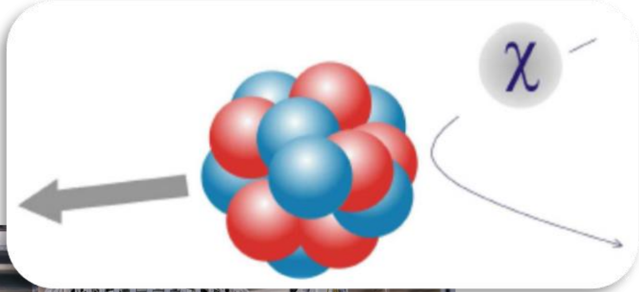
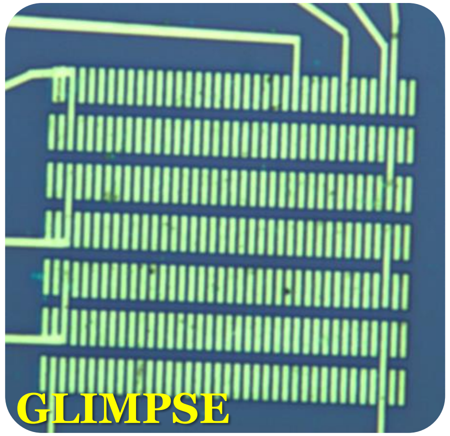
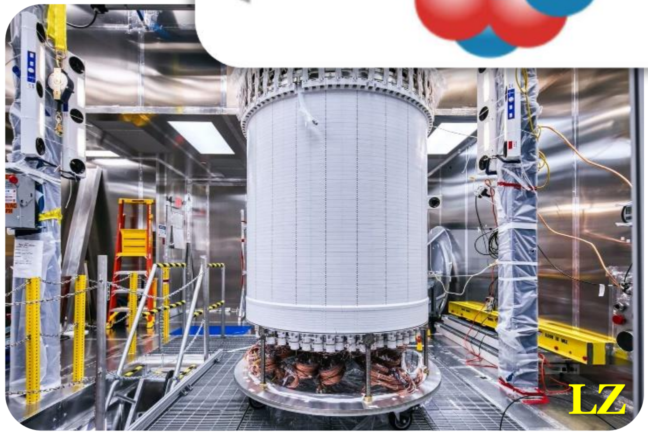
DM Mass from Angular Dependence

with D. Kim [In preparation]





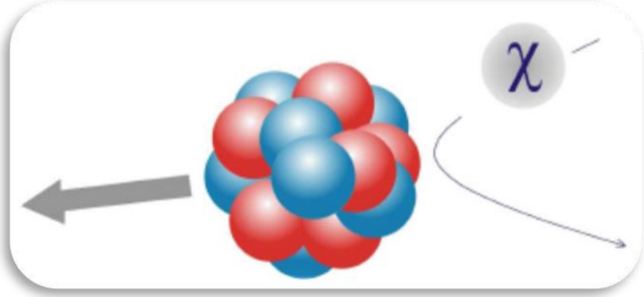


Jong-Chul Park

Chungnam National Univ.

PPC 2024, October 16 (2024)

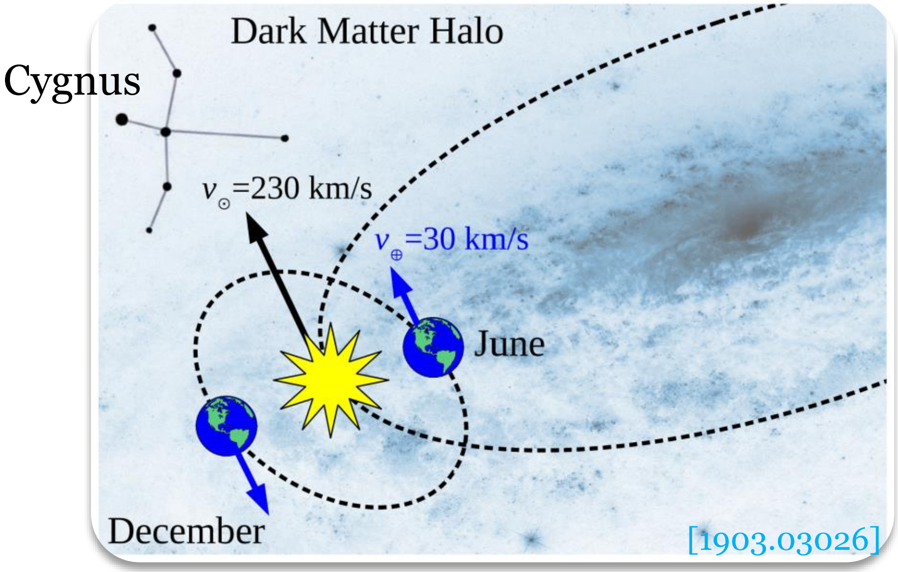
DM Direct Detection: Basics



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

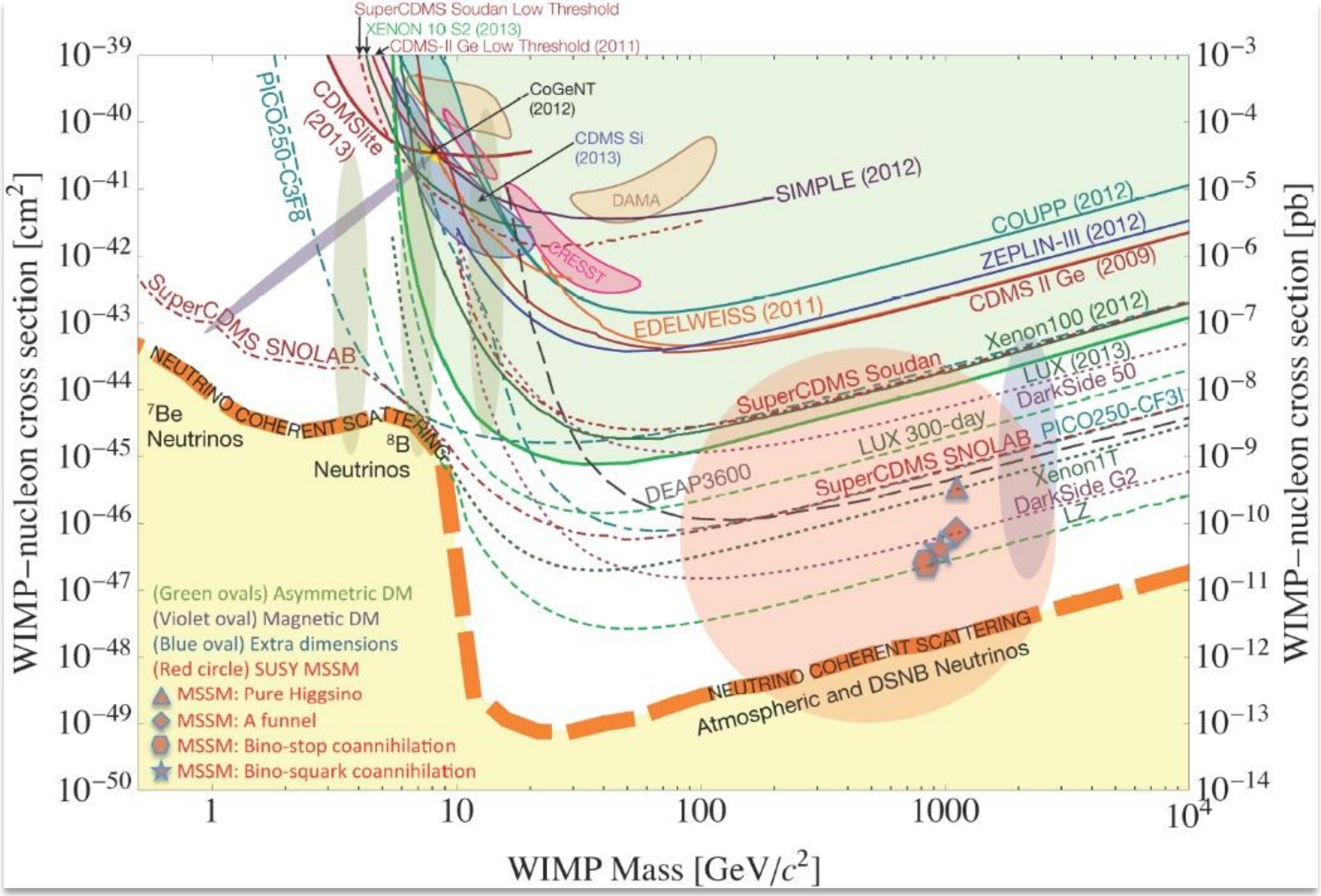
$$\frac{dN}{dE_R}(t) \propto N_T \frac{\rho_\chi}{m_\chi} \int_{v > v_{\rm min}} dv^3 \frac{d\sigma}{dE_R} v f_{\rm Earth}(\vec{v}, t)$$

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



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

DM (WIMP) Direct Detection: Results

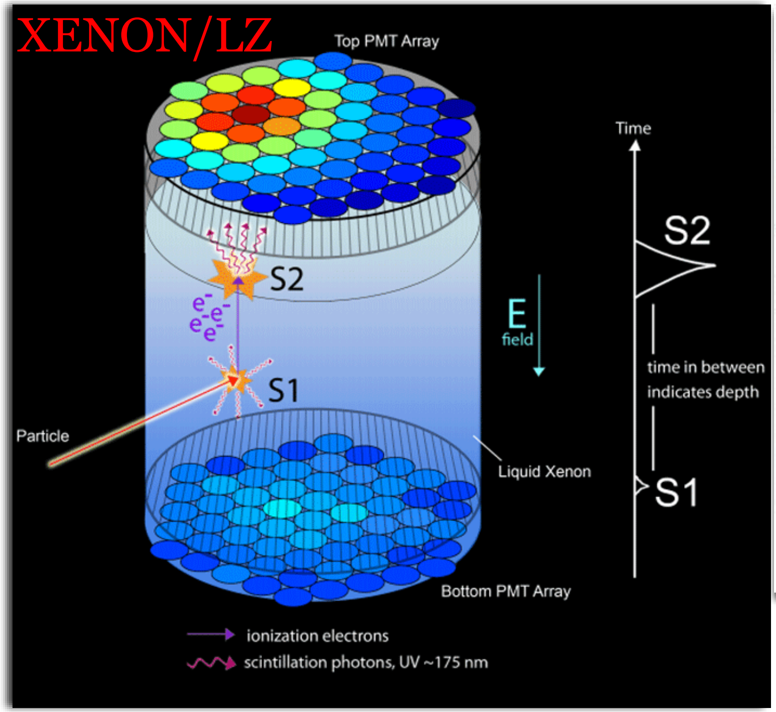


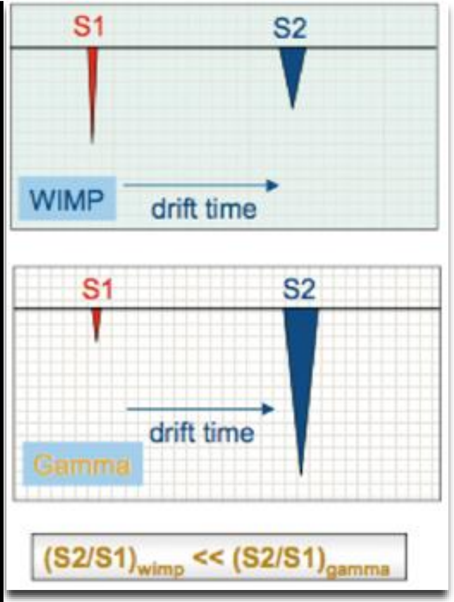
* Not most updated figure!

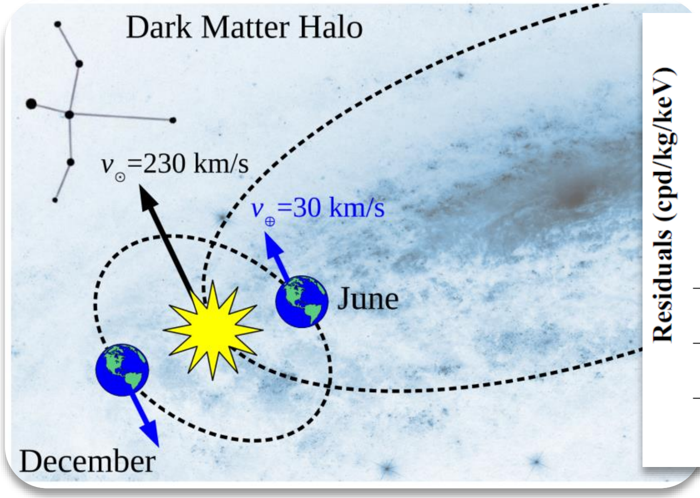
DM Direct Detection: Some Issues

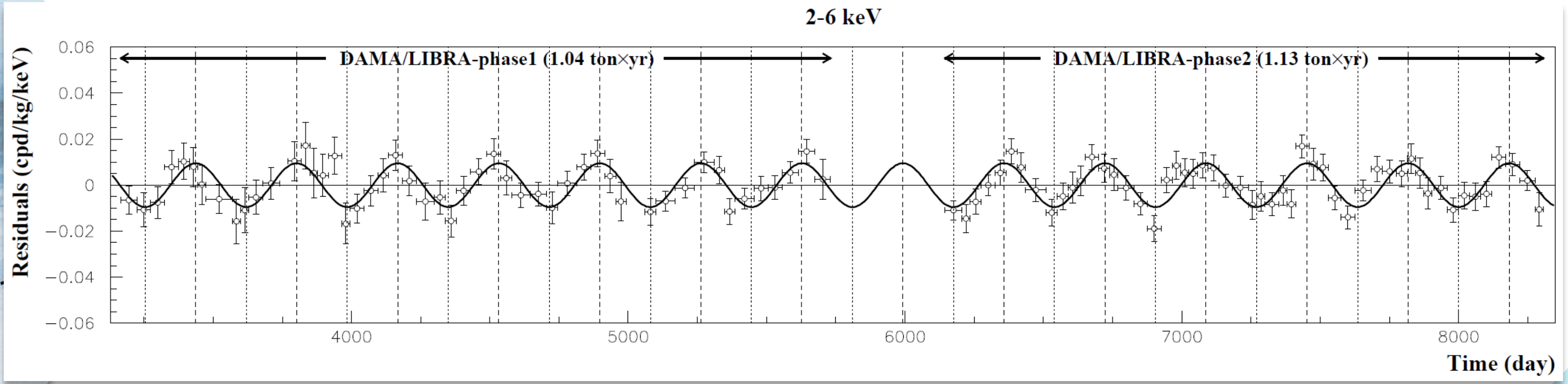
1. **DM signals vs Backgrounds**

- ✓ 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)





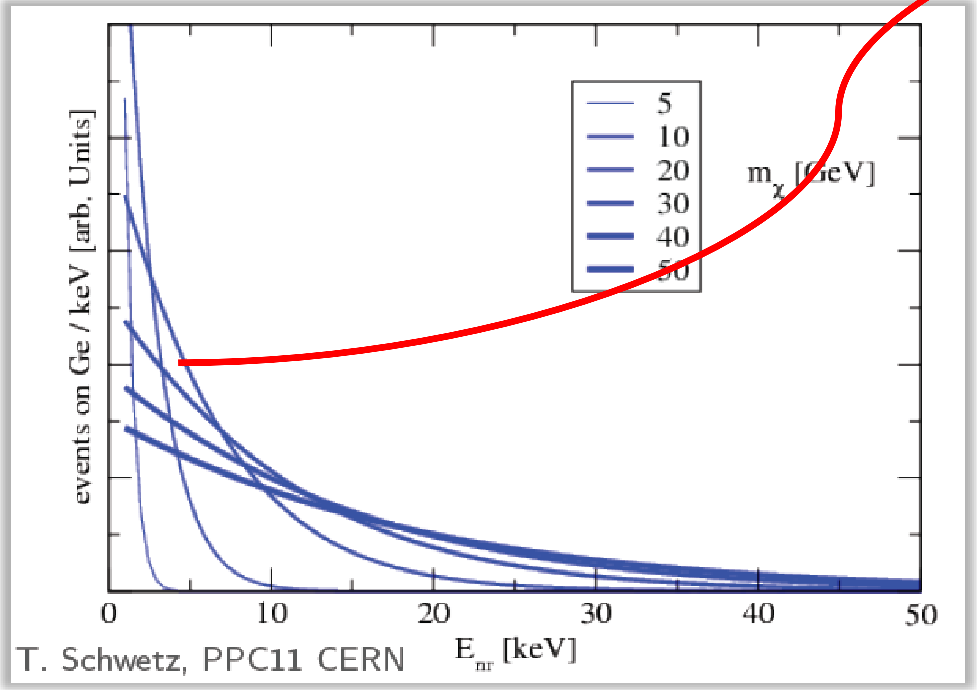


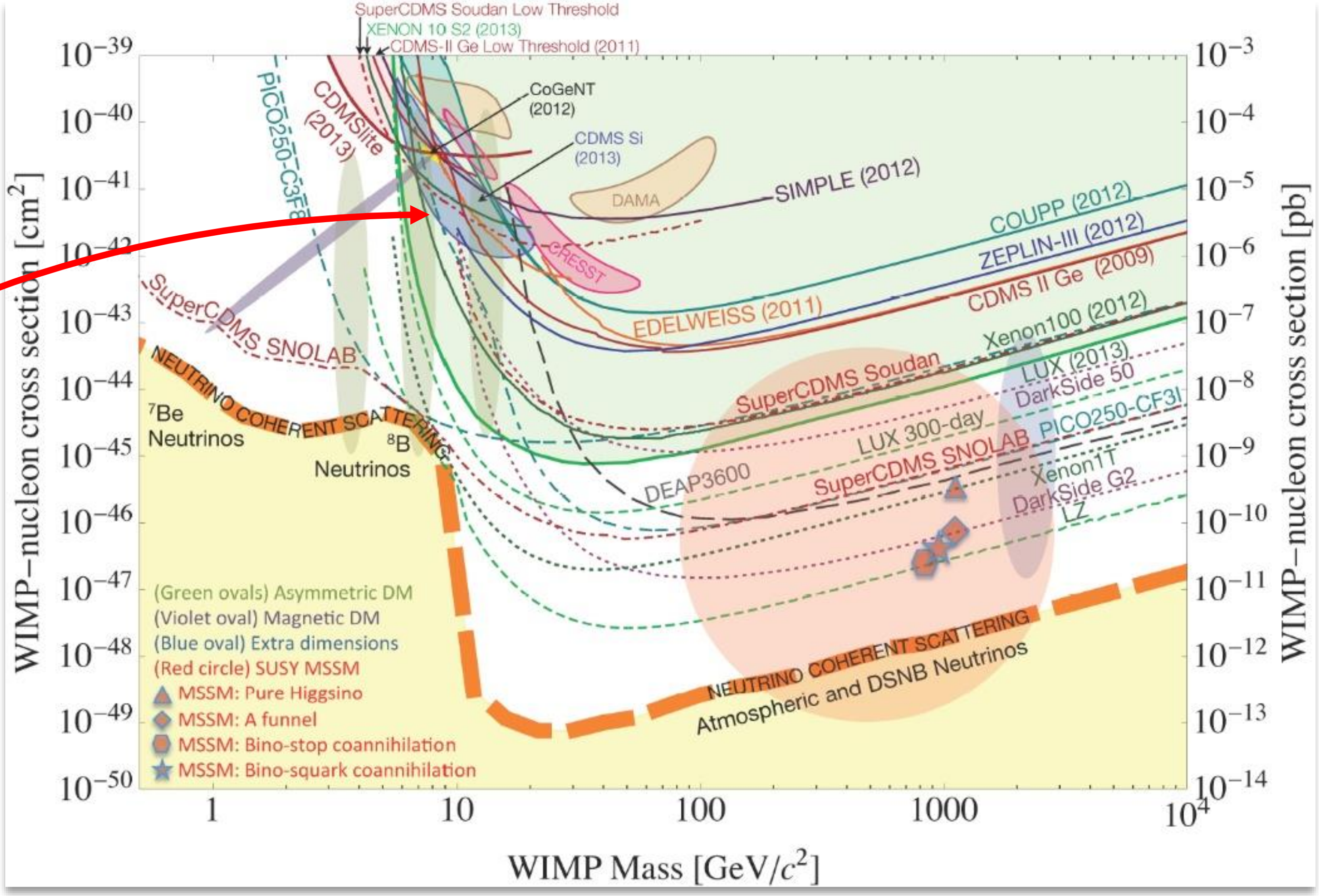


DM Direct Detection: Some Issues

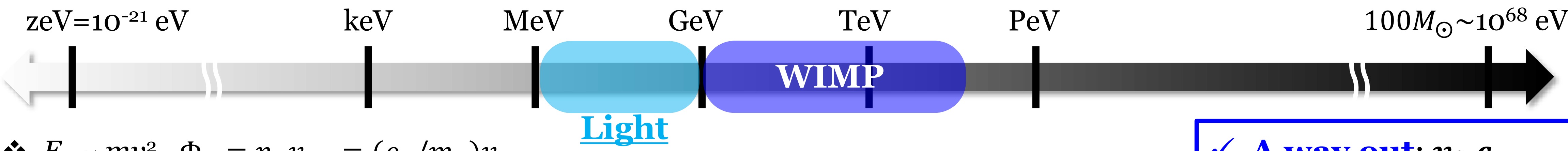
2. Mass & interaction of DM

- ✓ Differential recoil rate:
  - Amplitude ➔ Interaction strength
  - Curvature (~distribution) ➔ Mass





Light DM Direct Search



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

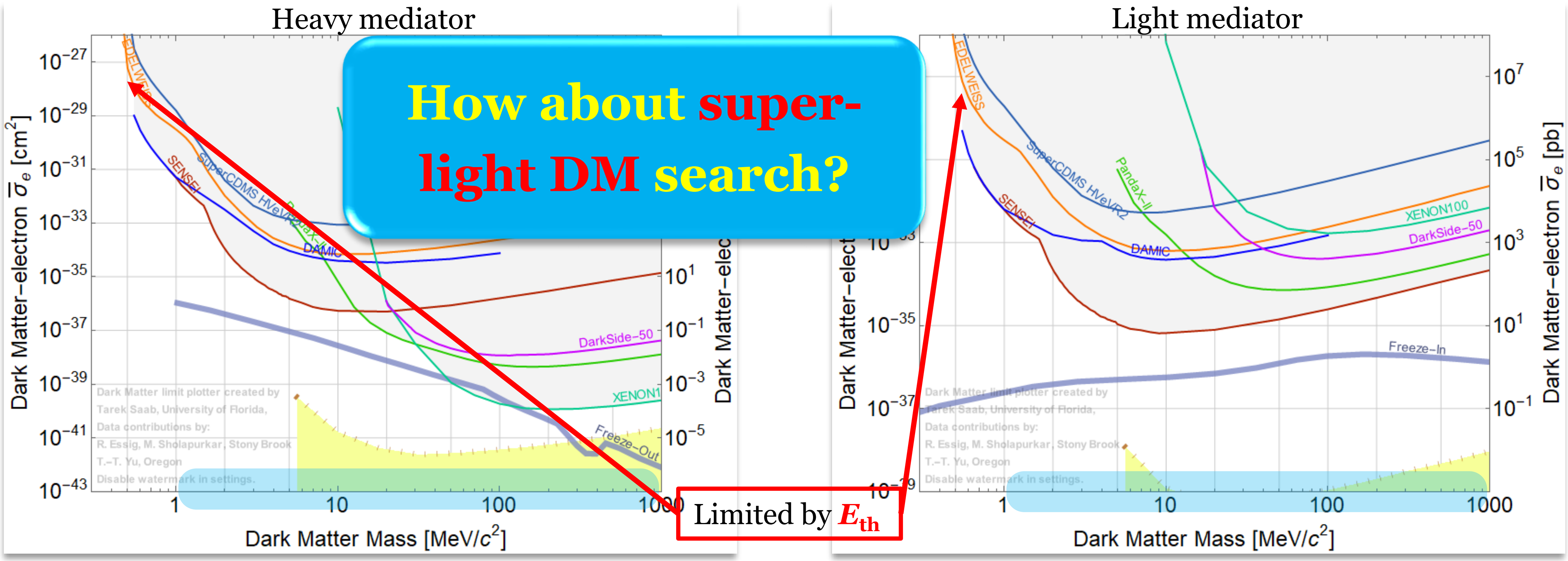
➔ **lighter DM**: **smaller E_r**, but **lager flux** (**lighter** target particle)

➔ **low E_th** preferred but even OK with **small target mass** (**e-recoil**)

✓ **A way out**: ***v~c***

e.g., **Boosted DM**

(Majumdar, Basu, **JCP**, …)

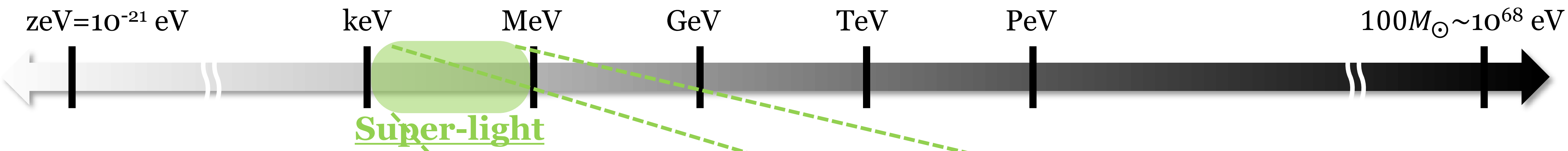


How about super-light DM search?

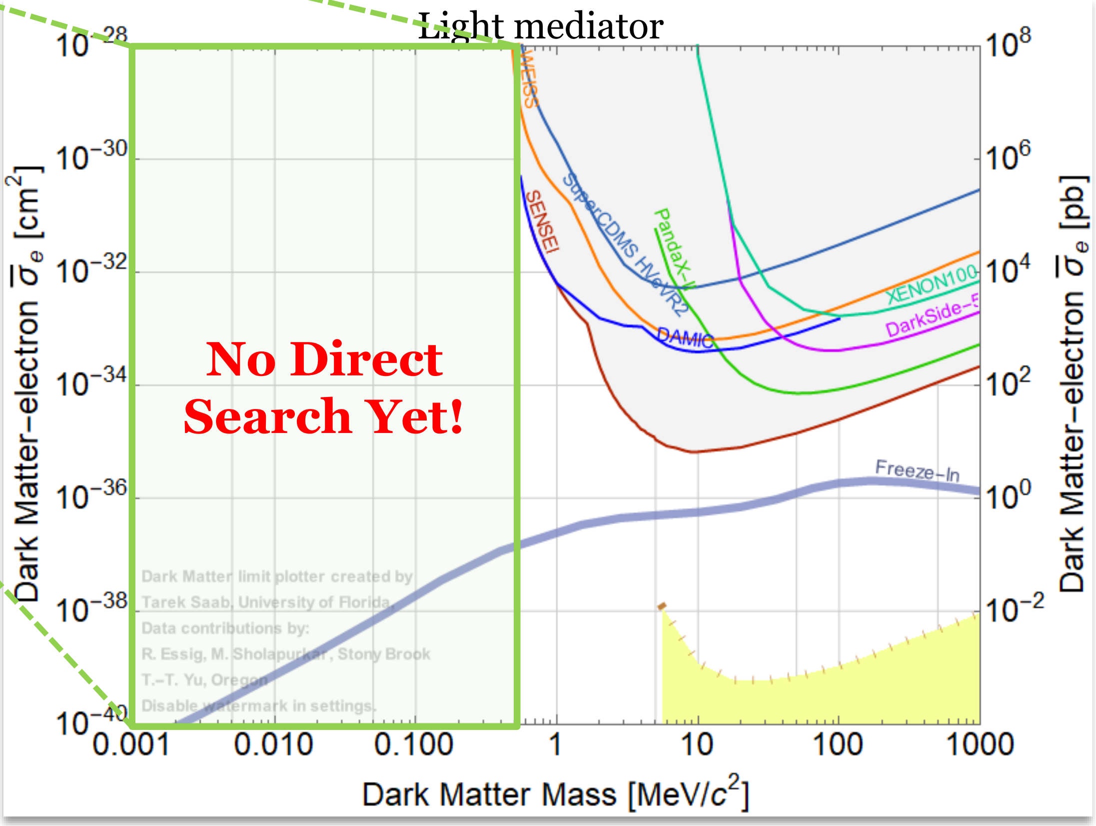
Limited by E_th

Dark Matter Limit Plotter

Super-Light DM Direct Search



- $E_k \sim mv^2 \sim O(\mathrm{meV})$ with $m\sim$keV & $v\sim10^{-3}$
- **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?**

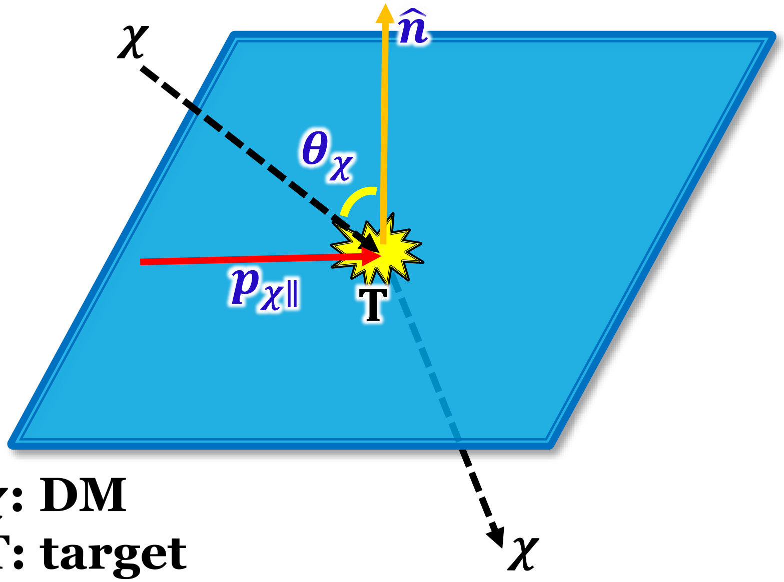
2. **Mass determination**:

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

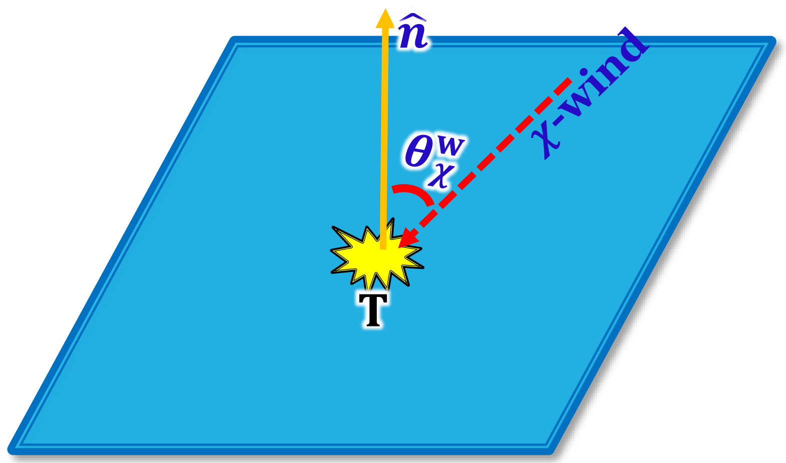


χ: DM
T: target

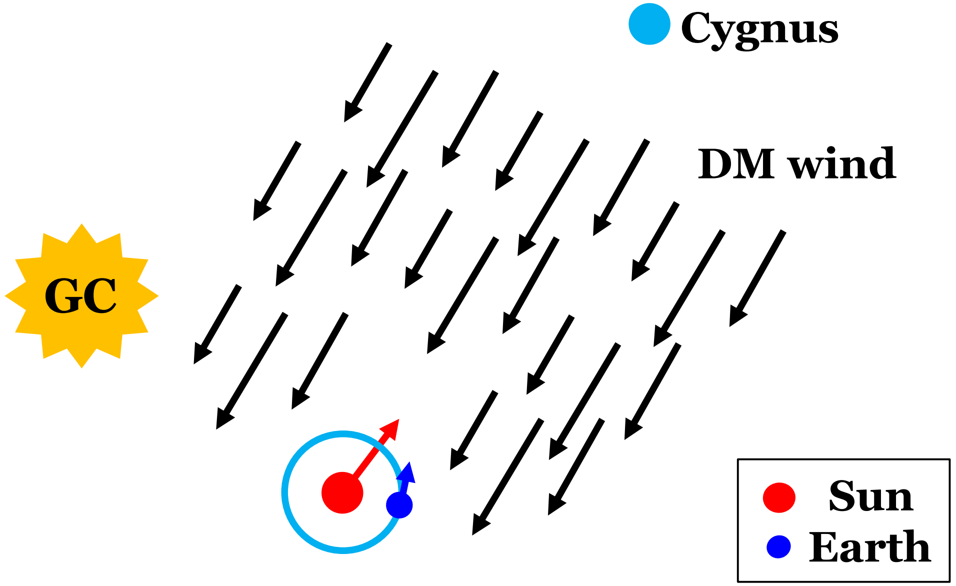
Answers for the Questions

- **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 ($\boldsymbol{\theta_\chi}$) 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 ($\boldsymbol{\theta_\chi^w}$) of the DM wind.



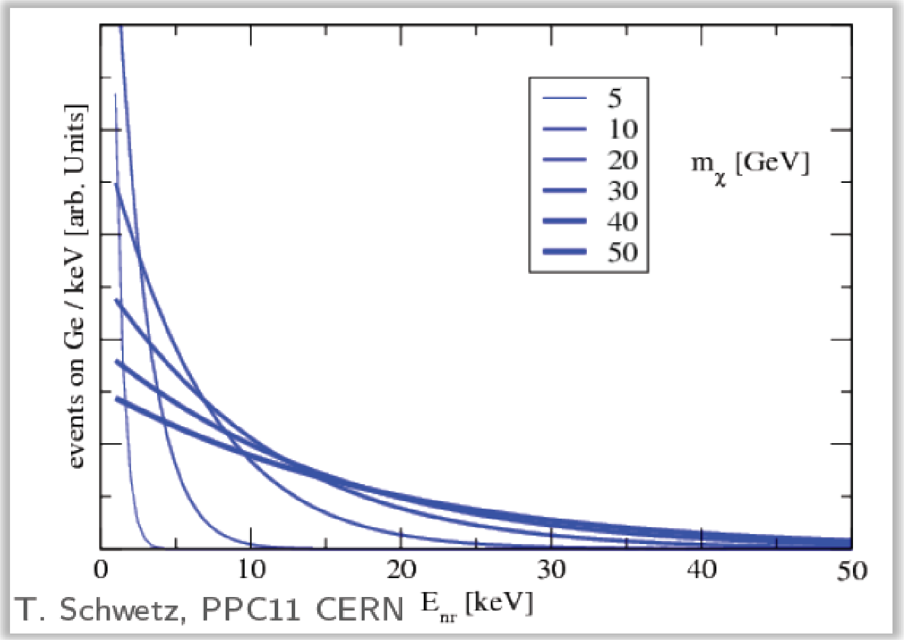
χ: DM
T: target



Answers for the Questions

- (effectively) 2D detectors: $\boldsymbol{v}_{\chi\parallel}$ 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 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

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

2D Detection:
Angular Dependence

Angular Dependence of Event Rates

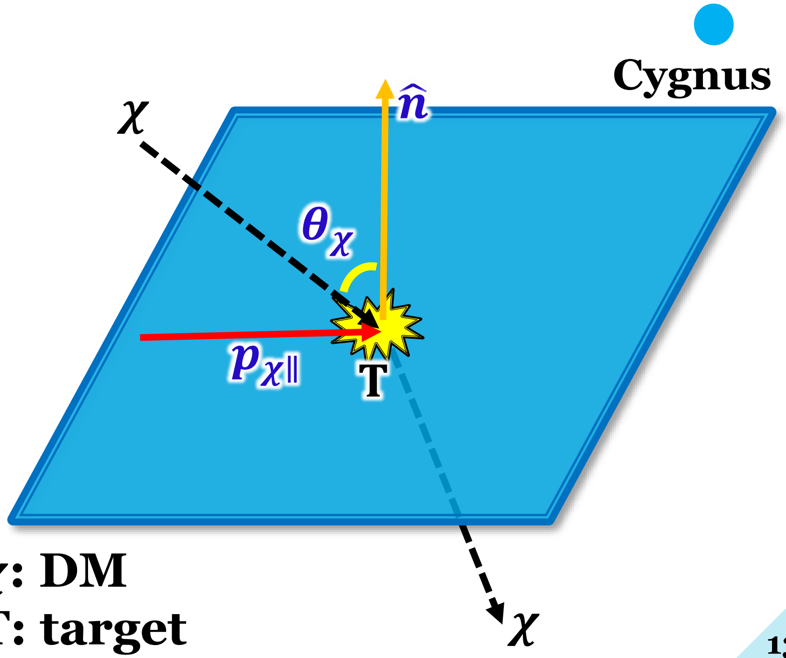
- Number of events/unit detector mass/unit run time: $n_{\rm eve} = \int dE_r dv_\chi\, f(v_\chi) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi {\rm T}} v_{\rm rel}\rangle \frac{\rho_\chi}{m_\chi}\right)$ with

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

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



χ: DM
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Angular Dependence of Event Rates

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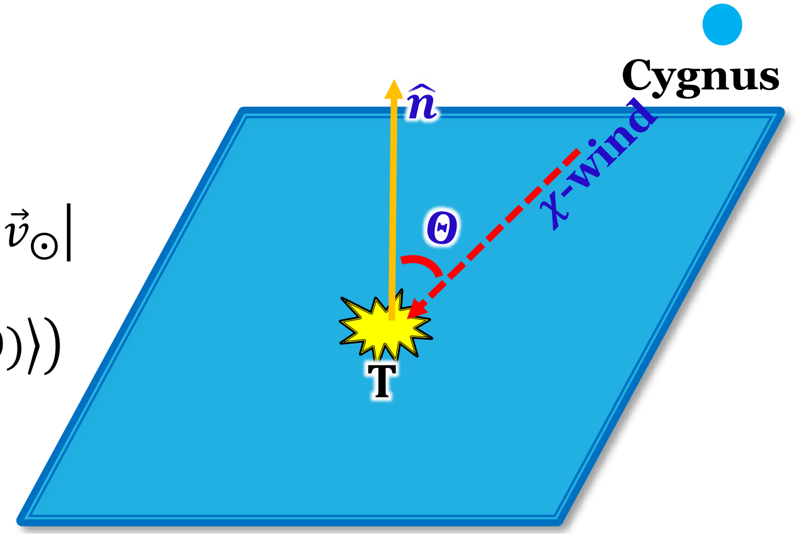
- Revolution of the solar system around the GC: $f(v_\chi) \to F(V_\chi)$ with $V_\chi \equiv |\vec{v}_\chi + \vec{v}_\odot|$

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

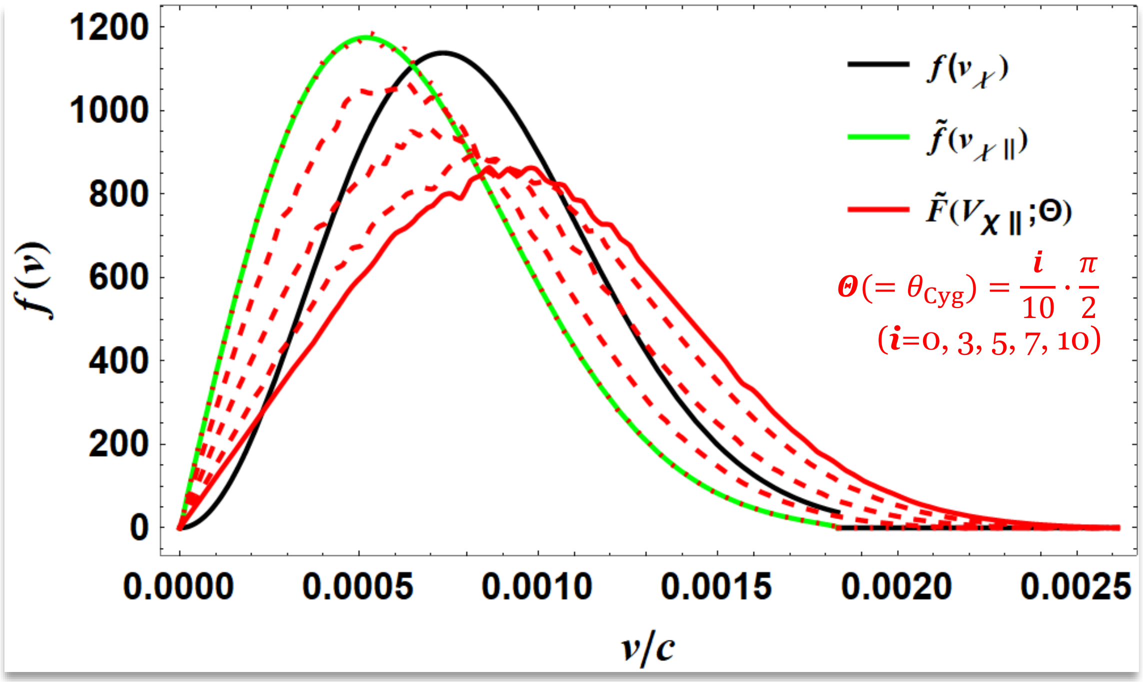
For Θ between the Cygnus direction and $\hat{n}$, a plane-projection procedure of $F(V_\chi)$ should be done individually ➔ $n_{\rm eve}$ depends on Θ non-trivially.



χ: DM
T: target

Angular Dependence ➔ Angular Modulation

- $E_{\rm th} \neq 0$ ➔ $V_{\chi\parallel,\rm min}$ 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**: $\boldsymbol{n}_{\rm eve}(\boldsymbol{\Theta}, \boldsymbol{m}_\chi) = \frac{\rho_\chi}{m_\chi}\int_{V_{\chi\parallel,\rm min}(m_\chi)}^{V_{\chi\parallel,\rm max}} dE_r dV_{\chi\parallel}\, \tilde{F}\left(V_{\chi\parallel};\, \Theta\right) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T} V_{\rm rel\parallel}(\Theta)\rangle\right)$ with $V_{\chi\parallel,\rm max} = v_{\rm esc} + v_\odot \sin\Theta$.



Angular Dependence ➔ Angular Modulation

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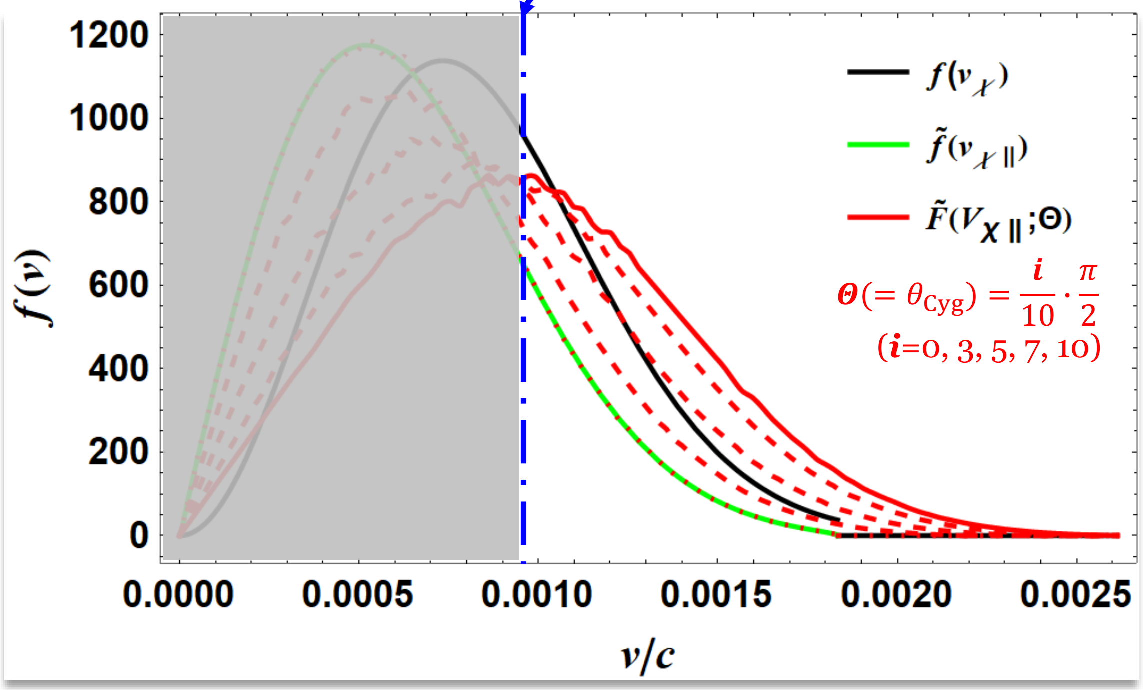
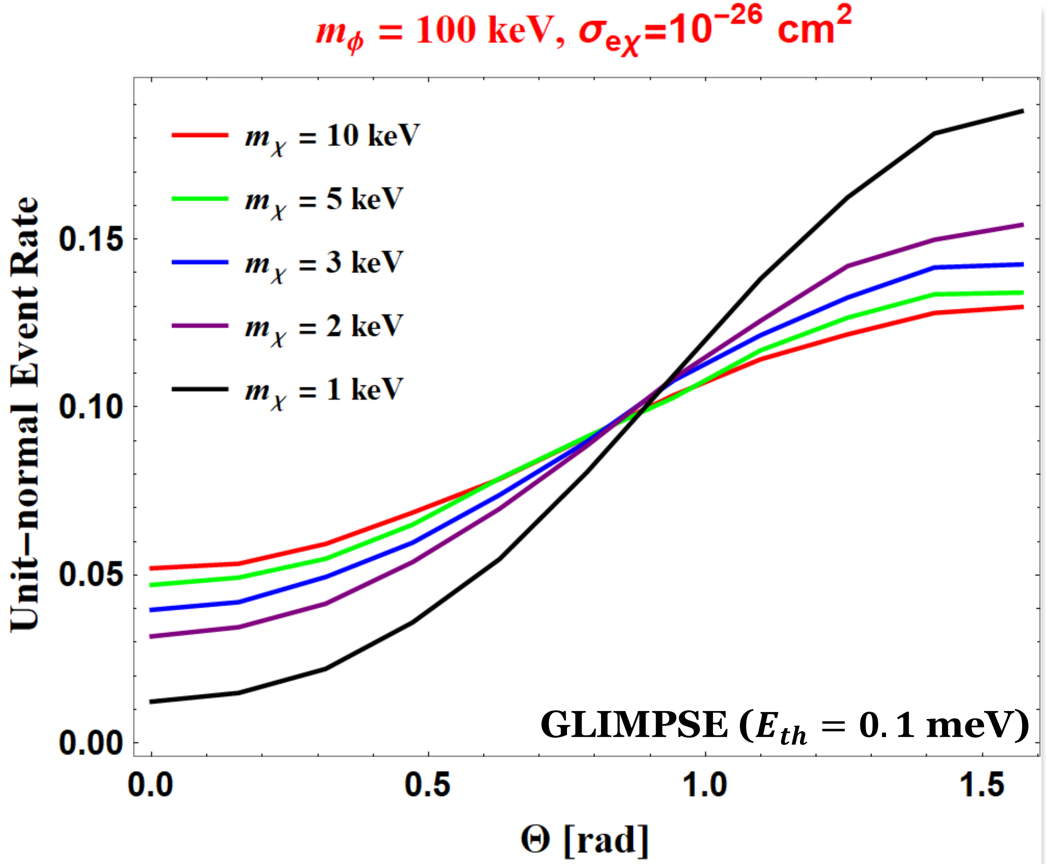
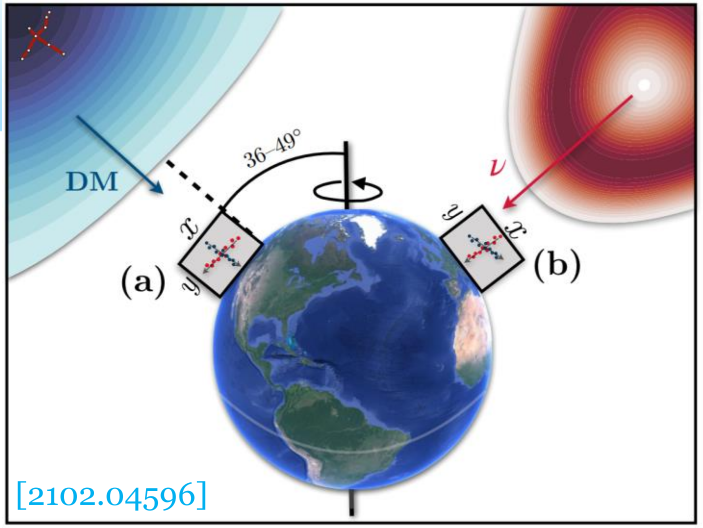
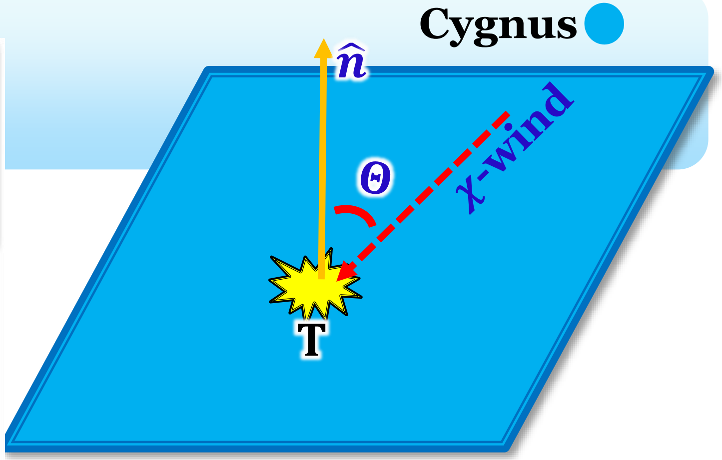




Summary





- 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

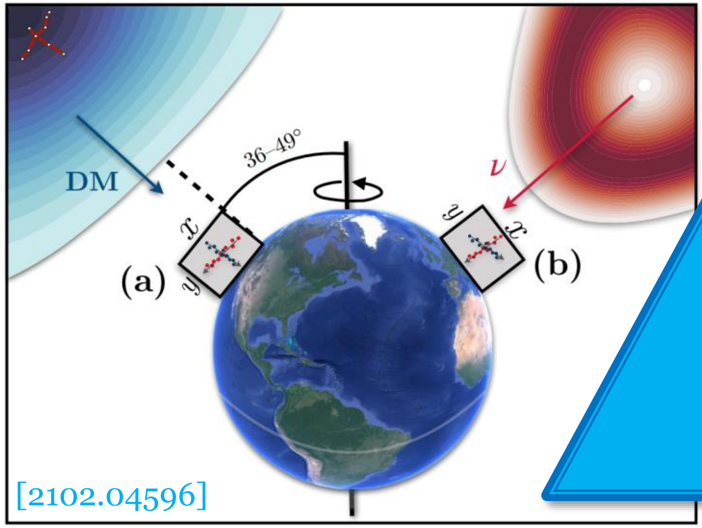
Thank You!

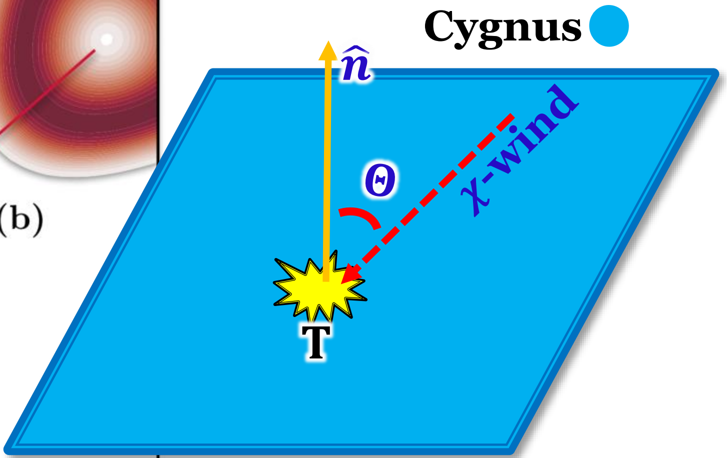
Supplemental

Angular Modulation vs Annual Modulation

❖ **Angular modulation (→ Daily!)**

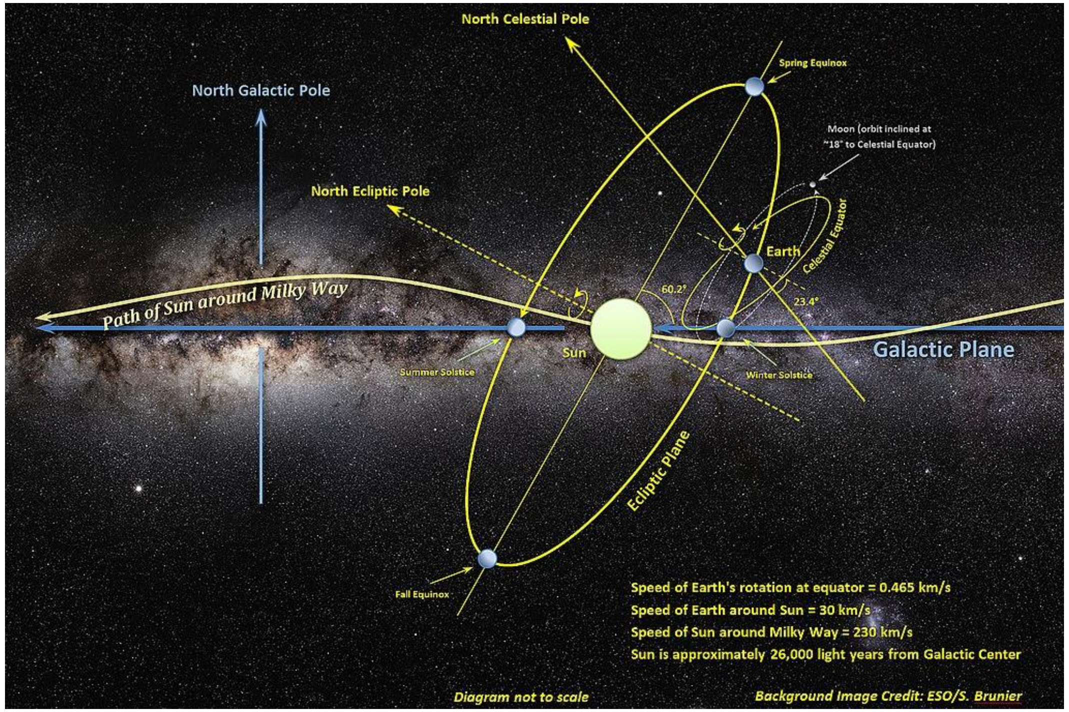
- ✓ Effects from the change of the DM wind direction (Θ) relative to the plane-normal direction due to Detector's motion
  - → contribution: **revolution ≈ rotation**
- ✓ $N_{\text{event}}(\boldsymbol{\Theta})$ from $N_{\text{event}}(t)$ using $\boldsymbol{\Theta}(\boldsymbol{t})$
  - → BG rejection + 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** ≫ rotation
- ✓ $N_{\text{event}}(\boldsymbol{t})$ → BG rejection



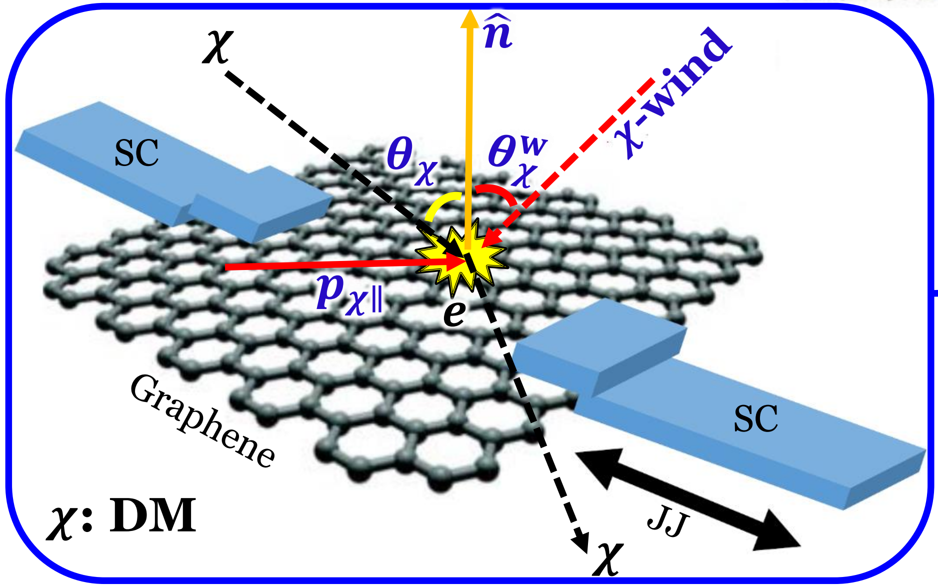
Directional Dependence: Angular Information?

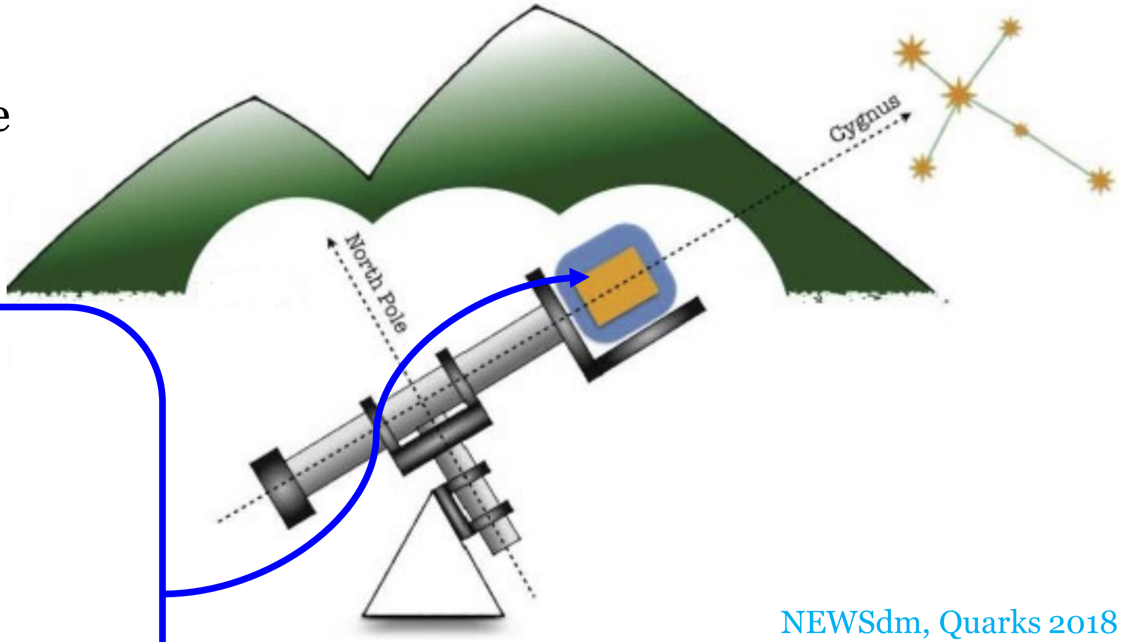
✓ **Actively rotating the detector** to run the experiment with a **fixed** $\boldsymbol{\theta_\chi^{\mathrm{w}}} = \boldsymbol{\Theta}$.

✓ **Timing information** of each signal ➔ **statistically** $\boldsymbol{\Theta}(\boldsymbol{t})$.

✓ $\boldsymbol{\theta_\chi}$: event-level unmeasurable

✓ $\boldsymbol{\theta_\chi^{\mathrm{w}}} = \boldsymbol{\Theta}$: controllable & (statistically) measurable





NEWSdm, Quarks 2018

Detector classes by directional information

Demonstrated (green) / R&D (blue) / Proposed (red)

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]

GLIMPSE

Graphene-based super-Light Invisible Matter Particle SEarch

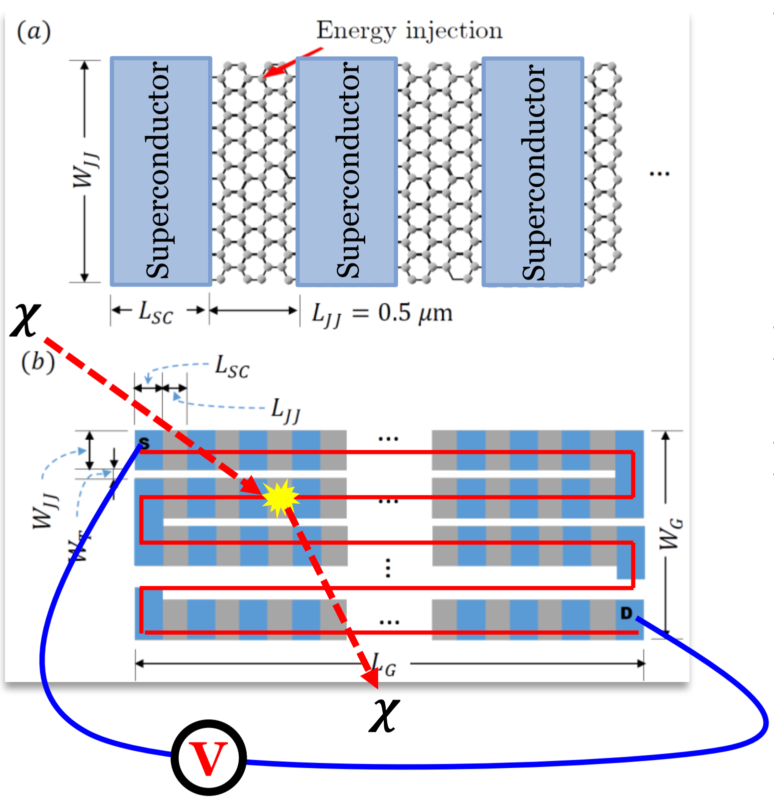
[Kim, **JCP**, Lee, Fong, 2002.07821 & in progress]

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).