Detecting keV-Range Super-Light Dark Matter Using Graphene Josephson Junction

TEXAS A&M UNIVERSITY
Physics & Astronomy

Doojin Kim

doojin.kim@tamu.edu

Phenomenology 2020 Symposium, May 4th, 2020

In collaboration with Jong-Chul Park, Kin Ching Fong, and Gil-Ho Lee [arXiv:2002.07821]

Dark Matter Landscape: A Very Wide Range of DM Masses

10^{-22} eV — keV — MeV — GeV — TeV — PeV — $100M_\odot \sim 10^{68}$ eV

Ultralight
- Scaler field
- (QCD) Axion
- Hidden photon

Non-thermal

Superlight
- WDM
- Sterile ν

May be thermal

Light

Particle DM can be thermal

WIMP
- Well-motivated
- Extensively studied

Thermal

Superheavy/Composite
- Wimpzilla
- Q-ball
- Dark-quark nugget

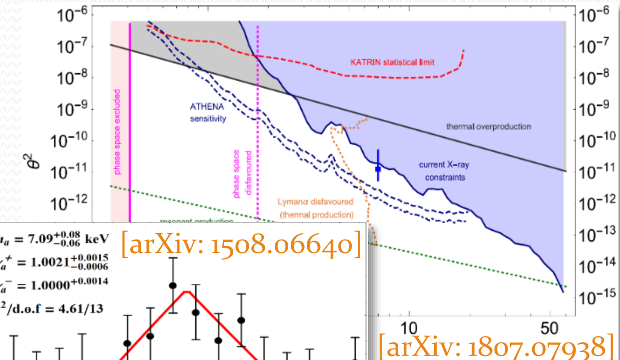
Non-thermal

MACHO/Primordial BHs

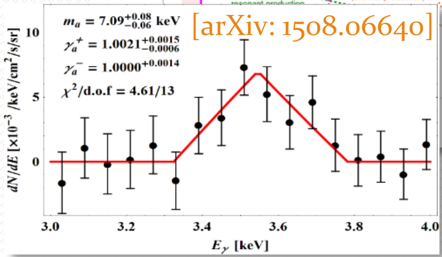
Non-particle

Main focus

- Sterile neutrinos [hep-ph/9303287, astro-ph/9810076]
- Mirror ν DM [hep-ph/9505385]
- Axino/gravitino [arXiv: 0902.0769, 1407.0017]
- Axion-like particles [arXiv:0912.0015, 1407.0017, 1510.07633]
- Super-light dark gauge bosons [arXiv:1105.2812, 1201.5902]
- Decaying DM for 3.5 keV line [arXiv:1403.1536, 1508.06640]
- ...

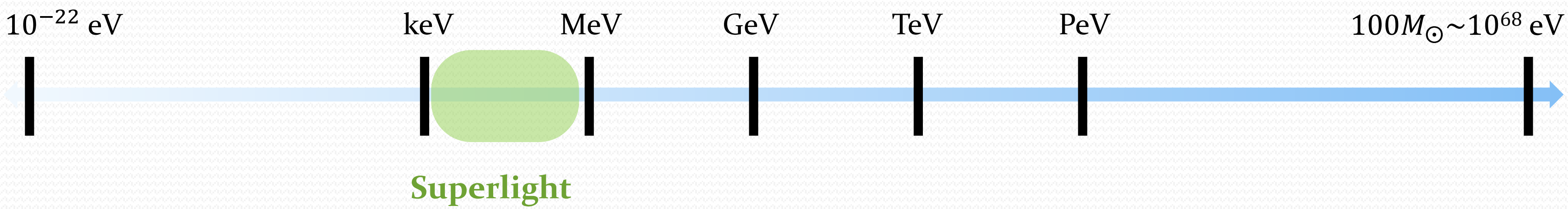


[arXiv: 1807.07938]



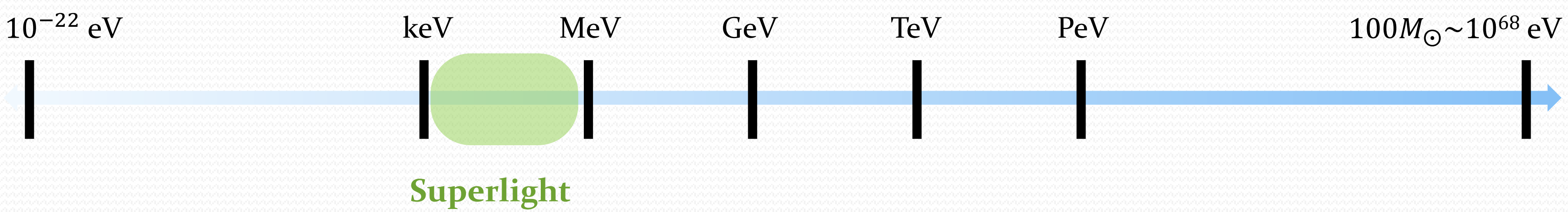
[arXiv: 1508.06640]

Super-Light Dark Matter Searches



- $E_k \sim mv^2 < \mathcal{O}(\text{eV}) \Rightarrow$ Very low $E_{r,\text{th}}$ required!
- New ideas with very low $E_{r,\text{th}}$
  - ✓ Superconductor target w/ TES or MKID [arXiv:1504.07237, 1512.04533]
  - ✓ Superfluid He w/ TES or MKID [arXiv:1604.08206, 1611.06228]
  - ✓ 3D Dirac materials [arXiv:1708.08929]
  - ✓ Polar materials w/ TES or MKID [arXiv:1712.06598, 1807.10291]
  - ✓ Superconducting-nanowire single-photon detector [arXiv:1903.05101]
  - ✓ …

Super-Light Dark Matter Searches: Technologies



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  - ✓ ...

- Transition edge sensor (TES): X-ray~near-IR, $E_{th}\sim$ sub-eV [Superconducting Devices in Quantum Optics (2016)]
- Microwave kinetic inductance device (MKID): X-ray~far-IR, $E_{th}\sim\mathcal{O}(10\text{ meV})$ [Annual Review of Condensed Matter Physics (2012)]
- Superconducting-nanowire single-photon detector (SNSPD): UV~mid-IR, $E_{th}\sim\mathcal{O}(100\text{ meV})$ [Techno. (2018)]

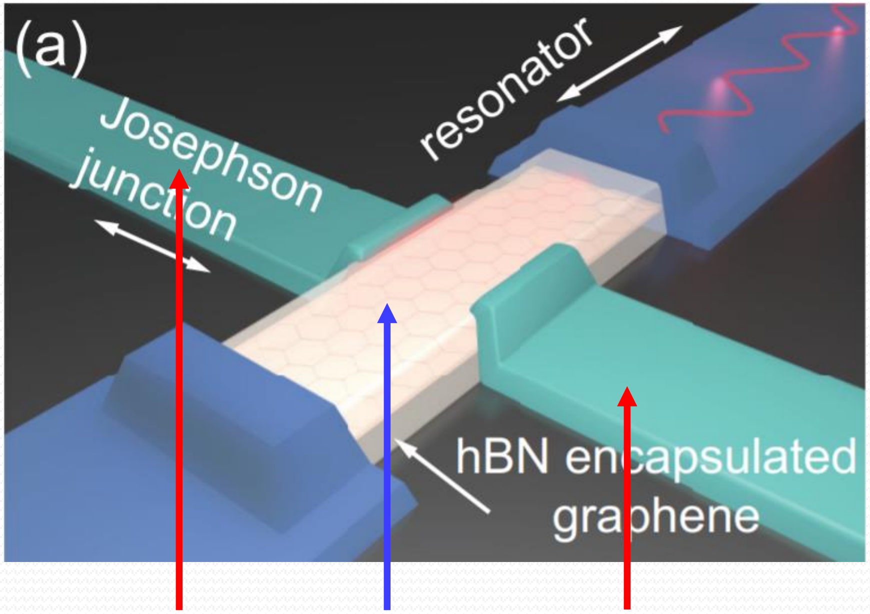
Well-developed in the lab in their respective E-bands.

But for the sensitivity to $E_{th} \lesssim$ meV,

further R&D is needed!

We proposed a new super-light DM direct detection strategy adopting the graphene-based Josephson junction (GJJ) – a "state-of-the-art" technology – microwave single photon detector.

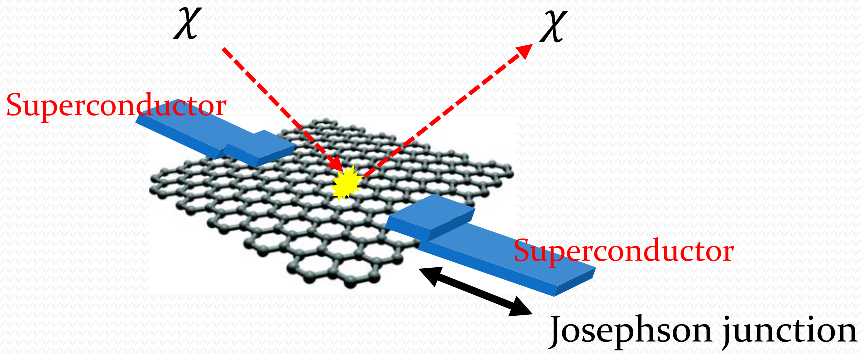
Graphene Josephson Junction Detector



Superconductor-Graphene-Superconductor (SGS)

- A Graphen Josephson Junction (GJJ) single-photon detector was proposed, covering from near-IR to microwave. [Phys.Rev.Applied (2017)]
- Very recently, K. C. Fong, G.-H. Lee, and their collaborators have **demonstrated** the GJJ microwave bolometer with a noise equivalent power (NEP) corresponding to the thermo-dynamic limit.
  - ⇒ This NEP corresponds to the E resolution of single 32 GHz photon, in a single photon detection mode, equivalent to $\sim\mathbf{0.13}$ meV energy quanta. [Lee et al, arXiv:1909.05413]
- Currently, a GJJ single-photon detector is under testing in the laboratory.

Detection Principle



i. DM (χ) scatters off (π-bond) free electrons, transferring some fraction of its incoming E_k.

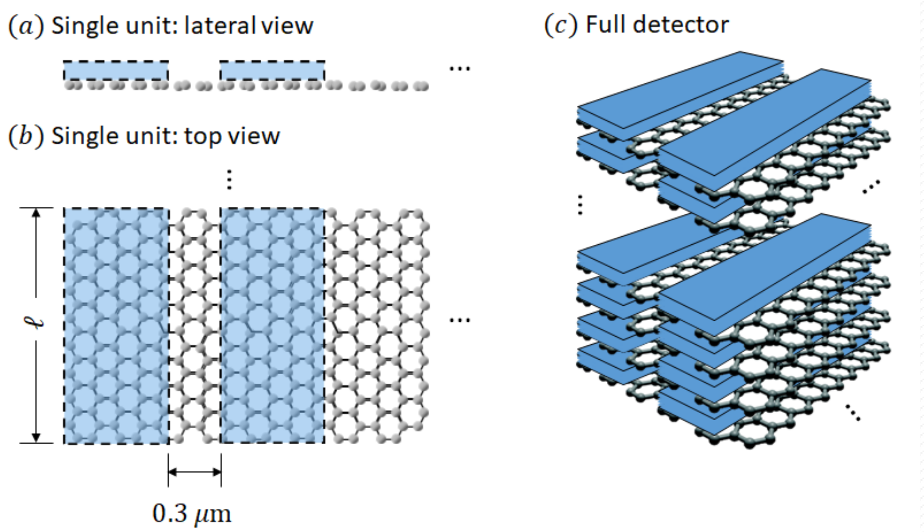
ii. The recoiling electron heats up & thermalizes with nearby electrons rapidly via $e-e$ interactions.

iii. The JJ is triggered: the temperature rise switches the zero-voltage of JJ to resistive state.

- $E_k \sim mv^2 \sim 0.1$ meV for $m_{DM} = 0.1$ keV

  $\Rightarrow$ The GJJ device can posses the sensitivity to the signal induced even by sub-keV DM.

Conceptual Design Proposal



- Single detector unit (a) & (b): the assembly of a graphene sheet & a number of superconducting material strips $\Rightarrow$ an array of SC-graphene-SC-graphene-SC-$\cdots$ (SGSGS$\cdots$).
- Each sequence of SGS represents a single GJJ device.
- A full detector (c) can be made of a stack of such detector units.

- E_{th} is determined by the strip length ℓ: $\ell = 3\ \mu\text{m}$ ($30\ \mu\text{m}$) $\Rightarrow E_{th} \approx 0.1$ meV (1 meV).

Calculating Signal Rates

- Goal: The rate of scattering between DM and free electrons in a 2-dimensional graphene sheet.
- Key point: An electron is still confined in the graphene after the collision.

  ⇒ No significant momentum change along the surface-normal (z-axis) direction.
- We will calculate the number of DM events per unit detector mass per unit run time:

$$n_{\rm eve} = \frac{N_{\rm eve}}{M_T t_{\rm run}}$$

($N_{\rm eve}$: total number of events, M_T: total detector mass, $t_{\rm run}$: total time exposure)

Calculation Procedure I

$$n_{\mathrm{eve}} = \frac{N_{\mathrm{eve}}}{M_T t_{\mathrm{run}}} = \frac{1}{M_T t_{\mathrm{run}}} \int_{E_r > E_{\mathrm{th}}} dE_r \frac{dN_{\mathrm{eve}}}{dE_r}$$

$$= \frac{1}{M_T t_{\mathrm{run}}} \int_{E_r > E_{\mathrm{th}}} dE_r dv_\chi f_{\mathrm{MB}}(v_\chi) \frac{d}{dE_r} N_e \sigma_{e\chi} v_{\mathrm{rel}} \frac{\rho_\chi}{m_\chi} t_{\mathrm{run}}$$

$$= \int_{E_r > E_{\mathrm{th}}} dE_r dv_\chi f_{\mathrm{MB}}(v_\chi) \frac{dn_e^{3\mathrm{D}} \sigma_{e\chi} v_{\mathrm{rel}}}{dE_r} \frac{1}{\rho_T^{3\mathrm{D}}} \frac{\rho_\chi}{m_\chi}$$

$$= \int_{E_r > E_{\mathrm{th}}} dE_r dv_{\chi\parallel} f_{\mathrm{MB}}(v_{\chi\parallel}) \frac{dn_e^{2\mathrm{D}} \sigma_{e\chi} v_{\mathrm{rel}\parallel}}{dE_r} \frac{1}{\rho_T^{2\mathrm{D}}} \frac{\rho_\chi}{m_\chi}$$

- $N_{\mathrm{eve}} = n_{\mathrm{eve}} M_T t_{\mathrm{run}}$
- $N_{\mathrm{eve}} = N_e \sigma_{e\chi} \Phi_\chi t_{\mathrm{run}}$
- $\Phi_\chi = n_\chi v_{\mathrm{rel}}$ & $n_\chi = \rho_\chi / m_\chi$

2D nature of graphen

- $\frac{N_e}{M_{\mathrm{T}}} = \frac{N_e/V}{M_{\mathrm{T}}/V} = \frac{n_e^{3\mathrm{D}}}{\rho_T^{3\mathrm{D}}}$
  $= \frac{N_e/(A\Delta l)}{M_{\mathrm{T}}/(V\Delta l)} = \frac{n_e^{2\mathrm{D}}}{\rho_T^{2\mathrm{D}}}$

$$n_e^{2D} = 2\int \frac{d^2 p_{e,i}^{(xy)}}{(2\pi)^2} f_{e,i}(E_{e,i}) = 2\int \frac{d^2 p_{e,i}^{xy}}{(2\pi)^2} \int \frac{dp_{e,i}^z}{(2\pi)} (2\pi)\delta(p_{e,i}^z - p_{e,f}^z) f_{e,i}(E_{e,i})$$

$$= 2\int \frac{d^3 p_{e,i}}{(2\pi)^3} (2\pi)\delta(p_{e,i}^z - p_{e,f}^z) f_{e,i}(E_{e,i})$$

- $f_{e,i}(E_{e,i}) = \frac{1}{1+\exp(\frac{E_{e,i}-\mu}{T})}$,

  ($\mu \sim E_F$): Fermi-Dirac distribution function

Consistent with the assumption of no significant momentum change along the surface-normal direction

Calculation Procedure II

- Graphene-surface-parallel DM velocity profile: $f_{\rm MB}(v_{\chi\parallel}) = \frac{2\left(e^{-v_{\chi\parallel}^2/v_0^2} - e^{-v_{\rm esc}^2/v_0^2}\right)}{\sqrt{\pi}v_0 {\rm erf}(v_{\rm esc}/v_0) - 2v_{\rm esc}e^{-v_{\rm esc}^2/v_0^2}}$

  ⇒ We take a **plane-projection** of a modified Maxwell-Boltzmann distribution.

- Event rate on a (sufficiently thin) 2D material: $\langle n_e^{\rm 2D}\sigma_{e\chi}v_{\rm rel\parallel}\rangle = \int \frac{d^3p_{\chi,f}}{(2\pi)^3}\frac{\overline{|\mathcal{M}|^2}}{16\pi m_e^2 m_\chi^2} S_{\rm 2D}(E_r,\ q)$

- **Structure function for the 2D system**: $S_{\rm 2D}(E_r,\ q)$

$$S_{\rm 2D}(E_r,\ q) = 2\int\frac{d^3p_{e,i}}{(2\pi)^3}\int\frac{d^3p_{e,f}}{(2\pi)^3}(2\pi)\delta\left(p_{e,i}^z - p_{e,f}^z\right)(2\pi)^4\delta^{(4)}(p_{\chi,i} + p_{e\ i} - p_{\chi,f} - p_{e,f})\ f_{e,i}\left(E_{e,i}\right)\left\{1 - f_{e,f}\left(E_{e,f}\right)\right\}$$

$$= (2\pi)\delta(p_{\chi,i}^z - p_{\chi,f}^z)\cdot\frac{1}{2\pi^2}\int d^3p_{e,i}\delta(E_r + E_{\chi,i} - E_{\chi,f})f_{e,i}\left(E_{e,i}\right)\left\{1 - f_{e,f}\left(E_{e,f}\right)\right\}$$

$$= (2\pi)\delta(p_{\chi,i}^z - p_{\chi,f}^z)\cdot S_{\rm 3D}(E_r,\ q)$$

⇒ The **Pauli blocking effects (=phase space suppression)** are encoded in the structure function. The analytic expression for $S_{\rm 3D}(E_r,\ q)$ is available in the non-relativistic limit. [astro-ph/9710115, 1512.04533]

Calculation Procedure III

$$n_{\text{eve}} = \int_{E_r > E_{\text{th}}} dE_r dv_{\chi\parallel} f_{\text{MB}}(v_{\chi\parallel}) \frac{d\langle n_e^{2\text{D}} \sigma_{e\chi} v_{\text{rel}\parallel}\rangle}{dE_r} \frac{1}{\rho_{\text{gr}}^{2\text{D}}} \frac{\rho_\chi}{m_\chi}$$

- ✓ ρ_χ =0.3 GeV/cm^3
- ✓ v_0=220 km/s, v_{esc}=500 km/s
- ✓ $\rho_{\text{gr}}^{2\text{D}} = 7.62 \times 10^{-8}$g/cm^2

$$f_{\text{MB}}(v_{\chi\parallel}) = \frac{2\left(e^{-v_{\chi\parallel}^2/v_0^2} - e^{-v_{\text{esc}}^2/v_0^2}\right)}{\sqrt{\pi} v_0 \operatorname{erf}(v_{\text{esc}}/v_0) - 2 v_{\text{esc}} e^{-v_{\text{esc}}^2/v_0^2}}$$

$$\langle n_e^{2\text{D}} \sigma_{e\chi} v_{\text{rel}\parallel}\rangle = \int \frac{d^3 p_{\chi,f}}{(2\pi)^3} \frac{\overline{|\mathcal{M}|^2}}{16\pi m_e^2 m_\chi^2} S_{2\text{D}}(E_r,\ q)$$

with $S_{2\text{D}}(E_r,\ q) = (2\pi)\delta(p_{\chi,i}^z - p_{\chi,f}^z) \cdot S_{3\text{D}}(E_r,\ q)$

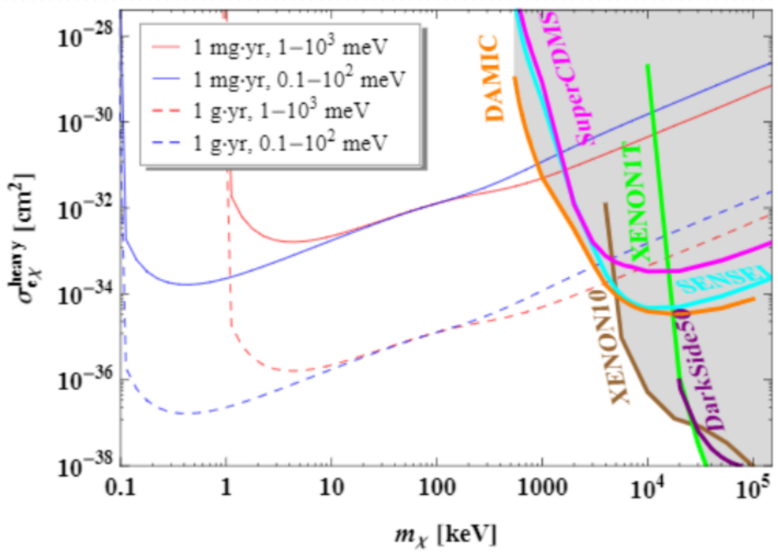
- We assume that DM interacts with electrons via an exchange of mediator ϕ as done in many of the preceding studies:

$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{(m_\phi^2 + q^2)^2} \Rightarrow \sigma_{e\chi}^{\text{heavy}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2) \ \ \& \ \ \sigma_{e\chi}^{\text{light}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{q^4} \text{ for } (m_\phi^2 \ll q^2)$$

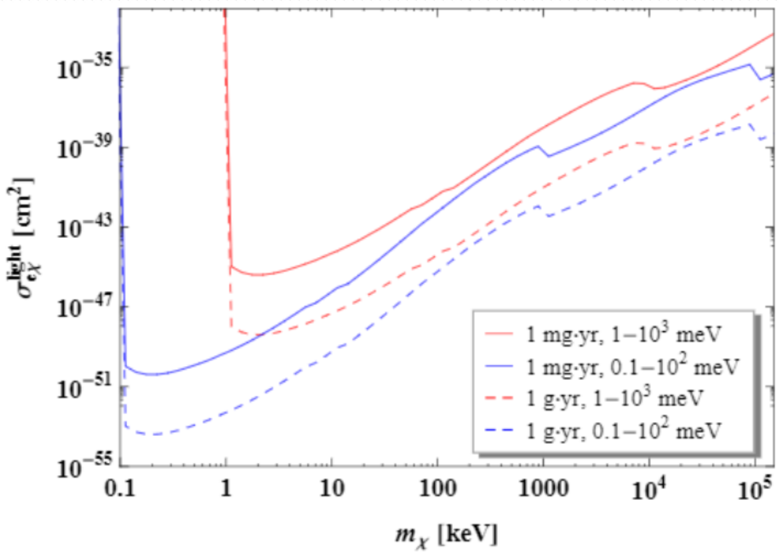
- The matrix element $\overline{|\mathcal{M}|^2}$ is related to the scattering cross section as $\sigma_{e\chi} = \frac{\overline{|\mathcal{M}|^2}}{16\pi\, m_e^2 m_\chi^2} \mu_{e\chi}^2$.
- From the **linear dispersion of graphene**: $E_F = v_F \sqrt{\pi n_c}$ with $v_F \sim 10^8$cm/s & $n_c \sim 10^{12}$/cm^2.

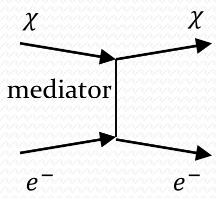
Expected Sensitivity Reaches

Heavy mediator: $F_{DM} = 1$



Light mediator: $F_{DM} \propto 1/q^2$ with $q_{\rm ref} = \alpha_e m_e$





- For the sensitivity reach estimation, we required $N_{\rm eve} = n_{\rm eve} M_T t_{\rm run} = 3.6$ for each target mass & runtime under the negligible-background assumption.
- The proposed GJJ-based detector is capable of probing sub-keV DM with great expected reaches due to its outstanding low E_{th}.

Future Plans & Conclusions

We are planning to do **first experiment** with the **existing GJJ device** samples.

- We have proposed a class of **new DM detectors**, **adopting the GJJ device** which has been **implemented & demonstrated experimentally**.
- For the **scattering between particles in 3D space & in 2D space**, we (for the first time) **built an effective model and computed the event rate**.
- The proposed detector is **capable of sensing sub-keV (warm) DM scattering off electrons** due to **its extremely low $E_{\rm th}\sim 0.1$ meV**.
- For **super-light (keV) DM**, we expect that it can achieve **higher experimental sensitivities** than those of other proposed experiments with the same target mass.

Bonus Slides

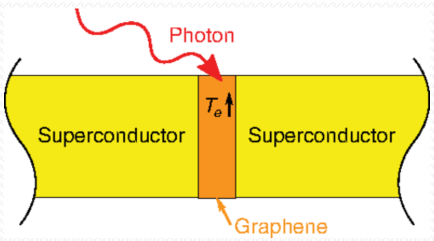
Backgrounds

- Solar neutrino (mostly *pp* neutrinos): scattering off an electron and depositing a small amount of energy.
  - ⇒ However, considering the volume of the detector, the expected number of events is negligible, $\ll 1/(\mathrm{g}\cdot\mathrm{year})$ [arXiv:1108.5383, 1512.04533].
- Instrumental backgrounds: It is crucial to keep the system temperature low enough to suppress potential thermal backgrounds or noise since the GJJ bolometer is extremely sensitive to small changes in temperature. To this end, we will place the detector in the cryogenic surroundings by cooling the detector system down to ~ 10 mK using dilution refrigerators as done in the original GJJ experiment [arXiv:1909.05413].

GJJ-Based SPD Scheme

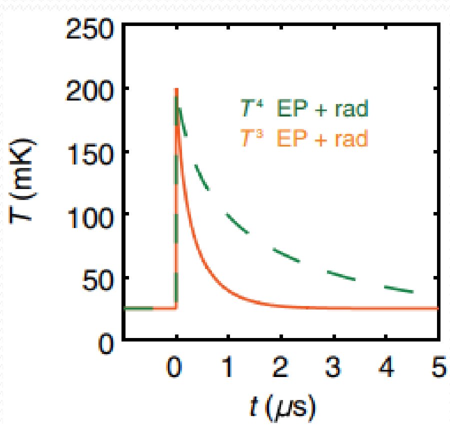
Graphene has

- **Ultra-broad** absorption spectrum
- **Record-low** specific heat capacity, $10k_B/\mu m^2$



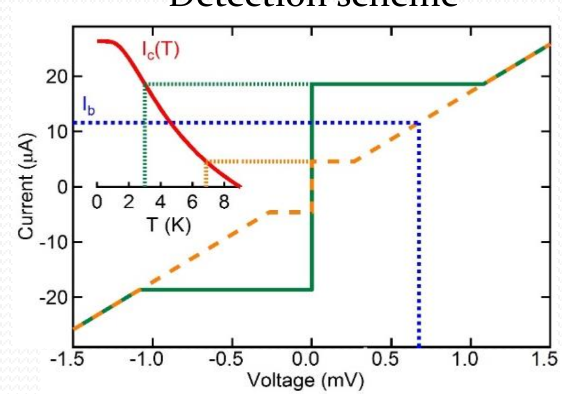
[K.C. Fong et al.]

Absorbing 26 GHz microwave single photon

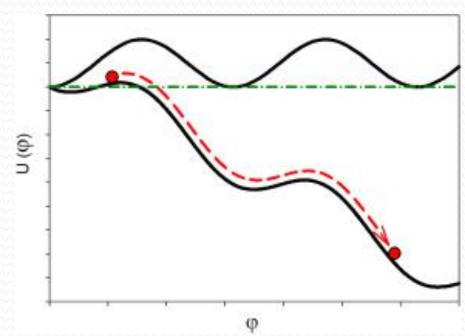


Josephson junction provides fast detection.

Detection scheme



- Plasma frequency
  ~ 100 GHz
- Response time
  ~ 0.1 ns

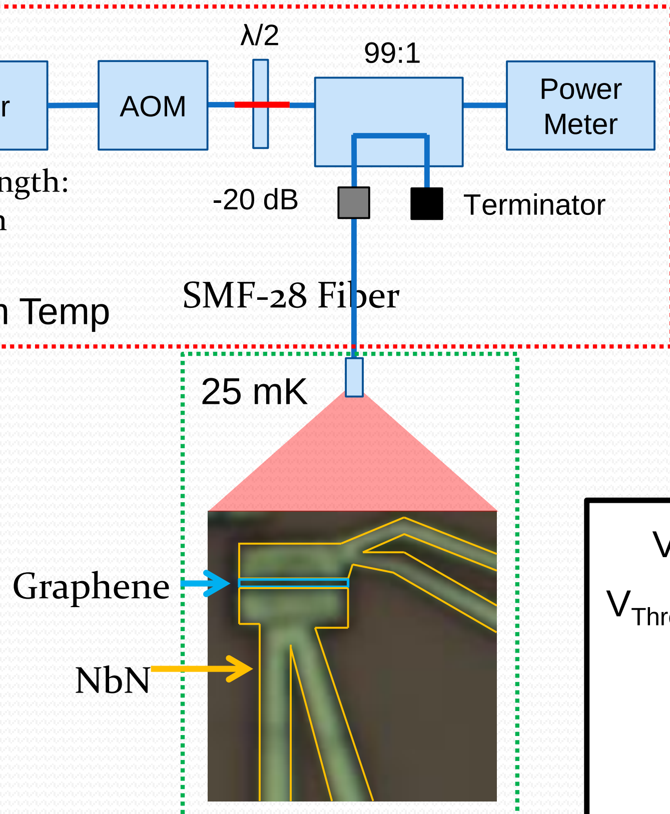


From Gil-Ho Lee

Experimental Setup (NIR-SPD)

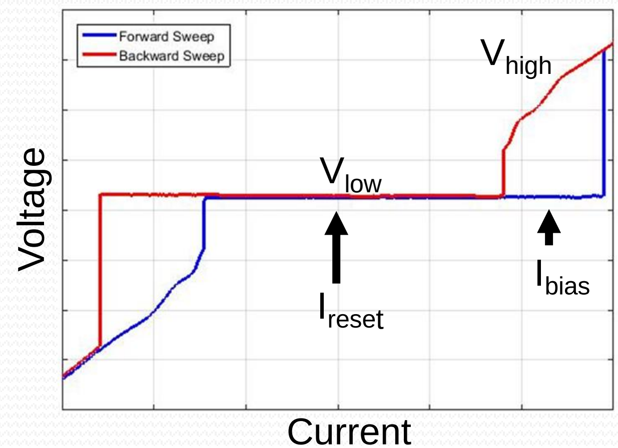
[E. D. Walsh et al., in preparation]

Optical setup

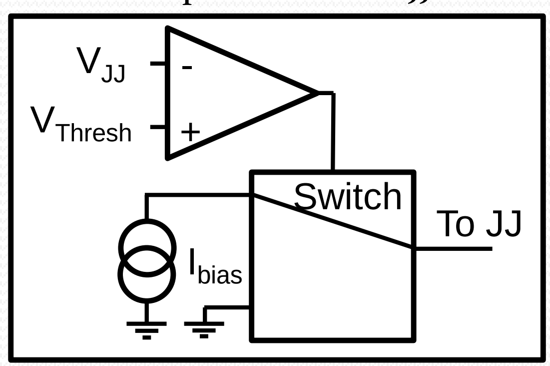


Electrical setup

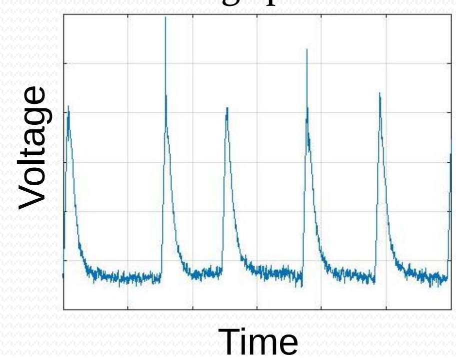
I-V Characteristics



Comparator resets JJ



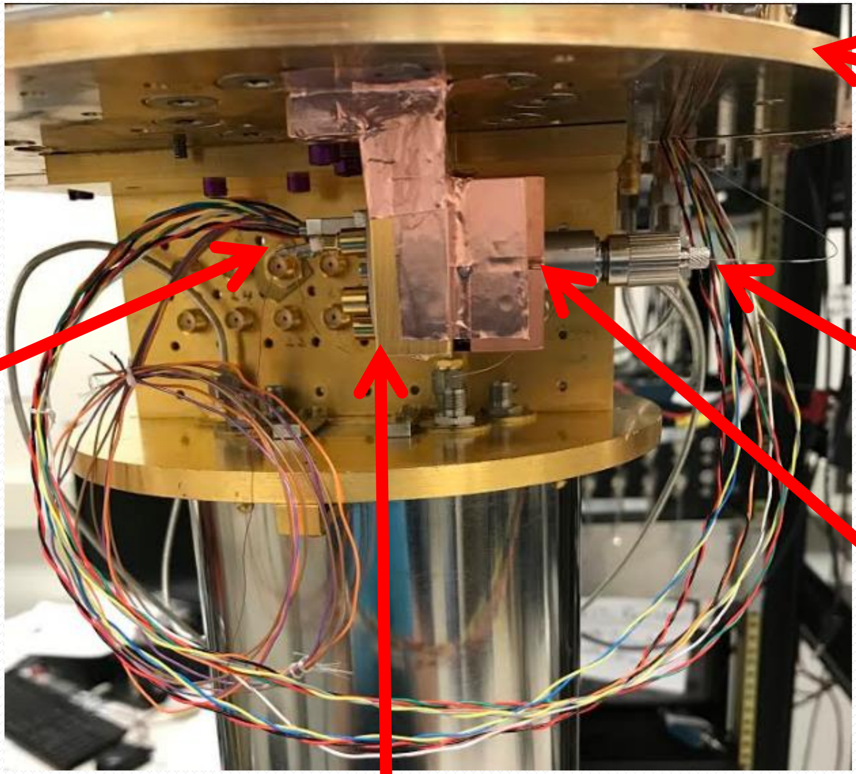
Voltage profile



From Gil-Ho Lee

Actual Setup

[E. D. Walsh et al., Phys. Rev. Applied **8**, 024022 (2017)]



Dilution Refrigerator
Mixing Chamber
(~30 mK)

DC Lines for
Current Bias and
Measurement

Fiber for
1550 nm Light

Fiber Collimator

Sample Holder

From Gil-Ho Lee