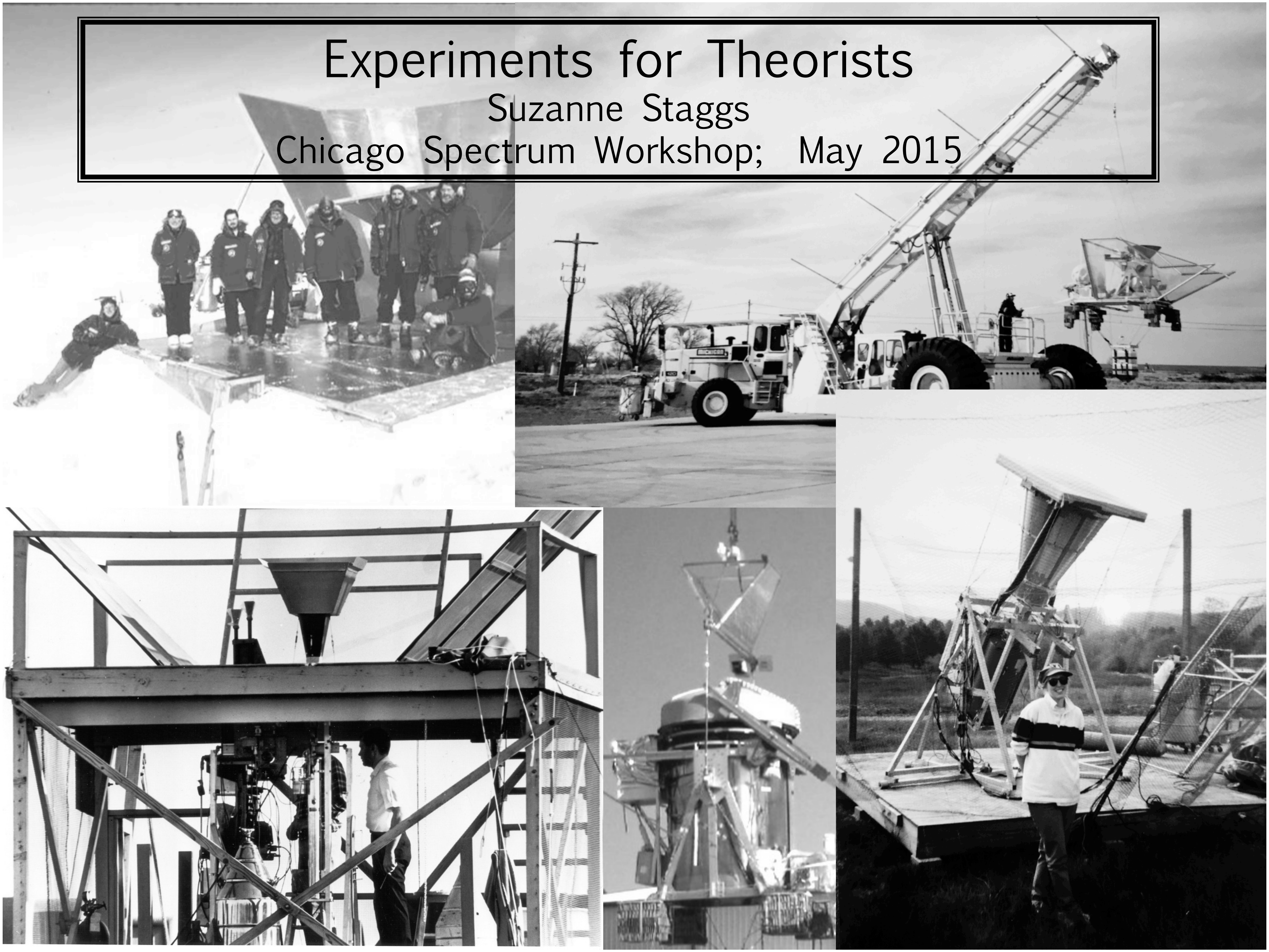
Experiments for Theorists

Suzanne Staggs

Chicago Spectrum Workshop; May 2015



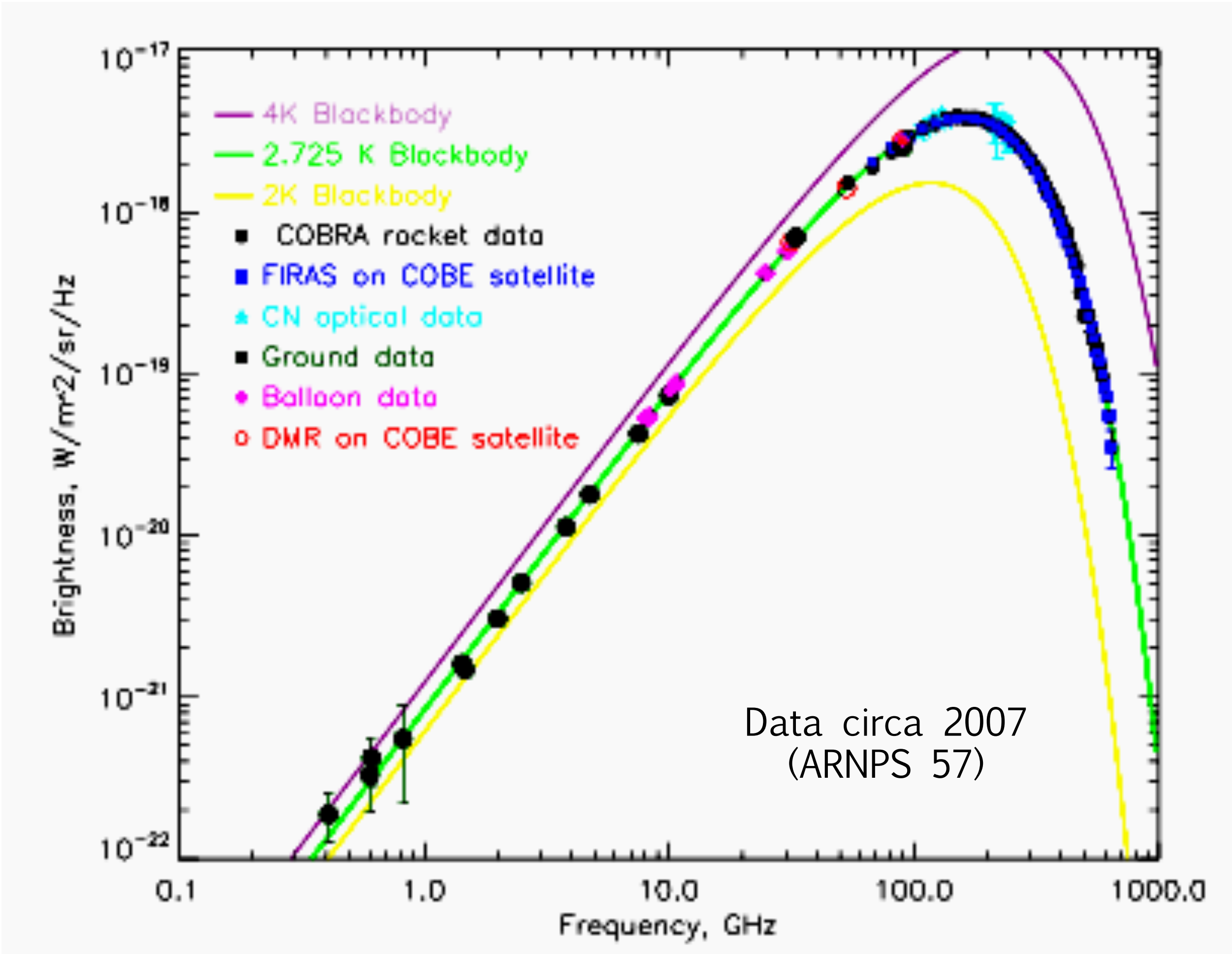
Measurements

Spectral Radiance:

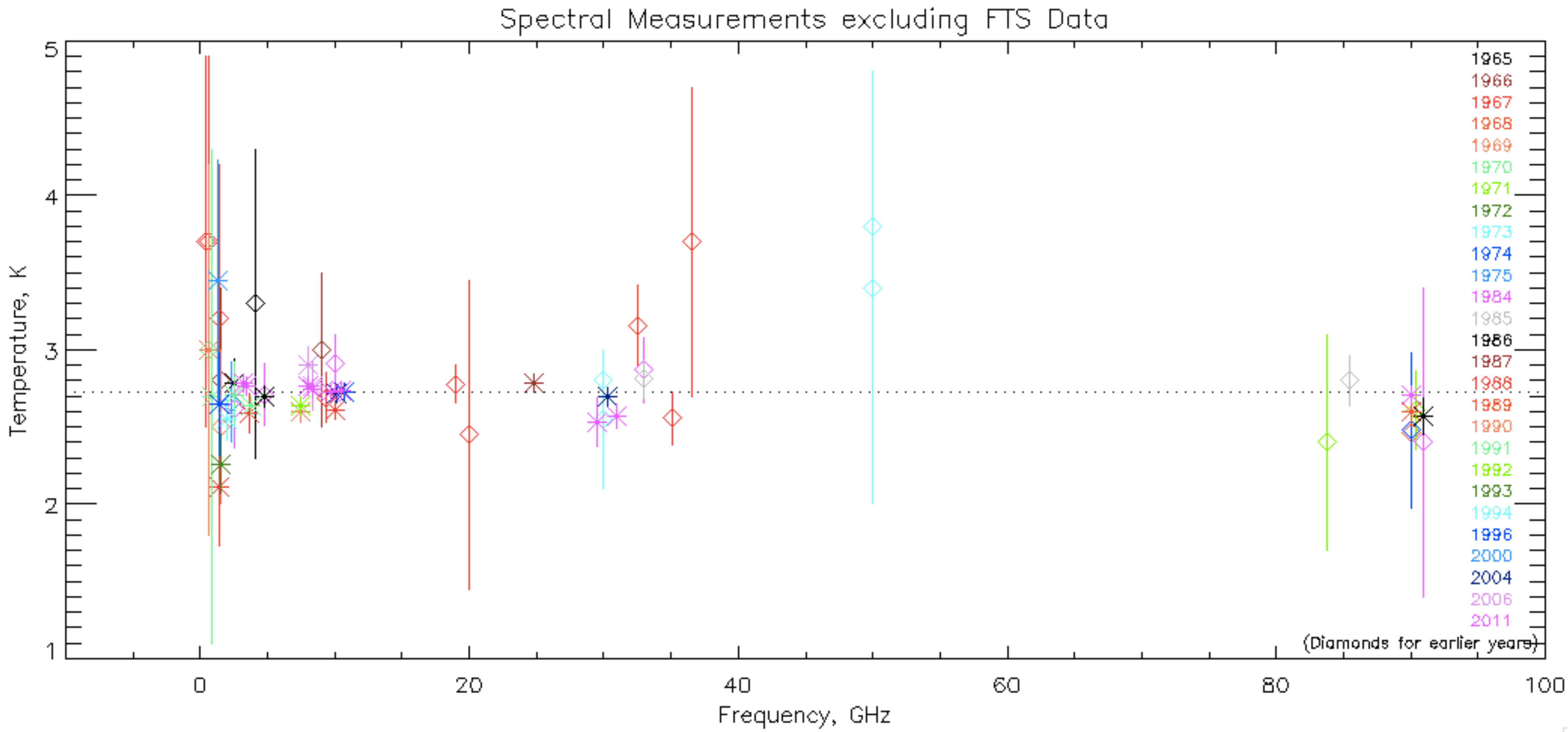
$$B(\nu, T) = \frac{2h\nu^3}{c^2}\left(\frac{1}{e^x - 1}\right)$$

Units: $\frac{\mathrm{W/m^2}}{\mathrm{sr\ Hz}}$, and $x \equiv \frac{h\nu}{kT}$

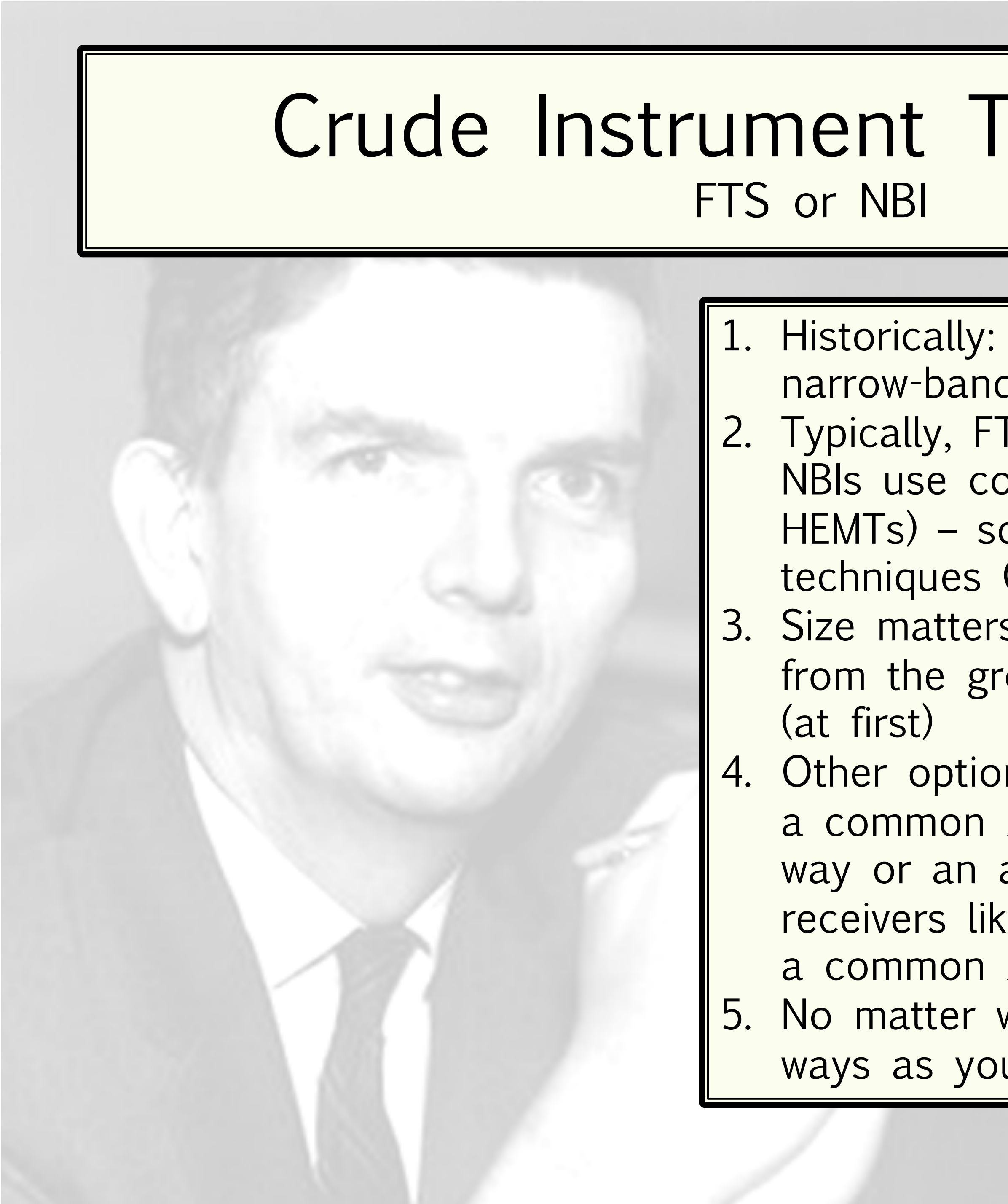
More decades of frequency than Dale showed earlier



Data across the Decades



Note the plethora in 1967!

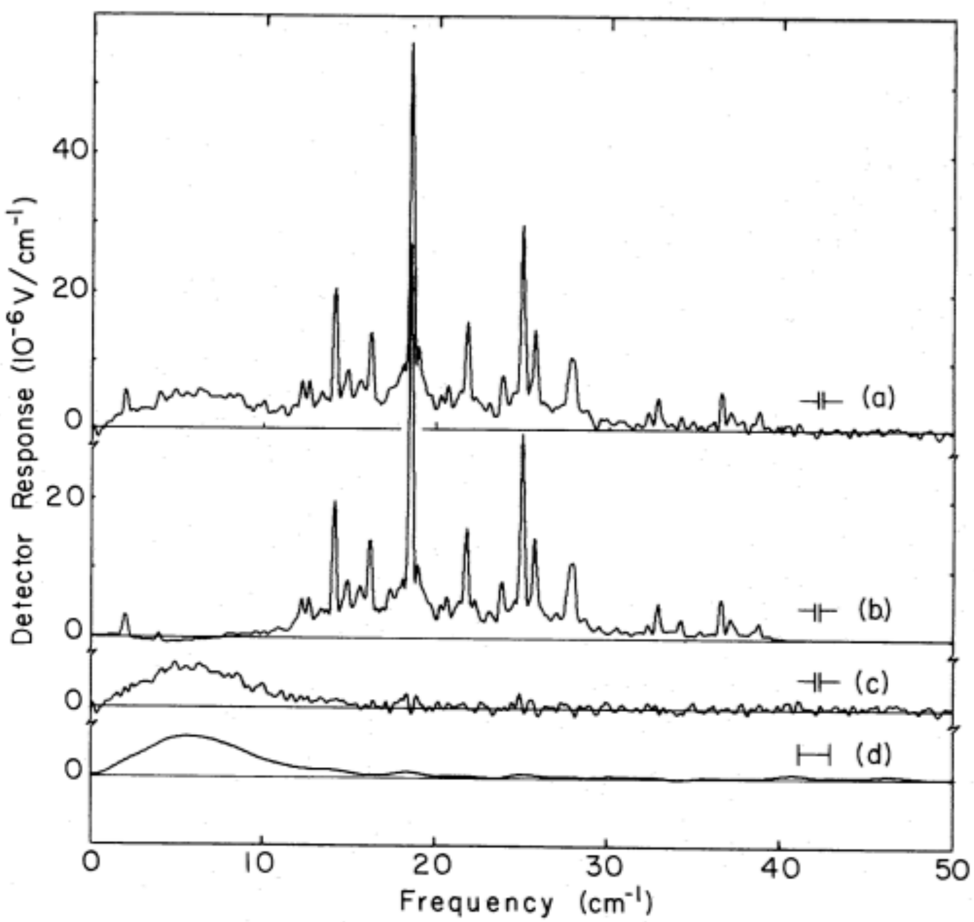


Crude Instrument Taxonomy

FTS or NBI

1. Historically: FTSes above 50 GHz, and narrow-band instruments (NBI) below.
2. Typically, FTSes use bolometers, and NBIs use coherent amplifiers (eg, HEMTs) – some using correlation techniques (XPER)
3. Size matters: lower frequencies done from the ground, others from balloons (at first)
4. Other options: broadband optics with a common XCAL, channelized in some way or an array of single-mode receivers like ARCADE, perhaps sharing a common XCAL.
5. No matter what: Modulate in as many ways as you can!

What Early FTS Measurements Fought



Atmosphere at 43 km float from Woody & Richards, 1981:

a) shows data,

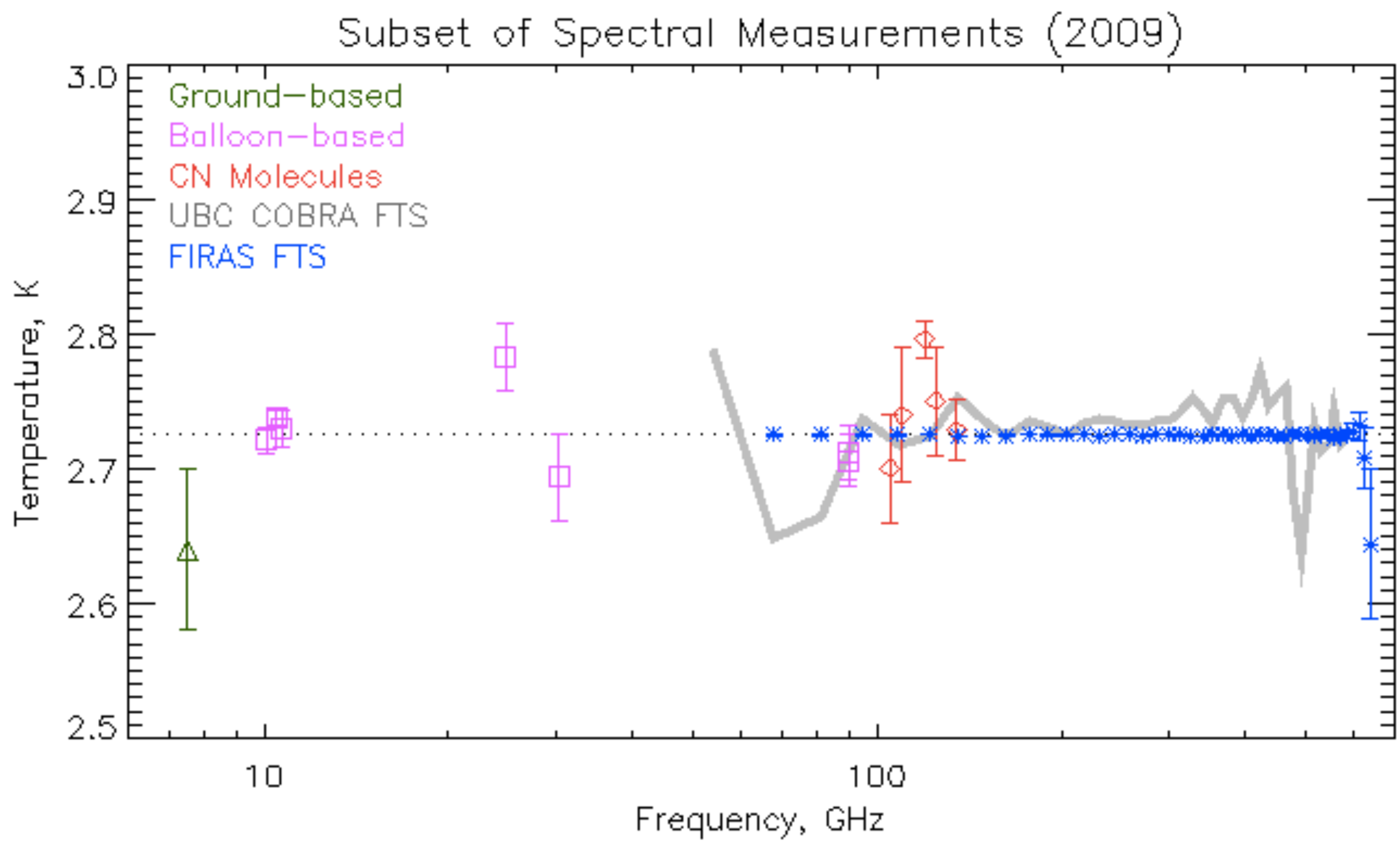
b) atmosphere **calculations**

c) Residual =? CMB (2.88 K to 3.09 K deduced)

Call the police & a fireman!

Data across the Decades

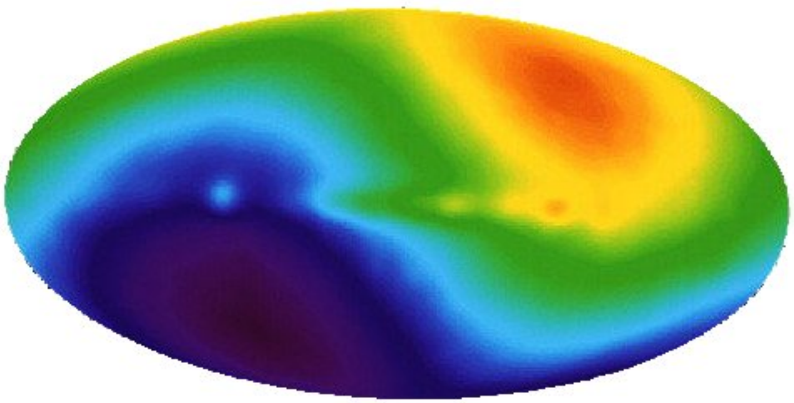
1990: TWO BEAUTIFUL FTS DATA SETS EMERGE!
(FIRAS data plotted here are from 1996 release.)



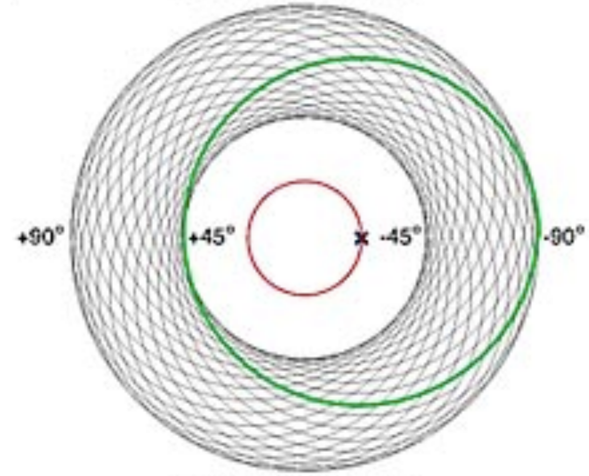
The data for the global average in Fixsen 2009. ;)

A Tale of Two Satellites

Being an old slide adapted & stuck in to expound on Rashid's sun-motion question to Dale, and Dale's comment on FIRAS calibrating everything



Map without mean → mostly dipole
Amplitude ~ 3.3 mK
(credit: COBE DMR)



1. Dipole amplitude (~ 370 km/s) ~ T_{CMB} v/c
2. That amplitude is annually modulated by ~10% by the satellite's rotation about sun (~30 km/s).
3. WMAP v known to ~ 1 cm/s (geocentric, and similar for earth ephemeris).
4. Thus WMAP satellite velocity is used in combination with FIRAS T_{CMB} to get WMAP 0.2% calibration for $\delta T/T$!

(See Fixsen 2011 to see this turned on its head!)

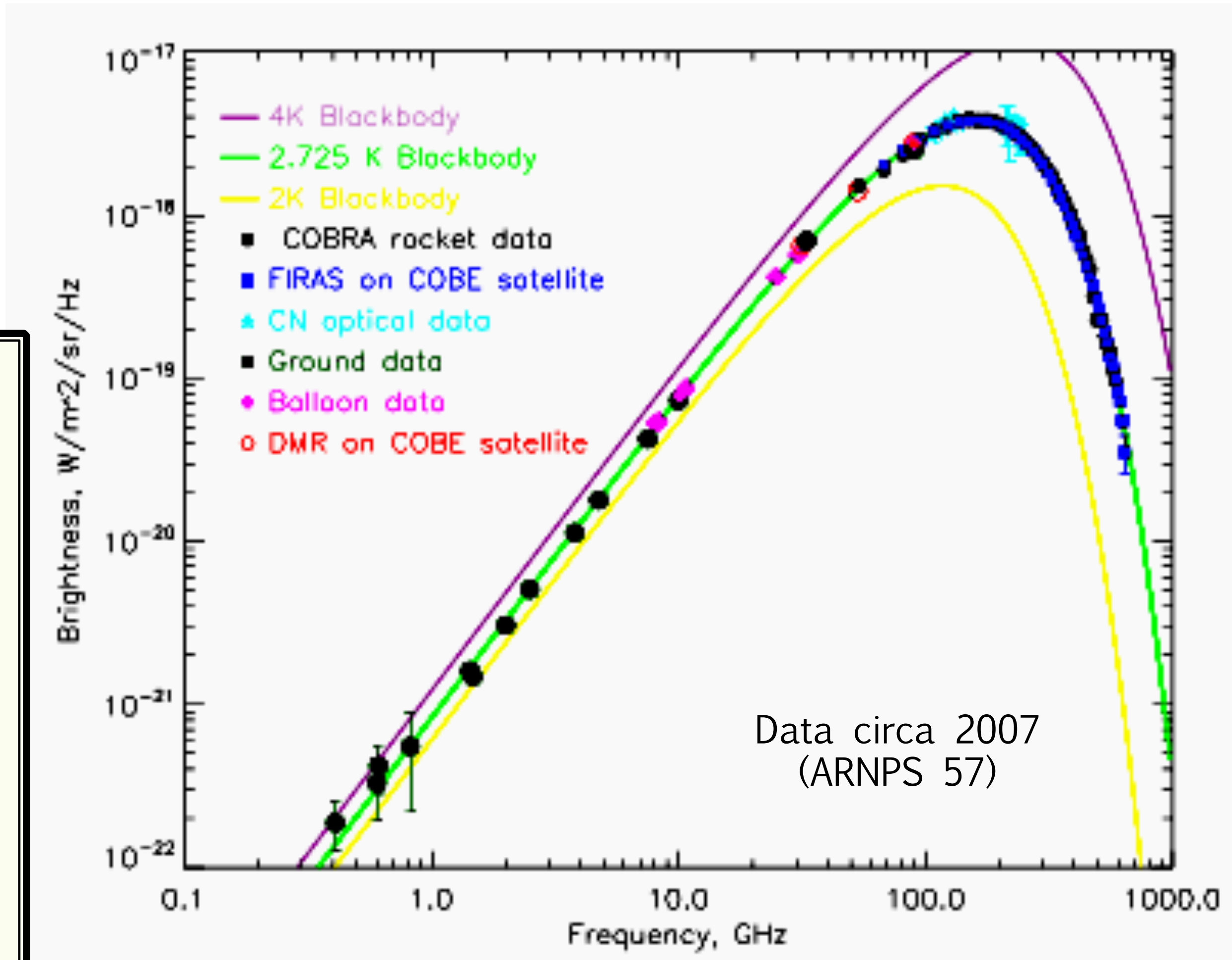
Measurements

Spectral Radiance:

$$B(\nu, T) = \frac{2h\nu^3}{c^2}\left(\frac{1}{e^x - 1}\right)$$

Units: $\frac{\mathrm{W/m^2}}{\mathrm{sr\ Hz}}$, and $x \equiv \frac{h\nu}{kT}$

1. Aim optics at sky
2. Define ν, $\Delta\nu$
3. Couple to detector of area A that sees the primary optic subtending Ω
4. Measure power on detector (W) in $\Delta\nu$ (Hz) with etendue ($A\Omega$, m^2 sr).
5. Repeat at other ν



Complications

Define beam that sees only the sky (not the ground, the Sun, airplanes, bits of the galaxy, unexpected internal surfaces of your instrument)

1. Aim optics at sky
2. Define ν, $\Delta\nu$
3. Couple to detector of area A that sees the primary optic subtending Ω
4. Measure power on detector (W) in $\Delta\nu$ (Hz) with etendue ($A\Omega$, m^2 sr).
5. Repeat at other ν

Complications

Define beam that sees only the sky (not the ground, the Sun, airplanes, bits of the galaxy, unexpected internal surfaces of your instrument)

There is a lot to defining ν, $\Delta\nu$ – more in a bit!

1. Aim optics at sky
2. Define ν, $\Delta\nu$
3. Couple to detector of area A that sees the primary optic subtending Ω
4. Measure power on detector (W) in $\Delta\nu$ (Hz) with etendue ($A\Omega$, m^2 sr).
5. Repeat at other ν

Complications

Define beam that sees only the sky (not the ground, the Sun, airplanes, bits of the galaxy, unexpected internal surfaces of your instrument)

There is a lot to defining ν, $\Delta\nu$ – more in a bit!

1. Aim optics at sky
2. Define ν, $\Delta\nu$
3. Couple to detector of area A that sees the primary optic subtending Ω
4. Measure power on detector (W) in $\Delta\nu$ (Hz) with etendue ($A\Omega$, m^2 sr).
5. Repeat at other ν

The more A you get, the more signal, but big detectors can catch cosmic rays and be slow, and have to think more about the optics when # modes > 1 per polzn.

Complications

Define beam that sees only the sky (not the ground, the Sun, airplanes, bits of the galaxy, unexpected internal surfaces of your instrument)

There is a lot to defining ν, $\Delta\nu$ – more in a bit!

The more A you get, the more signal, but big detectors can catch cosmic rays and be slow, and have to think more about the optics when # modes > 1 per polzn.

1. Aim optics at sky
2. Define ν, $\Delta\nu$
3. Couple to detector of area A that sees the primary optic subtending Ω
4. Measure power on detector (W) in $\Delta\nu$ (Hz) with etendue ($A\Omega$, m^2 sr).
5. Repeat at other ν

Reliance on understanding your detectors is greatly reduced if you are making a difference measurement such that you are measuring approximately zero.

But – you have to understand the thing you are differencing against!

Calibrations

1. Idea: compare to an extremely good blackbody (XCAL) at T_{CMB}
2. The chicken and the egg: how do you know the XCAL is as good as you need?
   a) Kirchoff helps – you can use precision instruments and measure reflections from a hot source in the lab
   b) Griffiths, Born & Wolf & Jackson help too
   c) If you ask for too much, materials may let you down (eg, by having unexpected resonances in their dielectric 'constants')
3. Borrowing a page from FIRAS: If you can parameterize the XCAL deviations from perfection you can fit them out… (PIXIE 30 thermometers: yeah, baby!)
4. Note that a 3 nK distortion of unkown shape requires -90 dB!
5. Measure as much as you can in situ (eg, change its DC temperature, force gradients, move it in and out, etc)

Frequencies

1. Defining bands and central frequencies
   a) any materials you put in the light path* can complicate the instrument's bandpass and thus move the effective central frequency of a band
   b) differencing experiments do not avoid this at 2nd order – but material properties generally vary slowly with frequency
   c) multi-pathing (causing suck-outs at resonant cavity frequencies between slightly reflective surfaces) can change from room T to cryogenic temperatures, or with shaking
2. You can measure the bandpasses – with an FTS or VNA in the lab subject to their own multipath issues etc (especially cryogenically) – but things might change in situ
3. Best are measurements in situ – like FIRAS's spot check with interstellar CO and [CI] lines
4. For an FTS -- could you make an excellent ICAL and show it has $B(\nu,T)$ equal to a BB? (Not likely, as Dale answered Lyman!)

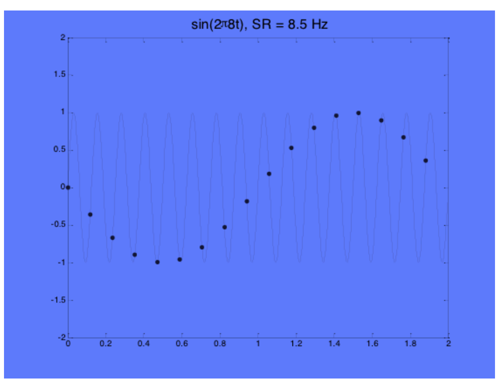
Memory Jog: the Fourier in FTS

$$I(x)=\int_0^{\infty} S(\nu)\cos 2\pi\nu x\,d\nu$$

$$S(\nu)=\int_0^{\infty} I(x)\cos 2\pi\nu x\,dx$$

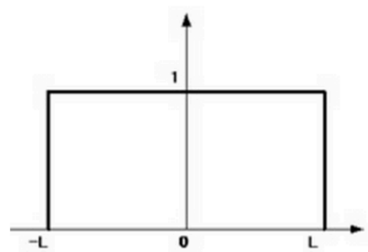
1. Inteferogram & source spectrum are Fourier partners.
2. $S(\nu)$ is continuous and not (necessarily) bandlimited
3. $I(x)$ is sampled discretely (even if motor scans) with limited range!

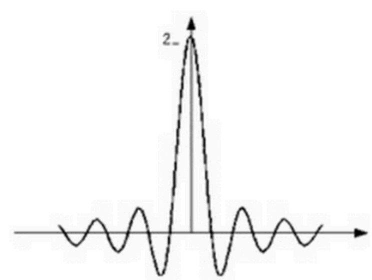
Discrete sampling imposes a Nyquist limit on $S(\nu)$ -- ν_{max}



Limited range applies a tophat window function (apodization) and thus a minimum resolution for $S(\nu)$, $\Delta\nu$

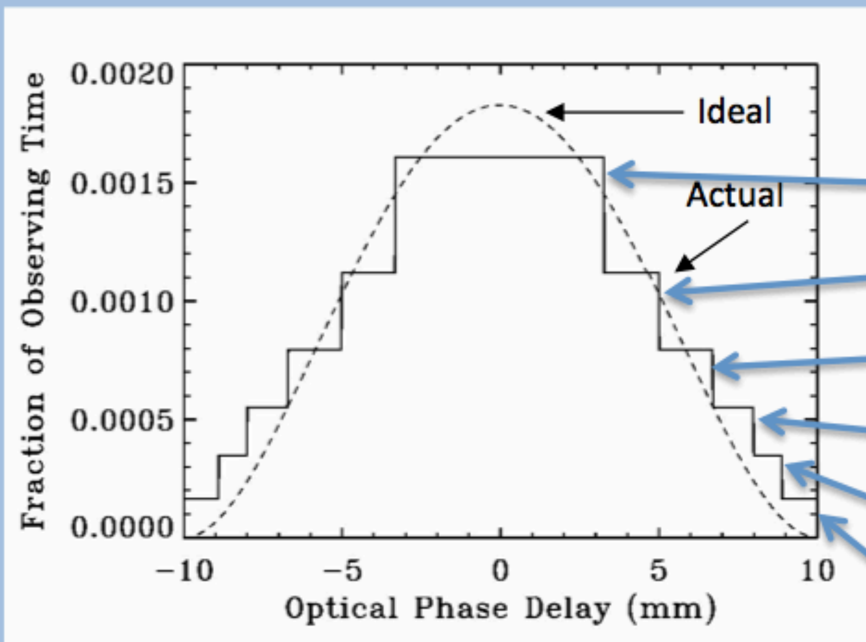
$$S(\nu)=\int_0^{\infty} W(x)I(x)\cos 2\pi\nu x\,dx$$





Repeating what Al said with different words & diagrams!

PIXIE Apodization



Optical Delay	Physical Stroke	Samples per Stroke	Strokes per Spin
±3.3 mm	±0.9 mm	341	24
±5.0 mm	±1.3 mm	512	16
±6.7 mm	±1.7 mm	683	12
±8.0 mm	±2.1 mm	819	10
±8.9 mm	±2.3 mm	910	9
±10 mm	±2.5 mm	1024	8

Vary stroke length to apodize Fourier transform

Slide borrowed from Dale Fixsen's Okinawa talk in 2012.

Detector Sensitivities

Converting between NEP (units W $Hz^{-1/2}$) and NET (units mK $s^{1/2}$)

$$B(\nu,T) = \frac{2h\nu^3}{c^2}\left(\frac{1}{e^x-1}\right) \xrightarrow{x\ll 1} \frac{2\nu^2}{c^2}kT$$

Units: $\frac{\mathrm{W/m^2}}{\mathrm{sr\ Hz}}$, and $x \equiv \frac{h\nu}{kT}$

Note, for CMB, x=1 for ν=59 GHz. Also note, for small x $n_\gamma=(e^x-1)^{-1}$ is large.

To get power for a single mode: integrate over frequency and the etendue AΩ.
For x <<1, and a tophat, eg: P = kTΔν

For x<<1, dP/dT = kΔν, independent of ν.

In general, $$\frac{\partial P}{\partial T} = k\Delta\nu\left[\frac{x^2 e^x}{(e^x-1)^2}\right]$$

Two last details:

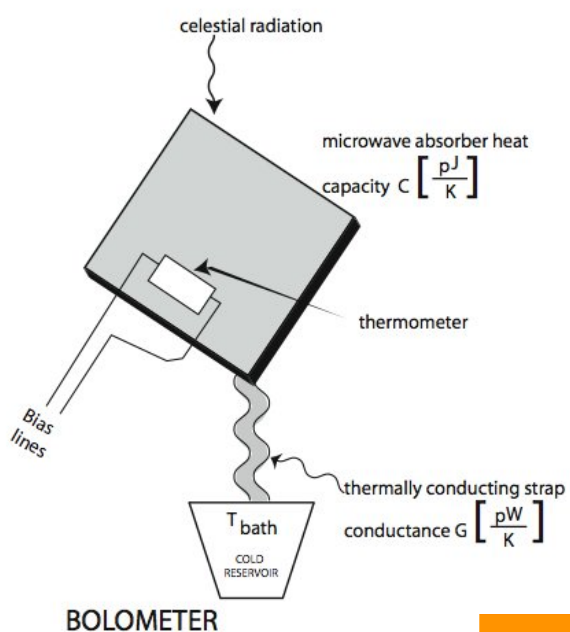
1. There is a conversion factor 2 between Hz^{-1} and s! The former implies sine waves and the latter square waves.
2. Need to account for instrument losses (throughput η<1).

$$\mathrm{NEP} = \eta\sqrt{2}\left(\frac{\partial \mathrm{P}}{\partial \mathrm{T}}\right)\mathrm{NET}$$

Detector Sensitivities: Bolometers

The slo-mo version of something Al showed this morning.

NEP (units W $Hz^{-1/2}$) and NET (units mK $s^{1/2}$)



$$\mathrm{NEP}_{Dicke} = \sqrt{\frac{p_\gamma^2}{b\,\Delta\nu}}$$

$$\mathrm{NEP}_{shot} = \sqrt{\frac{h\nu\, p_\gamma}{b}}$$

$$\mathrm{NEP}_G = \sqrt{4kT_0^2\, G\, f_\ell}$$

p_γ: the incident photon power
b: conversion factor (0.5) to get units $\mathrm{Hz}^{-1/2}$
$\Delta\nu$: bandwidth
ν: center frequency
f_ℓ: context dependent factor ≤ 1

Add these (++) in quadrature to get the total.

(Example of "++": cosmic ray hits in FIRAS!)

Note the NEP_G enters when the input power is transduced into a thermal signature for some kind of thermometer.

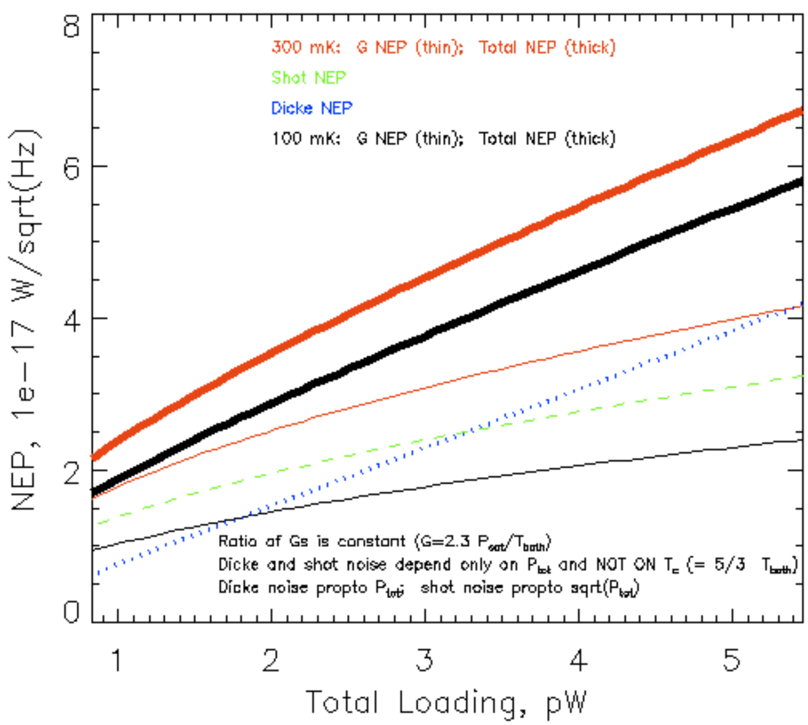
Detector Sensitivities: Bolometers

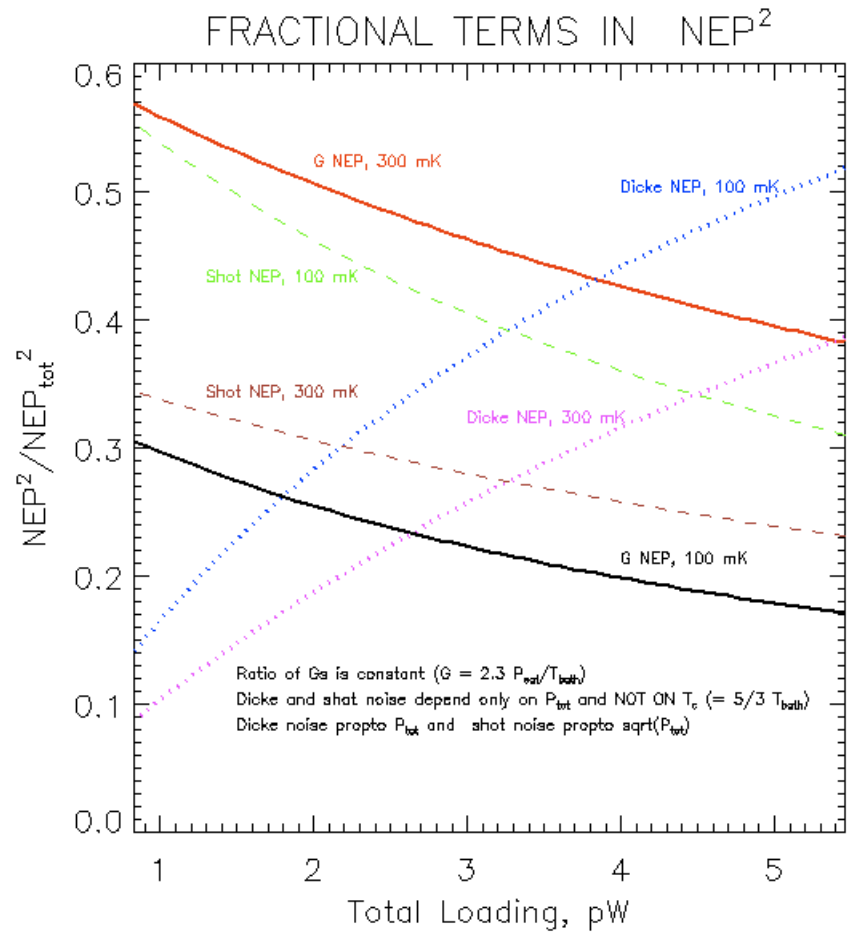
$$\text{NEP}_{Dicke} = \sqrt{\frac{p_\gamma^2}{b\,\Delta\nu}}$$

$$\text{NEP}_{shot} = \sqrt{\frac{h\nu\, p_\gamma}{b}}$$

$$\text{NEP}_G = \sqrt{4kT_0^2\, G\, f_\ell}$$

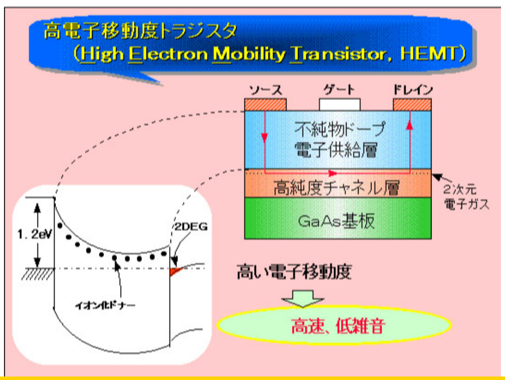
Example calculations for 150 GHz from the Atacama:





Detector Sensitivities: x << 1

NEP (units W $Hz^{-1/2}$) and NET (units mK $s^{1/2}$)



Fujitsu: first HEMT 1982

$$NEP_{Dicke} = \sqrt{\frac{p_\gamma^2}{b\,\Delta\nu}}$$

$$NEP_{shot} = \sqrt{\frac{h\nu\, p_\gamma}{b}}$$

Since $p_\gamma \propto h\nu\, n_\gamma = h\nu\,(e^x-1)^{-1}$,

$NEP_{Dicke} >> NEP_{shot}$ for $x<<1$
(The converse is also true.)

Since for $x<<1$, $p_\gamma \sim kT\Delta\nu$,

$NET_{Dicke} \sim T/\sqrt{\Delta\nu}$ for $x<<1$

For a coherent amplifier (cf a bolometer), $NET_{tot} = NET_{Dicke}$ for $x<<1$, with T the total system temperature – including an extra noise term T_N from the amplifier itself. For a high-gain linear amplifier, $T_N \geq h\nu/k$.
(NB: Bolometers do not amplify, and so do not experience this Q.L.)

Detector Sensitivities: Coda I

NEP (units W $Hz^{-1/2}$) and NET (units mK $s^{1/2}$)

Radiometer Equation: $\delta T = T_{sys} / \sqrt{(\Delta\nu)t}$

where δT is the error after t seconds of integration, and T_{sys} includes T_N for coherent amplifiers, and where $x \ll 1$ (but remember $x = x(T)$.)

> a linear amplifier as an essential element. The answer is intimately connected to the amplifier's gain. Confronted by a signal contaminated only by quantum noise, one uses an amplifier to increase the size of the signal without seriously degrading the signal-to-noise ratio. The noise after amplification being much larger than the minimum permitted by quantum mechanics, the signal can then be examined by crude, "classical" devices without addition of significant additional noise. Thus quantum-number gain is a crucial feature of a measurement. Indeed, the last essential quantum-mechanical stage of a measuring apparatus is a high-gain amplifier; it produces an output that we can lay our grubby, classical hands on.

If you want more – Caves, PRD 26, 1817 (1982) expounds on the quantum limit for linear amplifiers in general in a perspicuous and charming paper.

Detector Sensitivities: Coda II

NEP (units W $Hz^{-1/2}$) and NET (units mK $s^{1/2}$)

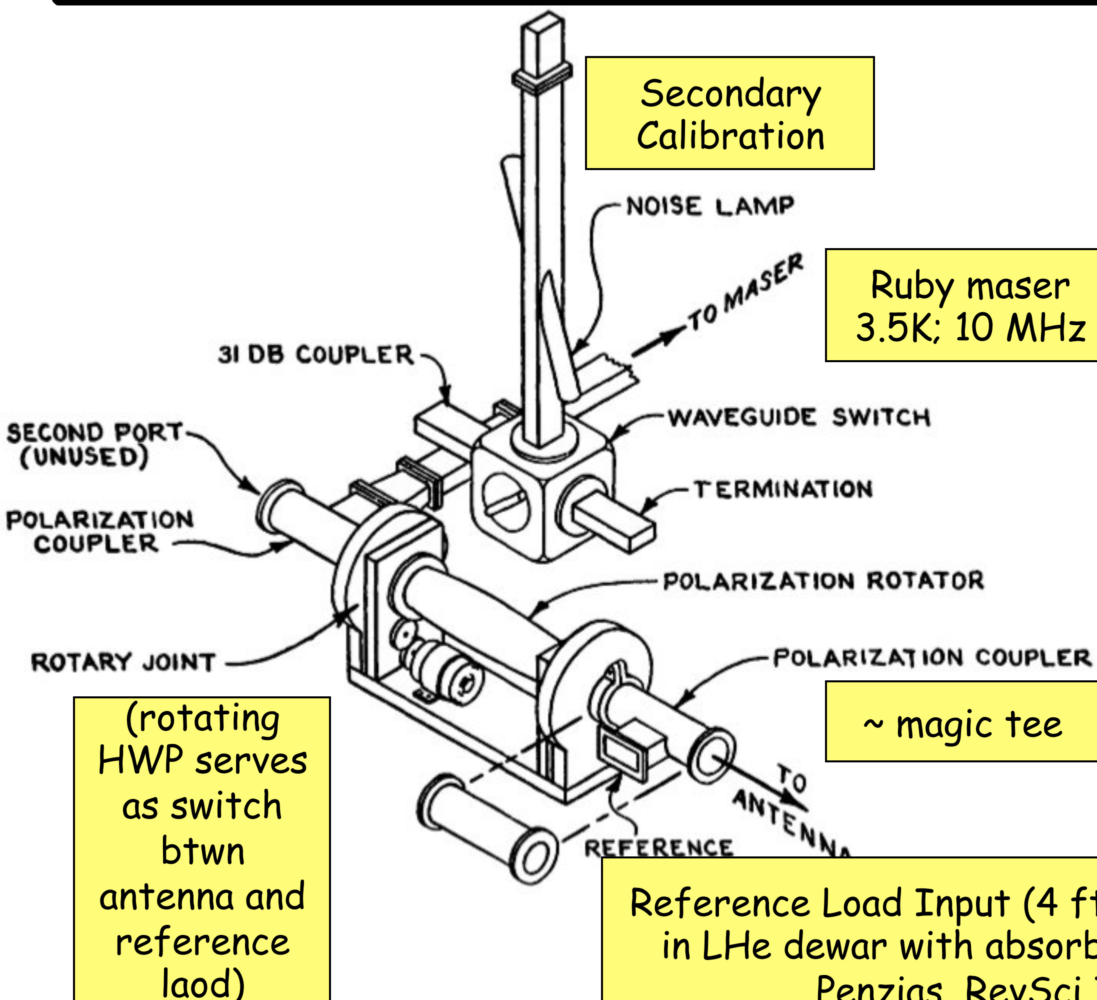
Radiometer Equation: $\delta T = T_{sys} / \sqrt{(\Delta\nu)t}$

This form makes clear why atmosphere 1/f noise is deadly: it means T^2_{sys} varies so as to exactly cancel integrating down with t.

Gain fluctuations in coherent systems can also prevent integration down:

$$\delta T = b T_{sys} \sqrt{\frac{1}{\Delta\nu\ \tau} + \left(\frac{\delta R}{R}\right)^2}$$

The First CMB Receiver



Reference Load Input (4 ft long piece of brass waveguide in LHe dewar with absorber cone at the bottom.) See Penzias, RevSci Instr, 36, 68 (1965)

- Penzias & Wilson, 1965, ApJ 142, 1149.
- Tsys = 20 K
- Expected S = 5 mK $s^{-1/2}$
- Helium bubbling in the maser caused gain fluctuations
- Achieved S = 25 mK $s^{-1/2}$
- Totally adequate for measuring T=3 K!

An FTS Aside: Why Martin-Puplett?

POLARISED INTERFEROMETRIC SPECTROMETRY FOR THE MILLIMETRE AND SUBMILLIMETRE SPECTRUM

D. H. MARTIN and E. PUPLETT

Queen Mary College, London E.1

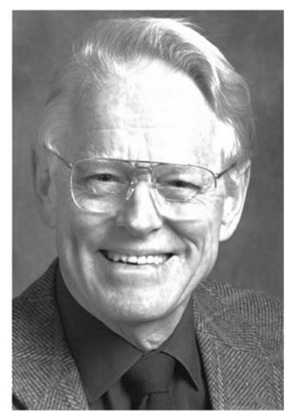
(*Received* 15 *December* 1969)

Abstract—A method of interferometric spectrometry based on polarising beam-splitters is described. This allows operation over a wide range of spectral frequency without strong variations in efficiency, and also the suppression of the mean-level of the interferogram, spurious modulation of which is a major source of error in conventional methods. Interferograms obtained with this kind of spectrometer, in the far infra-red, are presented.

1. Paul Richards was an early adopter!
2. NB: Richards 1964, J. Opt. Soc 54, 1474: pitted grating monochromator, lamellar grating interferometer (csb) & MPI against one another. Interferometry won for the FIR.
3. Of the FTSes used for CMB spectral work, all but one were the MPI type.

Derek Martin & Eddie Puplett

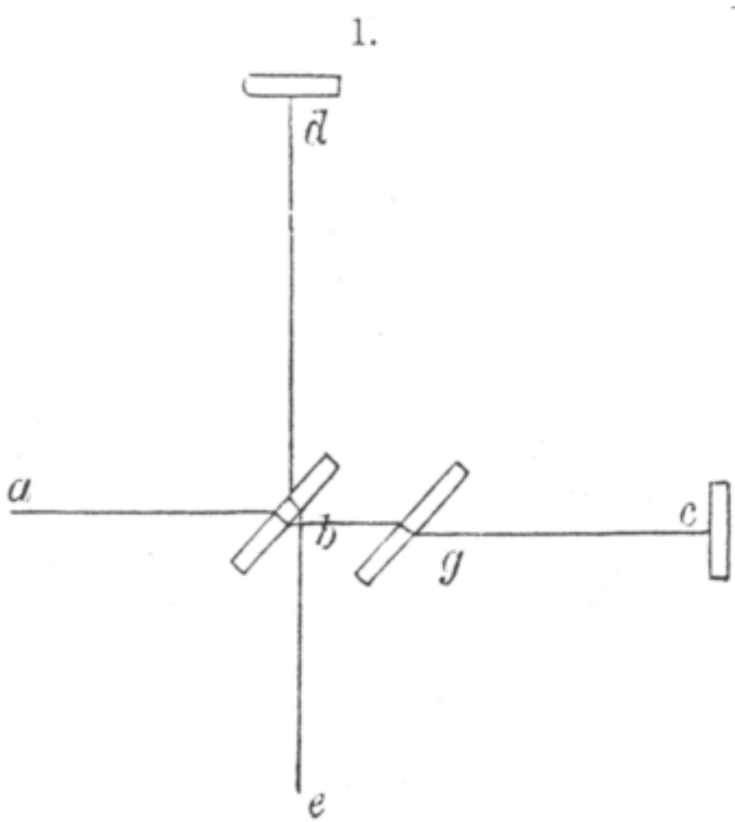
Paul Richards



An FTS Aside: Why Martin-Puplett?

Remember this Michelson diagram:
(Michelson, A. A., Am. J. Sci, 22: 120-129 (1881).)

The conditions for producing interference of two pencils of light which had traversed paths at right angles to each other were realized in the following simple manner.



Light from a lamp *a*, fig. 1, passed through the plane parallel glass plate *b*, part going to the mirror *c*, and part being reflected to the mirror *d*. The mirrors *c* and *d* were of plane glass, and silvered on the front surface. From these the light was reflected to *b*, where the one was reflected and the other refracted, the two coinciding along be.

The distance *bc* being made equal to *bd*, and a plate of glass *g* being interposed in the path of the ray *bc*, to compensate for the thickness of the glass *b*, which is traversed by the ray *bd*, the two rays will have traveled over equal paths and are in condition to interfere.

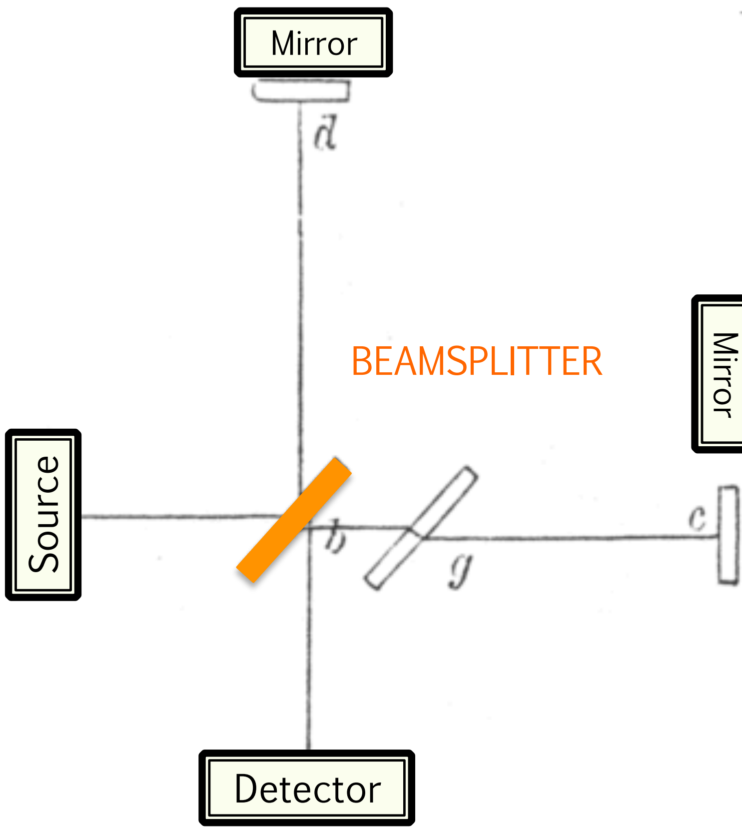
The instrument is represented in plan by fig. 2, and in perspective by fig. 3. The same letters refer to the same parts in the two figures.

The source of light, a small lantern provided with a lens, the flame being in the focus, is represented at *a*. *b* and *g* are the two plane glasses, both being cut from the same piece; *d* and *c* are the silvered glass mirrors; *m* is a micrometer screw which moves the plate *b* in the direction be. The telescope *e*, for observing the interference bands, is provided with a micrometer eyepiece. *w* is a counterpoise.

An FTS Aside: Why Martin-Puplett?

Remember this Michelson diagram:
(Michelson, A. A., Am. J. Sci, 22: 120-129 (1881).)

The conditions for producing interference of two pencils of light which had traversed paths at right angles to each other were realized in the following simple manner.



Light from a lamp *a*, fig. 1, passed through the plane parallel glass plate *b*, part going to the mirror *c*, and part being reflected to the mirror *d*. The mirrors *c* and *d* were of plane glass, and silvered on the front surface. From these the light was reflected to *b*, where the one was reflected and the other refracted, the two coinciding along be.

The distance *bc* being made equal to *bd*, and a plate of glass *g* being interposed in the path of the ray *bc*, to compensate for the thickness of the glass *b*, which is traversed by the ray *bd*, the two rays will have traveled over equal paths and are in condition to interfere.

The instrument is represented in plan by fig. 2, and in perspective by fig. 3. The same letters refer to the same parts in the two figures.

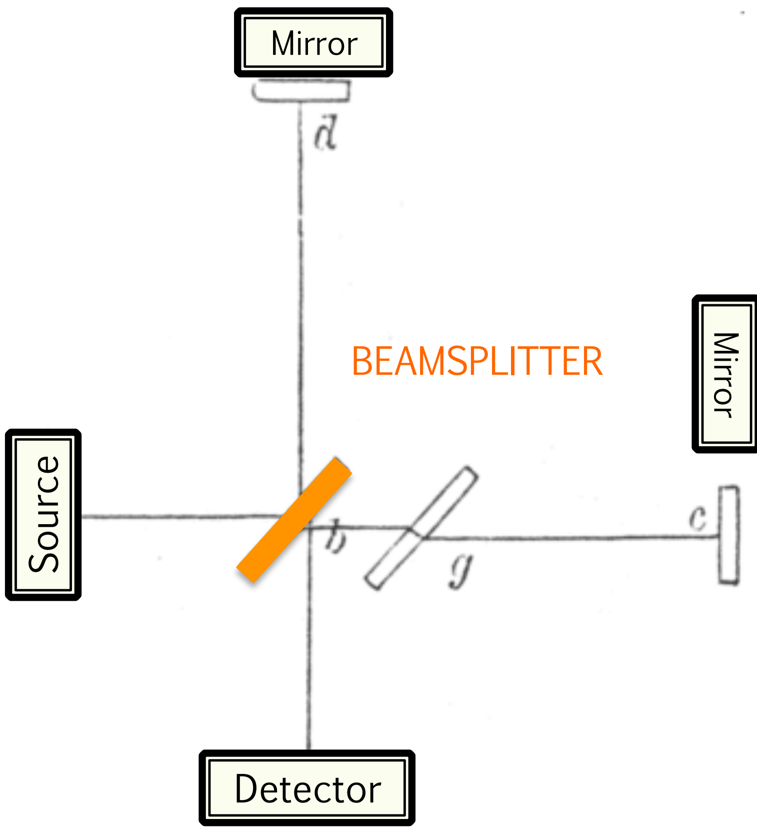
The source of light, a small lantern provided with a lens, the flame being in the focus, is represented at *a*. *b* and *g* are the two plane glasses, both being cut from the same piece; *d* and *c* are the silvered glass mirrors; *m* is a micrometer screw which moves the plate *b* in the direction be. The telescope *e*, for observing the interference bands, is provided with a micrometer eyepiece. *w* is a counterpoise.

An FTS Aside: Why Martin-Puplett?

Remember this Michelson diagram:

(Michelson, A. A., Am. J. Sci, 22: 120-129 (1881).)

The conditions for producing interference of two pencils of light which had traversed paths at right angles to each other were realized in the following simple manner.



Light from a lamp *a*, fig. 1, passed through the plane parallel glass plate *b*, part going to the mirror *c*, and part being reflected to the mirror *d*. The mirrors *c* and *d* were ... e the light was re... cted, the two coi...

BEAMSPLITTER BEHAVIOR IS FREQUENCY DEPENDENT:

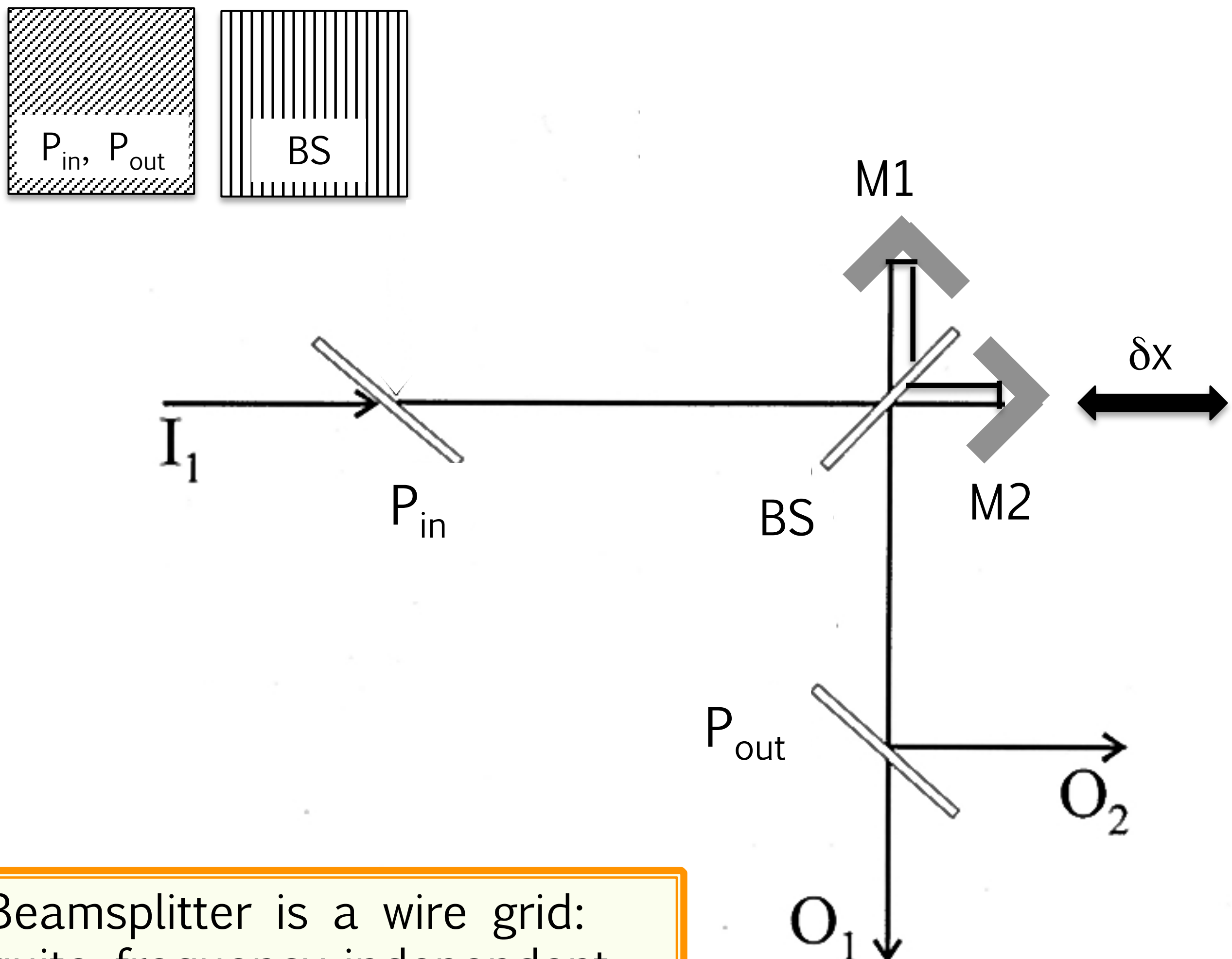
1) Here, ignoring absorption,. $r = (n-1)/(n+1)$ and $n = n(\nu)$
2) For far IR, early FTSes used thin dielectrics (also with $n=n(\nu)$) or lamellar gratings (cool story, bro)

The distan... being interposed ... of the glass *b*, wh... over equal paths...

The instrument is represented in plan by fig. 2, and in perspective by fig. 3. The same letters refer to the same parts in the two figures.

The source of light, a small lantern provided with a lens, the flame being in the focus, is represented at *a*. *b* and *g* are the two plane glasses, both being cut from the same piece; *d* and *c* are the silvered glass mirrors; *m* is a micrometer screw which moves the plate *b* in the direction be. The telescope *e*, for observing the interference bands, is provided with a micrometer eyepiece. *w* is a counterpoise.

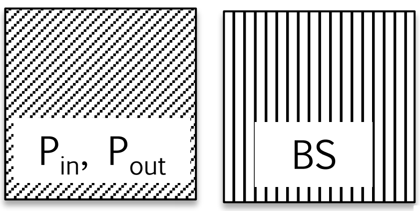
An FTS Aside: Why Martin-Puplett?

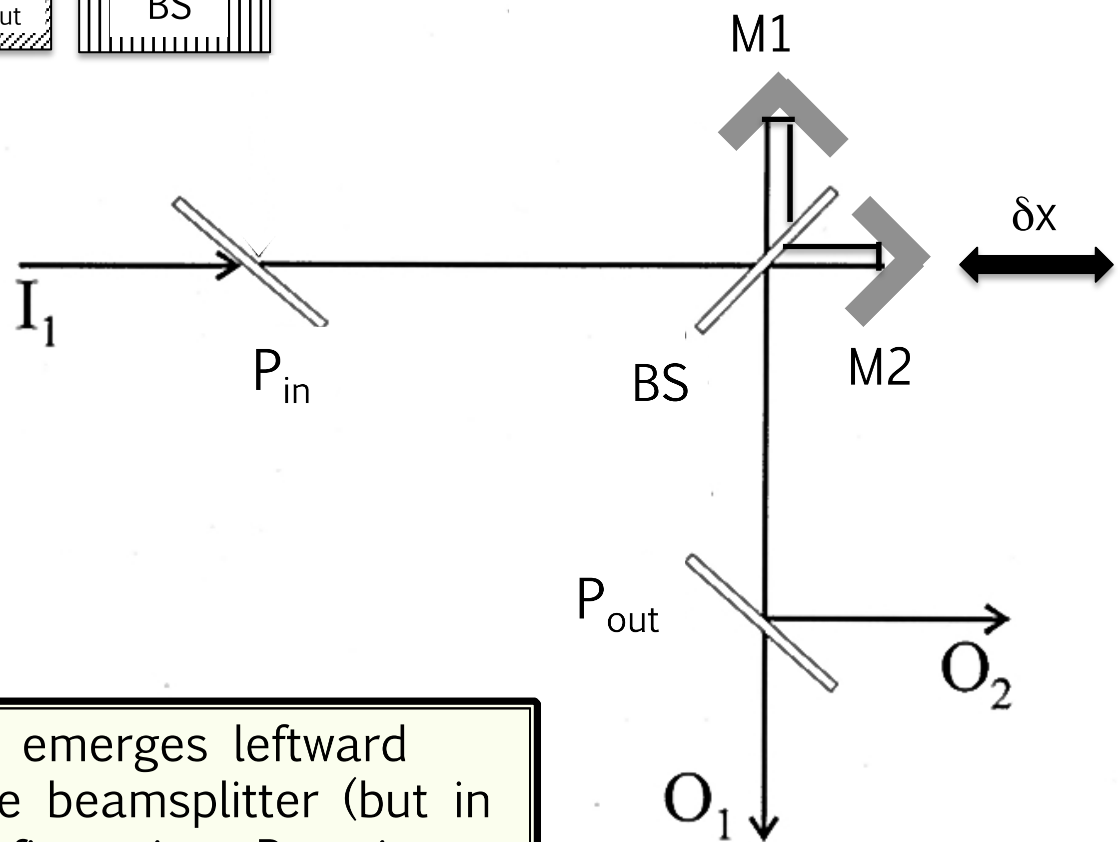


Rooftop mirrors cause $E_{\|} \leftrightarrow E_{\perp}$

Beamsplitter is a wire grid: quite frequency-independent for λ >> spacing.

An FTS Aside: Why Martin-Puplett?

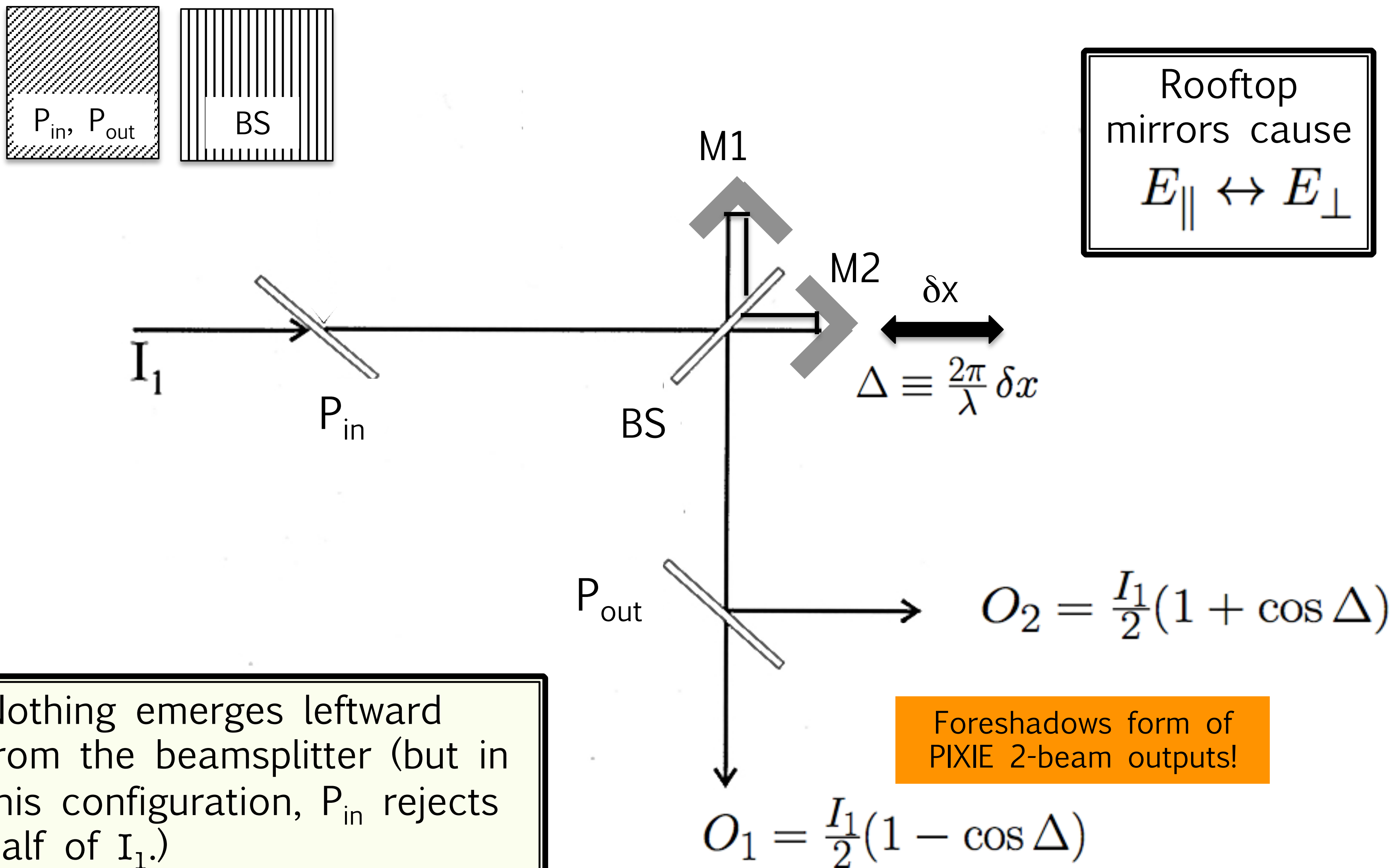




Rooftop mirrors cause $E_{\|} \leftrightarrow E_{\perp}$

Nothing emerges leftward from the beamsplitter (but in this configuration, P_{in} rejects half of I_1.)

An FTS Aside: Why Martin-Puplett?

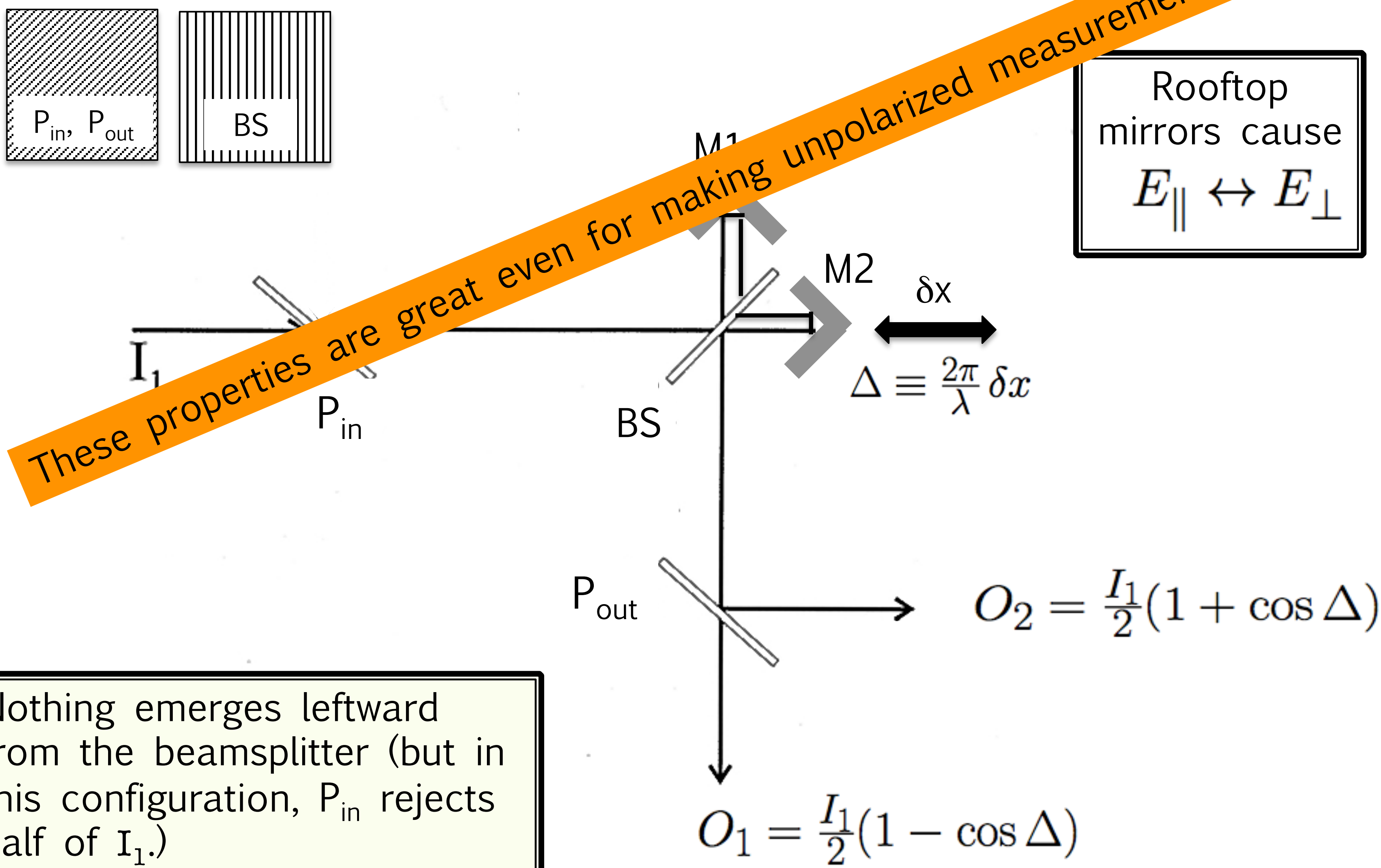


Rooftop mirrors cause $E_{\|} \leftrightarrow E_{\perp}$

Nothing emerges leftward from the beamsplitter (but in this configuration, P_{in} rejects half of I_1.)

Foreshadows form of PIXIE 2-beam outputs!

An FTS Aside: Why Martin-Puplett?



These properties are great even for making unpolarized measurements.

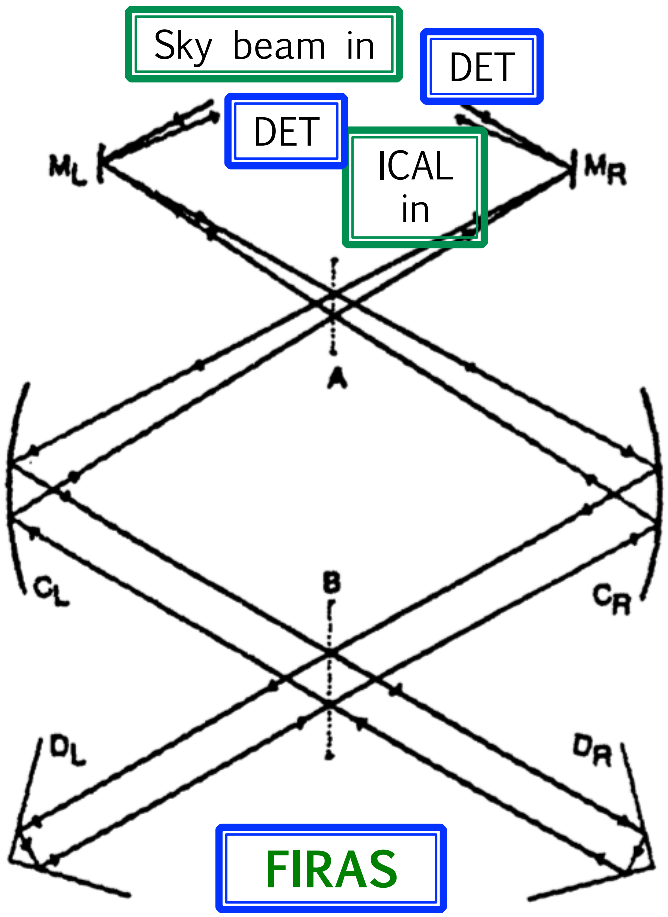
Rooftop mirrors cause $E_{\parallel} \leftrightarrow E_{\perp}$

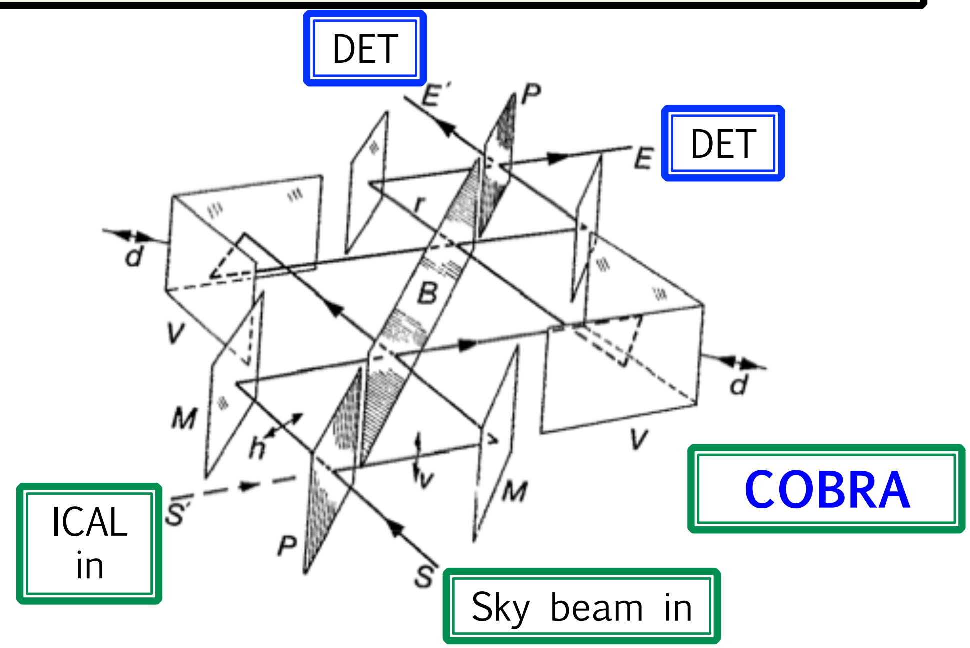
Nothing emerges leftward from the beamsplitter (but in this configuration, P_{in} rejects half of I_1.)

Martin-Puplett Configurations

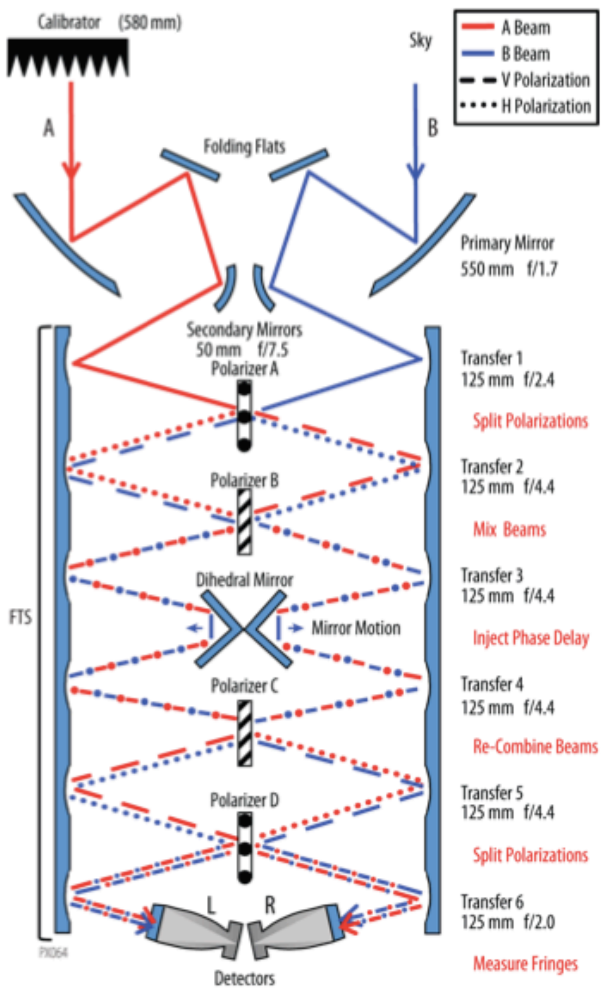
There are many configurations for an MPI; the “two beam” configurations (e.g. COBRA, FIRAS) avoid the loss of half the signal seen in the previous example AND produce difference spectra:

$$I(x) = \int \left(S_{sky}(\nu) - S_{ical}(\nu)\right)\left(1 \pm \cos(\pi\nu/c\,x)\right) d\nu$$





Martin-Puplett Configurations



Kogut et al, JCAP, 2011

As Al showed, PIXIE uses two beams, multiple foldings and collimations and an extra beam un-splitter to measure CMB polarization at the same time as measuring its spectrum!

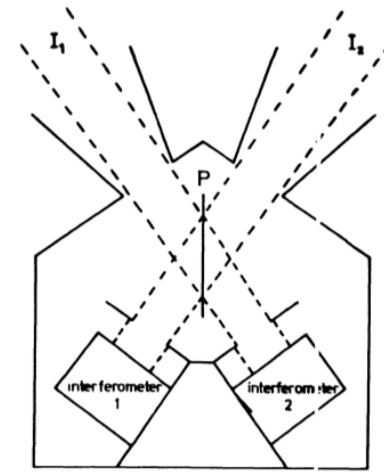
$$P_{Lx} = \frac{1}{2}\int \left(E_{Ay}^2 + E_{Bx}^2\right) + \left(E_{Bx}^2 - E_{Ay}^2\right)\cos(z\omega/c)\, d\omega$$

$$P_{Ly} = \frac{1}{2}\int \left(E_{Ax}^2 + E_{By}^2\right) + \left(E_{By}^2 - E_{Ax}^2\right)\cos(z\omega/c)\, d\omega$$

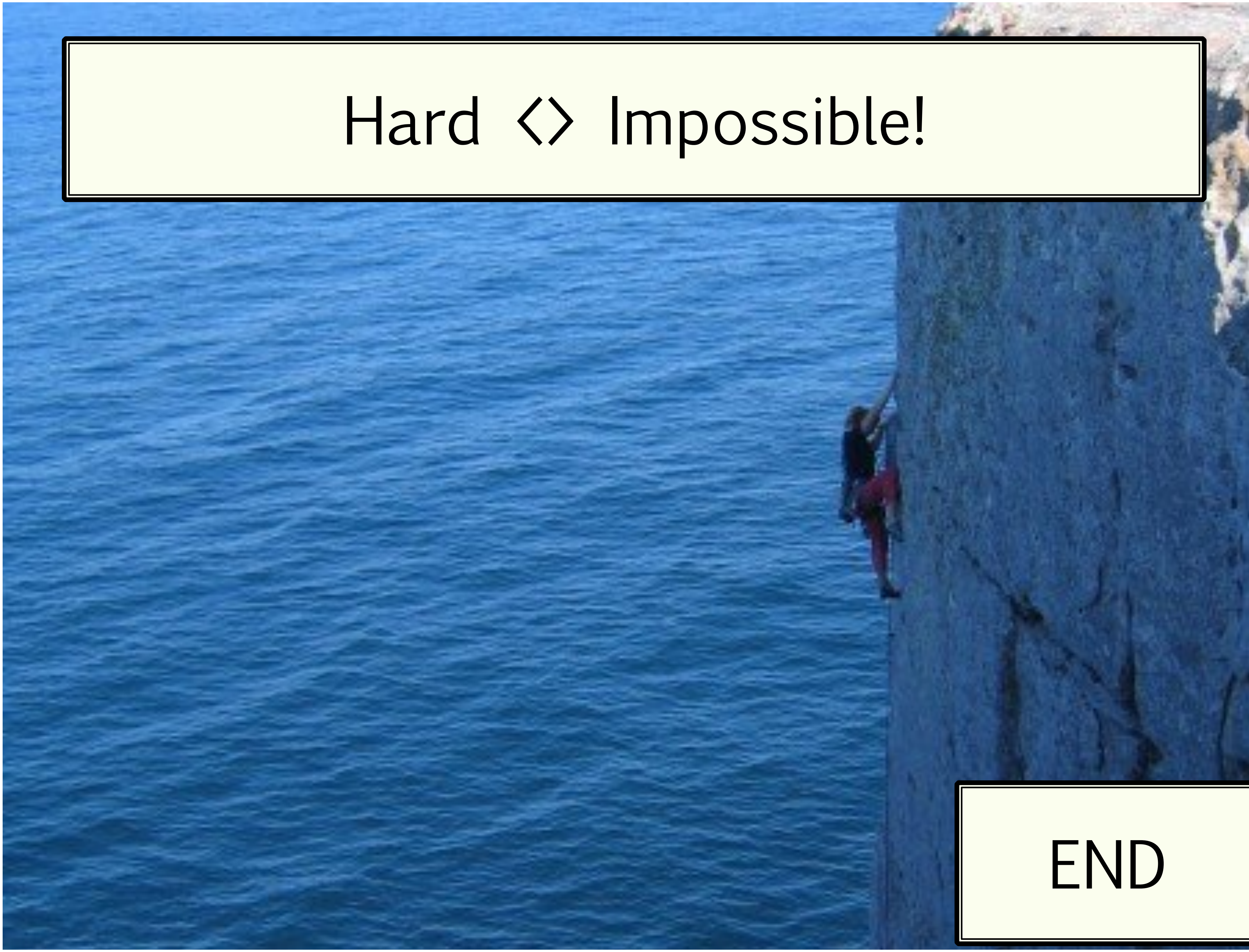
NB: to get $\Delta\nu$ = 15 GHz, need ΔOPL = 10 mm; with this design only have to move the mirrors 2.6 mm! Large movements require a larger diameter → bigger fairing, more mass, more stuff to get cold → big bucks.

Rashid – this is $\Delta\nu/\nu \sim 10^{-1}$ on CO lines..

What is Hard?



1. To make things big when they need to be cold (for thermal equilibrium operation) → low frequencies, small $\Delta\nu$
   (Martin et al 1978 – warm FTS on balloon with $\Delta\nu$ = 0.3 GHz; ΔOPL = 50 cm – scrubbed in Palestine.)
2. To understand and remove the atmosphere → ground-based instruments
3. To cool lots of mass or area to subKelvin temperatures → zillions of detectors in space
   a) Cooling power is expensive
   b) Gradients
4. To make a detector both large area and fast → huge etendues
5. Foregrounds
6. Discriminating nK-sized spectral features
7. (Getting funding)


Hard <> Impossible!
END