Multi-Object Spectrometers for CCAT

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Outline

- **Science with sub-mm Multi-Object Spectrometers (MOSs)**

  Randolmy located, sparse targets: Spatial multiplexing

  - **Galaxies, galaxy clusters, sub-mm galaxies**
  - **Protostellar cores:**
    clusters, massive star-forming regions
  - **Proto-planetary & debris disks in clusters**
  - **Moons of giant planets, KBOs, asteroids**

- **Types of Multi-Object Imaging & Spectroscopy**

  Continuum (R = $\Delta\lambda$ / λ ~ 5)

  - **Imaging MKID array sub-fields**

  Low-R (10^3) "broadband" spectroscopy with multiple Z-Specs

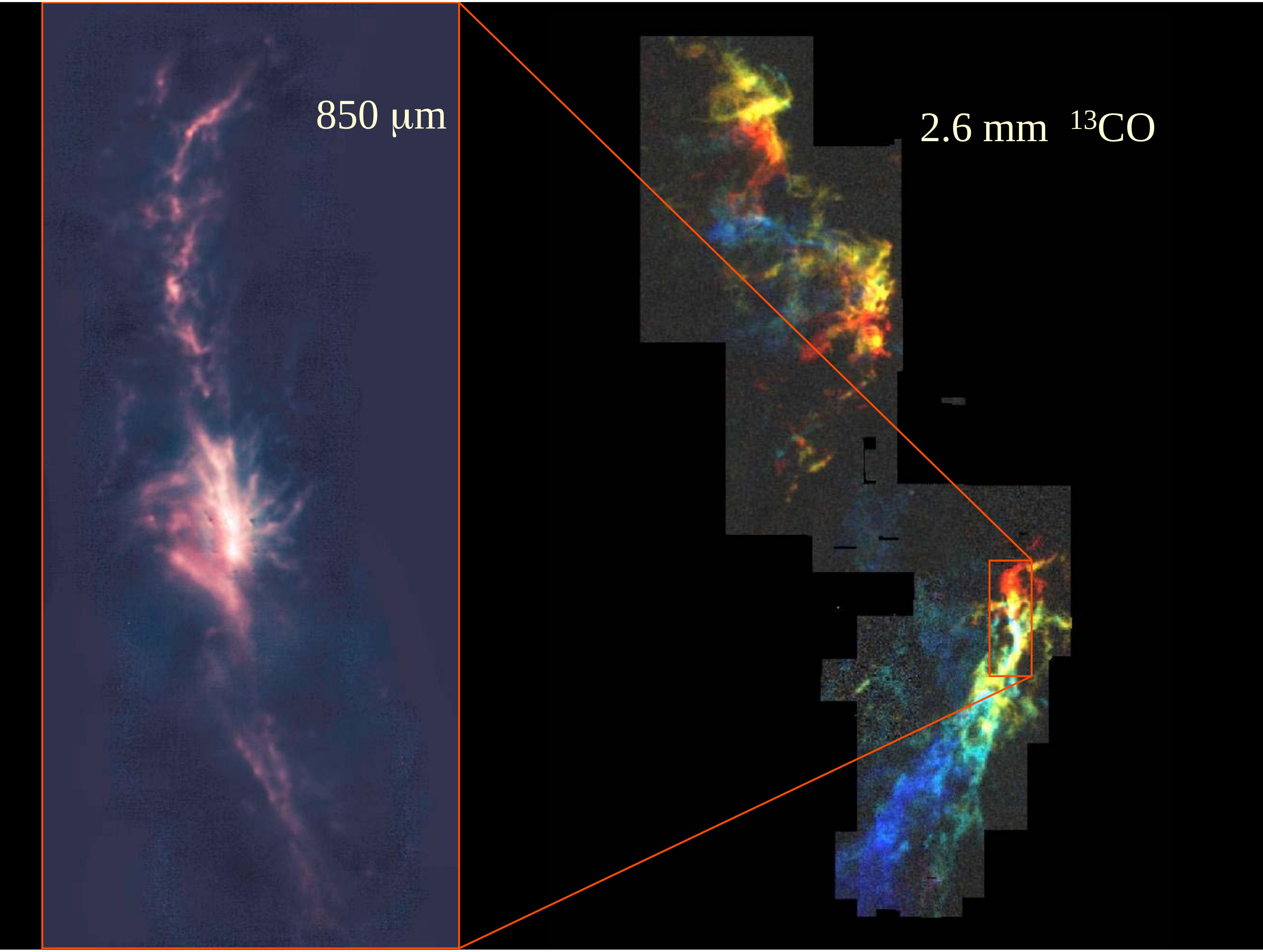
  - **Spectral index, organic forest, redshifts, dust properties**

  High-R (10^6) heterodyne spectroscopy

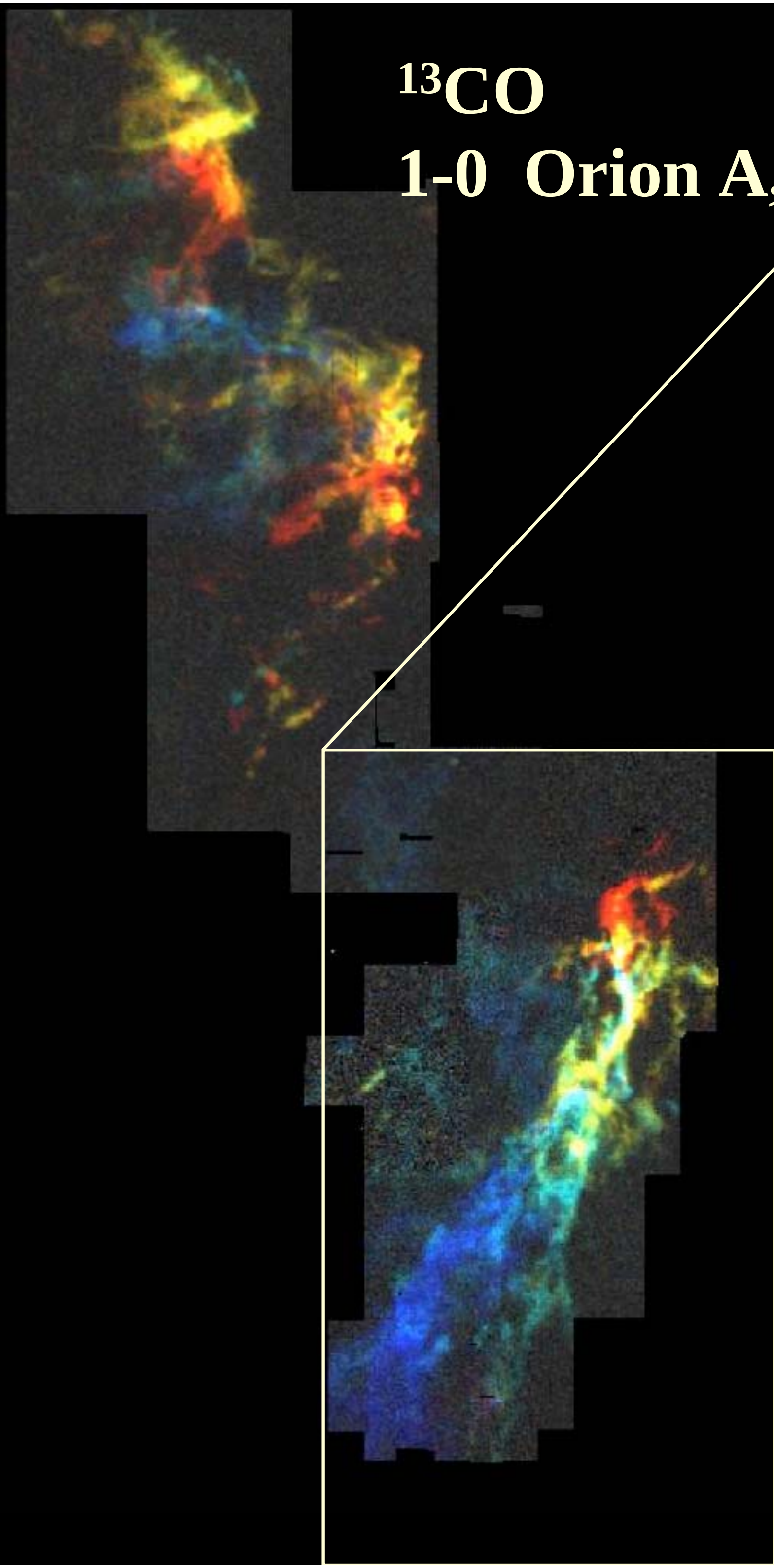
  - **Precision redshifts / radial velocity field mapping**
  - **Differential chemistry**

- **Implementation**
  - **Gaussian optics ("optical trombone" & "folded Offner periscope")**
  - **Flexible dielectric waveguide ("submm-optical fiber")**

- **Implications**
  - **Wide-FOV focal plane ; Focal plane needs to rotate!**

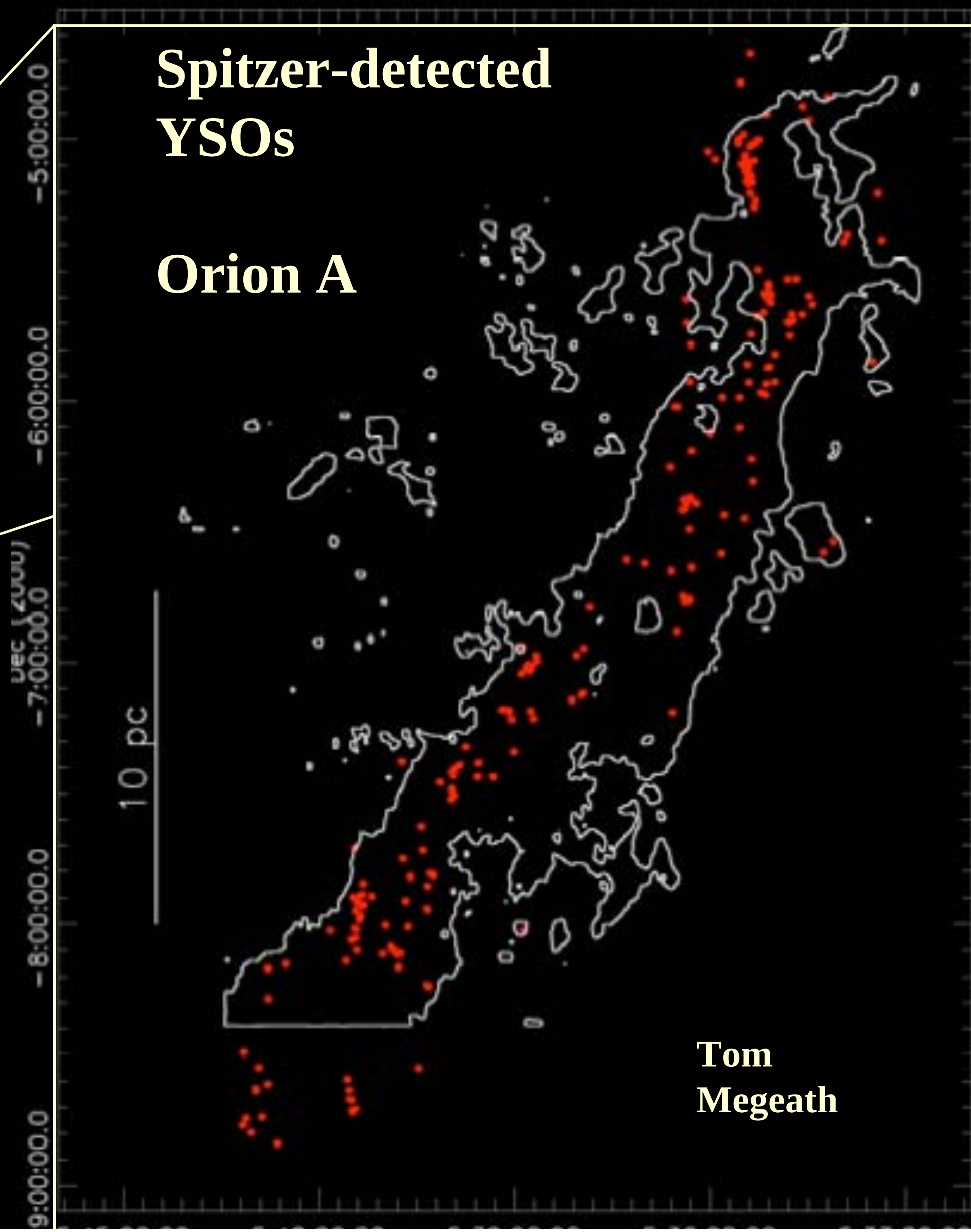

850 μm
2.6 mm 13CO

^{13}CO
1-0 Orion A,B



Spitzer-detected YSOs

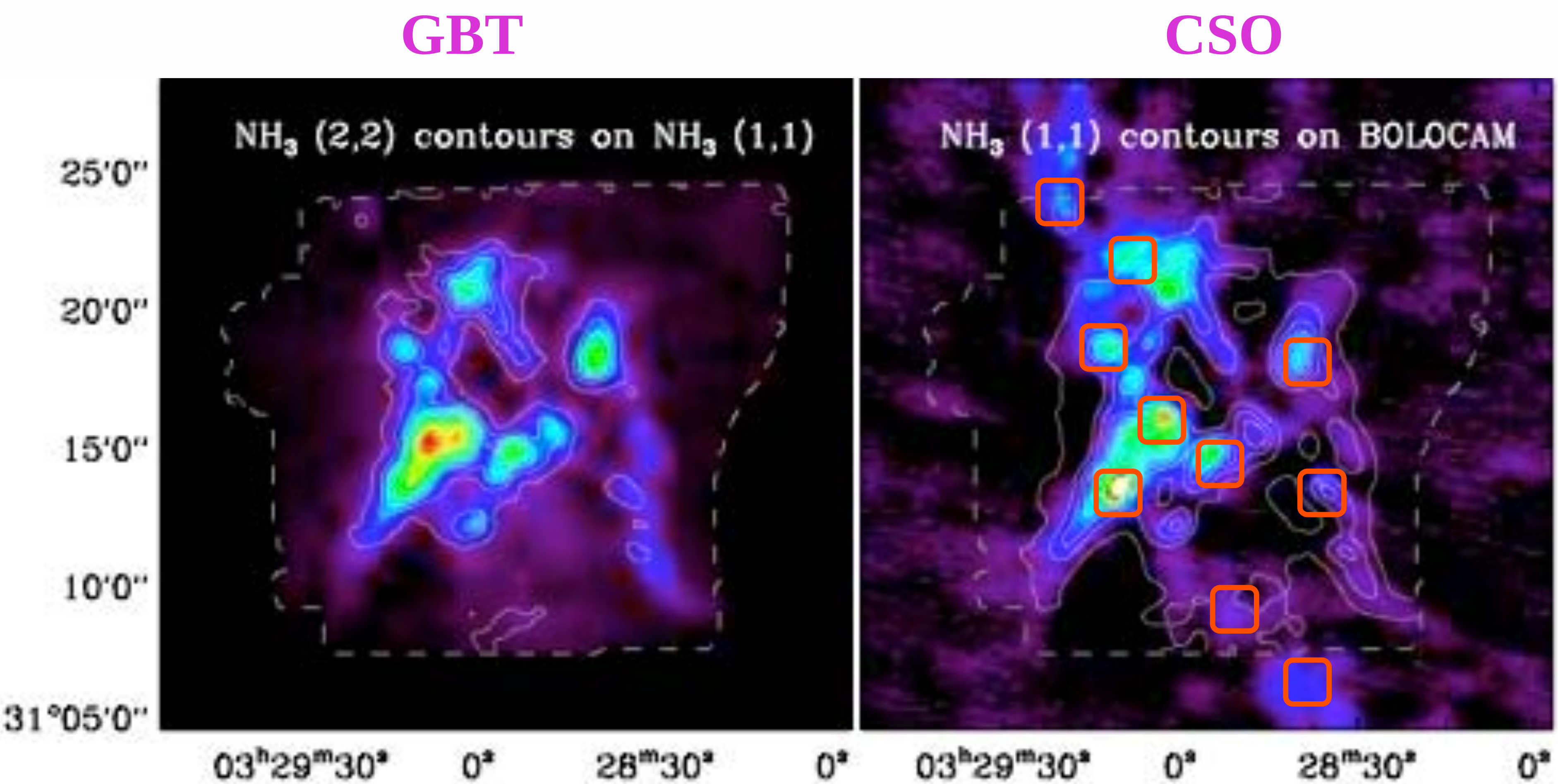
Orion A



Tom Megeath

Dense protostellar cores in NGC 1333
Perseus Molecular Cloud

(Courtesy E. Rosolowsky: CfA)

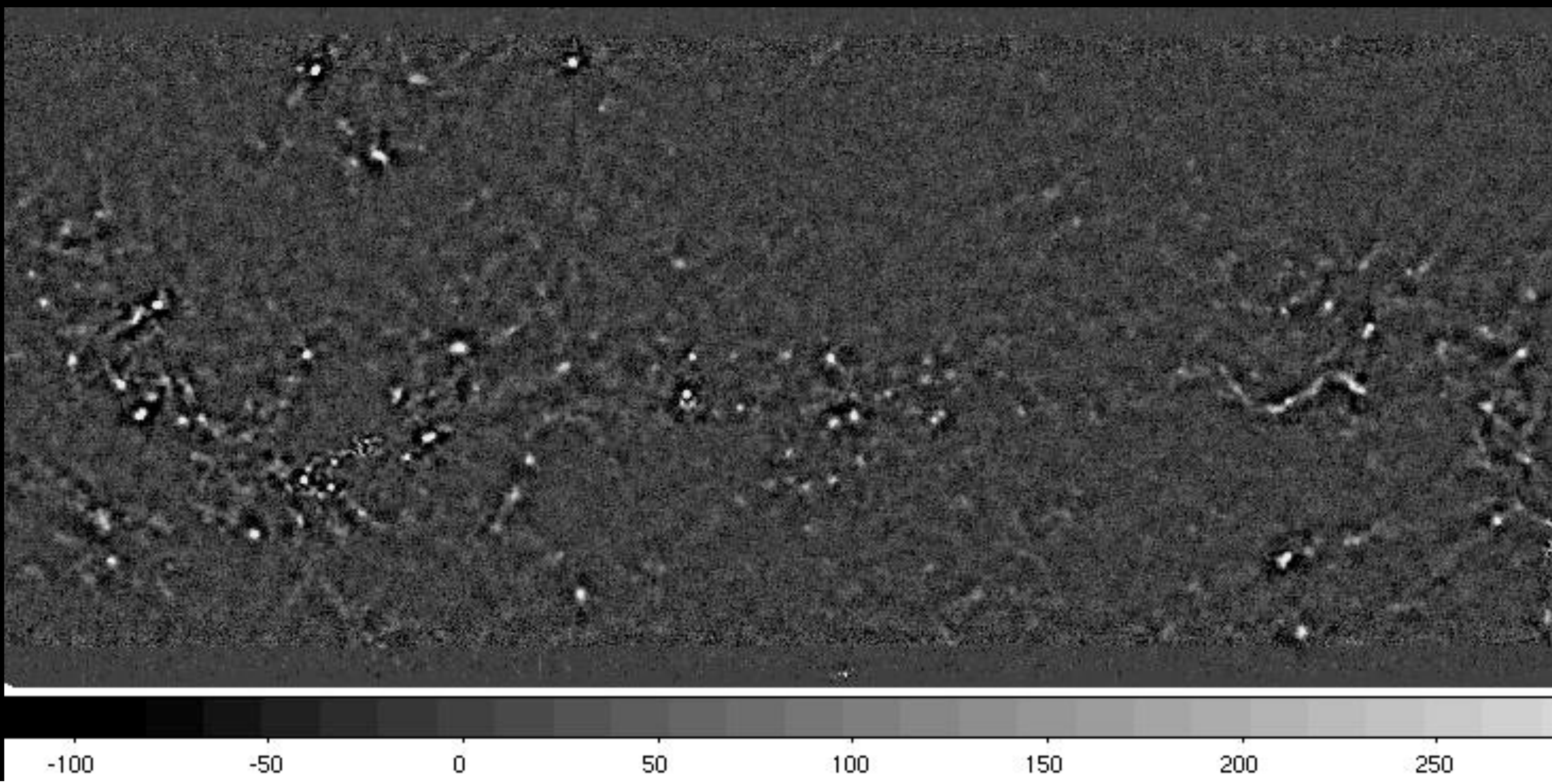


The Bolocam 1.1 mm survey (as of July 2007)

- ~ 90 square degrees of the Galactic Plane
- We have detected5,000 dense cloud cores (3 σ = 15 - 30 mJy / beam)
- Best tracer of star forming cores
- Key for massive star & cluster formation

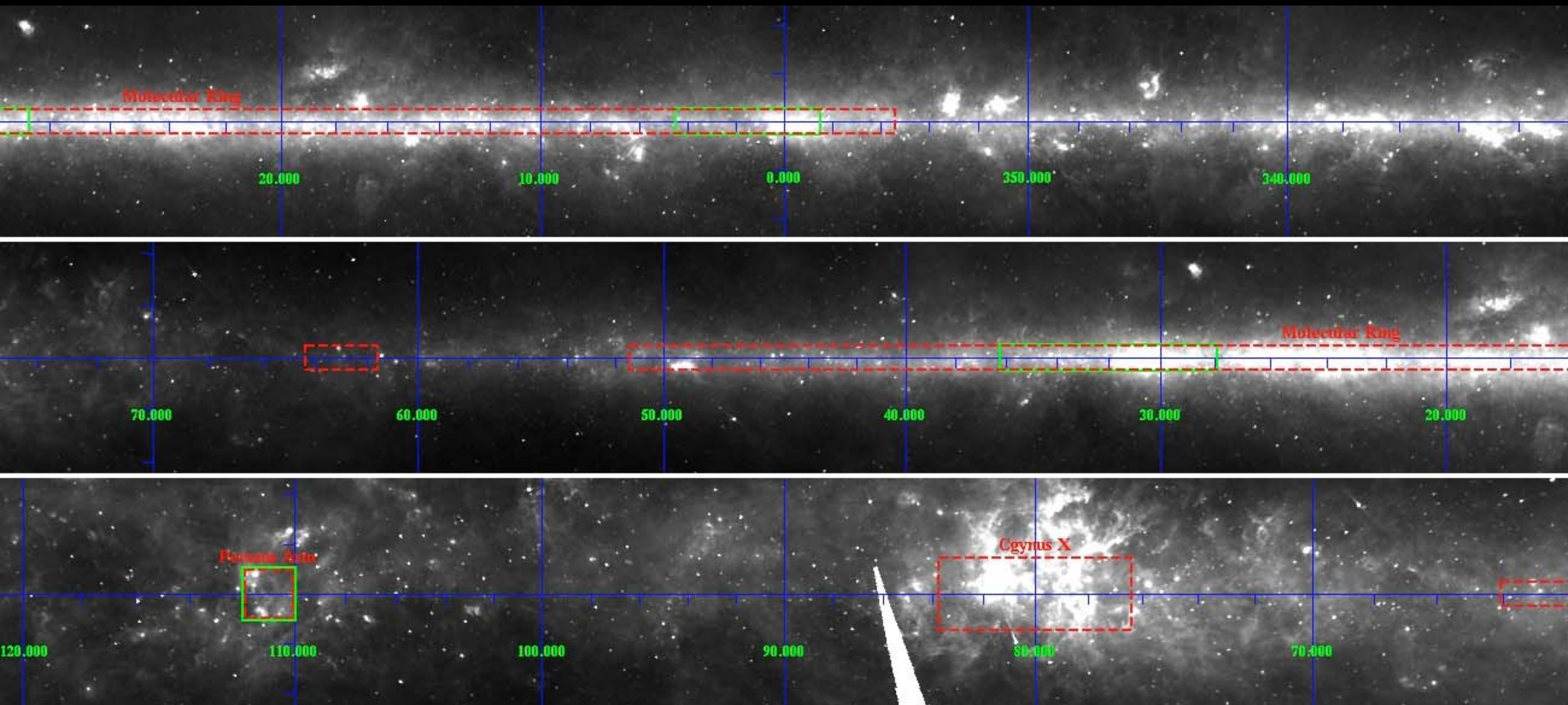
Single 45 min scan of 3 x 1 deg field in Plane

@ l = 10.5 - 13.5; b=+/- 0.5 $S_{r.m.s.}$ ~ 50 mJy / beam



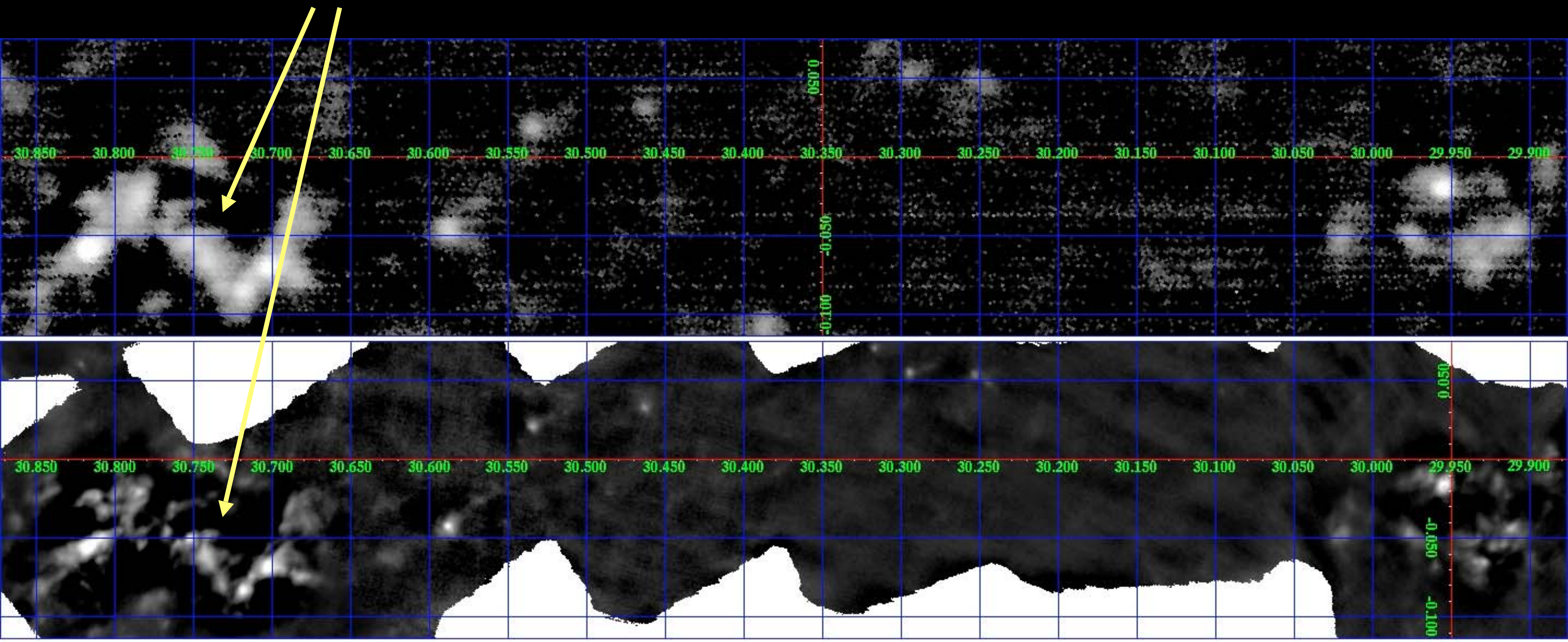
The Bolocam 1.1 mm survey (July 2007)

- 1.1 mm > 90 deg^2 τ_{350} $0.05 < \tau_{350} < 0.15$
- 0.35 mm (SHARC) on selected cores $\tau_{350} < 0.05$
- CS J=5-4 $\tau_{350} > 0.15$
- GBT 1.2 cm NH_3 (1,1)(2,2)(3,3) CCS (pending)

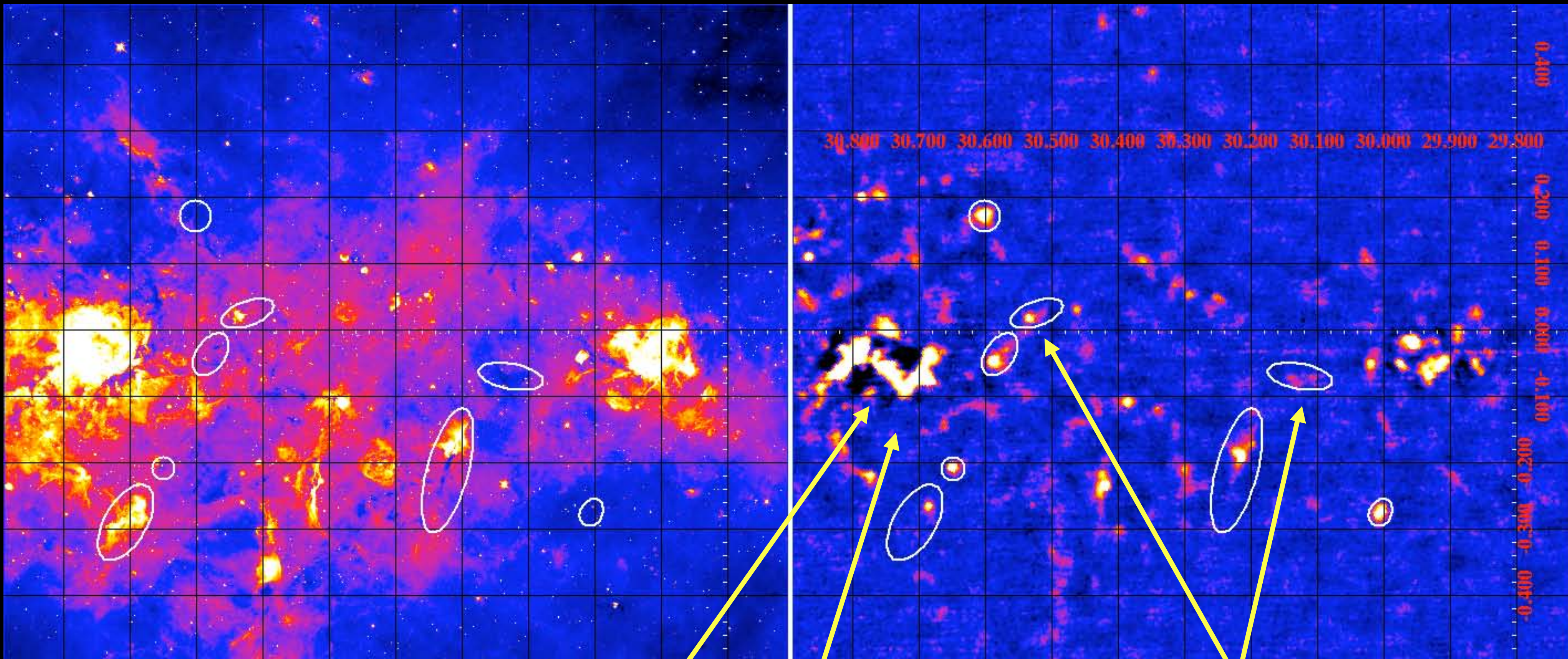


1.1 mm (top)   0.35 mm (bottom)

W43 cluster forming complex

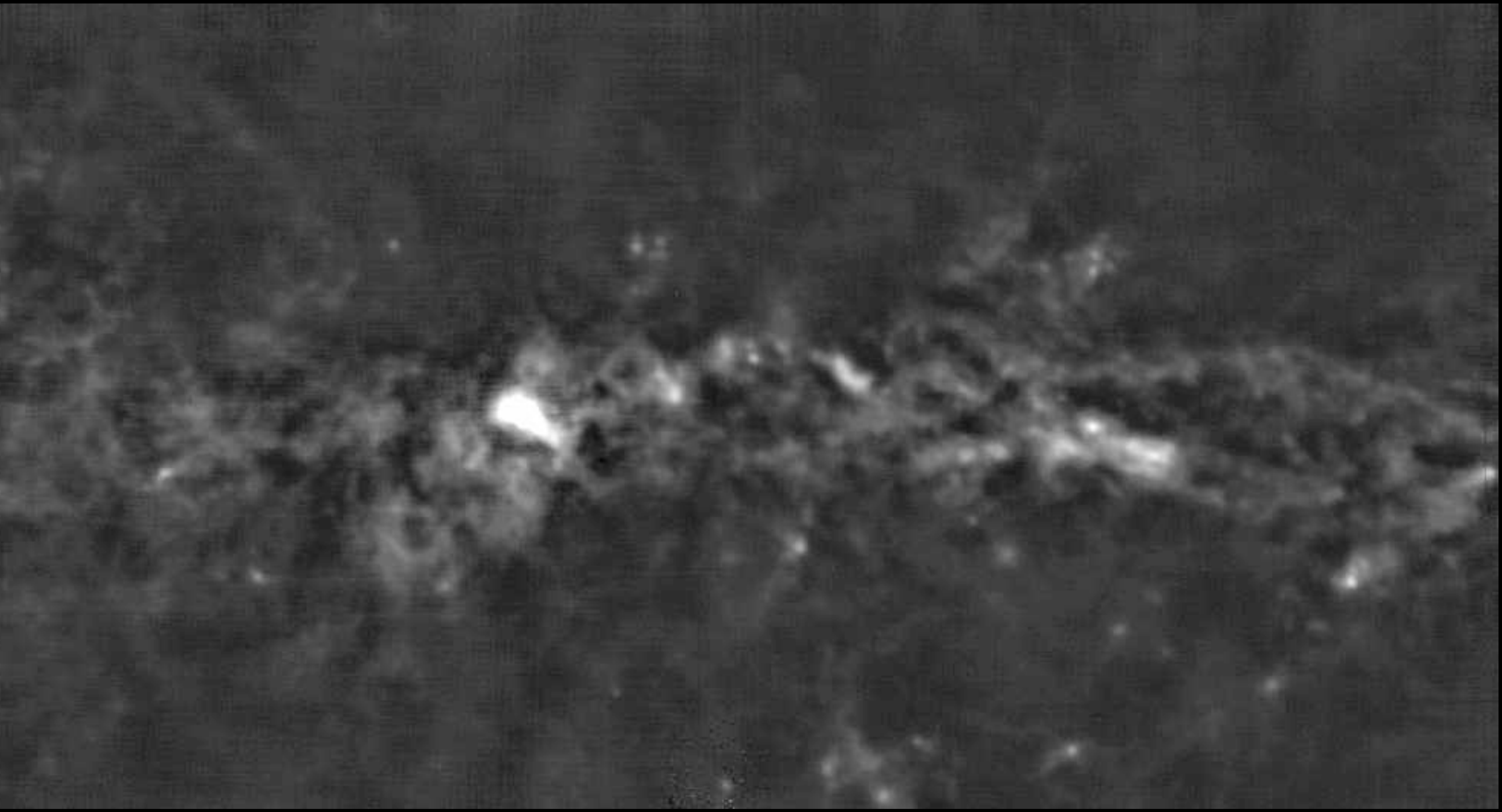


MSX 8 μm Bolocam 1.1 mm

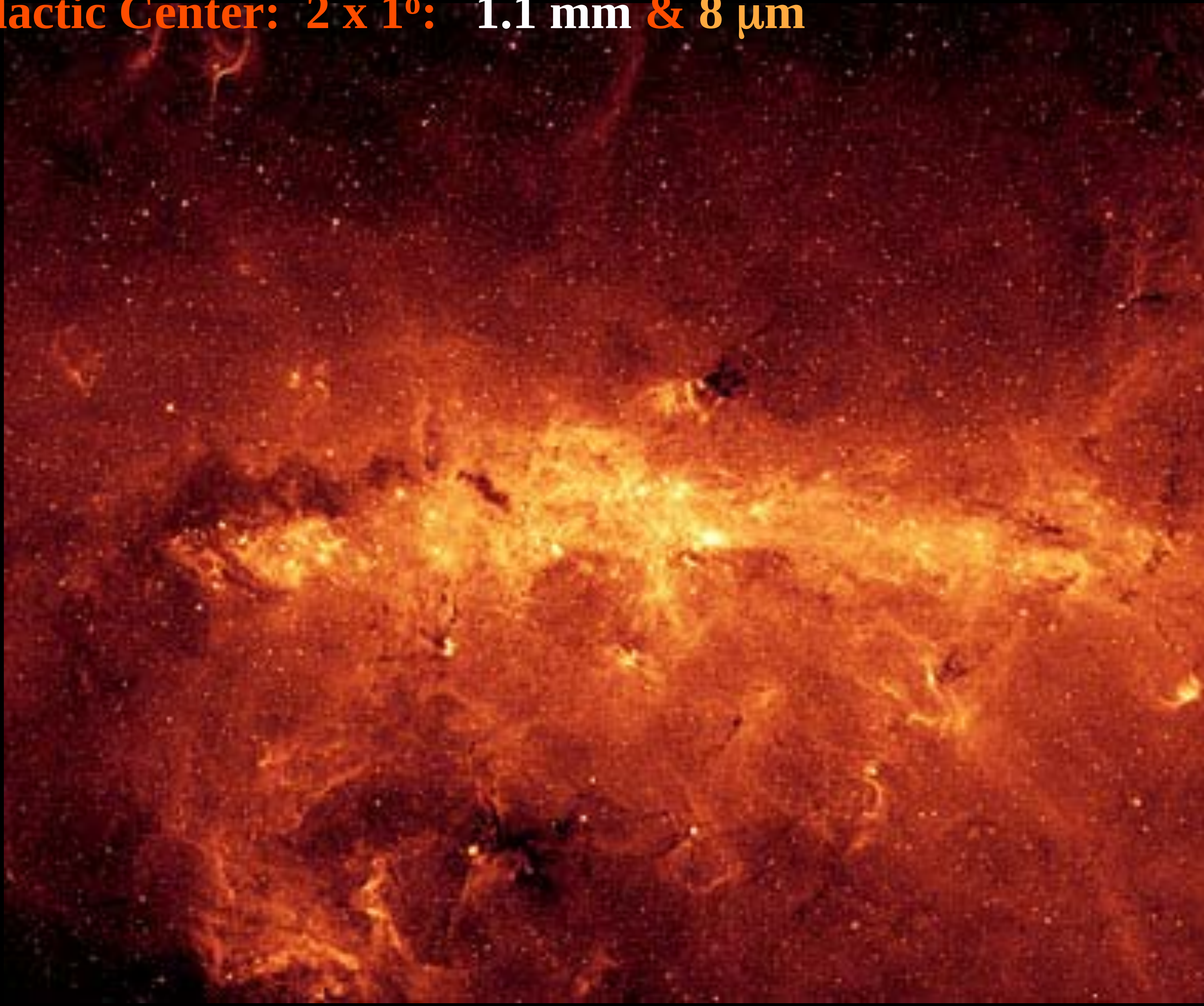


Bolocam 1.1 mm is best tracer of: pre-stellar cores, cluster-forming cores, and hot dust associated with hot cores, hypercompact & compact HII regions.

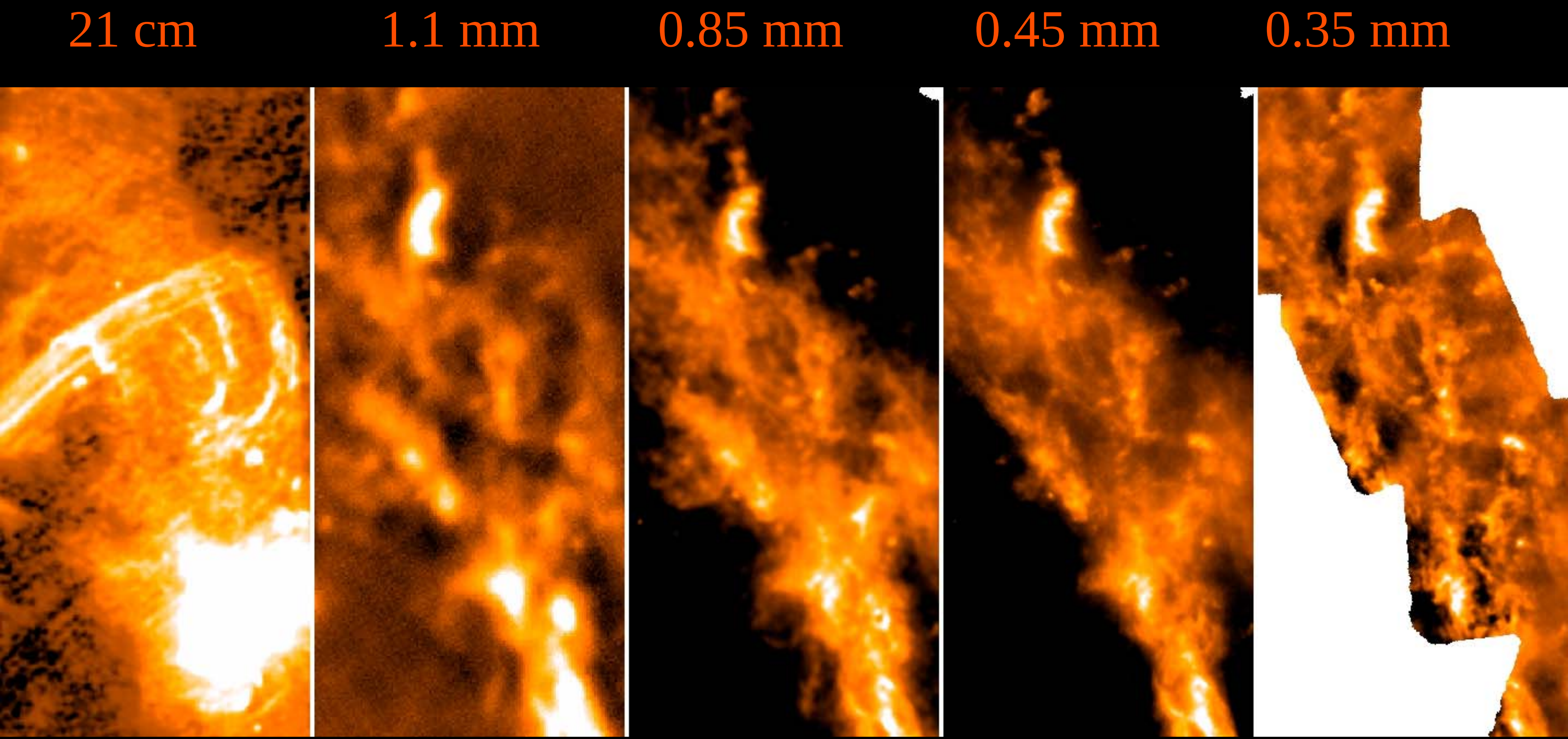
Galactic Center: 2 x 1°: 1.1 mm & 8 μm



Galactic Center: 2 x 1°: 1.1 mm & 8 μm



The Galactic Center



Previous CCAT MOS considerations

Thomas Nicola:

IRMOS (VLT) style pick-off mirrors and optical relays

- Requires complex mechanism / actuators

Matt Bradford, Jonas Zmuidzinas, Gordon Stacey,
Jason Glenn:

Various flexible dielectric waveguides.
solid core, powdered core, strip-line, ribbon cable,
split-rectangular, hollow-core guides

- Media not yet well characterized: geometry not well defined

- Large loss: 1 - 4 dB/m. Losses sensitive to bends.

I will advocate:

- Re-configurable folded re-imaging feeds:

Robotic with magnetic clamps (No actuators!)

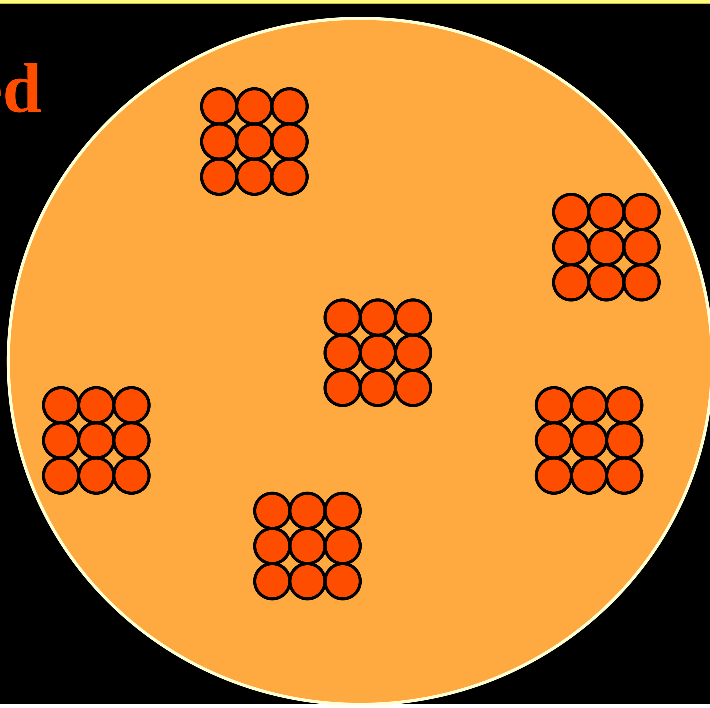
- Flexible waveguides

Types of MOS

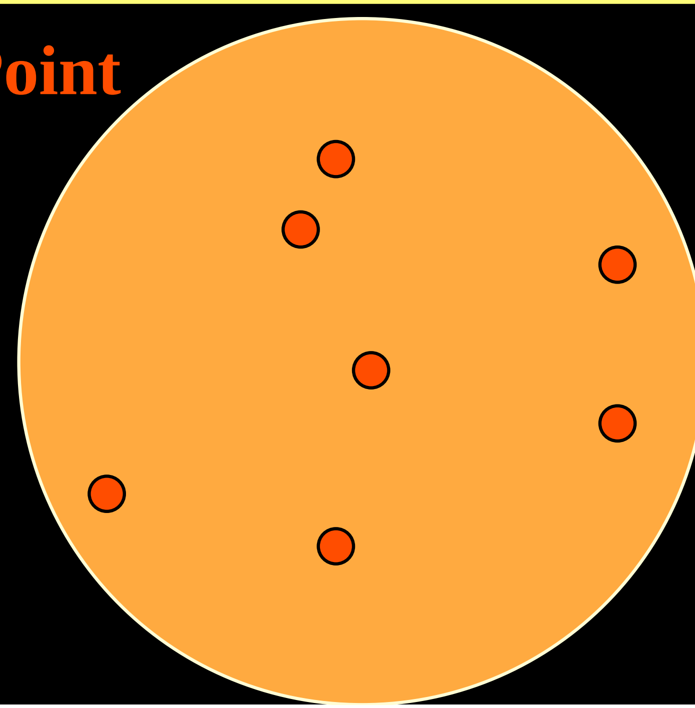
Sparse-field imaging vs. Multiple point sources

$R = \lambda/\Delta\lambda$	~ 5	10^3	10^6	Fore-optics	
Point	MKIDs	Z-Spec cluster	heterodyne	trombone or	fiber
Extended	MKID clusters	Z-Spec clusters	heterodyne cameras	folded Offner	fiber bundles

Extended



Point

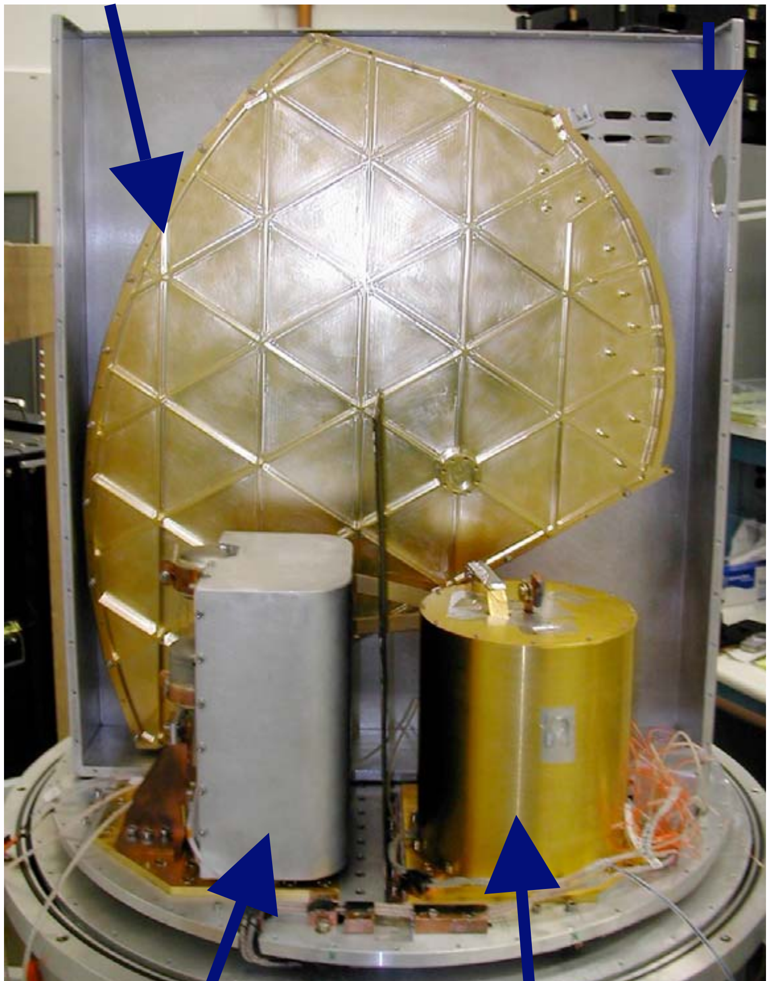


Z-Spec

Electromagnetics simulated end-to-end:
telescope to bolometers

Grating:
62 x 48 x 3.3 cm

Feedhorn
input



$^{3}He/^{4}He$
Fridge

60 mK ADR
(Salt pill courtesy Peter Timbie's group)

Parameters

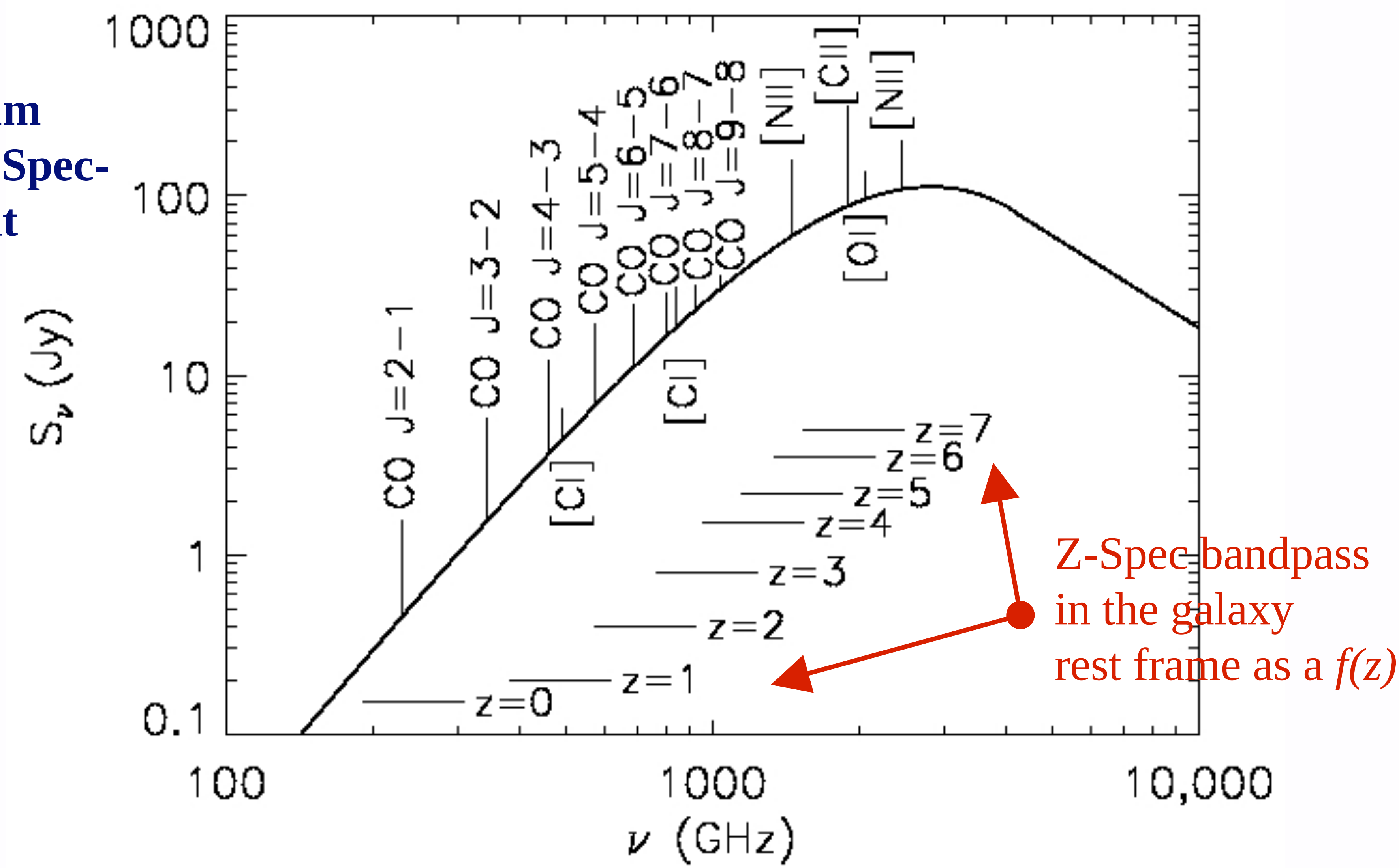
- λ = 1.0 to 1.5 mm (CSO)
- 160 bolometers
- $\Delta\nu$ ~ 900 MHz, Δv ~ 1,000 km s^{-1}
- Compact, stackable waveguide-coupled diffraction grating: technology demonstration for future instruments (e.g., BLISS, SAFIR, CCAT)

Caltech—Bret Naylor, Jonas Zmuidzinas
Cardiff—Peter Ade
CEA (France)—Lionel Duband
Colorado—James Aguirre, Lieko Earle, Jason Glenn, Phil Maloney, Corey Wood
JPL—Jamie Bock, Matt Bradford, Hien Nguyen
ISAS (Japan)—Hideo Matsuhara

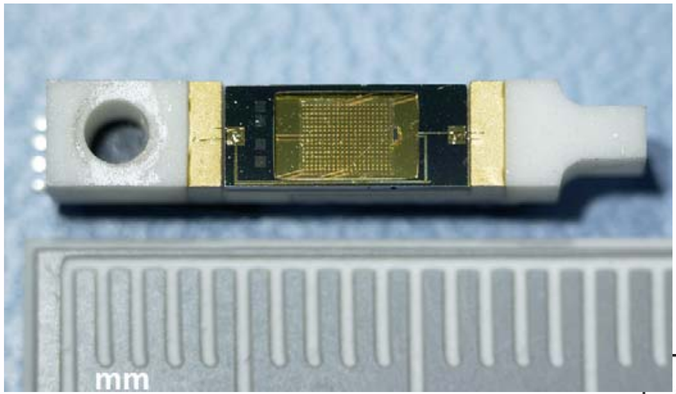
Millimeter-Wave Carbon Monoxide Redshifts

Deriving physical properties requires sub/millimeter spectroscopy for secure IDs

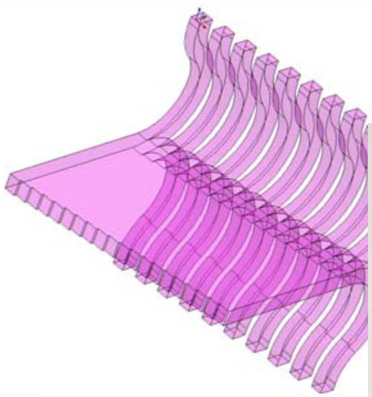
Model spectrum with Z-Spec-relevant lines

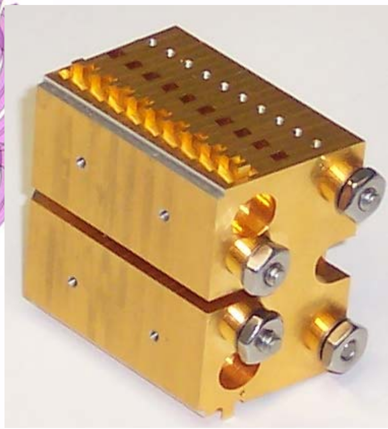


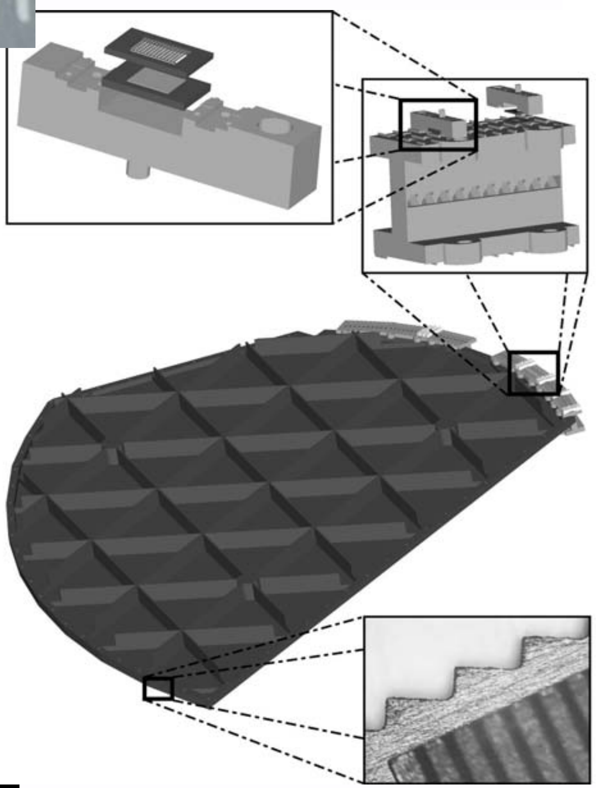
Technology: 2-D Waveguide-Coupled Diffraction Grating



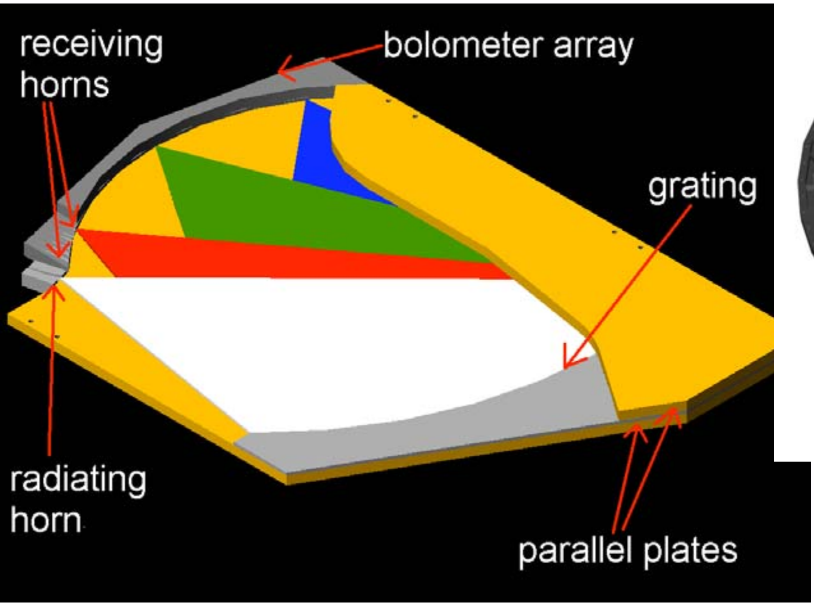
Bolometers are mounted on keys with reflecting backshorts





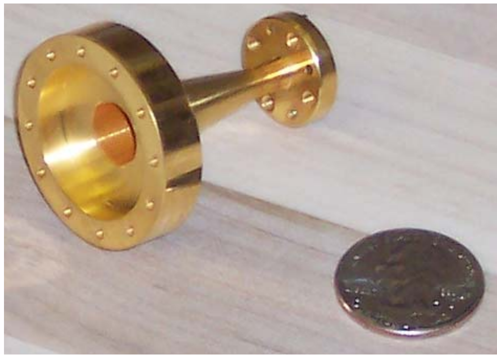


The parallel plate grating diffracts and focuses incoming radiation



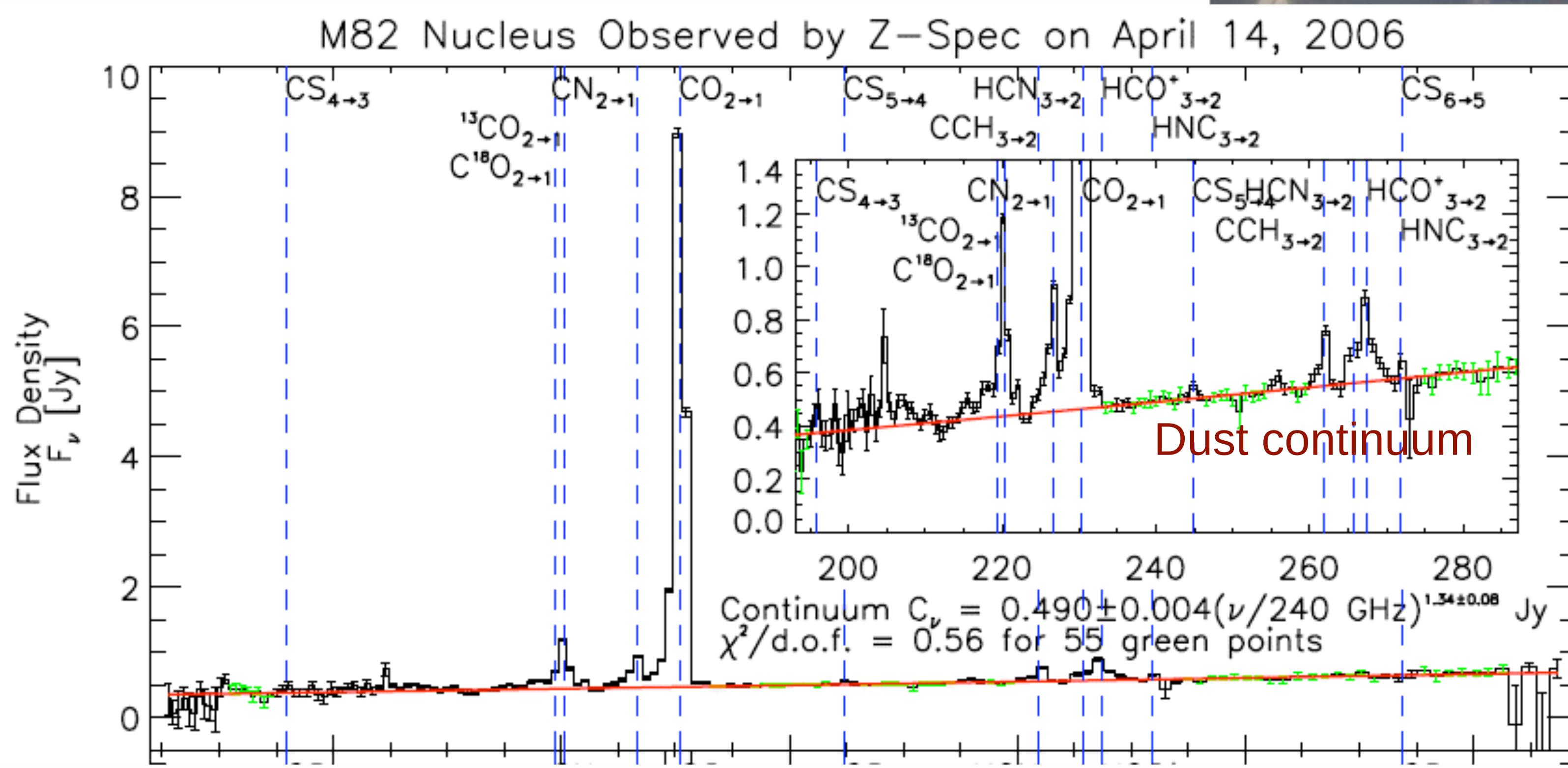
Waveguide "bend blocks" couple radiation from the parallel plate waveguide to the bolometers

Single broadband corrugated input feed

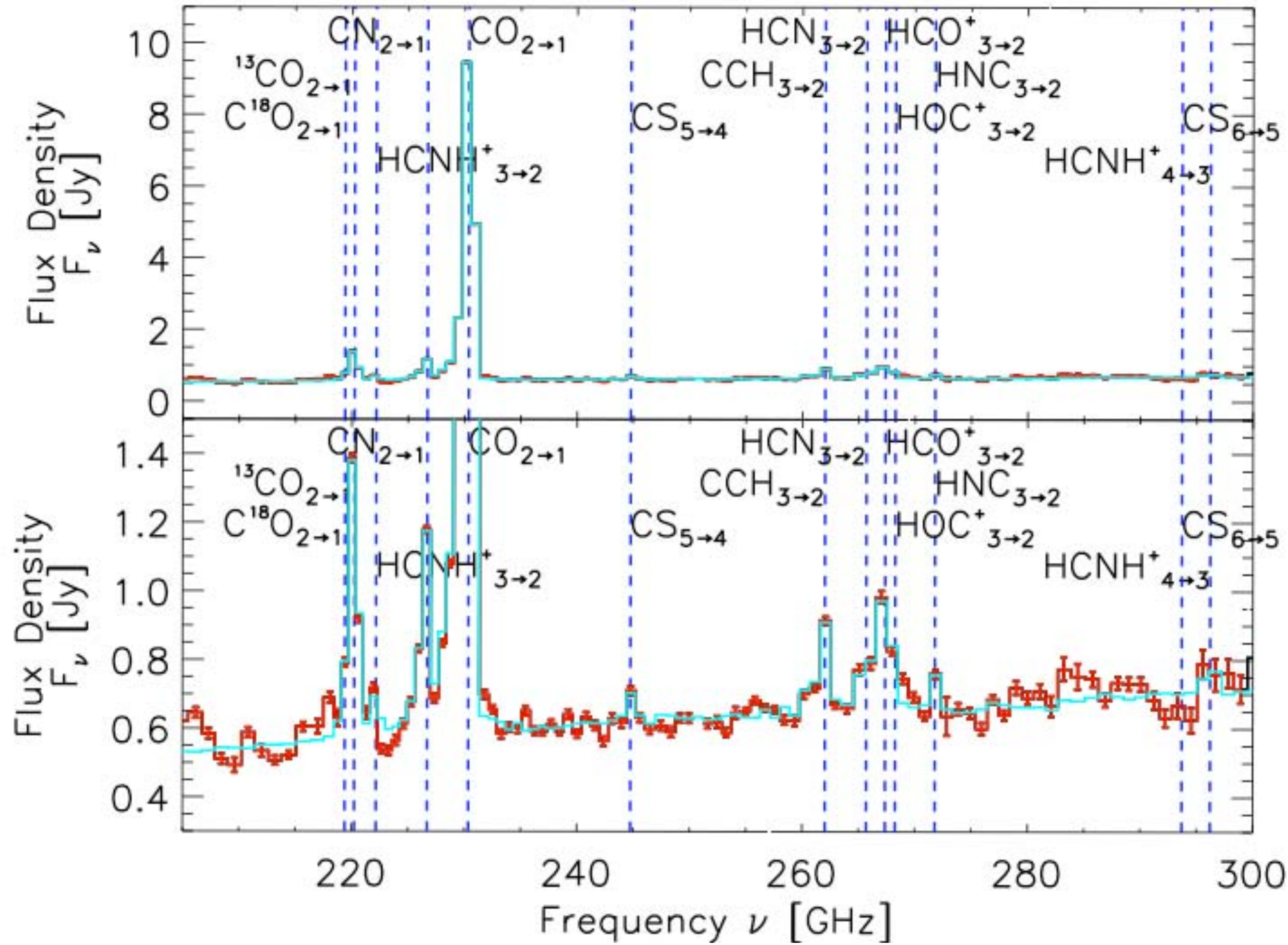


Z-Spec Status

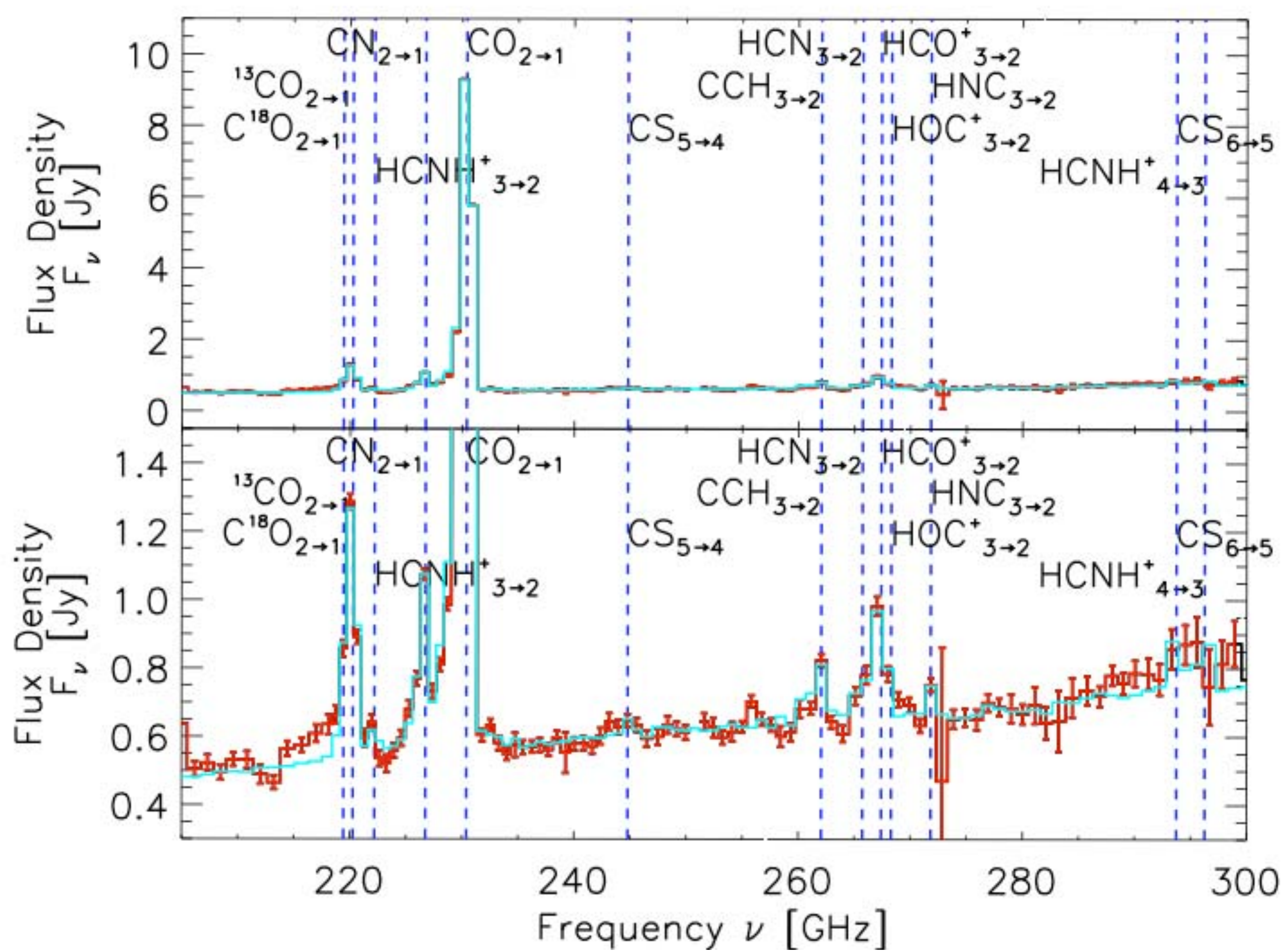
- Spectral resolution matches theoretical expectations
- Sensitivity 1.5× worse than ultimate goal – limited by sky noise (room for improvement)
- Local ULIRG survey underway & first high-z observations soon



Naylor et al. 2007 200GHz 220GHz 240GHz 260GHz 280GHz 300GHz



Flux Density F_ν [Jy]
Frequency ν [GHz]
$CN_{2\to1}$
$CO_{2\to1}$
$^{13}CO_{2\to1}$
$C^{18}O_{2\to1}$
$HCNH^+_{3\to2}$
$CS_{5\to4}$
$HCN_{3\to2}$
$CCH_{3\to2}$
$HCO^+_{3\to2}$
$HNC_{3\to2}$
$HOC^+_{3\to2}$
$HCNH^+_{4\to3}$
$CS_{6\to5}$

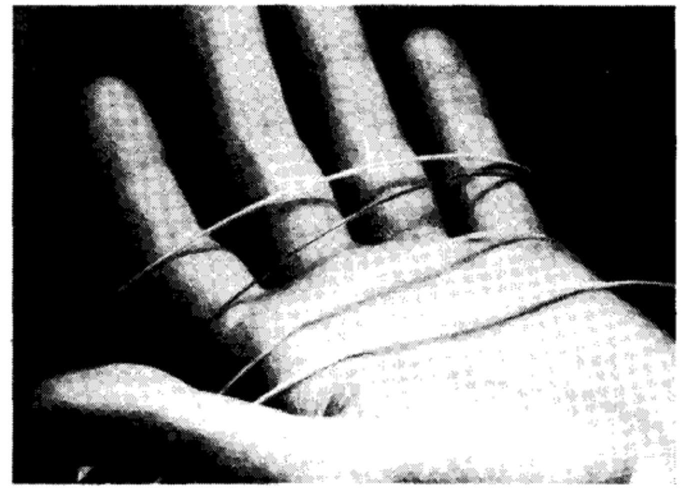


CN2→1
CO2→1
13CO2→1
C18O2→1
HCNH+3→2
CS5→4
CCH3→2
HCN3→2
HCO+3→2
HNC3→2
HOC+3→2
HCNH+4→3
CS6→5
Flux Density
Fν [Jy]
Frequency ν [GHz]
0
2
4
6
8
10
0.4
0.6
0.8
1.0
1.2
1.4
220
240
260
280
300

Flexible Dielectric Waveguides

Physics

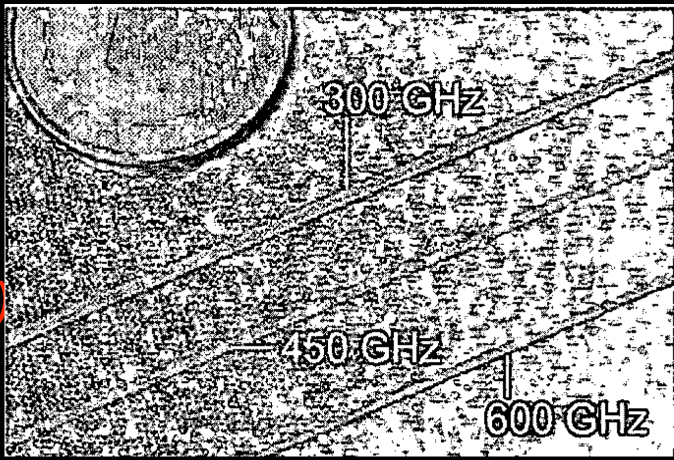
- Couple to optics & detectors via feedhorns
- Circular waveguide: HE_{11} is the fundamental mode
- Transverse EM field components described by Bessel (inside) and modified Bessel (outside) functions
- External fields are evanescent for large bend radii
- No proven theoretical description of bend radiative losses



Bruno & Bridges, IEEE Trans MTT 36, 882 (1988)

Previous Work

- Powder-filled waveguides
  - ➢Tested at 10 (X-band) & 94 GHz (W-band)
  - ➢PTFE cladding, 21-23 AWG (150 μm walls)
  - ➢Loss 25% over 10 cm in W-band (room temperature)
  - ➢"Unmeasurably small" loss for bend radii < 4cm
  - ➢Granularity would be a problem at submillimeter λs
- Monofilament (*Best choice from manufacturing perspective*)
  - ➢HDPE waveguide tested up to 300 GHz
  - ➢Rectangular: 560 μm x 280 μm
  - ➢Tapered coupling well thought out & simulated
  - ➢Loss 19% over 10 cm at room temperature; extrapolates to 35% @ 600 GHz



Hofman et al., (2003)

System Advantages: simple, compact, elegant

Challenges: absorption, high-frequency fabrication, radiation losses at bends

CCAT Reconfigurable Multiobject Spectrograph

Specifications

- Minimum ten 10-cm waveguides
- Bend radius ~ few cm
- Acceptable loss – push toward short λs, waveguide loss not dominant, for example, *assume*: $T_{sky}(\tau350\mu m=0.25) = 70$ K, T_{tel}(optimistic) = 20 K, T_{guide}(trans=60% @ room temperature) = 95 K
- BUT, reconfigure warm ; *PTFE is flexible at low temperatures*

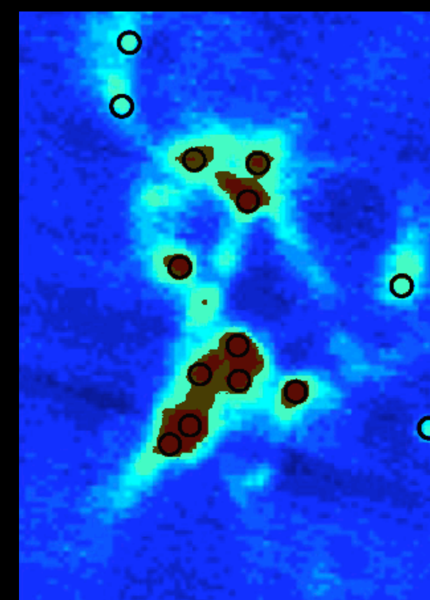
Zeus, Inc.

Manufacture

- Vendors – Zeus, custom extrusion houses
- Standard sizes – down to 710 μm
- Custom fabrication -- $1,200 per run of 2500 ft *– fishing anyone?*

CU Seed Grant Award (Jason Glenn)

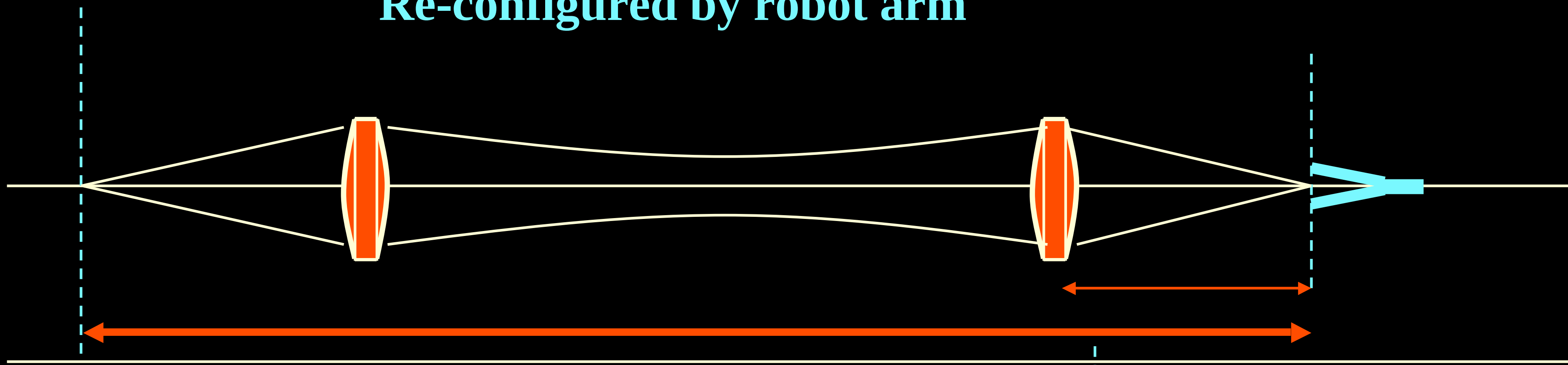
- $44k, 1 yr
- Collaboration: CU APS, EE, NIST, Colo. School of Mines
- Test setup: T ~ 300K diode detector; network analyzer – 400 GHz, *900 GHz*; cryo w/ TESs 850 μm; fiber vs. hollow metal
- Tests: HDPE vs. PTFE; 350 & 850 μm; room temp, cryogenic loss; loss vs. bend radius; loss after many bends & cooldowns
- EM field Simulations

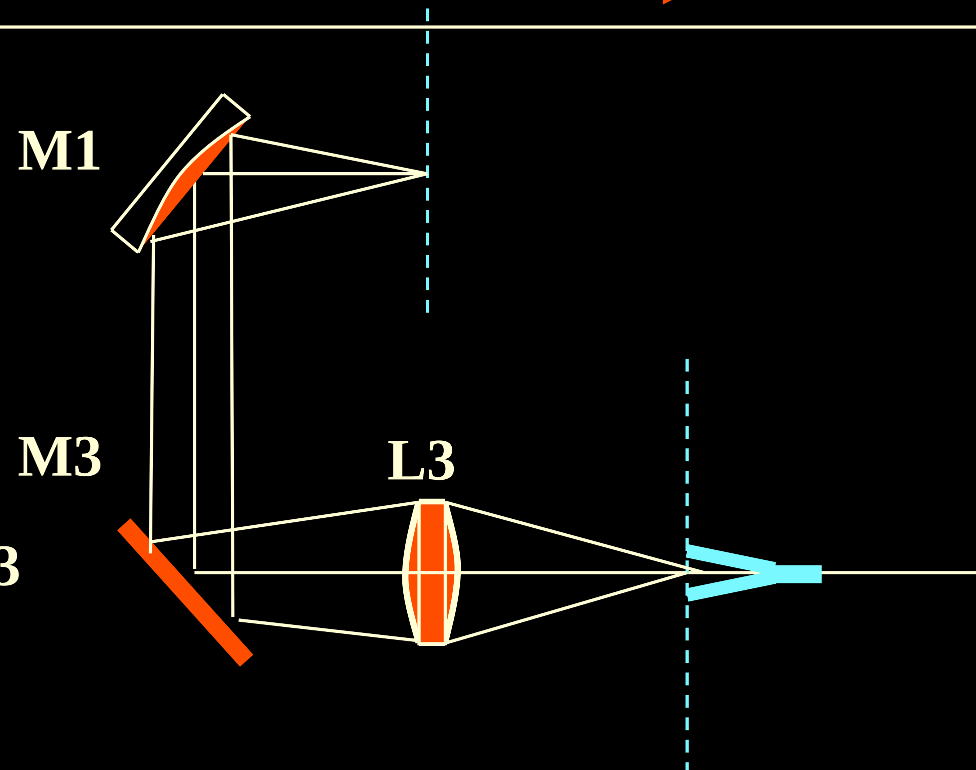


Ex. NGC1333

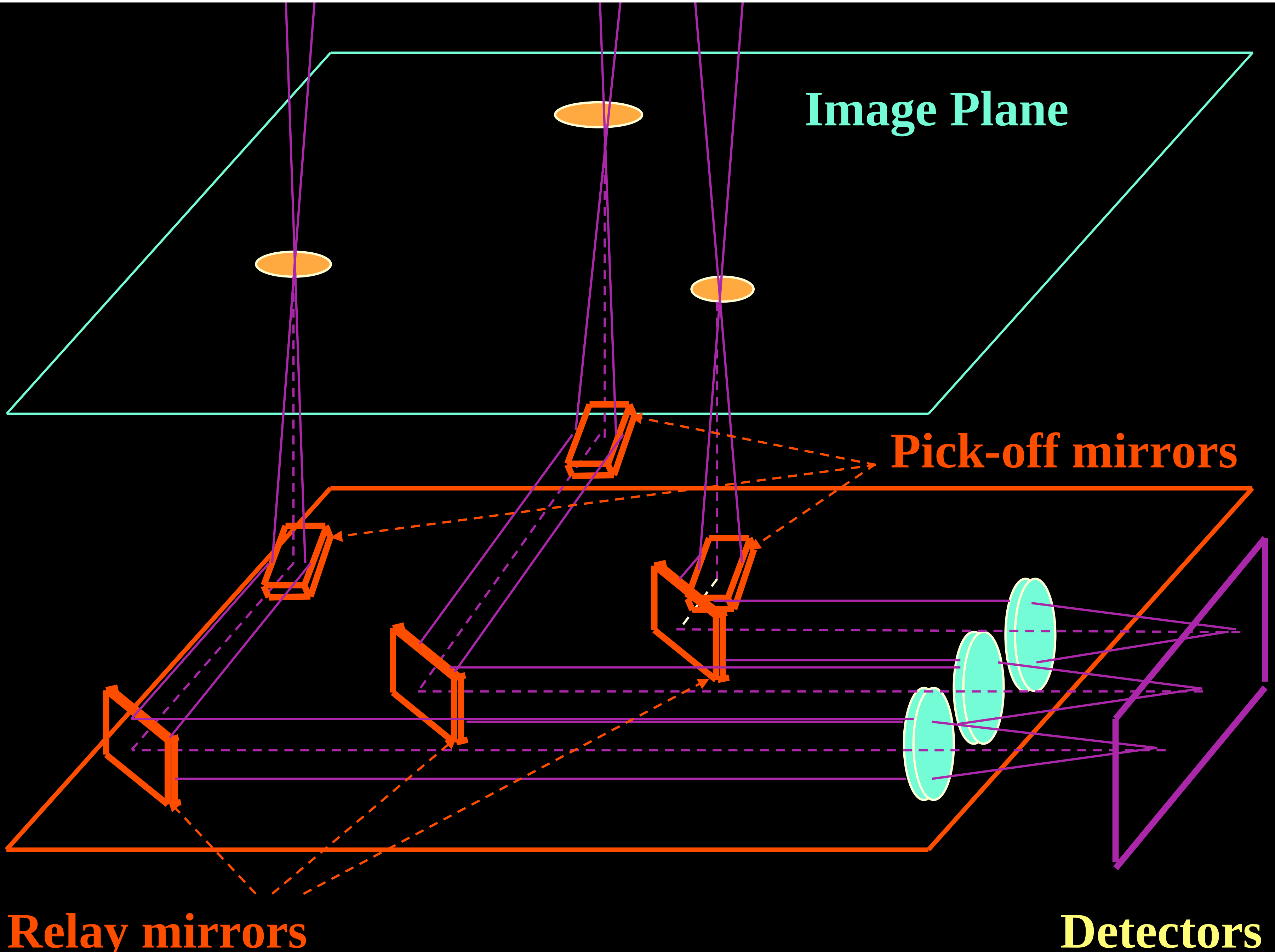
Gaussian Relays ("optical trombones")

Mirrors held by magnetic clamps
Re-configured by robot arm





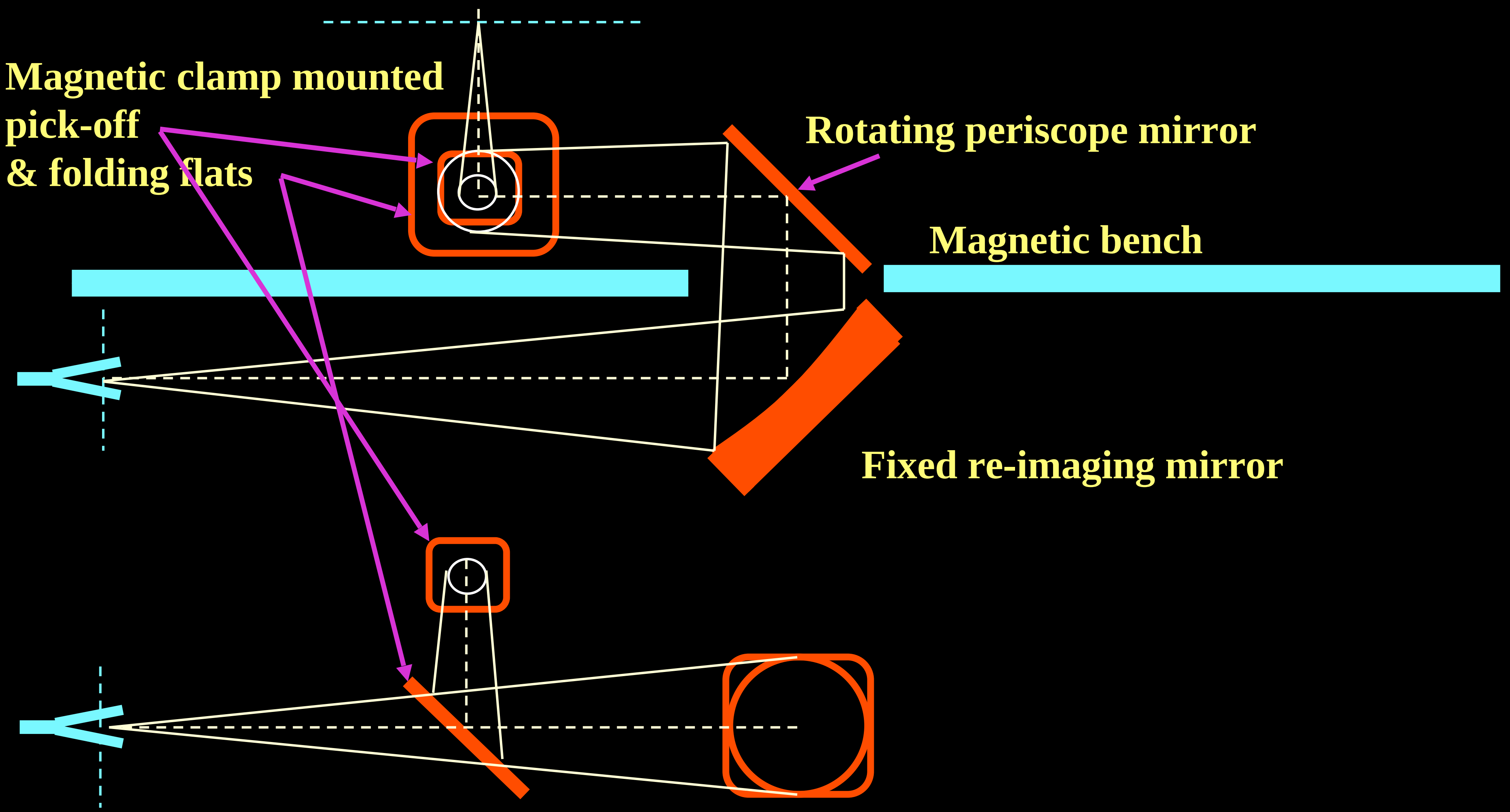
M1 "Parallel "beam
+ Y - axis steering M3
M2 X-axis steering flat
L3 Compensating lens



Flexible Feed (Target Randomly placed fields/objects)

Folded Re-imaging Relay

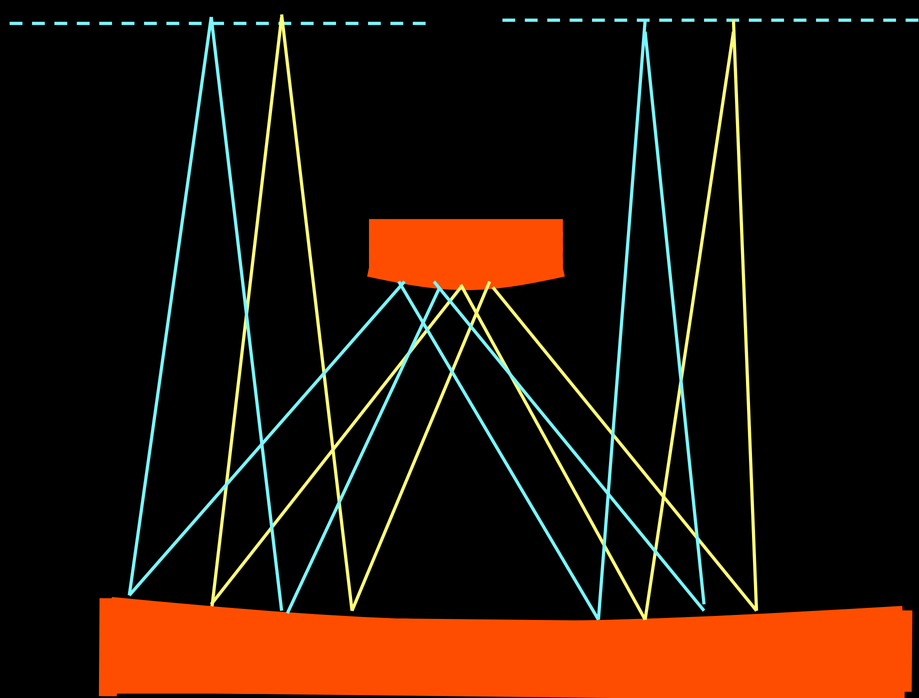
Robot-reconfigurable multiple imaging feeds



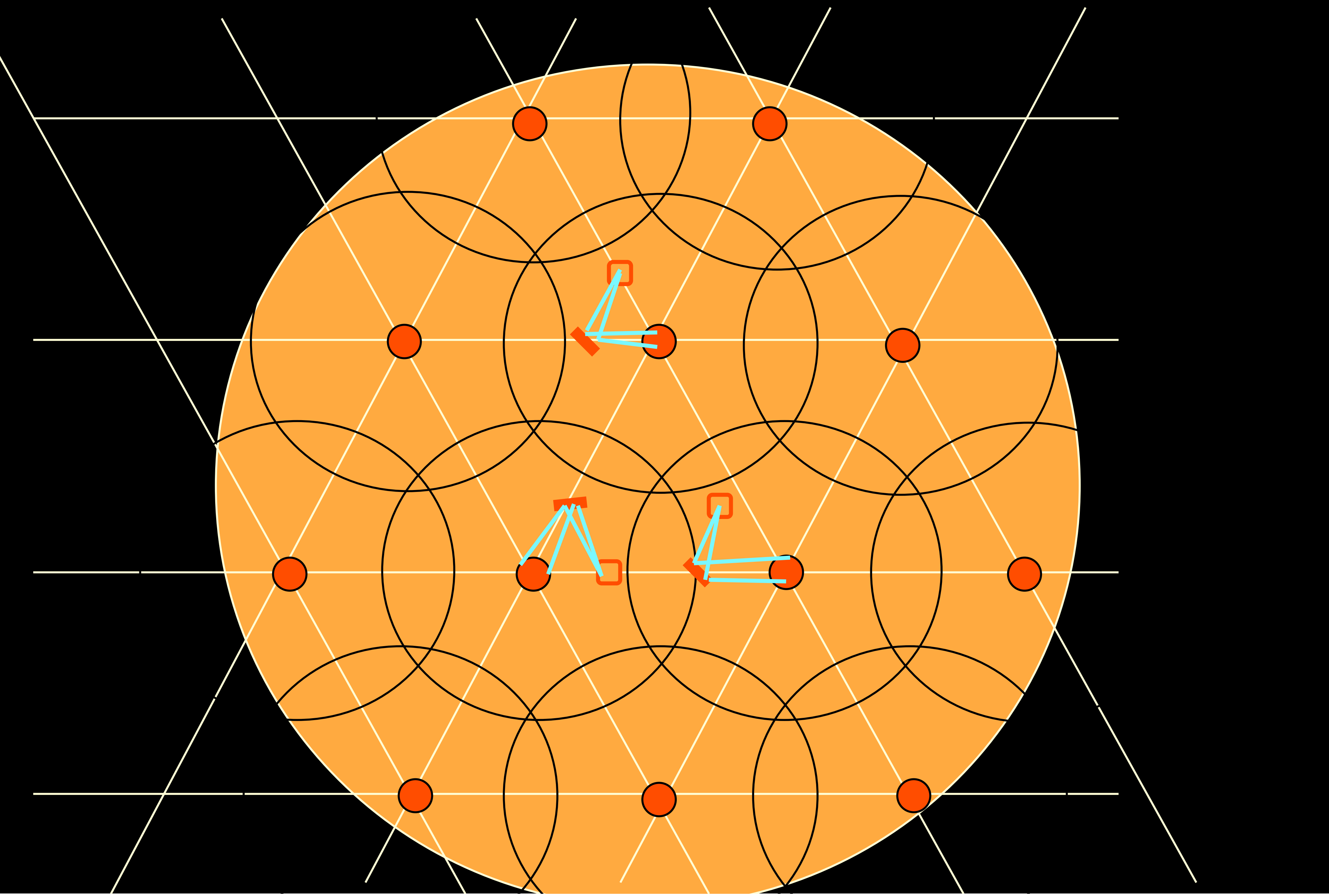
Optics Table Geometry: Offner Periscope

Offner Relay (e.g. Lithographic mask aligners)

- **1:1 image transfer with high fidelity**
- **All reflecting optics => low loss**
- **Wide, flat field**
- **Add flats to fold, and form periscope**



Optics Table Geometry: Offner Periscope



Conclusions

- Need MOS Capability on CCAT
- Two Types of Flexible Feed Geometry:

Reconfigure with magnetic clamps operated by robot arm

=> No linear actuators needed!

- Flexible Dielectric Waveguide (Glenn)
  Flexible Dielectric Fiber-bundle
  (mm-optical fiber - "fishing-line")
- Gaussian Optical Trombone
  (multiple point sources)
- Folded Offner Periscope:
  Multiple, randomly located imaging fields.

R ~ 5: Use image slicer to illuminate large Focal Plane Array
- or - Illuminate individual small FPAs

R ~ 10^3: Illuminate multi-order Z-Specs with linear MKID arrays (Simultaneous spectra in 2 windows)

R ~ 10^5: Illuminated heterodyne receivers /arrays


The End