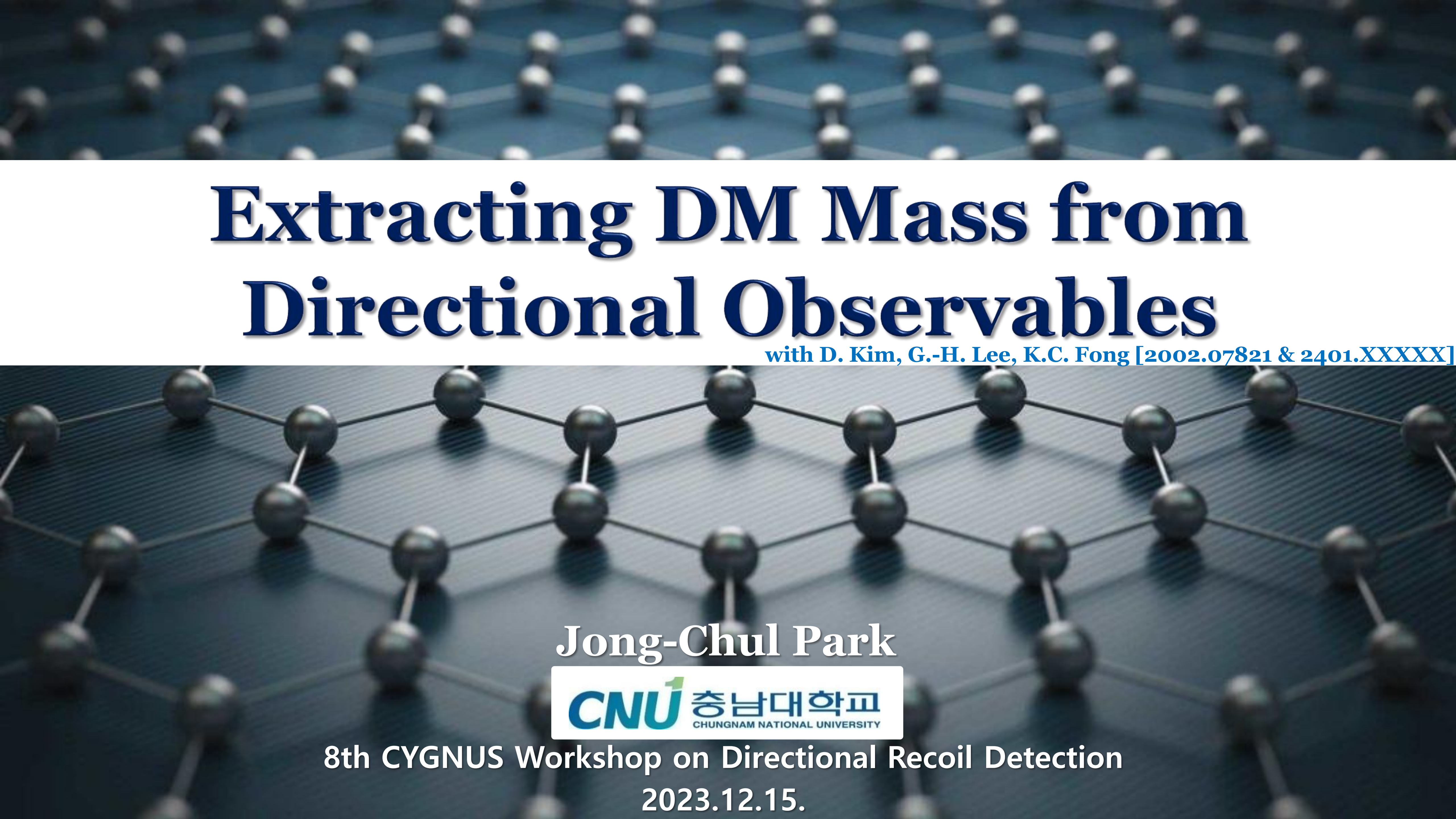


Extracting DM Mass from Directional Observables

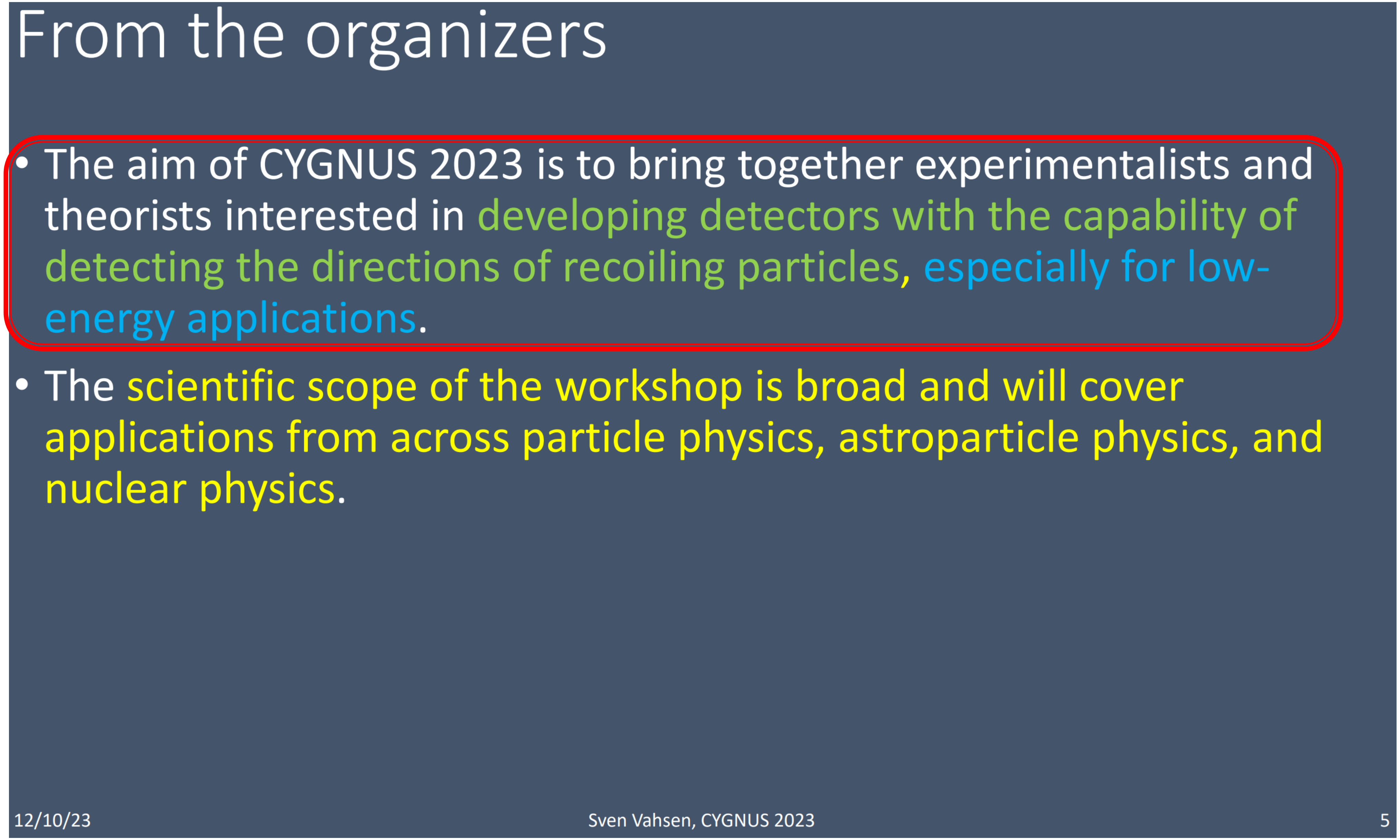
with D. Kim, G.-H. Lee, K.C. Fong [2002.07821 & 2401.XXXXX]

Jong-Chul Park

충남대학교
CHUNGNAM NATIONAL UNIVERSITY

8th CYGNUS Workshop on Directional Recoil Detection
2023.12.15.

Why Am I Here?

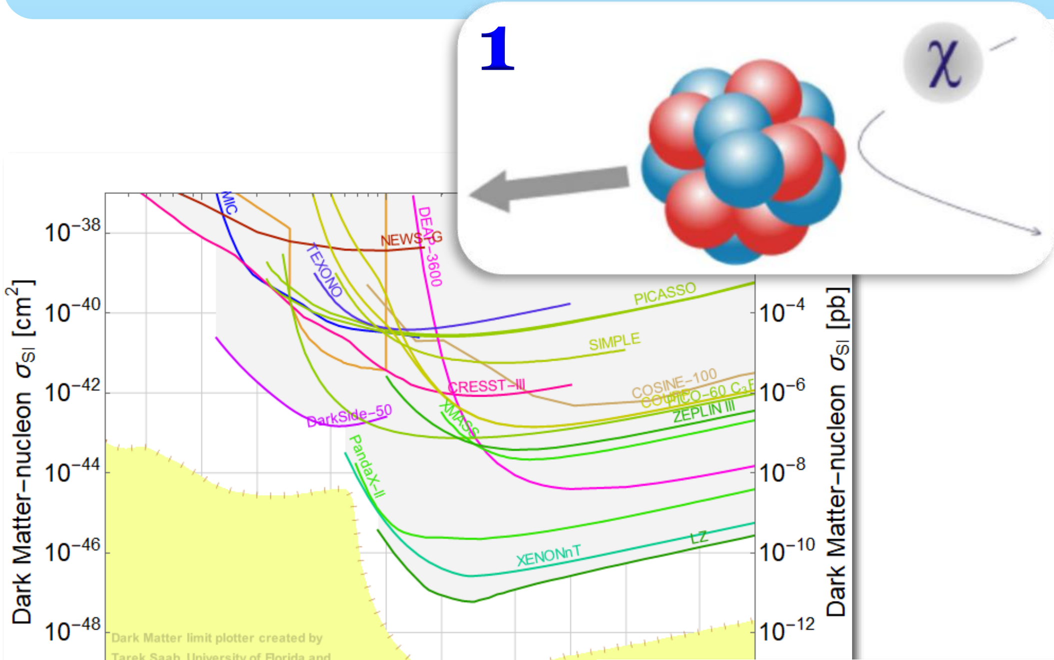


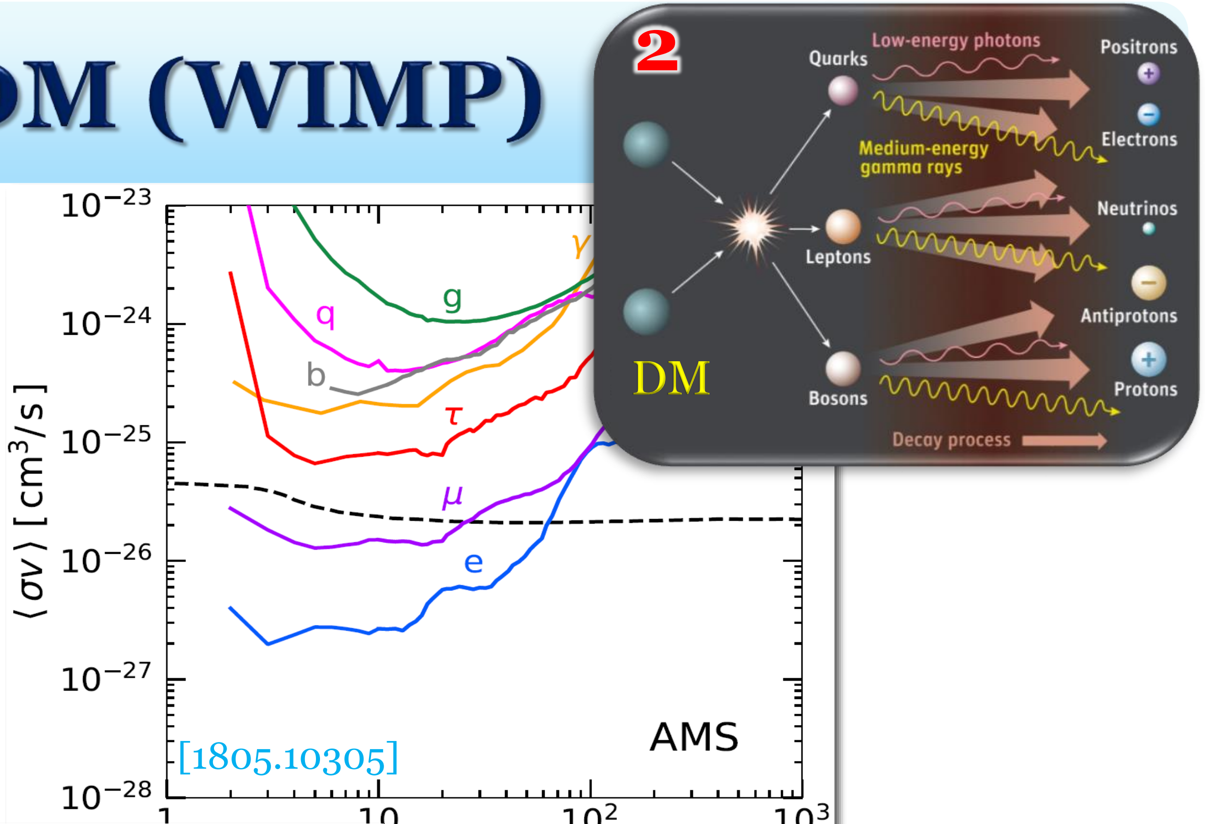
From the organizers

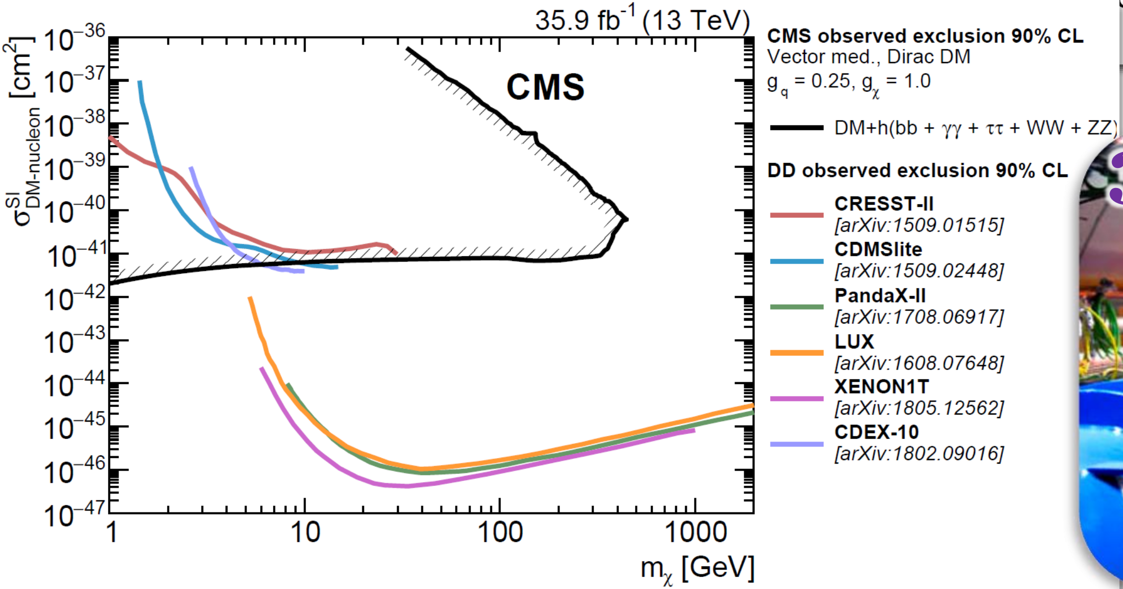
- The aim of CYGNUS 2023 is to bring together experimentalists and theorists interested in developing detectors with the capability of detecting the directions of recoiling particles, especially for low-energy applications.
- The scientific scope of the workshop is broad and will cover applications from across particle physics, astroparticle physics, and nuclear physics.

12/10/23 Sven Vahsen, CYGNUS 2023 5

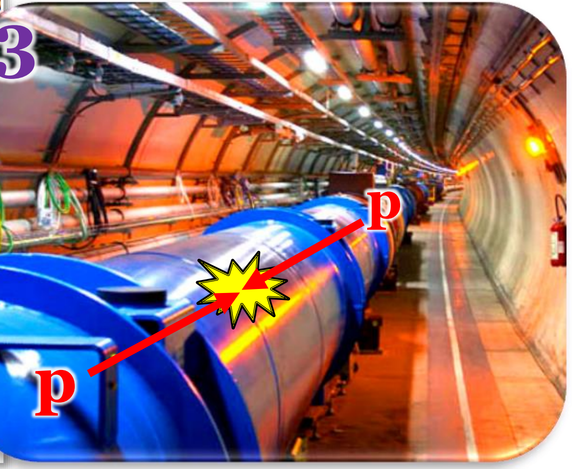
Current Search Status of DM (WIMP)







- ❖ **No solid observation**
- ➔ Stringent constraints on WIMP



Hmm…

WIMP Dead?

WIMP: Still Alive

Is there room left for WIMPs?

We need WIMPs to annihilate efficiently in the early Universe, but to have escaped detection in direct, indirect and collider searches

Direct detection	Suppressed if scattering cross section depends on spin, velocity or momentum
Indirect detection	Suppressed if annihilation cross section is p-wave
Collider production	Suppressed if DM couples to the SM through hidden-sector portal interactions (e.g. a dark photon mediator)

Time to extend our point of view?!

Even for models with unsuppressed signals, much of the parameter space has not yet been searched!

Dark Matter 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!

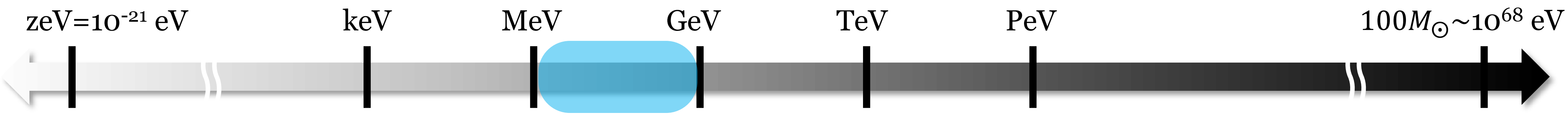
Super-heavy

composite,
WIMPzilla,
Q-ball,
Fermi-ball,
dark-quark
nugget,
non-thermal

Astrophysical object

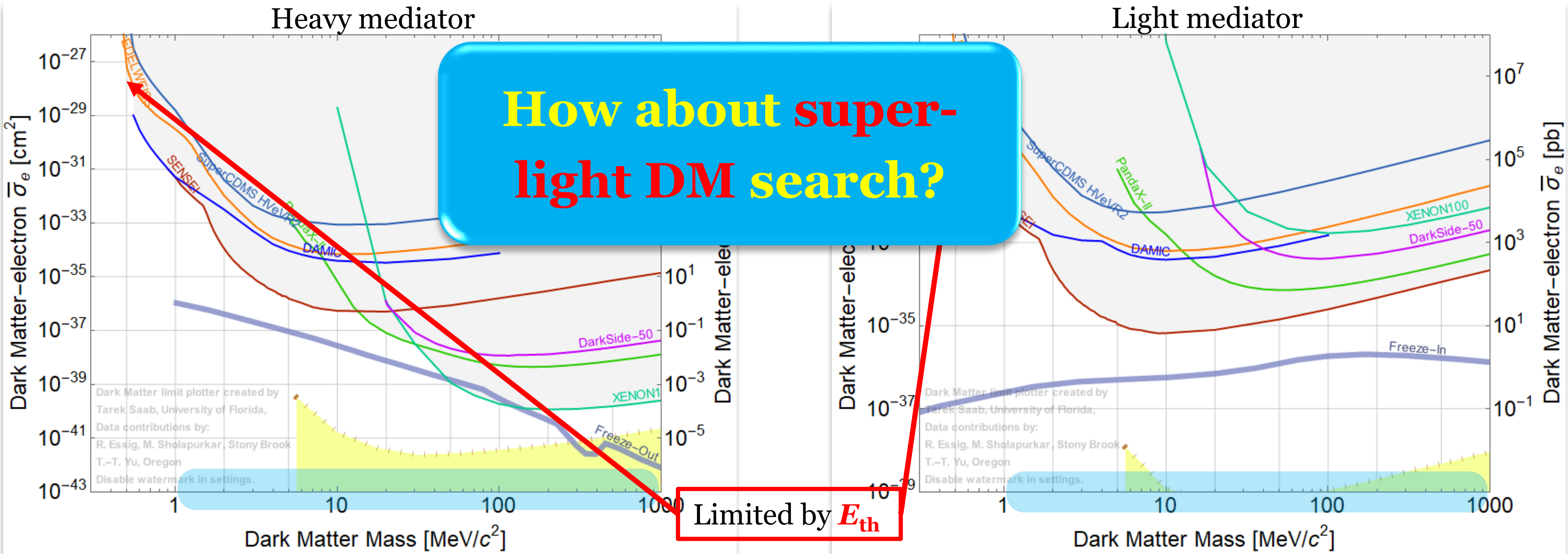
MACHO, PBH,
non-particle

Light DM Direct Search



- $E_\mathrm{k} \sim mv^2$, $\Phi_\chi = n_\chi v_\mathrm{rel} = (\rho_\chi/m_\chi)v_\mathrm{rel}$
  - ➔ **lighter DM**: **smaller E_r**, but **lager flux** (**lighter** target particle)
  - ➔ **low E_th** preferred but even OK with **small target mass** (**e-recoil**)

✓ **A way out: $v{\sim}c$**
e.g., BDM



How about super-light DM search?

Limited by E_th

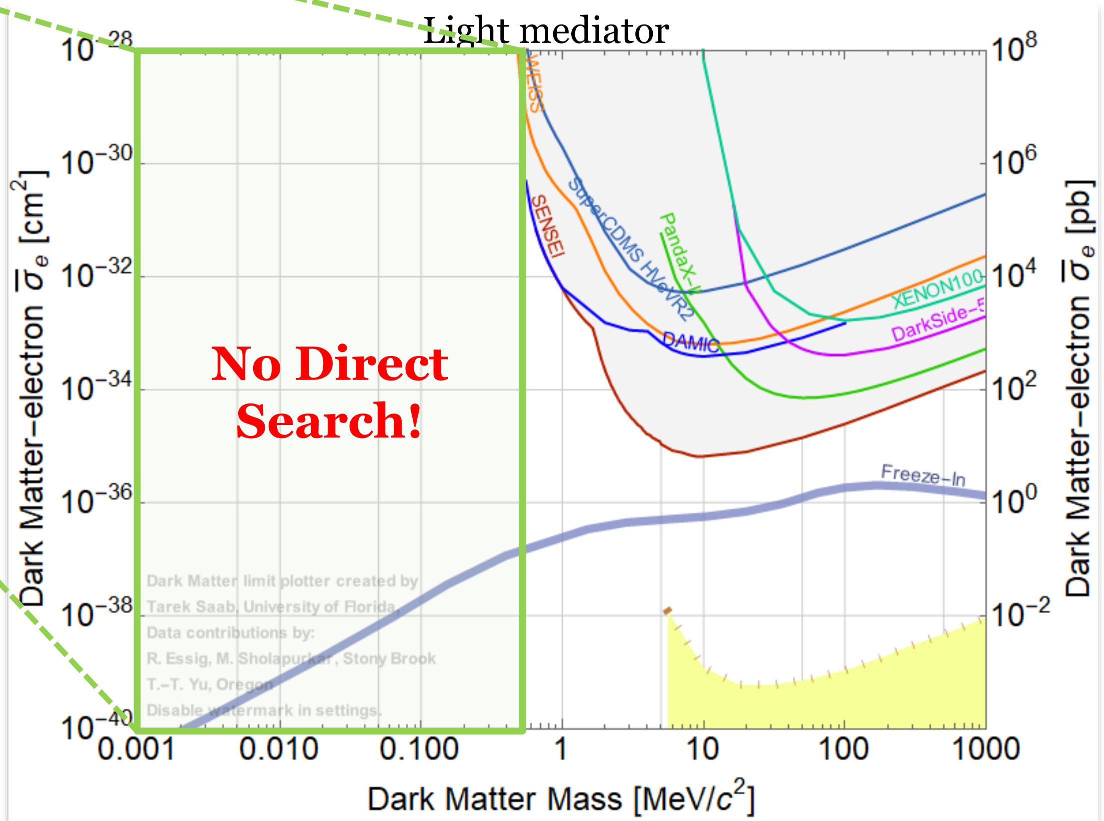
Dark Matter Limit Plotter v5.18 (April 07, 2023)

Super-Light DM Direct Search

- $E_k \sim mv^2 \sim O(\text{meV})$ with $m \sim \text{keV}$ & $v \sim 10^{-3}$
- **New approaches** are required!
  - ✓ Targets: Superconductor, Superfluid He, 3D Dirac material, Polar material, Graphene, Diamond, etc.
  - ✓ Sensor technologies: TES, MKID, STJ, SNSPD, GJJ, etc.

➔ The **race** to prove **super-light DM** has begun.

- **No experiment** for **O(keV) DM** so far.



Dark Matter Limit Plotter v5.18 (April 07, 2023)

Potential Questions

1. **Light DM ↔ Directional detection**:

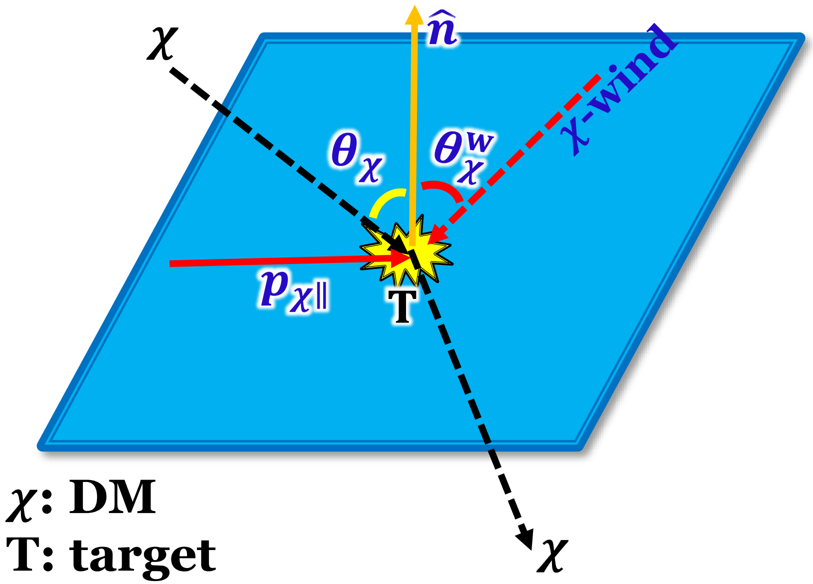
- ✓ For better directional recoil detection, higher E_r is mostly preferred, e.g., longer track.
- ✓ But, our focus is super-light DM.
  - ➔ Lighter DM induces lower E_r, and thus less visible signals (tracks).
  - ➔ **Can light DM be connected to directional recoil detection?**

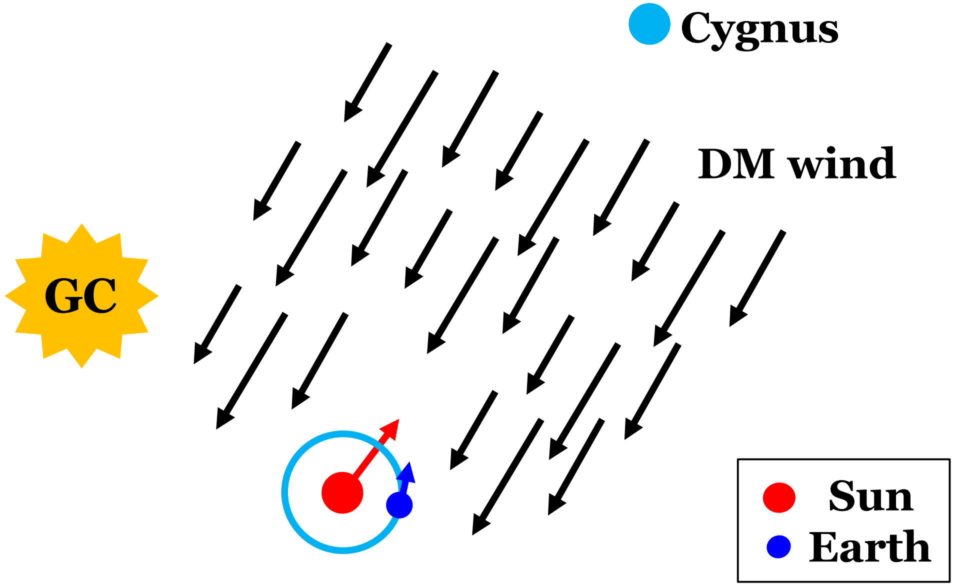
2. **Mass information**:

- ✓ Direct detection experiments utilize the differential E_r spectrum to identify the DM mass scale.
- ✓ But, various low E sensor technologies feature the "**on-off**" type working principle or relatively poor E resolution.
  - ➔ We may recognize a DM event occurrence, but not measure the magnitude of the E deposit.
  - ➔ **Is there any alternative method to determine the mass of DM?**

Answers for the Questions

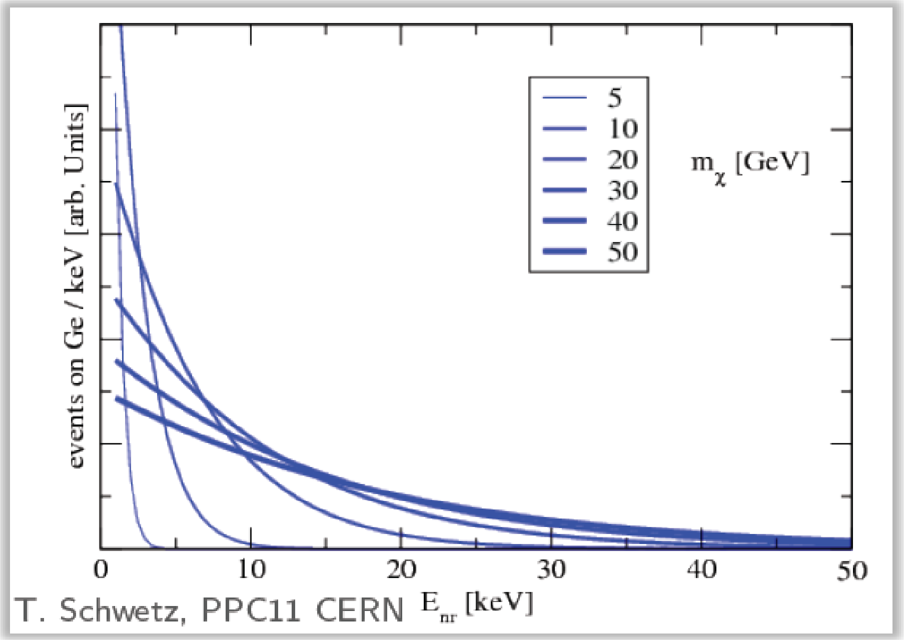
- Our approach is available for experiments using (effectively) 2D detectors: their experimental signatures are related to the behavior of targets scattered by DM along the detection plane, the incident angle ($\boldsymbol{\theta}_\chi$) of a DM particle with respect to the plane-normal direction affects the resulting event rate.
- The solar system moves around the galactic center. ➔ The resulting DM flux has a directional preference: CYGNUS! ➔ We expect a non-trivial dependence of event rates on the angle ($\boldsymbol{\theta}_\chi^{\mathbf{w}}$) between the plane-normal direction and the DM wind due to the motion of the solar system.





Answers for the Questions

- The velocity component parallel to the detection plane is more relevant to event rates than that normal to the plane for (effectively) 2D detectors.
- Heavy DM: a small v is good enough to get over the E_{th}, leaving a detectable signature + m via dR/dE_r. vs Light DM: a large v is preferred (+ no or poor dR/dE_r).
- 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.



T. Schwetz, PPC11 CERN

vs

$$m_\chi \leftrightarrow \theta\ ?$$

GLIMPSE

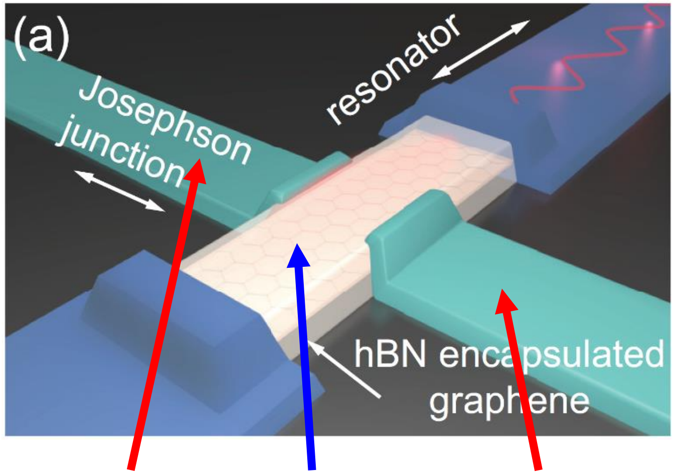
Graphene-based super-Light Invisible Matter Particle SEarch

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

GJJ Device

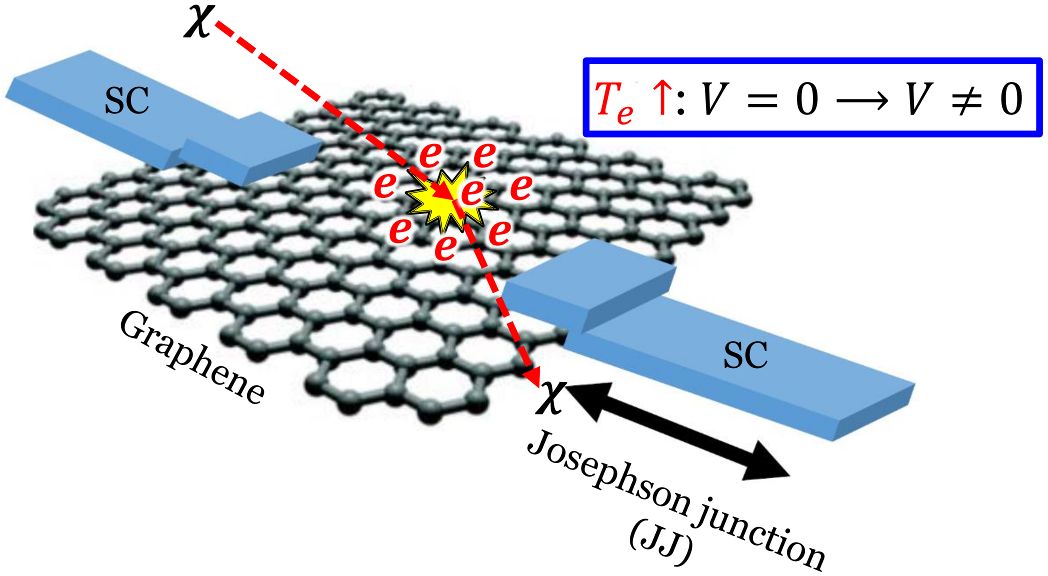


Superconductor-Graphene-Superconductor (SGS)
[G.-H. Lee et al. Nature (2020)]

Two sides of mono-layer graphene are joined to superconductors.
➔ a superconductor-normal metal-superconductor Josephson junction.

- A GJJ single-photon detector was proposed, covering from near-IR to microwave. [Phys. Rev. Applied (2017)]
- G.-H. Lee, K.C. Fong & their collaborators have **demonstrated experimentally** that the GJJ microwave bolometer can have **sensitivity to ~0.1 meV energy deposits**. [Nature (2020)]
- The detection of single near-IR photon (**E~1 eV**) has been done. [Science (2021)]
- Currently, a **GJJ single-photon detector** for **E~1 meV** is under testing.

Detection Principle with GJJ

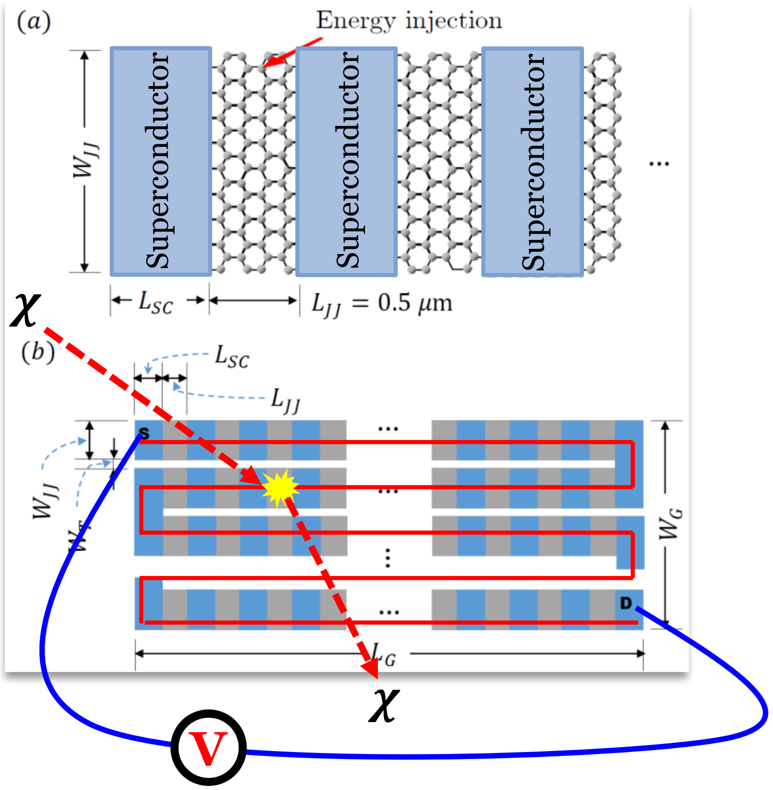


I. **DM scatters off (π-bond) free electrons**, transferring some fraction of its incoming E_k.

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 0-voltage of JJ to a **non-zero-voltage state**.

Super-Light DM Direct Search Using GJJs



I. Single graphene strip (a): the 1D assembly of a long graphene strip & a number of superconducting material pieces

➔ an array of SC-graphene-SC-graphene-SC-⋯ (SGSGS⋯).

II. Each sequence of SGS represents a single GJJ device.

III. 2D detector unit (b): all GJJs are connected in series so that even a single switched GJJ by DM interaction allows the series resistance between S & D

➔ V changes from 0 to a finite value.

❖ A much larger-scale detector can be made of a stack of such detector units (3D).

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.

Constrained elastic scattering

Calculation Procedure I

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

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

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

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

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

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

2D nature of graphene

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

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

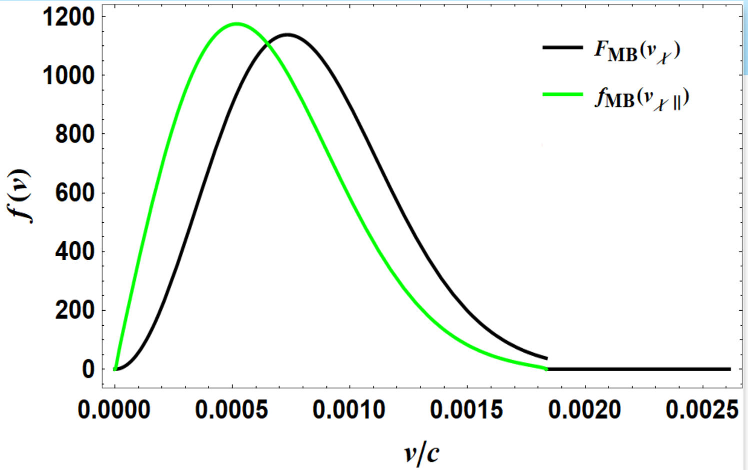
$$= 2 \int \frac{d^3 p_{e,i}}{(2\pi)^3} (2\pi) \underline{\delta(p_{e,i}^z - p_{e,f}^z)} f_{e,i}(E_{e,i})$$

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

➔ Fermi-Dirac distribution function

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

Calculation Procedure II



❖ **Graphene-surface-parallel DM velocity** profile:

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

➔ **A plane-projection** of a Maxwell-Boltzmann distribution.

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

❖ **Structure function** for the **2D** system:

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

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

$$= (2\pi)\delta(p_{\chi,i}^z - p_{\chi,f}^z)\cdot\boldsymbol{S}_{\mathbf{3D}}(\boldsymbol{E_r},\ \boldsymbol{q})$$

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

Calculation Procedure III

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

✓ ρ_χ =0.3 GeV/cm^3

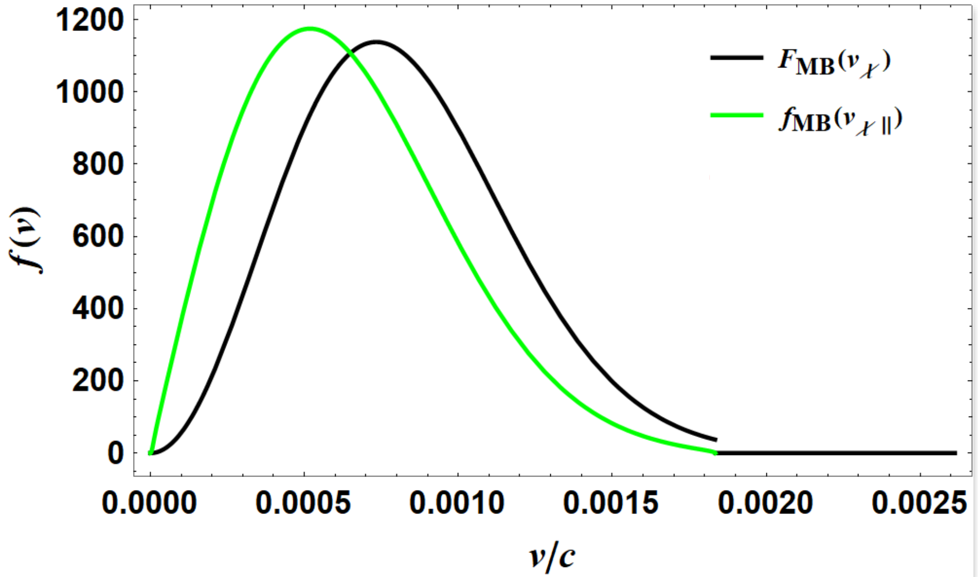
✓ v_0=220 km/s, $v_{\rm esc}$=550 km/s

✓ $\rho_{\rm gr}^{\rm 2D} = 7.62\times10^{-8}$g/cm^2

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

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

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



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

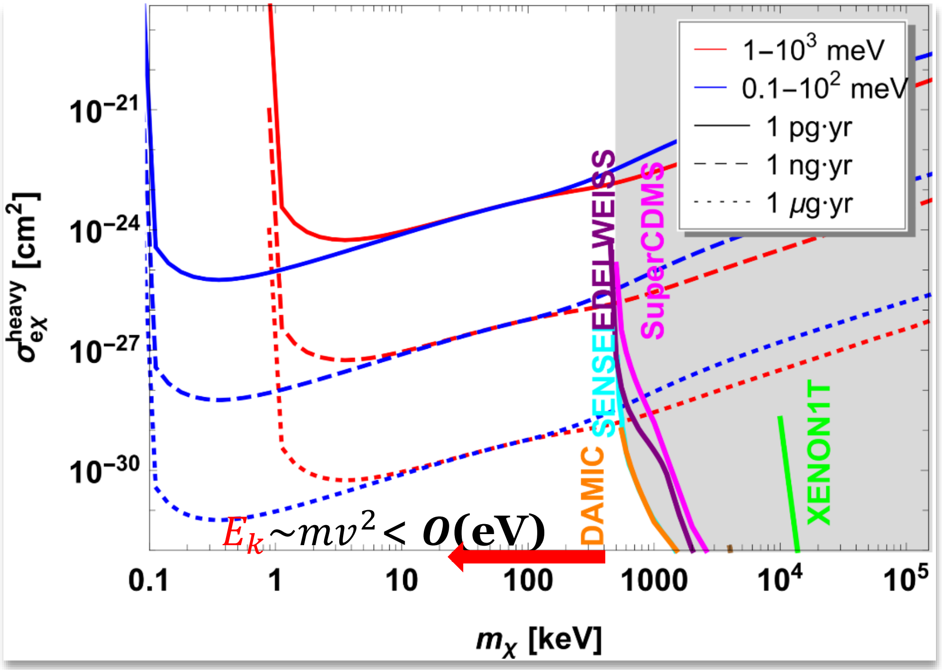
$$\sigma_{e\chi} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{(m_\phi^2+q^2)^2} \rightarrow \sigma_{e\chi}^{\rm heavy} \approx \frac{g_e^2 g_\chi^2}{\pi}\frac{\mu_{e\chi}^2}{m_\phi^4} \text{ for } (m_\phi^2 \gg q^2)$$

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

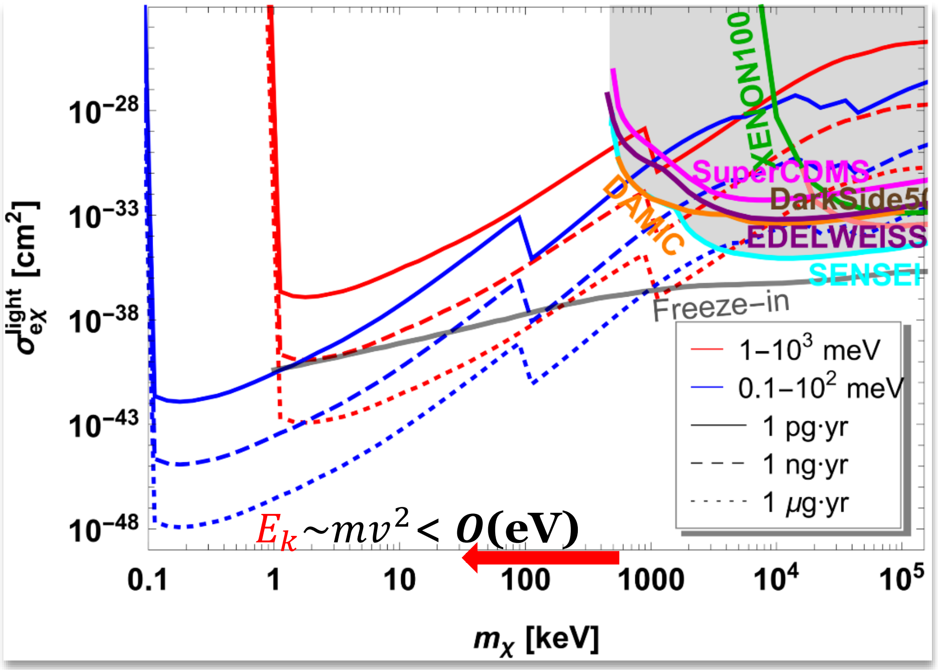
- From the linear dispersion of graphene: $E_F = v_F\sqrt{\pi n_c}$ with $v_F \sim 10^8$cm/s & $n_c \sim 10^{12}$/cm^2.

Expected Sensitivities of GLIMPSE

Heavy mediator: $F_{DM} = 1$



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

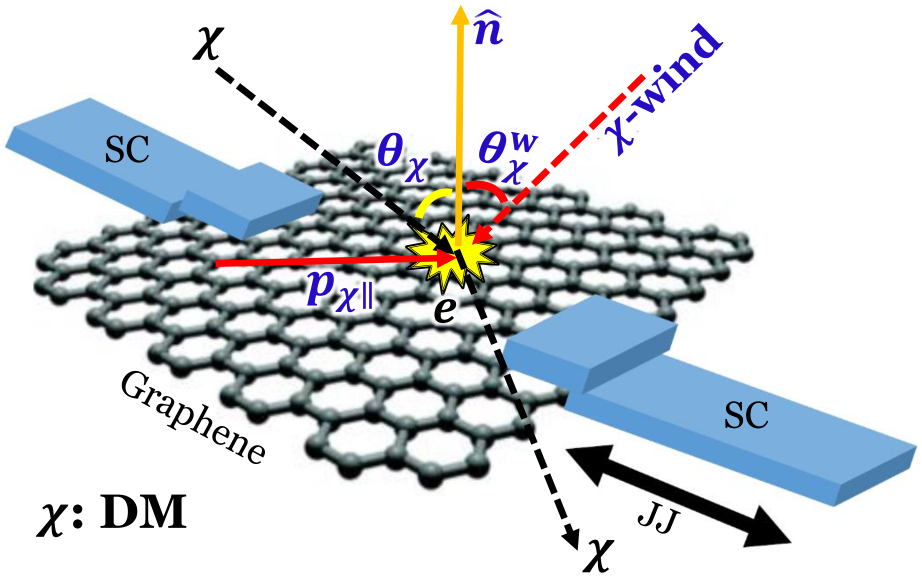


- ✓ The proposed detector (GLIMPSE) can improve the minimum detectable DM mass (**$m_{DM} \sim 0.1$ keV**) by more than 2-3 orders of magnitude over the ongoing/existing experiments.
- ✓ **Capable of probing** the prediction of **freeze-in** scenarios even with a pg-scale ($\sim 10^3$ GJJs) detector.

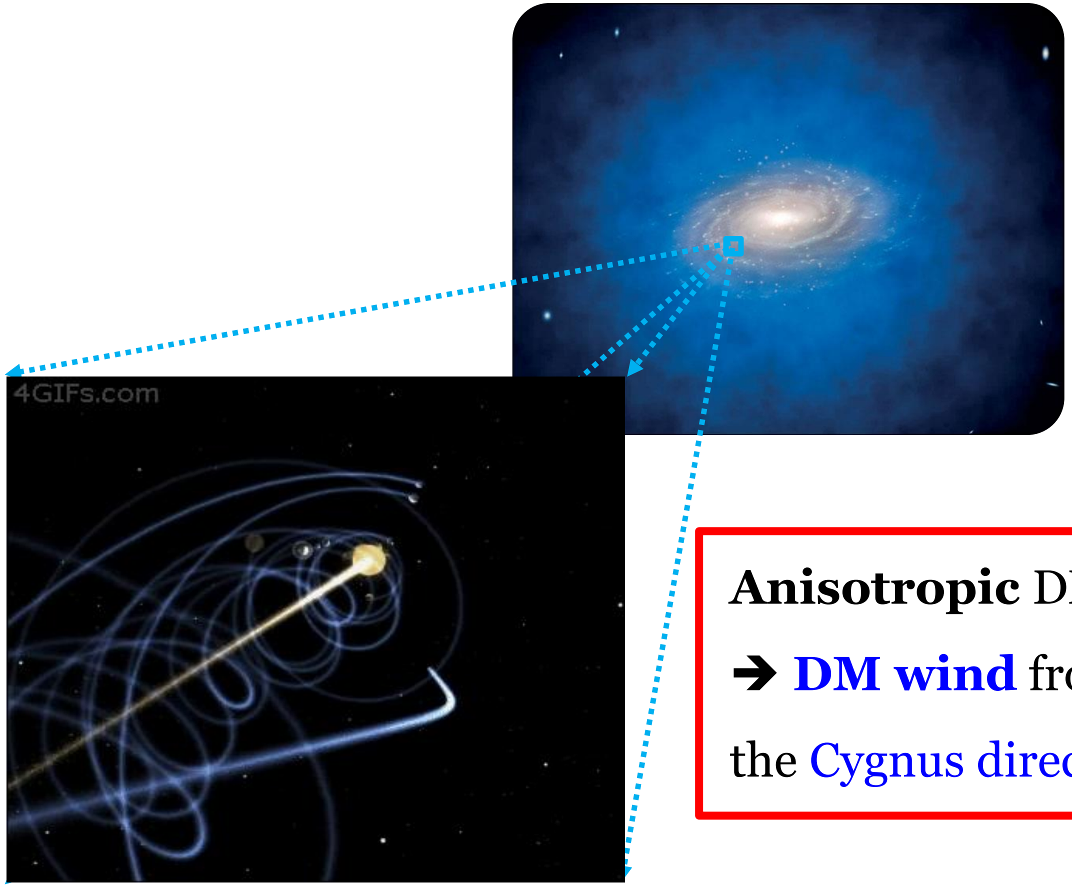
Signal Rate: Directional Dependence

❖ **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



χ: **DM**



Anisotropic DM flux

➔ **DM wind** from

the Cygnus direction

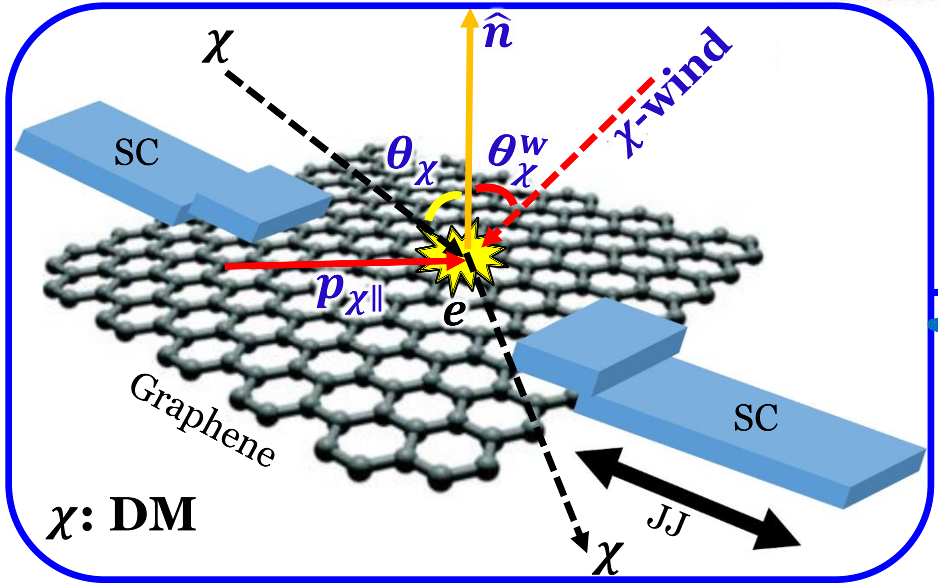
Signal Rate: Directional Dependence

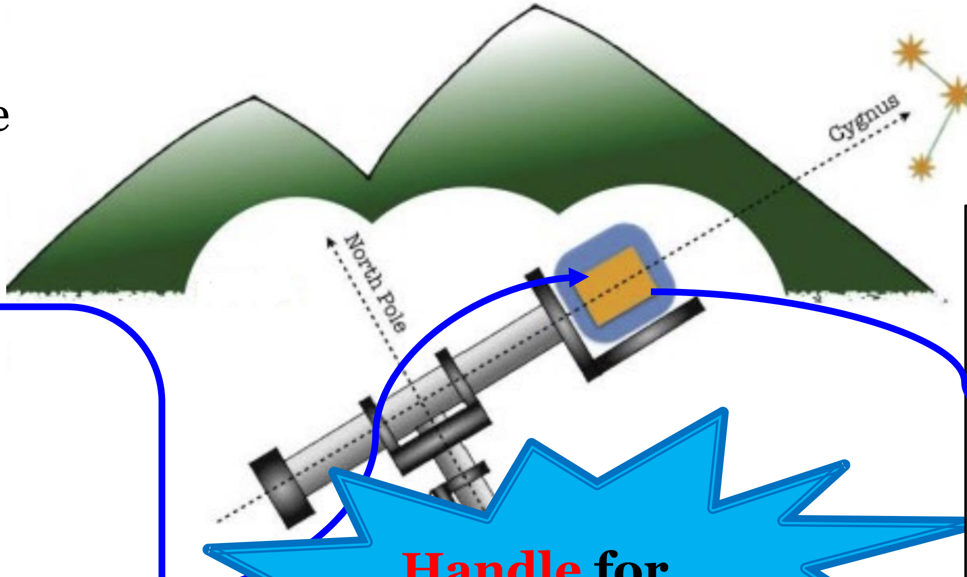
❖ **Constrained** elastic scattering: Electron confined in the 2D graphene sheet even after the collision.

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

➔ DM signals: in situ validation by **actively rotating the detector** or ***t* information of signals** (statistical)

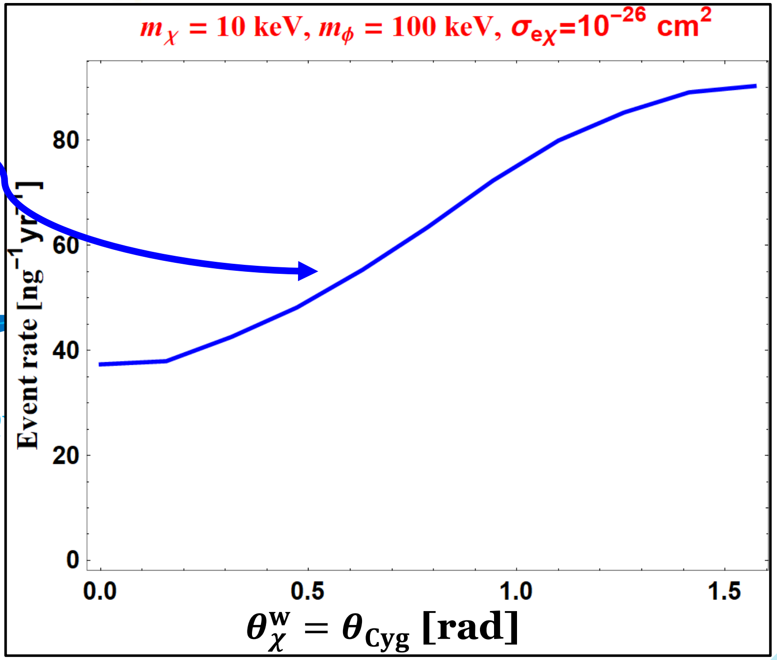
- ✓ $\boldsymbol{\theta_\chi}$: event-level unmeasurable
- ✓ $\boldsymbol{\theta_\chi^{w} = \theta_{\mathrm{Cyg}}}$: controllable & statistical measurable





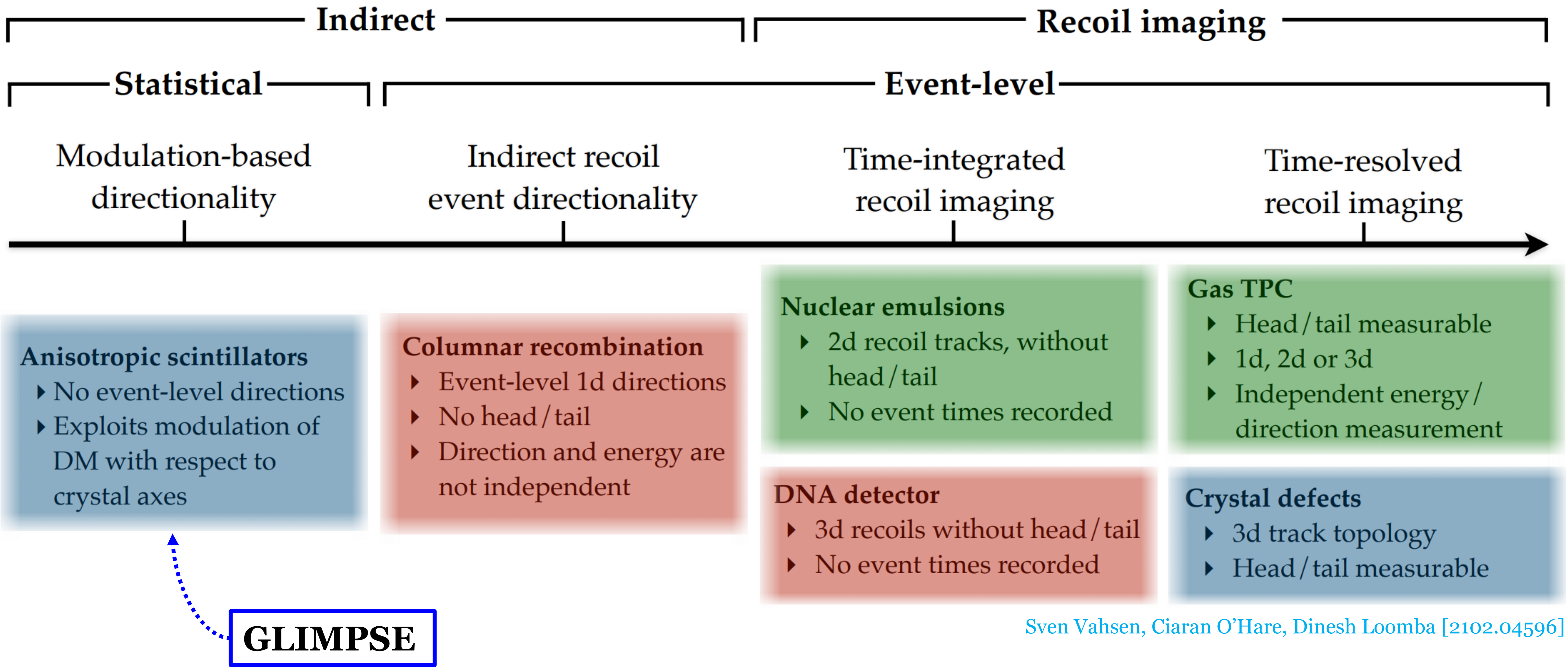
Handle for BG rejection!

EWSdm, Q



Detector classes by directional information

Demonstrated 🟩
R&D 🟦
Proposed 🟥



Indirect

Recoil imaging

Statistical

Event-level

Modulation-based directionality

Indirect recoil event directionality

Time-integrated recoil imaging

Time-resolved recoil imaging

Anisotropic scintillators
- No event-level directions
- Exploits modulation of DM with respect to crystal axes

Columnar recombination
- Event-level 1d directions
- No head / tail
- Direction and energy are not independent

Nuclear emulsions
- 2d recoil tracks, without head / tail
- No event times recorded

DNA detector
- 3d recoils without head / tail
- No event times recorded

Gas TPC
- Head / tail measurable
- 1d, 2d or 3d
- Independent energy / direction measurement

Crystal defects
- 3d track topology
- Head / tail measurable

GLIMPSE

Sven Vahsen, Ciaran O'Hare, Dinesh Loomba [2102.04596]

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 $\bar{N}_{\rm T}=N_{\rm T}/M_{\rm T}$.

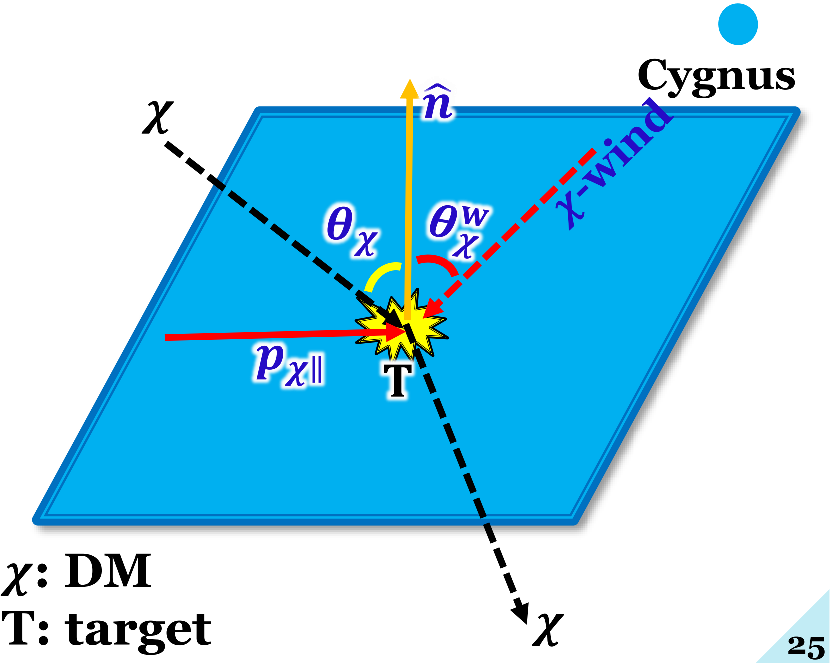
- If the detector of interest is 2D, $v_{\chi\parallel}$ (to the detection plane) affects the event rate, similarly to the case of GLIMPSE:

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

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

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

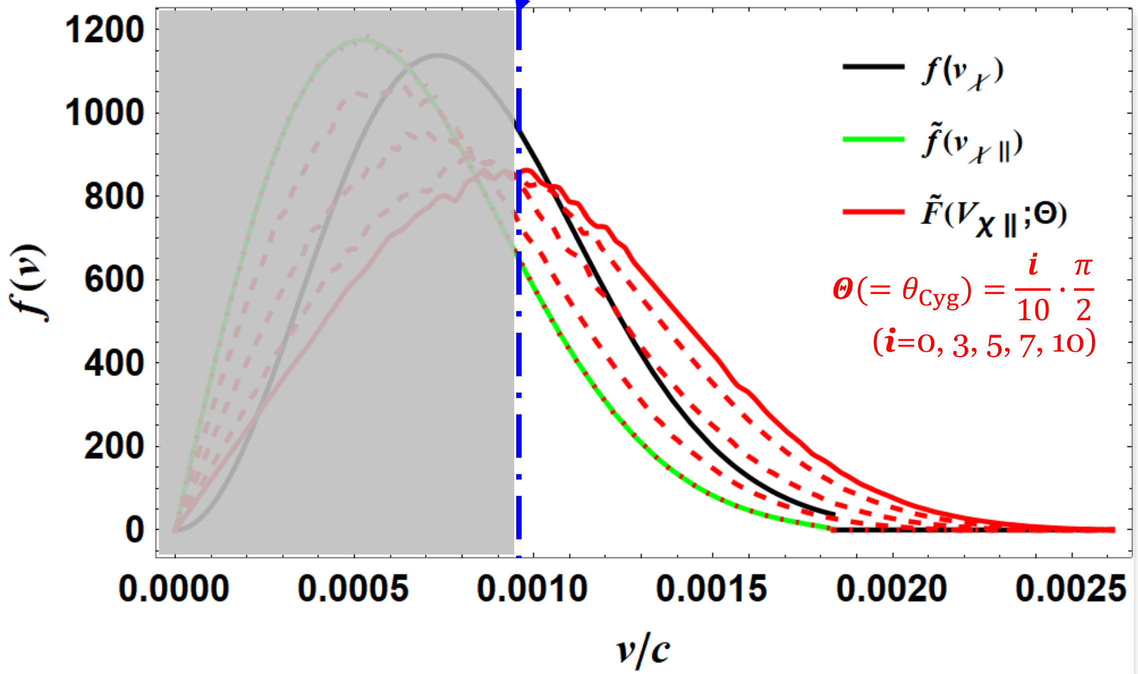
$$n_{\rm eve}(\Theta) = \frac{\rho_\chi}{m_\chi}\int dE_r dV_{\chi\parallel}\,\tilde{F}(V_{\chi\parallel};\,\Theta)\frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T}V_{\rm rel\parallel}(\Theta)\rangle\right)$$

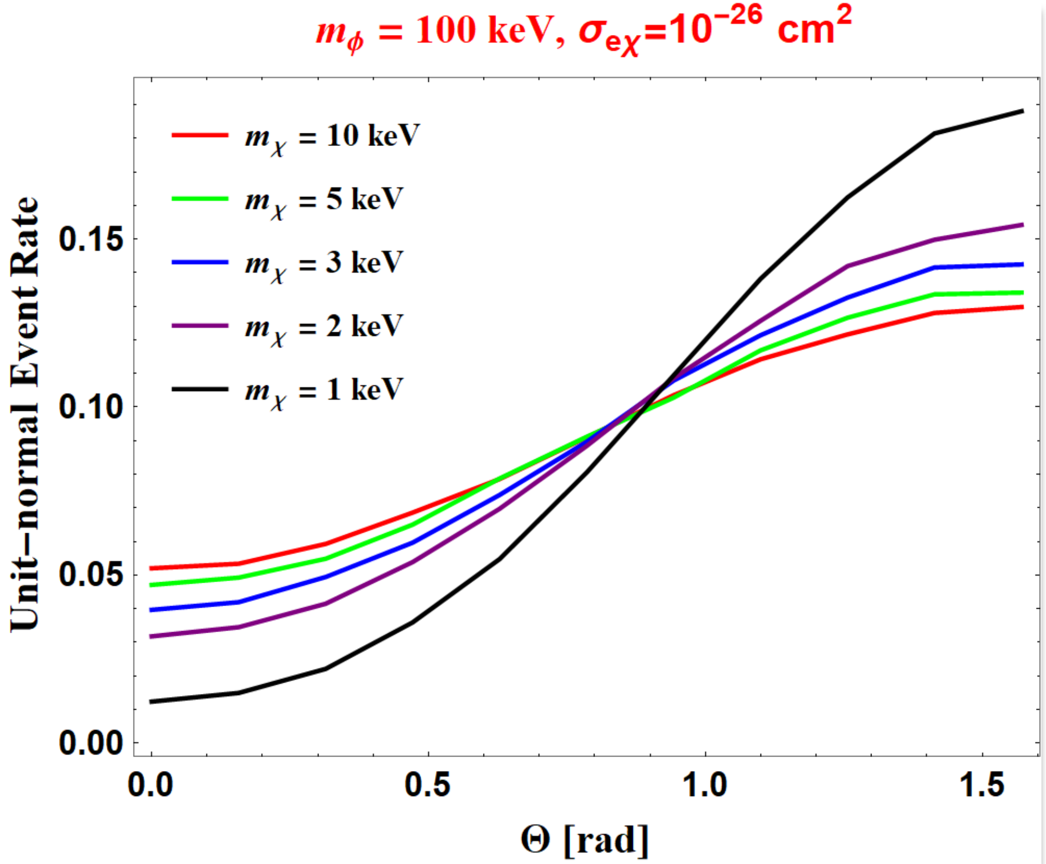


χ: DM
T: target

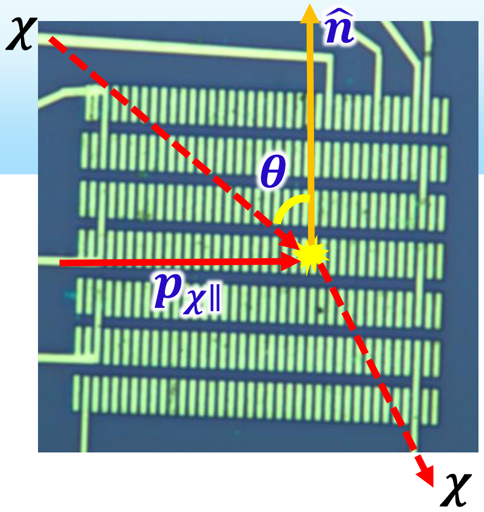
Angular Dependence of Event Rates

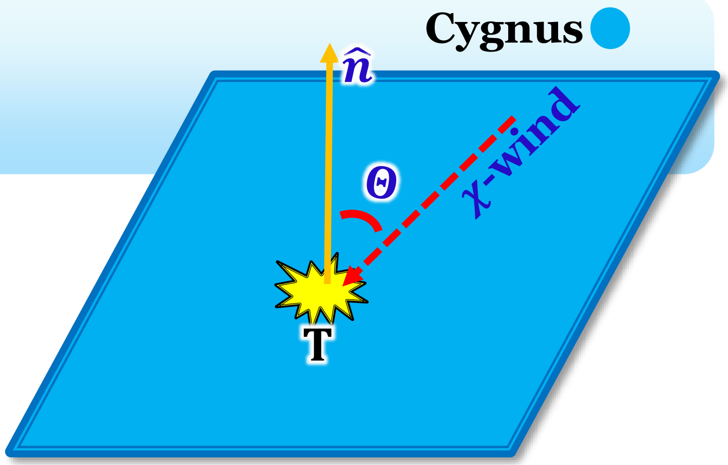
- $E_{\rm th} \neq 0$ ➔ $V_{\chi\parallel,\rm min}$ for DM signal detection.
- For smaller m_χ, larger $V_{\chi\parallel}$ is required. ➔ A dependence of $n_{\rm eve}$ on m_χ through $V_{\chi\parallel,\rm min}(m_\chi)$ ➔ **The curvature of the Θ dependence**: $\boldsymbol{n_{\rm eve}(\Theta, m_\chi)}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




m_ϕ = 100 keV, $\sigma_{e\chi}=10^{-26}$ cm^2

Summary





- **GLIMPSE**: Novel DM search strategy adopting a cutting-edge quantum sensor - GJJ.
- Constrained scattering: electron confined in **2D** graphene ➔ construction of an effective model with angular dependence ➔ **Signal rate: DM incident direction dependence**!
- Capable of sensing keV-range DM scattering off e's due to $\boldsymbol{E_{\text{th}} \sim 0.1\ \text{meV}}$.
- DM flux carries a directional preference: CYGNUS.
- New method to determine DM mass: **mass** from the **curvature of the angular spectrum**.
- Generally applied to the (effectively) 2D or 2D-projectable direct detection experiments allowing for directionality observables

Thank You!