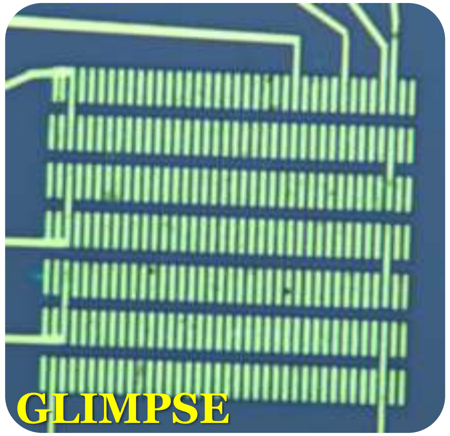
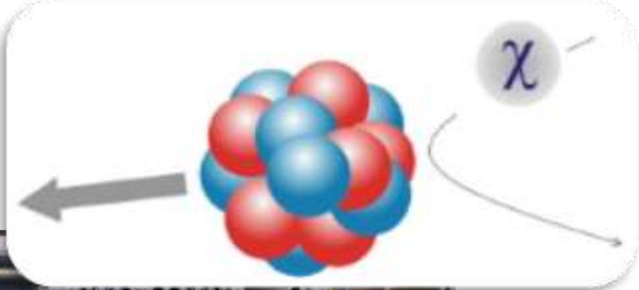
Search for Dark Matter: Dark Matter Direct Detection



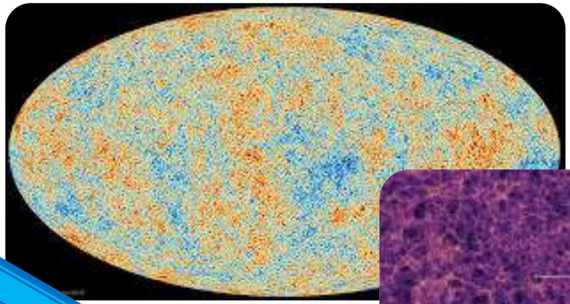


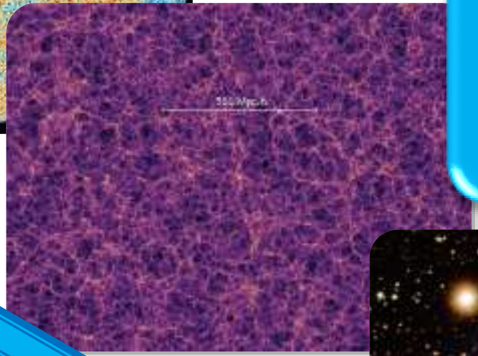
Jong-Chul Park

CNU 충남대학교
CHUNGNAM NATIONAL UNIVERSITY

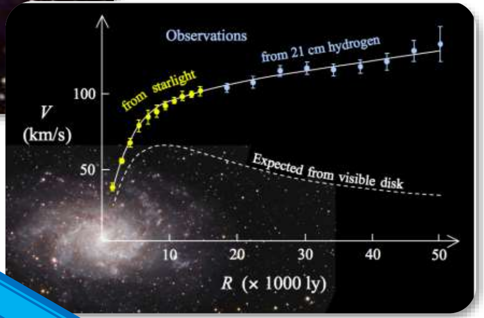
Saga-Yonsei Joint Workshop, November 07 (2024)

Message from Cosmology: Dark Matter (DM)





Dark Matter?



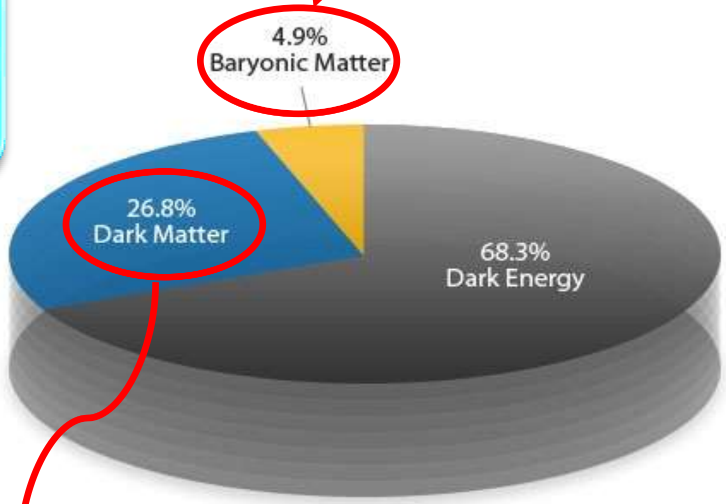
Larger scale
Earlier

Smaller scale
Later

Many more other observations!

❖ **Modern cosmology**:

The Standard Model

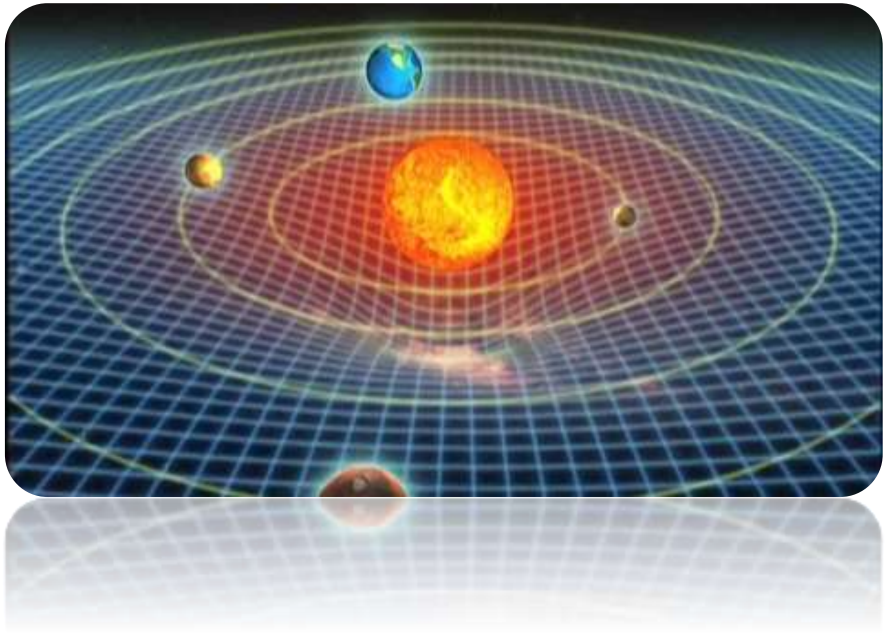


❖ **Compelling paradigm**:

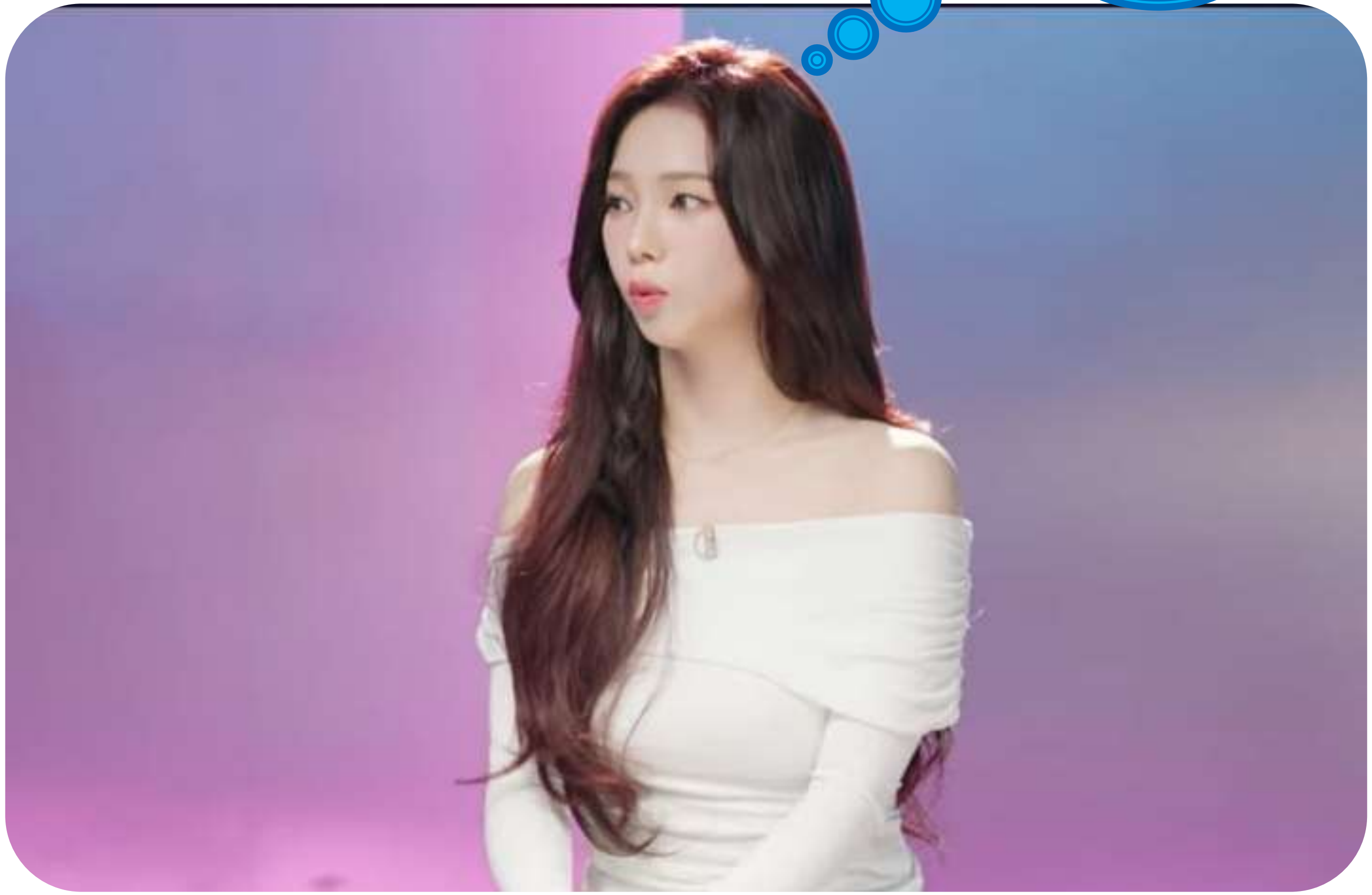
- ✓ Massive,
- ✓ Non-relativistic ($v \ll c$),
- ✓ Non-luminous (no/tiny EM interaction),
- ✓ Stable particles

More Observational Evidence of DM

- ✓ Galaxy rotation curve
- ✓ Coma cluster
- ✓ Gravitational lensing
- ✓ Bullet cluster
- ✓ Structure formation
- ✓ Cosmic microwave background radiation (CMBR)
- ✓ Sky surveys
- ✓ Type Ia supervovae
- ✓ Baryonic acoustic oscillation (BAO)
- ✓ ...



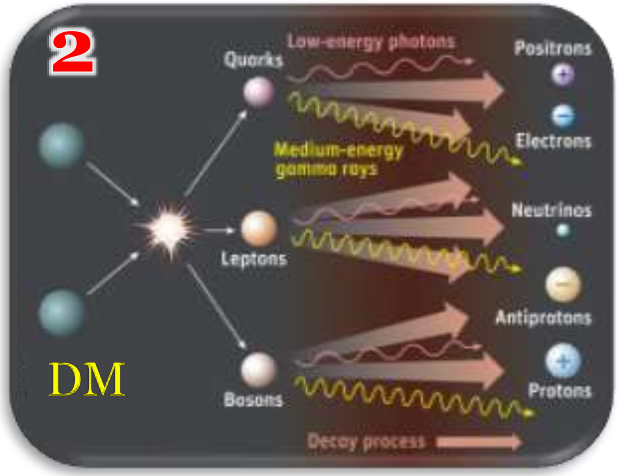
Nature of DM?

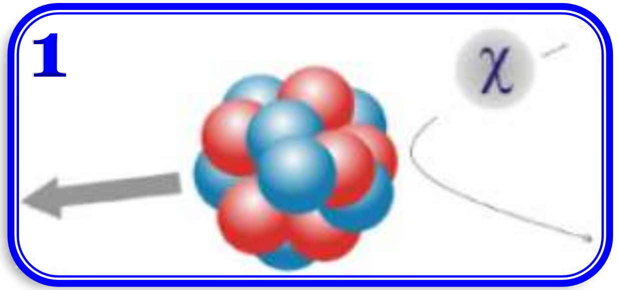


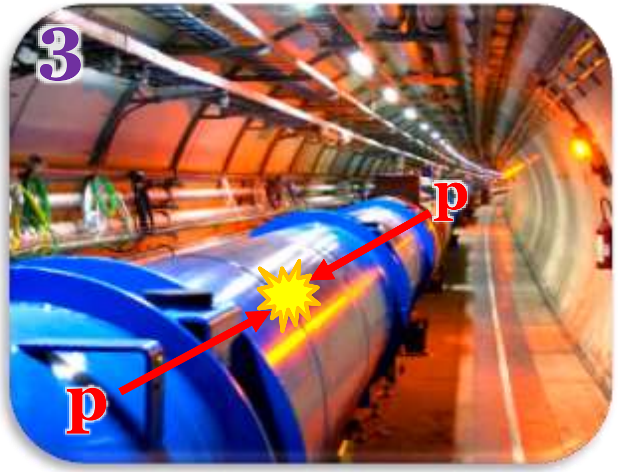
Karina $\in$ SM

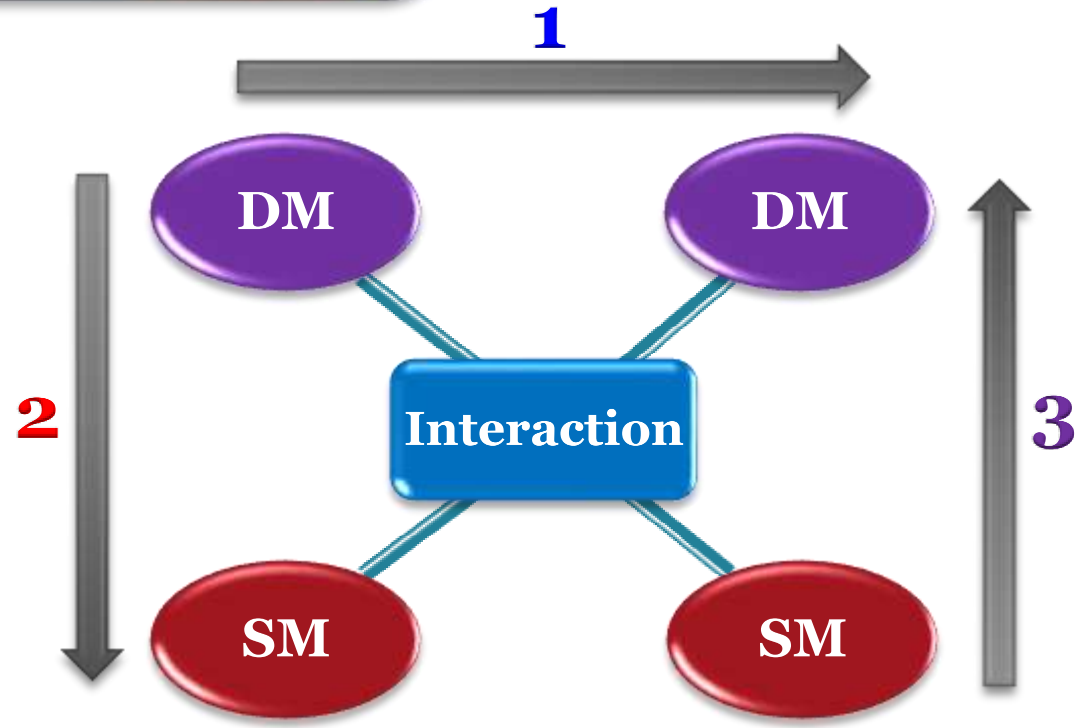
But DM $\notin$ SM

Conventional DM Search Strategies









❖ Based on the WIMP paradigm.

Cosmological Lower Bound on Heavy-Neutrino Masses

Benjamin W. Lee[(a)]
Fermi National Accelerator Laboratory,[(b)] *Batavia, Illinois 60510*

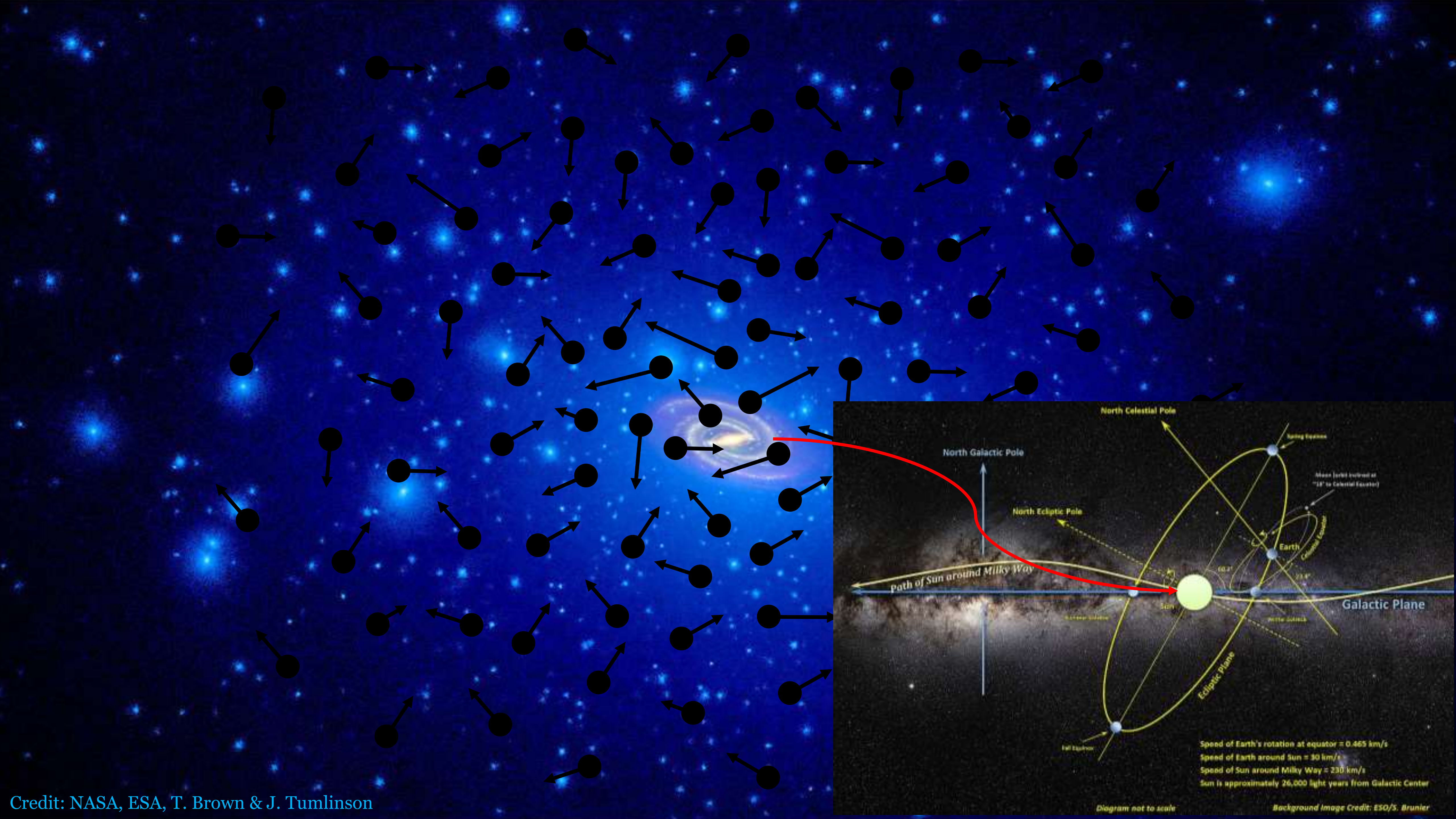
and

Steven Weinberg[(c)]
Stanford University, Physics Department, Stanford, California 94305
(Received 13 May 1977)

The present cosmic mass density of possible stable neutral heavy leptons is calculated in a standard cosmological model. In order for this density not to exceed the upper limit of 2×10^{-29} g/cm^3, the lepton mass would have to be *greater* than a lower bound of the order of 2 GeV.

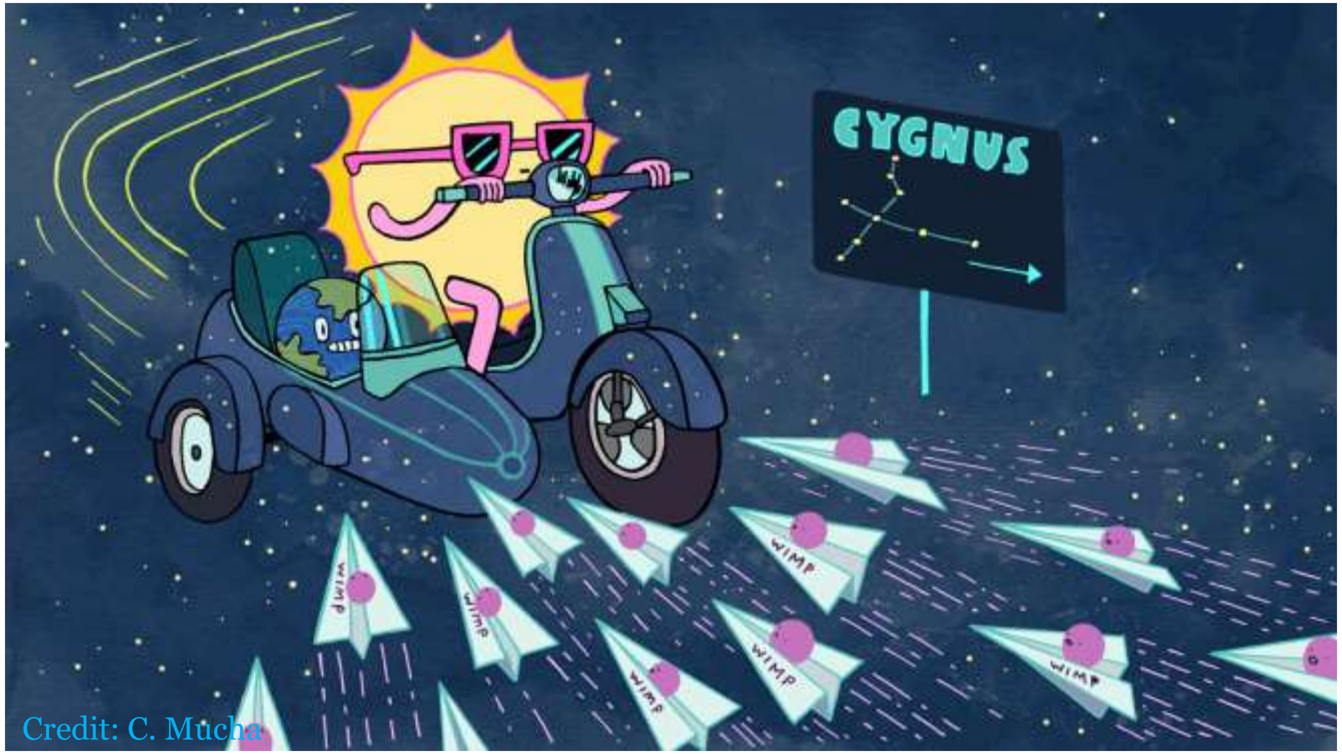
[PRL (1977)]

DM Direct Detection:
Target Particle Recoil



Credit: NASA, ESA, T. Brown & J. Tumlinson

DM Wind



Credit: C. Mucha

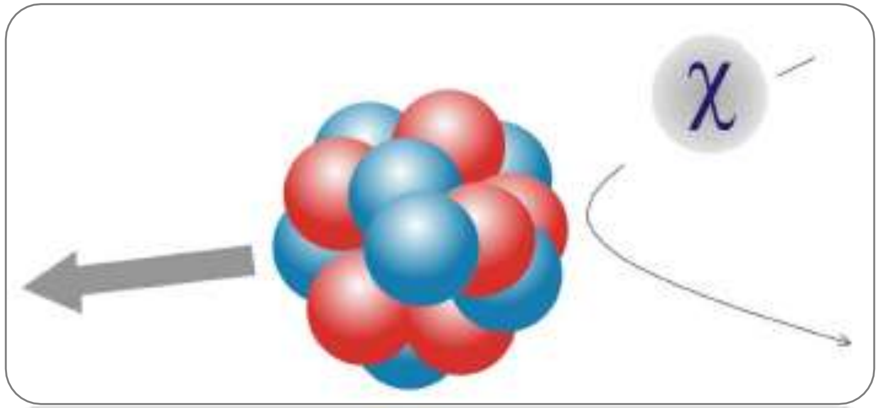
DM

❖ Assuming $m_{\mathrm{DM}} \sim m_{\mathrm{p}} \sim 0.94$ GeV: $\underbrace{300\ \mathrm{km/s} \times \frac{0.4\ \mathrm{GeV/cm^3}}{0.94\ \mathrm{GeV}}}_{\text{flux}} \times \underbrace{60\ \mathrm{cm} \times 170\ \mathrm{cm}}_{\text{area}}$

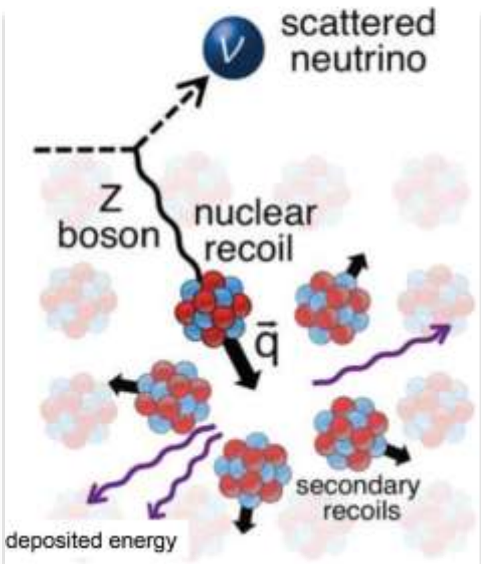
$\approx\ 10^{11}/\mathrm{s}$

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

DM Direct Detection



- DM: all around us! → recoil of DM-nucleus scattering from E & p conservation!



- What is measure: E of recoiling nucleus ~ 1-100 keV for m_{DM} ~ 1-100 GeV ($E_{\mathrm{k}} \sim mv^2$ with $v/c \sim 10^{-3}$)

- Challenges: very small E, small event rate, large backgrounds

Beginning of DM Direct Detection

❖ Coherent Elastic *ν*-Nucleus Scattering (CE*ν*NS)

PRD (1974) **Coherent effects of a weak neutral current**

PRD (1985) **Detectability of certain dark-matter candidates**

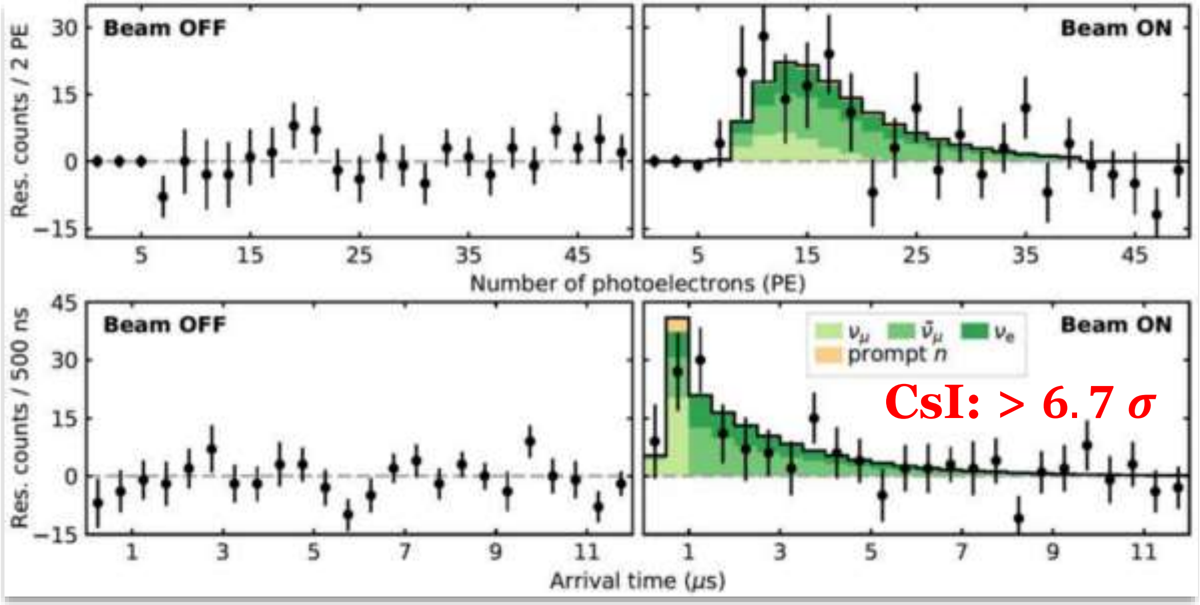
Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)

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.

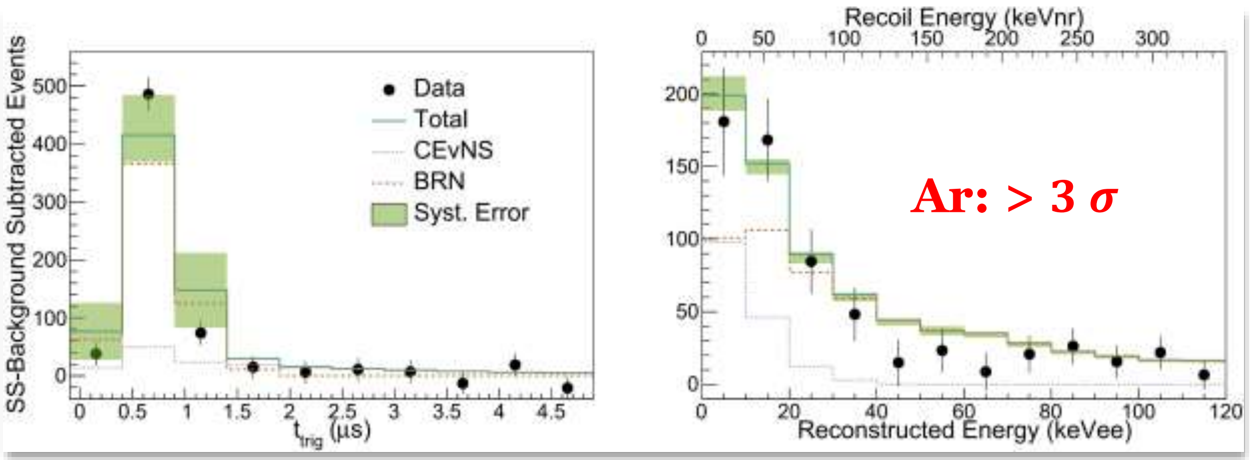
PRD (1984) **Principles and applications of a neutral-current detector for neutrino physics and astronomy**

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.

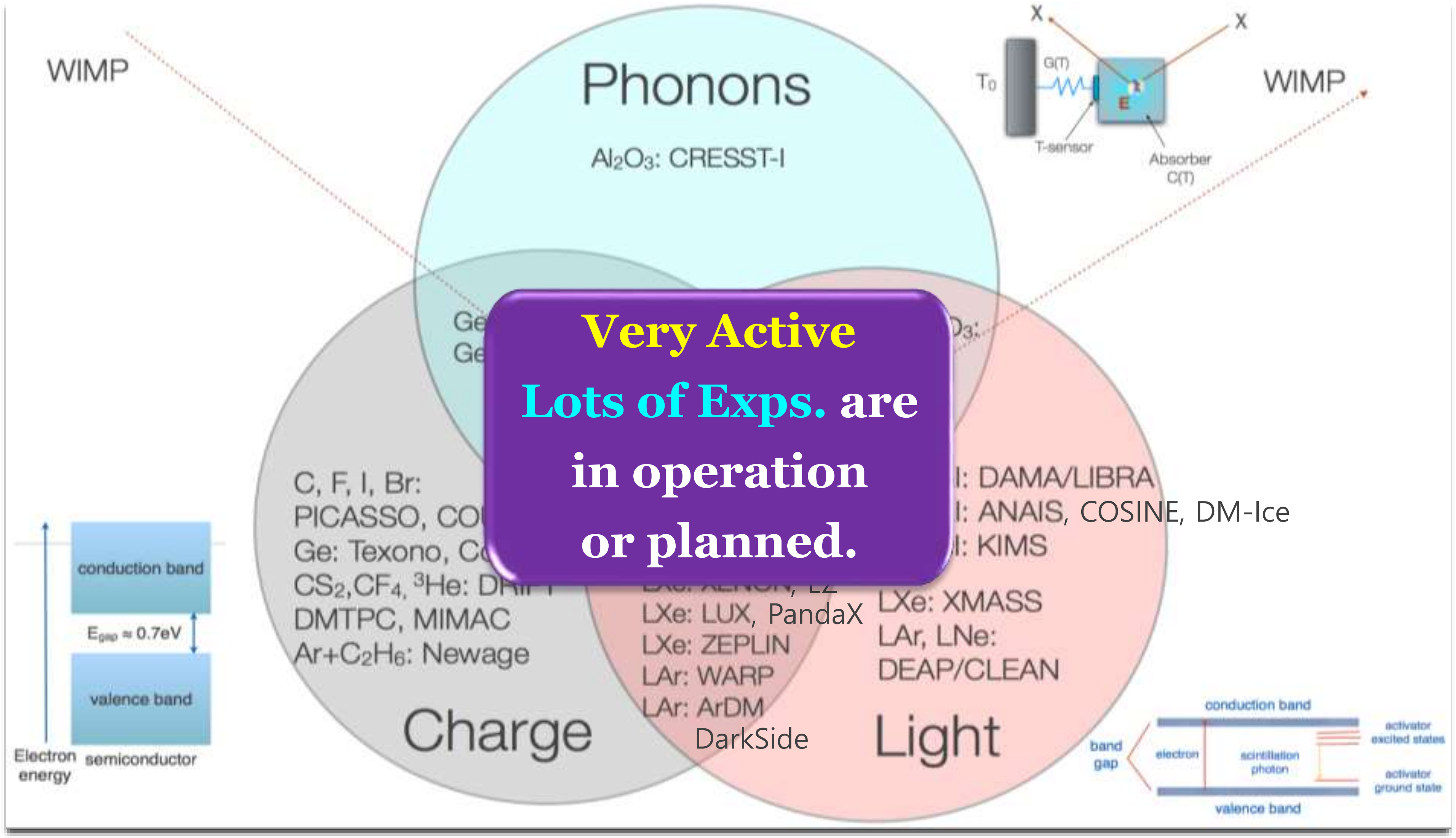


COHERENT [1708.01294]

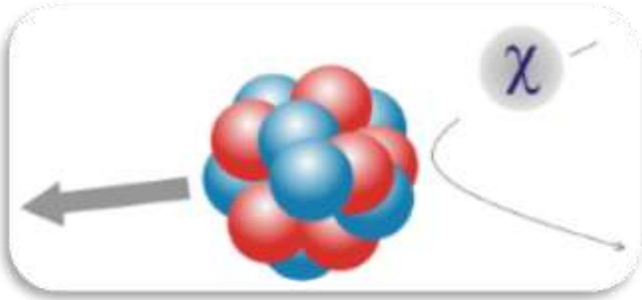


COHERENT [2003.10630]

Detection Techniques



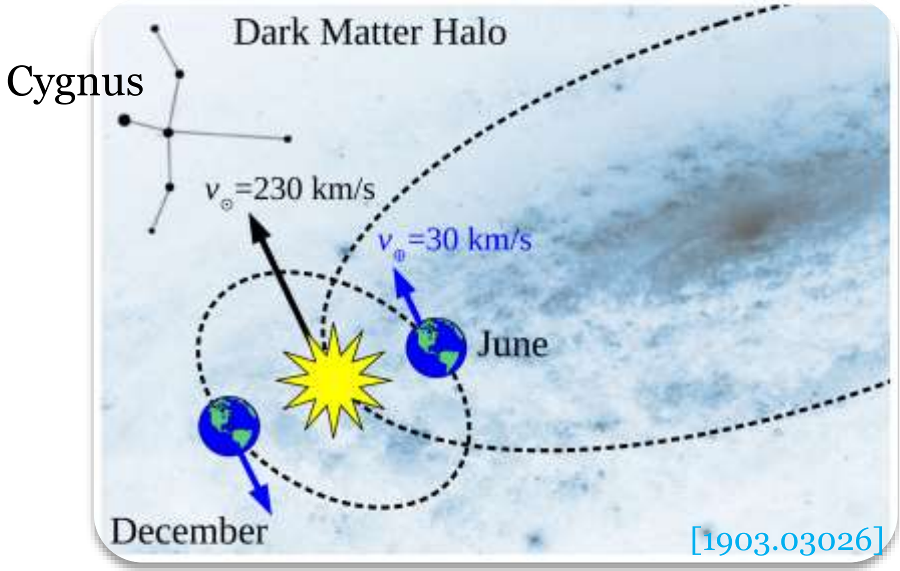
DM Direct Detection: Basics



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

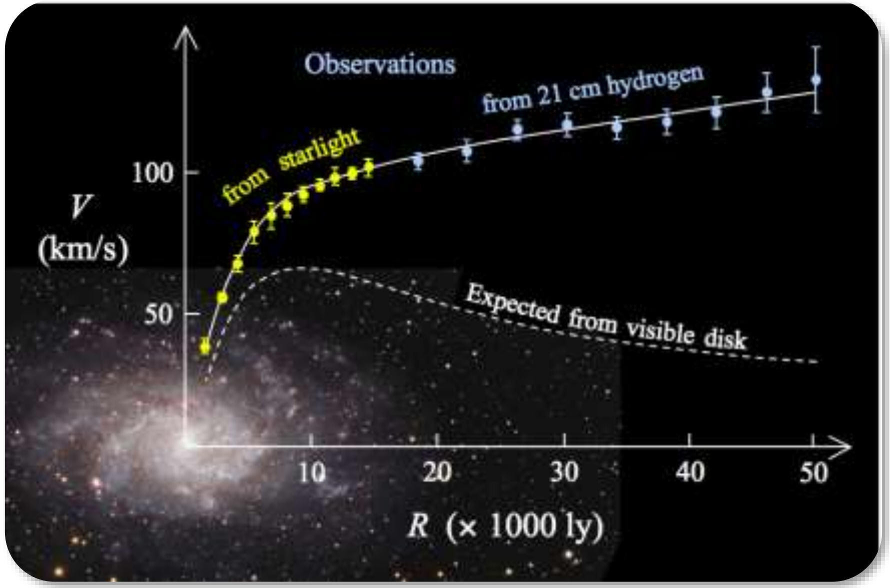
$$\frac{dN}{dE_R}(t) \propto N_T \frac{\rho_\chi}{m_\chi} \int_{v>v_{\rm min}} dv^3 \frac{d\sigma}{dE_R} v f_{\rm Earth}(\vec{v}, t)$$

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



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

DM Local Density



Mapping Dark Matter in the Milky Way using Normalizing Flows and Gaia DR3

Sung Hak Lim, Eric Putney, Matthew R. Buckley, and David Shih

NHETC, Dept. of Physics and Astronomy, Rutgers, Piscataway, NJ 08854, USA

We present a novel, data-driven analysis of Galactic dynamics, using unsupervised machine learning – in the form of density estimation with normalizing flows – to learn the underlying phase space distribution of 6 million nearby stars from the *Gaia* DR3 catalog. Solving the collisionless Boltzmann equation with the assumption of approximate equilibrium, we calculate – for the first time ever – a model-free, unbinned, fully 3D map of the local acceleration and mass density fields within a 3 kpc sphere around the Sun. As our approach makes no assumptions about symmetries, we can test for signs of disequilibrium in our results. We find our results are consistent with equilibrium at the 10% level, limited by the current precision of the normalizing flows. After subtracting the known contribution of stars and gas from the calculated mass density, we find clear evidence for dark matter throughout the analyzed volume. Assuming spherical symmetry and averaging mass density measurements, we find a local dark matter density of 0.47 ± 0.05 GeV/cm^3. We fit our results to a generalized NFW, and find a profile broadly consistent with other recent analyses.

[arXiv: 2305.13358]

- Two main approaches to measuring ρ_{DM}
  - Global measures: inter/extrapolating ρ_{DM} from the rotation curve
  - Local measures: the vertical kinematics of stars in the local Milky Way ➔ ‘tracers’
  - There have been attempts to bridge two scales.
- Recently, analysis of Galactic dynamics, even using machine-learning approaches.

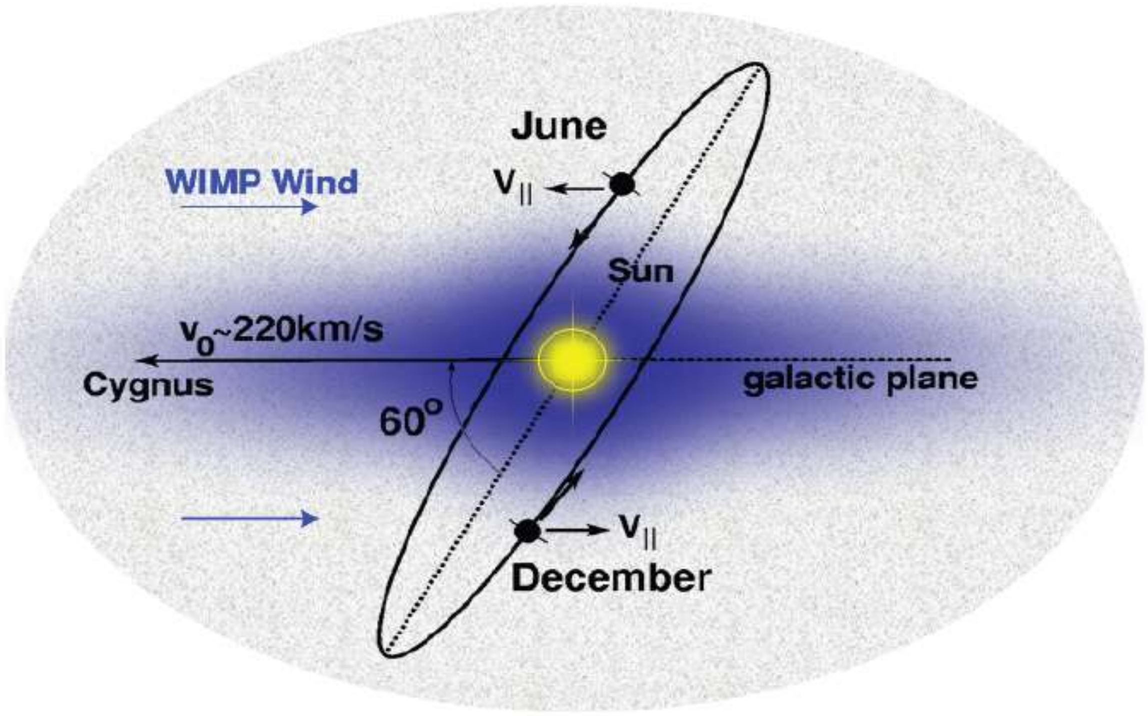
DM Velocity Distribution

$$f_\oplus(\vec{v}, t) = f_{\rm gal}(\vec{v} + \vec{v}_\odot + \vec{v}_\oplus(t)) \qquad f_{\rm gal}(\vec{v}) \approx \begin{cases} N \exp\left(-v^2/\bar{v}^2\right) & v < v_{\rm esc} \\ 0 & v > v_{\rm esc} \end{cases}$$

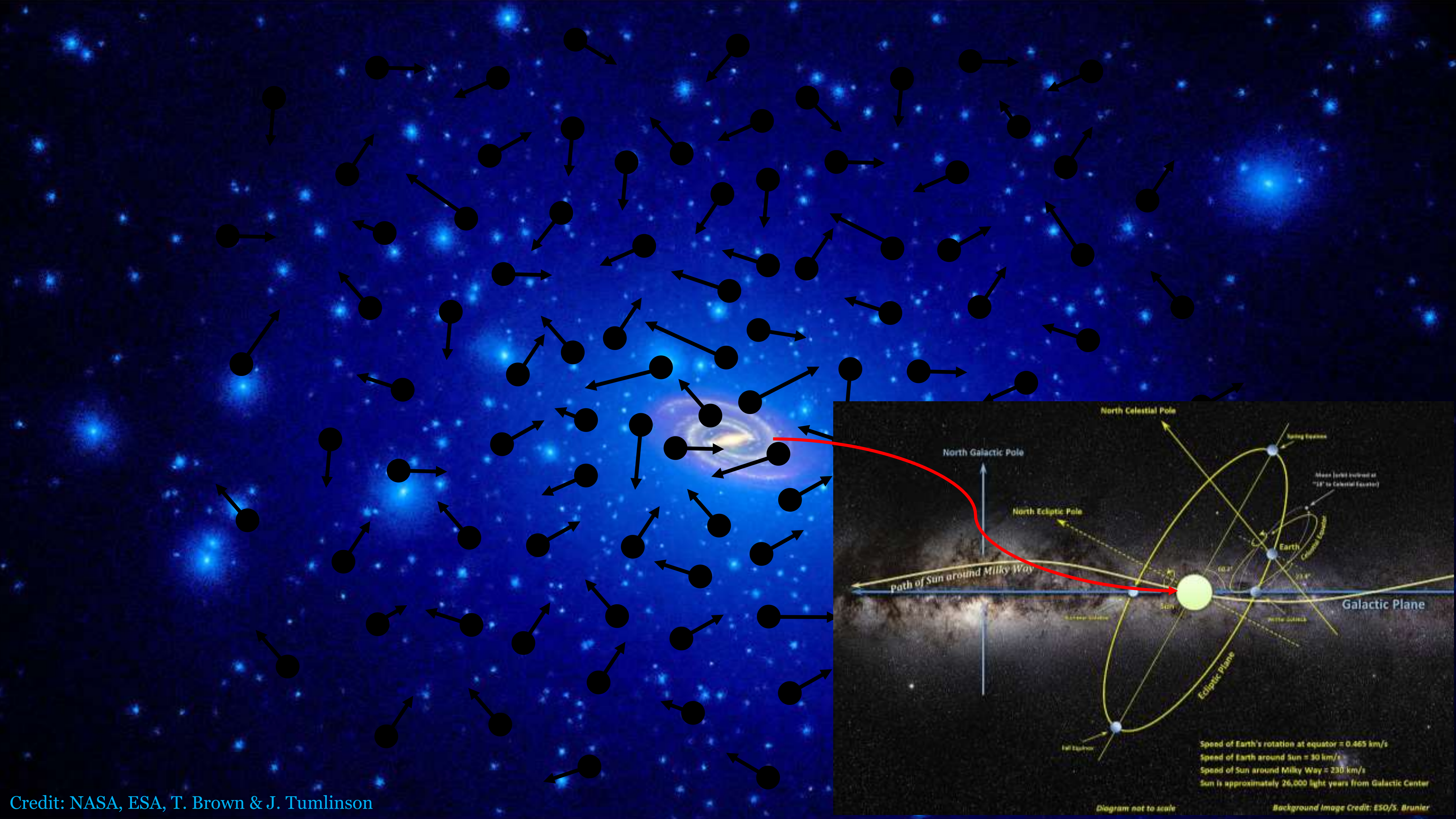
$\bar{v} \simeq 220\,\mathrm{km/s}$ $\quad v_{\rm esc} \simeq 550\,\mathrm{km/s}$

sun velocity: $\vec{v}_\odot = (0, 220, 0) + (10, 13, 7)\,\mathrm{km/s}$

earth velocity: $\vec{v}_\oplus(t)$ with $v_\oplus \approx 30\,\mathrm{km/s}$



T. Schwetz, PPC11 CERN

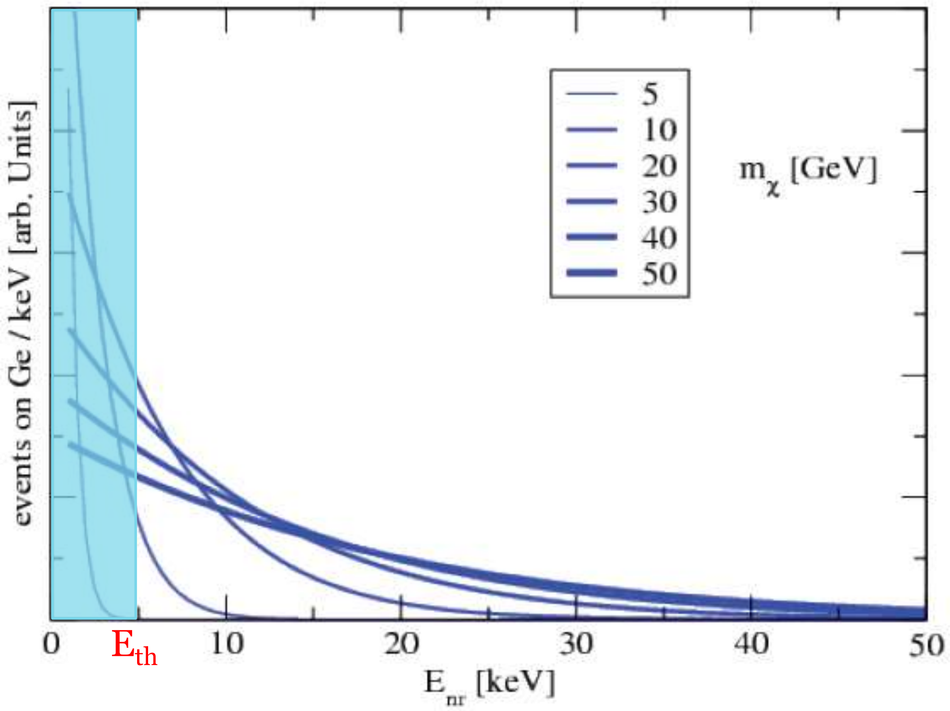


Credit: NASA, ESA, T. Brown & J. Tumlinson

Event Spectrum

$$\frac{dN}{dE_R}(t) = \frac{\rho_\chi}{m_\chi} \frac{\sigma_p |F(q)|^2 A^2}{2\mu_p^2} \int_{v>v_{\min}(E_R)} d^3v \, \frac{f_\oplus(\vec{v},t)}{v}$$

$v_{\min} = \frac{m_\chi + M}{m_\chi}\sqrt{\frac{E_R}{2M}}$: minimal DM velocity needed for recoil energy E_R



$m_\chi \ll M$:

$$v_{\min} \approx \frac{\sqrt{ME_R/2}}{m_\chi}$$

spectrum gets shifted to low energies for low WIMP masses

$\Rightarrow$ energy threshold is crucial

T. Schwetz, PPC11 CERN

Information of DM Models

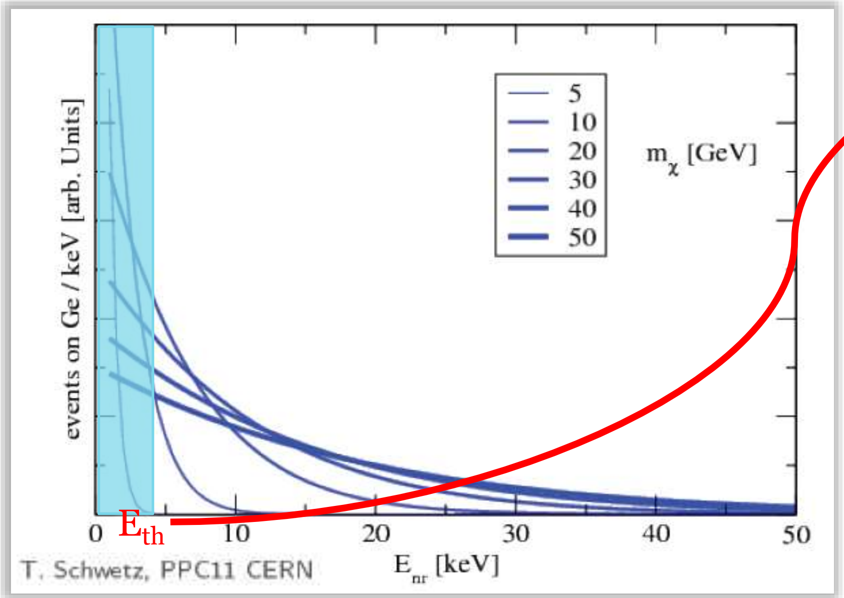
❖ **Mass & interaction strength of DM**

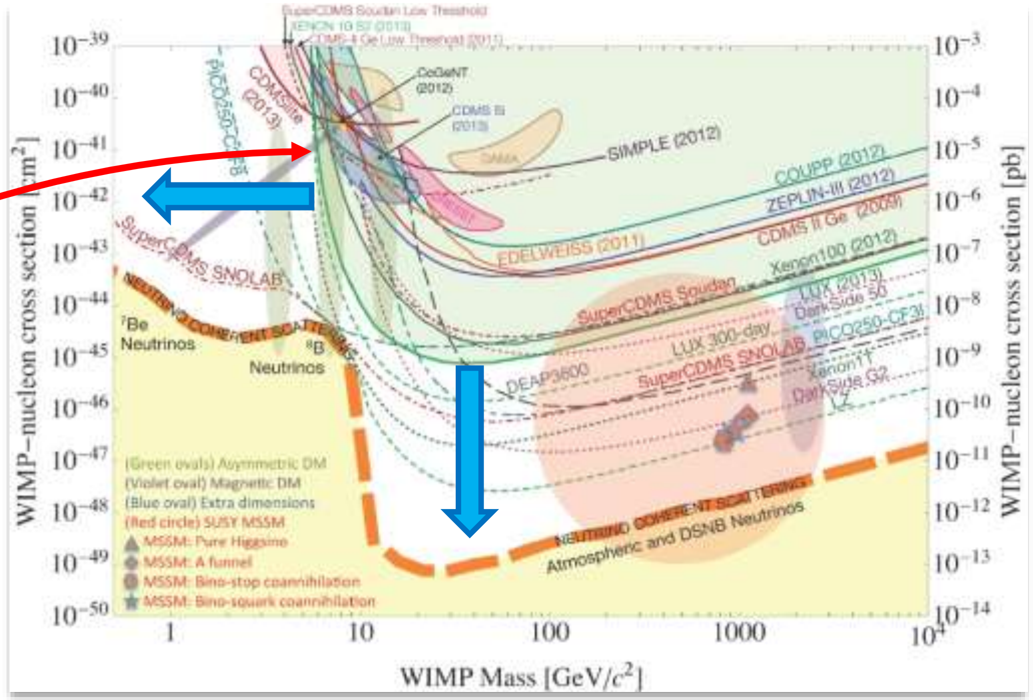
✓ Differential recoil rate:

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

Amplitude ➔ Interaction strength

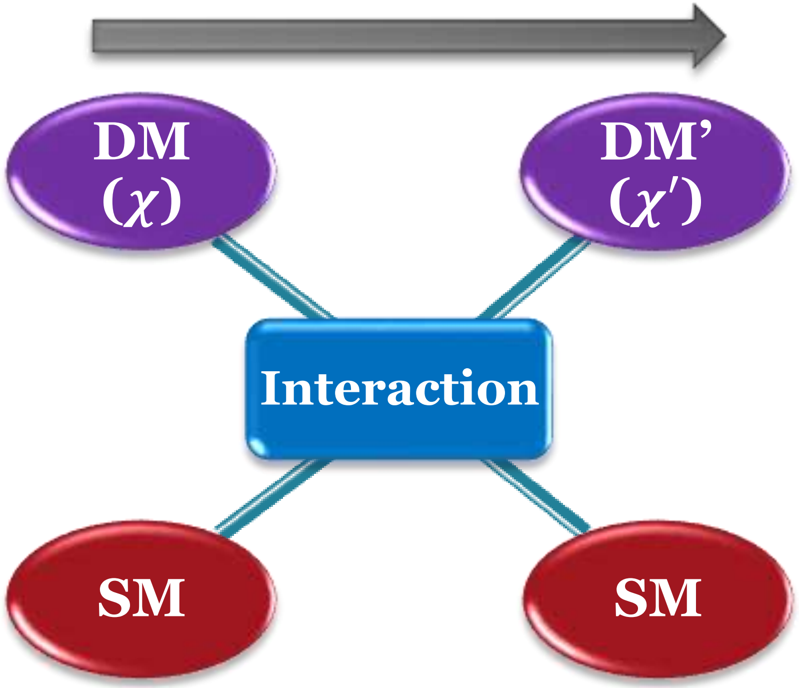
Curvature (~distribution) ➔ Mass





$$v_{\min}(E_R) \equiv \sqrt{\frac{m_T E_R}{2\mu_T^2}} = \frac{q}{2\mu_T}$$

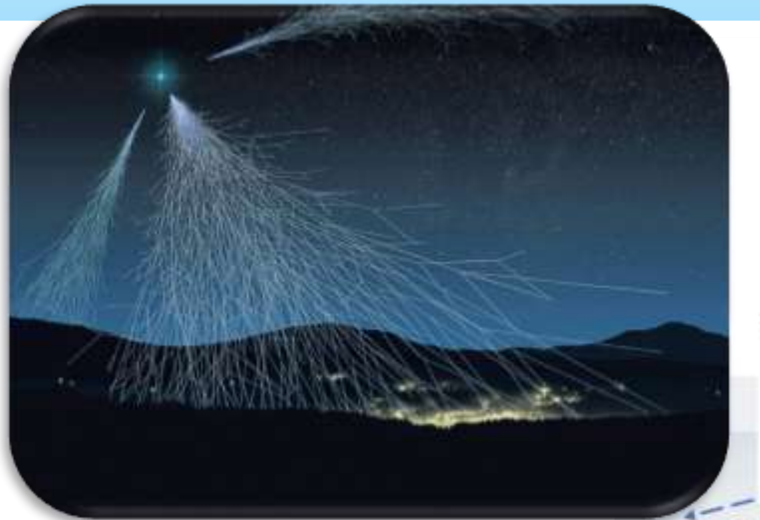
Check!: Inelastic Scattering of DM

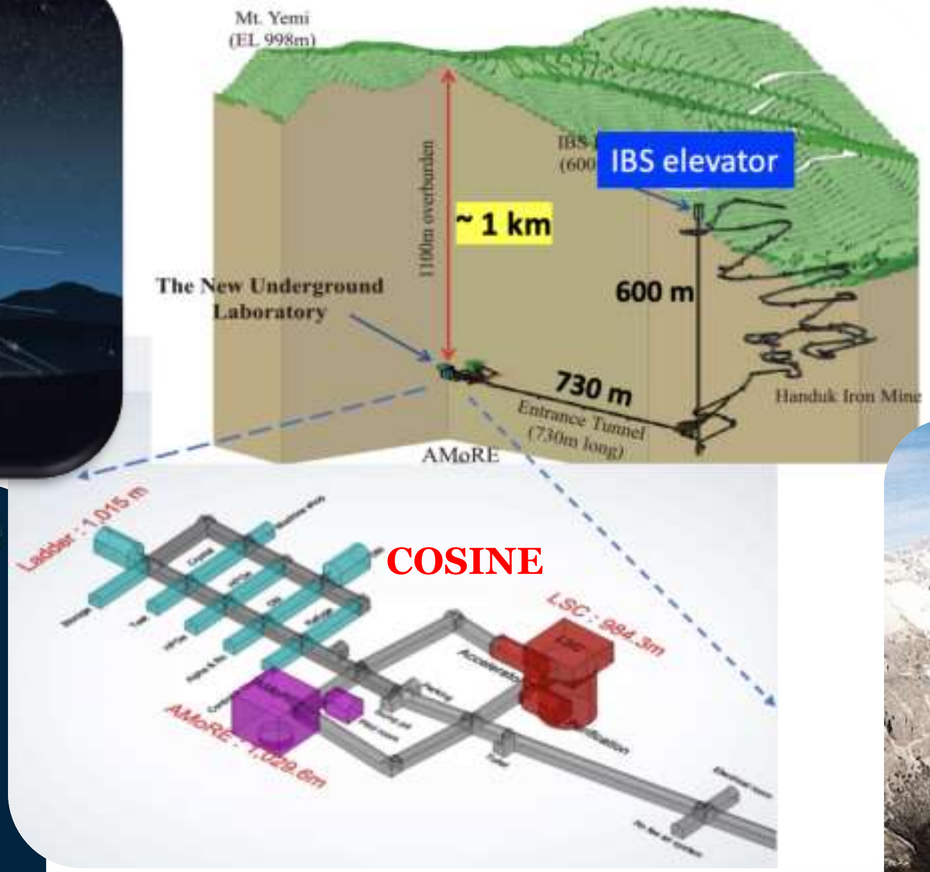


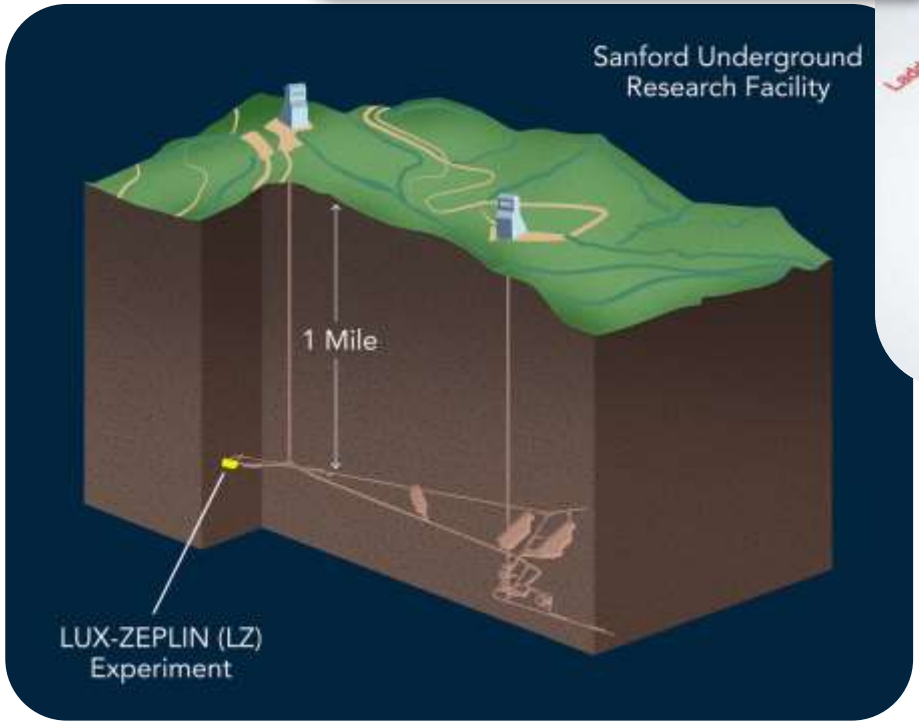
$$v_{\rm min}(E_{\rm R}) \equiv \left| \frac{q}{2\mu_T} + \frac{\delta}{q} \right| = \frac{1}{\sqrt{2m_T E_{\rm R}}} \left| \frac{m_T E_{\rm R}}{\mu_T} + \delta \right|$$

$$\delta = m_{\chi'} - m_\chi$$

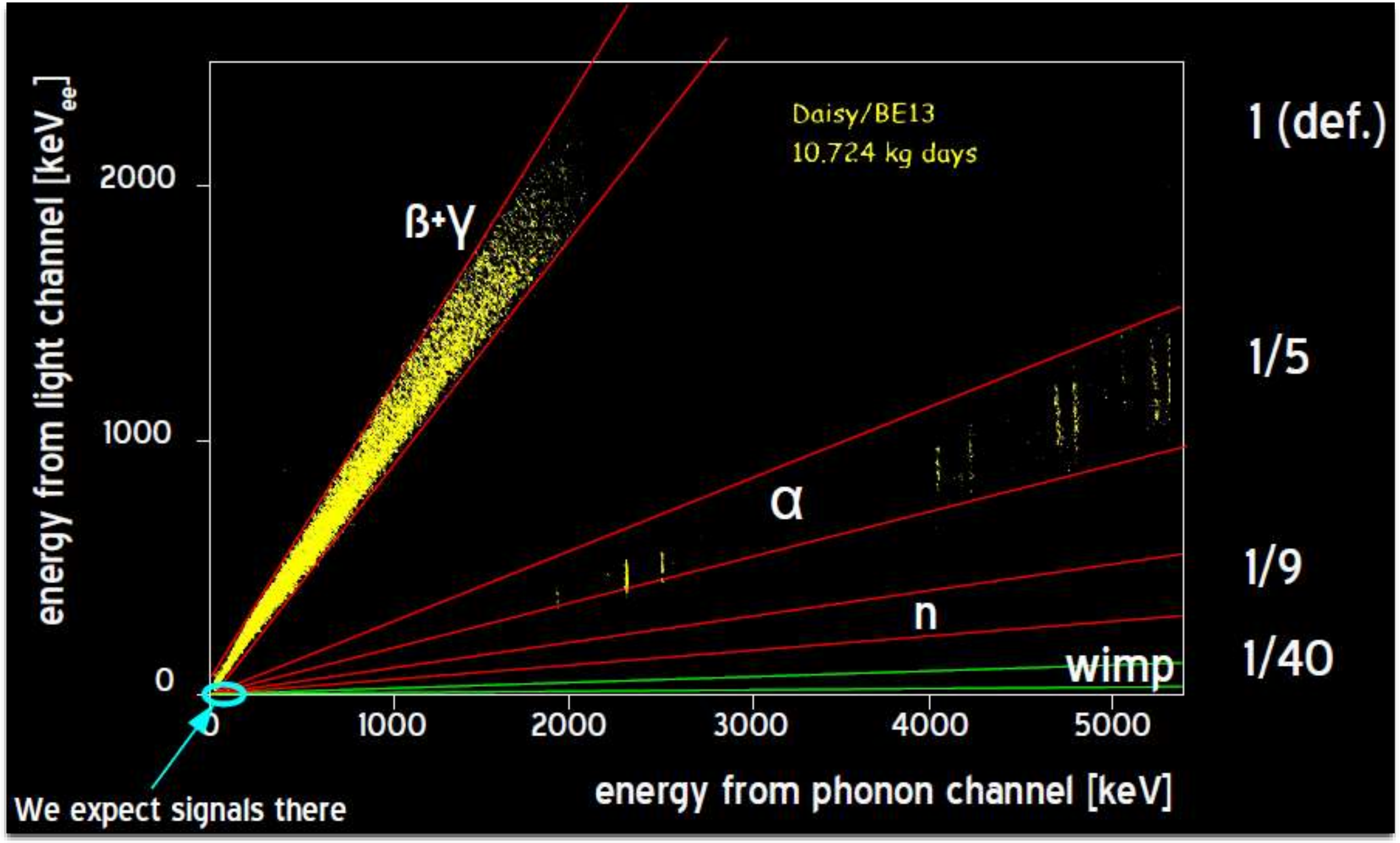
Why Deep Underground?





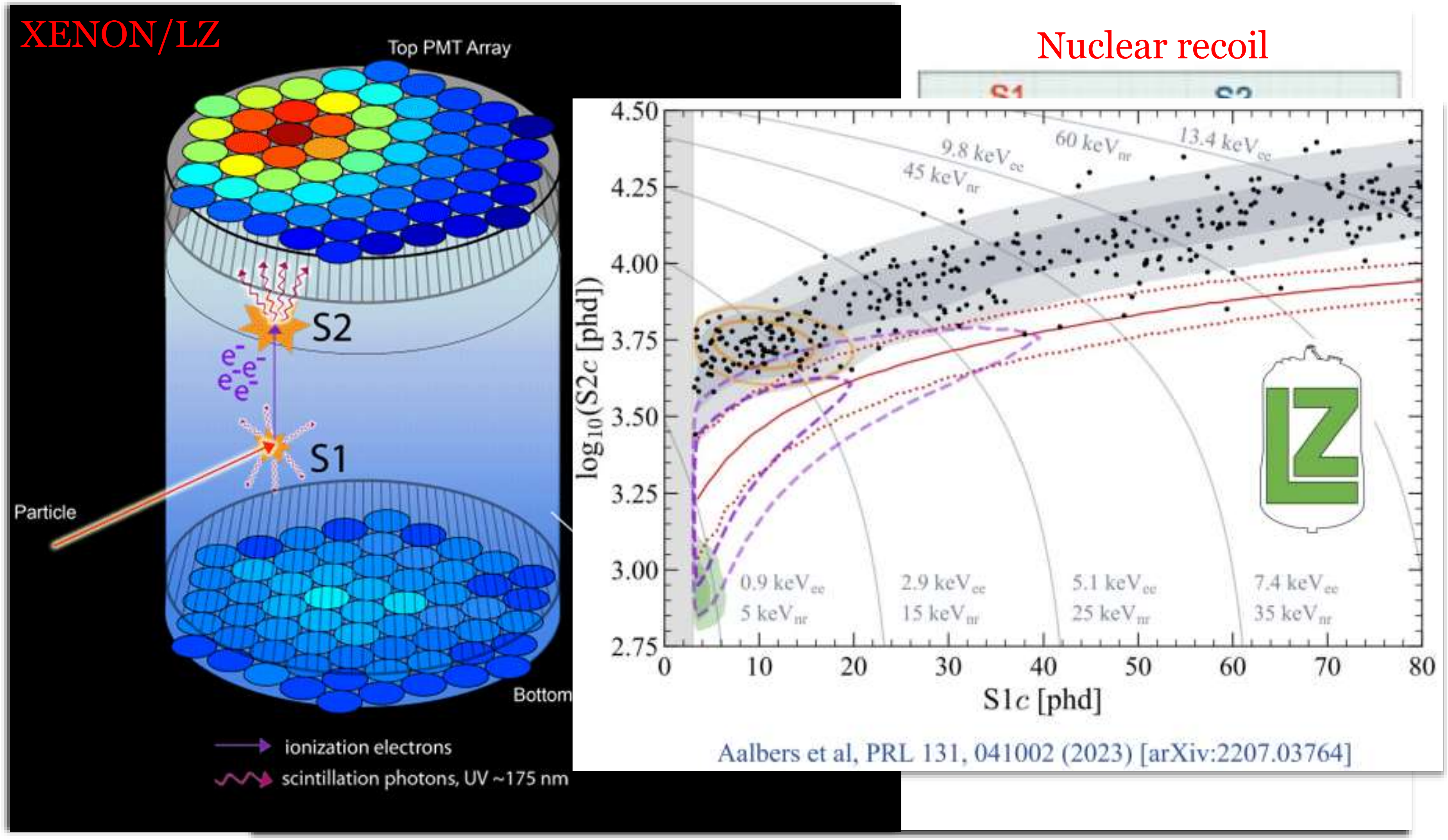


Event Discrimination



G. Deuter, Eurograd Workshop, Sept. 2010

Event Discrimination

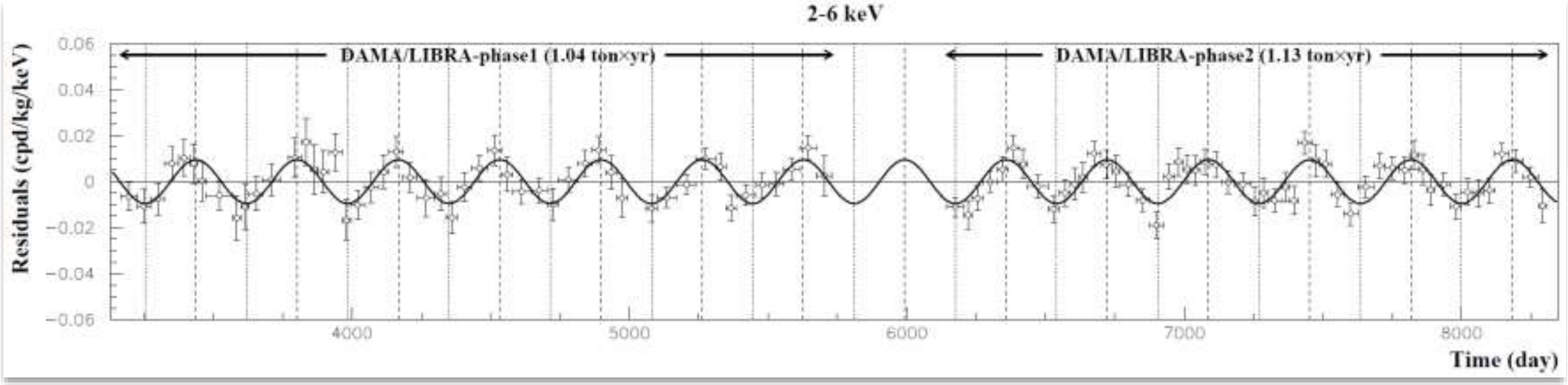


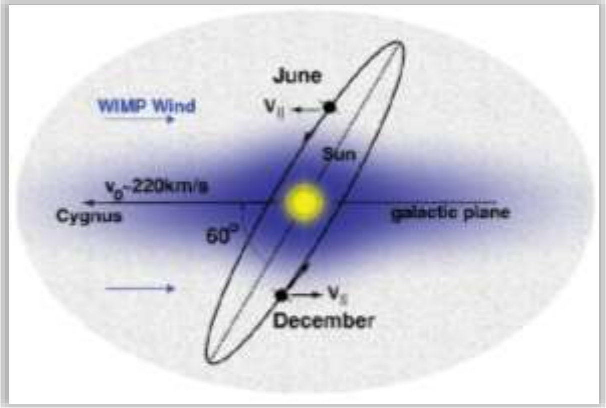
Aalbers et al, PRL 131, 041002 (2023) [arXiv:2207.03764]

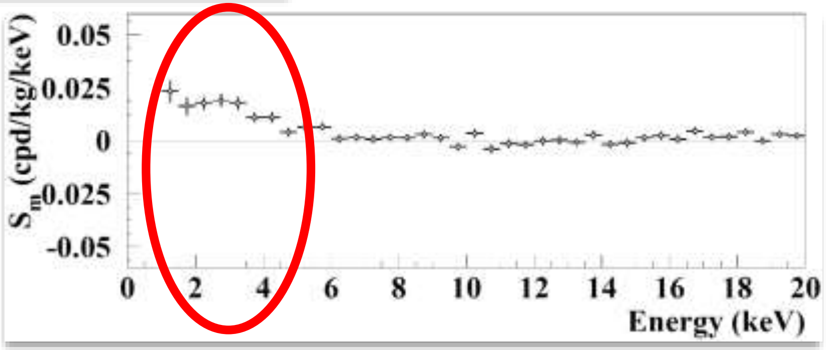
Annual Modulation

DAMA [arXiv: 1805.10486]

- As the Earth orbits the Sun, υ of the detector relative to the DM halo varies.
- DAMA has detected an annual modulation in the event rate (12.9 σ significance).
- 14 annual cycles, modulation amplitude: 0.0103 ± 0.0008 in the (2-6) keV
- Phase: 145 ± 5 days (cf. June 2nd), Period: 0.999 ± 0.001 yr



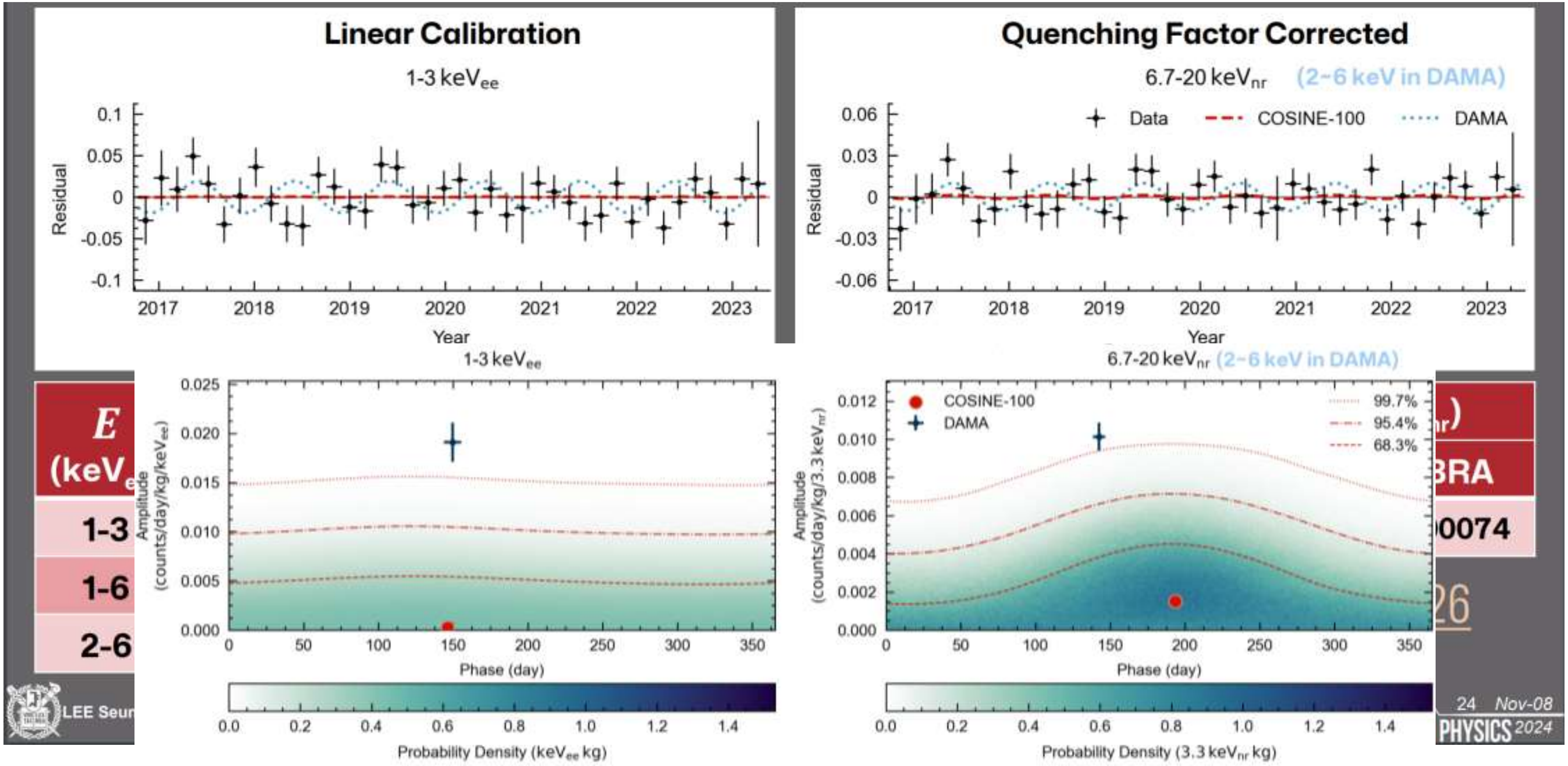




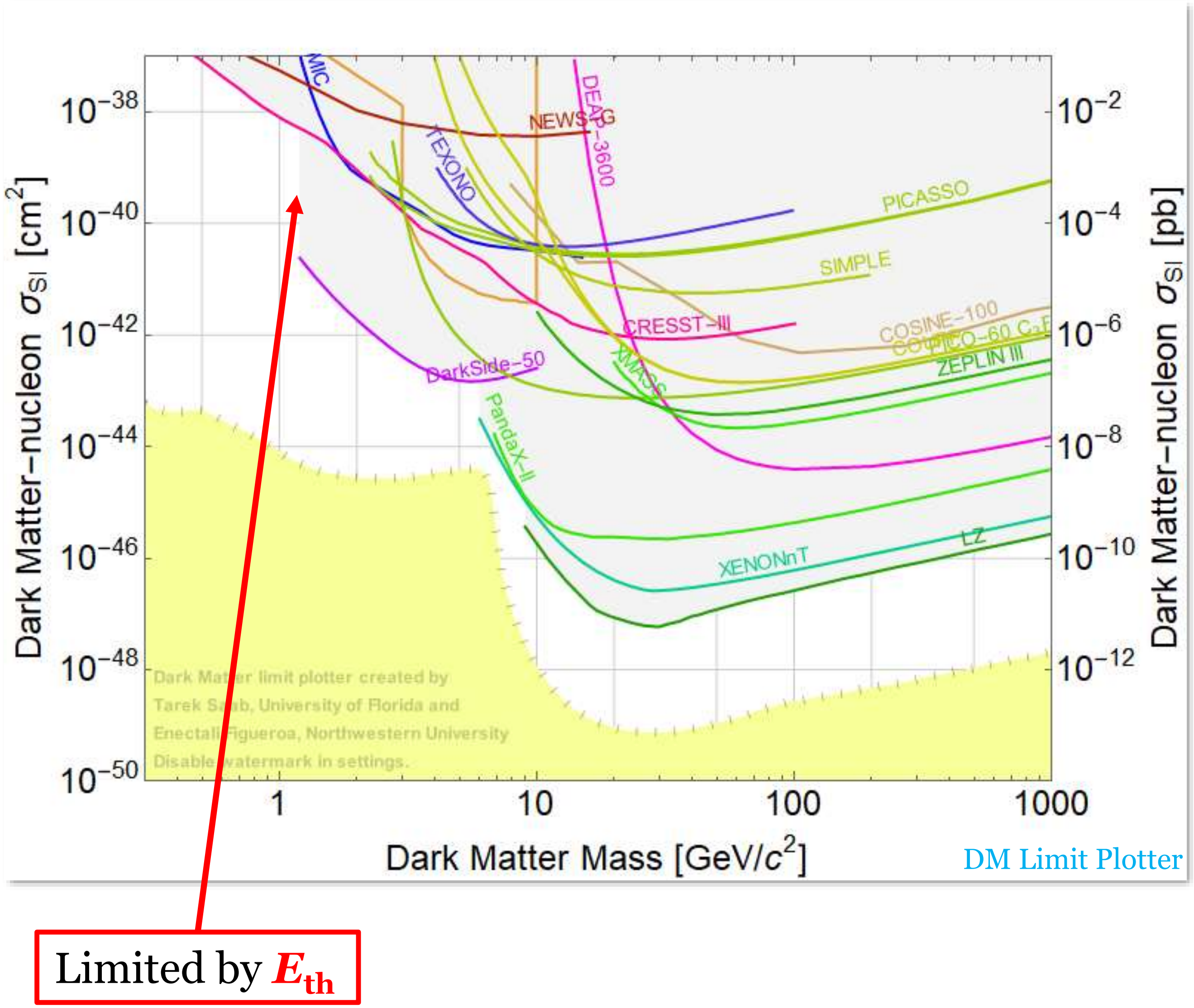
Current Status of Annual Modulation

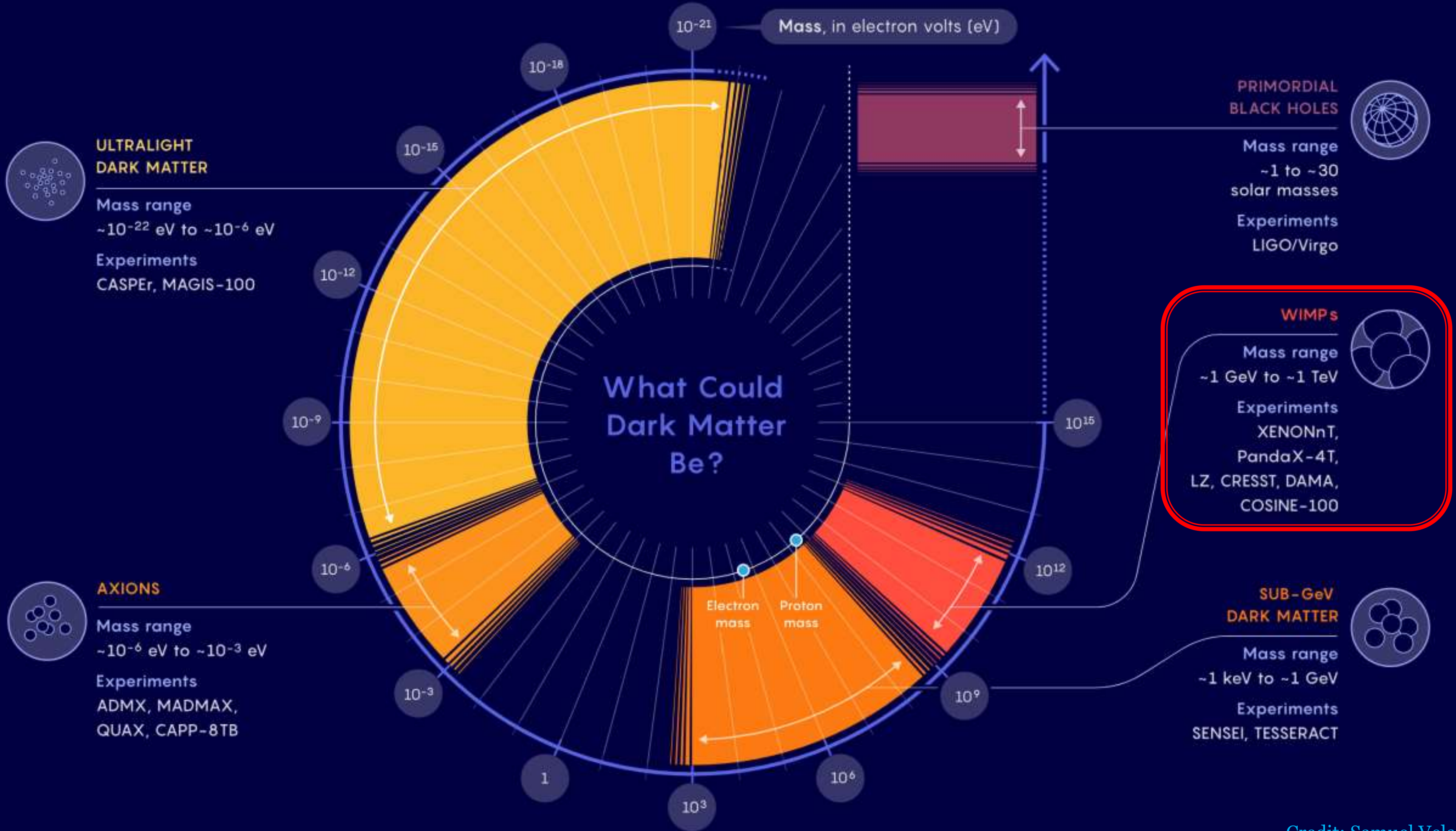
COSINE-100 [arXiv: 2409.13226]

- COSINE-100 w/ 106 kg NaI & 6.4 years: No annual modulation signal



Current Status of DM Direct Detection: Elastic





Credit: Samuel Velasco

Something
New ?

New Technologies for Light Dark Matter

Light DM (LDM) Direct Detection

1. **Energy threshold**
   - ✓ Need lower E thresholds (eV-scale or less)
   - ✓ R&D to push towards meV-scale E thresholds
   - ✓ **Electron** is preferred as a target.

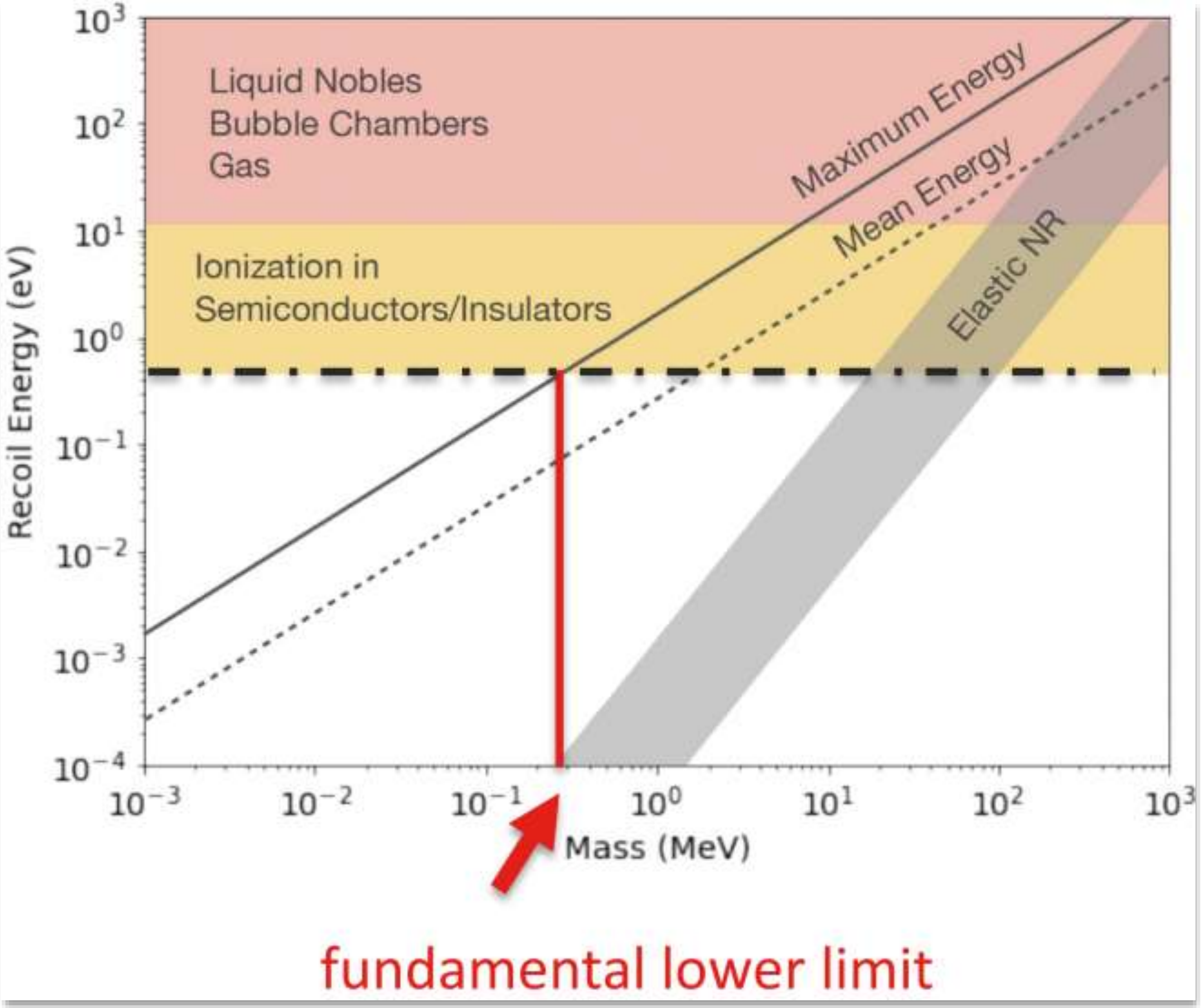
$$v_{\min}(E_{\mathrm{R}}) \equiv \sqrt{\frac{m_T E_{\mathrm{R}}}{2\mu_T^2}} = \frac{q}{2\mu_T}$$

2. **Exposure (target mass + runtime)**
   - ✓ Not as important as for WIMP searches

$$\Phi_\chi = n_\chi v_{\mathrm{rel}} = \frac{\rho_\chi}{m_\chi} v_{\mathrm{rel}}$$

3. **Backgrounds**
   - ✓ Complicated, non-radiogenic backgrounds at lower energies

Light DM (LDM) Direct Detection

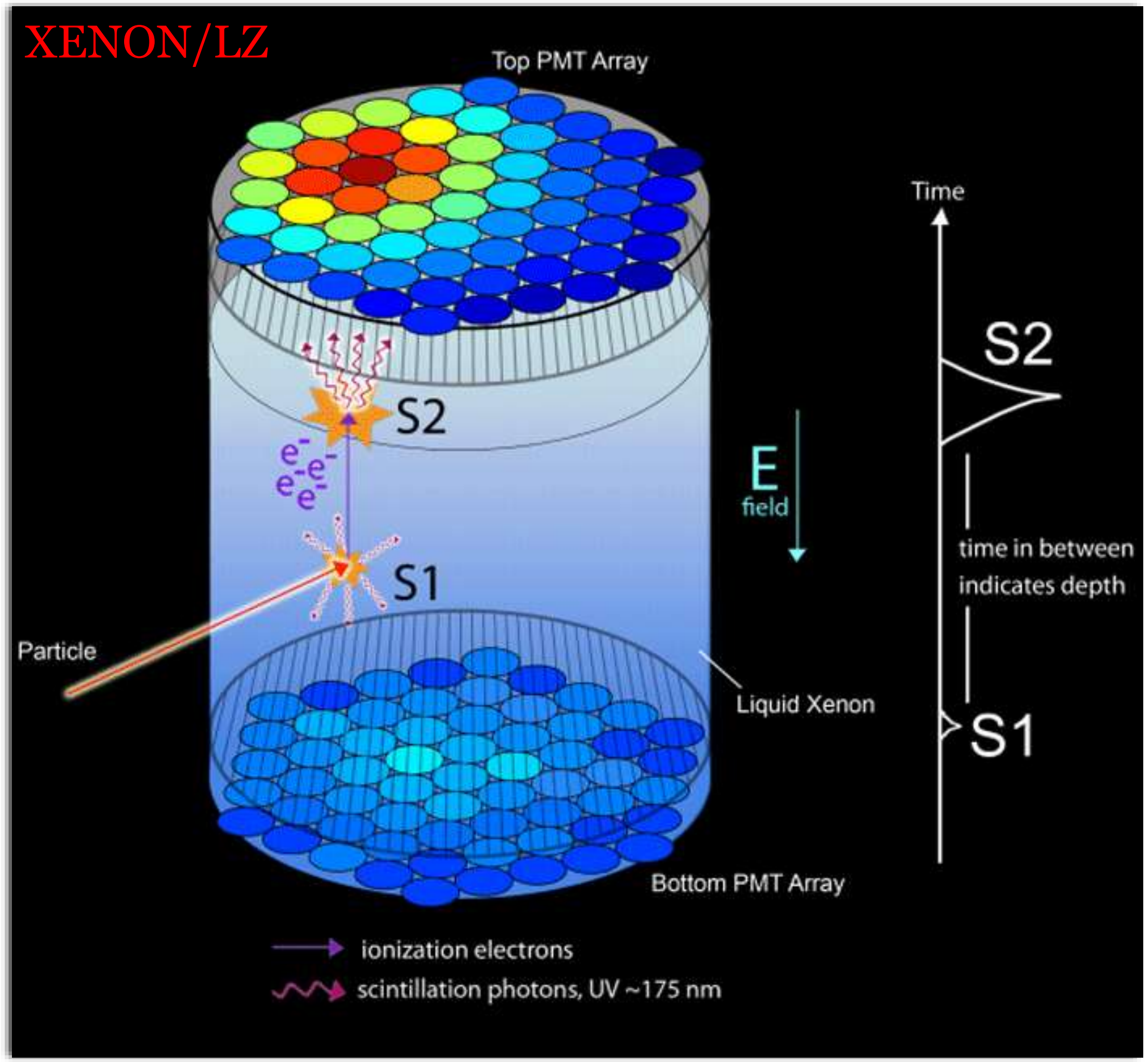


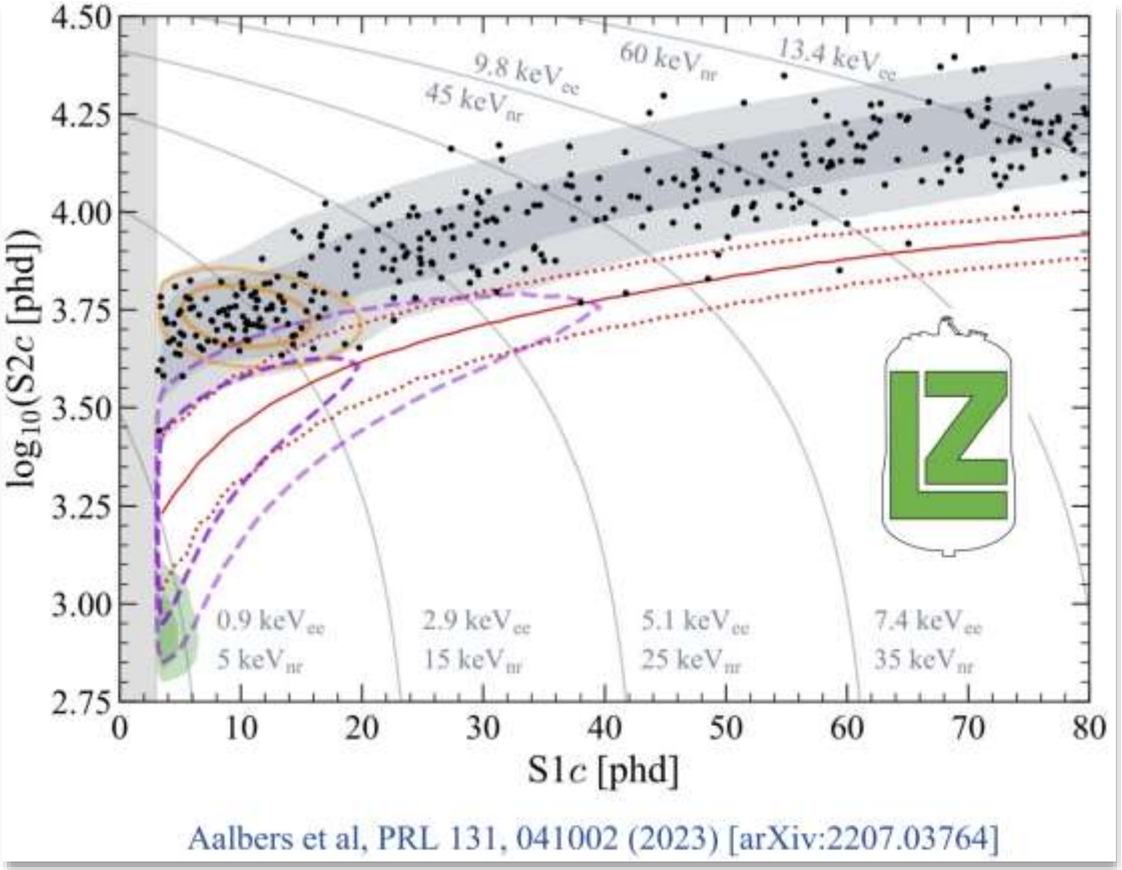
Daniel Baxter, IDM 2024

❖ **Detectors searching for ionization**

- ✓ S2-only searches in TPCs: XENON, DarkSide-50
- ✓ CCD: DAMIC, SENSEI
- ✓ Neganov–Trofimov Luke (NTL) effect: SuperCDMS-HVeV, EDELWEISS

S2-Only Search

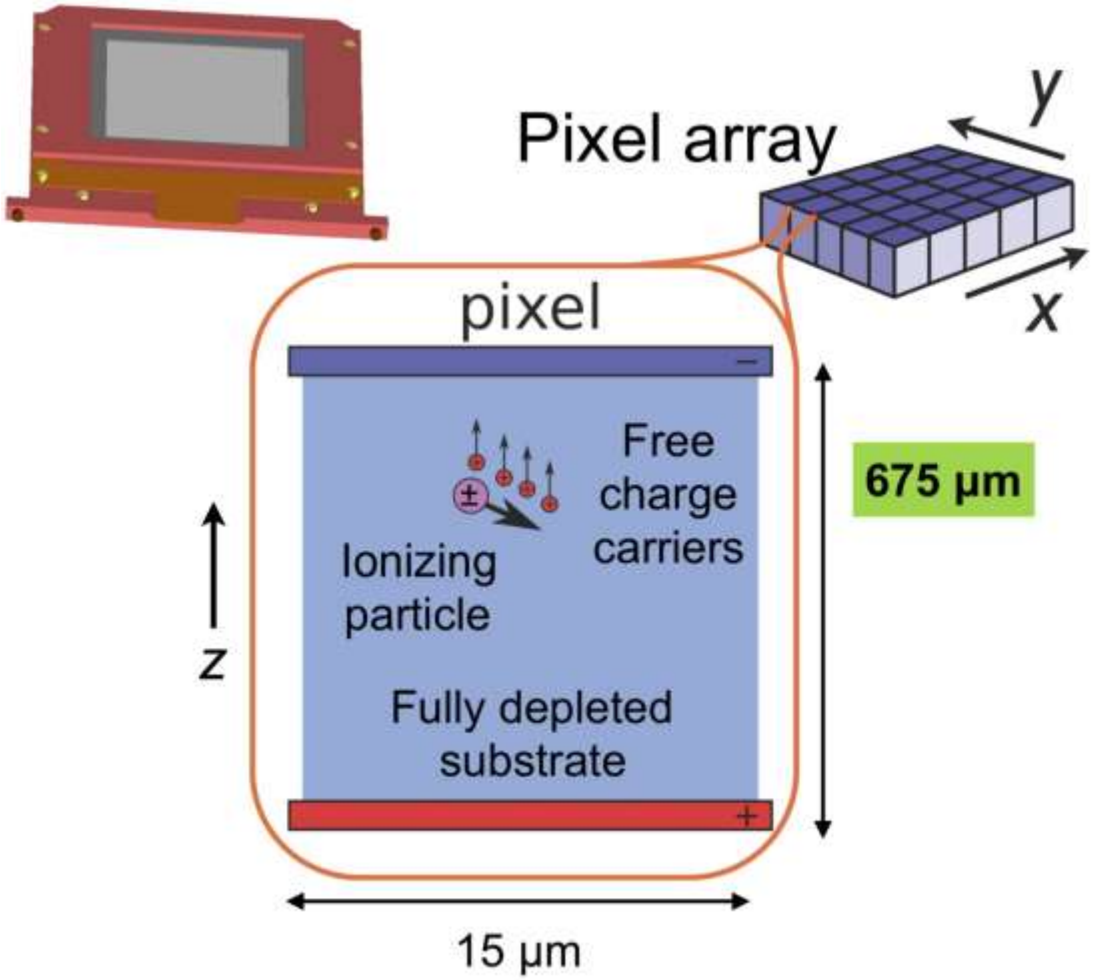




❖ e-recoil → stronger S2 ➔ Massive exposure, but large unmodeled dark rate (no discrimination)

CCD

Daniel Baxter, IDM 2024



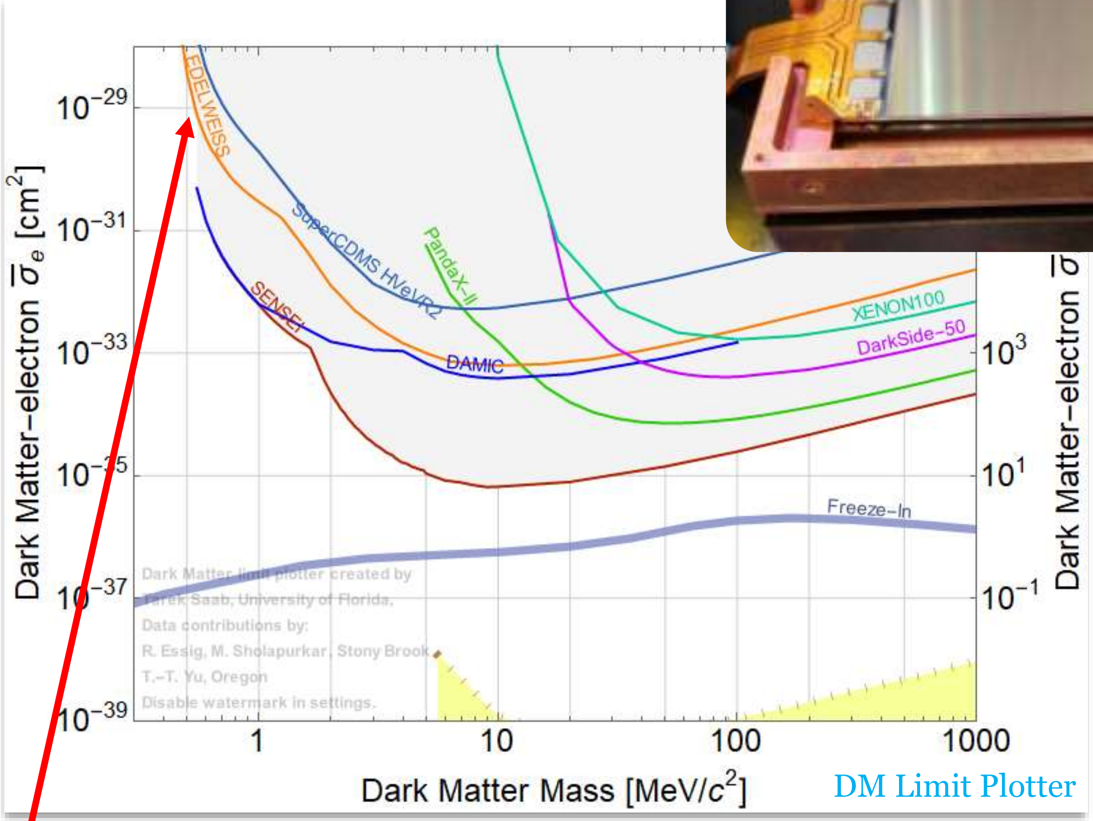
Interaction with silicon produces free charge carriers…

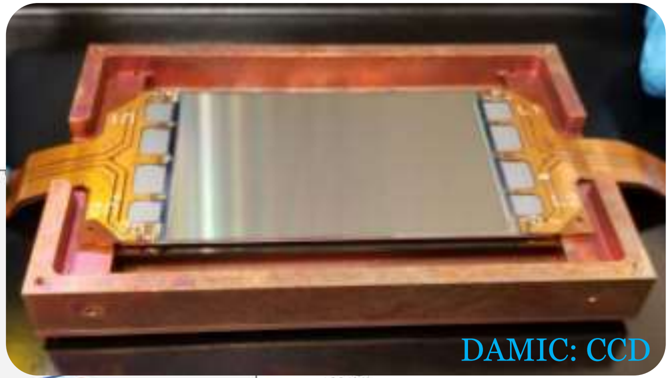
- …which are drifted across fully-depleted region…
  - *no loss of charge*
- …and collected in 15 micron square pixels…
  - *exceptional position resolution*
- …to be stored until a user-defined readout time after many hours.
  - *large exposures*

Pros: low dark rates, few eV threshold, 10 micron position resolution, 1-10 dru backgrounds

Cons: silicon target only, lack of timing, no discrimination below 10 keV

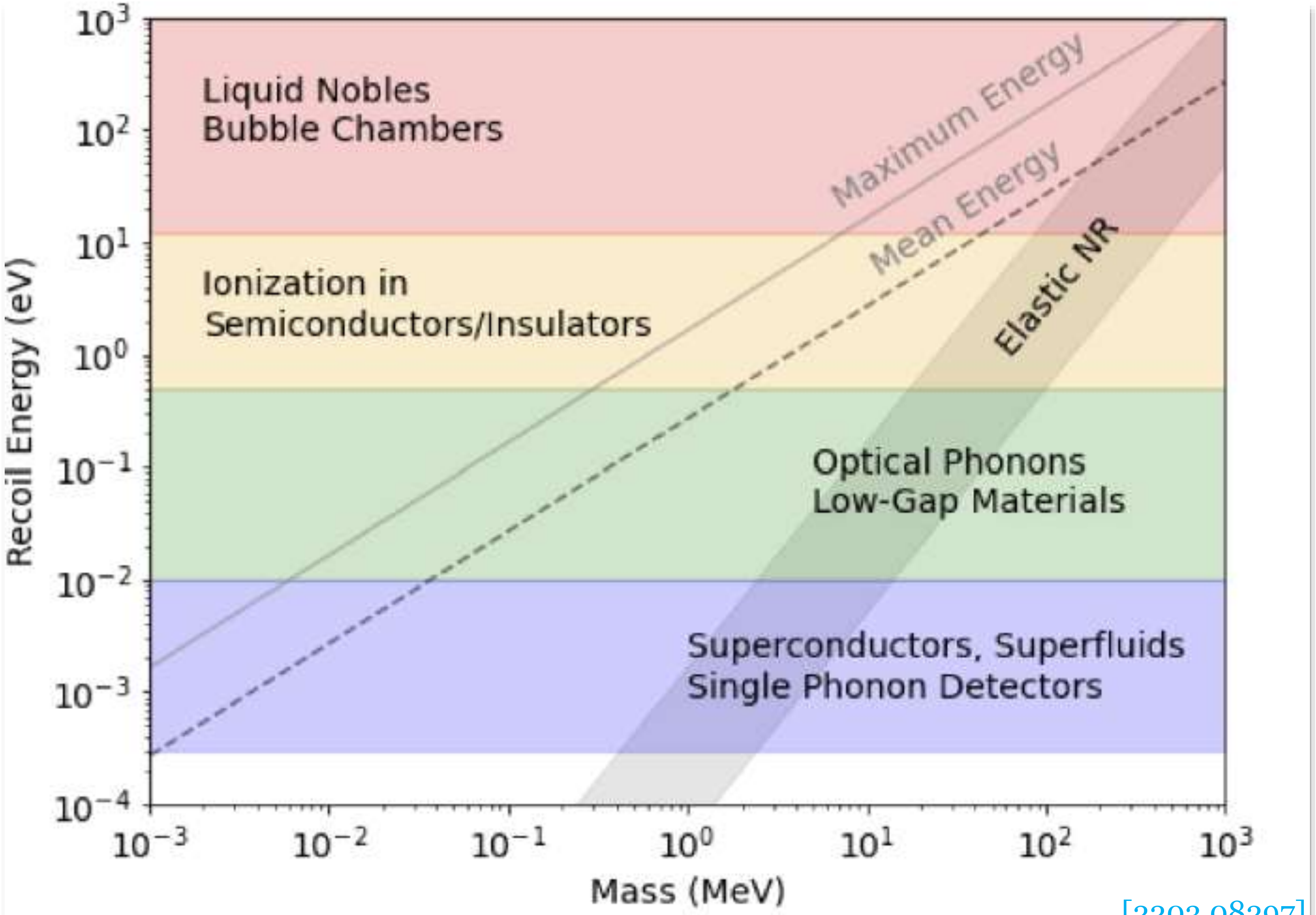
Current Status of Light DM Direct Detection





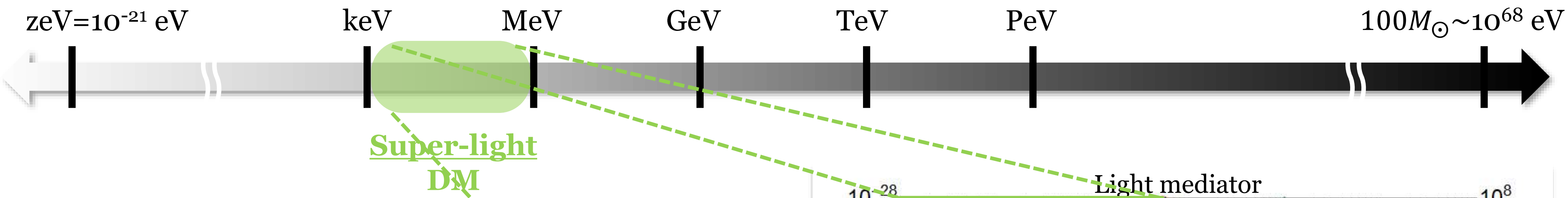
Limited by E_{th}

Super-Light DM Direct Detection



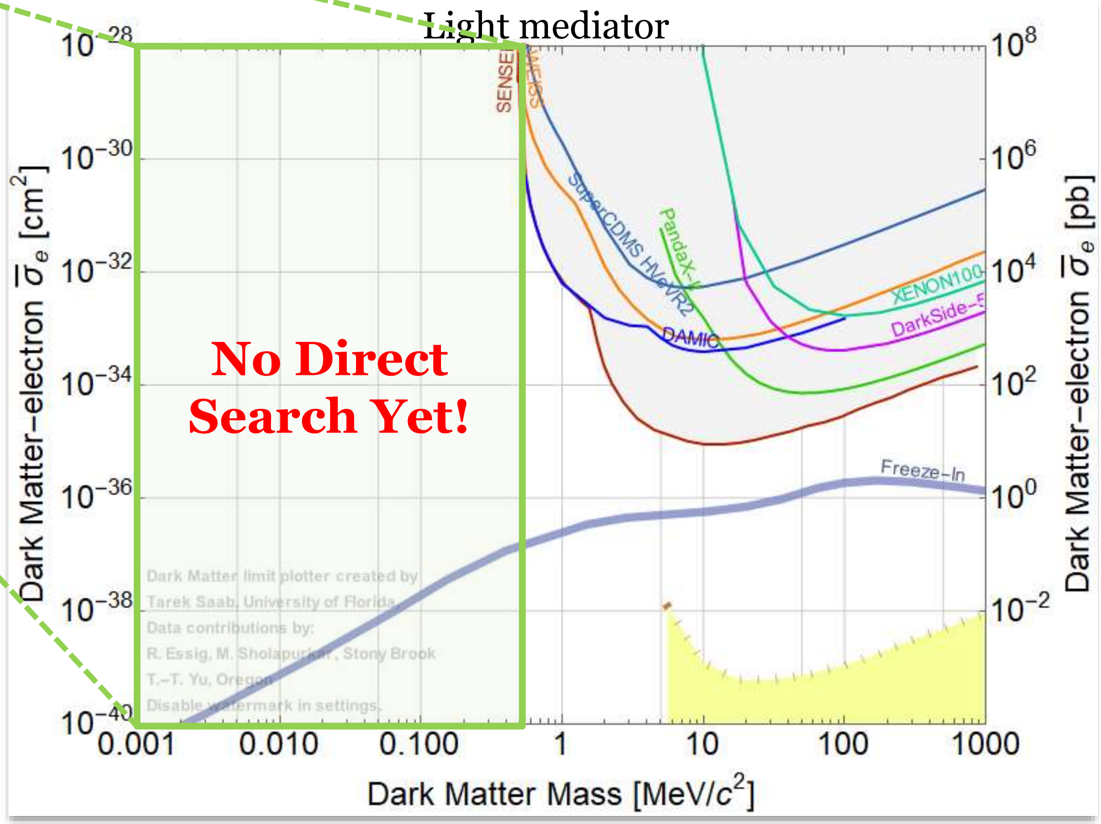
[2203.08297]

Super-Light DM Direct Search



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

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



Dark Matter Limit Plotter

Super-Light DM Direct Search Status

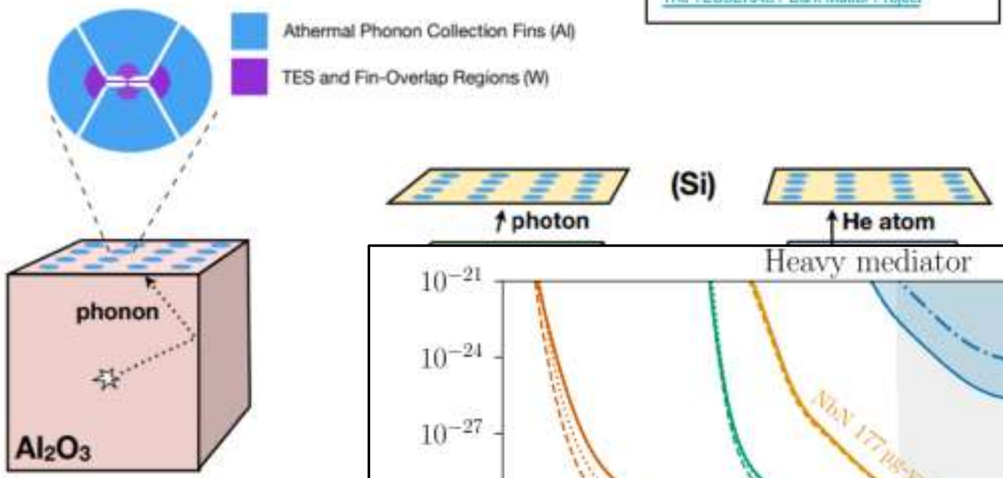
The TESSERACT project (part of the DMNI suite)

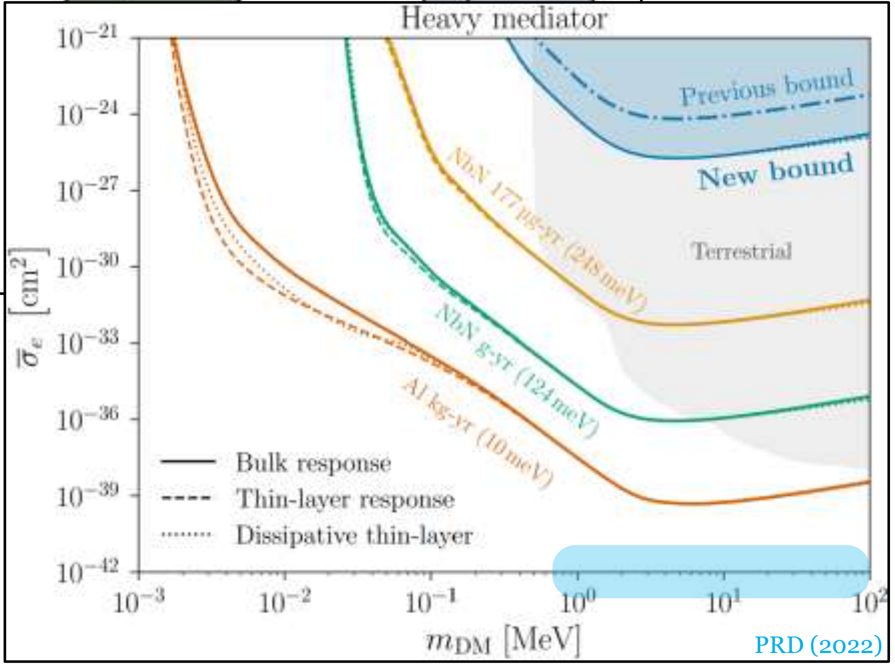
TESSERACT

Transition Edge Sensors with Sub-Ev Resolution And Cryogenic Targets

- Managed by LBNL
- Funding for R&D and project development began in June 2020.
- One experimental design, and different target materials with complementary DM sensitivity. Zero E-field.
- All using TES readout
- ~40 people from 8 institutions
- Includes SPICE (polar crystals) and HeRALD (superfluid helium).

Snowmass2021 - Letter of Interest
The TESSERACT Dark Matter Project

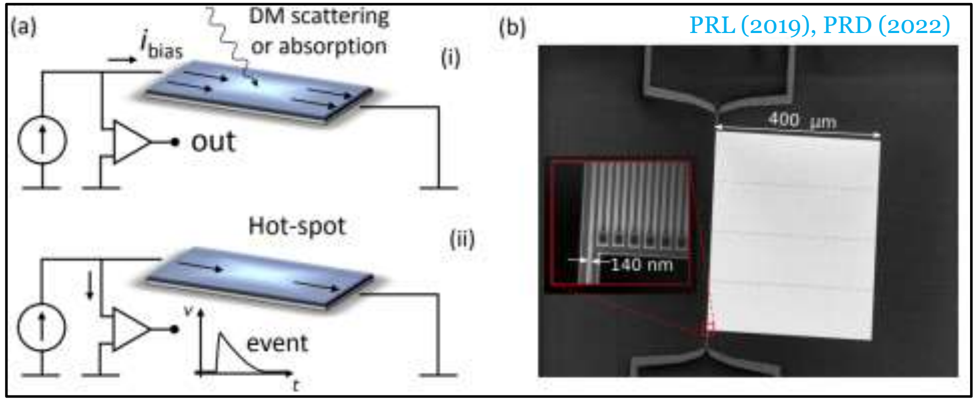




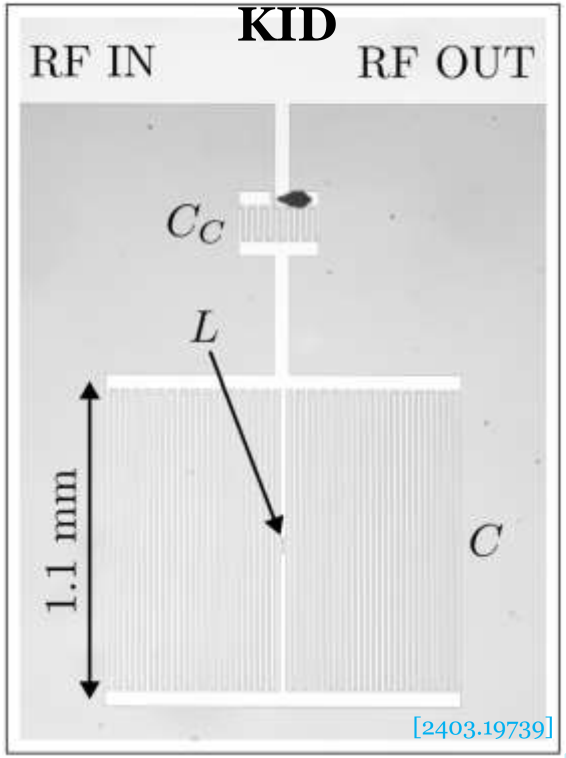
PRD (2022)

SNSPD

PRL (2019), PRD (2022)



KID



[2403.19739]

DM-Electron Scattering

1. **Single atom liquid/gas**

   - ✓ Noble gas
   - ✓ Electron binding E of the target atom: ionization E

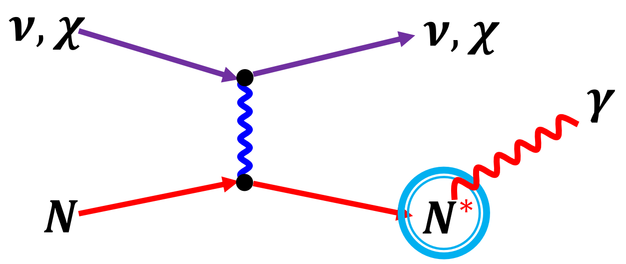
2. **Solid**

   - ✓ Single atom: Ge, Si, C
   - ✓ Composite: GaAs, NaI, Al_2O_3
   - ✓ Electron band structure

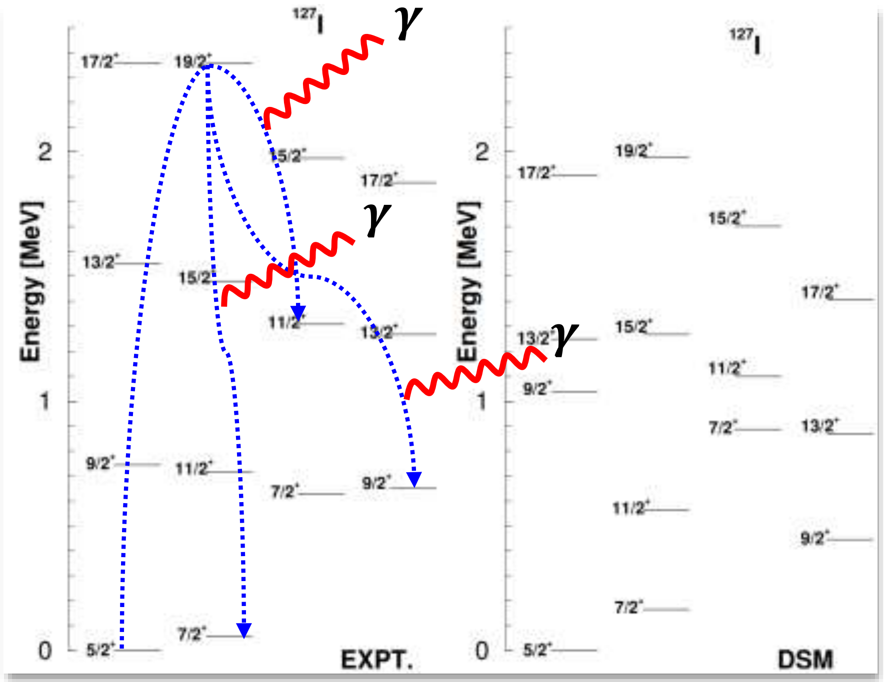

Other
Ideas?

Inelastic Nuclear Scattering

❖ Why **inelastic** channel?



$E_{in} \lesssim 50$ MeV

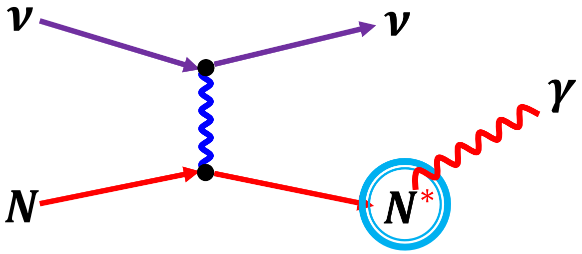


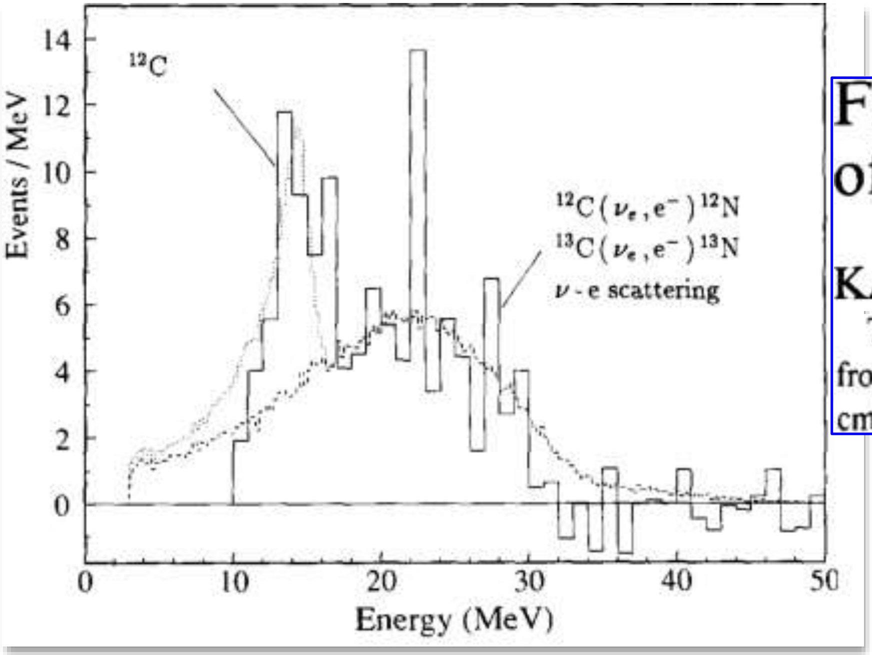
Sahu et al., [2004.04055]

- ➢ Signatures
  - ✓ **Elastic**: low energy nuclear recoil
  - ✓ **Inelastic**: γ cascade ($\Delta E \lesssim 10$ MeV), γ cascade + nucleons ($\Delta E \gtrsim 10$ MeV)
- ➢ Motivation
  - ✓ A new channel to study
  - ✓ Larger energy $\sim O(1-10)$ MeV
  - ✓ Better S/B ratio

*In*elastic Nuclear Scattering: Neutrino

❖ **Inelastic ν-Nucleus Scattering (IνNS)**





TESTING THE STRUCTURE OF WEAK NEUTRAL CURRENTS BY INELASTIC NEUTRINO SCATTERING FROM NUCLEI*

T.W. DONNELLY* and R.D. PECCEI

Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305

Received 13 June 1976
Revised manuscript received 17 September 1976

By using selected nuclear transitions specific pieces of the weak neutral current may be greatly enhanced, leading to widely different results for different models of the weak neutral current. Predictions for low-energy inelastic neutrino scattering from ^{12}C are examined within the framework of a variety of $SU(2)_W \times U(1)$ gauge theory models.

PLB (1976)

First observation of the neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ $(1^+, 1)$

KARMEN Collaboration

PLB (1991)

The neutral current nuclear excitation $^{12}C(\nu, \nu')^{12}C^*$ $(1^+, 1; 15.1$ MeV$)$ has been observed for the first time. For ν_e and $\bar{\nu}_\mu$ from μ^+-decay at rest the flux averaged cross section was determined to be $\langle \sigma_{NC}(\nu_e + \bar{\nu}_\mu) \rangle = [10.8 \pm 5.1(stat.) \pm 1.1(syst.)] \times 10^{-42}$ cm^2.

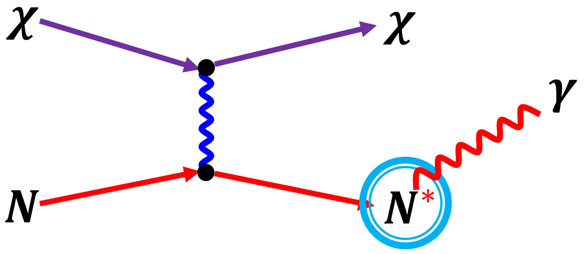
➢ Recent improvements

Dutta, Newstead et al., [2206.08590]

- ✓ Inclusion of multiple excited states
- ✓ Consistent handling of hadronic currents
- ✓ Exclusive cross sections for each state

Inelastic Nuclear Scattering: DM @ Direct Exps.

❖ **Inelastic** DM-Nucleus Scattering



RATES FOR INELASTIC NUCLEAR EXCITATION BY DARK MATTER PARTICLES

John ELLIS [a], R.A. FLORES [a,1] and J.D. LEWIN [b]

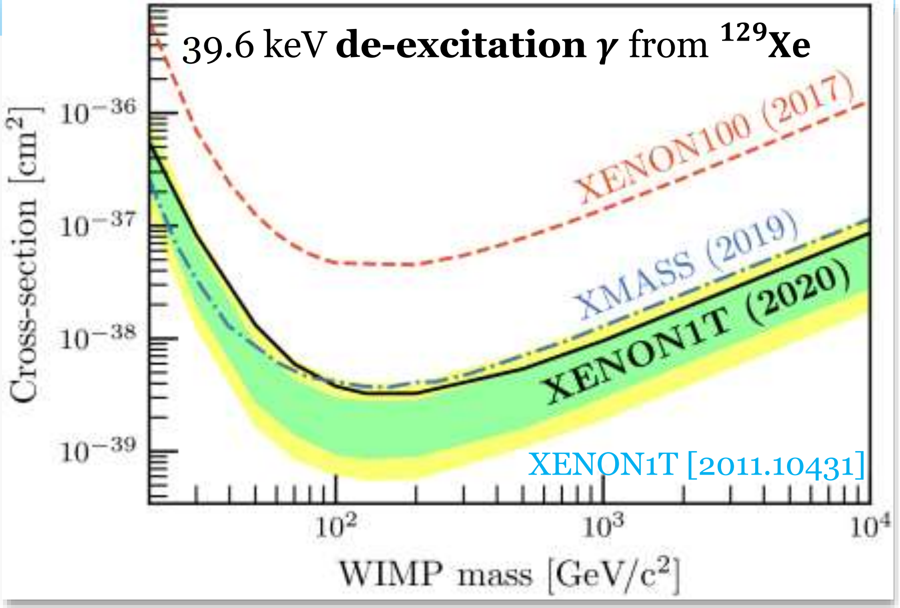
[a] *CERN, CH-1211 Geneva 23, Switzerland*

[b] *Rutherford-Appleton Laboratory, Chilton, Didcot, OX11 0QX, UK*

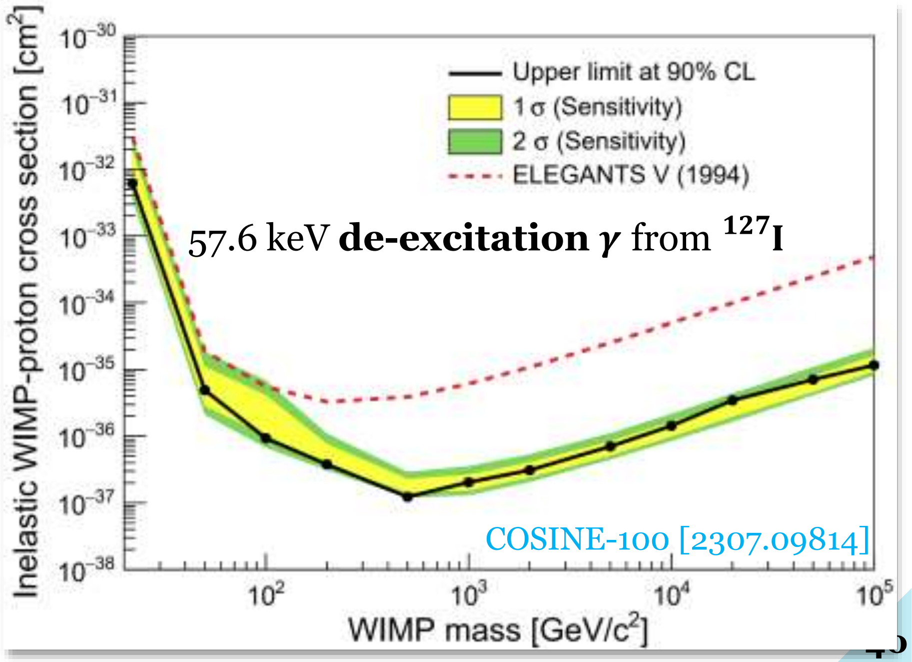
Received 29 June 1988

We calculate rates for the inelastic scattering of dark matter particles X on nuclei to produce low-lying excited nuclear states. Assuming a maxwellian velocity distribution for the dark matter particles X, the inelastic two-body phase space suppresses all rates by factors >10 for $m_X \leqslant 100$ GeV unless the excitation energy $\Delta E < 100$ keV. We catalogue all stable nuclei with excited states in this range, and we estimate inelastic scattering matrix elements by relating them to Ml transitions, after correcting for internal conversions. Our calculated rates are typically $\lesssim 10^{-4}$ events/kg·day, with the least unfavourable rates being for $^{169}_{69}$Tm and $^{187}_{75}$Os. Problems of natural radioactivity and expense disfavour these and many other materials, leaving $^{127}_{53}$I, $^{183}_{74}$W and $^{201}_{80}$Hg as the least unpromising isotopes.

PLB (1988)



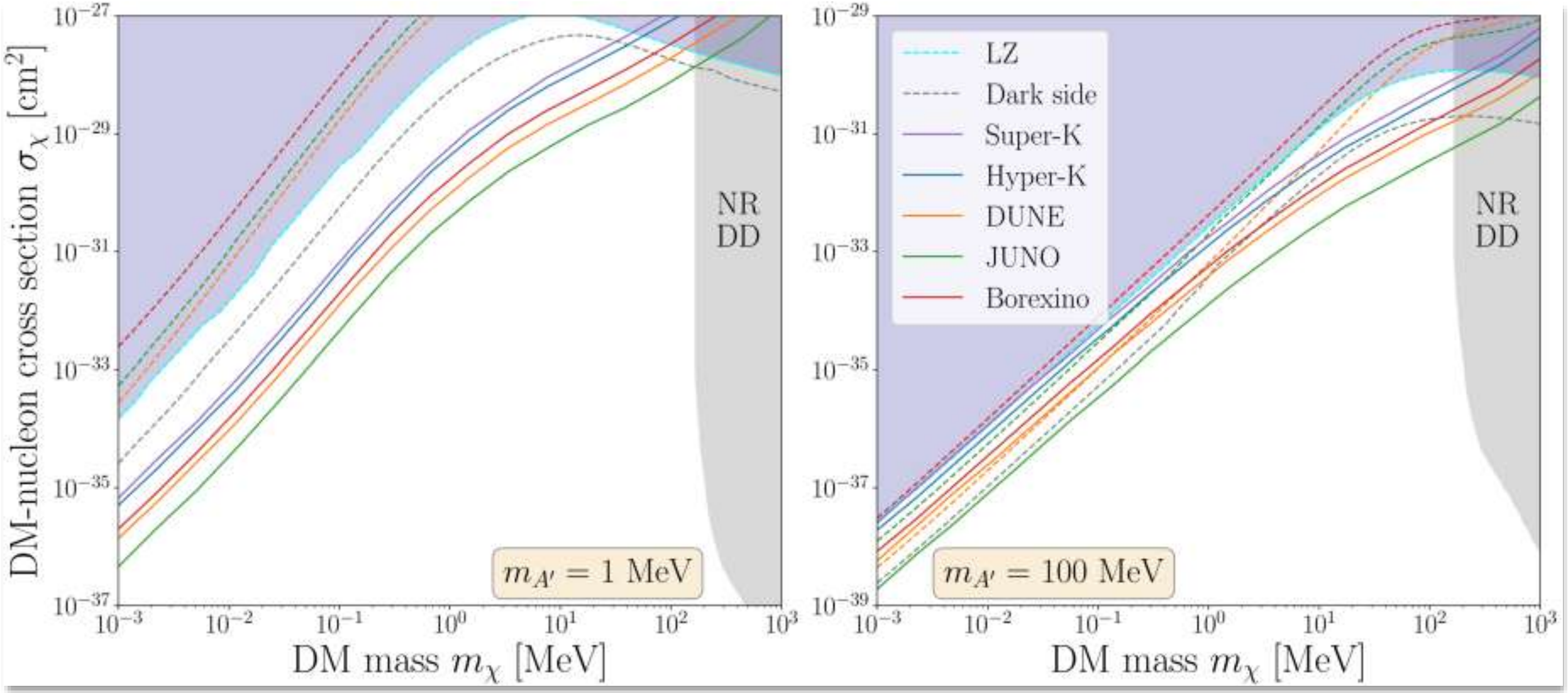
XENON1T [2011.10431]



COSINE-100 [2307.09814]

*In*elastic Nuclear Scattering: DM @ ν Exps.

B. Dutta, W.C. Huang, D. Kim, J. Newstead, **JCP**, I. Shaukat Ali
PRL (2024)

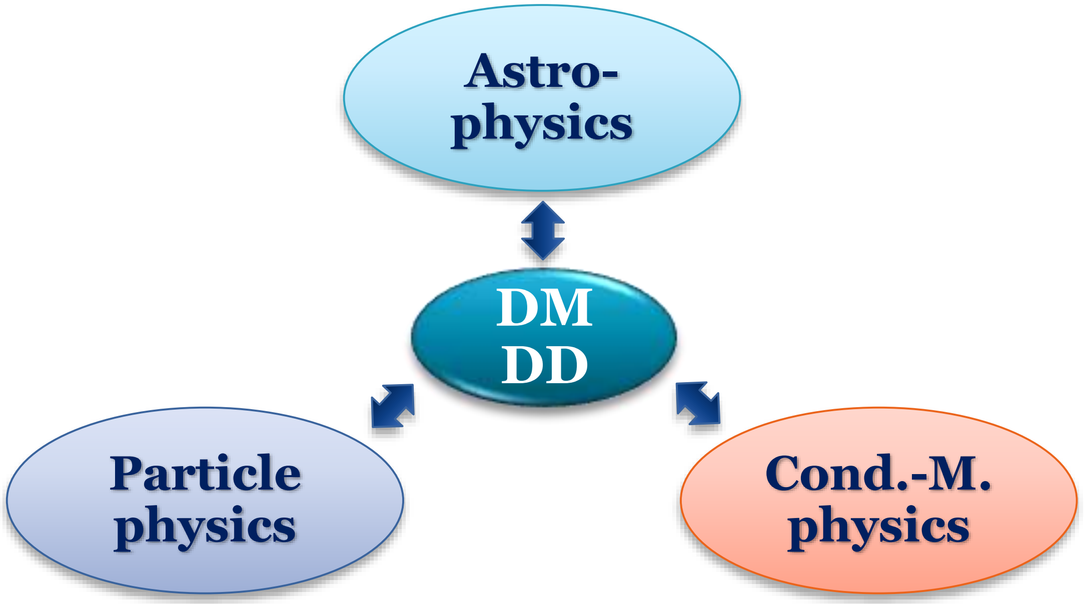


❖ Inelastic (solid) better than elastic (dashed)

❖ LZ - nuclear recoil data; others - projected/attainable; NR DD (gray) - standard direct detection

Summary

- DM: a clear sign of new physics (particle) beyond the Standard Model
- DM wind ➔ Searching for scattering between DM & SM particles
- So far most of Exps. focusing on WIMP, but no firm positive result yet
- New approaches (especially for light DM) by adapting new ideas & technologies



ありがとう

Thank you

감사합니다

Supplemental

GLIMPSE

Graphene-based Light Invisible Matter Particle SEarch

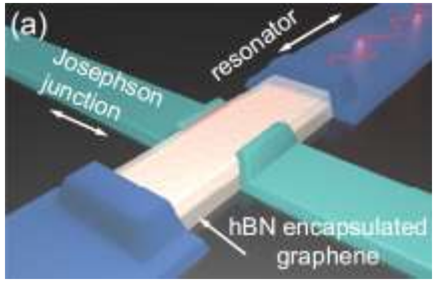
[Kim, **JCP**, Lee, Fong, 2002.07821 & in progress]

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

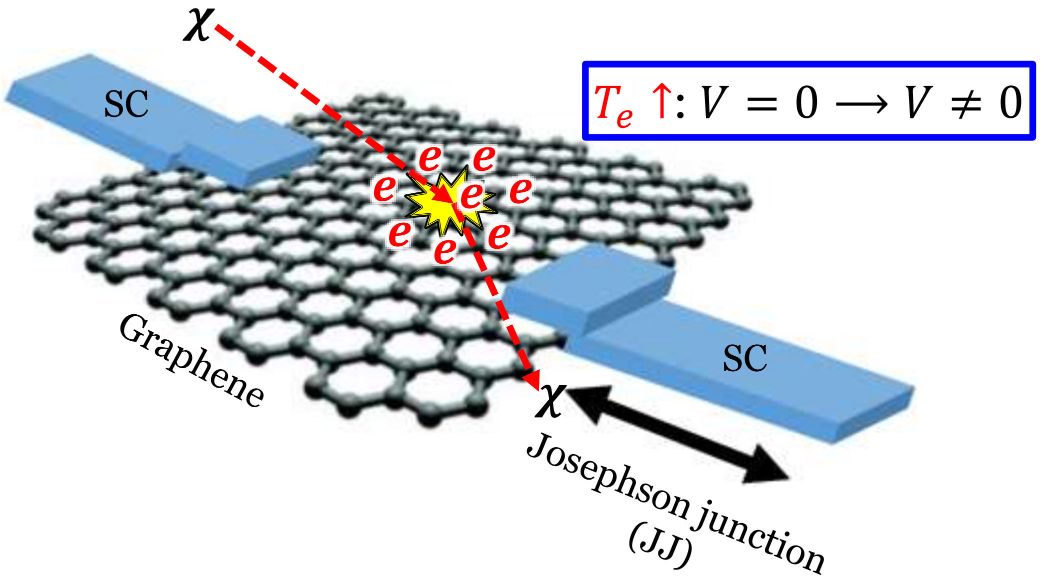
Our Super-light DM Search Strategy with GJJ

- **GJJ microwave bolometer**



- ✓ Achieved fundamental limit of sensitivity: NEP= 0.7 aW/Hz$^{1/2}$
- ✓ Corresponding Energy Threshold: ΔE=0.1 meV

[G.-H.Lee, D.K.E., W.C.Jung *et al.*, Nature (2020)]



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

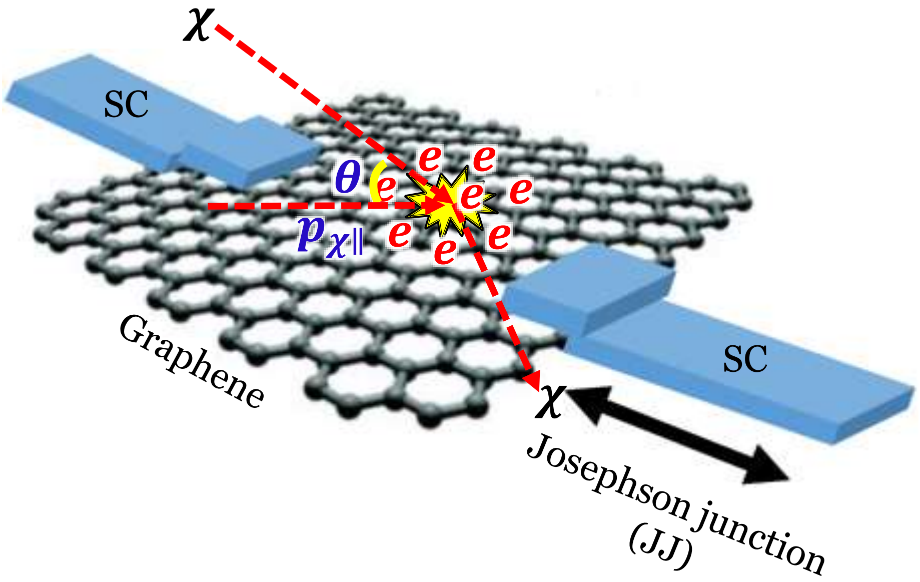
II. **The recoiling e heats up & thermalizes** with nearby e's rapidly via e-e interactions.

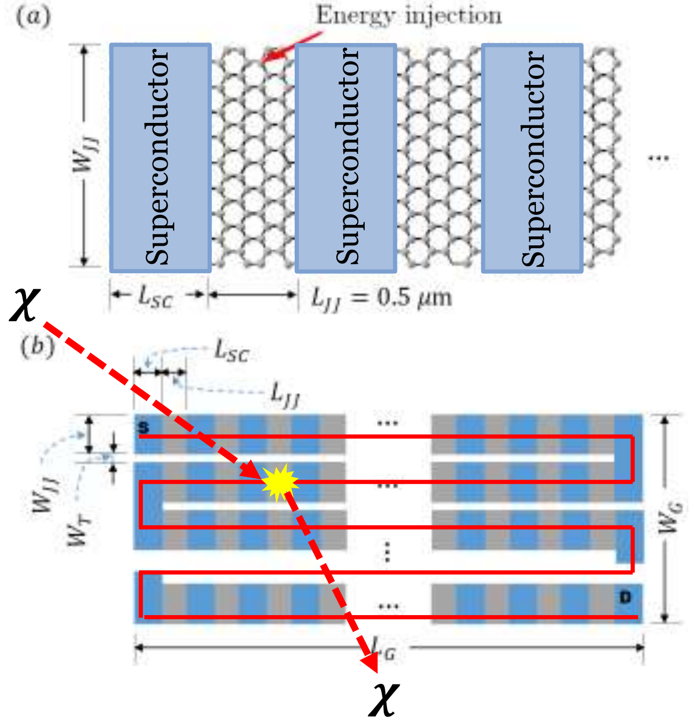
III. **The JJ is triggered**: the temperature rise switches the zero-voltage (non-resistive) of JJ to a **non-zero-voltage (resistive) state**.

- $E_k \sim mv^2 \sim 1$ meV for $m_{DM} = 1$ keV

➔ **GJJ detector: sensitivity** to the signal even by **sub-keV DM**.

Our Super-light DM Search Strategy with GJJ





- ✓ **Scattering**: DM traveling in 3D & electrons living in 3D but confined in 2D graphene layer.

  ➔ **Constrained elastic scattering**!

- ✓ **Prediction**: angular dependence of the signal rate ➔ applicable to background rejection.

- ✓ **2D detector unit**: a single switched GJJ by DM interaction allows the series resistance.