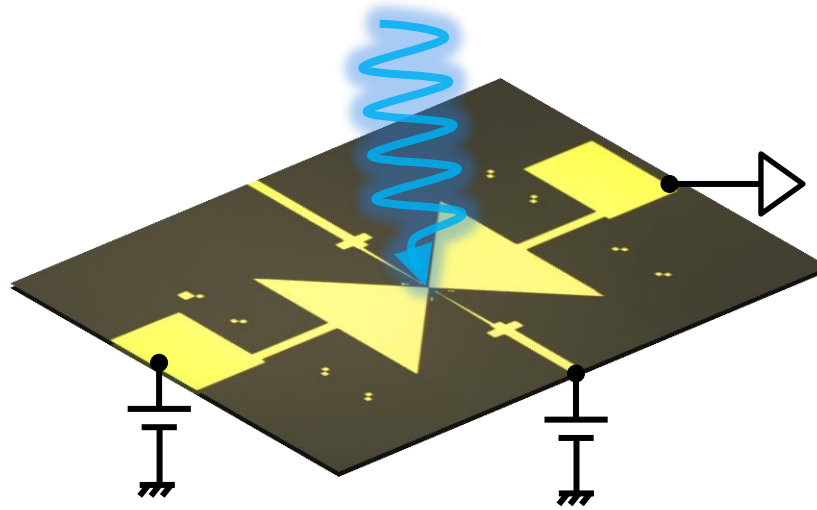


Photon-assisted shot noise in graphene in the Terahertz range

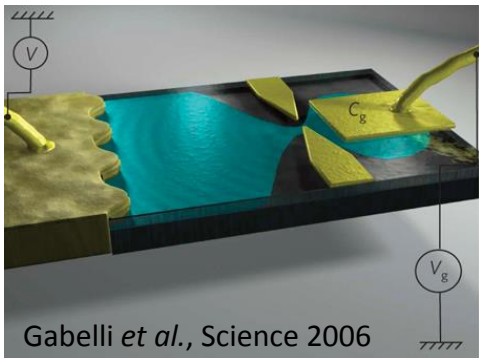


François D. Parmentier, Laura Serkovic-Loli, Preden Roulleau, D. Christian Glattli

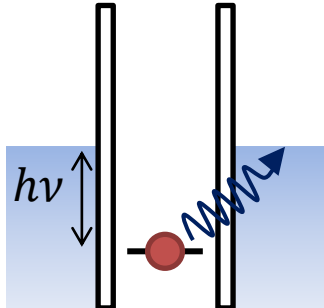
Nanoelectronics group, SPEC, CEA, CNRS, Université Paris-Saclay, CEA Saclay



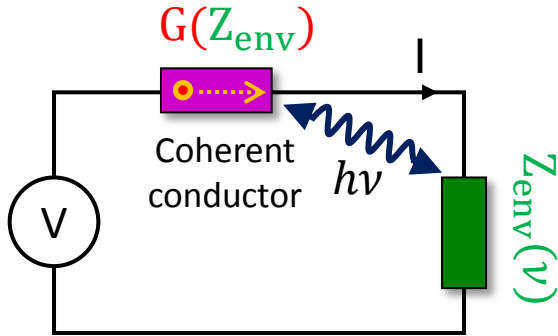
Light-matter coupling in mesoscopic transport



time dependent transport & quantum capacitances

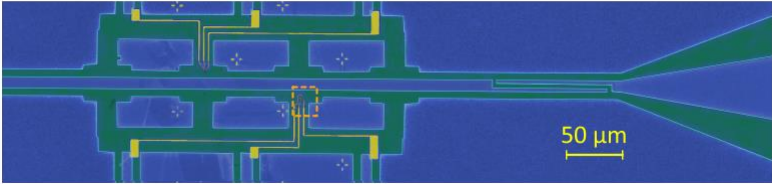
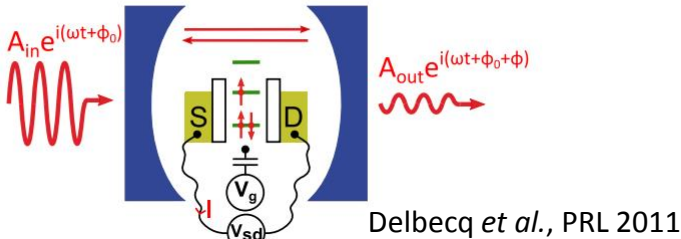


photon-assisted tunneling (PAT)

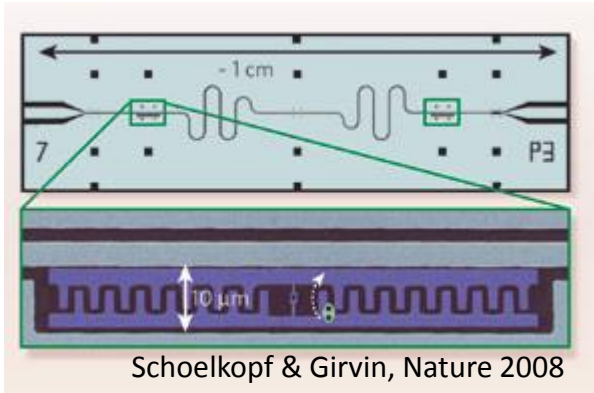


dynamical Coulomb blockade

cf C. Rolland, C. Mora & P. Joyez' talks

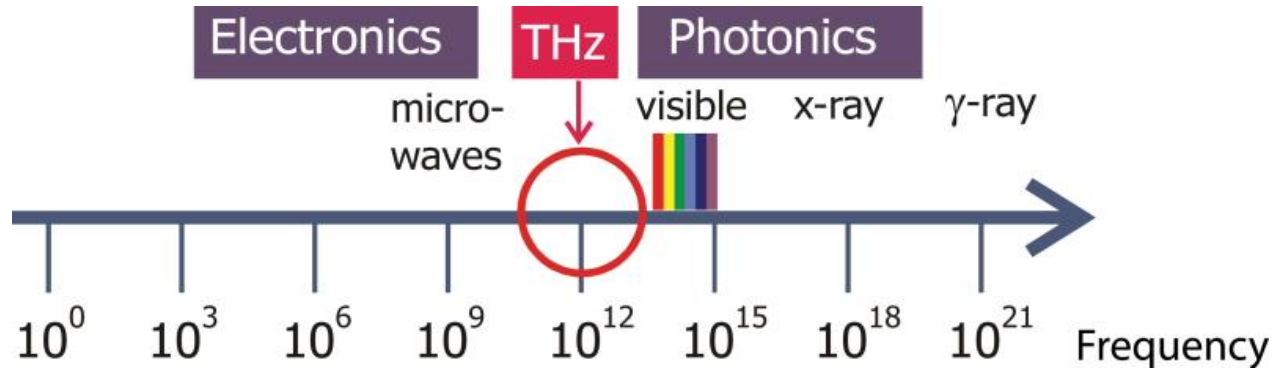


open quantum system dispersive readout



circuit quantum electrodynamics

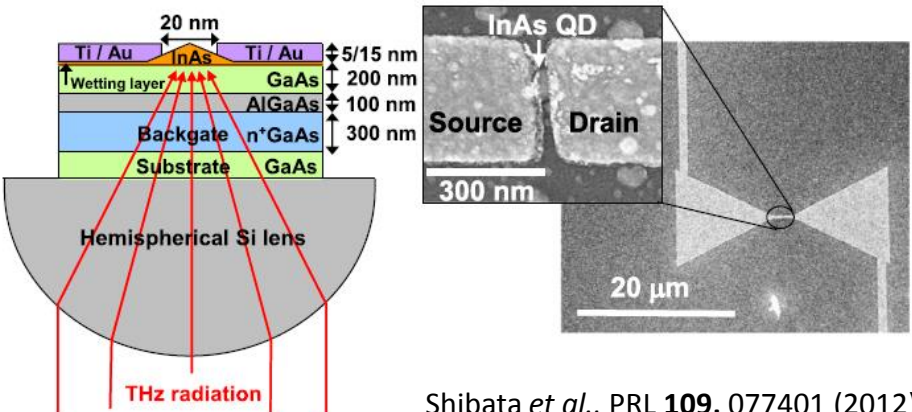
Quantum transport: from microwaves to THz?



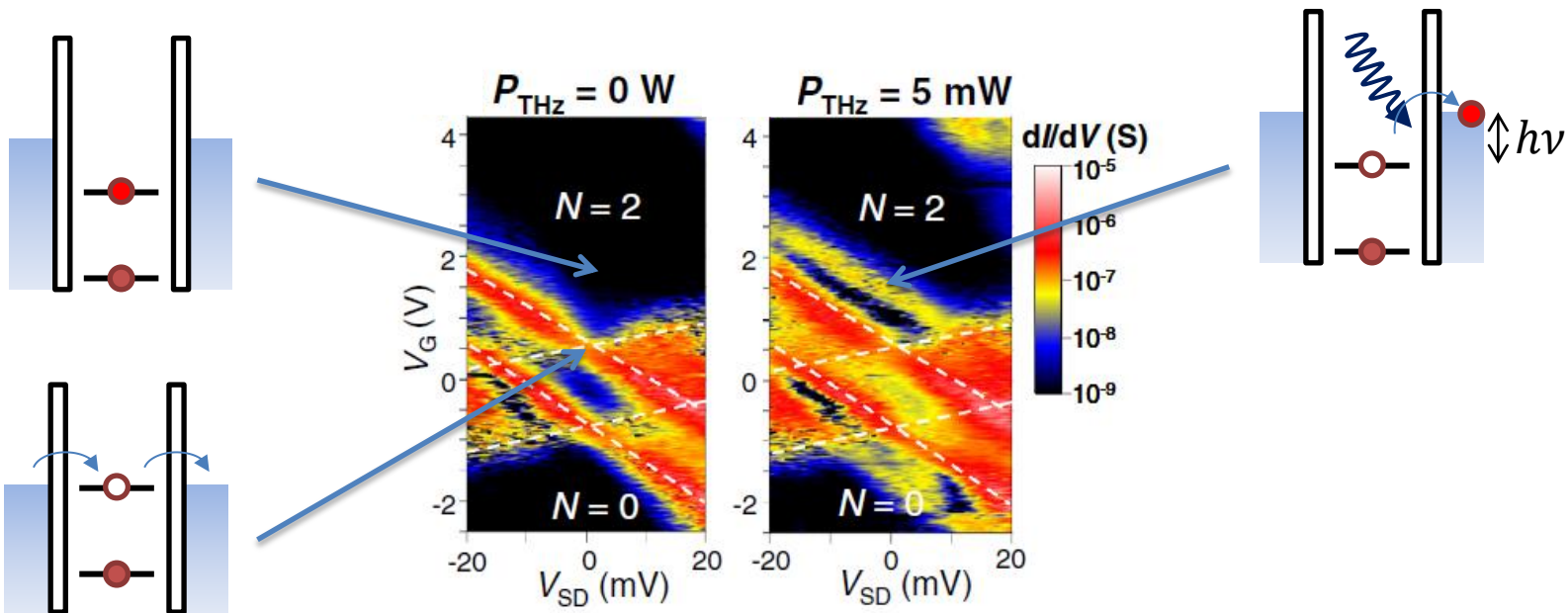
- smaller timescales
- systems w/ larger energy scales
- higher temperatures
 - $1 \text{ THz} \leftrightarrow 4.1 \text{ meV} \leftrightarrow 48 \text{ K}$
- on-chip generation/detection

Photon-assisted tunneling @ THz

self-assembled InAs quantum dots + 2.5 THz light



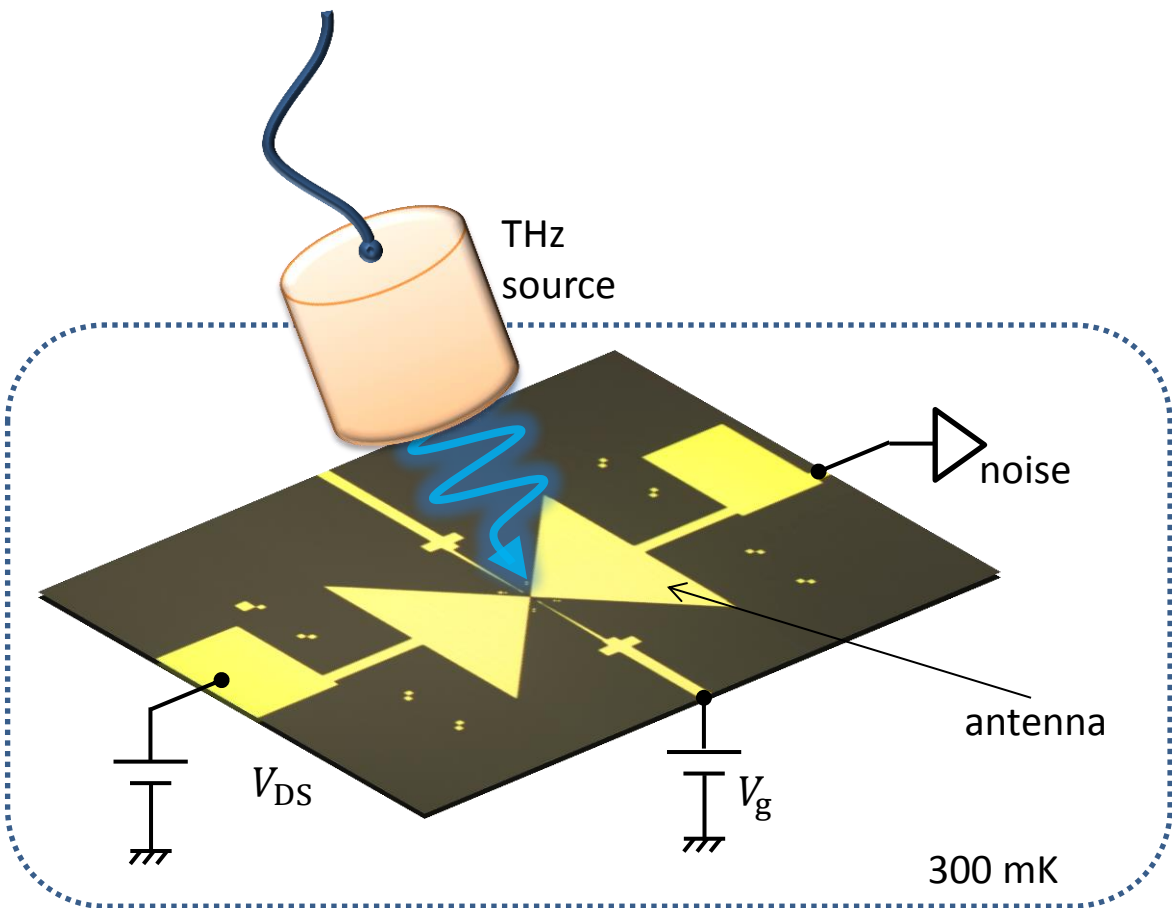
Shibata *et al.*, PRL **109**, 077401 (2012)



THz PAT in CNTs: Kawano *et al.*, JAP **103**, 034307 (2008)

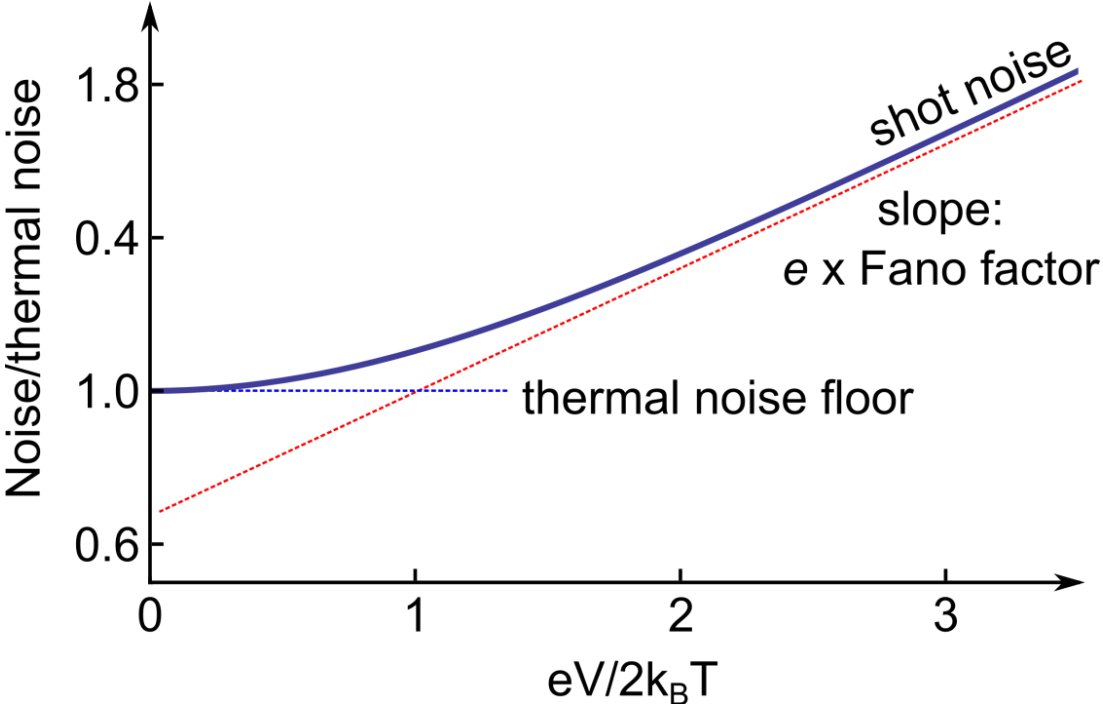
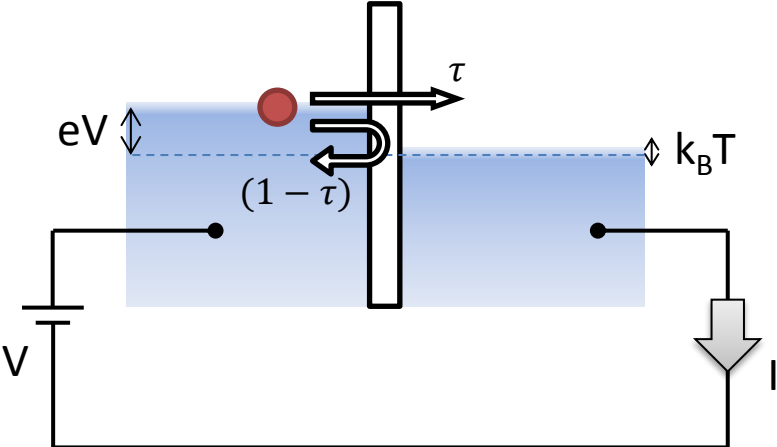
THz PAT in single molecule transistors: Yoshida *et al.*, PRL **115**, 138302 (2015)

Photon-assisted shot noise (PASN) @ THz



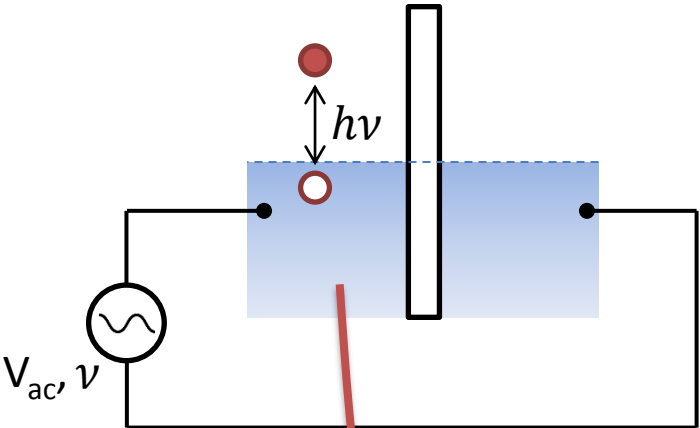
samples: graphene, Si nano-MOSFETs, ...

Quantum shot noise

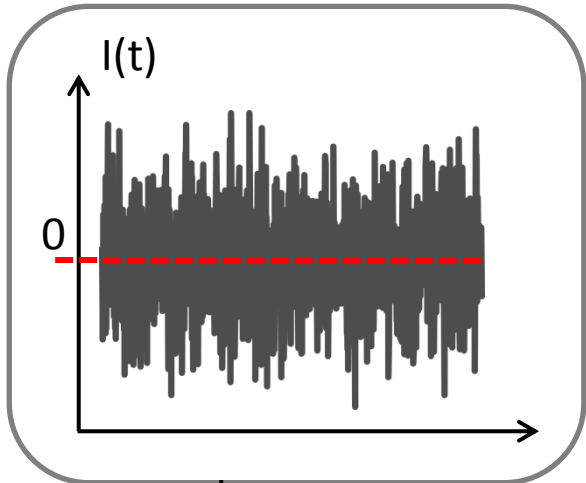
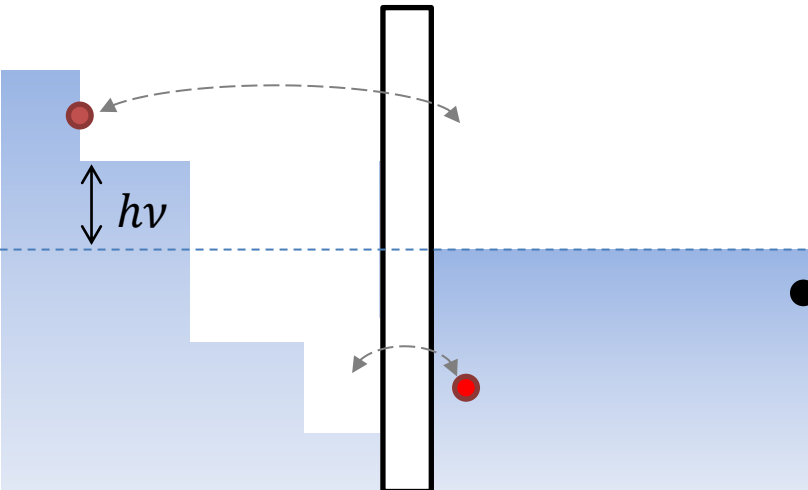


Photon-assisted shot noise (PASN)

Tien & Gordon, Physical Review **129**, 647 (1963)
 Lesovik & Levitov, PRL **72**, 538 (1994).

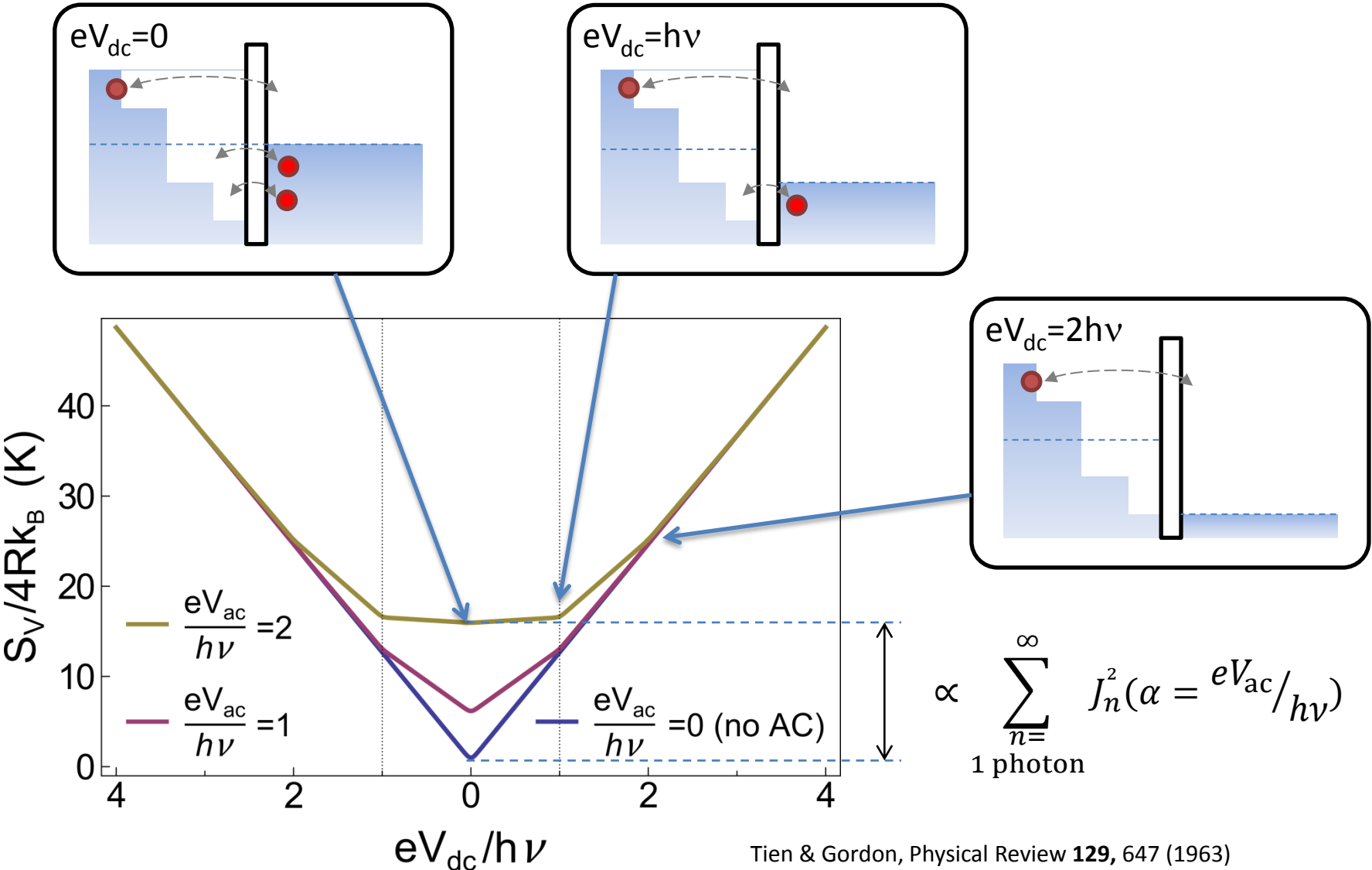


$$\tilde{f}(\varepsilon) = \sum_n J_n^2 \left(\frac{eV_{ac}}{h\nu} \right) \times f(\varepsilon - n h\nu)$$



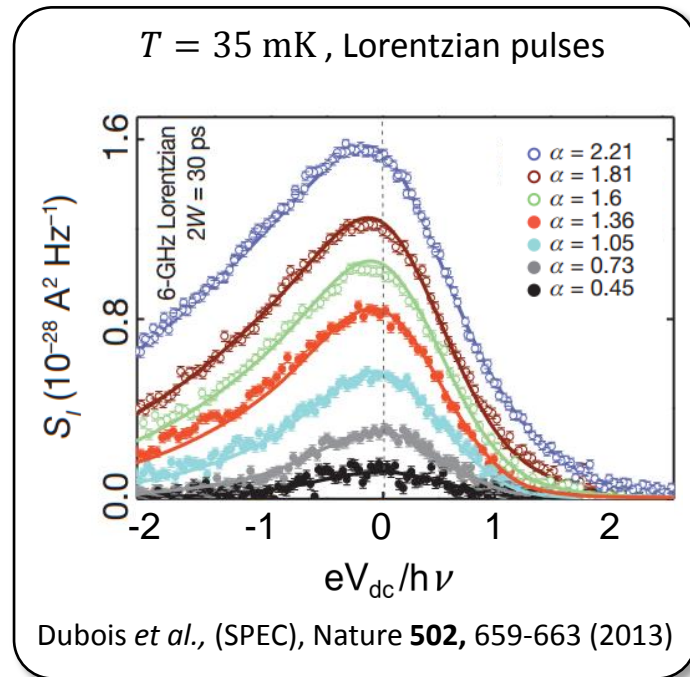
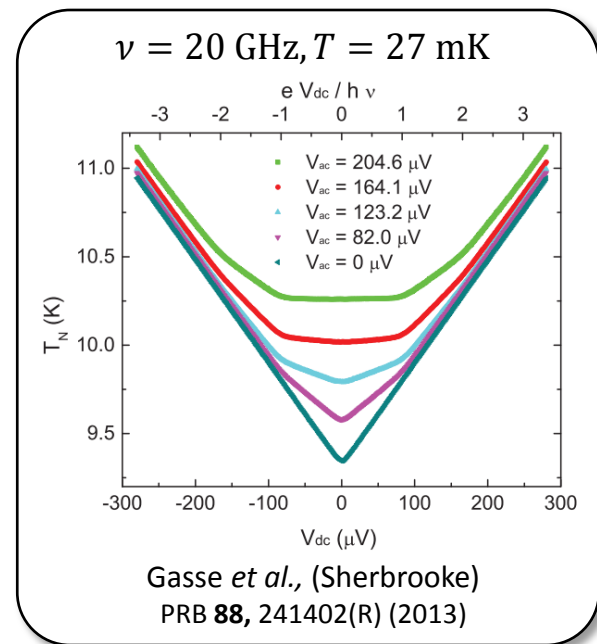
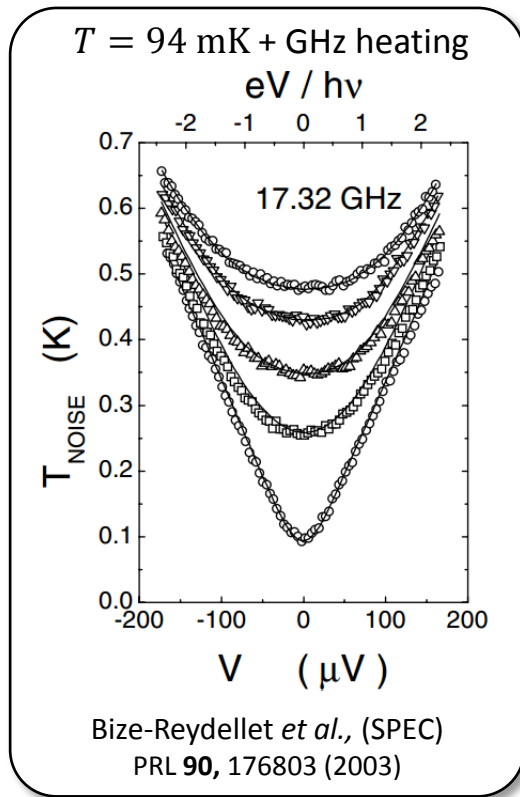
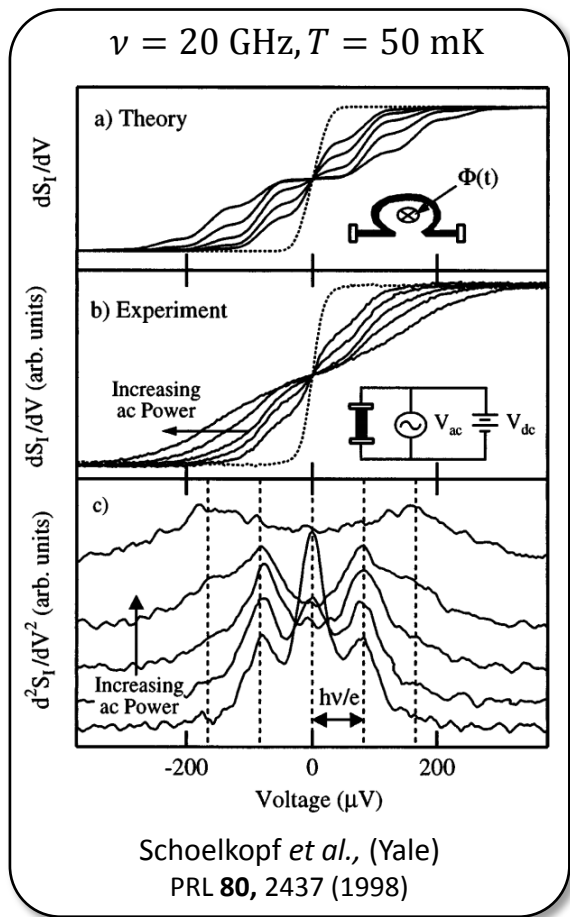
$\langle I \rangle = 0 @ V_{dc} = 0$
 BUT noise $\neq 0$

Photon-assisted shot noise, finite V_{dc}

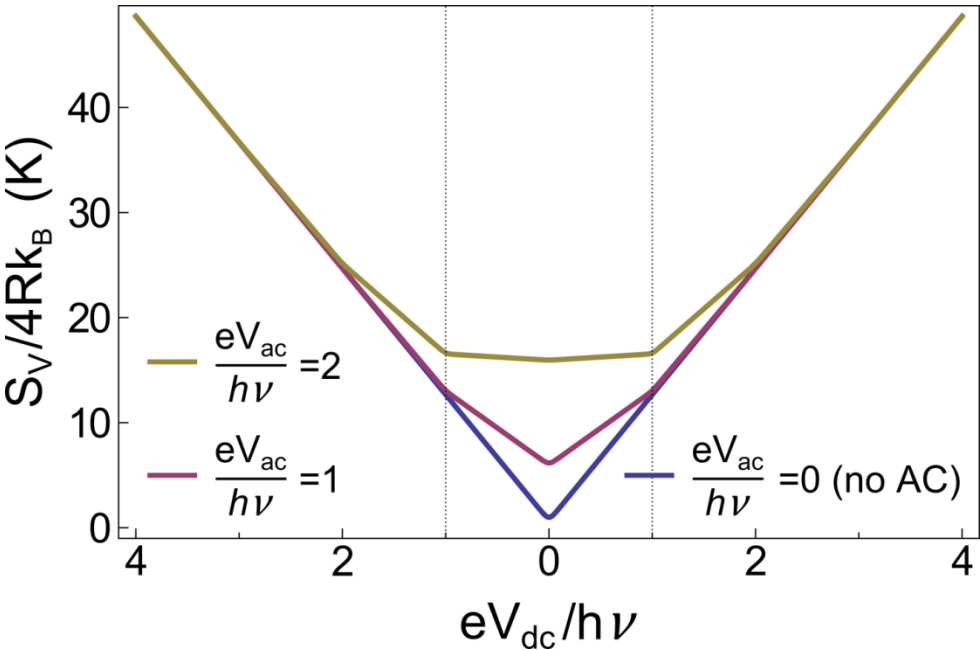


Tien & Gordon, Physical Review **129**, 647 (1963)
 Lesovik & Levitov, PRL **72**, 538 (1994).

Photon-assisted shot noise @ GHz

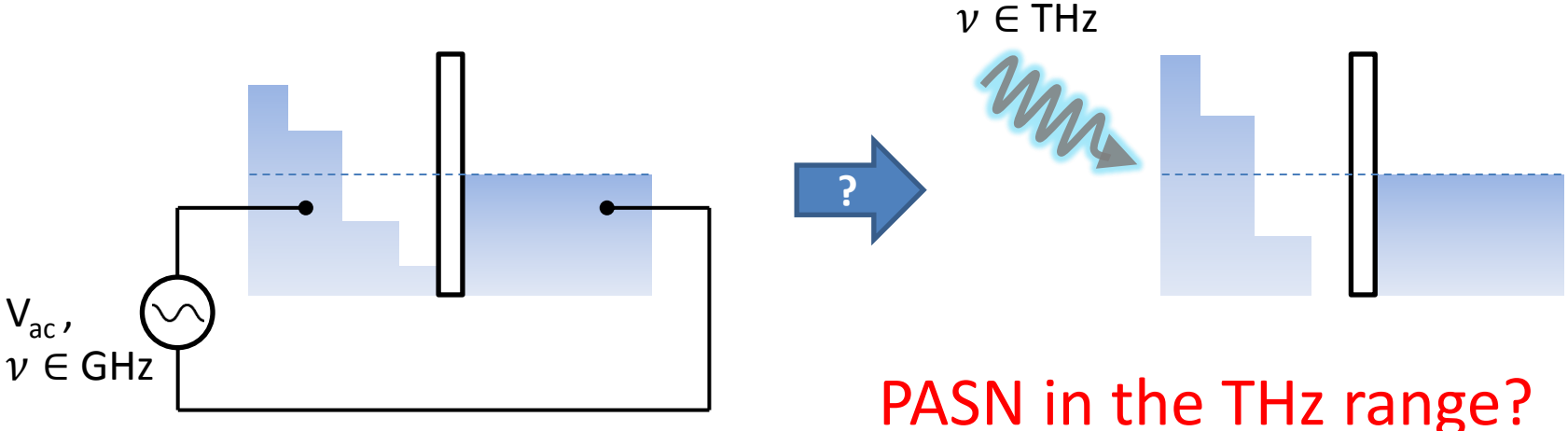


Photon-assisted shot noise (PASN)



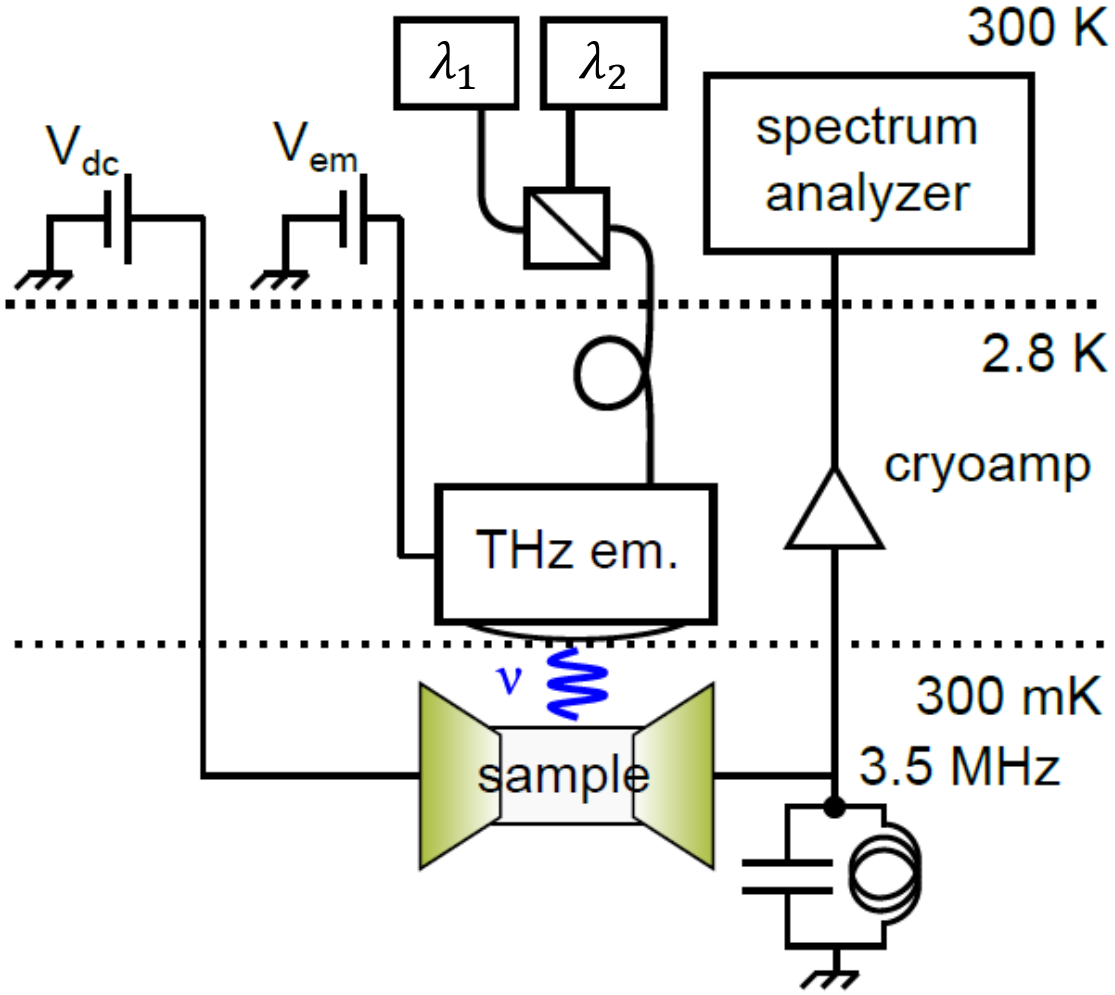
- generation and spectroscopy of out-of-equilibrium energy distrib. fct
- characterization of applied ac signal

$k_B T \ll h\nu \Rightarrow$ competition PASN / heating

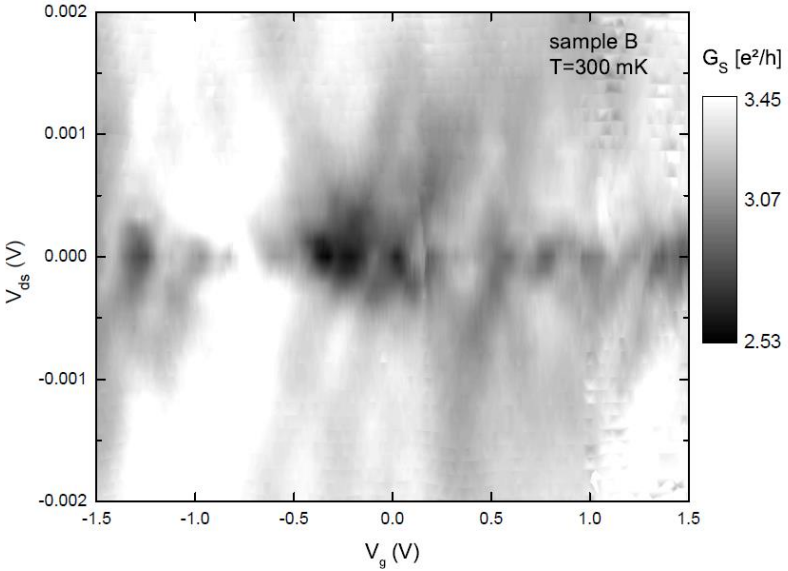
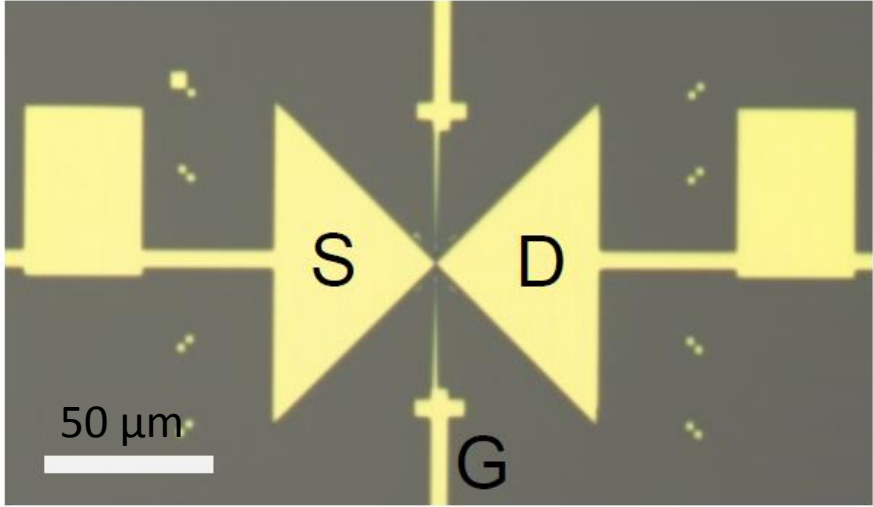
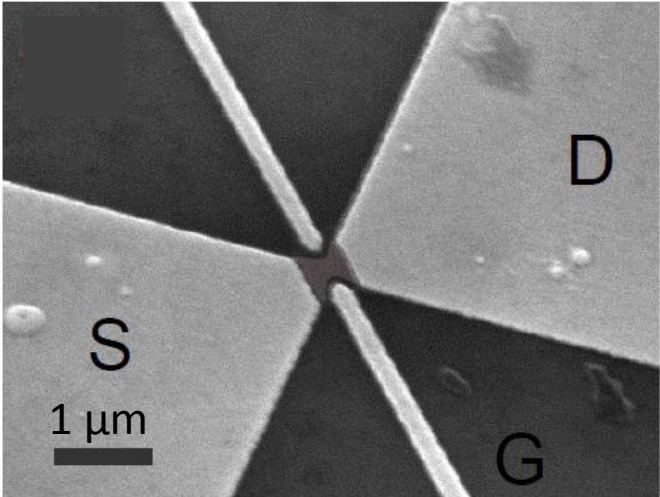


PASN in the THz range?

Experimental setup: THz + shot noise meas^t

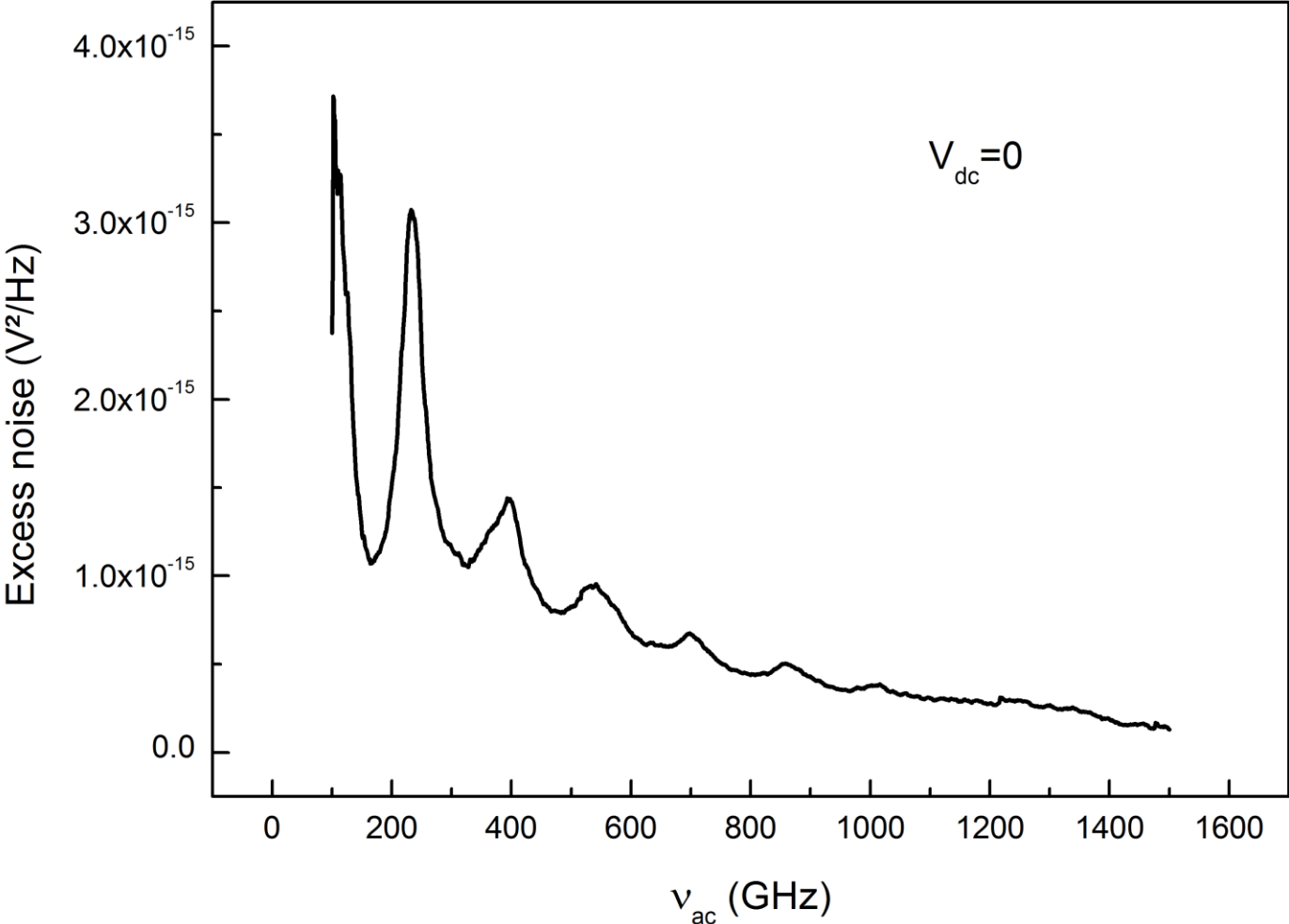


CVD graphene NR samples

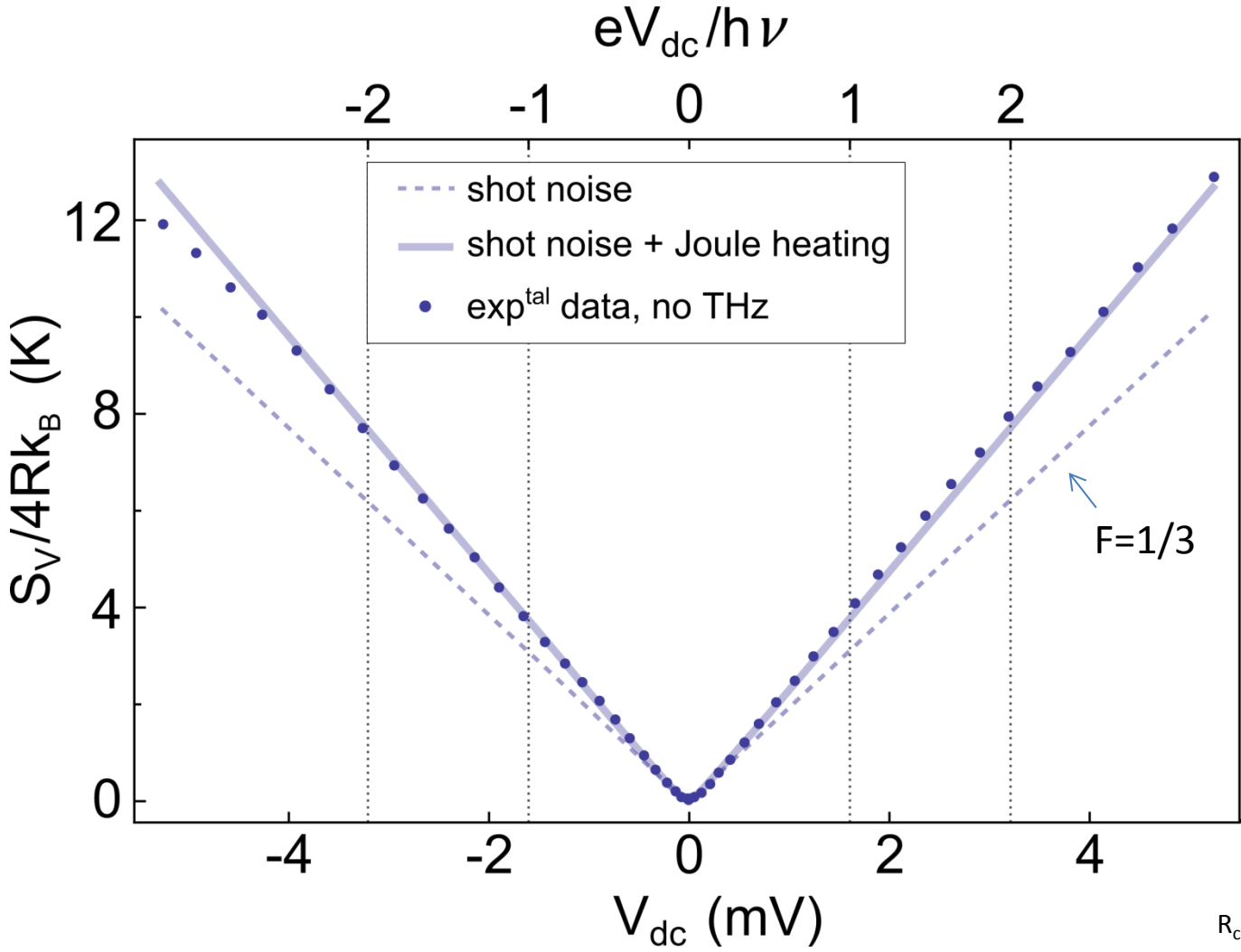


- low mobility disordered graphene
→ diffusive transport
- bow-tie antenna –shaped contacts
- sample aligned in vacuum w/ THz emitter

Equilibrium noise vs THz frequency



Shot noise

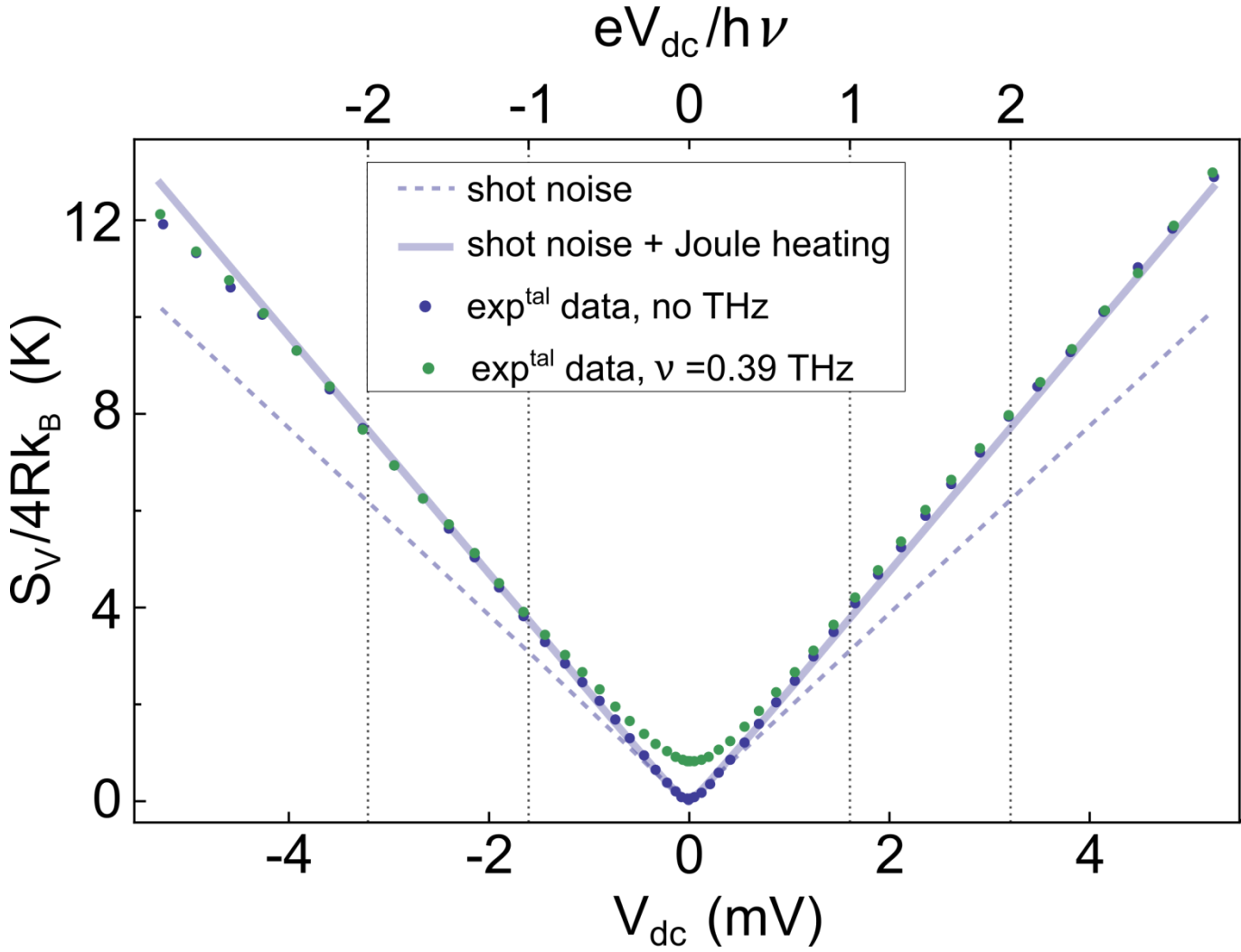


heating model: Wiedemann-Franz law
(no phonon contrib.)

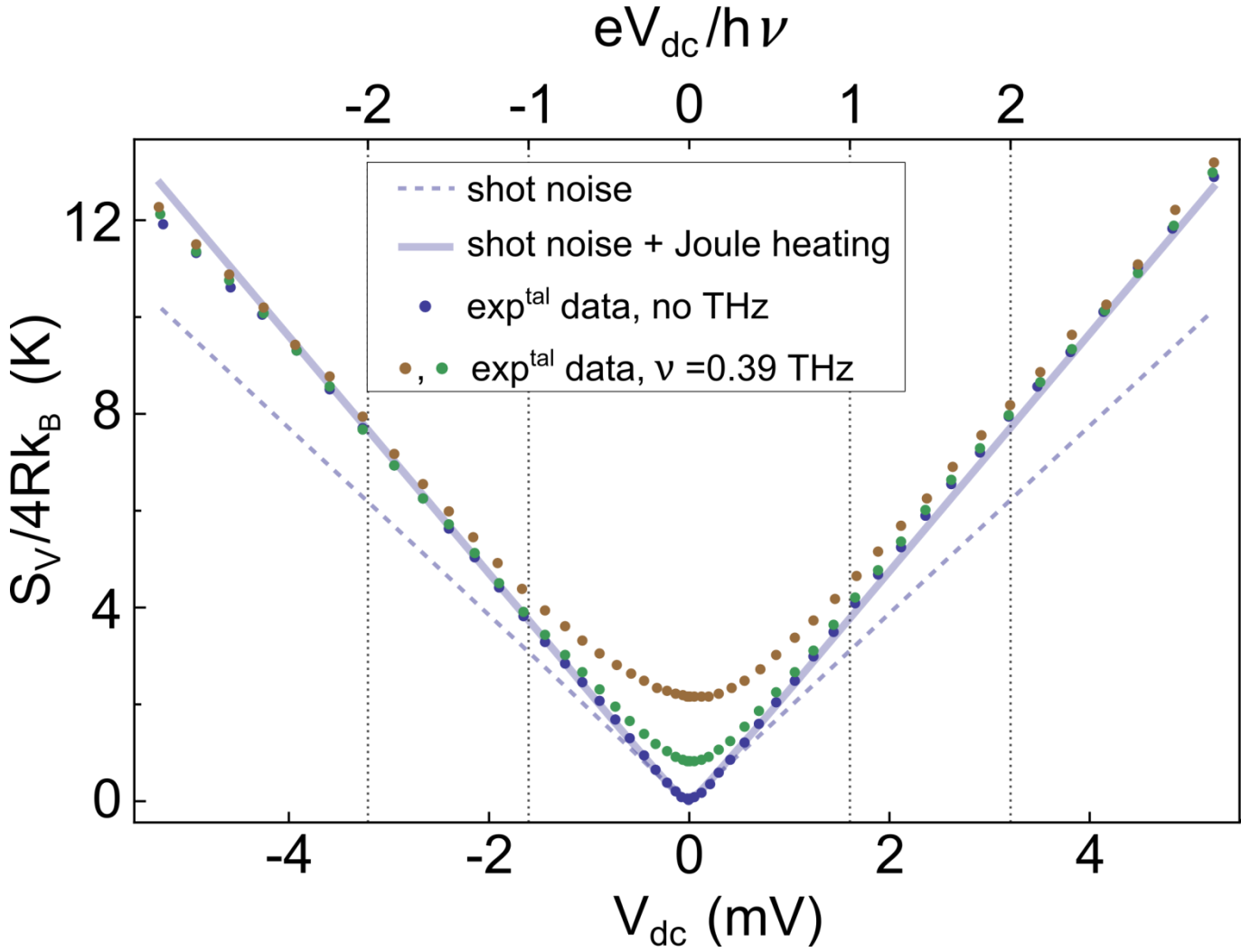
$$T_{el}(V_{dc})^2 = T_0^2 + 24 \left(\frac{eV_{dc}}{\pi 2k_B} \right)^2 \times \gamma (1 + 2\gamma)$$

\downarrow
 $R_{\text{contact}}/R_{\text{sample}}$

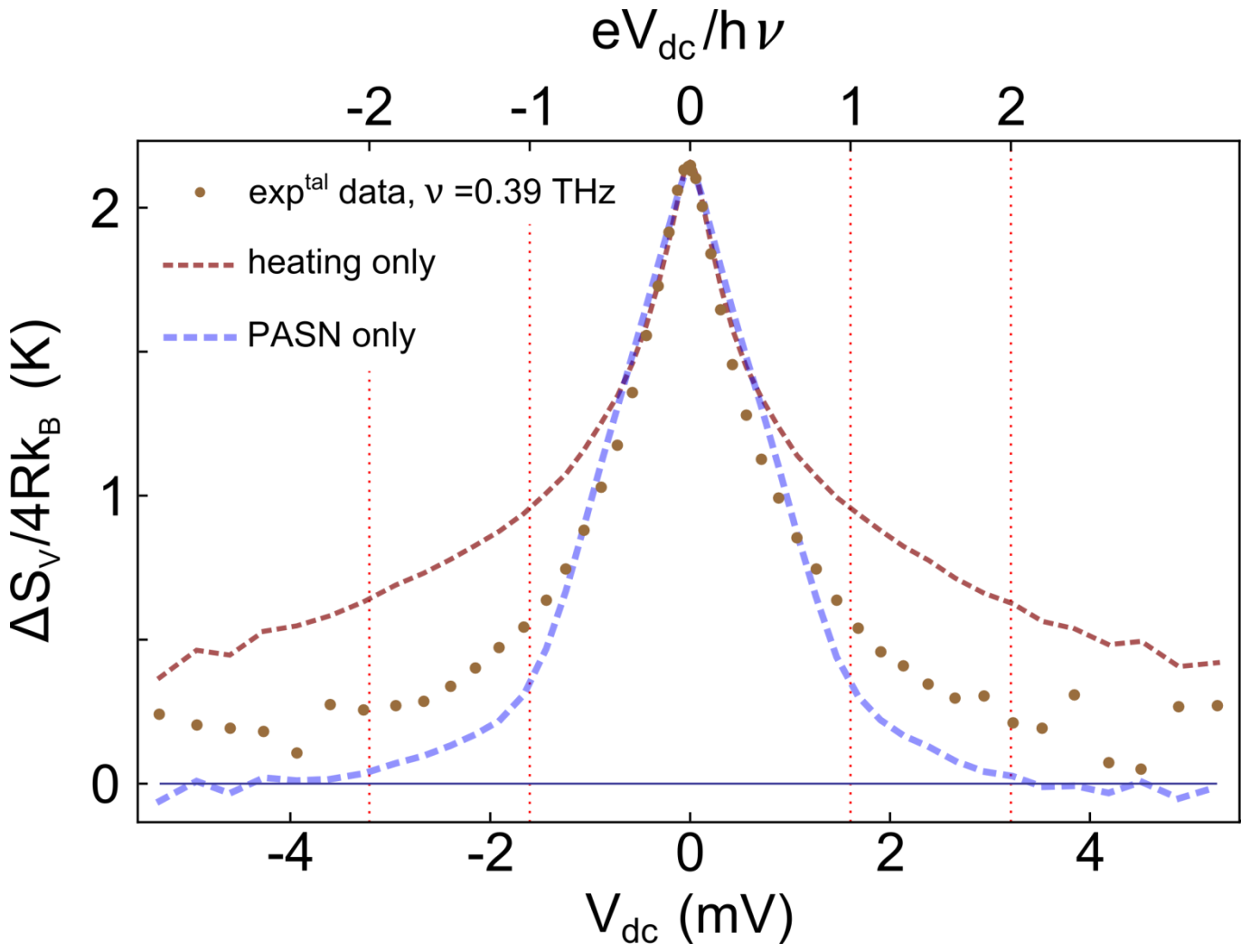
Shot noise + THz ($\nu=0.4$ THz)



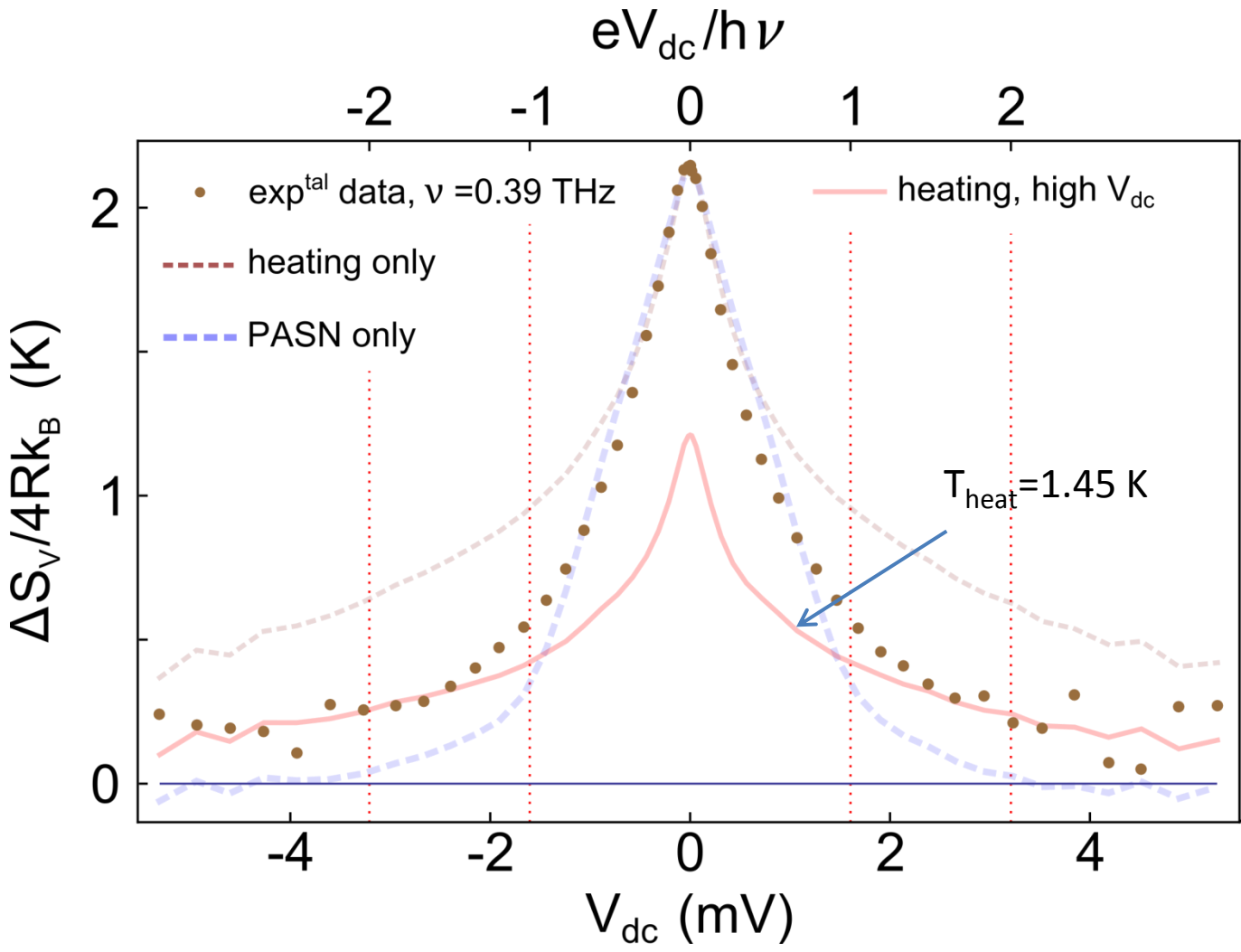
Shot noise + THz ($\nu=0.4$ THz)



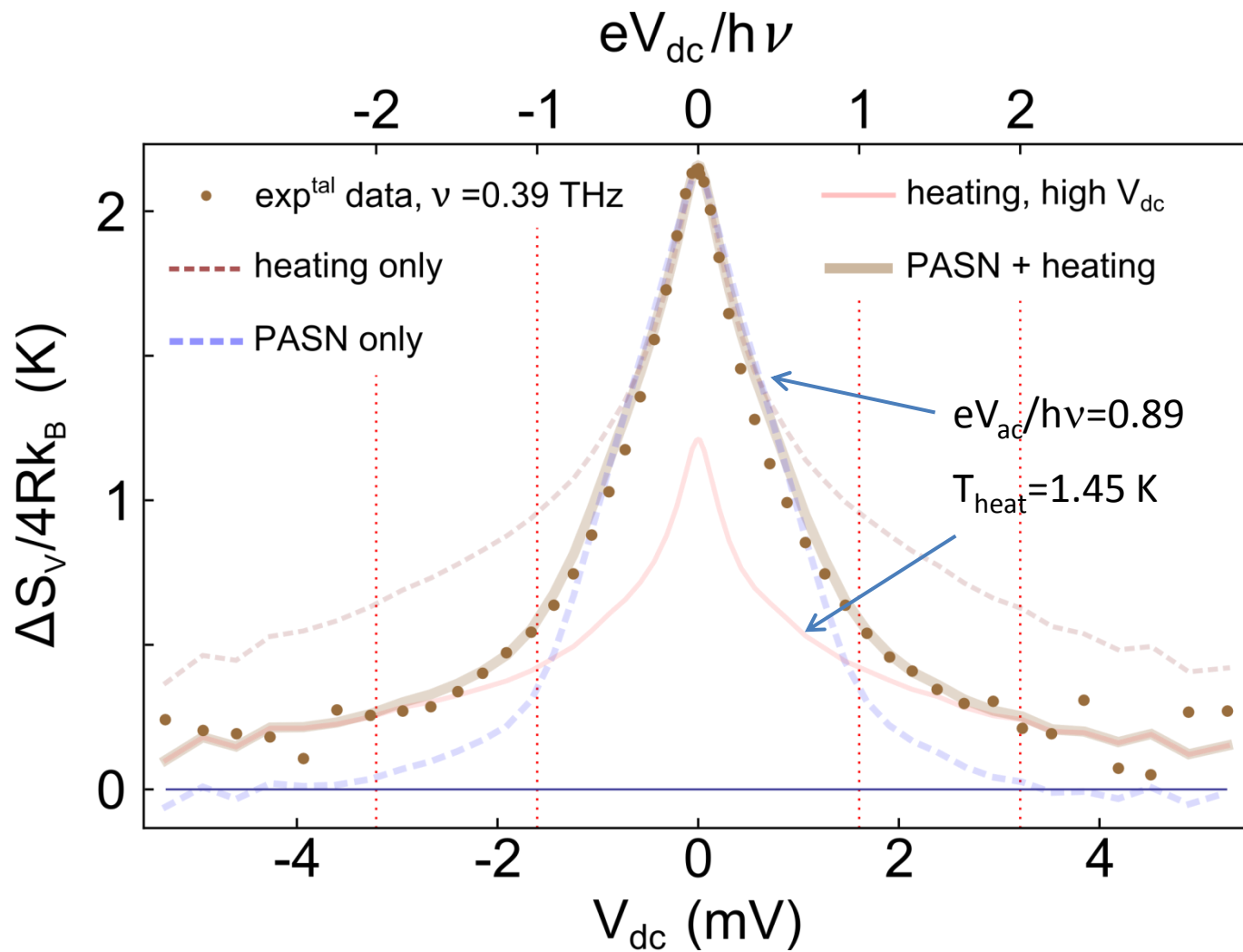
ON-OFF noise: PASN or heating?



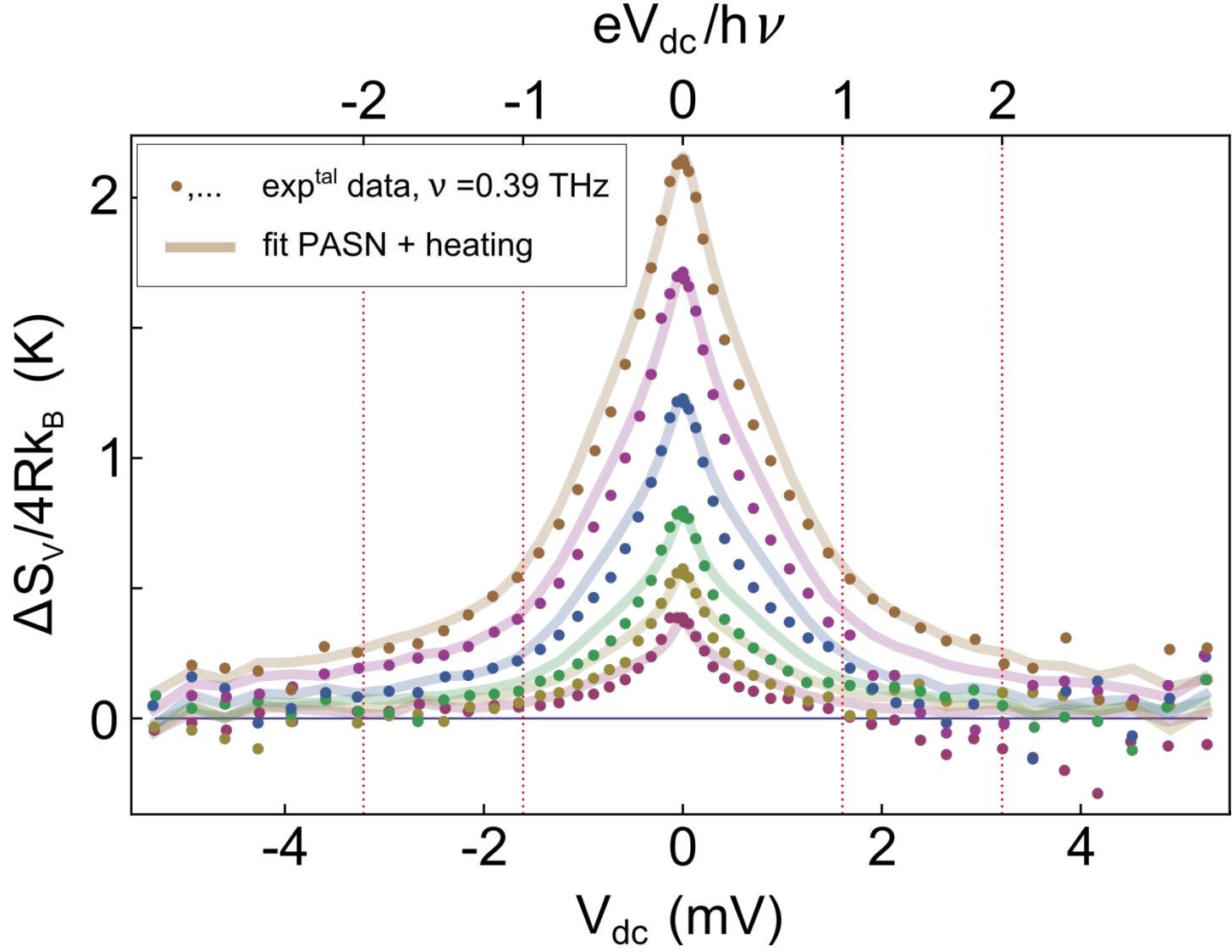
ON-OFF noise: PASN + heating?



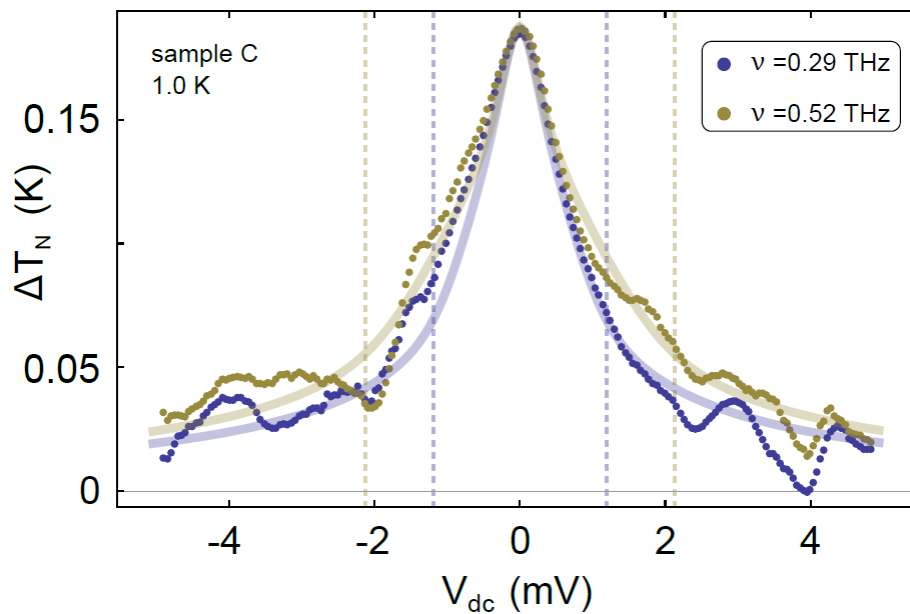
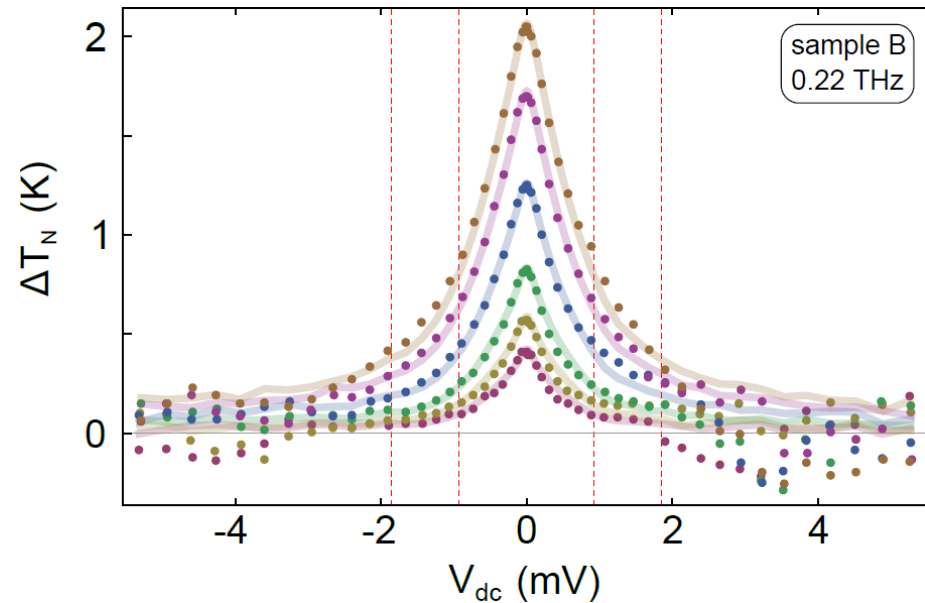
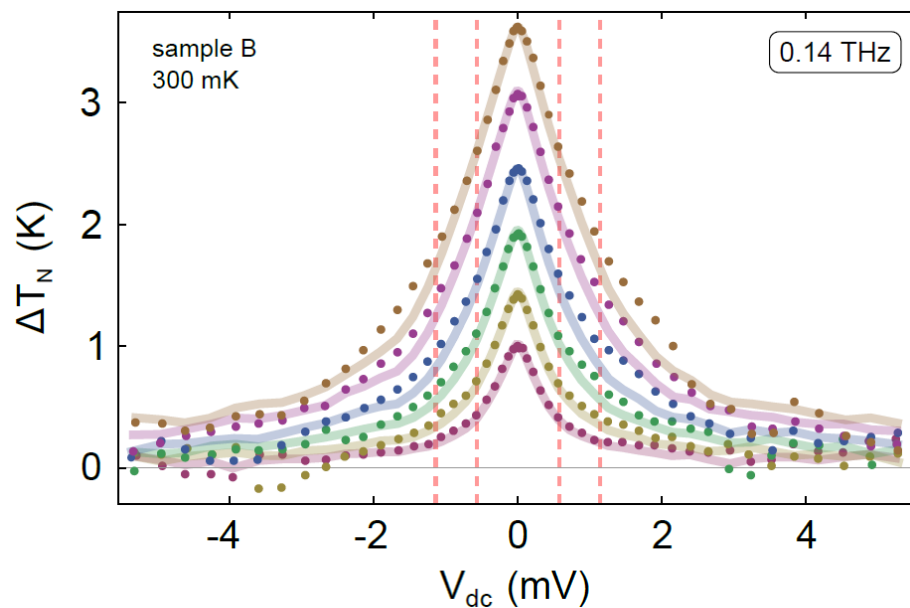
ON-OFF noise: PASN + heating



ON-OFF noise: PASN + heating



ON-OFF noise: PASN + heating



Conclusions & perspectives

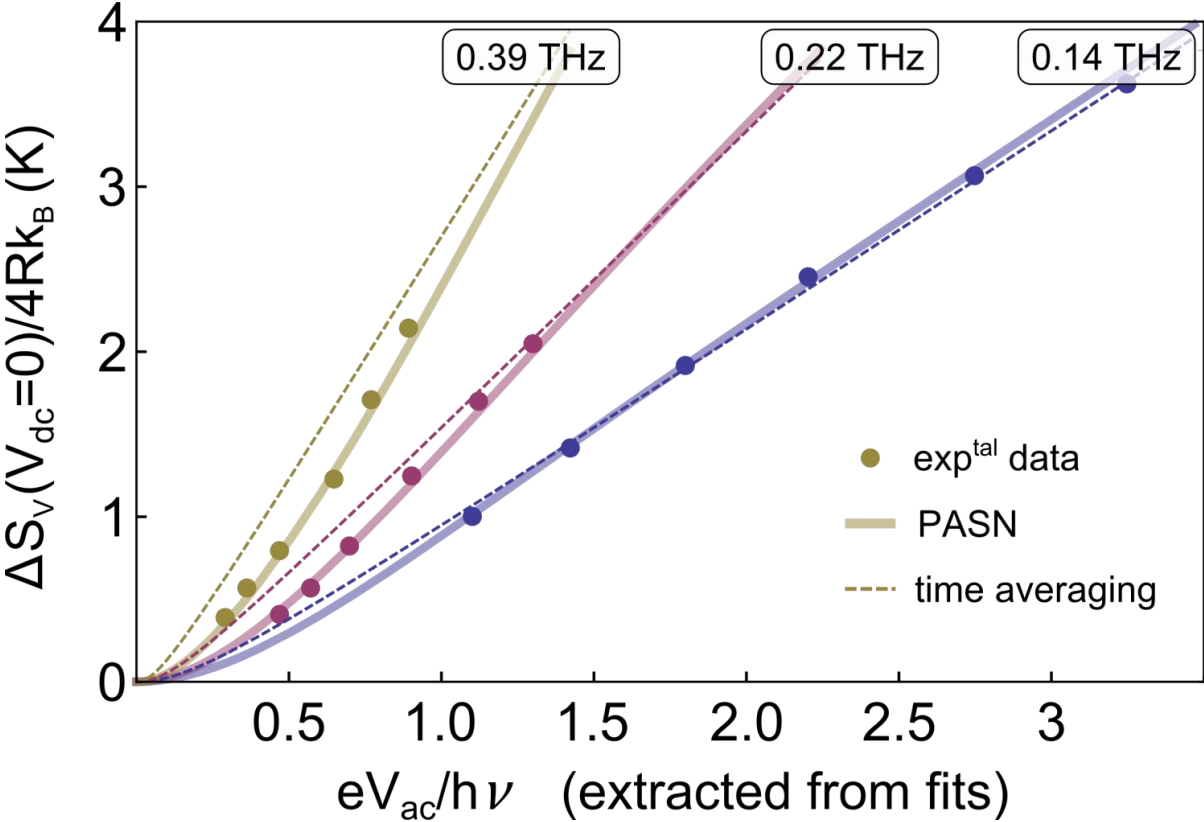
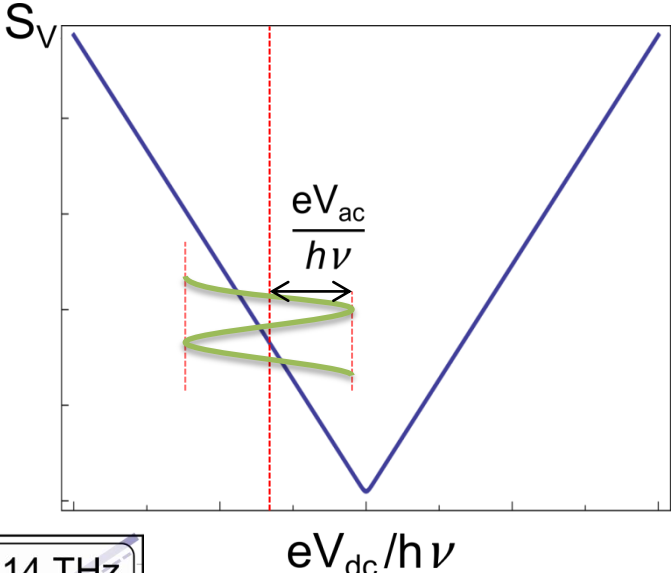
- signatures of PASN in GNR in the THz range
- non-negligible heating (dc and ac)



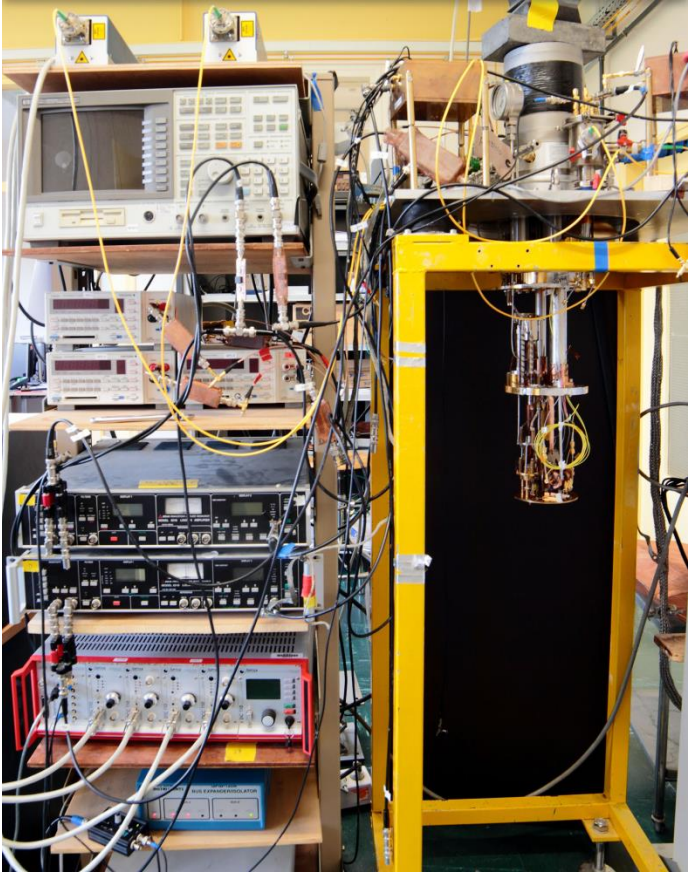
towards mesoscopic transport in the THz domain

- dynamical out-of-equilibrium energy distribution fct at the meV scale
- PASN THz detector:
 $NEP < 10 \text{ pW/Hz}^{1/2}$
- quantum plasmonics in ballistic devices (VdW heterostructures)

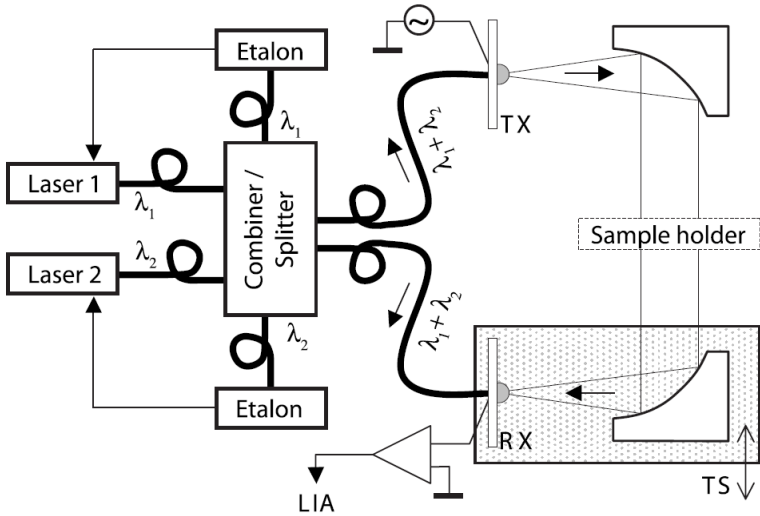
PASN vs time averaging



Experimental setup: THz emission

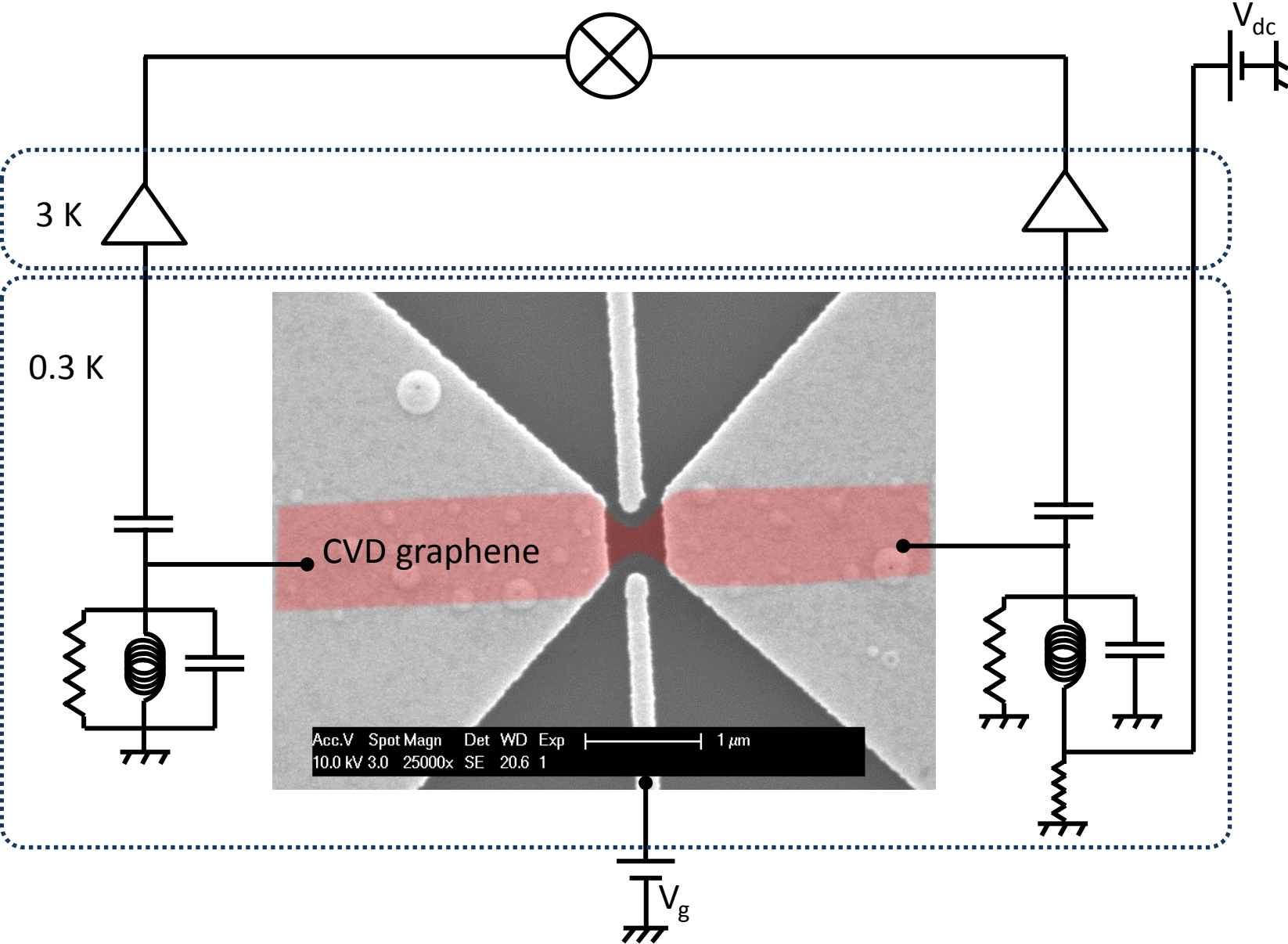


THz emitter in dry He3 fridge

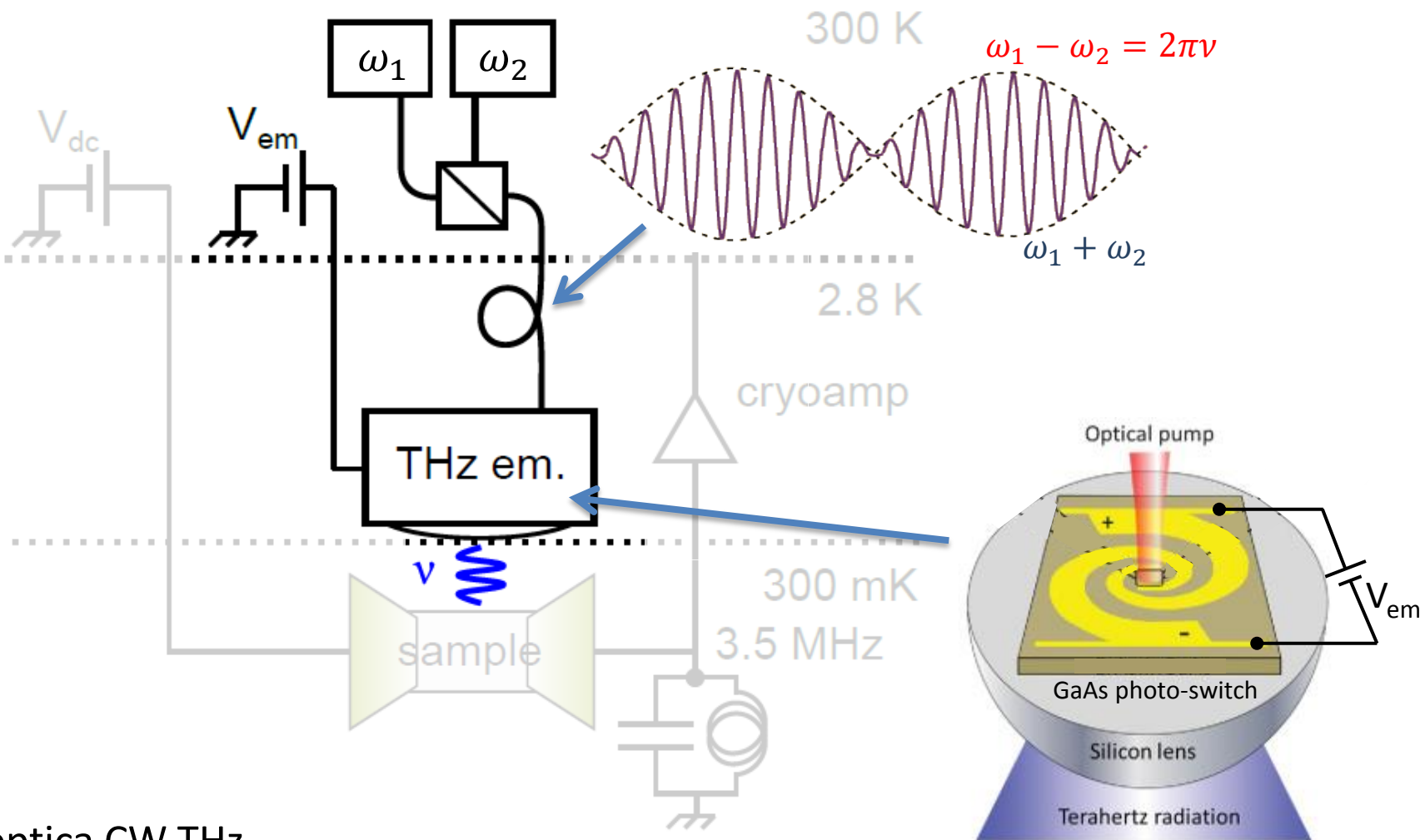


Topica cw TeraHertz (photomixing)
0.1 – 2 THz
1 μW @ 100 GHz

Experimental setup: sample & noise meas^{mt}



Experimental setup: THz + shot noise meas^t



Toptica CW THz
 50 GHz - 2 THz cw generation
 max ~1 μ W @ 0.1 THz

Deninger *et al.*, RSI **79**, 044702 (2008)
 Roggenbuck *et al.*, New Journal of Physics **12**, 043017 (2010)

Experimental setup: THz + shot noise meas^t

