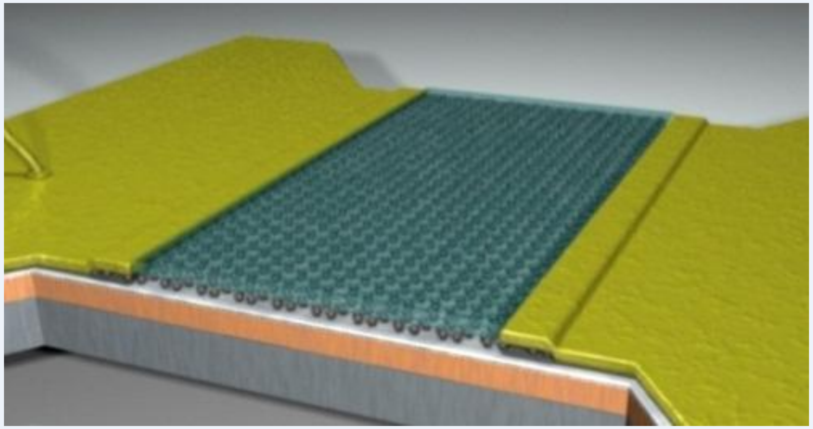
laboratoire pierre aigrain
électronique et photonique quantiques

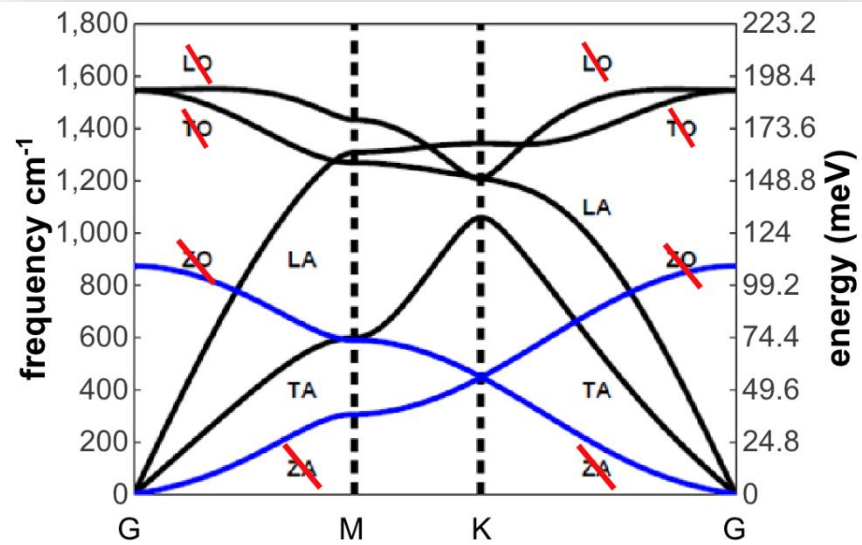
Hot electron cooling by acoustic phonons in graphene



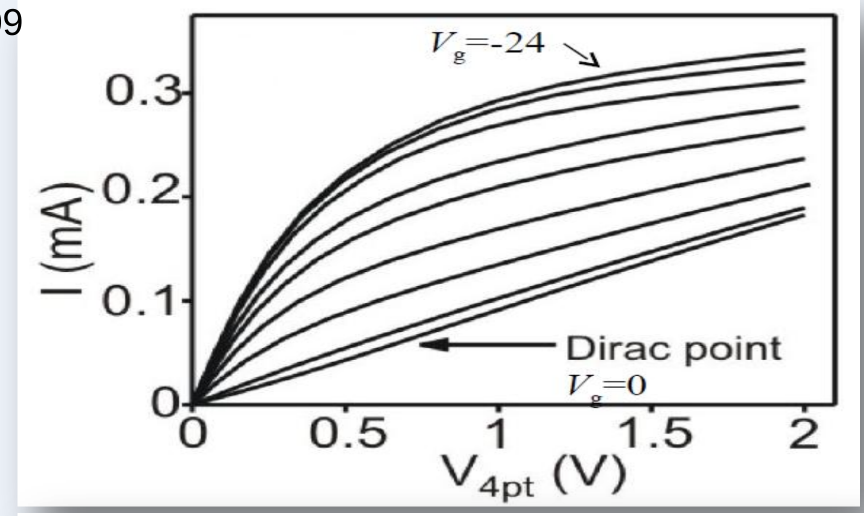
Andreas Betz, F. Vialla, D. Brunel, C. Voisin, G. Fève,
J.-M. Berroir, B. Plaçais, E. Pallecchi (Ecole Normale Supérieure)
M. Picher, A. Cavanna, A. Madouri
(Laboratoire de Photonique et Nanostructures)

Laboratoire Pierre Aigrain – Ecole Normale Supérieure
24 rue Lhomond, 75231 Paris Cedex 05 France
www.lpa.ens.fr

Electron-phonon in graphene

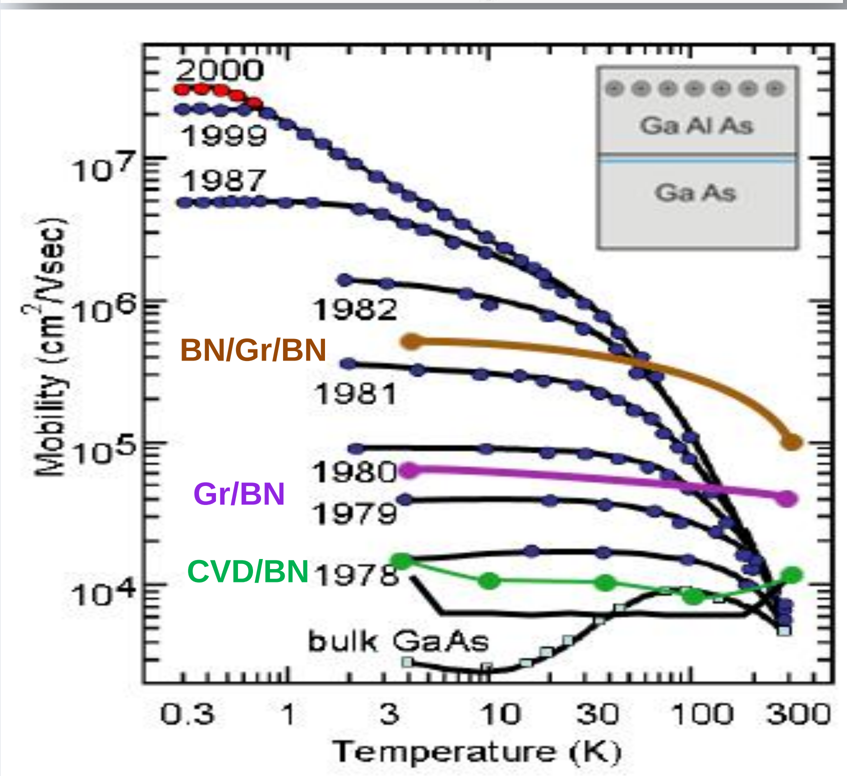


Barreiro, PRL 2009



optical → **strong interaction**

acoustic → **weak interaction**



- **large OP energy & strong interaction**
- **small AP energy & weak interaction**

Mayorov, Nano Lett., 2011, **11** (6)
Dean, Nature Nanotech **5**, 722–726 (2010)
Gannett, APL **98**, 242105(2011)

Questions:

What is the signature of 2D electron-acoustic phonon coupling?

How weak is acoustic phonon coupling in graphene?

Theory :

Kubakaddi, PRB 2009

Viljas,Heikkila PRB 2010

Bistrizer, PRL 2009

Experiments :

Fay et al. PRB 2011 (noise thermometry)

Efetov et al. PRL 2010 (conductivity)

Outline

1) Electron-phonon cooling at 2D
2) Fabrication & noise thermometry
3) Results

Theory: LA phonon cooling in 2D

Heat transfer to AP in the <u>ideal</u> metallic regime (high n_s)

cooling power

(metals)

$$Q = Volume \times \Sigma\left(T_e^5 - T_{ph}^5\right) \quad (3D)$$

$$Q = Area \times \Sigma\left(T_e^4 - T_{ph}^4\right) \quad (2D)$$

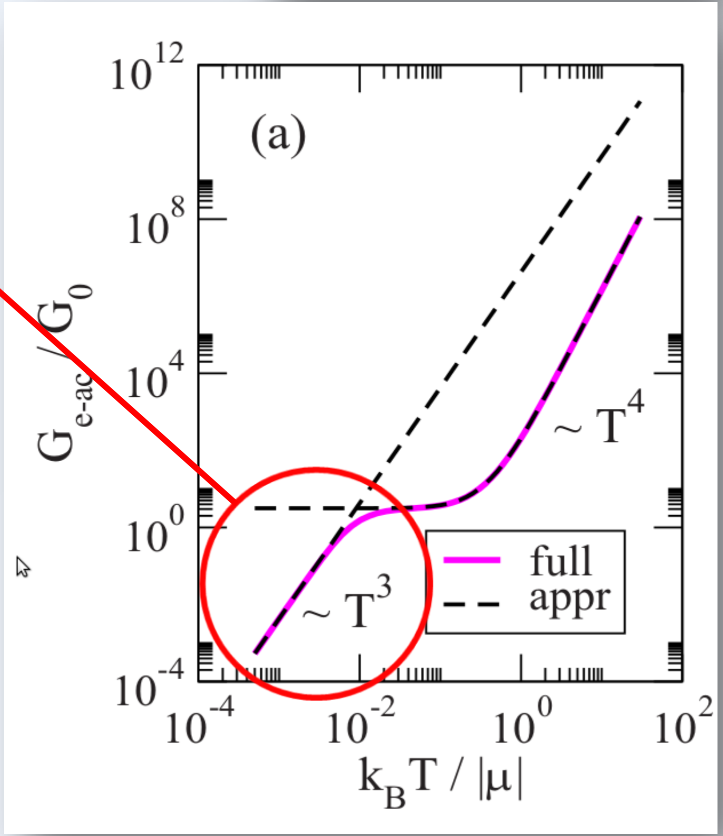
$$Q = Length \times \Sigma\left(T_e^3 - T_{ph}^3\right) \quad (1D)$$

(nanotubes)

$$\Sigma_{LA} = \frac{\pi^2 D^2 k_B^4}{15\rho\hbar^5 v_F^3 c^3} \times |E_F|$$

heat sink

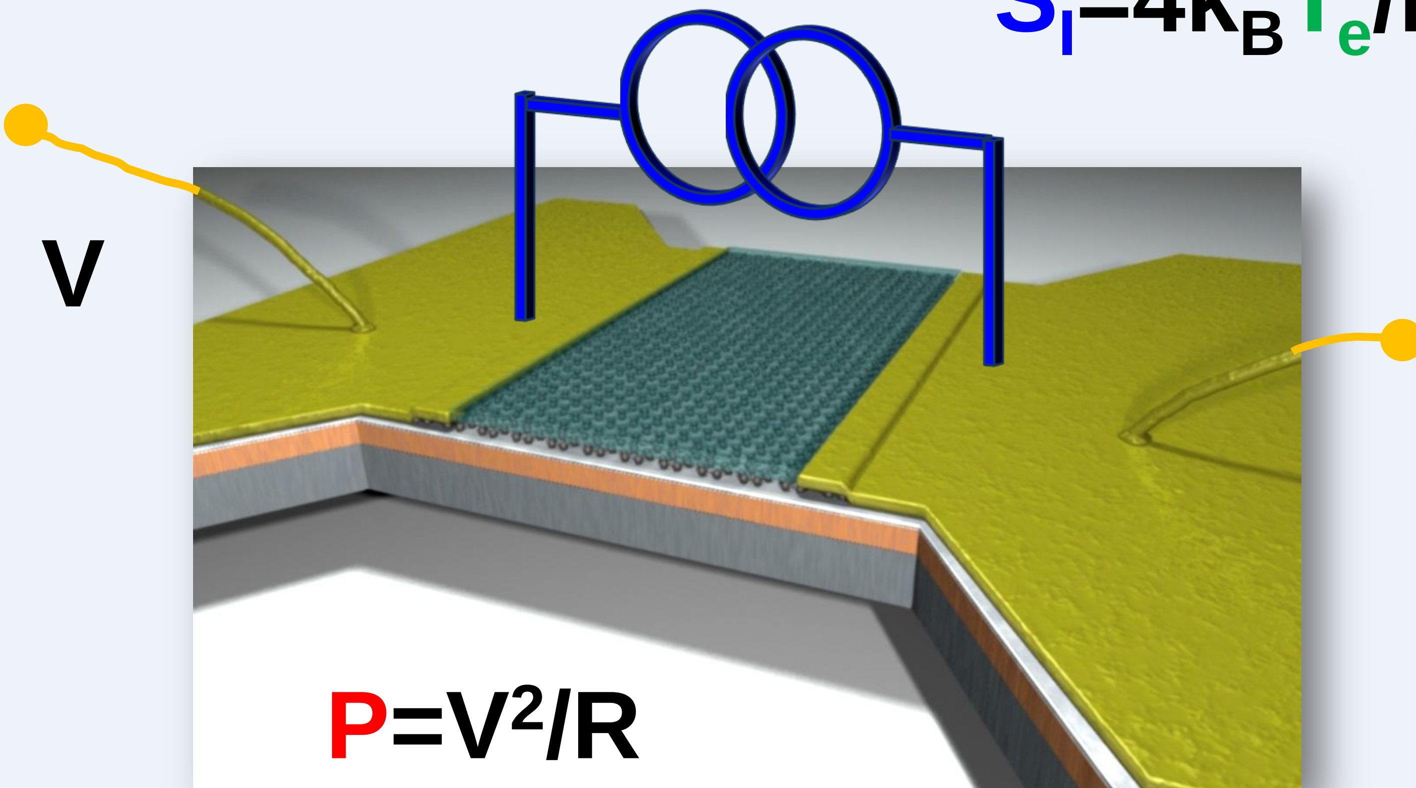
$$G = 4\Sigma T^3 \Delta T$$

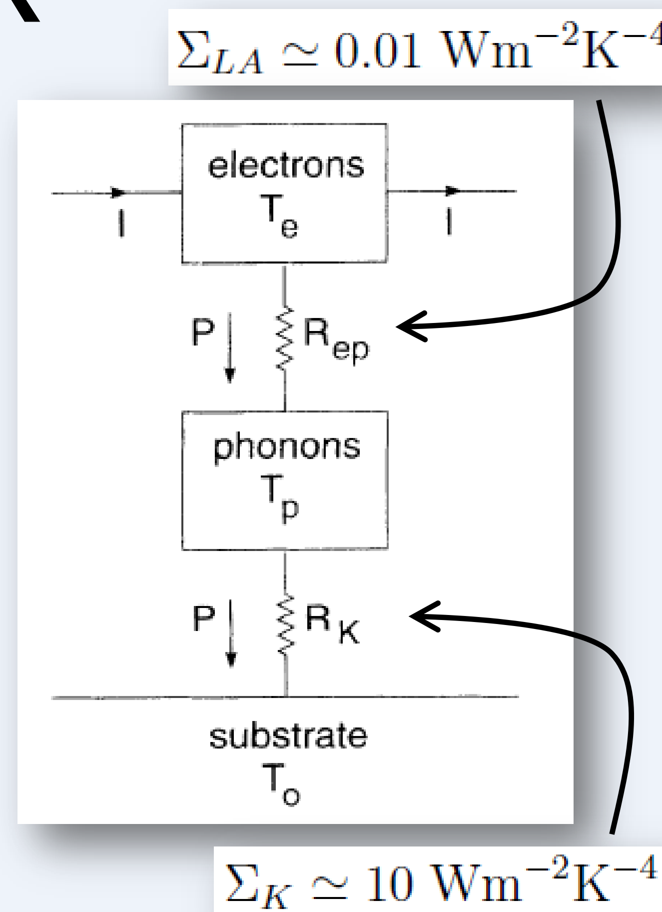


Viljas,Heikkila PRB 2010

Experimental principle

$S_I = 4k_B T_e / R$





Balandin, Nature Mat. 2011

Direct measurement of AP coupling

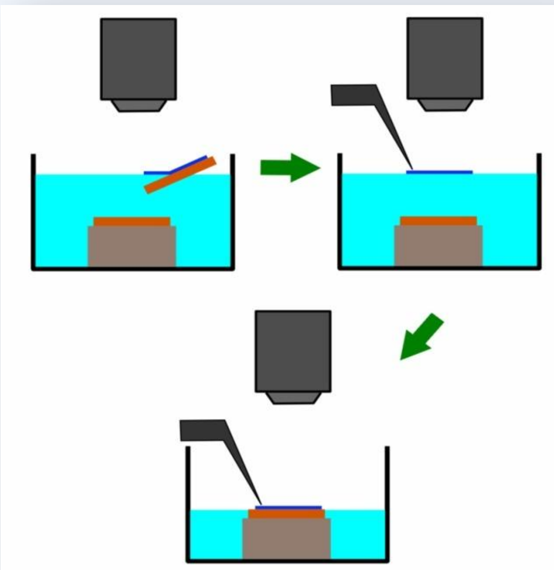
Electron cooling power ⟶ $P = LW\Sigma\,(T_e^4 - T_p^4)$

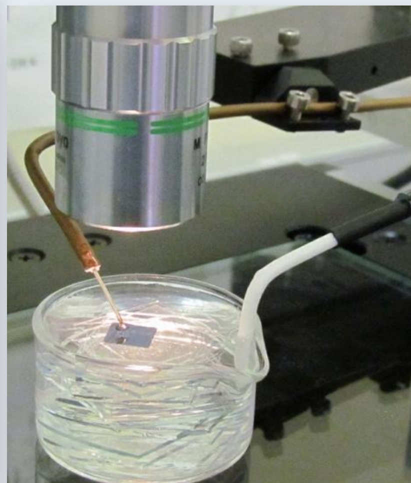
Device fabrication

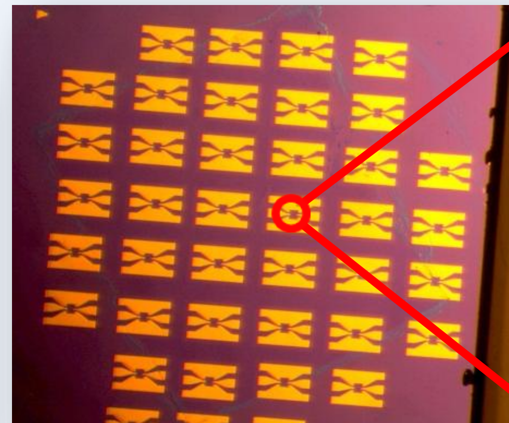
Gr/BN

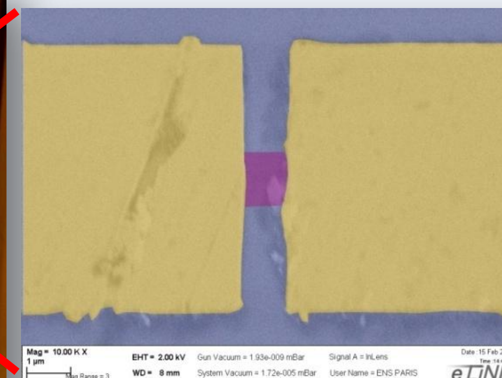
coplanar waveguide

CVD



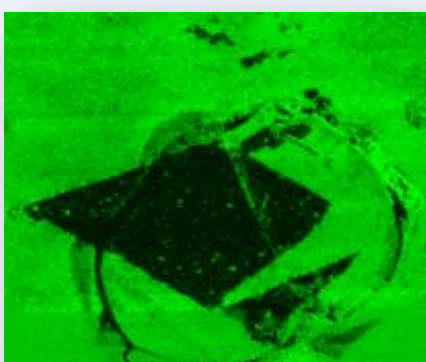


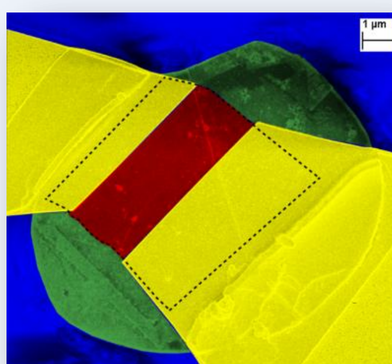


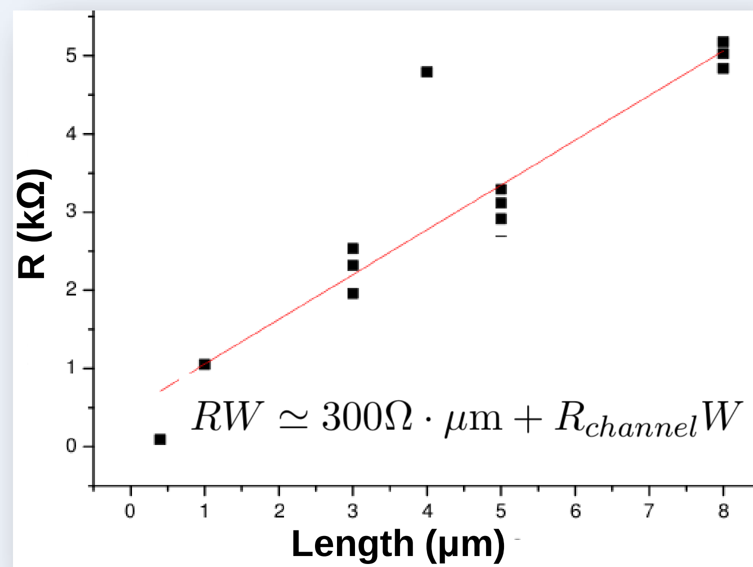


CVD grown on Cu

Wedging transfer: polymer CAB & water

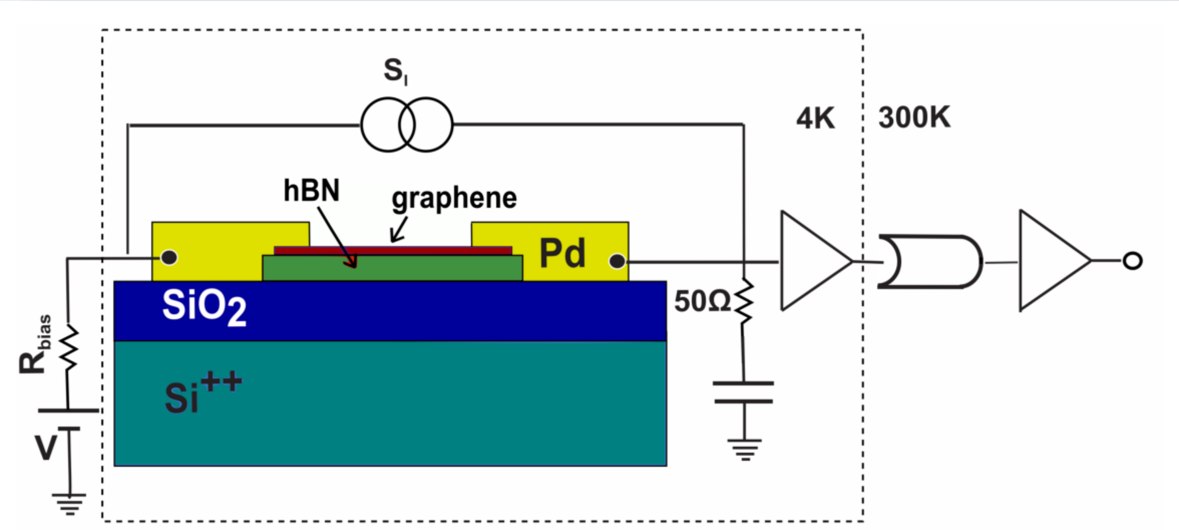


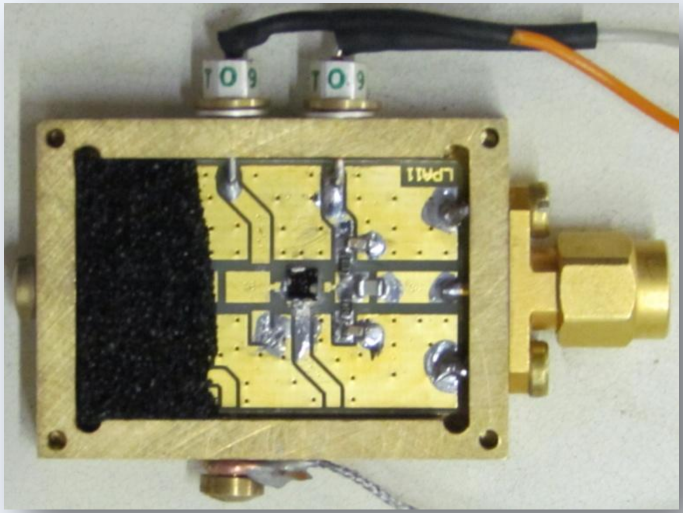




Schneider et al., Nano Letters ***2010*** *10 (5)*

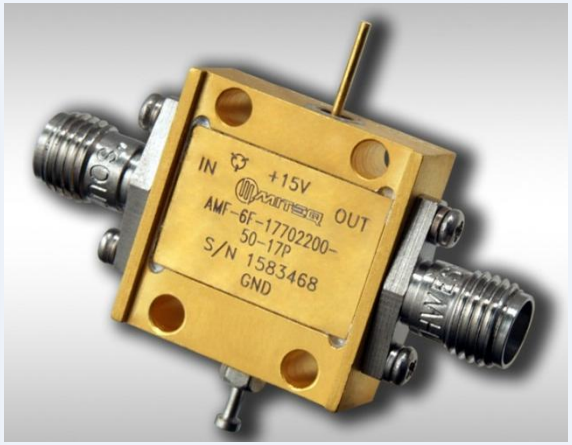
Broadband cryogenic noise setup



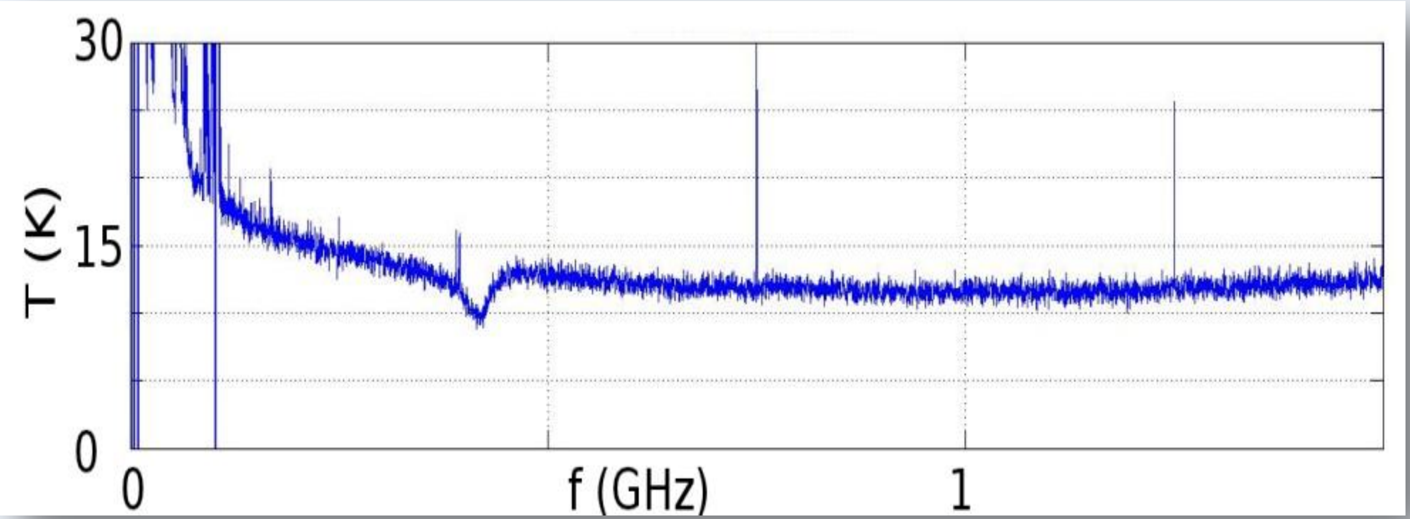


broadband GHz setup in liquid helium

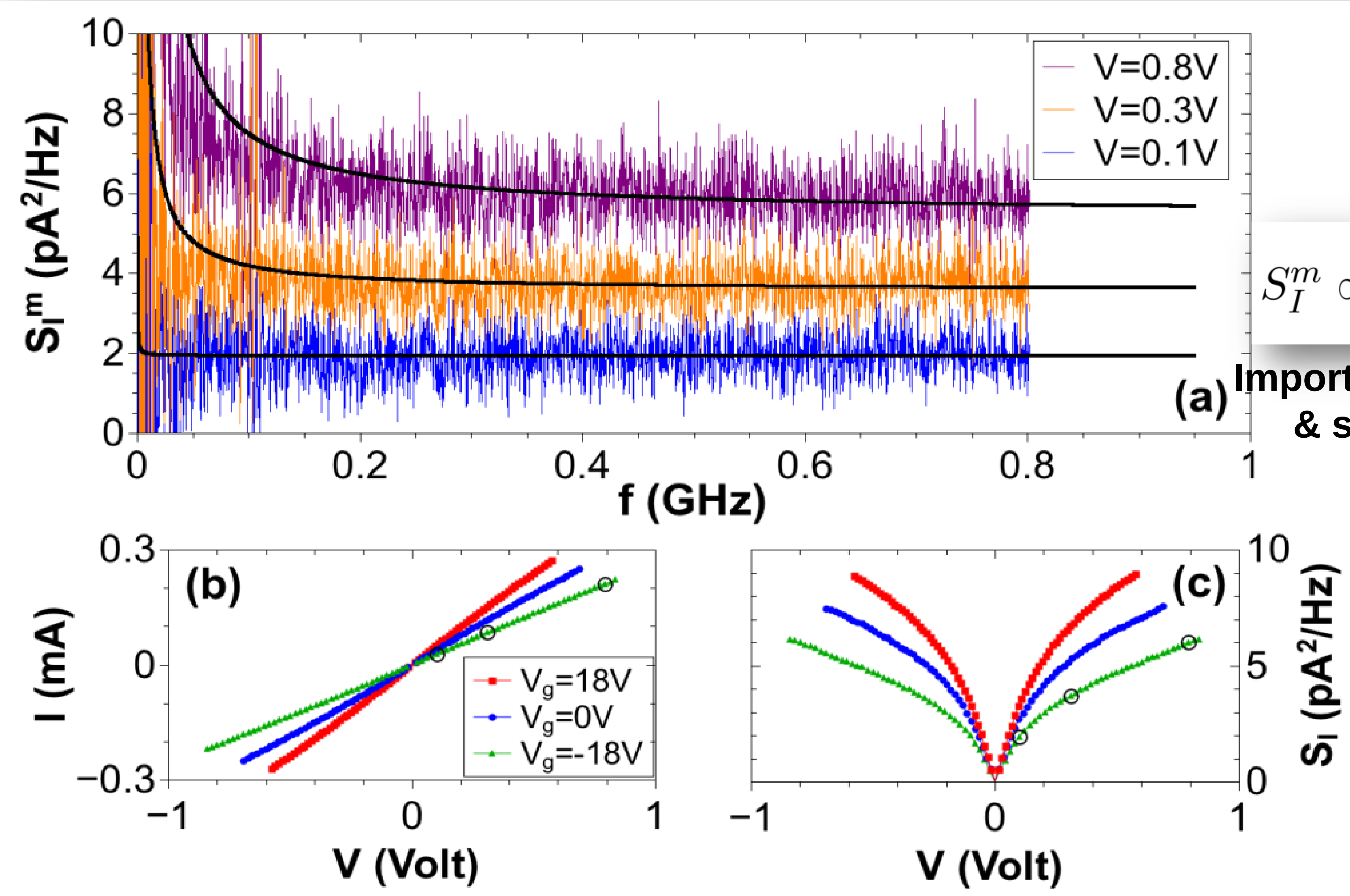
Cryogenic LNA



calibration: shot noise of an Al-AlOx-Al tunnel junction



GHz noise measurements



$$S_I^m \propto \frac{C \cdot I^2}{f} + S_I$$

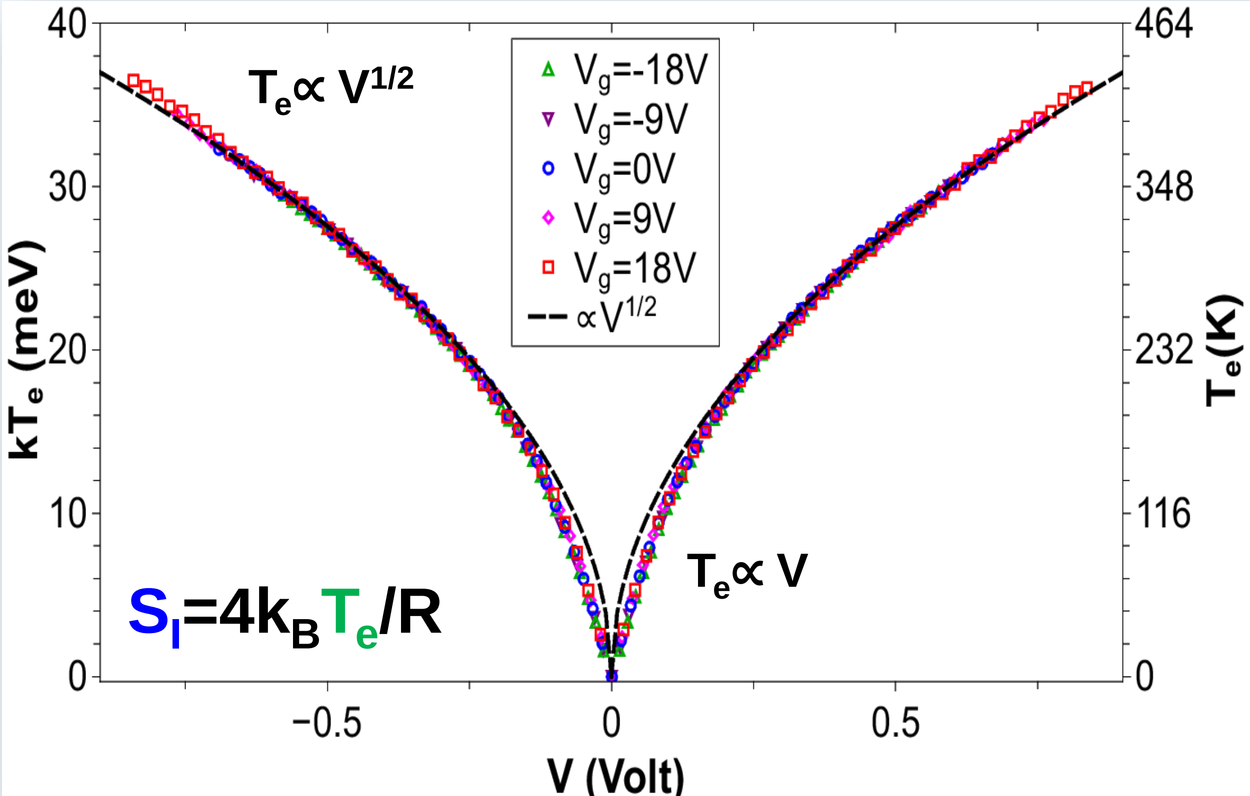
Important for high bias & small samples

linear I-V : metallic regime

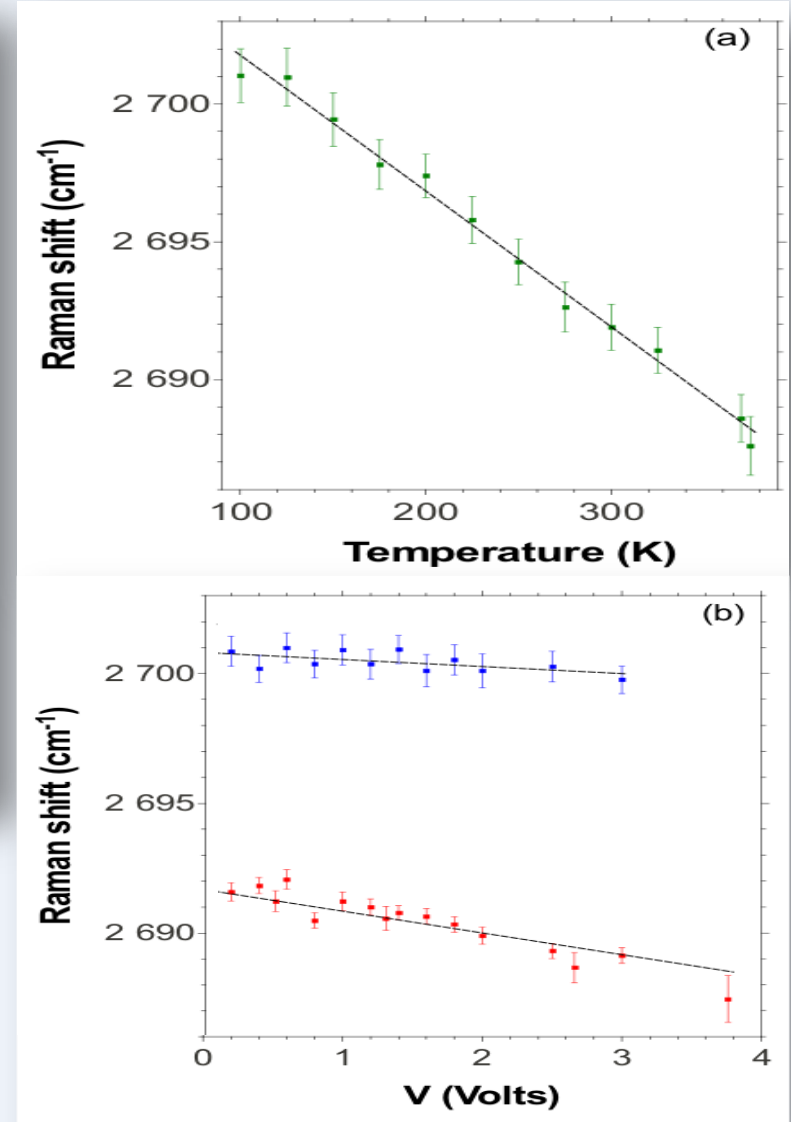
noise sub-linear

mobility = 350 - 3000 cm²/Vs

Noise temperature



$$P = \frac{V^2}{R} \simeq LW\,\Sigma\,\left(T_e^4 - \cancel{T_{ph}^4}\right)$$



→ **Hot electrons (~400K/V)**

→ **evidence for T^4 dependence**

Cold phonons (~30K/V)

Solving the heat equation

e⁻ heat diffusion — phonon cooling

$$\frac{\mathcal{L}}{2R}\frac{L^2\partial^2T^2(x)}{\partial x^2} = -\frac{V^2}{R} + LW\Sigma\left[T^4(x) - \cancel{T_{ph}^4}\right]$$

assumptions:

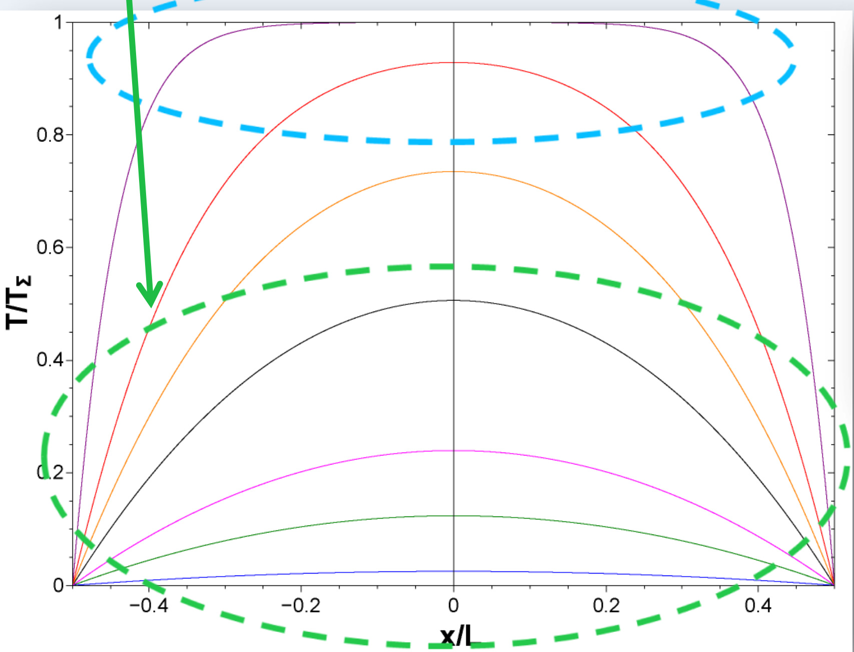
- **uniform Joule heating**
- **cold contacts**
- **cold phonons**

heat equation can be solved analytically:

Cold contacts ($T(\pm L/2) = 0$) and cold phonons ($T_{ph} = 0$) with $U = (T/T_\Sigma)^2$

$$G(X) = Elliptic\left[\text{Asin}\sqrt{\frac{1}{2}+\frac{U_0+2X}{2\sqrt{3}\sqrt{4-U_0^2}}}, \frac{2\sqrt{4-U_0^2}}{\sqrt{3}U_0+\sqrt{4-U_0^2}}\right]$$

$$\frac{2x}{L} = \frac{[G(U_0)-G(U(x))]}{[G(U_0)-G(0)]} \quad ; \quad \frac{V}{V_\Sigma} = \frac{16\,[G(U_0)-G(0)]^2}{U_0+\sqrt{(4-U_0^2)/3}}$$



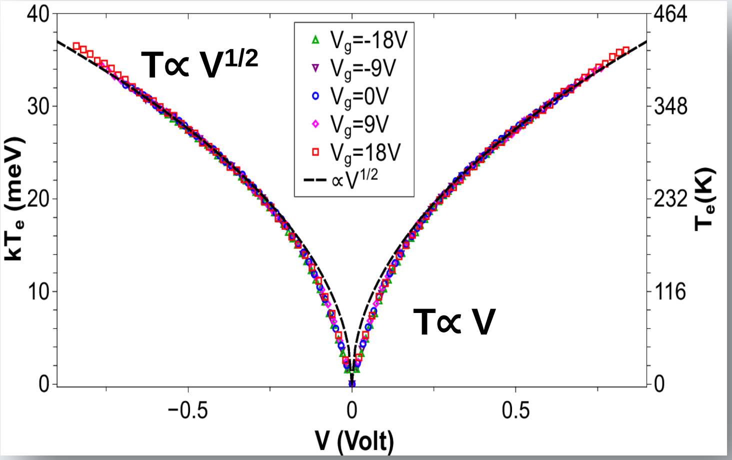
$$\text{T-scale}: \; T_\Sigma = \sqrt[4]{\frac{V^2}{RLW\Sigma}} = \sqrt[4]{\frac{P}{\Sigma}}$$

$$\text{V-scale}: \; V_\Sigma = \frac{\mathcal{L}}{\sqrt{4RLW\Sigma}}$$

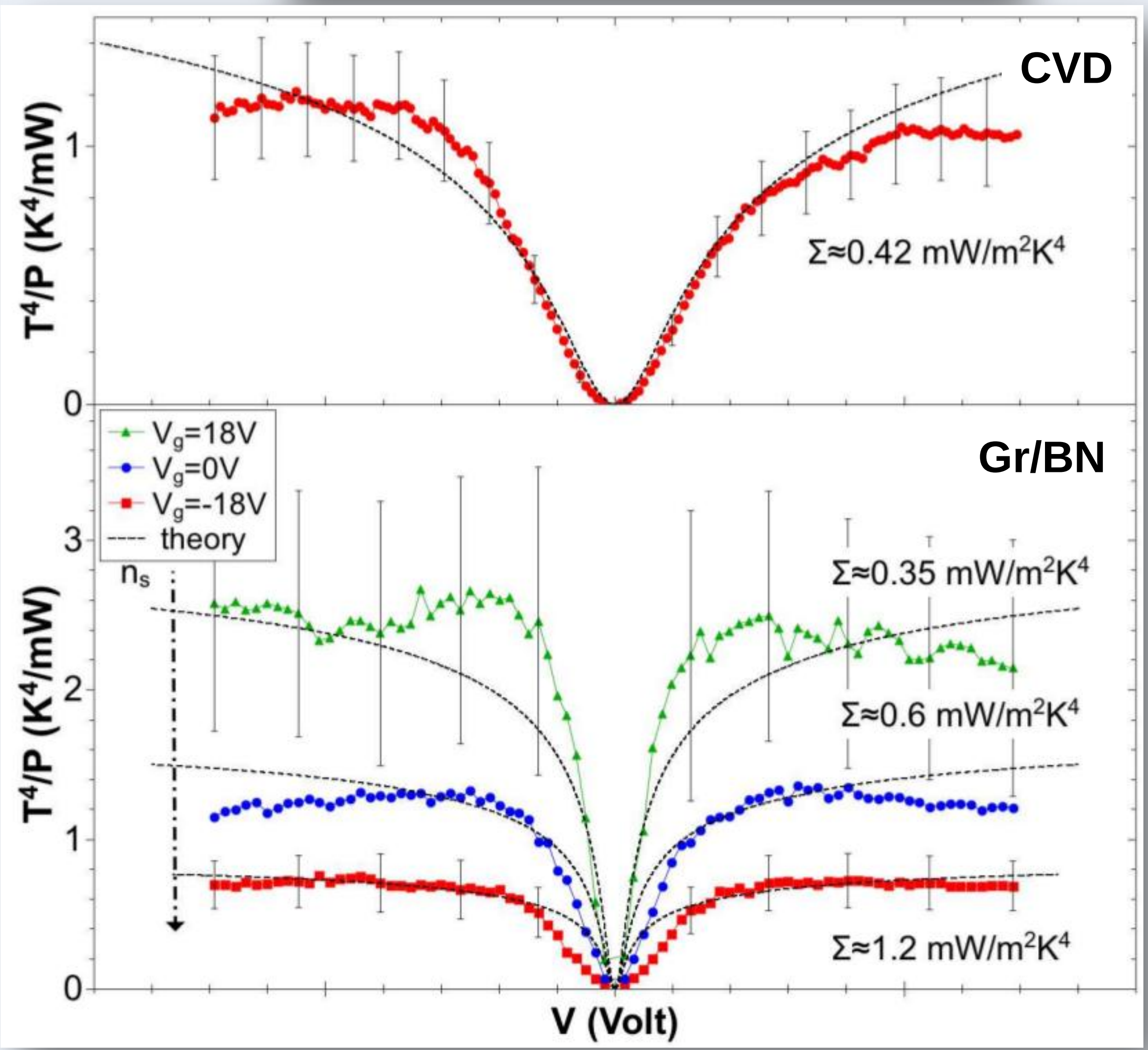
→ **global electron temperature $\langle T_e \rangle$**

$$S_I = \frac{4k_B}{R}\cdot\langle T_e\rangle$$

The $P=\Sigma T^4$ dependence



$$\frac{\mathcal{L}}{2R}\frac{L^2\partial^2T^2(x)}{\partial x^2} = -\frac{V^2}{R} + LW\Sigma\left[T^4(x) - T_{ph}^4\right]$$



Use heat equation to fit

ALL data (low & high V)

$S_I = 4k_BT_e / R$

$P = I*V / (LW)$

Normalise to power P

→ **pronounce features:**

e^- heat diffusion

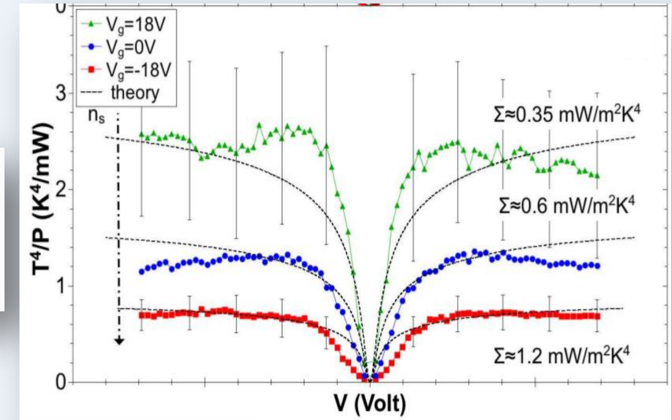
vs.

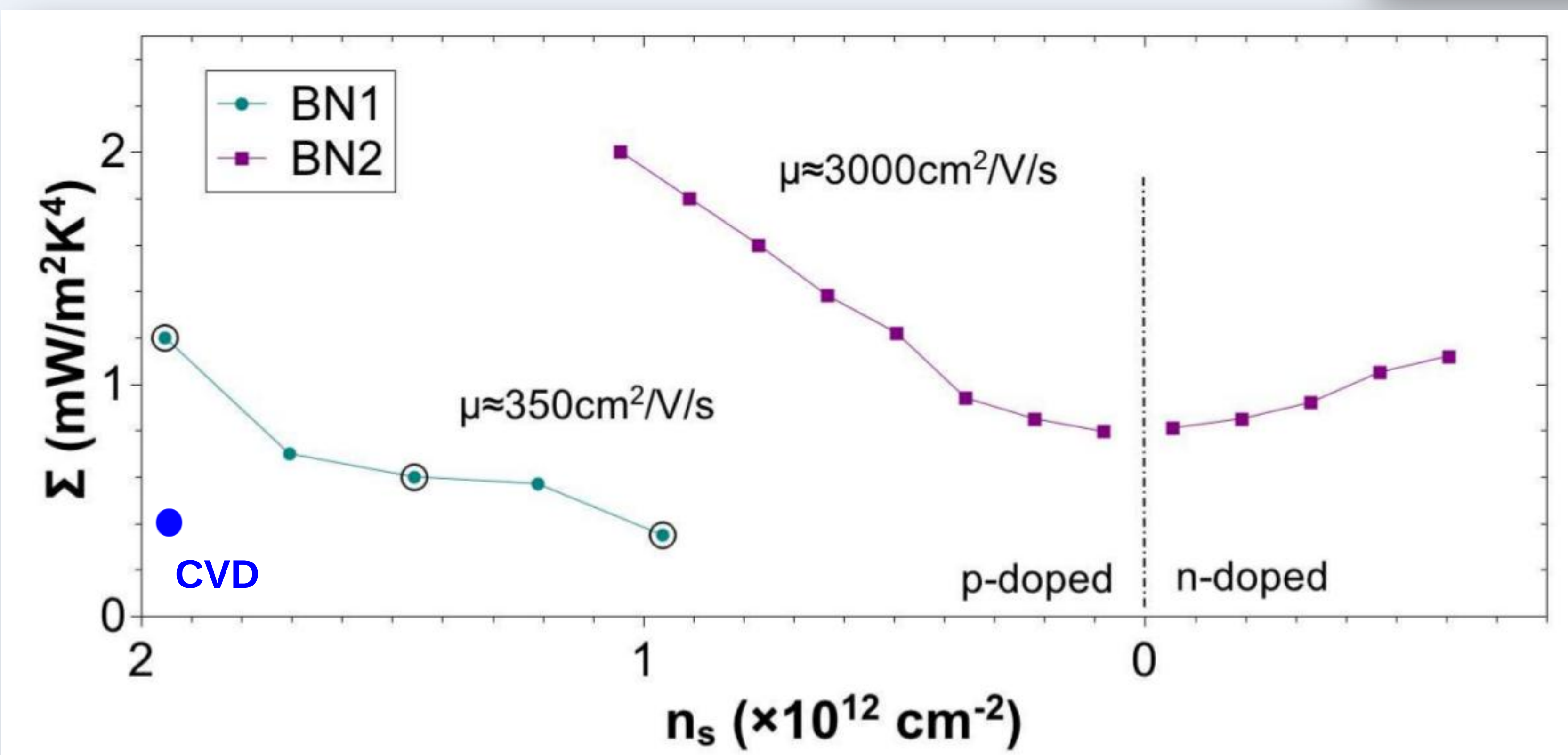
phonon cooling

Electron-AP coupling constant

Σ is the only free parameter in solution of

$$\frac{\mathcal{L}}{2R}\frac{L^2\partial^2T^2(x)}{\partial x^2} = -\frac{V^2}{R} + LW\Sigma\left[T^4(x) - T_{ph}^4\right]$$





Electron-AP coupling constant

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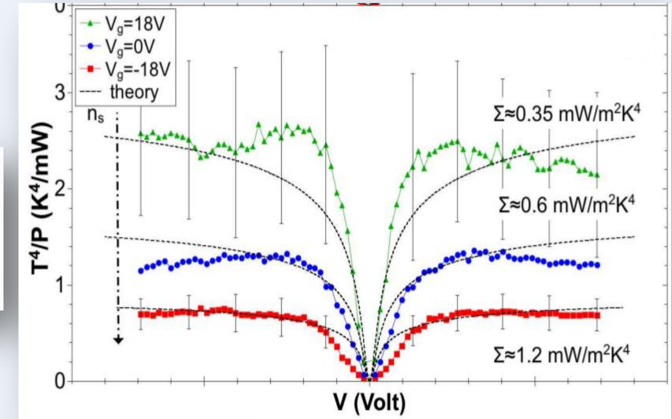
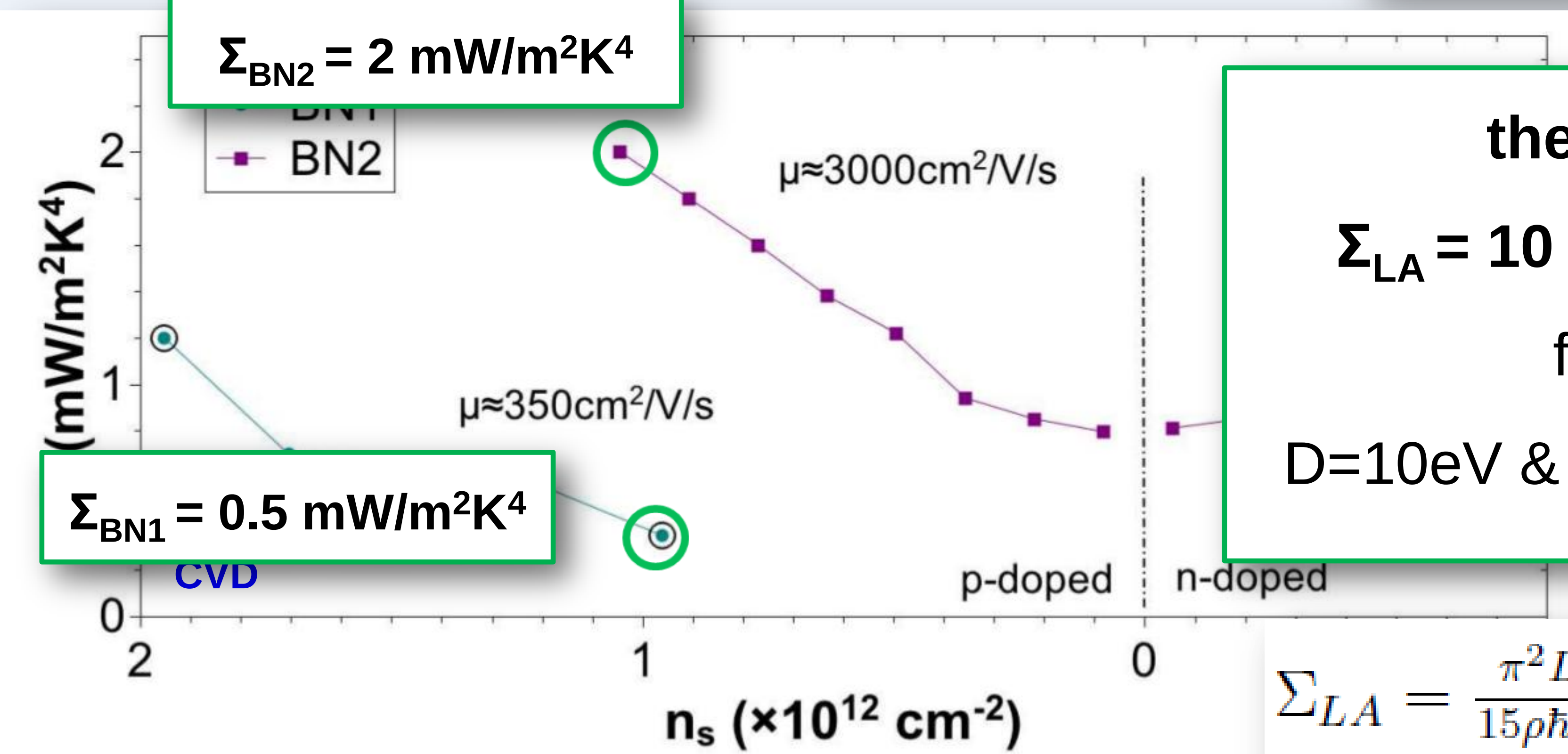




Σ_{BN2} = 2 mW/m^{2}K^4

Σ_{BN1} = 0.5 mW/m^{2}K^4

theory:

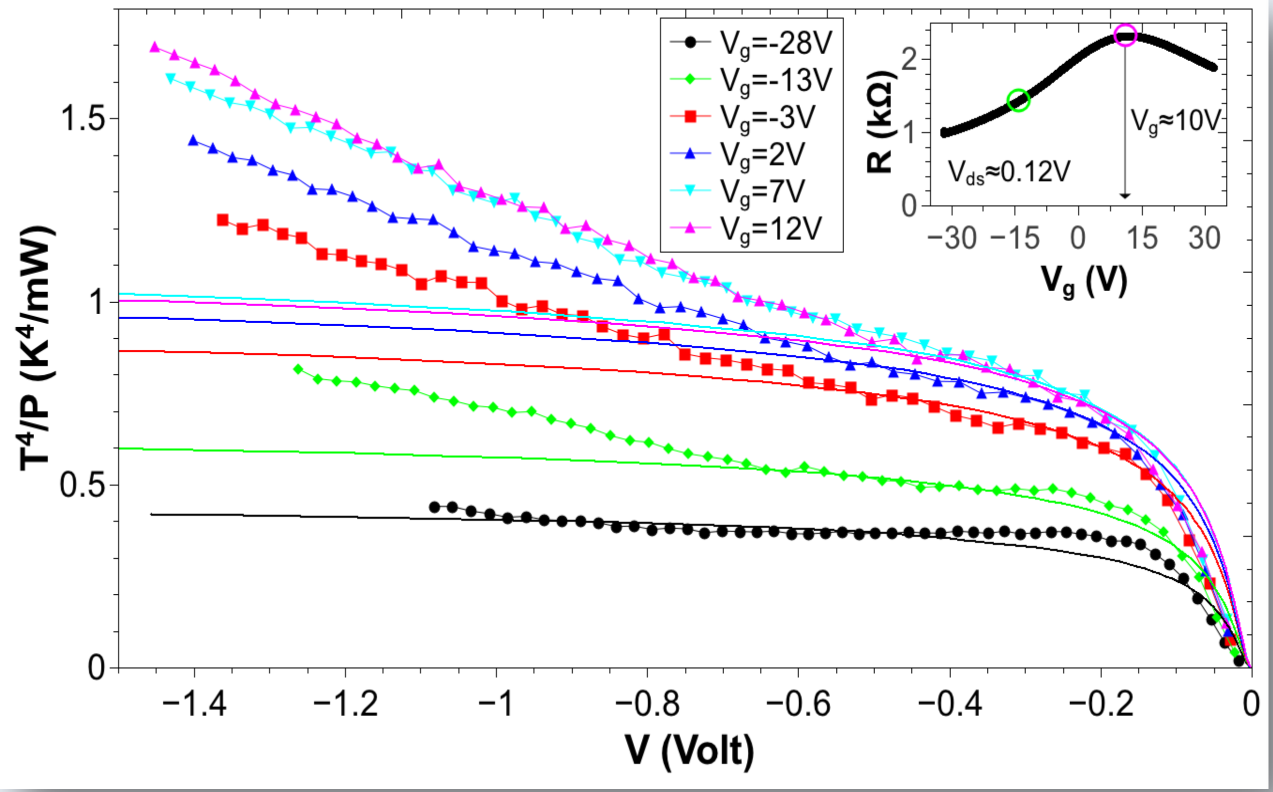
Σ_{LA} = 10 mW/m^{2}K^4

for

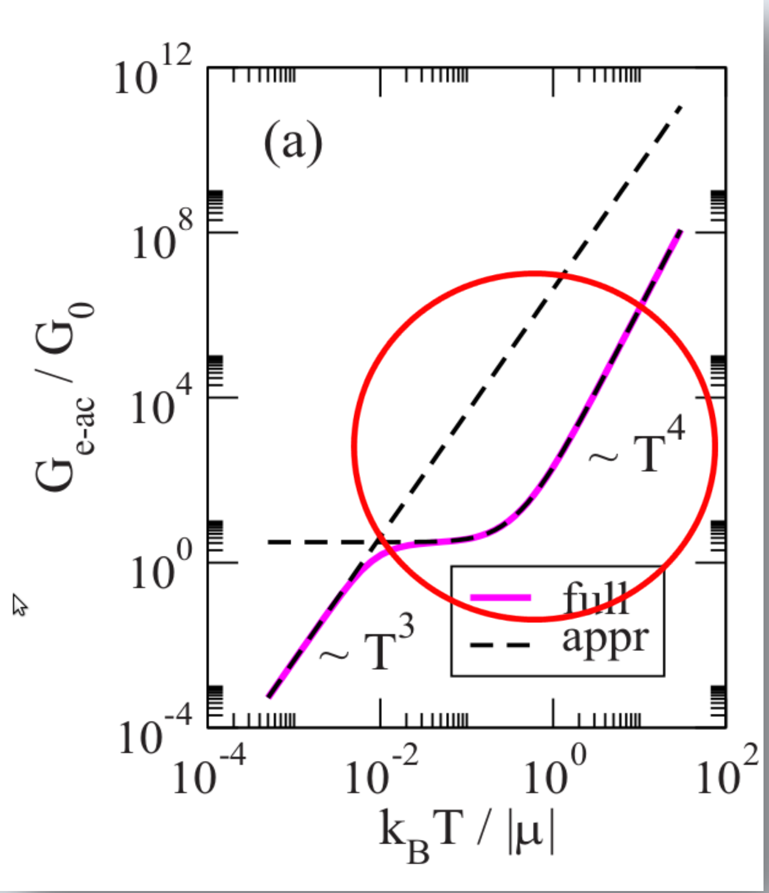
D=10eV & $n_s = 10^{12}$cm^{-2}

$$\Sigma_{LA} = \frac{\pi^2 D^2 k_B^4}{15\rho\hbar^5 v_F^3 c^3} \times |E_F|$$

Deviations from ΣT^4



heat sink



ongoing work

Conclusions

- GHz noise thermometry in graphene devices
- Qualitative signatures of acoustic phonon cooling
- Quantitative disagreement due to lattice disorder?
- Importance for graphene detectors

Bolometric detection:

Gabor, Science 2011 (MIT : photo-current)

Vora, arxiv:1110.5623 (Stony Brook : 0.6 GHz)

Yan et al, arxiv:1111.1202 (Maryland : fast IR detector)

Fong, arxiv:1202.5737 (CALTECH : 1.2 GHz)

Freitag, arxiv:1202.5342 (IBM : photo-conductivity)

Thank you for your attention!

Graphene team at LPA

Emiliano Pallecchi

Andreas Betz

Jean-Marc Berroir

Gwendal Fève

Bernard Plaçais

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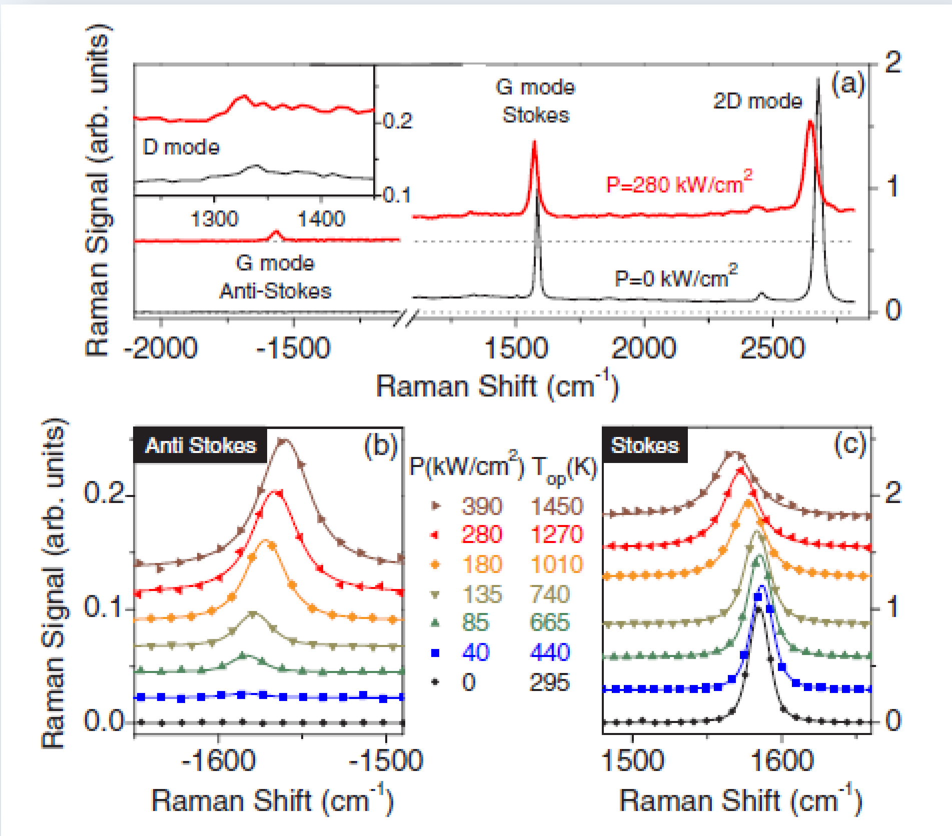
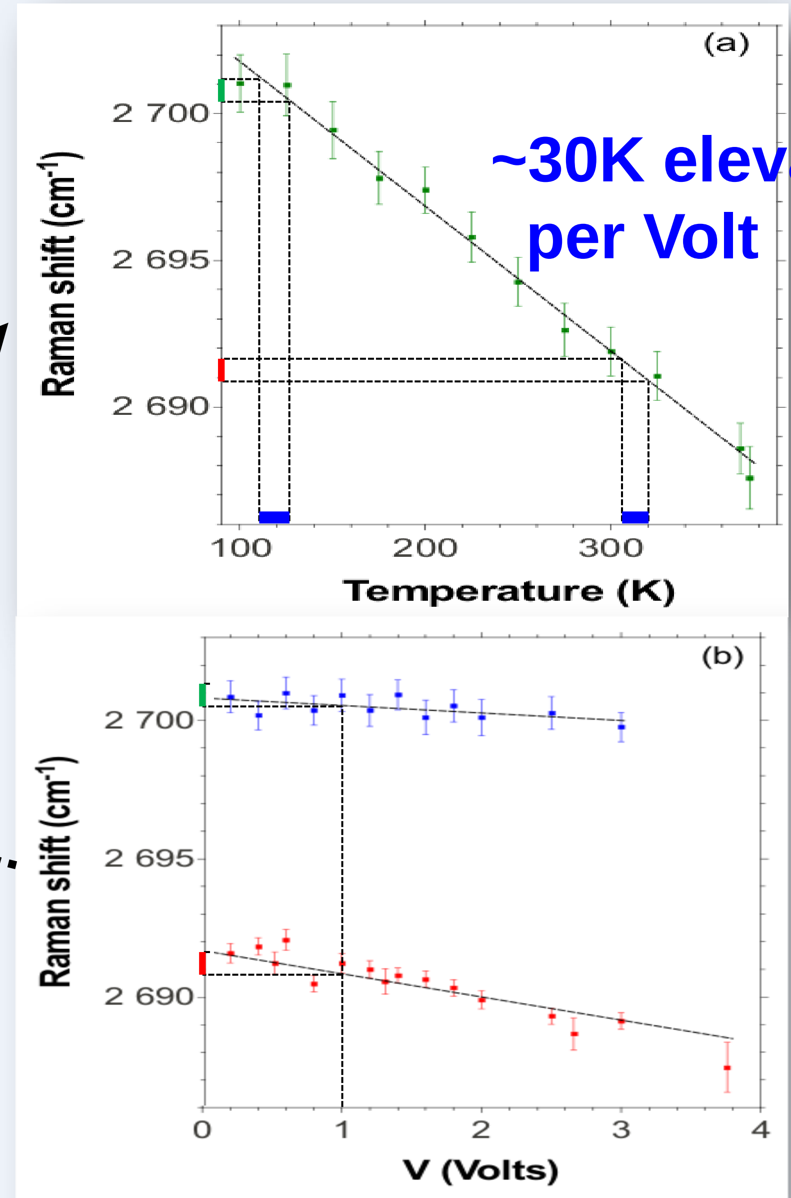
Raman experiments

OP/AP populations



(Berciaud, Han, Mak,Brus,Kim, Heinz, PRL2010)



~30K elevation per Volt

Fano factor analysis

$S_I/2eI \sim T_e/V$

$T_e/\sqrt{V}$