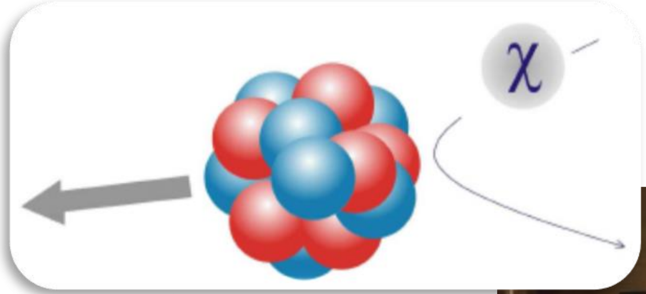
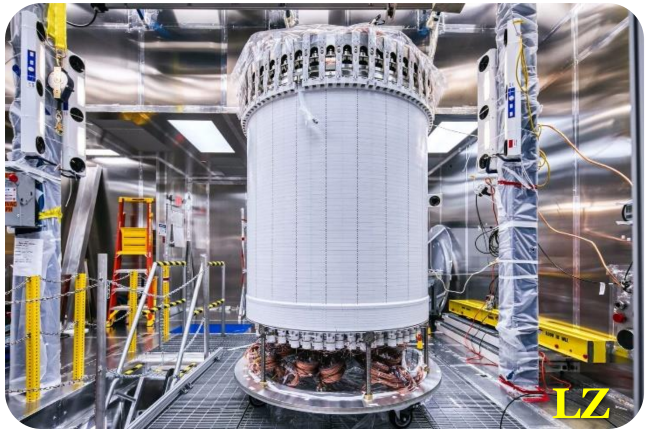
DM Mass from Angular Dependence

with D. Kim [In preparation]





Jong-Chul Park

CNU 충남대학교 CHUNGNAM NATIONAL UNIVERSITY

The 2024 Mitchell Conference, May 25 (2024)

DM Direct Detection

DM Direct Detection: Beginning

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

(Received 7 January 1985)

We consider the possibility that the neutral-current neutrino detector recently proposed by Drukier and Stodolsky could be used to detect some possible candidates for the dark matter in galactic halos. This may be feasible if the galactic halos are made of particles with coherent weak interactions and masses $1-10^6$ GeV; particles with spin-dependent interactions of typical weak strength and masses $1-10^2$ GeV; or strongly interacting particles of masses $1-10^{13}$ GeV.

PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

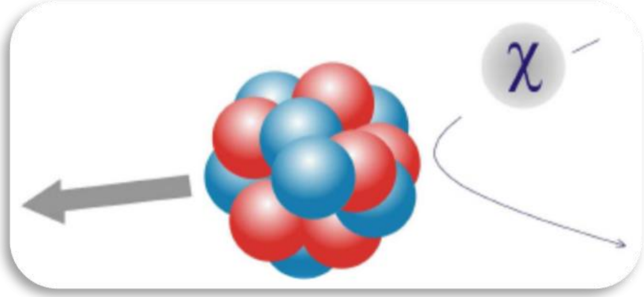
Principles and applications of a neutral-current detector for neutrino physics and astronomy

A. Drukier and L. Stodolsky
Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany

(Received 21 November 1983)

We study detection of MeV-range neutrinos through elastic scattering on nuclei and identification of the recoil energy. The very large value of the neutral-current cross section due to coherence indicates a detector would be relatively light and suggests the possibility of a true "neutrino observatory." The recoil energy which must be detected is very small ($10-10^3$ eV), however. We examine a realization in terms of the superconducting-grain idea, which appears, in principle, to be feasible through extension and extrapolation of currently known techniques. Such a detector could permit determination of the neutrino energy spectrum and should be insensitive to neutrino oscillations since it detects all neutrino types. Various applications and tests are discussed, including spallation sources, reactors, supernovas, and solar and terrestrial neutrinos. A preliminary estimate of the most difficult backgrounds is attempted.

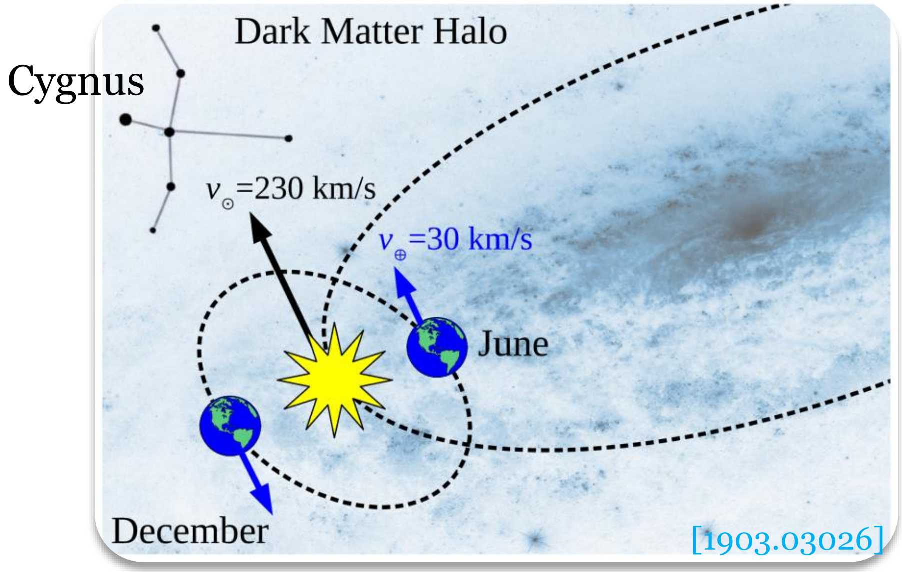
DM Direct Detection: Basics



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

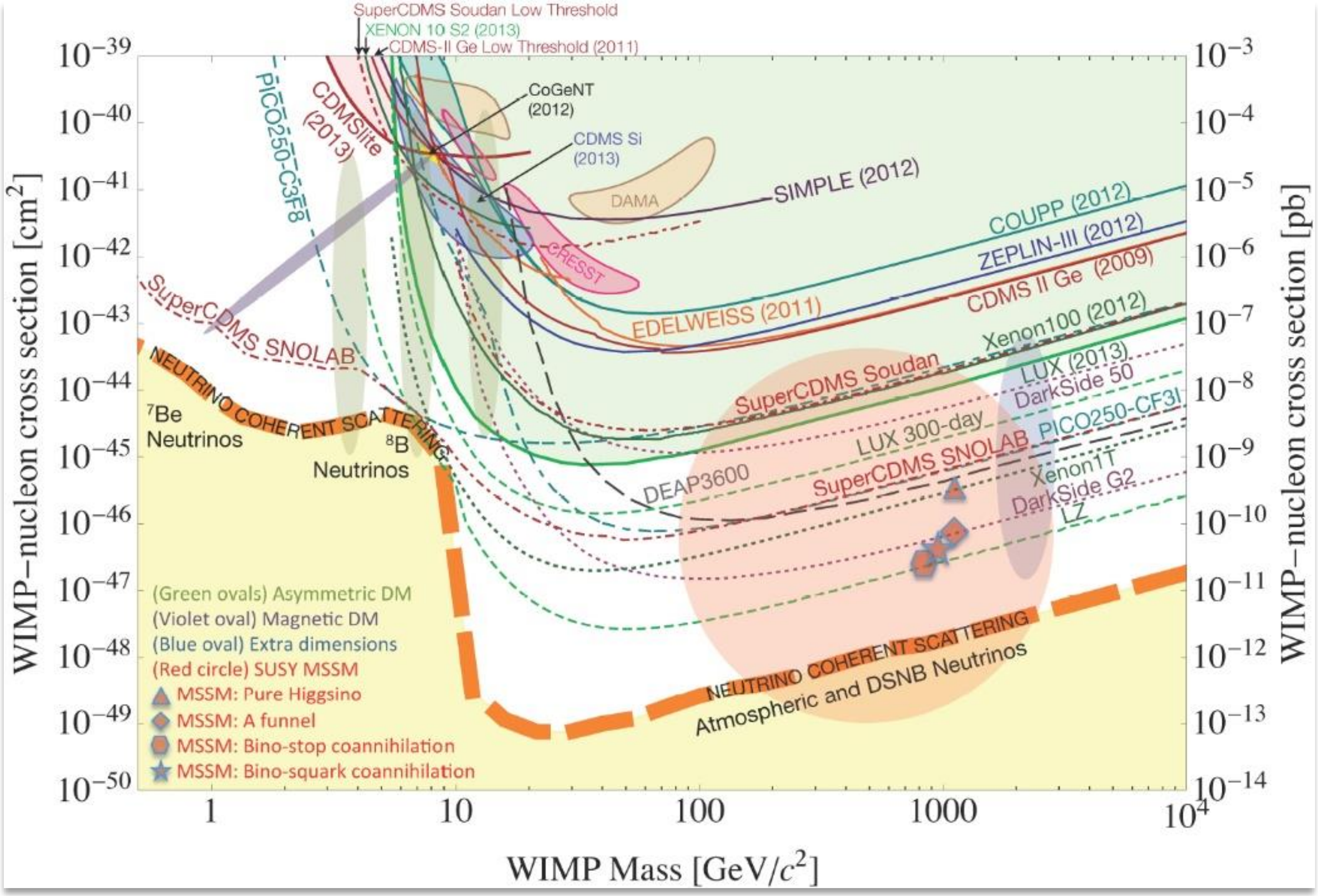
$$\frac{dN}{dE_R}(t) \propto N_T \frac{\rho_\chi}{m_\chi} \int_{v>v_{\rm min}} dv^3 \frac{d\sigma}{dE_R} v f_{\rm Earth}(\vec{v}, t)$$

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



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

DM Direct Detection: Results

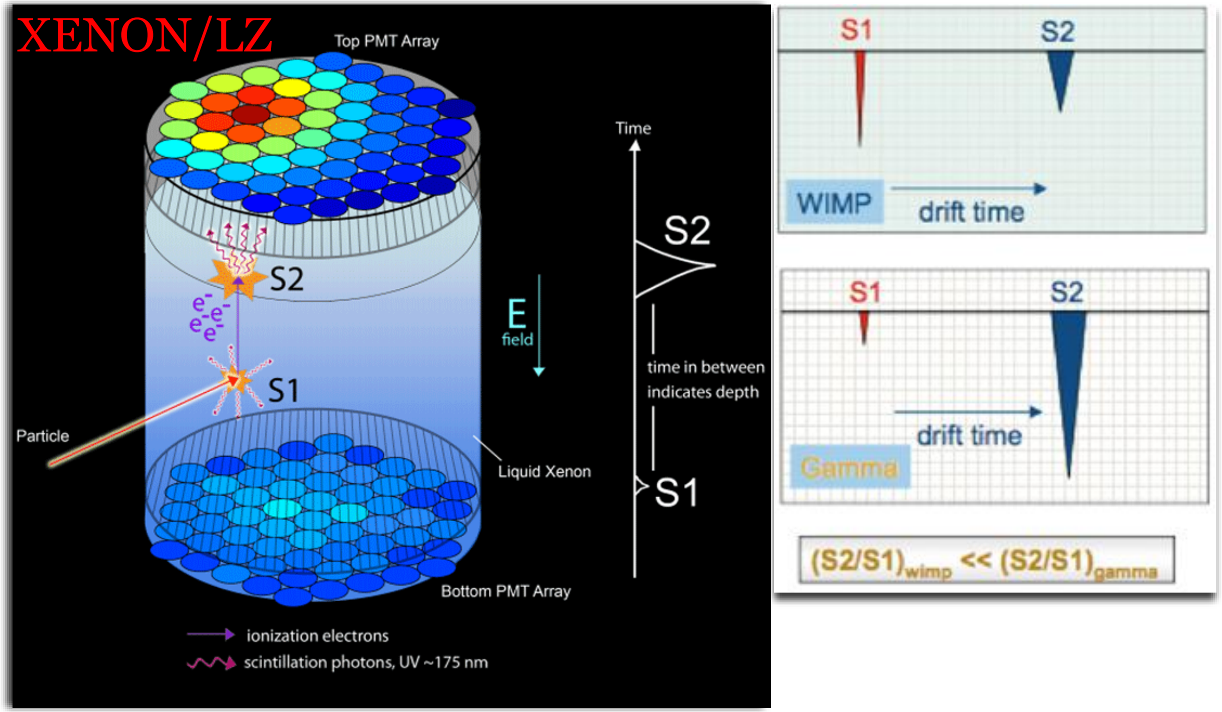


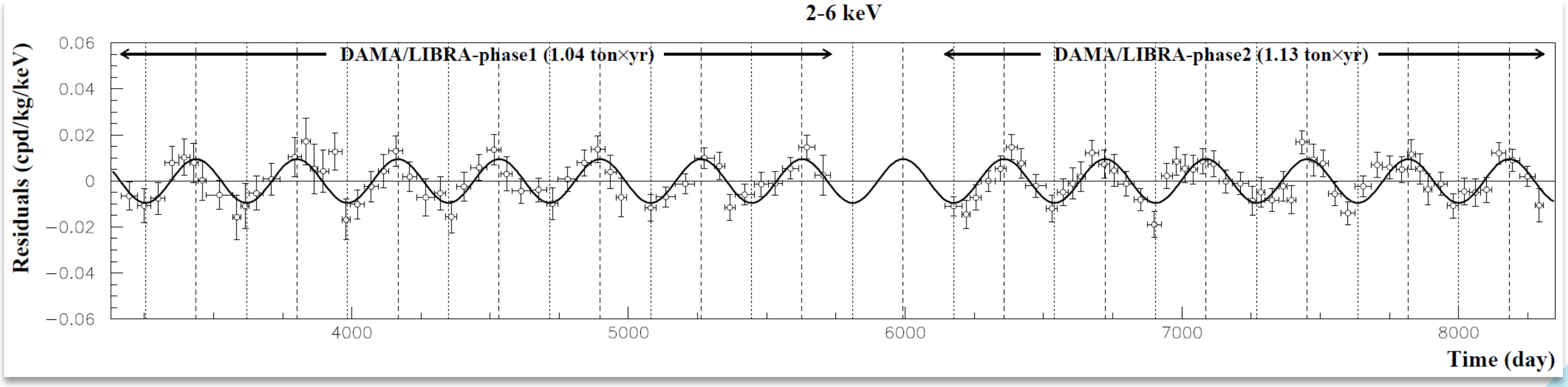
* Not most updated figure!

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), Directional detection (e.g. DRIFT, NEWSdm)





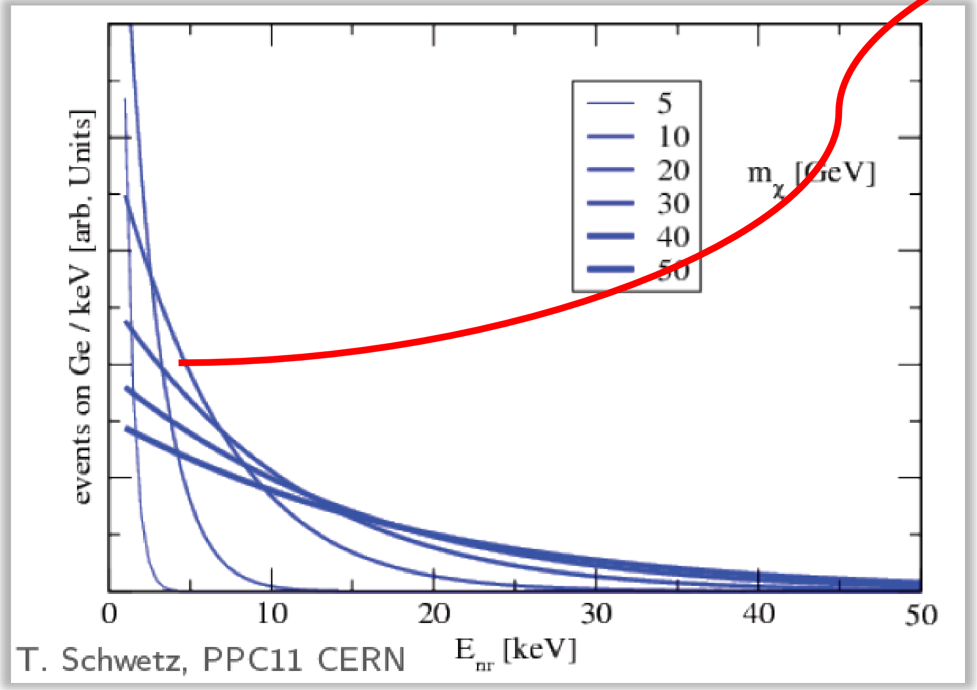
DM Direct Detection: Some Issues

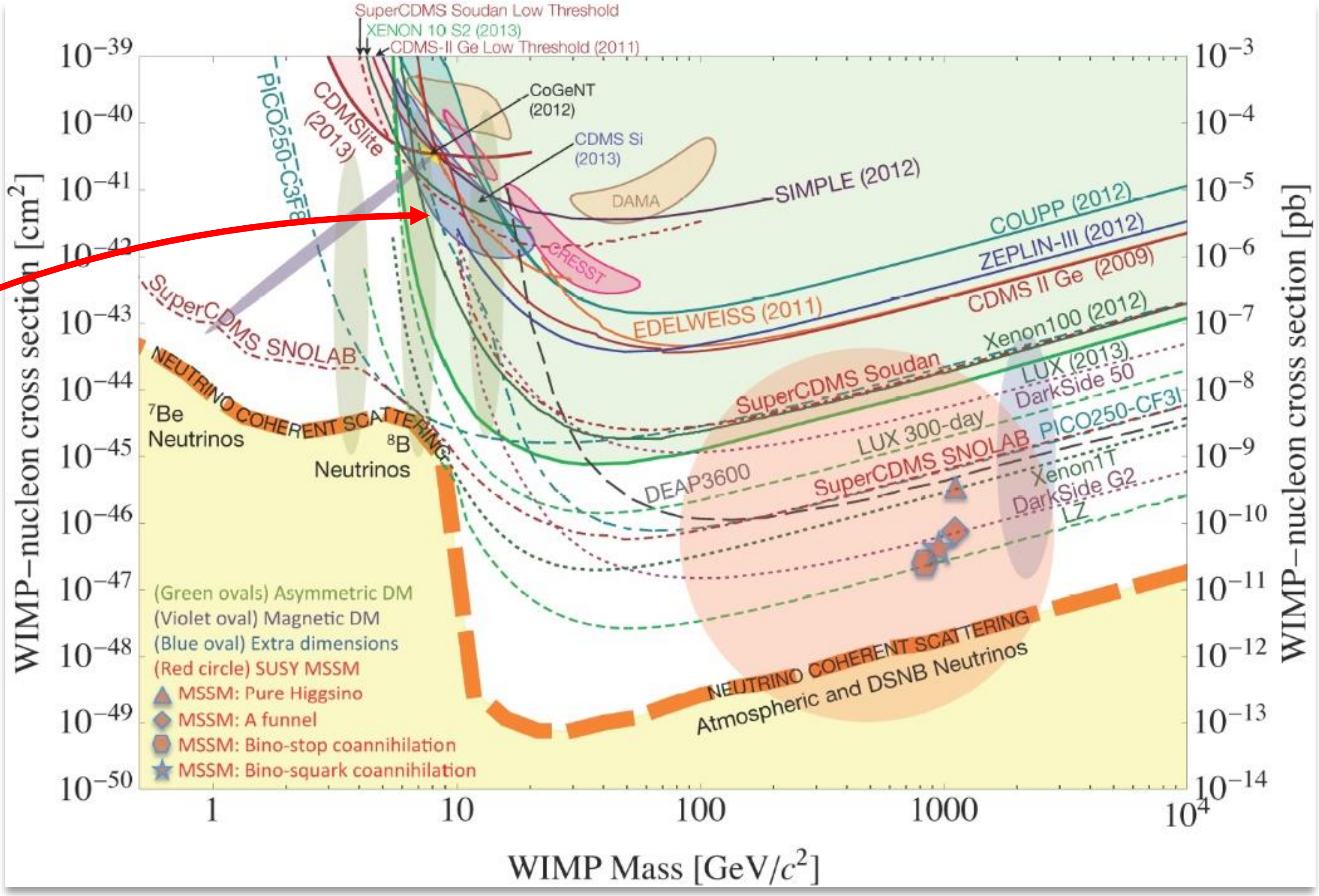
2. **Mass & interaction of DM**

✓ Differential recoil rate:

Amplitude ➔ Interaction strength

Curvature (~distribution) ➔ Mass





Light Dark Matter

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!

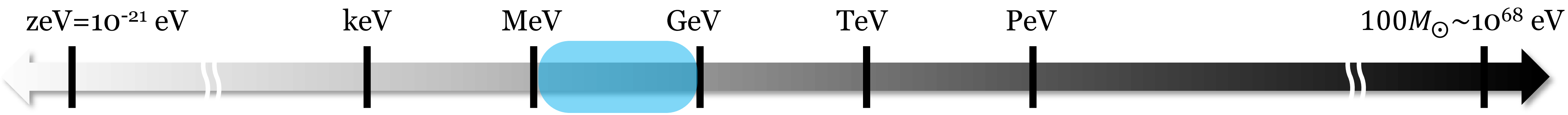
Super-heavy

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

Astrophysical object

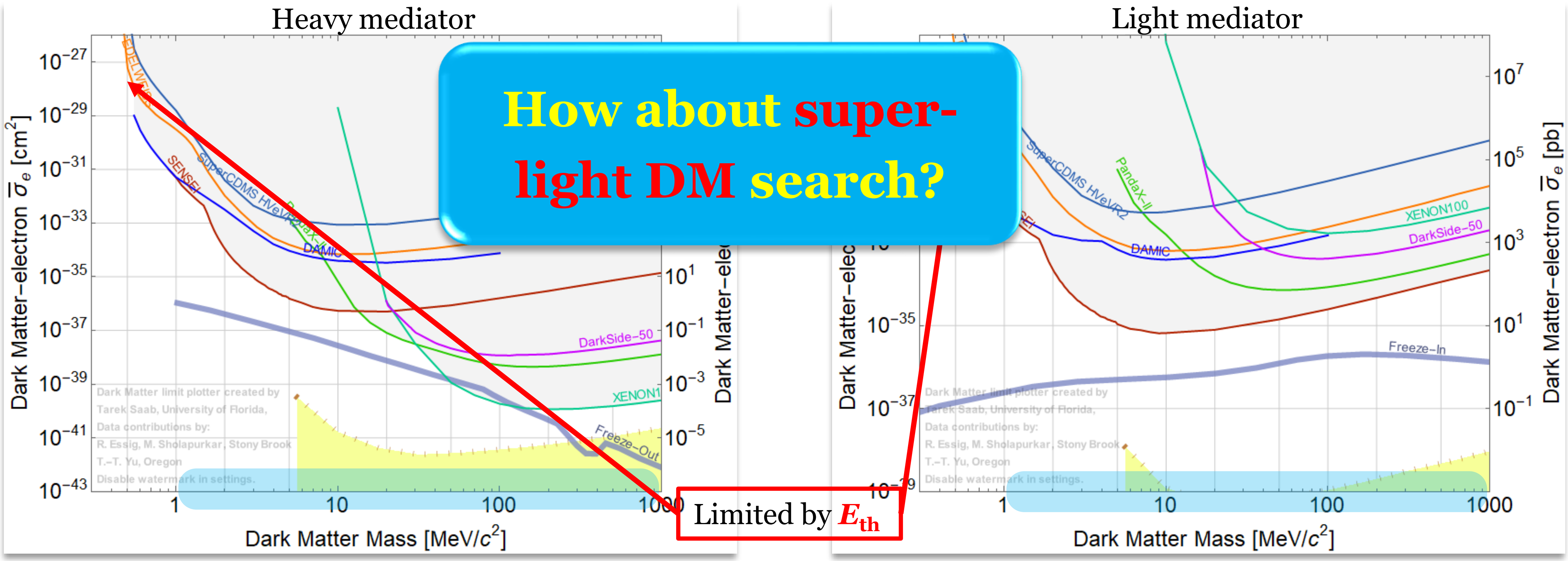
MACHO, PBH, non-particle

Light DM Direct Search



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

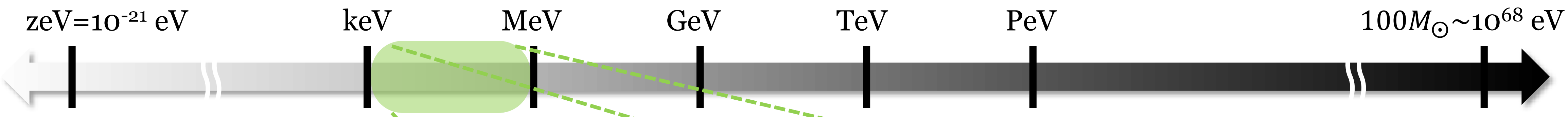
✓ **A way out**: $v \sim c$
e.g., **Boosted DM**



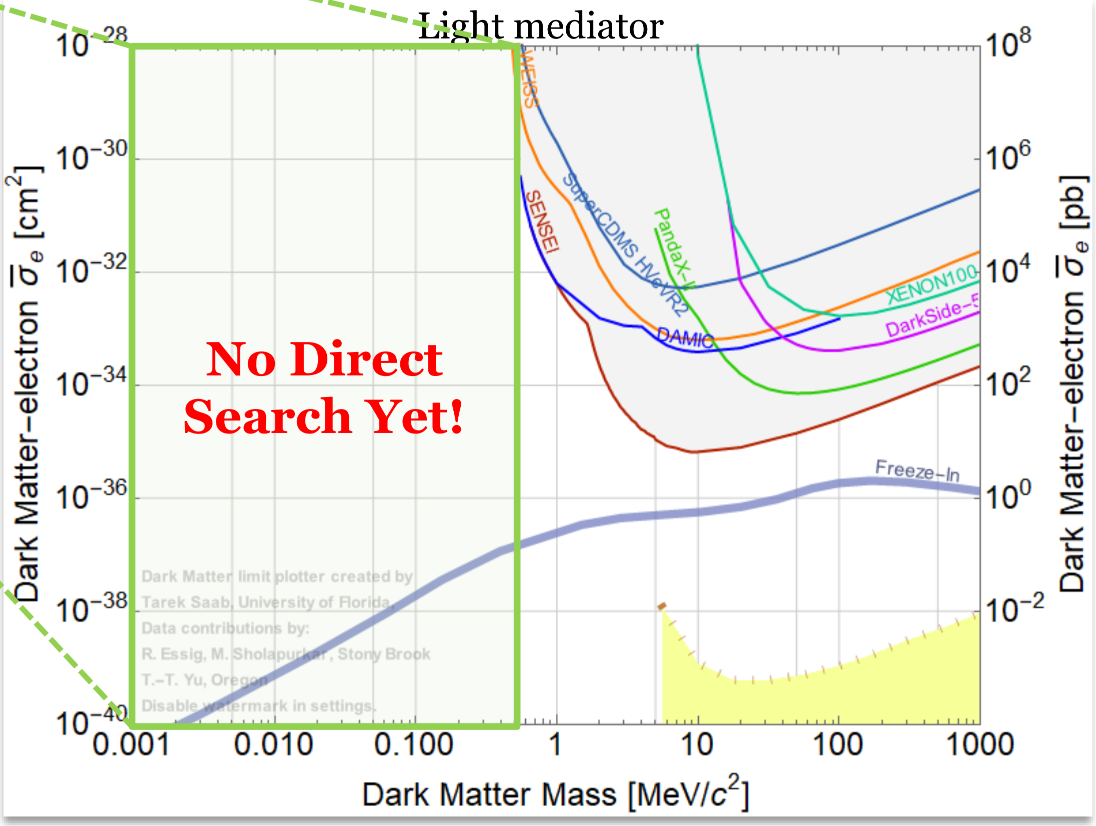
How about super-light DM search?

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)
- **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!

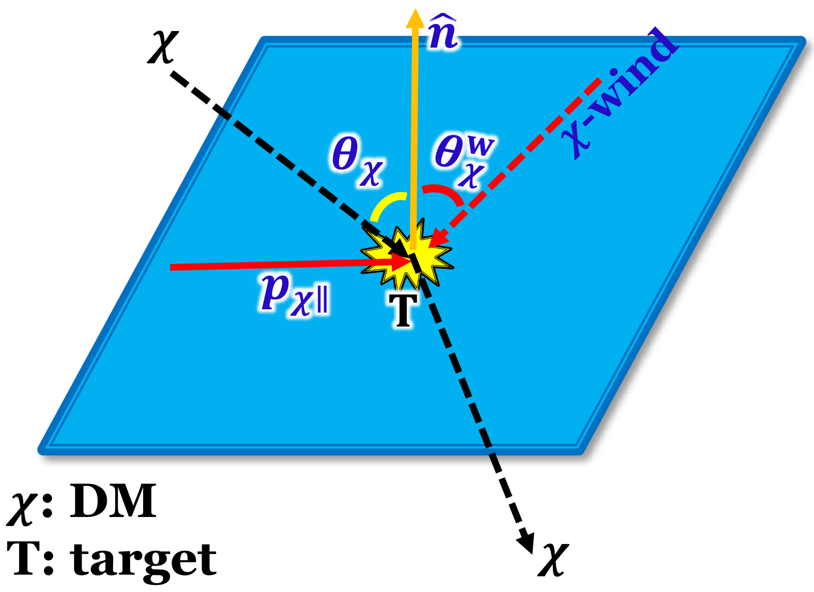
   ➔ **Is there any alternative method to determine the mass of DM?**

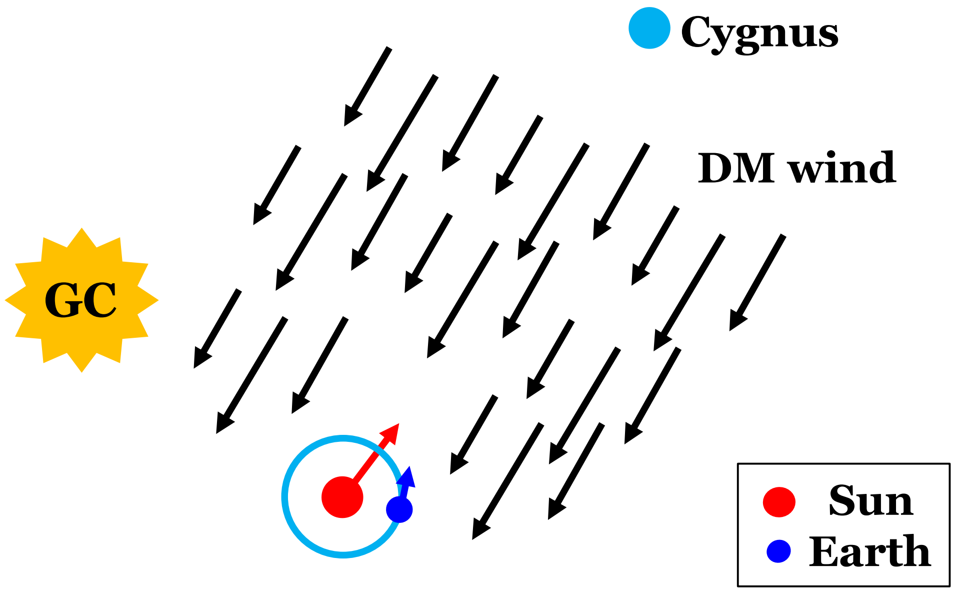
Answers for the Questions

❖ 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.

❖ 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.

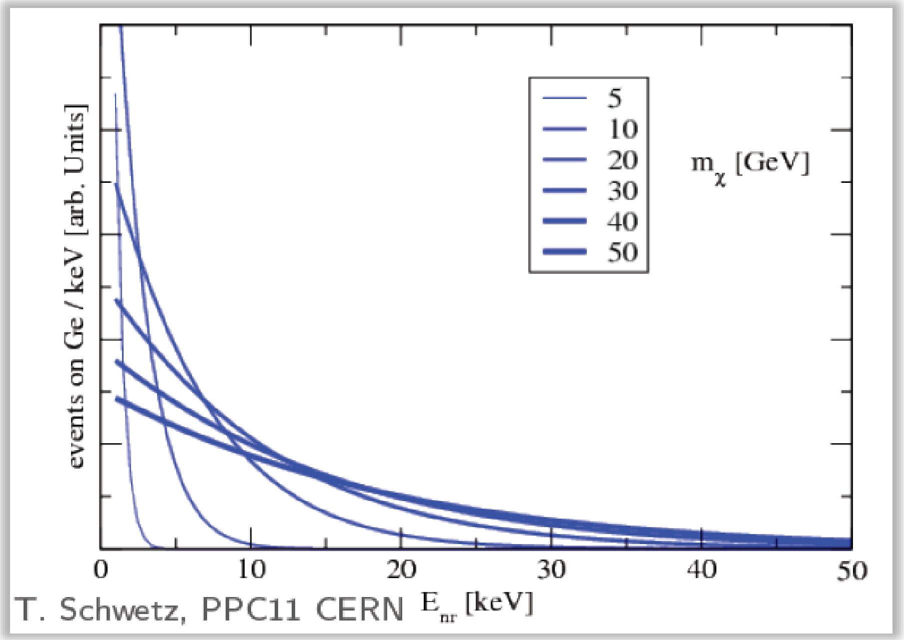




Answers for the Questions

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

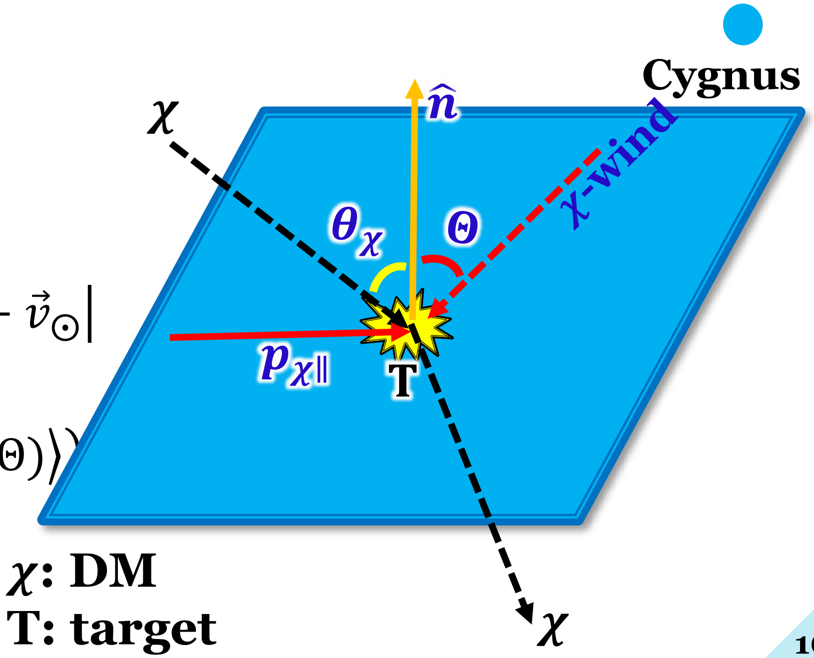
$$n_{\rm eve} = \frac{\rho_\chi}{m_\chi}\int dE_r dv_{\chi\parallel}\, \tilde{f}(v_{\chi\parallel}) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T} v_{{\rm rel}\parallel}\rangle\right)$$

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

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

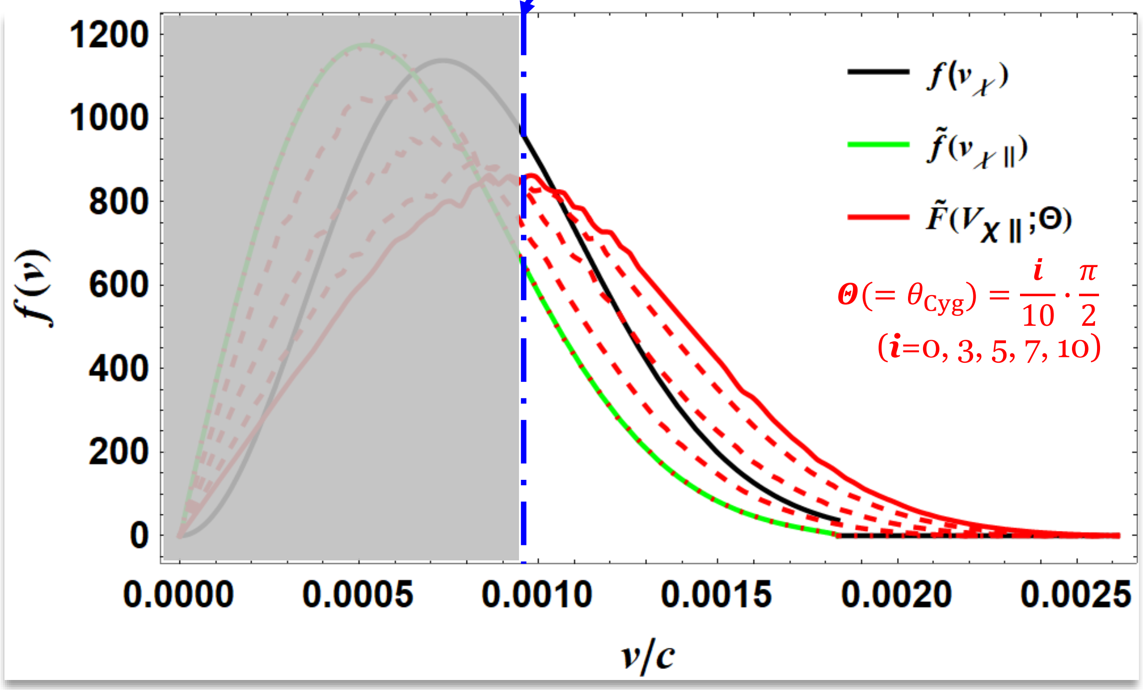
$$n_{\rm eve}(\Theta) = \frac{\rho_\chi}{m_\chi}\int dE_r dV_{\chi\parallel}\, \tilde{F}(V_{\chi\parallel};\Theta) \frac{d}{dE_r}\left(\bar{N}_{\rm T}\langle\sigma_{\chi T} V_{{\rm rel}\parallel}(\Theta)\rangle\right)$$

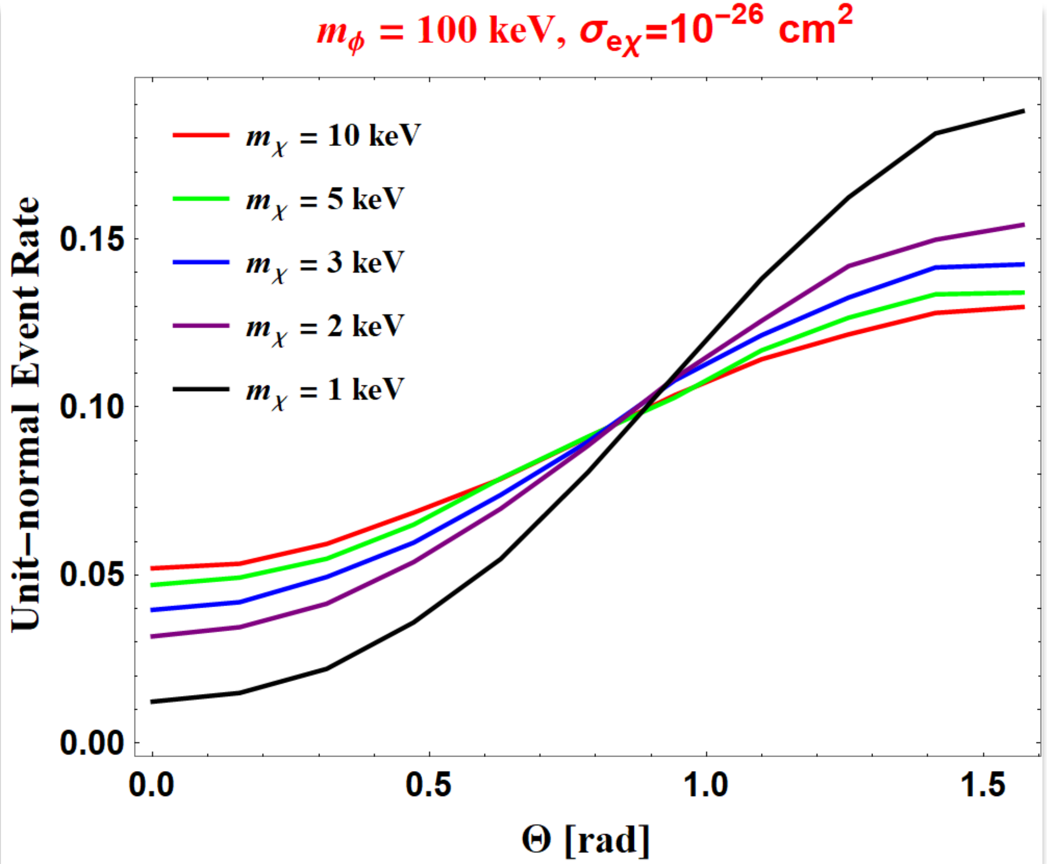
For Θ between the Cygnus direction and $\hat{n}$, a plane-projection procedure of $F(V_\chi)$ should be done individually ➔ $n_{\rm eve}$ depends on Θ non-trivially.



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

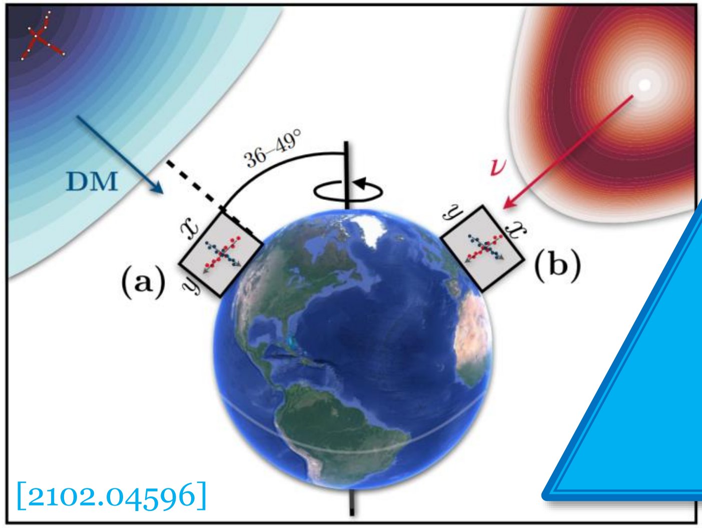


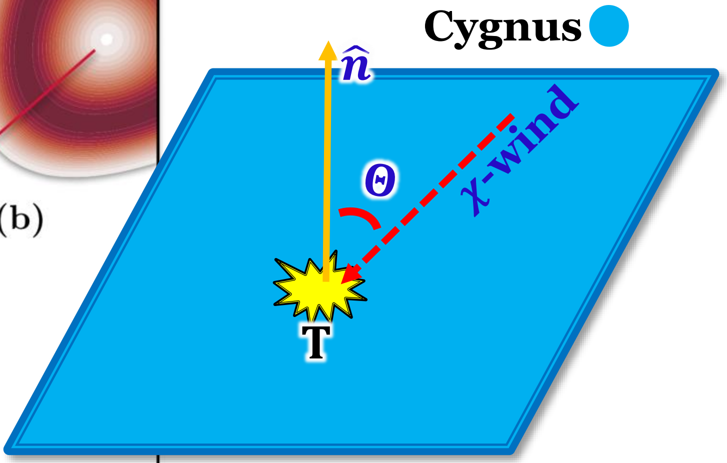


Angular Modulation vs Annual Modulation

❖ Angular modulation

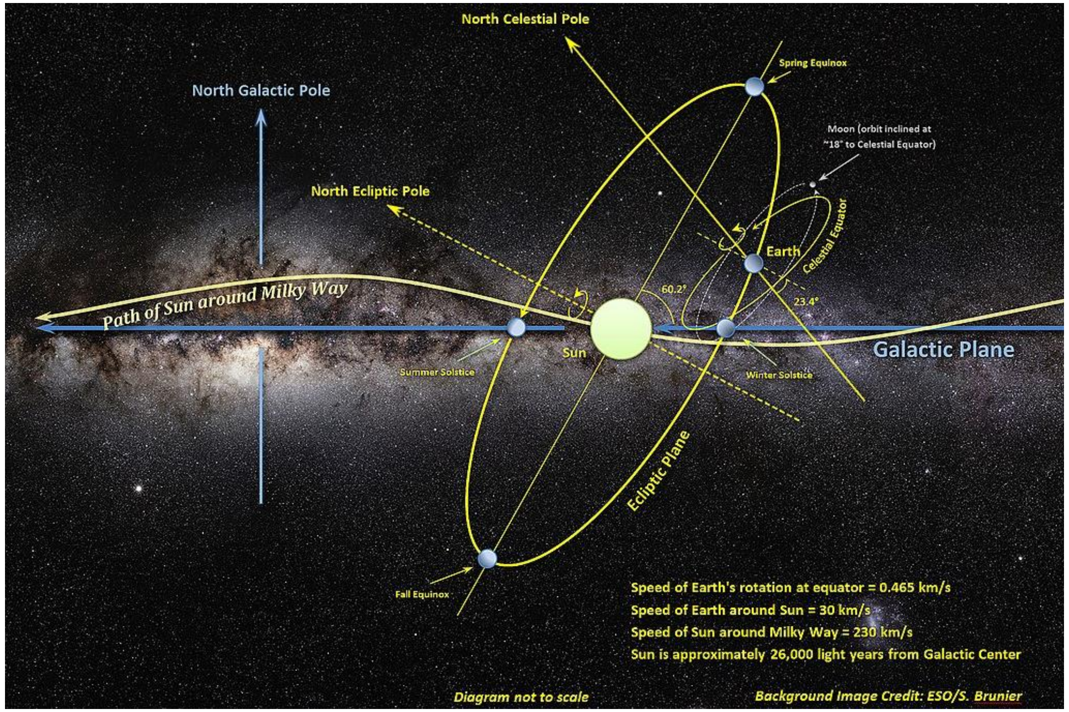
- ✓ Effects from the change of the DM wind direction (Θ) relative to the plane-normal direction due to Detector's motion
  - ➔ contribution: **revolution ≈ rotation**
- ✓ $N_{\text{event}}(\boldsymbol{\Theta})$ from $N_{\text{event}}(t)$ using $\boldsymbol{\Theta}(\boldsymbol{t})$
  - ➔ BG rejection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



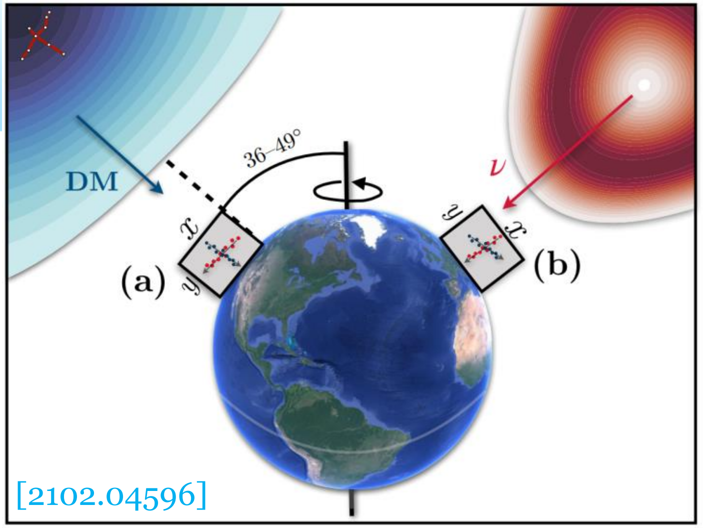


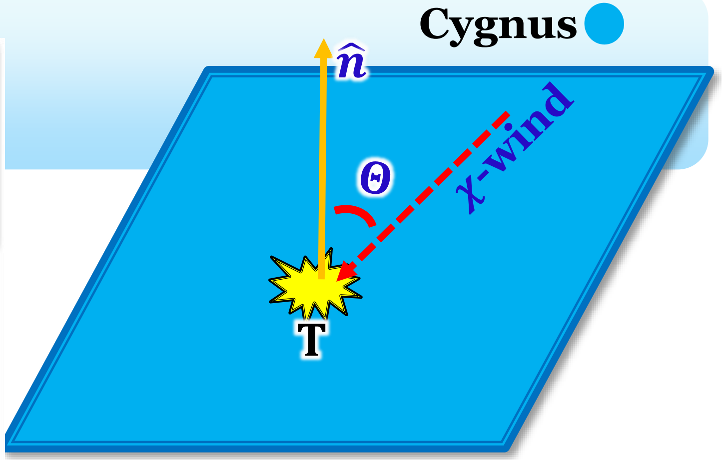
❖ Annual modulation

- ✓ 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



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!

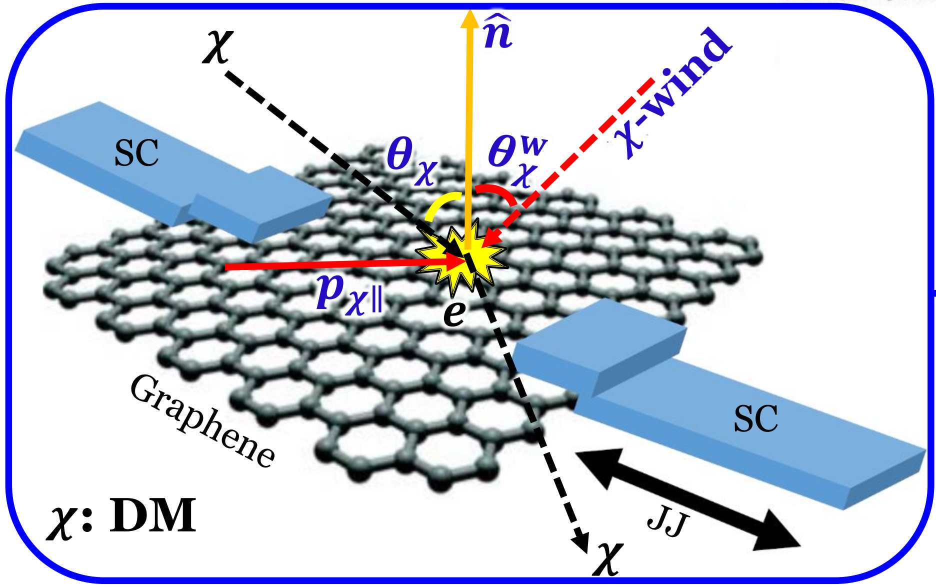
Supplemental

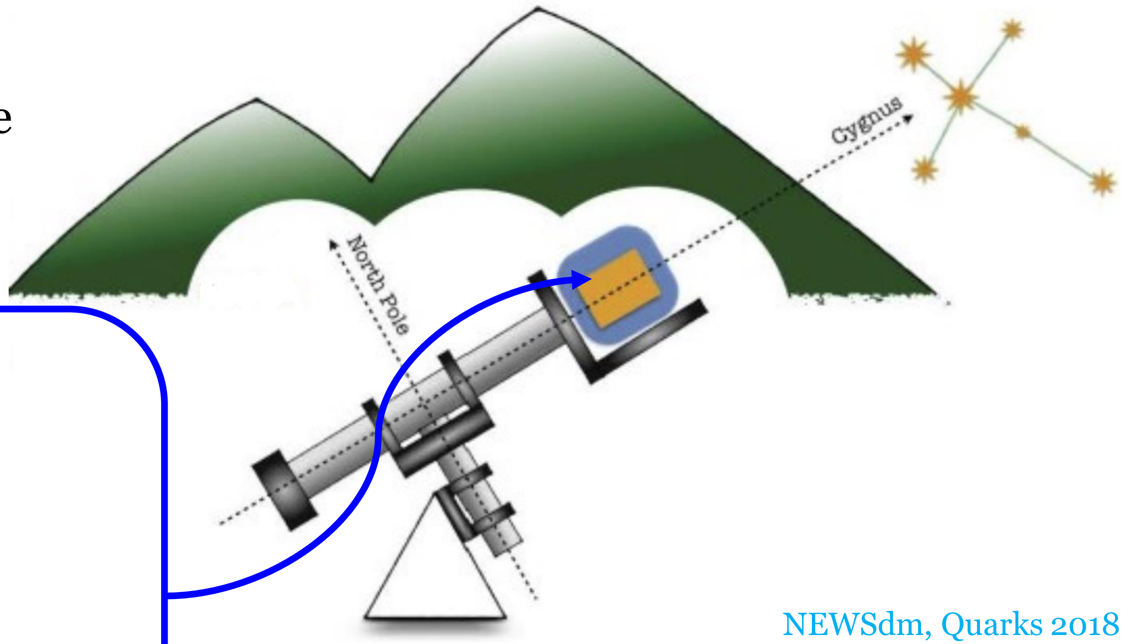
Directional Dependence: Angular Information?

✓ **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 $E_{th} \sim O(0.1 \text{ meV})$