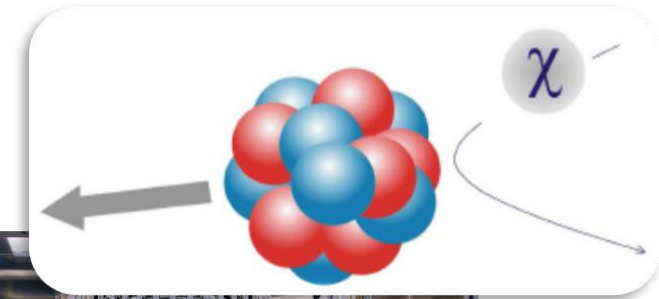
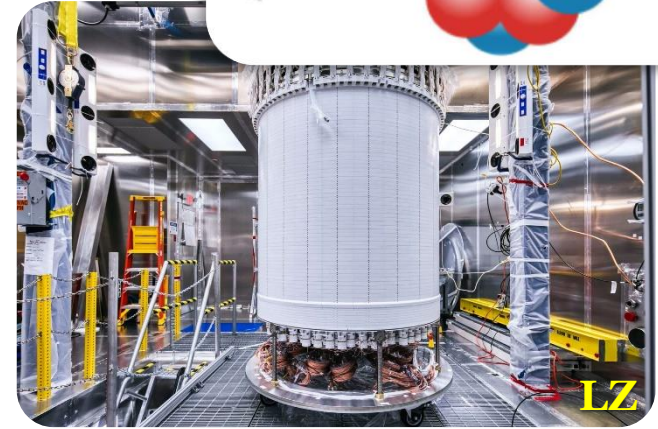
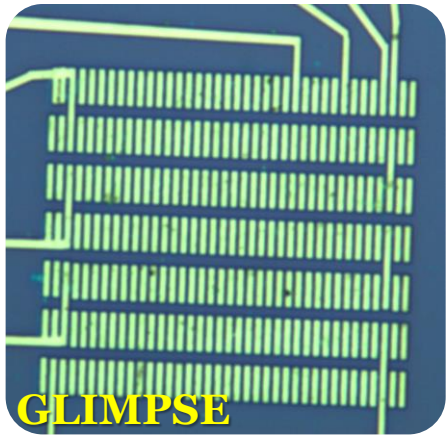


DM Mass from Angular Dependence

with D. Kim [In preparation]

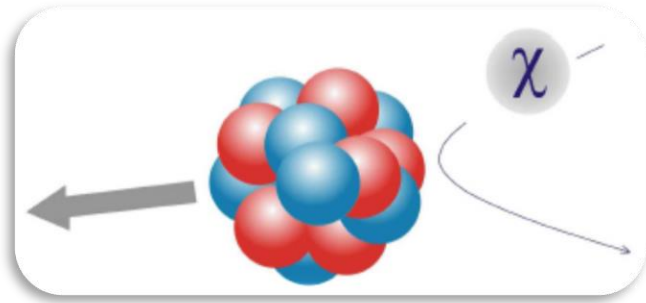


Jong-Chul Park

Chungnam National Univ.

PPC 2024, October 16 (2024)

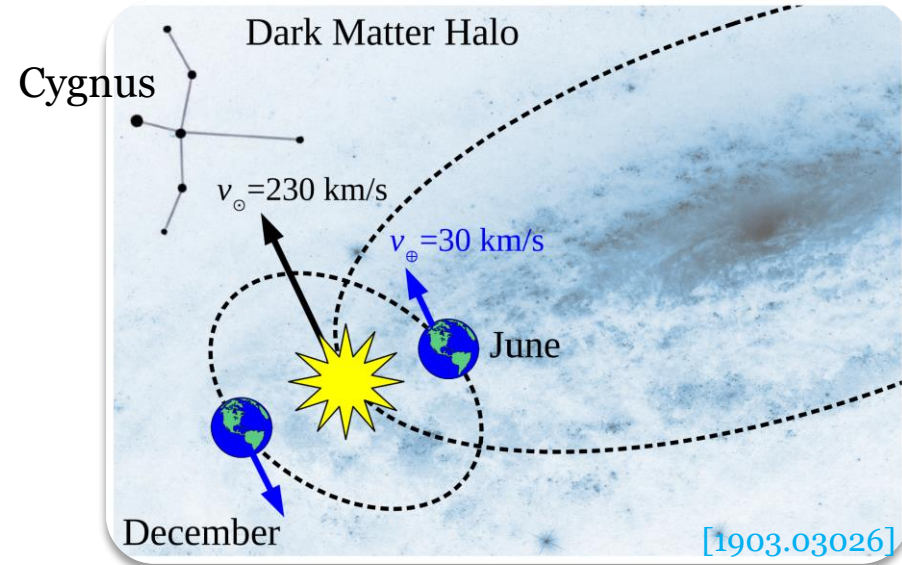
DM Direct Detection: Basics



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

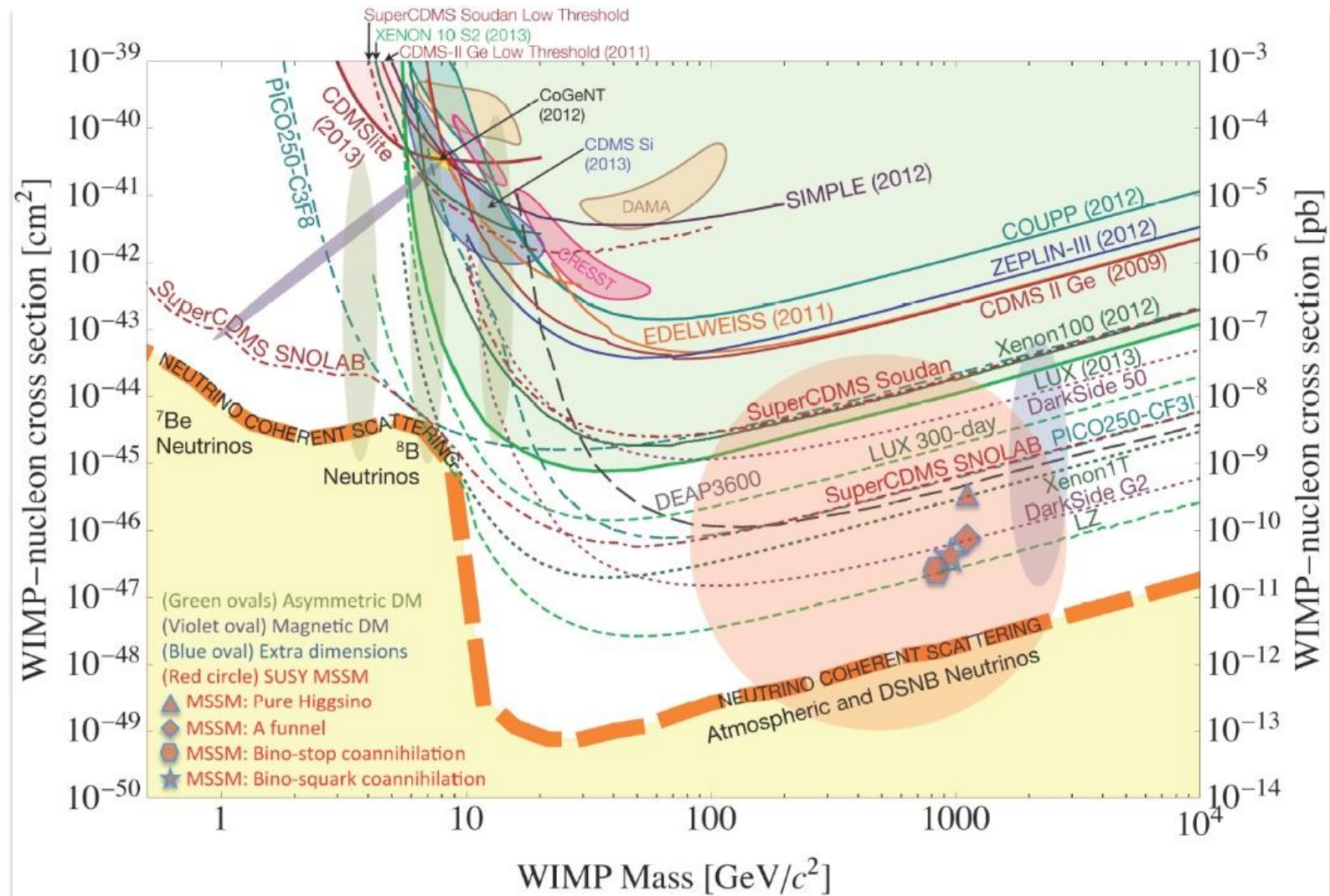
$$\frac{dN}{dE_R}(t) \propto N_T \frac{\rho_\chi}{m_\chi} \int_{v > v_{\text{min}}} dv^3 \frac{d\sigma}{dE_R} v f_{\text{Earth}}(\vec{v}, t)$$

$$v_{\text{min}} = \sqrt{m_T E_R / 2\mu_{\chi T}^2}$$



$$f_{\text{Earth}}(\vec{v}, t) = f_{\text{Galaxy}}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t))$$

DM (WIMP) Direct Detection: Results

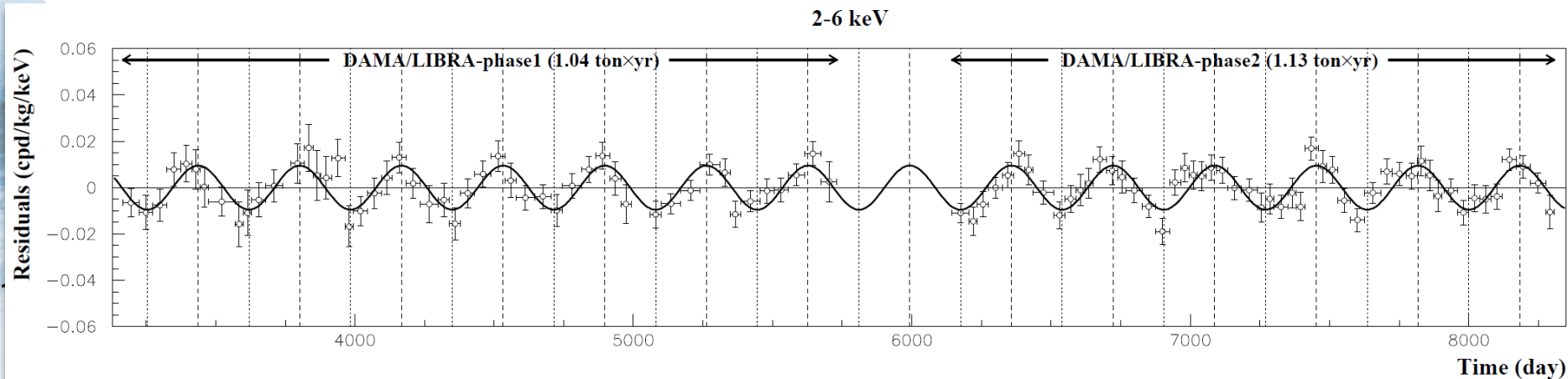
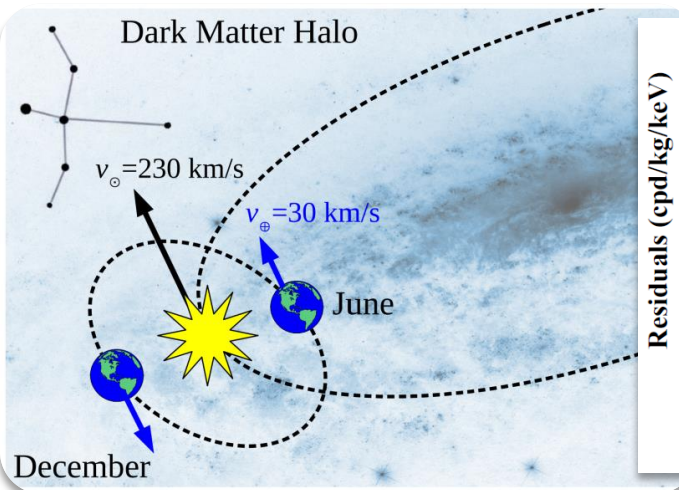
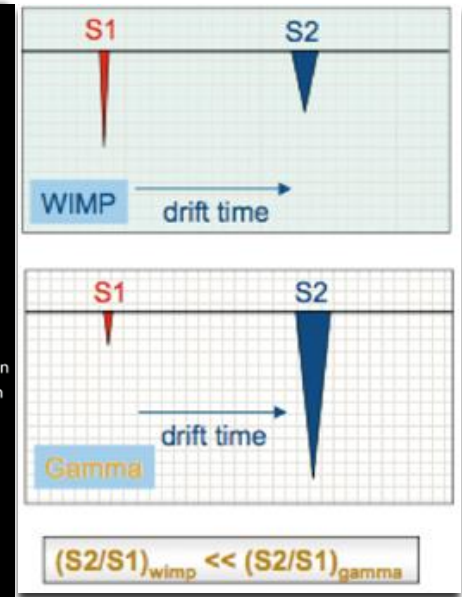
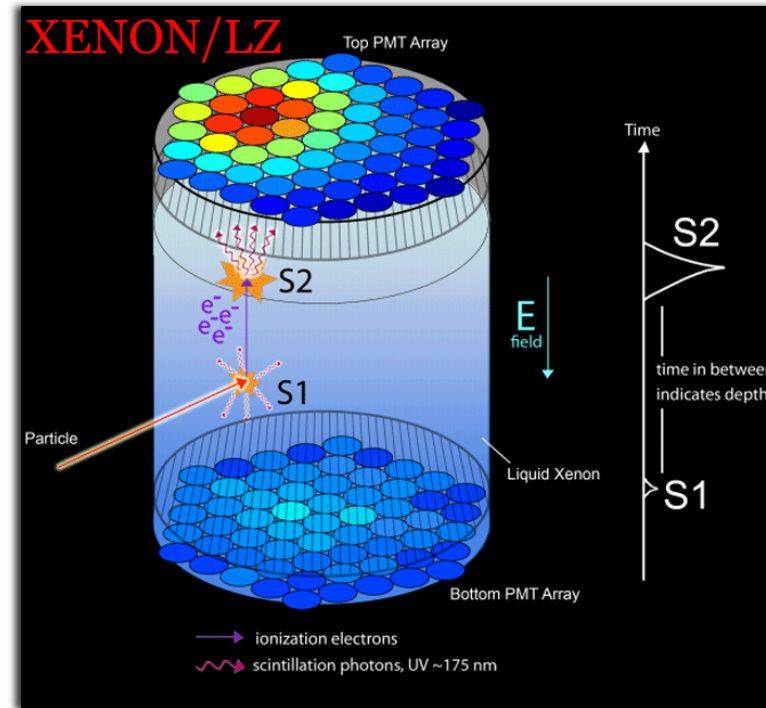


* Not most updated figure!

DM Direct Detection: Some Issues

1. DM signals vs Backgrounds

- ✓ Event discrimination via **signal characteristics**: most of experiments
- ✓ Earth's motion around the Sun → **Annual modulation** in event rate (e.g. DAMA, COSINE), **Directional detection** (e.g. DRIFT, NEWSdm)



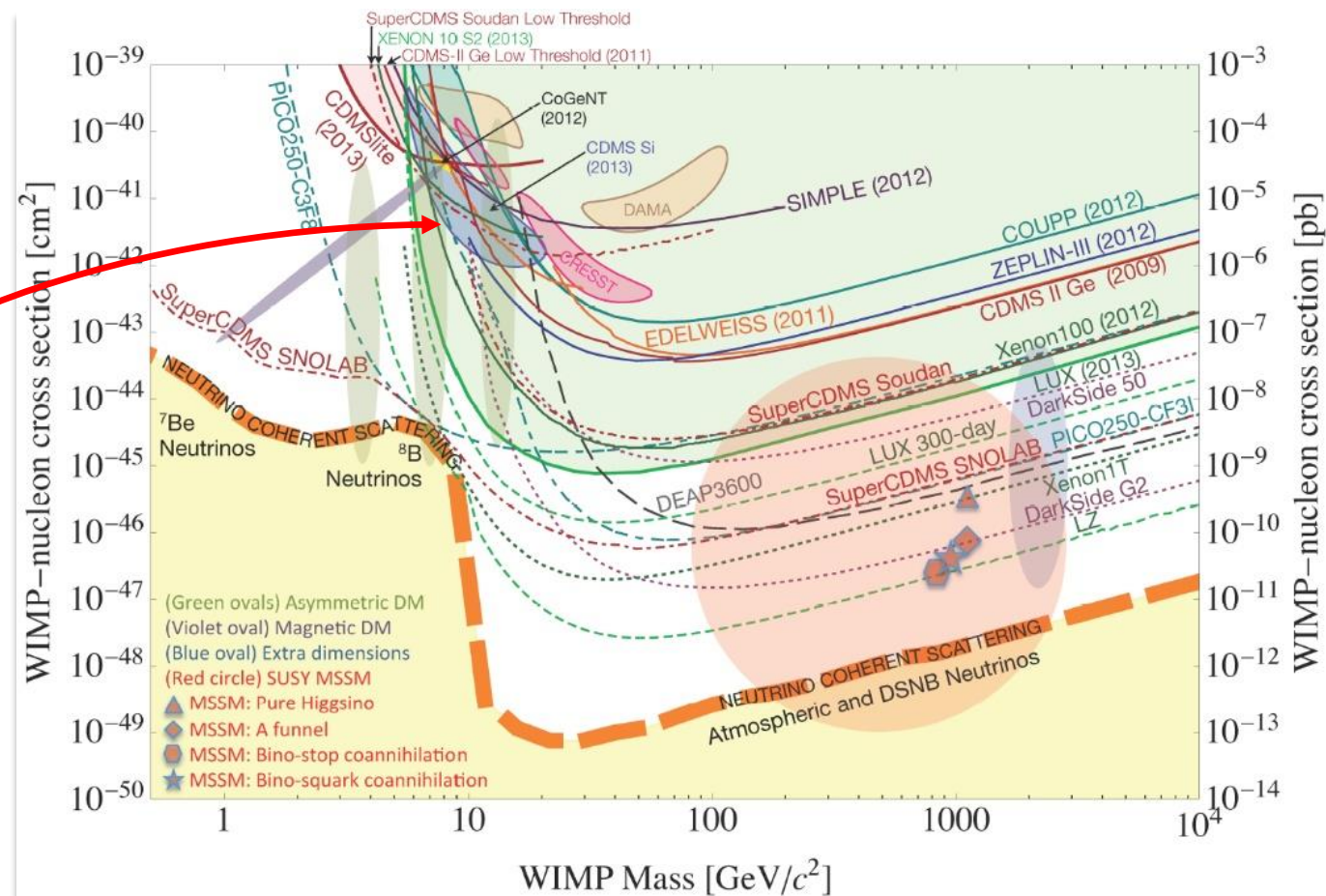
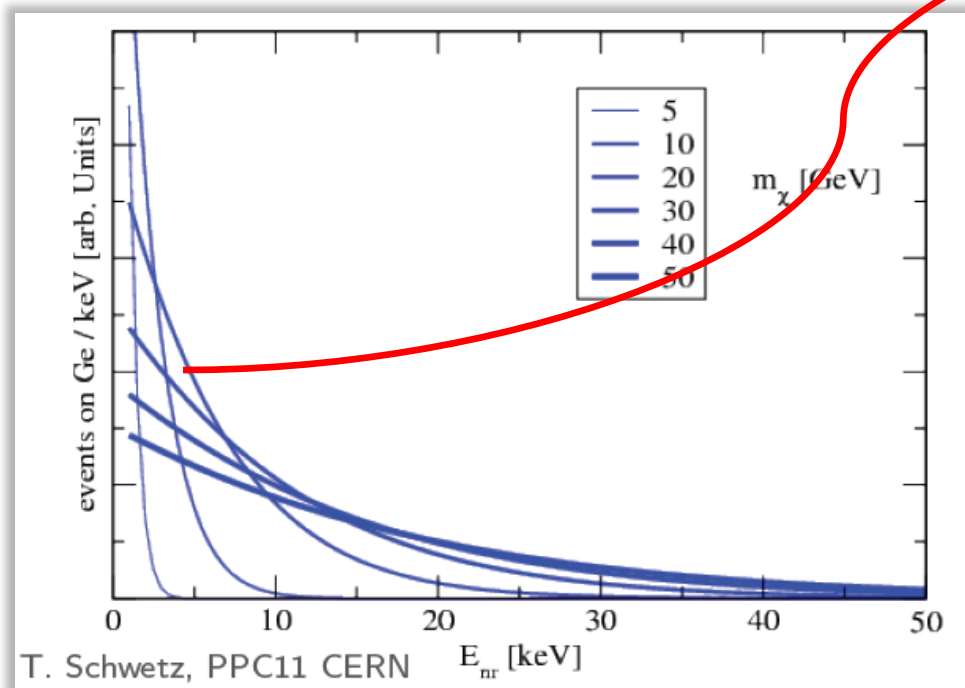
DM Direct Detection: Some Issues

2. Mass & interaction of DM

✓ Differential recoil rate:

Amplitude → Interaction strength

Curvature (~distribution) → Mass



Light DM Direct Search



❖ $E_k \sim mv^2$, $\Phi_{\chi} = n_{\chi} v_{rel} = (\rho_{\chi}/m_{\chi}) v_{rel}$

→ **lighter DM**: **smaller** E_r , but **larger flux** (lighter target particle)

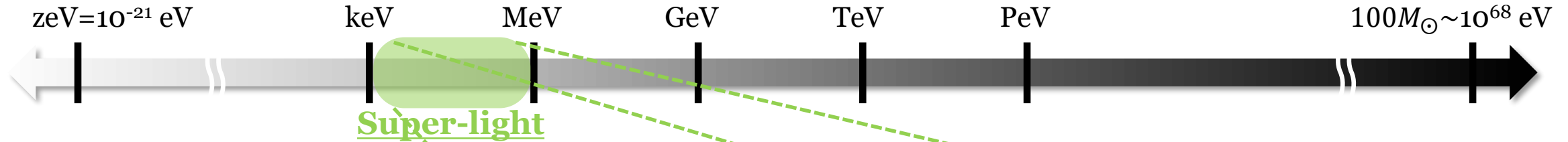
→ **low** E_{th} preferred but even OK with **small target mass** (e-recoil)

✓ **A way out: $v \sim c$**
 e.g., **Boosted DM**
 (Majumdar, Basu, **JCP**, ...)



Dark Matter Limit Plotter

Super-Light DM Direct Search



❖ $E_k \sim mv^2 \sim \mathbf{O(meV)}$ with $m \sim keV$ & $v \sim 10^{-3}$

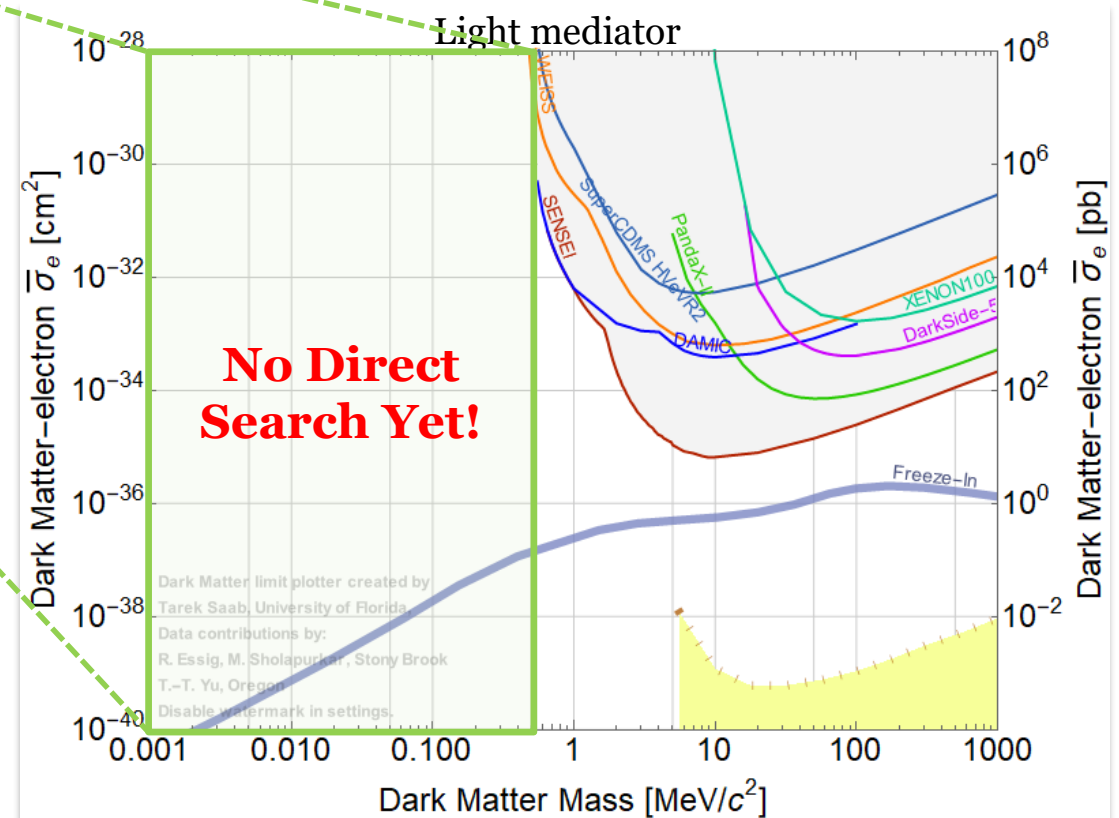
❖ **New approaches** are required!

✓ **Targets:** Superconductor, Superfluid He, 3D Dirac material, Polar material, Graphene, Diamond, etc.

✓ **Sensor technologies:** TES, MKID, STJ, SNSPD, GJJ, etc. (mostly based on superconductivity)

✓ **Experiments:** SPICE & HeRALD, GLIMPSE, etc.

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



Dark Matter Limit Plotter

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?

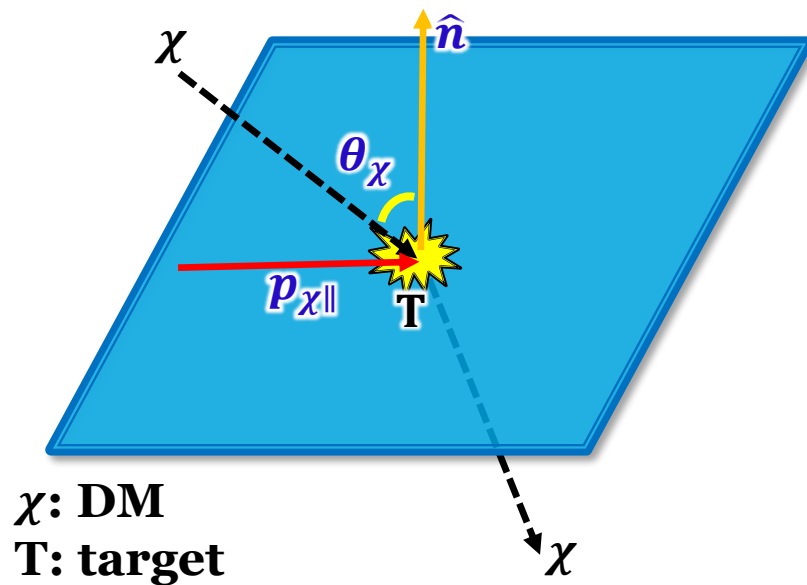
2. Mass determination:

- ✓ We may recognize a DM event occurrence, but **utilizing the differential E_R spectrum** is **difficult!**

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

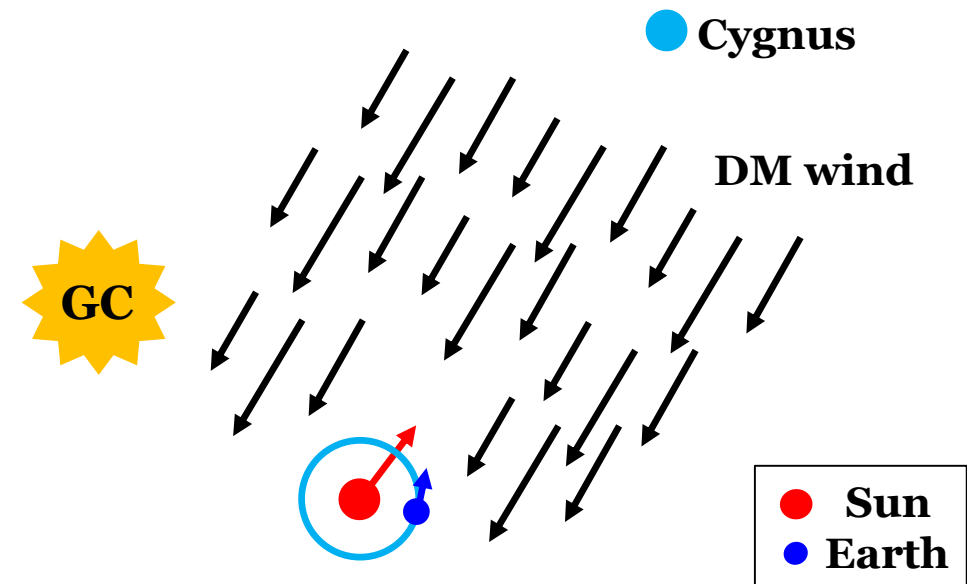
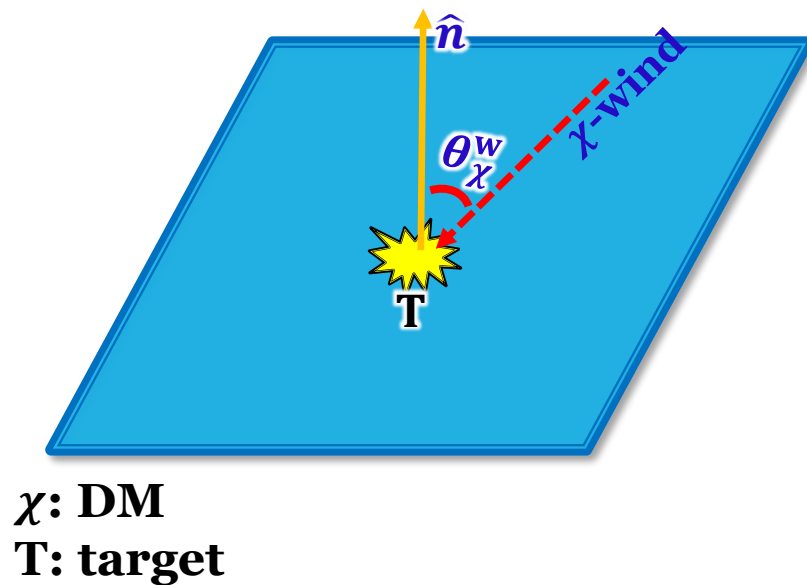
Answers for the Questions

- ❖ **Experiments using (effectively) 2D detectors:** the experimental **signatures** are related to the **behavior of targets scattered by DM along the detection plane** → the incident angle (θ_χ) of a DM particle affects the resulting event rate.



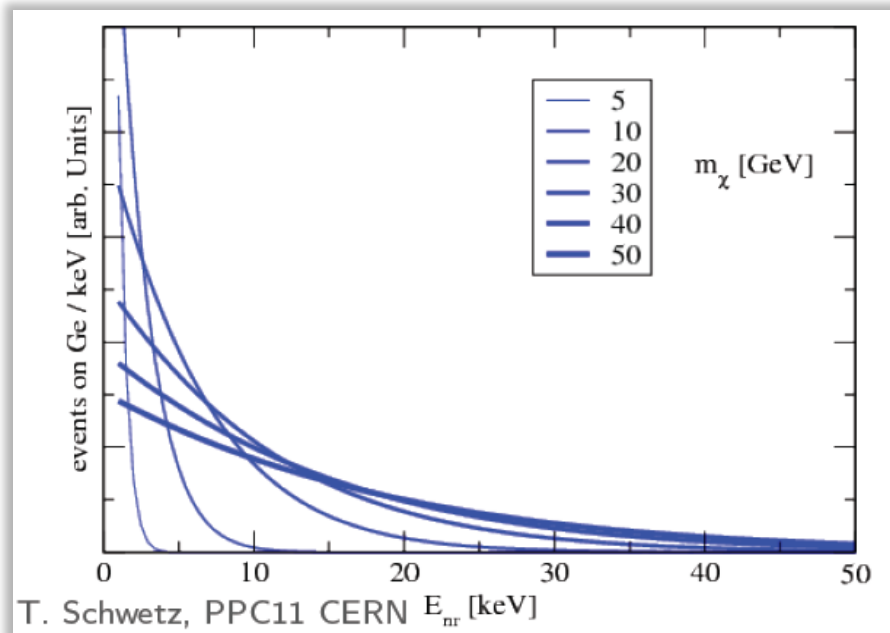
Answers for the Questions

- ❖ **Experiments using (effectively) 2D detectors**: the experimental **signatures** are related to the **behavior of targets scattered by DM along the detection plane** → the incident angle (θ_χ) of a DM particle affects the resulting event rate.
- ❖ Due to the motion of the Sun, the **DM flux (DM wind)** has a **directional preference**: **CYGNUS!**
→ Non-trivial **dependence of event rates on the incident angle** (θ_χ^w) of the DM wind.



Answers for the Questions

- ❖ (effectively) **2D detectors**: $v_{\chi\parallel}$ 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 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 **DM mass**.



vs

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



2D Detection: Angular Dependence

Angular Dependence of Event Rates

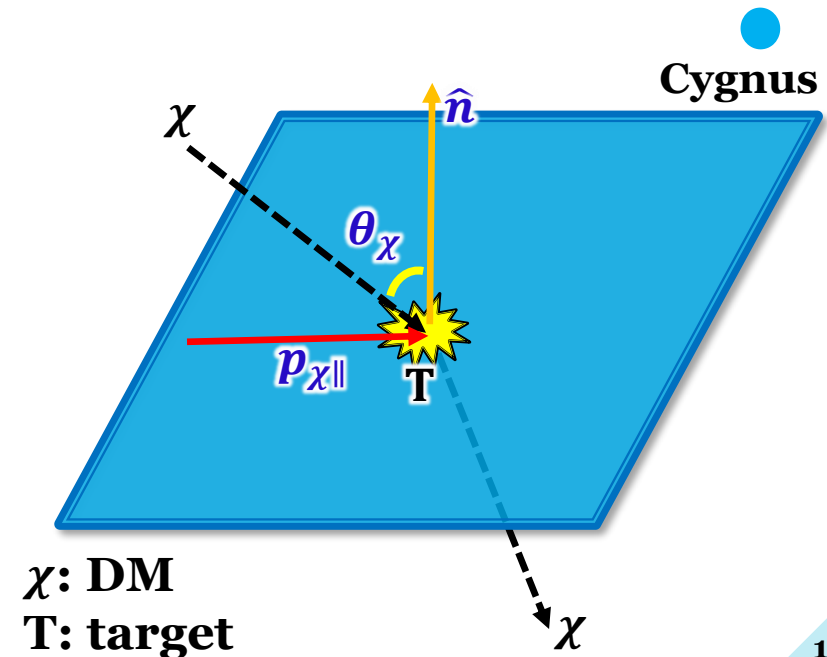
- ❖ Number of events/unit detector mass/unit run time: $n_{\text{eve}} = \int dE_r dv_\chi f(v_\chi) \frac{d}{dE_r} \left(\bar{N}_T \langle \sigma_{\chi T} v_{\text{rel}} \rangle \frac{\rho_\chi}{m_\chi} \right)$ with

$$\bar{N}_T = N_T / M_T.$$

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

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

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



Angular Dependence of Event Rates

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

$$\bar{N}_T = N_T / M_T.$$

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

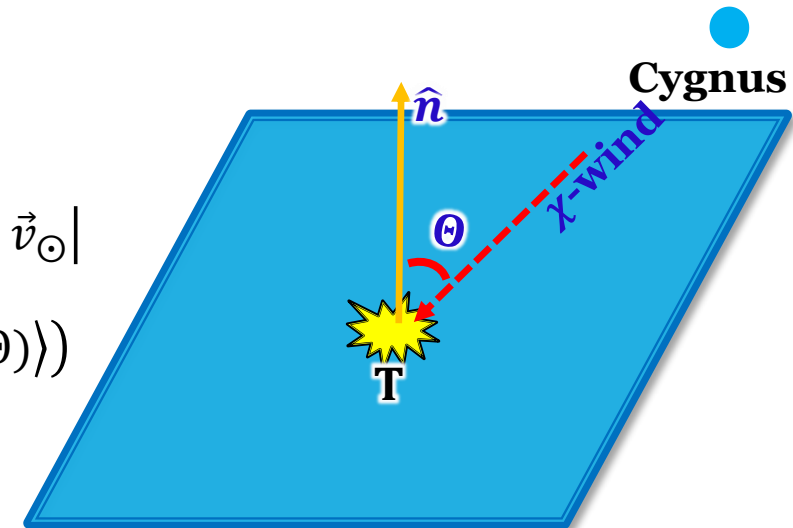
$$n_{\text{eve}} = \frac{\rho_\chi}{m_\chi} \int dE_r dv_{\chi\parallel} \tilde{f}(v_{\chi\parallel}) \frac{d}{dE_r} \left(\bar{N}_T \langle \sigma_{\chi T} v_{\text{rel}\parallel} \rangle \right)$$

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

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

For Θ between the Cygnus direction and \hat{n} , a plane-projection procedure of $F(V_\chi)$ should be done individually $\rightarrow n_{\text{eve}}$ depends on Θ non-trivially.

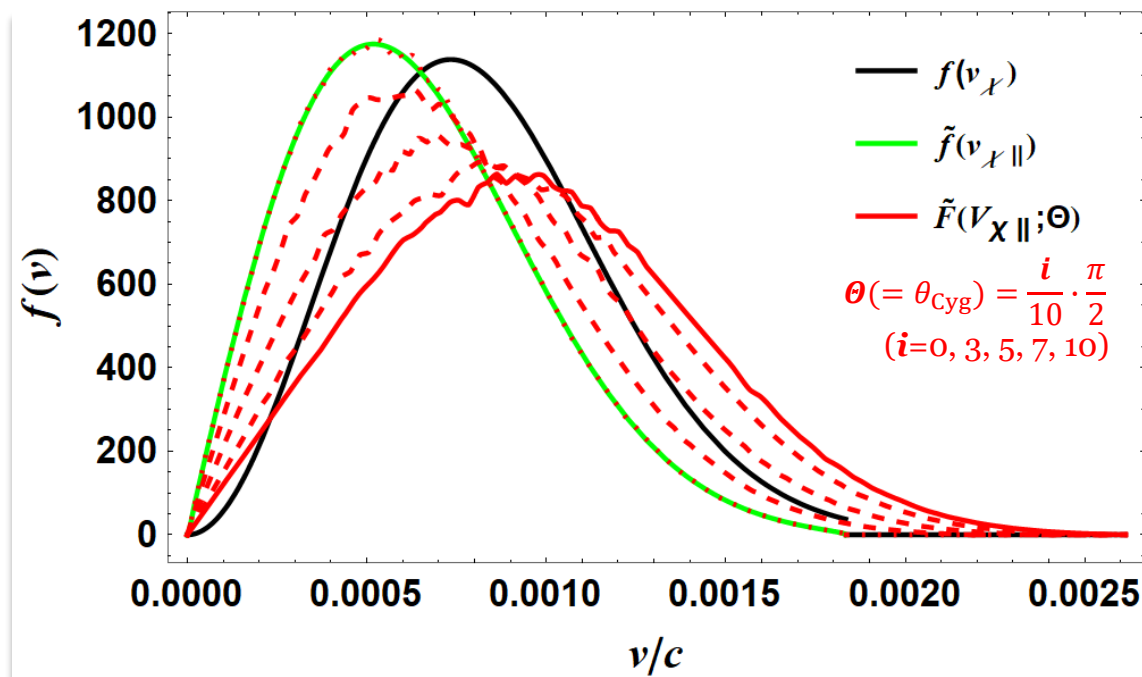


χ : DM
T: target

Angular Dependence → Angular Modulation

- ❖ $E_{\text{th}} \neq 0 \rightarrow V_{\chi\parallel, \text{min}}$ for DM signal detection.
- ❖ For smaller m_χ , larger $V_{\chi\parallel}$ is required. → A dependence of n_{eve} on m_χ through $V_{\chi\parallel, \text{min}}(m_\chi) \rightarrow$ **The curvature of the θ**

dependence: $n_{\text{eve}}(\theta, m_\chi) = \frac{\rho_\chi}{m_\chi} \int_{V_{\chi\parallel, \text{min}}(m_\chi)}^{V_{\chi\parallel, \text{max}}} dE_r dV_{\chi\parallel} \tilde{F}(V_{\chi\parallel}; \theta) \frac{d}{dE_r} (\bar{N}_T \langle \sigma_{\chi T} V_{\text{re}\parallel}(\theta) \rangle)$ with $V_{\chi\parallel, \text{max}} = v_{\text{esc}} + v_\odot \sin\theta$.

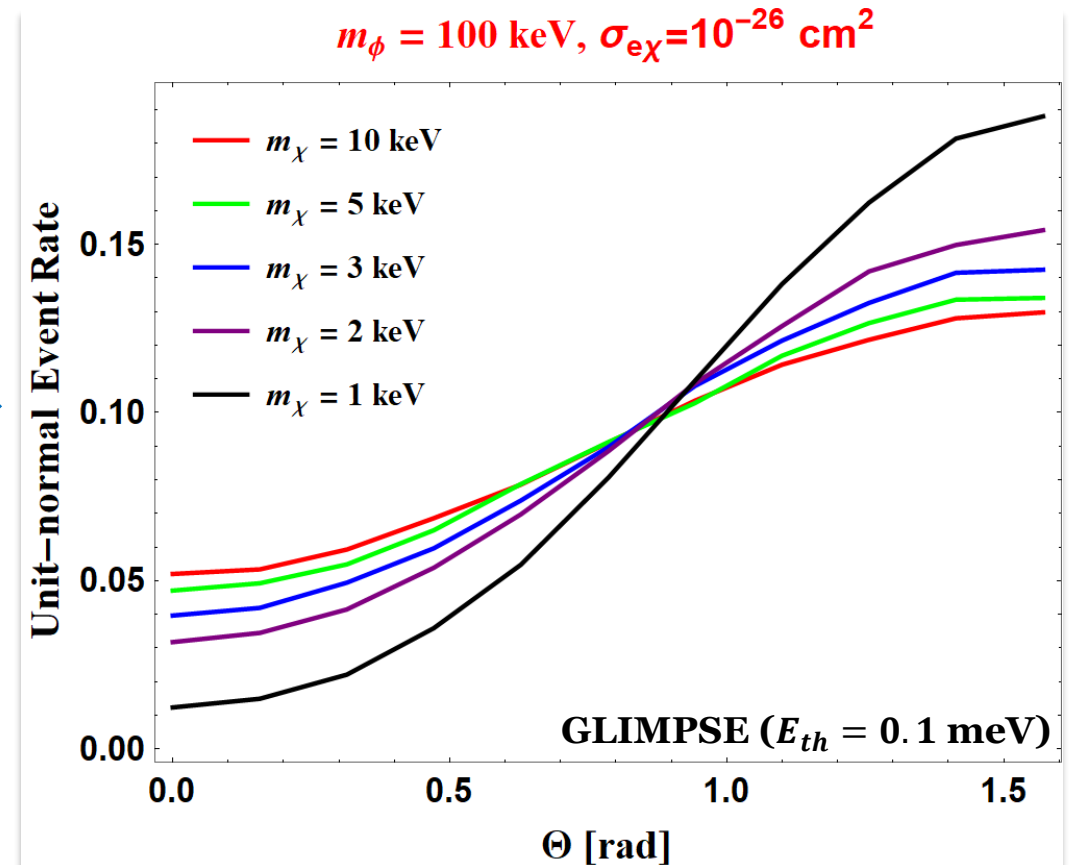
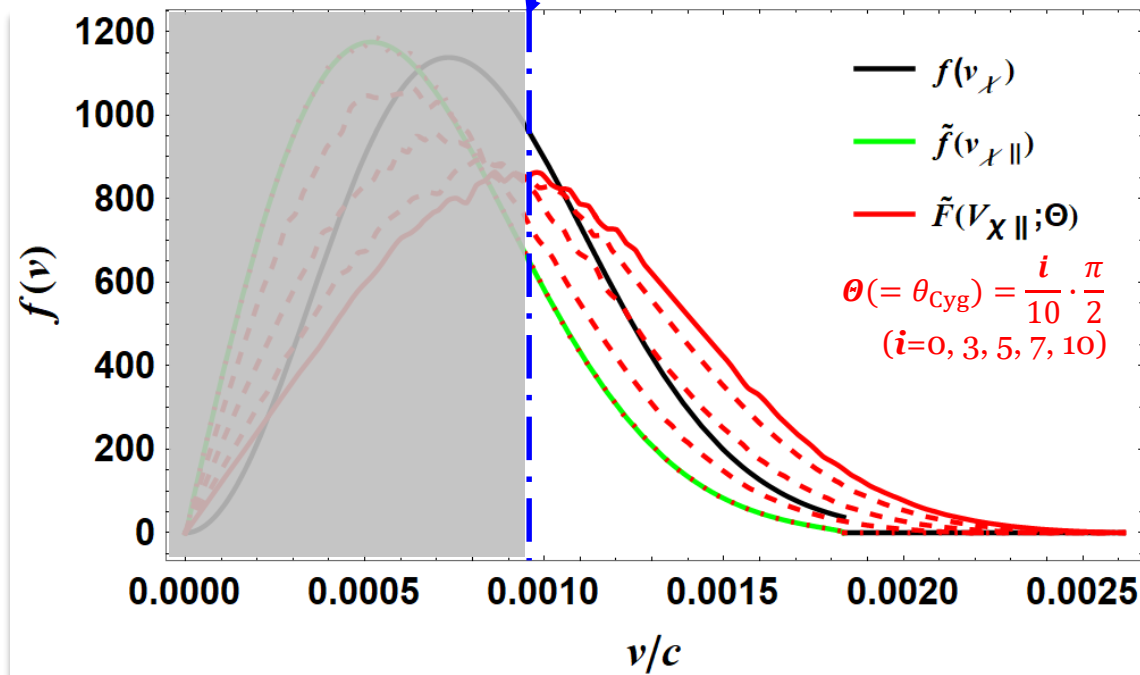


Angular Dependence → Angular Modulation

❖ $E_{th} \neq 0 \rightarrow V_{\chi\parallel, \min}$ for DM signal detection.

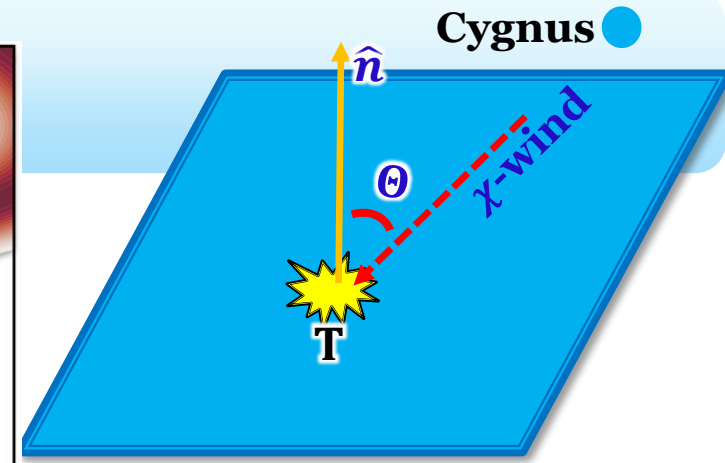
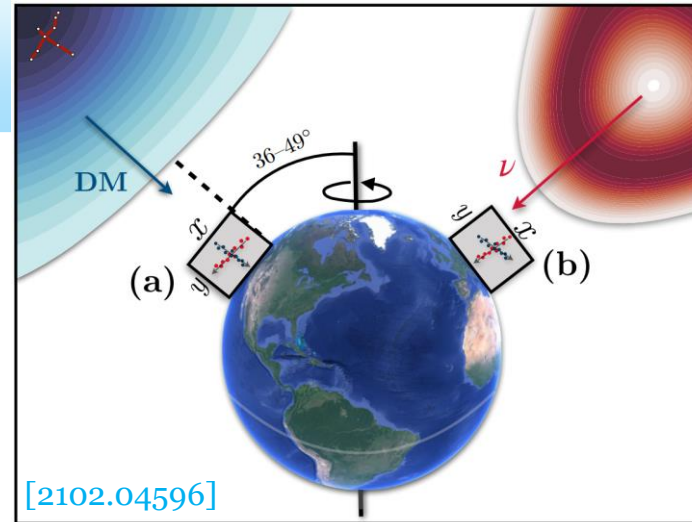
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dependence: $n_{eve}(\theta, m_\chi) = \frac{\rho_\chi}{m_\chi} \int_{V_{\chi\parallel, \min}(m_\chi)}^{V_{\chi\parallel, \max}} dE_r dV_{\chi\parallel} \tilde{F}(V_{\chi\parallel}; \theta) \frac{d}{dE_r} (\bar{N}_T \langle \sigma_{\chi T} V_{rel\parallel}(\theta) \rangle)$ with $V_{\chi\parallel, \max} = v_{esc} + v_\odot \sin\theta$.



Summary

- DM flux (DM wind) carries a **directional preference**: CYGNUS.



- **Angular modulation** → New method for **DM mass determination** as well as **BG rejection!**
- Generally applied to the **(effectively) 2D** or **2D-projectable** direct detection experiments allowing for directionality observables
- Experiments **even w/ good E_R** : an additional way **to cross-check their results**

Thank You!



Supplemental

Angular Modulation vs Annual Modulation

❖ Angular modulation (→ Daily!)

- ✓ Effects from the **change of the DM wind direction (θ) relative to the plane-normal direction due to Detector's motion**

→ contribution: **revolution \approx rotation**

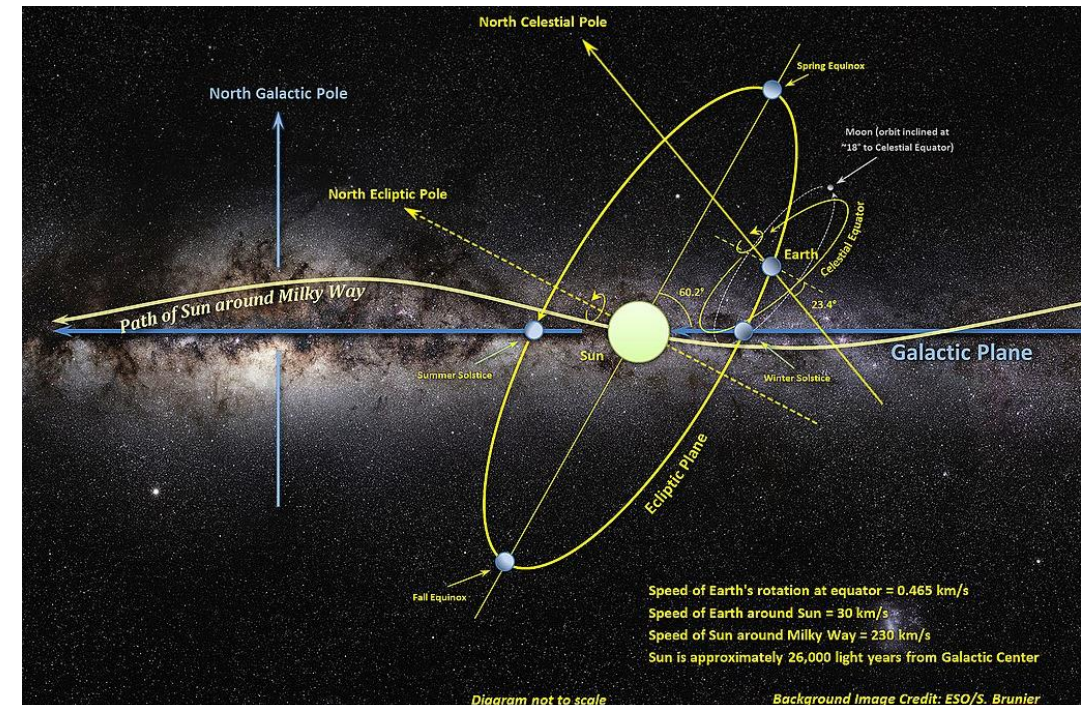
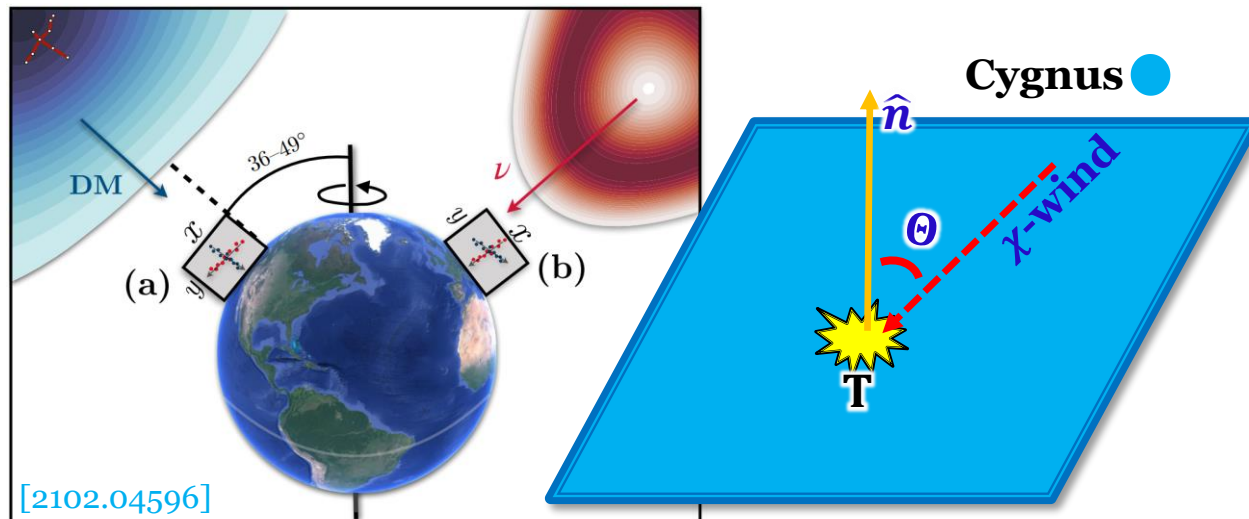
- ✓ $N_{\text{event}}(\theta)$ from $N_{\text{event}}(t)$ using $\theta(t)$

→ **BG rejection** + **mass** information

❖ Annual modulation

- ✓ Effects from the **change of $|\vec{v}_{\text{rel}}|$ due to Earth's motion relative to Sun's motion**
- contribution: **revolution \gg rotation**

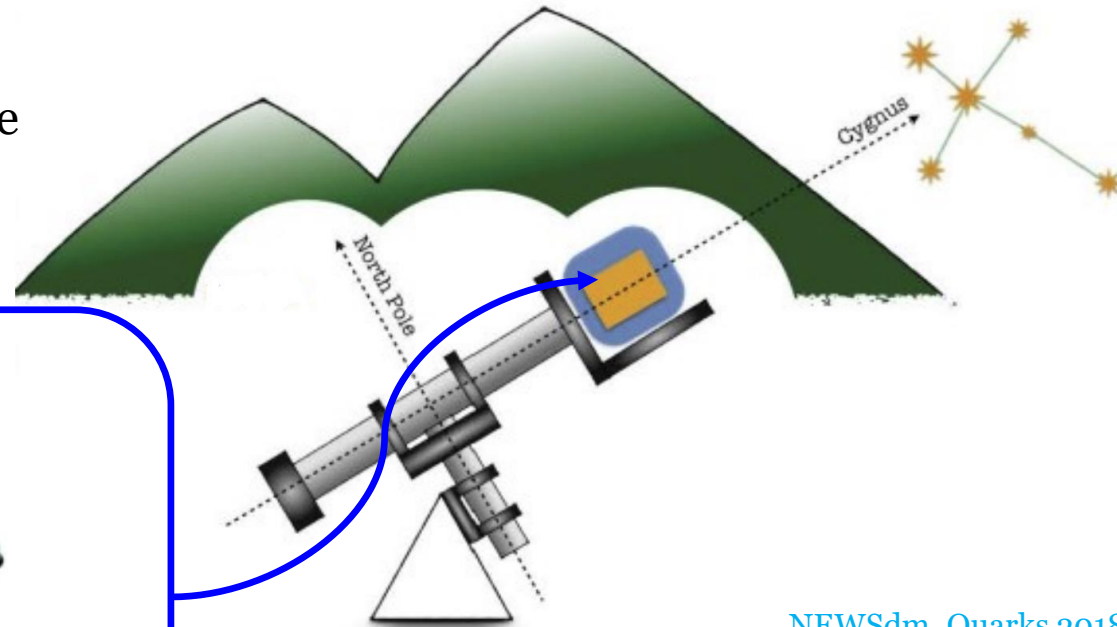
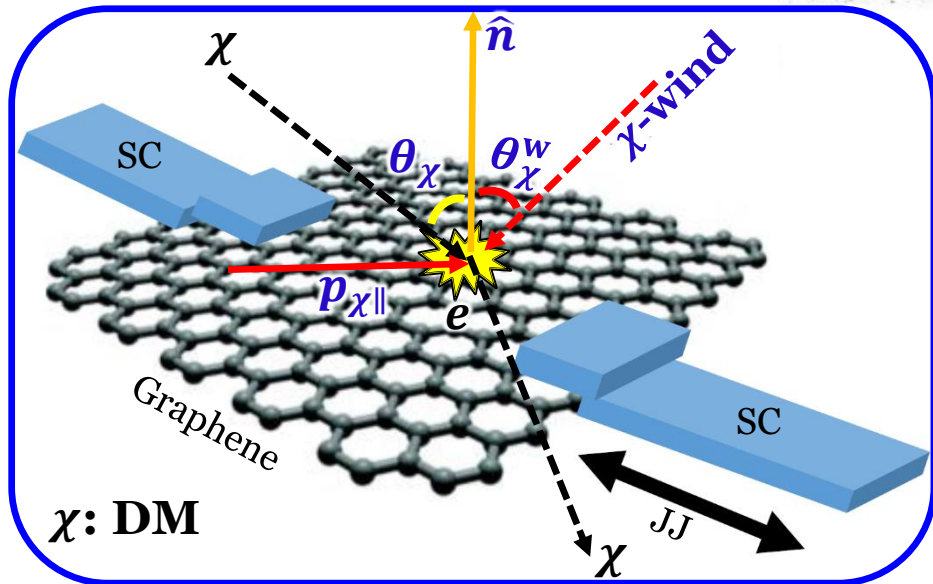
- ✓ $N_{\text{event}}(t)$ → **BG rejection**



Directional Dependence: Angular Information?

- ✓ **Actively rotating the detector** to run the experiment with a **fixed** $\theta_\chi^w = \theta$.
- ✓ **Timing information** of each signal \rightarrow **statistically** $\theta(t)$.

- ✓ θ_χ : event-level unmeasurable
- ✓ $\theta_\chi^w = \theta$: **controllable** & (statistically) **measurable**



NEWSdm, Quarks 2018



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

Gas TPC

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

DNA detector

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

Crystal defects

- ▶ 3d track topology
- ▶ Head/tail measurable

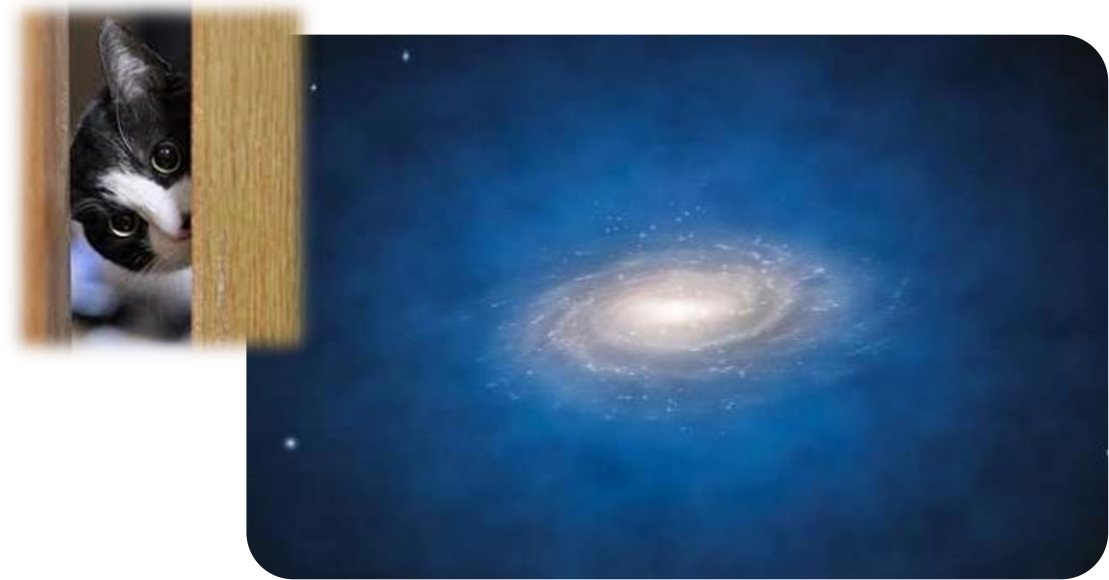
GLIMPSE

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

GLIMPSE

Graphene-based super-Light Invisible Matter Particle SEarch

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

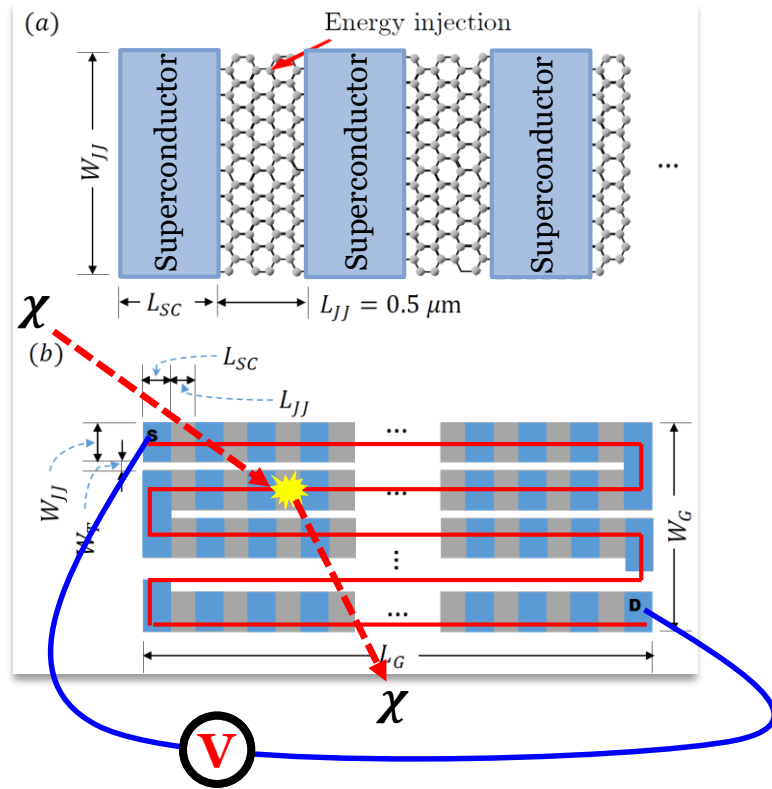


We proposed a **new super-light DM direct detection experiment**,
adopting the **Graphene-based Josephson Junction*** (GJJ)
microwave single photon detector.

* A “state-of-the-art” technology:
much lower $E_{th} \sim O(0.1 \text{ meV})$

Super-Light DM Direct Search Using GJJs

[Kim, JCP, Lee, Fong, 2002.07821]



- 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.**

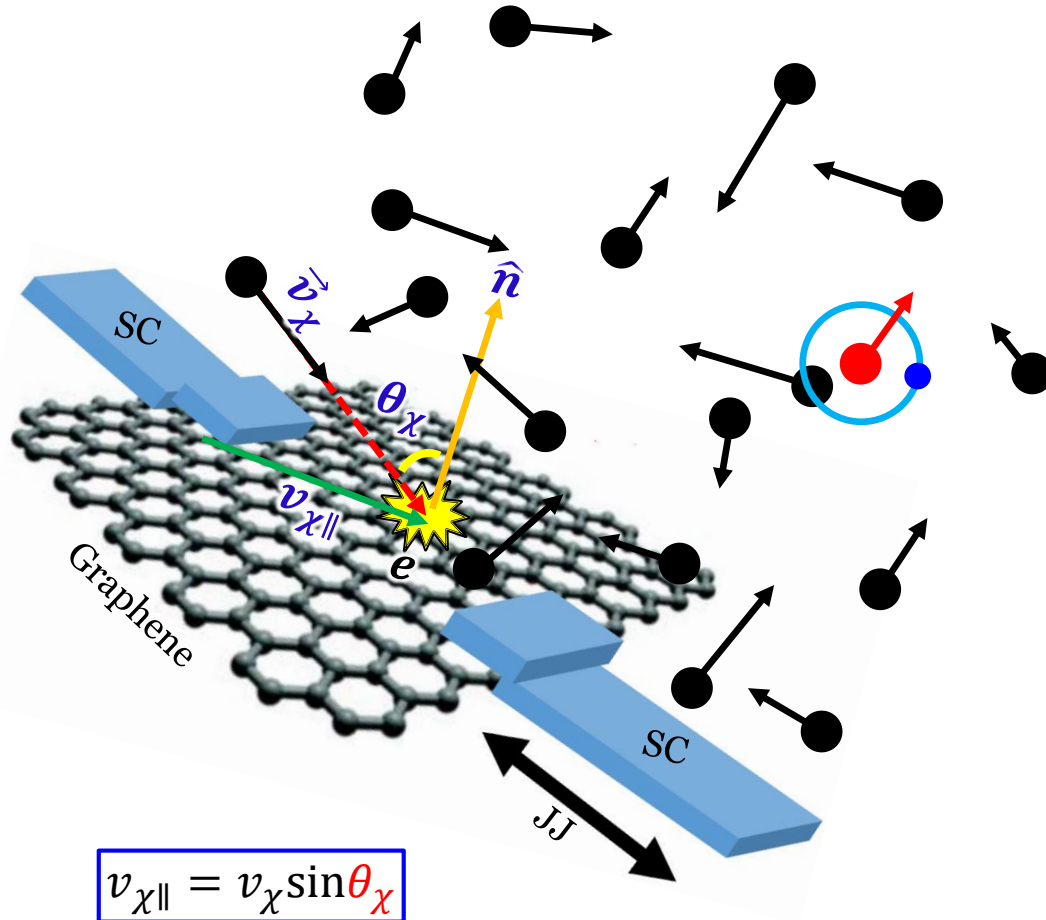
❖ A much larger-scale detector can be made of a **stack of such detector units** (3D).



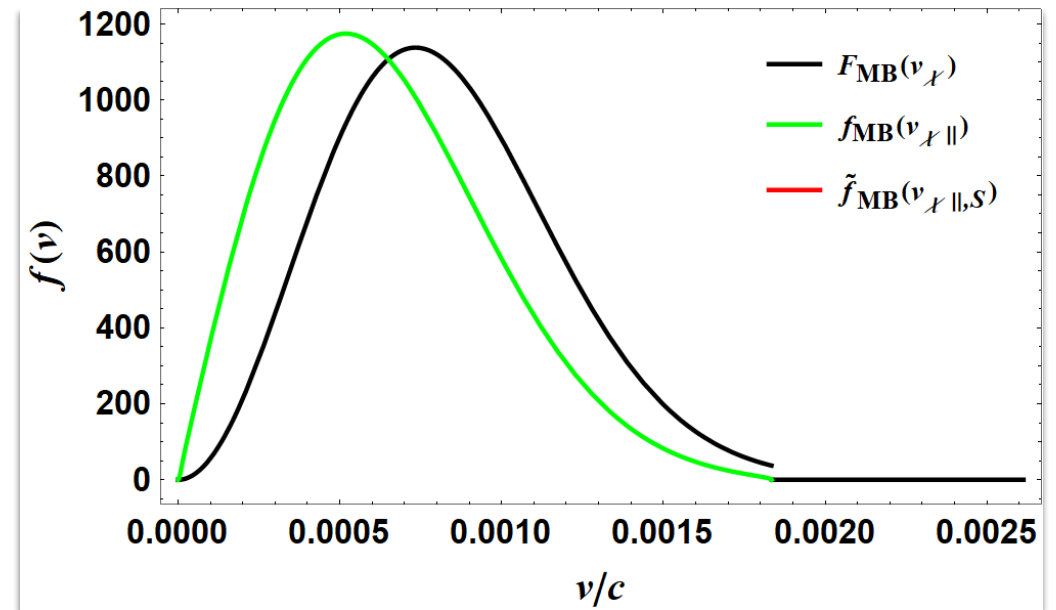
Angular Dependence

DM v Distribution: Angle Dependence

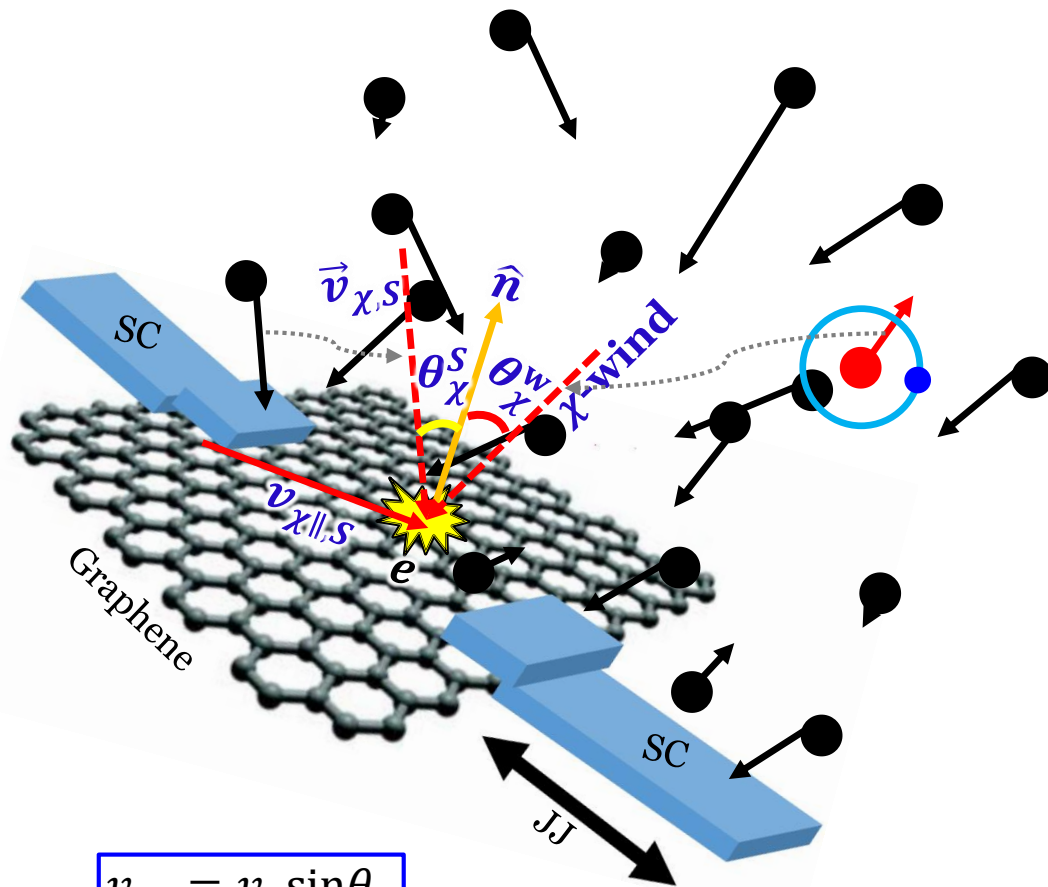
● Cygnus



- DM
- Sun
- Earth



DM v Distribution: Angle Dependence - Sun

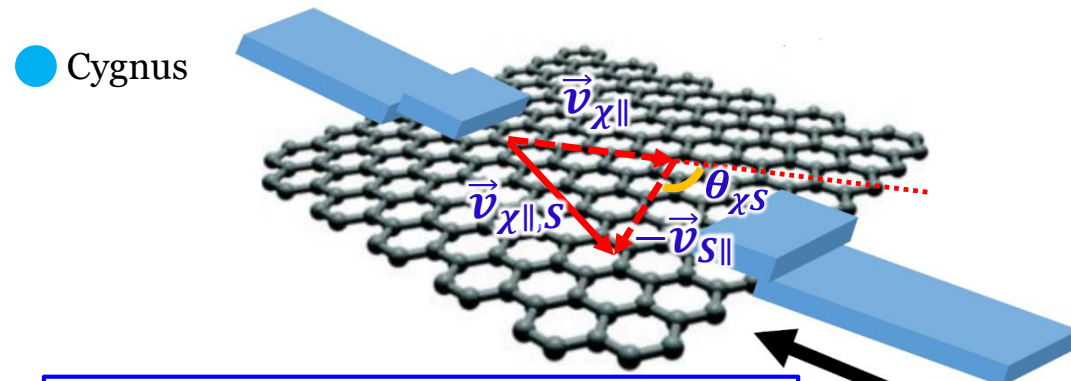


$$v_{\chi\parallel} = v_{\chi} \sin \theta_{\chi}$$

$$\vec{v}_{\chi,S} = \vec{v}_{\chi} - \vec{v}_S \Rightarrow \vec{v}_{\chi\parallel,S} = \vec{v}_{\chi\parallel} - \vec{v}_{S\parallel}$$

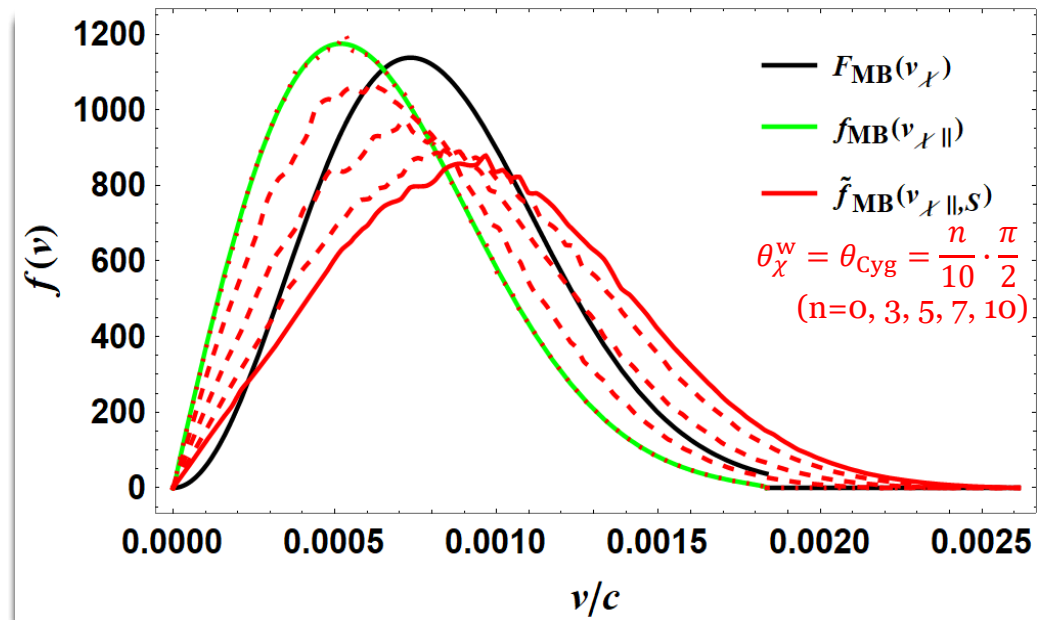
$$v_{\chi\parallel,S} = v_{\chi,S} \sin \theta_{\chi}^S = |\vec{v}_{\chi\parallel} - \vec{v}_{S\parallel}|$$

- DM
- Sun
- Earth

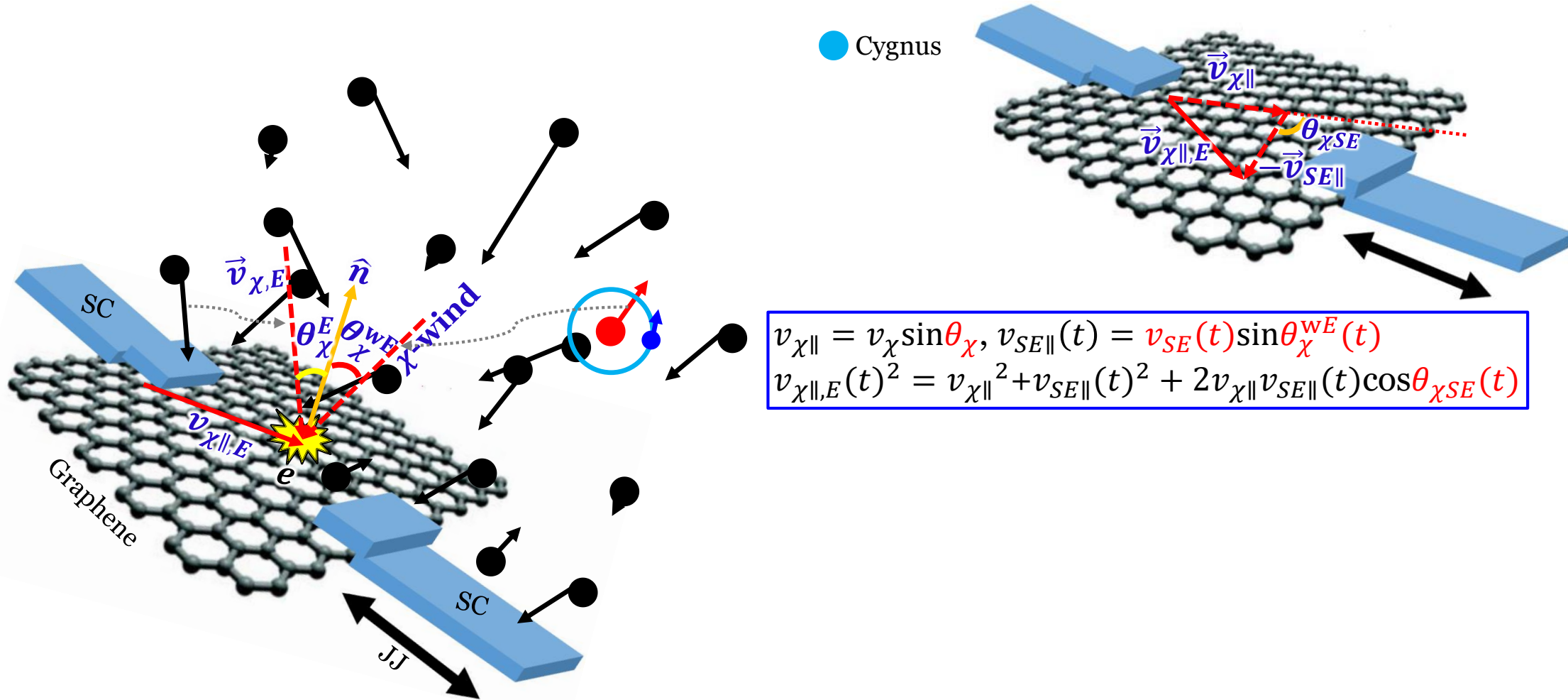


$$v_{\chi\parallel} = v_{\chi} \sin \theta_{\chi}, v_{S\parallel} = v_S \sin \theta_{\chi}^w$$

$$v_{\chi\parallel,S}^2 = v_{\chi\parallel}^2 + v_{S\parallel}^2 + 2v_{\chi\parallel}v_{S\parallel} \cos \theta_{\chi S}$$



DM v Distribution: Angle Dependence - Sun-Earth



$$v_{\chi\parallel} = v_{\chi} \sin\theta_{\chi}, v_{SE\parallel}(t) = v_{SE}(t) \sin\theta_{\chi}^{WE}(t)$$

$$v_{\chi\parallel,E}(t)^2 = v_{\chi\parallel}^2 + v_{SE\parallel}(t)^2 + 2v_{\chi\parallel}v_{SE\parallel}(t)\cos\theta_{\chi SE}(t)$$

- DM
- Sun
- Earth

$$\vec{v}_{\chi,E}(t) = \vec{v}_{\chi} - \vec{v}_{SE}(t) \Rightarrow \vec{v}_{\chi\parallel,E}(t) = \vec{v}_{\chi\parallel} - \vec{v}_{SE\parallel}(t)$$

$$\vec{v}_{SE}(t) = \vec{v}_S + \vec{v}_E(t)$$

$$v_{\chi\parallel,E}(t) = v_{\chi,E}(t) \sin\theta_{\chi}^E(t) = |\vec{v}_{\chi\parallel} - \vec{v}_{SE\parallel}(t)|$$

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 time information of each signal

