IceCube at the frontier of macroscopic dark matter direct detection

Mrunal Korwar

University of Wisconsin-Madison

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UCSC

Based on work with Yang Bai, and Joshua Berger
(arxiv: 2206.07928)

Macroscopic Dark Matter

- A composite of many constituent particles and fields. Mass could be larger than Planck scale.

- Models and Formation:

I. Dark confining, EM, or Yukawa force to form dark nuclei and their bound state. Could have formed via dark nucleosynthesis.

(Gresham et al.'17,18, Krnjaic et al.'14, Hardy et al.'15, Redi et al.'21)

II. Solitons and Q-ball state formed from balance of forces and stabilized by conserved symmetries. Formation via Phase Transition "Solitogenesis"
eg:- Monopoles, Fermi Balls, dark dwarfs

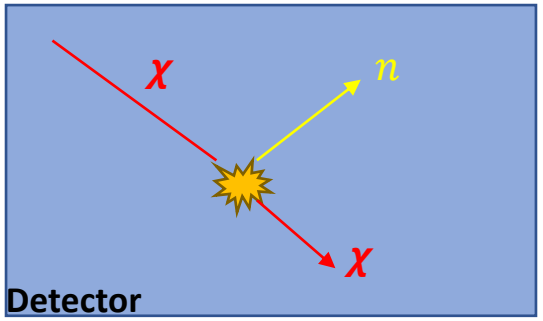
(Lee et al.'76, Coleman'85, Grabowska'18, Frieman'88, Bai et al.'18, Gross et al.'21, Hong et al.' 20)

III. Black holes including Primordial BH, magnetic black holes. Could form via gravitational collapse.

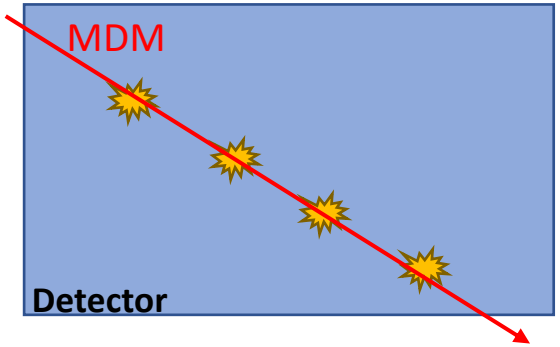
(Carr et al.'20, Bai et al. 20)

MDM Direct Searches

- Flux for 1 gram MDM $\mathcal{O}(1)\,\mathrm{events\,km^{-2}\,yr^{-1}}$
- Paleo-detection: use old rocks (~Gyr old) such as Mica or Quartz to search for dark matter tracks. Can search up to kg mass scale with cross section ~$10^{-17}\,\mathrm{cm}^2$
- Multi-hit signature in detector
- Elastic scattering : deposited energy of 10's of keV per interaction. Low threshold large volume detectors such as Borexino, JUNO could search for MDM by summing over energy of the hits and other track-like signature to pass the trigger.
- Inelastic Scattering: MDM inelastic scattering with nuclei and releasing $\mathcal{O}(1-100)\,\mathrm{MeV}$ is possible.



Single Hit (usual Particle DM)



Multi-hit (MDM)

(Bramante et al.'18, Acevedo et al.'21, Ebadi et al.'21, Bai et al. 22)

Examples of MDM inelastic scattering

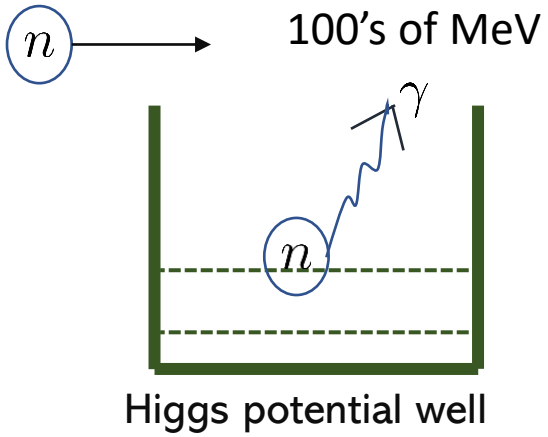
- GUT Monopole: Induced nucleon decay via Callen-Rubakov effect

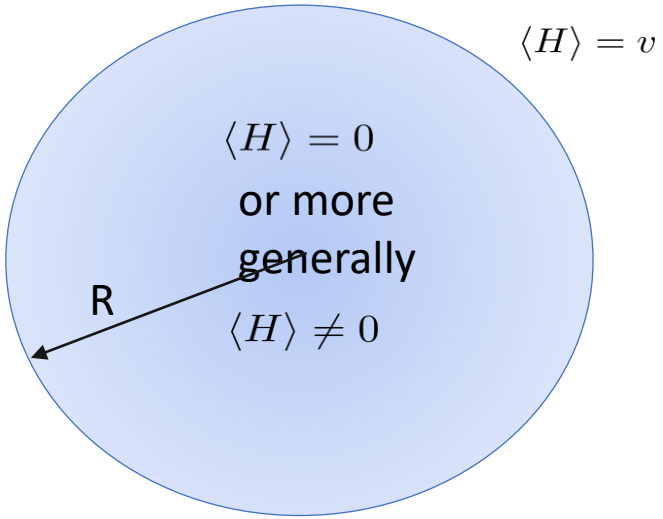
$$\text{monopole} + p \to \text{monopole} + e^+ + \pi^0 + \pi^0$$

(Rubakov'82, Callen'83)

- Electroweak-Symmetric Ball: Dark monopole or scalar Q-ball + Higgs-portal interaction. Produced via Phase transition

(Pontón et al.'19, Bai, **MK**, Orlofsky'20)





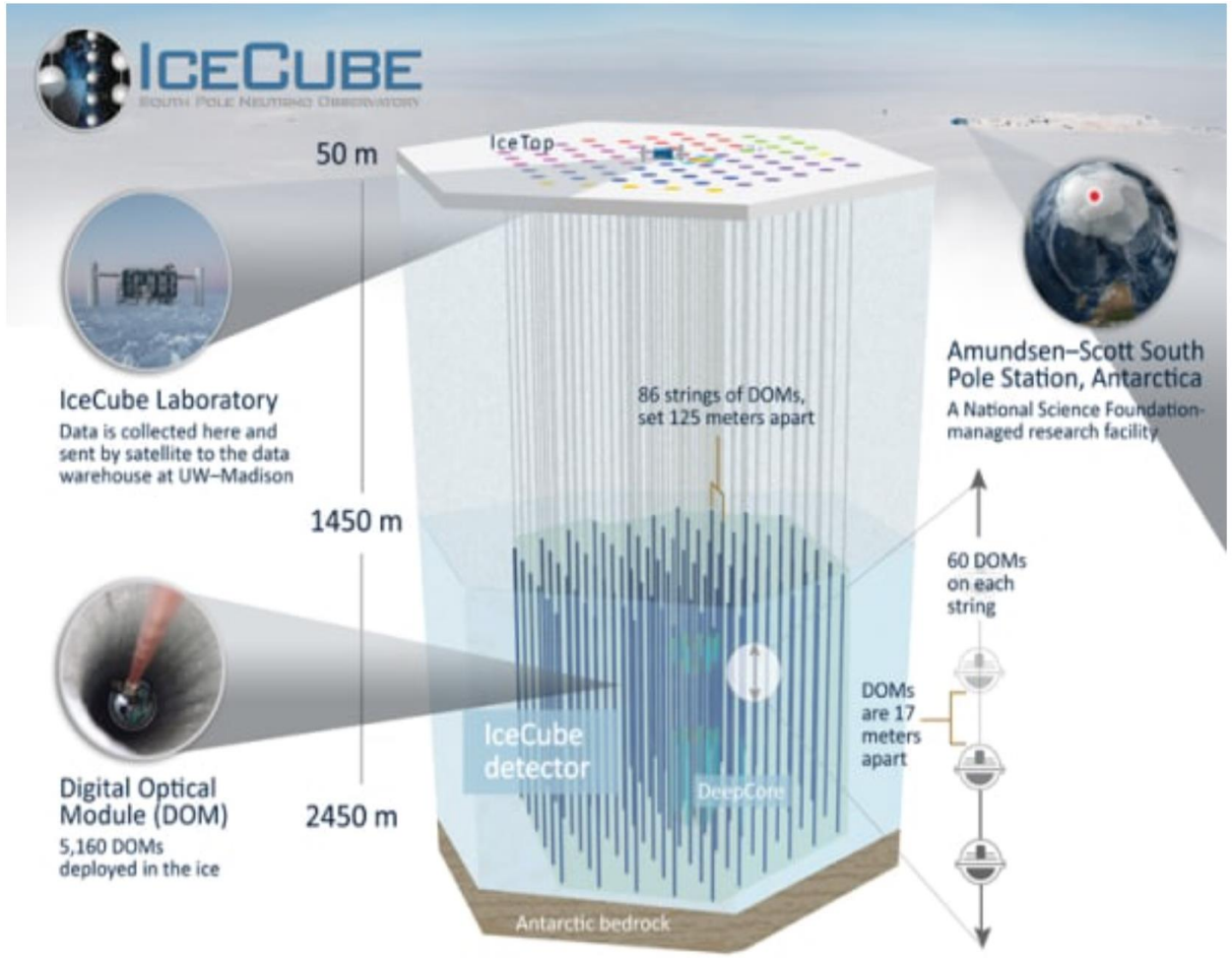
$$\sigma_{\rm inel} = 1.66 \times 10^{-26}\,{\rm cm}^2 \left(\frac{R}{10^{-9}\,{\rm cm}}\right)^{1/2}$$

(Bai, Berger ' 19)

Develop search strategy for
Multi-hit signature + Inelastic scattering
at Large-volume large-threshold neutrino detectors: IceCube

IceCube detector

- DeepCore (DC) region is more dense compared to IC region
- DOM: Digital Optical Module to detect the Cherenkov photons produced by relativistic charged particles
- These photons travel through ice and reach DOM and give photoelectron signal
- Two hits recorded on neighbor or next-to-nearest neighbor DOMs are High local coincidence (**HLC**) if time difference between the hits is less than 1 μs
- HLCs are basic of any trigger constructed at IC



(icecube.wisc.edu)

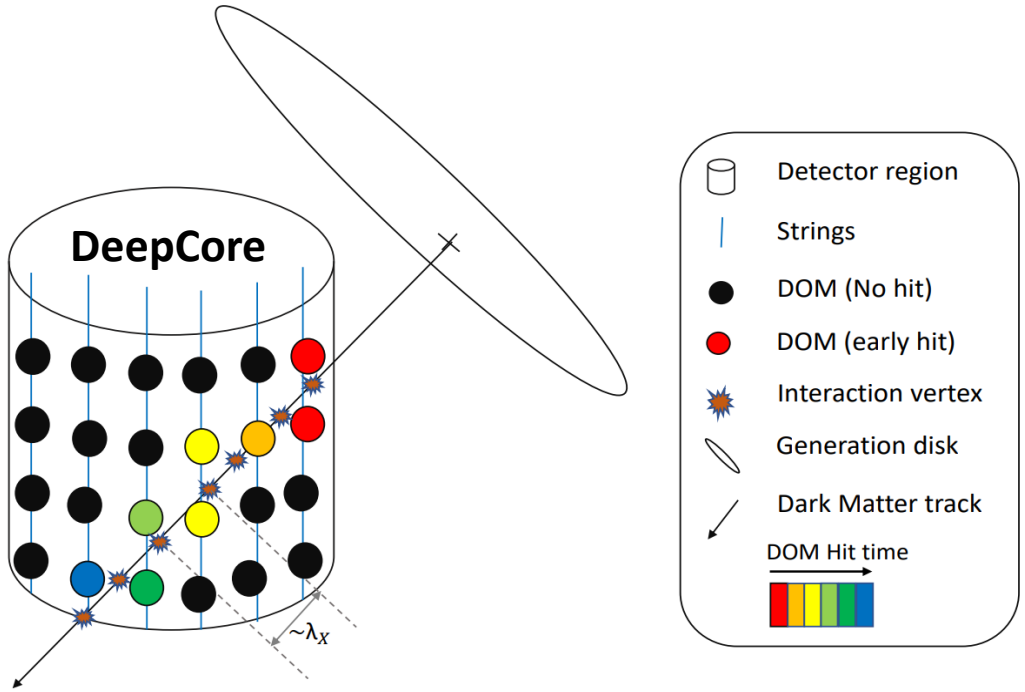
Signal from MDM

- Signal described two parameters:
  energy deposited at each interaction pt. E_X
  mean free path determined cross sec. λ_X

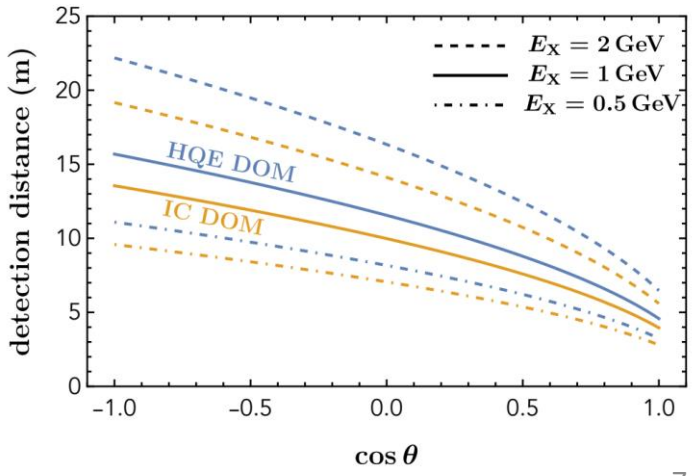
- For cross sec. $\sigma \approx 10^{-26}\,\mathrm{cm}^2$, we have $\lambda_X \approx 1\,\mathrm{m}$
  so multiple scatterings in the IC or DC region

- Number of Cherenkov photons produced

$$N_\gamma = 2 \times 10^5 (E_X/\mathrm{GeV})$$



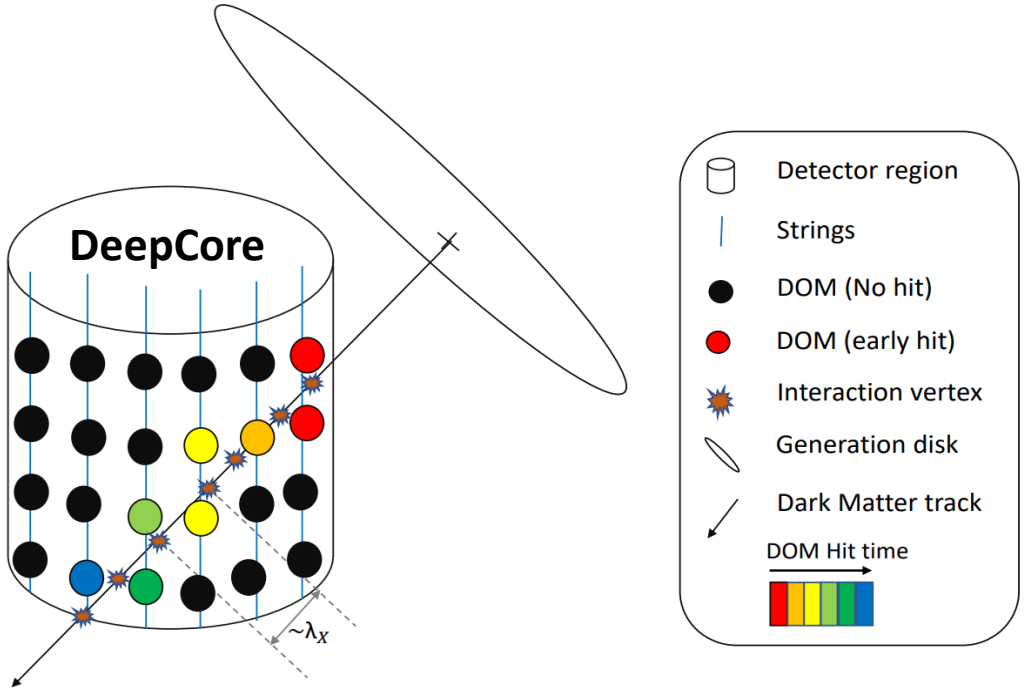
- Maximum detection distance between interaction vertex and DOM
  considering efficiency of the DOM, detection threshold, etc.

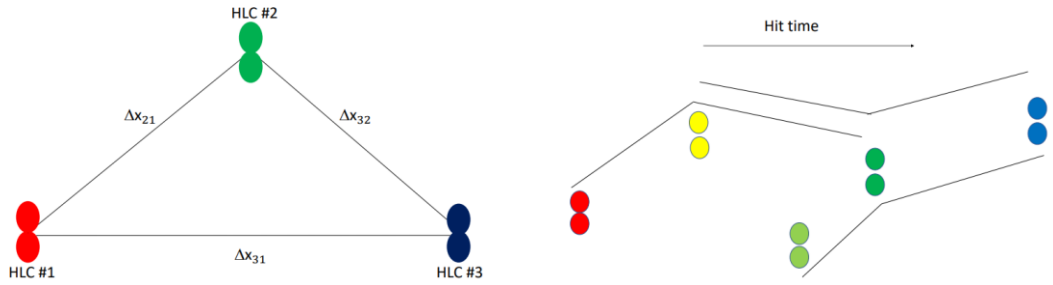


(Icecube collab.'08)

Slow Particle (SLOP) Trigger

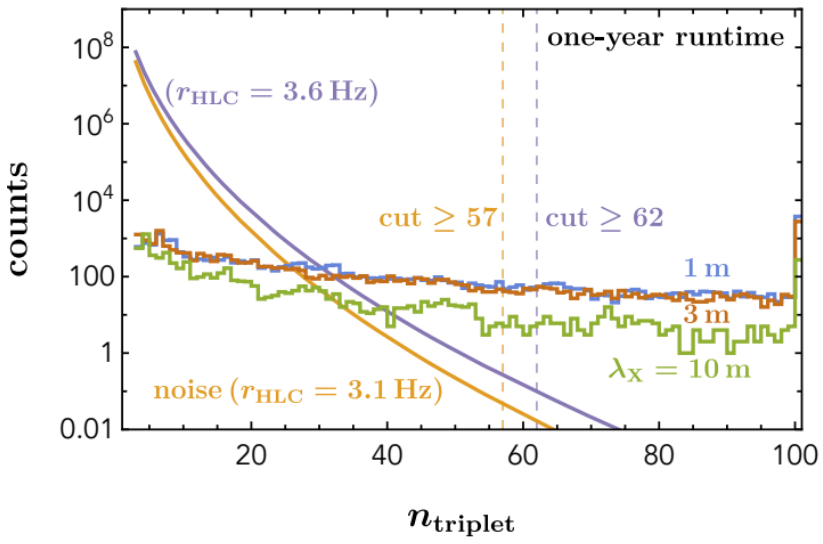
- DM travels at slow speed $v_X \approx 300\,\mathrm{km/s}$, takes about few ms to travel the detector
- Other track producing events from muons travel at relativistic speed takes few μs
- Dominant source of background is random noise from radioactive decay in the DOM, but they may not produce track like signature
- How to find a track, with constant speed: make triangles (triplets) out of HLC hits
- Parameter n_{triplet} if larger, larger the length of track
- Multiple hits near DOM can lead to multiple HLCs separated by time in a single DOM
- Parameter $R_{\mathrm{t}} = n_{\mathrm{triplet}}/N_{\mathrm{indep.-HLC}}$

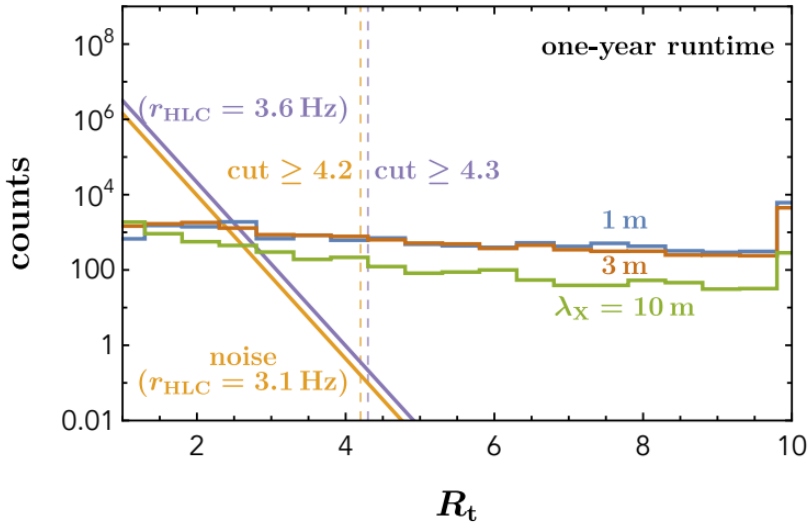




(Icecube collab.'14)
(Bai, Berger, **MK** ' 22)

Signal vs. Background





- We impose cuts to have zero expected background events

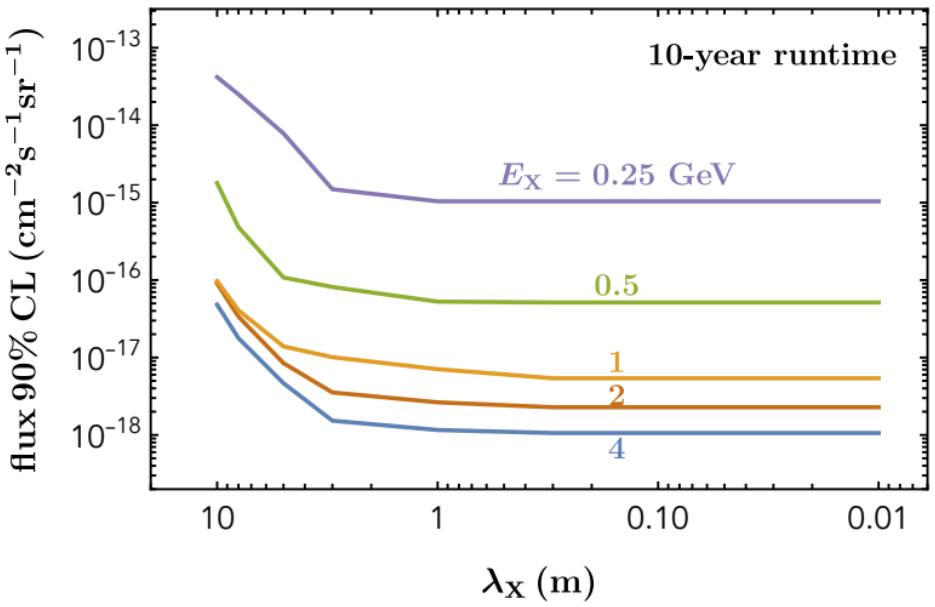
Cut	Background efficiency ($r_{\rm HLC}$)		Signal efficiency ($\lambda_{\rm X} = 1$m) ($E_{\rm X}$)				
	3.6 Hz	3.1 Hz	4 GeV	2 GeV	1 GeV	0.5 GeV	0.25 GeV
$n_{\rm DOM} \geq 1$	1.000	1.000	0.497	0.410	0.328	0.238	0.163
$n_{\rm HLC} \geq 1$	1.000	1.000	0.449	0.331	0.204	0.131	0.063
$\Delta t_{\rm HLC} \in (2.5, 500)\,\mu s$	0.764	0.649	0.307	0.191	0.0905	0.0236	0.00354
$\Delta d \leq 100\,{\rm m}$, $v_{\rm rel} \leq 0.5$	0.217	0.151	0.302	0.180	0.0898	0.0234	0.00354
$n_{\rm triplet} \geq 3$	0.0200	0.0105	0.299	0.174	0.0865	0.0212	0.00161
$n_{\rm triplet} \geq 57$	2.17×10^{-10}	3.70×10^{-11}	0.235	0.0822	0.0229	0.00298	0.000113
$R_{\rm t} \geq 4.2$	1.43×10^{-10}	6.48×10^{-11}	0.275	0.126	0.0465	0.00663	0.000375

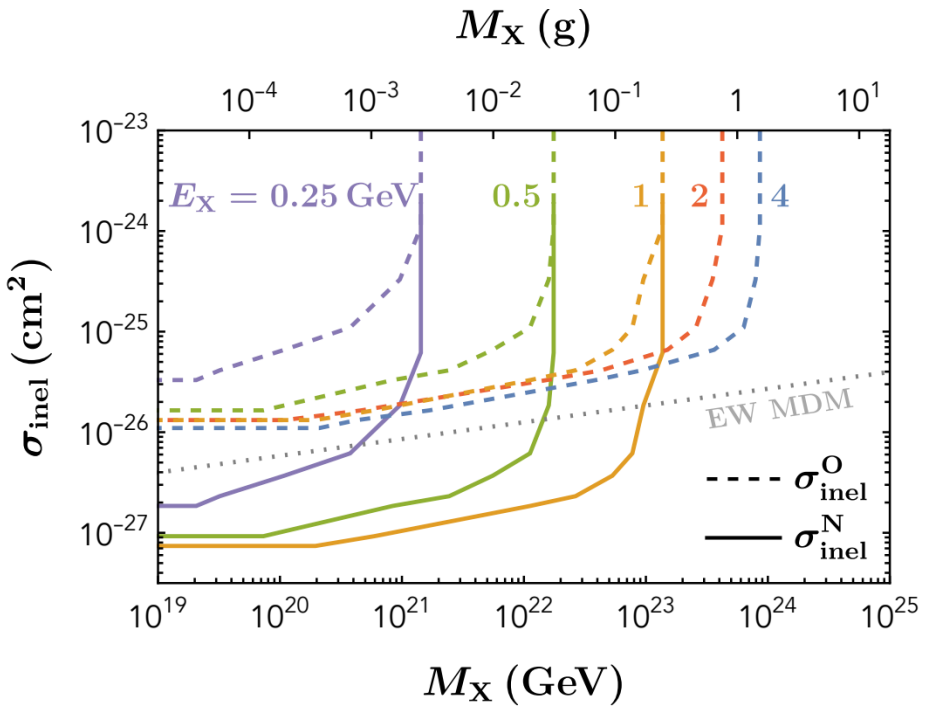
SLOP trigger

Cut

Flux limits

- Projected 90% CL limits with 10-yr runtime





$$M_X > 3\times 10^{24}\,\text{GeV} \times \left(\frac{\rho_{\rm DM}}{0.4\,\text{GeV/cm}^3}\right)\left(\frac{A_{\rm gen}}{2\times 10^5\,\text{m}^2}\right)\left(\frac{T}{10\,\text{yrs}}\right) \times \int dv_X\, f_{\rm DM}(v_X)\,\epsilon_{\rm eff}(v_X,\lambda_X,E_X)\left(\frac{v_X}{300\,\text{km/s}}\right)$$

$1\,\text{gram} \approx 5\times 10^{23}\,\text{GeV}$

(Bai, Berger, **MK** ' 22)

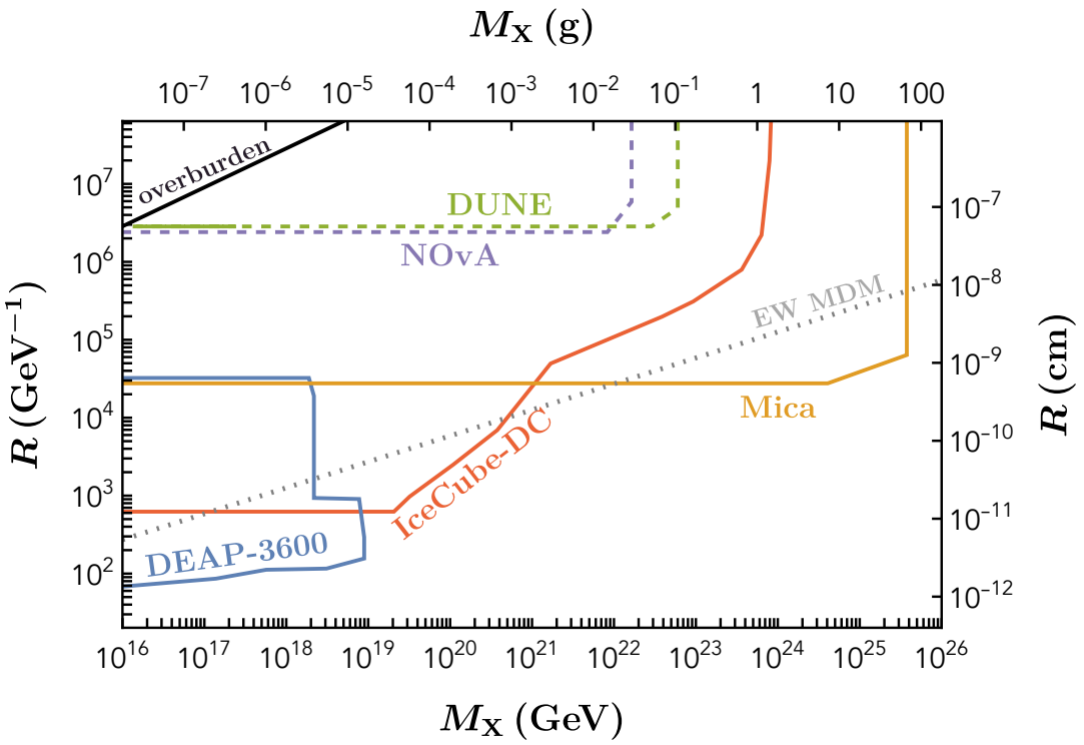
Direct Detection Constraints on EWS ball

- Constraint from Mica, DEAP-3600 are assuming elastic geometric cross section

- Sensitivity curves for DUNE, NOvA
  - 5 hits reconstructed with 100% efficiency in 5 yr and 10 yr runtime

$$A_{\rm eff} = (1.17, 2.14) \times 10^7\,{\rm cm}^2$$

- **Bounds are Model dependent**. Only relevant for the full electroweak symmetric case.



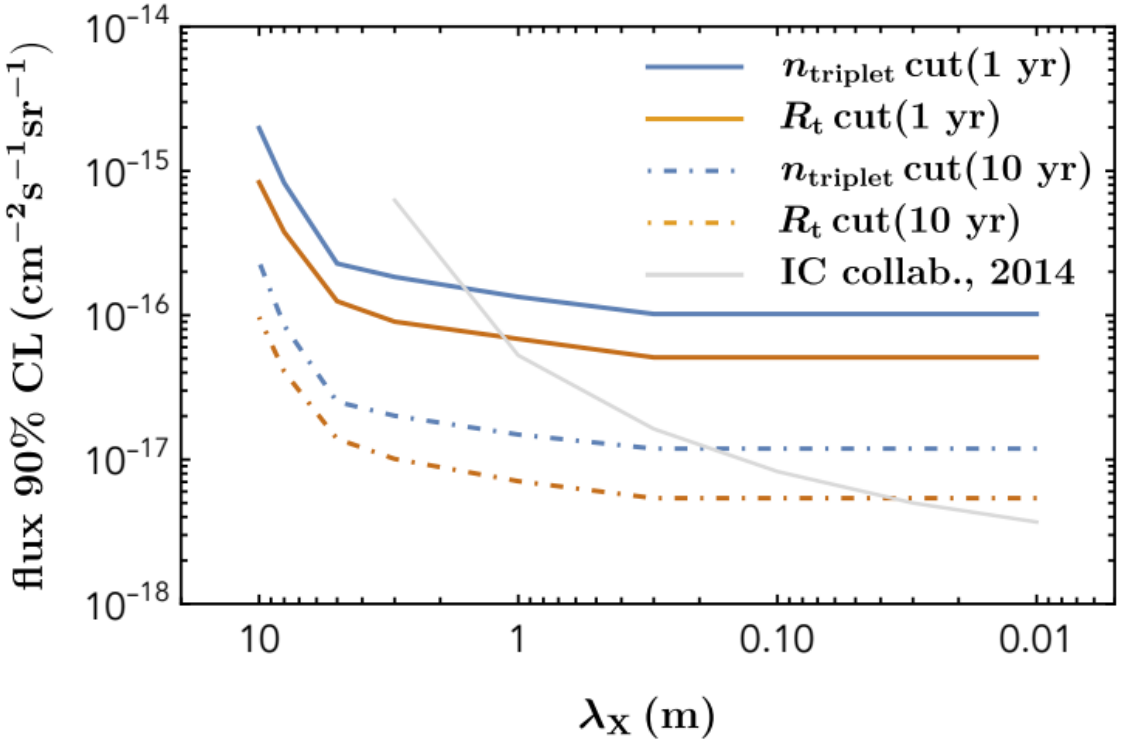
(Bai, Berger, **MK** ' 22)
(Acevedo et al' 21)
(DEAP Collab.' 21)
(DUNE Collab.' 15)
(NOvA Collab.' 05)

Summary

- Macroscopic dark matter gives multi-hit signatures in direct detection experiments.
- In some models, the MDM can undergo inelastic scattering with nucleons releasing large energy
- IceCube can search for this DM models with SLOP trigger, additionally with new parameters
- Sensitivity for 10-yr search: 1 gram in mass and $\sigma_{\rm inelastic} \approx 10^{-26} - 10^{-27}\,{\rm cm}^2$

Appendix

Comparison of two triggers and IceCube



Velocity dependent efficiency