非平衡载流子的弛豫机制

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北京计算科学研究中心, 2020/11/12

主要内容

1. 介观体系的热力学平衡与非平衡
2. 低维体系的非平衡载流子的产生和探测
3. 什么是噪音谱学
4. GHz 噪音谱学与高电场输运的研究
5. 碳管布朗运动与受限量子输运的关联

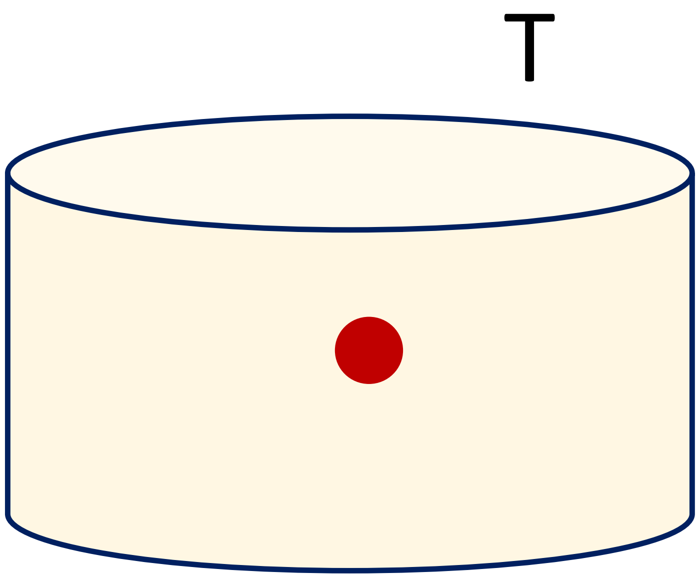
热力学的平衡与非平衡

热力学平衡
（equilibrium thermodynamics）

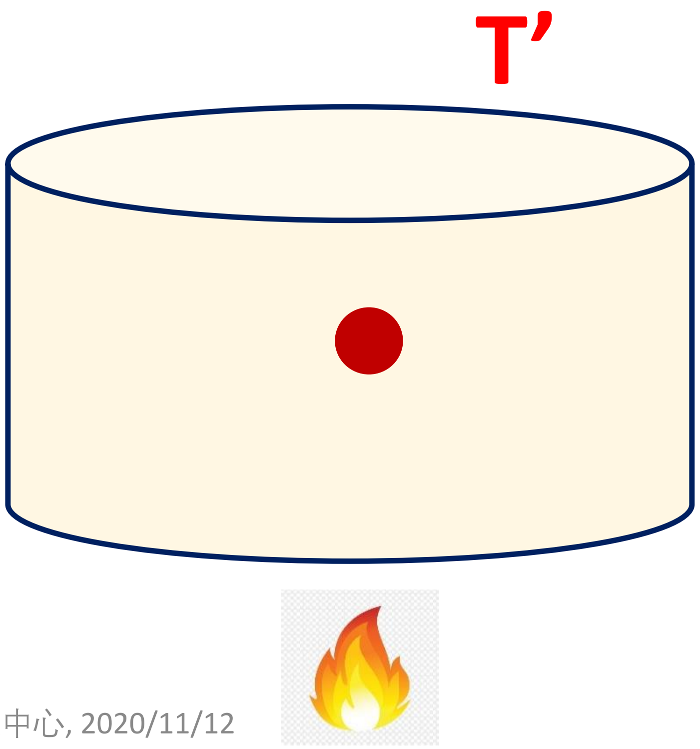
不受外界影响下，宏观性质是平衡的 （in balance），不随时间变化的状态

热力学非平衡
（Non-equilibrium thermodynamics）

宏观性质是非平衡（out of balance）， 随时间变化的状态

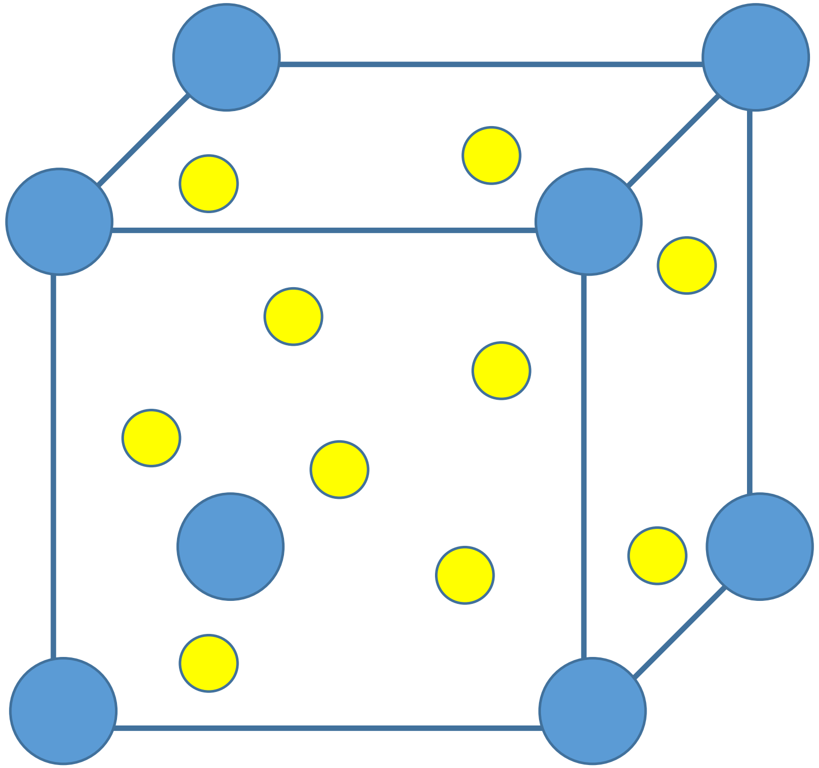


分子热运动或者布朗运动



温度
压强
体积
质量

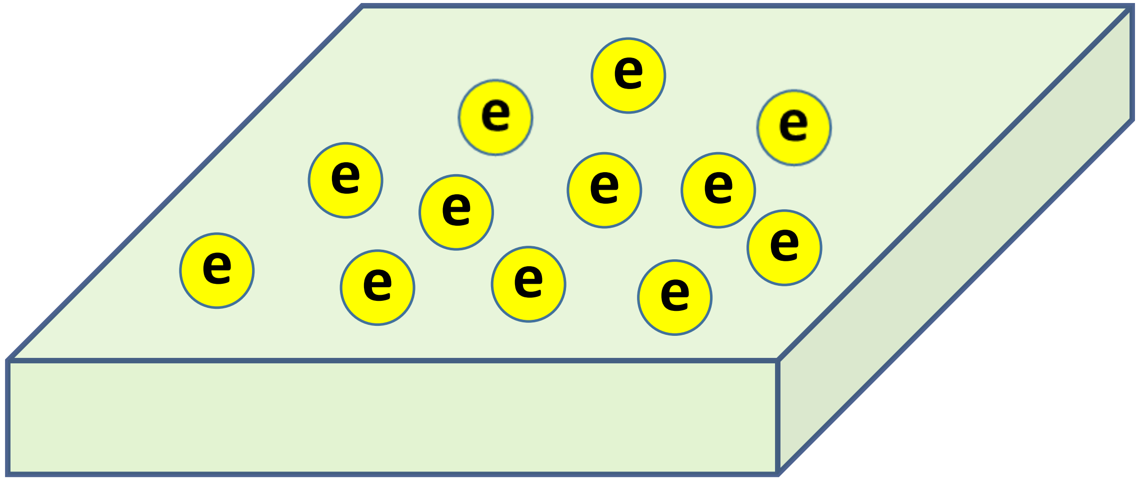
从经典热力学到固态量子/介观器件



Electrons in lattices

介观 (Mesoscopic system)

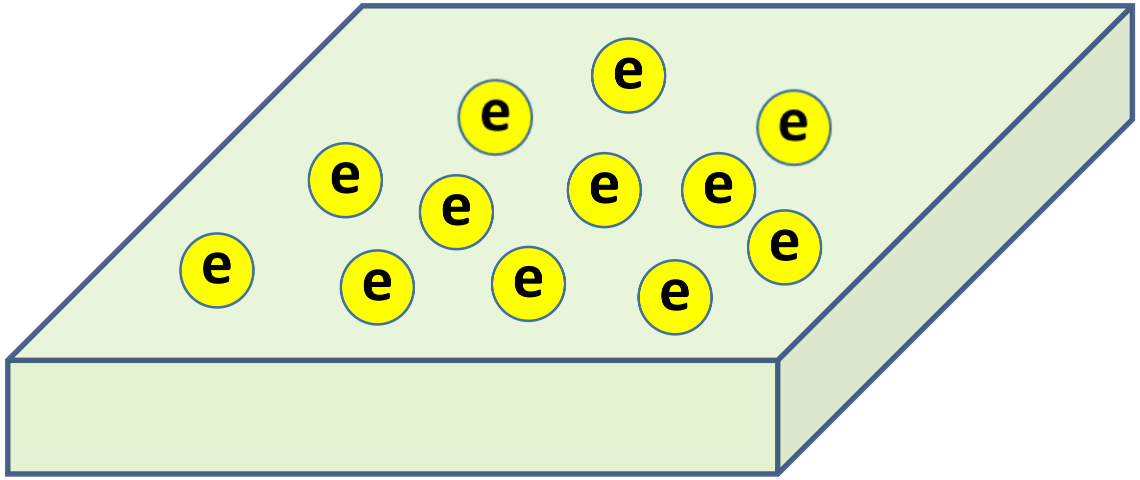
纳米-微米尺度



介观体系的热力学描述

介观 (Mesoscopic system)
纳米-微米尺度

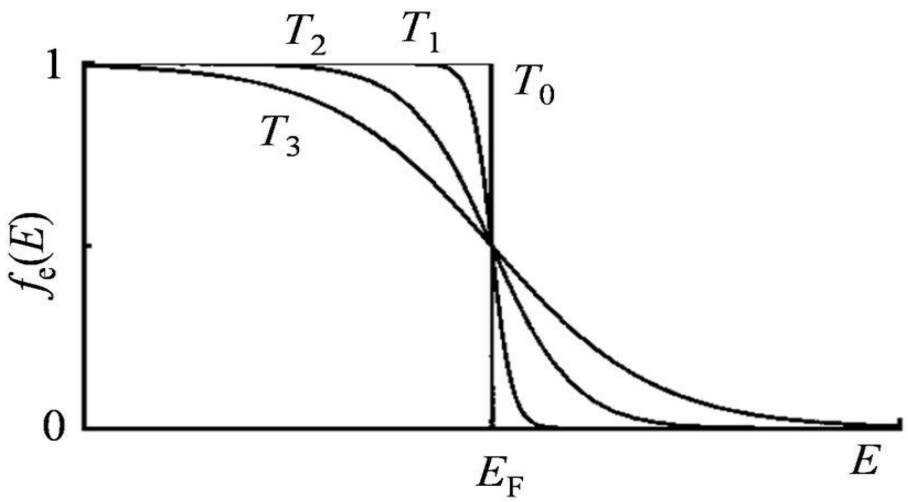
T



温度是描述微观体系的一个很直观和具有物理量

Fermi-Dirac distribution

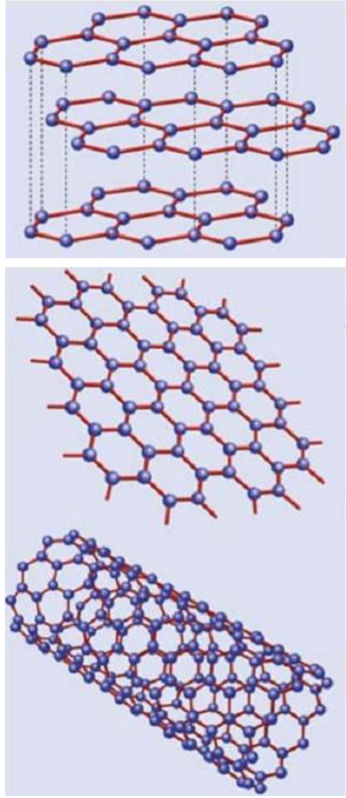
$$f(E) = \frac{1}{1 + e^{(E-E_F)/k_BT}}$$



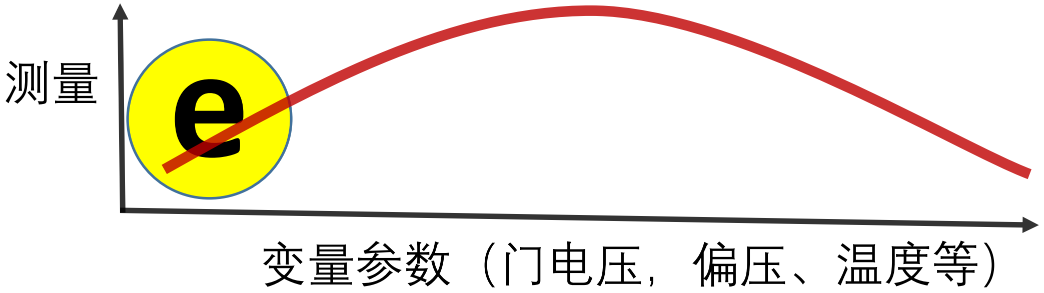
低维系统的电学输运测量

低维体系

电子输运



Rev. Mod. Phy. 81, 109 (2009)

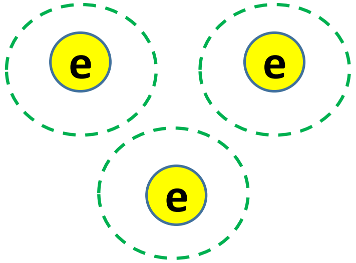


能带结构

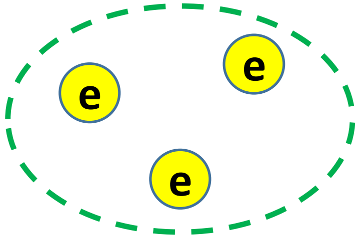
晶格声子

振动声子

单电子模型

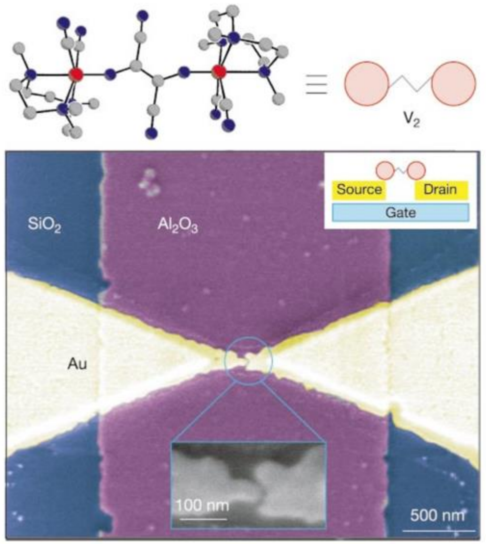


多电子相互作用

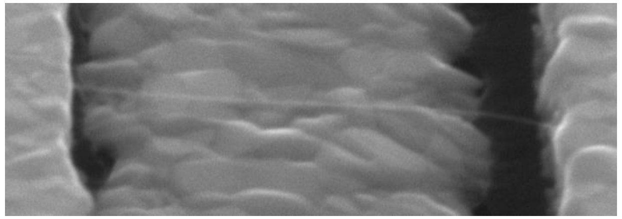


结构与物性的调控

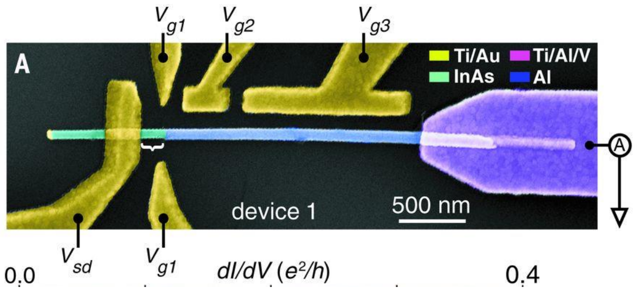
电子器件



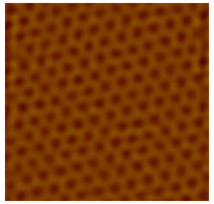
Liang, Nature 2002

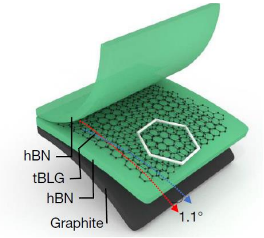


C. Urgell, Wei Yang# et al., Nature Physics 2020

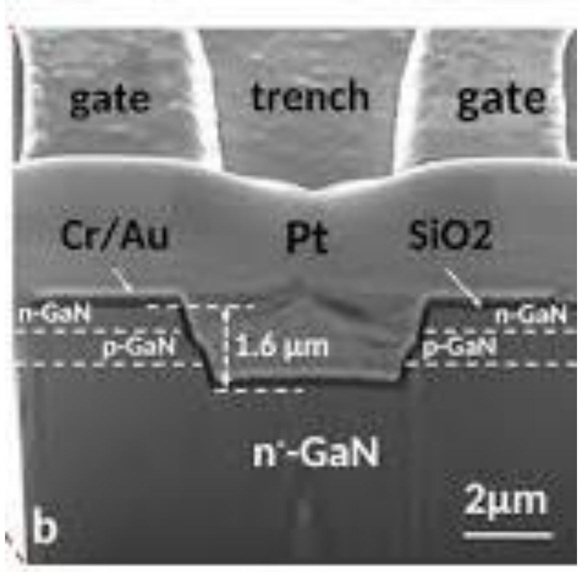


C. Marcus, Science 2016





Wei Yang, et al., Nature Mat. 2013
Wei Yang, et al., Nature Nano. 2018
X. Lu, P. S., Wei Yang, et al. Nature 2019



EPFL, 2018

0 D

Single molecular
C60

1 D

nanotube
nanowire, Si, InAs

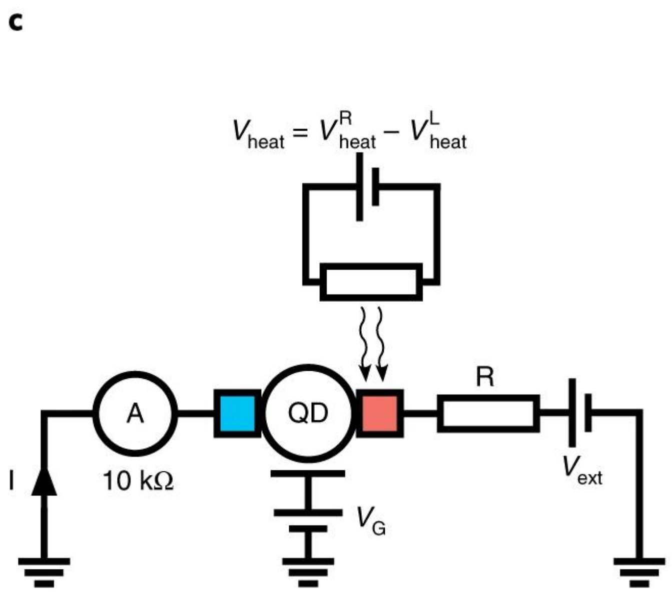
2 D

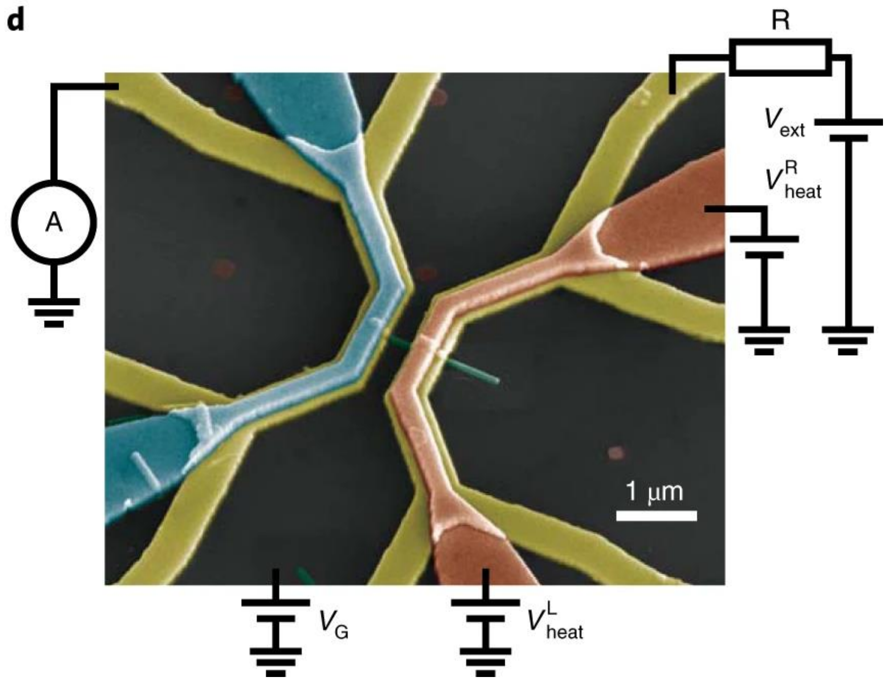
Graphene,TMD,
GaAs/AlGaAs…

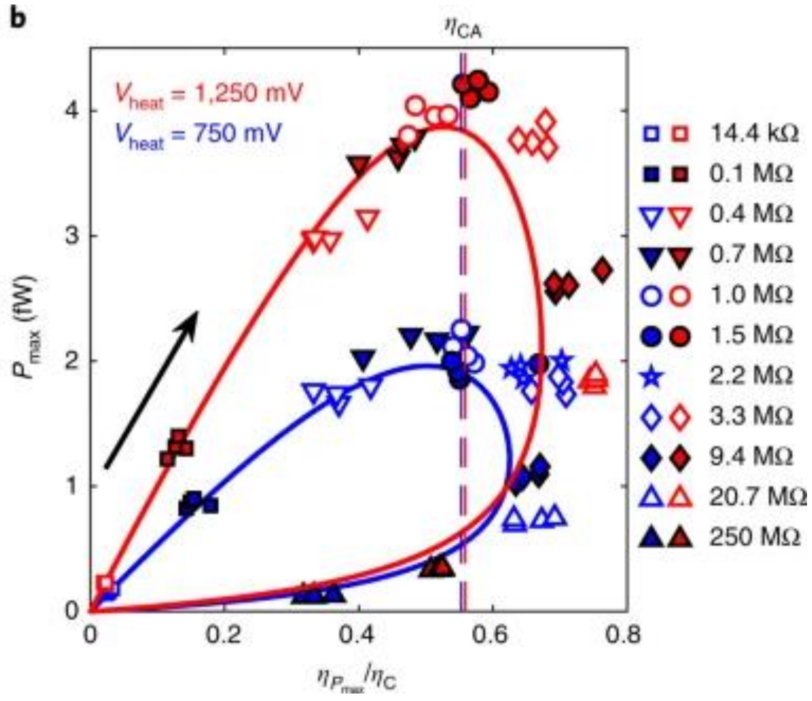
3 D

GaAs, GaN,Si…

量子点卡诺循环热机







Nature Nano. 13, 920(2018)

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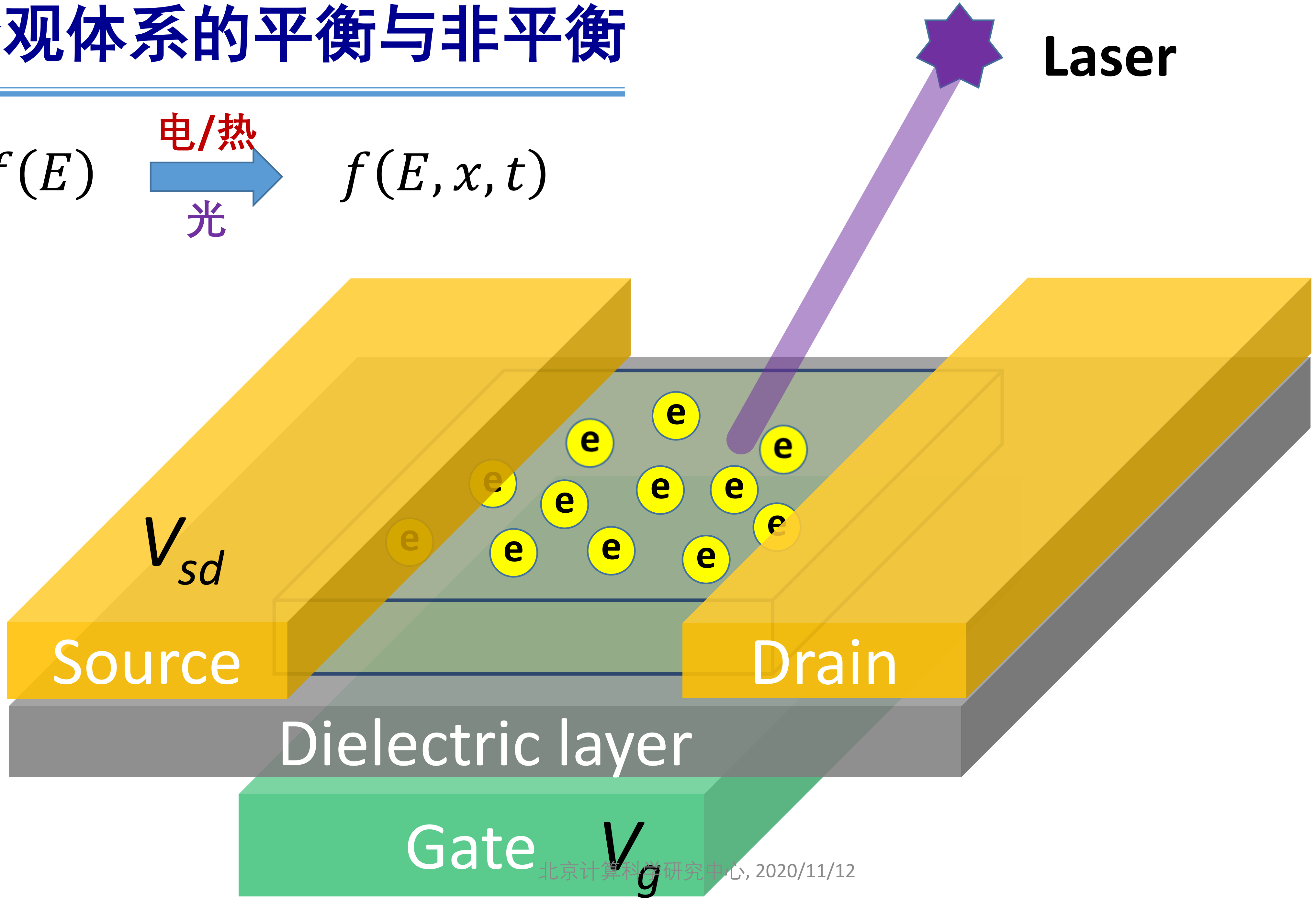
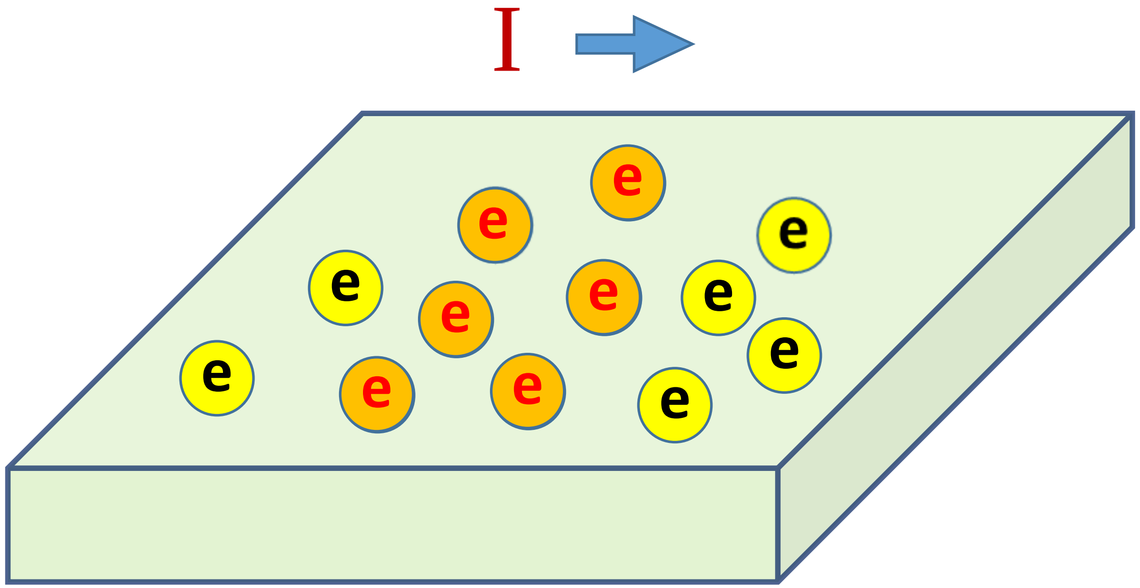
介观体系的平衡与非平衡

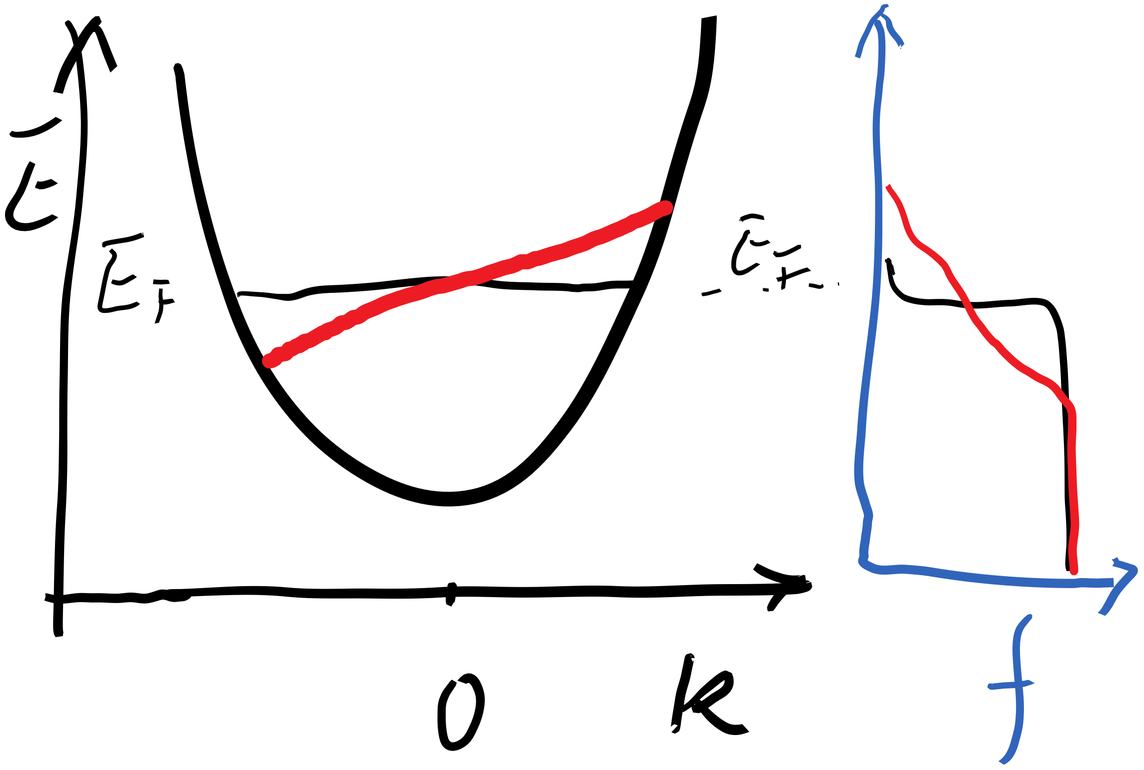
$$f(E) \xrightarrow[\text{光}]{\text{电/热}} f(E,x,t)$$



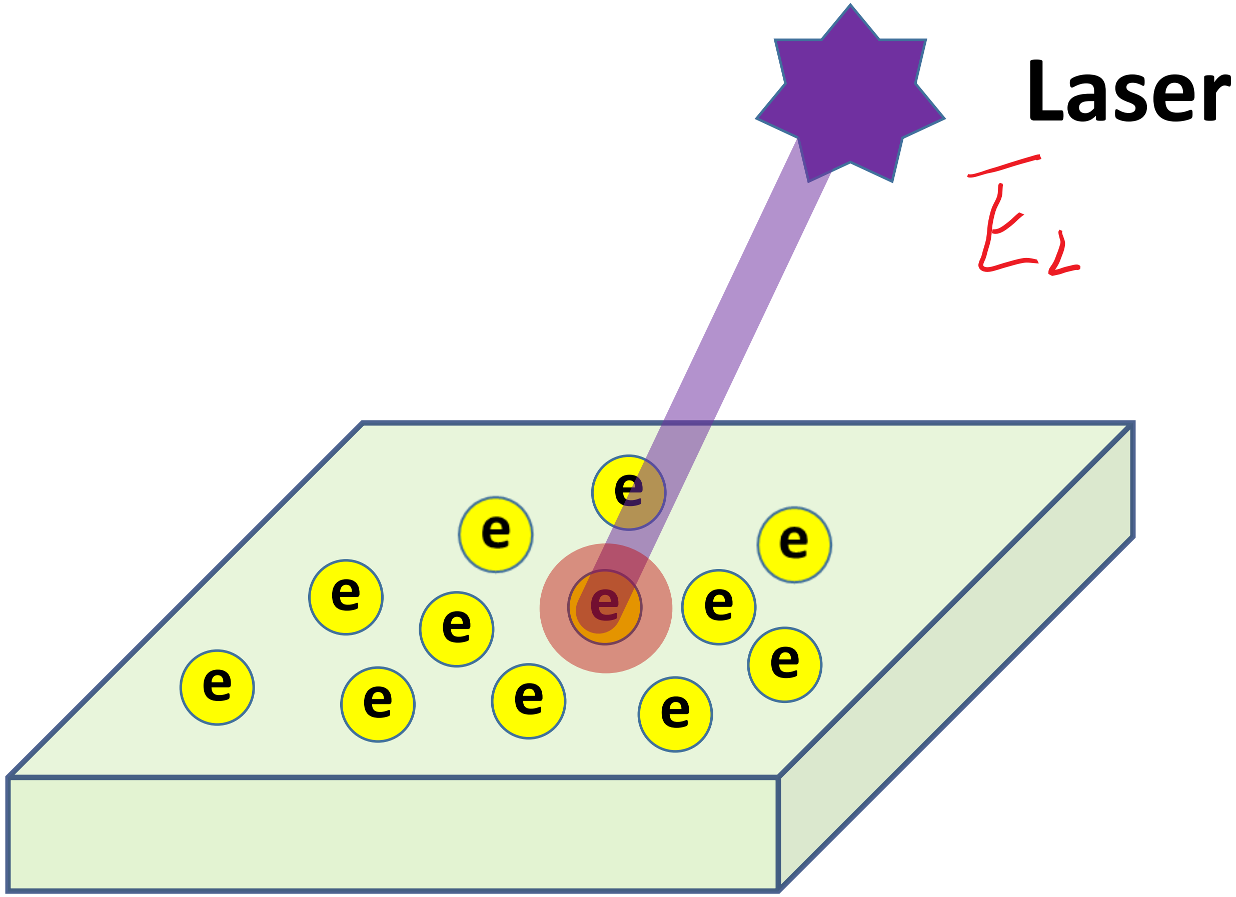
非平衡载流子的产生-电

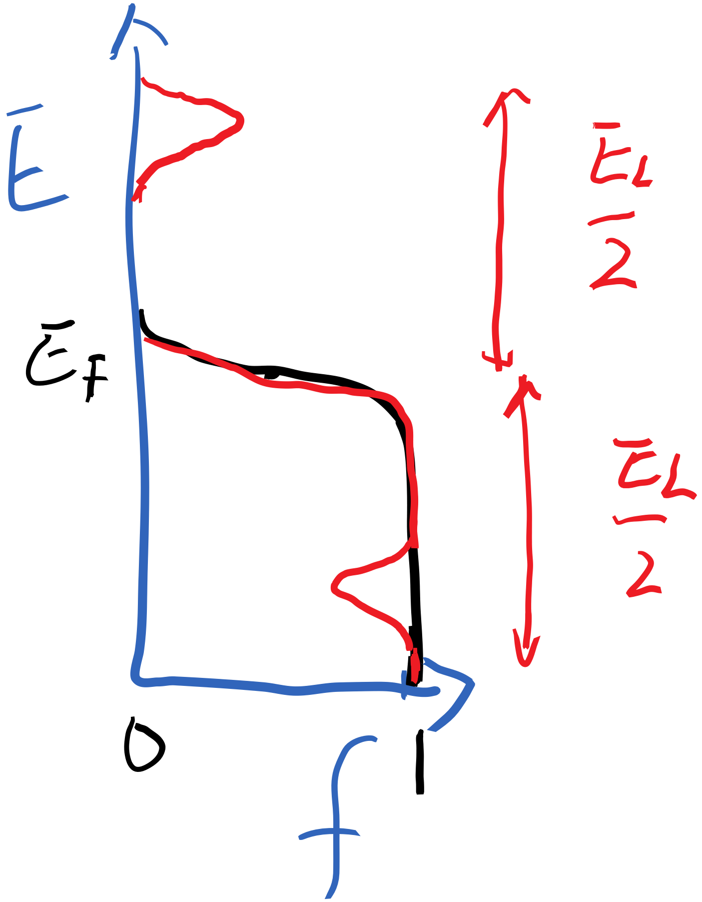


热载流子 hot electron

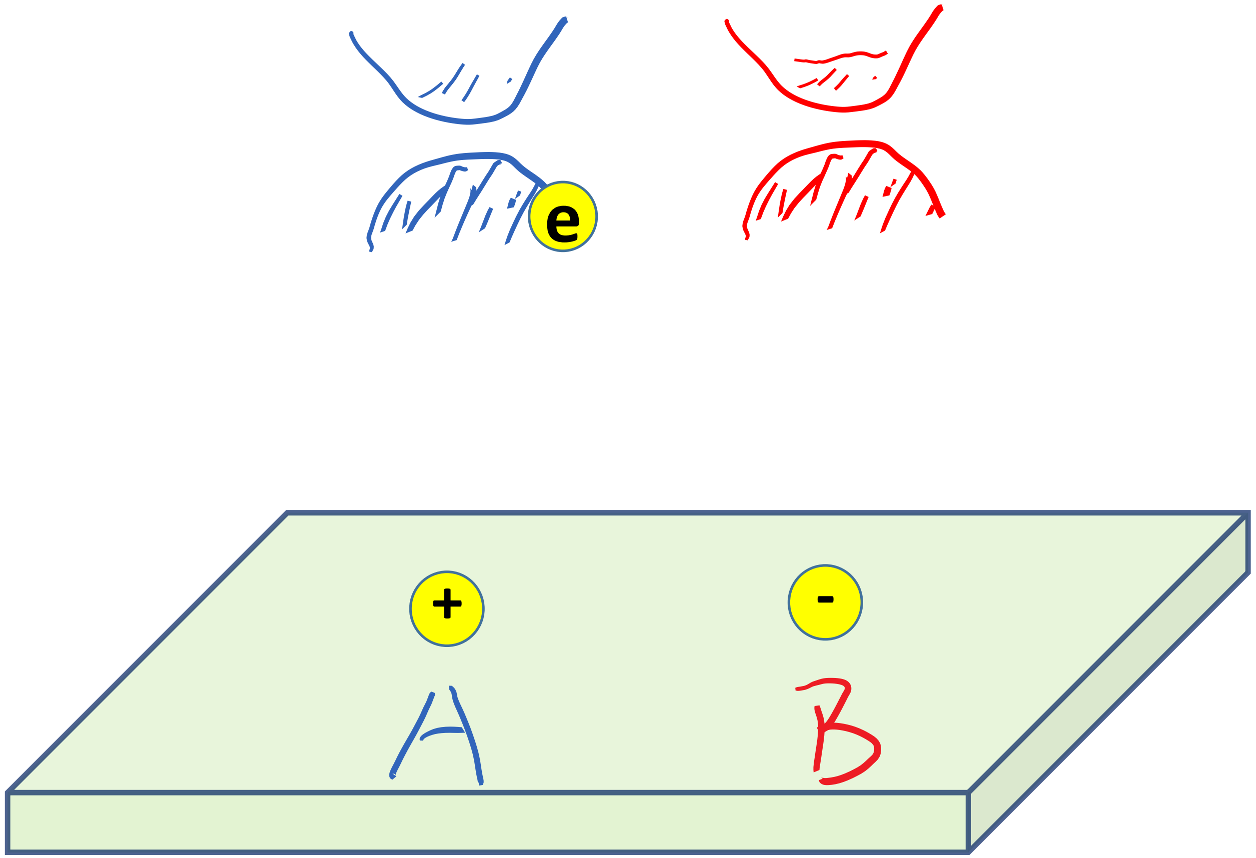


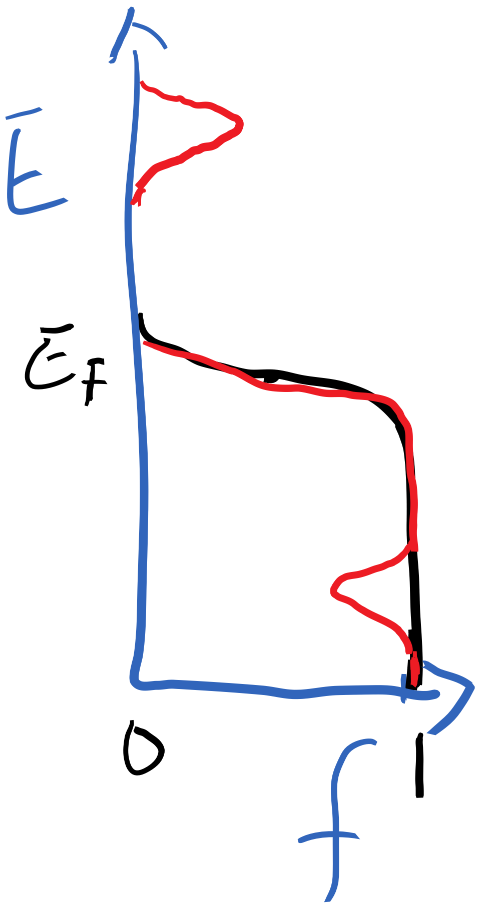
非平衡载流子的产生–光





非平衡载流子的产生-高电场下的Zener效应





电子的弛豫时间

$J = \sigma E$, $D = \varepsilon E$

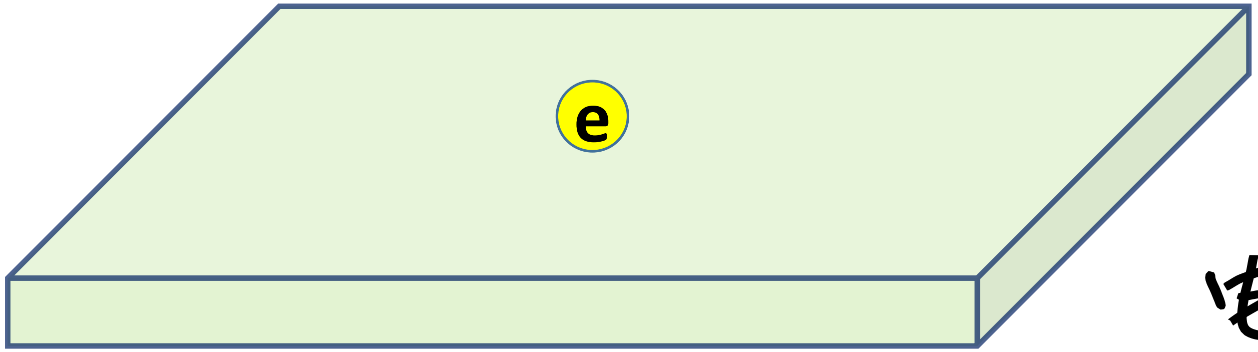
$\nabla \cdot \vec{J} + \frac{d\rho}{dt} = 0$

$\nabla \cdot D = \nabla \cdot (\varepsilon E) = \rho$

$\Rightarrow \frac{d\rho}{\rho} = -\frac{\sigma}{\varepsilon} dt$

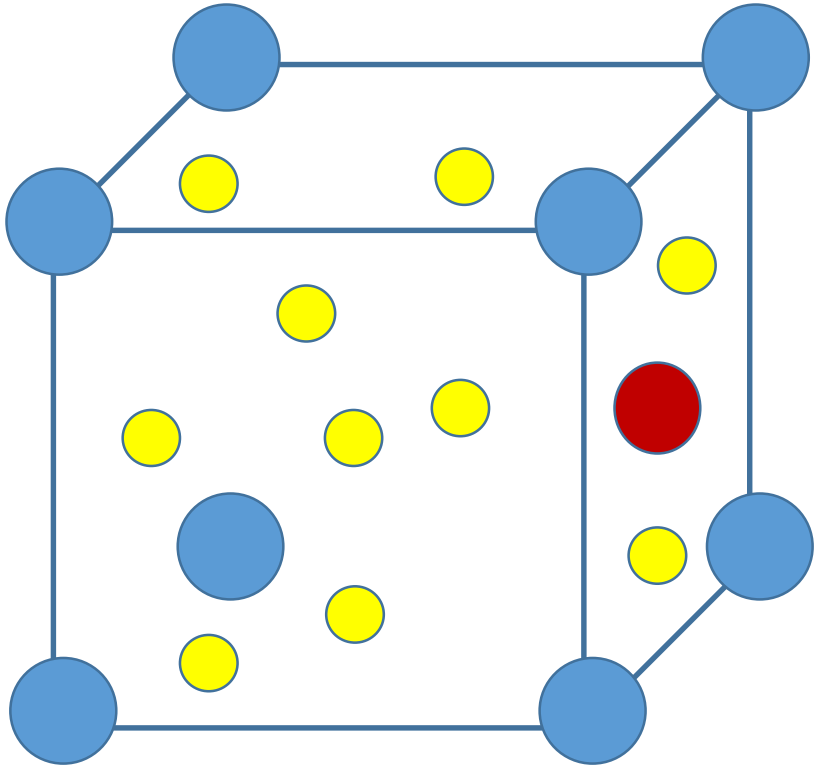
$\Rightarrow \rho(t) = \rho_0 \exp(-\frac{t}{\tau})$

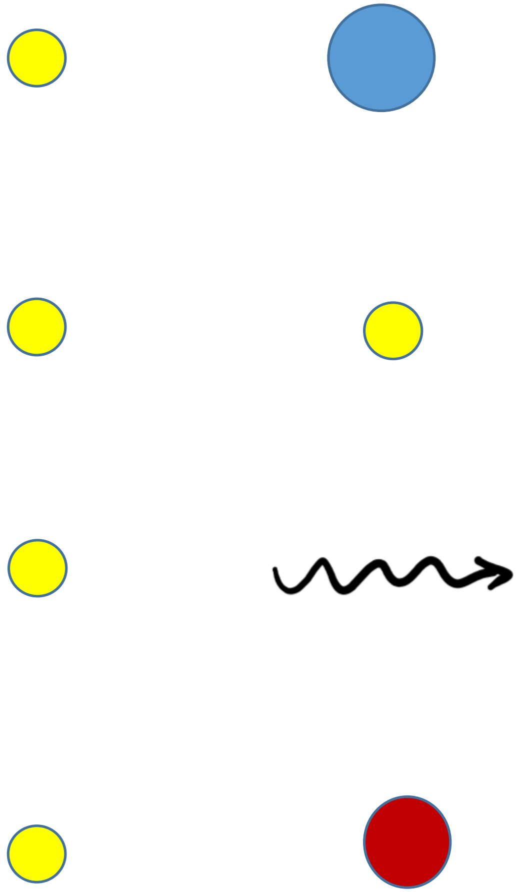
$\tau = \frac{\varepsilon}{\sigma}$



电子的弛豫时间 介电（常数） 电导

电子的散射和弛豫





电子-晶格散射

电子-电子相互作用

电子-晶格振动（声子）

声学声子/光学声子/表面声子

电子-杂质态以及衬底的散射/弛豫

$$\sigma = ne\mu$$

$$v = \mu \cdot E$$

$$j = nev$$

$$\mu = \frac{q \cdot l_{mfp}}{m^* \cdot v_F}$$

从低电场到高电场的电子输运

低电场下，group velocity v 不变

$$j = nev = ne\mu E$$

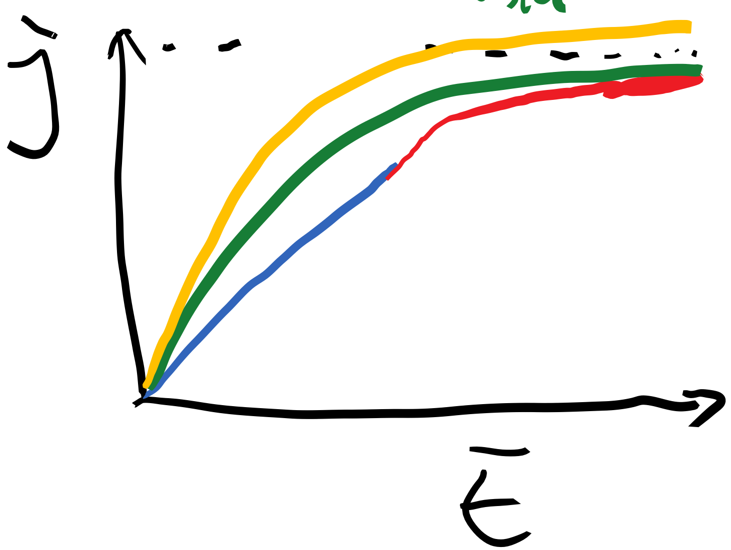
高电场下，$v(E)$

$$v = \frac{\mu E}{\left(1 + \frac{\mu E}{v_{sat}}\right)^2}$$

↑ 饱和速度

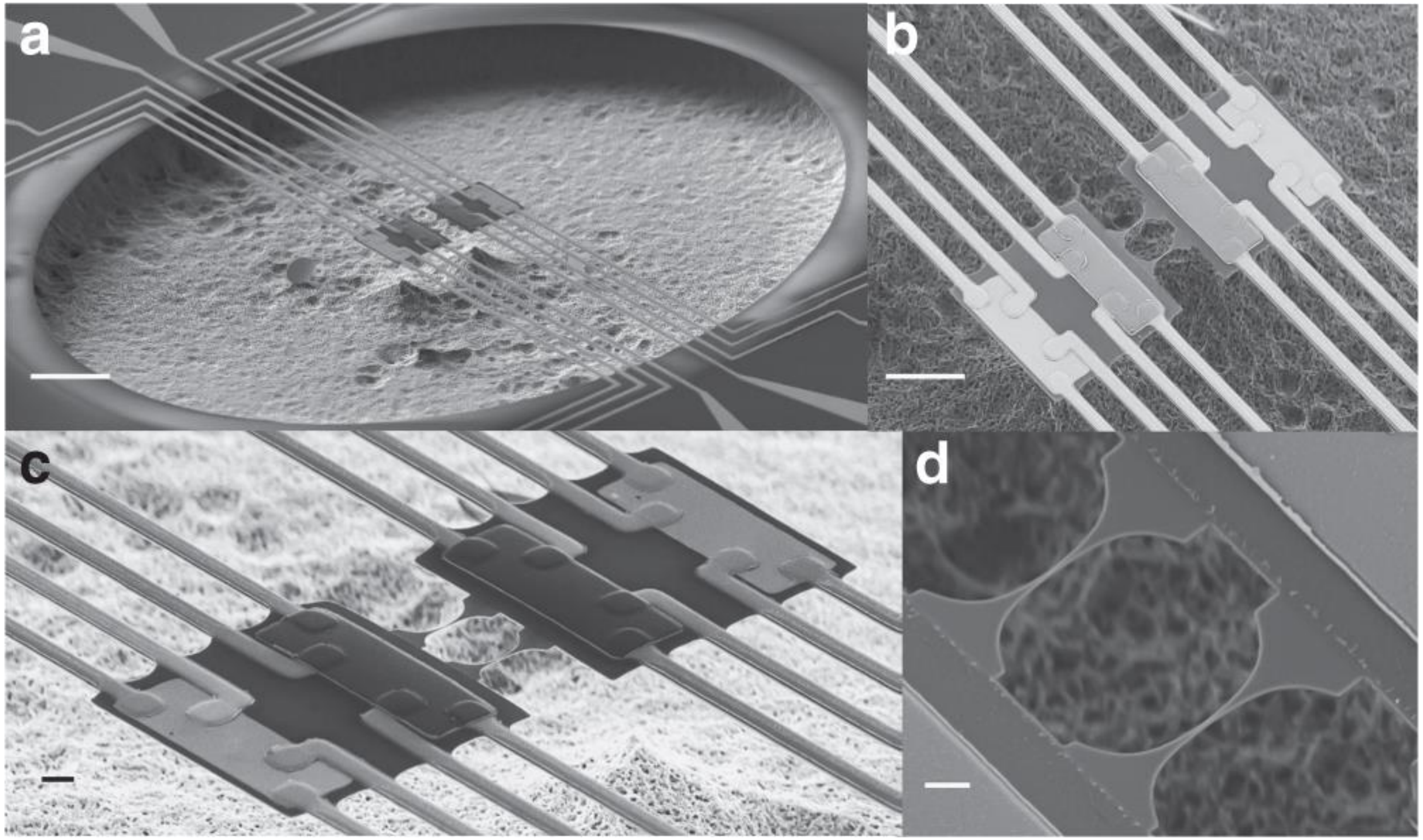
$\propto \sqrt{n} \propto k_F$

$j_{sat} = n e v_{sat}$

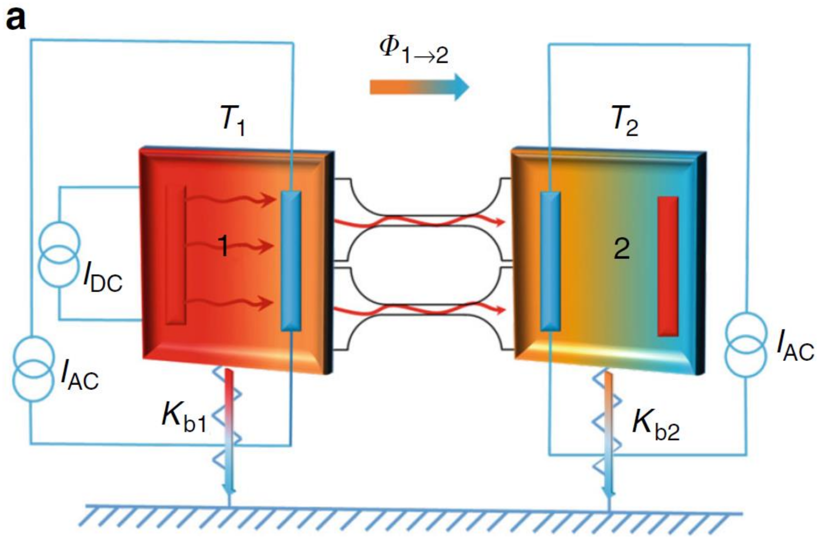


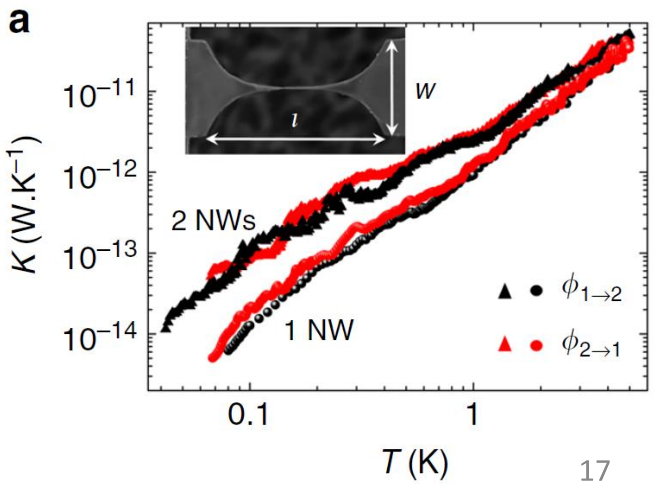
$v_{sat} = \frac{2}{\pi} \cdot \frac{\hbar\Omega}{\hbar k_F}$, $E_{sat} = \frac{v_{sat}}{\mu}$

非平衡载流子弛豫的探测–热输运



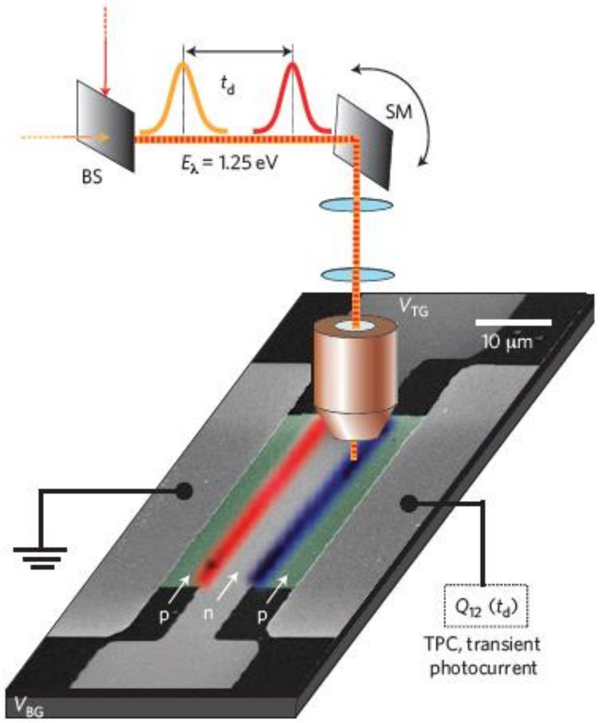
Grenoble, Nature Com. 2018

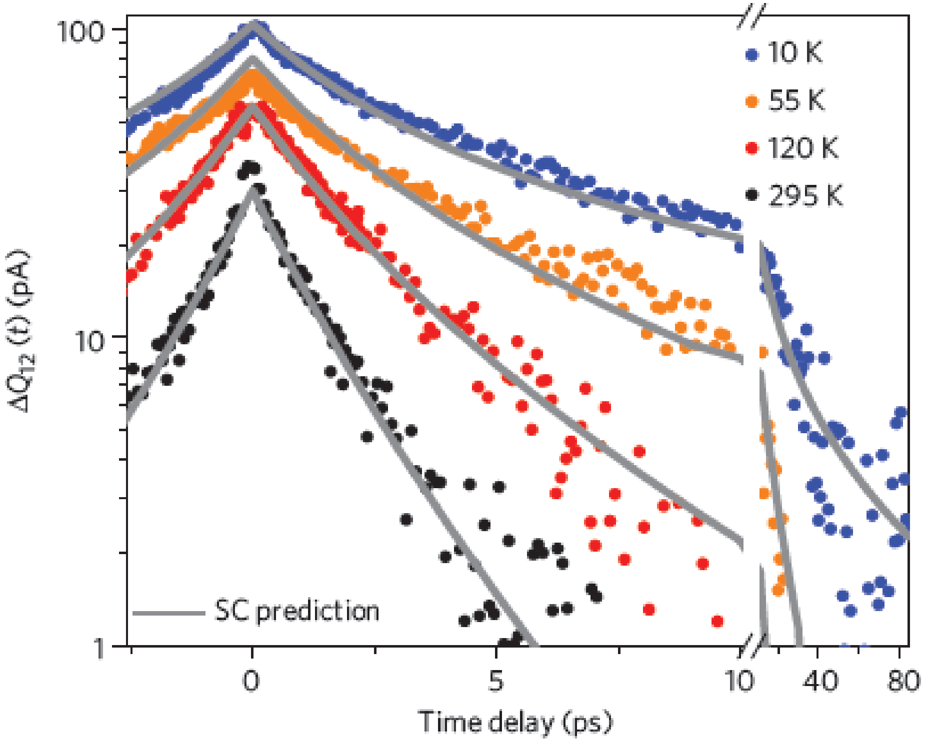




Suspended SiN-1D phonon waveguide

非平衡载流子弛豫的探测–光电流

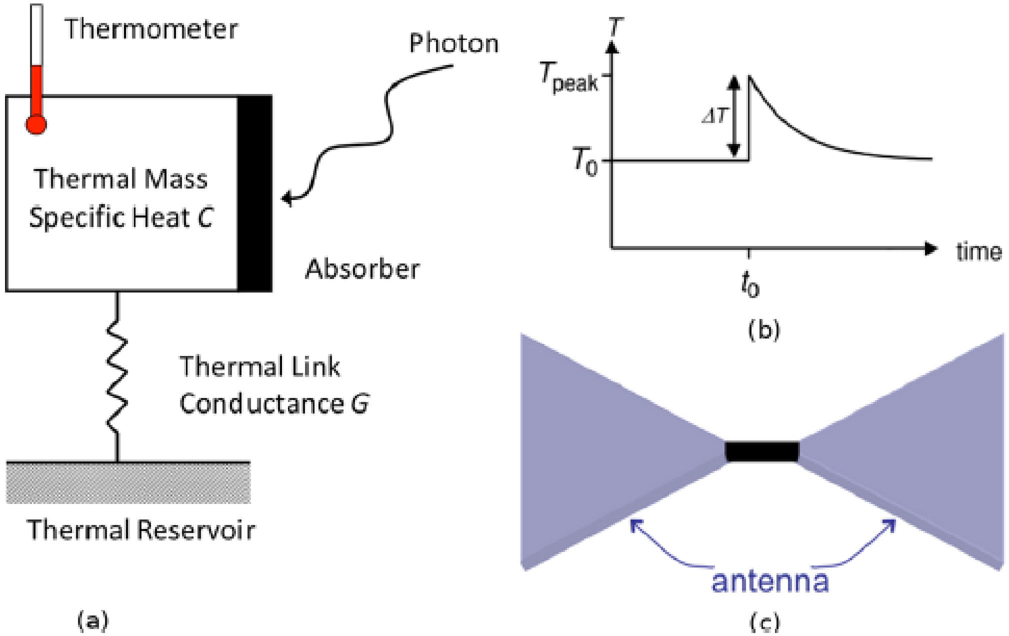


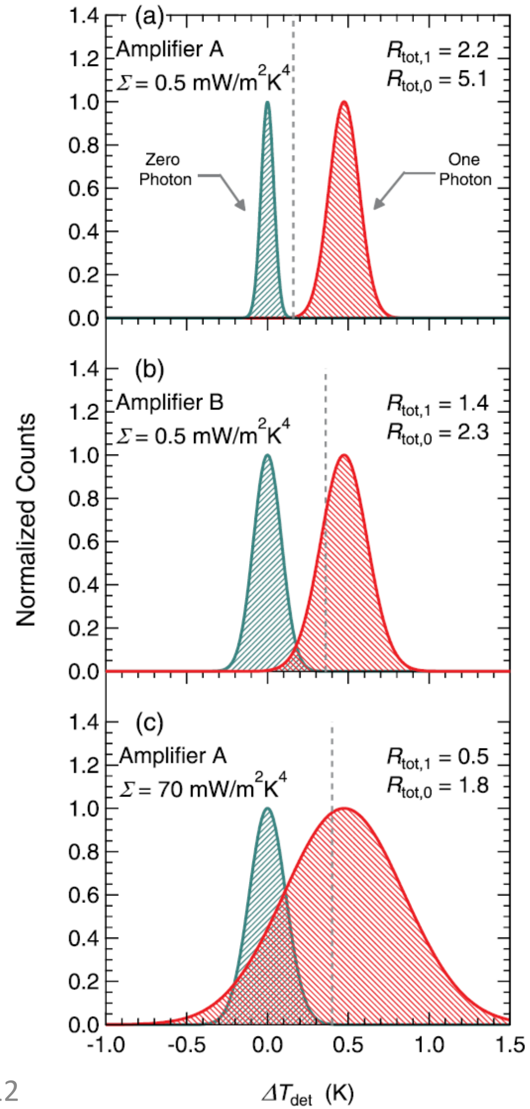


Graham et al. Nat Phys. 2013

非平衡载流子弛豫的探测–光+噪音

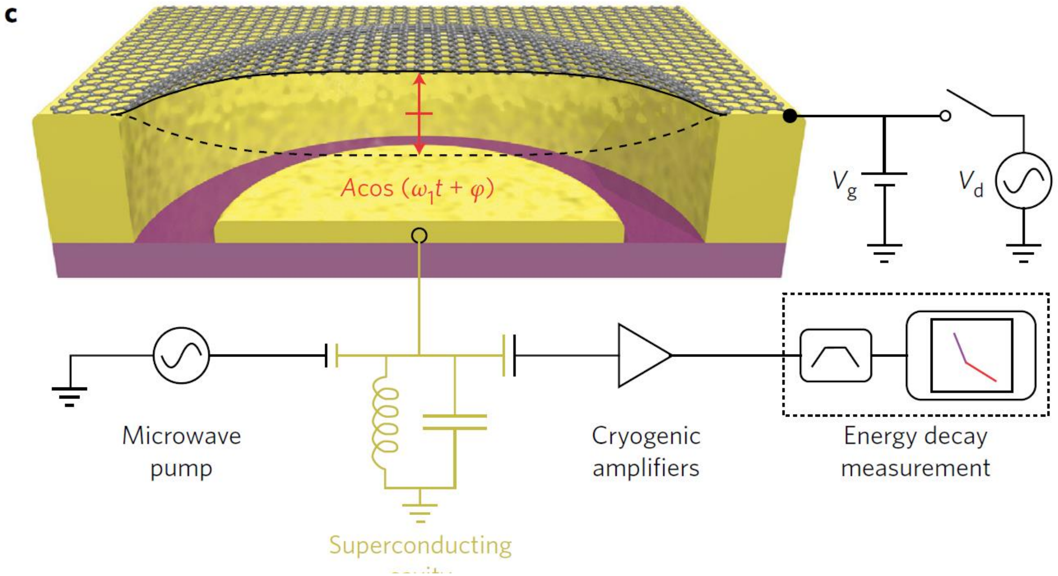
Photon absorption + Noise detection

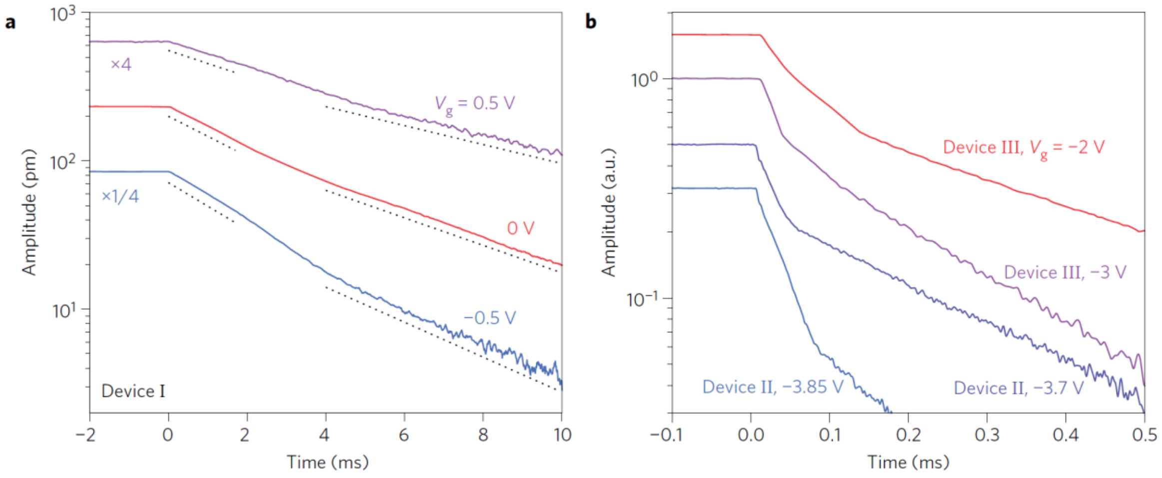


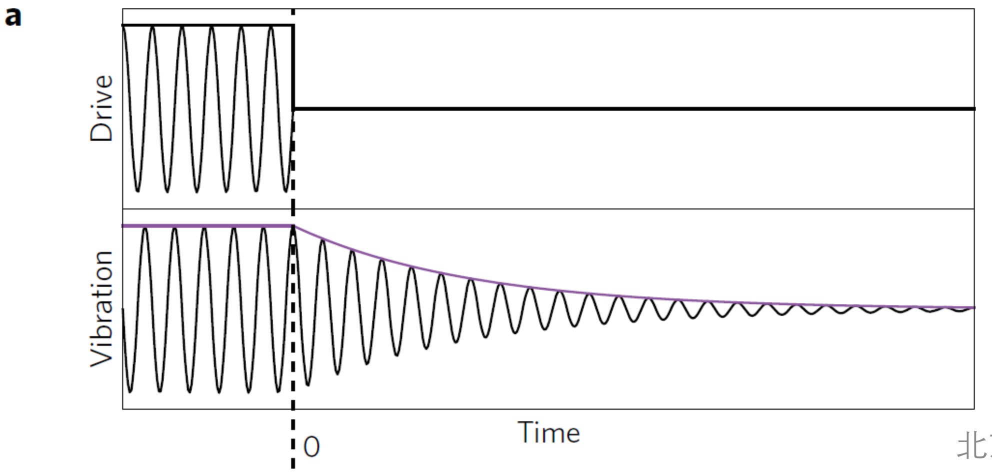


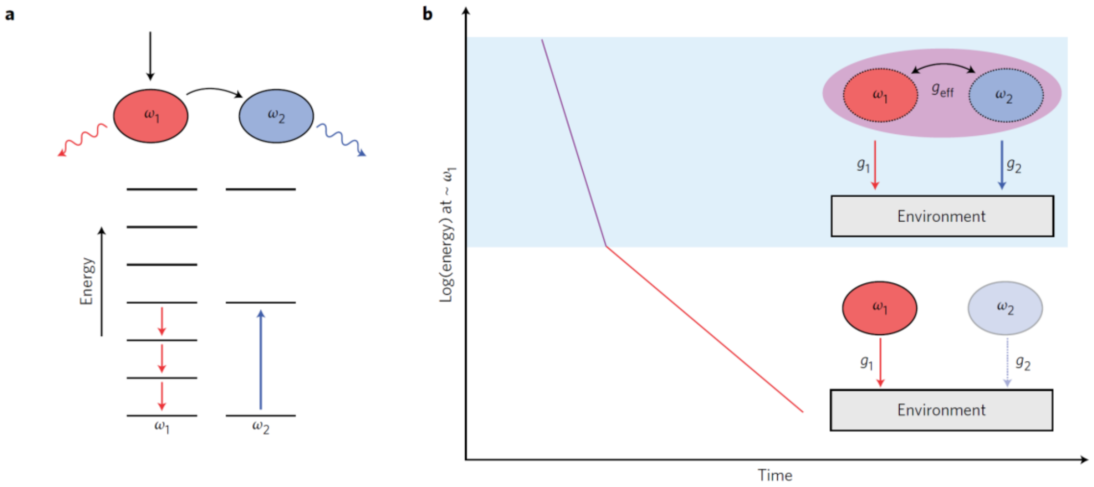
C. McKitterick et al., JAP 2013 ;
C. McKitterick et al., arXiv:1307.5012v1

非平衡载流子弛豫的探测–纳米机械学



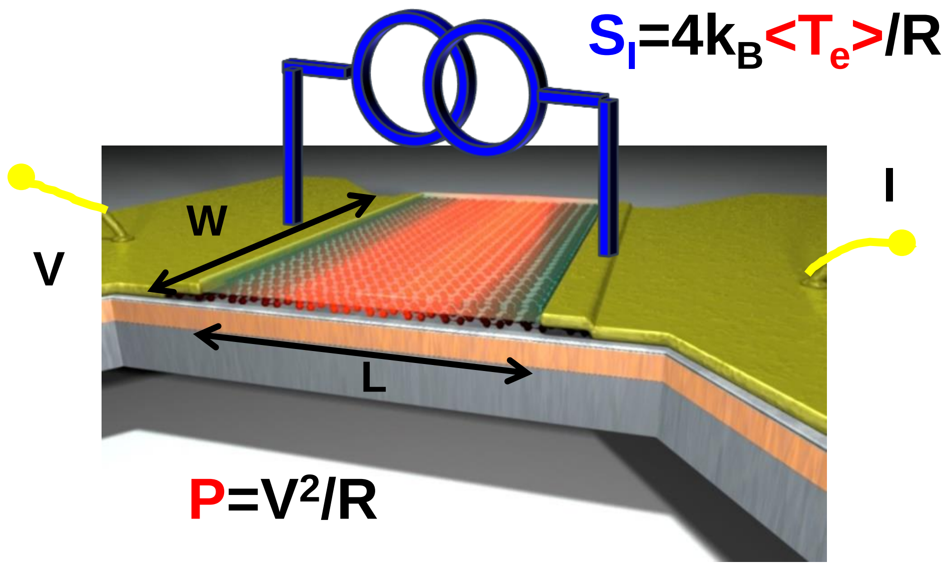




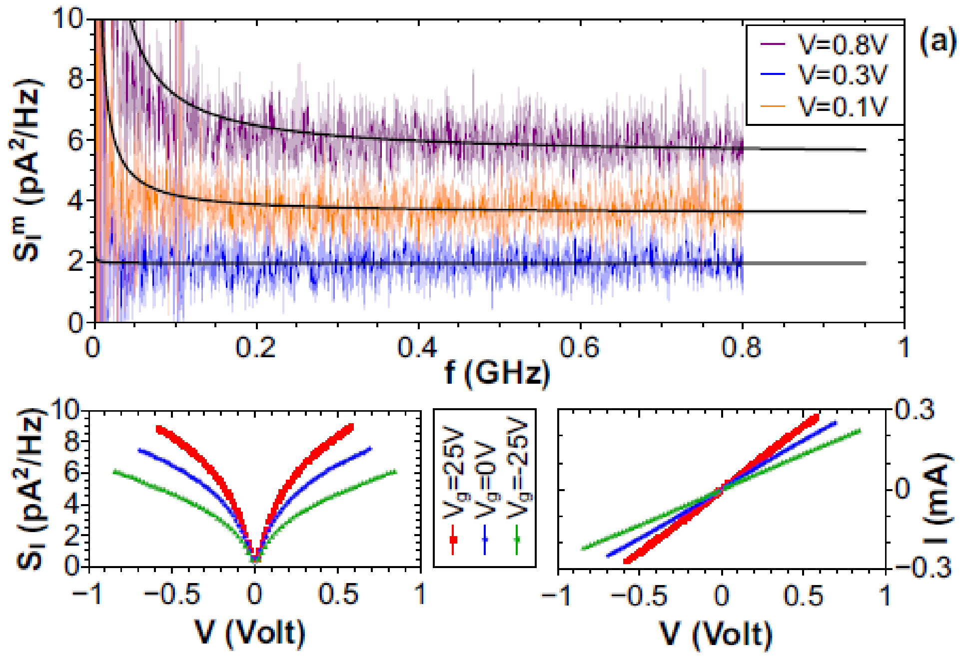


Bachtold, Nature Nano. 2018

非平衡载流子弛豫的探测–噪音谱学



Bernard Placais, PRL 2012 & Nature Physics 2013



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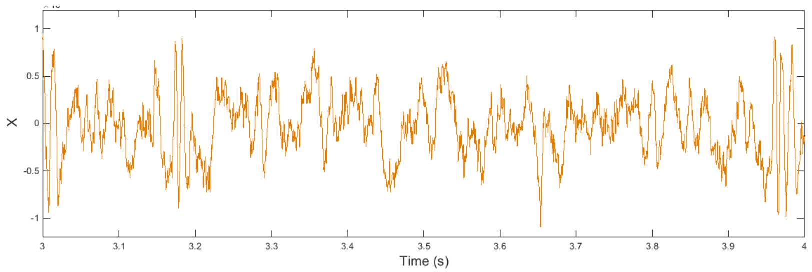
测量与噪音



measured signal is fluctuating in time

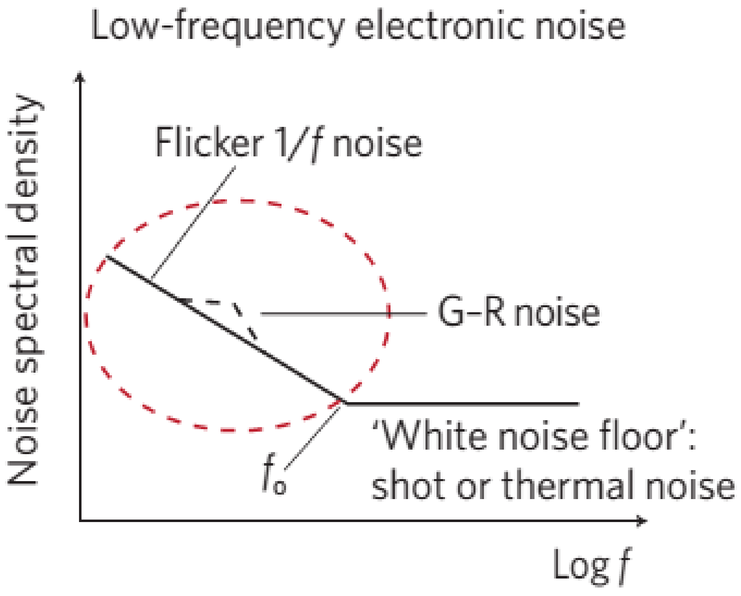
$$I(t) = < I > + \delta I(t)$$

$$S_{II} = \delta I^2 / f$$

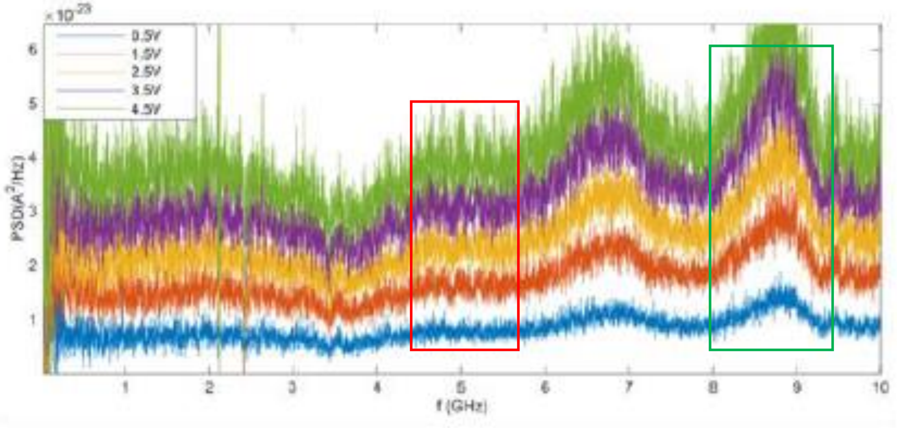
图片来自百度

50Hz 输电线
Wifi 信号
微波炉
…
接地
热噪音
电噪音
…
引力波
…

噪音的种类



Alexander A. Balandin, Nat. Nano. ***8****, 549 (2013).*



Resonances
RLC
Vibration
Microwave Cavity
...

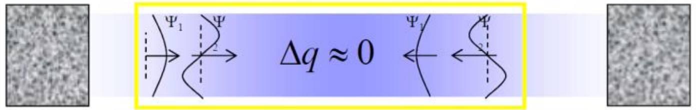
$$S_{total} = \alpha_H V^2/ N f + \boxed{S_V} \quad \textit{thermal noise, shot noise} \quad + \boxed{S_x}$$

1/f noise

$$S_I = F*2eI$$

噪音与电子输运特性-Fano factor

The Fano factor of quantum conductors



Conductance is transmission   Noisy scattering

$$G = 4\frac{e^2}{h}\sum_{1}^{N} T_n \qquad S_I = 2eI\frac{\sum T_n(1-T_n)}{\sum T_n} = 2eI \times \text{"Fano"}$$

R. Landauer and M. Büttiker

Curtsy of Bernard

Fano factor F<1 in mesoland with $F = \frac{1}{3}$ for a diffusive metal ①

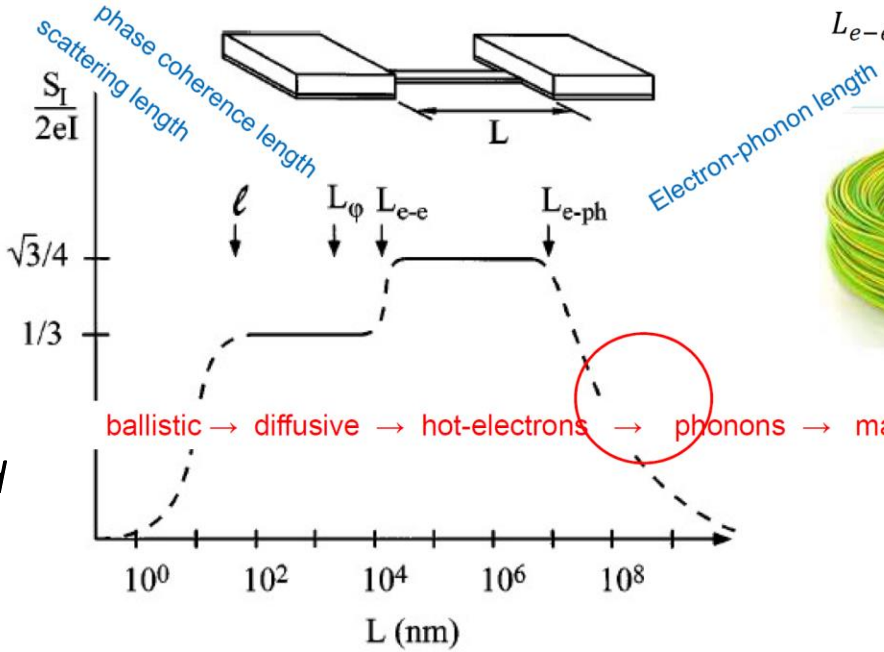
for a tunnel junction T ~ 0, F=1 ②

Ballistic channel T=1, F=0 ③

Conductors : from quantum to macro

… just increase the sample length L

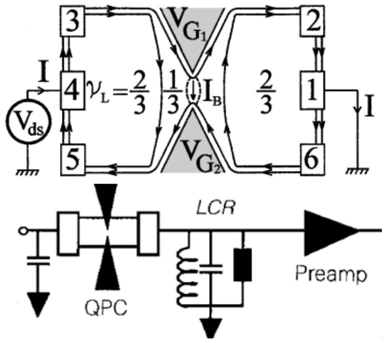
$$L_{e-e} \propto \frac{1}{(k_B T)^2}, \frac{1}{(eV_{ds})^2}$$



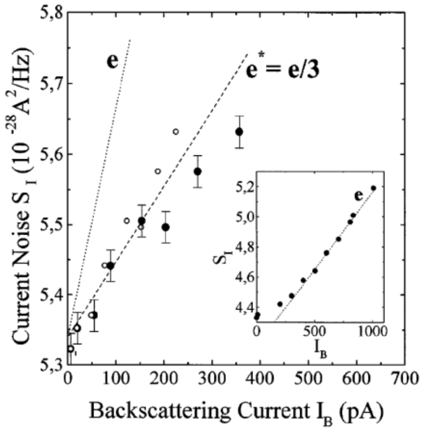
A.H. Steinbach et al., PRL1996 : Observation of Hot-Electron Shot Noise in a Metallic Resistor

噪音谱学的应用

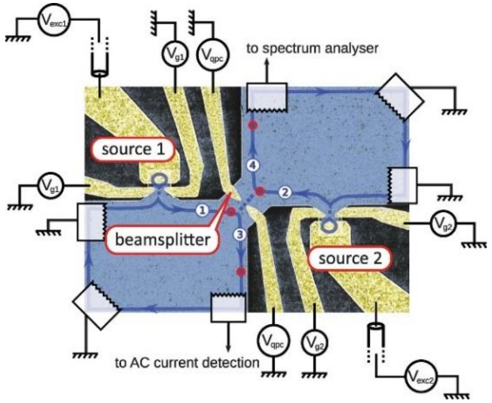
Fractional quasi-charge in FQHE

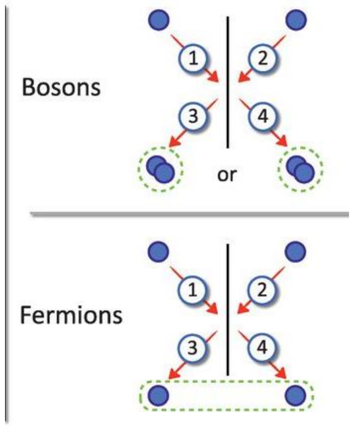


PRL 79,2526(1997)
Nature 389,162(1997)



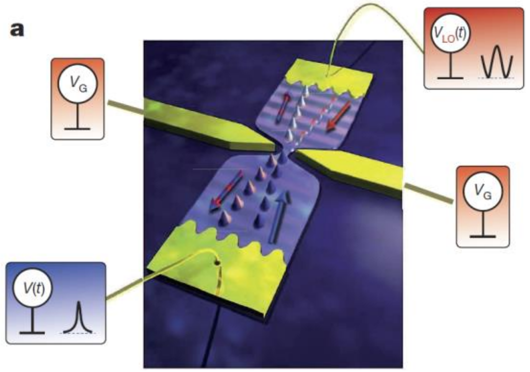
Single electron interference





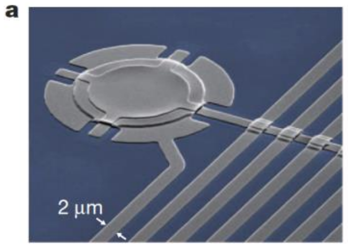
Science 339,1054(2013)

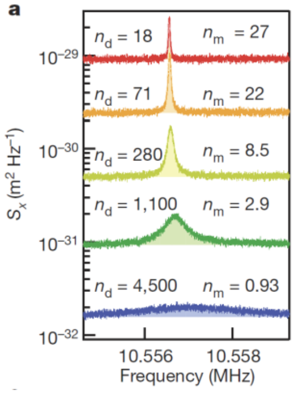
Quantum tomography of electron



Nature 514,603 (2014)

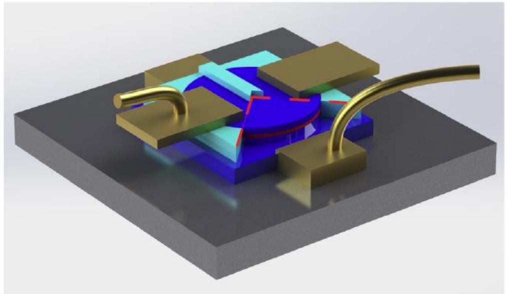
Ground state cooling





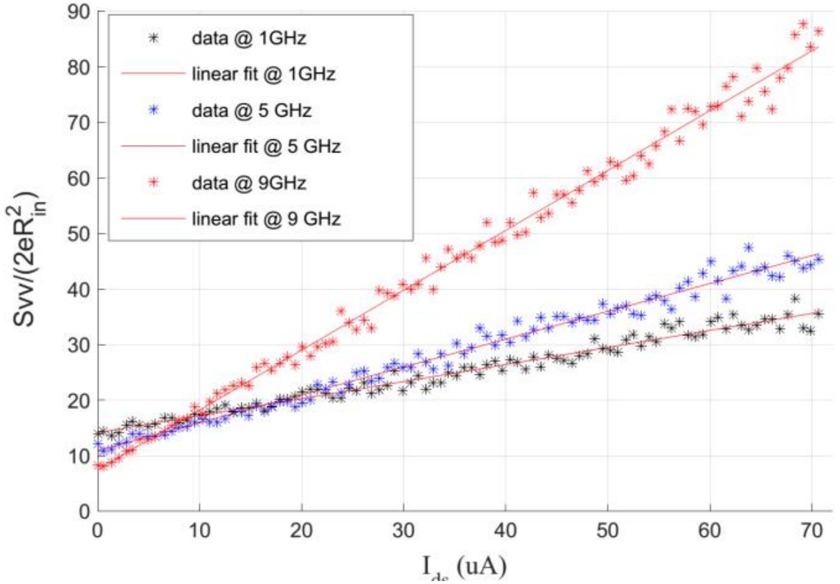
Nature 475,395 (2011)

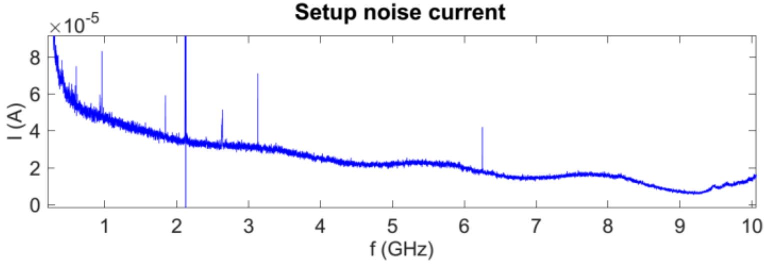
Electron pairing in LaSrCuO junction

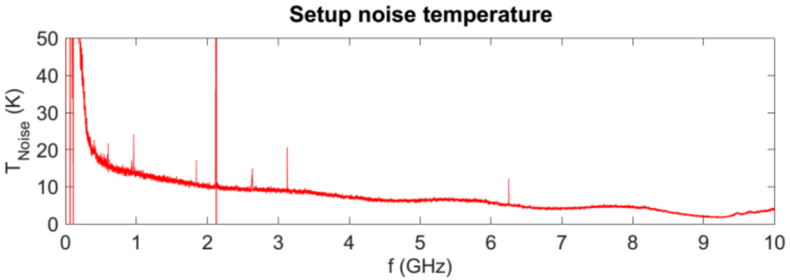


Nature 572,493 (2019)

GHz噪音谱的标定





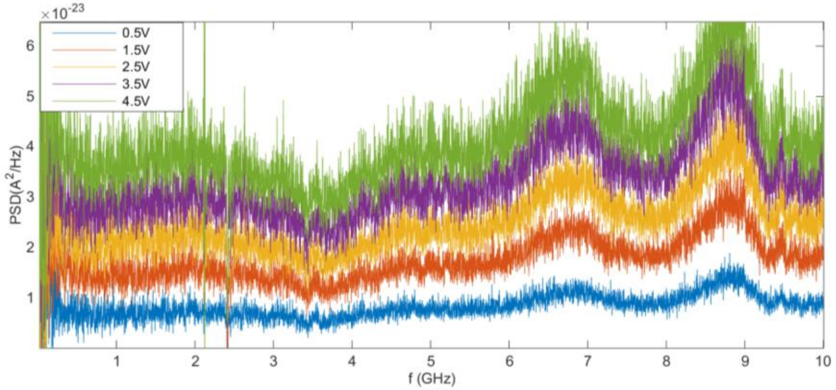


$$S_{VV}^{out} = S_{VV}^{sample} + S_{VV}^{amp.line}$$

A tunnel junction is used to calibrate the background noise

$$S_{VV}^{sample} = S_{VV}^{TJ} \propto 2eI_{ds} \Rightarrow \boldsymbol{I}_{noise}$$

$$S_I^{graphene} = \left(\frac{S_{VV}^{out}}{S_{VV}^{amp.line}} - 1\right) \cdot 2eI_{noise}$$



Noise spectra with a bandwidth of ~5 GHz

热噪音与电子温度

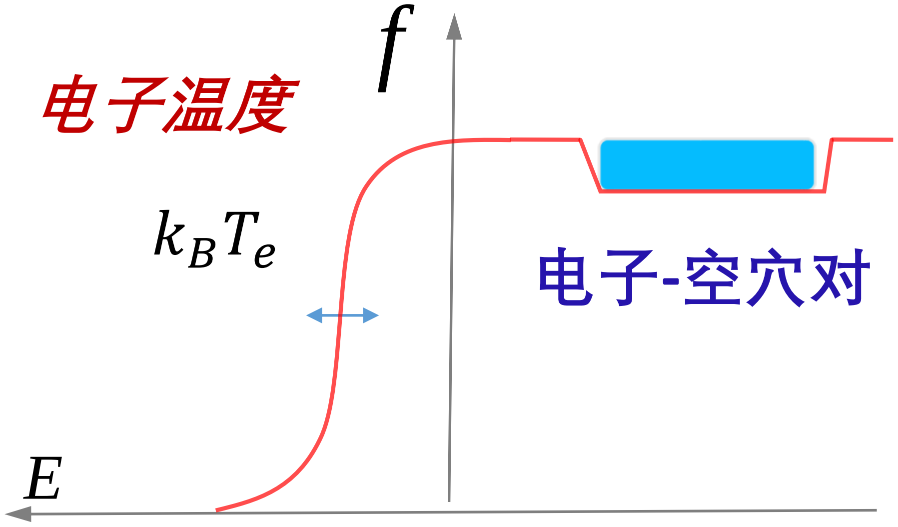
Noise temperature $k_B T_N \equiv S_I/4G_{diff}$

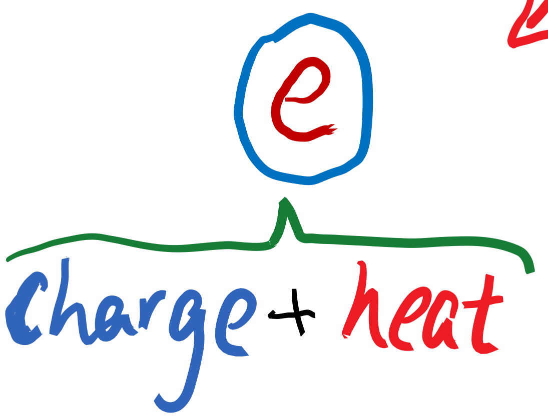
Hot electrons, heat equation, Wiedemann-Frantz

$$k_B T_N \equiv \langle k_B T_e \rangle = \frac{\sqrt{3}}{8} \times Length \times \sqrt{P/\sigma}$$

Hot Fermi sea + holes

$$k_B T_N \equiv \int_{-\infty}^{\infty} f(1-f)dE \approx k_B T_e + \frac{n_h}{DOS}$$





$$\kappa = \sigma \cdot L_0 T$$

$$L_0 = \frac{\pi^2}{3}\left(\frac{k_B}{e}\right)^2$$

1. 介观体系的热力学平衡与非平衡
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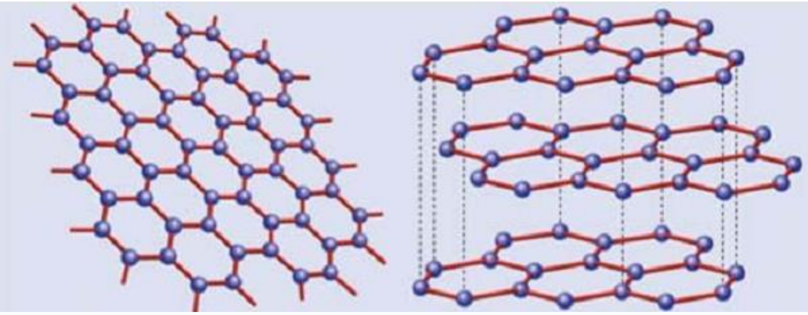
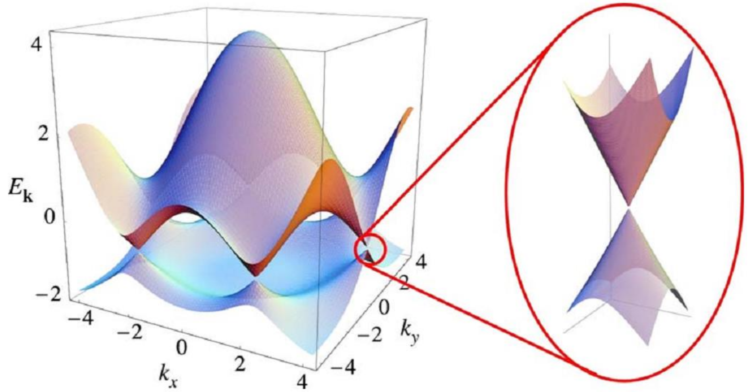
5. 碳管布朗运动与受限量子输运的关联

石墨烯

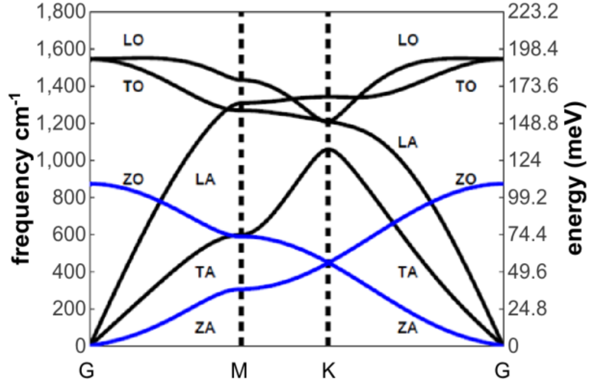

Scotch
Scotch®
Magic™ Tape
810 1 ROLL
3/4 IN × 1296 IN
(36 YD)
19 mm × 32,9 m
1" CORE

石墨烯的能带和声子谱





Rev. Mod. Phy. 81, 109 (2009)



Weak electron-phonon coupling

Weak thermal electron-phonon coupling

$$P(T \ll \theta_{BG}) = \Sigma \Delta T^4 = \frac{\pi^2 D^2 k_B^4 |\mu|}{15 \rho_m \hbar^5 s^3 v_F^3} \times (T_e^4 - T_{ph}^4)$$

$$P(T \gg \theta_{BG}) = G_o \Delta T = \frac{D^2 k_B |\mu|^4}{2\pi \rho_m \hbar^5 v_F^6} \times (T_e - T_{ph})$$

J. K. Viljas and T. T. Heikkilä PRB (2010)

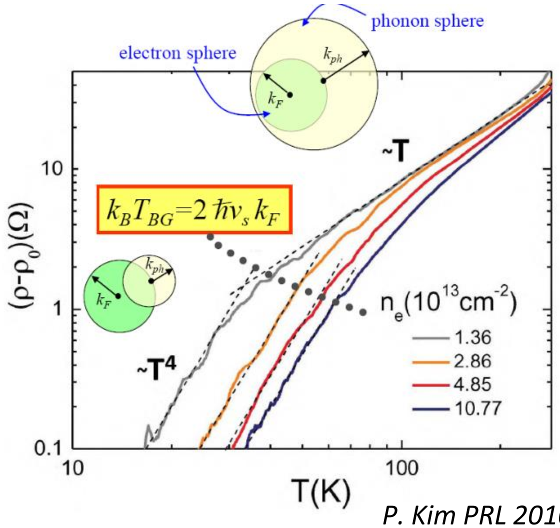
Weak electrical electron-phonon coupling

$$\Delta\rho(T) = \frac{8 D^2 k_F}{e^2 \rho_m s V_F^2} \times f_s \left(\frac{T_{BG}}{T}\right)$$

Large sound and Fermi velocities !

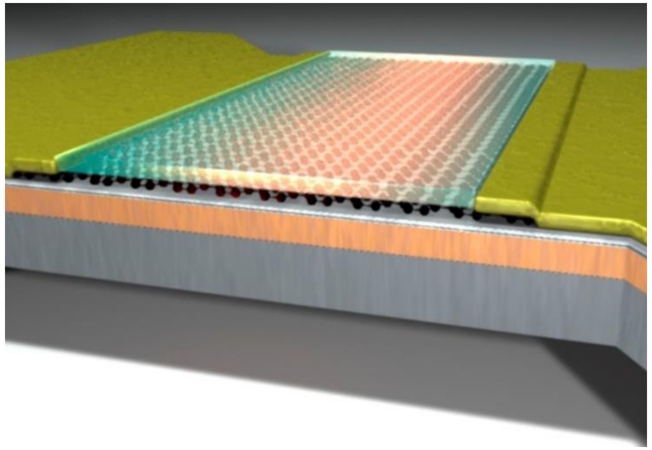
$$\left(s = 2.10^4 \text{ m/s} \; ; \; V_F = 1.10^6 \text{ m/s}\right)$$

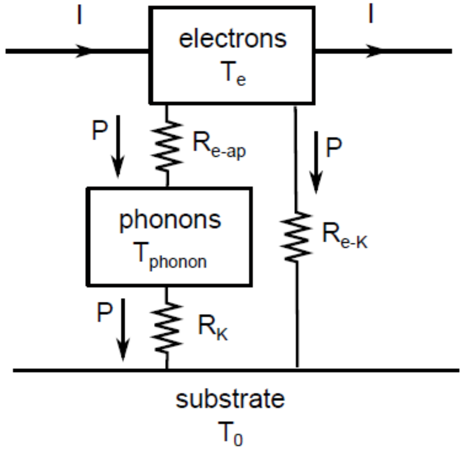
(Hwang-DasSarma PRB2008)

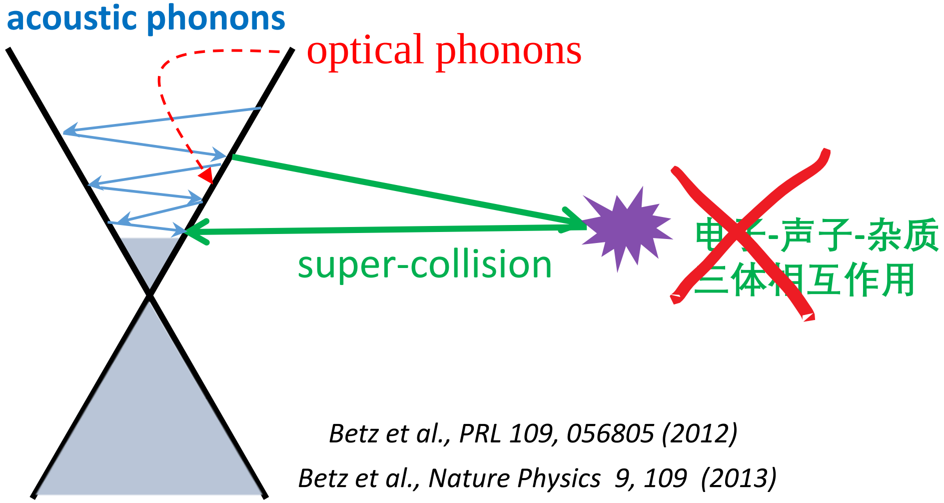


P. Kim PRL 2010

电子–声子弛豫的三种常见类型







Betz et al., PRL 109, 056805 (2012)

Betz et al., Nature Physics 9, 109 (2013)

$$-\frac{\sigma\pi^2 L^2}{6}\frac{\partial^2}{\partial x^2}\left(\frac{k_B T_e}{e}\right) = \varepsilon \cdot J - P(T_e, T_{ph}) - P_{OP}$$

Wiedemann-Frantz law | Joule power | Acoustic/Optical Phonon cooling

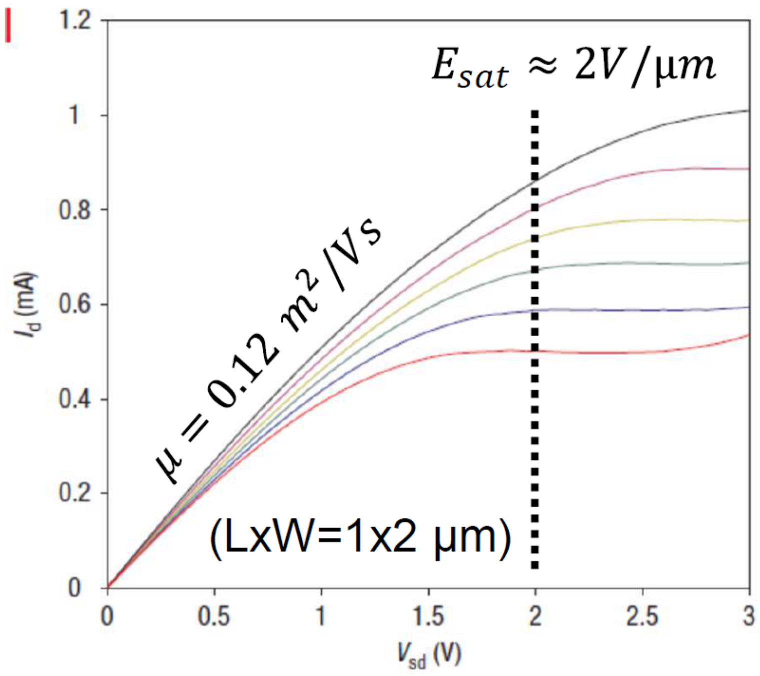
WF	Low-T AC	Super-collisions	OP
$P \propto T^2$	$\propto T^3$	$\propto T^4$	$\propto exp[T/\Omega_{OP}]$
$\leq 10^8\ W/m^2$	$10^8\ W/m^2$	$3\ 10^8\ W/m^2$	$10^9\ W/m^2$

热声子→热晶格→器件过热→烧坏

迁移率对器件的影响

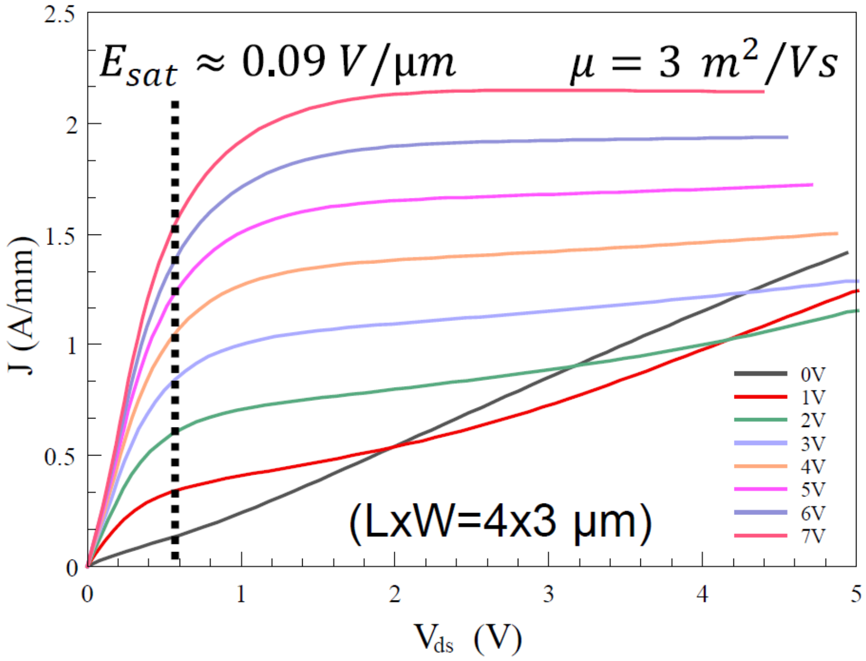
Graphene on SiO2

I Meric et al., Nat. Nano (2008)

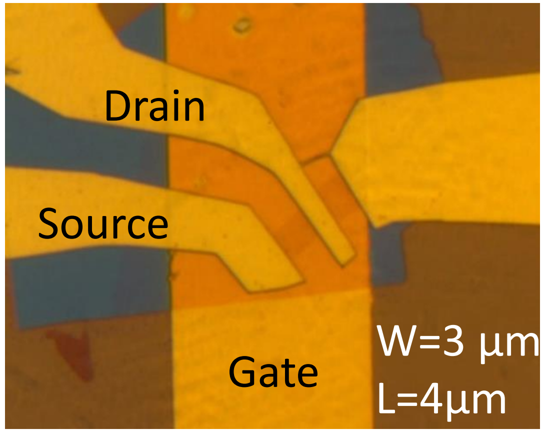


Graphene on BN

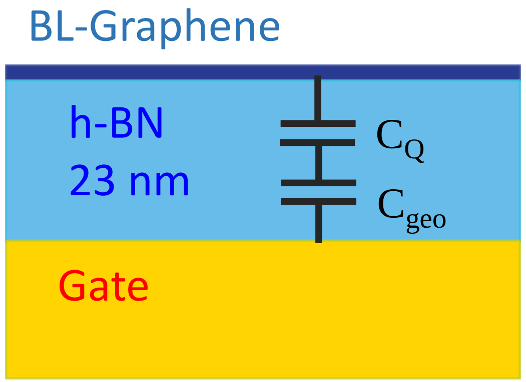
W. Yang et al., Nat. Nano (2018)

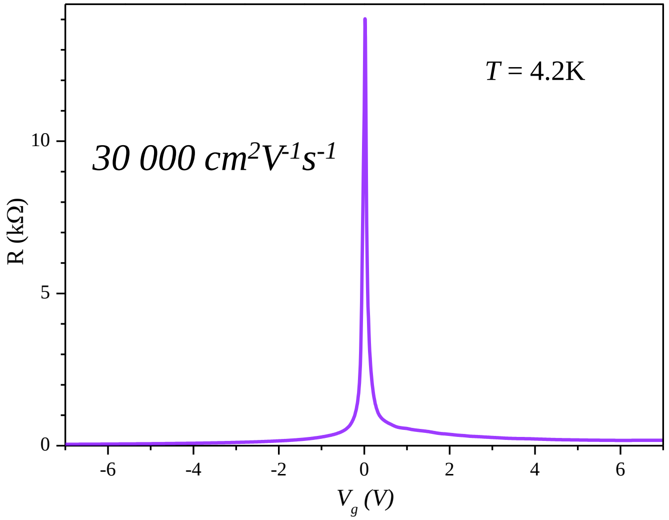


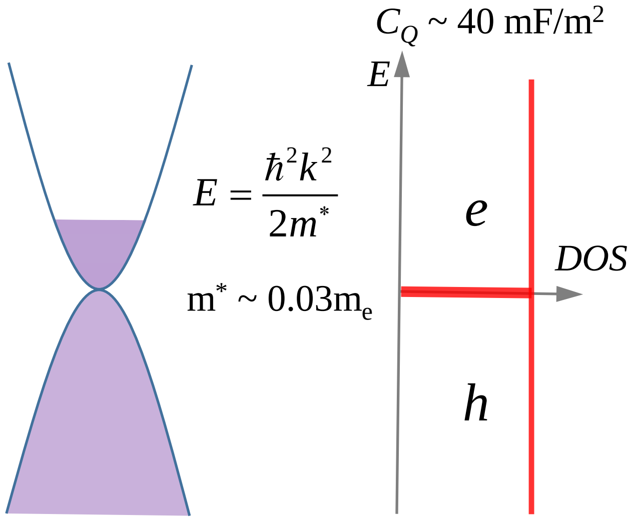
高质量G/hBN器件



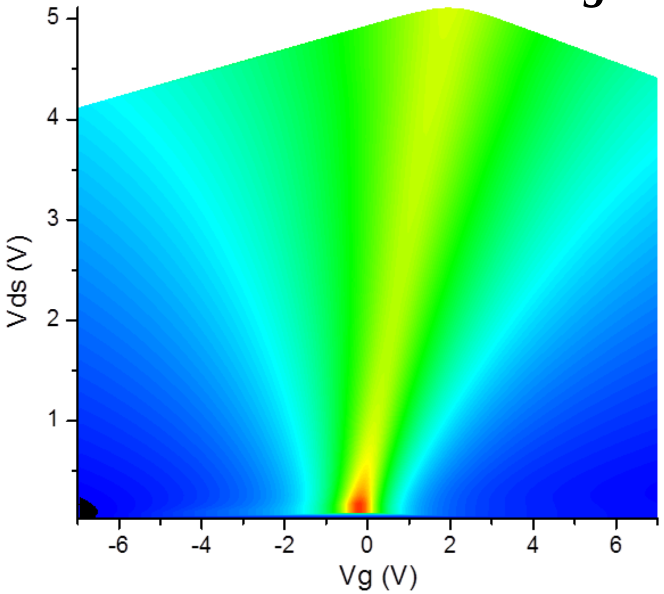
Hexagonal boron nitride
Flat surface
No dangling bonds
Wide band gap semiconductor
1.8% lattice mismatch

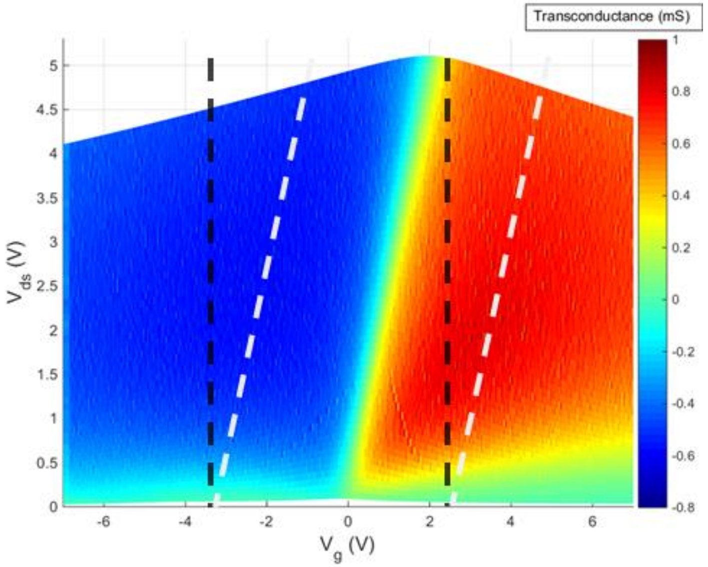






Bias is gating



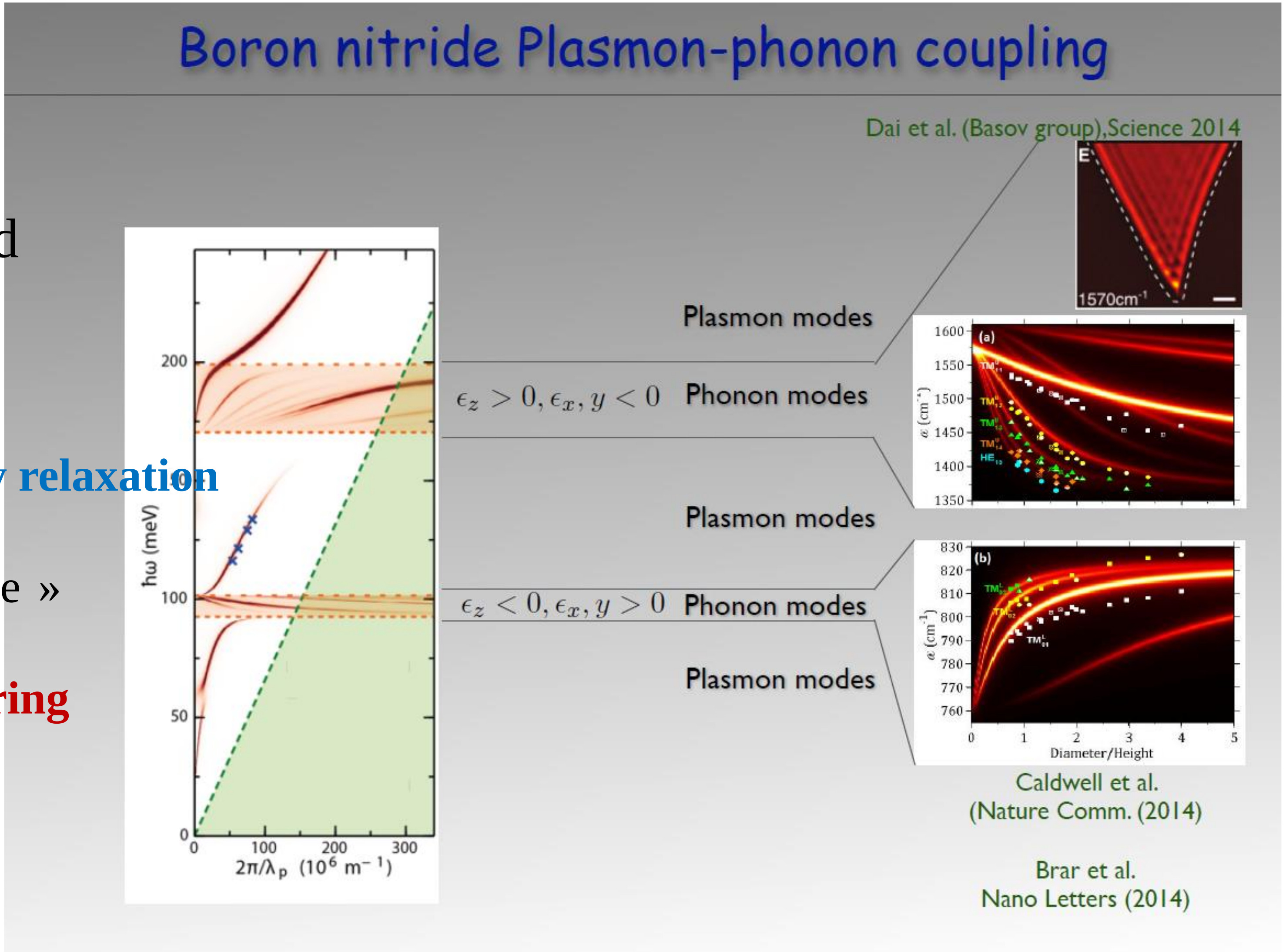


Hyperbolic phonons of hBN

Reststrahlen band

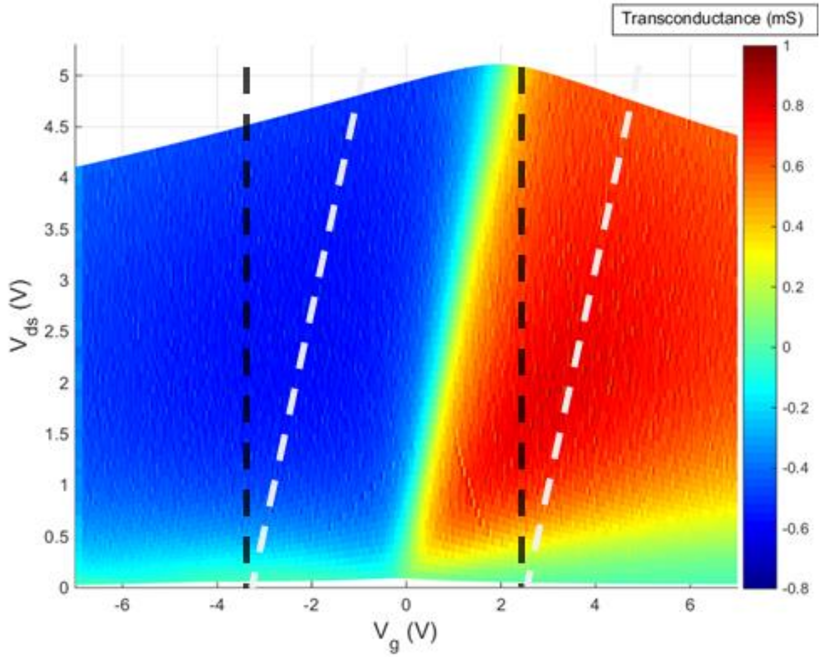
Type-II «in-plane »
~170-200meV
Efficient for energy relaxation

Type-I «out-of-plane »
~90-100meV
Efficient for scattering



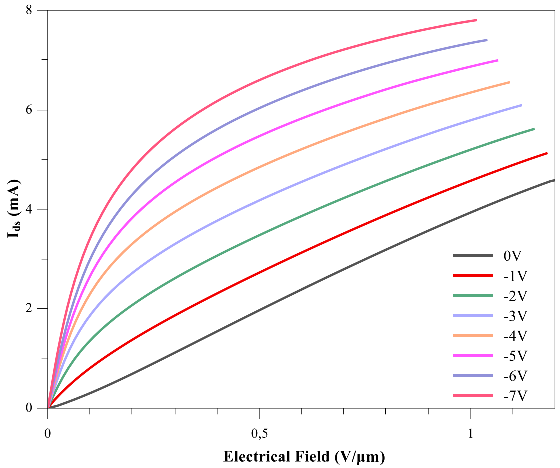
(Courtesy of F. Koppens, Kaprun School 2015)

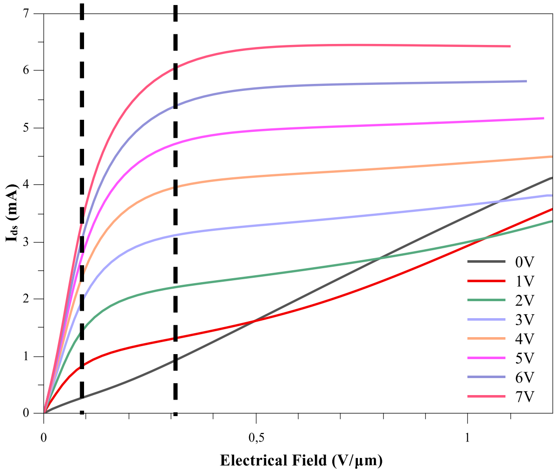
G/hBN 的高电场输运特性



Constant gate

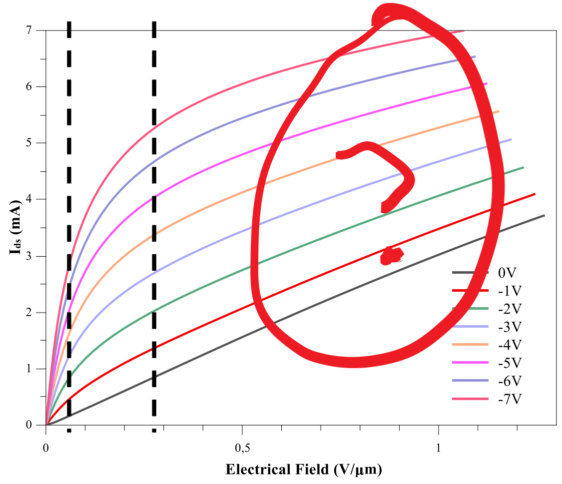
Dirac pinch-off

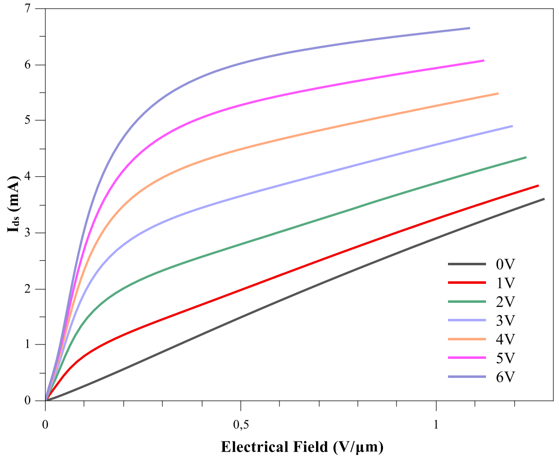




$J \propto E$

Constant carrier density

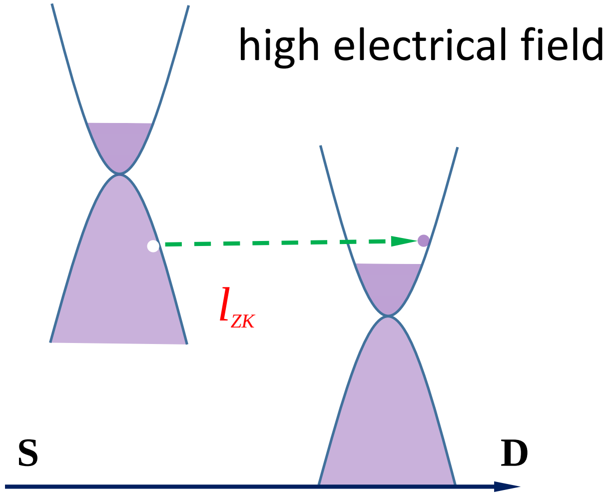


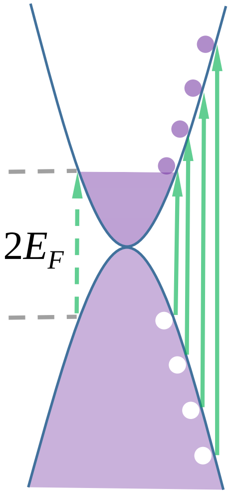


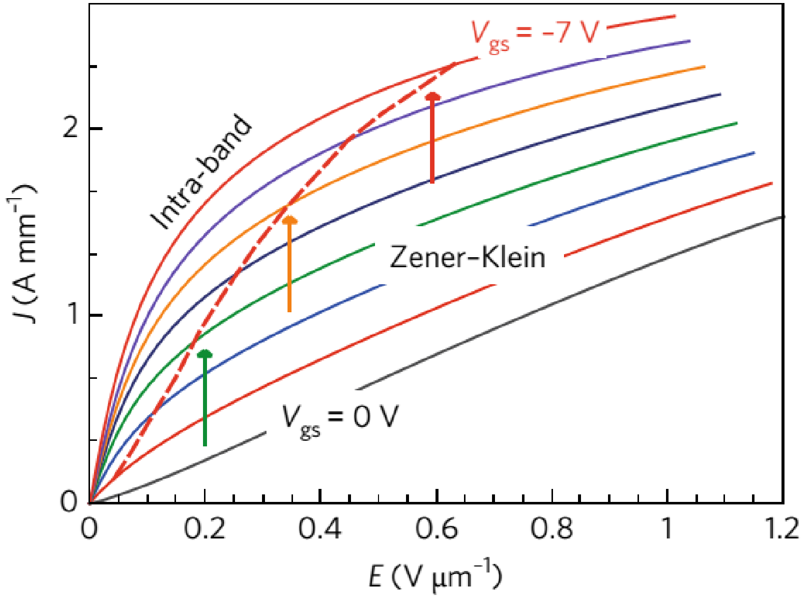
$$J = ne\mu\mathcal{E}/(1+\mu\mathcal{E}/v_{sat})^2$$

$+ \sigma_{zk} \cdot E$

Zener-Klein tunneling







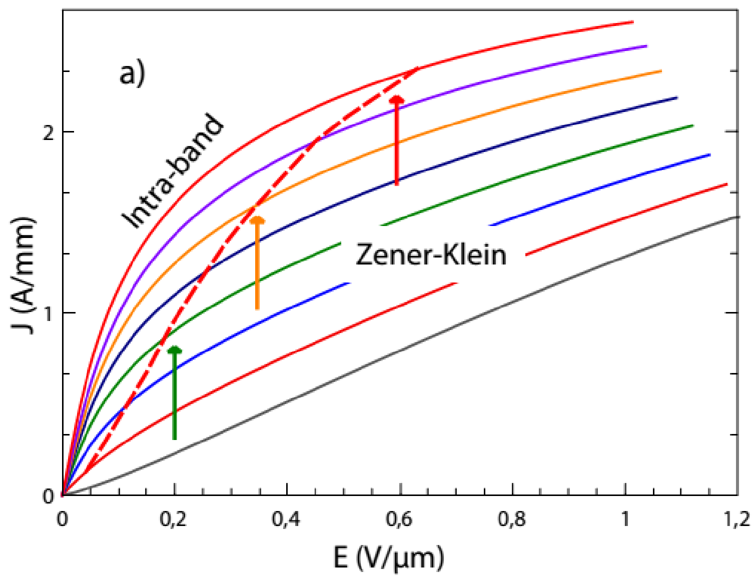
Wei Yang, et al. Nature Nano. 13, 47(2018)

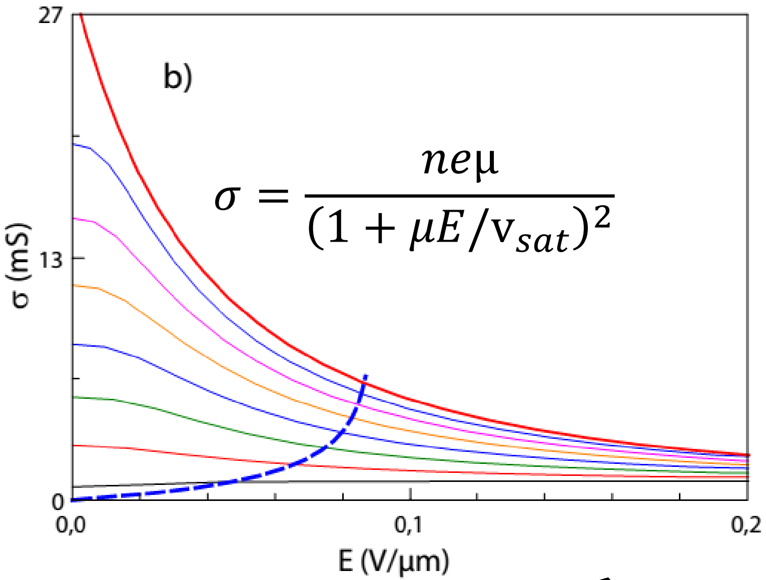
Zener-Klein Tunneling, Pauli blocking:

$$\sigma_{ZK} = \alpha \frac{4e^2}{h} \frac{k_F l_{ZK}}{4\pi} = Const. \quad ; \quad \dot{n}^{ZK}_{e-h} = \frac{e\, k_F}{\pi^2\, \hbar} (E - E_{ZK})$$

$$\boldsymbol{E_{zk}} = {}^{2E_F}\!/_{el_{zk}}$$ (dashed line)

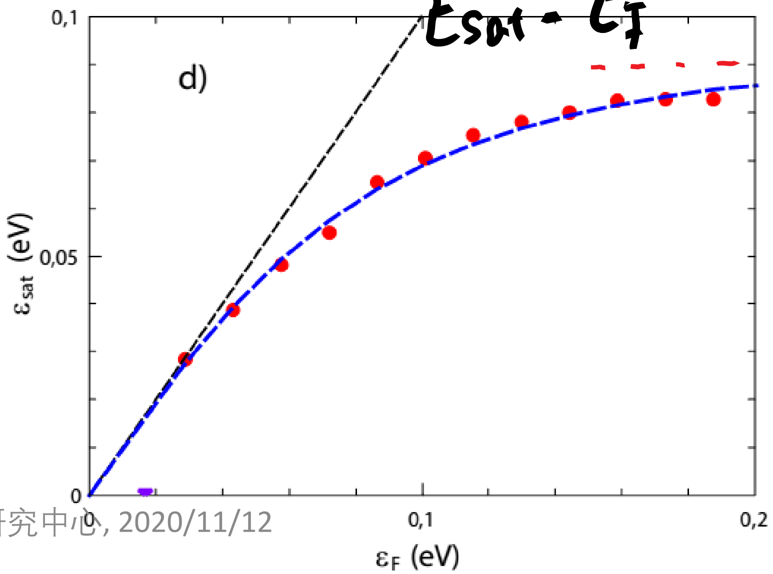
低电场下的电流饱和效应





$v_{sat} = \frac{2}{\pi} \cdot \frac{\bar{\varepsilon}_{sat}}{\hbar k_F}$

$\bar{\varepsilon}_{sat}$



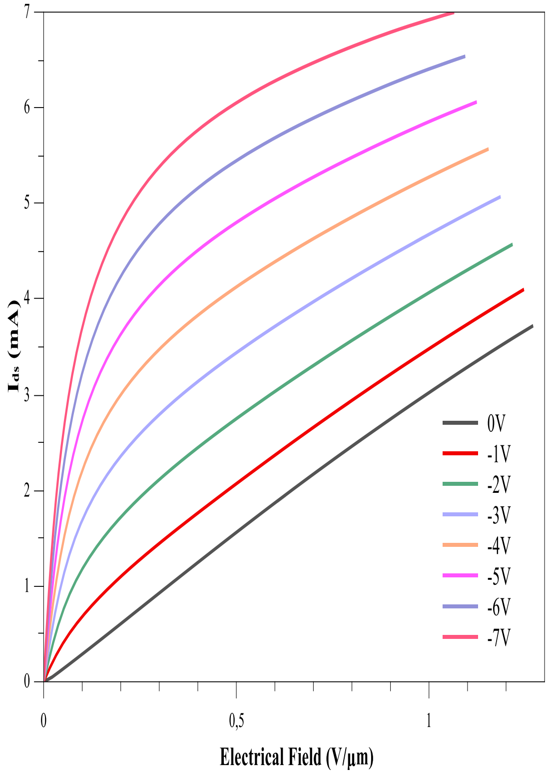
$\hbar\Omega \sim 90$ meV

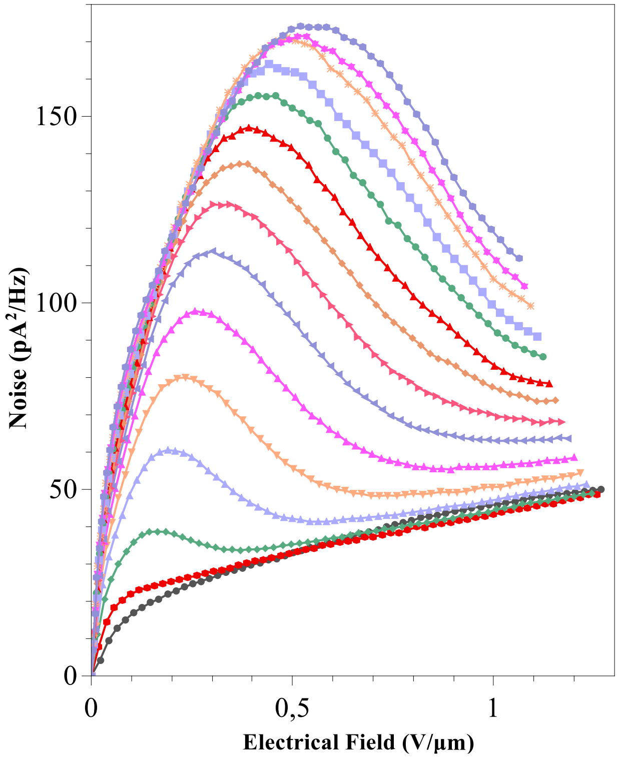
Saturation energy depends:

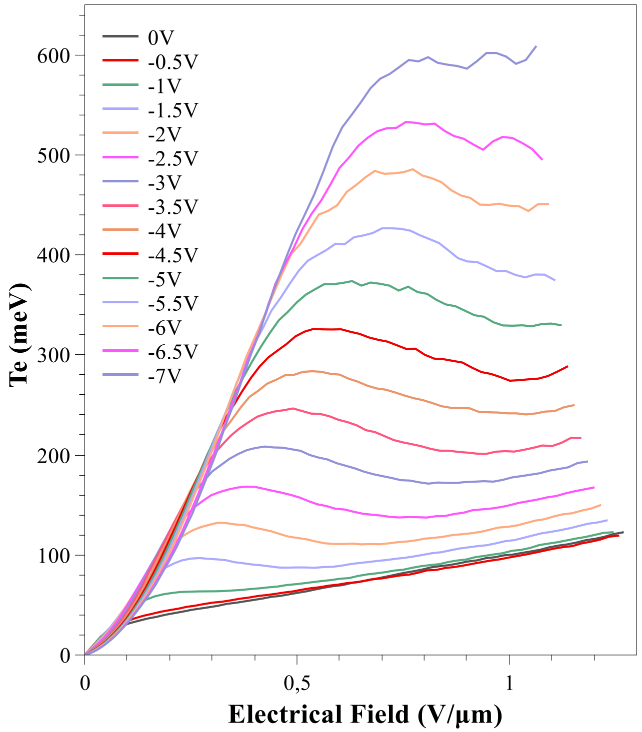
E_F at a low doping

90meV at a high doping

器件的直流测量与GHz 热噪音测量

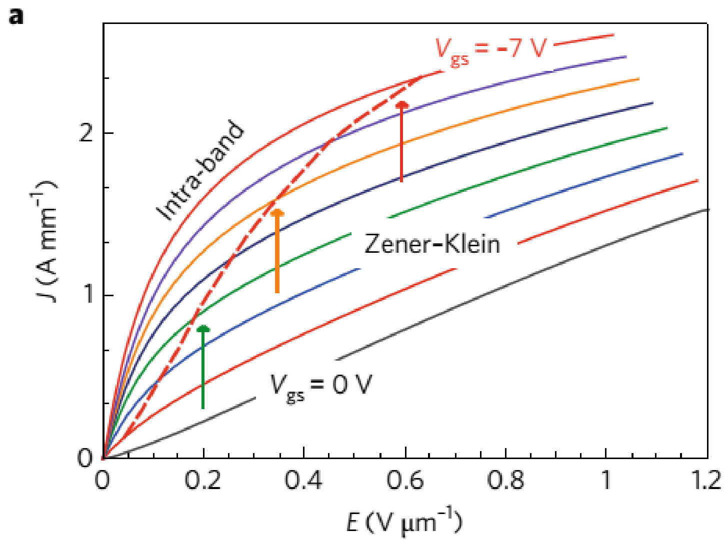






$$T_e = S_I * R / 4k_B$$

Zener Klein tunneling and Hyperbolic cooling

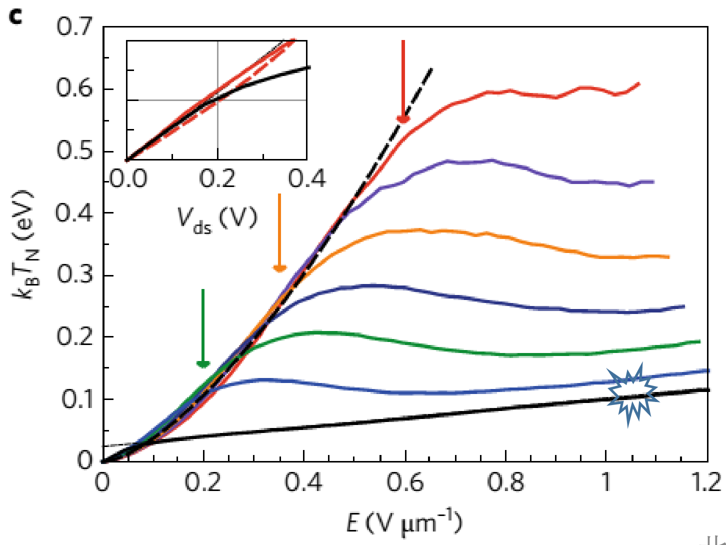


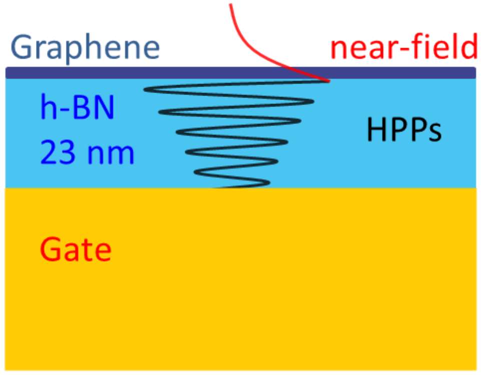
Onset of Zener-Klein tunneling

Wiedemann-Franz Law

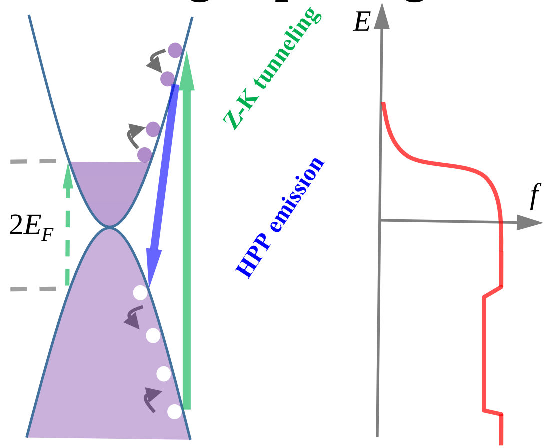
Hyperbolic cooling (~0.5ps)

Electron-hole pair creation



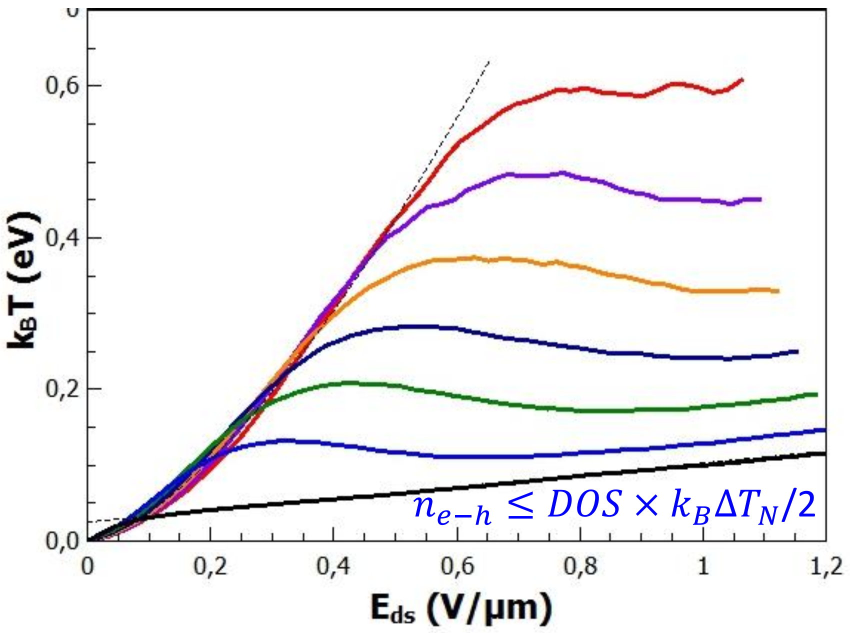


HPP cooling doped regime

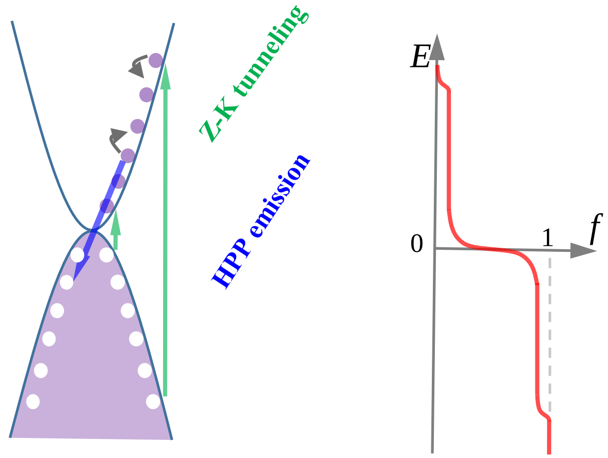


Wei Yang, et al. Nature Nano. 13, 47(2018)

ZK and HPP at CNP



ZK+HPP at charge neutrality

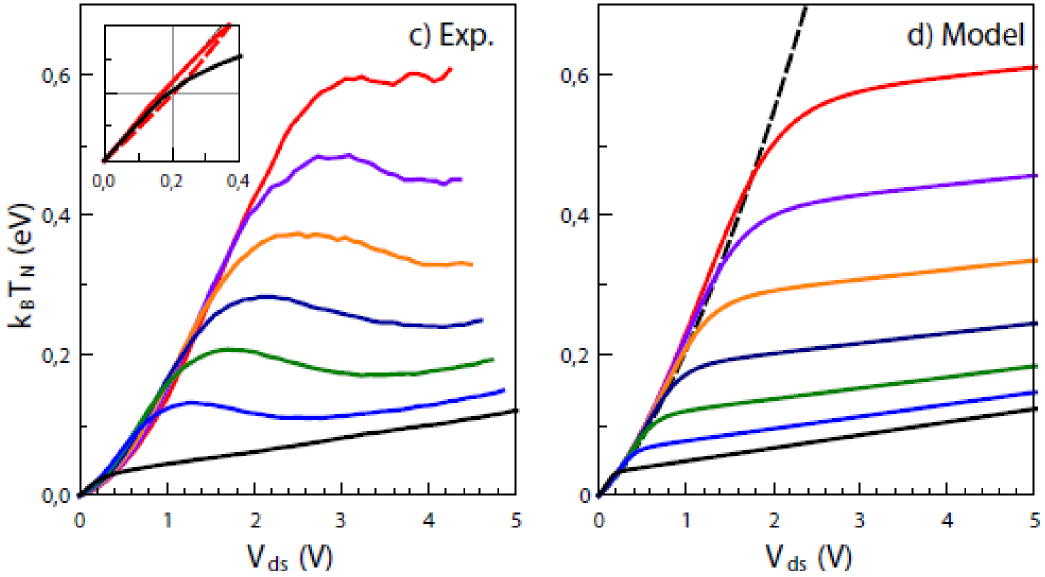


e-h pumping : $\dot{n}_{e-h}^{ZK} = \frac{e\,k_F}{\pi^2\,\hbar}(E - E_{ZK}) = \frac{n_{e-h}}{\tau_{HPP}}$ $\Rightarrow$ $\tau_{HPP} = \frac{\pi^2\,\hbar}{e\,k_F}\frac{dn_{e-h}}{dE}$

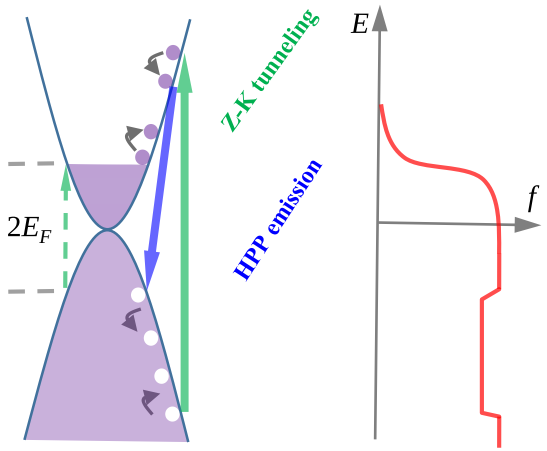
Noise temperature « Cold electron regime » $n_{e-h} \leq DOS \times k_B \Delta T_N/2$

$$\tau_{HPP} \leq \frac{\pi^2\,\hbar}{e\,k_F} DOS \frac{dk_BT_N}{dE} = 0.46\,ps \quad (n = 1.10^{12})$$

ZK and HPP at medium doping



HPP cooling doped regime



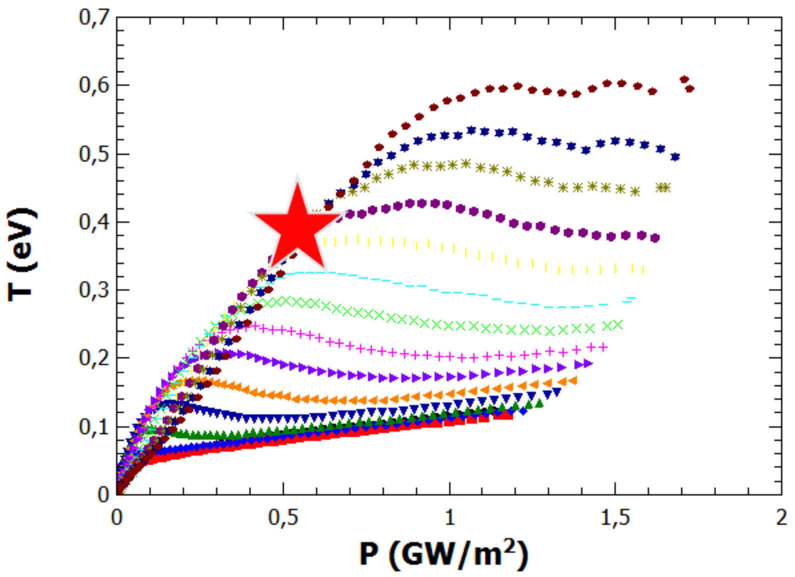
ZK current : $J_{zk} = \alpha \left(\frac{4e^2}{h} \frac{k_F l_{zk}}{4\pi} \right) (E - E_{zk})$ ZK pumping : $\dot{n}^{ZK}_{e-h} = \frac{e\, k_F}{\pi^2\, \hbar} (E - E_{ZK})$

HPP cooling : $P_{HPP} = \hbar\Omega\, \dot{n}^{HPP}_{e-h} = \hbar\Omega\, \dot{n}^{ZK}_{e-h} = \hbar\Omega \frac{e\, k_F}{\pi^2\, \hbar} (E - E_{zk})$

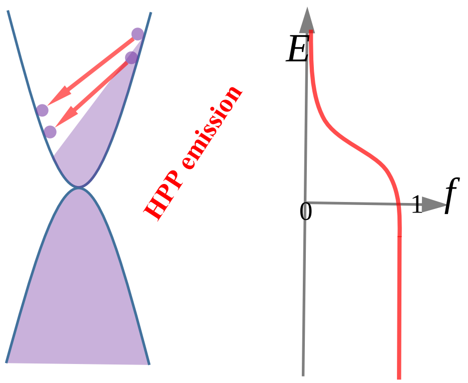
Joule Heating : $\Delta P_{Joule} = J_{sat}(E - E_{zk}) = \boldsymbol{2\varepsilon_{sat}} \frac{e\, k_F}{\pi^2\, \hbar} (E - E_{zk})$

in GoBN, where $\hbar\Omega_{II} \approx 2\hbar\Omega_{I} \approx 200\ meV$ ⇒ $\boldsymbol{P_{HPP} \approx P_{Joule}}$

Hot electrons and HPP emissions at high doping



HPP thermal emission



Super-Planck HPP thermal emission $(\sigma_{hot}(\omega, q)$ by Polini at al.)

$$P_J = 0.5 \frac{GW}{m^2}, \; kT = 0{,}4eV, \; n_e = 4\; 10^{12}$$

★ $$P_{HPP}^{th} = 2.4 \times M \frac{GW}{m^2} = 0{,}24 \frac{GW}{m^2} = P_J/2 = P_{WF} \quad by\ taking \quad M^{th} \approx 0.1$$

1. 介观体系的热力学平衡与非平衡

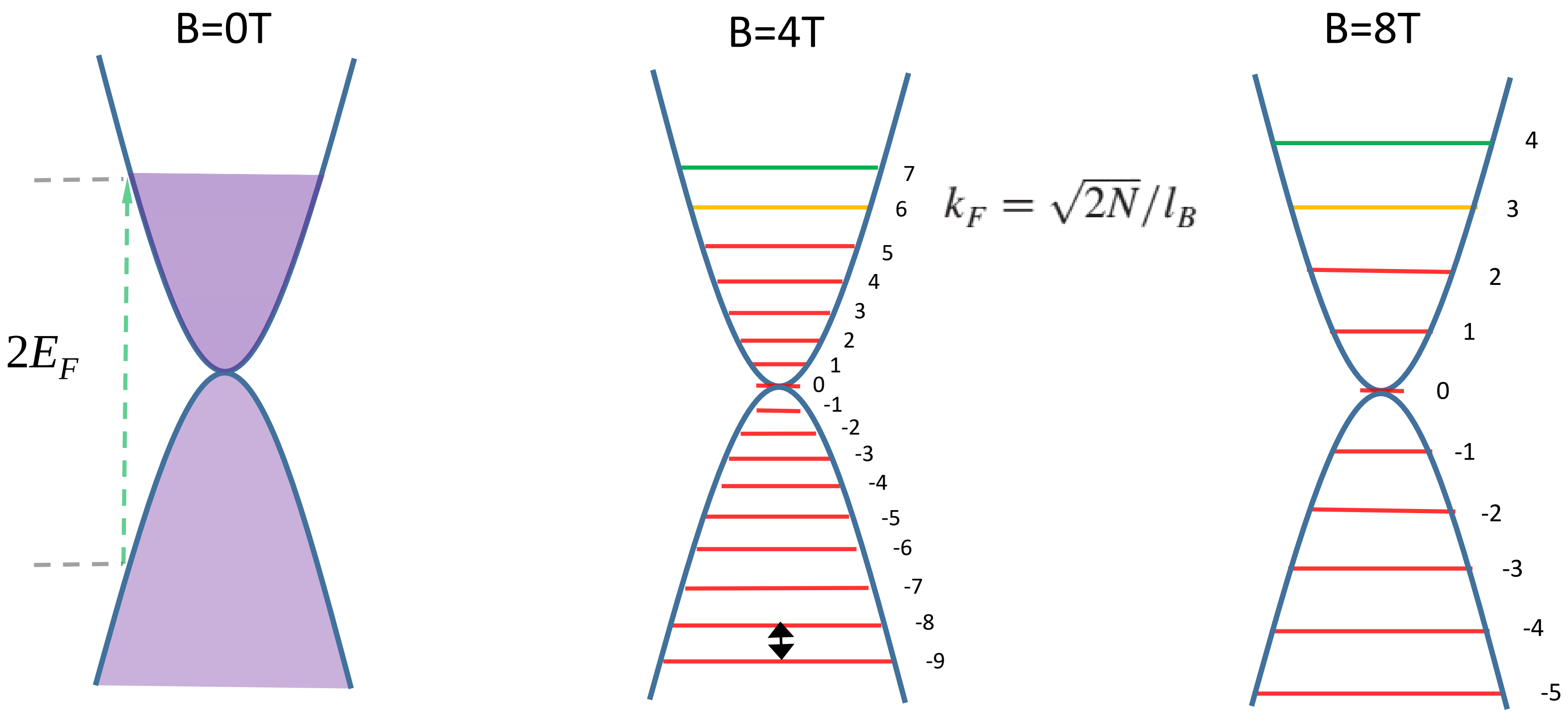
2. 低维体系的非平衡载流子的产生和探测

3. 什么是噪音谱学

4. GHz 噪音谱学与高电场输运的研究（磁场下）

5. 碳管布朗运动与受限量子输运的关联

Bilayer graphene in magnetic field

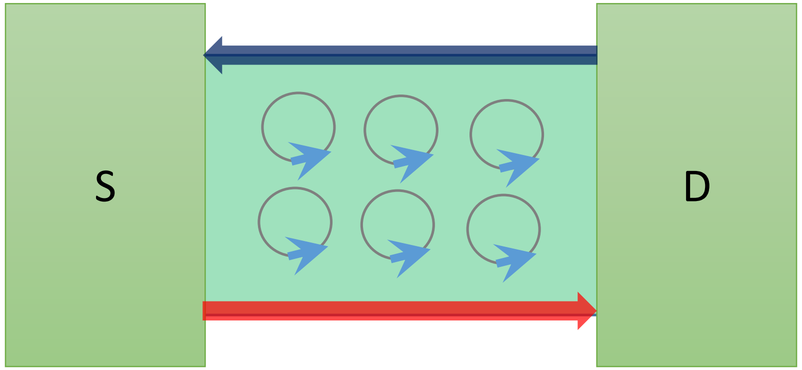


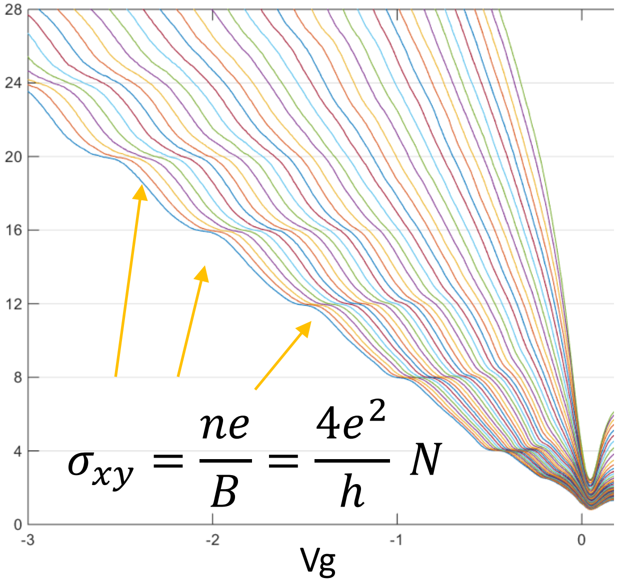
$k_F = \sqrt{2N}/l_B$

Zener field $E_c \sim \hbar\omega_c/eR_c$ $\quad \omega_c = eB/m^*$

$(R_c \sim \sqrt{N} l_B \quad l_B = \sqrt{\hbar/eB})$

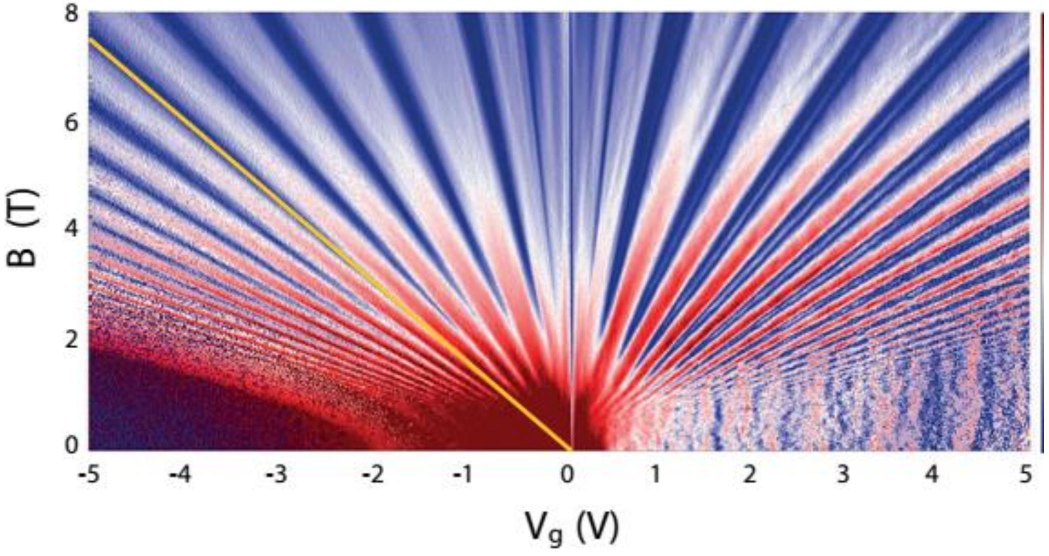
Two probe measurement of QHE in BLG





$$\sigma_{xy} = \frac{ne}{B} = \frac{4e^2}{h} N$$

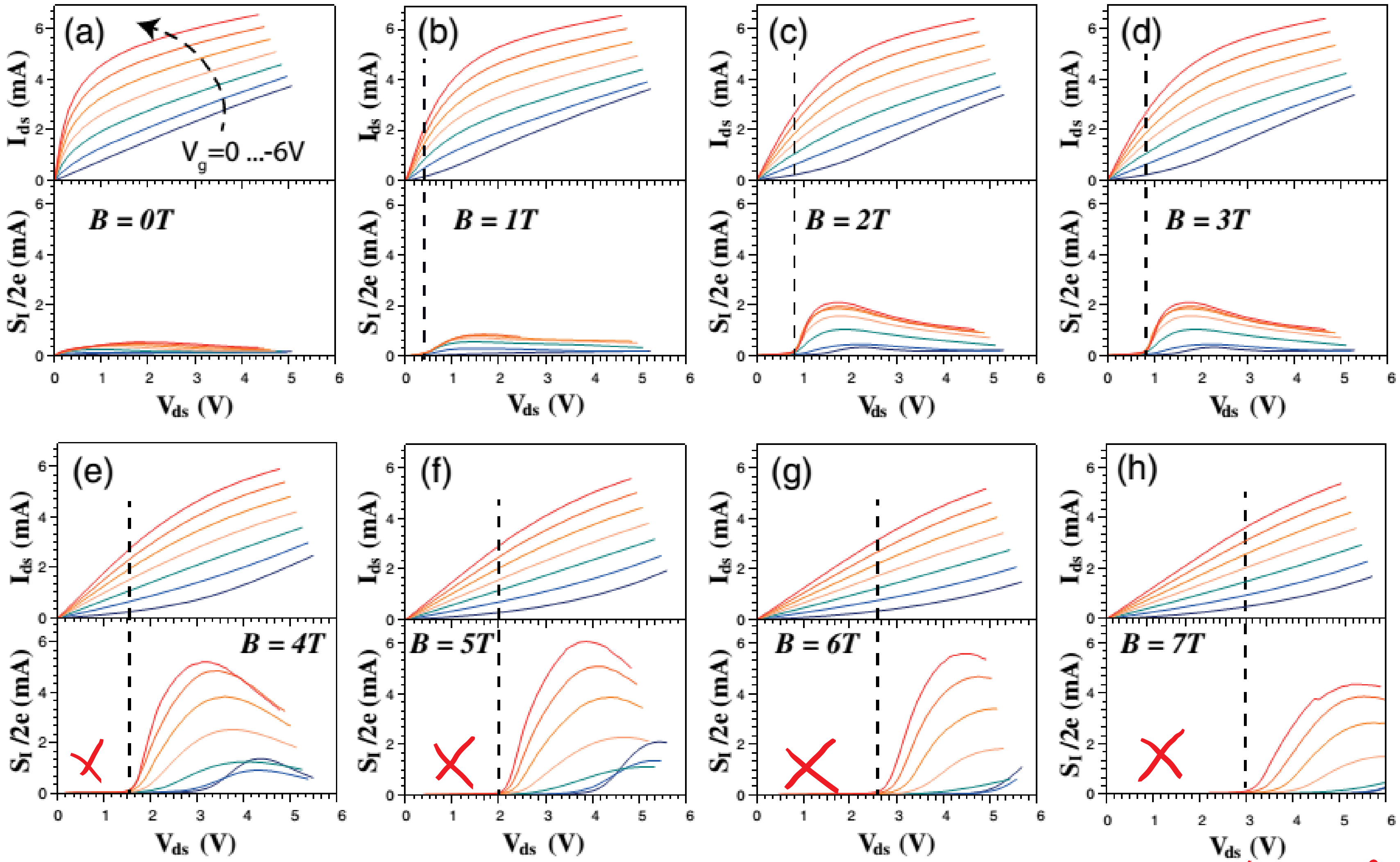
QHE Fans



Wei Yang et al, PRL.121, 136804 (2018).

Quantum Hall breakdown captured by noise avalanche

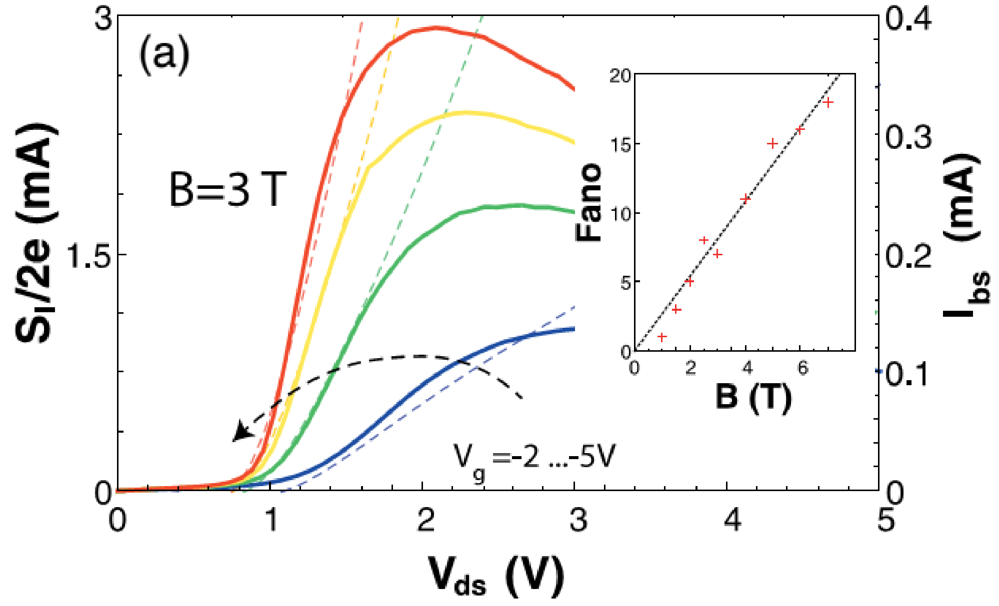
$E_{bd} \sim \; E_c \sim \hbar\omega_c / eR_c$



Wei Yang et al, PRL.121, 136804 (2018).

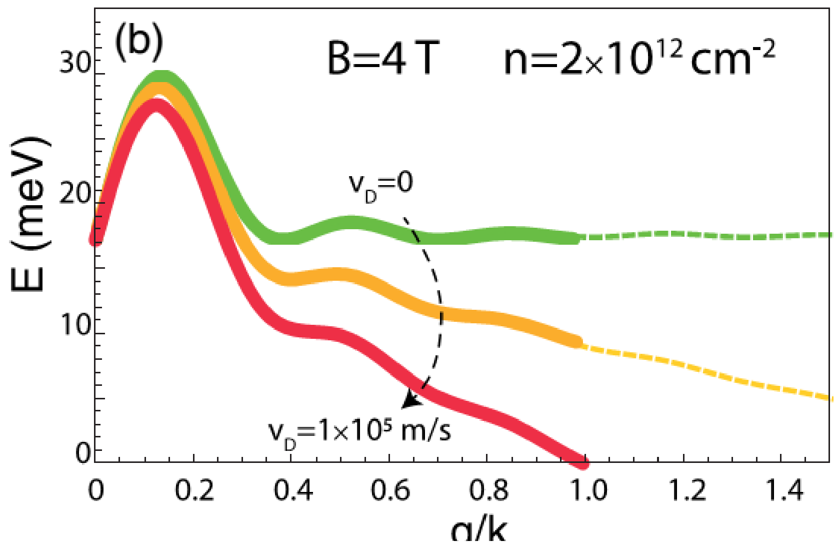
dissipationless edge state

Many-Body interaction induced QHE breakdown



S_I=Fano*2eI_{ds}

Fano >1, many body nature of breakdown

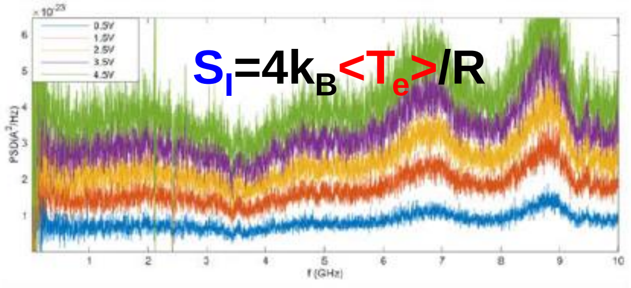


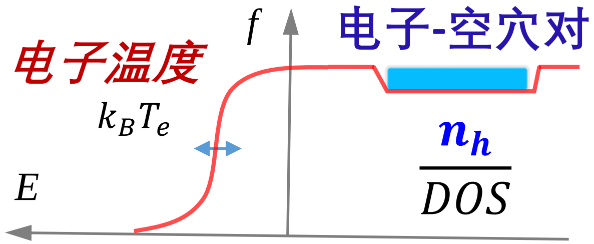
$$\omega_{\mathrm{ME}}^{E}(q) \simeq \omega_c \left(1 + \frac{r_s}{2\pi}\frac{k_F}{q}[J_1(2Nq/k_F)]^2\right) - \mathbf{v}_D \cdot \mathbf{q}$$

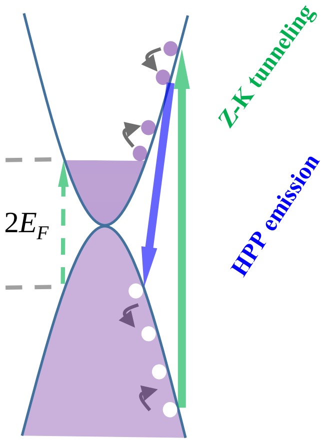
Wei Yang et al, PRL.121, 136804 (2018).

小结

GHz 噪音谱，克服1/f 噪音





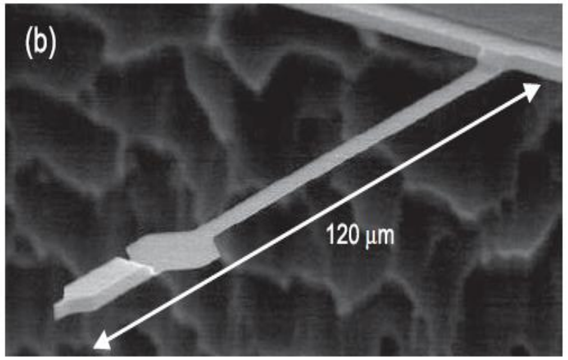


- 发现了Zener-Klein隧穿效应，揭示了非平衡电子-空穴对的存在
- 实现一种远程声子辅助的高效制冷，解决了电子器件高功率工作下热力学不稳定的问题
- 首次观测到量子霍尔效应的崩溃临界电场与本征齐纳临界电场吻合
- 提出一种磁激发不稳定引发量子霍尔效应崩溃的新机制，打破了长期采用单电子图像描述的局限性

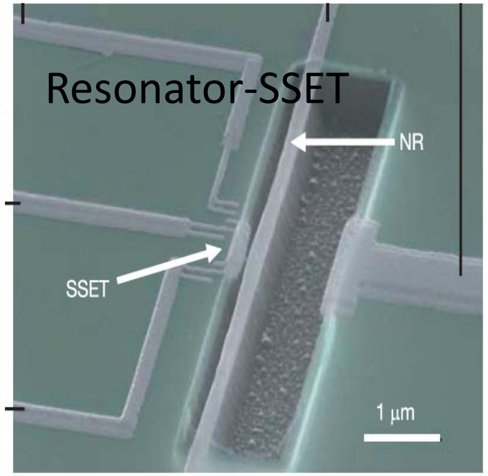
[1] **Wei Yang**, et al. Nature Nanotechnology, 13, 47 (2018).
[2] **Wei Yang**, et al. Phy. Rev. Lett., 121, 136804 (2018).

1. 介观体系的热力学平衡与非平衡
2. 低维体系的非平衡载流子的产生和探测
3. 什么是噪音谱学
4. GHz 噪音谱学与高电场输运的研究
5. 碳管布朗运动与受限量子输运的关联

Mechanical resonators



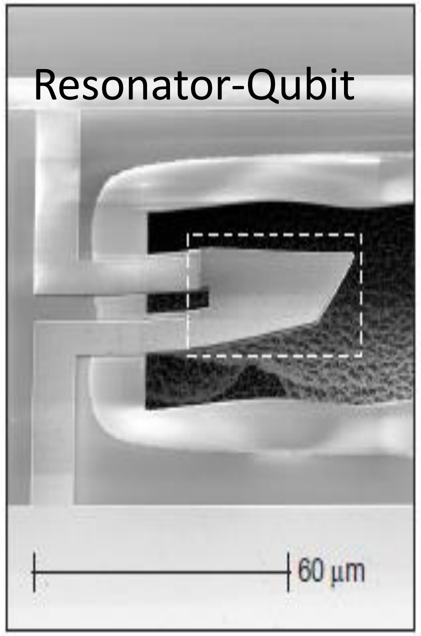
M. Poggio et al. PRL (2007)



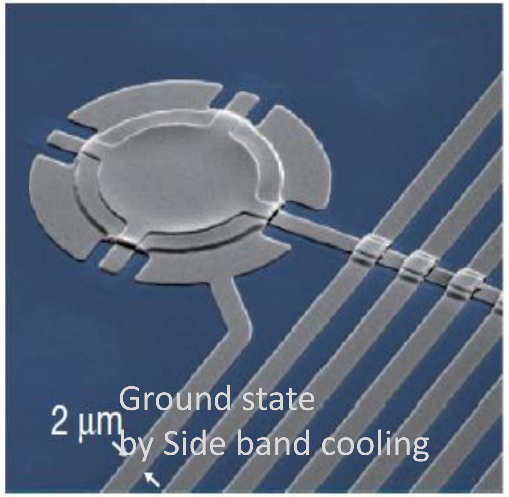
A. Naik et al. Nature (2006)

J. D. Thompson et al. Nature (2008)

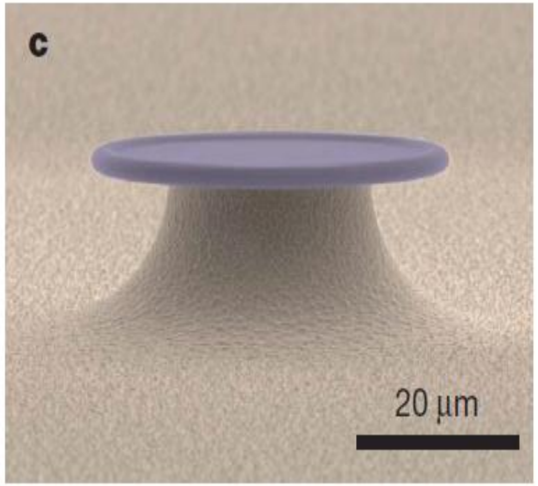
$$m\frac{d^2z}{dt^2} + 2m\Gamma\frac{dz}{dt} + kz = \delta F$$



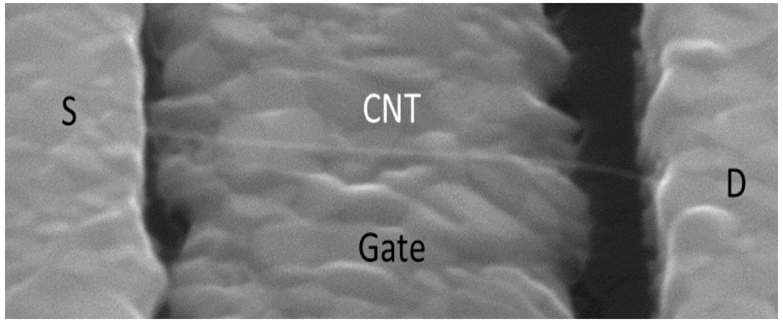
Cleland Group, Nature (2009)



J. D. Teufel al. Nature (2011)

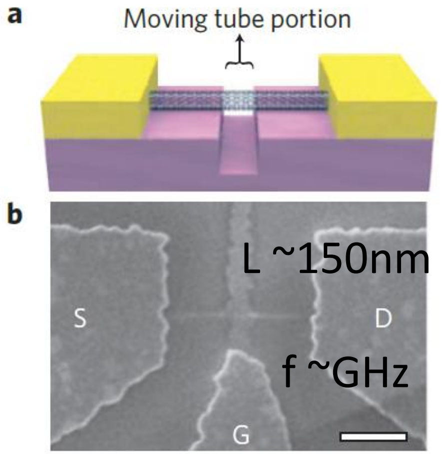


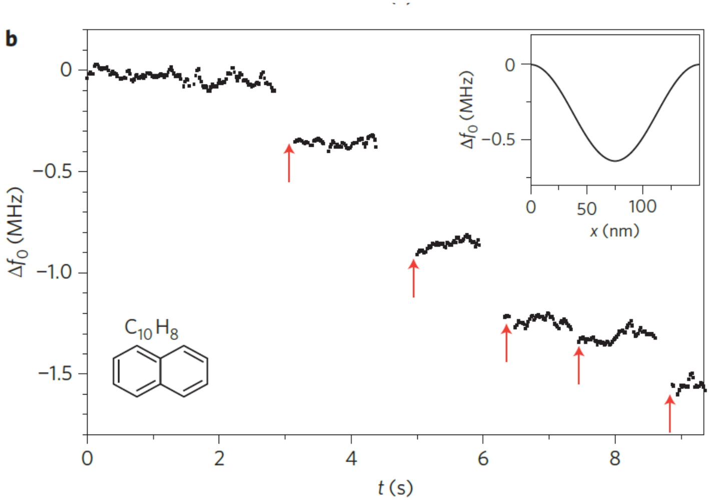
Kippenberg Group, Nature (2007)



CNT for sensing applications

Mass sensing with yg (10^{-24}g) resolution

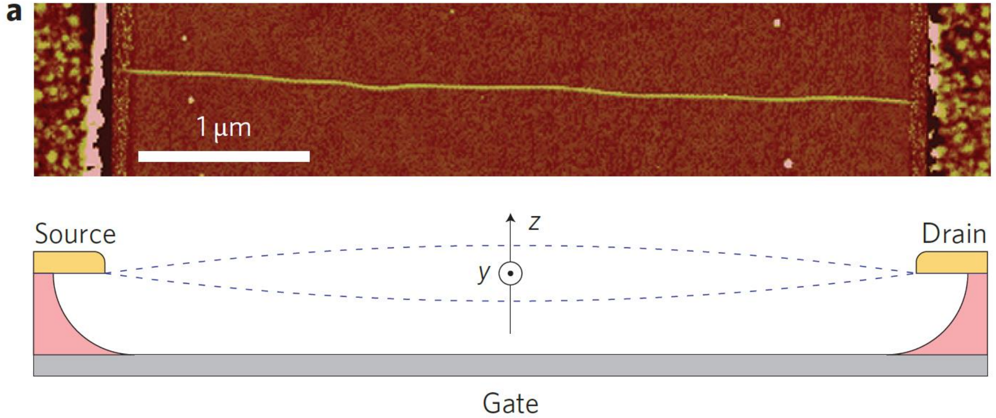


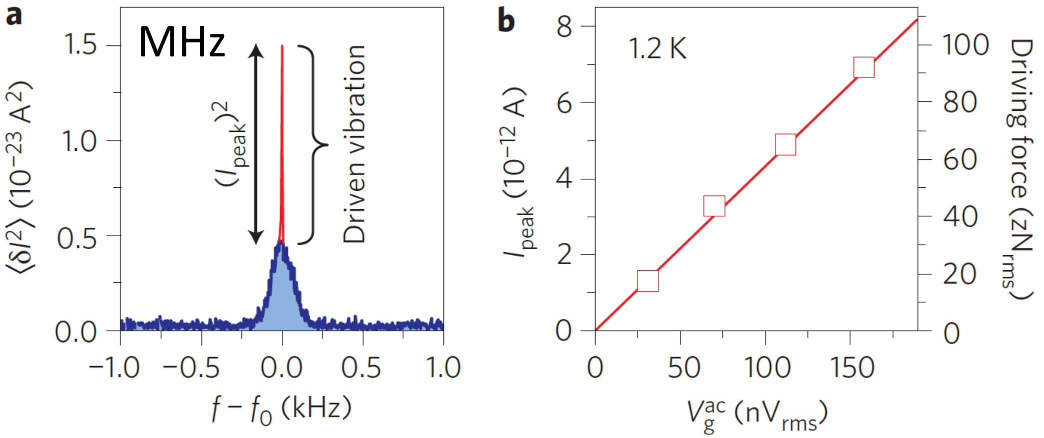


$$f = \sqrt{k/m}$$

Bachtold's Group
Nature Nano. 7, 301 (2012)

Force sensitivity of ~12 $zN/\sqrt{Hz}$

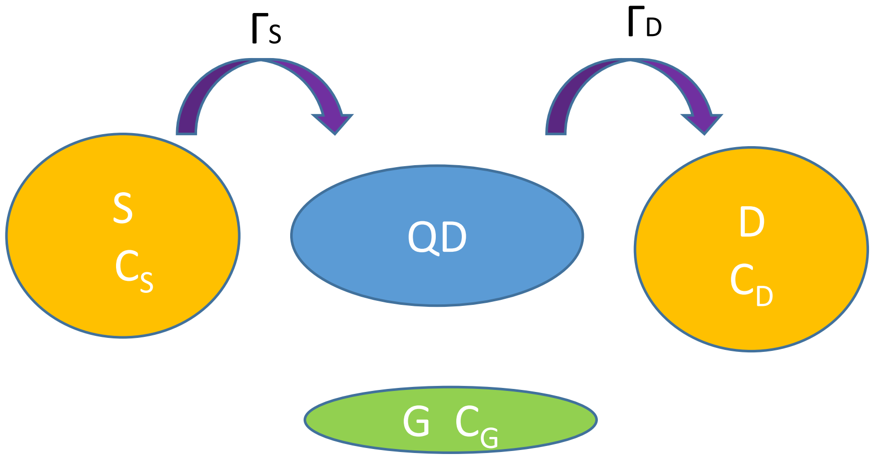




Bachtold's Group
Nature Nano. 8, 493 (2012)

$$S_F = 4k_B T\gamma = 4k_B T\sqrt{Mk_0}/Q$$

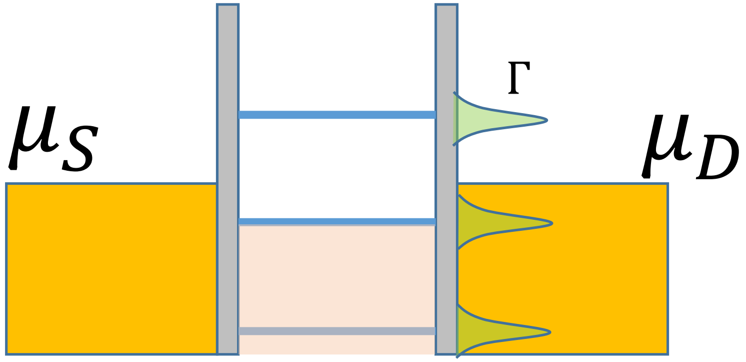
Basics about quantum transport in CNT



$E_C=e^2/C$

$C=C_D+C_S+C_G$

$$E_L=\frac{hv_f}{2L}$$

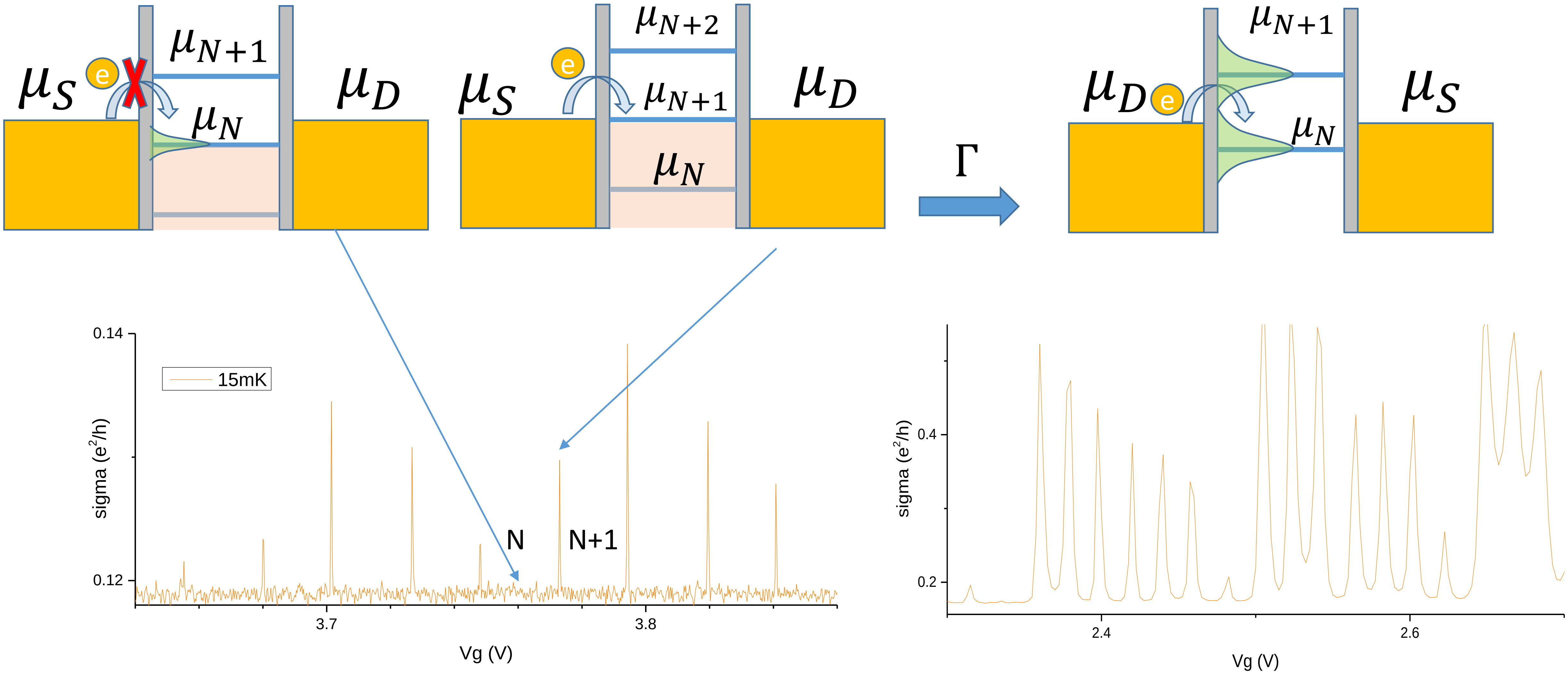


Coulomb Blockade

$$k_B T,\Gamma \ll E_C$$

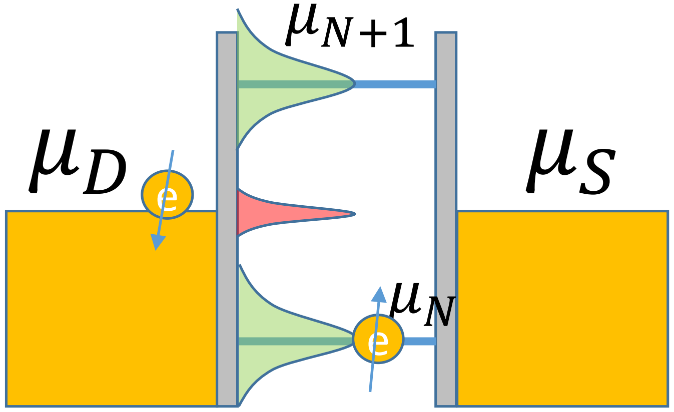
$$R>h/e^2$$

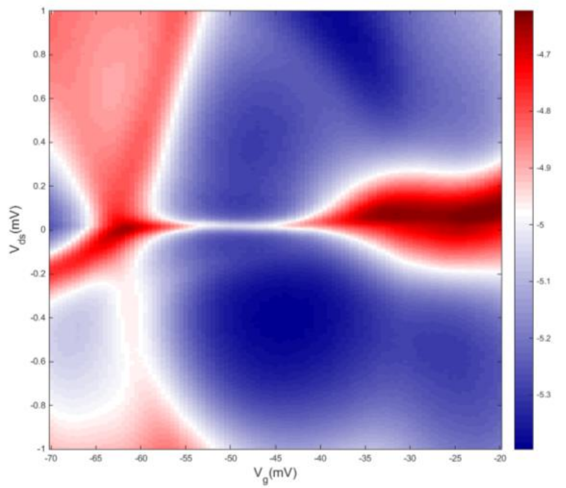
Coulomb Blockade

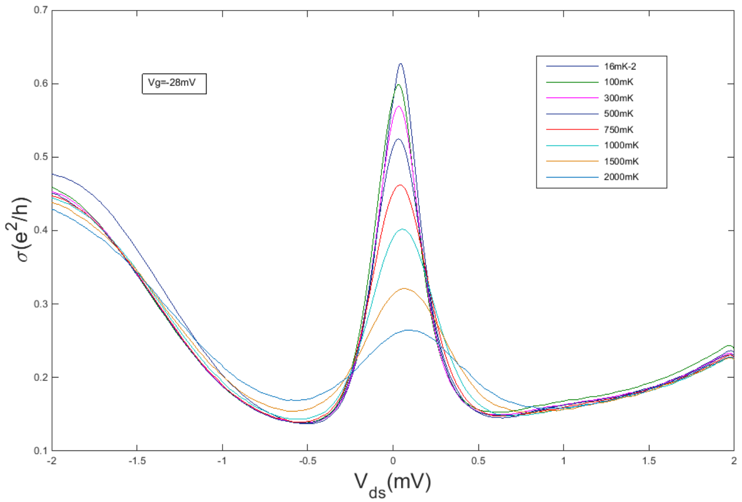


Kondo resonance

Zero bias conductance Kondo ridge



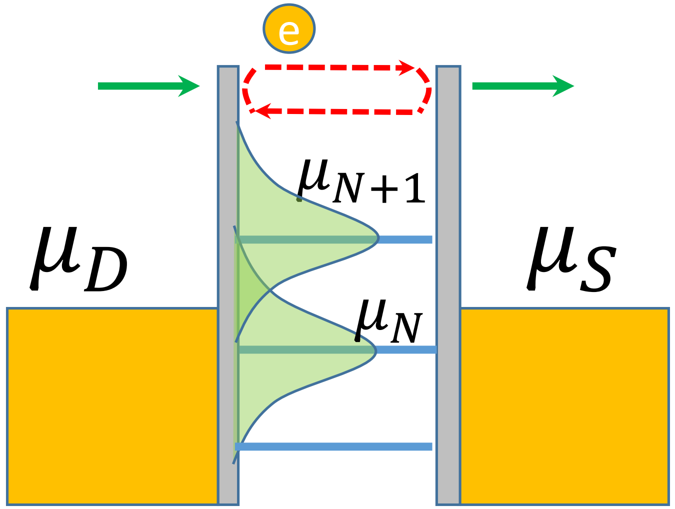


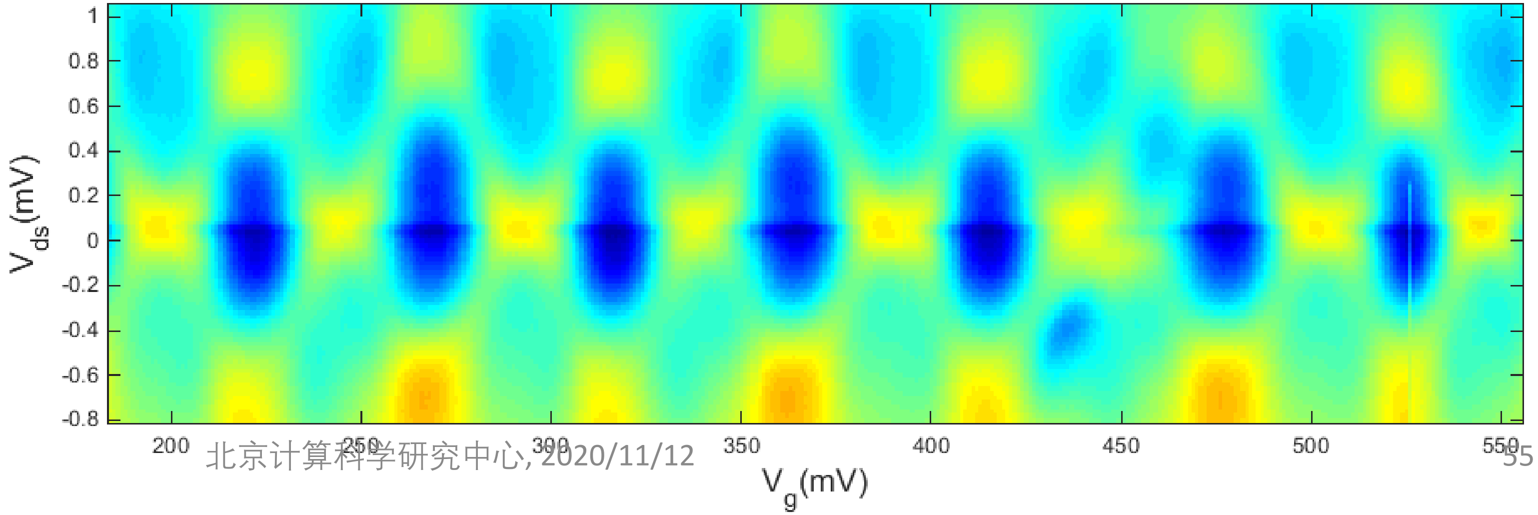


Transparent tunnelling *Fabry perot Interference*

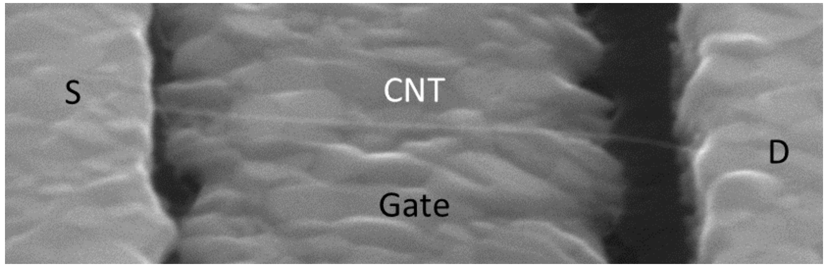
Checkboard Interference pattern

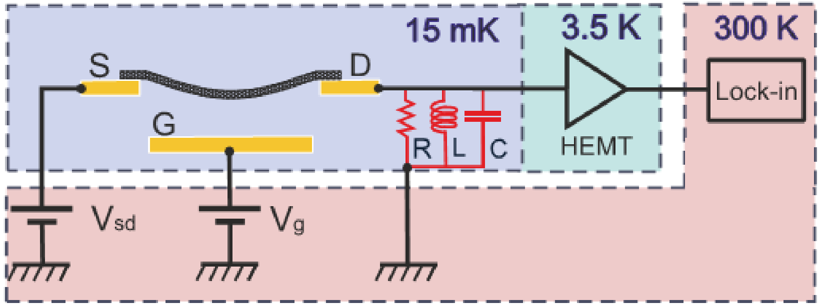
$$L = \frac{hv_f}{2eV_c} = 1.22\ \mu m$$





Detection of the nanotube’s vibration





C.Urgell#, W. Yang#*, et al. Nature Physics 16, 32(2020)

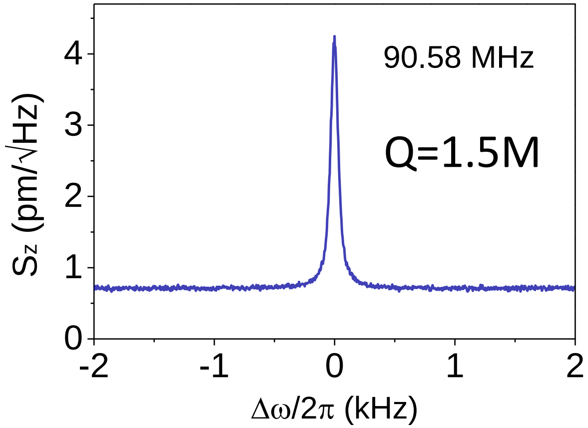
“纳米吉他”

振动信号

$$\delta I = \beta \delta z$$

电信号

$$\beta = \frac{1}{2}\frac{\mathrm{d}G_{\mathrm{diff}}}{\mathrm{d}V_{\mathrm{g}}} V_{\mathrm{g}} V_{\mathrm{sd}}^{\mathrm{ac}} \frac{C'_{\mathrm{g}}}{C_{\mathrm{g}}}$$



振动的信息

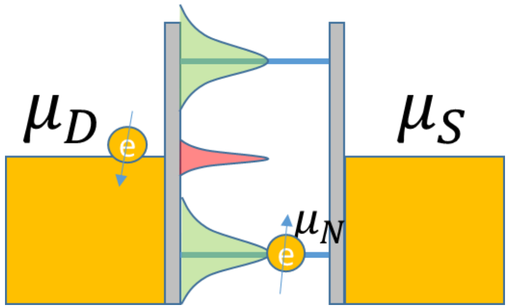
$$\int_{-\infty}^{+\infty} S_{xx}(\omega)\frac{d\omega}{2\pi} = \langle x^2 \rangle.$$

$$m\omega_0^2 \langle x \rangle^2 = k_B\, T$$

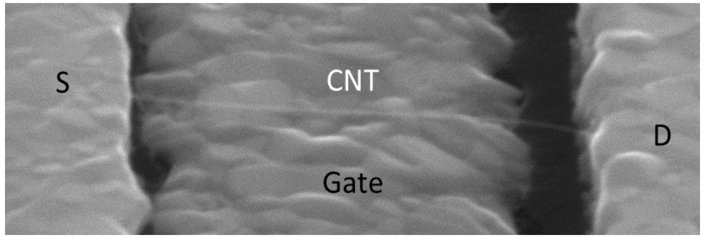
Adrian Bachtold

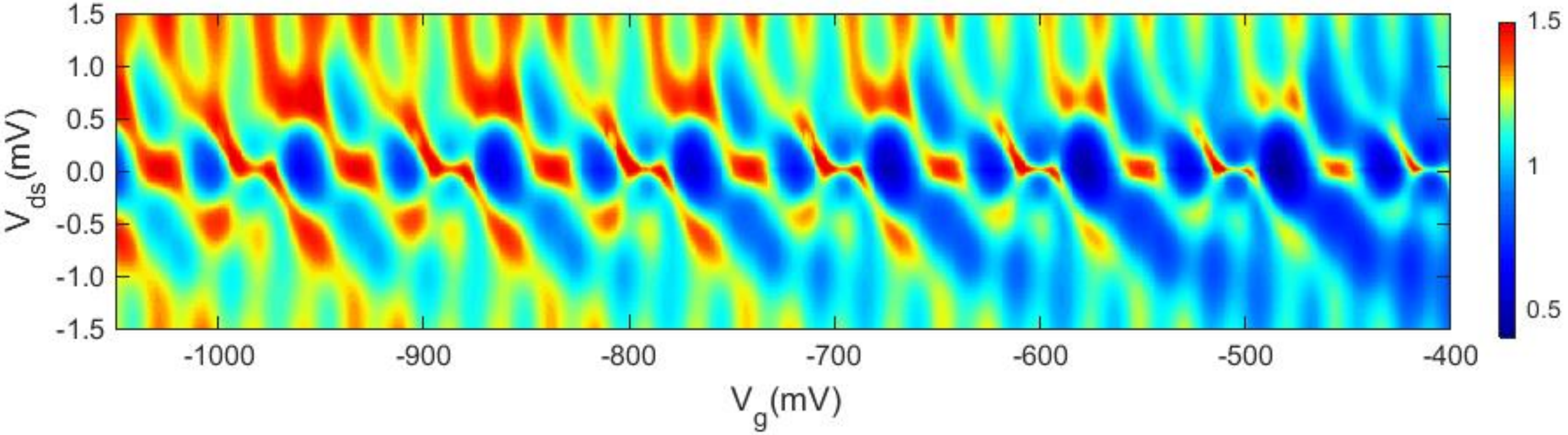
Carles Urgell

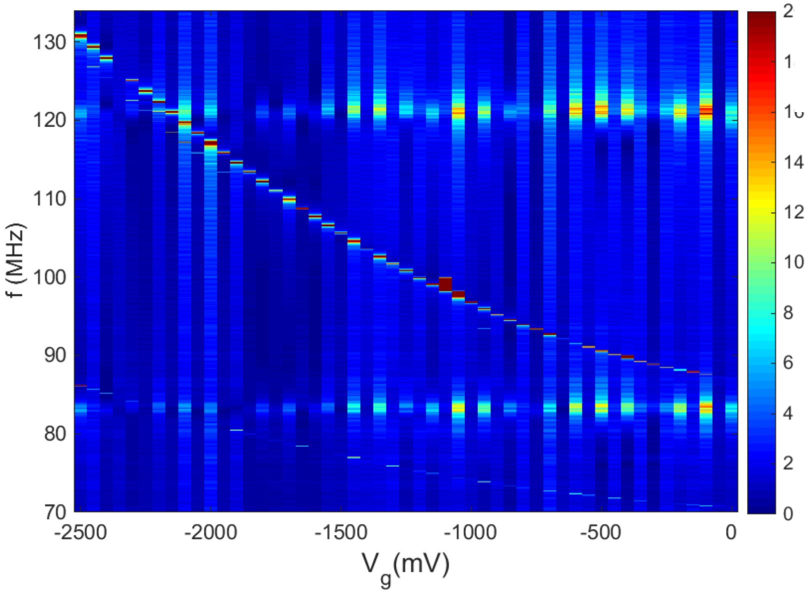
Ultra-clean CNT Resonator, also a good transistor

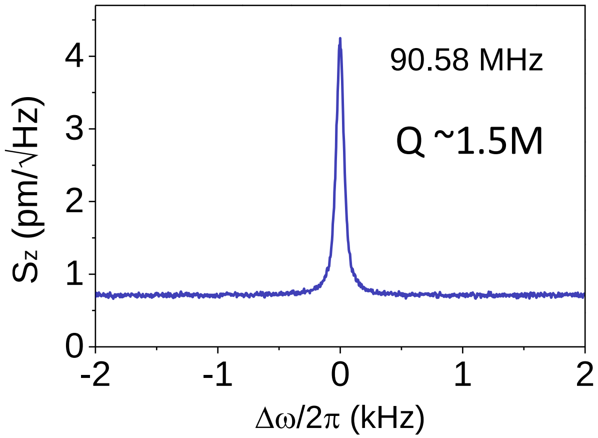


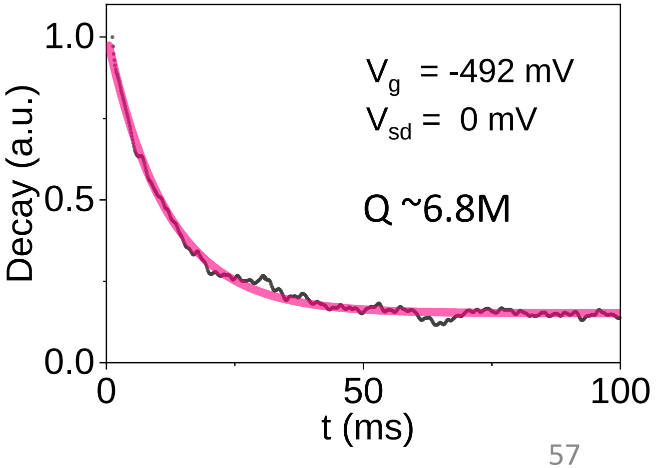
Kondo transport regime



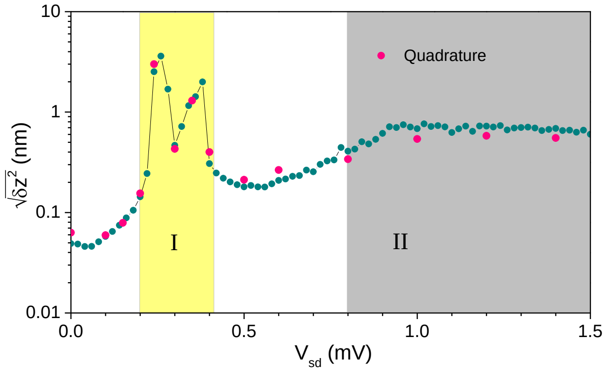








Dynamic heating and Self-Oscillations



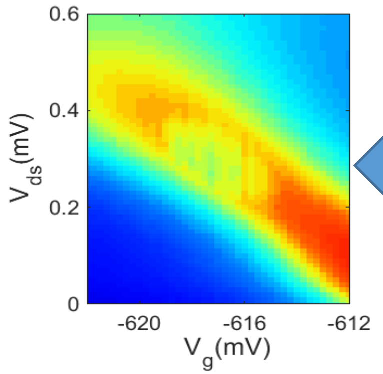
Dynamic heating

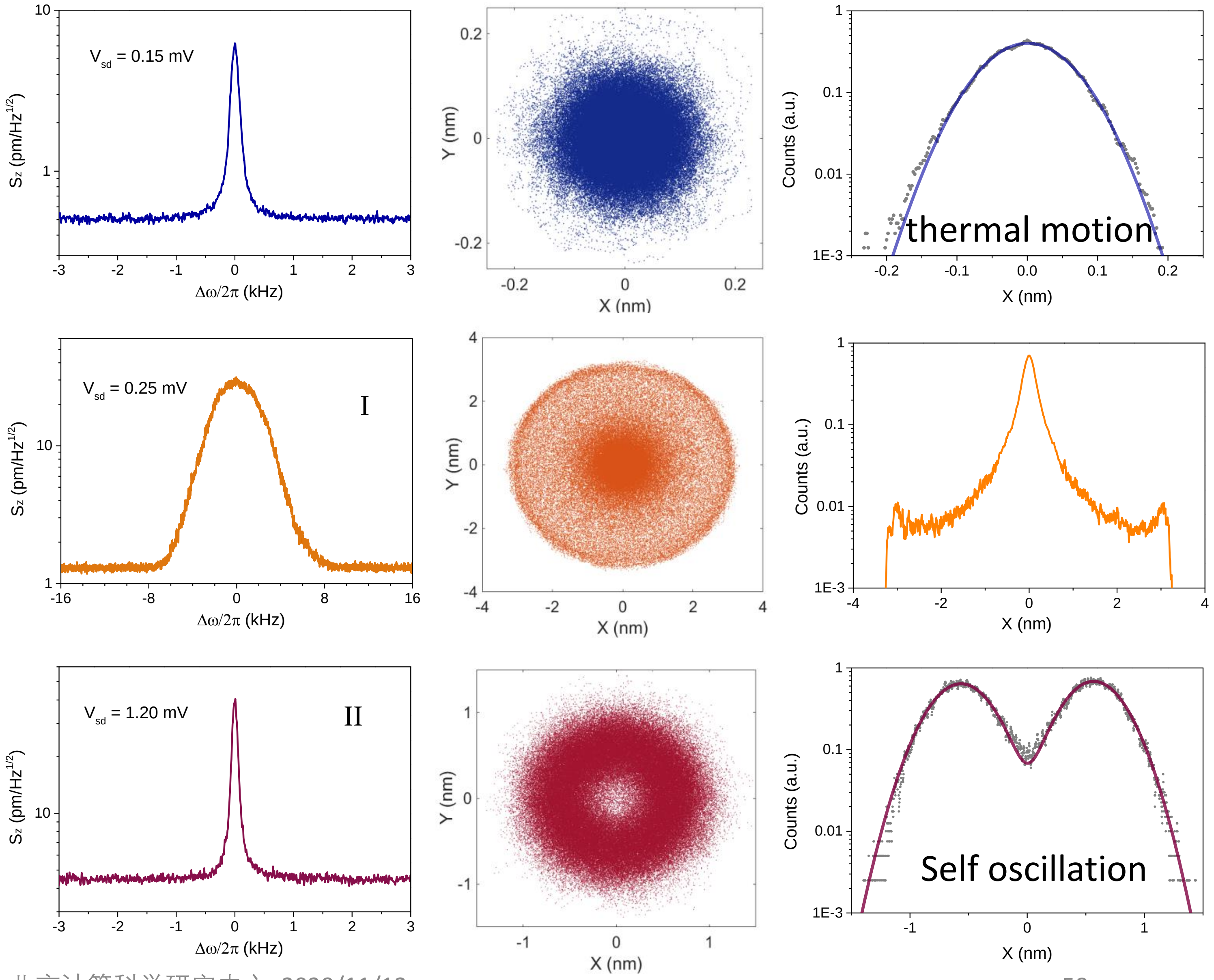
displacement ↑

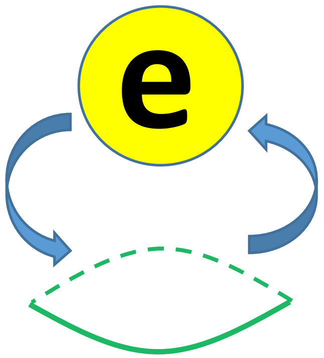
damping ↓

Self-Oscillations

damping <0

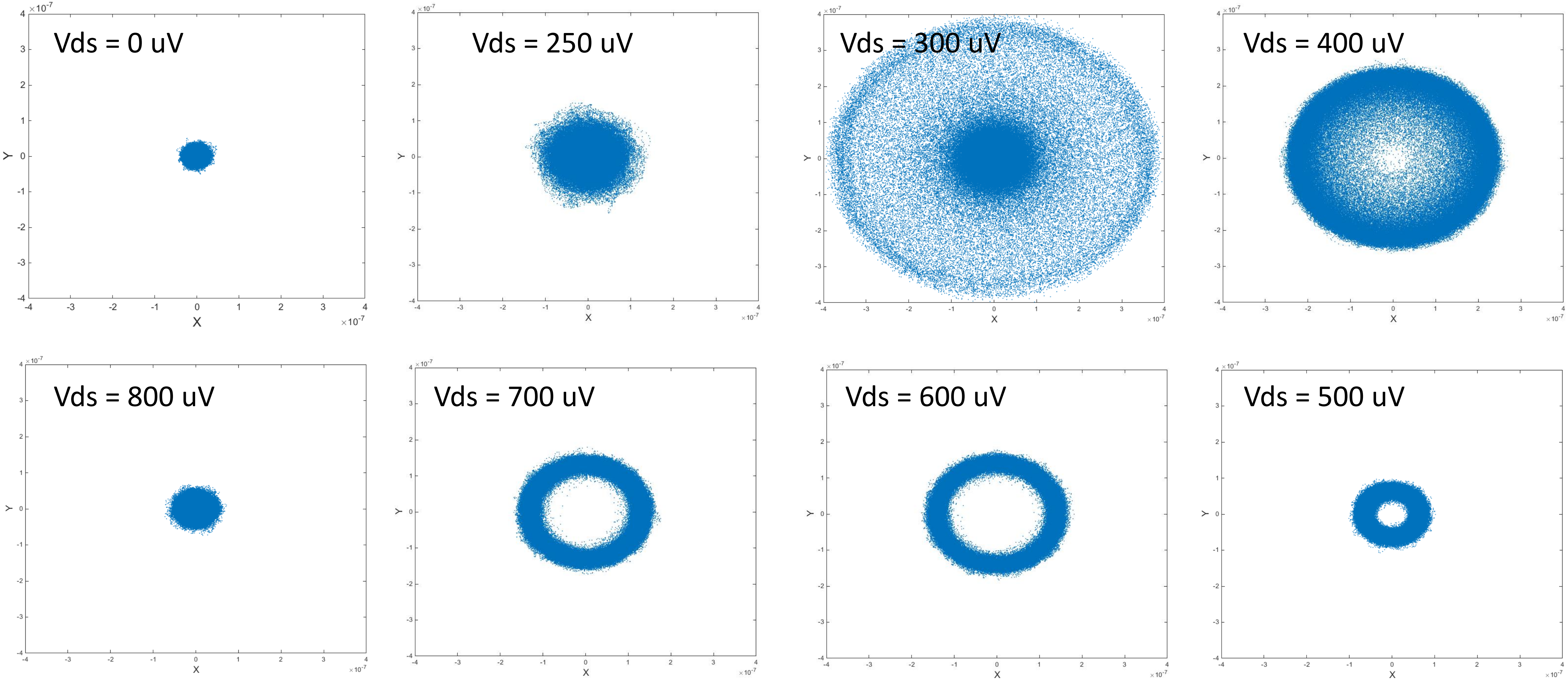




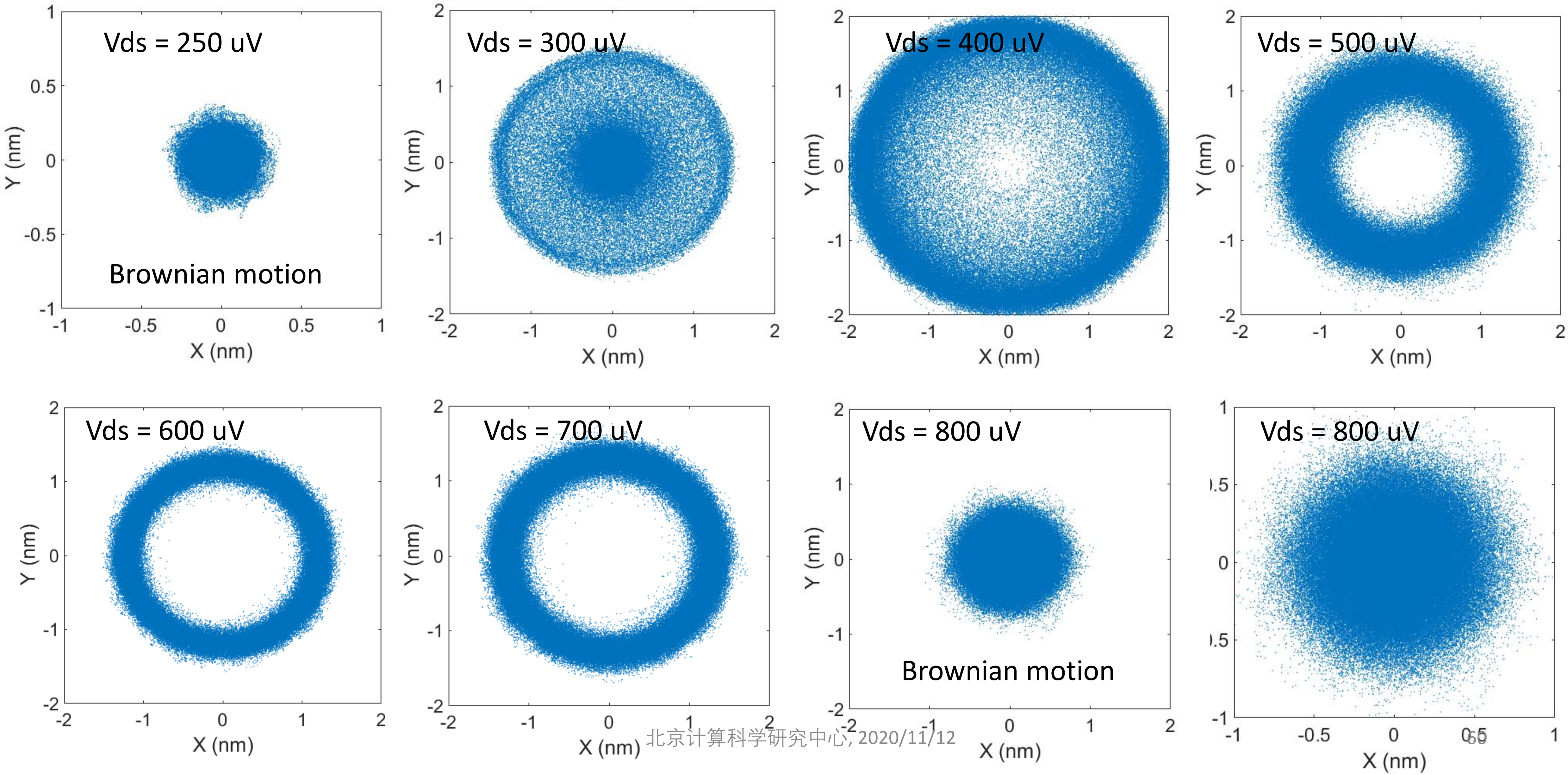


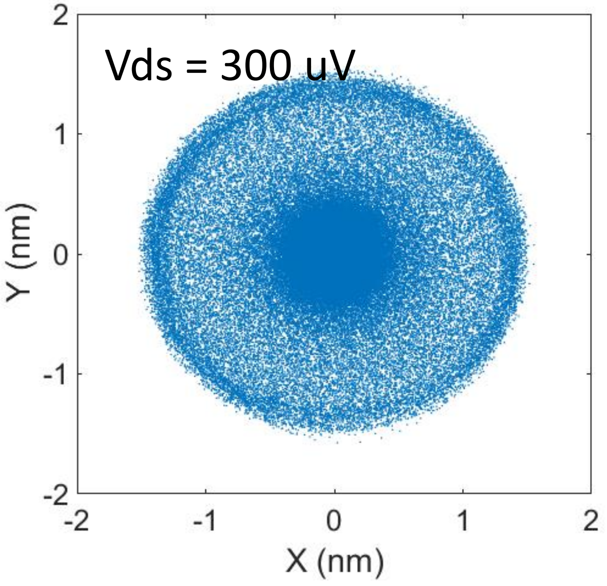
C.Urgell#, W. Yang#*, et al. Nature Physics 16, 32(2020)

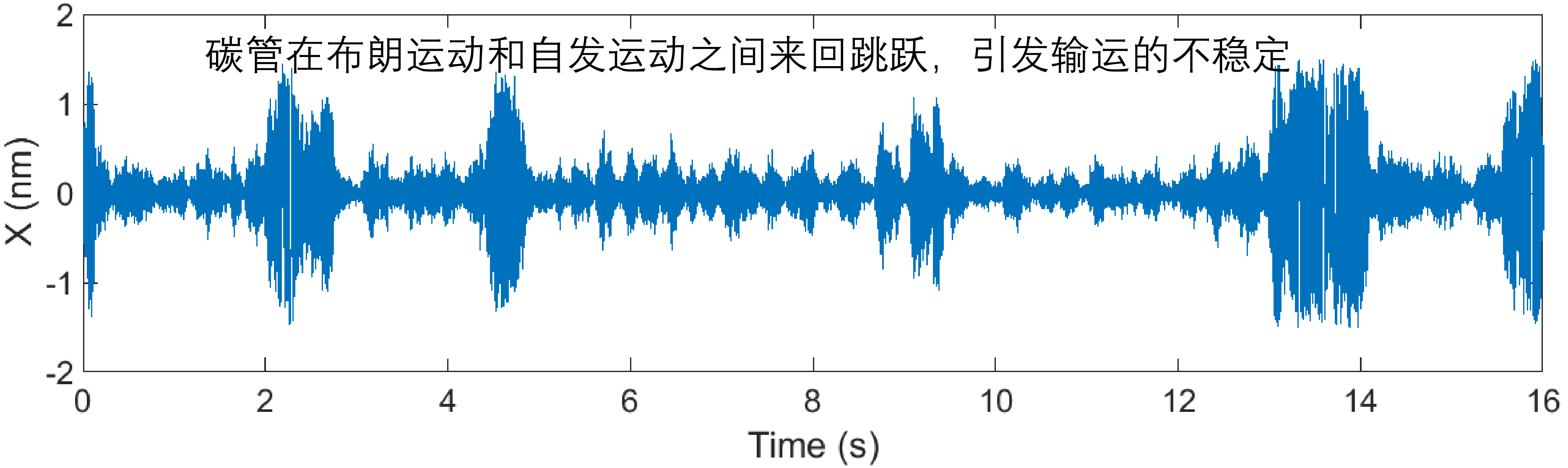
The measured voltage signal

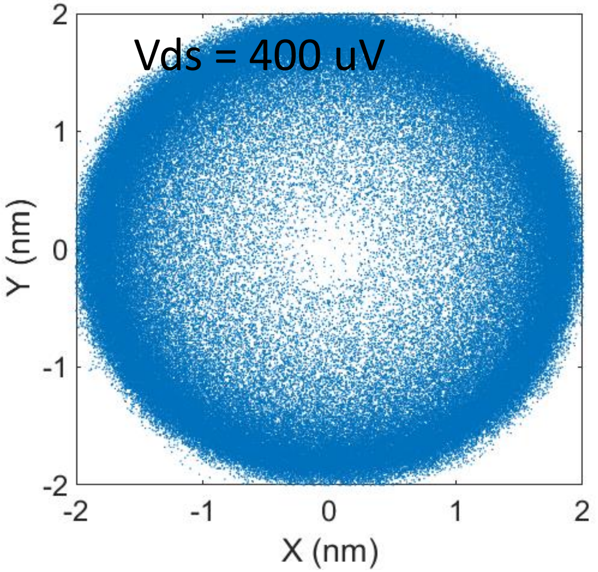


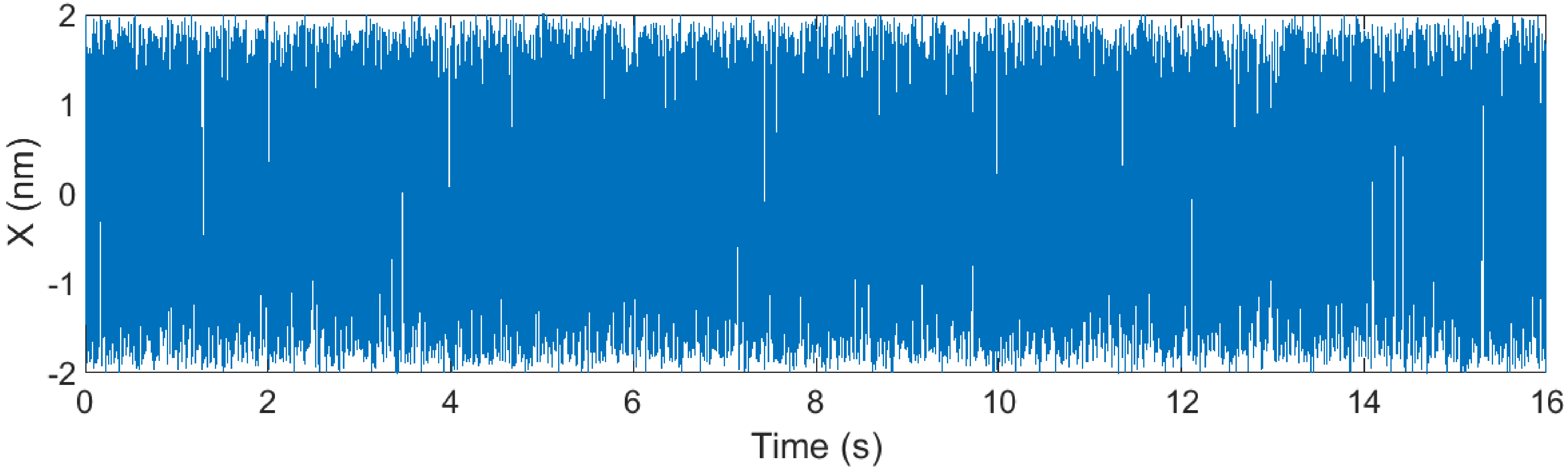
The extracted vibration motion




Vds = 300 uV
Y (nm)
X (nm)


碳管在布朗运动和自发运动之间来回跳跃，引发输运的不稳定
X (nm)
Time (s)


Vds = 400 uV
Y (nm)
X (nm)

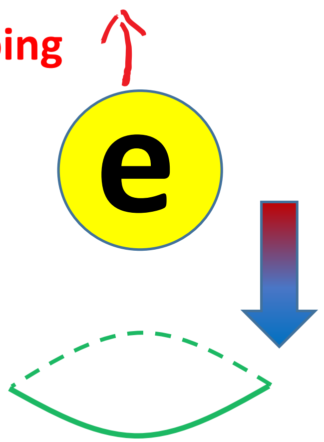

X (nm)
Time (s)

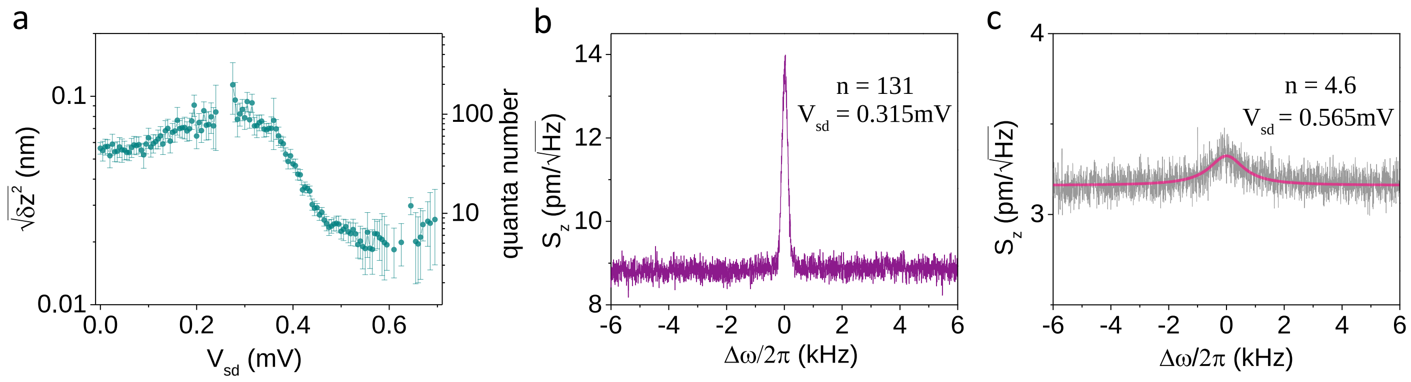
Dynamic cooling the resonator to a state of few quanta

Dynamic cooling

displacement

damping



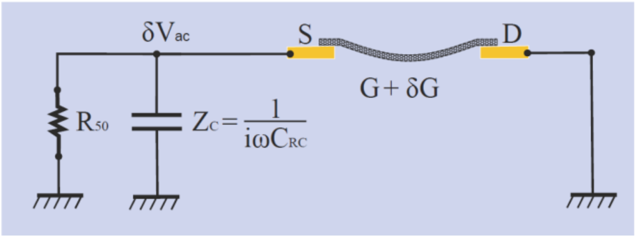


$$n = \frac{m\omega_0^2 \delta z^2}{\hbar \omega_0} - \frac{1}{2}$$

Ground state n<1

C.Urgell#, W. Yang#*, et al. Nature Physics 16, 32(2020)

Electrothermal model



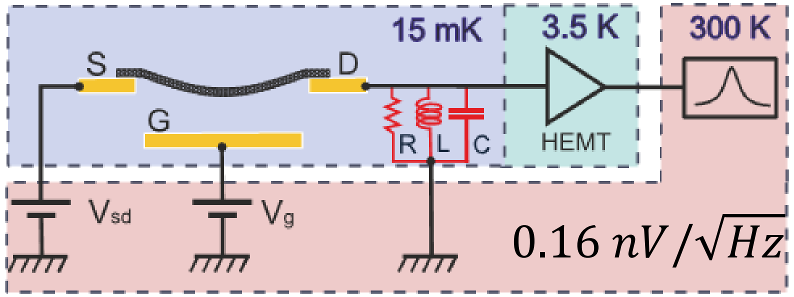
$$\Delta\Gamma_{\mathrm{back}} = -\alpha \frac{dG_{\mathrm{diff}}}{dV_{\mathrm{g}}} \frac{C'_{\mathrm{g}}}{C_{\mathrm{g}}} V_{\mathrm{g}} z_{\mathrm{s}} V_{\mathrm{sd}}^2.$$

$$\alpha = \frac{\pi^3 r}{L} \frac{\alpha_{\mathrm{TEC}} E_{2\mathrm{d}} \tau_{\mathrm{ph}}}{C_{\mathrm{heat}}} \frac{1}{m} \left(\frac{2C_{\mathrm{RC}} G R_{50}^2}{(\omega C_{\mathrm{RC}} R_{50})^2 + 1} \right)$$

Quantum backaction

小结

热振动的探测

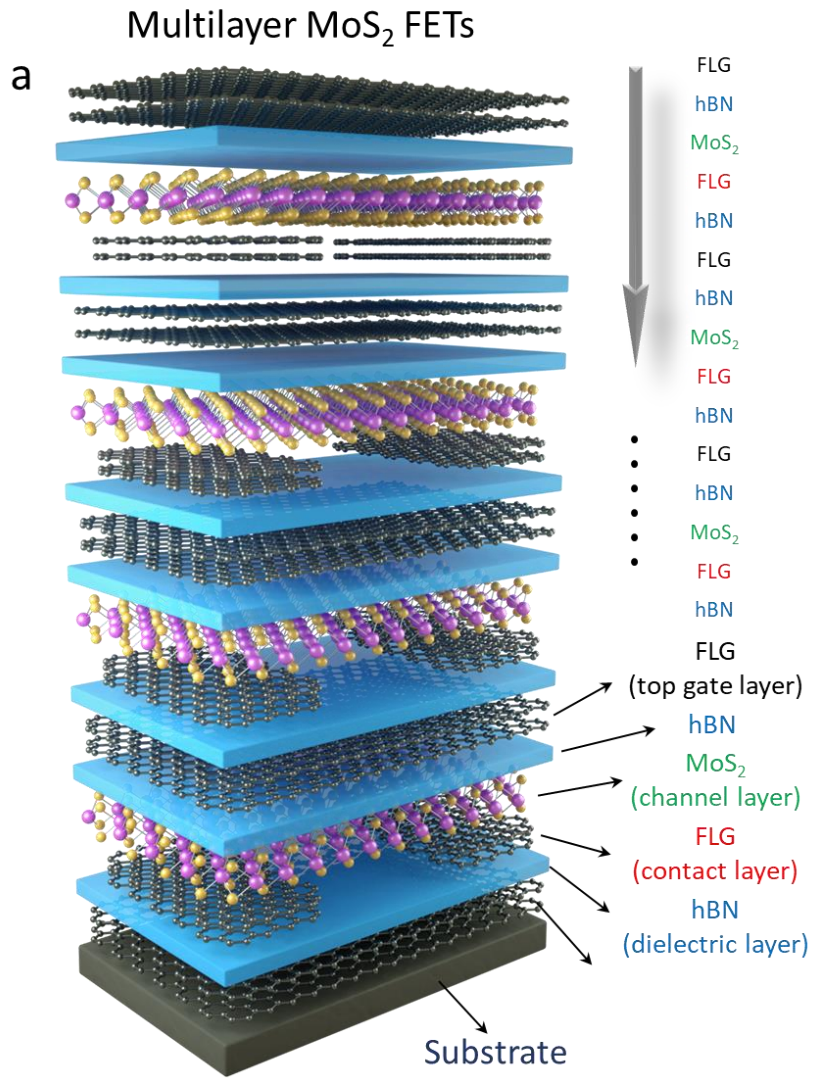


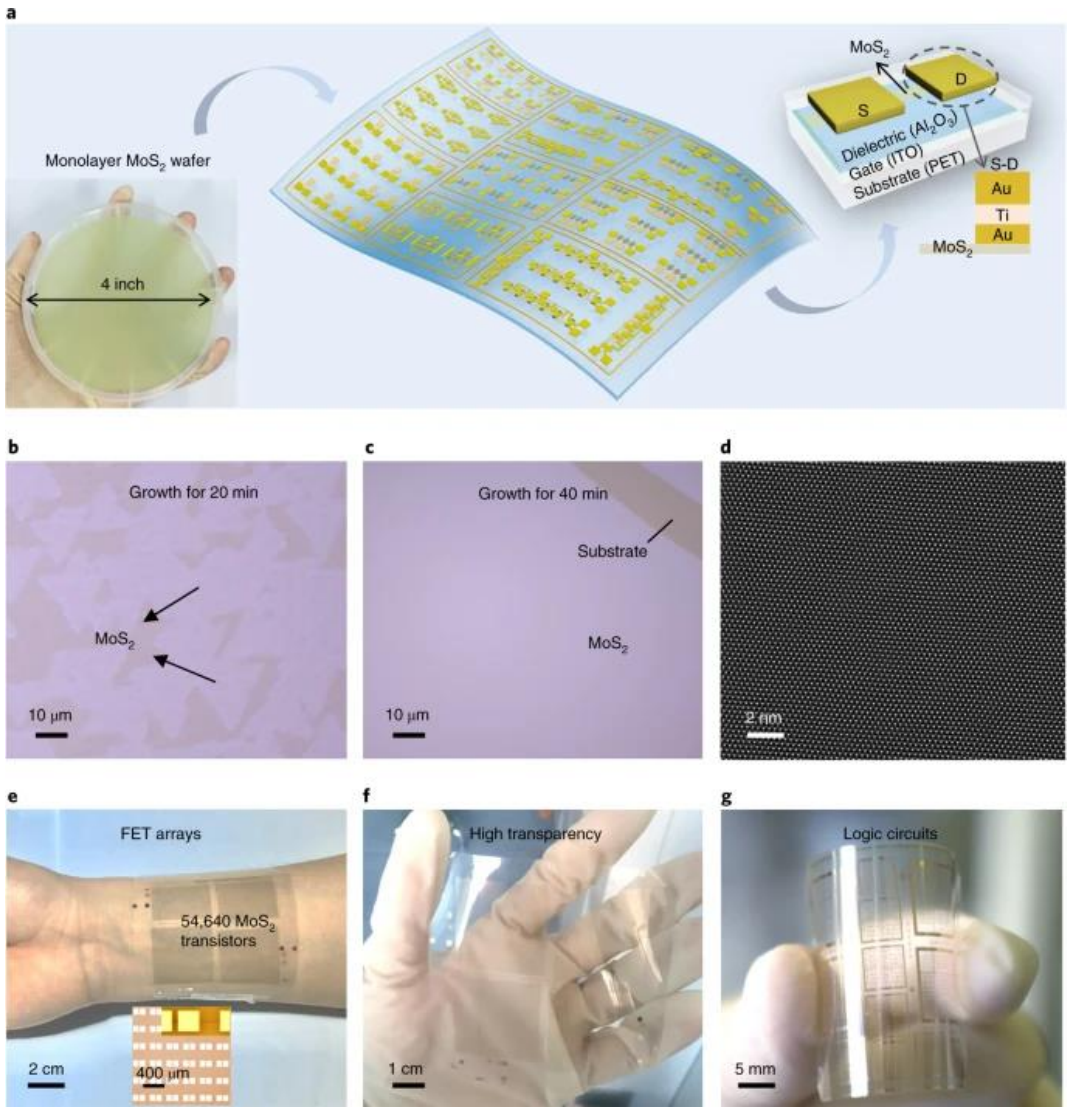
- 实现了高灵敏度的 MHz噪音测量($0.5\ \mathrm{pm}/\sqrt{Hz}$)
- 实现了电子对碳管热振动的量子反作用调控
- 实现将谐振子冷却到接近量子基态(~4.6 量子)

[1] C. Urgell#, **W. Yang**#* , et al. Nature Physics, 16, 32 (2020).
[2] S. L. de Bonis#, C. Urgell#, **W. Yang**, et al. Nano Letters, 18, 5324 (2018).

What Now?..........

Multilayer Van de Waals Devices



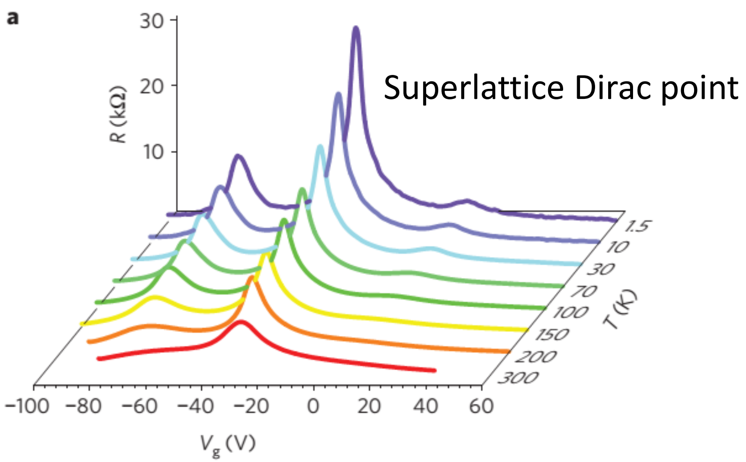


Jian Tang, et al., Advanced Electronic Materials, 2000550(2020)

Na Li, et al., Nature Electronics (2020)

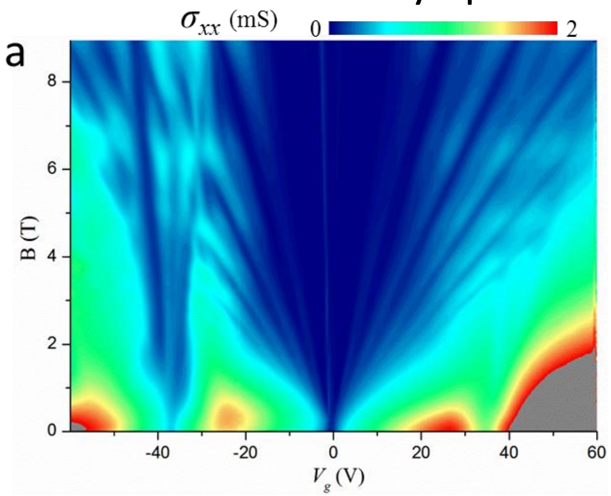
Moir é Physics-From single particle to many body interaction

G/hBN superalttice



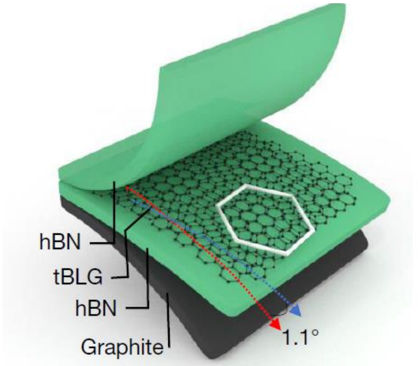
Wei Yang, et al. Nature Materials, 12, 792-797 (2013).

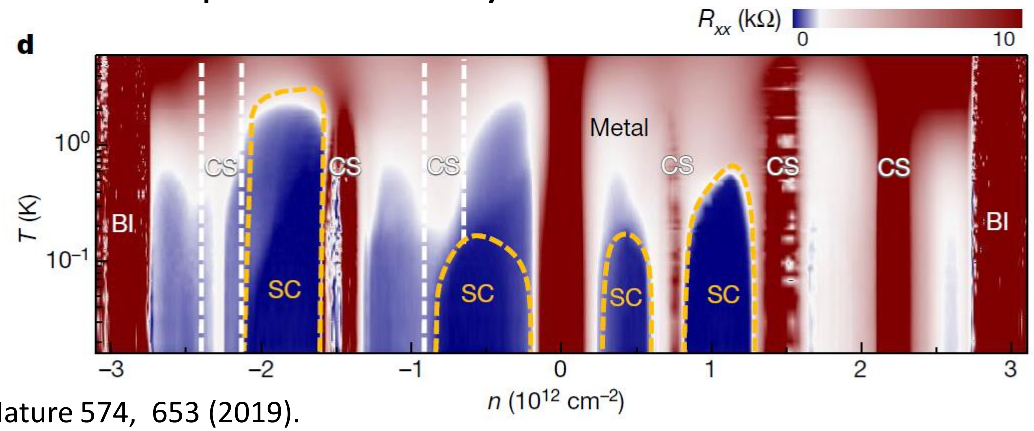
Hofstadter Butterfly Spectra



Wei Yang, et al. Nano Letters 16, 2387(2016)

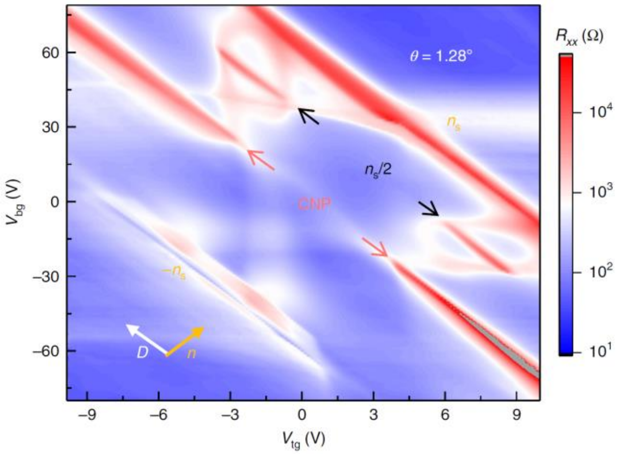
TBG Moire superlattice and superconductivity





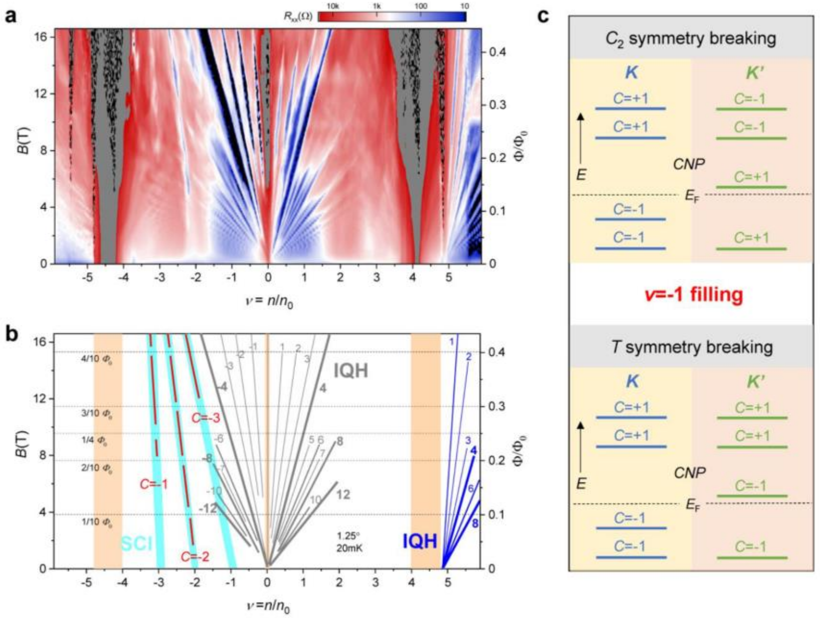
X. Lu, P. S., Wei Yang, et al. Nature 574, 653 (2019).

TDBG - correlated states



C. Shen, et al. Nature Physics 16, 520 (2020).

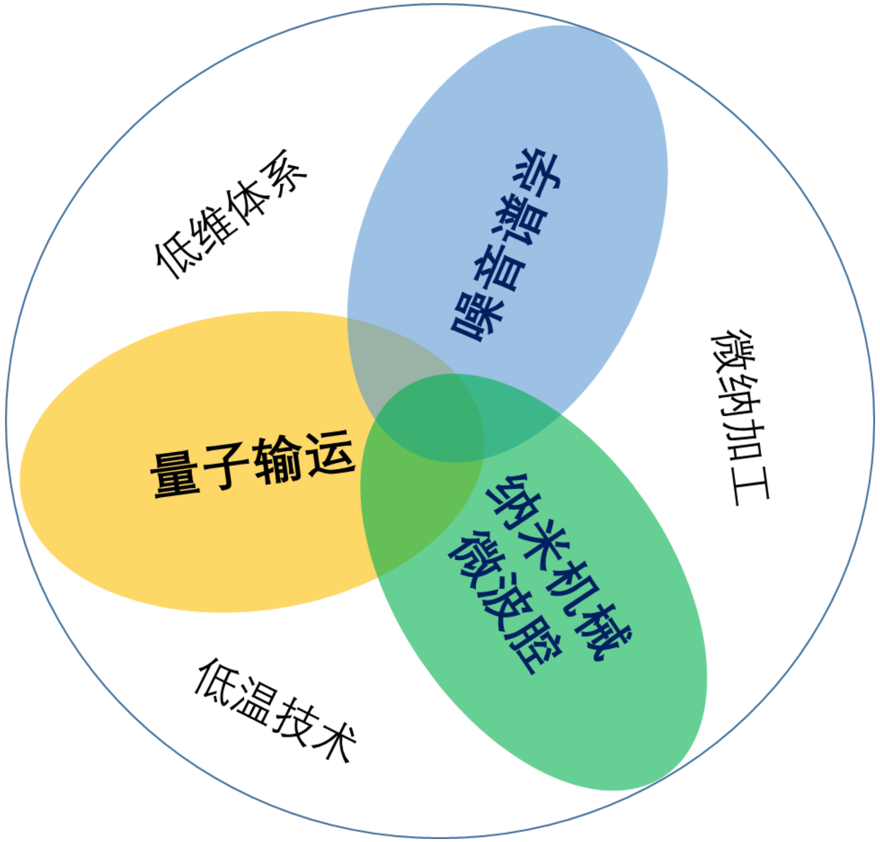
Nontrivial band topology in TBG



C. Shen, Wei Yang#, et al. arxiv:2010.03999 (2020).

THERE IS PLENTY OF ROOM AT THE BOTTOM

---Richard Feynman



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CNRS, ENS Paris

Prof. Bernard Pla çais

Dr. Holger Graef

LPS, Paris

Prof. M. O. Goerbig

ICFO, Barcelona

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Thanks very much!