Title: Prospects for future SZ interferometers

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Abstract:

Future SZ interferometry/GUBBINS

Oxford Physics

Mike Jones

University of Oxford

+lots of people in CBI, GUBBINS, 'SZI' (formerly known as Clanger…)

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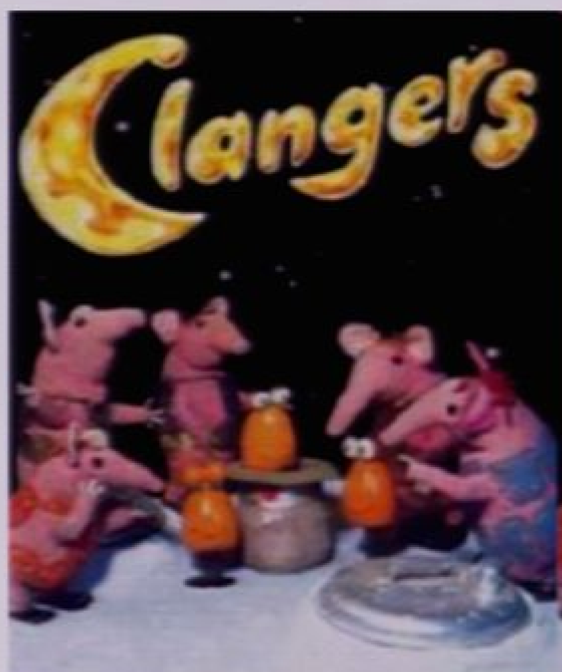

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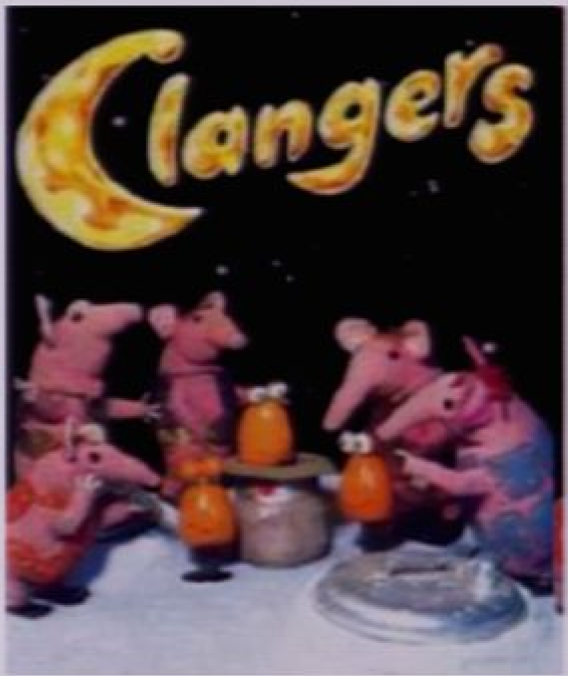


SZ/CMB interferometry

Interferometers have big advantages for CMB/SZ:

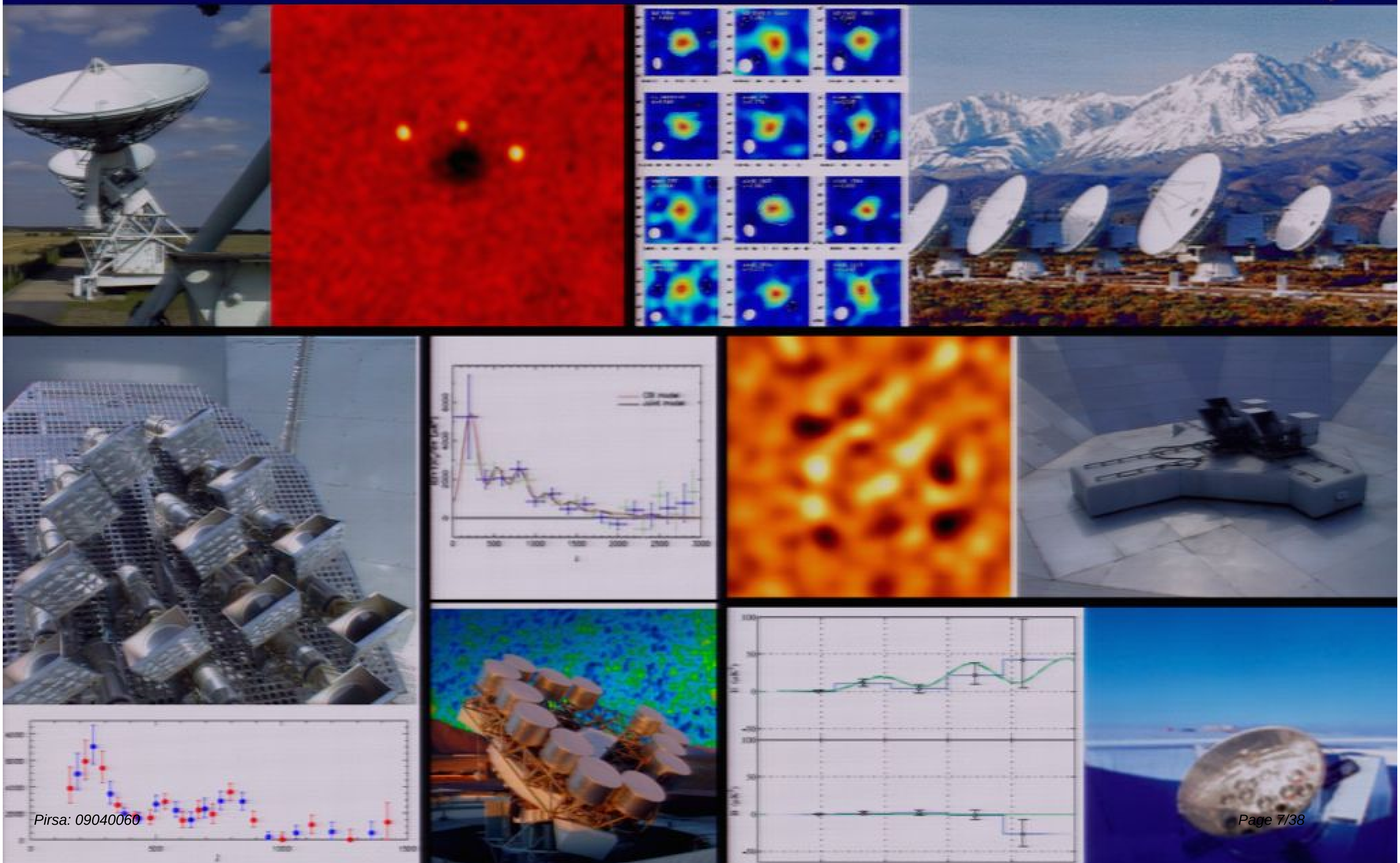
- Reject time-varying atmospheric power
- No scan-synchronous signals – no scan!
- Natural modulation of signal ('fringe rate') – 'lock-in' detection of sky
- Easy to scale to change resolution
- Natural measurement of polarization:

$$L1 * L2 = T + iV$$
$$R1 * R2 = T - iV$$
$$L1 * R2 = Q + iU$$
$$R1 * L2 = Q - iU$$

- You actually get thermal noise level in practice…

Problem: correlator scales as N_{ant}^2 – generally more complicated…

CMB interferometers through the ages



‘Proper’ interferometry

Cleanness of interferometry relies on various features…

- Spatial/temporal filtering of atmosphere
  - No response to atm total power fluctuations
  - Correlated atm emission modulated by wind (eg Lay & Halverson 2000)
- Downconversion at antenna
  - Enables phase switching of LO – PSD post-correlation
  - Correlation receiver insensitive to amplifier $1/f$ noise (Ryle 1957)
- Gain before splitting of signal to baselines
  - Arbitrary number of baselines possible without loss of sensitivity (cf optical (bolometric) interferometery)
- Tracking antennas
  - Requires path compensator
  - Path inserted in IF gives natural fringe rate

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Future SZ interferometer?

- Follow up survey clusters (100s? 1000s?)
- Resolution to see structure (gastrophysics essential for cosmology, and interesting anyway…) so long(ish) baselines (30 arcsec ~ 6kλ)
- Low resolution to get total fluxes so short(ish) baselines (30 arcmin ~ 100 λ)

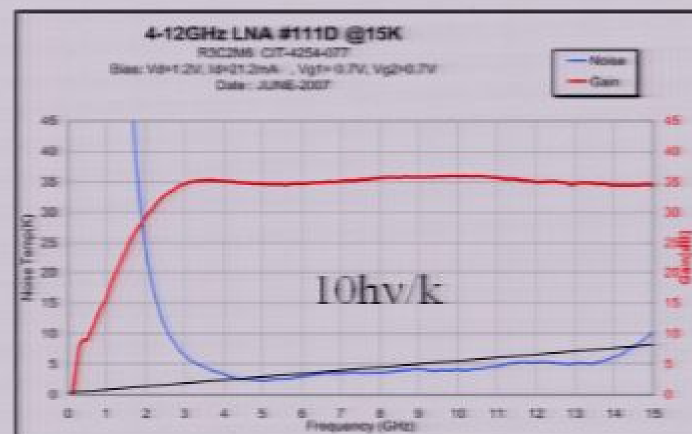
$$S(0) = \int \Delta T \, d\Omega \sim D_A^{-2} \int kT \, dV$$

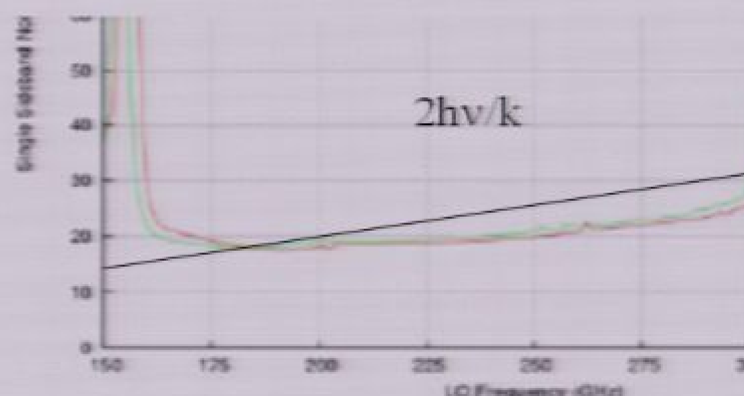
- Frequency coverage to allow
  - –Foregrounds removal (radio sources, IR sources)
  - –Kinetic SZ
  - –T_e from relativistic effect

  Need ~30 to ~250 GHz (Knox, Holder & Church 2004)
- Bandwidth: full atmospheric/waveguide windows ie up to ~40 GHz
- Frequency resolution
  - –$\Delta\nu/\nu$ ~ resolution/FOV required anyway for imaging
  - –Improved spectral mapping eg around null
  - –Line emission?

Front end technology

- Frequency range 30-250 GHz spans technology range
- HEMTs are getting better:
  - –Best InP MIC (discrete transistor) ~ 0.25K/GHz = 5 x hν/k
  - –Projected 3 x hν/k in MMIC (integrated) 35 nm process
  - –Eg 15K at 100 GHz, 40K at 250 GHz
- SIS mixers at 100 GHz and above:
  - –2 x hν/k possible with conversion gain
  - –HEMT amplifiers for IF at ν_{RF}/(5-10)





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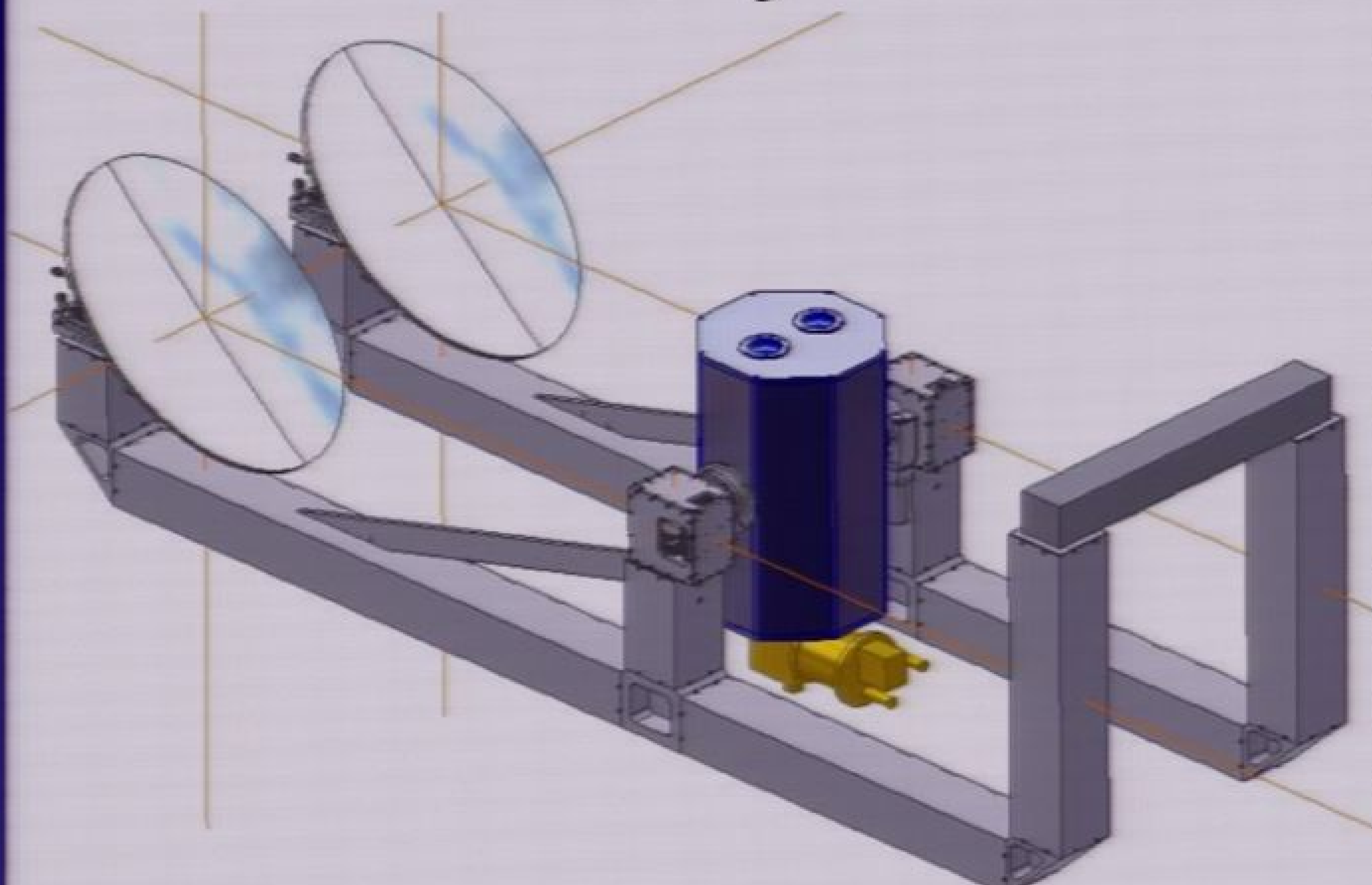
Correlator technology

- Need many 10s of GHz BW for competitive sensitivity
- Digital?
  - ~3 Gs/s 8b ADCs available at ~$2000 a go.
  - Current FPGAs deliver ~350 Gop/s for ~$2000 and consume ~100W (eg ROACH board with Virtex XC5VSX95T)
  - 100 baselines x 40 GHz x 32ch needs ~1500 FPGAs - $3M and 150 kW
  - Custom devices ~10x cheaper/less power but big NRE
  - Moore's law will rescue you eventually…
- Analogue?
  - 20 GHz multiplier chips possible for ~$10 each in bulk, ~100 mW
  - 100 baselines x 40 GHz x 32ch needs ~12,000 chips - $120k, 1.2 kW
- Analogue looks competitive for the next decade at least…

GUBBINS

GUBBINS: A novel millimeter-wave heterodyne interferometer



Angela Taylor
Matthew Brock
Paul Grimes
Christian Holler
Jaya John John
Mike Jones
Oliver King
Jamie Leech
Ghassan Yassin
Karl Jacobs (Cologne)
Chris Groppi (Arizona)
Andrew Harris (Maryland)

GUBBINS - Aims

Oxford Physics

Aims:-

- Prototype mm-wave heterodyne interferometer
  - Low to medium spectral and spatial resolution
  - High brightness sensitivity
- Technology demonstrator
- Funded by Royal Society's Paul Instrument Fund
- Builds on technology development projects at Oxford

Astronomical Observations:-

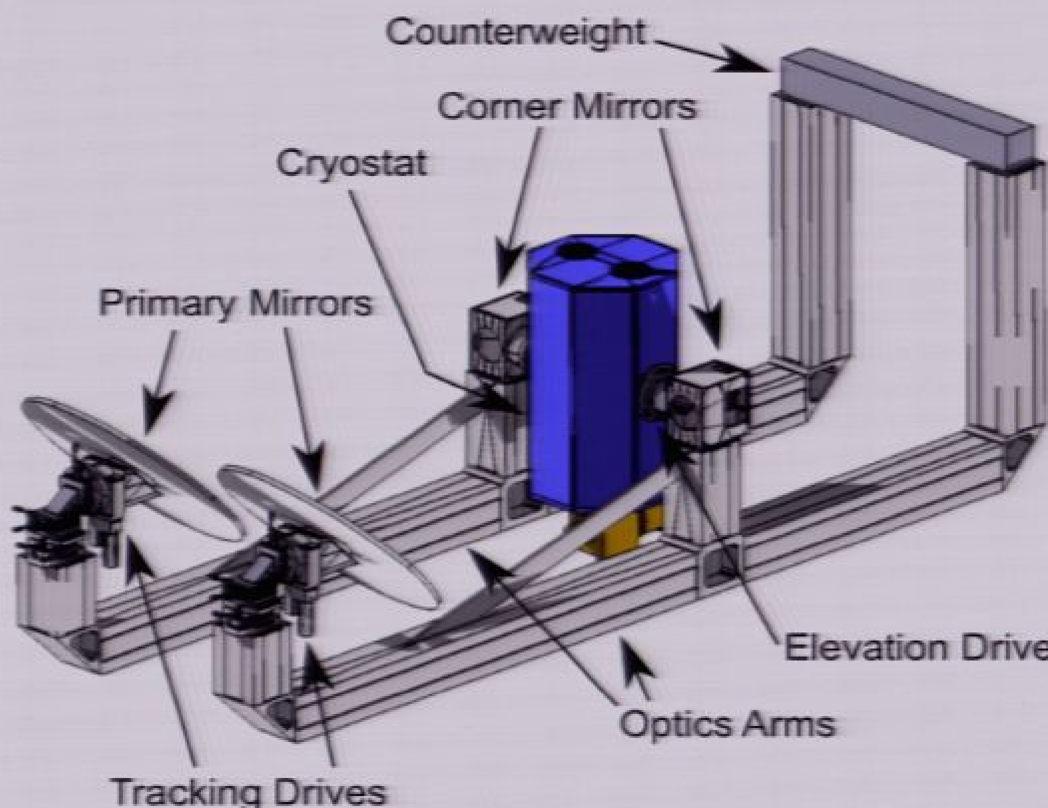
- Observe from Chajnantor Observatory (CBI/QUIET site), possibly initial observations from Tenerife
- Measure Sunyeav-Zeldovich effect for few brightest galaxy clusters in southern sky
- Other on sky tests of interferometer – atmosphere, planets etc.

GUBBINS - Specifications

220-**G**Hz **U**ltra-**B**road**B**and **IN**terferometer for **S**-Z – GUBBINS

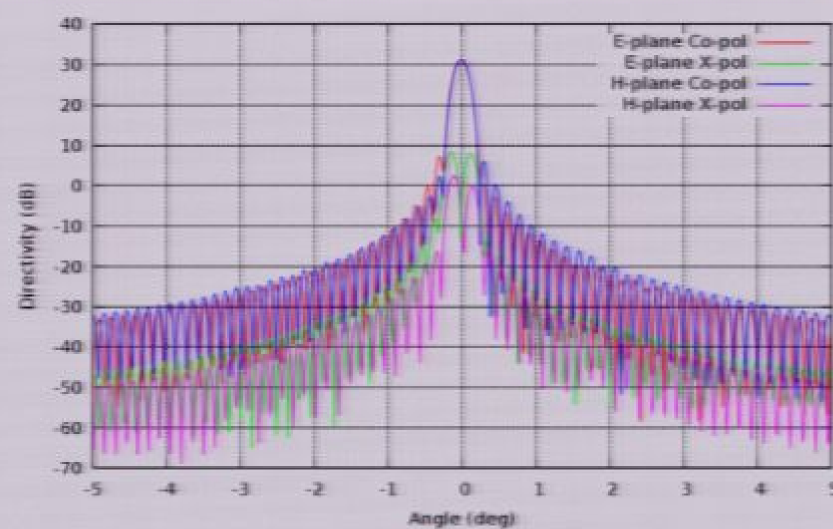
Single baseline interferometer at 185-275 GHz

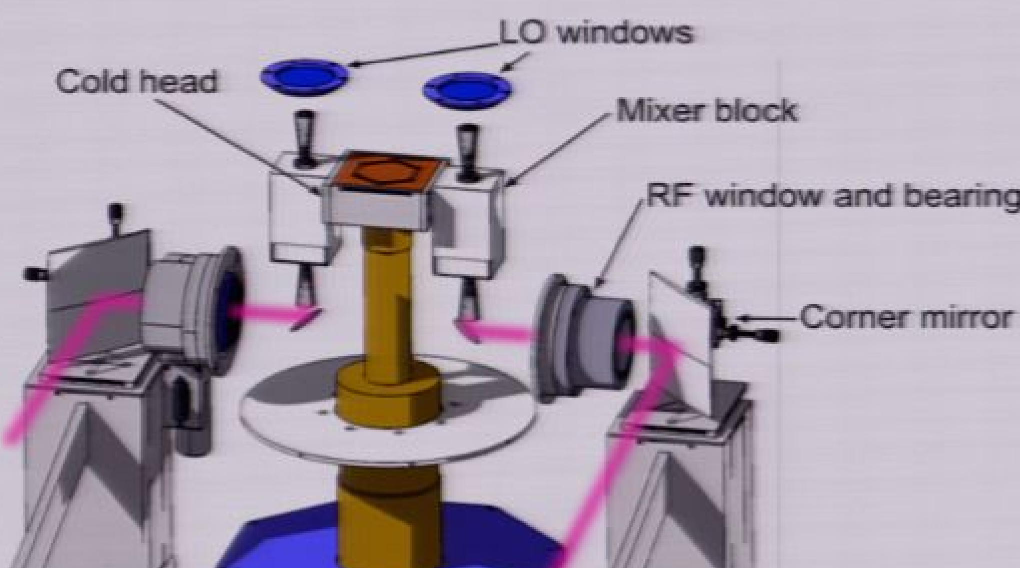
Frequency	185-275 GHz
Antenna aperture	0.4 m
Baseline	0.5-0.6 m
Primary beam	11' @ 220 GHz
Spatial resolution	7'-11' @ 220 GHz
Mixer IF band	3-13 GHz
Instantaneous bandwidth	2x 10 GHz
Spectral resolution	1.125 GHz
Target system temperature	50 K
Brightness sensitivity	350 μK/s$^{1/2}$

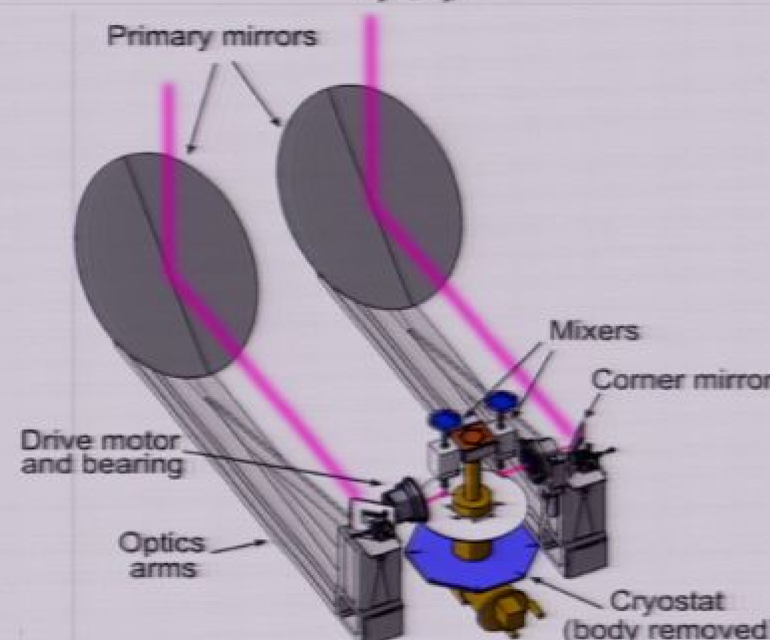


GUBBINS - Optics

- 45° offset parabolic primary mirrors (0.45x0.7m)
- Beam folded by a convex 45° offset mirror
- Fed by 8° FWHM corrugated horn-reflector antennas
- Telescope pointed by rotating optics about horn axis, and rotating primary about axis from primary to corner mirror

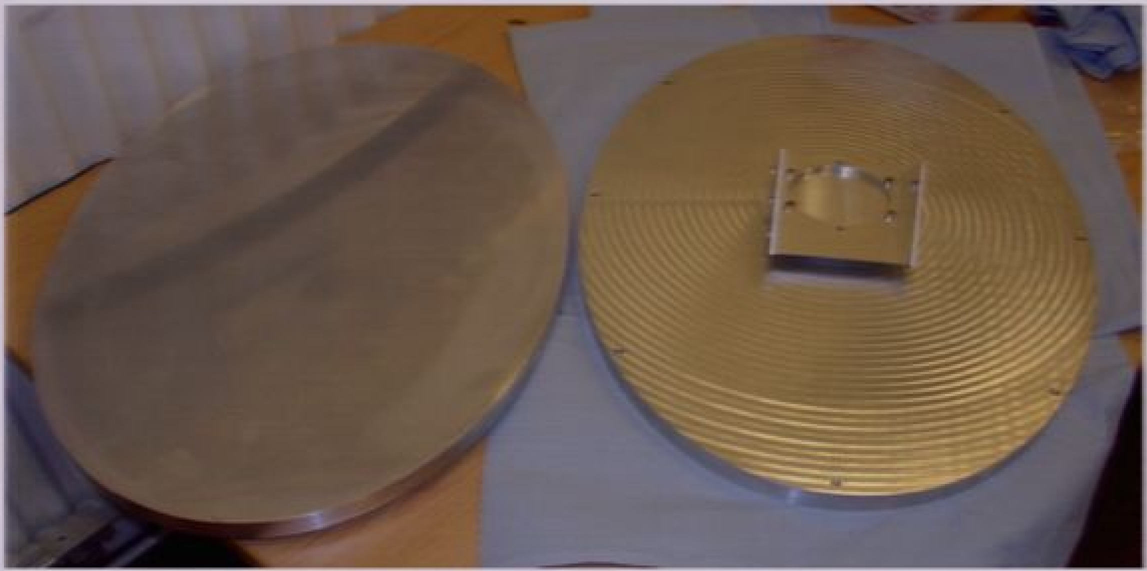






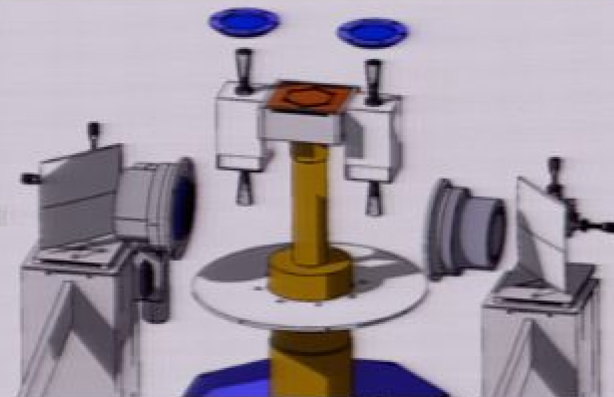
GUBBINS - Optics

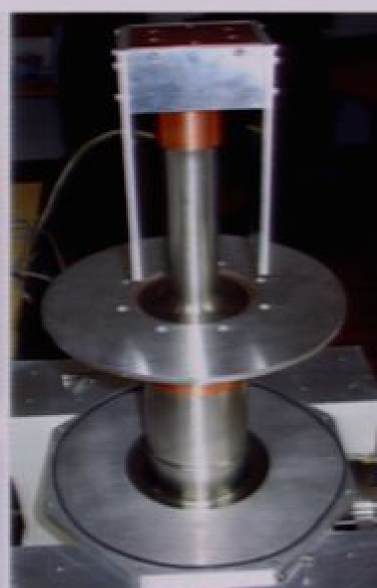
- Mirrors are CNC milled from solid aluminium
- Surface accuracy measured on CMM ~±10 μm
- Corner mirrors mounted on 2-axis goniometers
- Primary mirrors mounted on tip/tilt stage, XYZ translation stage and servo motor

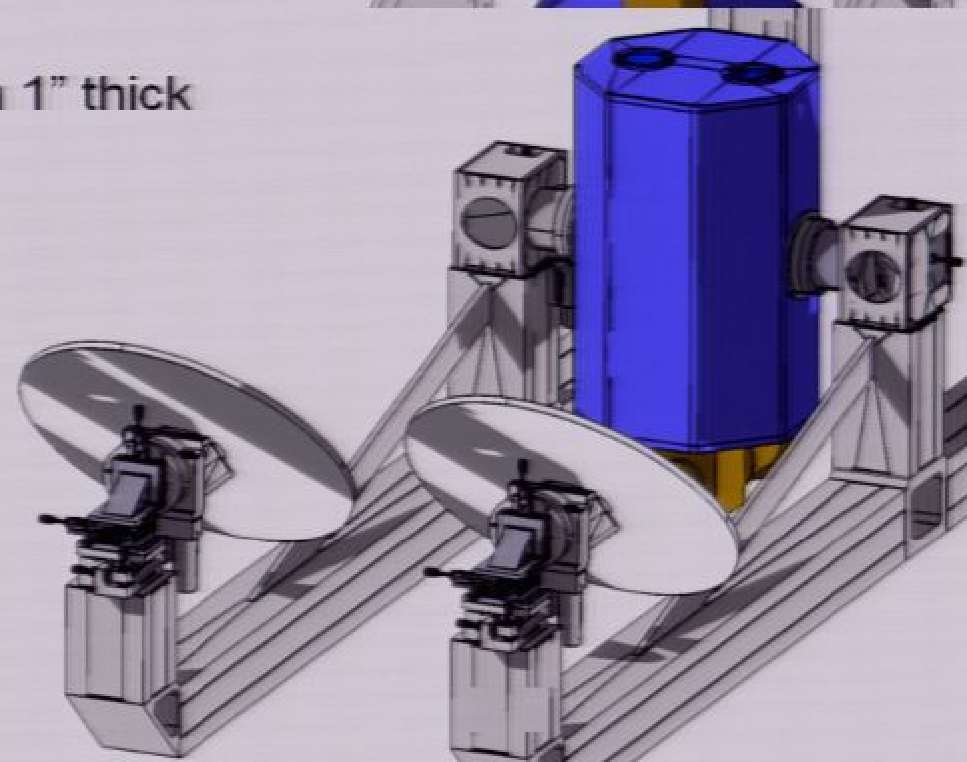


GUBBINS – Cryostat

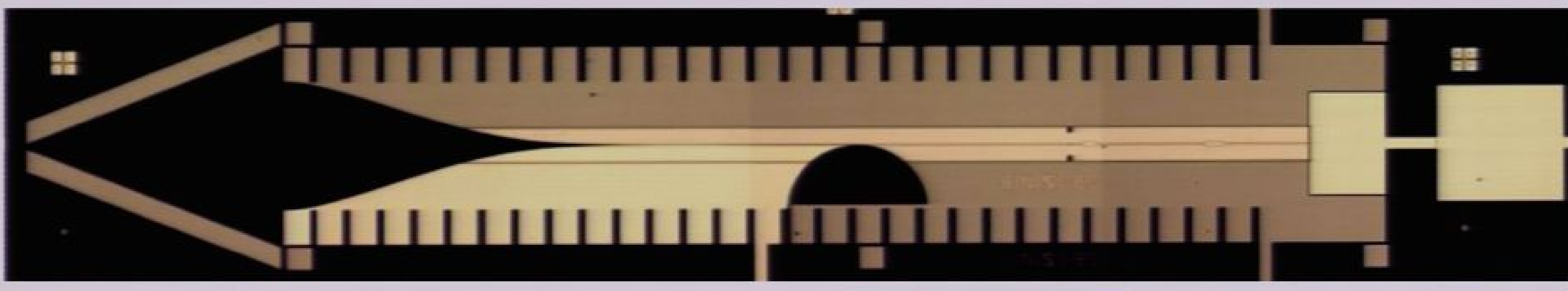
- Sumitomo G-M cooler (1W @ 4 K stage)
- Both SIS mixers mounted looking out of opposite sides of cryostat
- SIS mixers and 1st stage IF amps on 4 K stage, 2nd stage IF amps on 40 K stage
- Cryostat supports optics arms and is mounted on telescope plinth
- 50mm Cryostat windows made from 1" thick Zotefoam PPA-30



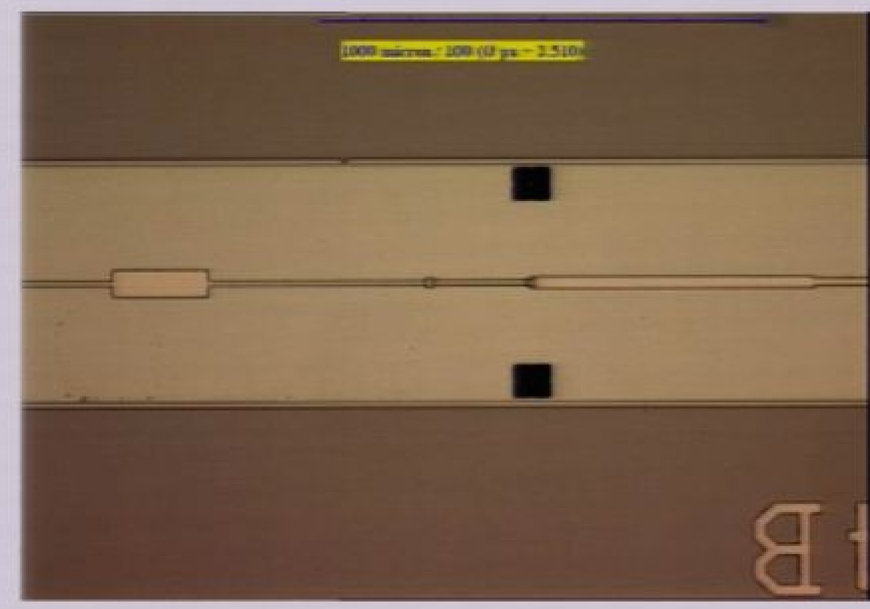




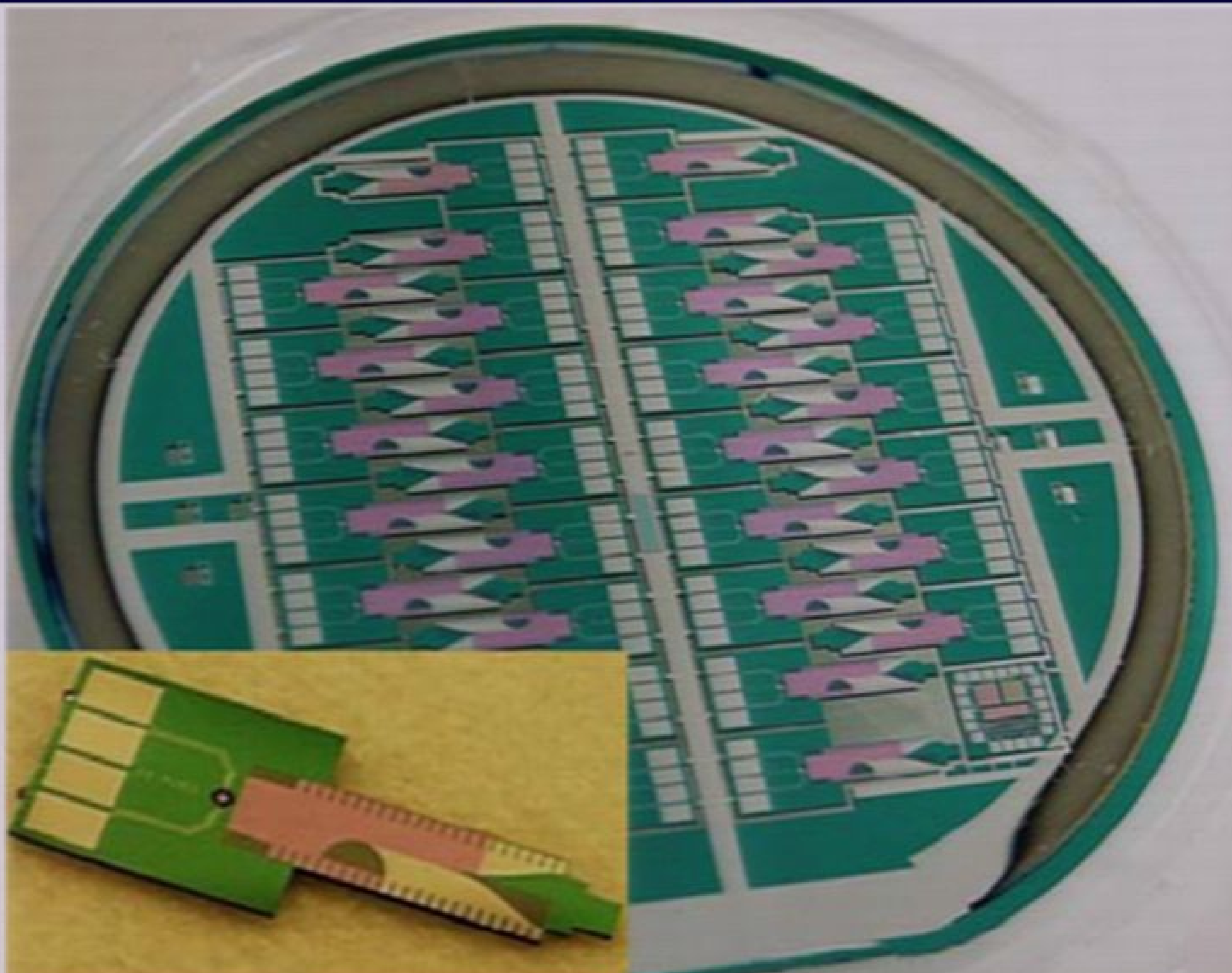
GUBBINS - Mixers



- Finline SIS mixers with IF band up to 2-20 GHz
- Fabricated by Paul Grimes at facility of Karl Jacobs, Cologne
- Currently testing single-ended mixer prototypes to prove wide IF band technology
- Eventually build and test single-chip balanced mixers and single-chip sideband separating mixers
- Grimes et al ISSTT 2008



…aside…Clover 97GHz finline TES detectors



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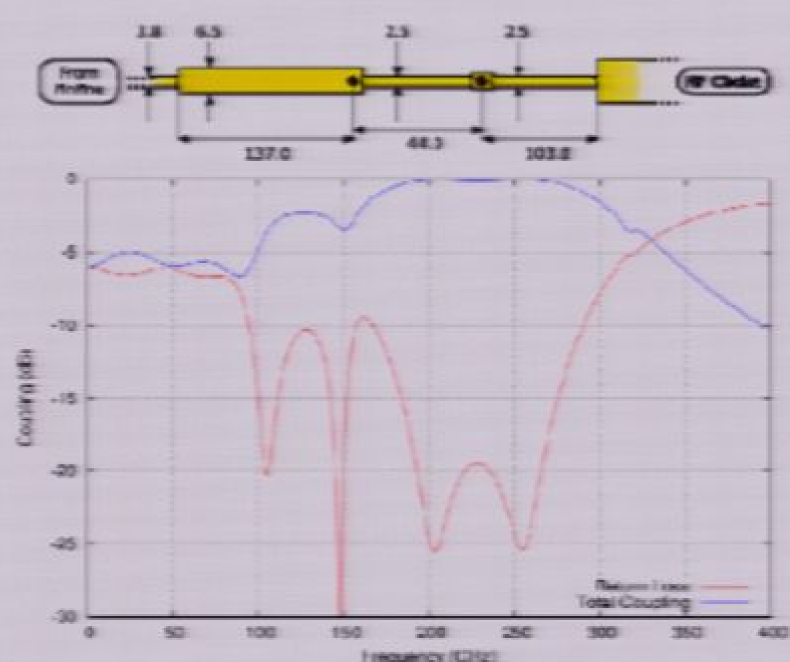
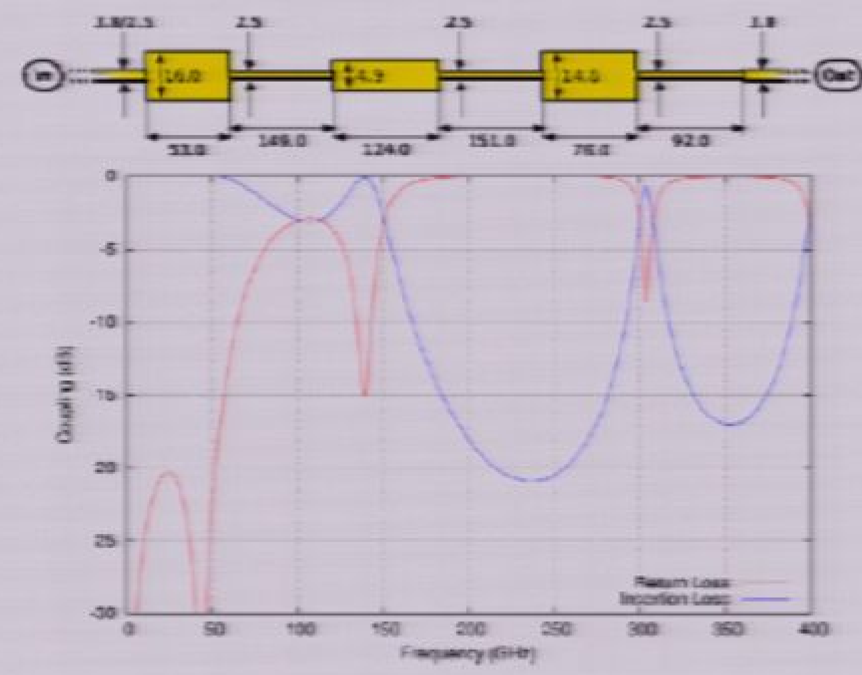
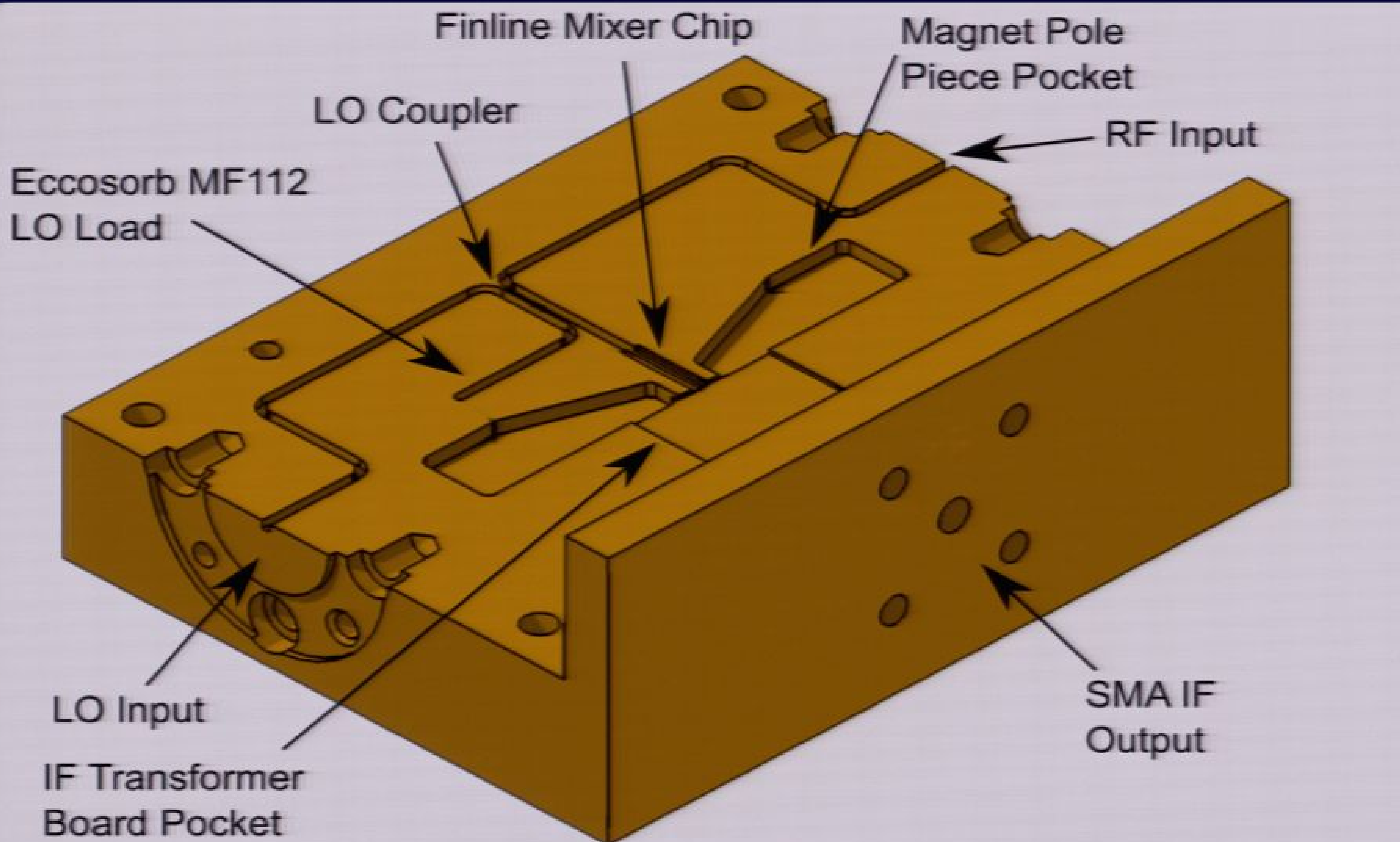
GUBBINS - Mixers





- Mixer tuning circuit to allow wide RF band 185 – 275 GHz
- RF choke gives wide IF band while isolating RF side
- Predicted noise temperature ~20K over full IF and RF band
- Measured noise temp ~50K with known problems with cryostat losses and LO power
- Conversion gain > -3dB over 0 – 20 GHz IF band.

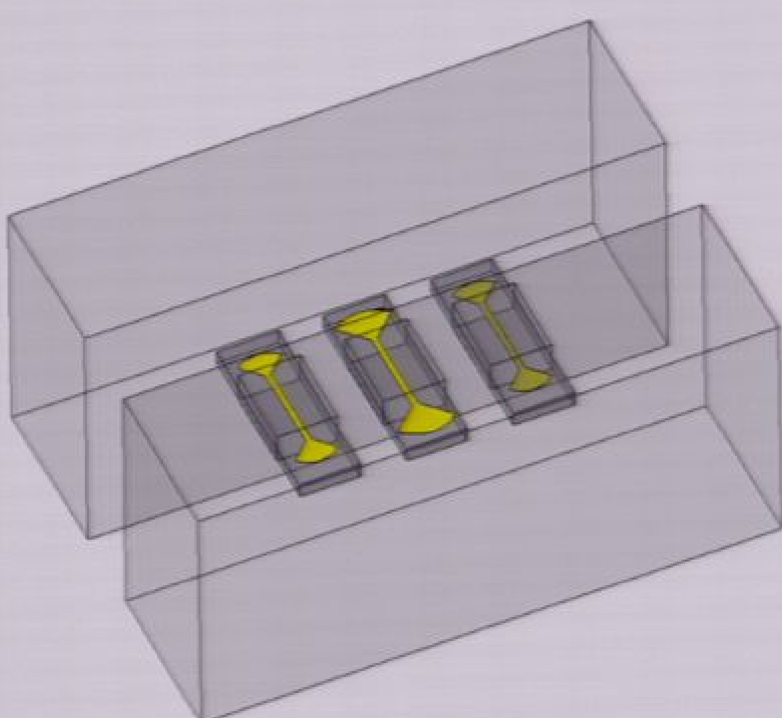
GUBBINS – Mixer Blocks

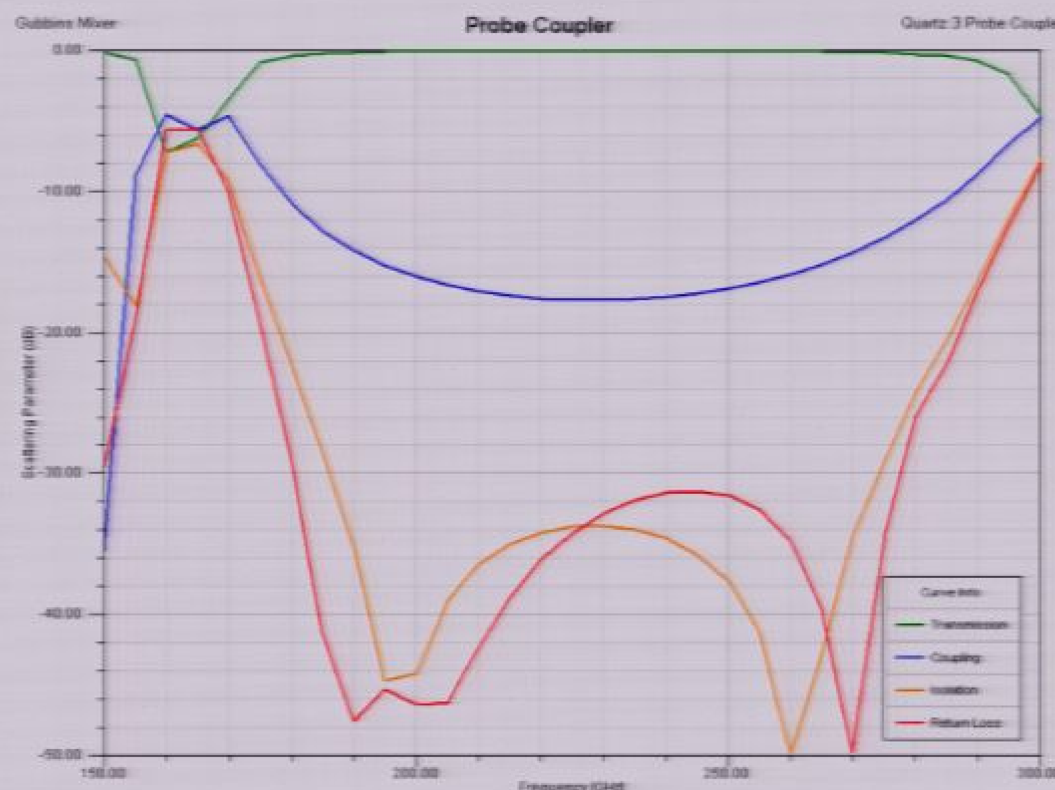


Currently being machined by Chris Groppi at University of Arizona

GUBBINS – LO Coupler

- LO is injected in mixer block
- Coupled via 3 section directional coupler
- Uses radial probe fed strip line couplers on quartz





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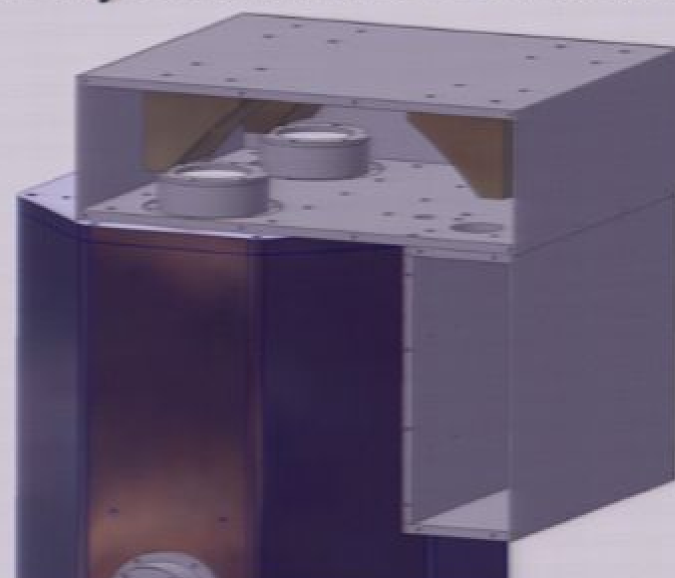
GUBBINS – LO

- Require 2 phase locked LO signals – 195-260 GHz
- One signal 180° phase switched against the other to modulate sky signal
- LO signal generated by microwave synth source (10.8-14.5 GHz)
- Signal split in power divider
- Phase shift introduced in one arm - 10° Schiffman phase switch
- LO signals multiplied x18 by Radiometer Physics multipliers
    - 200 μW ± 3dB – can be individually levelled with attenuators
- LO coupled quasi-optically to mixer blocks in cryostat via two Gaussian beam telescopes
- Feed with drilled smooth-wall horns



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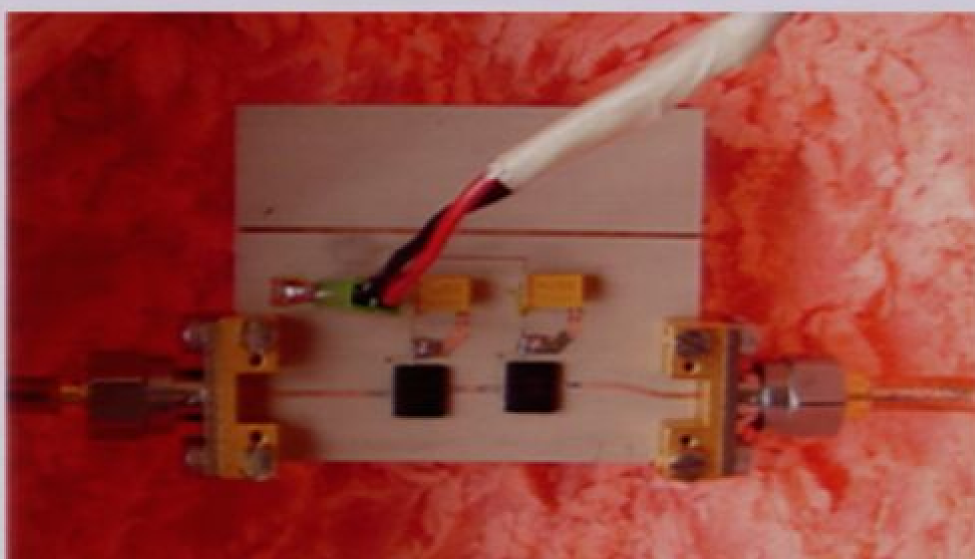
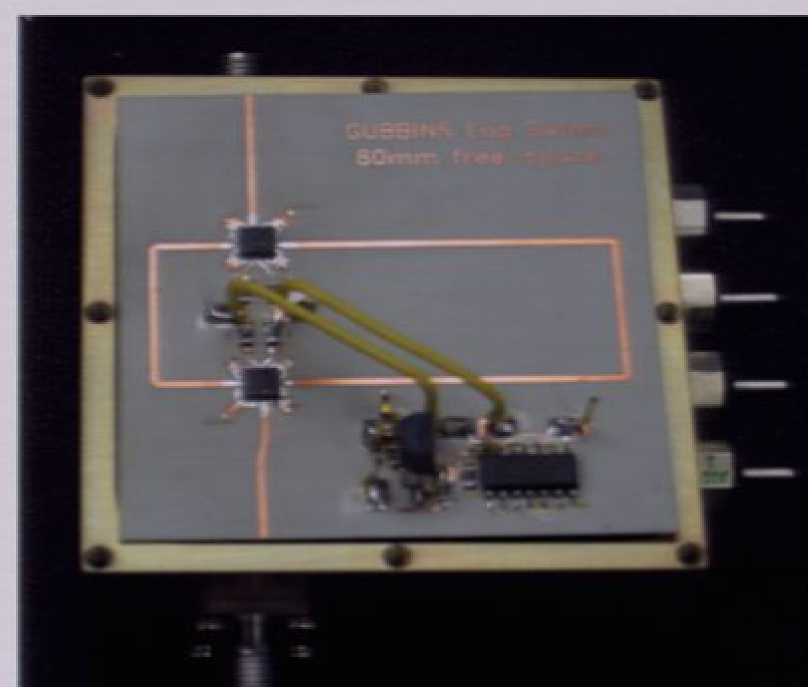
GUBBINS – IF System

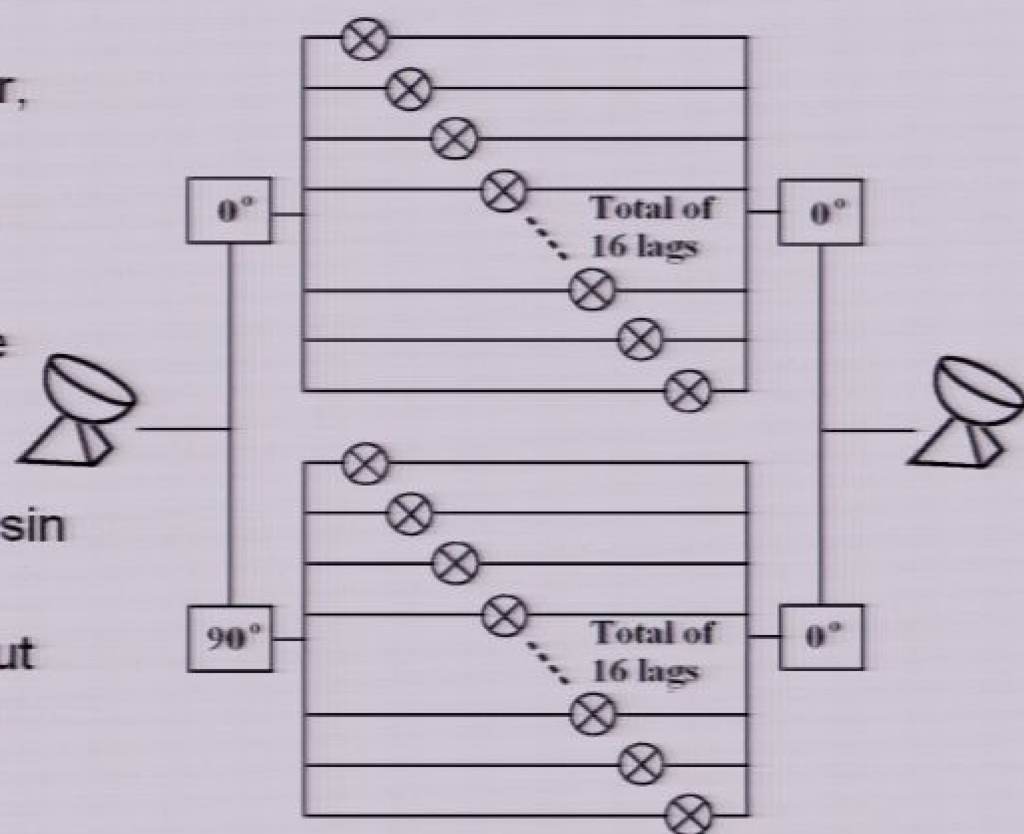
- Cryogenic LNAs from Sandy Weinreb – 3-13 GHz, 3-4 K at 4 K
- Subsequent gain stages based on off-the-shelf Hittite packaged LNA – 2-20 GHz, 13 dB gain, 3.5 dB NF, cascadable, ~$70 per chip – coolable to 4 K with significant improvement in noise: 30-80 K at 4 K from 2-20 GHz
- Further band-pass filters, slope compensation, automatic gain control
- 7-bit 2.5-160 mm Path Compensator built from switched microstrip delay lines





GUBBINS – Correlator

- Analogue 16 lag complex correlator, 2-20 GHz
- Signals from each antenna split in quadrature hybrids
- Signals combined with varying time delays, forming cross-correlations between antennas
- Forms all combinations of cos and sin fringes between two antennas
- Discrete Fourier Transform of output gives independent complex power spectra for each sideband



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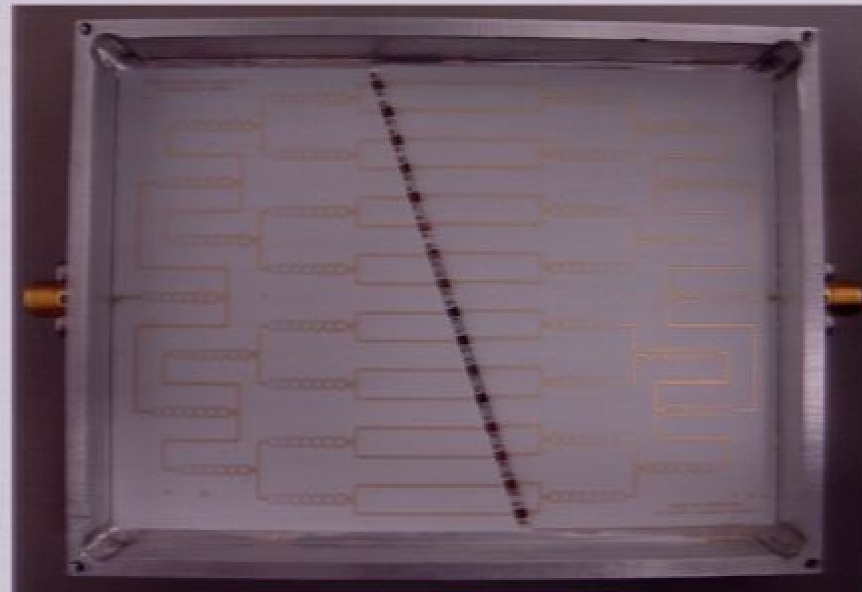
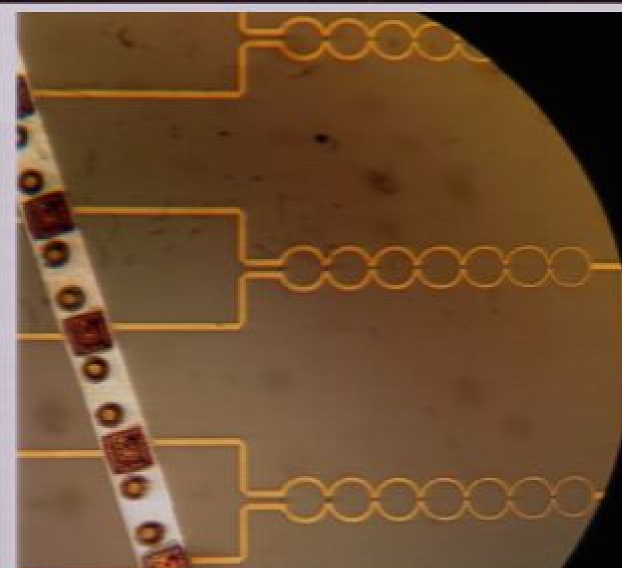
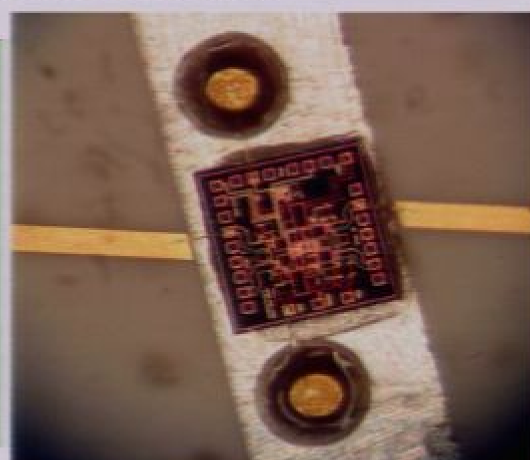
GUBBINS – Correlator

- Signals from antennas split in commercial quadrature hybrids
- Feed 4 lag correlator boards
- Each input signal split 16 ways in splitter tree
- Uses 7-stage Wilkinson power dividers fabricated on alumina
- Signals combined in Gilbert Cell multiplier chips – Andrew Harris and Steve Maas
- Multiplier chips read by Oxford-developed multichannel ADC and FPGA electronics







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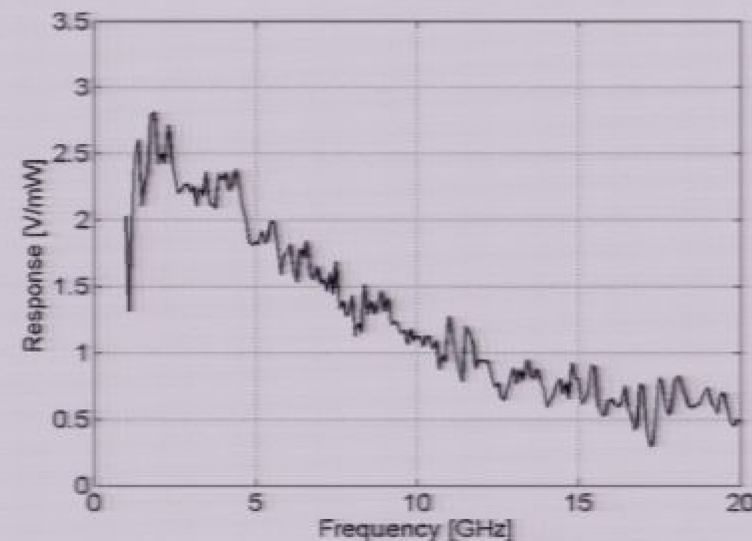
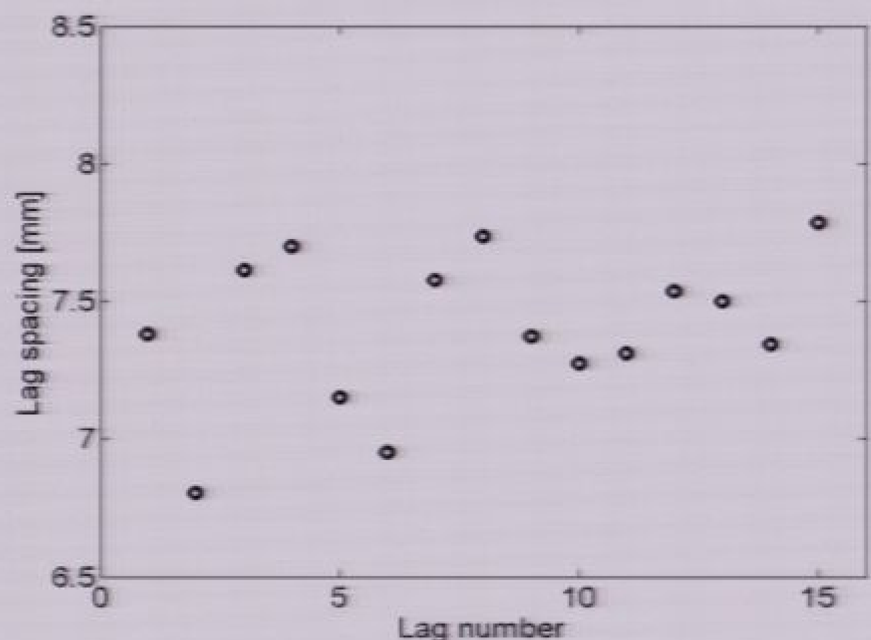
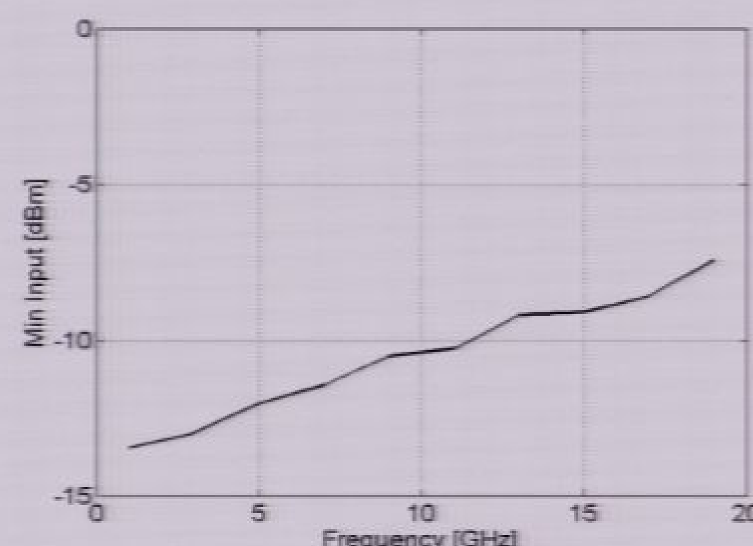
GUBBINS – Correlator

- First correlator board has been tested
- Bandwidth 2-20 GHz achieved
- Good lag spacing uniformity
- Good response and linearity
- Sideband separation will give 36 GHz usable RF bandwidth







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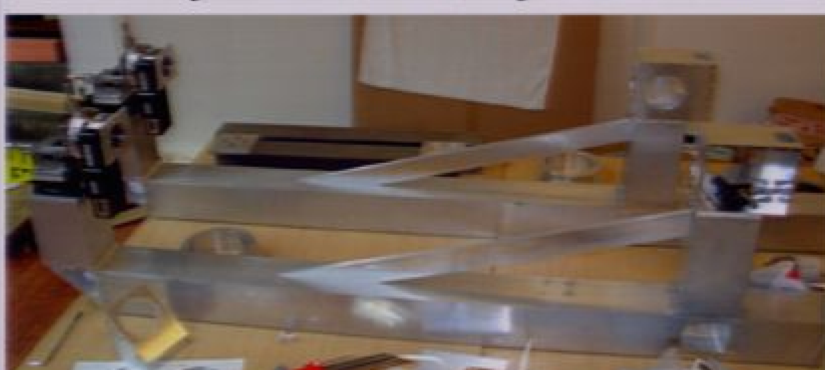
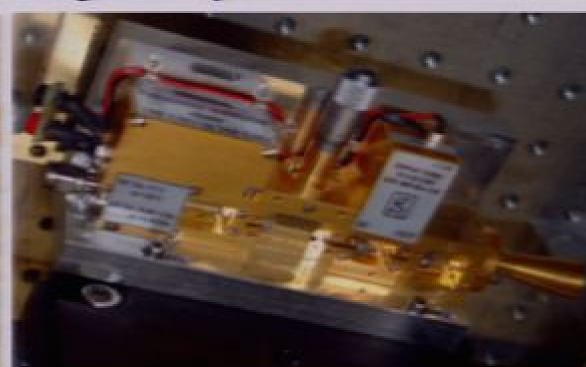
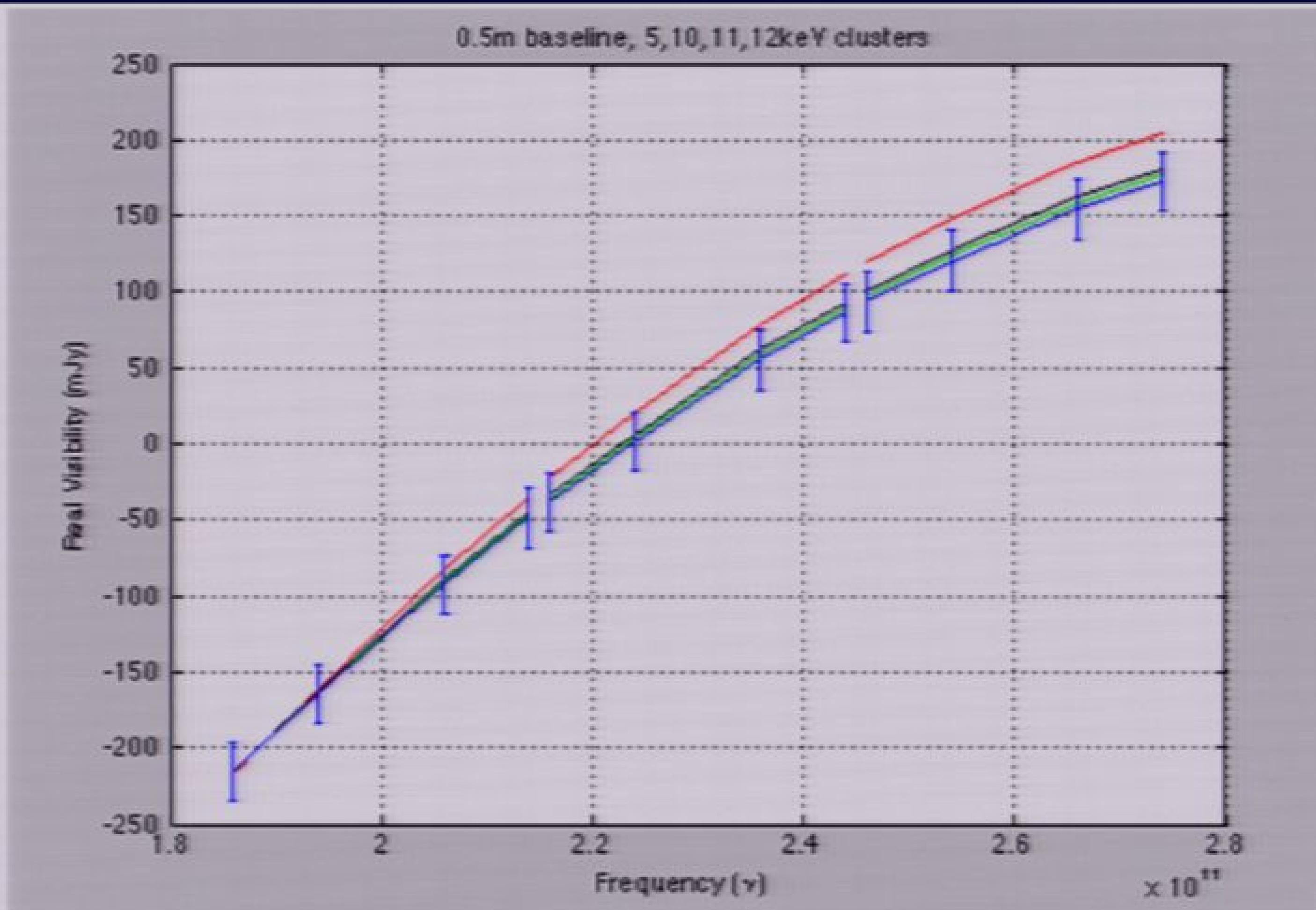
GUBBINS - Status

- Telescope parts are made and partially assembled
- Cryostat is being assembled
- Mixer blocks are in production
- First batch of mixers are being tested
- Cryogenic IF amplifiers delivered
- LO has been delivered, other parts in production
- IF system is awaiting assembly
- Correlator and backend have been prototyped, and are now in production
- Complete assembly and start testing this year





Gubbins sensitivity



10^{15} $M_\odot$ cluster observed for 10 x 6h at each of 3 LO tunings

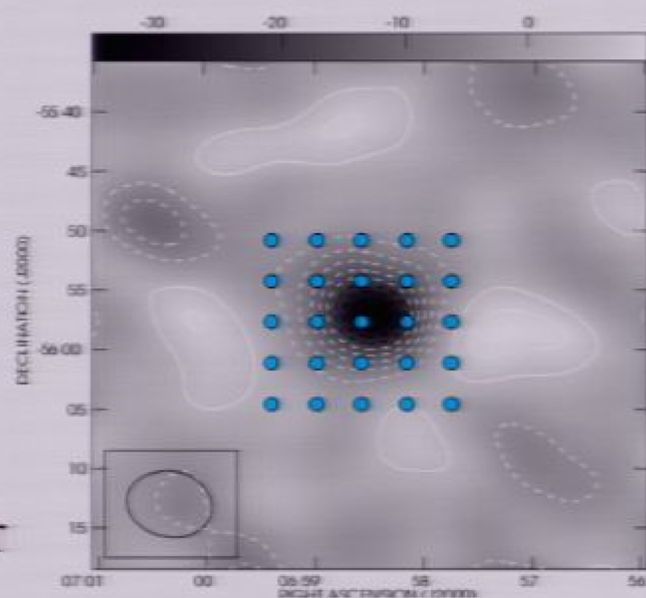
Can an interferometer compete with 1000 element bolometer arrays?

- For pointed observations, yes.
- Relatively few beams point at a cluster instantaneously:
  - $FOM = NET/(f N_{beam})^{1/2}$
    $\sim 700 \mu K s^{1/2} / (1/8 \times 25)^{1/2}$

  $\sim 400\ \mu K\ s^{1/2}$

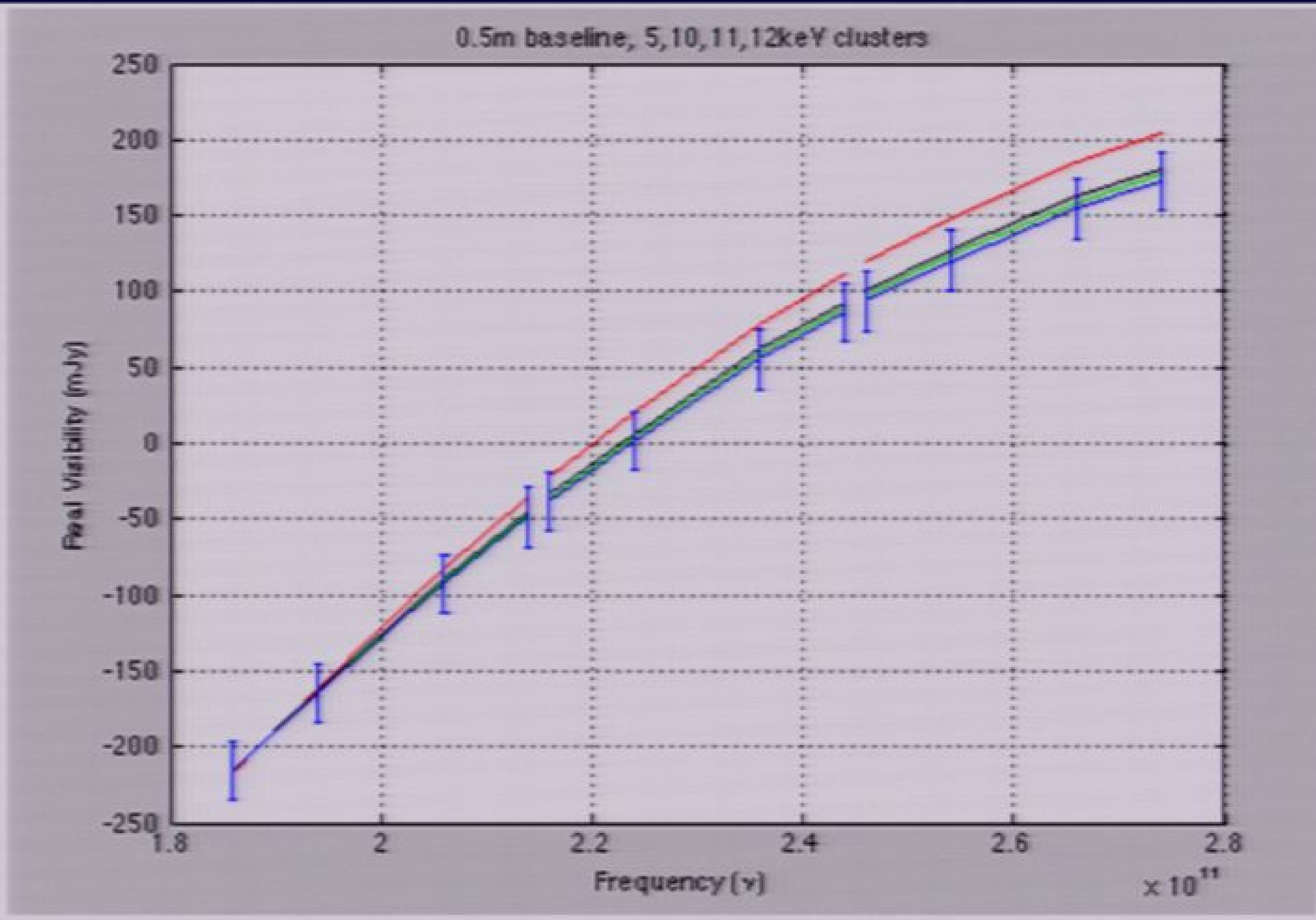
- All interferometer antennas point at cluster
  - $FOM = NET/f$
  - f = filling factor
    $= (FOV/resolution)^2 . N_{ant} \sim 0.5$
  - $NET = T_{sys} / \Delta\nu^{1/2} \sim 50K/(40\ GHz)^{1/2} \sim 250\ \mu K\ s^{1/2}$

  $\sim 500\ \mu K s^{1/2}$



1.5 arcmin beams spaced 0.7 fλ

Gubbins sensitivity



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Oxford Physics

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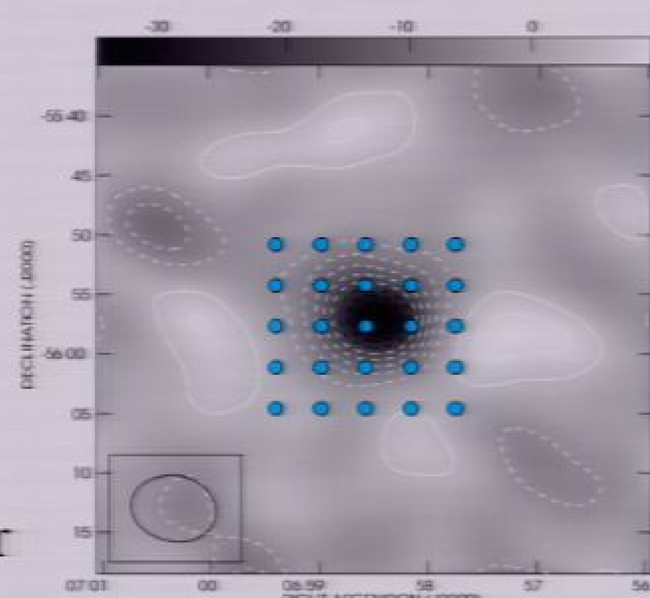
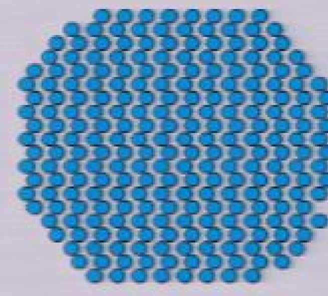


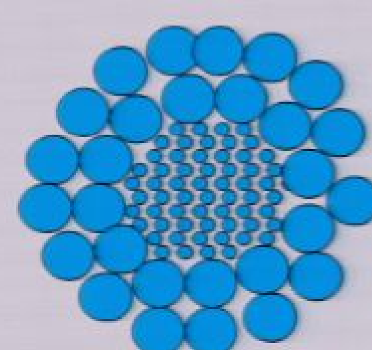
1.5 arcmin beams spaced 0.7 fλ.

The magic of foveated arrays

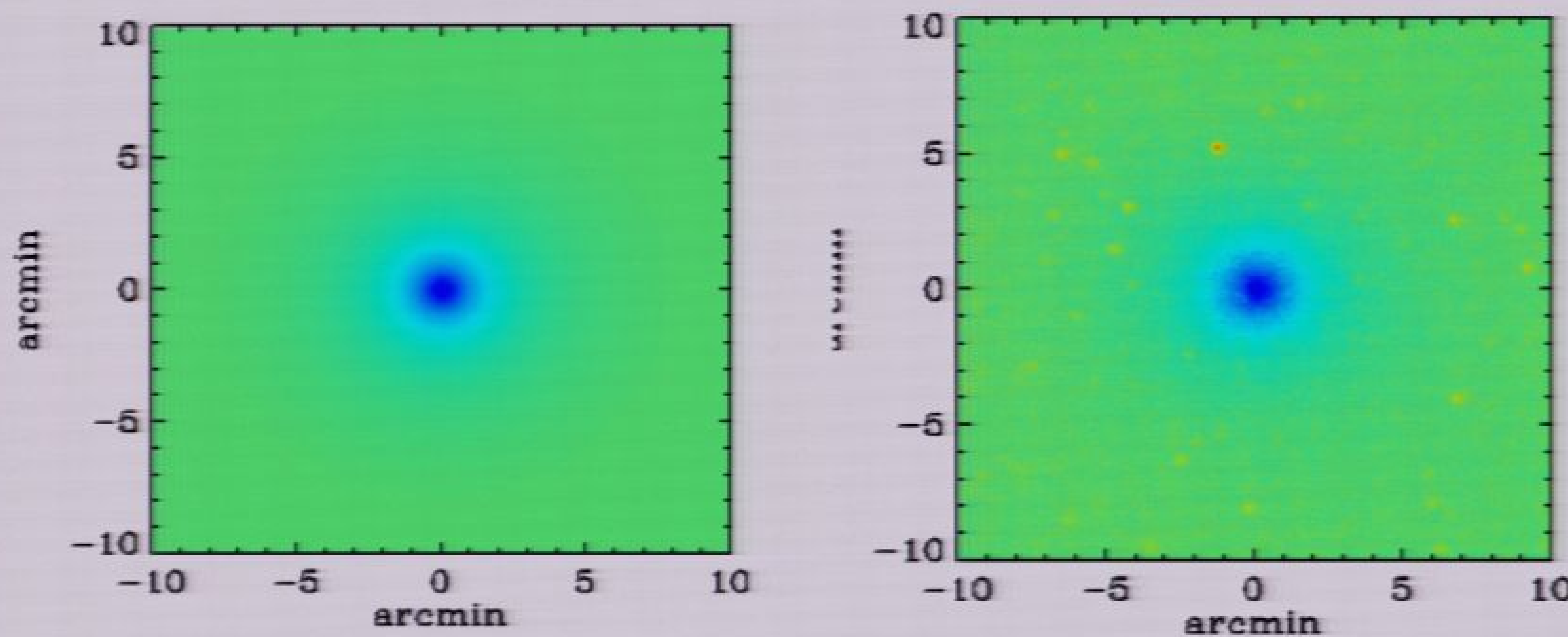
- Simple dense array with high filling factor:
  - $N_{ant} = f.(FOV/resolution)^2$
  - $N_{corr} \sim N_{ant}^2 = f^2(FOV/resolution)^4$
  - eg FOV = 10 arcmin, res = 30 arcsec,
    $N_{ant} = 600$,
    $N_{corr} \sim 360{,}000$



- Foveated array :
  - Core with small antennas, larger antennas around
  - May use multi-beams in larger antennas
  - Eg $N_{ant,small} = 150$, $N_{ant,big} = 45$
  - $N_{corr} \sim 38{,}000$



Simple simulation...



Sarah Church

- 100 1m dishes + 100 3m dishes where each 3m dish has 7 pixels, has 800 detectors, but requires ~ few x 10^5 correlations

Summary

Oxford Physics

- Interferometers are a great way to do pointed SZ (cf CBI, SZA…)
- Sufficiently low and high resolutions are feasible
- ALMA will give very hi-res… but not very low res
- HEMT and SIS front-end technologies give competitive noise temperatures and bandwidths to bolometers
- Analogue correlators can give ~40 GHz correlated bandwidth
- Digital correlators are at present expensive but will catch up
- GUBBINS will provide a test-bed for these technologies
- A really good SZ follow-up instrument with wide spectral coverage and angular scale coverage is technically feasible…

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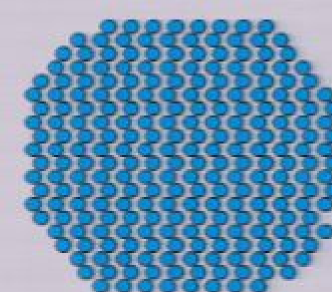
The magic of foveated arrays

- Simple dense array with high filling factor:
  - $N_{ant} = f.(\text{FOV/resolution})^2$
  - $N_{corr} \sim N_{ant}^2 = f^2(\text{FOV/resolution})^4$
  - eg FOV = 10 arcmin, res = 30 arcsec,
    $N_{ant} = 600$,
    $N_{corr} \sim 360{,}000$



- Foveated array :
  - Core with small antennas, larger antennas around
  - May use multi-beams in larger antennas
  - Eg $N_{ant,small} = 150$, $N_{ant,big} = 45$
  - $N_{corr} \sim 38{,}000$