Extracting Dark-Matter Mass from Angular Scanning

With Doojin Kim and Jong-Chul Park

arXiv:2604.18704

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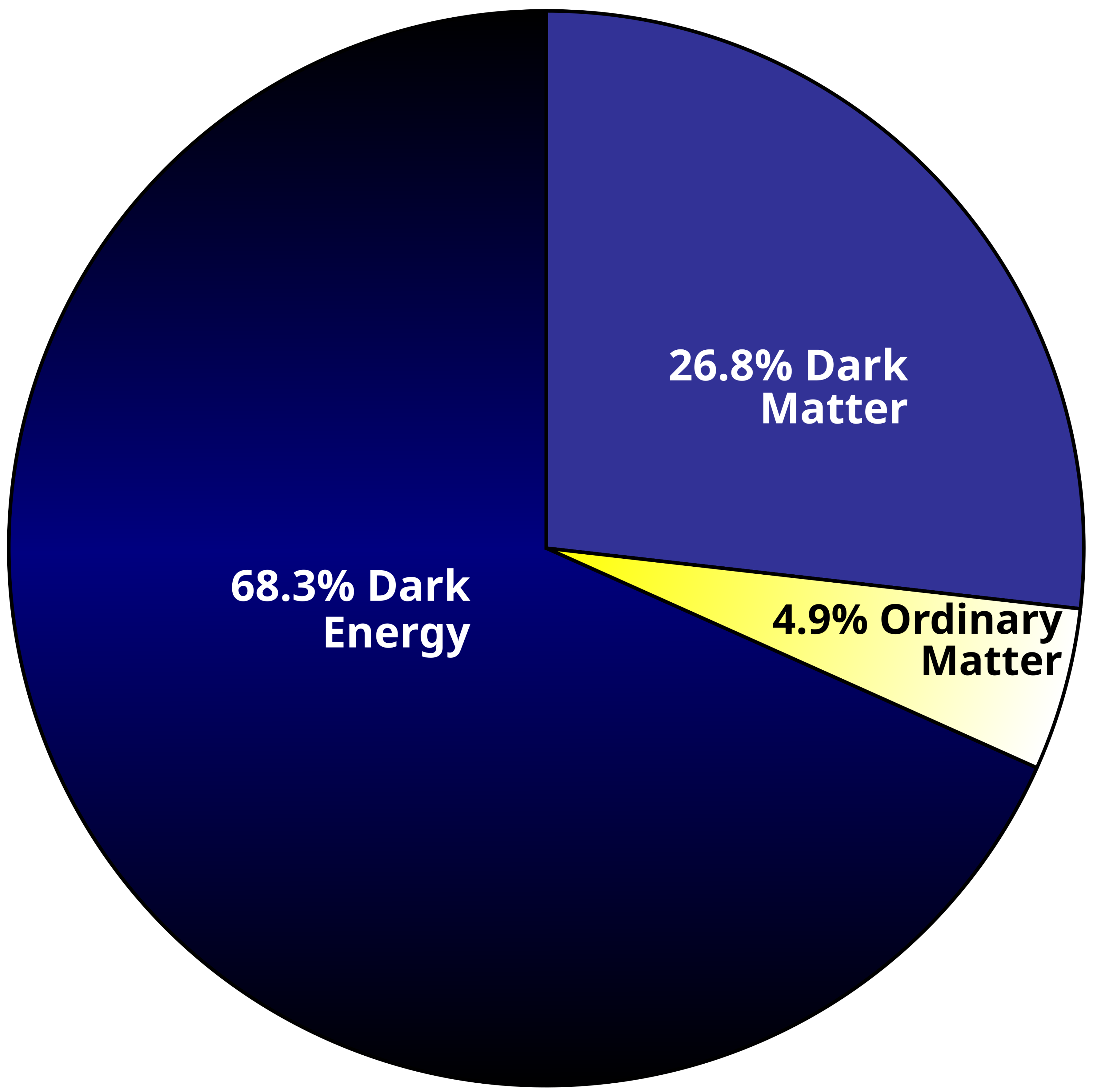
Dark Matter

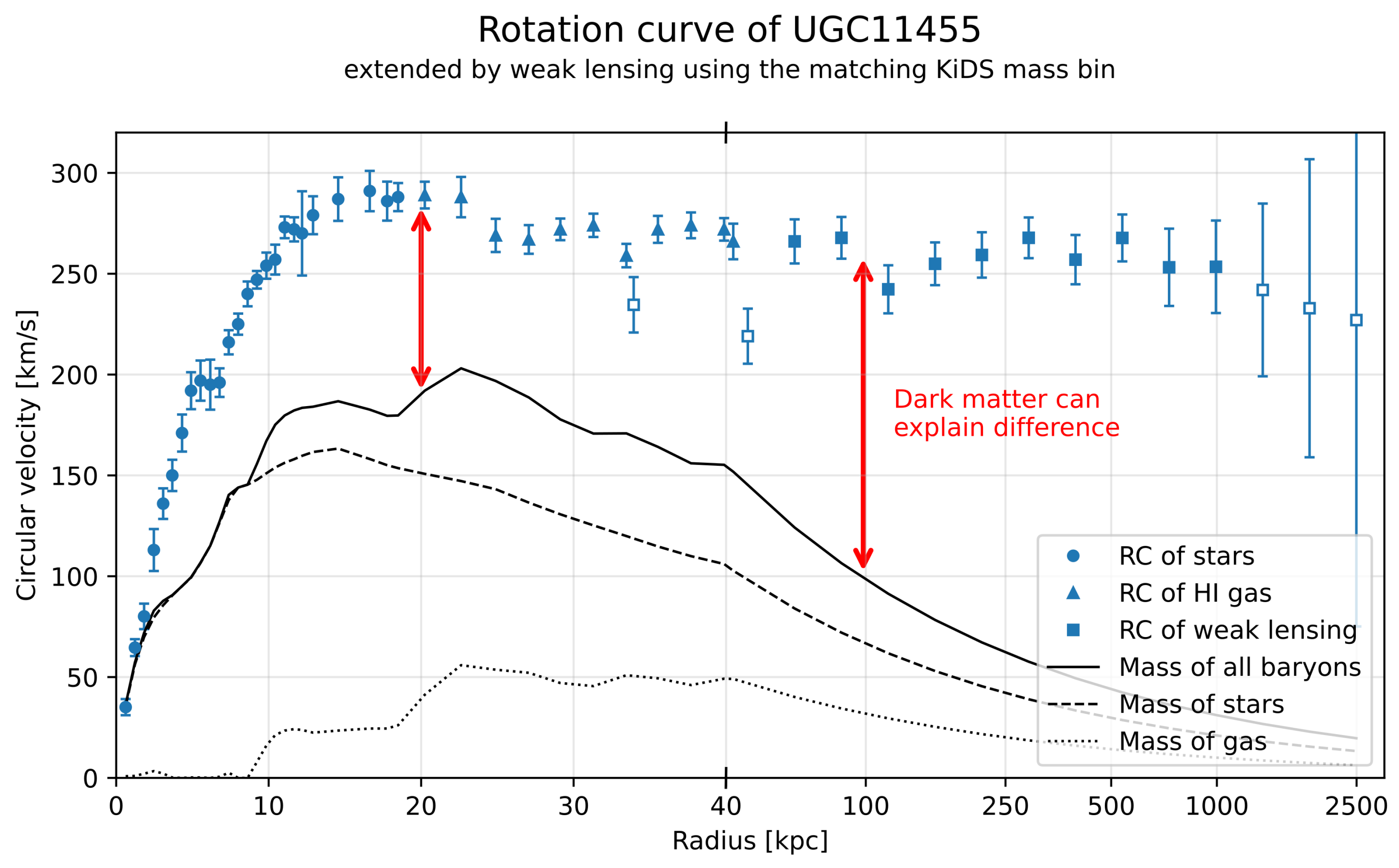
Dark-Matter

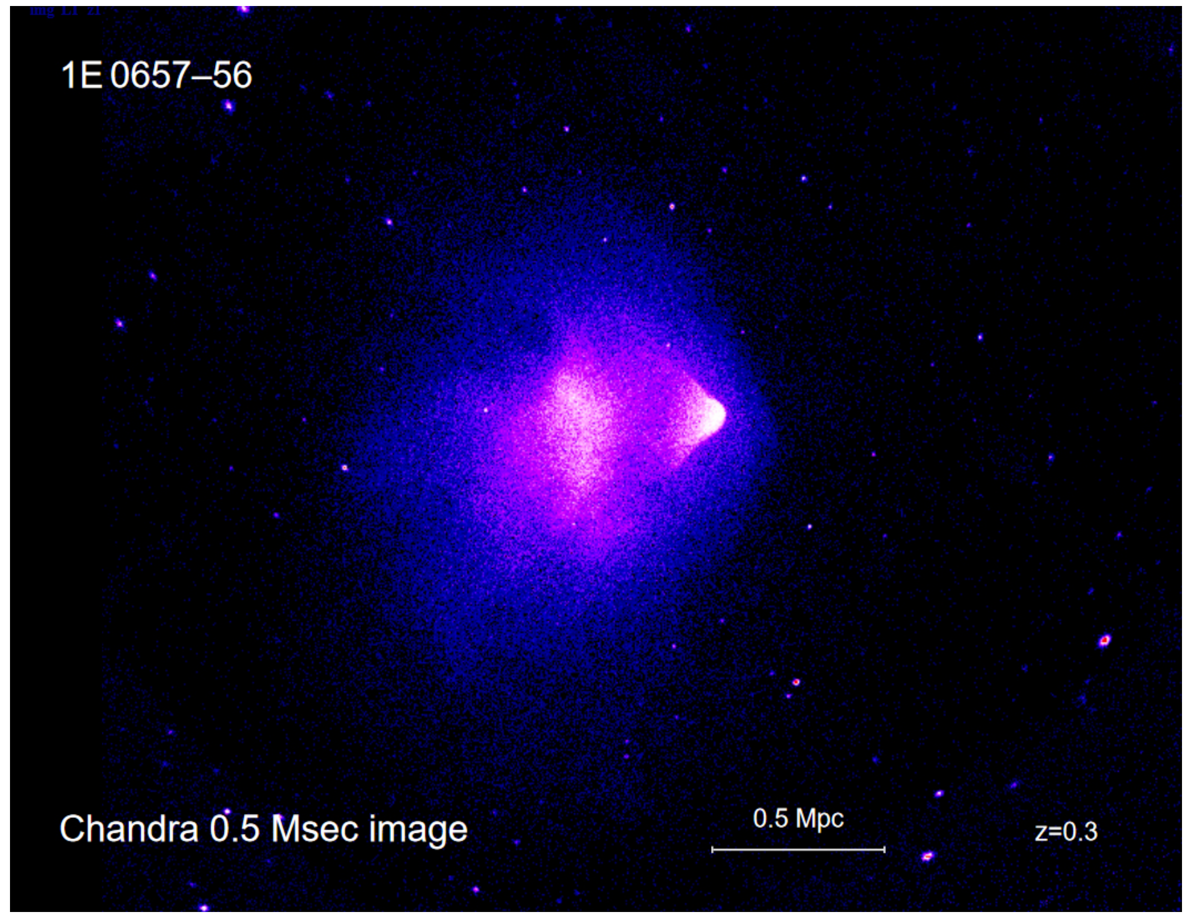
• **Invisible** and hypothetical form of matter that does **not interact with electromagnetic radiation**, including light.



Evidence

• Various observations, such as **Galaxy Rotation Curves** and the **Bullet Cluster**, suggest the existence of DM.

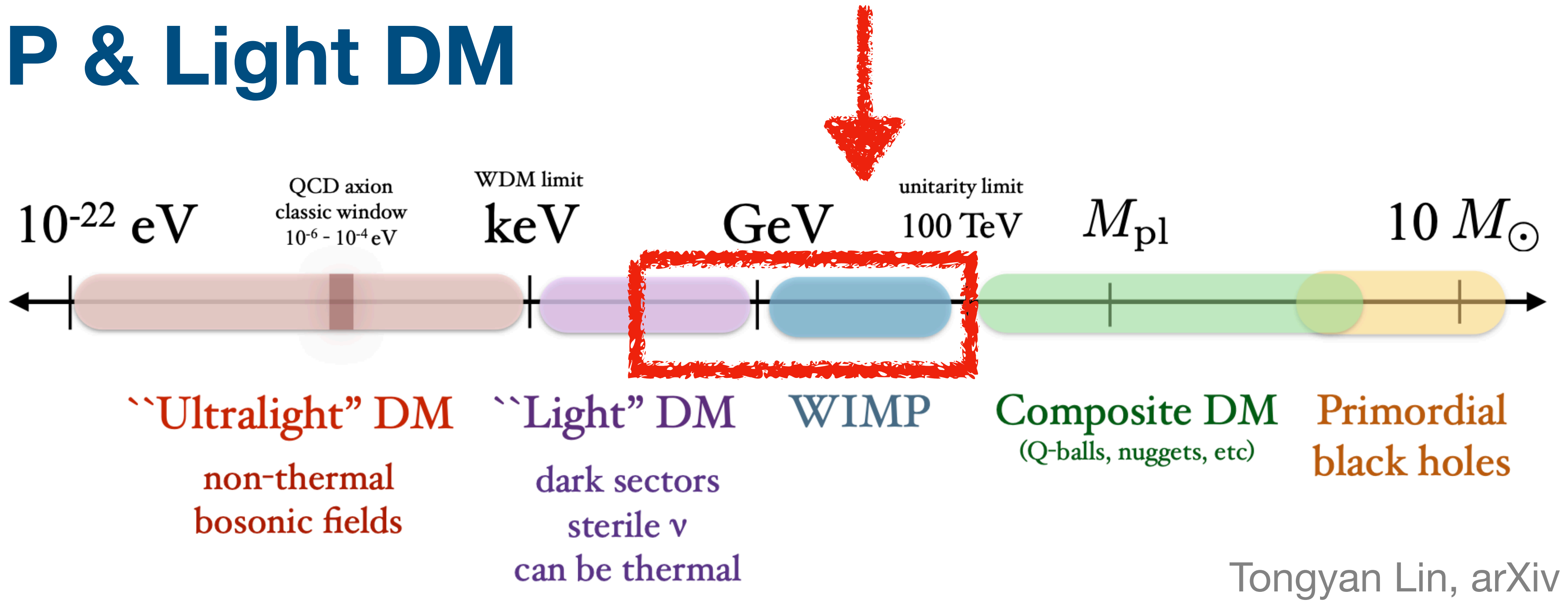




• However, the nature of dark matter and its non-gravitational interactions **remain unknown**.

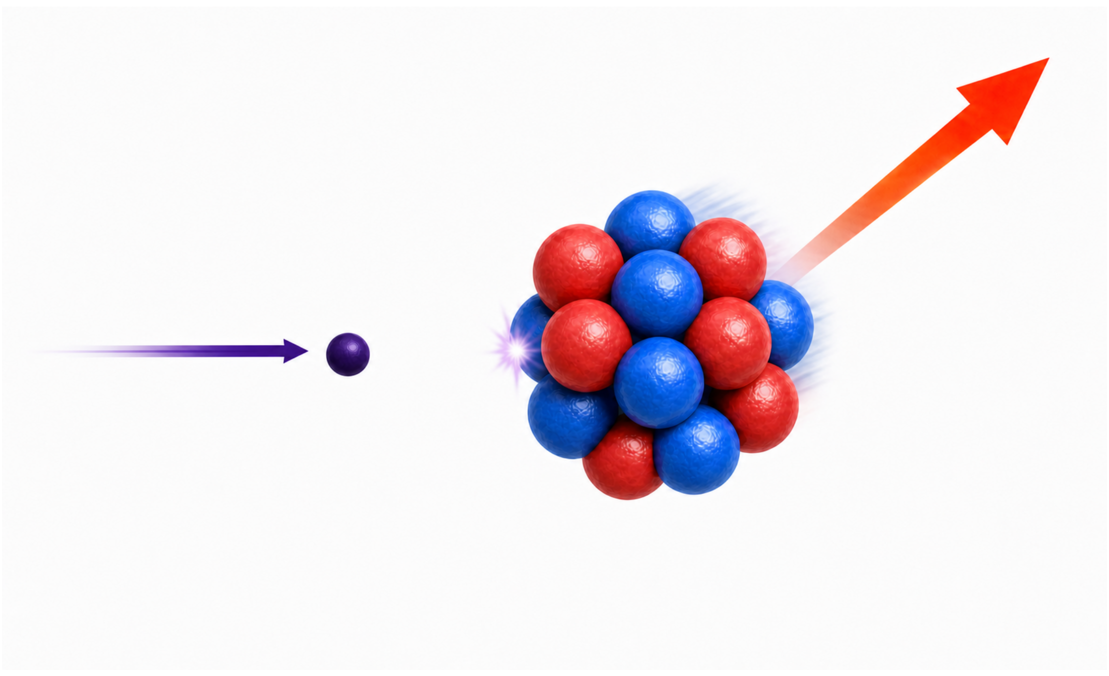
Dark Matter Direct Detection

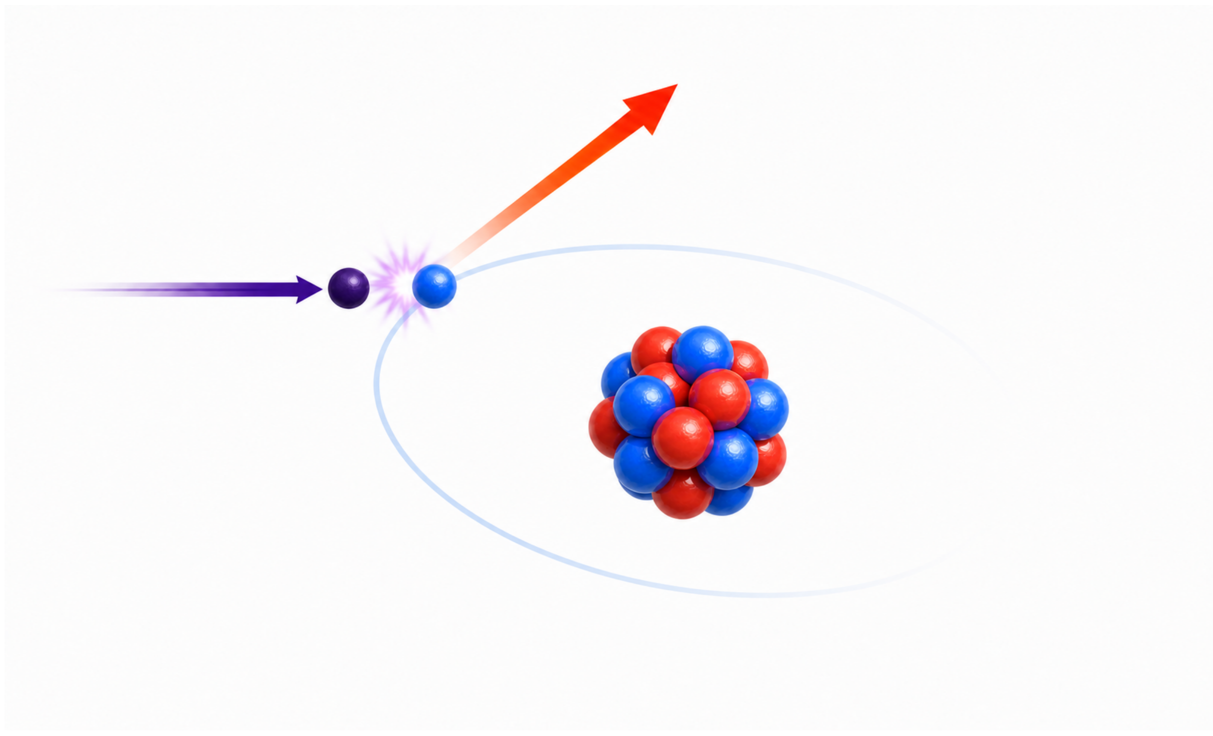
WIMP & Light DM



Tongyan Lin, arXiv : 1904.07915

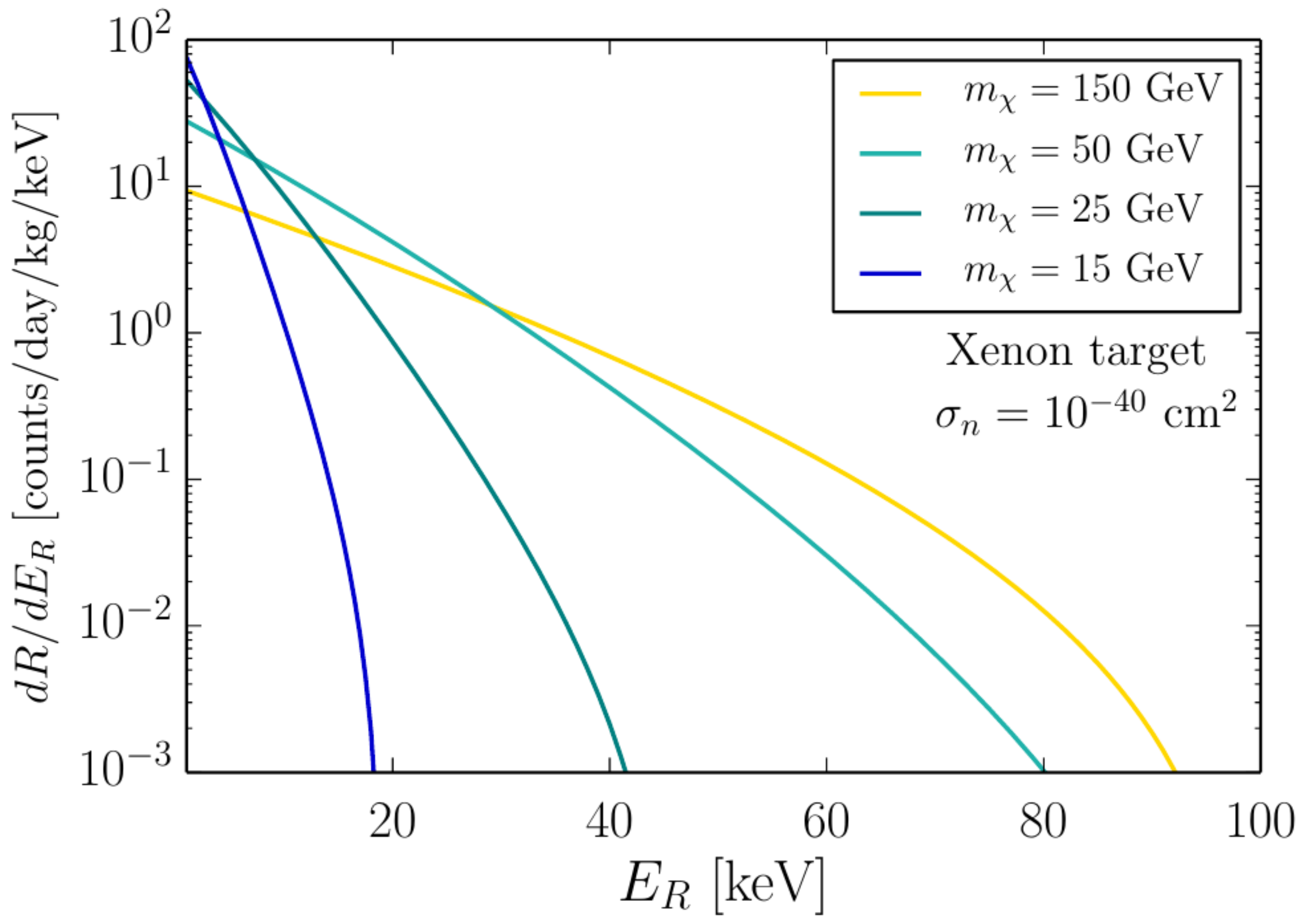
- **WIMP** : GeV–TeV
- **Light DM** : MeV–GeV





DM hits a nucleus/electrons and make it **recoil** with energy E_R.

Mass from the recoil spectrum



Tongyan Lin, arXiv:1904.07915, Fig. 17

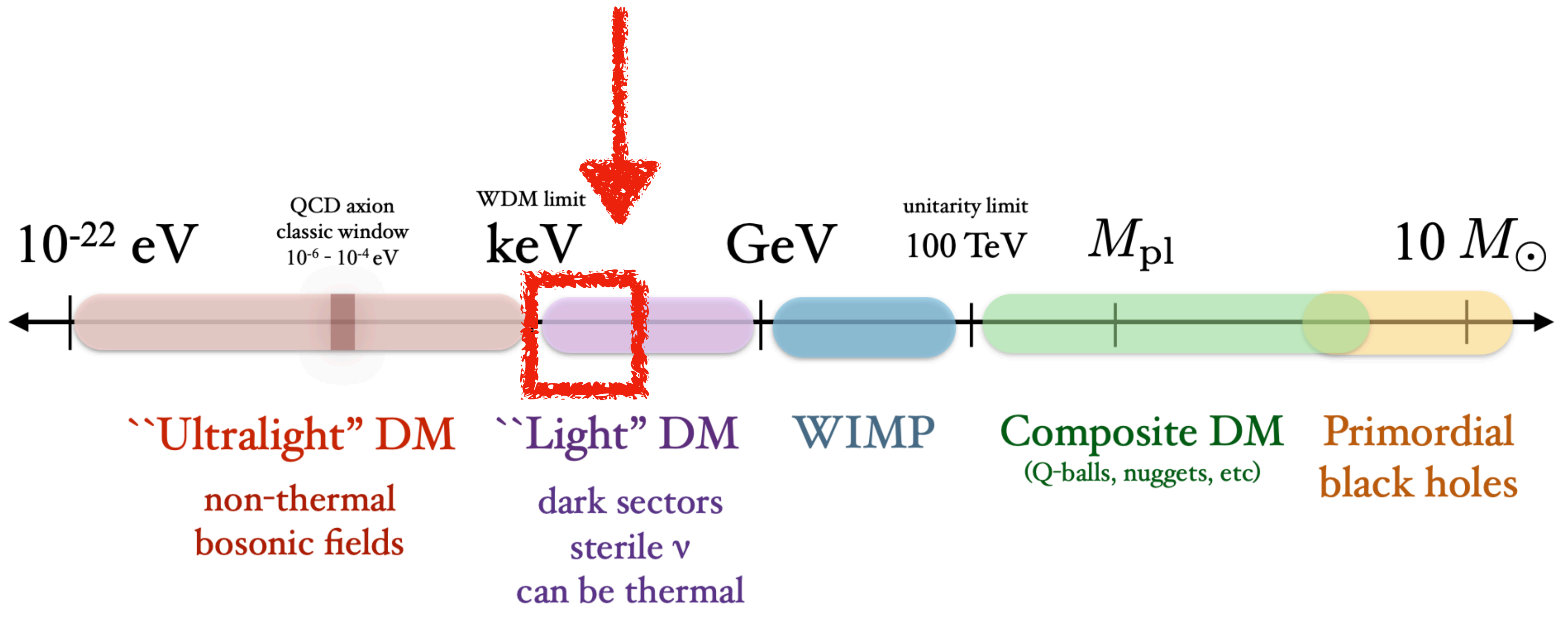
Lighter DMs → falls off steeply.

The shape of dR/dE_R infers the mass.

Recoil-energy spectrum → DM mass

Superlight Dark Matter

Superlight DM



Tongyan Lin, arXiv : 1904.07915

- Dark matter in the **keV–MeV** mass range

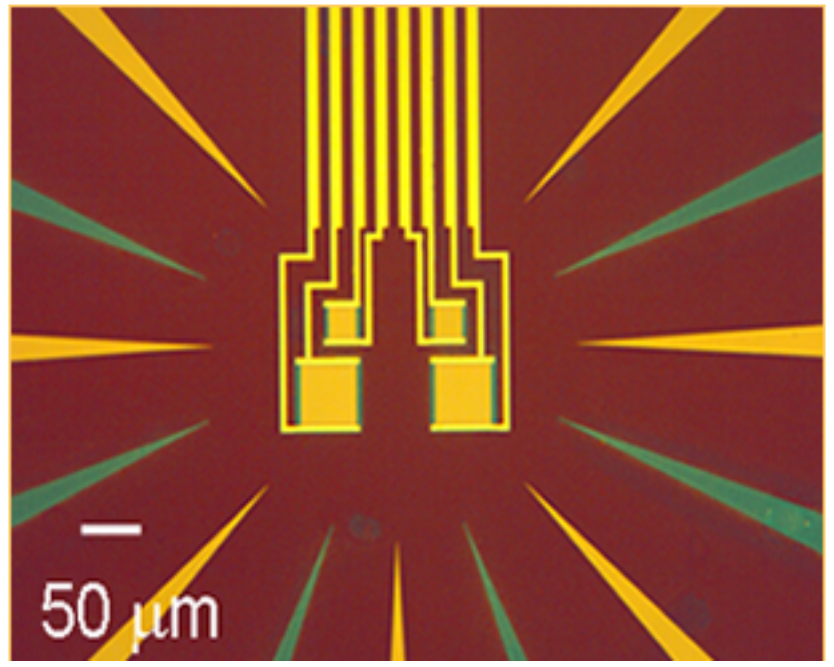
Why such a low threshold?

$$K_{DM} \simeq \frac{1}{2}mv^2 \simeq 0.5\,\mathrm{eV}\left(\frac{M_{DM}}{1\,\mathrm{MeV}}\right)\left(\frac{v}{10^{-3}c}\right)^2$$

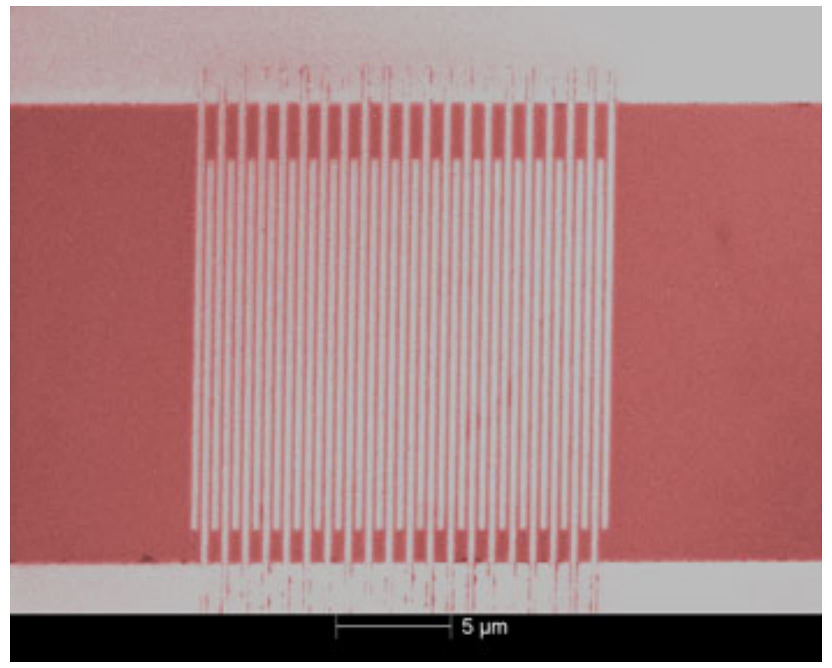
$$M_{DM} : 1\,\mathrm{GeV} \;\rightarrow\; K_{DM} : \sim 0.5\,\mathrm{keV}$$
$$M_{DM} : 1\,\mathrm{MeV} \;\rightarrow\; K_{DM} : \sim 0.5\,\mathrm{eV}$$

Lighter dark matter carries less kinetic energy,
so eV/sub-eV thresholds are essential.

Difficult to measure the recoil-energy spectrum precisely.



TES



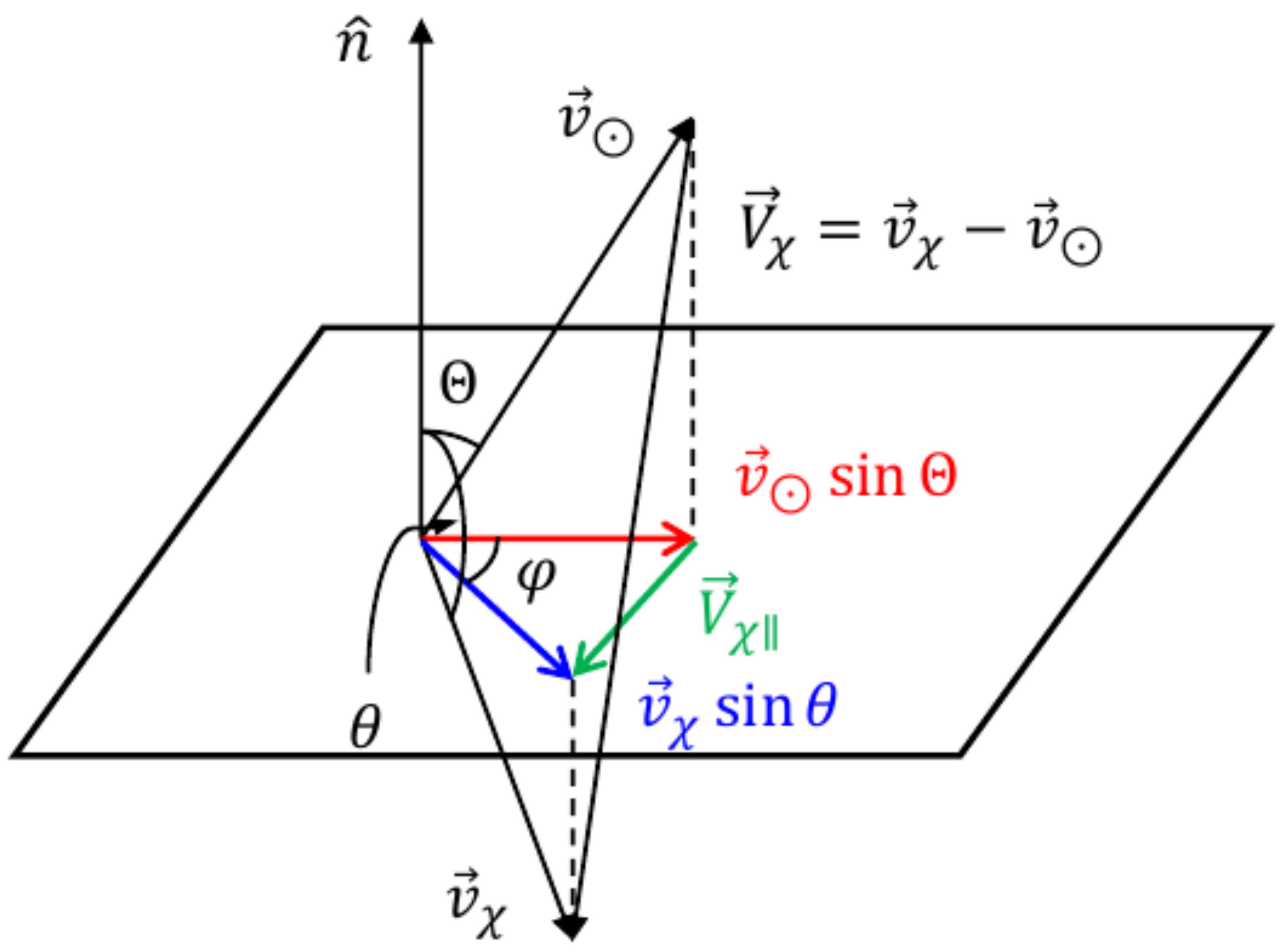
SNSPD

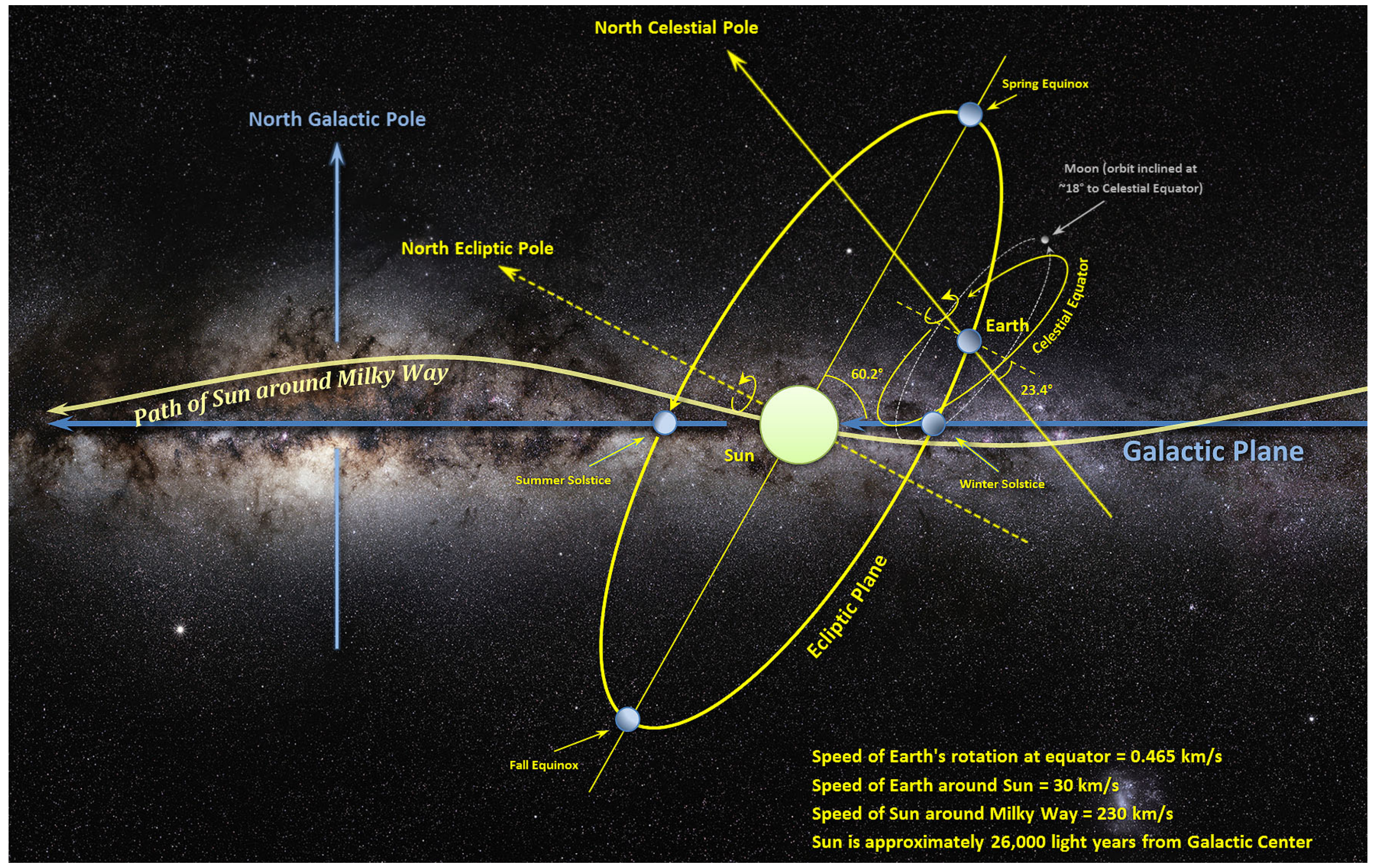
NIST, S. Kelley/NIST

“In detectors where the recoil-energy spectrum cannot be measured,
is there still a way to extract information about the mass of DM?”

“Yes — a 2D detector’s event rate changes with direction,
and that angular dependence still carries mass information.”

Angular dependence of event rates





- Assume Dark matter follows modified Maxwell-Boltzmann distribution $f(v_\chi)$

  However, because of the motion of Solar system; **DM wind** $(-\vec{v}_\odot)$,

  → **DM-wind-modified distribution** $F(V_\chi)$

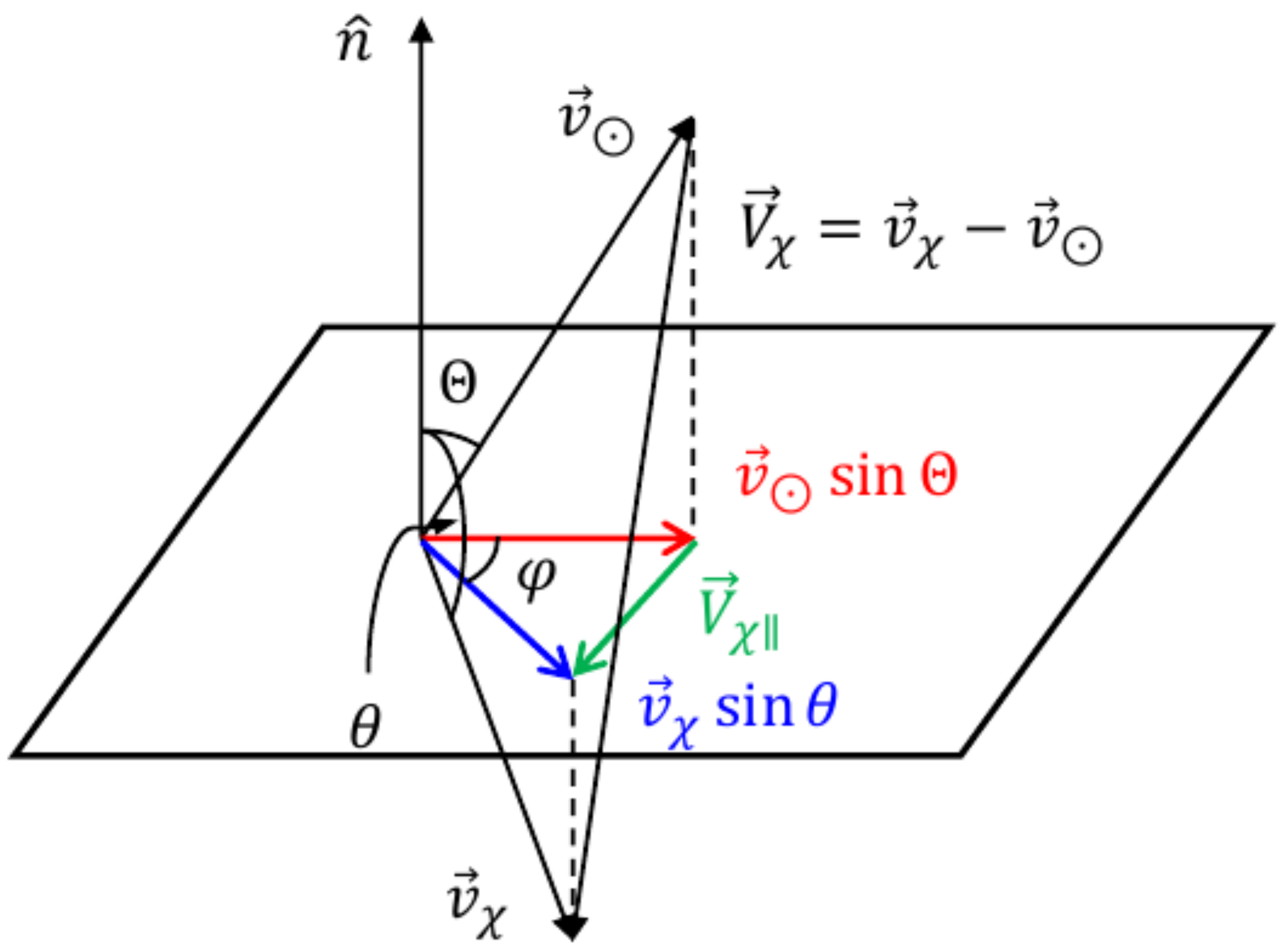
- Plane projected to the detector plane

  → **Plane projected DM-wind-modified distribution** $\tilde{F}(V_\chi)$

$$\tilde{F}(V_{\chi\parallel};\Theta) = \begin{cases} \displaystyle\int_0^\pi d\varphi \, \frac{\tilde{v}_\parallel}{\pi} \int_{-c_\theta^+}^{c_\theta^+} d\cos\theta \, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^+_{\chi\parallel}}{\sin\theta}\right) & \text{for } V_{\chi\parallel} \geq v_{\odot\parallel}, \\ \displaystyle\int_{\pi-\sin^{-1}\left(\frac{V_{\chi\parallel}}{v_{\odot\parallel}}\right)}^{\pi} d\varphi \, \frac{\tilde{v}_\parallel}{\pi} \left[\int_{-c_\theta^+}^{c_\theta^+} d\cos\theta \, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^+_{\chi\parallel}}{\sin\theta}\right) + \int_{-c_\theta^-}^{c_\theta^-} d\cos\theta \, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^-_{\chi\parallel}}{\sin\theta}\right) \right] & \text{for } V_{\chi\parallel} < v_{\odot\parallel}. \end{cases}$$

- Θ : Angle between the **DM wind** and the **plane normal**

θ vs Θ(t)



θ — individual incident angle

Between the incident direction of each DM particle and the detector-plane normal.

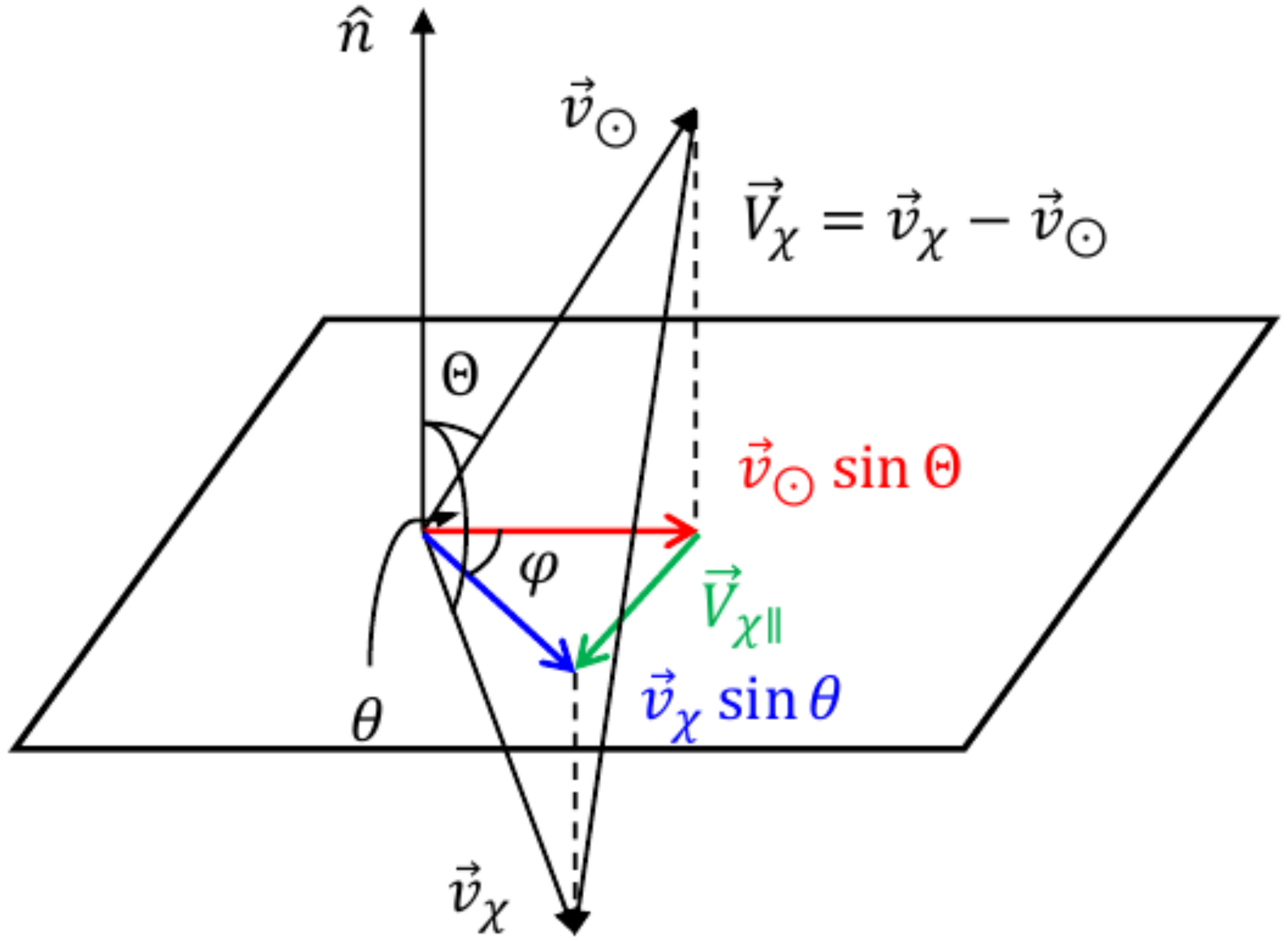
Varying for each particle; unmeasurable.

Θ(t) — average incident angle

Between the lab-frame DM-wind direction and the detector-plane normal.

→ predictable, controllable, measurable.

Angular dependence of event rates



- **Projected event rate**

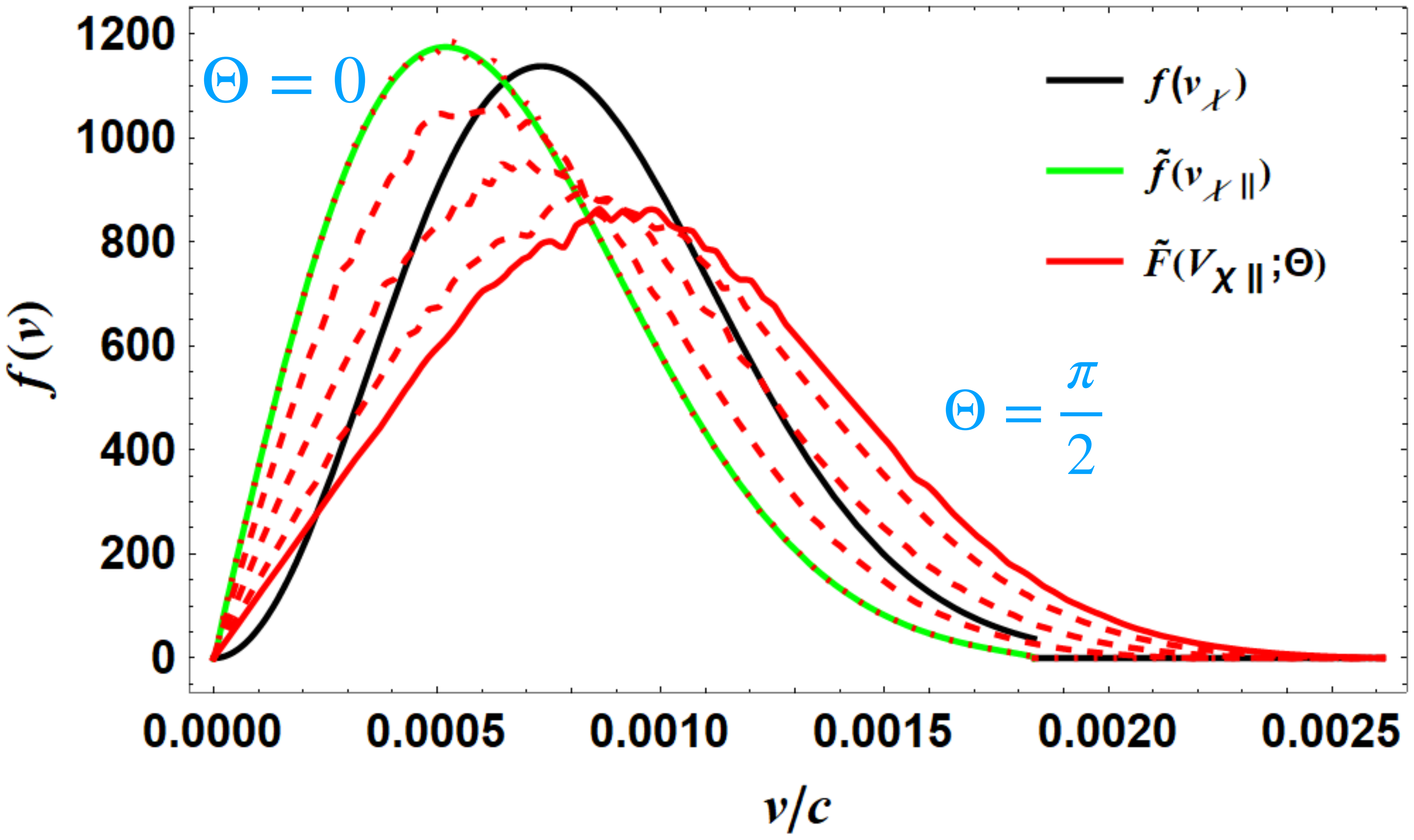
  $N =$ **DM number density** $\times$ **number of targets** $\times \left\langle \sigma \cdot v_{\textbf{rel}} \right\rangle$

- $$n_{\rm eve}(\Theta, m_\chi) = \frac{\rho_\chi}{m_\chi} \int dE_r \int_{V_{\chi\parallel,\,\min}(m_\chi)}^{V_{\chi\parallel,\,\max}} dV_{\chi\parallel}\, \tilde{F}(V_{\chi\parallel};\Theta)\, \frac{d\langle \overline{N}_T \sigma_{\chi T} V_{\rm rel\parallel}(\Theta)\rangle}{dE_r}$$

  $$V_{\chi\parallel,\,\max} = v_{\rm esc} + v_\odot \sin\Theta$$

  $V_{\chi\parallel,\,\min}$ **depends on** m_χ **(for a fixed** E_{th}**)**

Angular dependence of event rates



- Projected velocity distribution

$$\tilde{F}(V_{\chi\parallel};\Theta) = \begin{cases} \int_0^{\pi} d\varphi\ \frac{\tilde{v}_\parallel}{\pi} \int_{-c_\theta^+}^{c_\theta^+} d\cos\theta\, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^+_{\chi\parallel}}{\sin\theta}\right) & \text{for } V_{\chi\parallel} \geq v_{\odot\parallel}, \\ \int_{\pi-\sin^{-1}\left(\frac{V_{\chi\parallel}}{v_{\odot\parallel}}\right)}^{\pi} d\varphi\, \frac{\tilde{v}_\parallel}{\pi} \left[\int_{-c_\theta^+}^{c_\theta^+} d\cos\theta\, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^+_{\chi\parallel}}{\sin\theta}\right) + \int_{-c_\theta^-}^{c_\theta^-} d\cos\theta\, \frac{1}{2\sin\theta} f\left(\frac{\overline{V}^-_{\chi\parallel}}{\sin\theta}\right) \right] & \text{for } V_{\chi\parallel} < v_{\odot\parallel}. \end{cases}$$

Velocity distributions

Black : modified Maxwell-Boltzmann distribution

Red : Plane projected velocity distribution (with DM wind) $\tilde{F}(V_{\chi\parallel};\Theta)$

$$\Theta = \frac{i}{10}\frac{\pi}{2}, (i = 10,7,5,3,0 \text{ [solid to dotted]})$$

How to calculate Θ

The DM wind arises from the **motions of the Sun and the Earth**.

1. Galactic rotation : $\mathbf{v}_c = v_c \hat{\mathbf{y}}_g$
2. Sun's peculiar velocity : $\mathbf{v}_s = U\hat{\mathbf{x}}_g + V\hat{\mathbf{y}}_g + W\hat{\mathbf{z}}_g$
3. Earth's revolution : $\mathbf{v}_{\mathrm{e,rev}}$
4. Earth's rotation : $\mathbf{v}_{\mathrm{e,rot}}$

$$\mathbf{v}_{\mathrm{det,gal}} = \mathbf{v}_c + \mathbf{v}_s + \mathbf{v}_{\mathrm{e,rev}} + \mathbf{v}_{\mathrm{e,rot}}$$

After **transforming** from the Galactic frame to the **lab frame**,

$$\mathbf{v}_{\mathrm{wind}}(t) = -\mathbf{v}_{\odot} = -\mathbf{v}_{\mathrm{det,lab}}(t)$$

```
(base) ➜ theta python run_DM_velocity_calculator.py --lat 37.5666805 --lo

[Galactic-frame v_lab (x_g, y_g, z_g)]
  x_g = 11.468276 km/s  (+0.690, -0.750)
  y_g = 215.878911 km/s  (+6.018, -6.018)
  z_g = 32.404549 km/s  (+0.370, -0.360)
  |v_gal| = 218.598445 km/s

[Lab-frame v_lab (N, W, Z)]
  N = 93.183639 km/s  (+2.929, -2.918)
  W = -118.261738 km/s  (+3.845, -3.843)
  Z = 158.481075 km/s  (+3.681, -3.681)
  |v_lab| = 218.598445 km/s

[DM wind direction (v_wind = -v_lab, Lab frame)]
  N_wind = -93.183639 km/s  (+2.918, -2.929)
  W_wind = 118.261738 km/s  (+3.843, -3.845)
  Z_wind = -158.481075 km/s  (+3.681, -3.681)
  |v_wind| = 218.598445 km/s  (same as |v_lab|)

[Altitude/Azimuth of the DM wind direction (Alt/Az; north=0°, east=90°)]
  alt = -46.468 deg  (+0.269, -0.279)
  az  = 231.764 deg  (+0.247, -0.266)

[Theta (between DM wind and detection-plane-normal direction; 90-alt)]
  Theta = 136.468 deg  (+0.279, -0.269)
```

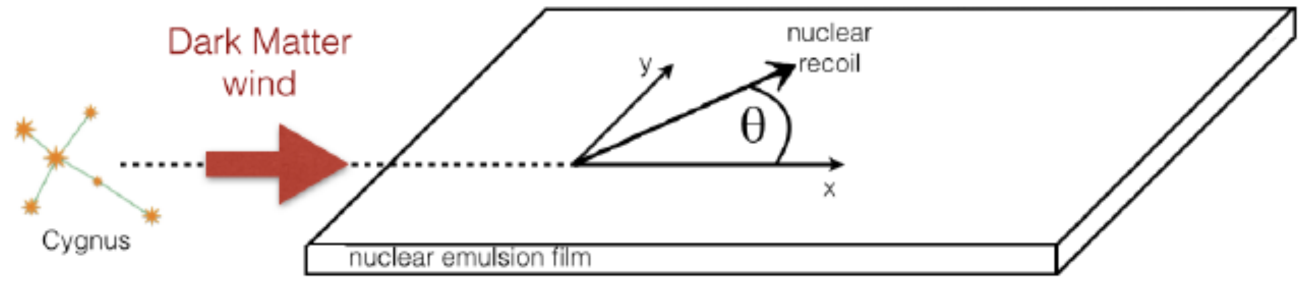
DarkWind

Event time + location → Θ(t)

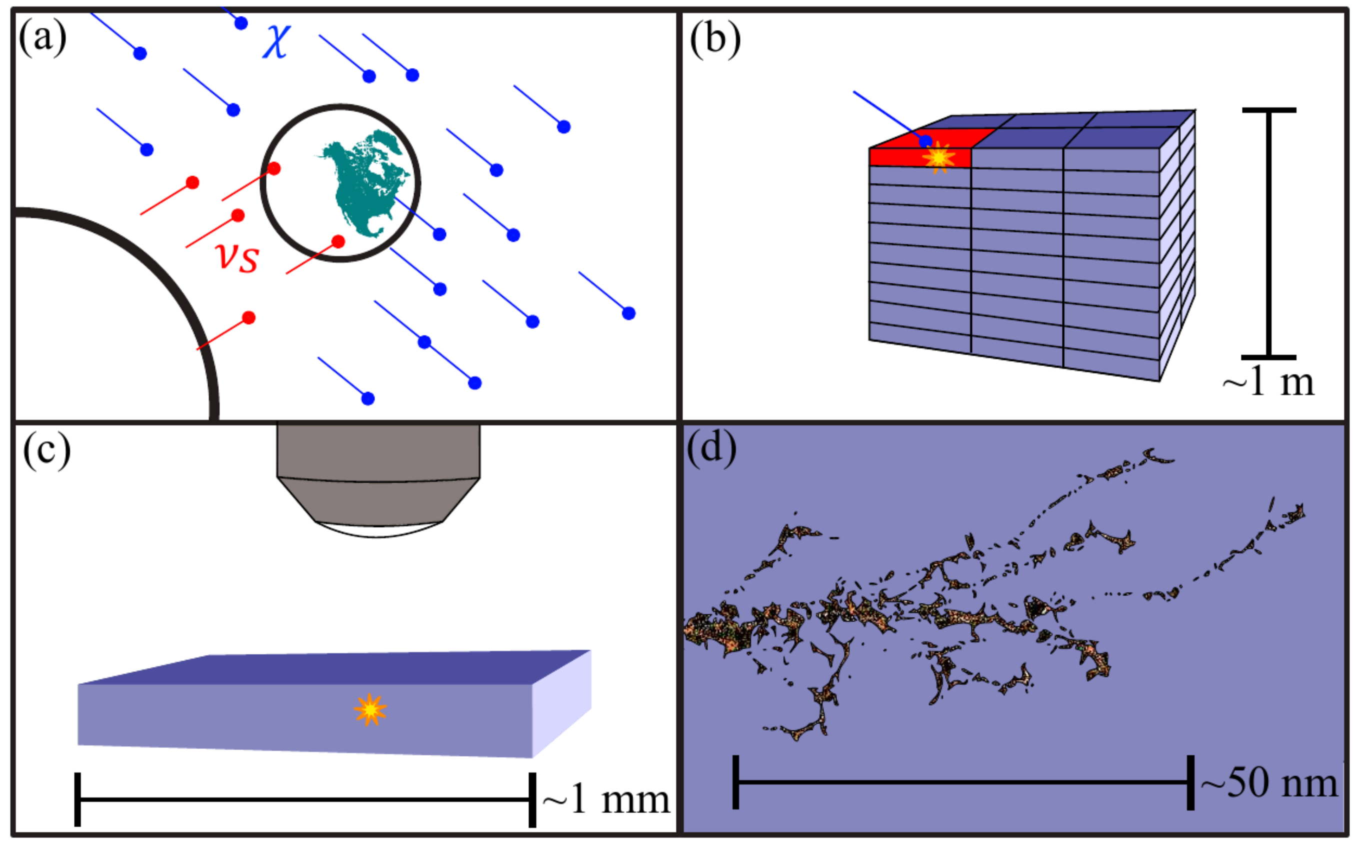
Applicable to many (effectively) 2D detectors

The detector need not be strictly two-dimensional.

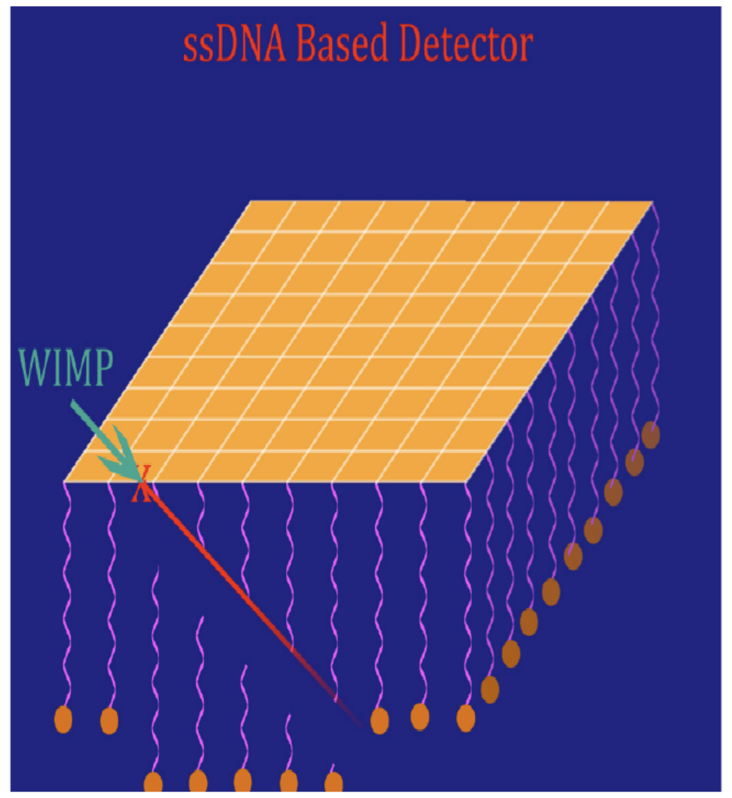
An **effectively planar directional response is sufficient**.



NEWSdm: Nuclear emulsion



Diamond detector: Crystal-damage imaging



DNA detector: Strand-break tracking

arXiv:2604.18704: Agafonova et al. (2018); Marshall et al. (2021); Drukier et al. (2012); OHare et al. (2022).

DM detection with graphene Josephson junction (GJJ)

Graphene provides a 2D target, while the Josephson junction converts electron heating into a voltage signal.

1 **DM-ELECTRON SCATTERING** : Dark matter scatters off an electron in graphene and deposits energy.

↓ Rapid e-e thermalization within a few picoseconds

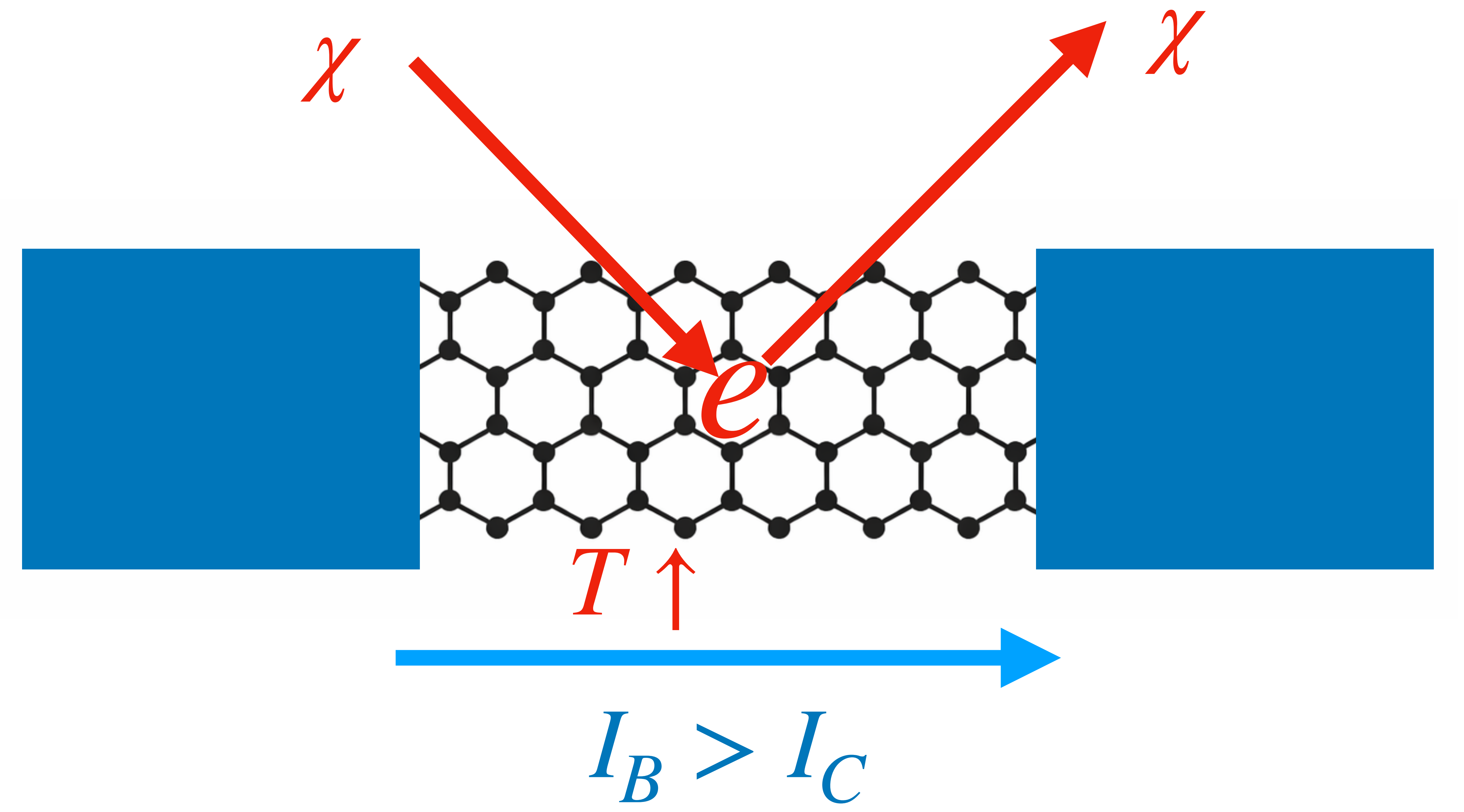
2 **ELECTRON HEATING** : Graphene's tiny electronic heat capacity produces a sizable rise in electron temperature.

↓

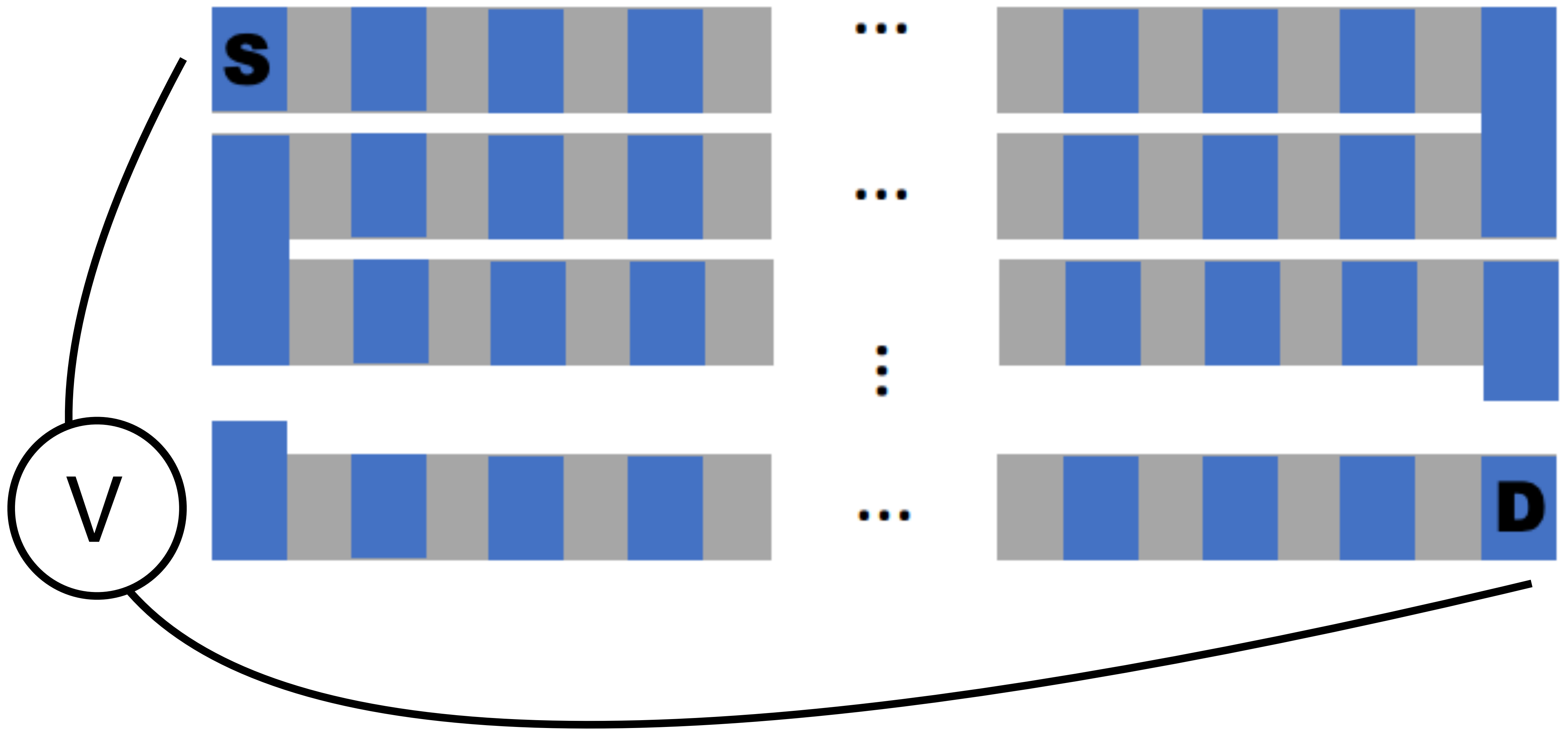
3 **CRITICAL-CURRENT DROP** : The higher electron temperature lowers the junction's critical current, I_C.

↓

4 **VOLTAGE READOUT** : When I_C falls below the fixed bias I_B, the junction switches to a finite-voltage state.

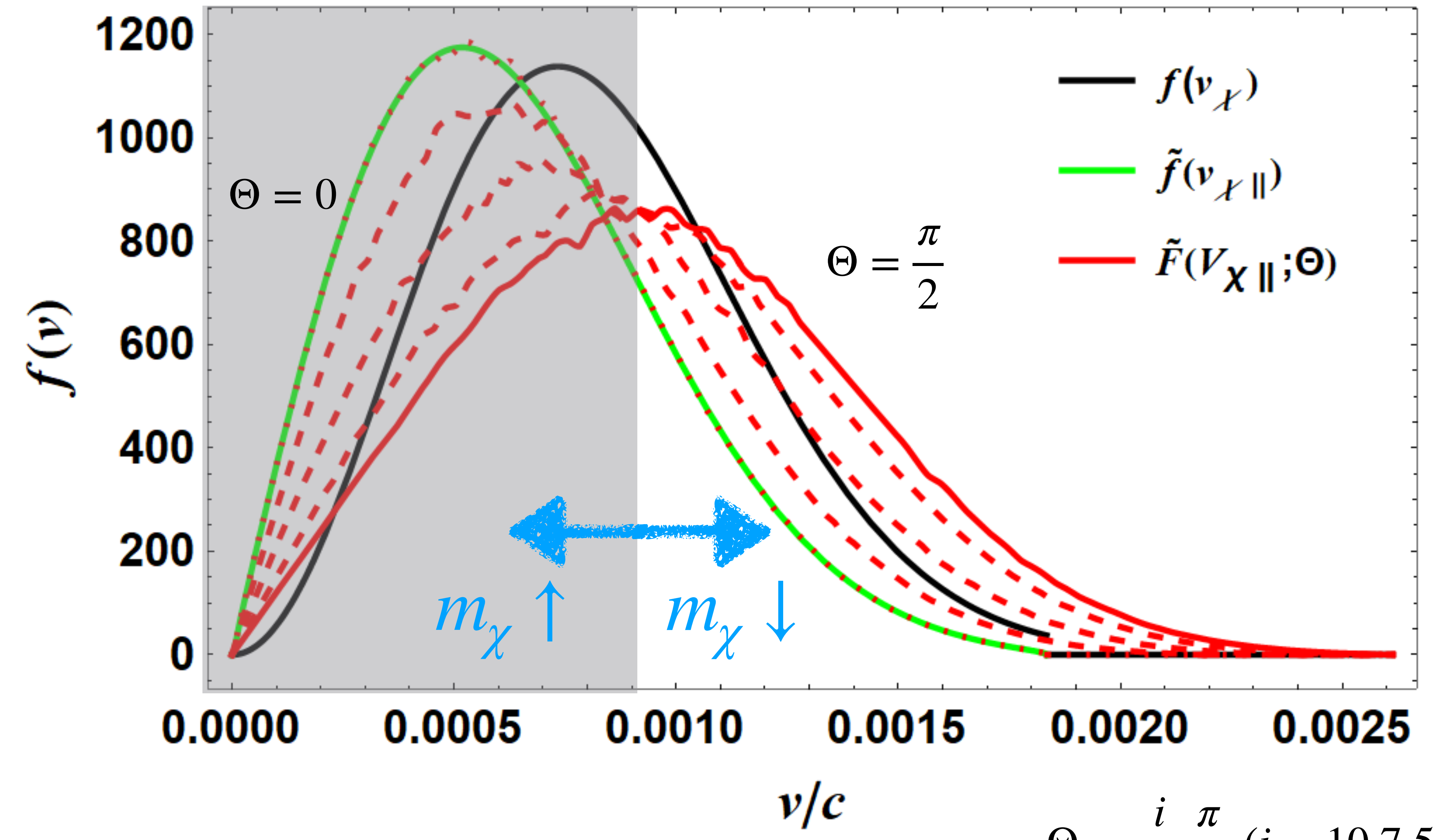


D. Kim et al., Phys. Rev. D 112, 015002 (2025)



Application to the 2D (GJJ) detector

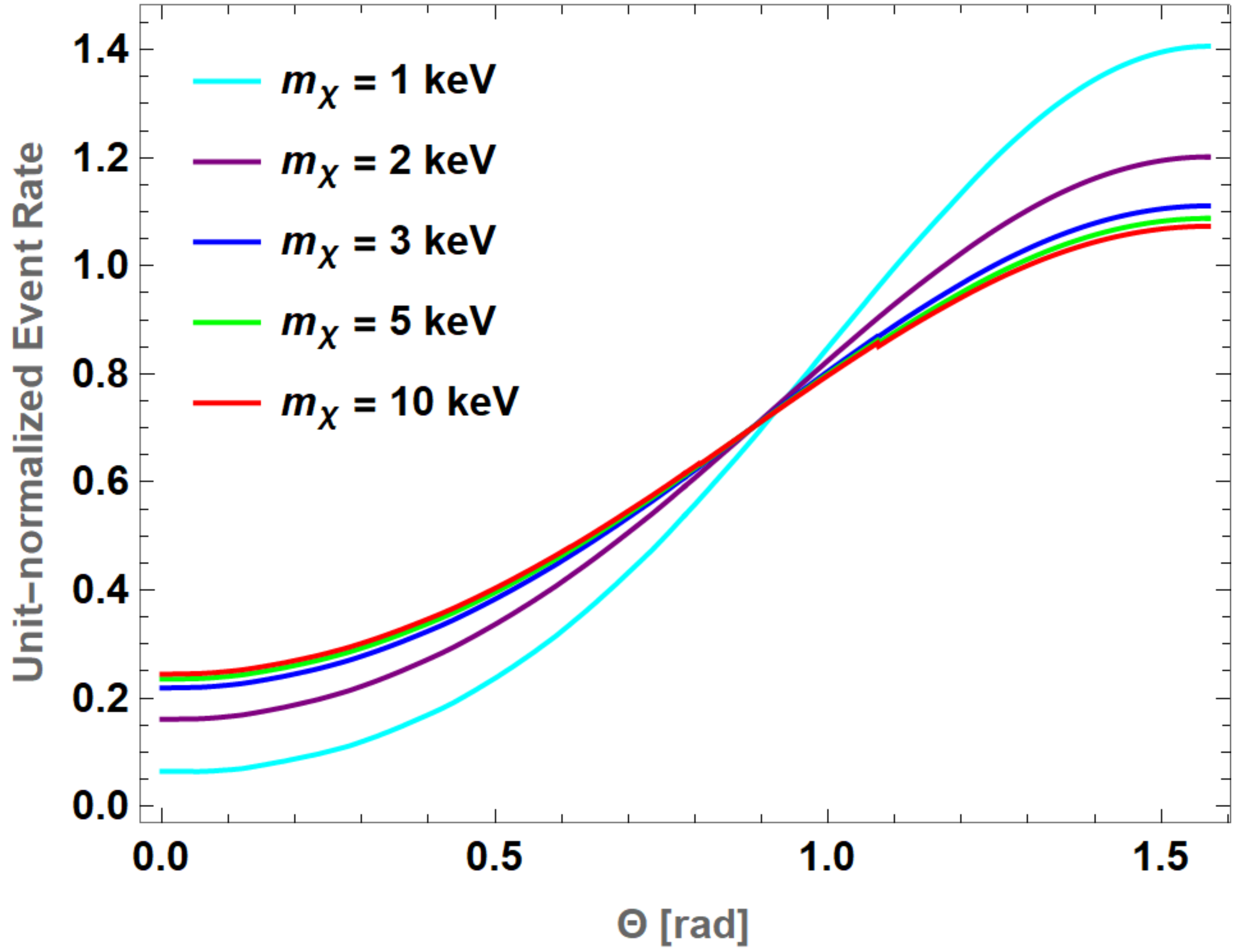
$$n_{\rm eve}(\Theta, m_\chi) = \frac{\rho_\chi}{m_\chi}\int dE_r \int_{\boxed{V_{\chi\|,\,\rm min}(m_\chi)}}^{V_{\chi\|,\,\rm max}} dV_{\chi\|}\,\tilde{F}(V_{\chi\|};\Theta)\,\frac{d\langle \bar{N}_T \sigma_{\chi T} V_{\rm rel\|}(\Theta)\rangle}{dE_r}$$



$\Theta = \frac{i}{10}\frac{\pi}{2}$, ($i = 10,7,5,3,0$ [solid to dotted])

$\mathbf{E_{th} = 1}$ **meV**

$\mathbf{m_\phi = 100}$ **keV**



For smaller m_χ, a larger **in-plane velocity** is required to overcome the threshold.

For lighter dark matter, the event rate changes more steeply with Θ

Summary

In a (effectively) 2D detector, the event rate depends on the angle between the DM wind and the detector plane.

For lighter dark matter, the event rate shows a stronger angular dependence.

Therefore, **even without the recoil spectrum, the shape of the angular spectrum encodes information about the dark-matter mass.**

Thank you

[Backup] Angular vs Annual modulation

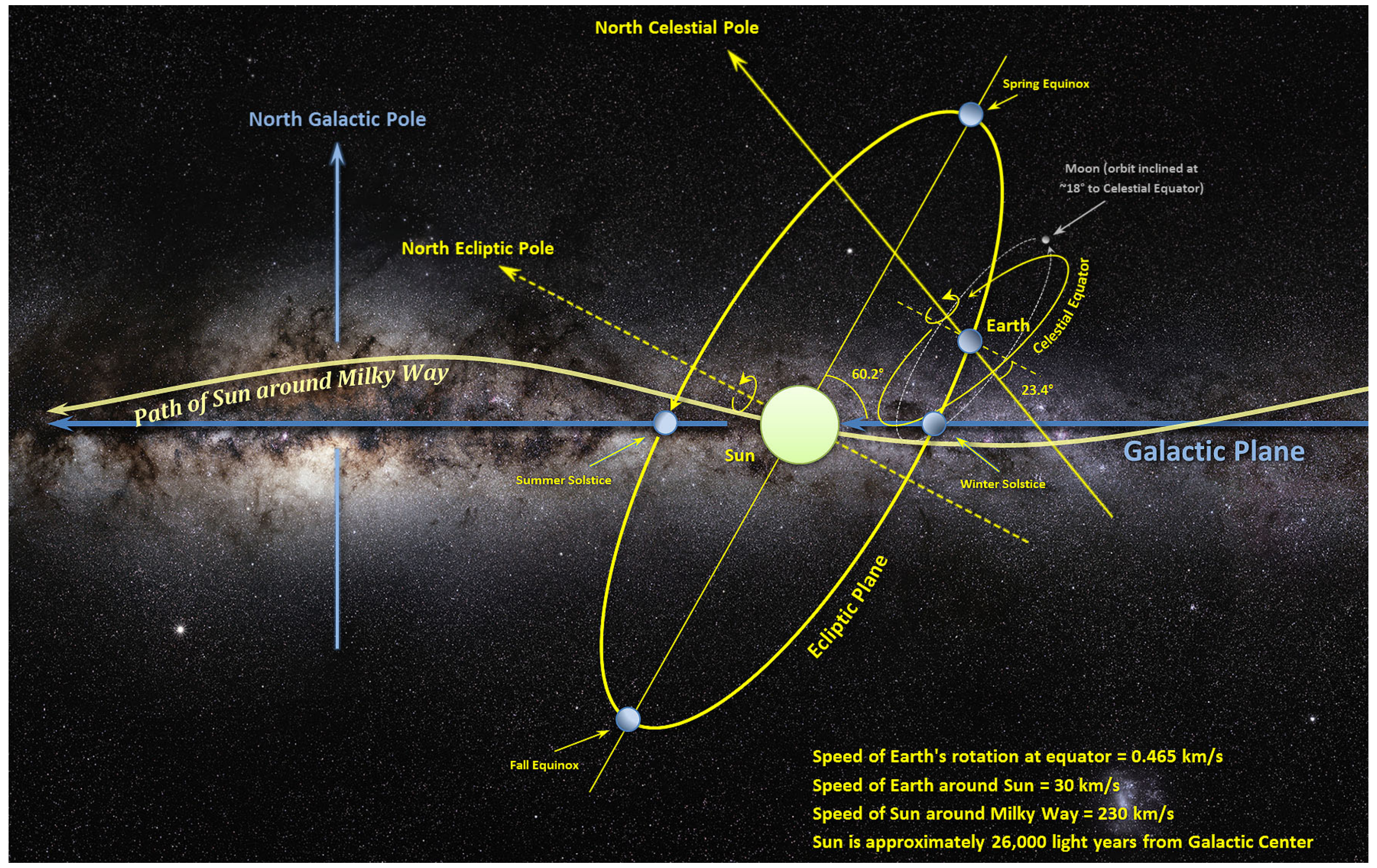
Angular modulation

What changes :

DM-wind **direction** relative to the detector plane, $\Theta(t)$

Contribution :

Annual = Daily



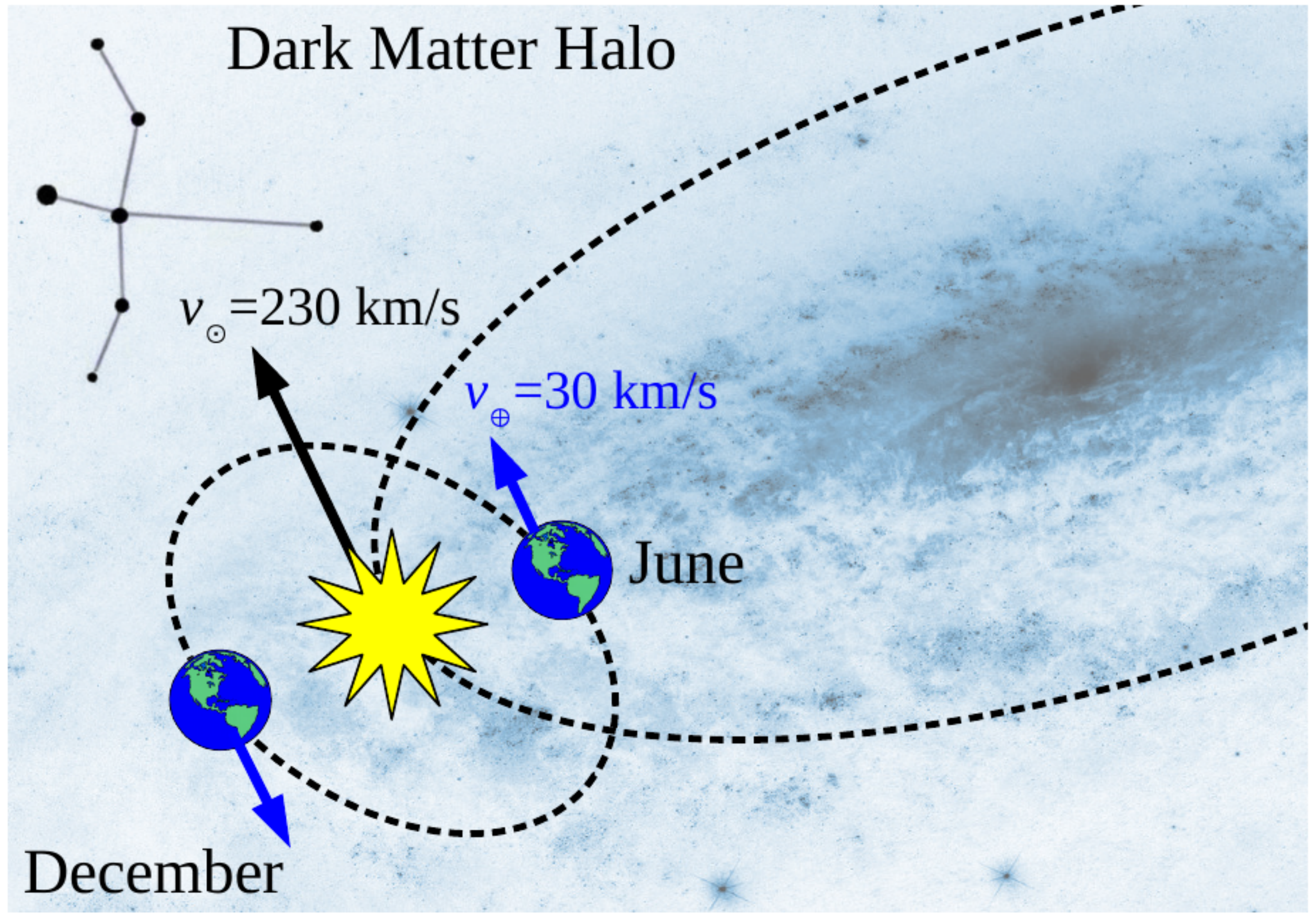
Annual modulation

What changes :

magnitude of the DM-detector relative velocity, $|v_{rel}(t)|$

Contribution :

Annual >> Daily

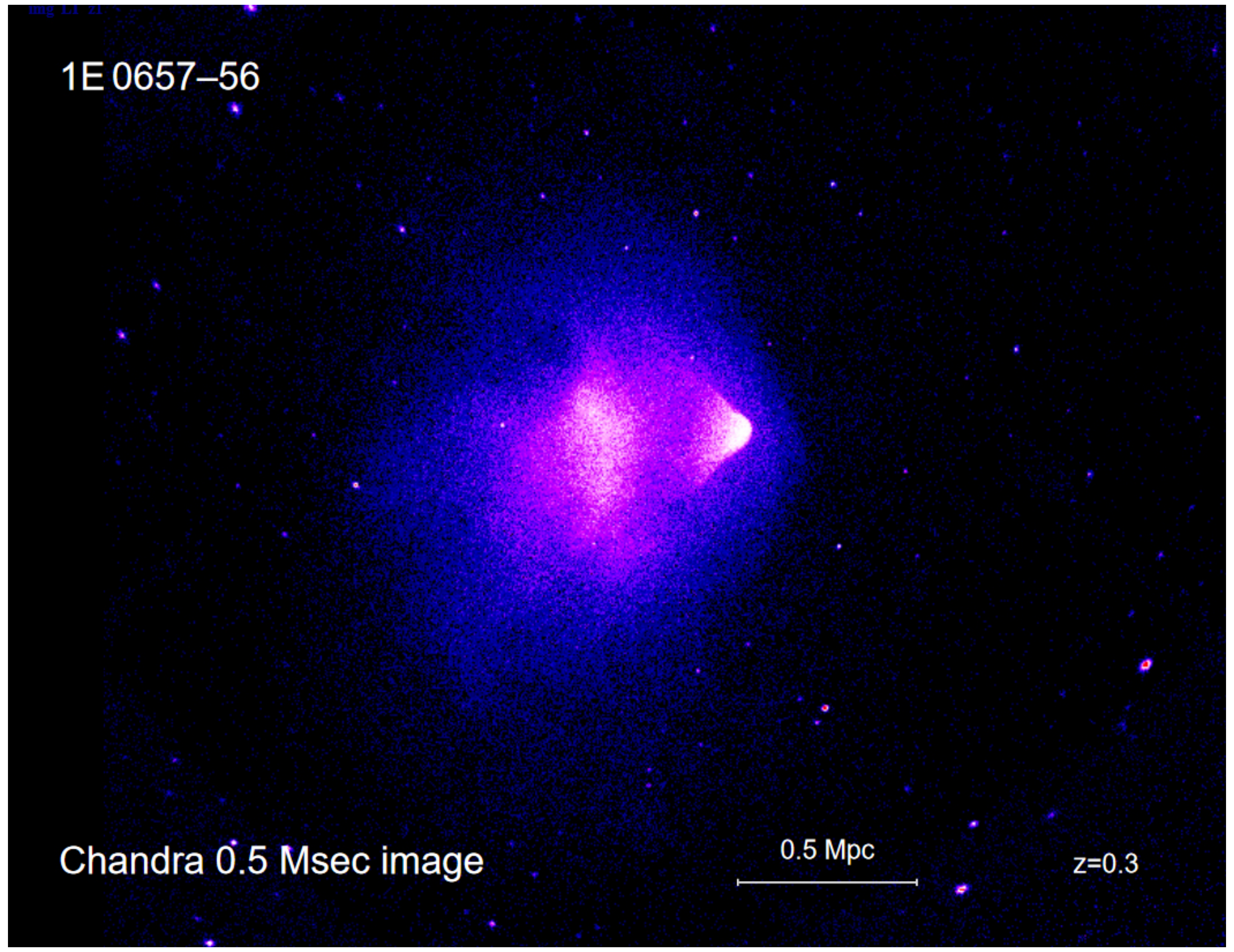


[Backup]Dark Matter

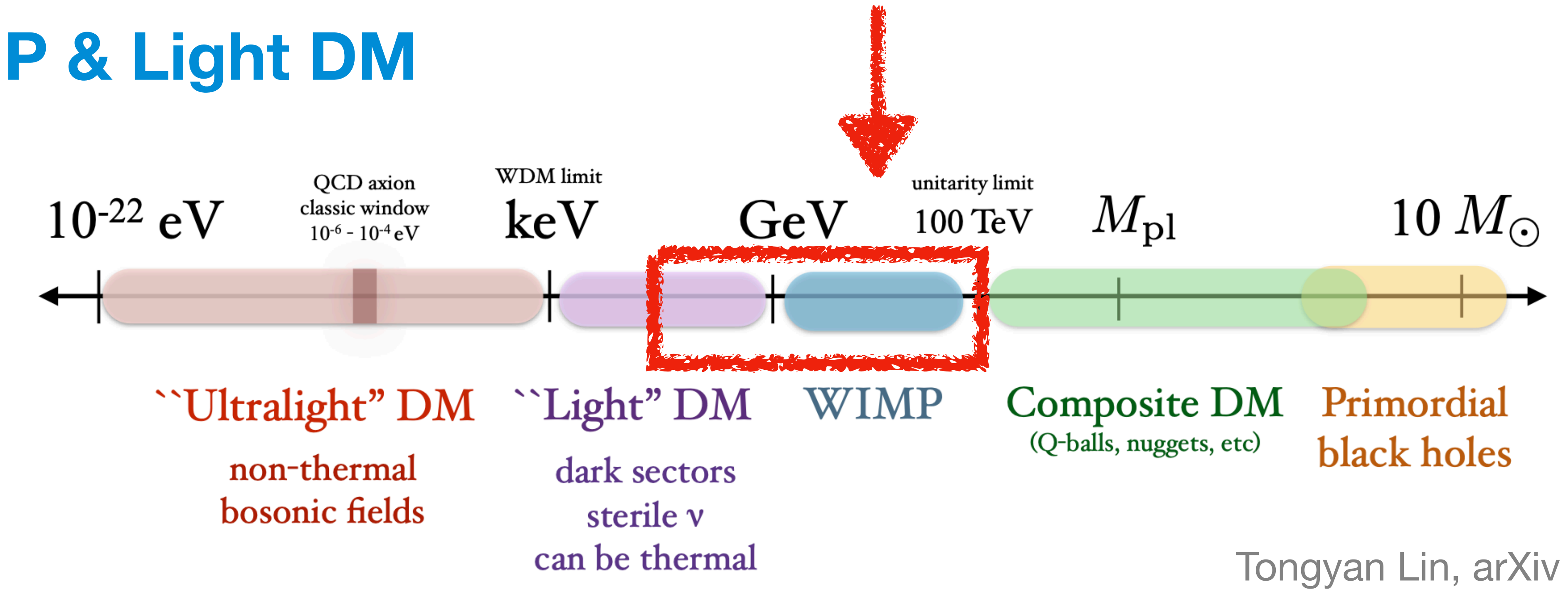
Dark-Matter

• Various observations, such as **galaxy rotation curves** and the **Bullet Cluster**, suggest the existence of dark matter.

• However, the nature of dark matter and its non-gravitational interactions remain unknown.



WIMP & Light DM

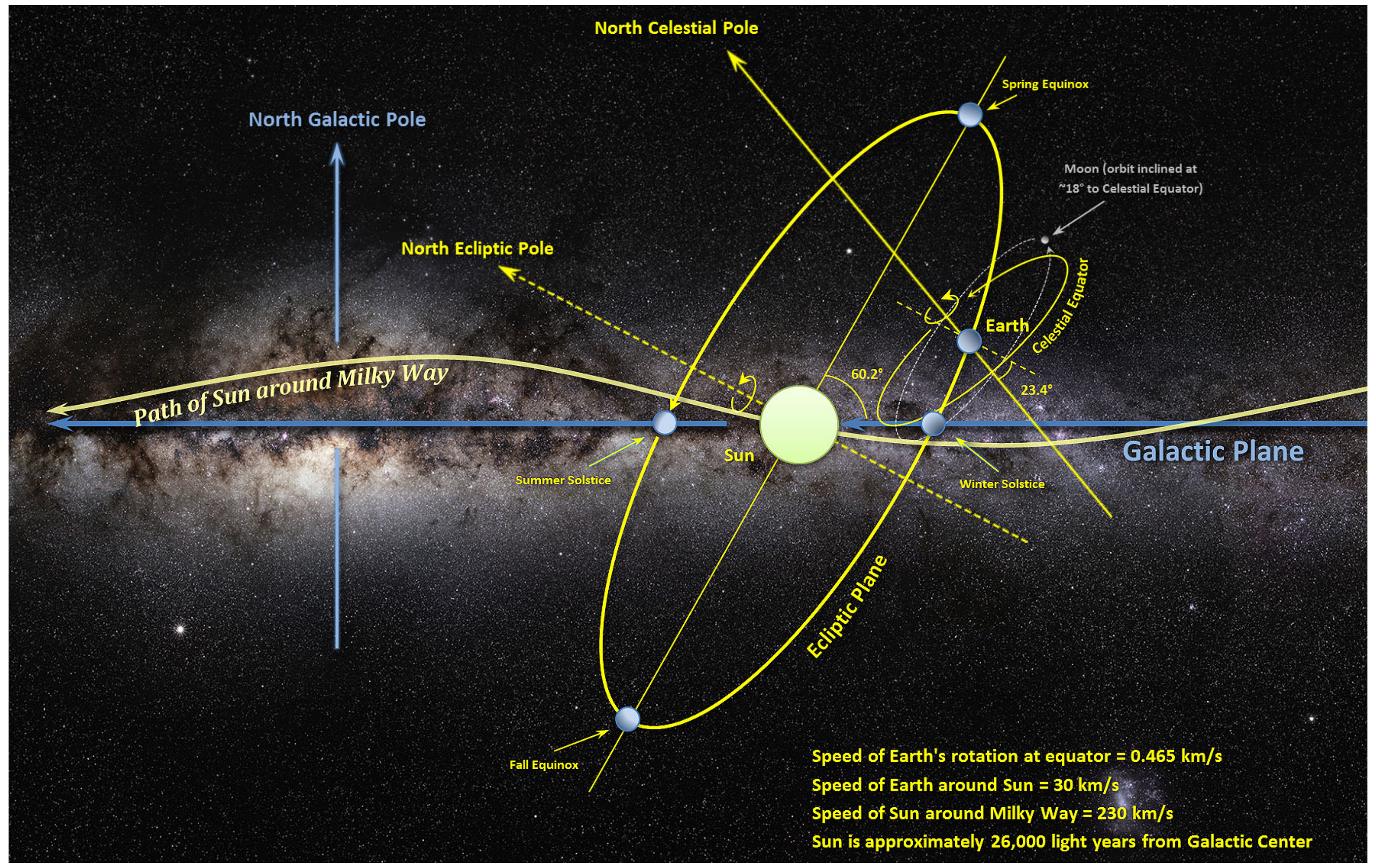


Tongyan Lin, arXiv : 1904.07915

- **WIMP** (**weakly interacting massive particle**): GeV–TeV
- **Light DM**: MeV–GeV

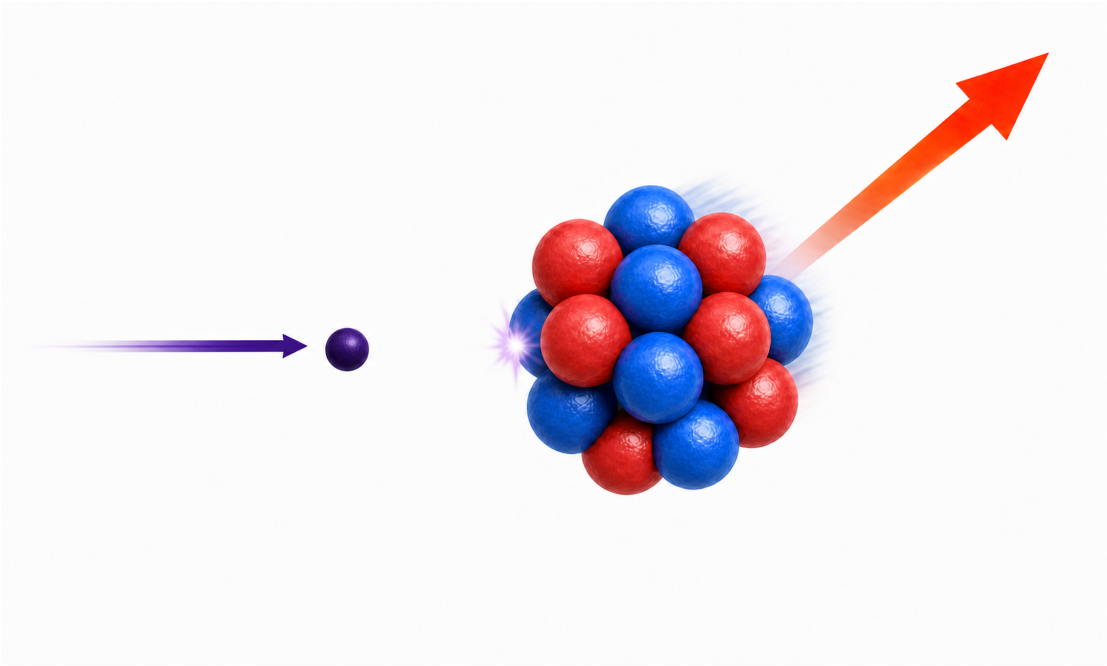
[Backup]WIMP Direct Detection

DM wind



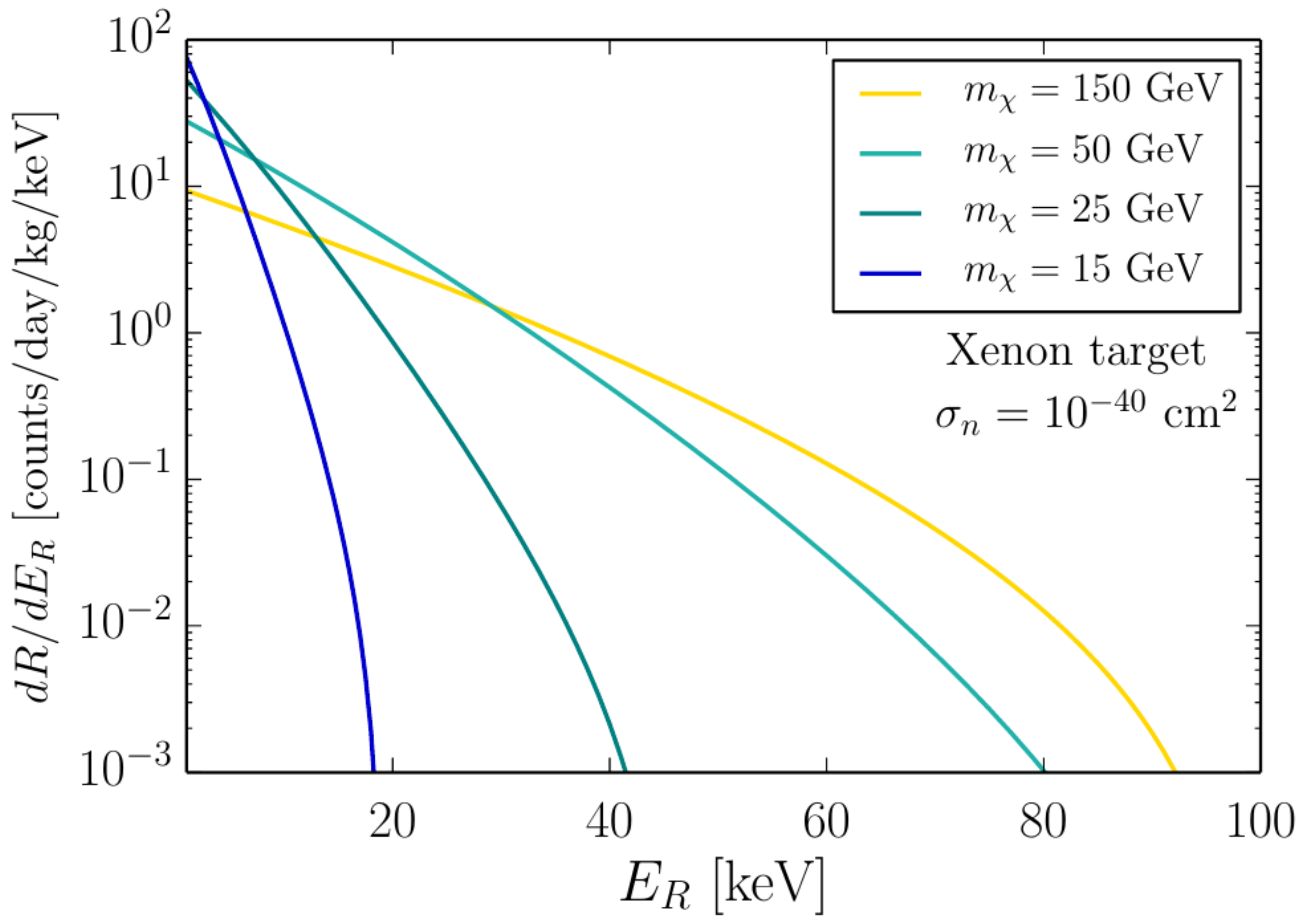
Wikipedia

The Solar System's motion through the halo → DM wind



A WIMP hits a nucleus and make it recoil with energy E_R.

Mass from the recoil spectrum



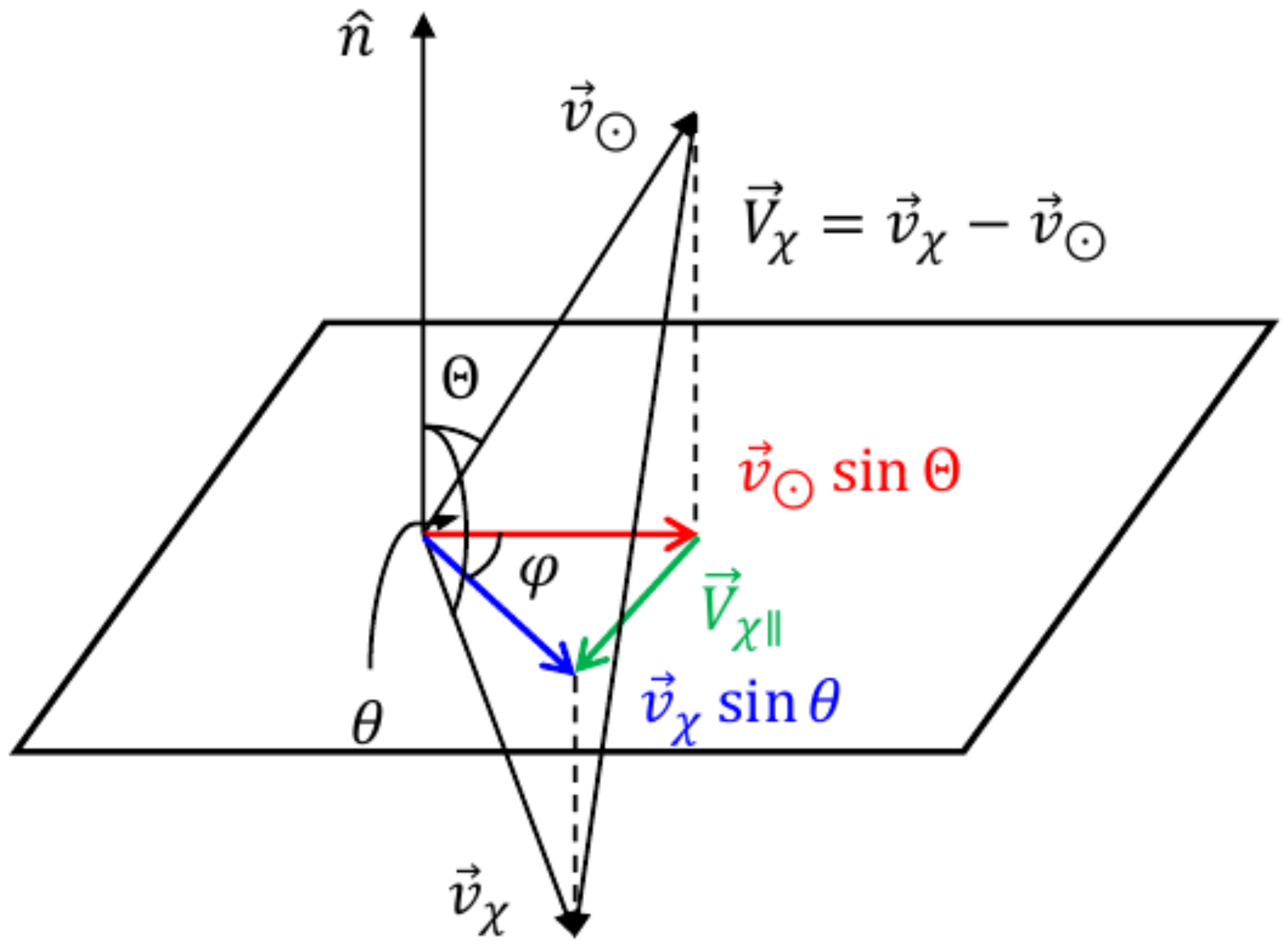
Tongyan Lin, arXiv:1904.07915, Fig. 17

Lighter WIMPs → steeper fall off.

The shape of dR/dE_R infers the mass.

Recoil-energy spectrum → WIMP mass

[Backup]Angular dependence of event rates



- Isotropic event rate (with the modified Maxwell–Boltzmann distribution $f(v_\chi)$)

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

- **Projection onto the detector plane** of a 2D detector

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

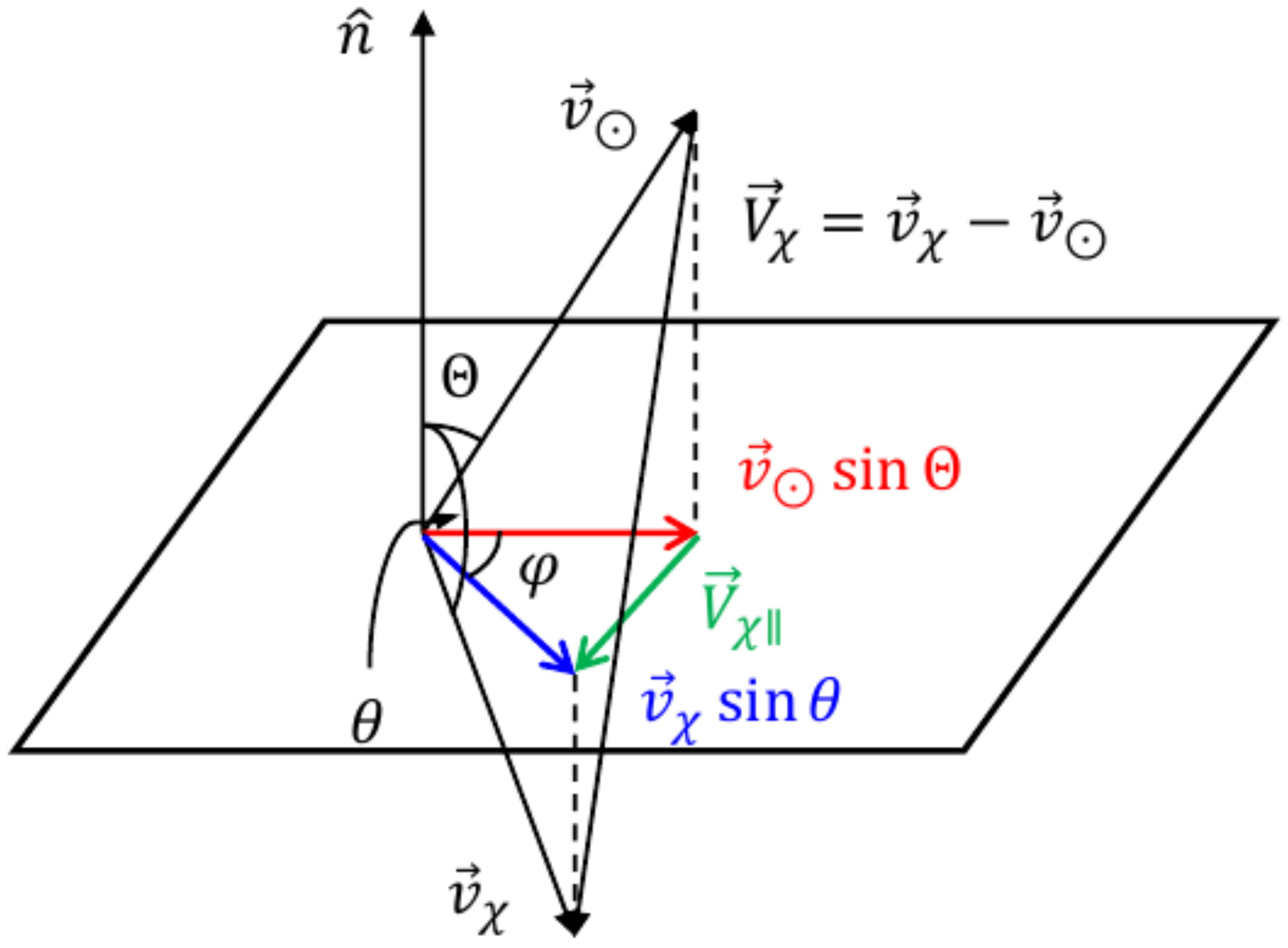
- Modified MB distribution → **plane-projected distribution**

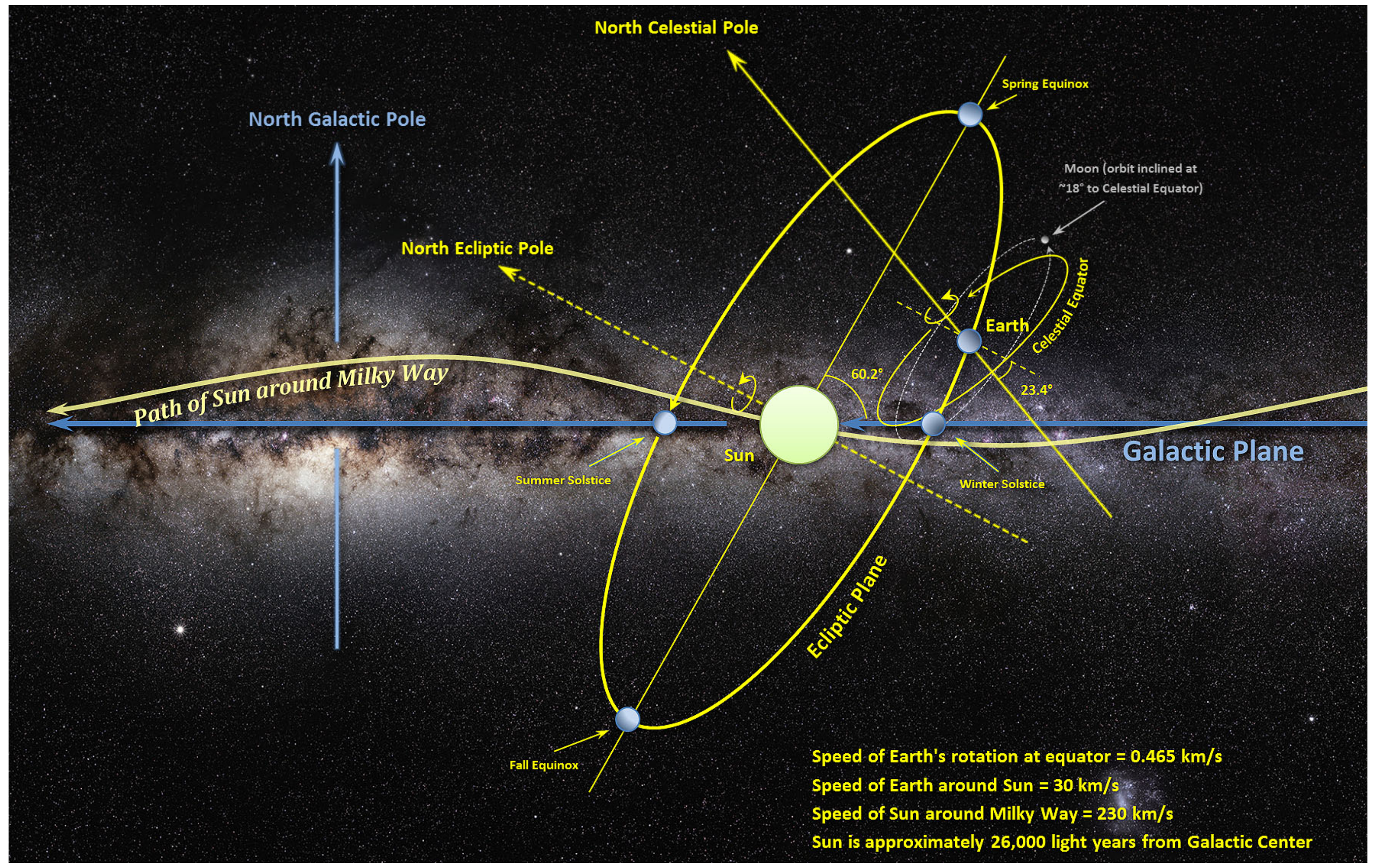
$$\tilde{f}(v_{\chi\parallel}) = \int_{-\sqrt{1-\left(v_{\chi\parallel}/v_{\text{esc}}\right)^2}}^{\sqrt{1-\left(v_{\chi\parallel}/v_{\text{esc}}\right)^2}} d\cos\theta \, \frac{1}{2}\frac{1}{\sin\theta} f\left(\frac{v_{\chi\parallel}}{\sin\theta}\right)$$

- **Plane-projected event rate**

$$n_{\text{eve}} = \frac{\rho_\chi}{m_\chi} \int dE_r \, dv_{\chi\parallel} \tilde{f}(v_{\chi\parallel}) \frac{d\langle N_T \sigma_{\chi T} v_{\text{rel}\parallel}\rangle}{dE_r}$$

[Backup]Angular dependence of event rates





- Dark matter follows modified Maxwell-Boltzmann distribution

  However, because of the **DM wind** $(-\vec{v}_\odot)$,

  modified Maxwell-Boltzmann distribution $f(v_\chi)$
  → **DM-wind-modified distribution** $F(V_\chi)$
  → **Plane projected DM-wind-modified distribution** $\tilde{F}(V_\chi)$

- Θ : Angle between the **DM wind** and the **plane normal**

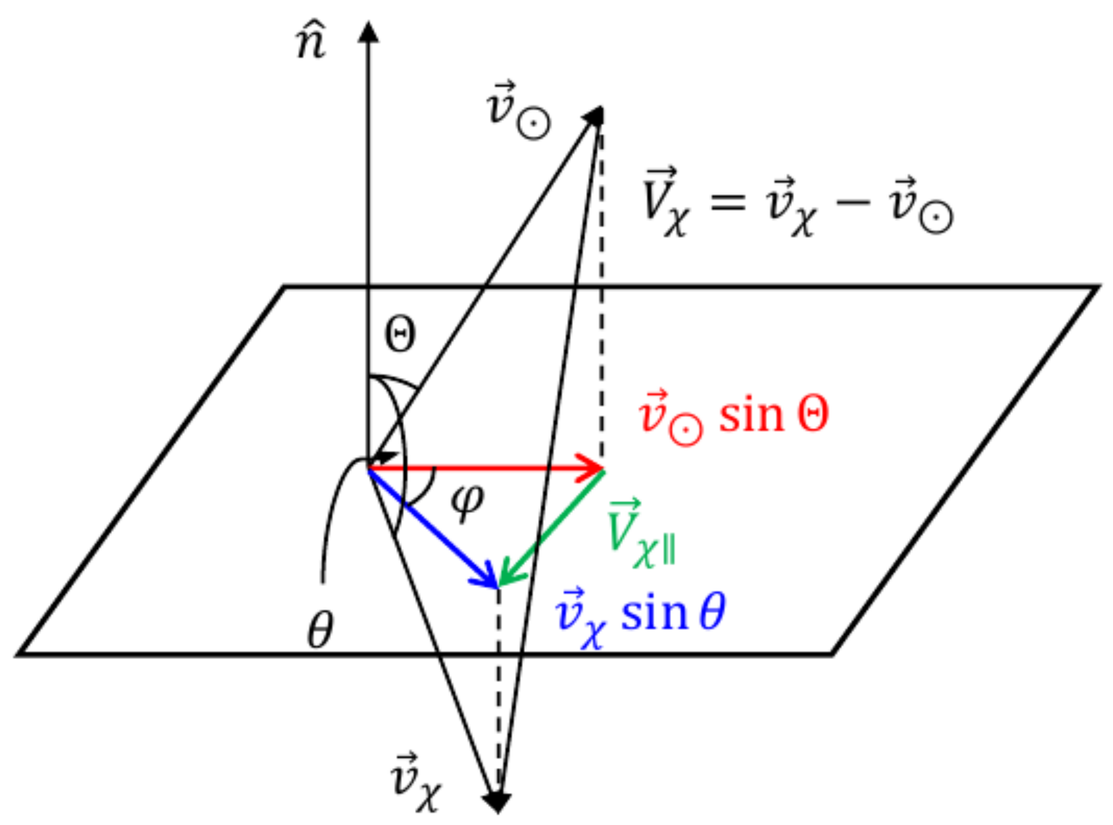
- **Projected event rate**

  $n =$ **DM number density** $\times$ **number of targets** $\times$ $\langle$**cross section** $\times$ **relative velocity**$\rangle$

$$n_{\rm eve}(\Theta, m_\chi) = \frac{\rho_\chi}{m_\chi}\int dE_r \int_{V_{\chi\parallel,\,\rm min}(m_\chi)}^{V_{\chi\parallel,\,\rm max}} dV_{\chi\parallel}\,\tilde{F}(V_{\chi\parallel};\Theta)\,\frac{d\langle \overline{N}_T\sigma_{\chi T}V_{{\rm rel}\parallel}(\Theta)\rangle}{dE_r}$$

$V_{\chi\parallel,\,\rm max} = v_{\rm esc} + v_\odot \sin\Theta$
$V_{\chi\parallel,\,\rm min}$ **depends on** m_χ **(for fixed** E_{th}**)**

[Backup] Derivation of the projected wind distribution



1. Plane geometry

$$v_{\chi\parallel} = v_\chi \sin\theta, \qquad v_{\odot\parallel} = v_\odot |\sin\Theta|$$

$$\vec{V}_{\chi\parallel} = \vec{v}_{\chi\parallel} - \vec{v}_{\odot\parallel}$$

2. Relation on the detector plane

Using the law of cosines on the detector plane,

$$V_{\chi\parallel}^2 = (v_\chi \sin\theta)^2 + v_{\odot\parallel}^2 - 2(v_\chi \sin\theta)\, v_{\odot\parallel} \cos\phi$$

Solving for $v_\chi \sin\theta$,

$$v_\chi \sin\theta = v_{\odot\parallel}\cos\phi \pm \sqrt{V_{\chi\parallel}^2 - v_{\odot\parallel}^2 \sin^2\phi} \equiv V_{\chi\parallel}^{\pm}$$

3. Physical branches

Since $v_\chi \sin\theta \geq 0$,

$$V_{\chi\parallel} \geq v_{\odot\parallel} \quad \Rightarrow \quad V_{\chi\parallel}^{+} \text{ only}$$

$$V_{\chi\parallel} < v_{\odot\parallel} \quad \Rightarrow \quad V_{\chi\parallel}^{\pm} \text{ are both allowed for}$$

$$\pi - \sin^{-1}\left(\frac{V_{\chi\parallel}}{v_{\odot\parallel}}\right) \leq |\phi| \leq \pi$$

4. Jacobian

$$\tilde{v}_\parallel \equiv \frac{V_{\chi\parallel}}{\sqrt{V_{\chi\parallel}^2 - v_{\odot\parallel}^2 \sin^2\phi}}$$

5. Projected wind distribution

Therefore, the projected wind distribution is obtained by integrating over the allowed branches:

$$\tilde{F}(V_{\chi\parallel};\Theta) = \int d\phi\, \frac{\tilde{v}_\parallel}{\pi} \int d\cos\theta\, \frac{1}{2\sin\theta}\, f\!\left(\frac{V_{\chi\parallel}^{\pm}}{\sin\theta}\right)$$

with the appropriate branch choice.

[Backup] The strategy: replace recoil energy with detector orientation

1 Predict how the event rate changes with the angle Θ.

2 Compute $\Theta(t)$ from each event's time and detector location.

3 Compare event counts across Θ $\rightarrow$ infer the dark-matter mass scale.

[Backup] DarkWind: coordinate transformation details

Coordinate frames

Galactic frame: $(\hat{x}_g, \hat{y}_g, \hat{z}_g)$
Equatorial frame: $(\hat{x}_e, \hat{y}_e, \hat{z}_e)$
Lab frame: $(\hat{N}, \hat{W}, \hat{Z})$

Galactic → Equatorial transformation

The Galactic basis is rotated into the equatorial basis by

$$\begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix} = A_G \begin{pmatrix} x_g \\ y_g \\ z_g \end{pmatrix}$$

where A_G is the standard Galactic-to-equatorial rotation matrix.

Equatorial → Lab transformation

Using the detector latitude $\lambda_{\rm lab}$ and local sidereal time $t_{\rm lab}$,

$$\begin{pmatrix} N \\ W \\ Z \end{pmatrix} = R_{\rm lab}(t_{\rm lab}, \lambda_{\rm lab}) \begin{pmatrix} x_e \\ y_e \\ z_e \end{pmatrix}$$

with

$$R_{\rm lab} = \begin{pmatrix} -\sin\lambda_{\rm lab}\cos t_{\rm lab} & -\sin\lambda_{\rm lab}\sin t_{\rm lab} & \cos\lambda_{\rm lab} \\ \sin t_{\rm lab} & -\cos t_{\rm lab} & 0 \\ \cos\lambda_{\rm lab}\cos t_{\rm lab} & \cos\lambda_{\rm lab}\sin t_{\rm lab} & \sin\lambda_{\rm lab} \end{pmatrix}$$

[Backup] GJJ scattering model and benchmark assumptions

- We now apply this formalism to a **graphene-based Josephson junction (GJJ) detector**.

- For DM–electron scattering,

$$\bar{N}_e = \frac{n_e^{2D}}{\rho_{gr}^{2D}}$$

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

Here, structure factors $S_{\mathrm{ims}}^2(E_r, q)$ and $S_{\mathrm{gr}}(E_r, q)$ account for **in-medium screening** and **Pauli blocking**, respectively.

- In the **heavy-mediator** scenario, the cross section is

$$\sigma_{\chi e}^{\mathrm{heavy}} \approx \frac{g_\chi^2 g_e^2}{\pi} \frac{\mu_{\chi e}^2}{m_\phi^4}$$

and the matrix element is given by

$$\overline{|\mathcal{M}|^2}_{\mathrm{heavy}} = 16\, g_\chi^2 g_e^2 \frac{m_\chi^2 m_e^2}{m_\phi^4}$$