Detection of Super-Light DM Using Graphene-based Sensor

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

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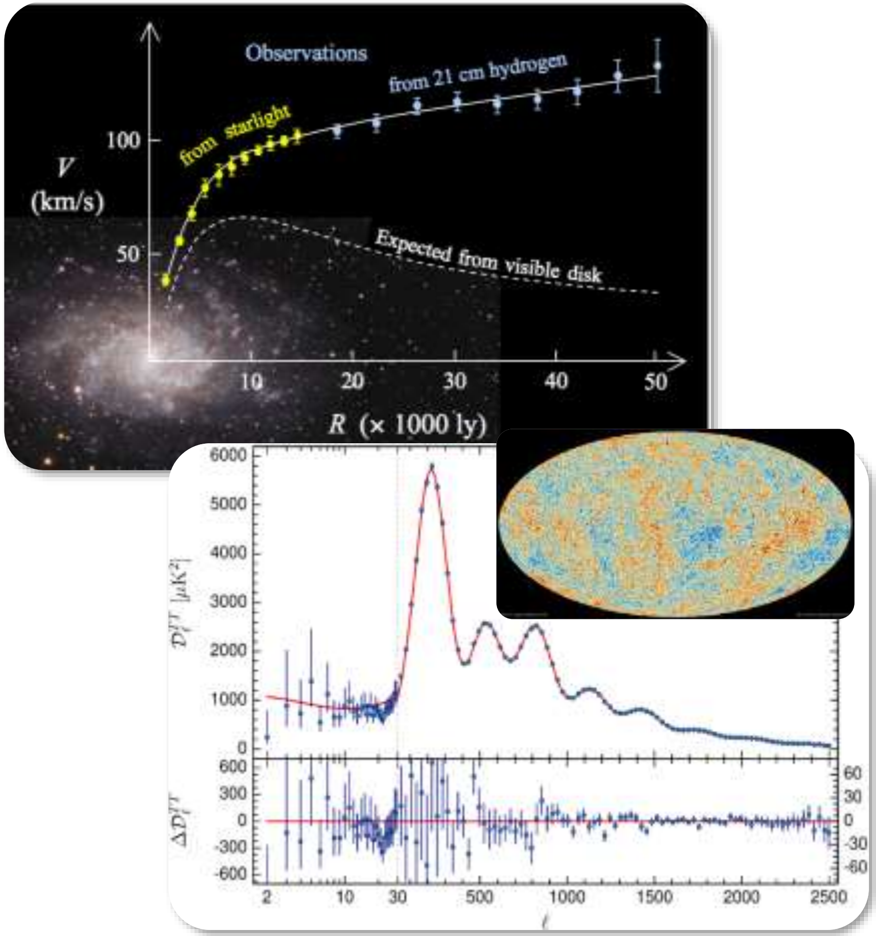
International Joint Workshop on the SM and Beyond

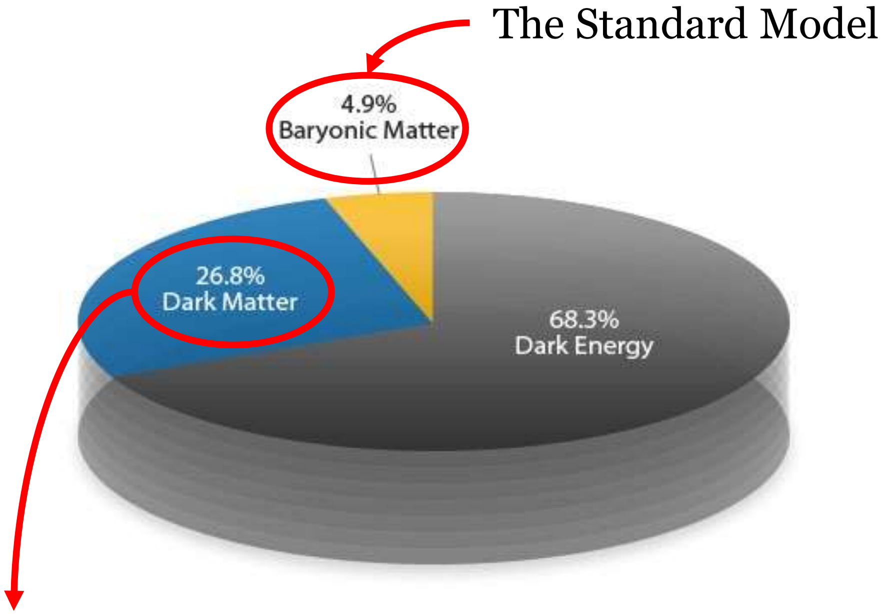
Why Light Dark Matter?

Dark Matter (DM)



❖ **Evidence**: Galactic rotation curve, Coma/Bullet cluster, Gravitational lensing, Structure formation, CMB, …

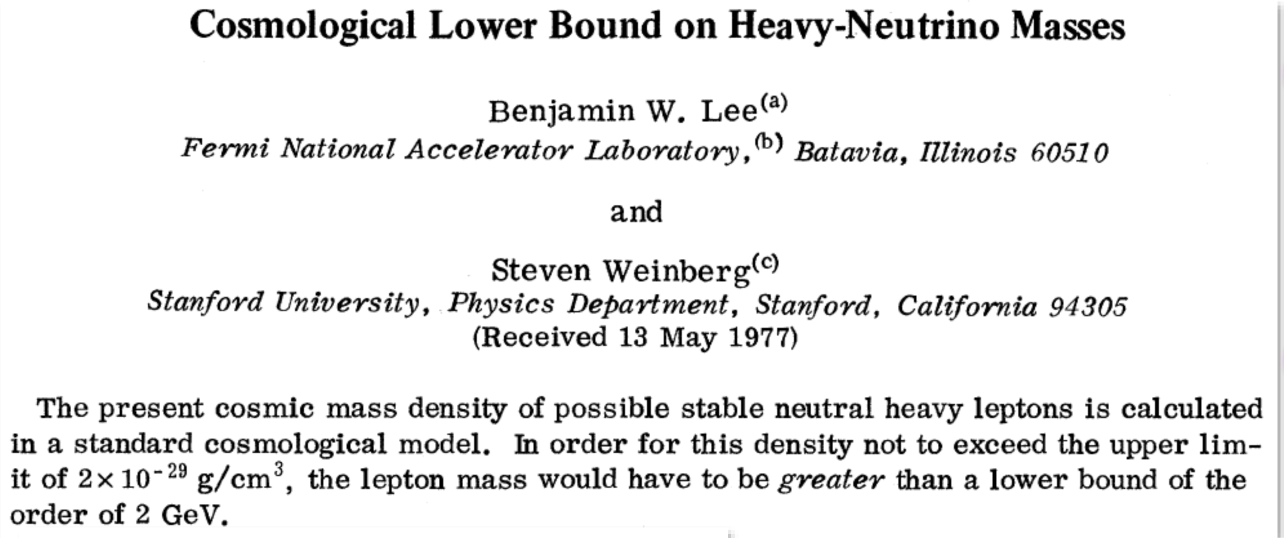
❖ **Modern cosmology**:



❖ **Compelling paradigm**:

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

Classic Solution*: WIMP



Cosmological Lower Bound on Heavy-Neutrino Masses

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and

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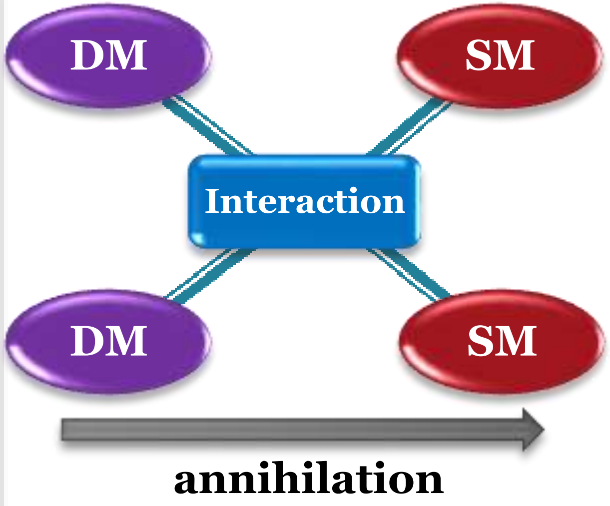
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



DM

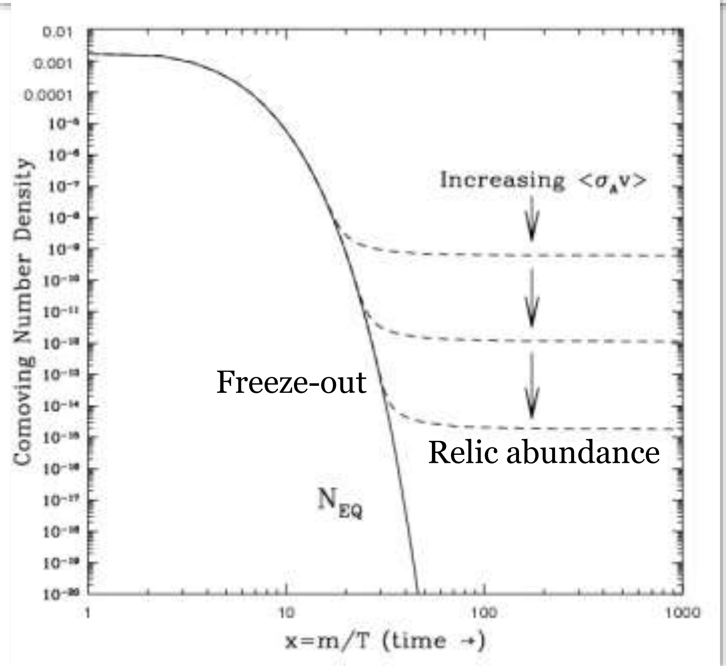
SM

Interaction

DM

SM

annihilation



- Correct thermal relic abundance:

$$\Omega h^2 \sim \frac{0.1\,pb}{\langle\sigma v\rangle} \text{ with } \langle\sigma v\rangle \sim \frac{\alpha_\chi^2 m_\chi^2}{M^4} \ (M\text{: dark scale/mediator})$$

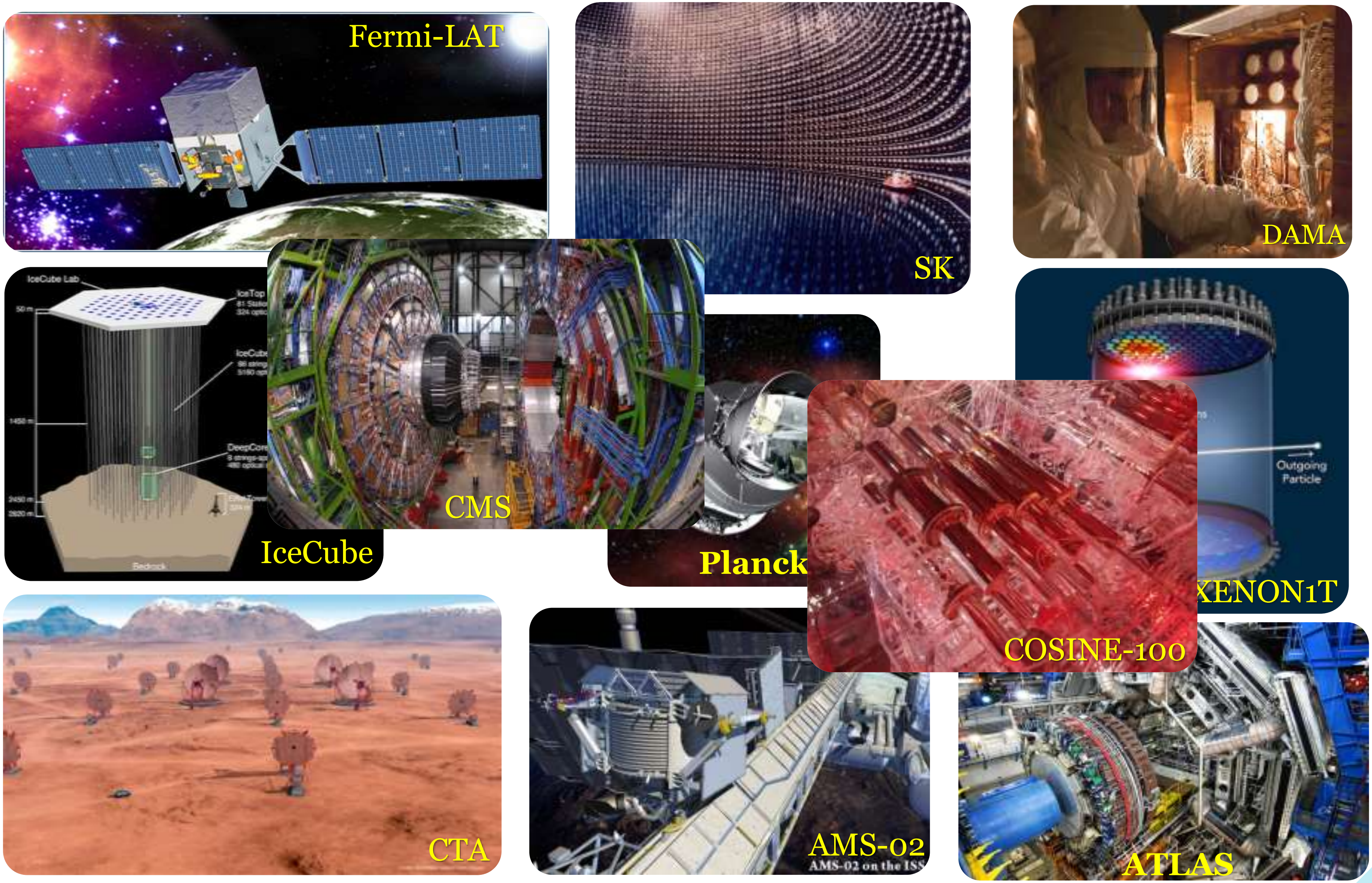
- Weak coupling ➔ naturally weak scale mass:

~1 GeV – 10 TeV mass range favored

➔ weak scale (new) physics

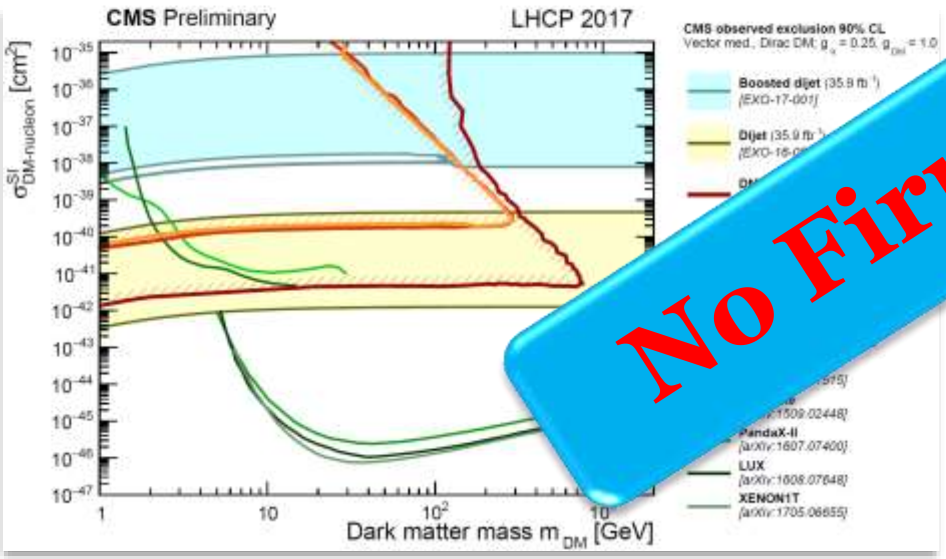
* Of course, **axion** is another classic solution. (This Morning)

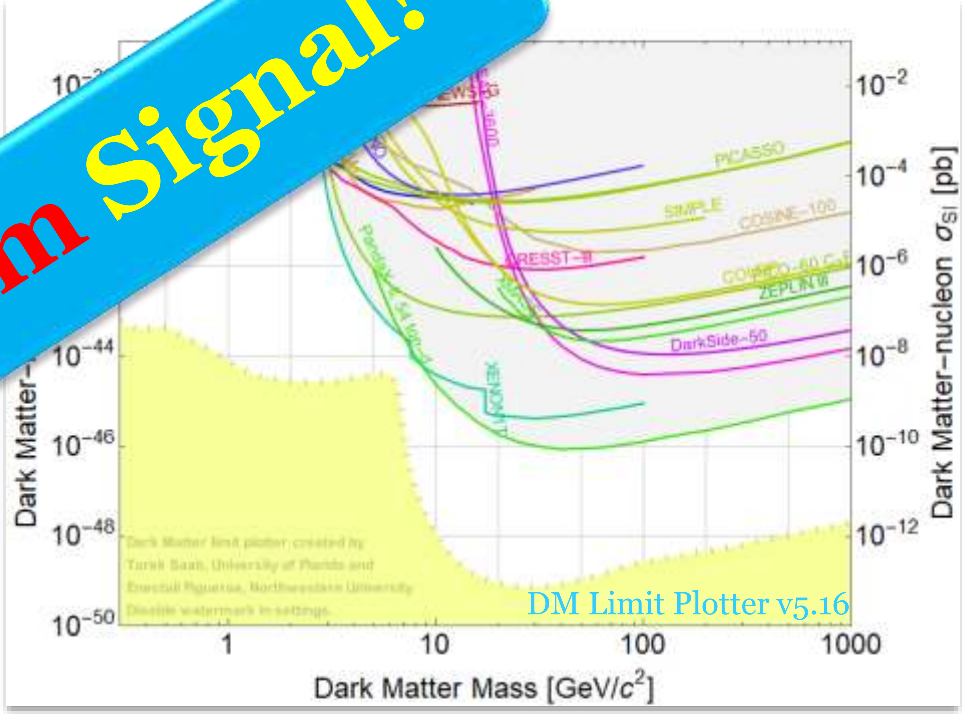
Diverging Efforts for WIMP Searches



Current Status of Conventional DM Searches

- ❖ No (solid) observation of DM signatures via non-gravitational interactions
- ❖ Many searches designed under WIMP/minimal dark sector scenarios
  - ➔ Just excluding more parameter space in DM models



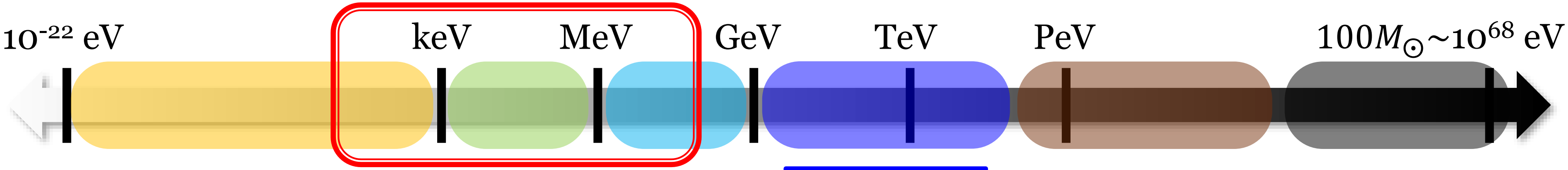


No Firm Signal!

Only
WIMP?

No!

Mass Scale of DM



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

Superlight
sterile ν,
axino,
warm DM,
can be
thermal

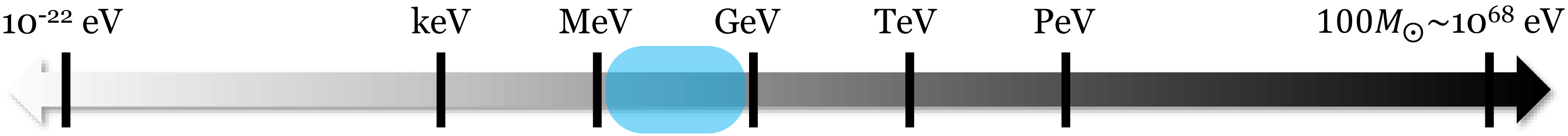
Light
dark
sector,
can be
thermal

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

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

MACHO /
Primordial BHs
non-particle

Light DM Sector



Light
particle
DM

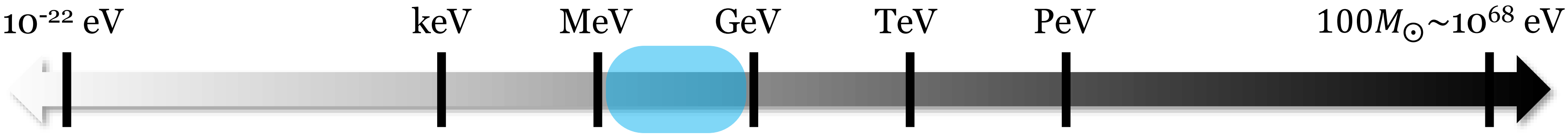
- ❖ For heavy mediator, $\langle \sigma v \rangle \sim \frac{\alpha_{\chi}^2 m_{\chi}^2}{M^4}$
- ❖ For weak scale physics,

  sub-GeV DM overproduction

  ➔ New mediator $< M_W$ for freeze-out

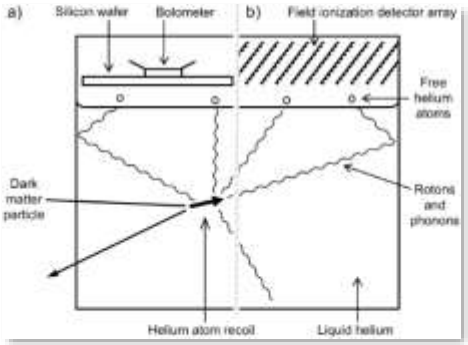
  or new mechanism e.g., freeze-in, …
- ❖ Various light DM/mediator scenarios:
  - ✓ MeV DM for GC 511 keV line observation [astro-ph/0309686]
  - ✓ Secluded MeV DM [arXiv:0711.3528, 0711.4866]
  - ✓ Sommerfeld enhancement for e^+ excess [arXiv:0810.0713]
  - ✓ $(g-2)_{e,\mu}$: $\sim 2-3\sigma$ discrepancy [arXiv:1806.10252]
  - ✓ New ν interactions for the MiniBooNE excess [arXiv:1807.09877]
  - ✓ Solutions of Yukawa coupling hierarchy prob. [arXiv:1905.02692]
  - ✓ …
- ❖ New DM relic determination mechanisms:
  - ✓ Assisted Freeze-Out [arXiv:1112.4491]
  - ✓ Cannibal DM [arXiv:1602.04219, 1607.03108]
  - ✓ Co-Decaying [arXiv:1105.1652, 1607.03110]
  - ✓ Semi-Annihilation [arXiv:0811.0172, 1003.5912]
  - ✓ SIMP [arXiv:1402.5143]
  - ✓ …

Light DM Sector

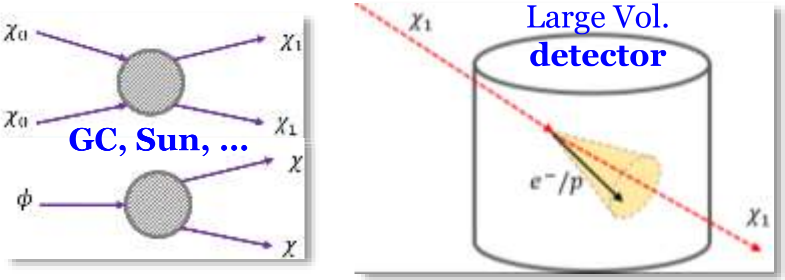


Light particle DM

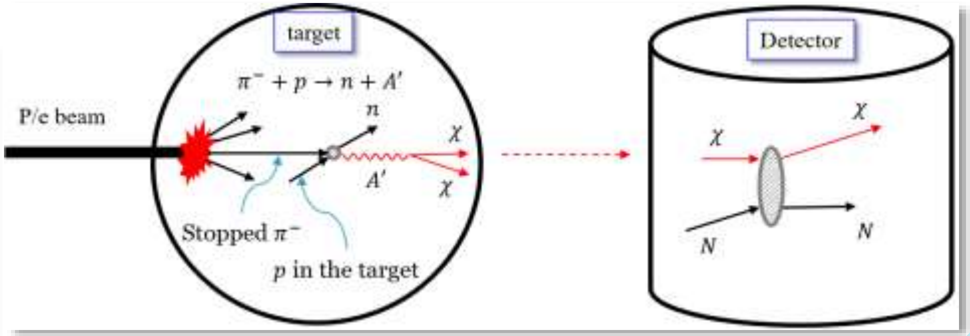
- ❖ $E_k \sim mv^2 < \boldsymbol{O}(\textbf{keV})$ with $v\sim10^{-3}$: $< E_r^{th}$ of typical DM direct detectors for nuclear recoils
- ❖ New ideas for <u>low E_r^{th} w/ e-recoil</u> are required!
  - ✓ Ionization by e-recoils (semiconductor) [arXiv:1108.5383, 1509.01598]
  - ✓ Ejection of e's (graphene,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

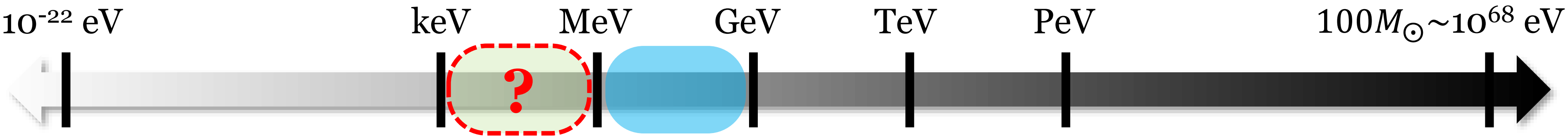


- ❖ Beam-produced light DM/mediator searches: Babar, BDX, Belle-II, CCM, COHERENT, DUNE, FASER, JSNS², LDMX, MATHSULA, NA64, SeaQuest, SHiP, …



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

Light DM: Direct Search Status



10^{-22} eV

keV

?

MeV

GeV

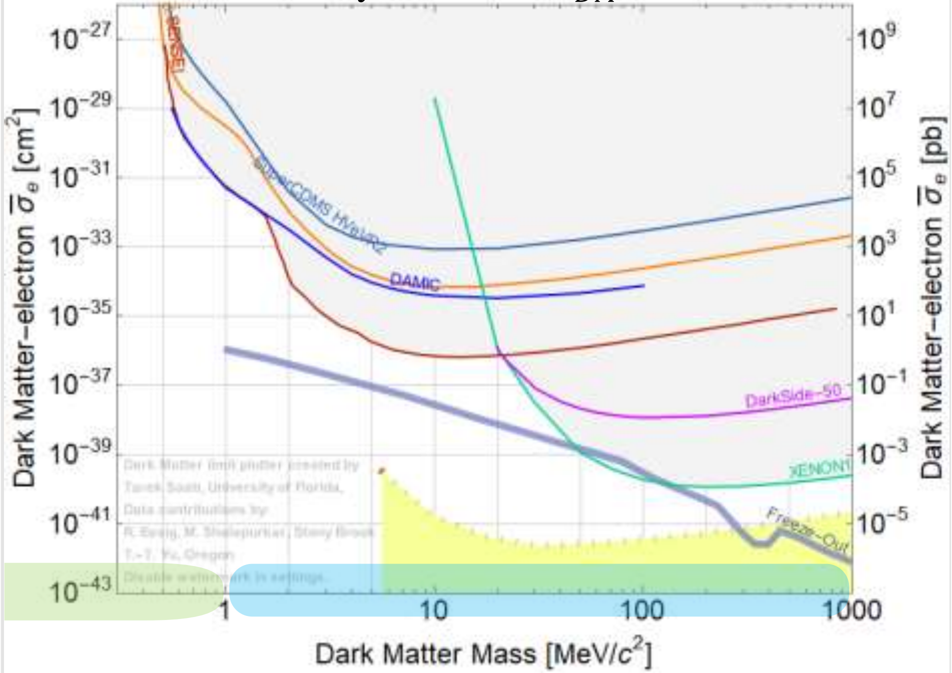
TeV

PeV

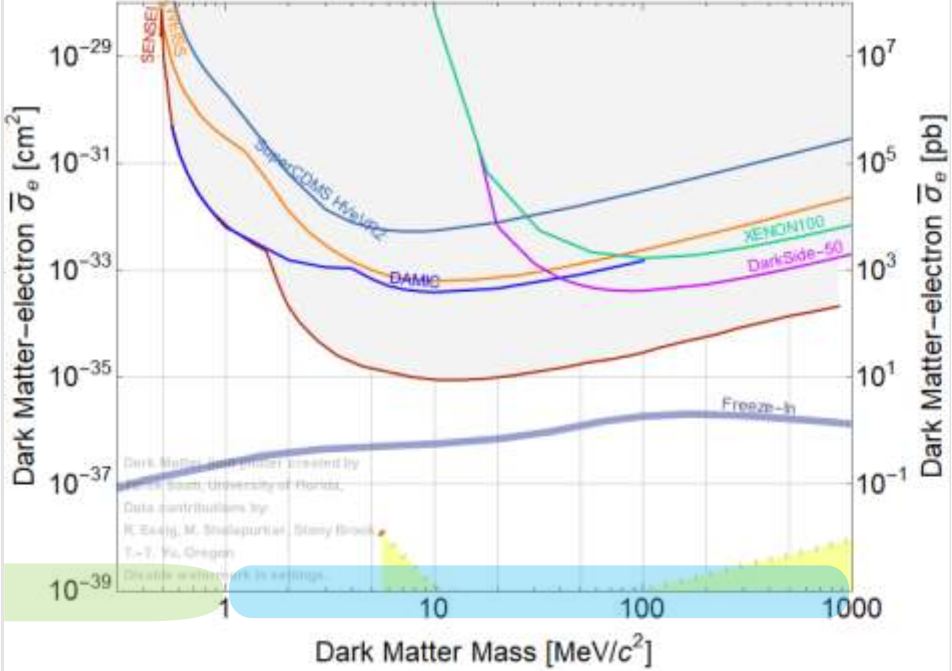
$100 M_{\odot} \sim 10^{68}$ eV

Super-light DM **Light**

Heavy mediator: $F_{DM} = 1$

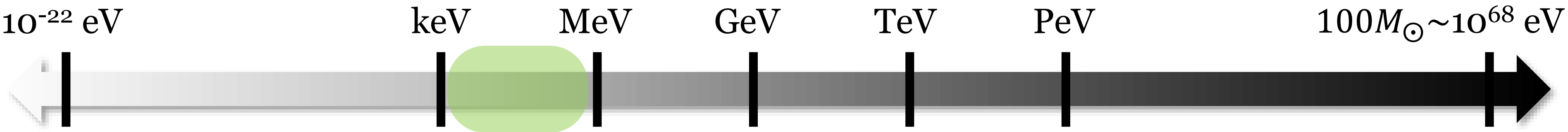


Light mediator: $F_{DM} \propto 1/q^2$



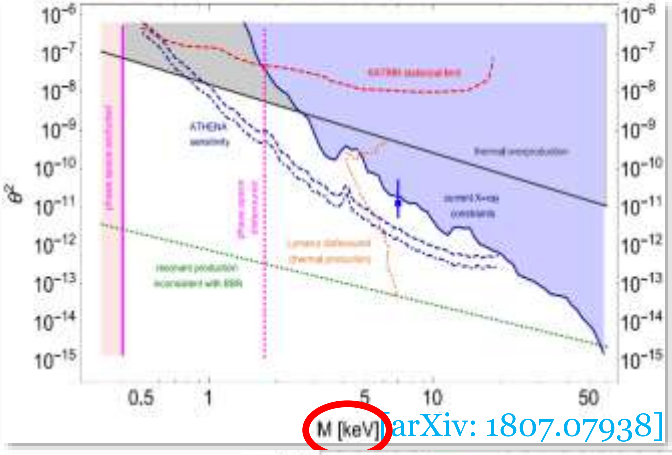
[Dark Matter Limit Plotter v5.16, updated Aug. 17, 2020]

Super-Light DM: Main Focus

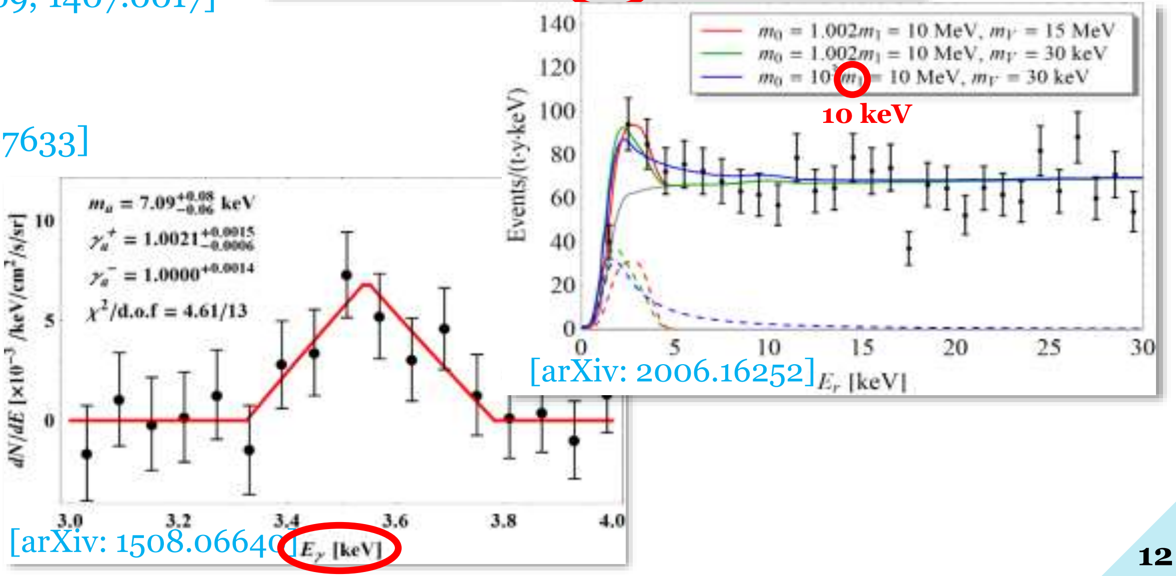


Super-light DM

- ❖ 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, …



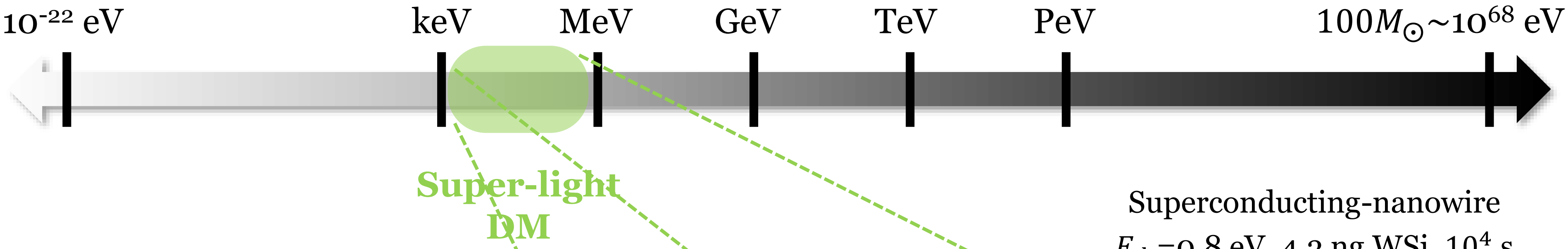
[arXiv: 1807.07938]



[arXiv: 2006.16252]

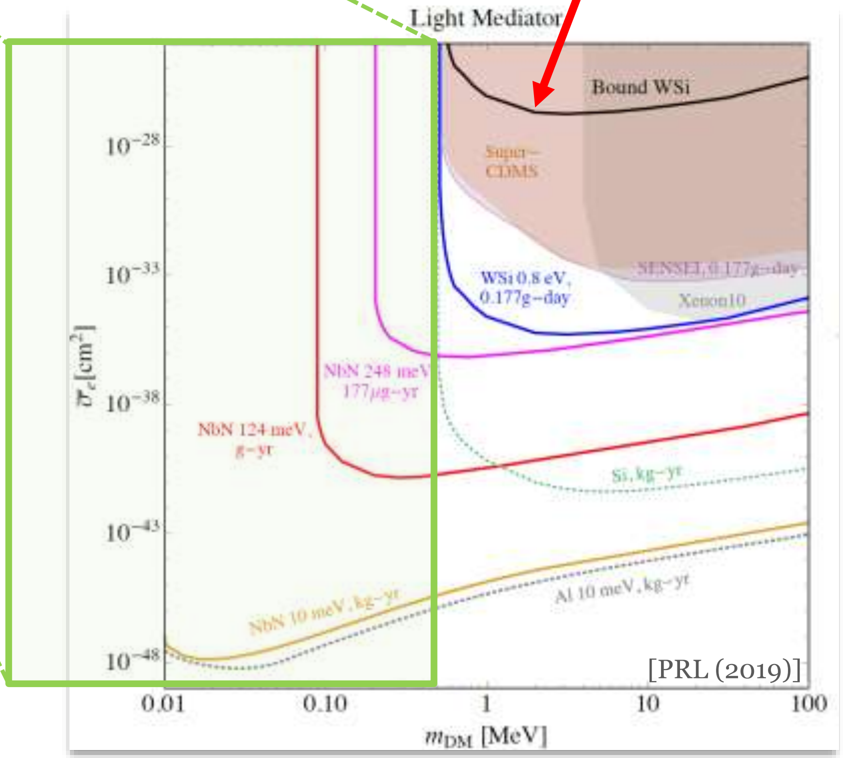
[arXiv: 1508.06640]

Super-Light DM: Current Status



- ❖ $\boldsymbol{E_k\sim mv^2\sim O(\mathrm{meV})}$ with $m\sim$keV & $v\sim10^{-3}$
- ❖ **New ideas** are required!
  - ✓ Superconductor [PRL (2016)]
  - ✓ Superfluid He [PRL (2016)]
  - ✓ 3D Dirac material [PRD (2018)]
  - ✓ Polar material [PLB (2018)]
  - ✓ Superconducting-nanowire [PRL (2019)]
  - ✓ …
- ❖ **World race** to prove **super-light DM**.
- ❖ **No experiment** for **O(keV) DM** so far.

Superconducting-nanowire
E_{th}=0.8 eV, 4.3 ng WSi, 10^4 s



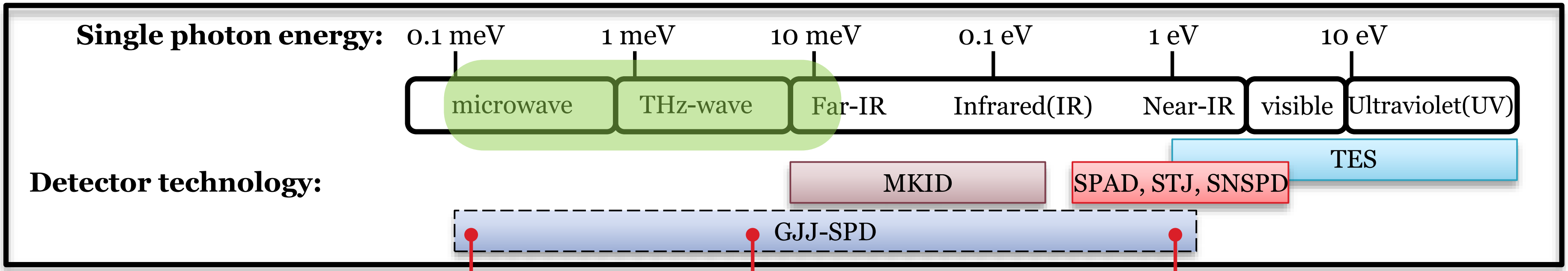
[PRL (2019)]

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

Status of Sensor Technologies


Single photon energy: 0.1 meV, 1 meV, 10 meV, 0.1 eV, 1 eV, 10 eV

microwave | THz-wave | Far-IR | Infrared(IR) | Near-IR | visible | Ultraviolet(UV)

Detector technology:

TES

MKID

SPAD, STJ, SNSPD

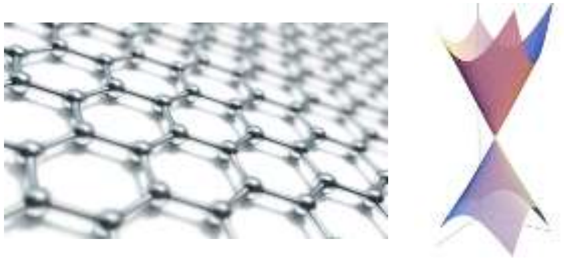
GJJ-SPD

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

"On-going"

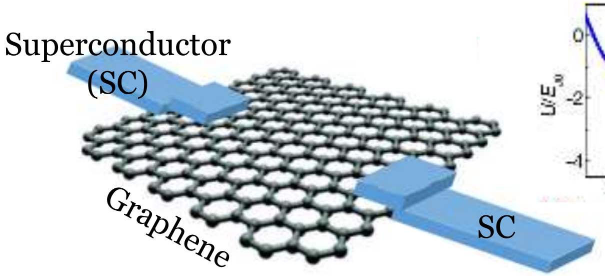
[E.W.,W.C.Jung,G.-H.Lee, *et al.*, Science (2021)]

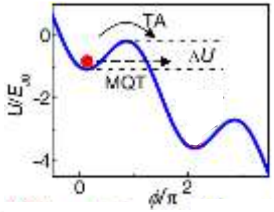
❖ Graphene



- ✓ 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

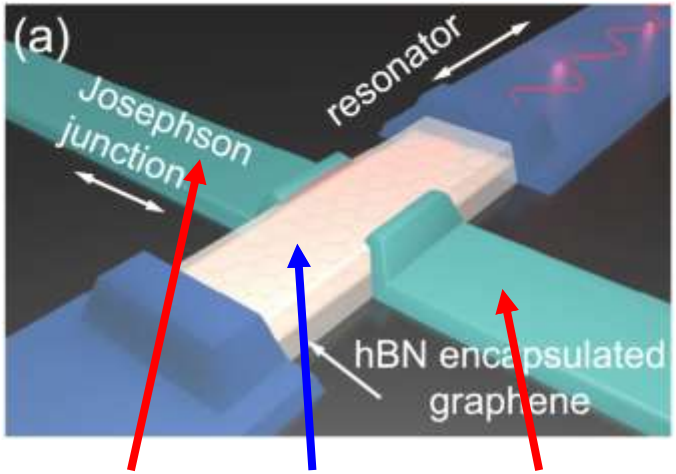




Plasma frequency:
$f_p \sim 100$ GHz

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

GJJ Device

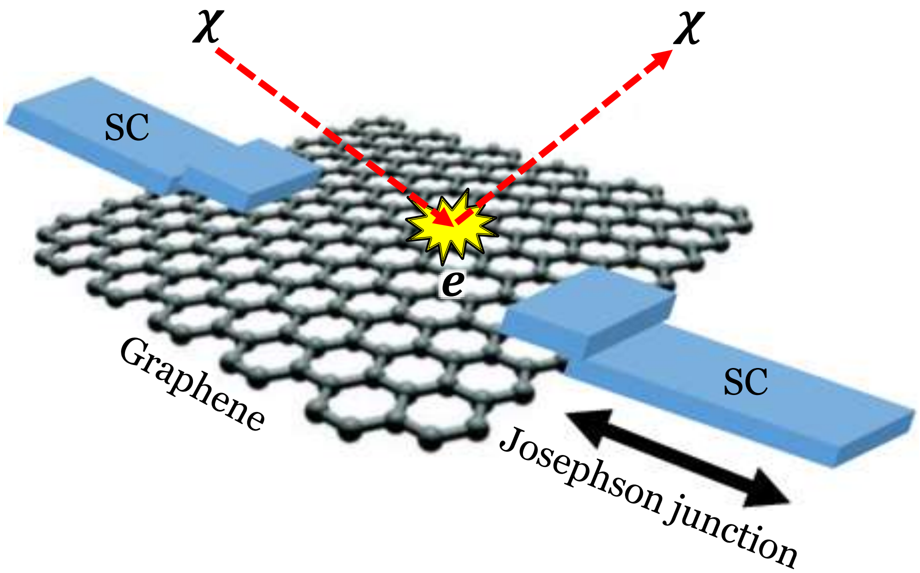


Superconductor-Graphene-Superconductor (SGS)

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



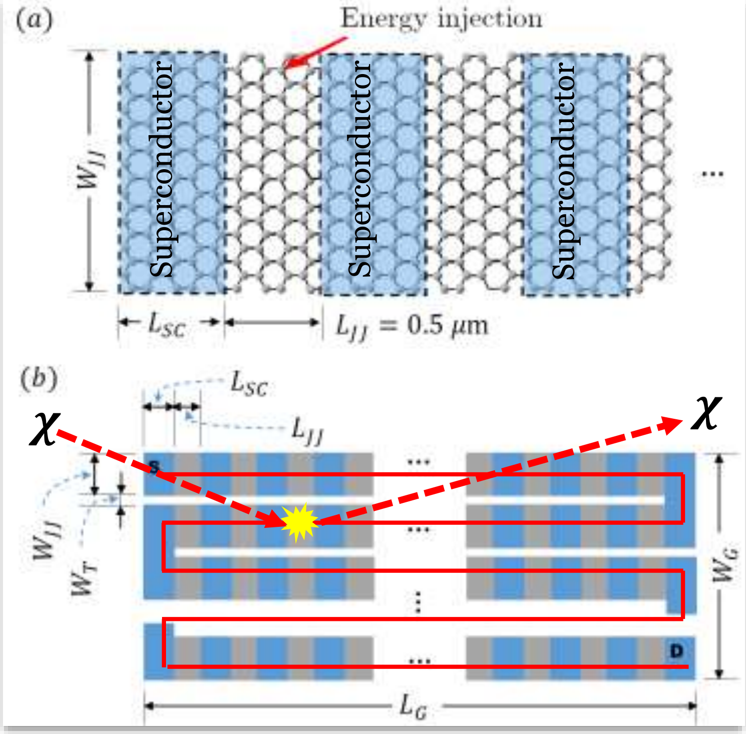
I. **DM scatters off (π-bond) free electrons**, transferring some fraction of its incoming E_k.

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 (non-resistive) of JJ to a **non-zero-voltage (resistive) state**.

- $E_k \sim mv^2 \sim 1$ meV for $m_{DM} = 1$ keV
  - ➔ **GJJ detector** ($E_{th} \sim 0.1$ meV): **sensitivity** to the signal 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 much larger-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 2D 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:

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

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

Calculation Procedure I

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

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

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

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

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

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

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

2D nature of graphene

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

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

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

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

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

➔ Fermi-Dirac distribution function

Calculation Procedure II

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

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

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

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

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

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

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

➔ 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.

[S. Reddy *et al.*, PRD (1998), Y. Hochberg *et al.*, JHEP (2016)]

Calculation Procedure III

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

✓ $\rho_\chi = 0.3\ \mathrm{GeV/cm^3}$

✓ $v_0 = 220\ \mathrm{km/s}$, $v_{\mathrm{esc}} = 500\ \mathrm{km/s}$

✓ $\rho_{\mathrm{gr}}^{2\mathrm{D}} = 7.62 \times 10^{-8} \mathrm{g/cm^2}$

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

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

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

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

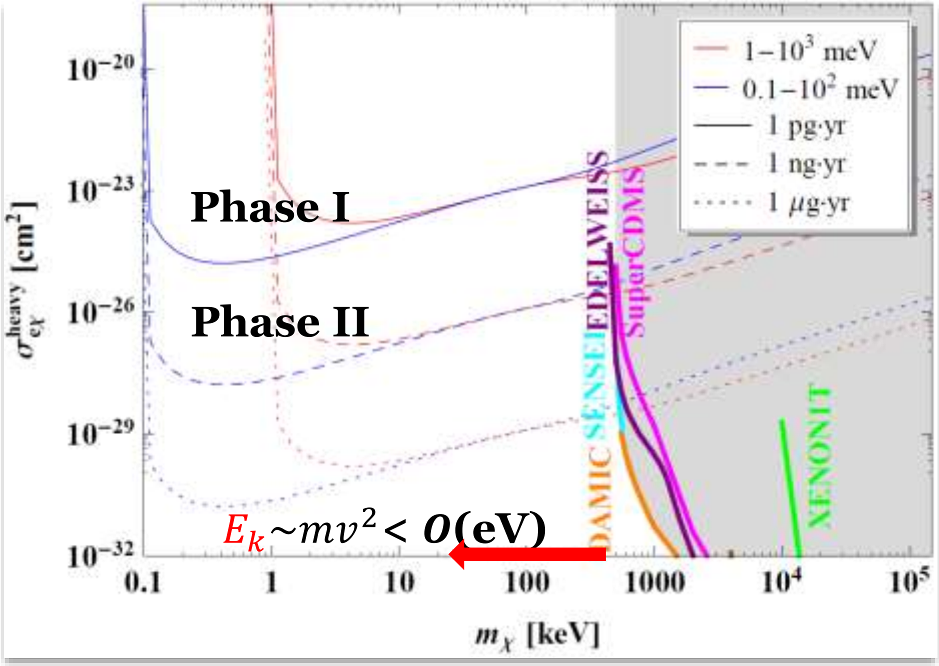
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{(m_\phi^2 + q^2)^2} \Rightarrow \sigma_{e\chi}^{\mathrm{heavy}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2) \text{ \& } \sigma_{e\chi}^{\mathrm{light}} \approx \frac{g_e^2 g_\chi^2}{\pi}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

- The matrix element $\overline{|\mathcal{M}|^2}$ is related to the scattering cross section as $\sigma_{e\chi} = \frac{\overline{|\mathcal{M}|^2}}{16\pi \, m_e^2 m_\chi^2} \mu_{e\chi}^2$.

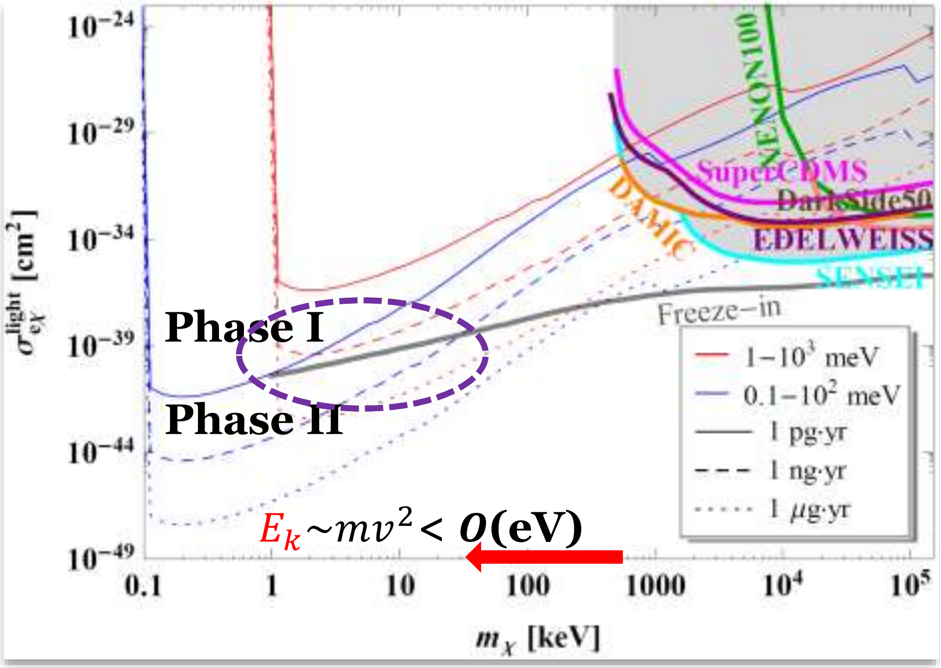
- From the linear dispersion of graphene: $E_F = v_F \sqrt{\pi n_c}$ with $v_F \sim 10^8 \mathrm{cm/s}$ & $n_c \sim 10^{12}/\mathrm{cm^2}$.

Expected Sensitivities

Heavy mediator: $F_{DM} = 1$



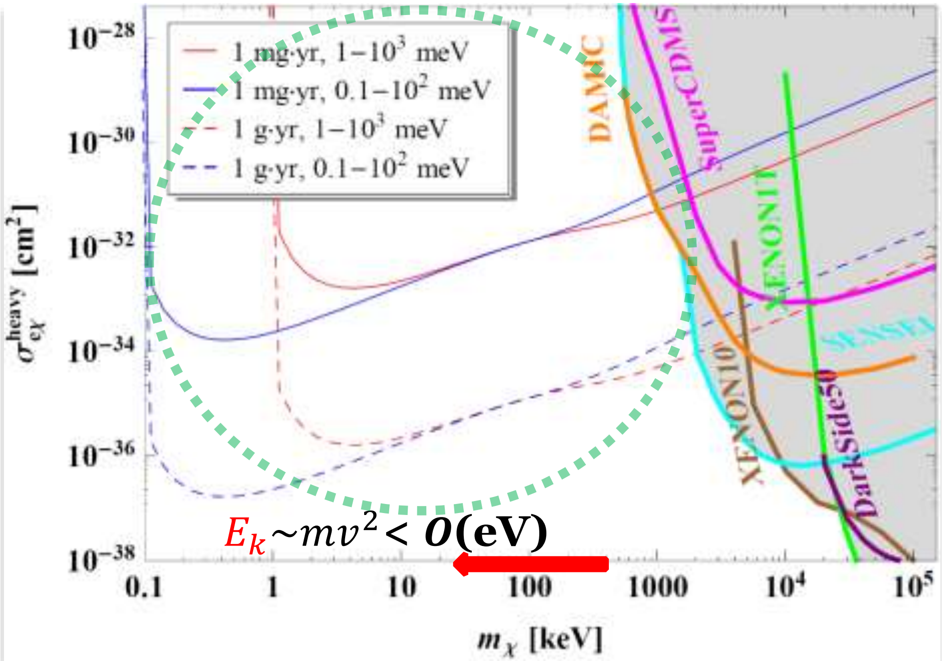
Light mediator: $F_{DM} \propto 1/q^2$ with $q_{\mathrm{ref}} = \alpha_e m_e$



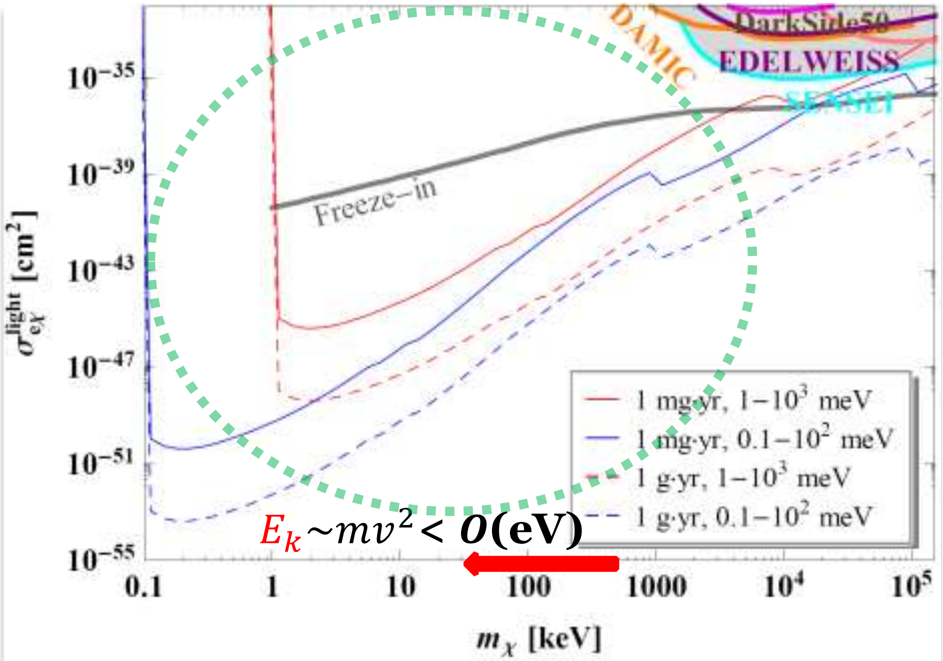
- ✓ The **proposed detector** can improve the minimum detectable DM mass (**$m_{DM} \sim 0.1$ keV**) by more than 3 orders of magnitude over the ongoing/existing experiments.
- ✓ **Capable of probing** the prediction of **freeze-in** scenarios even with a pg-scale detector.

Expected Sensitivities: (Far) Future

Heavy mediator: $F_{DM} = 1$



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



✓ **Capable of fully probing** the prediction of **freeze-in** scenarios with $\boldsymbol{m_{DM}} < \textbf{O(GeV)}$.

✓ **Great search prospect** even for **sub-keV DM**.

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 incident 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 GJJs & fabrication of GJJ array is in progress.

Thank you