HEMT CONCEPT FOR CMBPOL

C. R. Lawrence, JPL

M. Seiffert, T. Gaier, K. Górski, C. Heeg, A. Nash, D. Pearson, M. Prina, K. Warfield

S. Church, E. Wollack

TECHNOLOGY DEVELOPMENT FOR A CMB PROBE OF INFLATION

BOULDER, CO

2008 AUGUST 25

PILOT: (The) Primordial Inflation Telescope

- Scientific objectives
  - Search for evidence of primordial inflation by measuring B-mode polarization
  - Determine the ionization history of the Universe
  - Map CMB polarization at large angular scales
- Design fundamentals
  - Based on HEMT amplifiers
  - Designed to be a low-cost option for a future space mission
  - Scan strategy developed by K. Górski, same as for EPIC
- Study goal: an existence proof for a mission based on amplifiers at 20 K that:
  - Satisfies the sensitivity requirements of the TFCR
  - Demonstrates feasibility of the thermal, optical, and power systems
    - Meets straylight requirements
    - Meets thermal requirements, including temperatures and temp. stability, heat lift at 20 K
    - Provides bus power for cooler, etc.
    - Fits in rocket shroud
    - Can get data to the ground
  - Estimate rough cost

Key Questions

- Are amplifiers sensitive enough for CMBPol?
  - Over a wide enough frequency range?
- Amplifiers dissipate "a lot" of power. Is cooling in space practical?

Why Bother?

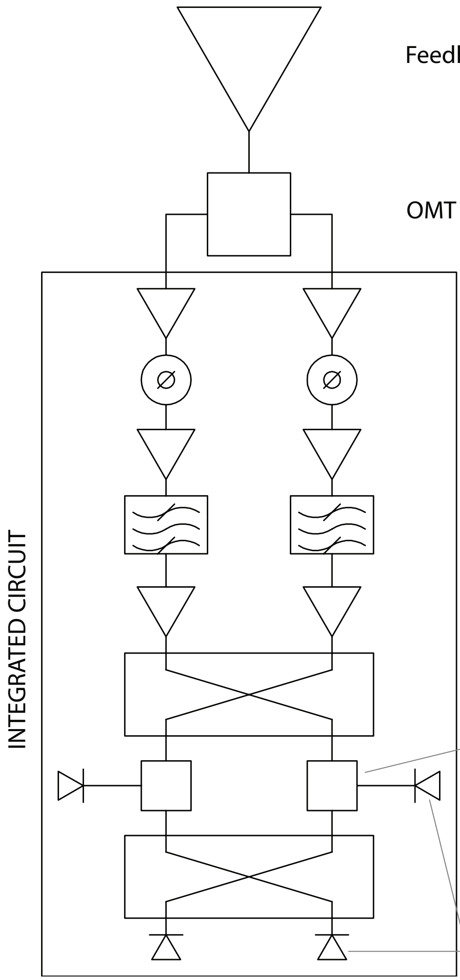
- Subject to foregrounds, it looks like amplifiers can do the job
- Systematics are different from bolometers. No detector technology system has been demonstrated in CMB observations at the noise/systematics levels required for CMBPol. Not all eggs should be put in one basket!
- Amplifier systems are (or can be) simpler
  - For example: detectors that require only 20 K physical temperature and can operate both physically at higher temperatures and looking at higher temperature targets are easier to test at system level than detectors that require 0.1 K physical temperature and targets at ~ 4 K.

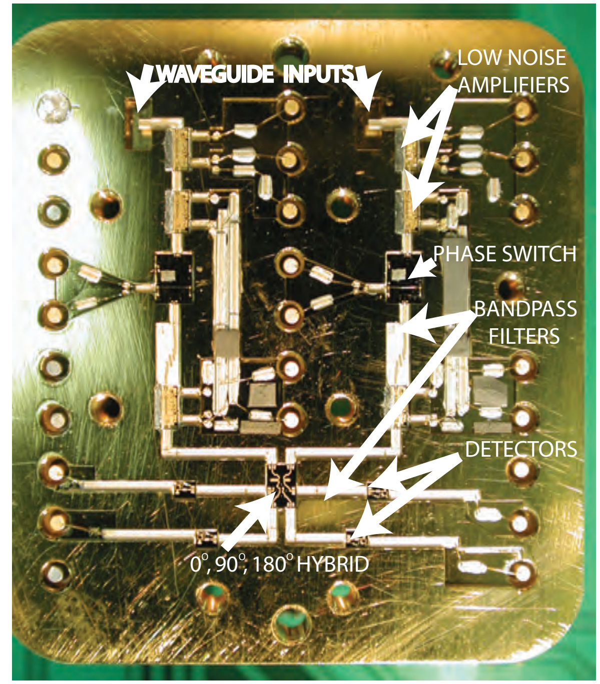
    There aren't that many LHe-shrouded test chambers big enough to take an entire spacecraft in the world, and they are exceeding expensive to operate.
  - This is a major reason why experiments using amplifiers have achieved so many key "firsts" in the CMB field (detection, dipole, temperature anisotropy, polarization)
- Simpler is cheaper and less risky

Mission Parameters

- L_2 halo orbit
- Five frequency bands between 30 and 150 GHz
- Launch vehicle: TBD
- Mission duration: 4 years nominal
- Instrument cold end temperature: 20 K
- Pointing control: $5'$ rms
- Reconstructed pointing knowledge: $10''$
- Daily data volume: 7.5 Gb/day
- Estimated instrument mass: 500 kg
- Estimated instrument power: 1500 W
- Cost target: $<$\$350 M

Radiometer Concept





OMT (L-R circular) $\Longrightarrow$ $\frac{E_x+iE_y}{\sqrt{2}}$ $\frac{E_x-iE_y}{\sqrt{2}}$

$\frac{A+B}{\sqrt{2}} = E_x$ $\frac{A-B}{\sqrt{2}} = iE_y$ with $\phi = 0^\circ$

180 deg combiner $\Longrightarrow$ $\frac{A+B}{\sqrt{2}} = iE_y$ $\frac{A-B}{\sqrt{2}} = E_x$ with $\phi = 180^\circ$

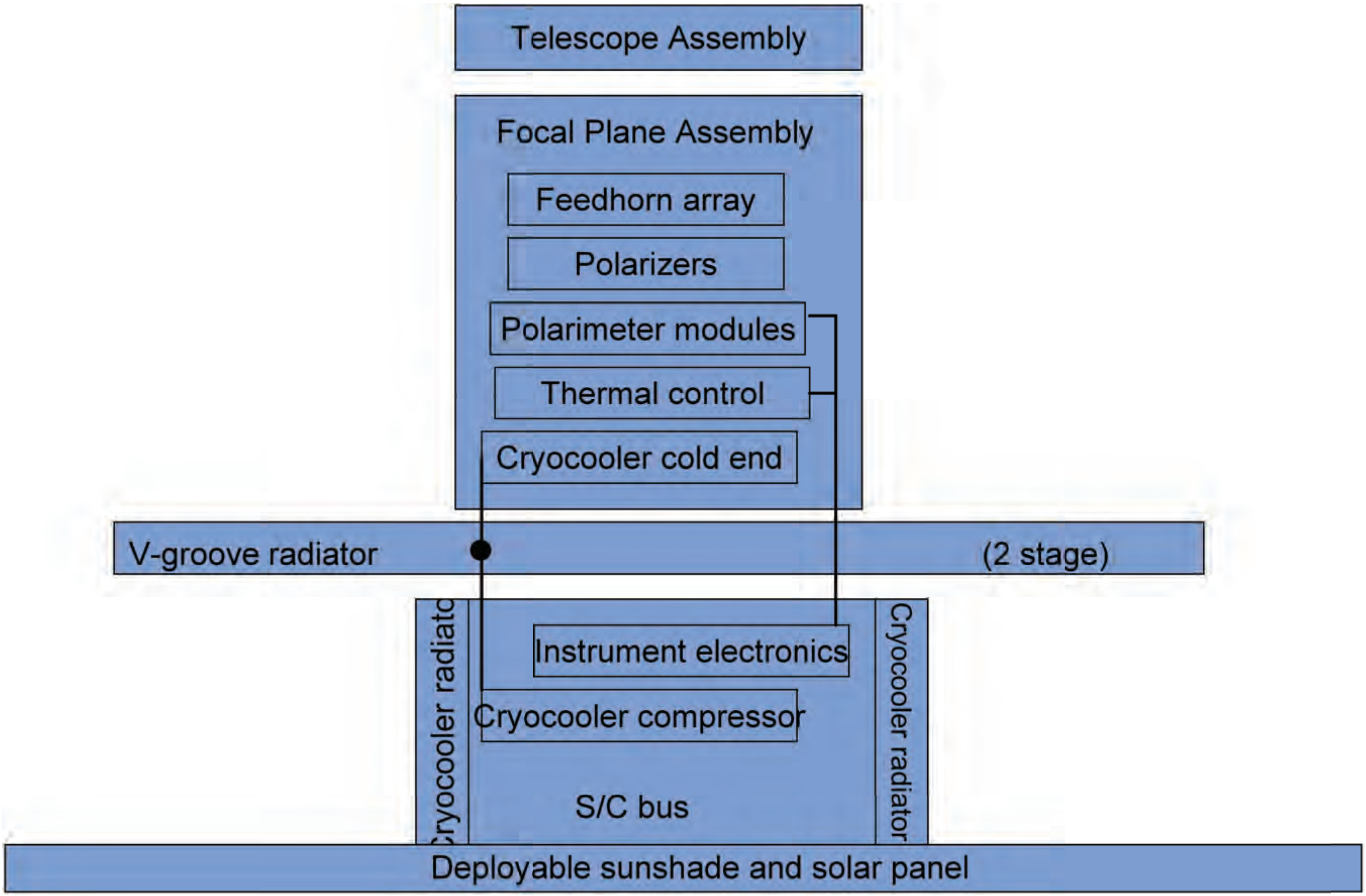
Power splitter $\Longrightarrow$ $VV^* = E_x^2$ E_y^2 $\Longrightarrow$ $E_x^2 - E_y^2 \equiv$ "Q"

90 deg combiner $\frac{A+iB}{\sqrt{2}} = E_x - E_y$ $\frac{B+iA}{\sqrt{2}} = i(E_x + E_y)$ with $\phi = 0^\circ$

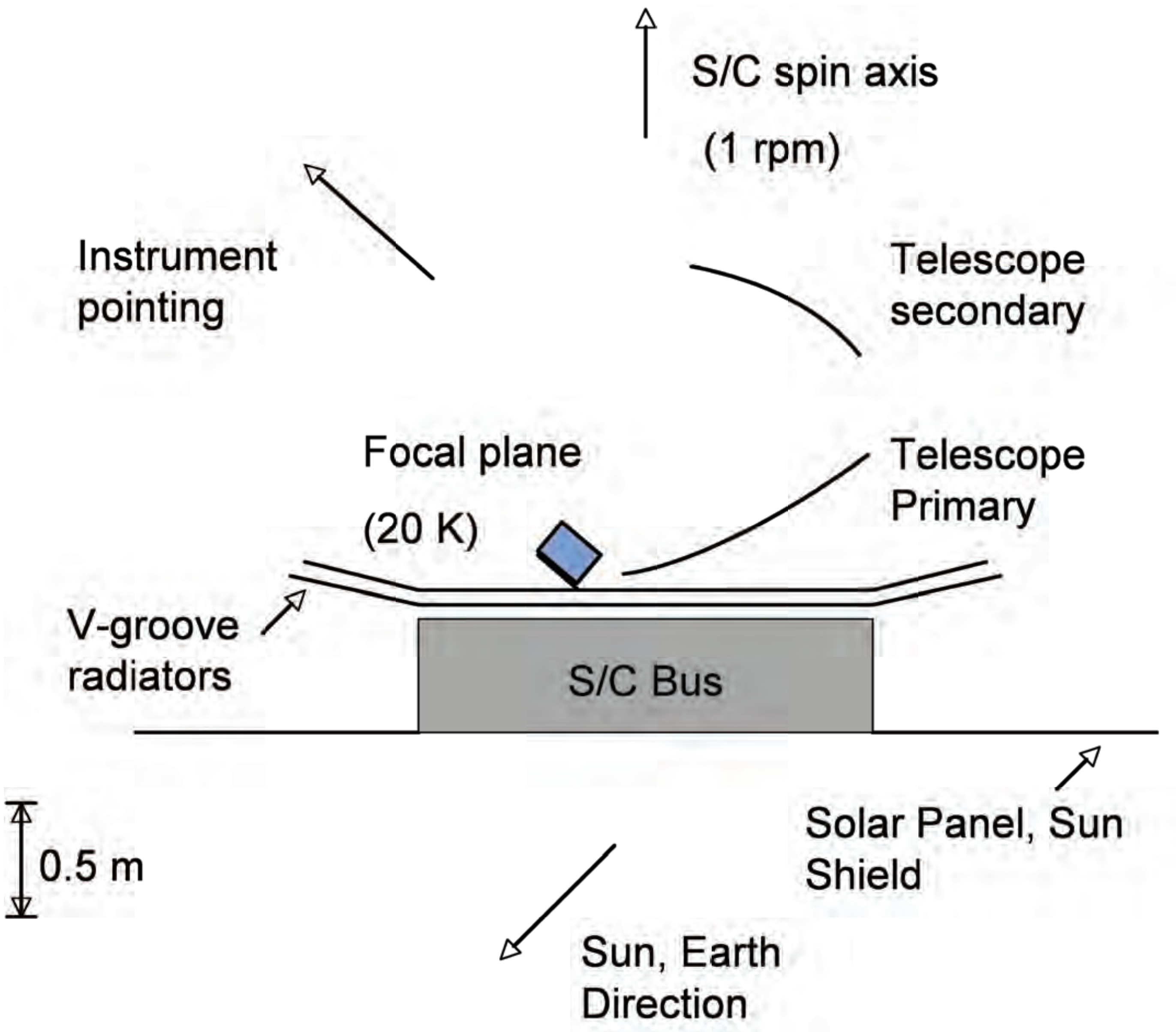
Diode detectors $\Longrightarrow$ $VV^* = -E_xE_y$ E_xE_y $\Longrightarrow$ $E_xE_y \equiv$ "U"

- Simultaneous measurement of Q and U

Configuration

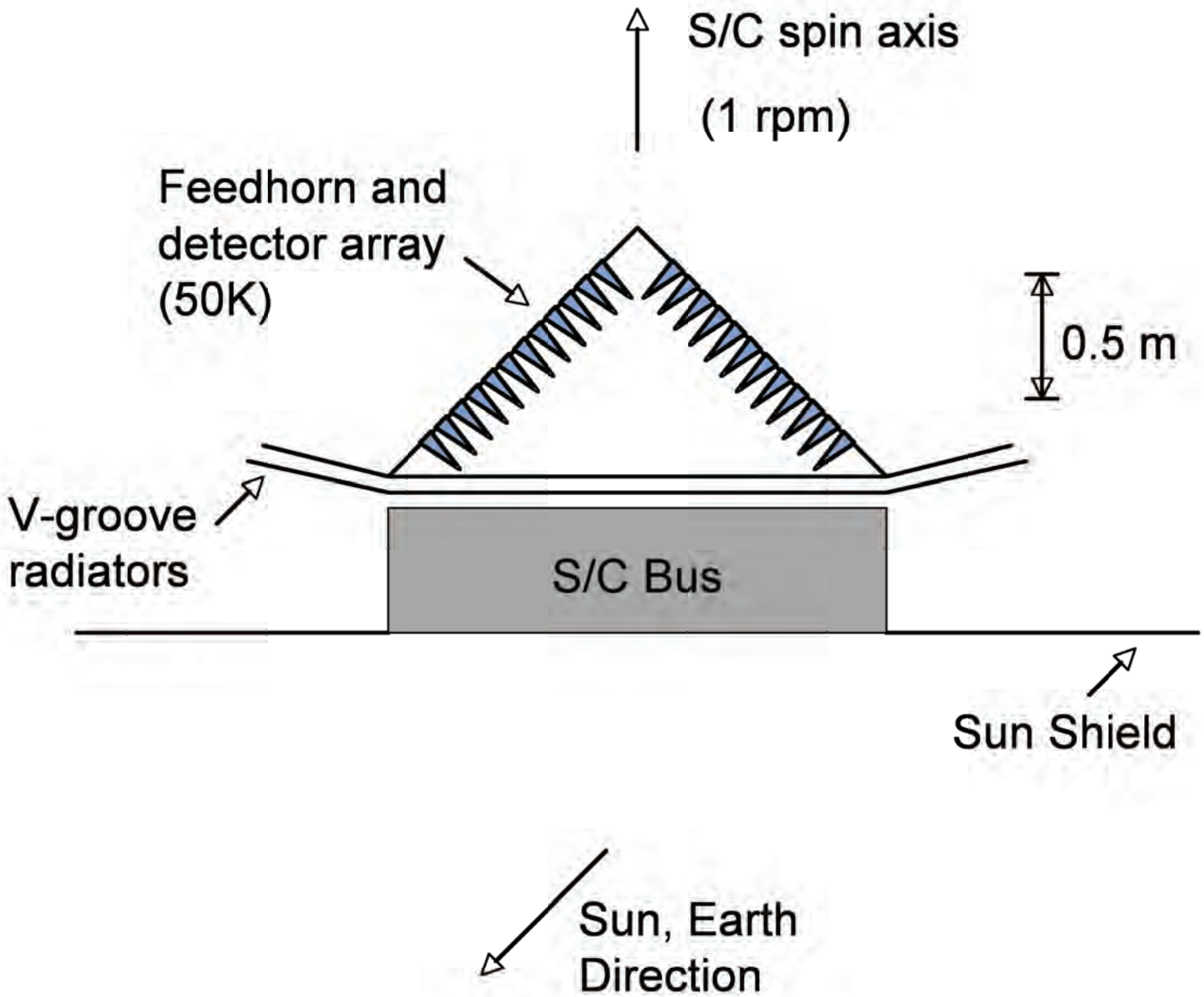


Schematic



S/C spin axis
(1 rpm)
Instrument pointing
Telescope secondary
Focal plane
(20 K)
Telescope Primary
V-groove radiators
S/C Bus
0.5 m
Solar Panel, Sun Shield
Sun, Earth Direction

Passively-Cooled, No-Telescope Version



Sensitivity, Frequency Coverage, Detectors

Frequency [GHz]	N	Power [mW]	$T_{\rm rcvr}$ [K]	$T_{\rm sys}$ [K]	NEQU [μK s$^{1/2}$]	NEQU/freq [μK s$^{1/2}$]	4-yr Noise/1 deg^2 [nK]
30	4	4	7	10	81.6	40.8	750
40	50	7	8	11	87.0	12.3	230
70	160	10	10	13	77.7	6.1	125
100	75	12	12	15	75.0	8.7	200
150	75	15	20	23	93.9	10.8	500
Total N	364						

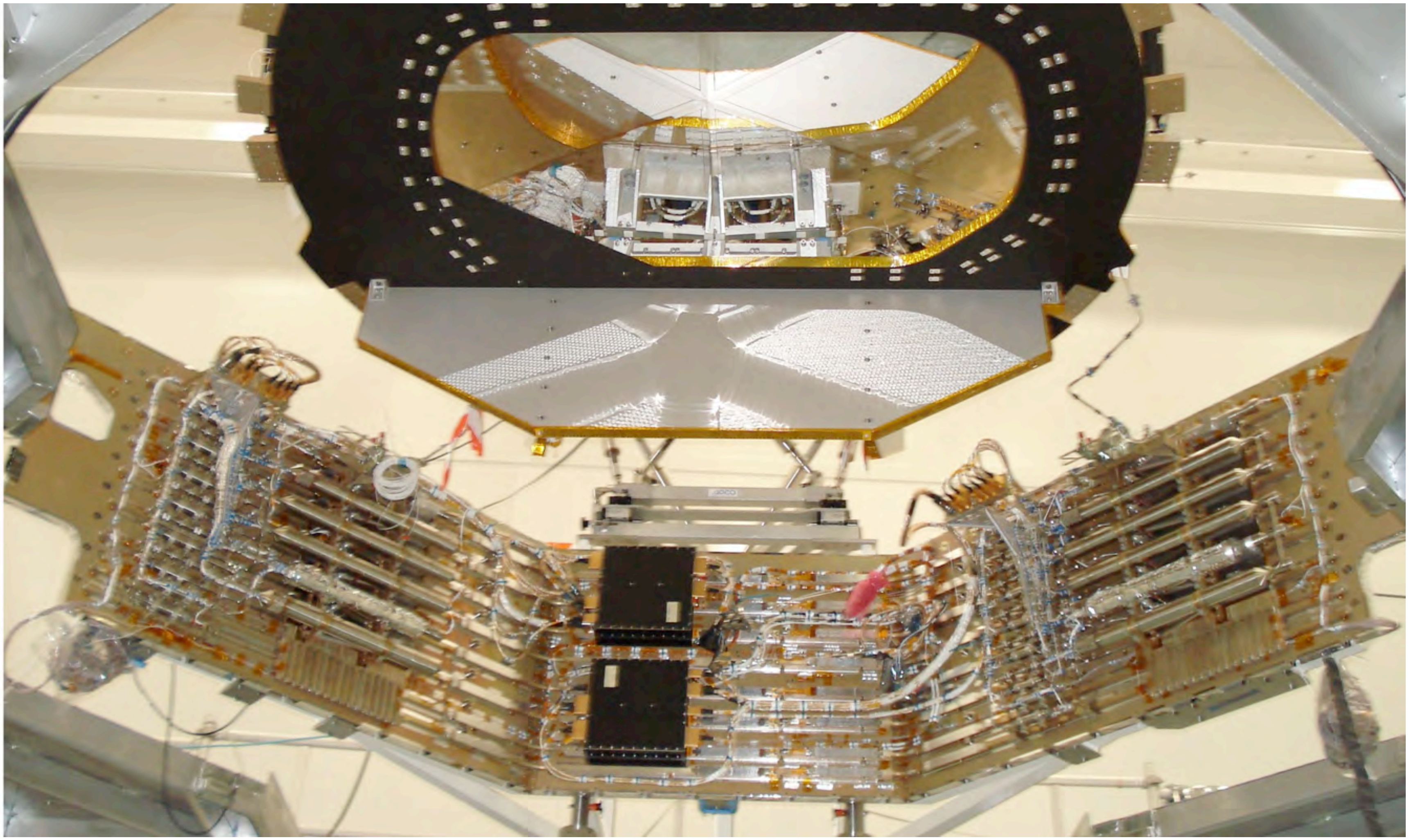
[a] Receiver noise and power values assume 35 nm-gate transistors. Noise is a model extrapolation from performance at 250–350 GHz at room temperature to the stated frequency at cryo temperatures. Power is scaled from a recent measurement in W band. We'll discuss these things on Wednesday.

- Total power dissipated by amplifiers = 4 W
  - Parasitics will add maybe 10 or 20%

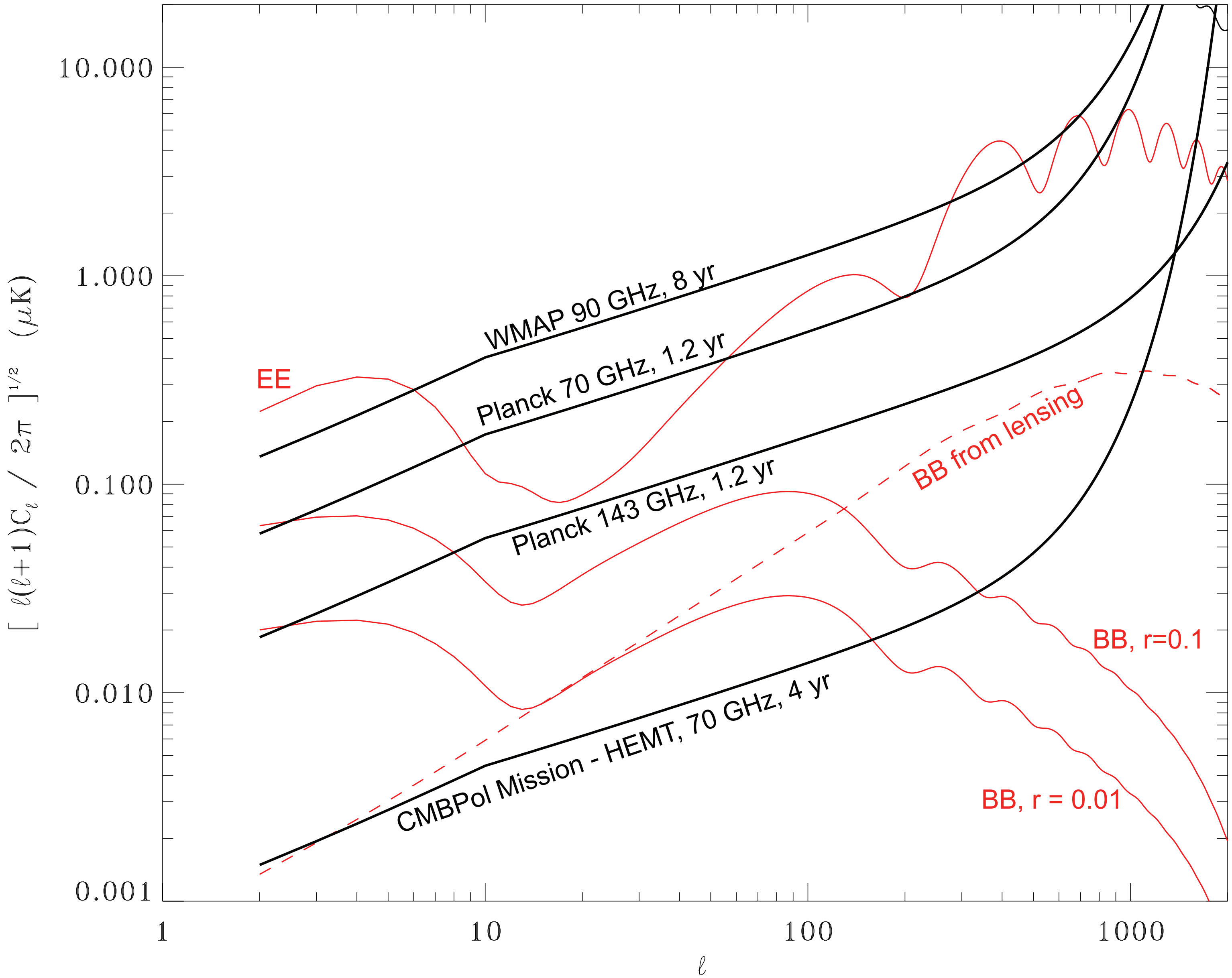
Existence Proof for Cooler

- 4 W of heat lift at 20 K is a substantial cooler
- As it happens, the Planck hydrogen sorption coolers (a redundant pair on Planck) combined together and set up for a precool temperature of 50 K (about what we now expect on Planck), would give 4 W of lift.
- It would need:
  - 1 kW of input power
  - 6 m^2 of V-groove radiator area at 50 K
  - 4 m^2 of 270-K radiator to dissipate the 1 kW of input power
- Features:
  - Easy integration with the instrument
  - High TRL level

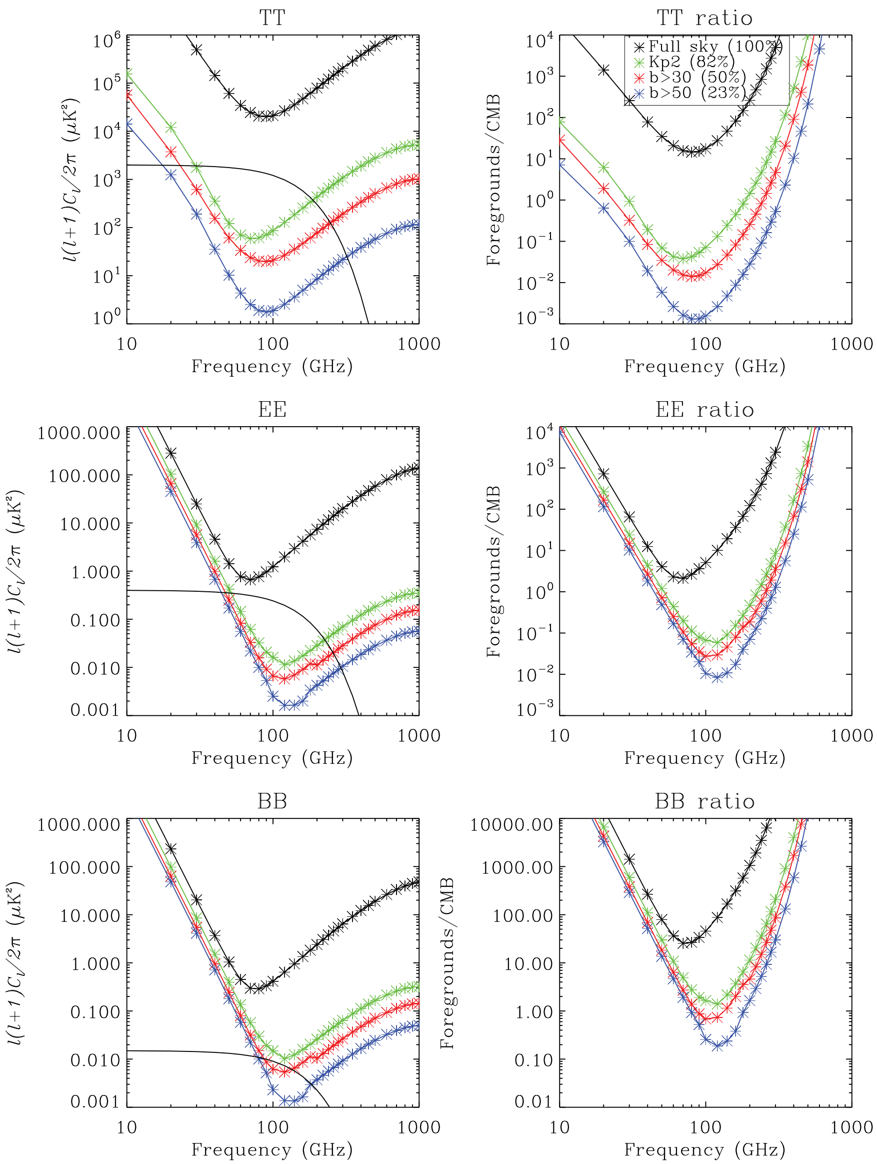
Planck Sorption Cooler



Taskforce Plot



Foregrounds



Clive Dickinson

Level of synchrotron and dust temperature fluctuations, in absolute units (left) and relative to the CMB fluctuations (right).

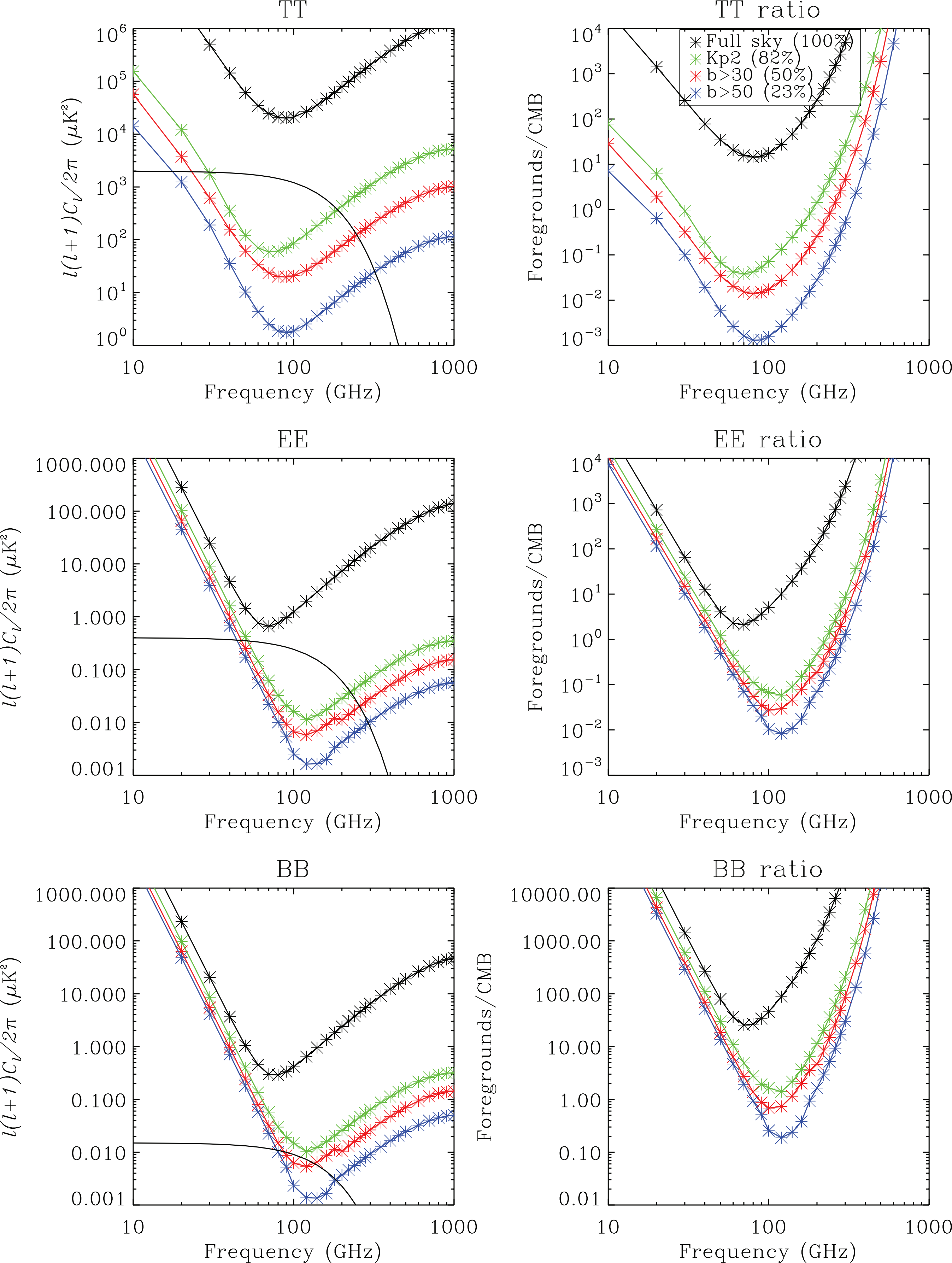
Maps were generated from the Planck Sky Model at many frequencies. Sky cuts made as indicated. Power spectra calculated with Polspice. Average value of $80 \leq \ell \leq 120$ plotted.

In TT for a Kp2 sky cut, for which the foregrounds are known moderately well from WMAP up to 94 GHz, at 40 and 130 GHz dust and synchrotron fluctuations are up by a factor of five over their values at the minimum at 70 GHz.

At 30 and 180 GHz the foregrounds are up by a factor of 25.

By 300 GHz, dust fluctuations are up by three orders of magnitude compared to CMB fluctuations, which drop fast on the Wien side of the spectrum. If the foreground spectra are complicated, a very wide frequency range may be disadvantageous.

In polarization, the variation in dust fluctuations over the sky is much larger, so the sky cut makes a big difference. For EE the foreground data are much more uncertain, especially concerning dust, for which there is suspicion that the Planck Sky Model underestimates polarization fluctuations.



TT
TT ratio
EE
EE ratio
BB
BB ratio
Full sky (100%)
Kp2 (82%)
b>30 (50%)
b>50 (23%)
$l(l+1)C_l/2\pi$ (μK^2)
Foregrounds/CMB
Frequency (GHz)

More Foregrounds

- Preliminary indications from component separation simulations are that the optimum way to divide focal plane real estate is to achieve uniform SNR across frequencies, where the signal is the total signal, including foregrounds.
- In this case, noise levels at low and high frequencies can be higher than at the foreground minimum.
- The foreground minimum frequency is higher for polarization than temperature, and depends on sky fraction.
- The requirement on noise as a function of frequency is still murky, but if really low noise is required above 150 or 200 GHz, amplifiers will not be the way to go.

Coherent Characteristics

- Noise of a coherent detection system has a fundamental minimum set by quantum noise, the "quantum limit" ($\sim 0.05\nu_{[\mathrm{GHz}]}$ K)
- Once the quantum tax is paid, the full signal with amplitude and phase preserved is available for use in ways that may allow greatly increased control of systematic effects
  - In principle, could digitize the raw signal after amplification and perform arbitrary phase and amplitude oprations in software with essentially unlimited fidelity.
  - Fundamentally different approach from bolometer technology
  - Attractive features for polarimetry

    Simultaneous measurement of Q and U

    Gain variations multiply a difference signal, not total power

    Modulation of phase, polarization state, etc.

    Multiplication of signals (i.e., interferometry)

$$$

- Complexity is expensive
- Testing in non-ambient conditions is expensive
- A mission with coherent detectors would be significantly simpler in may ways (e.g., no HWPs, no 0.1 K), and easier to test/validate before launch (HEMTs work fine at room temperature).

Summary

- A space mission based on amplifiers is feasible
  - Noise levels required for good B-mode sensitivity can be achieved, subject to foregrounds

    Requires continued development of MMICs and modules
  - Cooling requirements can be met

    Thermal/mechanical engineering of flight system needs to be done

    Options for coolers must be assessed
- The first realistic opportunity for a CMBPol mission is probably the planned 2012 Midex AO. A coherent mission may be possible.
- Frequency coverage for foregrounds is the critical open question