What We Know and Do Not Know About Cryogenic HFET's

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Outline

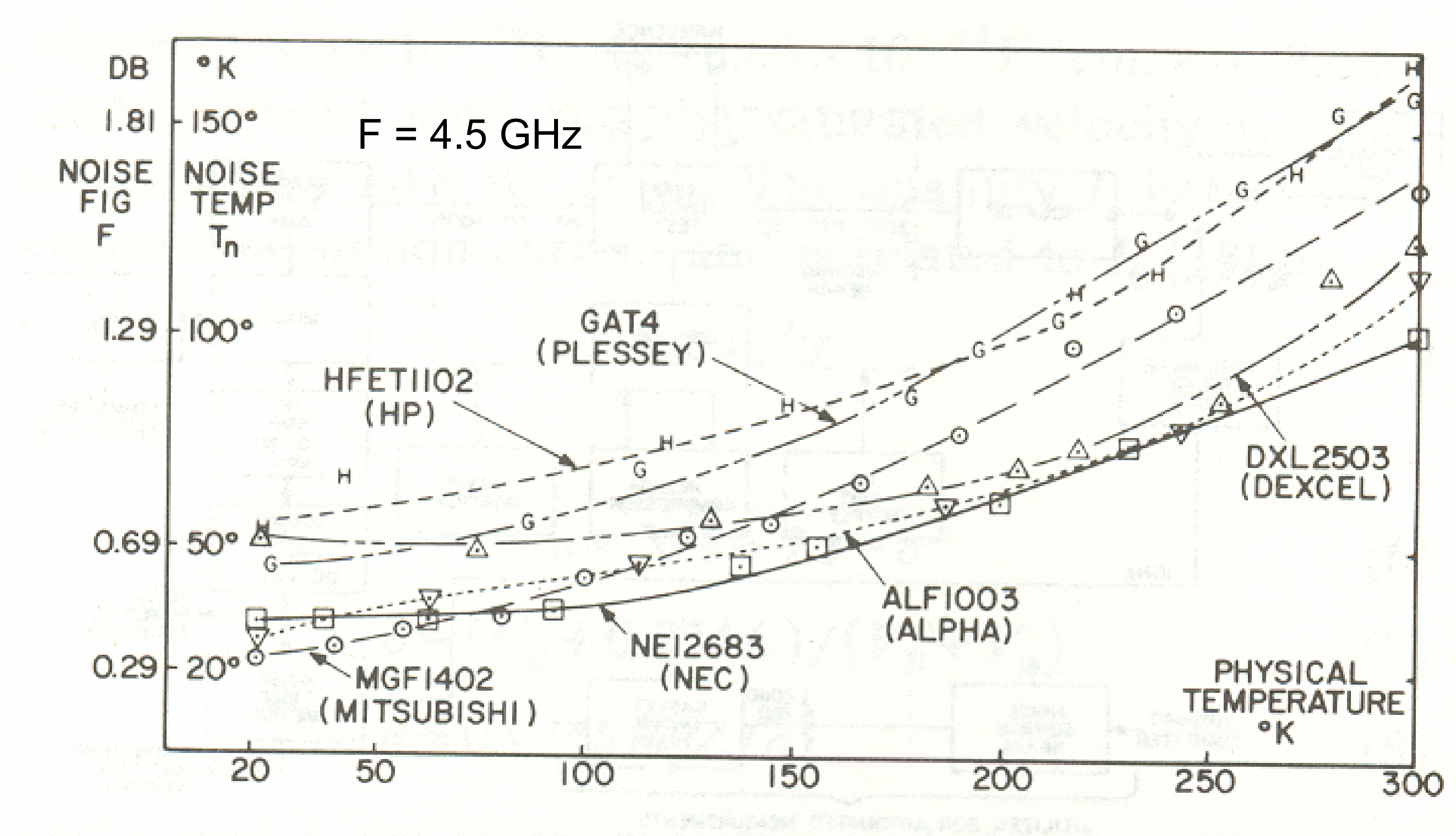
- Short history of cryogenic FETs
- Theory and experiment: examples of amplifiers (1989-2008)
- On minimum noise measure of InP HFETs
- Things we still do not know
- Where do we go from here?
    - ❖New devices
    - ❖Not so cold receivers
    - ❖Very broadband receivers

Cryogenic Experiments

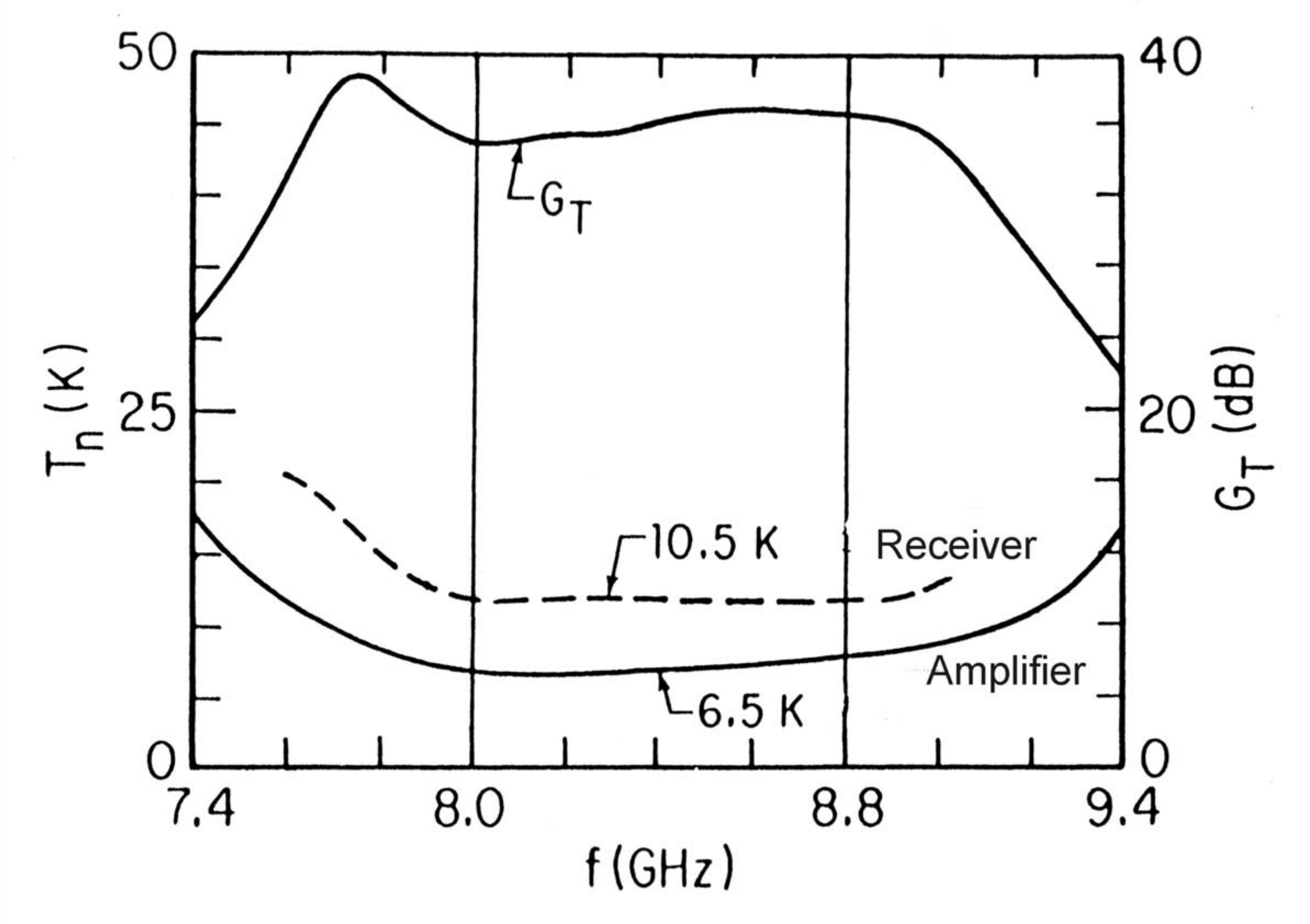
- 1970 − First cryogenic experiments, Loriou *et al* (France NTC), 120 K at 1 GHz L-band
- 1976 – Cryogenic experiments at X-band ,Liechti *et al*. (HP), 60 K at 12 GHz 1980
- 1980 – Practical cryogenic amplifiers using MESFET's demonstrated, Weinreb *et al*. (NRAO), 8 K at 1.5 GHz, 20 K at 5 GHz
- 1984 – GaAs/AlGaAs HFET at cryogenic temperatures, Pospieszalski, Weinreb (NRAO), 10 K at 8.4 GHz
- 1988 – PHEMT cooled, Weinreb *et al*. (NRAO), 25 K at 40 GHz
- 1989 – FET noise model suitable for CAD of cryogenic amplifiers
- 1993 – Evaluation of InP HFET's at cryogenic temperatures,
  Pospieszalski *et al.* (NRAO), 10 K at 40 GHz

Evaluation of Different MESFET's

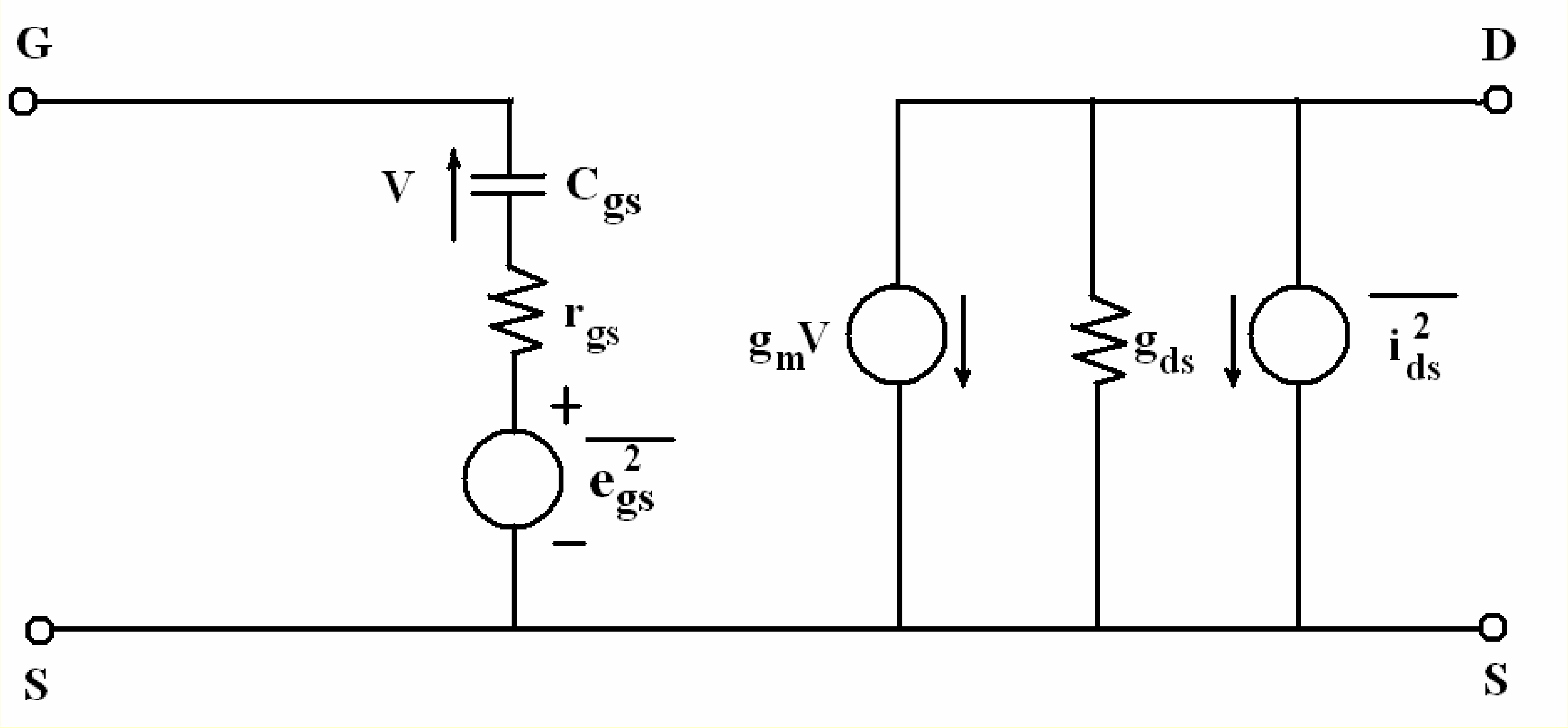
S.Weinreb (1980)



V-N Receiver and Amplifier with GE HFET's, (1987)



Simplest Noise Equivalent Circuit of a FET (1988)



$$\overline{e_{gs}^{2}} = 4\,kT_g\, r_{gs}\,\Delta f \qquad \overline{i_{ds}^{2}} = 4\,kT_d\, g_{ds}\,\Delta f$$

Noise Parameters of Intrinsic Chip – Approximation

For: $\frac{f}{f_t} << \sqrt{\frac{T_g}{T_d} \frac{1}{r_{gs}\, g_{ds}}}$

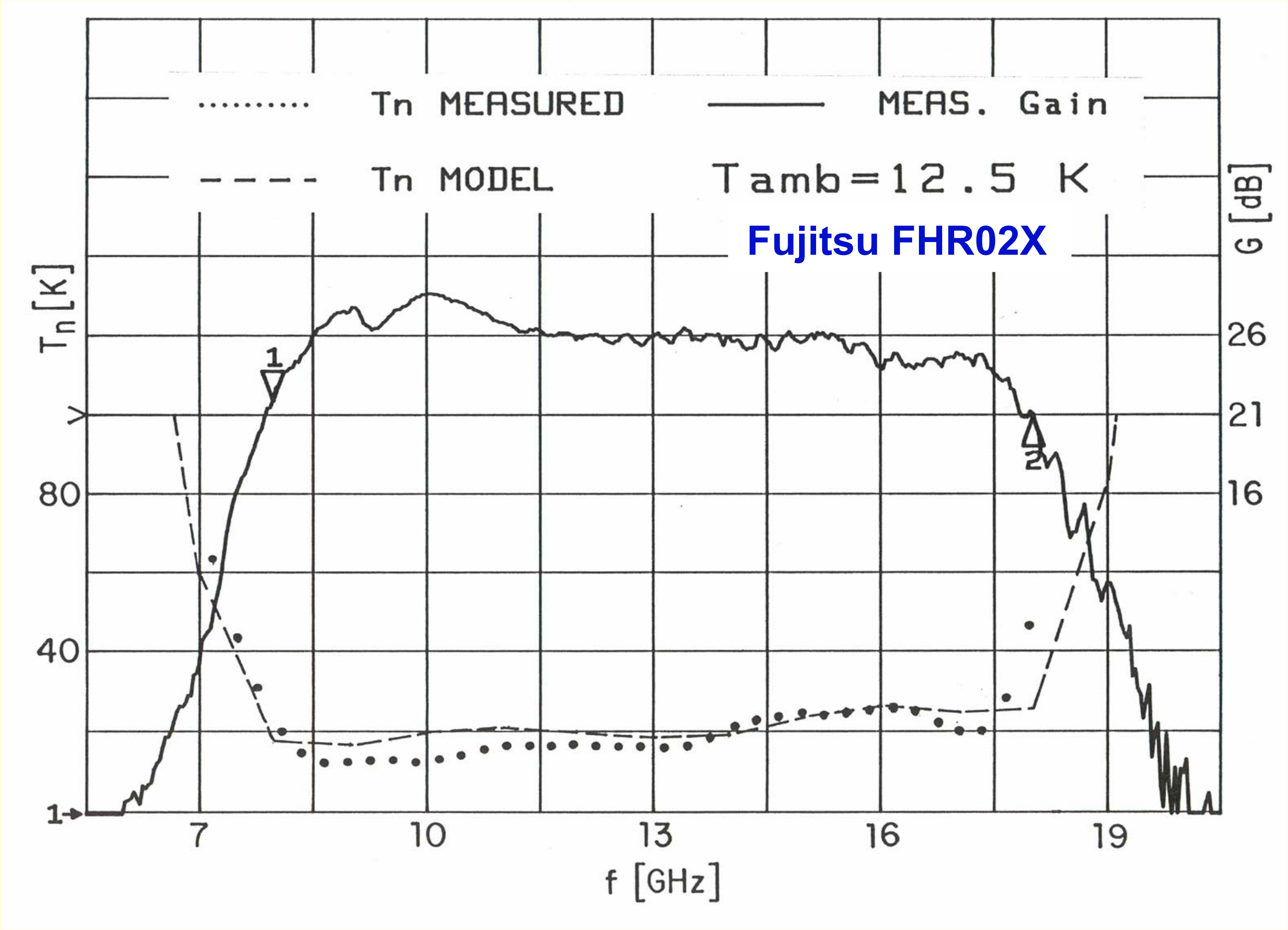
$$T_{min} \cong 2\frac{f}{f_t}\sqrt{g_{ds}\, T_d\, r_{gs}\, T_g}$$

$$f_t = \frac{g_m}{2\pi C_{gs}}$$

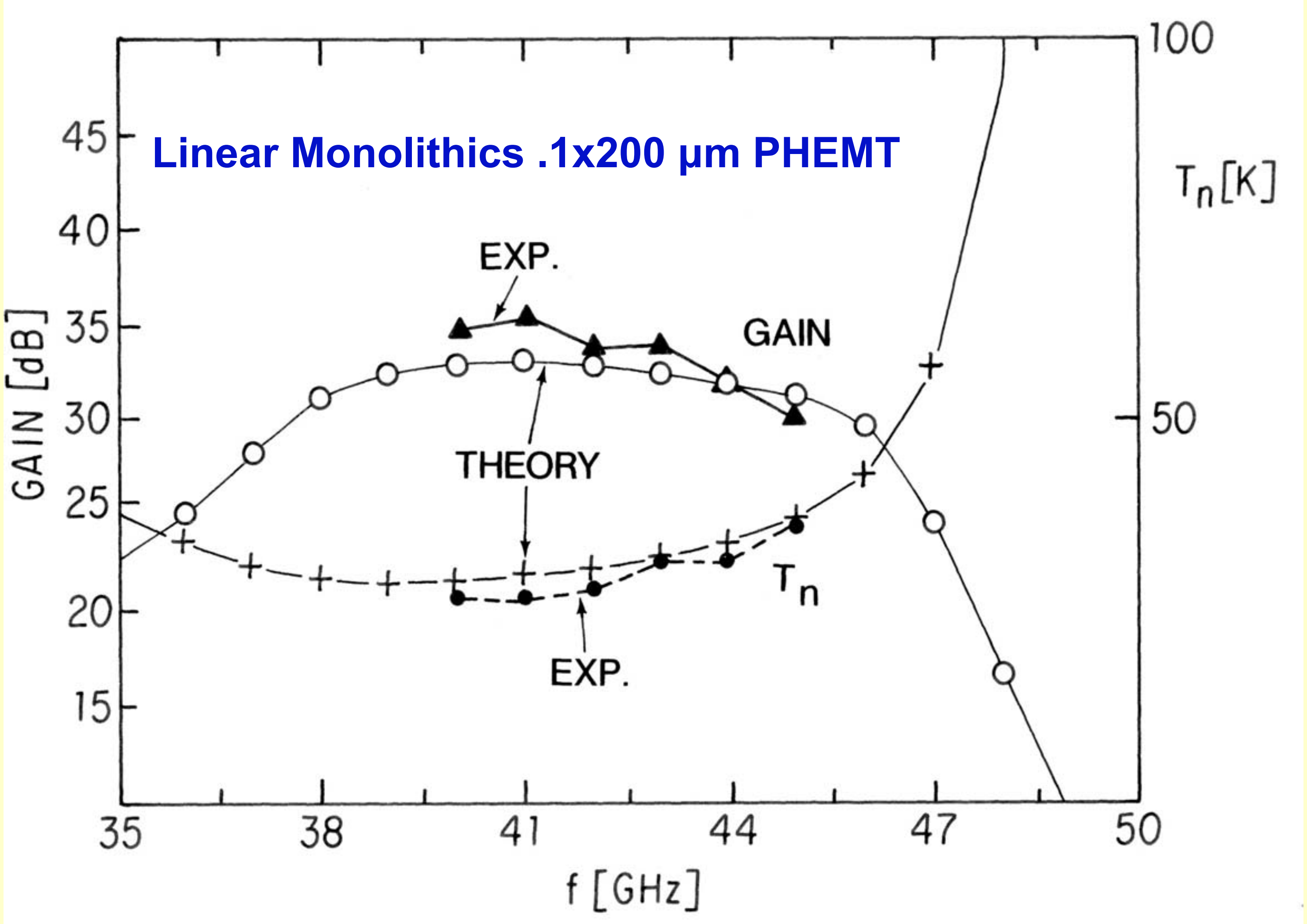
$$T_{min} \approx \frac{f}{f_{max}}\sqrt{T_g\, T_d}$$

$$f_{max} = f_t\sqrt{\frac{1}{4\, g_{ds}\, r_{gs}}}$$

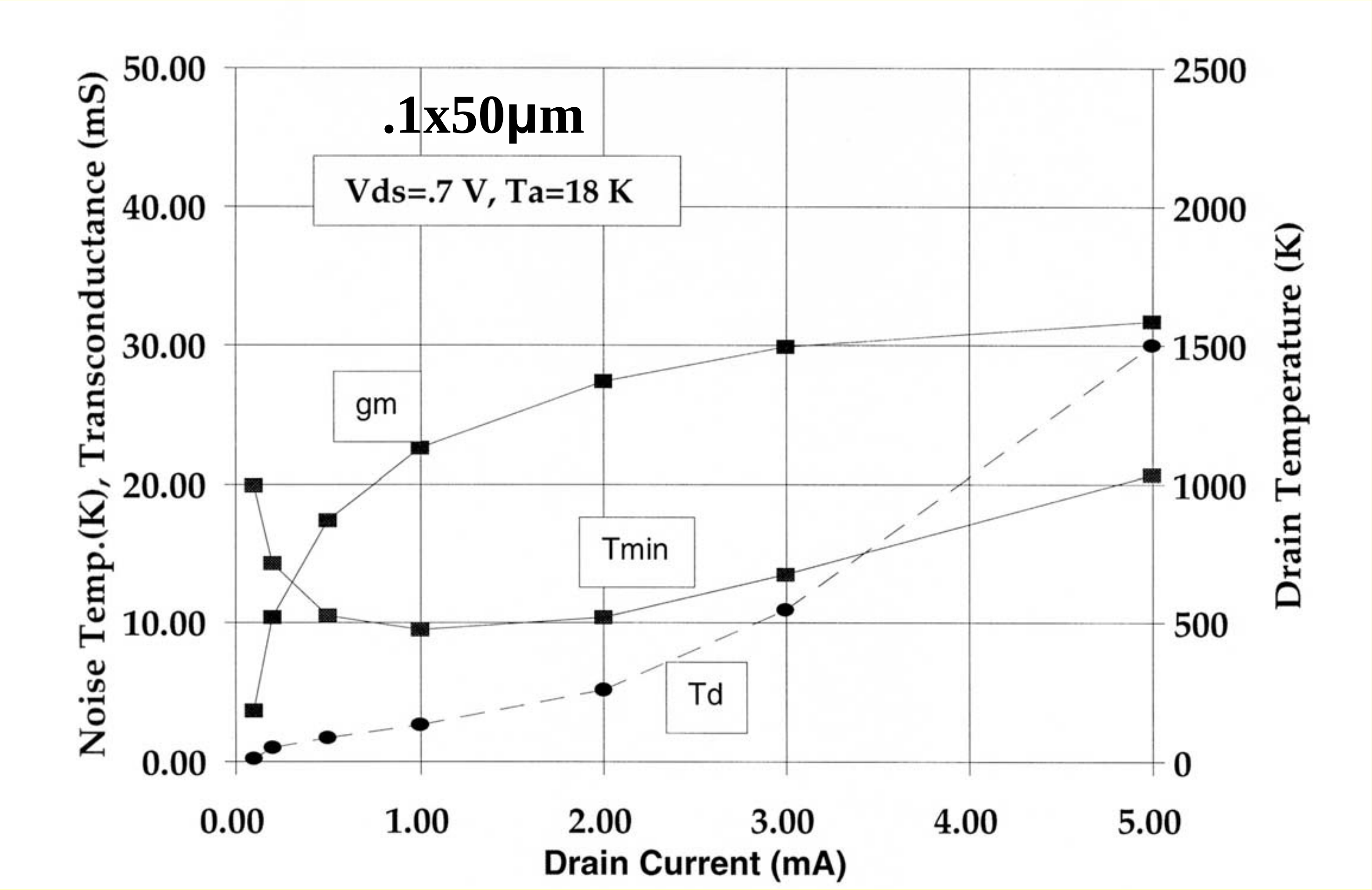
8-18 GHz Amplifier at 12.5 K (1988)



VLBA 40- 45 GHz Amplifier (1990)



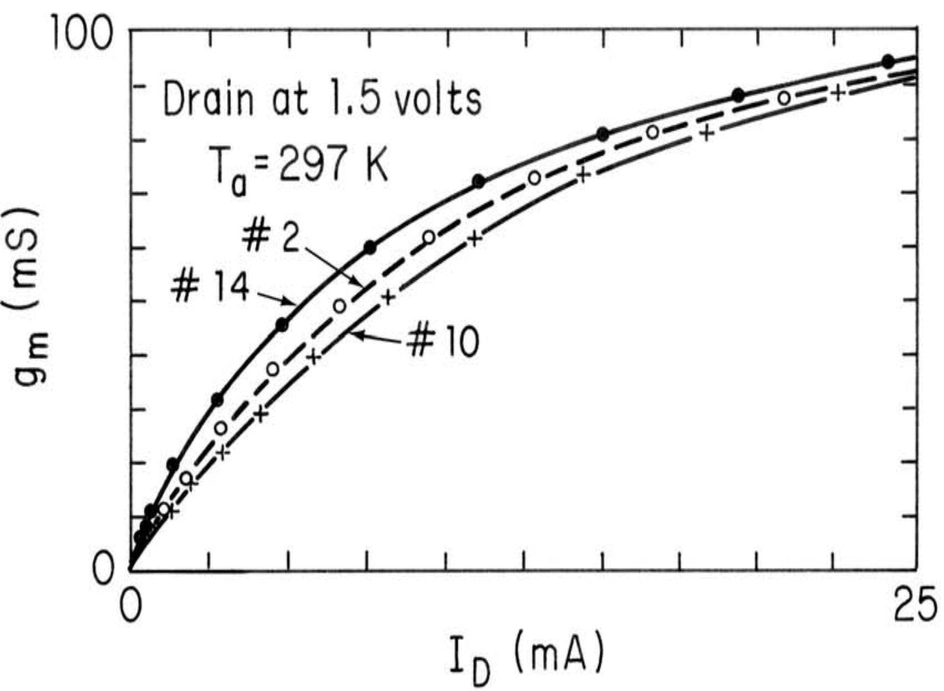
Optimal Noise Bias of InP HFET at 18 K (1993)

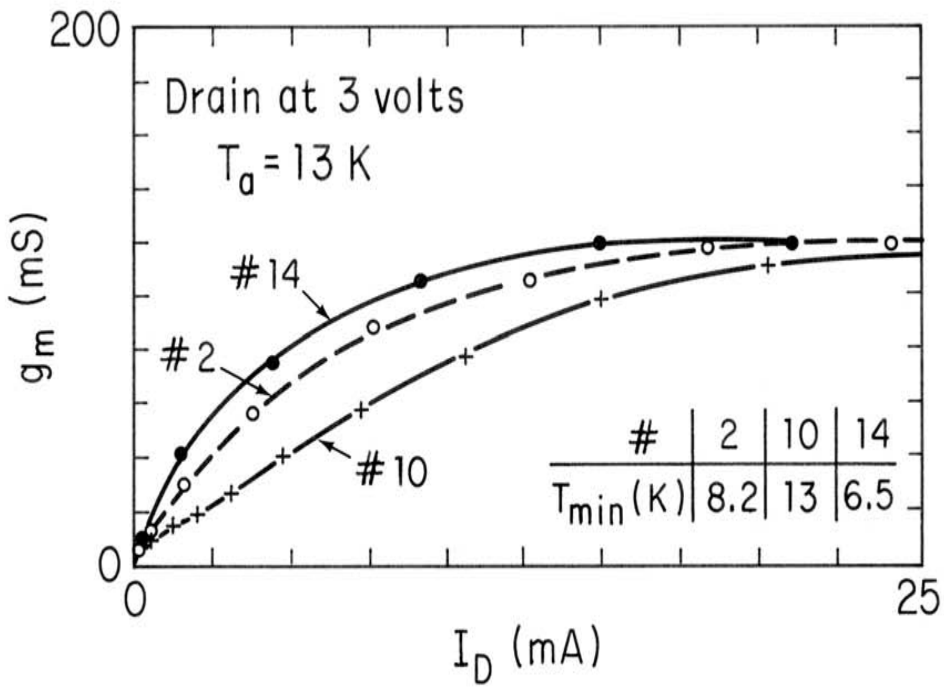


Optimal bias minimizes the value of:

$$f(V_{ds}, I_{ds}) \approx \frac{\sqrt{T_d g_{ds}}}{f_t} \approx \frac{\sqrt{I_D}}{g_m}$$

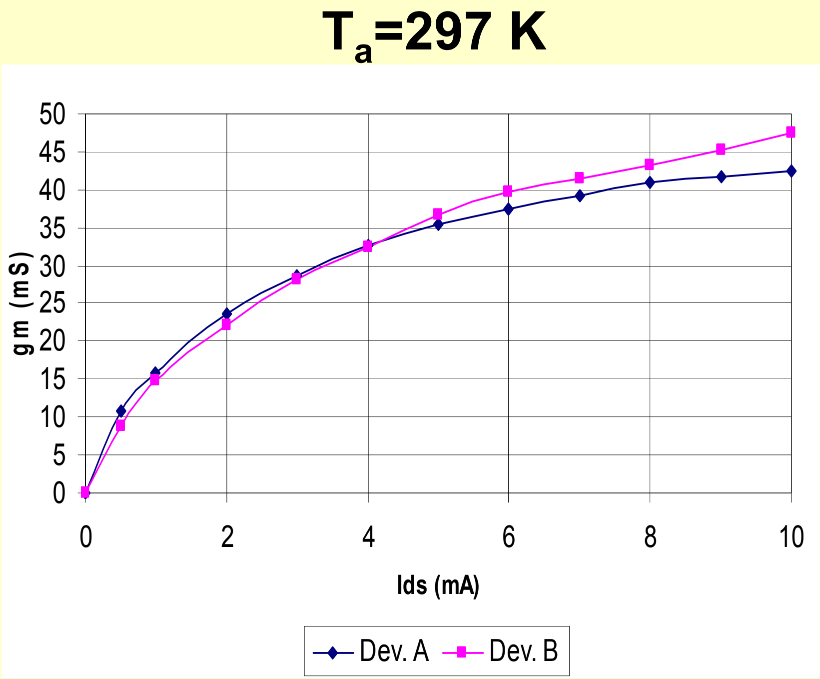
Cryogenic T_{min} at 8.4 GHz and DC Pinch–off Charactersitcs of GE HFET's (1987)

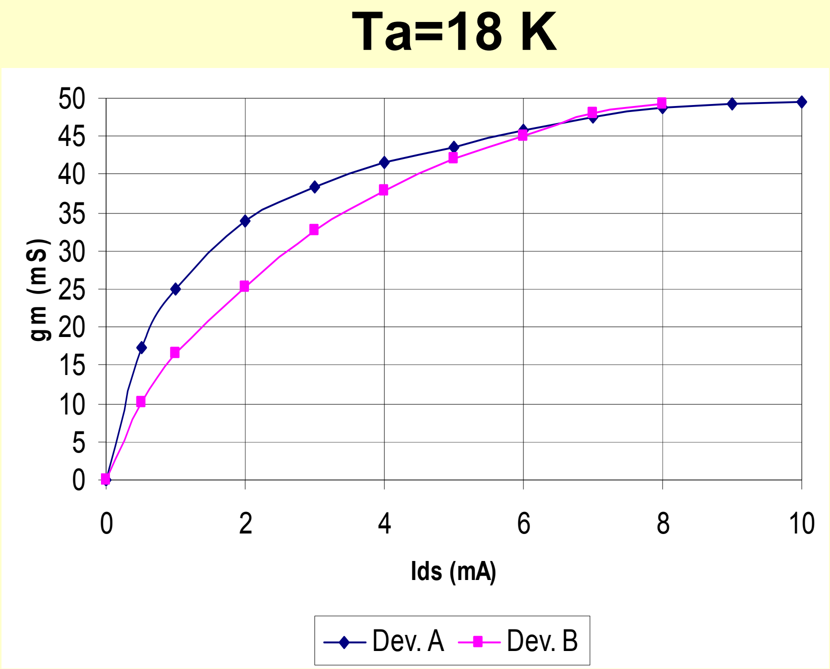




#	2	10	14
T_{min} (K)	8.2	13	6.5

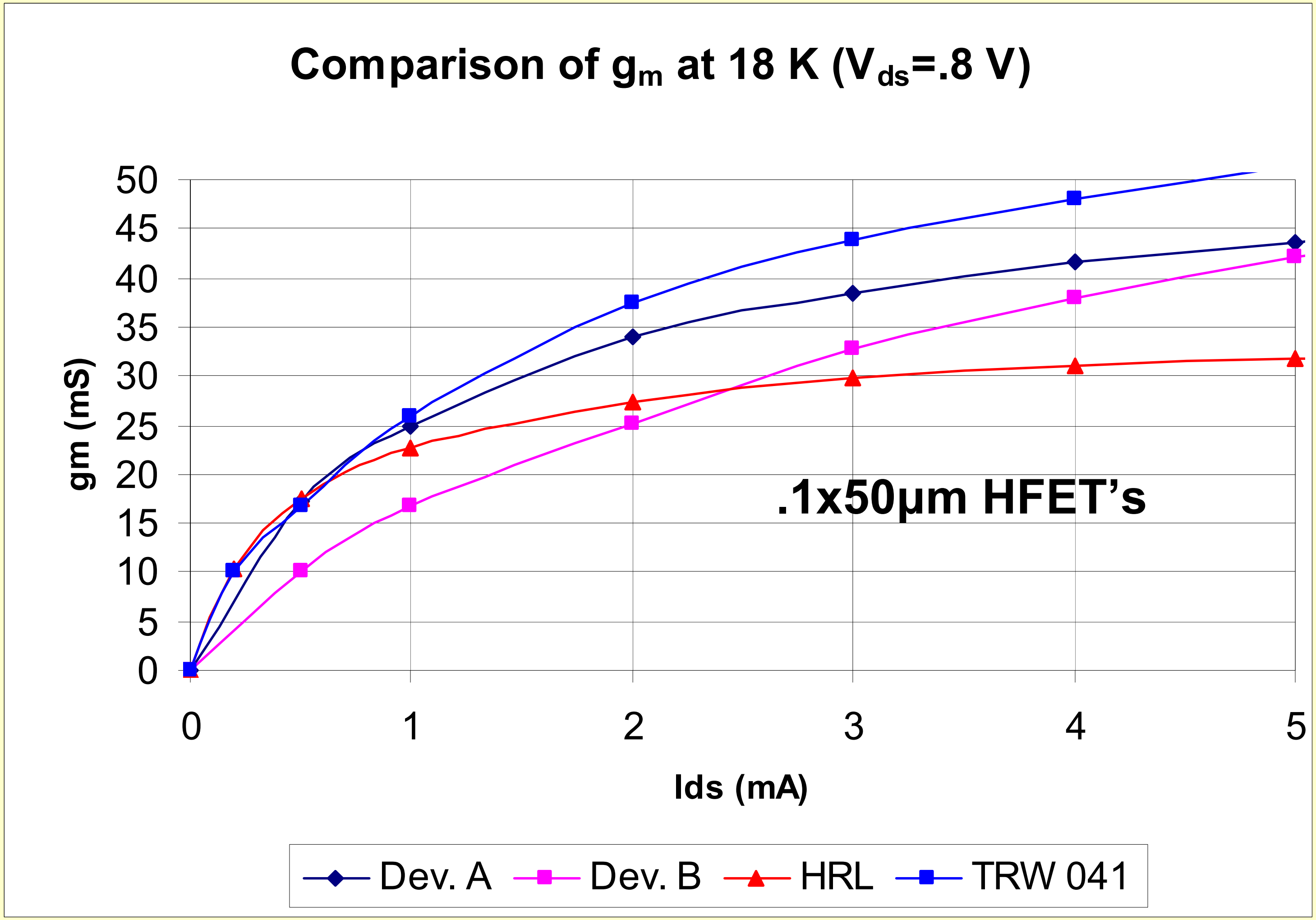
Example of "poor pinch off" InP HFET (1993)



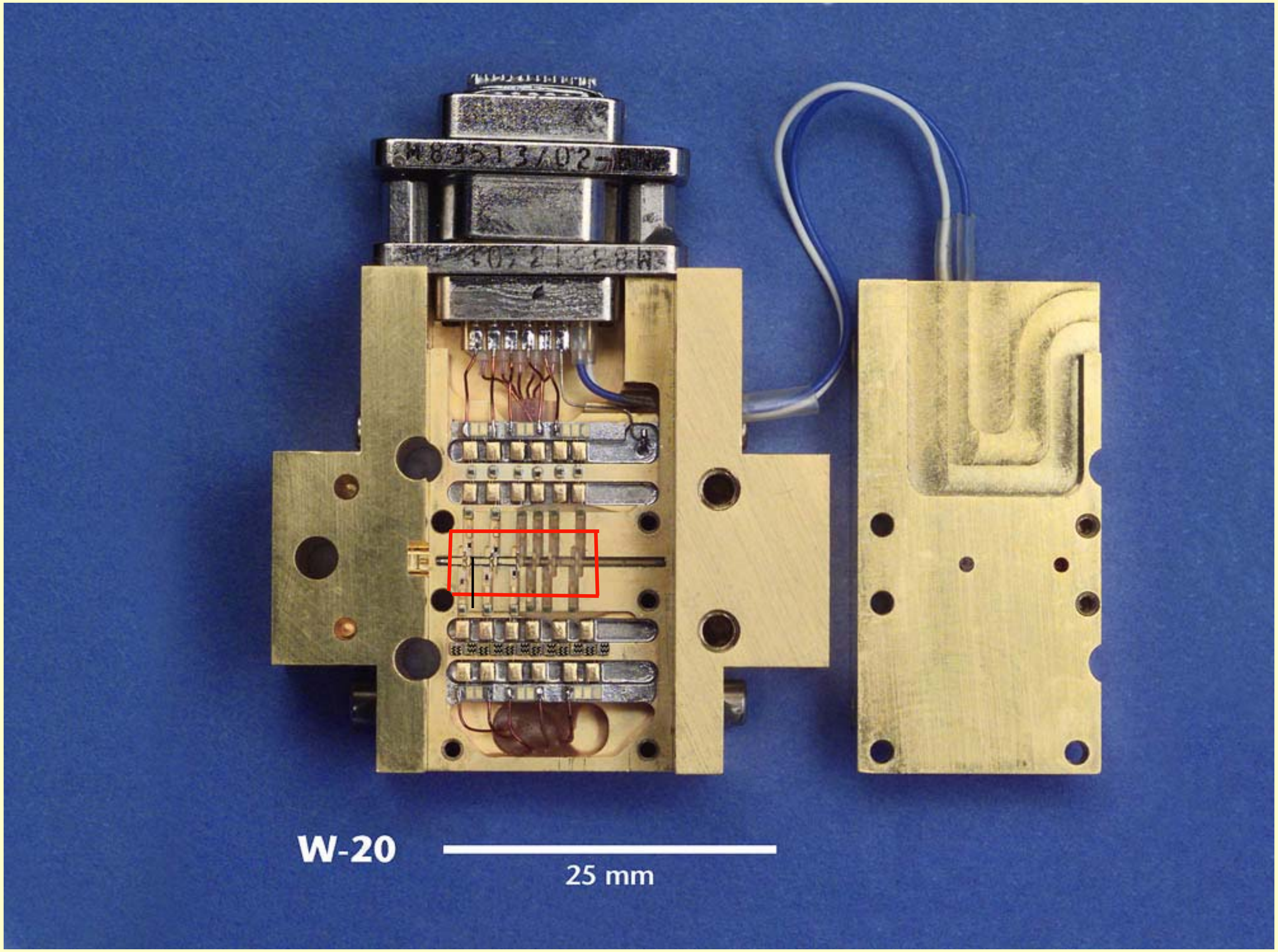


	T_{min}(297 K)	T_{min}(18 K)	at 40 GHz
Dev. A	**148**	**12**	
Dev. B	**134**	**21**	

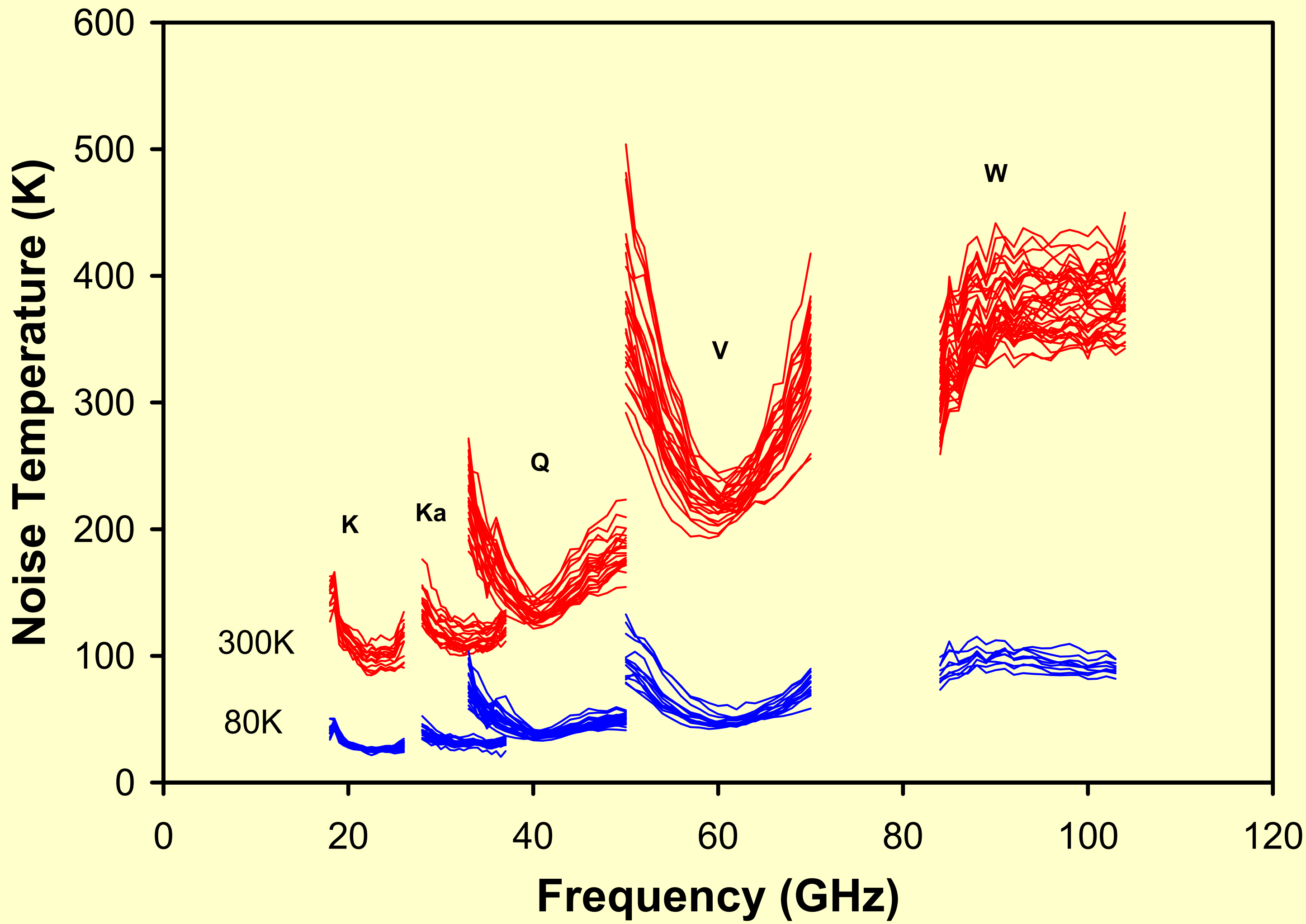
Comparison of GE/MM, HRL and TRW HFET's



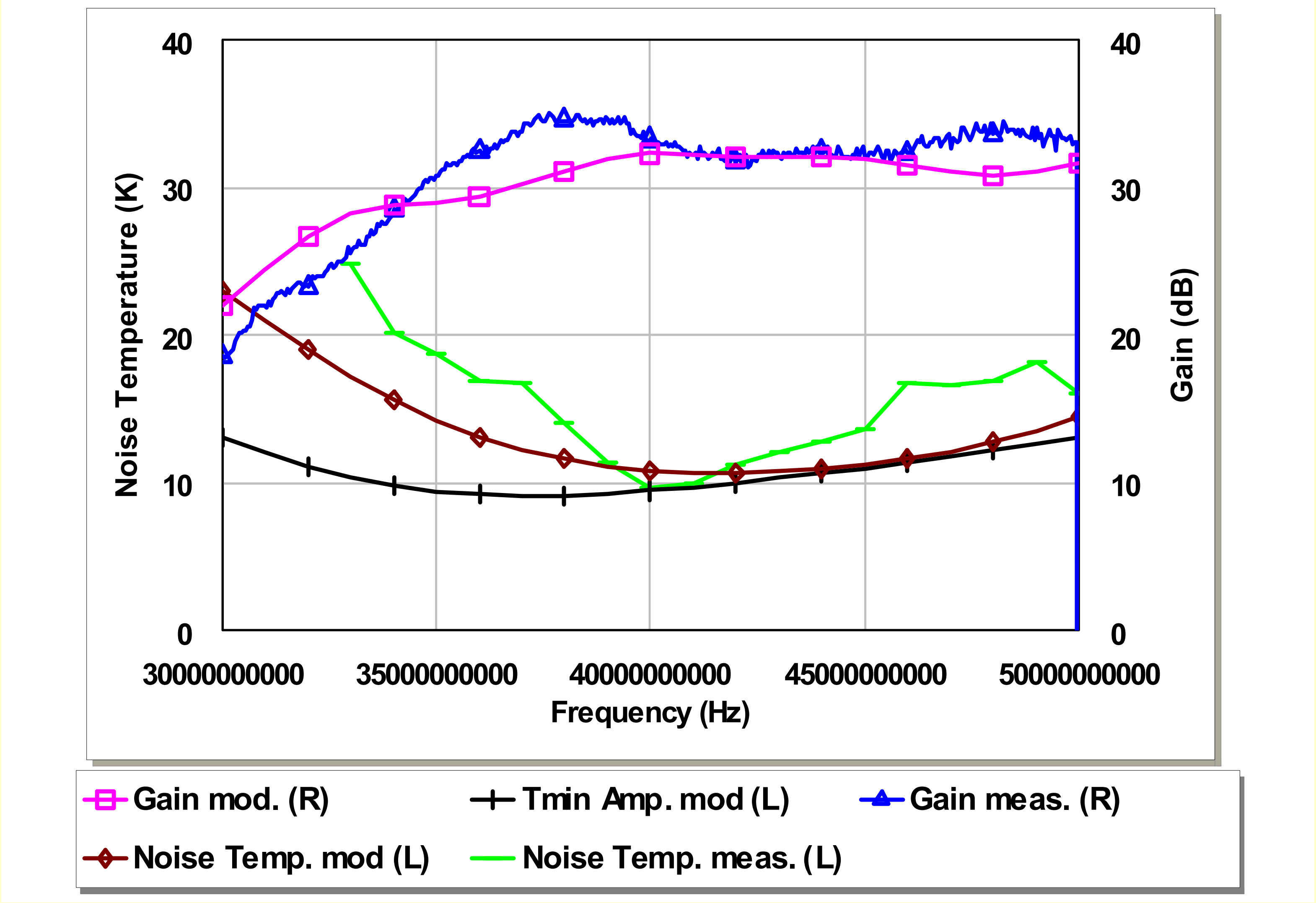
MAP Amplifier: W-Band (1998)



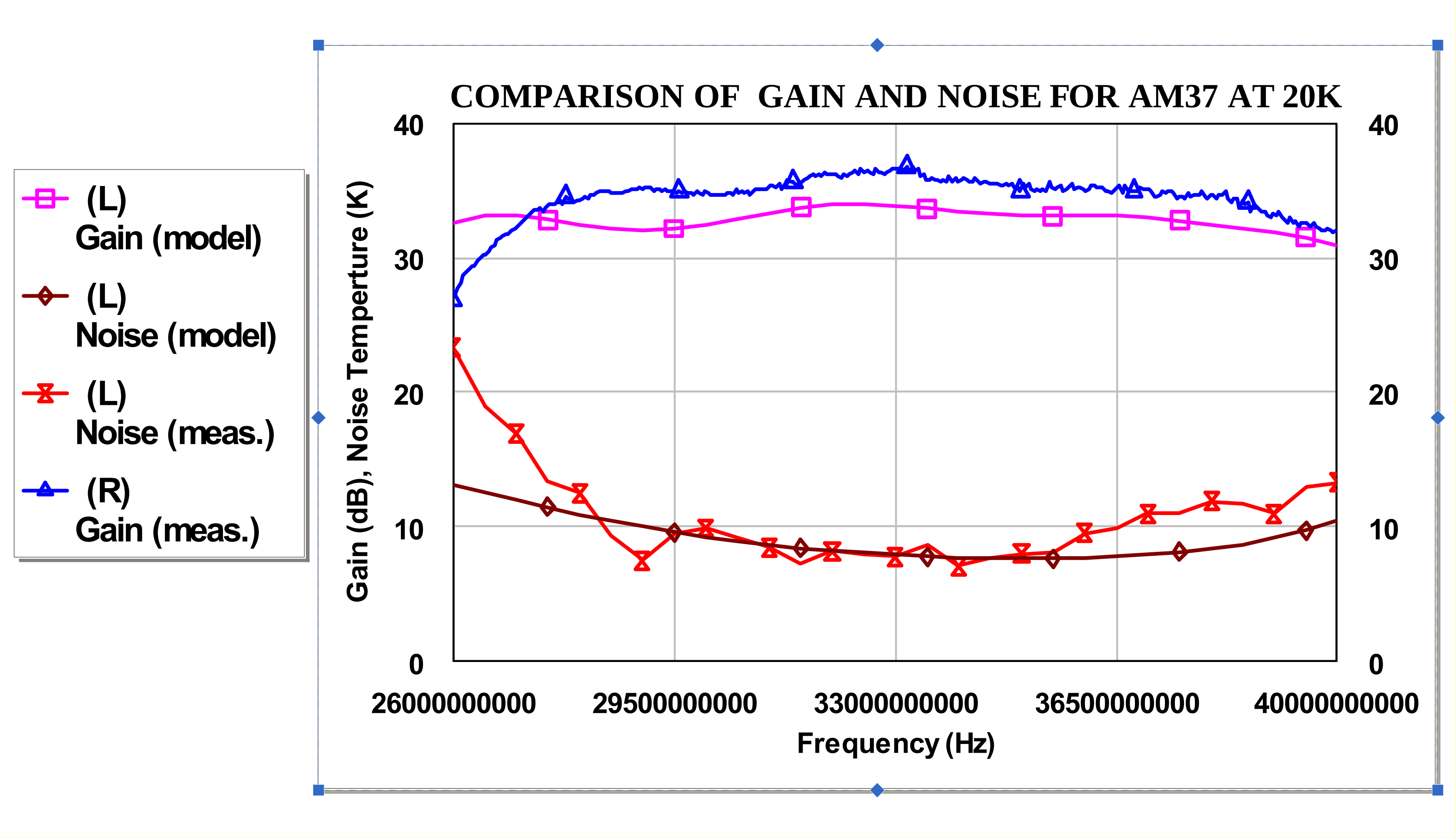
MAP Amplifier: Noise Temperature



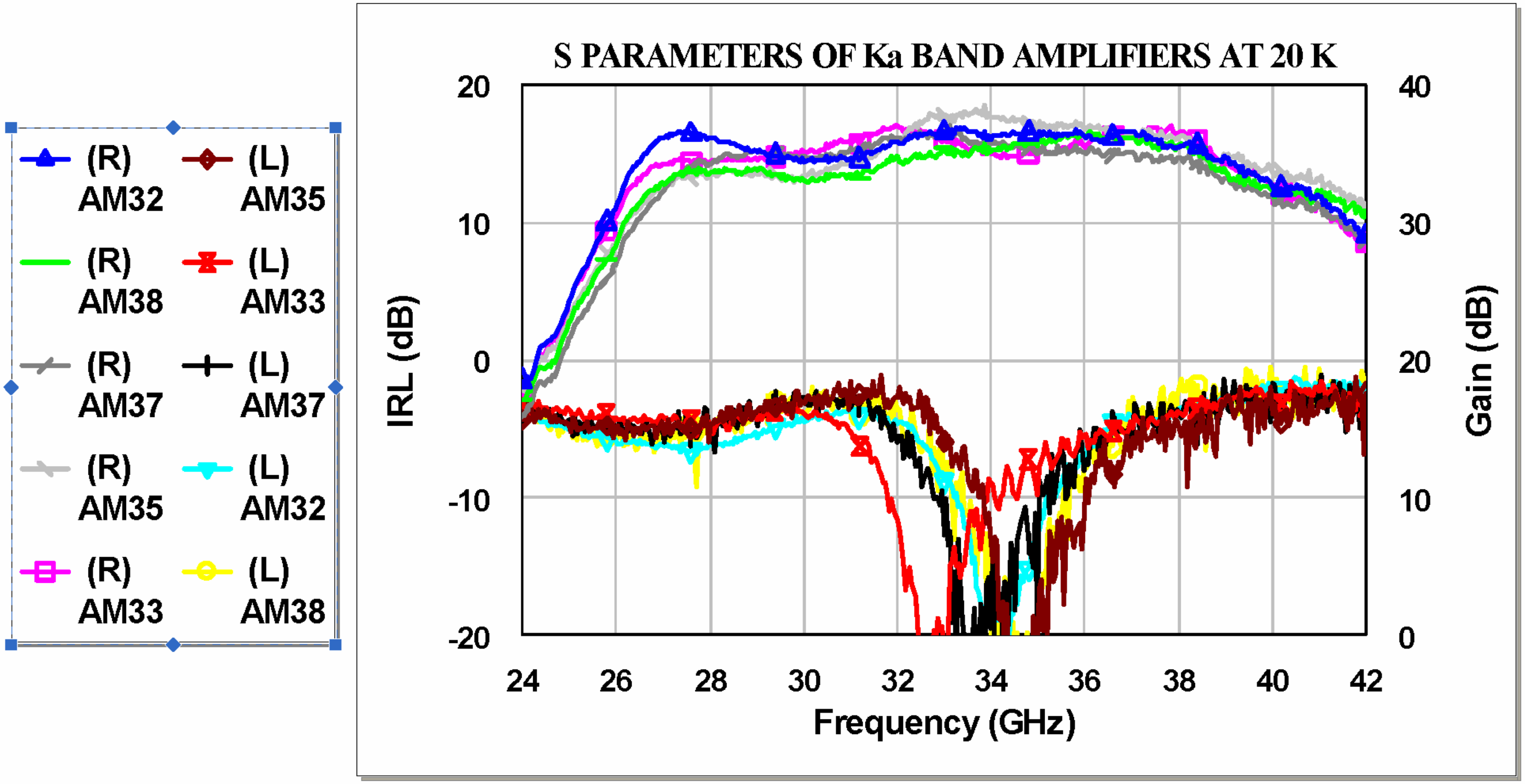
40-50 GHz Amplifier at 15 K



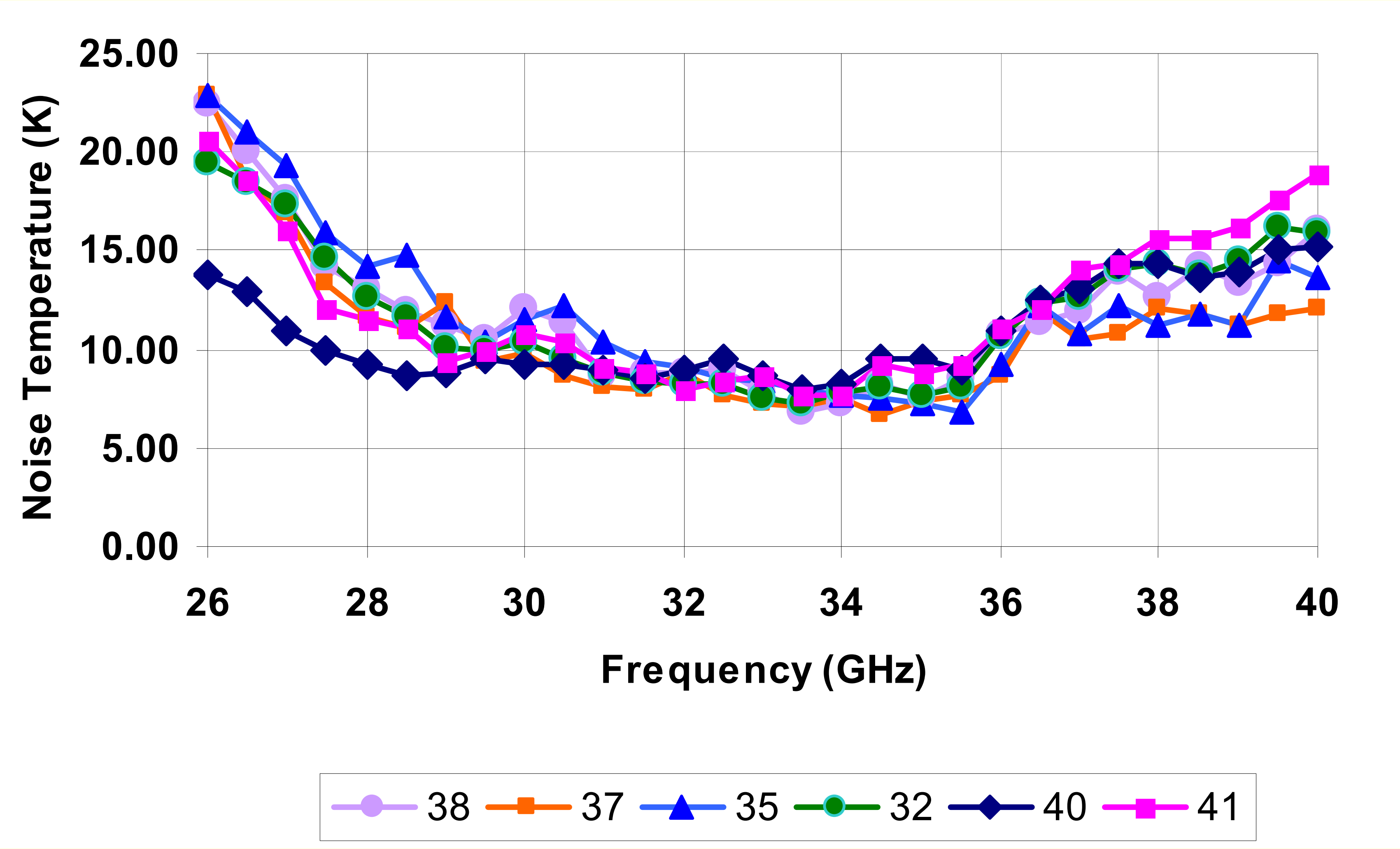
EVLA K_a Band Amplifier



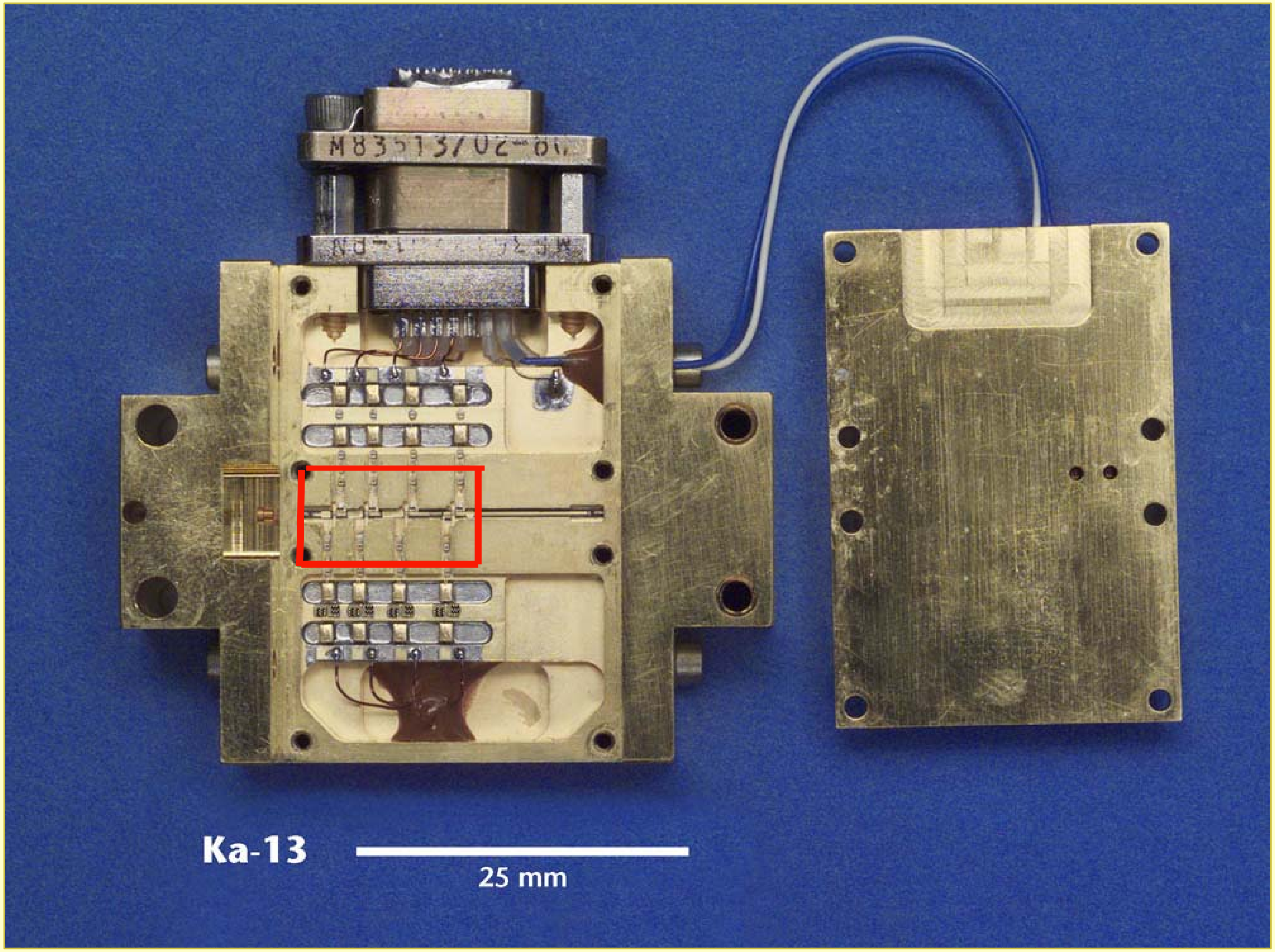
EVLA K_a Band Amplifier

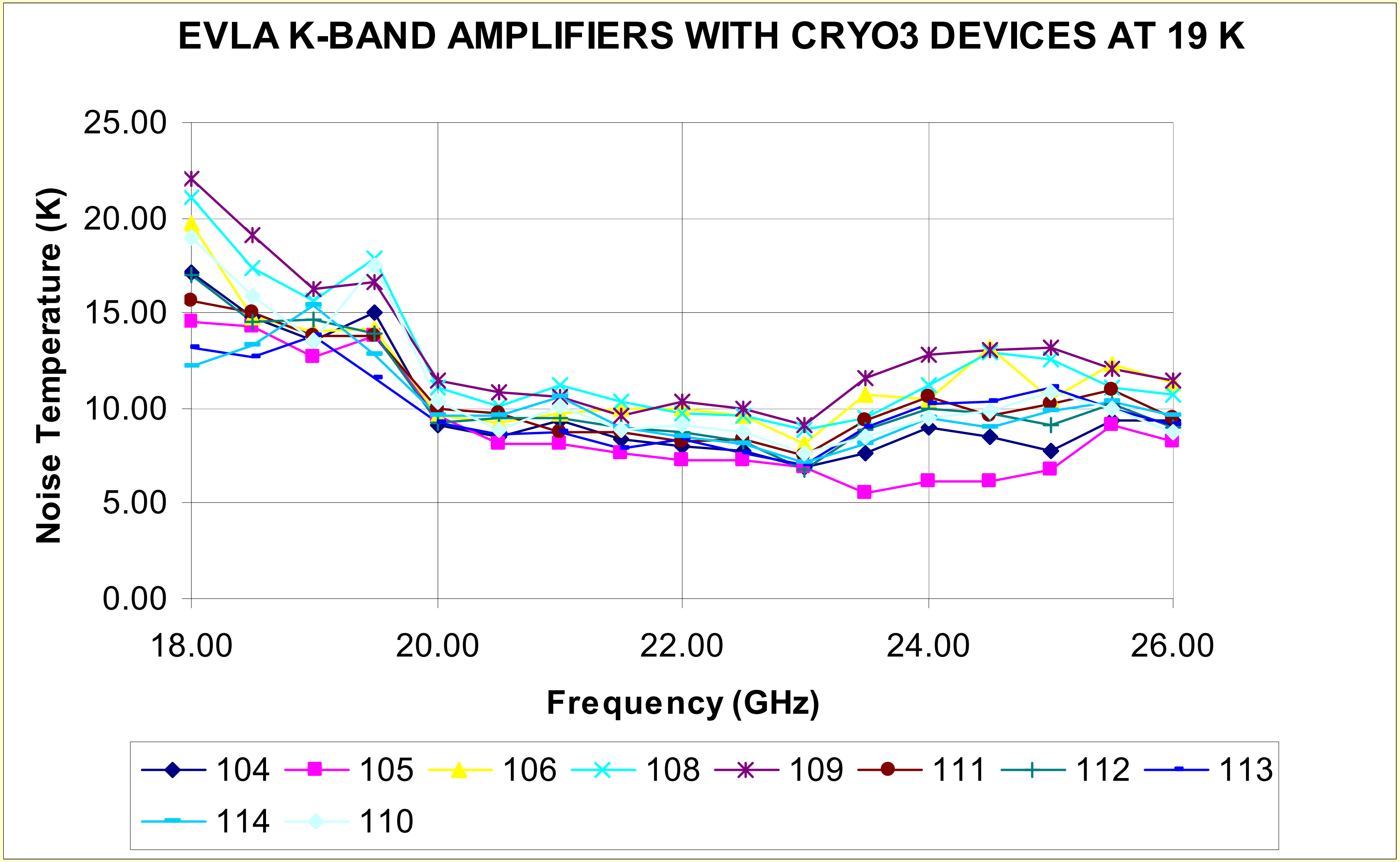


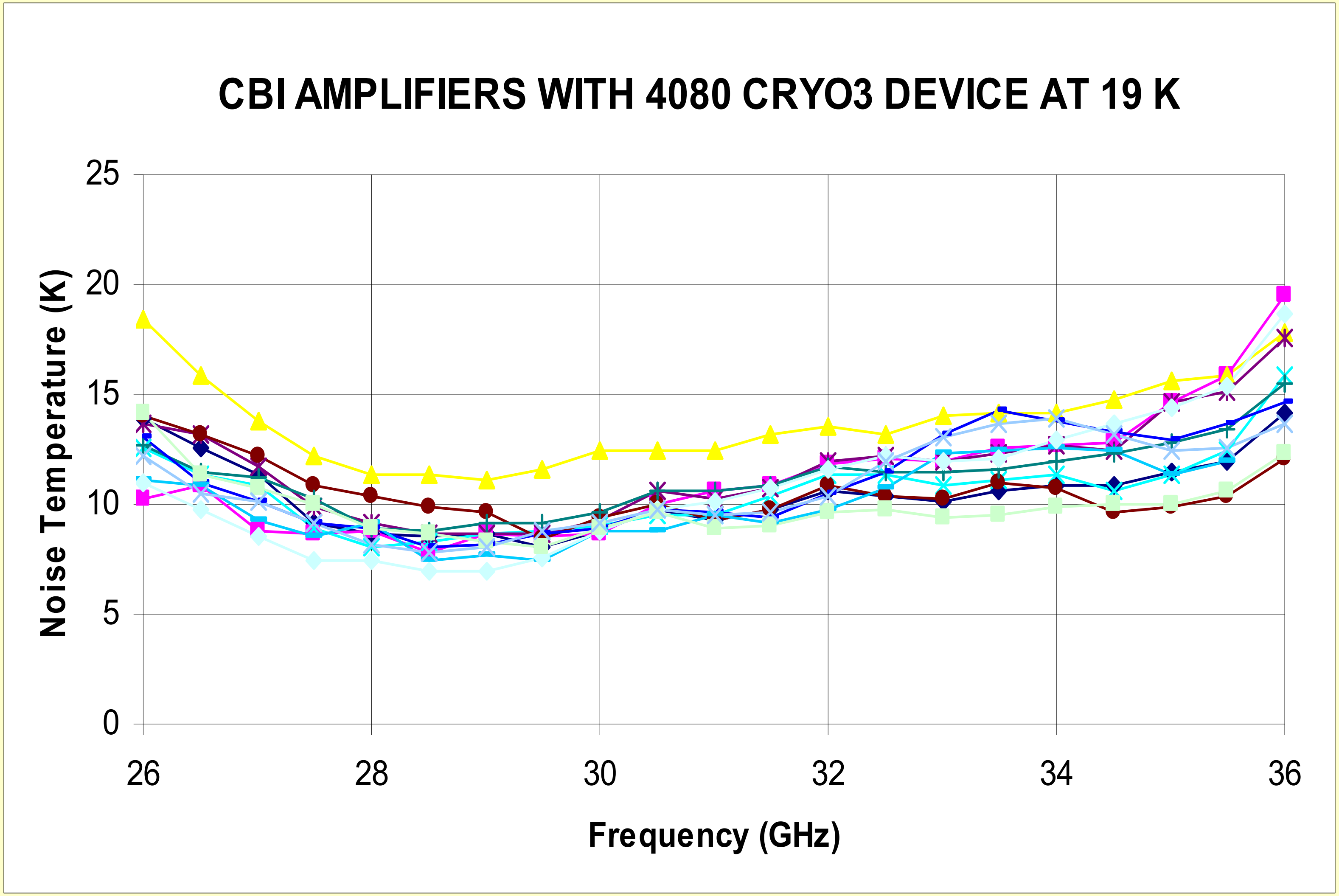
EVLA K_a-Band Amplifiers at 19 K



EVLA Ka Band Amplifier

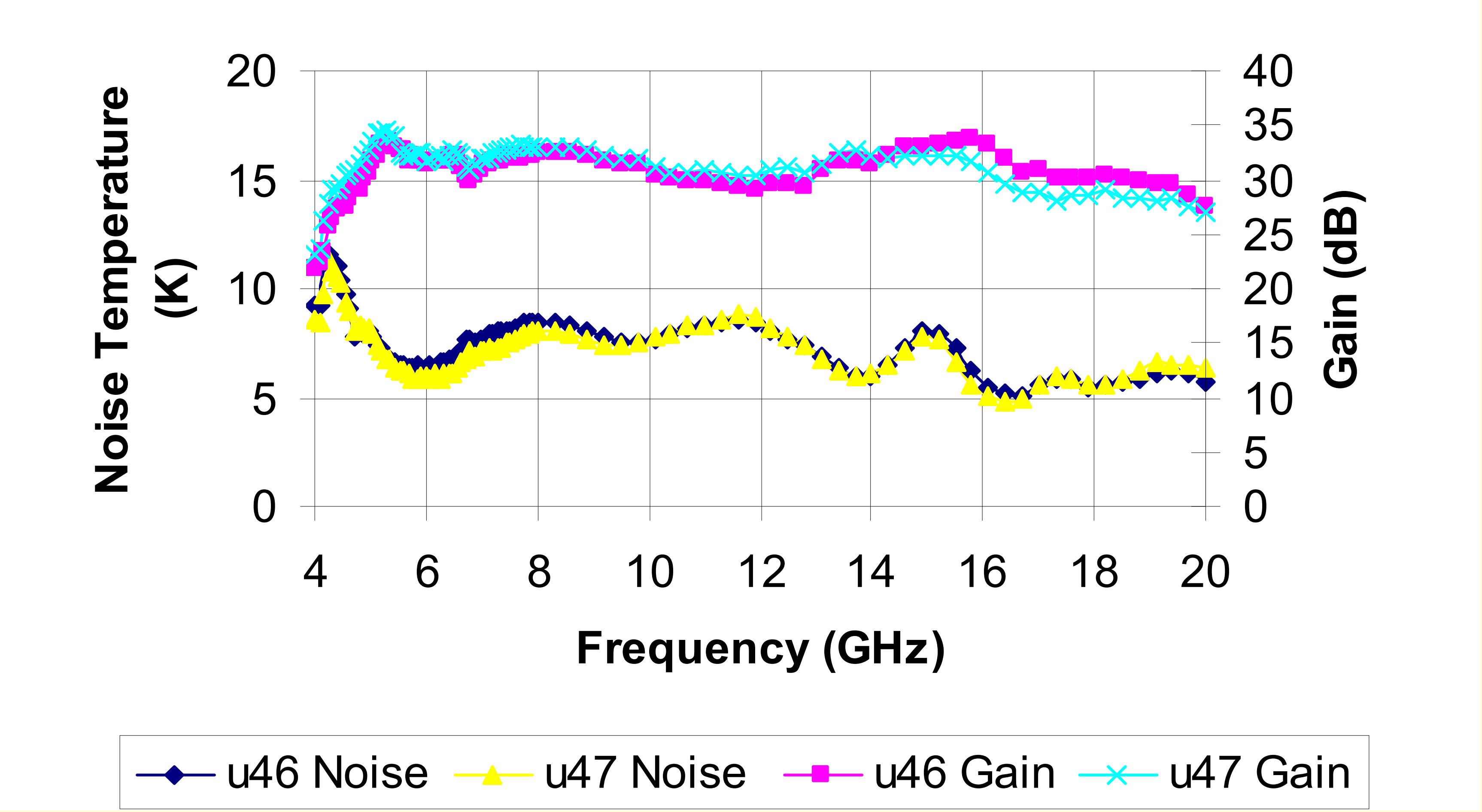



EVLA K-BAND AMPLIFIERS WITH CRYO3 DEVICES AT 19 K
Noise Temperature (K)
25.00
20.00
15.00
10.00
5.00
0.00
18.00
20.00
22.00
24.00
26.00
Frequency (GHz)
104
105
106
108
109
111
112
113
114
110

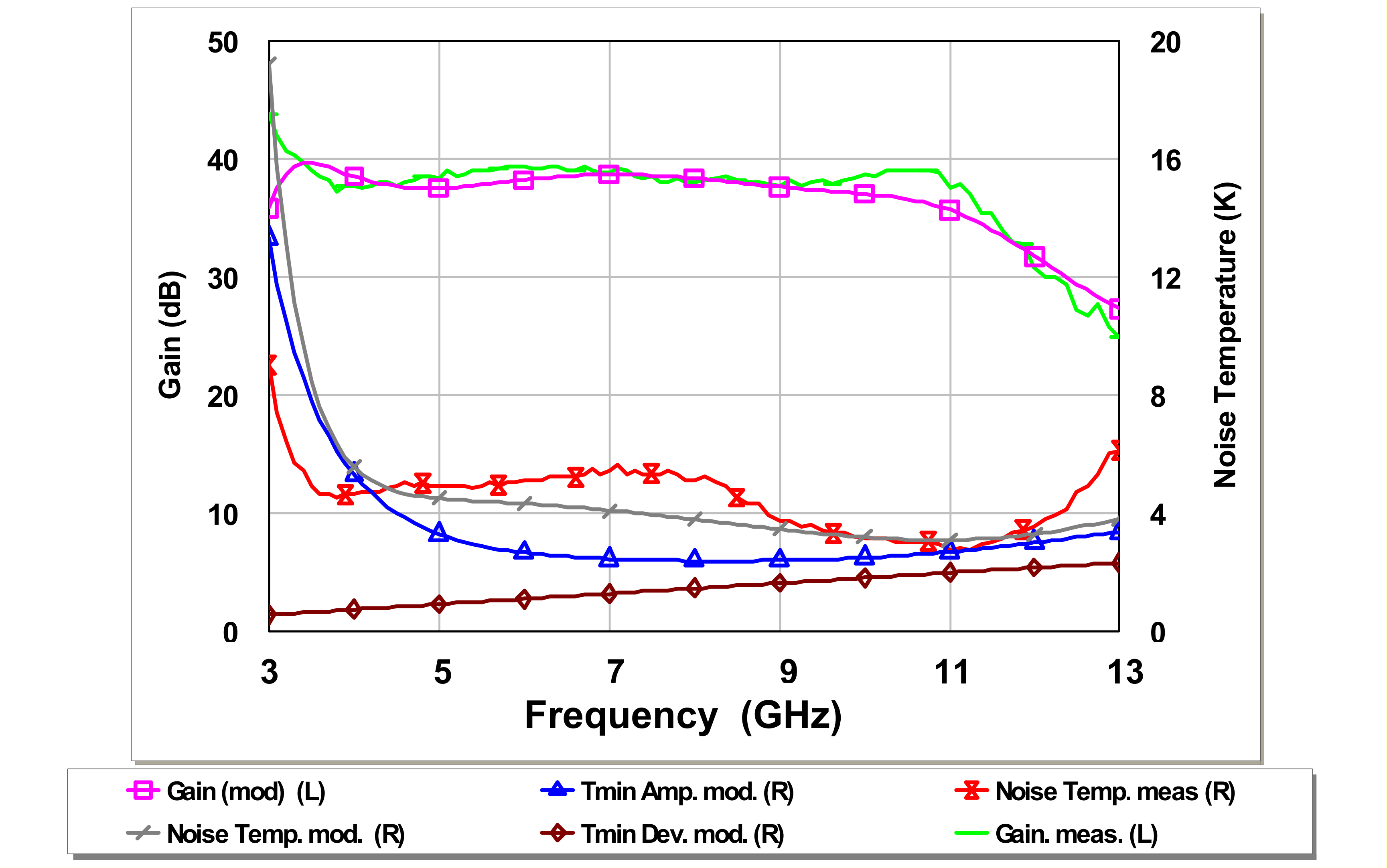


CBI AMPLIFIERS WITH 4080 CRYO3 DEVICE AT 19 K
Noise Temperature (K)
0
5
10
15
20
25
26
28
30
32
34
36
Frequency (GHz)

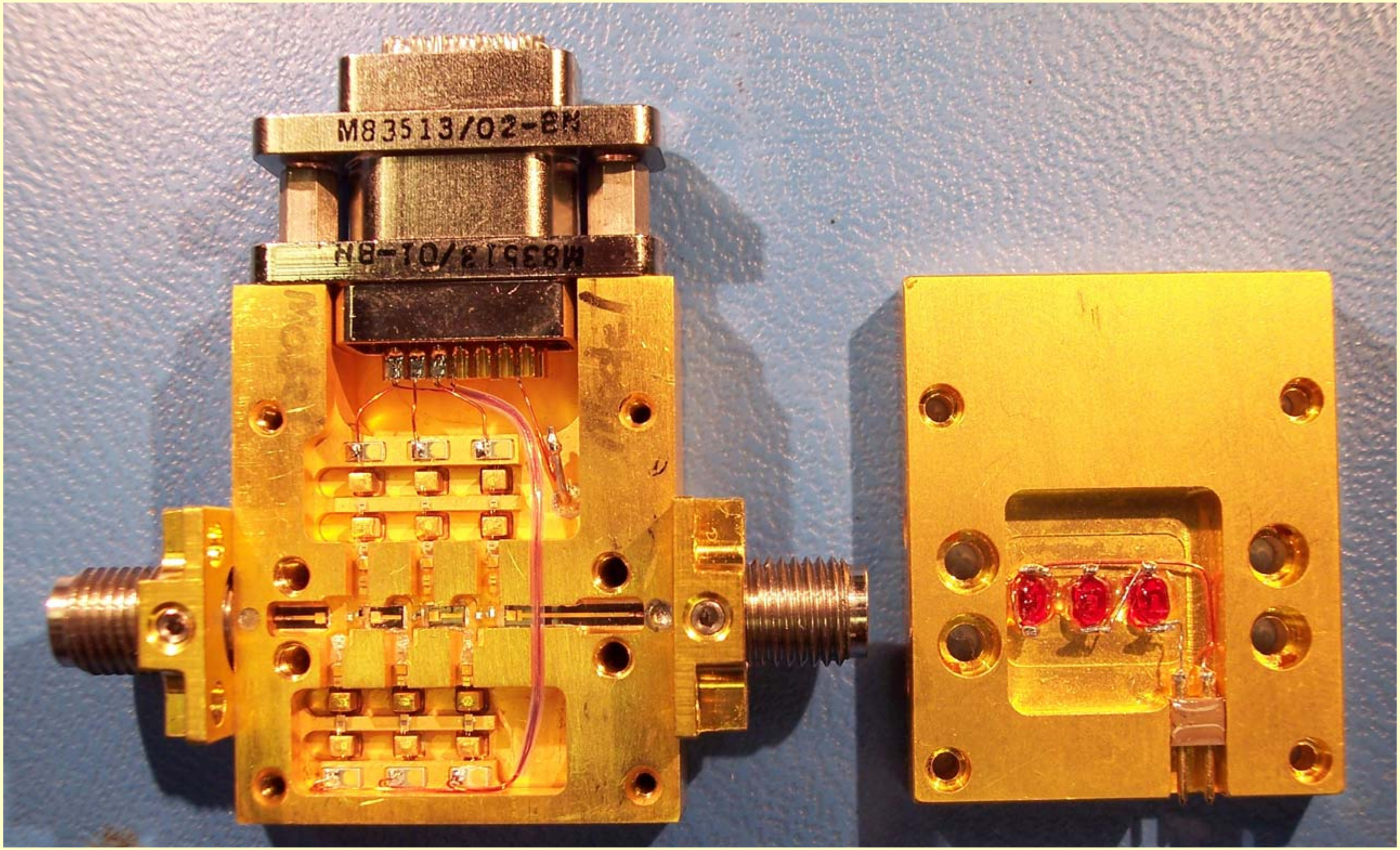
Noise and Gain of 5-20 GHz Amplifier at T_a=15 K



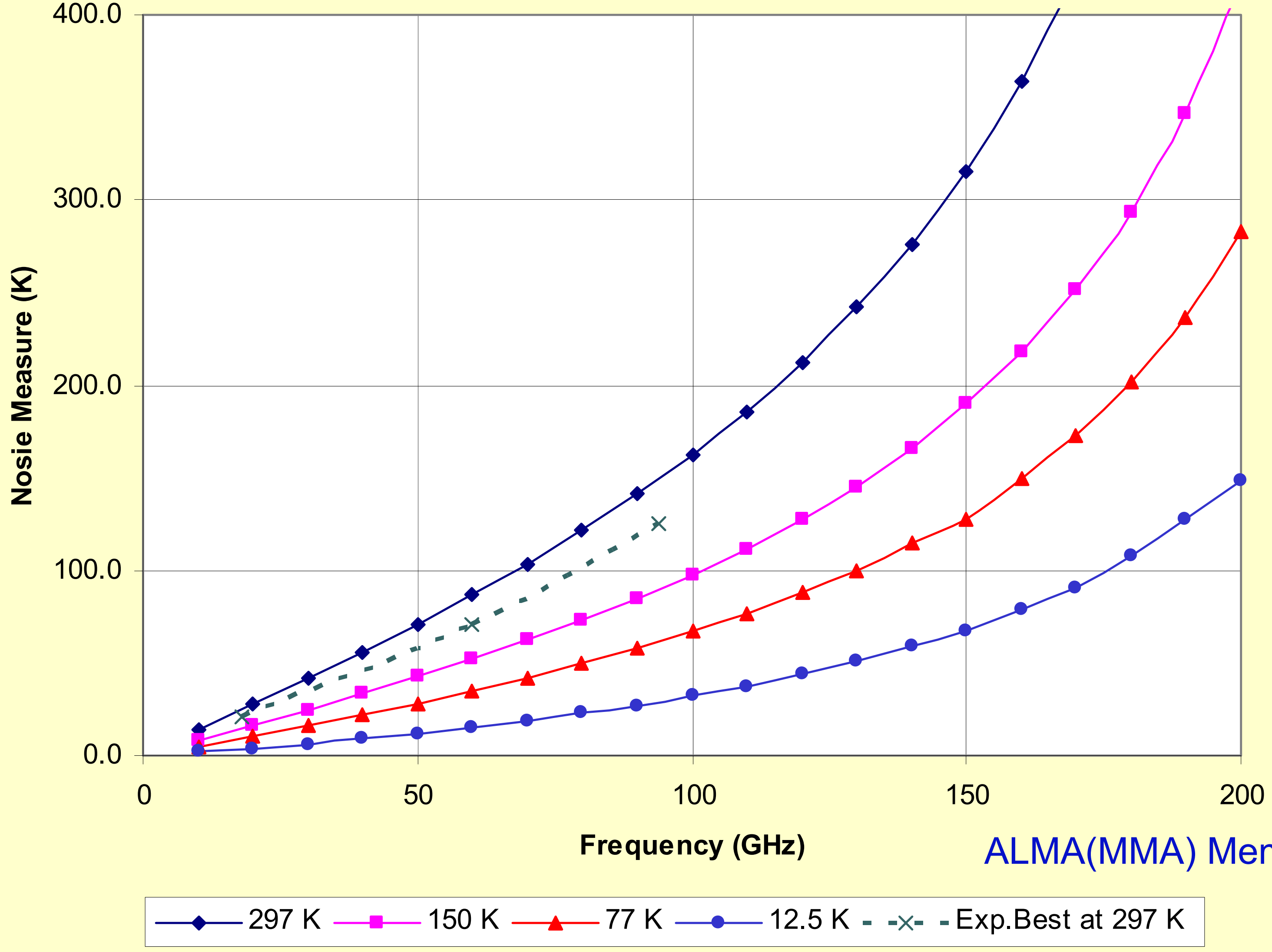
4-12 GHz Amplifier at 15 K



4-12 GHz Amplifier

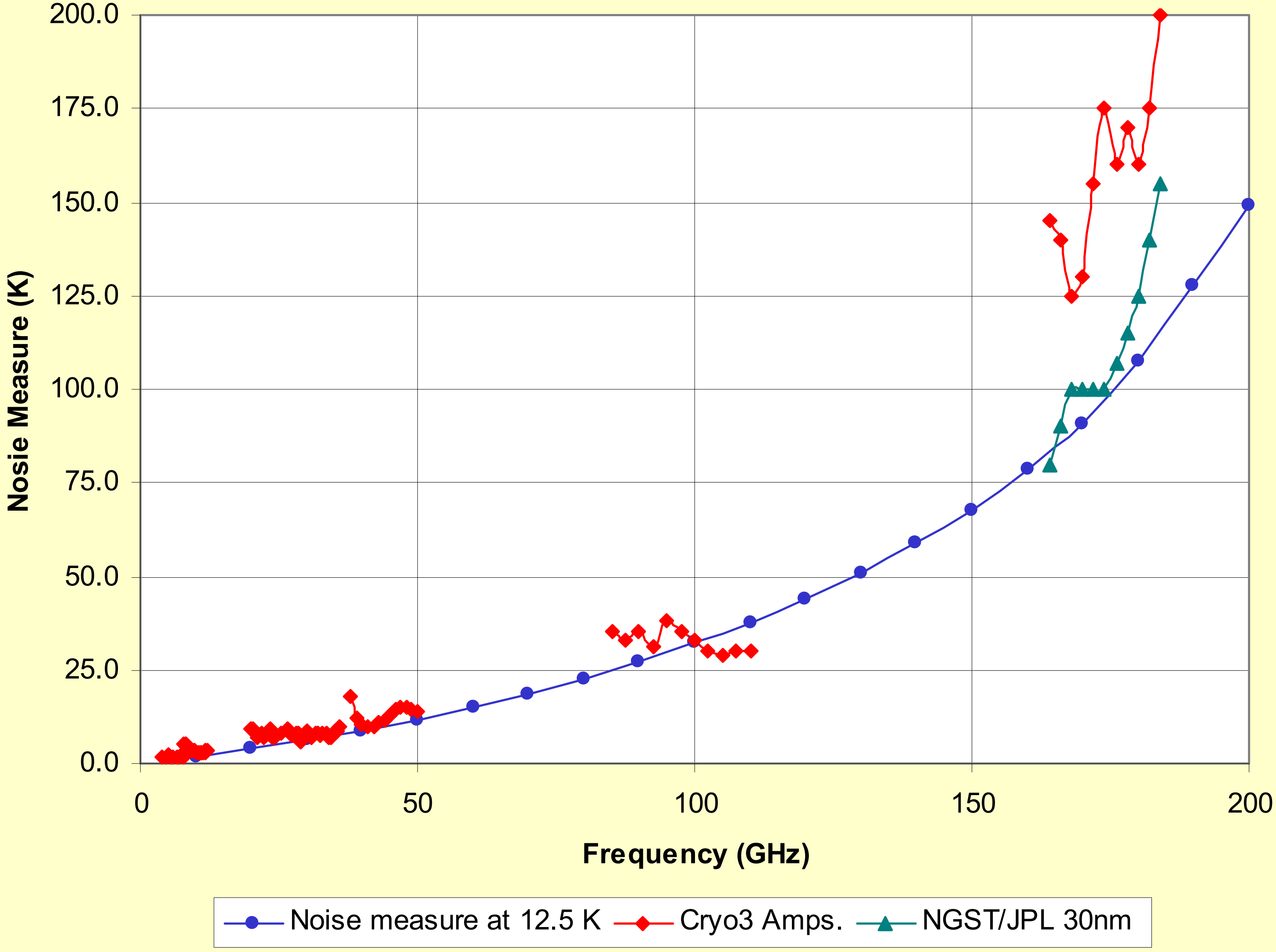


M_{min} Prediction (1991) and State of the Art (2008)



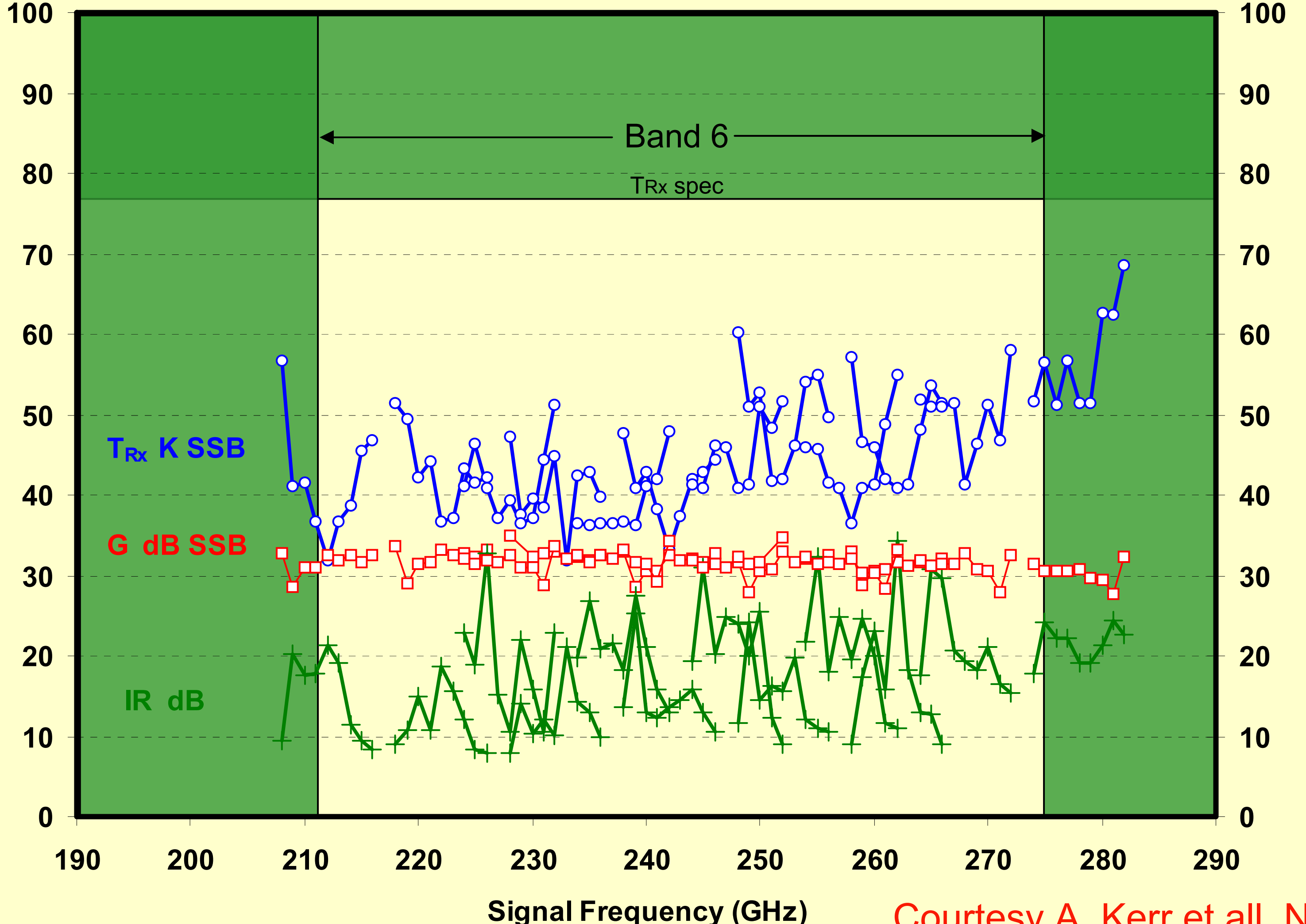
ALMA(MMA) Memo #67,1991

M_{min} Prediction (1991) and State of the Art (2008)



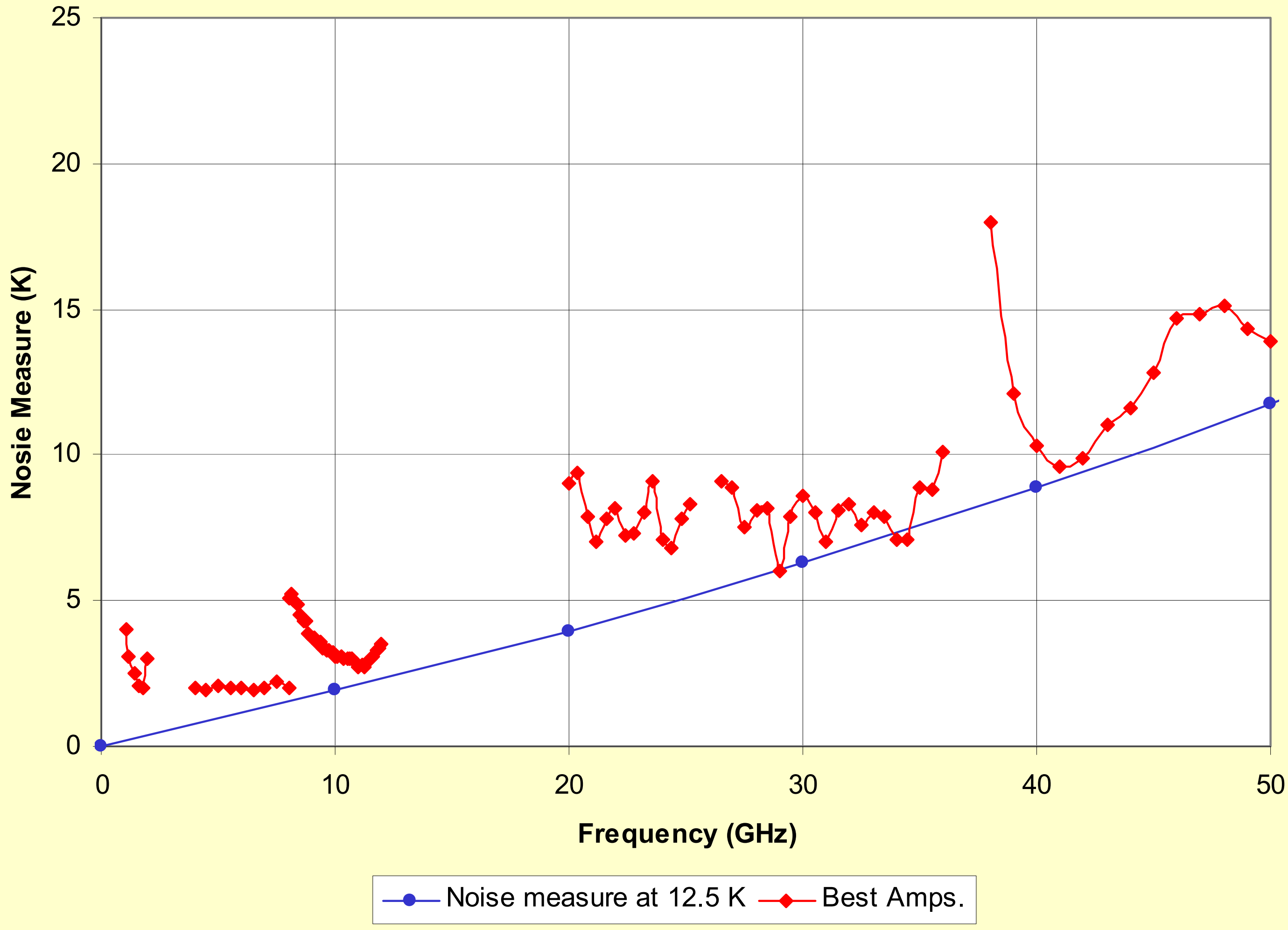
ALMA BAND#6 RECEIVER

LO: 220-270 GHz in 10 GHz steps



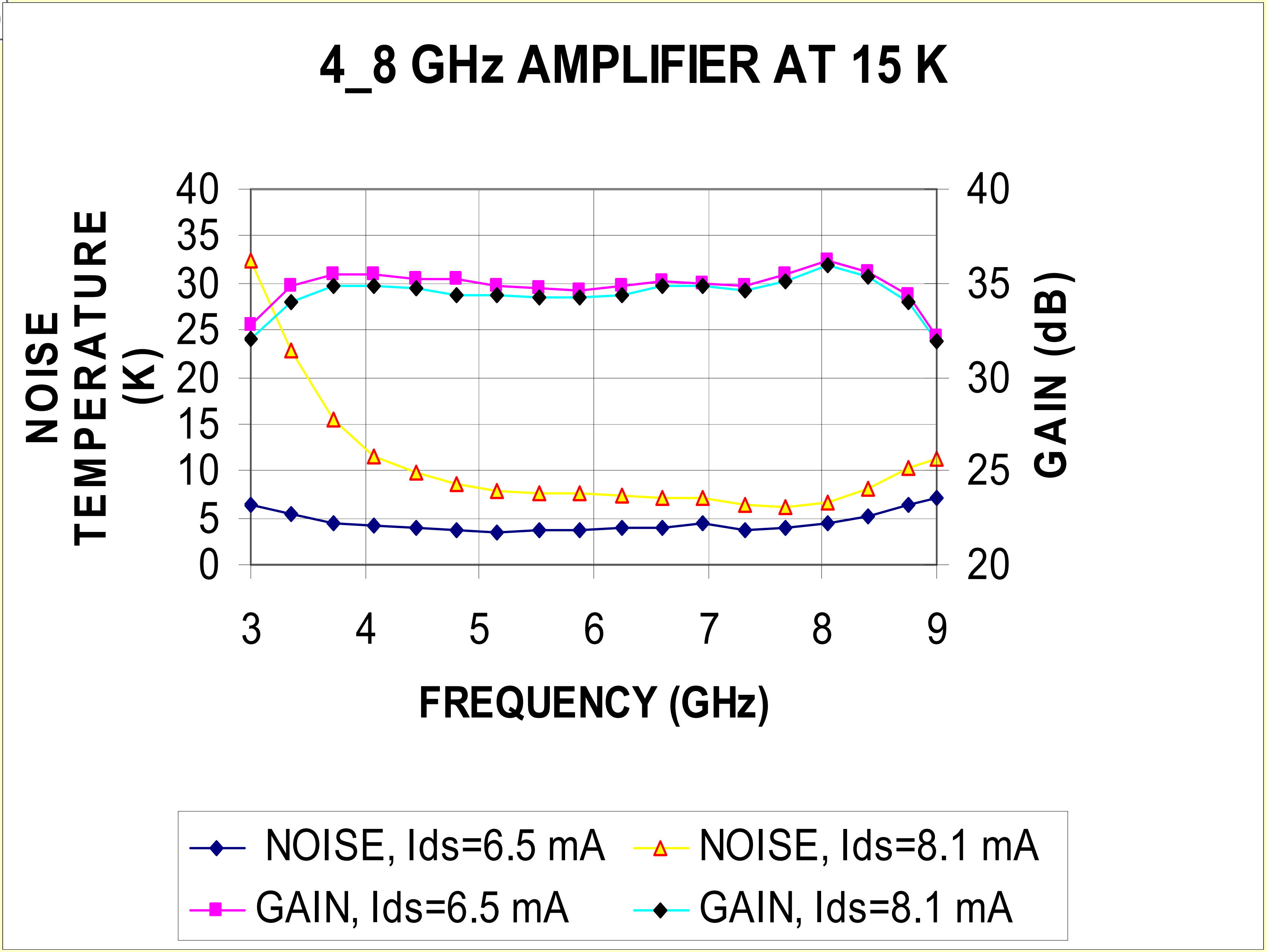
Courtesy A. Kerr et all, NRAO

M_{min} Prediction (1991) and State of the Art (2008)



Questions Still Open:

- Dependence of T_d on device structure and properties of electron transport in the channel is not known
- 300 µm wide InP HFET's do not behave as expected from scaling (this applies to all the discrete wafers evaluated at NRAO)
- 200 µm from cryo3 wafer exhibit a very strong dependence of noise on drain voltage at L, S and C bands
- 80 and 60µm wide devices from cryo3 4044-041 wafer exhibit (sometimes) dc instability which seems to be related to device layout



4_8 GHz AMPLIFIER AT 15 K
NOISE TEMPERATURE (K)
GAIN (dB)
FREQUENCY (GHz)
40
35
30
25
20
15
10
5
0
3
4
5
6
7
8
9
NOISE, Ids=6.5 mA
NOISE, Ids=8.1 mA
GAIN, Ids=6.5 mA
GAIN, Ids=8.1 mA

Is there a new low noise device just around the corner ?

Possible Future Technology: InAs/AlSb HFET

Advantages: very high μ, and $v_s \rightarrow$ high g_m
Disadvantages: impact ionization, high gate leakage currents
State-of-the-art: $f_t \approx 160$ GHz
$T_e \approx 180$ K at 32 GHz and T_a=297K

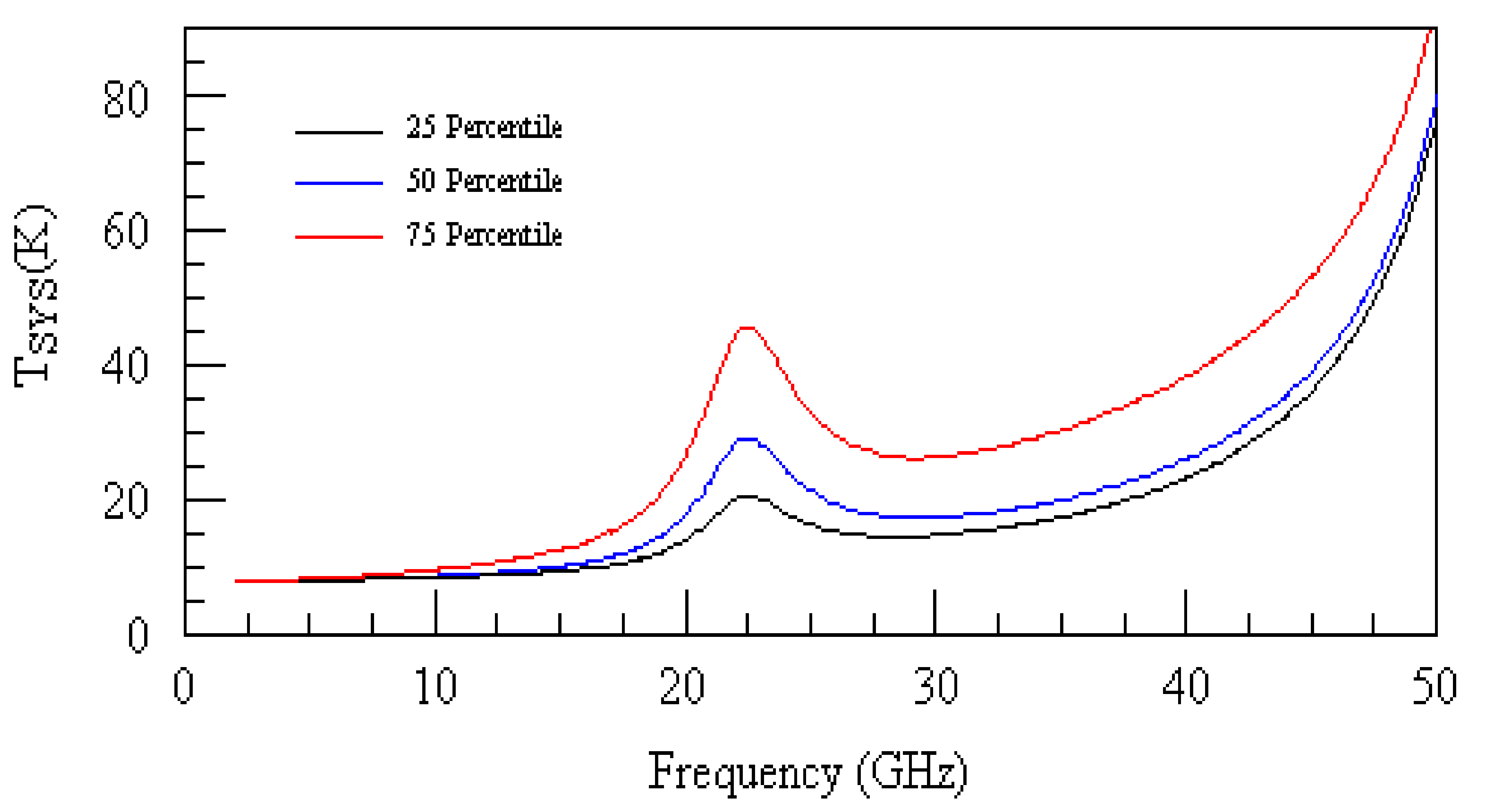
For cryo3 devices: f_t >180 GHz
$T_e \approx$ 80K at 32 GHz and T_a=297 K
$T_e \approx$ 8K at 32 GHz and T_a=18 K

Rick's Performance Metric for an Array

$$FOM = FOV \times B \times \left(\frac{A_{eff}}{T_{sys}} \right)^2$$

$$FOM_M = B \times \frac{A_{eff}\, n}{T_{sys}^2}$$

GBT T_{sys} at Zenith Except Receiver



Source:GBT/Planning Observations/R.Maddalena

To Cool or Not to Cool

Rule of thumb for amplifiers:

$$T_n(77K) \approx \sqrt{5} \times T_n(15K)$$

$$T_n(297K) \approx 10 \times T_n(15K)$$

For 1-2 GHz:

$$T_S(15) = 15K$$

$$T_S(297) = 40K$$

T_n=3 K

T_n=28 K

Wide Band Receivers

- Wide band amplifier: $T_{nav} = M_{min}(f_{max})$
- Wide band feeds: wire–like (lossy)
- Matching of wideband feeds to wide band amplifiers will always produce a structure in the baseline and degrade the noise performance