

Searching for Super-Light Dark Matter with a Graphene Josephson Junction Detector

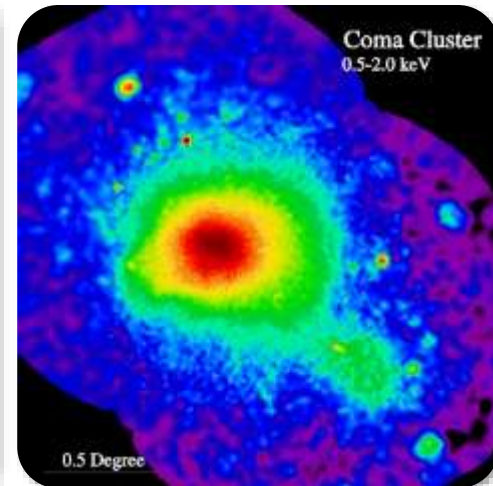
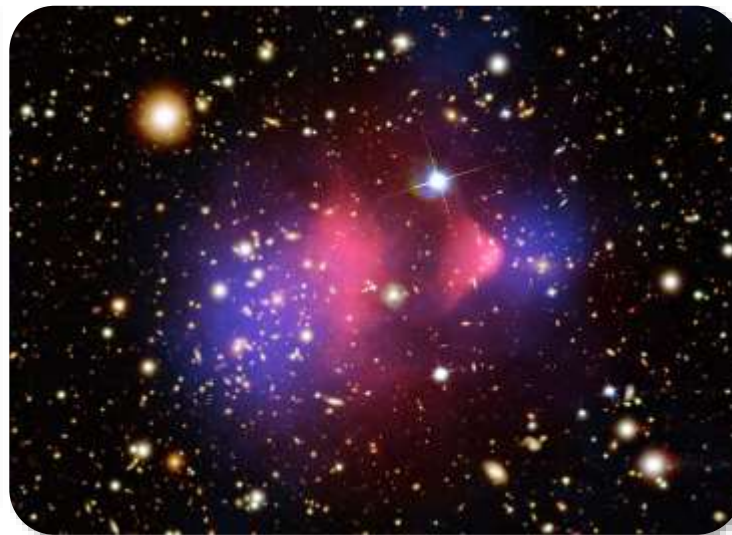
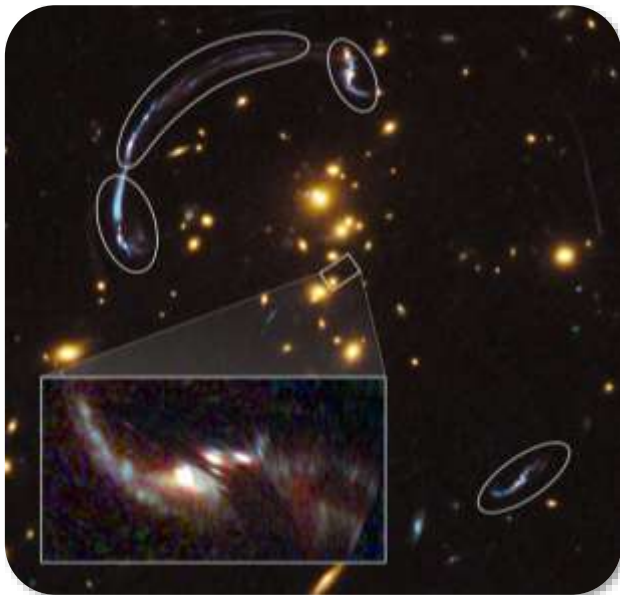
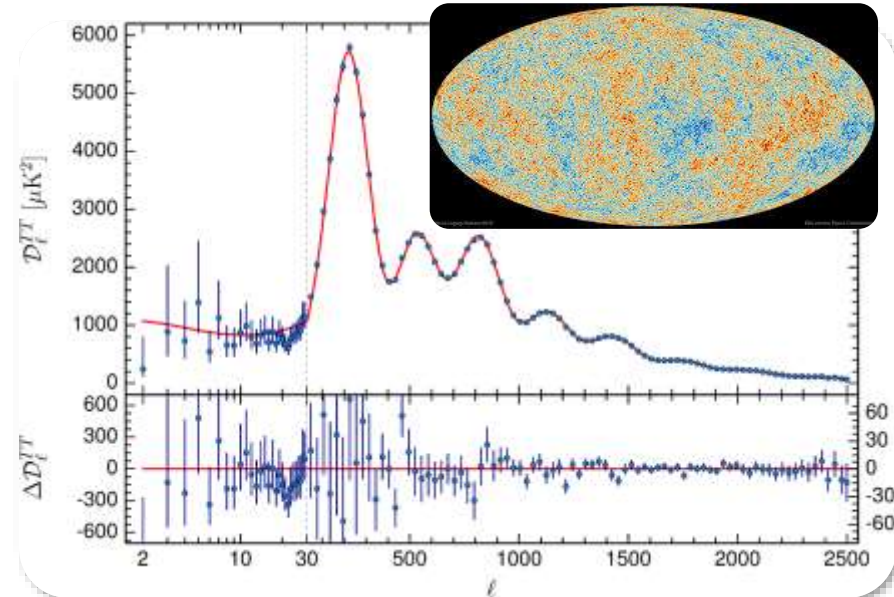
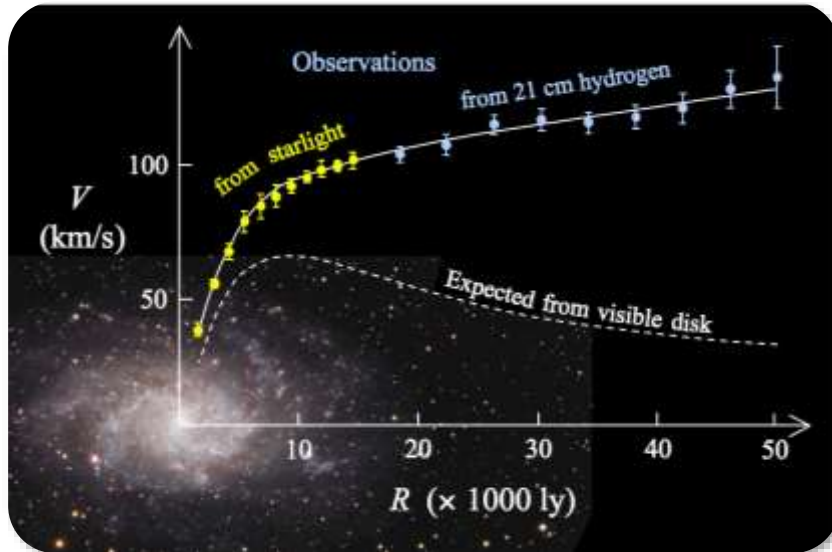
with D. Kim, K.C. Fong & G.-H. Lee [arXiv: 2002.07821]

Jong-Chul Park



Dark World to Swampland
October 16 (2020)

Observational Evidence for DM



**Dark
Matter?**



Classic Solution*: WIMP

Cosmological Lower Bound on Heavy-Neutrino Masses

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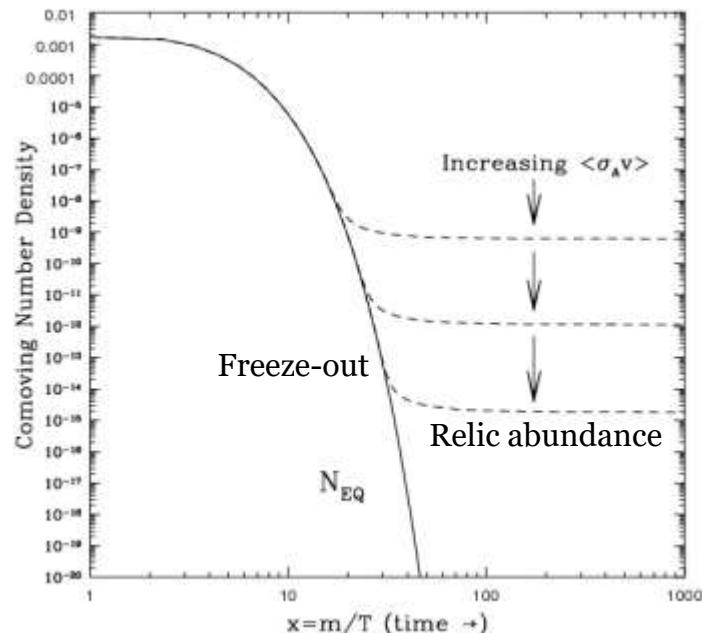
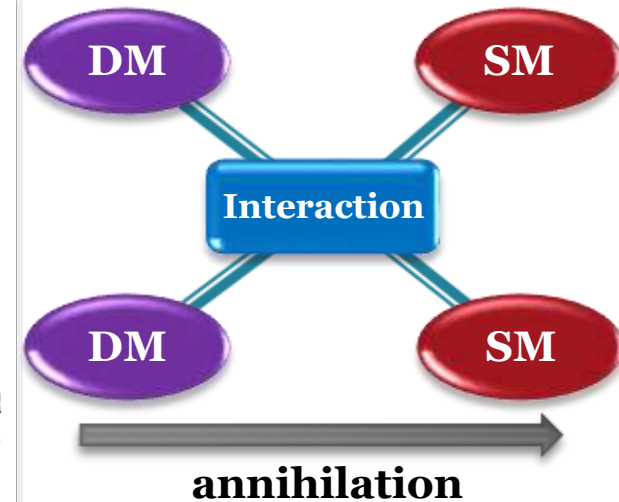
and

Steven Weinberg^(c)

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 $2 \times 10^{-29} \text{ g/cm}^3$, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.



- Correct thermal relic abundance:

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

- Weak coupling ➔ **naturally** weak scale mass:

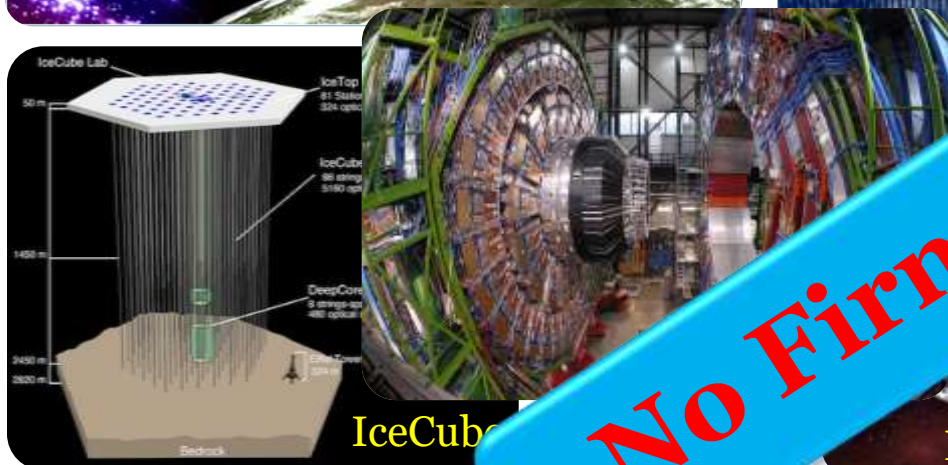
~1 GeV – 10 TeV mass range favored

➔ **weak scale (new) physics**

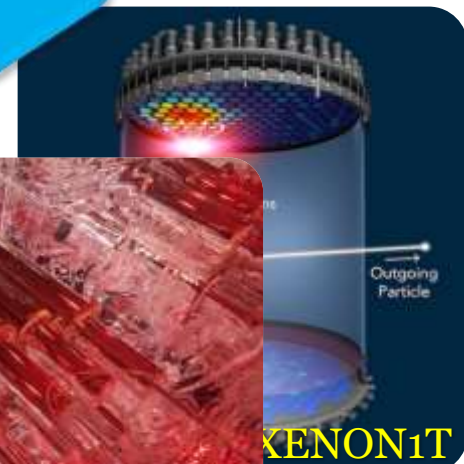
Of course, axion is another classic solution.

(Luca Visinelli's talk)

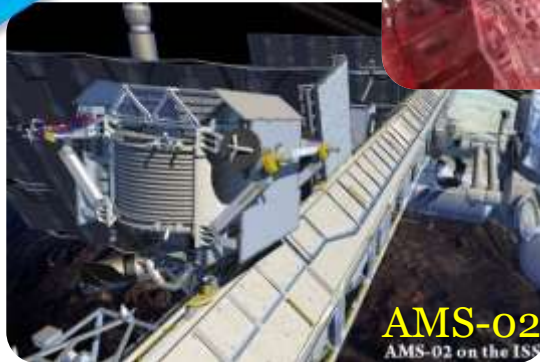
Diverging Efforts for WIMP Searches



Planck



COSINE-100

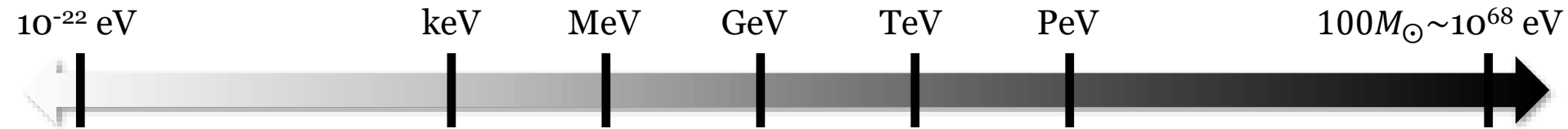


**Only
WIMP?**

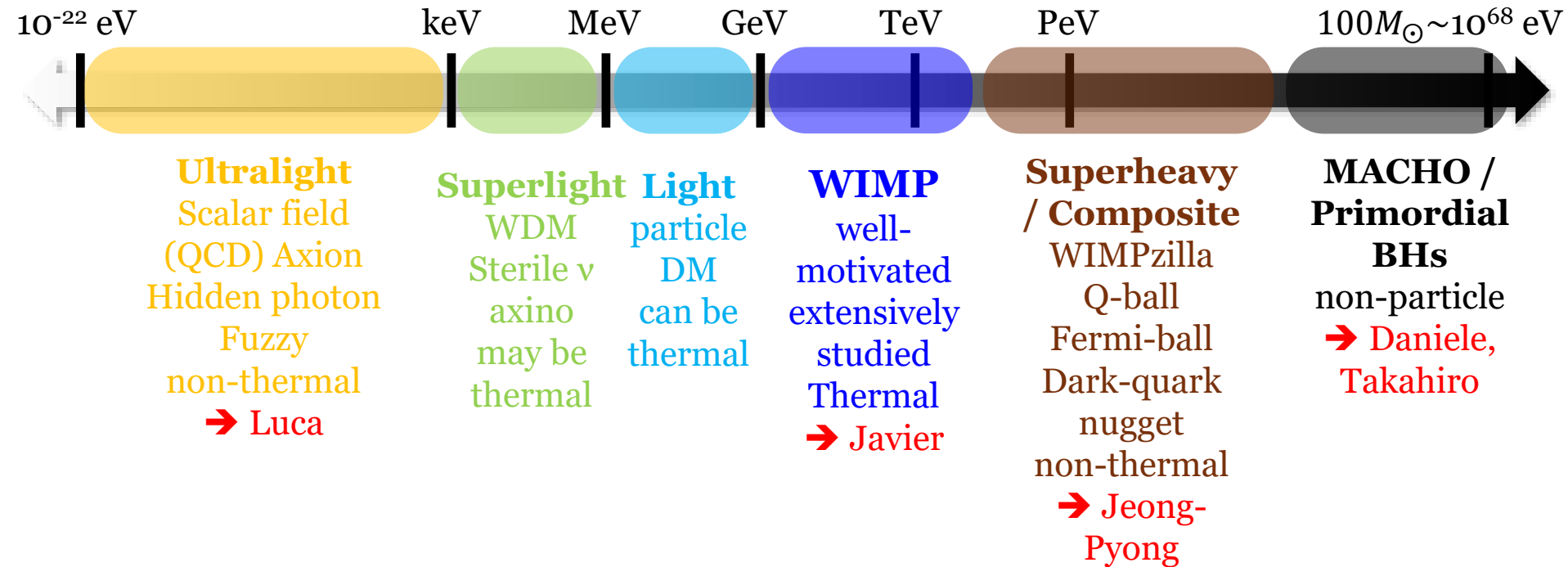
No!



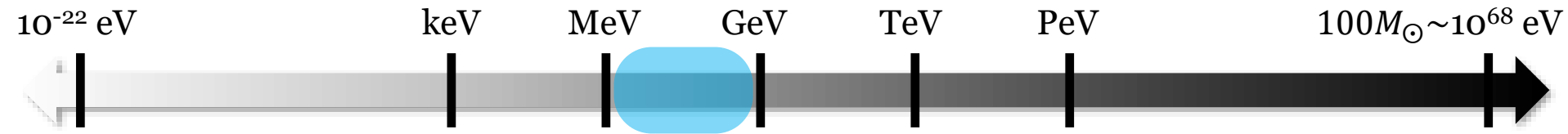
DM Landscape: A Very Wide Mass Range



DM Landscape: A Very Wide Mass Range



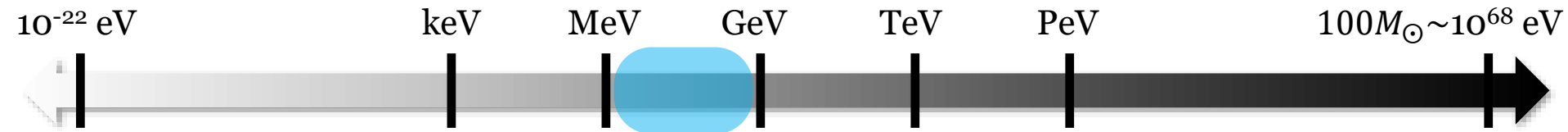
Light DM Sector



Light
particle
DM

- ❖ For heavy mediator, $\langle\sigma v\rangle \sim \frac{\alpha_X^2 m_\chi^2}{M^4}$
- ❖ For **weak scale** physics,
 - sub-GeV DM overproduction**
 - ➔ New mediator $< M_W$ for freeze-out or **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



- ❖ $E_k \sim mv^2 < \mathcal{O}(\text{keV})$ with $v \sim 10^{-3}$: **Light particle DM**
 $< E_r^{th}$ 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]

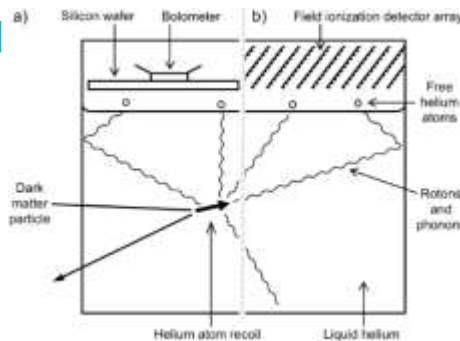
- ✓ Ejection of e's (graphene, C-nanotube)

[arXiv:1606.08849, 1706.02487, 1808.01892]

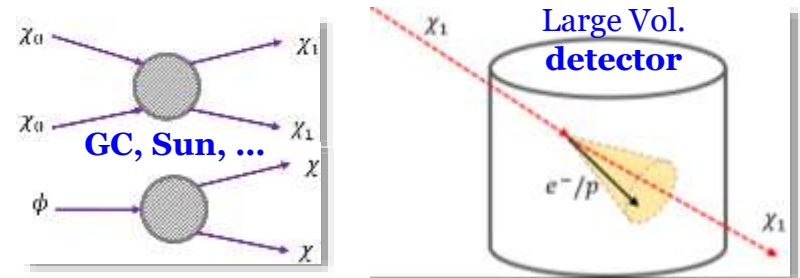
- ✓ Evaporation of He by nuclear-recoils

[arXiv:1706.00117]

- ✓ ...

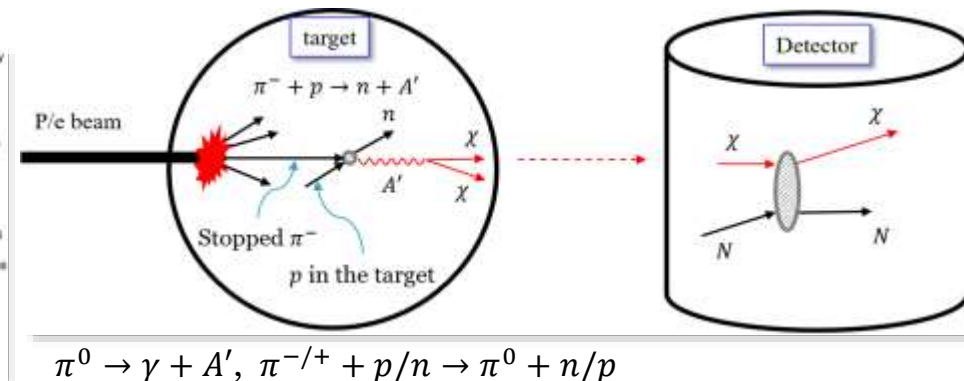


- ❖ Cosmogenic boosted DM searches: COSINE-100, DUNE/ProtoDUNE, IceCube, SK/HK/KNO, ...



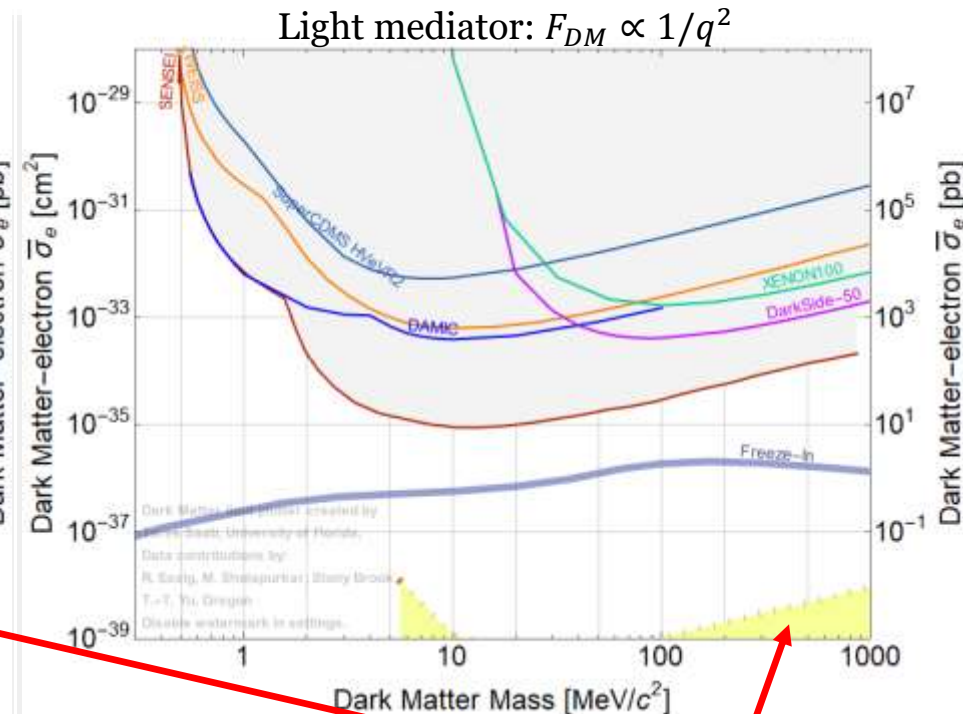
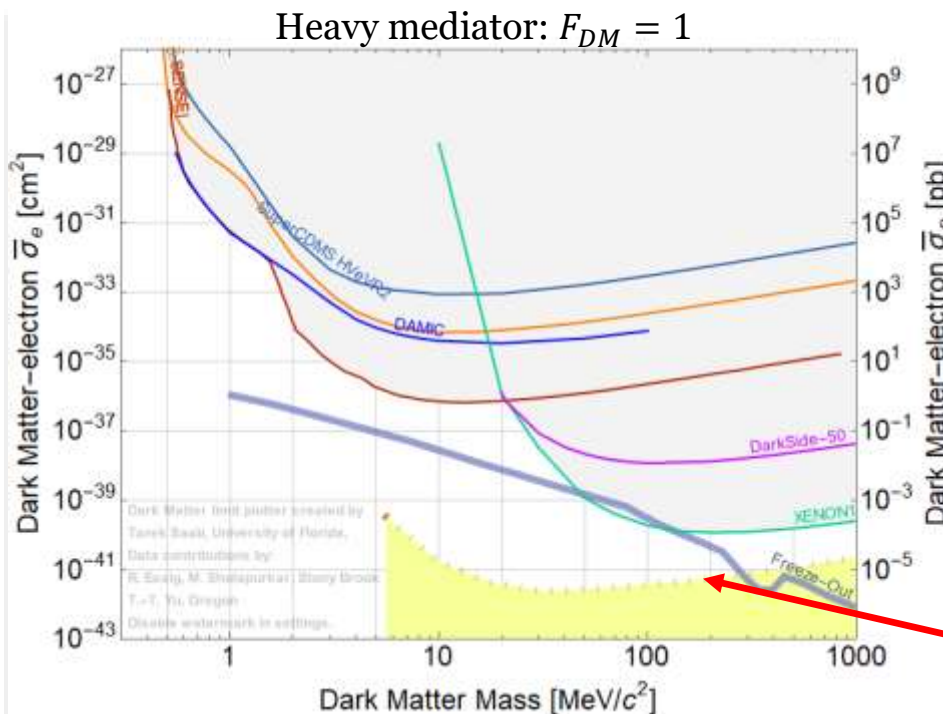
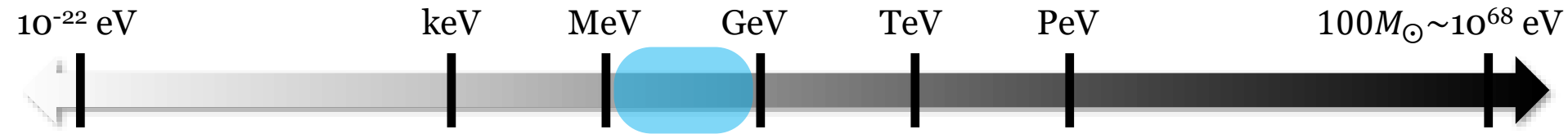
- ❖ Beam-produced light DM/mediator searches:

Babar, BDX, Belle-II, CCM, COHERENT, DUNE, FASER, JSNS², LDMX, MATHSULA, NA64, SeaQuest, SHiP, ...



$$\pi^0 \rightarrow \gamma + A', \pi^-/+ + p/n \rightarrow \pi^0 + n/p$$

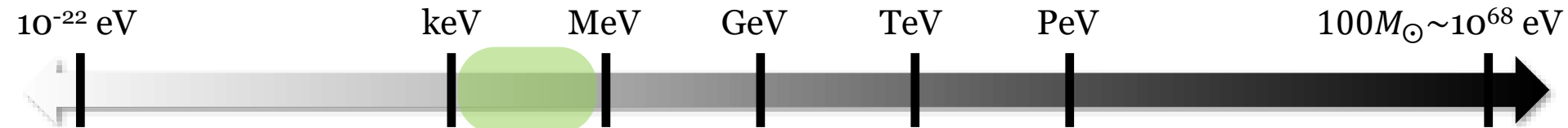
Light DM: Direct Search Current Status



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

ν BG for a Xe target (1t-yr)

Super-Light DM: Main Focus



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](#)]

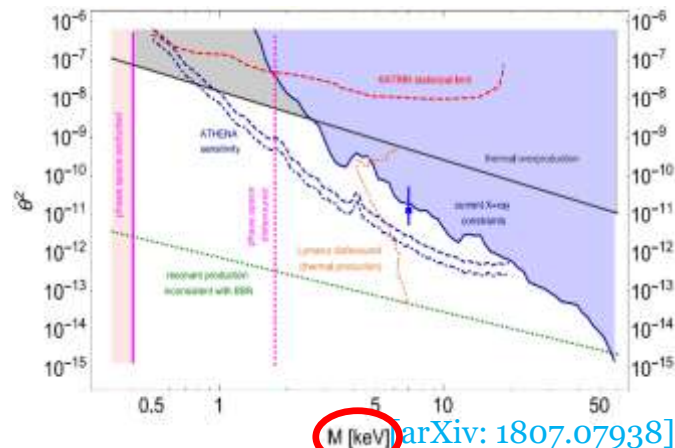
✓ Super-light dark gauge bosons

[[arXiv:1105.2812](#), [1201.5902](#)]

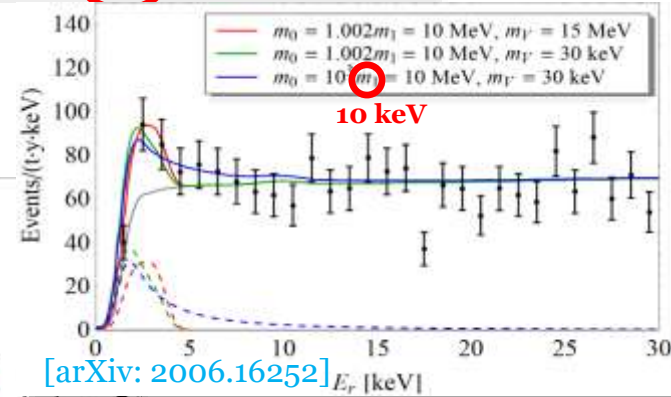
✓ Decaying DM for 3.5 keV line

[[arXiv:1403.1536](#), [1508.06640](#)]

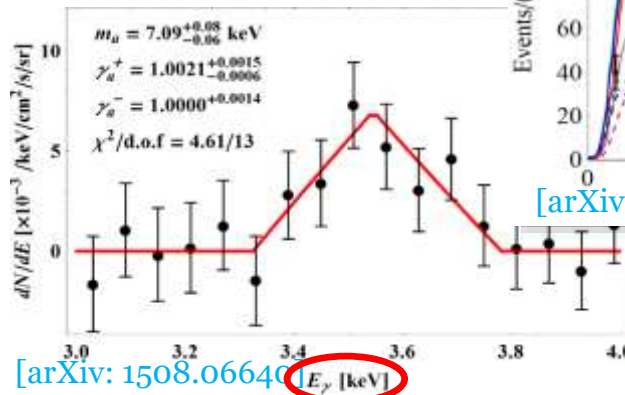
✓ keV DM for XENON1T, ...



[[arXiv: 1807.07938](#)]

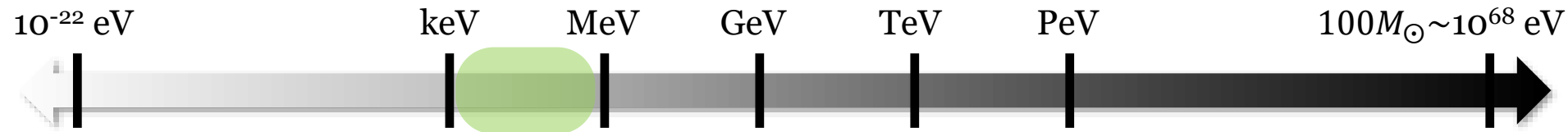


[[arXiv: 2006.16252](#)]



[[arXiv: 1508.06640](#)]

Super-Light DM: Main Focus



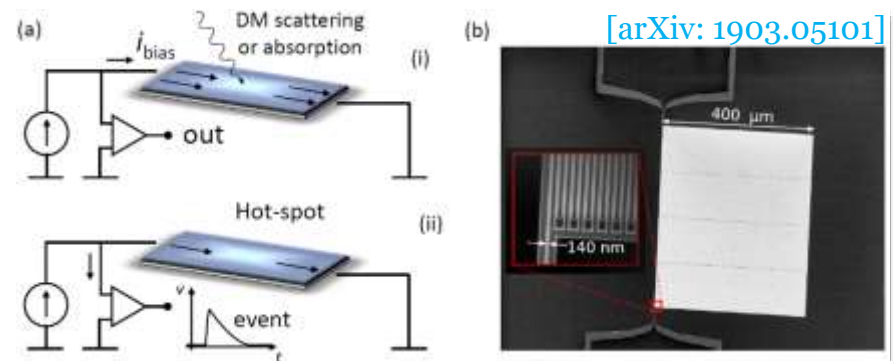
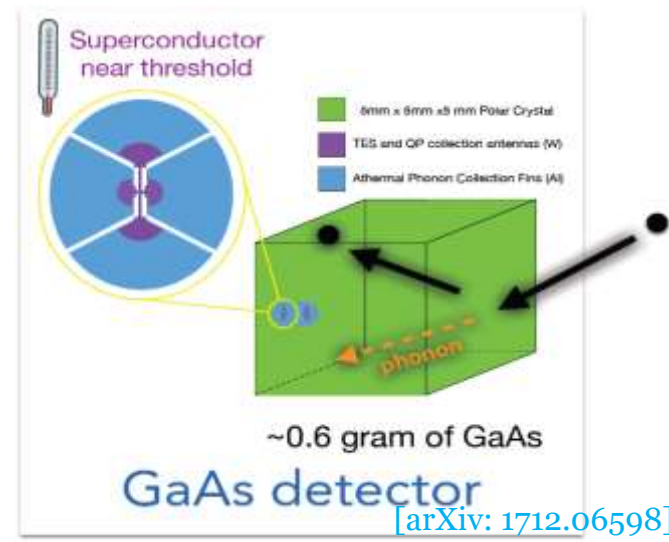
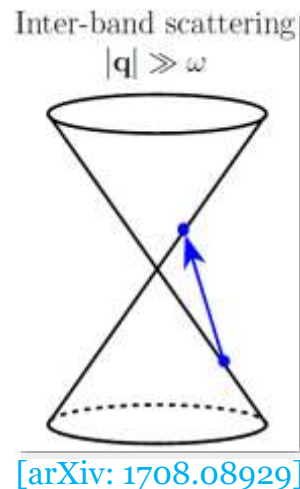
❖ $E_k \sim mv^2 < 0(\text{eV})$

**Superlight
DM**

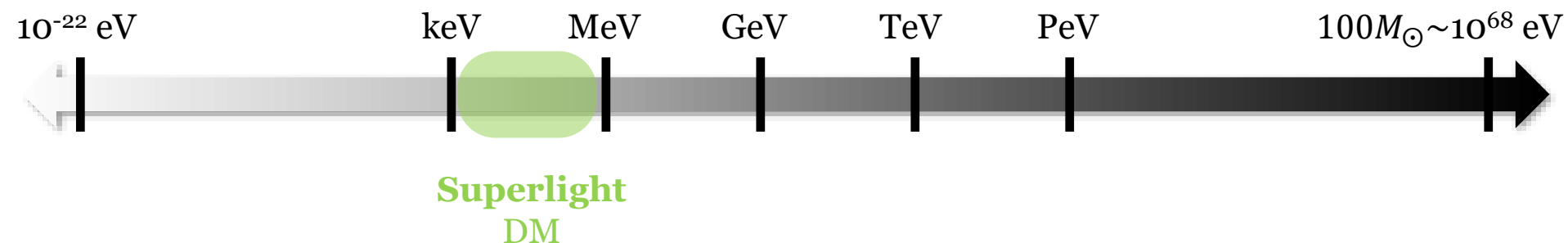
➔ Very low E_r^{th} required!

❖ 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]
- ✓ ...



Super-Light DM: Technologies



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

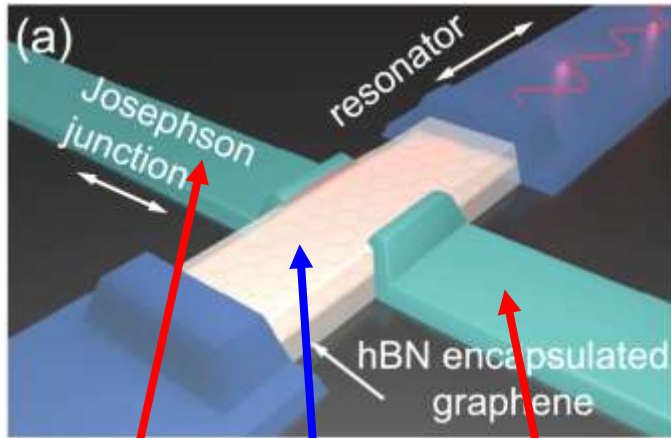
Well-developed in the laboratory in their respective E-bands.

But for the sensitivity to $E_{th} \lesssim \text{meV}$, 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 $E_{th} \sim O(0.1 \text{ meV})$

Graphene Josephson Junction Device

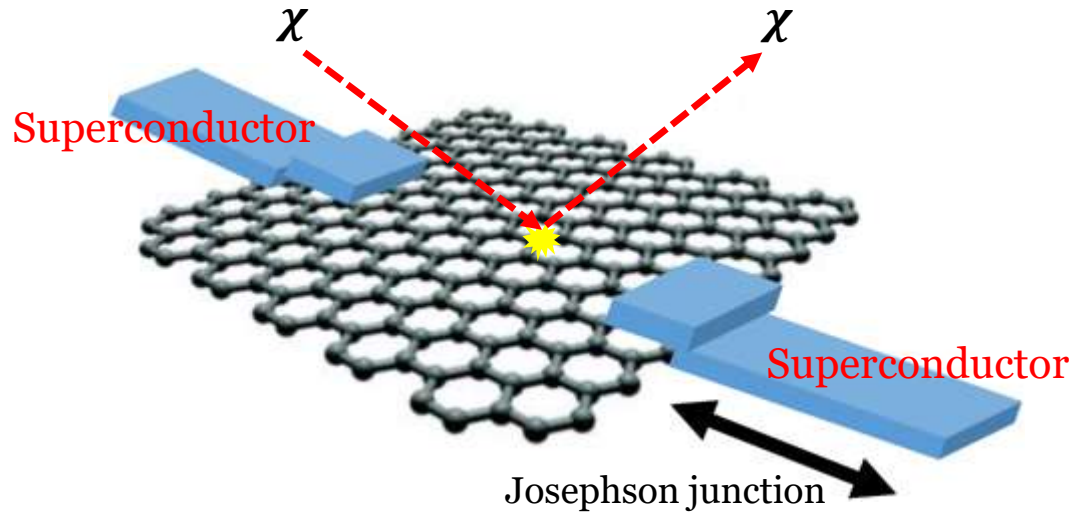


Superconductor-Graphene-Superconductor (SGS)

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 $E \sim 0.1$ meV energy deposit**. [Nature (2020)]
- ❖ Currently, a GJJ single-photon detector is **under testing** in the laboratory.

Detection Principle

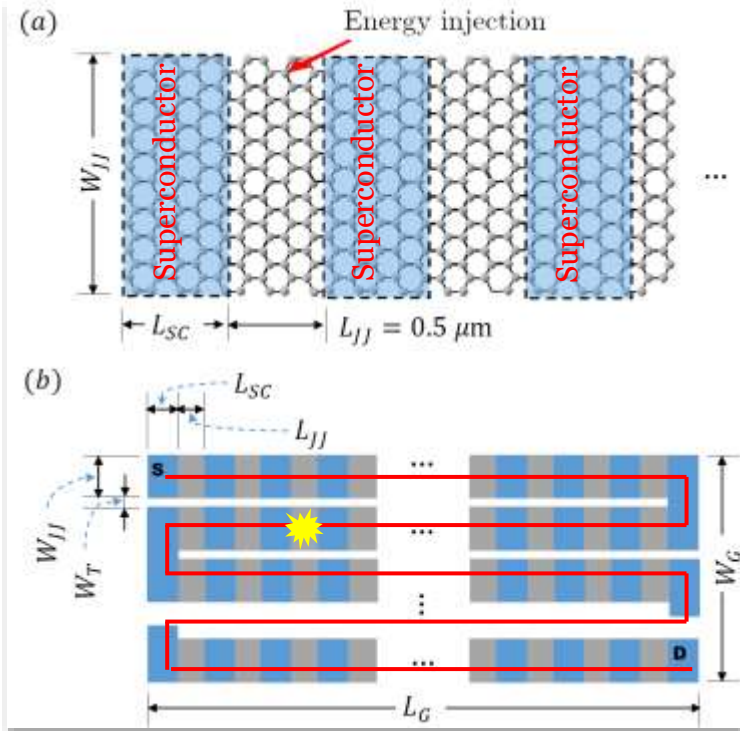


- I. DM scatters off (π -bond) free electrons, transferring some fraction of its incoming E_k .
- II. The recoiling e heats up & thermalizes with nearby e's rapidly via e-e interactions.
- III. The JJ is triggered: the temperature rise switches the zero-voltage of JJ to resistive state.

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

→ The GJJ device can possess 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 \rightarrow 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} : $W_{JJ} = 3 \mu\text{m}$ ($30 \mu\text{m}$) $\rightarrow E_{th} \approx 0.1 \text{ meV}$ (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.**
- ❖ We will calculate the **number of events/unit detector mass/unit run time**:

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

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

Calculation Procedure I

$$\begin{aligned} \diamond n_{\text{eve}} &= \frac{N_{\text{eve}}^{\text{total}}}{M_T t_{\text{run}}} = \frac{1}{M_T t_{\text{run}}} \int_{E_r > E_{\text{th}}} dE_r \frac{dN_{\text{eve}}}{dE_r} \\ &= \frac{1}{M_T t_{\text{run}}} \int_{E_r > E_{\text{th}}} \int dE_r dv_{\chi} f_{\text{MB}}(v_{\chi}) \frac{d}{dE_r} N_e \sigma_{e\chi} v_{\text{rel}} \frac{\rho_{\chi}}{m_{\chi}} t_{\text{run}} \end{aligned}$$

$$\begin{aligned} \checkmark N_{\text{eve}}^{\text{total}} &= n_{\text{eve}} M_T t_{\text{run}} \\ \checkmark N_{\text{eve}} &= N_e \sigma_{e\chi} \Phi_{\chi} t_{\text{run}} \\ \checkmark \Phi_{\chi} &= n_{\chi} v_{\text{rel}} \ \& \ n_{\chi} = \rho_{\chi} / m_{\chi} \end{aligned}$$

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

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

2D nature of
graphene

$$\begin{aligned} \checkmark \frac{N_e}{M_T} &= \frac{N_e/V}{M_T/V} = \frac{n_e^{3\text{D}}}{\rho_T^{3\text{D}}} \\ &= \frac{N_e/(A\Delta l)}{M_T/(A\Delta l)} = \frac{n_e^{2\text{D}}}{\rho_T^{2\text{D}}} \end{aligned}$$

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

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

$$\begin{aligned} \checkmark f_{e,i}(E_{e,i}) &= 1 / \left\{ 1 + \exp\left(\frac{E_{e,i} - \mu}{T}\right) \right\}, \ (\mu \sim E_F) \\ &\rightarrow \text{Fermi-Dirac distribution function} \end{aligned}$$

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

Calculation Procedure II

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

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

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

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

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

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

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

→ 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

[\[astro-ph/9710115, 1512.04533\]](#).

Calculation Procedure III

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

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

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

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

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

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

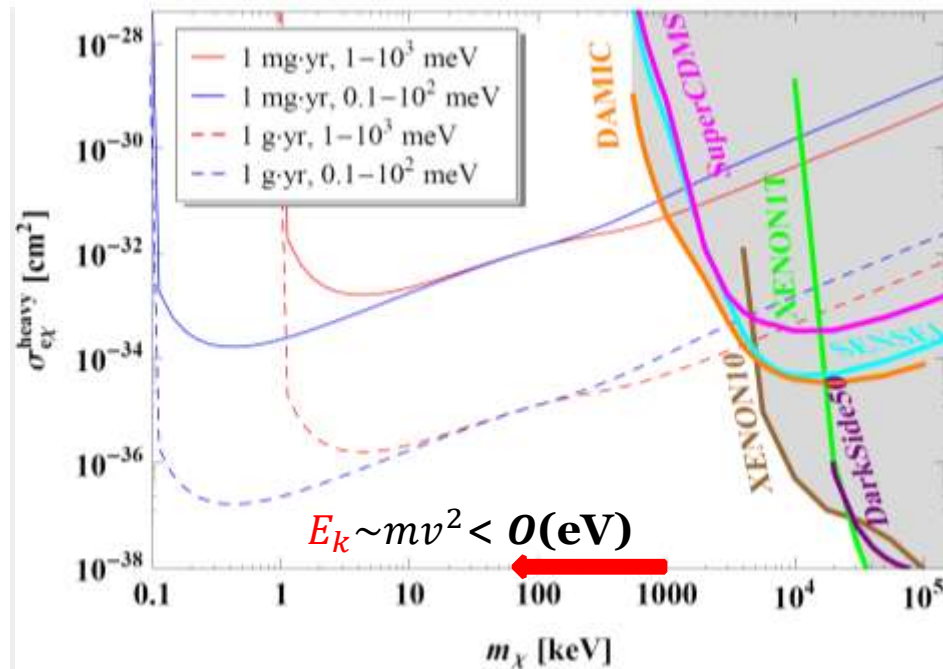
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{(m_\phi^2 + q^2)^2} \rightarrow \sigma_{e\chi}^{\text{heavy}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2) \text{ \& } \sigma_{e\chi}^{\text{light}} \approx \frac{g_e^2 g_\chi^2}{\pi}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

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

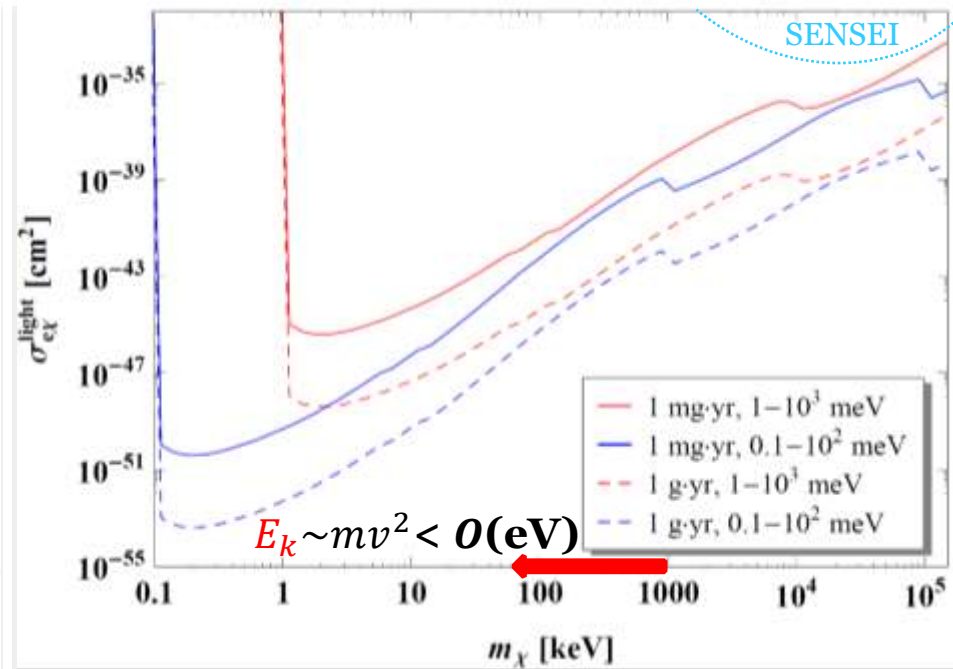
- ❖ From the **linear dispersion of graphene**: $E_F = v_F \sqrt{\pi n_c}$ with $v_F \sim 10^8 \text{ cm/s}$ & $n_c \sim 10^{12} / \text{cm}^2$.

Expected Sensitivities

Heavy mediator: $F_{DM} = 1$



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



- ✓ We **required** $N_{eve}=3.6$ under the negligible background assumption.
- ✓ The proposed GJJ DM detector can improve the **minimum detectable DM mass** ($m_{DM} \sim 0.1$ keV) by **more than 3 orders of magnitude** over the ongoing/existing experiments.
- ✓ Even capable of **probing sub-keV DM with great expected reaches**.

Future Plans & Conclusions

- 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 $E_{\text{th}} \sim 0.1 \text{ meV}$. ➔ Improving the minimum detectable DM mass ($m_{\text{DM}} \sim 0.1 \text{ keV}$) by more than 3 orders of magnitude.

We are planning to do the First Experiment with the Existing GJJ Device samples.

Thank you