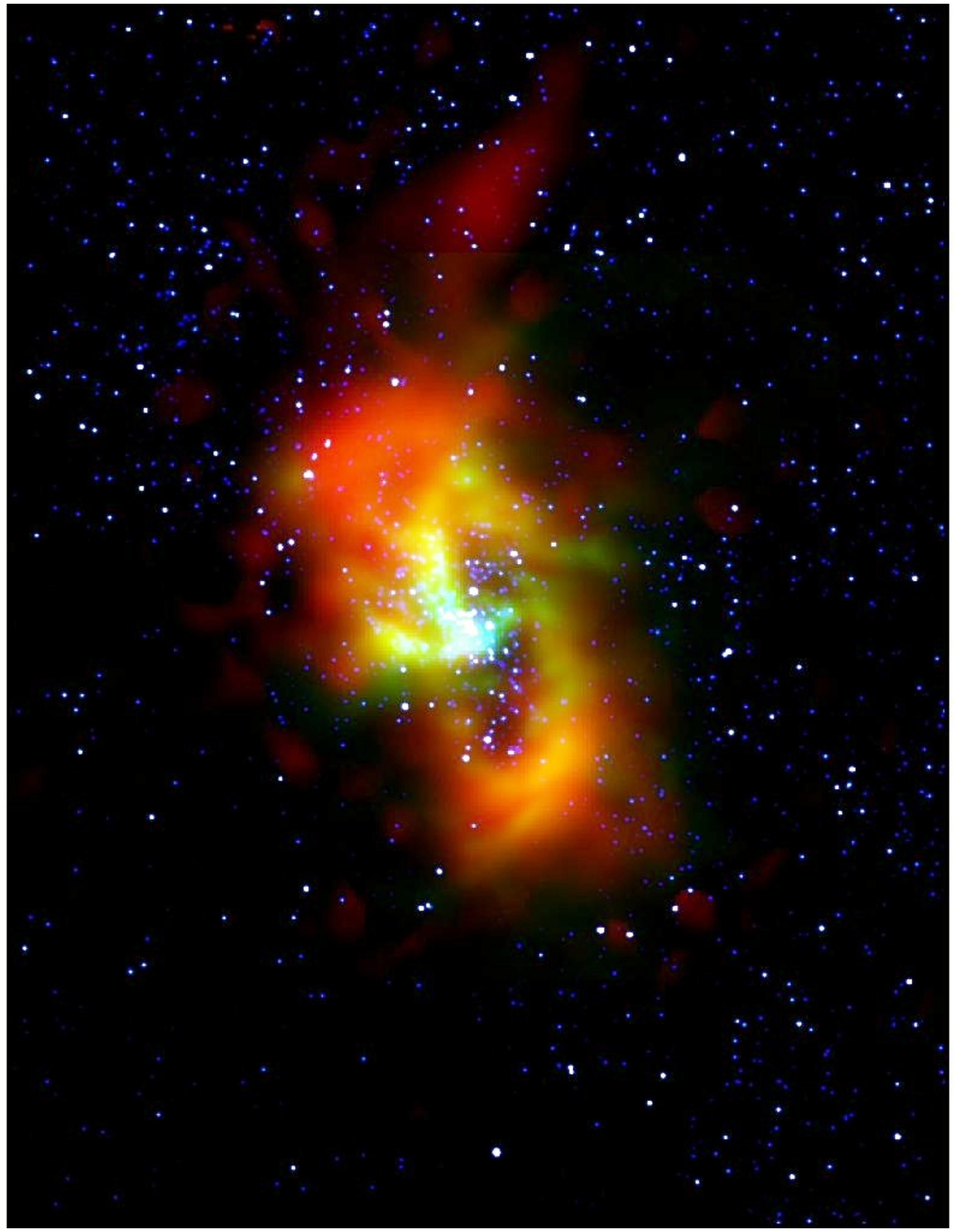

Examples of FIFI-LS programs: CNR Mapping (Iserlohe et al. 2019)

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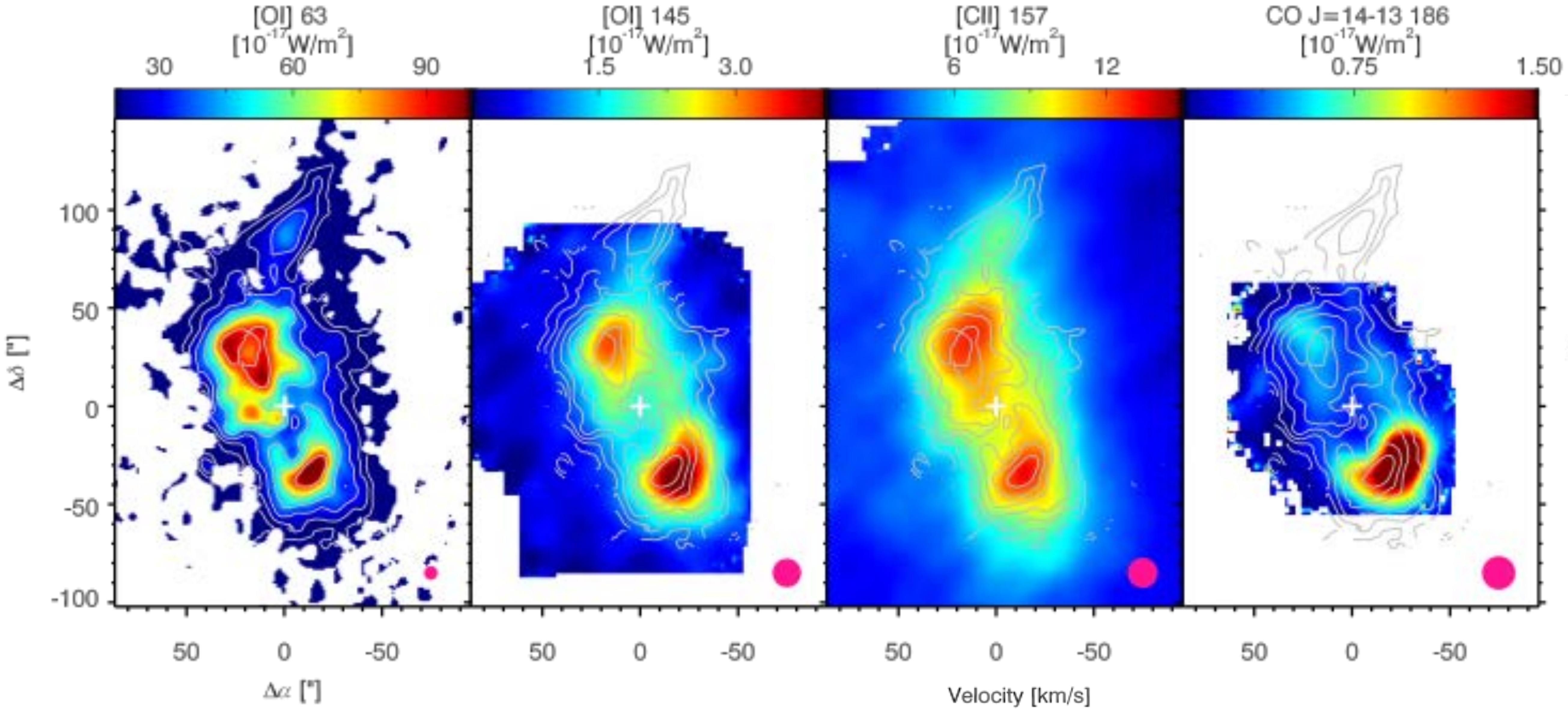
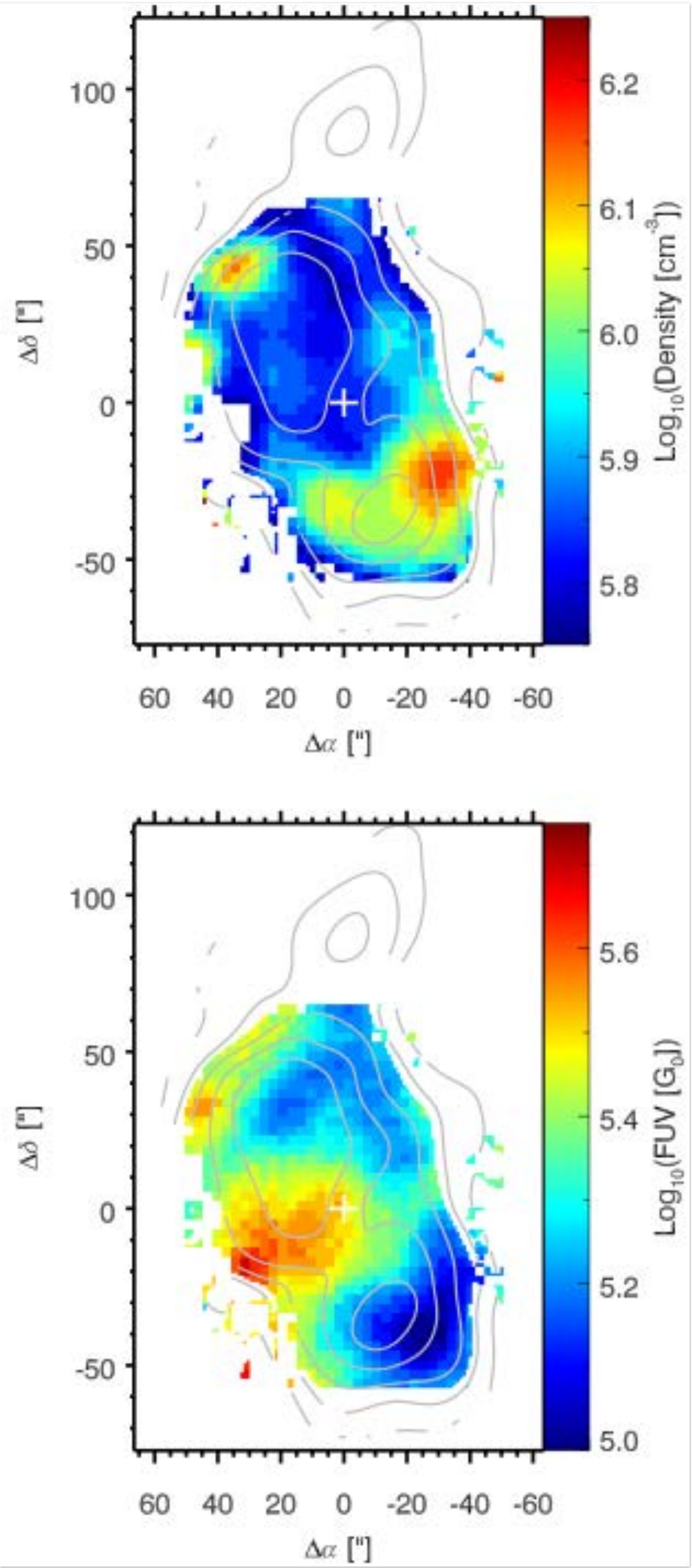
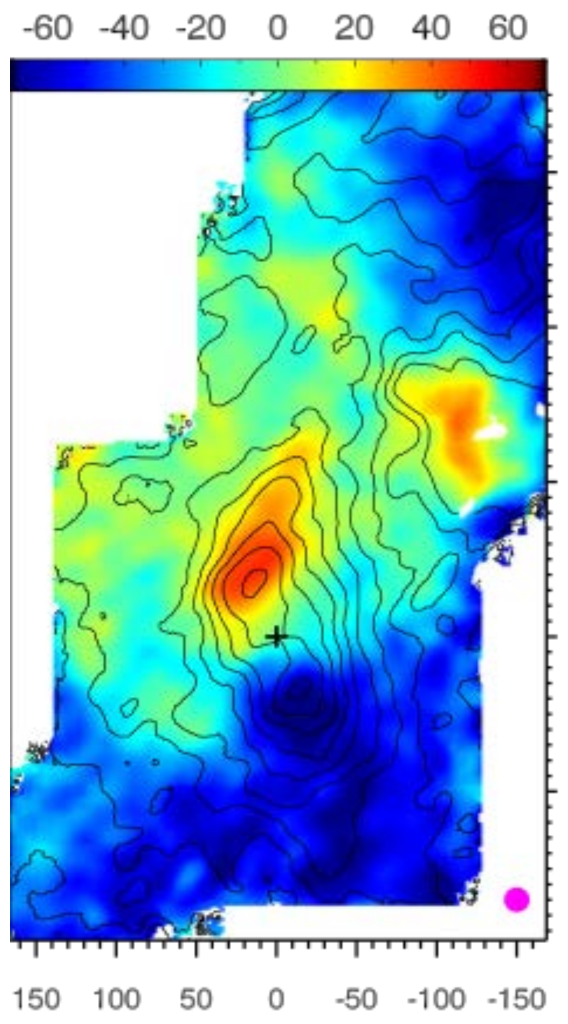




Density ($<10^7$ cm^{-3})

FUV Flux

- Almost 60% of the [O I] 63 μm line emission is self-absorbed
- Only ~15% of the [C II] 158 μm line emission is from the hot, high density phase of the PDR
- Densities in CNR < 10^7 cm^{-3}, below Roche limit for gas clumps to be gravitationally stable against tidal shear
- CNR is a transient phenomenon of gas streams, not a long-lived structure



Velocity Map

FIFI-LS Status

- 6+ years of observing with 27+ cooling cycles: instrument has been performing as expected.
- A workhorse instrument for mapping fine structure lines over a range of physical scales in galactic regions and nearby galaxies with moderate resolution and good sensitivity.
- Significant improvements in pipeline, including atmosphere calibration.
- Continue to develop new observing techniques for further efficiency improvement, e.g. observing modes using total power (unchopped) and On-The-Fly (OTF), as well as Chop/Nod with Dithering

FIFI+LS Science

- FIFI-LS doing great, but to make largest science impact, we are limited by # of flights for large projects.   We need faster mapping speed.

- Obvious place for improvement is the detector arrays.

- An increase in mapping speed (resulting from an increased FOV and sensitivity) opens up much more science opportunities.

- For example, survey of the FIR emission in nearby and intermediate distant galaxies for critical ISM diagnostics (e.g., metallicity, radiation field strength, AGN indicators, SFR), especially powerful when used with available multi-wavelength data.

FIFI+LS Science

- With mapping increase of ≥3.5 plus additional gains from increased observing efficiency line mapping observations of extended regions can be done in a fraction of the time for larger samples and fainter detection levels
  - 30 Dor: 11.5 h → < 3.3 h
  - NGC 6946: 9.5 h → < 2.7 h
  - M82: 9 h → < 2.6 h
  - M51: 15 h → < 4.3 h

- Mapping FS lines over a range of physical scales in a large sample of Galactic regions and nearby galaxies allows study of properties of the ISM over a range of environments (serving as templates for understanding galaxies at high z)
  - Physics behind the "FIR line deficit" (decrease in line/continuum ratio as a function of Σ_{FIR})
  - Reliability of [CII] as a tracer of SF
  - Abundances derived from extinction-free FIR lines vs optical lines
  - Studies of "CO-dark" gas
  - Properties of jets and outflows, HIIs, PDRs, SSCs, starburst regions

FIFI+LS: Upgrade

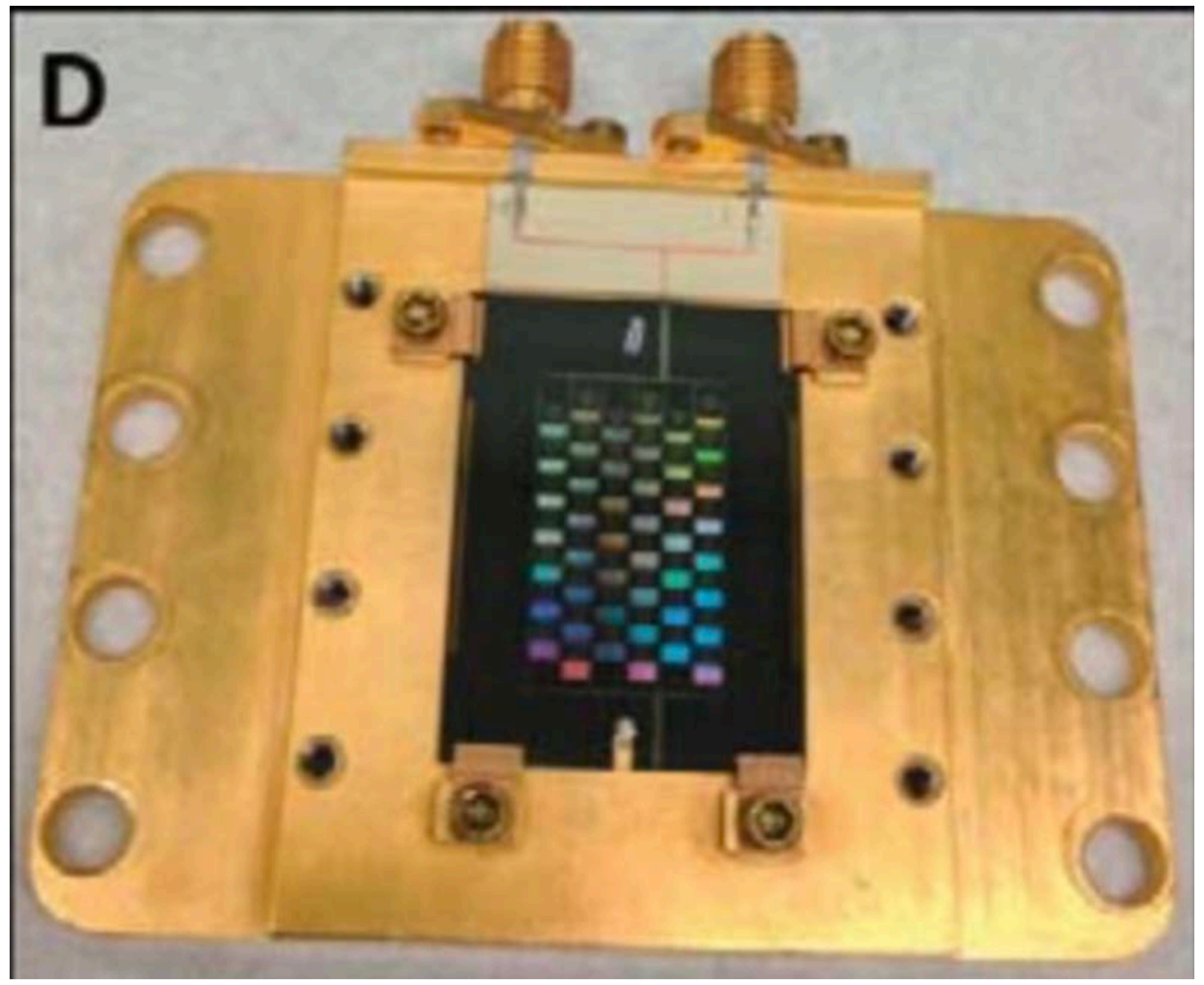
- FIFI+LS was selected for funding in 2018 instrument study call, but funds became unavailable

- Optical design of FIFI-LS allows for relatively easy upgrade to 9x7 spaxels, increase in FOV— important for mapping speed.
  - New slicer assemblies, collimators, and imaging optics, but no change needed to entrance optics or expensive gratings.

- Easy to increase spectral pixels (64 pixels vs. 16)— for atmospheric transmission calibration.

- Major change would be cooling process of new detectors— currently LHe2 down to ~1.8K but need <250 mK.

KID Arrays



- Need 77x64 pixels (4928) for FIFI+LS detectors, hand-made photometers not an option, and pressure design for Ge:Ga stressing is unlikely to scale uniformly load pixels for Red channel performance.

- KIDS array developed for STARFIRE/TIM at 350 μm by JPL, scalable for Red channel.

- Blue channel requires new absorber, but prototype simulations give an efficiency of at least 45% for the Blue channel wavelength range.

- FIFI+LS design not dependent on “best” QE, but comparable to their current devices, but we expect some improvements.

FIFI+LS Improvement

- Increase sensitivity by $\geq\sqrt{2}$ (possibly up to 2.5) and mapping speed by a factor of ≥ 3.5
- Increase number of spaxels to 9 x 7 (vs 5 x 5 currently) and FOV by factor of 1.75
  - 5" spaxels in the blue, giving 45" x 35" instantaneous spatial coverage
  - 10" spaxels in the red, giving 90" x 70" instantaneous spatial coverage
  - FOV allows Lissajous observing without chopping, reaching FIFI-LS noise level in 1/3 the clock time.
- Increased spectral pixels to 64 (vs 16) will allow better, simultaneous determinations of PWV from the target spectra themselves, providing more observing efficiency.

FIFI+LS Stats

Increase in FOV, spectral range, and sensitivity (conservatively)

	FIFI+LS Blue Chan.	FIFI+LS Red Chan.	FIFI-LS Blue Chan.	FIFI-LS Red Chan.
Wavelength Range [μm]	51-125	115-206	51-125	115-203
Spect. Res. [km/s]	130-435	160-425	155-550	160-425
Instant Spect. Range [km/s]	2500-9000	3200-10000	800-3000	800-2550
Field-Of-View	$45''$x $35''$	$90''$x $70''$	$30''$x $30''$	$60''$x $60''$
Spatial Pixels	9 x 7	9 x 7	5 x 5	5 x 5
Spatial Pixel Pitch	$5''$	$10''$	$6''$	$12''$
Spect. Pixels per Spaxel	64	64	16	16
Image Slices	7	7	5	5
Slit Width in Pixel*	(9+2)×7=77	(9+2)×7=77	5×5=25	5×5=25
Detector Size in Pixel	77×64=4928	77×64=4928	25×16=400	25×16=400

*2 additional pixels per slice to allow for gaps and avoid crosstalk

Cooling Redesign

- Possible major change to instrument.
- Designs are still being considered, but least invasive is hopefully best option
- Leave FIFI-LS nitrogen system (entrance optics) and LHe (optics), but remove LHe2 (detectors) for upgrade to KID arrays.
- Compact space should allow for an ADR backed by a He-4-sorption-fridge linked to the 4K.

Budget/Schedule/Impact

- Leveraging existing hardware and personnel synergy with DSI, estimated cost is $4M, of which $2.5M is detector estimate.
- Estimated time-scale of 2.5 years for completion of FIFI+LS, dependent on detectors
- FIFI-LS would be down for 1.5 years— depending on cooling solution.

Sensitivity Comparison Estimate

$t_{HIRMES}/t_{FIFI+LS}$

λ	line	R FIFI+LS	t_{ratio} narrow line	t_{ratio} extragalactic line	t_{ratio} Lissajous	t_{ratio} array chop
51.815	[OIII]	1150	1.4	2.0	3.6	3.6
57.317	[NIII]	1150	1.7	2.3	4.3	4.8
63.184	[OI]	1700	2.1	2.9	5.3	5.9
88.356	[OIII]	870	1.1	1.5	2.7	3.0
121.898	[NII]	1300	1.6	2.2	4.0	4.5

- Conservative comparison of HIRMES and FIFI+LS
- Narrow line ~20 km/s and extragalactic ~100 km/s
- Source is ~½ the Blue array in angular extent

Sensitivity Comparison Estimate

$$(\mathrm{t}_{upGREAT}/(\mathrm{t}_{FIFI-LS} \text{ or } \mathrm{t}_{FIFI+LS})$$

FWHM line in km/s	t_{ratio} [CII] FIFI-LS	t_{ratio} [OI] FIFI-LS	t_{ratio} [CII] FIFI+LS	t_{ratio} [OI] FIFI+LS
2	0.33	1.43	0.66	2.9
5	0.81	3.7	1.6	7.4
10	1.6	7.4	3.3	14.7
20	3.3	14.7	6.6	29.4
40	6.6	29.4	13	59

- Conservative comparison of upGREAT and FIFI+LS
- Detection of point source— for mapping there is an increase of 25:7 for OI lines and 25:14 for CII (based on pixels) for FIFI-LS and more for FIFI+LS.
- Spectrally unresolved in both cases, for velocity-resolved science, need upGREAT (with more observing time).

Going Bluer? Redder?

- There are interesting science goals down to 42 μm (water ice) and up to 205 μm [NII].

- [NII] is planned for FIFI+LS. The stressed photoconductors drop off quickly with wavelength, but the KIDS do not.

- FIFI+LS needs to add filter capability to allow the 42 μm functionality, but the wide feature will be helped by the wider wavelength coverage.

US-DE Synergy

- FIFI-LS has a strong US-DE partnership
- FIFI+LS will continue with instrument upgrade with a collaboration between Stuttgart, Illinois, DSI, JPL, and Caltech with a strong international team for science program
- FIFI+LS will continue to be housed at Armstrong during development.

FIFI+LS Conclusion

- For modest investment in money and time, FIFI+LS will increase sensitivity, FOV, data quality, and spatial and spectral sampling for workhouse FIR line spectrometer.

- Significant increase in mapping speed ≥ 3.5 making mapping surveys easily feasible.

- Primary science goals from team: large mapping survey of nearby galaxies in the FIR emission lines to study the properties and physics of the ISM in star forming regions with a large variety of environmental conditions and that can serve as local templates for high redshift objects

- Moderate resolution mapping is critical to understand science in many regions. FIFI+LS mapping speed would be a good pathfinder for upGREAT and future HIRMES-like instrument.