CMB B-modes: experimental considerations

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Exploring the Physics of Inflation
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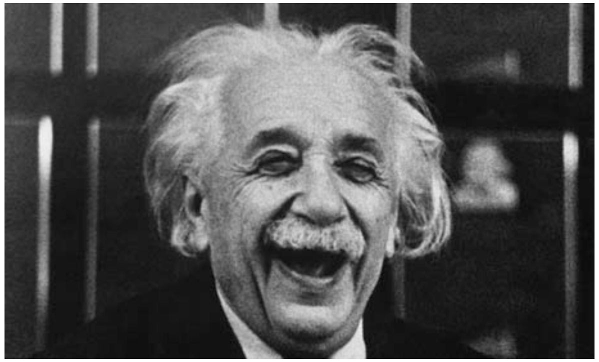
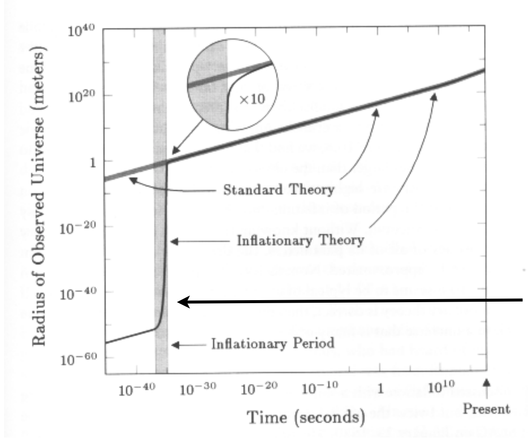
The quest for GW



Primordial GWs

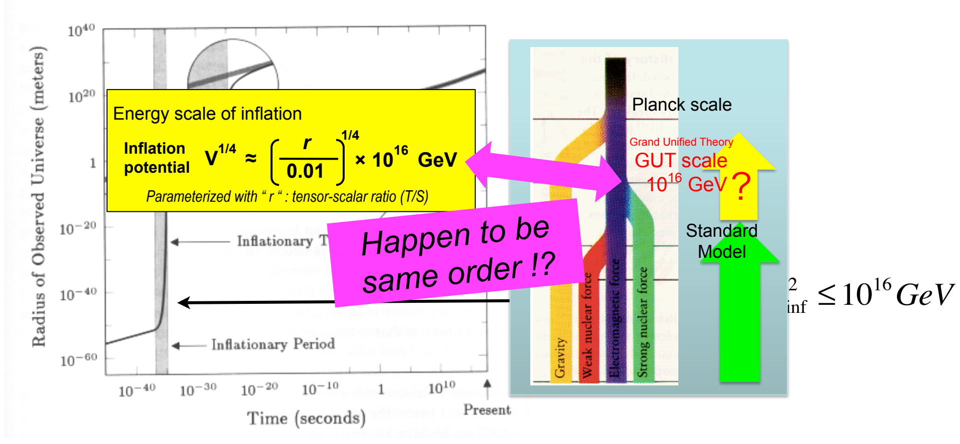


$$GW_{\text{amplitude}} \propto H \propto E_{\text{inf}}^2 \leq 10^{16}\,GeV$$

Energy scale of inflation = GUT scale?

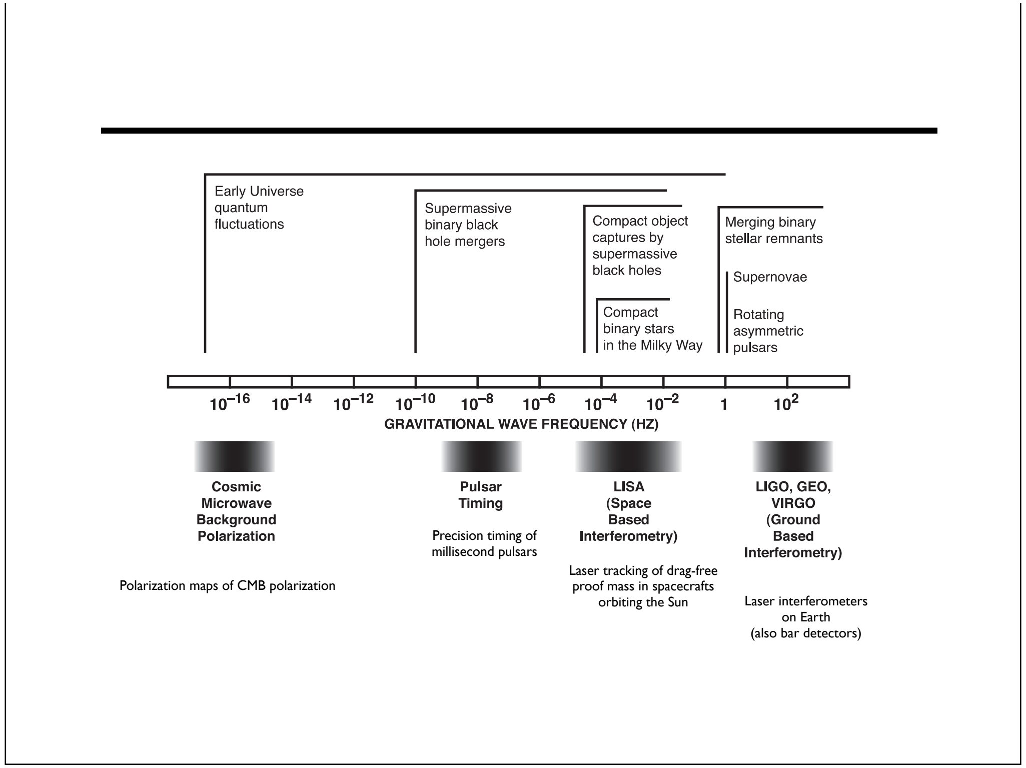
The huge expansion must have generated a GW background. Its amplitude is related to the energy scale of inflation.

Primordial GWs

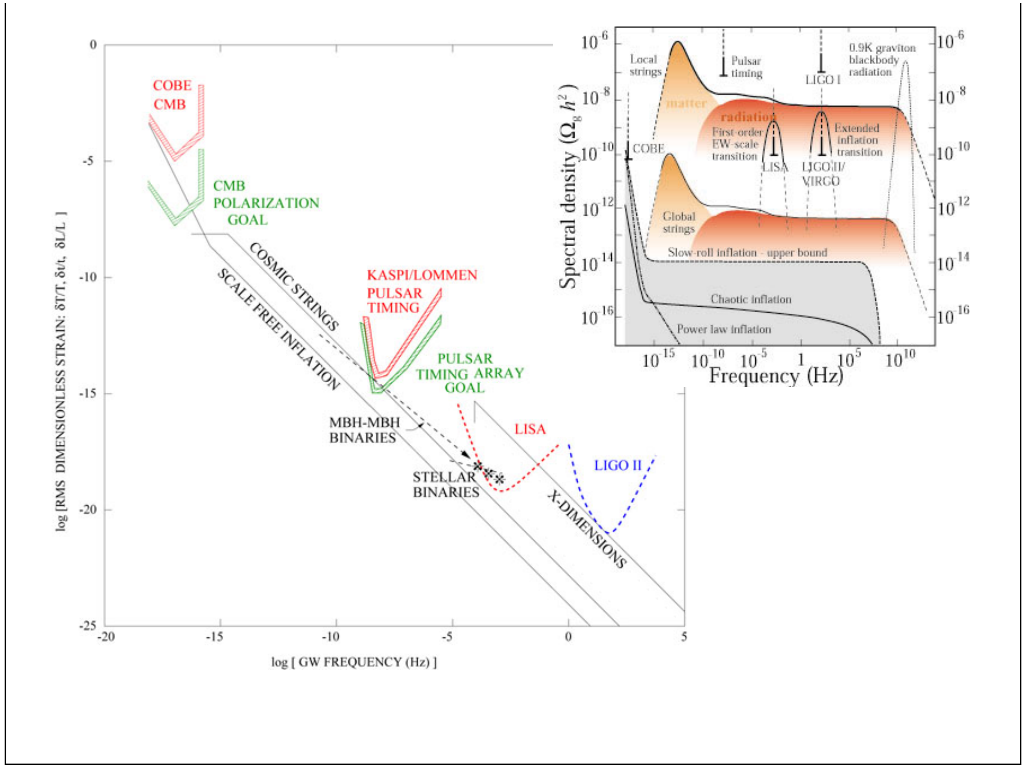


Energy scale of inflation = GUT scale?

The huge expansion must have generated a GW background. Its amplitude is related to the energy scale of inflation.



The spectrum of the GW in Hz, its various sources and the various techniques for detection. Mention Microwave Frequency Gravitational Waves as additional window.



CMB has a real chance to probe the GW produced during inflation.
Extremely interesting is the 0.9K primordial GW background with blackbody spectrum!

CMB B-modes

- One of the various techniques (indirect!)
- Trying to detect primordial gravitational waves originated during inflation using CMB polarization
- Only technique exploring the effects of the very low frequency (large wavelengths) GWs
- SYSTEMATICS!!!!!!

George Gabriel Stokes

Born 13 Aug 1819 in Ireland

Theoretical AND experimental physicist

The polarisation ellipse is an amplitude description of the polarised light and cannot be directly measured.
In 1852 GGS showed that the polarization state of e.m. radiation can be characterised in terms of four intensity parameters. The pol ellipse and its associated orientation and ellipticity angles are directly related to the Stokes parameters.

Few concepts about polarization of e.m. waves. Apologies for the english spelling of polarization!

$$\begin{cases} E_x(z,t) = E_{0x}\cos(\omega t - kz) \\ E_y(z,t) = E_{0y}\cos(\omega t - kz + \delta) \end{cases}$$

$$\frac{E_x^2(z,t)}{E_{0x}^2} + \frac{E_y^2(z,t)}{E_{0y}^2} - \frac{2E_x(z,t)E_y(z,t)}{E_{0x}E_{0y}}\cos\delta = \sin^2\delta$$

taking the time average

$$\langle E_i(z,t)E_j(z,t)\rangle = \lim_{T\to\infty}\frac{1}{T}\int_0^T E_i(z,t)E_j(z,t)dt$$

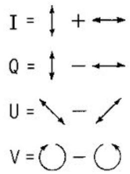
the polarization ellipse becomes

$$S_0^2 = S_1^2 + S_2^2 + S_3^2$$

where

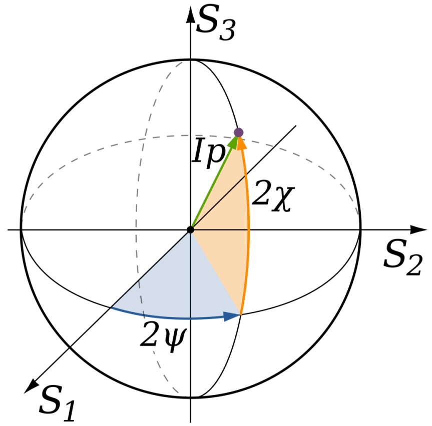
Stokes parameters →

$$\begin{cases} S_0 = E_{0x}^2 + E_{0y}^2 = I \\ S_1 = E_{0x}^2 - E_{0y}^2 = Q \\ S_2 = 2E_{0x}E_{0y}\cos\delta = U \\ S_3 = 2E_{0x}E_{0y}\sin\delta = V \end{cases}$$



The two equations on top describe a propagating e.m. wave along the z direction. Eliminating the propagator (omegat-kz)

Henri Poincare'



$$\begin{cases} U = S_1 = pI\cos(2\psi)\cos(2\chi) \\ Q = S_2 = pI\sin(2\psi)\cos(2\chi) \\ V = S_3 = pI\sin(2\chi) \end{cases}$$

Jones calculus

- Applicable to light fully polarized
- Incident polarized light identified by Jones vectors
$$\begin{pmatrix} E_x(t) \\ E_y(t) \end{pmatrix} = \begin{pmatrix} E_{0x} e^{i(kz-\omega t+\phi_x)} \\ E_{0y} e^{i(kz-\omega t+\phi_y)} \end{pmatrix} = \begin{pmatrix} E_{0x} e^{i\phi_x} \\ E_{0y} e^{i\phi_y} \end{pmatrix} e^{i(kz-\omega t)}$$
- Linear optical elements are described by Jones matrices
- Describes amplitudes and therefore coherent light

Mueller calculus

- Matrix method to manipulate Stokes vectors
- Describes intensities (measurable)
- 4 x 4 matrices
- generalization of Jones matrices
- Can treat fully, partial or no polarized light

Optical elements

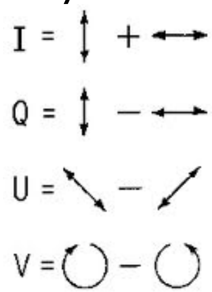
- Represented by Mueller matrices
- Example, HWP with fast axis vertical:

$$\begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & -1 \end{pmatrix}$$

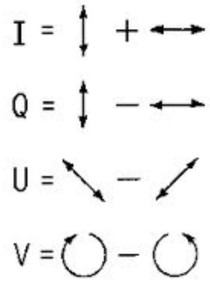
- Any optical element can be represented

Measuring polarization: bolometers

- Bolometers are classical detectors: sensitive to $\langle EE^* \rangle$
- To get U and Q only way is to rotate the instrument by 45^0, or rotate the pol sky with a HWP
- Mechanical means systematics!
- (see bolometric interferometry)



Measuring polarization: HEMT



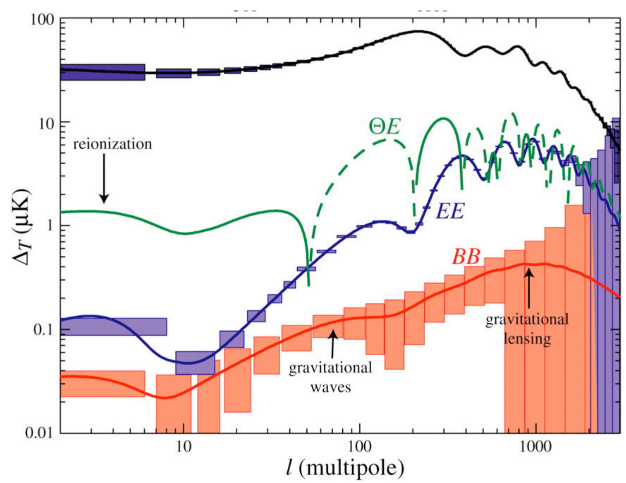
- Cryo LNA do not detect. They amplify amplitudes!
- After amplification, amplitudes can be processed to determine U and Q without mechanical rotations
- No mechanical means less systematics!

CMB polarization experiments

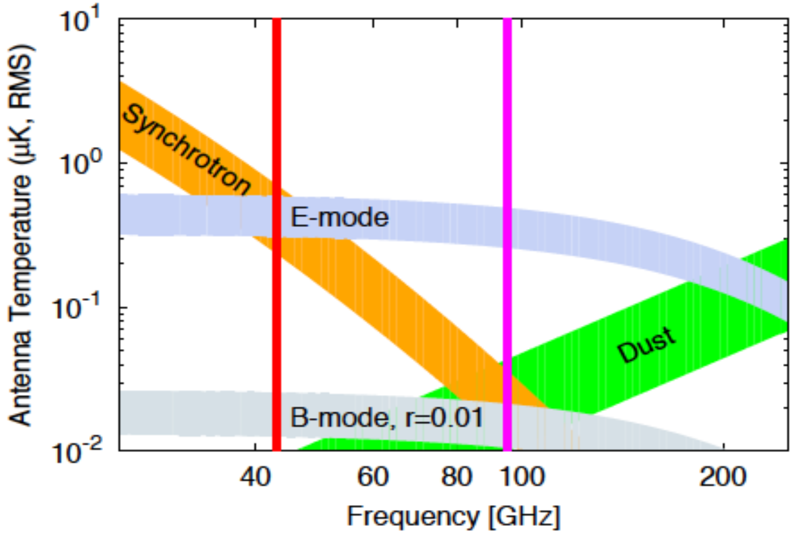
- Observing site, frequency bands
- Optics
- Detectors
- Observing strategy
- Calibration
- Foregrounds

When designing a CMB B-mode experiment we need to take into account, and optimise, several components.

B-modes << 100 nK!

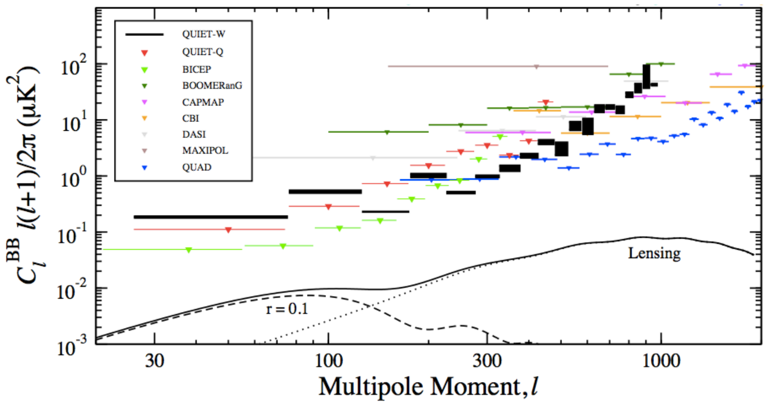


Then we must realise that we are trying to detect a very tiny signal about 9 order of magnitude lower than the sky background. Not easy...



Synchrotron
E-mode
Dust
B-mode, r=0.01
Antenna Temperature (μK, RMS)
10^1
10^0
10^{-1}
10^{-2}
40
60
80
100
200
Frequency [GHz]

Upper limit for *B*-modes



Upper bounds at 95% C.L.
43 GHz band: r < 2.2
95 GHz band: r < 2.7

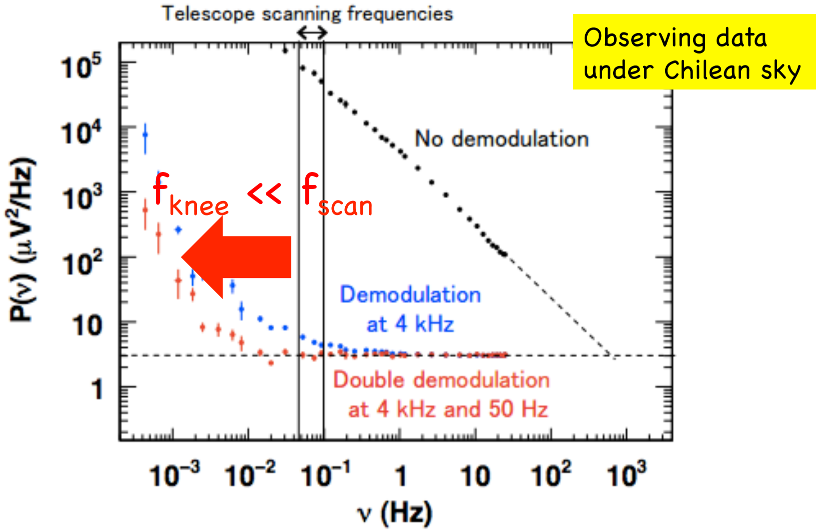
Design of CMB B-modes experiments

- Very challenging
- Problems: receivers, optics, atmosphere(*)
- 1/f noise and scan strategy
- side-lobes
- other instrumental effects
- calibration
- (*) from ground

Measurements strategies

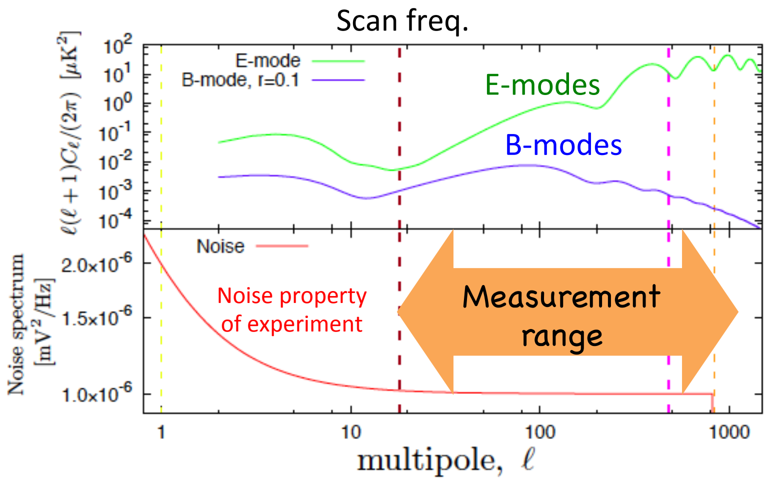
Direct Imagers		Interferometers	
Bolometers	**Coherent**	**Bolometers**	**Coherent**
1,000s pixels sensitivity 1/f noise!	100 pixels stability low system. ***room for improvement***	No QL No amplif. Measure \ell 1/f noise!	Complex electronics QL stability ***room for improvement***

QUIET: Very small 1/f knee



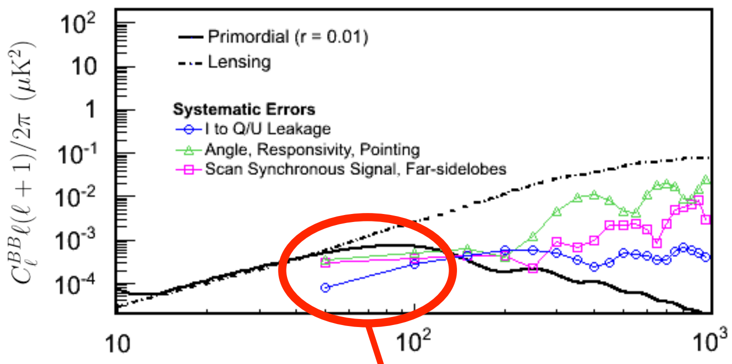
Double demodulation suppressed 1/f noise !!

QUIET: Very small 1/f knee



QUIET is free from effects of 1/f noise !!

QUIET: Systematic error for *B* modes



The smallest syst. error to date: δr<0.01
Major inflation models could be covered with large statistics

Bolometric interferometry

- Adding interferometry with bolometers as sensitive detectors
- Puts together two good things: sensitivity of detectors and interferometry
- First proposed in 1999 by LP (and PT) while in Wisconsin
- Produced MBI instrument
- Inspired BRAIN/QUBIC and EPIC-WISC
- Cheap way to make very large correlators

Ryle's Adding Interferometer (1952)

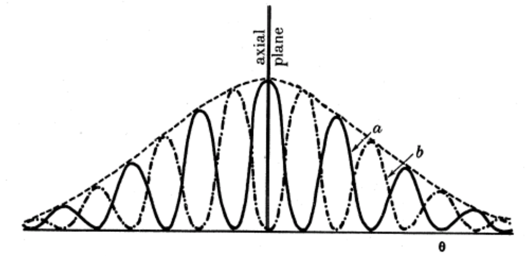


FIGURE 1. Reception pattern of two spaced aerials: (*a*) connected in phase and (*b*) connected in anti-phase.

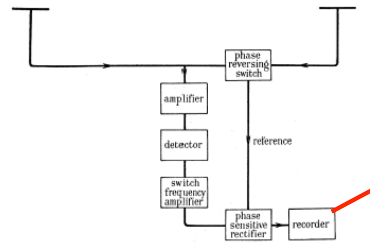


FIGURE 2. Block diagram of the phase-switching system.

"visibility"

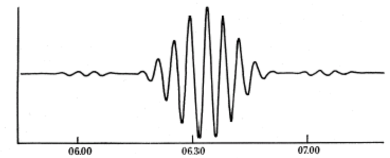
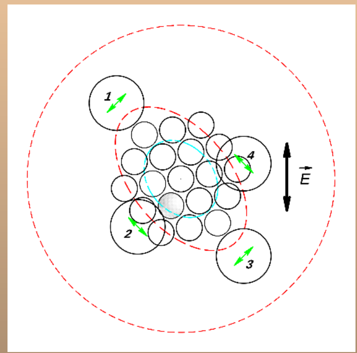
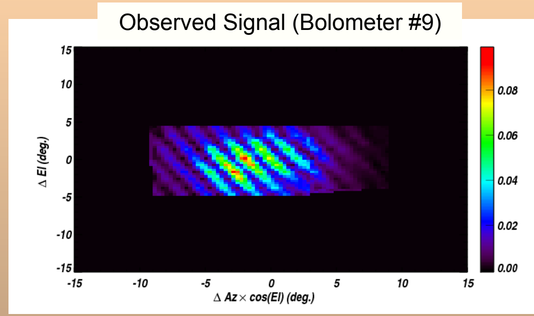
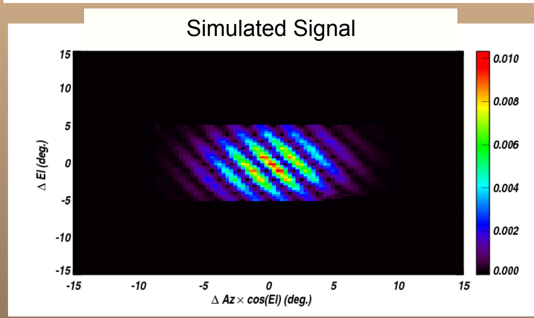


FIGURE 3. Record of the intense radio star in Cassiopeia obtained with the phase-switching system on a wave-length of 3·7 m.

MBI-4 interference fringes

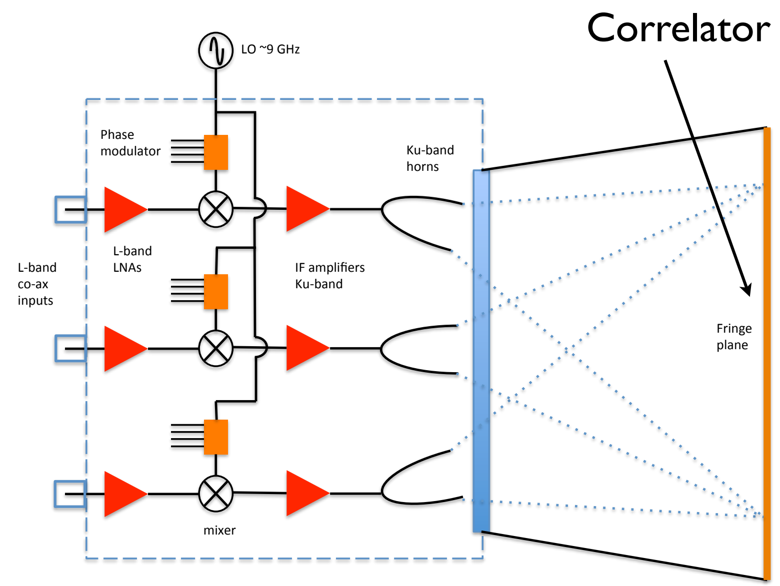






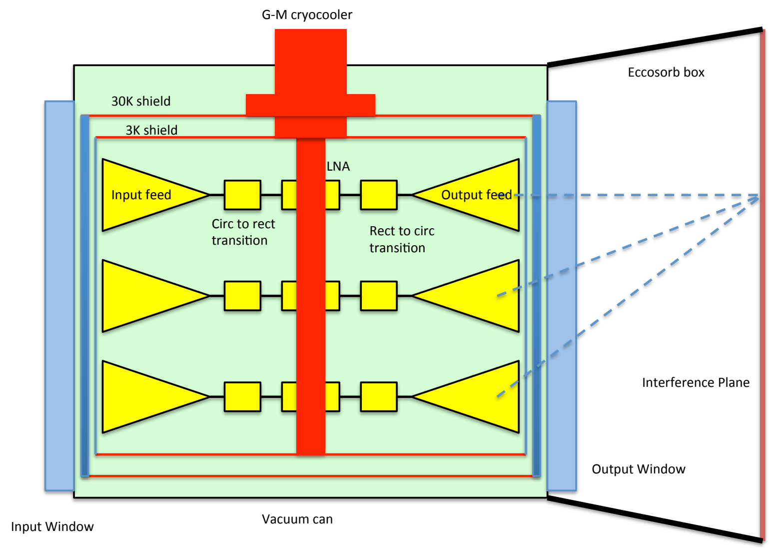
- Baseline formed by horns 2 and 3
- Observed Gunn oscillator on tower

A simple correlator



See Watson's talk for an alternative proposal

Can be used as polarimeter for CMB B-modes



Active Quasi-Optical Correlators: good for space?
Correlator does not use power! (It is passive)

Table 2: Comparison of current, future and ultimate achievable sensitivity to CMB polarization

Frequency [GHz]	PLANCK HFI NET/feed[a] [μK_{CMB} sec$^{1/2}$]	Bolometer NET/feed [b] [μK_{CMB} sec$^{1/2}$]	3xQL HEMT $2^{-1/2}$ NET/feed[c] [μK_{CMB} sec$^{1/2}$]	1 x QL	CMB BLIP NET/feed[d] [μK_{CMB} sec$^{1/2}$]
30	120 (LFI)	45	40	13	19
45	140 (LFI)	38	42	14	18
70	180 (LFI)	33	48	16	17
100	220 (LFI)	31	59	20	16
150	60 (HFI)	33	91	30	16
220	90 (HFI)	48	185	62	18
350	275 (HFI)	160	882	290	28

a) Goal sensitivity of each feed to $\Delta T = (\Delta Tx+\Delta Ty)/2$ and Stokes parameter Q **or** U, defined as $(\Delta Tx-\Delta Ty)/2$.
b) Sensitivity for 100 mK, Ge thermistor, Polarization-Sensitive Bolometer pair, assuming 1.0K RJ instrument background, 50% optical efficiency and 30% bandwidth.
c) Same for HEMT amplifier with noise 3x quantum limit over 30% bandwidth. The sensitivity quoted is $2^{-1/2}$ x NET to take into account the ability to measure Q and U simultaneously with appropriate post-amplification electronics.
d) The ultimate limit to sensitivity to Q or U, for zero instrument background and a noiseless direct detector.

LNAs above the blue line can be BLIP even with working at QL

Hints for a space mission multi-wavelength
20, 30, 40, 50, 60 and 70 GHz

HEMT better than bolos?

- Operating characteristics of HEMT are generally superior to bolometers
- Dynamic range, linearity, dependance of responsivity on cryostat temperature, reproducibility, infrared power loading, speed, sensitivity to RFI, required operating temperature, etc.

HEMT in space

- A space mission for low frequencies (<70 GHz) will be competitive with bolometric missions.
- Example: a cluster of small, simple satellites forming an interferometer for measuring the B-modes
- Interferometer vs imaging → it is the subject for another talk!
- From the ground, having the atmosphere, if we reach the QL, LNAs will be competitive with bolometers above 70 GHz.

Comparing bolometers and HEMTs 1

- Bolometers
  - Detect power
  - No quantum limit
  - Broadband thermal
  - Large format
  - Need $T_0 < 300$ mK
  - Little power dissipation
  - 1/f dealt mechanically
  - Interferometry possible
  - Little digital
- Cryo LNAs
  - Amplitude/phase
  - Quantum limit
  - Sensitive only RF
  - Medium format
  - Need $T_0 \approx 20$K
  - Power hungry
  - 1/f dealt electronically
  - Interferometry standard
  - Totally digital

Comparing bolometers and HEMTs 2

- Bolometers
  - Need optics to form images
  - Polarimeter complex (no simult. U&Q)
  - Need band-pass filters
  - Microphonics
  - Sensitive to Temp fluctuations
  - Complex back-end electronics
- Cryo LNAs
  - Interferometer with no optics
  - Polarimeter integrated (measure U&Q)
  - Thermal filters
  - Little microphonics
  - Sensitive to RFI
  - Complex back-end electronics but digital sampling possible

Imagers need FT of maps
Interferometers measure \ell directly

Imagers difficult multiplexing
Interferometers complex correlators
(mention QO and AQC)

1/f noise of bolo require mechanical modulation
After amplification, electronic modulation give stability to coherent systems

Bolo more sensitive than coherent

Bolo >70 GHz (dust)
Coherent < 70 GHz (sync)

Advantage of interferometers over imagers because of no aberrations on the edge of the array

Bolometers are better (?)

- No QL
- Large format arrays
- Limited by photon noise – in principle
- Sensitive up to sub-mm/IR
- Relatively simple fabrication techniques

HEMTs are better (?)

- Dynamic range
- Linearity
- Dependence of responsivity on T_0
- Dependence of responsivity on IR power loading
- Speed
- Required operating temperature T_0

➡ **Stability!**

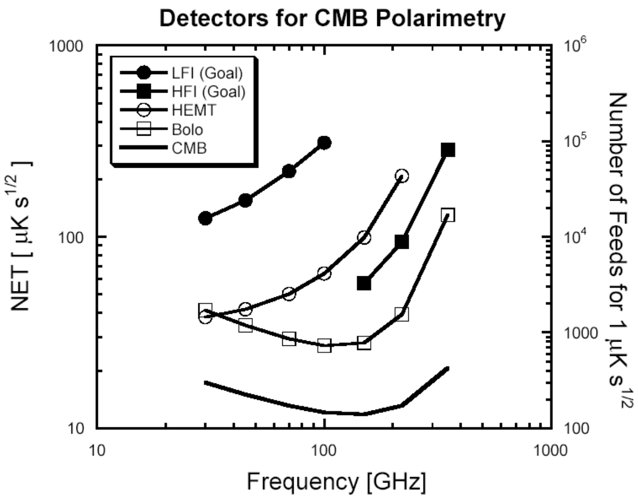
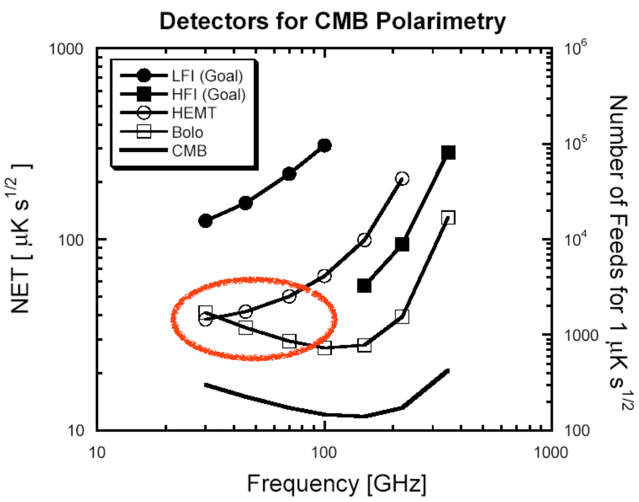


Figure 4: Sensitivity of bolometer- and HEMT-based receiver systems for CMB polarimetry. The goal sensitivities per feed for Planck LFI (HEMT-based, solid circles) and Planck HFI (bolometer-based, solid squares) in polarization-sensitive channels. The sensitivity achievable with 100 mK bolometers, assuming 50 % optical efficiency, 30 % bandwidth, 5x dynamic range, and a 1 % emissive 60 K telescope (open squares) is about a factor of three better than Planck HFI, but does not allocate sensitivity to systems noise sources. Bolometer sensitivity compares favorably to that of future HEMT amplifiers (open circles), calculated assuming 3x quantum-limited noise performance, 30 % bandwidth, and simultaneous detection of both Q and U. The ultimate background-limited sensitivity from the CMB, assuming 100 % efficiency and a noiseless detector, is shown by the solid curve.



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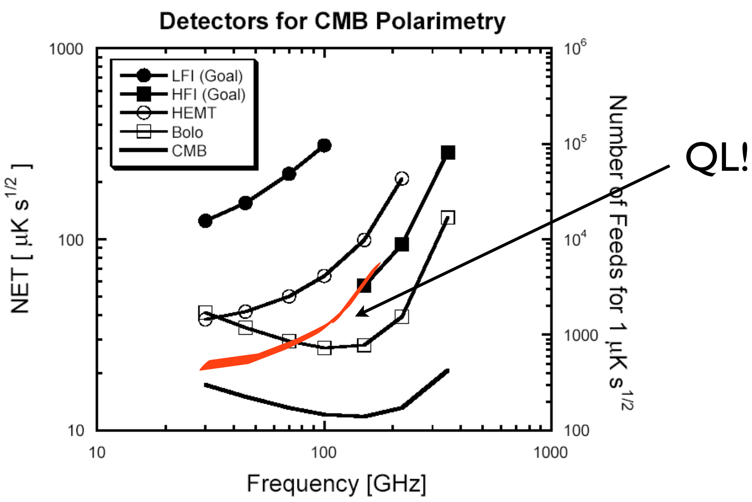

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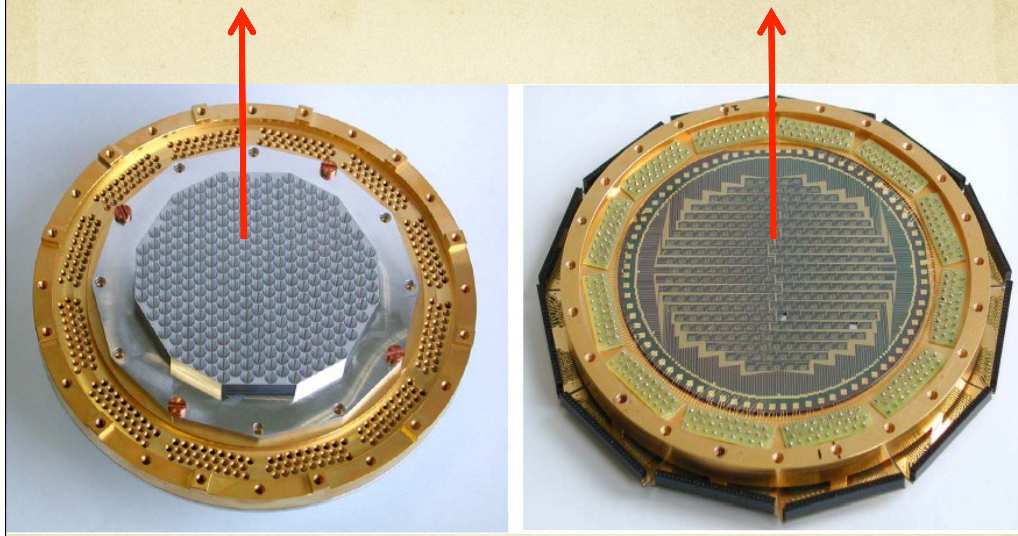
Inside an LNA

- Integrate a complete radiometer on a single module (MMIC)

Figure 1: A 95-GHz module with the radiometric components integrated (left) and the 90-element 95-GHz array under assembly (right).

SKY

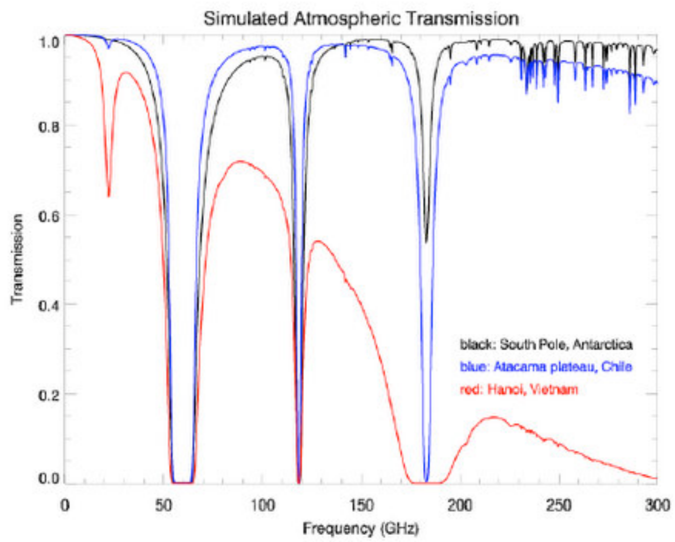
Optics and then SKY



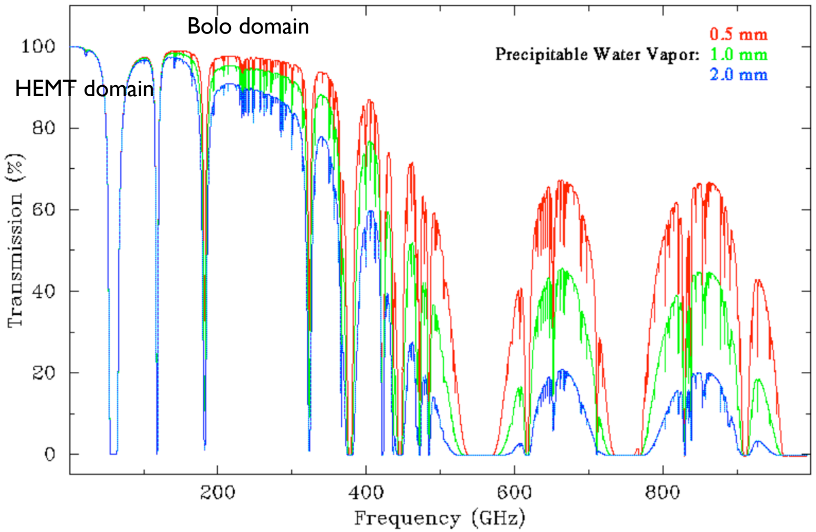
Horn array and bolometer array: which one is cleaner electromagnetically?

In addition, if interferometer, each pixel is as good as the others. Imagers suffer from aberration on the edge pixels

S. Pole vs Atacama

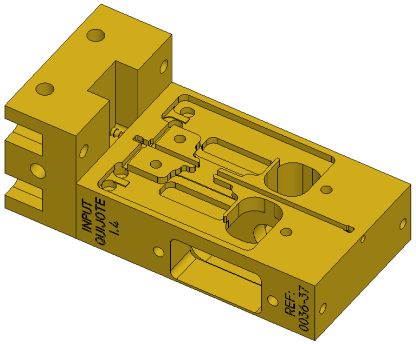


≤110 GHz PWV not critical (better go high altitude)



Transistor + MMIC

- Towards Quantum Limit
- Reduce physical temperature of cryo LNAs
- Improve input matching



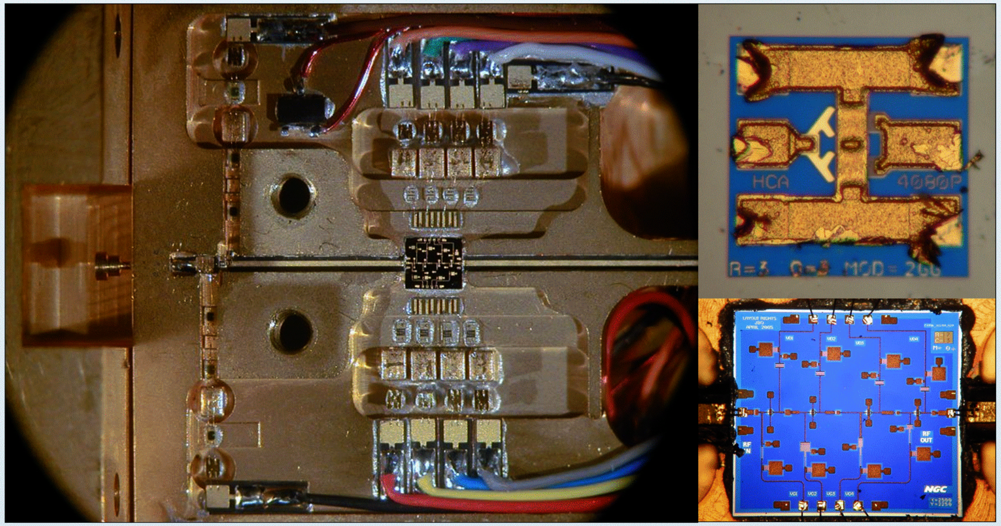


Figure 1. The T+MMIC LNA (main); from left to right the various components are a broadband waveguide to microstrip transition, the cryo-3 discrete transistor and its bias chains, the Faraday MMIC and its bias chains. Top right, a cryo-3 transistor, bottom right the Faraday MMIC.

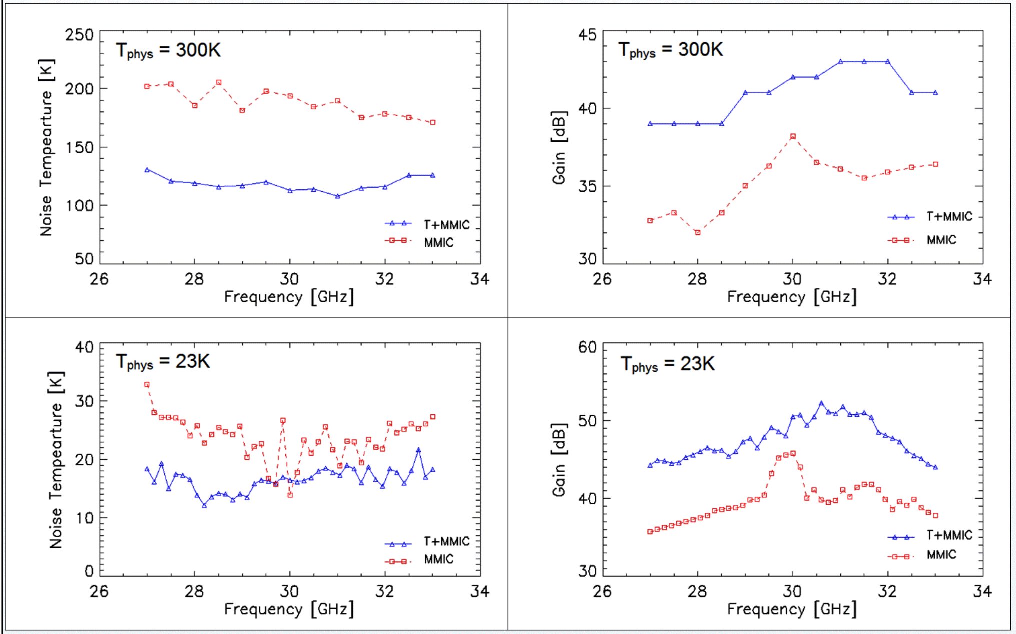
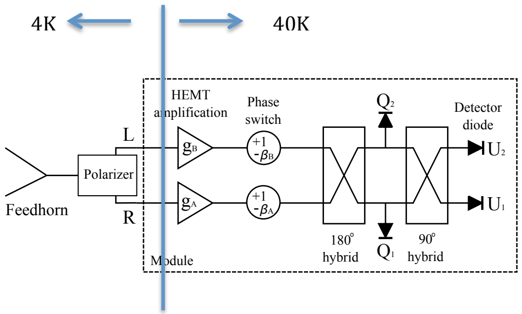
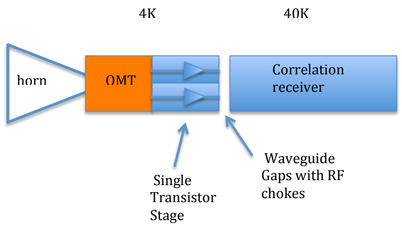
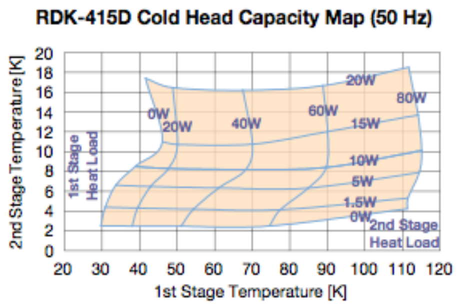
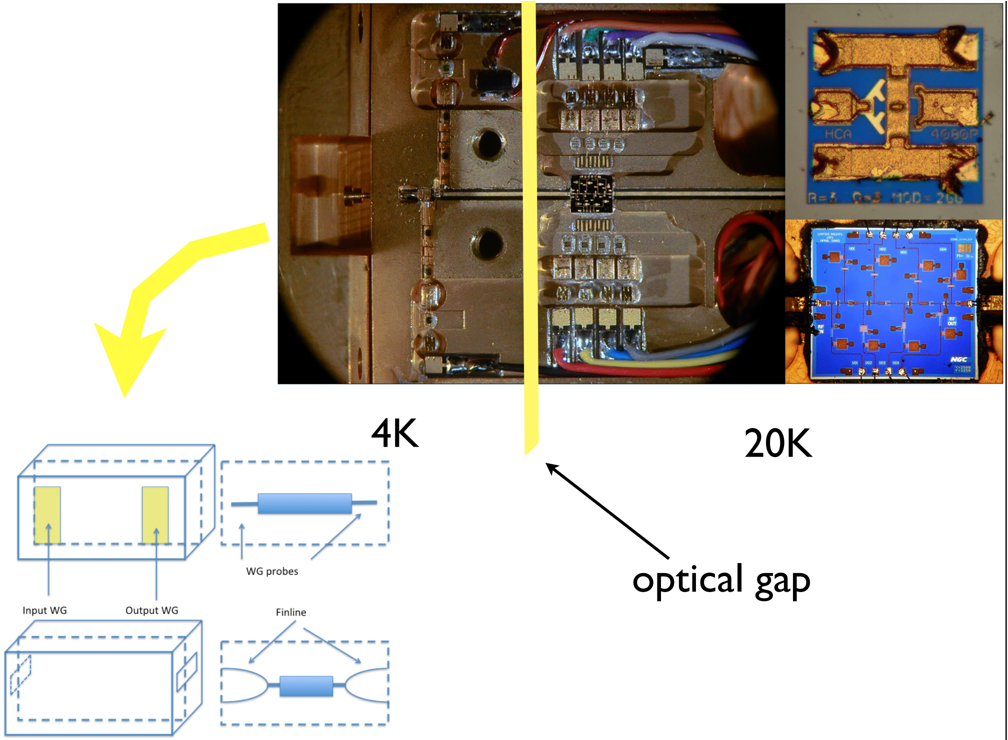


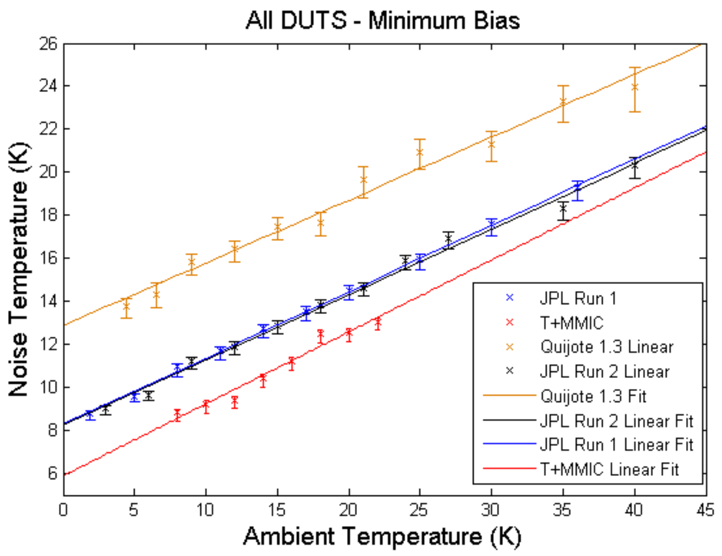
Figure 2. The cryogenic and room temperature noise and gain performance of the T+MMIC LNA and a Faraday MMIC only LNA. The LNAs were biased for minimum noise.

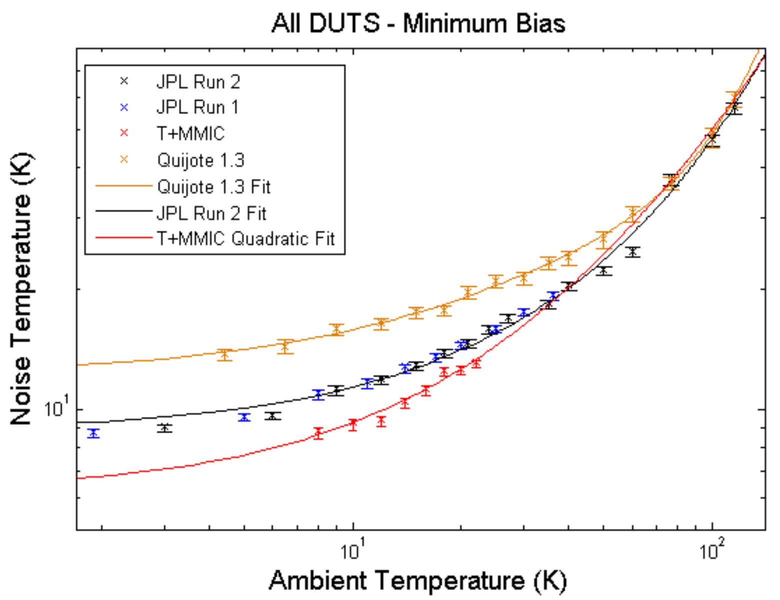

4K
40K
HEMT amplification
Phase switch
Detector diode
Polarizer
Feedhorn
L
R
Module
180° hybrid
90° hybrid
Q2
Q1
U2
U1


4K
40K
horn
OMT
Correlation receiver
Single Transistor Stage
Waveguide Gaps with RF chokes


RDK-415D Cold Head Capacity Map (50 Hz)
2nd Stage Temperature [K]
1st Stage Temperature [K]
1st Stage Heat Load
2nd Stage Heat Load
0W
20W
40W
60W
80W
15W
10W
5W
1.5W


4K
20K
optical gap
WG probes
Input WG
Output WG
Finline


All DUTS - Minimum Bias
Noise Temperature (K)
Ambient Temperature (K)
26
24
22
20
18
16
14
12
10
8
6
0
5
10
15
20
25
30
35
40
45
JPL Run 1
T+MMIC
Quijote 1.3 Linear
JPL Run 2 Linear
Quijote 1.3 Fit
JPL Run 2 Linear Fit
JPL Run 1 Linear Fit
T+MMIC Linear Fit



All DUTS - Minimum Bias
JPL Run 2
JPL Run 1
T+MMIC
Quijote 1.3
Quijote 1.3 Fit
JPL Run 2 Fit
T+MMIC Quadratic Fit
Noise Temperature (K)
10^1
10^1
10^2
Ambient Temperature (K)

Let's go to space!

High Efficiency Cryocoolers

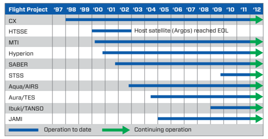
With more than 20 years experience developing cryocooler technology, Northrop Grumman has produced and delivered over 35 space-qualified cooler systems to date, more than the rest of U.S. industry combined.

Designed to operate over 10 years with unchanged performance, Northrop Grumman coolers have accumulated more than 100 years of on-orbit performance without failure.

Northrop Grumman's reliable, efficient and light-weight pulse tube cryocoolers are designed for cooling scientific instruments, sensors and optics over a wide temperature range from 1.7K to 300K (-456°F to 80°F). The wide temperature and cooling power ranges are produced using four sizes of non-wearing, flexure-bearing compressors and passive (no moving part) pulse tube cold heads that assure longevity without performance degradation. Simple mechanical and thermal interfaces facilitate payload integration.

The four standard scaled compressor designs use a vibrationally balanced, back-to-back configuration. Available configurations include single or multi-temperature linear, coaxial and Joule Thomson cold head versions. Cooling can be provided at distances of 10's of meters from the cryocooler device.

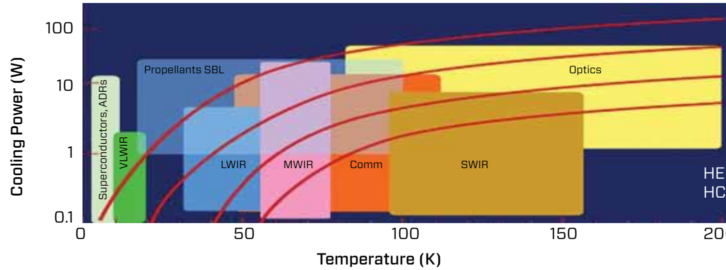
Northrop Grumman Cryocooler Flight History



The range of available cooler configurations and associated control electronics allows for optimal size and mass scaling for the capacity requirement of a particular application. The autonomous control electronics incorporate high stability temperature and active self-induced vibration control as well as fault management.

Northrop Grumman's space-flight proven cryocoolers and electronics offer scalability, efficient performance and demonstrated reliability to enable critical instrument/optical performance with assured mission success.

Key Parameters for Northrop Grumman Cryocooler Product Line



Cryocooler	Typical Input Power Range (W) *	Mass (Kg)
HCC	180-700	18.7
HEC	40-180	4.1
Mini	20-80	1.5
Micro	5-40	0.6

HEC = High Efficiency Cryocooler
HCC = High Capacity Cryocooler

* These values apply to Earth orbiting missions. Power for deep space missions can be reduced (lower end of power range) given greater heat rejection on thermal radiators with deep space views.

Small space mission?

- 1st stage cryo LNA @ 20K (~1W)
- 2nd stage MMIC @ 60K (rad. cooled)
- >1,000 polarimeter with current commercially available space coolers
- Could be the "COBE-like" mission for B-modes: "detect but not characterise"

The next technology for PRISM-like?

- IDEAL: amplifiers with no QL
- KIDs parametric amplifiers?
- Can beat QL by "squeezing" quantum noise into the quadrature component
- Very little power dissipation: 10,000s pixels in space?
- Perhaps Mega-pixel mm/sub-mm polarimetric camera/interferometer in space?

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Observation of 4.2-K Equilibrium-Noise Squeezing via a Josephson-Parametric Amplifier

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(Received 9 October 1987)

We have demonstrated 42% squeezing of 4.2-K therma! noise using a Josephson-parametric amplifier operated at 19.4 GHz. The amplifier has been operated at 0.1 K with an excess noise of 0.28 K referred to the input port. This is less than the vacuum fluctuation noise $h\nu/2k = 0.47$ K at 19.4 GHz. The amplifier thus is less noisy than a linear phase-insensitive amplifier such as a maser could in principle be.

PACS numbers: 05.40.+j, 42.50.Dv, 84.30.Ey, 85.25.Cp

A Wideband, Low-Noise Superconducting Amplifier with High Dynamic Range

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(Dated: January 12, 2012)

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Amplifiers are ubiquitous in electronics and play a fundamental role in a wide

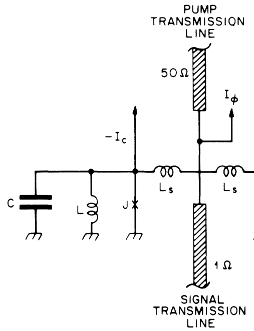

FIG. 1. A Josephson-parametric amplifier. See text for details.

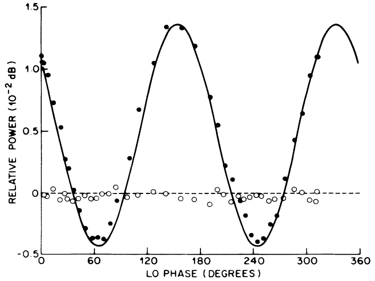

FIG. 3. Thermal-equilibrium-noise squeezing at 4.2 K. The open-circle data, taken with AT of Fig. 2 set for a maximum attenuation, establish the baseline. When pump power is delivered to the Josephson-parametric amplifier the noise (filled circles) drops below the baseline for certain settings of the relative phase between the LO and the pump. The smooth curve is a comparison of theory with experiment with no adjustable parameters.