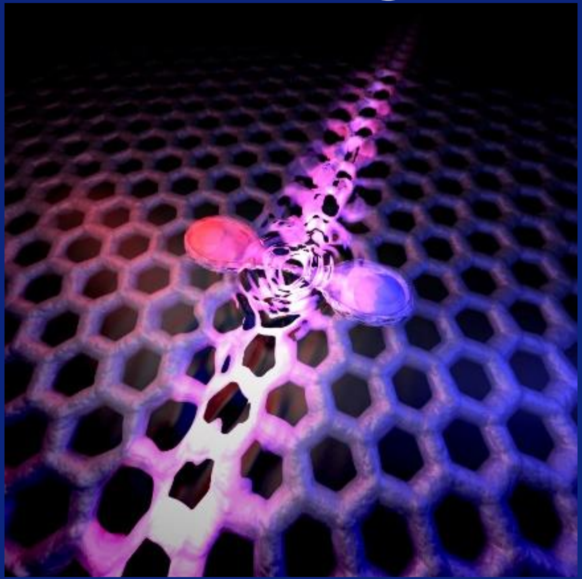
LPENS
LABORATOIRE DE PHYSIQUE DE L'ÉCOLE NORMALE SUPÉRIEURE

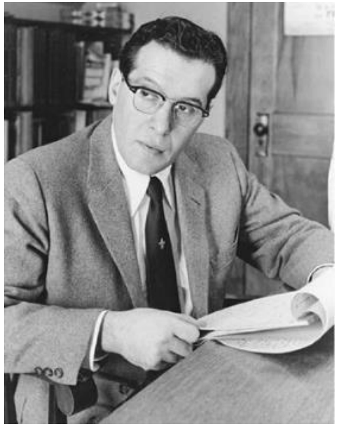
Mesoscopic Klein-Schwinger effect in graphene



Aurélien Schmitt, P. Vallet, D. Mele, M. Rosticher, T. Taniguchi, K. Watanabe, E. Bocquillon, G. Fève, J.M. Berroir, C. Voisin, J. Cayssol, M.O. Goerbig, J. Troost, E. Baudin and B. Plaçais

SFP 2023

Schwinger effect: breaking vacuum in a high electric-field



F. Sauter, Z. Phys. 1931
J. S. Schwinger, PRB 1951

- Instability of vacuum in presence of an intense electric field
- Electron-positron pair creation rate from non-perturbative theory

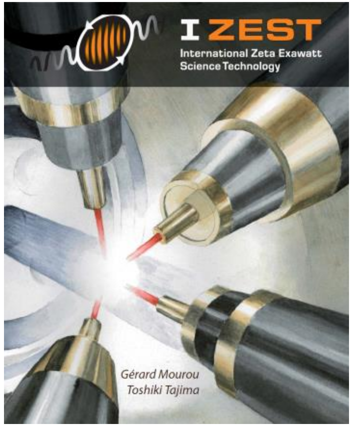
$$w(E) \propto \sum_{n\geq 1} \left(\frac{E}{n}\right)^{\frac{d+1}{2}} e^{-\pi \frac{n\,\boldsymbol{E_S}}{E}}$$

d : spatial dimension
E : electric field

- Schwinger field : $\boldsymbol{E_S} = \frac{\Delta_S^2}{e\hbar c} = \frac{m^2 c^3}{e\hbar} = 1.32\ 10^{18}\ \frac{V}{m}$

(for electron-positron : $\Delta_S = mc^2 = 511\ keV$)

… on the roadmap of Zeta/Exawatt Lasers

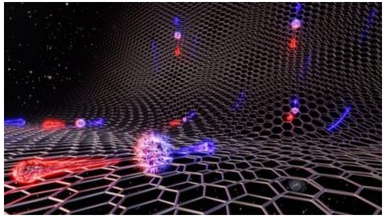


Prefactors in C. Itzykson et J. B. Zuber, Quantum Field Theory, McGraw-Hill (2006)

2d-Schwinger in gapless neutral 2d-graphene

$$E = v_F \hbar k$$

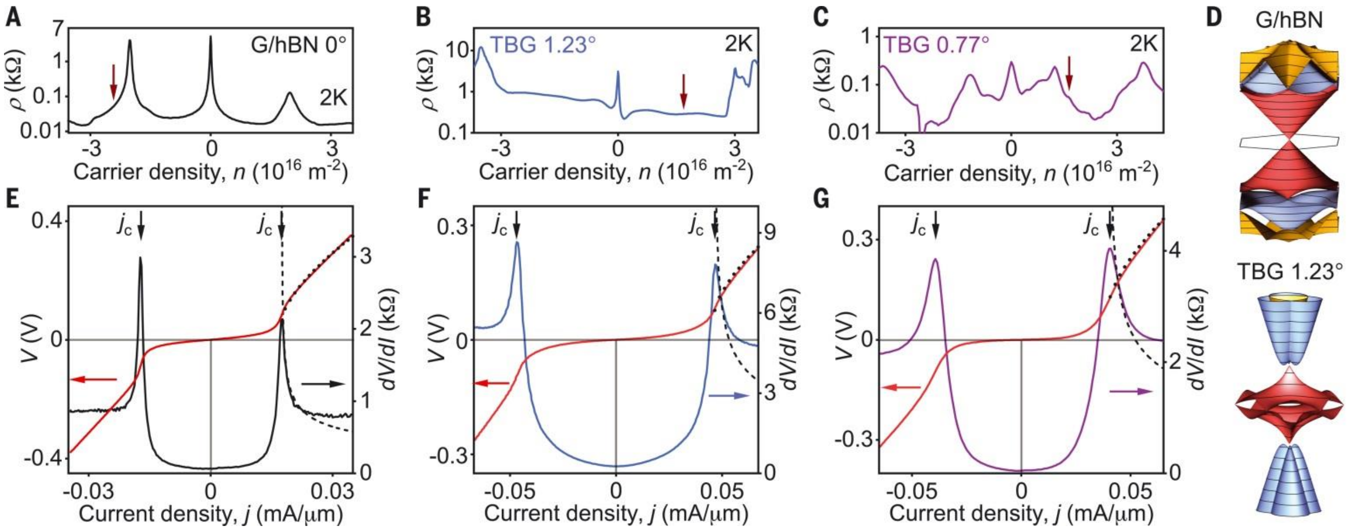
$c \to v_F$ and electron-hole symmetry



$$w_{2d} = \frac{eE}{2\pi^2\hbar}\sqrt{\frac{eE}{v_F\hbar}}\sum_{n\geq 1}\frac{e^{-n\pi\frac{E_S}{E}}}{n^{3/2}} \propto E^{3/2}$$

$$E_S = 0$$

Dora-Moessner, PRB (2010),
Katsnelson-Volovik, ZhETF (2012),...



$j \propto E^{3/2}$

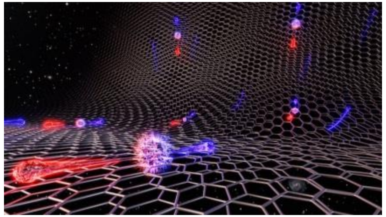
+ sign reversal of the Hall resistance

Berdyugin, Science (2022)

2d-Schwinger in gapless neutral 2d-graphene

$$E = v_F \hbar k$$

$c \to v_F$ and electron-hole symmetry



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$$E_S = 0$$

Dora-Moessner, PRB (2010),
Katsnelson-Volovik, ZhETF (2012),...

BUT

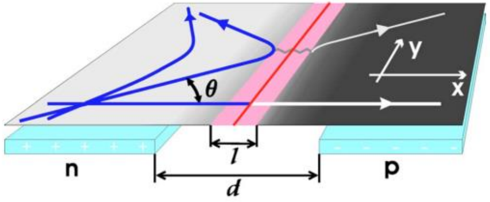
- $E^{3/2}$ **law is similar to Zener tunneling** Vandecasteele et al., PRB (2010)
- **Electric-field induces doping-gradient, p-n junction, and 1d-collimation ....**

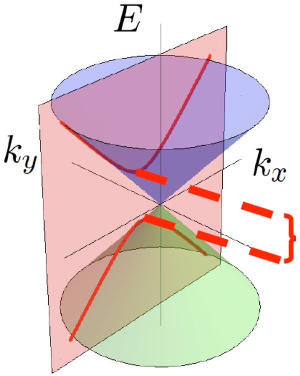
Klein-Schwinger effect

Klein collimation mimics massive 1d-Dirac fermions

Collimating p-n junction

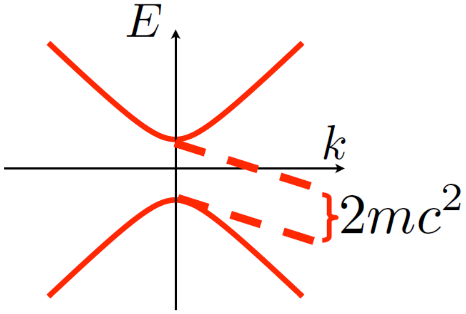
$$E = \mp\sqrt{(v_F \hbar k_y)^2 + (v_F \hbar k_x)^2}$$





massive Dirac fermions

$$E = \mp\sqrt{(mc^2)^2 + (c\hbar k)^2}$$



Long junction $\mathrm{T}(k_y) = e^{-\pi\hbar v_F k_y^2/eE_x}$

$\mathrm{T}(k_C) = e^{-\pi\hbar c k_C^2/eE_x}$

V. V. Cheianov, V. I. Falko, PRB-2006
J. Cayssol, B. Huard, D. Goldhaber-Gordon, PRB-2009
E.B. Sonin, PRB-2009
P.E. Allain, J.N. Fuchs, EPJB-2011

F. Sauter, Z-Phys 1931

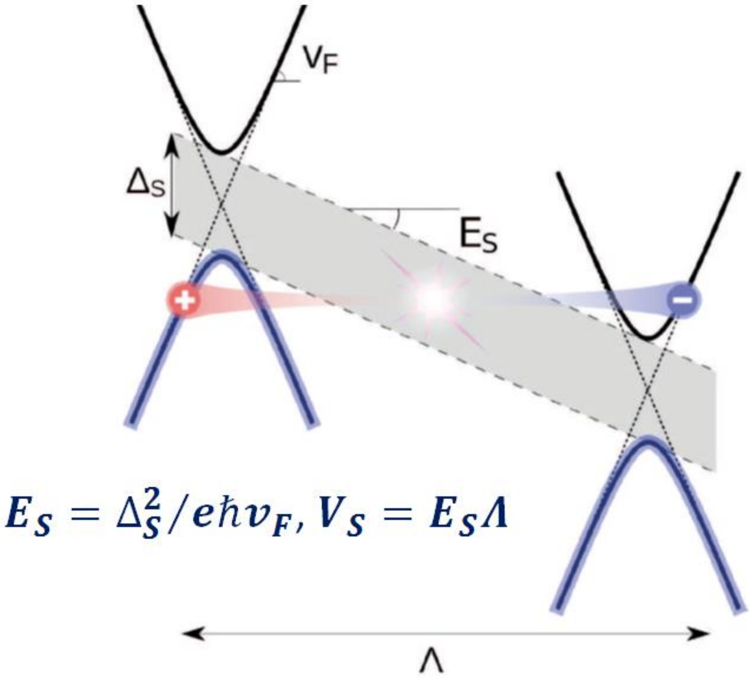
Schwinger effect with massive 1d Dirac fermions in graphene

a universal 1d-Schwinger pair-creation rate

$$w_{1d} = \left(\frac{2e}{h}\right) E \sum_{n \geq 1} \frac{e^{-n\pi\frac{E_S}{E}}}{n}$$

$$E_S = \frac{\Delta_s^2}{e\hbar v_F} \sim 6\ 10^7\ \frac{V}{m}$$

for $\Delta_S \sim \varepsilon_F \leq 0{,}2eV$



Universal quantized 1d-Schwinger conductance

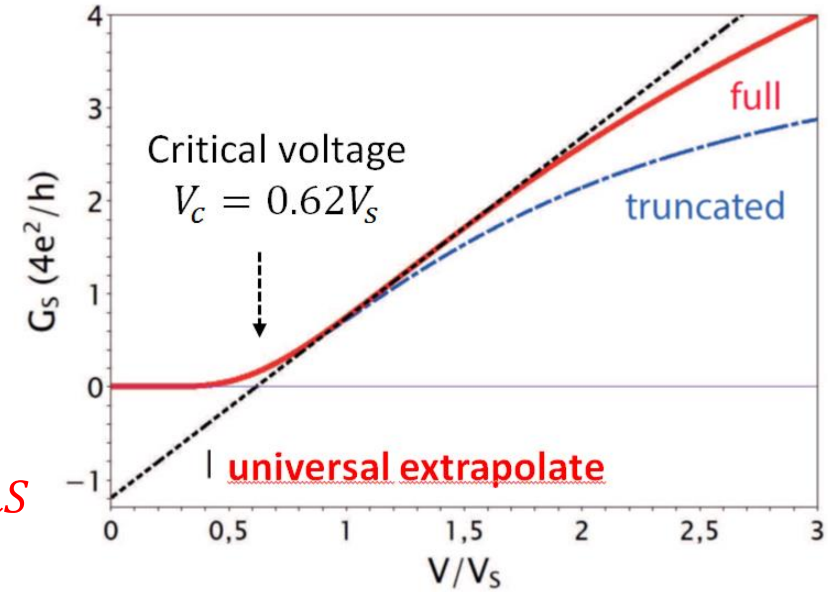
Schwinger current over a length Λ $(g_s = g_v = 2)$

$$I_{1d} = 2 \times g_s g_v \times \Lambda \times w_{1d} = 2 g_s g_v \left(\frac{2e^2}{h}\right) V\, Ln\left(\frac{1}{1-e^{-\pi V_S/V}}\right)$$

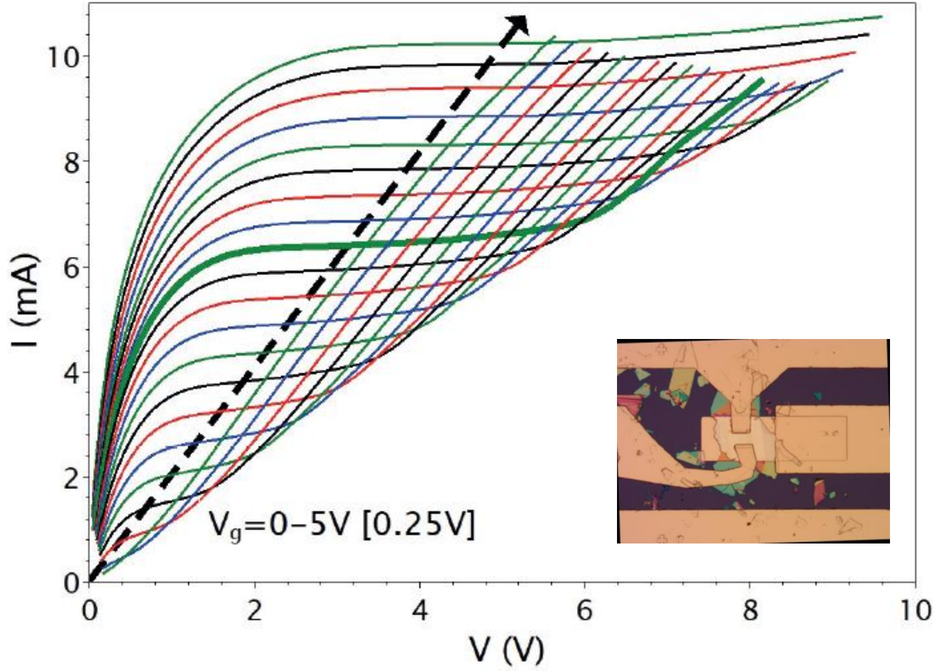
$$V_S = E_S \times \Lambda$$

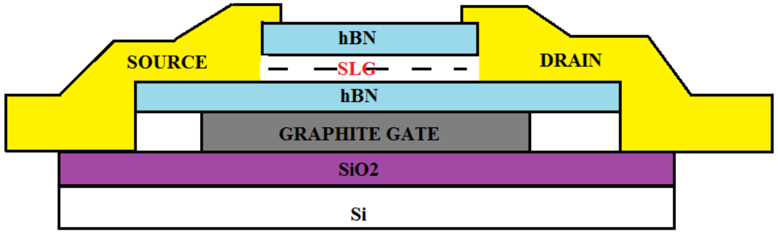
$$\boldsymbol{G_S = 4\left[Ln\left(\frac{1}{1-e^{-\pi V_S/V}}\right) + \frac{\pi V_S}{V}\frac{1}{e^{\pi V_S/V}-1}\right] \times 4e^2/h \approx 2 \times 0.60\left[\frac{V}{V_S} - 1\right] \times 4e^2/h}$$

$$G_0 = -0.186\, mS$$

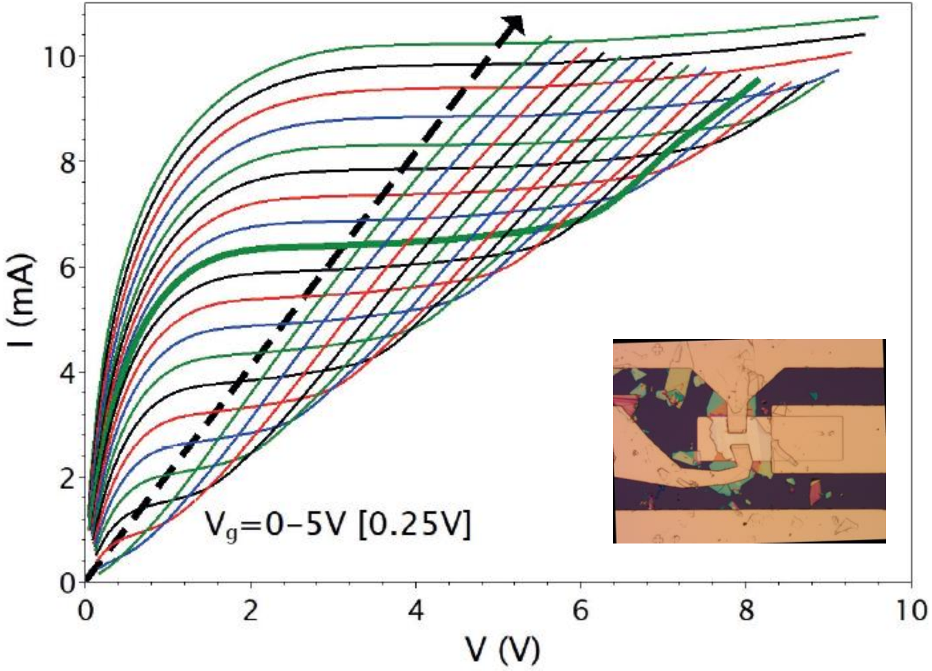


Current saturation in hBN-encapsulated graphene FET

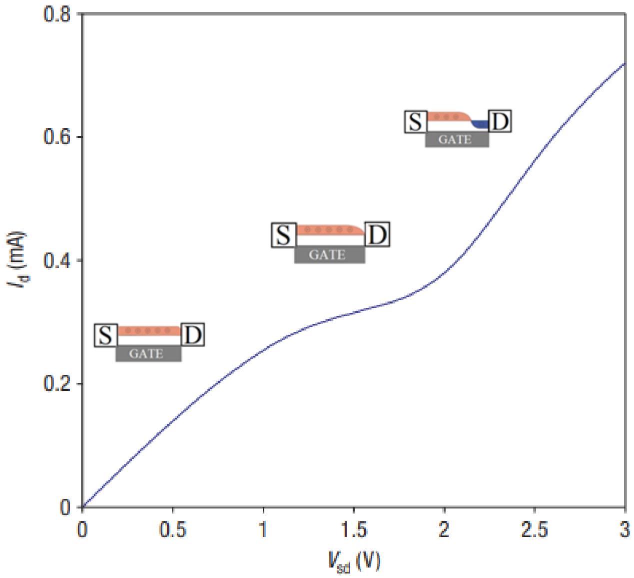




Current saturation in hBN-encapsulated graphene FET

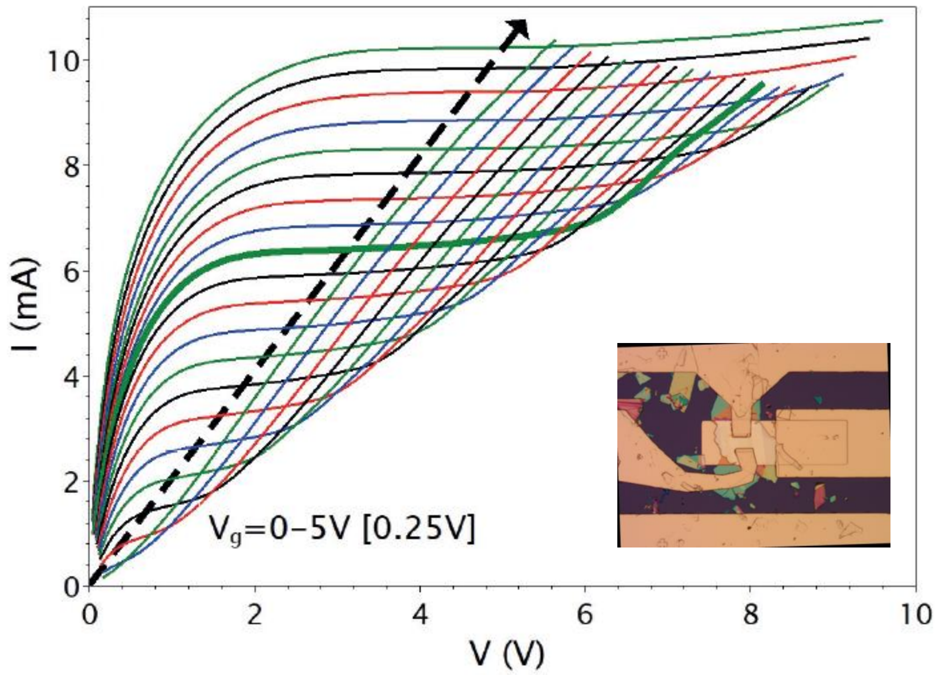


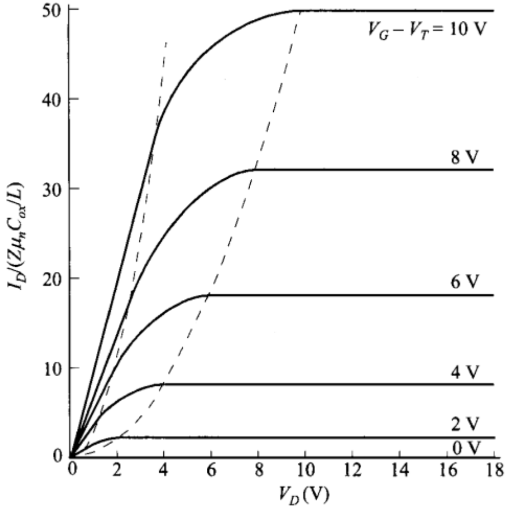
Diffusive graphene



Meric et al. *Nature Nanotechnology* 3, 654–659 (2008)

Current saturation in hBN-encapsulated graphene FET



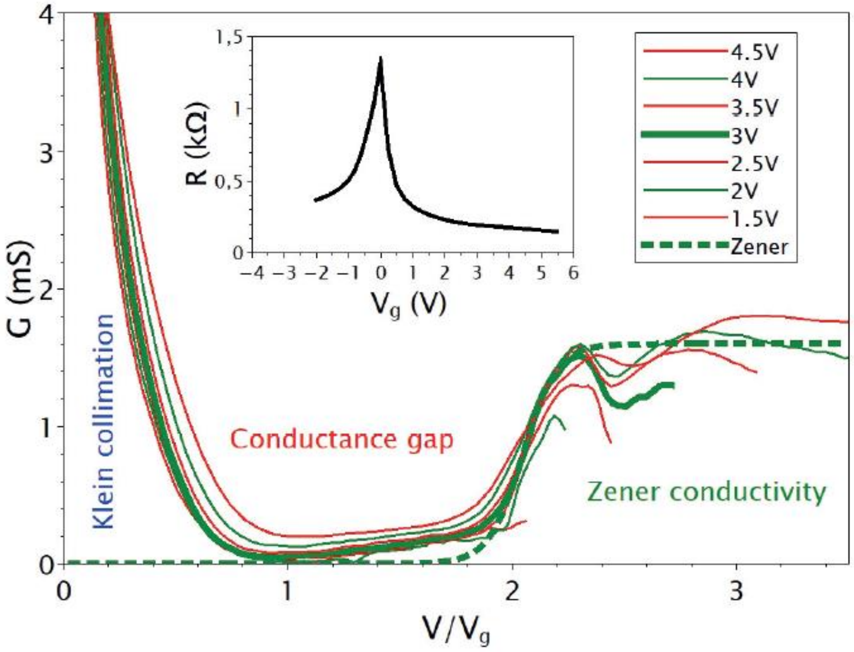


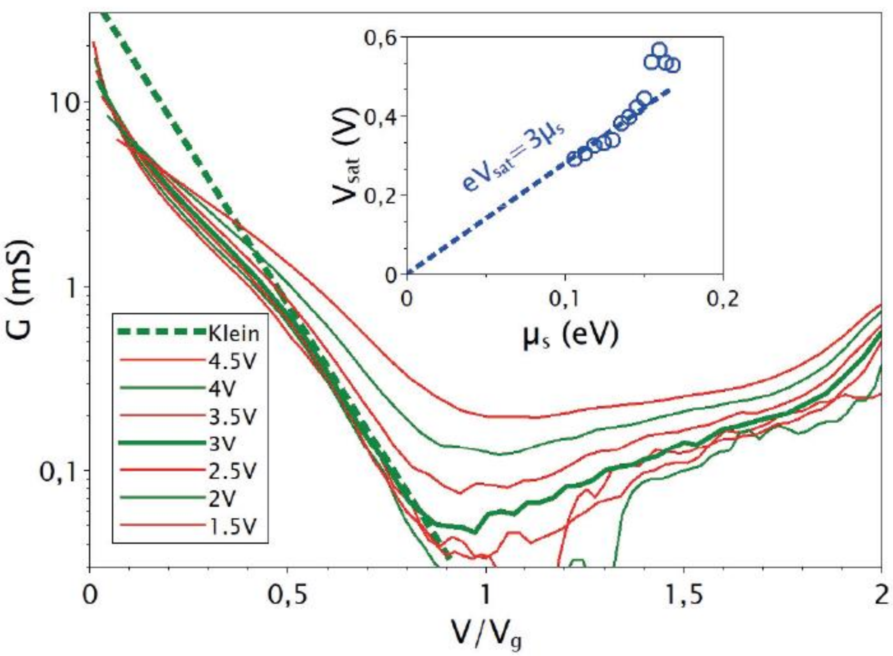
Si MOSFET (Sze, 2006)

reminiscent of MOSFET pinchoff (carrier depletion at the drain side), albeit semimetallic

From current to differential conductance

Vanishing Klein-tunneling conductance $G_K \approx G(0)e^{-V/V_{sat}}$



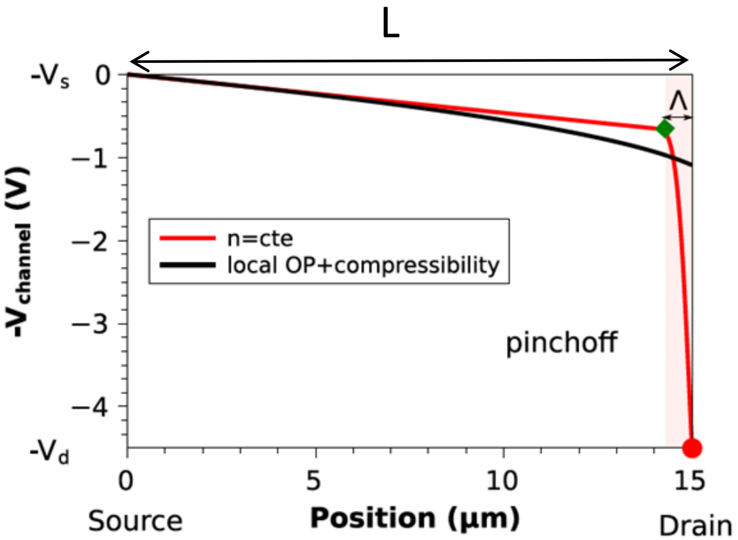


Giant Klein collimation model : $$\mathrm{T}(V) \propto e^{-\pi \frac{eV\Lambda}{\hbar v_F} sin^2\theta_{sat}} = e^{-V/V_{sat}}$$

Toy-model of the Klein-collimation junction

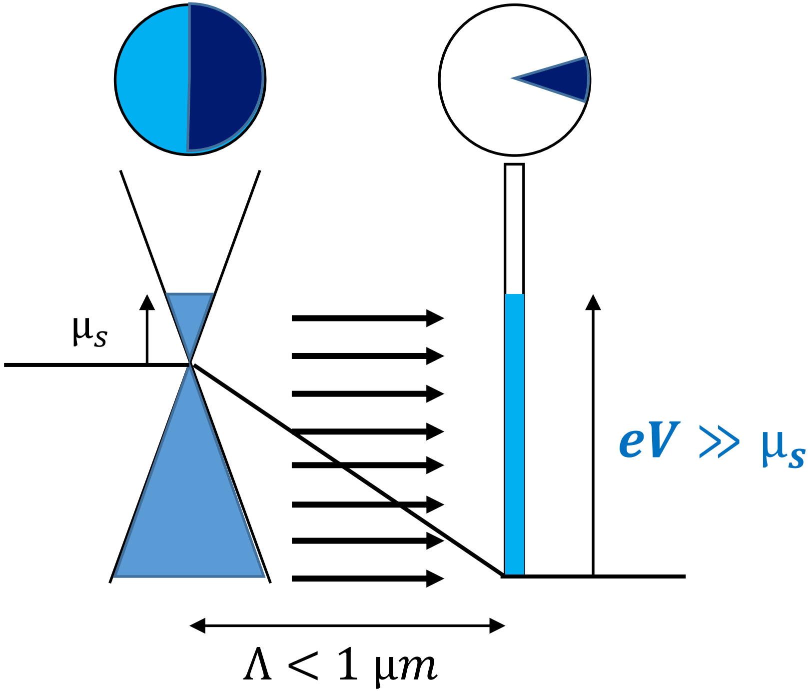
Semi-metallic Pinchoff

$$E_x = V/\Lambda$$



Long-junction model

$$T \propto e^{-\pi\hbar v_F k_y^2/eE_x}$$

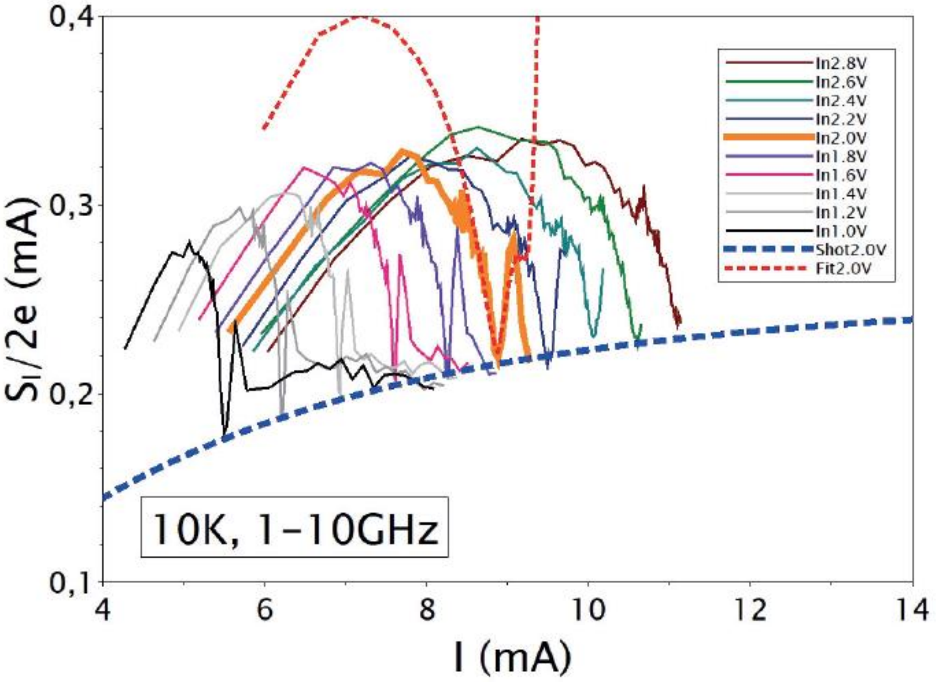


noise signatures of Klein collimation

Klein tunneling junction : shot-noise

White GHz noise

$$S_I = 4Gk_BT_e + 2eIF$$



Klein tunneling junction : shot-noise

White GHz noise

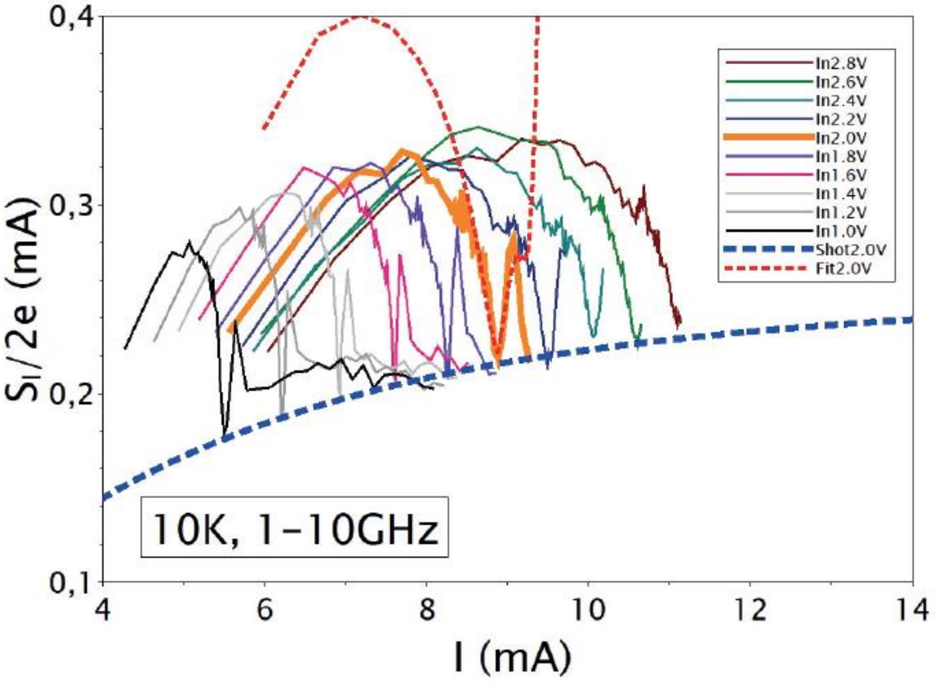
$$S_I = 4Gk_BT_e + 2eIF$$

Sweet noise dip

$$G \rightarrow 0, S_{th.} \rightarrow 0$$

Shot-noise limited

$$S_I(V_{dip}) \approx 2eIF$$



Klein tunneling junction : shot-noise

White GHz noise

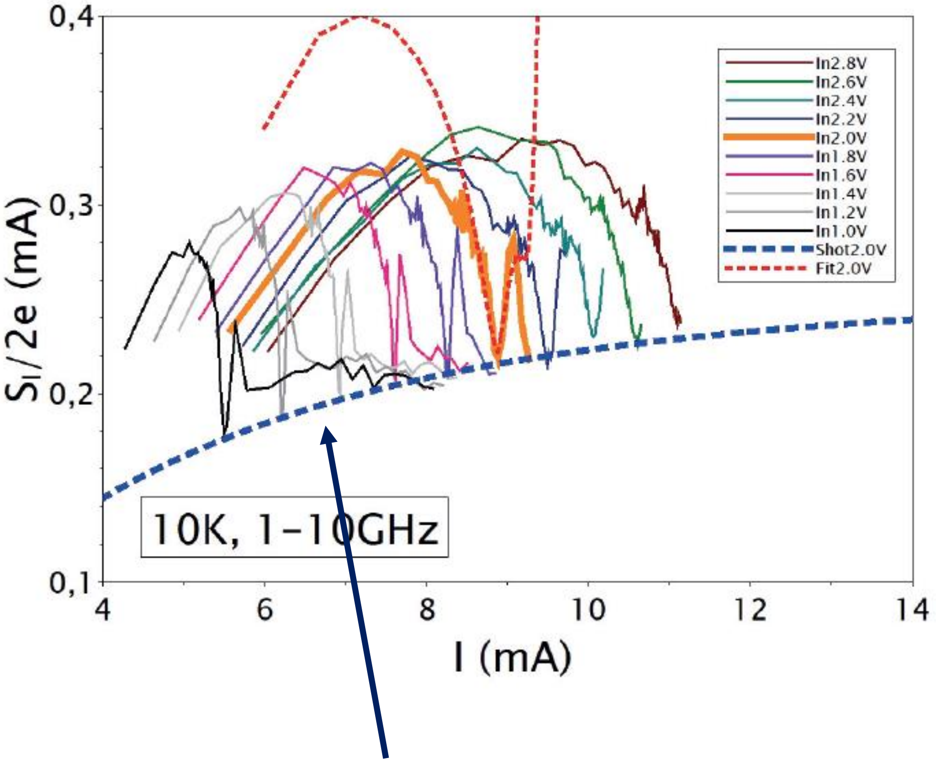
$$S_I = 4{\color{blue}G}k_BT_e + 2eIF$$

Sweet noise dip

$${\color{blue}G \to 0}, S_{th.} \to 0$$

Shot-noise limited

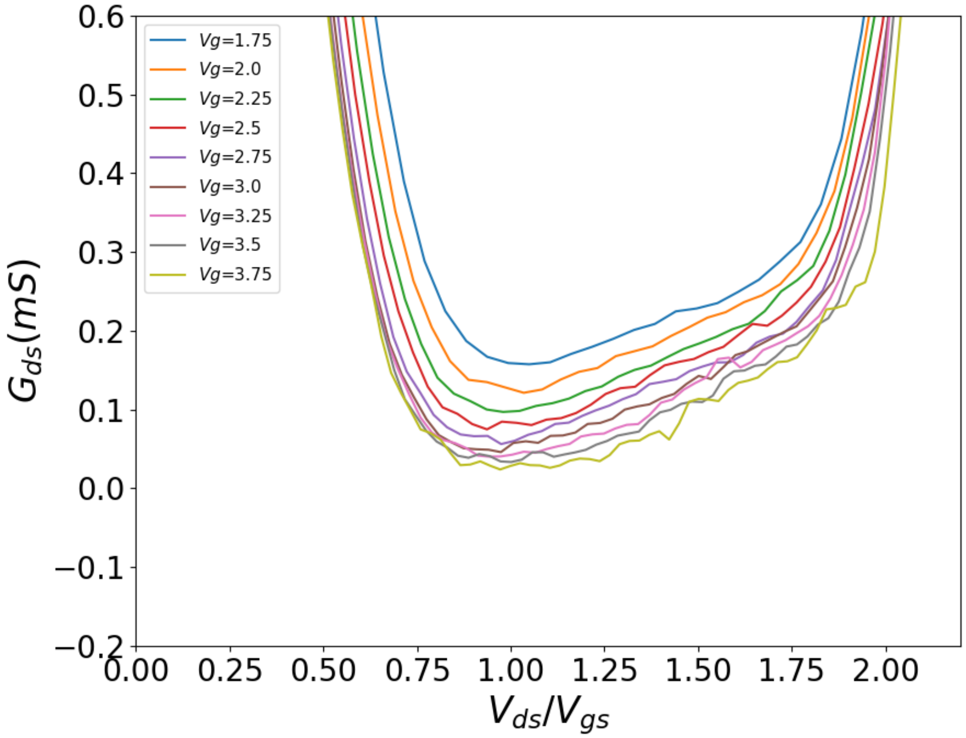
$$S_I(V_{dip}) \approx 2eIF$$



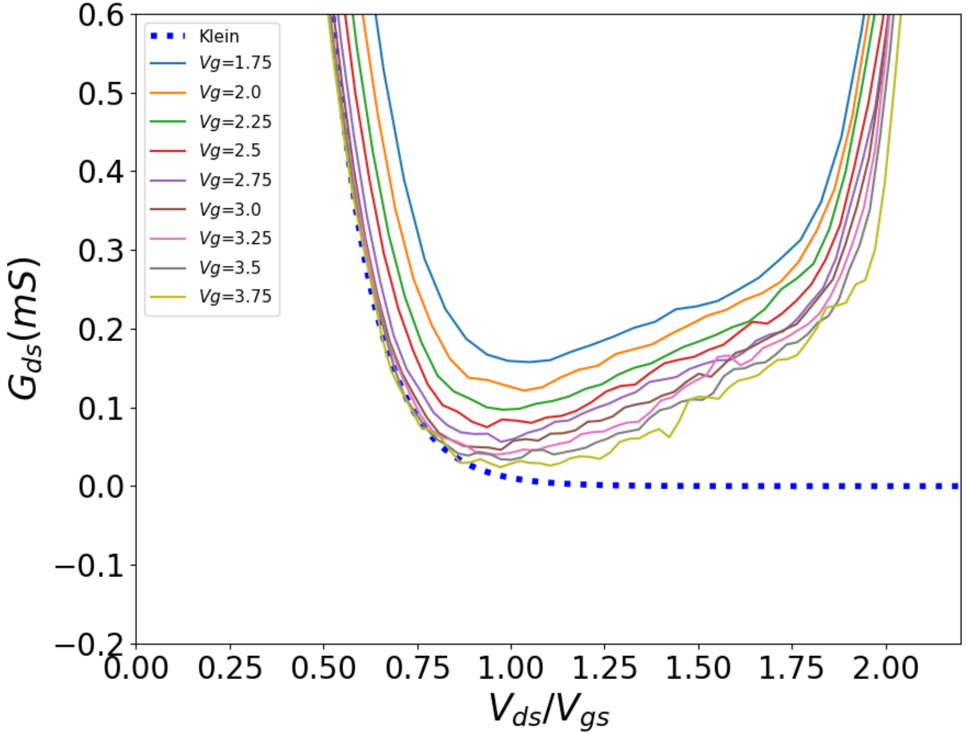
Mesoscopic junction with a Fano factor $\boldsymbol{F \leq 0.04}$

Universal 1d Schwinger effect

Evidence of mesoscopic Klein-Schwinger effect



Evidence of mesoscopic Klein-Schwinger effect



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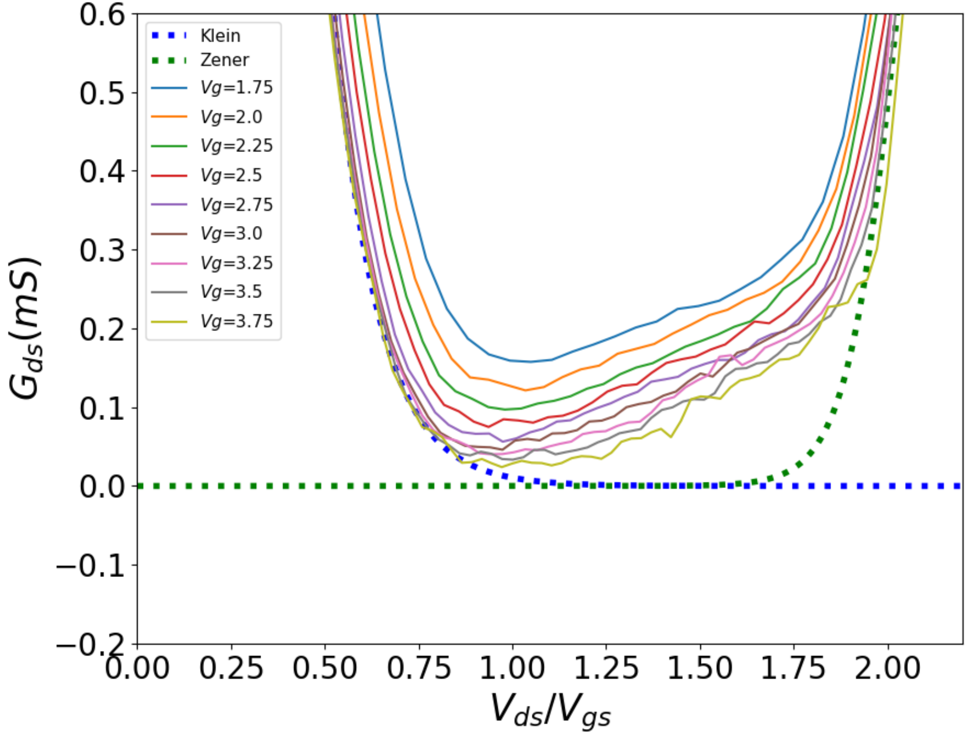
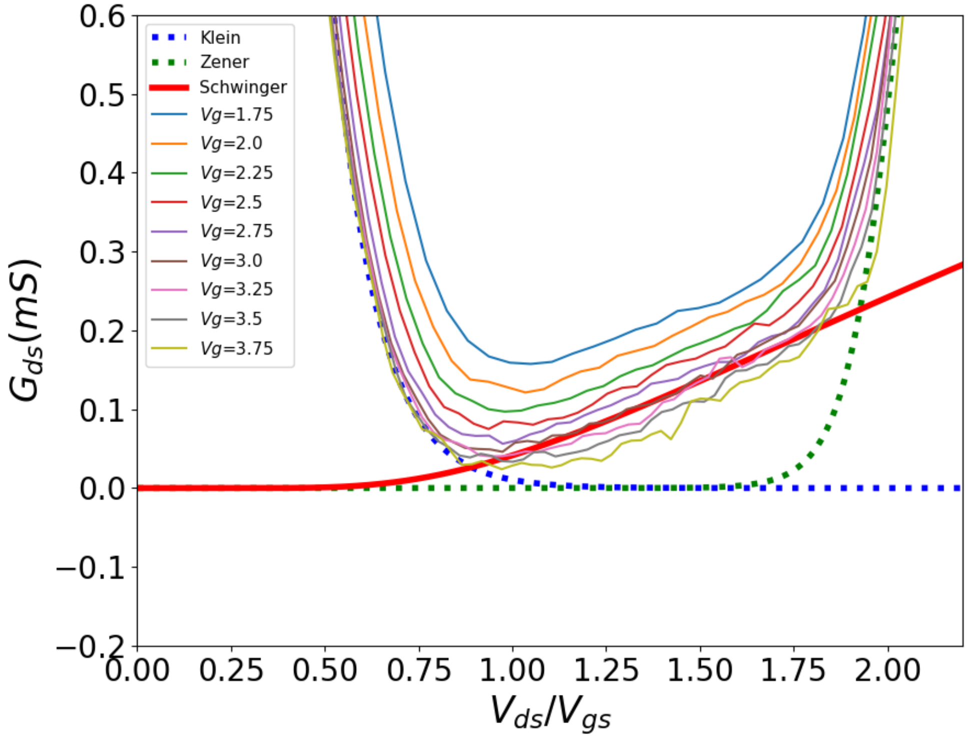


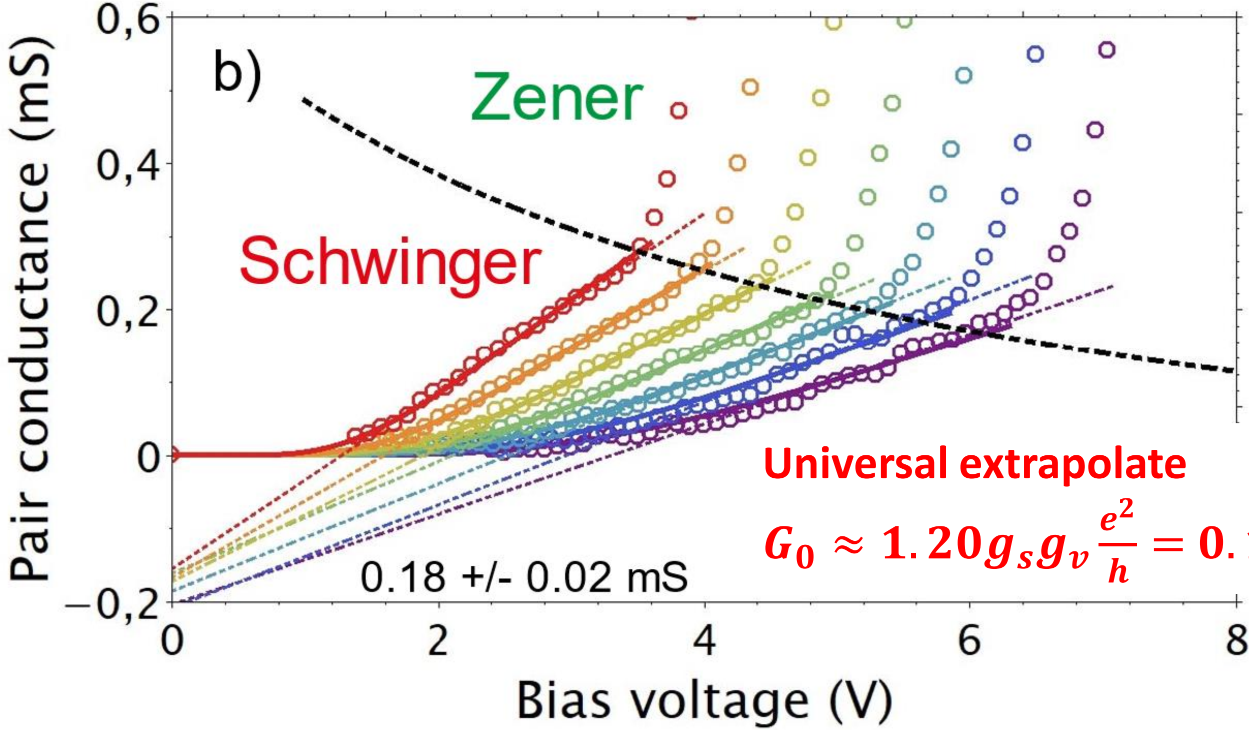
Evidence of mesoscopic Klein-Schwinger effect



$$\mathbf{G} \approx \boldsymbol{G_S}(\mathbf{V})$$

$$16\left[Ln\left(\frac{1}{1-e^{-\pi V_S/V}}\right)+\frac{\pi V_S/V}{e^{\pi V_S/V}-1}\right]\frac{e^2}{h}$$

Universal 1d-Schwinger scaling: $G_S(V) = G - G(0)e^{-V/V_{sat}}$



Universal extrapolate

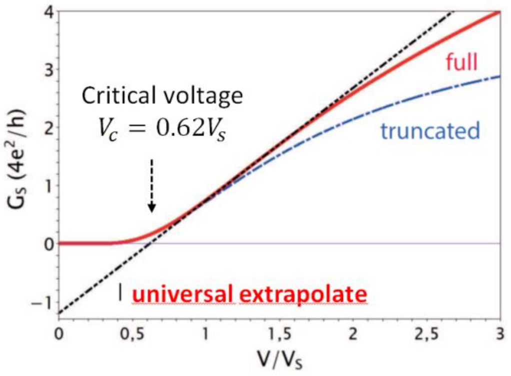
$G_0 \approx 1.20 g_s g_v \frac{e^2}{h} = 0.186\, mS$

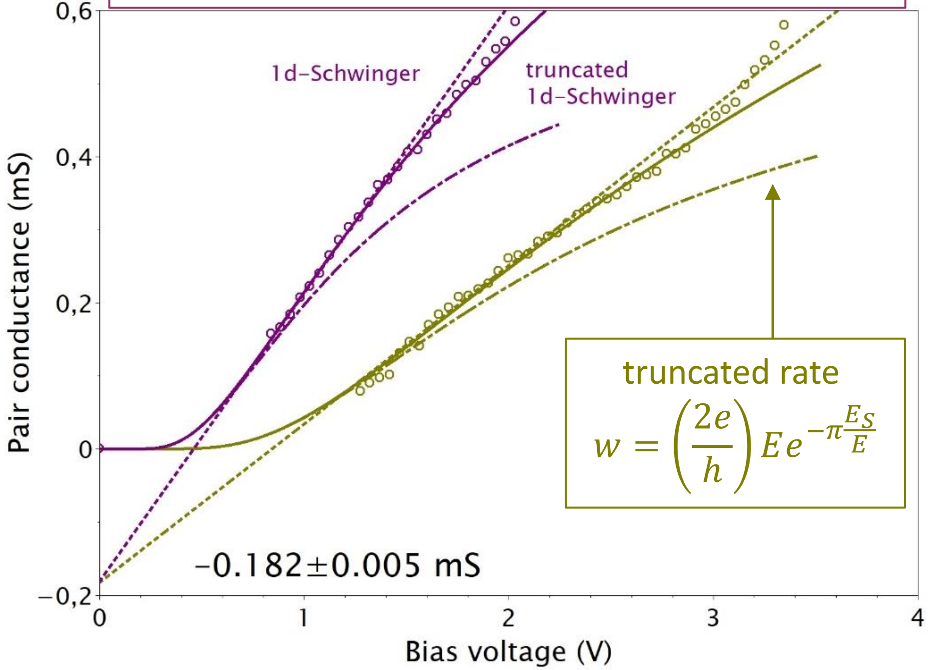
One parameter : Schwinger voltage V_S

The N-loop Schwinger prediction verified in detail

A device with a thin hBN dielectric (32nm) :
early onset of Schwinger pair creation $V_S \leq 0.5\ V_g$

Full 1d-Schwinger $w = \frac{2eE}{h} Ln\left(\frac{1}{1-e^{-\pi E_S/E}}\right)$



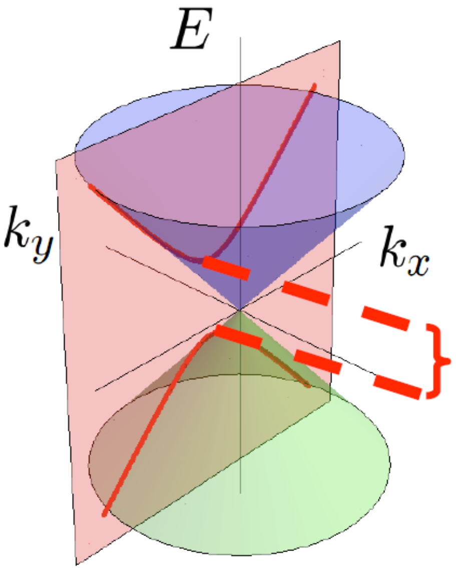


an important result for field theory

Schwinger gap and length

Klein-collimation origin of the Schwinger gap

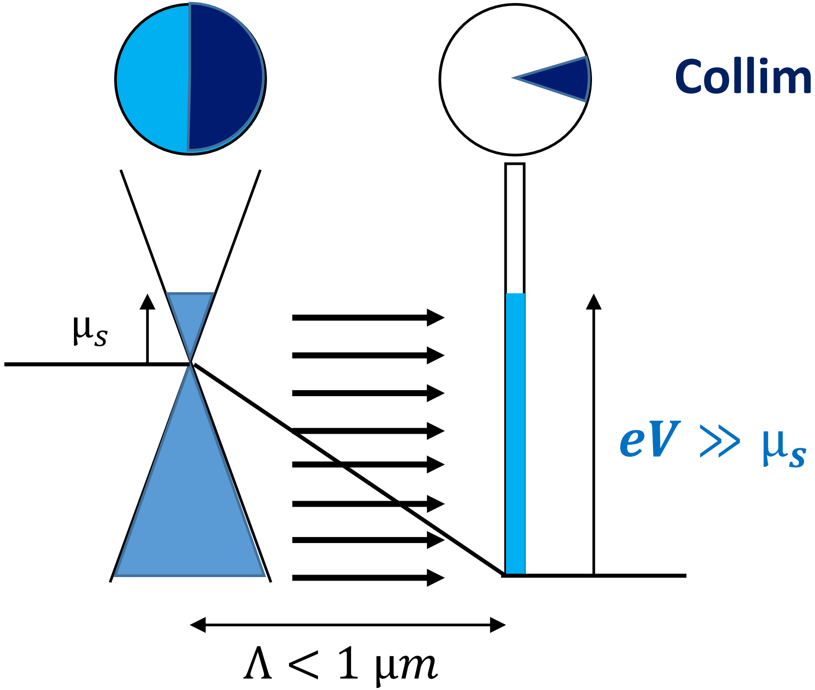
$$E = \mp\sqrt{(v_F \hbar k_y)^2 + (v_F \hbar k_x)^2}$$



$\Delta_S = 2 v_F \hbar k_S$

Why finite-k_S Schwinger pairs ?

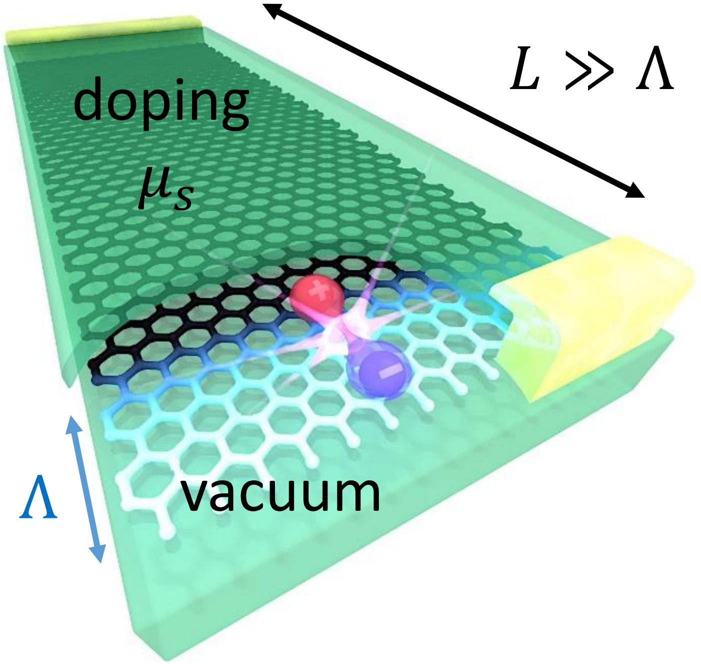
Pauli-blocking of low-k_y by collimated transmitted carriers

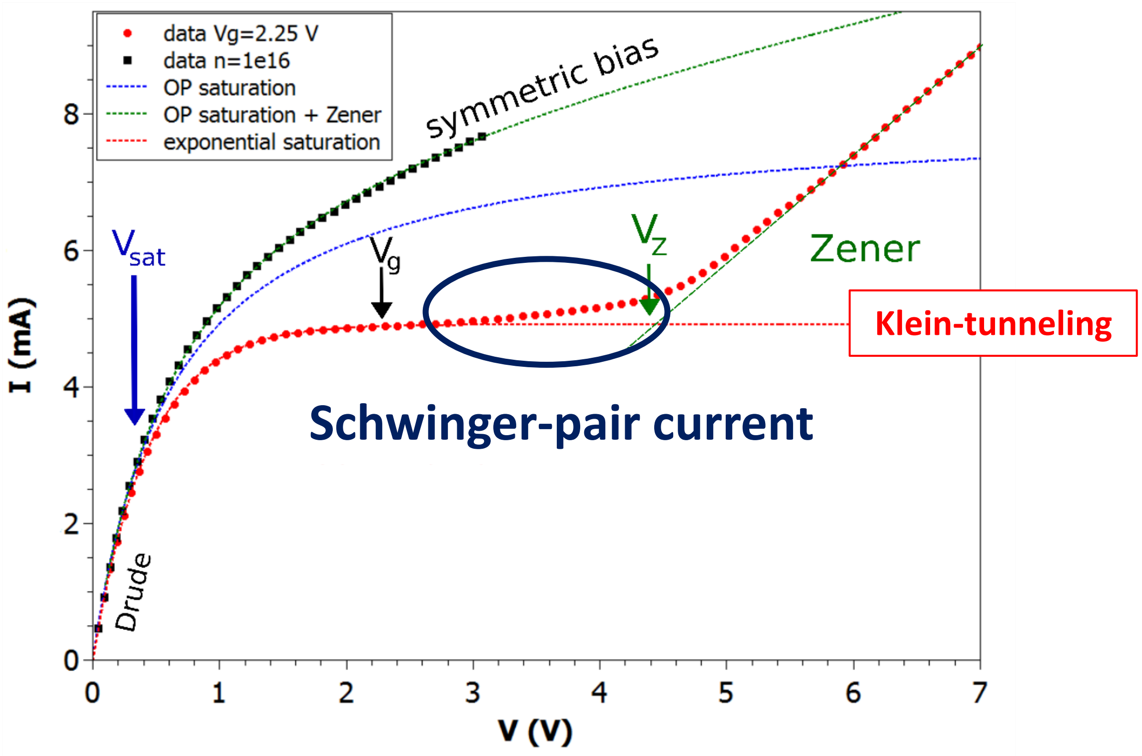


Collimated saturation current

Ansatz: Schwinger-pairs created at a finite k_y with $\Delta_S \sim \mu_s$

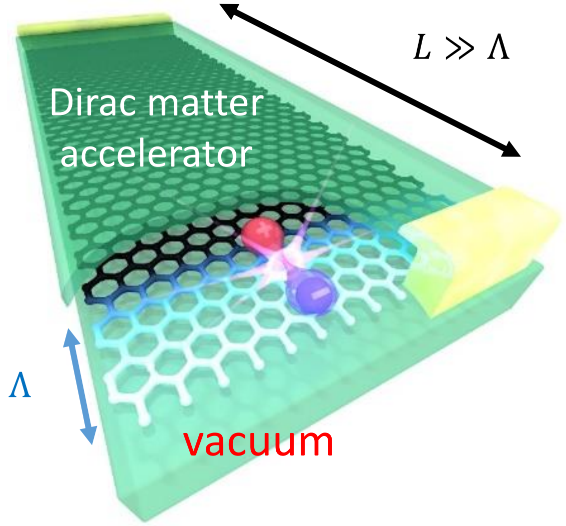
Schwinger as the intrinsic breakdown of Klein collimation





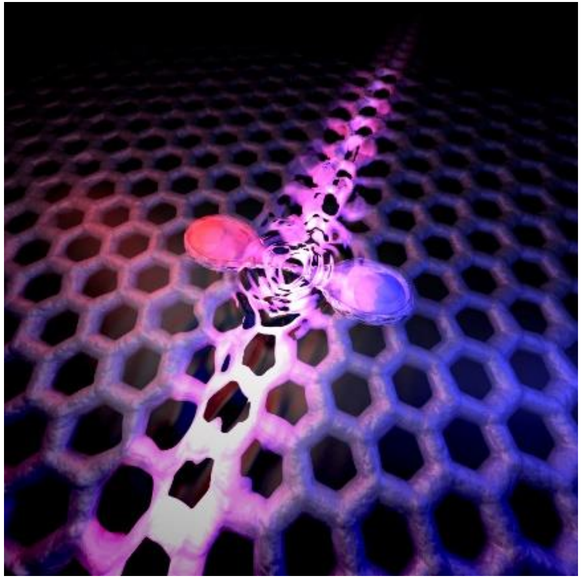
« QED in a pencil trace » → « QED in a graphene mosfet »

- ✓ Experimental observation of 1d-Schwinger effect
- ✓ Schwinger is the breakdown of Klein collimation
- ✓ Outlook: lifting spin/valley degeneracy ?
- ✓ Outlook: Full counting statistics ? Vacuum polarization ?



A. Schmitt et al., Nat. Phys. **19**, 830–835 (2023)
N&V R.K. Kumar **19**, 768–769 (2023)

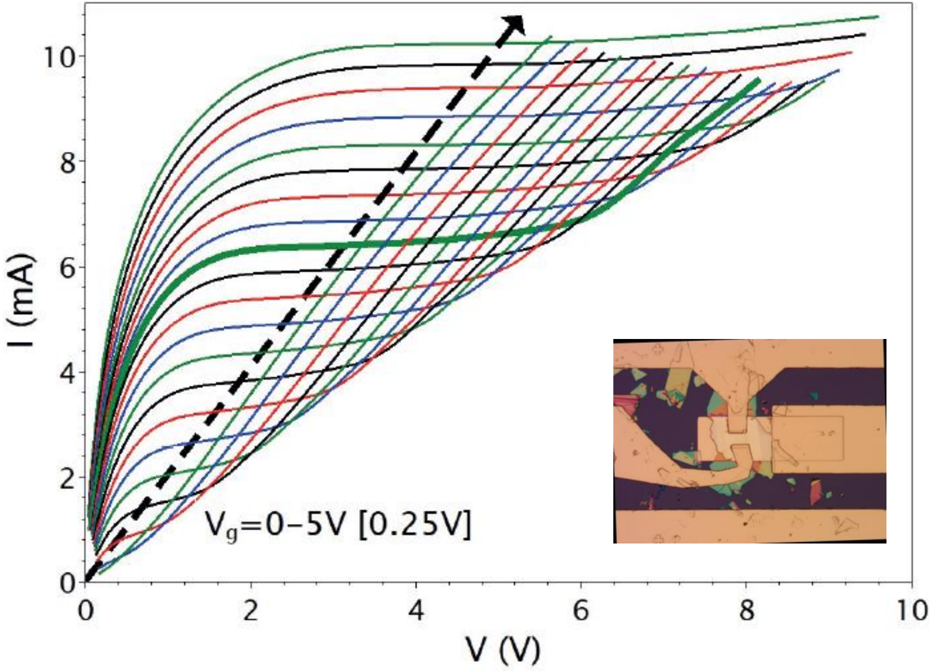
« QED in a pencil trace » → *« QED in a graphene mosfet »*

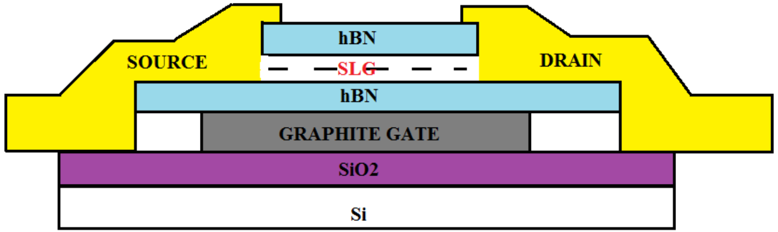


Thank you !

A. Schmitt et al., Nat. Phys. **19**, 830–835 (2023)
N&V R.K. Kumar **19**, 768–769 (2023)

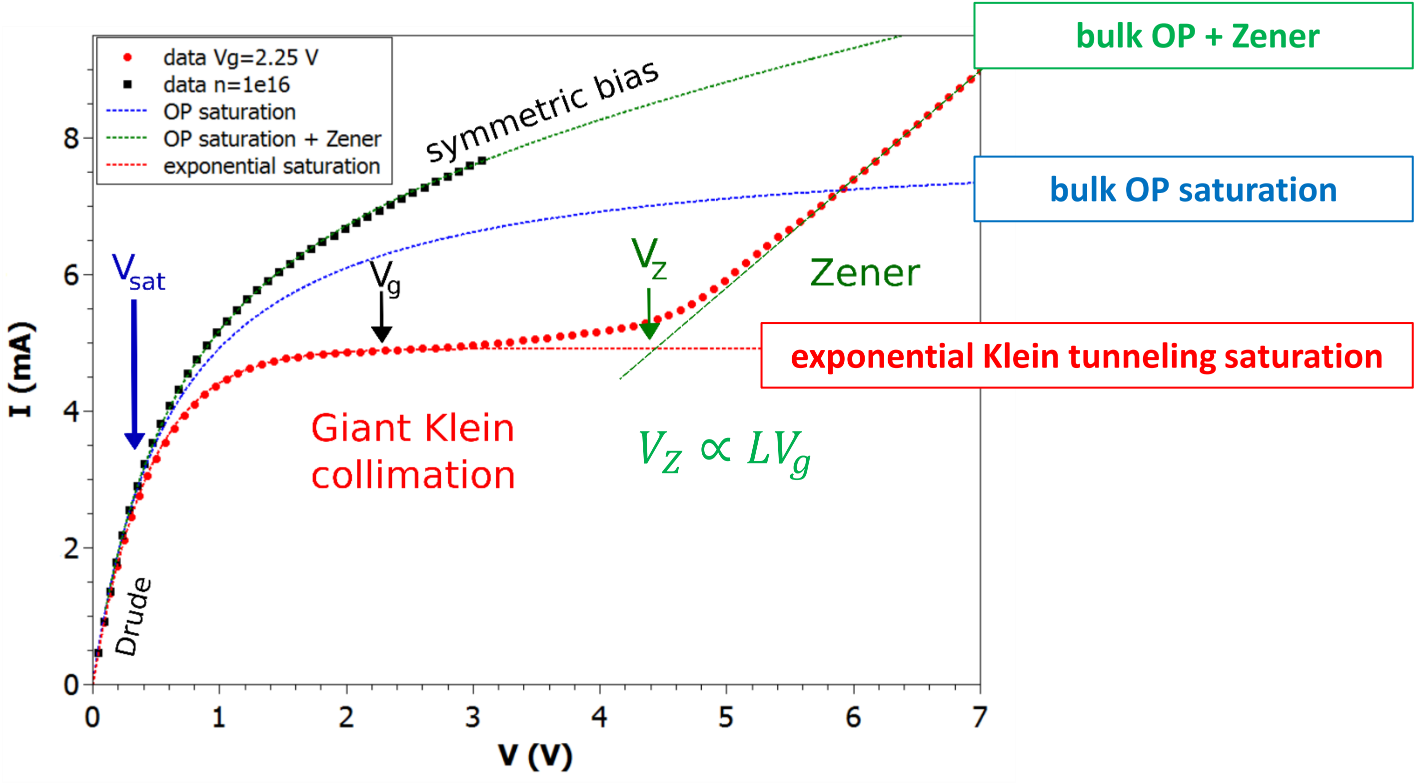
Current saturation in hBN-encapsulated graphene FET





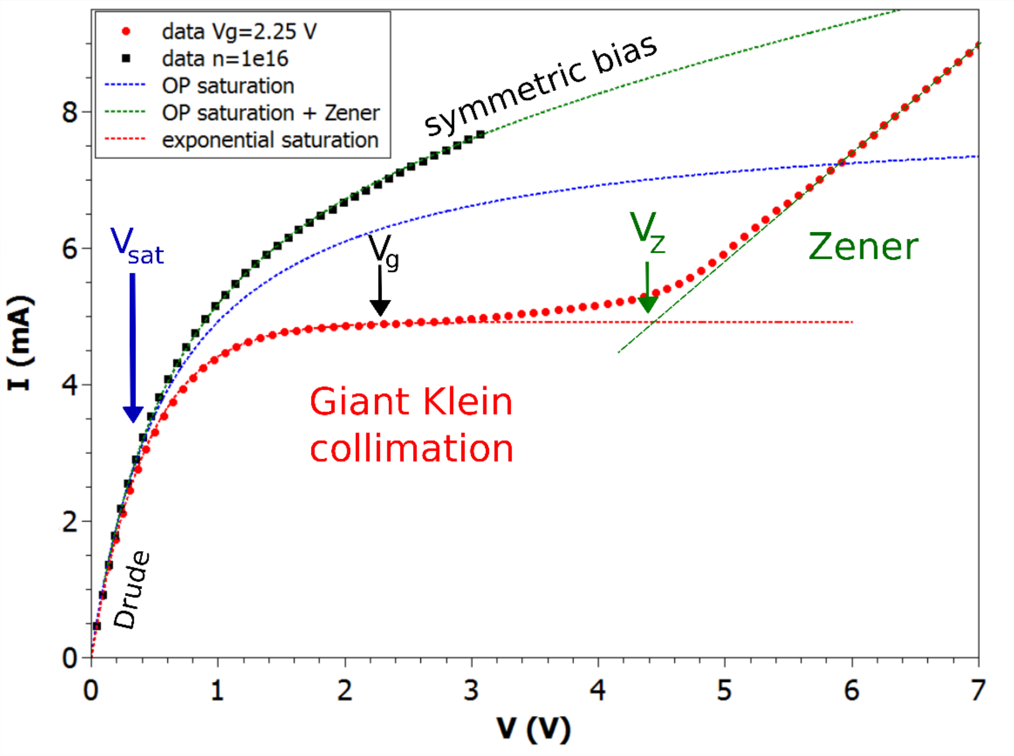
- Long devices $L \sim W \geq 10\ \mu m$
- High-mobility > $100\ 000\ cm^2/Vs$
- Low edge contact resistance
- Room temperature

Saturation controlled by a « Klein collimation junction »



Exponential saturation is extrinsically limited by a Zener instability

Saturation controlled by a « Klein collimation junction »



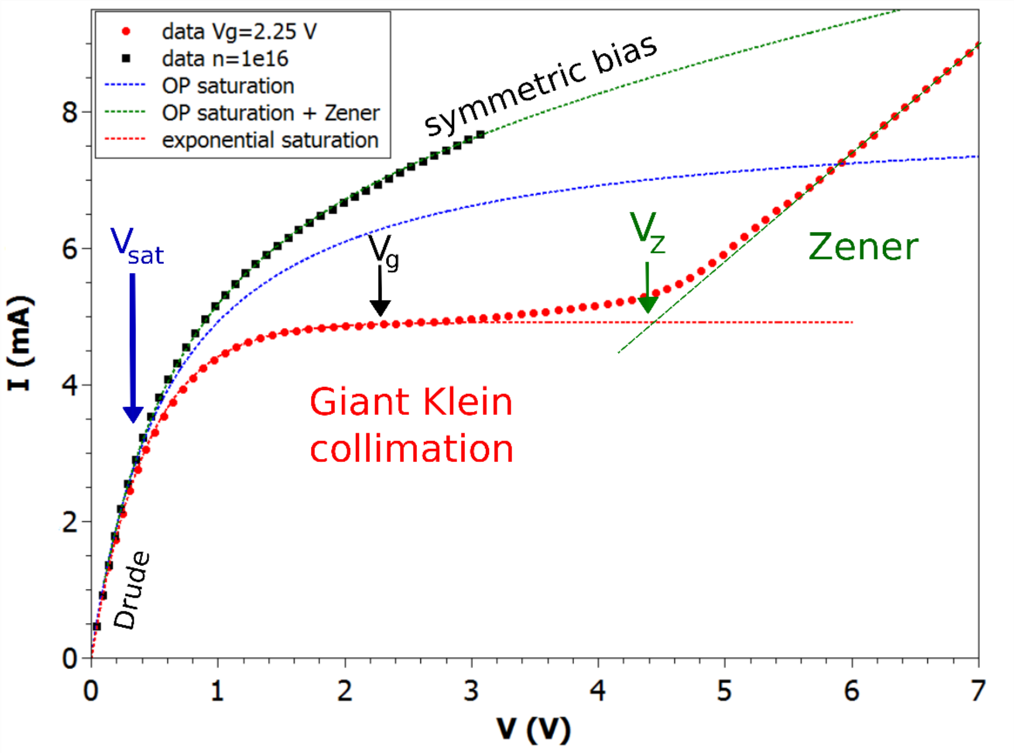
Pinch-off free regime

$$V_g(V) = V_g(0) + aV$$

Bulk current saturation controlled by optical phonons:

$$I = n_s e \left[\frac{\mu}{1+V/V_{OP}} + \sigma_Z\right]\frac{W}{L}\,V$$

Saturation controlled by a « Klein collimation junction »



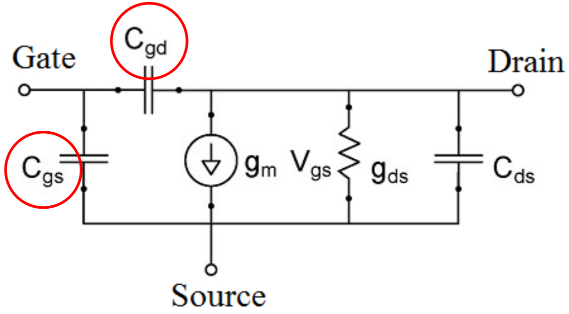
Pinch-off regime $V_g = Cst.$

Exponential current saturation :

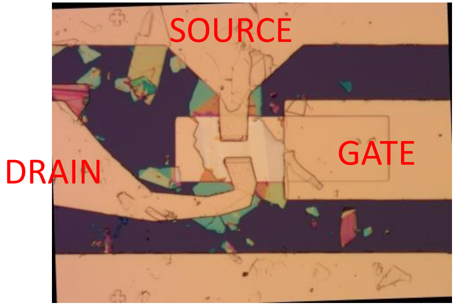
$$I(V) = I_{sat}(1 - e^{-\frac{V}{V_{sat}}})$$

Pinchoff regime : RF measurements

Small-signal equivalent circuit

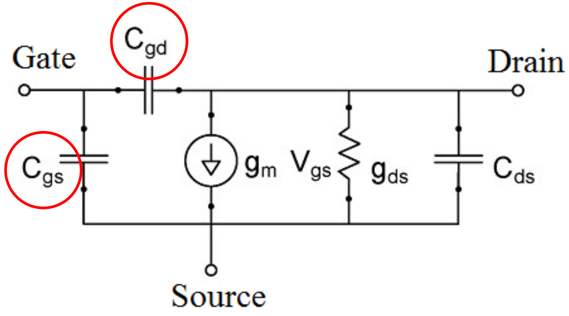


(cf Sze, 2006)



Pinchoff regime : RF measurements

Small-signal equivalent circuit



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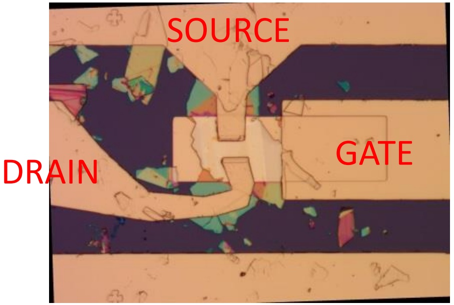
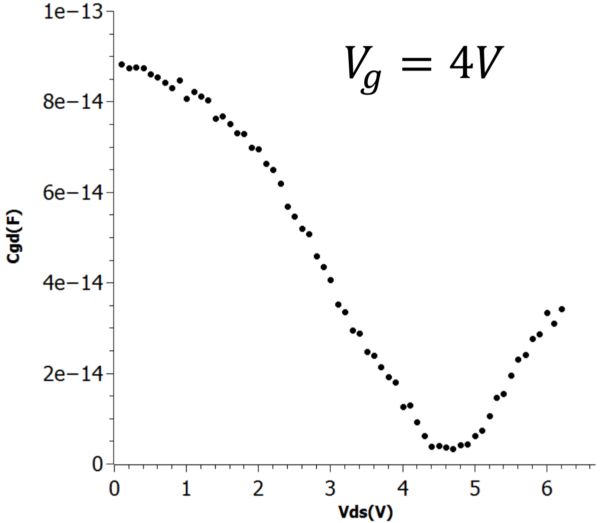
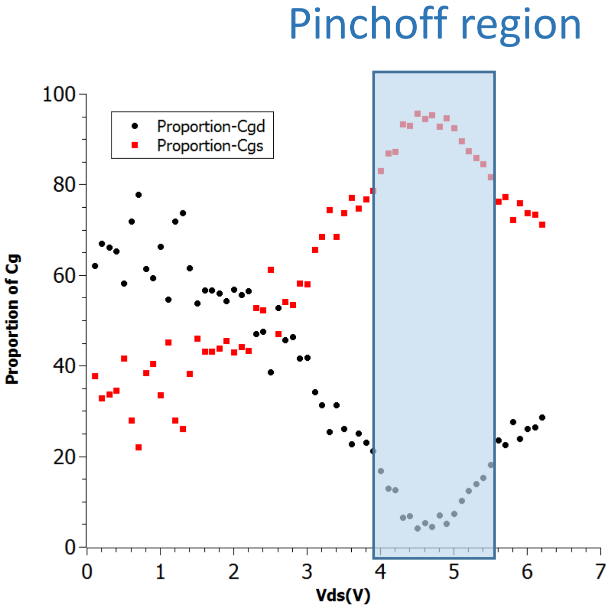






Toy-model of the Klein-collimation junction

Pinchoff-free case : velocity saturation (OPs) + electronic compressibility + **doping gradients** in the presence of a local gate

Current density : $J = \mu(E) n\, \partial_x \mu_c^*$

$\mu(0)$: low-bias mobility
E_{OP} : saturation field

where $\mu(E) = \mu(0)/(1 + \frac{|E|}{E_{OP}})$

$\mu_c^* = \mu_c(x) - e\, V_c(x)$ (electrochemical potential)

For monolayer graphene on a local gate :

$$\mu_c^* - \mu_g^* = \hbar v_F \sqrt{\pi n} + \frac{e^2}{C_g} n$$

+ electrostatics : $V_c(x) - V_g = \frac{-e}{C_g} n(x)$

v_F : Fermi velocity
C_g : areal gate capacitance
$n(x)$: carrier density
μ_g^*: electrochemical potential of the gate

Toy-model of the Klein-collimation junction

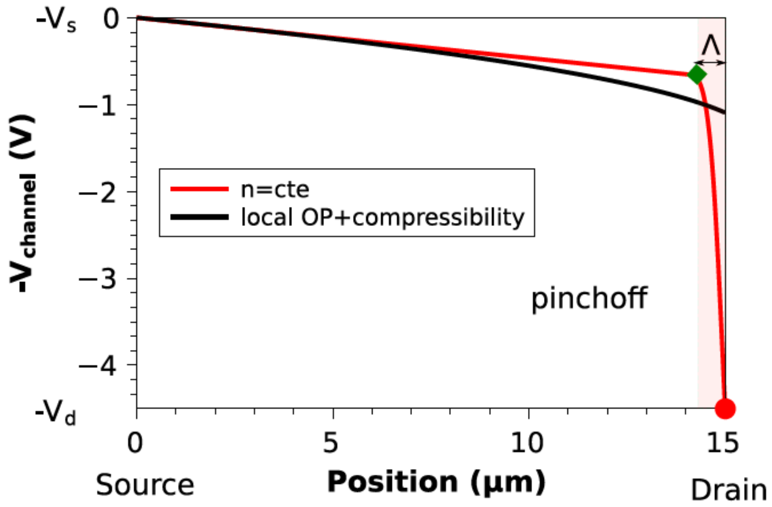
Pinchoff-free case : velocity saturation (OPs) + electronic compressibility + **doping gradients** in the presence of a local gate

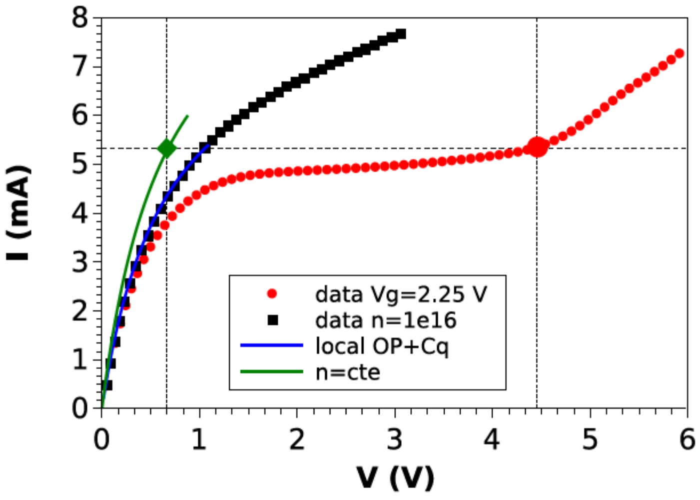
Pinchoff case : constant density in the channel → constant μ_c^* and uniform E

$$J = -\frac{\mu(0)}{1 + \frac{|\partial_x V_c|}{E_{OP}}} n \, \partial_x V_c$$

Toy-model of the semi-metallic pinchoff

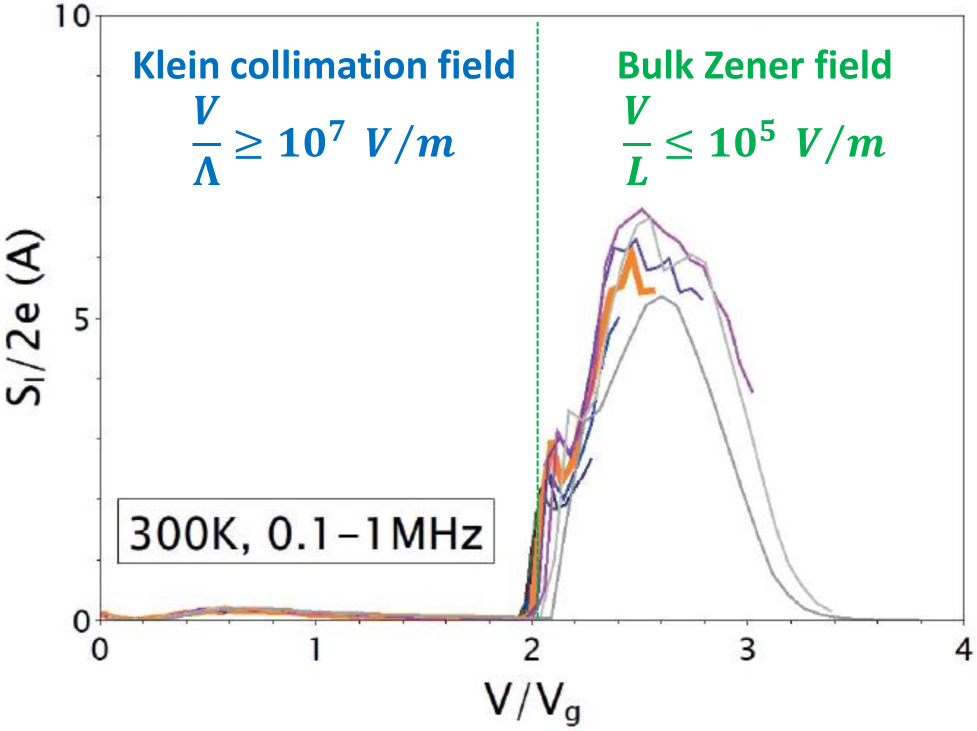
Local drift-diffusion model : velocity saturation + electronic compressibility + doping gradients with a local gate





Estimate of the voltage drop in the channel / in the pinchoff junction

Zener instability : flicker-noise

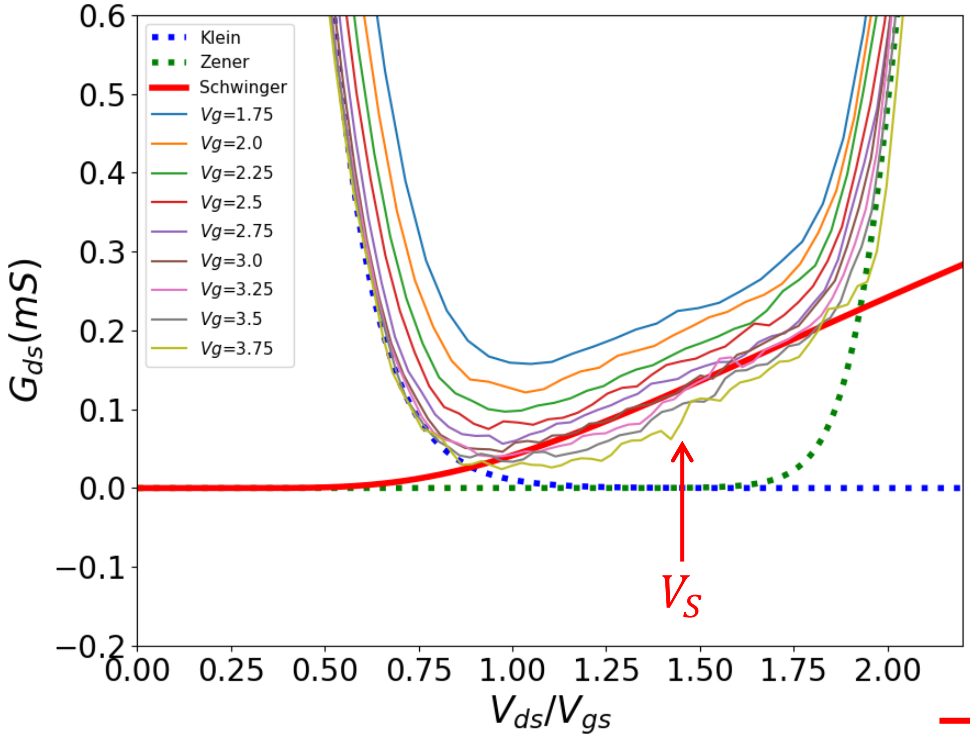


$V_Z \propto L V_g$

Zener instability is pushed to large $V_Z \approx 2V_g$ in long ($L \geq 10\ \mu m$) devices

A huge noise signals the destruction of the collimation junction

Evidence of mesoscopic Klein-Schwinger effect



$$\mathbf{G} \approx \boldsymbol{G_S}(\mathbf{V})$$

$$16\left[Ln\left(\frac{1}{1-e^{-\pi V_S/V}}\right)+\frac{\pi V_S/V}{e^{\pi V_S/V}-1}\right]\frac{e^2}{h}$$

$\underline{V_g = 3V:}$

$V_S = 4.2V$ and $\Lambda \sim t_{hBN}$

→ $E_S \sim 5.10^7 V/m$, $\Delta_S \sim 0.2eV \sim \mu_S$

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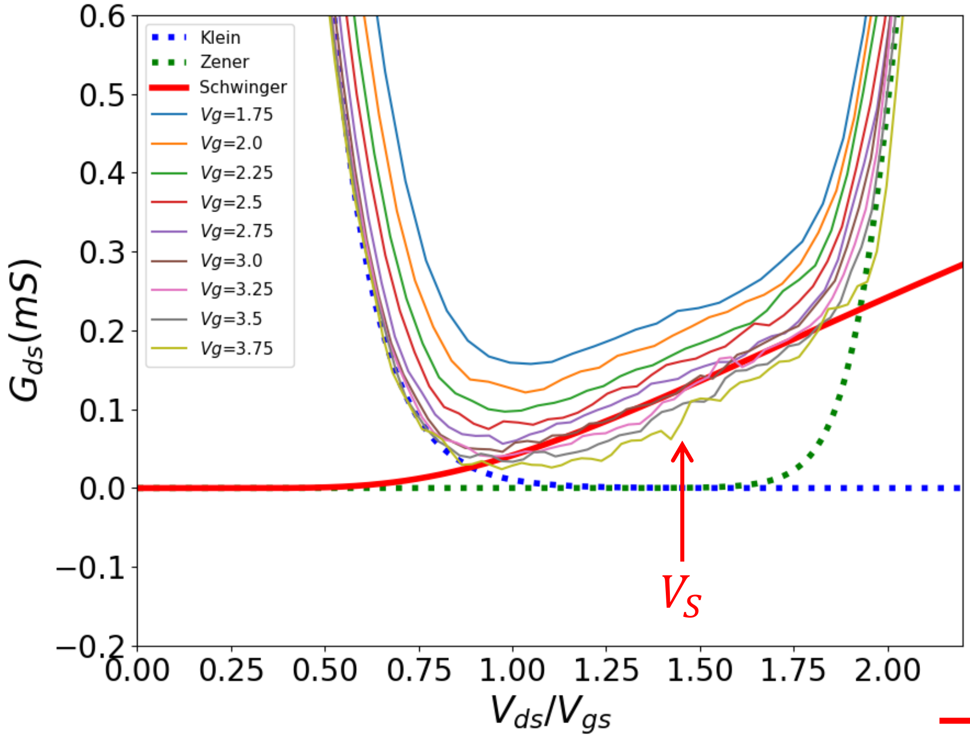

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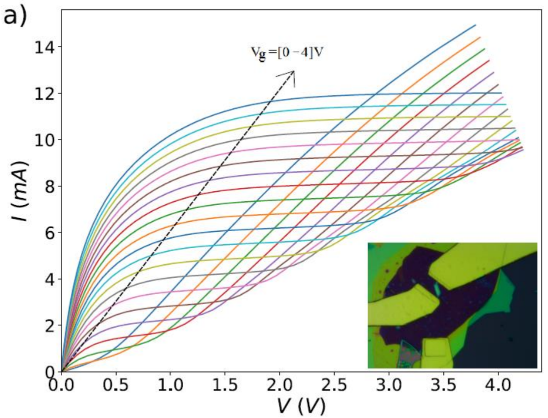
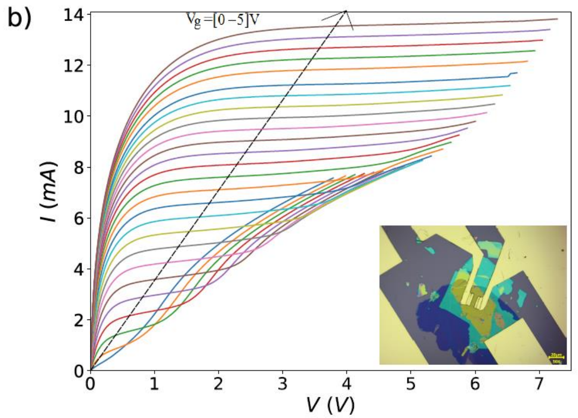
but obscured by Klein tunneling at low doping : $\mathbf{G} = \boldsymbol{G_S}(\mathbf{V}) + \boldsymbol{G_K}(\mathbf{V})$

Varied I-V according to hBN thickness / geometry ….

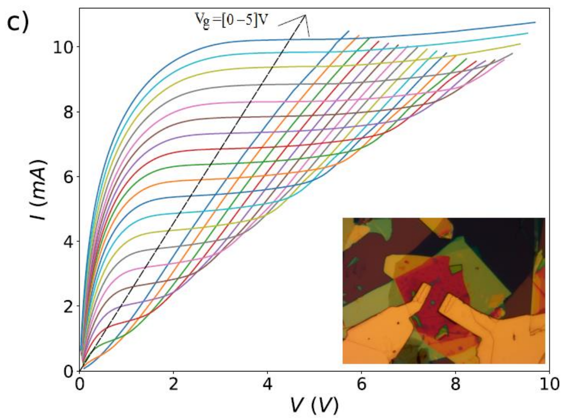
GrS1-25nm (L/W=0.75)



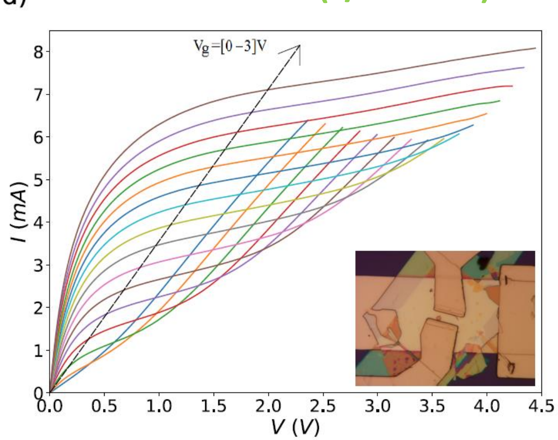
GrS2-35nm (L/W=0.7)



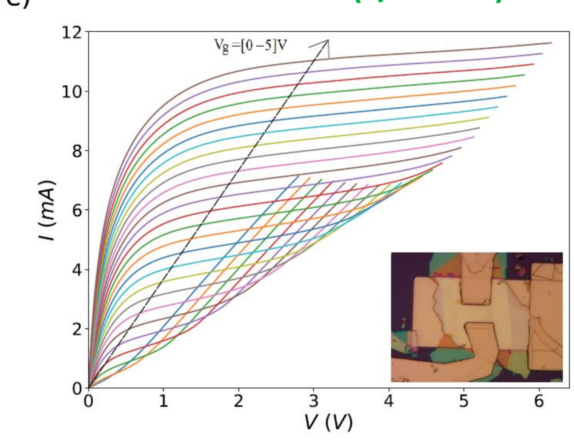
GrS3-42nm (L/W=1.5)



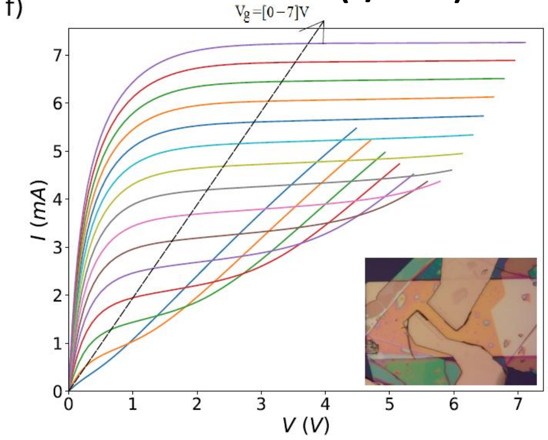
AuS1-34nm (L/W=0.75)



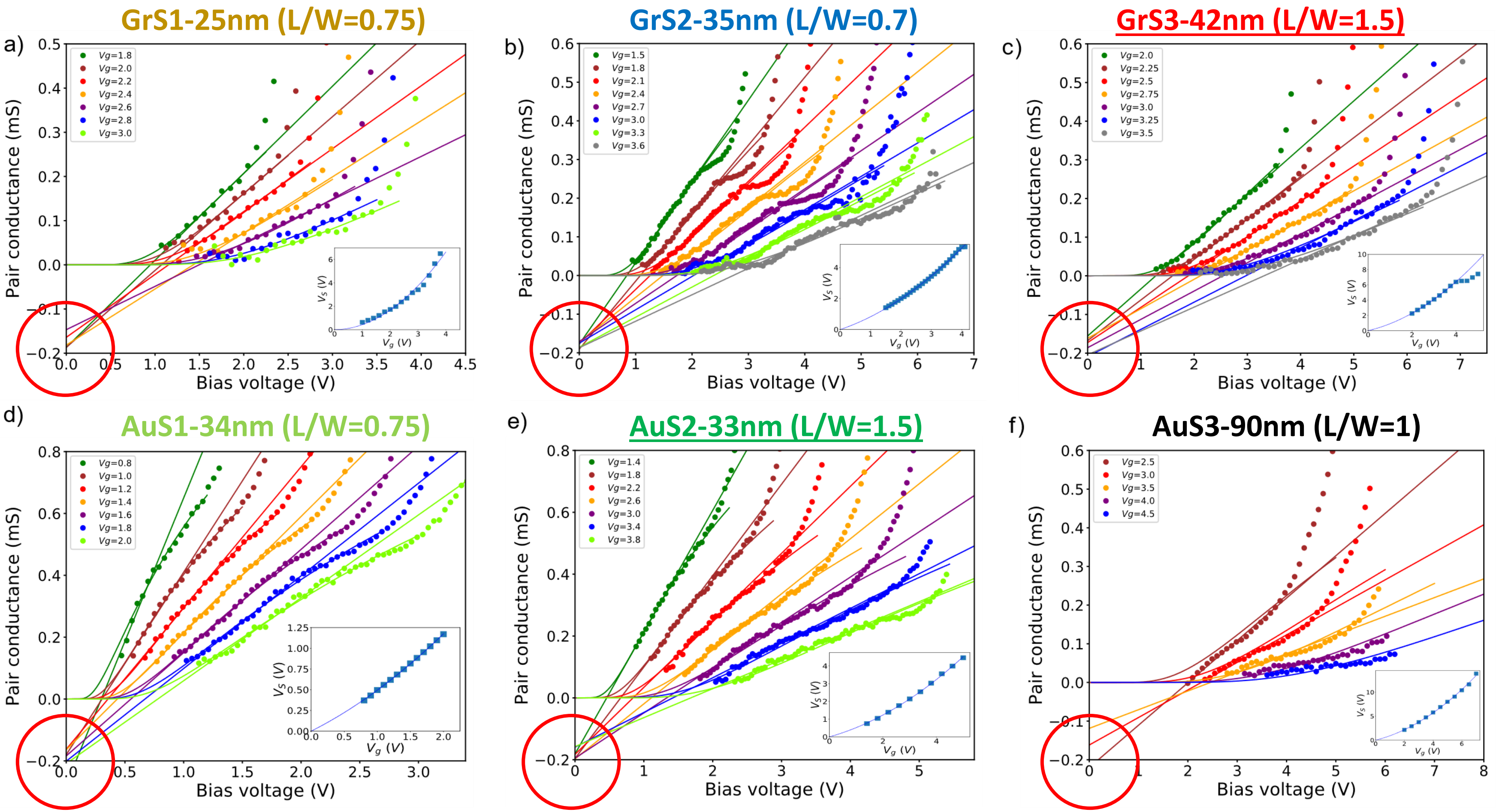
AuS2-33nm (L/W=1.5)



AuS3-90nm (L/W=1)

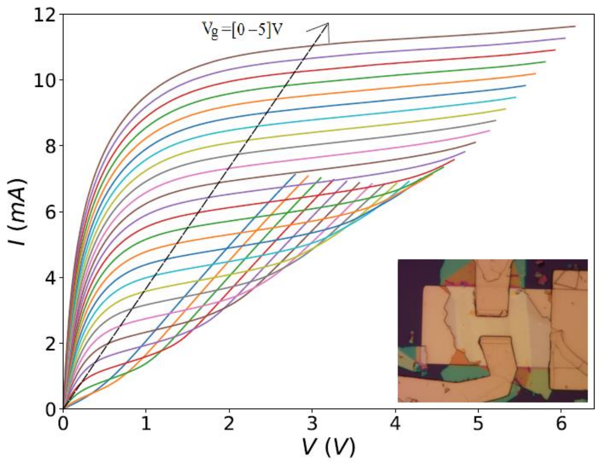


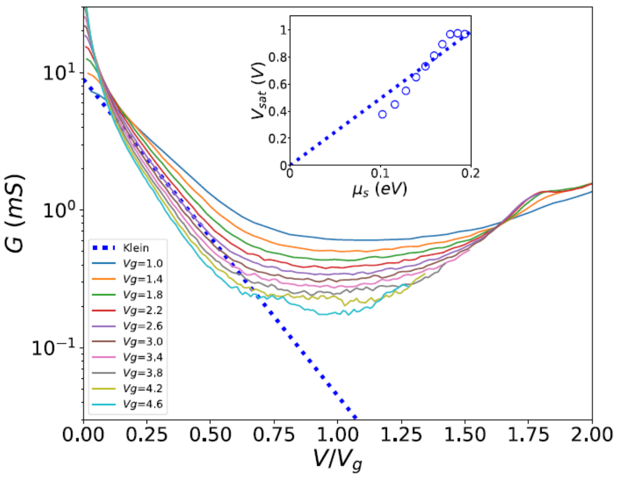
Same 1d-Schwinger scaling in various geometry !

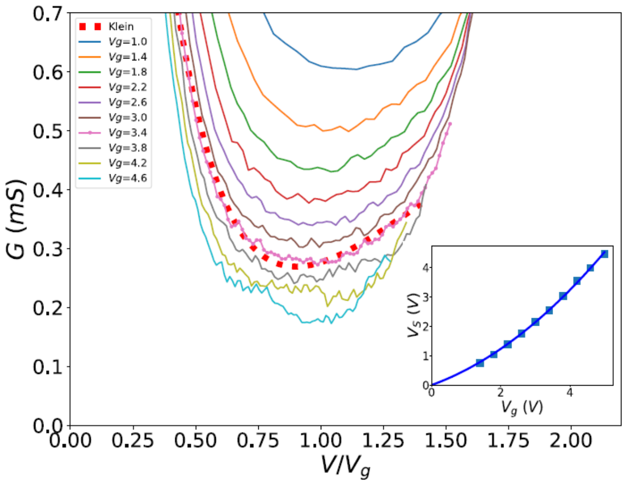


The non-perturbative Schwinger prediction verified in detail

A device with a thin hBN dielectric (32nm)

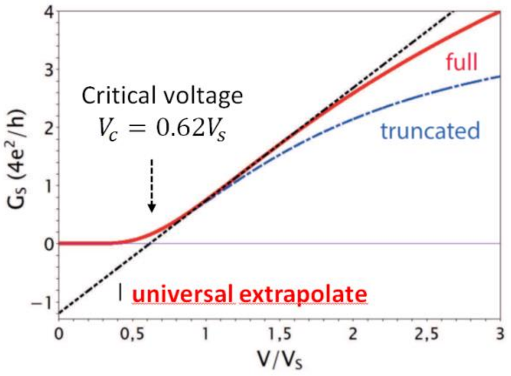






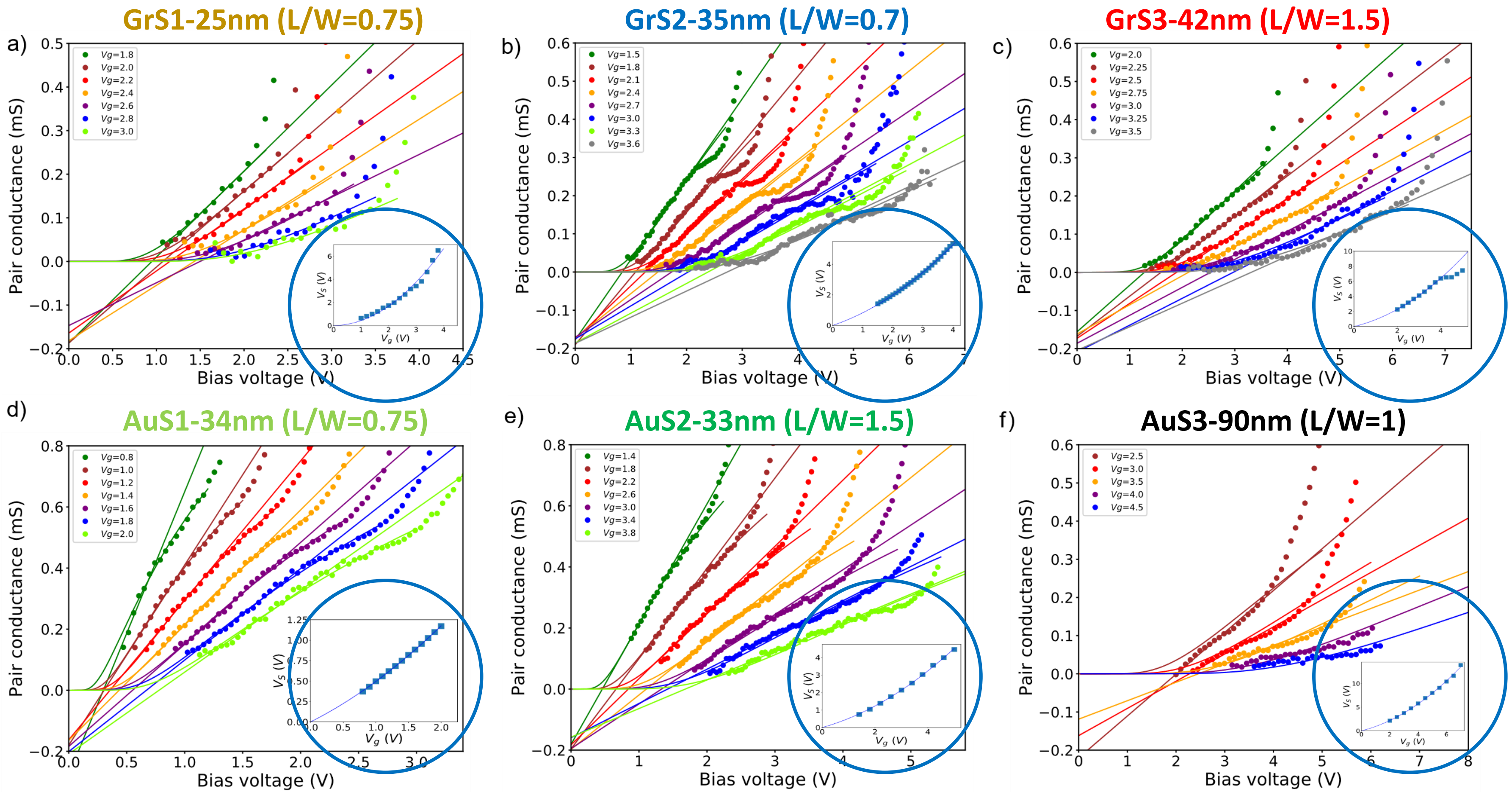
Early onset of Schwinger pair creation $V_S \leq 0.5\ V_g$

The non-perturbative Schwinger prediction verified in detail

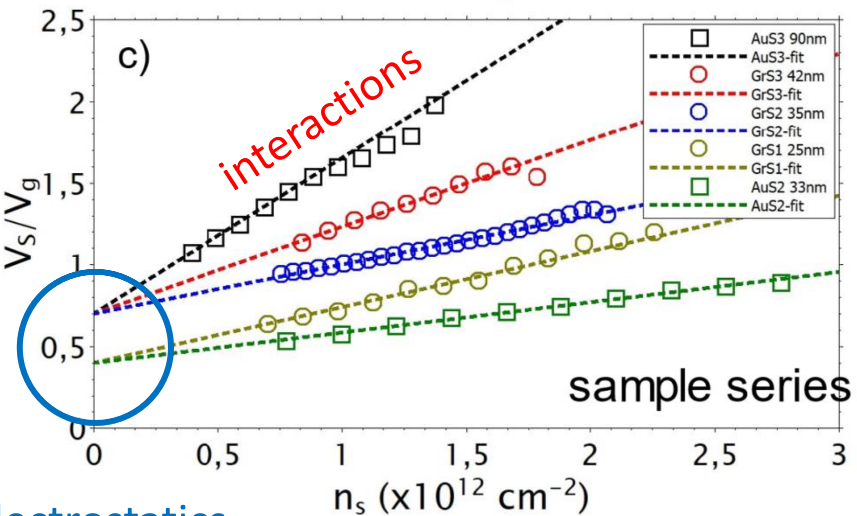


an important result for field theory

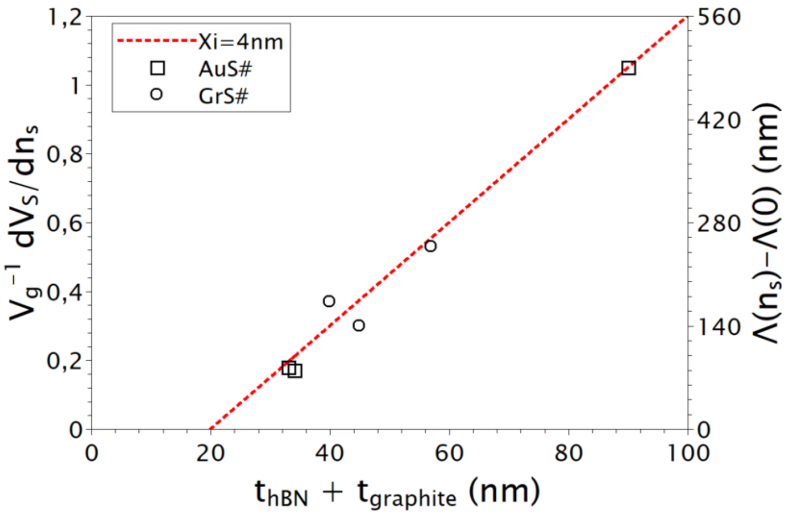
Measured $V_S(V_g)$ dependence



Length of the Klein collimation junction



electrostatics



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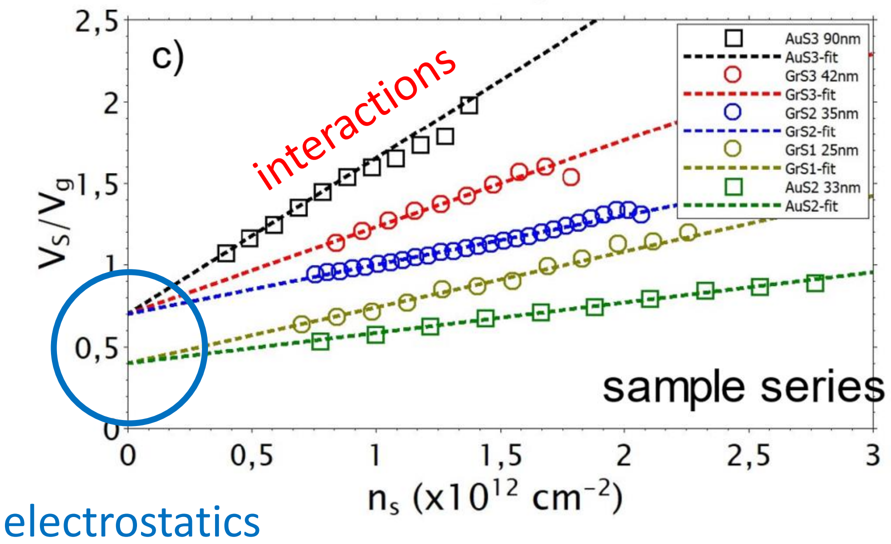
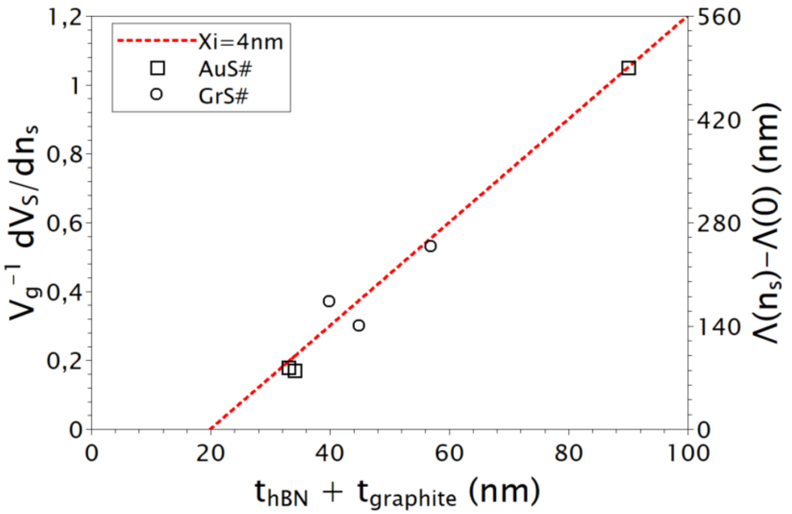
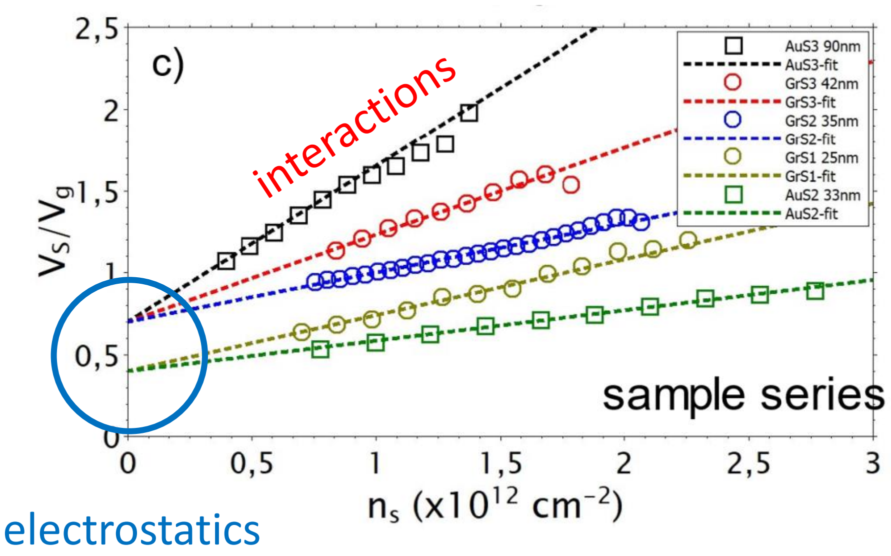


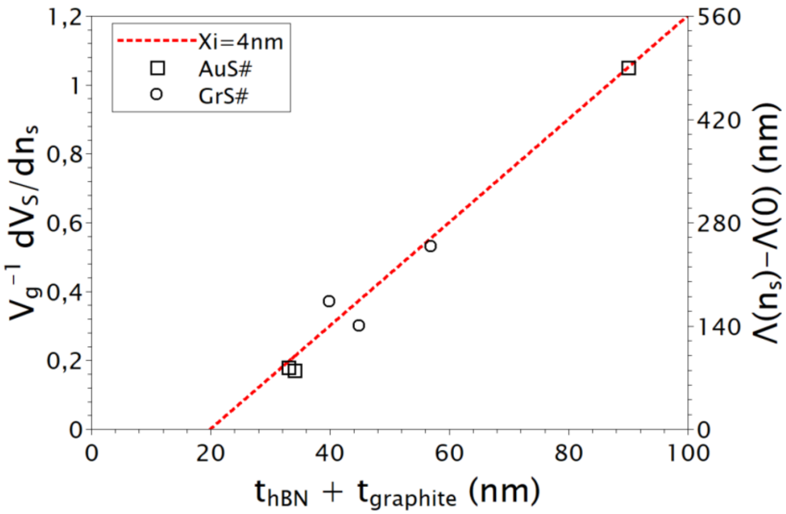


$$\Lambda \approx 2.8\frac{V_S}{V_g}t_{hBN} \approx (1-2)t_{hBN} + (4\ nm) \times n_s t_{hBN}^2 = (1-6)t_{hBN}$$

NB: $\frac{\Lambda(n_s,t_{hBN})}{t_{hBN}} = \frac{V_S/E_S}{V_g/E_{hBN}} = 4\alpha_g\frac{V_S}{V_g}\left(\frac{\mu_S}{\Delta_S}\right)^2 \approx 2.8\frac{V_S}{V_g}$ with $\alpha_g = \frac{e^2}{4\pi\epsilon_0\epsilon_{hBN}\hbar v_F} = 0.70$

Length of the Klein collimation junction





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The $\Delta_S \approx \mu_s$ ansatz gives consistent Klein-junction lengths