A Review of Some Superconducting Technologies for AtLAST:
Parametric Amplifiers, Kinetic Inductance Detectors, and on-chip Spectrometers

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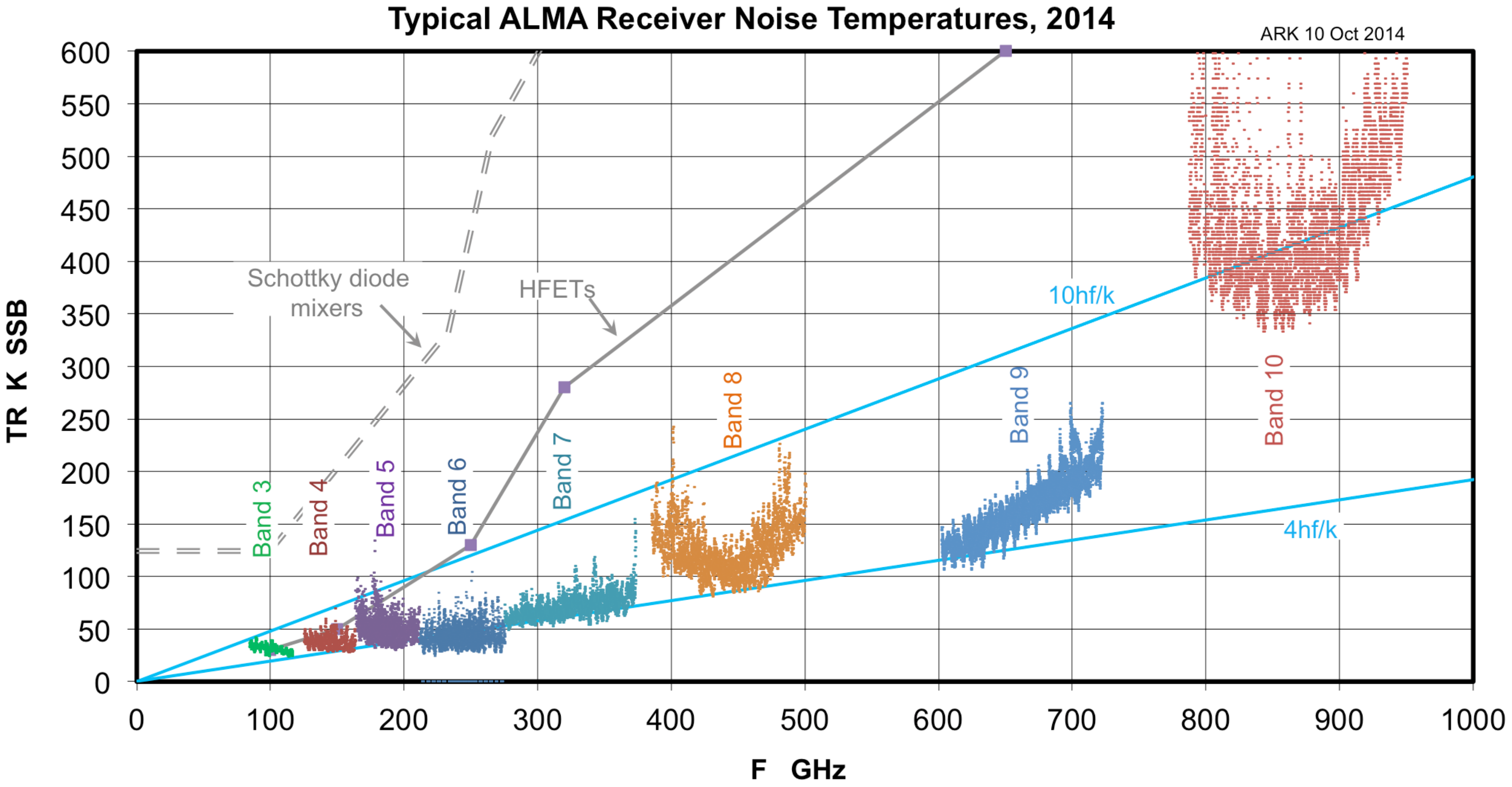
JHU/STScI:
Klaus Pontoppidan

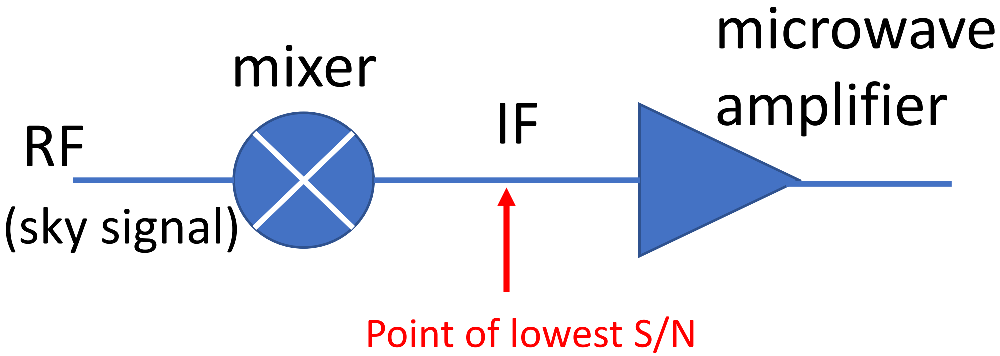
ALMA receiver performance: room for improvement



Credit: Tony Kerr

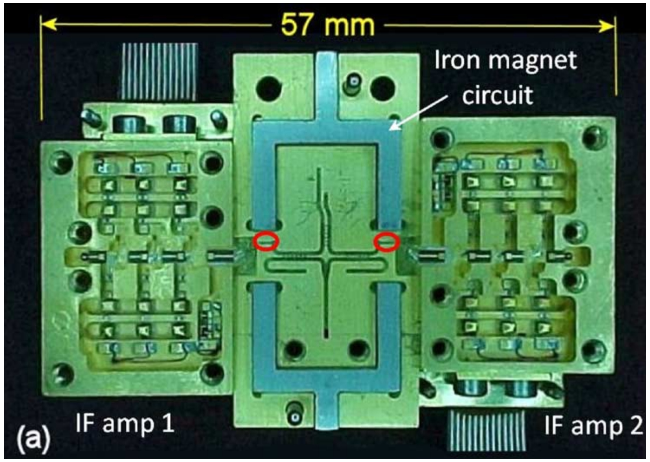
SIS receiver sensitivity limits

- SIS heterodyne *mixers* are primarily limited by tunneling shot-noise from the local oscillator, and are nearly quantum-noise-limited, which is great!
- But the frequency conversion process from RF to IF in mixer is lossy and reduces S/N at the input of the IF amplifier.



Point of lowest S/N

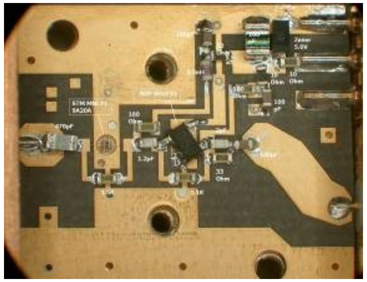
Band-6 SIS mixer + IF amplifiers



- Therefore the IF amplifier must have very low noise level to not further reduce the signal integrity.
- *Achieving a low IF noise over a wide bandwidth is the fundamental reason why SIS receiver instantaneous bandwidth has been limited to ~ 10 GHz using current amplifier technologies.*

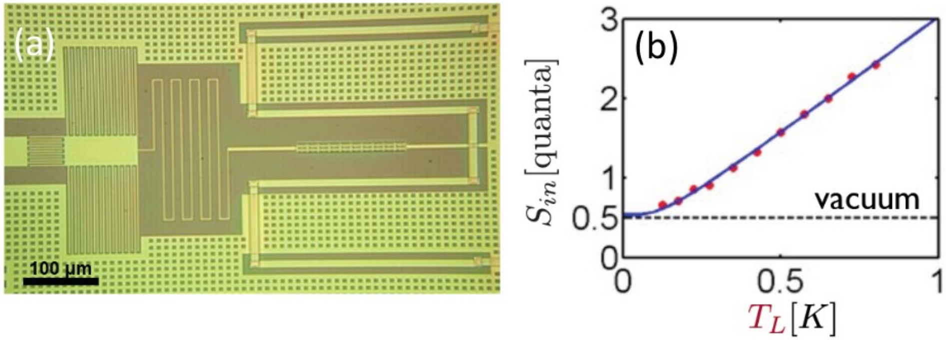
Current technology options for low-noise microwave amplifiers

1. Transistor-based cryogenic amplifiers: HEMT, SiGe
   - Broadband, High dynamic range
   - Best Noise $\lesssim 5 \times h\upsilon/k \sim 2.5$ K (@10 GHz)
   - 4–15 K operation temperature



0.5-4 GHz SiGe, S. Weinreb (Caltech)

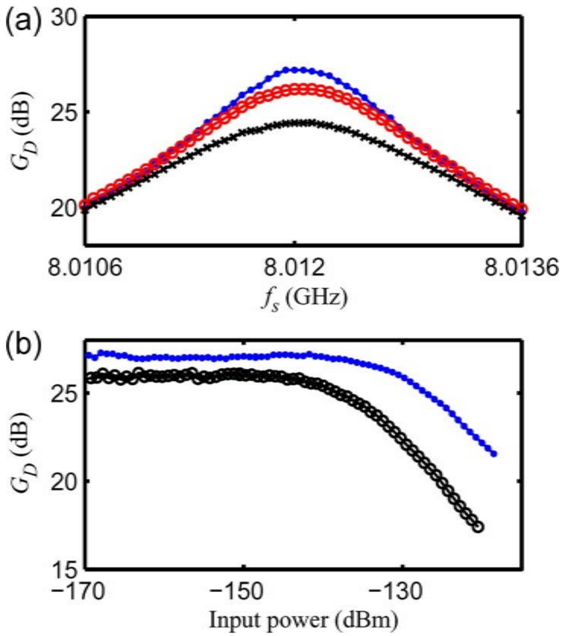
2. Superconducting tunnel-junction-based parametric amplifiers
   - Demonstrated to be truly quantum-limited (Noise ~ $h\upsilon/k \sim 0.5$ K (@10 GHz)



- Disadvantages:

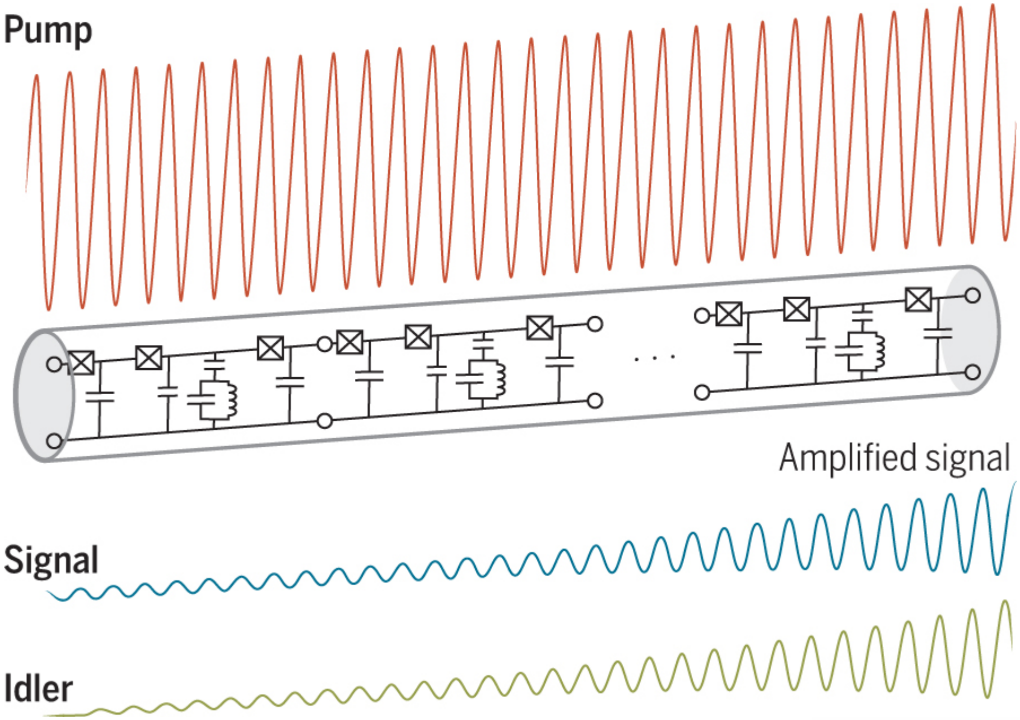
a) Resonant tuning-based → narrow-band (~10 MHz)

b) Very low input dynamic range due to junctions (<-100 dBm)

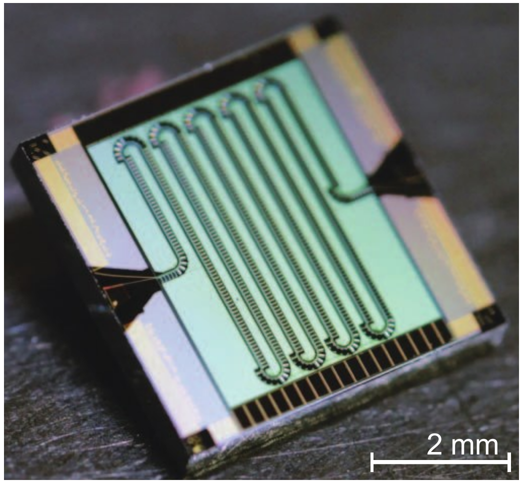


Credit. K. Lehnert (JILA/NIST)

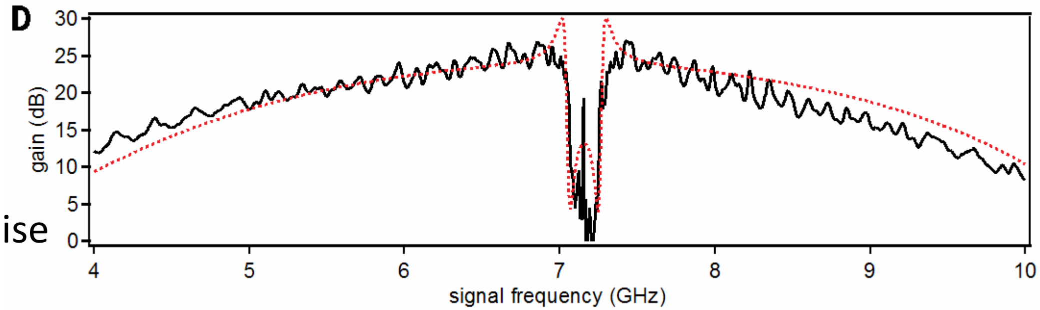
Traveling-wave Parametric amplifiers based on Josephson-Junctions



Andrew N. Cleland Science 2015;350:280



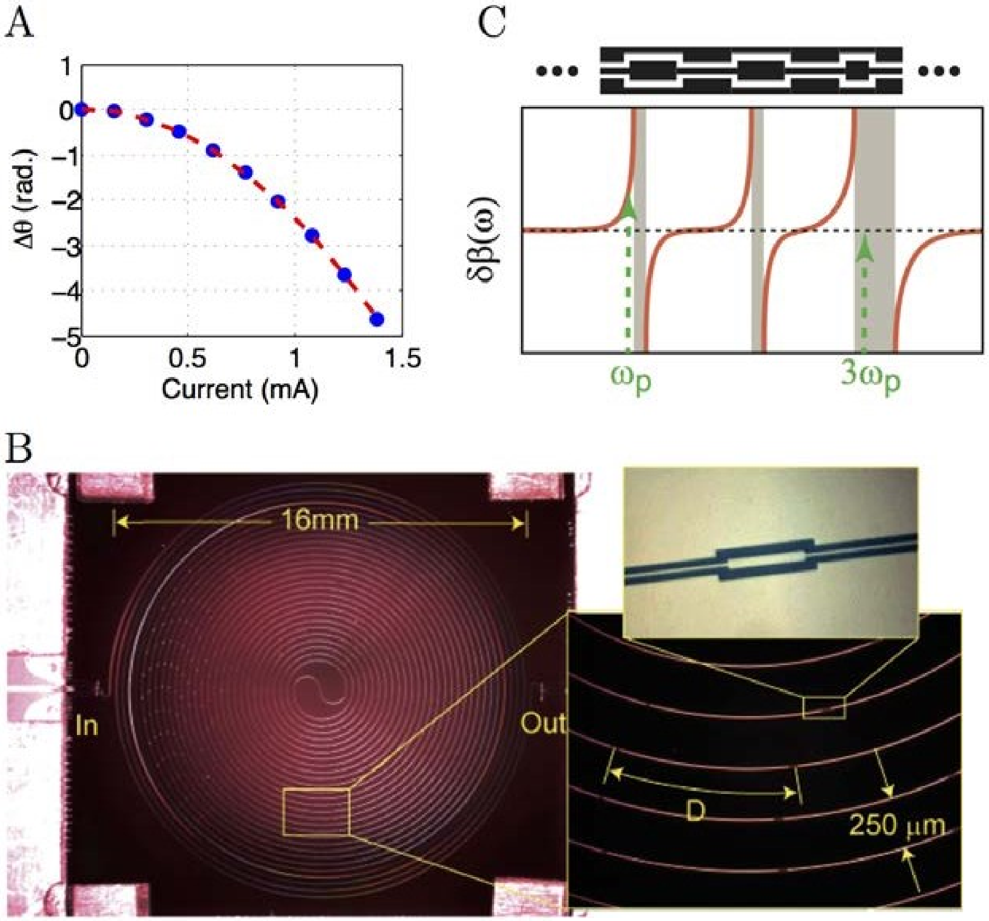
C. Macklin, Science, 350 (6258), p. 307, 2015

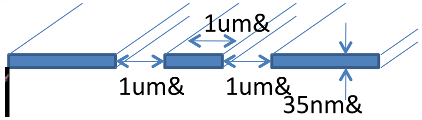


- Good gain, wide bandwidth (~5GHz), low noise
- Suitable for quantum-computing
- Disadvantage: low dynamic range (<-100 dBm) -> Not usable for ground-based astronomy

Traveling-wave Kinetic Inductance Parametric (TKIP) Amplifiers

- Proposed at Caltech in 2010 as a spinoff from MKID detector development
- Uses current-dependence of kinetic inductance of superconducting films (e.g. NbTiN) in a transmission line architecture
- Naturally orders of magnitude higher dynamic range than Josephson junction-based amplifiers (I_c ~ mA vs I_c ~ μA) → $P_{1\ dB}$ (at output) ~ 0.1 mW
- High gain-bandwidth achieved by engineering dispersion to maintain phase matching, and bandgap filters for blocking 3rd harmonic propagation
- Fabrication: Single layer of NbTiN superconductor on silicon or sapphire





B. Eom, Nature Physics 8, 623–627 (2012)

Tradeoffs and improvements in TKIPs

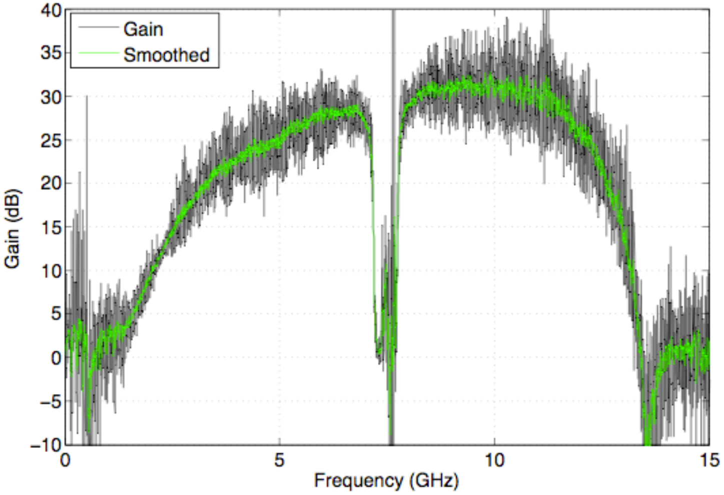
Main issues:

- High pump power ~-30 to -10 dBm -> Chip heating -> excess thermal noise
- Amplifiers are very long (1-2 m) CPWs -> reduced yield
- Impedance matching -> gain ripple

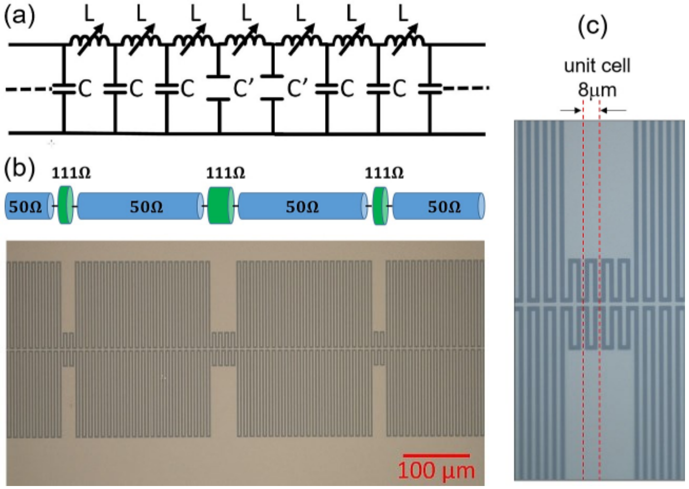
Improved designs:

- Lower impedance lines result in reduced pump power absorption and less heating
- Slow-wave lines reduce length
- Better heat sinking on sapphire
- Noise has been reduced to 2 photons (Q-limit = 1 photon)

NIST-fabricated TKIP (2014), J. Gao



NIST device based on artificial transmission-lines

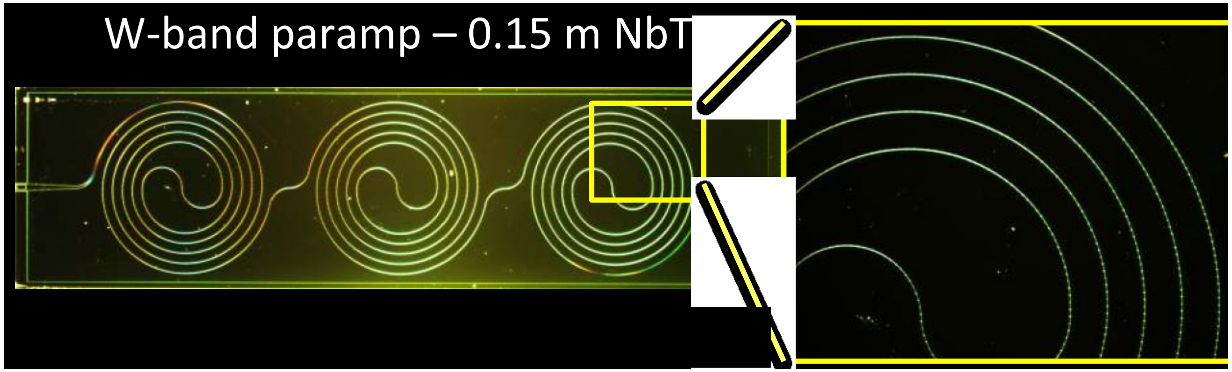


S. Chardhuri, arXiv:1704.00859, 2017

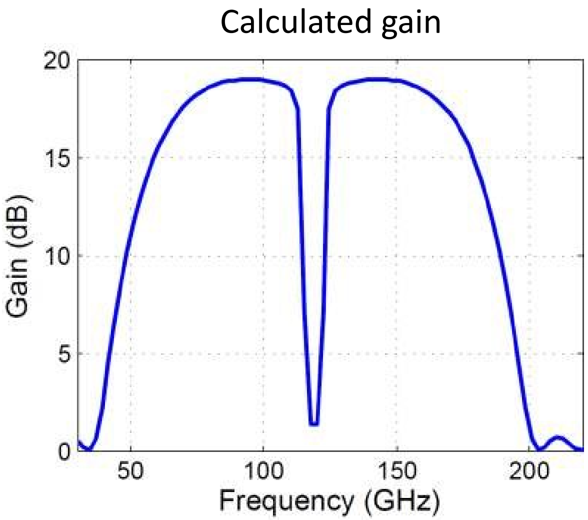
Extension of paramps to mm/submm-wave frequency (NRAO study, 2017, PI: Noroozian)

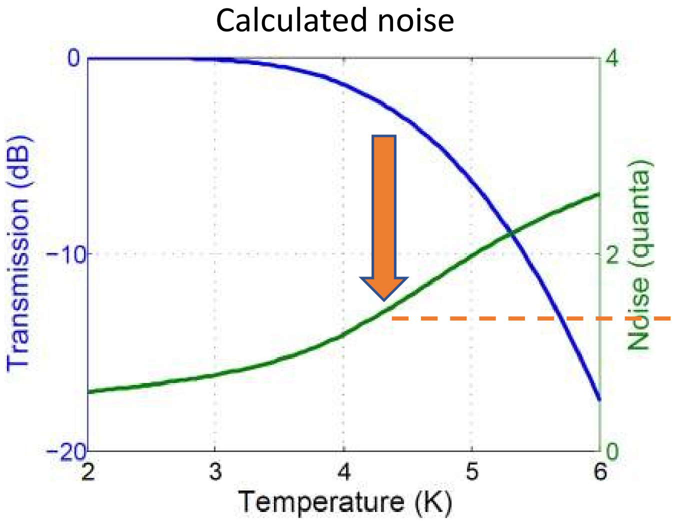
- TKIP amplifiers in principle can be extended up to superconducting gap (~1.2 THz for NbTiN).
- Physics and operation principle remains the same

A 55-175 GHz TKIP amplifier made at JPL, courtesy H. Leduc, P. Day

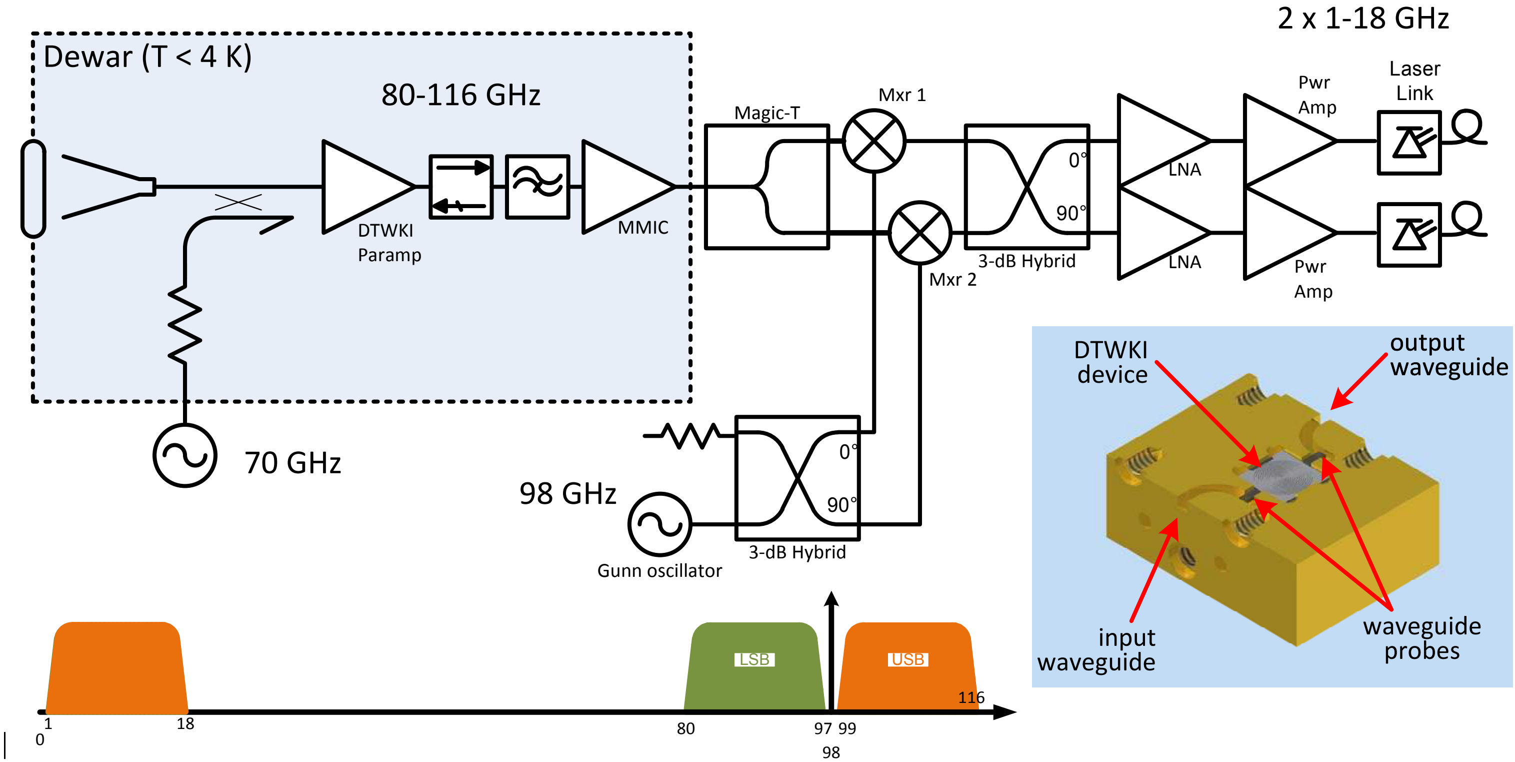


D. Woody, ALMA study, Cycle 1, 2012


Calculated gain


Calculated noise

An example TKIP amplifier as a mm-wave receiver front-end (W-band)



D. Woody, ALMA final study report, 2013

Example ALMA receiver noise improvement using ***mm-wave*** TKIP amplifier at front-end (instead of SIS mixer)

ALMA Band-3

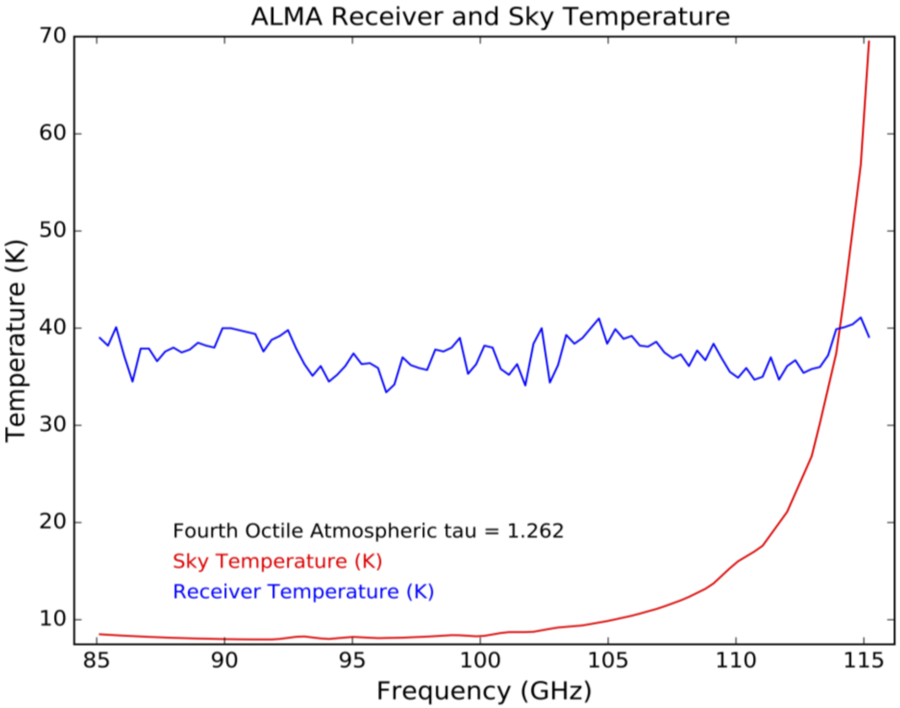
Band 3	**L (dB)**	**T_{PHYS} (K)**	**T_N (K)**	**T_R (K) SIS**	**T_R (K) TKIP**
Window	0.02	298	1.4	27.0 _(38.0)_*	**7.5**
IR filter	0.01	77	0.2	25.5	6.1
Horn+OMT	0.37	4.2	0.4	25.3	5.9
Waveguide	0.03	4.2	0.0	22.8	5.1
Image term. noise		4.2	4.6	22.6	5 (w/ cold filter)
LO noise			3.0	18.0	5 (no LO)
SIS Mixer or TKIP			15.0	15.0	5.0

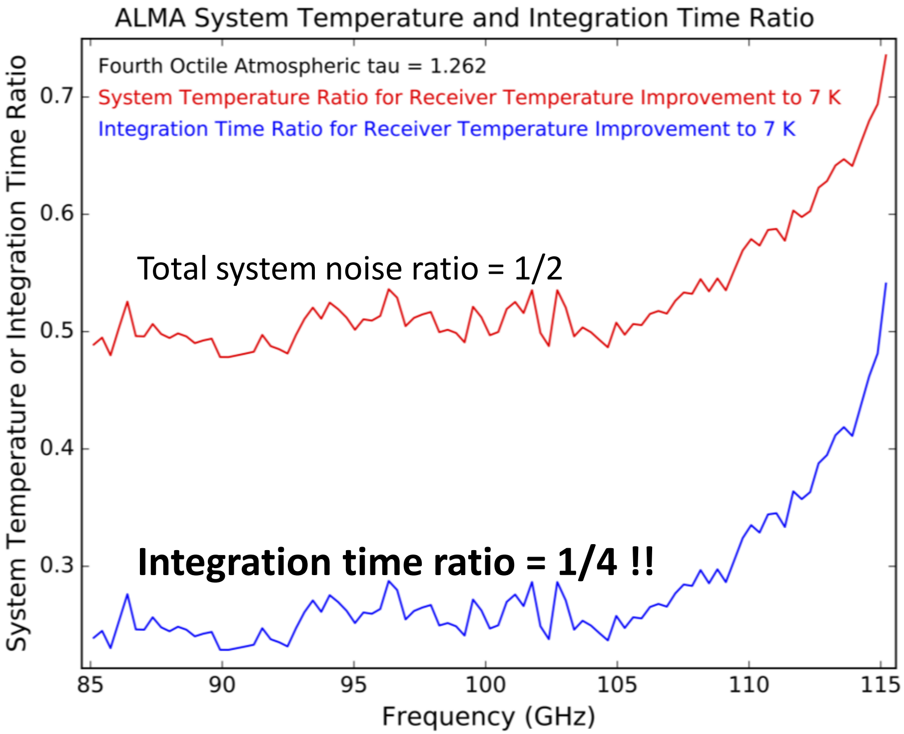
ALMA Band-6

Band 6	**L (dB)**	**T_{PHYS} (K)**	**T_N (K)**	**T_R (K) SIS**	**T_R (K) TKIP**
Window	0.04	298	2.8	44.4 _(60.0)_*	**15.3**
IR filter	0.02	77	0.4	41.2	12.4
Horn+OMT	0.20	4.2	0.3	40.7	12.0
Waveguide	0.30	4.2	0.5	38.6	11.2
Image term. noise		4.2	6.6	35.6	10 (w/ cold filter)
LO noise			3.0	29.0	10 (no LO)
SIS Mixer or TKIP			26.0	26.0	10.0

* Typical value

Reduced ALMA array integration time: Example calculation for Band 3





Total system noise ratio = 1/2

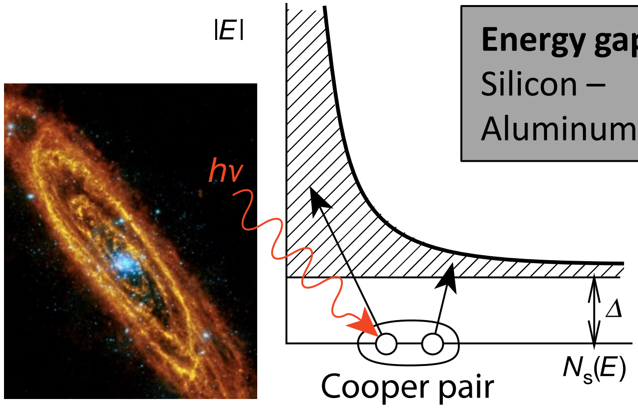
Integration time ratio = 1/4 !!

Courtesy of Jeff Mangum

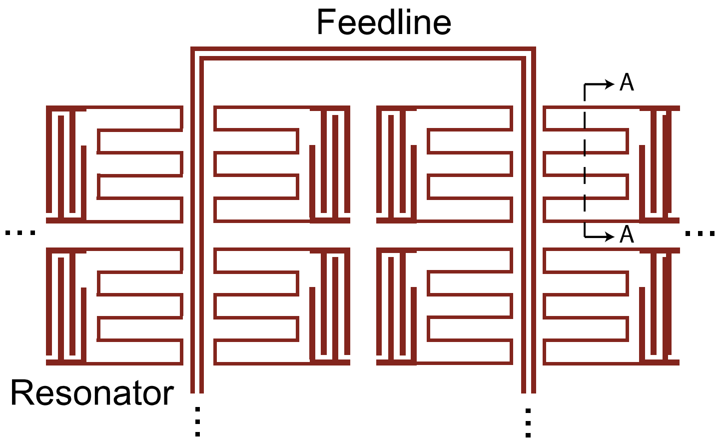
Also:

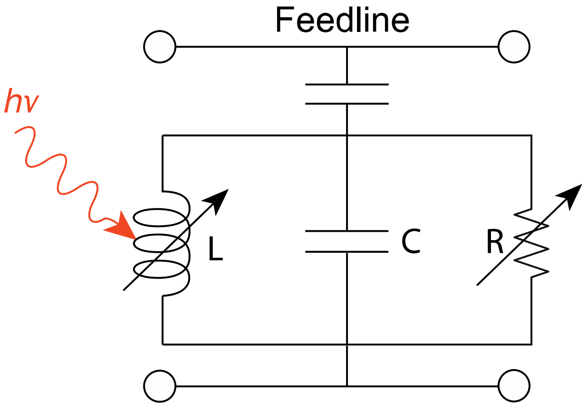
- Increased receiver sensitivity relaxes IF amplifier noise requirements. → Trade-off noise with bandwidth. → A simple increase from 4 to 8 GHz will provide another factor of 2 reduction in integration time! → 8 × shorter integration time!
- Similar enhancement in all bands will impact all science investigations in all bands!

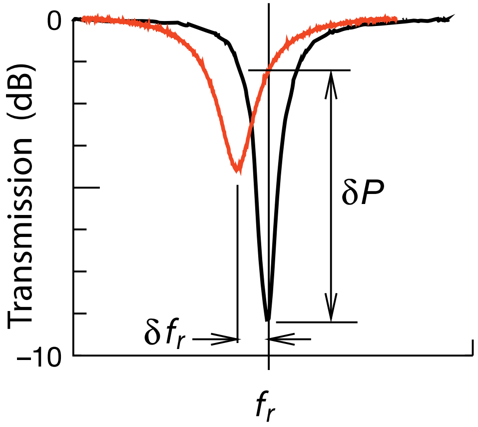
The Kinetic Inductance Detector (KID)
(an incoherent detector)

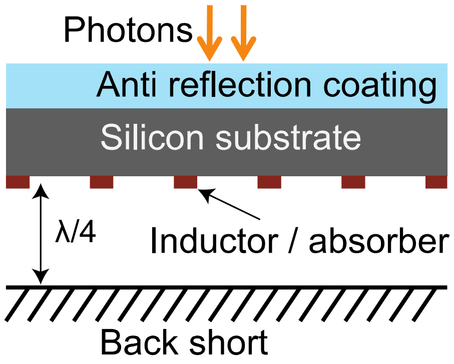


Energy gap:
Silicon – 1.10000 eV
Aluminum – 0.00018 eV





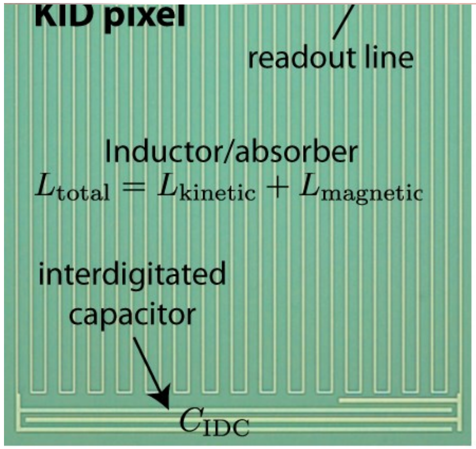


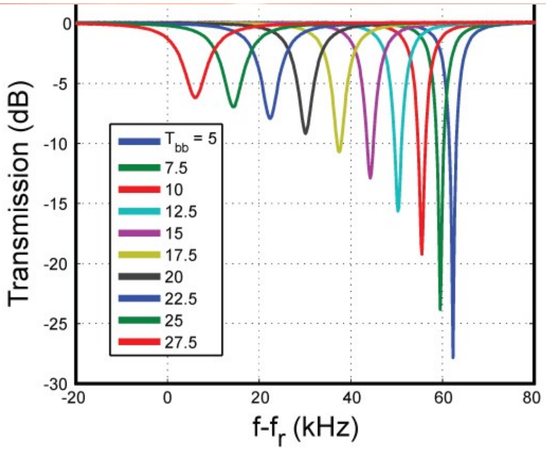


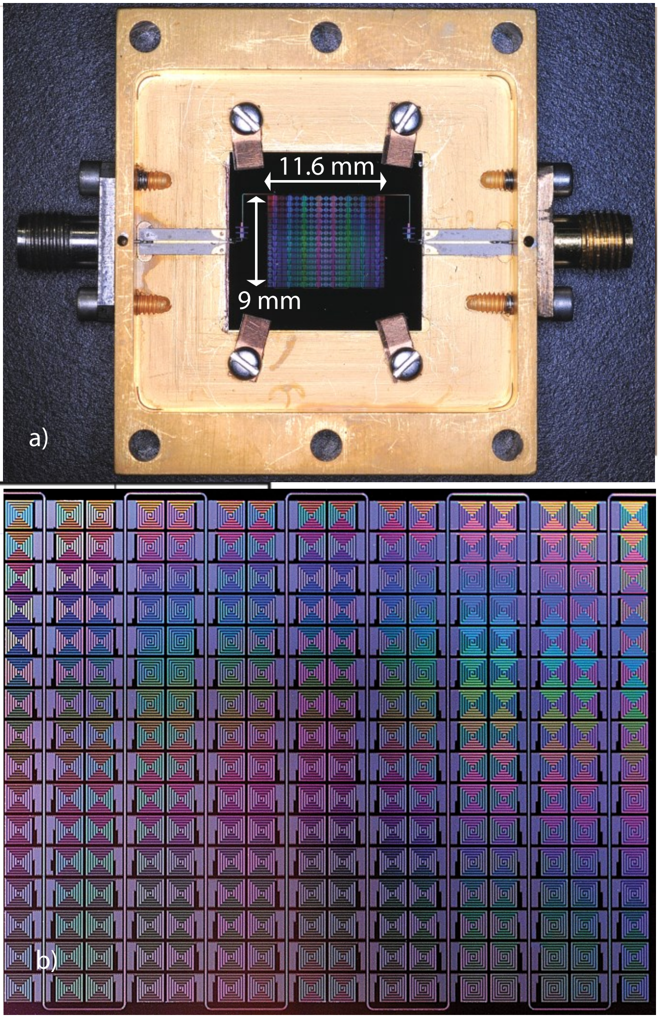
In superconductor: $L = L_m + L_{ki}(n_{qp}(h\nu))$

P. Day et al, *Nature* 425, 2003 (JPL, Caltech
O. Noroozian, PhD thesis, 2012 (Caltech)

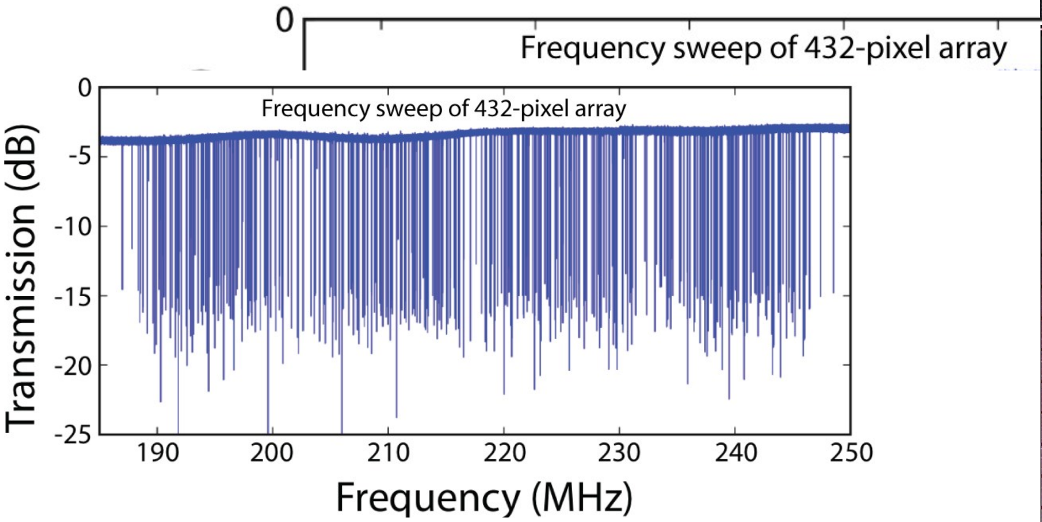
KID multiplexing and readout: a big advantage

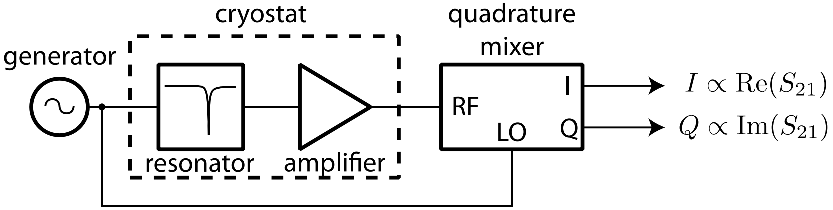




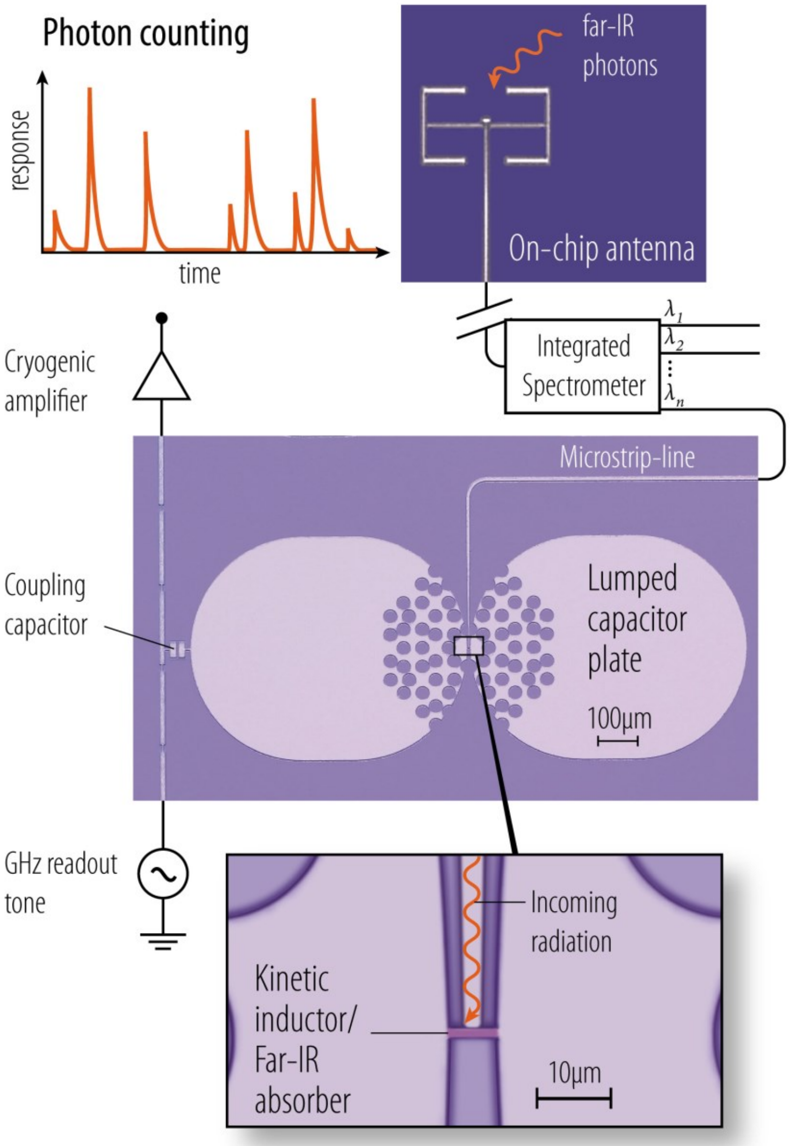


O. Noroozian et al., *IEEE MTT* **60** (2012)





Ultrasensitive KIDs with *photon counting* capability at THz/Submillimeter (NASA APRA, PI: Noroozian)

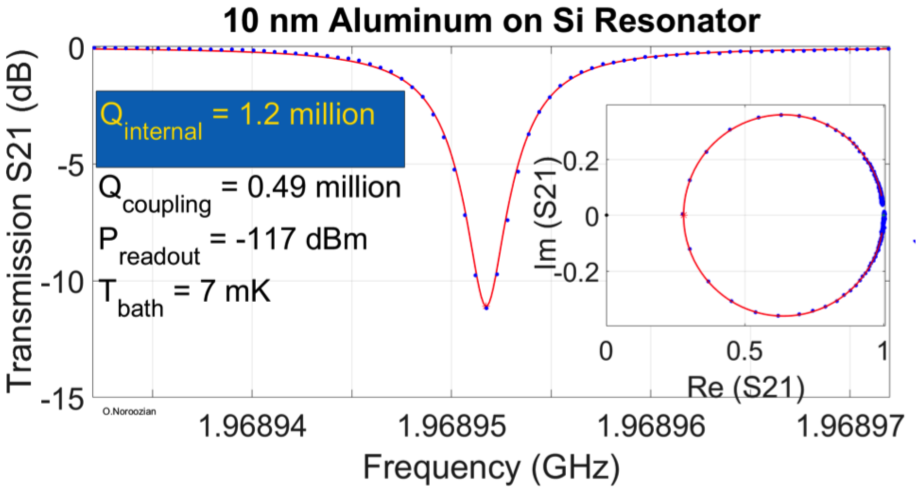


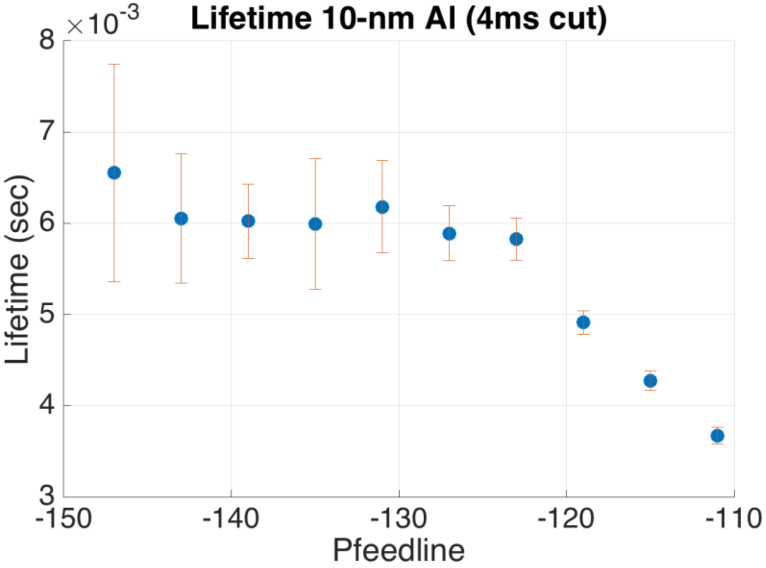
- Primary motivation:
  On the OST, using R = 1000 spectrometer, background photon rate is: $10^2 – 10^4$ photons/sec, so photon counting is advantageous.

The NASA/GSFC KID design and benefits:

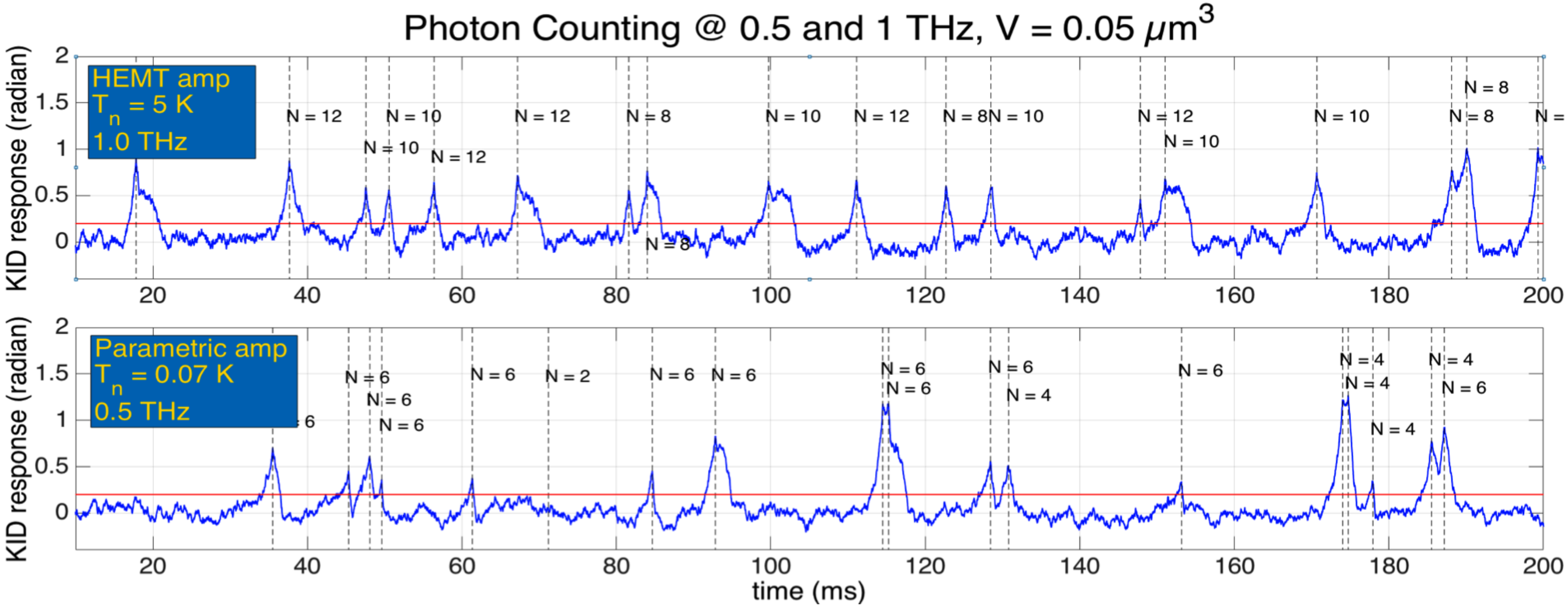
- Ultra-small volume aluminum kinetic inductor for increased response to single photons
- SOI wafer (currently 0.45 µm Si substrate)
- Parallel-plate capacitor on single-crystal Si for integration with on-chip spectrometer (µ-Spec) and reduced TLS frequency noise
- Choke filter for confinement of submm radiation inside sensitive inductor
- All-microstripline elements and no cuts in ground plane -> Immunity to stray radiation
- *Work in this direction naturally leads to power detectors in the $10^{-20} – 10^{-19}$ W/Hz$^{1/2}$* sensitivity *for ground-based low/mid-resolution spectroscopy*

Key material for ultrasensitive KIDs: thin aluminum





Photon counting with a 10-nm aluminum KID at 0.5 -1.0 THz



Credit: Thomas Stevenson, GSFC

- Integrated over the signal bandwidth, TLS noise is sub-dominant to amplifier white noise, because internal Q is low during pulse. ✓
- Recombination time and ring time are fast compared to photon arrival rate. ✓
- **Counting photons with > 95% efficiency!**

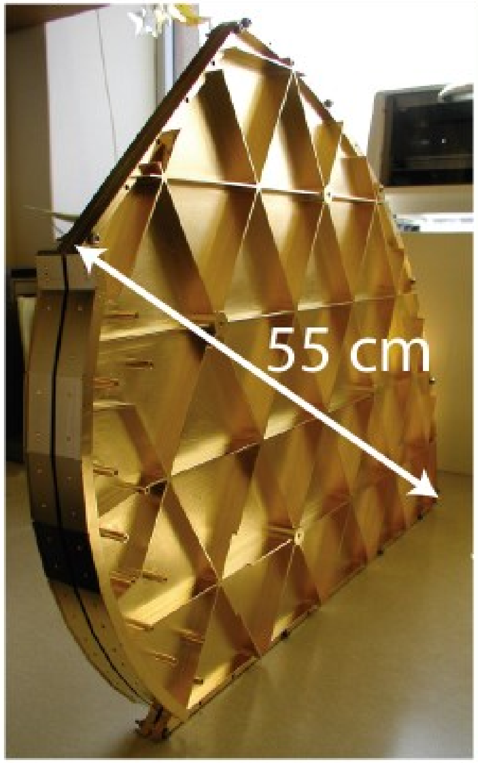
Assumptions:

photon rate = 100/s, spectrometer resolution = 1000, optical coupling efficiency = 25%, 4K telescope
detector volume = 0.05 μm^3, bath temperature = 100 mK, readout power = -137 and -156 dBm
Material properties take from our films measured at GSFC.

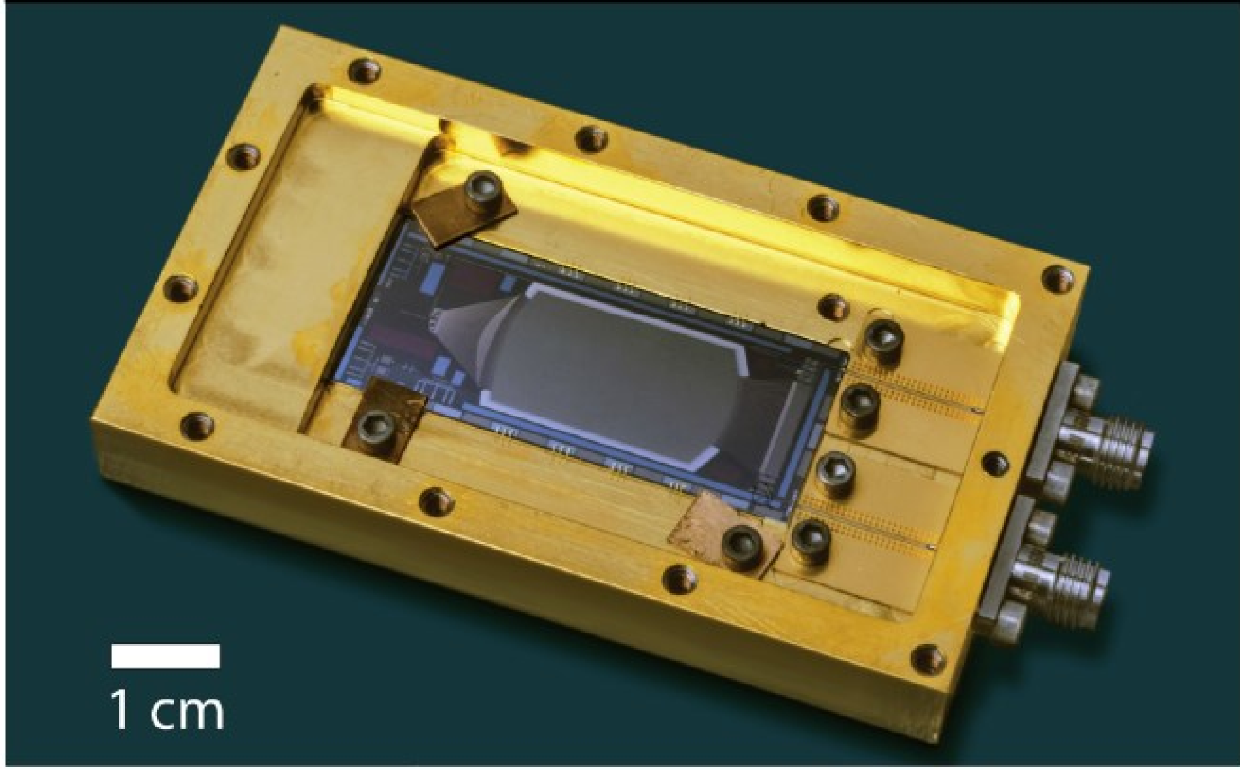
µ-Spec: an integrated spectrometer for submm spectroscopy

(NASA APRA, PI: Moseley, co-I: Noroozian)

Z-Spec spectrometer (R~300)



µ-Spec spectrometer (R=64 version)

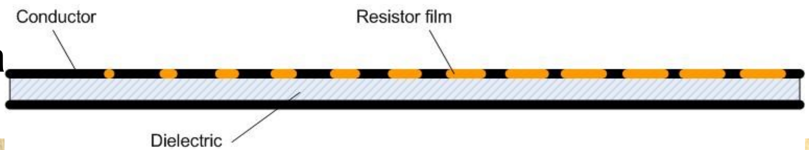


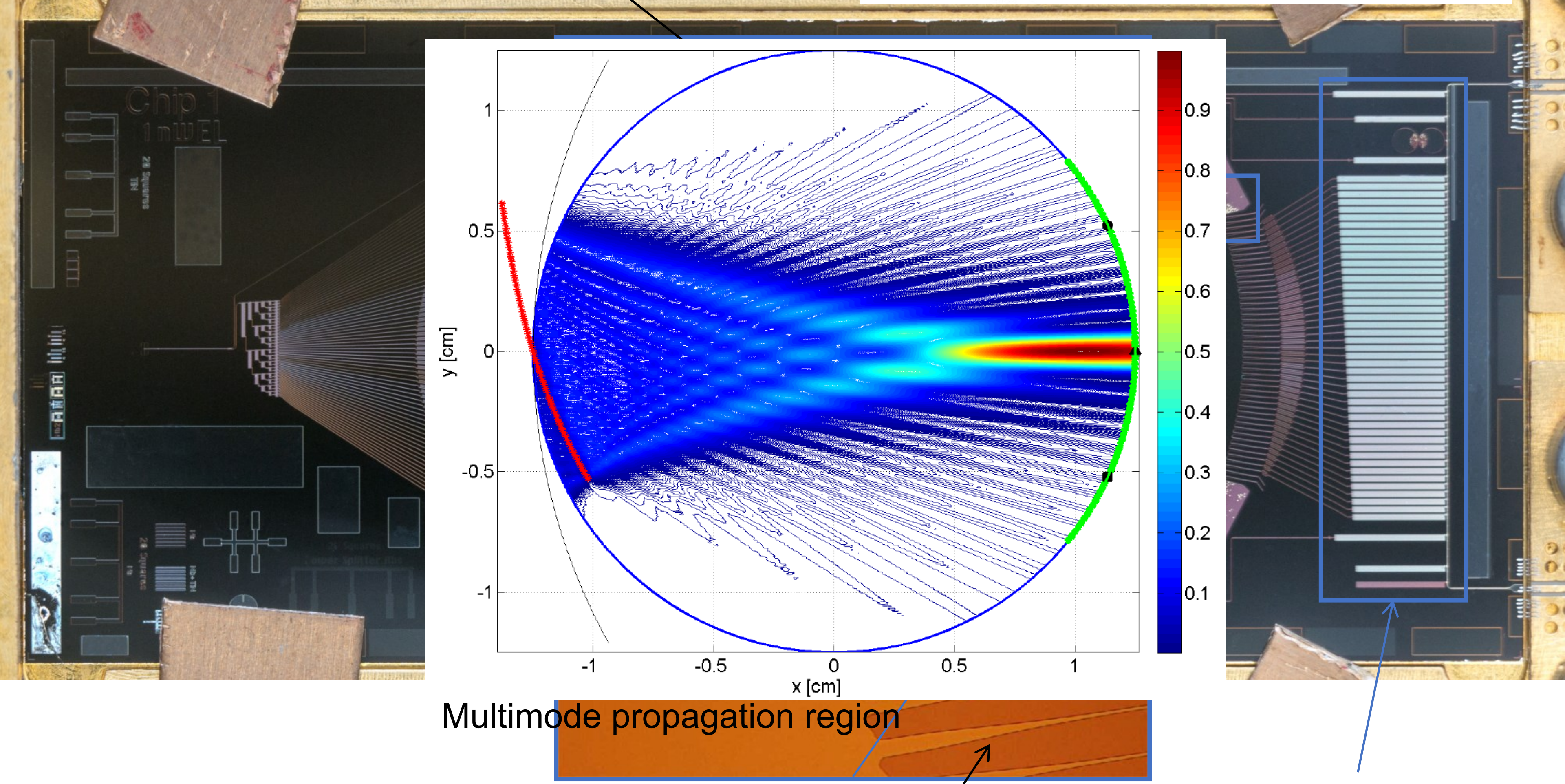
Orders of magnitude reduction in the mass and volume of our spectrometer are achieved by using ***superconducting microstrip transmission lines*** with ***low-loss single-crystal silicon dielectric*** substrates (0.45 µm thick).

μ-Spec: an integrated spectrometer for submm spectroscopy

Photon detectors (MKIDs) for each channel

Plane-wave absorber bounda
(Au/Pd resistor dots on Si)





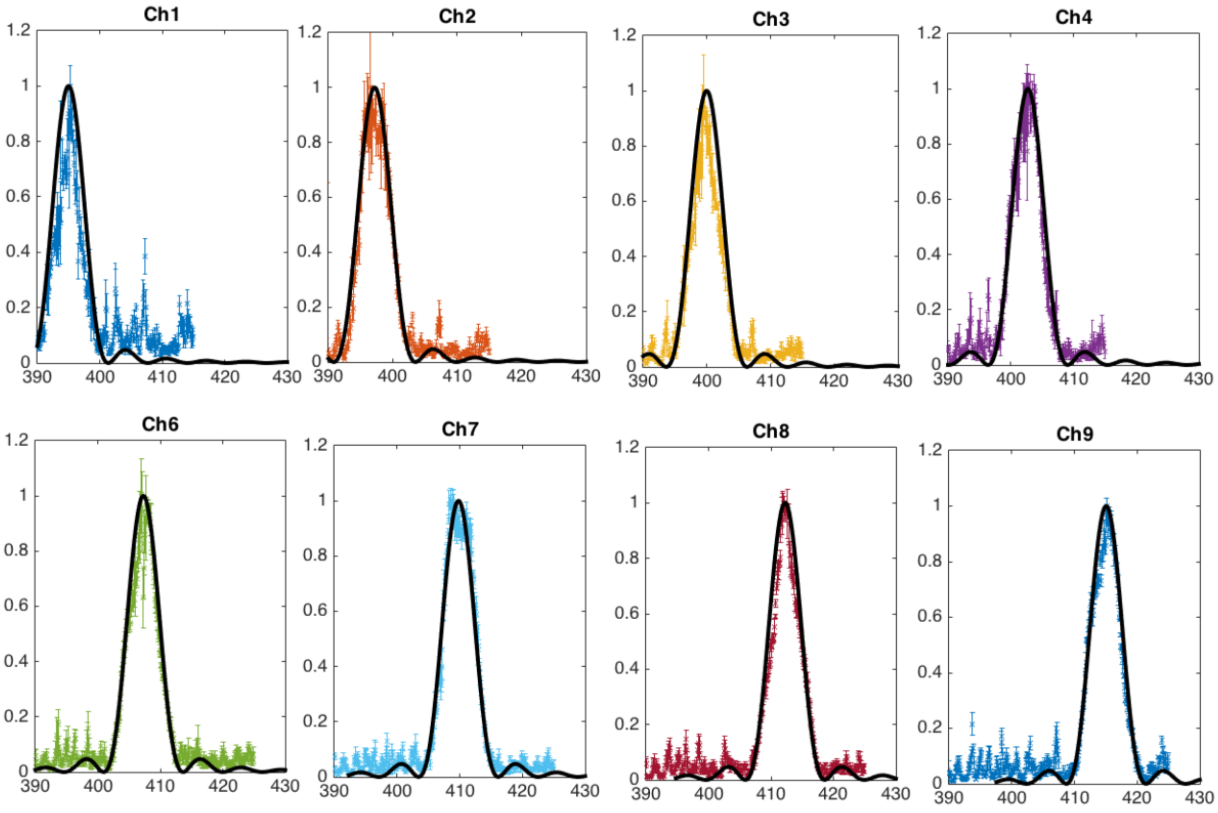
Multimode propagation region

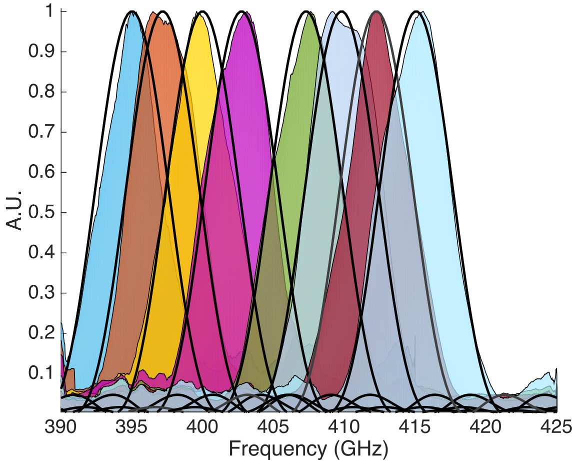
G. Cataldo, *Applied Optics*, 53(6), 1094, 2014

2-D receiver feedhornes

Photon detectors (MKIDs) for each channel

Successful demonstration of R=64 μ-Spec





<u>Demonstrated results:</u>

- Sharp line profile of $(\sin x/x)^2$ (as opposed to Lorentzian in filterbank-based spectrometers)
- Resolution of R=64
- Absolute frequency position within ±1 GHz as designed.

Conclusions

- Paramps can have great impact on mapping/observation speed and sensitivity for AtLAST
  (x8 speed for ALMA band-3 assuming the current 8 GHz IF bandwidth and correlator)
- Kinetic Inductance Detector technology is already background-limited for large-format imaging arrays and mid-resolution spectroscopy (R~1000) using AtLAST.
- On-chip spectrometers such as µ-Spec, Deshima, Superspec are great tools for Multi-Object Spectroscopy (n~100) using AtLAST.

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