Status of GLIMPSE & Angular Scanning

with D. Kim, G.-H. Lee, K.C. Fong [2002.07821]
with D. Jeong, D. Kim [2604.18704]
In progress

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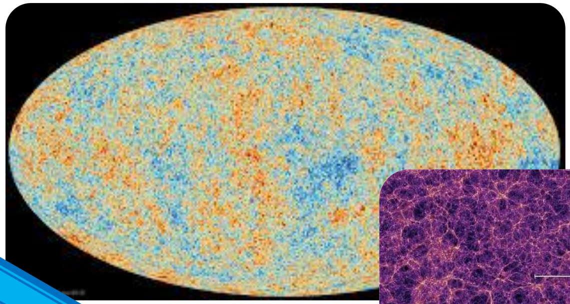
ISU 우주과학연구소 Institute for Sciences of the Universe

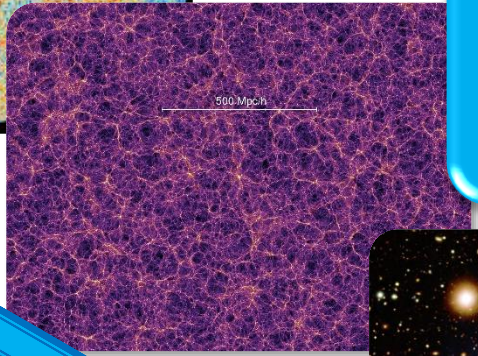
Outline

- ❖ Why Light Dark Matter?
- ❖ GLIMPSE
- ❖ Achievements
- ❖ (Potential) Issues
- ❖ 2D Detection: Angular Dependence
- ❖ Summary

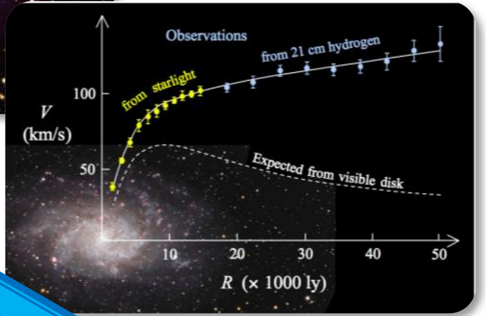
Why Light Dark Matter?

Message from Cosmology: Dark Matter (DM)





Dark Matter?



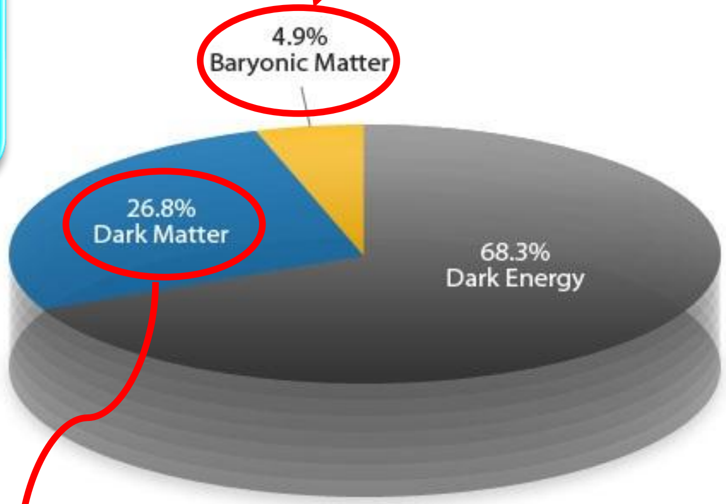
Larger scale
Earlier

Smaller scale
Later

Many more other observations!

❖ **Modern cosmology**:

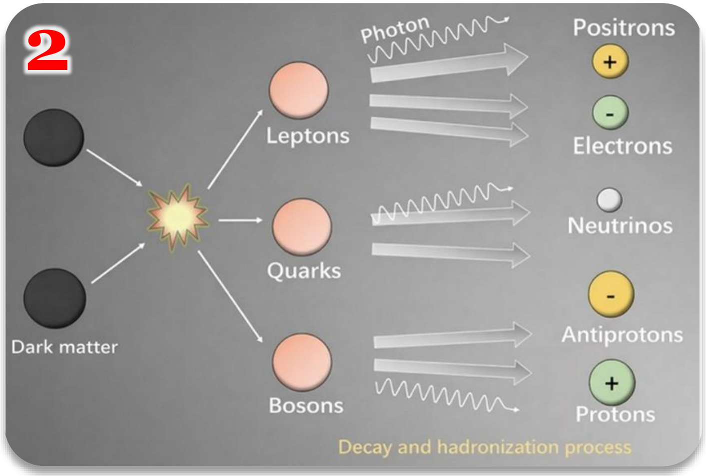
The Standard Model

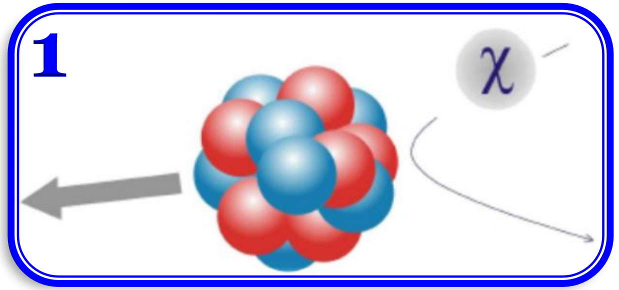


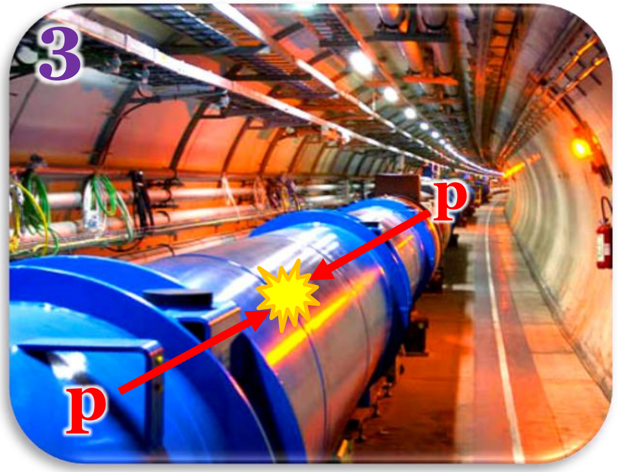
❖ **Compelling paradigm**:

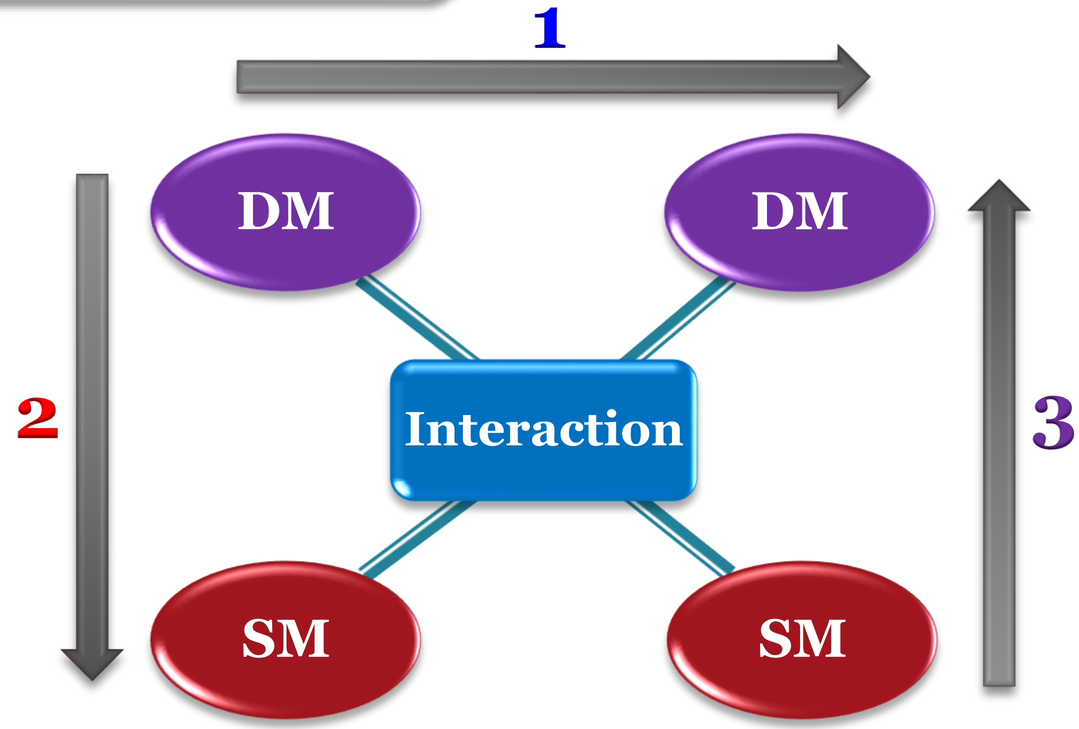
- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

Conventional DM Search Strategies









❖ Based on the WIMP paradigm.

Cosmological Lower Bound on Heavy-Neutrino Masses

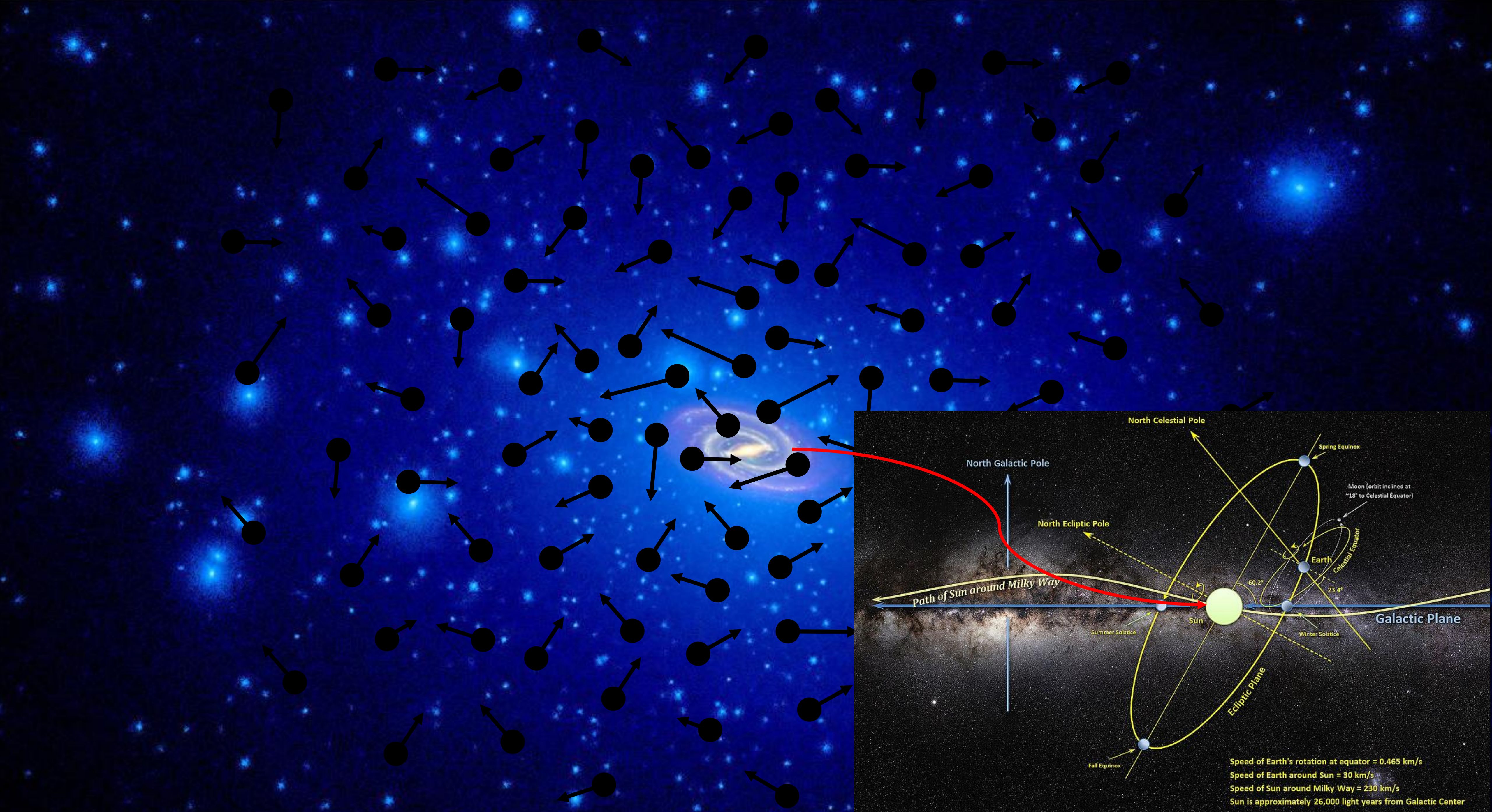
Benjamin W. Lee[a]
Fermi National Accelerator Laboratory,[b] *Batavia, Illinois 60510*

and

Steven Weinberg[c]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

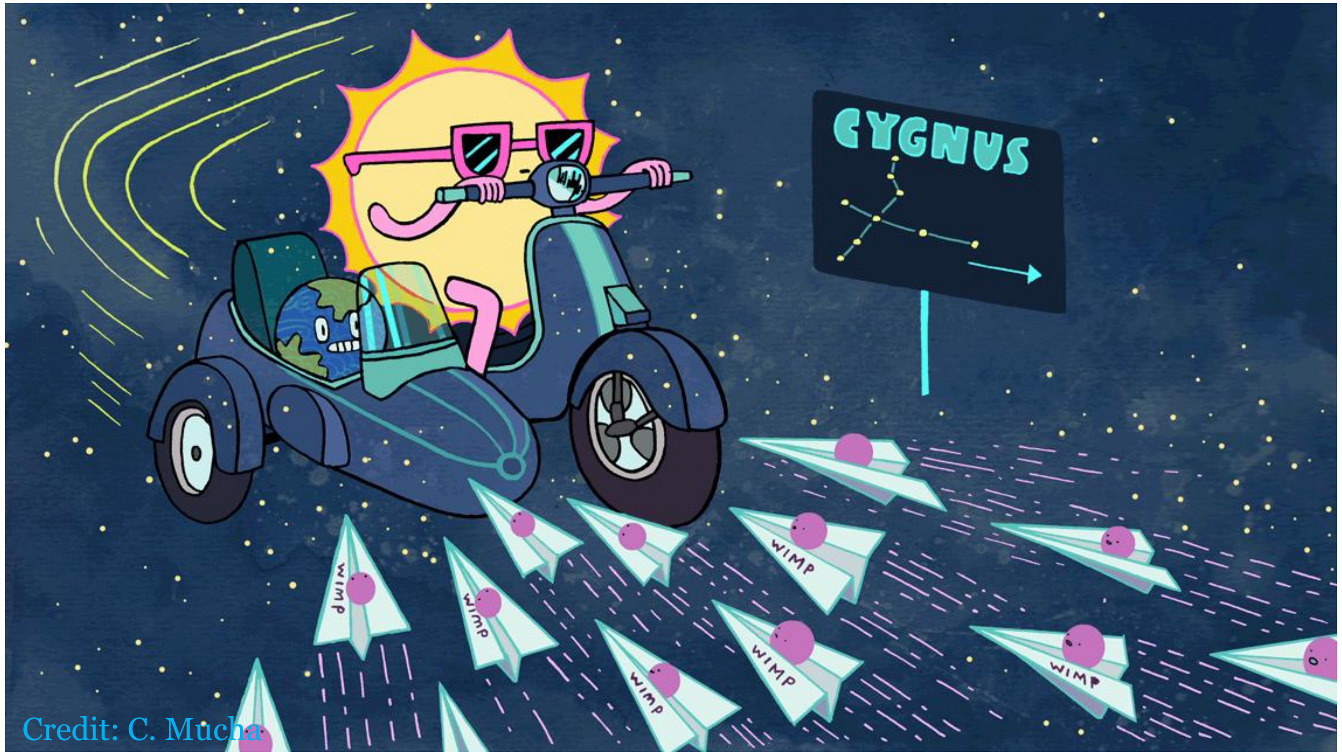
The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

[PRL (1977)]

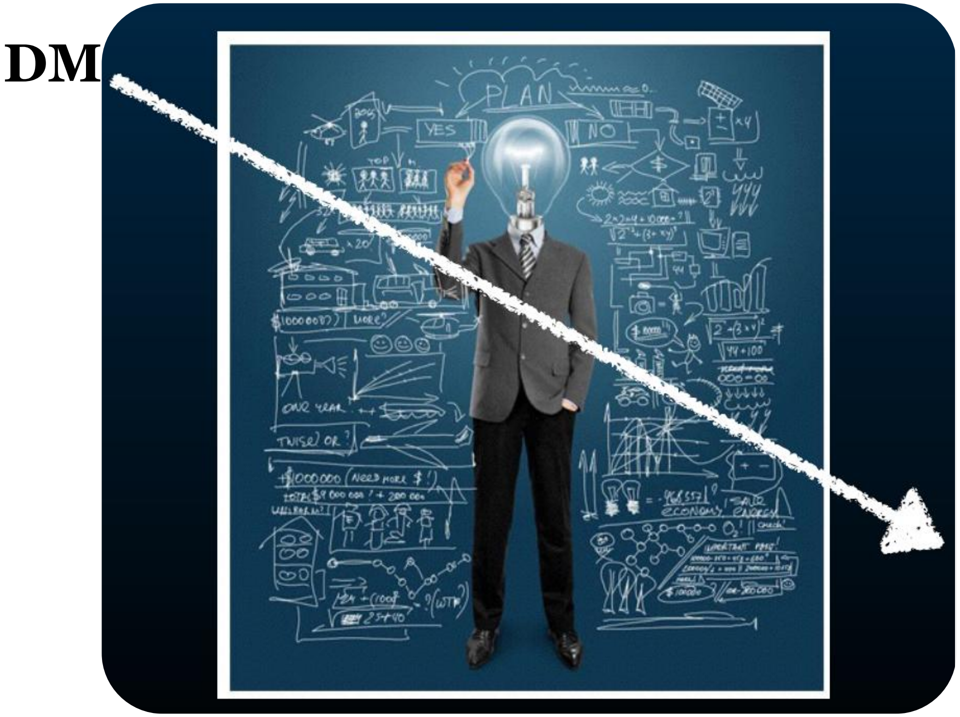


Credit: NASA, ESA, T. Brown & J. Tumlinson

DM Wind ➔ DM Direct Scattering



Credit: C. Mucha

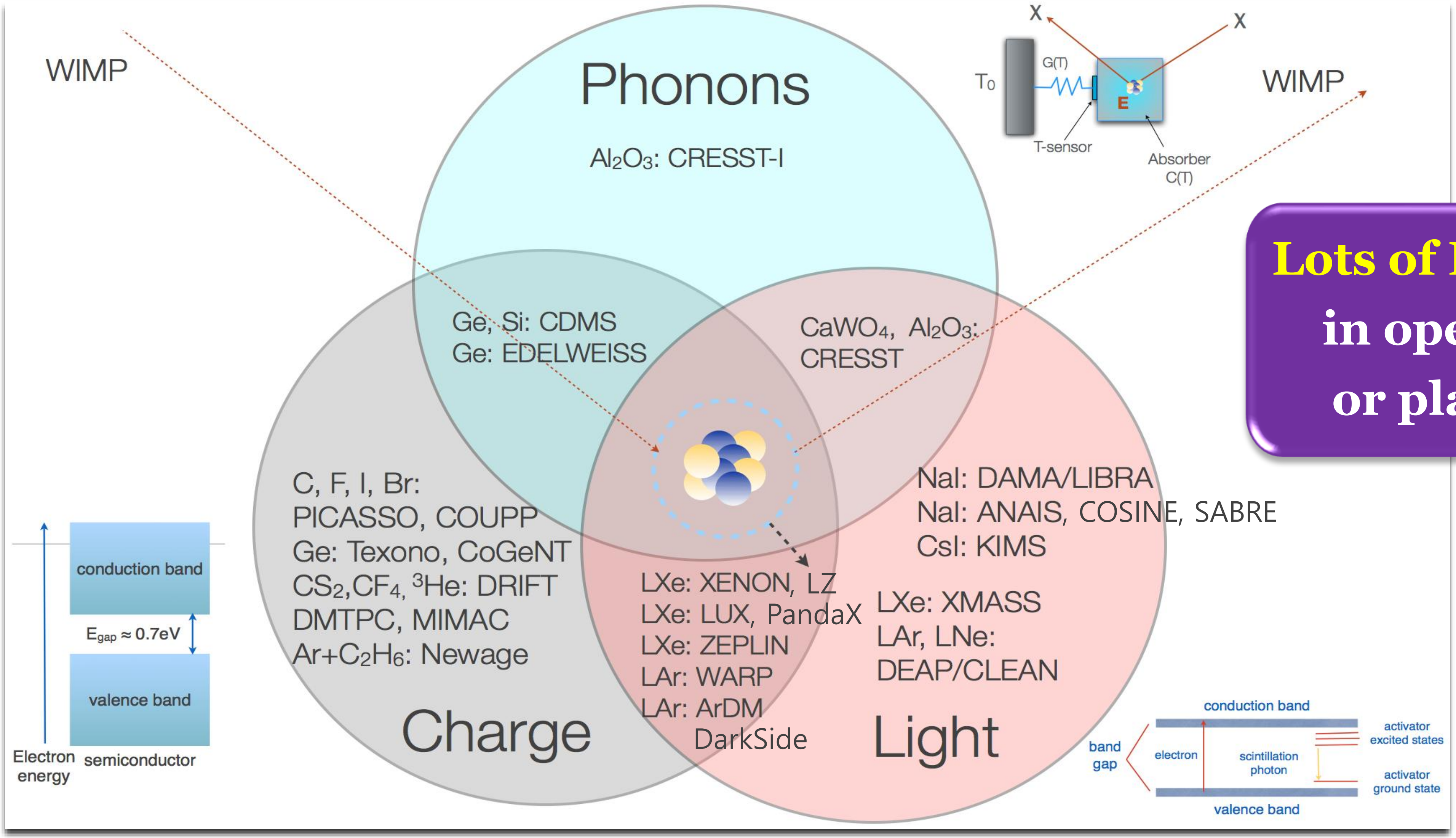


❖ Assuming $m_{\rm DM} \sim m_{\rm p} \sim 0.94$ GeV: $$\overbrace{300\ \mathrm{km/s}\times\frac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}}}^{\text{flux}}\times\overbrace{60\ \mathrm{cm}\times 170\ \mathrm{cm}}^{\text{area}}$$

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

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

DM Direct Detection Experiments



Lots of Exps. are in operation or planned.


~~Nespresso.~~ What else ?
WIMP


FIFA
WORLD CUP
2026
VS
FRANCE
QUARTERFINAL
MOROCCO
JULY 10, 2026
FRIDAY
01:45 AM
NEPAL TIME
METLIFE STADIUM
NEW JERSEY, USA
ONE STEP CLOSER TO GLORY

DM Landscape: A Very Wide Mass Range

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

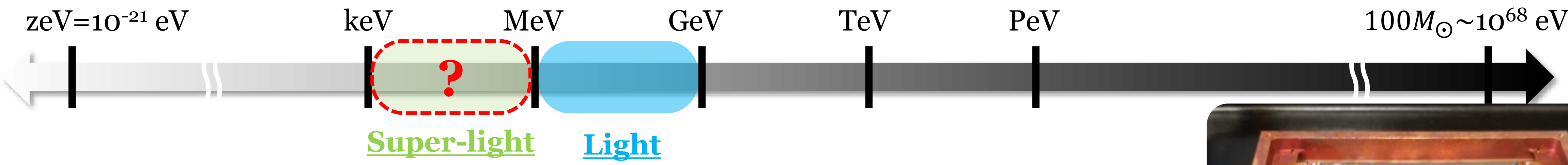
Astrophysical object
MACHO, PBH, non-particle

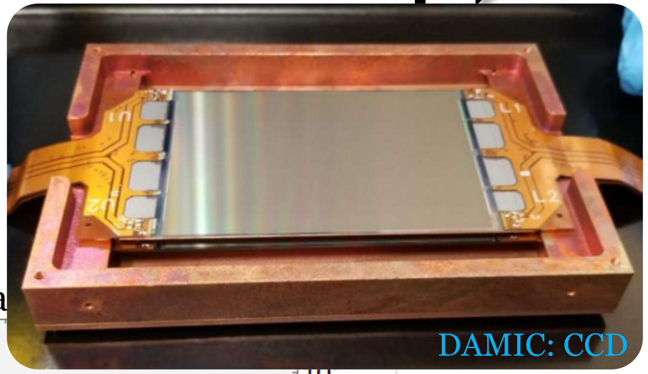
Thermal DM:
Too hot

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

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

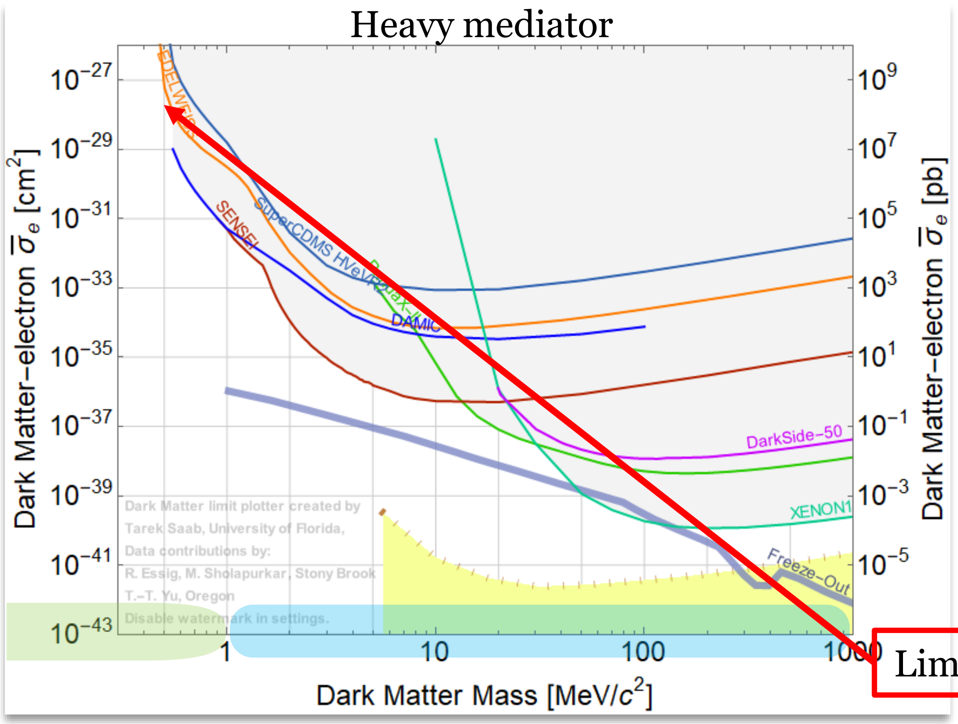
Light DM Direct Search: Current Status



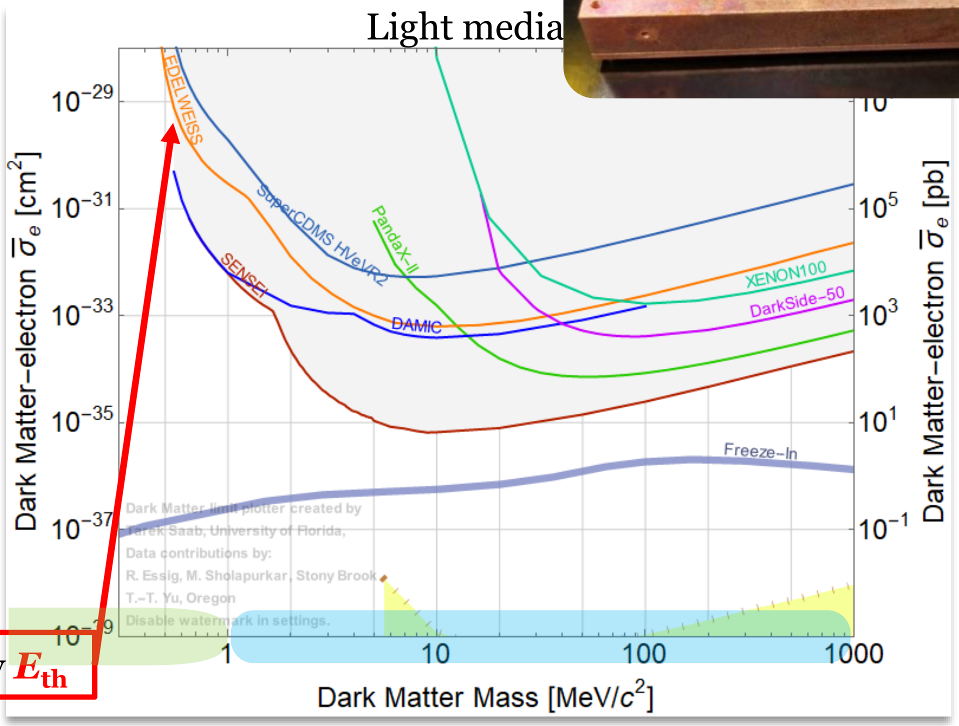


- $E_k \sim m_\chi v^2$, $\Phi_\chi = (\rho_\chi / m_\chi) v_{rel}$ ➔ **lighter DM**: **smaller E_r**, but **lager flux** (**lighter** target)

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

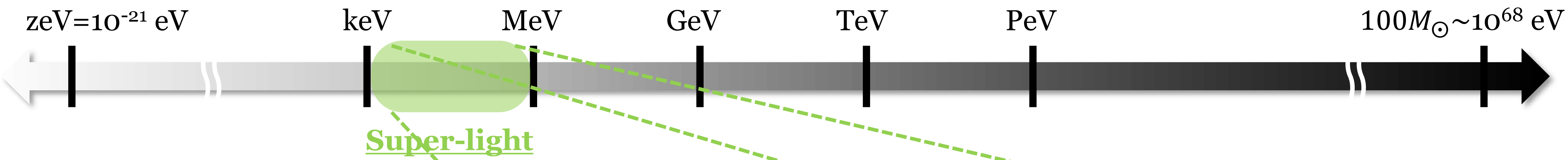


Limited by E_{th}



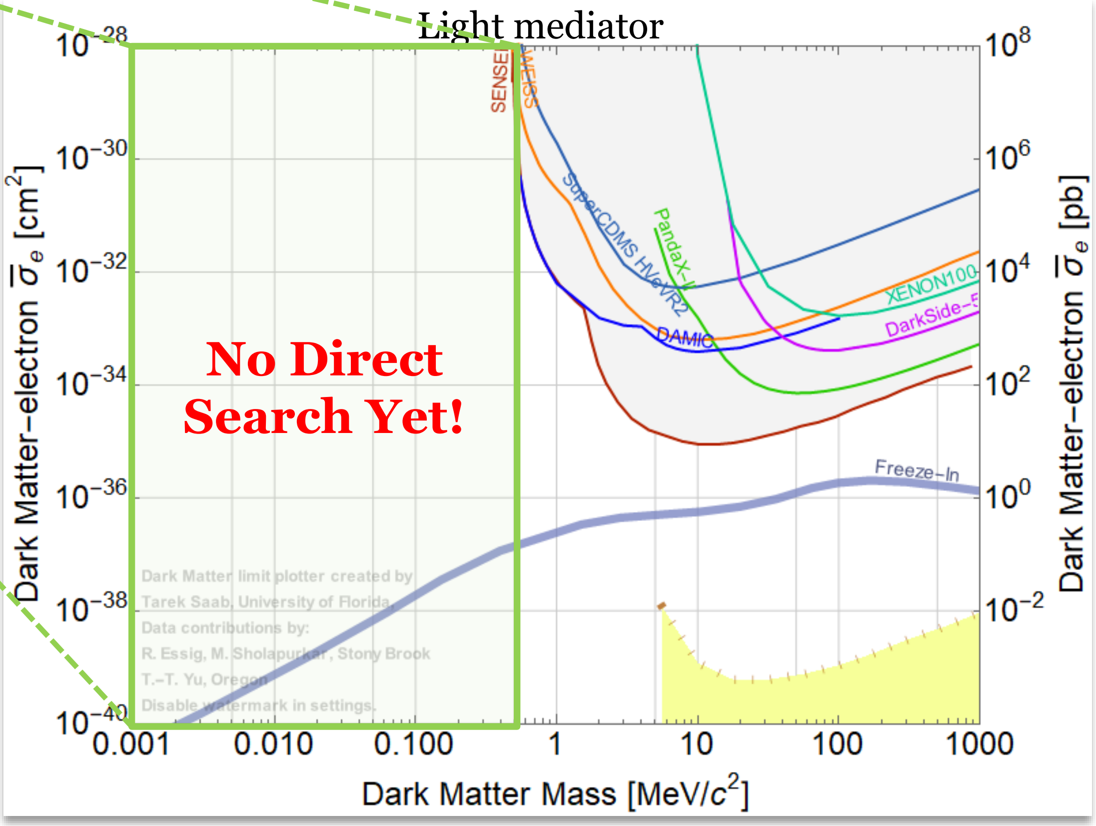
Dark Matter Limit Plotter v5.18

Super-Light DM Direct Search



- ❖ $E_r \sim \boldsymbol{E_k} \sim mv^2 \sim \boldsymbol{O}$**(meV)** with $m \sim$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

Our Proposal: GLIMPSE

GLIMPSE

Graphene-based Light Invisible Matter Particle SEarch

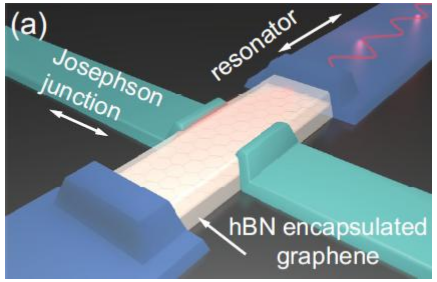
[Kim, **JCP**, Lee, Fong, 2002.07821 & in progress]

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

Super-light DM Search Strategy with GJJ

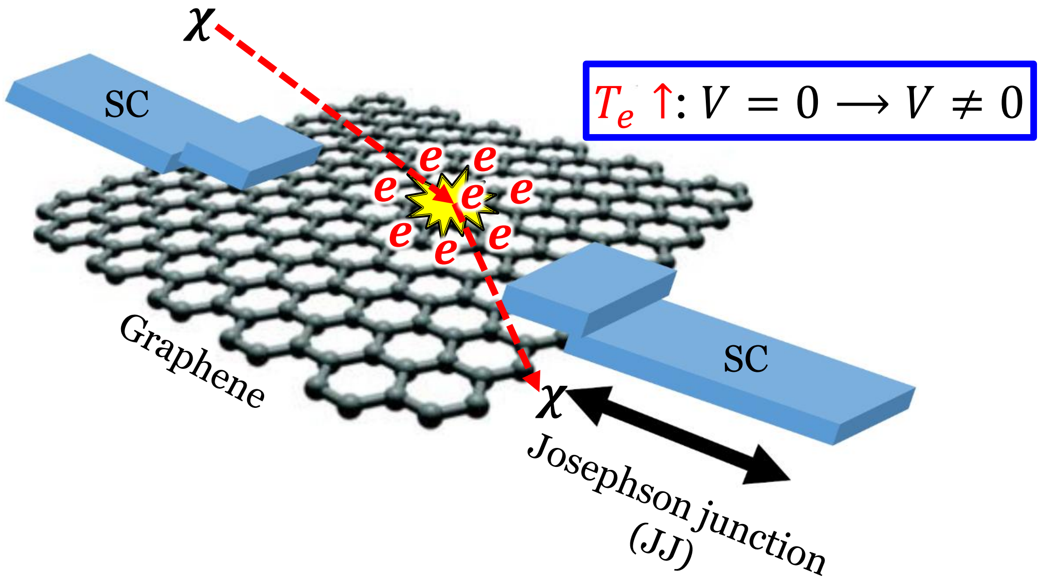
❖ **GJJ microwave bolometer**



✓ 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.

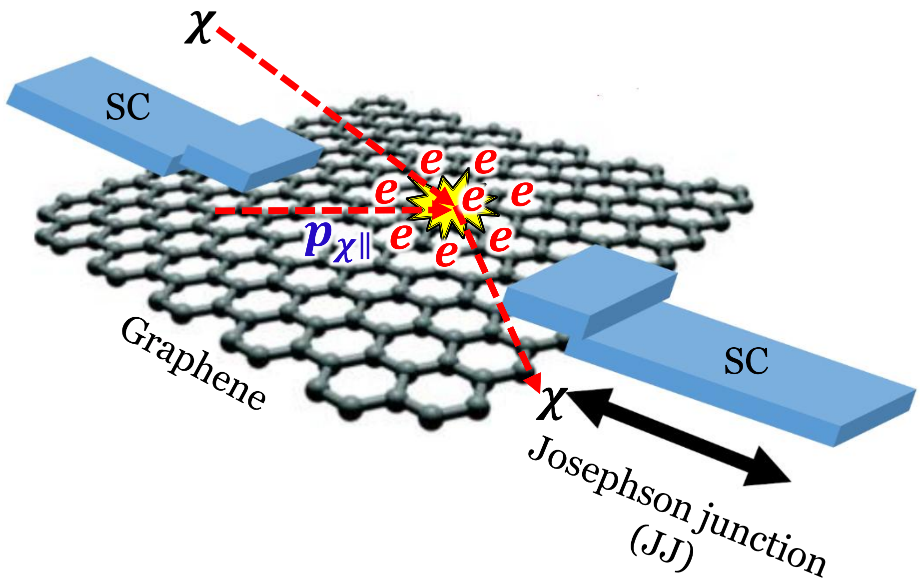
II. **The recoiling e heats up & thermalizes** with nearby e's rapidly via e-e interactions.

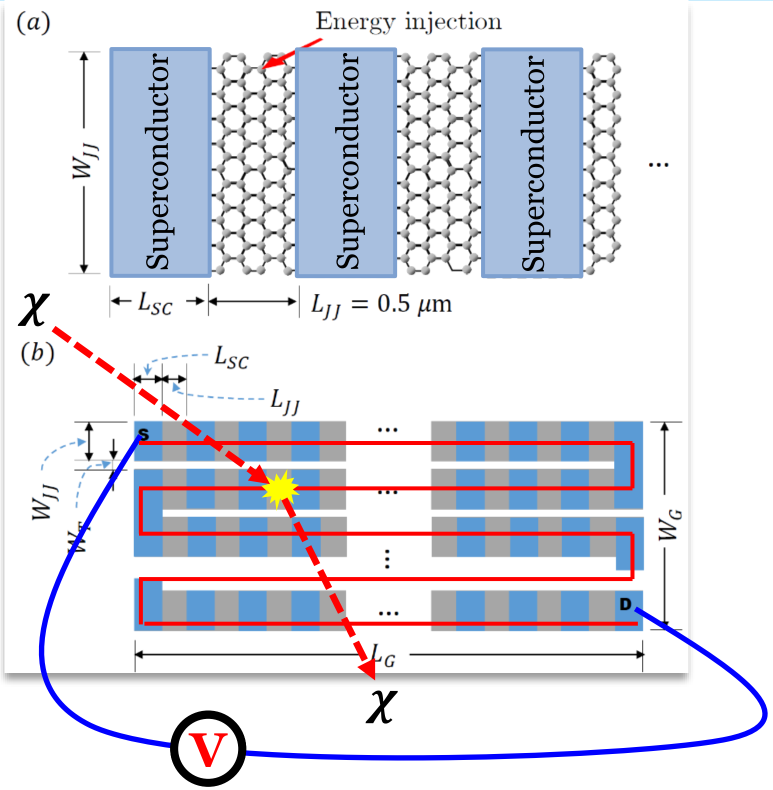
III. **The JJ is triggered**: the temperature rise switches the zero-voltage (non-resistive) of JJ to a **non-zero-voltage (resistive) state**.

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

➔ **GJJ detector: 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

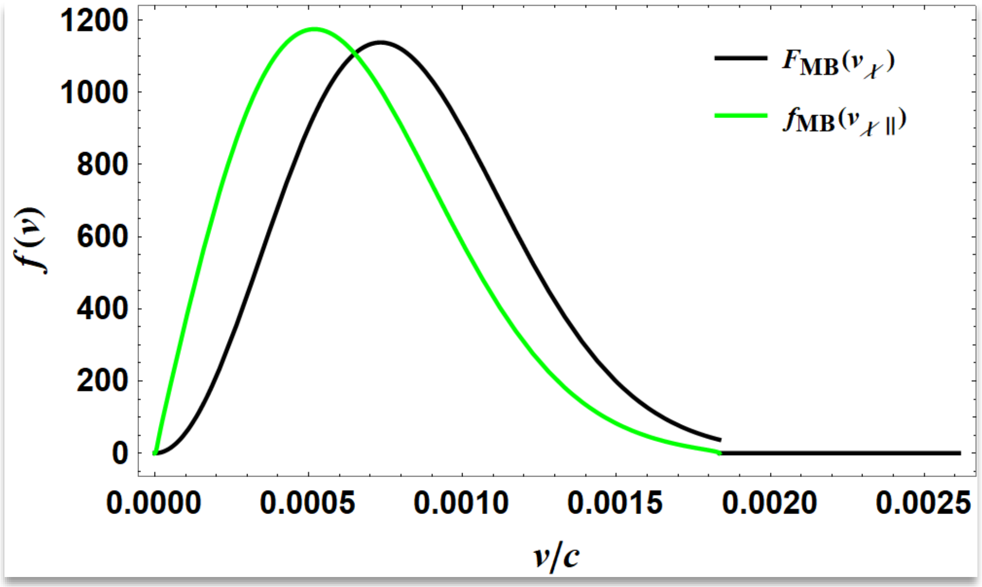
- $n_{\rm eve} = \int_{E_r>E_{\rm th}} dE_r dv_{\chi\parallel} f_{\rm MB}(v_{\chi\parallel}) \frac{d\langle n_e^{\rm 2D}\sigma_{e\chi}v_{\rm rel\parallel}\rangle}{dE_r}\frac{1}{\rho_{\rm gr}^{\rm 2D}}\frac{\rho_\chi}{m_\chi}$

- ✓ 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

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

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

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



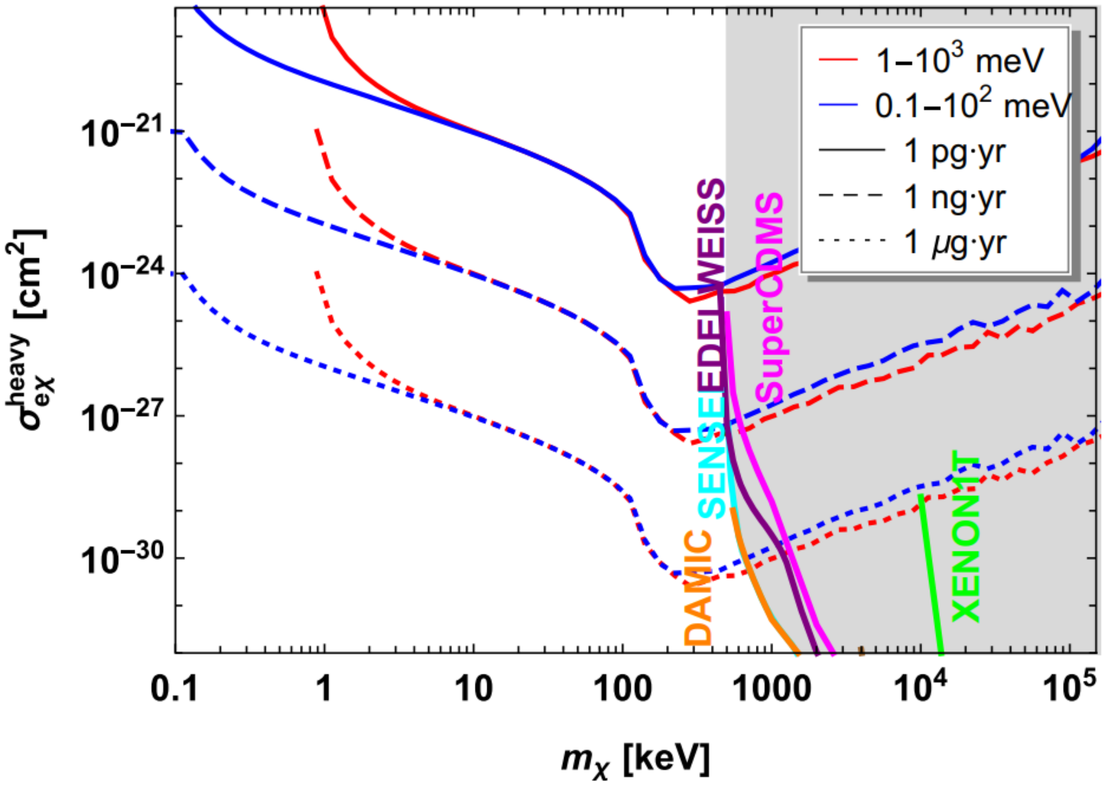
- We assume that DM interacts with electrons via an exchange of mediator ϕ:

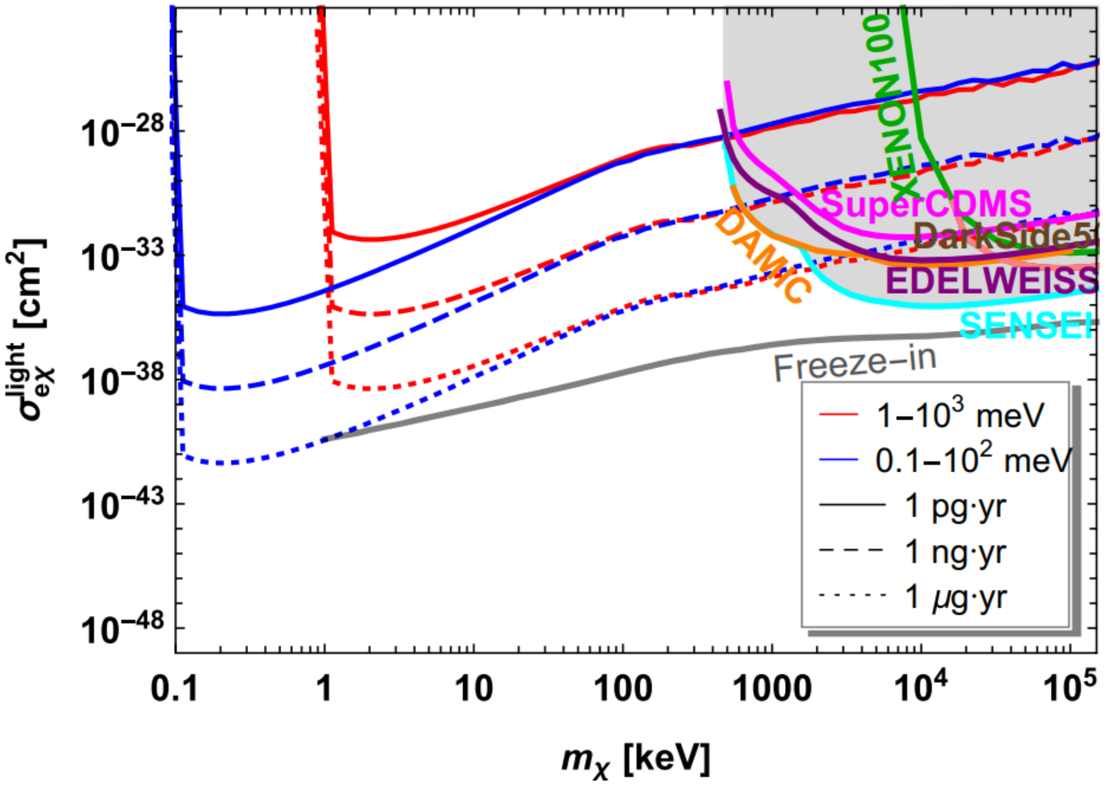
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{(m_\phi^2+q^2)^2} \rightarrow \sigma_{e\chi}^{\rm heavy} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2)$$

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

- 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



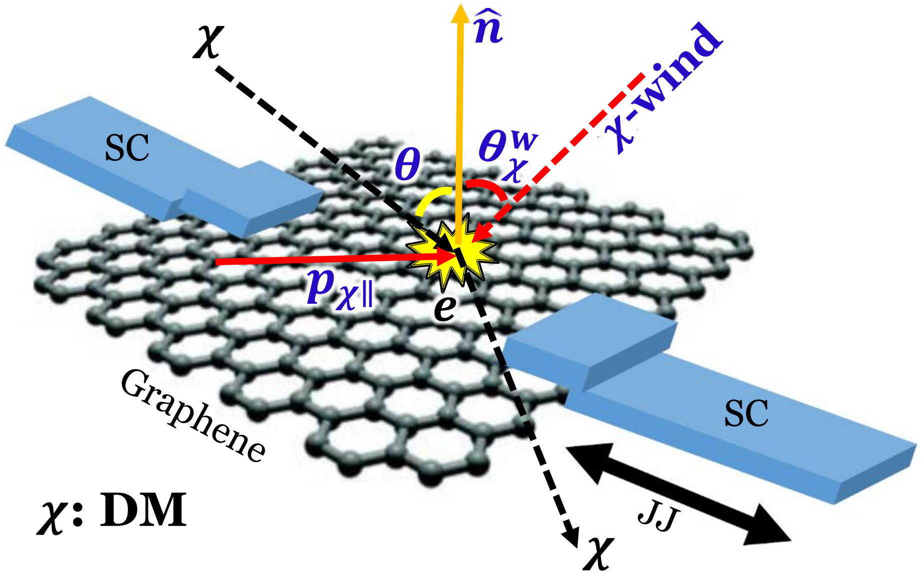


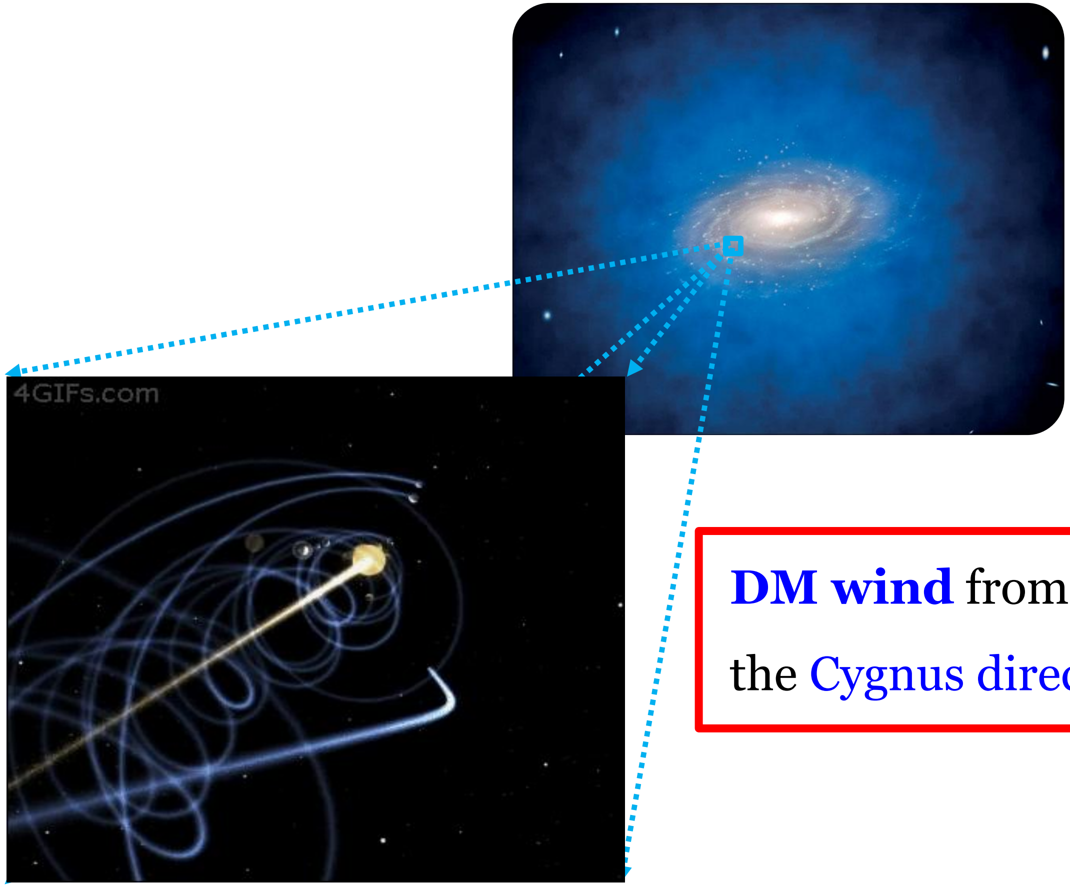
- ✓ The proposed detector (GLIMPSE) can improve the minimum detectable DM mass (**m_{DM}~O(keV)**) by more than 2-3 orders of magnitude over the ongoing/existing experiments.
- ✓ **Capable of probing** the prediction of **freeze-in** scenarios.

Signal Rate: Directional Dependence

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

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





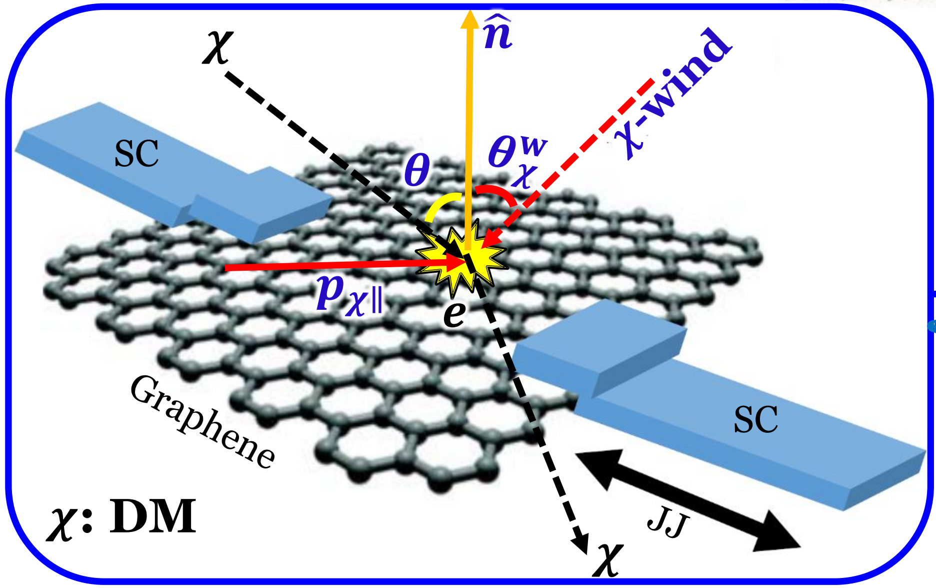
DM wind from
the Cygnus direction

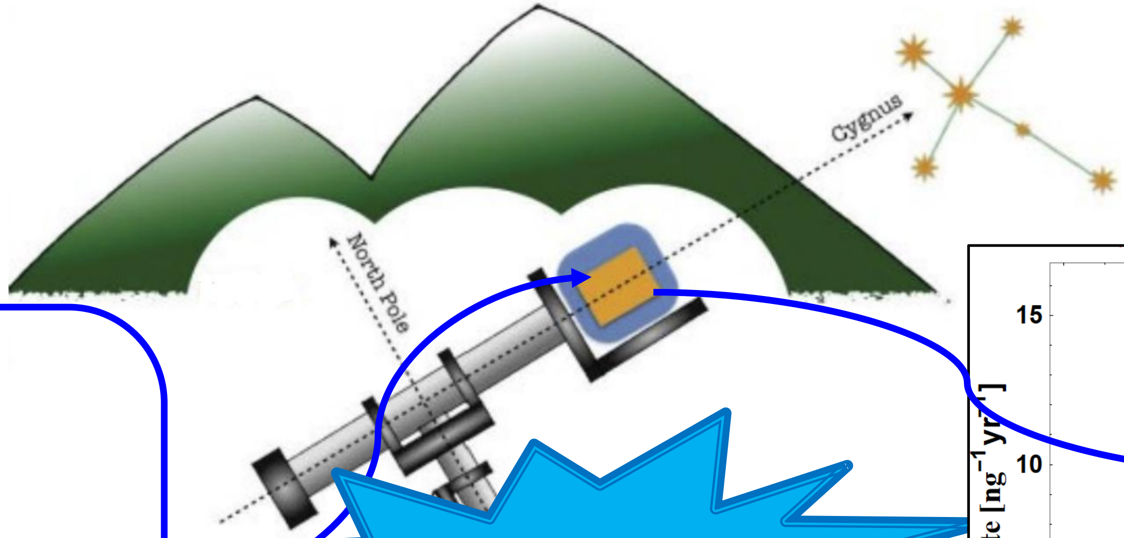
Signal Rate: Directional Dependence

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

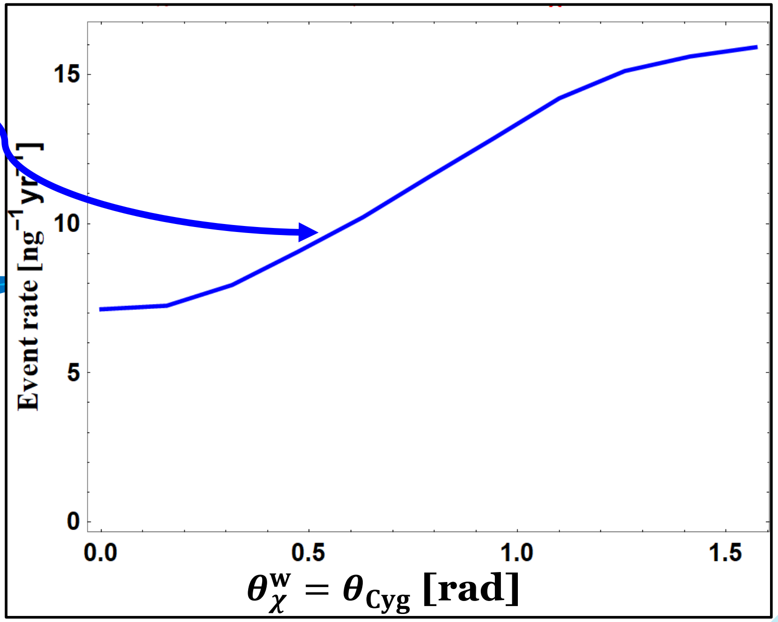
➔ Momentum transfer: the change of $p_{\chi\parallel}$ ➔ **Signal rate**: **DM incident direction** dependence

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





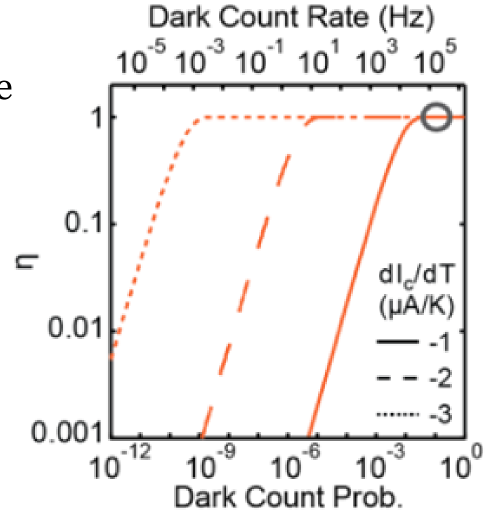
Handle for BG rejection!

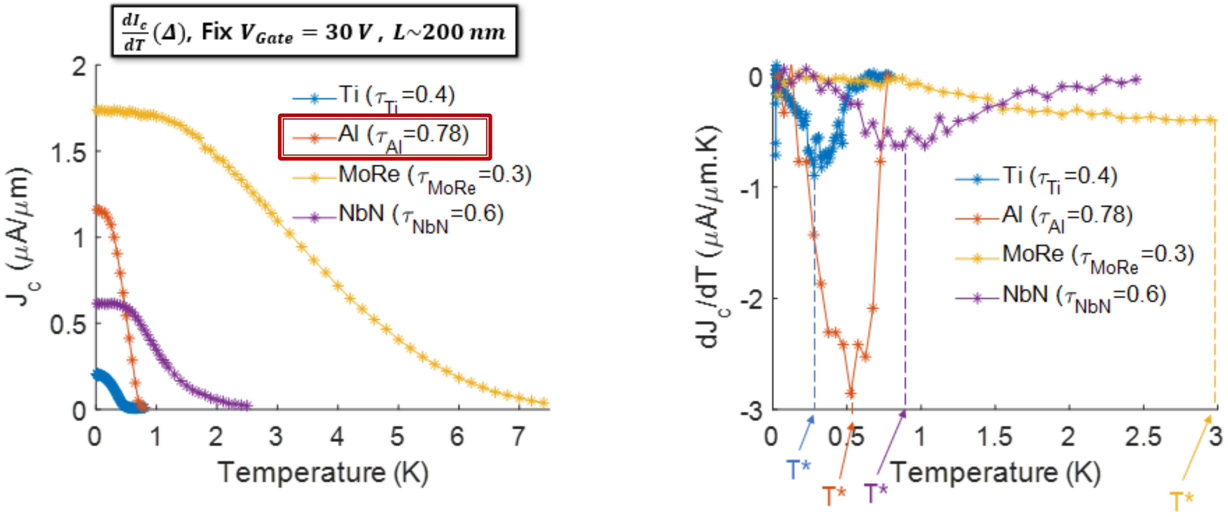


Optimization of $|dI_c/dT|$ for GJJ

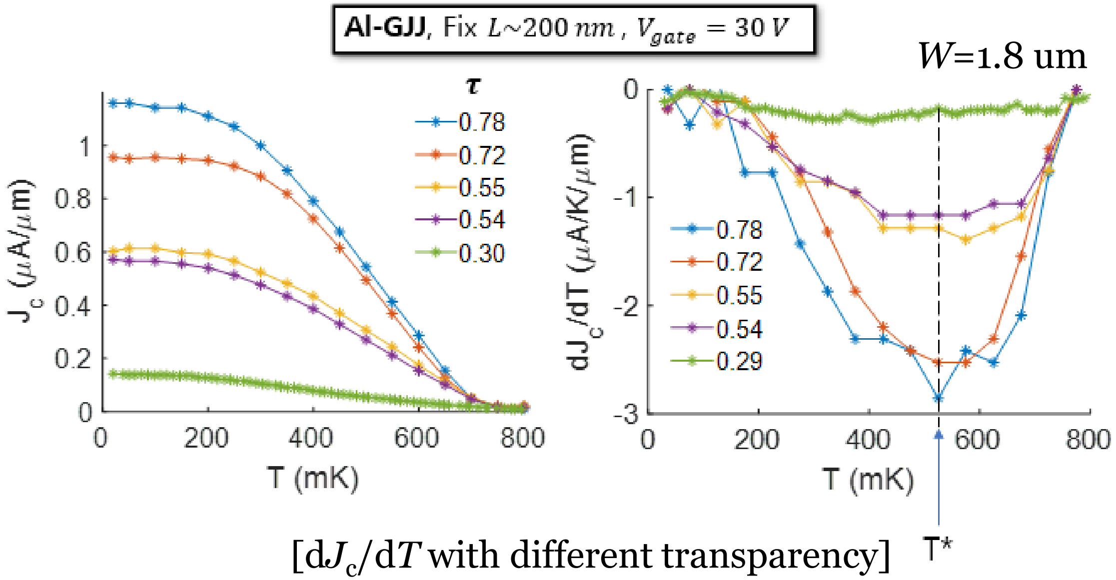
- ✓ $|dI_c/dT|$ ↑ ➔ Detection efficiency ↑ & Dark count rate ↓
- ✓ Lower T_c of $J_c(=I_c/W)$ & larger J_c at low temperature ➔ Aluminum
- ✓ Contact transparency (τ)↑ ➔ $|dJ_c/dT|$ ↑
- ✓ For Al & τ=0.78, $|dI_c/dT|$ ~ 5 μA/K (@ T=500 mK) is realized.

[Detector performance with different dI_c/dT]



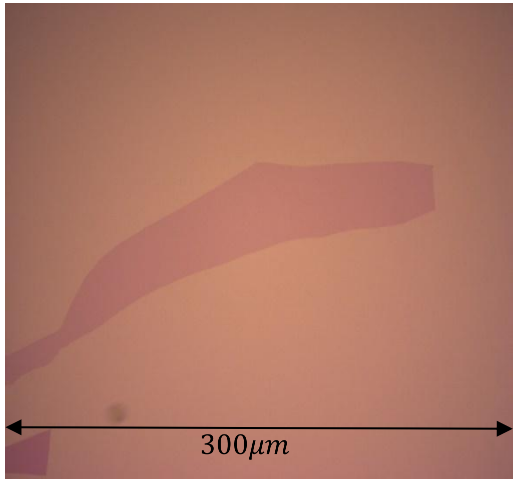


[dJ_c/dT of GJJ with various superconductors]

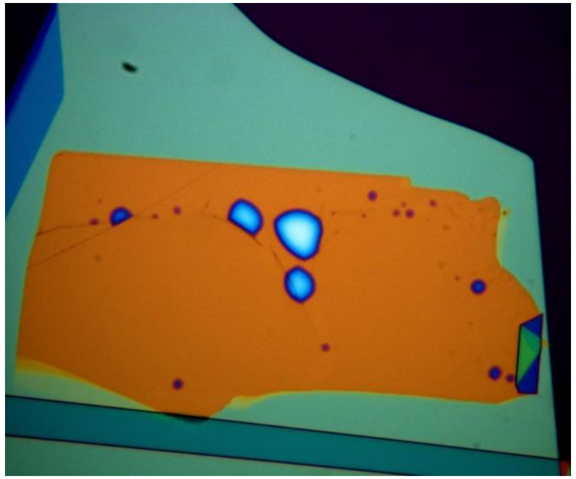


[dJ_c/dT with different transparency]

Progress in Fabrication: O(100) GJJs in Series



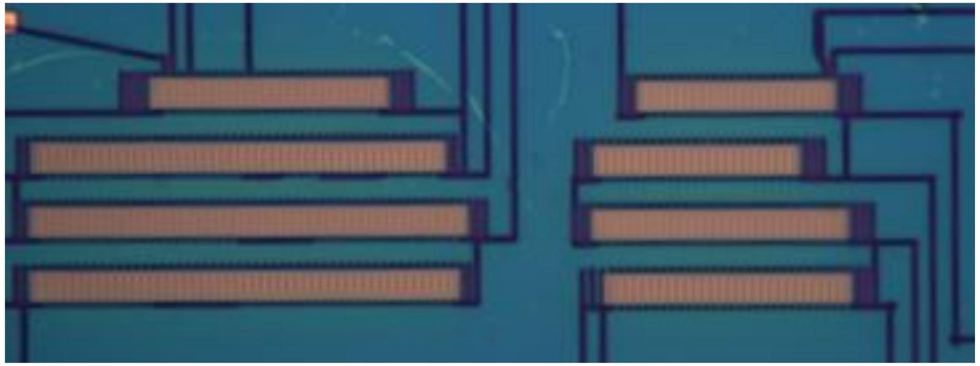
Large piece of graphene



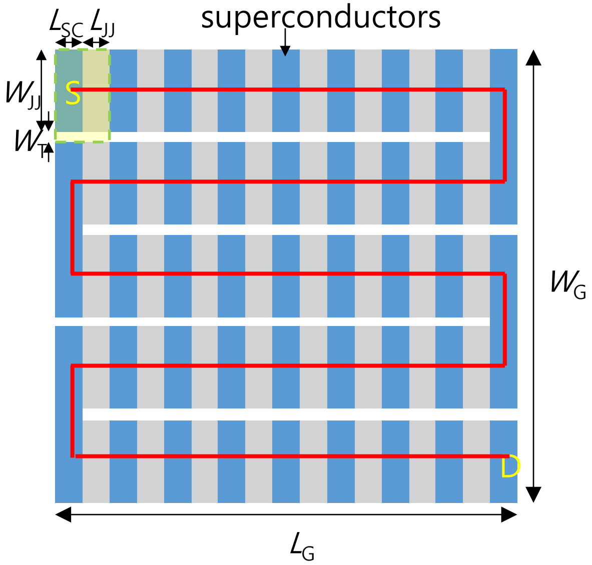
hBN-encapsulated graphene

Etched hBN/Graphene/hBN stack

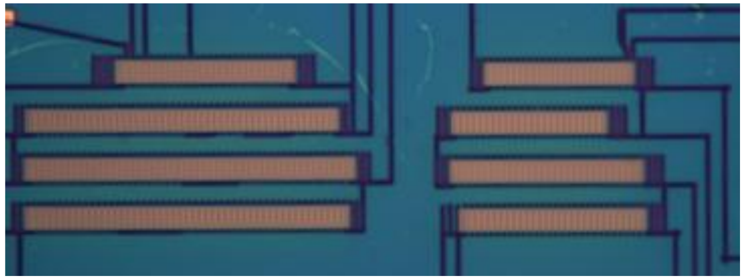
<u>216 GJJs</u> connected in series



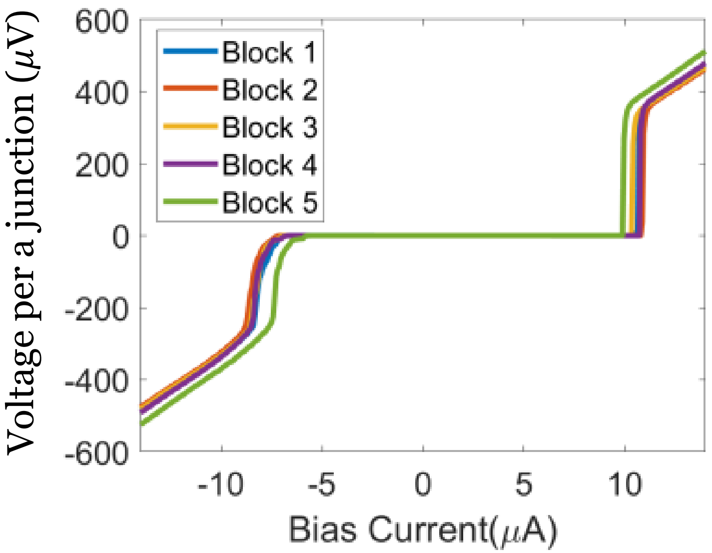
Schematics



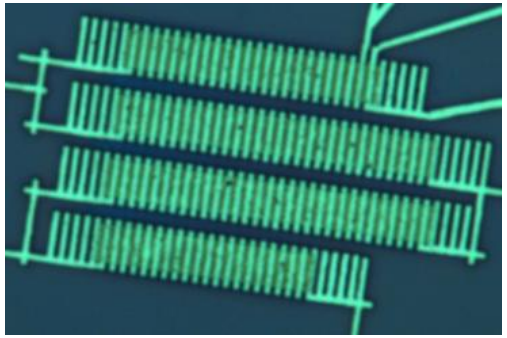
Uniformity of Multiple GJJs



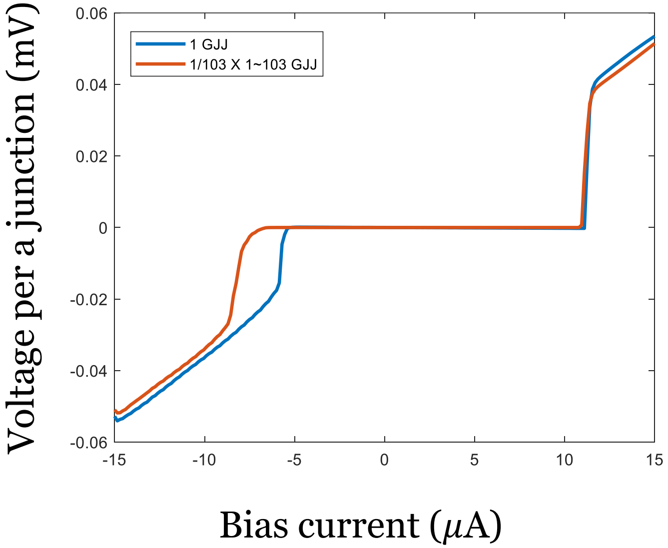
216 GJJ array



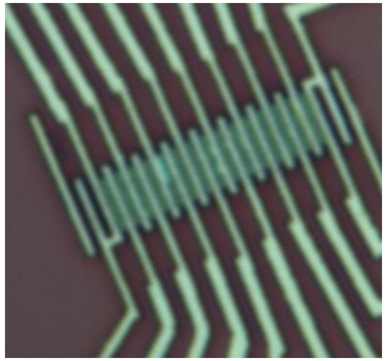
Almost same I-V curve when scaled



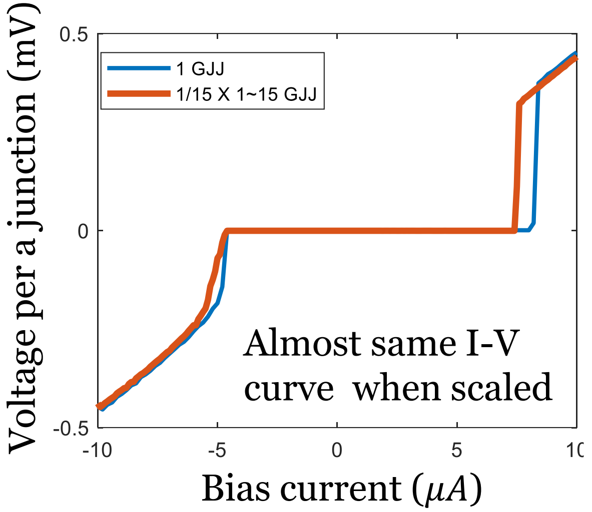
103 GJJ array

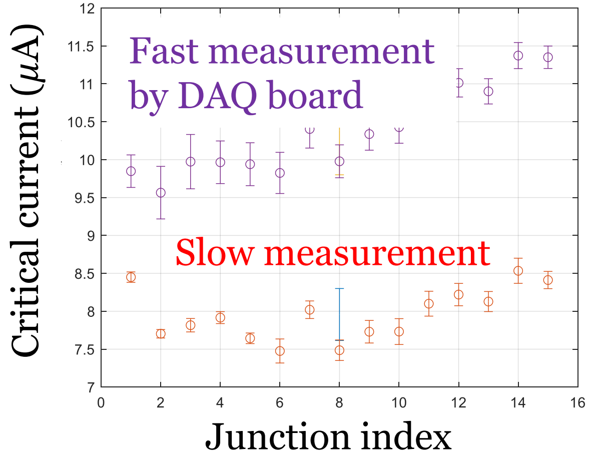


Almost same I-V curve when scaled



15 GJJs array



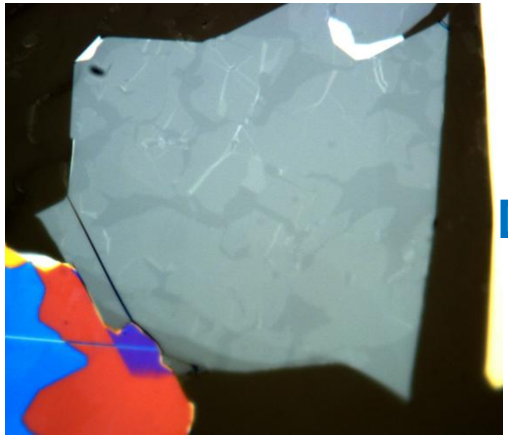


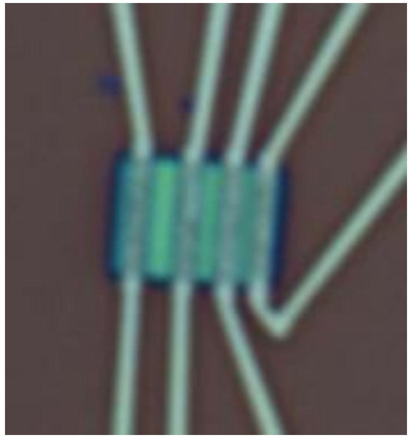
±9% variation in switching current

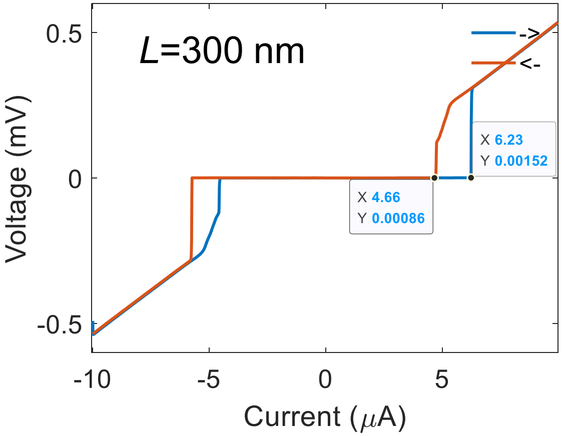
Uniform Josephson junctions in series were fabricated!

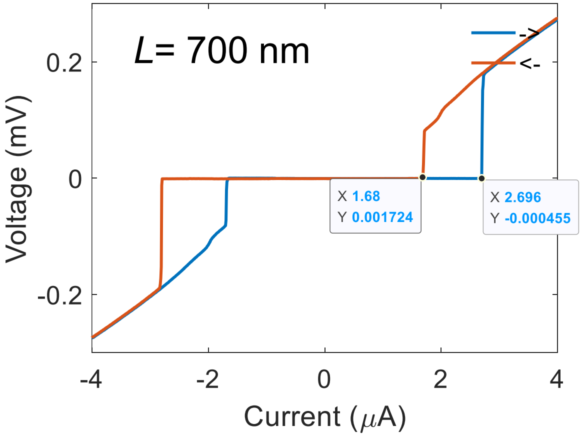
Fabrication Test on Large-scale Graphene

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

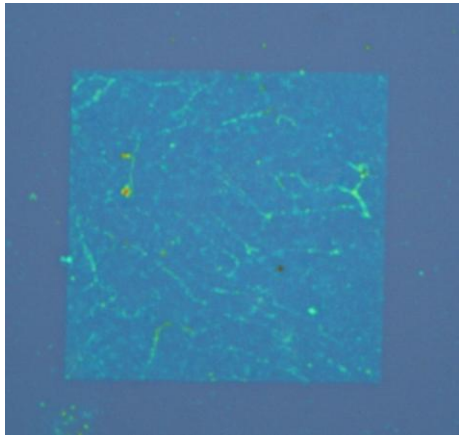




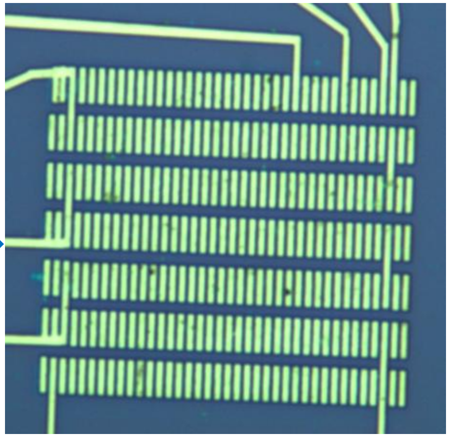




- ❖ CVD-grown Graphene with CVD-grown hBN

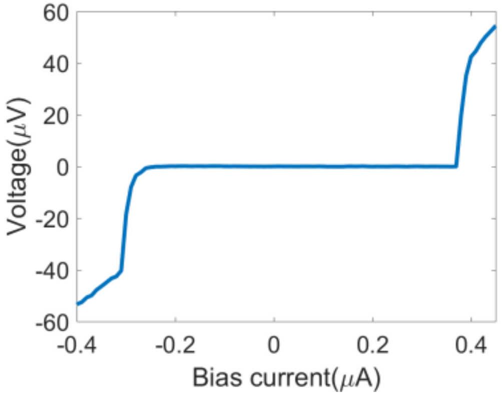


hBN/Graphene/hBN stack



231 GJJ array

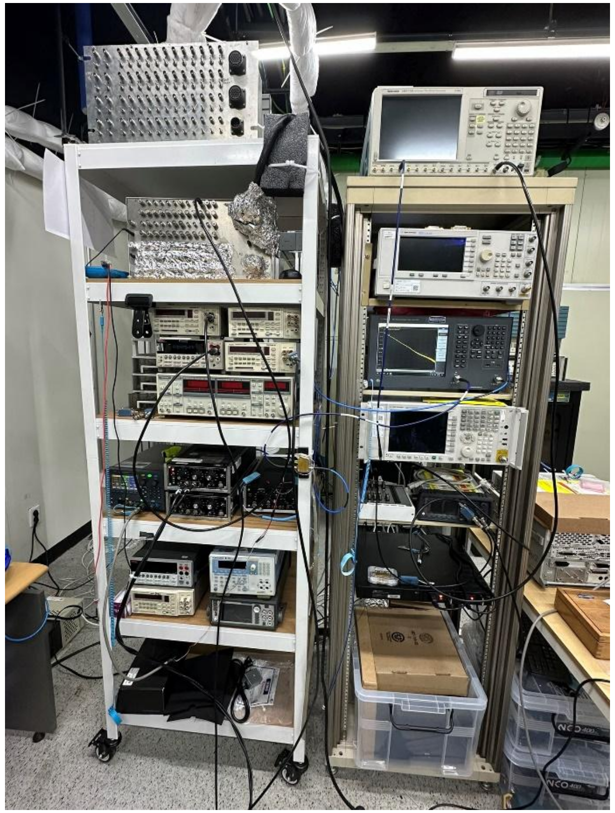
W~3μm, L~300nm



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

Overview of Our Measurement Set-up

Dedicated Dilution refrigerator



Arbitrary Waveform Generator

Analog Signal Generator

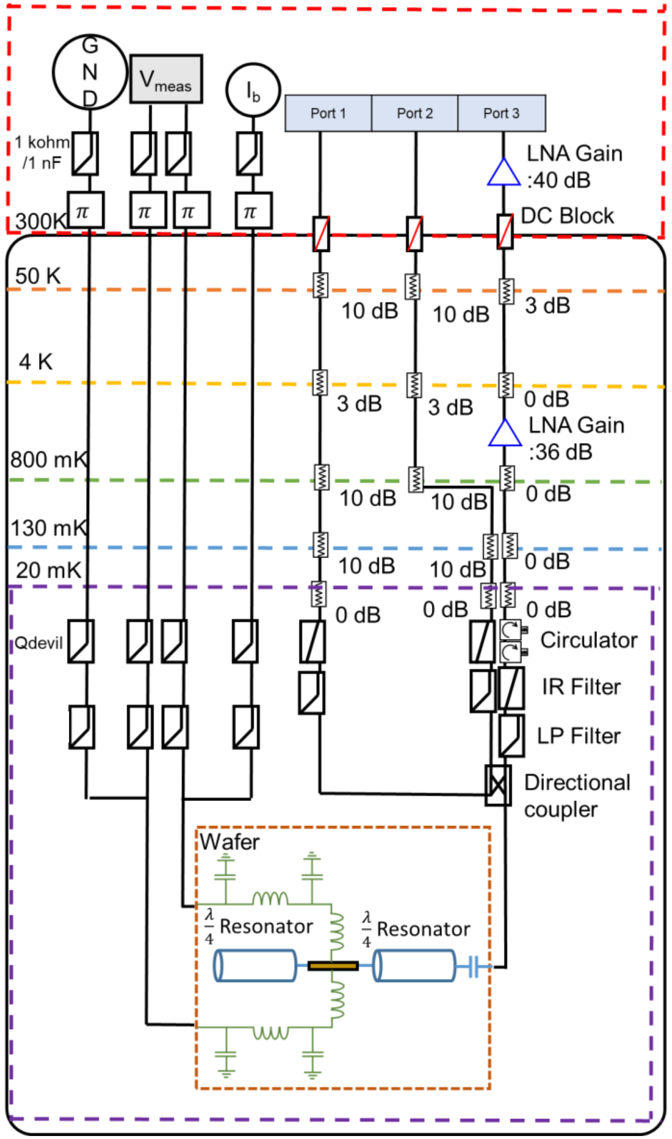
Vector Network Analyzer

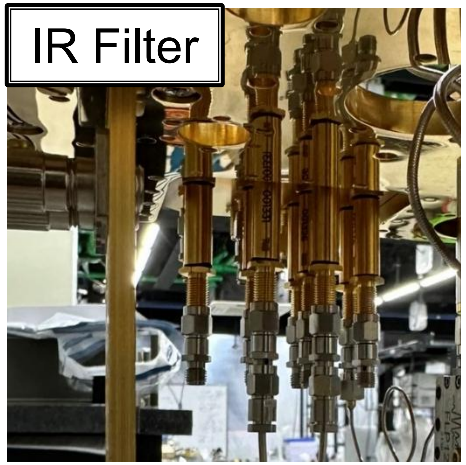
Spectrum Analyzer

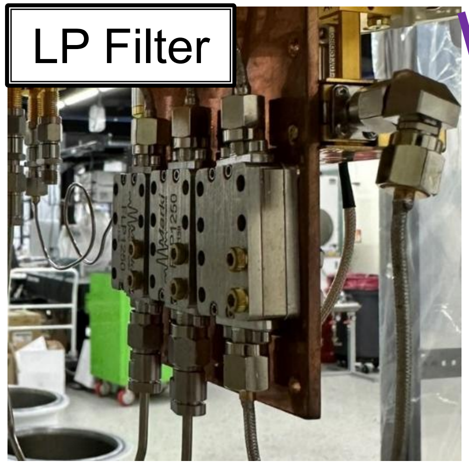
DC Instrument

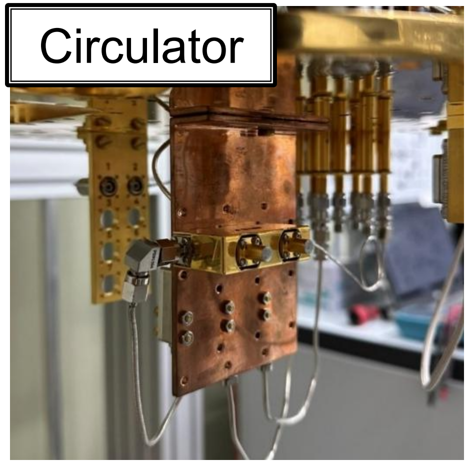
RF Instrument

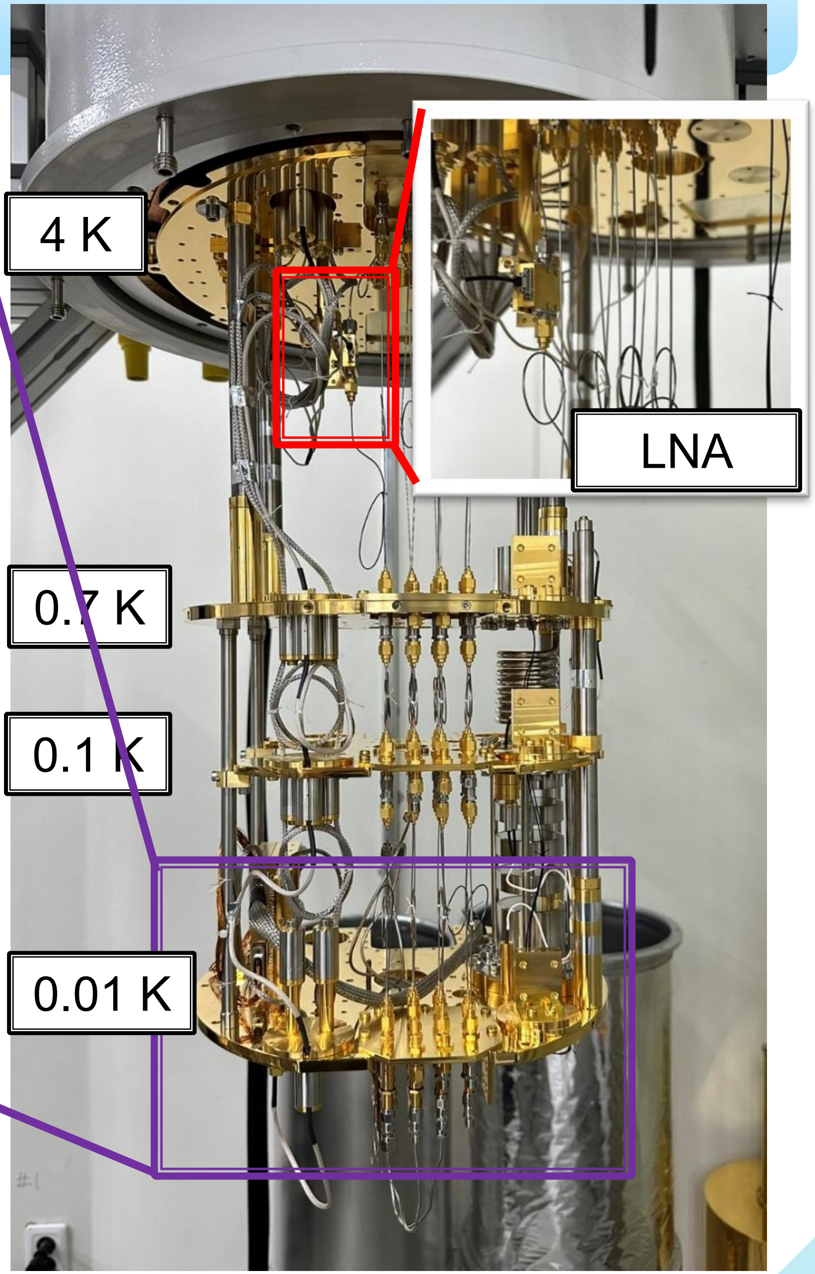
Our Measurement Set-up (RF)











(Potential) Issues

Potential Questions for LDM Direct Detection

❖ **Low *E* sensor technologies** mostly feature the **"on-off" type** working principle or relatively **poor *E* resolution**.

1. **DM signals vs Backgrounds** :

✓ Event discrimination via signal characteristics: difficult!

✓ For better directional detection, higher E_R is preferred, e.g., longer track.

✓ But, light DM induces lower E_R: less visible signals (tracks)

➔ **Can light DM be connected to directional recoil detection?**

2. **Mass determination**:

✓ We can recognize a DM event occurrence, but utilizing the dR/dE_R spectrum is difficult!

➔ **Is there any alternative method to determine the mass of DM?**

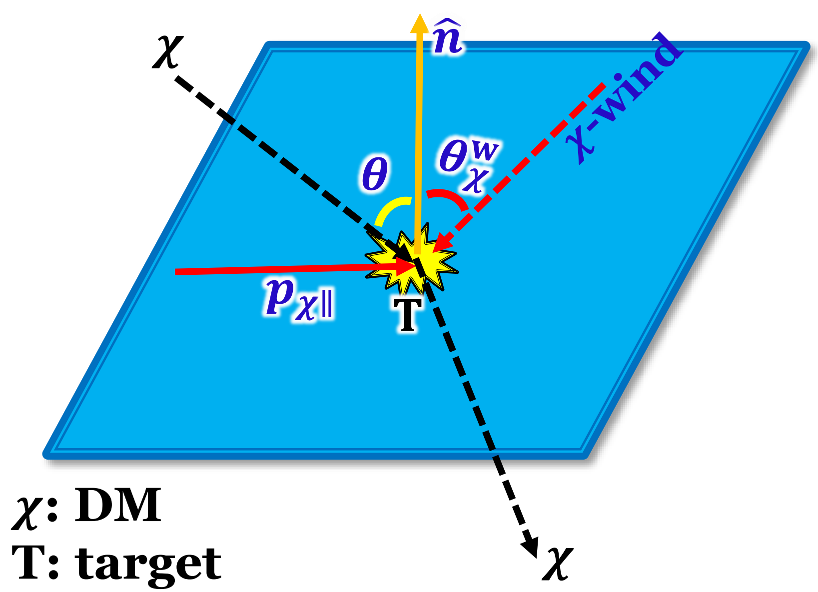
Answers for the Questions

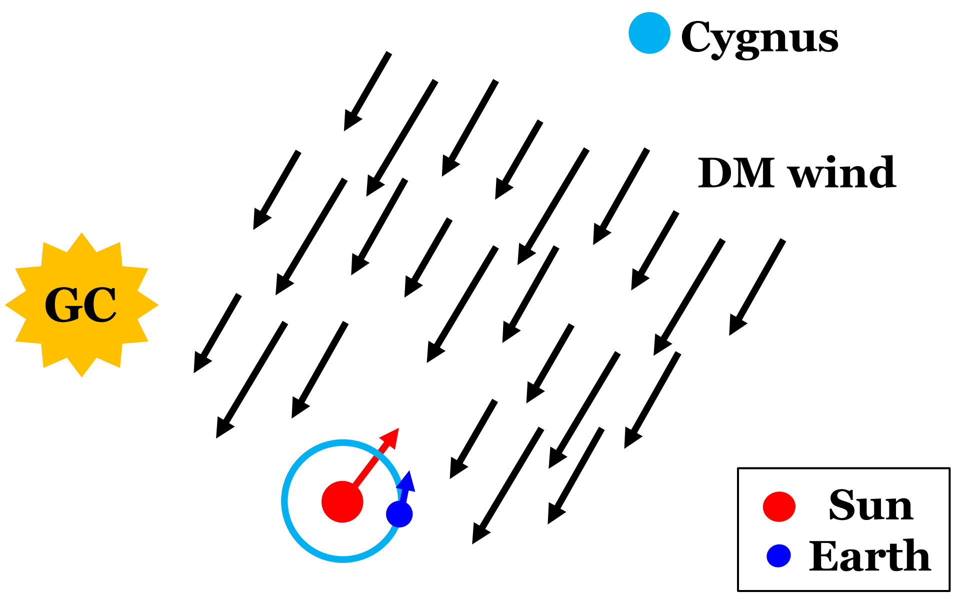
- ❖ **Experiments using (effectively) 2D detectors**: The experimental signatures are related to the behavior of target particles scattered by DM along the detection plane.

  ➔ The incident angle ($\boldsymbol{\theta}_\chi$) of a DM particle affects the resulting event rate.

- ❖ Motion of the Sun ➔ The DM wind has a directional preference: CYGNUS!

  ➔ Non-trivial dependence of event rates on the incident angle ($\boldsymbol{\theta}_\chi^{\mathrm{w}}$) of the DM wind.

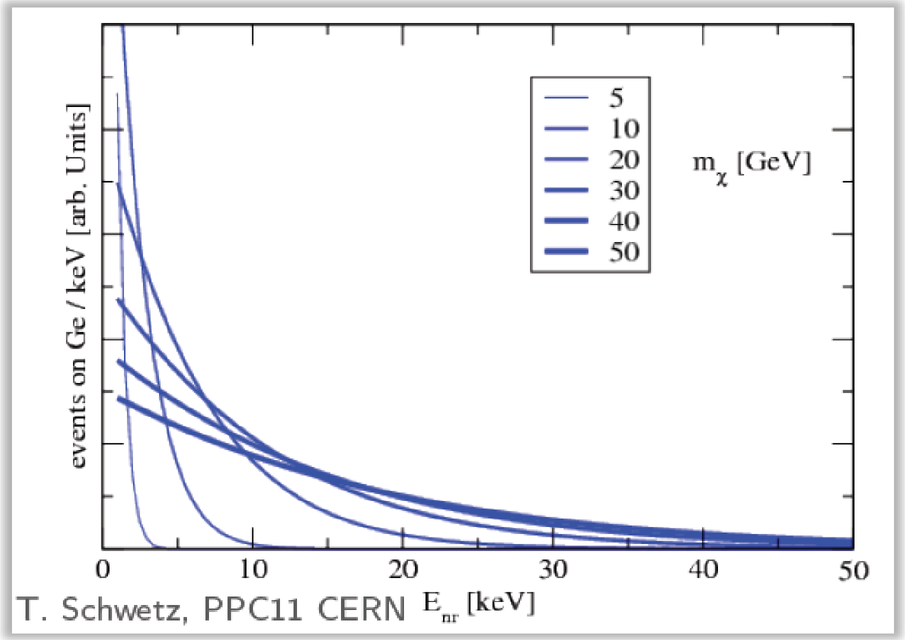




Answers for the Questions

- **<u>(effectively) 2D detectors</u>**: $\boldsymbol{v}_{\chi\parallel}$ is more relevant to event rates than $v_{\chi\perp}$ w.r.t. the detector plane.
- Heavy DM: a small v is good enough to overcome the E_{th}.

  vs Light DM: a large v is preferred.
- The 2D detection plane gets **exposed to the DM wind at various angles**. The resultant angular distribution of event rates per unit exposure time allows for the determination of the mass of DM.



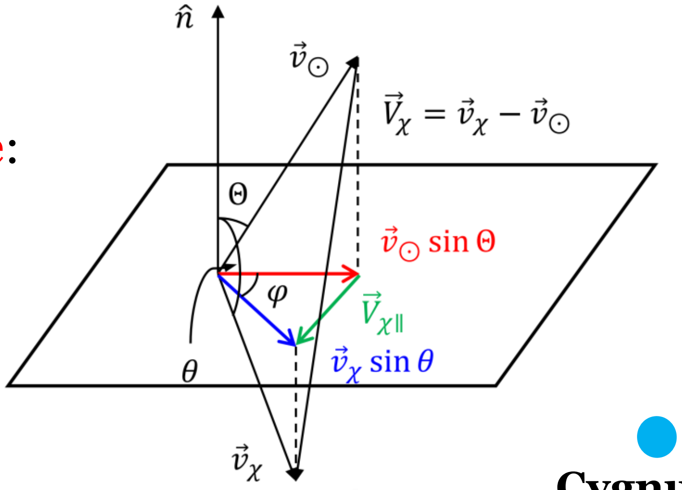
vs

$$\boldsymbol{m_\chi \leftrightarrow \theta}\ ?$$

2D Detection: Angular Dependence

Angular Dependence of Event Rates

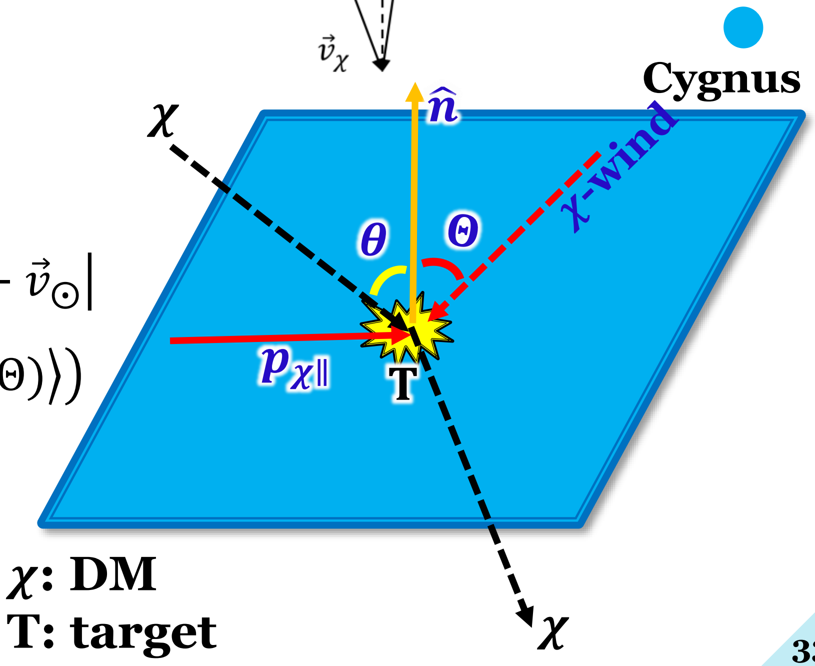
- Number of events/unit detector mass/unit run time: $n_{\rm eve} = \int dE_r dv_\chi\, f(v_\chi) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi \rm T} v_{\rm rel}\rangle \frac{\rho_\chi}{m_\chi}\right)$ with $\bar{N}_{\rm T}{=}N_{\rm T}/M_{\rm T}$.



- If the detector of interest is **2D**, $v_{\chi\parallel}$ (to the detection plane) affects the event rate:

$$n_{\rm eve} = \frac{\rho_\chi}{m_\chi}\int dE_r dv_{\chi\parallel}\, \tilde{f}(v_{\chi\parallel}) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T} v_{\rm rel\parallel}\rangle\right)$$

- Plane-projection of $f(v_\chi)$: $\tilde{f}(v_{\chi\parallel}) = \int_{-\sqrt{1-(v_{\chi\parallel}/v_{\rm esc})^2}}^{\sqrt{1-(v_{\chi\parallel}/v_{\rm esc})^2}} d\cos\theta \frac{1}{2\sin\theta} f(\frac{v_{\chi\parallel}}{\sin\theta})$



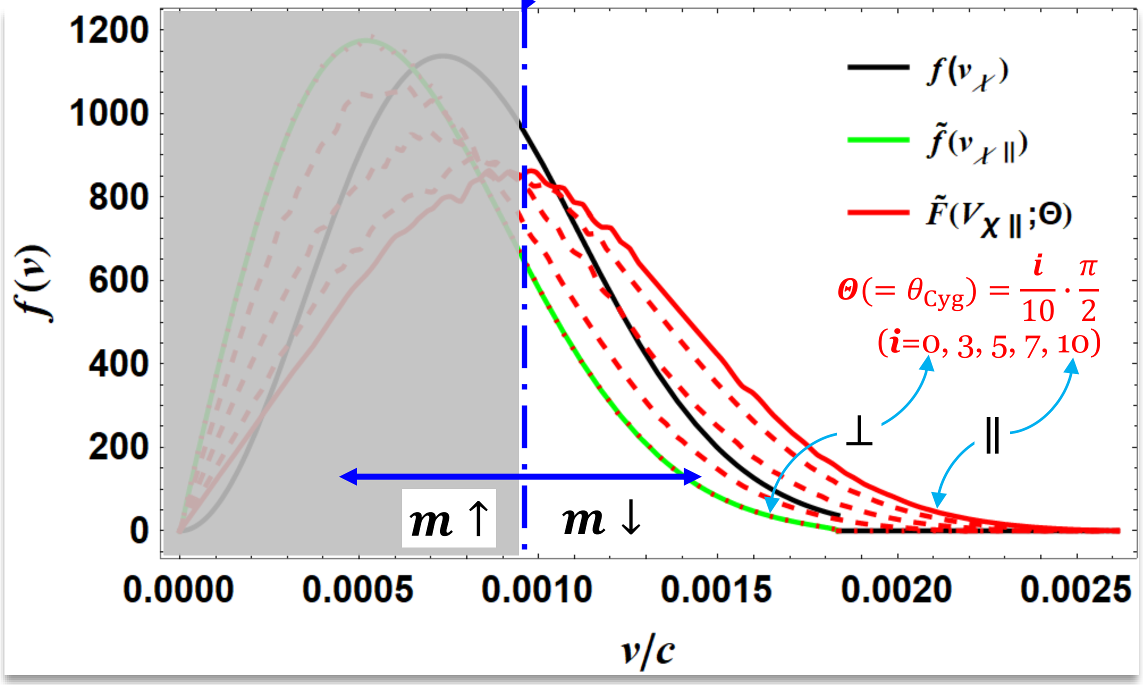
- Revolution of the solar system around the GC: $f(v_\chi) \to F(V_\chi)$ with $V_\chi \equiv |\vec{v}_\chi - \vec{v}_\odot|$

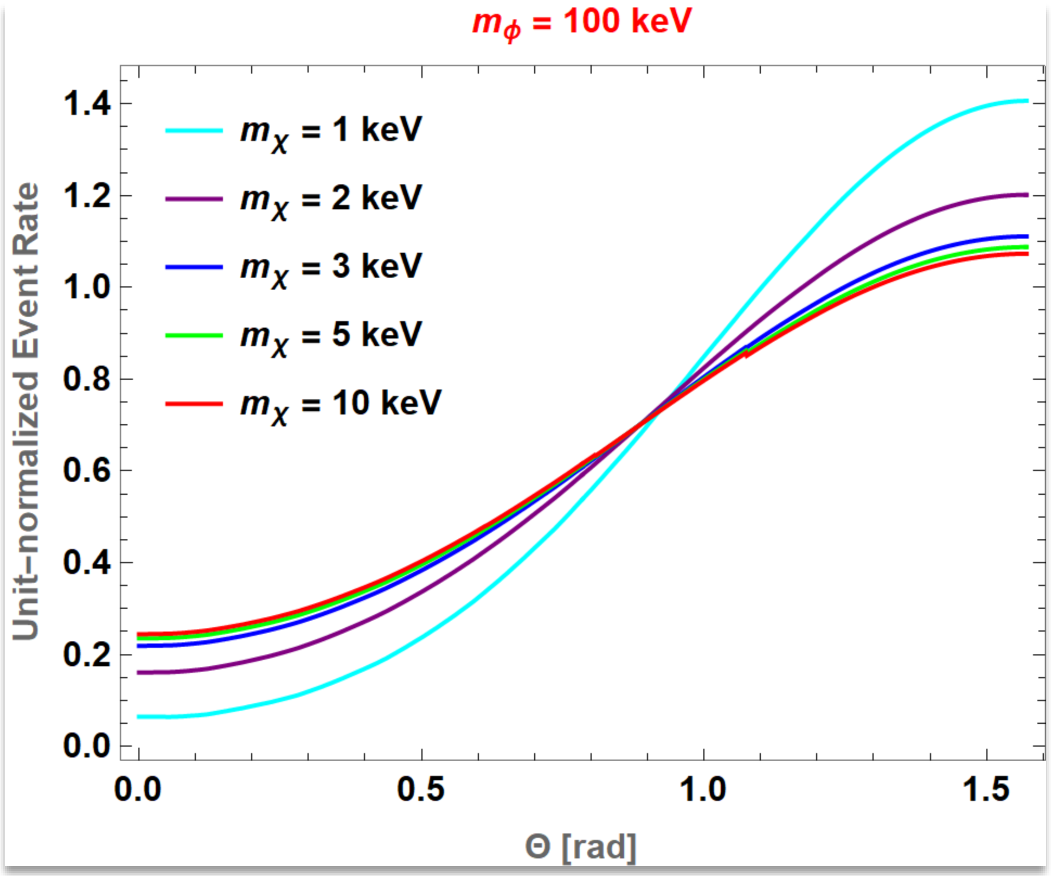
$$n_{\rm eve}(\Theta) = \frac{\rho_\chi}{m_\chi}\int dE_r dV_{\chi\parallel}\, \tilde{F}(V_{\chi\parallel};\, \Theta) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T} V_{\rm rel\parallel}(\Theta)\rangle\right)$$

For a given Θ between the Cygnus direction and $\hat{n}$, a plane-projection procedure of $F(V_\chi)$ should be done individually ➔ $\boldsymbol{n_{eve}}$ **depends on Θ**!

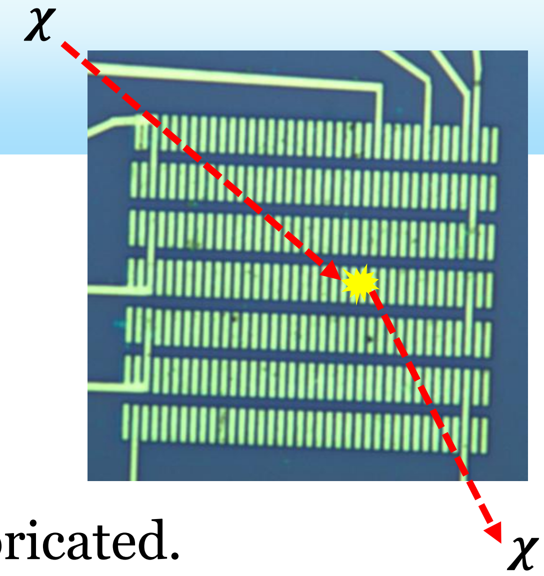
Angular Dependence ➔ Angular Scanning ➔ m

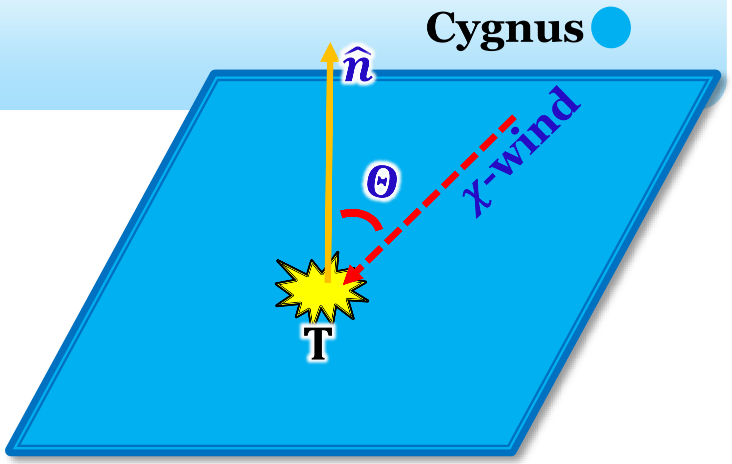
- $E_{\rm th} \neq 0$ ➔ $V_{\chi\parallel,\rm min}$ for DM signal detection.
- For smaller m_χ, larger $V_{\chi\parallel}$ is required. ➔ A dependence of $n_{\rm eve}$ on m_χ through $V_{\chi\parallel,\rm min}(m_\chi)$ ➔ **The curvature of the $\boldsymbol{\Theta}$ dependence**: $\boldsymbol{n_{\rm eve}(\Theta, m_\chi)} = \frac{\rho_\chi}{m_\chi}\int dE_r \int_{V_{\chi\parallel,\rm min}(m_\chi)}^{V_{\chi\parallel,\rm max}} dV_{\chi\parallel}\, \tilde{F}\left(V_{\chi\parallel};\, \Theta\right) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\left\langle \sigma_{\chi T} V_{\rm rel\parallel}(\Theta)\right\rangle\right)$ with $V_{\chi\parallel,\rm max} = v_{\rm esc} + v_{\odot}\sin\Theta$.





Summary





- **<u>GLIMPSE</u>**: 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 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!**: **<u>BG</u>** <u>rejection</u> & **<u>mass</u>** <u>determination</u>
- Generally applied to the **(effectively) 2D** or **2D-projectable** direct detection experiments allowing for **directionality observables**

Thank You!

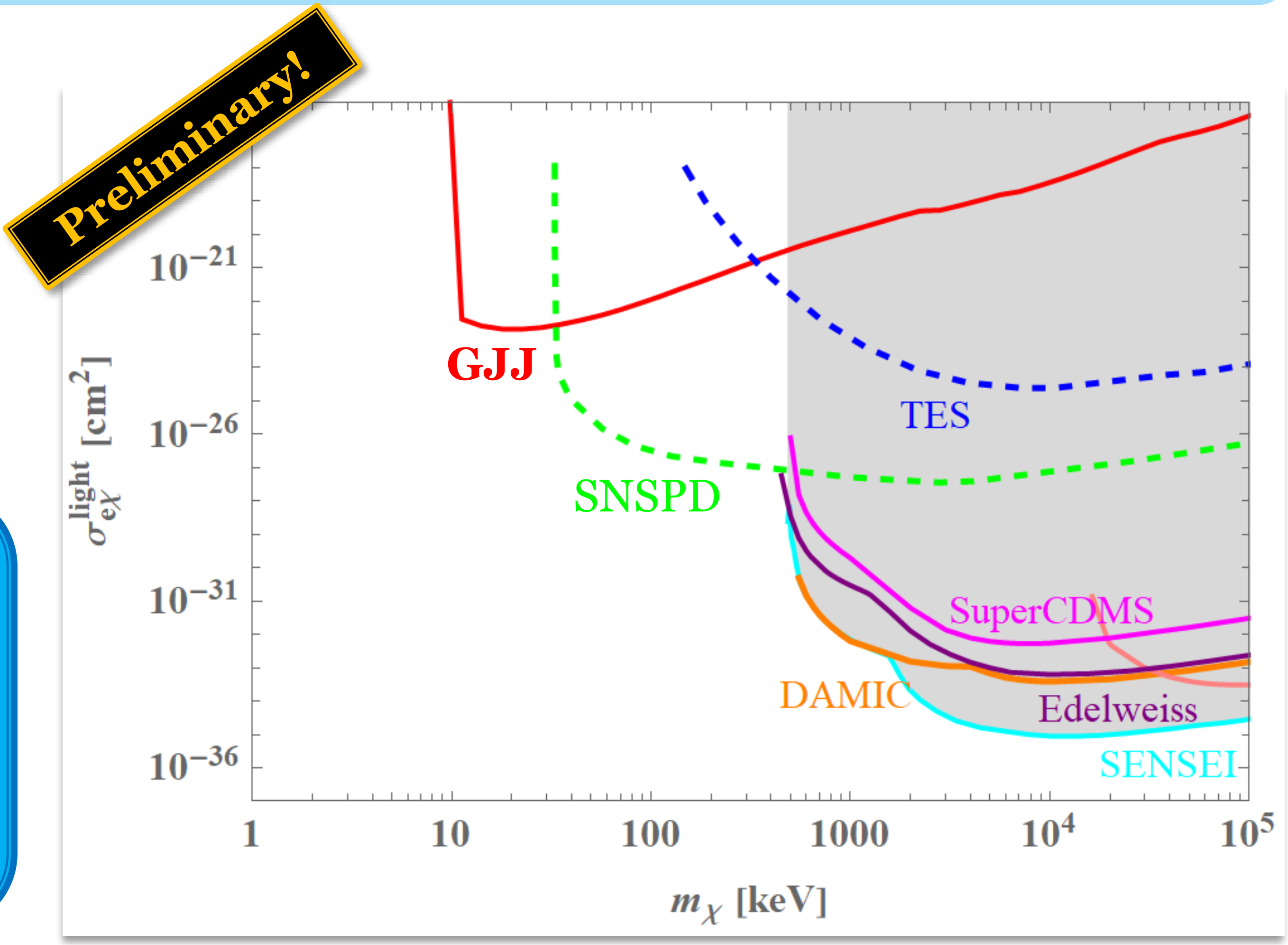
Supplemental

Expected Limits from Calibration

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

Requirements for sensitivities

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

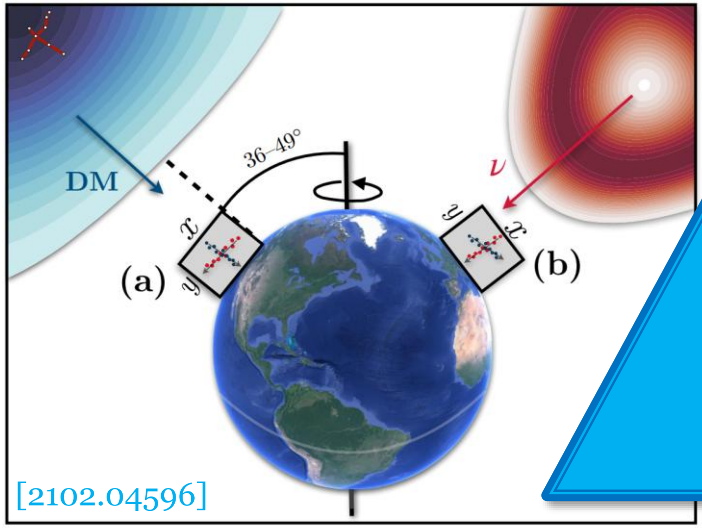


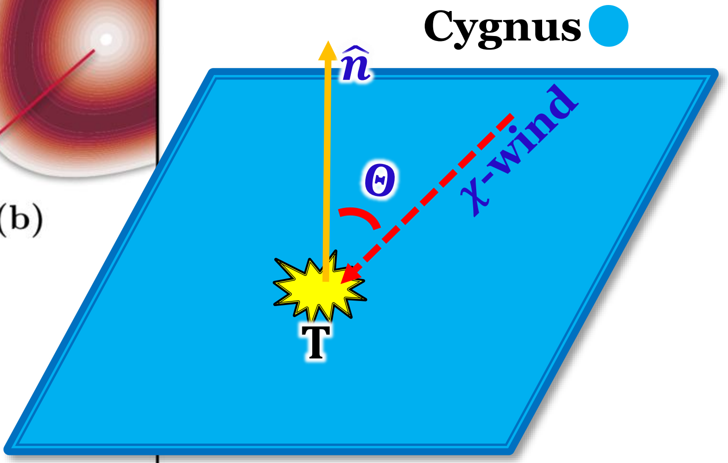
- ✓ SNSPD: $E_{th}\sim 0.11$ eV [PRL (2025)]
- ✓ TES: $E_{th}\sim 0.3$ eV [2506.18982]

Angular Modulation vs Annual Modulation

❖ **Angular modulation**

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





❖ **Annual modulation**

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