Upgrade to FIFI-LS: FIFI+LS

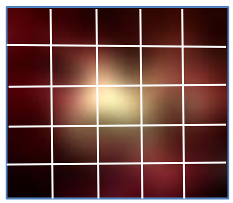
W. D. Vacca

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

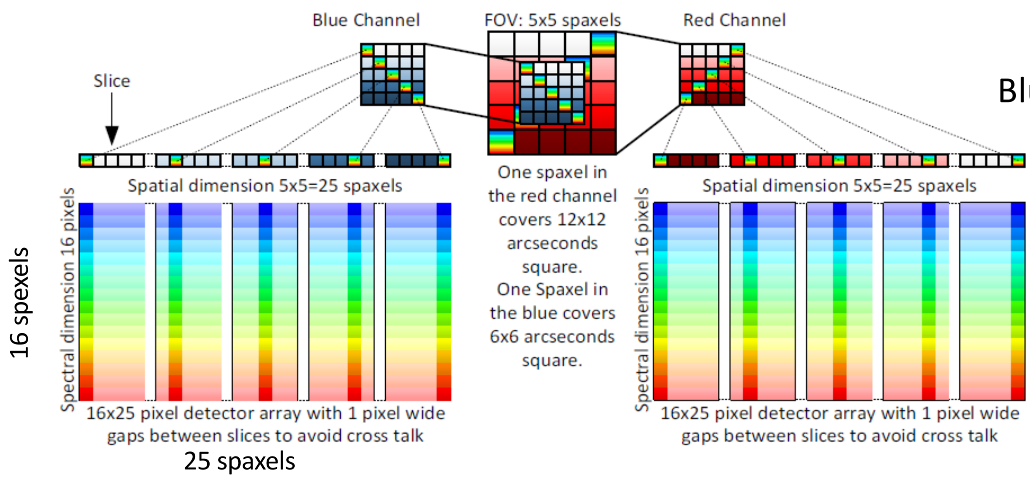
- Far-IR spectrometer with two independent channels operating simultaneously via a dichroic:
  - Blue 50-125 µm (6” pixels, 30”x30” FOV; FWHM ~ 4.3-10’’)
  - Red 105-200 µm (12” pixels, 60”x60” FOV; FWHM ~ 10-17’’)
  - Two separate and independent spectrographs: Can map two spectral lines simultaneously and control detectors independently
- Integral field spectrograph: spectrum obtained at each spatial pixel
  - Image slicer, grating, hand-made Ge:Ga detector (25x16 pixels = 400 pixels) for each channel
  - For each channel, 5x5 spatial pixels (‘spaxels’)
  - 16 spectral pixels (‘spexels’) at each spatial pixel
  - Instantaneous coverage ~800 – 3000 km/s depending on wavelength
  - Output product is a cube: X x Y x λ (2 spatial dimensions and 1 spectral dimension)
- Moderate Resolving power
  - R ~ 500-2000 (Δv ~ 150-600 km/s) depending on wavelength
  - Spectral sampling obtained by tilting (‘stepping’) the grating, to sample different wavelength ranges
- Chop/Nod with Dithering, Total Power (unchopped), and On-The-Fly (OTF; Lissajous scanning) mapping modes

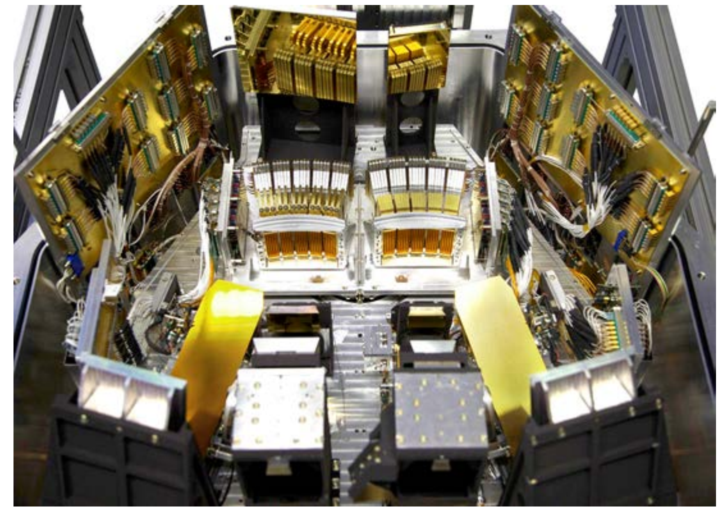
FIFI-LS Design:

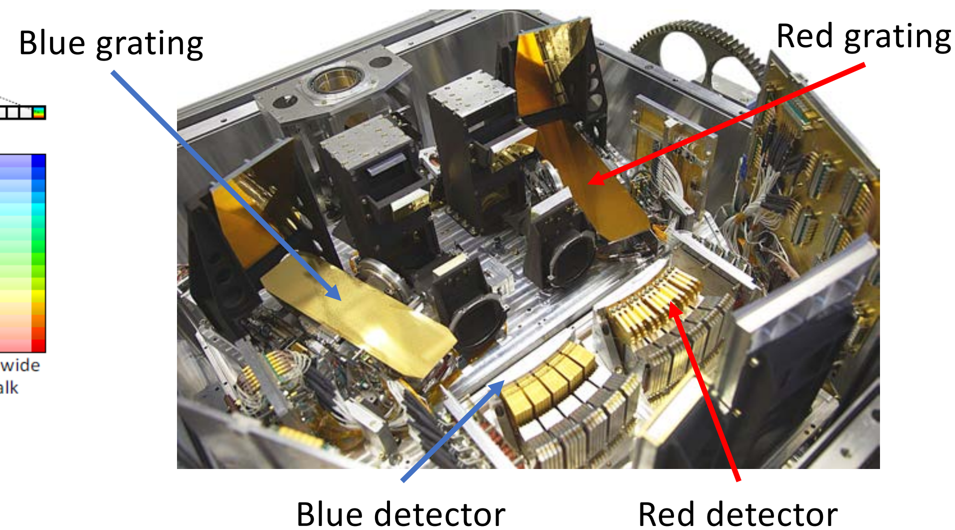
The 2-D field of view is re-imaged as a 1-D long slit via the image slicer



The footprints of the red and blue channels are approximately concentric but the red spaxels and FOV are twice as large as the blue

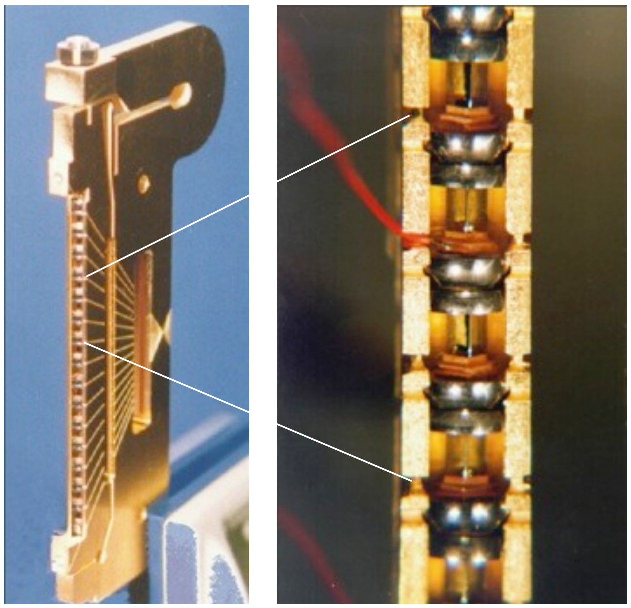




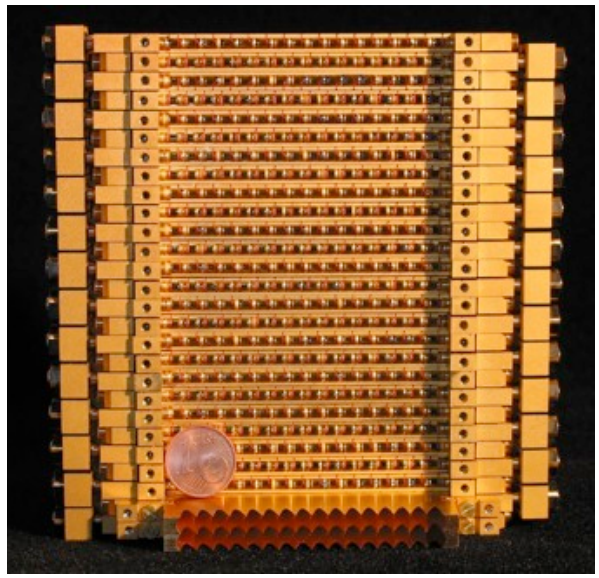


Hand-made 400 Pixel Photoconductor Detector

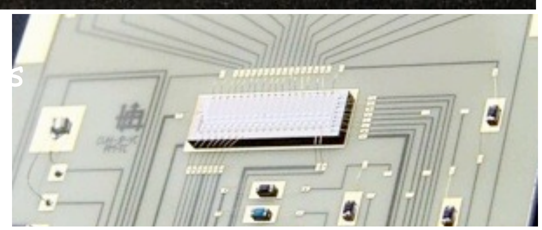
16 spexels

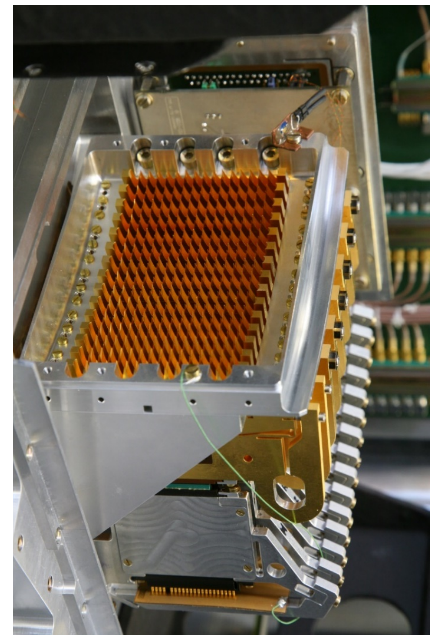


16 spexels



25 spaxels





Proposed upgrade of FIFI-LS to FIFI+LS:

- Replace photoconductor arrays with Kinetic Inductance Detectors (KIDs)
  - Increase sensitivity by factor of $\geq \sqrt{2}$ (possibly up to 2.5), and mapping speed by a factor of ≥ 2
  - Existing designs for 350 μm can be scaled down for red channel
  - New design needed for blue channel
  - Requires new cooling system (cryocooler for the optics and ADR for the detectors)
- Enlarge the FOV and improve the spatial sampling
  - 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
  - Requires some new optics, including the IFUs, collimators, and imaging optics (but **not** the gratings)
- Increase the instantaneous spectral coverage and improve the spectral sampling
  - 64 spectral pixels (vs 16) increases the spectral coverage by factor of 3-4, better baselines
  - 2500-9000 km s^{-1} in the blue channel
  - 3200-10000 km s^{-1} in the red channel
  - Should allow better, simultaneous determinations of PWV from the target spectra themselves
- Cost/Schedule:
  - ~$4M
  - ~2.5 years (depending on detector development work); FIFI-LS would be down for ~1.5 yrs

Proposed upgrade of FIFI-LS to FIFI+LS:

	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*	$(9+2)\times7=77$	$(9+2)\times7=77$	$5\times5=25$	$5\times5=25$
Detector Size in Pixel	$77\times64=4928$	$77\times64=4928$	$25\times16=400$	$25\times16=400$
NEP $\left[WHz^{-1/2}\right]$	1.5×10^{-17}	1.5×10^{-17}	1.5×10^{-16}	1.5×10^{-16}

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

Science Case for FIFI-LS *and* FIFI+LS: Mapping Far IR Emission Lines in Extended Regions

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

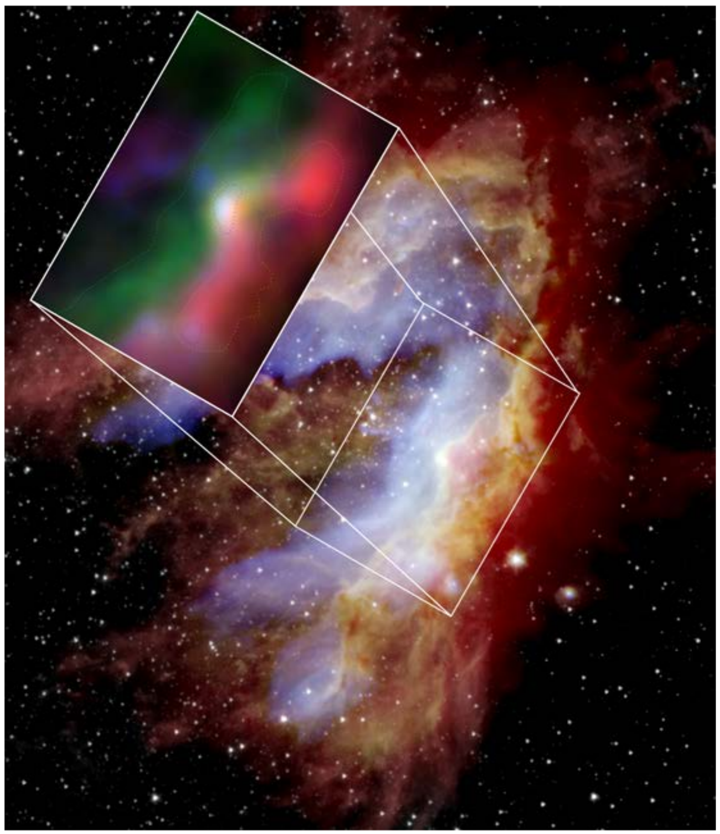
Not covered by *Herschel*/PACS → [OIII] 51.8

line	λ[μm]	line	λ[μm]	line	λ[μm]	line	λ[μm]	line	λ[μm]
[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	[NII]	205.2
C_2H_2	69.7	CO	87.2	[NII]	122	CO	162.8		

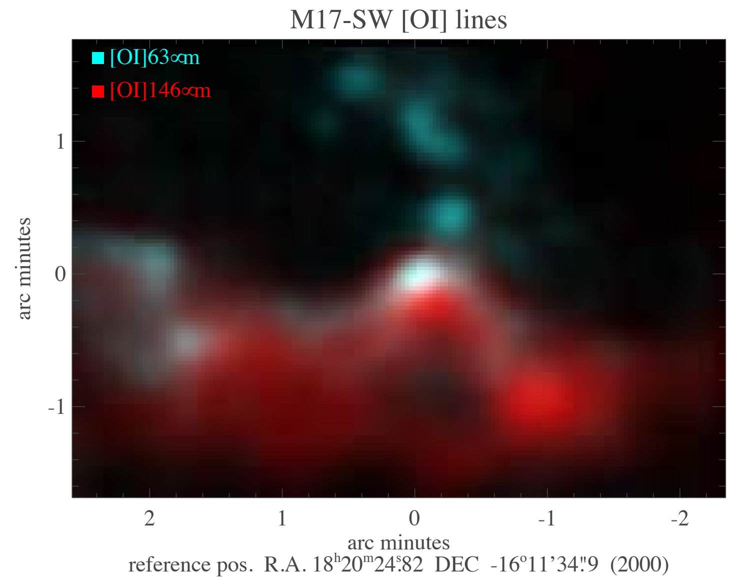
- Fine Structure lines are particularly important:
  - Transitions between collisionally-excited levels within the ground state
  - Easily excited at temps and densities typical of ISM, PDRs, HII regions
  - Generally optically thin
  - Relatively unaffected by extinction
  - Major gas coolants
  - [C 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
- Mapping of extended regions was difficult with now-defunct *Herschel*/PACS

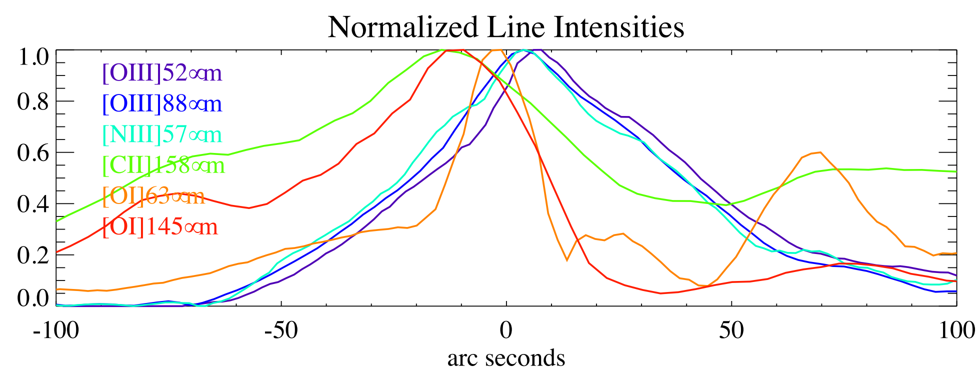
Examples of FIFI-LS programs: M17 (Klein et al. 2020)

FIFI-LS: [O I] 63 µm (blue), [OIII] 88 µm (green), [O I]145 µm (yellow), [C II] 158 µm (red)

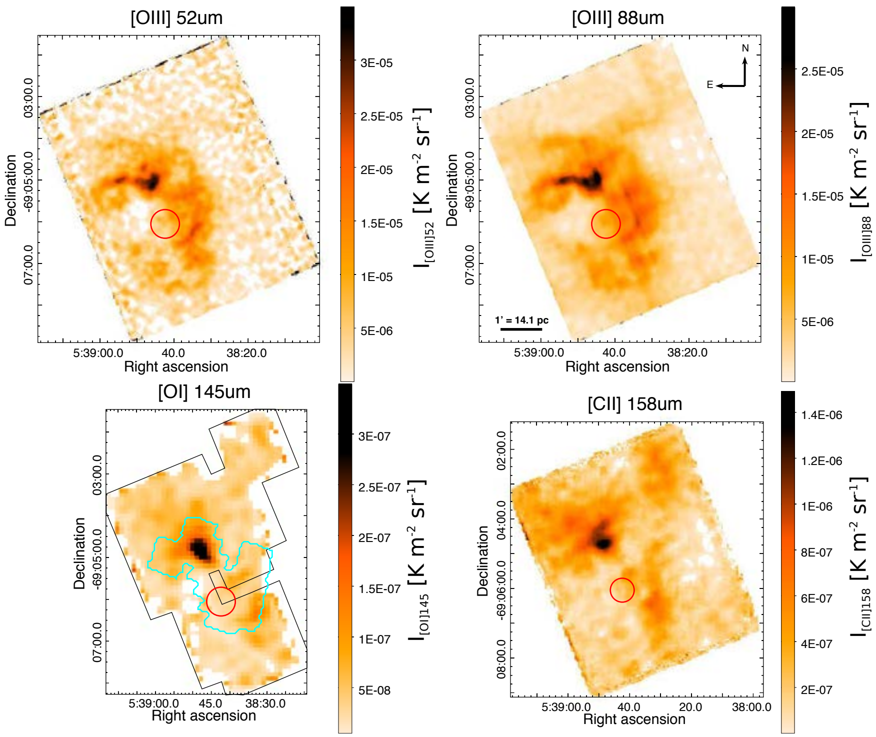


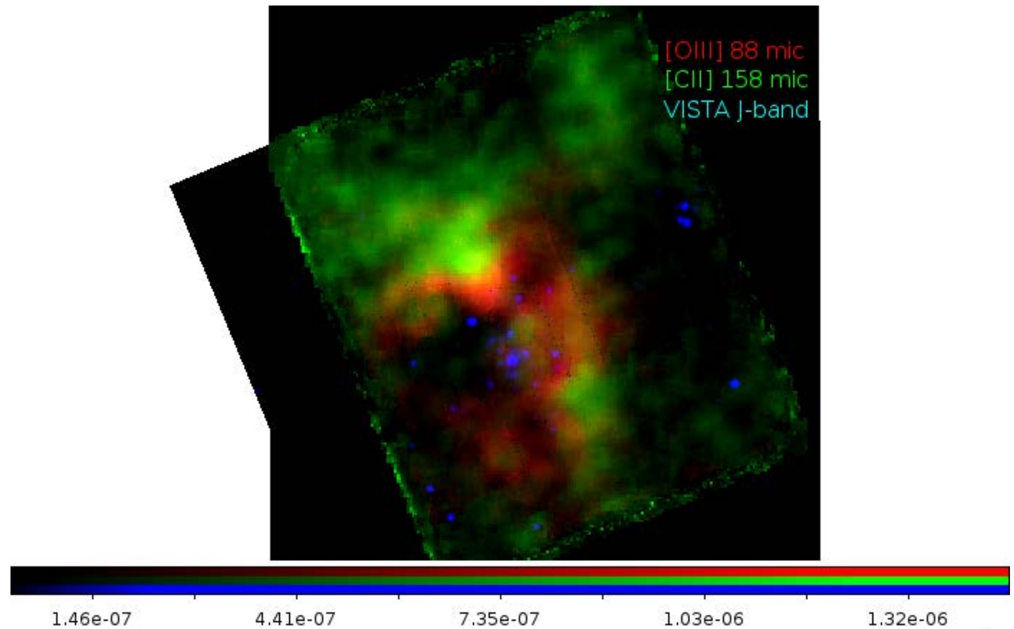
Background: FORCAST/PACS/2MASS



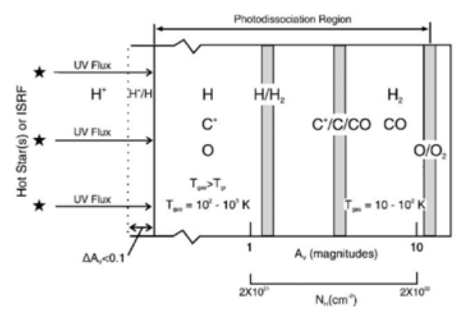


Examples of FIFI-LS programs: 30 Dor (Chevance et al. 2020)



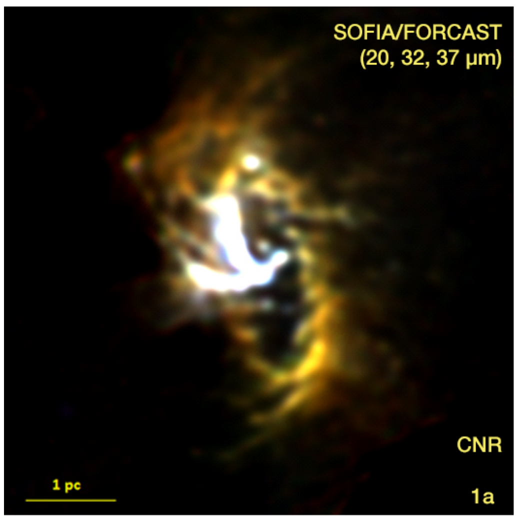


- Clear separation of high ionization lines from low ones, revealing HII/PDR structure
- PDR Modeling gives P ~ 10^6 K cm^{-3}, G_{UV} ~ 700-7000 G_0, A_V < 2-3 mag
- [O III] lines give the density in the H II region (n_e < 500 cm^{-3})
- [C II] traces large reservoir of “CO-dark” gas (≥75% of H_2)
- Similar studies are being carried out on M17 and Orion

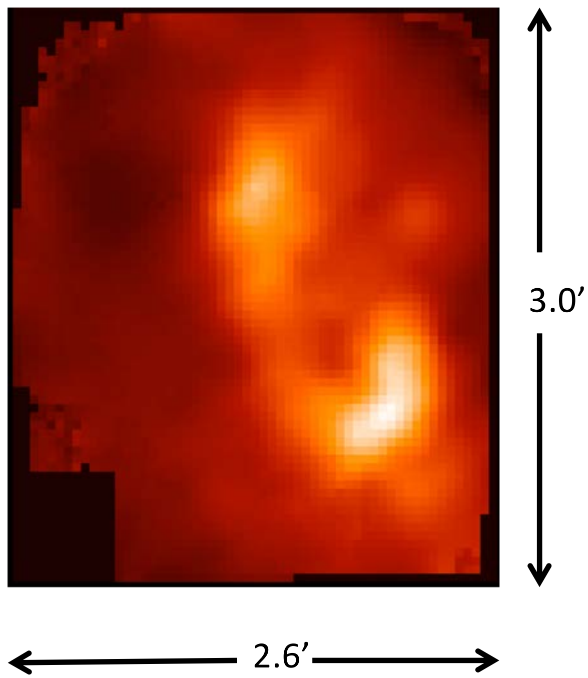


Examples of FIFI-LS programs: Mapping the CNR in the GC (Iserlohe et al. 2019)

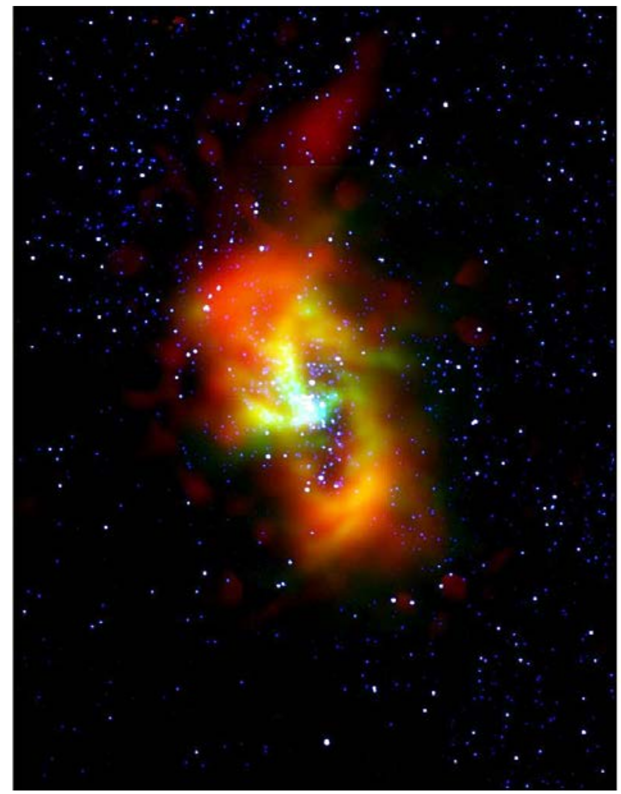
FORCAST Observations of the CNR
(Lau et al. 2013)



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



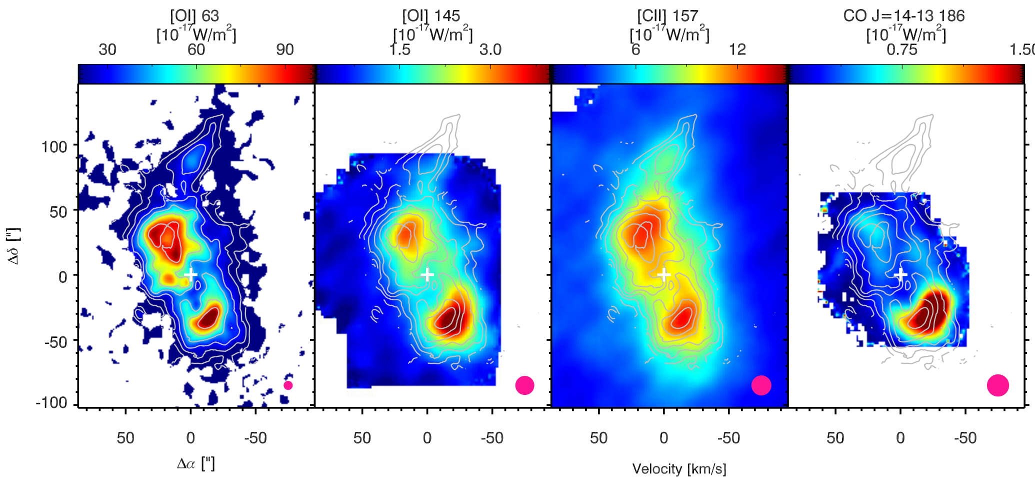
Blue: HST NICMOS
Green: FORCAST 31 µm
Red: FIFI-LS [OI] 63 µm

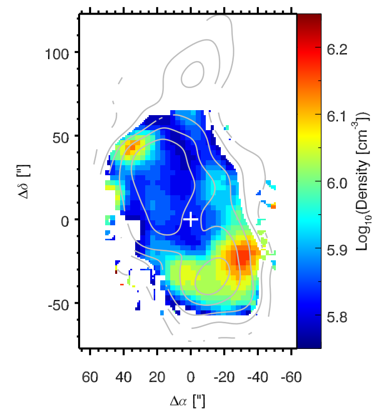


Examples of FIFI-LS programs: CNR Mapping (Iserlohe et al. 2019)

FORCAST

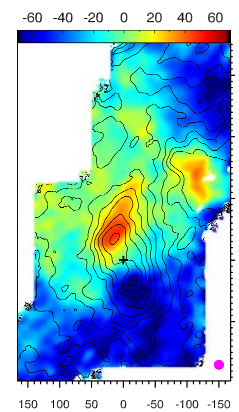
Lau et al. 2013



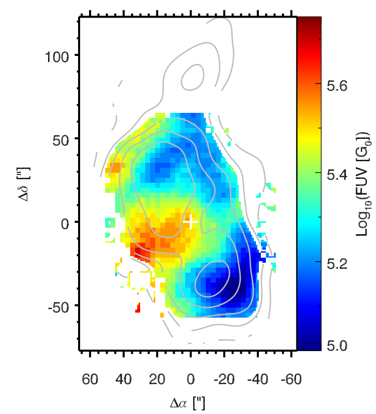


Density (<10^7 cm^{-3})

- 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

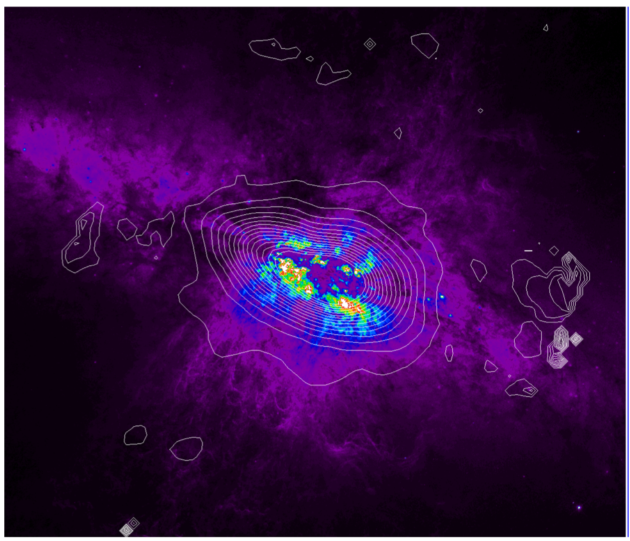


FUV Flux

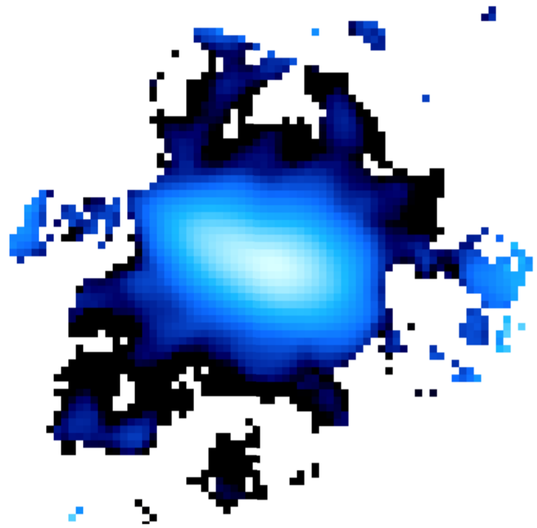
Examples of FIFI-LS programs: M82 (Fischer et al. 2020)

Hα

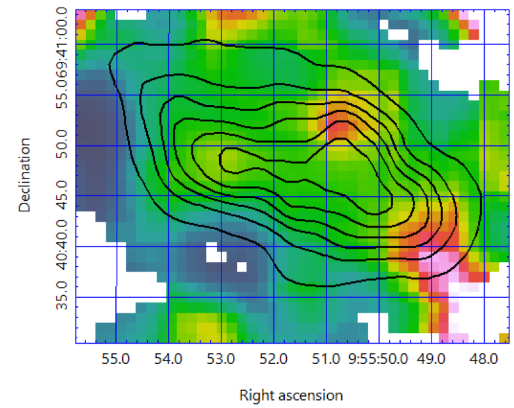
~75"

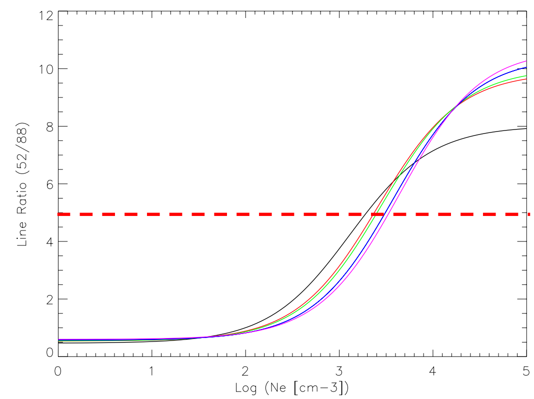


FIFI-LS [O III] 52 μm



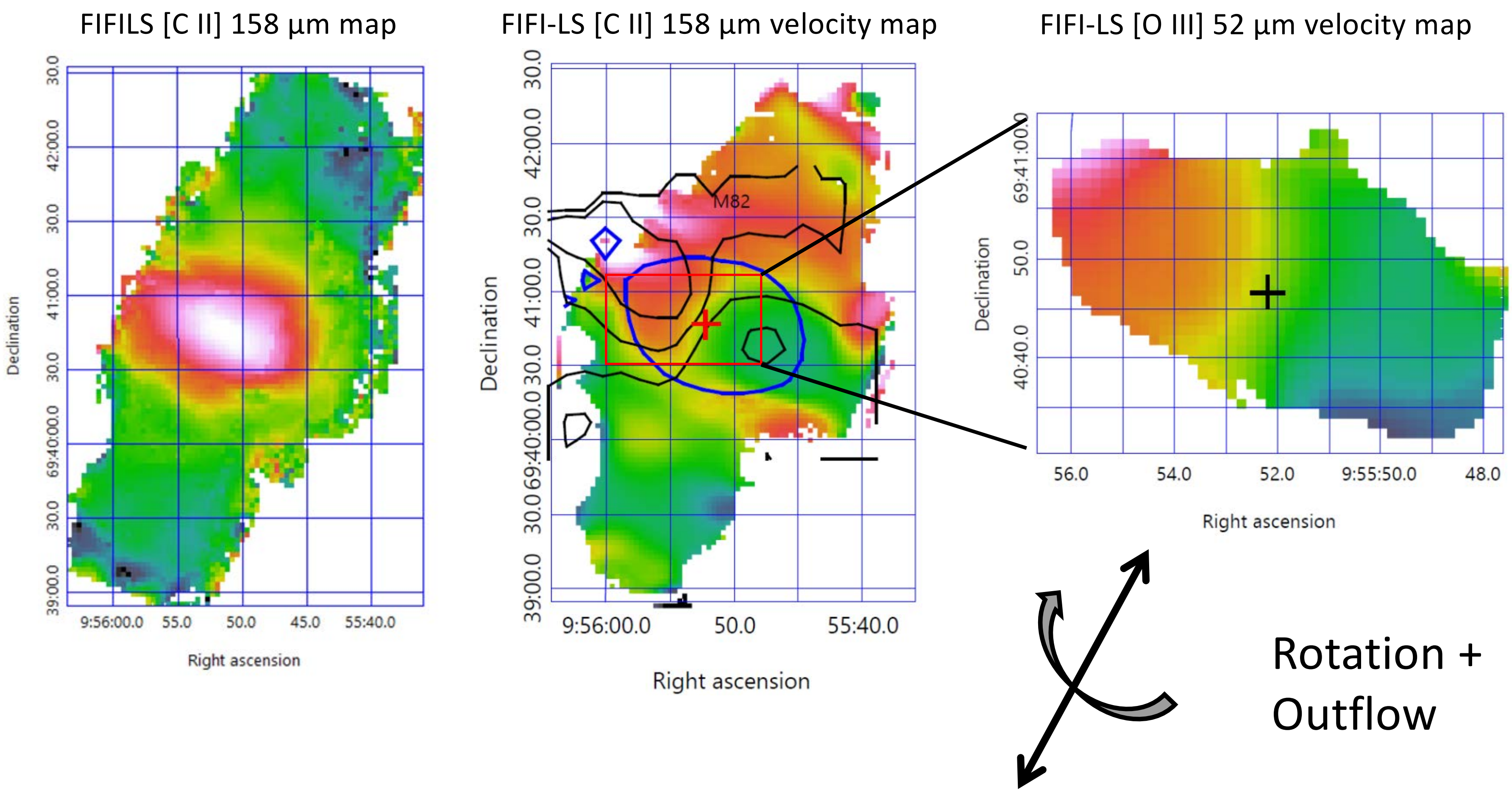
FIFI-LS [O III] 52 μm / PACS [O III] 88 μm





N_e at central peak is ~4500 cm^{-3}

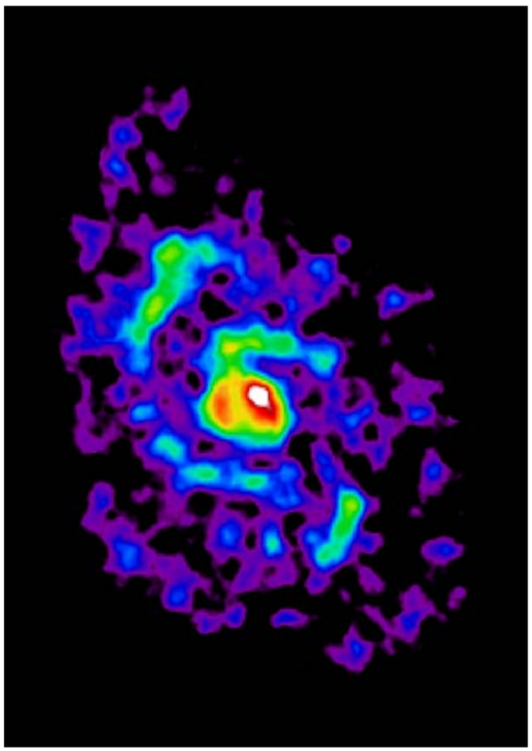
Examples of FIFI-LS programs: M82 (Fischer et al. 2020)

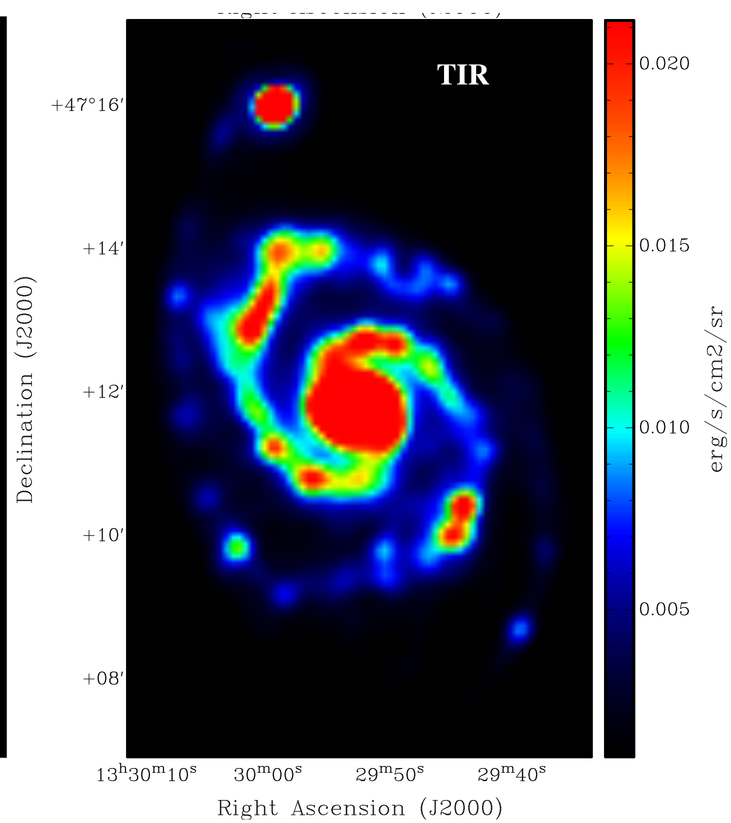


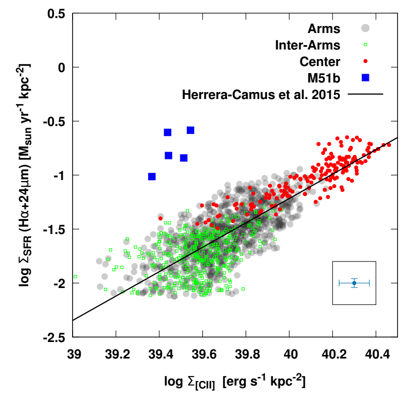
Examples of FIFI-LS programs: M51 (Pineda et al. 2018)

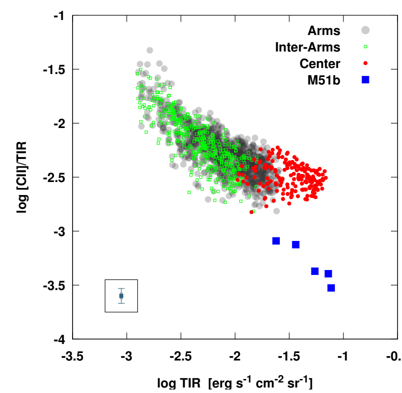
Tracing the [C II]-deficit, in M51 and M51b

FIFI-LS [C II] 158 μm

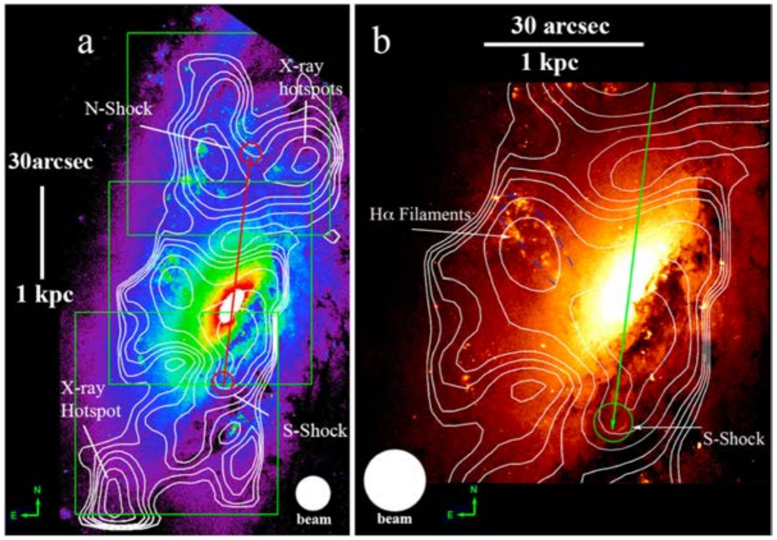


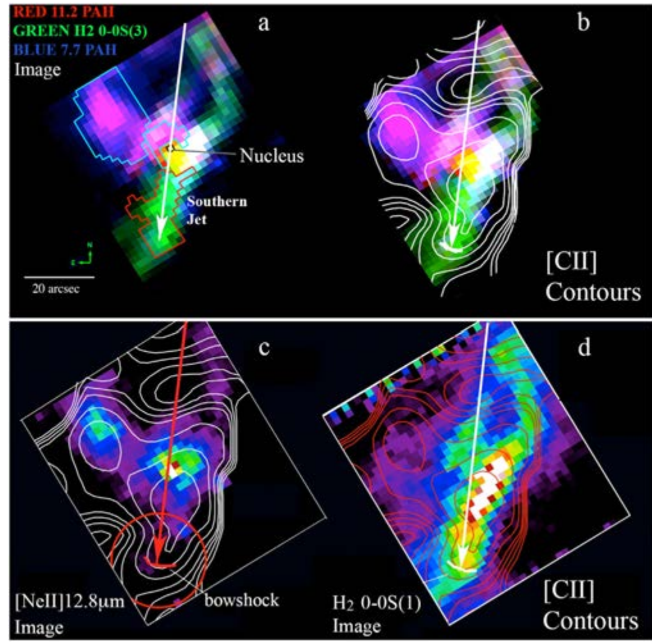


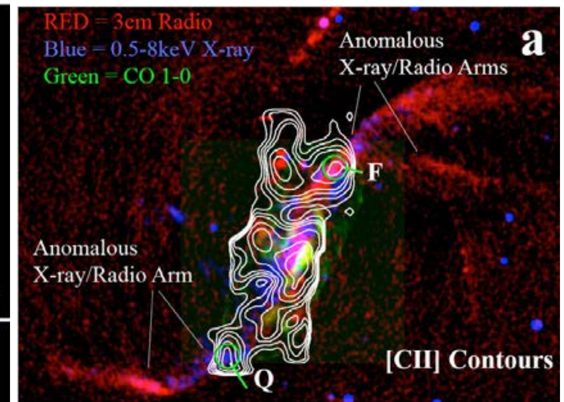


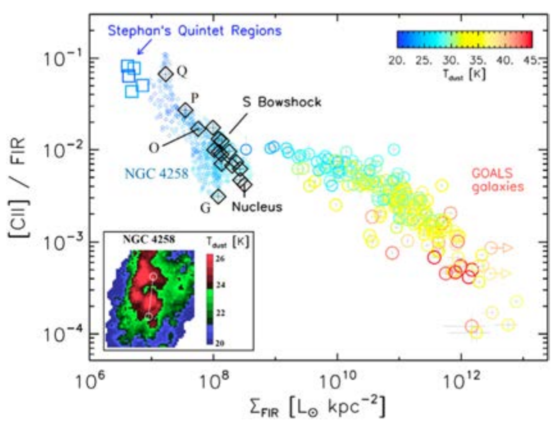


Examples of FIFI-LS programs: NGC 4258 (Appleton et al. 2018)









- [C II] tracing warm molecular gas in shocks and jet turbulence
- ~40% of the total [C II] luminosity arises from shocks and turbulence

Science Case for FIFI-LS ⇨ FIFI+LS

- With an increase in mapping speed of ≥3.5, plus additional gains from TP/OTF observing modes, and additional spectral coverage and sampling (for better telluric-corrected output data products), similar line mapping observations of extended regions can be done in a fraction of the time, so that larger samples can be studies and fainter detection levels can be reached
  - 30 Dor: 11.5 h → < 3.3 h
  - M82: 9 h → < 2.6 h
  - NGC 6946: 9.5 h → < 2.7 h
  - M51: 15 h → < 4.3 h
  - NGC 4258: 3.5 h → < 1 h
- Mapping FS lines over a range of physical scales in a large sample of Galactic regions and nearby galaxies, to study the properties of the ISM in a range of environments, to serve as templates for understanding galaxies at high z
  - Physics behind the "FIR line deficit" (decrease in line/continuum ratio as a function of $\sum_{FIR}$)
  - 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

Summary

- For a modest amount of money and time, the proposed upgrade to FIFI-LS (primarily the detectors) would increase the sensitivity, FOV, and spatial and spectral sampling of the instrument, leading to a significant increase in the mapping speed (a factor of ≥ 3.5) and data quality, and allowing the mapping of a large sample of nearby galaxies in the FIR emission lines that can be used to study the properties and physics of the ISM in star-forming regions in a variety of environmental conditions and that can serve as local templates for high redshift objects