Instrumentation for CCAT

Sunil Golwala/Caltech
May 13, 2011

on behalf of the CCAT Consortium

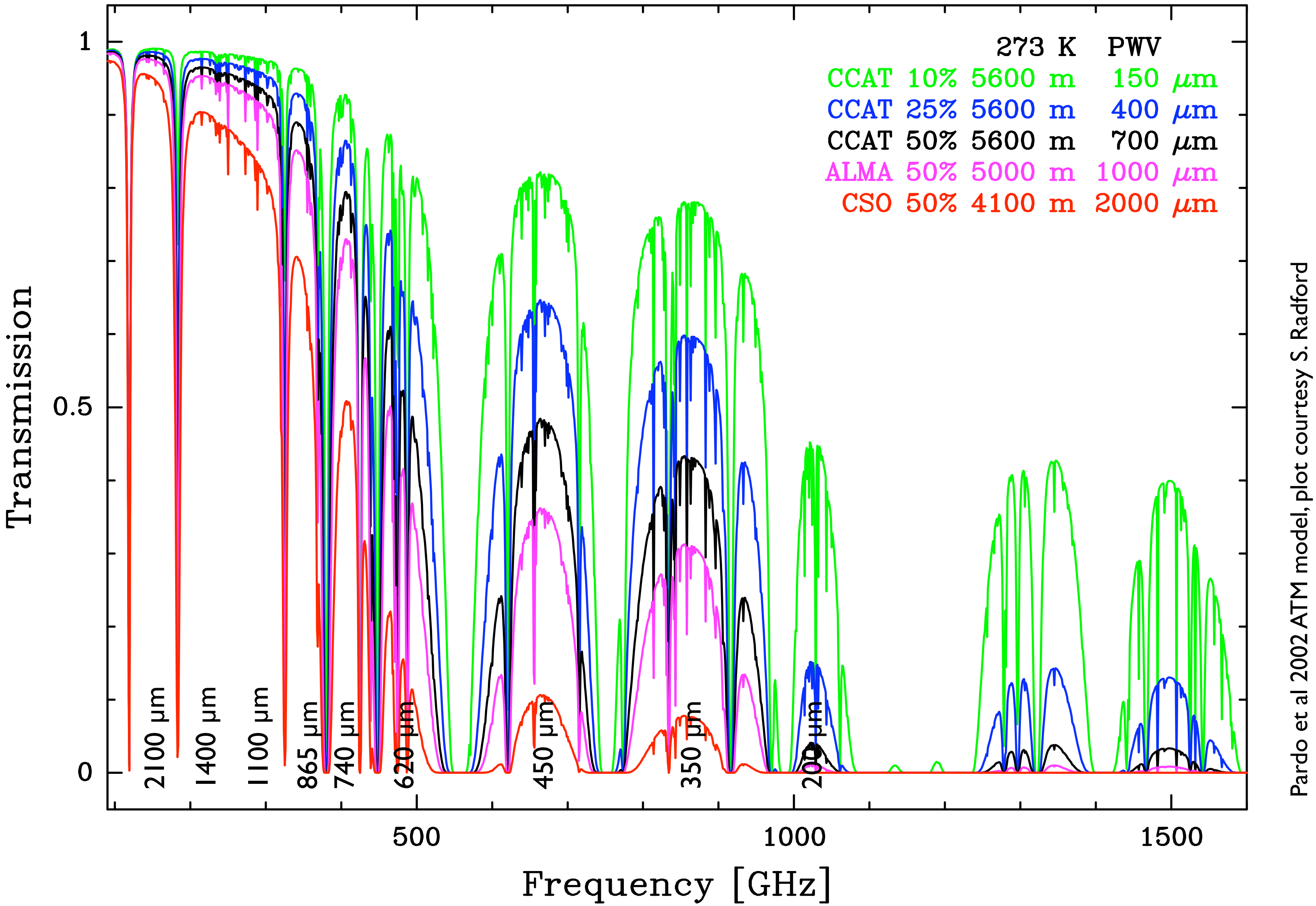
and with many thanks to
the CCAT science and instrument working groups

Tools for CCAT Science: First Light

- There is general consensus on what is needed for CCAT to do the most exciting science quickly:
  - Multicolor, broadband wide-field imaging with N ~ 10,000-50,000 and R ~ 3-10
    - Enough colors to measure SEDs of galaxies and do T/(1+z) selection of high-z sources
    - FoV large enough (= enough detectors) to yield high-statistics studies in multiple z bins
    - FoV wide enough to study clustering of ~confusion-limit sources on interesting scales
      - Criterion relaxes if one only wants to study clustering of high-S/N sources
    - *Not the ultimate photometric survey at first light*
      - Except perhaps at long λ where filling FoV is not challenging
  - Multi-object (N ~ 10) moderate resolution (R~1000) spectrometers
    - Focus is on sensitivity to CO and [CII] in very broad redshift ranges at R appropriate to velocity dispersions in high-z galaxies
    - Use SED and T/(1+z) selection to define target list for such followup

Tools for CCAT Science: Long-Term

- One person's view of what is needed for CCAT to do *definitive* science (given D = 25 m) during its lifetime:
  - Imaging large fractions of visible sky with FoV-filling cameras
    - Finding unique and rare objects
    - First serious study of transients in submm/mm
    - Not discussed here except to note that focal planes with 5×10^6 detectors are expected during CCAT lifetime
  - High spectral resolution heterodyne imaging spectroscopy in the galaxy and nearby galaxies
    - Wide-field mapping in many lines, with spectral resolution sufficient to separate dominant species, obtain infall information.
  - Imaging spectroscopy with N = 1000-10000, R ~ 100-1000, NxR ~ 5×10^6
    - N = 50,000 @ R = 100 for finer spectral bins for continuum SED studies in wide fields
    - N = 10,000 @ R = 1000 for definitive extragalactic imaging spectroscopy in smaller but cosmologically representative fields



273 K PWV
CCAT 10% 5600 m 150 μm
CCAT 25% 5600 m 400 μm
CCAT 50% 5600 m 700 μm
ALMA 50% 5000 m 1000 μm
CSO 50% 4100 m 2000 μm
Transmission
Frequency [GHz]
1
0.5
0
500
1000
1500
2100 μm
1400 μm
1100 μm
865 μm
740 μm
620 μm
450 μm
350 μm
200 μm
Pardo et al 2002 ATM model, plot courtesy S. Radford

Weather - Wavelength Allocation, Mappable Area

- best 30-50% devoted to "short submm" ($\lambda \leq 620$ μm)
- substantial fraction for "trans-mm" ($\lambda \geq 740$ μm)
  - focal plane technologies can obviate choosing between "long submm" and mm

Band λ (μm)	Band ν (GHz)	Time to CL[a] (hr)	Ref. PWV[b] (mm)	CCAT (5612 m) Time Available[c] (hr yr^{-1})	CCAT (5612 m) Time Available[c] (%)	CCAT (5612 m) CL fields[d] (yr^{-1})	1st light ∅FoV (')	area to CL (deg^2 yr^{-1})
200	1500	1248	0.26	281	3			
350	857	0.86	0.47	1936	22	2244	7	26
620	484	1.14	0.64	716	8	629	13	23
740	405	0.43	0.75	639	7	1488		
865	347	0.28	0.86	1223	14	4413	20	319
1400	214	0.30	1.00	1517	17	5093	20	436
Total time for PWV < 1.1 mm:				6312	72			

[a] Time to reach the confusion limit (CL) – see Table 2.

[b] The reference precipitable water vapor (PWV) is the adopted maximum value for observations in a given wavelength band. Several bands have equivalent thresholds (e.g. 350/450 μm) and for simplicity only one band is listed.

[c] Time available at Ref. PWV or better, not already used at lower λ.

[d] Number of confusion-limited fields per year.

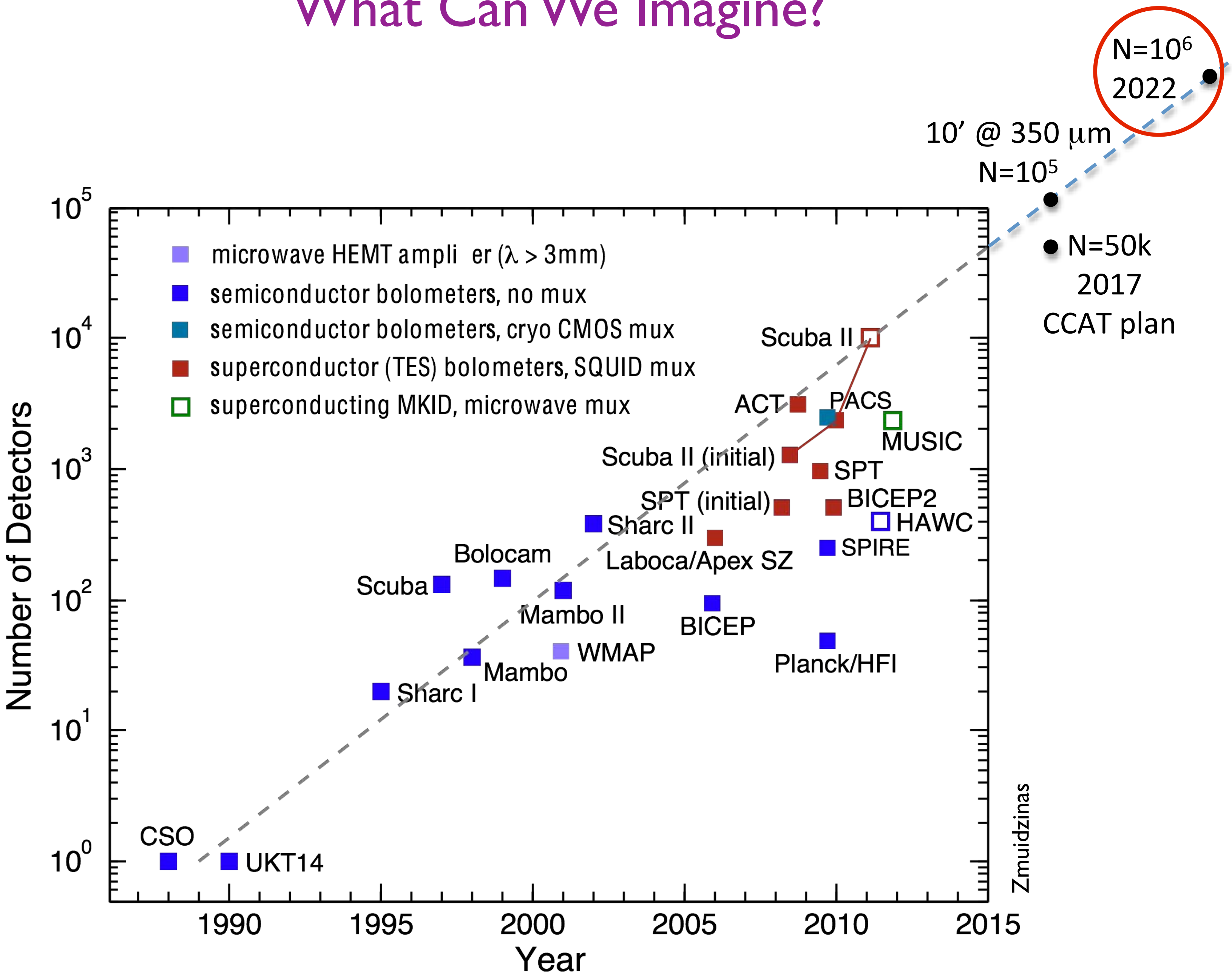
first-light access to cosmological volumes:
access to largest structures,
beat down cosmic variance

(assumes ~50 kpix/band)

c.f.: CSO typically does 350 μm observations in 20-25% of time with PWV ≲ 1 mm; CCAT much better!

CCAT facility submission to Astro2010

What Can We Imagine?

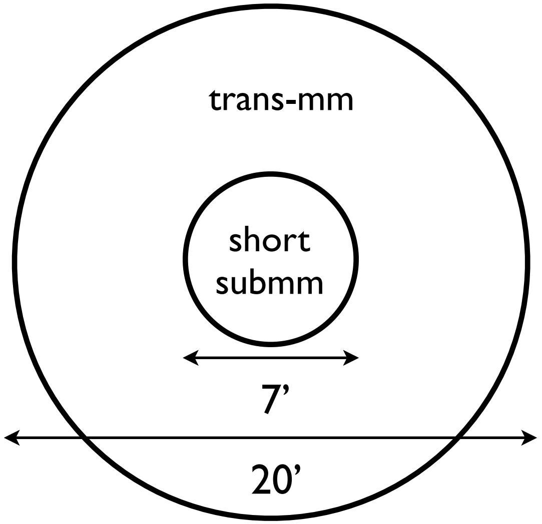


Why to Focus on Multi-Object Spectroscopy

- CCAT is being designed for maximum FoV possible
  - Don't want to preclude future developments
  - Minimal Δ$ for FoV up to 1°
- But cosmological volumes and high stats accessible w/first-light cameras
  - 10s of deg^2/yr at 350 μm w/7' FoV: 38,000 srces/deg^2, 10^6 srces/yr
  - 100s of deg^2/yr at 1.4 mm w/20' FoV: 2,400 srces/deg^2, 10^6 srces/yr
  - >> 10^4 galaxies needed to measure lum. f'n over $1 < z < 5$ in 10x10 bins in (Δz, $\Delta \log(L)$) (c.f., Glenn talk): basic imaging studies easily done
- Bottleneck quickly becomes spectroscopic followup needed to
  - Obtain precise z
  - Measure physical conditions in gas, reveals cooling and excitation mechanisms, ionizing photon flux, etc.
- Conclusion: *Use the detector revolution in the spectral dimension*
  - need MOS immediately: N = O(10) @ R = 1000 in multiple bands
  - MOS development will provide quickest evolution of capabilities: not just more area, but qualitatively more interesting science: $N \times R = 5 \times 10^6 \rightarrow N = 10{,}000$ @ R = 1000, N = 50,000 @ R = 100

Imager Strategy

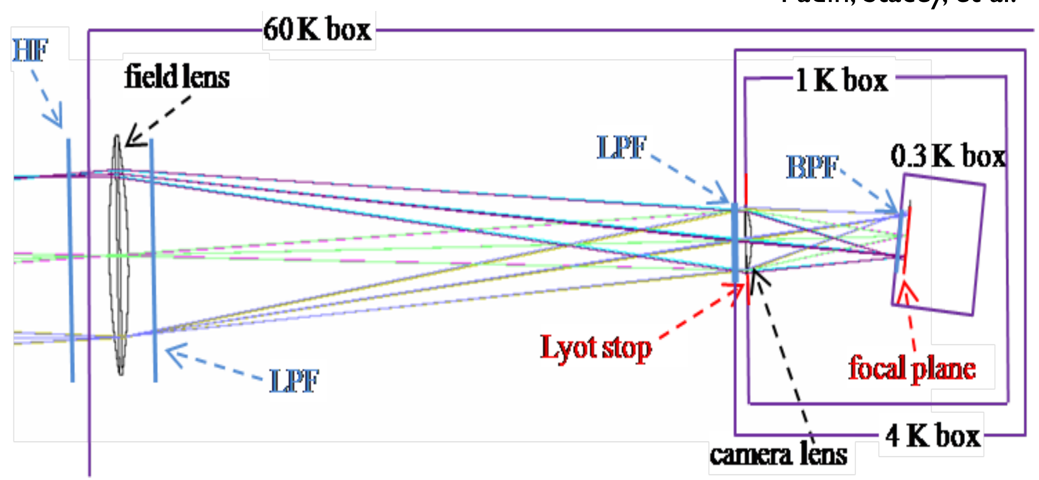
- Drivers
  - Color information is more useful than higher statistics in particular bands
  - At shorter λ, filling FoV is technically challenging. 1° @ 350 μm = 4 Mpix!
- Could do the usual thing and put one instrument on at a time...
- ...or, possibly novel strategies:
  - Split FoV by color?
    - Central, higher-image-quality region used for short-submm imaging,
      λ = 350 μm – 620 μm (200 μm?)
    - Outer regions used for trans-mm imaging,
      λ = 740 μm – 2000 μm (3000 μm?)
    - Enables simultaneous imaging in all colors at once:
      no need for weather splits in survey mode
      = Planck at 10-20x the resolution on sub-arcminute to degree scales
  - Alignment/overlap?
    - FoV is large enough to have separate cameras for individual bands
    - But sky noise could motivate spatial overlap
      - short-submm: use mesh dichroics
      - trans-mm: wide-bandwidth feeds and microstrip bandpass definition

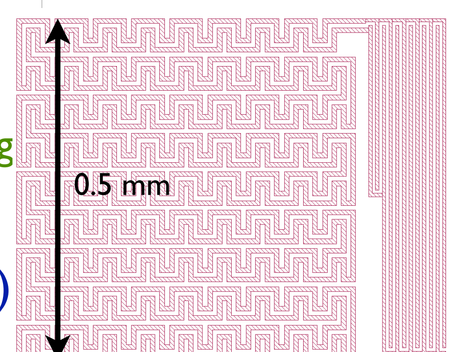


Short-Submm Imager

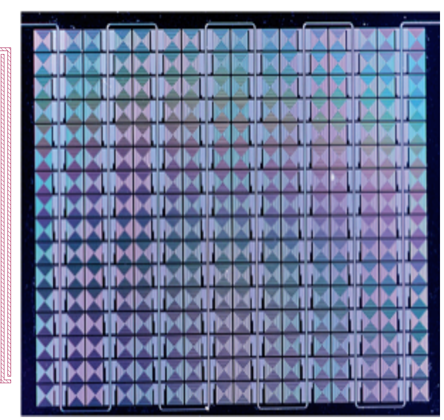
- All transmissive design
  - Compact, minimizes aberrations (vs. off-axis powered reflective relay)
  - Transmissive losses acceptable at shorter λ
- Substantial pixel count
  - Nyquist sampled, 40 kpix @ 350 m, 20 kpix @ 620 μm
  - Three 3' subfields (128×128): minimizes aberrations and window size
  - Could use dichroic in dewar to overlap arrays on sky
    - Need broadband anti-reflection coating
- Detectors
  - SCUBA-2 TESs: proof of principle (10^4)
  - Absorber-coupled TiN MKIDs in dev't to minimize readout complexity, cost

Padin, Stacey, et al.





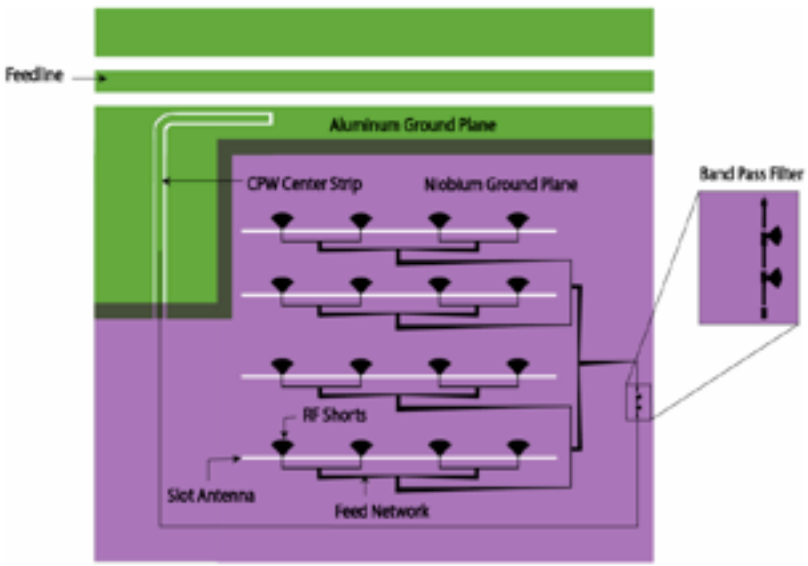
Lumped-element direct-absorption TiN MKID 350 μm pixel w/ spiral inductor/absorber and interdigitated capacitor



16×16 array of such pixels coupled to one microwave feedline

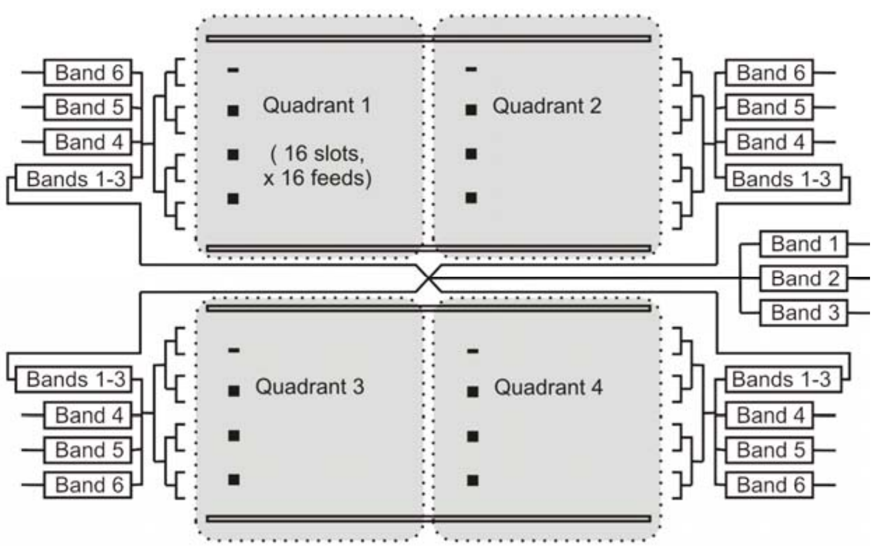
Trans-mm Imager

antenna-coupled pixel

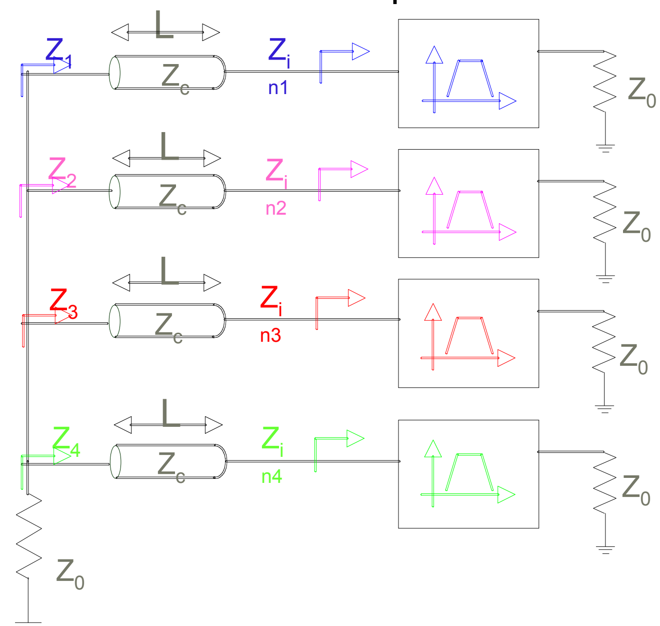


- Antenna coupling v. attractive
  - hν < 2Δ of niobium (440 μm): superconductors enable microwave engineering at trans-mm λ
  - Pixel size can be rescaled to match diffraction spot size
  - 4:1 spectral reach: monolithic FP covers 740 μm to 3000 μm

multi-scale pixel

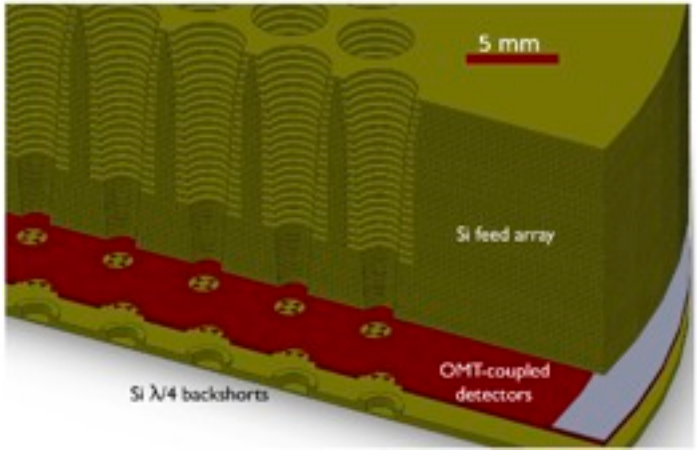


multi-color bandpass filters



Trans-mm Imager

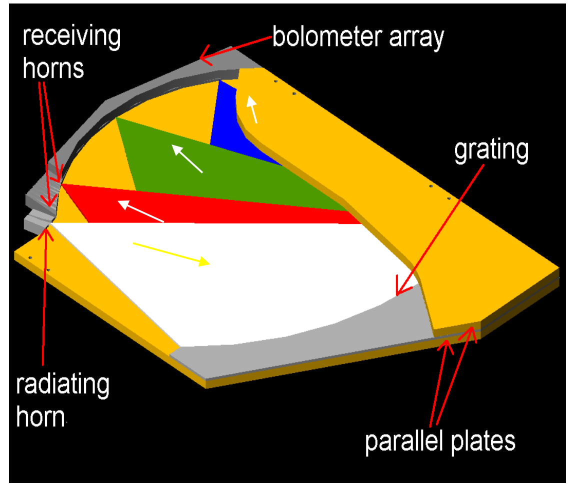
- Horn-coupled designs
  - Broadband horns for submm/mm under design (McMahon (UM), NIST)
  - Micromachining and platelet arrays enable monolithic mass manufacture
  - Use waveguide probes to feed detectors, similar filters to select colors
  - Use mesh dichroics to split colors to different horn sizes



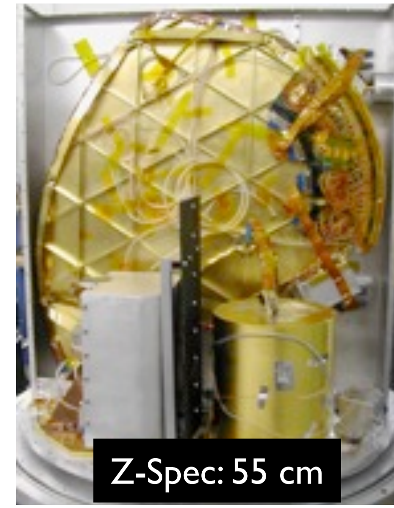
- Optical configuration
  - Aim for ~20'-equivalent FoV with transmissive lens focal reducer and ~30 cm diameter lenses (silicon). Perhaps in multiple subcameras à la short-submm.
  - Need to develop broadband anti-reflection coatings.
- Detectors
  - Both TESs and MKIDs present good options. Pixel counts at mm bands comparable to SCUBA-2 if conservative on sampling at longer wavelengths (i.e., low spillover), short-submm-like if want Nyquist sampling at λ = 740 μm.
  - See Sayers talk on MUSIC (Saturday 9:45): CSO-based prototype for antenna-coupled MKID-based trans-mm imager.

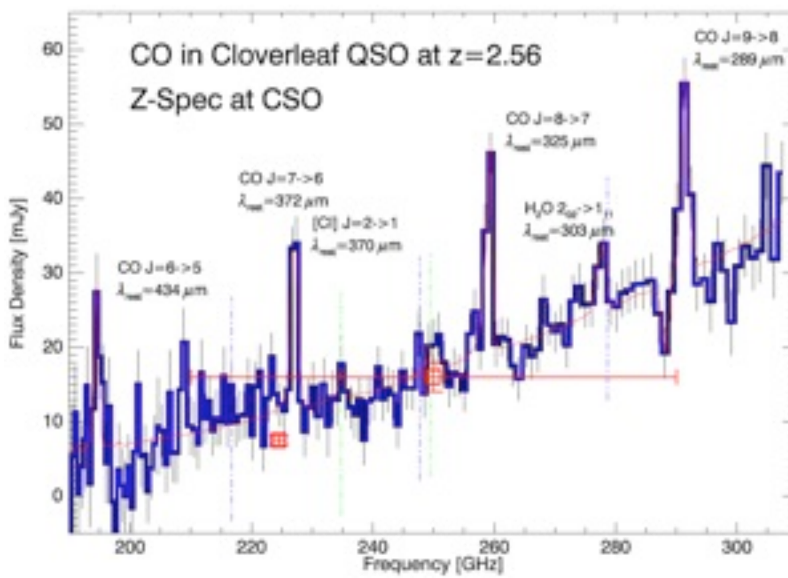
Waveguide-Grating Spectrometers

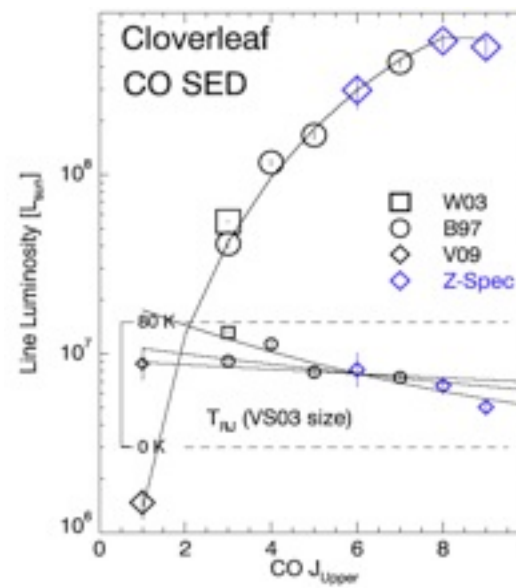
- Disperses light from single input feed in 2D waveguide structure, grating at edge
- Demonstrated at R~300 w/Z-Spec on CSO in 1-1.4 mm window
- v. nice detection of CO ladder, water in Cloverleaf, CO in lensed H-ATLAS srces
- Access to [CII] at z = 5-7 on CCAT



Bock, Bradford, Glenn, Zmuidzinas



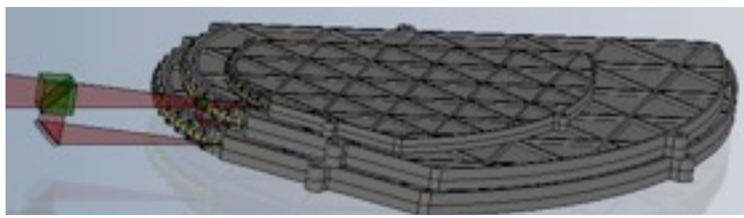


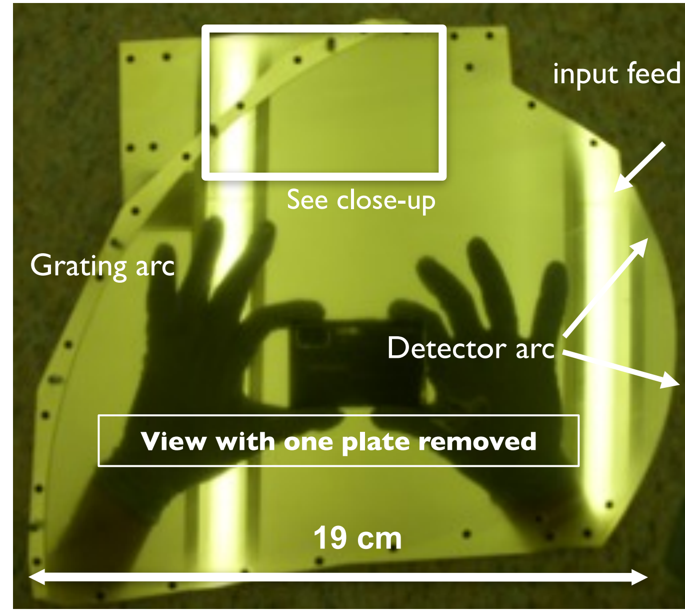


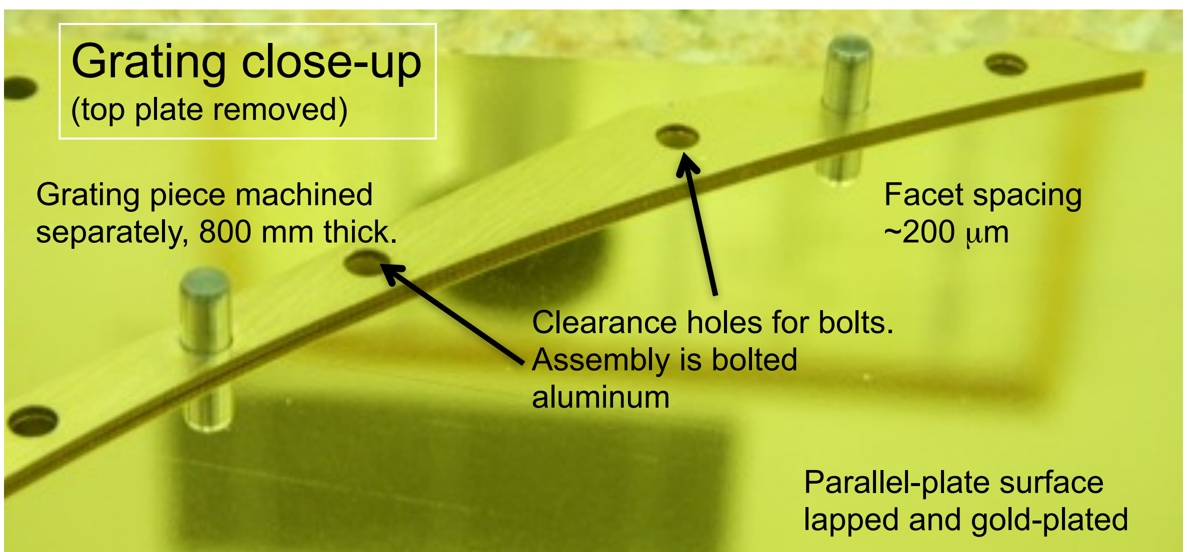
Waveguide-Grating Spectrometers

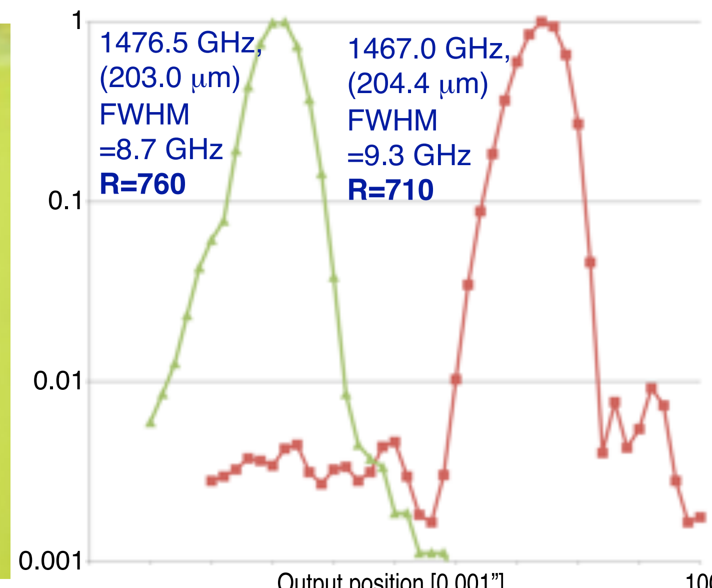
Bradford, Hodis

- Z-Spec can be scaled to shorter wavelengths
  - prototype for 180 - 300 μm band of BLISS: R > 700 achieved, 60-70% efficiency warm
- More compact 1-1.4 mm version using Si
- Dichroics to match atmos. windows
- Stackable N = O(10)



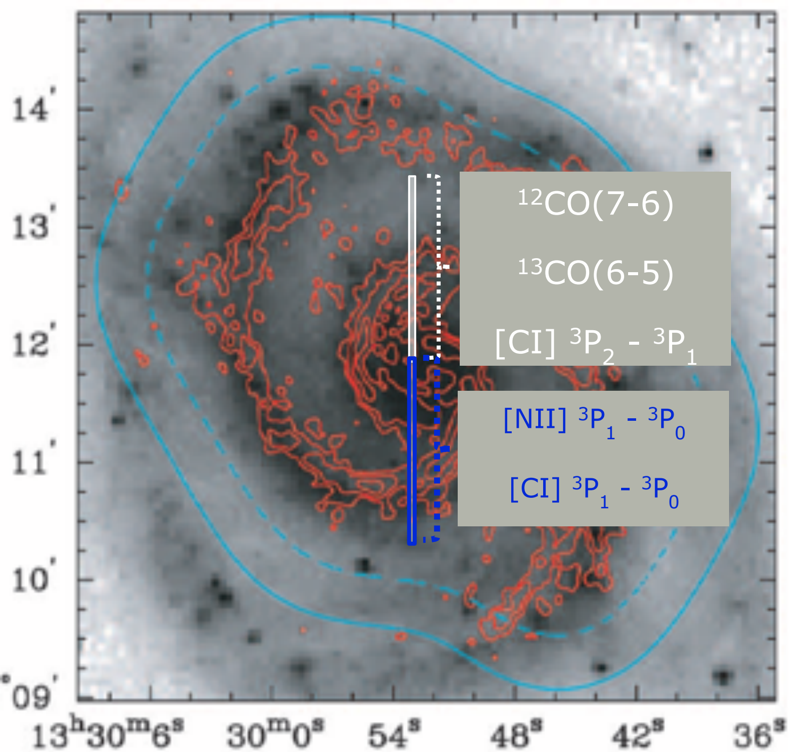






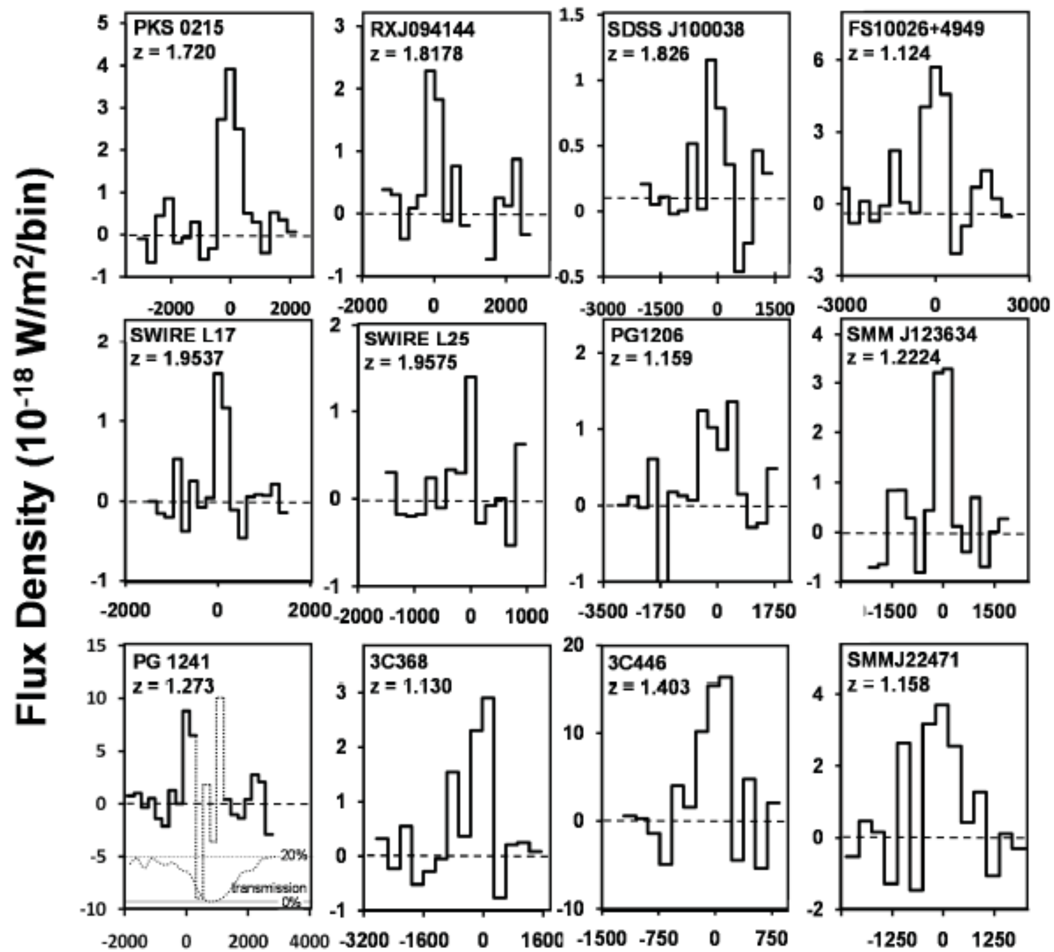
Free-Space Grating Spectroscopy

- ZEUS-2: long slit + grating spectrometer R ~ 1000, ~1000 detectors
- Route different objects over slit to do MOS



M51 - CO(1-0): BIMA Song (Helfer et al. 2003)

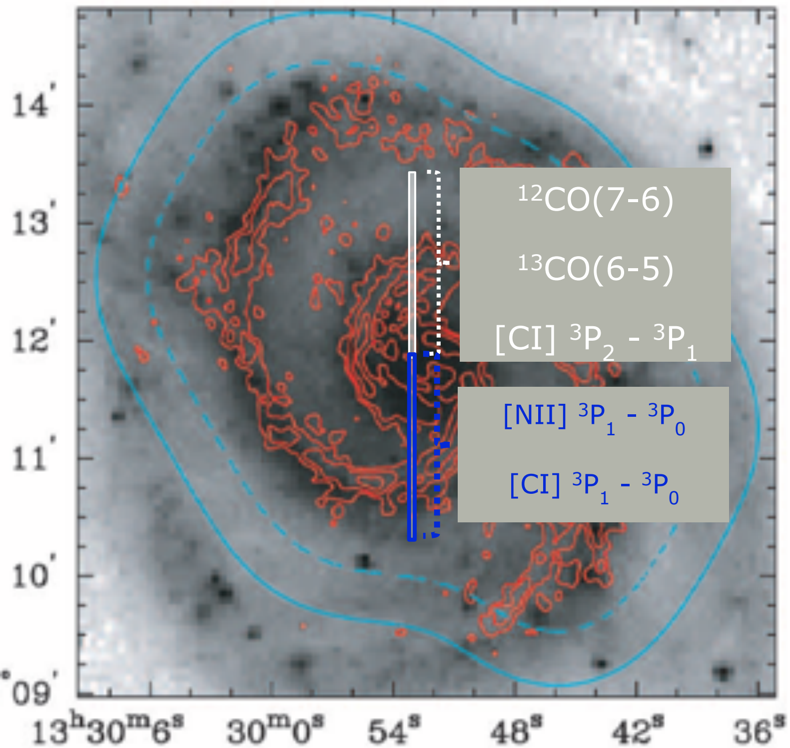
[CII] detections in z = 1-2 starburst galaxies by ZEUS @ CSO



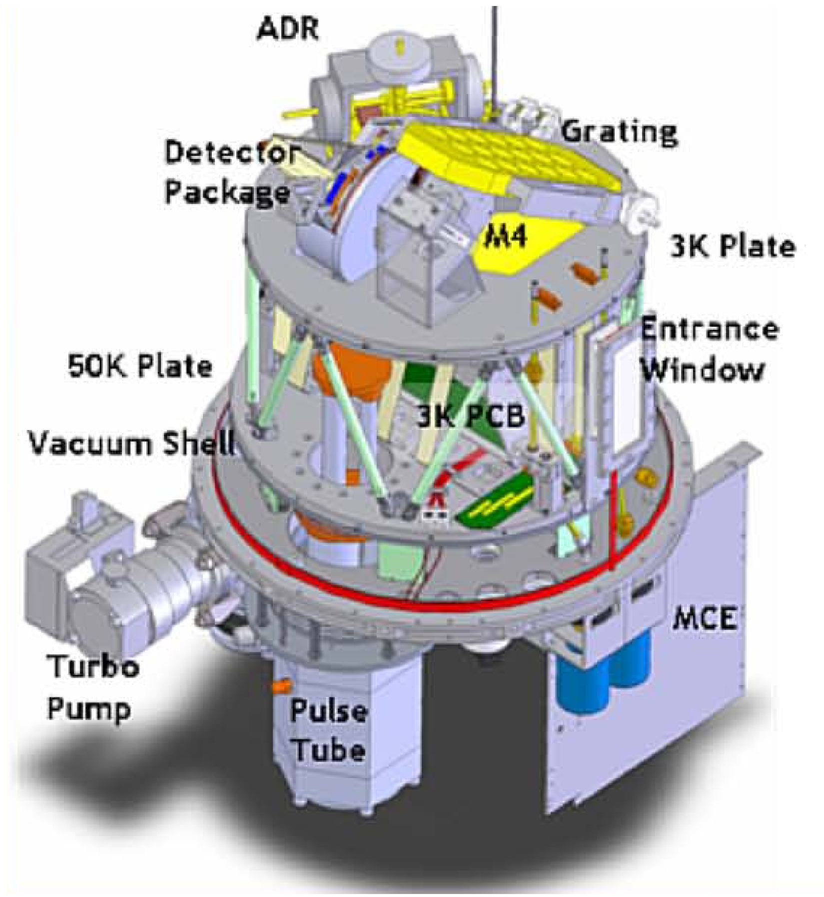
Stacey et al 2010

Free-Space Grating Spectroscopy

- ZEUS-2: long slit + grating spectrometer R ~ 1000, ~1000 detectors
- Route different objects over slit to do MOS

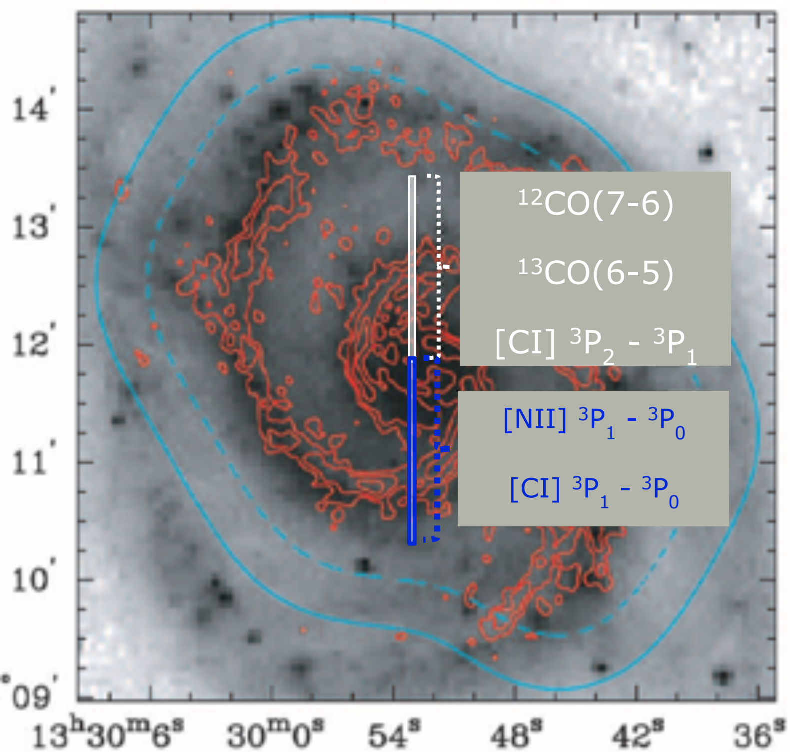


M51 - CO(1-0): BIMA Song (Helfer et al. 2003)

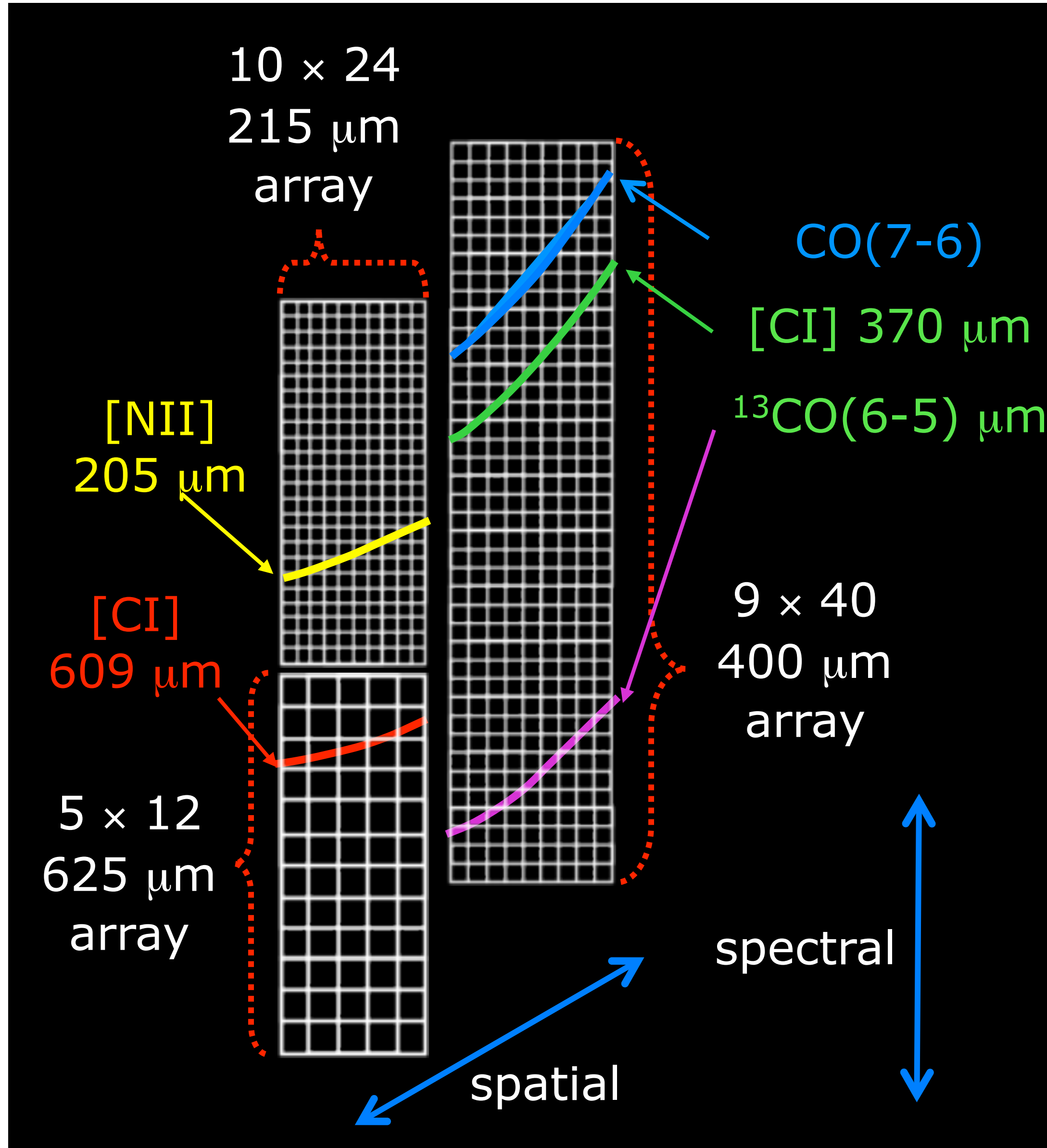


Free-Space Grating Spectroscopy

- ZEUS-2: long slit + grating spectrometer R ~ 1000, ~1000 detectors
- Route different objects over slit to do MOS

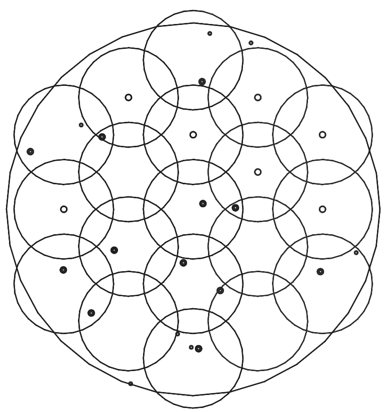


M51 - CO(1-0): BIMA Song (Helfer et al. 2003)

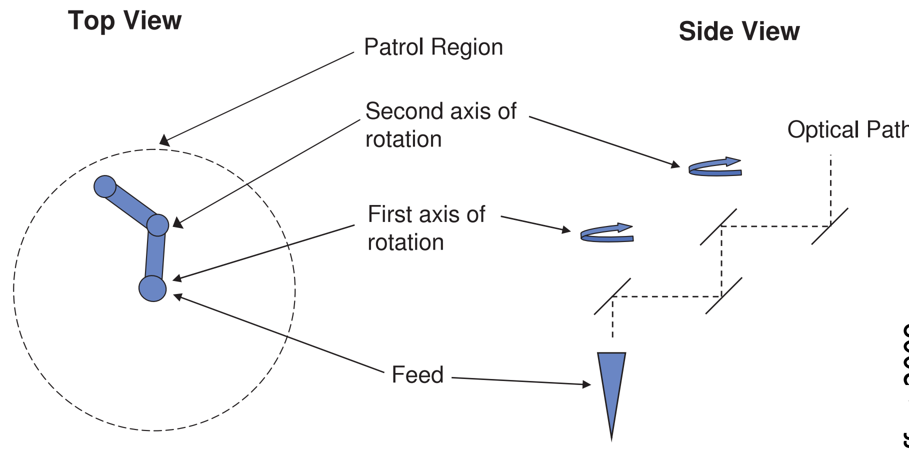


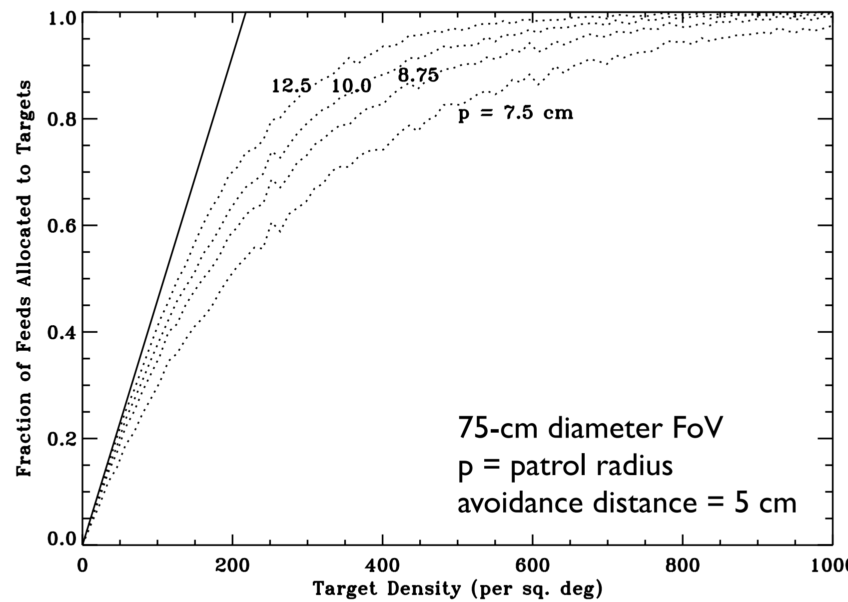
Multi-Object Optical Coupling

- Periscope-based patrol mirrors
  - quasi-optical coupling, all reflective, send to array of feeds for Z-Spec or ZEUS slit
  - e.g.: N ~ 20 over 20' FoV



- Flexible waveguide
  - Hollow, interior-metallized polycarbonate tubes
  - Being pursued by CU (Glenn, Maloney)

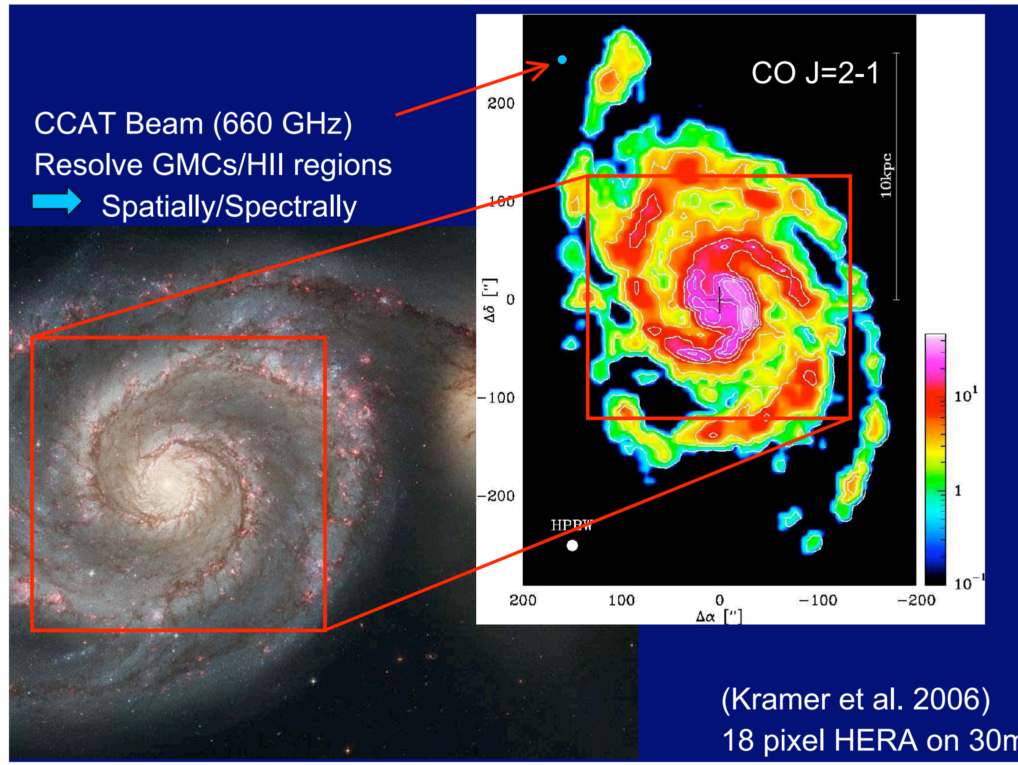




Goldsmith and Seiffert 2009

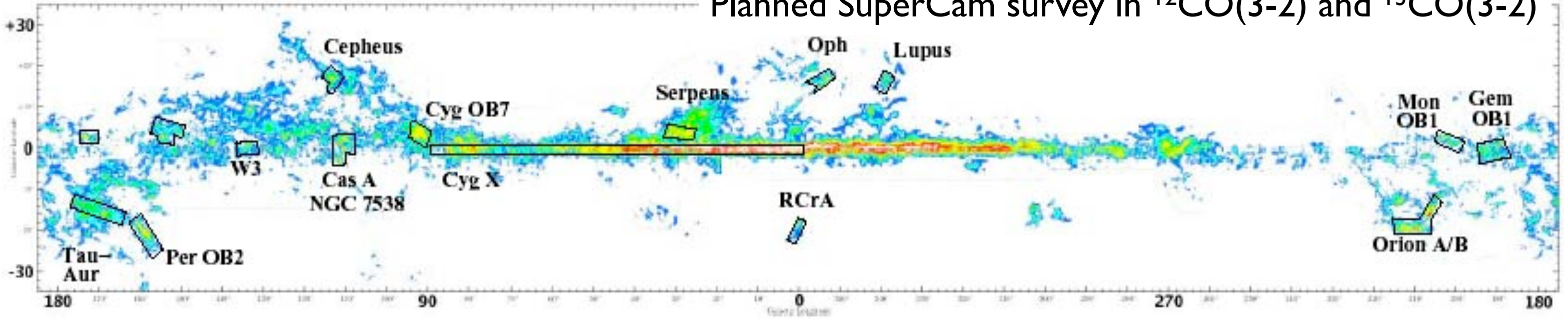
High-Resolution Imaging Spectroscopy

- Heterodyne arrays in use and under development for galactic mapping
  - HERA/IRAM 18 pixels, 1-1.4 mm window, 1 GHz/pixel
  - SuperCam for SMT, 64 pixels, 865 μm window, 250 MHz/pixel
- Kilopixel array for CCAT
  - 16 x 32 array, 2 GHz/pixel, 350 μm and 450 μm windows
  - Mapping our and nearby galaxies in multiple lines at $R \sim 10^6$



Walker

Planned SuperCam survey in $^{12}CO(3\text{-}2)$ and $^{13}CO(3\text{-}2)$

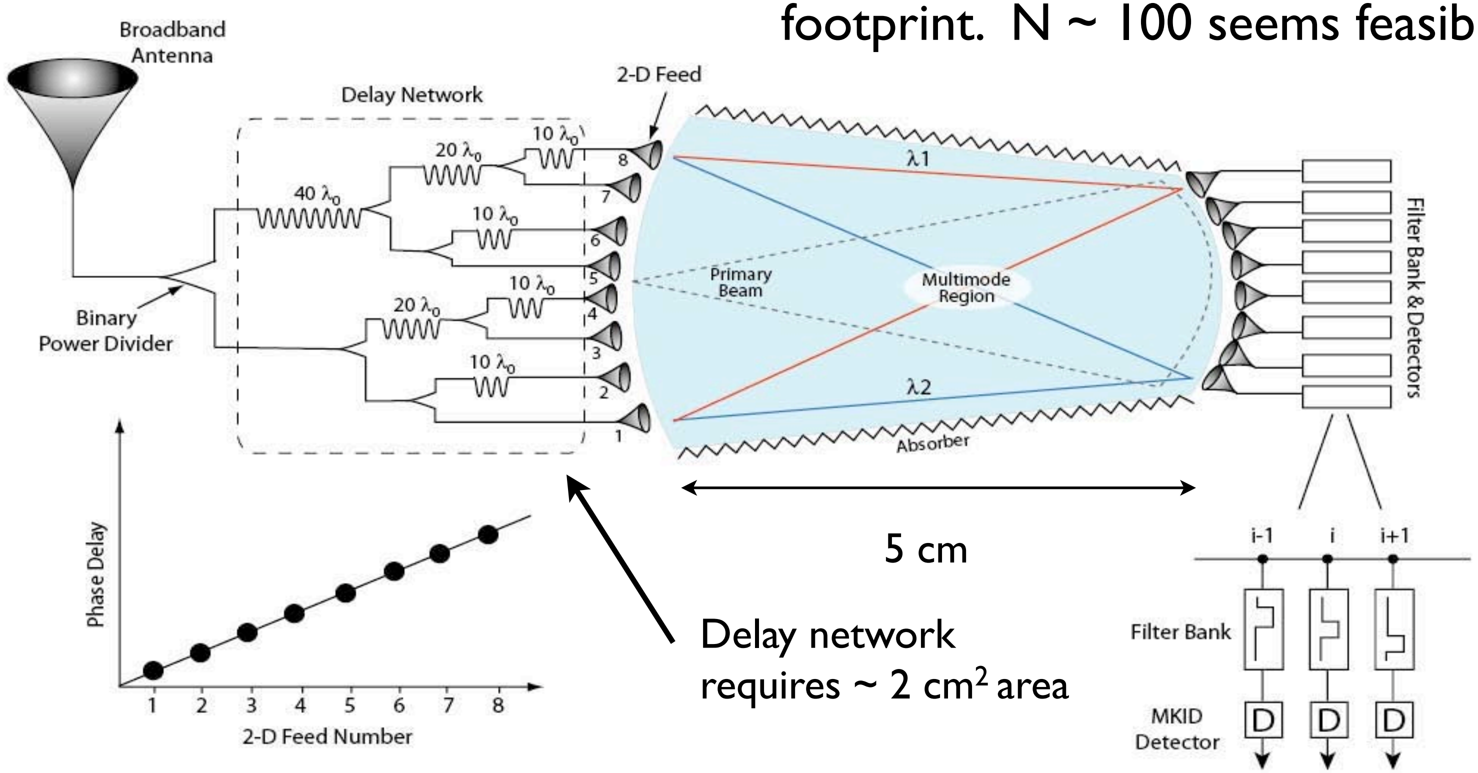


Long-Term: Supporting Developments

- Broadband antireflection coatings to enable multicolor focal planes
- Image slicer: would enable "imaging ZEUS"
- Higher T_c superconductors
  - Split between quasi-optical/free-space waveguide and antenna/dielectric microstrip techniques set by 2Δ for niobium at λ = 440 μm
  - Development of high-Q higher-T_c superconductors (e.g., NbTiN) would enable extension to 450 μm and 350 μm bands.
- RF-muxed microwave SQUIDs
  - Would enable MKID-like multiplex factors for TESs
- Alternate MKID geometries
  - silicon-on-insulator capacitors to reduce dielectric fluctuation noise (and possibly direct pickup)
  - lower-frequency MKIDs (100s of MHz to 1 GHz) + SiGe amplifiers
  - "resonator bolometers": use MKID to measure temperature of leg-isolated island à la TES bolometers
- Readout development
  - This will be the driver for pixel count and instrument cost.

Long-Term: Innovative Imaging Spectrometers

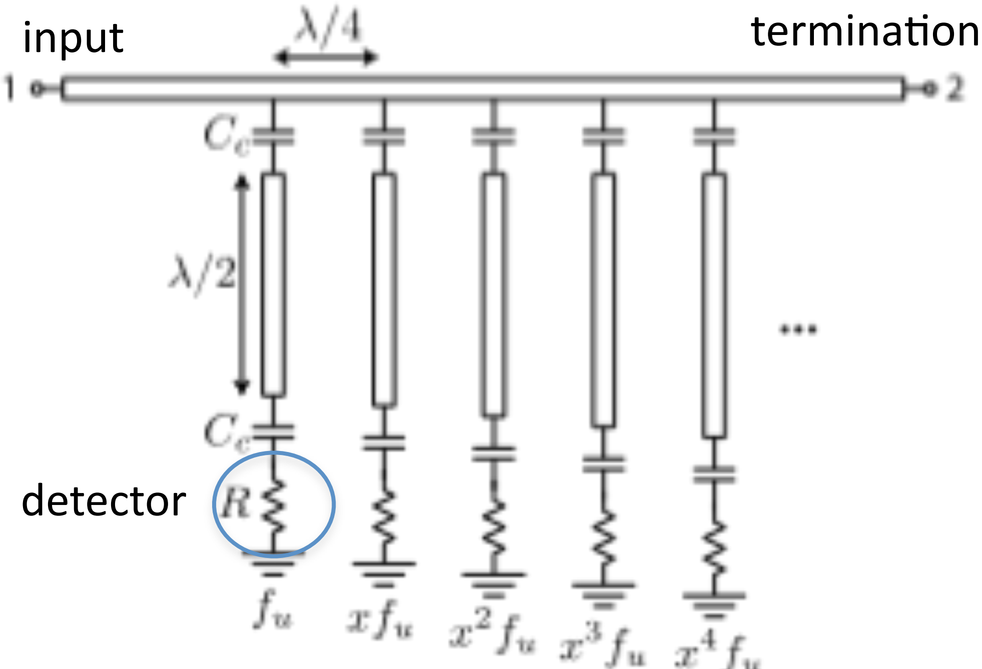
- µSpec "spectrometer on a chip", R ~ 1000
  - Z-Spec-like idea, but do initial delay in microstrip rather than in waveguide; no physical grating required. Gives multiple orders at each exit feed.
  - Sort orders using filter banks on exit feeds.
- With low-loss microstrip from feed (e.g., crystalline Si), could build a horn or antenna array to feed off-FP spectrometers and accommodate µSpec footprint. N ~ 100 seems feasible.



Moseley et al (GSFC)

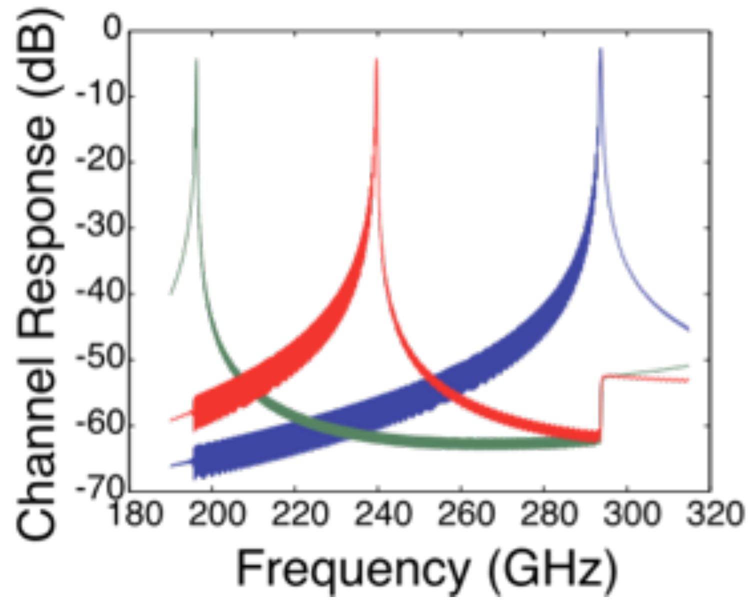
Long-Term: Innovative Imaging Spectrometers

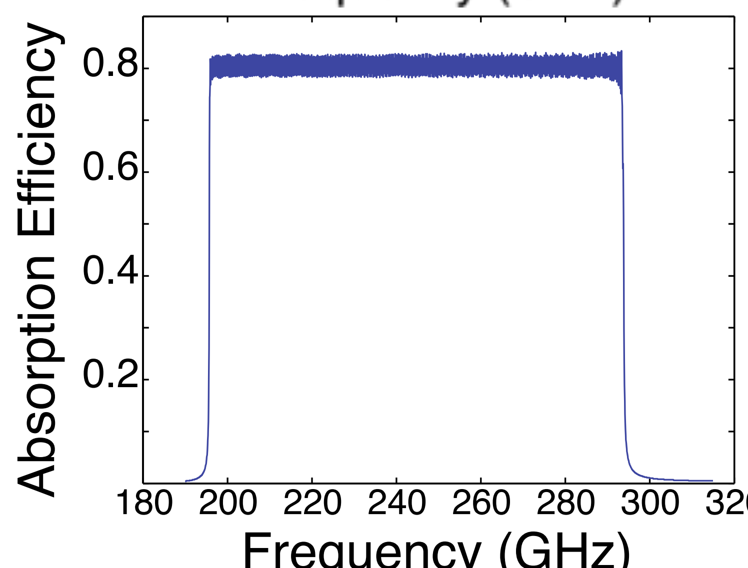
- Use mm-wave resonators to define R ~ 1000 channelizer
- Can be fed directly from horn or antenna
- Compact: can live on FP with feeds



$$A_{\text{total}} = N\left(\frac{\lambda^2}{8} + A_{\text{det}}\right)$$

$$A_{\text{total}} < 1\ \text{cm}^2 \text{ for } R = 700,\ \lambda = 1\ \text{mm}$$





Kovacs & Zmuidzinas, 2010

Conclusions

- Seems technically feasible to develop instrumentation that delivers the critical science at first light.
  - Imaging needs well within reach with 10^4-10^5 pixel counts.
  - Single-pixel Z-Spec spectrometer needs to be extended to short-submm and multiplied by N ~ 10.
  - Need MOS feed system
- Imagers will eventually grow to 10^6 pixels and map large fractions of visible sky across submm/mm bands
- Innovative concepts and new developments will provide CCAT with ever-growing capabilities for spectroscopy
  - Important supporting device and readout developments
  - Heterodyne imaging spectroscopy at R ~ 10^6 and N ~ 1000 for our and nearby galaxies.
  - Direct detection imaging spectroscopy at RxN ~ 5×10^6 for mapping large extragalactic fields