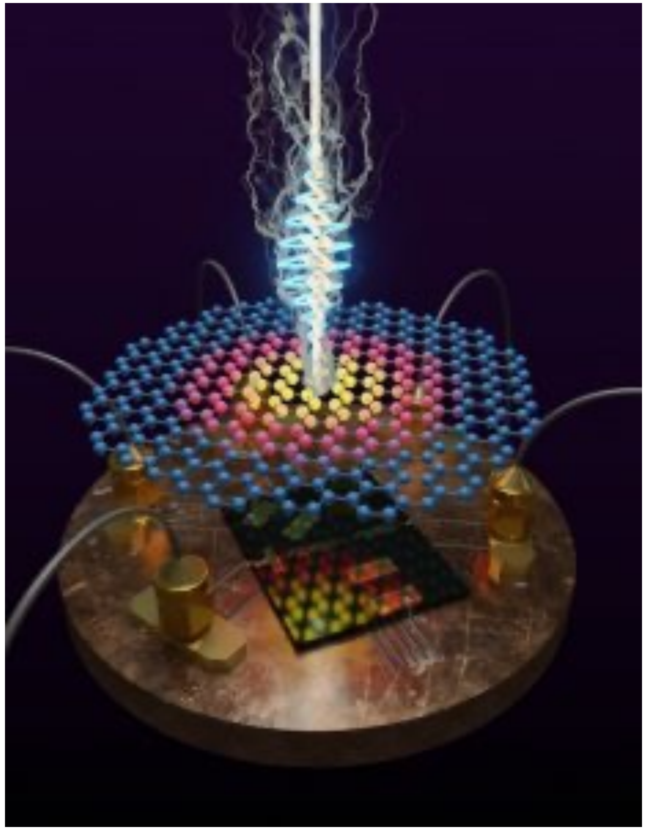
Engineering graphene Josephson junction for sensitive photon detector



Gil-Ho Lee

Dept. of Physics, POSTECH, Korea

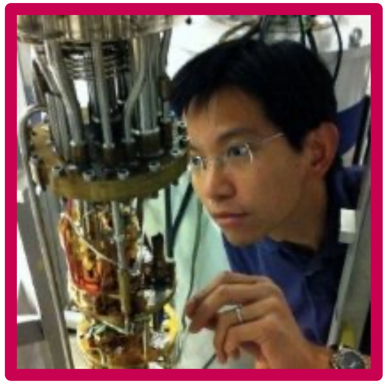
[**GHL** et al., Nature **586**, 42–46 (2020),
[E. Walsh et al., Science **372**, 409-412 (2021)]

POSTECH

Acknowledgement

POSTECH, Korea
- Woo-Chan Jung

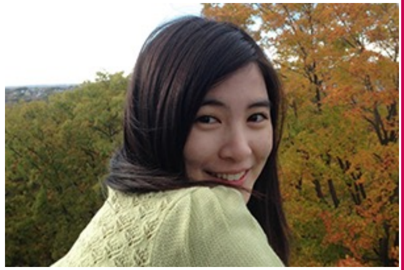
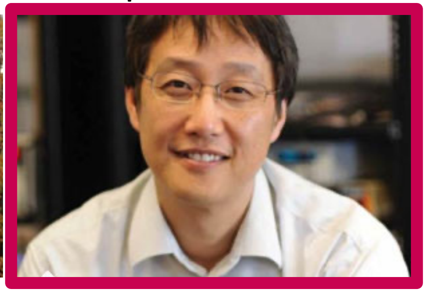
Raytheon BBN technology, USA
- Kin Chung Fong
- Leonardo Ranzani
- Thomas A. Ohki



MIT, USA
- Evan D. Walsh
- Dmitri K. Efetov
- Dirk Englund



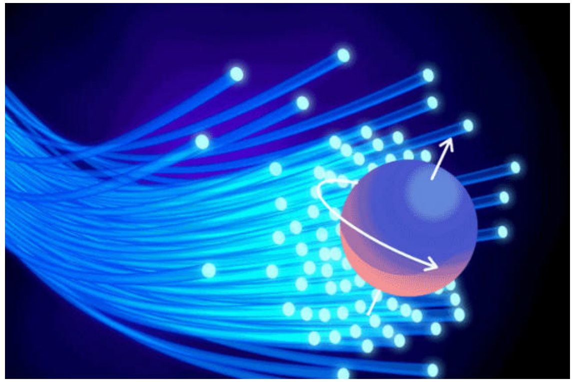
Harvard University, USA
- Katie Huang
- Philip Kim

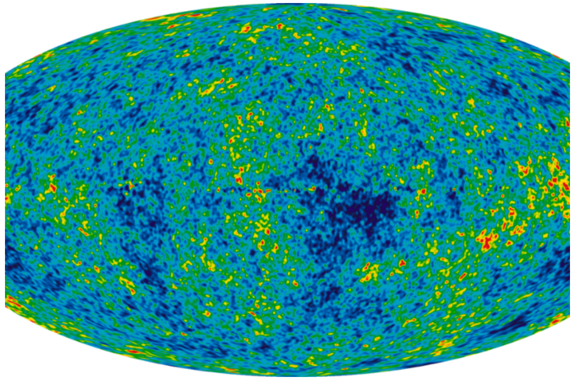
NIMS, Japan
- Takashi Taniguchi
- Kenji Watanabe

Sensitive Detectors

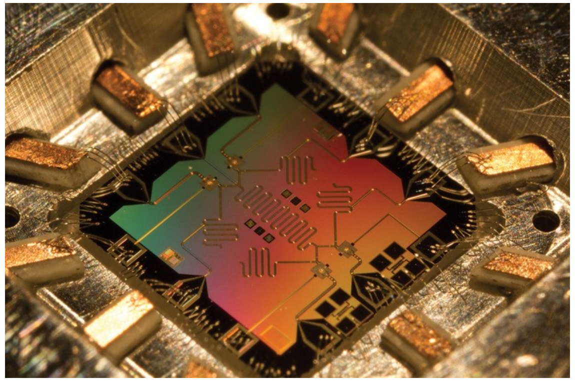
- in **IR** range
  - optical quantum communication
  - quantum key distribution



- in **THz** range
  - galaxy formation via cosmic radiation

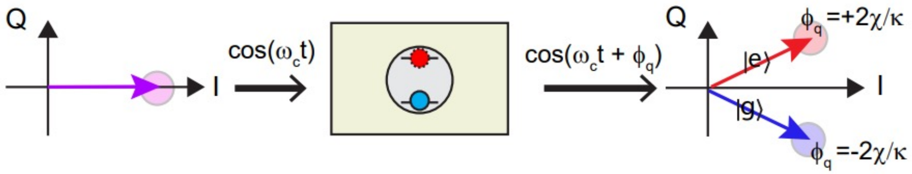


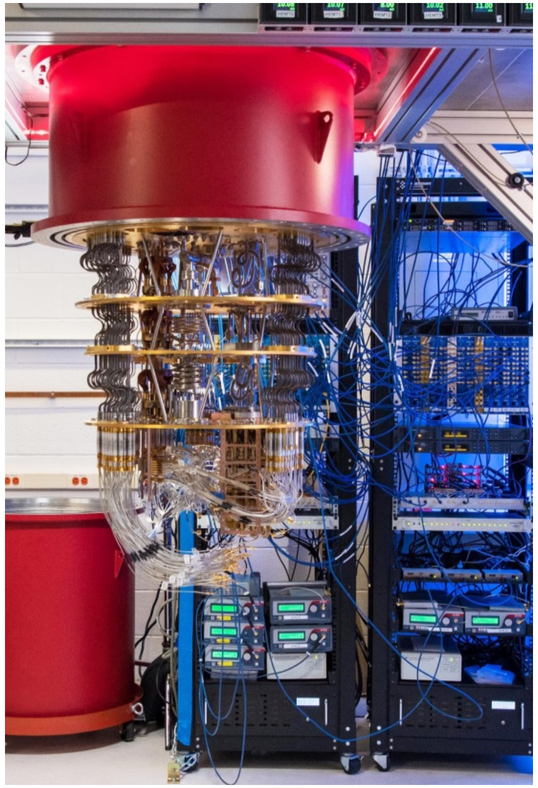
- in **GHz** range
  - remote entanglement of superconducting
  - high-fidelity quantum measurements
  - microwave quantum illumination



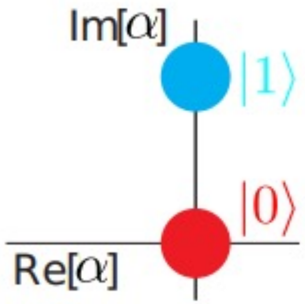
For Qubit Measurement

- Dispersive phase shift readout





- **Photon-counting readout**



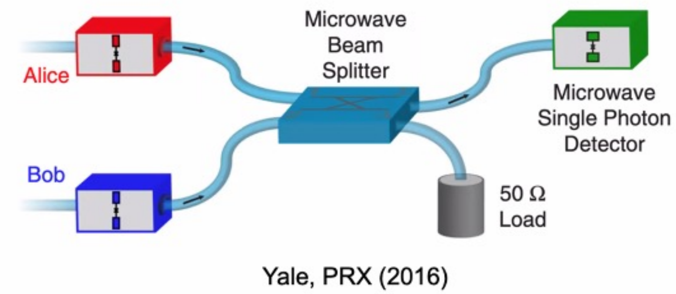
No need for room-temperature detection

↓

Fast, High-fidelity, **Scalable** measurement

[L.C.G. Govia et al., PRA 90, 062307 (2014)]

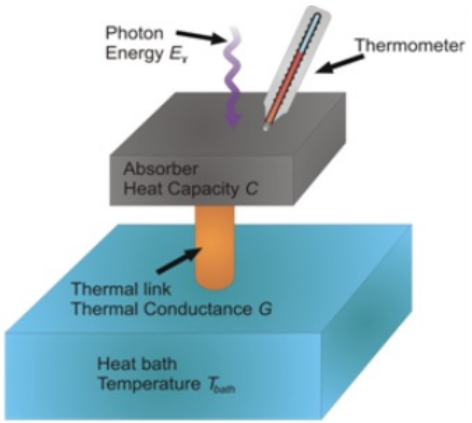
- **Remote entanglement**

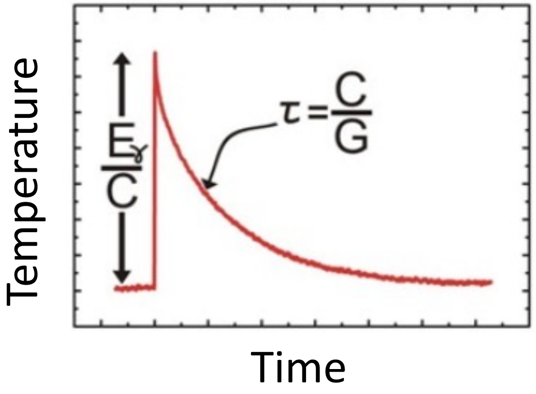


POSTECH

Thermal Detector

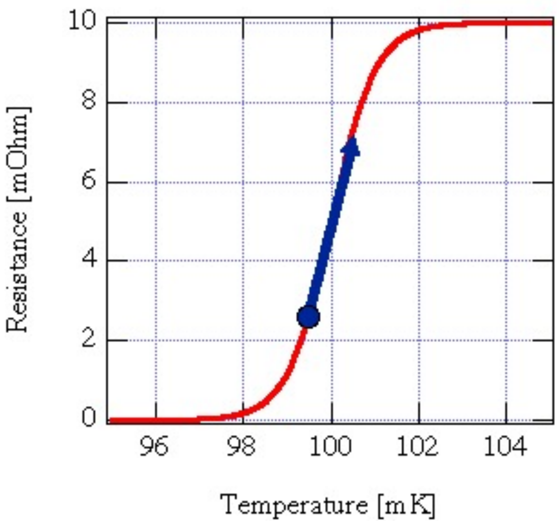
- No need to collect electron
- No threshold
- Robust against impurities
- More freedom to choose material



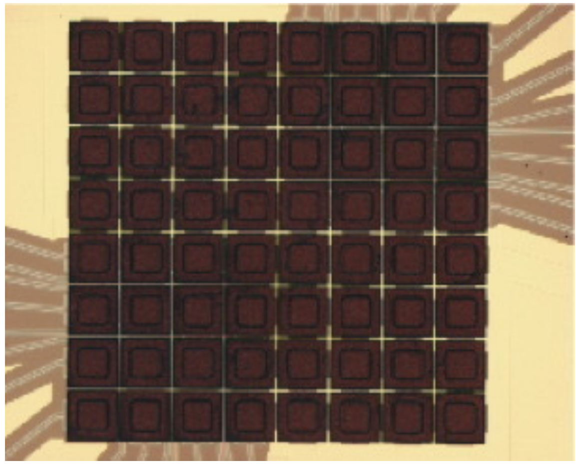


- E_γ: Photon energy
- C : Heat capacity
- G : Thermal conductance

Transition Edge Sensor (TES)



Array of TES



Smaller C

↓

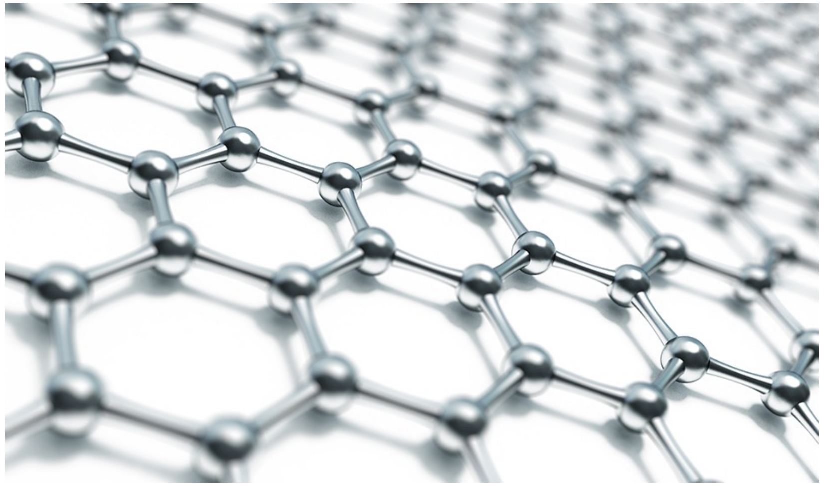
Higher temperature rise

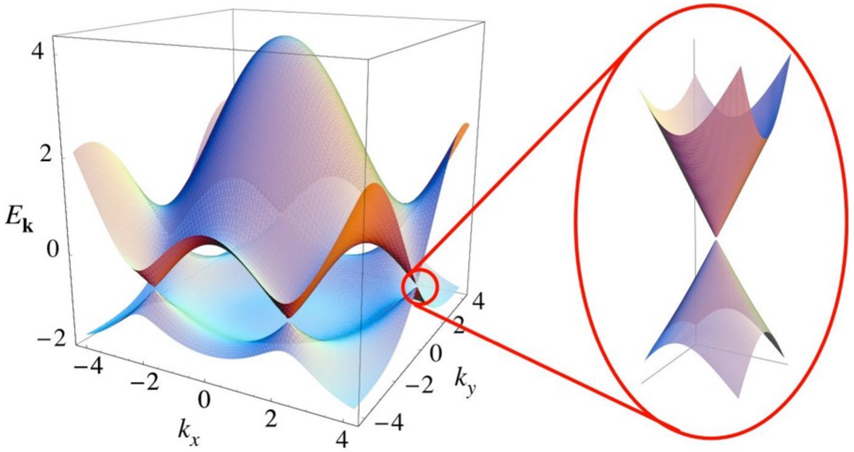
↓

Faster cooldown

(shorter deadtime)

Graphene for Sensor





- **Very small electronic heat capacity** due vanishing density of state, *D*(*E*) near Dirac point (*E*=0).

$$D(E) = 2|E|A/\pi(\hbar v_F)^2$$

- **Faster thermalization**, thanks to short el-el scattering time.

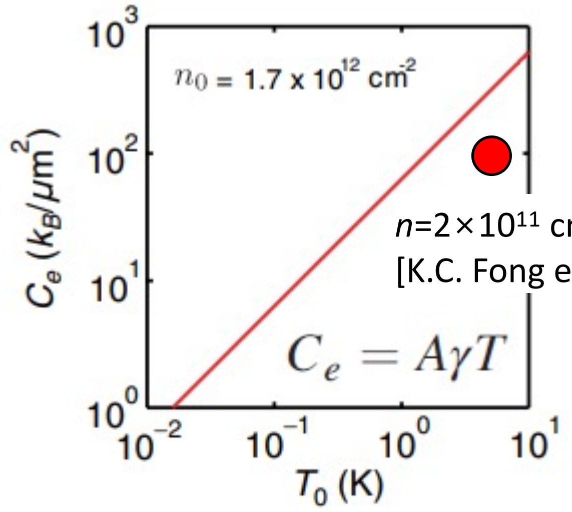
[Nat. Phys. 9, 248 (2013)]

- Broad absorption bandwidth by impedance matching

Small Electronic Heat Capacity, C_e

Specific heat capacity of monolayer graphene:

$\boldsymbol{C_e \sim 10k_B/\mu m^2}$ (@ T=0.1 K, n=1.7×10^{12} cm^{-2})



n=2×10^{11} cm^{-2}

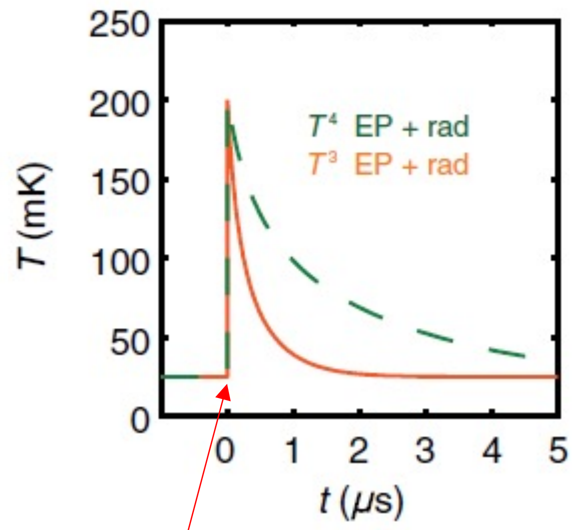
[K.C. Fong et al., PRX 2012)]

Sommerfeld coefficient:

$$\gamma = (4\pi^{5/2}k_B^2\boxed{n}^{1/2})/(3hv_F)$$

Carrier density

Significant heating of electrons !



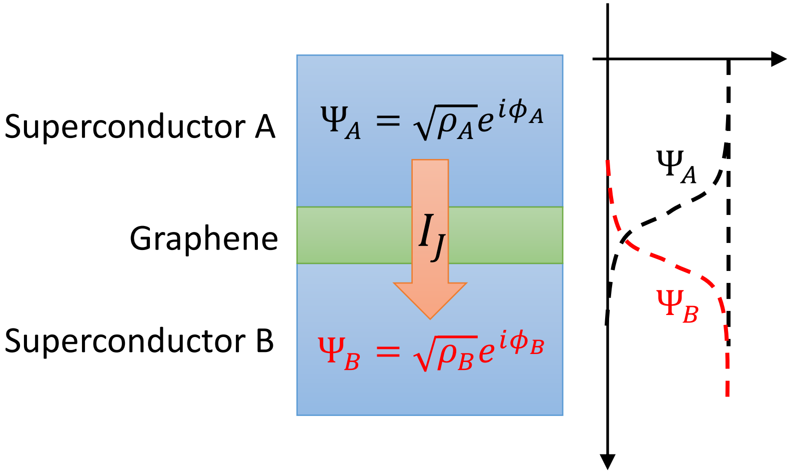
Absorbing 26-GHz μw-single-photon

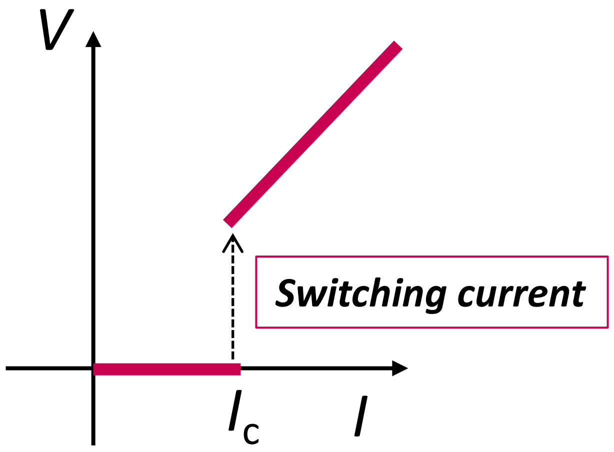
For $\underline{\mu\text{w-SPD}}$, we need to detect temperature rise $\boldsymbol{\Delta T \sim 200}$ **mK** within $\tau_{el\text{-}ph}\sim$ 100 ns.

[E.D. Walsh et al., PRApplied 8, 024022 (2017)]

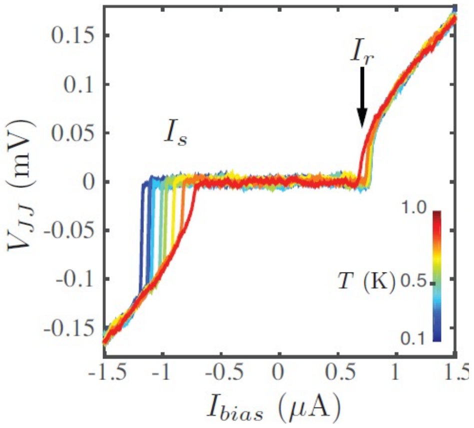
Josephson Junction

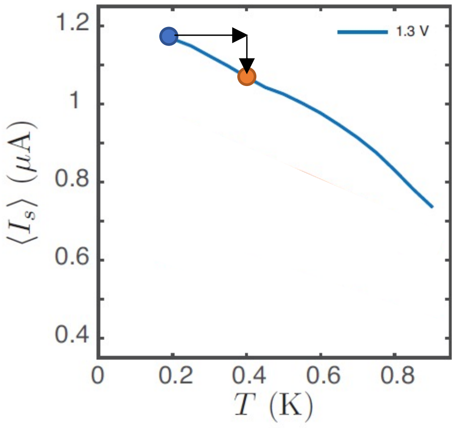
Josephson coupling by overlap of macroscopic quantum wave-functions across junction





Al/Graphene/Al Josephson junction,





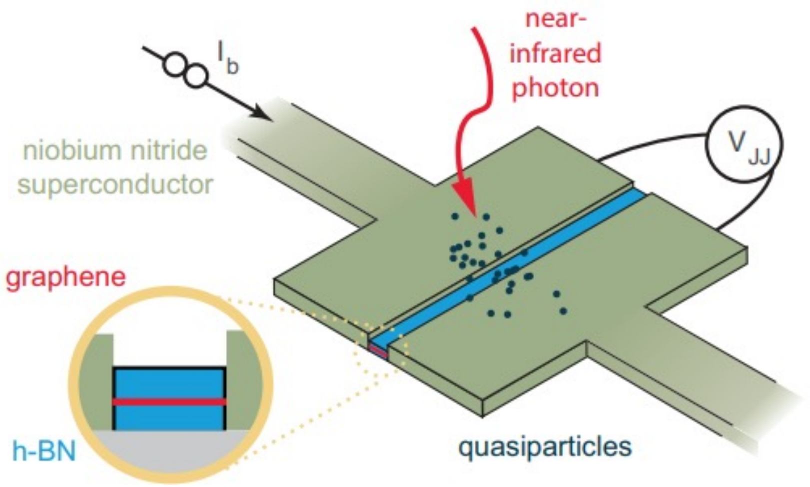
- Switching current, $\langle I_s \rangle$, strongly depends on **electron temperature of graphene.**

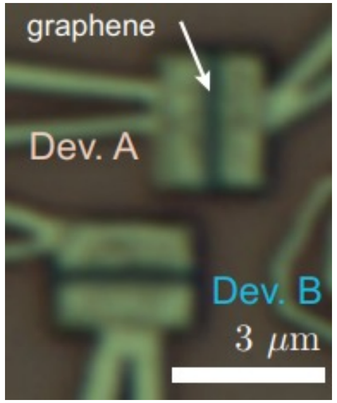
$d\langle I_s \rangle/dT$ **~-0.5 μA/K**

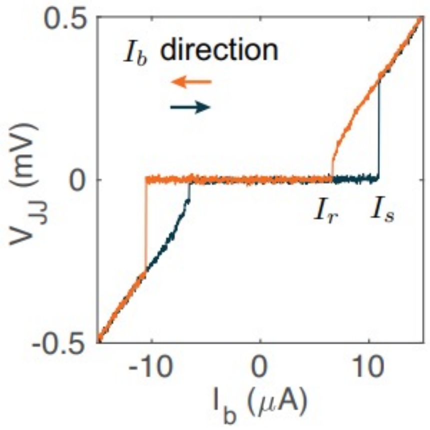
- Switching happens very fast, **within ~10 ps**.

ω_p ~ 100 GHz

1,550-nm NIR Single Photon Detection

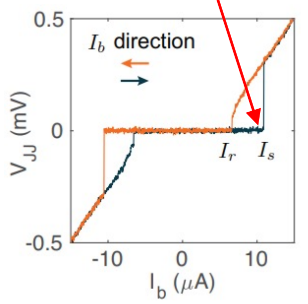


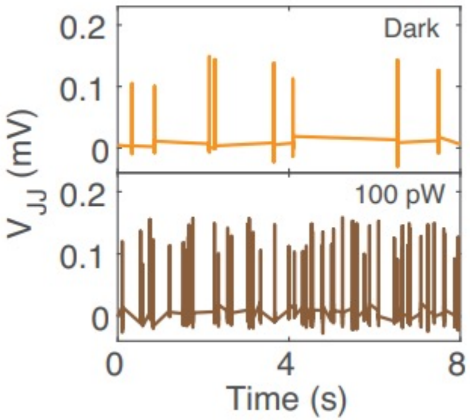


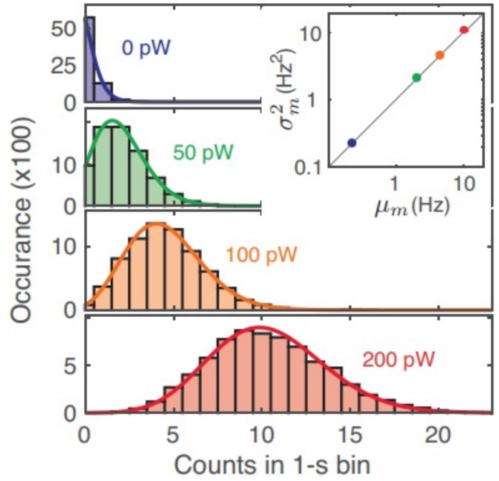


[E. Walsh, W. Jung, **GHL**, …, Kin Chung Fong, Science 372, 409-412 (2021)]

$I_b = 10.90\ \mu A$





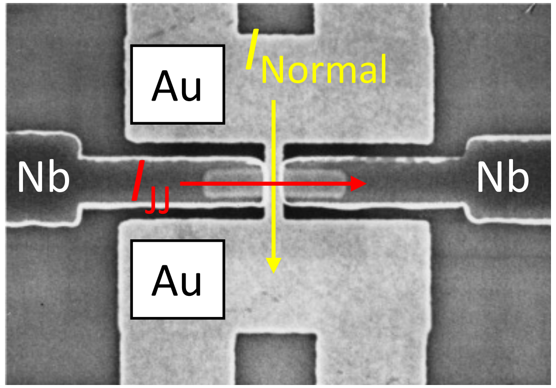


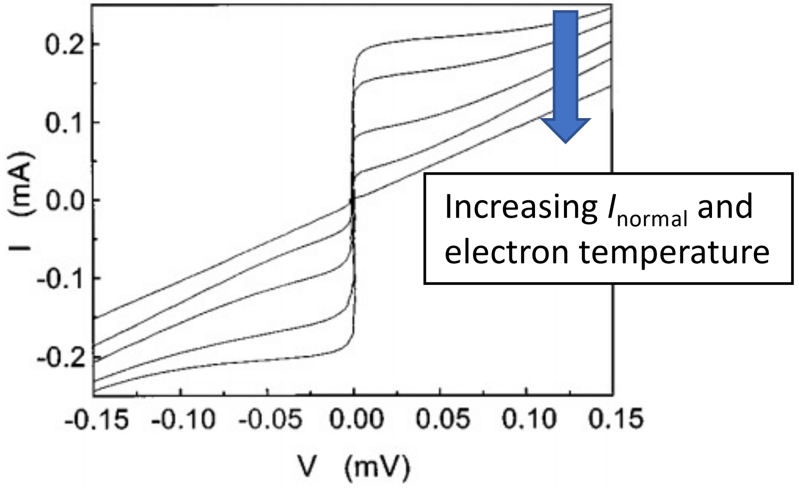
1. Poisson distribution
2. Mean count ∝ Laser power

Single photon detection

Orthogonal-Terminal Josephson Junction

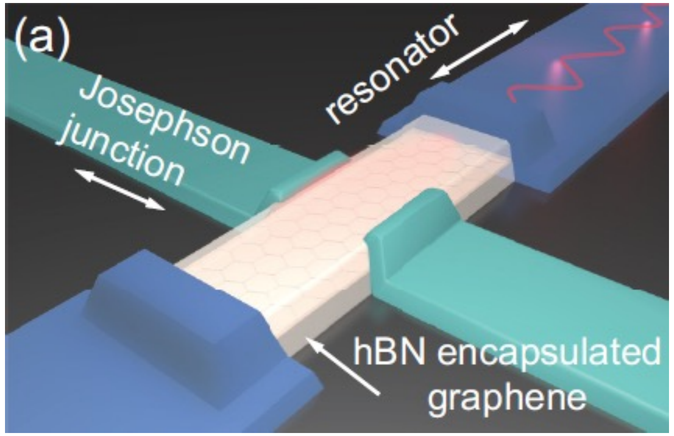
Previous work on orthogonal-terminal JJ

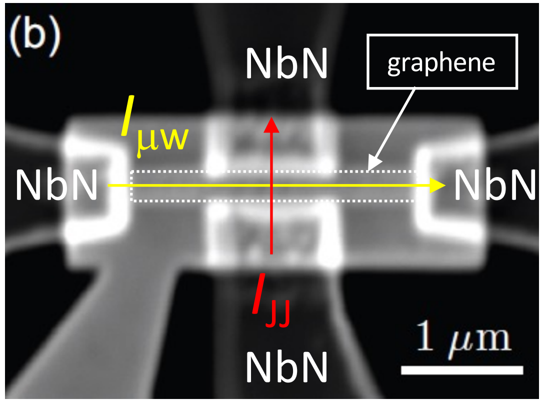




[A. F. Morpurgo *et al.*, APL 72, 23 (1998)]

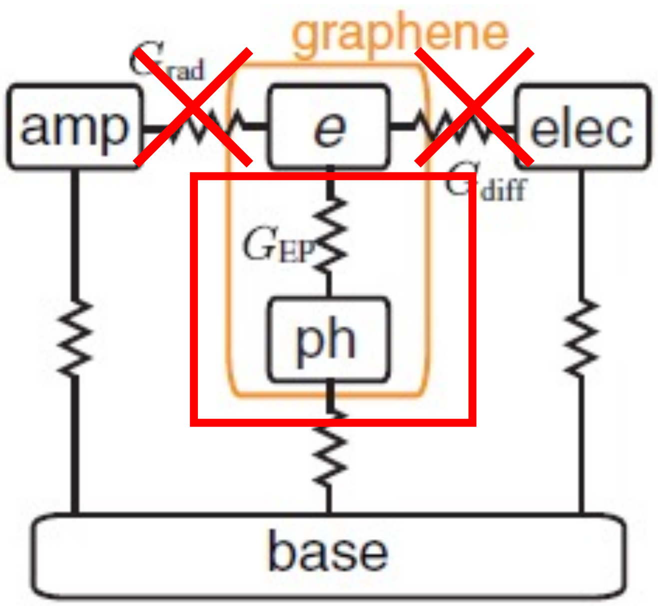
In this work





[GHL *et al.*, Nature 586, 42–46 (2020)]

Thermal Circuit



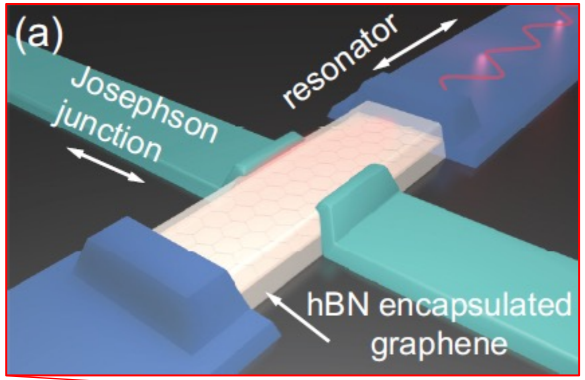
- G_{rad}: radiation to environment → very <u>small</u>
- G_{diff}: hot electron diffusion to electrode → <u>negligible</u> with superconducting electrode

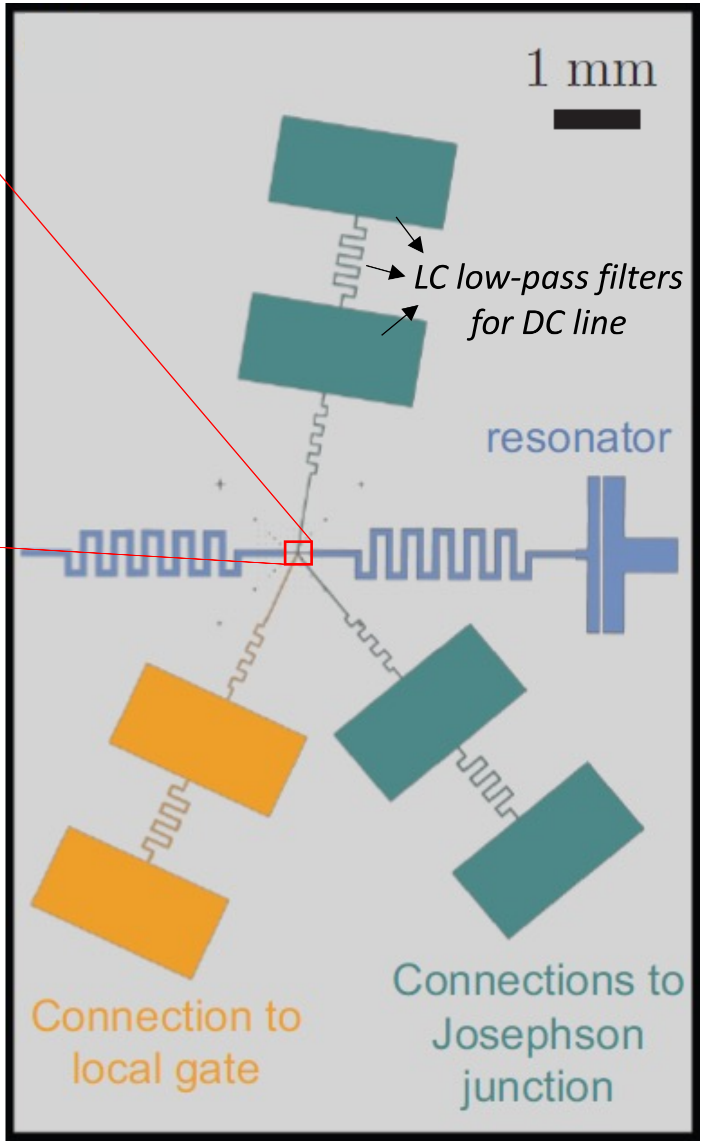
*Cooper pair doesn't carry momentum.

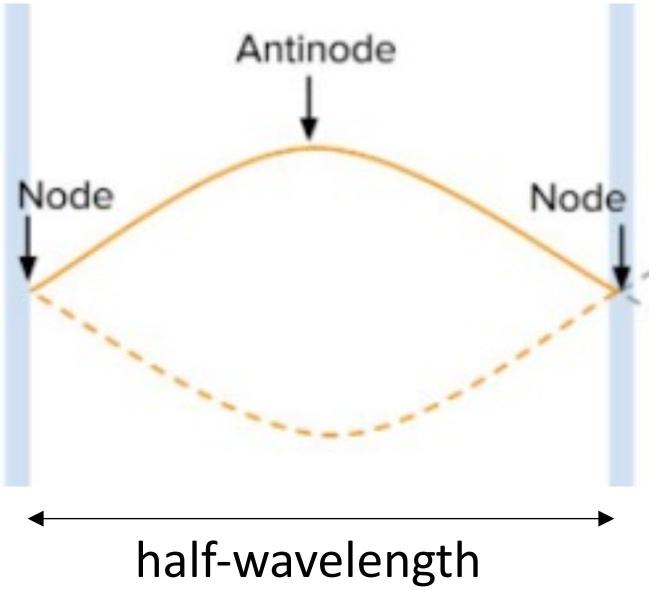
- **G_{EP}: electron-phonon cooling** → **dominant cooling channel**

POSTECH

GJJ-embedded Resonator







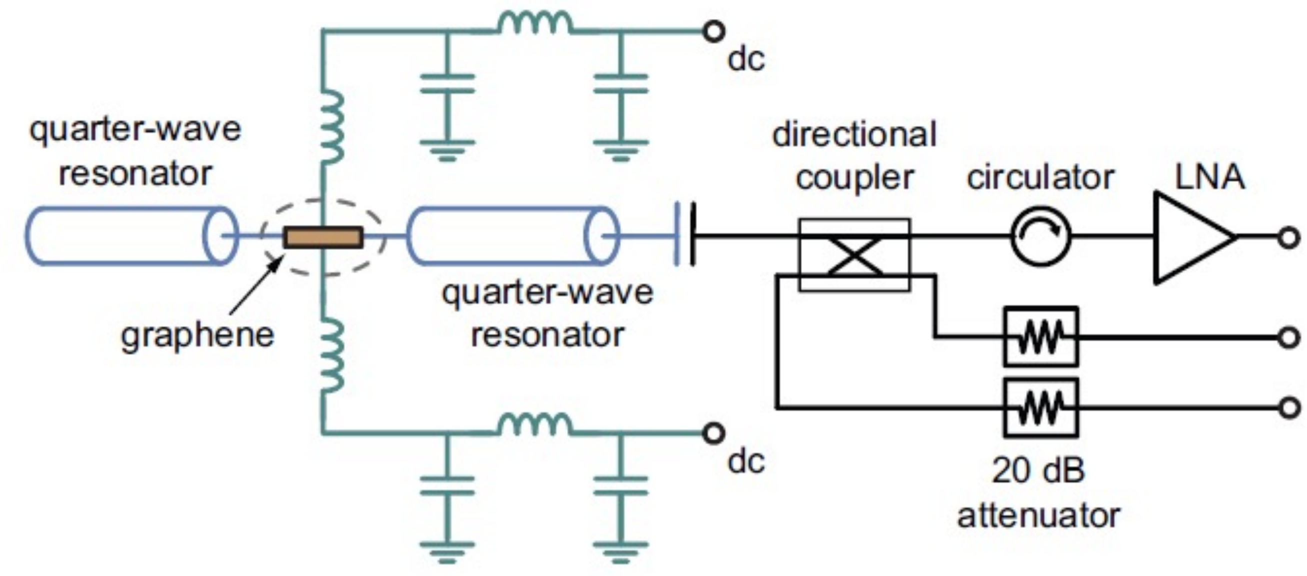
Graphene in current antinode (critically coupled)

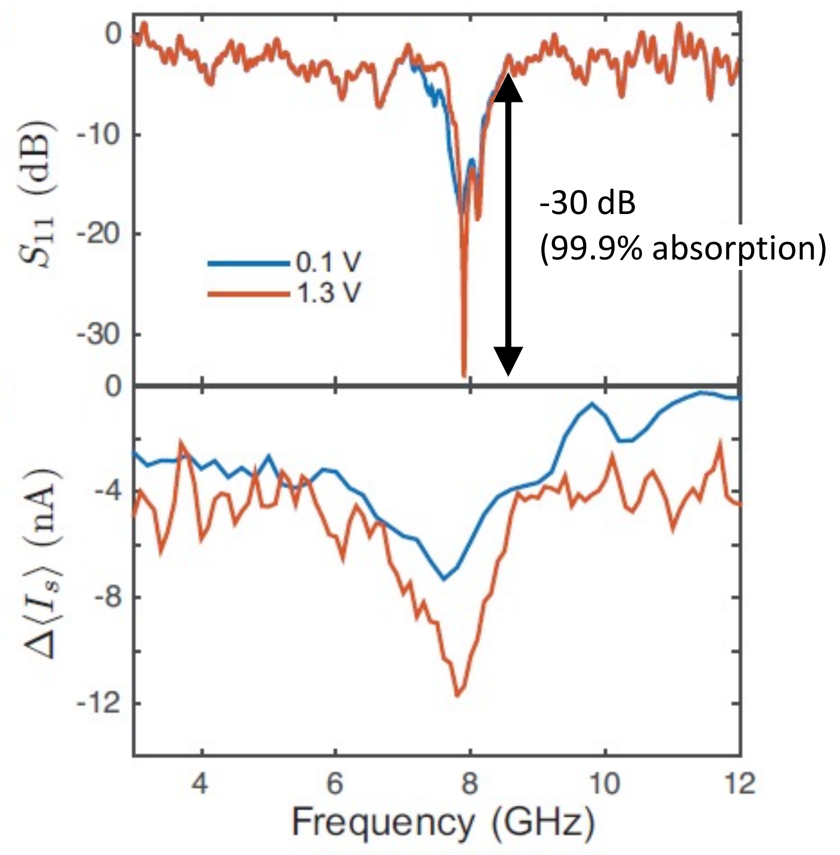
↓

Maximum power dissipation in graphene

Graphene Absorbing Microwave

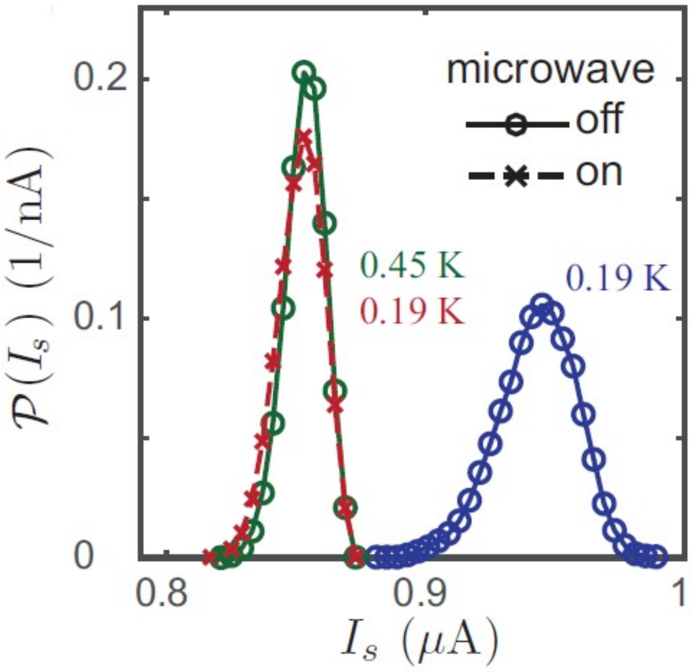
With continuous microwave, P_{in}=-112 dBm (6 fW),





$\langle I_s \rangle$ get suppressed at the resonance frequency, f=7.9 GHz.

Switching Current Distribution

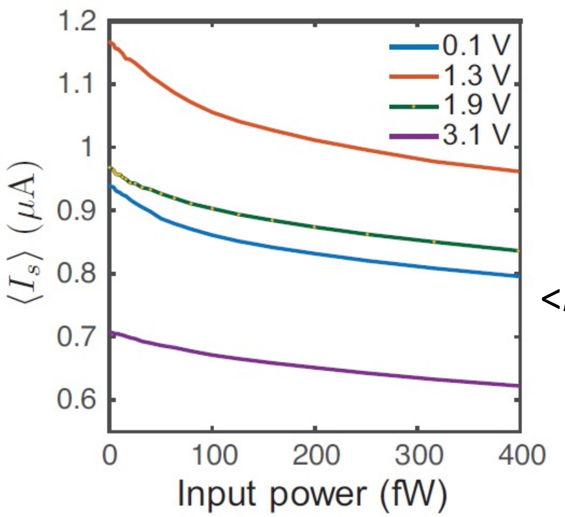


P(I_s) with microwave input has <u>same shape</u> of *P*(I_s) with elevated temperature.

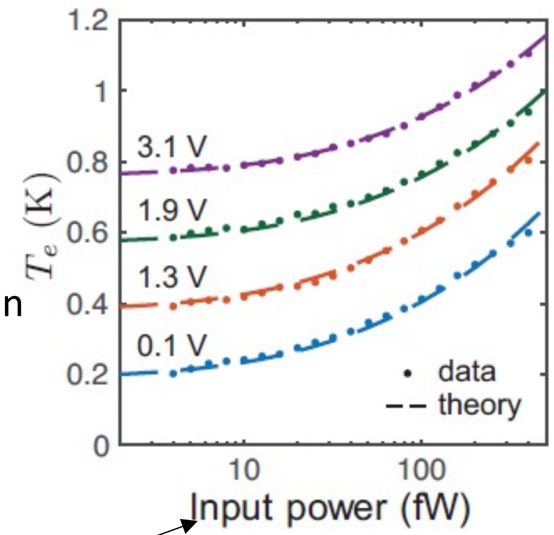
↓

Heated electrons get **fully equilibrated**.

Estimation of Electron Temperature, T_e



<I_s>-to-T_e conversion



Power due to electron-phonon coupling: $P = \Sigma A \left(T_e^{\delta} - T^{\delta}\right)$

- A: Area of graphene
- Σ: electron-phonon coupling parameter
- δ: temperature power law
- T: bath temperature

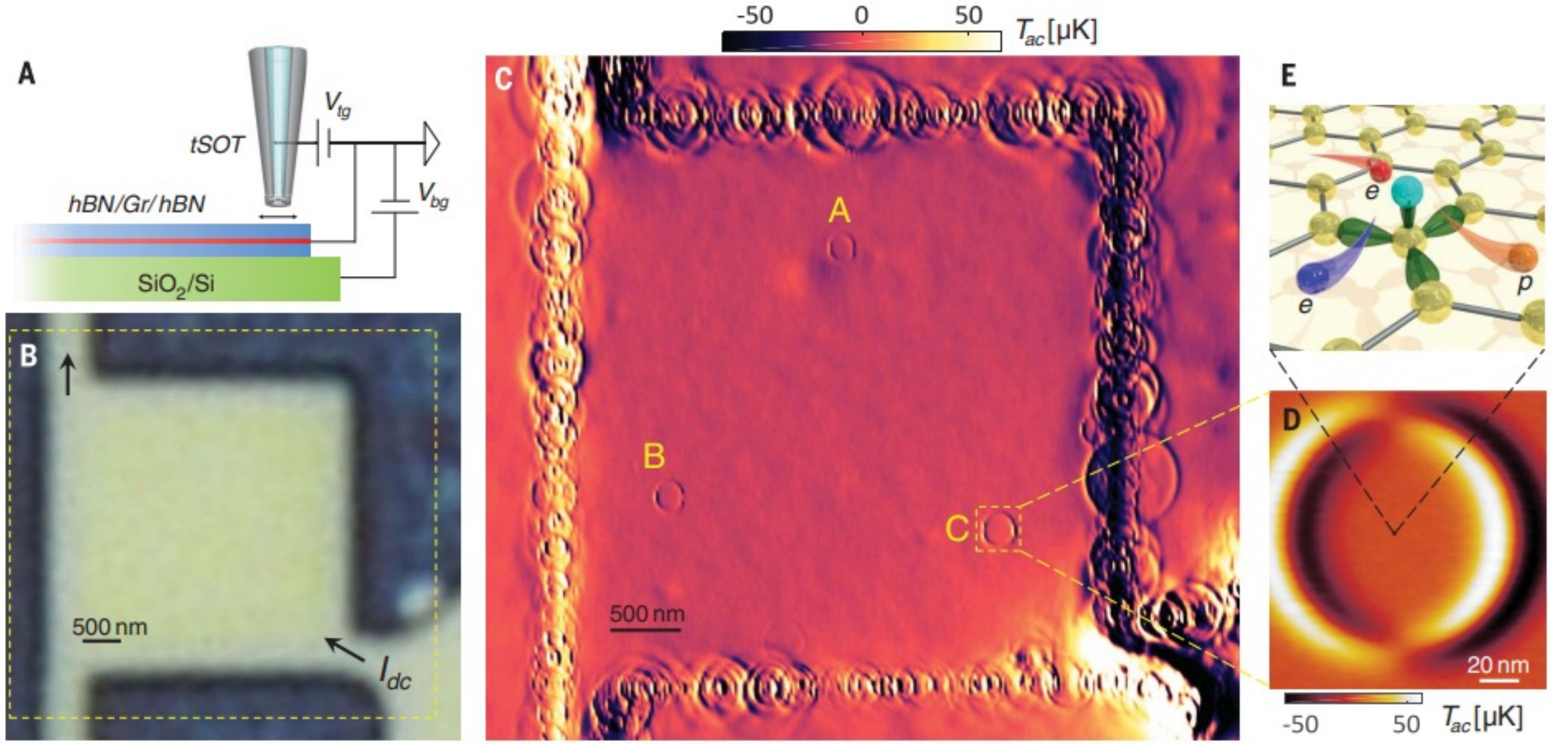
Fitting parameters: δ=3, $\Sigma_{e\text{-}ph}$ = 2.14~3.30 $Wm^{-2}K^{-3}$

el-ph coupling due to **disorder**

Large discrepancy. Why?

Estimated $\Sigma_{e\text{-}ph}$ with bulk mobility 20,000 cm^2/Vs ~ 0.01 $Wm^{-2}K^{-3}$

Cooling Mechanism via Atomic Edge Disorder



[D. Halbertal et al., Science 358, 1303 (2017)]

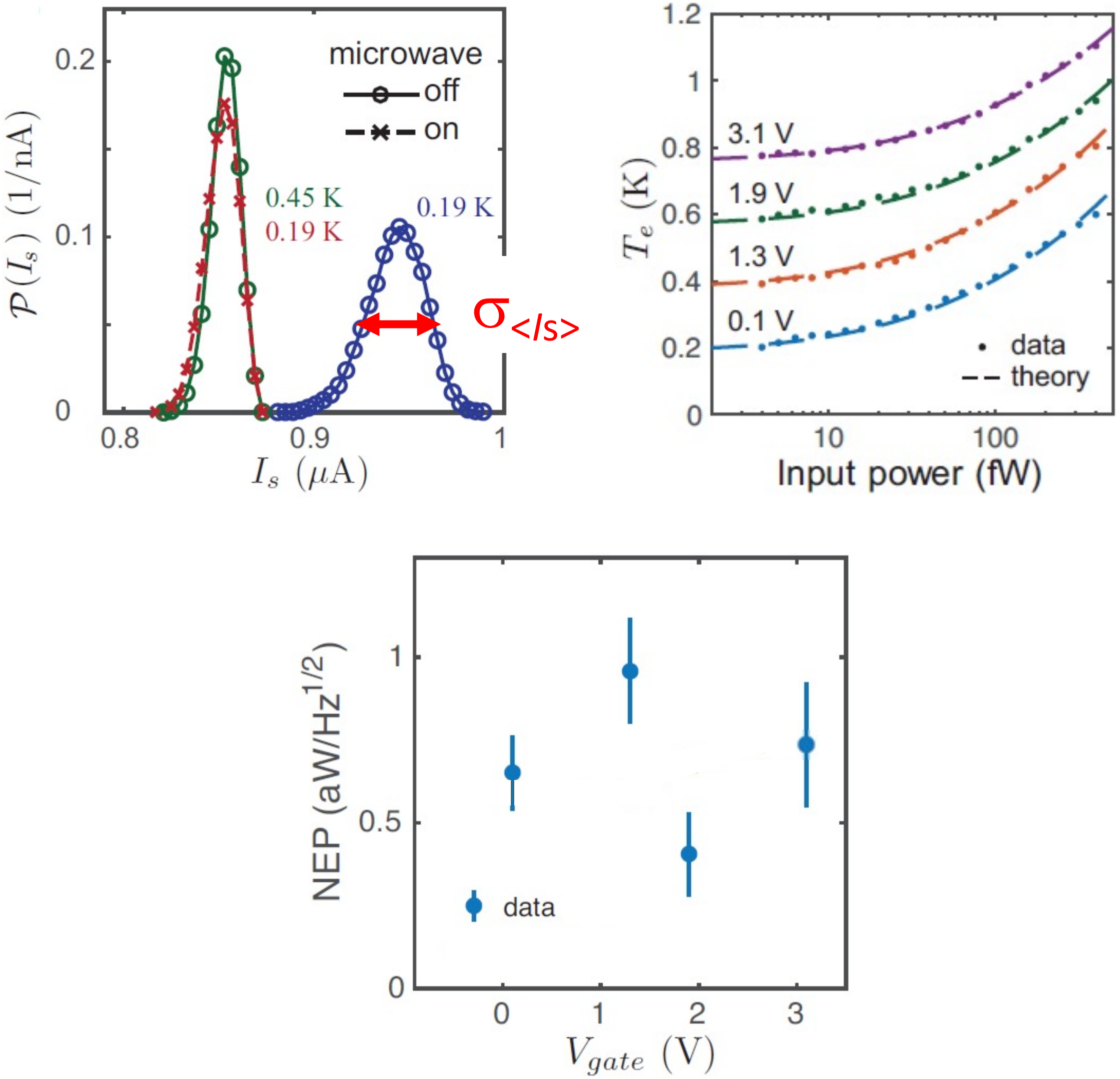
Atomic disorders at the edges could greatly enhance the electron-phonon coupling, Σ.

Theoretically estimated $\Sigma \sim 0.01\ \mathrm{Wm^{-2}K^{-3}} \ll$ Measured $\Sigma \sim 3\ \mathrm{Wm^{-2}K^{-3}}$

Noise Equivalent Power (NEP)

<u>Measure of sensitivity of a bolometer</u>

Noise equivalent power (NEP):
Signal power that gives signal-to-noise ratio of one.



- Minimum power P_{min} for changing $\langle I_s \rangle$ by $\sigma_{\langle Is \rangle}$.
  → P_{min} ~ 11.4 fW @ V_{gate}=1.9 V

- Time needed for sensing P_{min}
  1. Resonator input coupling time, τ_{in}~1.6 ns (**slowest**)
  2. Resonator dissipation time , τ_{dis}~ ~ 1.3 ns
  3. Thermal time constant, τ_{th}~ ~ 0.6 ns

→ **NEP=** $P_{min}/\sqrt{f_{in}}$**=0.45 aW/Hz$^{1/2}$**

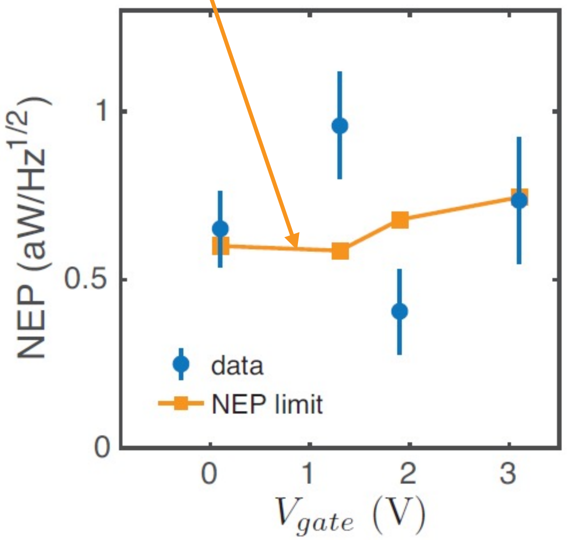
POSTECH

Fundamental Limit of NEP

Intrinsic thermal fluctuation imposes the fundamental limit of,

- energy resolution, $\Delta E \sim C_e\sqrt{\langle \Delta T^2 \rangle} = \sqrt{C_e k_B T^2}$
- Fundamental sensitivity of a bolometer,

  $\mathrm{NEP} = \sqrt{4G_{th}k_BT^2}$



Fluctuation of temperature:
$\sqrt{\langle \Delta T^2 \rangle} = \sqrt{k_B/C_e} \times T$

e.g.) for C_e=10k_B, T=0.1 K, ΔE~ 6 GHz

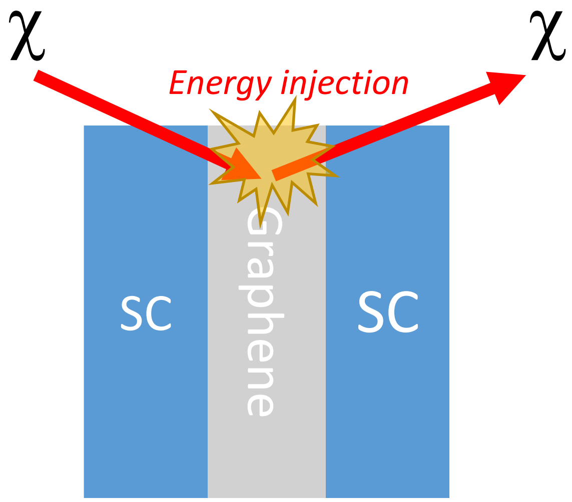
We reached the ***fundamental limit***

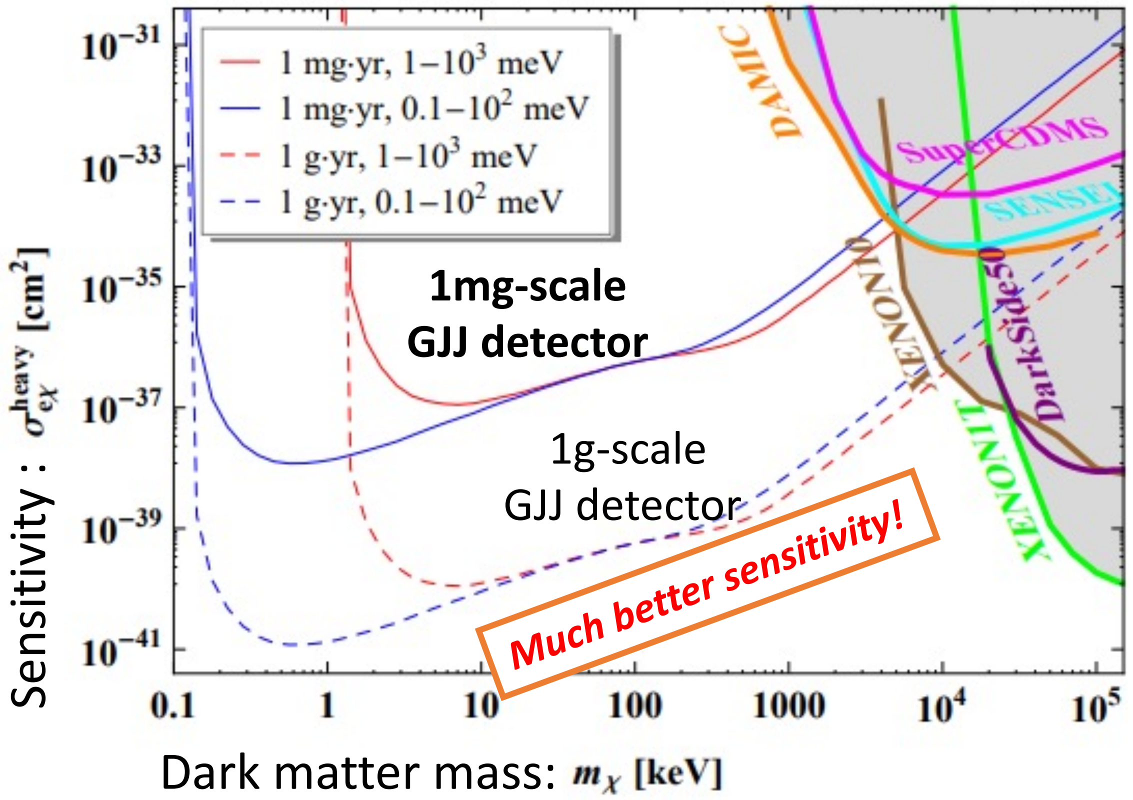
Expected energy resolution:
$\Delta E = NEP \cdot \sqrt{\tau_{in}}$ **~30 GHz**

[S. H. Moseley et al., JAP 56, 1257 (1984)]

c.f.) graphene-based bolometer with Johnson noise thermometry,
NEP ~ 0.4 pW/Hz$^{1/2}$ @ 2 K [K.C. Fong et al., PRX (2012)]
NEP ~ 10 pW/Hz$^{1/2}$ @ 5 K [D. K. Efetov et al., Nat. Nano. (2018)]

GJJ for Dark Matter Detection ?





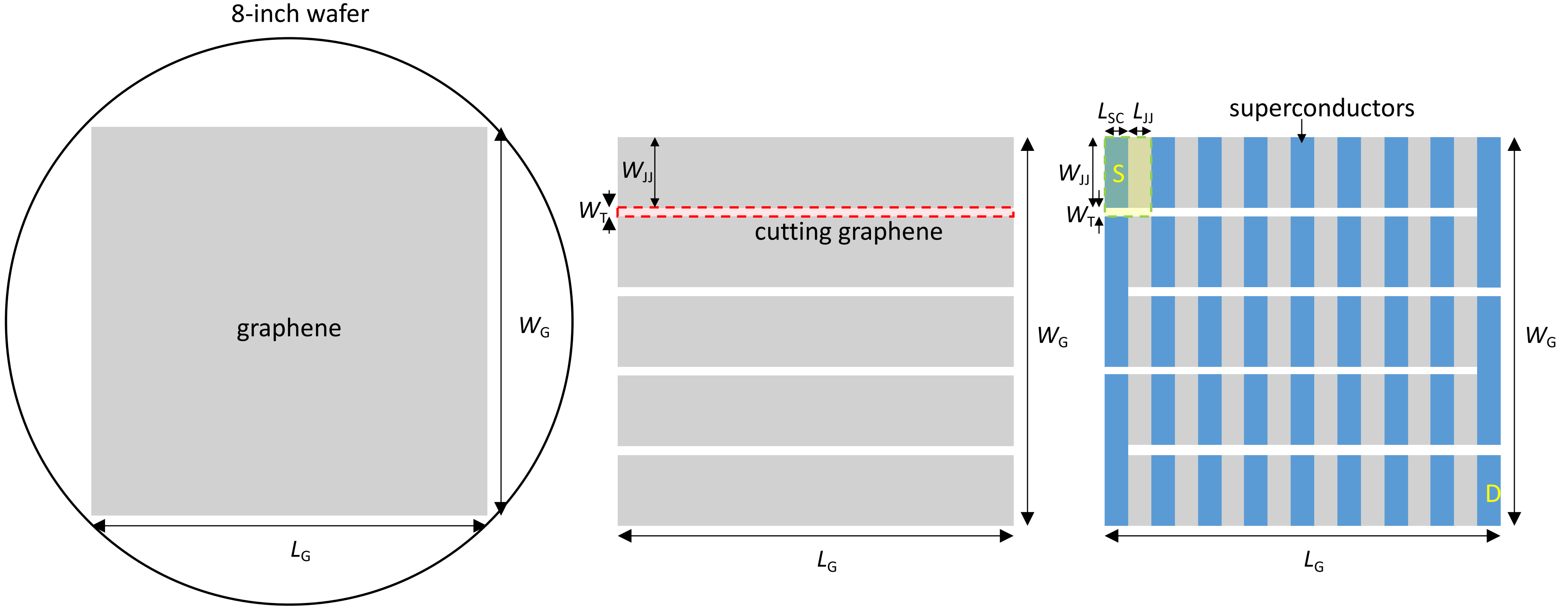
How can we make mg-scale GJJ detector?

Graphene-Based Bolometer for Detecting keV-Range Superlight Dark Matter, Doojin Kim, Jong-Chul Park, Kin Chung Fong, and **GHL**, arXiv:2002.07821 (submitted)

Proposal of 1mg-scale GJJ

For 1mg-scale GJJ, we need ~870 billion (8.7×10^{11}) GJJs.

*mass density of graphene: agr = 7.62×10^{-8} g·cm^{-2}
*GJJ dimension: L_{JJ}=0.5 μm, W_{JJ}=3 μm.

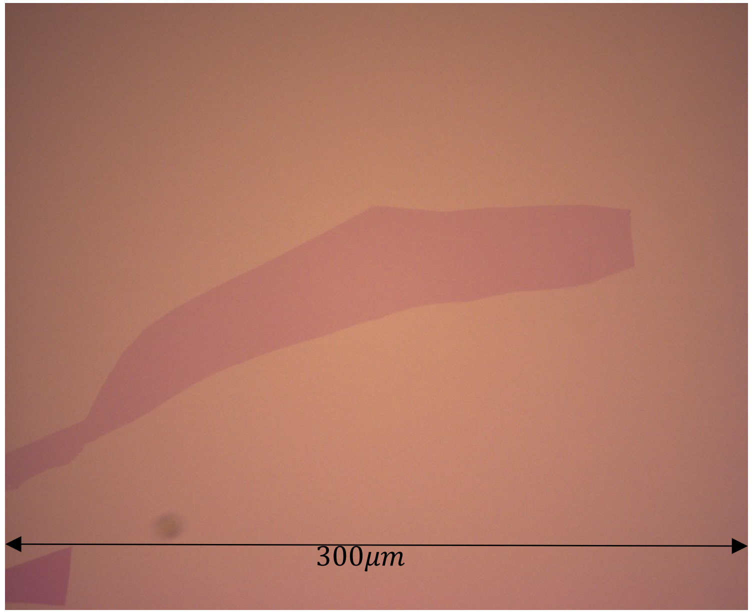


Number of GJJ in a single wafer: N_W= 5.6 billion (5.6×10^9)

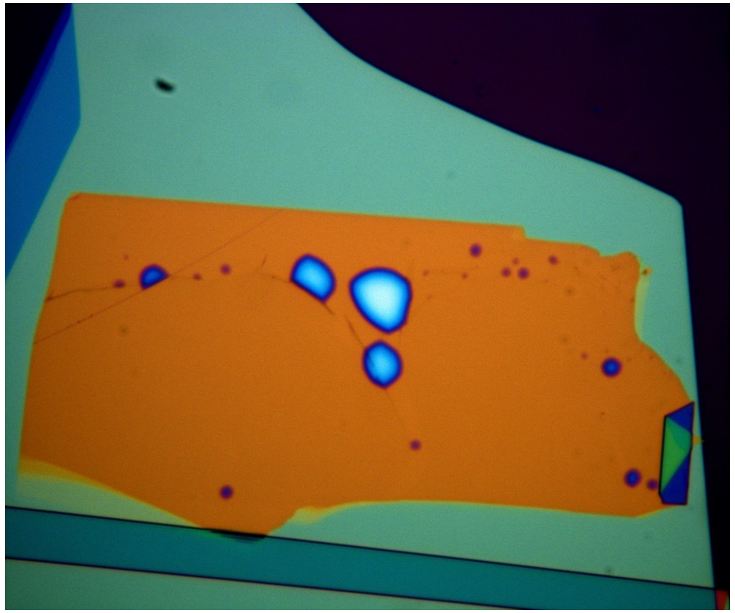
Then, we need 150 wafers connected.

* number of transistors in modern integrated circuit chips: 10 billion

Progress in Nano-fabrication – 216 GJJs in series (1)



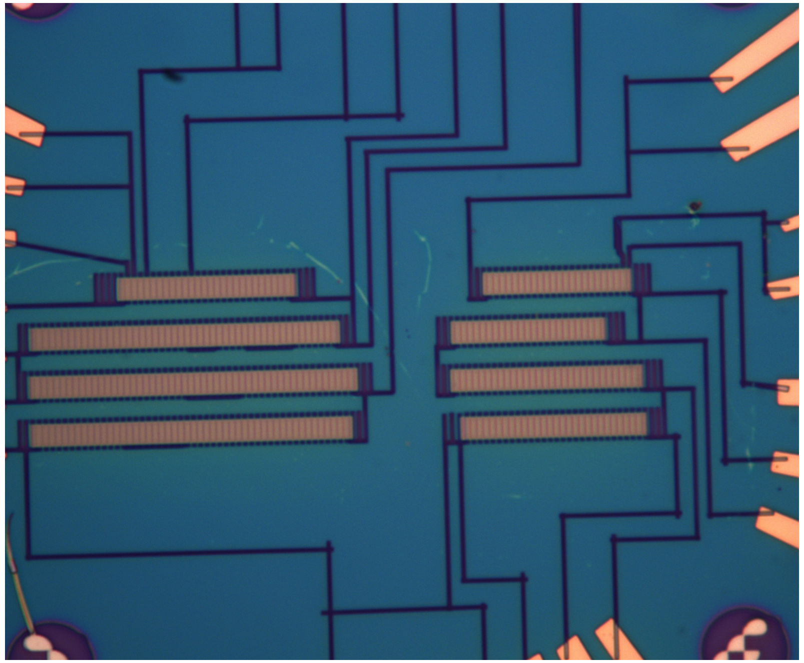
Large piece of graphene



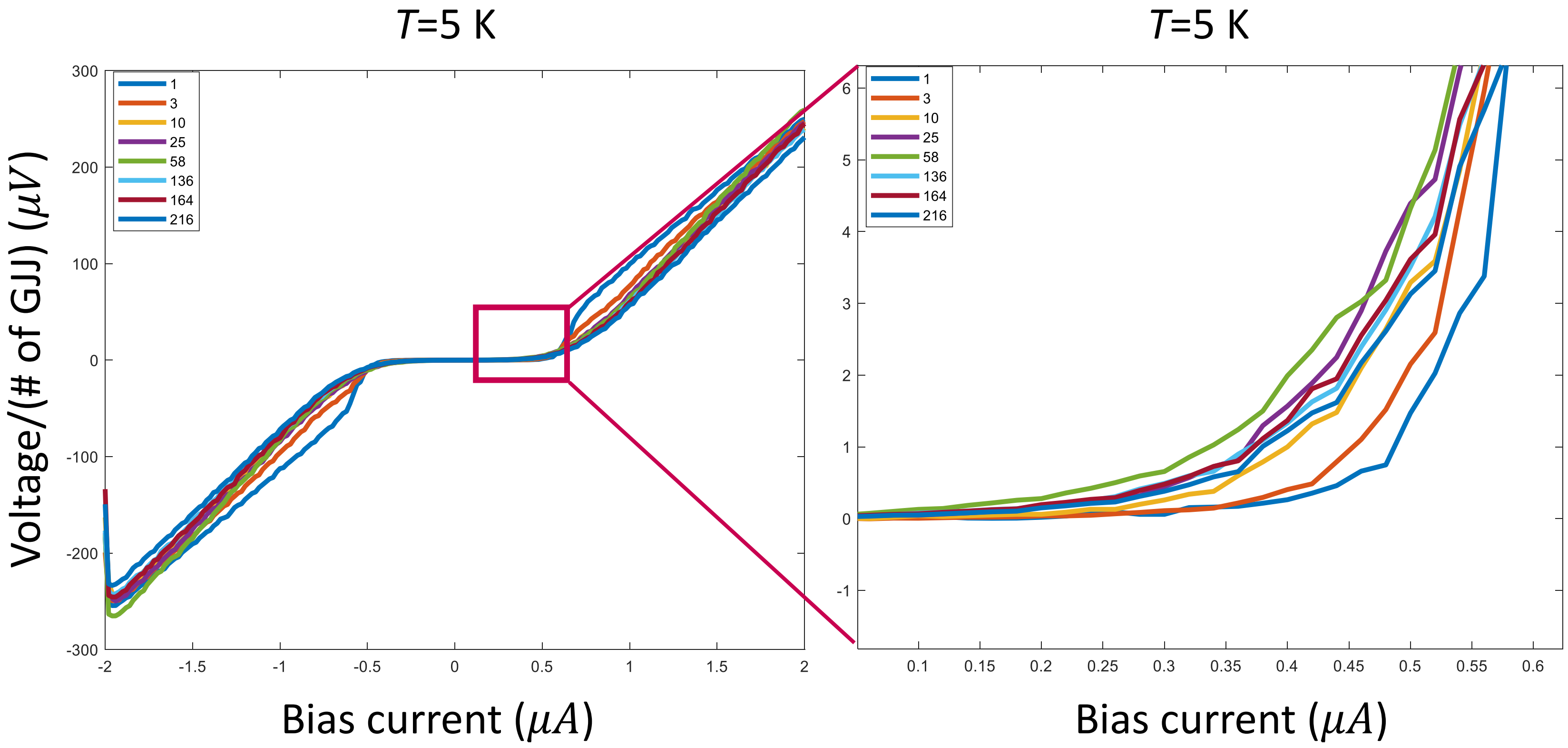
hBN-encapsulated graphene

Etched hBN/Graphene/hBN stack

Progress in Nano-fabrication – 216 GJJs in series (2)



216 GJJ electrode patterned



216 GJJ electrode patterned

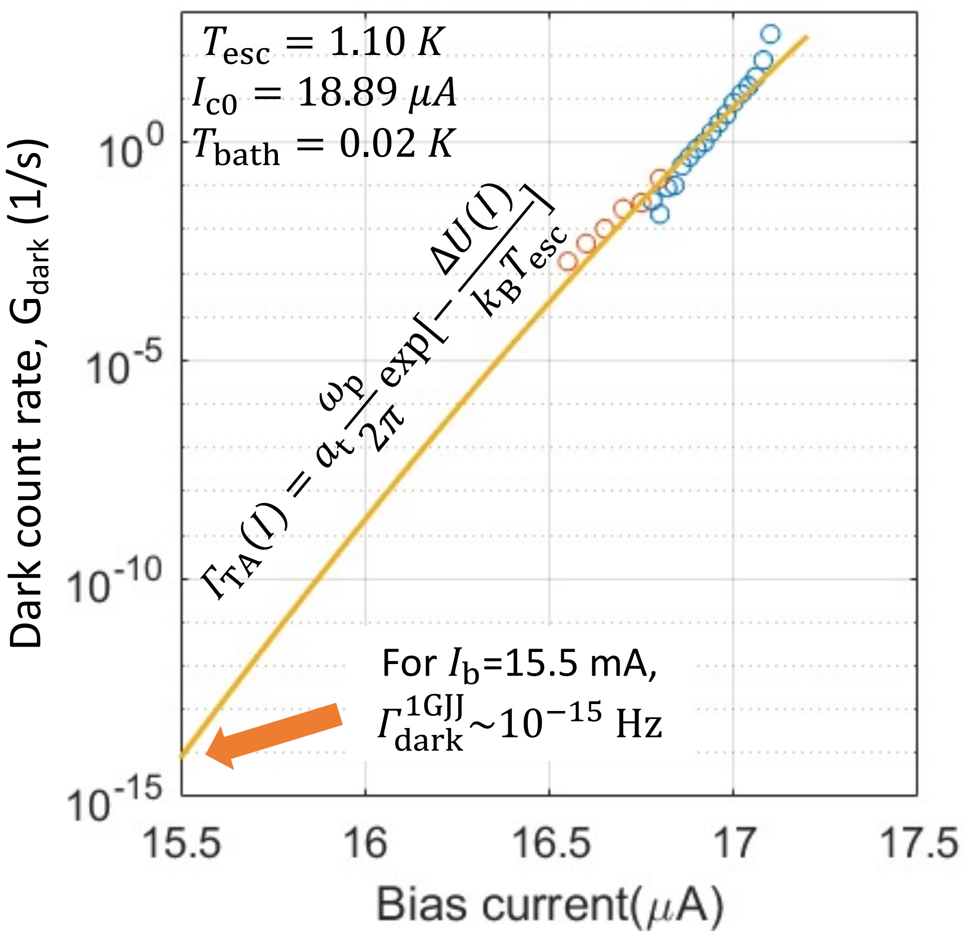
216 GJJ electrode patterned

Uniform 216 GJJs were successfully fabricated.

POSTECH

Dark Count Estimation

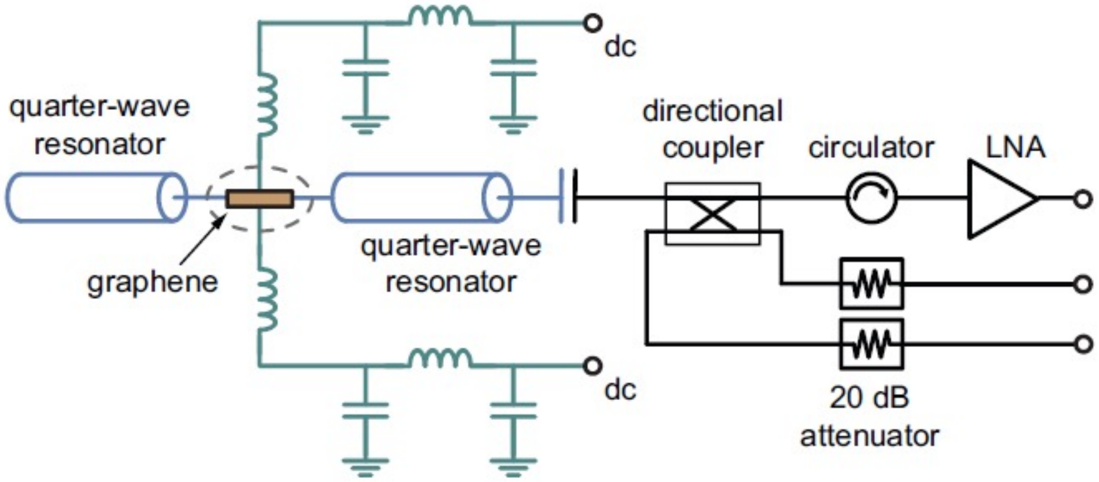
[Dark count rate measurement]

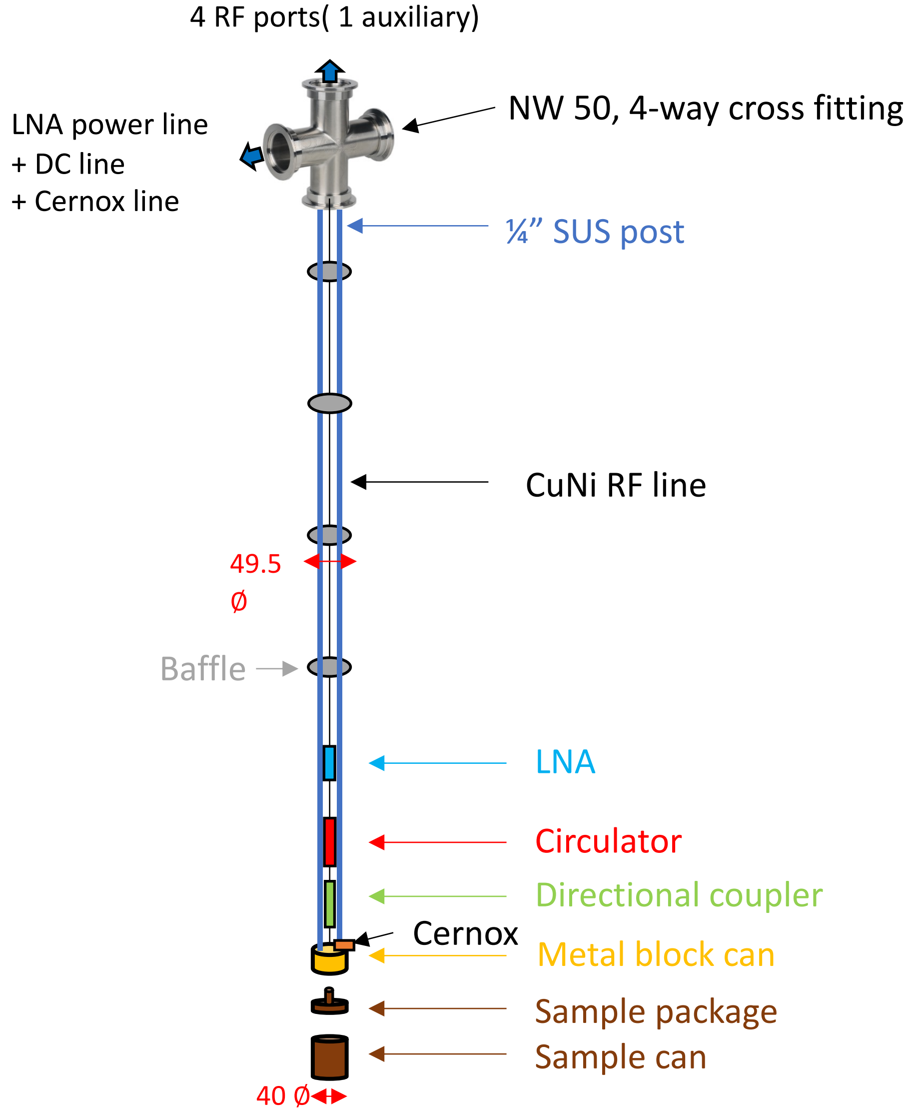


For 10^6-GJJ array $\Gamma_{\mathrm{dark}}^{10^6\mathrm{GJJ}} \sim 10^{-9}$ Hz, and
Dark count ~ 0.03 for 1-year.
(assuming all JJs have uniform I_c .)

POSTECH

Plan for Detector Calibration

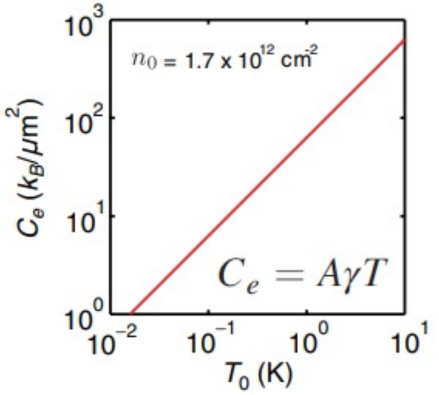


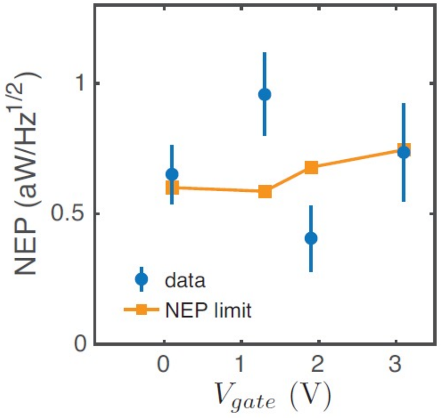


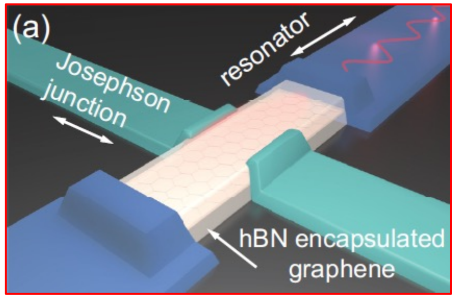
- Resonator absorbs only 8 GHz microwave
- Generate fake-signal with **8-GHz mw pulse** with varying its height
- Threshold measurement scheme for detection

Summary

- Graphene of minute heat capacity was utilized for sensitive microwave bolometer.
- Graphene Josephson junction was embedded in the resonator and measured with continuous microwave.
- Achieved fundamentally limited NEP of **0.7 aW/Hz$^{1/2}$**, which corresponds to the energy resolution of **~30 GHz (~0.1 meV)**.
- Implementing fast measurement is underway for microwave single photon detector.
- Detector development and calibration is on going for dark matter search.

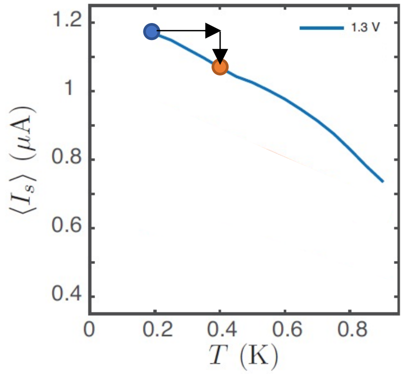




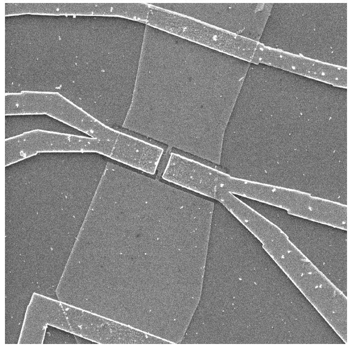


Current Efforts – Microwave Single Photon Detector

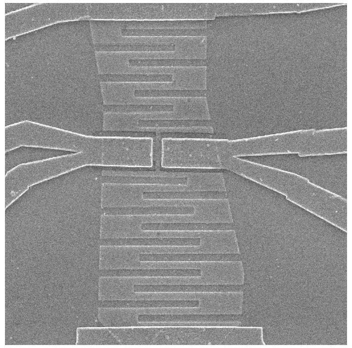
- Maximizing temperature sensitivity of I_c, (dI_c/dT ↑)
  - Optimization of junction geometry
  - Optimization of superconducting materials



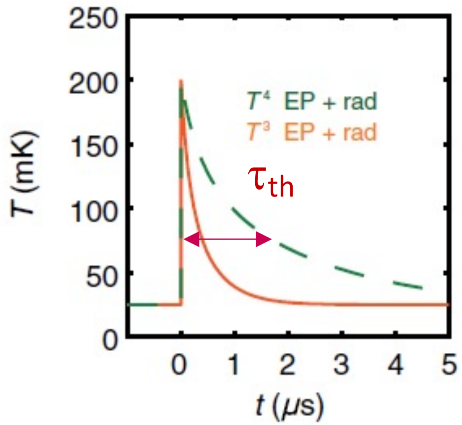
- Minimizing heat leakage to phonon, ($\Sigma_{e\text{-}ph}$ ↓, τ_{th} ↑)
  - Understanding the role of disordered graphene edge for $\Sigma_{e\text{-}ph}$



Pristine graphene



Etched graphene



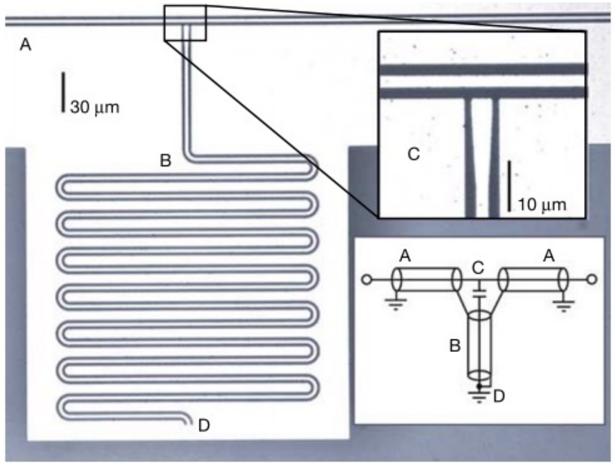
- Developing fast-enough (faster than τ_{th}) measurement of I_c change

For broadband microwave single photon detector !

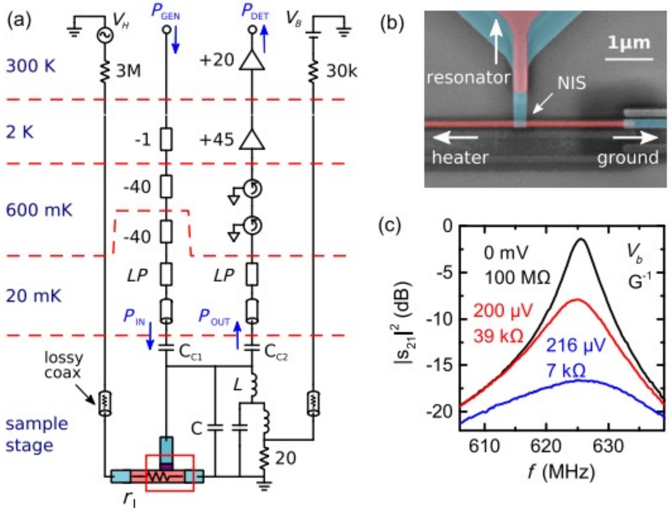
POSTECH

Examples of S/N-based Sensor

NEP = 6 aW/Hz$^{1/2}$ @ 0.1 K

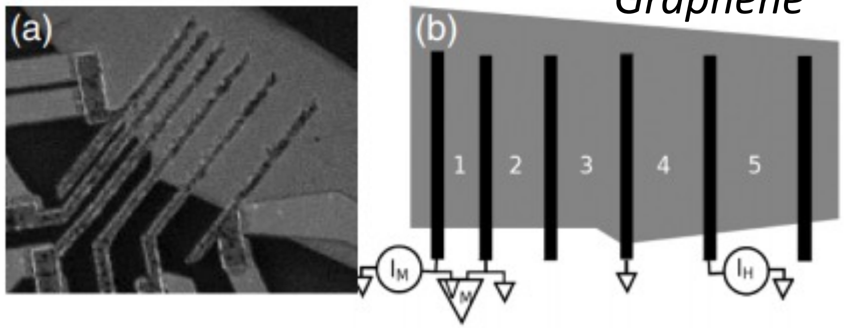


[P. K. Day et al., Nature 425, 817 (2003)]

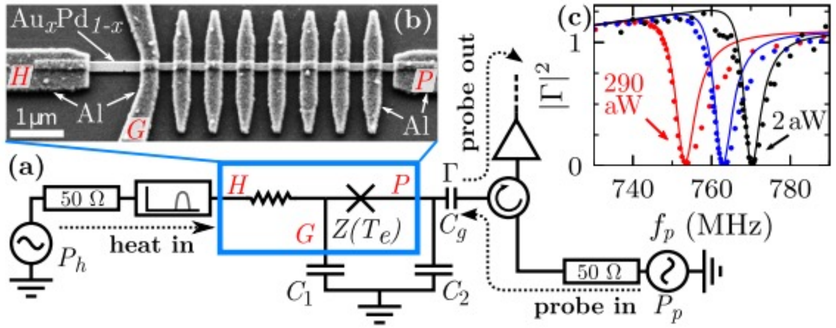


[S. Gasparinetti et al., PRApplied 3, 014007 (2015)]

Graphene



[I. V. Borzenets et al., PRL 111, 027001 (2013)]

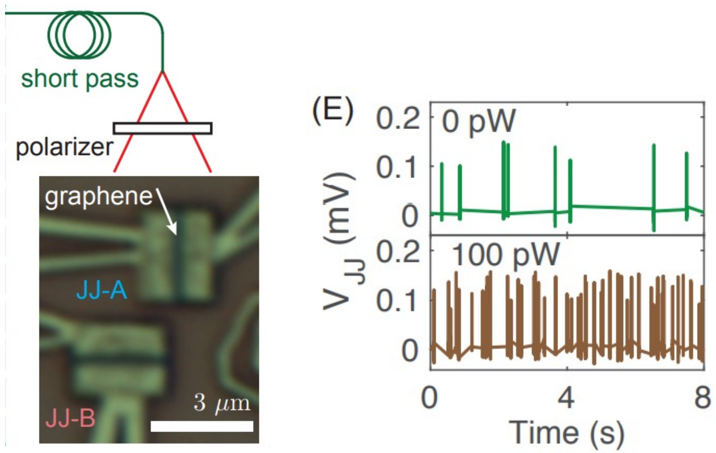


[J. Govenius et al., PRL 117, 030802 (2016)]

Single Photon Detector v.s. Bolometer

	Single Photon Detector	Bolometer
Quantity measured	One photon at a time	The power of photon flux
Energy resolving	No	Have information
Sensitivity	No fundamental limit	Fundamentally limited by thermodynamics

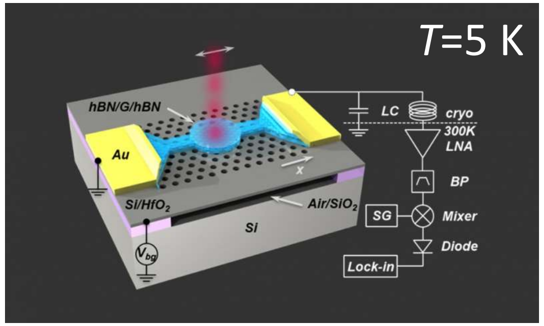
Demonstration of graphene-based IR-SPD



[E. Walsh, W. Jung, **GHL** et al., Science 372, 409-412 (2021)]

Complementary technology

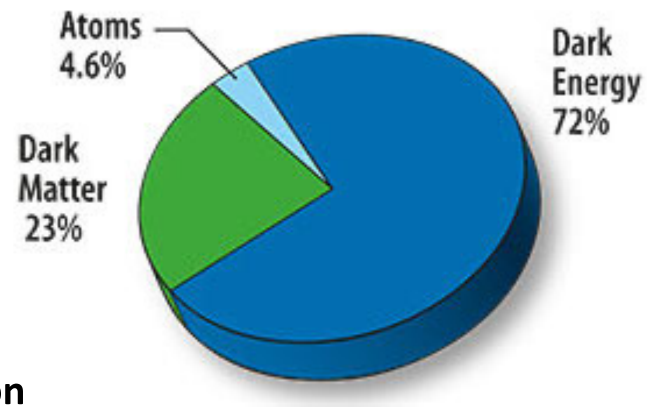
Demonstration of graphene-based bolometer



- Noise equivalent power (NEP): 10 pW/Hz$^{1/2}$
- Fast thermal relaxation time: < 35 ps

[D. K. Efetov et al., Nat. Nano. 13, 797 (2018)]

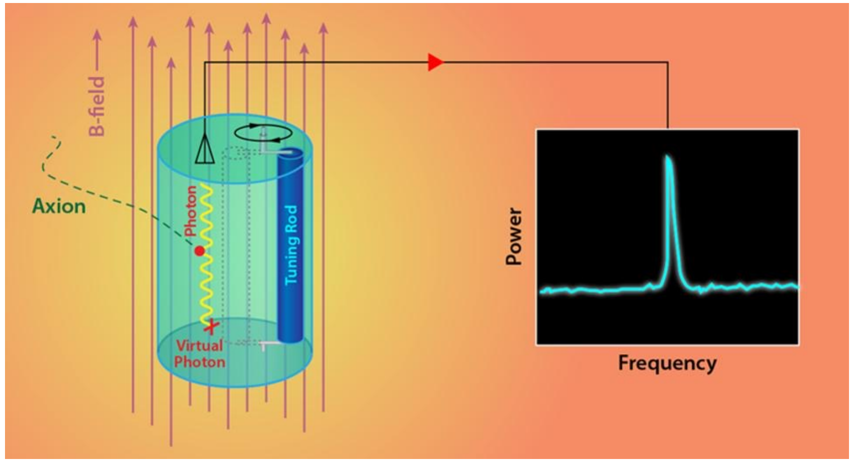
For Dark Matter Search



Axion

- Candidate for cold dark matter
- Mass: 10 μeV ~ 1meV (**2 ~ 200 GHz**)

[Peccei–Quinn theory (1977)]



CAPP-PACE detector setup in Korea