Status of GLIMPSE

Graphene-based Light Invisible Matter Particle SEarch

with D. Kim, G.-H. Lee, S. Lee, D. Jeong, , K. C. Fong
[2002.07821, 2604.18704, in Progress]

Jong-Chul Park

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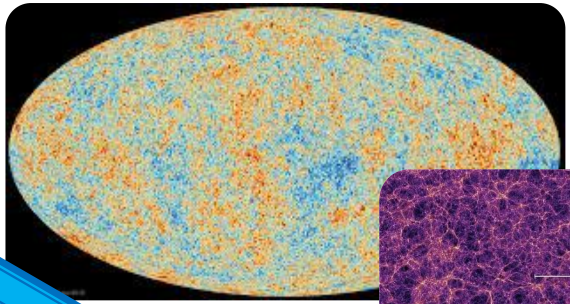
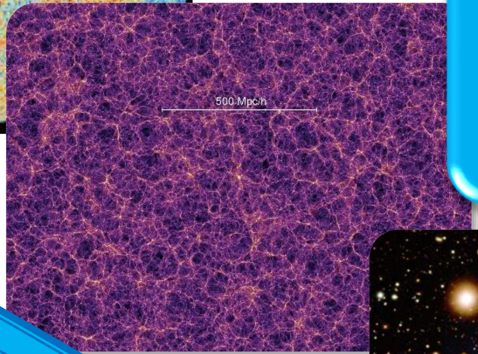
ISU 우주과학연구소 Institute for Sciences of the Universe

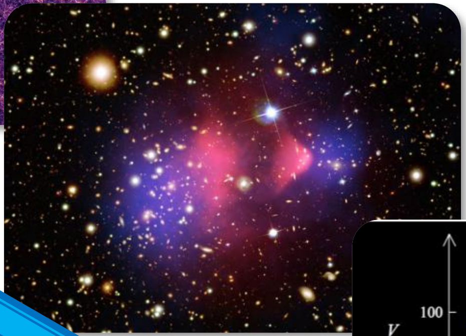
Why Light Dark Matter?

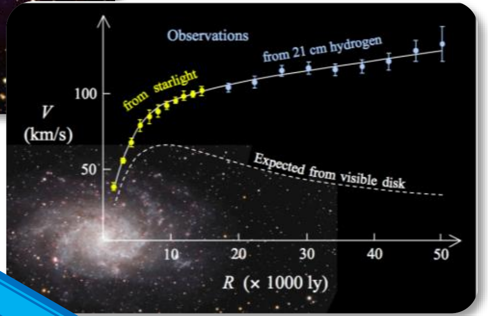
Message from Cosmology: Dark Matter (DM)





Dark Matter?





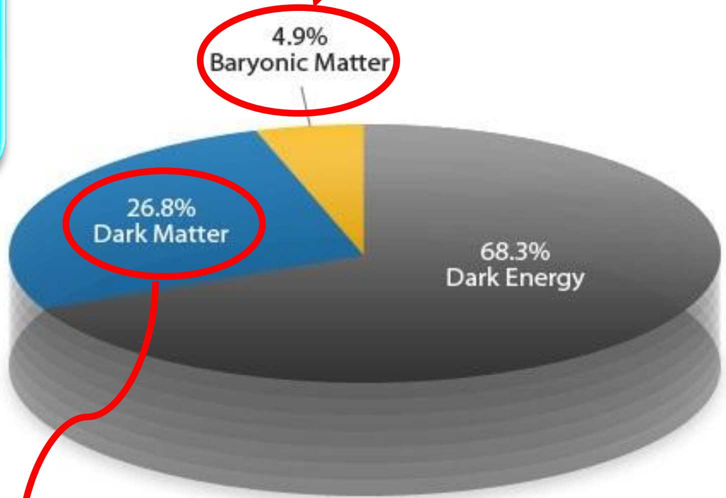
Larger scale
Earlier

Smaller scale
Later

Many more other observations!

❖ **Modern cosmology**:

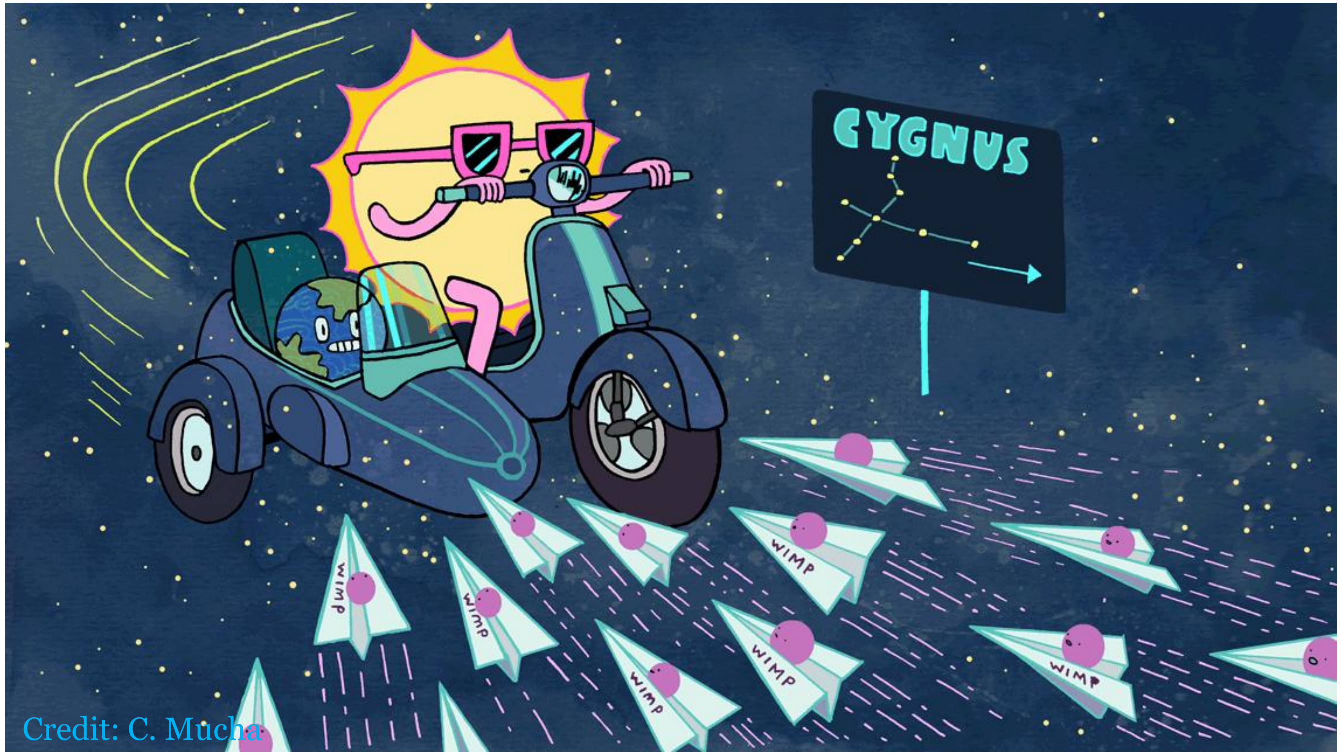
The Standard Model



❖ **Compelling paradigm**:

- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

DM Wind ➔ DM Direct Scattering



Credit: C. Mucha

DM

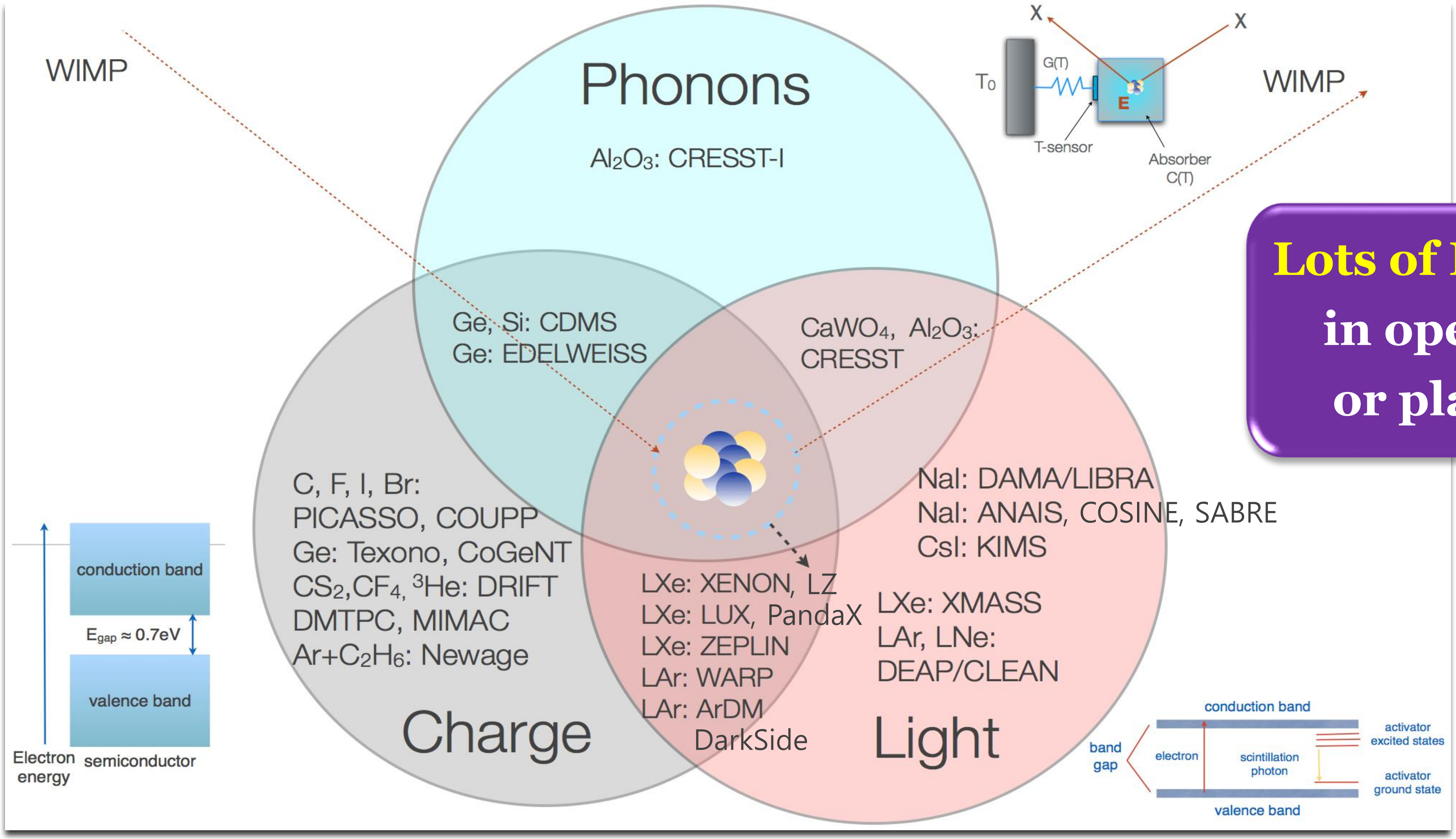

❖ Assuming $m_{\rm DM} \sim m_{\rm p}$ ~ 0.94 GeV: $\underbrace{300\ \mathrm{km/s} \times \frac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}}}_{\text{flux}} \times \underbrace{60\ \mathrm{cm} \times 170\ \mathrm{cm}}_{\text{area}}$

$\approx\ 10^{11}/\mathrm{s}$

✓ $\Phi_\chi = n_\chi v_{\rm rel}$ & $n_\chi = \rho_\chi / m_\chi$

DM Direct Detection Experiments

By Hyunsu Lee



Lots of Exps. are in operation or planned.


~~Nespresso.~~ What else?
WIMP

DM Landscape: A Very Wide Mass Range

By Hyunsu Lee

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

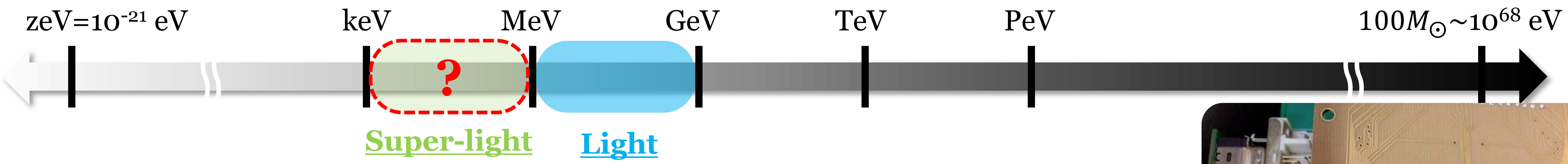
Thermal DM:
Too hot

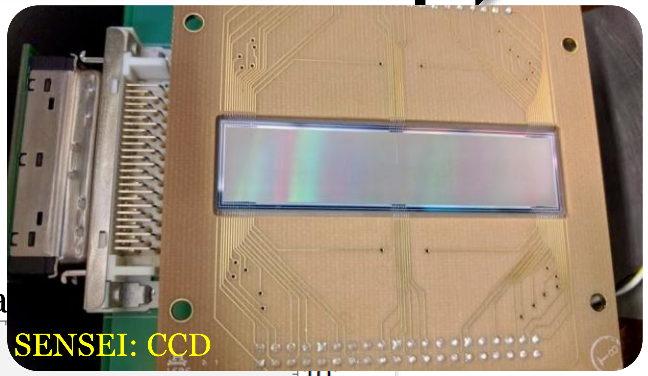
$\boldsymbol{m_e}$
$\boldsymbol{E_k \sim mv^2}$
~eV

$\boldsymbol{m_p}$
$\boldsymbol{E_k \sim mv^2}$
~keV

Light DM Direct Search: Current Status

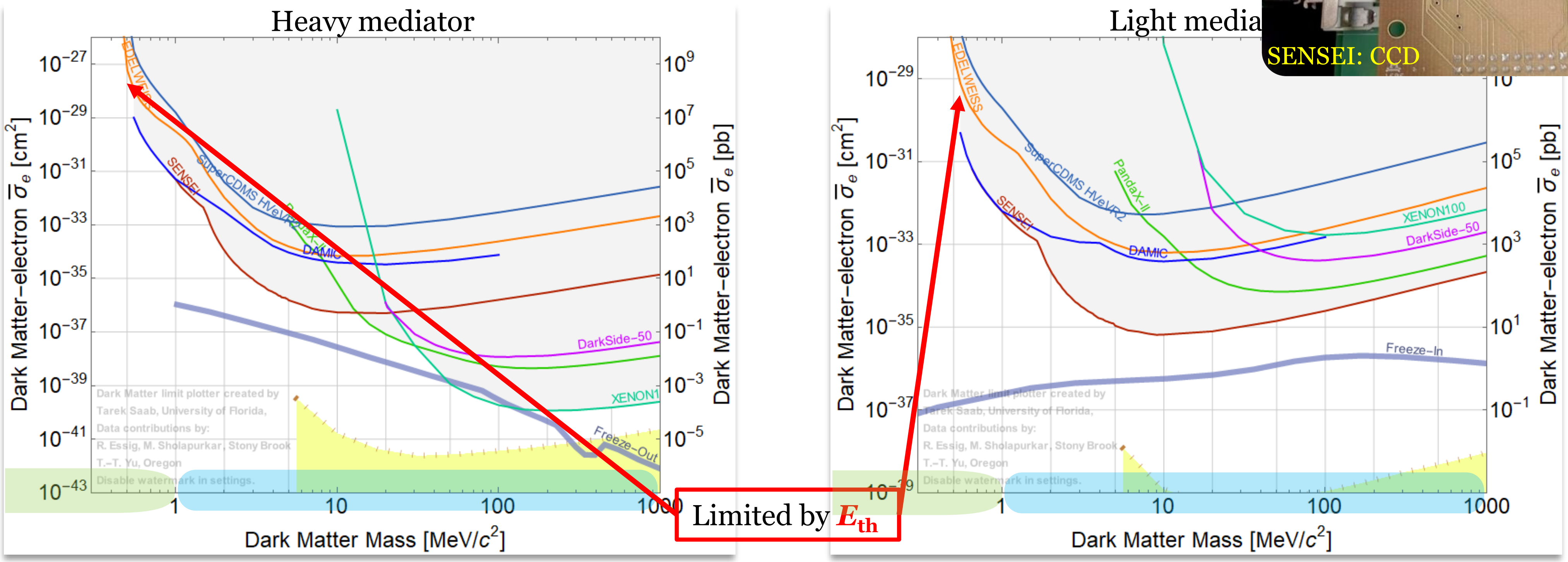
By Hyunsu Lee





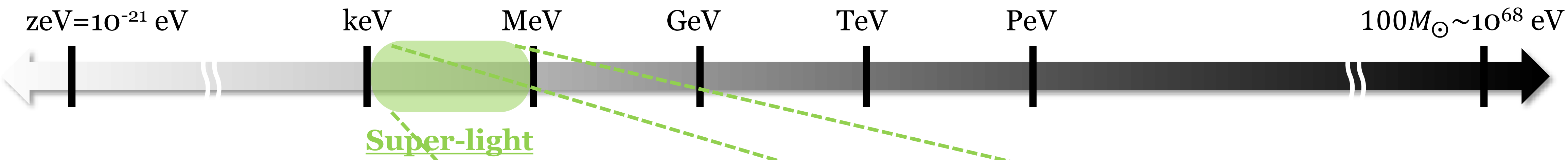
- $E_k \sim m_\chi v^2$, $\Phi_\chi = (\rho_\chi / m_\chi) v_{rel}$ ➔ **lighter DM**: **smaller E_r**, but **lager flux** (**lighter** target)

➔ **low E_{th}** preferred but even OK with **small target mass** (**e-recoil**)

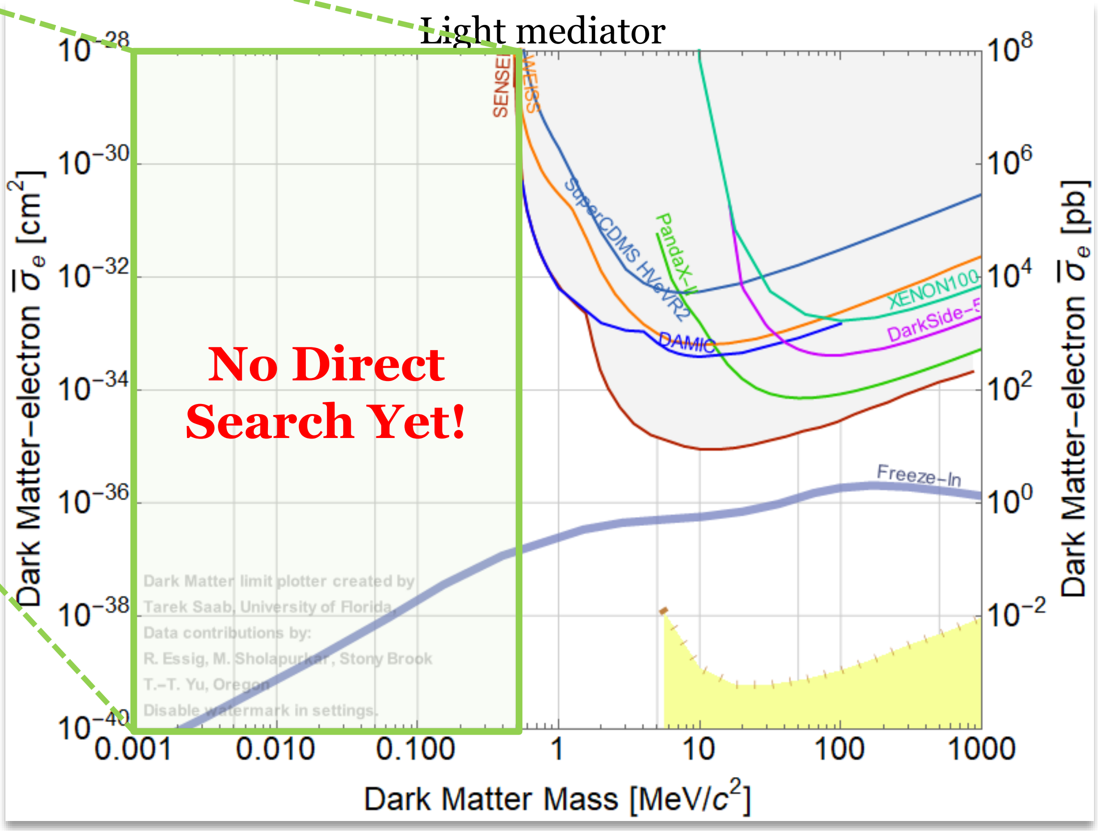


Dark Matter Limit Plotter v5.18

Super-Light DM Direct Search



- ❖ $\boldsymbol{E_r \sim E_k \sim mv^2 \sim O(\mathrm{meV})}$ with m~keV & $v \sim 10^{-3}$
- ❖ **New approaches** are required!
  - ✓ **Targets**: Superconductor, Superfluid He, 3D Dirac material, Polar material, Diamond, etc.
  - ✓ **Sensor** technologies: TES, MKID, STJ, SNSPD, GJJ, etc. (mostly based on superconductivity)
- ➔ The **race** to prove **super-light DM** has begun.



Dark Matter Limit Plotter v5.18

GLIMPSE

Graphene-based Light Invisible Matter Particle SEarch

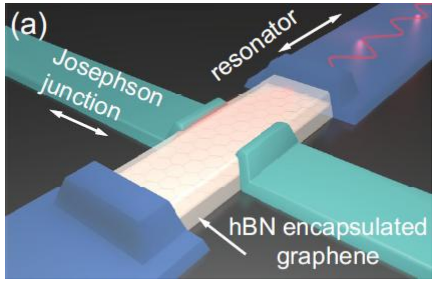
[Kim, **JCP**, Lee, Fong, 2002.07821]

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

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

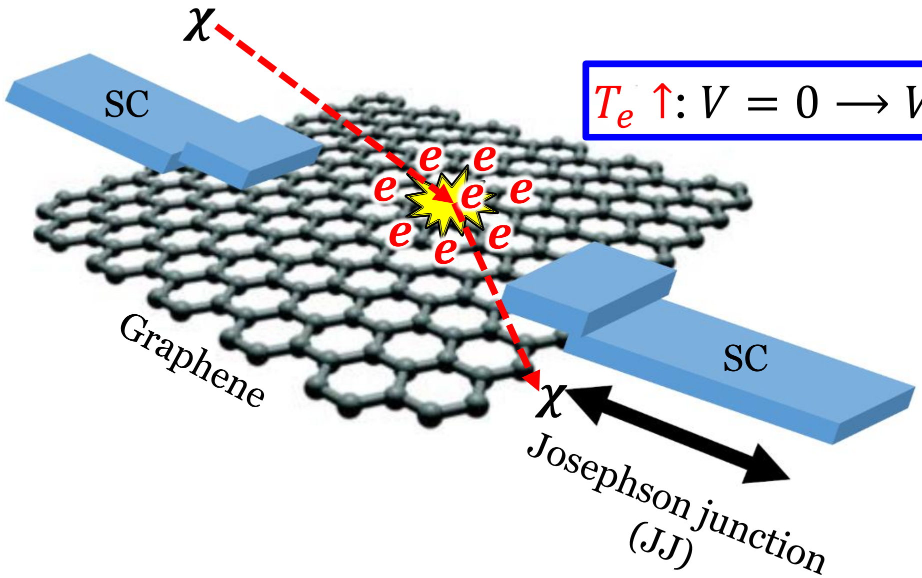
Super-light DM Search Strategy with GJJ

- **GJJ microwave bolometer**



- ✓ Achieved fundamental limit of sensitivity: NEP= 0.7 aW/Hz$^{1/2}$
- ✓ Corresponding Energy Deposit: ΔE=0.1 meV

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



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

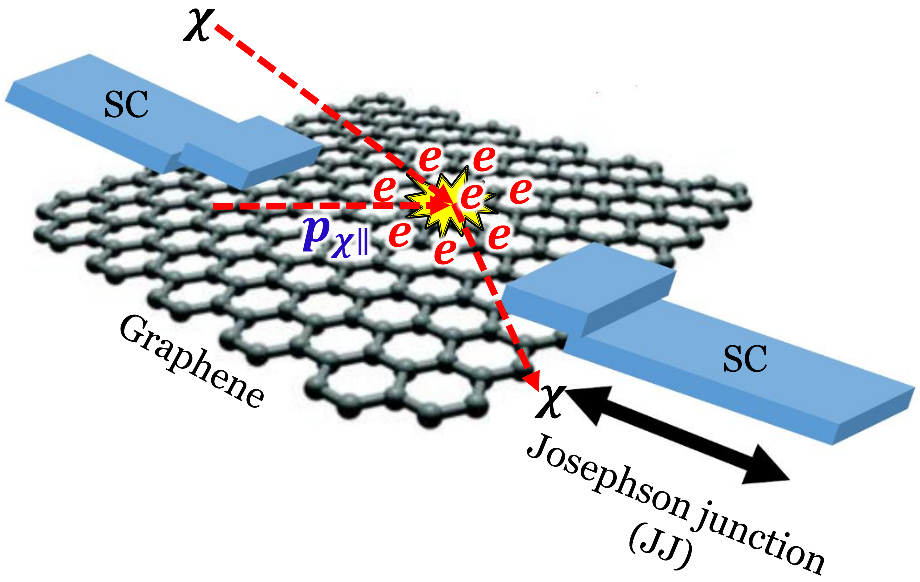
II. **The recoiling e heats up & thermalizes** with nearby e's rapidly via e-e interactions.

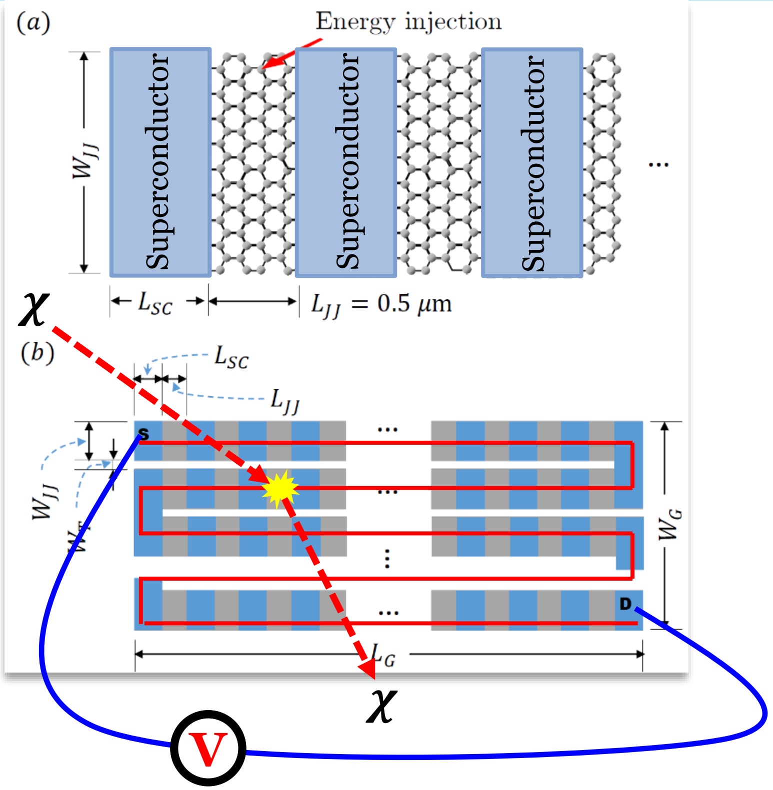
III. **The JJ is triggered**: $T_e \uparrow$ (➔ $I_c \downarrow$) switches $V = 0$ $(R = 0)$ of JJ to a $\boldsymbol{V \neq 0}$ $\boldsymbol{(R \neq 0)}$.

- $E_k \sim mv^2 \sim 1$ meV for $m_{DM} = 1$ keV

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

Super-light DM Search Strategy with GJJ





- ✓ **Scattering**: DM traveling in 3D & electrons living in 3D but confined in 2D graphene layer.

  ➔ **Constrained elastic scattering**!

- ✓ **Prediction**: angular dependence of the signal rate ➔ applicable to background rejection.
- ✓ **2D detector unit**: a single switched GJJ by DM interaction allows the series resistance.

Achievements

Calculation of Event Rate

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

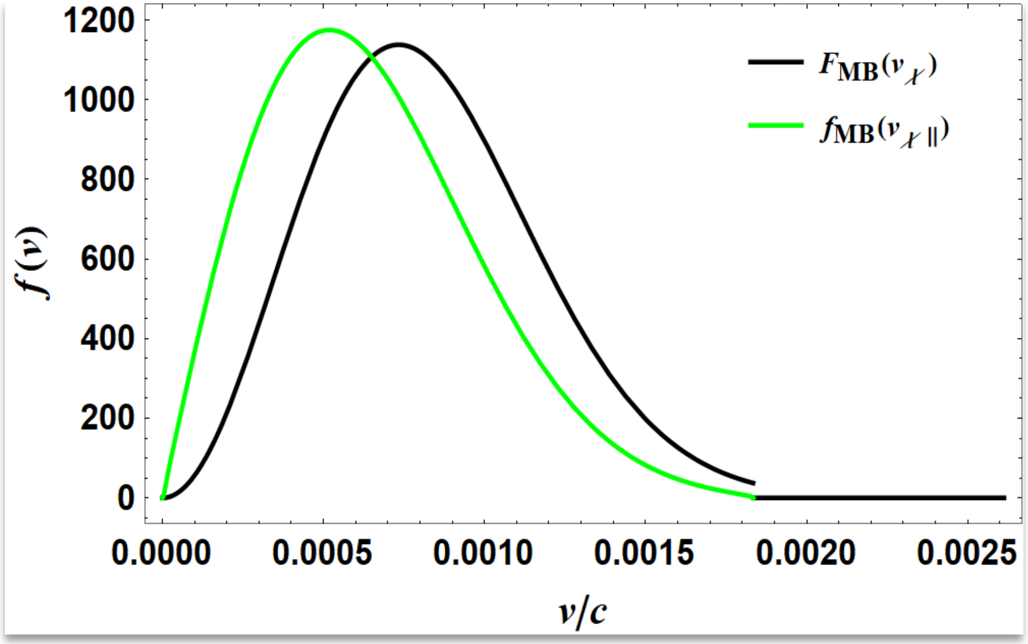
- ✓ ρ_χ =0.3 GeV/cm^3
- ✓ v_0=220 km/s, $v_{\rm esc}$=550 km/s
- ✓ $\rho_{\rm gr}^{\rm 2D} = 7.62\times10^{-8}$g/cm^2

$$f_{\rm MB}(v_{\chi\parallel}) = \int_{-\sqrt{1-(v_{\chi\parallel}/v_{\rm esc})^2}}^{\sqrt{1-(v_{\chi\parallel}/v_{\rm esc})^2}} d\cos\theta \frac{1}{2\sin\theta} F_{\rm MB}\left(\frac{v_{\chi\parallel}}{\sin\theta}\right)$$

in-medium　　Pauli blocking

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

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



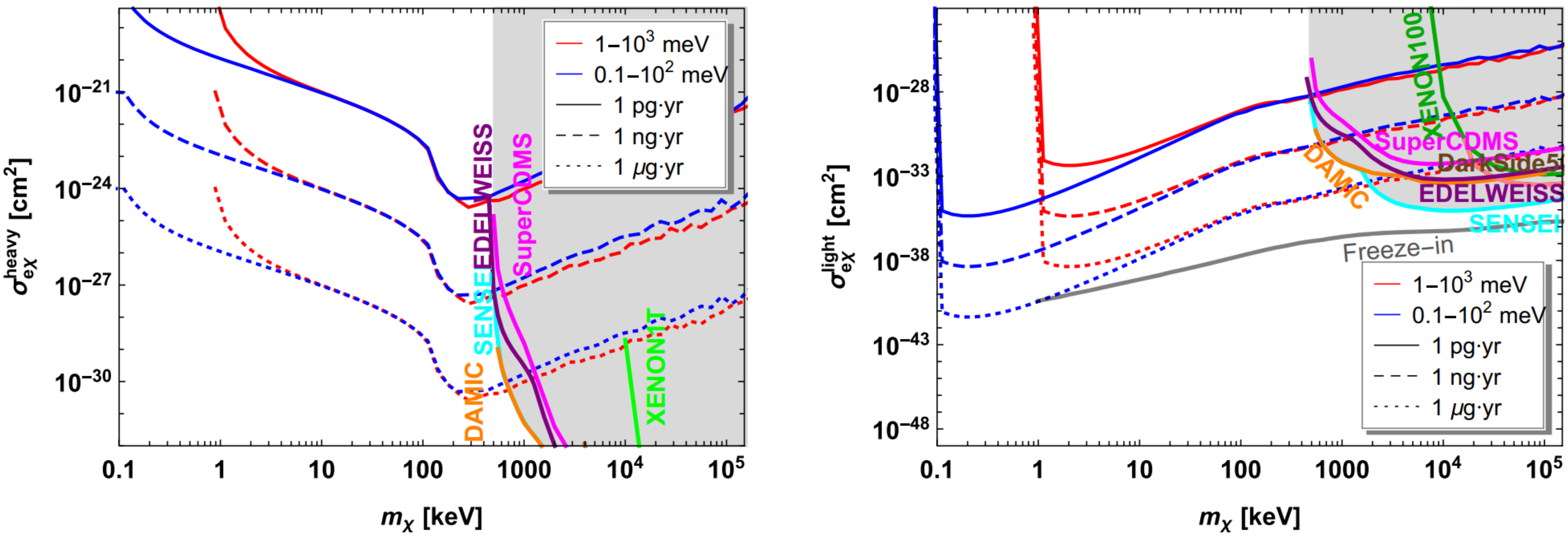
- We assume that DM interacts with electrons via an exchange of mediator ϕ:

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

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

- From the linear dispersion of graphene: $E_F = v_F\sqrt{\pi n_c}$ with $v_F\sim10^8$cm/s & $n_c\sim10^{12}$/cm^2.

Expected Sensitivities

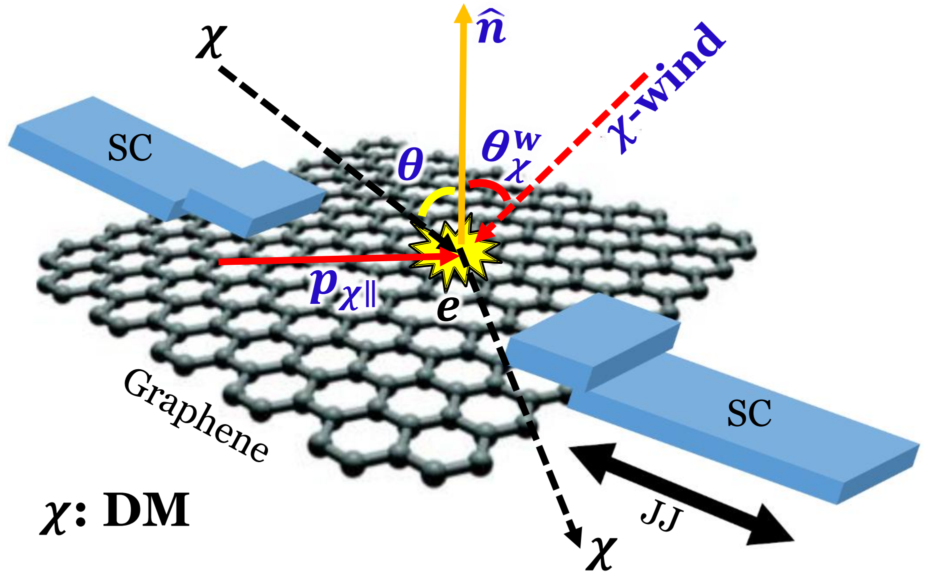


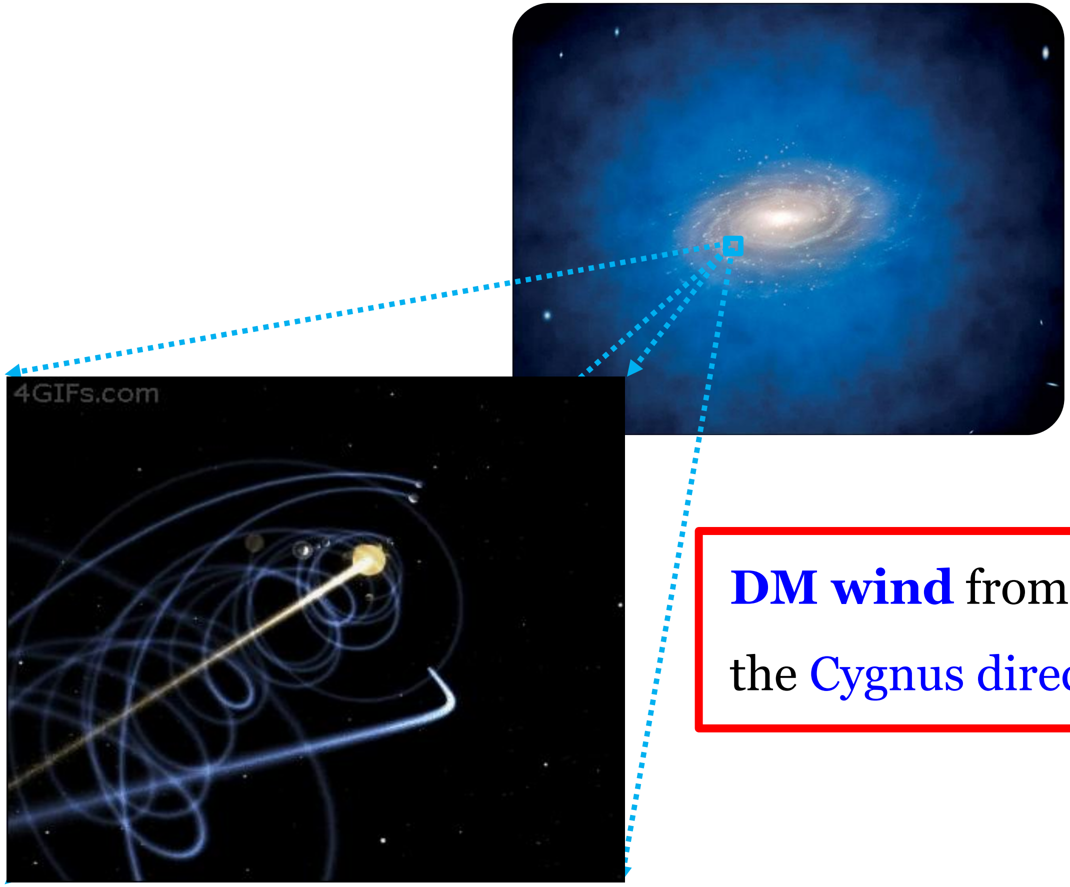
- ✓ The proposed detector (GLIMPSE) can improve the minimum detectable DM mass (m_{DM}~ **O(keV)**) by more than 2-3 orders of magnitude over the ongoing/existing experiments.
- ✓ **Capable of probing** the prediction of **freeze-in** scenarios.

Signal Rate: Directional Dependence

❖ **Constrained** elastic scattering: Electron <u>confined in the 2D graphene sheet</u> even after the collision.

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





DM wind from the Cygnus direction

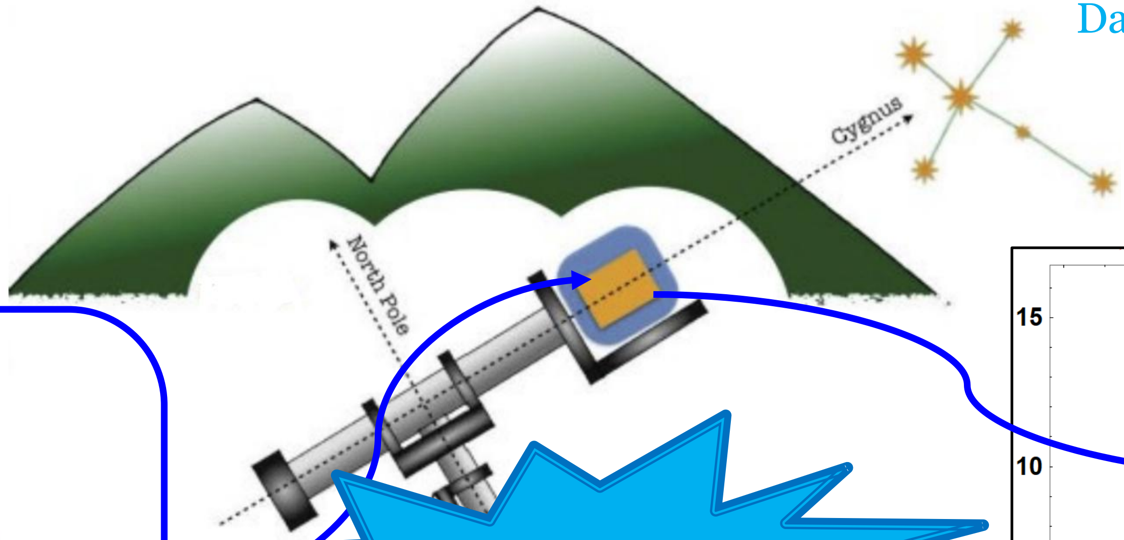
Signal Rate: Directional Dependence

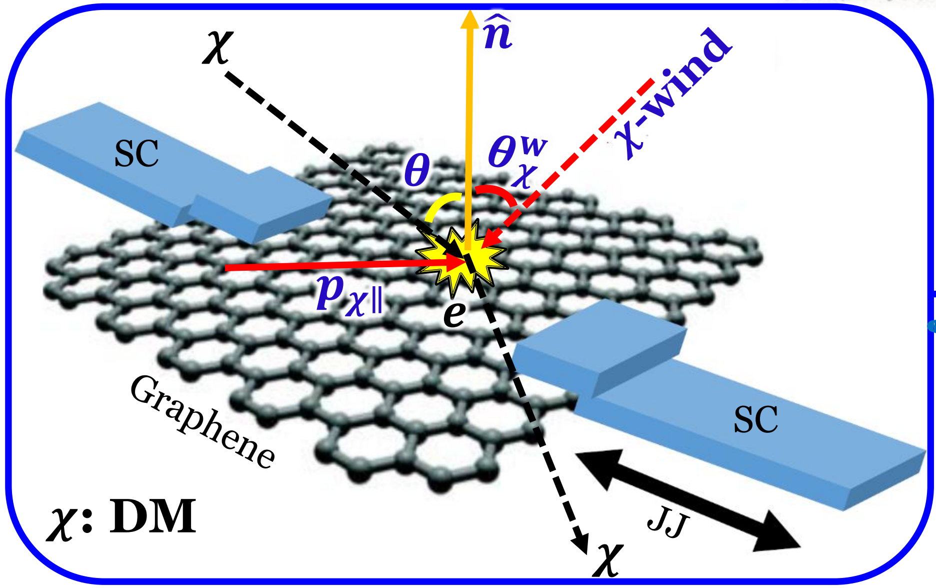
❖ **Constrained** elastic scattering: Electron confined in the 2D graphene sheet even after the collision.

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

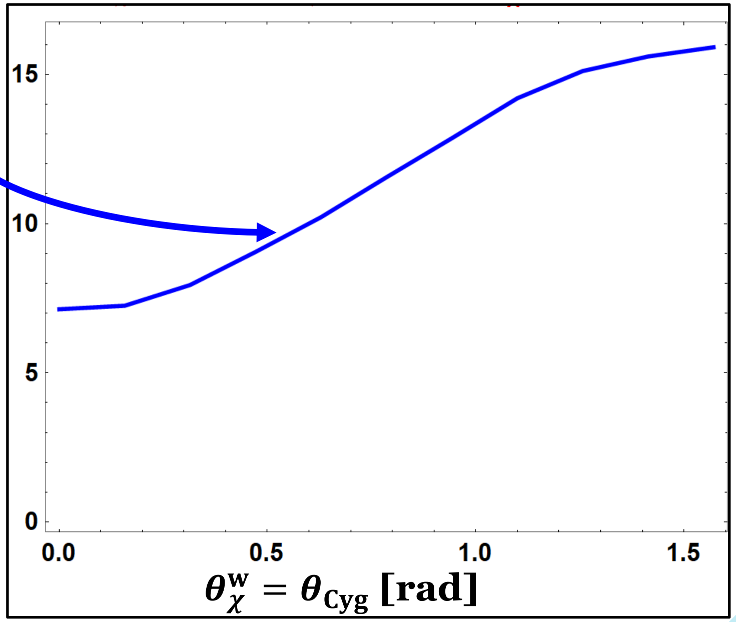
➔ DM signals: **in situ validation** by **actively rotating the detector** or **time information of each signal**

Daeyeong Jeong's Talk





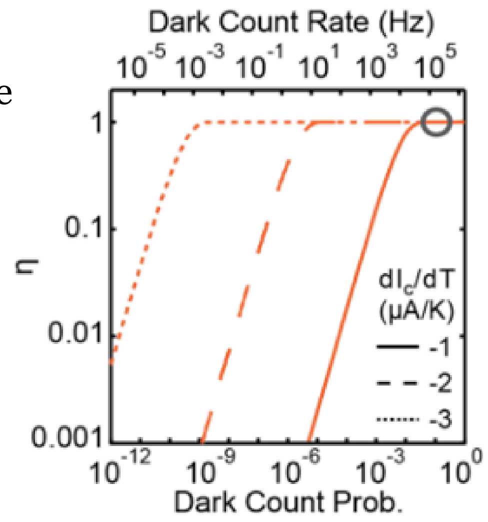
Handle for BG rejection!

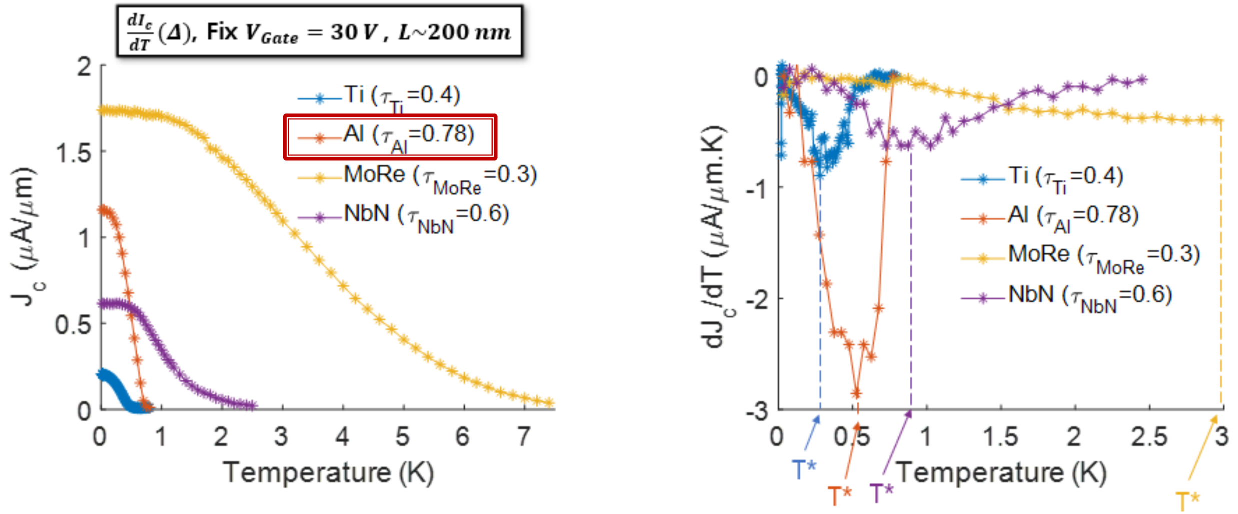


Optimization of $|dI_c/dT|$ for GJJ

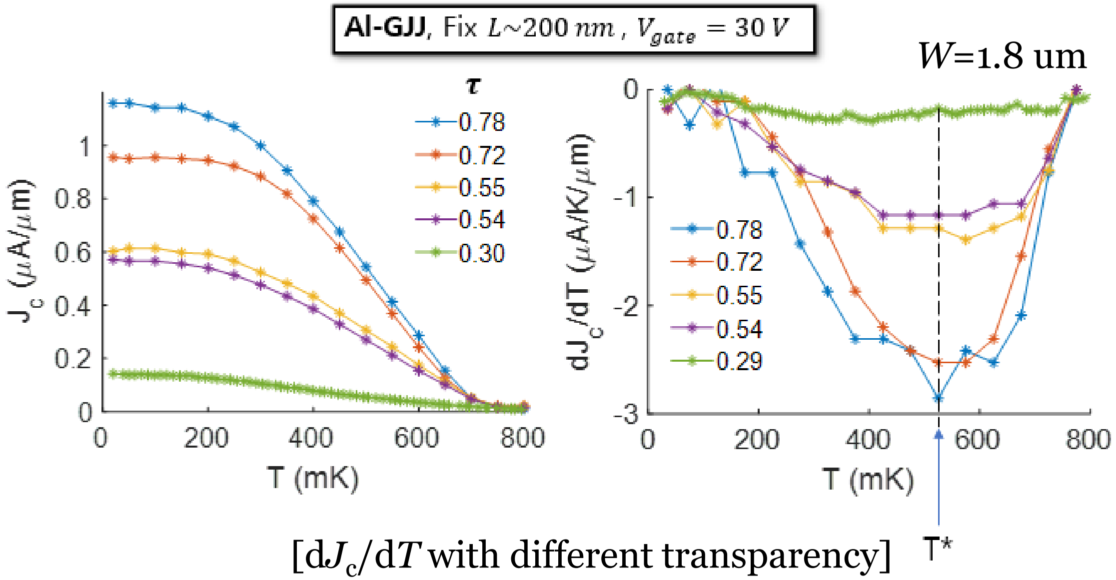
- ✓ $|dI_c/dT|$ ↑ ➔ Detection efficiency ↑ & Dark count rate ↓
- ✓ Lower T_c of $J_c(=I_c/W)$ & larger J_c at low temperature ➔ Aluminum
- ✓ Contact transparency (τ)↑ ➔ $|dJ_c/dT|$ ↑
- ✓ For Al & τ=0.78, $|dI_c/dT|$ ~ 5 μA/K (@ T=500 mK) is realized.

[Detector performance with different dI_c/dT]



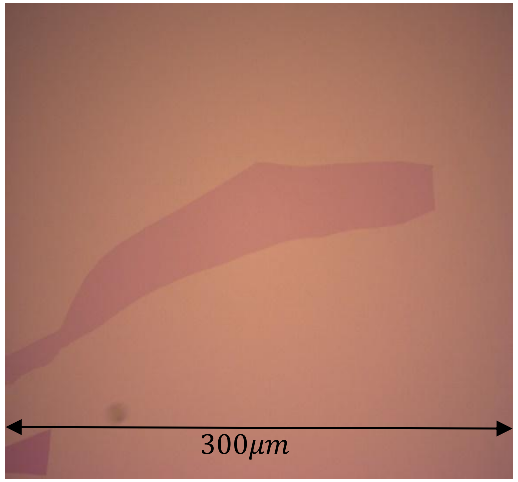


[dJ_c/dT of GJJ with various superconductors]

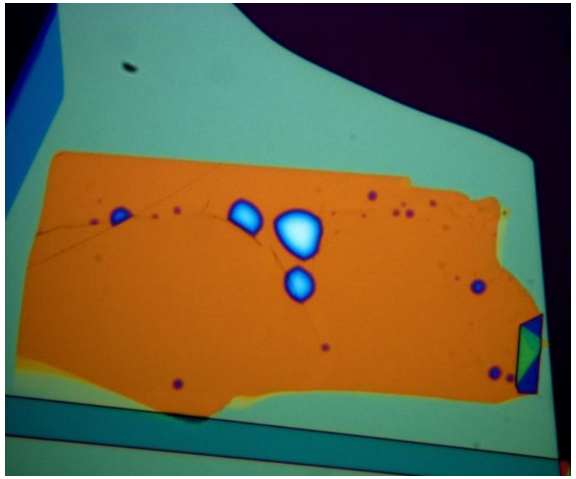


[dJ_c/dT with different transparency]

Progress in Fabrication: O(100) GJJs in Series



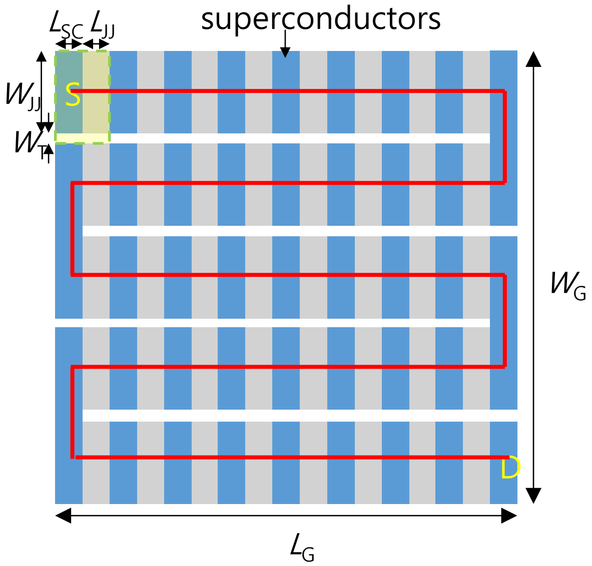
Large piece of graphene



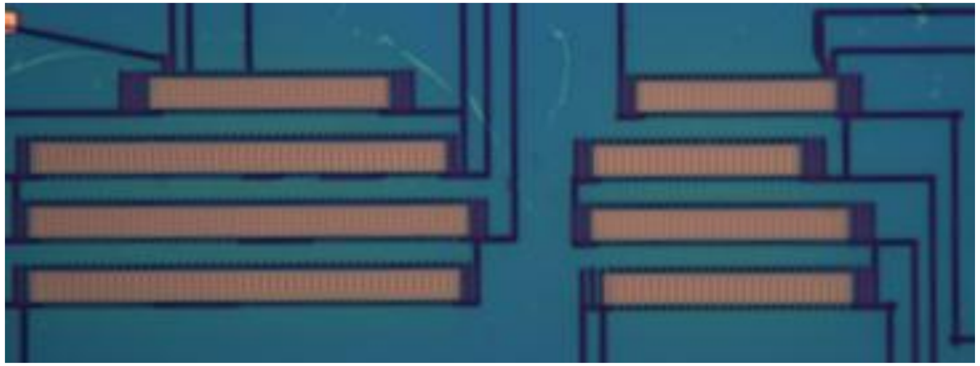
hBN-encapsulated graphene

Etched hBN/Graphene/hBN stack

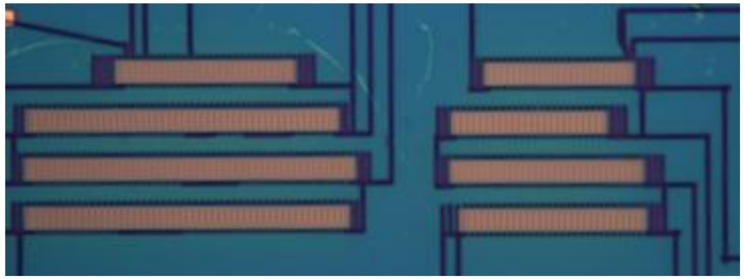
Schematics



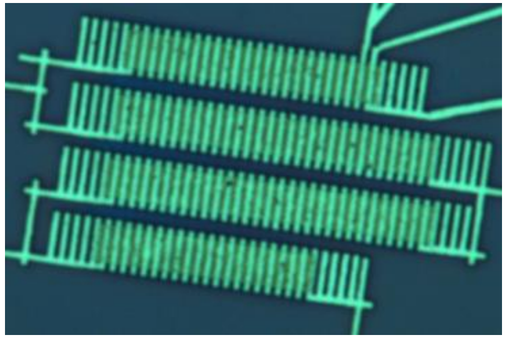
216 GJJs connected in series



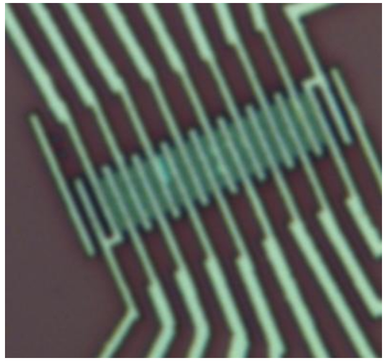
Uniformity of Multiple GJJs



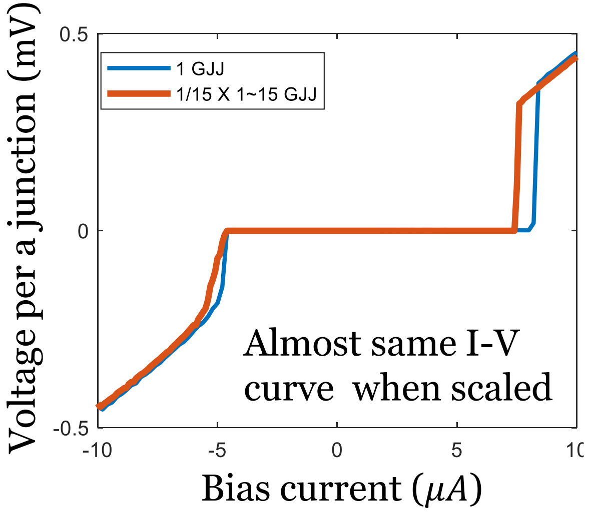
216 GJJ array

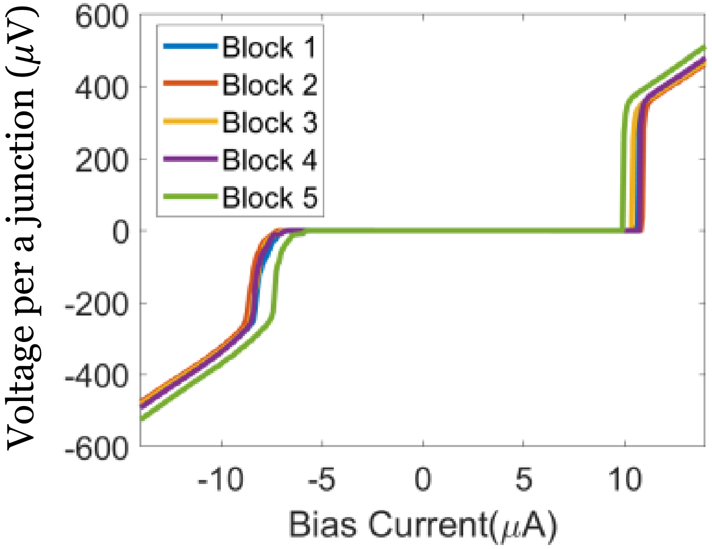


103 GJJ array

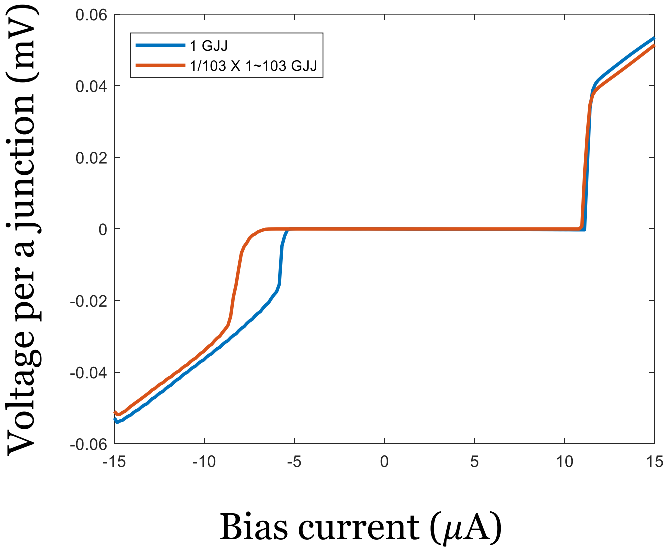


15 GJJs array

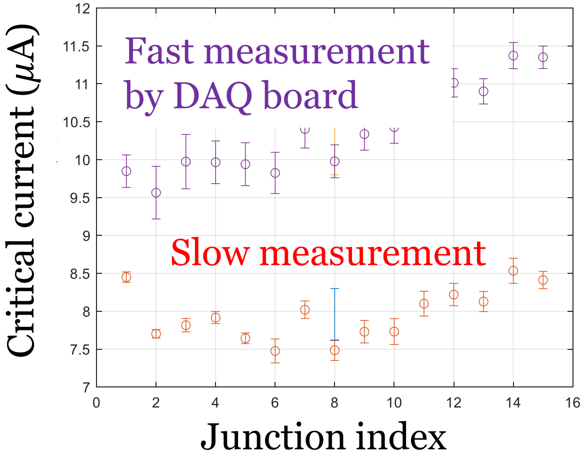




Almost same I-V curve when scaled



Almost same I-V curve when scaled

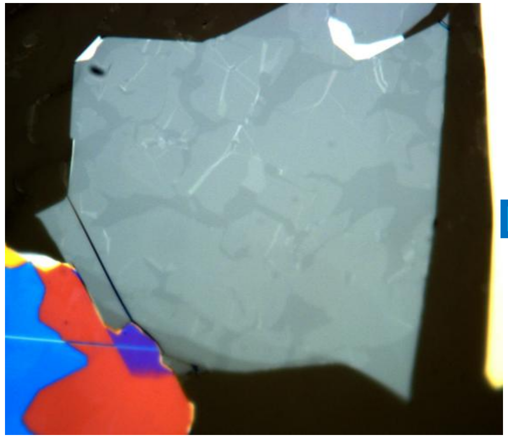


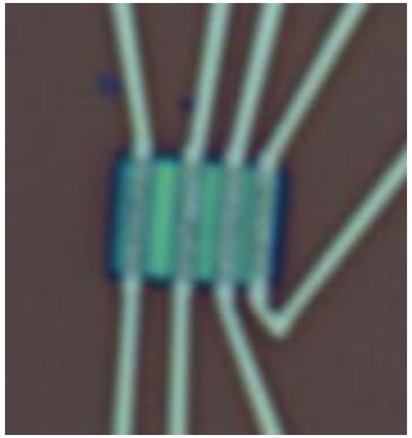
±9% variation in switching current

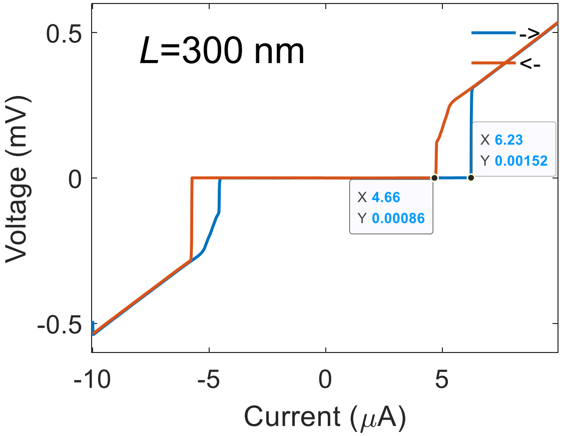
Uniform Josephson junctions in series were fabricated!

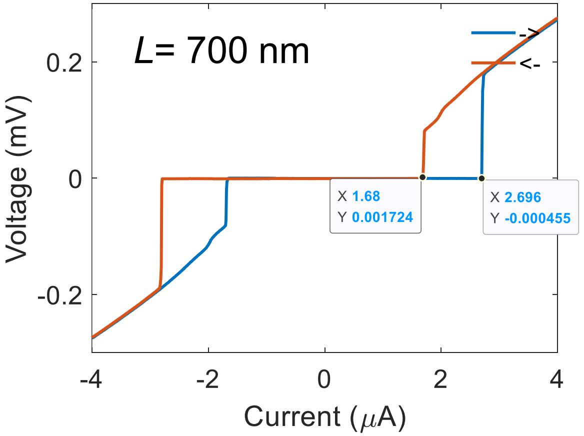
Fabrication Test on Large-scale Graphene

❖ CVD-grown Graphene with exfoliated hBN (Chemical Vapor Deposition)

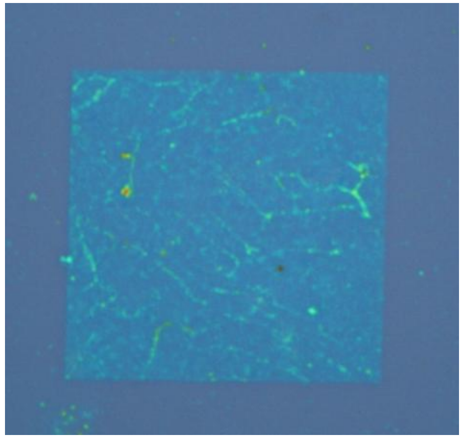




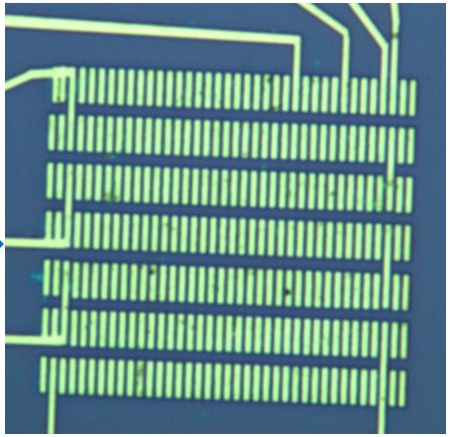




❖ CVD-grown Graphene with CVD-grown hBN

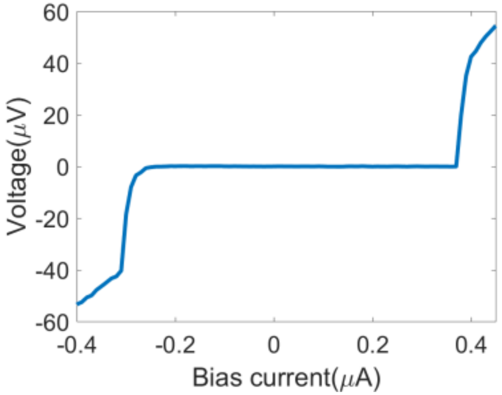


hBN/Graphene/hBN stack



231 GJJ array

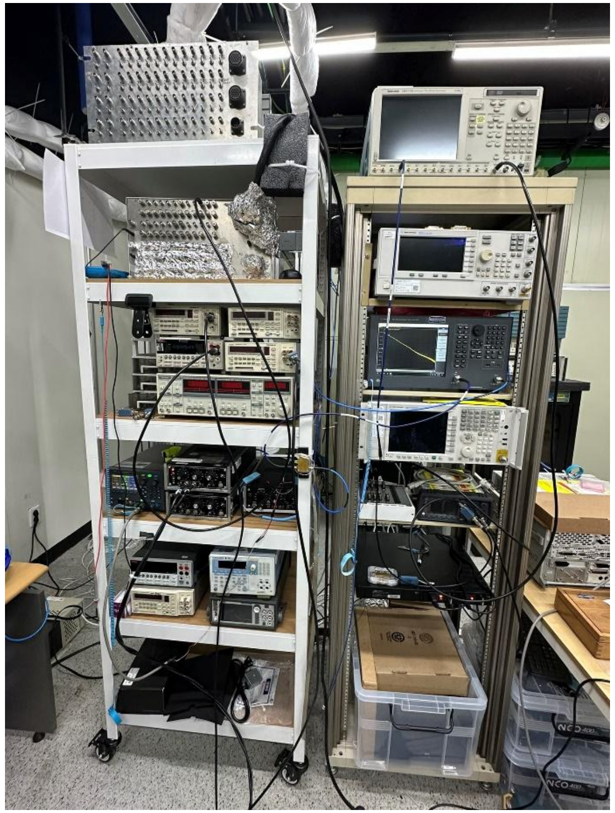
W~3μm, L~300nm



GJJs were demonstrated with CVD-grown large-scale graphene.

Overview of Our Measurement Set-up

Dedicated Dilution refrigerator



Arbitrary Waveform Generator

Analog Signal Generator

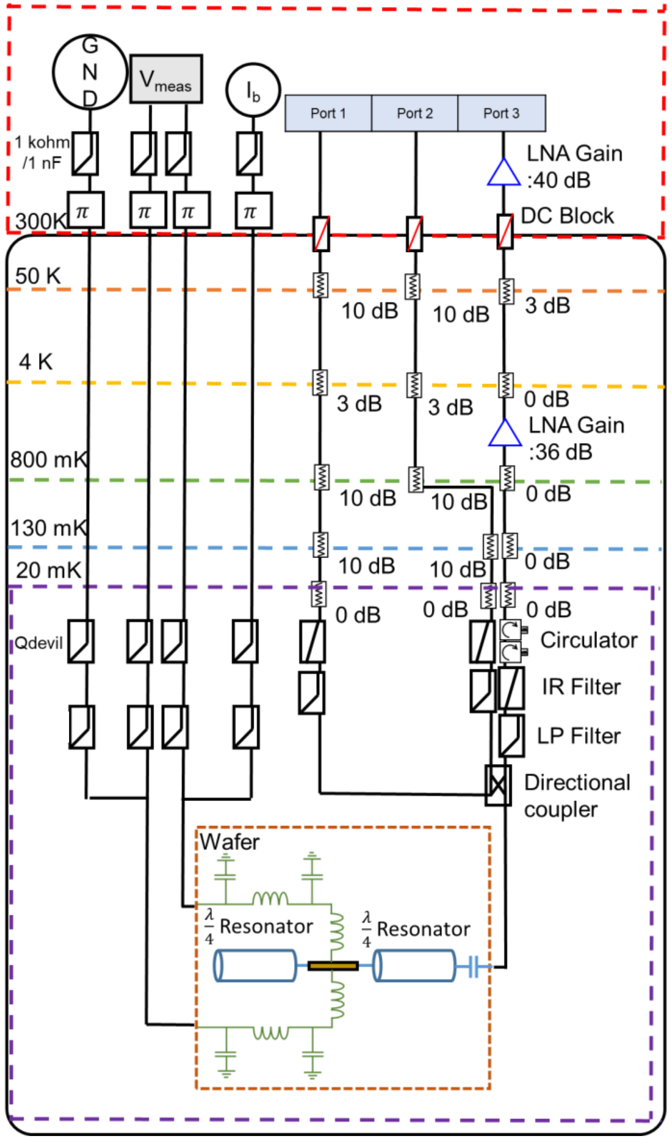
Vector Network Analyzer

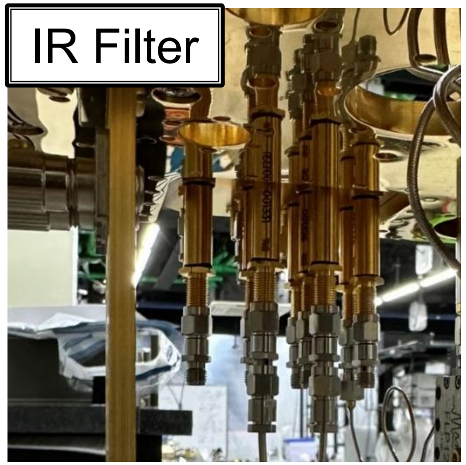
Spectrum Analyzer

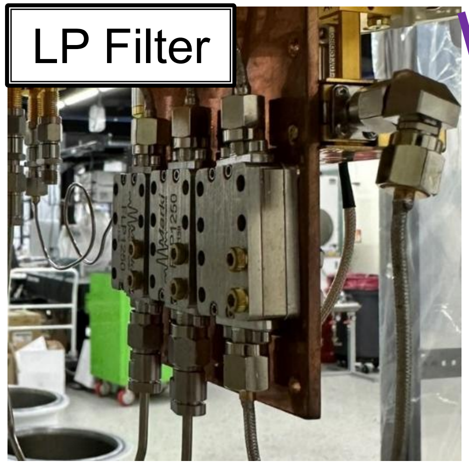
DC Instrument

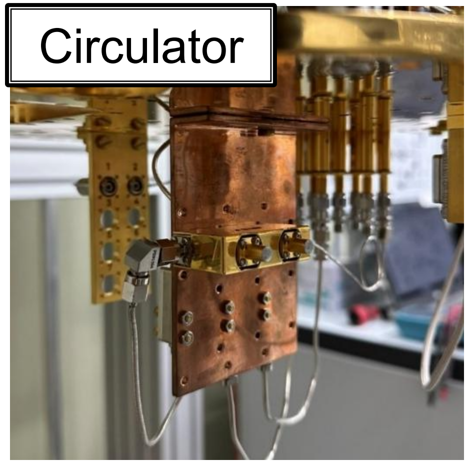
RF Instrument

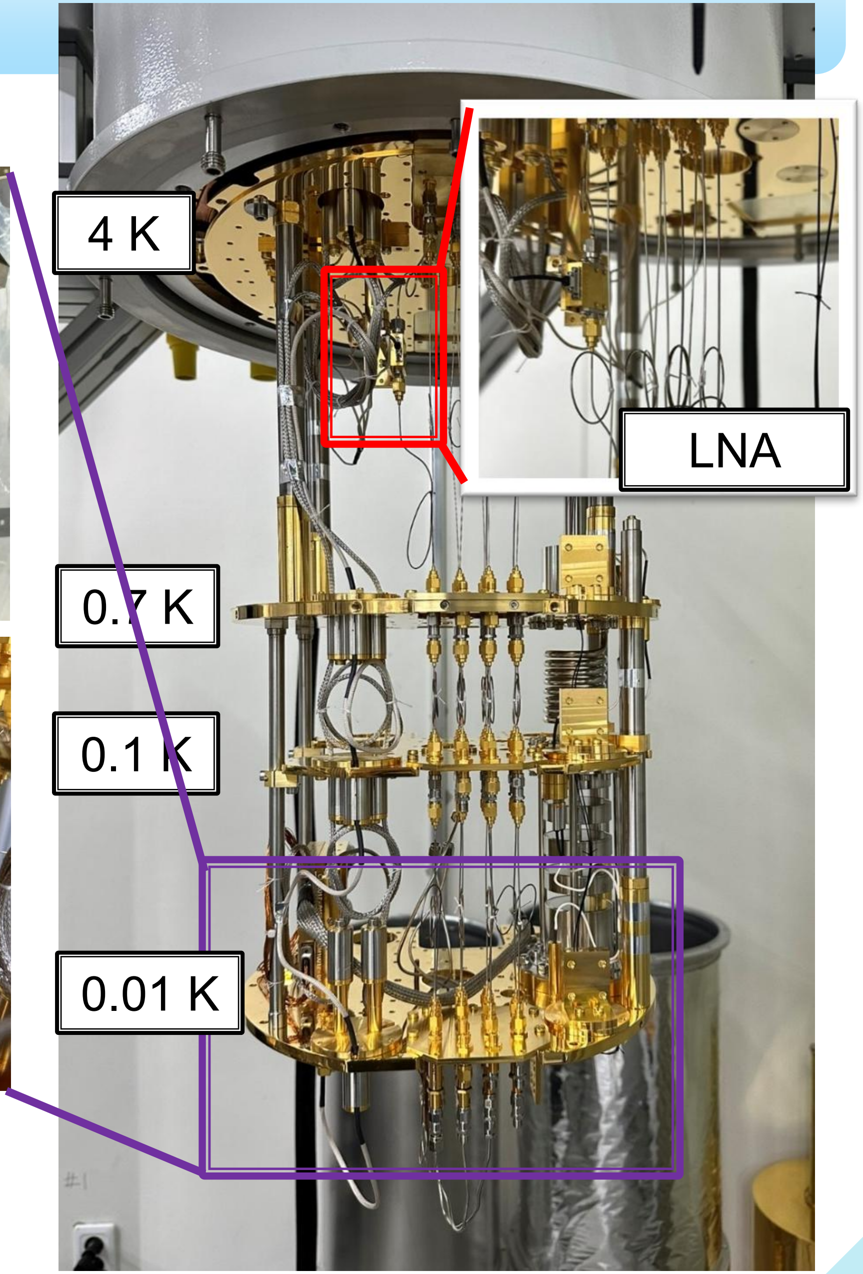
Our Measurement Set-up (RF)









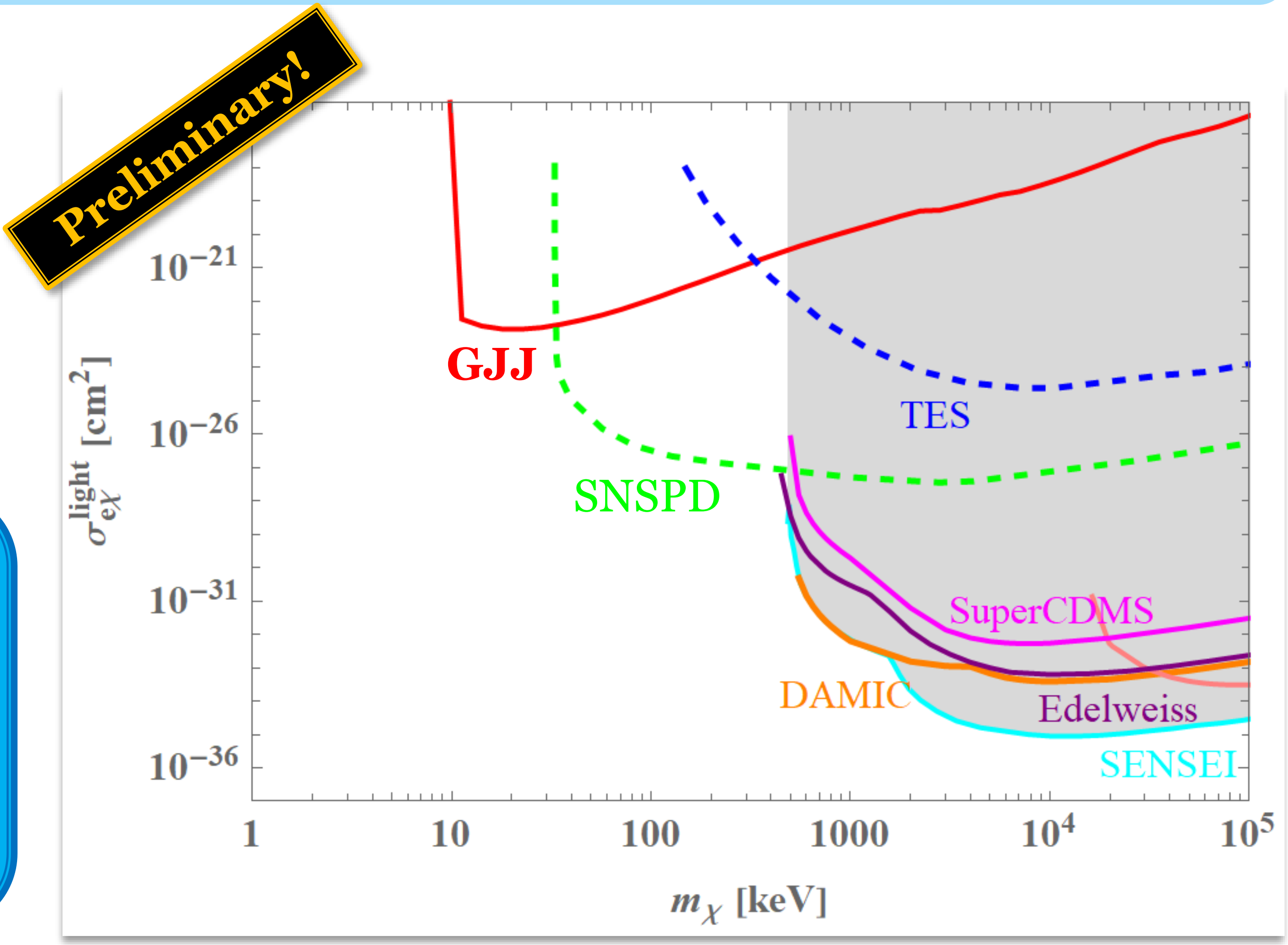


Preliminary Limit from Calibration Run

- **GLIMPSE:** Super-light DM Search w/ **GJJ**
  - ✓ Test sample graphene area: $\sim\mu\mathrm{m}^2$
  - ✓ Calibration: $E_{th}\sim 10$ meV
  - ✓ $t_{\mathrm{run}}\sim 10^4 - 10^5$ sec

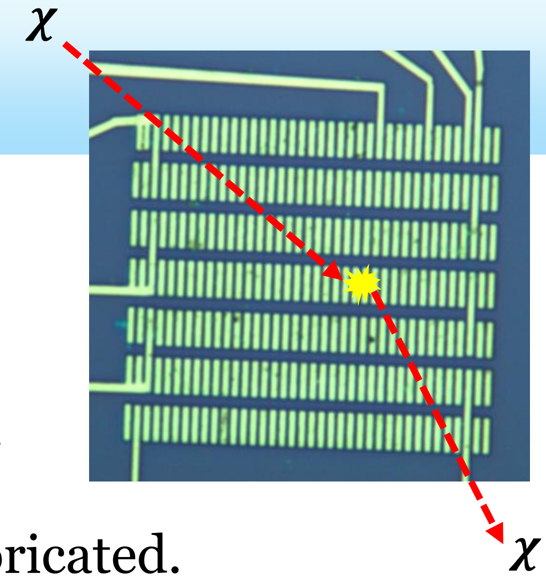
Requirements for better sensitivities

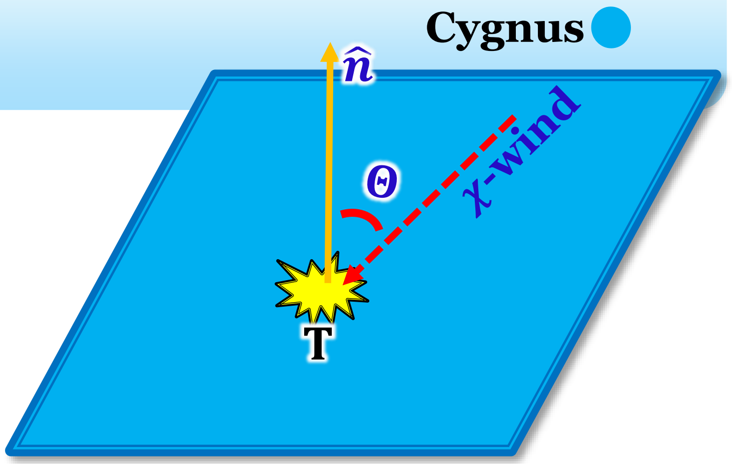
1. **Understanding & Reduction of LEE**
2. **Larger area & Longer runtime**
3. **Lower E_{th} w/ Good efficiency**



- ✓ SNSPD: $E_{th}\sim 0.11$ eV [PRL (2025)]
- ✓ TES: $E_{th}\sim 0.3$ eV [PRD (2026)]

Summary





- **GLIMPSE**: Novel DM search strategy

  adopting a cutting-edge quantum sensor - **GJJ**.
- Uniform O(100) GJJs in series: successfully fabricated.
- **Calibration**: on-going / **1st DM search result**: expected to be released soon.
- Goal: **World first & best results** for DM (<100 keV) direct search.
- **Constrained** scattering: e's confined in 2D graphene ➔ construction of an effective model with

  angular dependence ➔ **Signal rate: Angular Modulation!**: **BG** rejection & **Mass** determination

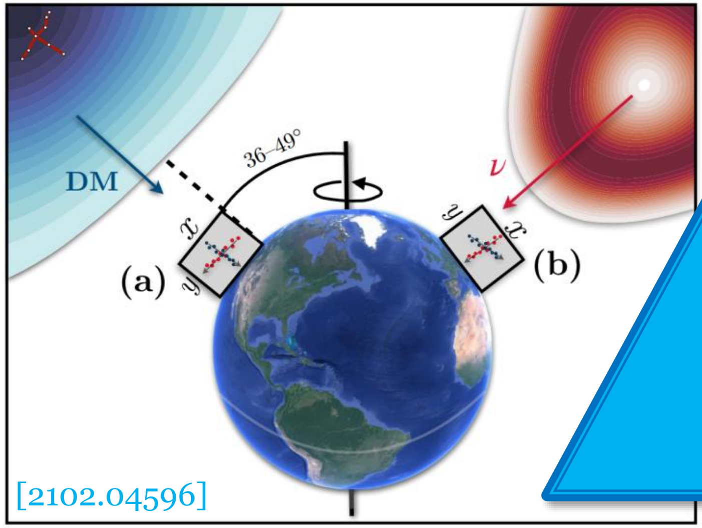
Daeyeong Jeong's Talk

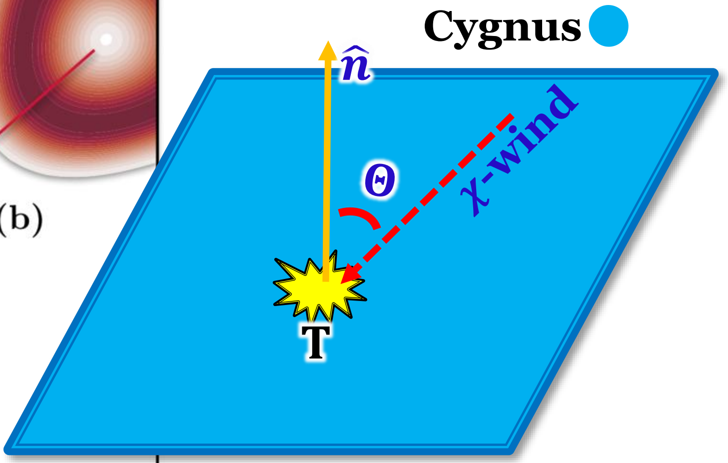
Thank You!

Supplemental

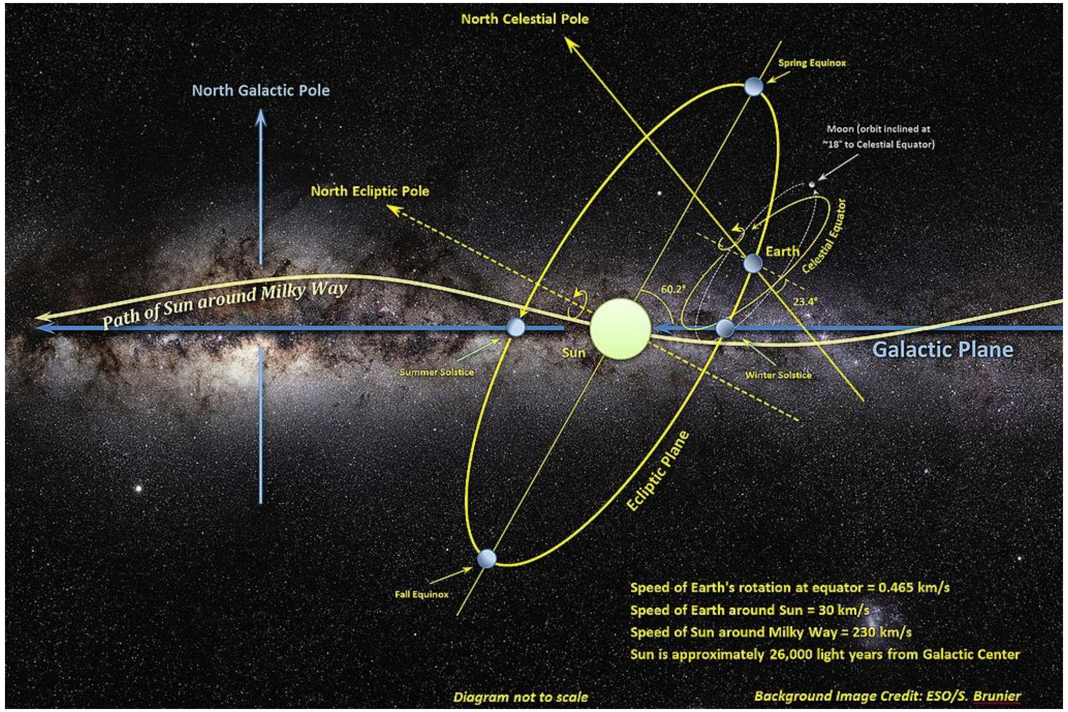
Angular Modulation vs Annual Modulation

- **Angular modulation**
  - ✓ Effects from the **change of the DM wind direction (Θ)** relative to the plane-normal direction due to **Detector's motion**
    ➔ contribution: **annual ≈ daily motions**
  - ✓ $N_{event}(\Theta(t))$ using $\Theta(t)$
    ➔ **BG rejection** + **mass** information





- **Annual modulation**
  - ✓ Effects from the **change of $|\vec{v}_{\mathrm{rel}}|$** due to Earth's motion relative to Sun's motion
    ➔ contribution: **annual ≫ daily**
  - ✓ $N_{\mathrm{event}}(t)$ ➔ **BG rejection**



In-medium Effects

- Vacuum: simply 2→2 scattering matrix elements, familiar from standard QFT calculations.
- Target medium: may receive corrections due to screening effects.
- Vector mediator: in-medium effects can cause screening and affect direct detection rates.

  → Must be taken into account when deriving the target response and hence the structure function.

- Relate the dielectric function with the scattering rate, which also properly incorporates screening effects, by adapting the dynamical dielectric function of graphene used to find the screening of the Coulomb interaction in a graphene layer within the random phase approximation.

E. H. Hwang & S. Das Sarma, PRB (2007)

- The structure function parameterizing the in-medium screening effects:

$$S_{\text{ims}}(E_r, q) = (\hat{q} \cdot \epsilon \hat{q})^{-1} \quad [\epsilon\text{: dynamical dielectric function}]$$

Backgrounds

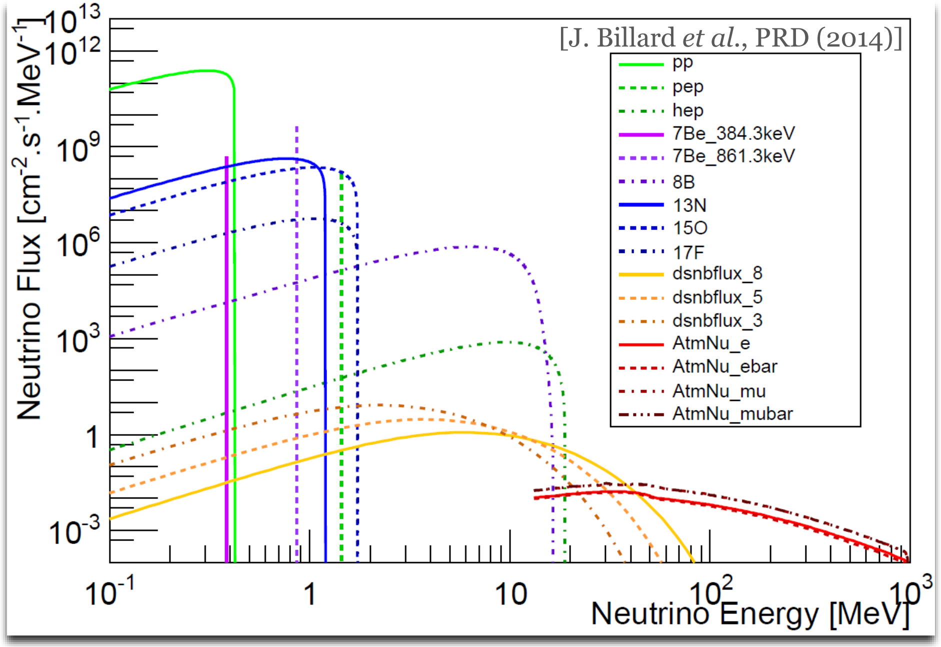
- Neutrino (mostly pp solar neutrinos): irreducible!

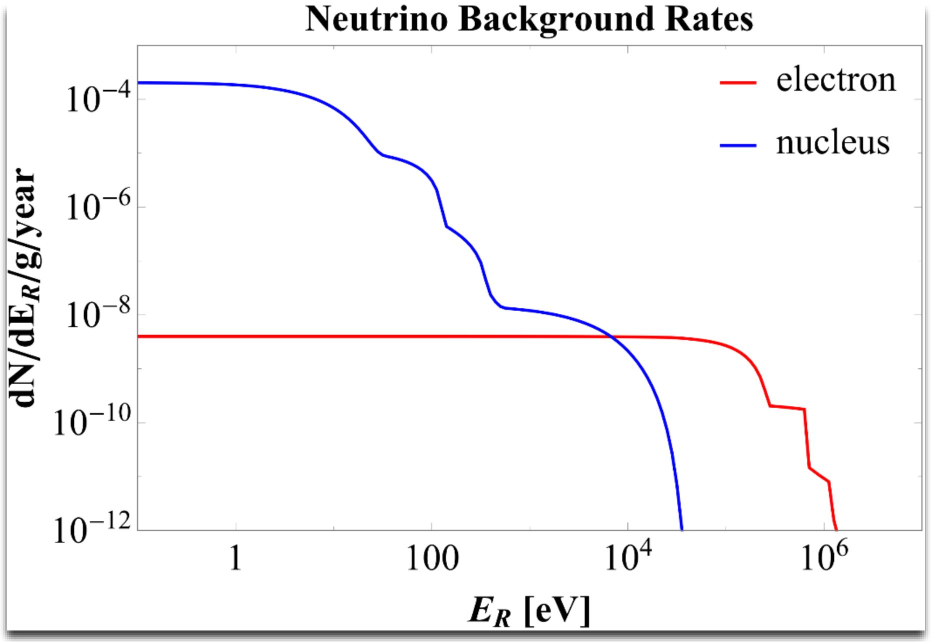
  Scatter off nuclei/electrons and deposit a small amount of E ➔ The expected number of events is $\mathcal{O}(1)$/(kg·year).

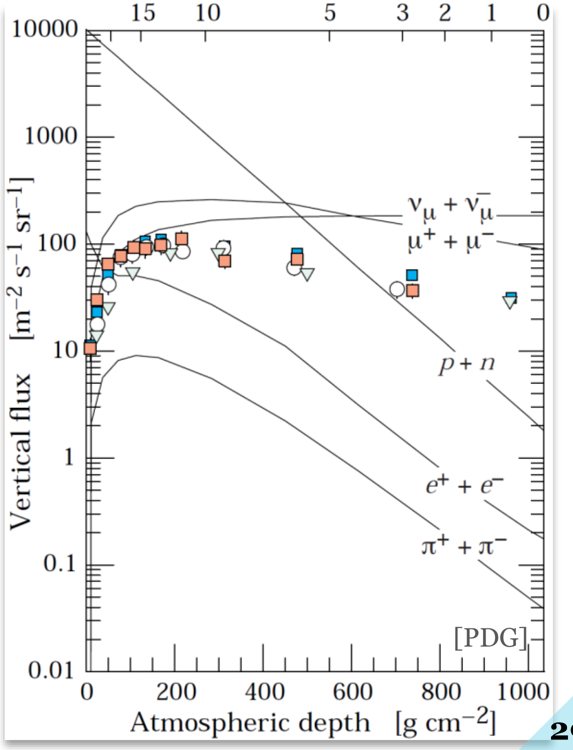
- Cosmic muon: $\mathcal{O}(1)$/(g·year). Reducible in the deep underground lab.

- Radiogenic: (relatively) reducible! Have characteristic E scales ≫ region of our interest (< eV) ➔ negligible

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



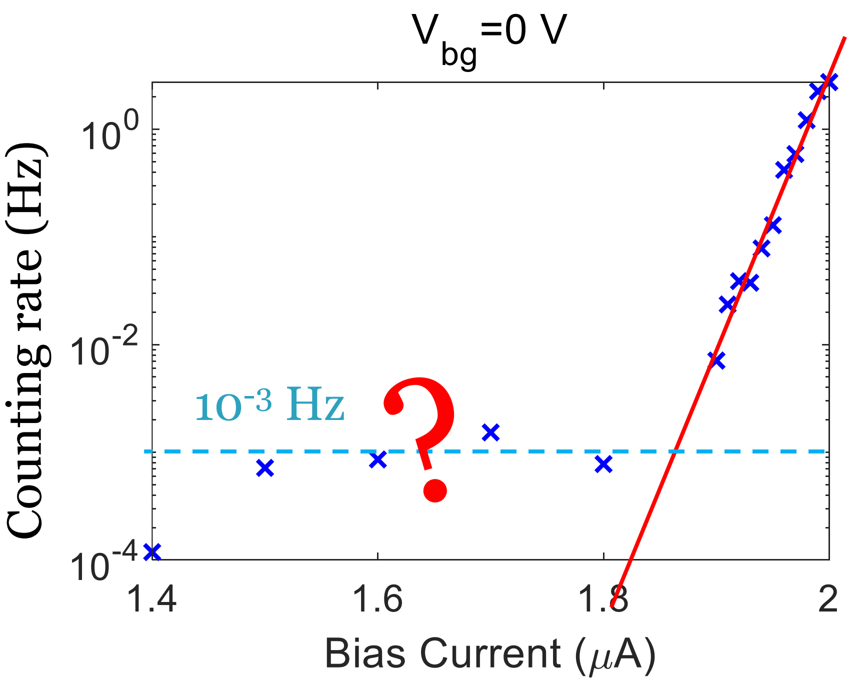




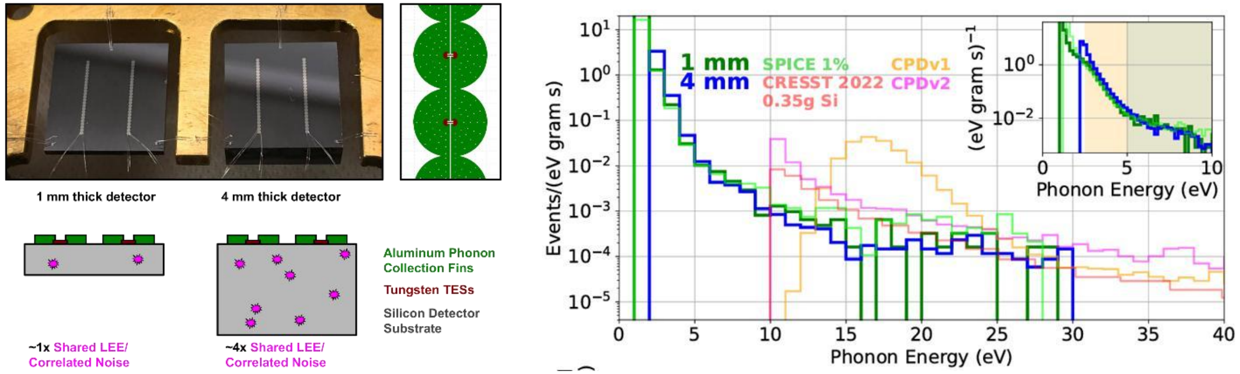
Low Energy Excess (LEE) in GJJ Detector

- Dark matter search was performed at various bias currents.
- Counting rate saturates around 10^{-3} Hz, which is too high to be due to dark matter.

  ➔ Low Energy Excess (LEE)
- Cosmic ray may cause such dark counts.

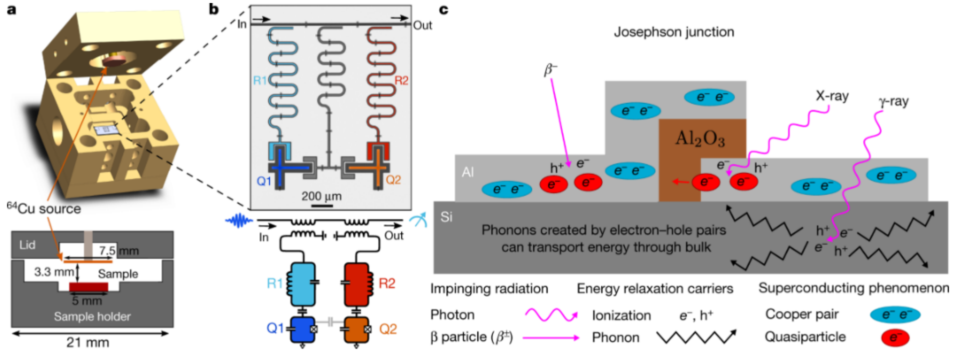


Counting rate of GJJ vs. Bias current



Substrate volume ↑, DCR ↑

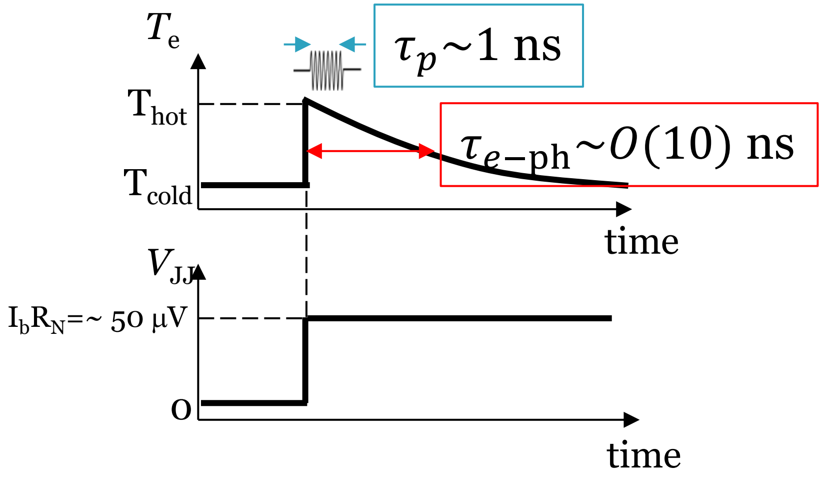
[arXiv:2505.16092]



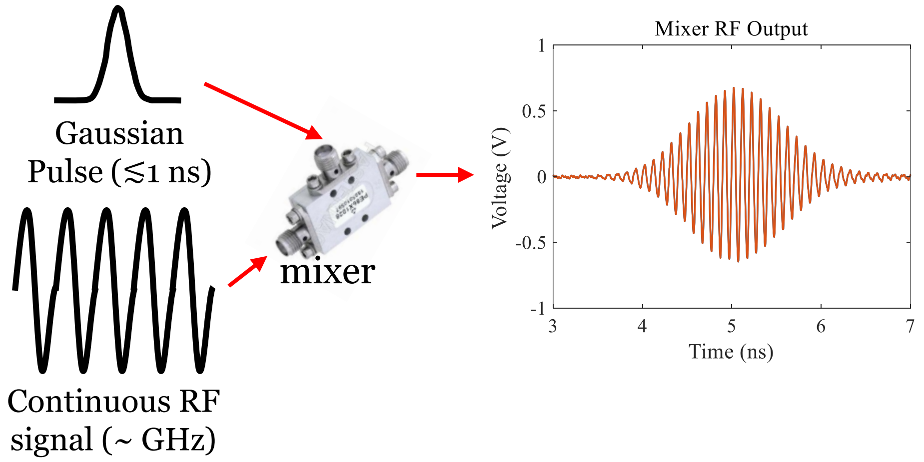
[Nature 584, 551–556 (2020)]

Detector Calibration Scheme

Temporal profile

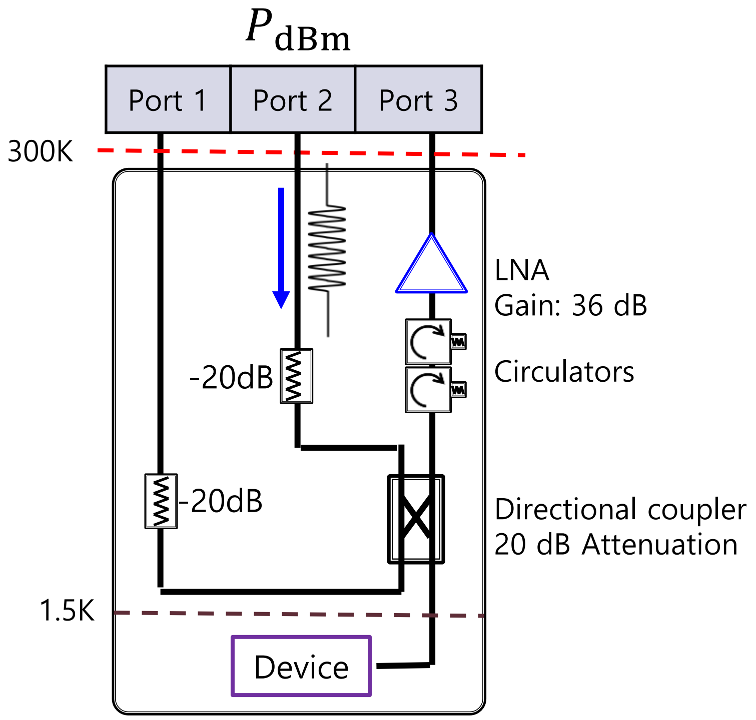


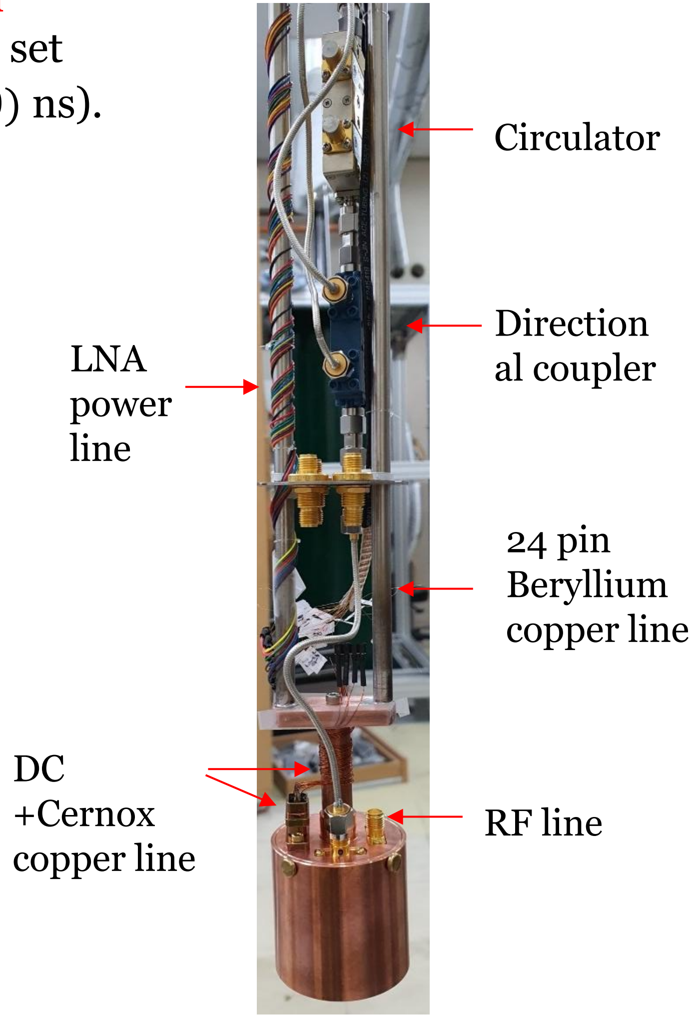
Microwave pulse generation



- ✓ Using microwave pulse as a fake signal
- ✓ Microwave pulse duration ($\tau_p \sim 1$ ns) is set shorter than cooling time ($\tau_{e-ph} \sim O(10)$ ns).

Calibration circuit

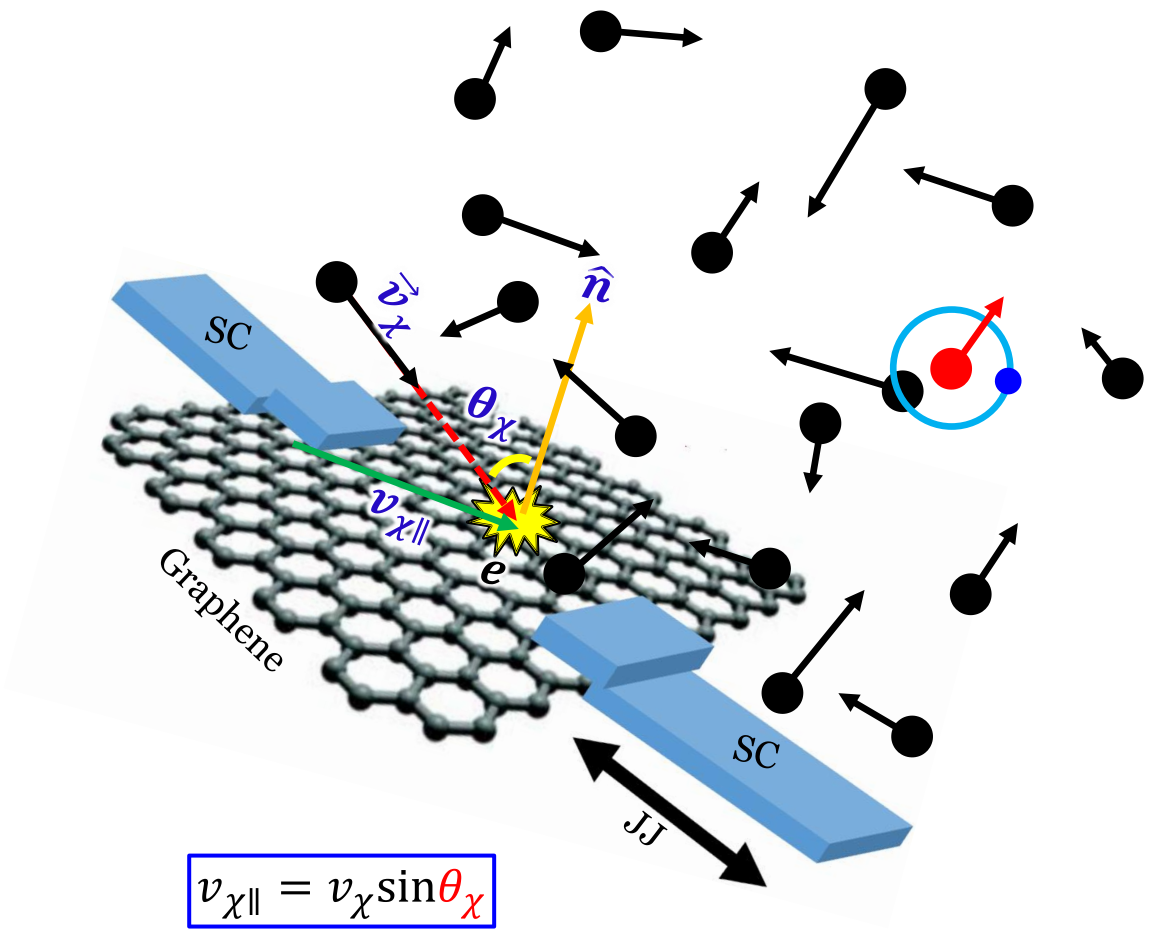




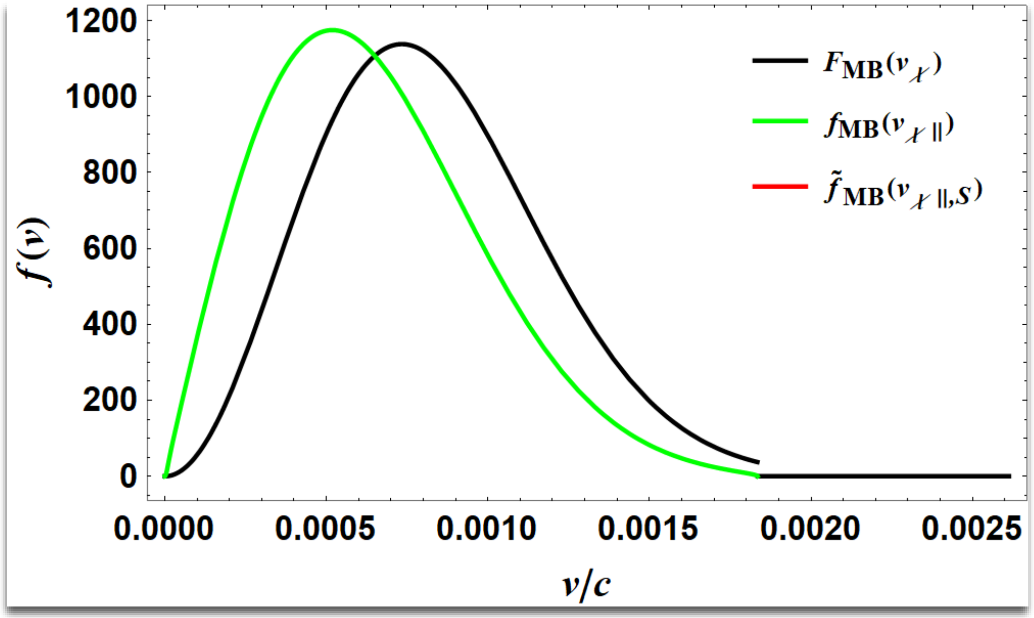
RF setup working @ 4.2 K

DM v Distribution: Angle Dependence

Cygnus

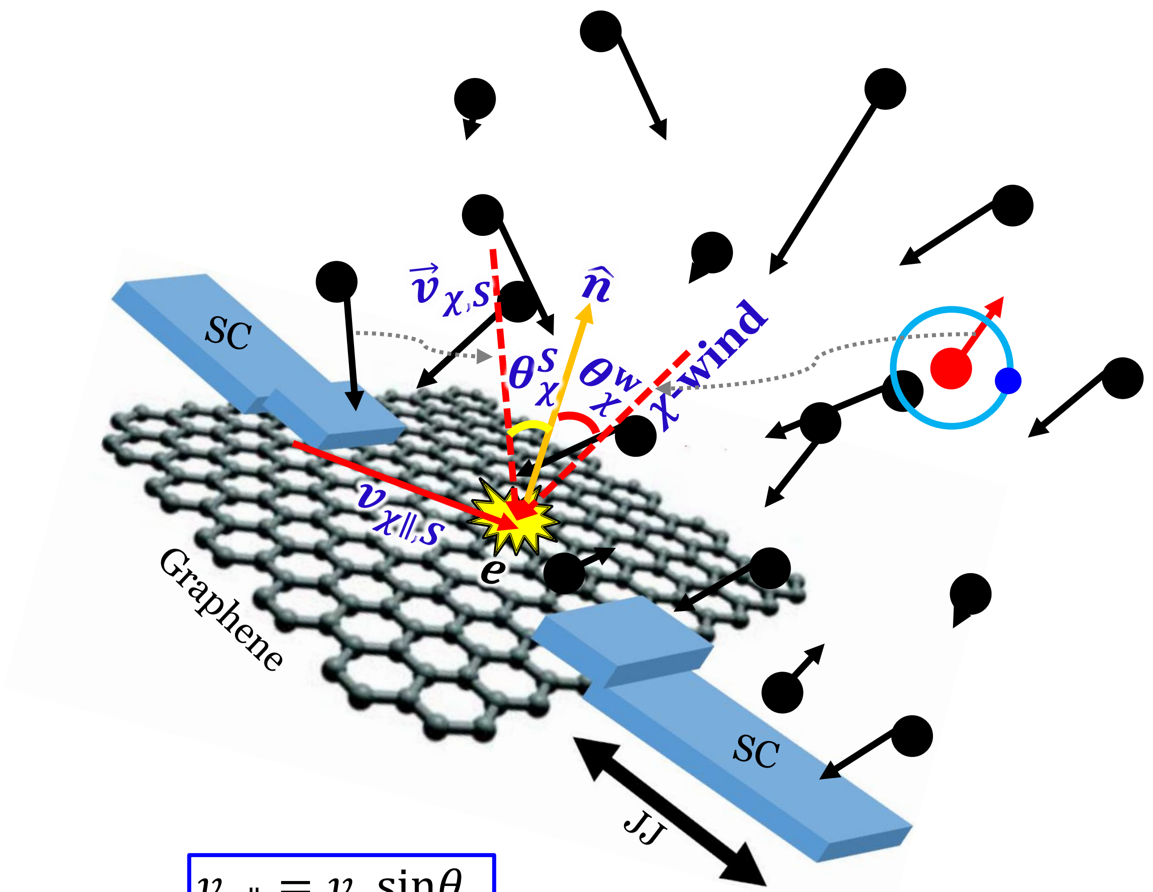


$v_{\chi\parallel} = v_\chi \sin\theta_\chi$



DM
Sun
Earth

DM v Distribution: Angle Dependence - Sun

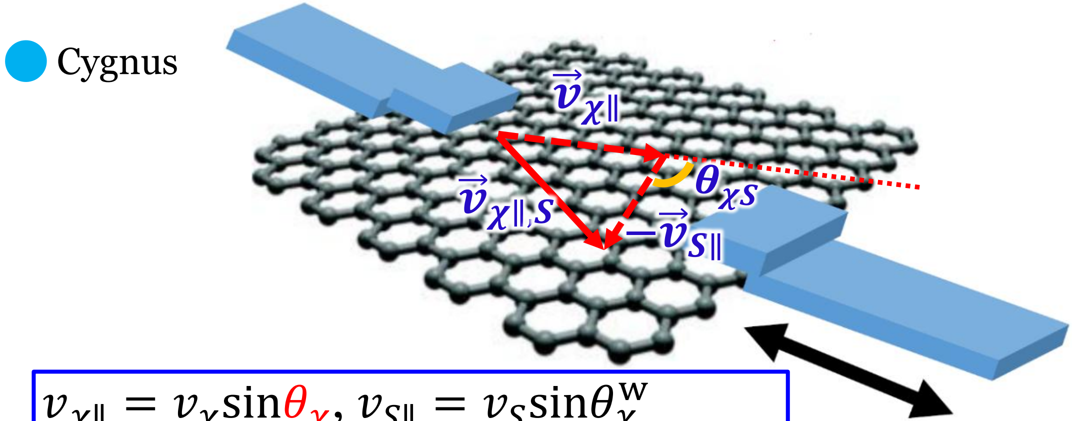


- DM
- Sun
- Earth

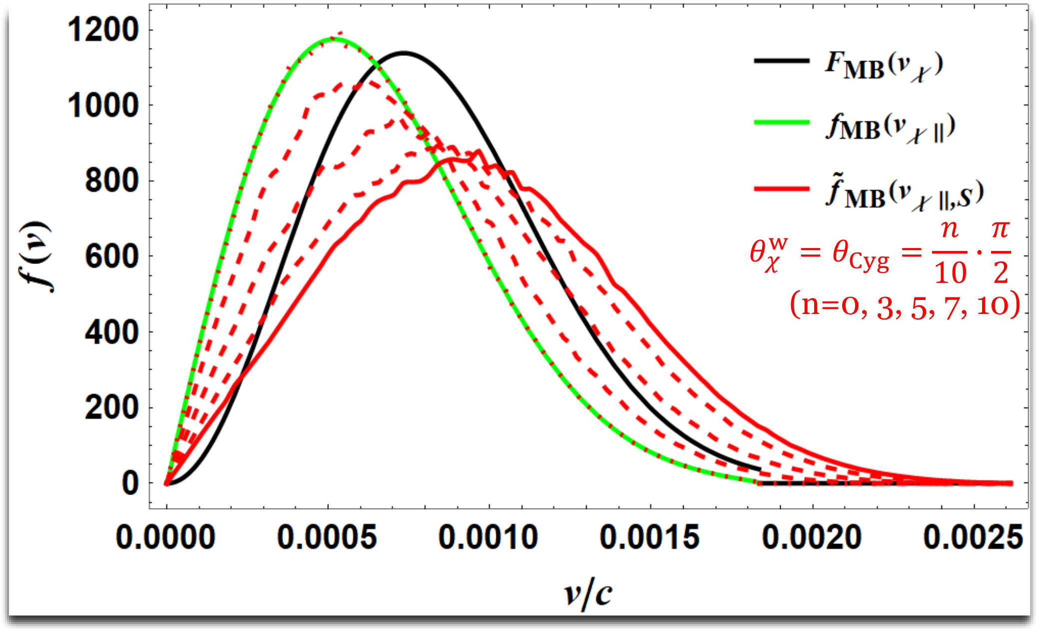
$$v_{\chi\parallel} = v_\chi \sin\theta_\chi$$

$$\vec{v}_{\chi,S} = \vec{v}_\chi - \vec{v}_S \Longrightarrow \vec{v}_{\chi\parallel,S} = \vec{v}_{\chi\parallel} - \vec{v}_{S\parallel}$$

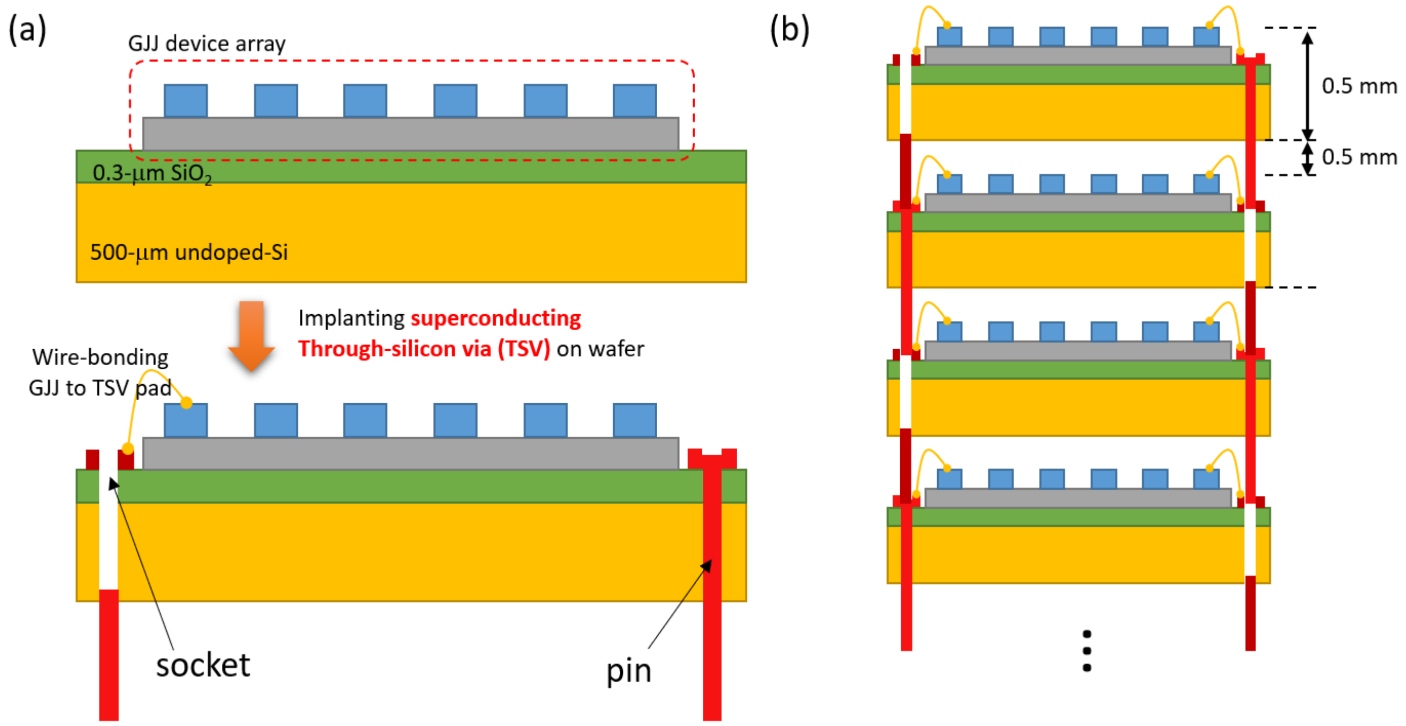
$$v_{\chi\parallel,S} = v_{\chi,S}\sin\theta_\chi^S = \left|\vec{v}_{\chi\parallel} - \vec{v}_{S\parallel}\right|$$



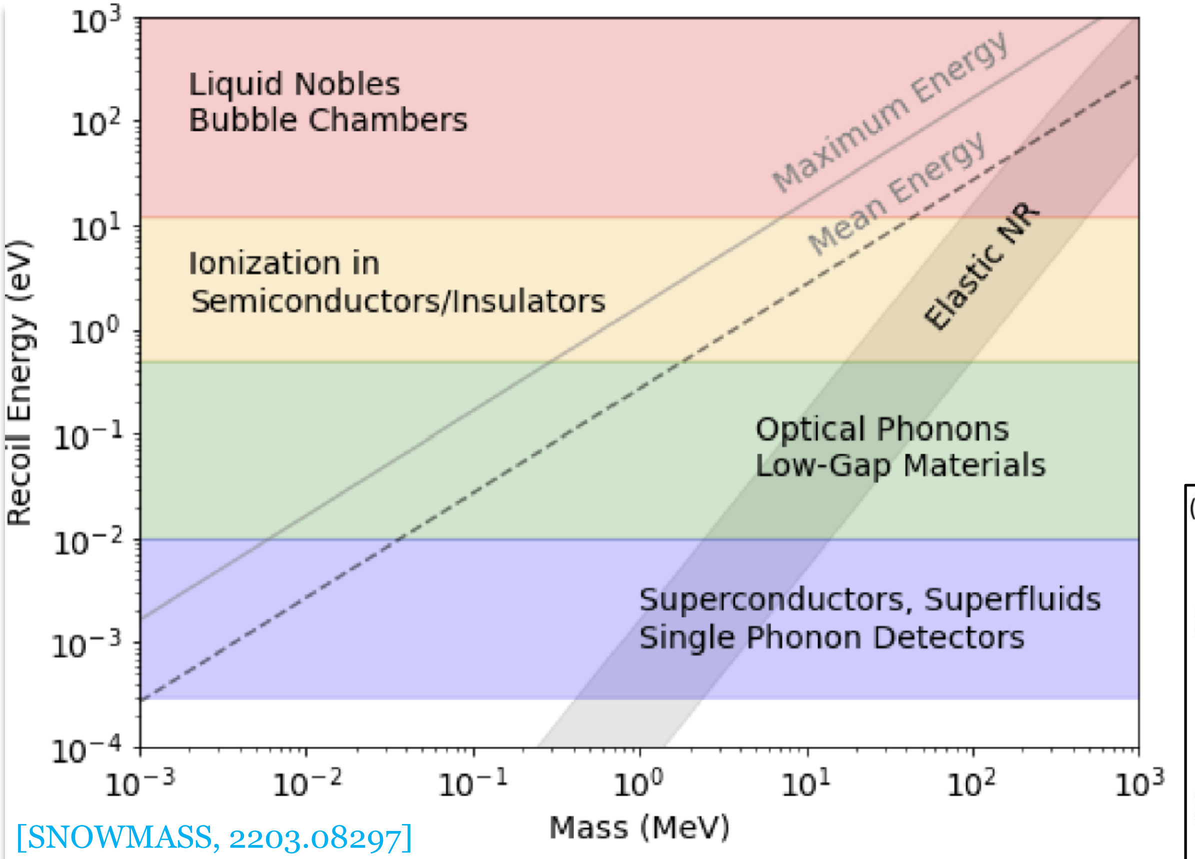
$$v_{\chi\parallel} = v_\chi \sin\theta_\chi,\ v_{S\parallel} = v_S \sin\theta_\chi^{w}$$
$$v_{\chi\parallel,S}{}^2 = v_{\chi\parallel}{}^2 + v_{S\parallel}{}^2 + 2 v_{\chi\parallel} v_{S\parallel}\cos\theta_{\chi S}$$



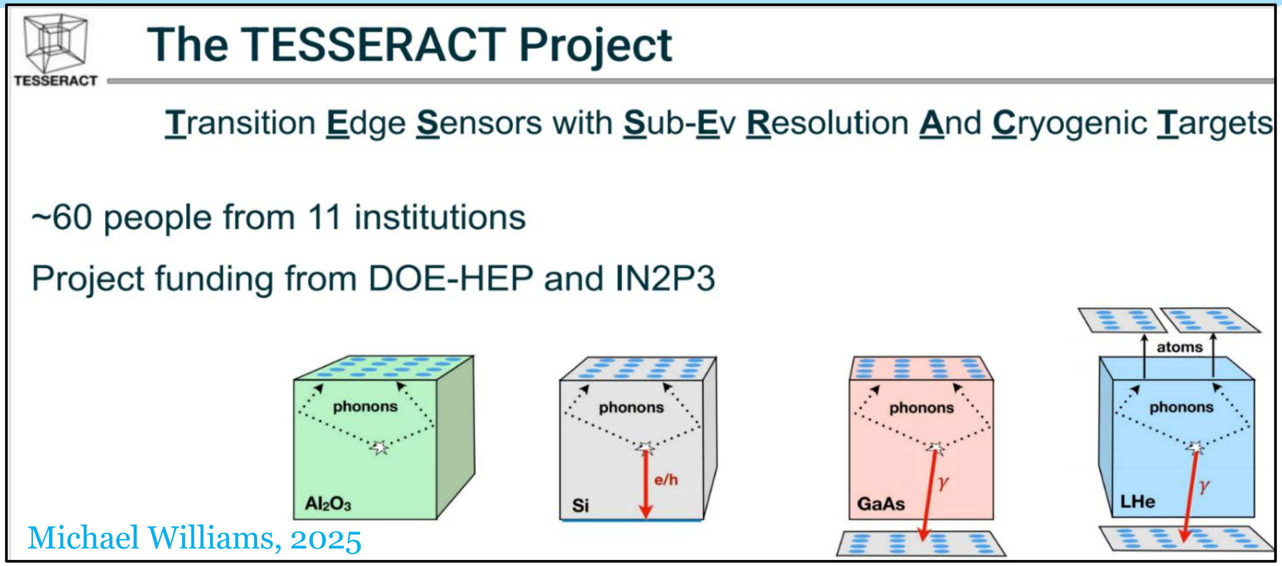
Schematics of Realistic Interconnection for 3D



Super-Light DM Direct Search Status

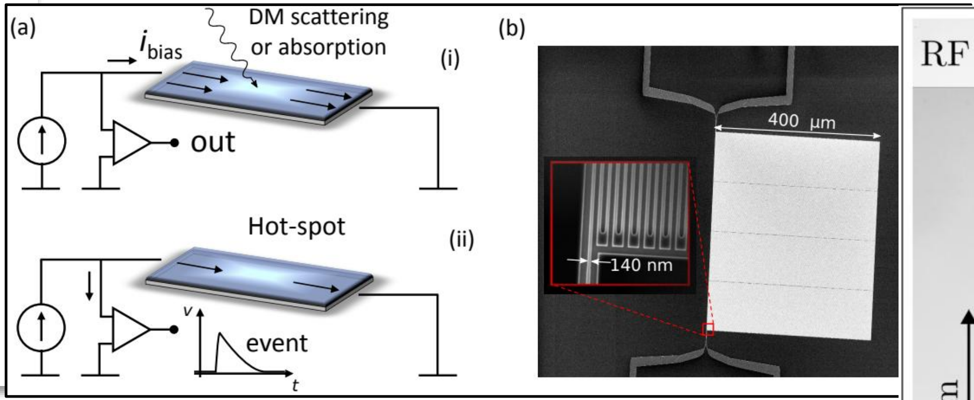


[SNOWMASS, 2203.08297]



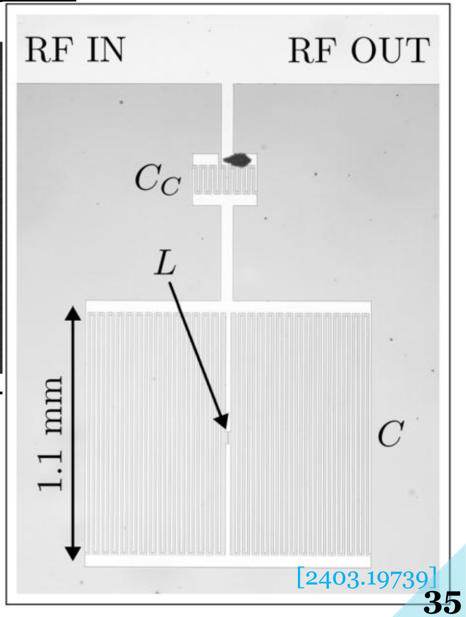
Michael Williams, 2025

SNSPD



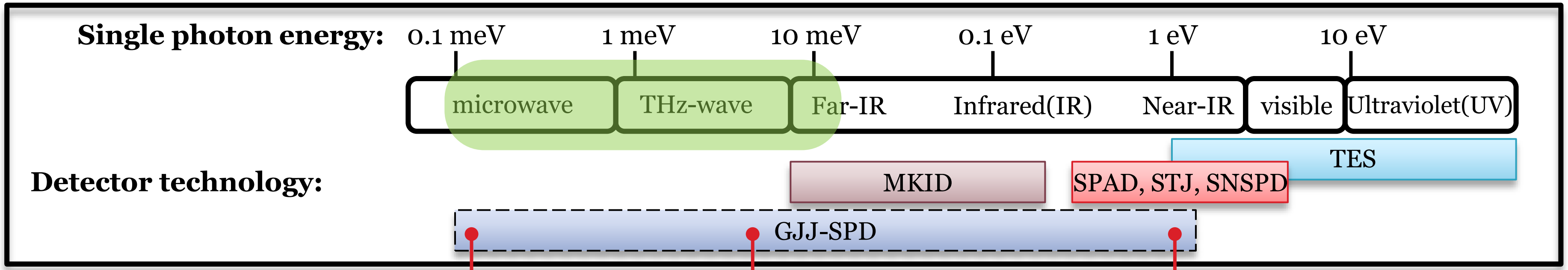
PRL (2019), PRD (2022), PRL (2025)

KID



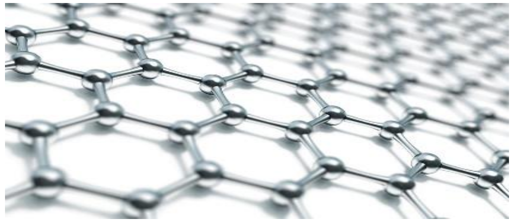
[2403.19739]

Status of Sensor Technologies



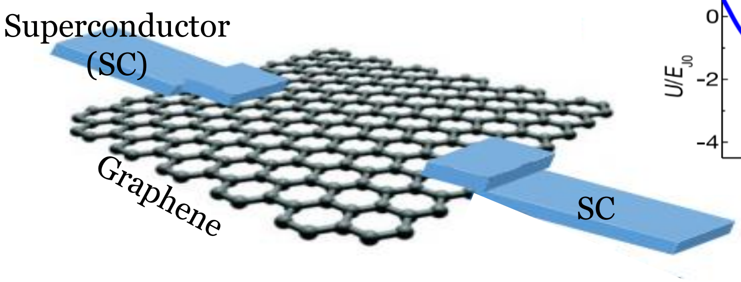
[G.-H.Lee,D.K.E.,W.C.Jung *et al.*, Nature (2020)] *"On-going"* [E.W.,W.C.Jung,G.-H.Lee, *et al.*, Science (2021)]

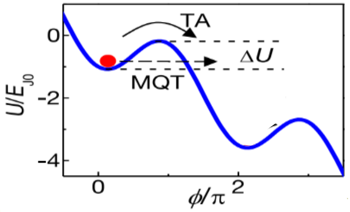
❖ **Graphene**



- ✓ 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: $\tau_{e\text{-}ph} > 10$ ns

❖ **Josephson junction**





Plasma frequency: f_p ~ 100 GHz

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

Detector classes by directional information

Demonstrated
R&D
Proposed

Indirect — **Recoil imaging**

Statistical — **Event-level**

Modulation-based directionality | Indirect recoil event directionality | Time-integrated recoil imaging | Time-resolved recoil imaging

Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Columnar recombination
- Event-level 1d directions
- No head / tail
- Direction and energy are not independent

Nuclear emulsions
- 2d recoil tracks, without head / tail
- No event times recorded

DNA detector
- 3d recoils without head / tail
- No event times recorded

Gas TPC
- Head / tail measurable
- 1d, 2d or 3d
- Independent energy / direction measurement

Crystal defects
- 3d track topology
- Head / tail measurable

Sven Vahsen, Ciaran O'Hare, Dinesh Loomba [2102.04596]

GLIMPSE

✓ No track ➔ Not imaging

✓ Target: 2D structure ➔ directionality & mass