GLIMPSE:

Graphene-based Light Invisible Matter Particle SEarch

with D. Kim, K.C. Fong & G.-H. Lee [arXiv: 2002.07821 & In preparation]

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The Dark Side of the Universe 2022

2022.12.06

Particle Physics

❖ Chungnam National Univ., Korea

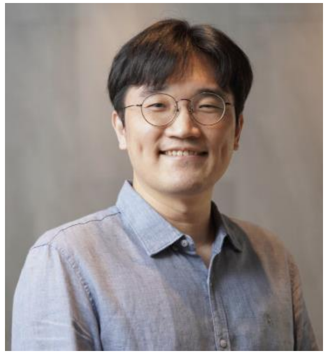
- Jong-Chul Park
- Bi Shin $+\alpha$

❖ Texas A&M Univ., USA

- Doojin Kim

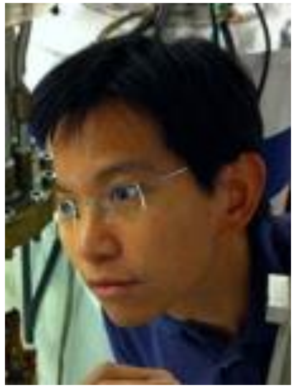
Condensed Matter Physics

❖ POSTECJ, Korea



- Gil-Ho Lee
- Seong Jang
- Seunghan Lee $+\alpha$

❖ Raytheon BBN Technology, USA



- Kin Chung Fong

Dark Matter Landscape: A Very Wide Mass Range

Ultra-light
(QCD) axion,
hidden photon,
scalar field,
fuzzy,
non-thermal

Super-light
sterile ν,
axino,
warm DM,
can be
thermal

Light
SIMP,
ELDER,
can be
thermal

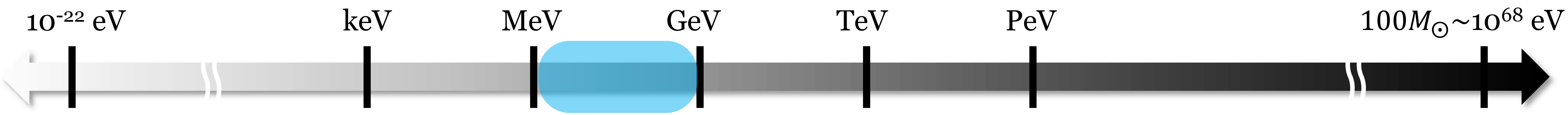
WIMP
well-motivated,
extensively
studied,
thermal
No firm signal yet!

Super-heavy
composite,
WIMPzilla,
Q-ball,
Fermi-ball,
dark-quark
nugget,
non-thermal

Astrophysical object
MACHO, PBH,
non-particle

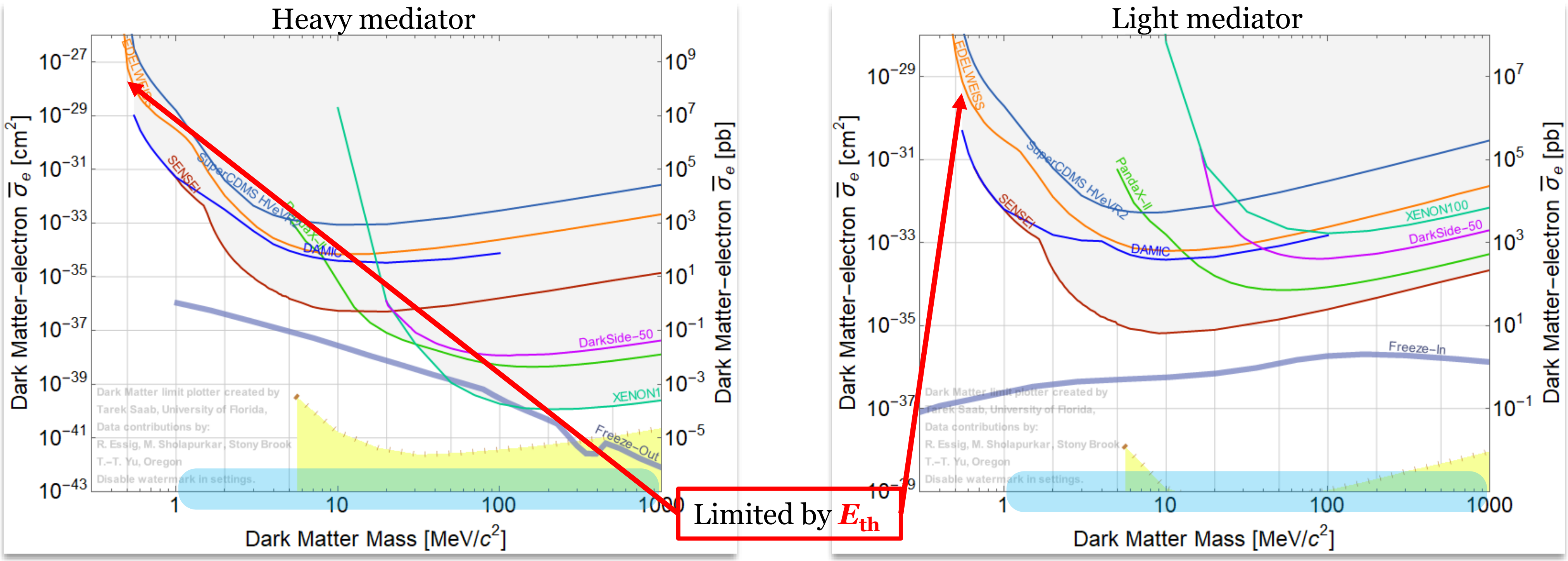
* Also Adam Ritz's, Theresa Fruth's & Tom Melia's Talks!

Light DM Direct Search



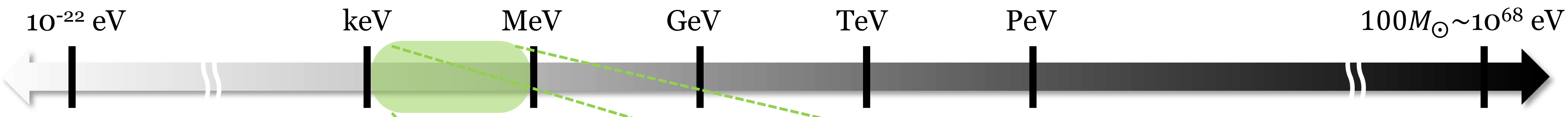
- $E_k \sim mv^2$, $\Phi_\chi = n_\chi v_{rel}$ & $n_\chi = \rho_\chi / m_\chi$
  - ➔ **lighter DM**: **smaller E_r**, but **lager flux** (**lighter** target particle)
  - ➔ **low E_{th}** preferred but even OK with **small target mass** (**e-recoil**)

✓ **A way out**: ***v~c***
e.g., Boosted DM



Dark Matter Limit Plotter v5.17 (Sep. 12, 2022)

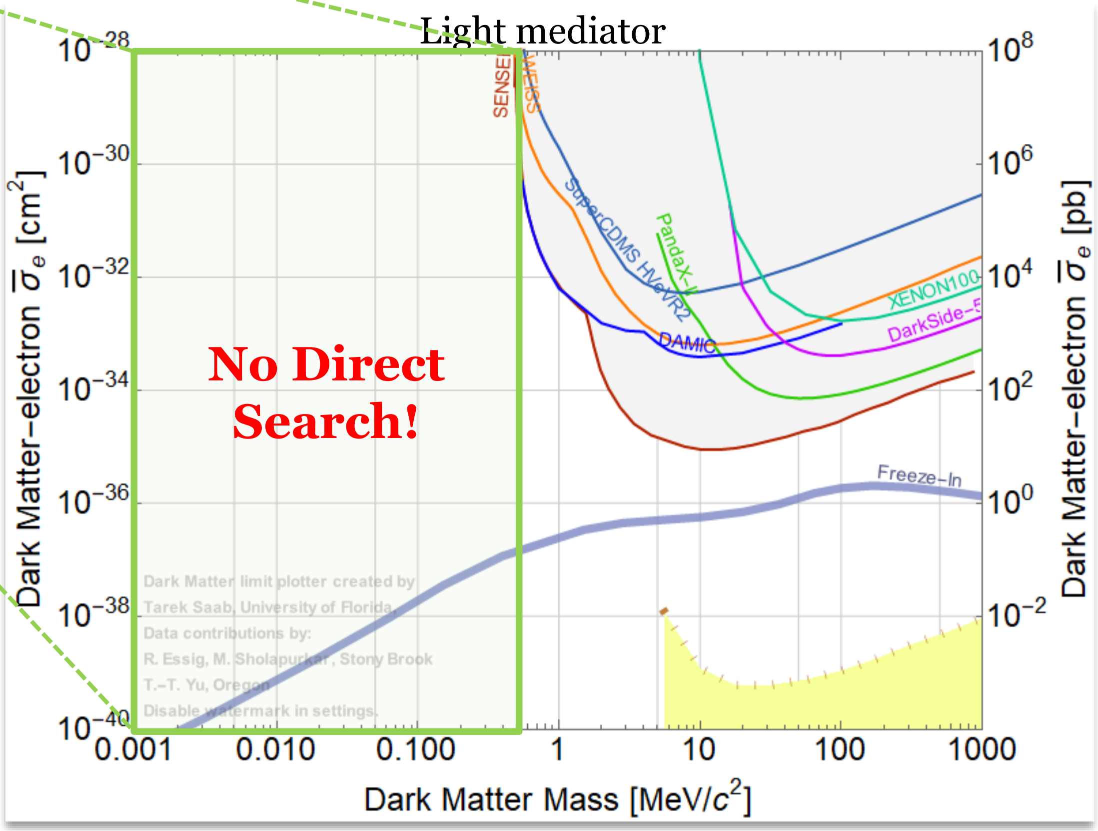
Super-Light DM Direct Search



- $E_k \sim mv^2 \sim$ **O(meV)** with $m \sim$keV & $v \sim 10^{-3}$
- **New approaches** are required!
  - ✓ Superconductor [PRL (2016)]
  - ✓ Superfluid He [PRL (2016)] (PRL (1987) for pp solar ν)
  - ✓ 3D Dirac material [PRD (2018)]
  - ✓ Polar material [PLB (2018)]
  - ✓ Superconducting-nanowire [PRL (2019)]
  - ✓ Graphene Josephson junction (GJJ) [**JCP** et al. 2002.07821 & In progress]
  - ✓ …

➔ The **race** to prove **super-light DM** has begun.

- **No experiment** for **O(keV) DM** so far.



Dark Matter Limit Plotter v5.17 (Sep. 12, 2022)

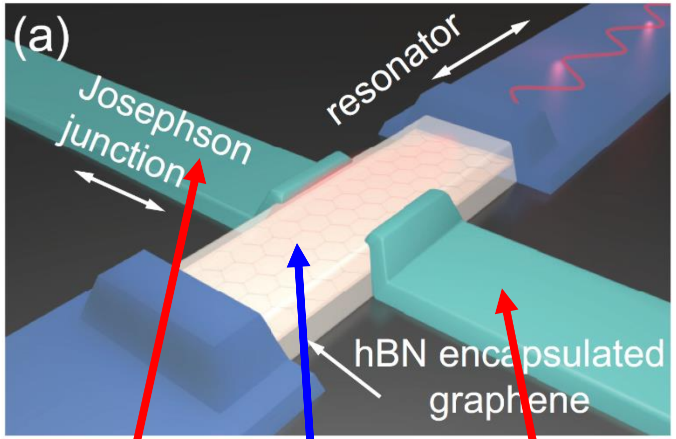
GLIMPSE

Graphene-based Light Invisible Matter Particle SEarch

We proposed a new super-light DM direct detection strategy adopting the Graphene-based Josephson Junction* (GJJ) microwave single photon detector.

* A "state-of-the-art" technology: much lower $E_{th} \sim O(0.1\ \text{meV})$

GJJ Device



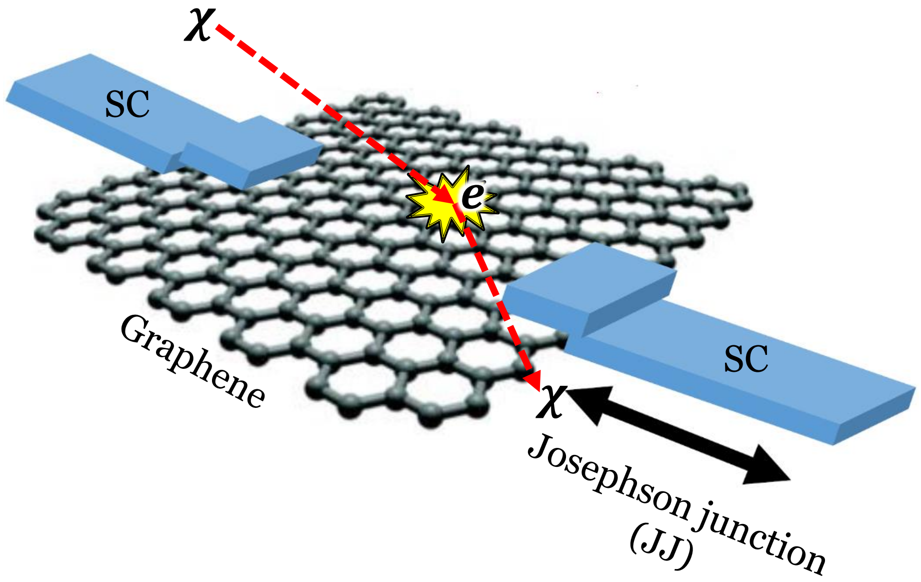
Superconductor-Graphene-Superconductor (SGS)
[G.-H. Lee et al. Nature (2020)]

The device consists of a sheet of mono-layer graphene two sides of which are joined to superconductor, forming a superconductor-normal metal-superconductor Josephson junction.

- A GJJ single-photon detector was proposed, covering from near-IR to microwave. [Phys. Rev. Applied (2017)]
- G.-H. Lee, K.C. Fong & their collaborators have **demonstrated experimentally** that the GJJ microwave bolometer can have **sensitivity to ~0.1 meV energy deposit**. [Nature (2020)]
- Currently, a **GJJ single-photon detector** is under testing.

  The detection of single near-IR photon (***E*~1 eV**) has been done. [Science (2021)]

Detection Principle with GJJ



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

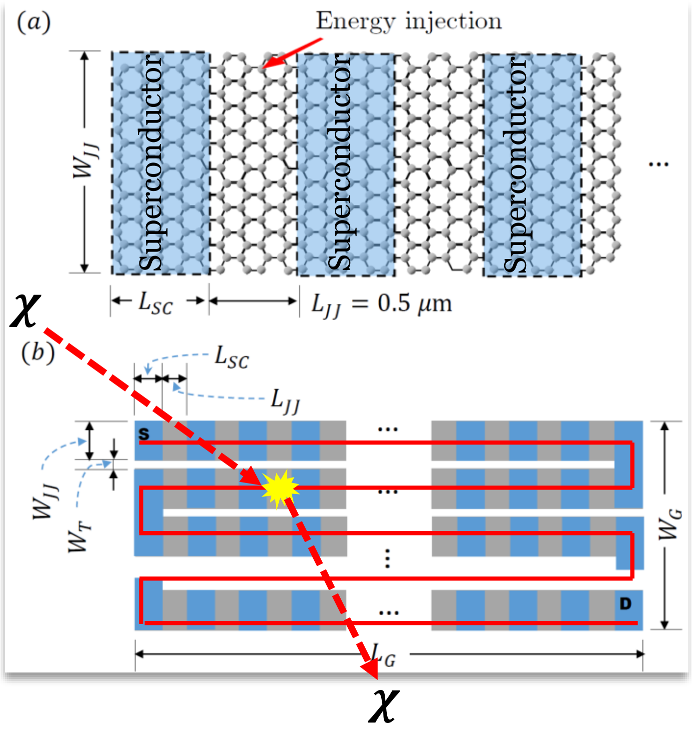
II. **The recoiling e heats up & thermalizes** with nearby e's rapidly via e-e interactions.

III. **The JJ is triggered**: the temperature rise switches the zero-voltage (non-resistive) of JJ to a **non-zero-voltage (resistive) state**.

❖ **GJJ**: sensitivity to ~0.1 meV E deposit [Nature (2020)]

➔ **GJJ detector: sensitivity** to the signal even by **sub-keV DM**.

Super-Light DM Direct Search Using GJJs



I. Single graphene strip (a): the 1D assembly of a long graphene strip & a number of superconducting material strips ➔ an array of SC-graphene-SC-graphene-SC-⋯ (SGSGS⋯).

II. Each sequence of SGS represents a single GJJ device.

III. 2D detector unit (b): all GJJs are connected in series so that even a single switched GJJ by DM interaction allows the series resistance measured between S & D to switch from 0 to a finite value.

- ❖ E_{th} is determined by the strip width W_{JJ}: $W_{JJ} = 3\ \mu m\ (30\ \mu m)$ ➔ $E_{th} \approx 0.1$ meV (1 meV).
- ❖ A much larger-scale detector can be made of a stack of such detector units (3D).

To calculate experimental sensitivities, we should consider the scattering between DM traveling in 3D & free electrons living in 3D but confined in 2D graphene layer.

Calculating Signal Rates

- Goal: The event rate of DM scattering off free electrons in a 2D graphene sheet.

- Key point: The electron is still **confined** in the 2D graphene plane even after the collision.

  → No significant momentum change along the surface-normal (z-axis) direction.

  → **Signal rate depending on the DM incoming direction**

- We will calculate the number of events/unit detector mass/unit run time:

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

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

Calculation Procedure I

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

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

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

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

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

2D nature of graphene

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

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

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

- ✓ $f_{e,i}(E_{e,i}) = 1/\left\{1 + \exp\left(\frac{E_{e,i} - \mu}{T}\right)\right\}$, $(\mu \sim E_F)$

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

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

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

- **Structure function** for the **2D** system:

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

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

$$= (2\pi)\delta(p_{\chi,i}^z - p_{\chi,f}^z) \cdot \boldsymbol{S}_{\mathbf{3D}}(\boldsymbol{E_r},\ \boldsymbol{q})$$

➔ The Pauli blocking effects(=phase space suppression) are encoded in the structure function.

- The analytic expression for $S_{3\text{D}}(E_r,\ q)$ is available in the non-relativistic limit. [S. Reddy *et al.*, PRD (1998), Y. Hochberg *et al.*, JHEP (2016)]

Calculation Procedure III

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

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

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

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

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

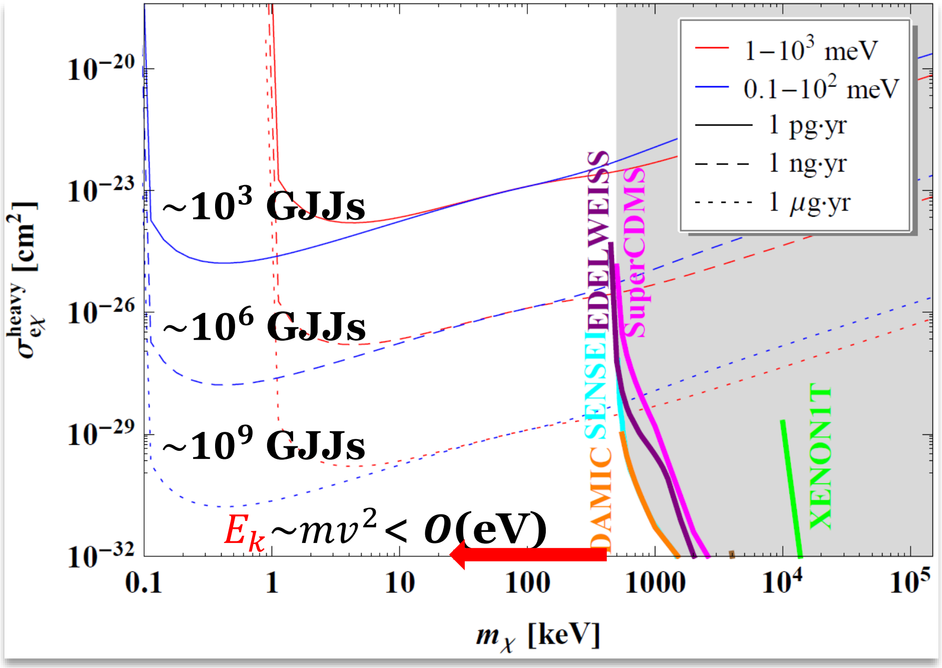
- We assume that DM interacts with electrons via an exchange of mediator ϕ as done in many of the preceding studies :

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

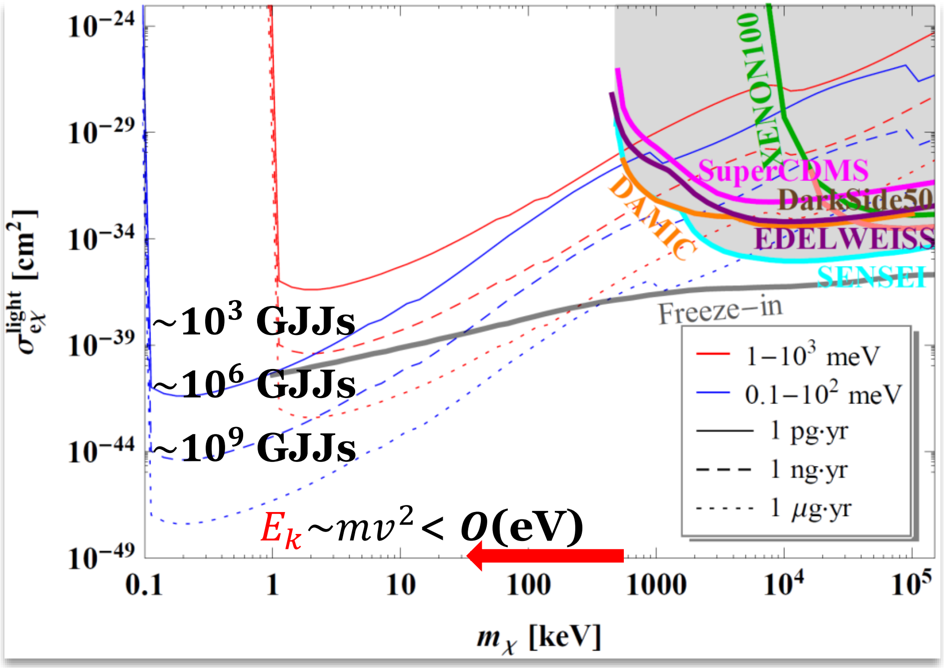
- The matrix element $\overline{|\mathcal{M}|^2}$ is related to the scattering cross section as $\sigma_{e\chi} = \frac{\overline{|\mathcal{M}|^2}}{16\pi\, m_e^2 m_\chi^2} \mu_{e\chi}^2$.
- From the linear dispersion of graphene: $E_F = v_F \sqrt{\pi n_c}$ with $v_F \sim 10^8$cm/s & $n_c \sim 10^{12}$/cm^2.

Expected Sensitivities of GJJ Detectors

Heavy mediator: $F_{DM} = 1$



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



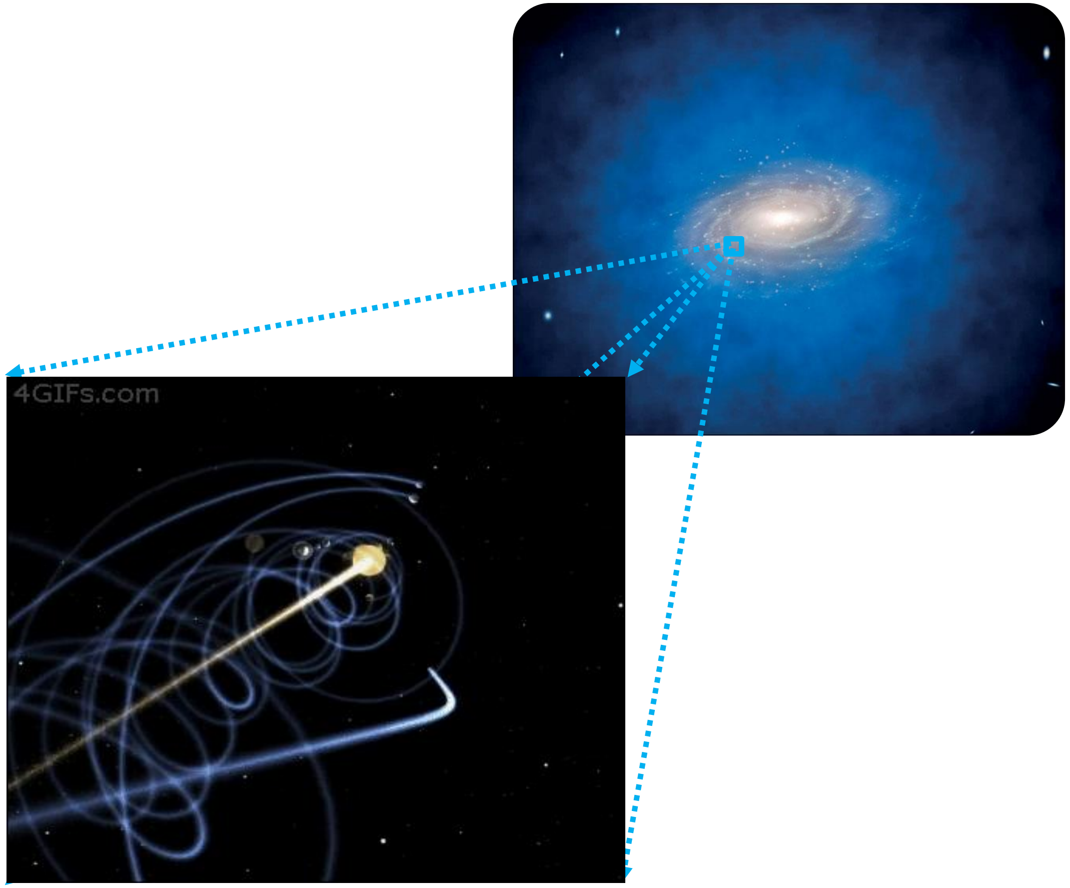
- ✓ The **proposed detector** can improve the minimum detectable DM mass (**m_{DM}~0.1 keV**) by more than 3 orders of magnitude over the ongoing/existing experiments.
- ✓ **Capable of probing** the prediction of **freeze-in** scenarios even with a pg-scale (**~10^3 GJJs**) detector.

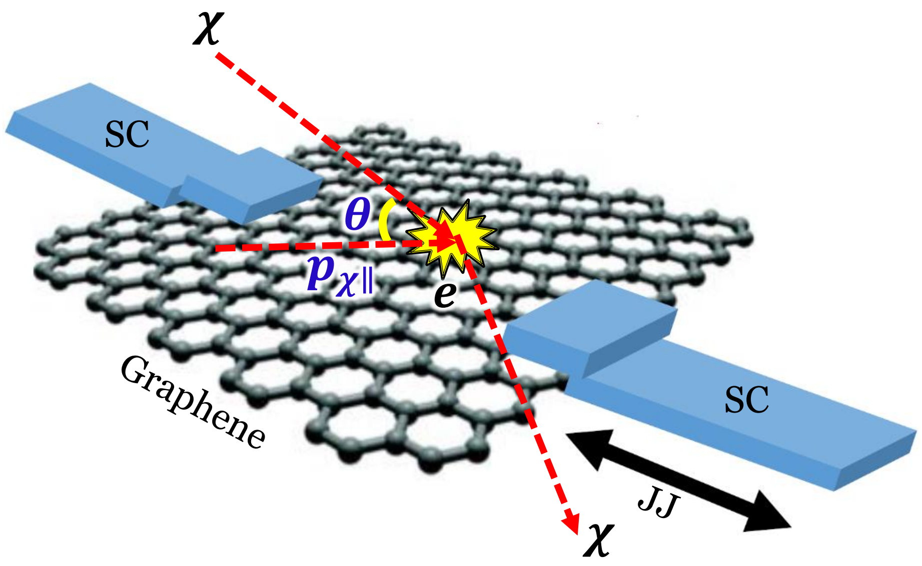
Signal Rate: Directional Dependence

❖ Electron: **confined in the 2D graphene sheet** even after the collision.

➔ Momentum transfer: the change of $p_{\chi\parallel}$ ➔ Signal rate: **DM incident direction** dependence

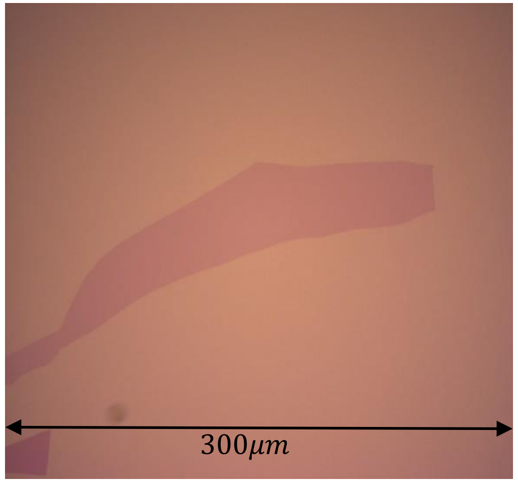
➔ DM signals: **in situ validation** by **actively rotating the detector** or **time information of each signal**



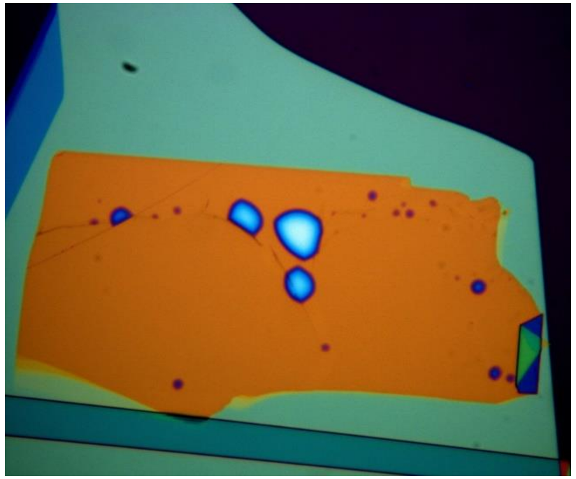


Experimental Status

Progress in Fabrication: ~100 GJJs in Series



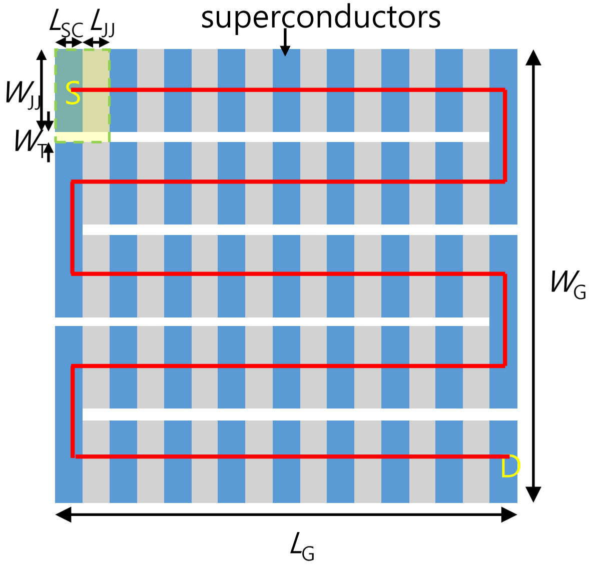
Large piece of graphene



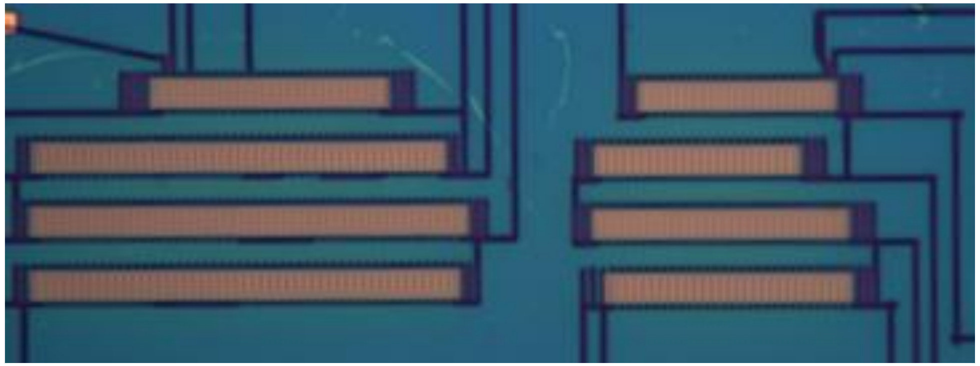
hBN-encapsulated graphene

Etched hBN/Graphene/hBN stack

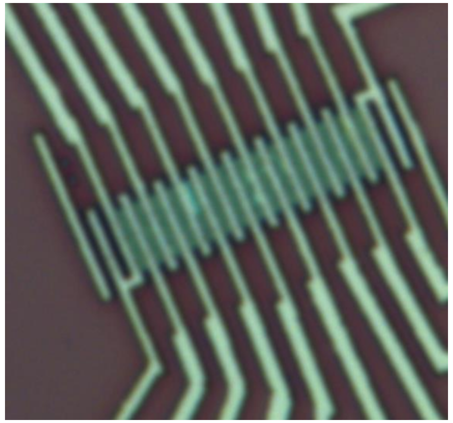
Schematics



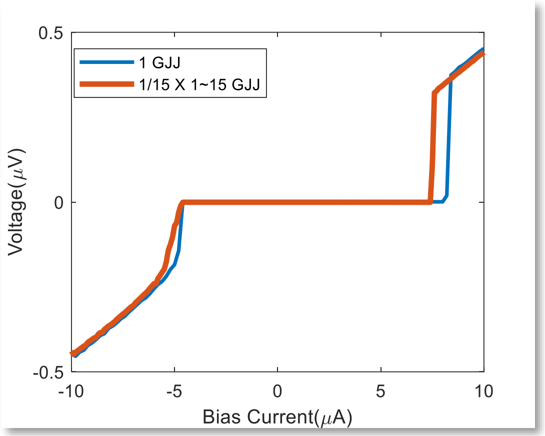
216 GJJs connected in series



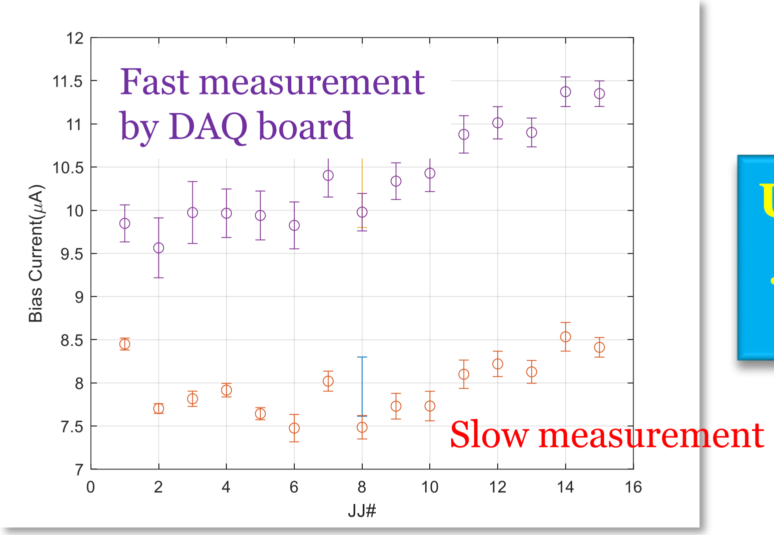
Uniformity of Multiple GJJs



Device optical image (15 GJJs)

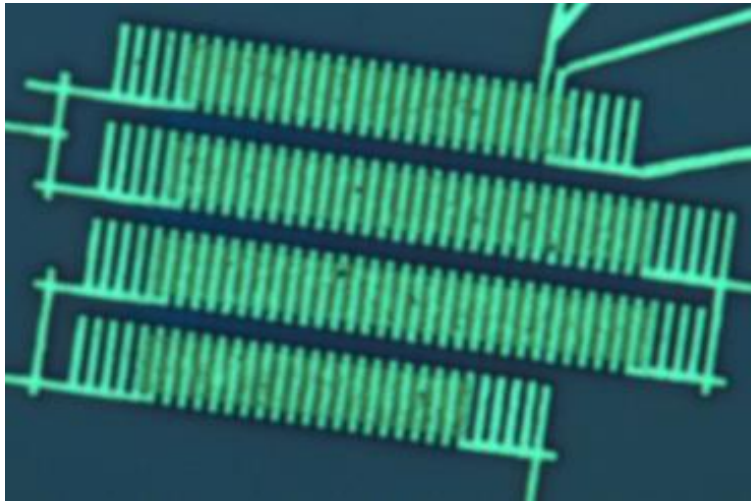


Almost same I-V curve when scaled

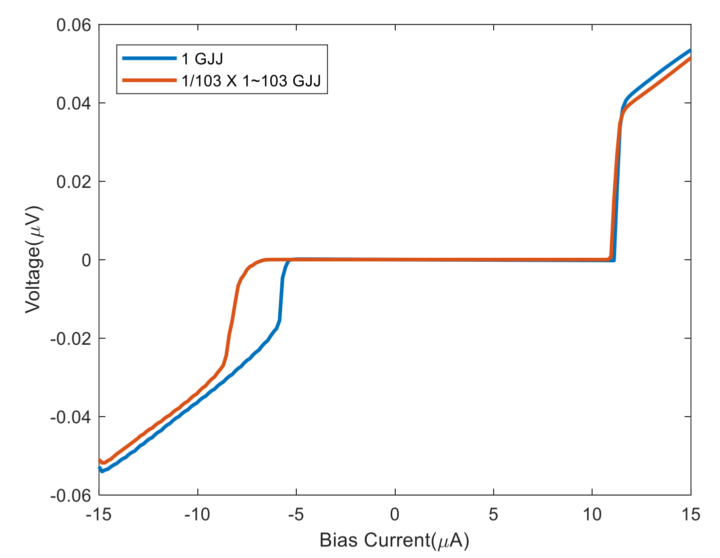


$\pm$9% variation in switching current

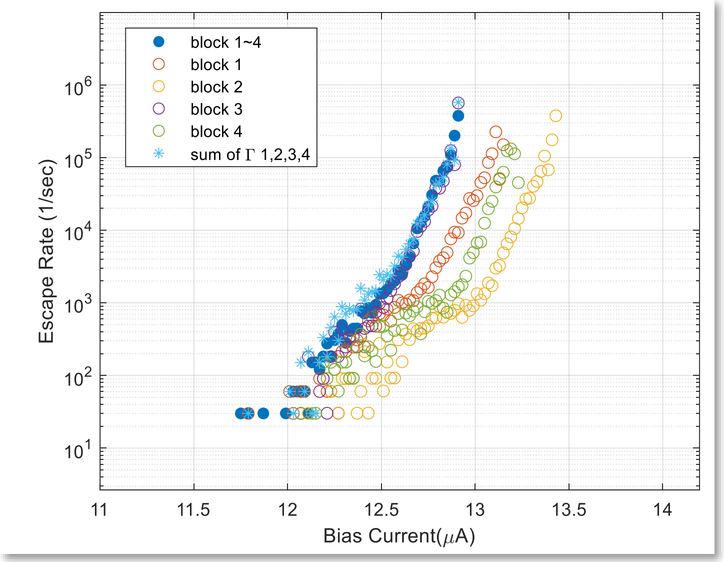
Uniform Josephson junctions in series was fabricated!



Device optical image of ~100 GJJ array

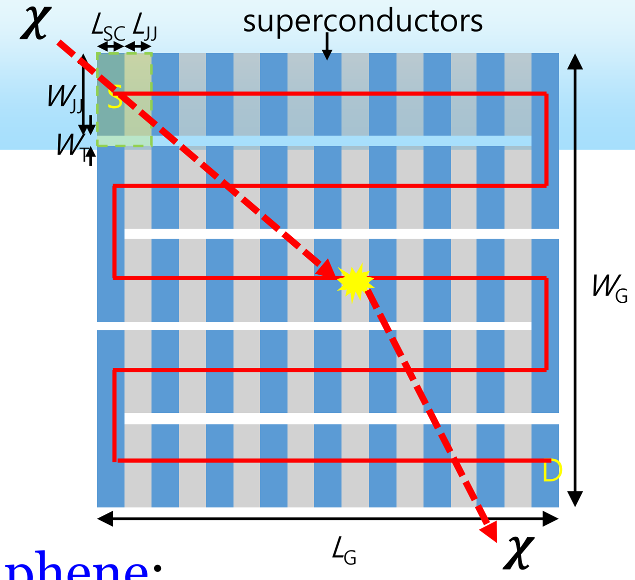


Almost same I-V curve when scaled



Escaping rate measurement: $\pm$4% variation

Summary



- **GLIMPSE**: a new DM detector,

  adopting the **GJJ device**

- Scattering between **DM moving in 3D space** & **e's confined in 2D** graphene:

  Event rate making an effective model ➔ **Signal rate: DM incident direction dependence**!

- Capable of sensing keV-range DM scattering off e's due to $\boldsymbol{E_{\mathrm{th}} \sim 0.1\ \mathrm{meV}}$.

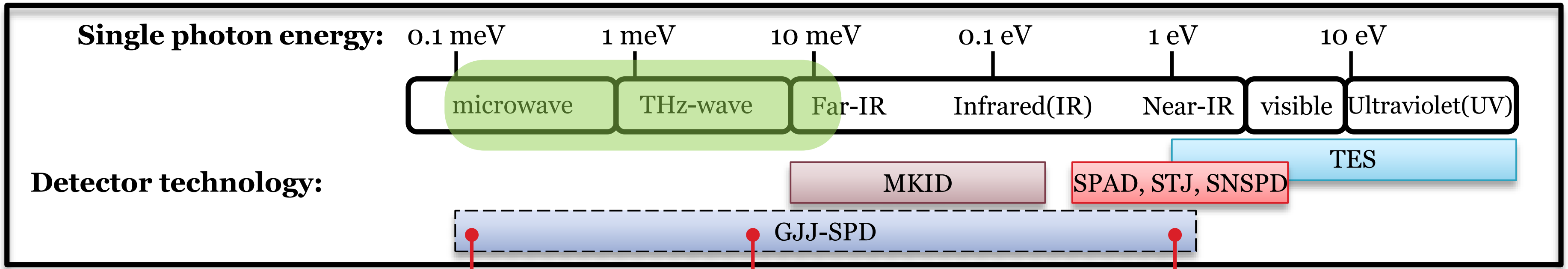
  ➔ Improving the minimum detectable mass: $\boldsymbol{m_{DM} \sim 0.1\ \mathrm{keV}}$.

- Uniform O(100) GJJs in series: fabricated and under testing.

- Other light invisible particle searches: ultra-light DM (e.g. dark photon, axion), new possibilities?

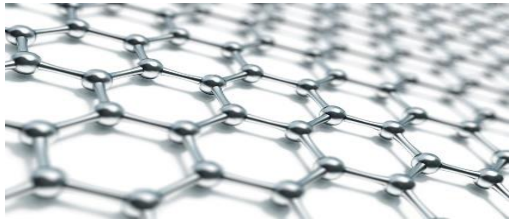
Supplemental

Status of Sensor Technologies



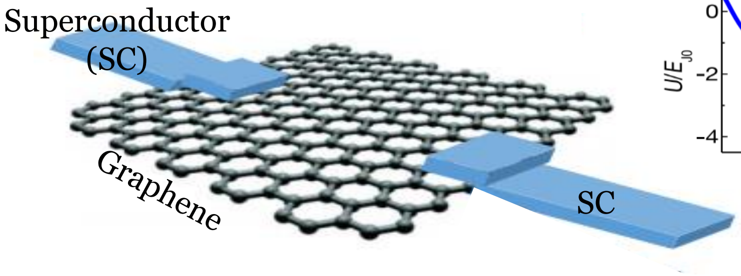
[G.-H.Lee,D.K.E.,W.C.Jung *et al.*, Nature (2020)] *"On-going"* [E.W.,W.C.Jung,G.-H.Lee, *et al.*, Science (2021)]

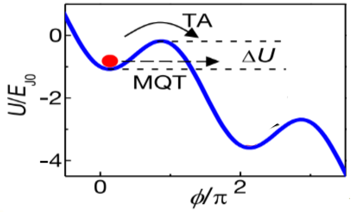
❖ **Graphene**



- ✓ Minute electronic heat capacity: ~ 10 $k_B/\mu m^2$
  - → **Large response** in electron temperature (T)
  - *e.g.*, E=1 meV raises from T=0.01 K to **1.3 K**
- ✓ **Fast thermalization** time: $\tau_{e\text{-}e} < 1$ ps
- ✓ **Slow cooling** time: $\tau_{e\text{-}ph} \sim 1$ ns

❖ **Josephson junction**





Plasma frequency: $f_p \sim 100$ GHz

- ✓ **Sensitive** response: $dI_c/dT \sim$ a few μA/K
- ✓ **Fast** response: $\tau_p = 1/f_p \sim 0.1$ ns ($\ll \tau_{e\text{-}ph}$)

Backgrounds

- Neutrino (mostly pp solar neutrinos): irreducible!

  Scatter off nuclei/electrons and deposit a small amount of E ➔ The expected number of events is $O(1)/(\mathrm{kg}\cdot\mathrm{year})$.

- Cosmic muon: $O(1)/(\mathrm{g}\cdot\mathrm{year})$. Reducible in the deep underground lab.

- Radiogenic: (relatively) reducible!

  Have characteristic E scales ≫ region of our interest (< eV) ➔ negligible [R. Essig *et al.*, PRD (2012), Y. Hochberg *et al.*, JHEP (2016)]

- Intrinsic Radiogenic: C-14 ➔ $O(1)/(\mu\mathrm{g}\cdot\mathrm{year})$. Reducible by growing a graphene layer with C-14 removed methane gas.

- Josephson junction detector backgrounds:
  - ✓ Thermal fluctuation: Lowering temperature using dilution refrigerator down to ~10 mK.
  - ✓ Quantum fluctuation: Lowering bias current enough to have low enough dark count
  - ✓ Electrical fluctuation: Using thermo-coax DC wires to suppress high-frequency noise and galvanically isolated measurement circuit
  - ✓ Electromagnetic radiation: Multiple metal-can shielding in dilution refrigerator

- Dark count analysis: depending on $I_c(W_{JJ}, L_{JJ})$ and I_b

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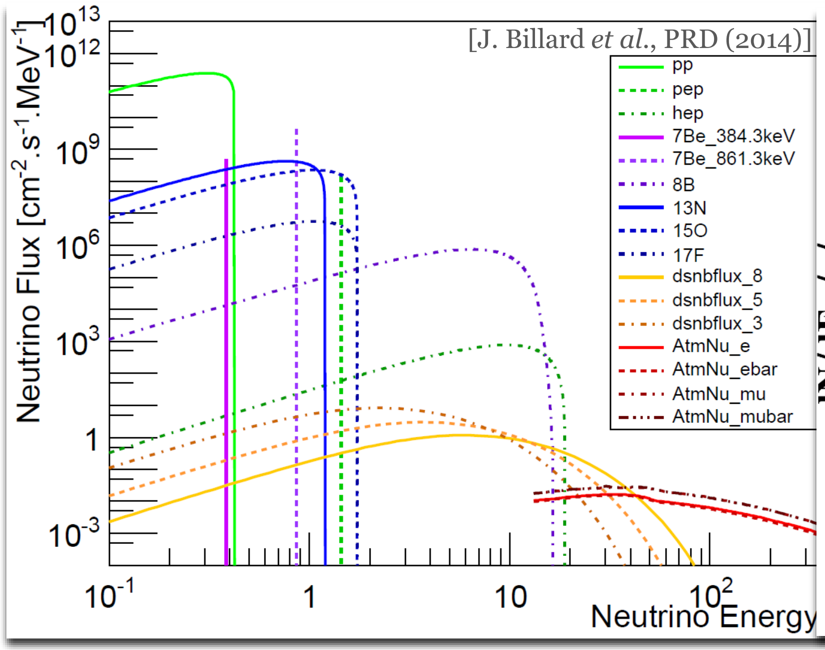
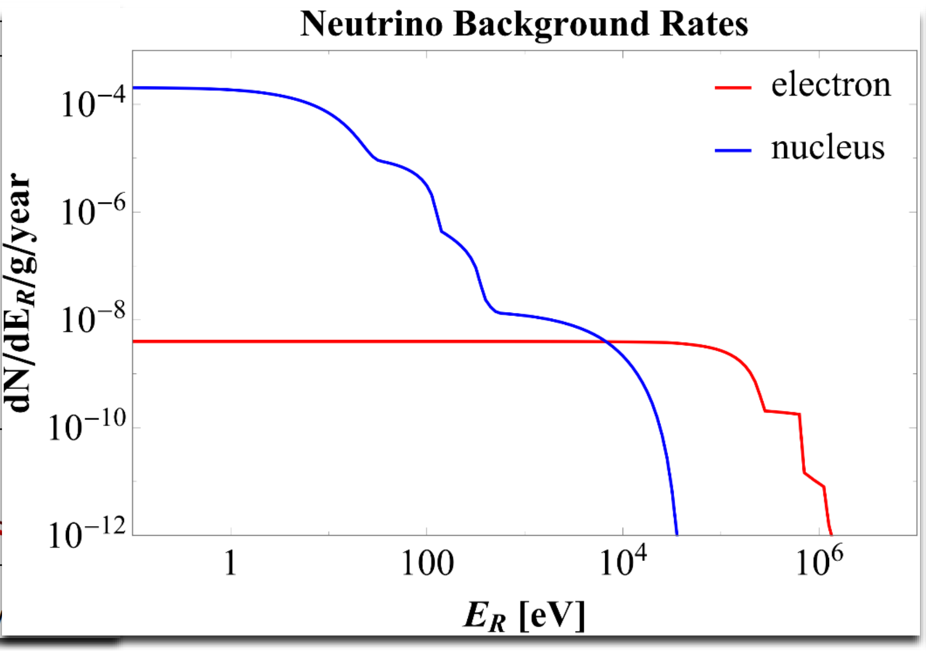
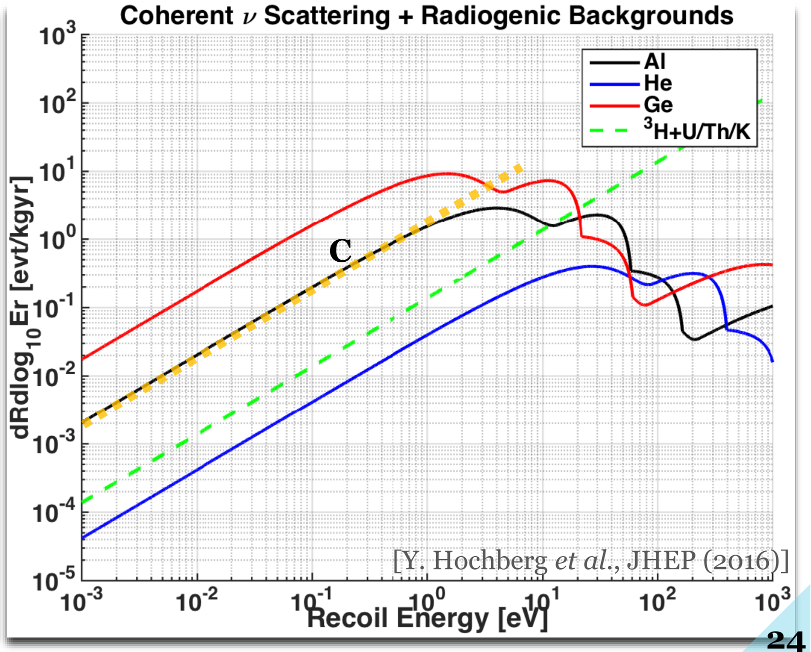
  Have characteristic E scales ≫ region of our interest (< eV) ➔ negligible [R. Essig *et al.*, PRD (2012), Y. Hochberg *et al.*, JHEP (2016)]

- Intrinsic Radiogenic: C-14 ➔ $\mathcal{O}(1)$/(μg·year). Reducible by growing a graphene layer with C-14 removed methane gas.

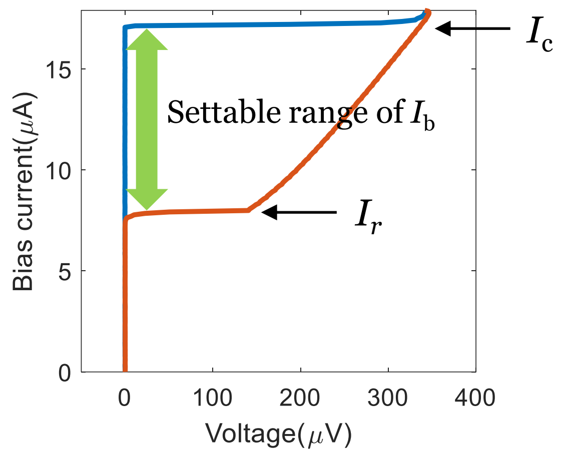






Progress in Dark Count Rate Estimation

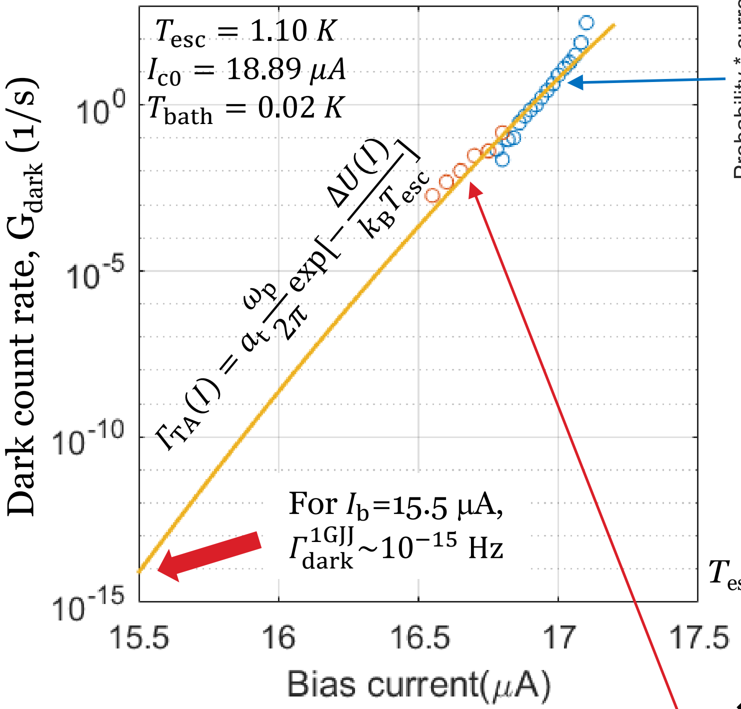
[Current-voltage characteristics]



❖ 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.)

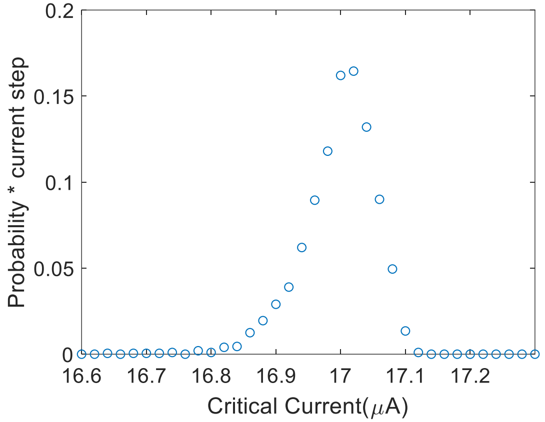
❖ For non-uniform I_c of JJs, the smallest I_c will dominate the dark count rate.

[Dark count rate measurement]



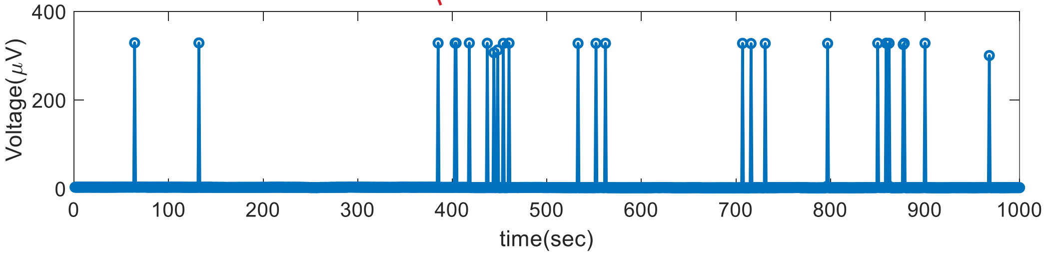
$T_{\mathrm{esc}} > T_{\mathrm{bath}}$: MQT regime

❖ Sweep I_b and record I_c

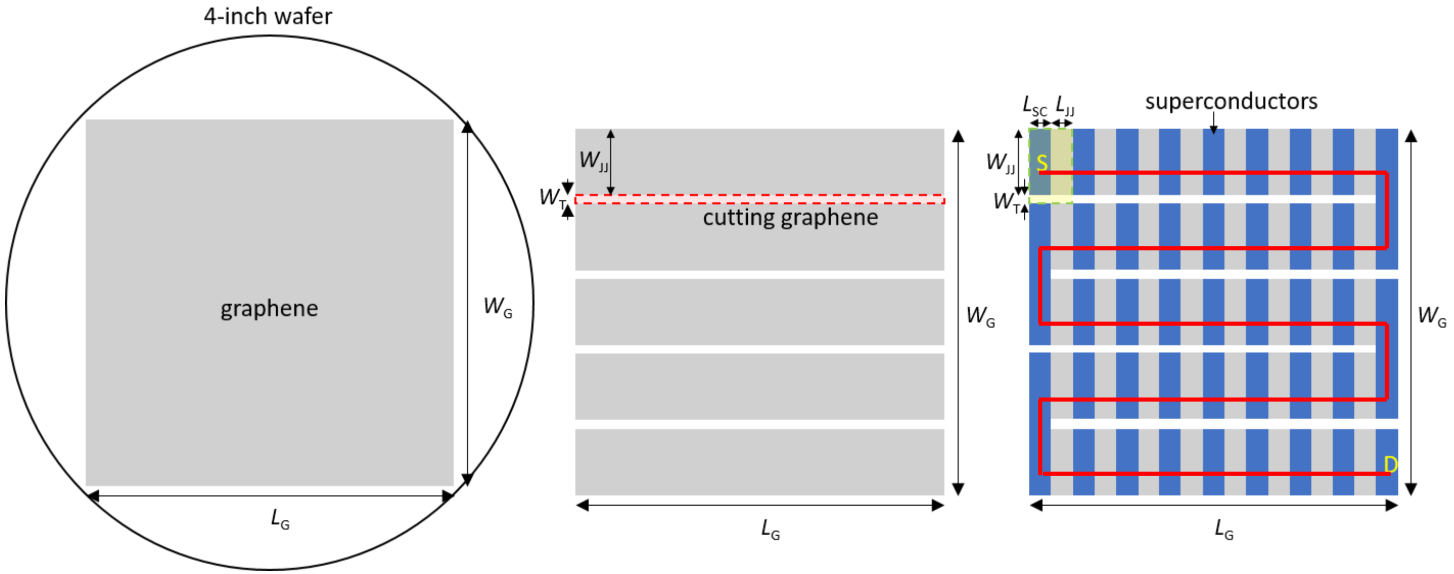


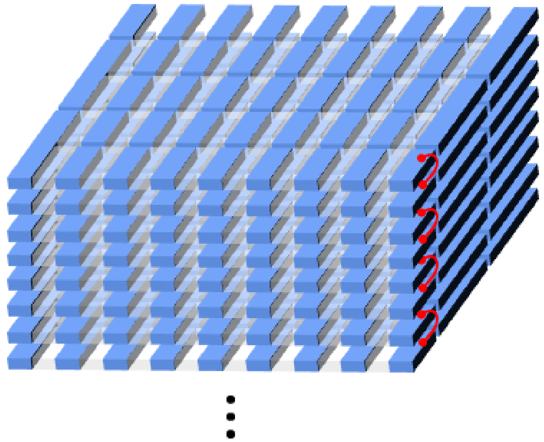
$$P(I) = \frac{\Gamma(I)}{dI/dt}\left[1 - \int_0^I P(I')\,dI'\right]$$

❖ Fix I_b and wait JJ switches



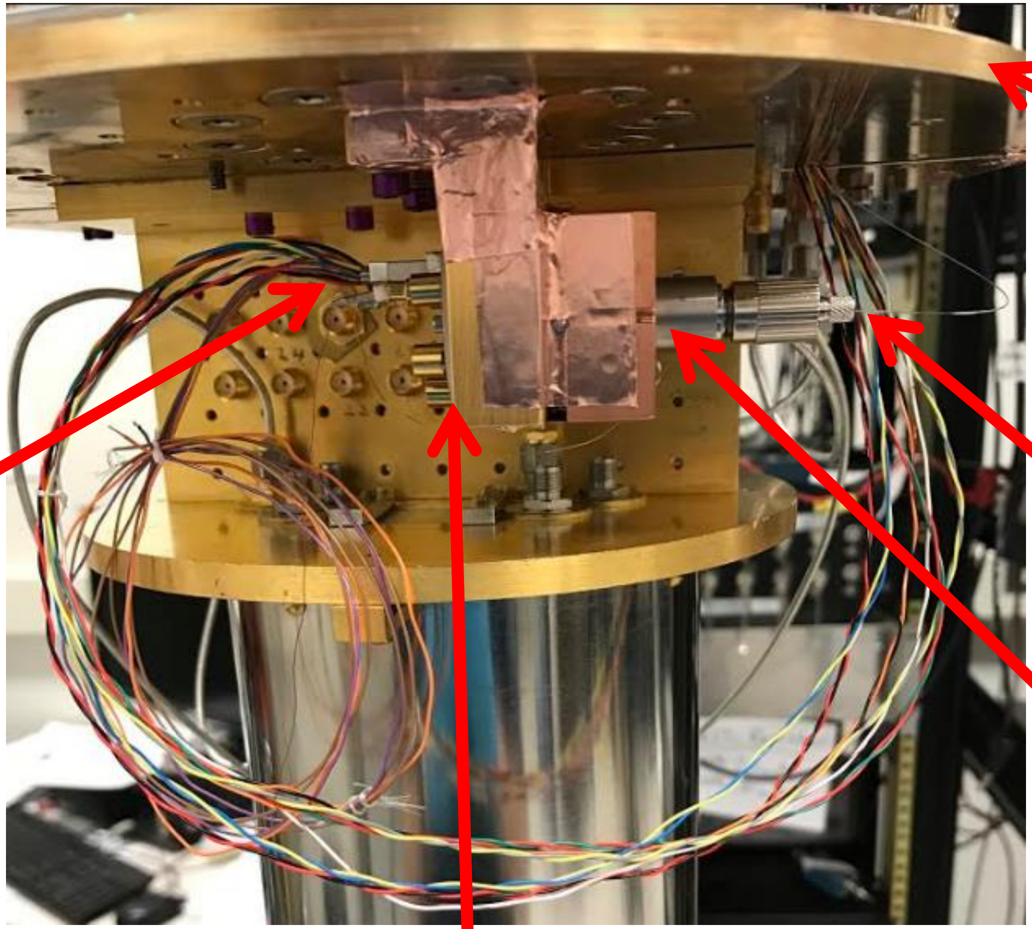
Schematics of 2D Fabrication & 3D Detector





- Currently available nanofabrication technology could achieve the device that we propose.
- We can keep connect multiple GJJs in series without introducing any resistive part in the device.

Actual Set-up



Dilution Refrigerator
Mixing Chamber
($O(10)$ mK)

DC Lines for
Current Bias and
Measurement

Fiber for
1550 nm Light

Fiber Collimator

Sample Holder