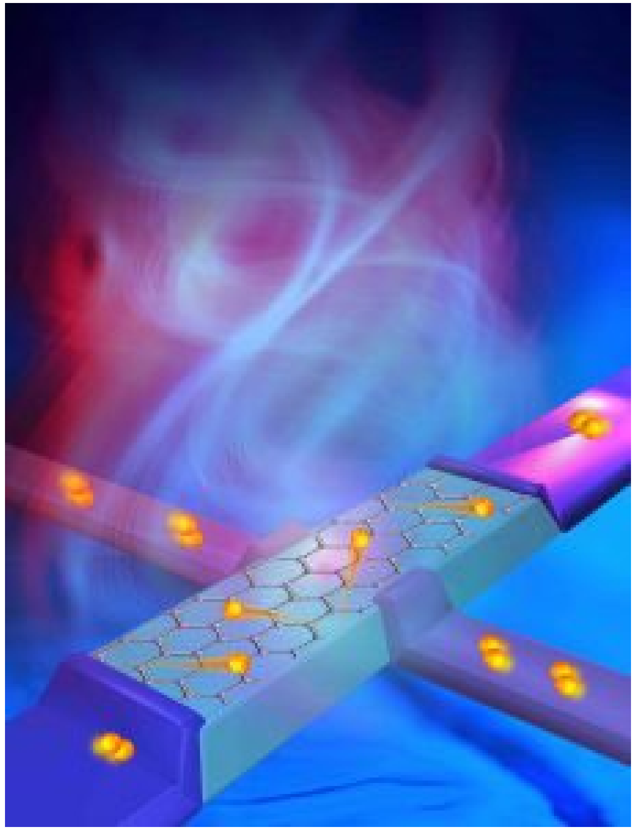
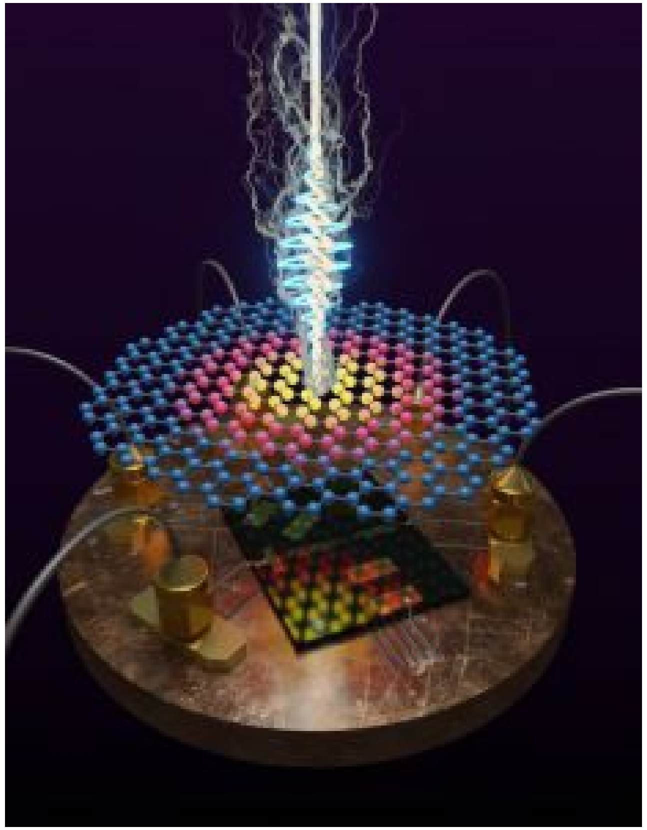
Developing graphene Josephson junction-based microwave detector



Gil-Ho Lee

Dept. of Physics, POSTECH, Korea

(https://ghleelab.postech.ac.kr/)



POSTECH

Quantum Nano-Electronics Lab in POSTECH

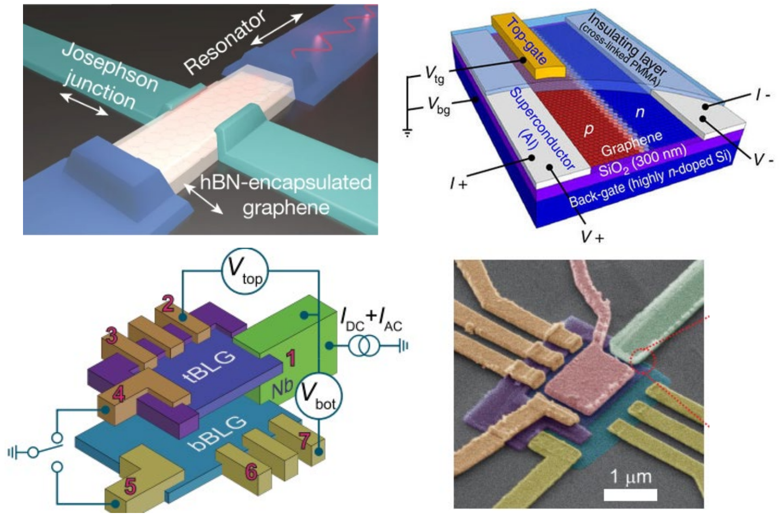
10 PhD students & 3 postdocs

Nano-fabrication

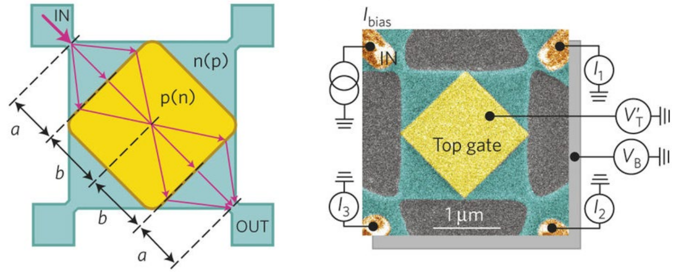
low temperature measurement

Research in QNL lab @ POSTECH

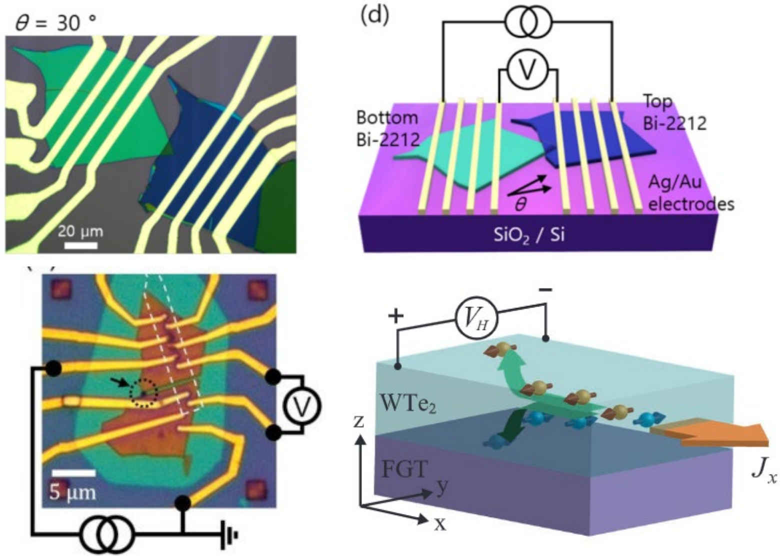
Graphene-Superconductor hybrid quantum devices



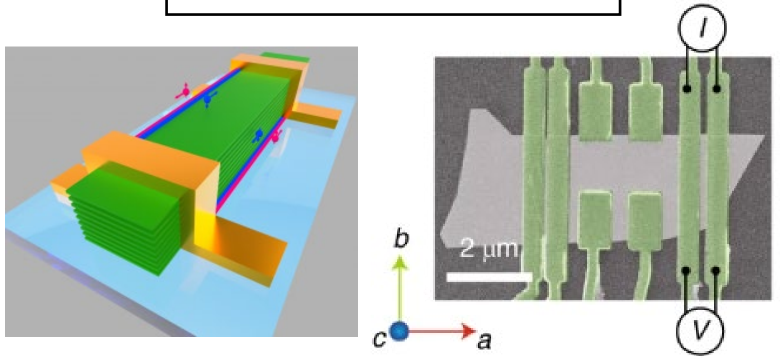
Dirac Fermionic Optics



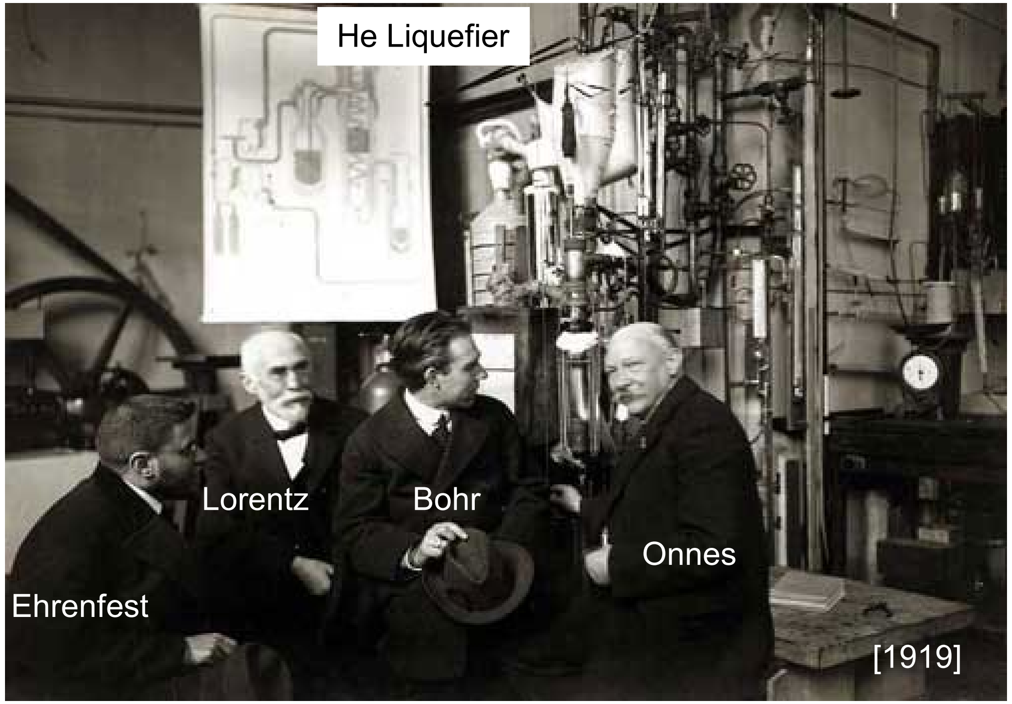
Van der Waals based quantum devices



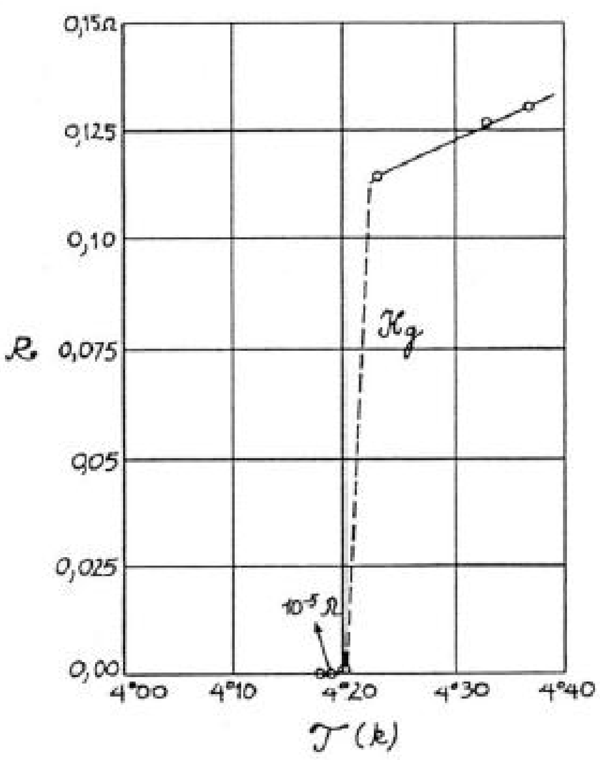
Topological materials



Superconductivity



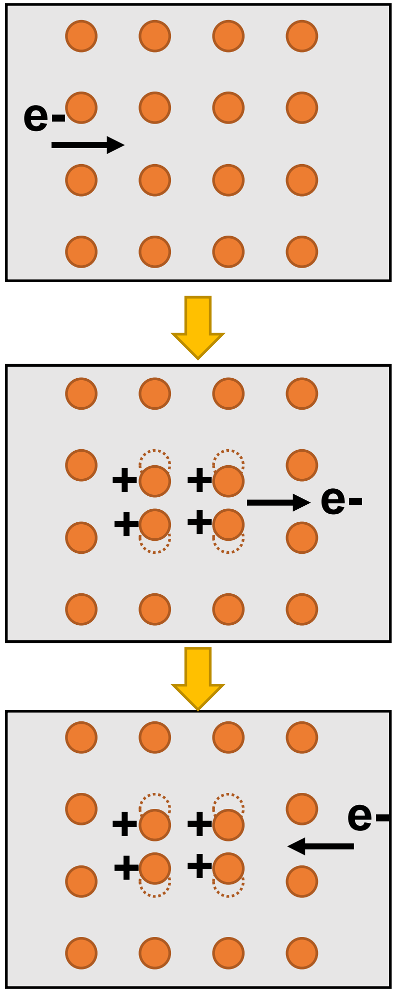
Superconductivity of Mercury (1911)

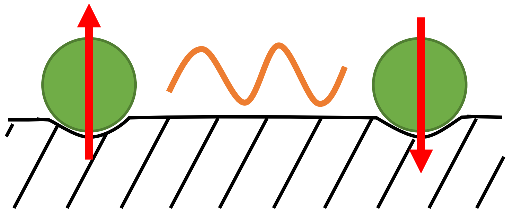


POSTECH

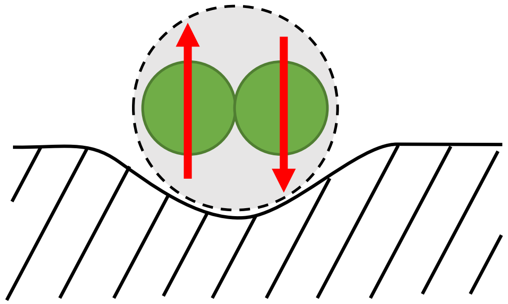
Superconductivity: Macroscopic Quantum Phenomena

Microscopic mechanism – BCS theory (1957)





Cooper pair



in BCS superconductor

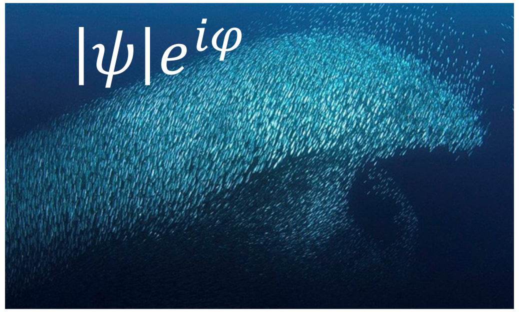
Spin-singlet (anti-sym.)

$$|S\rangle = \frac{1}{\sqrt{2}}(|\uparrow\downarrow\rangle - |\downarrow\uparrow\rangle)$$

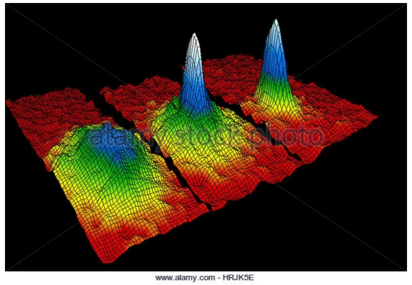
Orbital : *s*-wave (sym.)

Macroscopic quantum phenomena

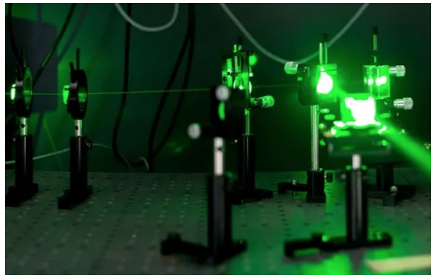
10^{23}-electroncs in superconductor behaves as a single quantum object



BEC condensate of atoms



Laser

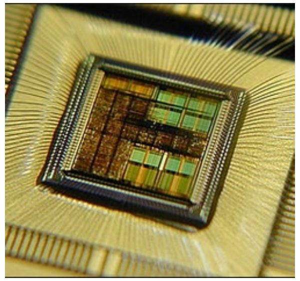


Quantum Electronics

- Study of quantum mechanical behavior of electrons in solids

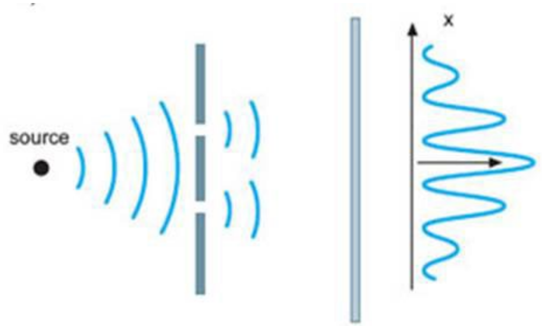
Fundamental Science		Applied Science
Classical Mechanics	→	Mechanical Engineering
Electromagnetics	→	Electrical Engineering
Quantum Mechanics	→	**Quantum Engineering**

e.x.) Engine



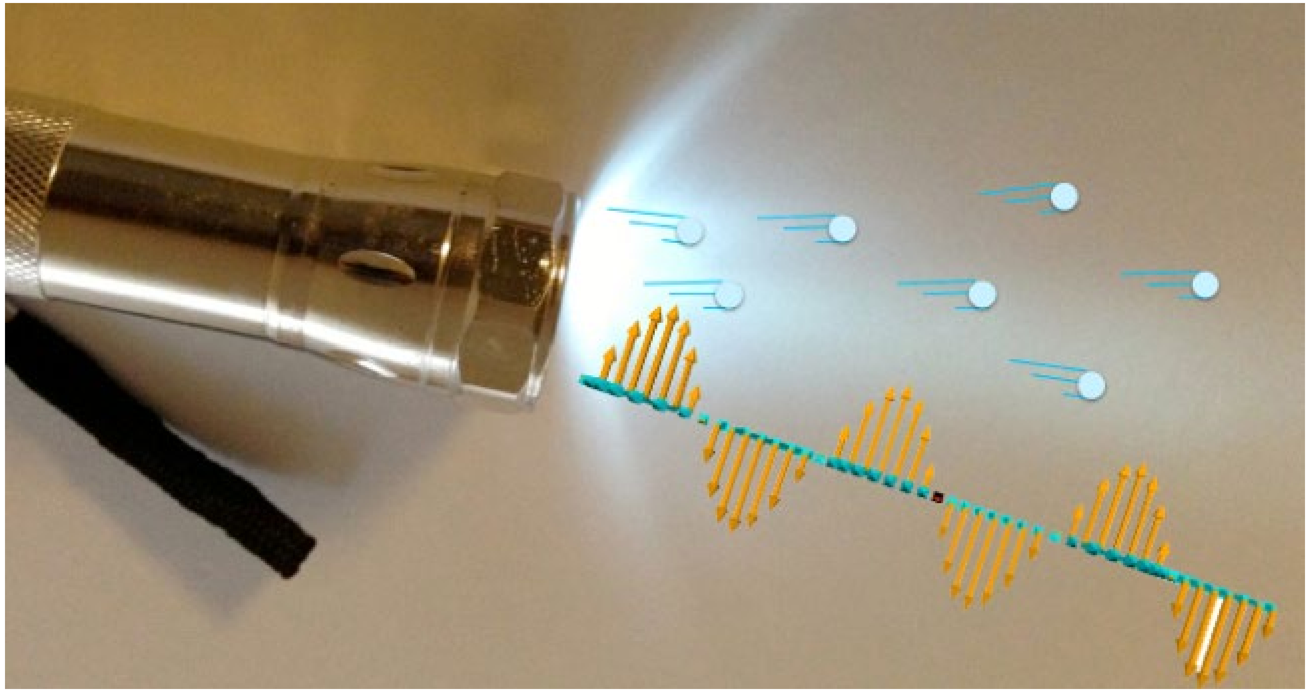
e.x.) CPU

e.g.) quantum coherence, superconductivity



e.x.) Quantum Computers

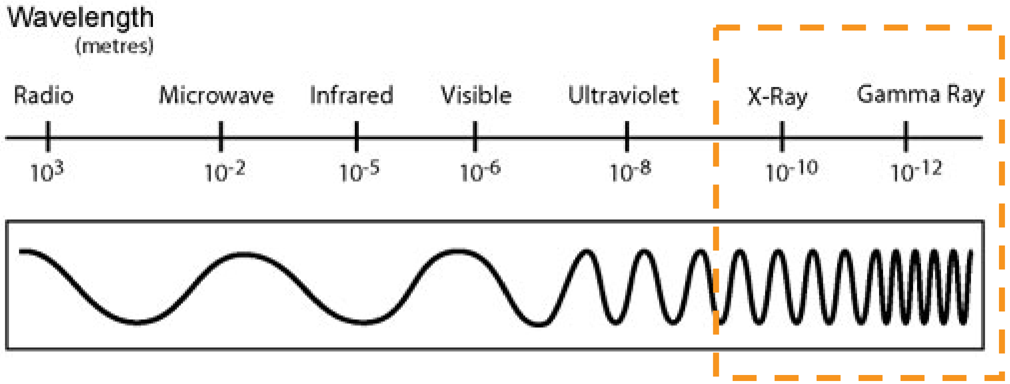
Light



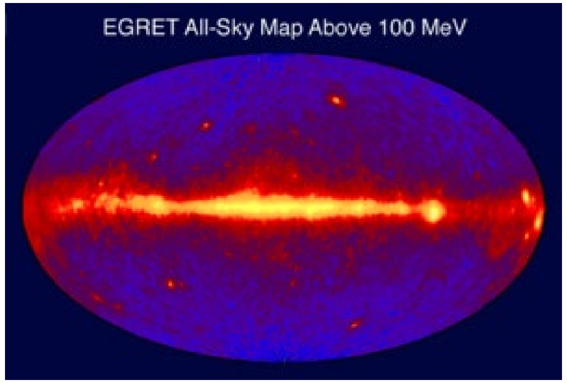
(Photon number, *n*) = (Light power, *P*) x (time, *t*) / (photon energy, *hf*)

Detecting single photons would be the ultimate detector for light.

X/γ-Ray



Medical X-ray imaging

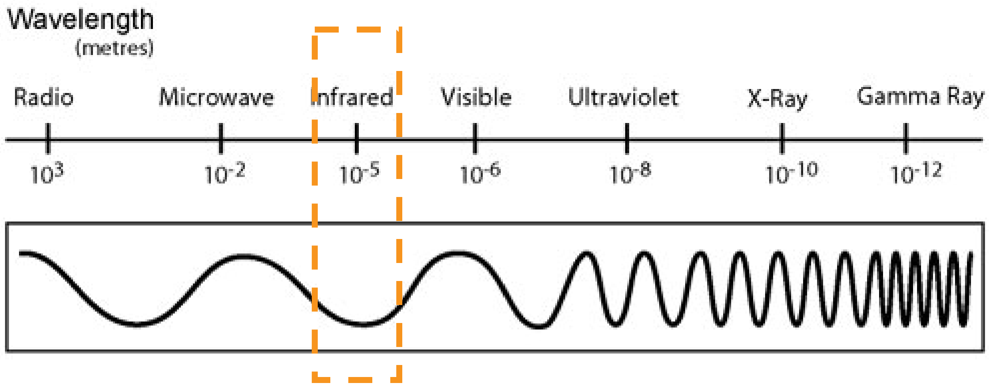


Gamma ray sky

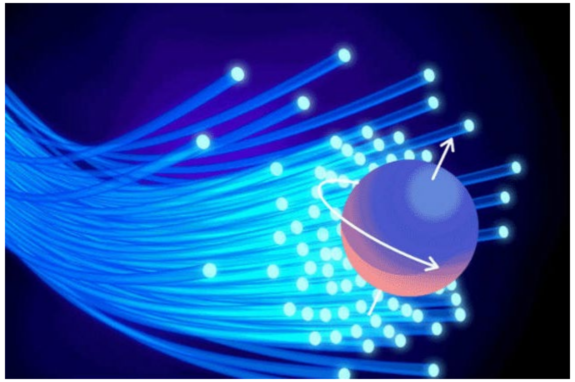
- in **X/γ-ray** range
  - Medical imaging
  - Material science
  - Astronomy science

Material Science suing synchrotrons

Infra-red

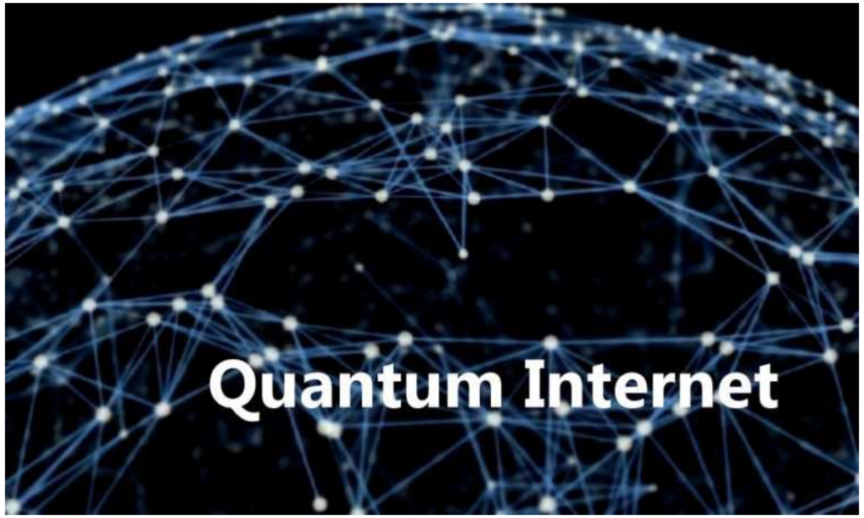


Infrared camera

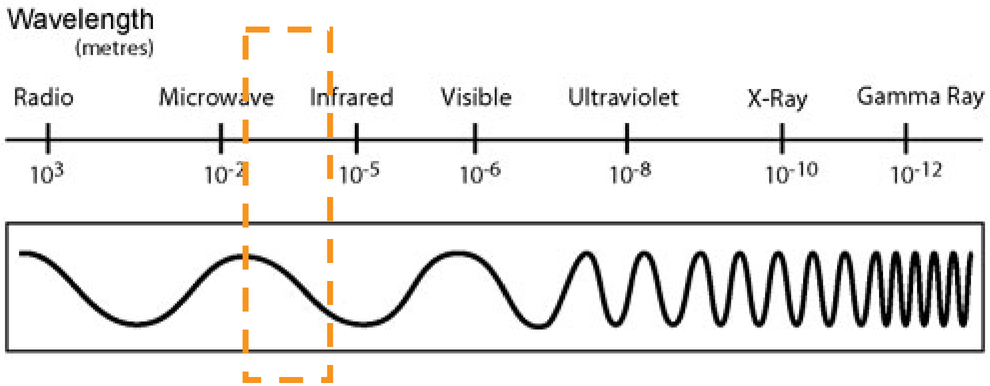


Optical cable

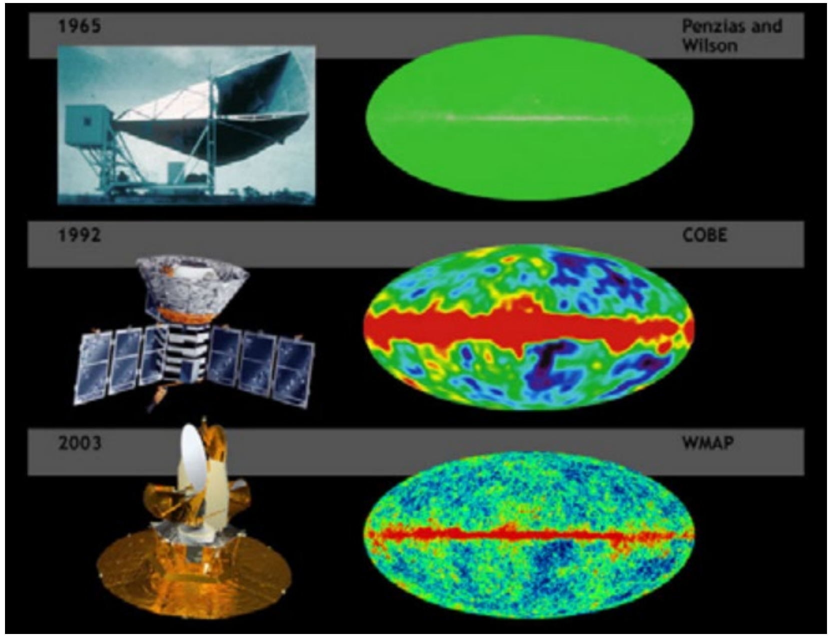
- in **IR** range
  - optical quantum communication
  - quantum key distribution



Terahertz

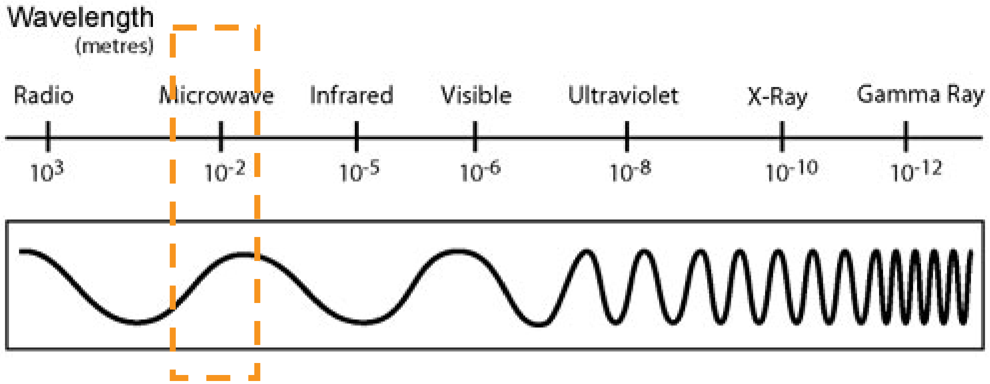


- in **THz** range
  - galaxy formation via cosmic radiation

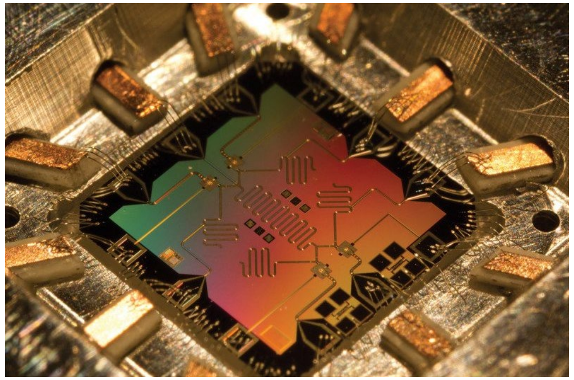


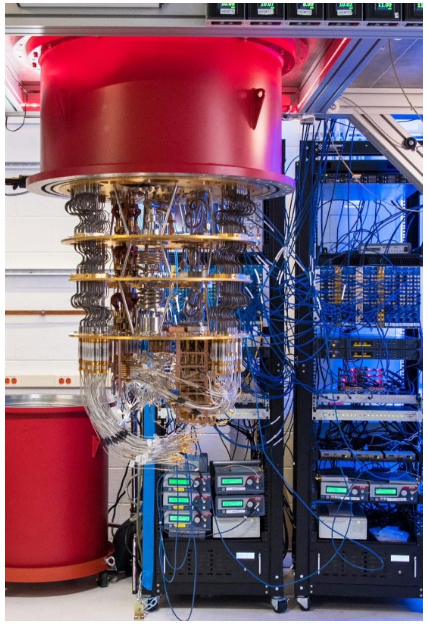
POSTECH

Microwave



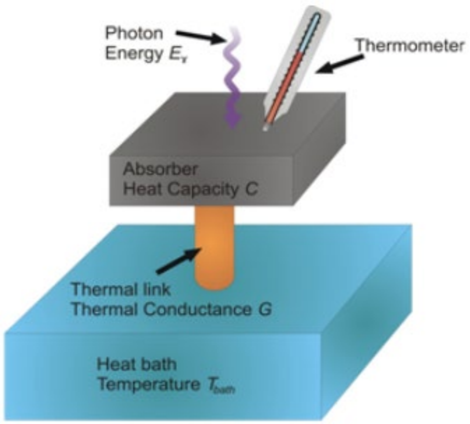
- in **GHz** range
  - remote entanglement of superconducting qubits
  - high-fidelity quantum measurements
  - microwave quantum illumination

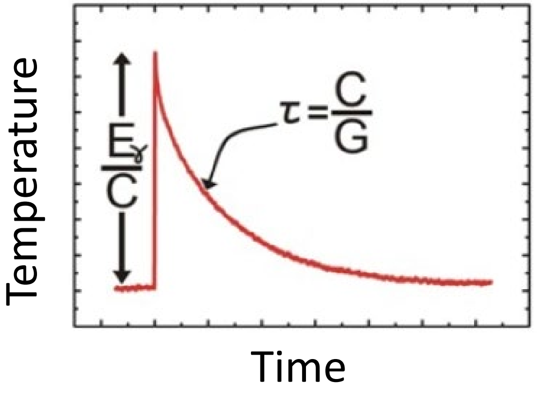




Thermal Detector

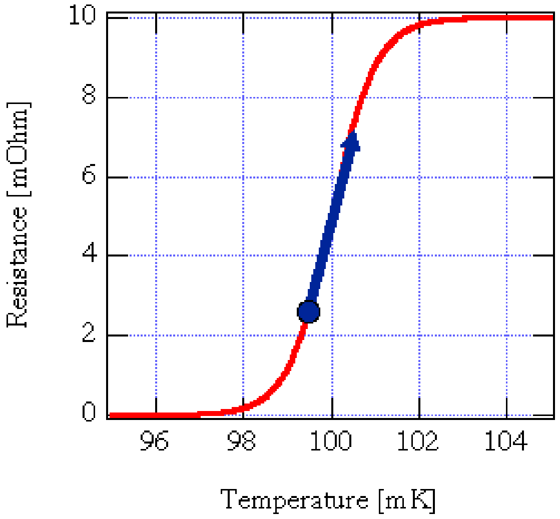
- No need to collect electron
- No threshold
- Robust against impurities
- More freedom to choose material



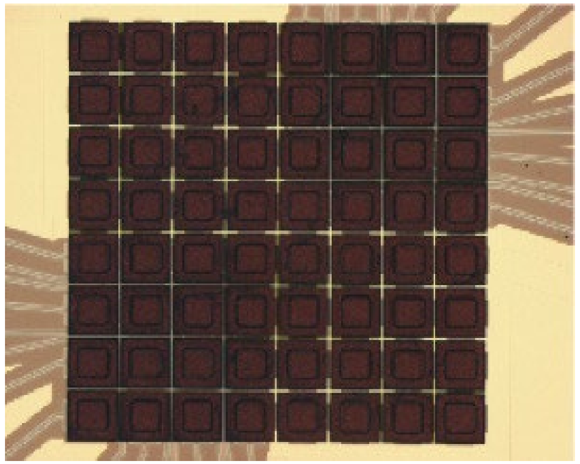


- E_Γ: Photon energy
- C : Heat capacity
- G : Thermal conductance

Transition Edge Sensor (TES)



Array of TES



Smaller C

↓

Higher temperature rise

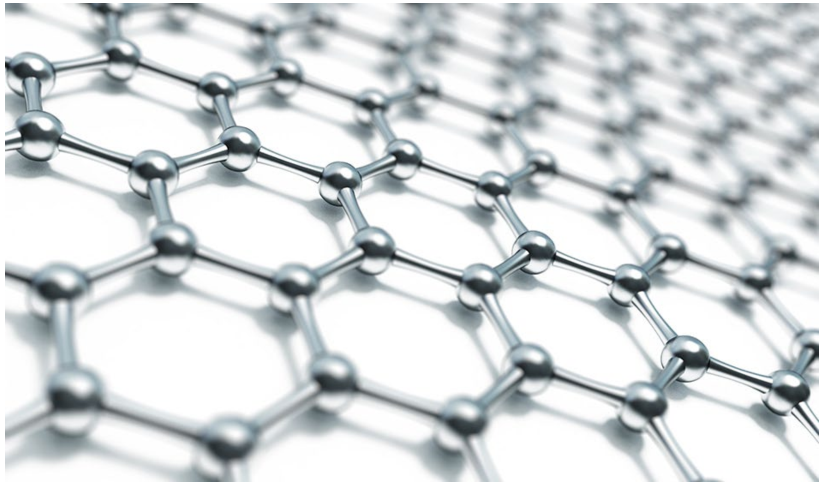
↓

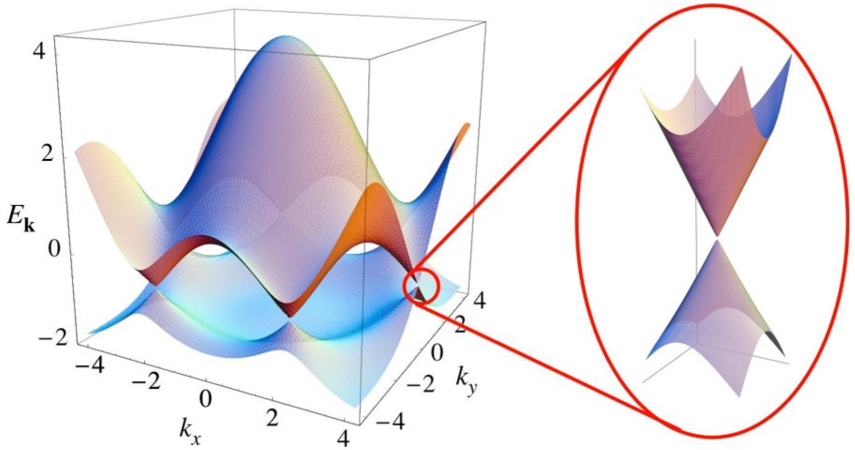
Faster cooldown

(shorter deadtime)

POSTECH

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.

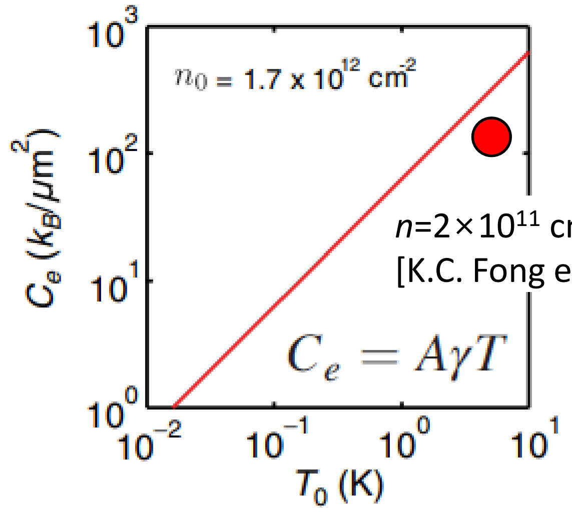
[Nat. Phys. 9, 248 (2013)]

- Broad absorption bandwidth by impedance matching

Small Electronic Heat Capacity, C_e

Specific heat capacity of monolayer graphene:

C_e **~ 10k$_B$/μm^2** (@ T=0.1 K, n=1.7×10^{12} cm^{-2})



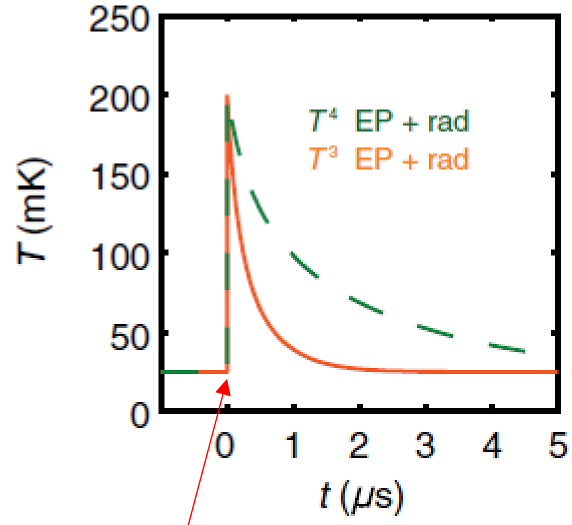
n=2×10^{11} cm^{-2}
[K.C. Fong et al., PRX 2012)]

Sommerfeld coefficient:

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

Carrier density

Significant heating of electrons !



Absorbing 26-GHz μw-single-photon

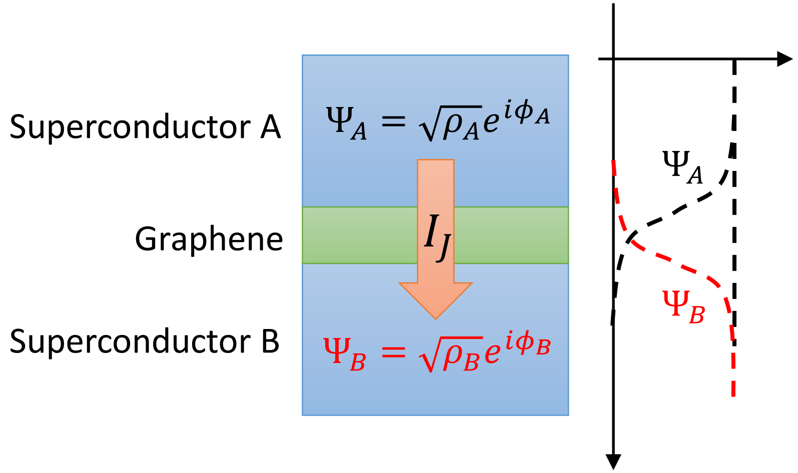
For μw-SPD, we need to detect temperature rise **Δ*T* ~ 200 mK** within $\tau_{el\text{-}ph}$ ~ 100 ns.

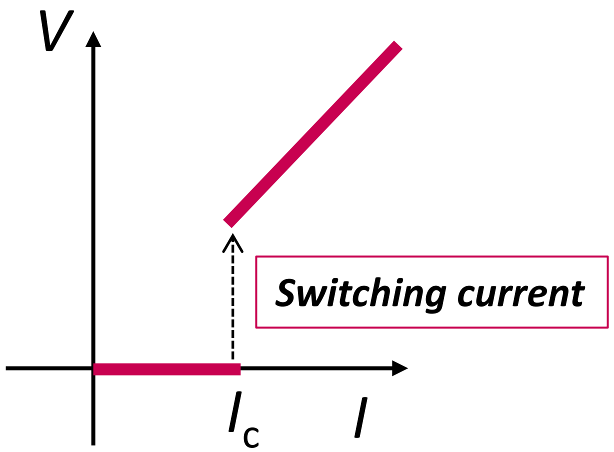
[E.D. Walsh et al., PRApplied 8, 024022 (2017)]

POSTECH

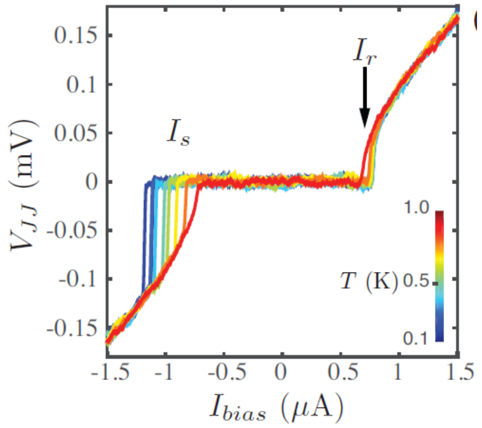
Josephson Junction

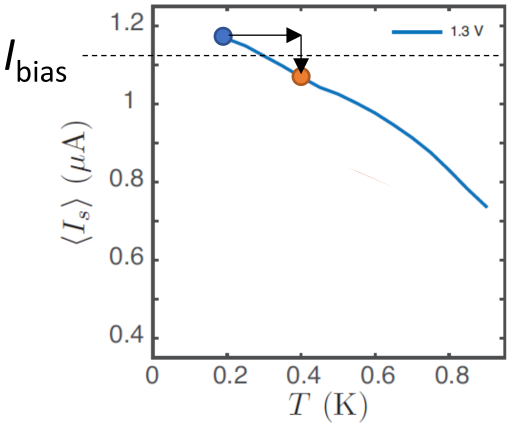
Josephson coupling by overlap of macroscopic quantum wave-functions across junction





Al/Graphene/Al Josephson junction,





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

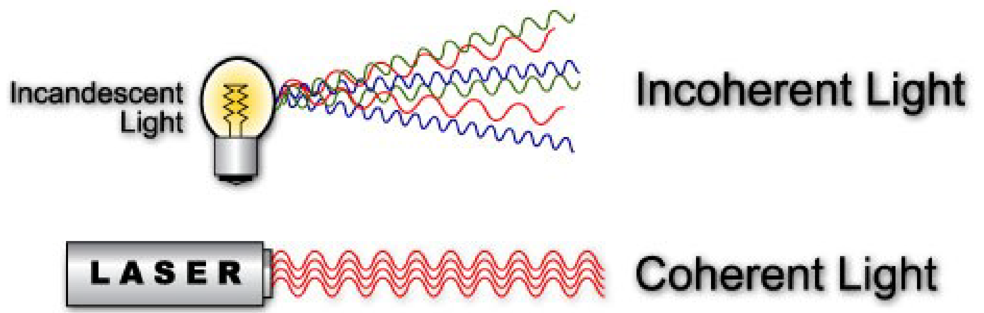
$d\langle I_s \rangle/dT$ **~-0.5 μA/K**

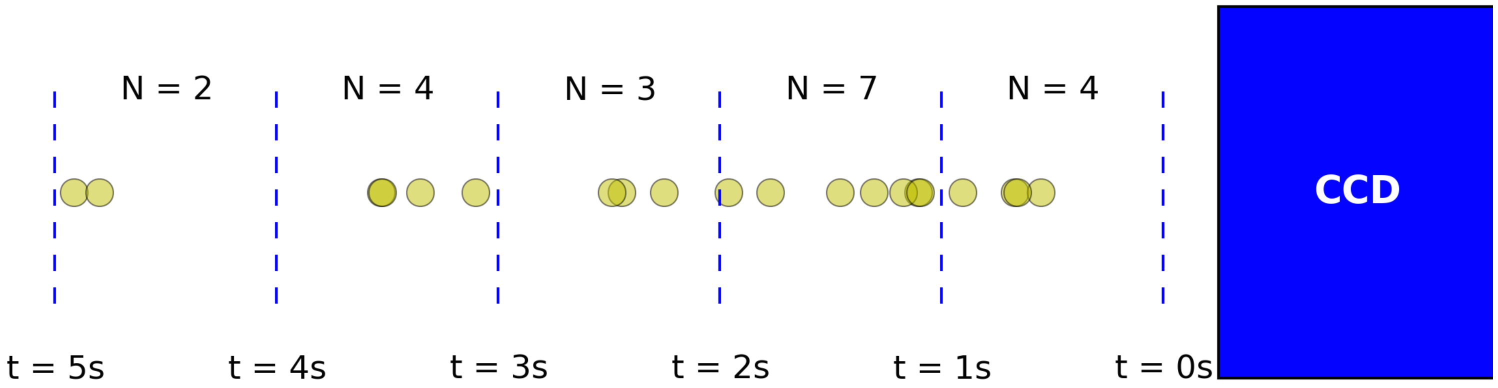
- Switching happens very fast, **within ~10 ps**.

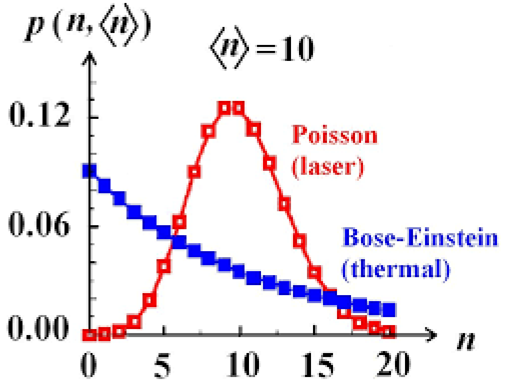
ω_p ~ 100 GHz

POSTECH

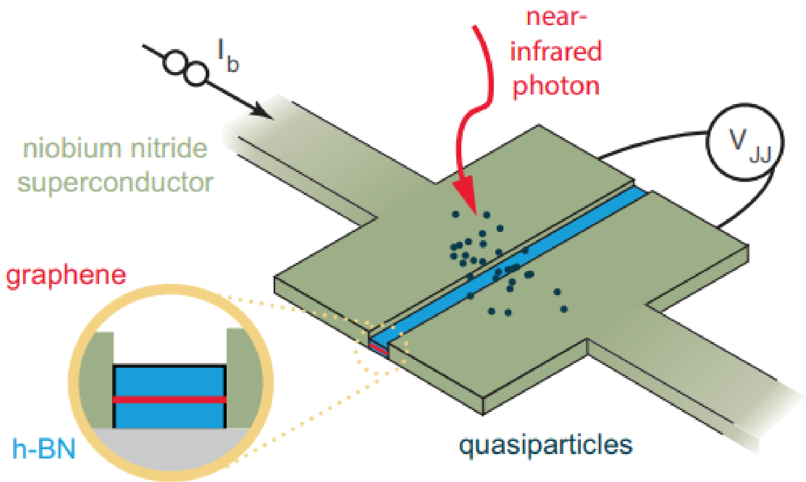
Particle-Wave Duality and Photon Statistics

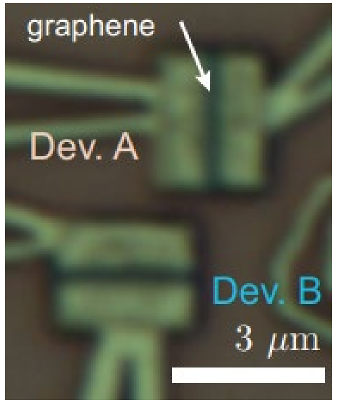


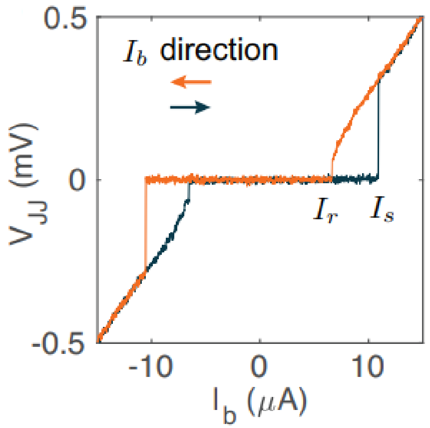




1,550-nm NIR Single Photon Detection

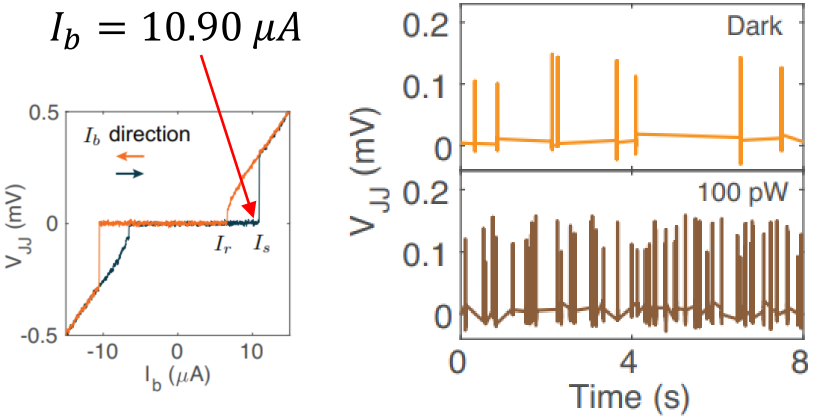


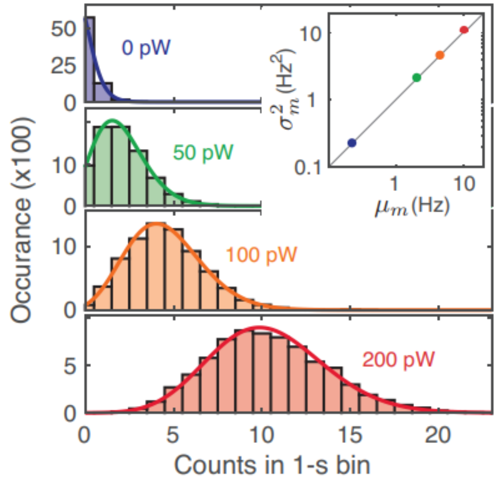




[E. Walsh, W. Jung, **GHL**, …, Kin Chung Fong, Science 372, 409-412 (2021)]

$I_b = 10.90\ \mu A$





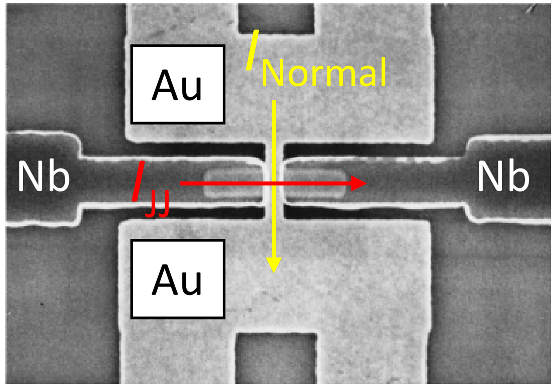
1. Poisson distribution
2. Mean count ∝ Laser power

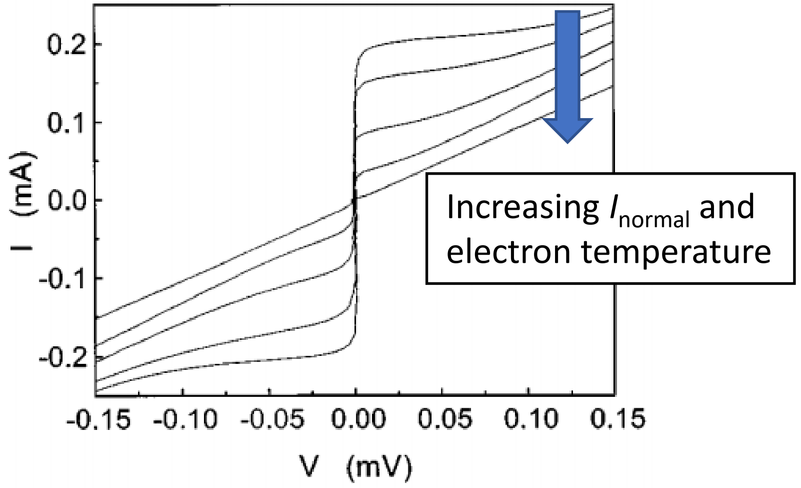
Single photon detection

POSTECH

Orthogonal-Terminal Josephson Junction

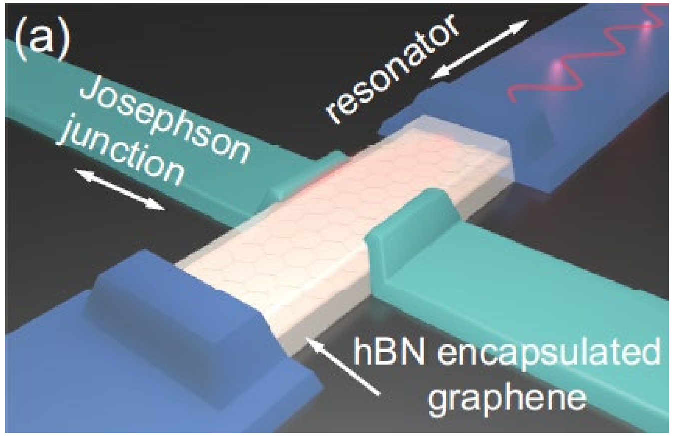
Previous work on orthogonal-terminal JJ

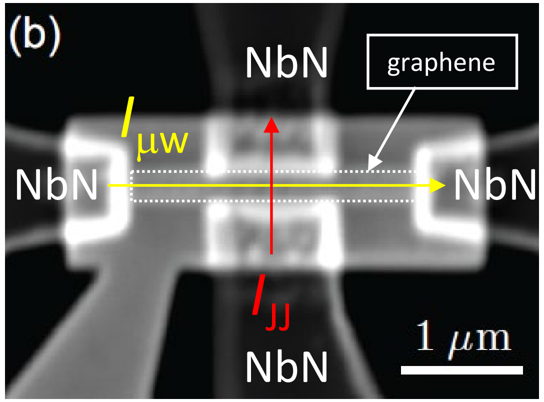




[A. F. Morpurgo *et al.*, APL 72, 23 (1998)]

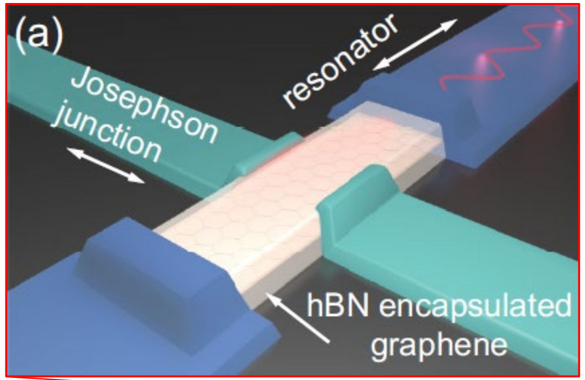
In this work

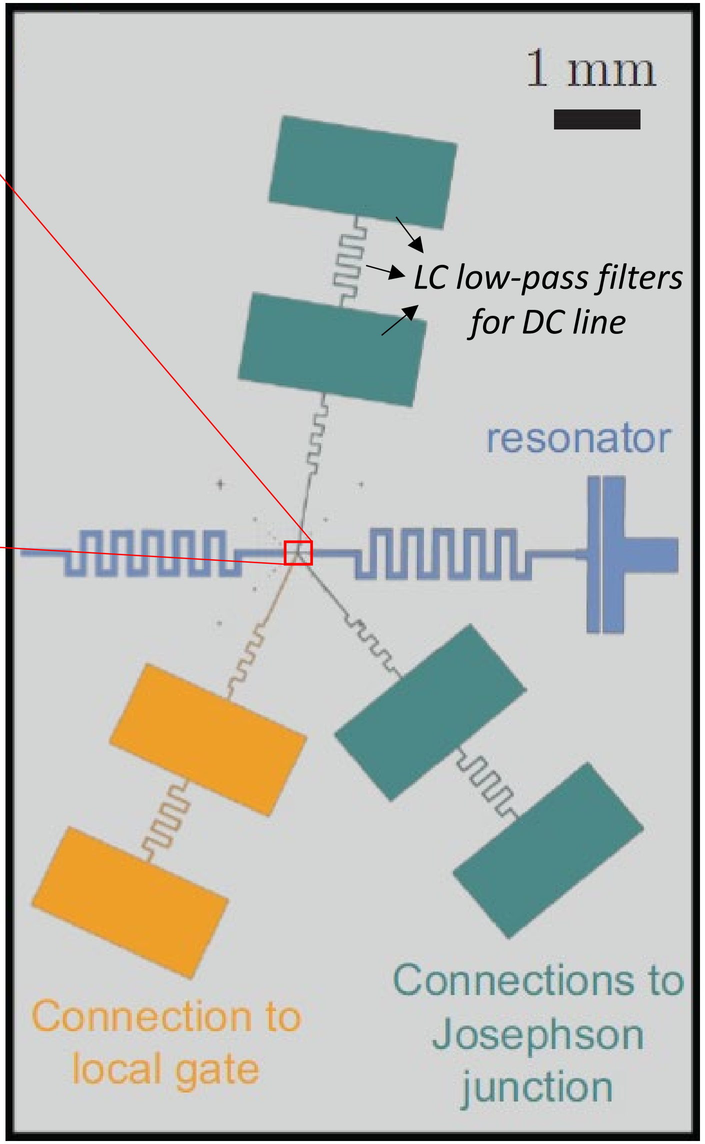


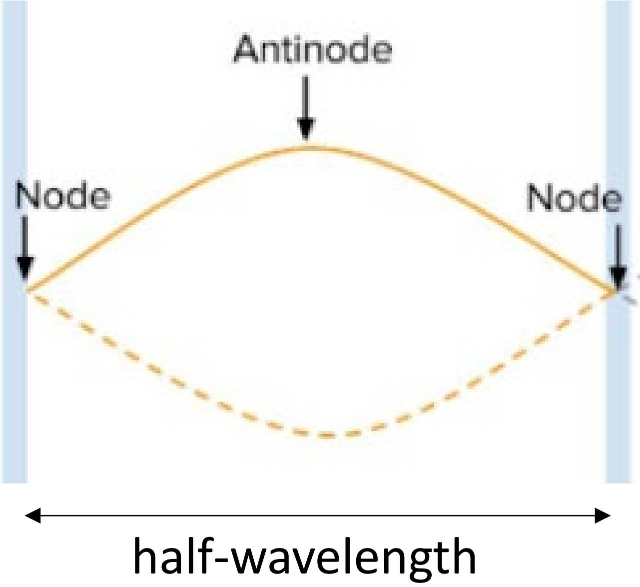


[GHL *et al.*, Nature 586, 42–46 (2020)]

GJJ-embedded Resonator





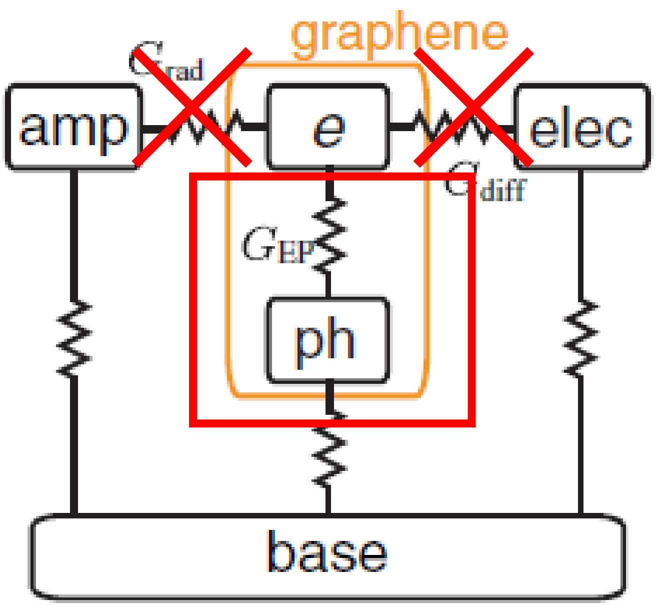


Graphene in current antinode (critically coupled)

↓

Maximum power dissipation in graphene

Thermal Circuit



- G_{rad}: radiation to environment ➡ very small
- G_{diff}: hot electron diffusion to electrode ➡ negligible with superconducting electrode

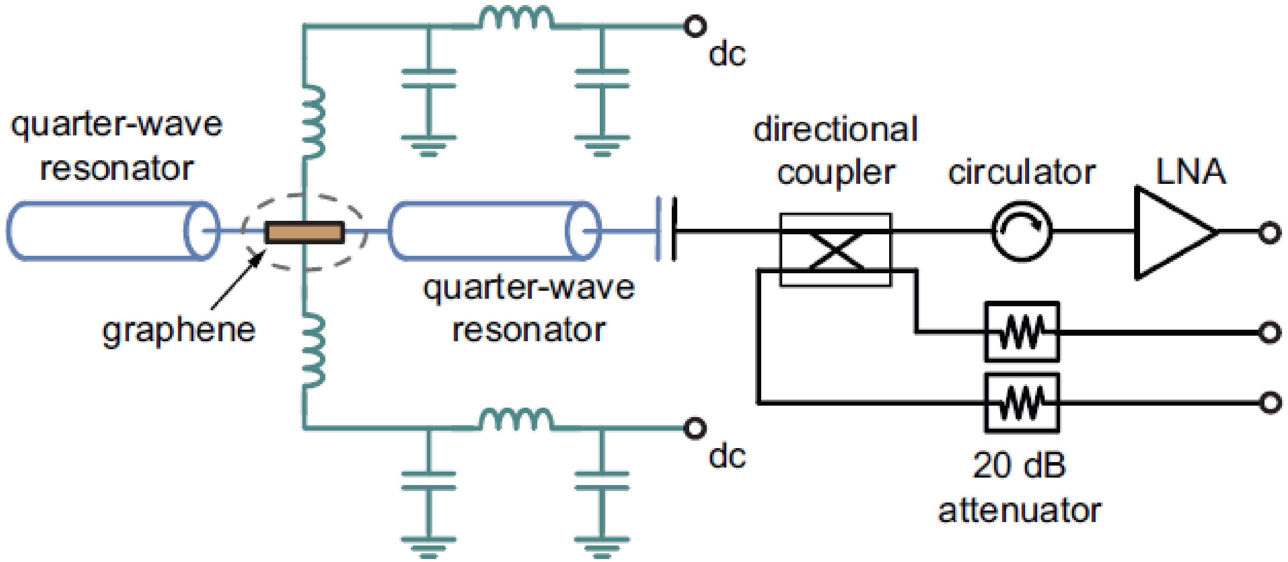
*Cooper pair doesn't carry momentum.

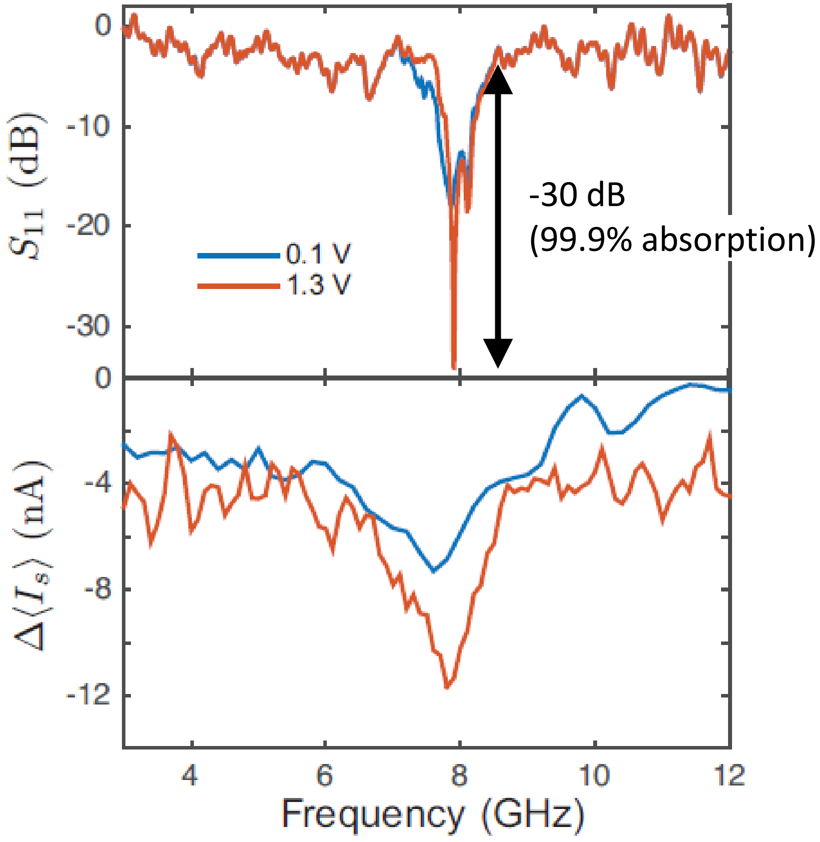
- **G_{EP}: electron-phonon cooling** ➡ **dominant cooling channel**

POSTECH

Graphene Absorbing Microwave

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

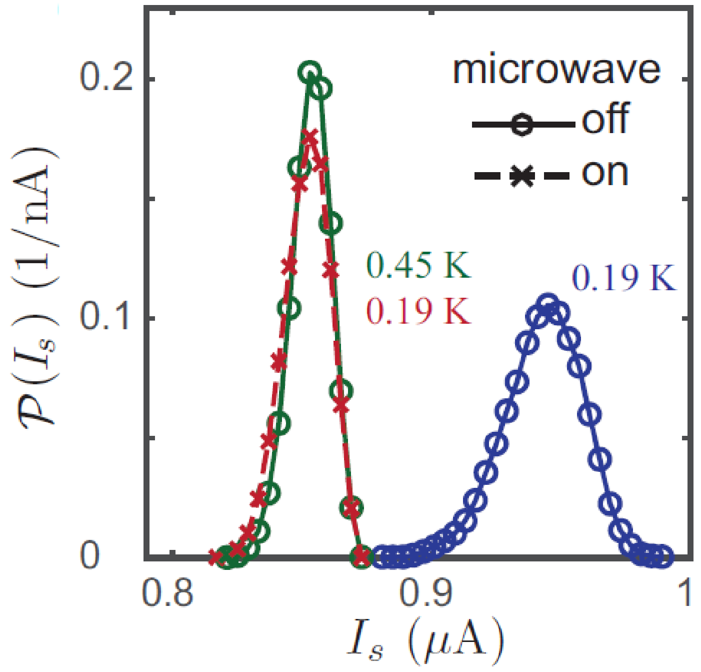




<I_s> get suppressed at the resonance frequency, f=7.9 GHz.

POSTECH

Switching Current Distribution



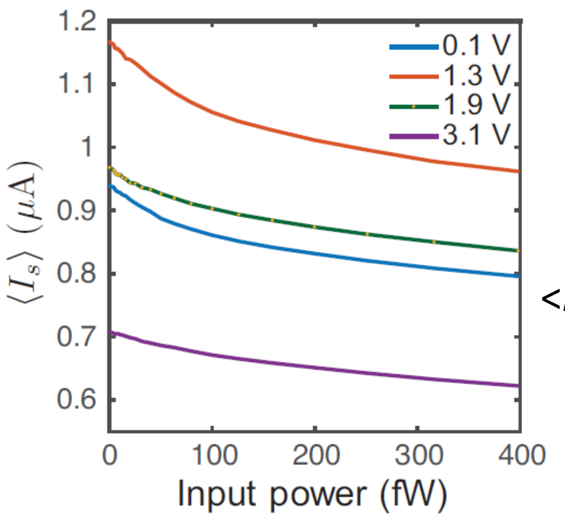
$P(I_s)$ with microwave input has same shape of $P(I_s)$ with elevated temperature.

↓

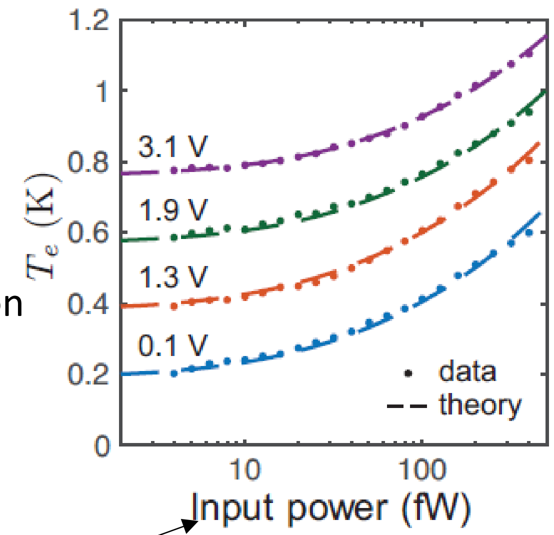
Heated electrons get fully equilibrated.

POSTECH

Estimation of Electron Temperature, T_e



$\langle I_s \rangle$-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 $Wm^{-2}K^{-3}$

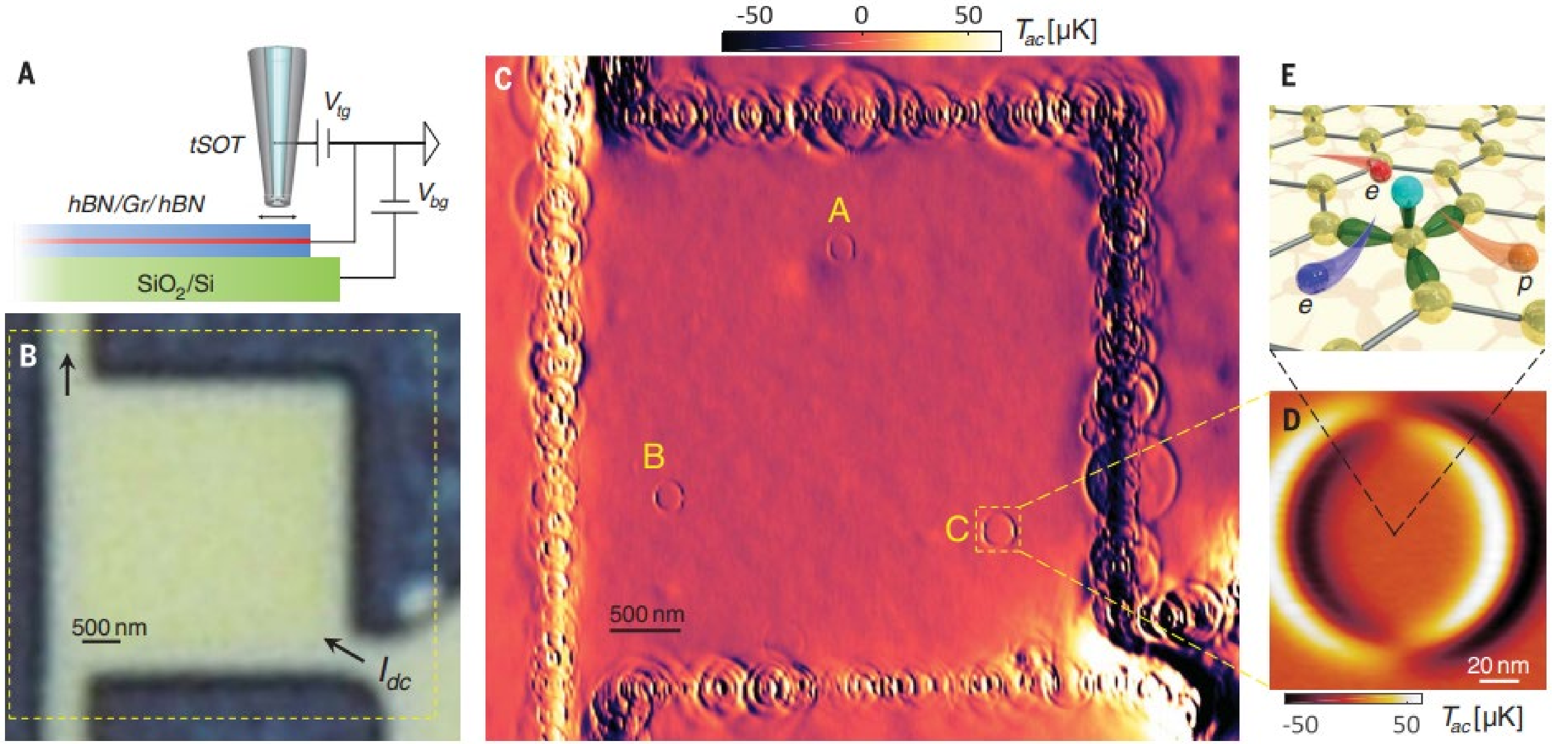
el-ph coupling due to **disorder**

Large discrepancy. Why?

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

POSTECH

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.

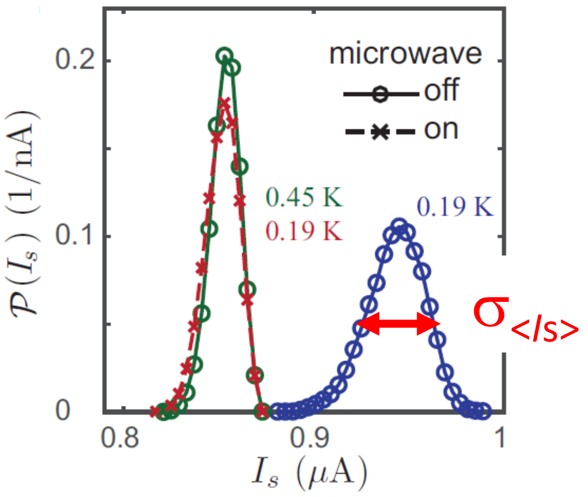
Theoretically estimated Σ ~ 0.01 $Wm^{-2}K^{-3}$ << Measured Σ ~ 3 $Wm^{-2}K^{-3}$

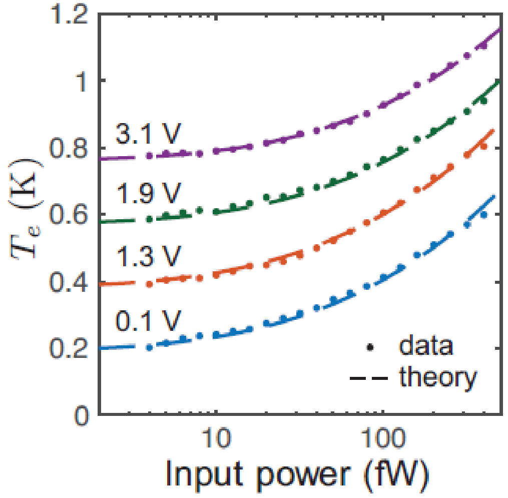
POSTECH

Noise Equivalent Power (NEP)

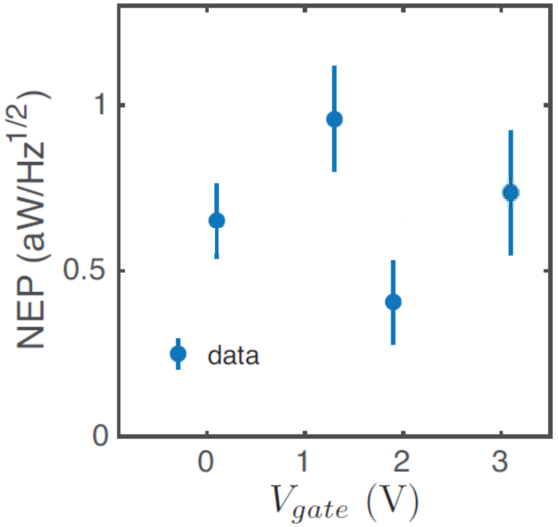
Measure of sensitivity of a bolometer

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





- Minimum power P_{min} for changing $<I_s>$ by $\sigma_{<I_s>}$.
  → 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



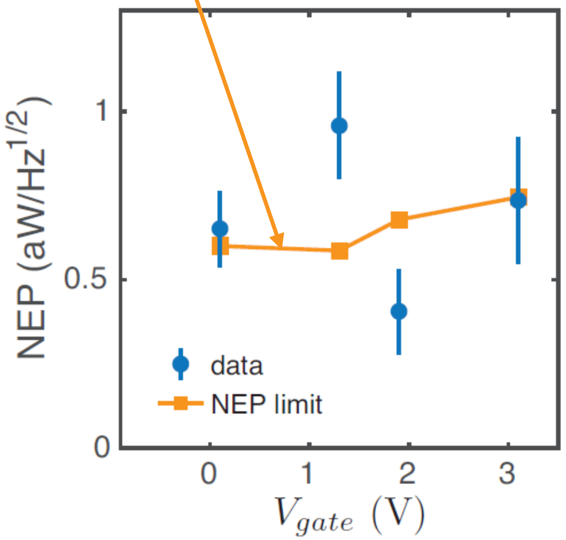
→ **NEP**$= P_{min}/\sqrt{f_{in}}$**=0.45 aW/Hz$^{1/2}$**

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,
  $\text{NEP} = \sqrt{4 G_{th} k_B T^2}$



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***

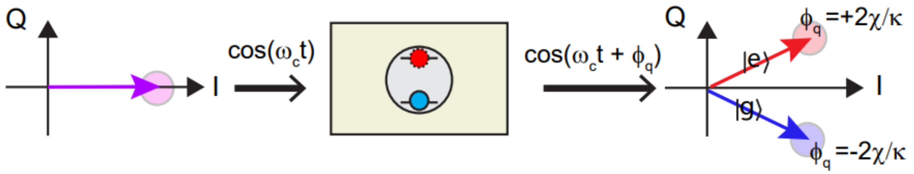
Expected energy resolution:
$\Delta E = NEP \cdot \sqrt{\tau_{in}}$ ~**30 GHz**

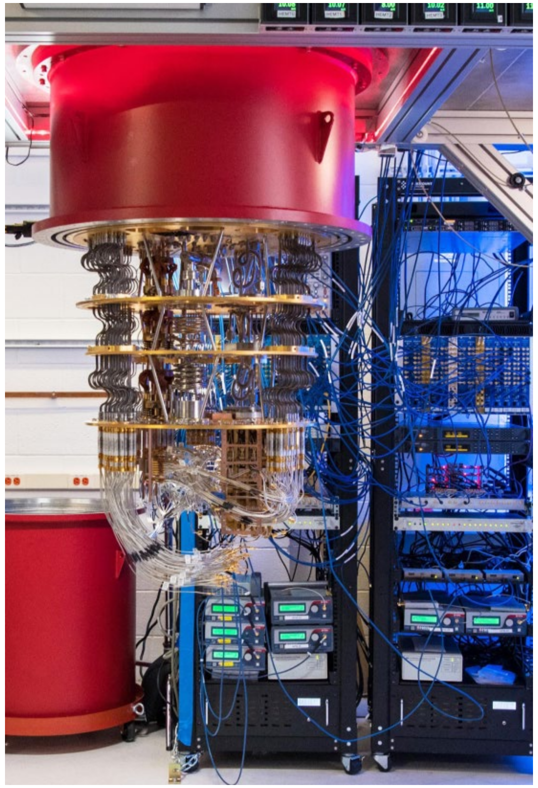
[S. H. Moseley et al., JAP 56, 1257 (1984)]

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)]

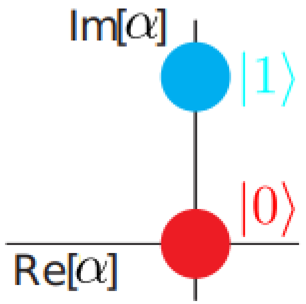
mw SPD for Qubit Measurement

- Dispersive phase shift readout





- **Photon-counting readout**



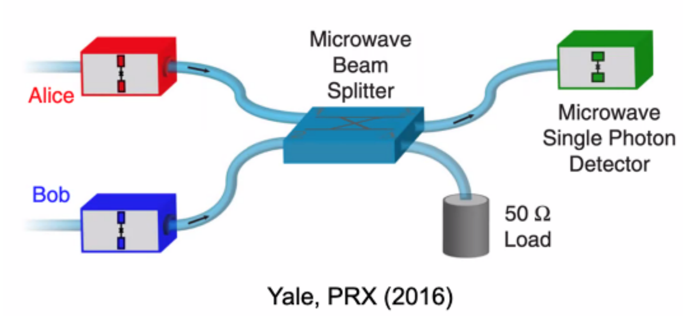
No need for room-temperature detection

↓

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

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

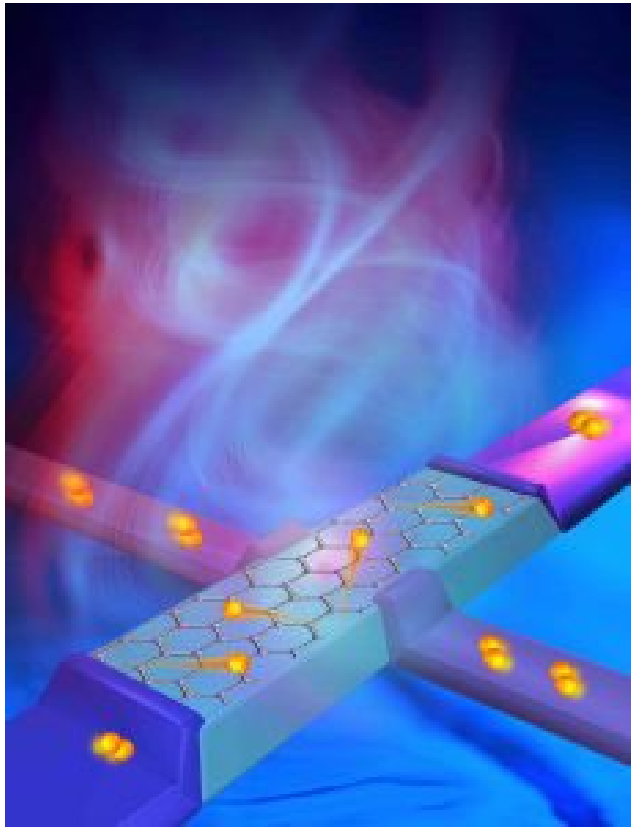
- **Remote entanglement**



POSTECH

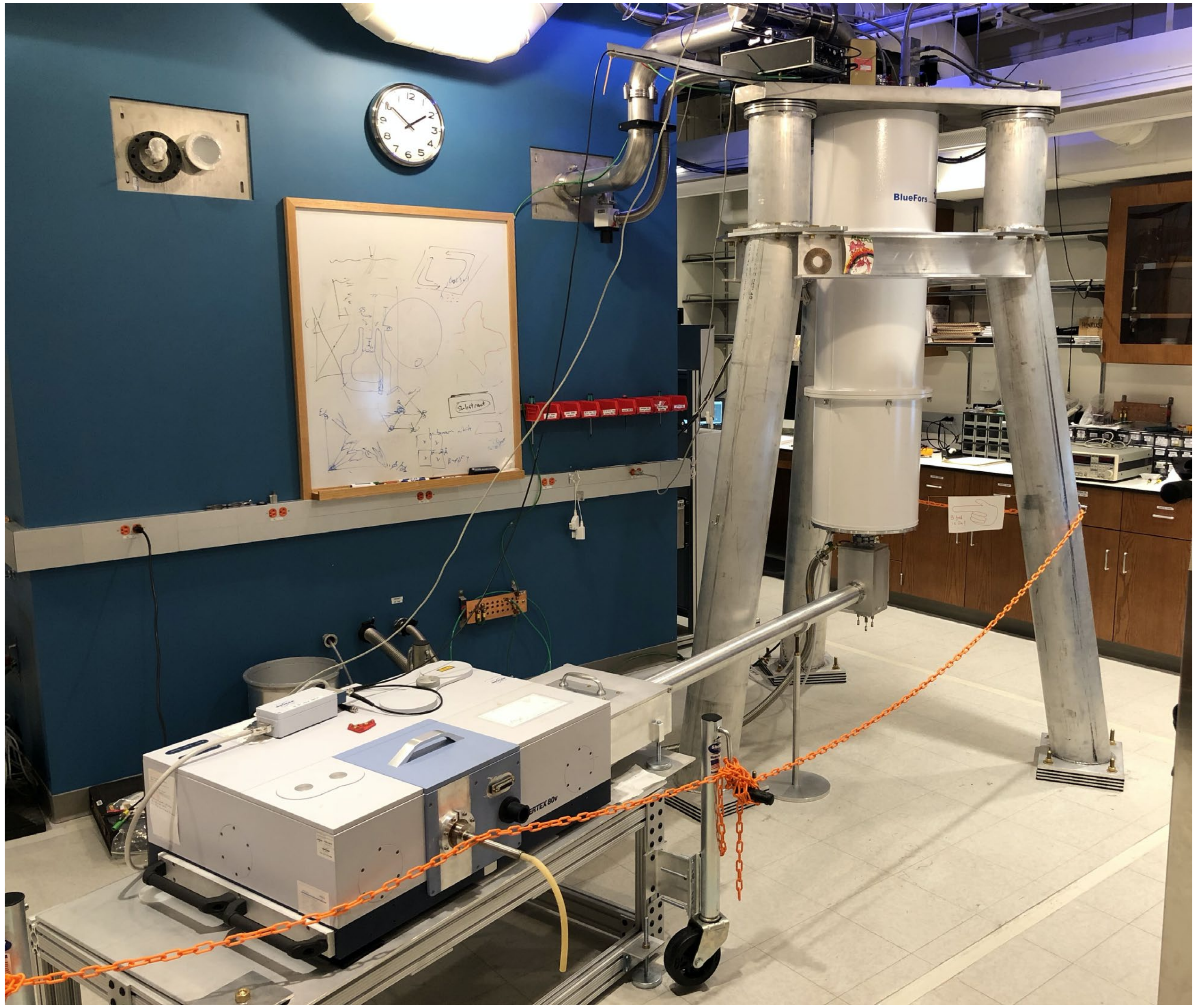
Acknowledgement

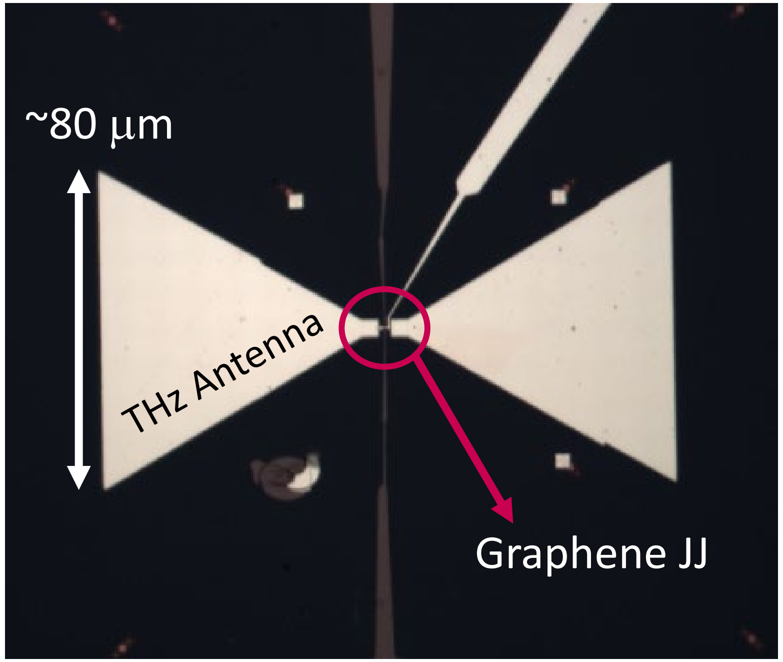
Team



- POSTECH
  - Woochan Jung
- Raytheon BBN technologies
  - Leonardo Ranzani
  - Thomas A. Ohki
  - **Kin Chung Fong**
- MIT
  - Evan D. Walsh
  - Dmitri K. Efetov
  - **Dirk Englund**
- NIMS Japan
  - Takashi Taniguchi
  - Kenji Watanabe
- Harvard University
  - **Philip Kim**

THz-SPD Project with Washington Univ.

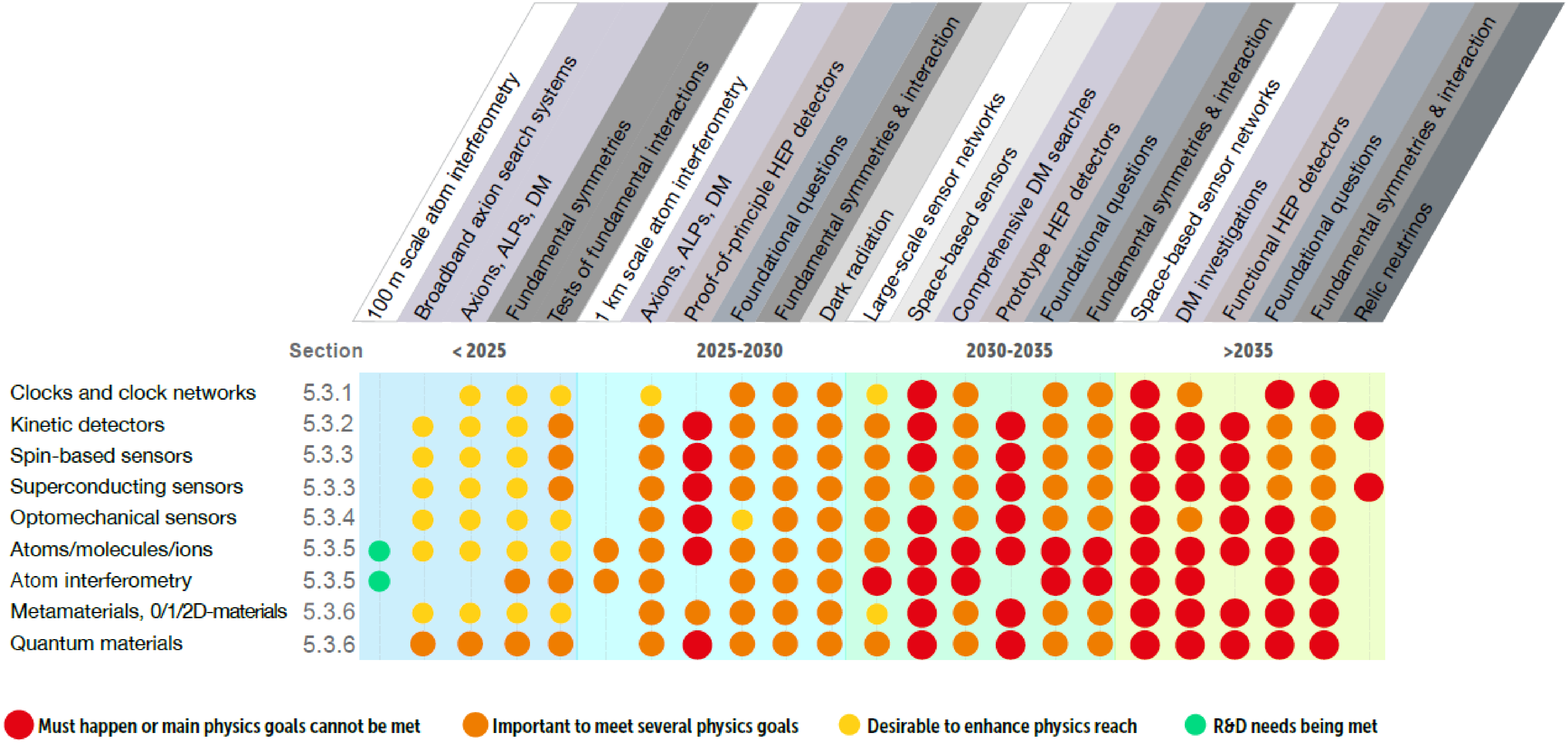




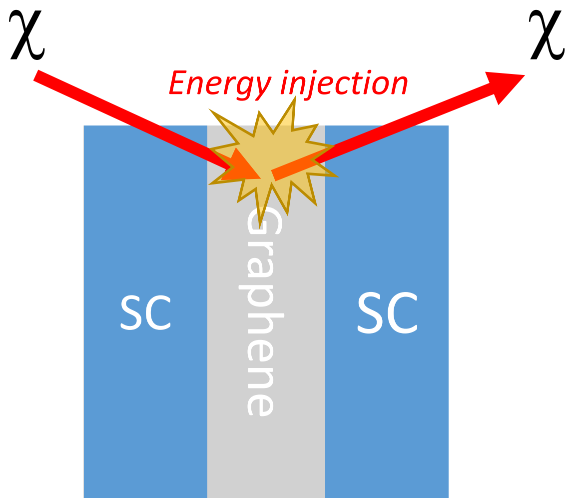
[Setup at Washington University]

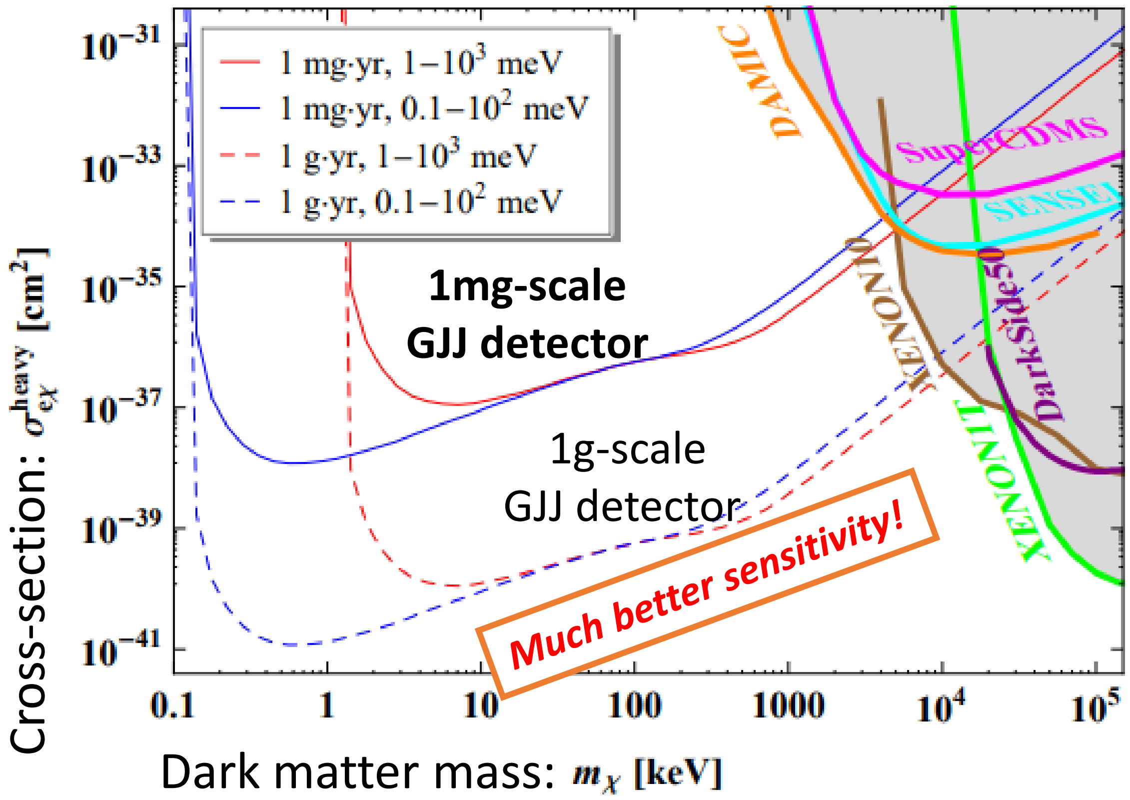
ECFA Detector R&D Roadmap (2021)

The European Committee for Future Accelerators (ECFA)



GJJ for Dark Matter Detection ?





How can we make mg-scale GJJ detector?

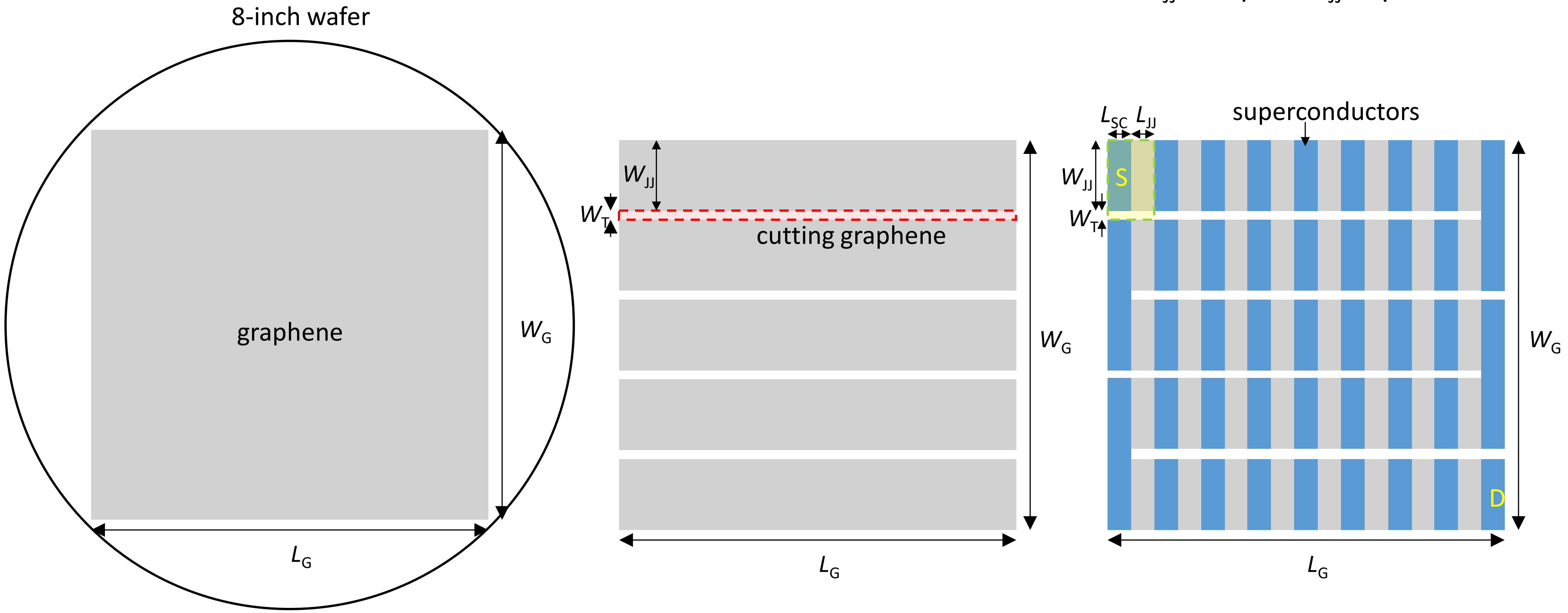
Graphene-Based Bolometer for Detecting keV-Range Superlight Dark Matter,
Doojin Kim, Jong-Chul Park, Kin Chung Fong, and **GHL**, arXiv:2002.07821 (submitted)

POSTECH

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.

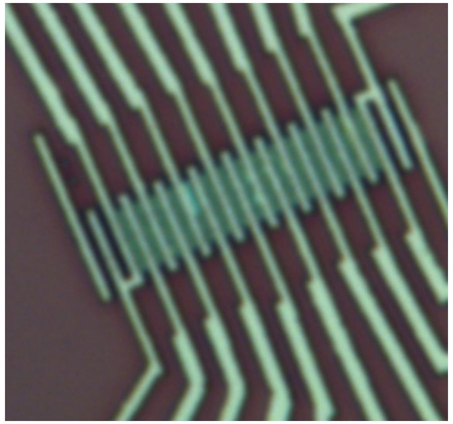


Number of GJJ in a single wafer: N_W= 5.6 billion (5.6×10^9)

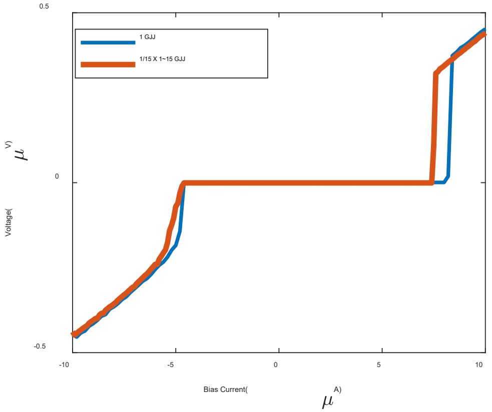
Then, we need 150 wafers connected.

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

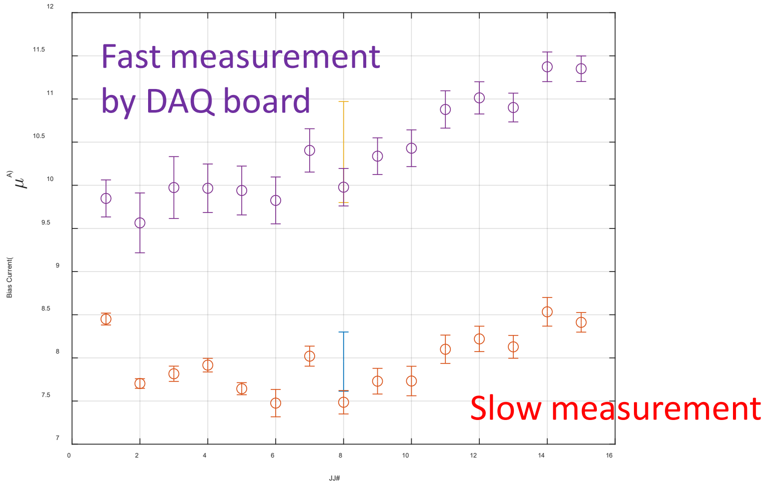
Uniformity of multiple Graphene Josephson junction (GJJ)



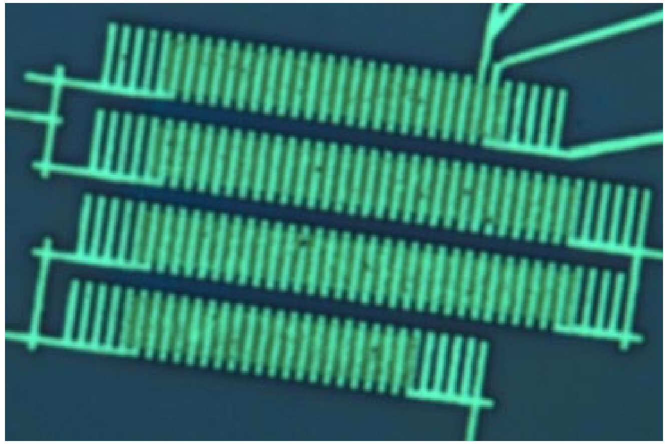
Device optical image



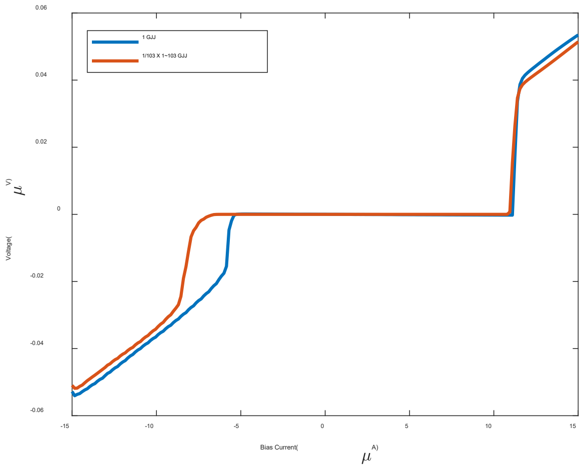
Almost same I-V curve when scaled



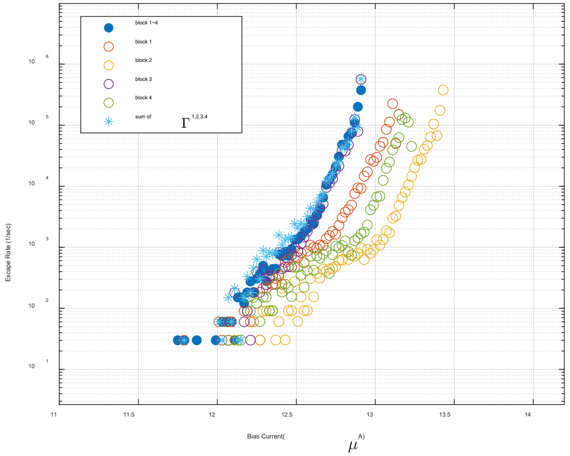
~9% variation in switching current.



Device optical image of ~**100** GJJs



Almost same I-V curve when scaled



Escaping rate measurement for four GJJs

~4% variation in switching current.

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)**.
- Various future directions:
  microwave single photon detector (MIT, BBN), detecting ultralight dark matter (CNU), terahertz single photon detector (WashU, BBN)