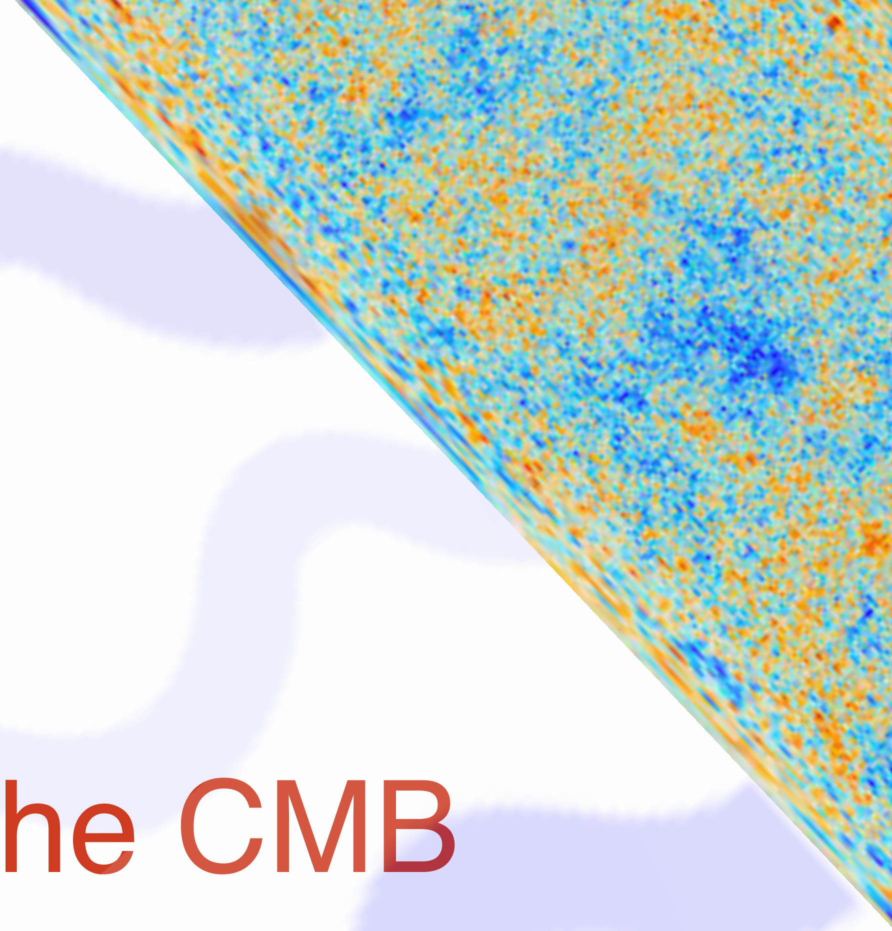
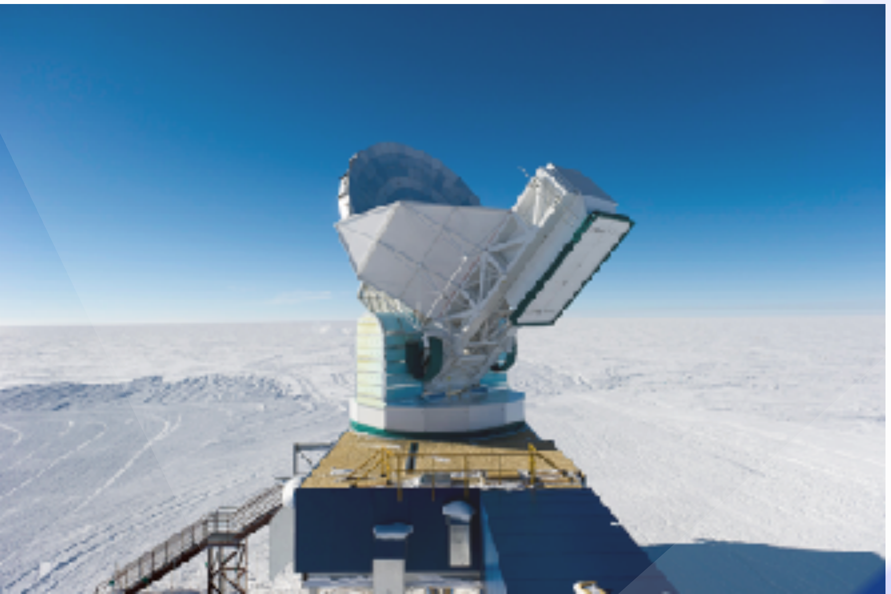
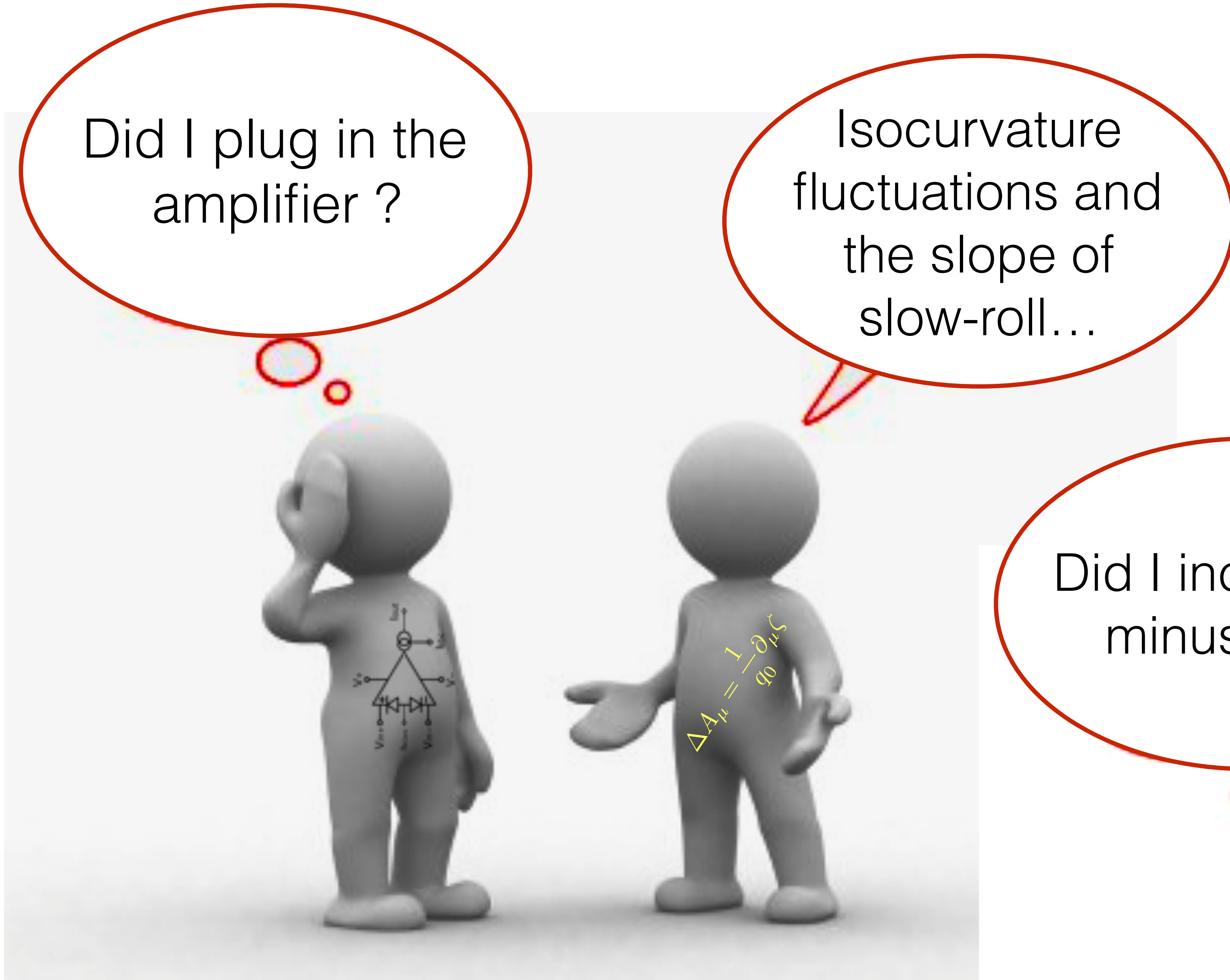
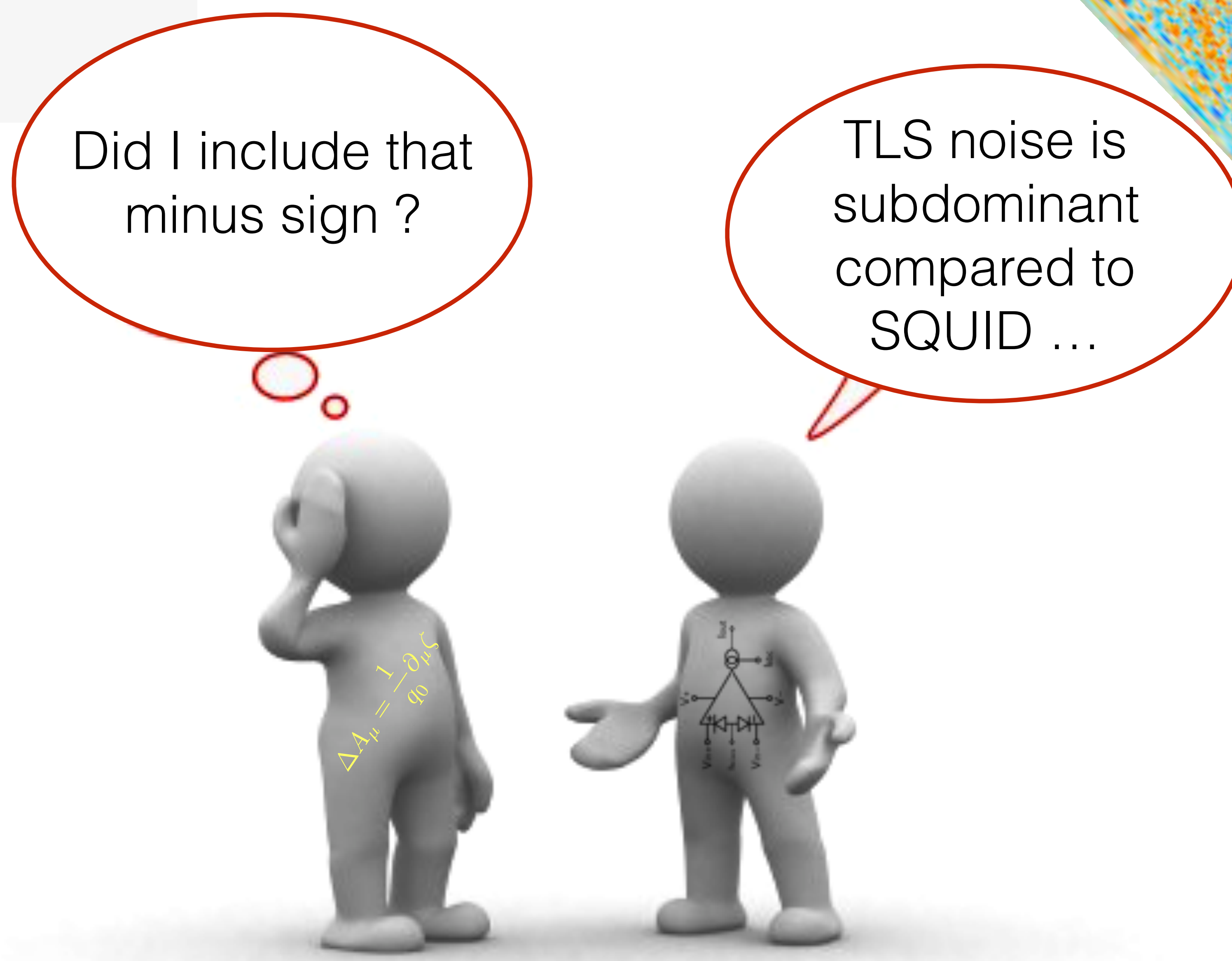
How we really measure the CMB

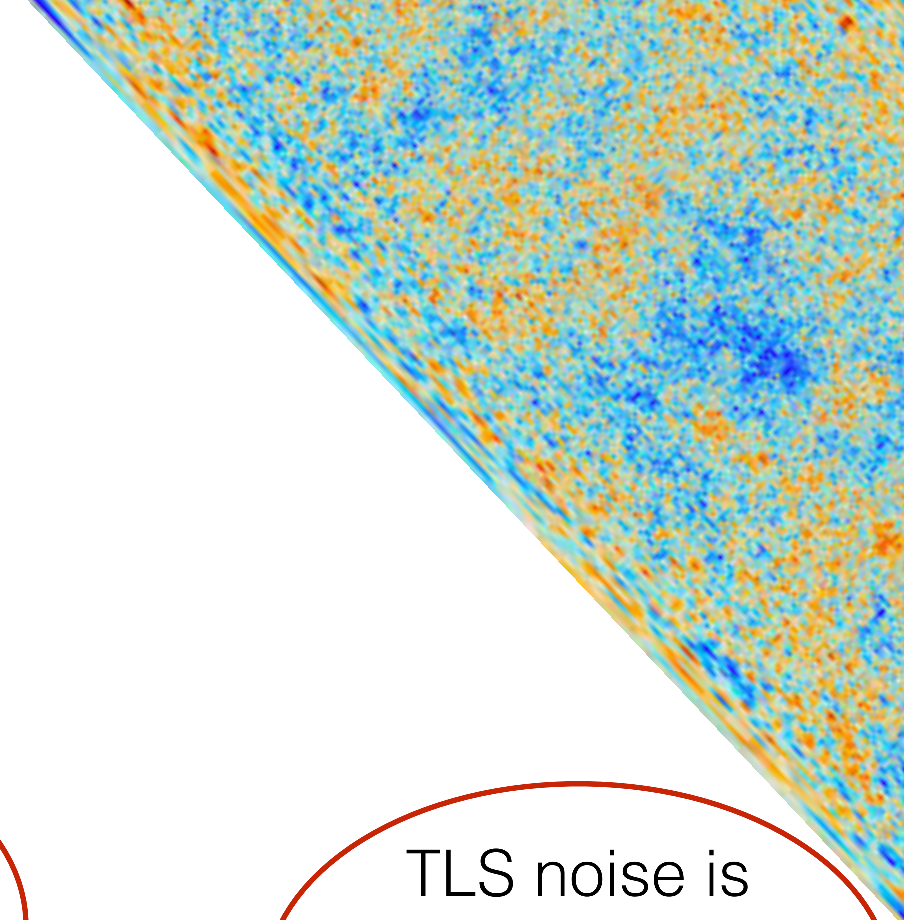


Ritoban Basu Thakur
Astro 448




Did I plug in the amplifier ?
Isocurvature fluctuations and the slope of slow-roll…


Did I include that minus sign ?
TLS noise is subdominant compared to SQUID …



Outline

The what-to and how-to of measuring ?

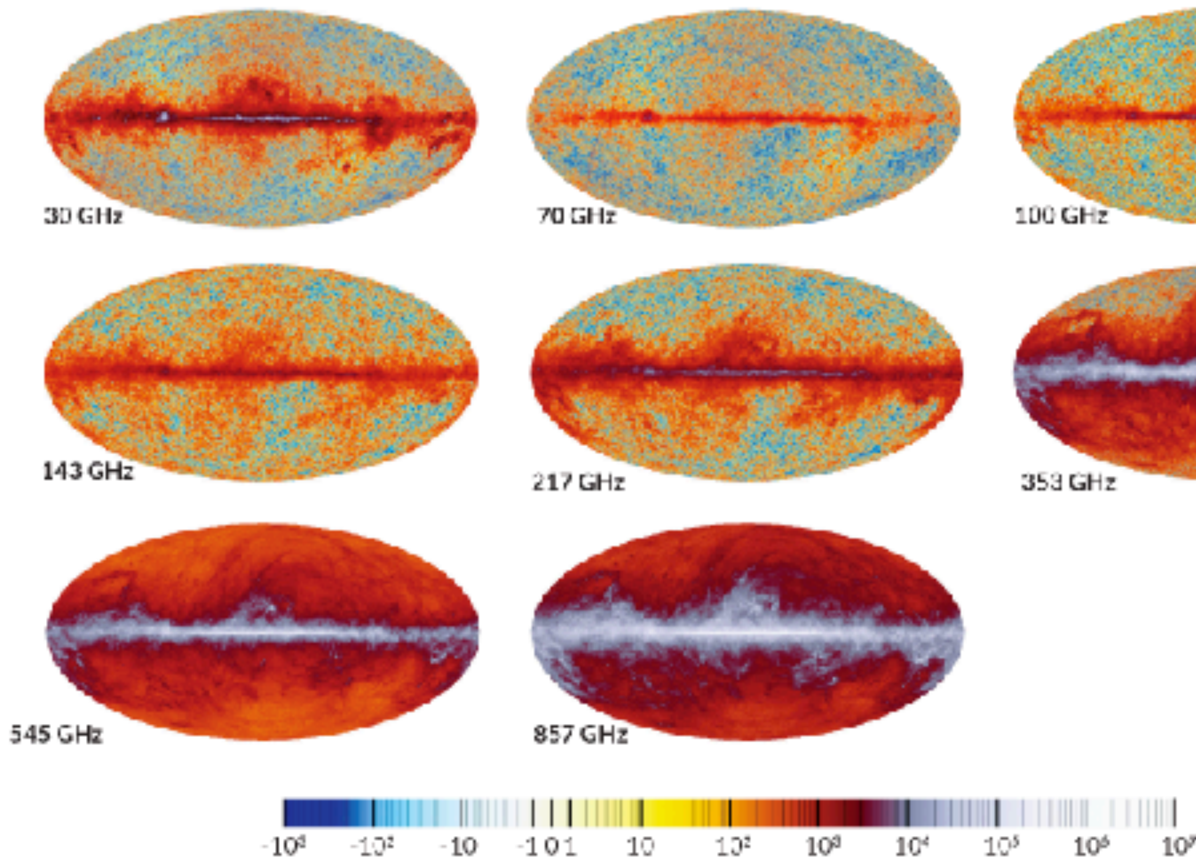
How to get the light in ?

How to measure the light ?

Some detectors in detail

The light

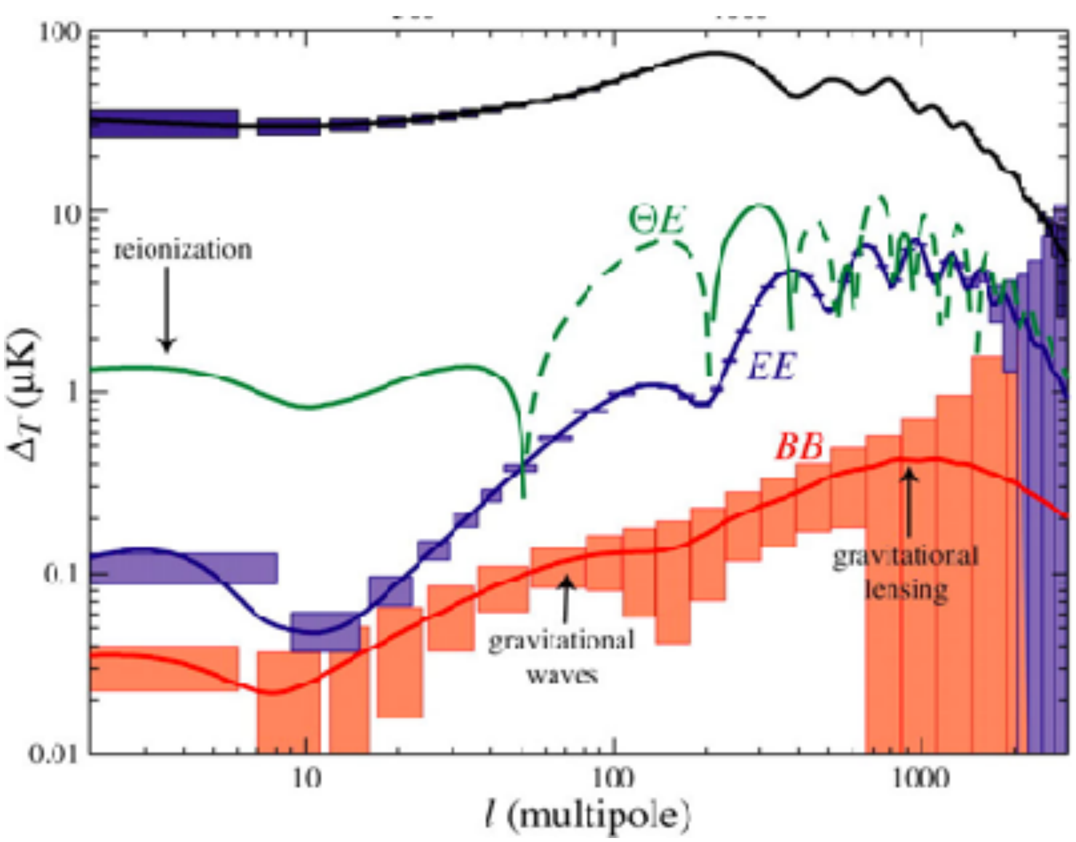
The light

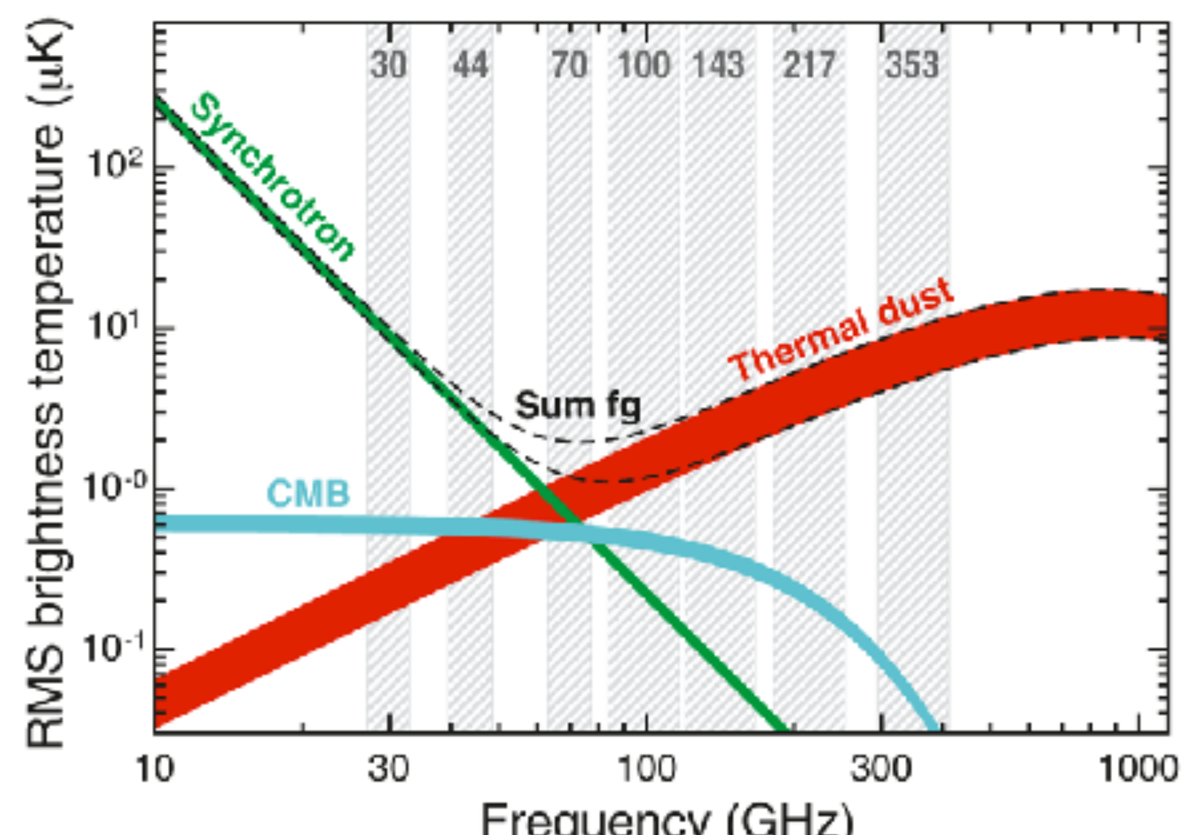


Top three rows: Deviation in microkelvin from average CMB temperature
Bottom row: Surface brightness in kilojanskys per steradian

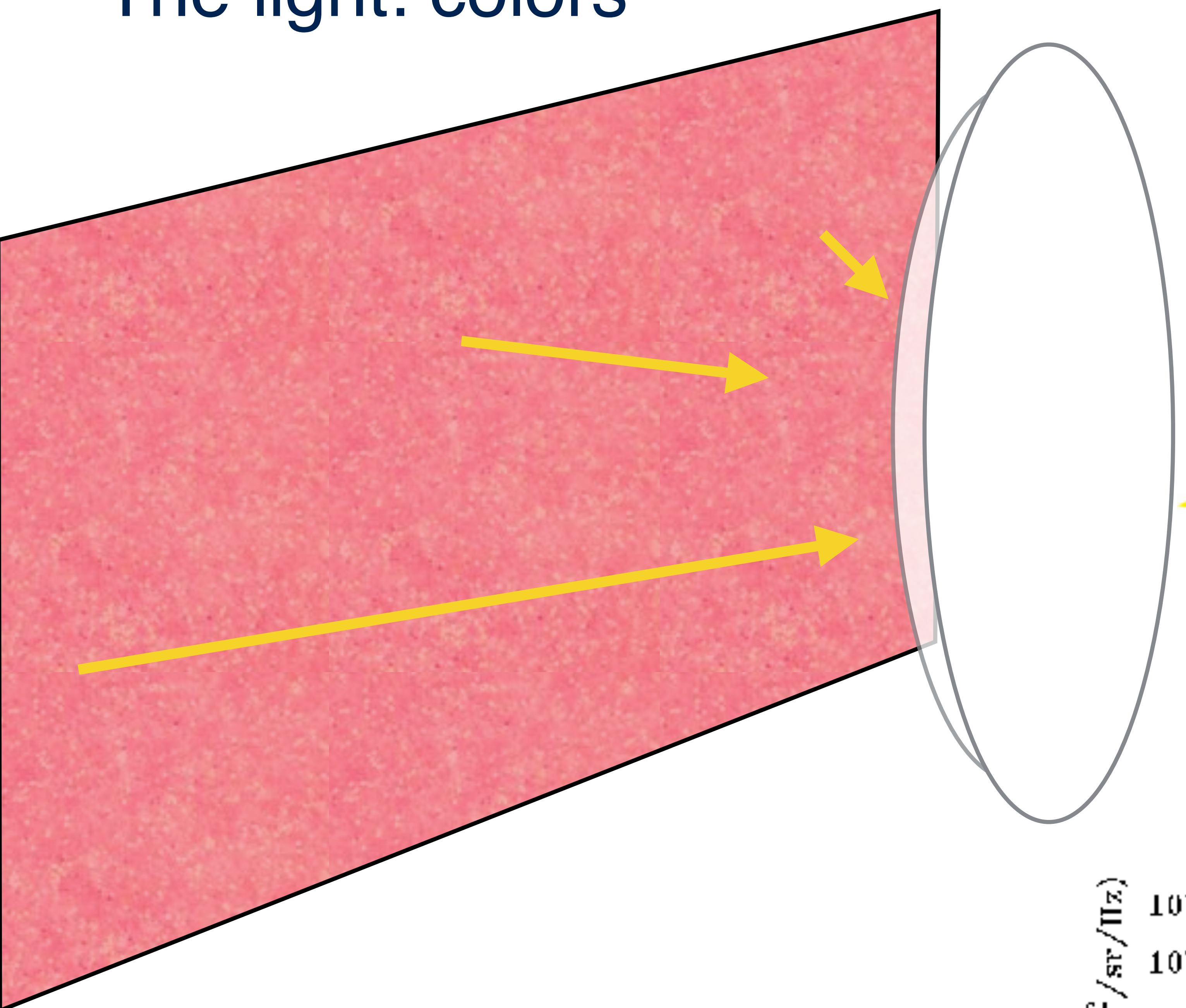
CMB is ~2.7 K Black Body, with maximal signal over foregrounds ~100 GHz

Tiny intensity fluctuations in frequency and location contain a plethora of interesting physics

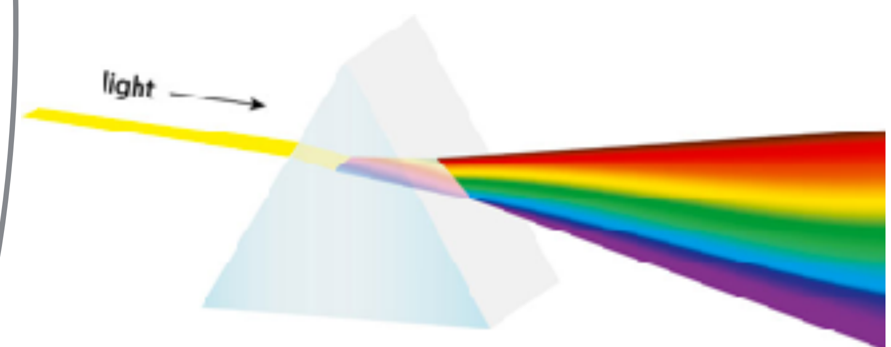




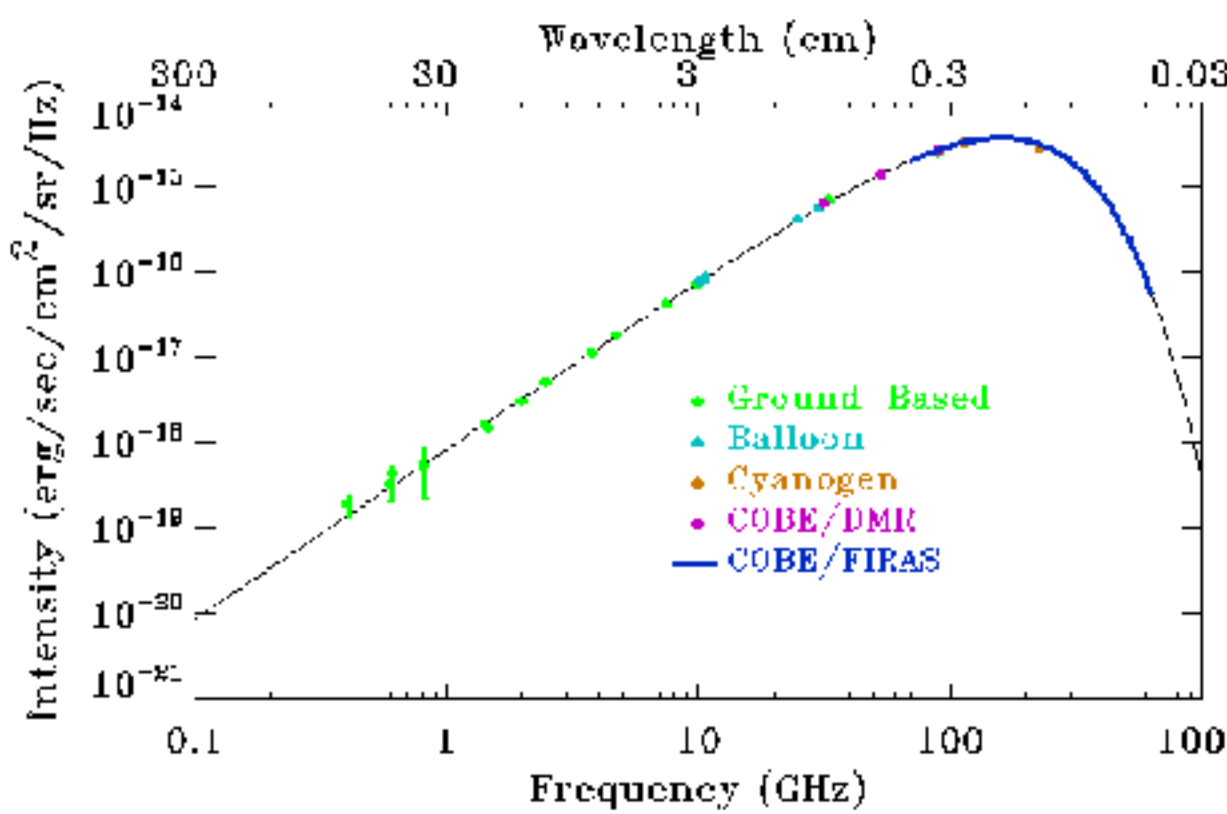
The light: colors



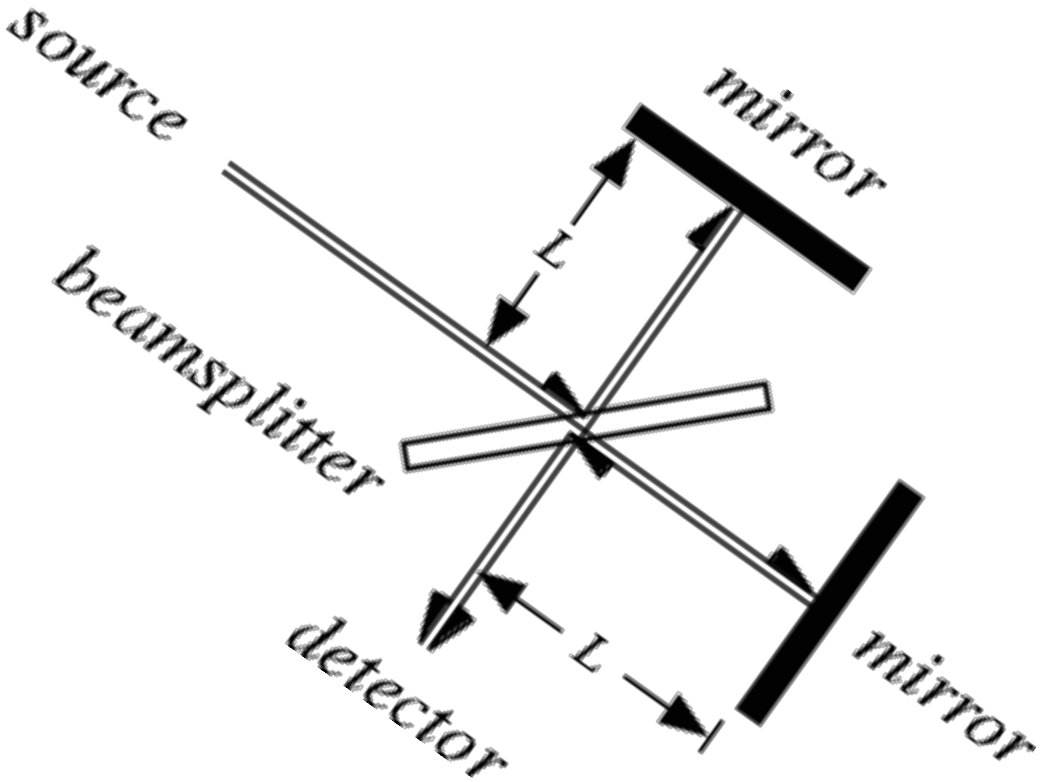
Large area collector
+ collimator



Broad-band 2.7 K BB
spectrum measured
across three decades

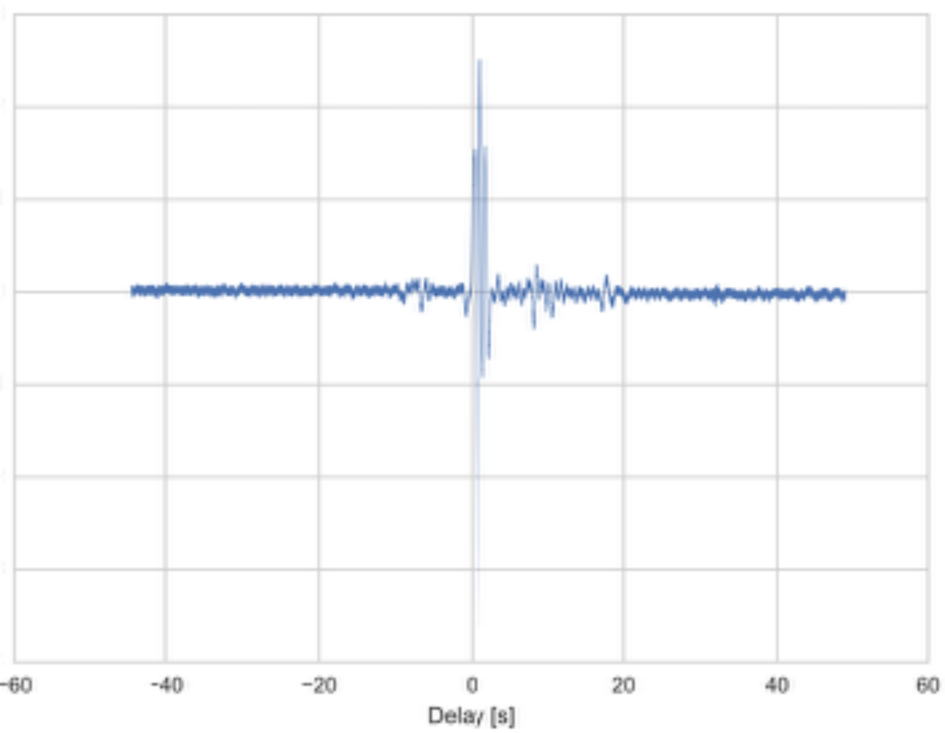


The light: colors

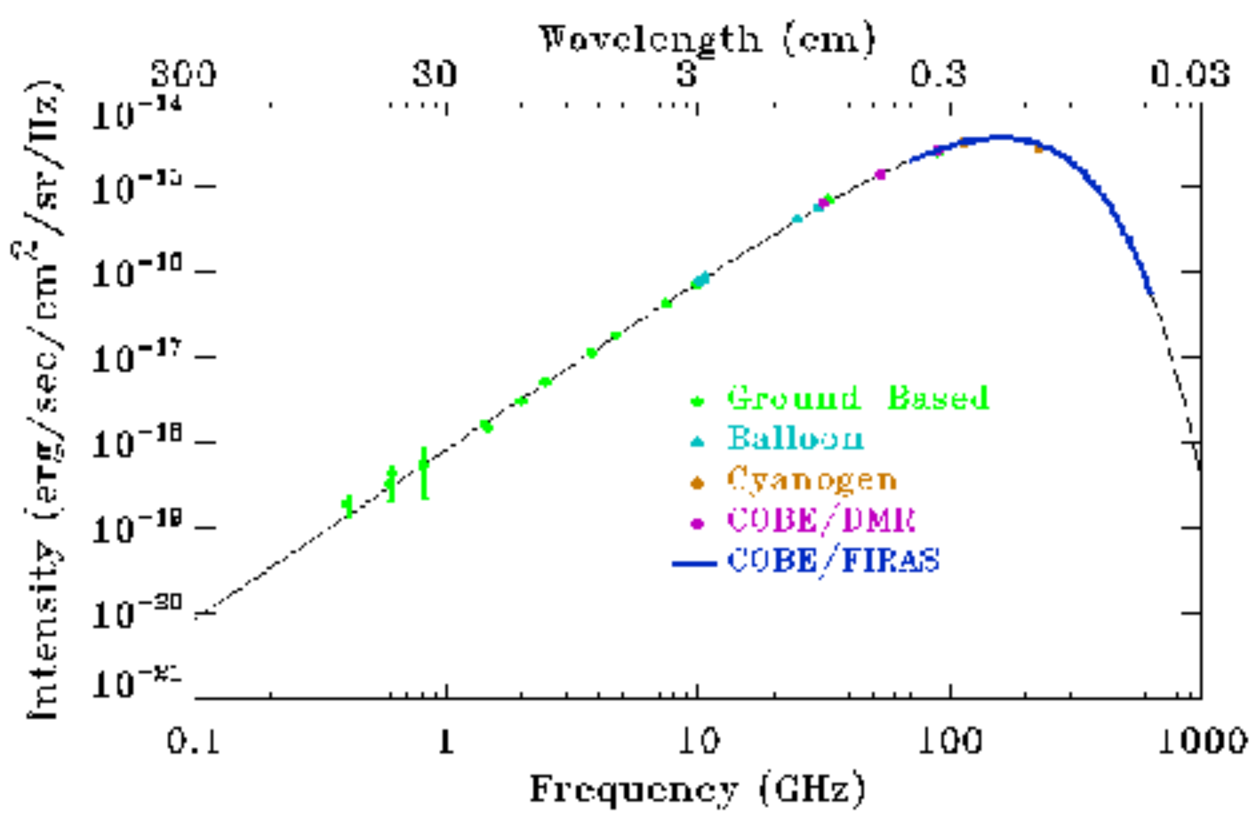


Not prisms …

Fourier Transform Spectrometry at the heart measurements.

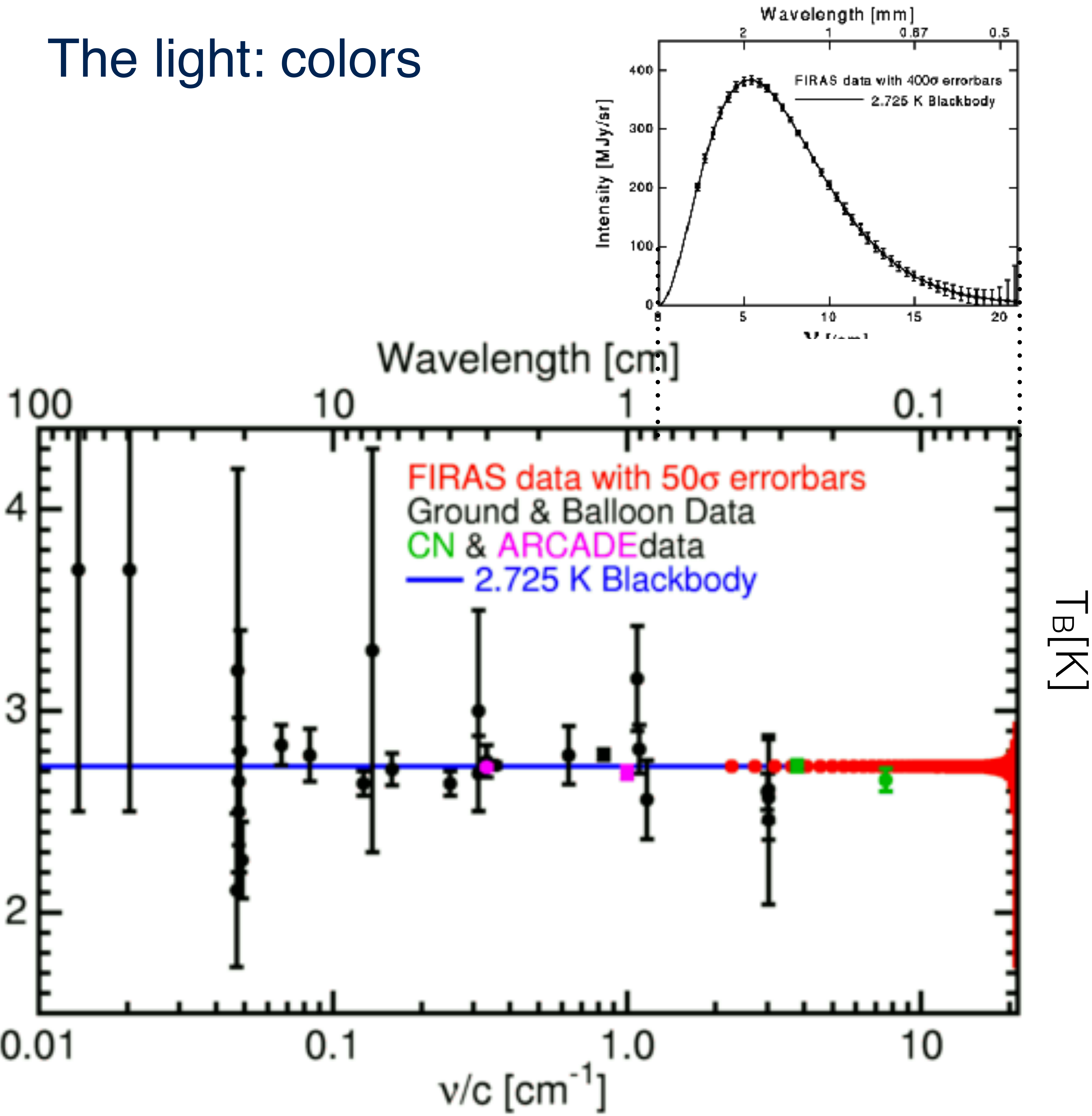


$$\tilde{I}(\lambda^{-1}) = 4\int_{-L}^{L}\{I(\Delta) - 0.5\, I(\Delta = 0)\}\cos(2\pi\nu\Delta/\lambda)$$



Fourier transform of Interferogram

The light: colors

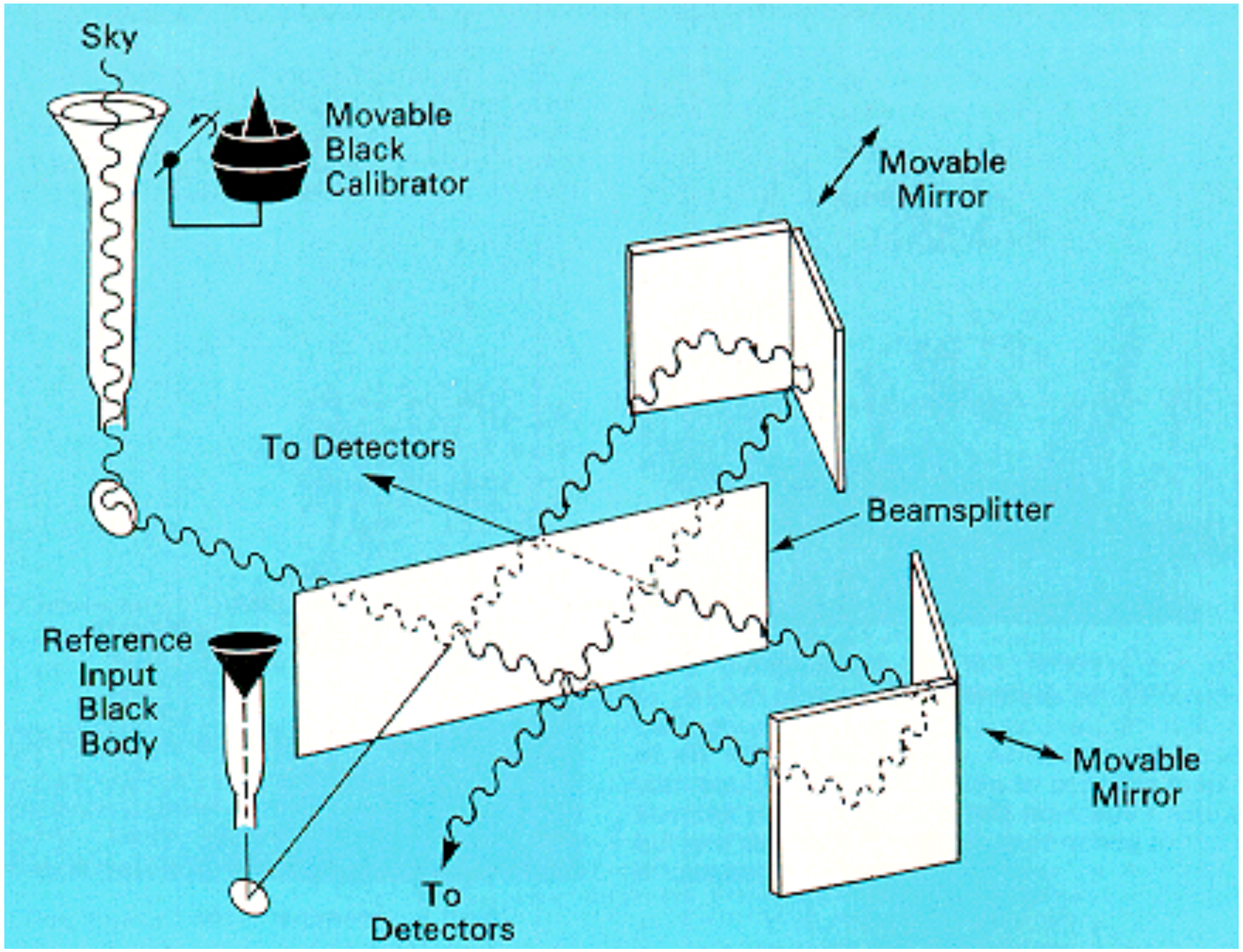


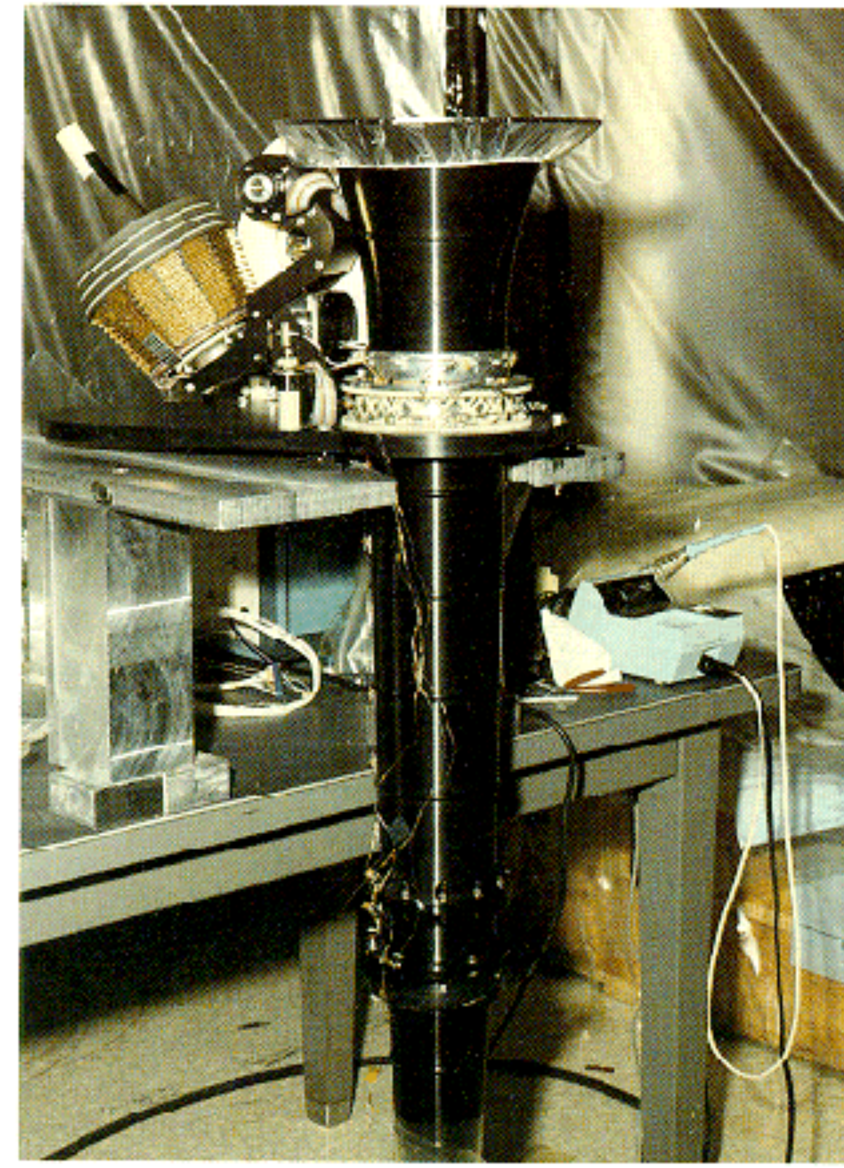
COBE FIRAS has the best spectral measurements, constraining dI/I to $\lesssim 10^{-5}$

https://lambda.gsfc.nasa.gov/product/cobe/

The light: colors

COBE Far Infrared Absolute Spectrophotometer (FIRAS)



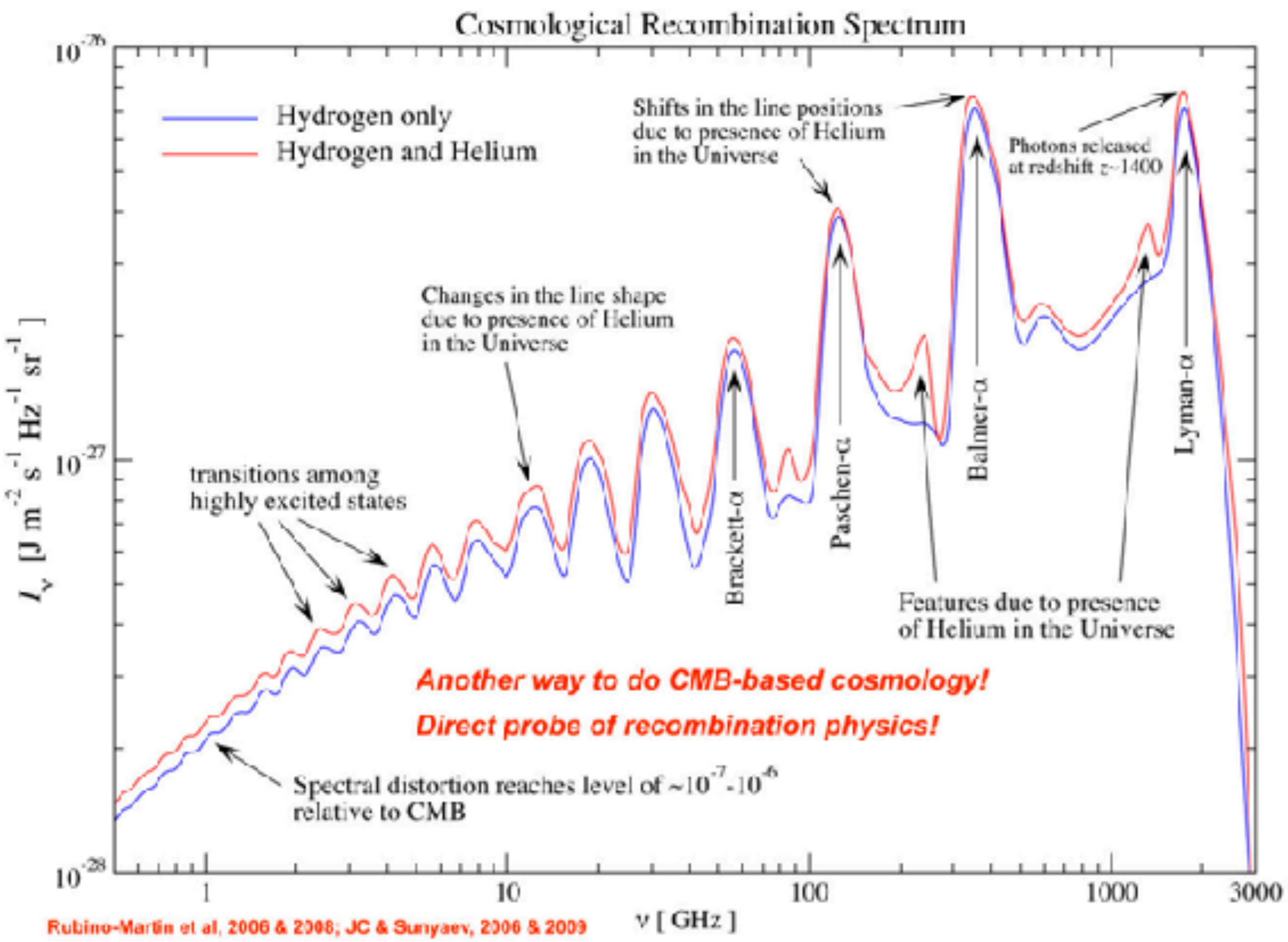


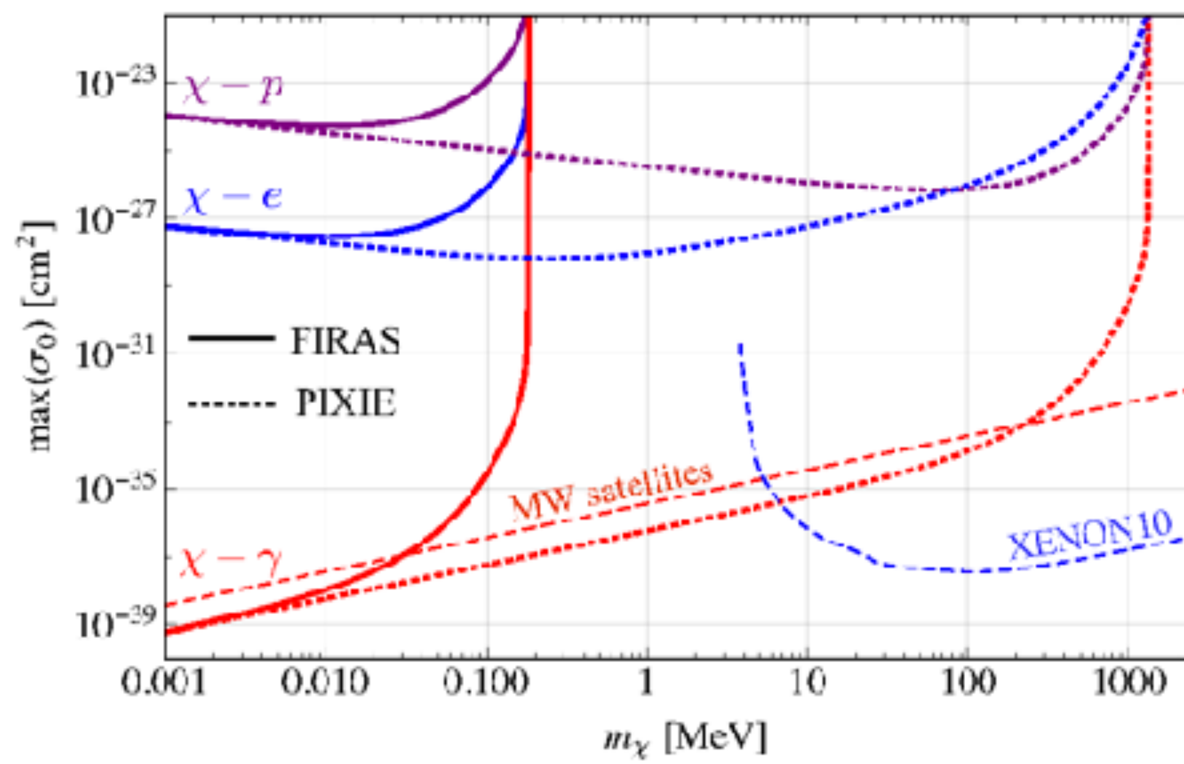
Horn antenna with movable calibrator. Protective plastic covers will be removed.

Fits to the cosmic spectral distortion parameters give 95% confidence limits of $|\mu/kT| < 3.3 \times 10^{-4}$ and $|y| < 2.5 \times 10^{-5}$.

The light: colors

Lot of interesting physics in CMB Spectral Distortions

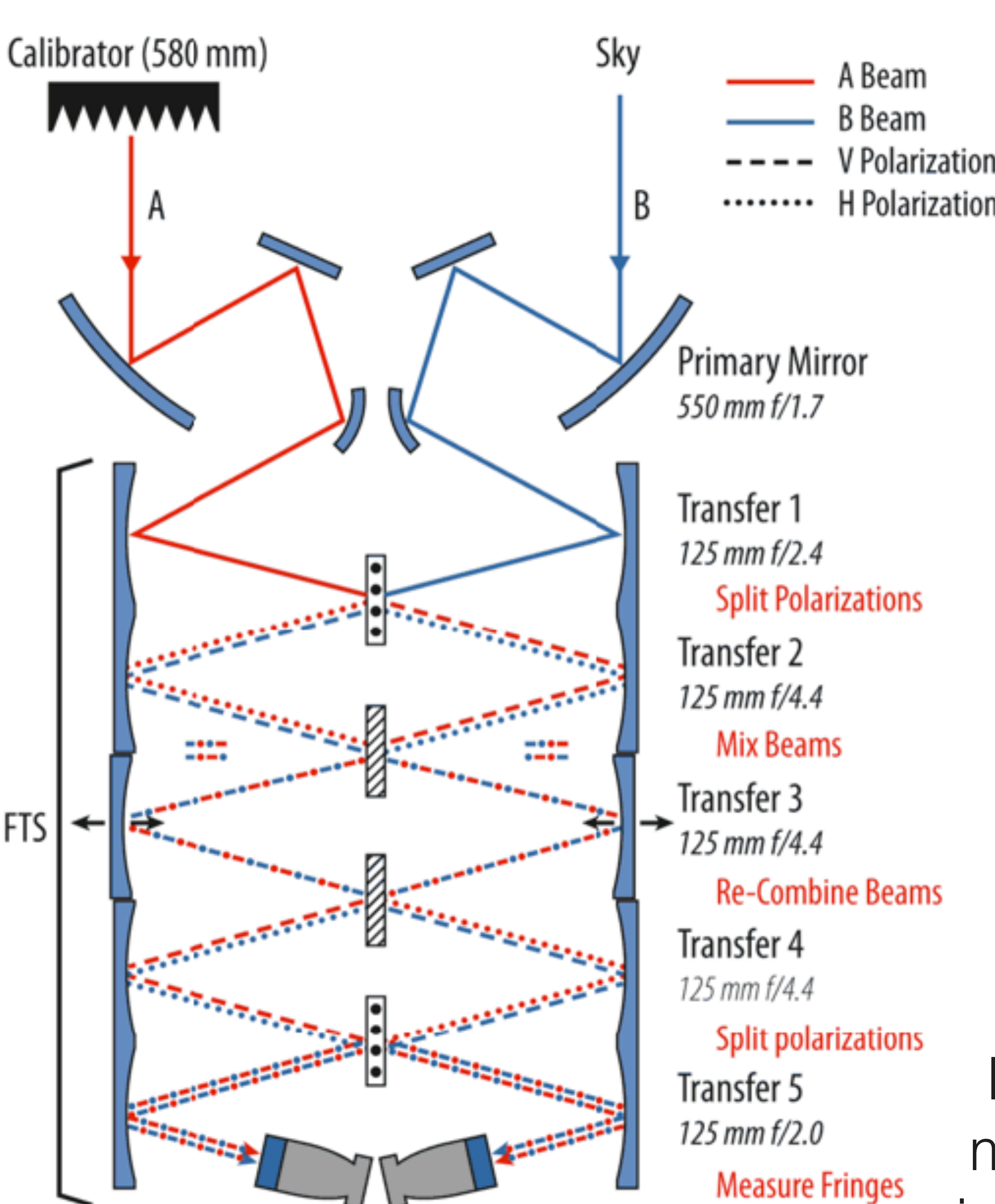


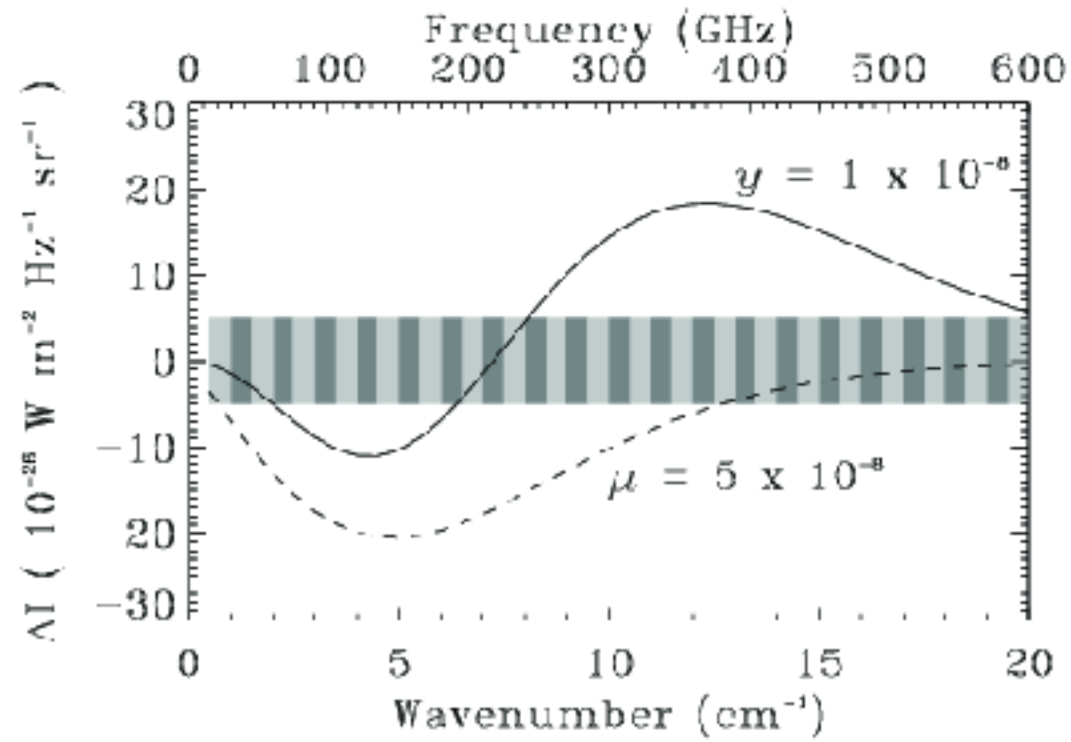


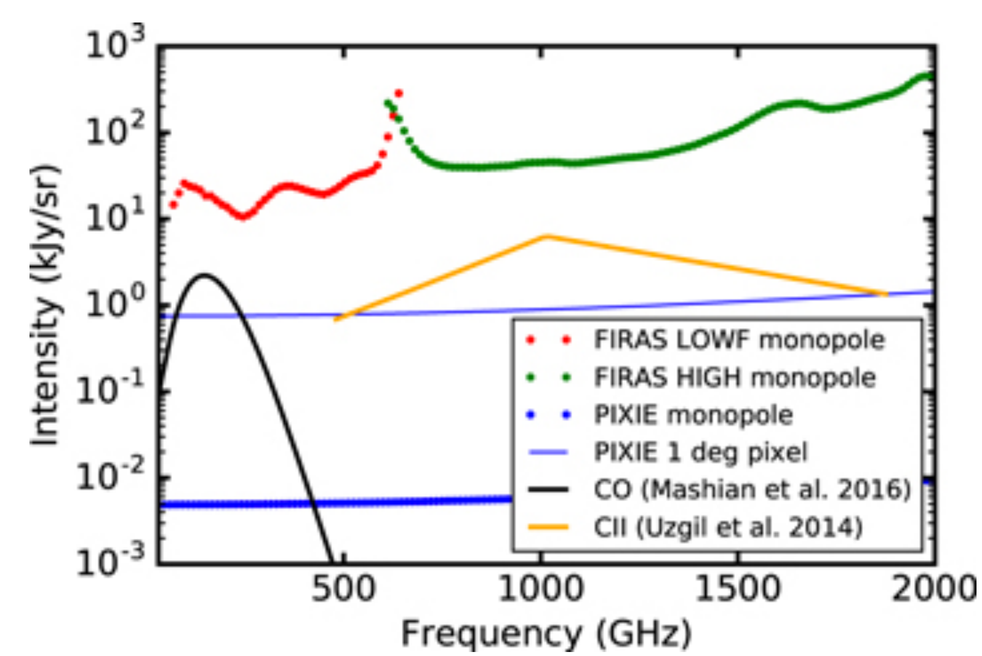
Probing energy injection from DM interactions / decays

Recombination lines etc. Several papers by Jens Chulba et al.

The light: colors



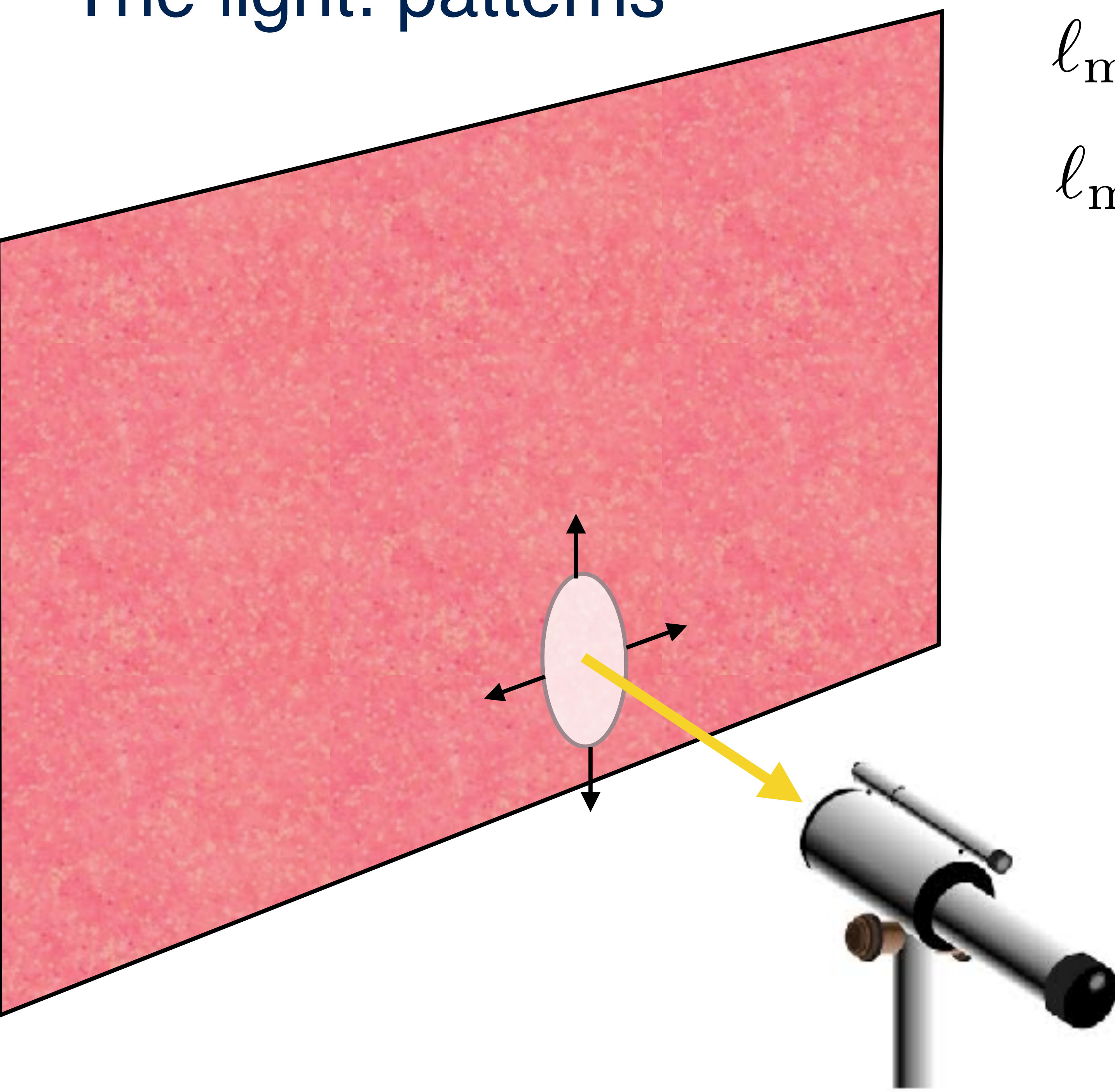




Proposed PIXIE satellite FTS can do much better than FIRAS can open up interesting avenues. Ask Steve Meyer!

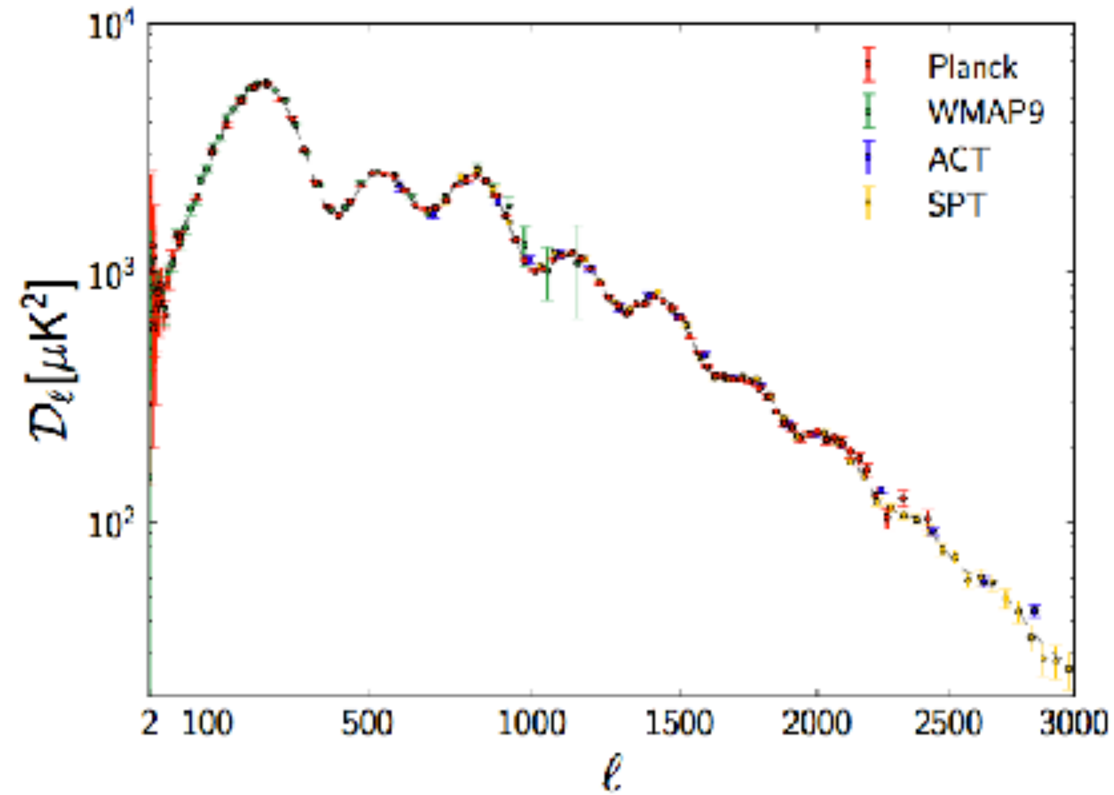
https://arxiv.org/pdf/1105.2044.pdf

The light: patterns



$$\ell_{\rm min} = \pi/(N\theta_{\rm res})$$ Map-size

$$\ell_{\rm max} = \pi/\theta_{\rm res}$$ Beam-size



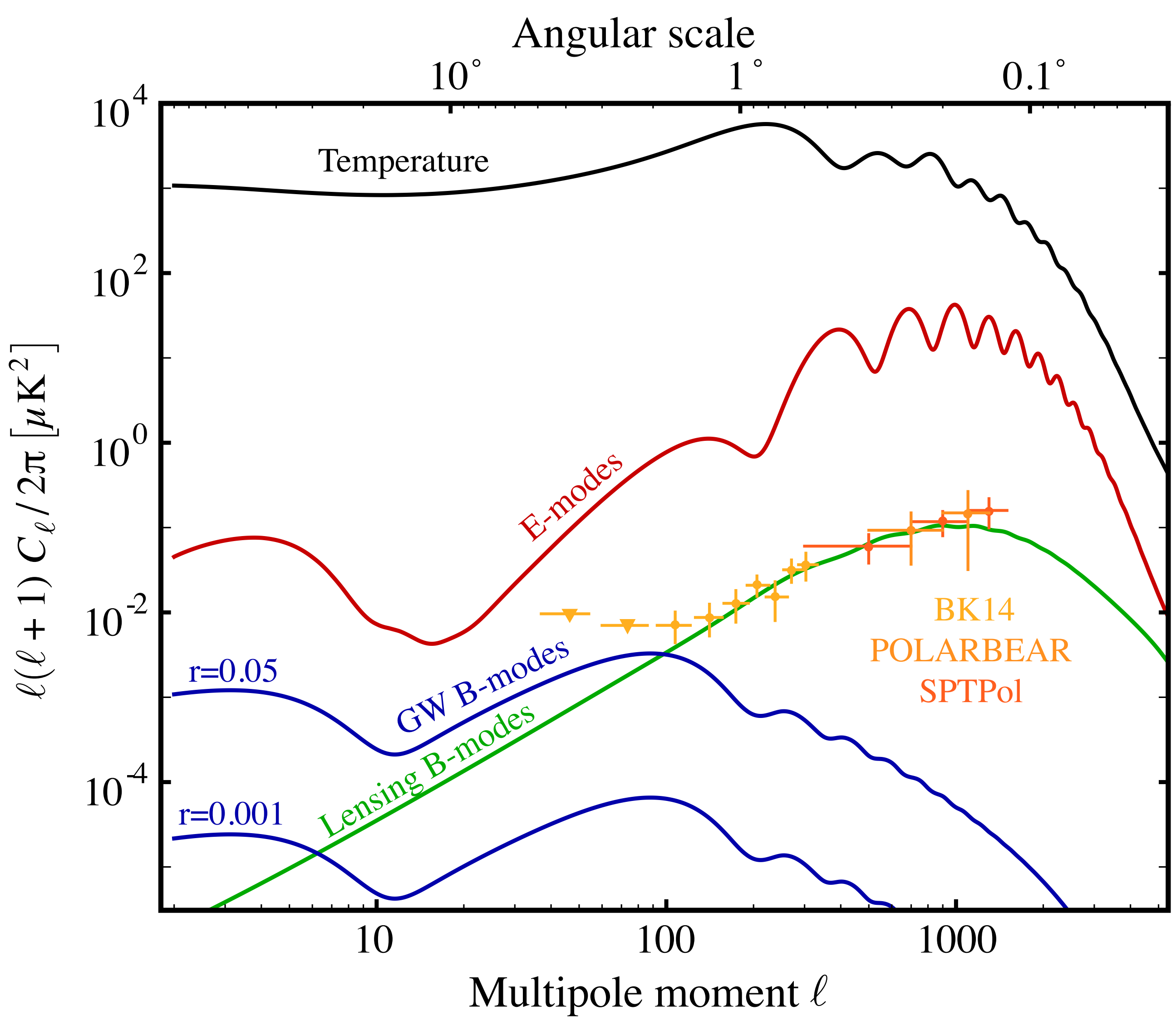
Small(ish) area collector
+ Scanning

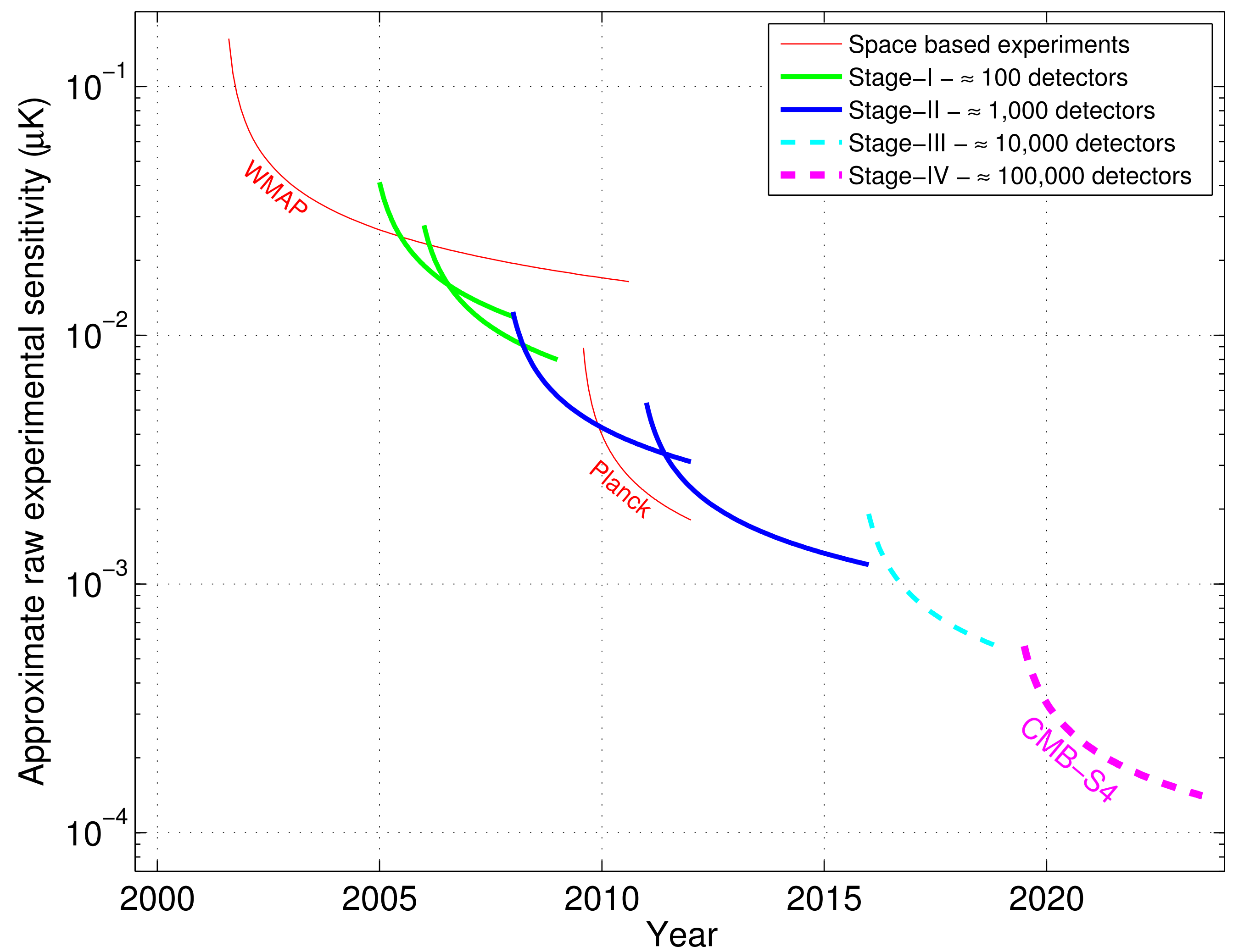
Relation between time/frequency and ell, given a scan speed

$$\frac{f\,[\mathrm{Hz}]}{\ell} = \frac{v_x[\mathrm{rad/s}]}{\pi} = \frac{v_x[\mathrm{deg/s}]}{180}$$

The light: patterns

Very roughly, sensitivity to some ΔT scales with # detectors





Noise-Equivalent-Temperature (NET) of a detector is measured /estimated.

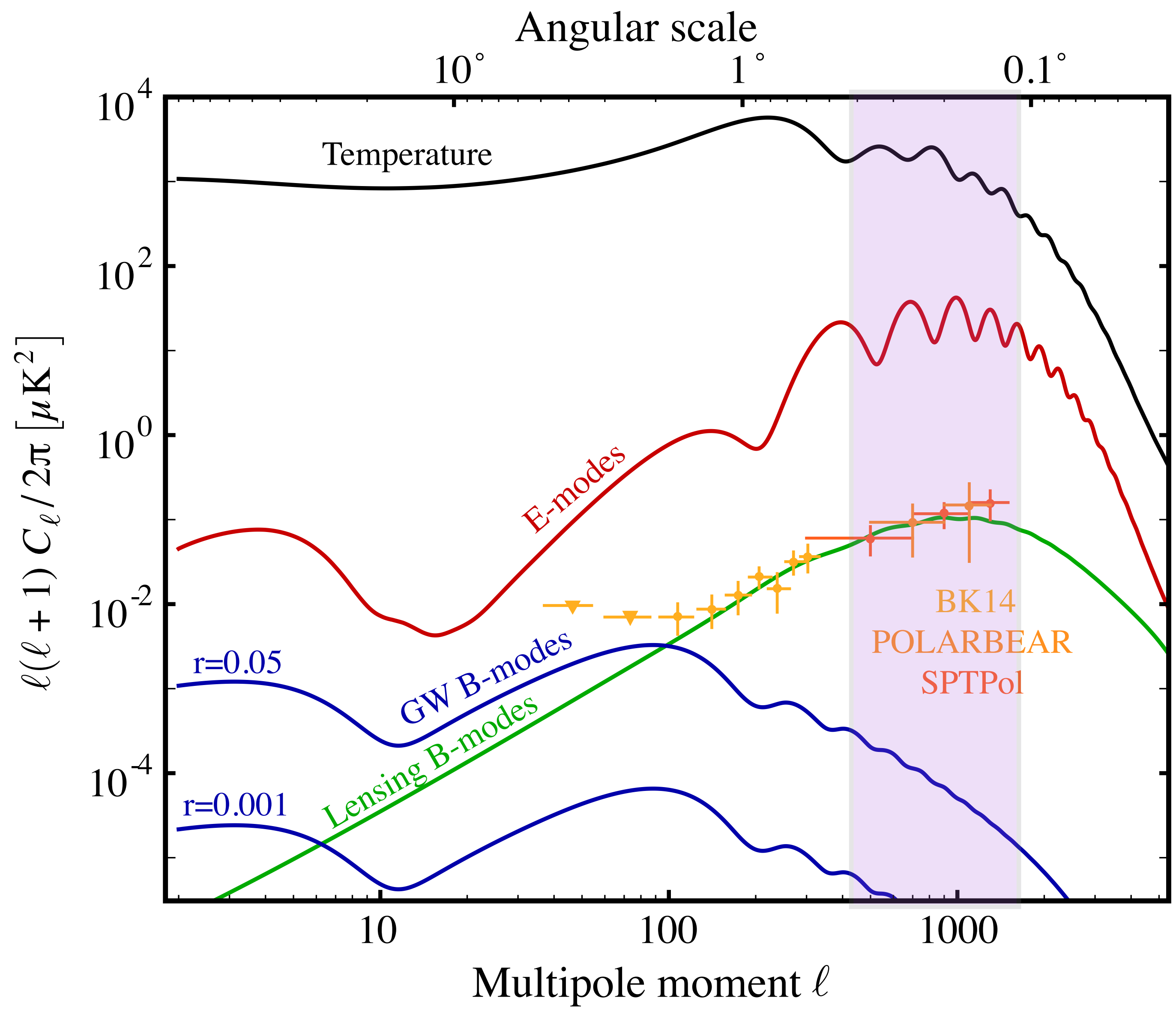
Temperature-power of desired CMB feature is noted (P_x)

$NET/N_{dets} < P_x$

In detail …

The light: patterns

Suppose we want to *discover* E-modes at $\ell \sim 10^3$



Beam has to small enough

Need to resolve our mode

$$\theta_{\rm res}\,[\rm rad] < \pi/(\ell = 10^3)$$

Sky has to be big enough

Need to capture a wavelength

$$\theta_{\rm sky}\,[\rm rad] > \pi/(\ell = 10^3)$$

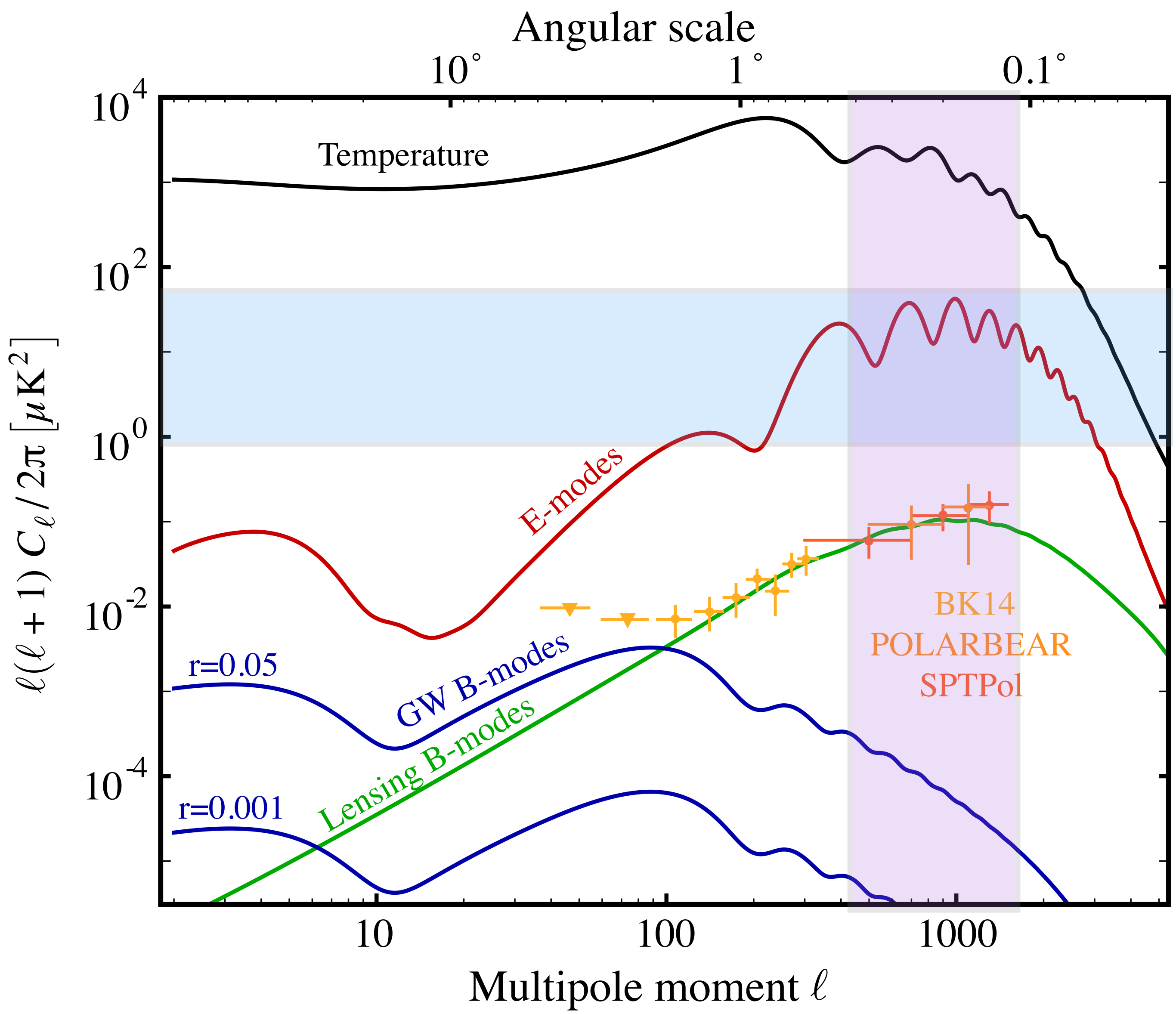
Here sky area mapped is $\sim\theta_{\rm Sky}^2$

**for a real experiment this will be > 100 Hz*

The light: patterns

Suppose we want to *discover* E-modes at $\ell \sim 10^3$

The experiment needs sensitivity
$\mathcal{D}_\ell > 1$ μK^2 or $\mathcal{C}_\ell > 2\pi$ (nK rad)^2



Suppose that we are scanning
at 1 deg/sec = π/180 rad/s

-> f ($\ell = 10^3$)= $10^3/180$ = 5.55 Hz

-> Sampling rate >> 11.11 Hz*
and sampling time >> 0.18 sec

For every 0.18 sec of scanning time
we collect one more $\ell = 10^3$ mode

The light: patterns

Suppose we want to *discover* E-modes at $\ell \sim 10^3$

The experiment needs sensitivity $\mathcal{C}_\ell > 2\pi$ (nK rad)^2

Suppose that *one* detector has noise RMS given by **w_1** [μK/√Hz], simplified white noise power spectral density

Suppose we have **N_{dets}** and we are scanning for **T_s** (>> 0.18 s) s

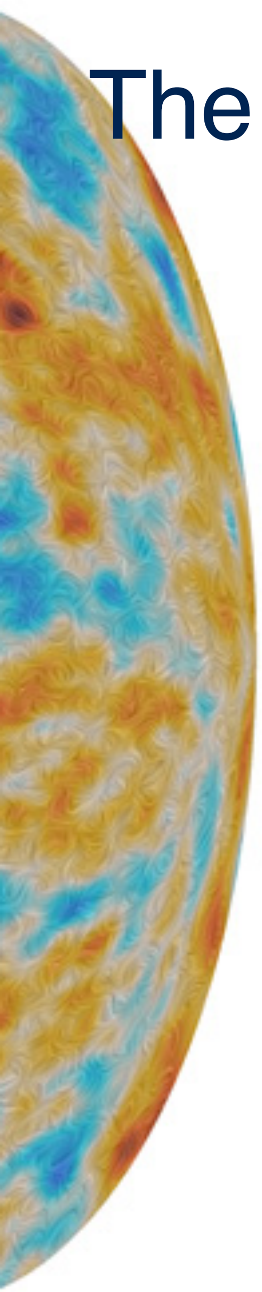
We know that the noise variance will scale with 1/**N_{dets}**

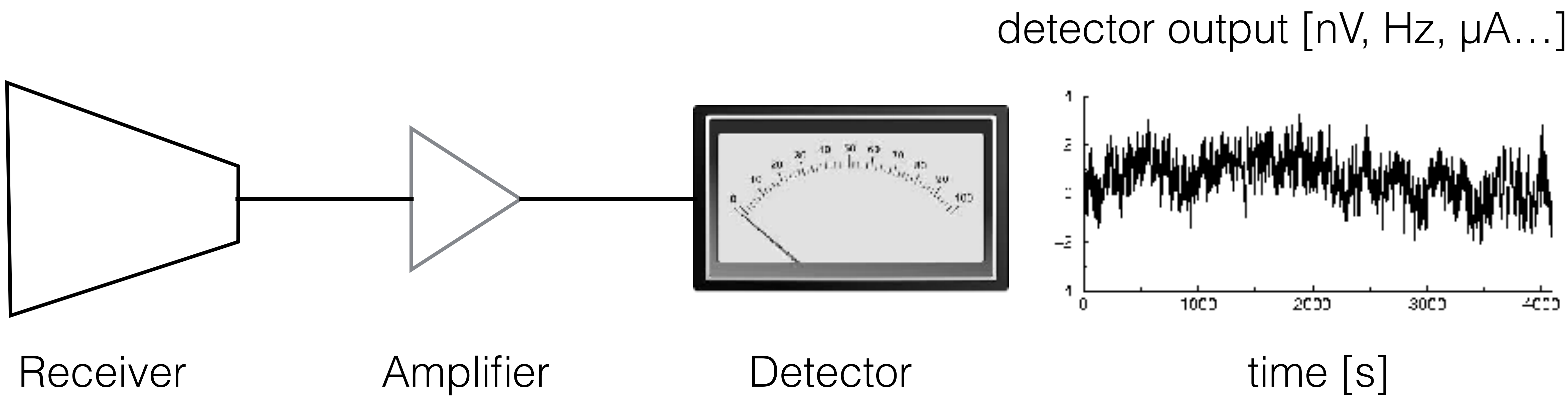
Longer scan duration (**T_s**) -> more modes captured, i.e. higher SNR

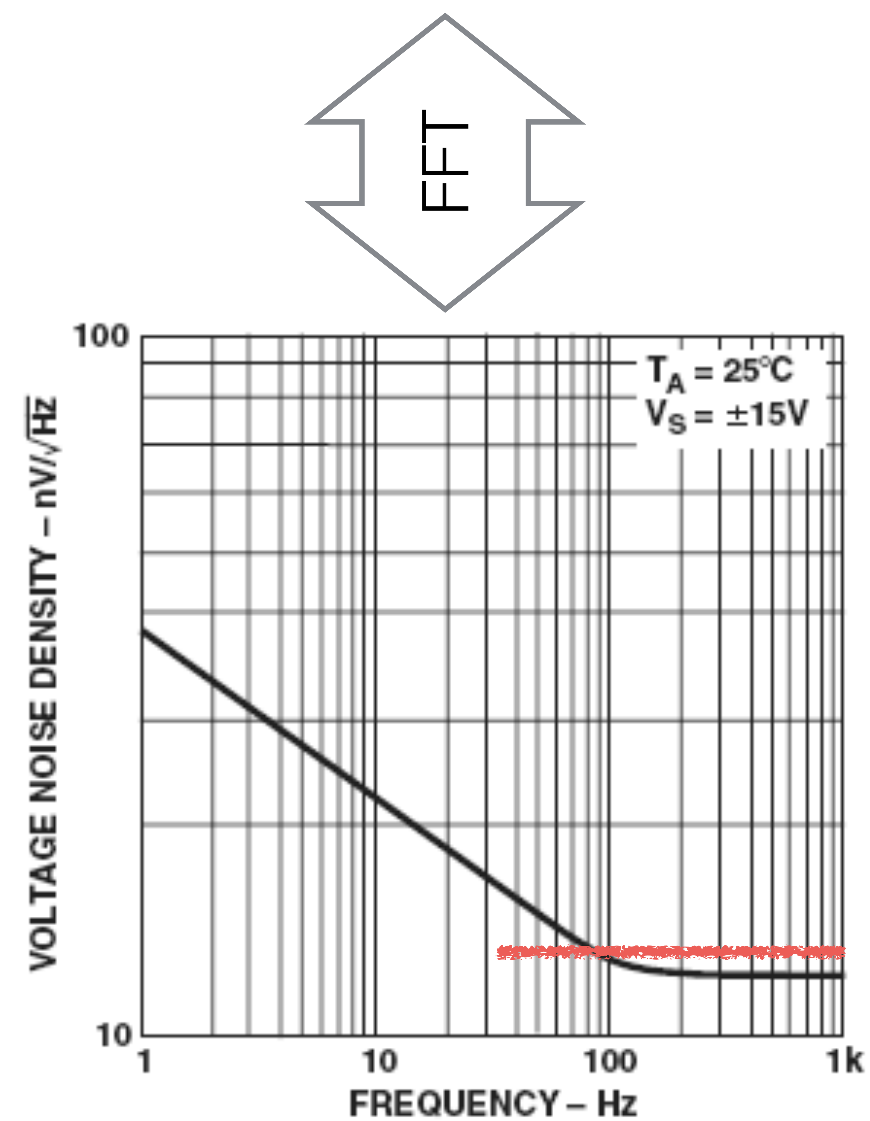
$$\frac{w_1^2 \theta_{\rm sky}^2}{N_{\rm dets} T_{\rm s}} \leq 2\pi \left[\text{nK-rad}\right]^2$$

This is the (Knox) sensitivity limit for our case

The light: patterns

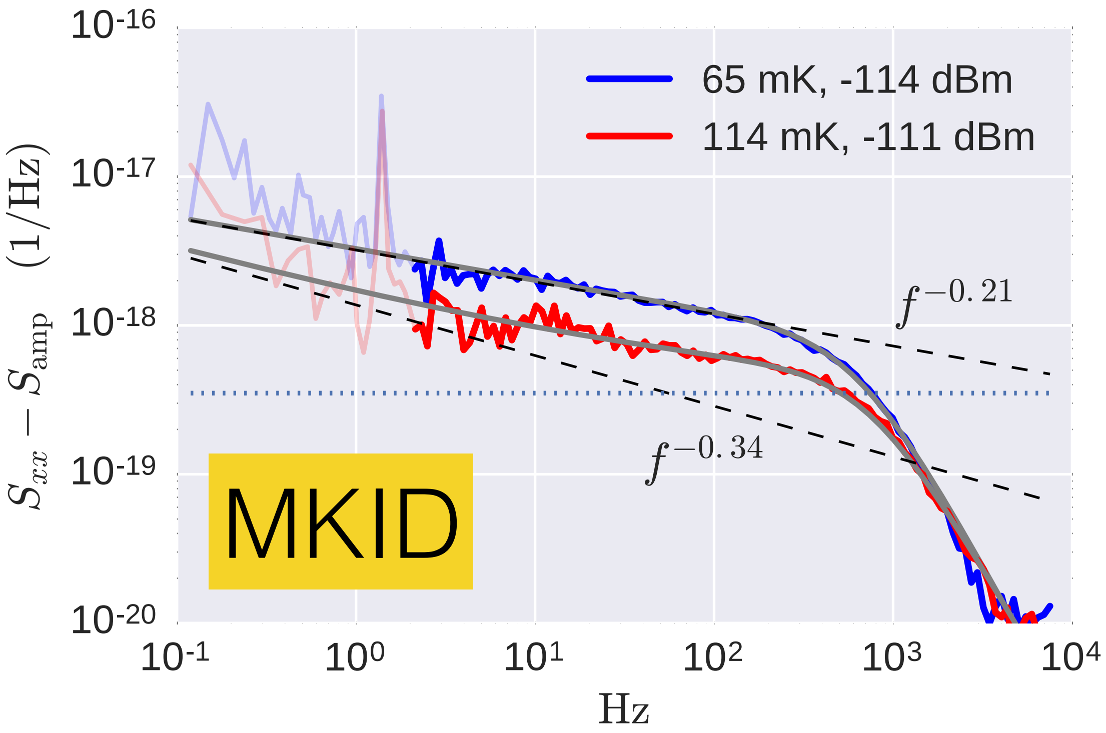




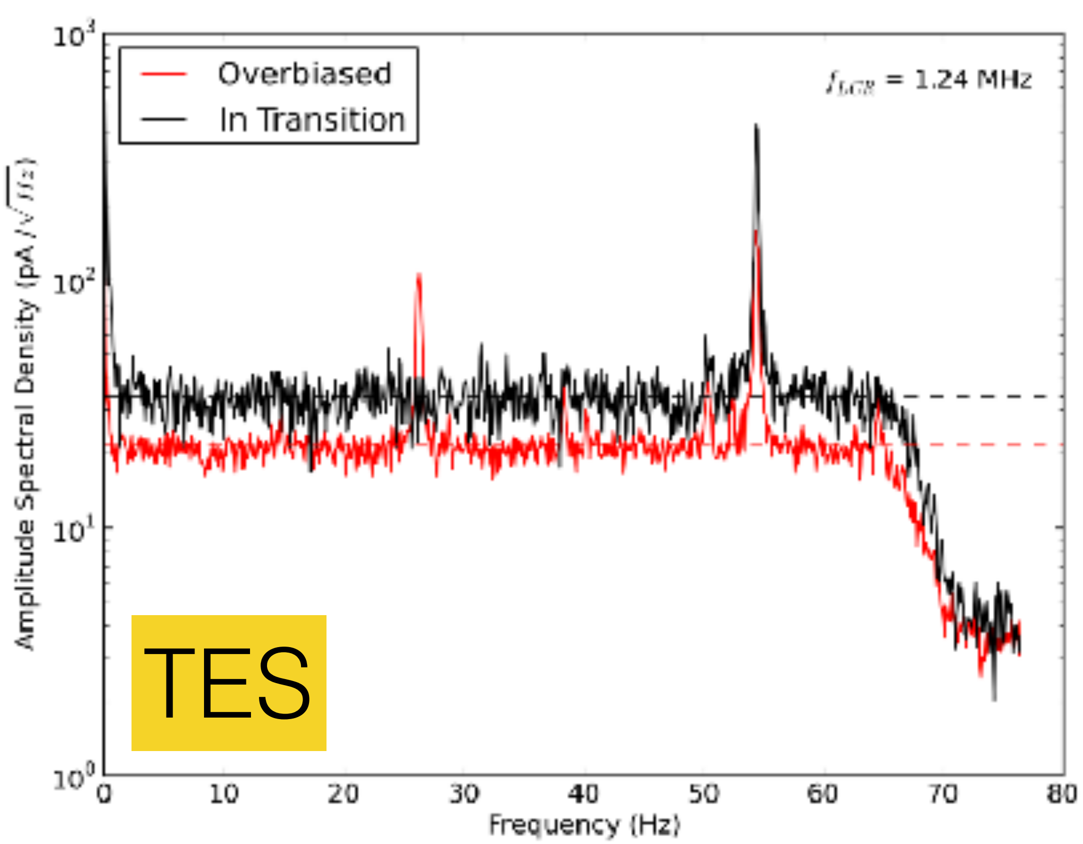


The noise RMS **w_1** [µK/√Hz], is the white noise level value, or the median value of the noise power spectral density, *referenced to a temperature scale*.

The light: patterns



Example of noise power spectra for two different detectors, in units of y_{det} vs. frequency



The noise RMS $\mathbf{w_1}$ [μK/√Hz], is the Noise Equivalent Temperature (NET)

Measurement / detector units are usually Voltage, frequency etc. as a function of time (or freq. by FFT). Let's call these units $\mathbf{y}_{det}$.

1. Convert this to NEP or noise equivalent power.

2. Convert to NET by using a *Black-Body-Jacobian*

The light: patterns

Black-Body intensity I has dimensions of W/Sr/m^2/Hz

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1},$$

1. Conversion to NEP or noise equivalent power:

Measure $\mathbf{y}_{\text{det}}$ for varying incident BB power and obtain the responsivity, as a function of frequency (or FFT of time streams)

$$\mathcal{R} = \frac{\delta y_{\text{det}}}{\delta P} \rightarrow P_{\text{det}}(f) = \mathcal{R}(f) y_{\text{det}}(f)$$

Spectral density of this power is the NEP

2. Conversion to NET by using a *Black-Body-Jacobian*

$$P(T) = \int d\nu \, dA \, d\Omega \ \left(W(\nu) \cdot I(\nu, T)\right)$$

$$\rightarrow \ J = \frac{\partial P}{\partial T}$$

$$w_1 = \text{NET} = \text{NEP} J^{-1}$$

The light: patterns

NEP and photon noise limit

Noise Equivalent Power: input signal power that produces SNR = 1 at the output of a detector, given data-signaling rate / modulation frequency, and effective noise bandwidth.

Thus it is the minimum detectable power per √bandwidth.

The response of a detector can vary with frequency: NEP(f)

The light: patterns

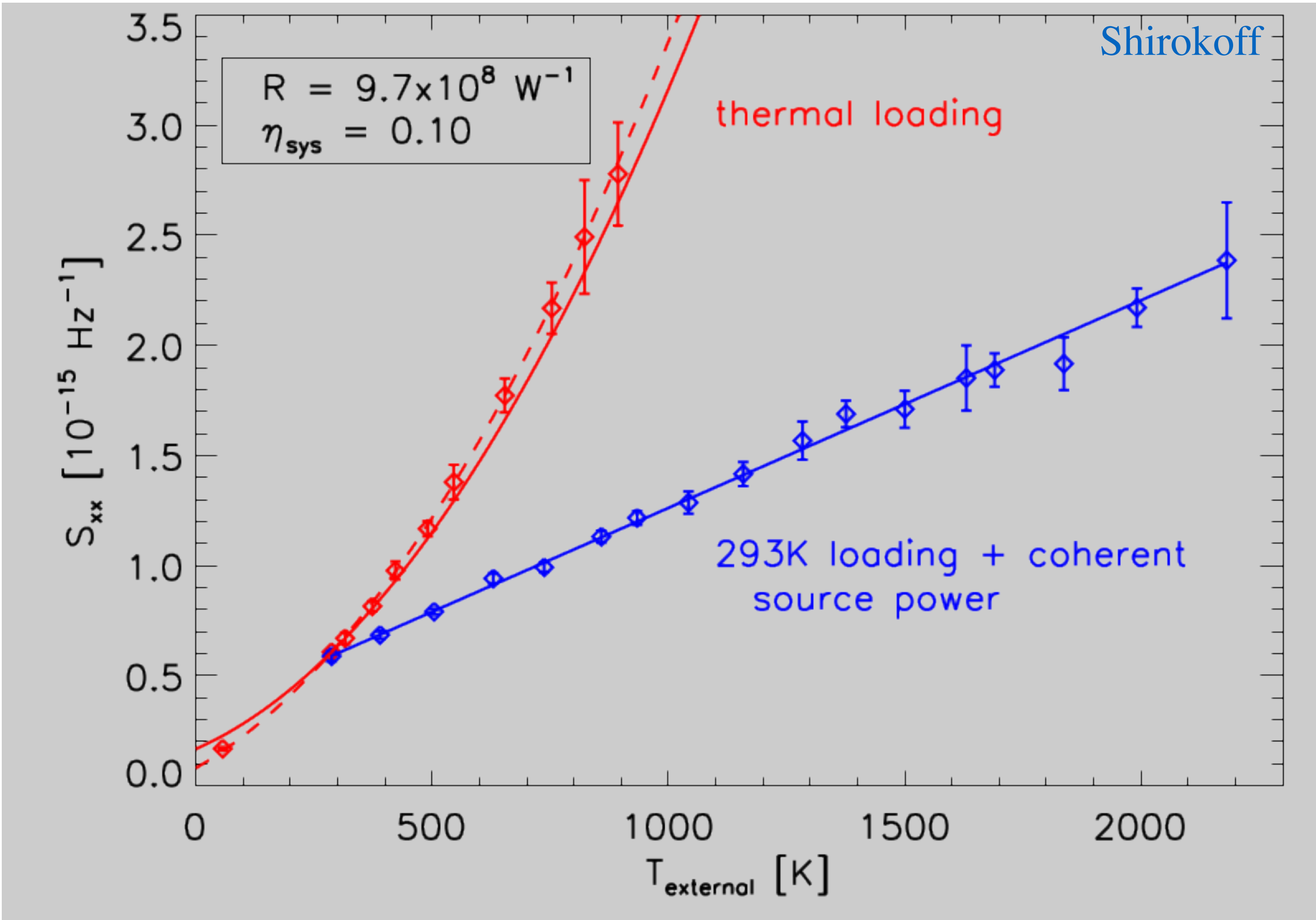
NEP and photon noise limit

For a detector with negligible intrinsic (thermal) and readout (laboratory) noise, photon counting determines the measurement limit

$$\langle n_{\mathrm{rms}} \rangle = \sqrt{n + n^2}$$

$h\nu \ll k_B T$ Bose bunching

$h\nu \gg k_B T$ Poisson



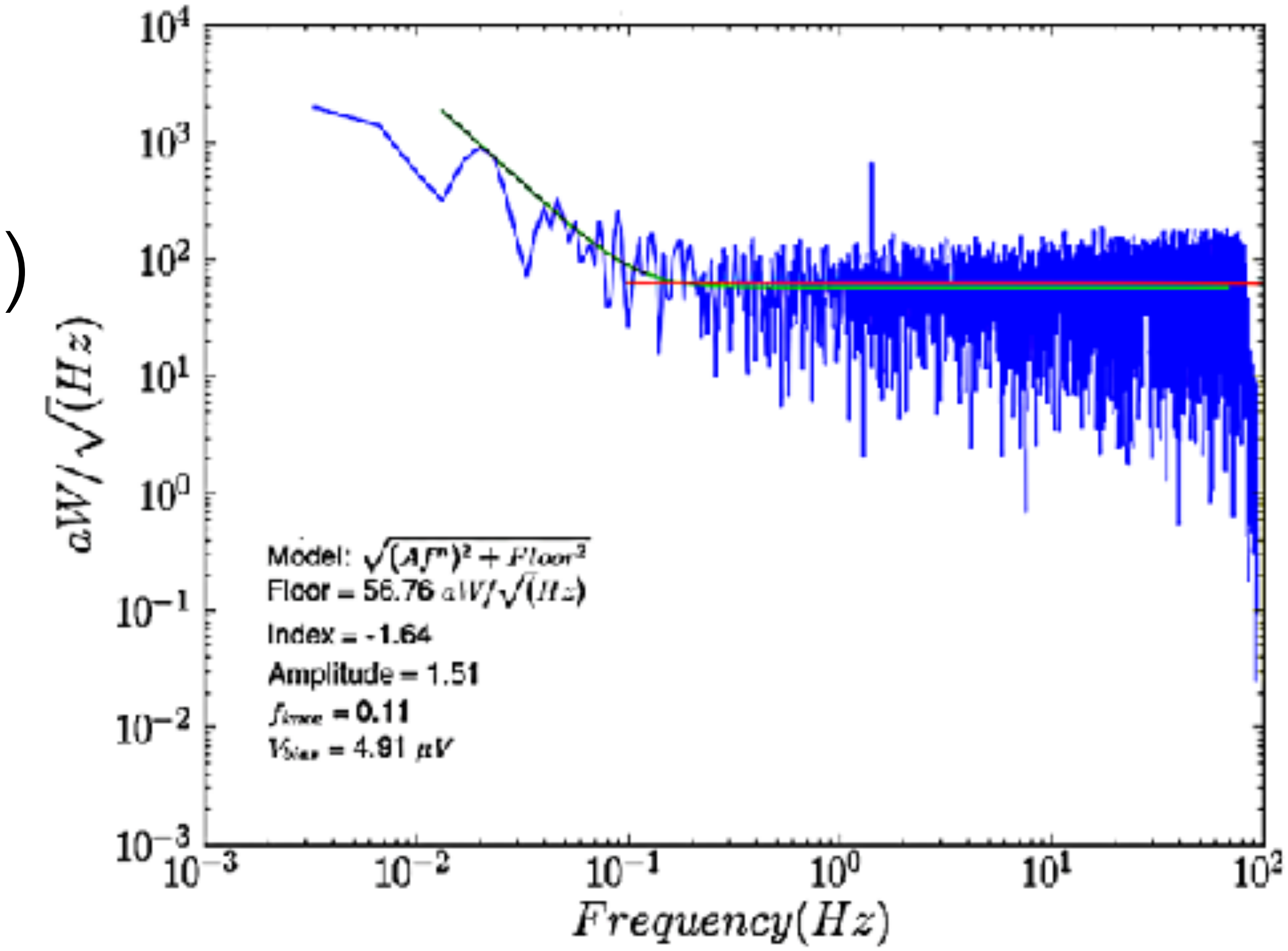
Discussion about Noise Equivalent Power and its use for photon noise calculation. Samuel Leclercq. 2007-03-02.

The light: patterns

NEP and photon noise limit

For ground based experiments NEP (CMB + hot optics + hot Sky) limit is ~50 aW*/√Hz

SPTpol, single detector <10^2 aW, therefore with >10^3 detectors CMB can be measured.

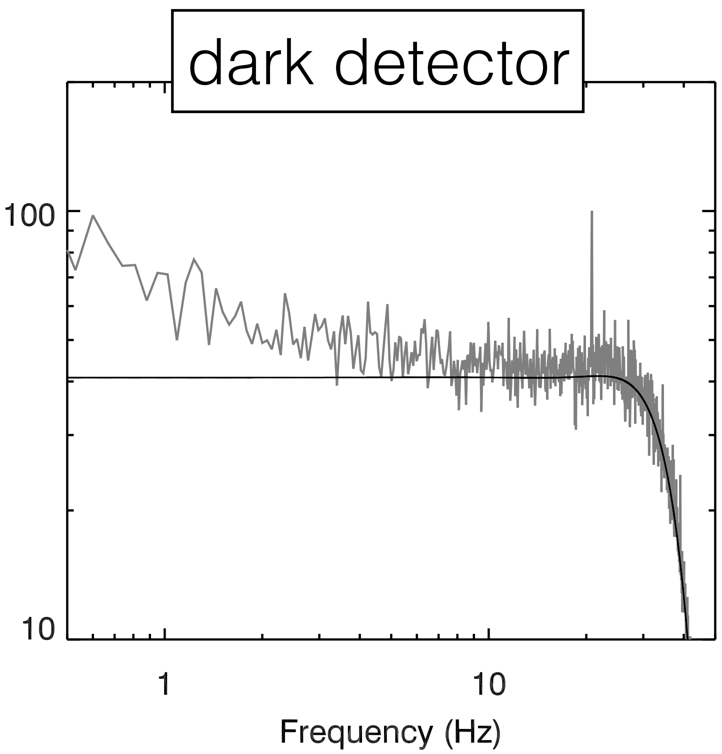


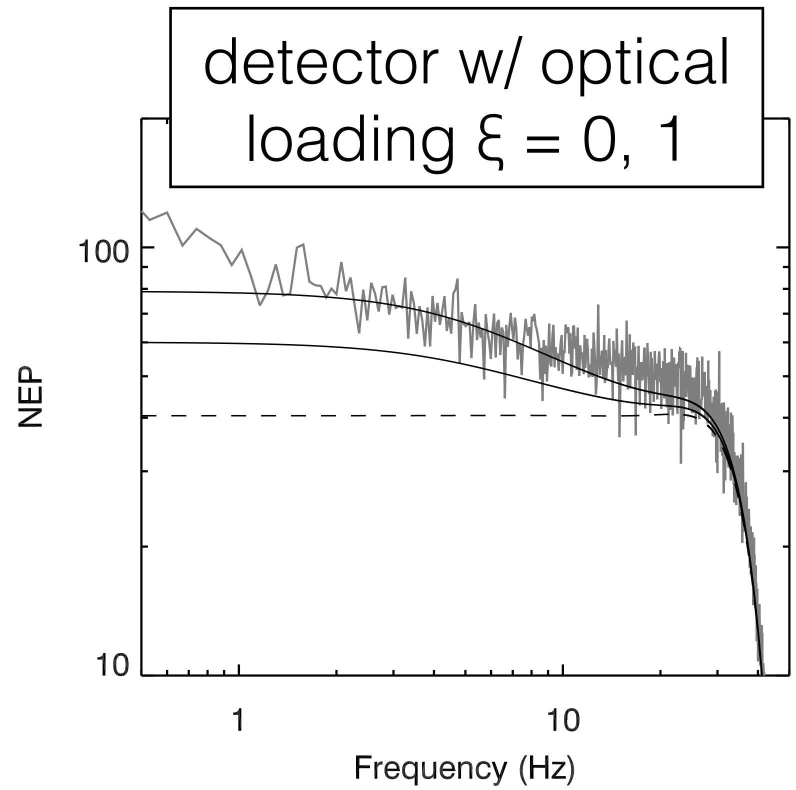
*1 aW = 10^{-18} W

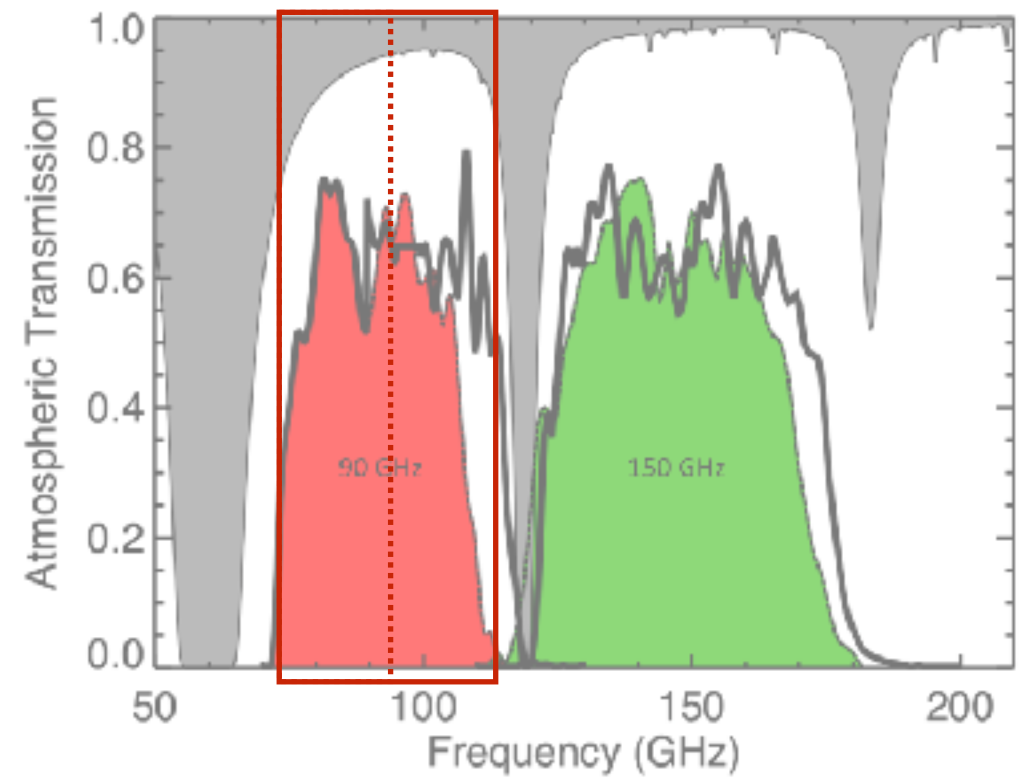
Journal of Low Temperature Physics June 2012, Volume 167, Issue 5, pp 865–871

The light: patterns

NEP and photon noise limit







$$\langle n_{\rm rms} \rangle = \sqrt{n + n^2}$$

$$\mathrm{NEP}^2 = \left(2h\nu_0 P_{\rm opt} + \frac{\xi P_{\rm opt}^2}{\Delta\nu} \right)$$

band-center

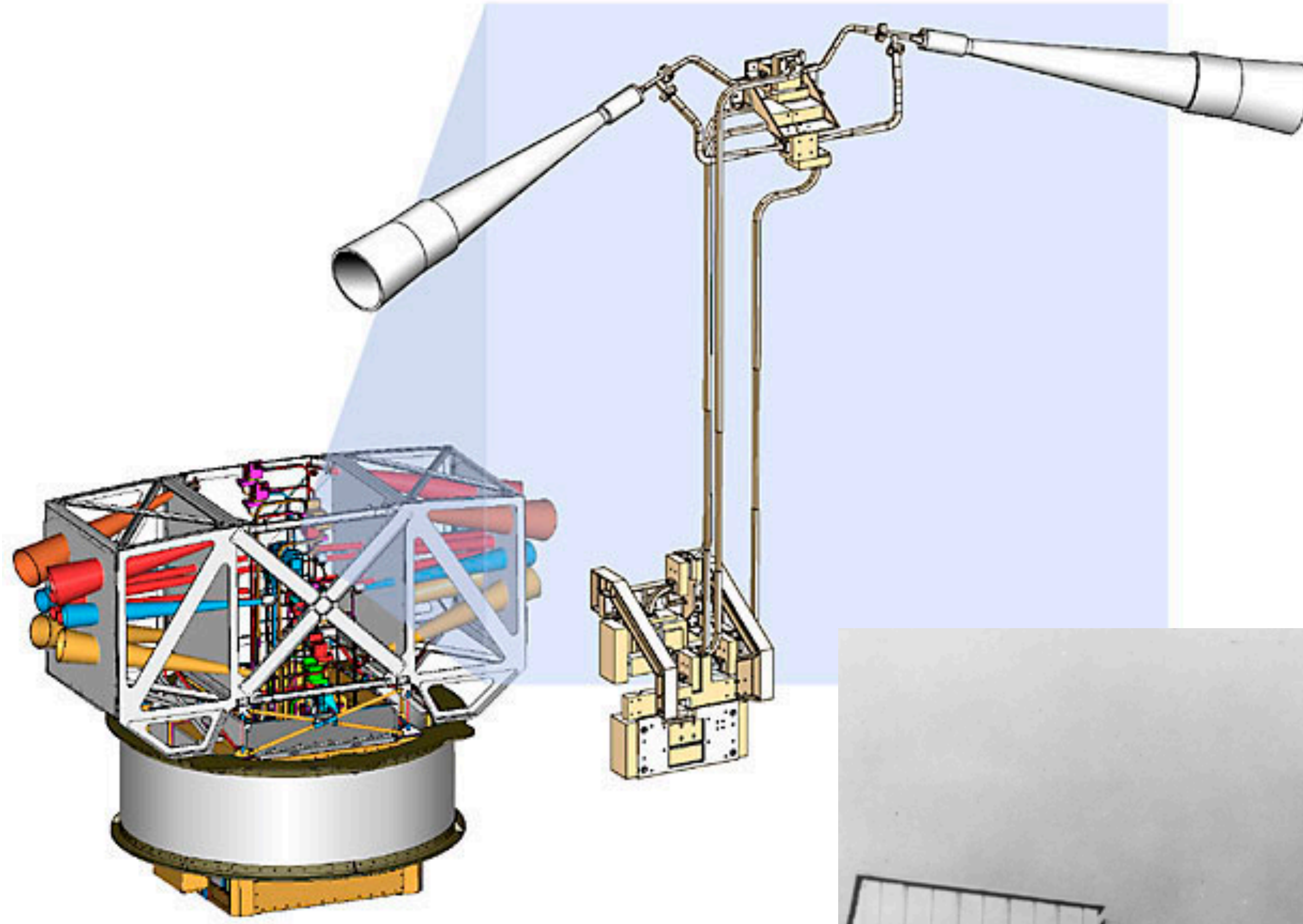
band-width

Bose-bunching- mode collection efficiency

Shirokoff

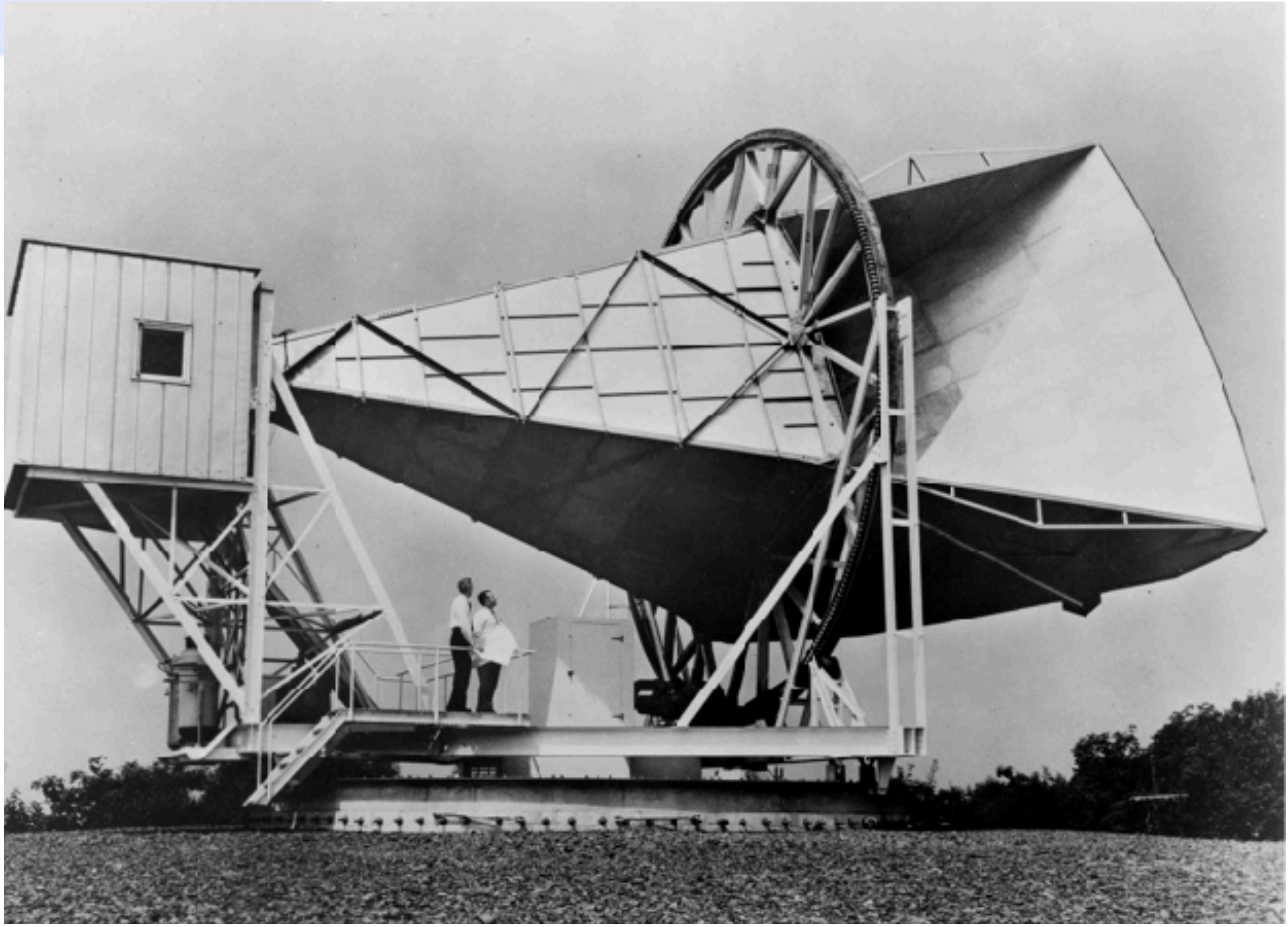
Let the light in

Let the light in



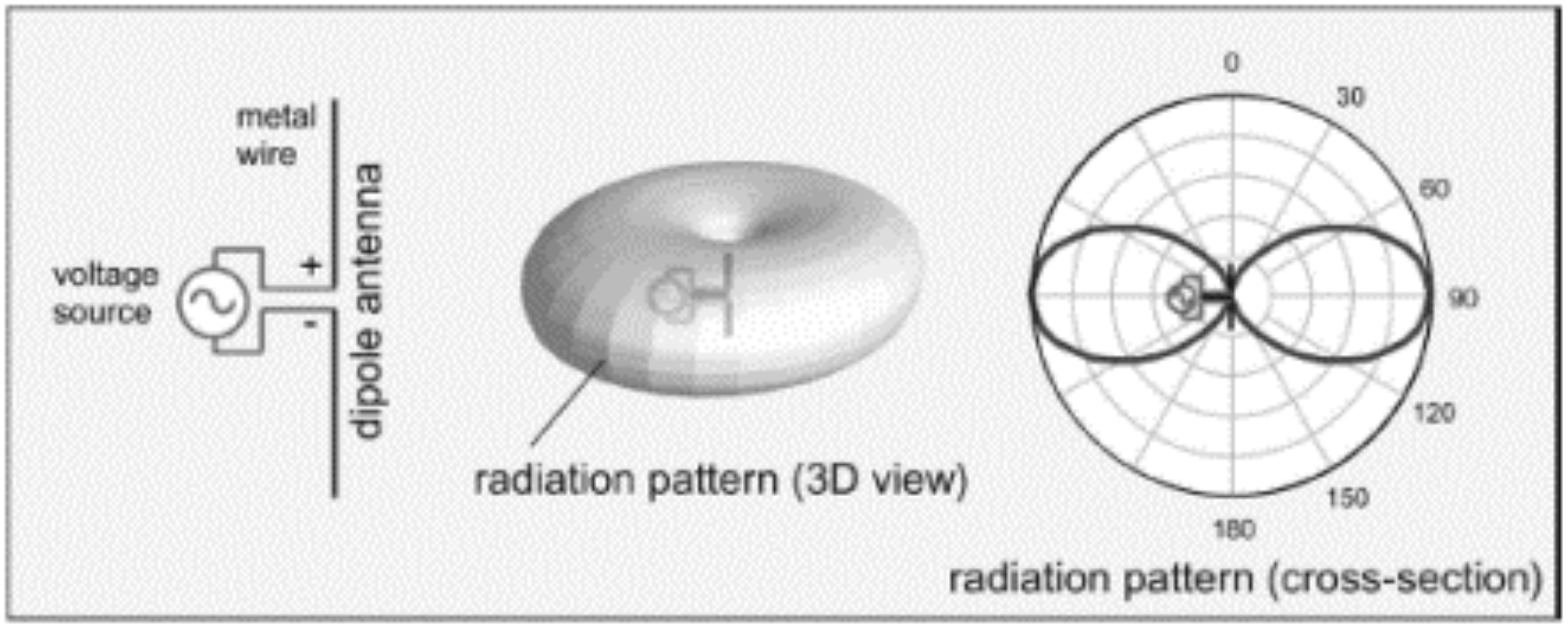
WMAP

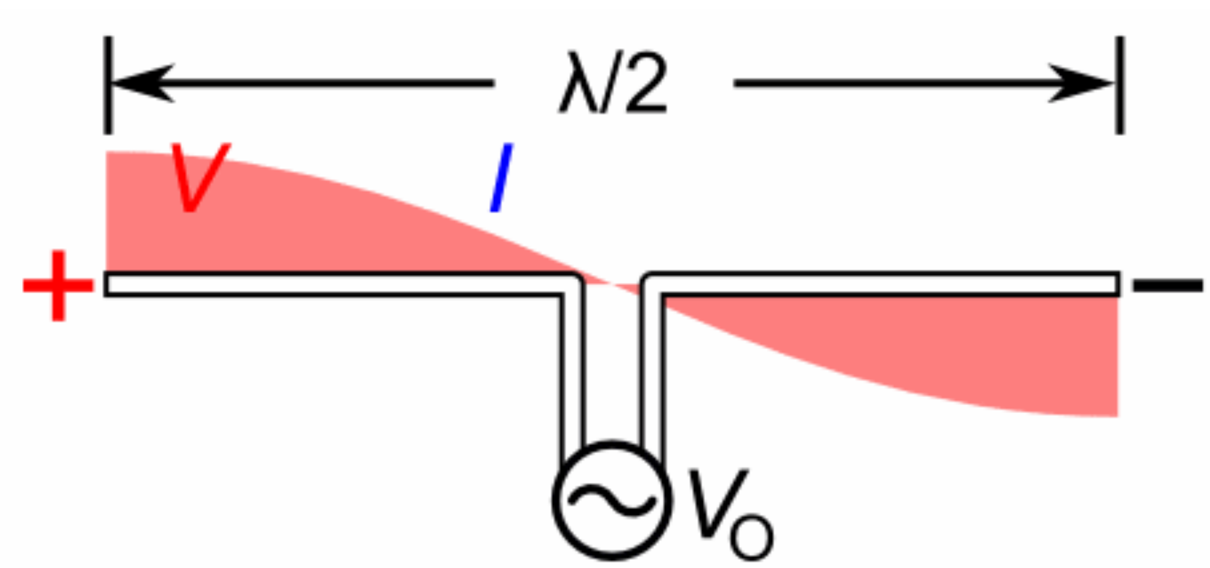
Penzias
& Wilson



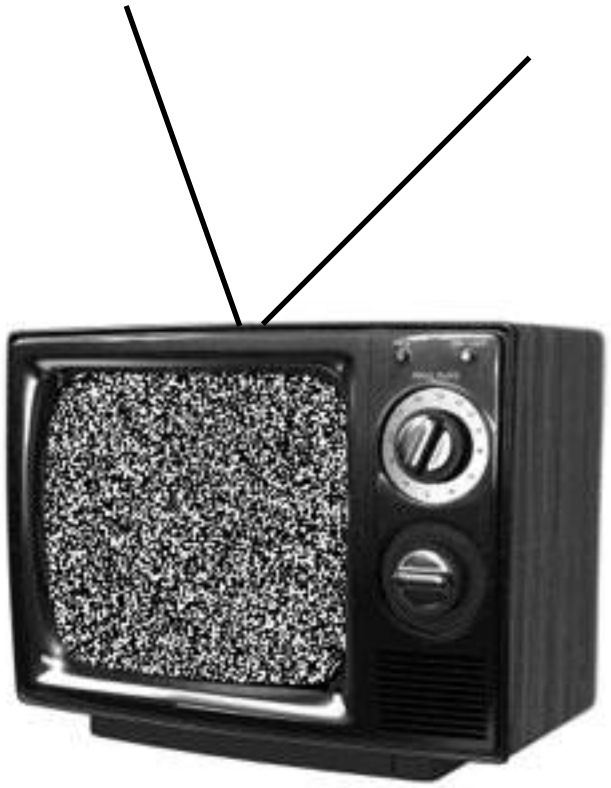
Reciprocity theorem:

Receive and *transmit* properties of an antenna are identical.
Radiation pattern in transmit mode = pattern in the receive mode.





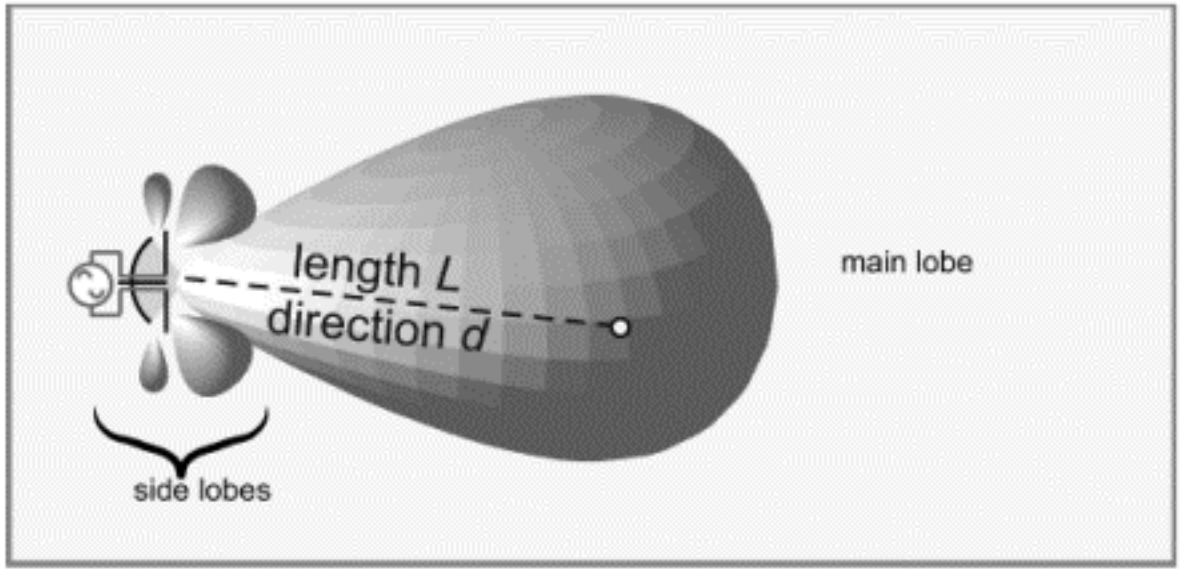
Let the light in



~1% of TV noise is the CMB

But we can do better using horns …

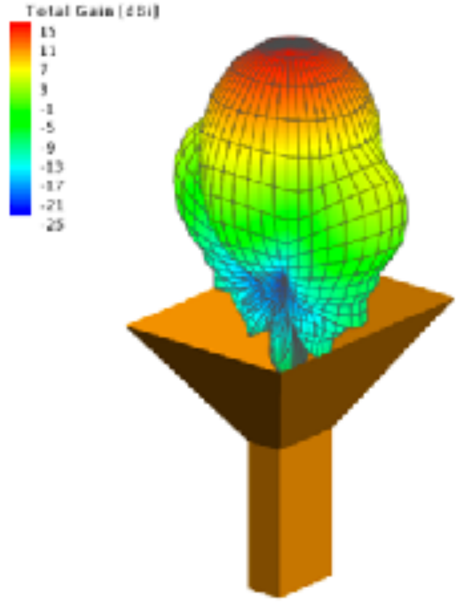
Let the light in

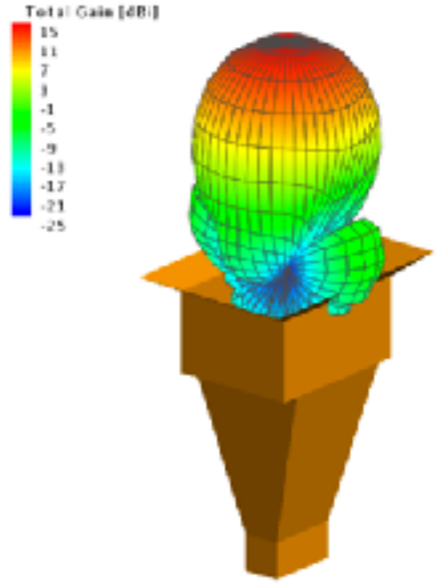


Shape the lobes, so as to focus the CMB from the sky and not pick up terrestrial junk

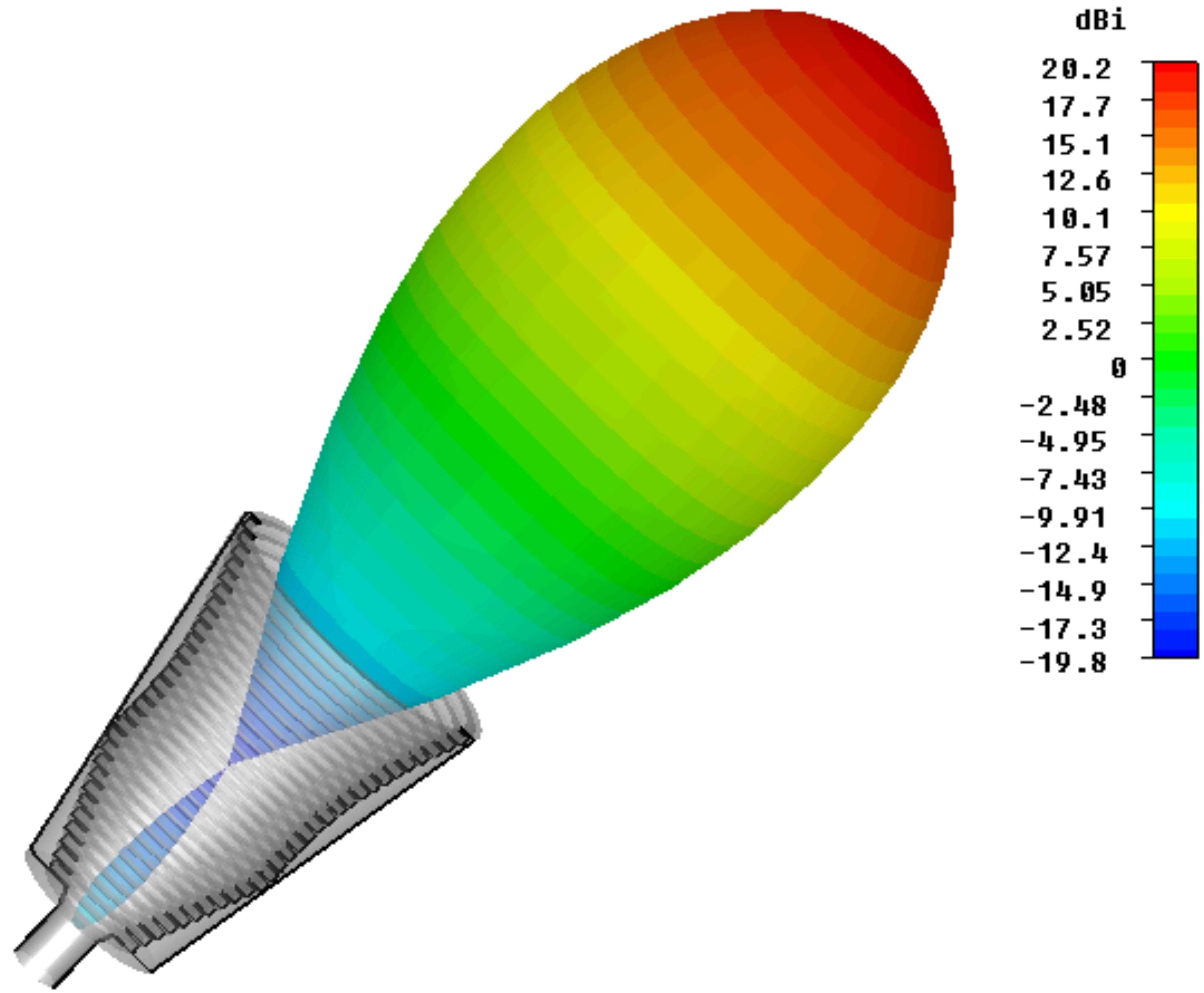
Horsing around, but more seriously….

Let the light in

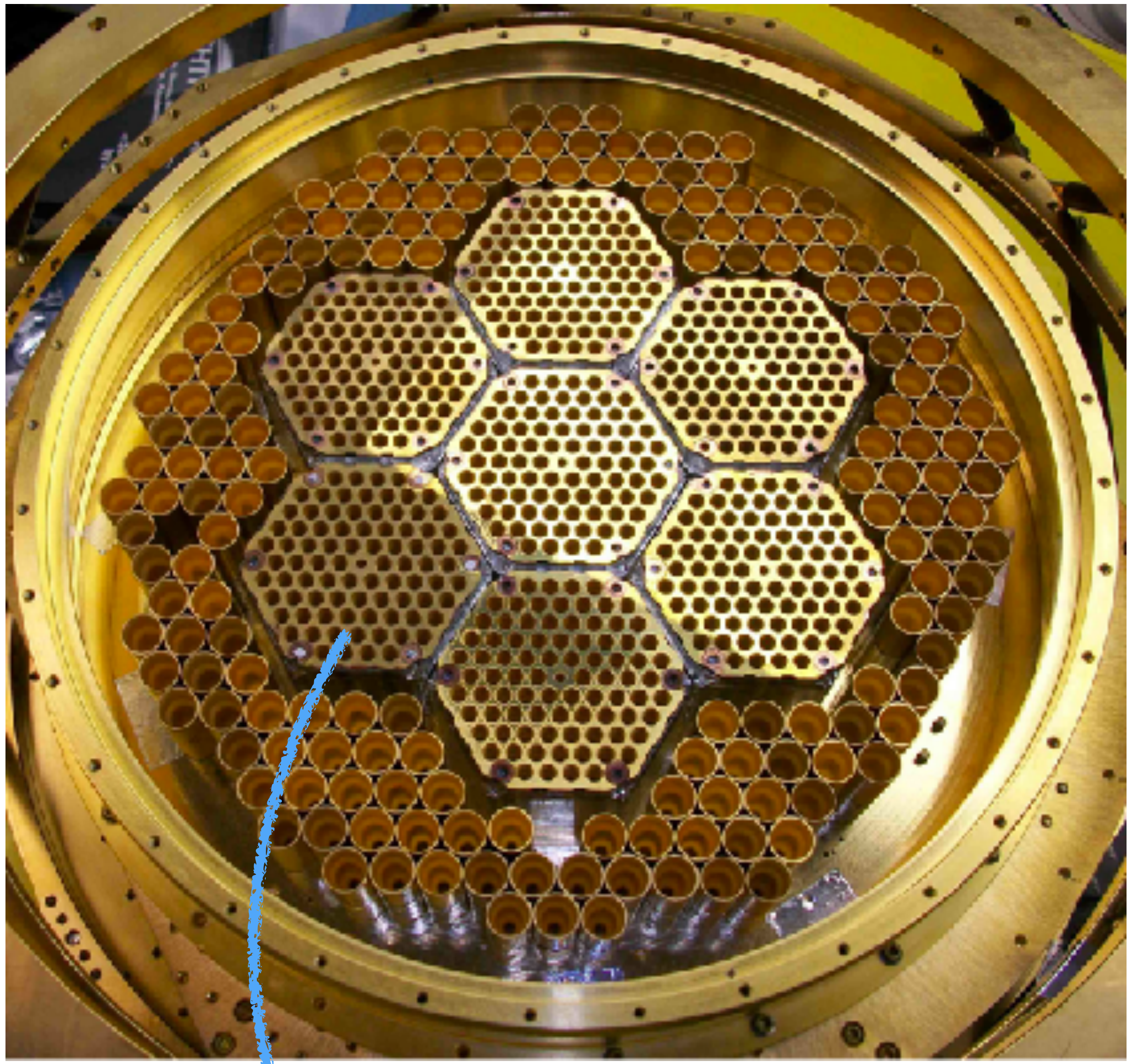


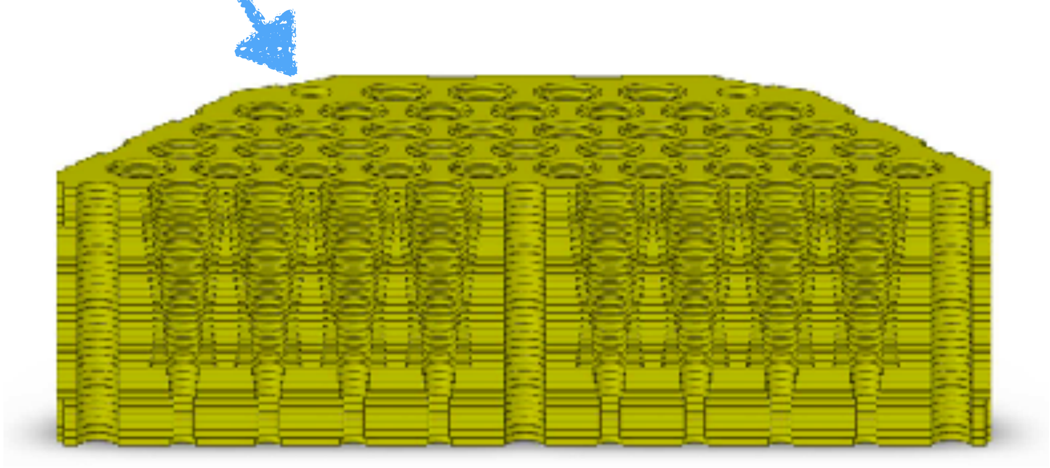


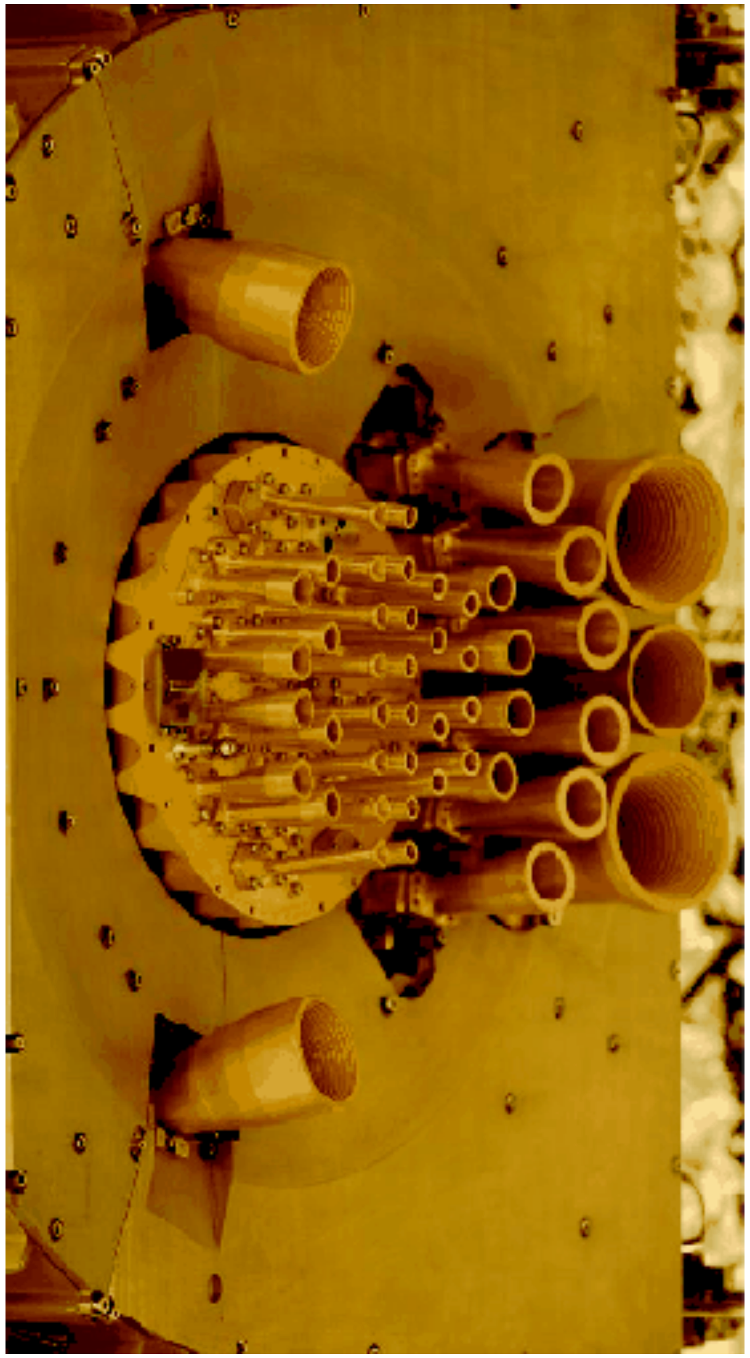
A well defined corrugated horn antennae can couple the entire power in the main lobe



Let the light in





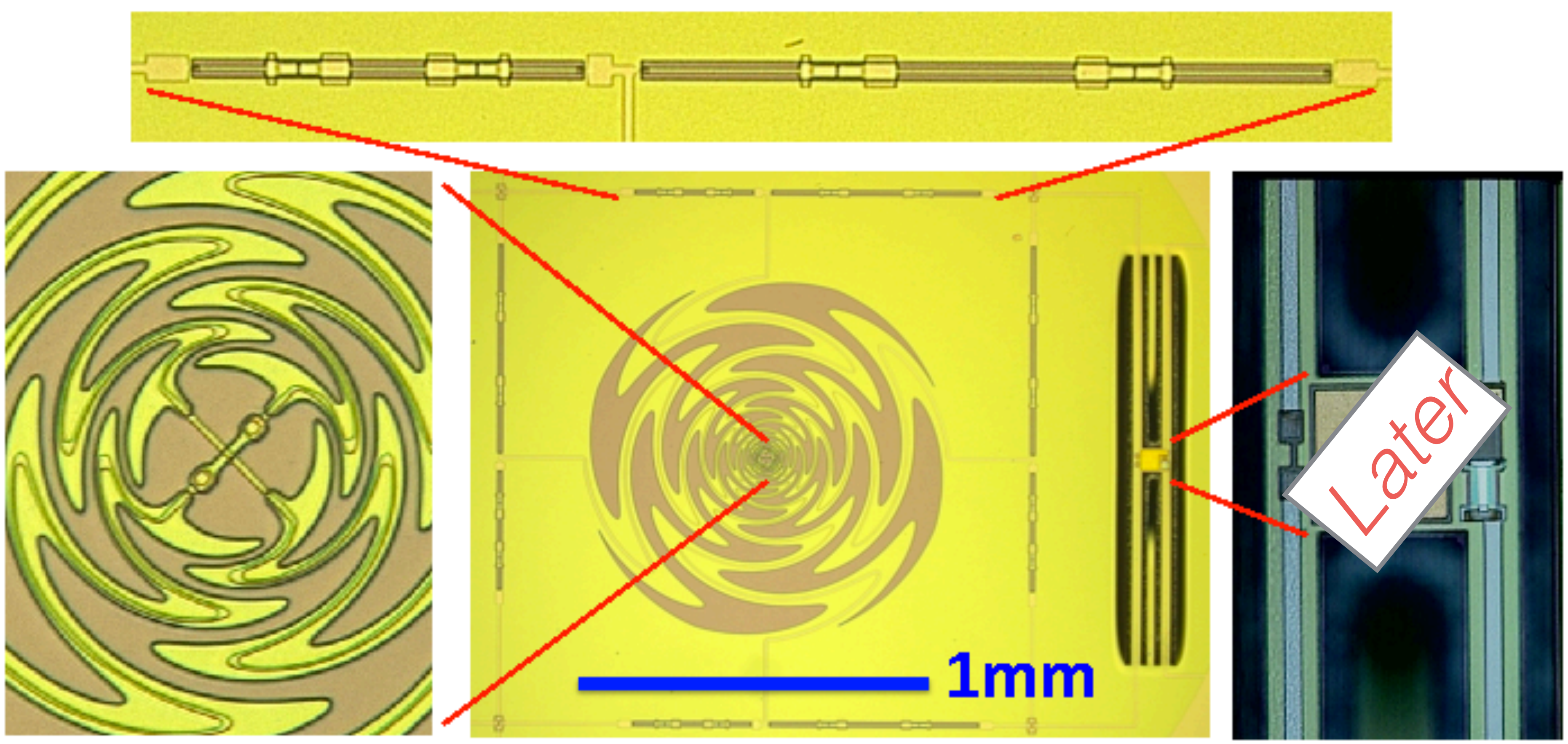


Planck

SPTPol

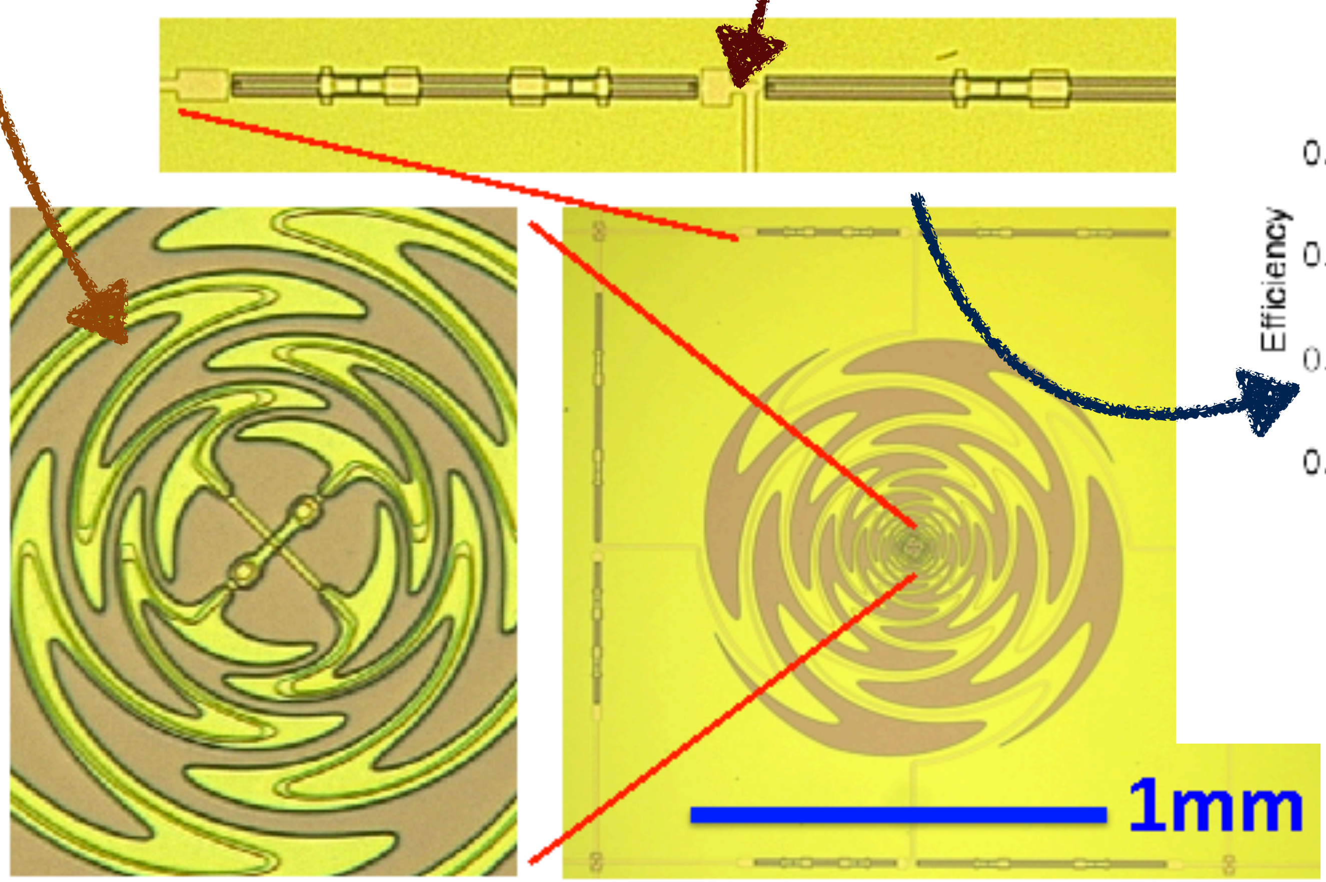
A horn has one well defined length-scale (L_H), and thus the response or gain will drop for all $\nu < c/L_H$

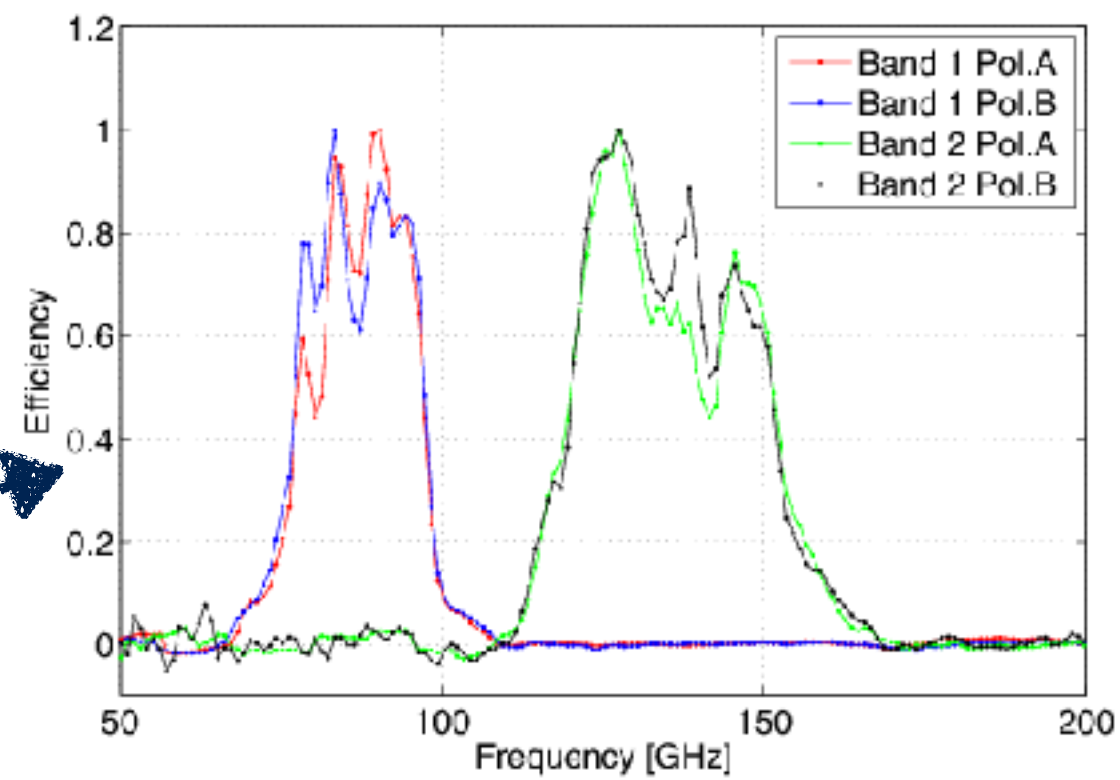
But ideally we want to pick up "equally" at large bandwidths and then chop it into bands that we care for



Log periodic / fractal shape is “coherent” across decades

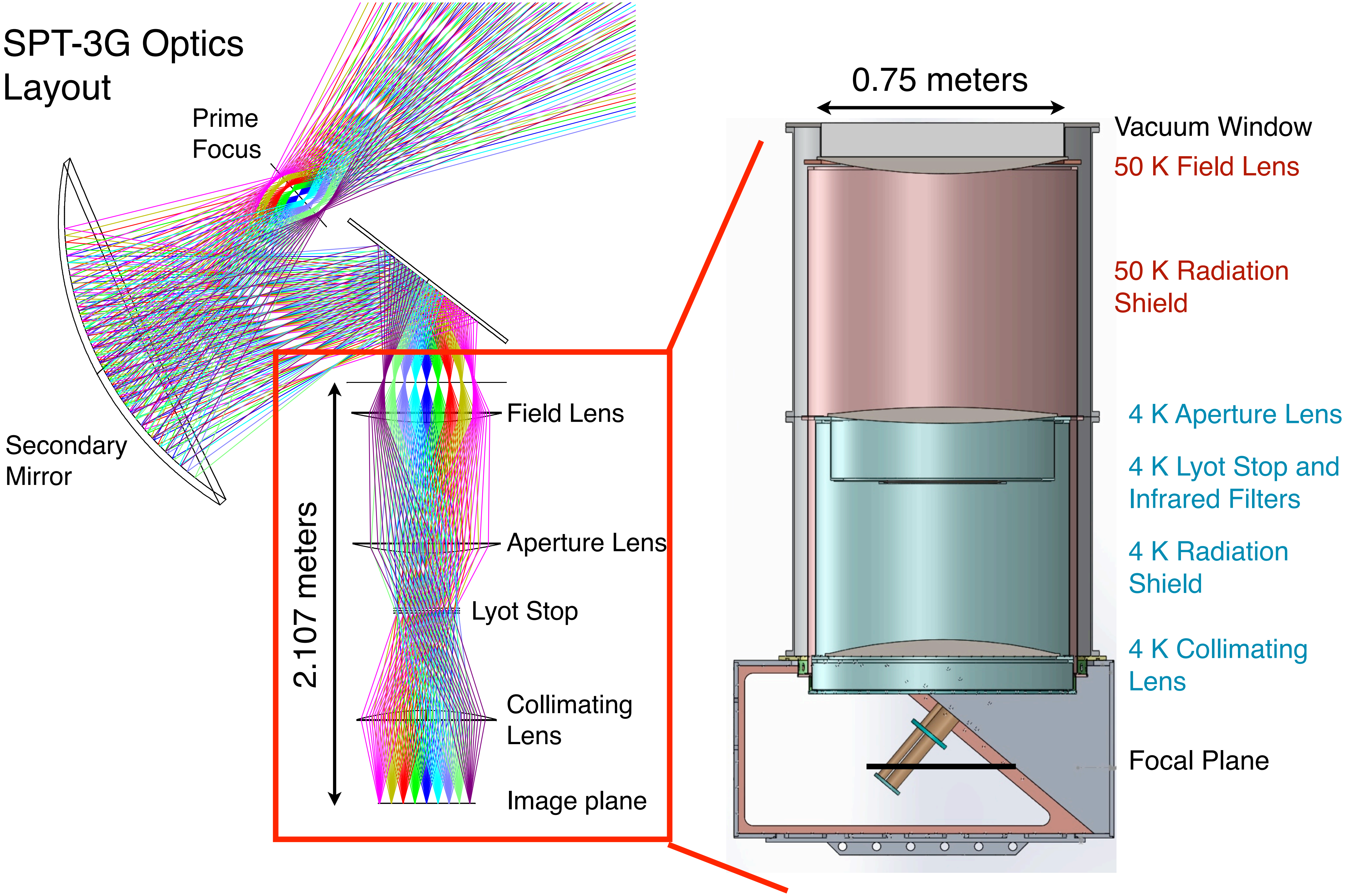
The broad-band signal is segmented by lumped-element on-chip filters (RLC) and passed to detectors for measurement





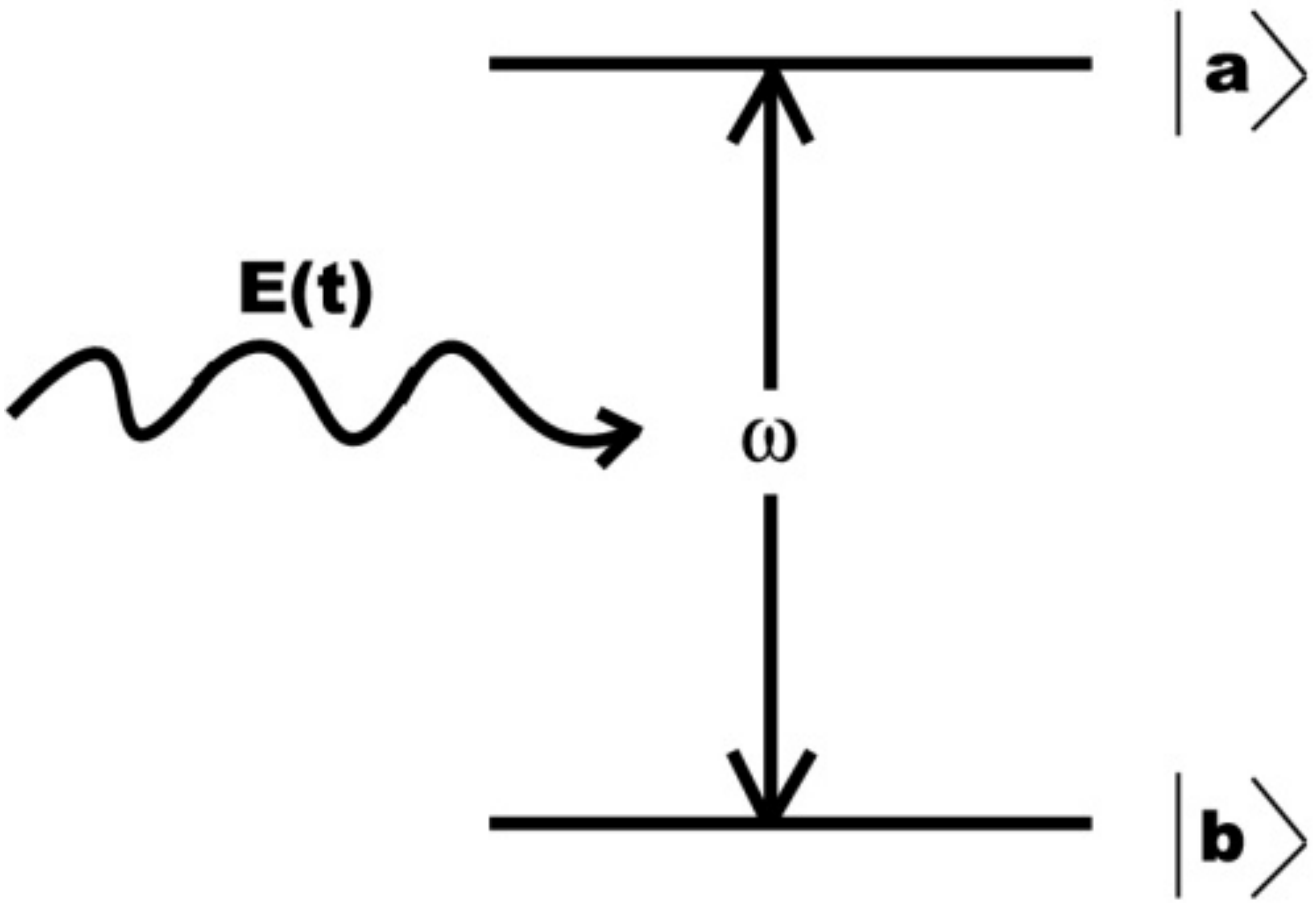
SPT3G, PB2 etc.

Let the light in



Various optical elements, lenses, collimators, filters etc. are non-trivial at mm waves, especially for big (3G-like) instruments. R&D in microwave material science is happening, and more effort is required

Seeing the light



At the heart of all CMB experiments, is quantum excitation

We will discuss:
WMAP receivers, SPT detectors and one CMBS4 technology

Seeing the light: WMAP

WMAP looked at the difference in signals from two horns

The “radio” signals are amplified by HEMT amplifiers

The amplified power is measured with diodes

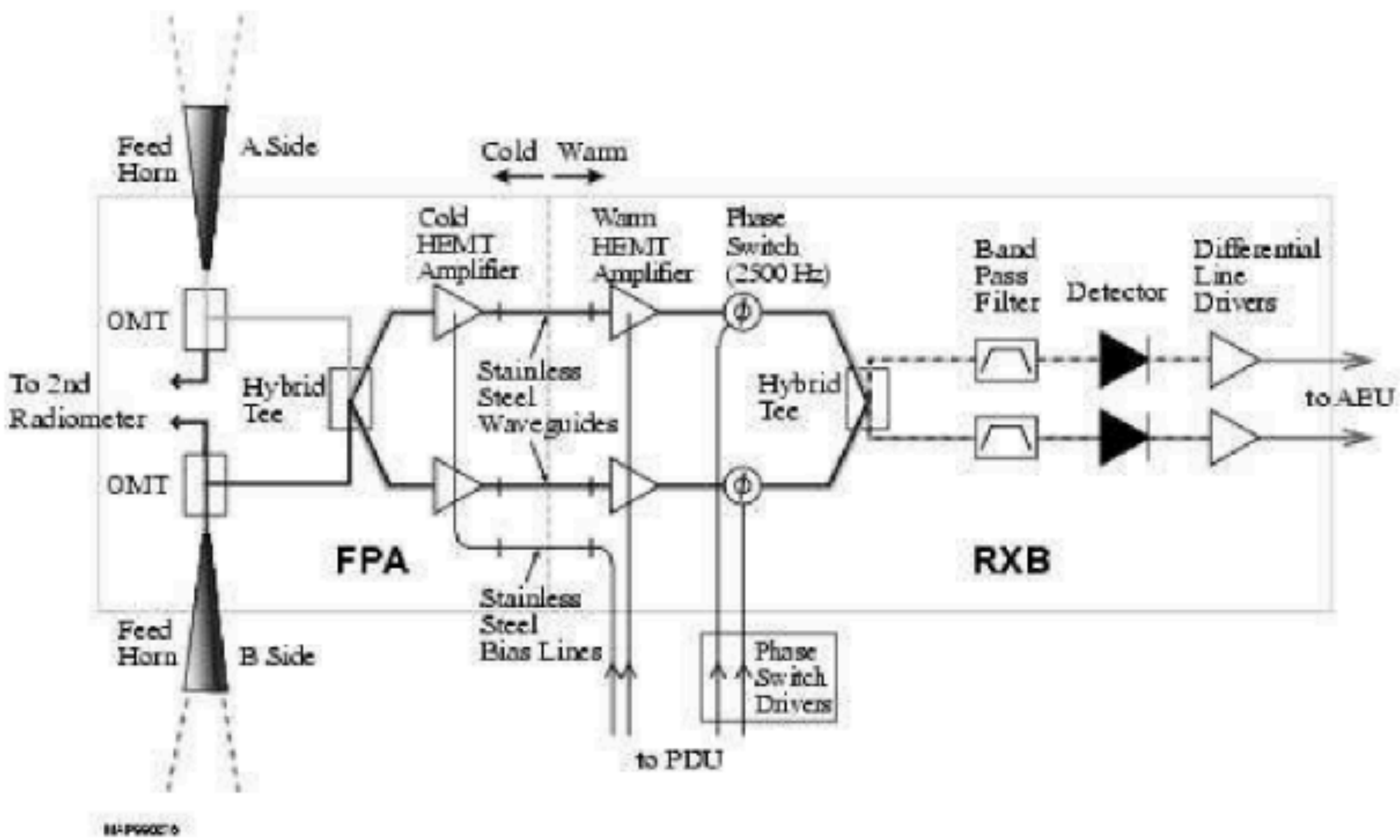
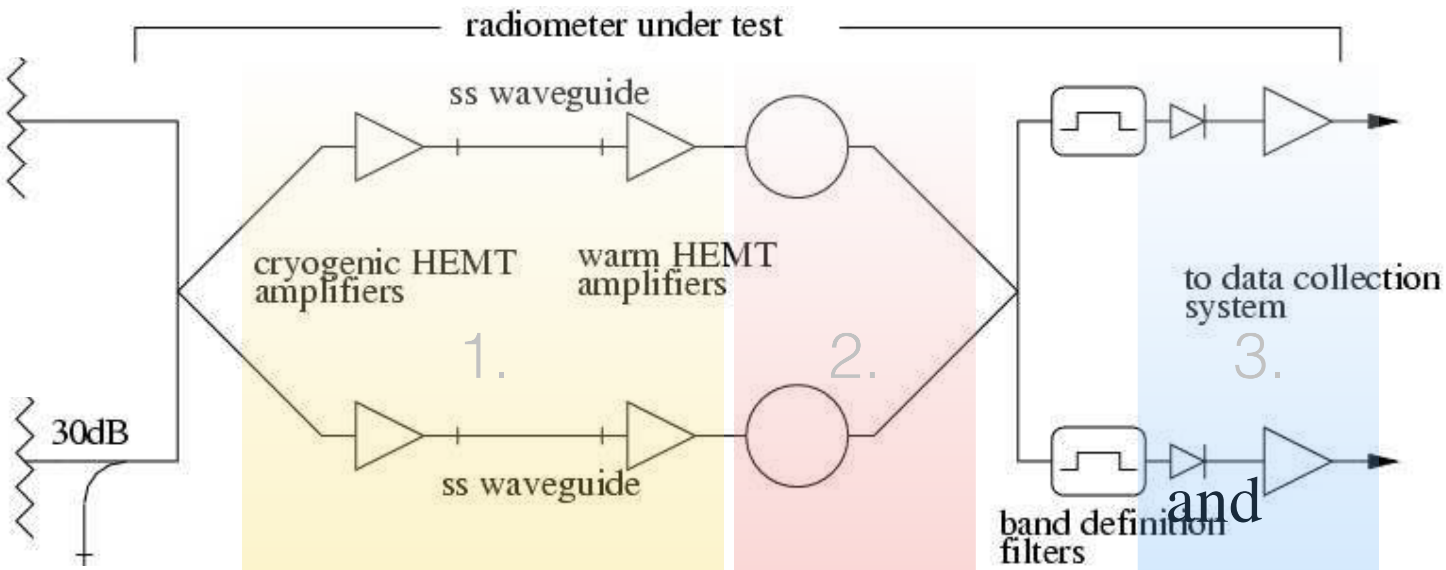


FIG. 1.— Layout of an individual *MAP* radiometer. Components on the cold (left) side of the stainless steel waveguides are located in the FPA, and are passively cooled to 90 K in flight.

https://arxiv.org/pdf/astro-ph/0301164.pdf

Seeing the light: WMAP

$$\sigma_A^2 \propto k_b T_A \Delta\nu$$



$$\sigma_B^2 \propto k_b T_B \Delta\nu$$

The outputs of the two detectors then become

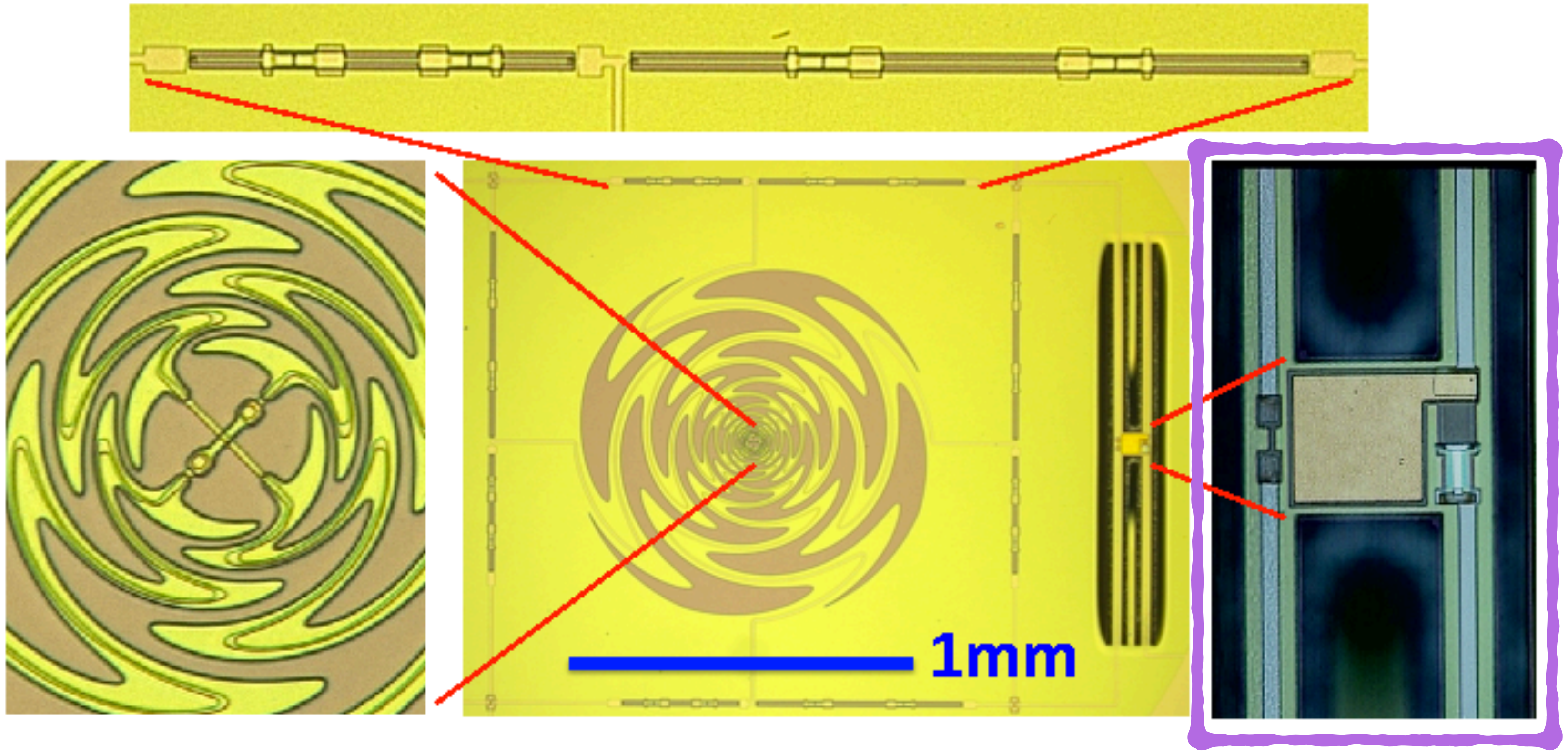
$$V_l = \frac{s}{2}\left\{\left(\frac{A^2+B^2}{2}+n_1^2\right)g_1^2(t) + \left(\frac{A^2+B^2}{2}+n_2^2\right)g_2^2(t) \mp (A^2-B^2)g_1(t)g_2(t)\right\}$$

and

$$V_r = \frac{s}{2}\left\{\left((\frac{A^2+B^2}{2}+n_1^2\right)g_1^2(t) + \left(\frac{A^2+B^2}{2}+n_2^2\right)g_2^2(t) \pm (A^2-B^2)g_1(t)g_2(t)\right\}$$

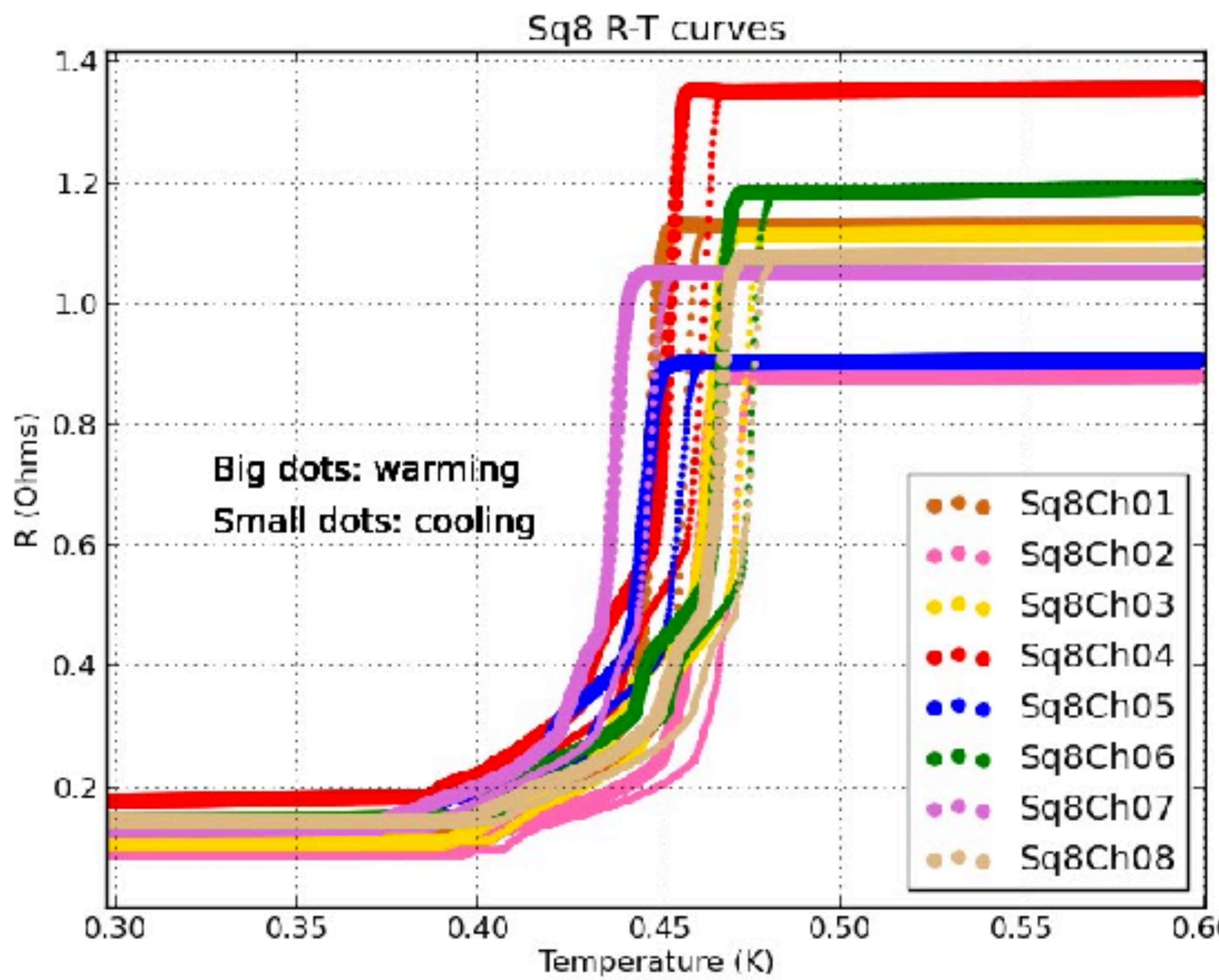
1. Amplifiers (HEMT) with gain $g_{1/2}$ and noise $n_{1/2}$
2. Phase offsets
3. Diodes responds linearly to input power
4. Answer => V_r - V_l

Seeing the light: SPT

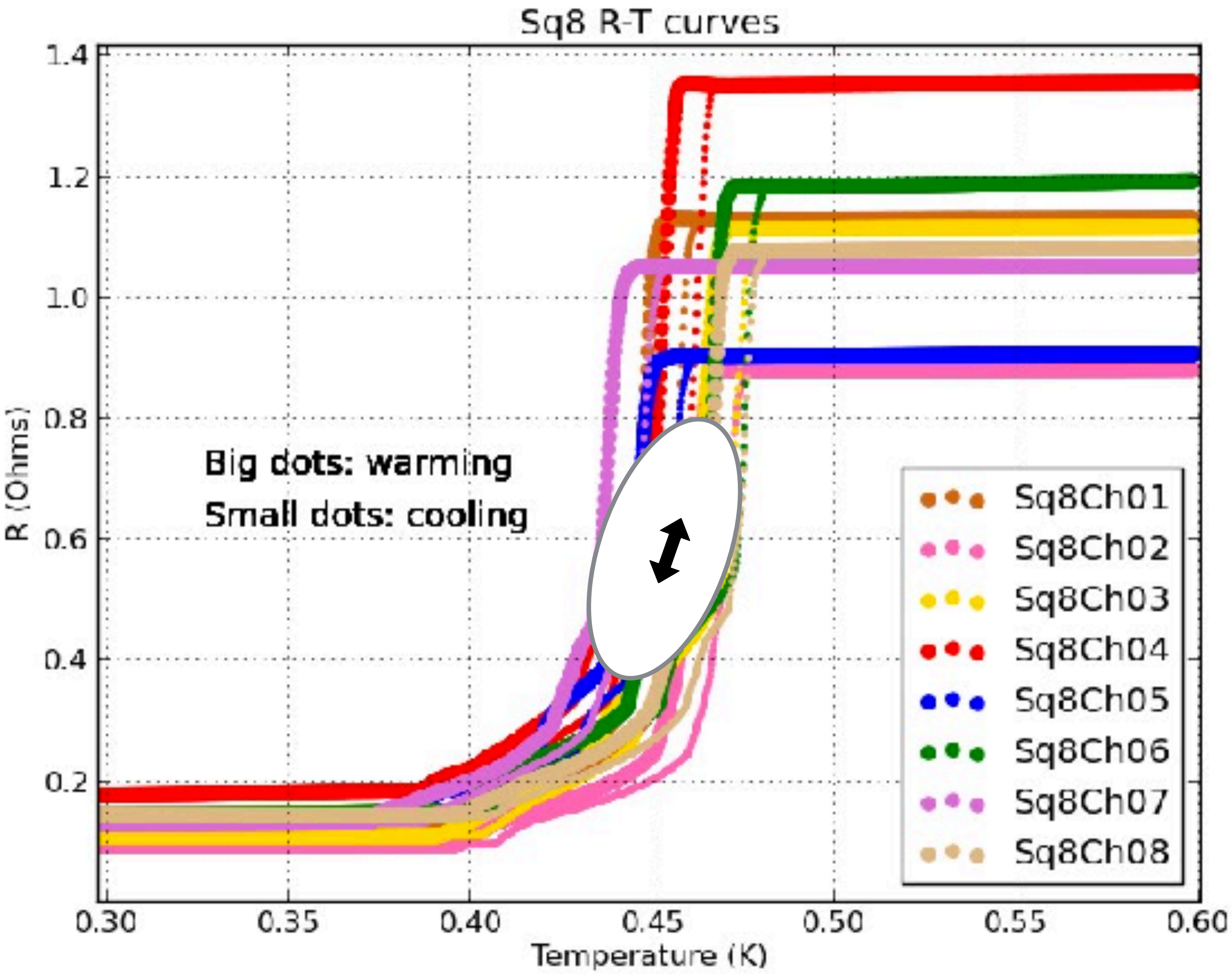


Transition edge sensors (TESs)

Resistance change of a superconductor as you heat it up a bit.

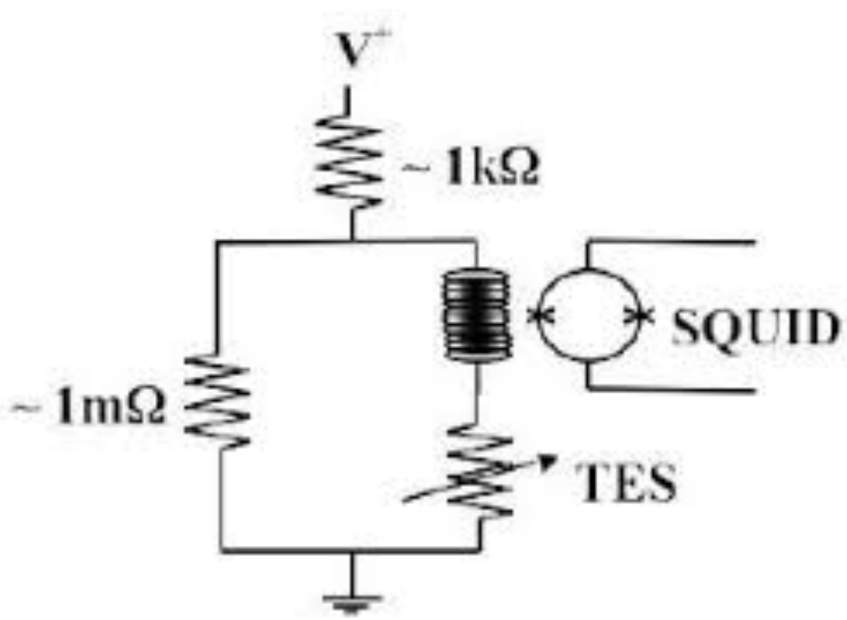


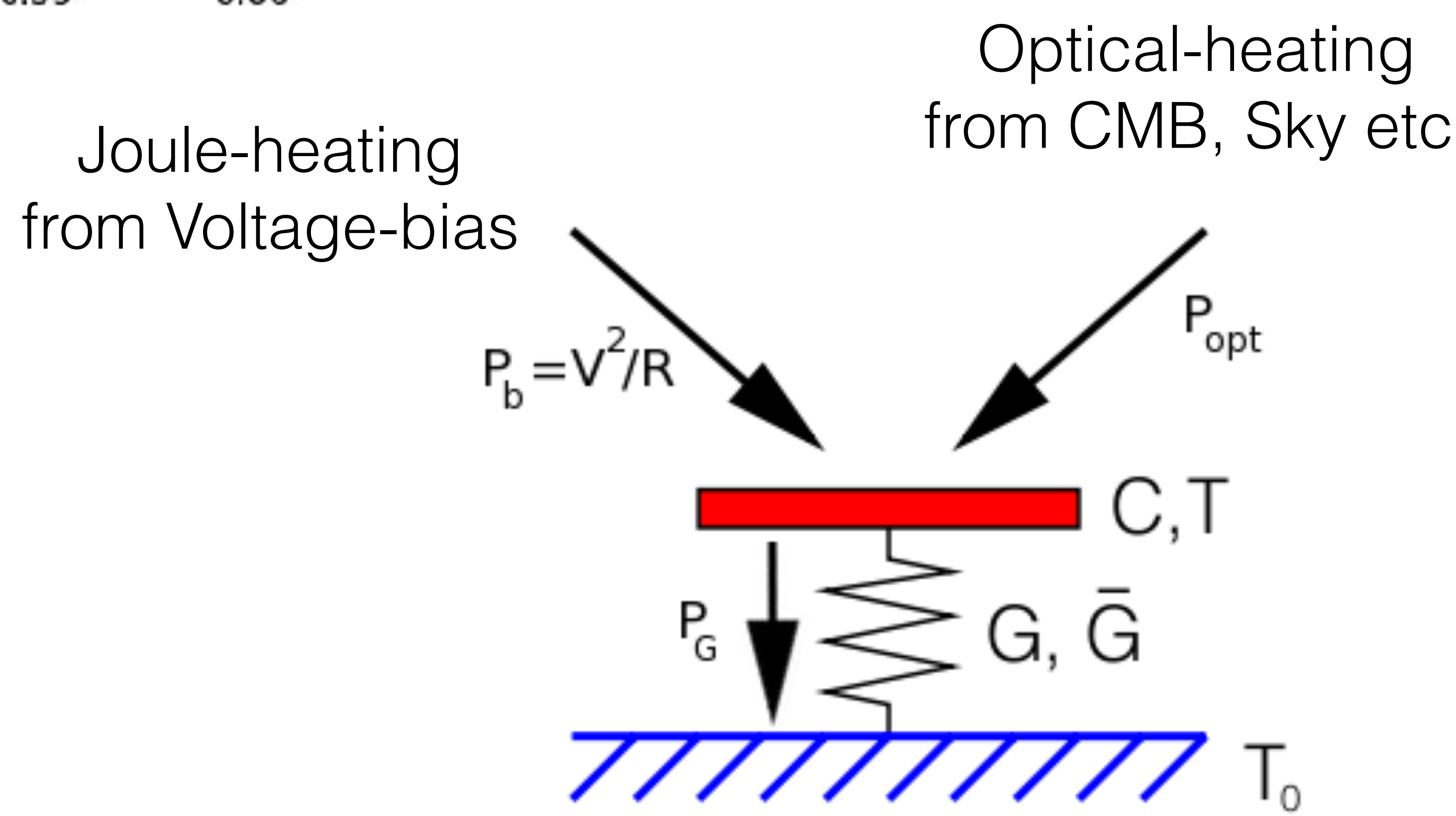
Seeing the light: SPT



Voltage-bias the detector to sit on transition:

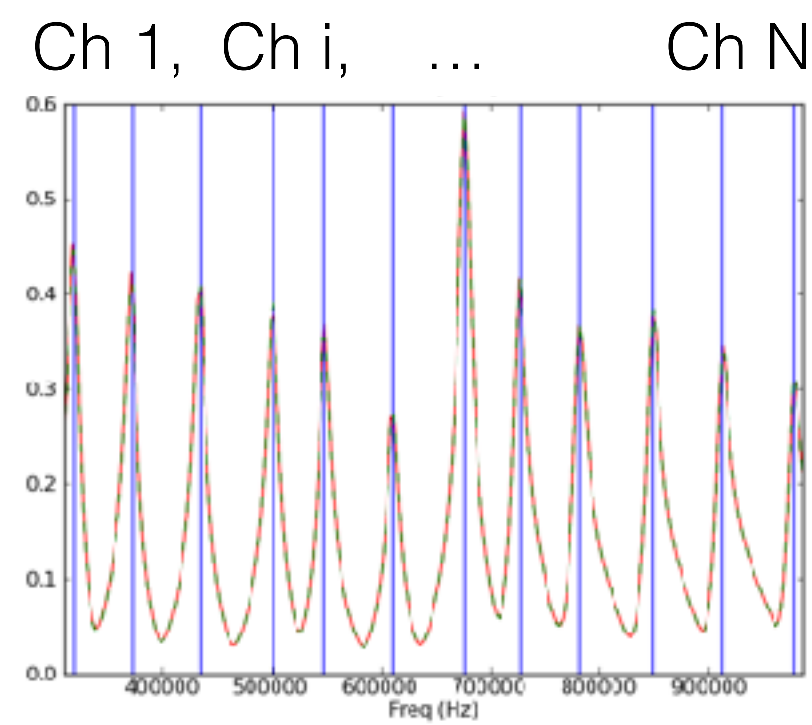
Small dT -> large dR
large dR -> large dI

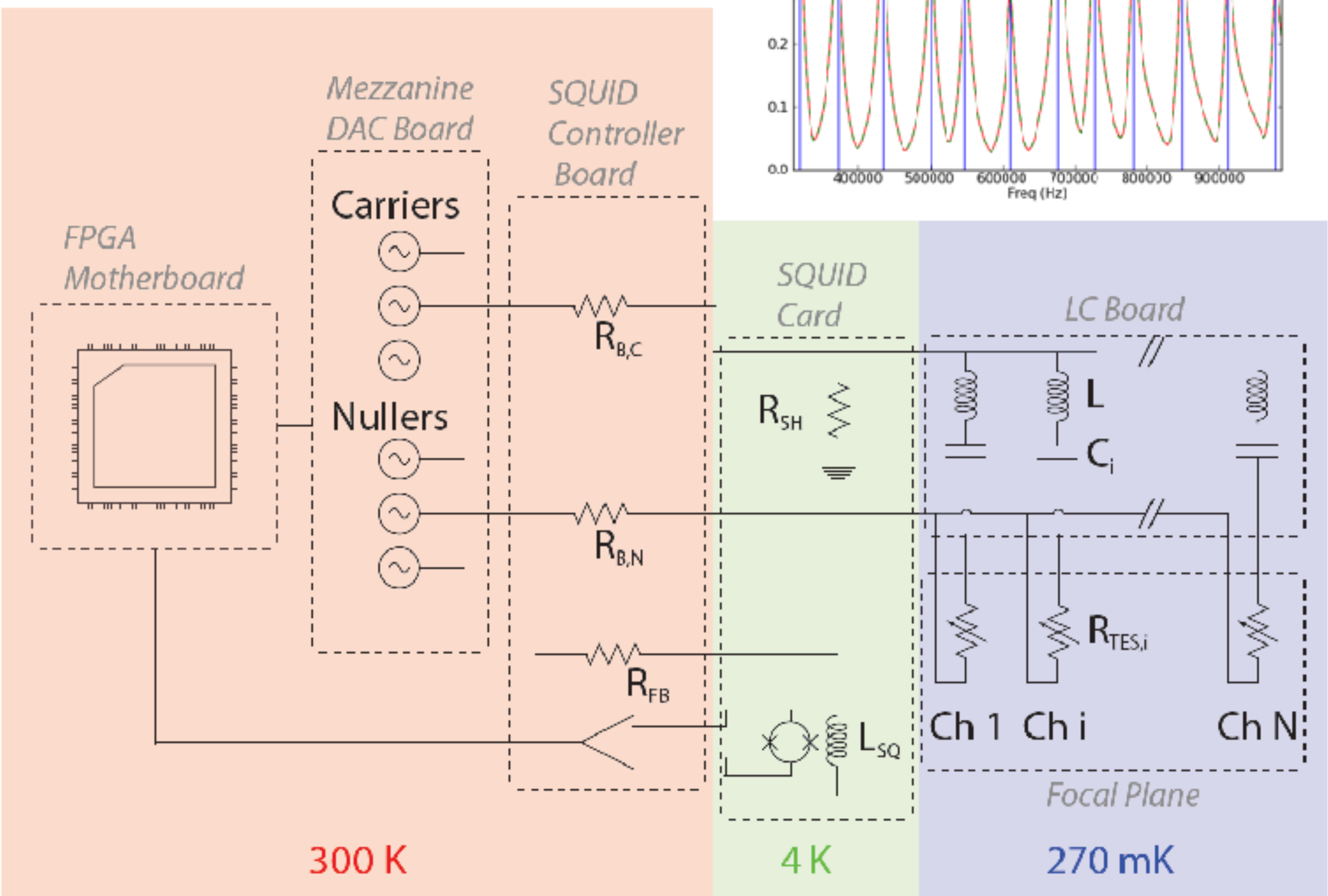




Seeing the light: SPT

We have to read thousands of TESs!
Clever but complicated





Seeing the light: SPT

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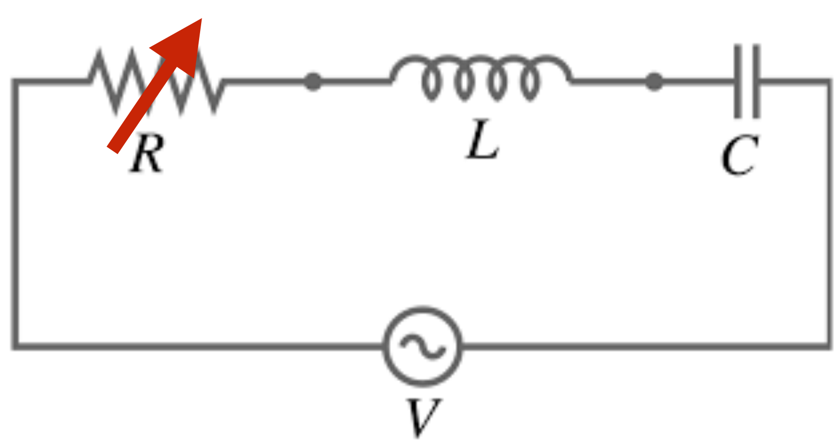
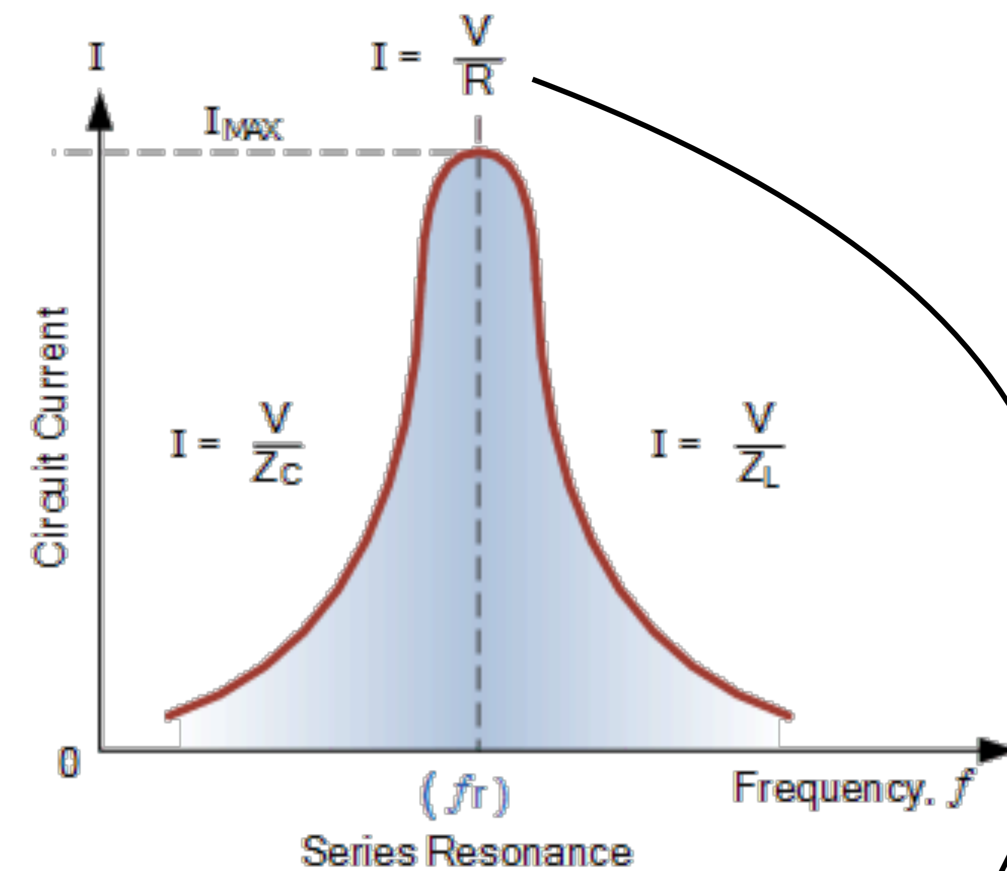
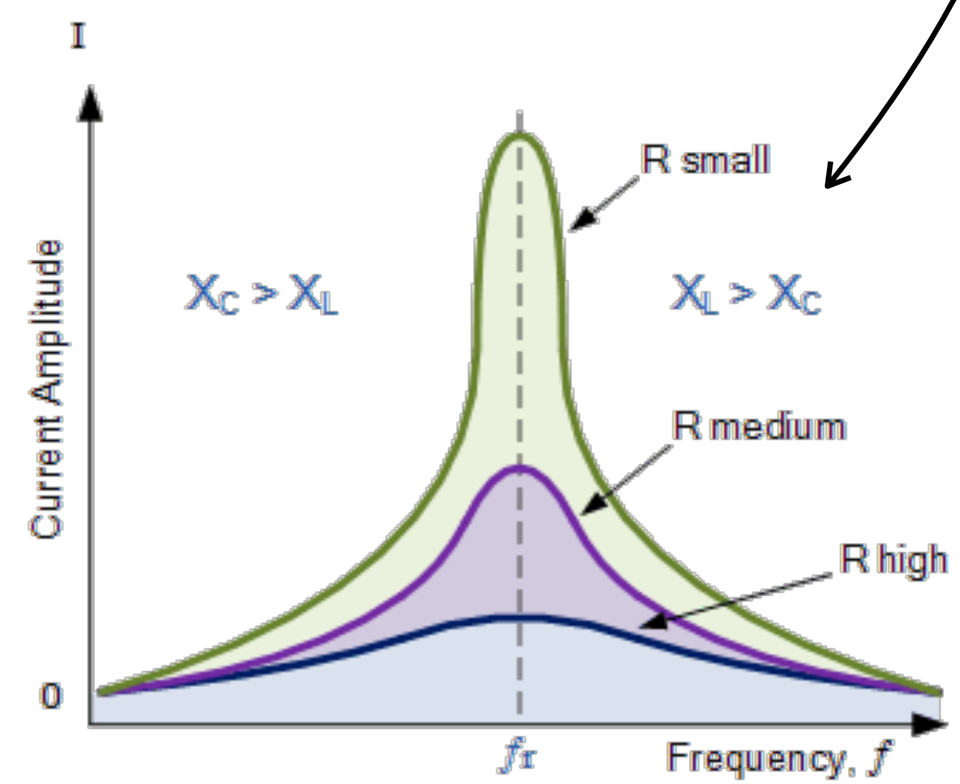
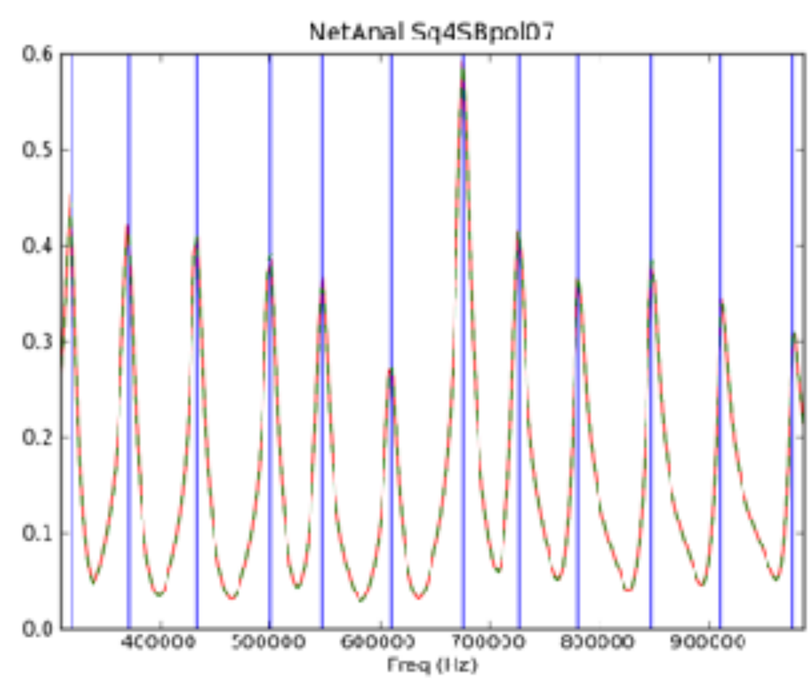




Couple a TES to a LC system. Amplitude is modulated by R(T), and each TES gets a resonant f_r…. therefore we multiplex

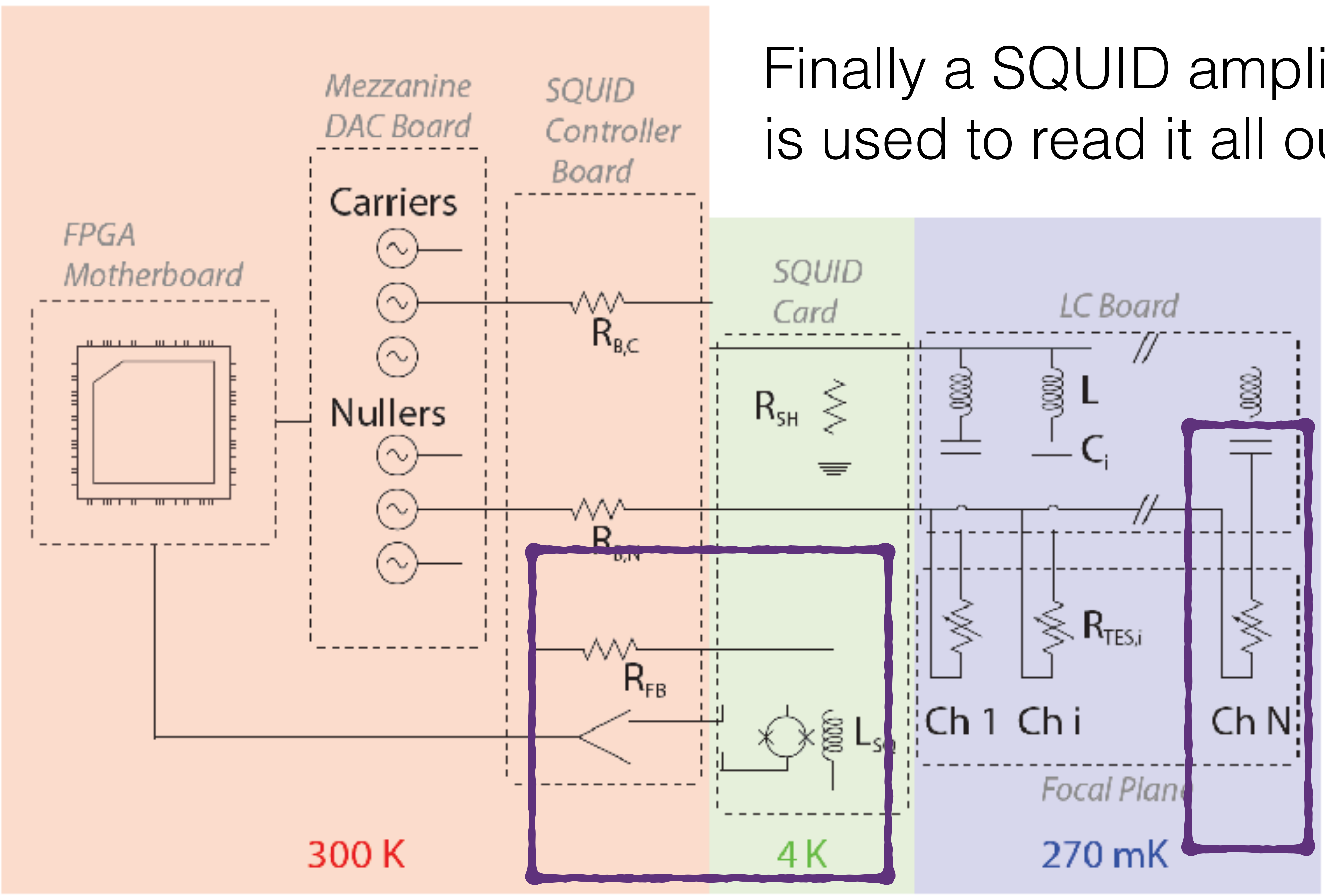




Seeing the light: SPT

Superconducting **Q**uantum **I**nterference **D**evice: sensitive magnetometer for measuring tiny (fT) magnetic fields

Finally a SQUID amplifier is used to read it all out



Seeing the light: S4 (potential)

Multiplexing factor is good, but not great: SPT-3G has 15,234 detectors at 68× multiplexing

0.5E6 detectors for CMB S4, thus naively multiplexing factor should scale up by > 2E3

Of-course, we are likely to split the 0.5E6 detectors across a few focal planes, and the readout can be further segmented

These can help us by O(10-100), but pushing by another decade is going to very very challenging.

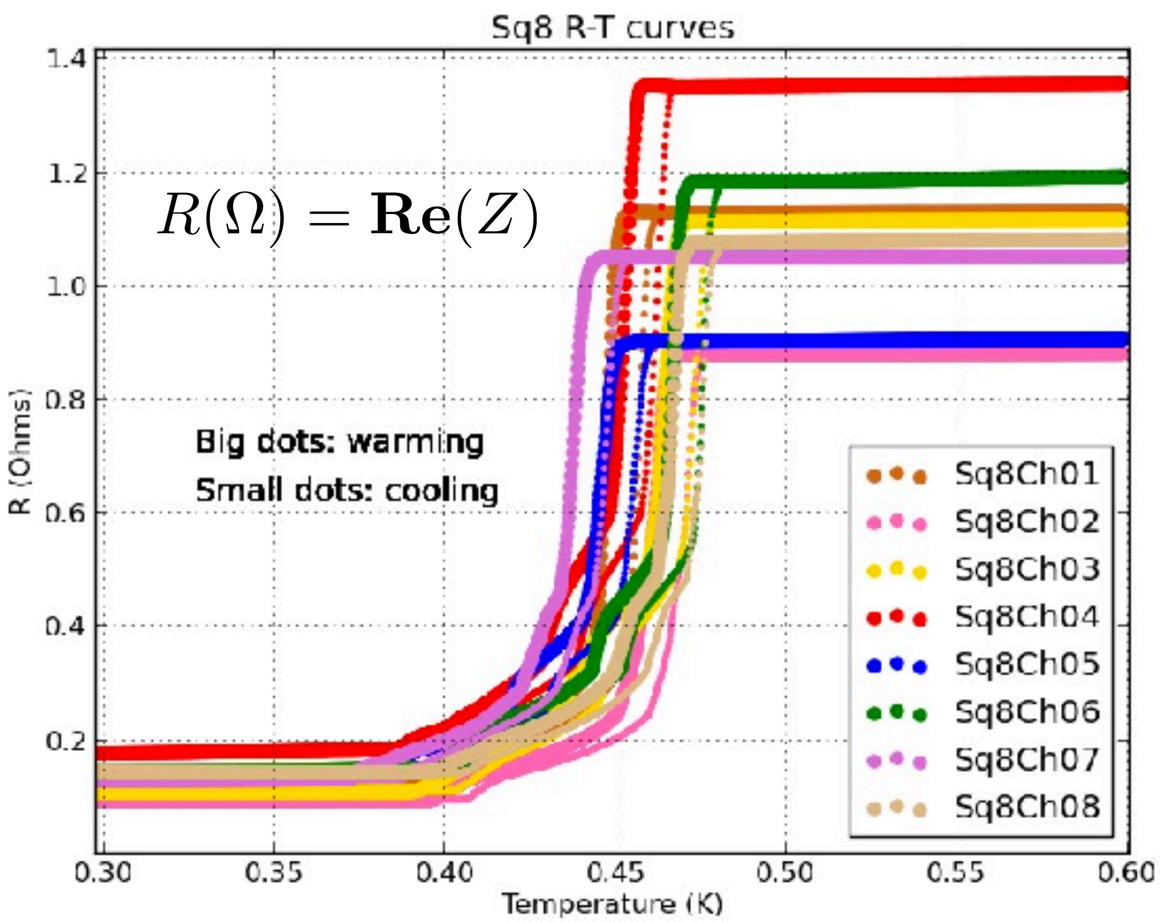
While 3G operations will be extremely illuminating, we recognize it is not smooth sailing

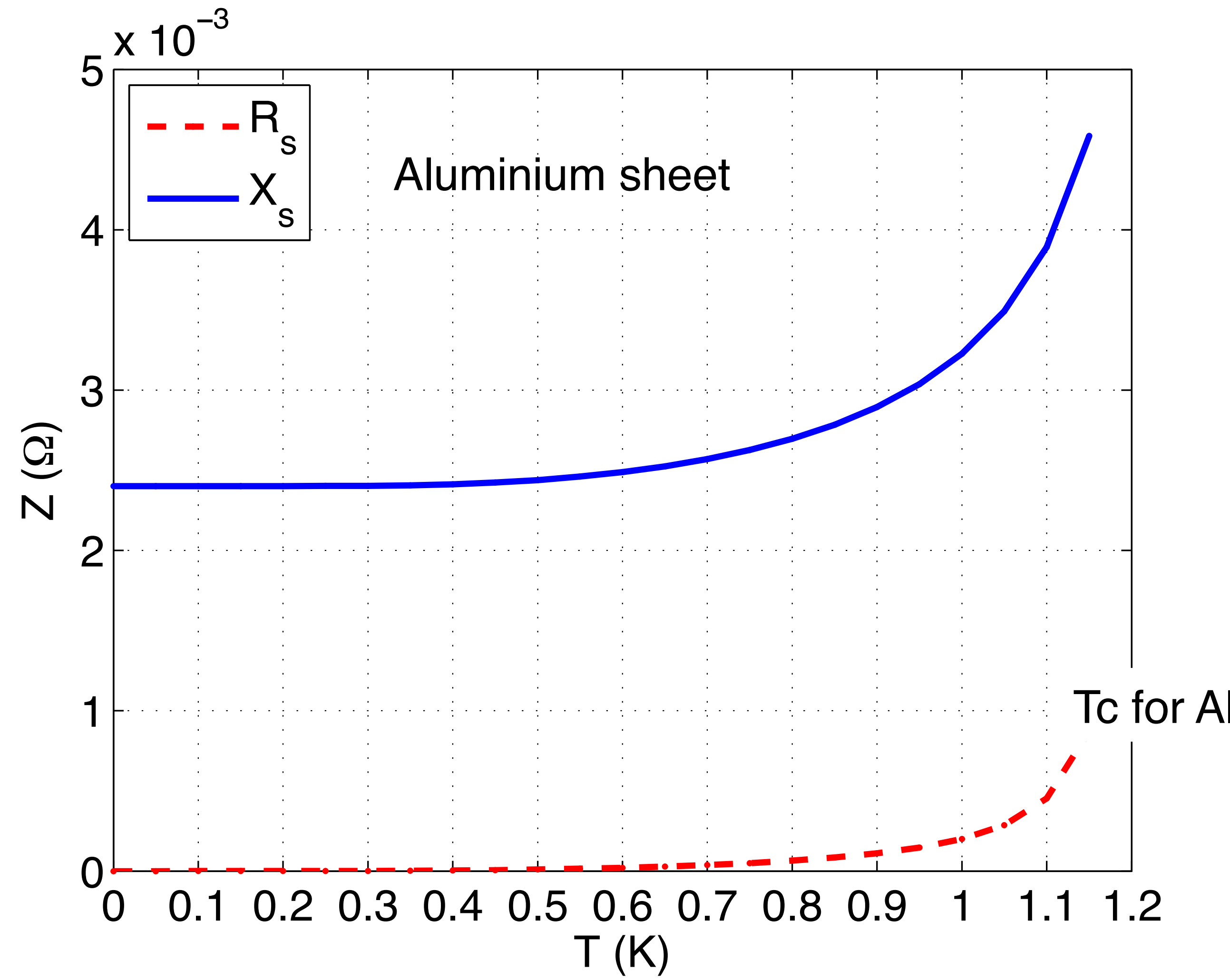
Native multiplexing …

Seeing the light: S4 (potential)

Kinetic Inductance: Superconductors electronics in all generality

$$Z(\omega) = R + i(X_c + X_L) = R + i(1/\omega C + \omega L)$$

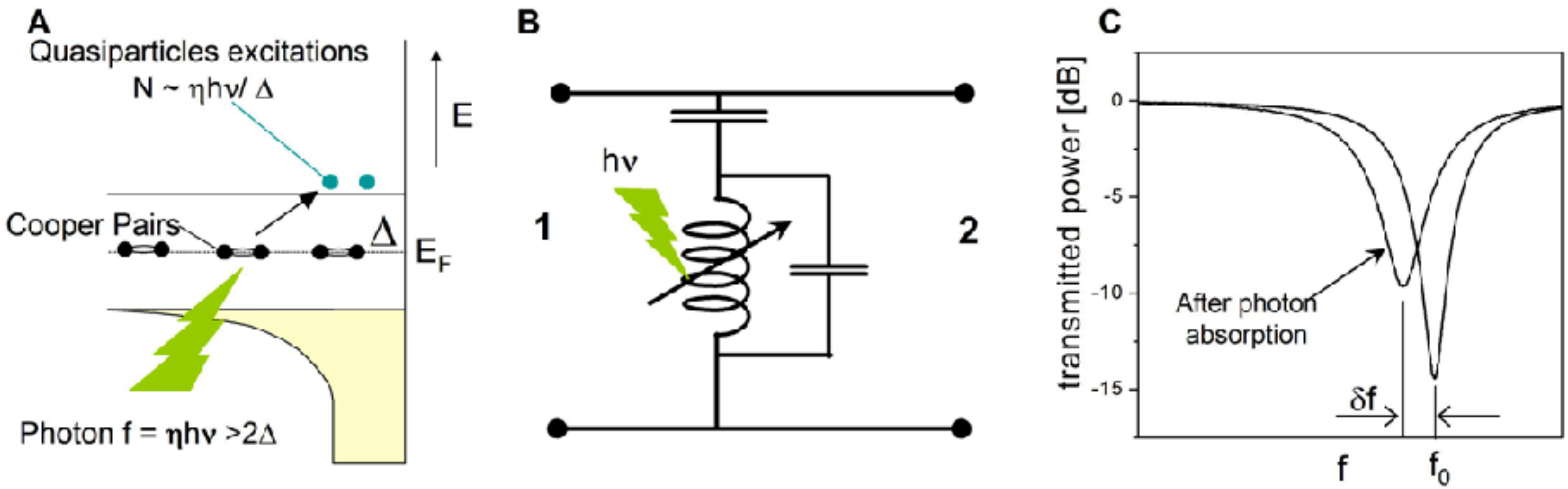




High frequency oscillating fields will see a "mass" for the Cooper pairs, leading to a phase lag, or $\dfrac{\mathbf{Im}}{\mathbf{Re}}(Z) > 0$

Microwave **K**inetic **I**nductance **D**etectors (MKIDs)

$$S_{21} = \frac{1}{1 + jQ(1 - \omega_0^2/\omega^2)}$$

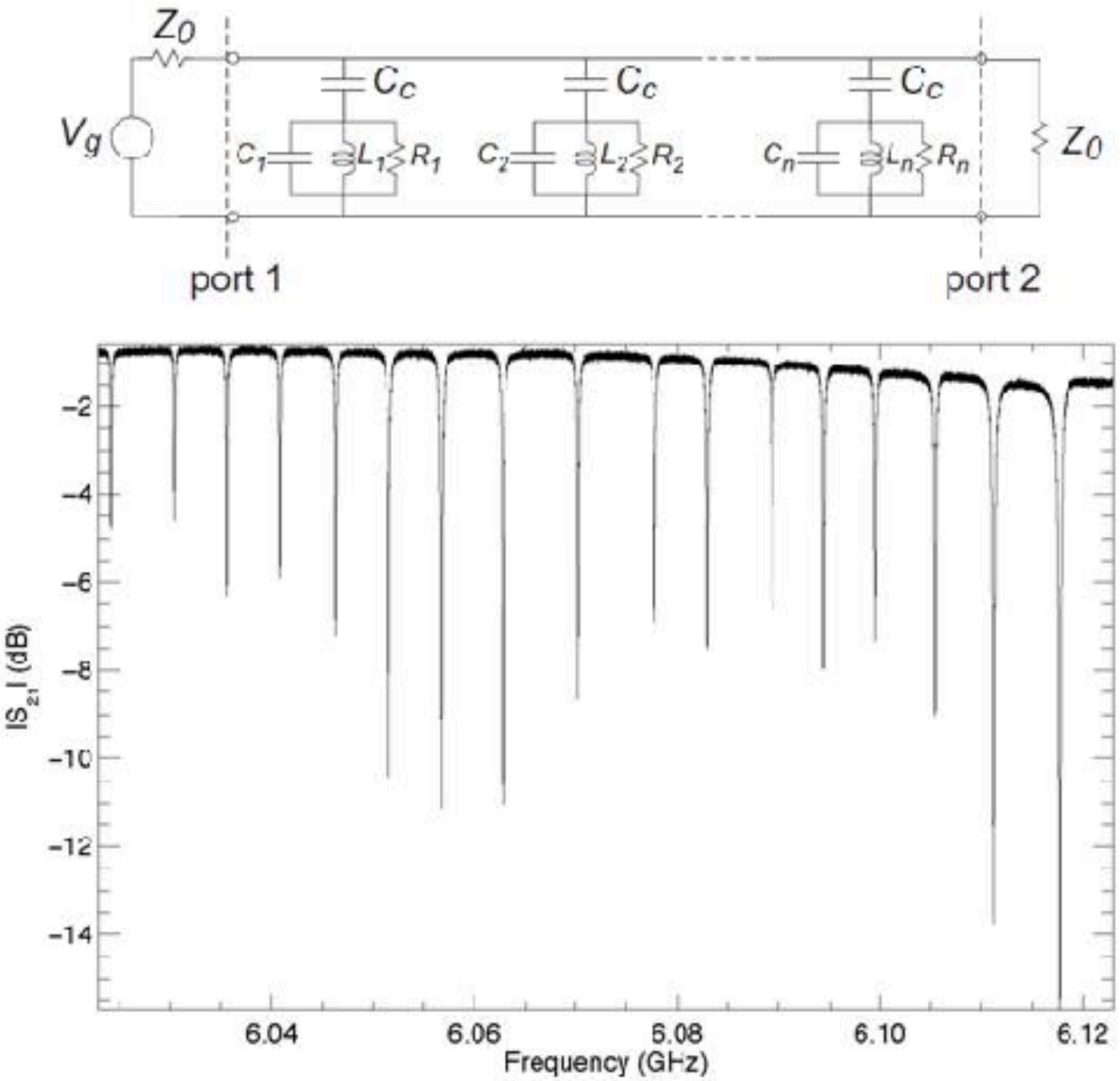


Photon absorption -> Cooper pair breaking -> Change in R & L -> Resonance frequency shift, phase shift, peak broadening

Ben Mazin and SRON

Seeing the light: S4 (potential)

Microwave **K**inetic **I**nductance **D**etectors (MKIDs)



Because each detector is a mode, we can connect them in series, i.e. a comb of modes

The amplitude of a mode ~ photon power on that detector

Thus MKIDs are naturally multiplexed photon detectors

Ben Mazin and SRON

For efforts at KICP and further details, see Amy Tang's talk

Conclusions

We discussed how colors and patterns of the CMB can be measured

Rest of 448 course has shown the physics behind these fluctuations

General sensitivity calculations were presented

Types of technologies were outlined

We did not cover: foreground subtraction, map making algorithms and parameter estimations

Questions ?