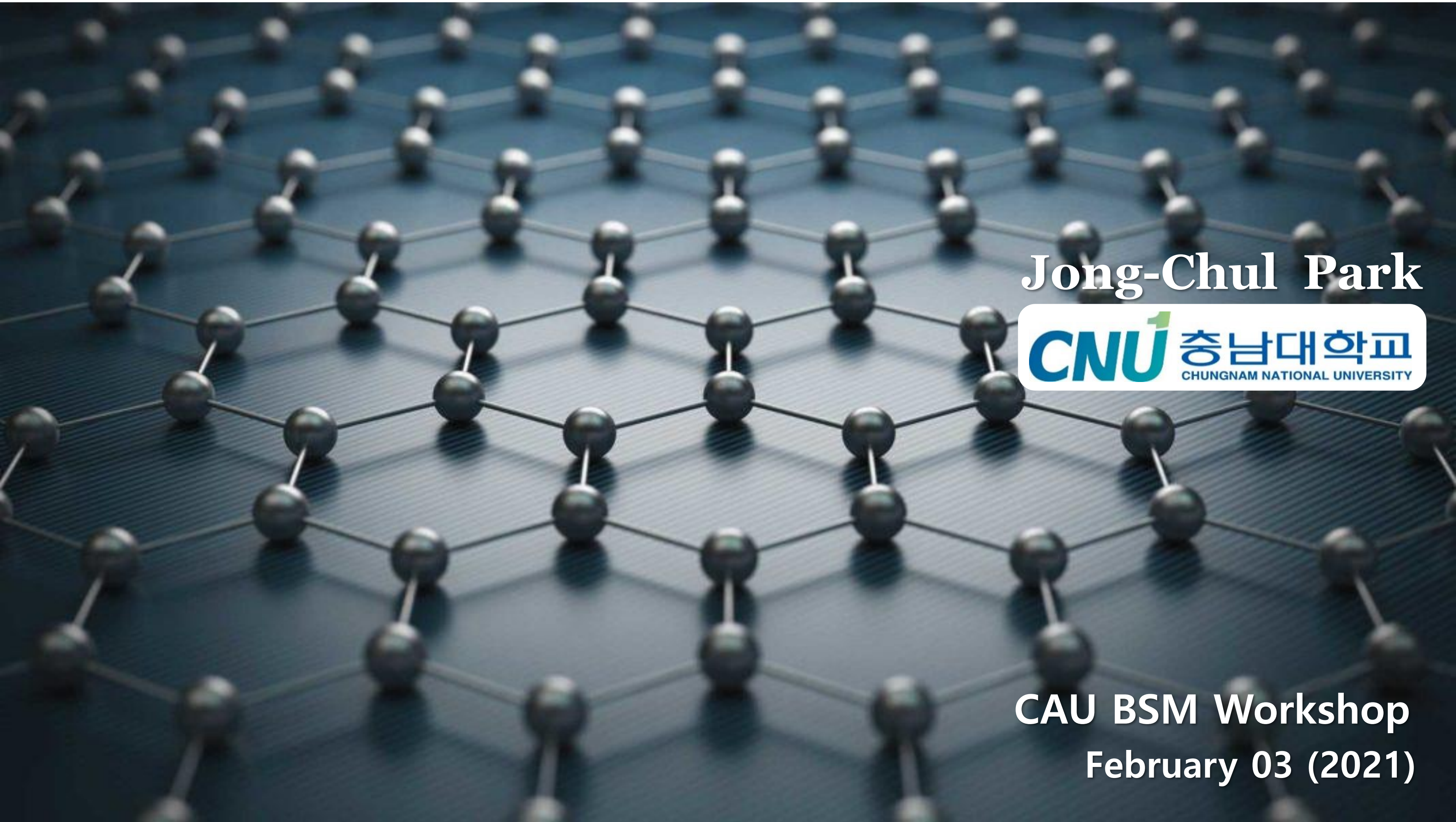
Detecting Super-Light Dark Matter with Graphene Josephson Junction

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



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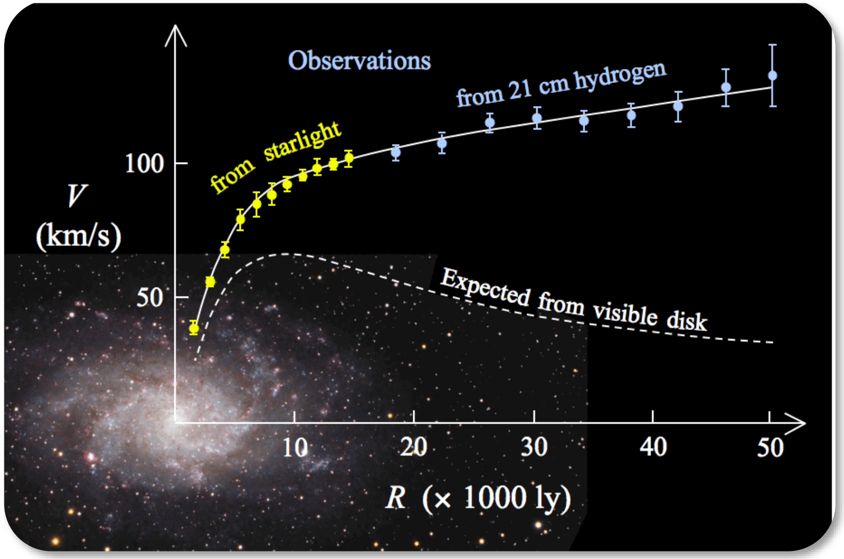
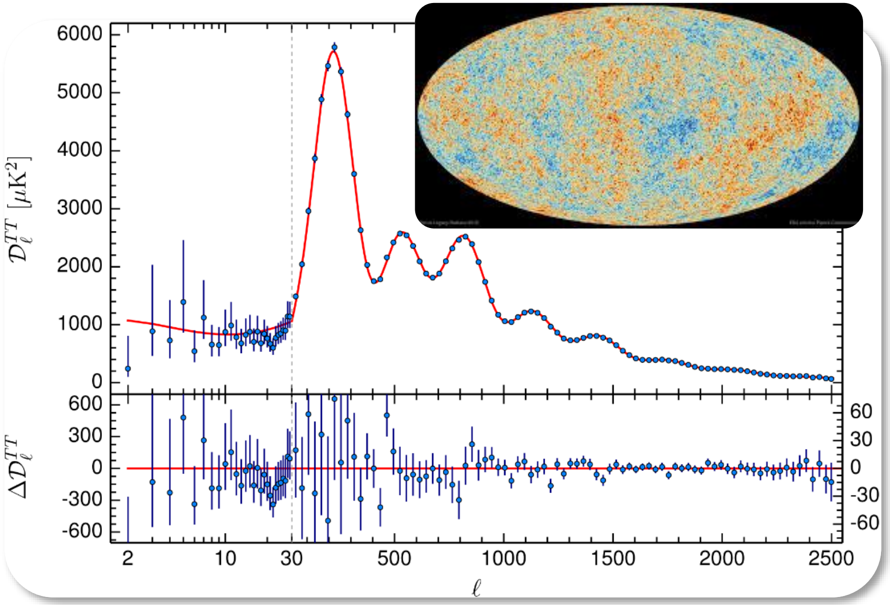
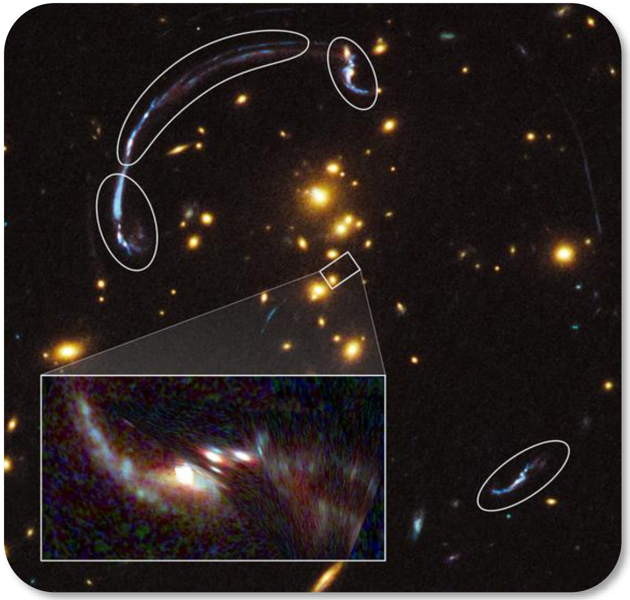
CHUNGNAM NATIONAL UNIVERSITY

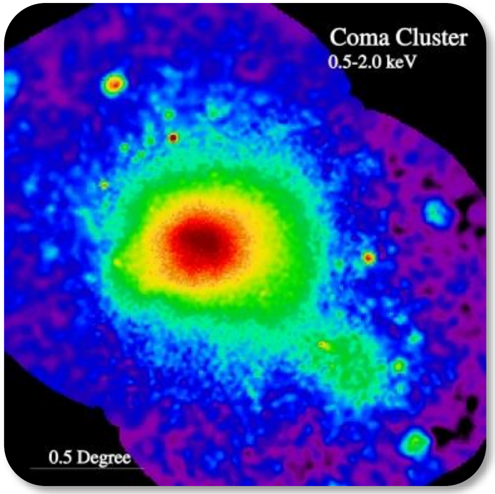
CAU BSM Workshop
February 03 (2021)

Observational Evidence for DM



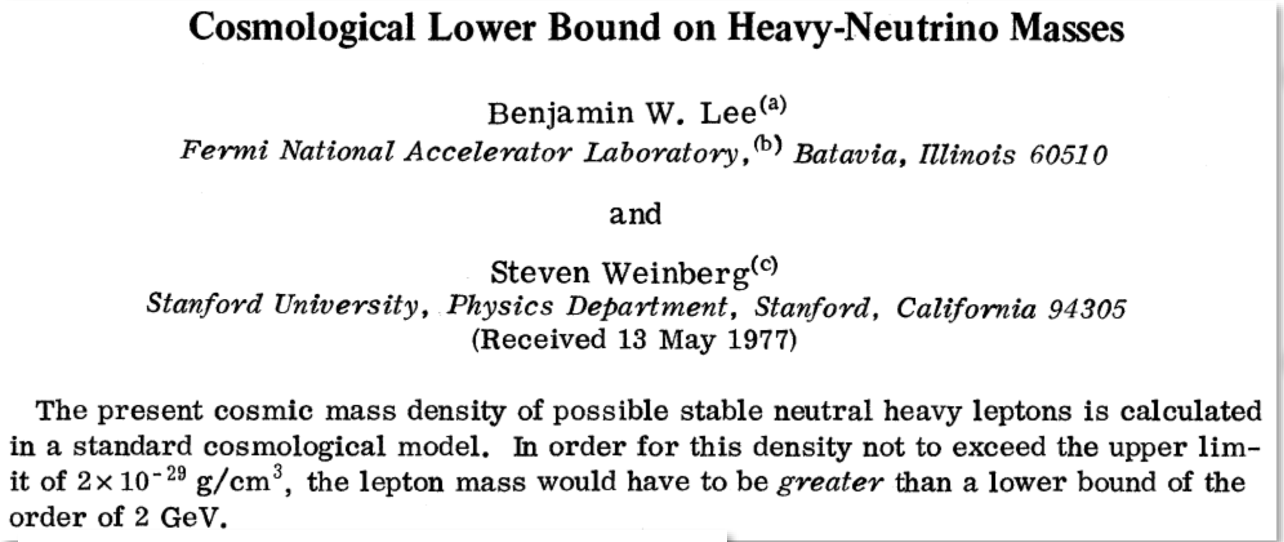






Dark
Matter?

Classic Solution*: WIMP



Cosmological Lower Bound on Heavy-Neutrino Masses

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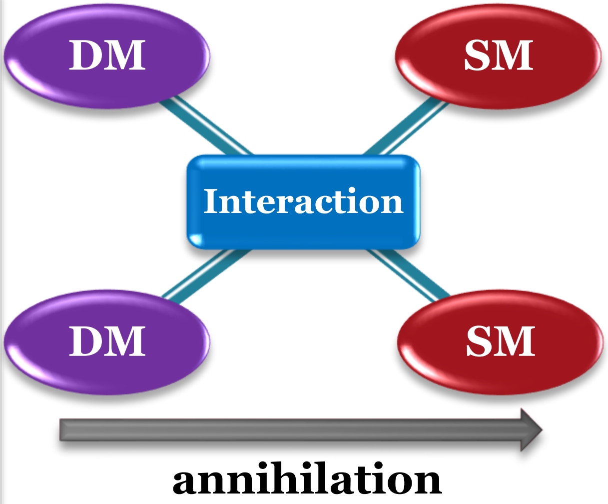
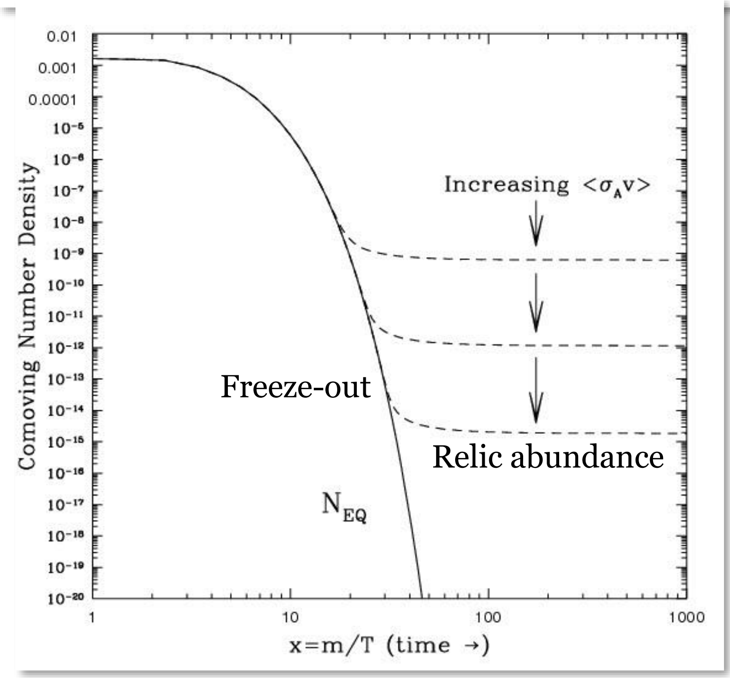
and

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 2×10^{-29} 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:

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

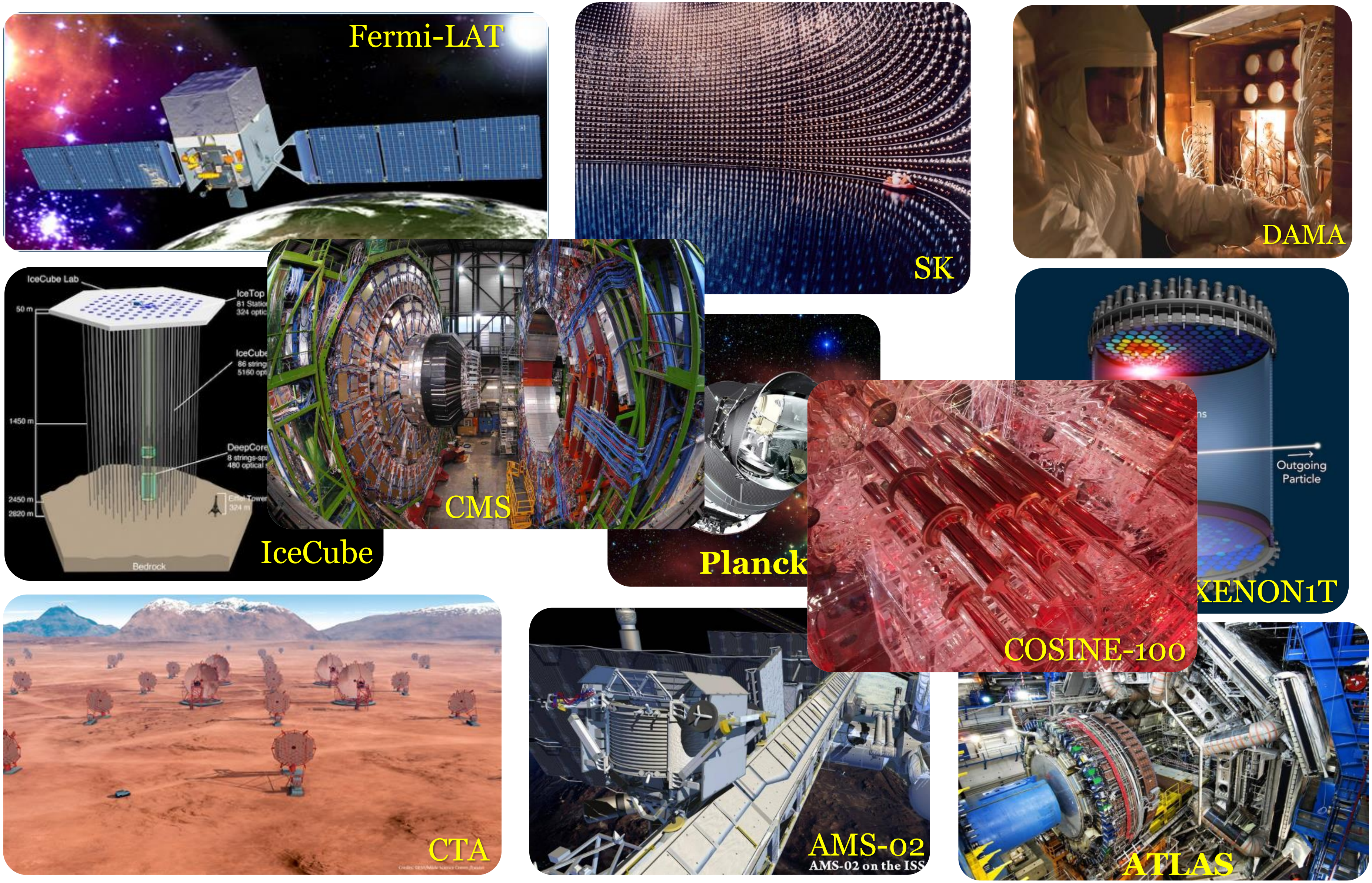
- Weak coupling ➔ naturally weak scale mass:

~1 GeV – 10 TeV mass range favored

➔ weak scale (new) physics

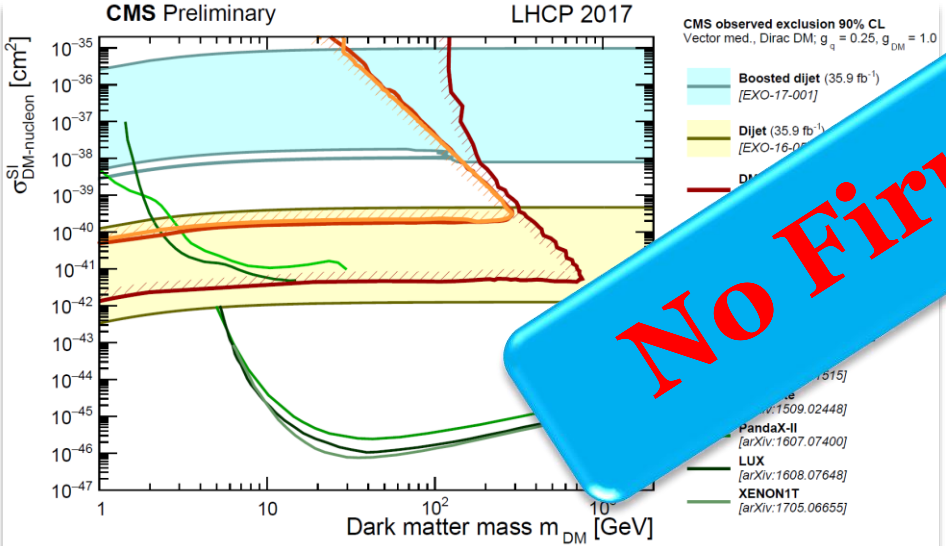
Of course, **axion** is another classic solution.

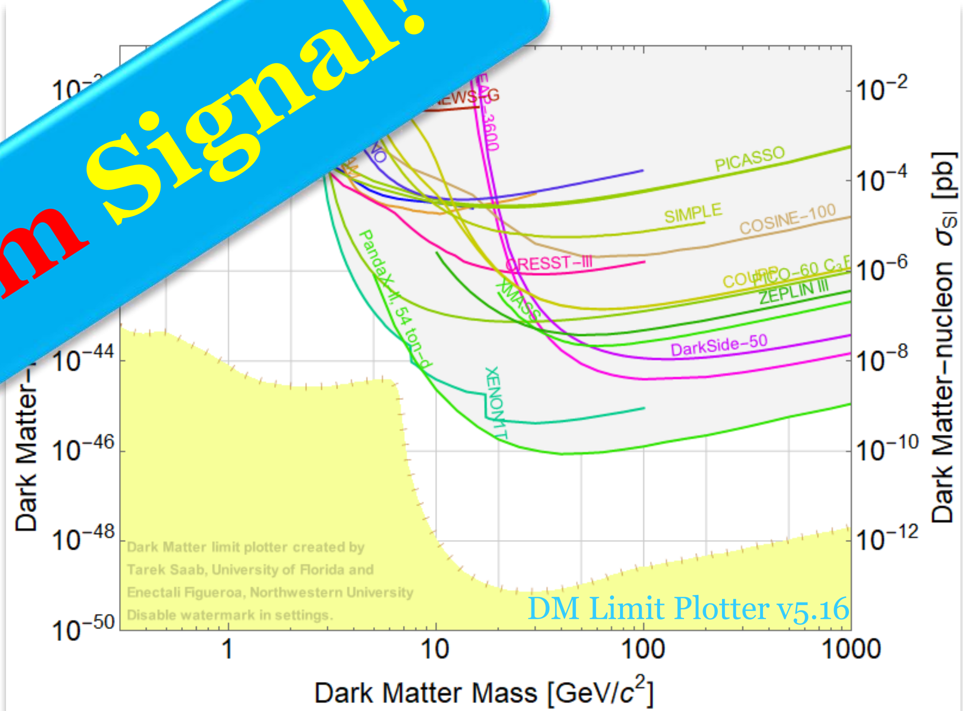
Diverging Efforts for WIMP Searches



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



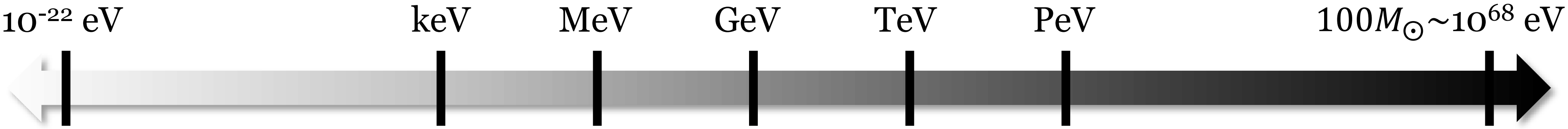


No Firm Signal!

Only WIMP?

No!

DM Landscape: A Very Wide Mass Range



10^{-22} eV

keV

MeV

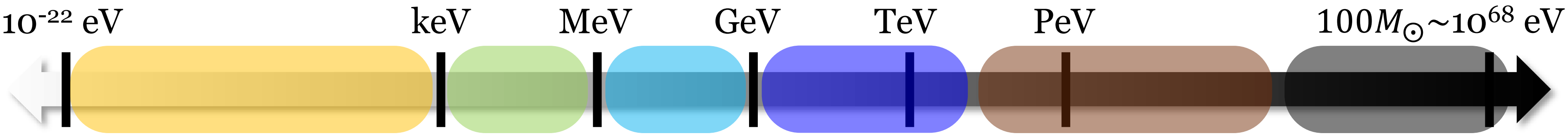
GeV

TeV

PeV

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

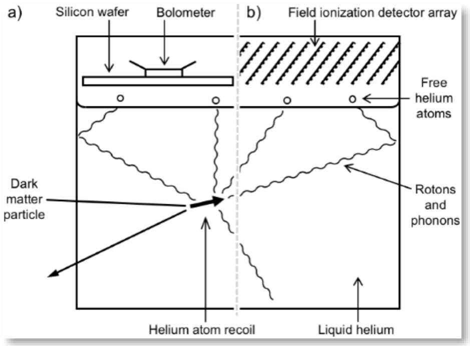
WIMP
well-motivated
extensively
studied
Thermal

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

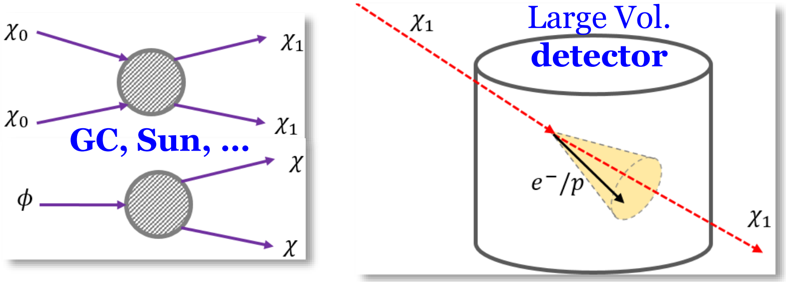
MACHO / Primordial BHs
non-particle

Light DM: Searches

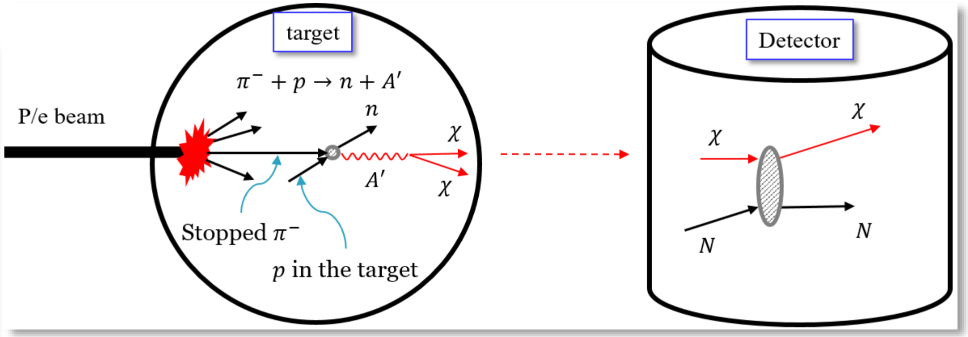
- ❖ $E_k \sim mv^2 < \mathcal{O}(\text{keV})$ with $v \sim 10^{-3}$: $< E_r^{th}$ of typical DM direct detectors for nuclear recoils
- ❖ New ideas for low E_r^{th} w/ e-recoil are required!
  - ✓ Ionization by e-recoils (semiconductor) [arXiv:1108.5383, 1509.01598]
  - ✓ Ejection of e's (graphene, C-nanotube) [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

10^{-22} eV

keV

MeV

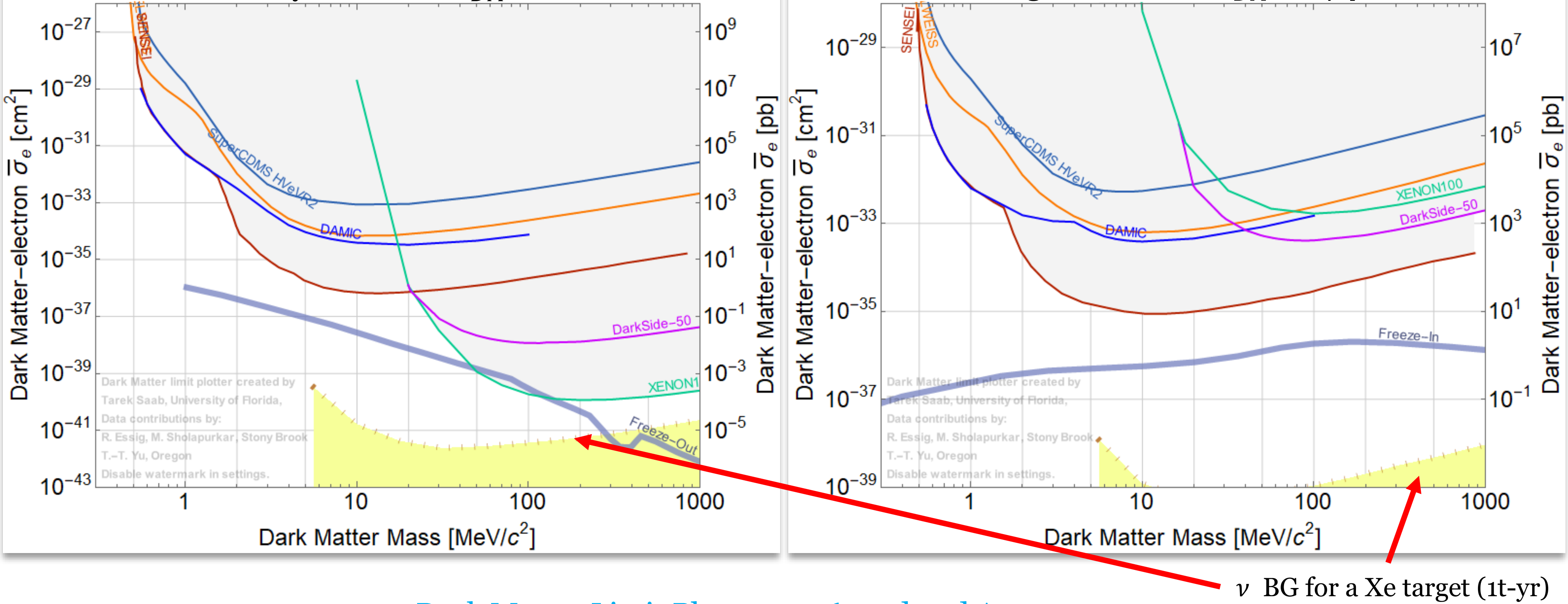
GeV

TeV

PeV

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

Light
particle
DM



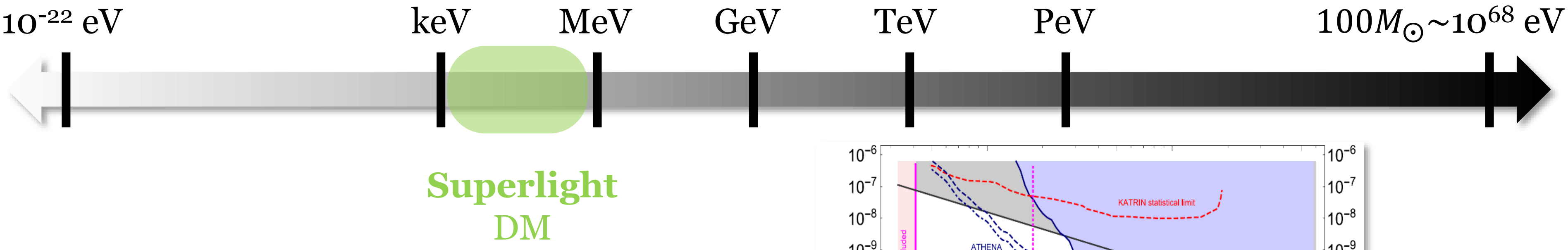
Heavy mediator: $F_{DM} = 1$

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

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

Superlight
DM

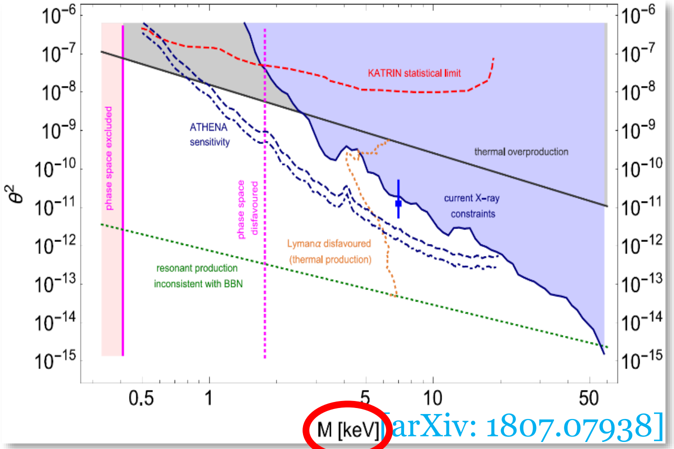
- ❖ Various well-motivated super-light DM pheno.:
  - ✓ Sterile neutrinos

    [hep-ph/9303287, astro-ph/9810076]
  - ✓ Mirror ν DM [hep-ph/9505385]
  - ✓ Axino/gravitino [arXiv: 0902.0769, 1407.0017]
  - ✓ Axion-like particles

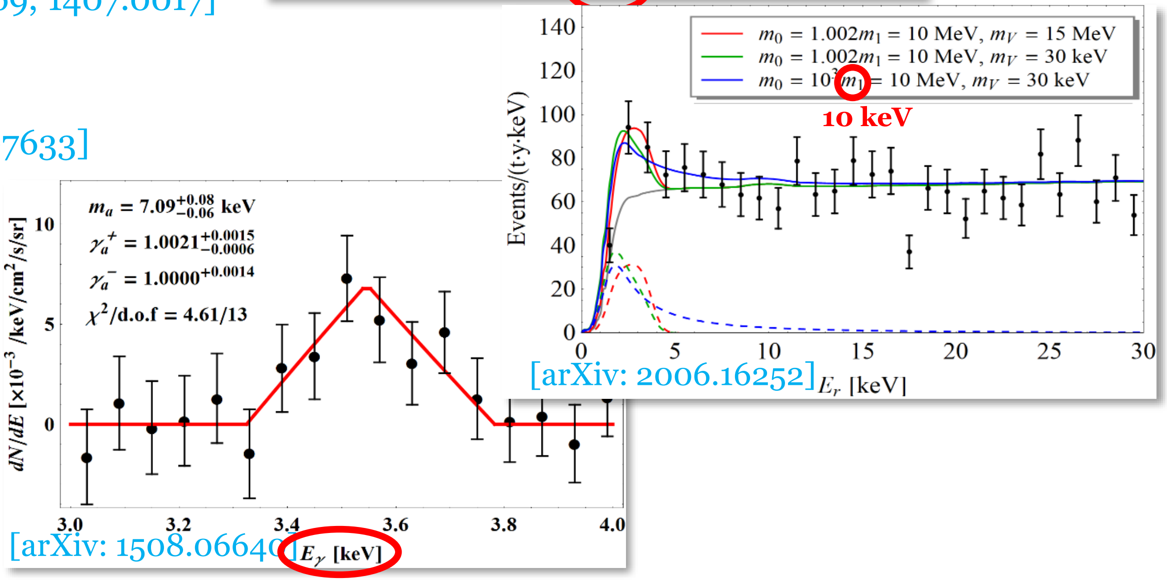
    [arXiv:0912.0015, 1407.0017, 1510.07633]
  - ✓ Super-light dark gauge bosons

    [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]

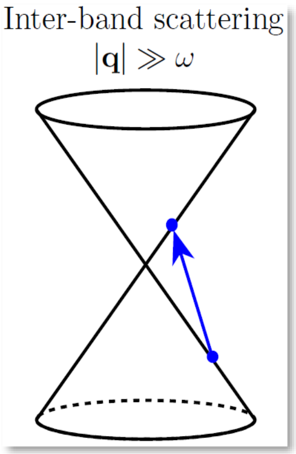
Super-Light DM: Search Ideas

Superlight DM

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

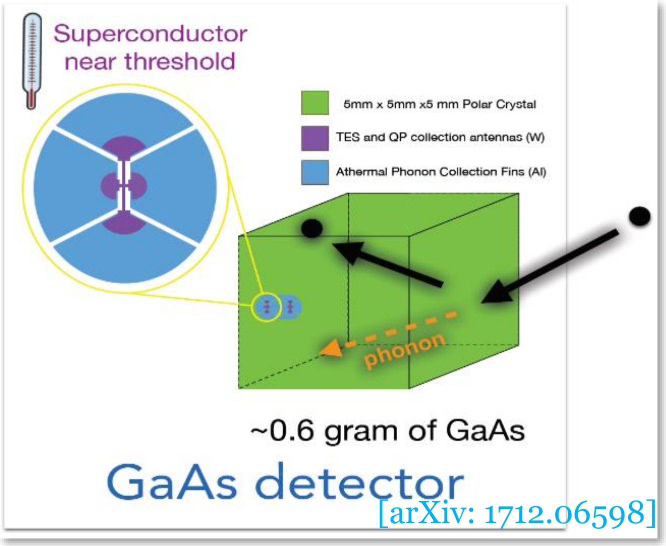
➔ Very low E_r^{th} required!

- ❖ 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]
  - ✓ …



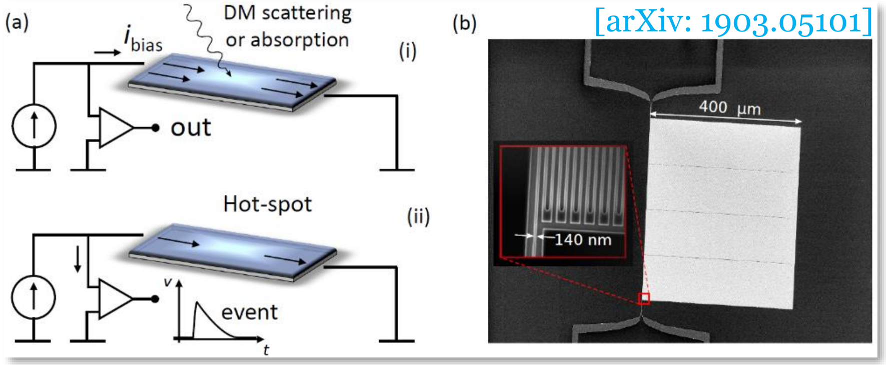
Inter-band scattering $|\mathbf{q}| \gg \omega$

[arXiv: 1708.08929]



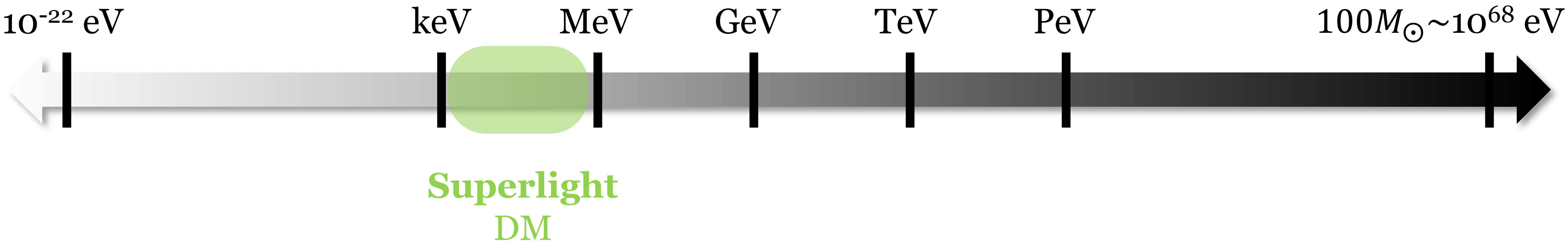
GaAs detector

[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)]

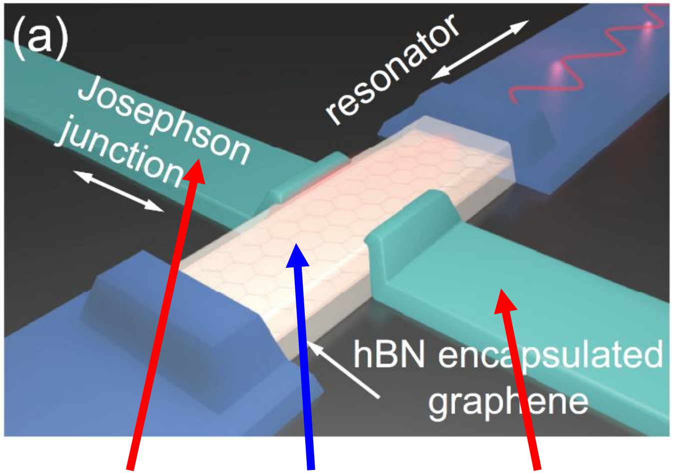
Well-developed in the laboratory in their respective E-bands.

But for the sensitivity to $E_{th} \lesssim O(10\text{ meV})$, 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 $E_{th} \sim O(0.1\ \mathrm{meV})$

Graphene Josephson Junction Device

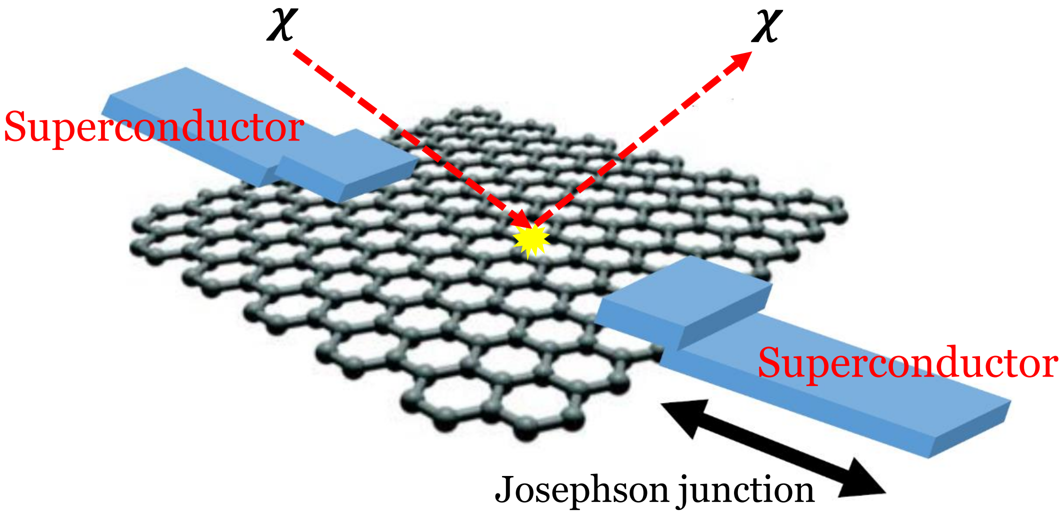


Superconductor-Graphene-Superconductor (SGS)

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 $E\sim 0.1$ 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.

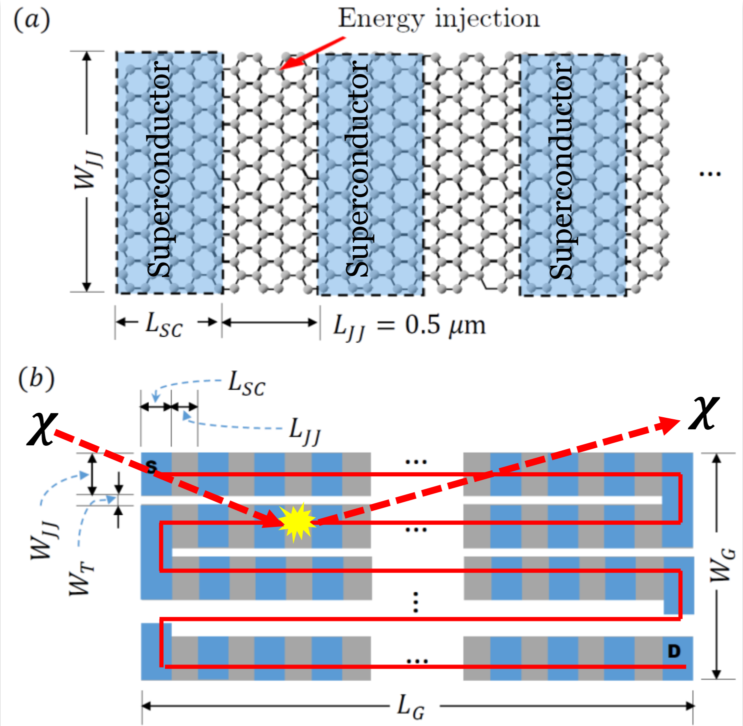
II. The recoiling e heats up & thermalizes with nearby e's rapidly via e-e interactions.

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

- $E_k \sim mv^2 \sim 1$ 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 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 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

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

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

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

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

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

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

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

2D nature of graphene

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

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

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

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

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

  ➔ 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: $S_{2\mathrm{D}}(E_r,\ q)$

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

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

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

➔ 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

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

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

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

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

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:

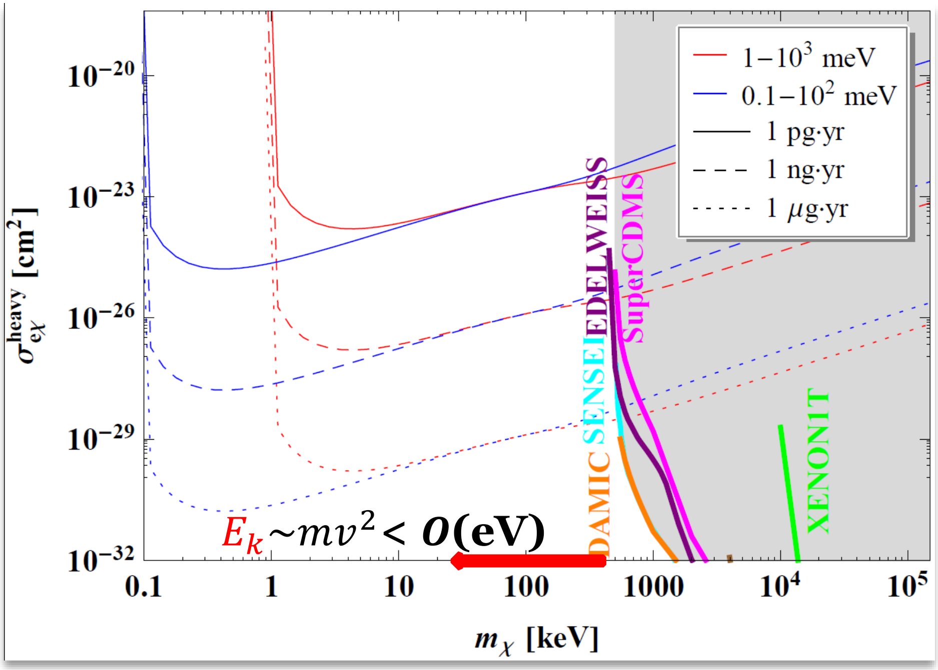
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{(m_\phi^2 + q^2)^2} \Rightarrow \sigma_{e\chi}^{\text{heavy}} \approx \frac{g_e^2 g_\chi^2}{\pi} \frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2) \ \&\ \sigma_{e\chi}^{\text{light}} \approx \frac{g_e^2 g_\chi^2}{\pi}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

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

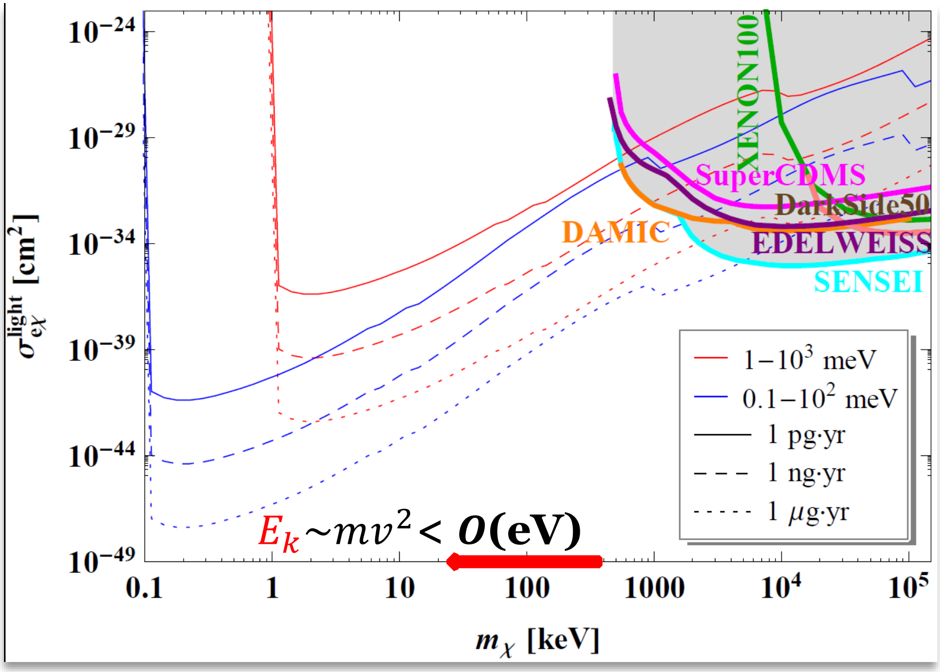
- ❖ From the linear dispersion of graphene: $E_F = v_F \sqrt{\pi n_c}$ with $v_F \sim 10^8\text{cm/s}$ & $n_c \sim 10^{12}/\text{cm}^2$.

Expected Sensitivities: Near Future

Heavy mediator: $F_{DM} = 1$



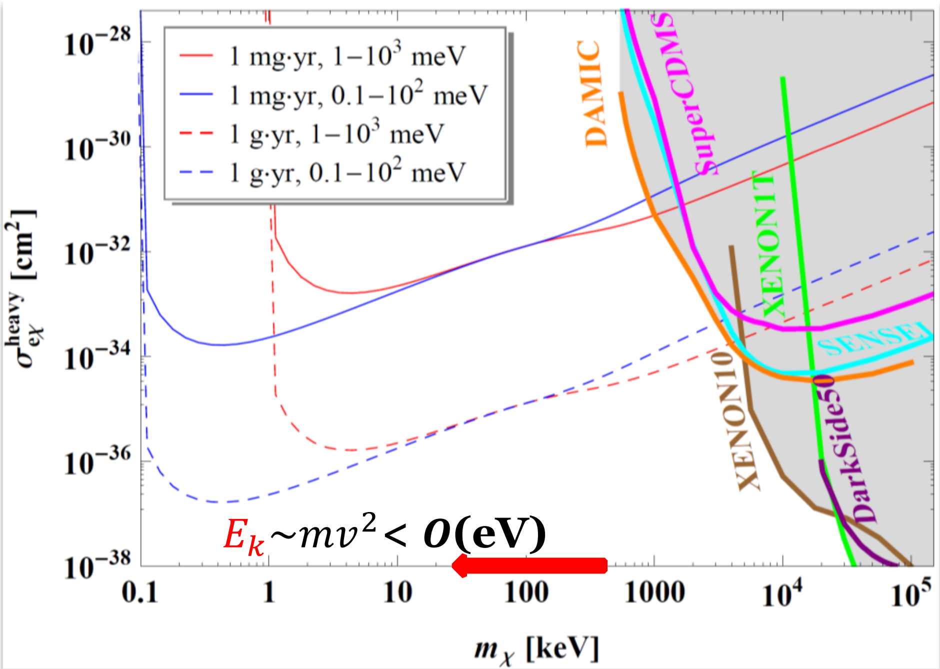
Light mediator: $F_{DM} \propto 1/q^2$ with $q_{\text{ref}} = \alpha_e m_e$



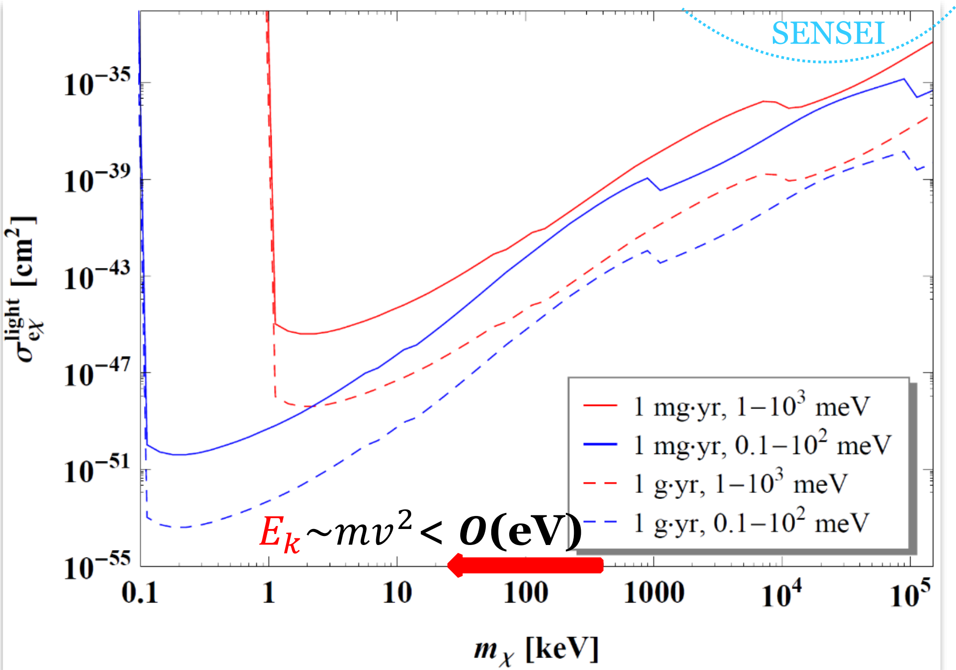
- ✓ We required N_{eve}=3.6 under the negligible background assumption.
- ✓ The proposed GJJ DM detector can improve the minimum detectable DM mass ($m_{\text{DM}}\sim 0.1$ keV) by more than 3 orders of magnitude over the ongoing/existing experiments.
- ✓ Even capable of probing sub-keV DM with great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

Expected Sensitivities: (Far) Future

Heavy mediator: $F_{DM} = 1$



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



- ✓ We required $N_{\rm eve}$=3.6 under the negligible background assumption.
- ✓ The proposed GJJ DM detector can improve the minimum detectable DM mass ($m_{\rm DM}$~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.

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

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