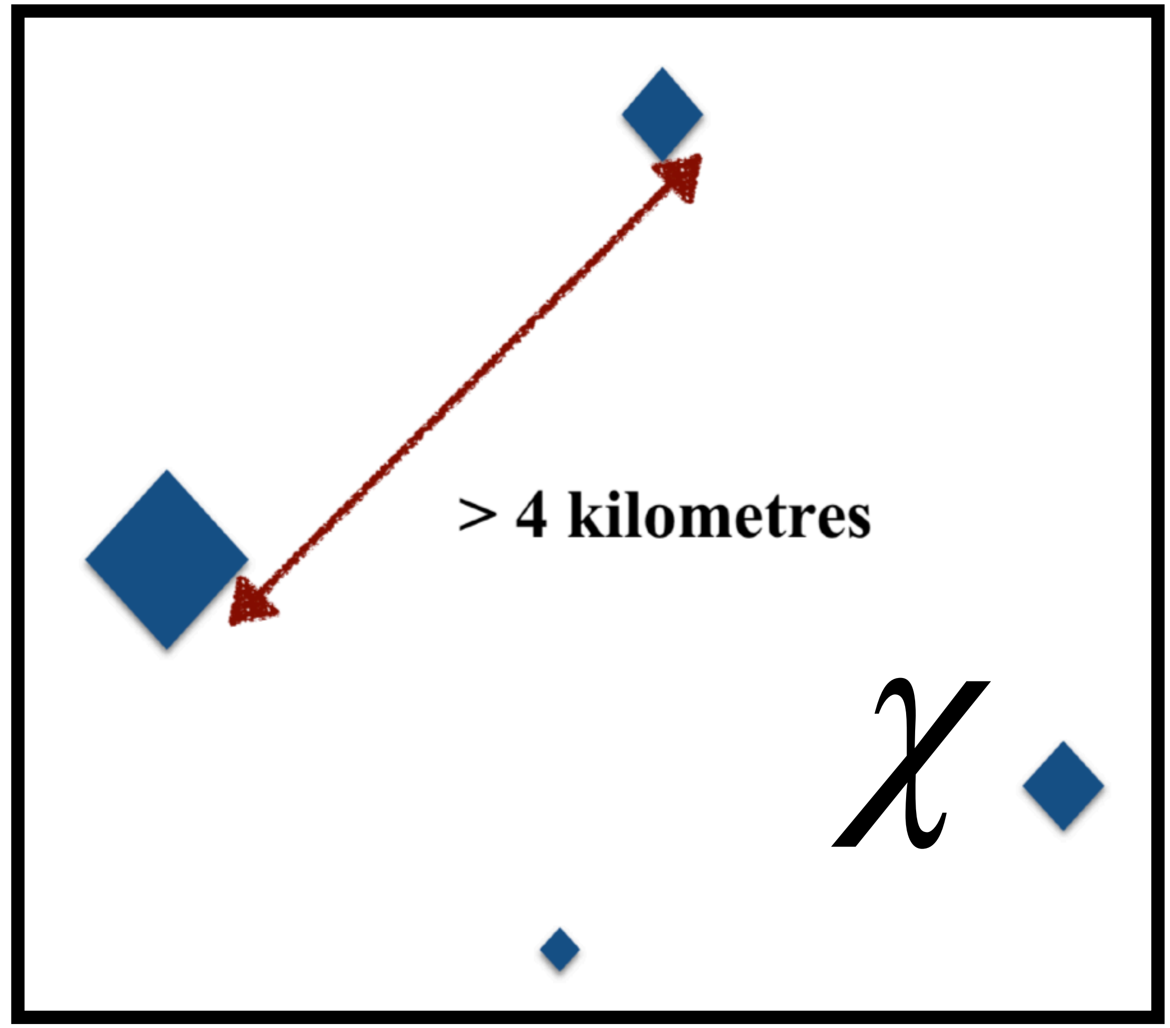
Ultraheavy Dark Matter

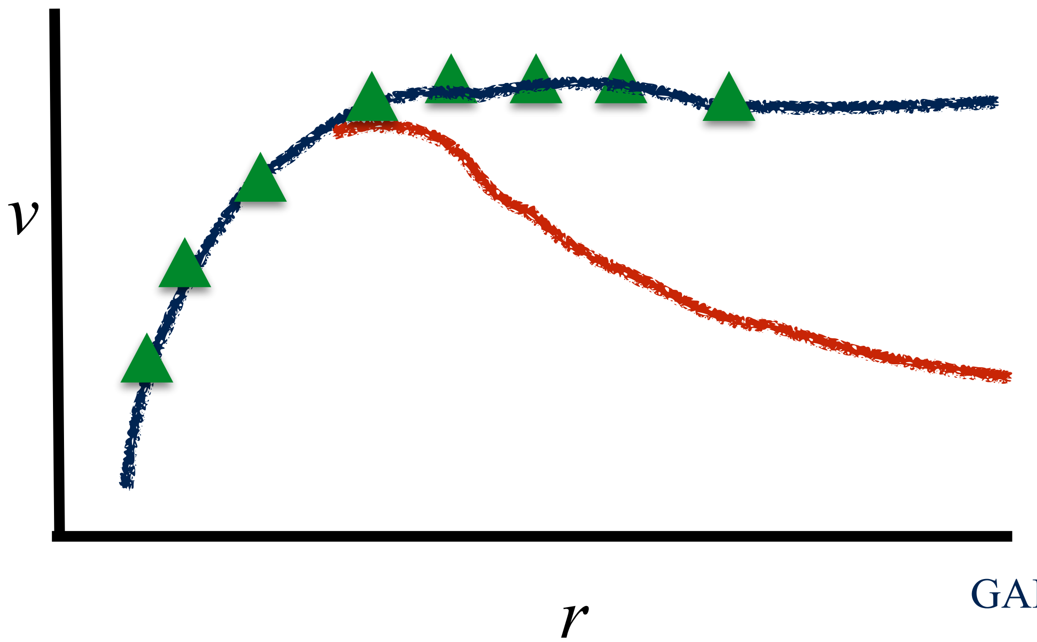
Nirmal Raj
TRIUMF



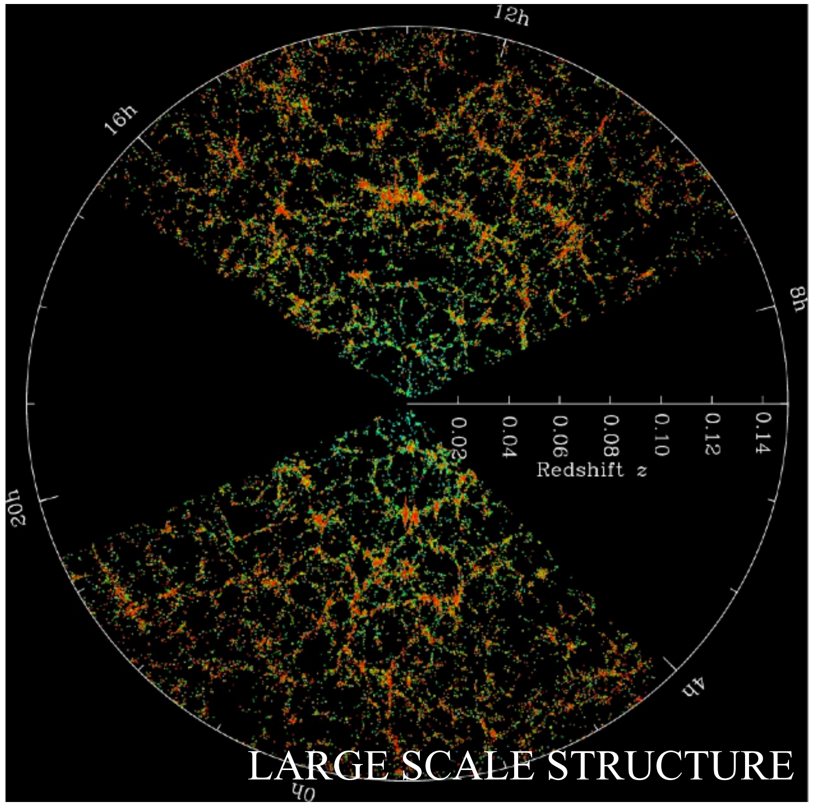
based on **2203.06508** — Snowmass white paper,
work with **DEAP-3600** (S. Garg, M. Lai, S. Westerdale) &
J. Bramante, B. Broerman, J. Kumar, R. Lang, M. Pospelov

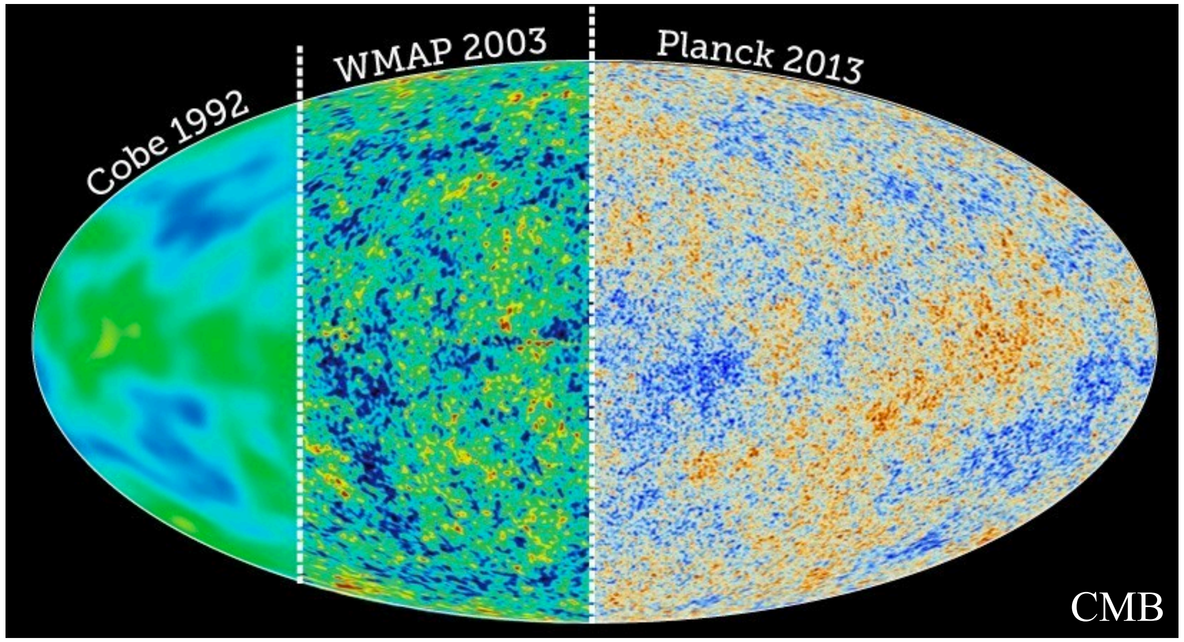
***Dark Interactions*, 14 Nov 2022**

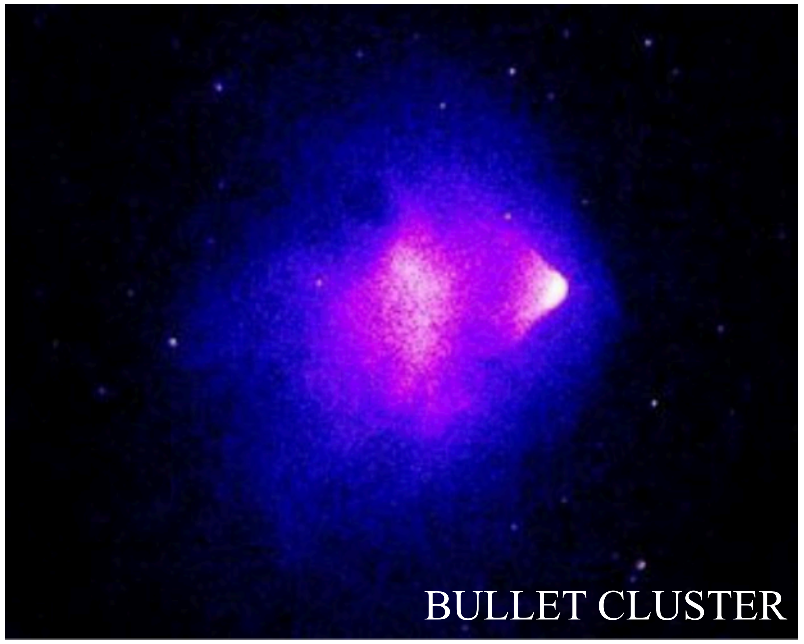
Dark reality



GALACTIC ROTATION







Mass scale of dark matter

(not to scale)

(10^{58} GeV)

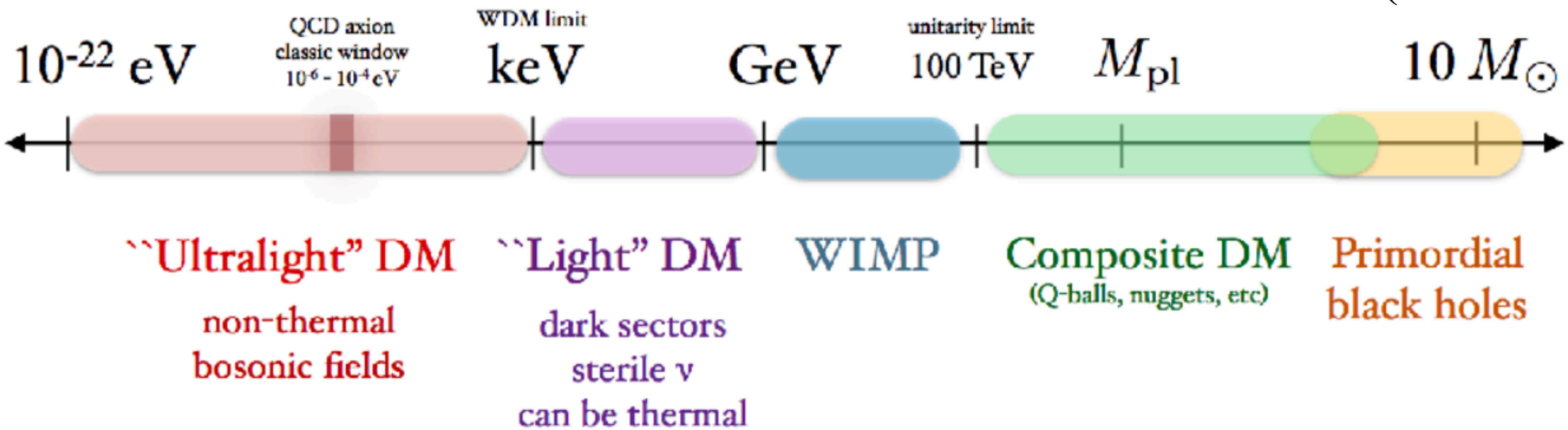
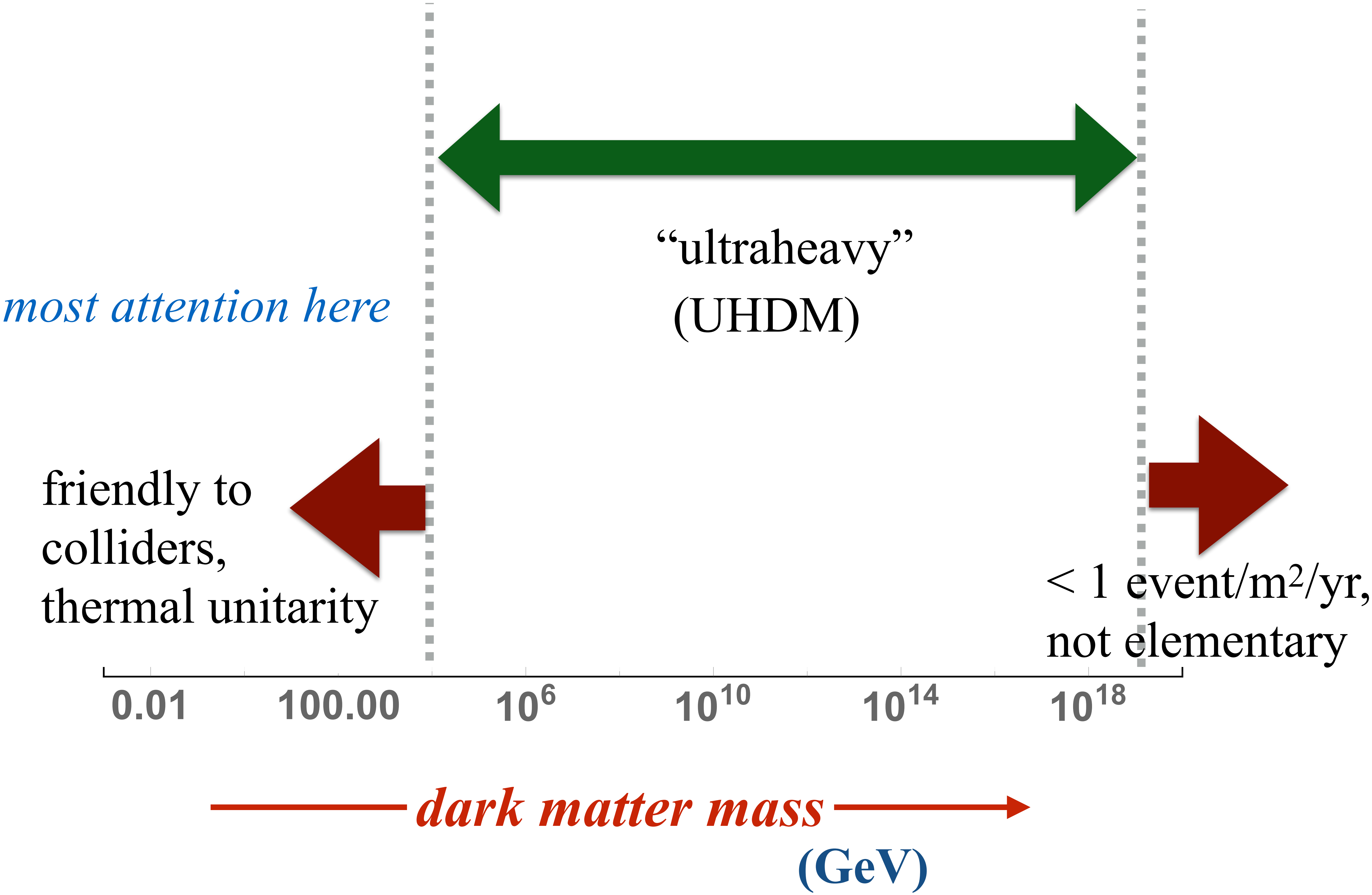


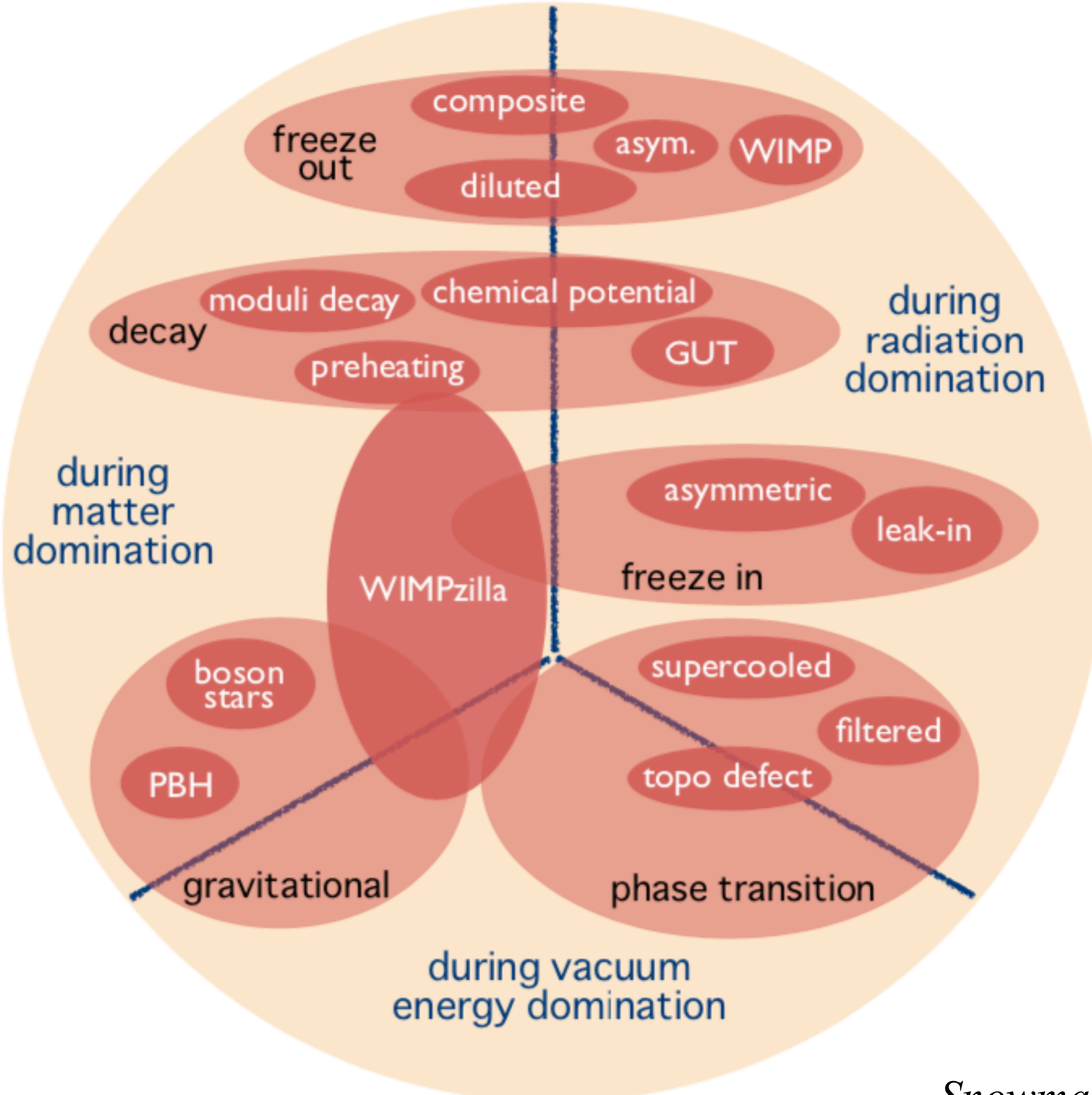
image: T. Lin

Focus

Snowmass **2203.06508**

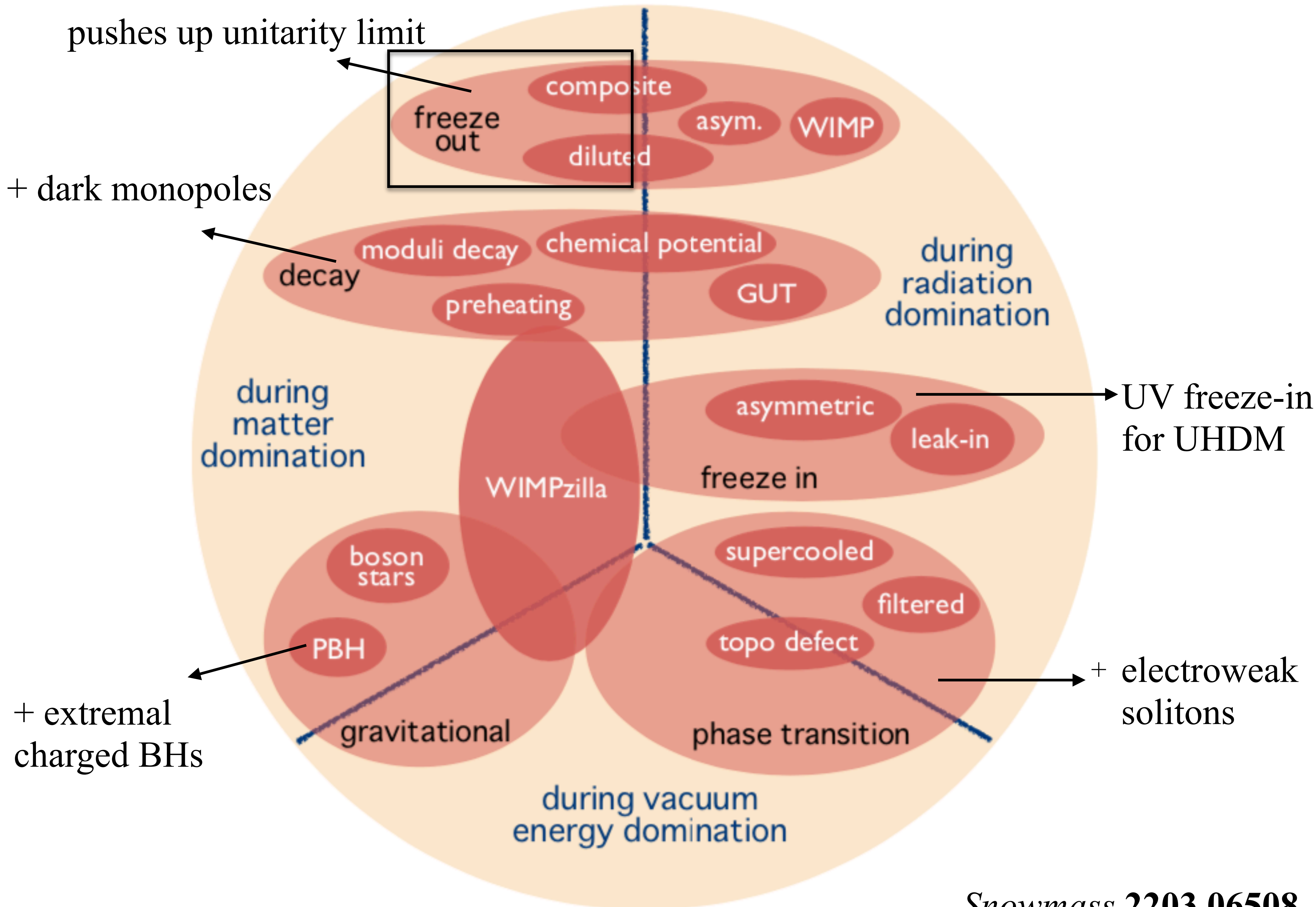


Make & model



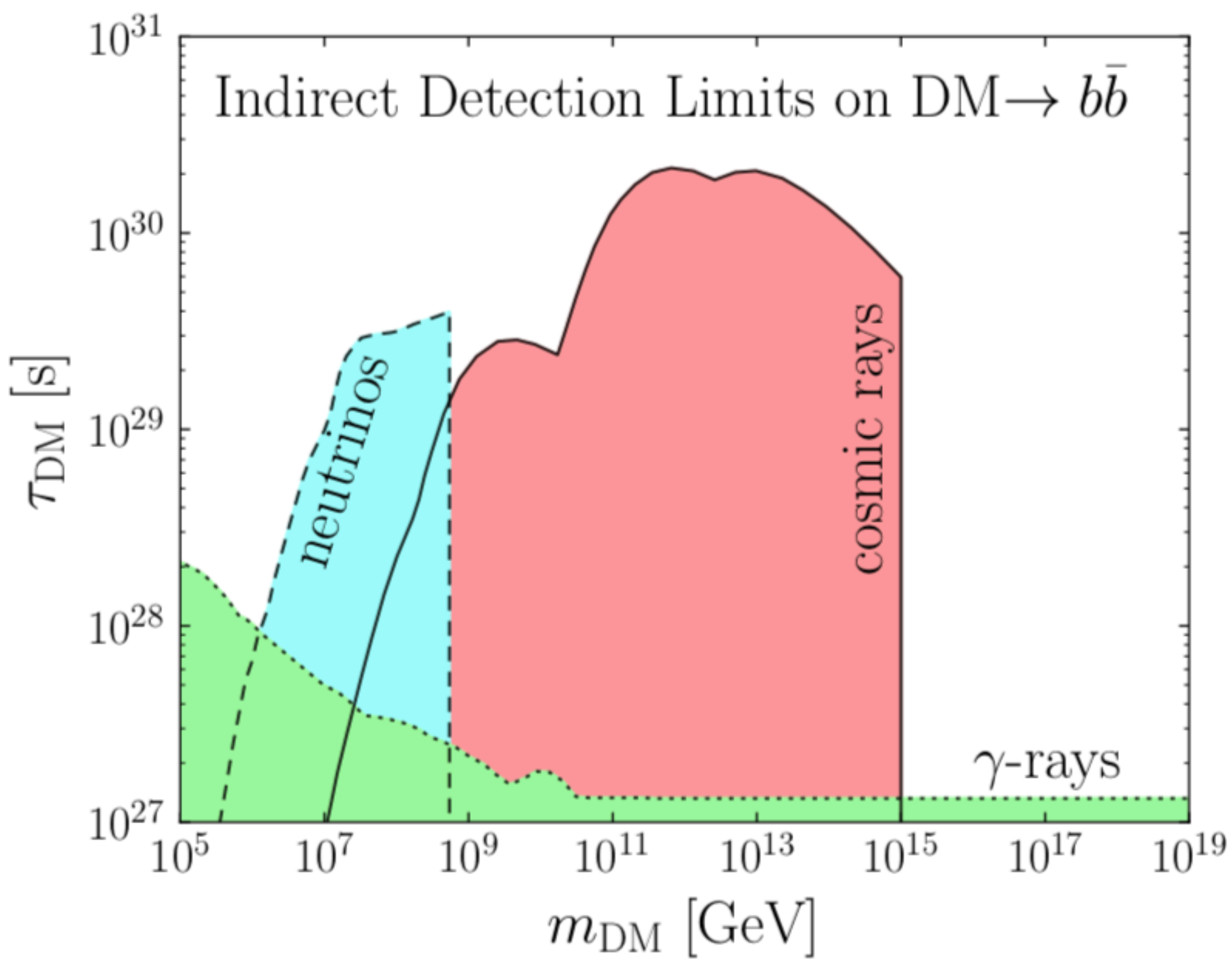
Snowmass **2203.06508**

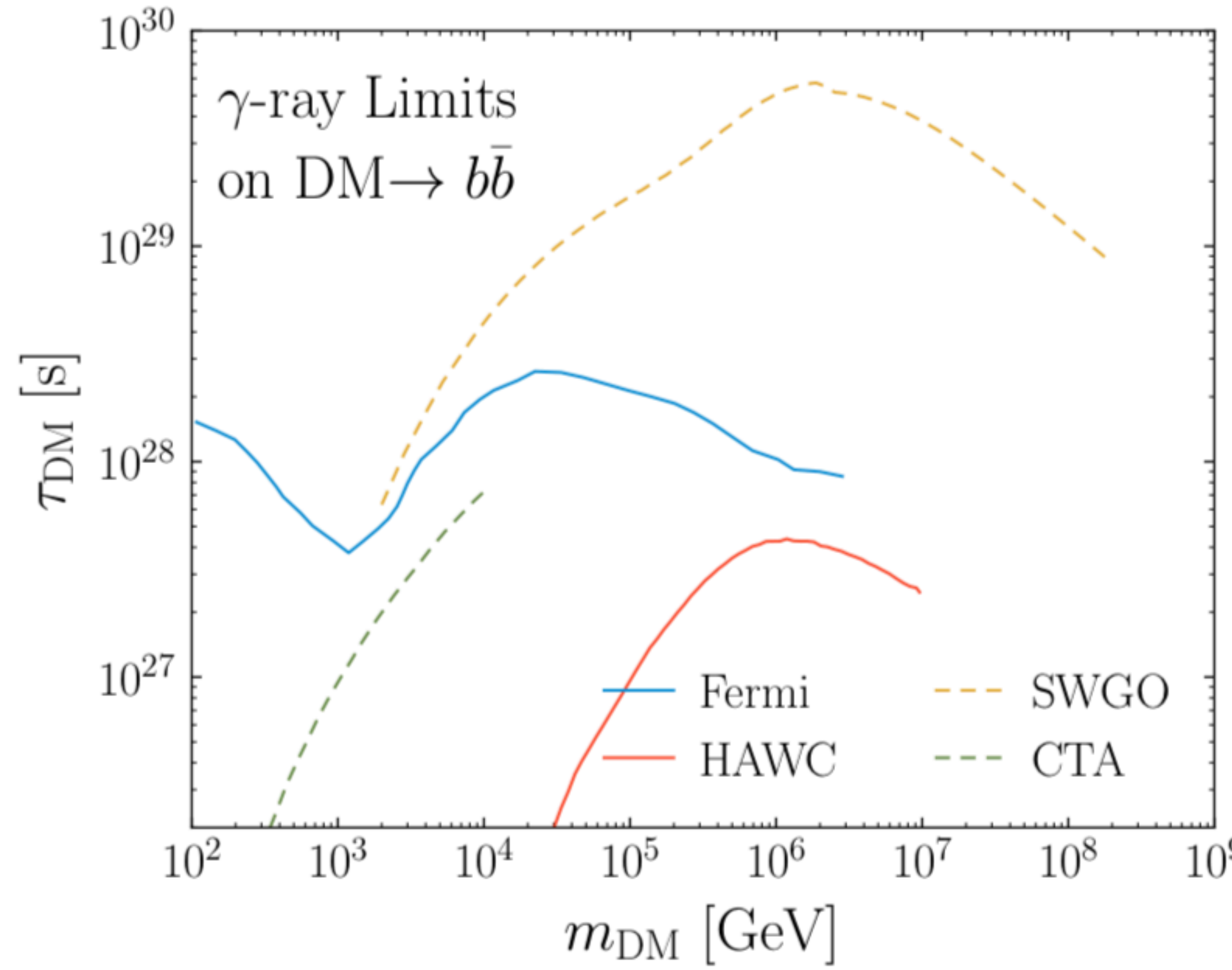
Make & model



Snowmass **2203.06508**

"Break it"





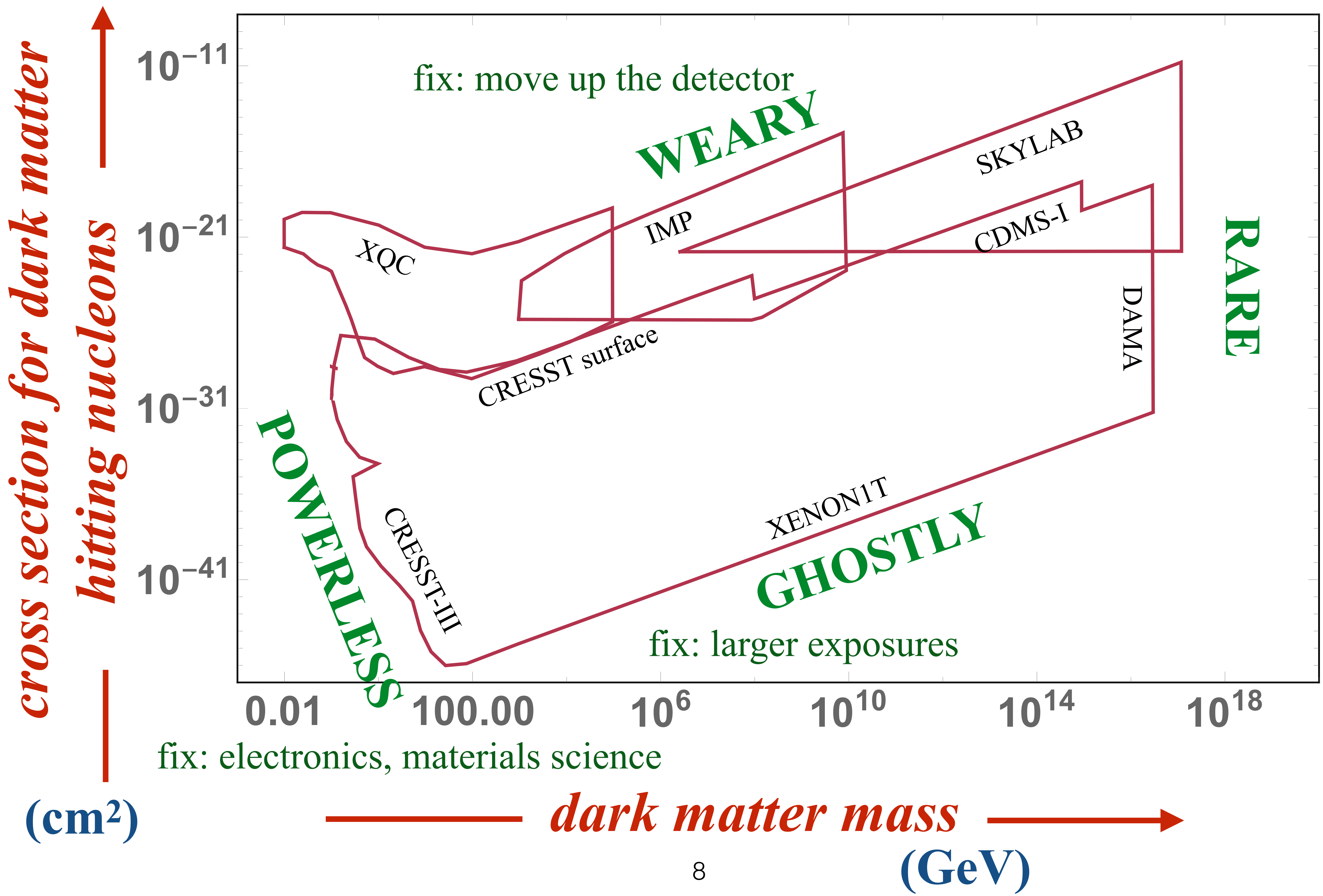
+ inherently **multi-messenger** since $m_{\rm DM} \gg \Lambda_{\rm EW}$

+ cascading via CMB interaction => low-energy detectors important!

Snowmass2021 Cosmic Frontier White Paper:
Ultraheavy particle dark matter

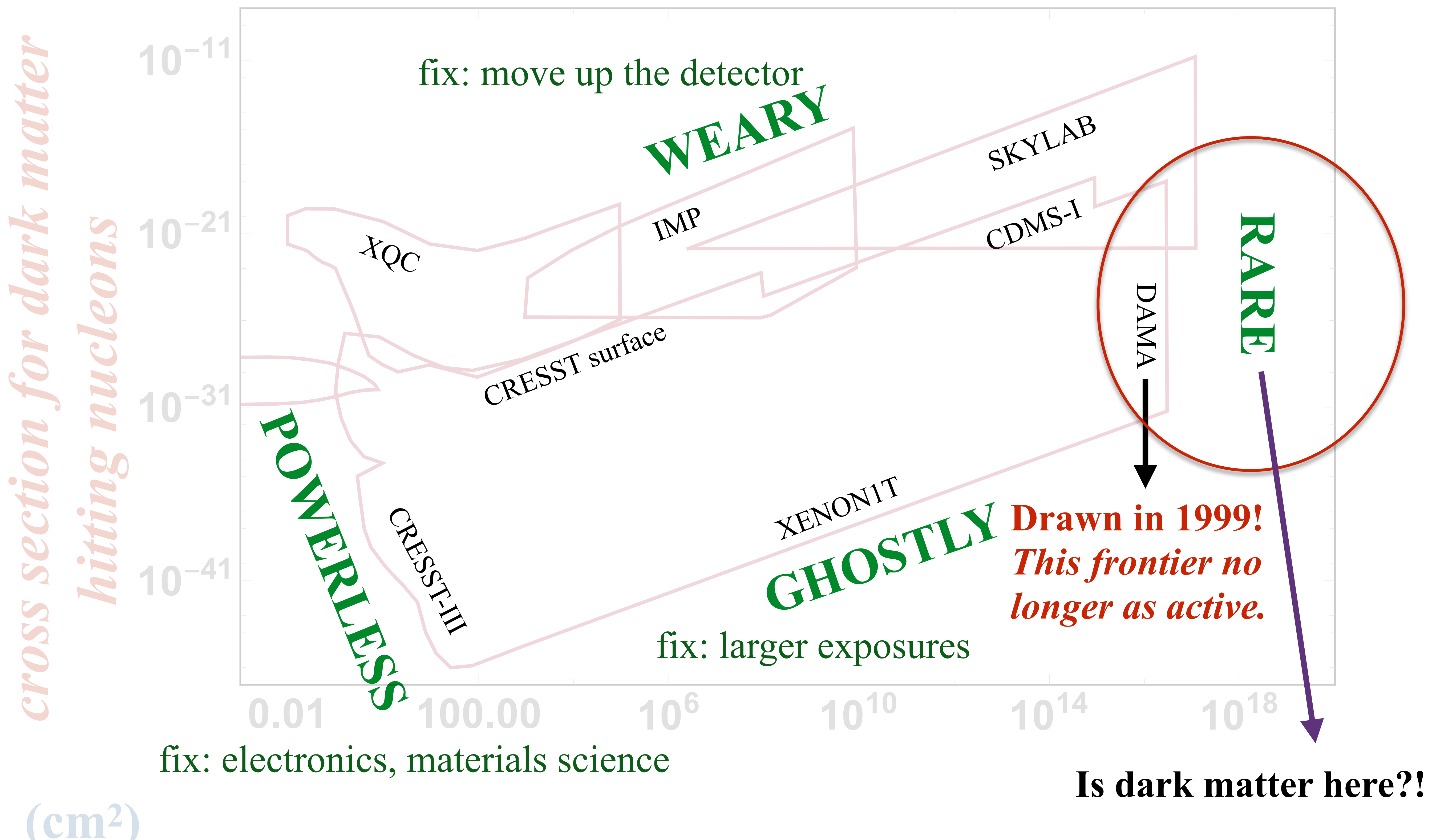
Daniel Carney,[1,*] Nirmal Raj,[2,†] Yang Bai,[3] Joshua Berger,[4] Carlos Blanco,[5,6] Joseph Bramante,[7,8] Christopher Cappiello,[7] Maíra Dutra,[9] Reza Ebadi,[10,11] Kristi Engel,[10] Edward Kolb,[12] J. Patrick Harding,[13] Jason Kumar,[14] Gordan Krnjaic,[15,16] Rafael F. Lang,[17] Rebecca K. Leane,[18,19] Benjamin V. Lehmann,[20,21] Shengchao Li,[17] Andrew J. Long,[22] Gopolang Mohlabeng,[7,8] Ibles Olcina,[1,23] Elisa Pueschel,[24] Nicholas L. Rodd,[25] Carsten Rott,[26,27] Dipan Sengupta,[28,29] Bibhushan Shakya,[30] Ronald L. Walsworth,[10,11] and Shawn Westerdale[31]

“Shake it”

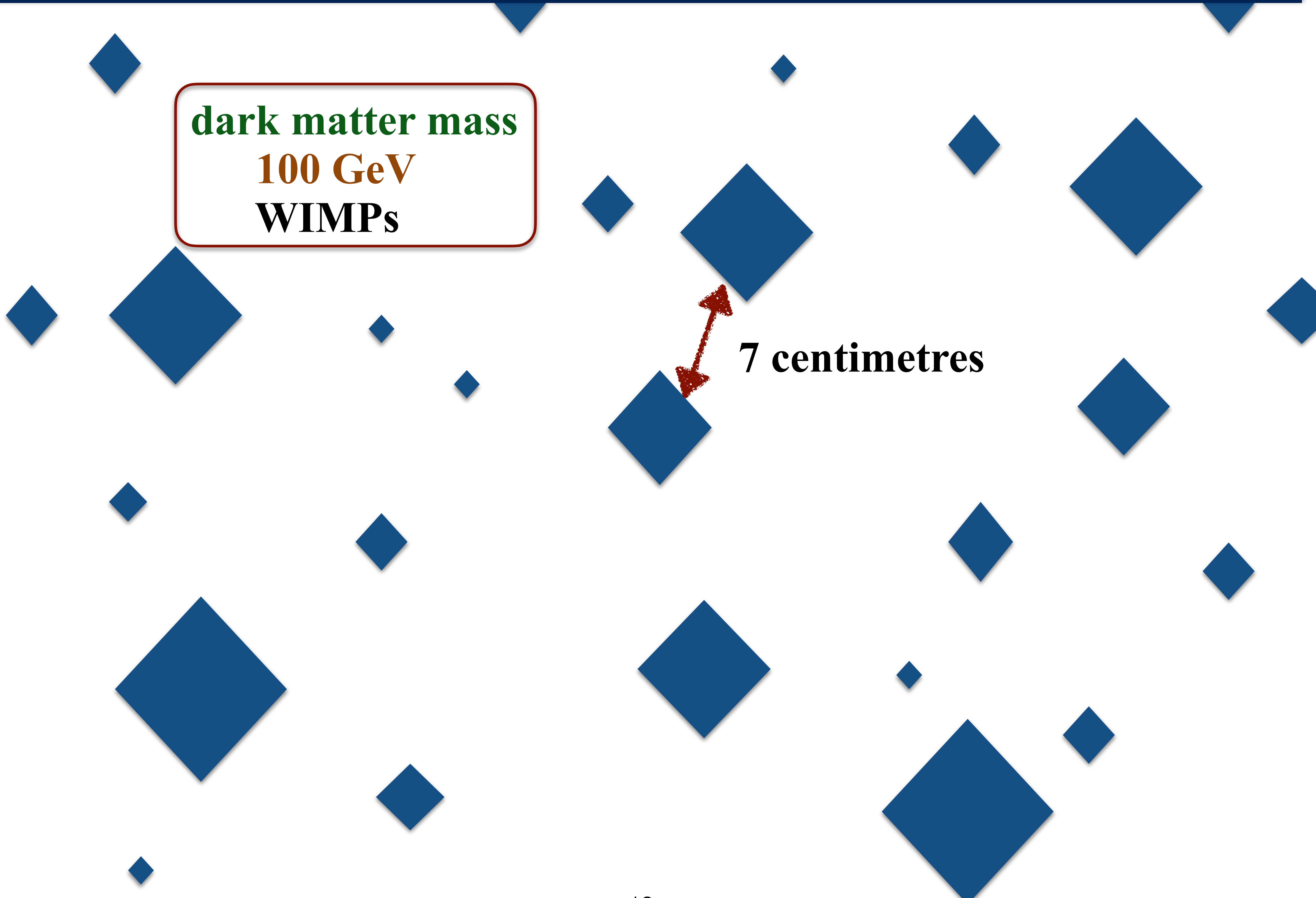


cross section for dark matter hitting nucleons
(cm²)
10−11
10−21
10−31
10−41
fix: move up the detector
WEARY
SKYLAB
IMP
XQC
CDMS-I
DAMA
RARE
CRESST surface
POWERLESS
CRESST-III
XENON1T
GHOSTLY
fix: larger exposures
0.01
100.00
10^6
10^10
10^14
10^18
fix: electronics, materials science
dark matter mass
(GeV)

Ultra-ultraheavy



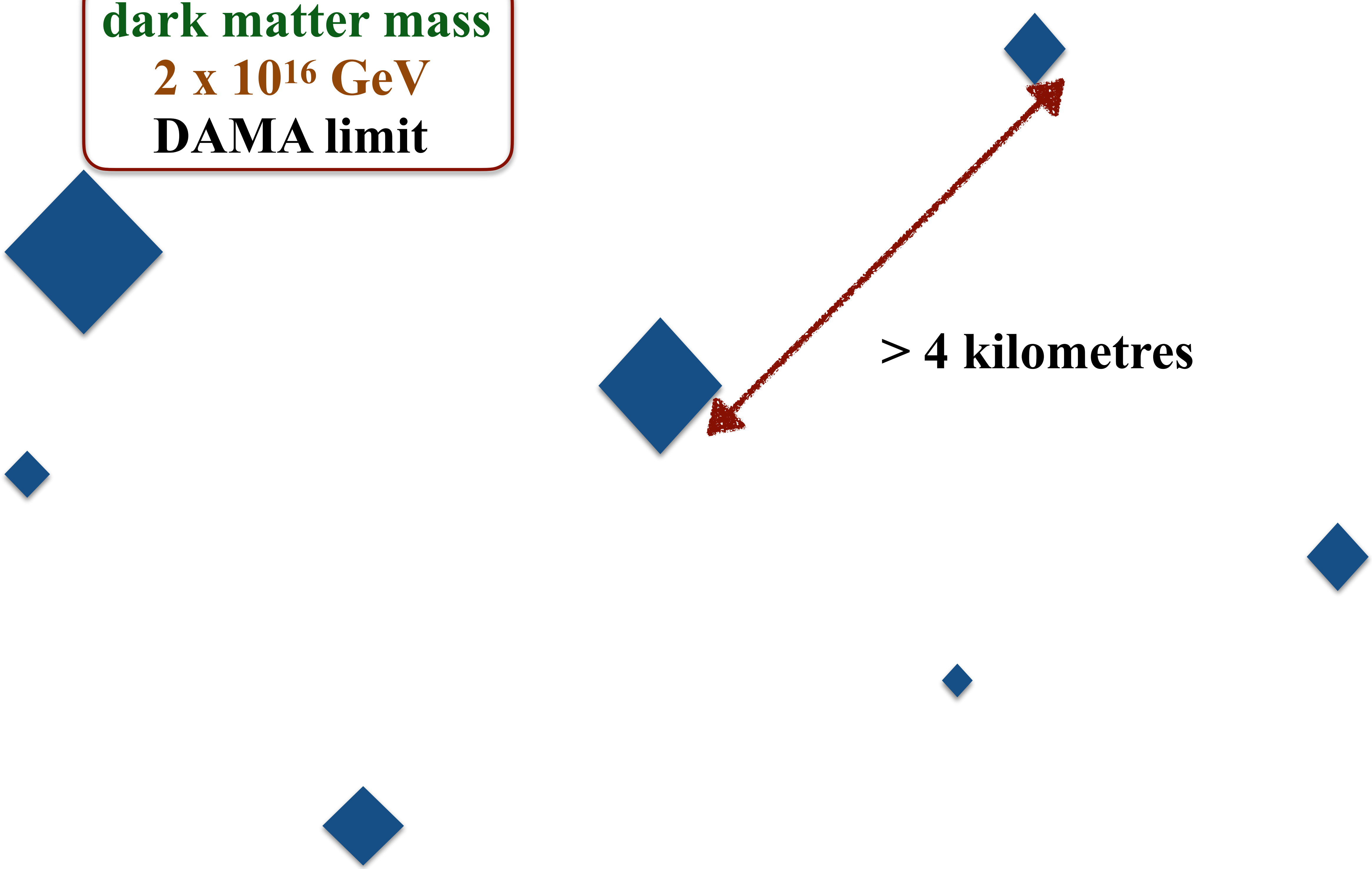
Profusion



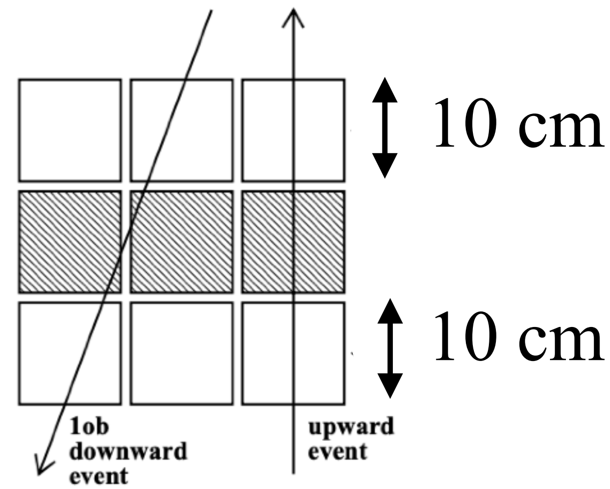
dark matter mass

2 x 10^{16} GeV

DAMA limit



DAMA 1999 search



350 days

TODAY

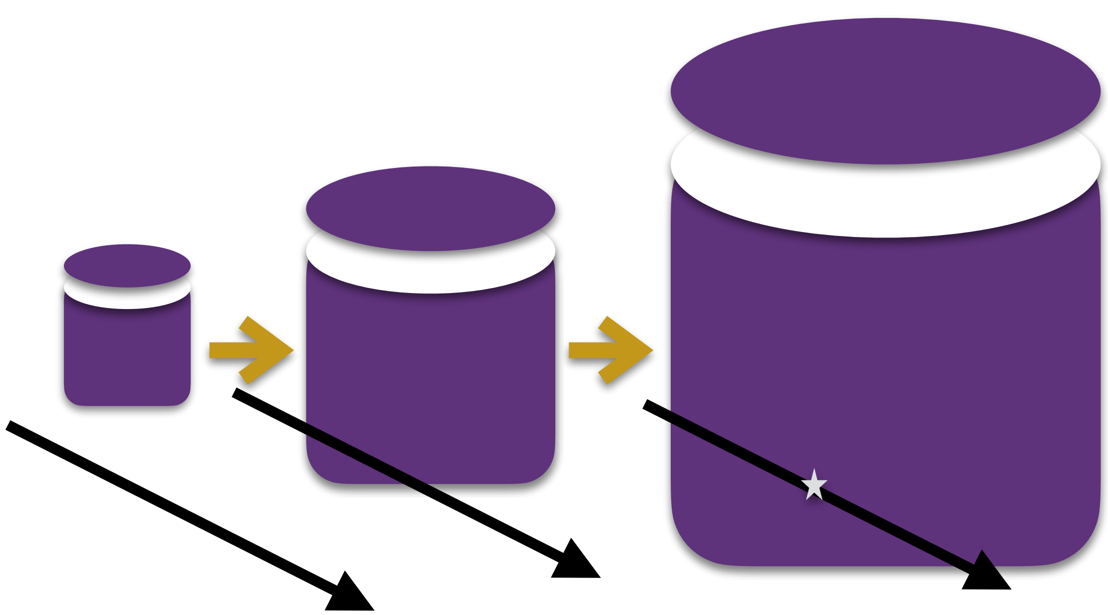
(Q1) Can our **dark matter detectors** hunt the rarest huntable?

N. Raj, *B. Broerman, J. Bramante, R. Lang*

Phys.Rev.D. *(2018)*

N. Raj + DEAP-3600 experiment

Phys. Rev. Lett. (2022)



(Q2) Are there **bigger detectors** that can join the hunt?

N. Raj, *B. Broerman, J. Bramante, J. Kumar, R. Lang, M. Pospelov*

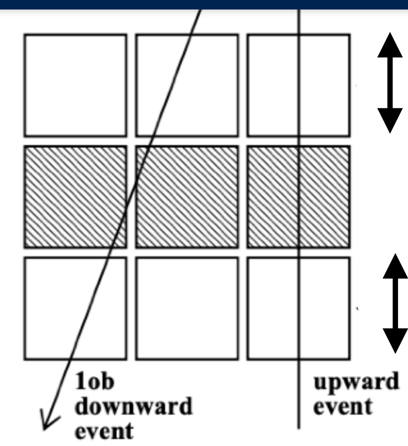
Phys.Rev.D. *(2018)*

N. Raj, *J. Bramante, J. Kumar*

Phys.Rev.D. *(2019)*

Today's dark matter detectors

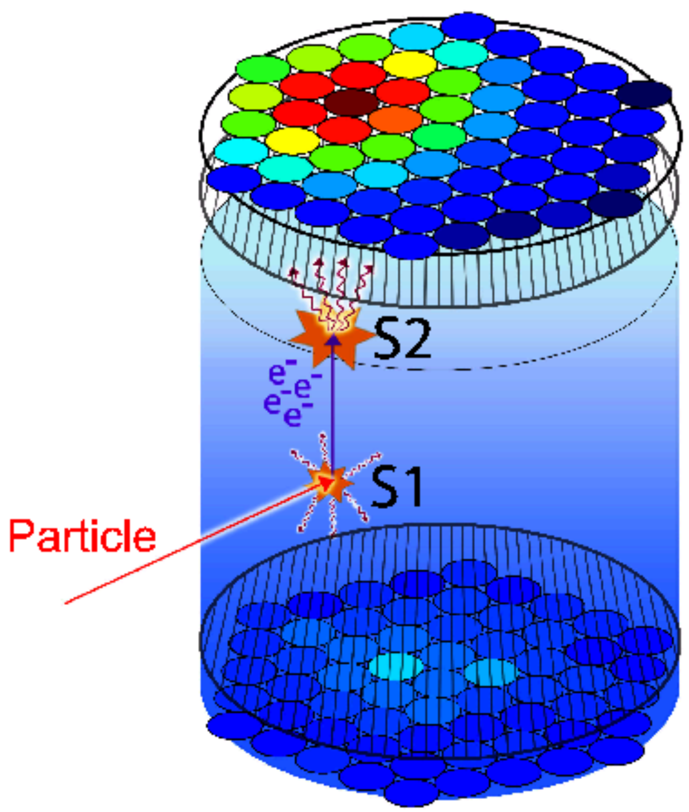
DAMA 1999 search



↕ 10 cm

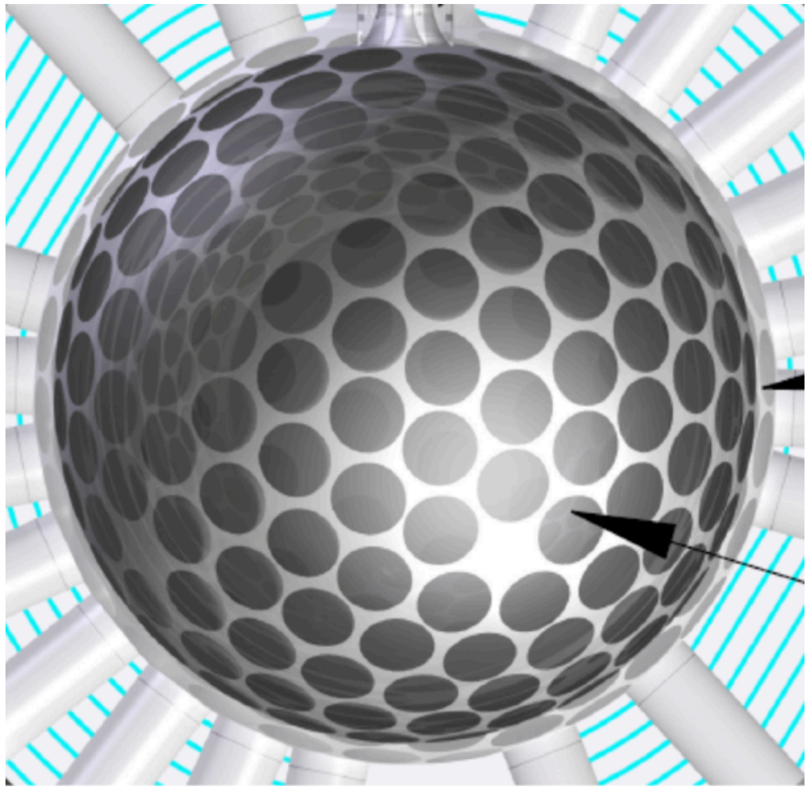
↕ 10 cm

← 100 cm →



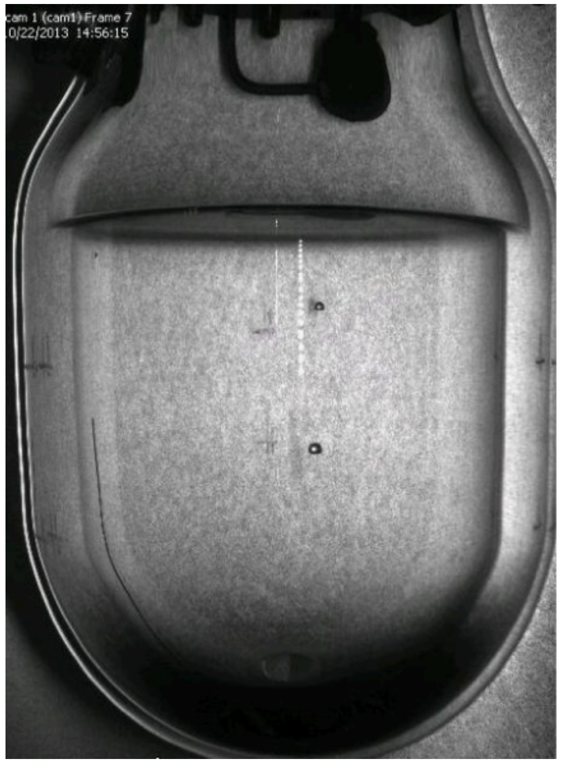
XENON1T/ LUX/ PANDAX-II

← 130 cm →



DEAP-3600

← 50 cm →



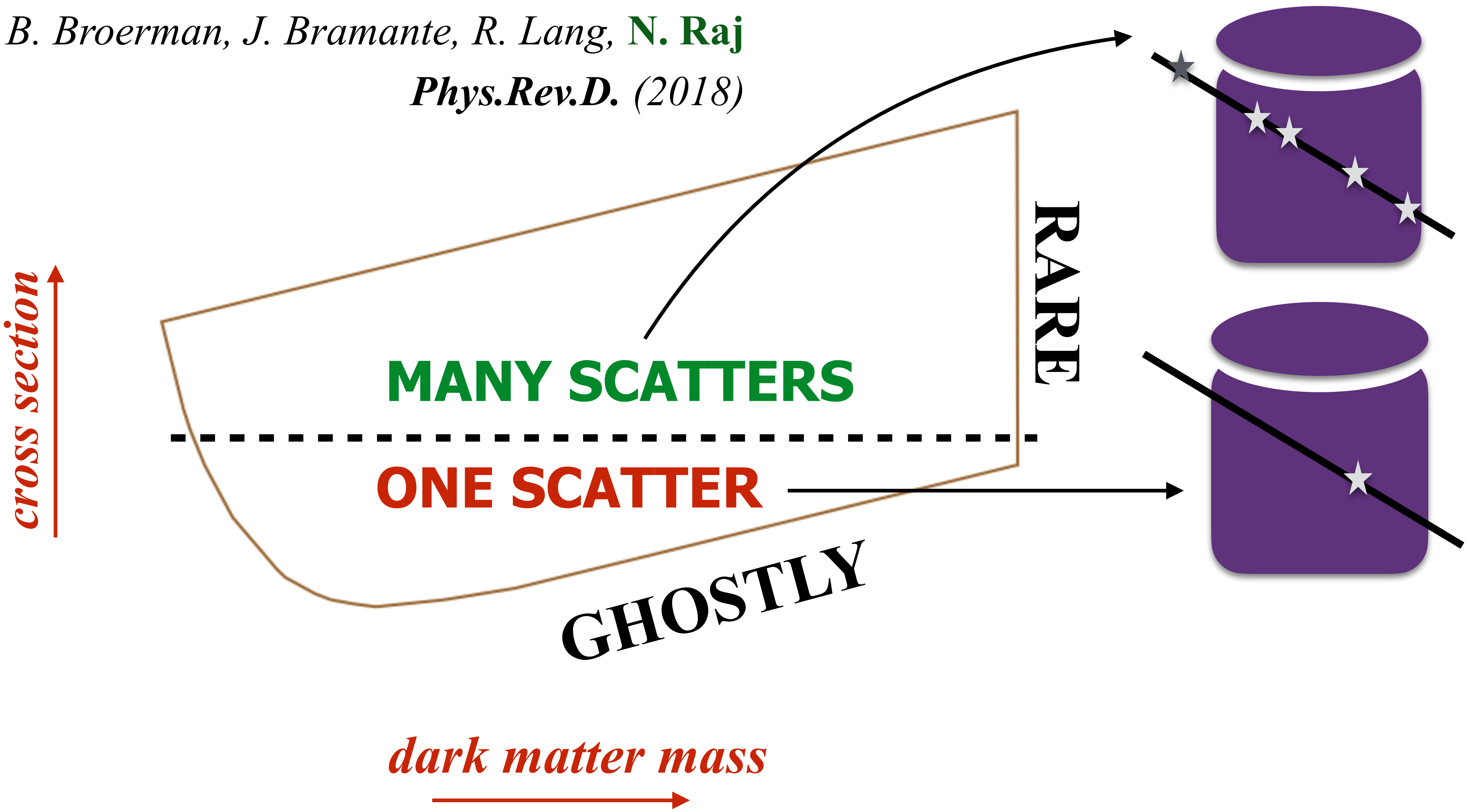
PICO-40L

Multiscatter signatures essential

 # scatters per transit = σ x target number density x path length

B. Broerman, J. Bramante, R. Lang, **N. Raj**

Phys.Rev.D. *(2018)*



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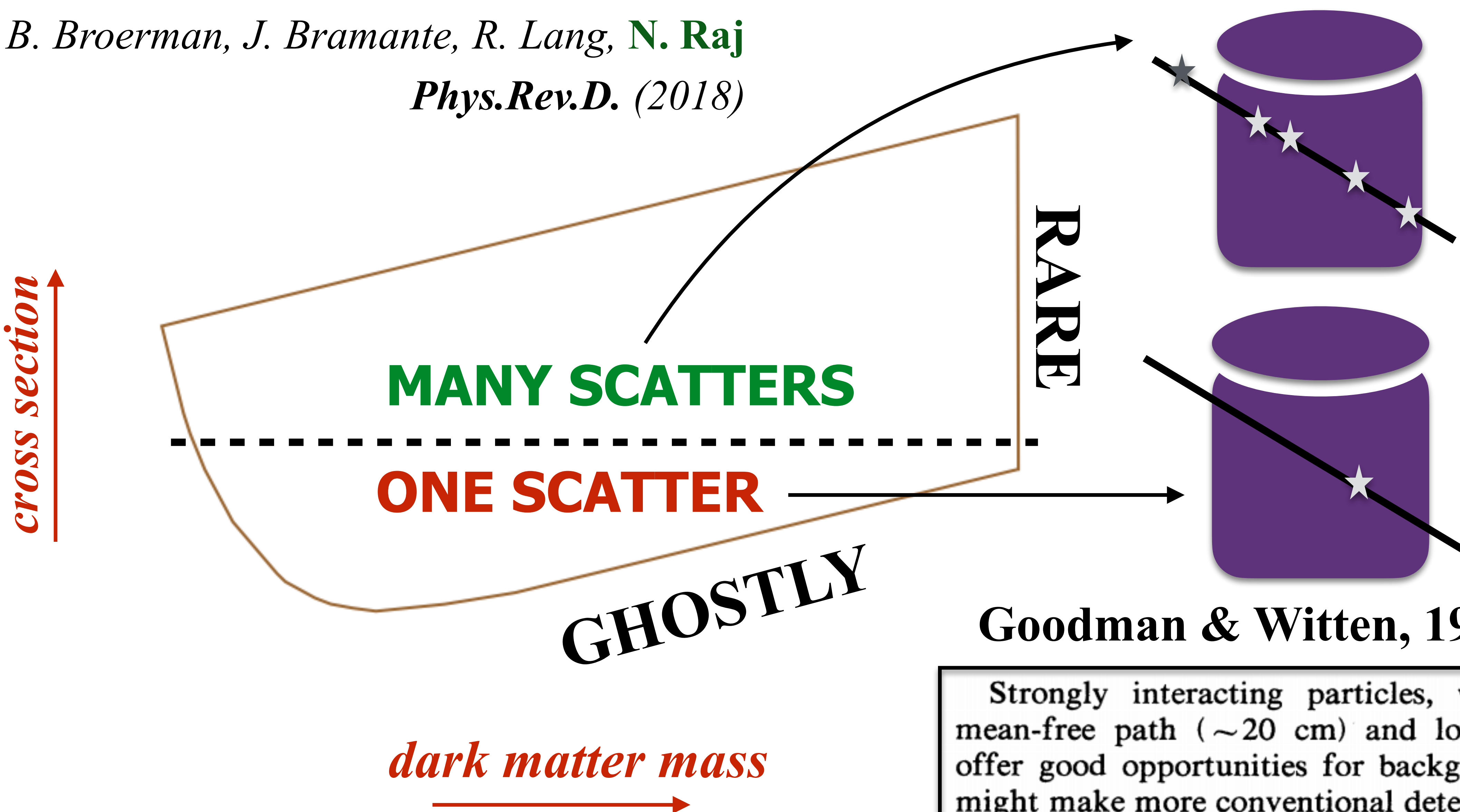


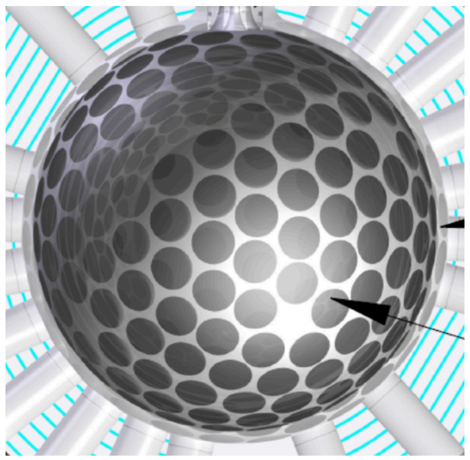
Goodman & Witten, 1985:

Strongly interacting particles, with their observable mean-free path ($\sim$20 cm) and low velocity ($\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 $\sim$10 keV ($\sim$10 photons detected) separated by $\sim$20 cm and by $\sim$1 μsec.

. 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!

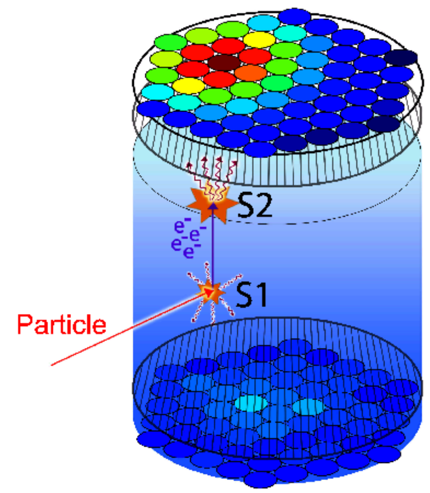
Experiment 2



DEAP-3600

liquid Ar

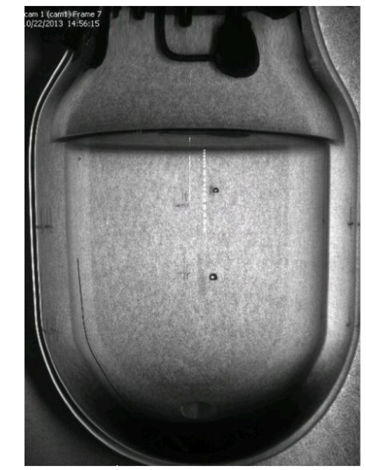
this talk



XENON1T & LUX

liquid Xe

analyses ongoing

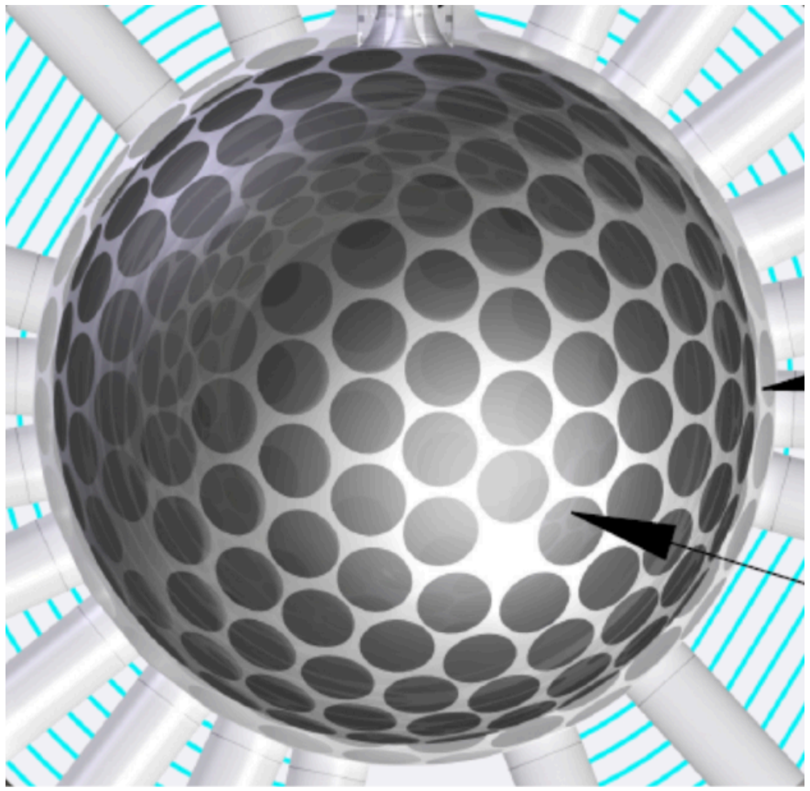


PICO-40L

bubble chamber

result to appear in Broerman's PhD thesis

DEAP-3600 @ SNOLAB



← 130 cm →

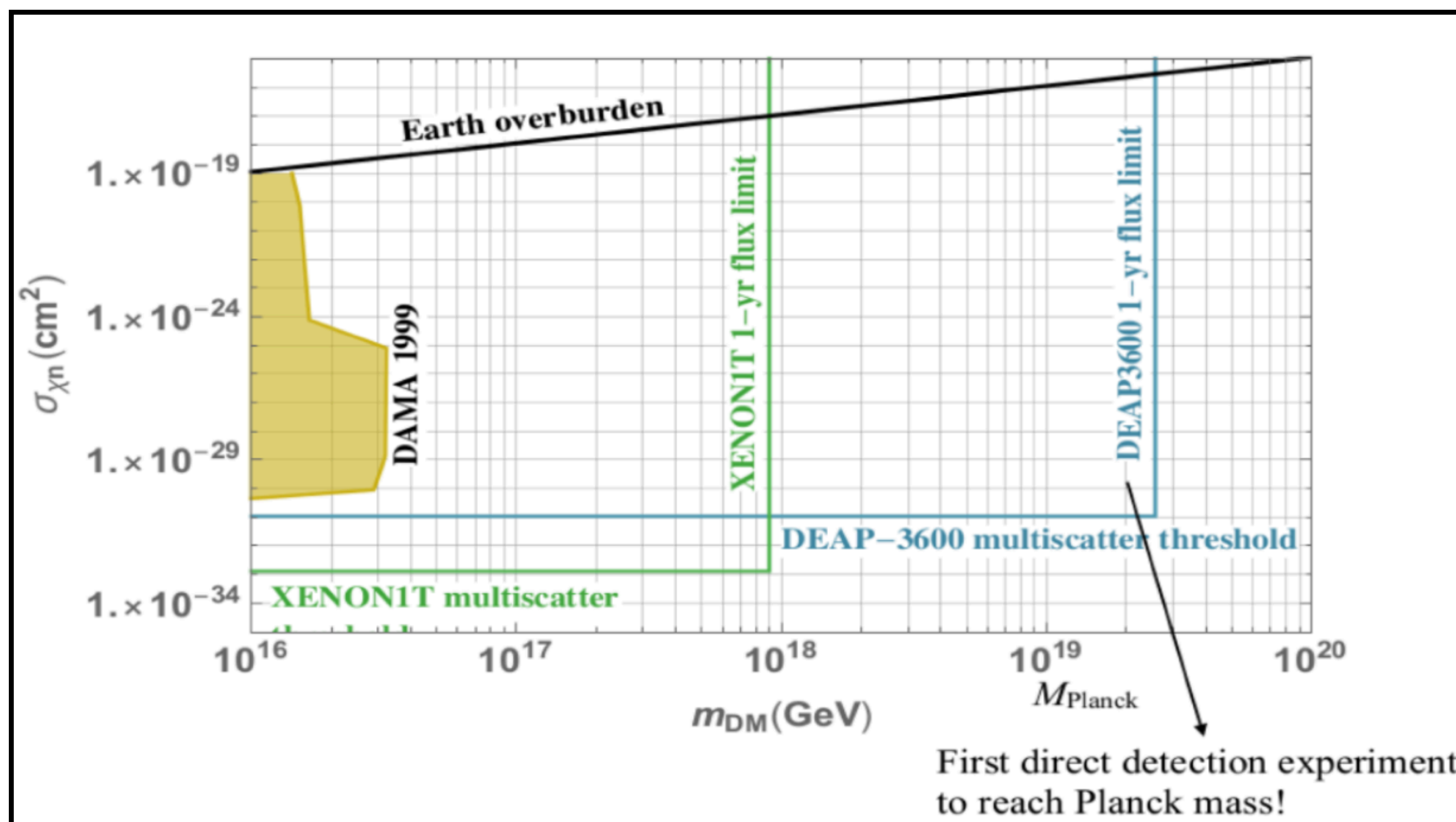
largest dark matter detector in operation

=>

greatest flux of dark matter admitted

=>

back-of-the-envelope (2019):



(Q1) Going to the Planck mass

DEAP-3600 @ SNOLAB

PHYSICAL REVIEW LETTERS

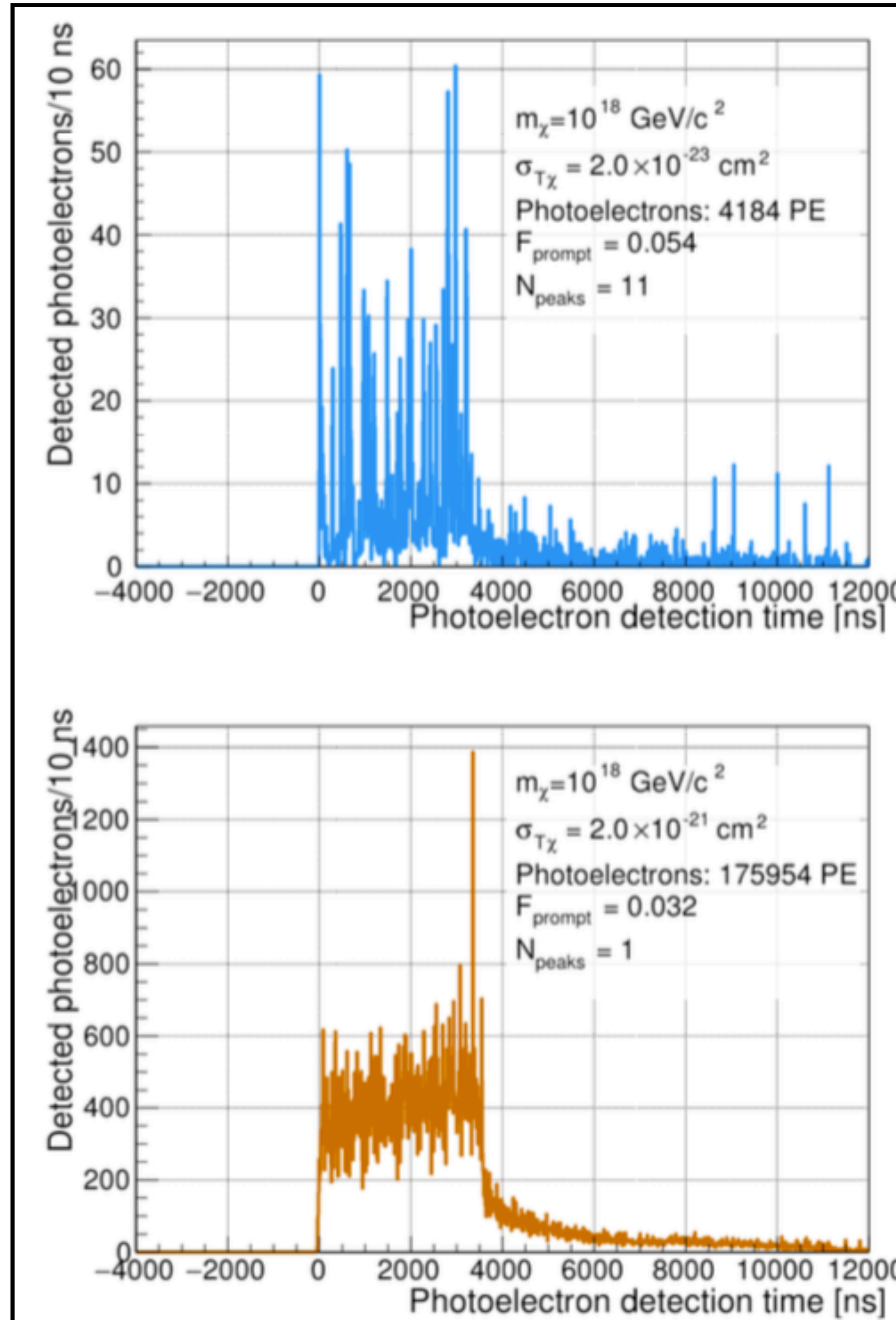
Highlights Recent Accepted Collections Authors Referees Staff

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

<u>working group</u>

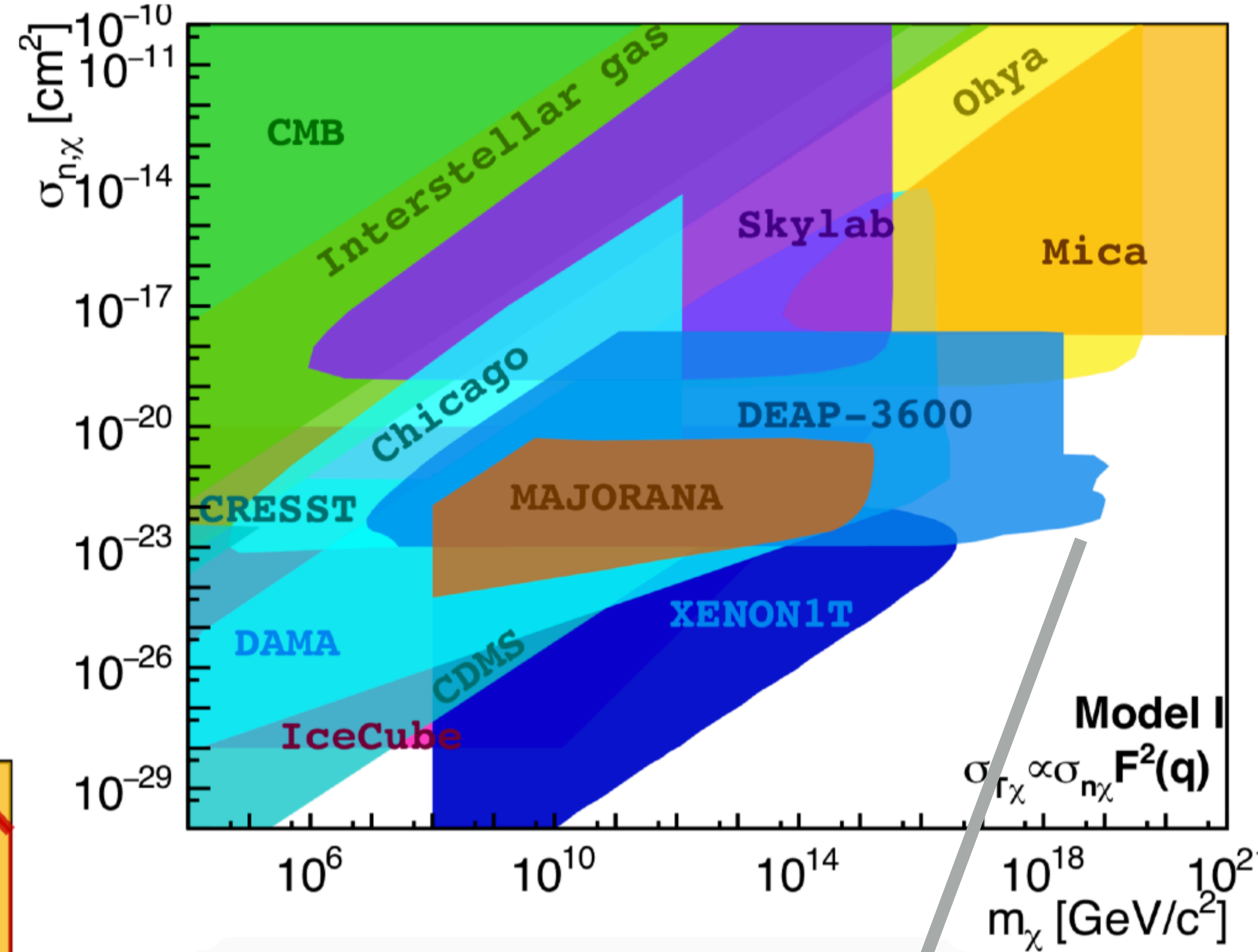
W. Bonivento, S. Garg, M. Lai, **N. Raj**, *S. Westerdale.*

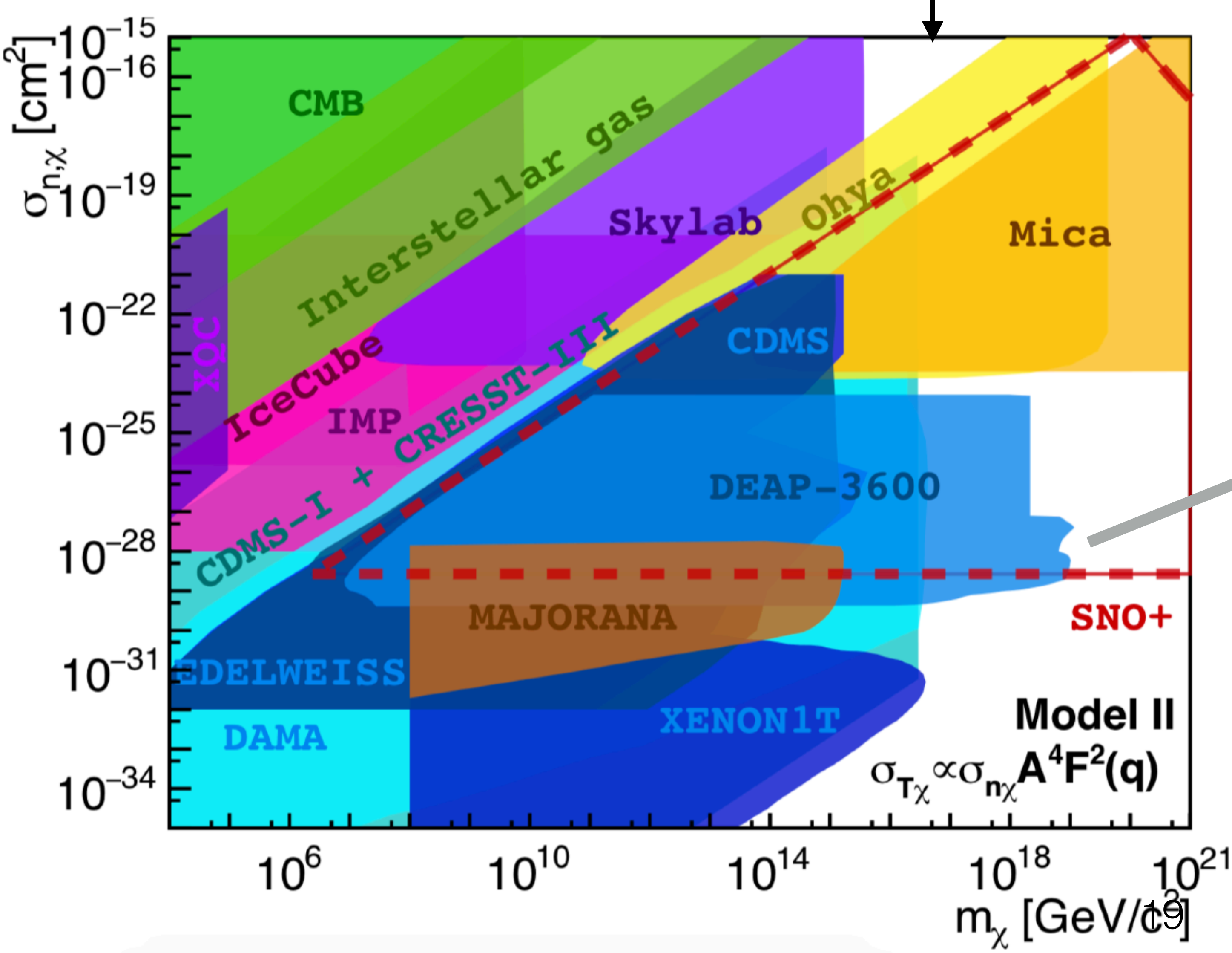


multiscatter signatures:
waveforms of energy deposition in liquid argon

(Q1) Going to the Planck mass

$$\frac{\text{per-nuclear cross section}}{\text{per-nucleon cross section}} = \frac{1}{A^4}$$





limit:

$$m_\chi \geq 1.2 \times 10^{19}\ \text{GeV}$$
$$(M_{\text{Planck}})$$

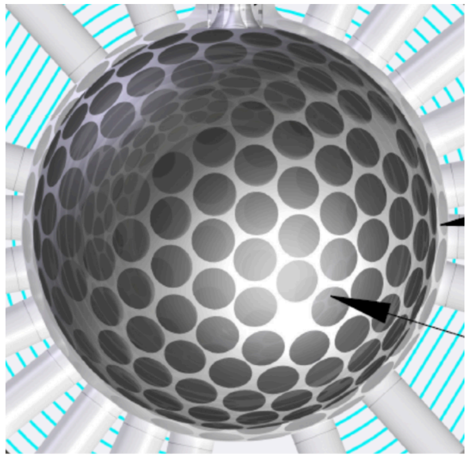
(like hitting the sound barrier)

N. Raj & *DEAP-3600*

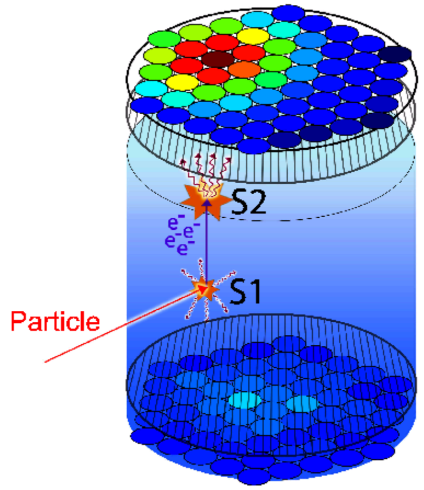
Phys.Rev.Lett. *(2022)*

(Q2) Are there **bigger detectors** that can join the hunt?

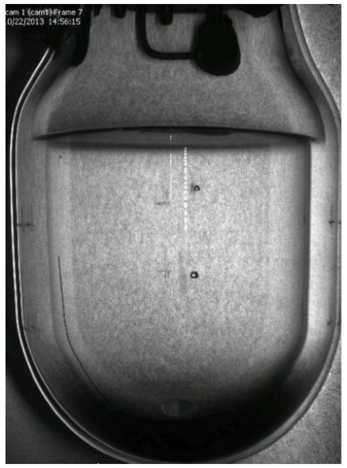
N. Raj, *B. Broerman, J. Bramante,*
J. Kumar, R. Lang, M. Pospelov
***Phys.Rev.D.** (2018)*



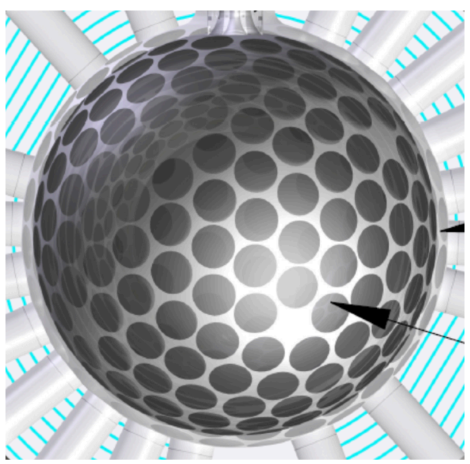
DEAP-3600



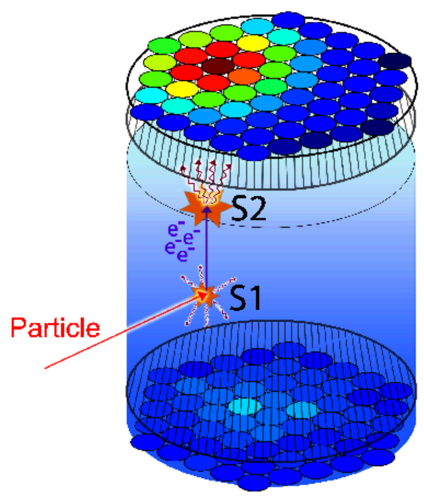
XENON1T



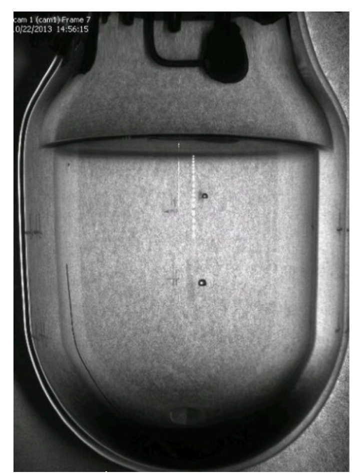
PICO-40L



DEAP-3600

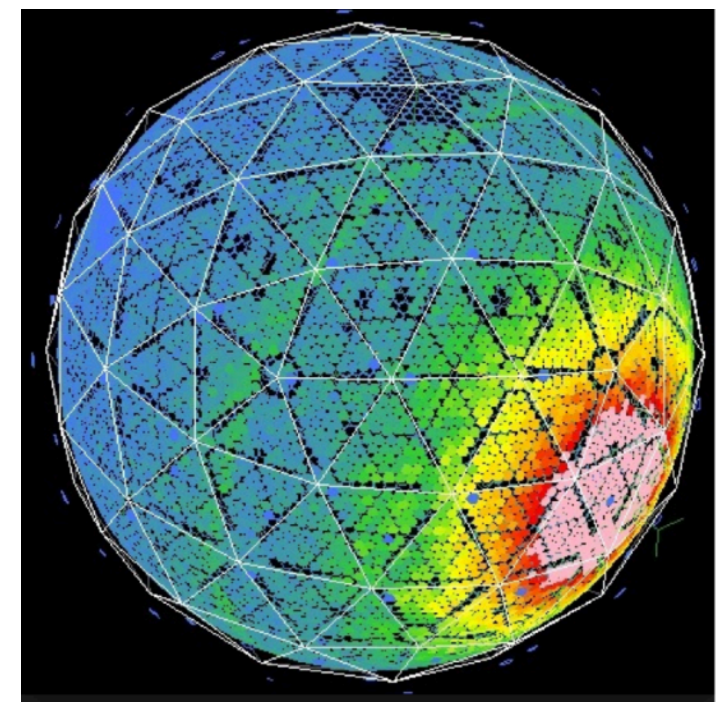


XENON1T



PICO-40L

+

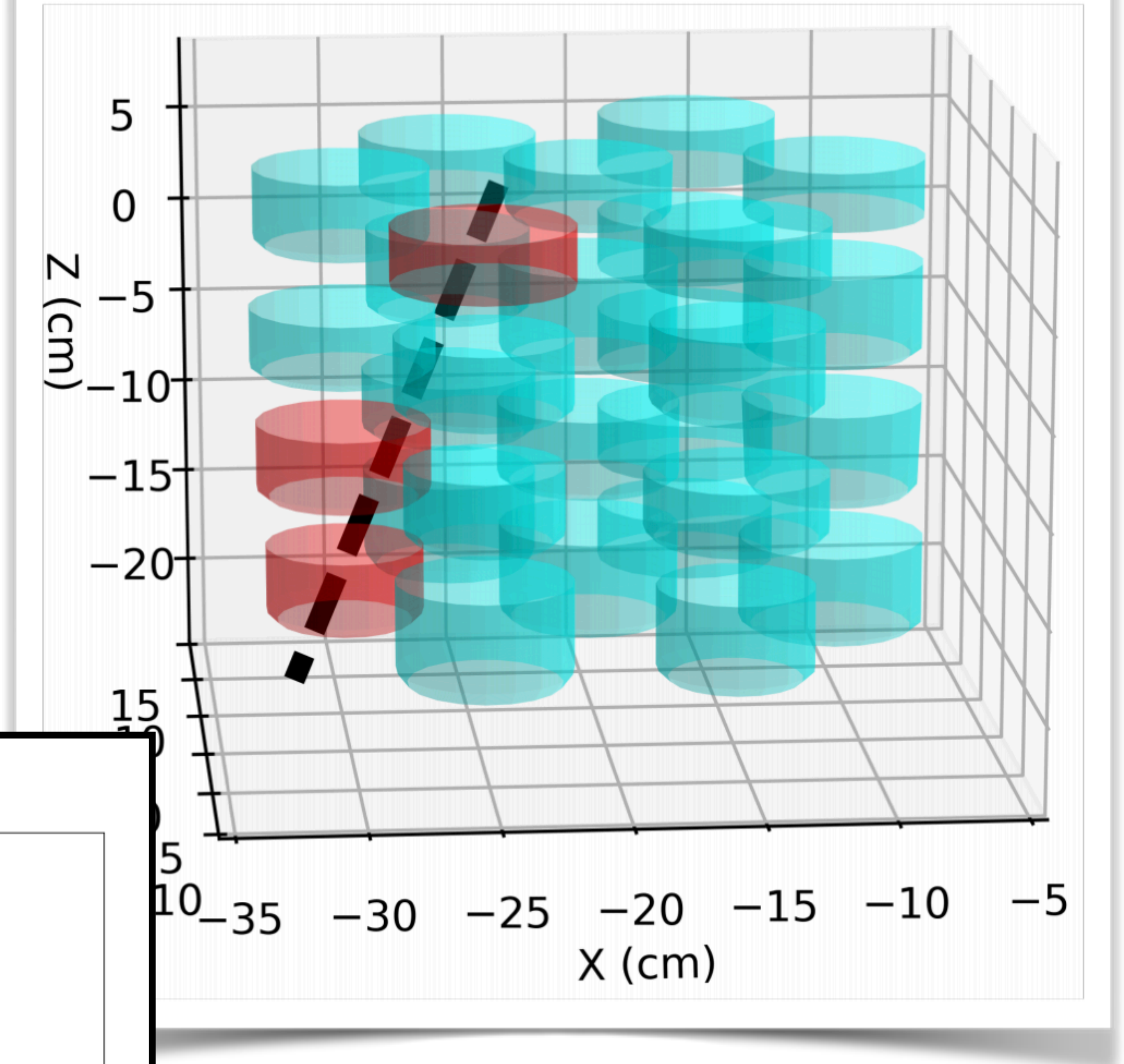


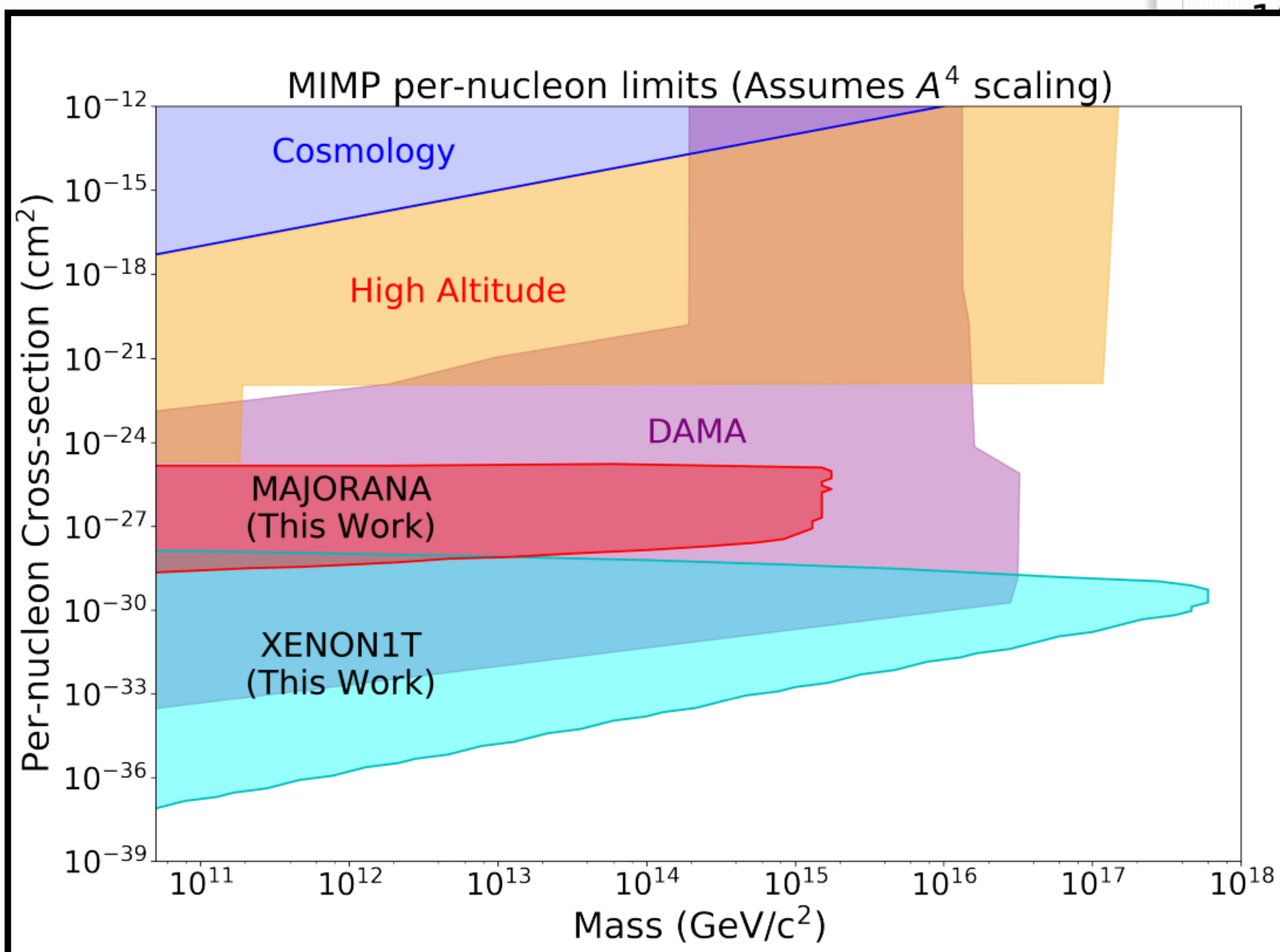
neutrino detectors

recasting

MAJORANA DEMONSTRATOR

search for lightly ionizing particles





'Direct Detection Limits on Heavy Dark Matter'

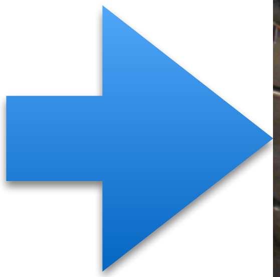
2009.07909

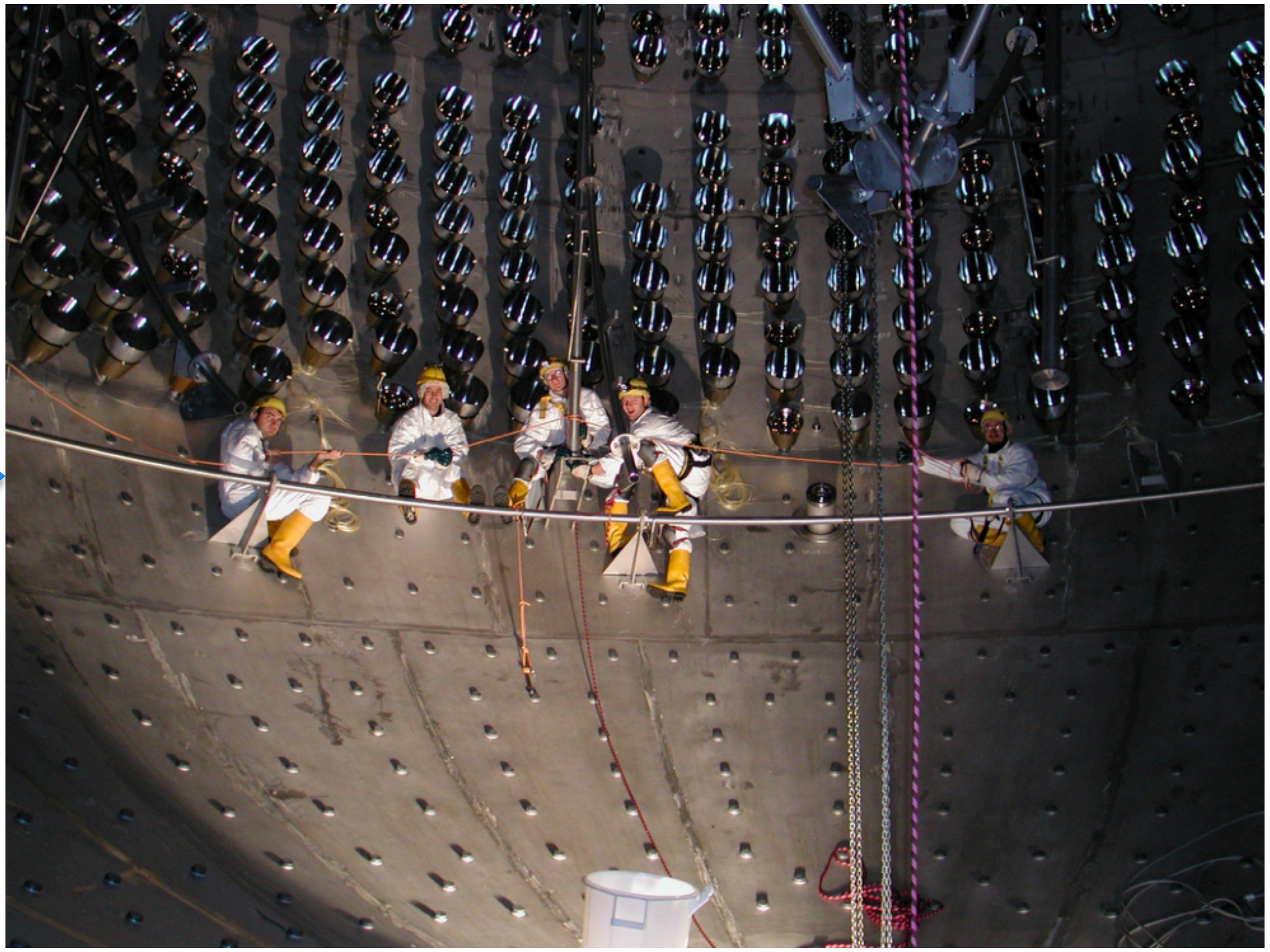
M. Clark, R. Lang et al

Liquid scintillator neutrino detectors

XENON1T, DEAP, PICO, …

BOREXINO, SNO+, JUNO





Direct detection @ liq. scint. neutrino detectors

Mass sensitivity: dark matter fluxes at least 100 times greater

Cross section sensitivity: Satisfy selection trigger

SNO+ signal

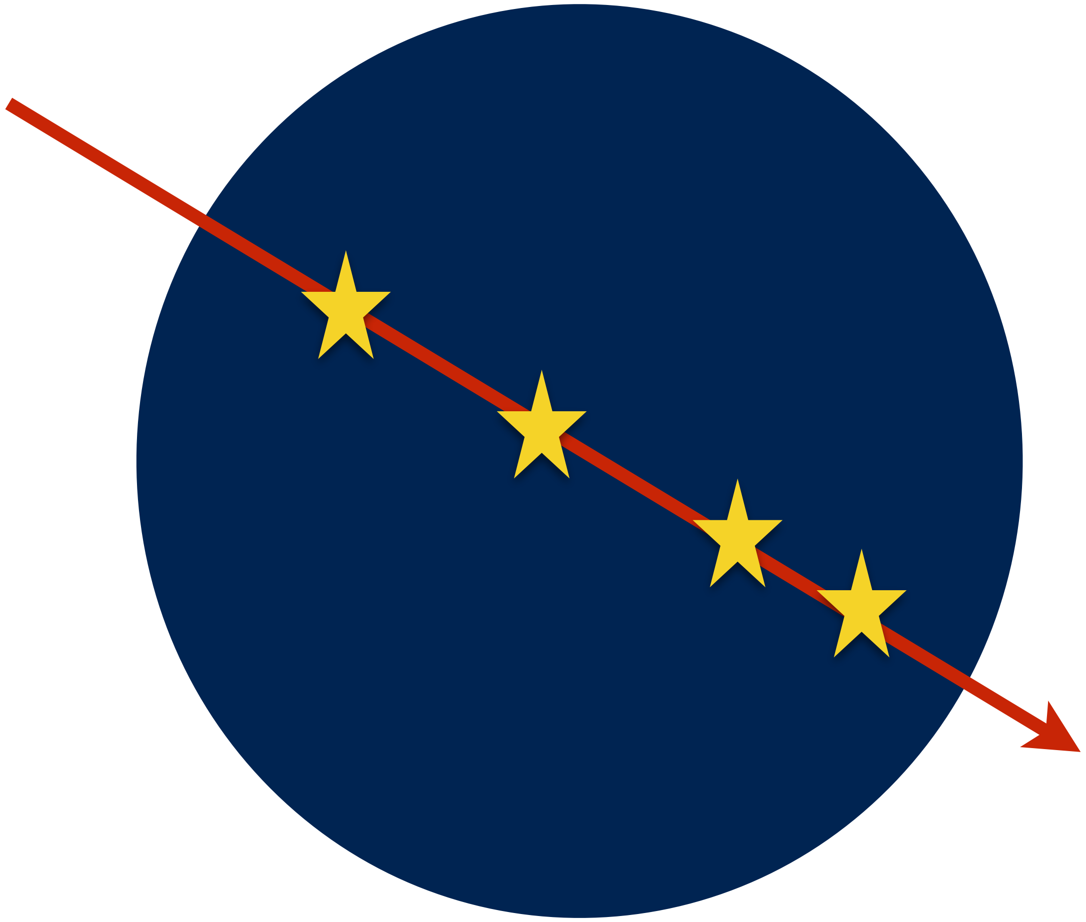
DM transit = 10 μs

- Continuous deposition of photoelectrons over transit time

- Collinearity

$$\Delta\theta \lesssim \frac{m_T}{m_\chi} \simeq 10^{-16} \left(\frac{10^{17}\ \text{GeV}}{m_\chi}\right) \left(\frac{m_T}{11\ \text{GeV}}\right)$$

may be exploited with
vertex reconstruction/ timing information

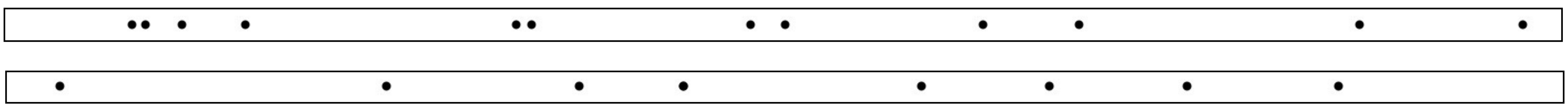


Signal vs background windows

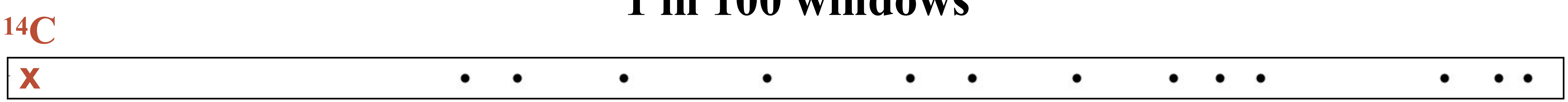
BOREXINO, 10 μs windows

dark matter signal, $\sigma_{nx} = 10^{-28}$ cm^2 (spin-independent)

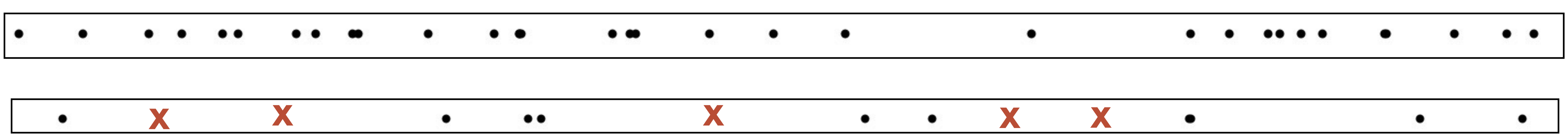
typical windows with dark counts



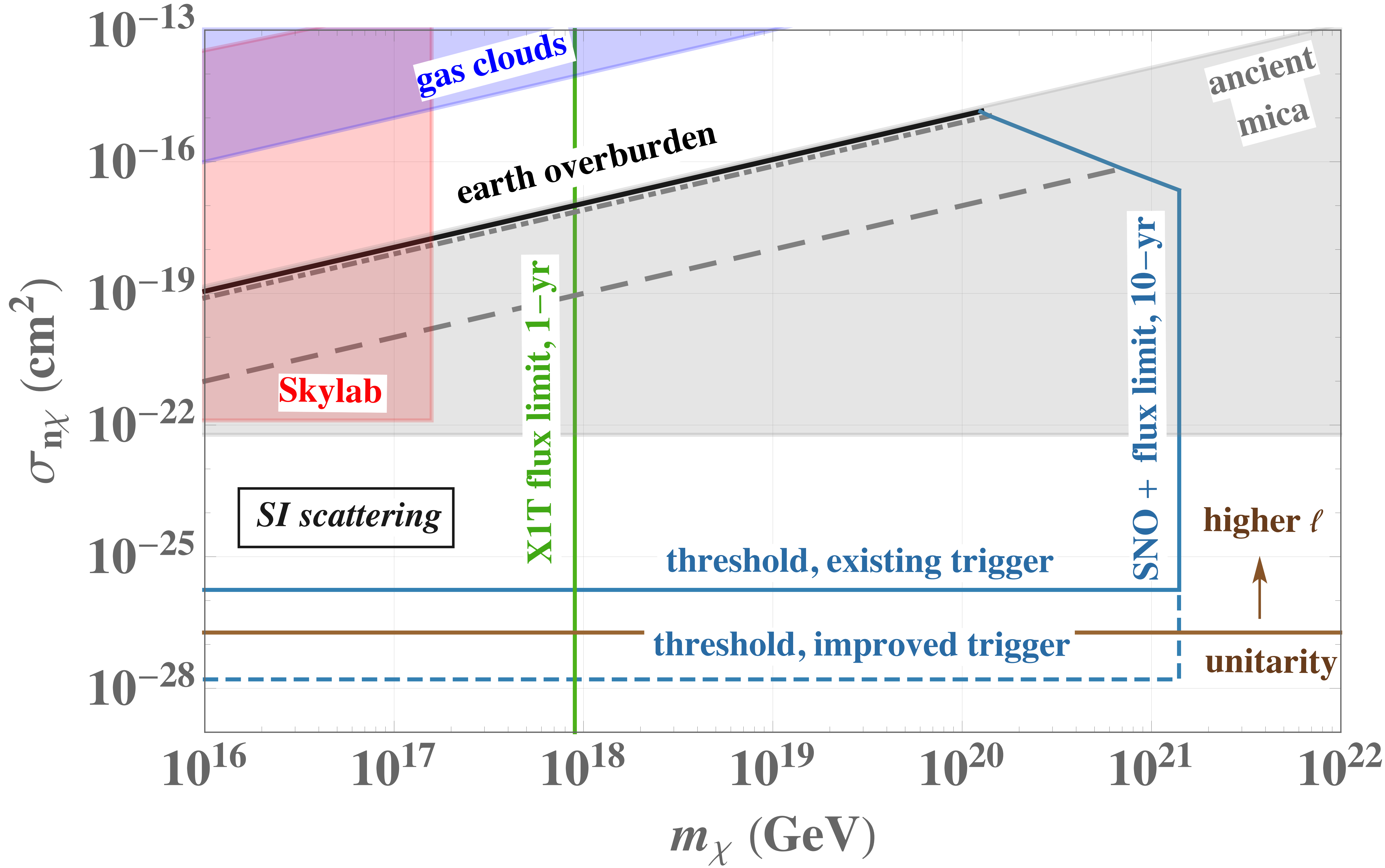
1 in 100 windows



once in 10 years

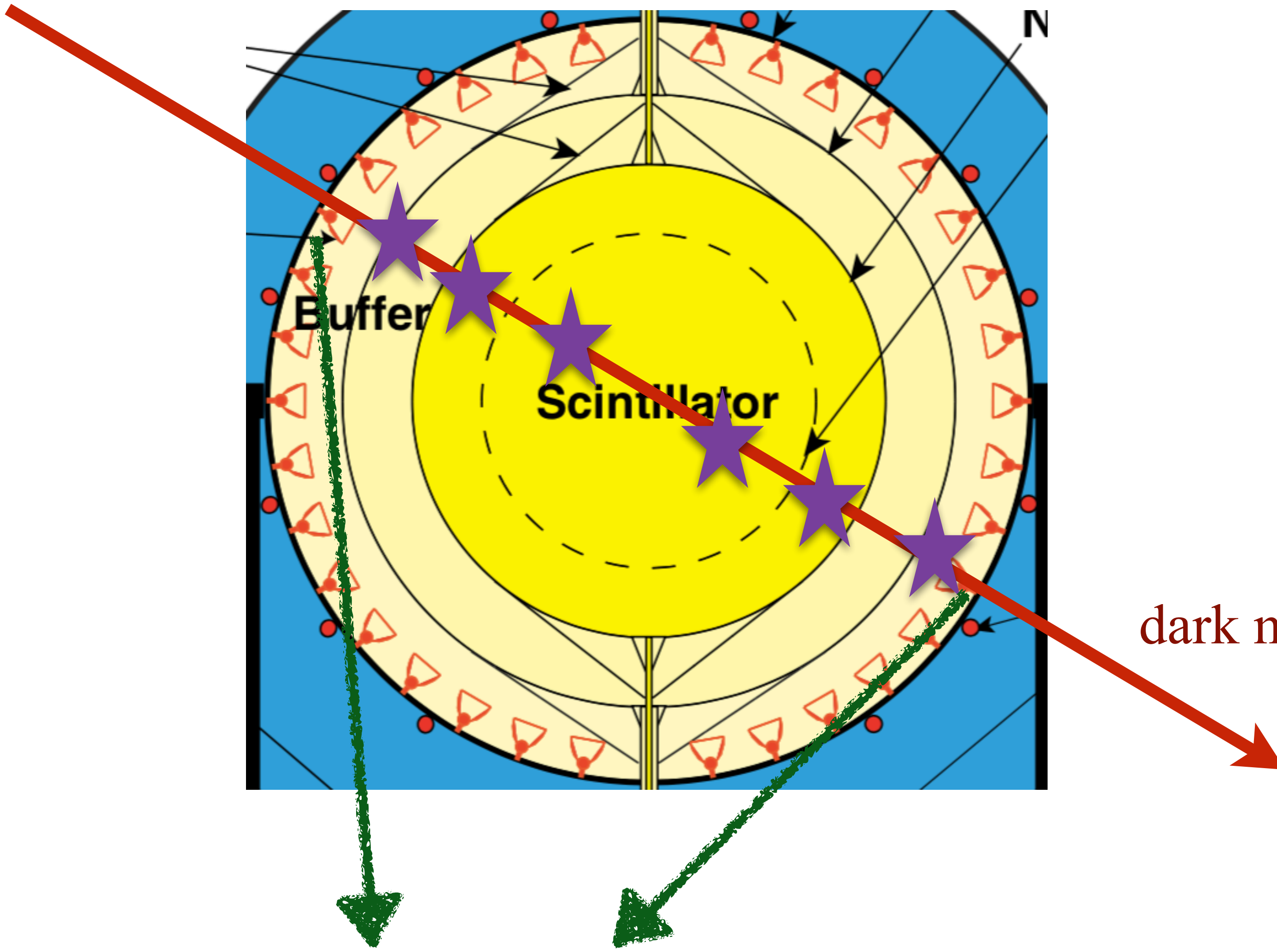


SNO+ cross section reach



Reconstructing dark matter velocity vector

Image: Borexino 1308.0443



PMT “hot spots”
with numerous illuminations

=> **dark matter direction & path length**

\+ timestamps

=> **dark matter speed**

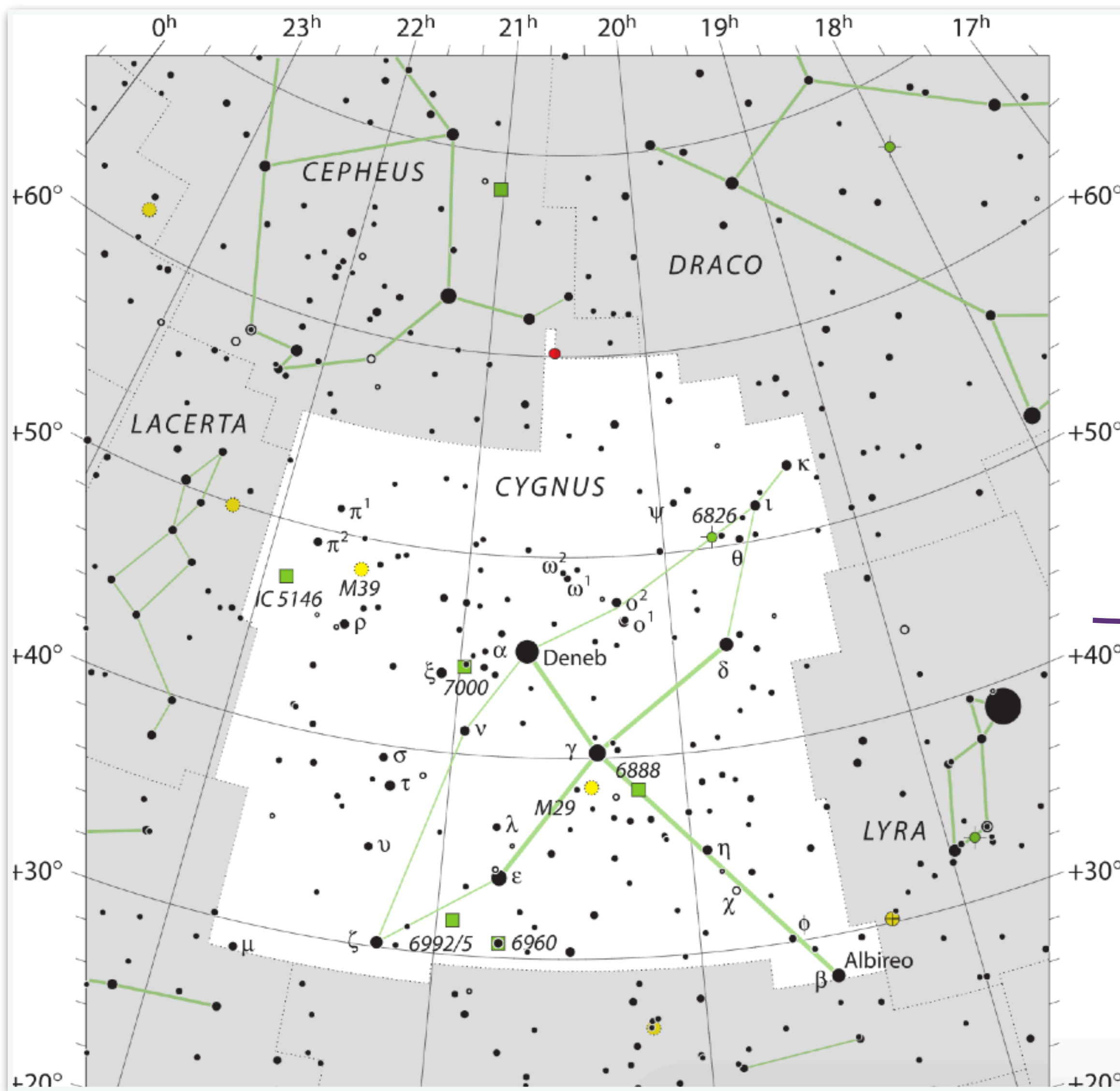
J. Bramante, J. Kumar, **N. Raj**
***Phys Rev D* (2019)**

Detector resolutions

J. Bramante, J. Kumar, **N. Raj**
***Phys Rev D* (2019)**

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

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



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

Detector resolutions

J. Bramante, J. Kumar, **N. Raj**
***Phys Rev D* (2019)**

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

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

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

(< 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)

Dark astrometry

reconstruct velocity vector event-by-event

↓

assemble distributions of speed and angle

↓

determine **halo properties**!

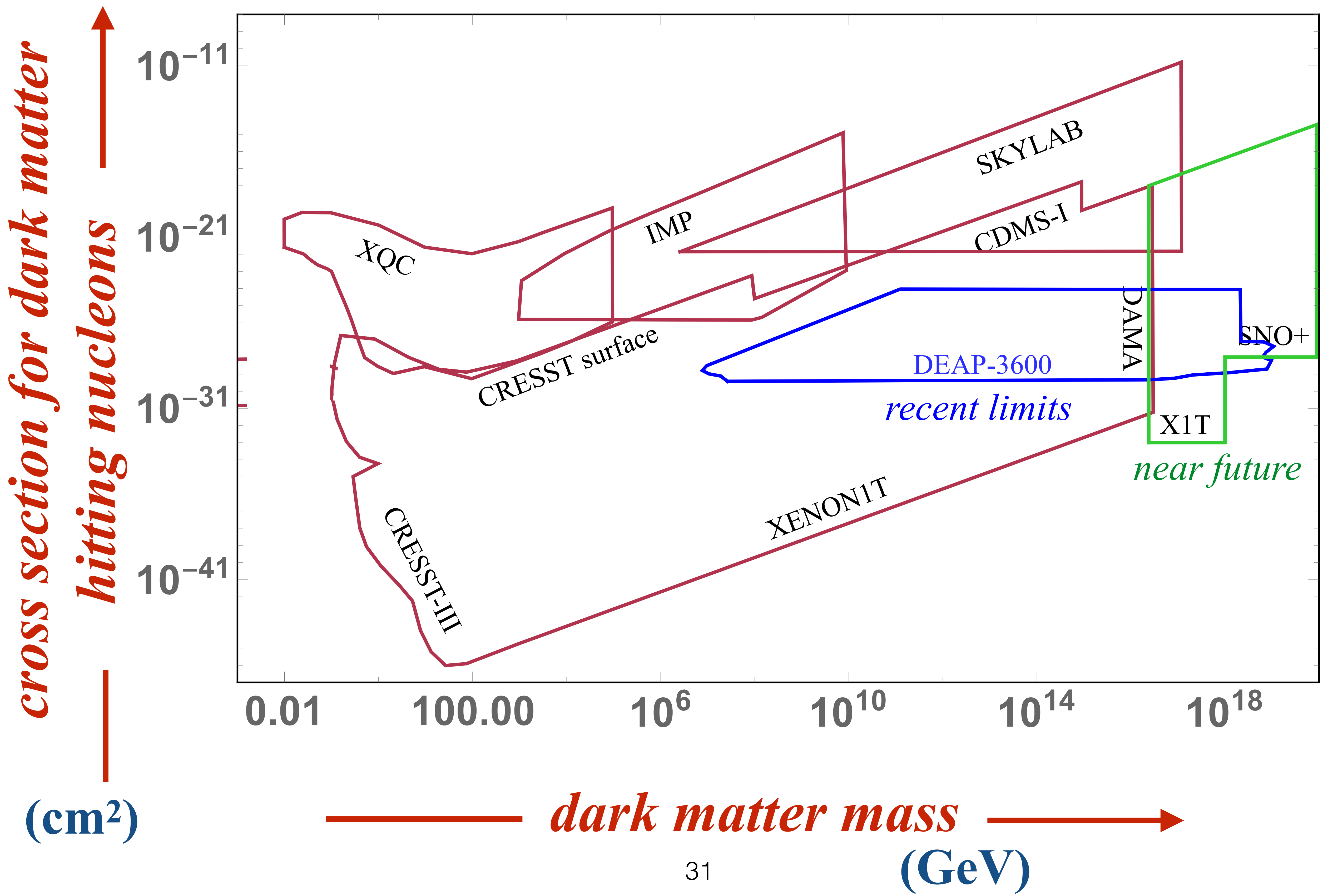
dispersion speed | **escape speed** | **anisotropies**

+

bonus: **reject backgrounds**

J. Bramante, J. Kumar, **N. Raj**
***Phys Rev D* (2019)**

need multiscatter + repurposed neutrino detectors



?

Windchime

for Planck-mass dark matter

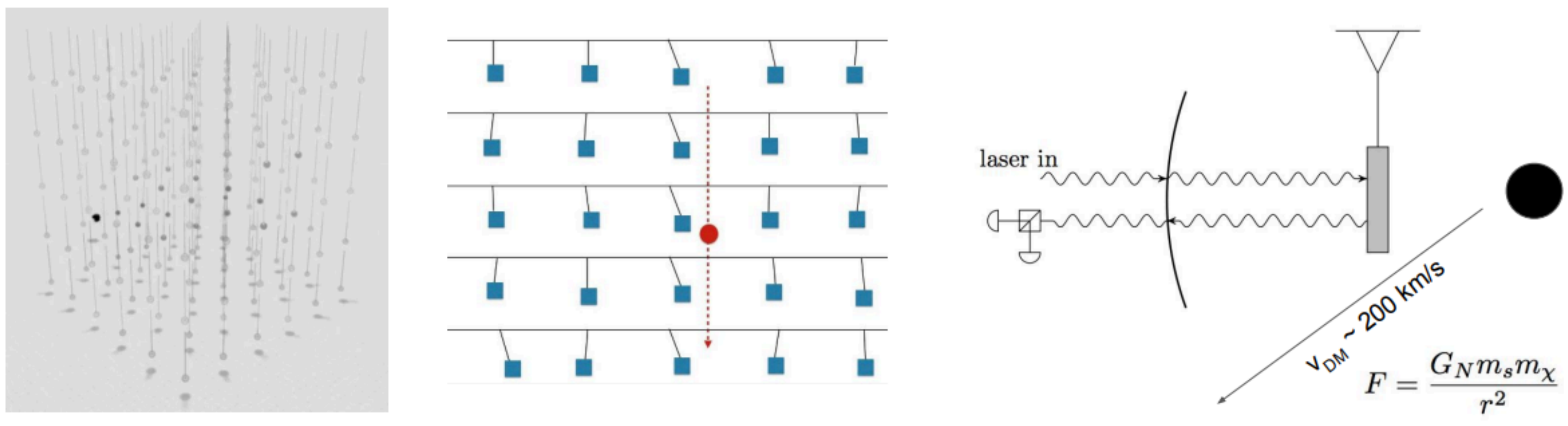


FIG. 1. Schematic illustration of the Windchime detector concept. Left: an array of mechanical sensors, here depicted as suspended pendula, with a potential DM track signal. Center: cross-section, emphasizing the "track" signal. Right: single-sensor depiction of a gravitational DM event. Here, for conceptual illustration, the sensor is depicted in a small optical cavity with laser readout. In practice, readout through either fibers or microwave transmission lines will be more convenient for a densely packed array.

Snowmass 2203.07242

Future annihilations

Experiment	Final state	Threshold/sensitivity	Field of view	Location
Current experiments				
Fermi	Photons	10 MeV – 10^3 GeV	Wide	Space
HESS	Photons	30 GeV - 100 TeV	Targeted	Namibia
VERITAS	Photons	85 GeV - $>$ 30 TeV	Targeted	USA
MAGIC	Photons	30 GeV - 100 TeV	Targeted	Spain
HAWC	Photons	300 GeV - $>$100 TeV	Wide	Mexico
LHAASO (partial)	Photons	10 TeV - 10 PeV	Wide	China
KASCADE	Photons	100 TeV - 10 PeV	Wide	Germany
KASCADE-Grande	Photons	10 - 100 PeV	Wide	Italy
Pierre Auger Observatory	Photons	1 - 10 EeV	Wide	Argentina
Telescope Array	Photons	1 - 100 EeV	Wide	USA
IceCube	Neutrinos	100 TeV - 100 EeV	Wide	Antarctica
ANITA	Neutrinos	EeV - ZeV	Wide	Antarctica
Pierre Auger Observatory	Neutrinos	0.1 - 100 EeV	Wide	Argentina
Future experiments				
CTA	Photons	20 GeV - 300 TeV	Targeted	Chile & Spain
SWGO	Photons	100 GeV - 1 PeV	Wide	South America
IceCube-Gen2	Neutrinos	10 TeV - 100 EeV	Wide	Antarctica
LHAASO (full)	Photons	100 GeV - 10 PeV	Wide	China
KM3NeT	Neutrinos	100 GeV - 10 PeV	Wide	Mediterranean Sea
POEMMA	Neutrinos	20 PeV - 100 EeV	Wide	Space

TABLE I. A non-exhaustive list of current and future indirect detection experiments sensitive to ultraheavy dark matter. See Refs. [132, 141–148].

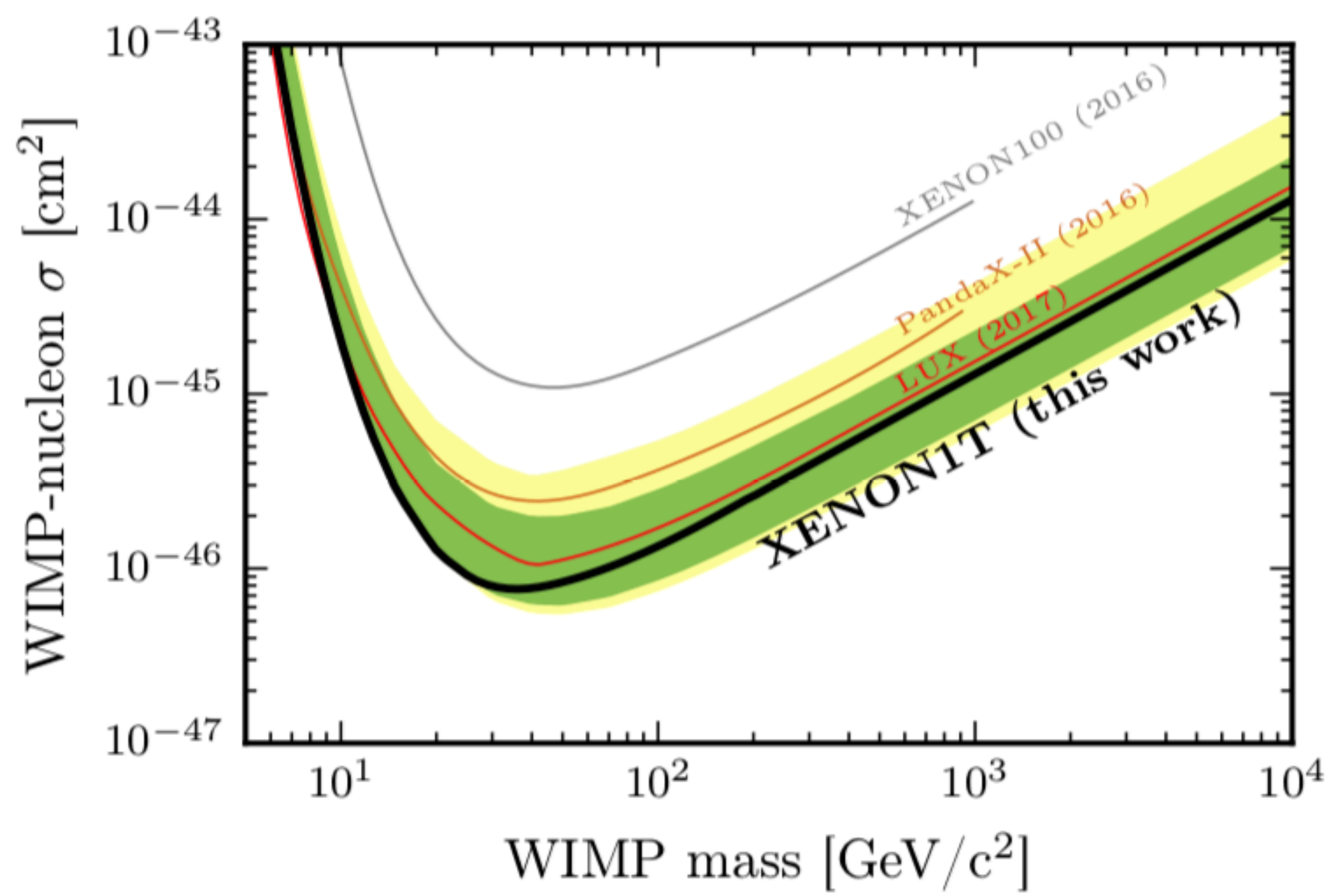
Snowmass 2203.06508

Characterizing WIMPs

Encounter rate (spin-independent) =

$$6.8 \text{ events} \times \left(\frac{\sigma_{\chi N}}{10^{-39}\ \text{cm}^2}\right)\left(\frac{A}{27}\right)^4\left(\frac{1000\ \text{GeV}}{m_{\text{DM}}}\right)\left(\frac{27}{A}\right)\left(\frac{\rho_{\text{DM}}}{0.3\ \text{GeV/cm}^3}\right)\left(\frac{v_{\text{DM}}}{220\ \text{km/s}}\right)/\text{kg/day}$$

$\frac{\rho_{\text{DM}}}{0.3\ \text{GeV/cm}^3}$ x



Redundancy in {cross-section, mass, local density}

Characterizing MIMPs

$$\tau = n_{\mathrm{det}} \sigma_{T\chi} L_{\mathrm{det}}$$

cross-section

scatters per transit

target number density

detector dimension

Characterizing MIMPs

N(scatters) $\propto$ DM kinetic energy / recoil energy

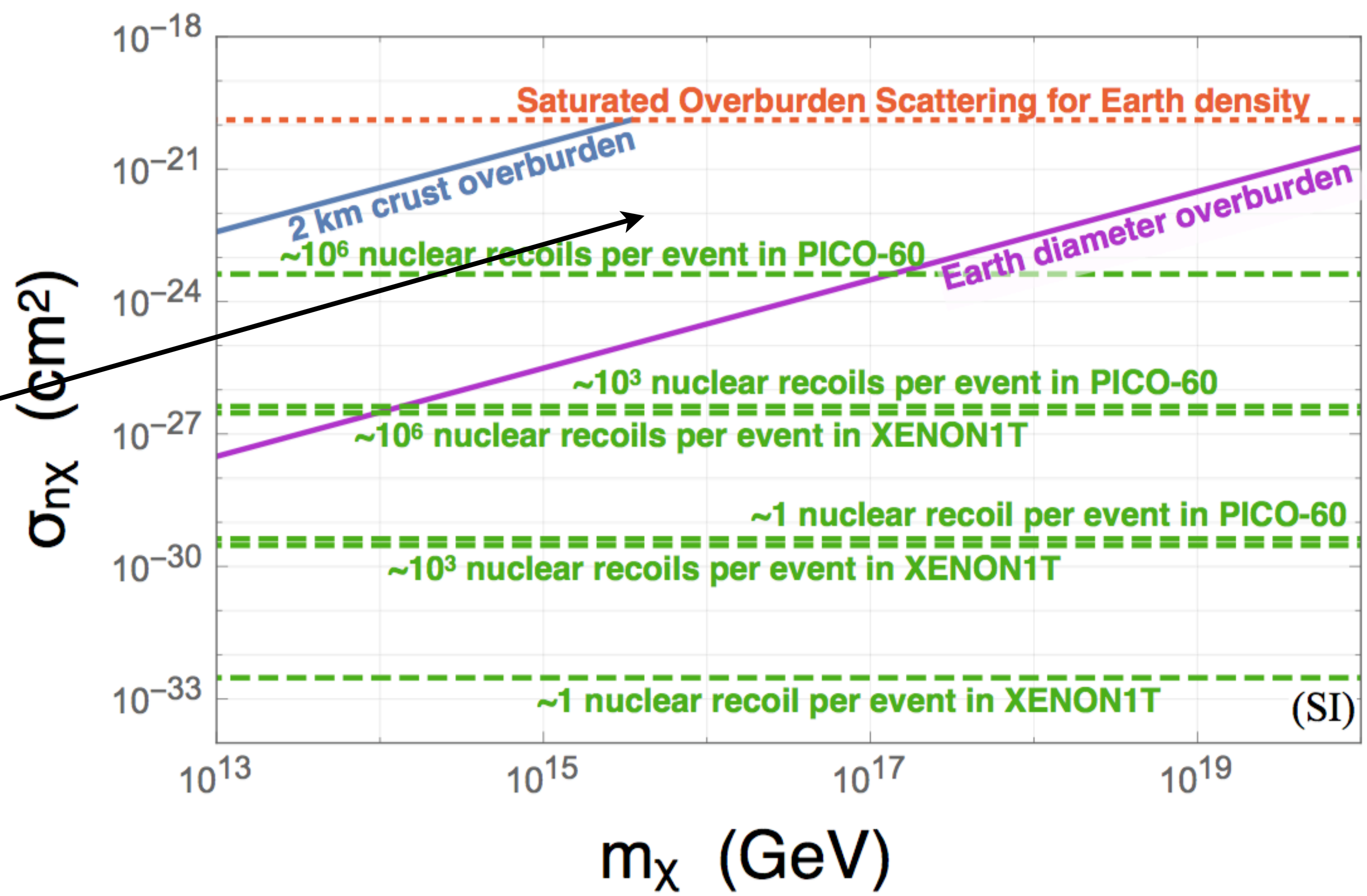
$n_{\mathrm{shield}} L_{\mathrm{shield}} \sigma \propto m_\chi v_\chi^2$ / recoil energy

(More accurately:

$$\frac{E_f}{E_i} = \prod_i^{\mathrm{nuclei}} (1 - z\beta_i)^{\tau_{\mathrm{od},i}}$$

$$z\beta_i = z\, 4 m_i m_\chi / (m_\chi + m_i)^2$$)

Dark matter tracks
=> measure max angle of entry
=> angle of rejection in
Earth underburden in this band
=> mass



Characterizing MIMPs

$$\Phi = (\rho_\chi / m_\chi) A_{\text{det}} v_\chi t_{\text{exp}}$$

flux

local density

mass

detector area

velocity

run-time

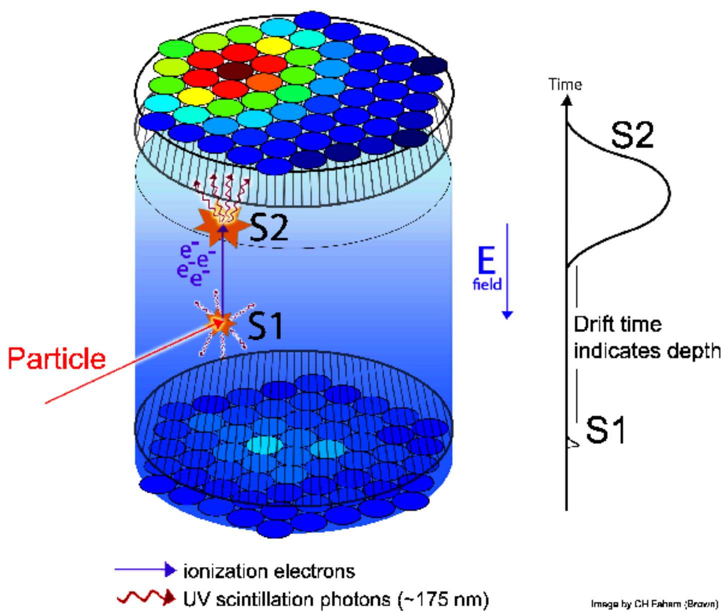
(Q1) Identifying multiscatterers

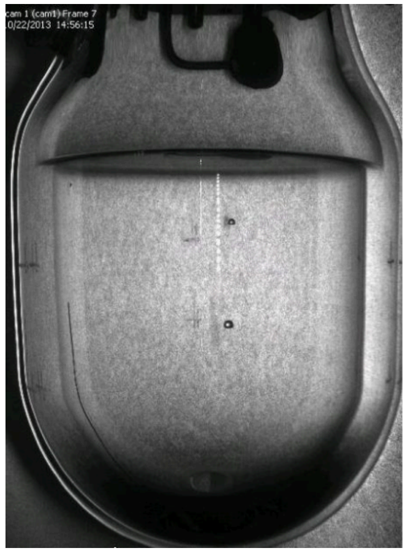
DM transit = 2.5 μs

LUX/PANDAX/XENON1T

PICO-60

single hit:





multi-hit:

Train of scintillation pulses + electroluminescence pulses

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

Track of bubbles

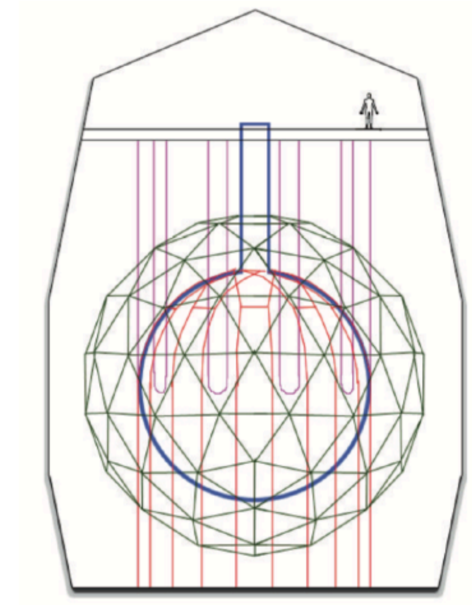
Stereo cameras can image up to 100 bubbles (mm resolution)

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

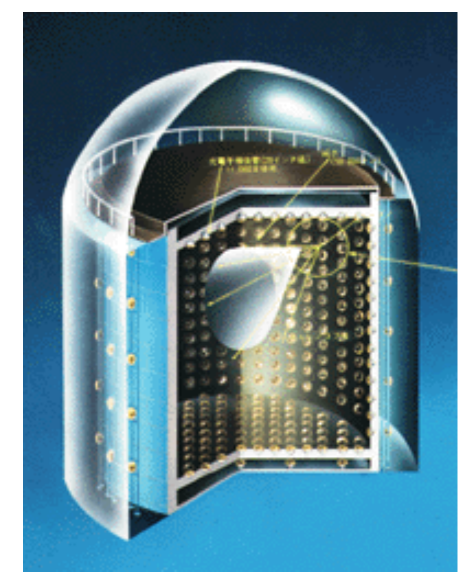
Searches ongoing…

(Q2) Large volume neutrino detectors?

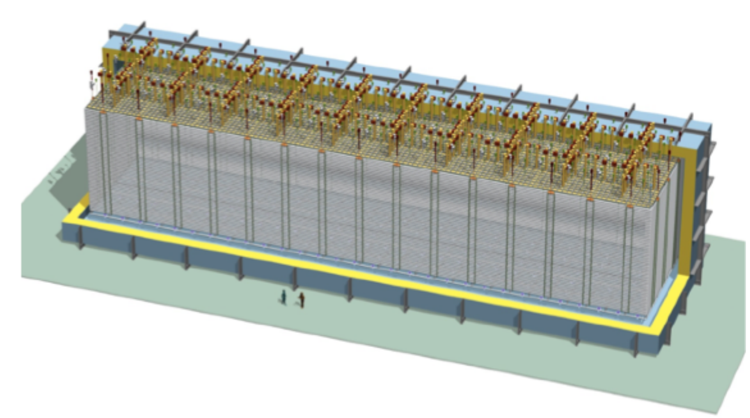
Organic liquid scintillator (SNO+, Borexino, etc.):
well-suited for dark matter search!
collect enough light in PMTs => in business



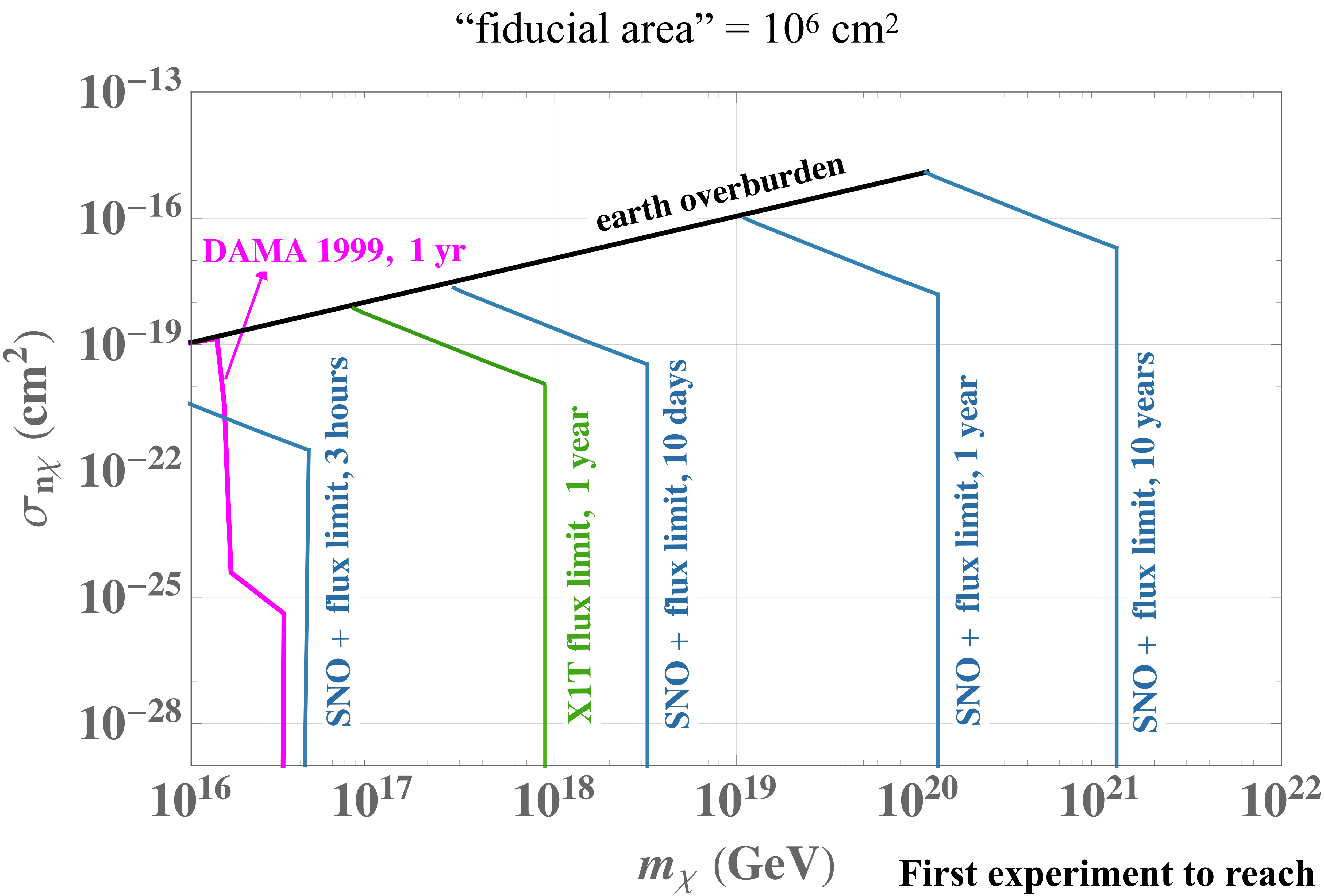
Water Cerenkov (Super-K, SNO, etc.) unsuitable:
non-relativistic scattering



Liquid argon TPCs (DUNE, etc.):
threshold too high



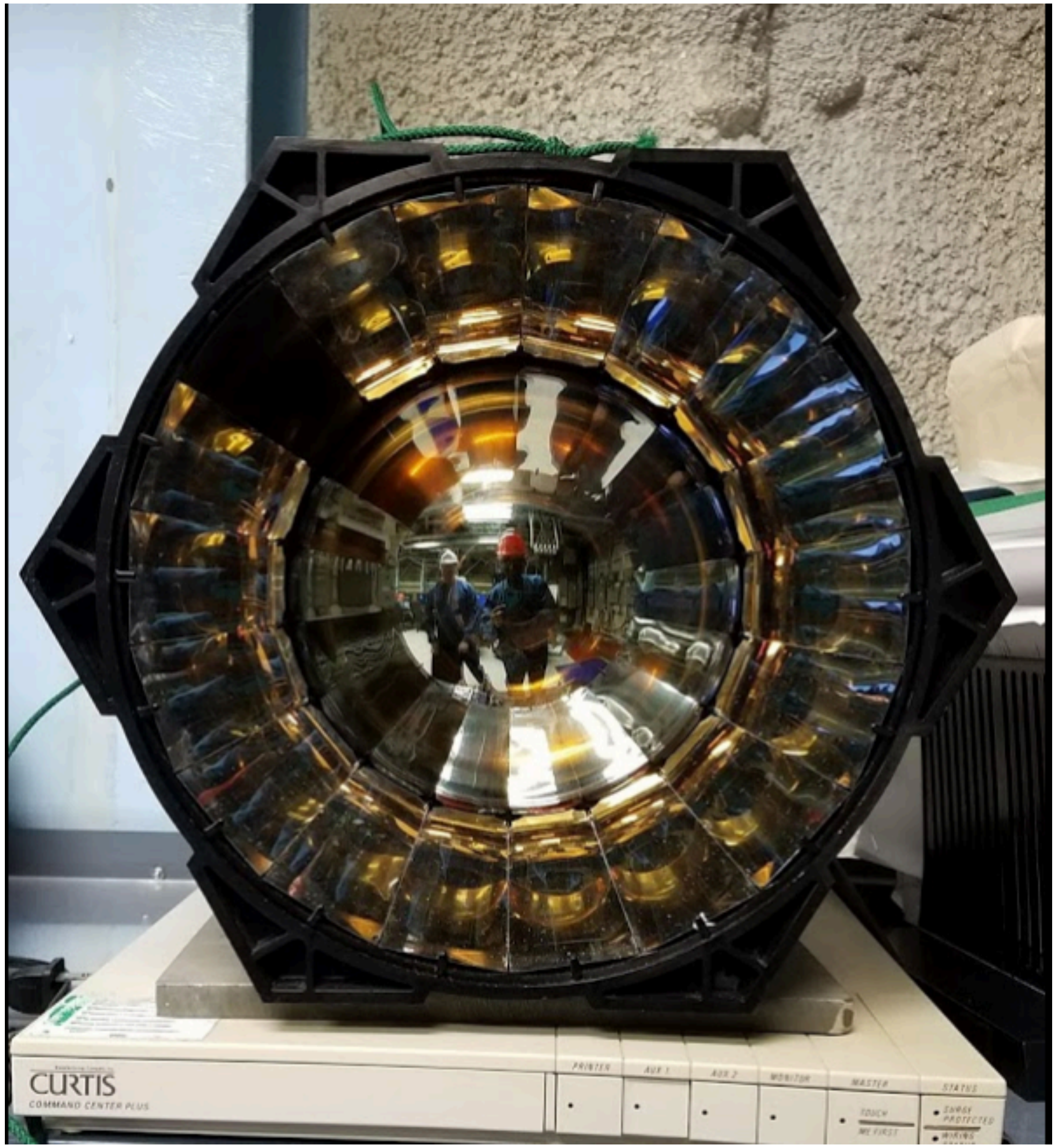
SNO+ mass reach



First experiment to reach Planck mass!

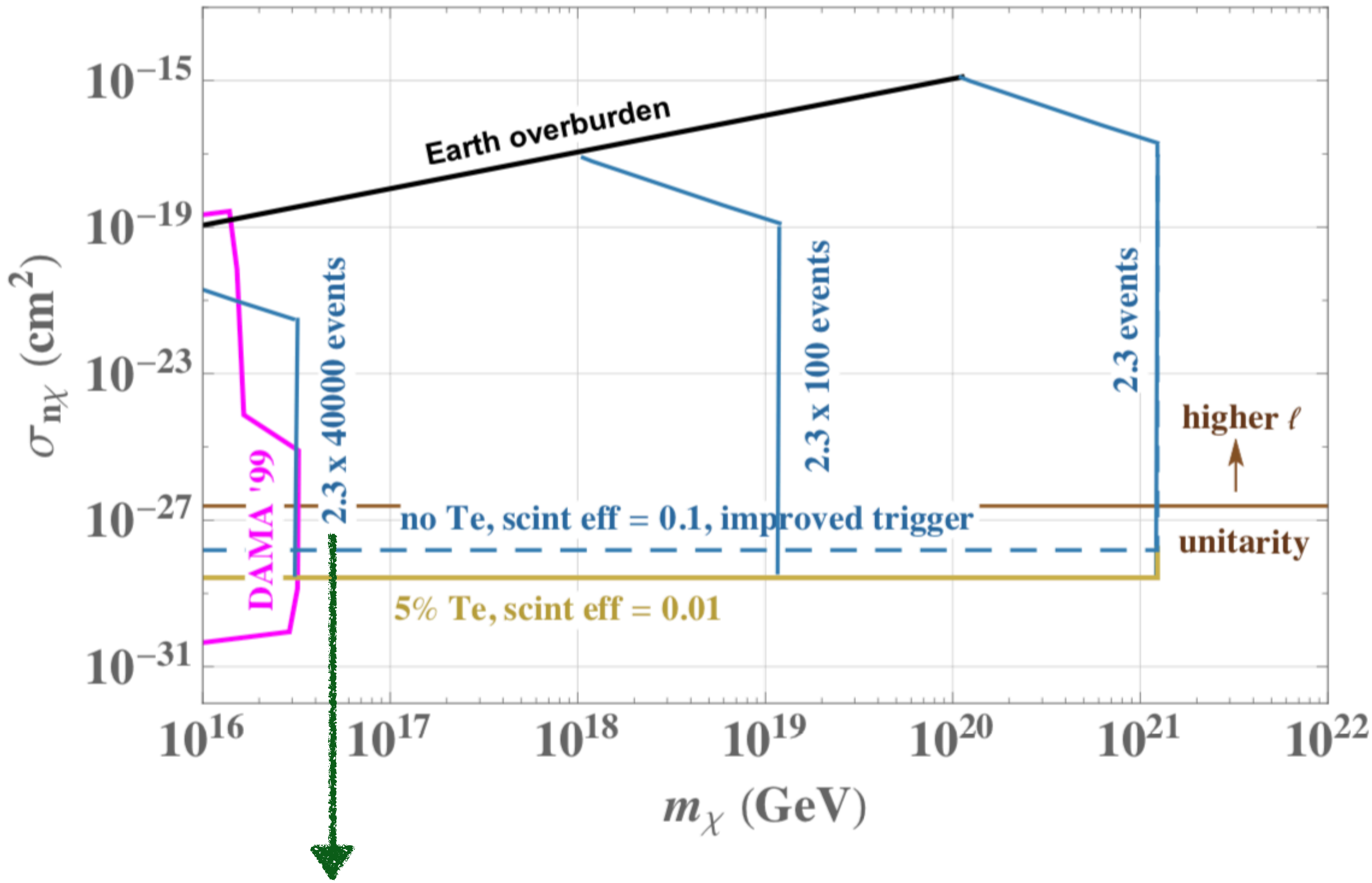
SNO+

scale model @ SNOLAB



PMT selfie 2 km underground

Statistics



SNO+ could potentially collect these many events

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SNO+ cross section reach: triggers

Existing @ BOREXINO

50 keV/ 100 ns =>

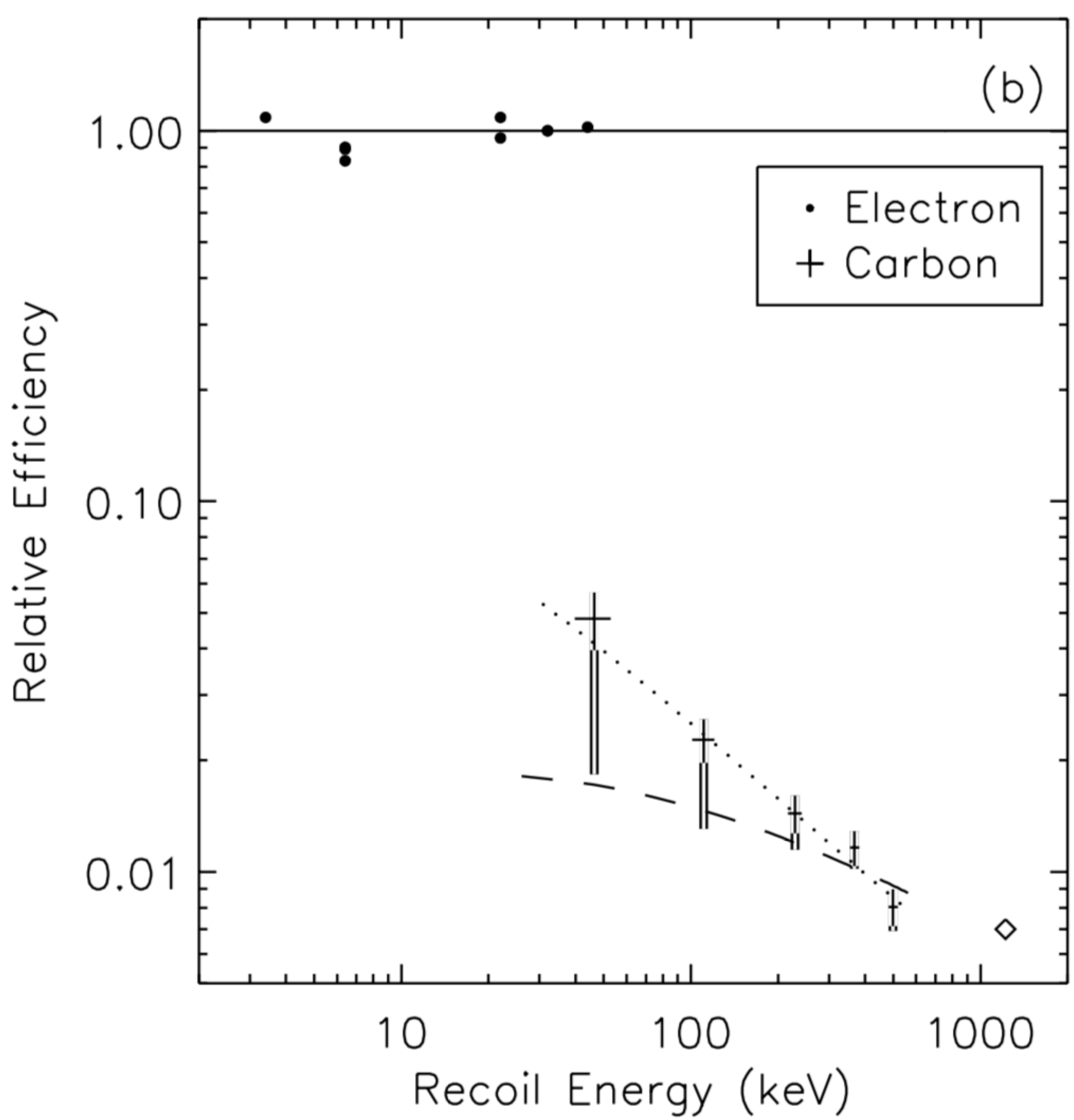
50 PE /100 ns, or

5000 PE/ 10 μs.

The Scintillation Efficiency of Carbon and Hydrogen Recoils in an Organic Liquid Scintillator for Dark Matter Searches

Hong, Craig, Graham, Hailey, Spooner, Tovey

[Bicron scintillator (BC505)]



SNO+ cross section reach: triggers

DM transit = 10 μs

Existing @ BOREXINO

50 PE /100 ns, or

5000 PE/ 10 μs.

Proposed improvement

42 PE/ 10 μs.

Dark count rate reported by Borexino (1308.0443):

$N_{\rm bg}$ = **10 PE/ 10 μs.**

— Get required trigger from trial factors (solve for $N_{\rm c}$)

$$\sum_{N_{\rm c}}^{\infty} \frac{(N_{\rm bg})^{N_{\rm c}}}{N_{\rm c}!} e^{-N_{\rm bg}} = \frac{10\ \mu{\rm s}}{t_{\rm life}}$$

(10 yr)

— Enhance cross section sensitivity by ~100.

SNO+ cross section reach

B. Broerman, J. Bramante, J. Kumar, R. Lang, M. Pospelov, **N. Raj**
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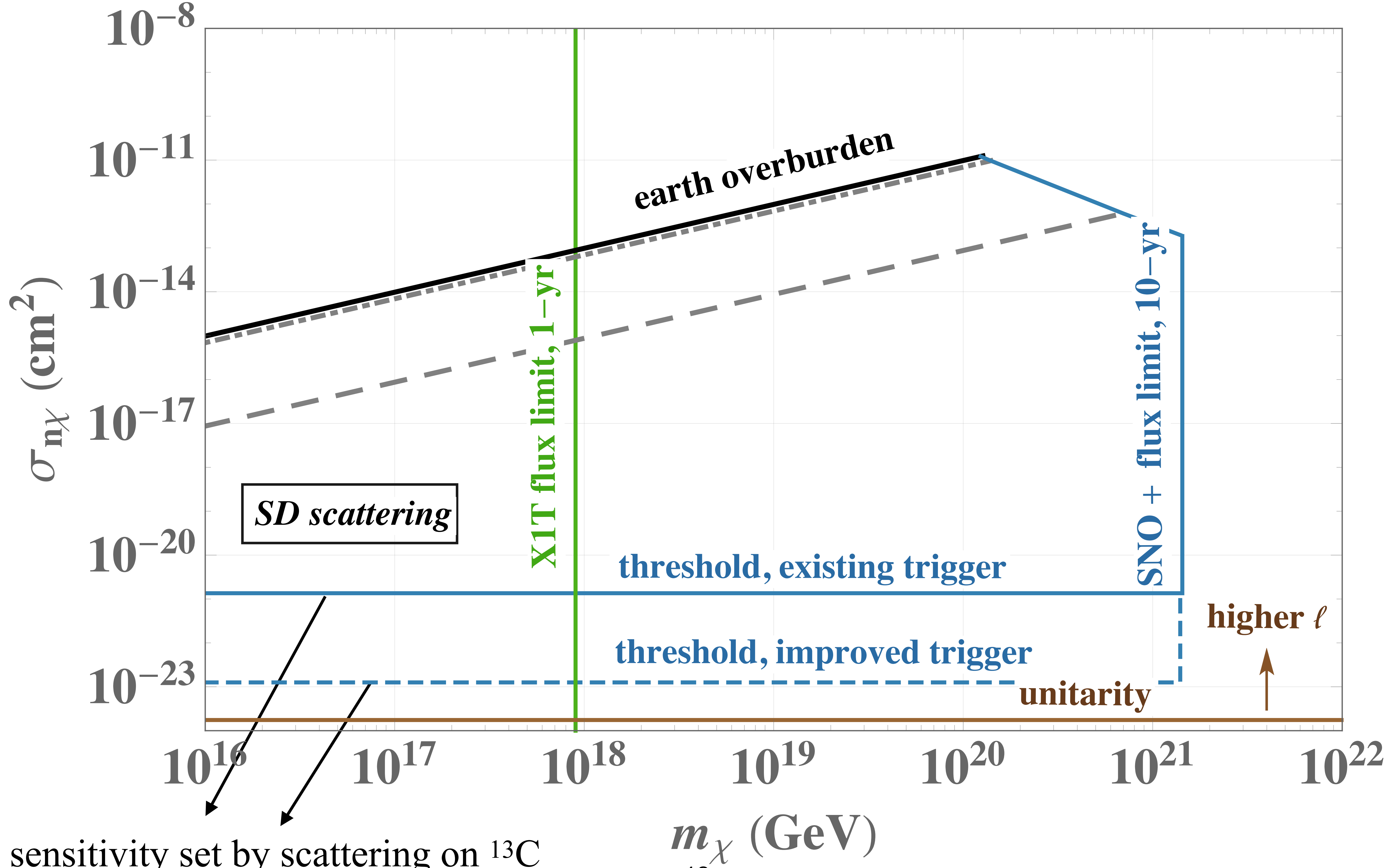


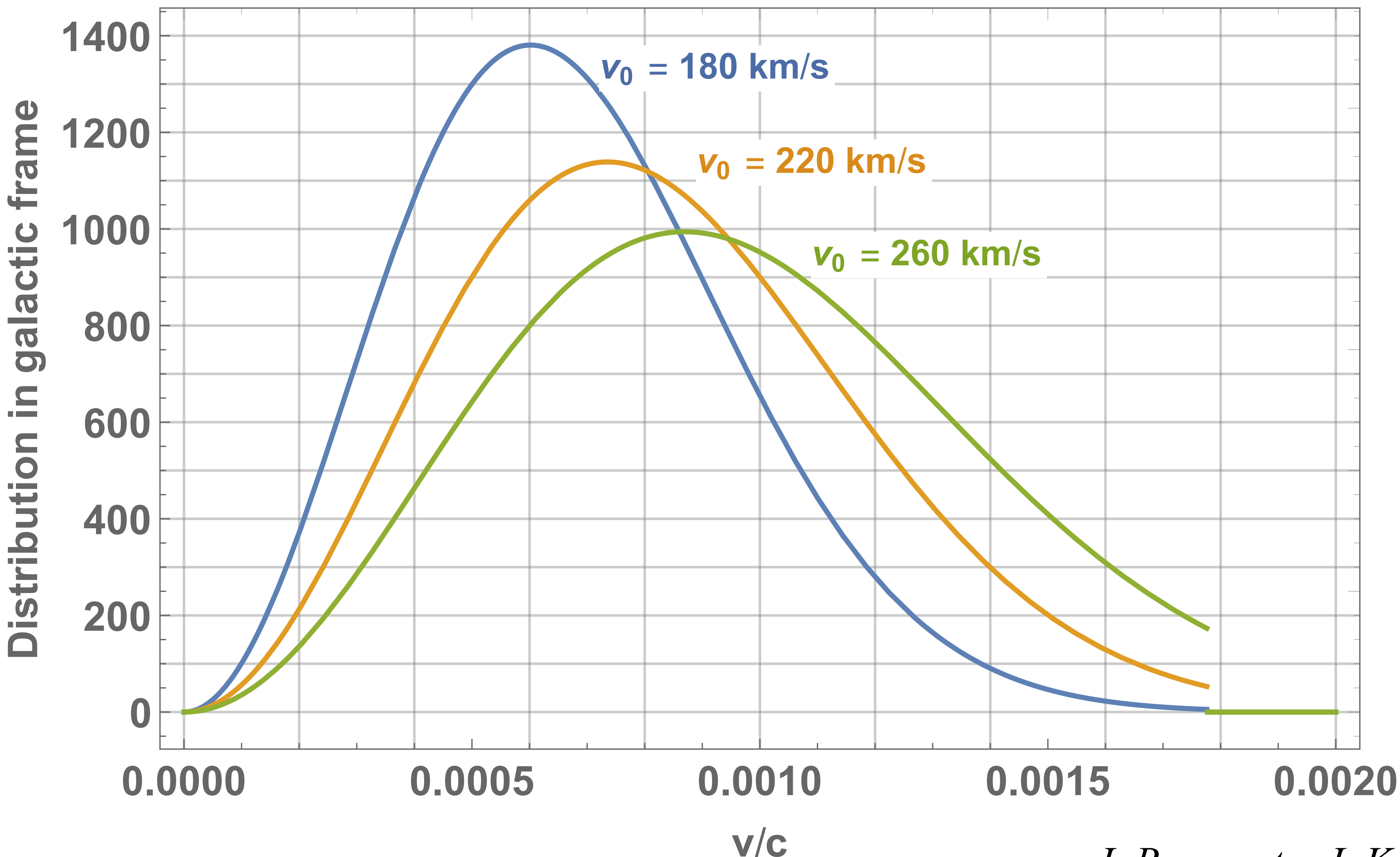
sensitivity set by scattering on ^{13}C

Pinpointing mean speed

galactic frame

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

v_0 = circular speed = √(2/3) dispersion speed



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Pinpointing mean speed

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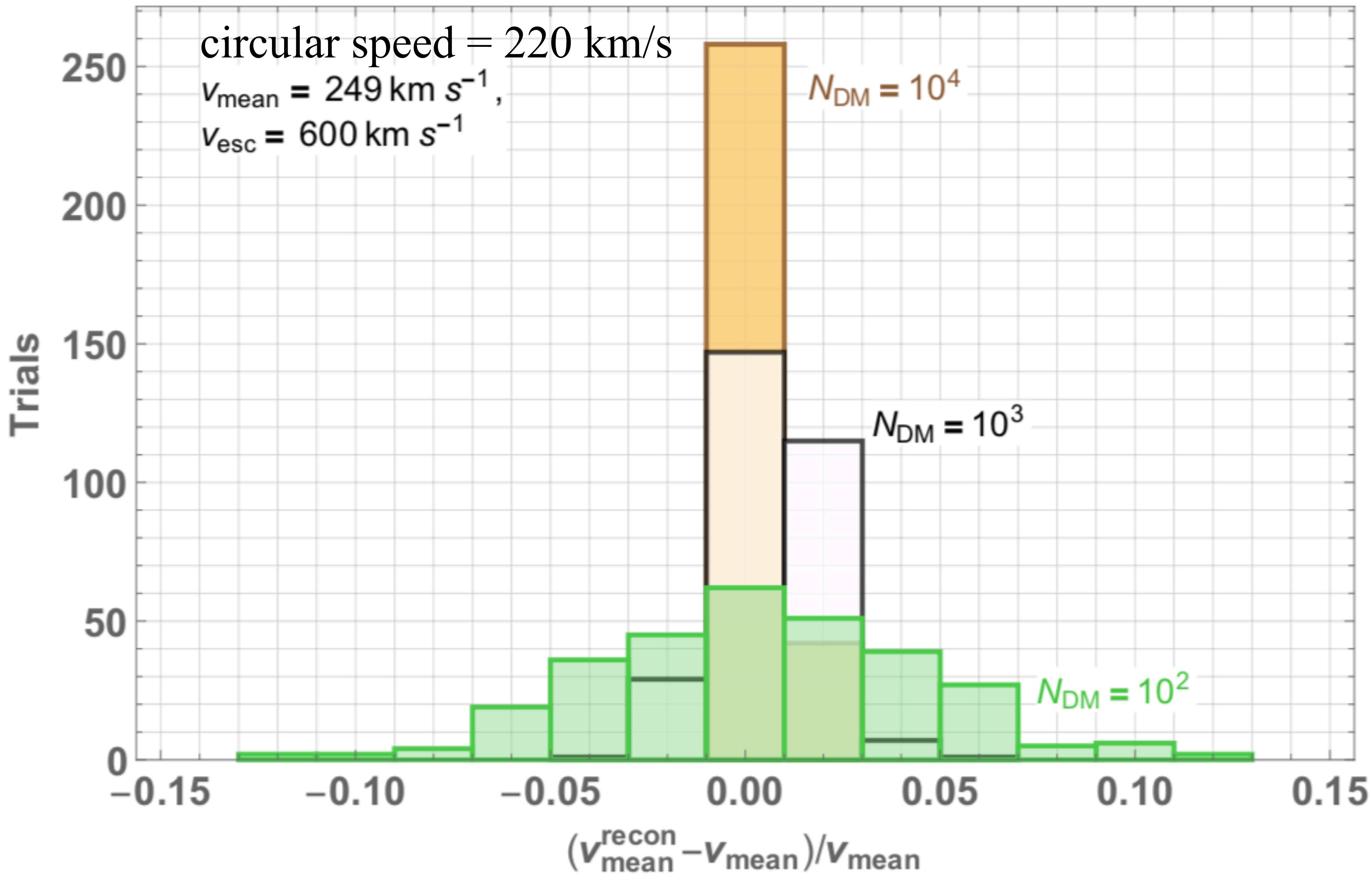

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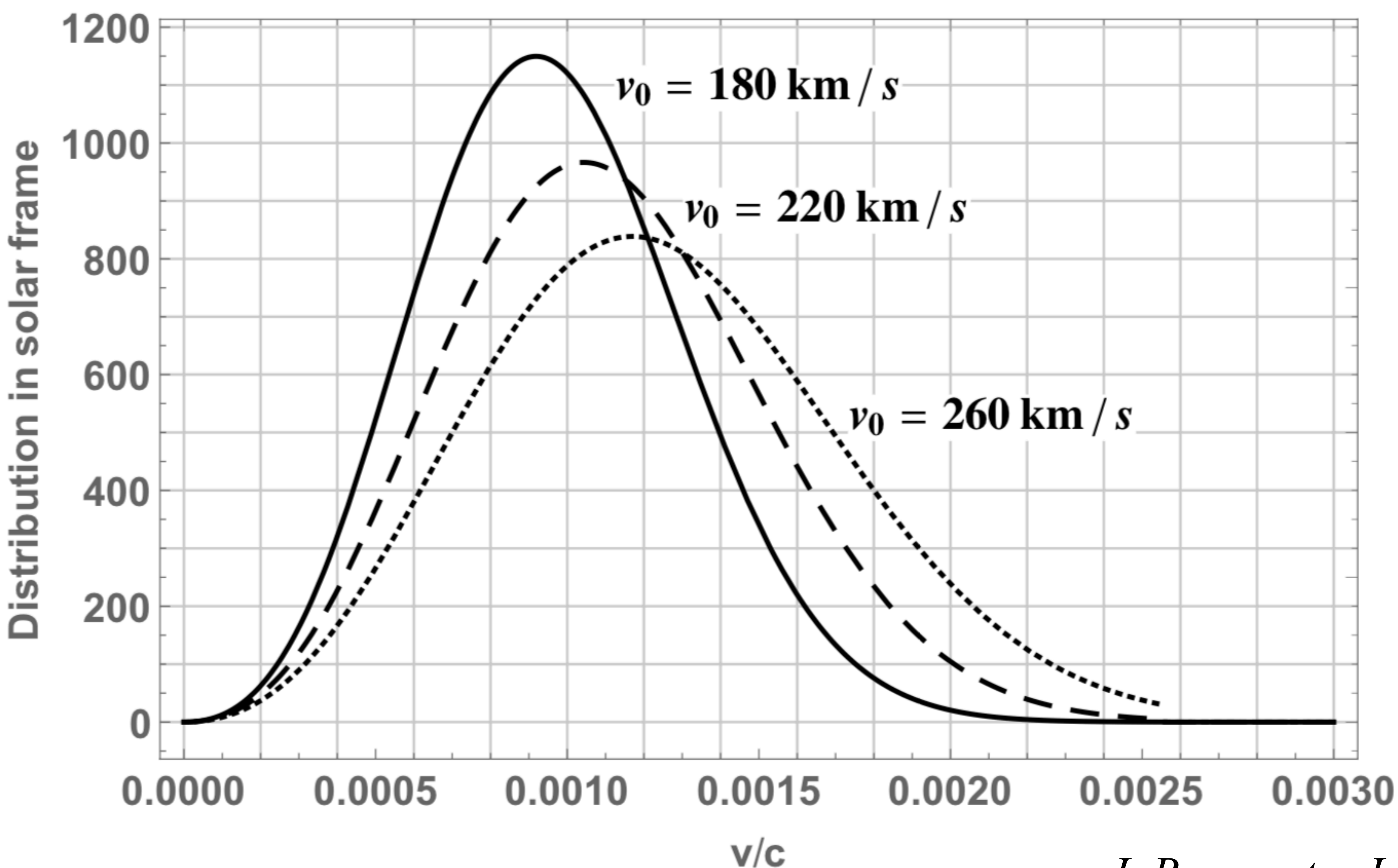
Testing dispersion speed

Sun's frame

$$v f_\oplus(v) \propto v^2 \exp\left(\frac{-(v^2+v_\oplus^2)}{v_0^2}\right) \times$$

$$\left[\exp\left(\frac{2vv_\oplus}{v_0^2}\right) - \exp\left(c_{\min}\frac{2vv_\oplus}{v_0^2}\right)\right]\Theta(v_{esc}+v_\oplus - v)$$



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Testing dispersion speed

Sun's frame

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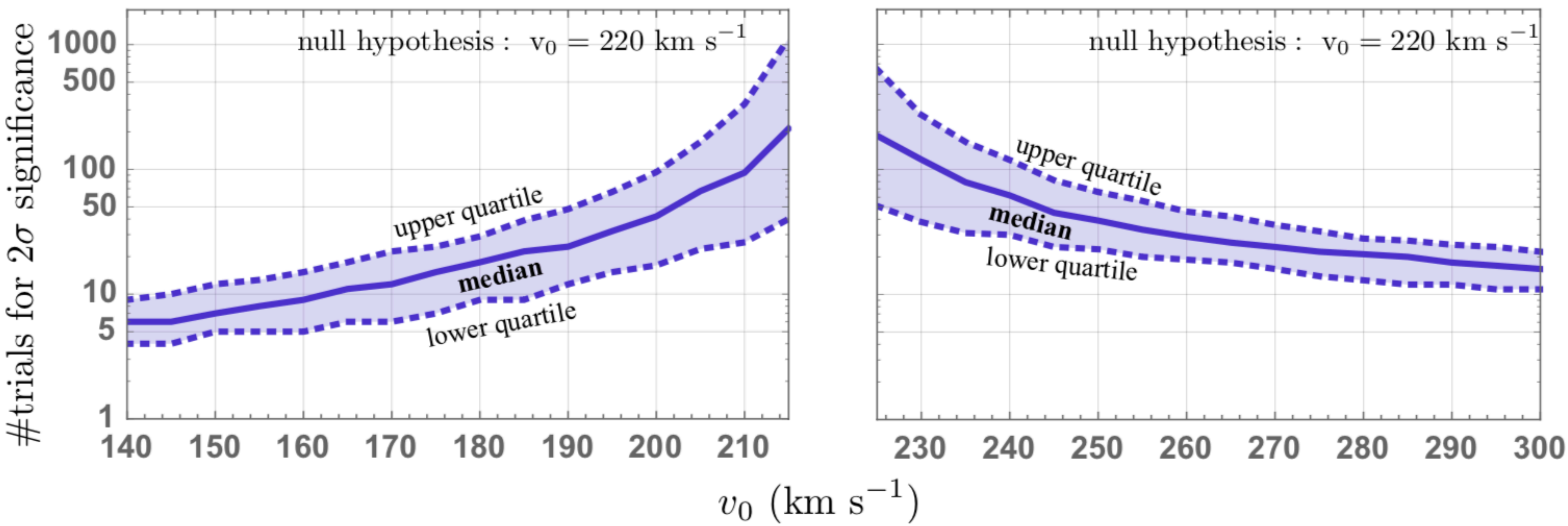
Perform a Kolmogorov-Smirnov test
("How many events to reject null hypothesis at given significance?")



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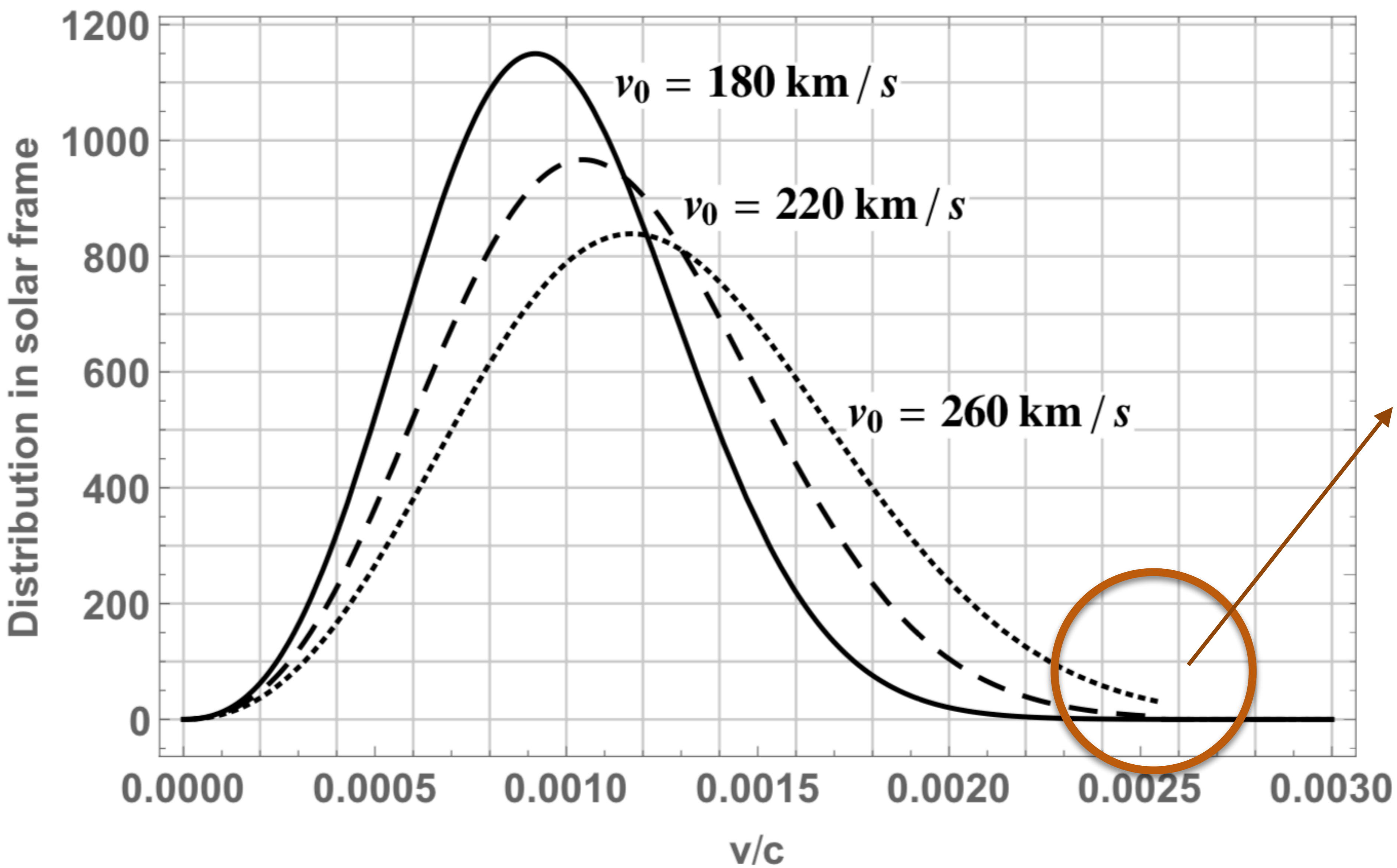
Pinpointing escape speed?

Sun's frame

$$v f_{\oplus}(v) \propto v^2 \exp\left(\frac{-(v^2 + v_{\oplus}^2)}{v_0^2}\right) \times \left[\exp\left(\frac{2vv_{\oplus}}{v_0^2}\right) - \exp\left(c_{\min}\frac{2vv_{\oplus}}{v_0^2}\right)\right]\Theta(v_{esc} + v_{\oplus} - v)$$



escape speed on tail => hard to reconstruct faithfully from moments of distribution

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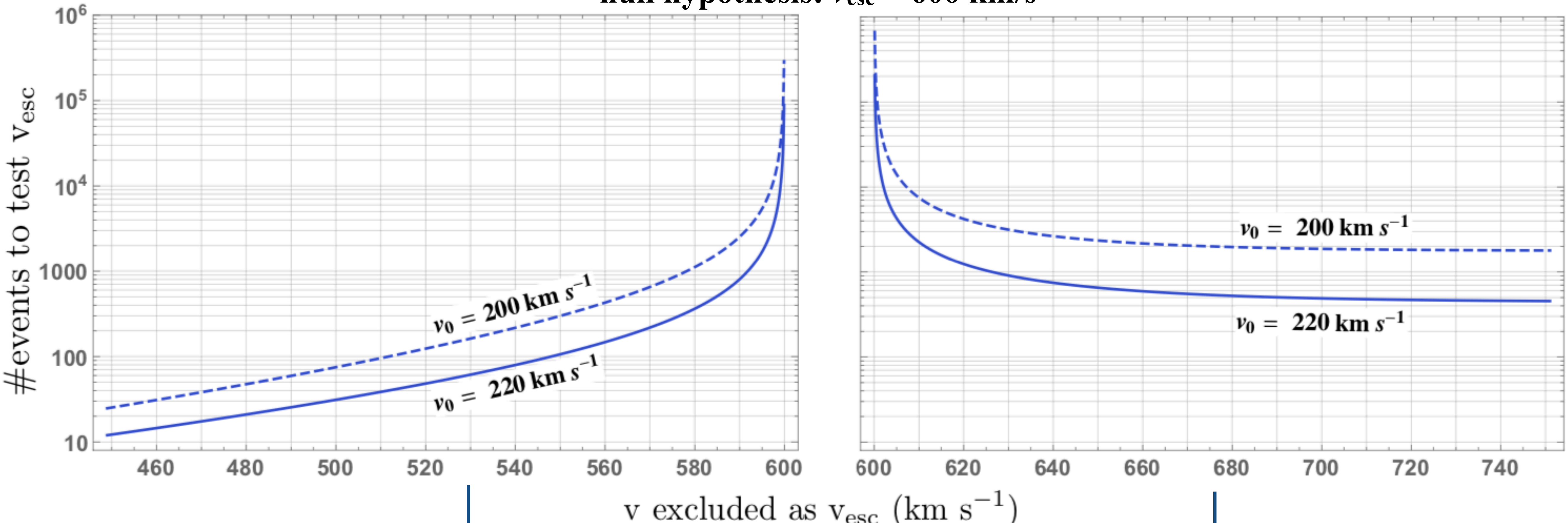
Testing escape speed

Sun's frame

$$v f_{\oplus}(v) \propto v^2 \exp\left(\frac{-(v^2+v_{\oplus}^2)}{v_0^2}\right) \times$$
$$\left[\exp\left(\frac{2vv_{\oplus}}{v_0^2}\right) - \exp\left(c_{\min}\frac{2vv_{\oplus}}{v_0^2}\right)\right]\Theta(v_{esc}+v_{\oplus}-v)$$

null hypothesis: v_{esc} = 600 km/s



1 event above v

2.3 events in [600 km/s, v]
(90% C.L., Poissonian)

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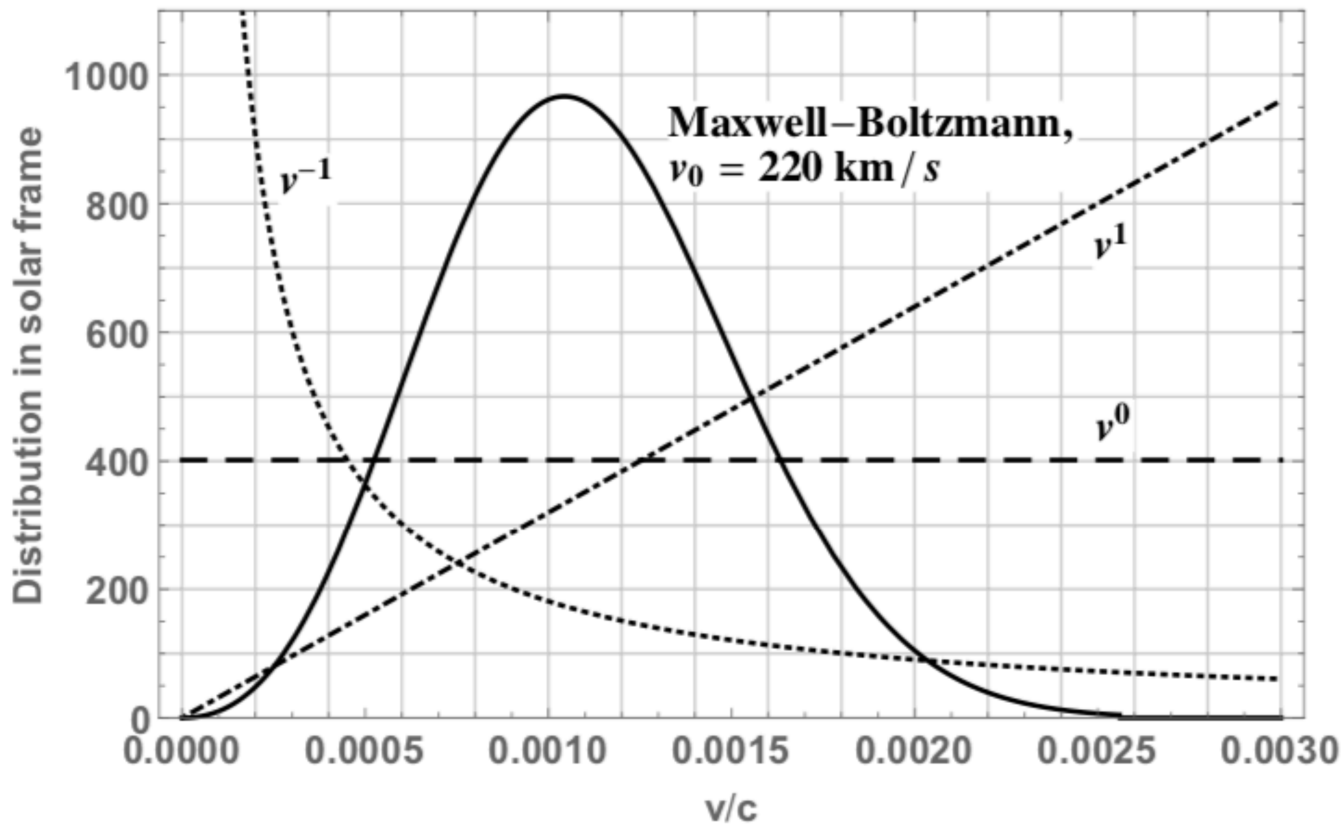
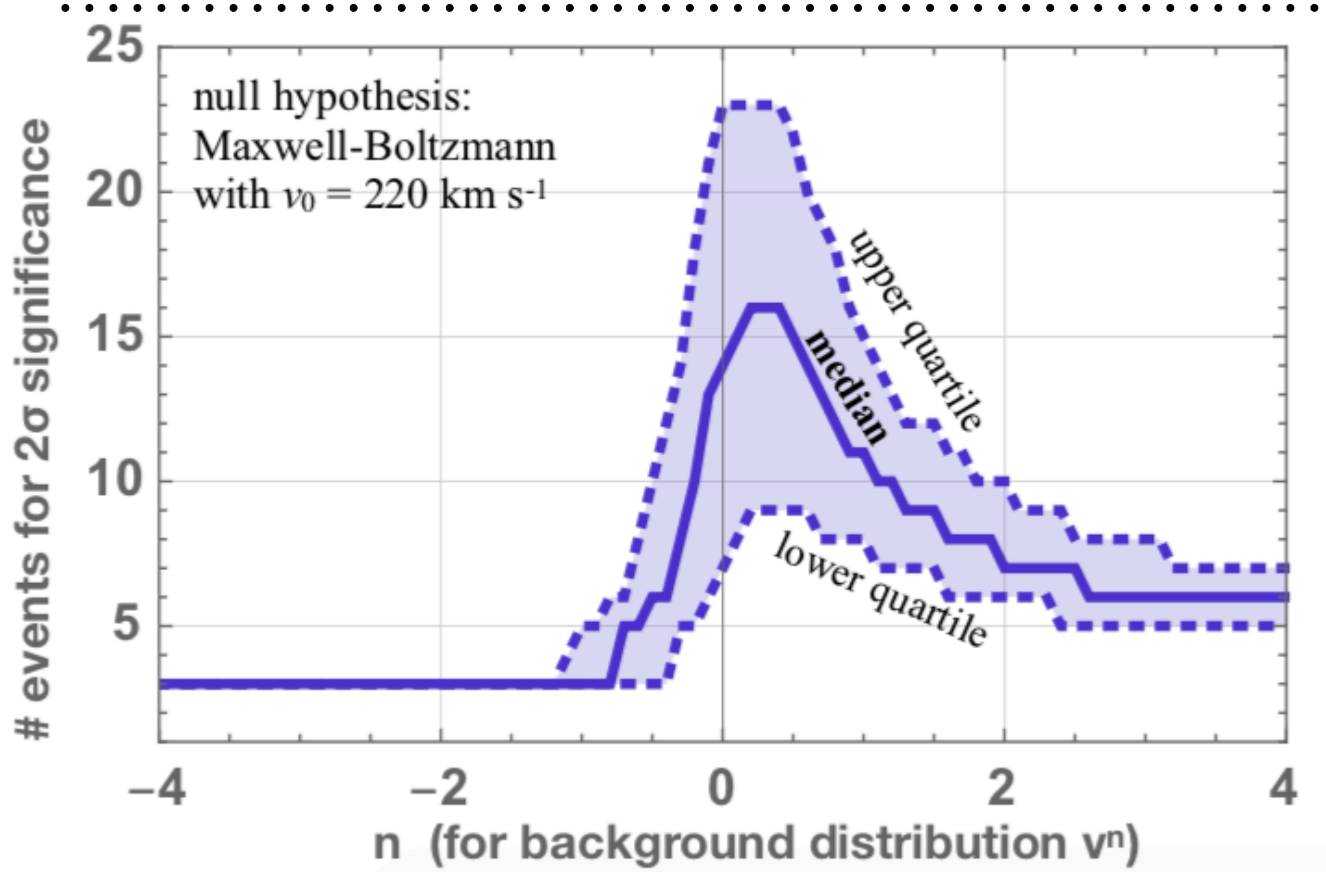
Rejecting backgrounds



Unknown instrumental/ radiogenic/ cosmogenic background modelled as power-law.

(NB: in all probability, search would be background-free.)



Kolmogorov-Smirnov test to determine # events required to reject background

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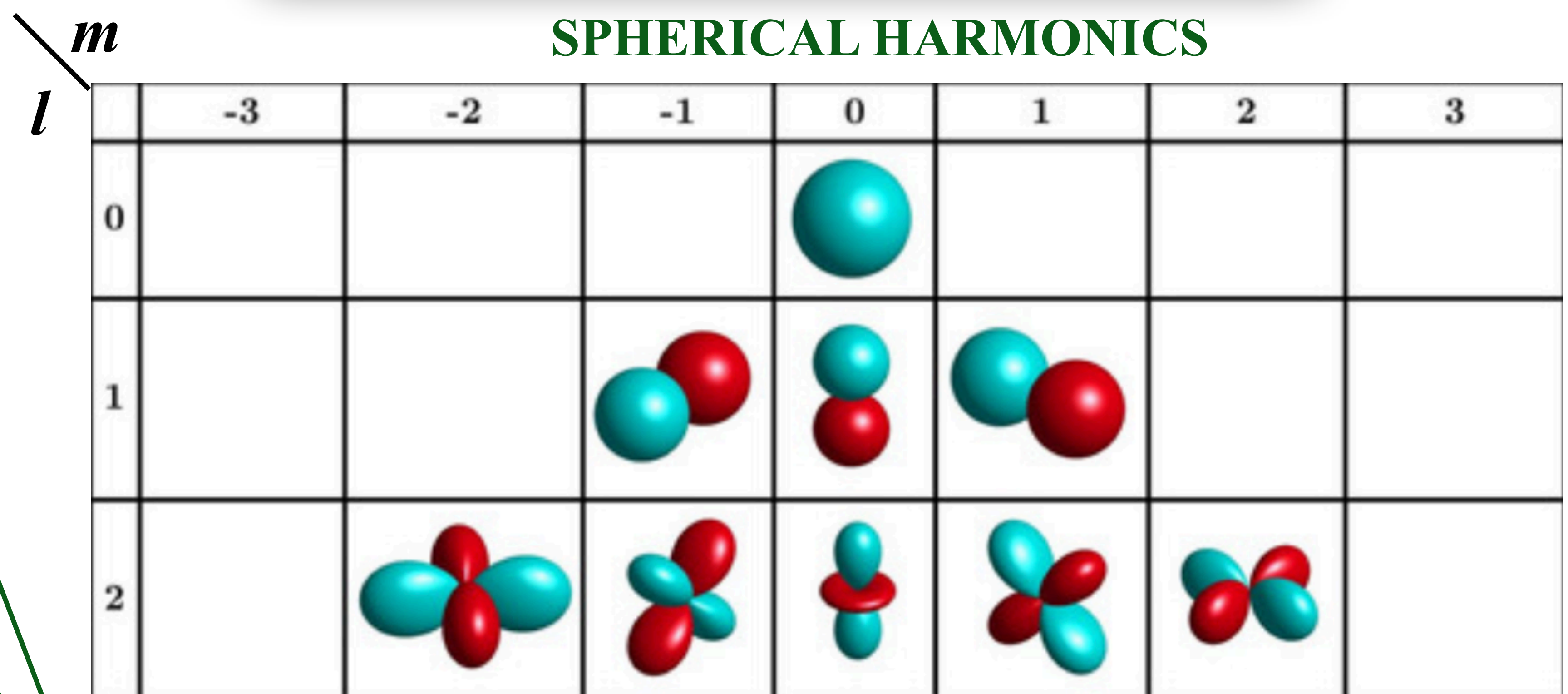
Testing velocity anisotropies

galactic frame

angular distribution:

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



contribution

monopole ~ 1

dipole ~ ε

quadrupole ~ ε

test anisotropy, ε << 1

Benchmark:

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

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Testing velocity anisotropies

monopole coefficient

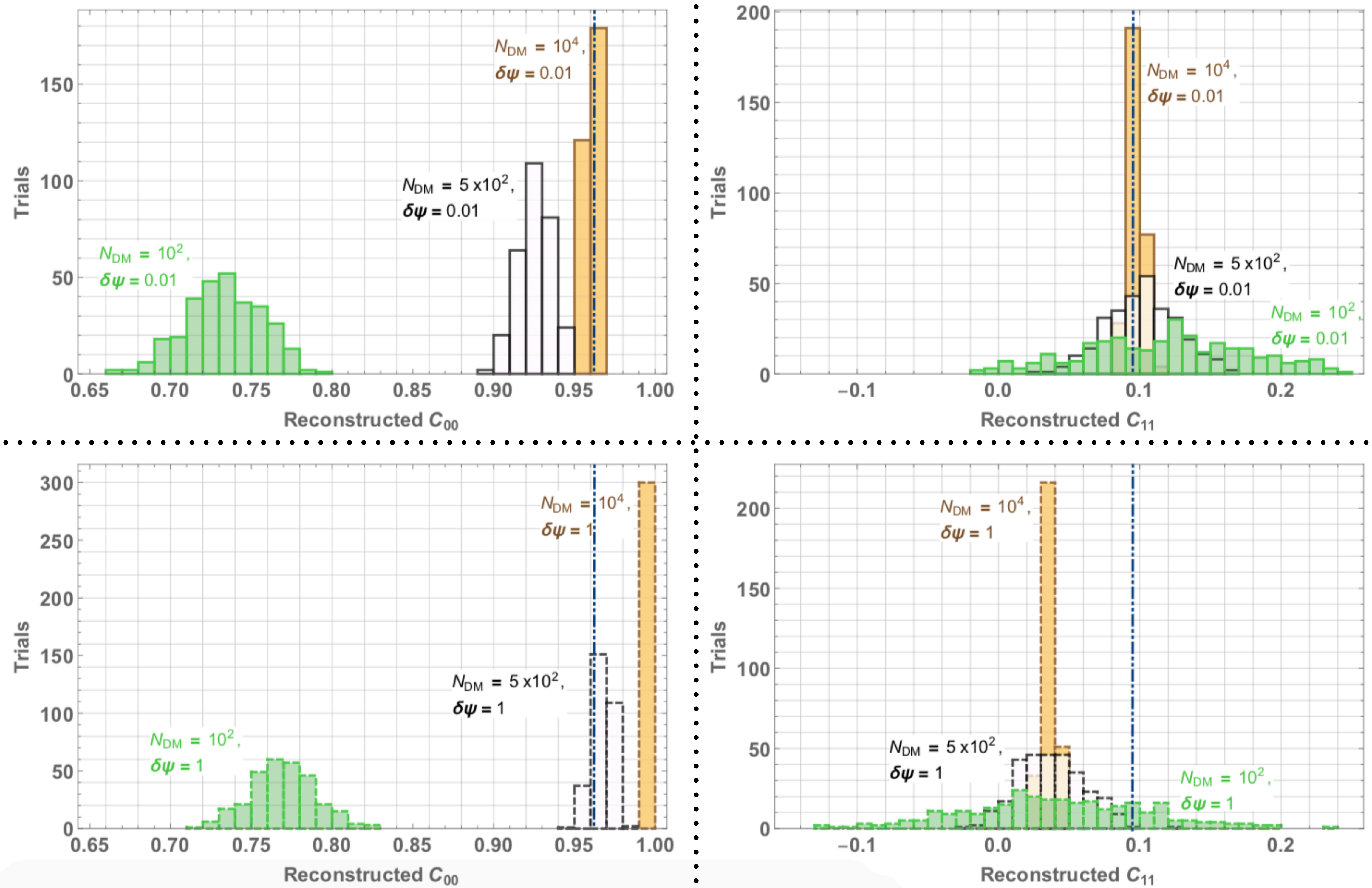
dipole coefficient

good angular resolution

(smearing negligible)

poor angular resolution

(smearing significant)



LESSONS: good statistics => accuracy & precision,
smearing => anisotropies wash out.

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