

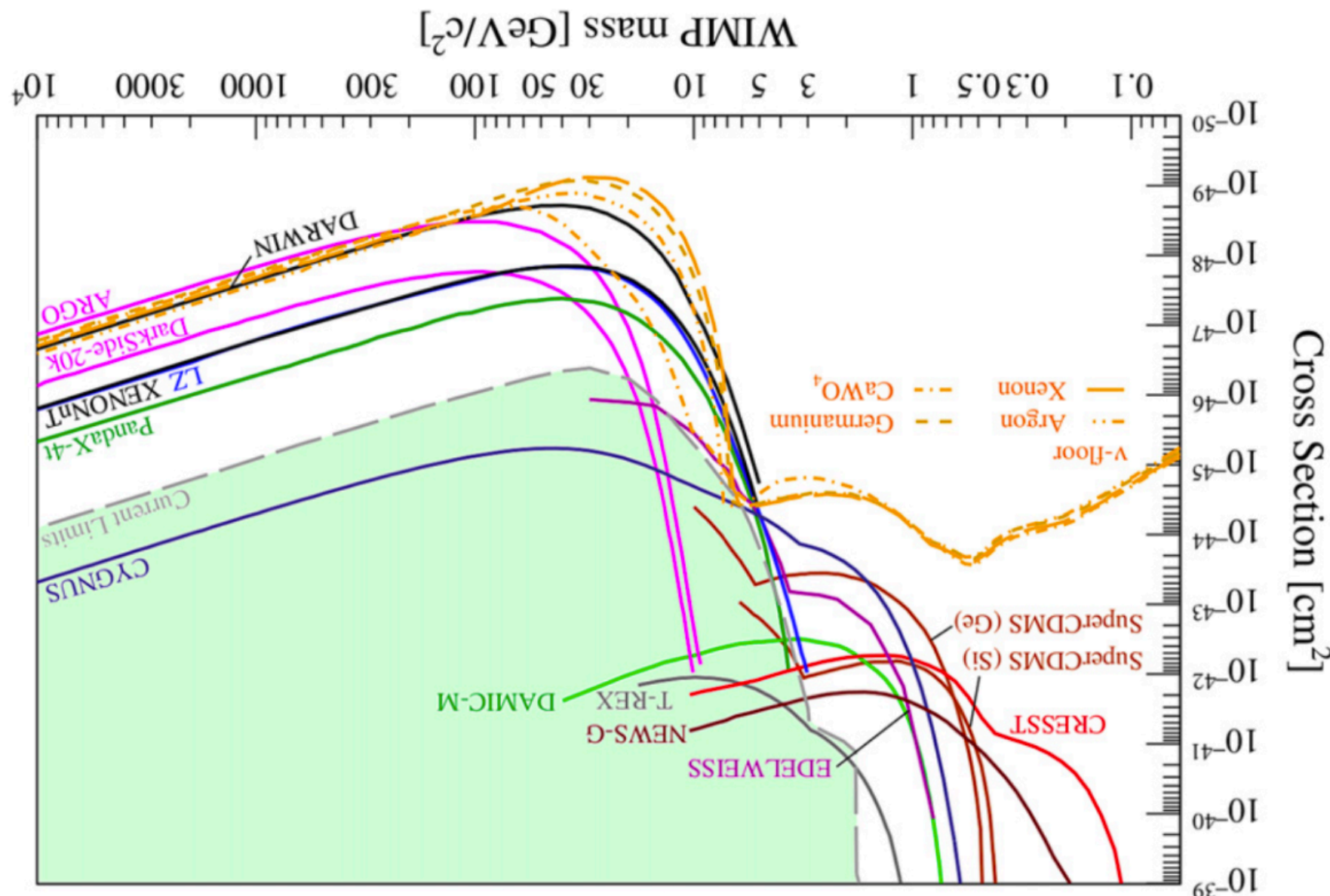
The Neutrino Roof: Direct Searches of Dark Matter Around the Planck Mass

NIRMAL RAJ



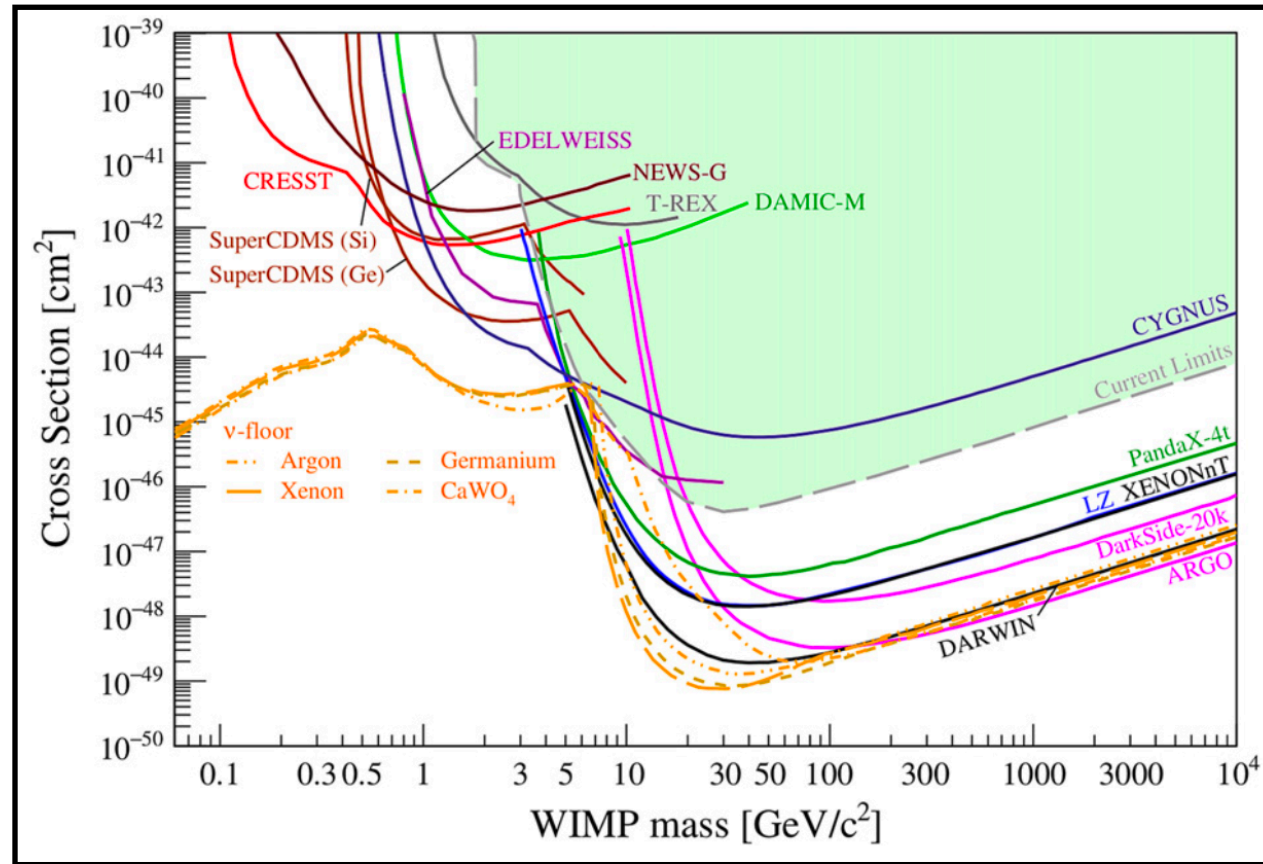
collaborators

Joe Bramante, Ben Broerman,
Shivam Garg, Jason Kumar,
Michela Lai, Rafael Lang,
Biprajit Mondal,
Maxim Pospelov, Shawn Westerdale

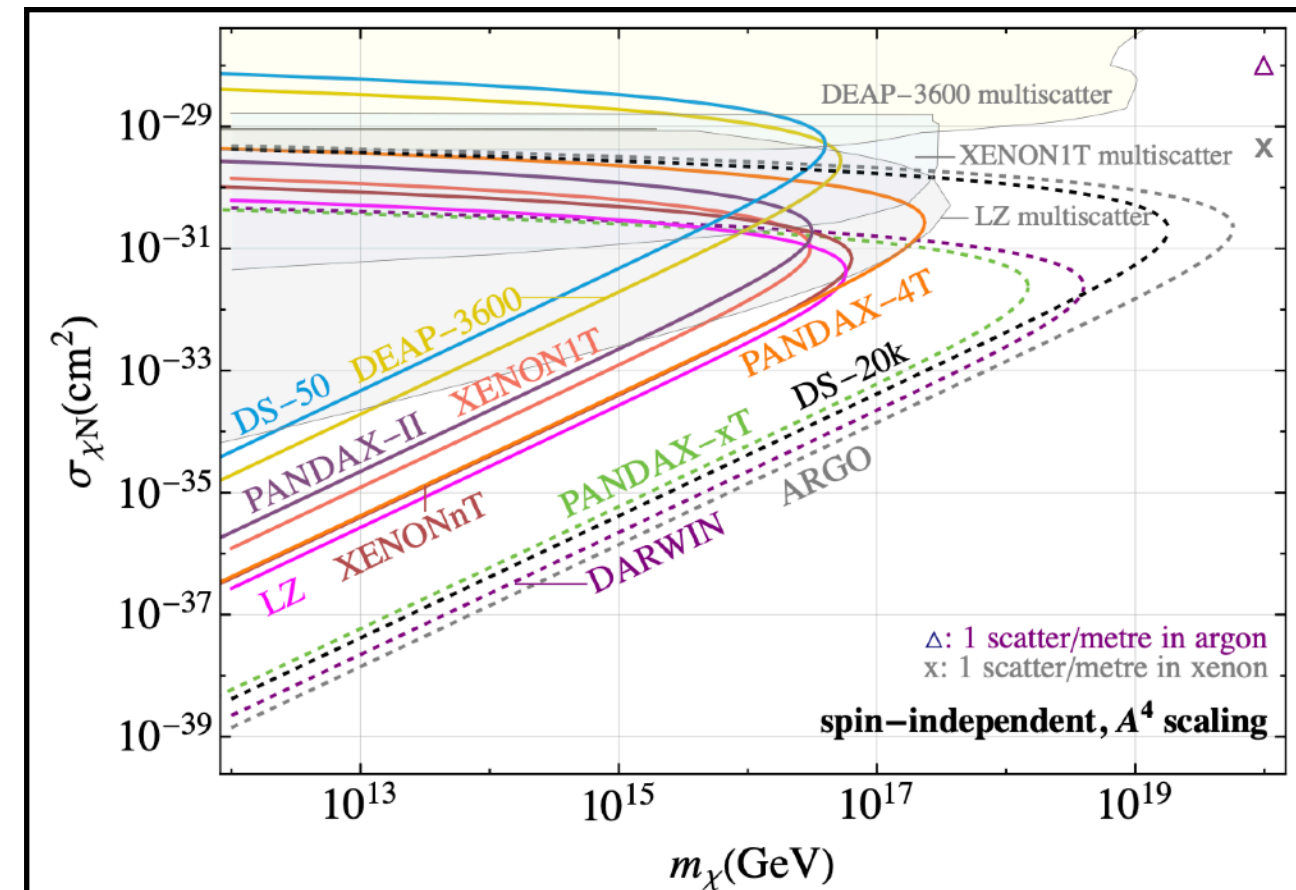


BB2Now 2025, 25 Jan 2025

Punchline for experts

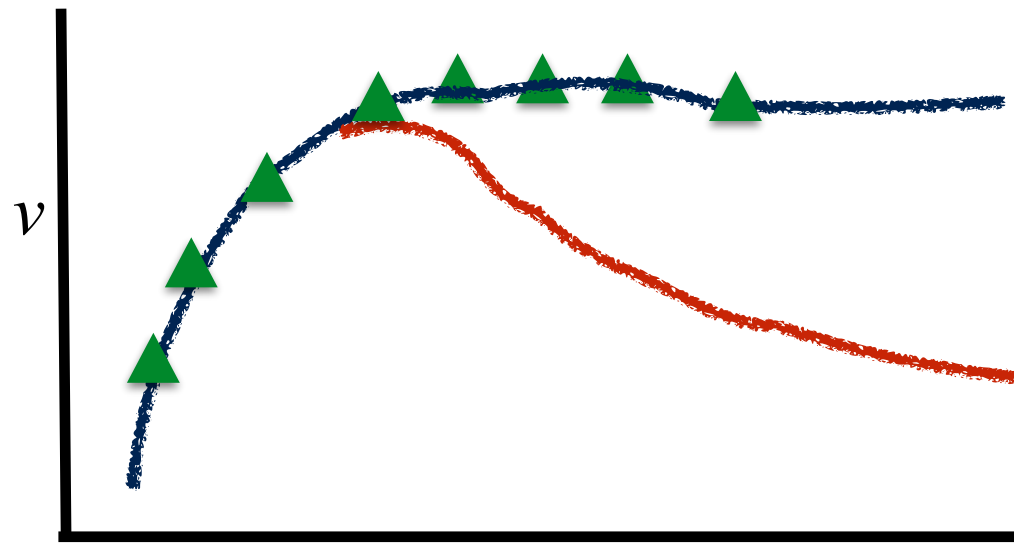


APPEC report, 2104.07634

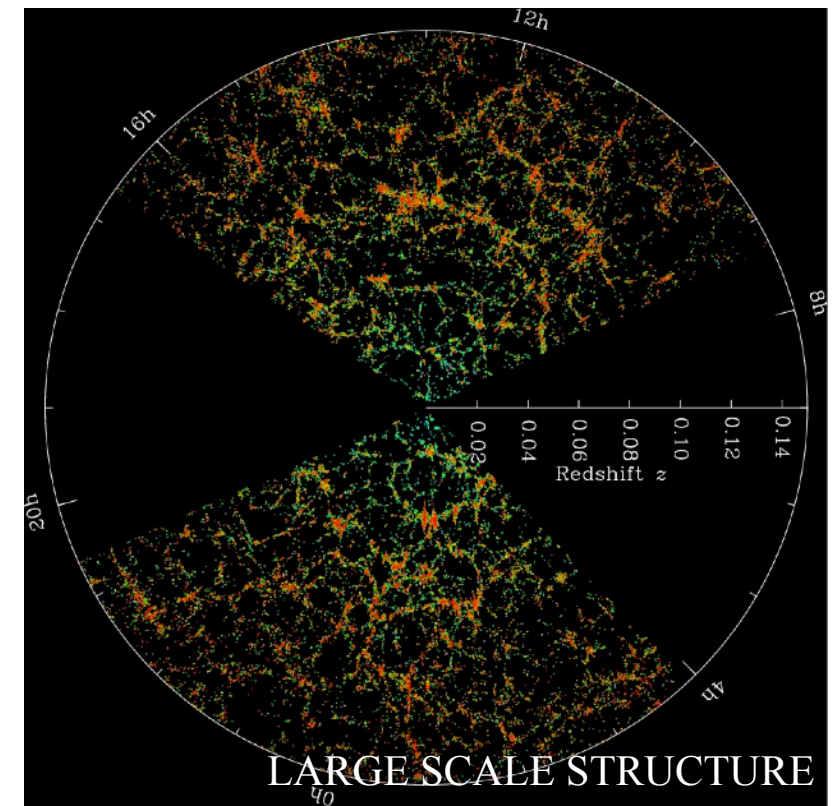


Raj & Mondal, 2406.17015

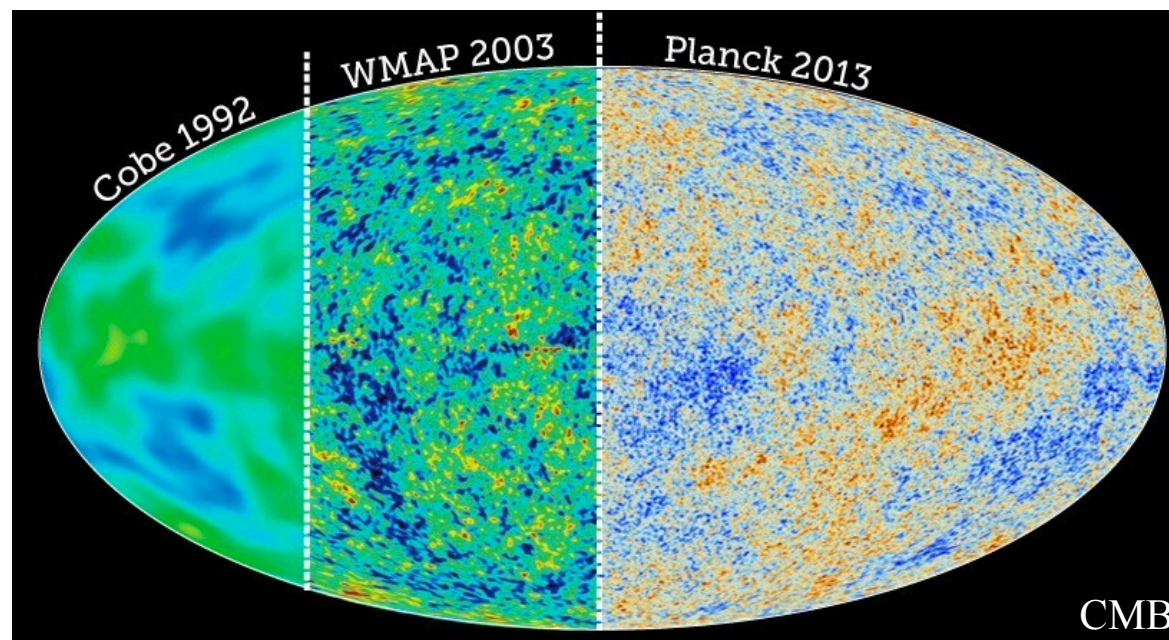
Dark reality



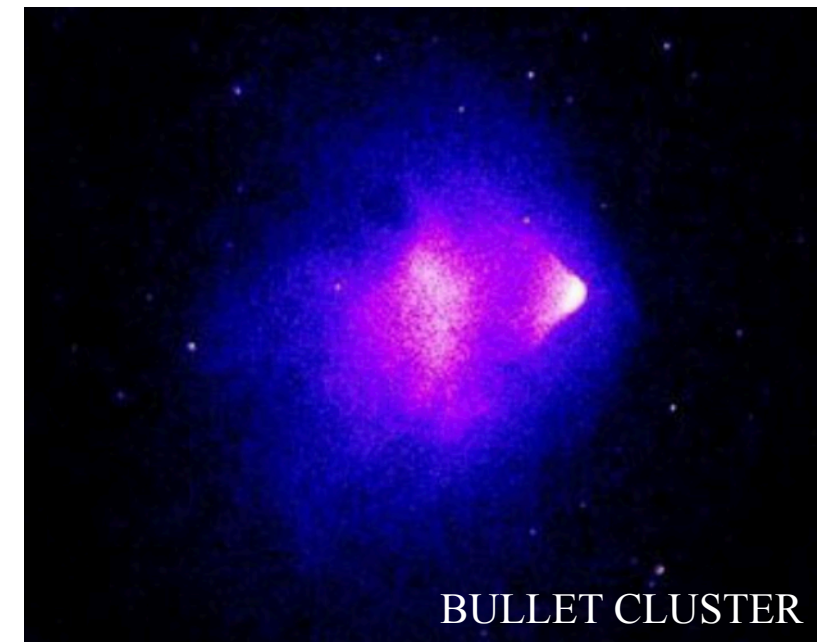
GALACTIC ROTATION



LARGE SCALE STRUCTURE



CMB

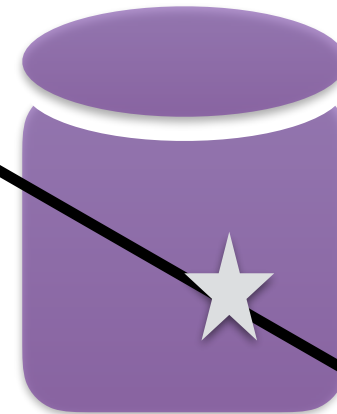


BULLET CLUSTER

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544

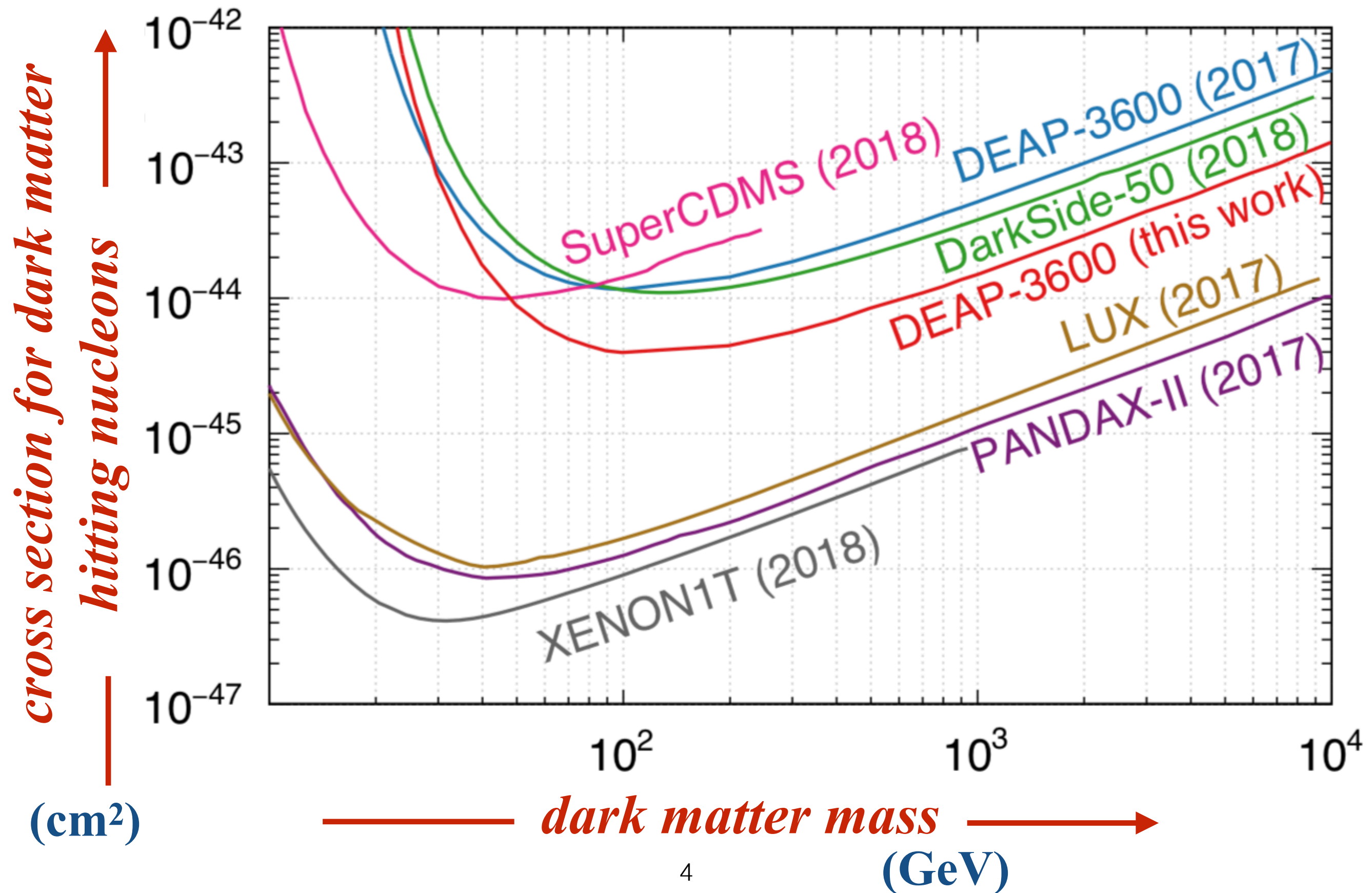


Encounter rate (spin-independent) =

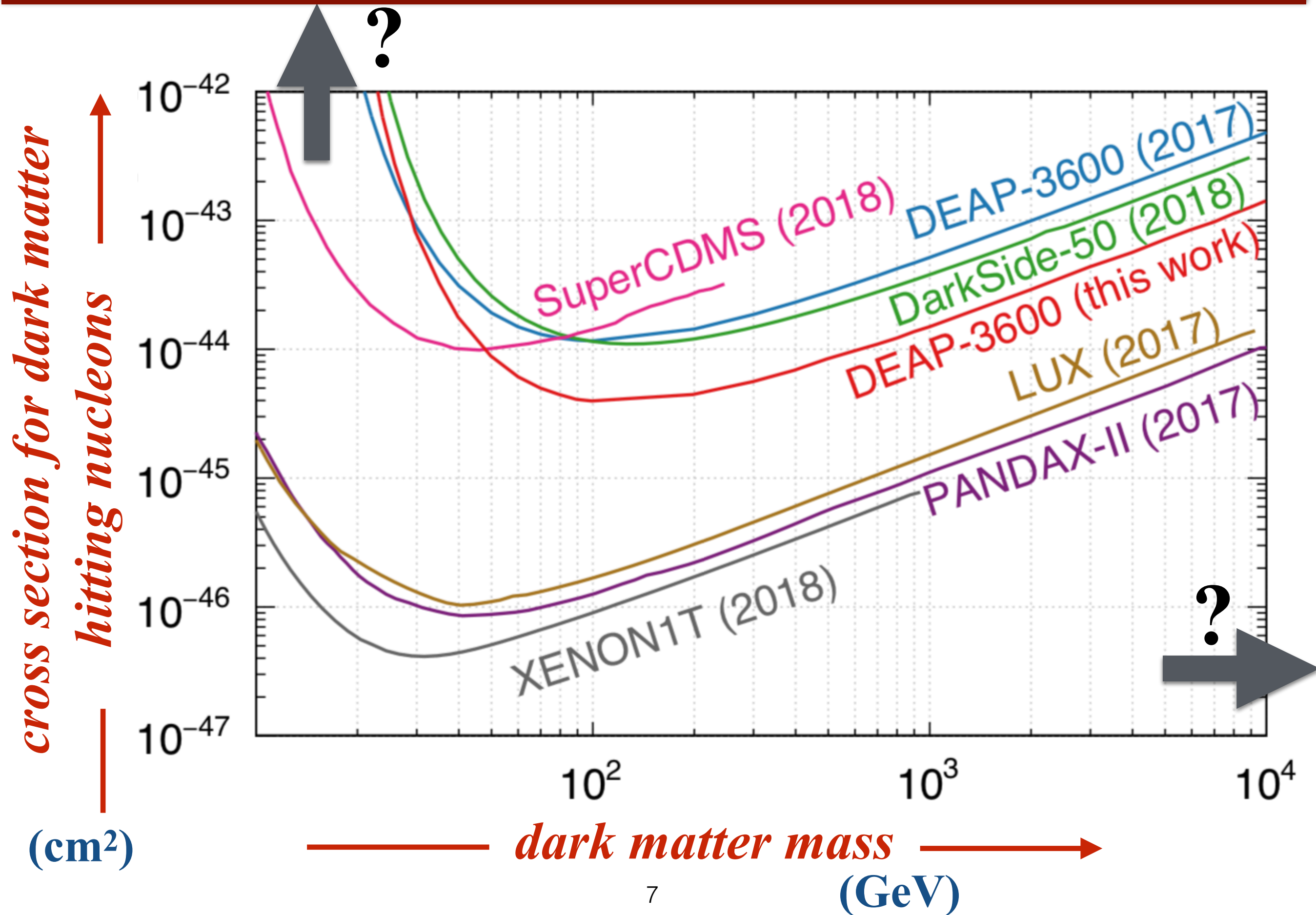
6.8 events $\times$

$$\left(\frac{\sigma_{\chi N}}{10^{-39} \text{ cm}^2} \right) \left(\frac{A}{27} \right)^4 \left(\frac{1000 \text{ GeV}}{m_{\text{DM}}} \right) \left(\frac{27}{A} \right) \left(\frac{\rho_{\text{DM}}}{0.3 \text{ GeV/cm}^3} \right) \left(\frac{v_{\text{DM}}}{220 \text{ km/s}} \right) / \text{kg/day}$$

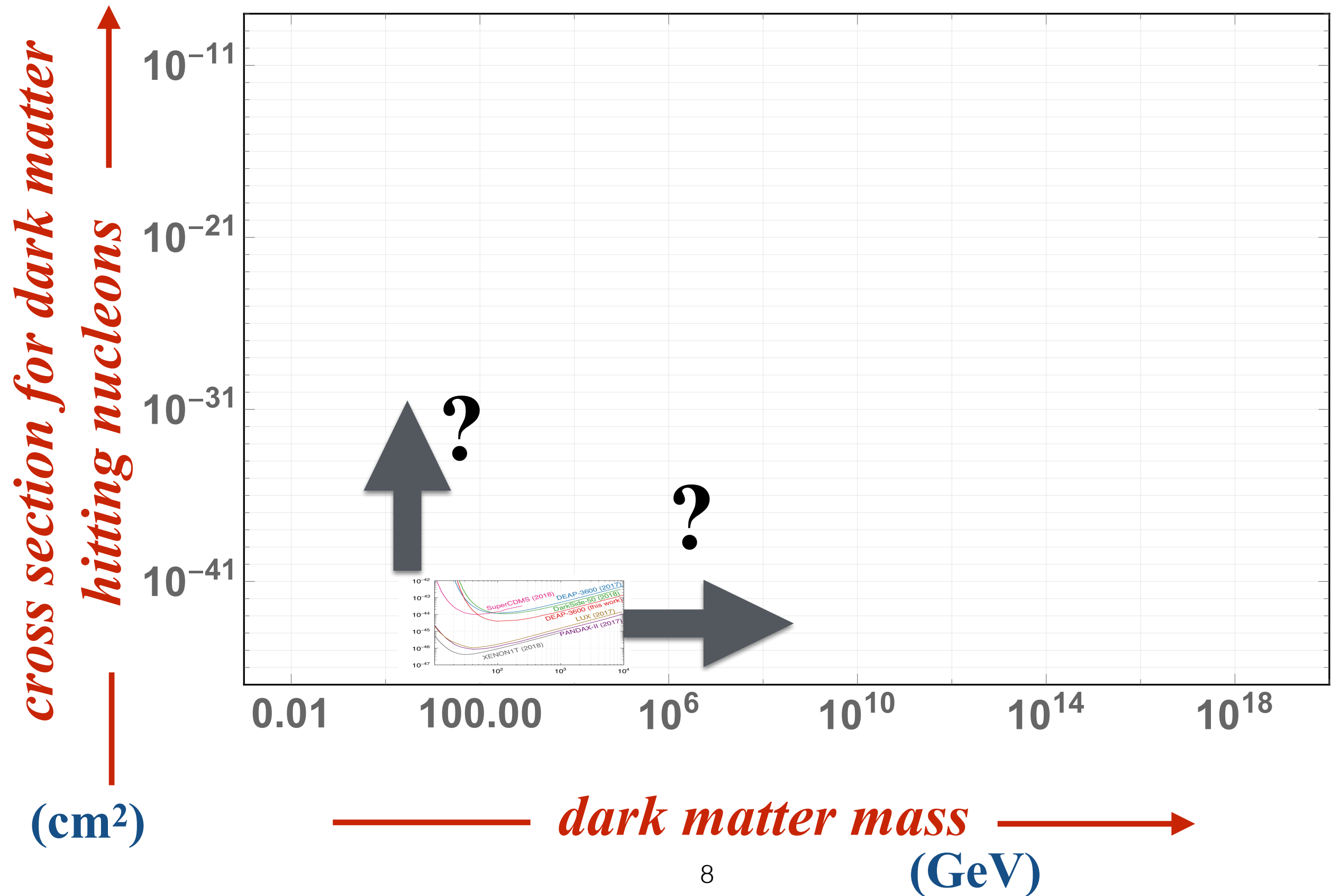
Preview: modern searches



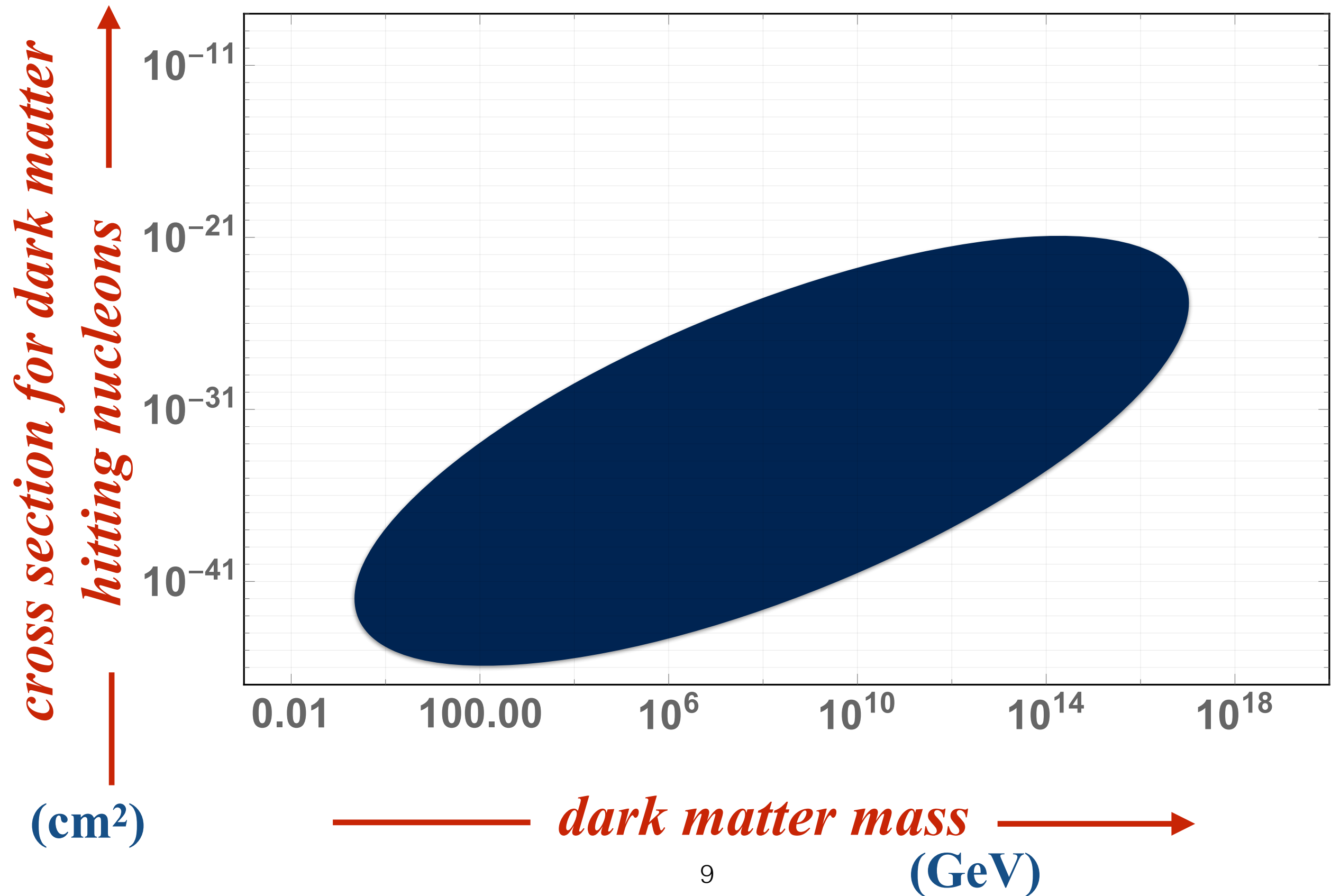
Direct detection status



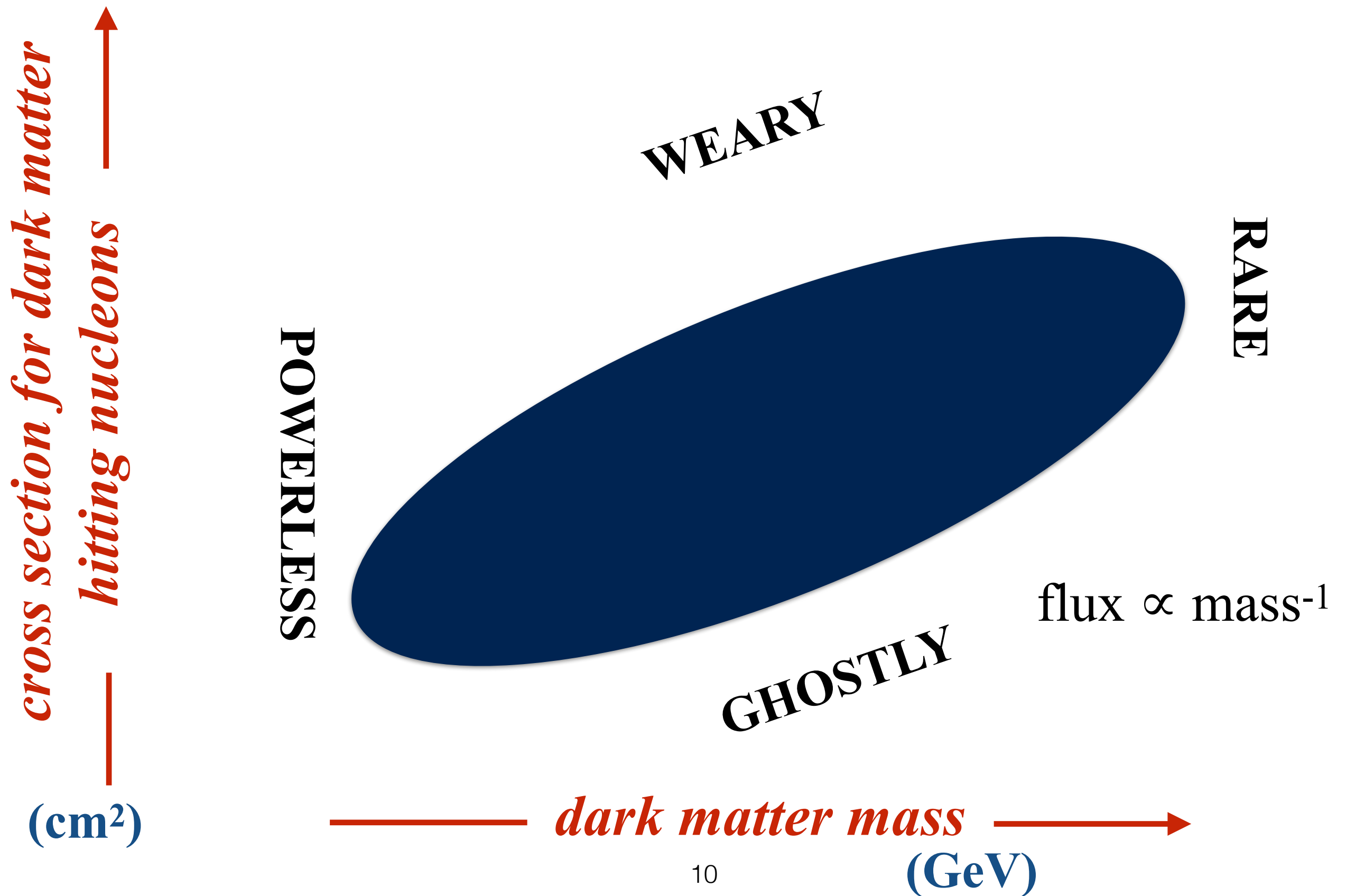
Bird's-eye view



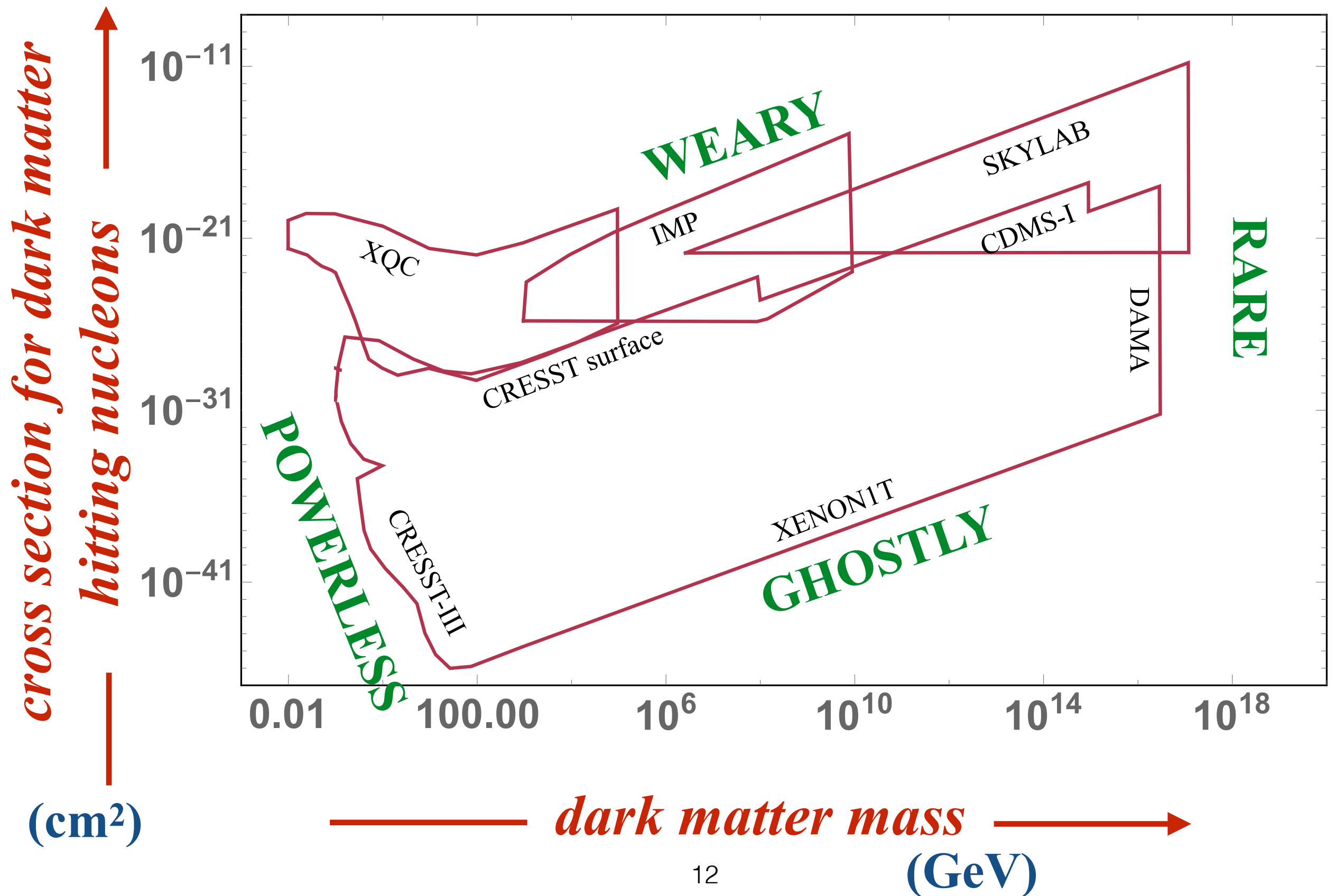
An educated guess



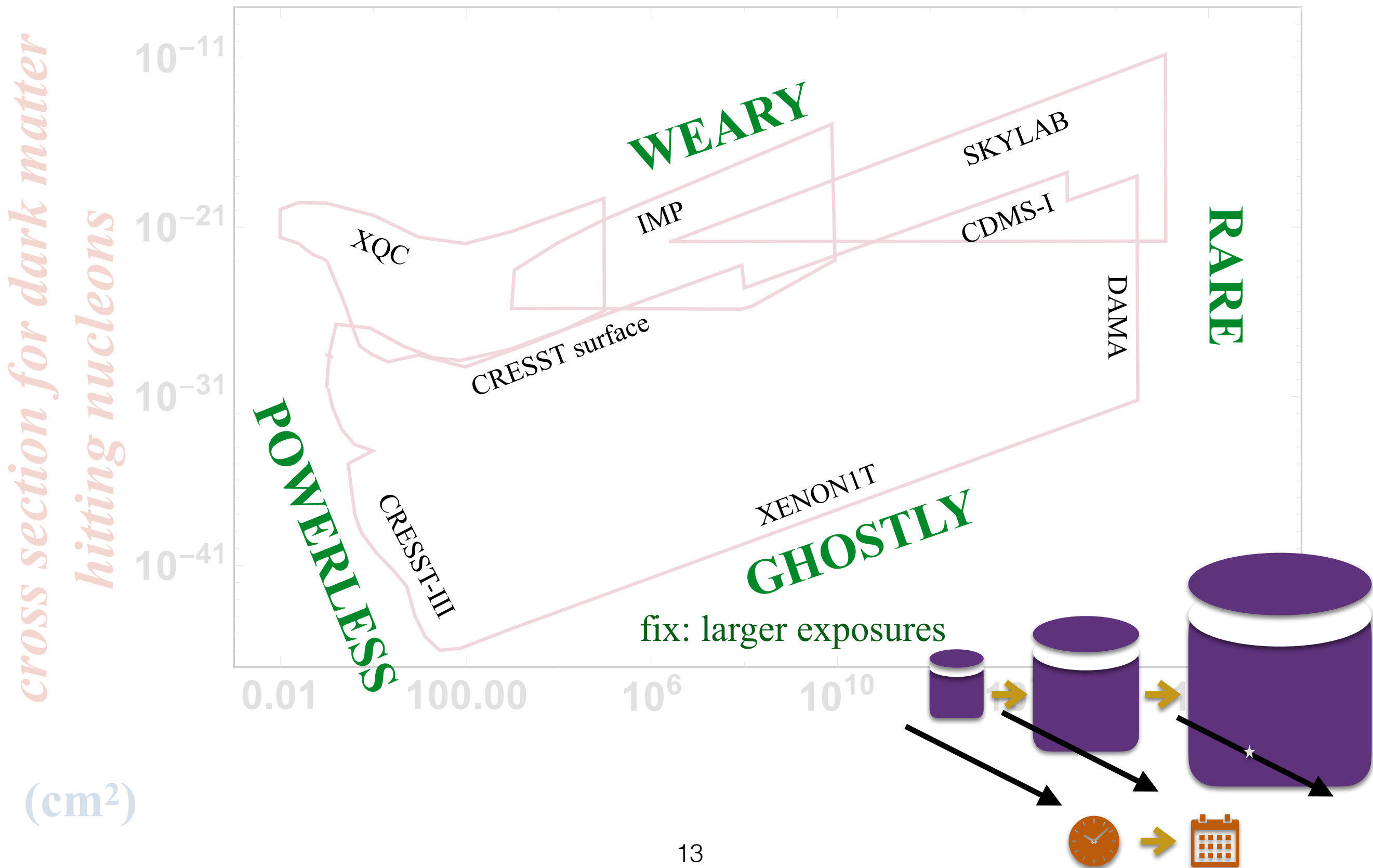
The four frontiers



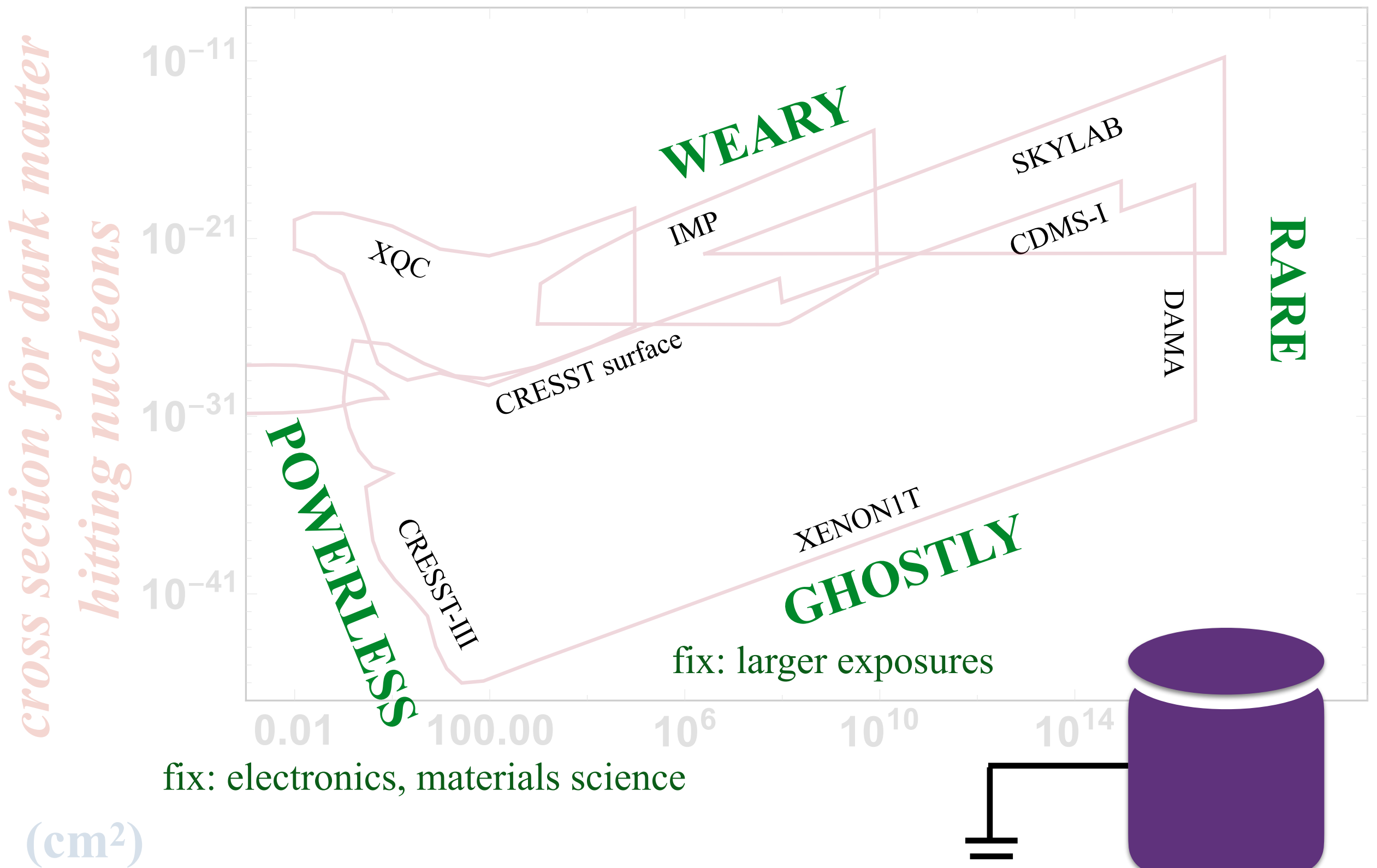
All the Earth-based constraints



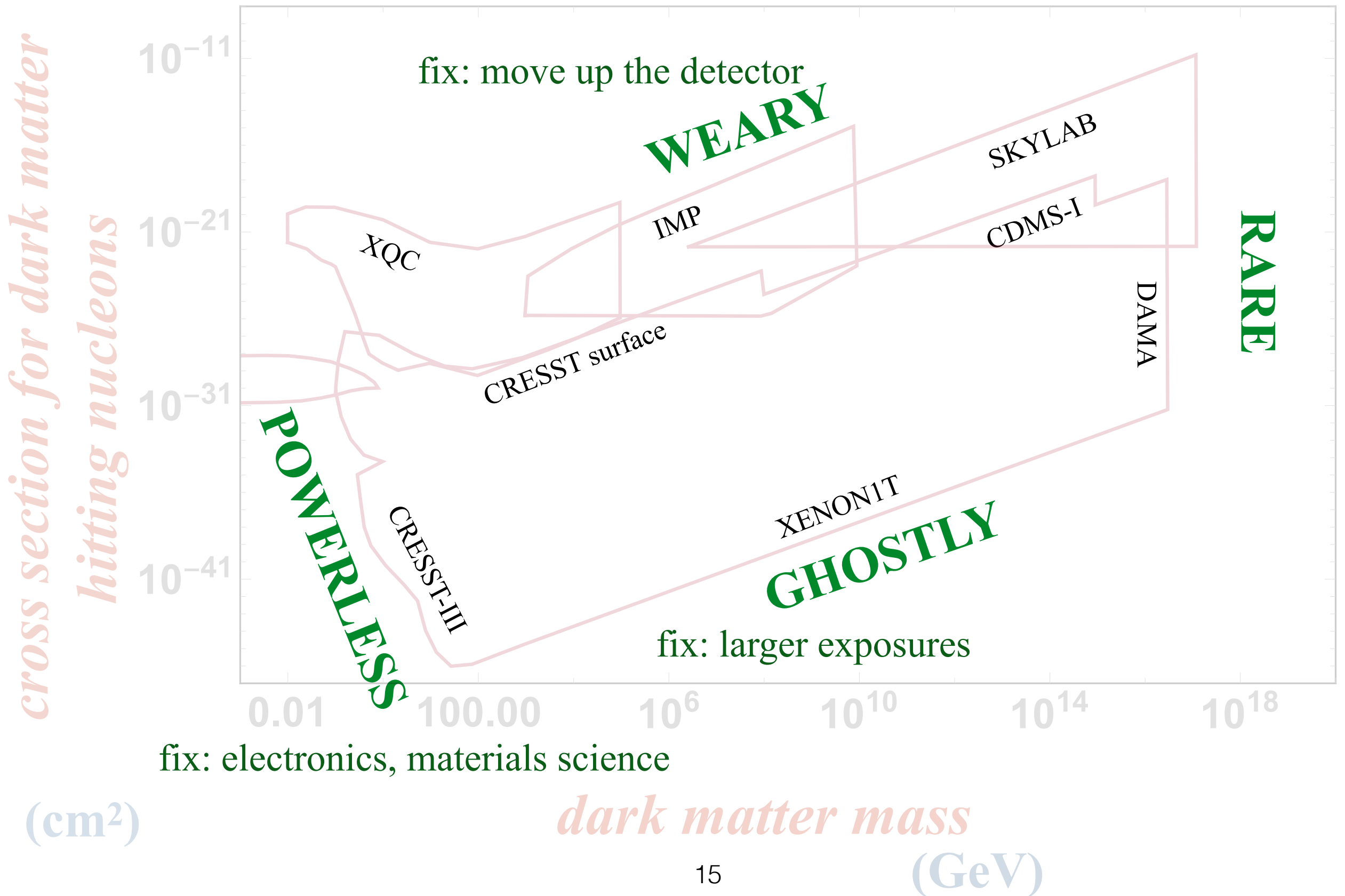
All the Earth-based constraints



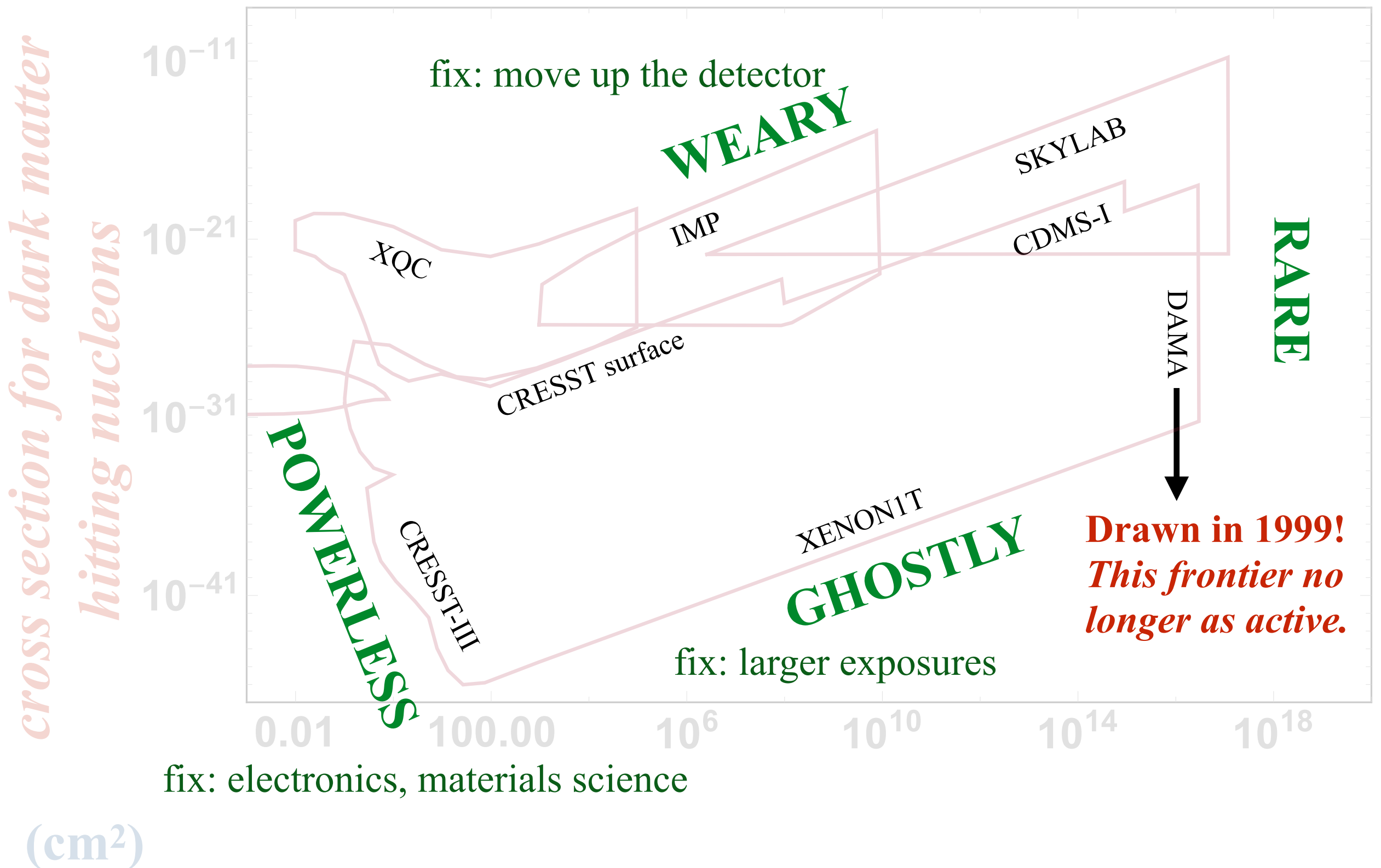
All the Earth-based constraints



All the Earth-based constraints



All the Earth-based constraints



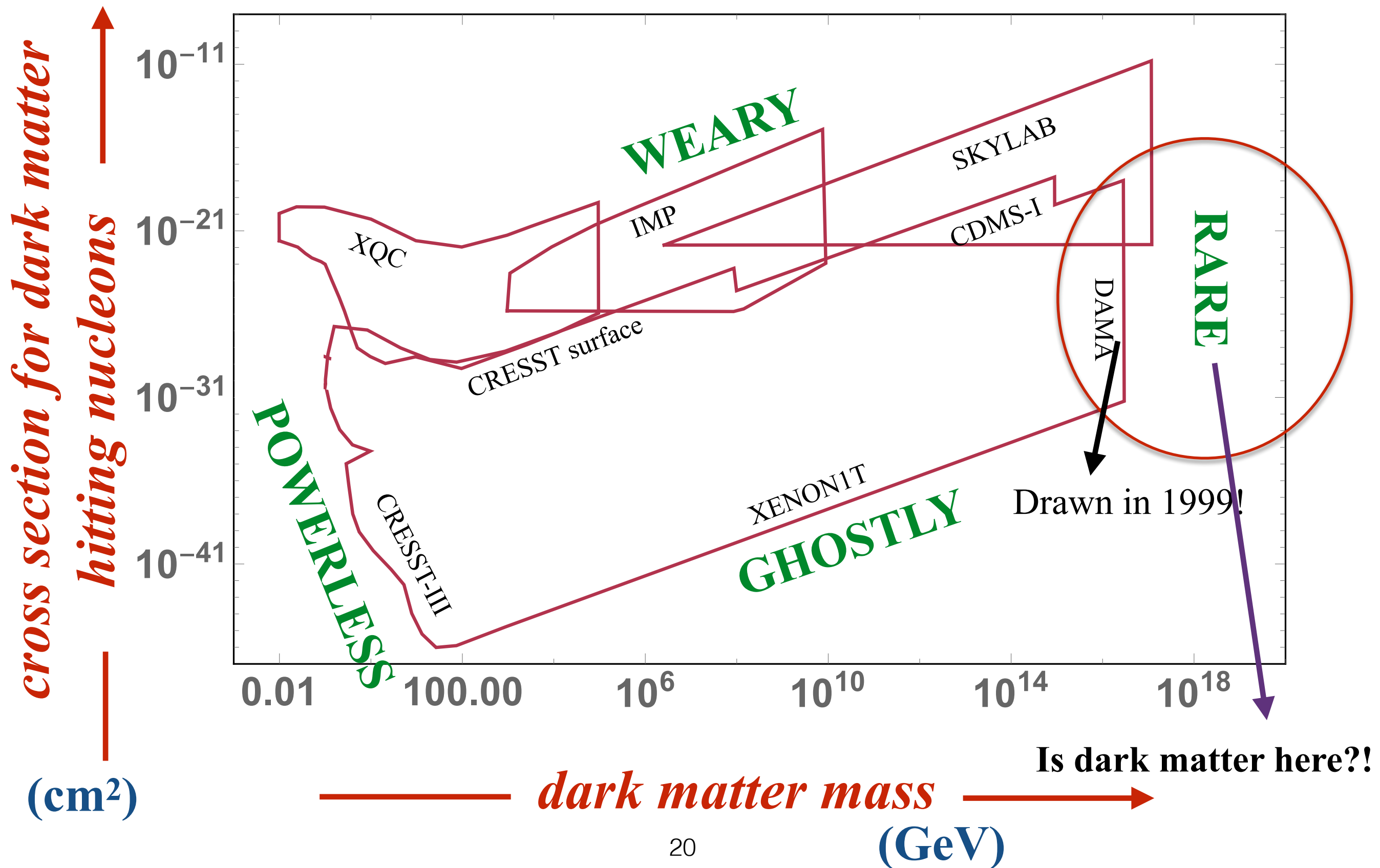
dark matter mass
100 GeV
WIMPs

7 centimetres

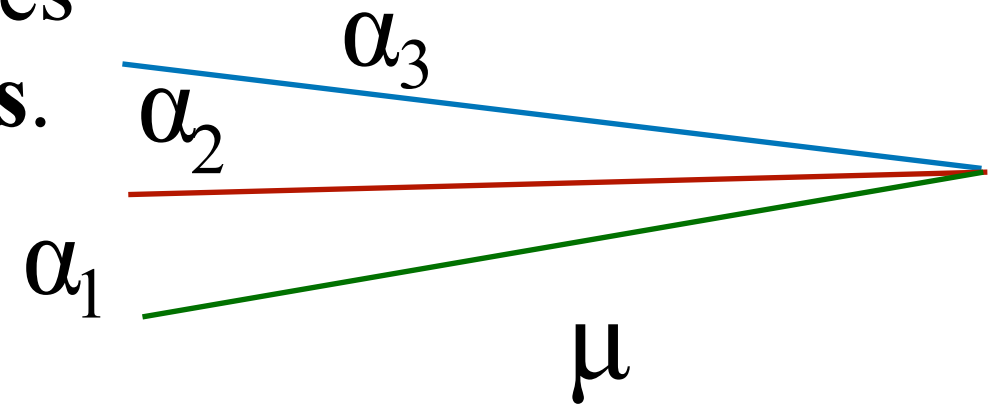
dark matter mass
 2×10^{16} GeV
DAMA limit

> 4 kilometres

Hunting even rarer dark matter



- Super-heavy states appear in theories of **grand unification of forces**.



- Can make them in early universe:
 - * Hawking radiation from primordial black holes
Hooper, Krnjaic, McDermott (2019)
 - * Gravitationally @ final stages of inflation
Chung, Crotty, Kolb, Riotto (2001), Harigaya, Lin, Lou (2016)
 - * Pre-heating: parametric resonance $\longrightarrow$ rapid decay of inflaton
Giudice, Peloso, Riotto, Tkachev (1999), Bai, Korwar, Orlofsky (2020)
 - * Thermally!
Kim, Kuflik (2019)

Heavy, strong, stable: recent wave

Electroweak symmetric monopoles

Bai, Korwar, Orlofsky

2005.00503

Electroweak symmetric solitons

Bai, Jain, Ponton

1906.10739

Charged primordial black holes

Lehmann, Johnson, Profumo, Schwemberger

1906.06348

Asymmetric dark matter nuggets

Coskuner, Grabowska, Knapen, Zurek

1812.07573

Dark blobs

Grabowska, Melia, Rajendran

1807.03788

Colored relics

Gross, Mitridate, Redi, Smirnov, Strumia

1811.08418

Heavy dark baryons

Davoudiasl, Mohlabeng

1809.07768

Heavy dark skyrmions

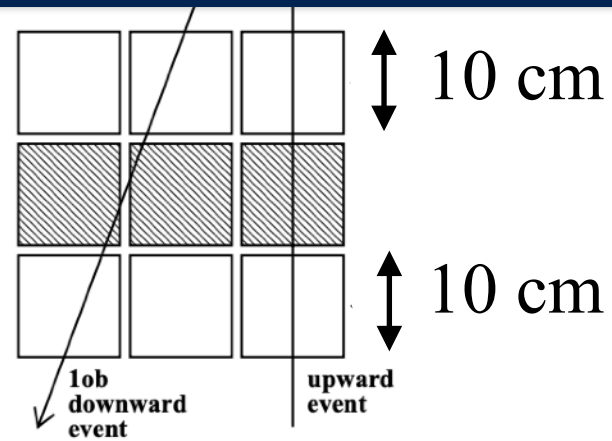
Berezowski, Dick

Sep 2019

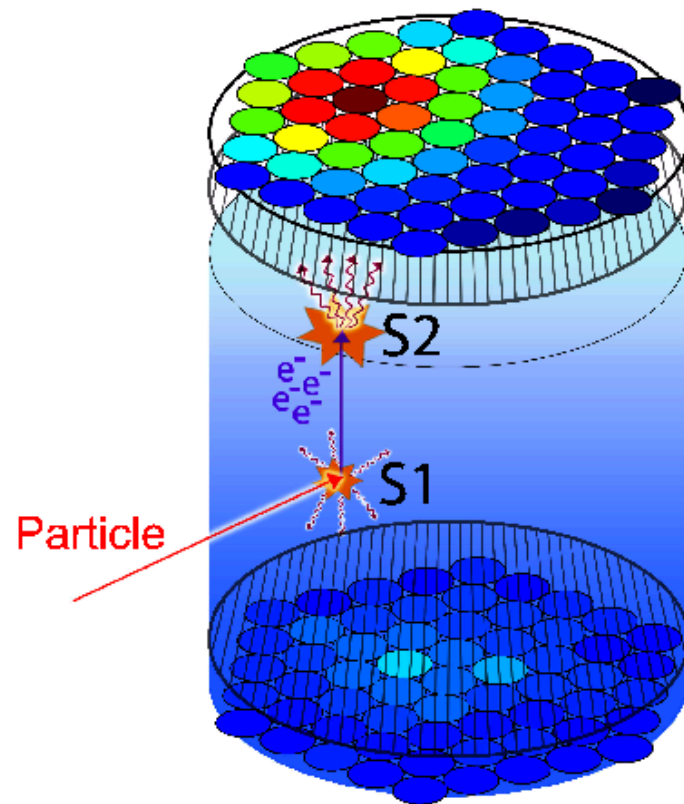
**Why now?
Can detect them now!**

Today's dark matter detectors

DAMA
1999
search

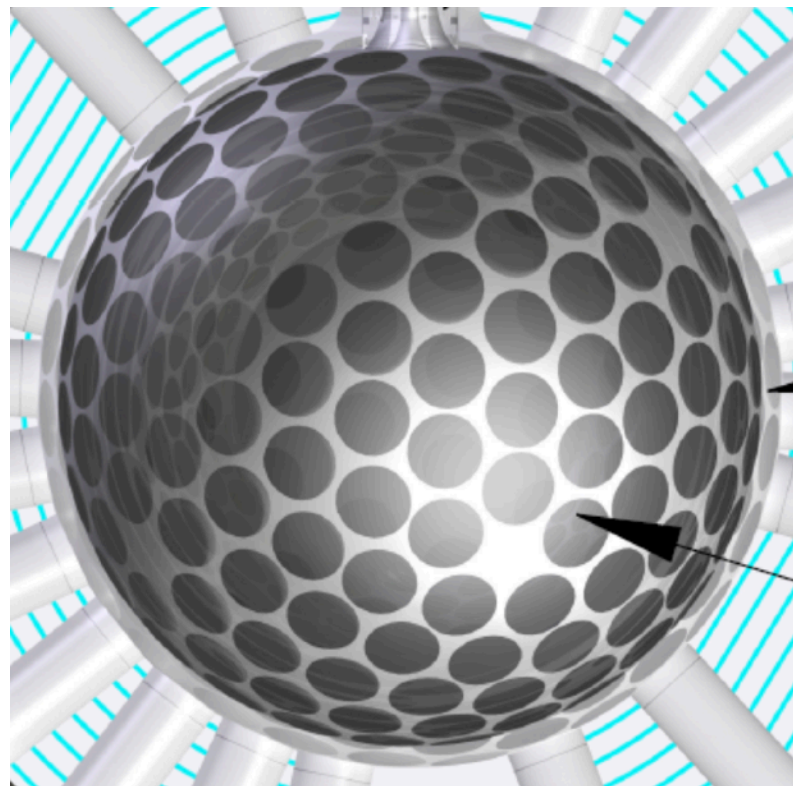


← 100 cm →



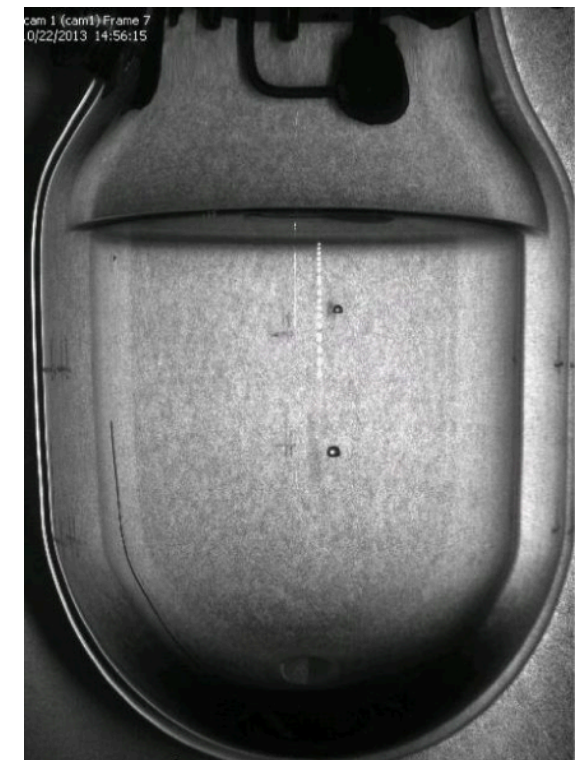
XENON1T/
LUX/
PANDAX-II

← 130 cm →



DEAP-3600

← 50 cm →

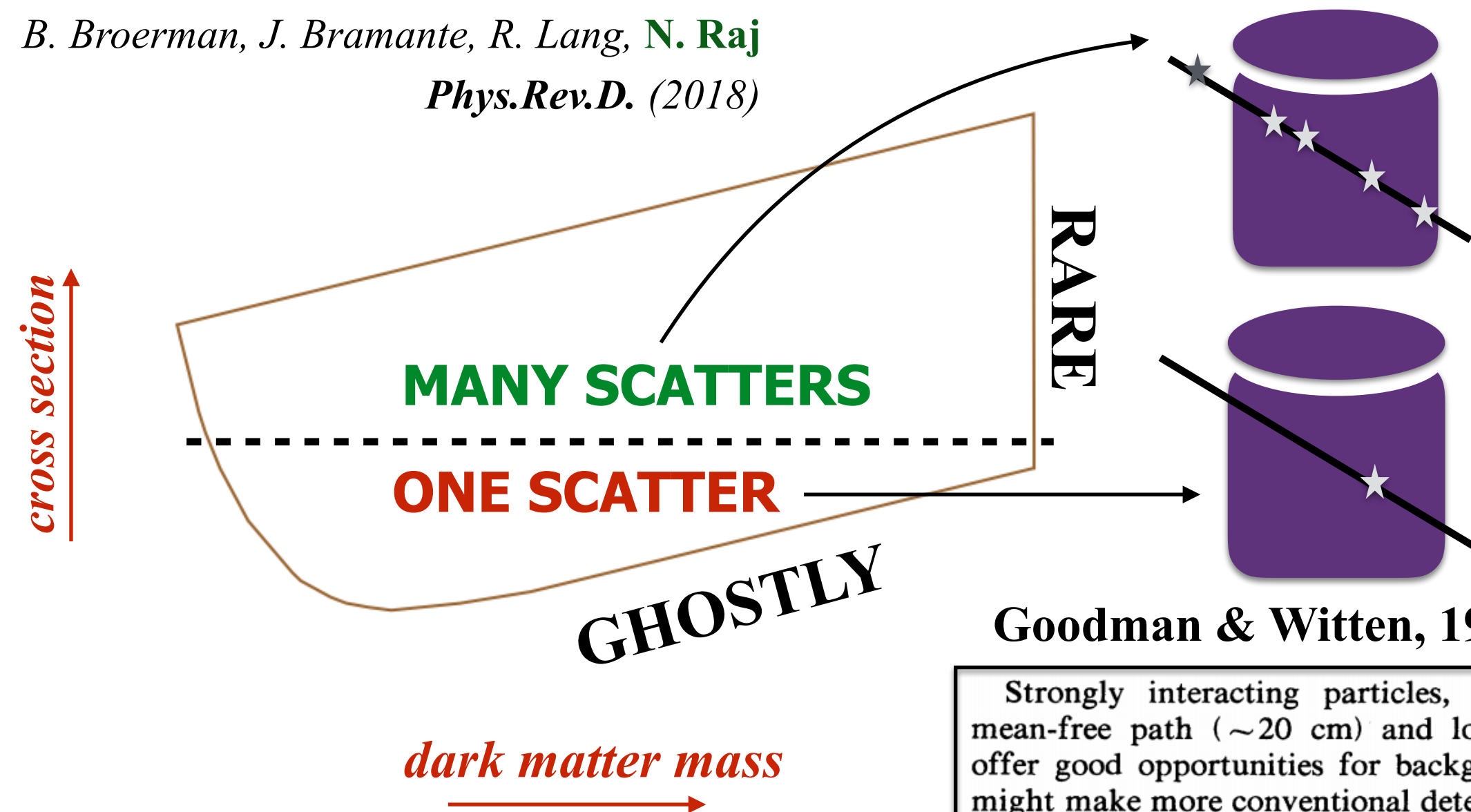


PICO-40L

Multiscatter signatures essential

$$\# \text{ scatters per transit} = \sigma \times \text{target number density} \times \text{path length}$$

B. Broerman, J. Bramante, R. Lang, N. Raj
Phys.Rev.D. (2018)



Goodman & Witten, 1985:

Strongly interacting particles, with their observable mean-free path (~ 20 cm) and low velocity ($\beta \lesssim 10^{-3}$) offer good opportunities for background rejection which might make more conventional detection schemes feasible. A distinctive signal in a NaI crystal would be a pair of events with energy deposit ~ 10 keV (~ 10 photons detected) separated by ~ 20 cm and by ~ 1 μ sec.

a large range of masses for strongly interacting dark-matter particles is probably already ruled out by the simple observation that NaI does not “glow in the dark.”

- DAMA '99 based on this ‘multiple scatters’ signature
- **Not** sought any more. Would double the reach of all current experiments!

DEAP-3600 @ SNOLAB

PHYSICAL REVIEW LETTERS

Highlights Recent Accepted Collections Authors Referees
Staff

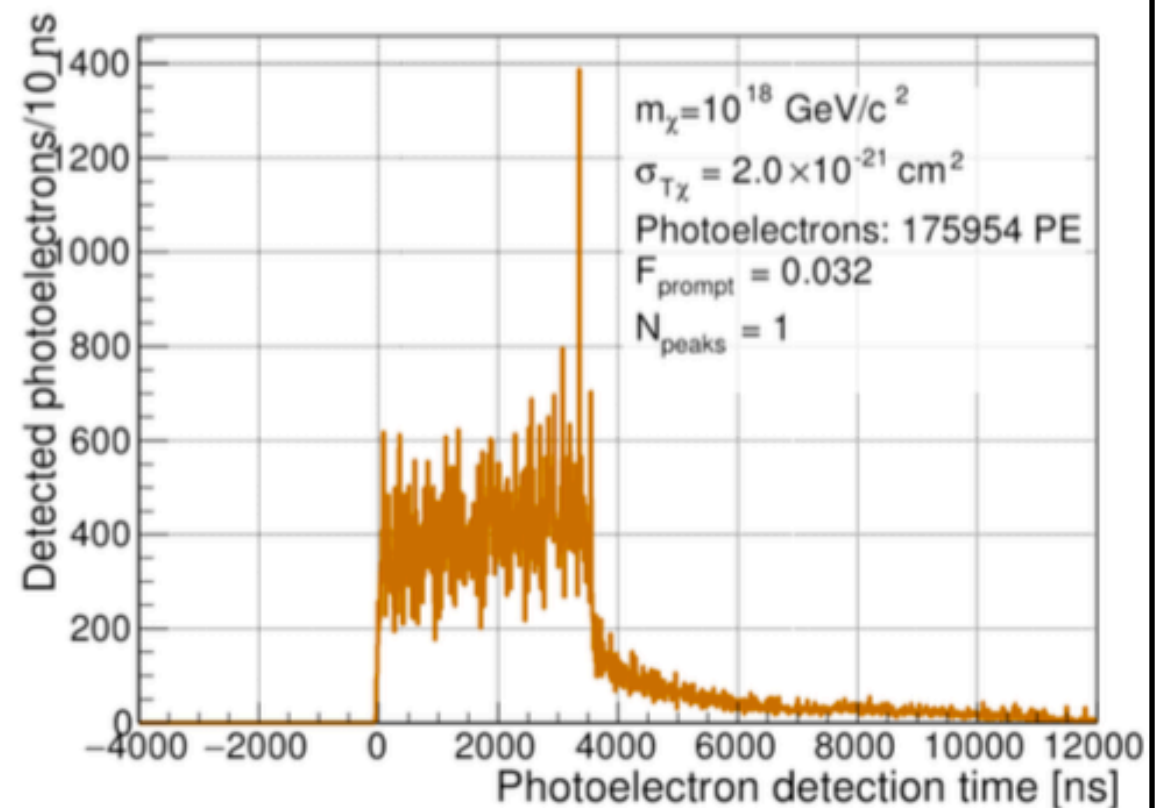
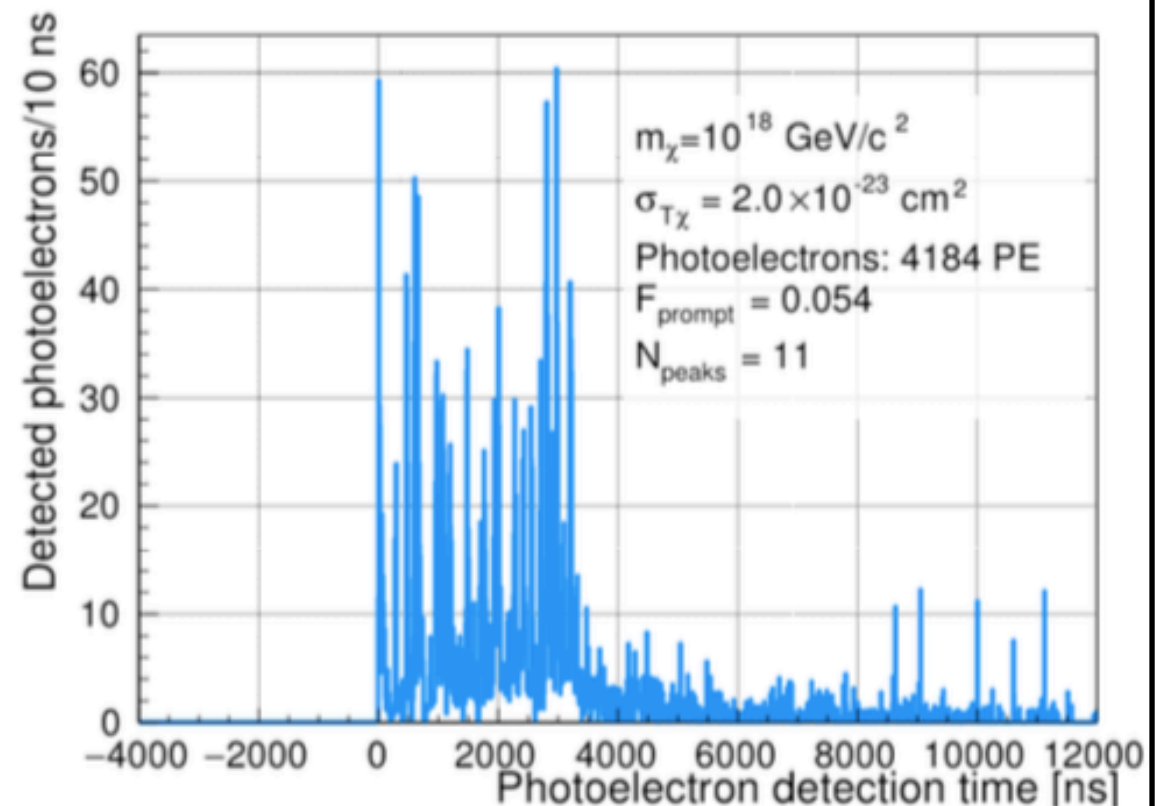
First Direct Detection Constraints on Planck-Scale Mass Dark Matter with Multiple-Scatter Signatures Using the DEAP-3600 Detector

P. Adhikari *et al.* (DEAP Collaboration)
Phys. Rev. Lett. **128**, 011801 – Published 5 January 2022

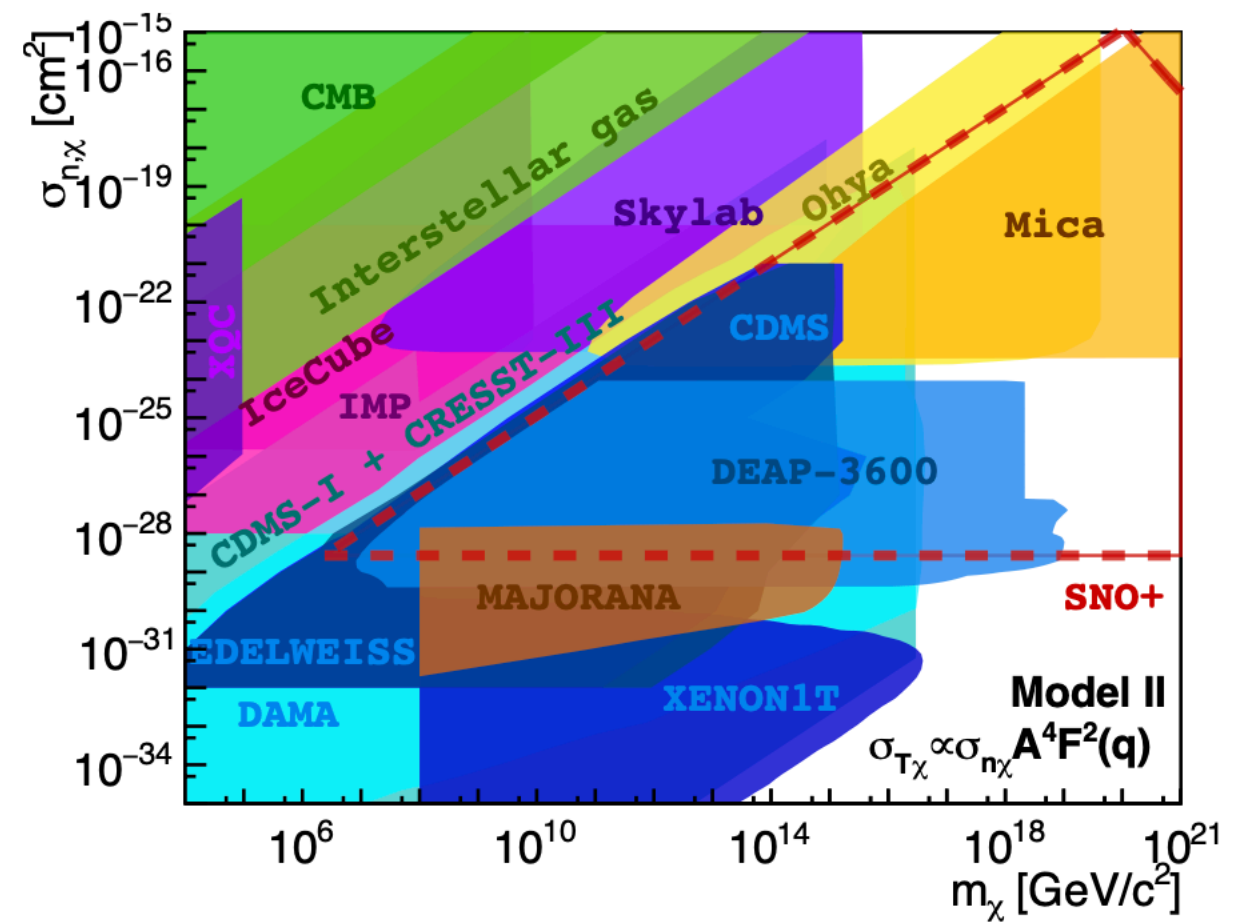
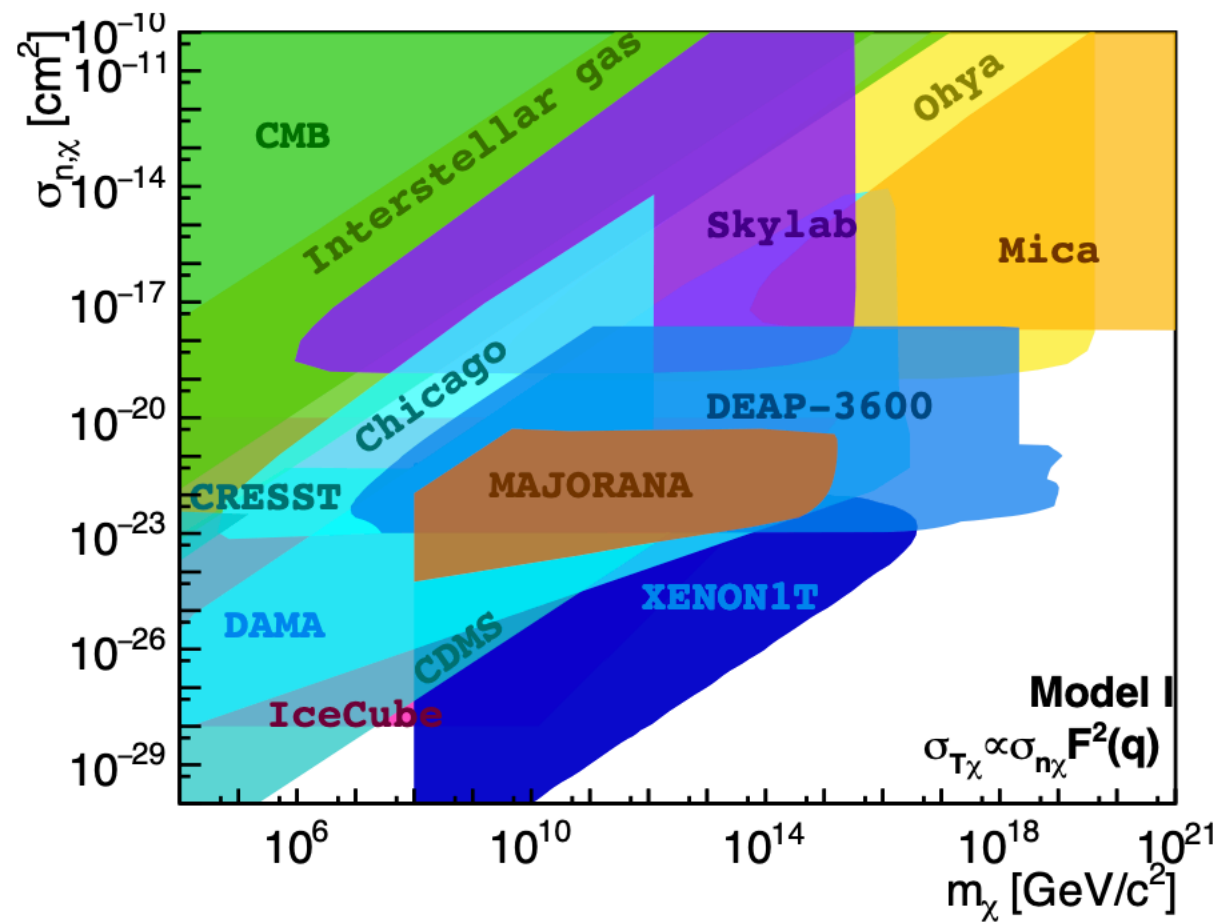
working group

W. Bonivento, S. Garg, M. Lai, N. Raj, S. Westerdale.

multiscatter signatures:
waveforms of energy
deposition in liquid argon

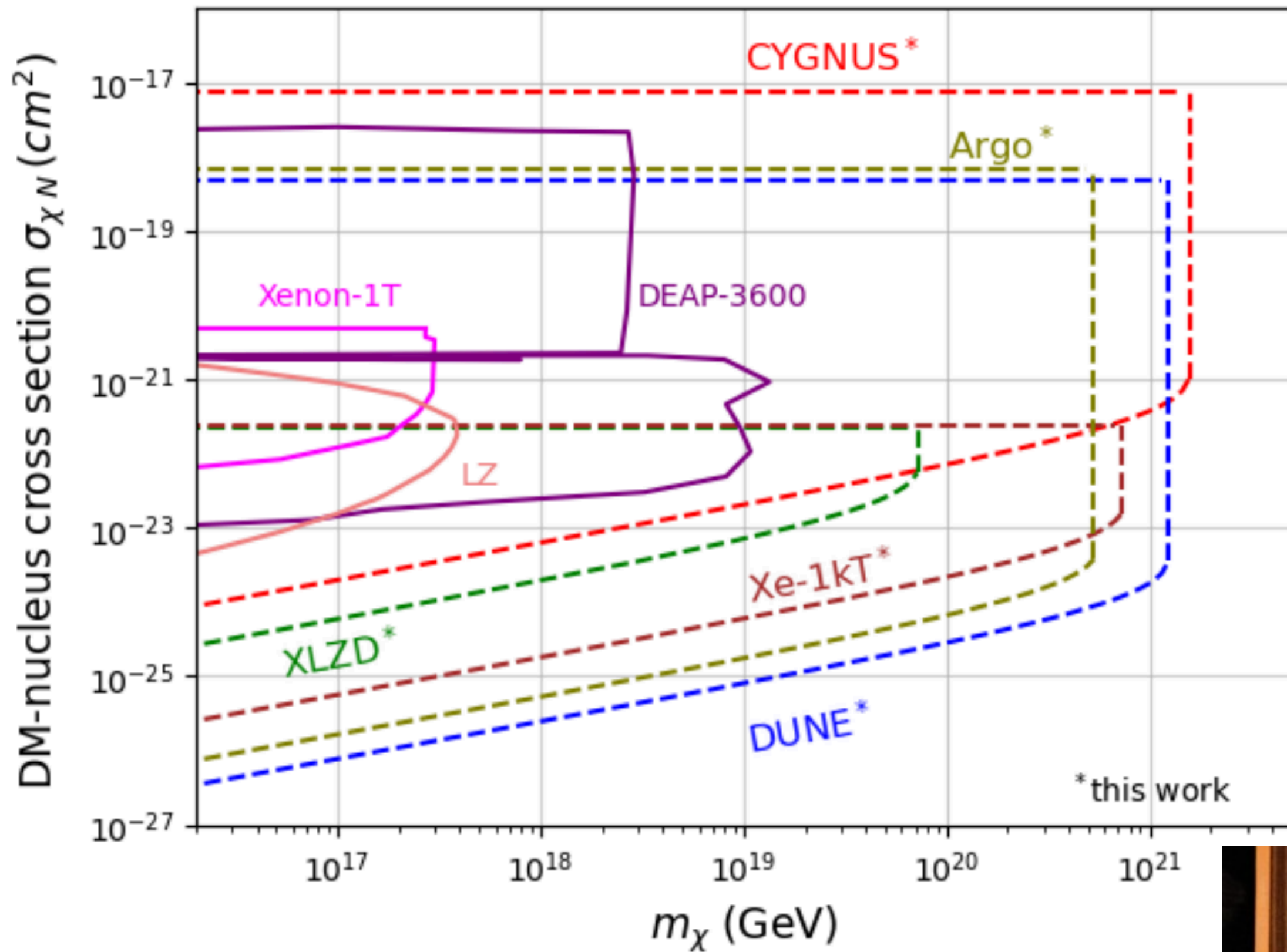


Landscape of ultraheavy dark matter



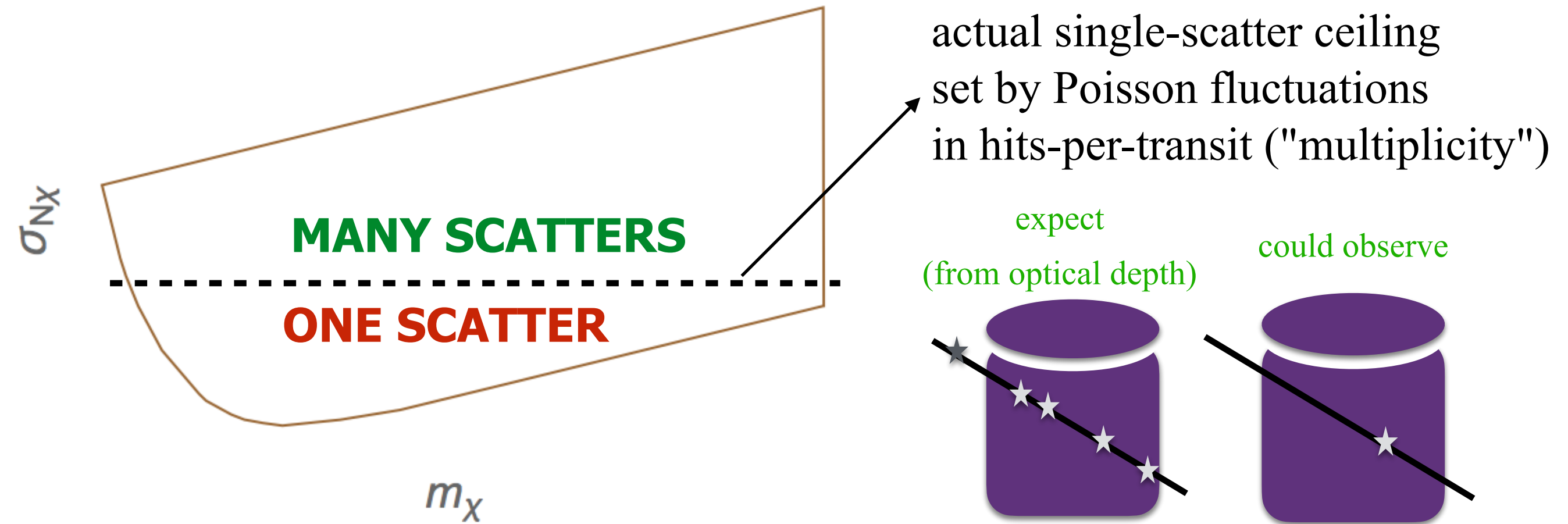
Snowmass whitepaper co-ordinated with Dan Carney; SciPost Phys Core 2023.

plus Yang Bai, Joshua Berger, Carlos Blanco, Joseph Bramante, Christopher Cappiello, Thomas Y Chen, Maira Dutra, Reza Ebadi, Kristi Engel, Edward Kolb, J. Patrick Harding, Jason Kumar, Gordan Krnjaic, Rafael F. Lang, Rebecca K. Leane, Benjamin V. Lehmann, Shengchao Li, Andrew J. Long, Gopolang Mohlabeng, Ibles Olcina, Elisa Pueschel, Nicholas L. Rodd, Carsten Rott, Dipan Sengupta, Bibhushan Shakya, Ronald L. Walsworth, Shawn Westerdale



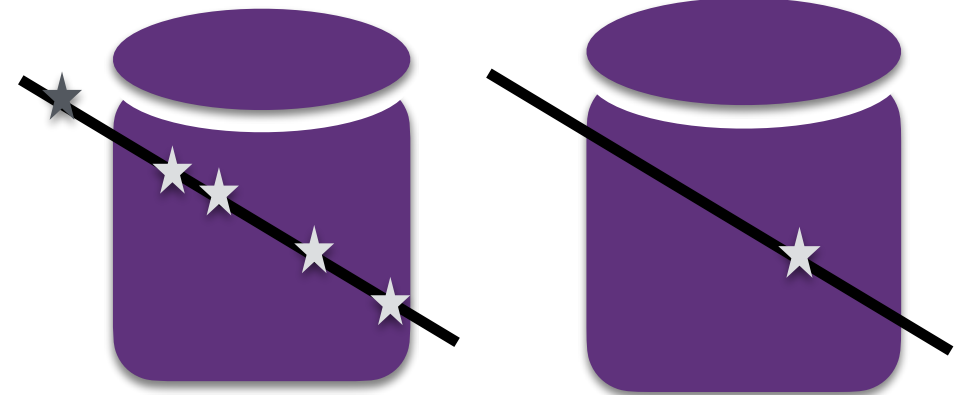
2410.22168, PRD 2025
with Harsh Aggarwal @ IIT-KG

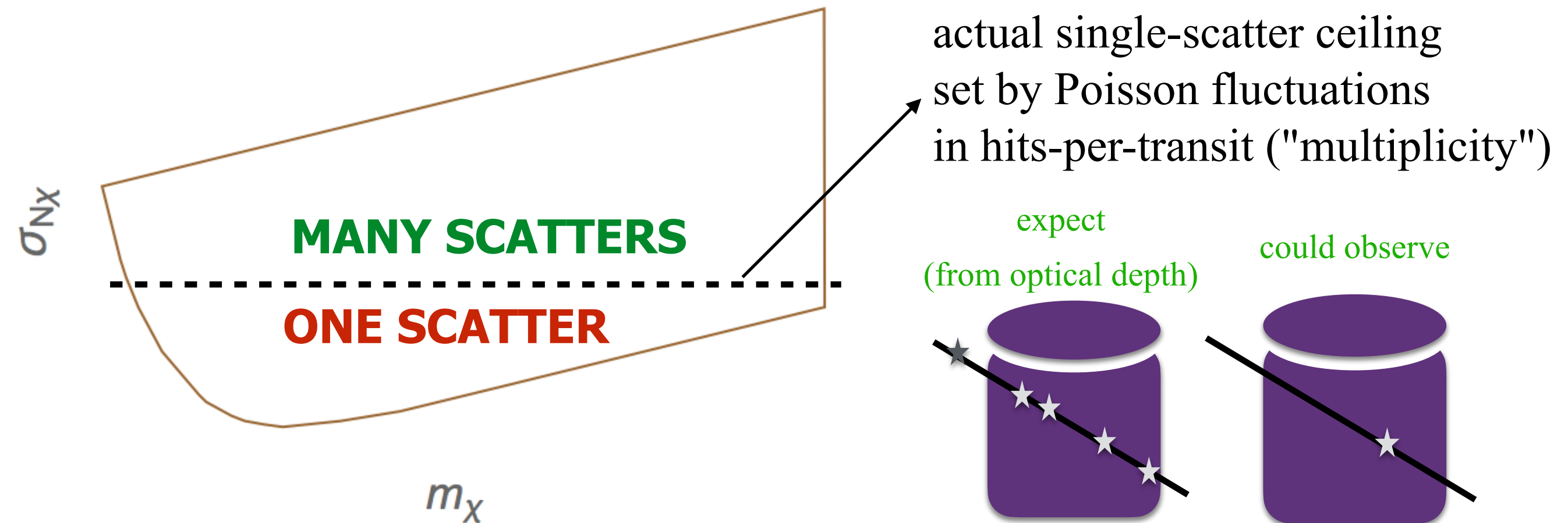




expect
(from optical depth)

could observe





Why care?

(i) identify correctly where "WIMP" searches apply!

(ii) Poisson fluctuations $\Rightarrow$ overlap with multi-scatter regions
 $\Rightarrow$ cross-confirmation of search results

gets tricky & interesting in the presence of
(imminent) neutrino background!

At "ghostly frontier", problem already tackled: "*neutrino floor*"
by analogy, we have "*neutrino roof*"

“WIMP” event rate familiar from literature

$$\begin{aligned} \frac{dR}{dE_R} &= \left(\frac{\rho_\chi}{m_\chi} \right) \epsilon_{\text{NR}} \int_{v_{\text{min}}}^{v_{\text{esc}}} d^3v v f_{\text{lab}}(\vec{v}) \frac{d\sigma_{\text{T}\chi}}{dE_R} , \\ \frac{d\sigma_{\text{T}\chi}}{dE_R} &= \frac{m_{\text{T}}}{2\mu_{\text{T}\chi}^2 v^2} \sigma_{\text{T}\chi} S(E_R) \end{aligned}$$

.....

“WIMP” event rate familiar from literature

$$\frac{dR}{dE_R} = \left(\frac{\rho_\chi}{m_\chi} \right) \epsilon_{\text{NR}} \int_{v_{\text{min}}}^{v_{\text{esc}}} d^3v v f_{\text{lab}}(\vec{v}) \frac{d\sigma_{T\chi}}{dE_R},$$

$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{m_T}{2\mu_{T\chi}^2 v^2} \sigma_{T\chi} S(E_R) \quad \text{--- detection efficiency}$$

$$\frac{d\sigma_{T\chi}}{dE_R} = \frac{m_T}{2\mu_{T\chi}^2 v^2} \sigma_{T\chi} S(E_R) \quad \text{--- structure factor}$$

.....

our generalization

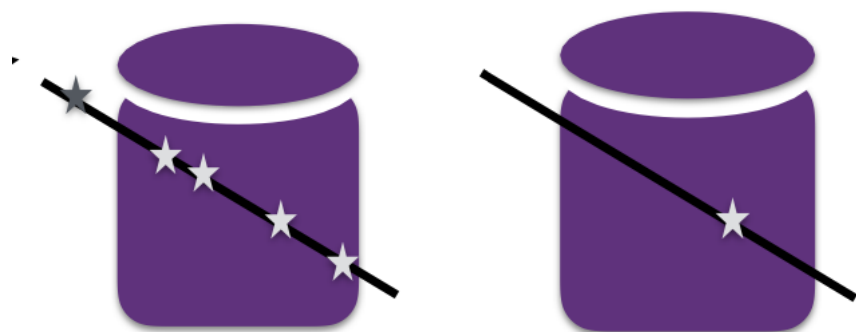
$$N_{\text{ev}}^{\text{SS}} = \epsilon_{\text{NR}} p_{\text{hit}}(1, N_{\text{hit}}^{\text{exp}}) \left(\frac{\rho_\chi}{m_\chi} \right) \pi R_{\text{fid}}^2 \bar{v} t_{\text{exp}}$$

“multiplicity”/ optical depth: $\sigma_{T\chi}^{\text{eff}} n_T L_{\text{ave}}$

$$p_{\text{hit}}(k, \lambda) = \frac{\lambda^k e^{-\lambda}}{k!}$$

expect

get

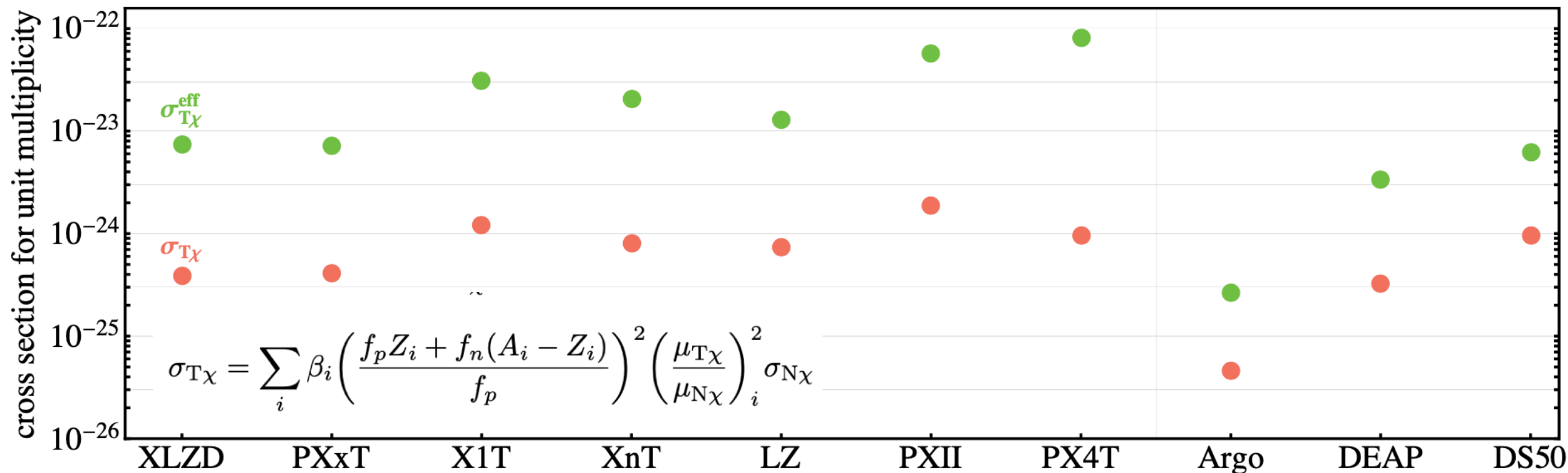


detectable total cross section:

$$\sigma_{T\chi} \frac{m_T}{2\mu_{T\chi}^2 \bar{v}} \int_{E_{R,\text{min}}}^{E_{R,\text{max}}} dE_R S(E_R) \eta(E_R)$$

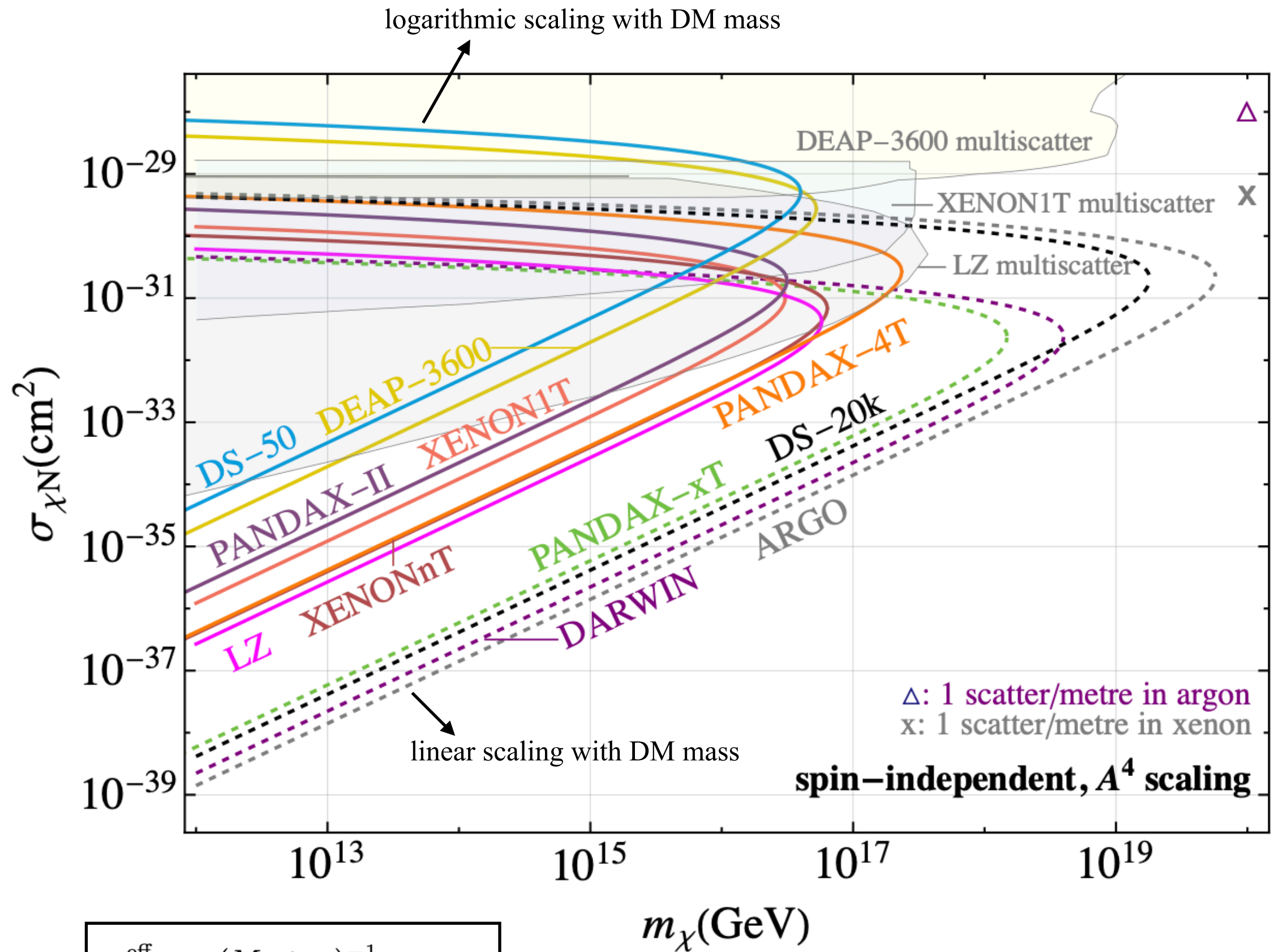
usual “velocity integral”

$N_{\text{hit}}^{\text{exp}} \ll 1$

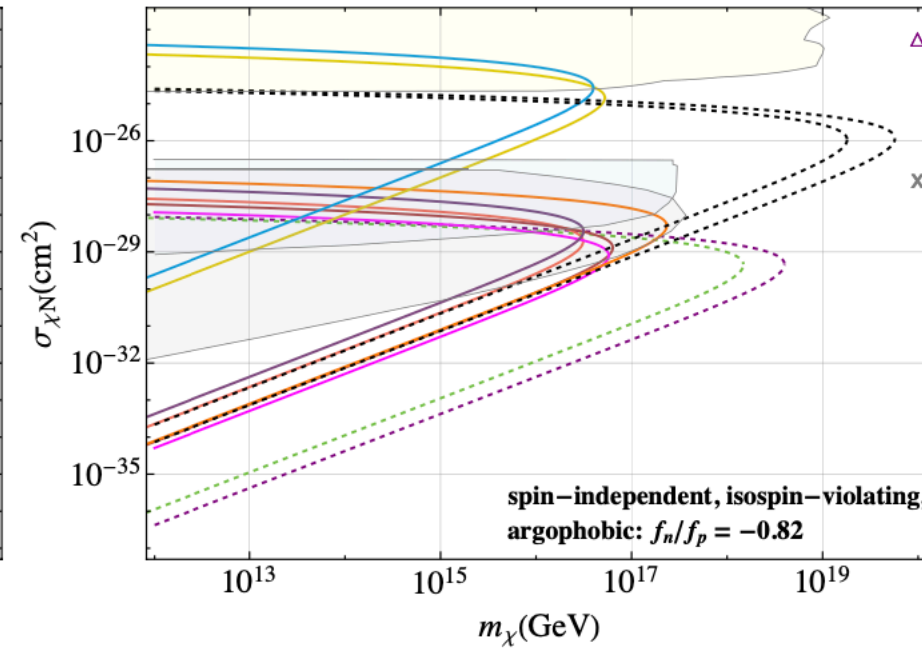
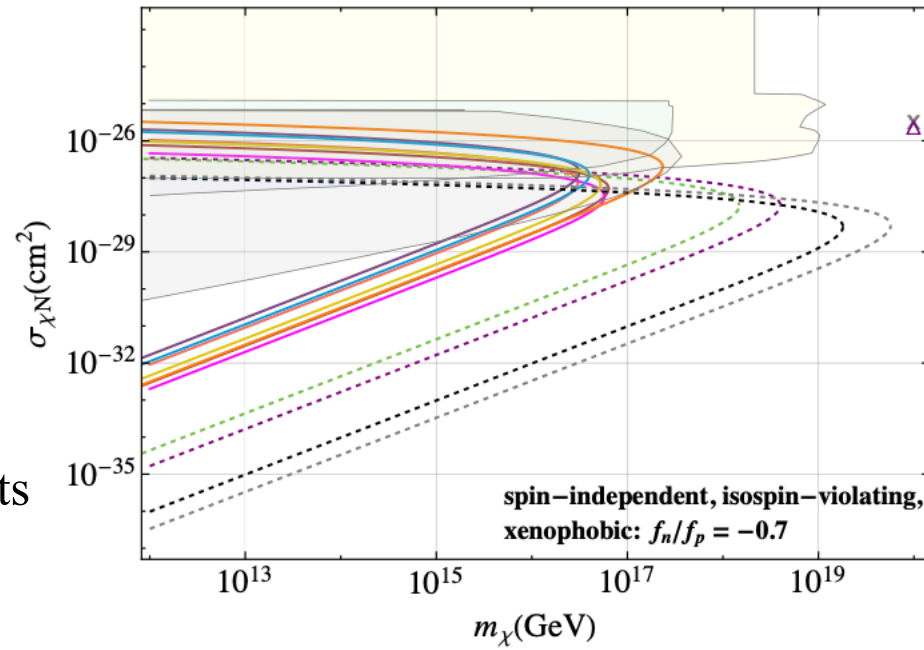
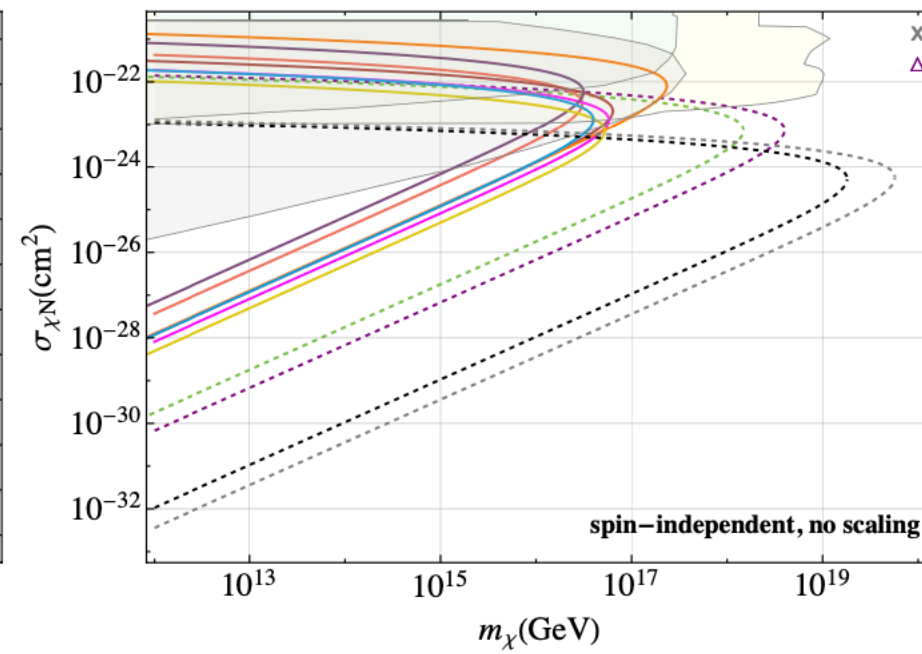
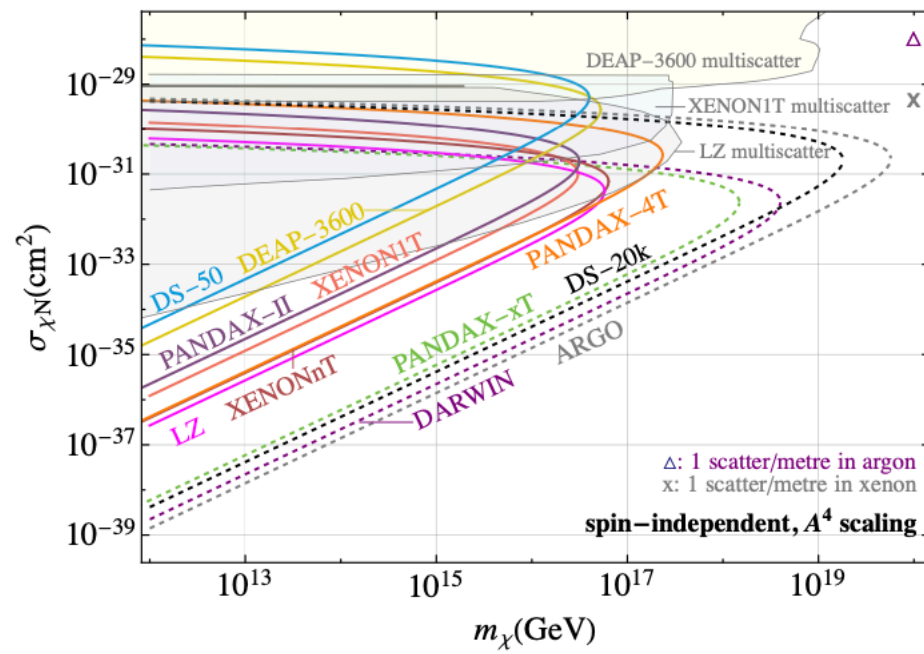


target	detector	$M_{\text{fid}} \times t_{\text{exp}}$ (ton × yr)	E_R (keV)	ϵ_{NR}	$(N_B \pm \sigma_B, N_{\text{obs}}, N_{\text{exp}}^{90\text{CL}})$
xenon 2.94 g/cm ³ ¹²⁸ 1.9%, ¹²⁹ _{SD} 26.4%, ¹³⁰ 4.1% ¹³¹ _{SD} 21.2%, ¹³² 26.9%, ¹³⁴ 10.4%, ¹³⁶ 8.9%	DARWIN/XLZD [21]	40 × 5	[5, 35]	0.50	(4.1, 4.1, 4.0)
	PANDAX-xT [23]	34.2 × 5.85	[4, 35]	0.50	(48±6.9, 48, 11.4)
	XENON1T [19]	1.3 × 0.76	[10, 40]	0.80	(7.4±0.6, 14, 12.8)
	XENONnT [34]	4.18 × 0.26	[10, 40]	0.80	(2.03±0.16, 3, 4.7)
	LZ [35]	5.5 × 0.16	[5, 50]	0.90	(-, -, 4.4)
	PANDAX-II [36]	0.33 × 1.1	[10, 30]	0.85	(40.3±3.1, 38, 7.8)
	PANDAX-4T [37]	2.67 × 0.24	[30, 90]	0.75	(9.8±0.6, 6, 0.8)
	KILOXENON	40 × 25	[5, 35]	0.50	(20.6±6.1, 20.6 $\times \frac{2}{2}$, 10.9 $^{+6.3}_{-6.7}$)
argon 1.40 g/cm ³ ³⁶ 0.33%, ³⁸ 0.06%, ⁴⁰ 99.6%	MYRIAXENON	10 ³ × 10	[5, 35]	0.50	(206±44, 206 $\times \frac{2}{2}$, 60 $^{+44}_{-45}$)
	DarkSide-20k [24]	20 × 10	[30, 200]	0.90	(3.2, 3.2, 3.7)
	Argo [25]	300 × 10	[55, 100]	0.90	(15.6±5, 15.6, 6.4)
	DarkSide-50 [38]	0.031 × 1.46	[80, 200]	0.70	(0, 0, 2.3)
	DEAP-3600 [39]	0.824 × 0.63	[70, 100]	0.24	(0, 0, 2.3)
	MYRIARGON	300 × 33.3	[55, 100]	0.90	(51.5±12.6, 51.5 $\times \frac{2}{2}$, 19.7 $^{+13.1}_{-13.2}$)
	DECIMEGARGON	10 ⁴ × 10	[55, 100]	0.90	(515±106, 515 $\times \frac{2}{2}$, 174 $^{+106}_{-106}$)

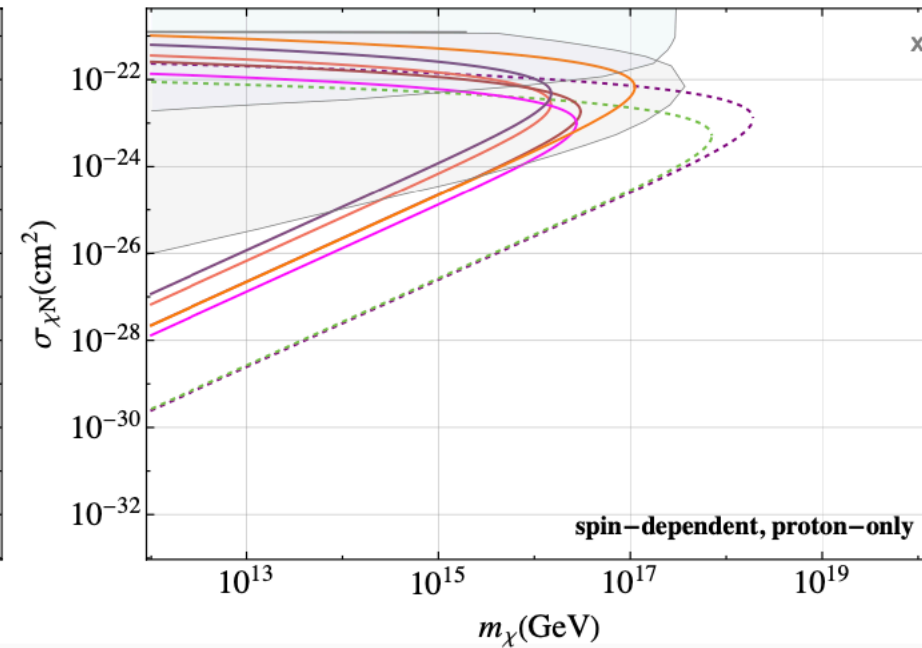
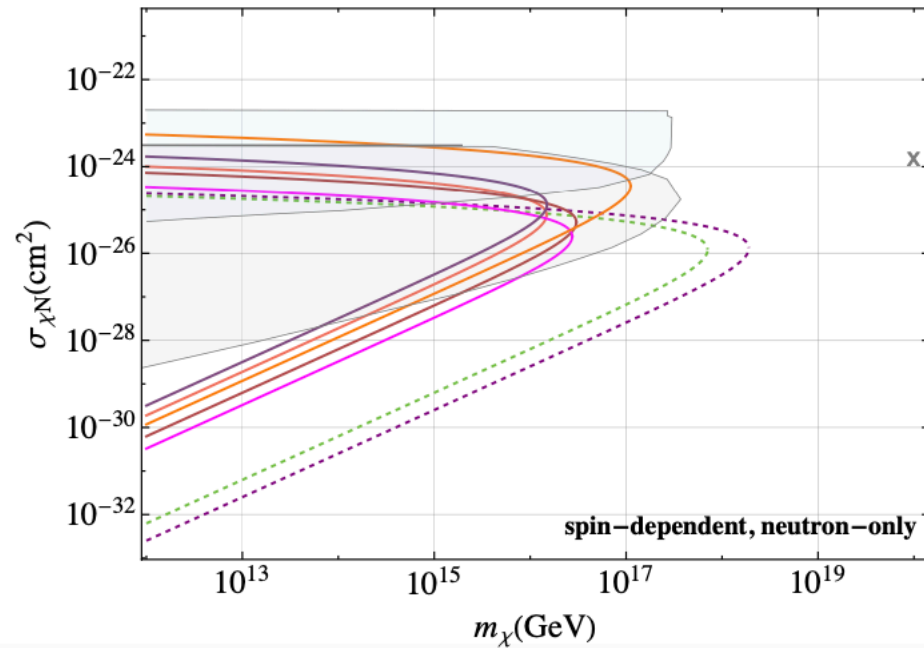
noble detector masses motivated by $0\nu\beta\beta$ -driven research & DUNE: see 2404.19050, 2301.11878, ...



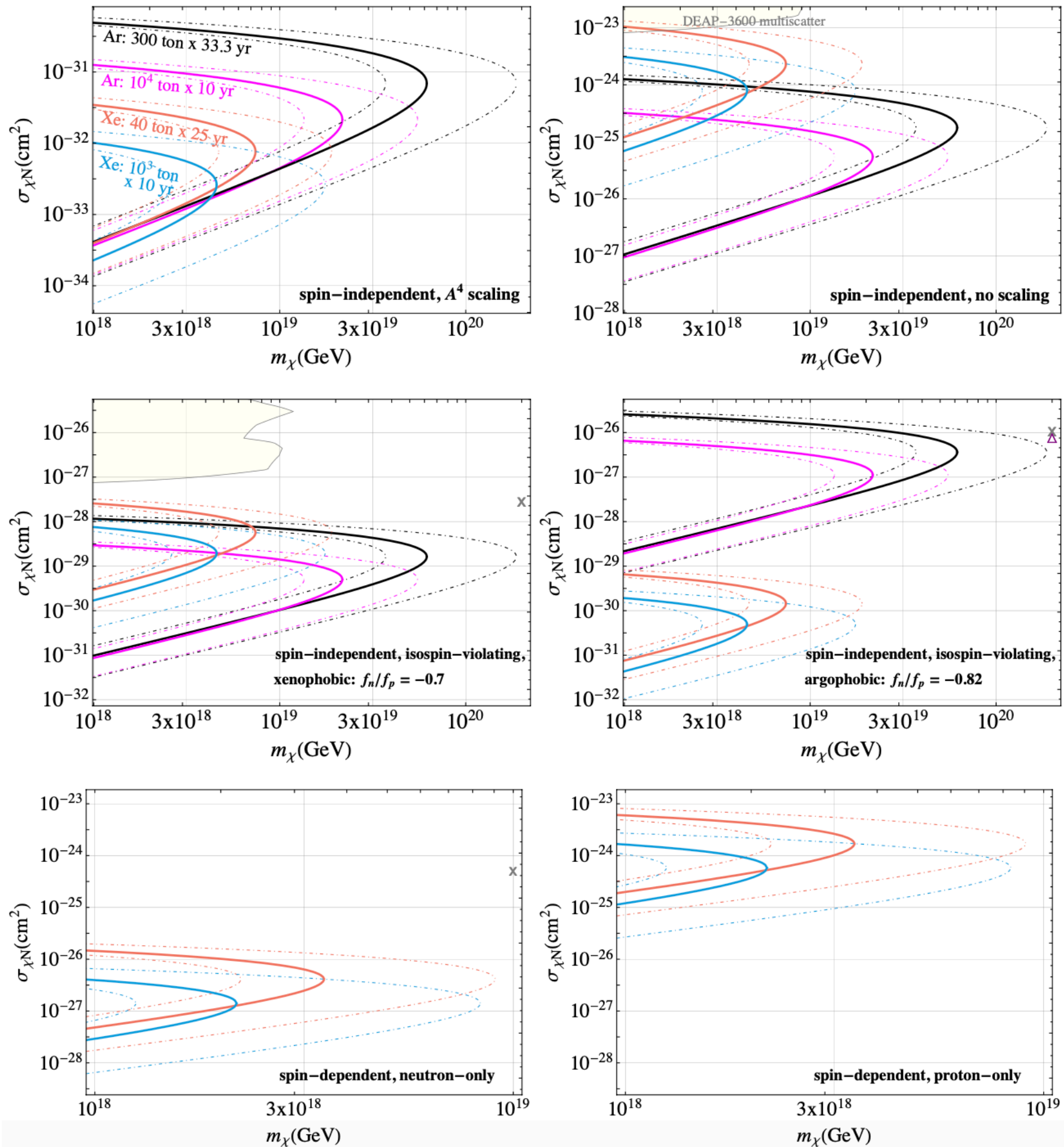
floor	$b\sigma_{T\chi}^{\text{eff}} \propto (M_{\text{fid}} t_{\text{exp}})^{-1},$
ceiling	$t\sigma_{T\chi}^{\text{eff}} \propto M_{\text{fid}}^{-1/3} \log(M_{\text{fid}}^{2/3} t_{\text{exp}})$



Ar-phobic roofs
good news for
argon experiments

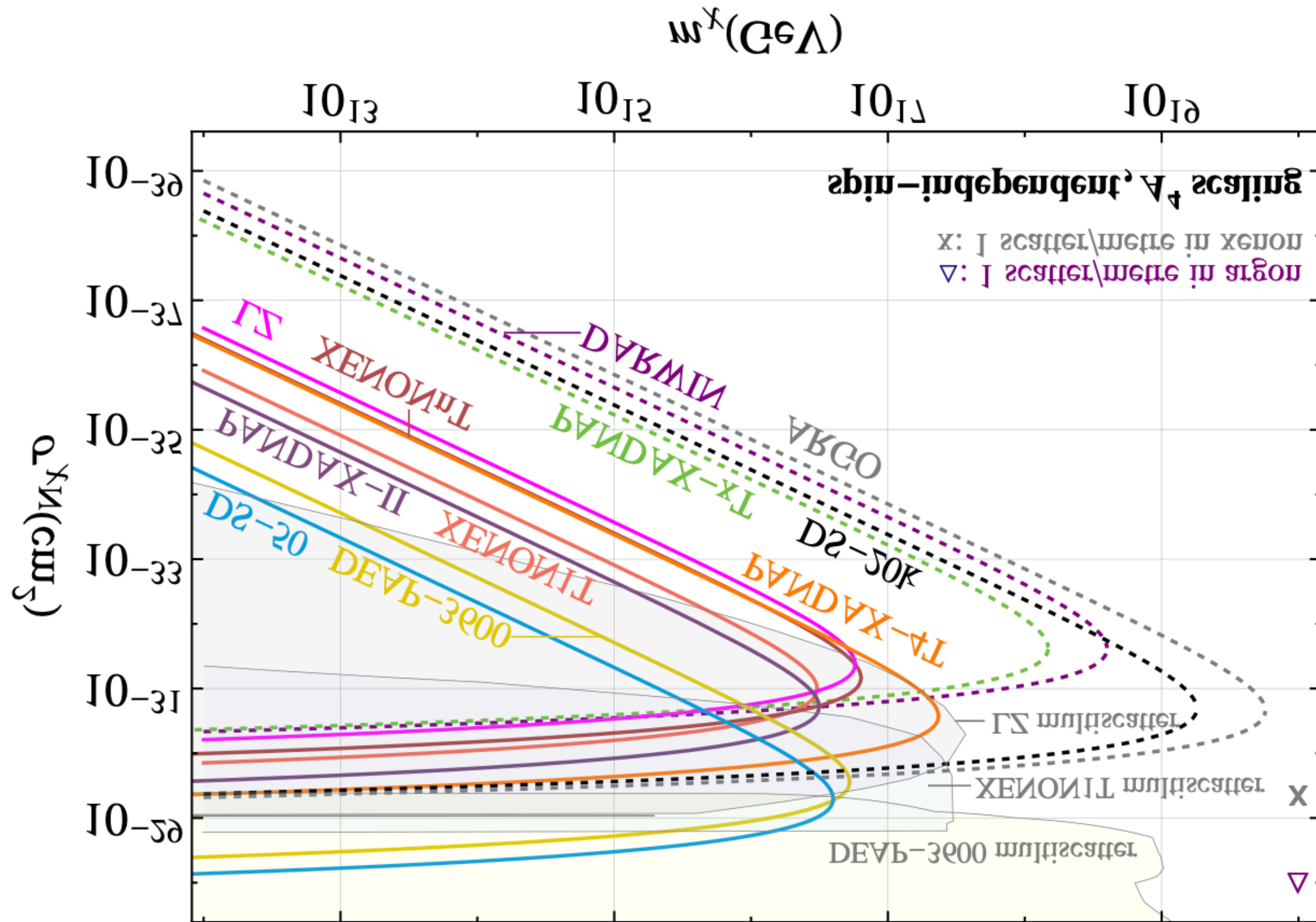


Xe-phobic floors
good news for
argon experiments

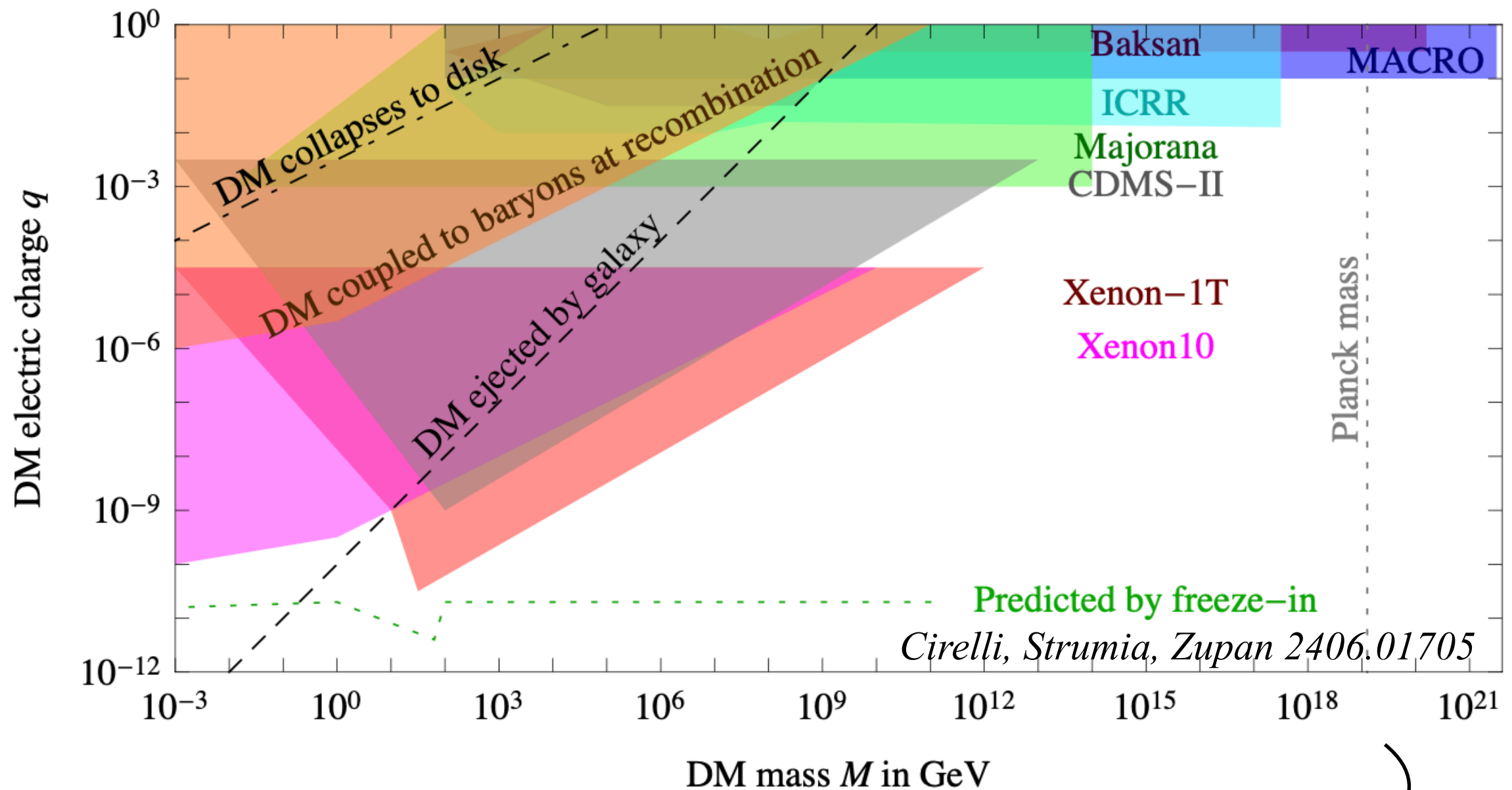


Conclusion

Ceilings are as important as floors!



Dark Maxwell



update for

$$\mathcal{L}_{\text{int}} = Q_{\chi} e \bar{\chi} \gamma^{\mu} \chi A_{\mu} + \frac{\mu_{\chi}}{2} \bar{\chi} \sigma^{\mu\nu} \chi F_{\mu\nu} + \frac{d_{\chi}}{2} i \bar{\chi} \sigma^{\mu\nu} \gamma^5 \chi F_{\mu\nu} + \mathcal{A}_{\chi} \bar{\chi} \gamma^{\mu} \gamma^5 \chi \partial^{\nu} F_{\mu\nu} + b_{\chi} \bar{\chi} \gamma^{\mu} \chi \partial^{\nu} F_{\mu\nu}$$

ongoing work with B. Mondal, G. Muralidhara, S. Saini

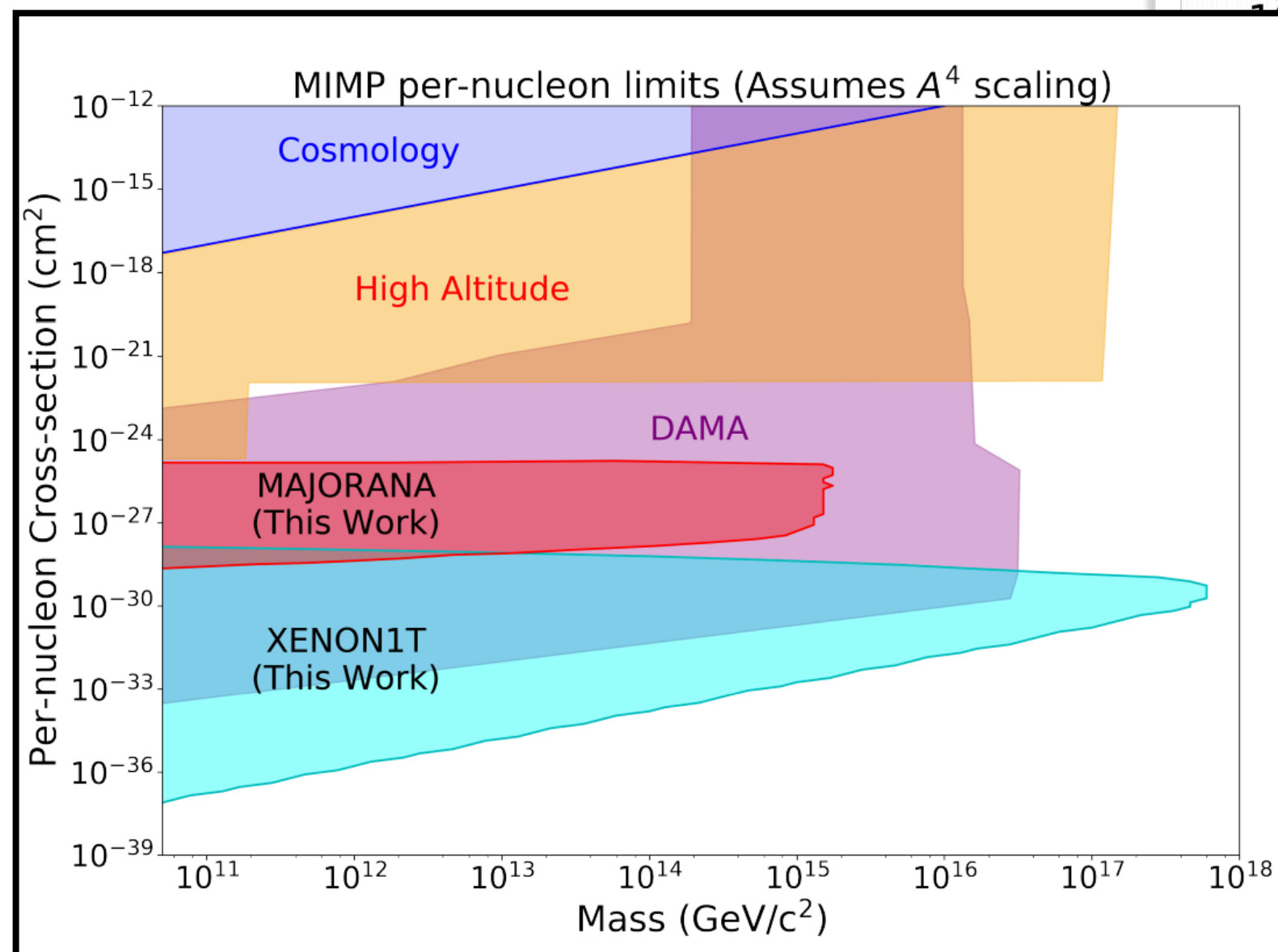
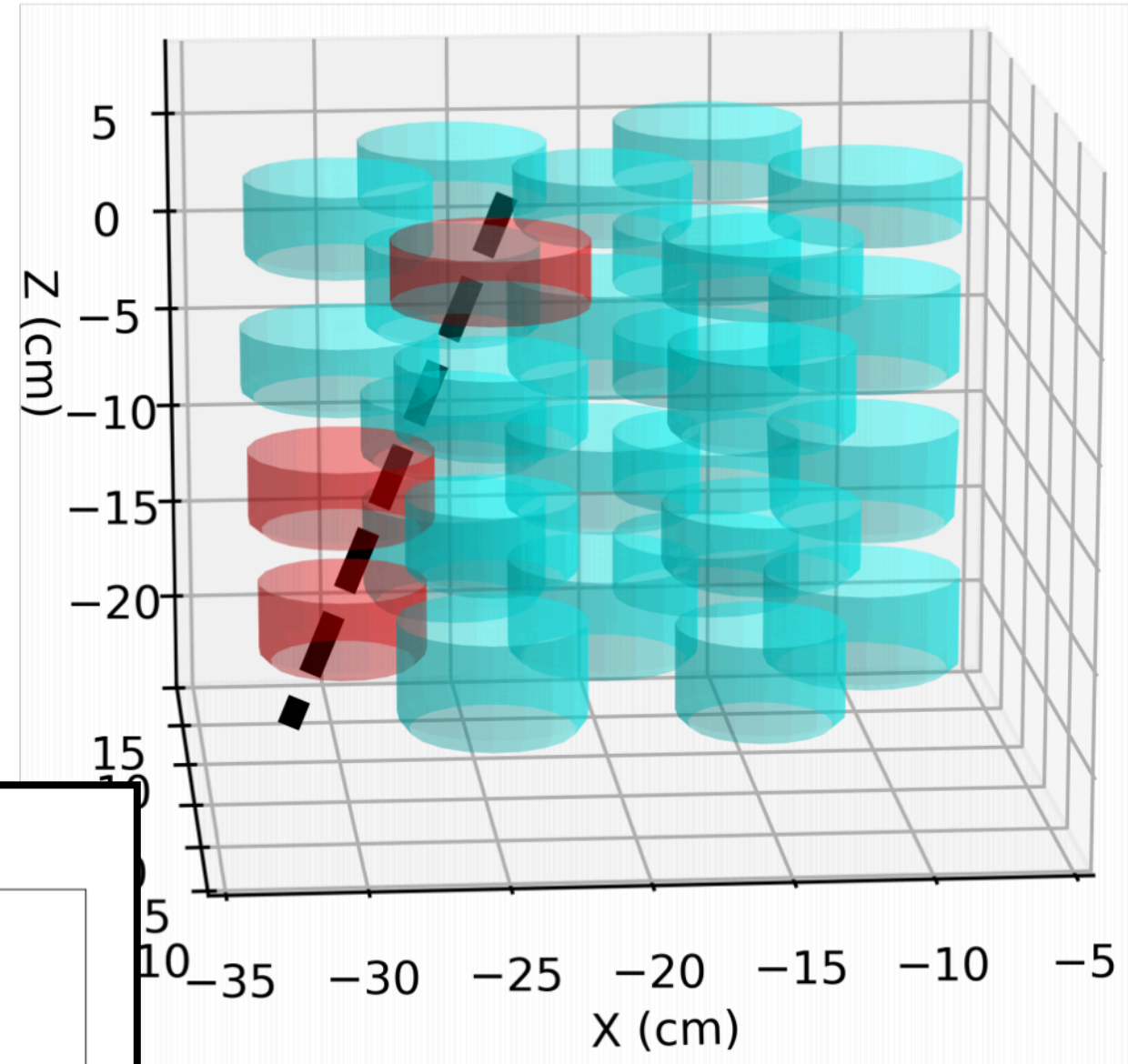


?

recasting

MAJORANA DEMONSTRATOR

search for lightly ionizing particles



‘Direct Detection Limits on Heavy Dark Matter’

2009.07909

M. Clark, R. Lang et al

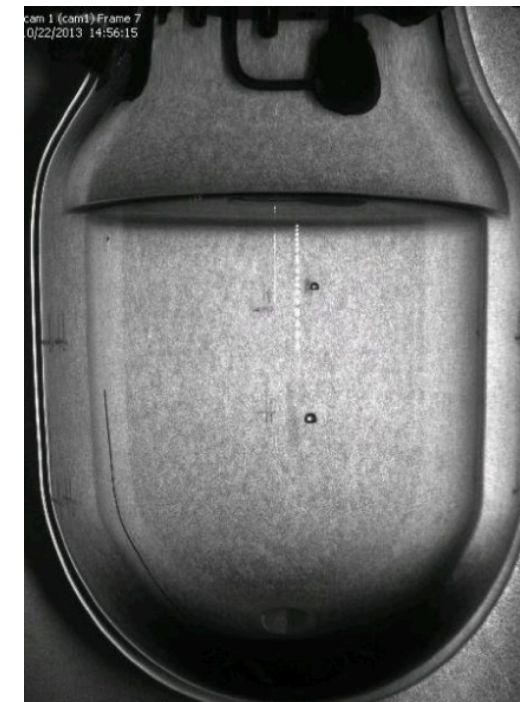
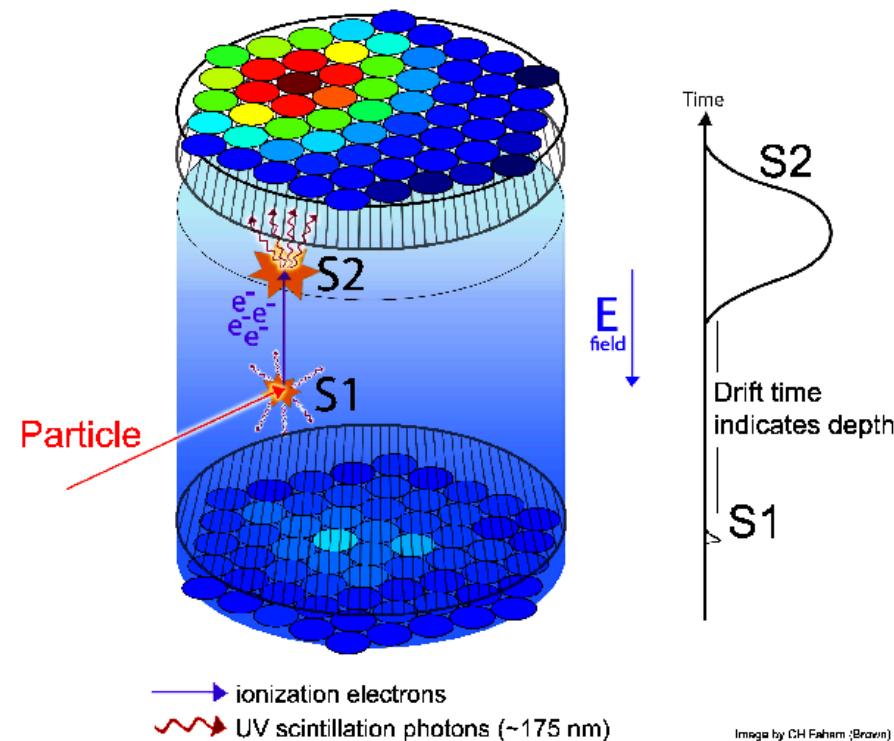
(Q1) Identifying multiscatterers

DM transit = $2.5 \mu\text{s}$

LUX/PANDAX/XENON1T

PICO-60

WIMP:



MIMP:

Train of scintillation pulses +
electroluminescence pulses

For multiplicity > 5 (> 500), S2 (S1)
pulses merge into elongated pulses

Track of bubbles

Stereo cameras can image up to
100 bubbles (mm resolution)

- Background ~ 0 (from daughter neutrons of surrounding material &
coincident electron recoils)

(Q1) Going to the Planck mass

DEAP-3600 @ SNOLAB

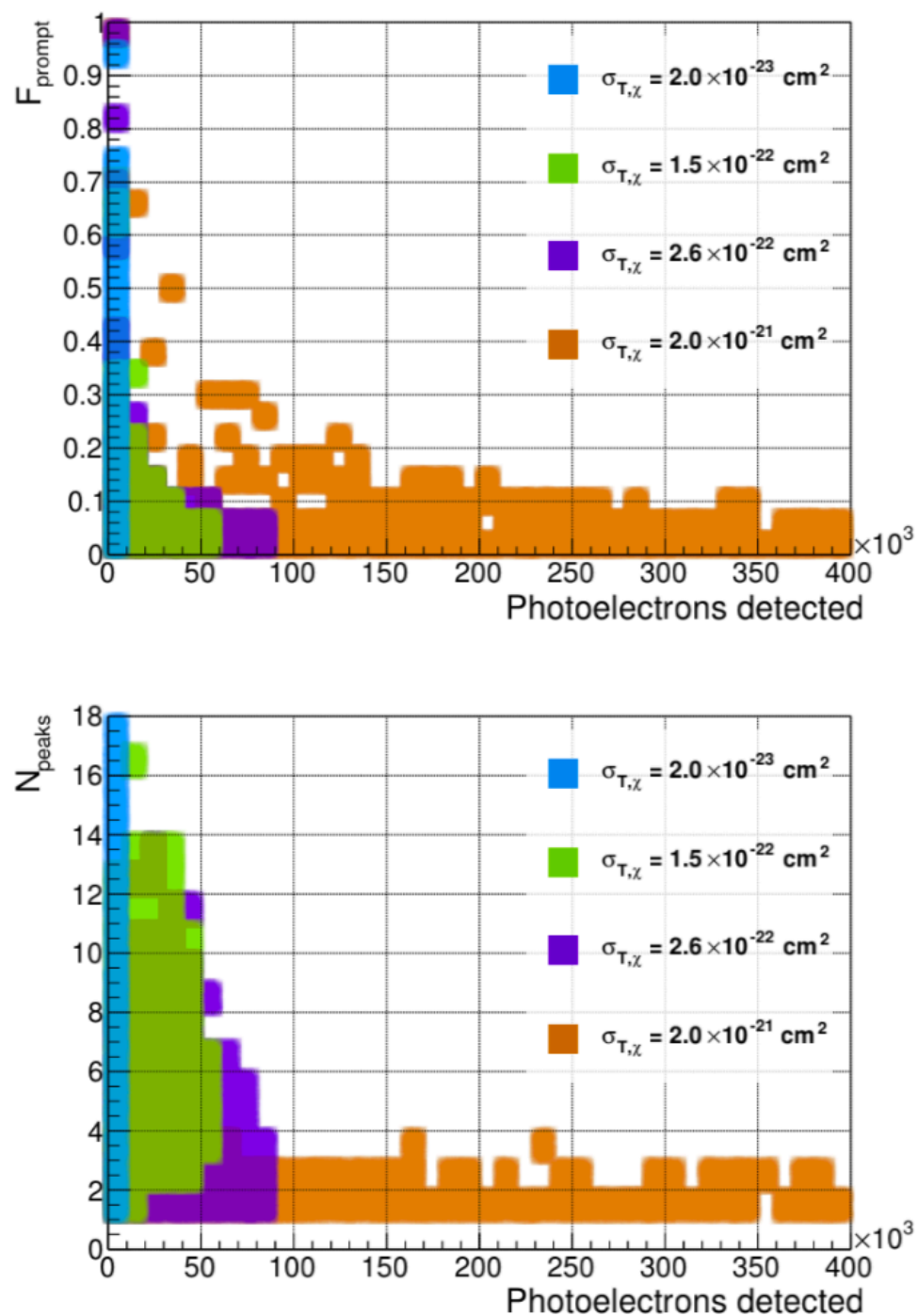


FIG. 2. Simulated F_{prompt} and N_{peaks} distributions for DM with $m_\chi = 10^{18} \text{ GeV}/c^2$ for various $\sigma_{T\chi}$.

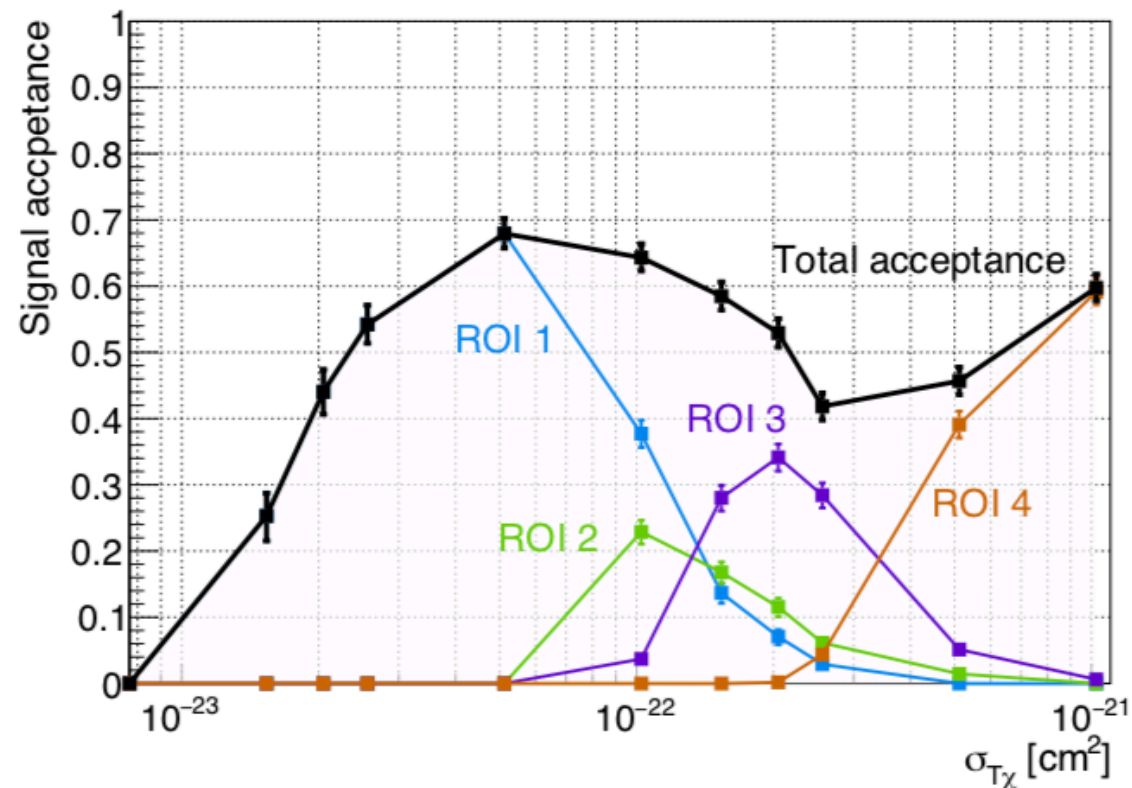
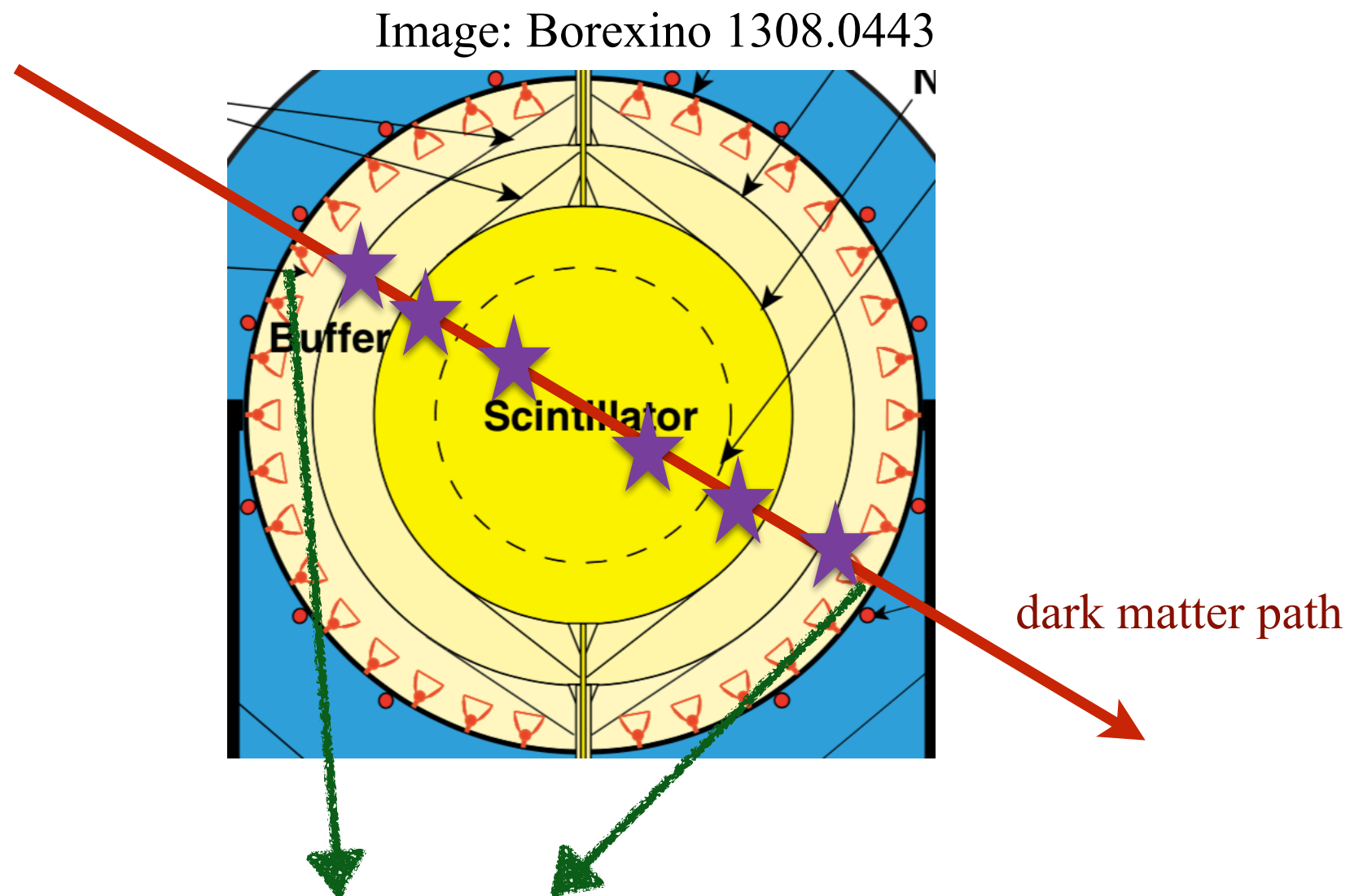


FIG. 3. Probability of DM with $m_\chi = 10^{18} \text{ GeV}/c^2$ populating each ROI and surviving all cuts at varying $\sigma_{T\chi}$.

ROI	PE range	Energy [MeV]	$N_{\text{peaks}}^{\text{min}}$	$F_{\text{prompt}}^{\text{max}}$	μ_b	$N_{\text{obs.}}$
1	4000–20 000	0.5–2.9	7	0.10	$(4 \pm 3) \times 10^{-2}$	0
2	20 000–30 000	2.9–4.4	5	0.10	$(6 \pm 1) \times 10^{-4}$	0
3	30 000–70 000	4.4–10.4	4	0.10	$(6 \pm 2) \times 10^{-4}$	0
4	70 000– 4×10^8	10.4–60 000	0	0.05	$(10 \pm 3) \times 10^{-3}$	0

Reconstructing dark matter velocity vector



PMT “hot spots”
with numerous illuminations
=> **dark matter direction & path length**
+ timestamps
=> **dark matter speed**

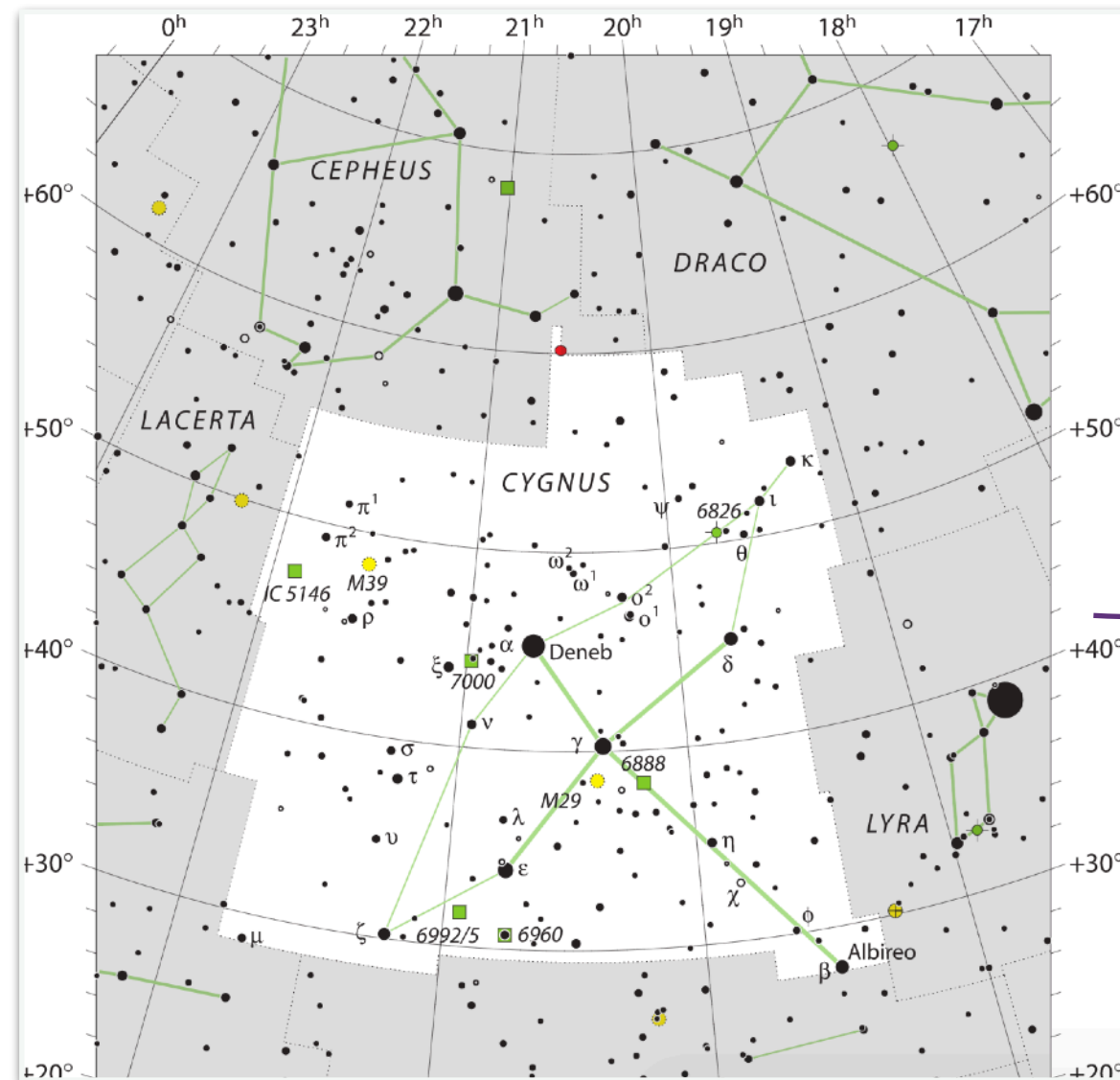
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Detector resolutions

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$$\delta\psi \simeq \frac{\Delta d}{L} \quad (\text{PMT spacing/ path length})$$

Variable uncertainty	Baseline resolution
angle: $\delta\psi$	3.7×10^{-2}



~2 degrees,
c.f. Cygnus
spanning > 20 degrees

Detector resolutions

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$$\delta\psi \simeq \frac{\Delta d}{L} \quad (\text{PMT spacing/ path length})$$

$$(\delta\psi)^2 / 2$$

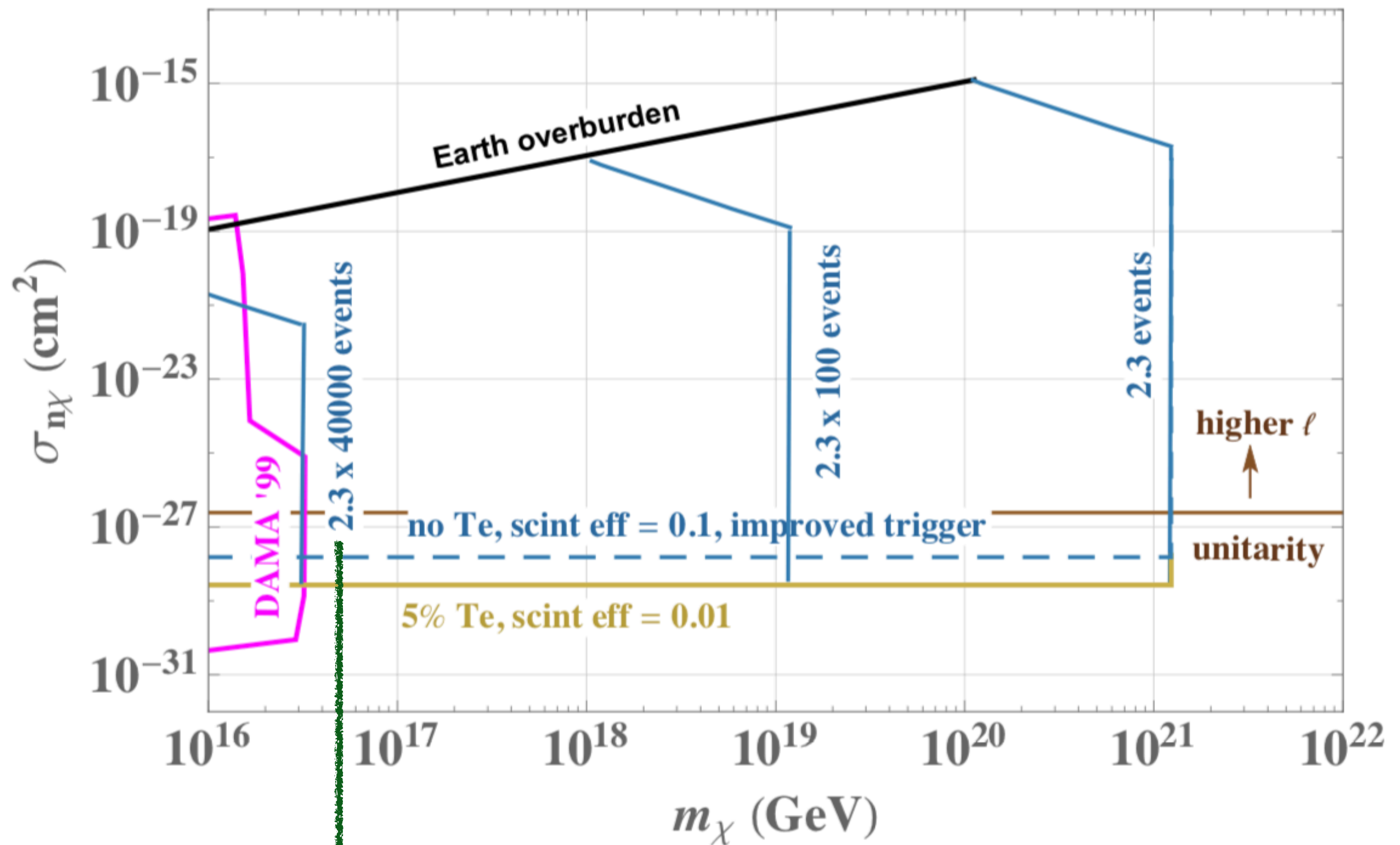
Variable uncertainty	Baseline resolution
angle: $\delta\psi$	3.7×10^{-2}
longitudinal path length: $\delta L/L$	6.7×10^{-4}
timing: $\delta T/T$	10^{-4}
speed: $\delta \mathbf{v}/\mathbf{v}$	6.7×10^{-4} (< 1 km/s)

detector timing resolution

$$\frac{\delta v}{v} = \sqrt{\left(\frac{\delta L}{L}\right)^2 + \left(\frac{\delta T}{T}\right)^2}$$

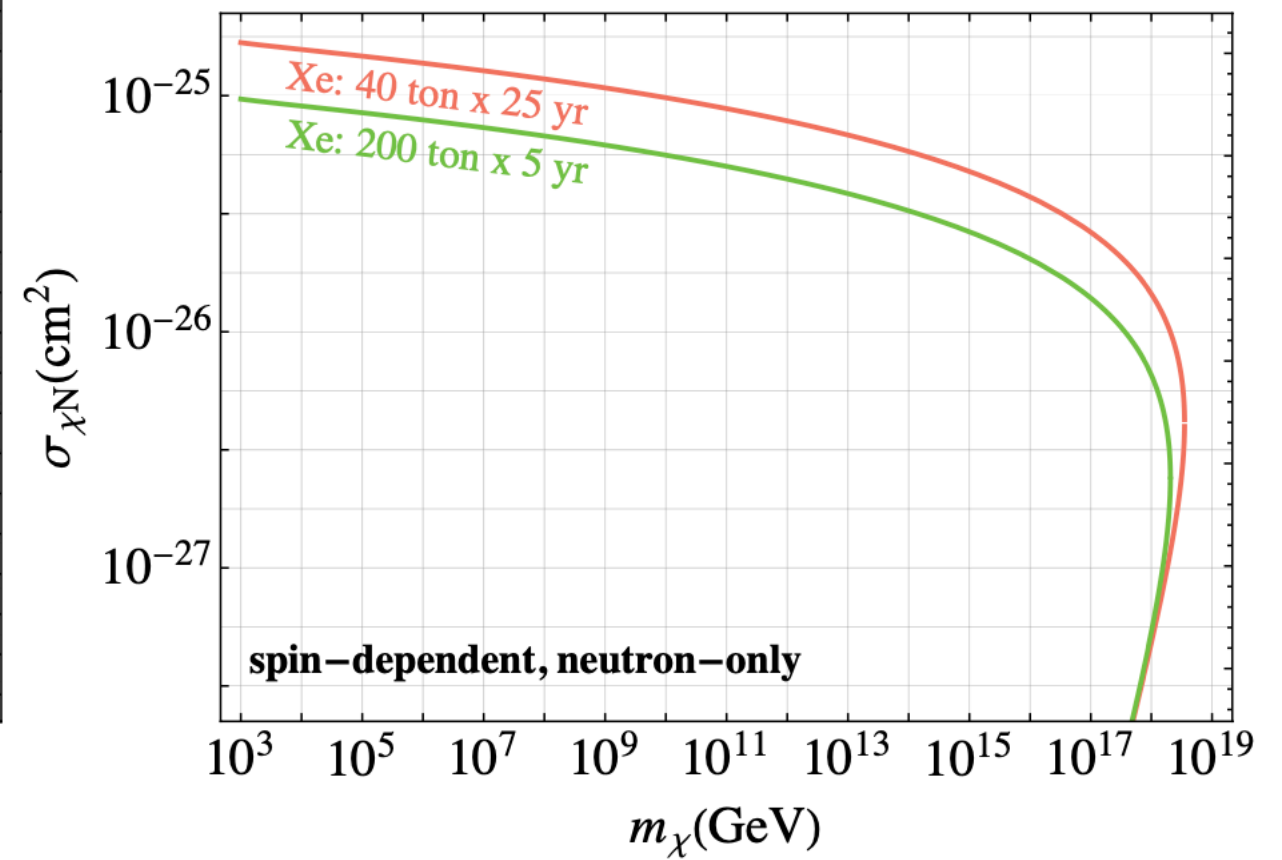
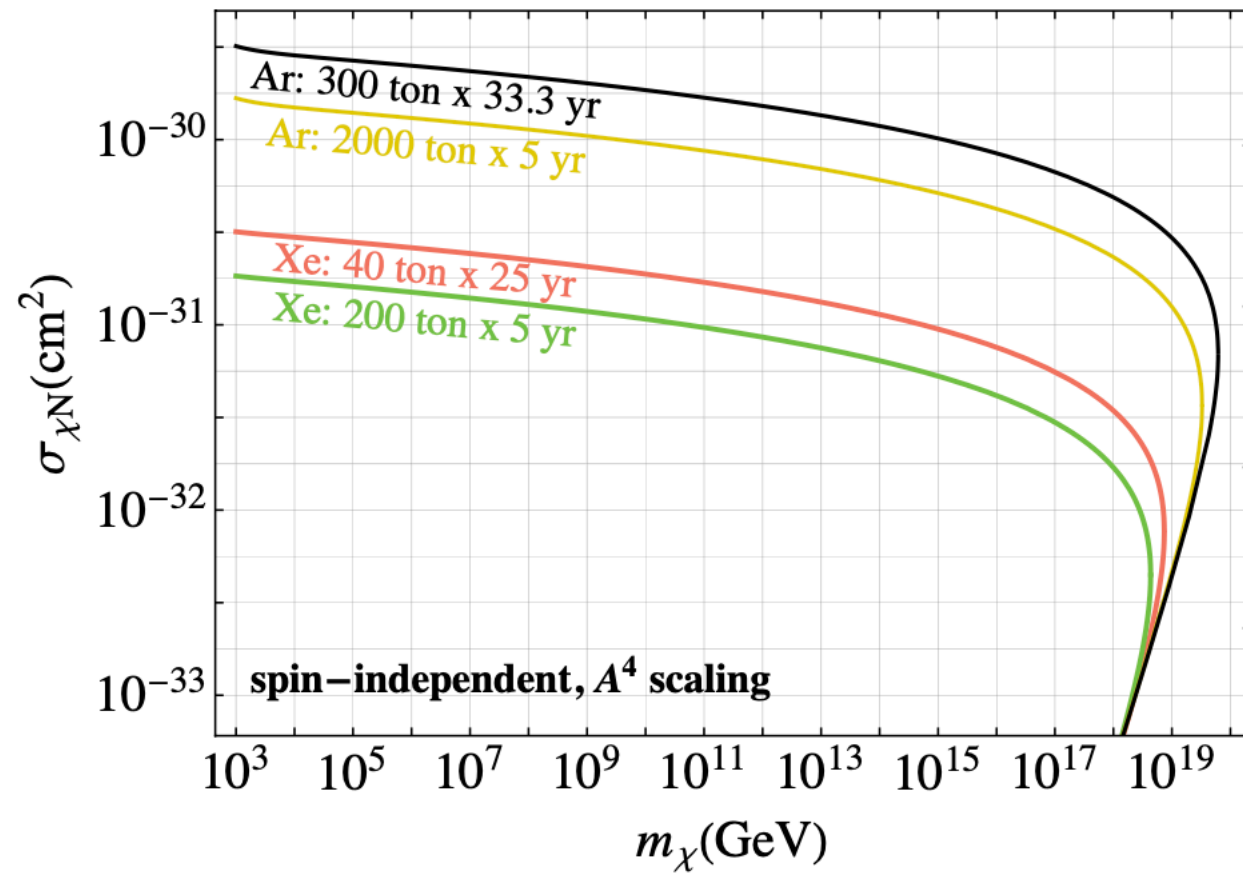
detector uncertainties tiny => smearing negligible => main limitation is statistics!
 (triumph of experimental progress)

Statistics

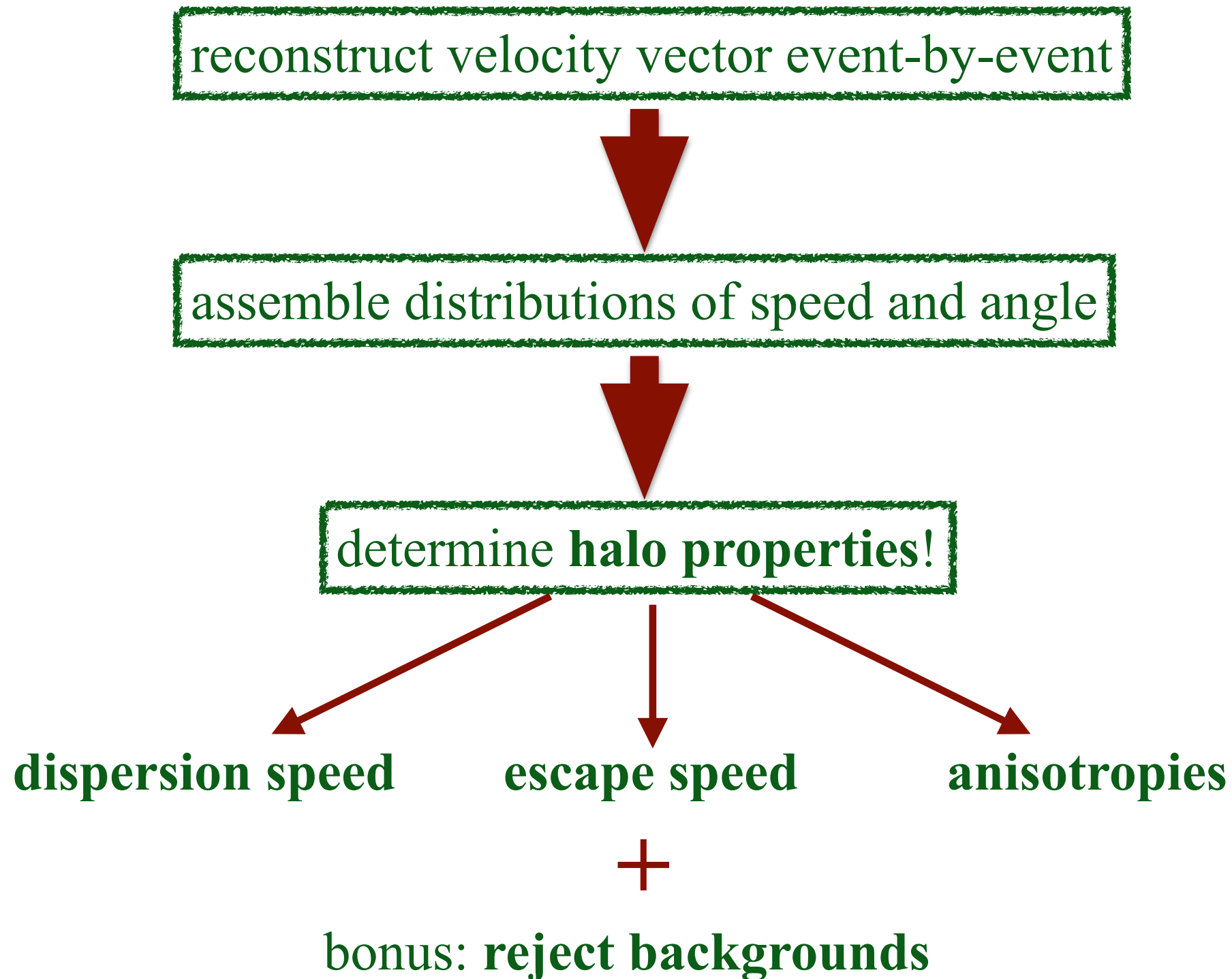


SNO+ could potentially collect these many events

different scalings with detector mass & exposure



Dark astrometry

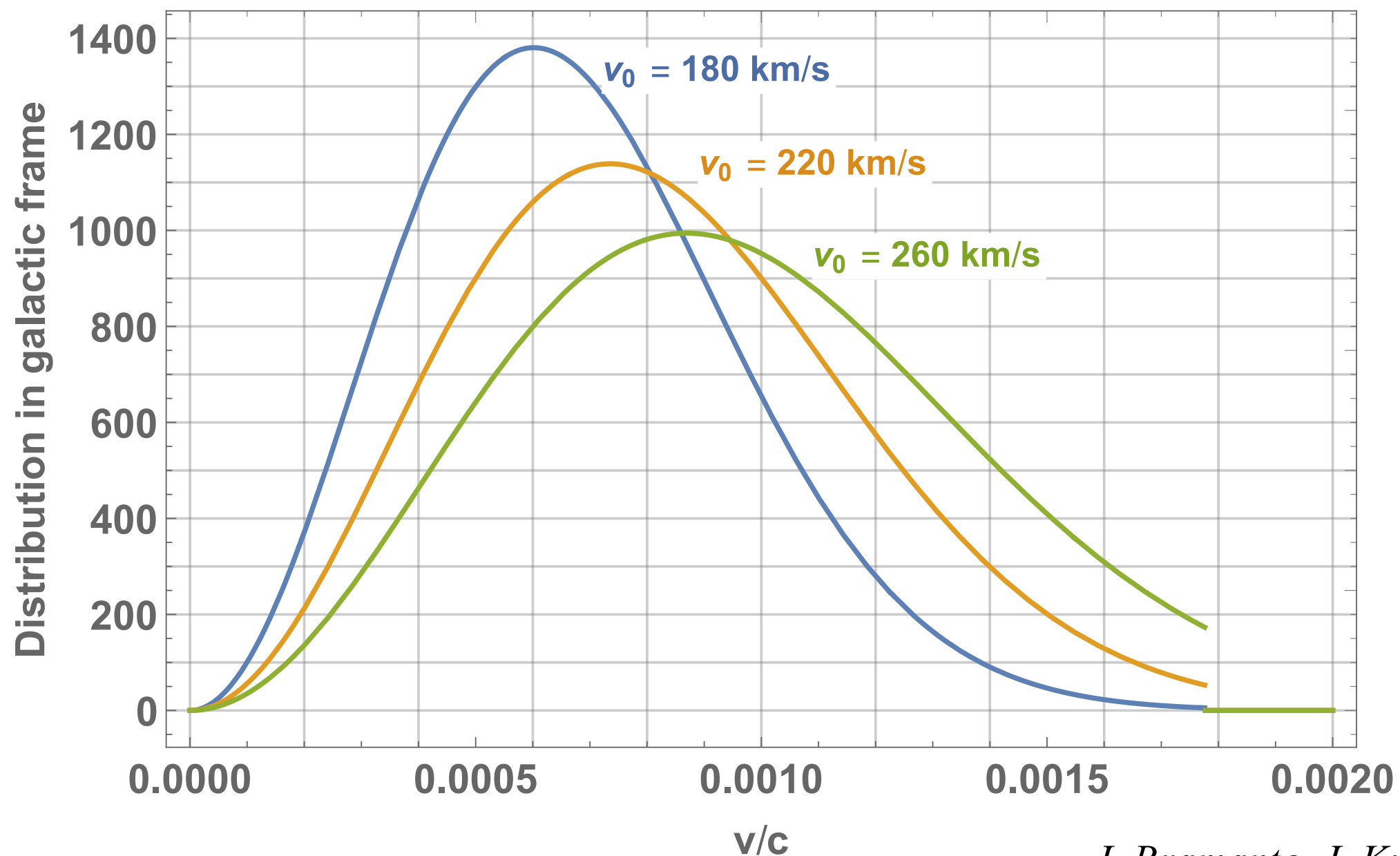


Pinpointing mean speed

galactic frame

$$f(v) = \frac{1}{\mathcal{N}} v^2 \exp\left(-\frac{v^2}{v_0^2}\right) \Theta(v_{\text{esc}} - v)$$

v_0 = circular speed = $\sqrt{2/3}$ dispersion speed

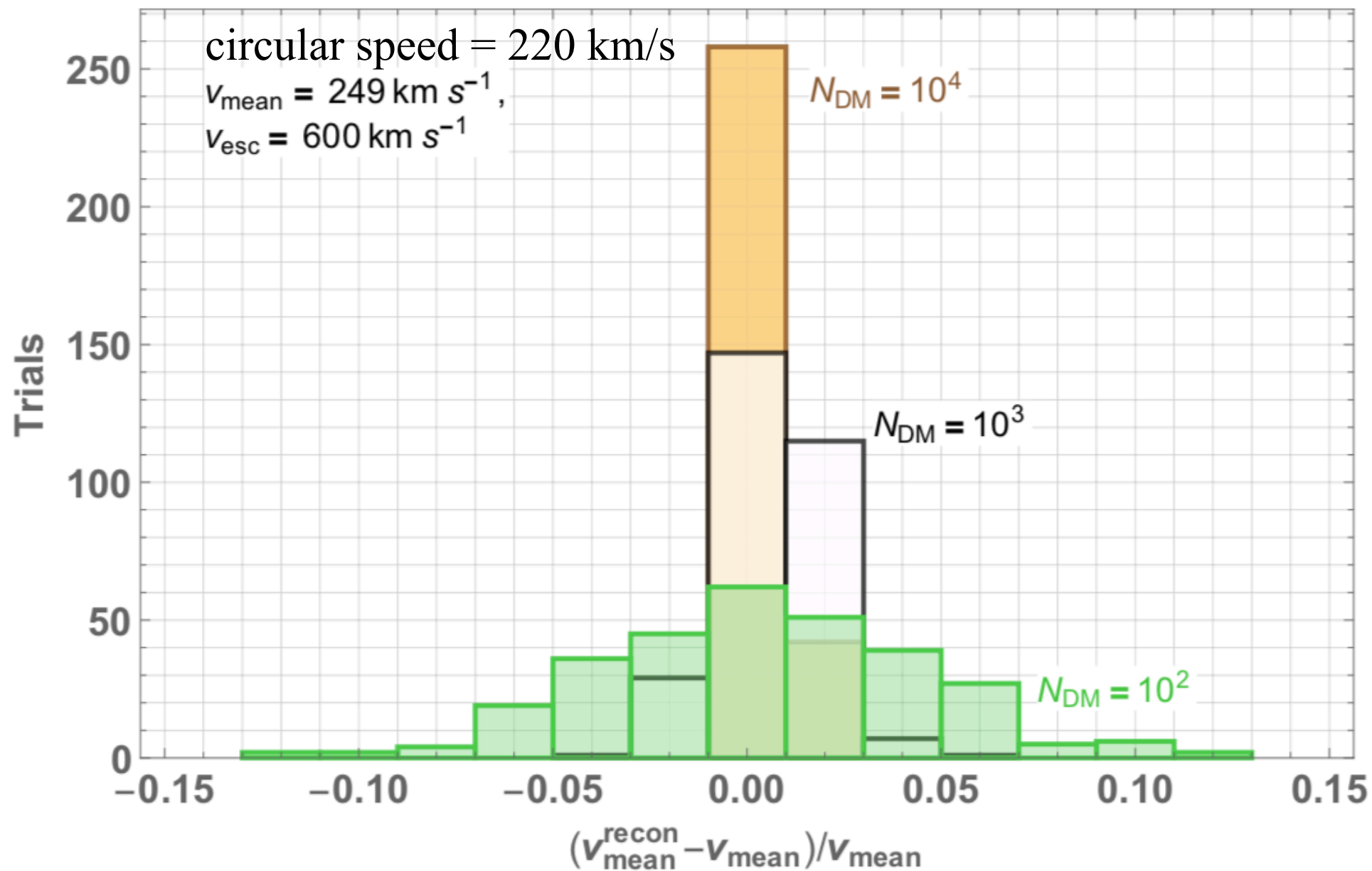


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Pinpointing mean speed

galactic frame

$$f(v) = \frac{1}{\mathcal{N}} v^2 \exp\left(-\frac{v^2}{v_0^2}\right) \Theta(v_{\text{esc}} - v)$$



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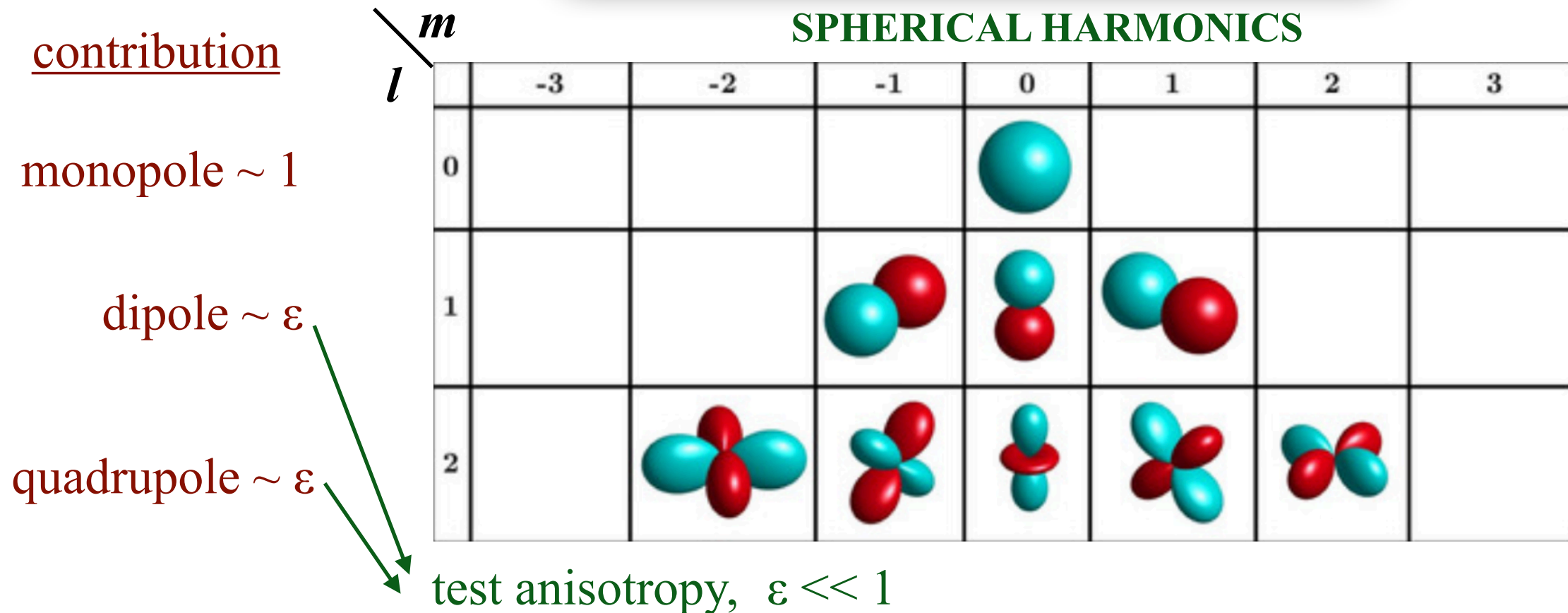
Testing velocity anisotropies

galactic frame

angular distribution:

$$g(\theta, \phi) = c_{00}Y_{00} + c_{\ell m} \sum_{\ell=1,2} Y_{\ell m}$$

SPHERICAL HARMONICS



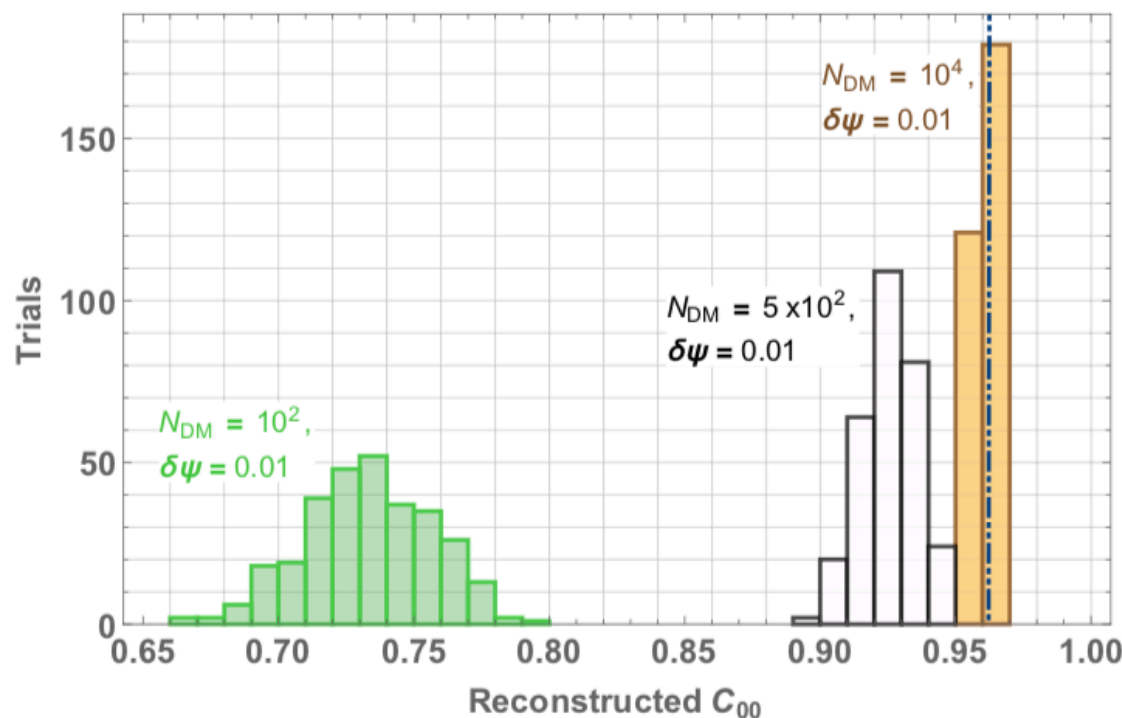
Benchmark:

$$\varepsilon = 0.1 \Rightarrow c_{\ell m} = \begin{cases} \sqrt{1 - \varepsilon^2} / \sqrt{1 + 7\varepsilon^2} = 0.962; & \ell = 0, m = 0, \\ \varepsilon / \sqrt{1 + 7\varepsilon^2} = 0.097; & \ell \neq 0. \end{cases}$$

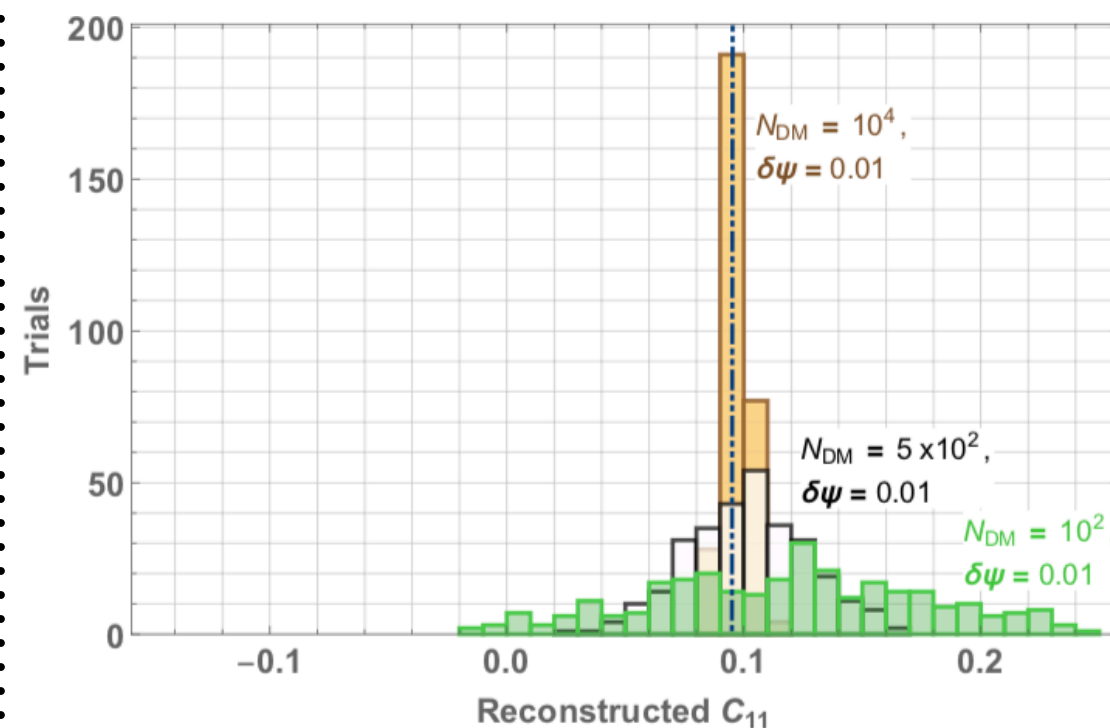
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Testing velocity anisotropies

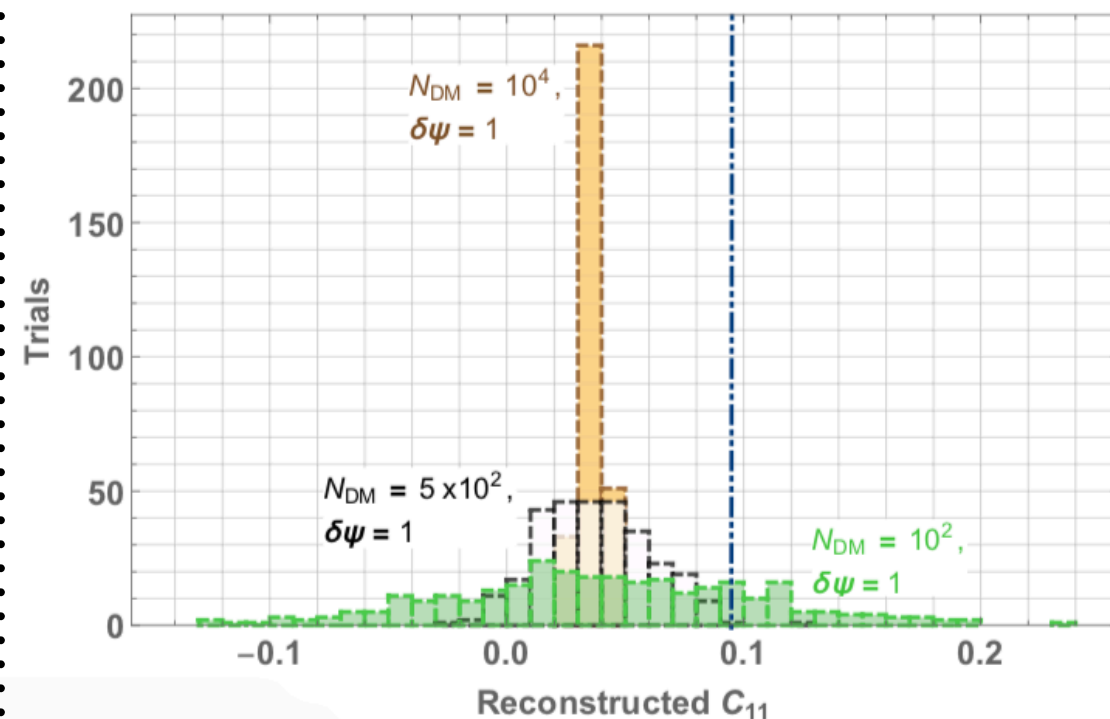
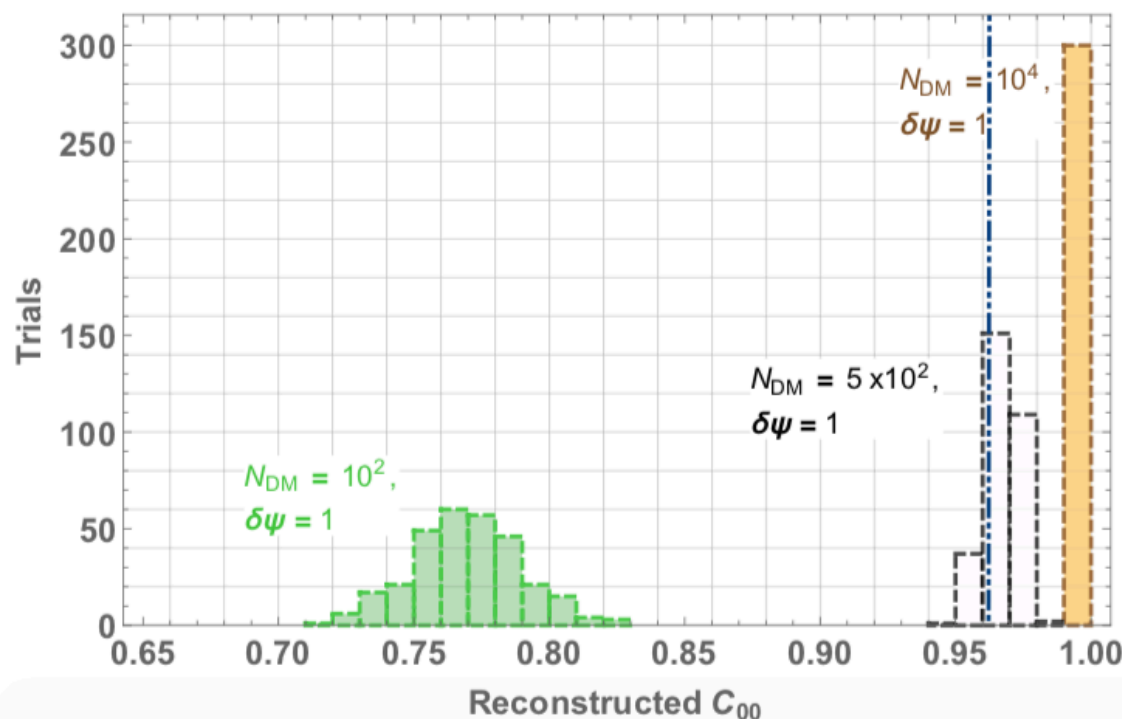
monopole coefficient



dipole coefficient



poor
angular
resolution
(smearing
significant)



LESSONS: good statistics $\Rightarrow$ accuracy & precision,
smearing $\Rightarrow$ anisotropies wash out.

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