Ultra-low noise and low-temperature readout electronics *f*<1GHz based on cryoHEMTs made at C2N (formerly LPN): performance and applications

Y. Jin, Q. Dong, L. Couraud, A. Cavanna, U. Gennser, C. Ulysse, E. Cambril

C2N, CNRS, Univ. Paris-sud, Univ. Paris-Saclay, Marcoussis, France
moving to:
C2N, CNRS, Univ. Paris-sud, Univ. Paris-Saclay, Palaiseau, France

Invited talk at WOLTE13, Sorrento, 2018

Outline

- Introduction
  - Motivation
  - Low temperature and low noise *vs* FETs
  - From HEMT to cryoHEMT

- Performance
  - Noise voltage: sub-nV/$\sqrt{Hz}$
  - Noise current: aA/$\sqrt{Hz}$

- Applications

- Conclusions and further developments

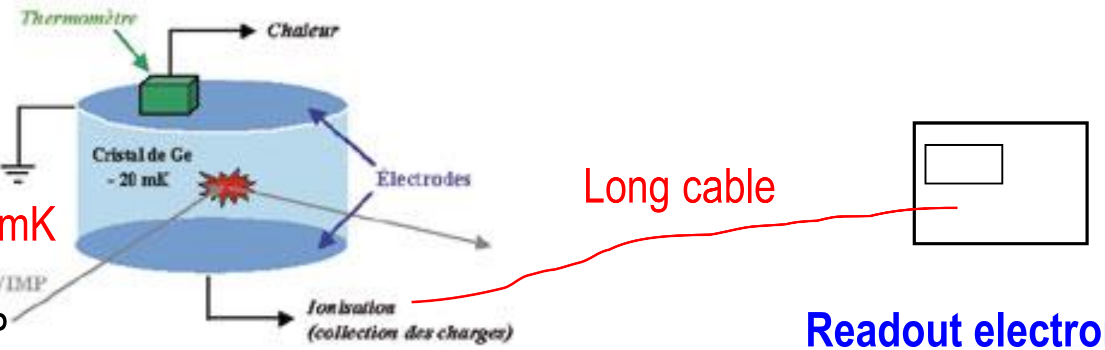
Why low-temperature electronics and the challenge 1/2

- **For most ultra-sensitive detectors: low-temperature → low thermal noise**
- $(4kTR)^{1/2} \rightarrow 50\mathrm{M}\Omega$: at 300K ⇔ 910nV/Hz$^{1/2}$; at 30mK ⇔ 9.1nV/Hz$^{1/2}$

Edelweiss

CDMS
Cryogenic Dark Matter Search

weakly interacting massive particle: WIMP



20mK

Long cable

High impedance Ge detector at 20 mK

Readout electronics at 150 K

due to the long cable:

- **High capacitance → slow down the data acquisition rate**
- **Microphonic noise**
- **Triboelectricity**
- **Capacitive coupling**

} **degrade the intrinsic detectors' performance**

➡ **High performance electronics for high-impedance cryogenic readout electronics**

Low temperature, low power and low-frequency noise

Why low-temperature electronics and the challenge 2/2

Present Low Noise Electronics & Operating Conditions

	Low Frequency		High Frequency	
	Low Impedance	High Impedance	Low Impedance	
Room Temperature	**HEMTs** **BJTs**	**JFETs**	**HEMTs**	commercially available devices
Low Temperature (T < 100 K)	**HEMTs** $f \geq$ MHz	?	**HEMTs** $f > 1$ GHz	commercially available devices

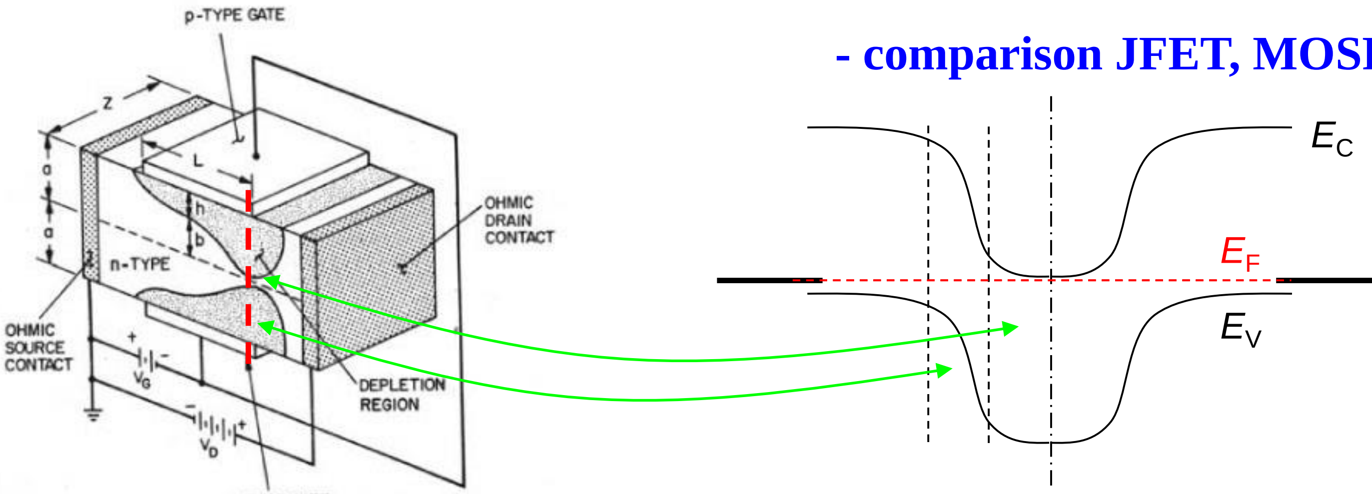
➡The challenge is to fill the above gap:

High performance electronics for high-impedance cryogenic readout electronics

Low temperature, low power and low-frequency noise

Low temperature (LT) and low-frequency (LF) noise *vs* FETs

- comparison JFET, MOSFET and HEMT



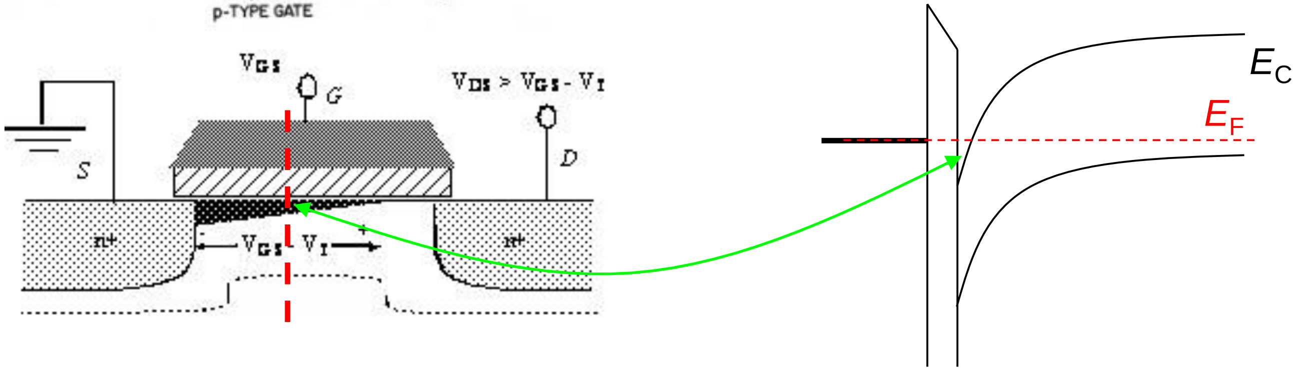
non degenerate e-

freeze-out at LT

limit: T>100K

gate // P-N

low 1/f noise

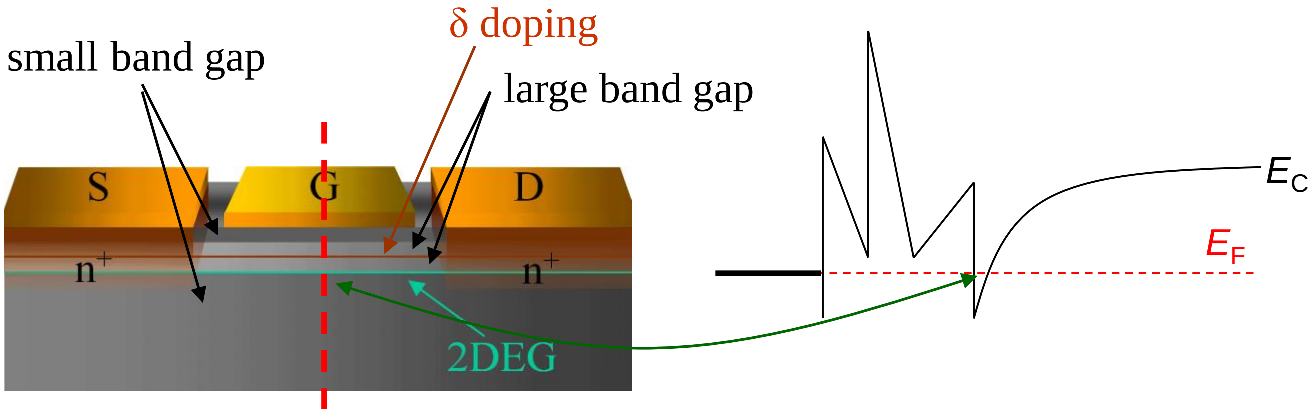


degenerate e-

no LT limit

gate // oxide layer

high 1/f noise



degenerate e-

no LT limit

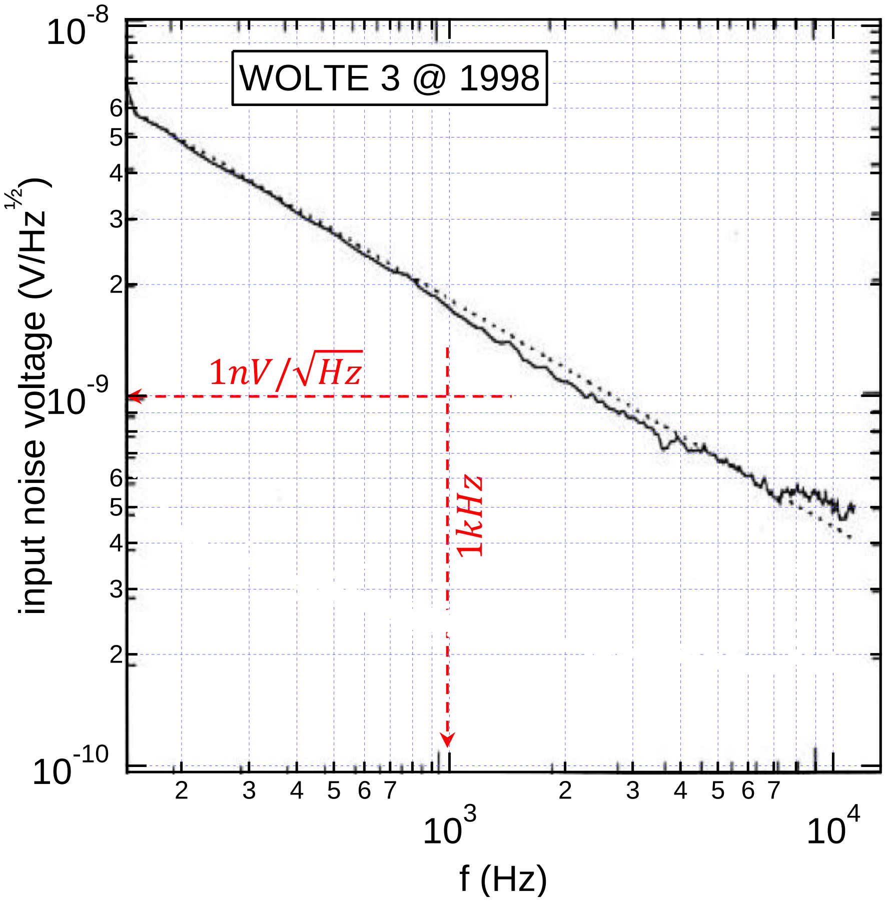
gate // large bandgap

1/f noise ?

From HEMT to cryoHEMT

During a long period:

the input noise voltage > 1 nV/$\sqrt{Hz}$ @ 1kHz and 4.2 K



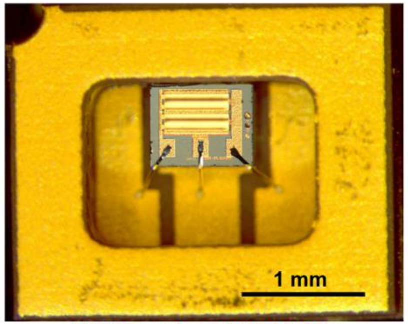
From HEMT to cryoHEMT

More than 10 years collective efforts for optimizing:

Heterostructures by Molecular Beam Epitaxy:

A. Cavanna; U. Gennser

several tens of heterostructures tested



HEMT made at CNRS/LPN

Ohmic and Schottky contacts:

L. Couraud, L. Leroy, A. Durnez, C. Ulysse

EBL (Electron Beam Lithography) and IBE (Ion Beam Etching):

E. Cambril, S. Guilet

several thousands of HEMTs with 4 to 6 steps of EBL

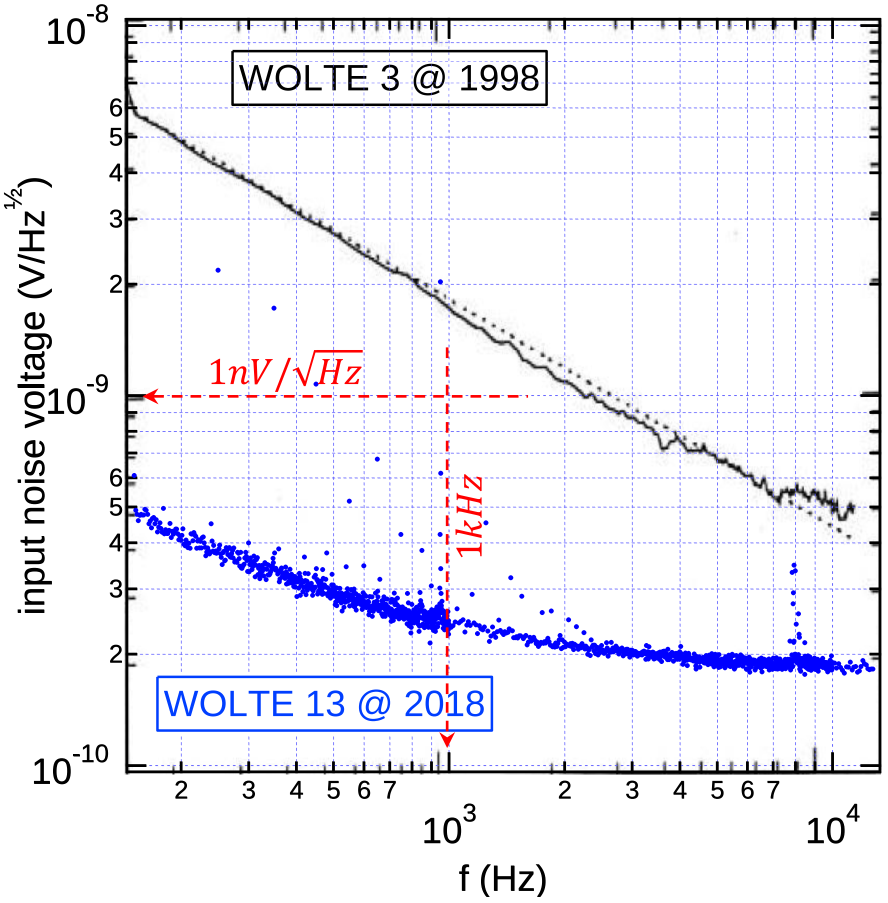
Characterization and simulation:

Q. Dong (PhD & Postdoc since 2009),
YX. Liang (Postdoc 2007-2012), E. Grémion (PhD 2005-2008),
M.C. Cheng, Clarkson Univ. NY (visiting scientist 2007)

several hundreds transistors measured from 300 K to 4.2 K

From HEMT to cryoHEMT

The breakthrough was achieved in 2012 and since then:
the input noise voltage can be « 1 nV/$\sqrt{Hz}$ @ 1kHz and 4.2 K



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Characterization: Noise voltage & noise current

Directly measurable parameters:

Channel voltage PSD

$S_{v-drain}$ **(Power Spectral Density)**

Voltage gain

$$A_v = \delta V_{out(ds)} / \delta V_{in(gs)}$$

Deduced parameters:

Equivalent input voltage PSD

$$e_{nt}^2 = S_{v\text{-drain}} / A_v^2$$

Total equivalent input noise voltage

$$e_{nt} = \sqrt{e_n^2 + e_{ni}^2}$$

Input noise voltage (with R input)

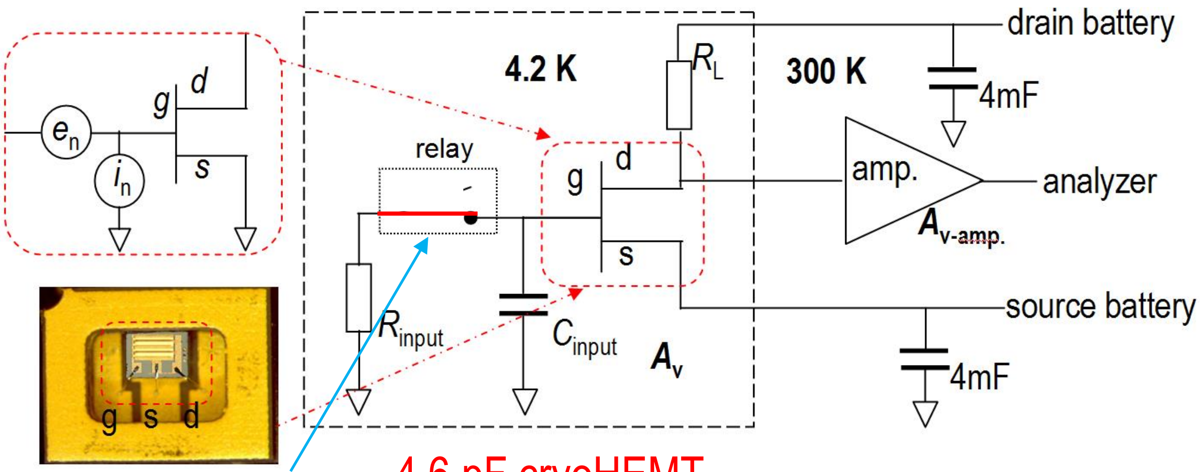
when $e_{ni} \ll e_n$

$$e_n = e_{nt}$$

Input noise current (with R & C input)

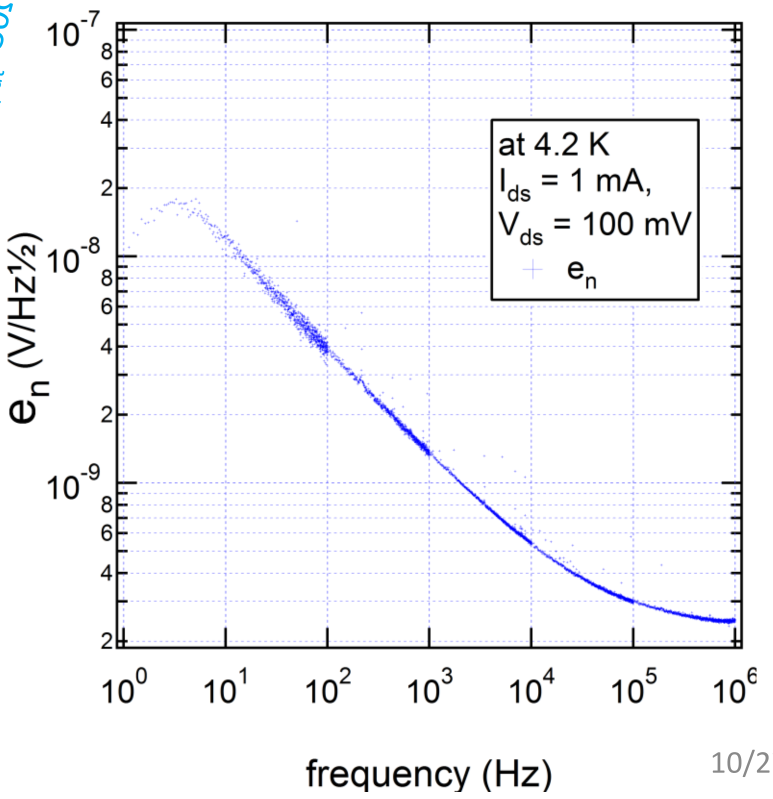
$$i_n = \sqrt{e_{nt}^2 - e_n^2} / |z| = e_{ni} / |z|$$

Appl. Phys. Lett. **105,** 013504 (2014)



4.6 pF cryoHEMT

Noise voltage measurement setup with R_{input}=50Ω



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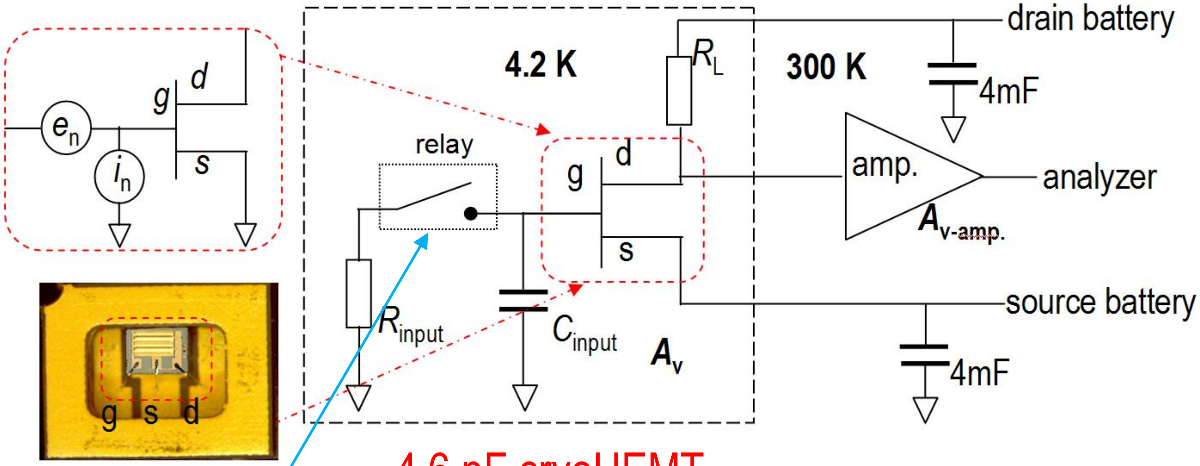
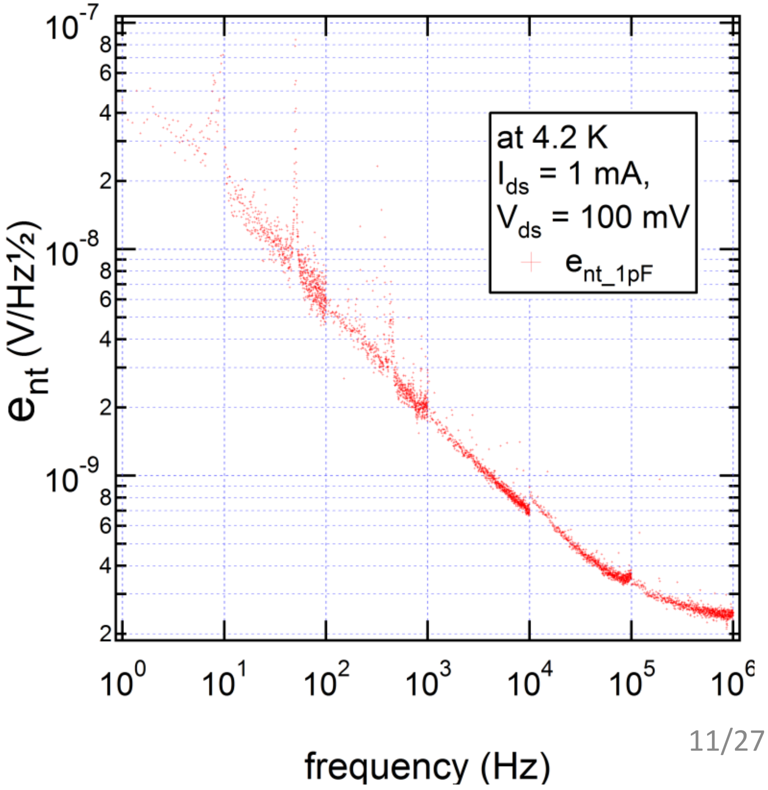


4.6 pF cryoHEMT

Total noise voltage measurement setup with C_{input}=1pF



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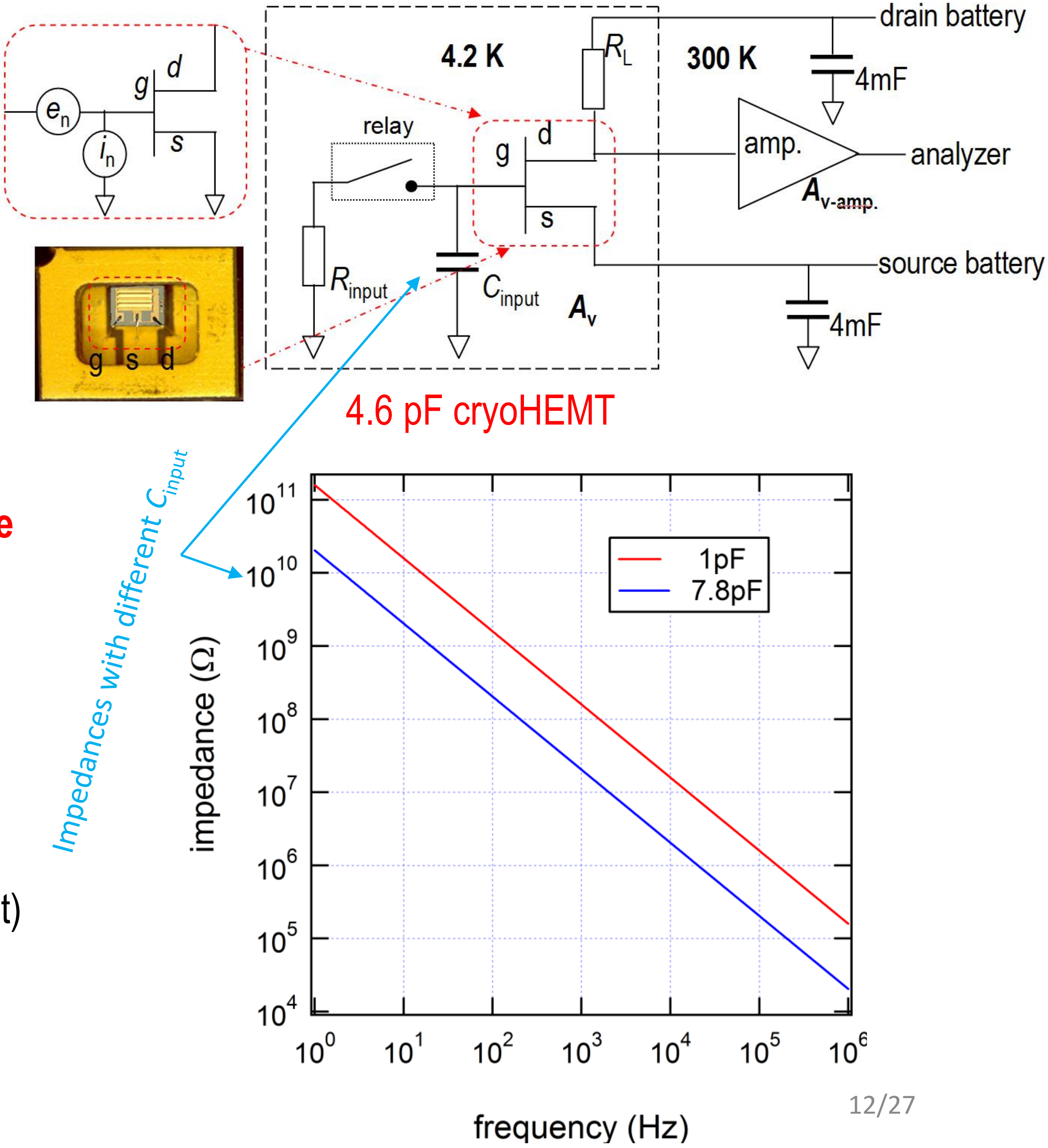
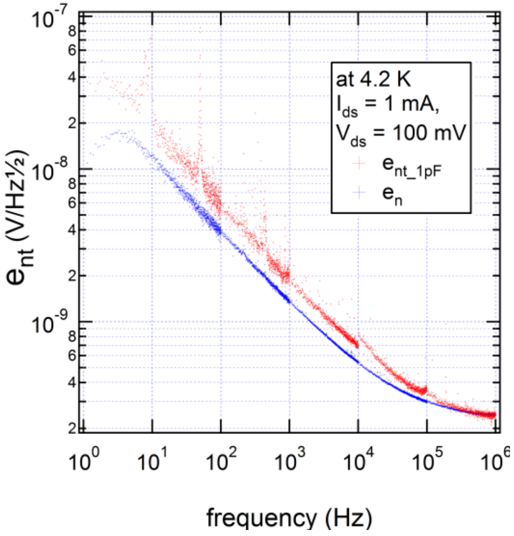
Appl. Phys. Lett. **105,** 013504 (2014)

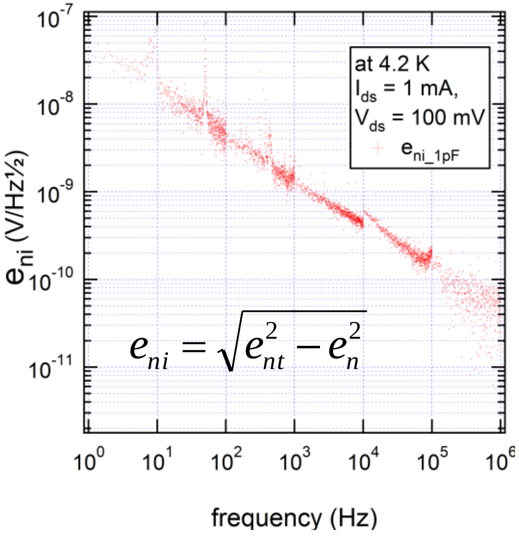


Characterization: noise current measurement

Comparison of capacitor and resistor input

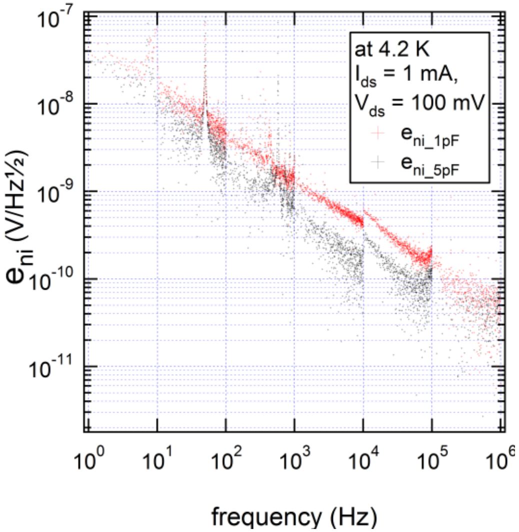


Noise current induced noise voltage



$$e_{ni} = \sqrt{e_{nt}^2 - e_n^2}$$

With two different C_{input}

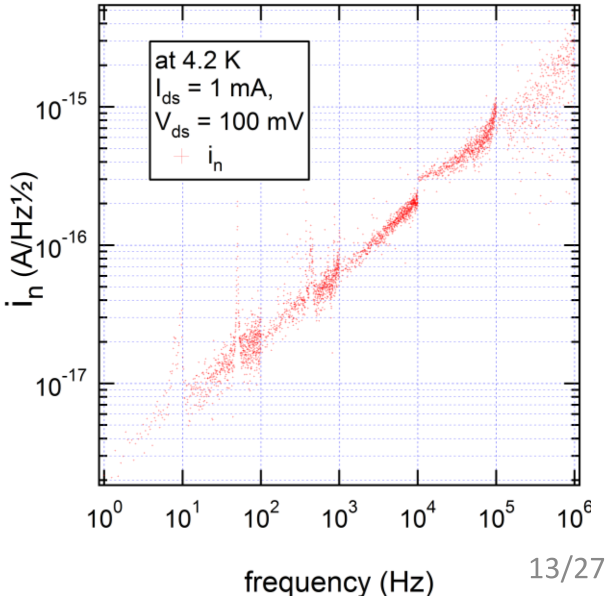


$$e_{ni\_1} = i_n\left(\frac{1}{2\pi f\,(C_{input\_1} + C_{HEMT})}\right)$$

$$e_{ni\_2} = i_n\left(\frac{1}{2\pi f\,(C_{input\_2} + C_{HEMT})}\right)$$

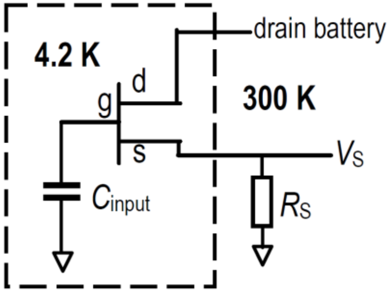
$$C_{HEMT} \approx 6.8\,pF$$

The deduced noise current



Characterization: gate leakage current measurement

Using a follower configuration, the gate leakage current can be deduced by measuring the variation of the source voltage



For the working point

V_{ds} = 100 mV, I_{ds} =1 mA

V_{gs} = -90 mV

Using C_{input} setup,

e.g., C_{input} = 5 pF

$\delta V_{Cinput} = \delta V_S = 0.5$ mV

$\delta t = 480$ s

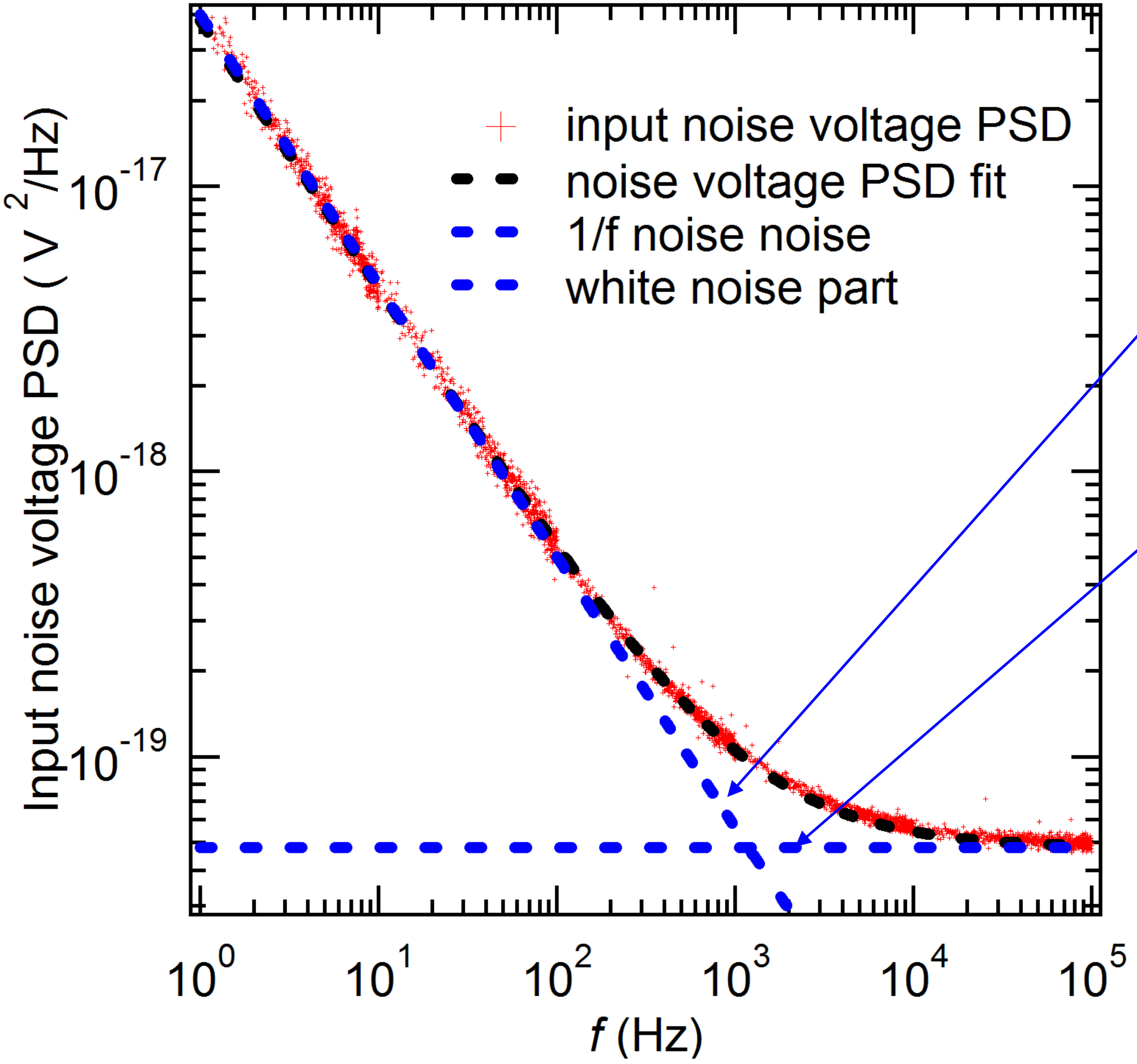
$I_{gs} = \delta V_{Cinput} C_{input} / \delta t \approx 5.2$ aA!

Input impedance $V_{gs}/I_{gs} \approx 17$ PΩ!

Appl. Phys. Lett. **105,** 013504 (2014)

Understanding (1/3): noise voltage spectrum compositions

Noise voltage spectrum = 1/f noise + white noise



PSD: Power Spectrum Density

Noise voltage PSD:

1/f noise component:

$$e^2_{n-1/f} = 4.0\times10^{-17} / f^{0.95}$$

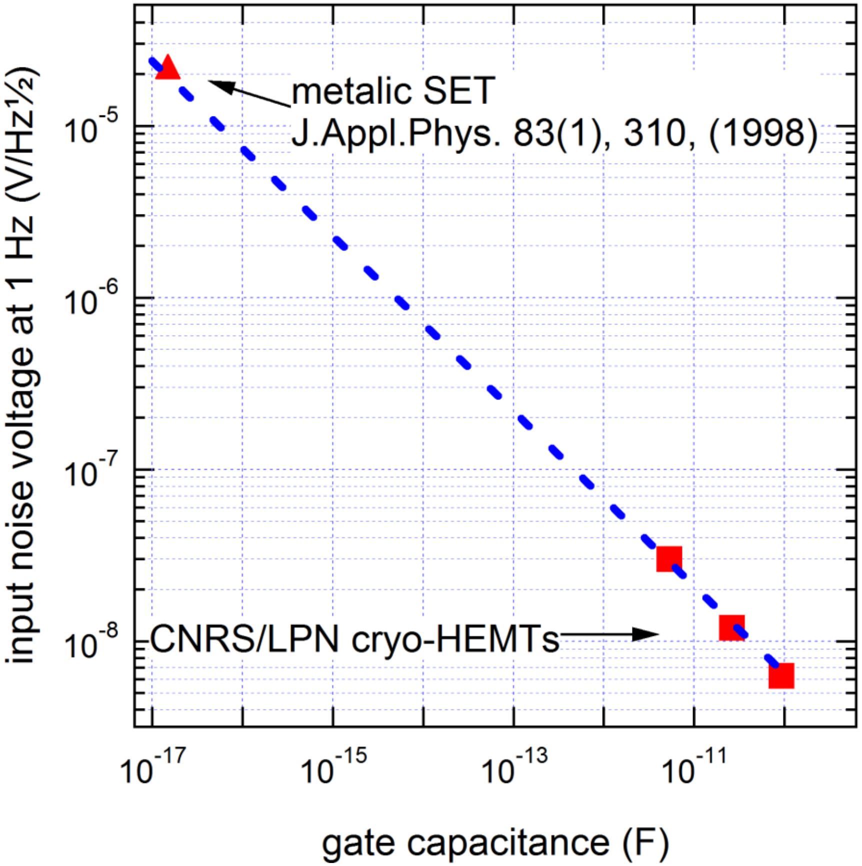
White noise component:

$$e^2_{n-white} = 4.8\times10^{-20}$$

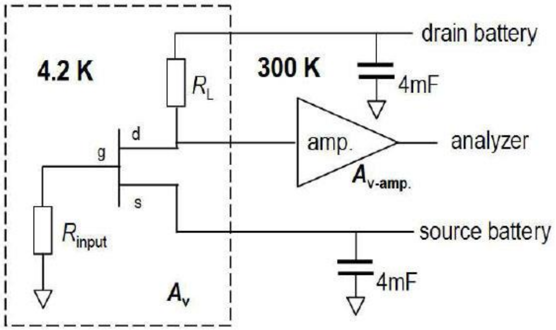
APL 105, 013504 (2014)

Understanding (2/3): input 1/f noise voltage

Input noise voltage e_n vs. gate capacitance C_{gs}



50Ω input: $R_{\mathrm{input}} = R_{\mathrm{in}} = 50\ \Omega$, $R_L = 300\ \Omega$



$$e_n \propto \frac{1}{\sqrt{C_{gs}}}$$

$$e_n \propto \frac{1}{\sqrt{C_{gs}}} \sim \frac{1}{\sqrt{N}}$$

fundamental of the 1/*f* noise voltage in field-effect devices: standard deviation of the average value <*N*> in an open system *N* (grand canonical ensemble) - central limit theorems

Understanding (3/3): input white noise voltage

Reduced thermal shot noise

$$e_{n-white}^{2} \approx \frac{F\,2eI_{ds}^{2}}{g_{m}^{2}}$$

***F*: Fano factor which depends on the gate length**

APL 105, 013504 (2014)

Performance: Input noises *vs.* gate capacitance C_{gs}

Noise voltage e_n, Total noise voltage e_{nt}, Noise current i_n (at 4.2 K)

L_gxW (µm²)		1.5×10^5	6.4×10^4	2.0×10^4	2.0×10^3	4.0×10^2
C_{gs} (pF); C_{gd} (pF)		236; 8.9	103; 8.9	33; 3.5	4.6; 1.0	1.8; ~0.6
V_{ds}(mV); I_{ds}(mA)		100; 1.0	100; 1.0	100; 1.0	100; 1.0	100; 0.5
g_m (mS); g_d (mS)		52; 0.4	40; 1.2	115; 1.3	44; 1.3	15; 0.8
$ft = g_m/(2\pi C_{gs})$ (Hz)		3.5×10^7	6.2×10^7	5.5×10^8	1.5×10^9	1.3×10^9
e_n (nV/Hz$^{1/2}$)	@1Hz @10Hz @100Hz @1kHz	5.4 1.7 1nV/Hz$^{1/2}$ @30Hz 0.52 0.24	6.3 2.1 0.76 0.34	14 4.5 1.5 0.57	30 12 4.5 1.4	100 30 10 2.7
$e_{n\text{-white}}$ (nV/Hz$^{1/2}$)		0.18	0.22	0.12	0.21	0.4
i_n (aA/Hz$^{1/2}$)	@1Hz @1kHz	21 6.8×10^2	15 5.1×10^2	9.1 2.4×10^2	2.2 70	3.6 57
R_n (Ω)	@1Hz @1kHz	2.6×10^8 3.5×10^5	4.2×10^8 6.3×10^5	1.5×10^9 2.2×10^6	1.4×10^{10} 2.0×10^7	2.8×10^{10} 3.7×10^7
T_{nt} (mK)	@1Hz @1kHz	4.1 5.9	3.4 6.2	4.6 5.0	2.4 3.6	13 5.6

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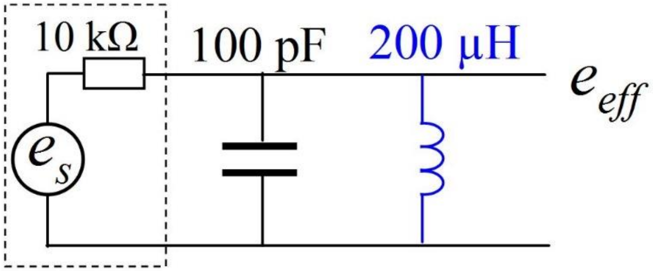
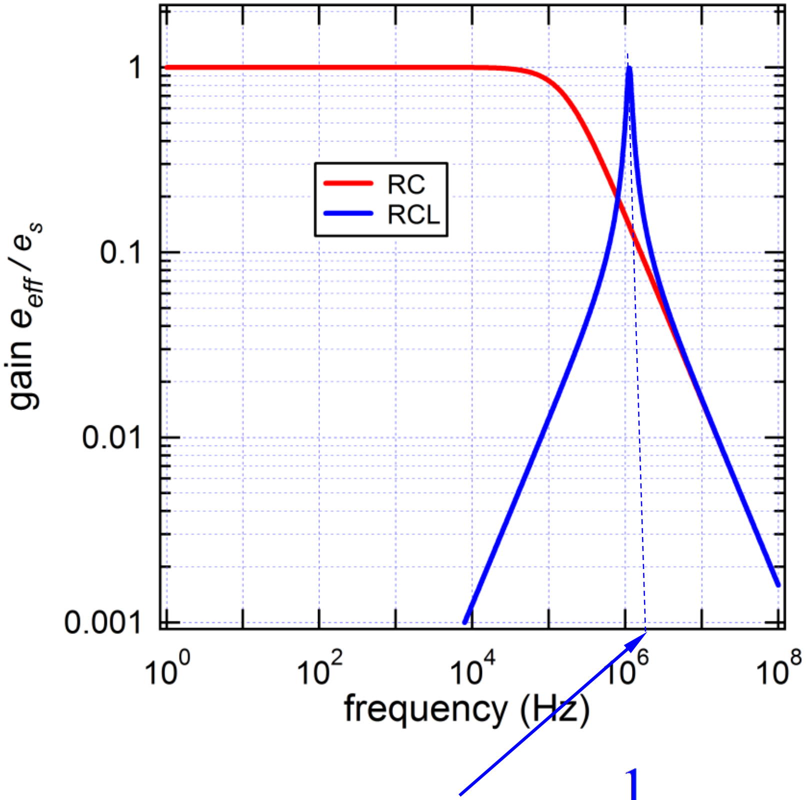
Applications: Mesoscopic Physics - I

First cryo-preamplifier by F. Pierre, A. Anthore *et al* at C2N (formerly LPN)

In a mK dilution refrigerator, to readout signals at ~ 1 MHz:
Capacitance of the cable from mK to K: 100 pF
Impedance of to be measured system: 10 kΩ
At 1 MHz, signal gain < 0.2

To avoid signal loss at high *f*:
Introducing an inductor *L* for a chosen *f*
At 1 MHz, signal gain ≈ 1





$$f_0 = \frac{1}{2\pi\sqrt{LC}}$$

CryoHEMTs based cryogenic amplifier facilitates:

Quantum limit of heat flow across a single electronic channel **Science 342, 601 (2013)**

Primary thermometry triad at 6mK in mesoscopic circuits **Nature Commun. 7, 12908 (2016)** **±9x10^{-32} A^2/Hz**

Heat Coulomb blockade of one ballistic channel **Nature Phys. 14, 145 (2018)**

Applications: Mesoscopic Physics - II

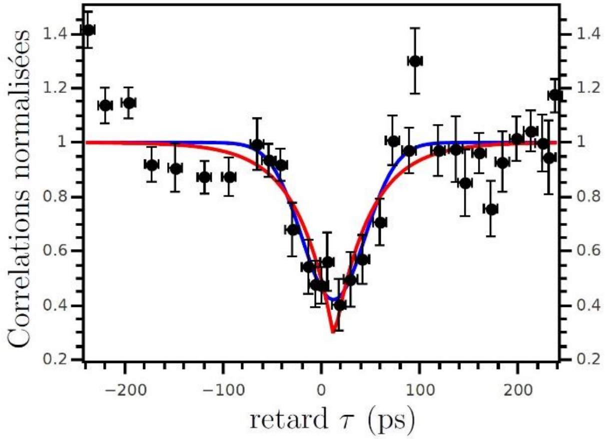
Based on the work by F. Pierre, A. Anthore *et al* @ LPN

G. Fève *et al* at LPA, ENS Paris

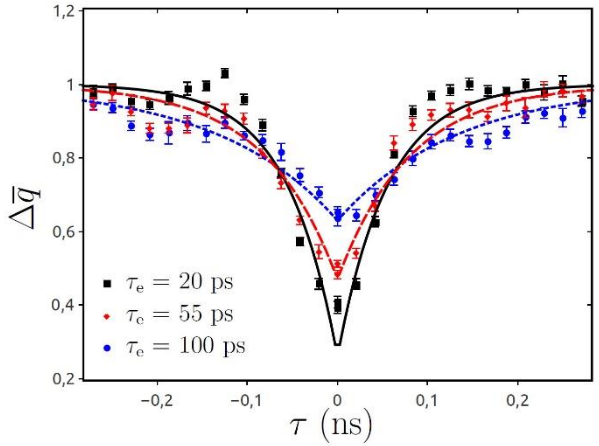
Comparisons: NF LI-75A and cryoHEMT (from V. Freulon thesis at LPA, ENS Paris)

Signal-to-noise ratio *SNR*: $$SNR = \frac{\int_{f_{min}}^{f_{max}} du\, S_v^p(u)}{\left[\int_{f_{min}}^{f_{max}} du\, (S_v^a)^2/2\right]^{1/2}} \sqrt{T_{meas}}$$

PSD of the measured voltage: S_v^p; PSD of the amp input noise voltage e_n: $S_v^a = e_n^2$ and measurement duration T_{meas} ➡For a fixed *SNR*: $T_{meas} \sim e_n^4$



By NF LI-75A at 300 K,
for one point: 2.56×10^4s ≈ 7 hours!
SNR = 10!



By cryoHEMT preamplifier at ≤ 4.2 K,
for one point: 2.25×10^2s ≈ 4 minutes!
SNR = 30!

Hong-Ou-Mandel experiment for temporal investigation of single-electron fractionalization,

Nature Commun. 6, 20 (2015)

Comparisons: NF LI-75A at 300 K and cryoHEMT amplifier at 4.2 K

	According to NF Corporation	4.6 pF cryoHEMT Made at CNRS/LPN
Operating temperature	300 K	0 K to 77 K
	NF LI-75A Data obtained @ 300 K	CryoHEMT amplifier Data obtained @ 4.2 K Power consumption: 0.25mW
Input impedance	100 MΩ // 50 pF Voltage gain of 100	10 PΩ* // 15 pF Voltage gain of about 10
Noise voltages	2 nV/Hz½ at 1 kH	1.42 nV/Hz½ at 1 kHz 0.3 nV/Hz½ at 100 kHz 0.24 nV/Hz½ at 1 MHz
Noise currents	*14 fA/Hz½ **	60 aA/Hz½ at 1 kHz 0.7 fA/Hz½ at 100 kHz 2 fA/Hz½ at 1 MHz

Eur. Phys. J. Special Topics* ***172**, 163 (2009)*

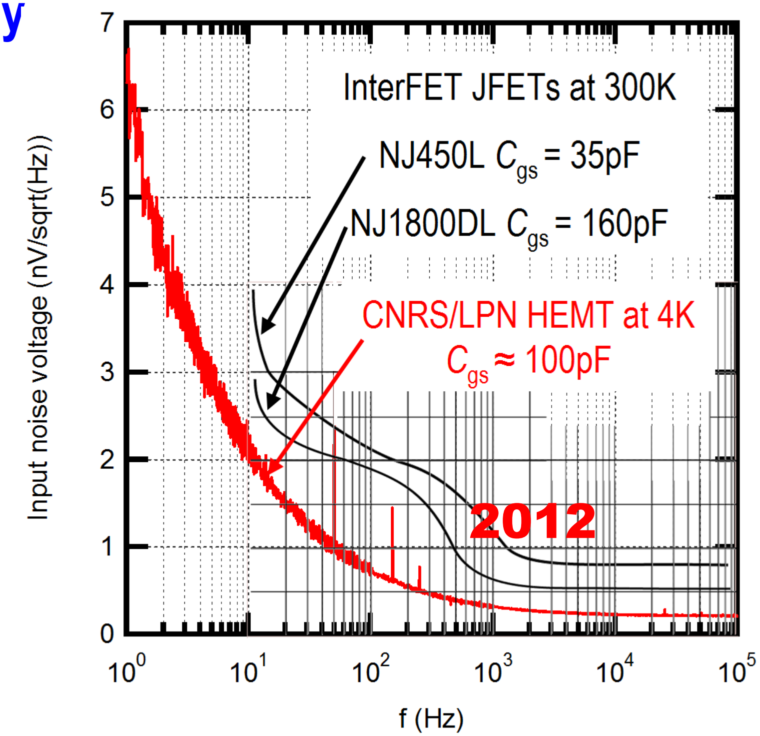
*cryoHEMT input impedance > 10 PΩ: 10^{16} Ω

Applications: Astrophysics CDMS

B. Sadoulet team at UC Berkeley

- Comparison of the input noise voltage between cryoHEMT and JFETs

  (by the C2N)



- Comparison of the heat dissipation and the sensibility threshold

	Temperature	Heat dissipation	Sensibility threshold
JFET	150 K	5.5 mW	133 electrons
CryoHEMT	4.2 K	0.1 mW	35 electrons

An HEMT-Based Cryogenic Charge Amplifier for Sub-kelvin Semiconductor Radiation Detectors, J. Low Temp. Phys. 184, 505 (2016)

A HEMT-Based Cryogenic Charge Amplifier with sub-100 eVee Ionization Resolution for Massive Semiconductor Dark Matter Detectors

http://arxiv.org/abs/1611.09712 (2018)

Applications of cryoHEMTs and Publications in

- Mesoscopic Physics: C2N, Palaiseau; LPA ENS Paris; IN, Grenoble

1 ***Science***; 1 ***Nature Physics***; 2 ***Nature Commu.***

- Low Temperature STM: LPS, Orsay; Leiden Univ.

Charge trapping and super-Poissonian noise centers in a cuprate superconductor

Nature Physics (accepted) (2018)

Atomic scale shot-noise using cryogenic MHz circuitry

Review of Scientific Instruments (accepted) (2018)

- Low Temperature Nano-mechanical Resonators: ICFO, Barcelona

Ultrasensitive displacement noise measurement of carbon nanotube mechanical resonators

Applied Physics Letters 113, 063104 (2018)

Improving the read-out of the resonance frequency of nanotube mechanical resonators

Nano Letters 18, 5324 (2018)

- Low Temperature Detectors: IRFU, CEA-Saclay

Toward large µ-calorimeters x-ray matrices based on metal-insulator sensors and HEMTs/SiGe cryo-electronics

Proc. SPIE 2016, vol.9905, 99050S (2016) (for *X-ray detection*)

High impedance TES with classical (cryogenic HEMTs) readout electronics: a new scheme toward large x-ray matrices

Proc. SPIE 10699, *Space Telescopes and Instrumentation 2018: Ultraviolet to Gamma Ray, 106995T* (2018)

- Superconductor Circuits: LPS, Orsay; Collège-de-France, Paris

- Cryogenic Dark Matter Detection: Edelweiss III: IPNL, Lyon; Super-CDMS: SLAC-Stanford, Berkeley; Tsinghua Univ. Beijing

- CryoHEMTs Based Amplifiers by « Stahl Electronics »

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Conclusions

High impedance and low frequency cryoelectronics

	Low Frequency		High Frequency	
	Low Impedance	High Impedance	Low Impedance	
Room Temperature	**JFETs** **BJTs**	**JFETs**	**HEMTs**	Commercially available devices
Low Temperature (T < 100 K)	**HEMTs** *f* ≥ MHz **CryoHEMTs**	**CryoHEMTs**	**HEMTs** *f* > 1GHz **CryoHEMTs** Tested up to 150MHz	Commercially available devices Made at CNRS/C2N Formerly: CNRS/LPN

Our cryoHEMTs facilitate the following accomplishments:

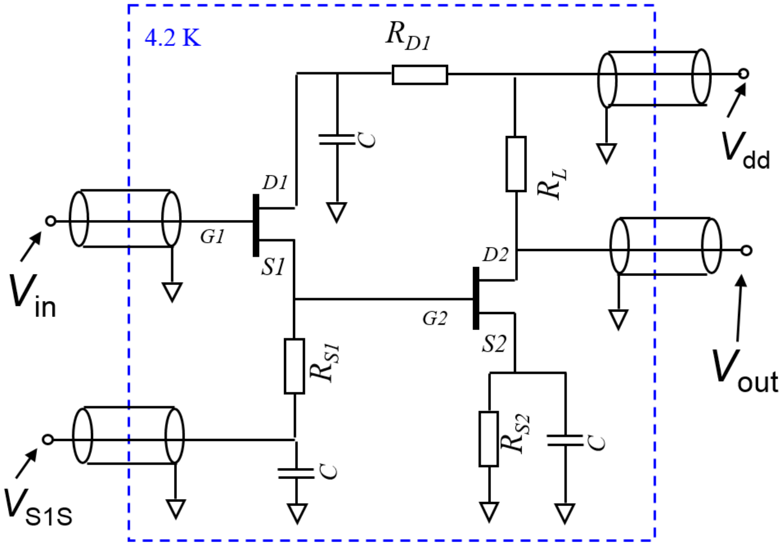
- **Reaching unprecedented low noise current and decrease significantly noise voltage**
- **Attaining unrivaled readout rates and improve the *Signal-to-Noise Ratio***
- **Realizing novel experimental observations**

Their implementation has already resulted in the publications of

1 *Science*, 2 *Nature Phys.*, 2 *Nature commu.* 1 *Nano Lett.*

Further Developments: LT and LF amplifier

- Follower + Amplifier: low input capacitance and low noise voltage at LF



Using two C_{gs} = 236pF cryoHEMTs:
C_{input} = 10pF and $R_{input} > 10^{15}\Omega$
e_n = 1nV/Hz @60Hz

$g_{m1}R_S > 100 \rightarrow C_{in} \approx C_{gd1}$ instead of C_{gs1}

Benefits of the follower:

- enabling cryoHEMTs with very large C_{gs} (to reduce LF noise)
- minimizing feedback effect
- having low output impedance $1/g_{m1}$

Disadvantage of "follower + amplifier":

- minimum input noise voltage e_1 increases to $\sqrt{e_1^2 + e_2^2}$