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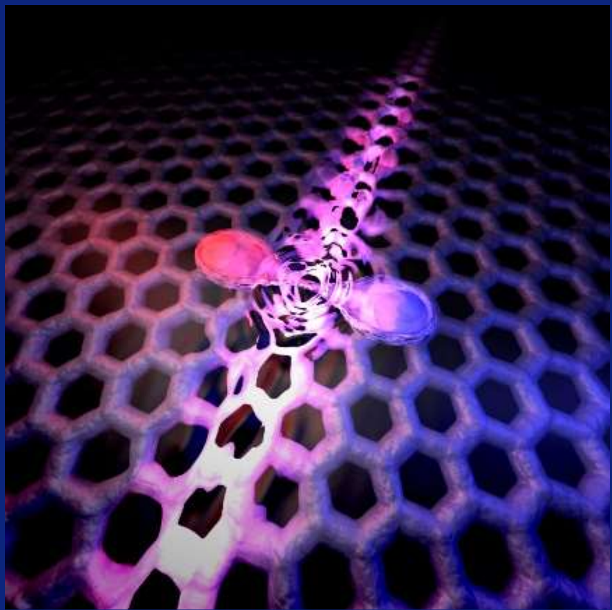
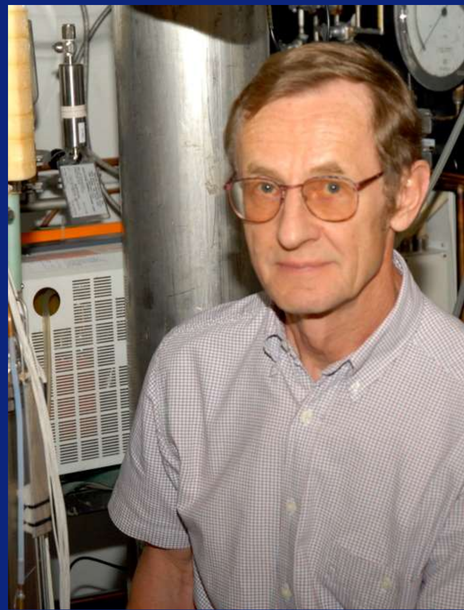
LABORATOIRE DE PHYSIQUE
DE L'ÉCOLE NORMALE SUPÉRIEURE

QED in the Laboratory: the Schwinger effect in graphene



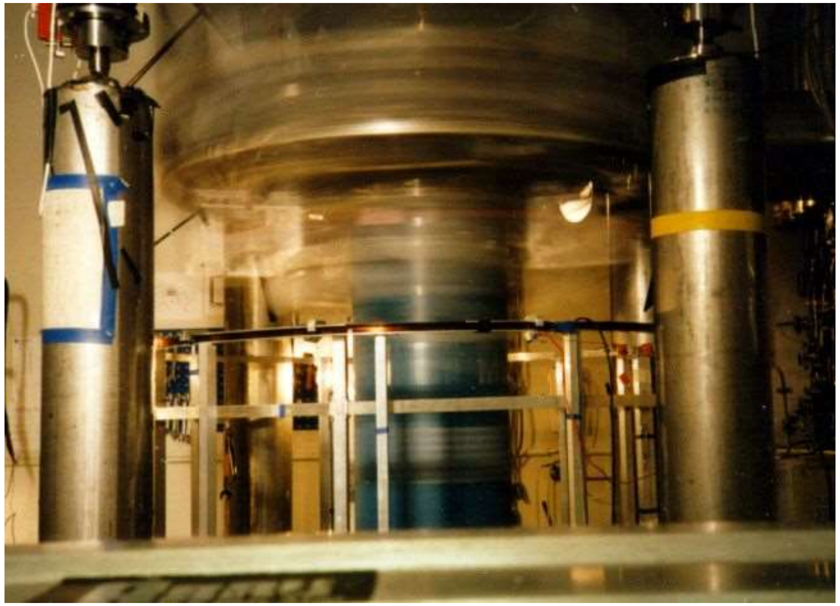


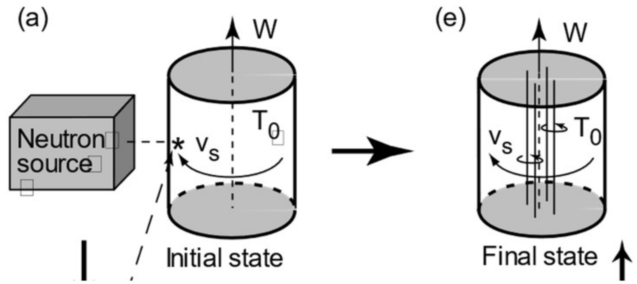
Bernard Plaçais

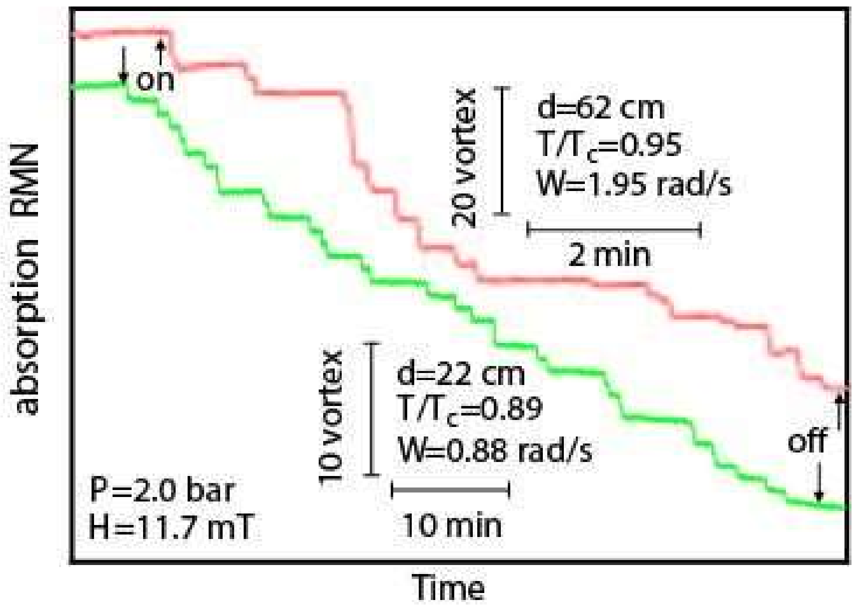
Matti Krusius TQM Symposium
(Aalto, 4-5 Nov 2022)

With Matti in 1995-1996 : Kibble-Zurek vortex creation

The old ROTA-1 at full speed

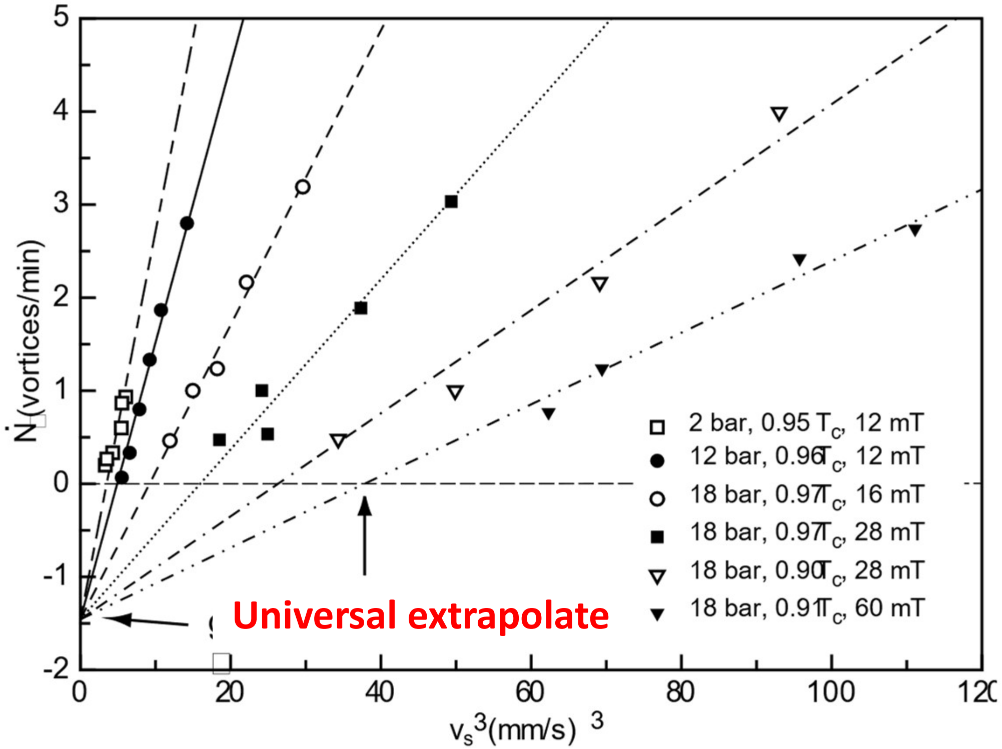






the universal vortex creation rate

Blind measurement, but broad (P-T-B) range



$$\dot{N} = \dot{N}_n \frac{\pi C}{9}\left[\left(\frac{v_s}{v_{cn}}\right)^3 - 1\right]$$

Universal $C = 0.40$

and parameter-dependent

$v_{cn}(P, T, B) \Leftrightarrow$ fireball diameter

Everything opposes He3 and graphene, but the Universe

Antagonisms

- Tough milli-Kelvin experiments — Easy room-T kilo-Kelvin experiments
- Super-heavy He3 fermions — Massless Dirac fermions

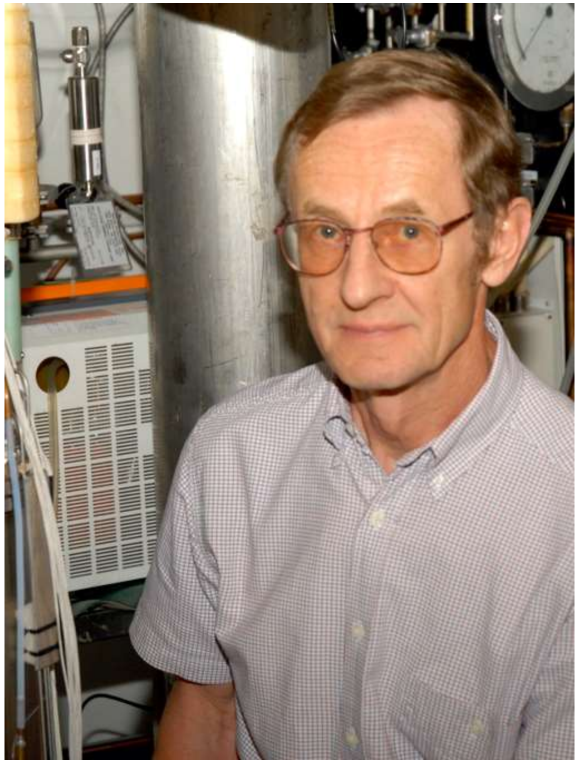
Similarities

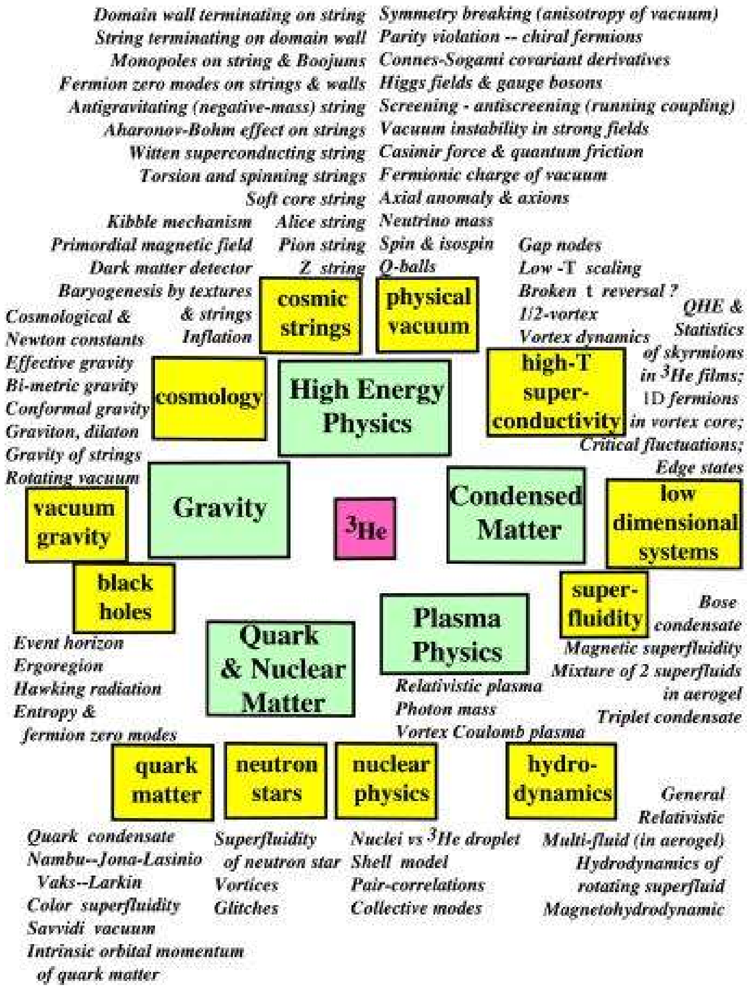
- The purest system in the universe — The cleanest conductor (room-T)
- Model system for field-theory — Model system for condensed matter

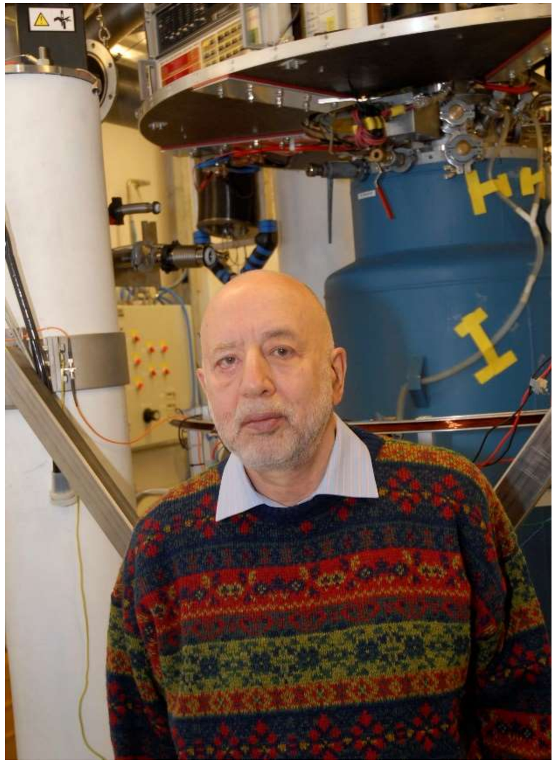
But at the end of the day, both can be used as high-energy physics analogs

- *The universe in a Helium droplet* G. Volovik — *Quantum electrodynamics in a pencil trace* K. Novoselov

He-3 Universe

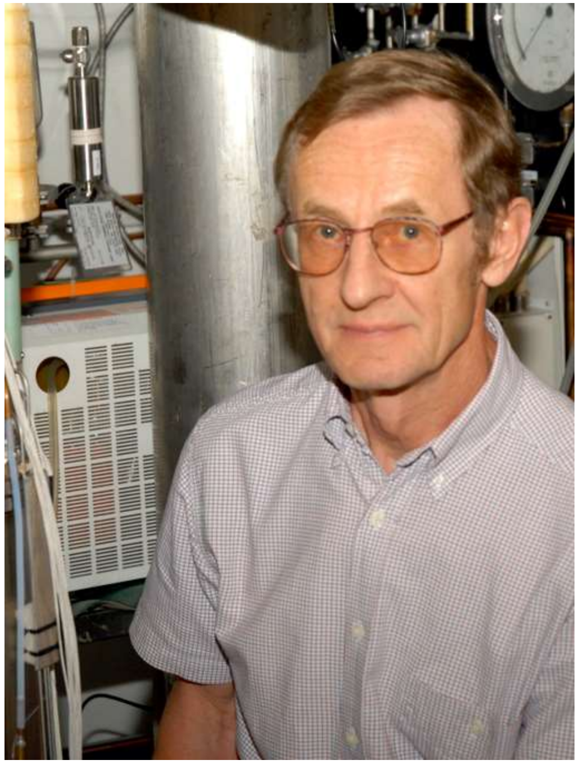


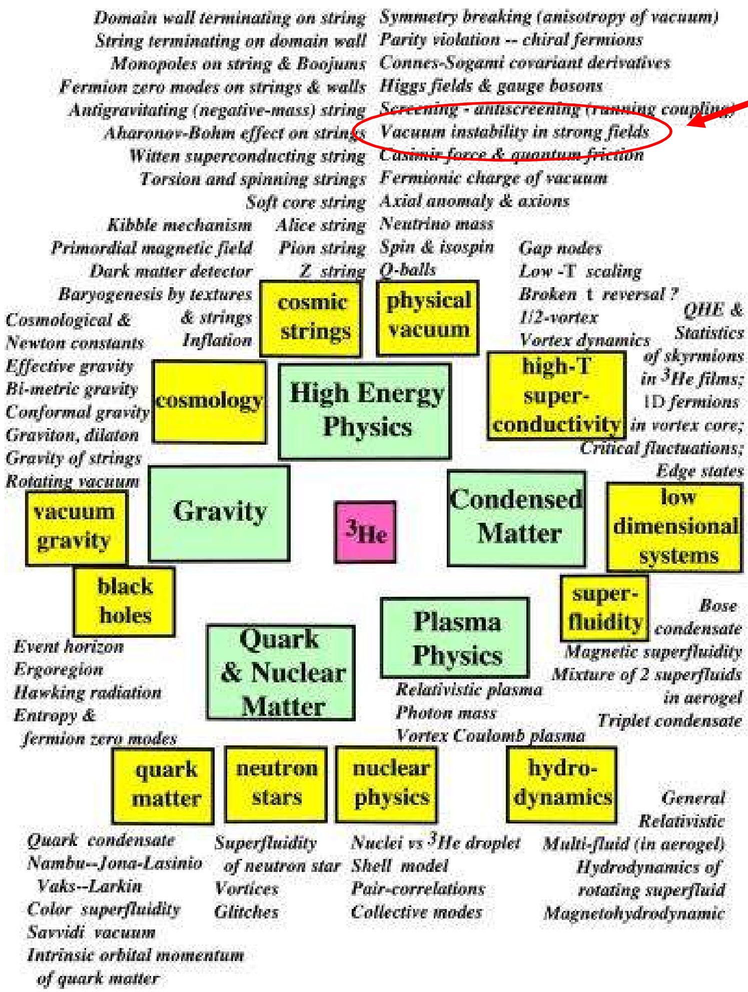




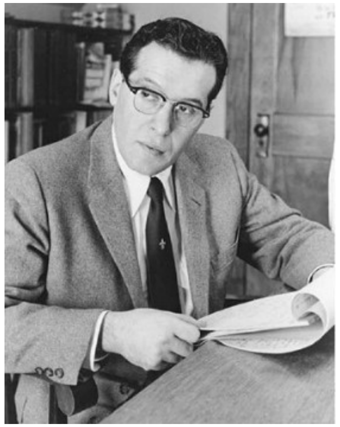
He-3 Universe

QED in graphene





Schwinger effect: breaking vacuum in a high electric-field



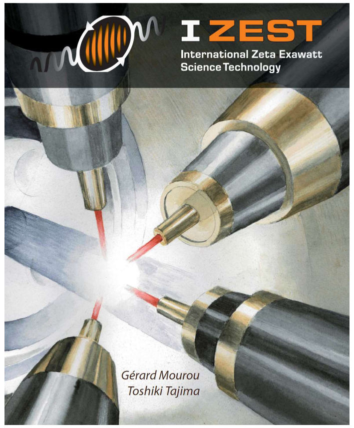
F. Sauter, Z. Phys. 1931
J. S. Schwinger, PRB 1951

- QED Schwinger field beyond reach ….

$$E_S = \frac{m^2 c^3}{e\hbar} = 1.32\ 10^{18}\,\frac{V}{m}$$

Electron-positron : $\Delta_S = mc^2 = 511\ keV$

… on the roadmap of Zeta/Exawatt Lasers



- pair creation rate from non-perturbative theory,

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

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

Schwinger effect in relativistic graphene $E = v_F \hbar k$

$c \to v_F$ and electron-hole symmetry

2d-Schwinger in gapless neutral 2d-graphene

$$w_{2d} = \frac{eE}{2\pi^2\hbar}\sqrt{\frac{eE}{v_F\hbar}}\sum_{n\geq 1}\frac{e^{-n\pi\frac{E_S}{E}}}{n^{3/2}} \propto E^{3/2} \qquad E_S = 0$$

Theory : Dora-Moessner, PRB (2010)
Katsnelson-Volovik, ZhETF (2012)
TBLG : Berdyugin et al., Science (2022)

But …..

2d-Schwinger competes with single-electron Zener tunneling with same $E^{3/2}$ law

Exp.: Vandecasteele et al., PRB (2010)

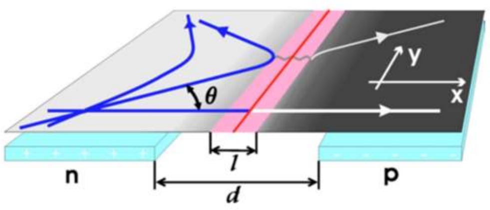
field-induced p-n junction at finite bias due to drain doping

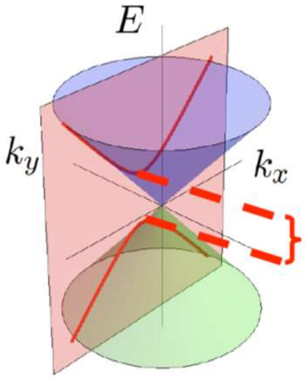
is undoped graphene suitable for Schwinger effect at all ?

Electric-field E_x induces 1d-transport by Klein collimation

Klein-collimation junction

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





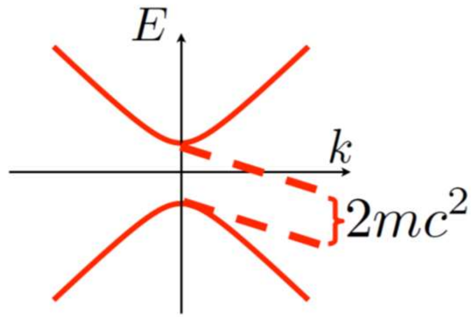
$$2 v_F \hbar k_y$$

Klein-tunneling $\quad \mathrm{T}(k_y) = e^{-\pi \hbar v_F k_y^2 / e E_x}$

V. V. Cheianov, V. I. Falko, PRB-2006
J. Cayssol, B. Huard, D. Goldhaber-Gordon, PRB-2009
E.B. Sonin, PRB-2009

emergent massive Dirac fermions

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



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

F. Sauter, Z-Phys 1931
Uber das Verhalten eines Elektrons im homogenen elektrischen Feld nach der relativistischen Theorie Diracs

Schwinger pair-creation of massive Dirac 1d-fermions

a universal 1d-Schwinger pair-creation rate

$$w_{1d} = \left(\frac{2e}{h}\right) E \sum_{n \geq 1} \frac{e^{-n\pi \frac{E_S}{E}}}{n} \qquad E_S = \frac{\Delta_S^2}{e\hbar v_F} \sim 6\ 10^7\ \frac{V}{m} \quad \text{for} \qquad \Delta_S \sim \varepsilon_F \leq 0{,}2eV$$

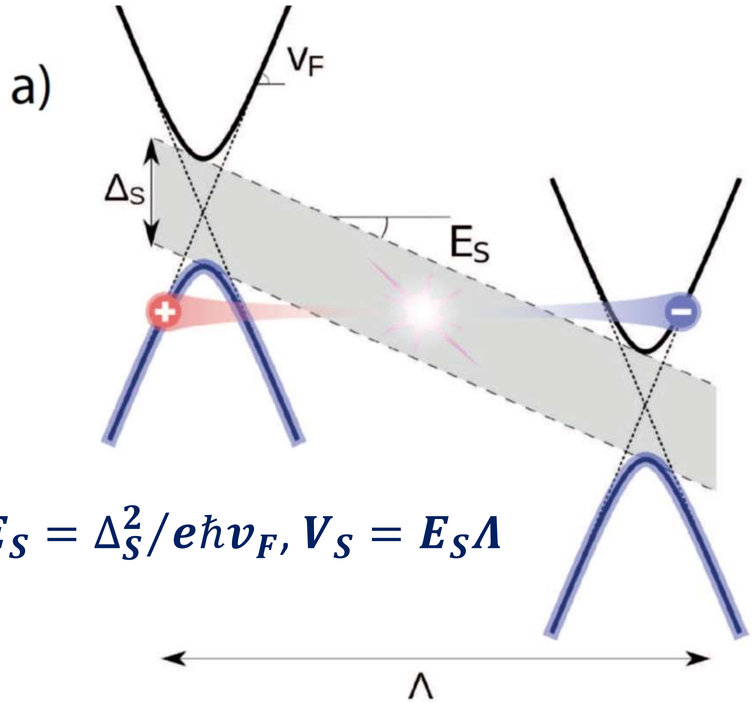
Pair current over the Schwinger length Λ

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

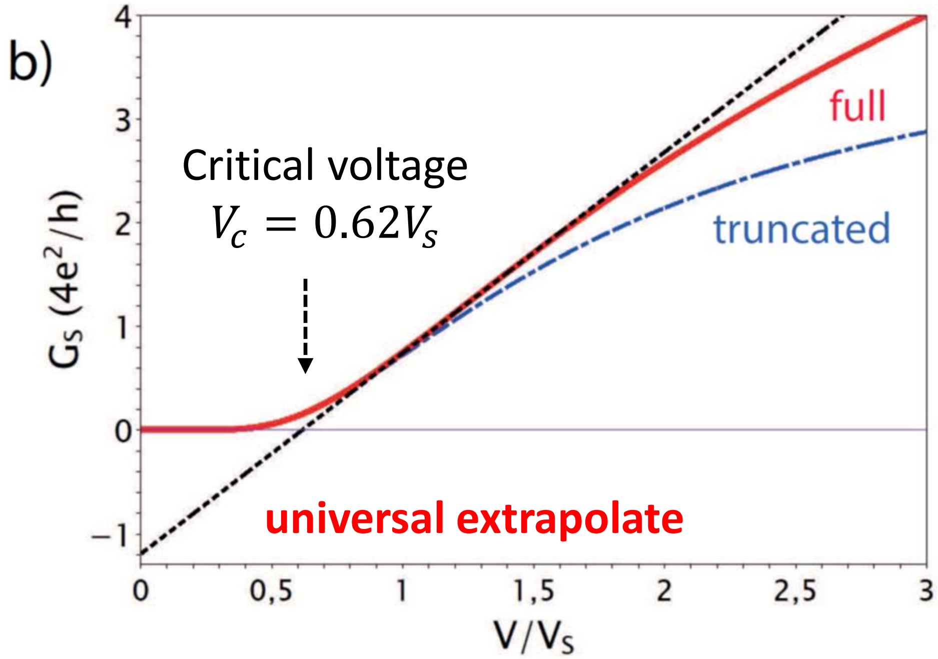
1d-Schwinger conductance in graphene ($g_s = g_v = 2$) …/…

Universal quantized 1d-Schwinger conductance

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

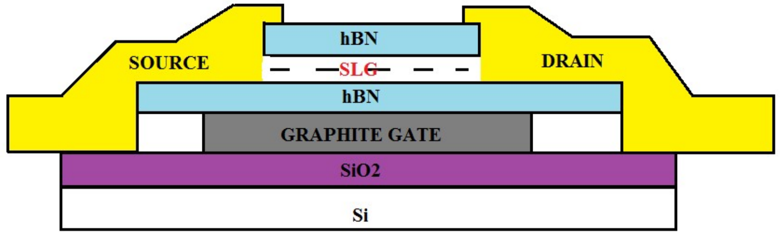


$$E_S = \Delta_S^2/e\hbar v_F, V_S = E_S \Lambda$$



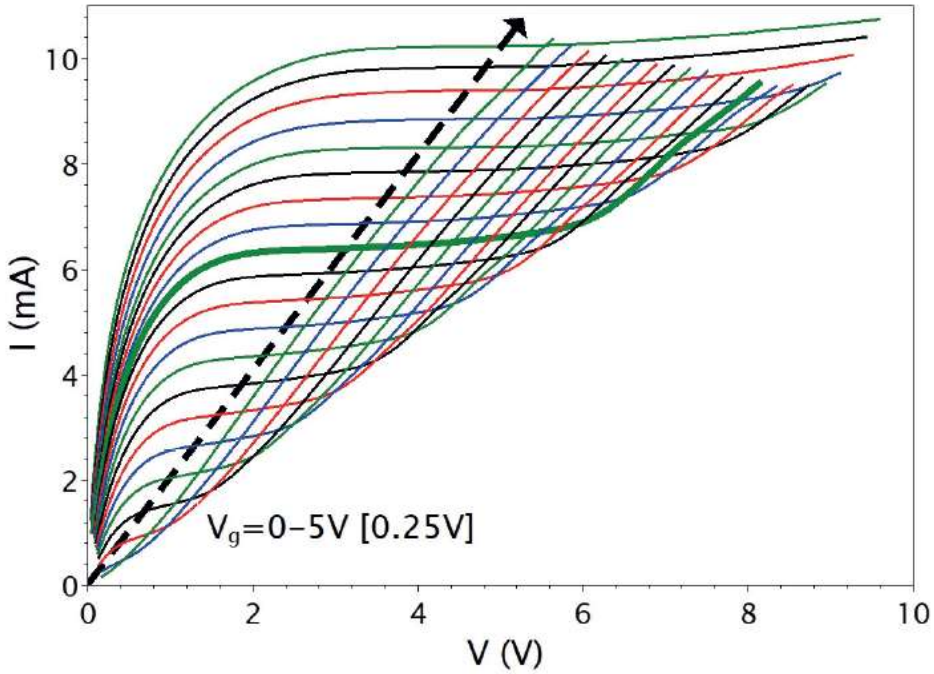
Differs from Klein-tunneling by a factor 2, and a characteristic bias dependence !

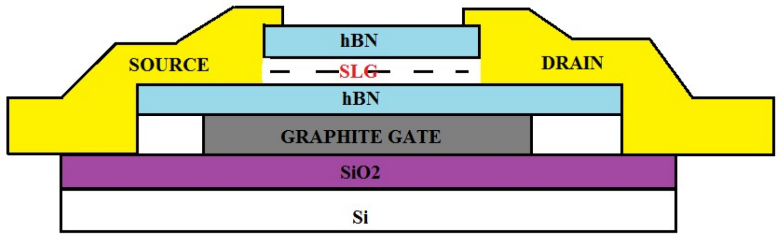
hBN-encapsulated graphene FET



- Long devices $L \sim W \geq 10\ \mu m$
- High-mobility $100\,000\ cm^2/Vs$
- Room temperature

hBN-encapsulated graphene FET

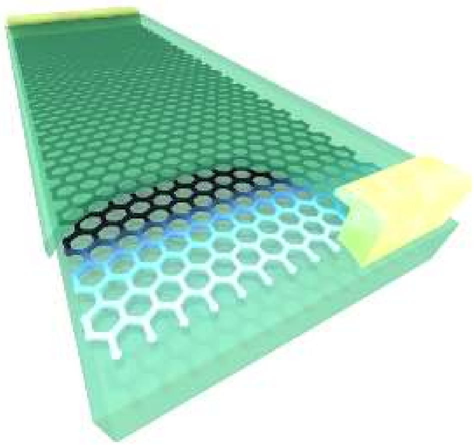


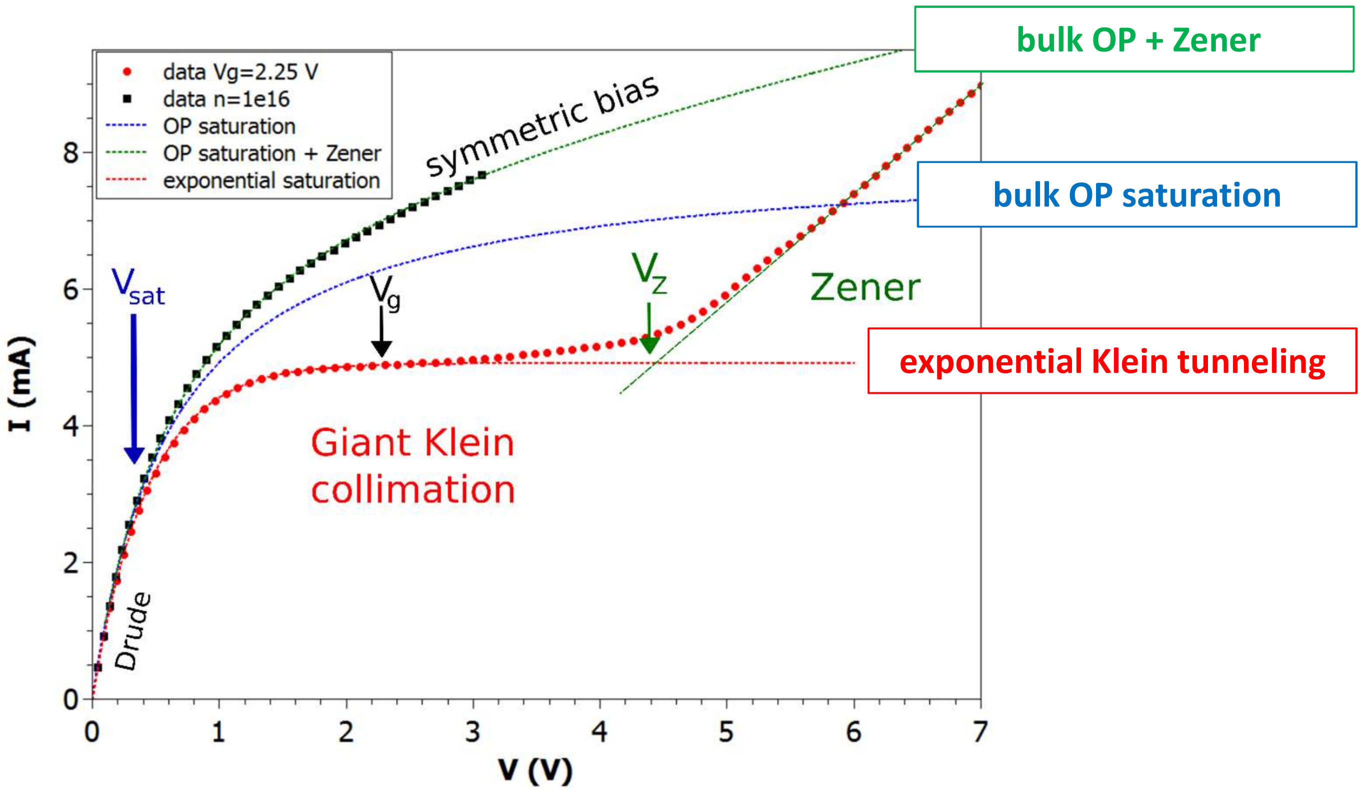


- Long devices $L \sim W \geq 10\ \mu m$
- High-mobility $100\,000\ cm^2/Vs$
- Room temperature

Current saturation is reminiscent of MOSFET pinchoff, albeit semimetallic

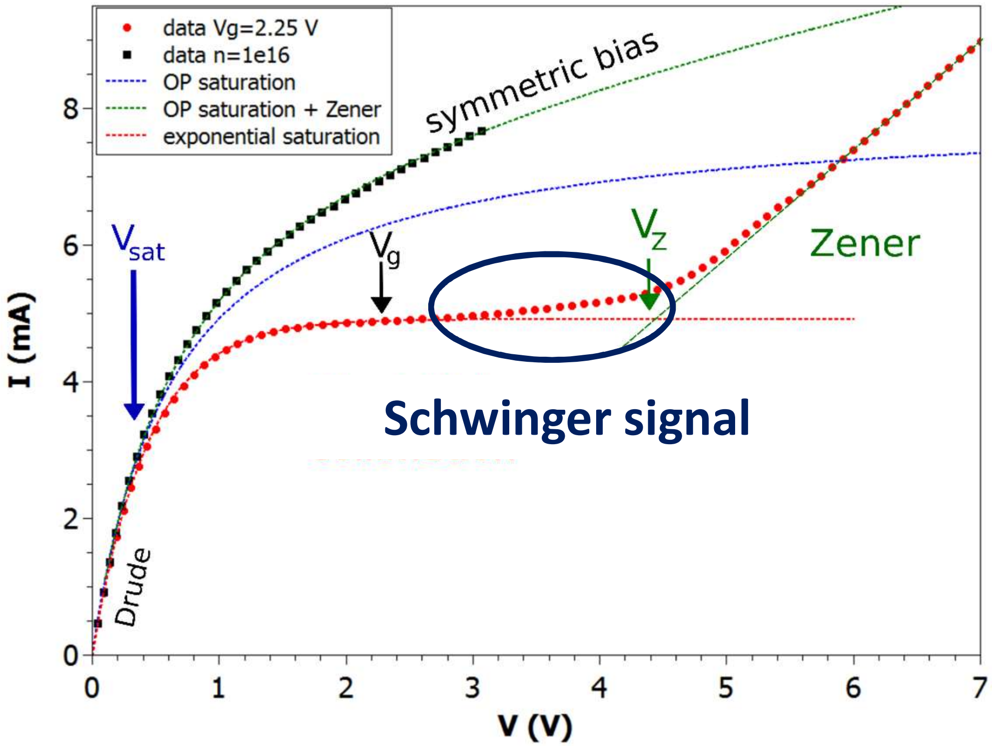
Current saturation by the Klein collimation junction





Up to a collective Zener instability

A small Schwinger current on top …



Lets first look at noise signatures of Klein collimation and Zener instability

Klein tunneling junction : its shot-noise signature

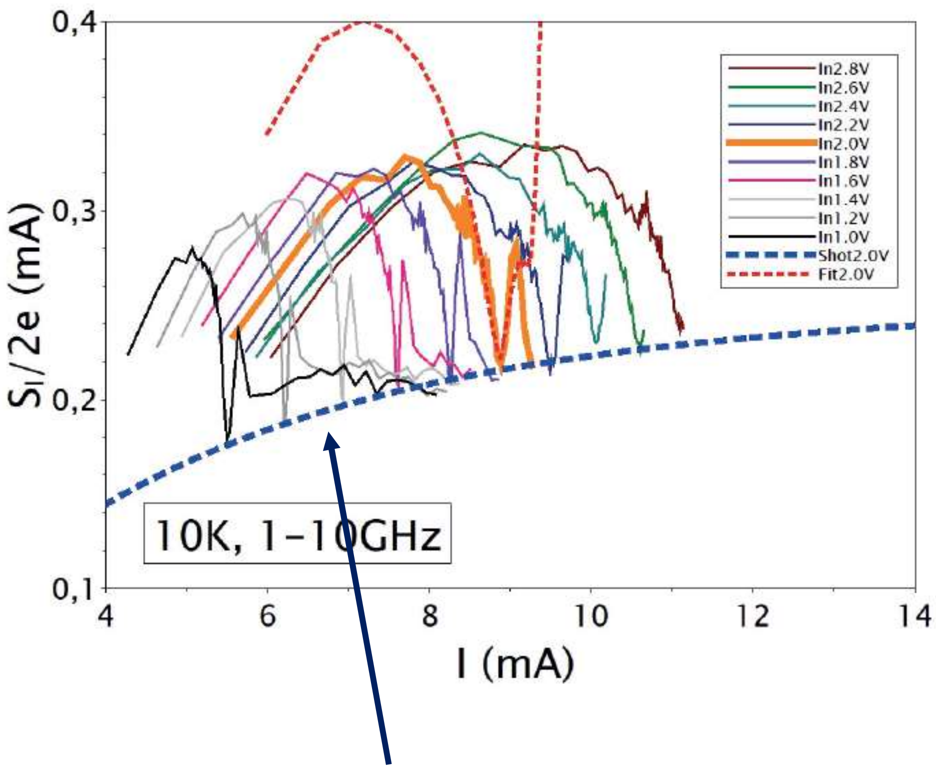
White GHz noise

$S_I = 4Gk_BT_e + 2eIF$

Sweet noise dip

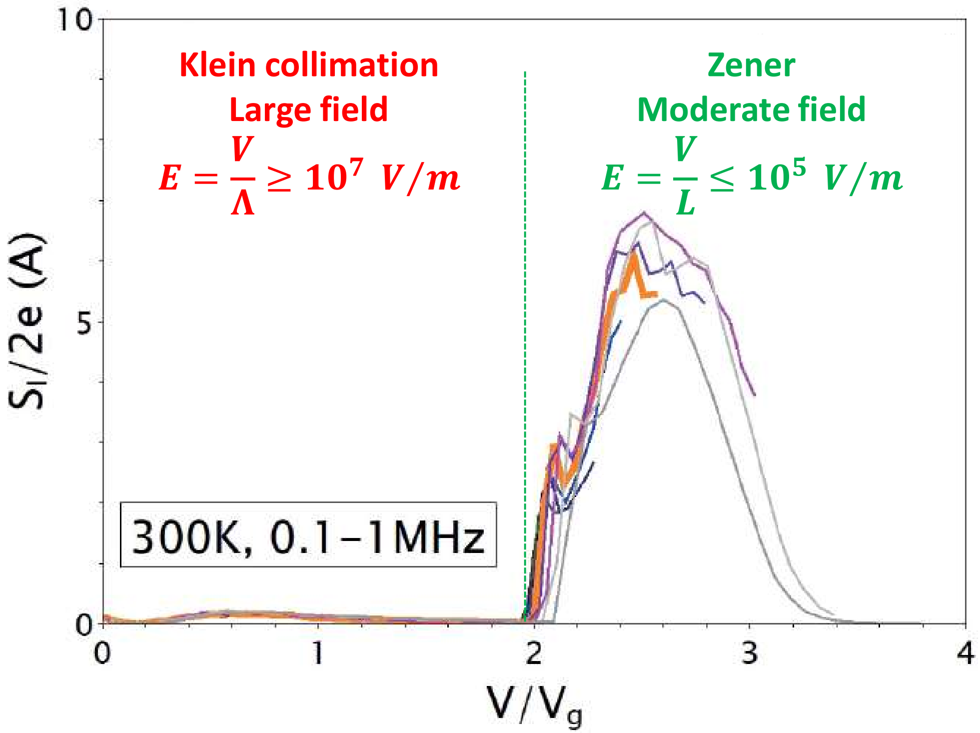
$G \to 0, S_{th.} \to 0$

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



Mesoscopic junction with a Fano factor $F \leq 0.04$

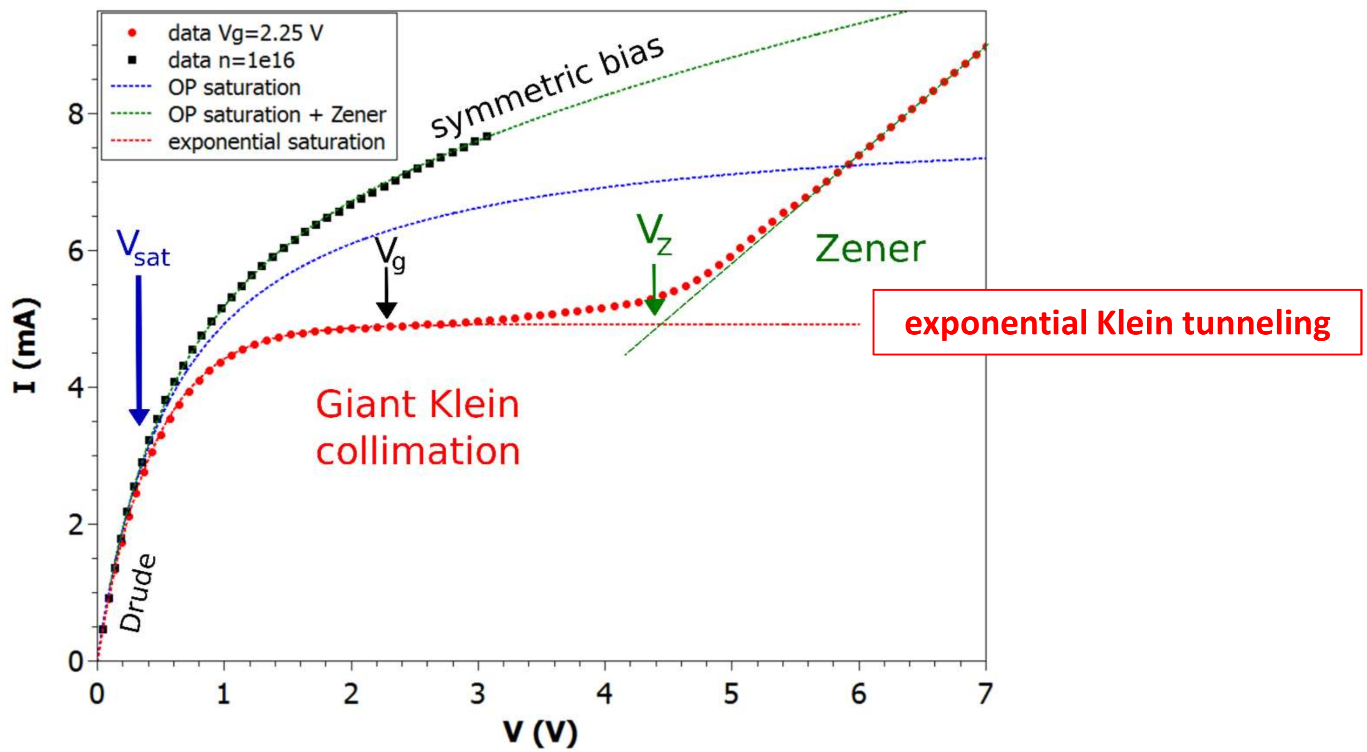
Zener instability : its flicker-noise signature



- Long devices $L \sim W \geq 10\ \mu m$

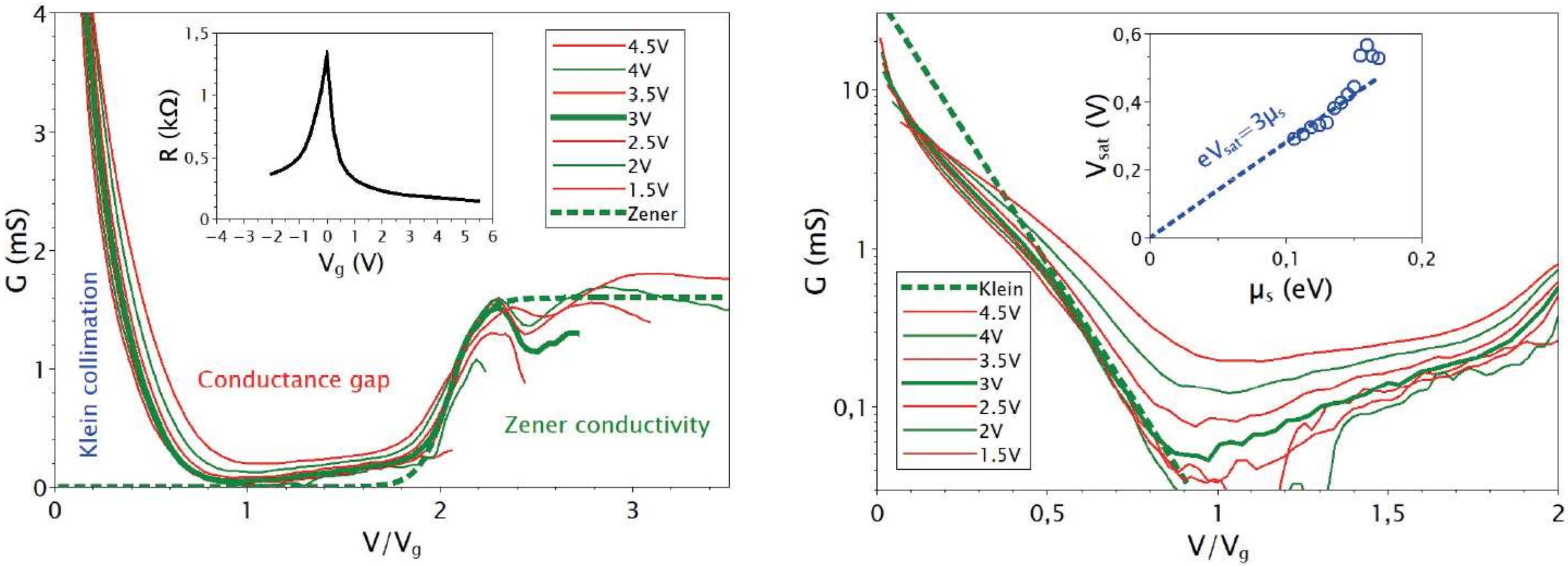
Huge noise signals the destruction of the Klein-collimation electric-peak effect

Exponential current saturation by giant Klein collimation



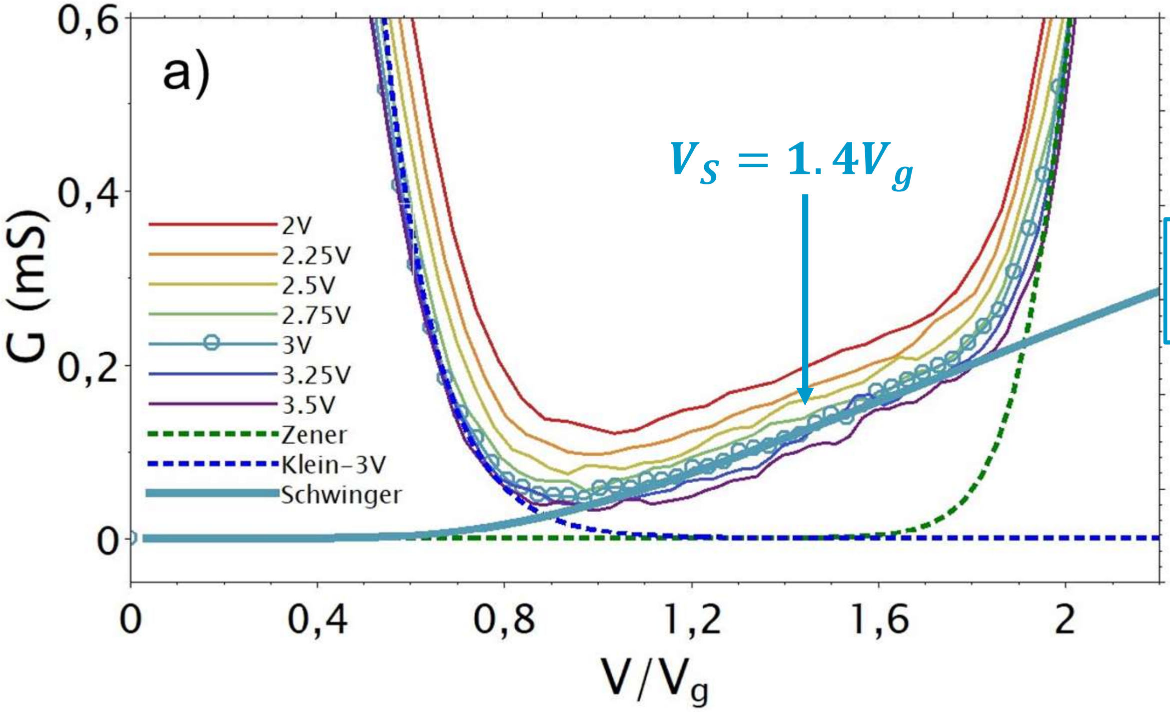
Differential conductance is more sensitive …/…

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



Zooming in the Klein-collimation conductance gap $\Delta_K \approx 3\mu_s$

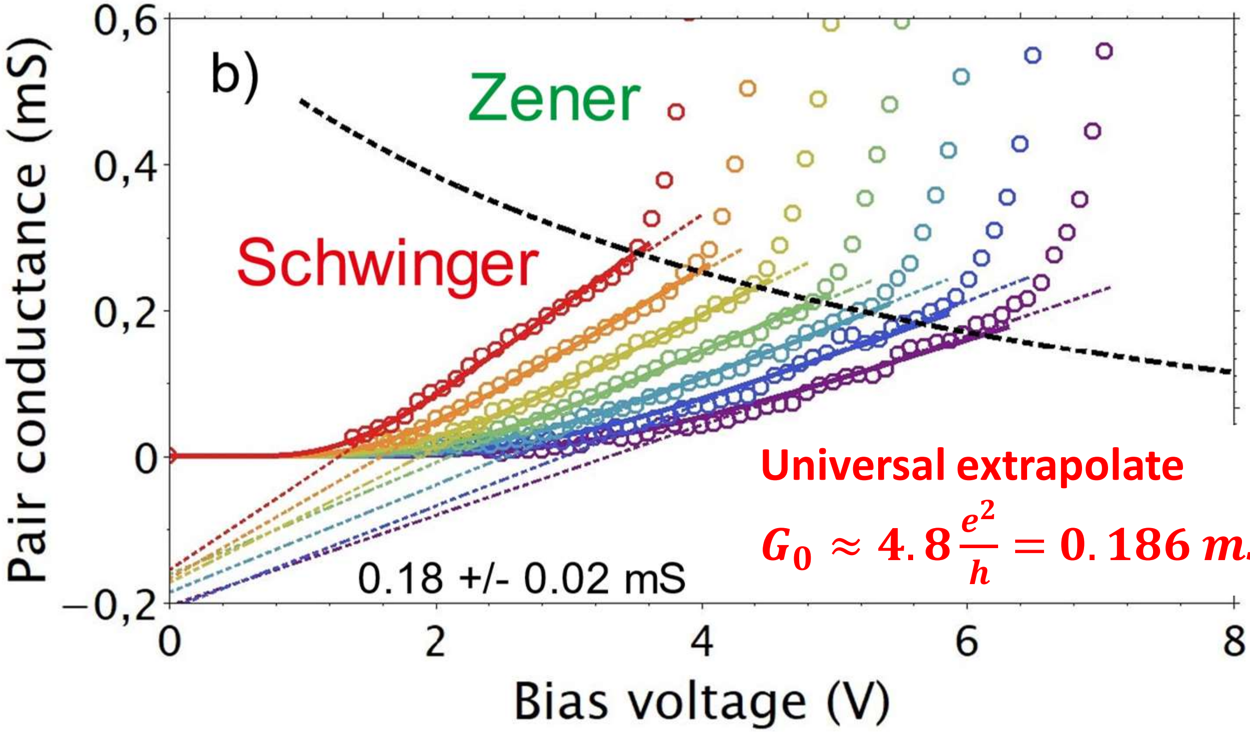
Schwinger conductance revealed at large doping



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

In general (smaller doping) one has $G = G_K(V) + G_S(V)$

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

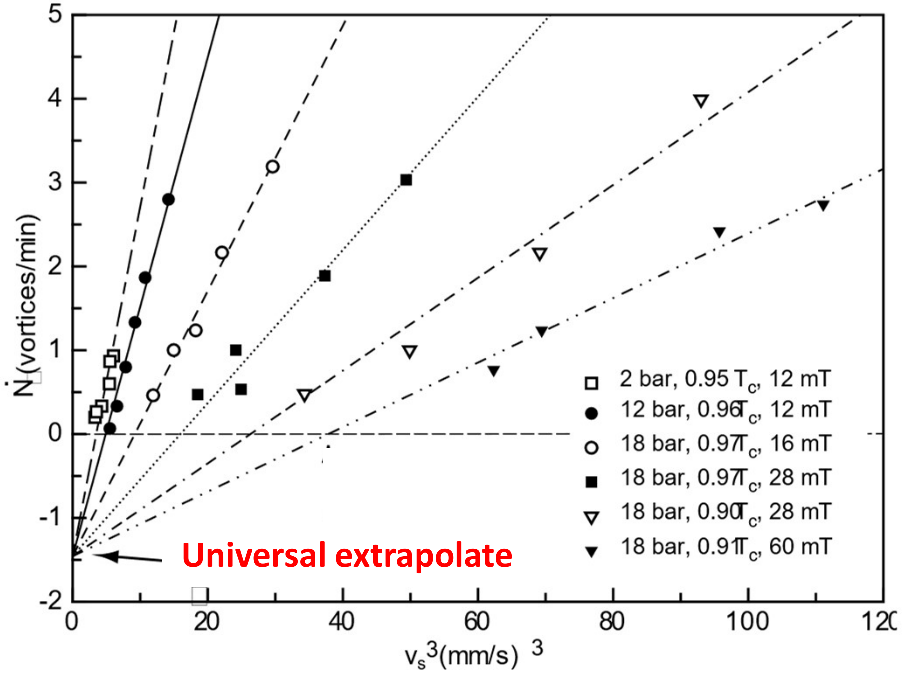


Universal extrapolate

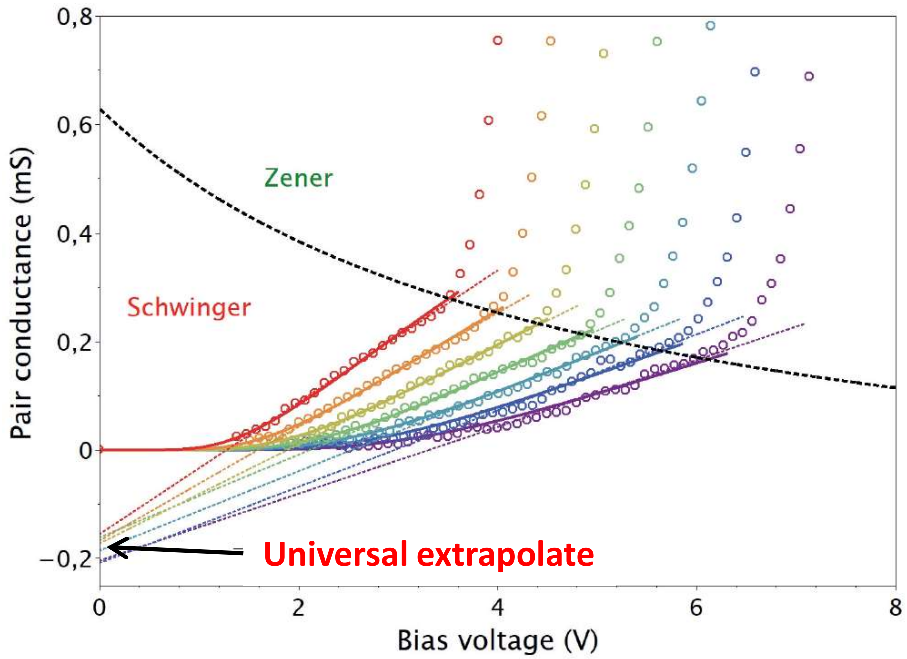
$G_0 \approx 4.8\frac{e^2}{h} = 0.186\ mS$!

… reminiscent of Kibble-Zurek universal scaling

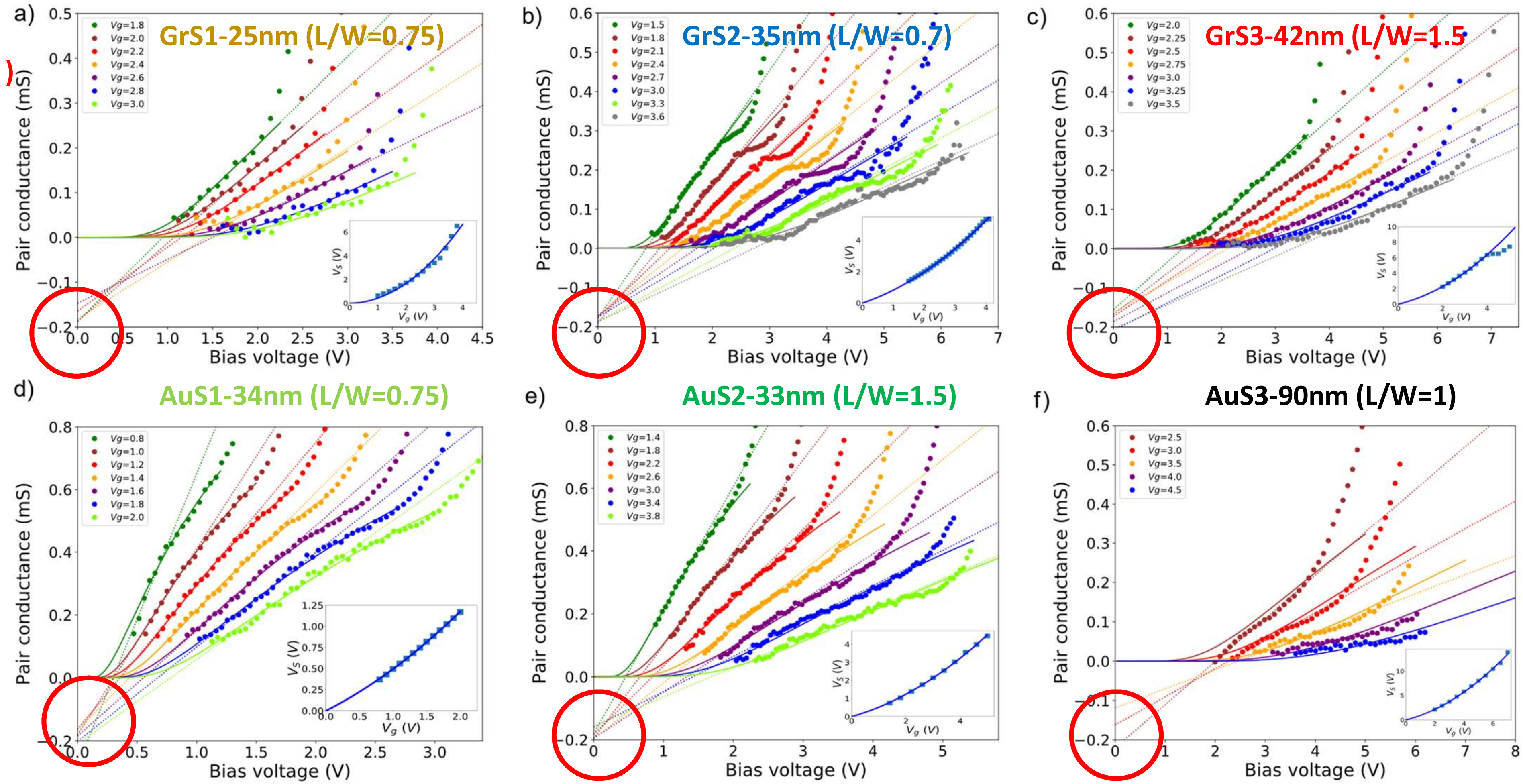
Vortex loops in He-3



Schwinger-pairs in graphene

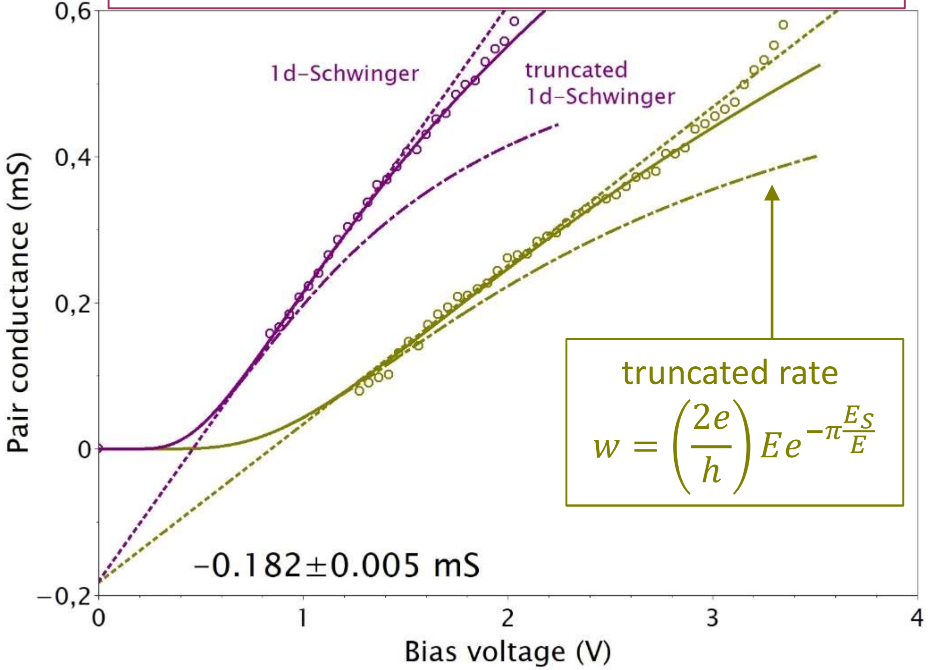


Ubiquitus 1d-Schwinger scaling



Its non-perturbative prediction verified in detail

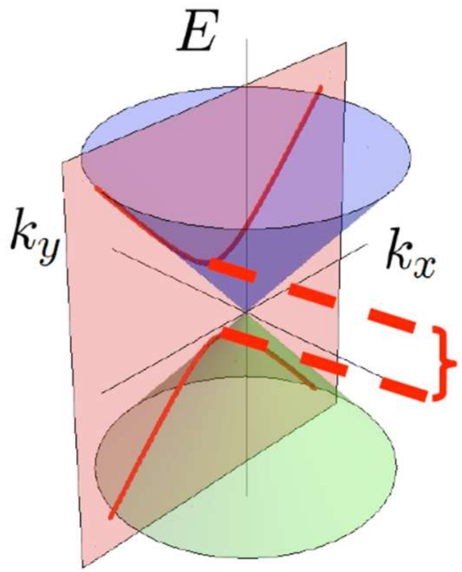
Full 1d-Schwinger $w = \frac{2eE}{h} Ln\left(\frac{1}{1-e^{-\pi E_S/E}}\right)$



Next question : parameter-dependent Schwinger voltage $V_S(t_{hBN}, n)$ **?**

Klein-collimation origin of the Schwinger gap ?

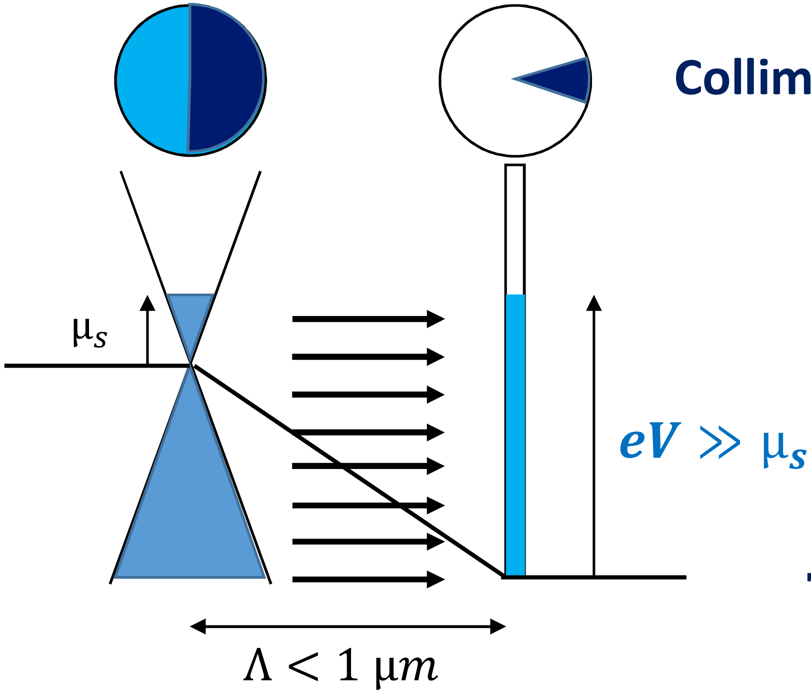
$$E = \mp\sqrt{\left(v_F \hbar k_y\right)^2 + (v_F \hbar k_x)^2}$$



$$\Delta_S = 2 v_F \hbar k_y = 2\mu_s \sin\theta$$

Why finite-k_y Schwinger pairs ?

Pauli-blocking by low-k_y current carrying states !



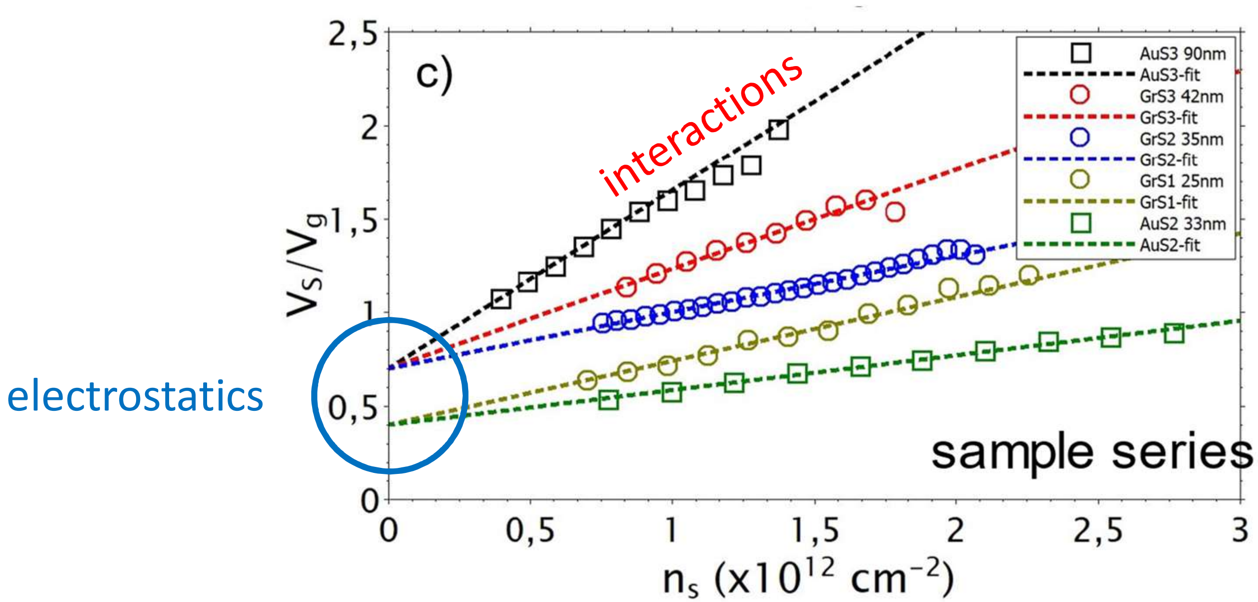
Collimated saturation current

$$\mathbf{T}(V,\theta) = e^{-\pi \frac{eV\Lambda}{\hbar v_F} \sin^2\theta}$$

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

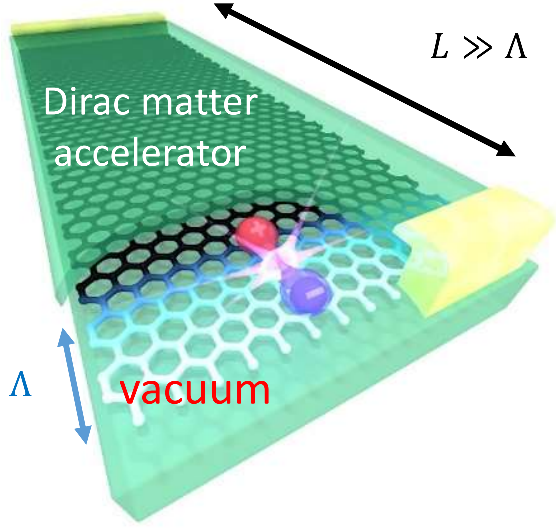
$\Delta_S \approx \mu_s$ consistent with a Klein-junction length

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



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 $\alpha_g = \frac{e^2}{4\pi\epsilon_0\epsilon_{hBN}\hbar v_F} = 0.70$

« QED in a graphene mosfet »



- ✓ First experimental observation of 1d-Schwinger effect
- ✓ Schwinger is the breakdown of Klein collimation
- ✓ Outlook: Full counting statistics ? Vacuum polarization ?
- ✓ Toward a fully Relativistic Field-Effect-Transistor (R-FET)

Schmitt et al., arXiv:2207.13400v1

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

Acknowledgement to Matti and Aalto

- ✓ Lessons of my visit in Matti's group (25-AD: After Discovery of superfluidity)
  Science of course, but also meeting a wealth of brillant scientists
  Matti's smartness, kindness, and art of human management

- ✓ Beautifull and Welcoming Finland, … « Finns make good cakes » (Olli Lounasma)

- ✓ Thanks Edouard Sonin for connecting me to Matti in Cargèse-1993 (Nokia inside !)

- ✓ An orthogonality catastrophy for my carrier, my personnal life with new friends

Penguin one year, penguin ever

Direct observation of 1d-Schwinger in doped graphene