- # Basic concepts in CMB detectors for poets and theorists – Part 2

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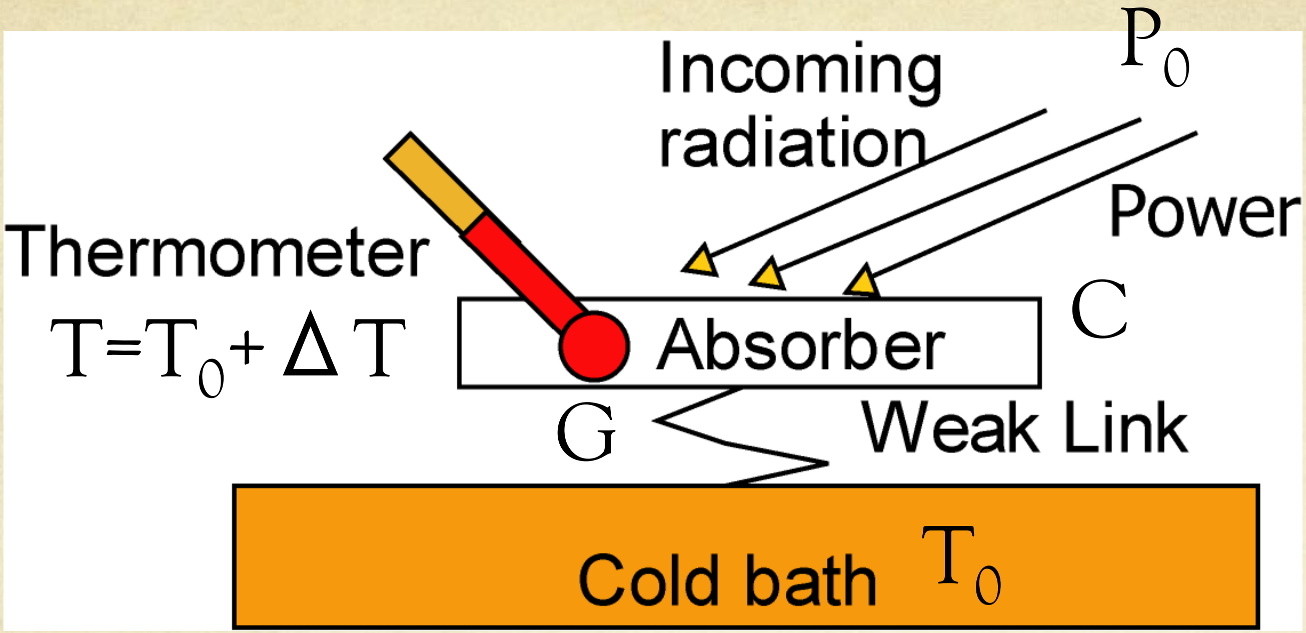
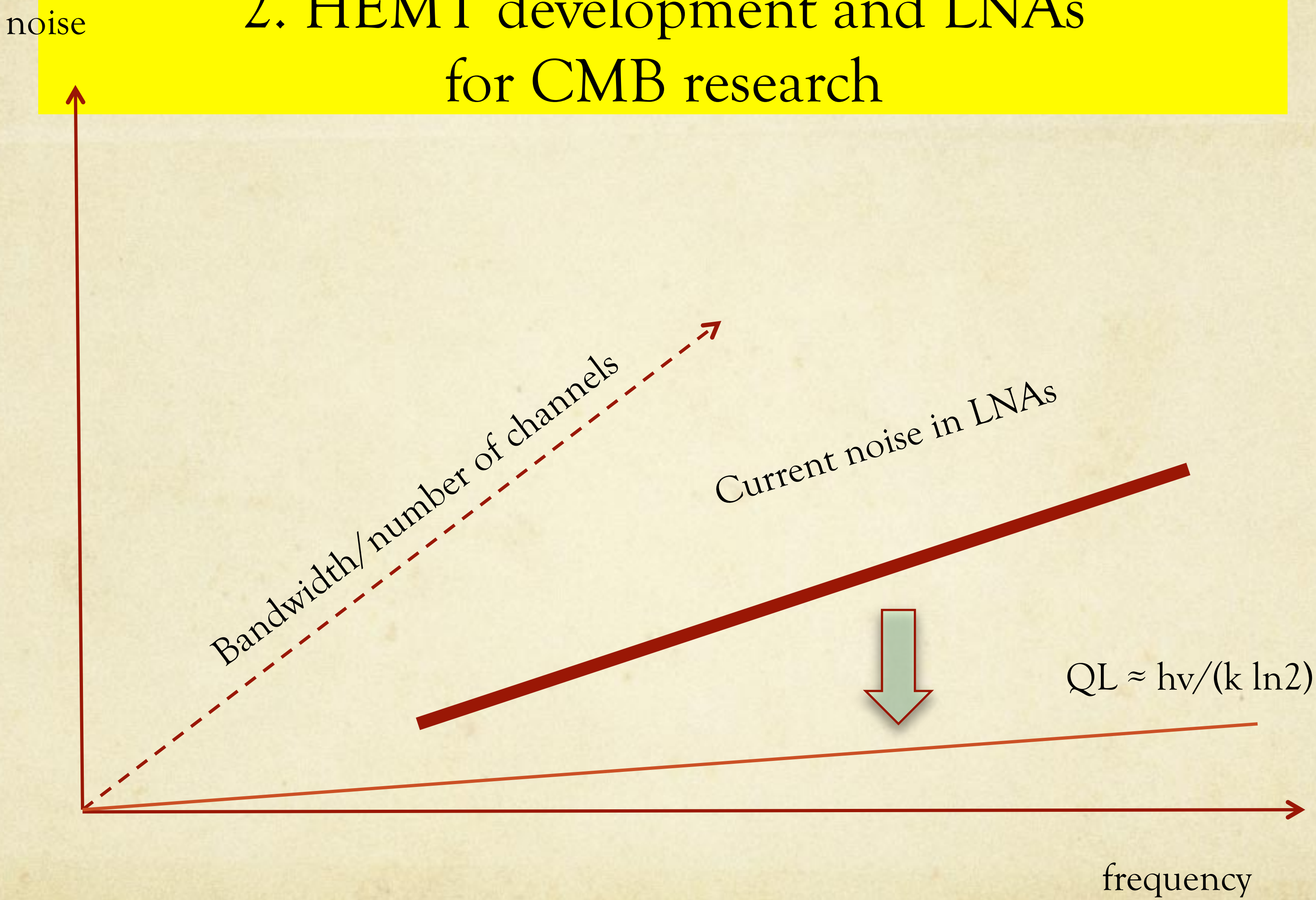
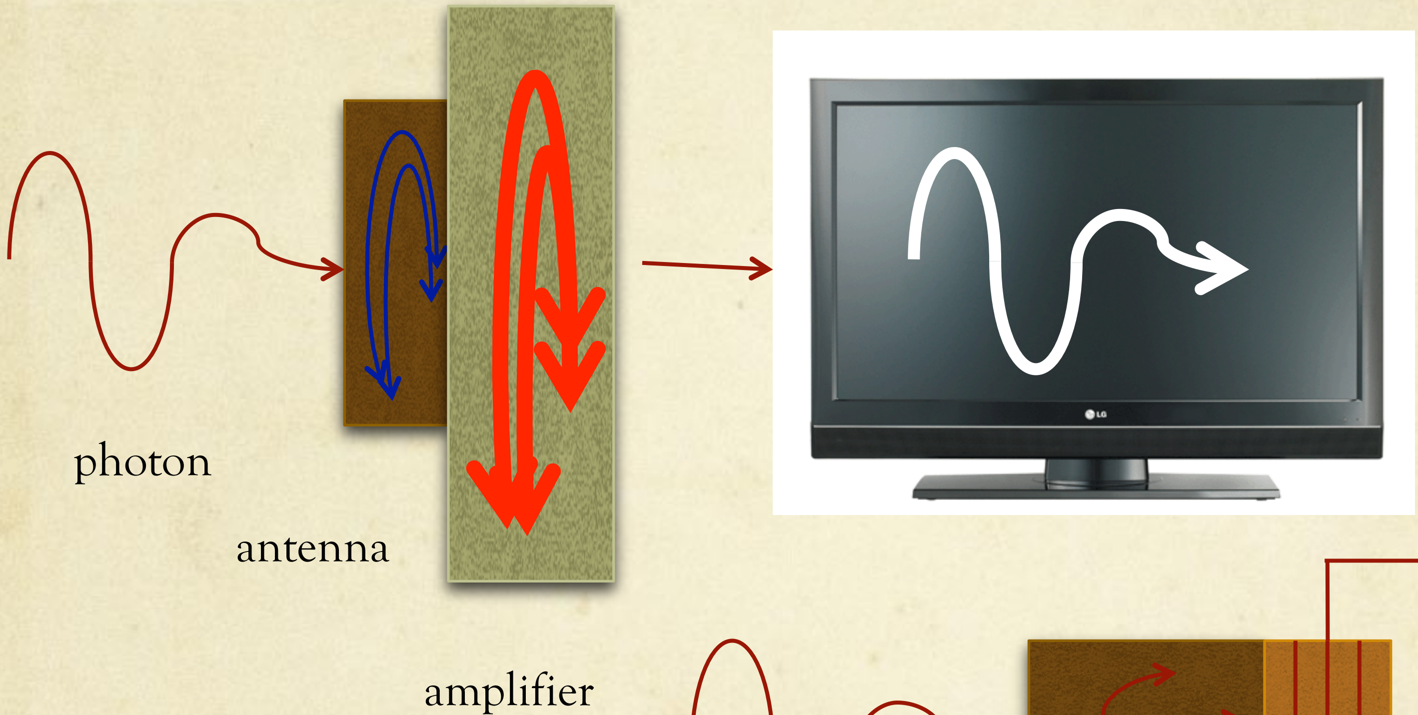


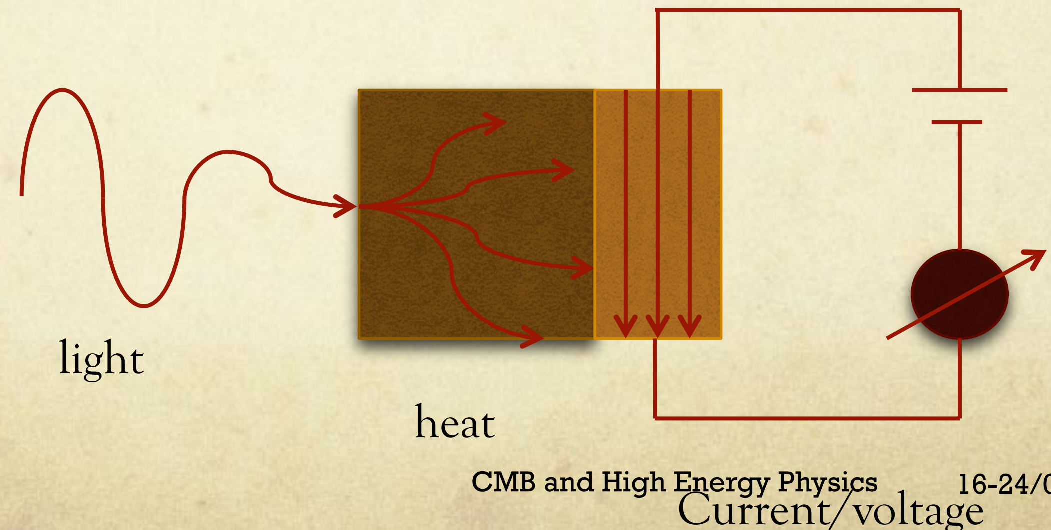
1. Bolometer is a classical detector
2. Produces a Voltage prop. to the incident power
3. Is not sensitive to the phase of the incoming photon
4. Can be very sensitive (limited by photon noise) but relatively slow response time
5. Detects all kind of power: electrical, light, particles, etc.

2. HEMT development and LNAs for CMB research



How coherent radiometry works





Amplifier: from quantum to classical world

Quantum view of amplifier

- Linear device that takes an input signal and produces an output signal by allowing the input signal to interact with the amplifier's internal degrees of freedom
- The input and output signals are carried by a set of "bosonic" modes [usually modes of the e.m. field]
- Increases the size of the Signal without degrading (too much) the signal-to-noise ratio
- Noise after amplification is much larger that the minimum allowed by QM
- The signal can therefore be analyzed by our "dirty", "grubby", classical hands
- Brings very delicate QM systems to our classical world

Quantum limit

PHYSICAL REVIEW D

PARTICLES AND FIELDS

THIRD SERIES, VOLUME 26, NUMBER 8 15 OCTOBER 1982

Quantum limits on noise in linear amplifiers

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(Received 18 August 1981)

How much noise does quantum mechanics require a linear amplifier to add to a signal it processes? An analysis of narrow-band amplifiers (single-mode input and output) yields a fundamental theorem for phase-insensitive linear amplifiers; it requires such an amplifier, in the limit of high gain, to add noise which, referred to the input, is at least as large as the half-quantum of zero-point fluctuations. For phase-sensitive linear amplifiers, which can respond differently to the two quadrature phases ("$\cos\omega t$" and "$\sin\omega t$"), the single-mode analysis yields an amplifier uncertainty principle—a lower limit on the product of the noises added to the two phases. A multimode treatment of linear amplifiers generalizes the single-mode analysis to amplifiers with nonzero bandwidth. The results for phase-insensitive amplifiers remain the same, but for phase-sensitive amplifiers there emerge bandwidth-dependent corrections to the single-mode results. Specifically, there is a bandwidth-dependent lower limit on the noise carried by one quadrature phase of a signal and a corresponding lower limit on the noise a high-gain linear amplifier must add to one quadrature phase. Particular attention is focused on developing a multimode description of signals with unequal noise in the two quadrature phases.

PHYSICAL REVIEW VOLUME 128, NUMBER 5 DECEMBER 1, 1962

Quantum Noise in Linear Amplifiers

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(Received May 10, 1962; revised manuscript received August 23, 1962)

The classical definition of noise figure, based on signal-to-noise ratio, is adapted to the case when quantum noise is predominant. The noise figure is normalized to "uncertainty noise." General quantum mechanical equations for linear amplifiers are set up using the condition of linearity and the requirement that the commutator brackets of the pertinent operators are conserved in the amplification. These equations include as special cases the maser, the parametric amplifier, and the parametric up-converter. Using these equations the noise figure of a general amplifier is derived. The minimum value of this noise figure is equal to 2. The significance of the result with regard to a simultaneous phase and amplitude measurement is explored.

Quantum Noise in Linear Amplifiers Revisited

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***Abstract*— This paper presents a model for radiation as a photon gas. For each frequency, the photon distribution is a mixture of Bose-Einstein and Poisson distributions, respectively for thermal noise and the useful signal. Poisson (shot) noise contributes with noise at all frequencies. When applied to the operation of linear amplifiers and attenuators, the model gives a natural interpretation to the noise figure in terms of the uncertainty in the amplification process itself.**

at optical frequencies, $\mathrm{Var}(w_k) = \langle w_k \rangle \gg \langle x_k \rangle \simeq \mathrm{Var}(w_k)$. We reproduce the behaviour in Eq. (1) in both extremes. The difference between the two regimes is now a function of not only ν and T, as in the usual analysis, but also of the signal energy as well. As noise is not additive, but signal dependent, it may well happen that the shot noise prevails over the thermal noise, even if $h\nu \ll k_B T$.

Amplification corresponds to a change in the distribution of ζ_k. We model this change statistically: for each input photon, a (random) number of output photons γ is generated. The probability that γ photons are effectively output is $\mathrm{Pr}_{\mathrm{amp}}(\gamma)$. Linearity implies that amplification takes place for every individual photon, independently of the remaining photons in the mode. The mean of the amplifier output ζ_{out} is $\langle\zeta_{\mathrm{out}}\rangle = \langle\gamma\rangle\langle\zeta_{\mathrm{in}}\rangle$, and its variance,

$$\mathrm{Var}(\zeta_{\mathrm{out}}) = \langle\gamma\rangle^2 \,\mathrm{Var}(\zeta_{\mathrm{in}}) + \mathrm{Var}(\gamma)\langle\zeta_{\mathrm{in}}\rangle. \tag{3}$$

The change in signal-to-noise ratio between input and output is

$$\frac{\mathrm{SNR}_{\mathrm{in}}}{\mathrm{SNR}_{\mathrm{out}}} = 1 + \frac{\mathrm{Var}(\gamma)}{\langle\gamma\rangle^2}\frac{\langle\zeta_{\mathrm{in}}\rangle}{\mathrm{Var}(\zeta_{\mathrm{in}})}. \tag{4}$$

This ratio depends on the signal statistics. For a coherent state, for which $\langle\zeta_{\mathrm{in}}\rangle = \mathrm{Var}(\zeta_{\mathrm{in}})$. We then define the noise figure F as

$$\mathrm{F} \triangleq 1 + \frac{\mathrm{Var}(\gamma)}{\langle\gamma\rangle^2} = \frac{\langle\gamma^2\rangle}{\langle\gamma\rangle^2}. \tag{5}$$

As expected, $\mathrm{F} \geq 1$, an amplifier can only worsen the signal-to-noise ratio. Linear amplification admits a natural interpretation as the change in the number of particles, and of their statistics. Added amplification noise is related to the uncertainty in the amplification process itself.

With a thermal input, a noise temperature T_{eq} can be defined

$$T_{\mathrm{eq}} = T(\mathrm{F}-1) = T\frac{\mathrm{Var}(\gamma)}{\langle\gamma\rangle^2}\left(1 - e^{-\frac{h\nu}{k_B T}}\right) \simeq \frac{\mathrm{Var}(\gamma)}{\langle\gamma\rangle^2}\frac{h\nu}{k_B}, \tag{6}$$

where we assumed that $\frac{h\nu}{k_B T} \ll 1$.

We recover the well-known formula $\mathrm{F} = \mathrm{L}$ for the noise figure of an attenuator, a device which independently removes every photon with probability π and lets it through with probability $1-\pi$; its loss L is $\mathrm{L} = (1-\pi)^{-1} \geq 1$.

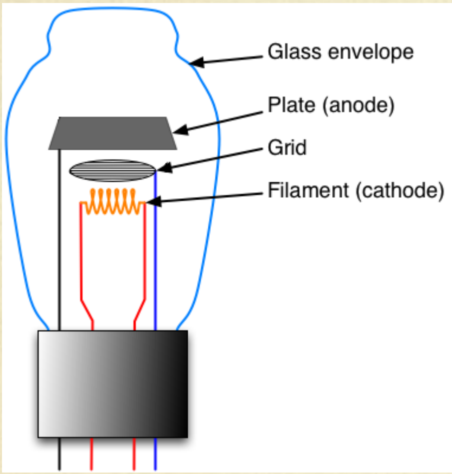
This model can be easily used to derive Friis's formula for a chain of n amplifiers, each with gain γ_ν, it is easy to generalize Eq. (3) to obtain a formula for total change in SNR,

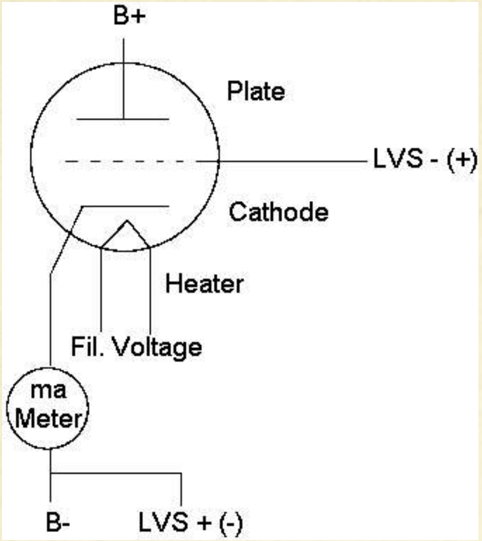
$$\frac{\mathrm{SNR}_{\mathrm{in}}}{\mathrm{SNR}_{\mathrm{out}}} = 1 + \left(\sum_{\nu=1}^{n}\frac{\mathrm{F}_\nu - 1}{\prod_{\nu'=1}^{\nu-1}\langle\gamma'_\nu\rangle}\right)\frac{\langle\zeta_{\mathrm{in}}\rangle}{\mathrm{Var}(\zeta_{\mathrm{in}})}. \tag{7}$$

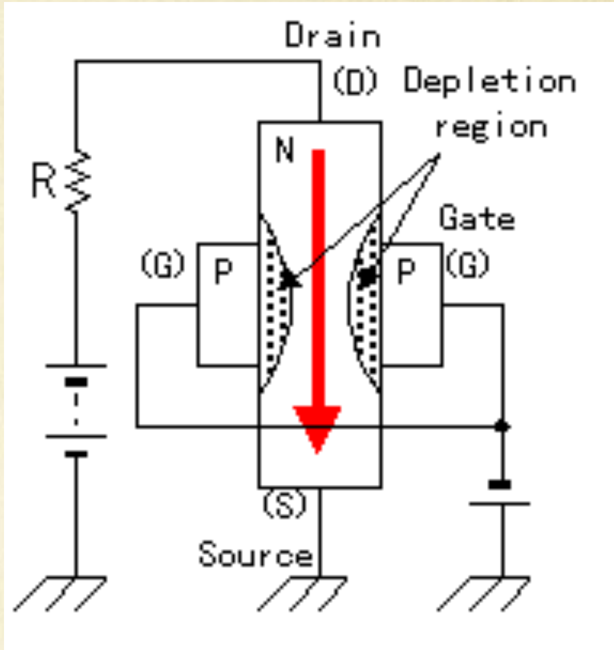
Here it is!

$$QL = \frac{h\nu}{k_B \ln 2}$$

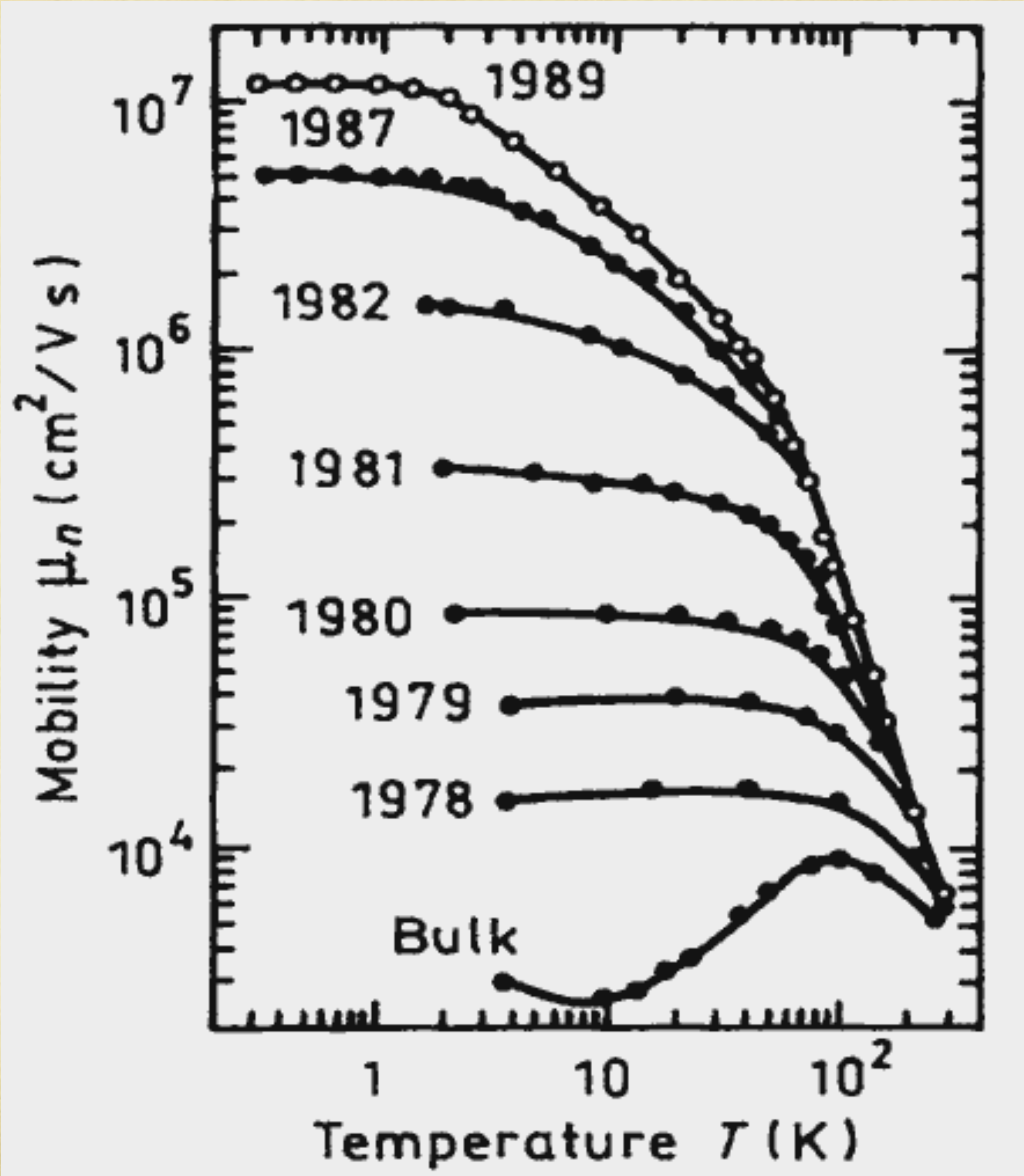
Amplifiers from the past







High frequency → Low noise → high carrier mobility

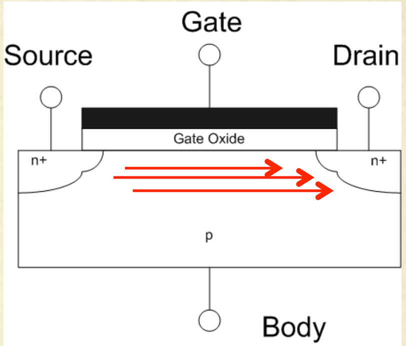


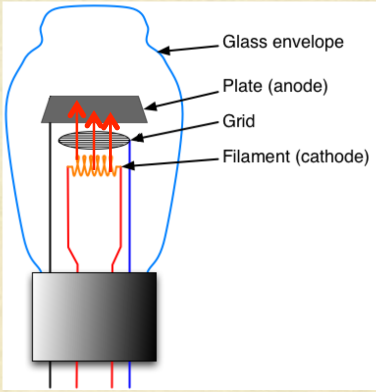
Mobility μ_n (cm^2/V s)
10^7
10^6
10^5
10^4
1989
1987
1982
1981
1980
1979
1978
Bulk
1
10
10^2
Temperature T (K)

2. High Electron Mobility Transistors (HEMTs)

- Mobility μ of electrons:
  $v = \mu E$

  $[\mu] = [cm^2 / (Vs)]$

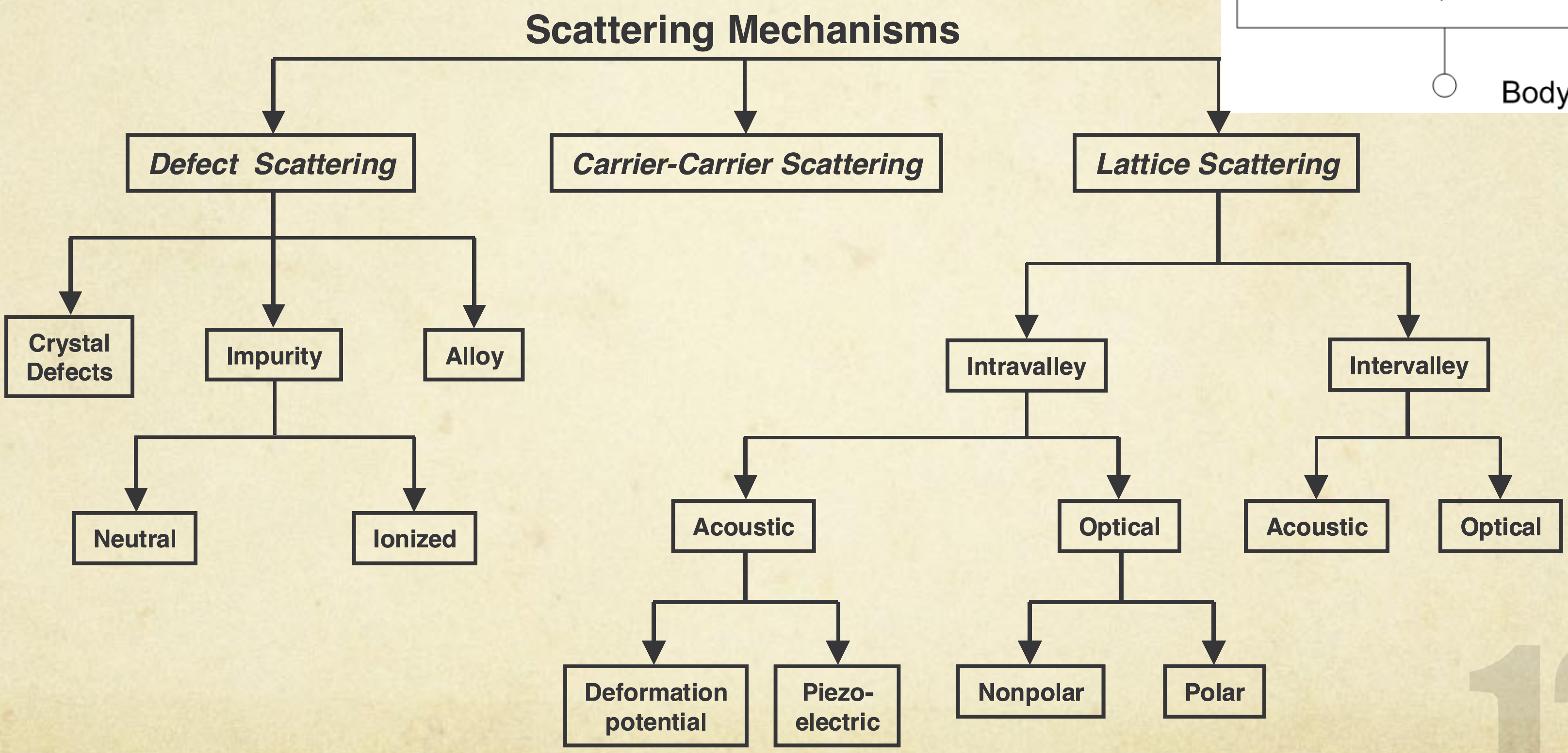


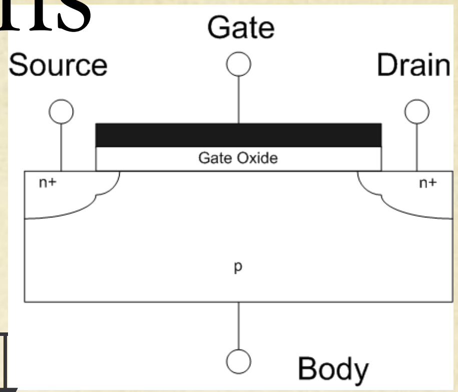


Material	Electron mobility (cm^2/Vs)	Hole mobility (cm^2/Vs)
GaAs	8000	320
GaP	110	70
InP	5600	150
Si	1360	460
Ge	3900	1900

Scattering mechanisms

- Scattering is important for noise





Scattering vs temperature (noise better at low temperatures?)

- Ionized impact scattering

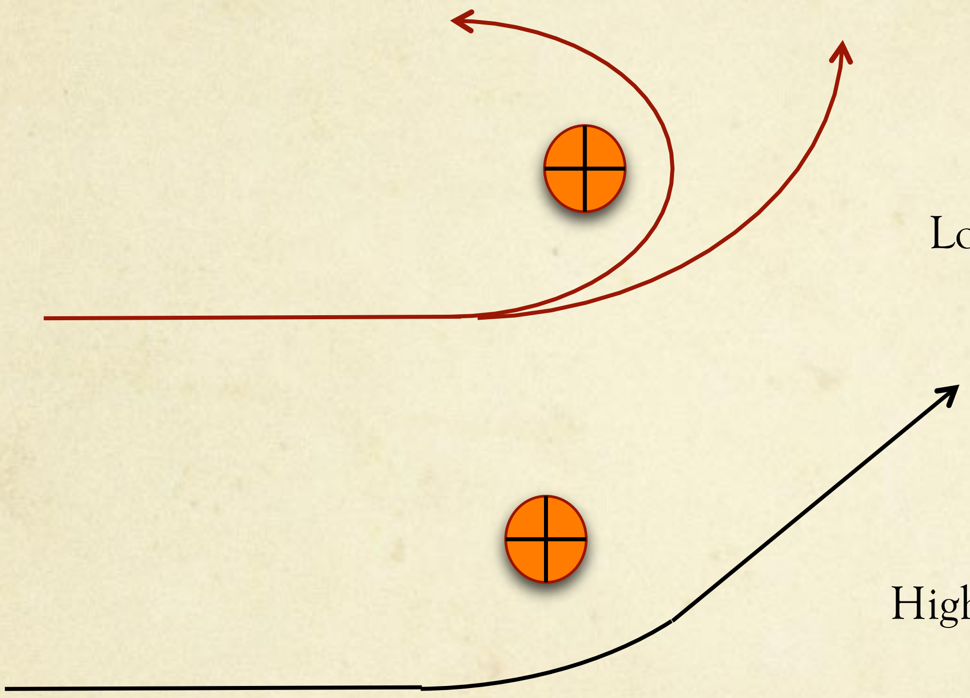
$$\mu_{II} \propto T^{3/2}$$

- Acoustic phonon scattering

$$\sigma \propto 1/\mu$$

$$\mu_{AC} \propto T^{-3/2}$$

Ionized Impact scattering

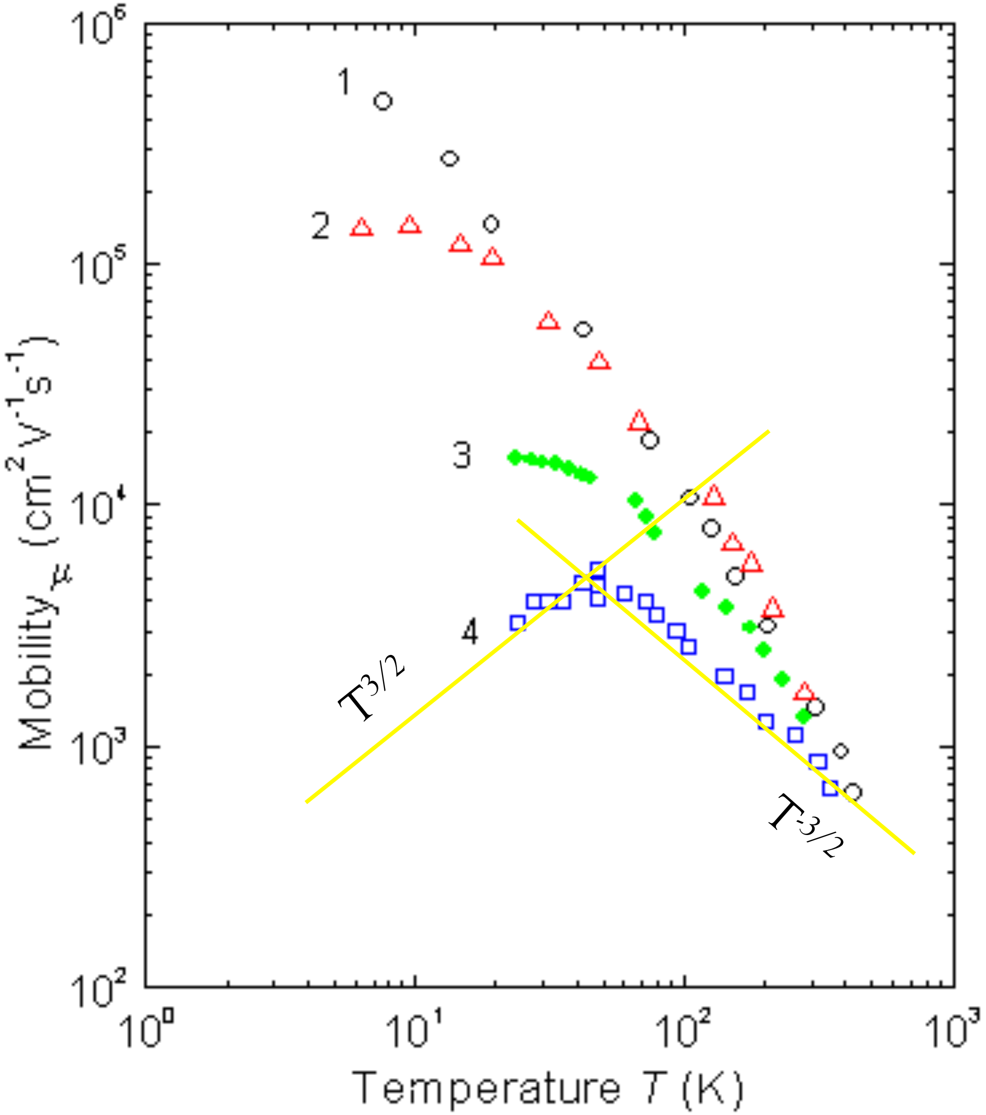


Low electron velocity

High electron velocity

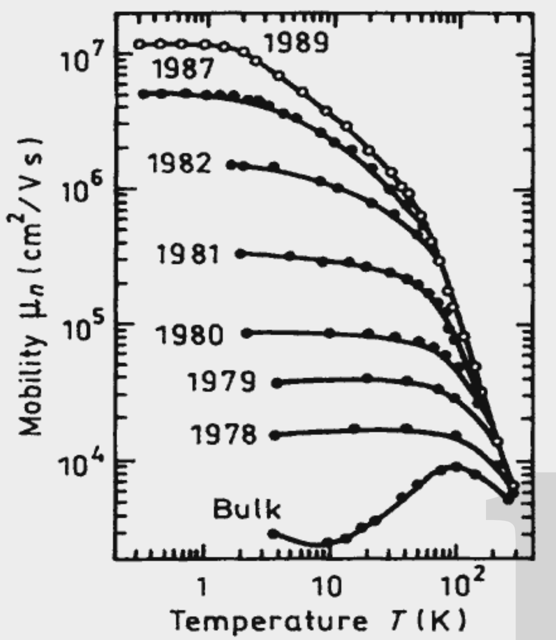
Higher temperature lower scattering

Doping concentration and mobility versus temperature



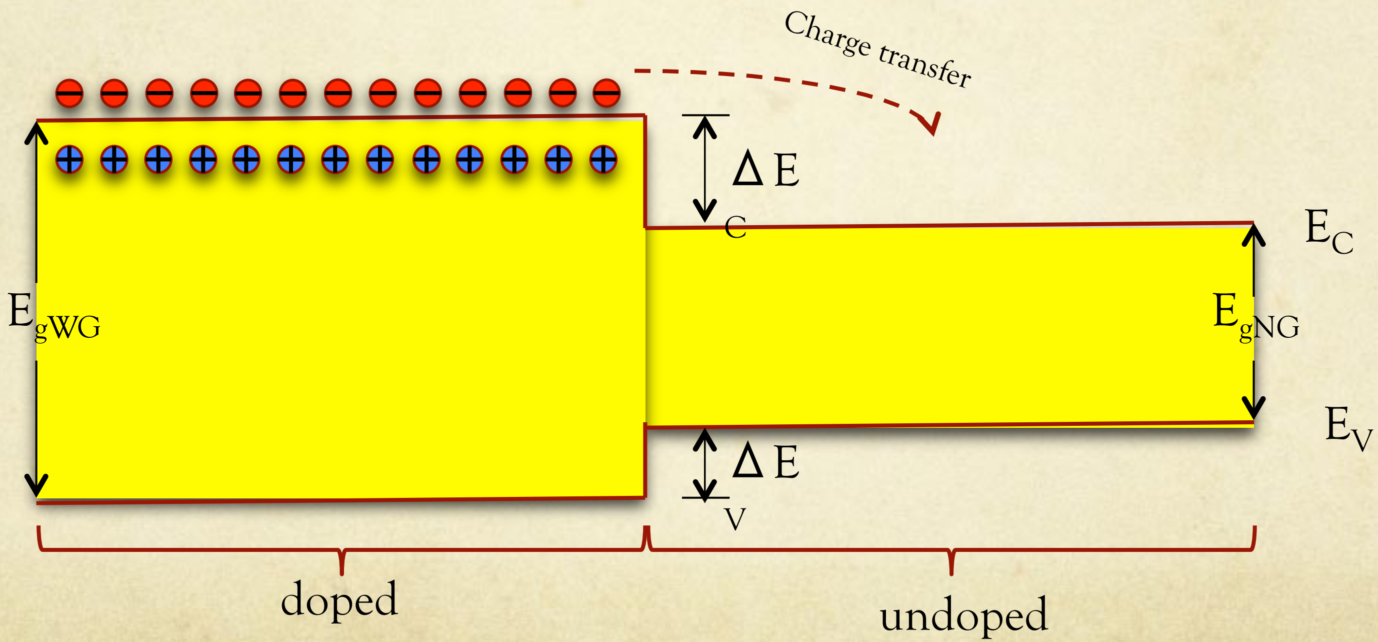
High purity Si
1: N = 10^{12} cm^{-3}
2: N = 10^{14} cm^{-3}
3: N = 2.3 10^{15} cm^{-3}
4: N = 4.9 10^{15} cm^{-3}

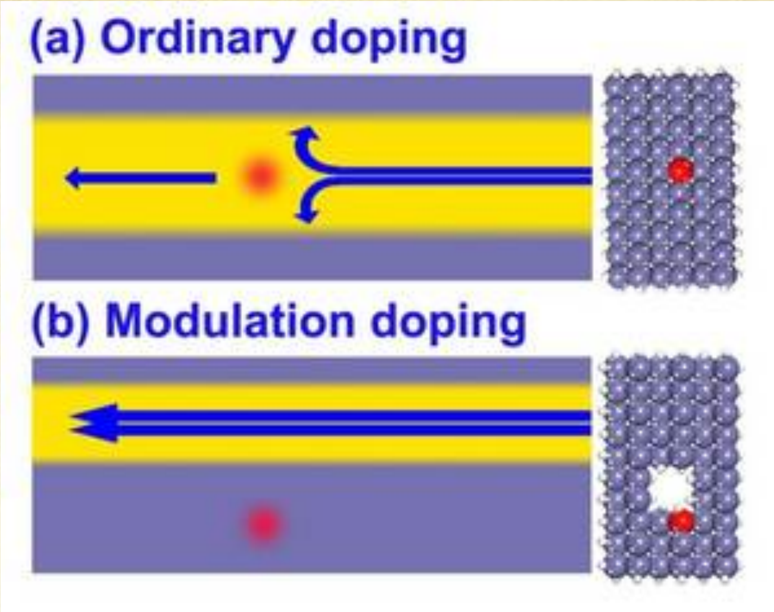
Penalty in mobility when doping concentration increases!

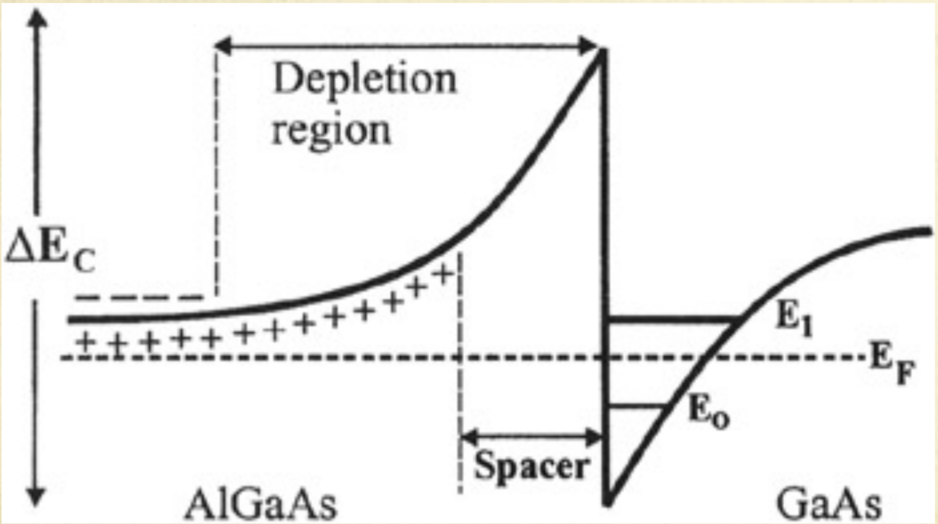


- We need carriers! Is there a way to avoid the mobility penalty as the doping concentration increases?

- YES! Modulation doping: a mechanism that produces a 2D electron gas with high carrier mobility

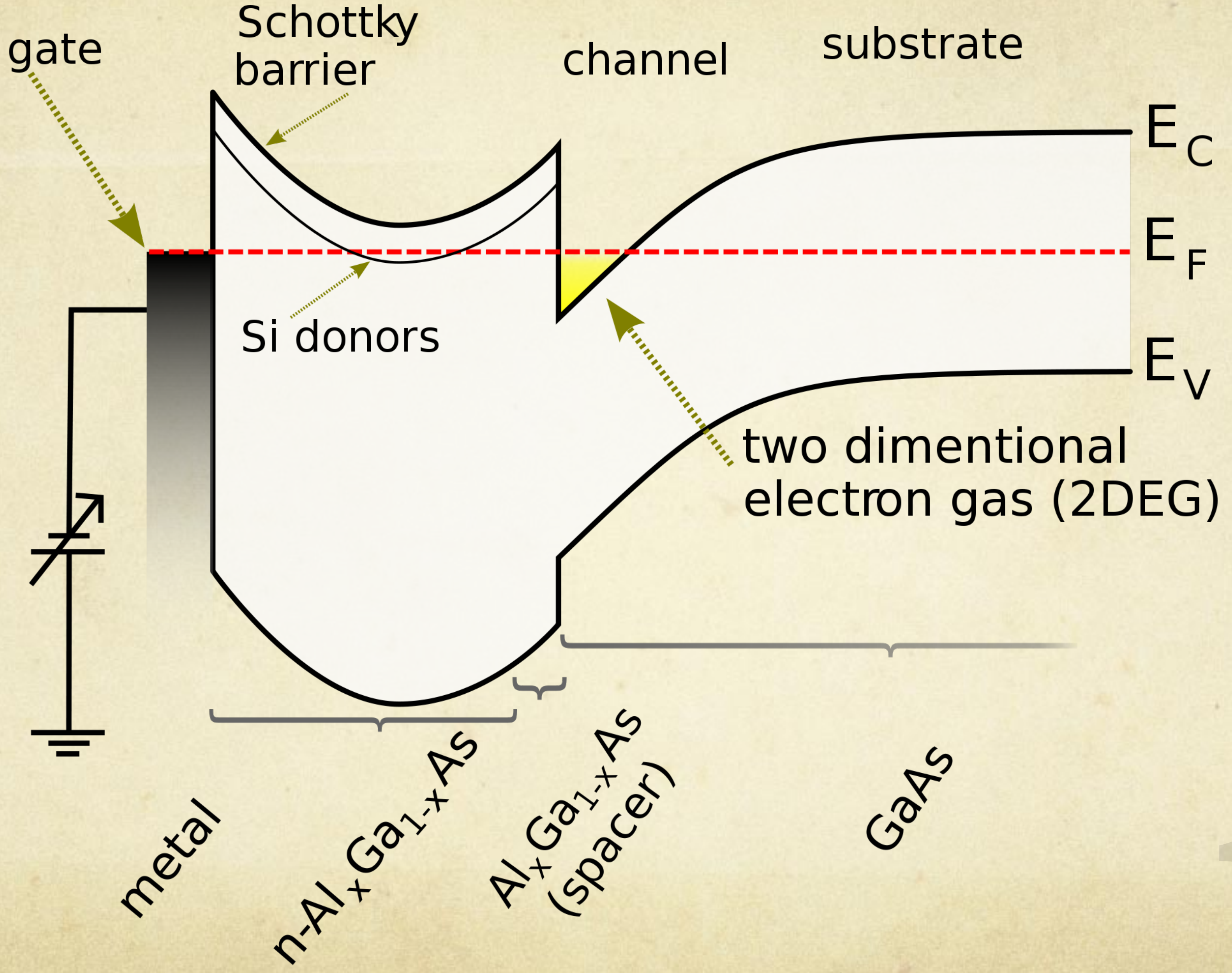




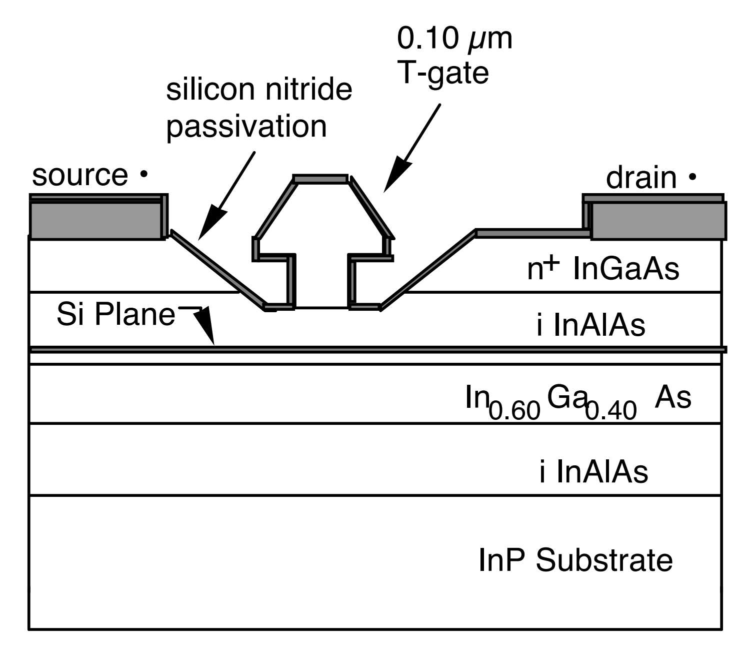


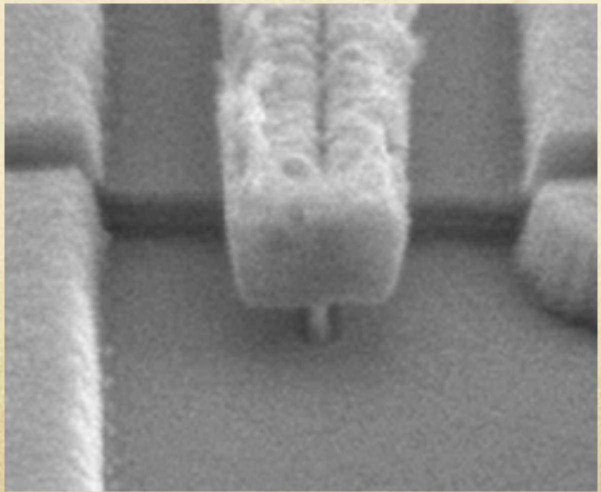
Electrons are spatially separated by donors thus reducing the ionized impurity scattering

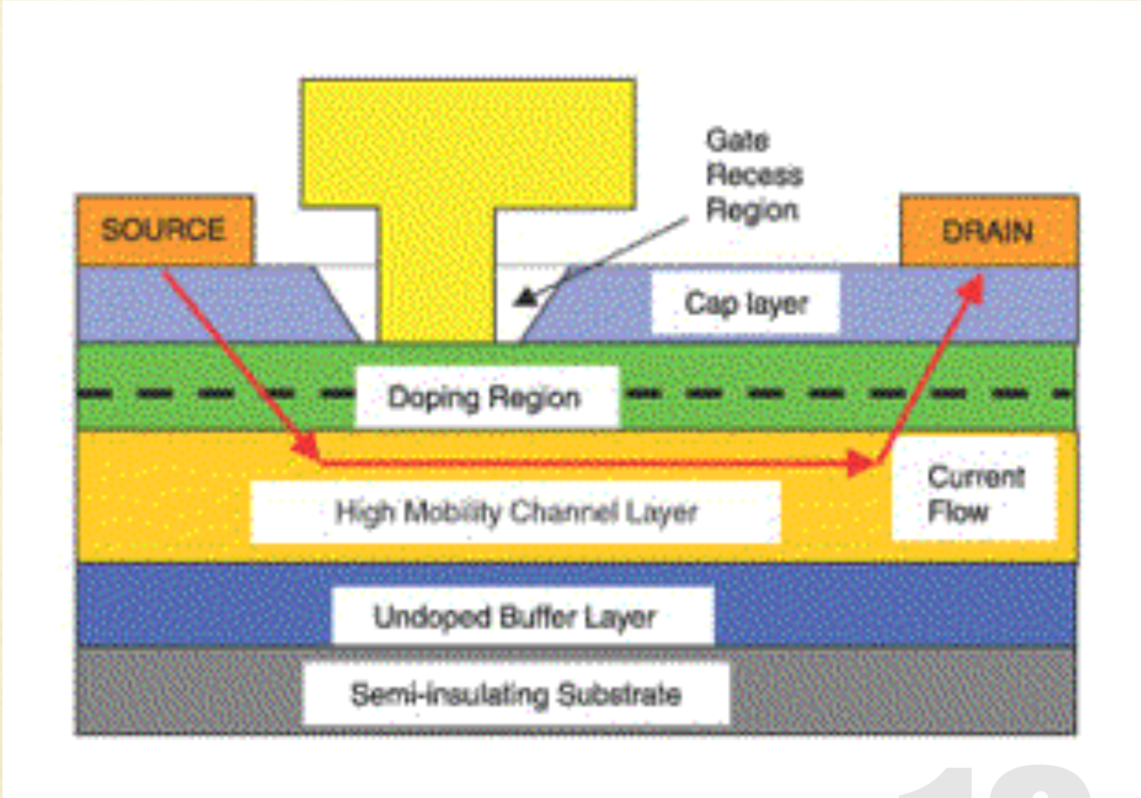
Band bending results as a consequence of the charge transfer and a 2D electron gas is generated with very high mobility. The spacer increases the separation between donors and electrons.


gate
Schottky barrier
channel
substrate
E_C
E_F
E_V
Si donors
two dimentional electron gas (2DEG)
metal
n-$Al_xGa_{1-x}As$
$Al_xGa_{1-x}As$ (spacer)
GaAs

Section of a HEMT







NOISE in FETs

- For good low-noise devices:
  - Good pinch-off
  - Low parasitics R_g, R_s
  - High g_m

$$T_{\min} = K \cdot \omega \cdot C \sqrt{\frac{t(R_g + R_s)}{g_m} + \frac{K_r}{g_m^2}}$$

K, K_r : noise coefficients

R_g : gate resistance

R_s : series resistance including ohmic contacts and channel resistance

$t = T_a/290$

g_m : transconductance

Low Noise Amplifiers

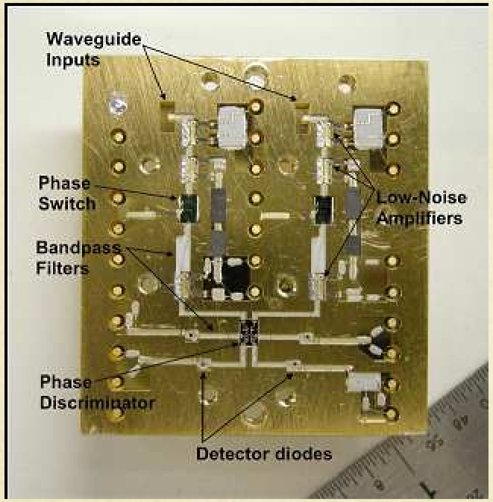
- Use HEMTs
- We characterize them with the radiometer formula:

$$\Delta T_{rms} = \frac{T_{sys}}{\sqrt{\Delta \nu}} \qquad \mathrm{K}/\sqrt{Hz}$$

$$\Delta T_{rms} = \frac{T_{sys}}{\sqrt{2 \cdot \Delta \nu}} \qquad \mathrm{K} \cdot \sqrt{\sec}$$

Inside an LNA

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



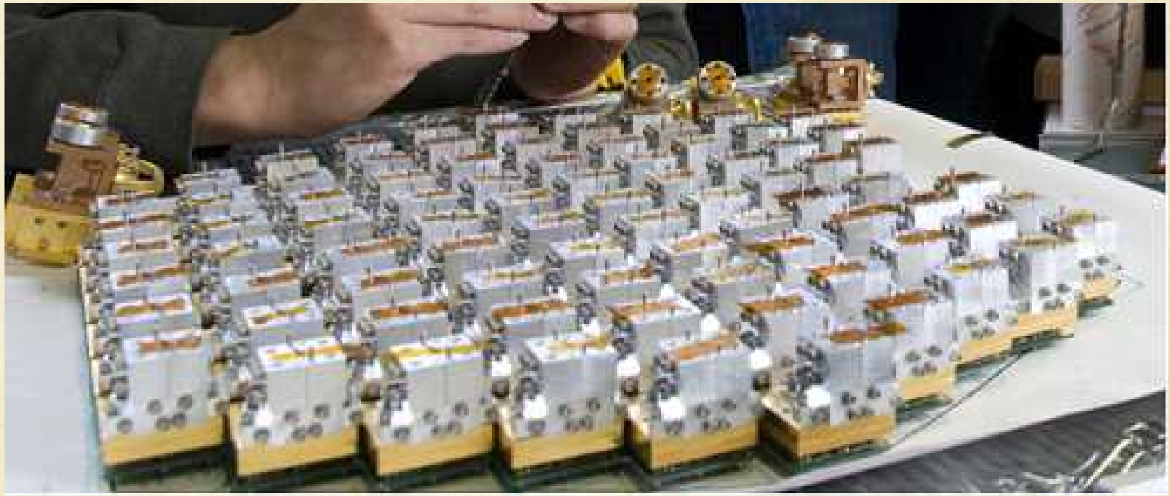
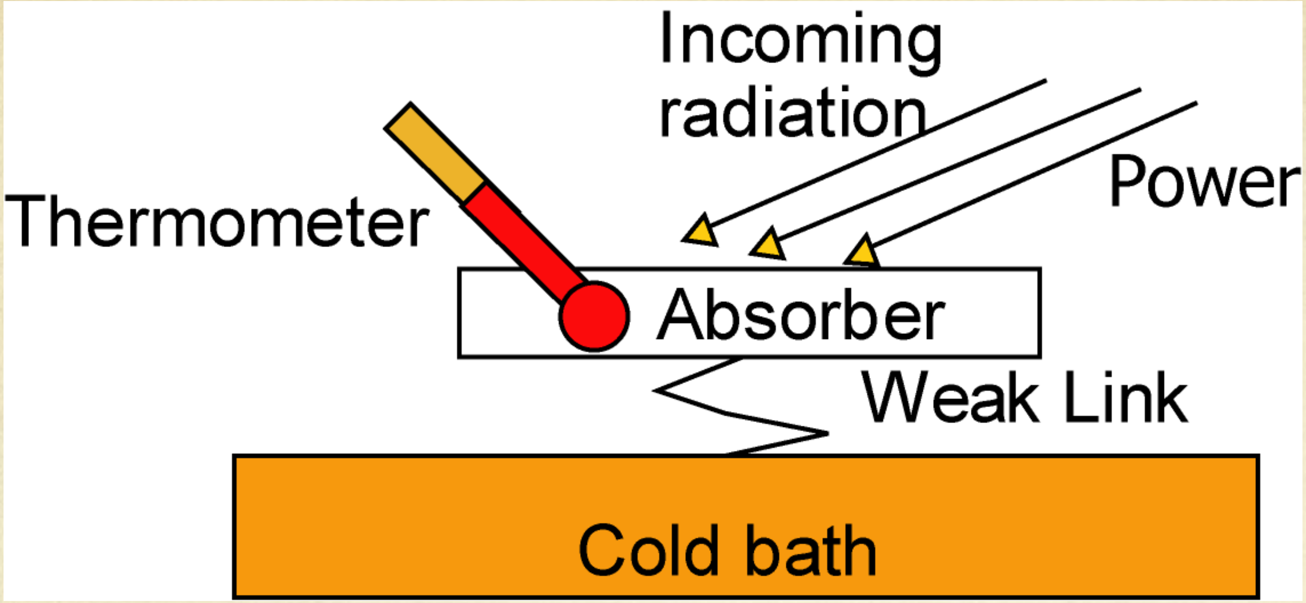
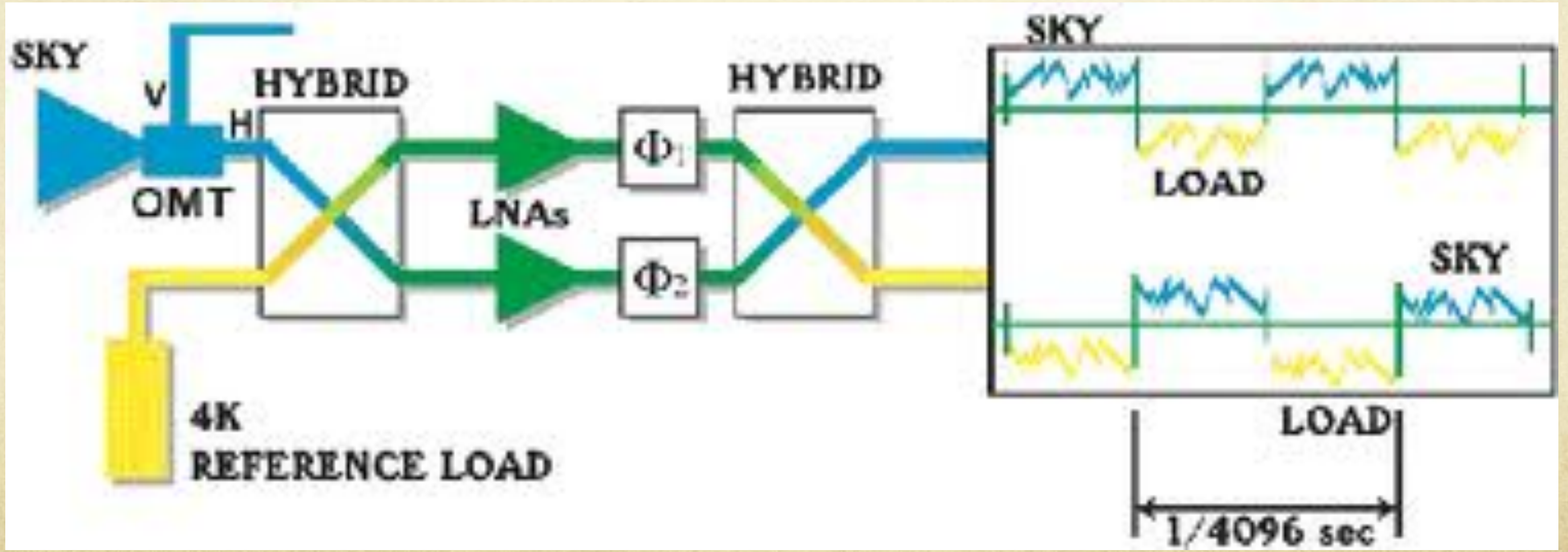


Figure 1: A 95-GHz module with the radiometric components integrated (left) and the 90-element 95-GHz array under assembly (right).


Incoming
radiation
Power
Thermometer
Absorber
Weak Link
Cold bath


SKY
V
H
HYBRID
OMT
LNAs
HYBRID
SKY
LOAD
SKY
LOAD
4K
REFERENCE LOAD
1/4096 sec

Let's compare the noise

1 x QL

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

Frequency	**PLANCK HFI NET/feed**[a]	**Bolometer NET/feed**[b]	**3xQL HEMT $2^{-1/2}$ NET/feed**[c]	1 x QL	**CMB BLIP NET/feed**[d]
[GHz]	**[μK_{CMB} sec$^{1/2}$]**	**[μK_{CMB} sec$^{1/2}$]**	**[μK_{CMB} sec$^{1/2}$]**		**[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 ΔT = (ΔTx+ΔTy)/2 and Stokes parameter Q **or** U, defined as (ΔTx-ΔTy)/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

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

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

From J. Bock, "Polarimetry in Astronomy", 2003

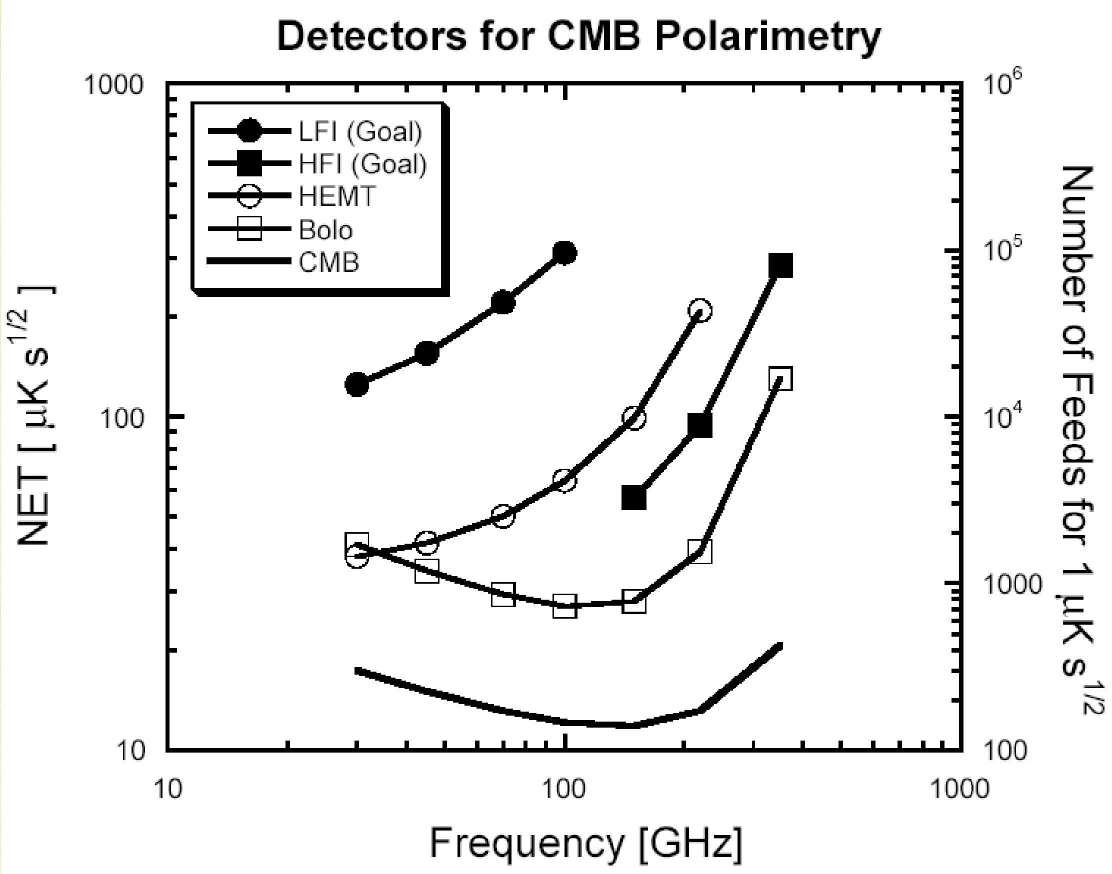


Figure 4: Sensitivity of bolometer- and HEMT-based receiver systems for CMB polarimetry. The goal sensitivities per feed for Planck LFI (HEMT-based, solid circles) and Planck HFI (bolometer-based, solid squares) in polarization-sensitive channels. The sensitivity achievable with 100 mK bolometers, assuming 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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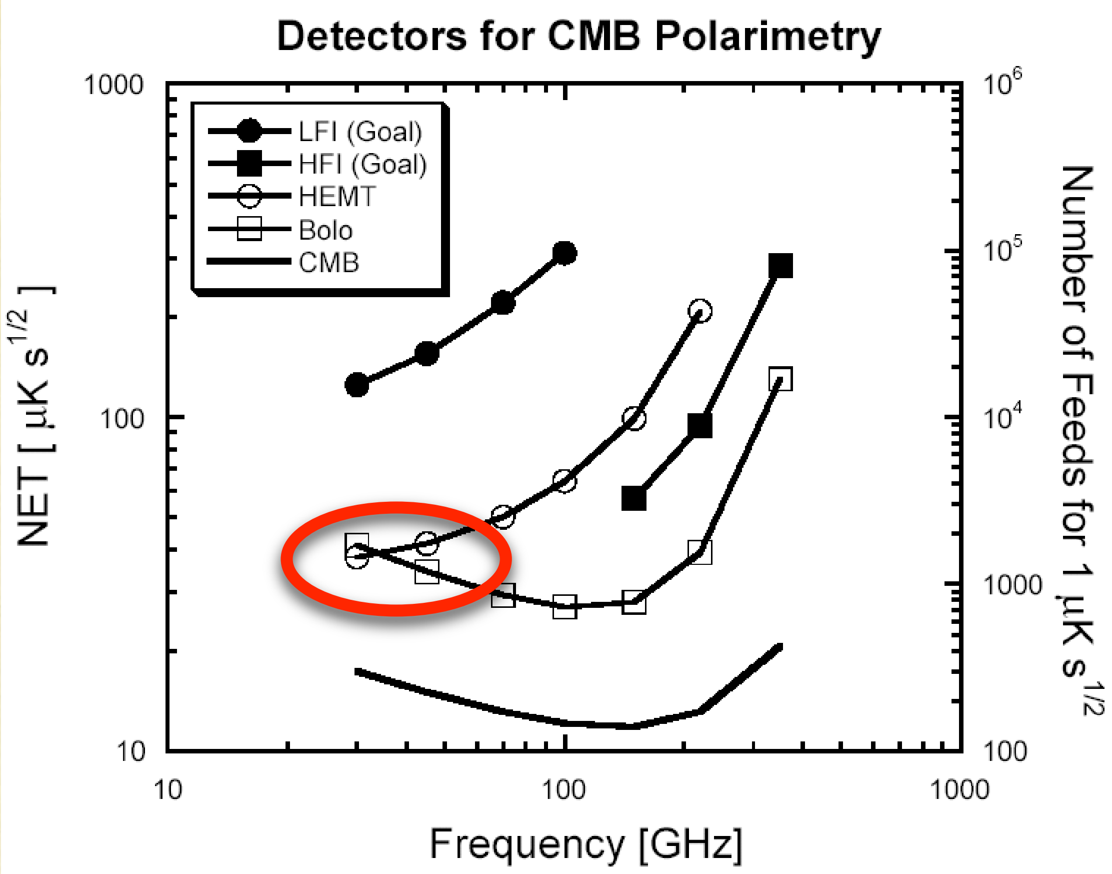

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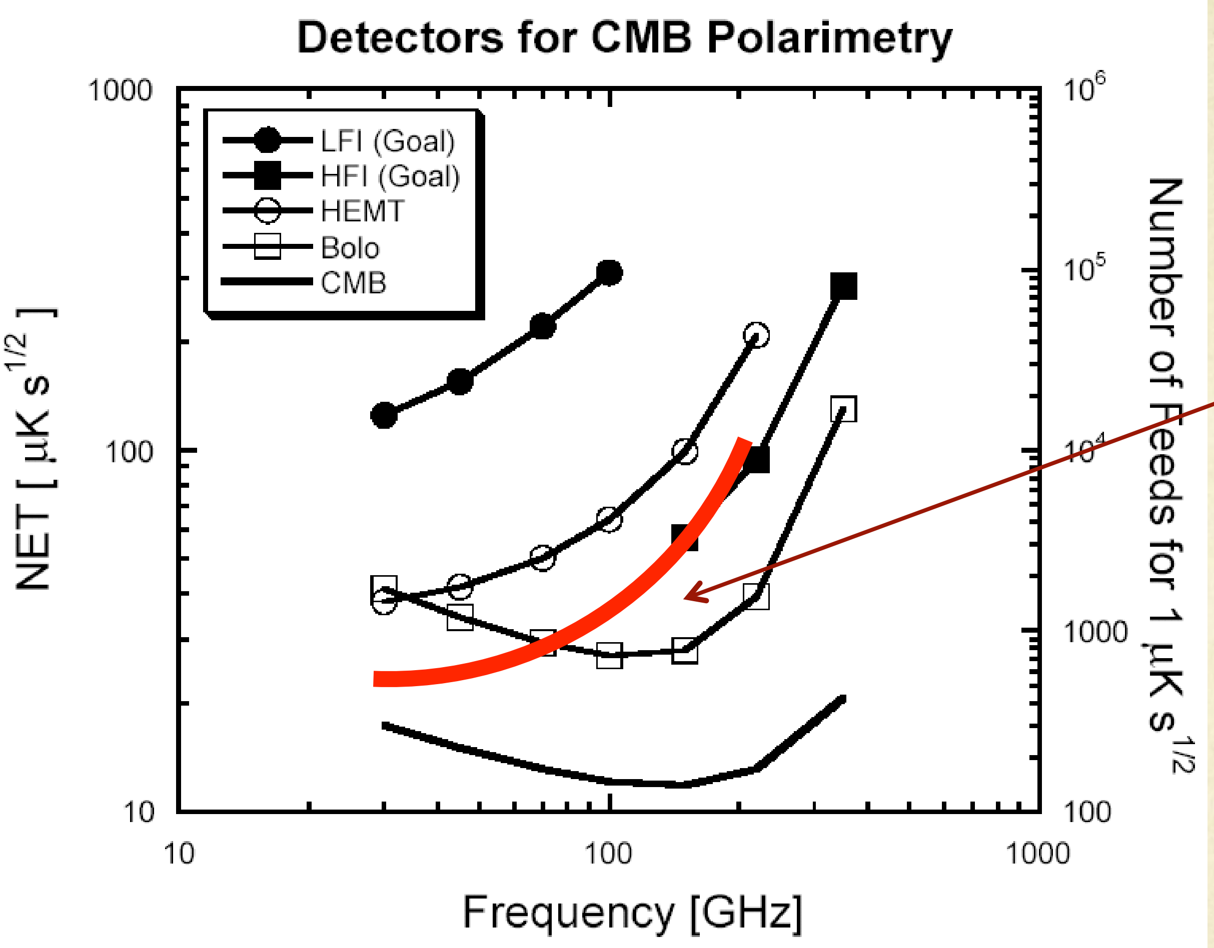
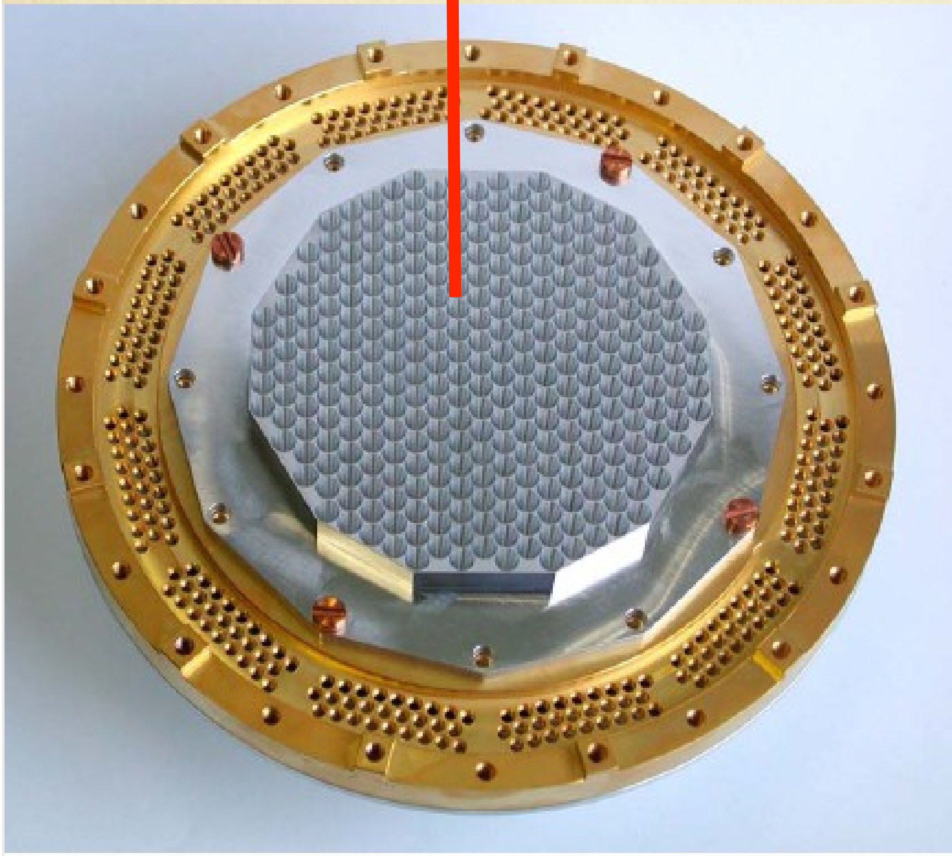
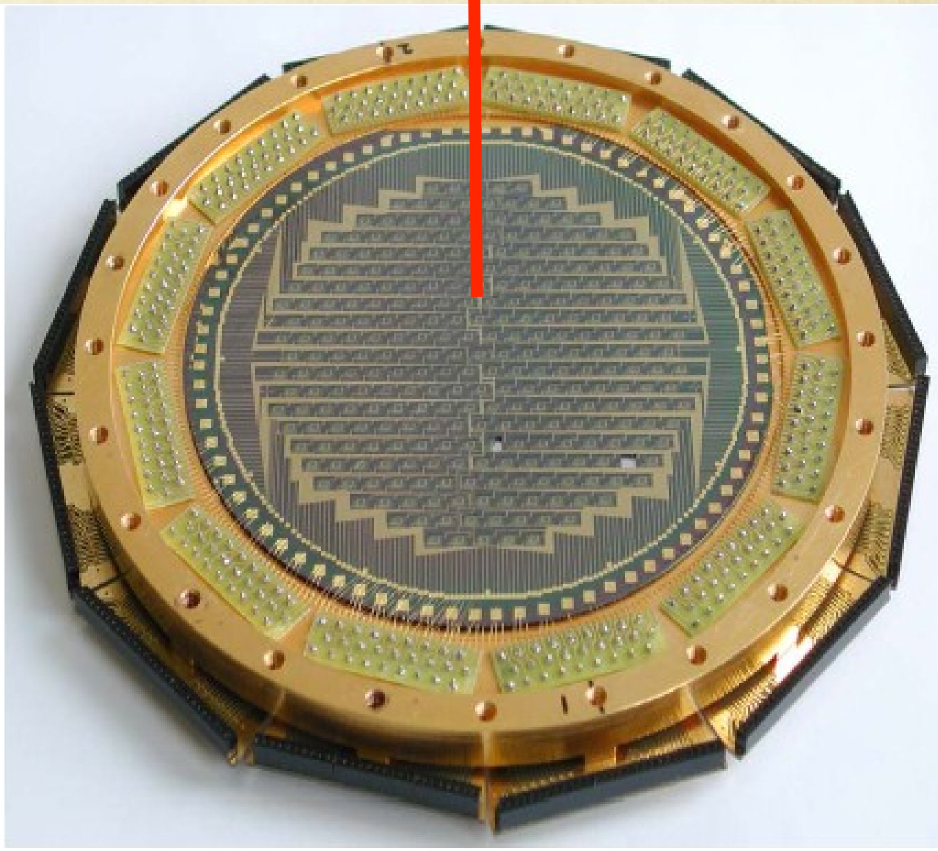


~ quantum limit!

SKY

Optics and then SKY





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

And now…
A few interesting instruments

3. HF Gravitational waves

- Ground or space interferometers
- Pulsars
- CMB B-modes

- What about different frequencies… like very high frequencies?

Gravitational Wave Frequency Ranges

- Strong science cases- well understood technology
  - Pulsar timing ~10^{-8} Hz
  - LISA/DECIGO $10^{-4} – 10^{-2}$ Hz
  - Advanced LIGO $10^{2} – 5 \times 10^{3}$ Hz

  } First Detections?

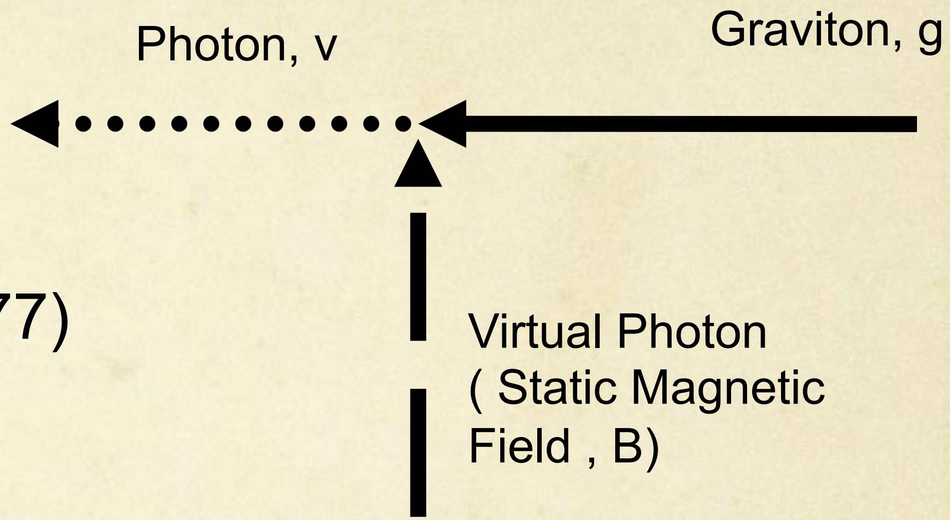
- Emerging science cases- new technology
  - Microwave Frequencies $10^{8} – 10^{10}$ Hz
  - IR and Optical Frequencies $10^{12} – 10^{15}$ Hz or higher

Possible Sources at Very High Frequencies ?

- Early Universe
  - *Garcia-Bellido, Easther, Leblond, etc*
- Kaluza-Klein modes from Black Holes in 5-D gravity
  - Seahra, Clarkson and Maartens, Clarkson and Seahra
- EM-GW mode conversion in magnetised plasmas
  - Servin and Brodin

Detector Possibilities

- Laser interferometers lose sensitivity as n increases
- Use Graviton to Photon conversion in B Field
- De Logi and Mickelson (1977)
- Cross section for g → v



$$\Gamma = \frac{8\pi G B^2 L^2}{c^3} \sum \text{Spin states of g, B and v}$$

B is magnetic field, *L* is path length

What are the fluxes ?

- Cross Section G is small due to G/c^3 factor but this is per incoming graviton

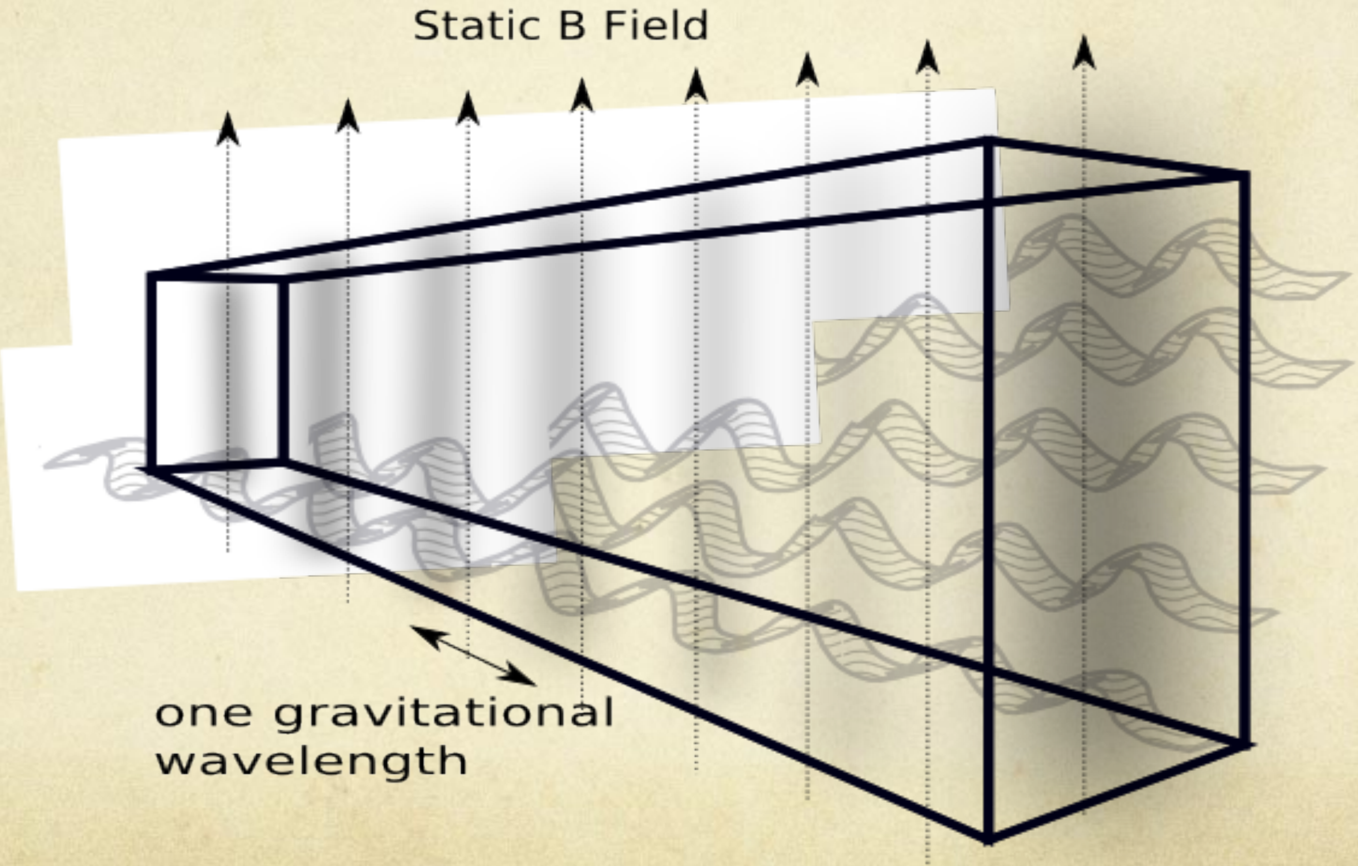
- Flux of gravitons is large due to c^2/G factor

$$Photon\ Flux = \Gamma \frac{c^2}{16\pi G}\omega_{gw}^2 h^2 \frac{1}{\hbar\omega_{gw}}$$

- Signal Power is $$P_{EMW} = \frac{1}{8\mu_0} B^2 L^2 K_{gw}{}^2 h^2 c Sin^2(\alpha)$$

Conversion GW → e.m waves

Inverse-Gertsenshtein effect



Conversion GW → e.m waves

- Need smart transducer

  GW →EMW → waveguides → LNA → detection, or

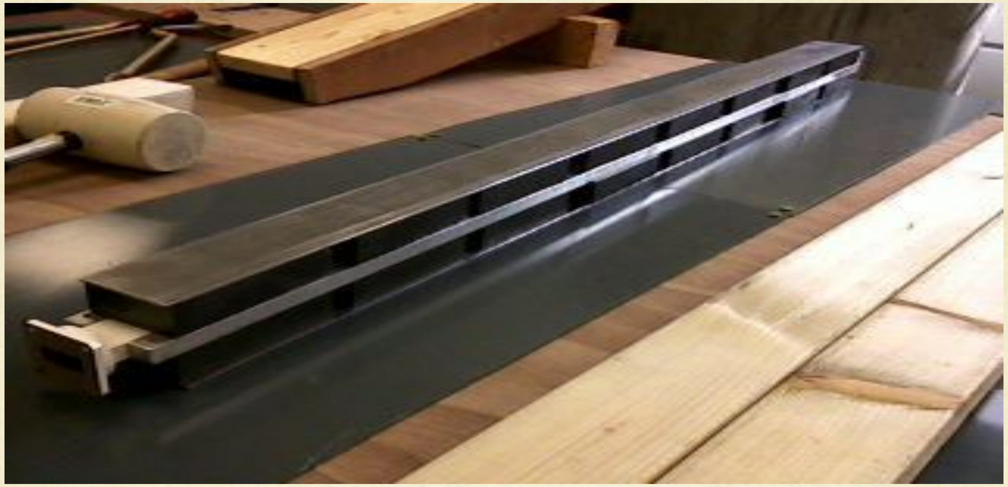
  GW →EMW → lenses → CCD → detection

- With EMW's we can use standard techniques

- Correlation receiver for a single baseline GW detector or an imaging detector at optical wavelengths

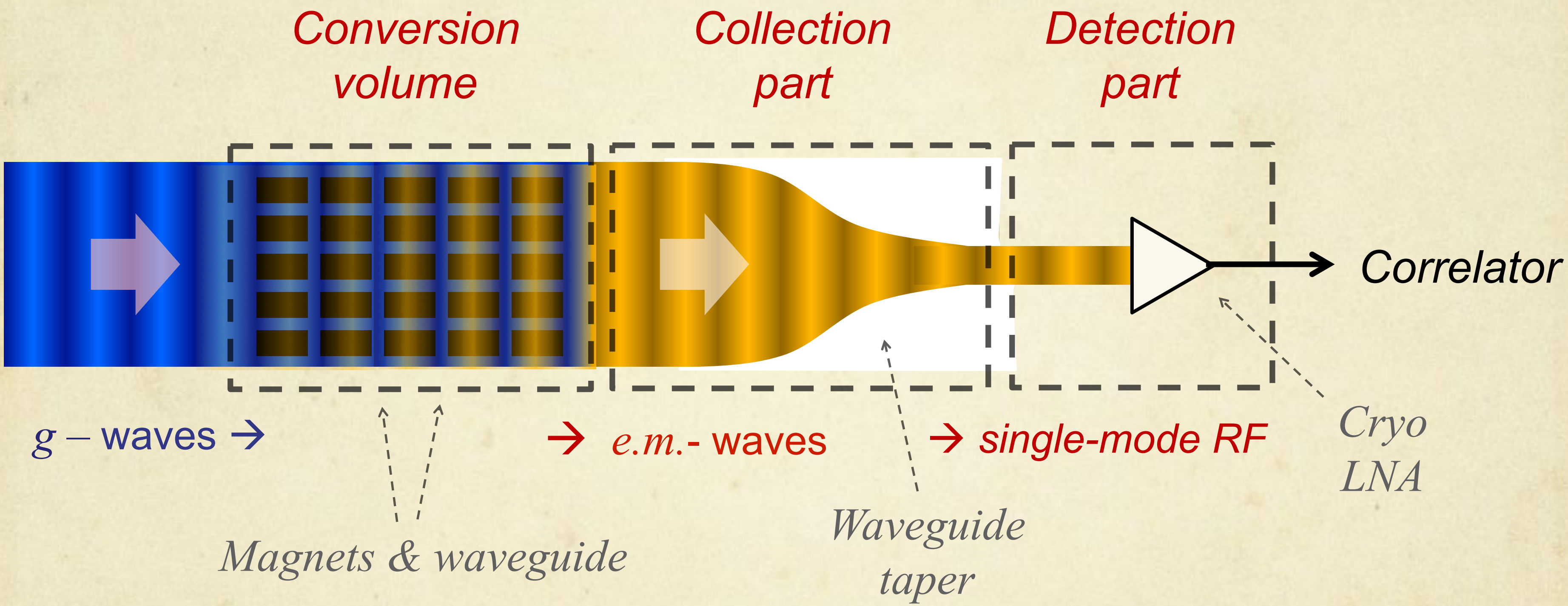
Instrument angular-acceptance/beam

- First tests at Birmingham create EMW's completely inside single mode waveguide- simple geometry

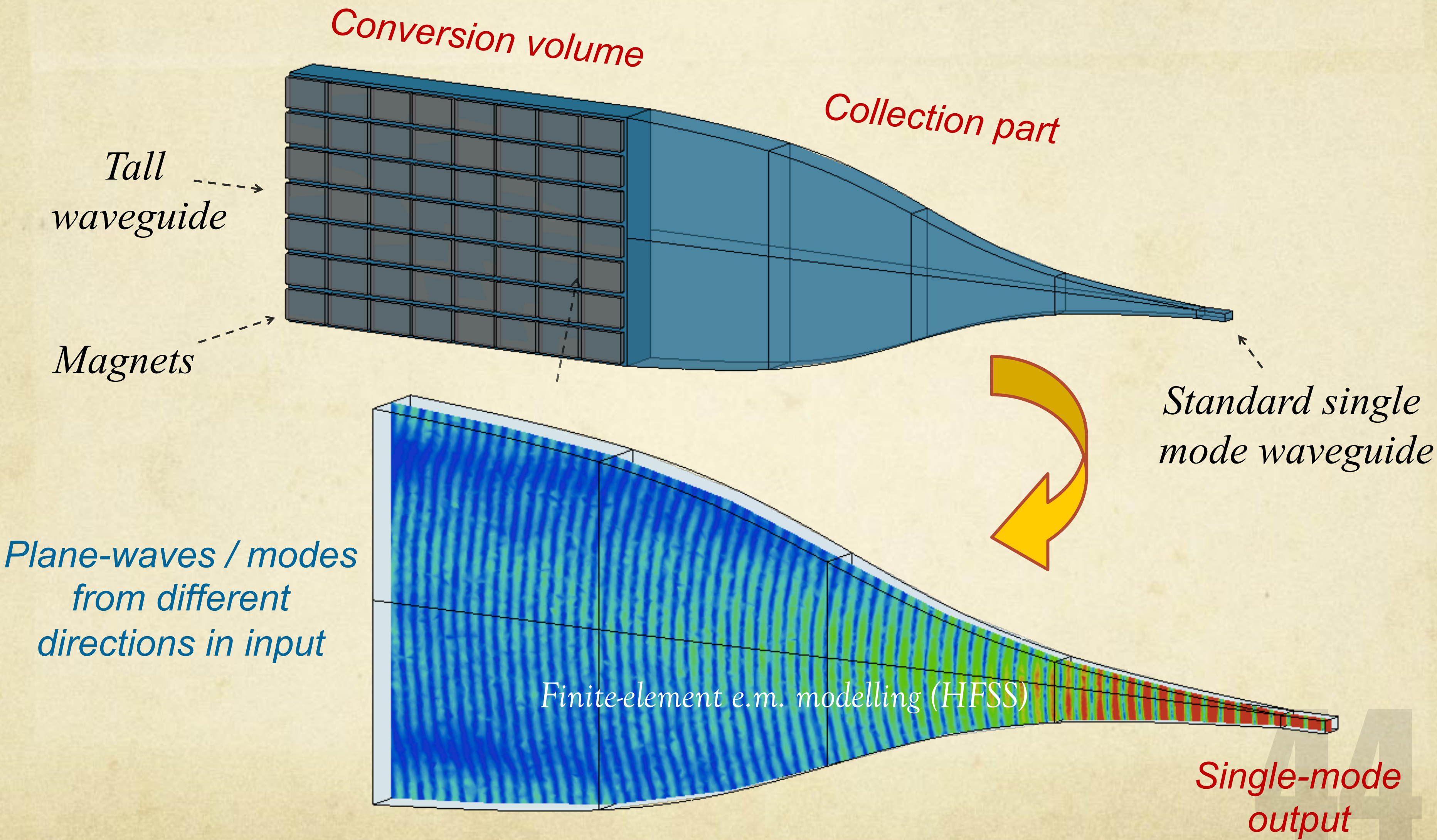


- New detector requires GW-EMW conversion **outside** modified waveguide and at **many angles**

New instrument concept



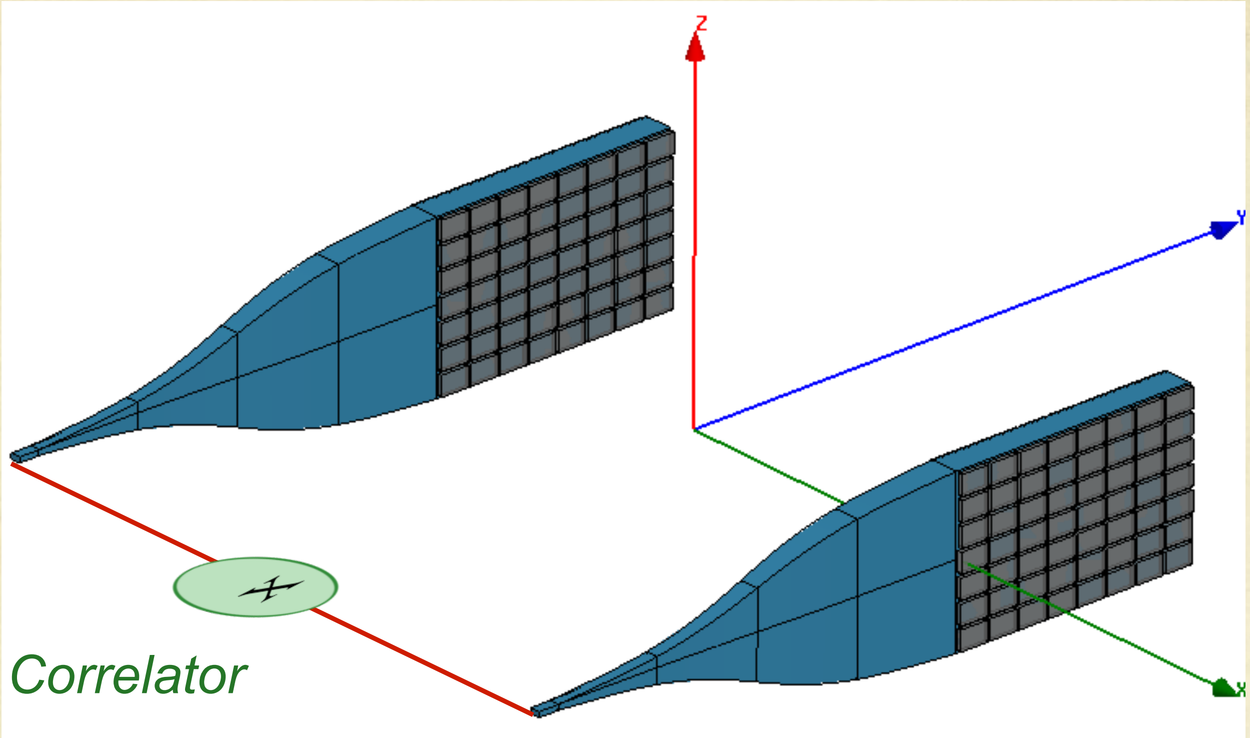
Collection part



New Detector- microwave

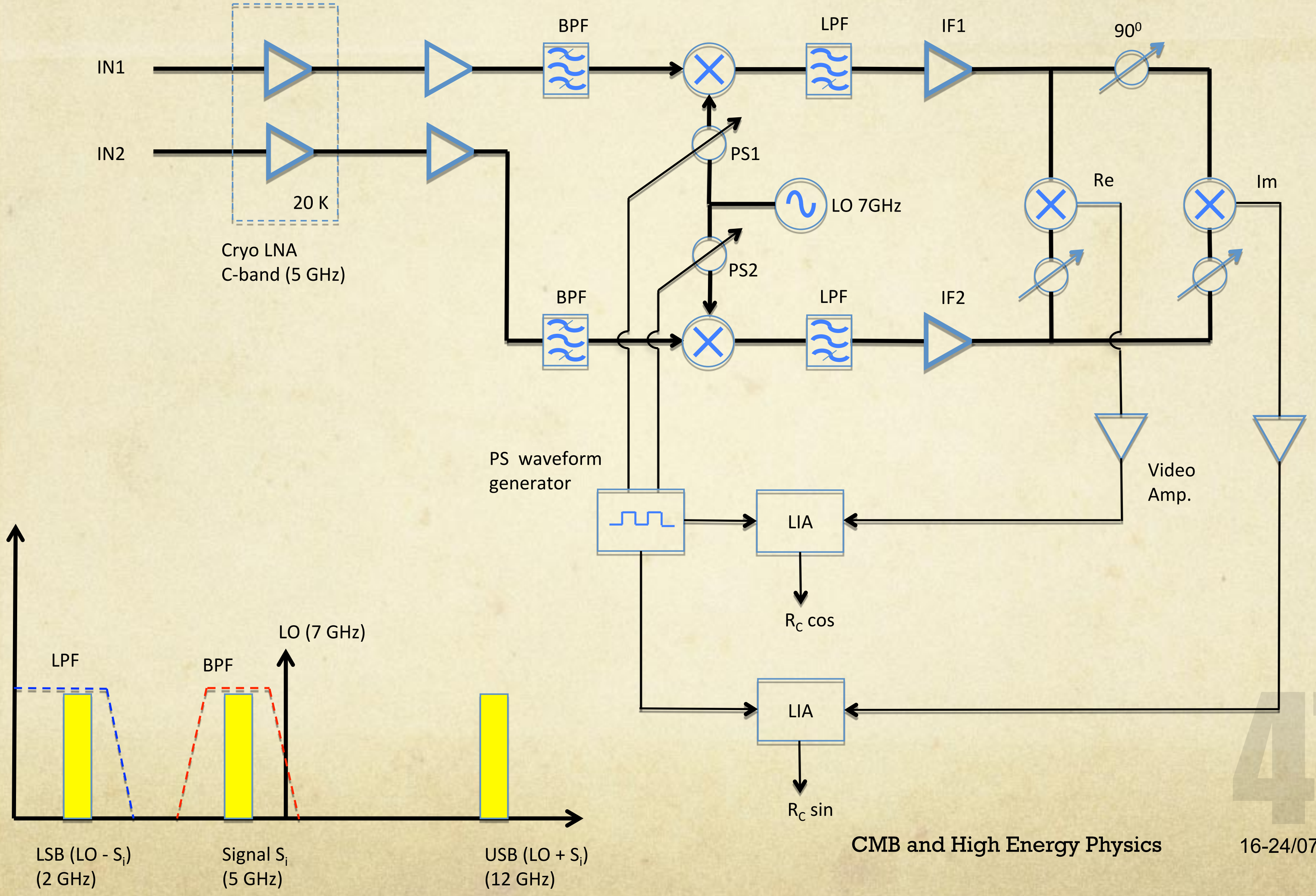
- Partial list of problems:
  - Conversion plane-wave → waveguide modes
  - Waves from different directions → Mismatch with the main waveguide mode
  - Gradient of e.m. intensity along conversion volume
  - Magnetic field projection effects
  - Difference in waveguide phase-velocity
  - Multiple reflections inside the waveguide structure
  - Etc…

GW Correlation Receiver

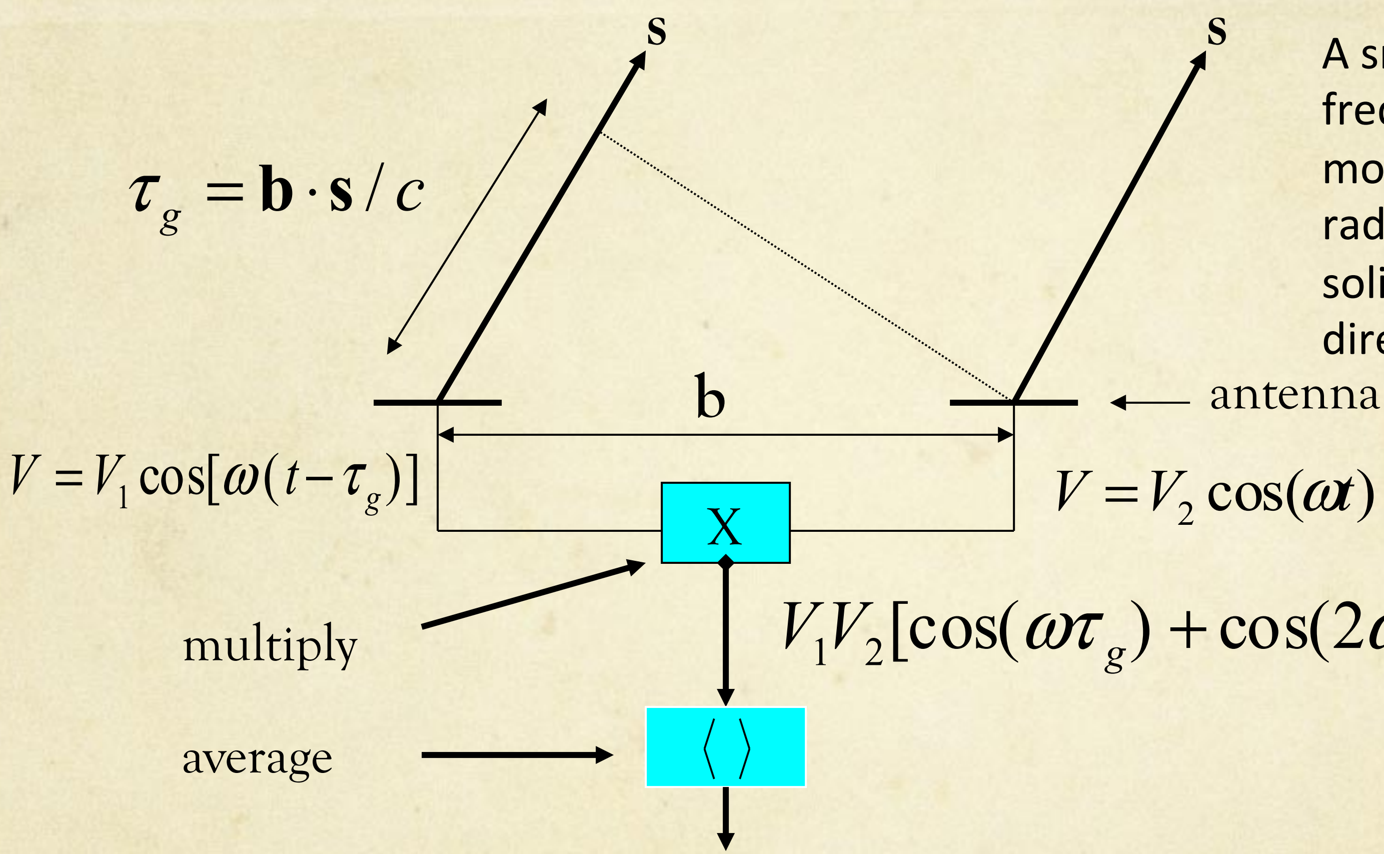


- Sensitivity increase
- Narrower beam in the z direction
- …

Correlation receiver circuitry



Correlation receiver
B' ham/M' cr GW prototype experiment

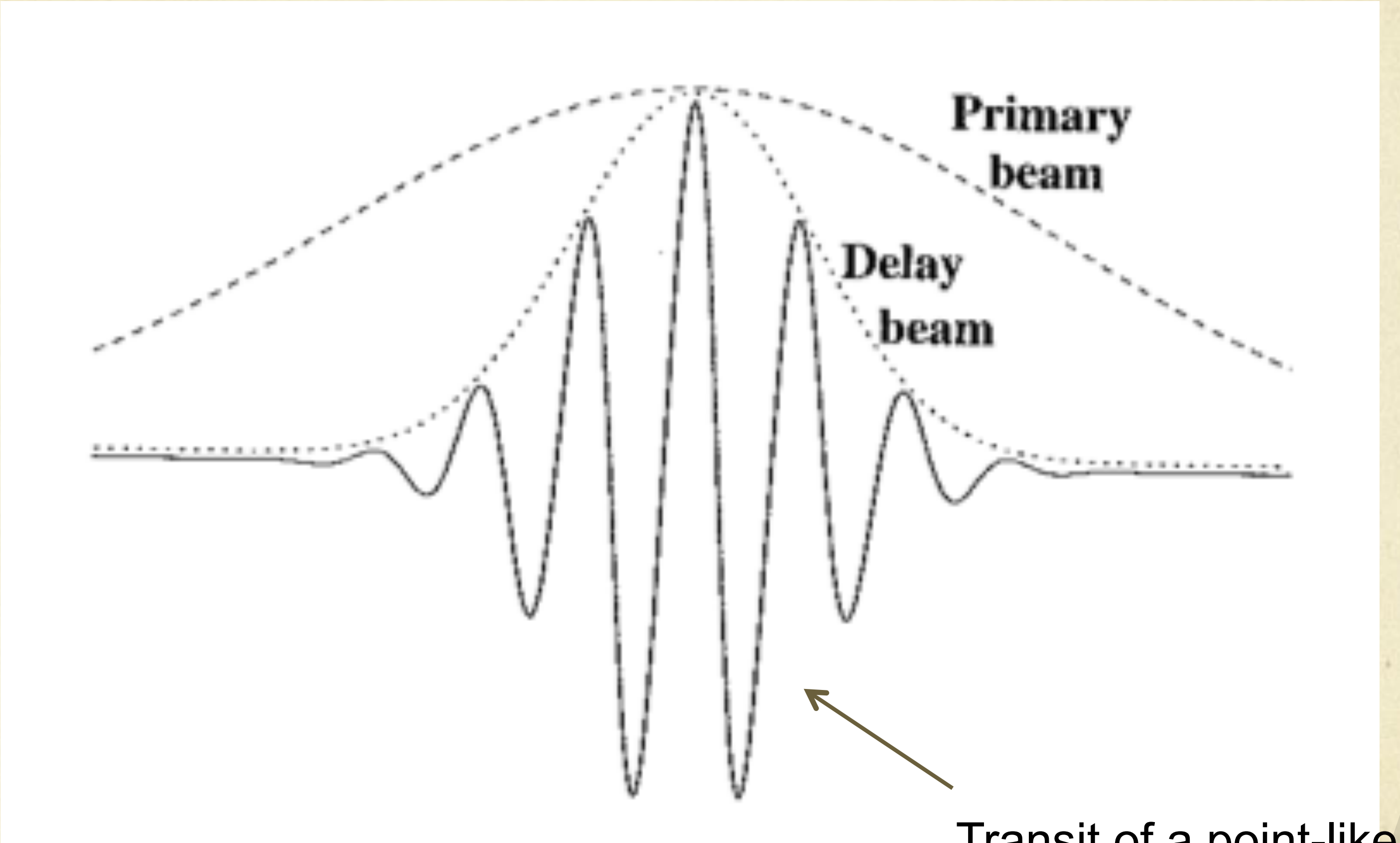


A small (but finite) frequency width, and no motion. Consider radiation from a small solid angle dW, from direction **s**.

$$V_1 V_2 [\cos(\omega\tau_g) + \cos(2\omega t - \omega\tau_g)]/2$$

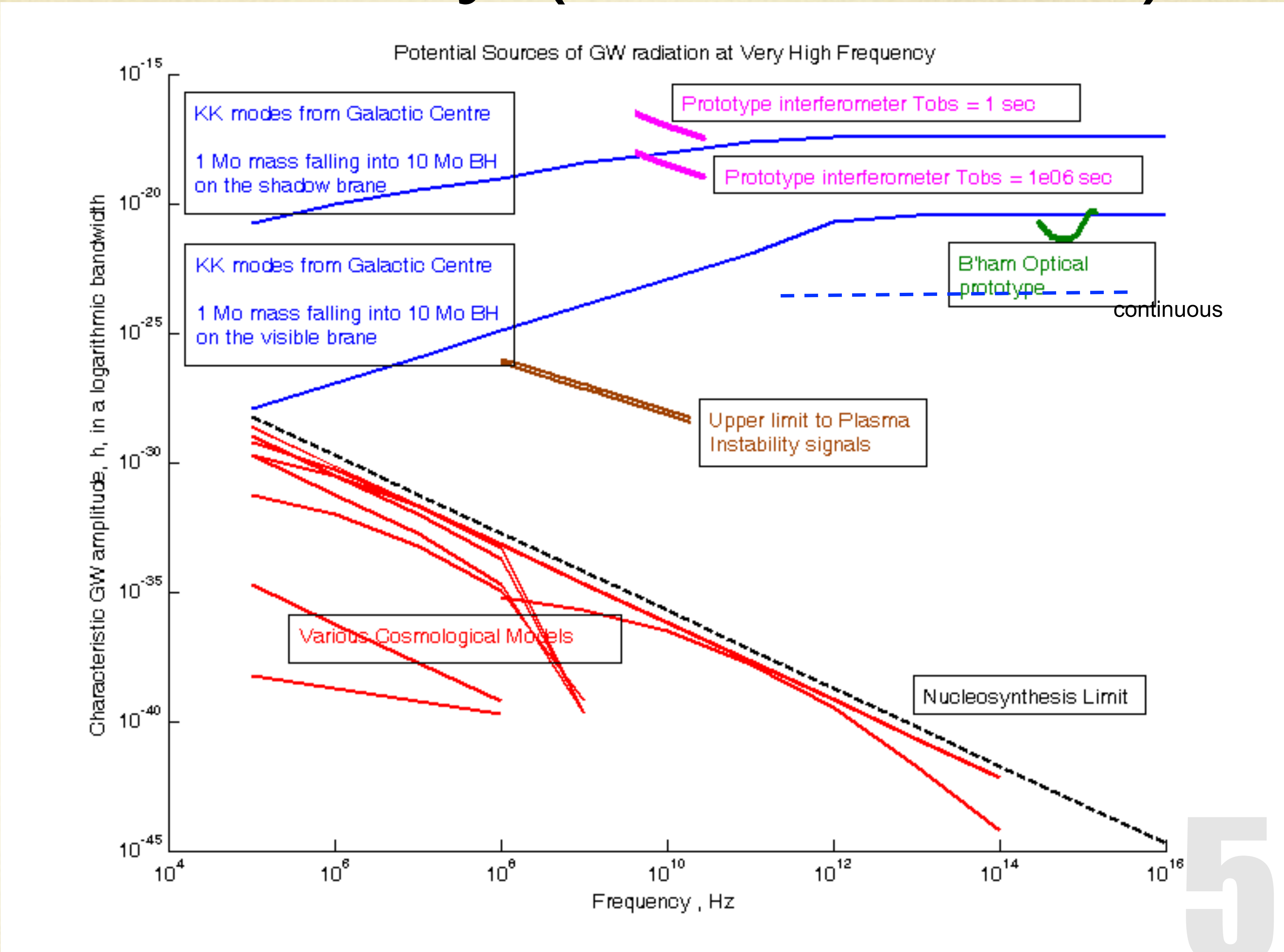
Cosine output $R_c = [V_1 V_2 \cos(\omega\tau_g)]/2 = [V_1 V_2 \cos(2\pi\upsilon \mathbf{b} \cdot \mathbf{s}/c)]/2$

Synthesizing beams…



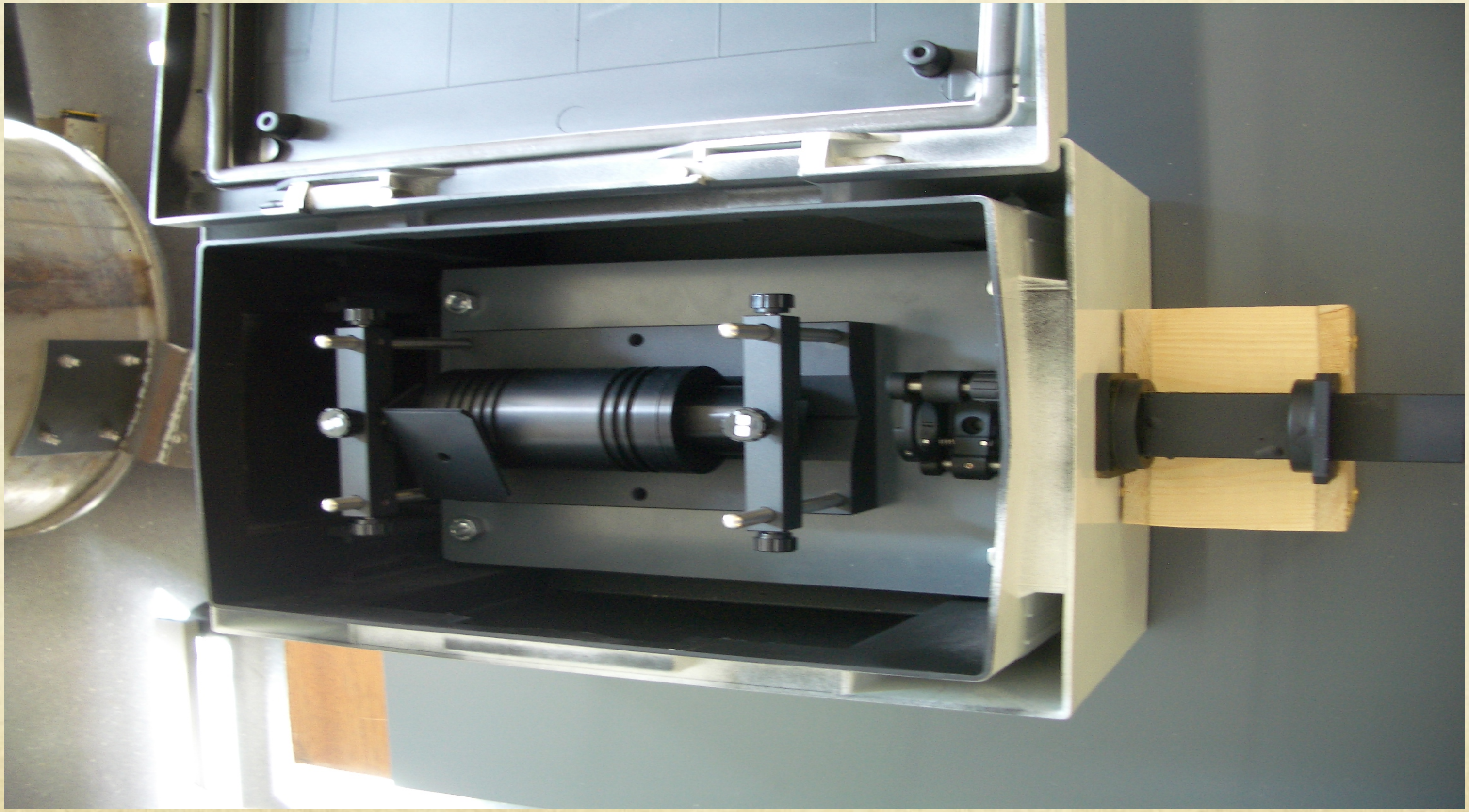
Transit of a point-like source

Sensitivity (Provisional)



Ideas for the (not so distant) future

We are considering extending the Birmingham optical detector work using larger arrays feeding CCD detectors

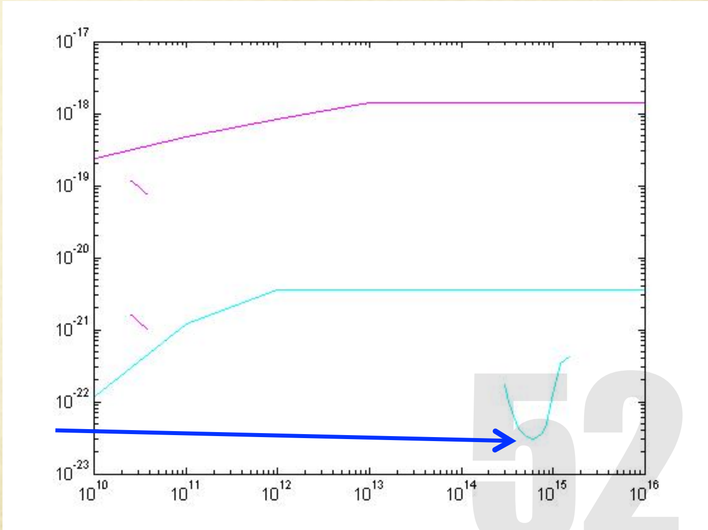


Conclusion

- In addition to the obvious sources at LIGO and LISA frequencies there may be GW radiation at microwave and optical although the sources are speculative
- The prototype detectors using the graviton to photon conversion are relatively cheap to build
- The Jodrell – Birmingham collaboration is studying the design of a single baseline interferometer operating at 5GHz and an optical detector (*).
- The detector will locate sources in the sky

(*) PMTs/CCDs coupled to superconducting

Magnets inside a cryostat to give very high sensitivity



END

Thank you