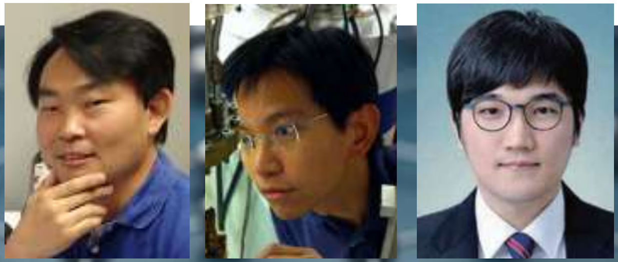
Detection of Superlight Dark Matter Using Graphene Josephson Junction

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



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CHUNGNAM NATIONAL UNIVERSITY

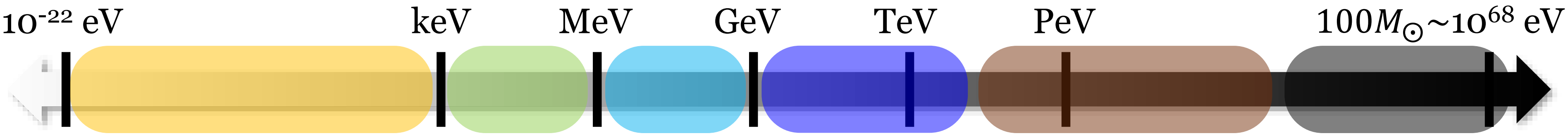
2020 KPS-DPF Meeting

December 04 (2020)

DM Landscape: A Very Wide Mass Range

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

DM Landscape: A Very Wide Mass Range



Ultralight
Scalar field
(QCD) Axion
Hidden photon
Fuzzy
non-thermal

Superlight
WDM
Sterile ν
axino
may be
thermal

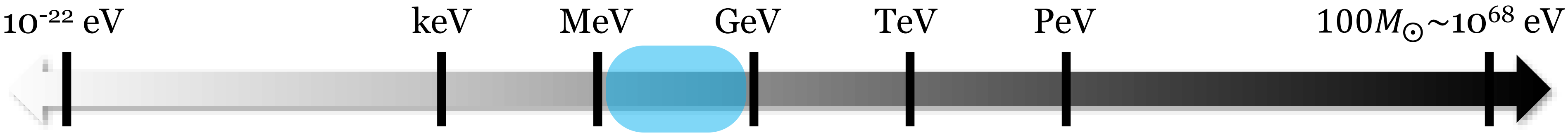
Light
particle
DM
can be
thermal

WIMP
well-motivated
extensively studied
Thermal

Superheavy / Composite
WIMPzilla
Q-ball
Fermi-ball
Dark-quark nugget
non-thermal

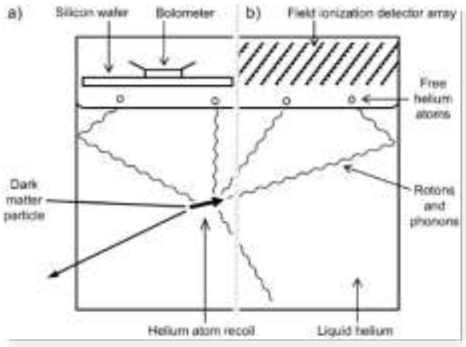
MACHO / Primordial BHs
non-particle

Light DM Sector

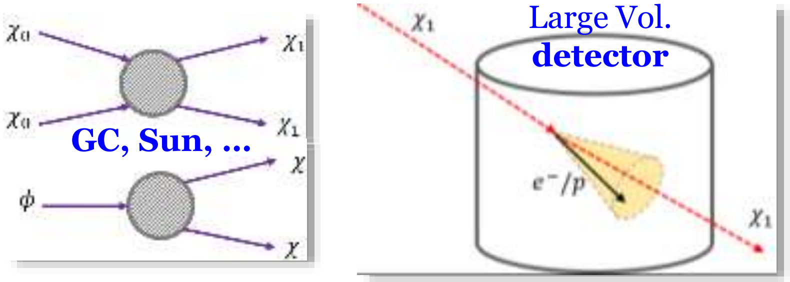


Light particle DM

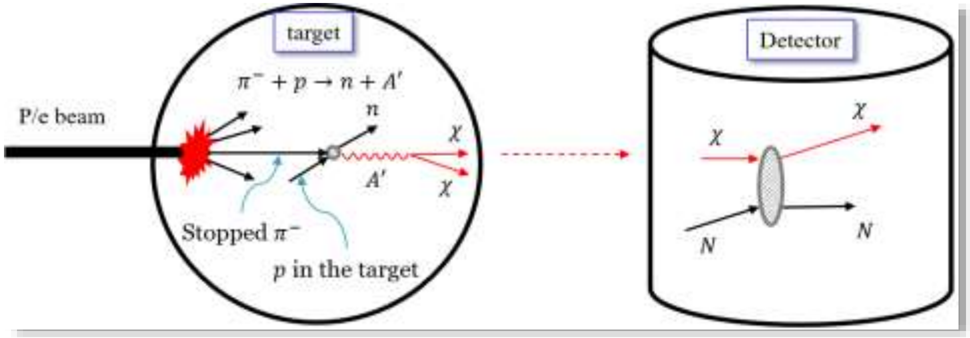
- ❖ $E_k \sim mv^2 <$ $\boldsymbol{O}$**(keV)** with $v\sim10^{-3}$: $< E_r^{th}$ of typical DM direct detectors for nuclear recoils
- ❖ New ideas for low E_r^{th} w/ e-recoil are required!
  - ✓ Ionization by e-recoils (semiconductor) [arXiv:1108.5383, 1509.01598]
  - ✓ Ejection of e's (graphene, C-nanotube) [arXiv:1606.08849, 1706.02487, 1808.01892]
  - ✓ Evaporation of He by nuclear-recoils [arXiv:1706.00117]
  - ✓ …



- ❖ Cosmogenic boostedDM searches: COSINE-100, DUNE/ProtoDUNE, IceCube, SK/HK/KNO, …

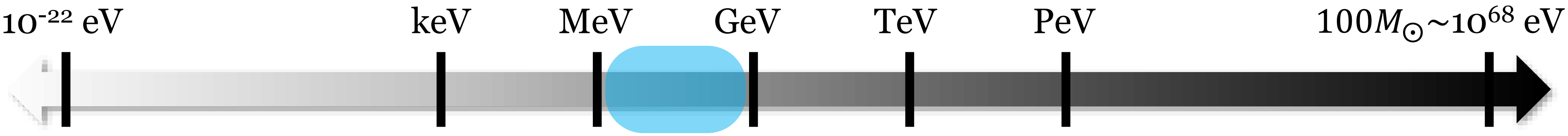


- ❖ Beam-produced light DM/mediator searches: Babar, BDX, Belle-II, CCM, COHERENT, DUNE, FASER, JSNS², LDMX, MATHSULA, NA64, SeaQuest, SHiP, …

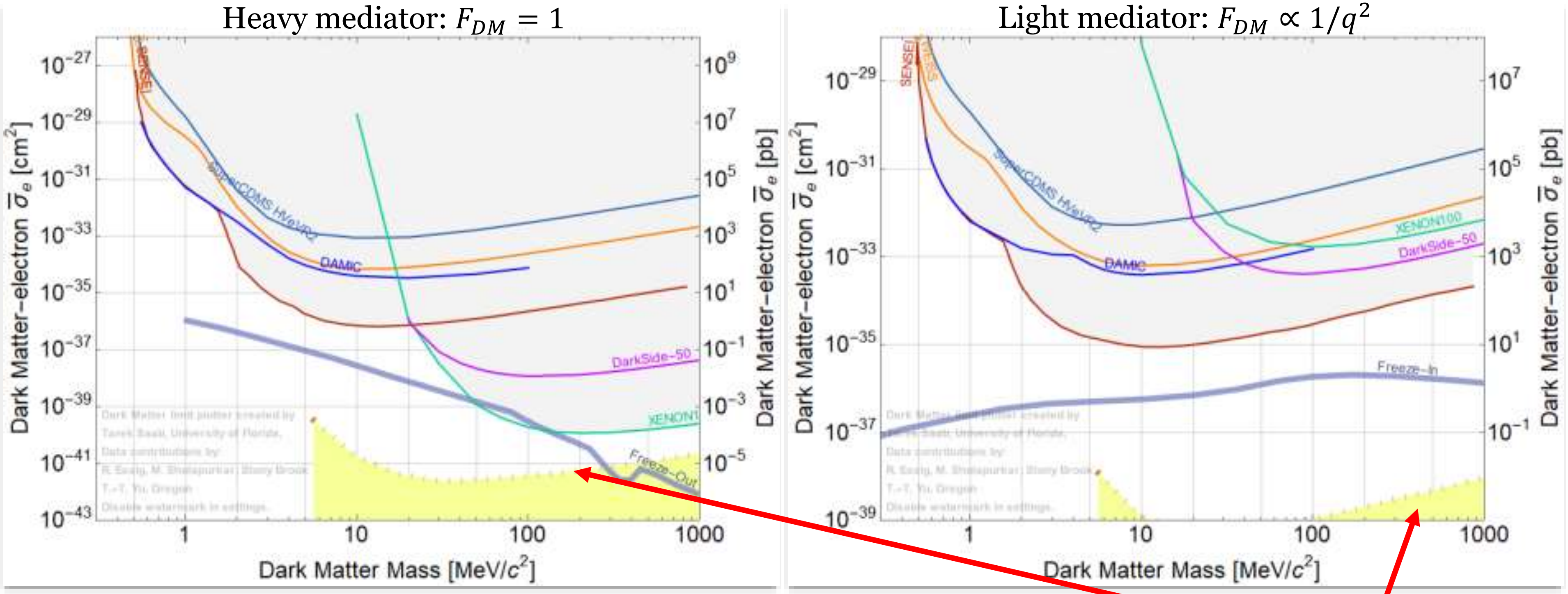


$\pi^0 \to \gamma + A',\ \pi^{-/+} + p/n \to \pi^0 + n/p$

Light DM: Direct Search Current Status



Light
particle
DM



ν BG for a Xe target (1t-yr)

Dark Matter Limit Plotter v5.16, updated Aug. 17, 2020

Super-Light DM: Main Focus


10^{-22} eV

keV

MeV

GeV

TeV

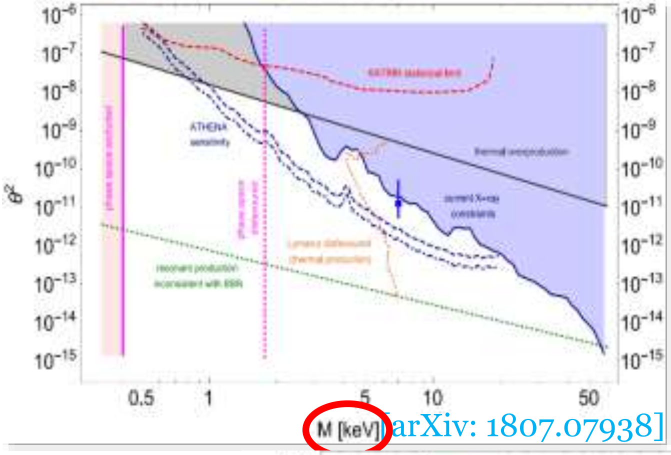
PeV

$100M_{\odot}\sim10^{68}$ eV

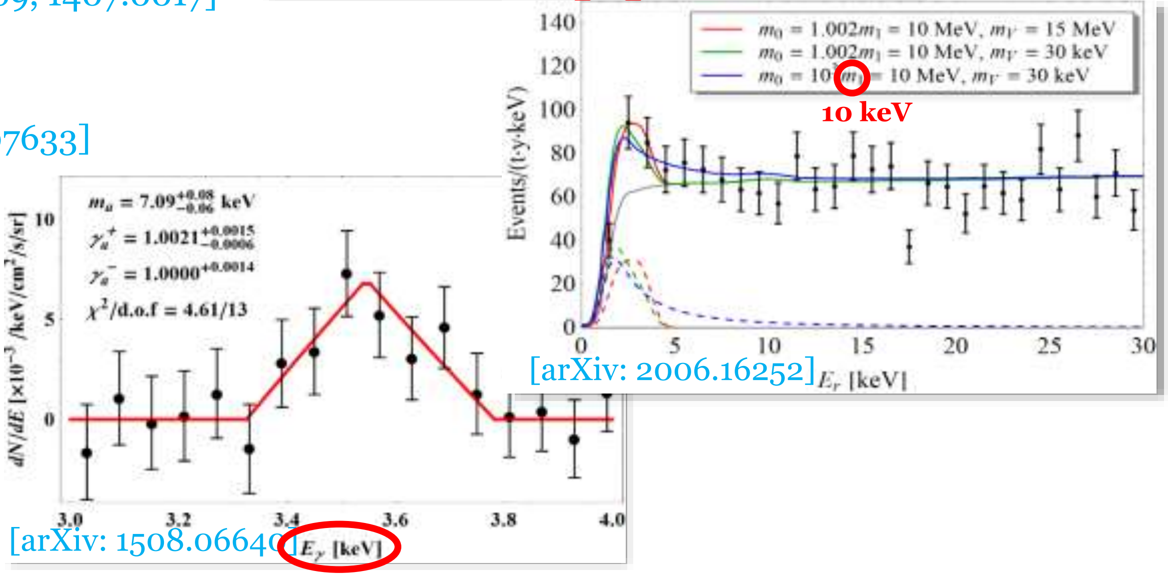
Superlight
DM

❖ Various well-motivated super-light DM pheno.:

- ✓ 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]
- ✓ keV DM for XENON1T, …



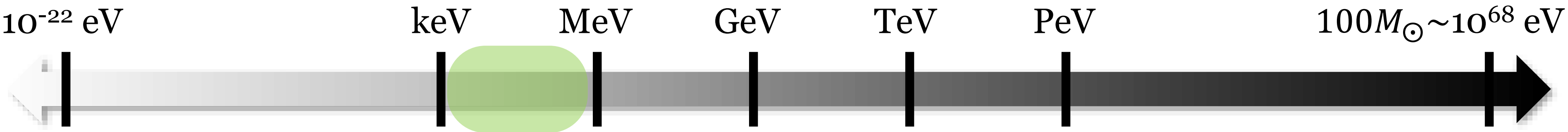
[arXiv: 1807.07938]



[arXiv: 2006.16252]

[arXiv: 1508.06640]

Super-Light DM: Main Focus

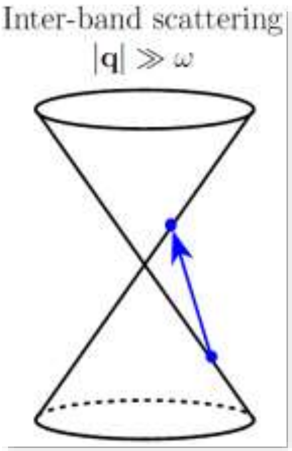


Superlight DM

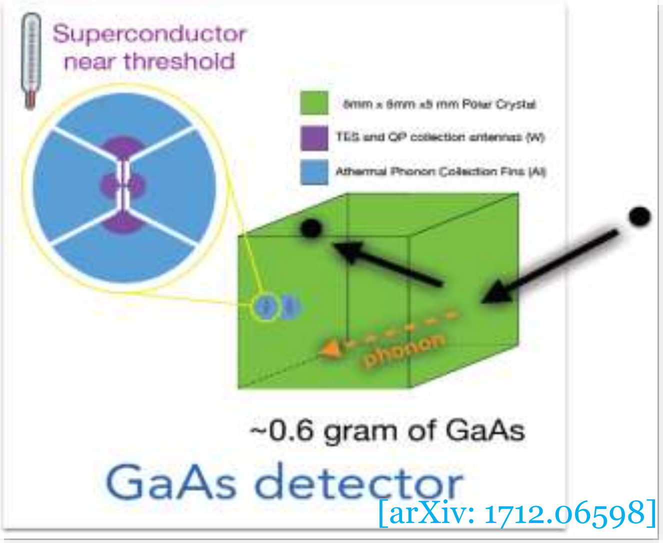
- ❖ $E_k \sim mv^2 < O(\mathrm{eV})$

➔ Very low E_r^{th} required!

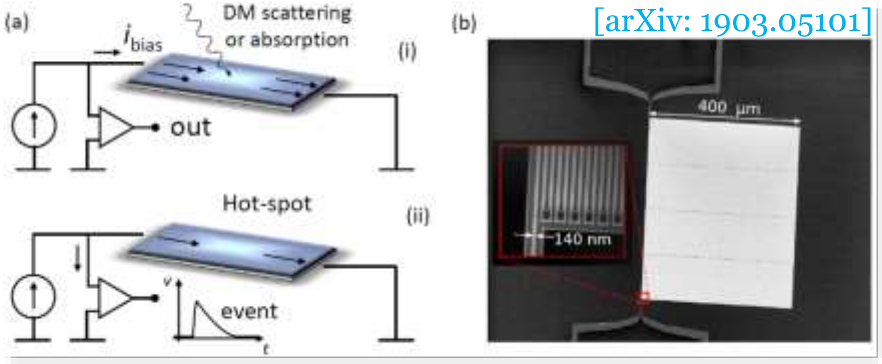
- ❖ New ideas for **very low E_r^{th}** w/ e-recoil:
  - ✓ Superconductor target w/ TES or MKID [arXiv:1504.07237, 1512.04533]
  - ✓ Superfluid He w/ TES or MKID [arXiv:1604.08206, 1611.06228]
  - ✓ 3D Dirac materials [arXiv:1708.08929]
  - ✓ Polar materials w/ TES or MKID [arXiv:1712.06598, 1807.10291]
  - ✓ Superconducting-nanowire single-photon detector [arXiv:1903.05101]
  - ✓ …



[arXiv: 1708.08929]

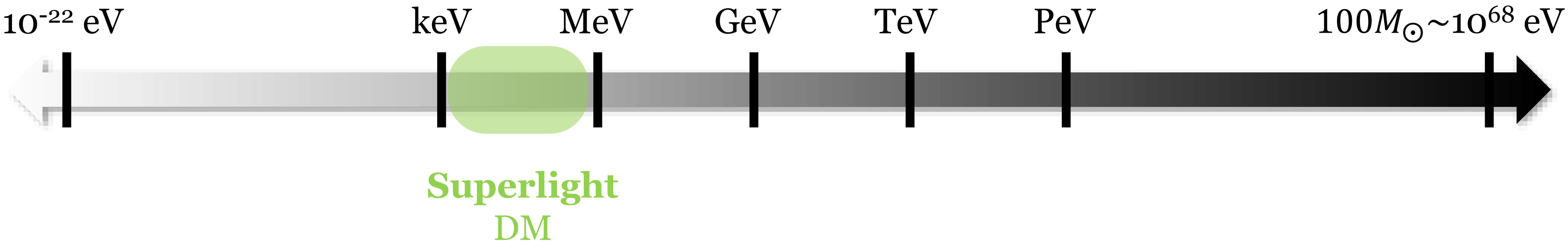


[arXiv: 1712.06598]



[arXiv: 1903.05101]

Super-Light DM: Technologies



- 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, $E_{th}\sim O(10\text{ meV})$

  [Annual Review of Condensed Matter Physics (2012)]

- Superconducting-nanowire single-photon detector (SNSPD): UV ~ mid-IR, $E_{th}\sim O(100\text{ meV})$

  [Techno. (2018)]

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

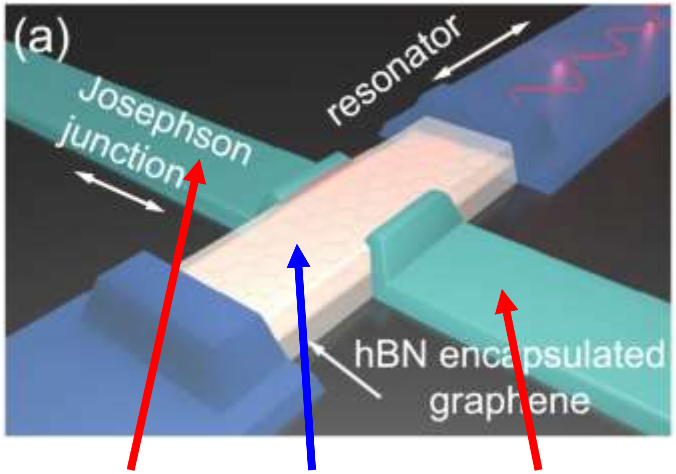
But for the sensitivity to $E_{th}\lesssim$ meV, further R&D is needed!

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

* A “state-of-the-art” technology:

much lower $E_{th} \sim O(0.1\ \mathrm{meV})$

Graphene Josephson Junction Device

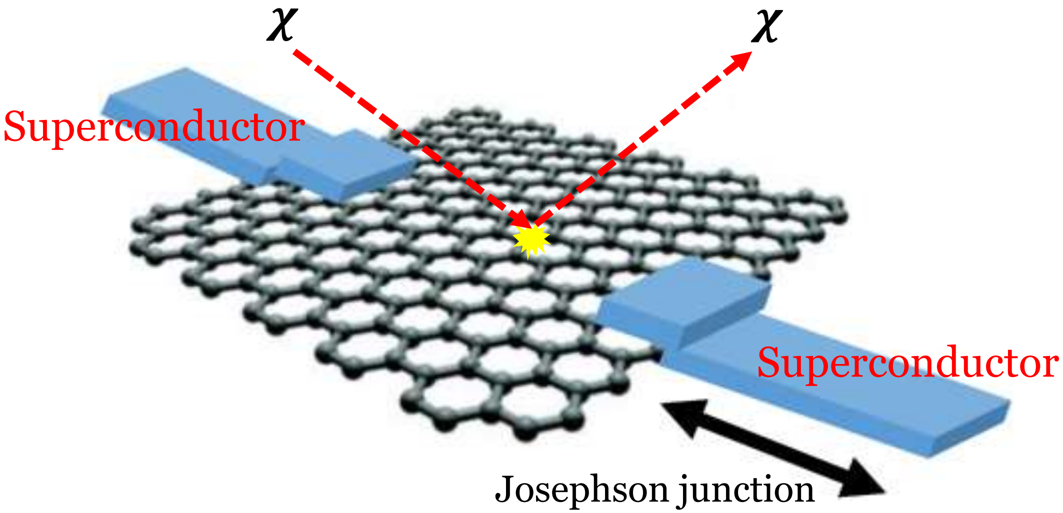


Superconductor-Graphene-Superconductor (SGS)

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)]
- K.C. Fong, G.-H. Lee & their collaborators have **demonstrated experimentally** that the GJJ microwave bolometer can have **sensitivity to $E\sim0.1$ meV energy deposit**. [Nature (2020)]
- Currently, a GJJ single-photon detector is under testing in the laboratory.

Detection Principle



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

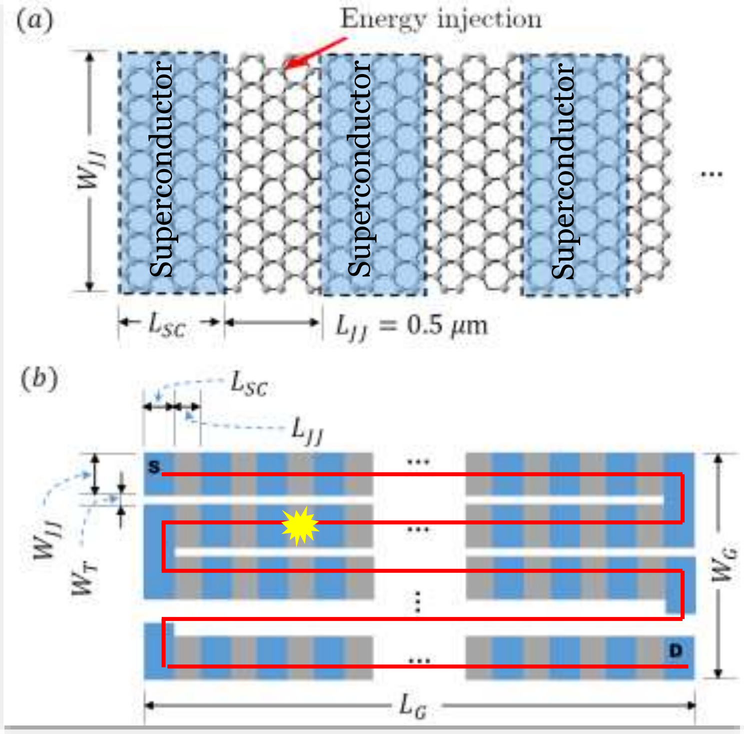
II. The recoiling e heats up & thermalizes with nearby e's rapidly via e-e interactions.

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

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

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

Conceptual Design Proposal



I. Single graphene strip (a): the assembly of a 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. Full detector unit (b): all GJJs are connected in series so that even a single switched GJJ 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}: $W_{JJ} = 3\ \mu\text{m}\ (30\ \mu\text{m})$ ➔ $E_{th} \approx 0.1$ meV (1 meV).
- ❖ A large-scale detector can be made of a stack of such detector units.

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 2-dimensional graphene sheet.

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

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

  ➔ Signal rate depending on the DM direction

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

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

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

Calculation Procedure I

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

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

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

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

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

✓ $N_{\rm eve} = N_e \sigma_{e\chi} \Phi_\chi t_{\rm run}$

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

2D nature of graphene

✓ $\frac{N_e}{M_{\rm T}} = \frac{N_e/V}{M_{\rm T}/V} = \frac{n_e^{\rm 3D}}{\rho_T^{\rm 3D}}$

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

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

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

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

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

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

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

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

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

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

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

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

The analytic expression for $S_{3\mathrm{D}}(E_r,\ q)$ is available in the non-relativistic limit

[astro-ph/9710115, 1512.04533].

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

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

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

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

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

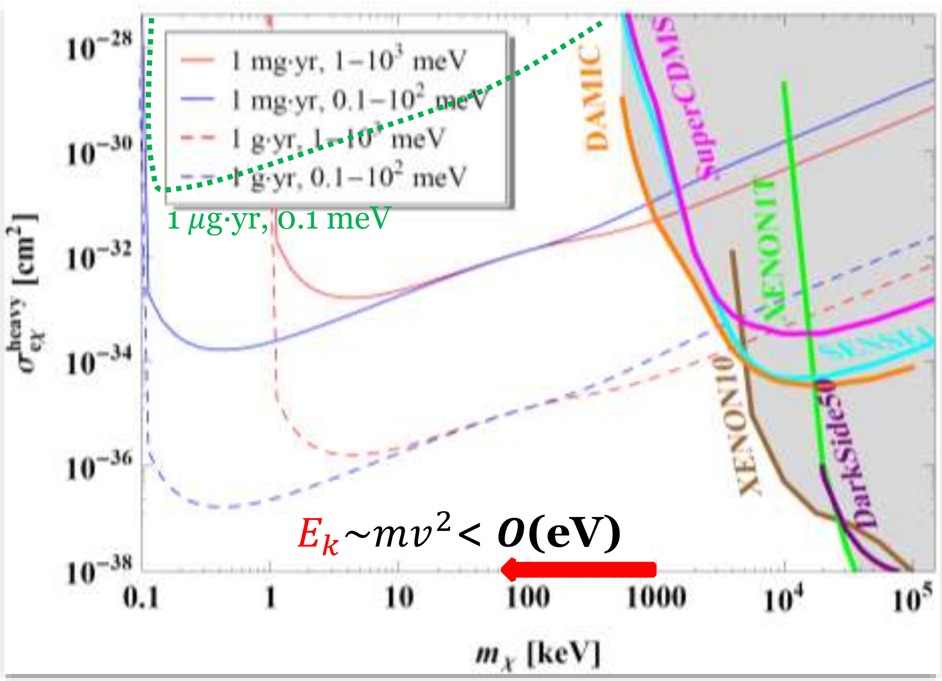
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{(m_\phi^2+q^2)^2} \rightarrow \sigma_{e\chi}^{\rm heavy} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2)\ \&\ \sigma_{e\chi}^{\rm light} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{q^4}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

- 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.

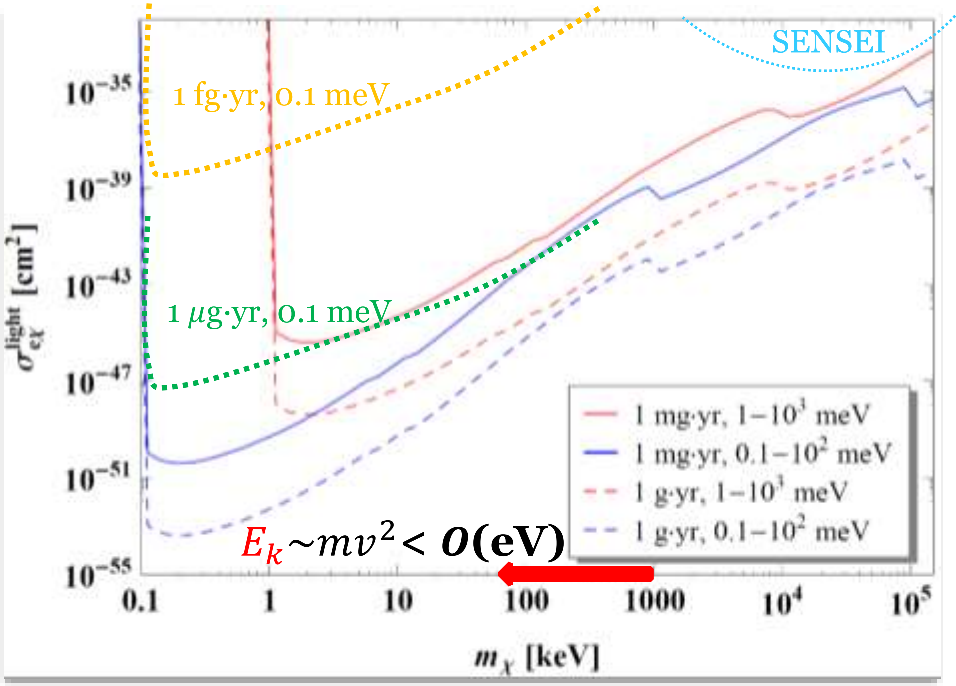
Expected Sensitivities

Heavy mediator: $F_{DM} = 1$



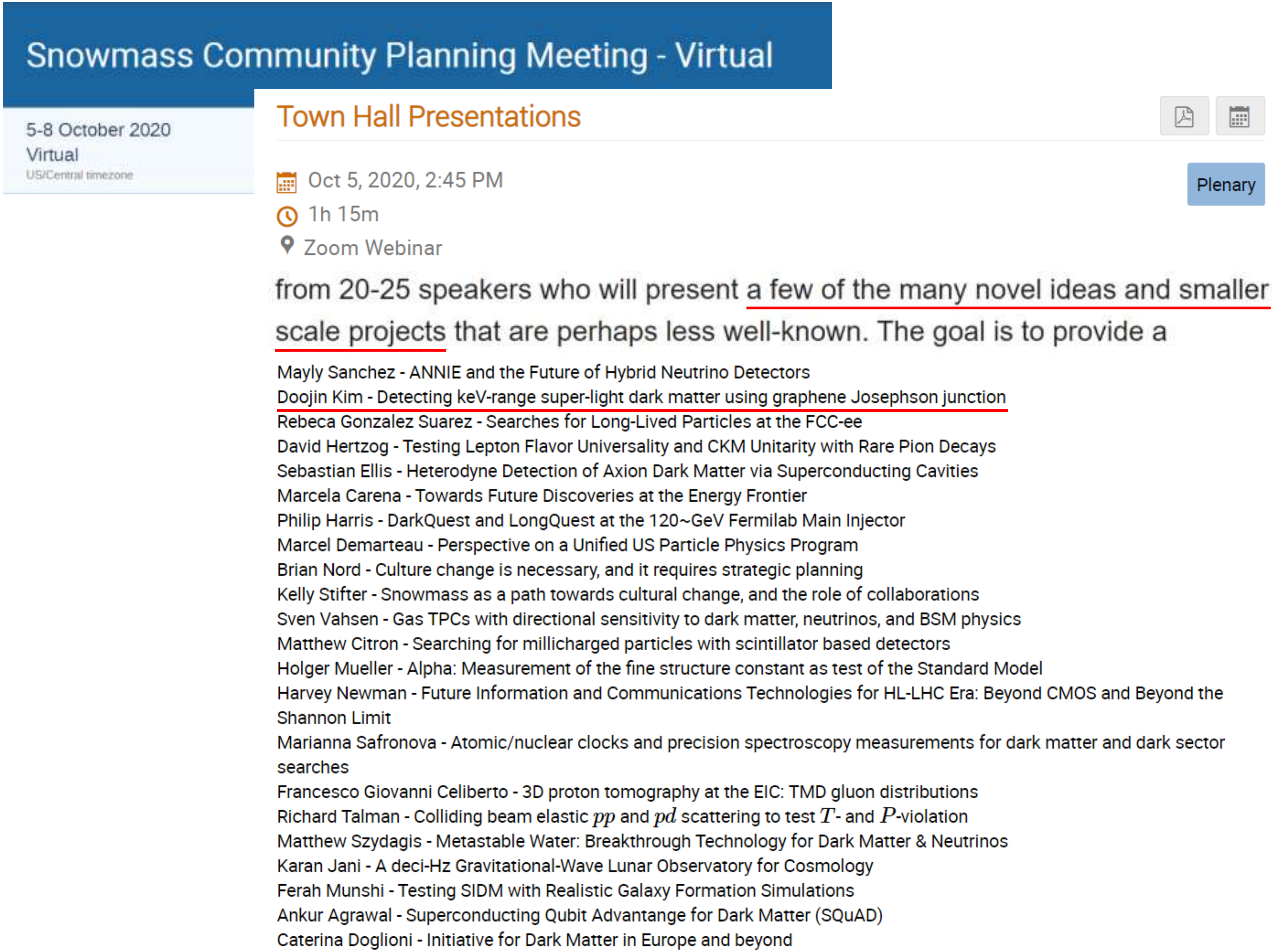
$E_k \sim mv^2 < \mathcal{O}(\text{eV})$

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



$E_k \sim mv^2 < \mathcal{O}(\text{eV})$

- ✓ We required N_{eve}=3.6 under the negligible background assumption.
- ✓ The proposed GJJ DM 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.
- ✓ Even capable of probing sub-keV DM with great expected reaches.



Snowmass Community Planning Meeting - Virtual

5-8 October 2020
Virtual
US/Central timezone

Town Hall Presentations

Oct 5, 2020, 2:45 PM
1h 15m
Zoom Webinar

Plenary

from 20-25 speakers who will present a few of the many novel ideas and smaller scale projects that are perhaps less well-known. The goal is to provide a

Mayly Sanchez - ANNIE and the Future of Hybrid Neutrino Detectors
Doojin Kim - Detecting keV-range super-light dark matter using graphene Josephson junction
Rebeca Gonzalez Suarez - Searches for Long-Lived Particles at the FCC-ee
David Hertzog - Testing Lepton Flavor Universality and CKM Unitarity with Rare Pion Decays
Sebastian Ellis - Heterodyne Detection of Axion Dark Matter via Superconducting Cavities
Marcela Carena - Towards Future Discoveries at the Energy Frontier
Philip Harris - DarkQuest and LongQuest at the 120~GeV Fermilab Main Injector
Marcel Demarteau - Perspective on a Unified US Particle Physics Program
Brian Nord - Culture change is necessary, and it requires strategic planning
Kelly Stifter - Snowmass as a path towards cultural change, and the role of collaborations
Sven Vahsen - Gas TPCs with directional sensitivity to dark matter, neutrinos, and BSM physics
Matthew Citron - Searching for millicharged particles with scintillator based detectors
Holger Mueller - Alpha: Measurement of the fine structure constant as test of the Standard Model
Harvey Newman - Future Information and Communications Technologies for HL-LHC Era: Beyond CMOS and Beyond the Shannon Limit
Marianna Safronova - Atomic/nuclear clocks and precision spectroscopy measurements for dark matter and dark sector searches
Francesco Giovanni Celiberto - 3D proton tomography at the EIC: TMD gluon distributions
Richard Talman - Colliding beam elastic pp and pd scattering to test T- and P-violation
Matthew Szydagis - Metastable Water: Breakthrough Technology for Dark Matter & Neutrinos
Karan Jani - A deci-Hz Gravitational-Wave Lunar Observatory for Cosmology
Ferah Munshi - Testing SIDM with Realistic Galaxy Formation Simulations
Ankur Agrawal - Superconducting Qubit Advantange for Dark Matter (SQuAD)
Caterina Doglioni - Initiative for Dark Matter in Europe and beyond

Summary

- We have proposed a class of new DM detectors, adopting the GJJ device which has been implemented & demonstrated experimentally.
- For the scattering between DM moving in 3D space & e's confined in 2D graphene, we (for the first time) built an effective model and computed the event rate.

➔ **Signal rate** depends on the **DM flow direction**!

- The proposed detector is capable of sensing sub-keV (warm) DM scattering off electrons due to its outstanding $\boldsymbol{E_{\mathrm{th}} \sim 0.1\ \mathrm{meV}}$. ➔ Improving the minimum detectable DM mass ($\boldsymbol{m_{DM} \sim 0.1\ \mathrm{keV}}$) by more than 3 orders of magnitude.

The Test Run with the Existing GJJ Device samples is in progress.

Future Plans

- We can use the same GJJ-based devices to detect ultra-light DM of $m \approx$ (sub-meV – eV) via **DM absorption**: e.g., axion/axion-like particle and dark gauge boson.

  ➔ Theoretical calculation: work in progress now.

- **Directional dependence of signals**: the angle between the DM wind flow and the graphene ← using angle information for each event or rotating the detector.

- The proposed GJJ detector can be used as **a sensor**. ➔ A sensor made of a few GJJ units can be attached to the target material, e.g., superconductor, Superfluid He, or polar material.

- **[Schedule]** Multiple GJJs & test (E-beam litho.) ➔ Fabrication w/ inch-scale graphene & long-time measurement (photo-litho.) ➔ Stacking of GJJ sheets & year-scale measurement

- We need more Collaborators & Research grant.

Thank you