FORCAST Science

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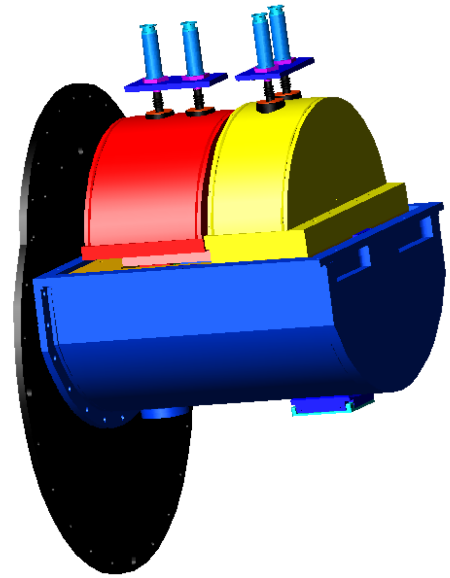
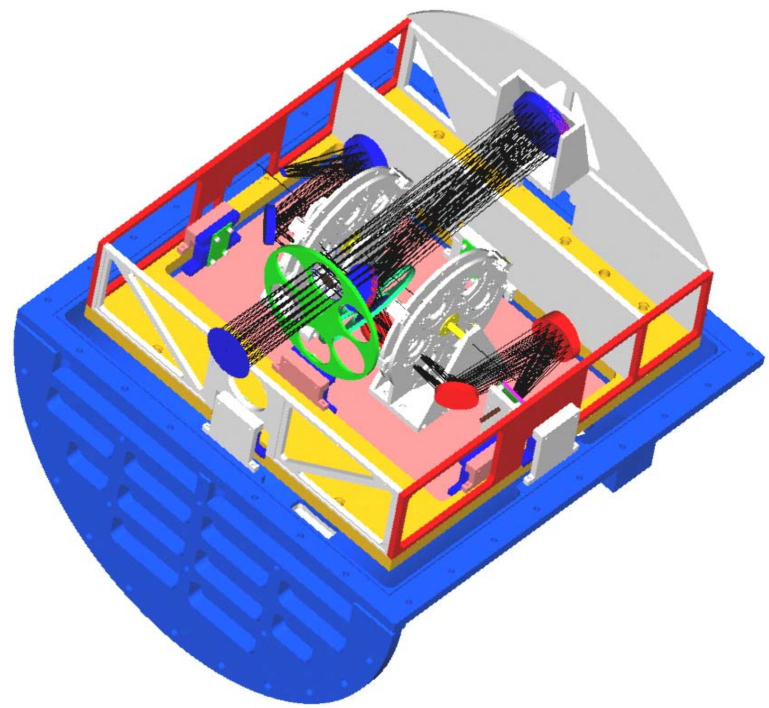
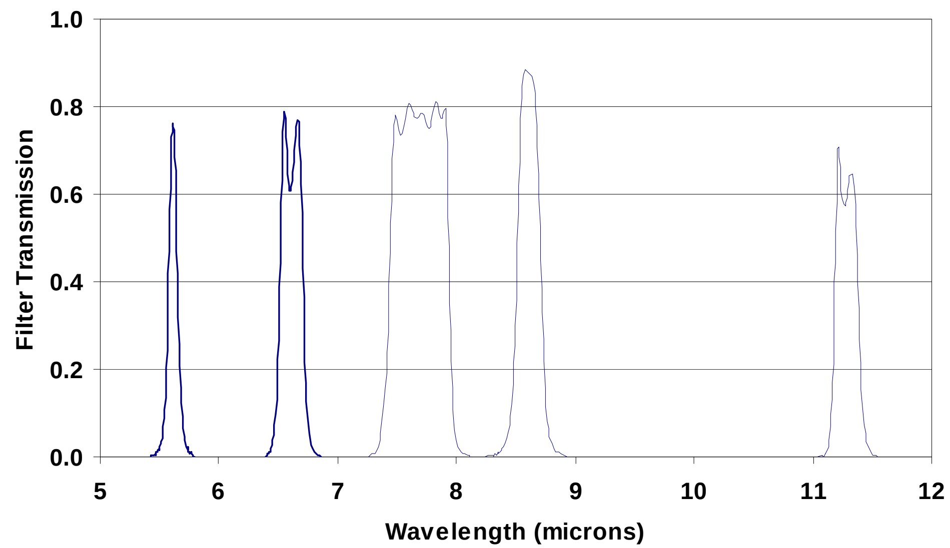
FORCAST Description

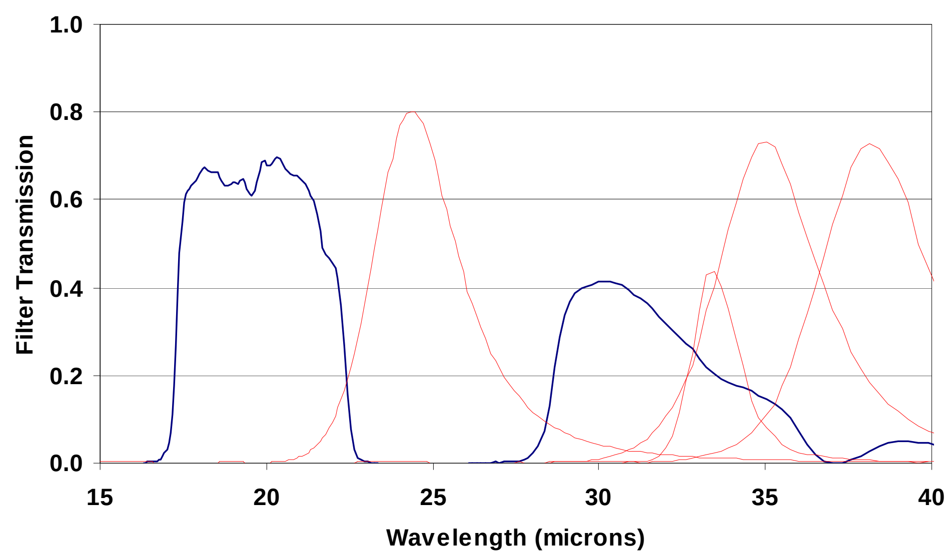
- Facility Instrument
- Dual-Channel 256x256 Camera w/ Si BIB arrays
  - 5-25 μm with Si:As array
  - 25-38 μm with Si:Sb array
- 0.75 arcsec/pixel giving 3.2×3.2 arcmin FOV
- Selectable Filters in 5-38 μm range





FORCAST Filters



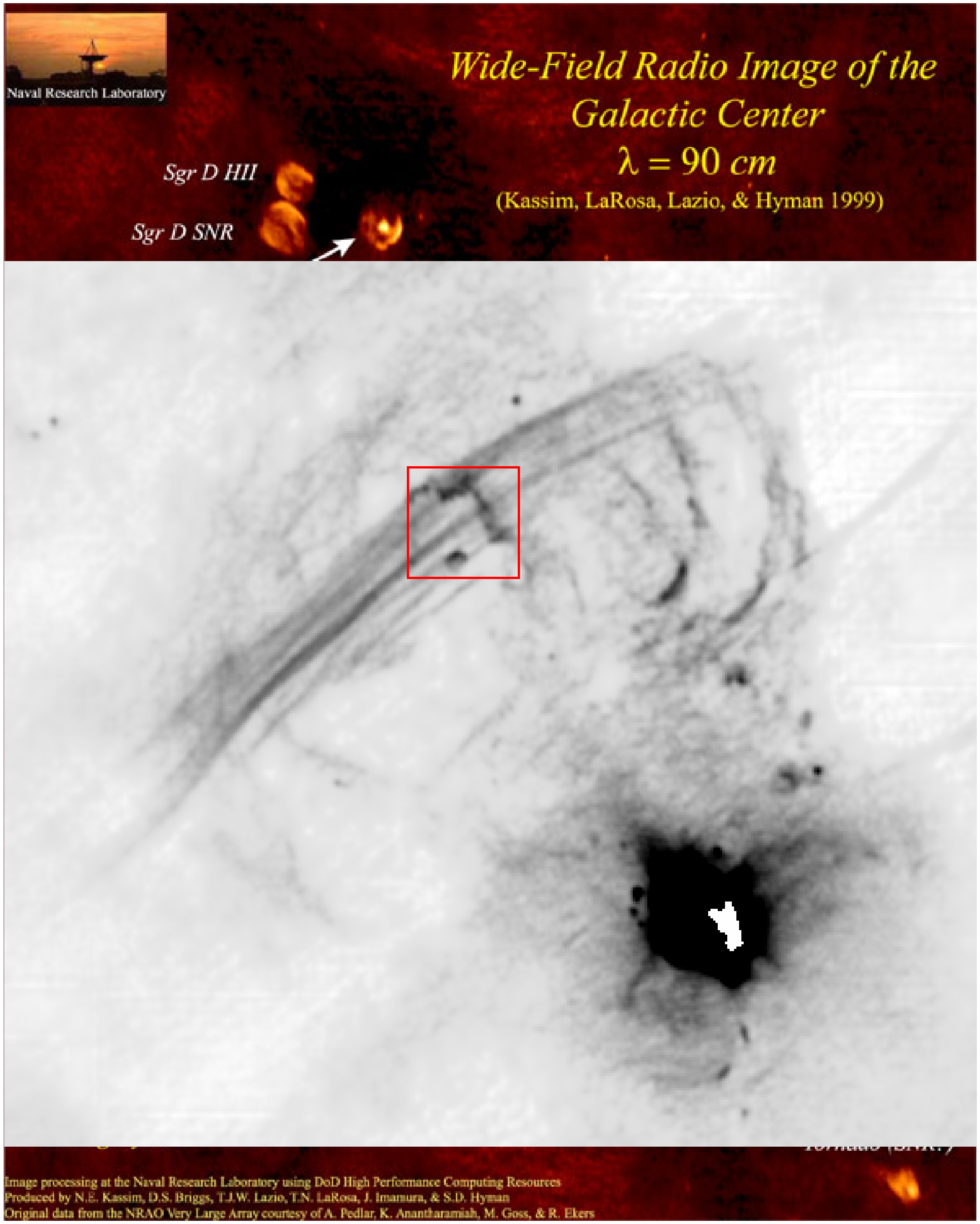


Filter (μm)	R (λ/Δλ)
5.3	33
6.3	48
6.6	34
7.6	15
8.6	42
11.0	12
11.28	56
19.5	3.8
24.4	7.5
30.6	5.7
33.4	18
34.8	8.3
38.0	8.8

Left: representative FORCAST filter curves (not including atmospheric transmission or detector response).

“Original” Team Science Objectives

- The galactic center region (Early Science)
  - Nature of circumnuclear ring (CNR)
  - Excitation of “arches”
- Star formation
  - Census of “protostars” in nearby molecular clouds
  - Spiral arms of nearby galaxies
- Circumstellar disks
  - Spatially resolve Vega phenomena
  - Spectral energy distribution of Young Stellar Objects



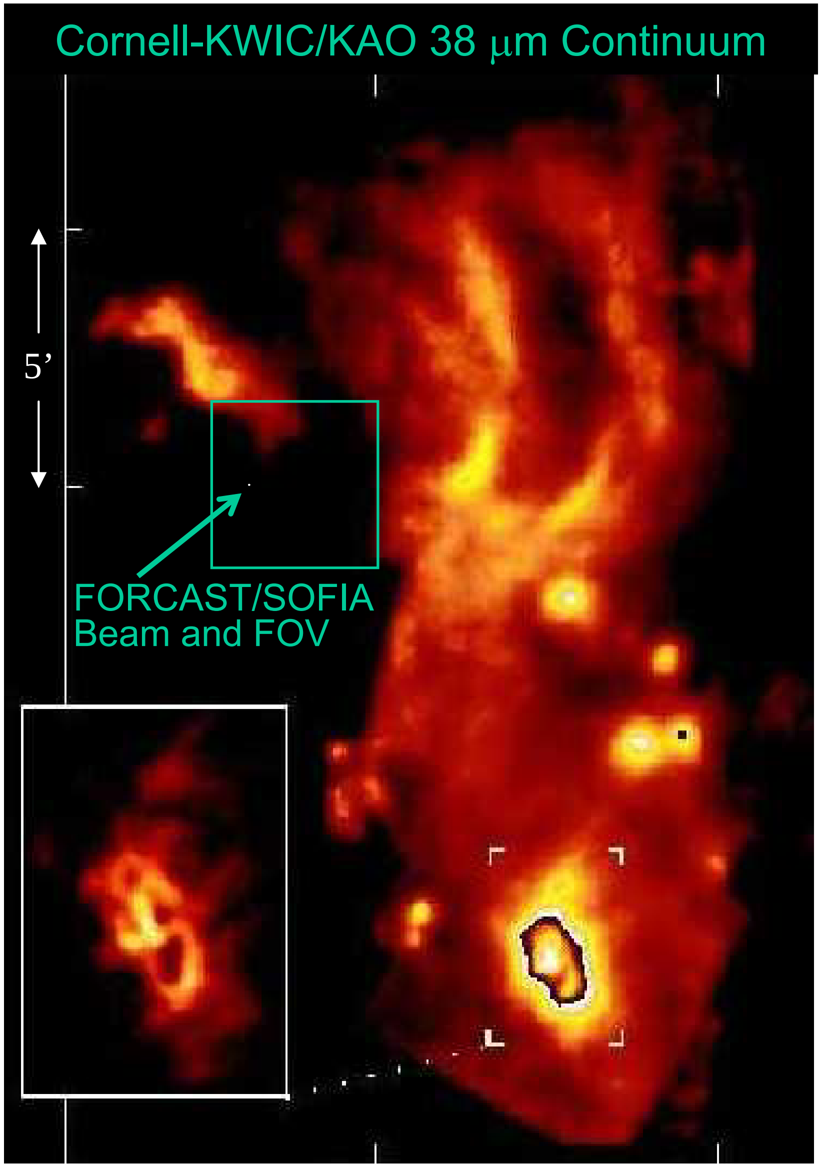
The Galactic Center

- **Filaments**
- **Sickle/pistol**
- **Star Forming Regions**
- **Sgr A West**
  - **CNR**
  - **Sgr A***
  - **Mini-spiral**

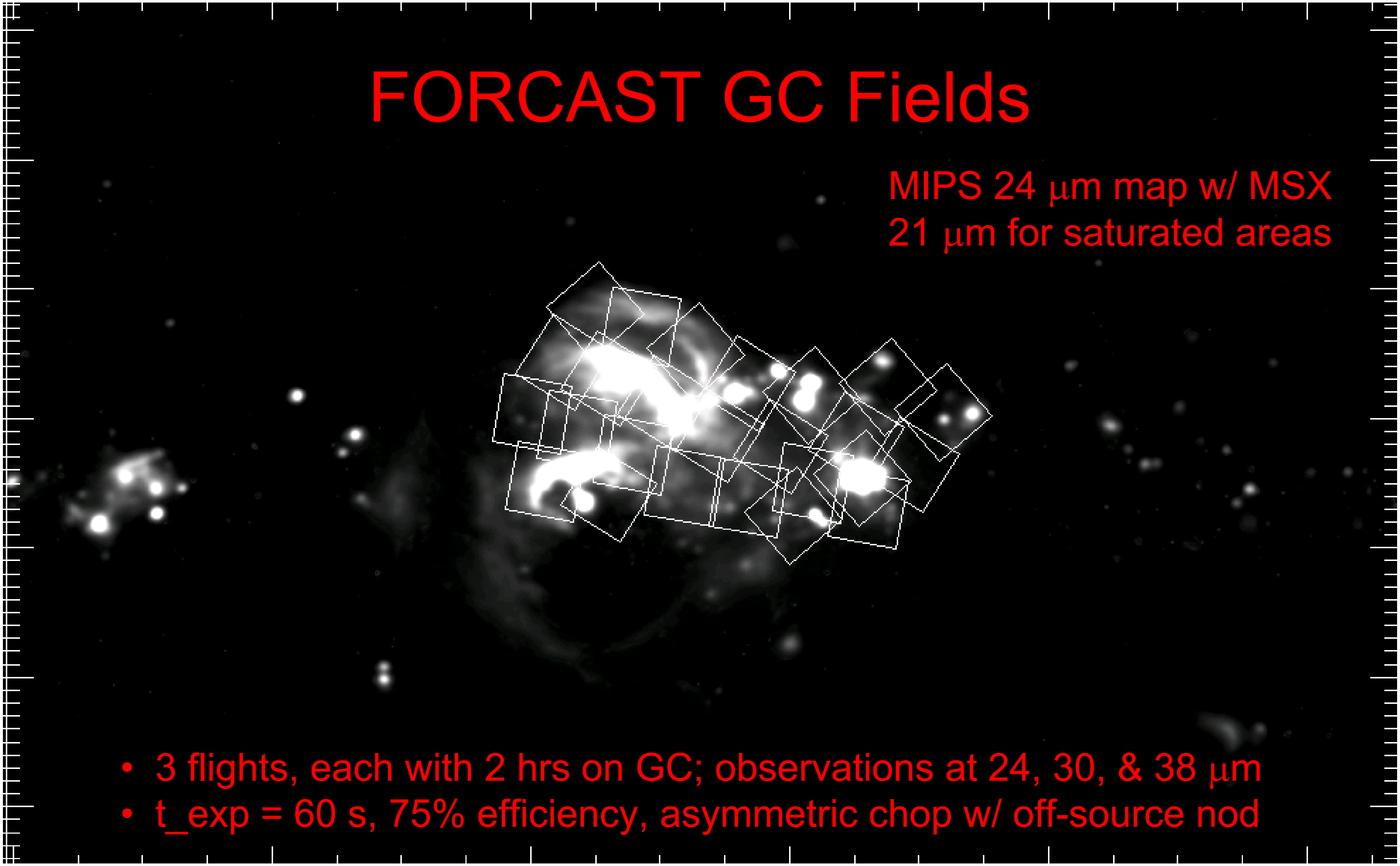
FORCAST Imaging of the Galactic Center Radio Arcs

FORCAST Multi-band Imaging

- Conventional wisdom suggests that the starlight for heating the arches originates in the Arches Cluster
- The KWIC data are inconsistent with heating from the Arches Cluster ($2.5 \times 7\ L_{\odot}$, Cotera et al.)
  - No temperature gradient.
  - The luminosity of the arches in the far-IR require are four times the observed luminosity of the Arches Cluster.
  - The 37.7 μm to 31.5 μm color temperature requires > 10 times the observed luminosity of the cluster.
- The much higher spatial resolution of FORCAST on SOFIA addresses these issues
  - Expect color temperature peaks in arches for internal heating
  - Expect temperature gradient for external heating
- Future:
  - Probe CNR and arches through [SiII] 34.814 fine-structure lines – map PDR and heating.

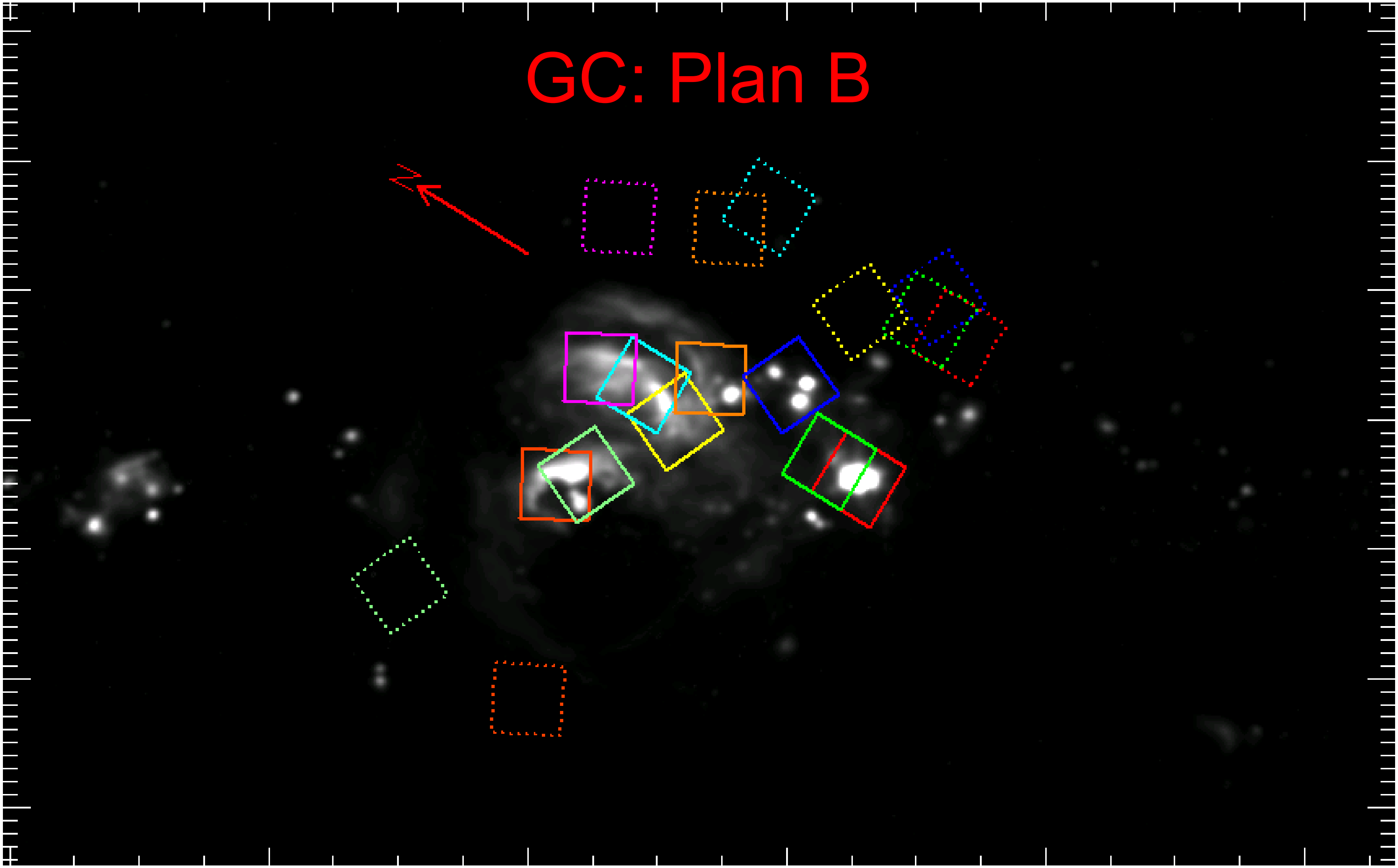


FORCAST GC Fields



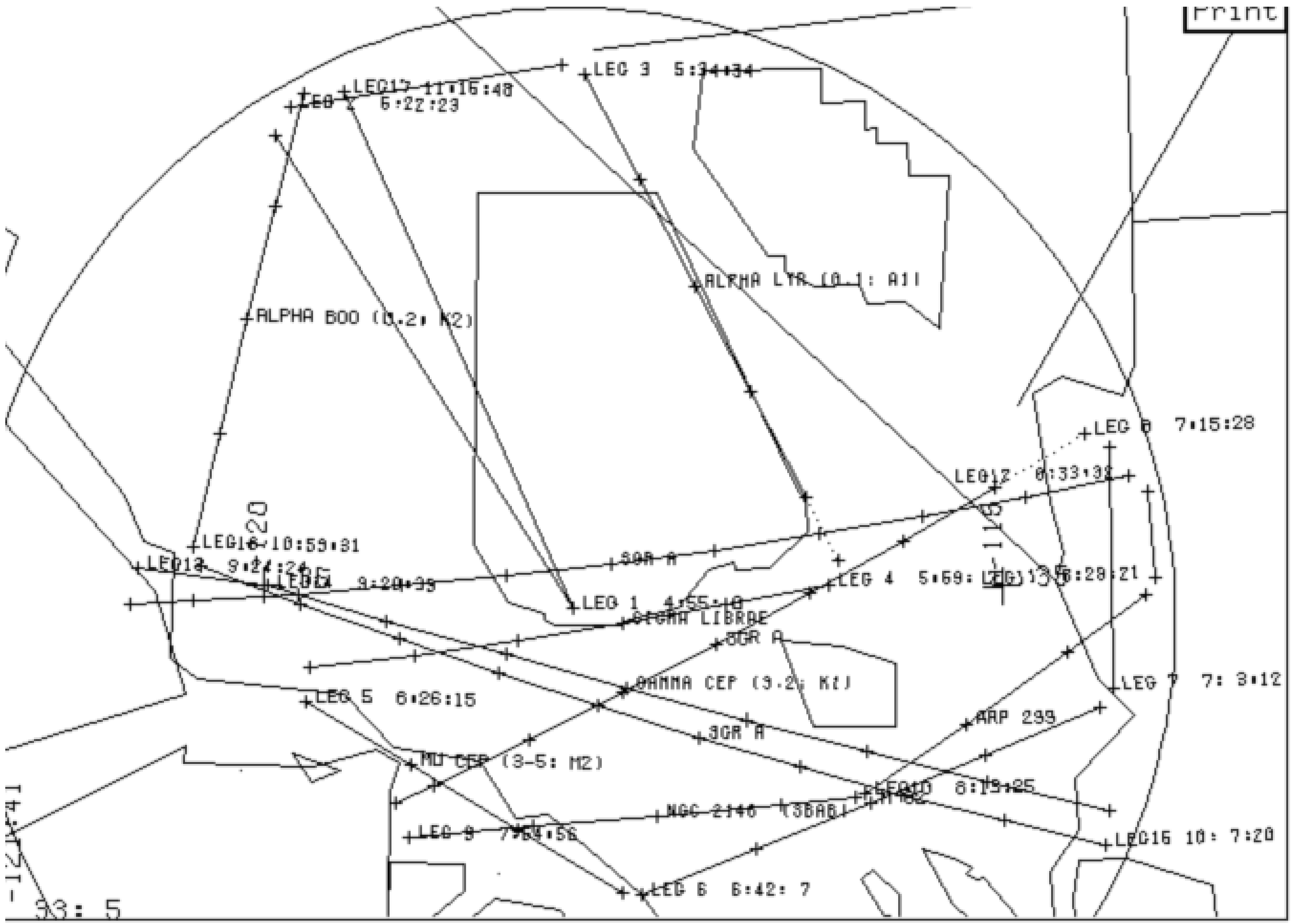
- 3 flights, each with 2 hrs on GC; observations at 24, 30, & 38 μm
- t_exp = 60 s, 75% efficiency, asymmetric chop w/ off-source nod

Working on more pessimistic plans and identifying chop and nod fields.



Conservative plan: one field per
observing leg/segment (3 colors)

Galactic Center Flight Plan



KNAV /SGR-A-3LEGS-7CALIB-7H/FLIGHT PLAN FOR MAY 2

Galactic Center Flight Plan

Parameter File: SGR_A_3legs_7calib_7h
Leg 1 Start UT: 4:54

LEG#	OBJECT NAME	OBJ#	DUR	WIND DIR	WIND SPD	OBJECT ELEV.	ROTATION ANGLE	SUN ELEV.
1	DEAD LEG	-1	26	270	40	0=> 0	0=> 0	-21=>-21
2	DEAD LEG	-1	11	270	40	0=> 0	0=> 0	-20=>-22
3	ALPHA LYR (0.1, A1)	36	23	270	40	36=>40	296=>290	-23=>-29
4	SIGMA LIBRAE	961	25	270	40	29=>30	353=>355	-29=>-31
5	MU CEP (3-5, M2)	31	15	270	40	21=>23	304=>299	-31=>-34
6	M 82	19	20	270	40	35=>34	92=> 84	-34=>-34
7	DEAD LEG	-1	11	270	40	0=> 0	0=> 0	-34=>-33
8	SGR A	131	37	270	40	19=>23	337=>340	-33=>-35
9	NGC 2146 (SBab)	169	18	270	40	24=>23	31=> 25	-36=>-35
10	Arp 299	1538	14	270	40	34=>32	83=> 78	-35=>-33
11	DEAD LEG	-1	4	270	40	0=> 0	0=> 0	-33=>-32
12	SGR A	131	48	270	40	25=>26	354=>358	-32=>-31
13	DEAD LEG	-1	5	270	40	0=> 0	0=> 0	-31=>-30
14	GAMMA CEP (3.2, K1)	1517	35	270	40	34=>36	281=>267	-30=>-25
15	SGR A	131	45	270	40	26=>24	15=> 19	-24=>-20
16	ALPHA BOO (0.2, K2)	368	20	270	40	26=>21	62=> 59	-20=>-15
17	DEAD LEG	-1	24	270	40	0=> 0	0=> 0	-13=> -8

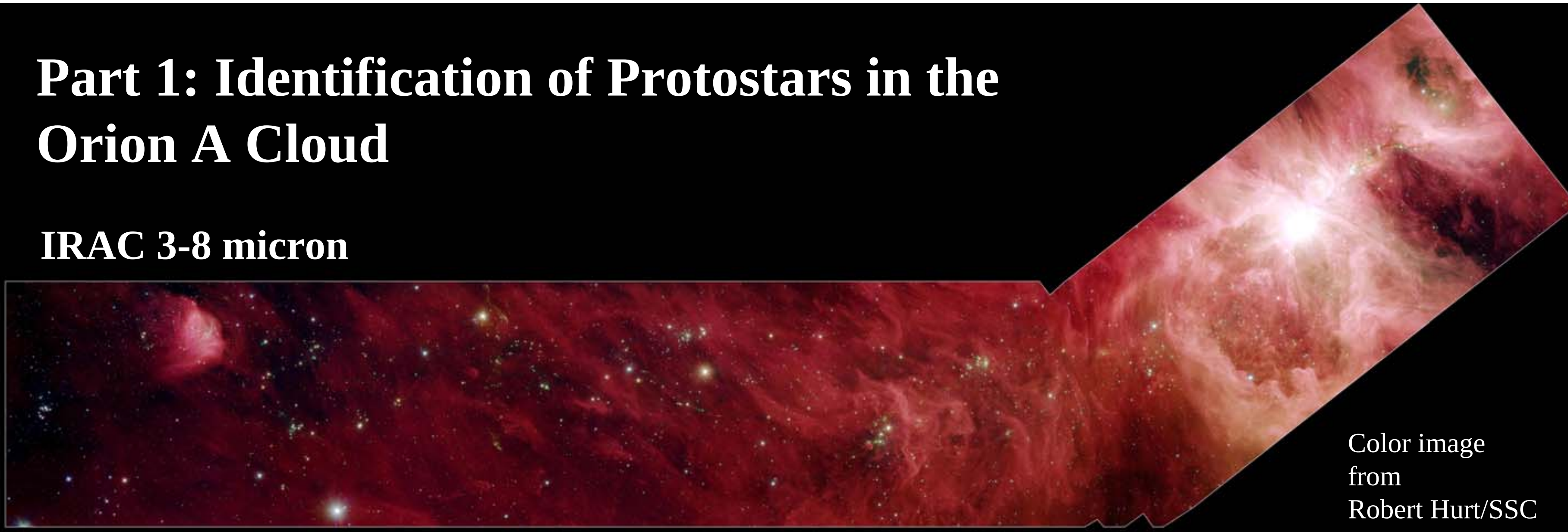
Total duration: 6h 44m
Observing time: 5h 0m

Star Formation Studies

- Map Orion nebula core (BN/KL, Trapezium, Bar region)
  - Follow-up to KAO observations of Orion at 19.5, 30.3, 38.0 μm
  - Determine thermal structure of dust, search for embedded protostars, and detect proplyds
  - 8´ × 12´ region at short integrations (2 minutes per pointing, 12 pointings)
  - Deeper (12 minute) integrations in the central nebula to search for proplyds
- Perform deep mapping in the Orion nebula
  - Follow-up to *Spitzer*/IRAC/MIPS mapping of Orion at 3.6 – 24 μm (SI team to collaborate with T. Megeath (Toledo))
  - Get SED of embedded protostars
  - Cover 15´ × 15´
  - Cover wavelengths 19.5, 24.4, 30.3, 38.0 μm
  - Use FORCAST MOSMAP mode if possible
  - At least 1 hour integrations per pointing per band
  - Reach ~100 mJy or fainter at 24.4 μm
- Target selected young low mass stars in Taurus
  - Followup to *Spitzer* Taurus legacy project (SI team to collaborate with D. Padgett, L. Rebull, & C. McCabe (SSC)))
  - Multiplicity and SED of embedded protostellar systems

Part 1: Identification of Protostars in the Orion A Cloud

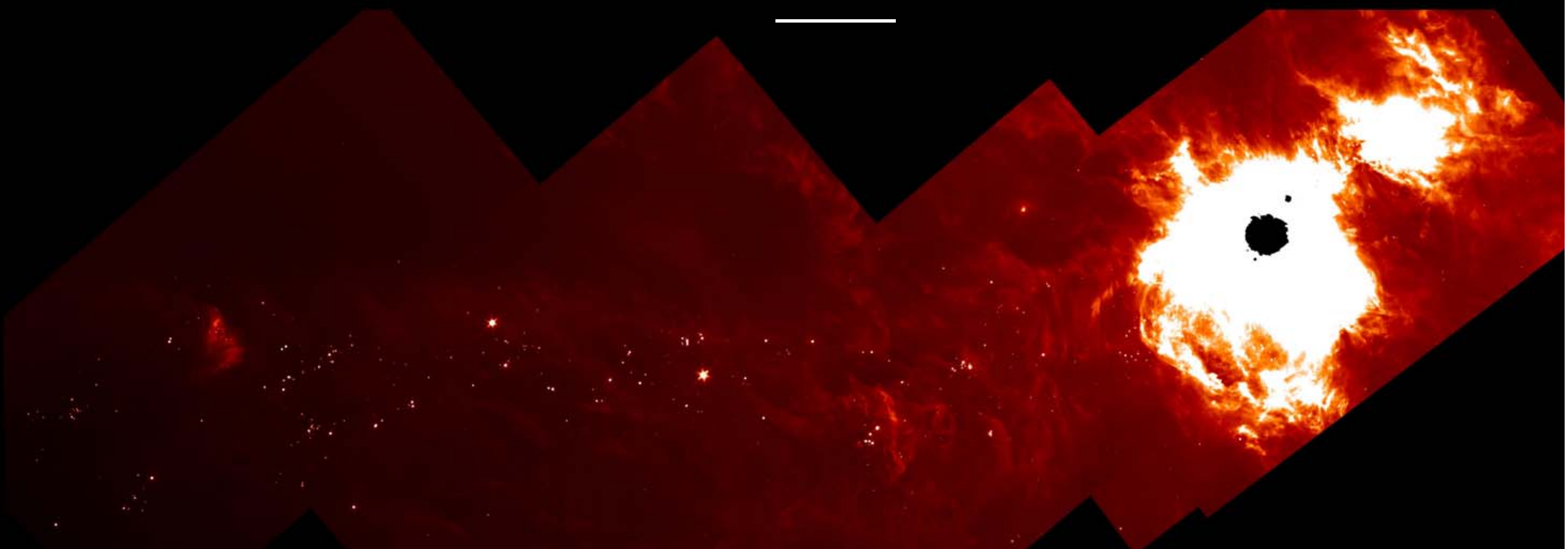
IRAC 3-8 micron



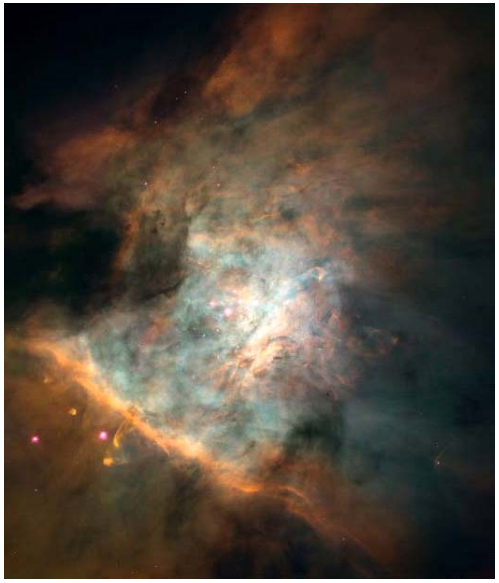
Color image from Robert Hurt/SSC

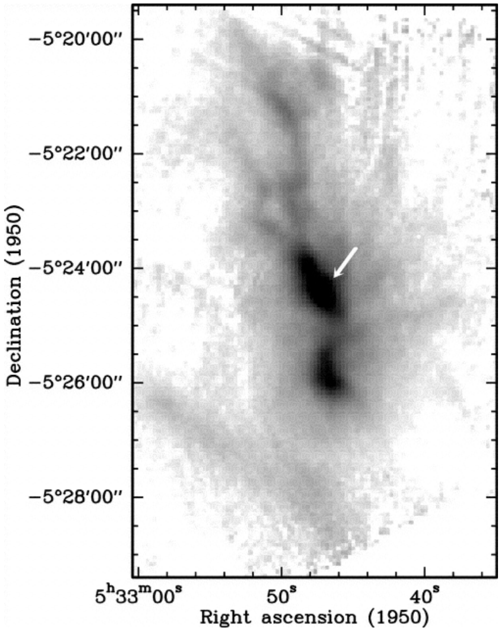
MIPS 24 micron

1 pc = 3.26 light years

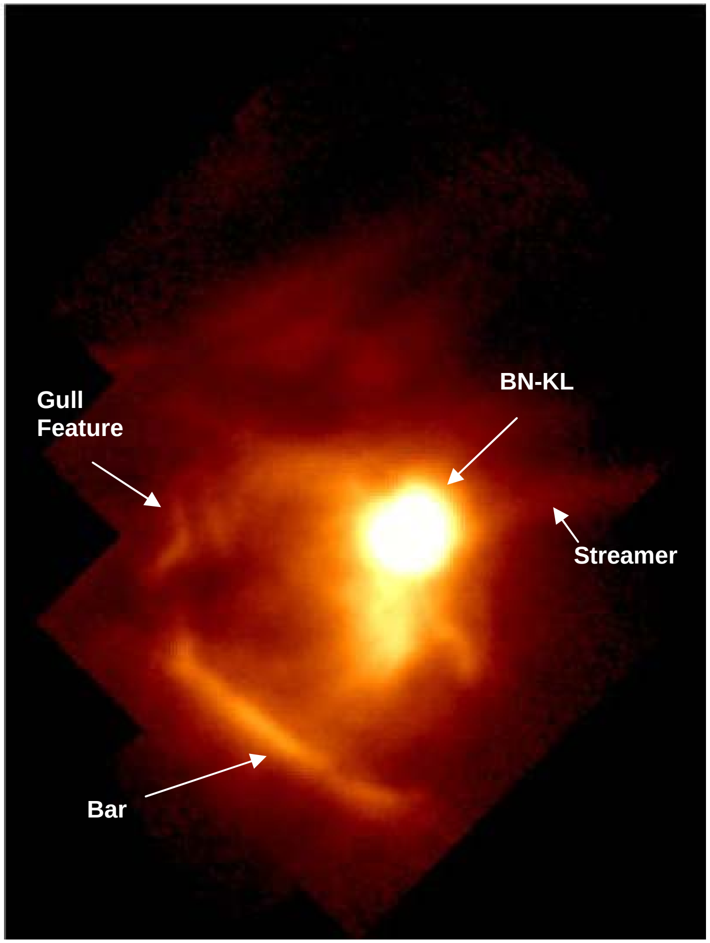


Orion Nebula at various λ's





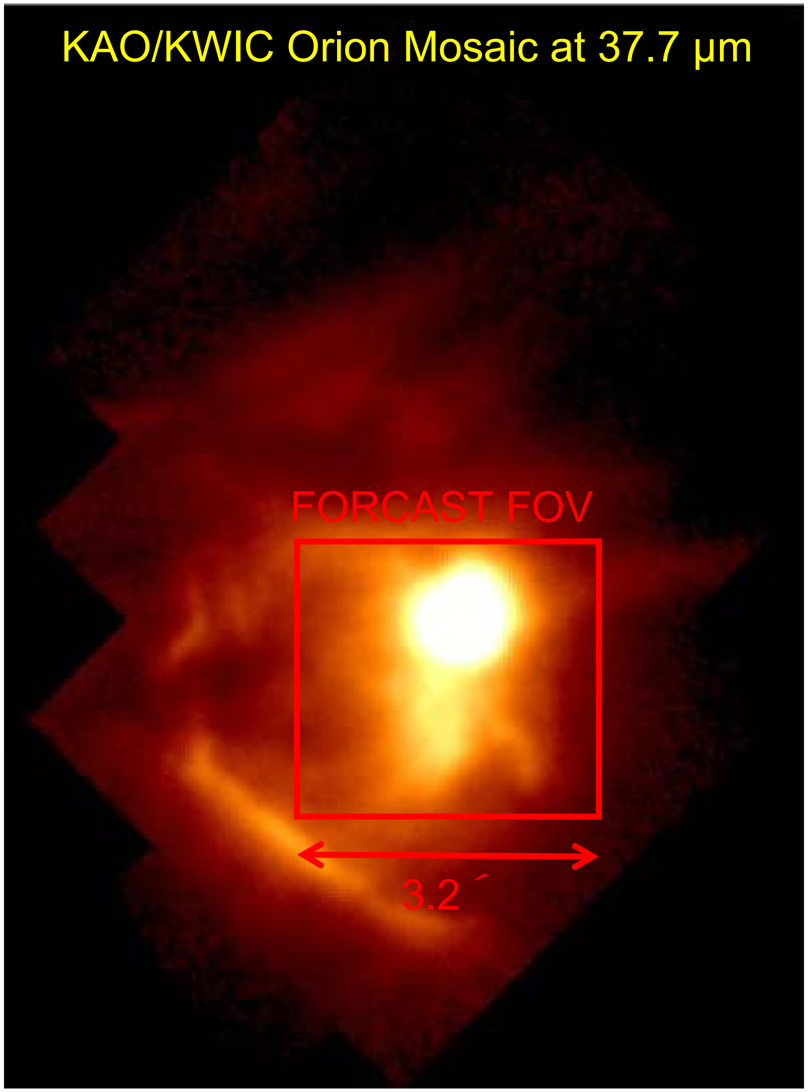
Orion Molecular Cloud – Top: Optical image. Bottom: 350 μm map (from Darren Dowell).



KWIC (KAO): 38 μm 8x12' map of the Orion Nebula region (Stacey et al. 1995).

Orion Trapezium Region Observations

1. Map the Orion Nebula at 19.5, 30.5, and 38.0 μm
   - Obtain fully sampled images with 3 times the raw spatial resolution and more than 8 times the sensitivity of the KWIC/KAO image.
2. Fully sample color temperature maps
   - Reveal PDR and embedded sources, dust temperature, and dust physical parameters.
   - Enables search for embedded sources including protostars
3. Detection of dust disks and other material around young stars
   - Proplyds seen in reflection or silhouette in Trapezium cluster region.
   - Can detect $M > 0.06\ M_{earth}$ (5σ in 12 minutes) for 80 K dust – Johnstone et al (1998) find median mass of $0.01\ M_{earth}$.



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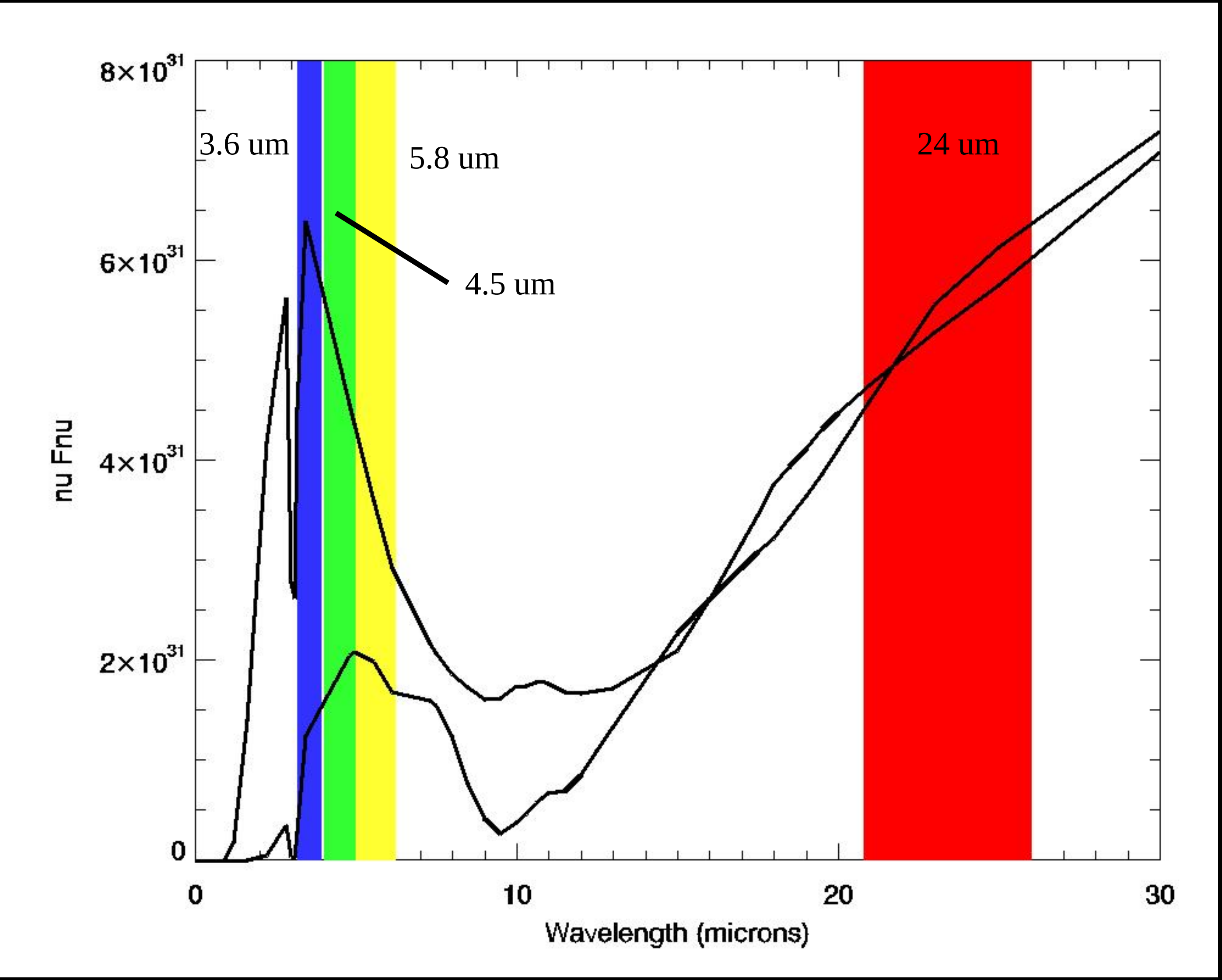
Dust Continuum Diagnostics

- The 19 – 38 μm continuum emission is usually featureless
- Comes from dust grains in the 50 – 200 K range which radiate in equilibrium with local radiation sources
- Previous work shows that this emission arises from photo-dissociation regions (PDRs) and tracks the far-IR luminosity.
- The F_{31}/F_{38} ratio is a good indicator of temperature (varying from 0.2 to 1.4 as $30 < T_{dust} < 200$ K).
  - Comparing the color to brightness temperature yields the optical depth.
  - Assuming an extinction law and a gas-to-dust ratio gives the gas column density in the emitting region.
- With a favorable geometry, grain parameters can be deduced from a color temperature map (e.g. ε_{IR}/A_v).

Spectral Energy Distributions of Protostars

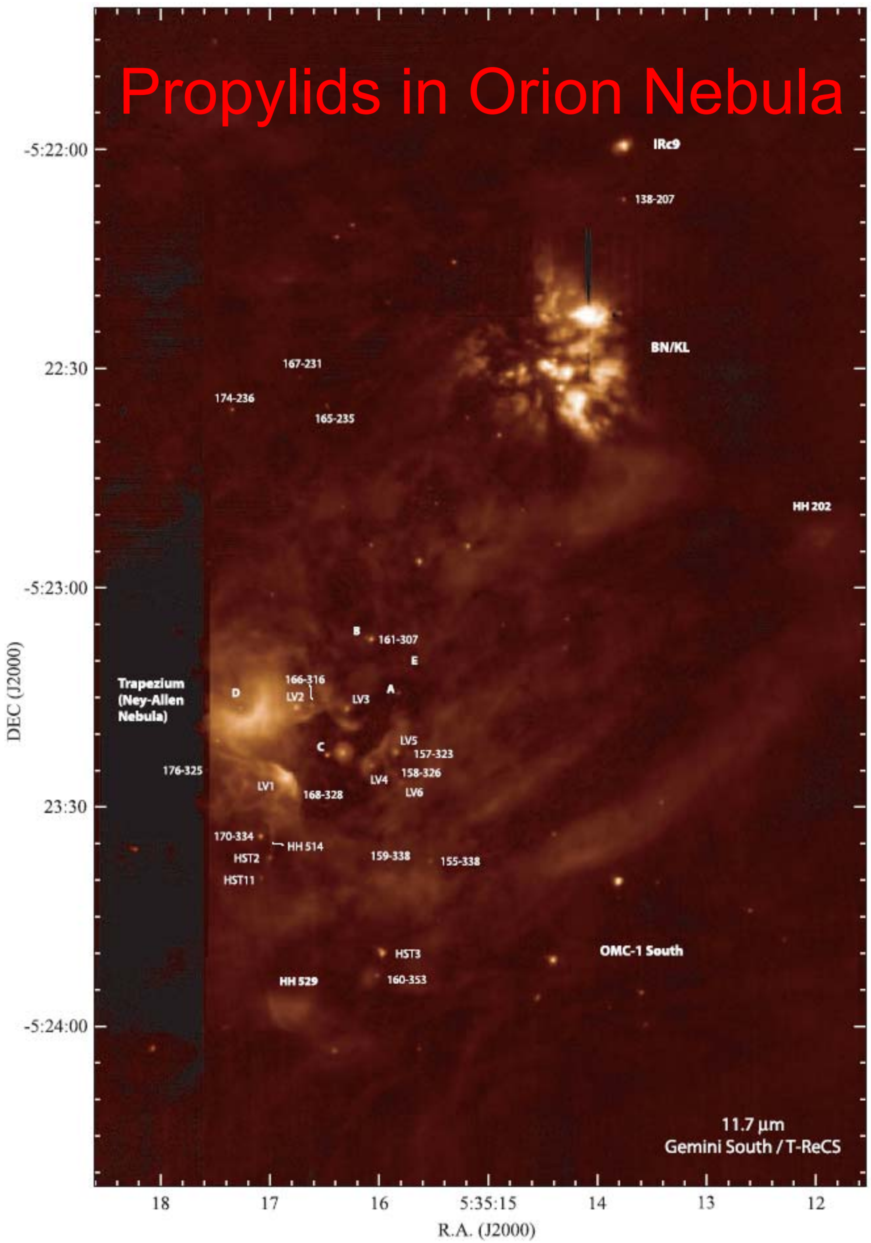


Protostar Models from Nuria Calvet using method of Kenyon, Calvet & Hartmann (1993)

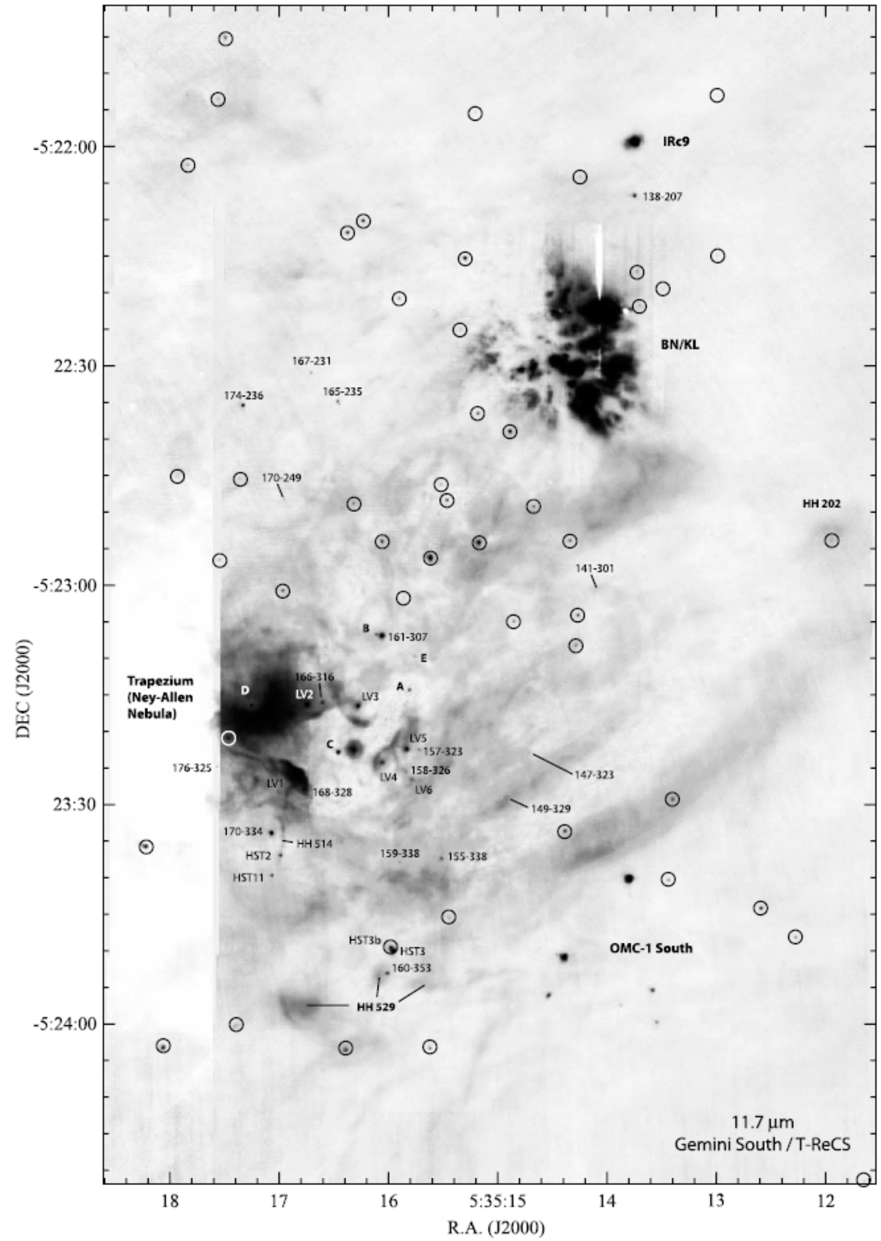
1-24 micron regime dependent on:

inclination, rotation, accretion rate, mass of central star, …..

$F_\nu(38\mu m) \sim 2.6\times F_\nu(24\mu m)$

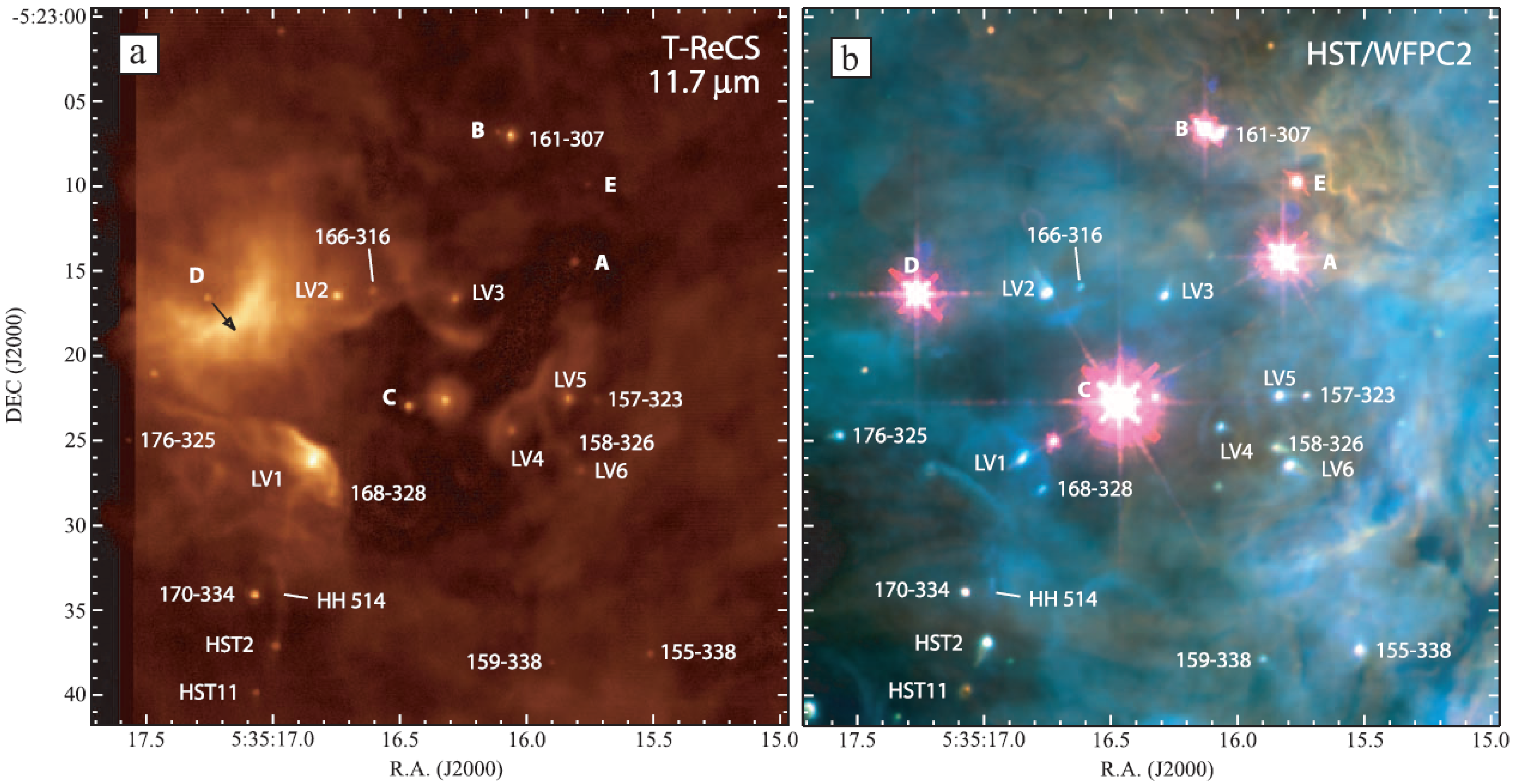


Proplyds seen in HST images are identified (from Smith et al. 2005.)



Same as Figure at left but with a deeper gray scale to show fainter emission and with faint and unresolved (nonproplyd) IR stars circled.

Proplyds in Orion Nebula

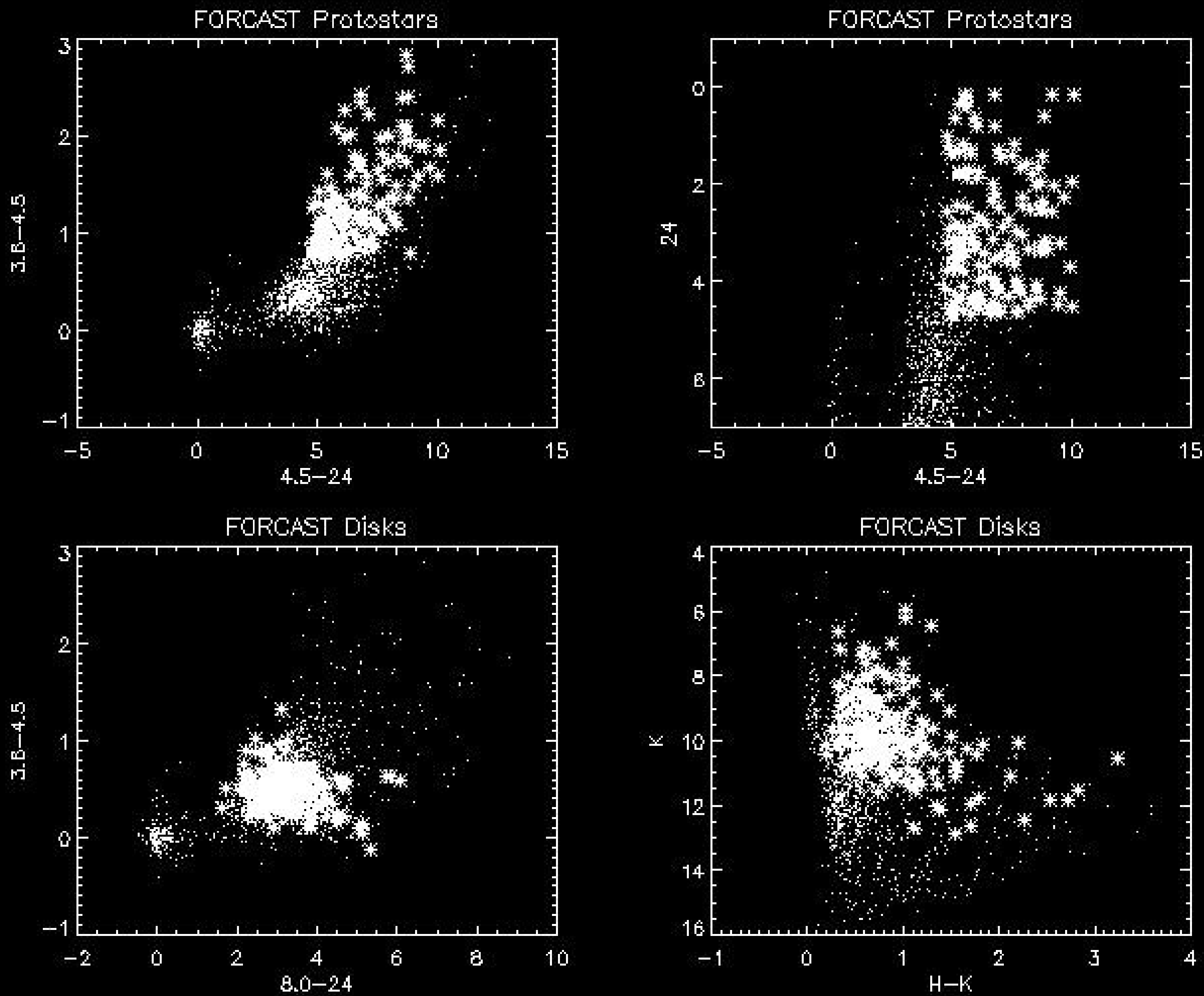


Close-up of the Trapezium region (a) at 11.7 m with T-ReCS and (b) with HST WFPC2. The 11.7 µm image is in false color, while the HST WFPC2 image has [O III] in blue, H in green, and [N II] in red. (Figure from Smith et al. 2005.)

Deep Orion Nebula Map: Identification and Distribution of Protostars and Young Stellar Objects

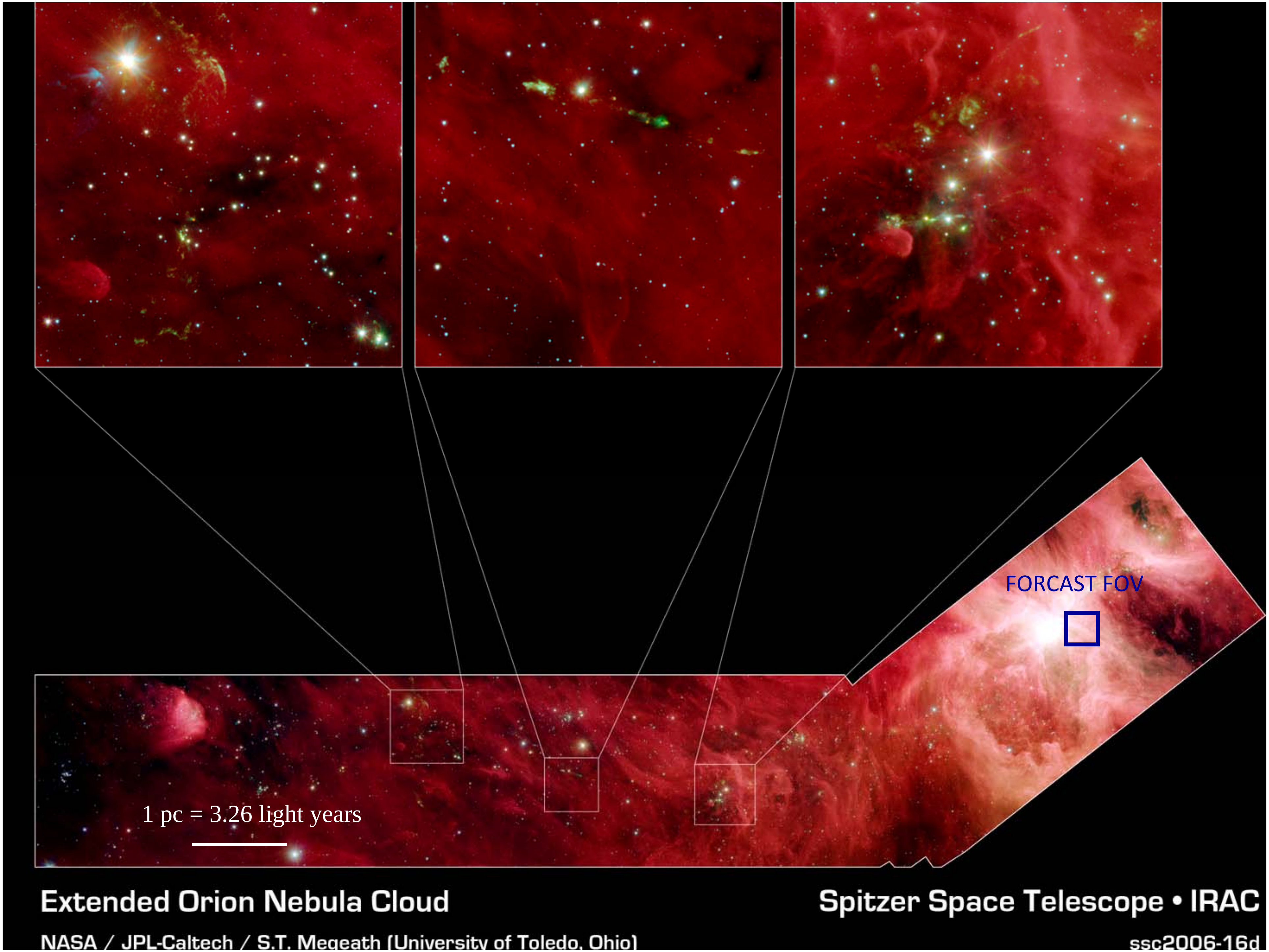
- FORCAST to cover (central) regions that are too bright for *Spitzer*/MIPS at 24.4 μm
  - Central Orion Nebula is the densest region
- 24.4, 30.3, and 38.0 μm observations can extend *Spitzer*/IRAC observations at 3.6-8.0 μm
  - Detailed SEDs can constrain protostellar envelope (class I) and circumstellar disk (class II) inclinations, masses and geometry
  - Presence of young, energetic high mass stars allows probe of the role of photoevaporation of circumstellar disks around neighboring stars
- Multi-wavelength observations can be used to classify young objects over a large region
  - The distribution of protostars and young stellar objects reveals the star formation history in the molecular cloud
  - What is the structure of star forming groups and clusters? What are the properties of the distributed population?

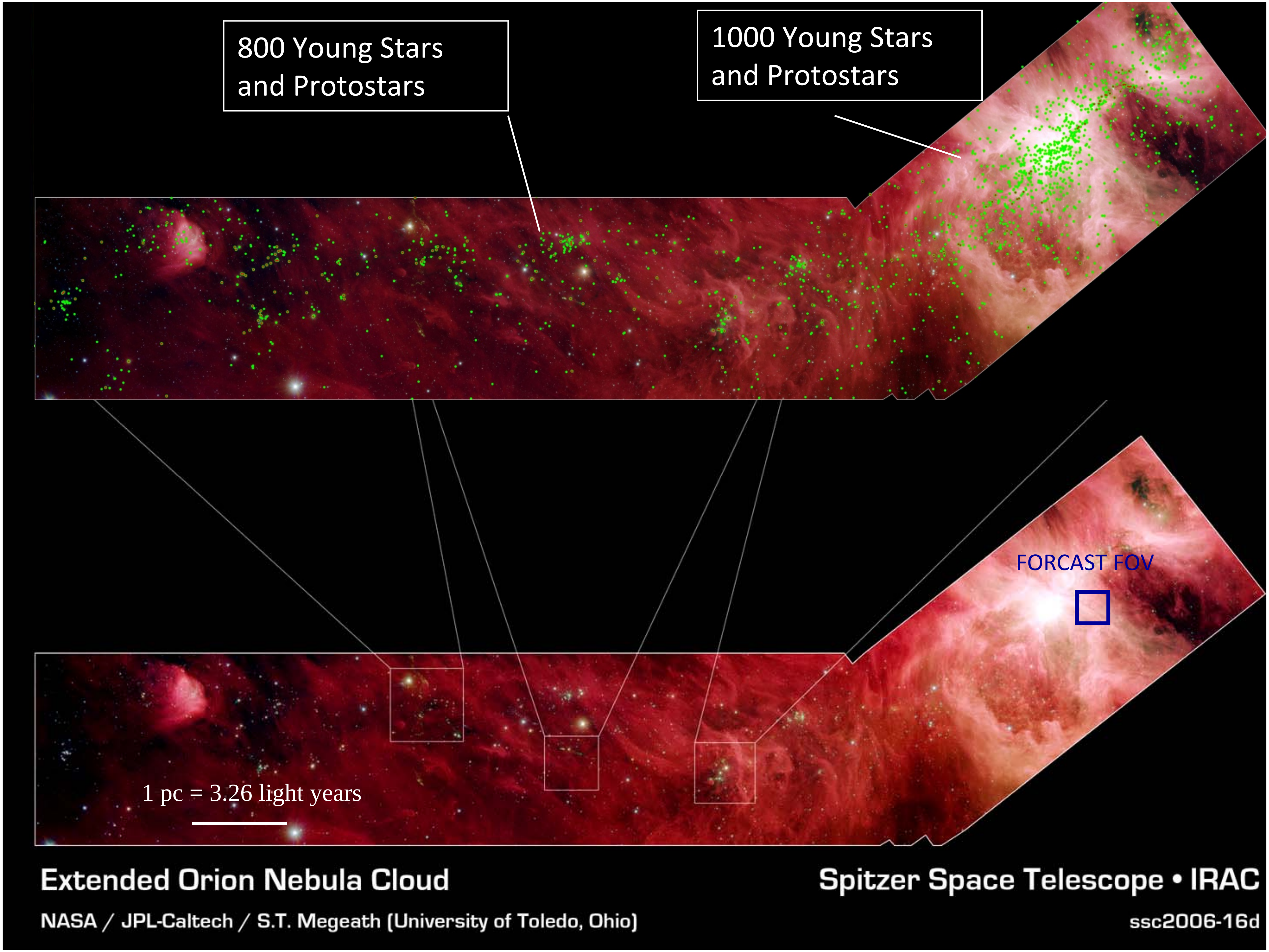
Identifying Protostars and Circumstellar Disks with FORCAST/SOFIA



- Spitzer identified

* > 100 mJy (FORCAST/SOFIA detectable)


FORCAST FOV
1 pc = 3.26 light years
Extended Orion Nebula Cloud
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / S.T. Megeath (University of Toledo, Ohio)
ssc2006-16d

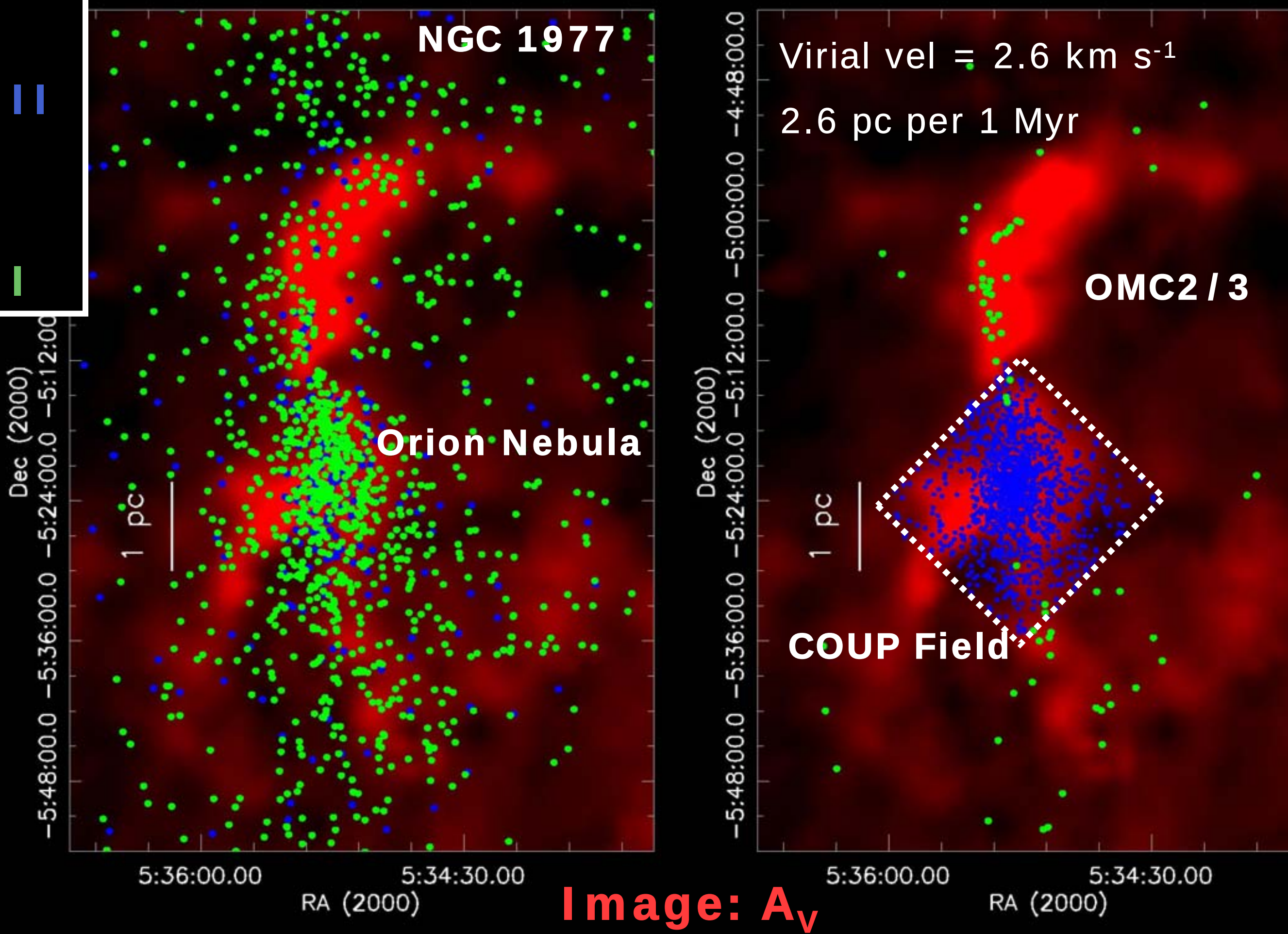


800 Young Stars and Protostars
1000 Young Stars and Protostars
FORCAST FOV
1 pc = 3.26 light years
Extended Orion Nebula Cloud
Spitzer Space Telescope • IRAC
NASA / JPL-Caltech / S.T. Megeath (University of Toledo, Ohio)
ssc2006-16d

Spatial Distribution of Young Stellar Objects in the Orion Nebula Cluster (450 pc)

Blue: 255 Class III

Green: 1055 Class II



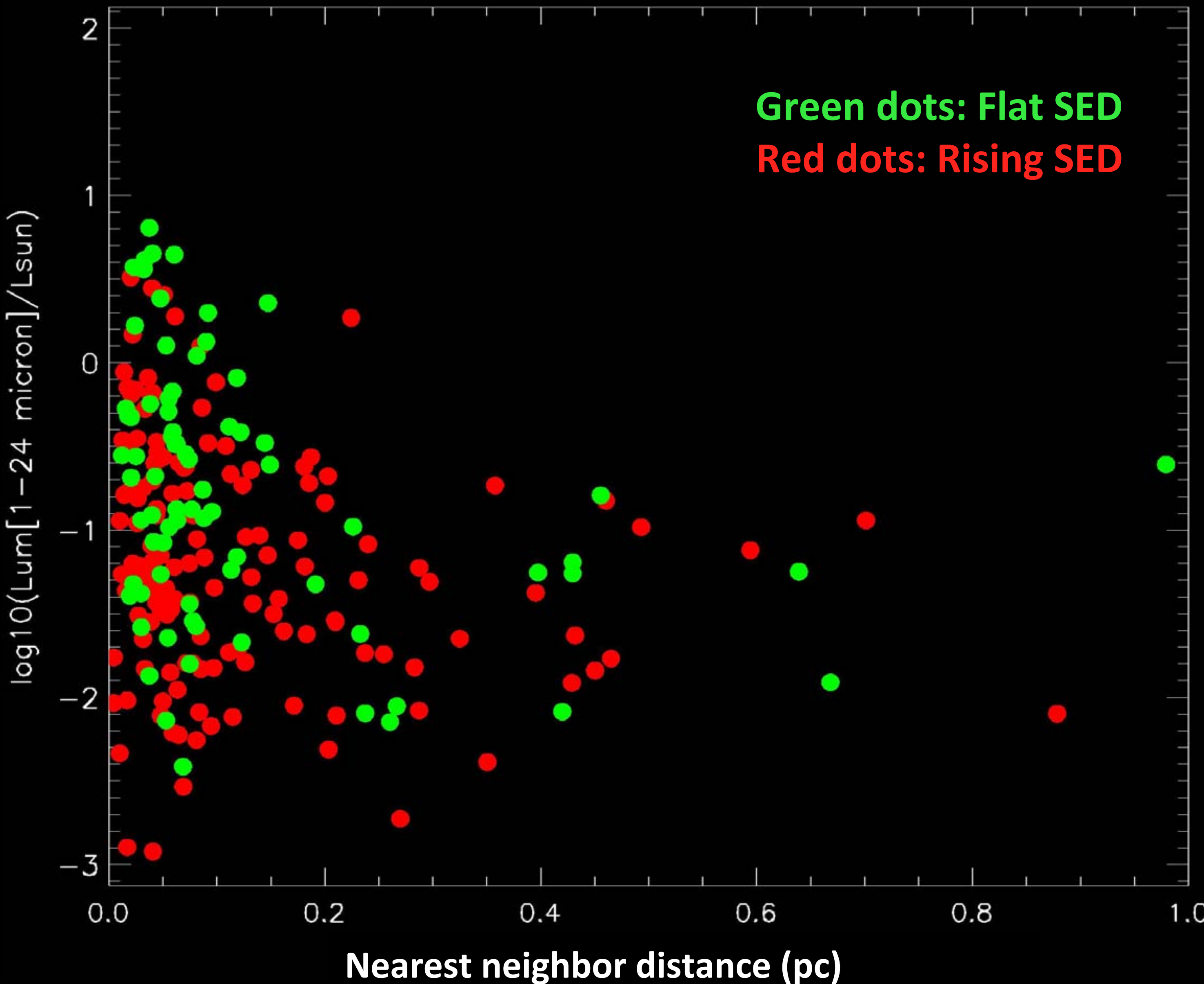
Blue: 1322 COUP X-ray Sources

Green: 72 Class 0/1

223 infrared protostars identified with Spitzer Note lack of identified protostars in the center of the Orion Nebula due to lack of 24 micron data.

Megeath et al in prep., Carpenter et al. 2001, Feigelson et al. 2005

Luminosity of Protostars as a Function of Crowding in Orion A



For each protostar in the Orion A molecular cloud, we calculated the projected distance to nearest infrared excess source

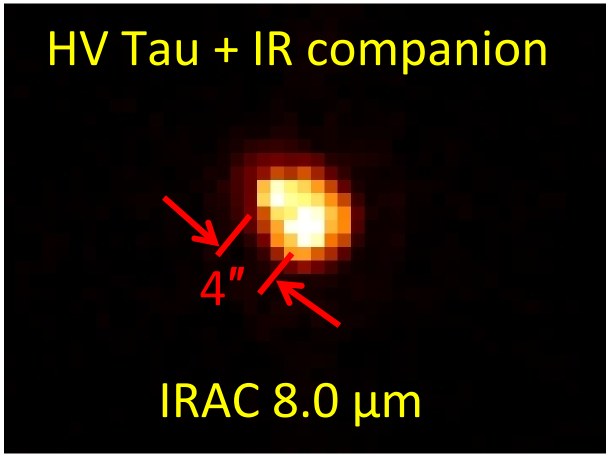
Sources with closer neighbors are more luminous

Statistical show that this effect is not the result of sampling.

Megeath et al. In prep

Taurus: Follow-up to Spitzer Legacy Project

- FORCAST/SOFIA can resolve close binaries (1″ - 4″) with infrared excesses
  - SEDs of components can be used to study properties of circumstellar disks (size, flaring, gaps) in a binary environment
    - 3″ corresponds to ~500 AU separation
    - For low mass stars, the 30-40 μm wavelengths probe the disk at > 1 AU
  - Several binary sources in the FORCAST sensitivity range have been identified as potential targets
- Brown dwarf disks?
  - Disks around brown dwarfs may be clues to brown dwarf formation processes (Bate et al. 2003)
  - Need to resolve components to isolate disk(s) – do properties of disk vary with separation and/or multiplicity
  - Due to faintness, probably should wait until telescope and instrument performance are well understood from other early science projects



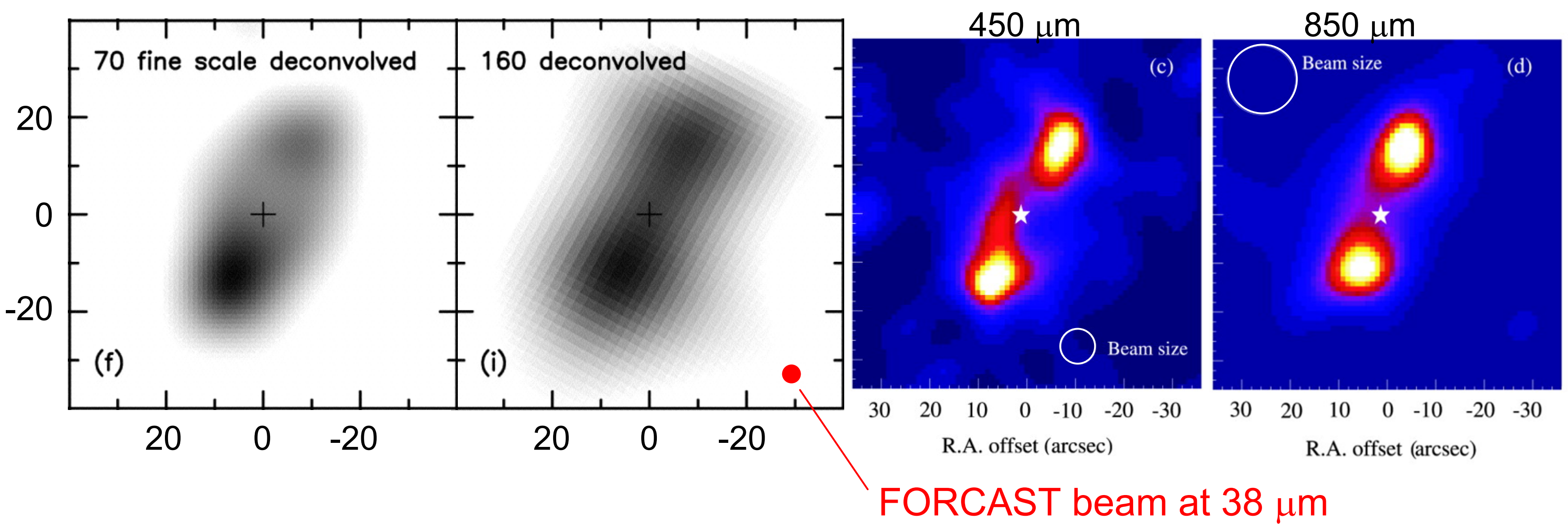
Debris Disks

- Goal is to provide high-resolution far-infrared observations of the “big” debris disks discovered by IRAS
  - Look for structure and fill in SED (vs. position)
  - Would be highest resolution in FIR
  - Very tough problem for SOFIA/FORCAST because of extended, faint nature of the emission.

- Our plans here are still open pending results from Herschel.

Debris Disks: Fomalhaut

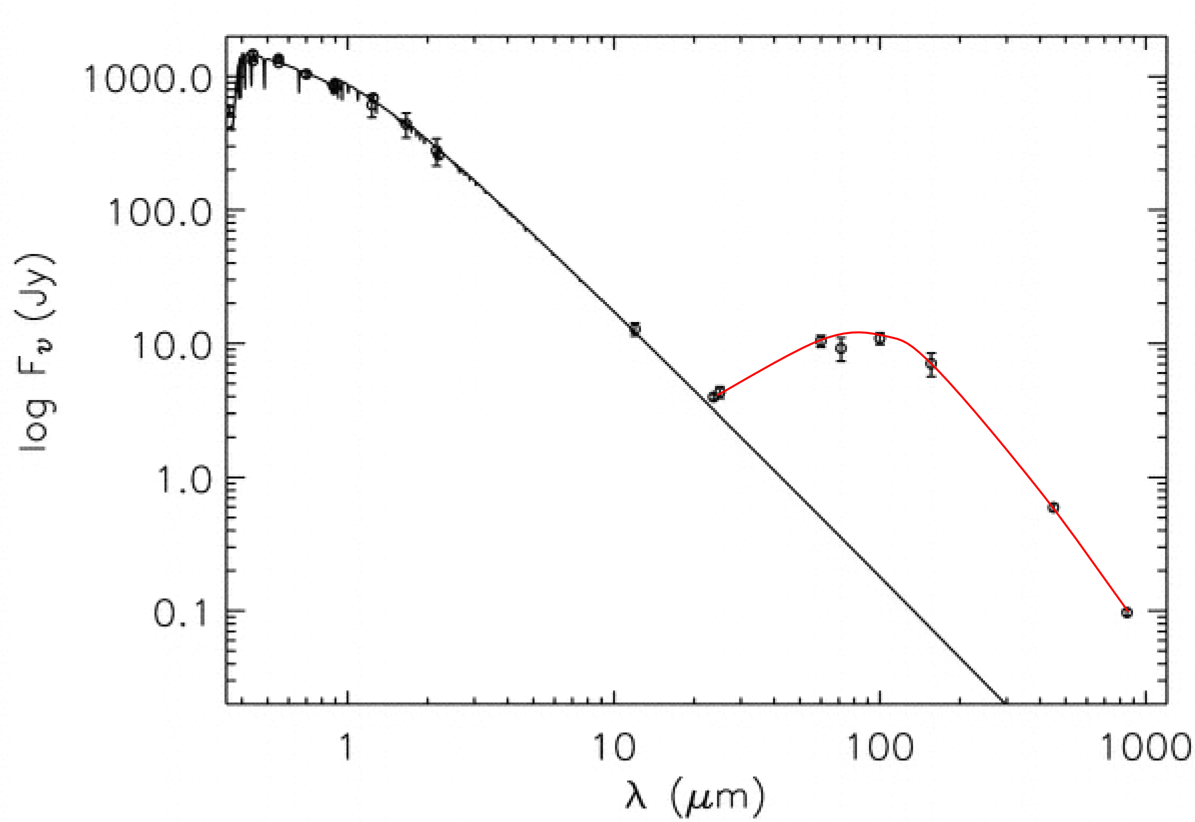
Asymmetries of debris (Fomalhaut, Vega, Epsilon Eridani, Beta Pic) disks. FORCAST will provide the highest spatial resolution measurements to date.

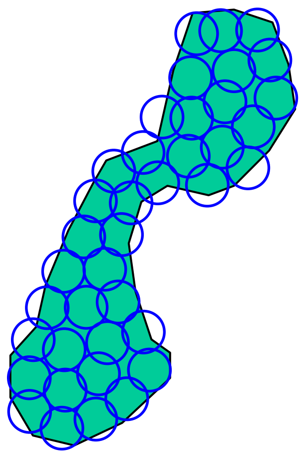


Images of Fomalhaut at 70, 160, 450, and 850 µm. (Stapelfeldt et al. 2004, ApJS, 154, 458; Holland et al. 2003, ApJ, 582, 1141). All maps have been deconvolved. FORCAST beam size is shown in red. Fomalhaut is at ($\alpha = 22^h\ 57^m\ 39.0^s \quad \delta = -29°\ 37'\ 20''$)

Images are on the same scale with north up and east on the left.

Spectrum of Fomalhaut





450 μm "map" overlaid w/ FORCAST beams

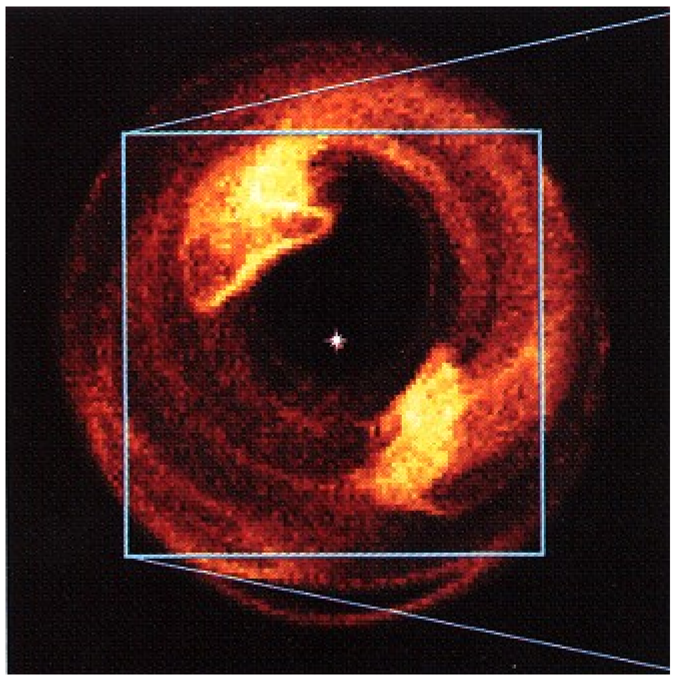
Spectrum of Fomalhaut (Stapelfeldt et al. 2004, ApJS, 154, 458). Red line is smooth curve (eyeball) fit to data. Expect an integrated flux of ~5 Jy at 38 μm which gives ~ 125 mJy/beam averaged over source (40 beams). For chopping on chip estimate 5σ in one hour is 50 mJy/beam (Includes read noise. Assumes chopping on chip – but not dithering).

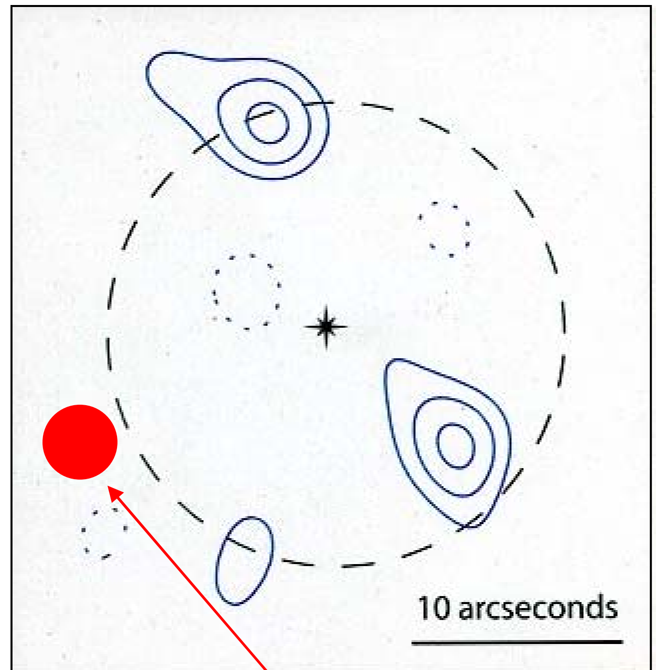
Vega Disk Update

- Dust emission from disks surrounding ~ 20 to 50% of nearby stars – peak at $\lambda > 30$ μm.
- Dust lifetime much less than stellar age.
- Indirect evidence for planets – ground up asteroids and cometary debris, asymmetries, etc.

Left: Model fitting mm observations $M < 30\ M_{jup}$ planet ~ 30 AU from star

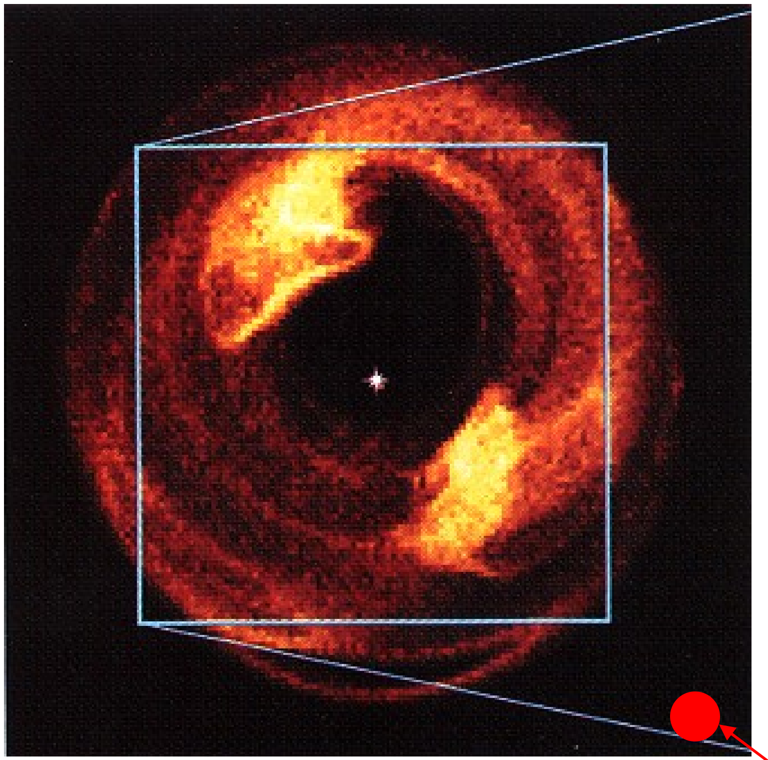
Right: mm map of Vega disk (Wilner et al.)





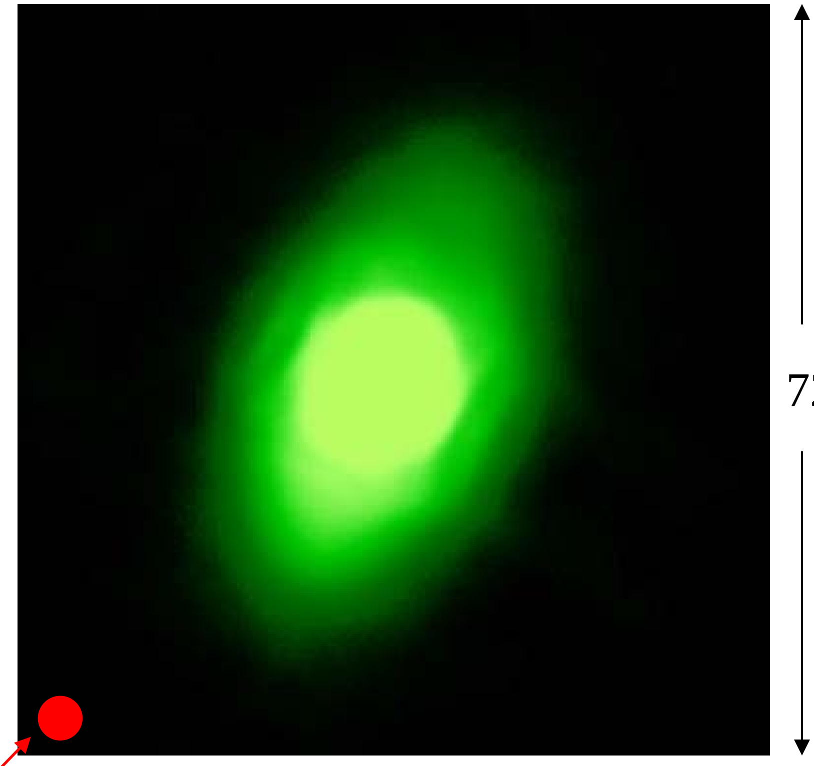
FORCAST beam size at 37 μm

Will SOFIA reveal debris disks @37 μm?



Vega model SOFIA @37 μm

?



Fomalhaut Spitzer MIPS @24 μm

FORCAST beam size at 37 μm

Wilner et al. model of Vega predicts resolved structure when convolved with SOFIA resolution @ λ=37 μm (LEFT), but Spitzer finds Fomalhaut (RIGHT) and Vega (not shown) amorphous at λ=24 μm. *Due to small grains or small inner disk radius??* - ask SOFIA!

Debris Disks: The Fantastic Four

Disk	S/N in 1 hour @ 38 μm			S/N in 1/100 sec
	per pix	per beam		@ 5.6 μm on star
Fomalhaut	3	13		27
Vega	7	35		66
beta Pic	82	395		5
epsilon Eri	0.12	0.6		12

- Will do shift and add on the fly to correct SOFIA pointing with observations of star at 5.6 microns
- S/N estimates
  - Assume uniform disk (no clumpiness)
  - Assume chopping on chip [improves S/N by factor of 1.4]
  - Assume beta*G ~ 1