# Dark Matter in Neutrino Facilities

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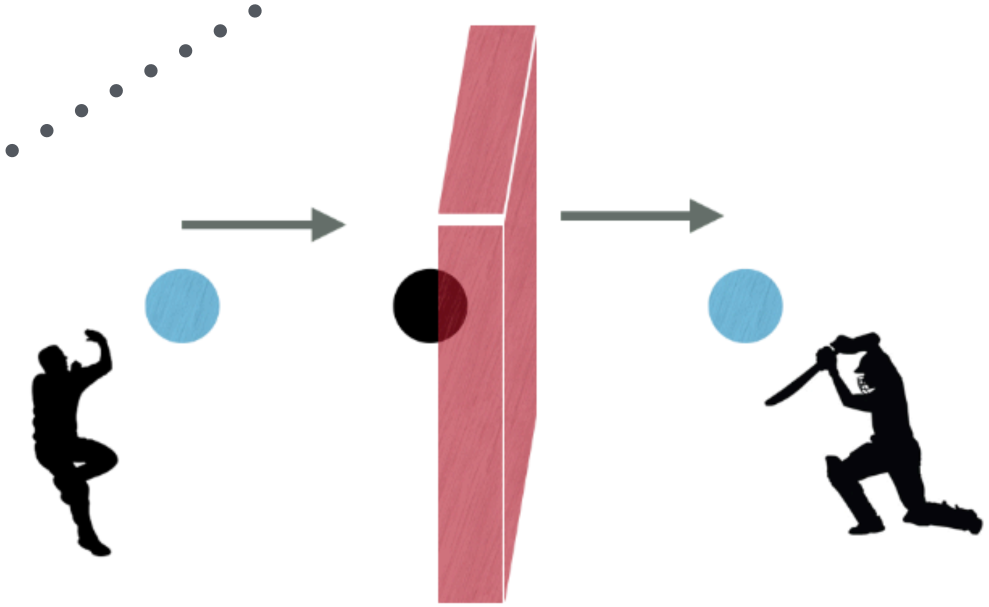
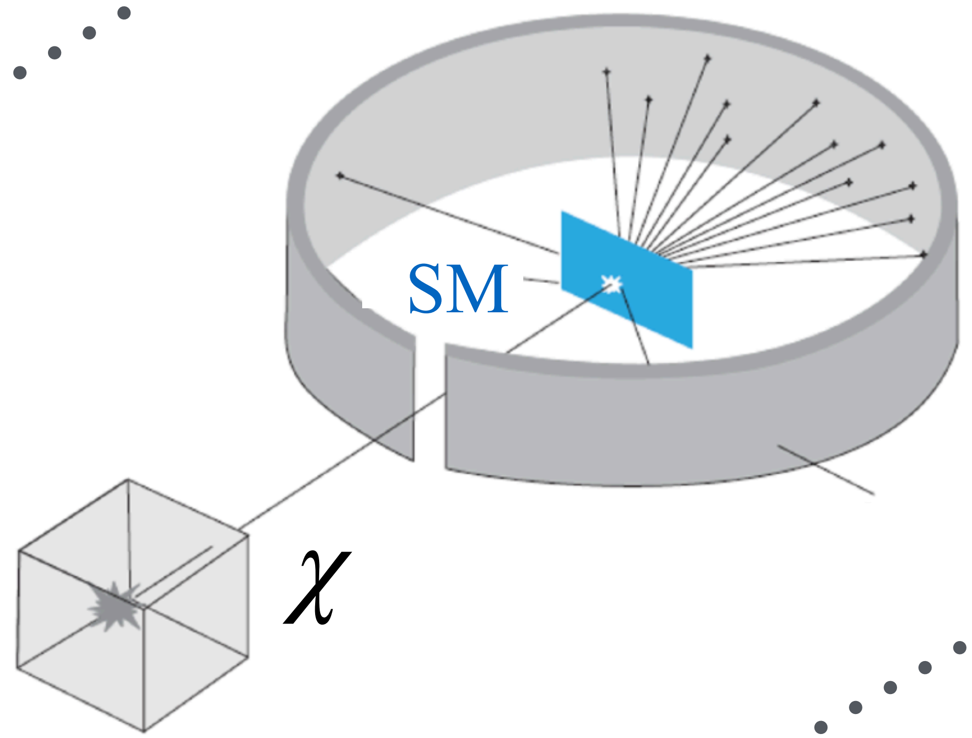
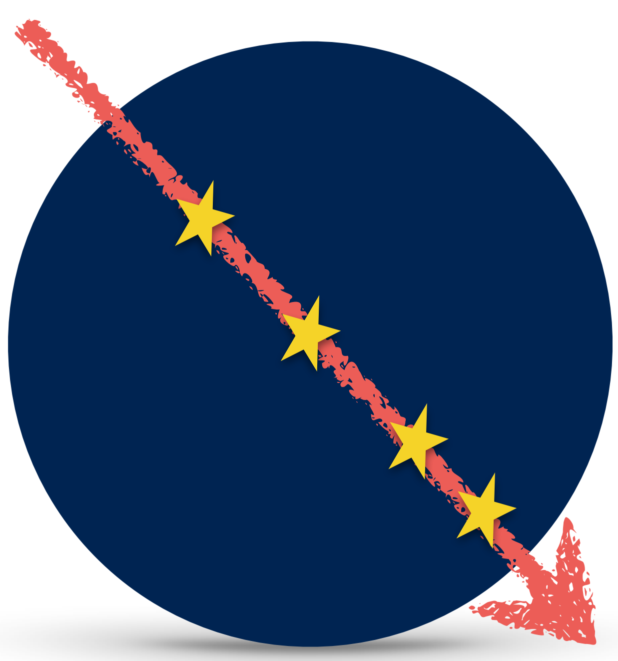
Indian Institute of Science

@PhysicsNirmal





## Understanding the Universe Through Neutrinos

Apr 25 2024

ICTS

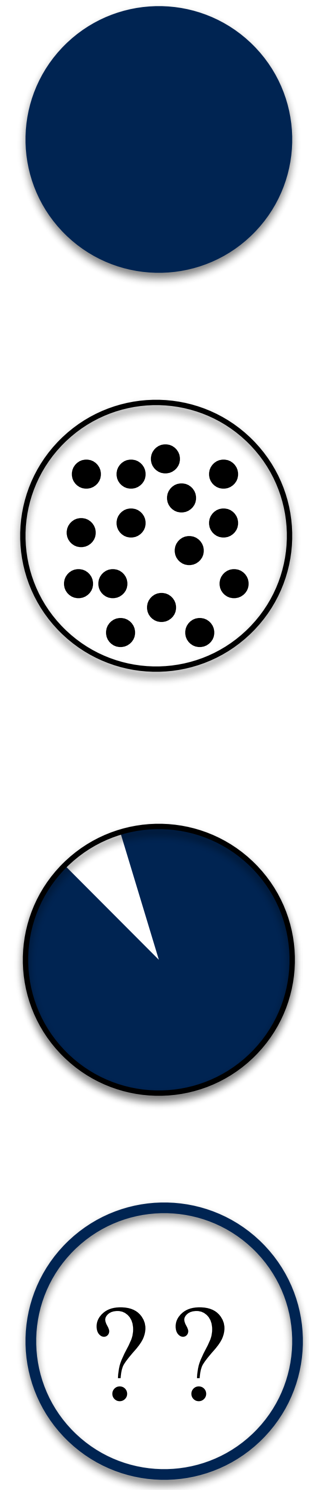
# Dark matter

**dark**

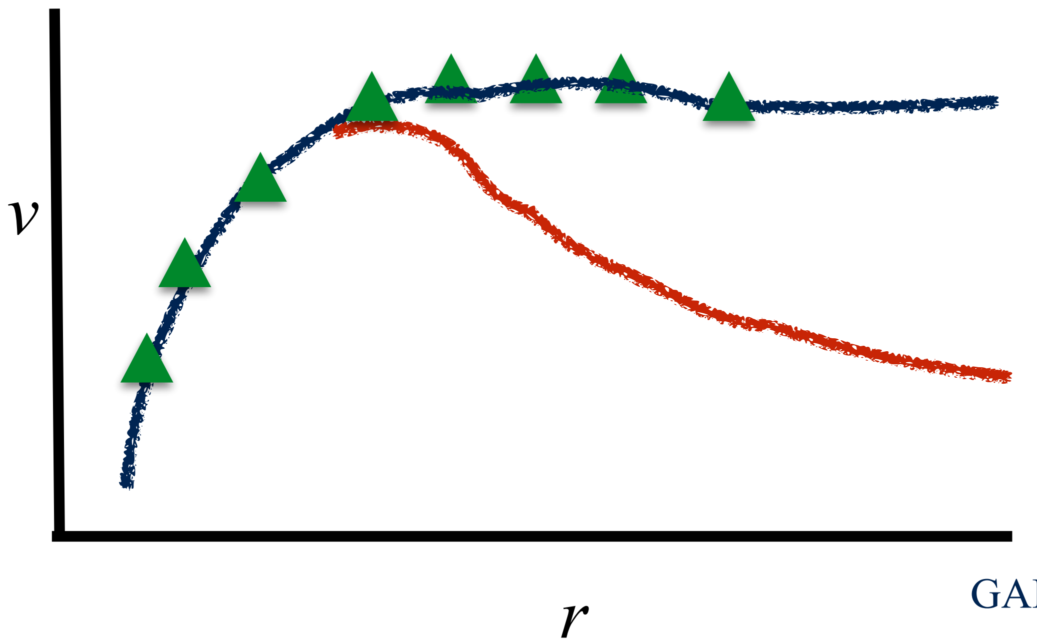
**ubiquitous**

**plentiful**

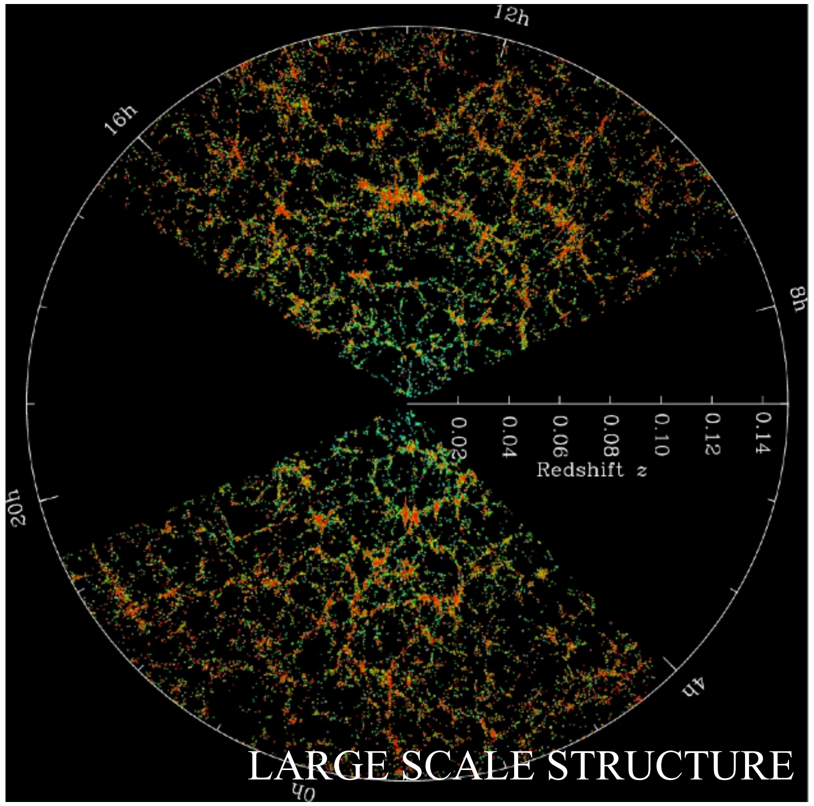
**mysterious**



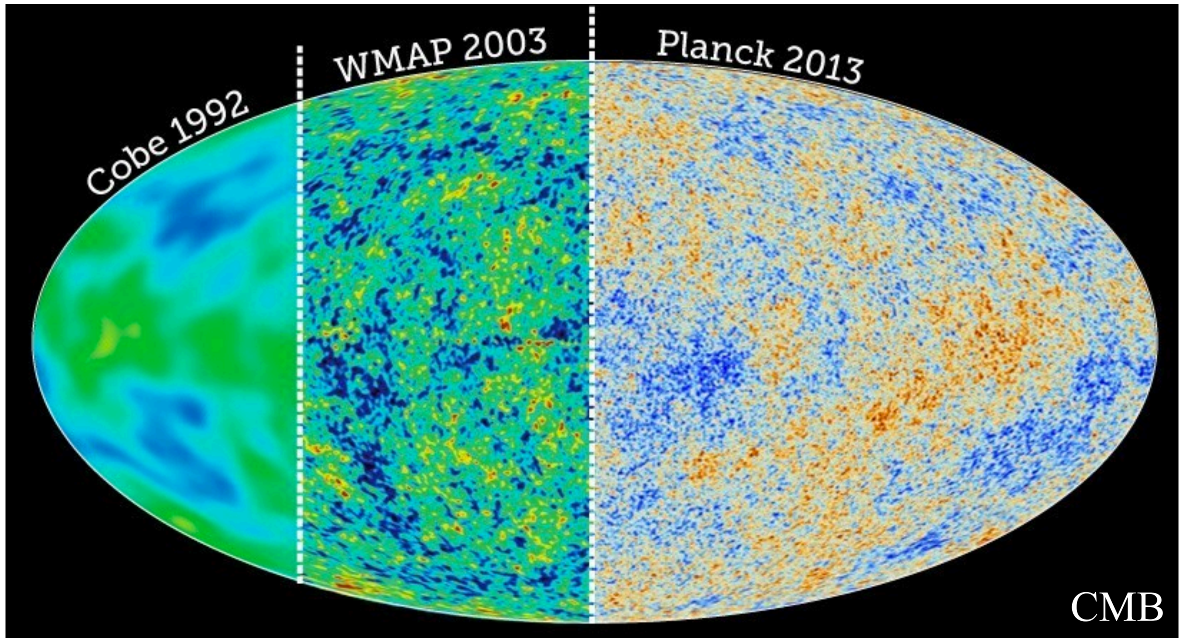
# Dark reality



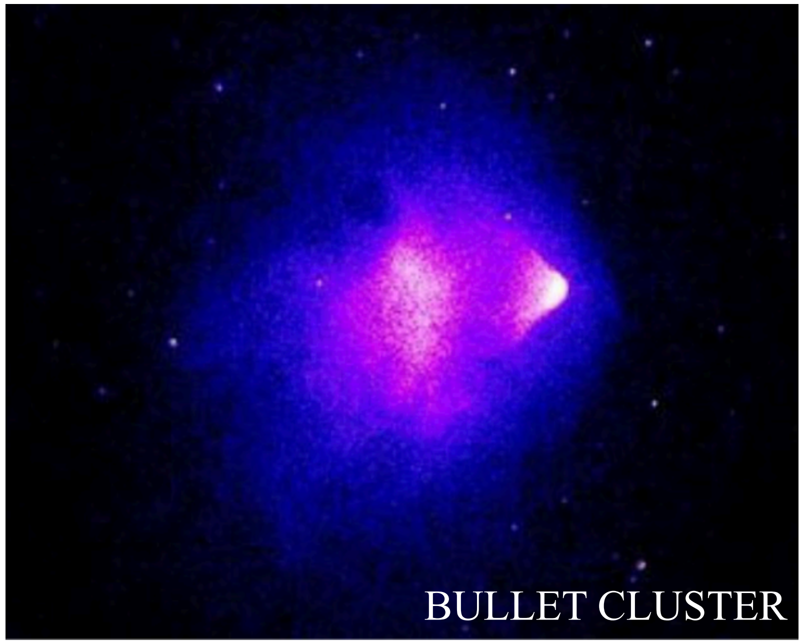

GALACTIC ROTATION




LARGE SCALE STRUCTURE



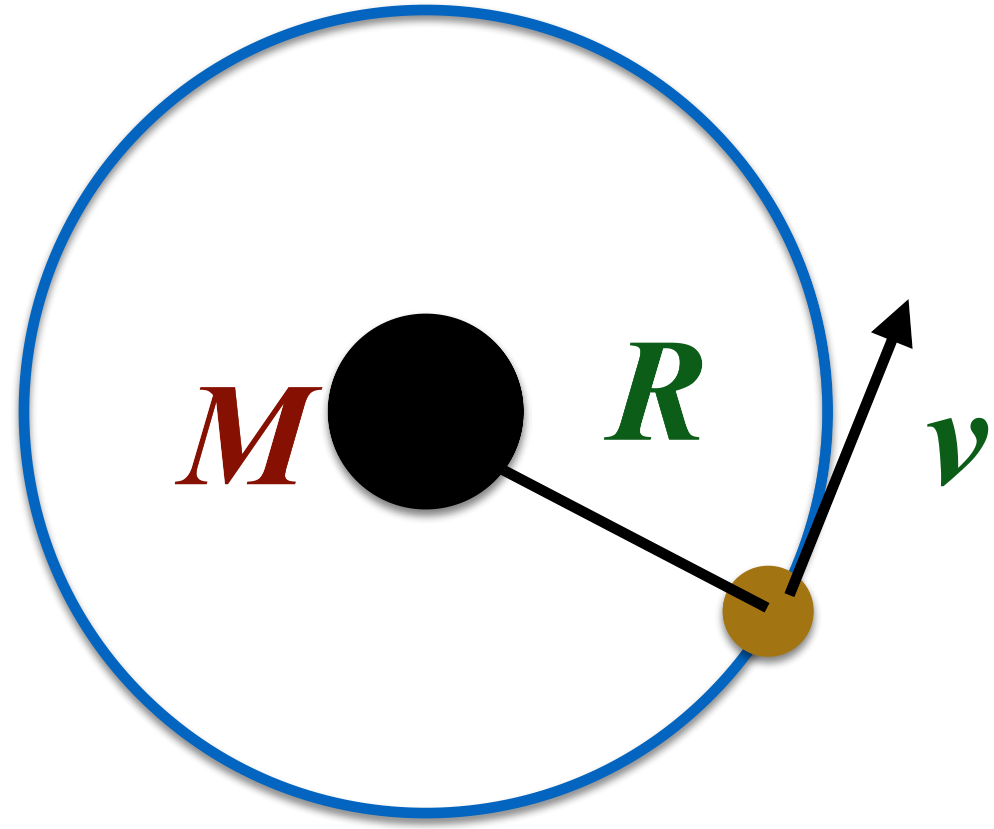

CMB

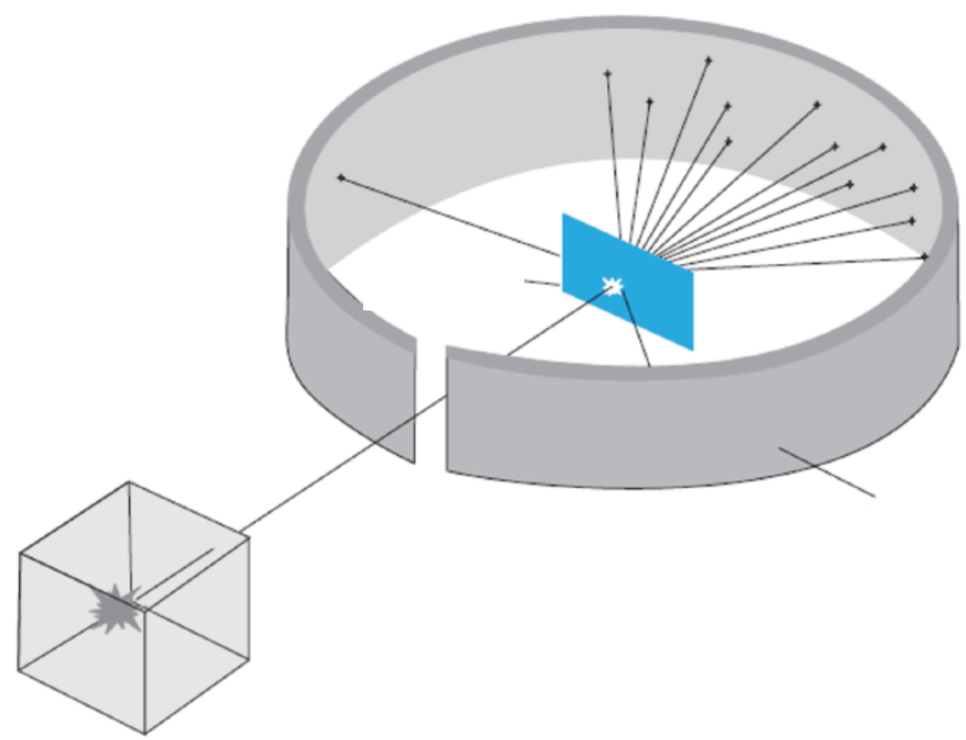


BULLET CLUSTER

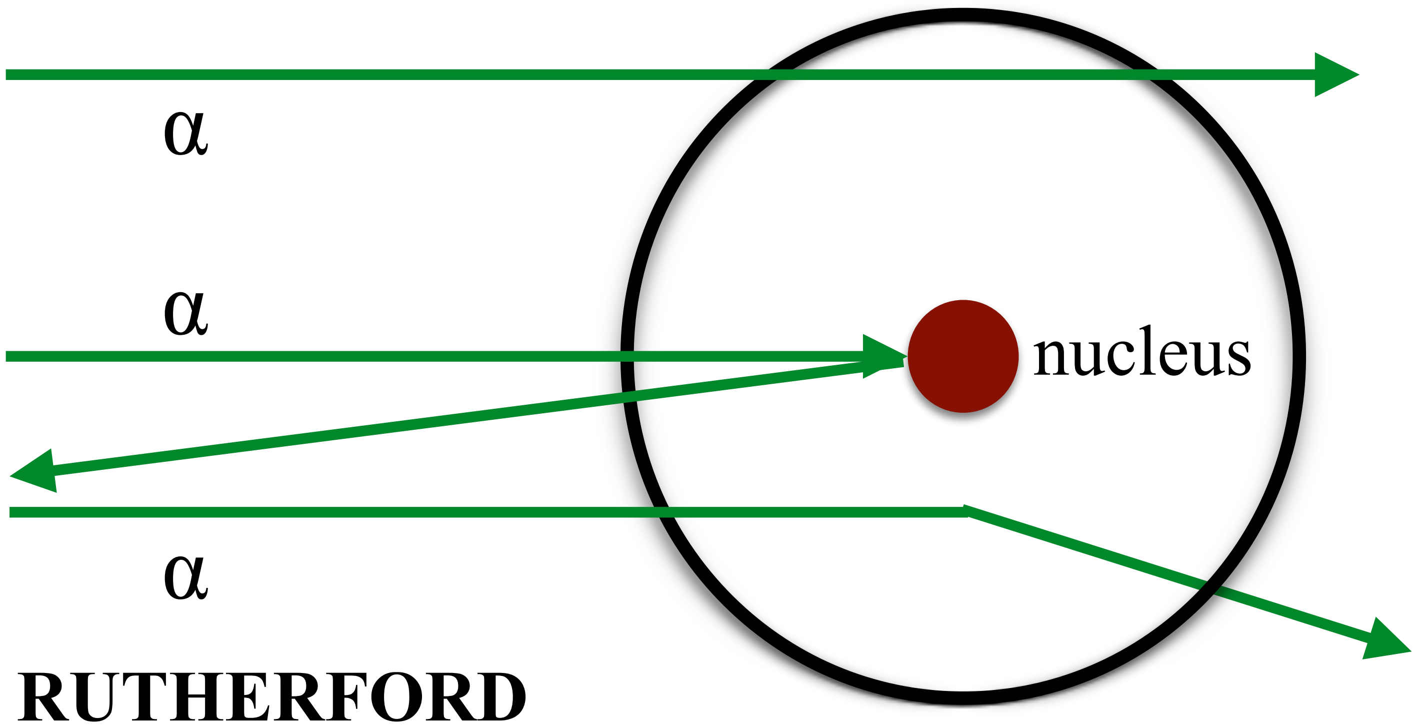
✔ astronomical evidence

? particle physics knowledge



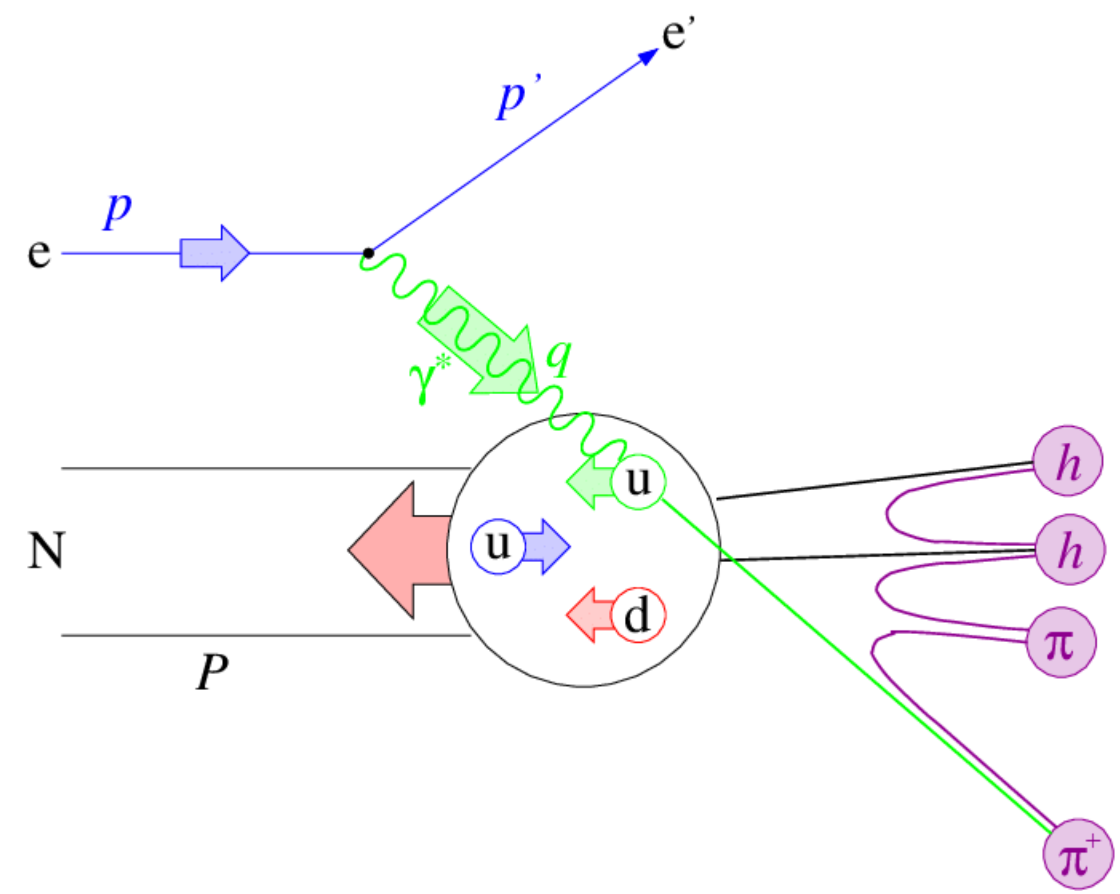



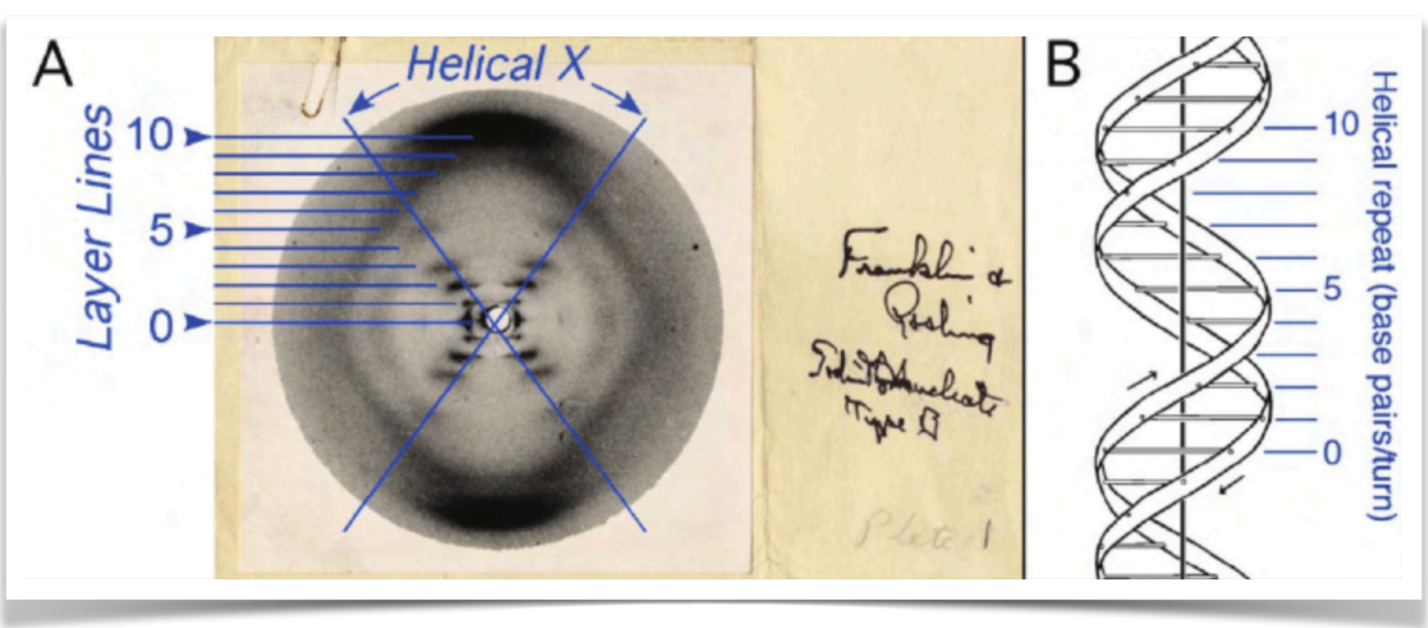
# Scattering!




**RUTHERFORD**
**1909**
**Discovery: atomic nucleus**

**DEEP INELASTIC**
**1968 —**
**Discovery: quarks**




**X-RAY CRYSTALLOGRAPHY**
**1952**
**Discovery: DNA structure**

# How to pinpoint the identity of dark matter

***goal***

Determine
**dark matter-on-nucleon scattering cross section**

Intrinsic quantity: helps identify dark matter

***strategy***

## Reverse Rutherford scattering

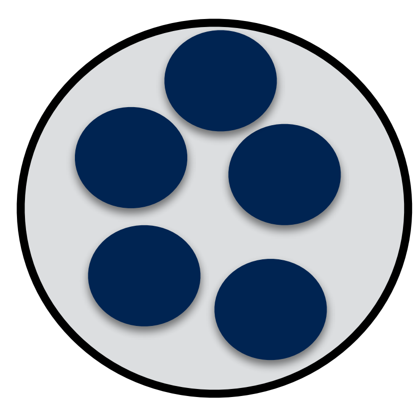
Beam of ambient dark matter (unknown species) hits target of nuclei (well-understood species).

Energy and momentum transferred => study changes in target.

***inputs***

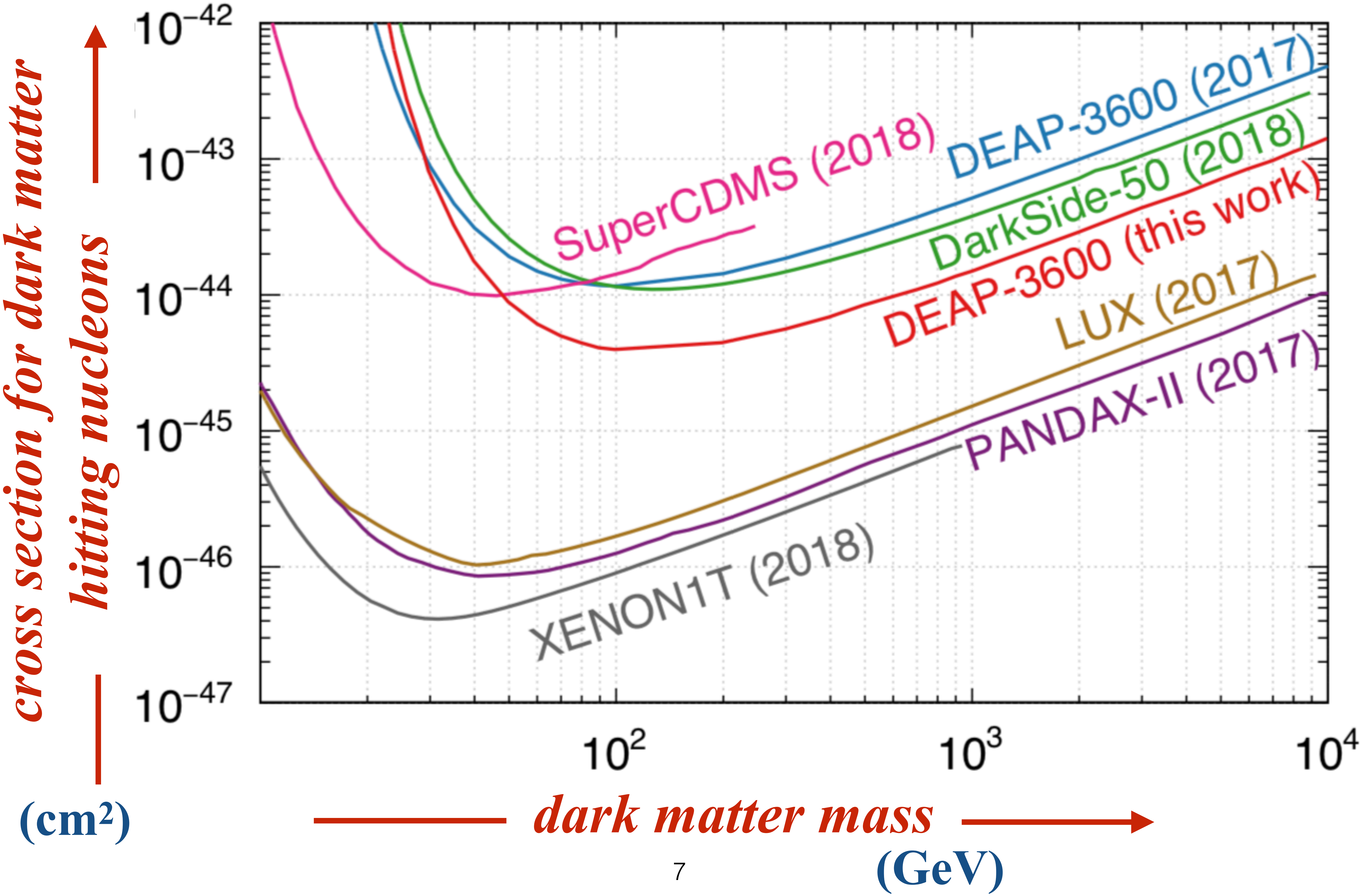
[inferred from star motion]

300 km/s

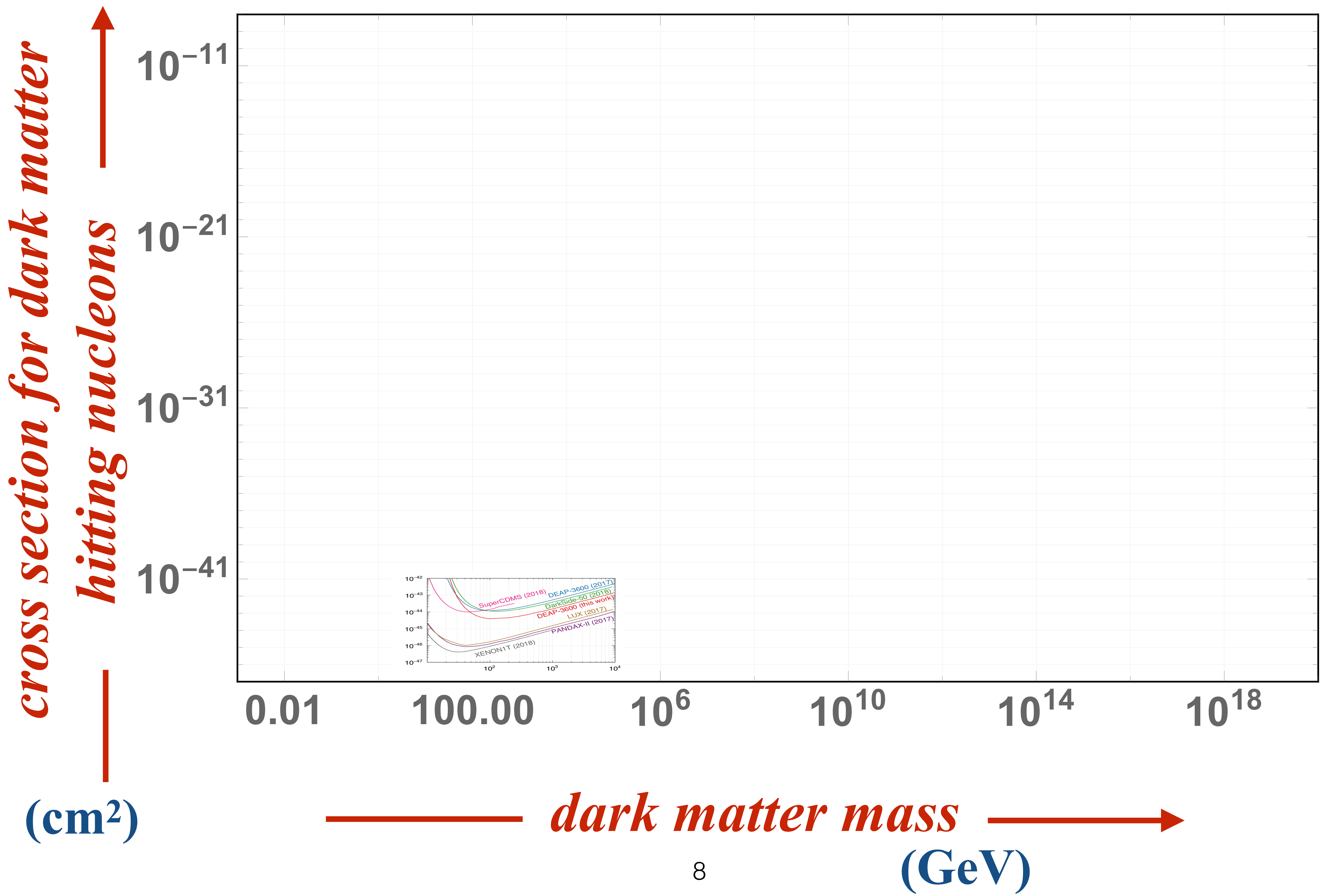


0.3 GeV/$cm^3$

# Preview: modern searches



# Bird's-eye view



## Past and present probes

— **since 1985**

— **great swathes of cross section vs mass space already constrained**

# How it began

PHYSICAL REVIEW D — VOLUME 30, NUMBER 11 — 1 DECEMBER 1984

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

A. Drukier and L. Stodolsky

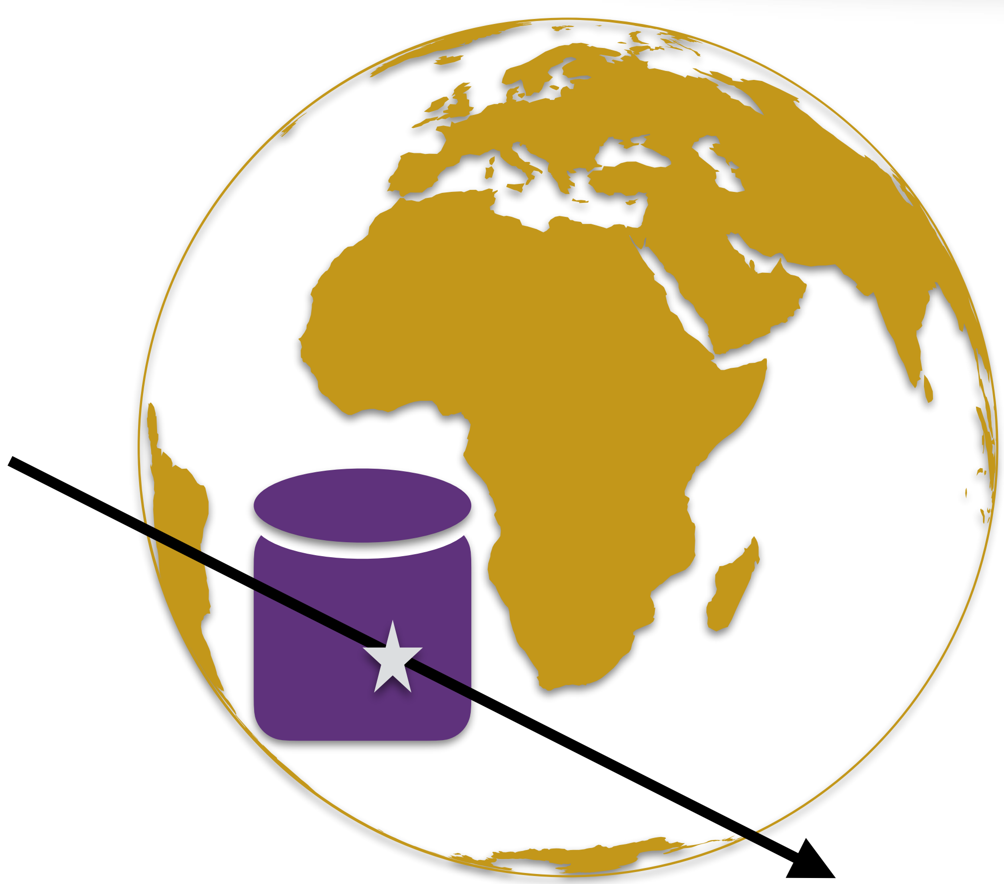
*Max-Planck-Institut für Physik und Astrophysik, Werner-Heisenberg-Institut für Physik, Munich, Federal Republic of Germany*

PHYSICAL REVIEW D — VOLUME 31, NUMBER 12 — 15 JUNE 1985

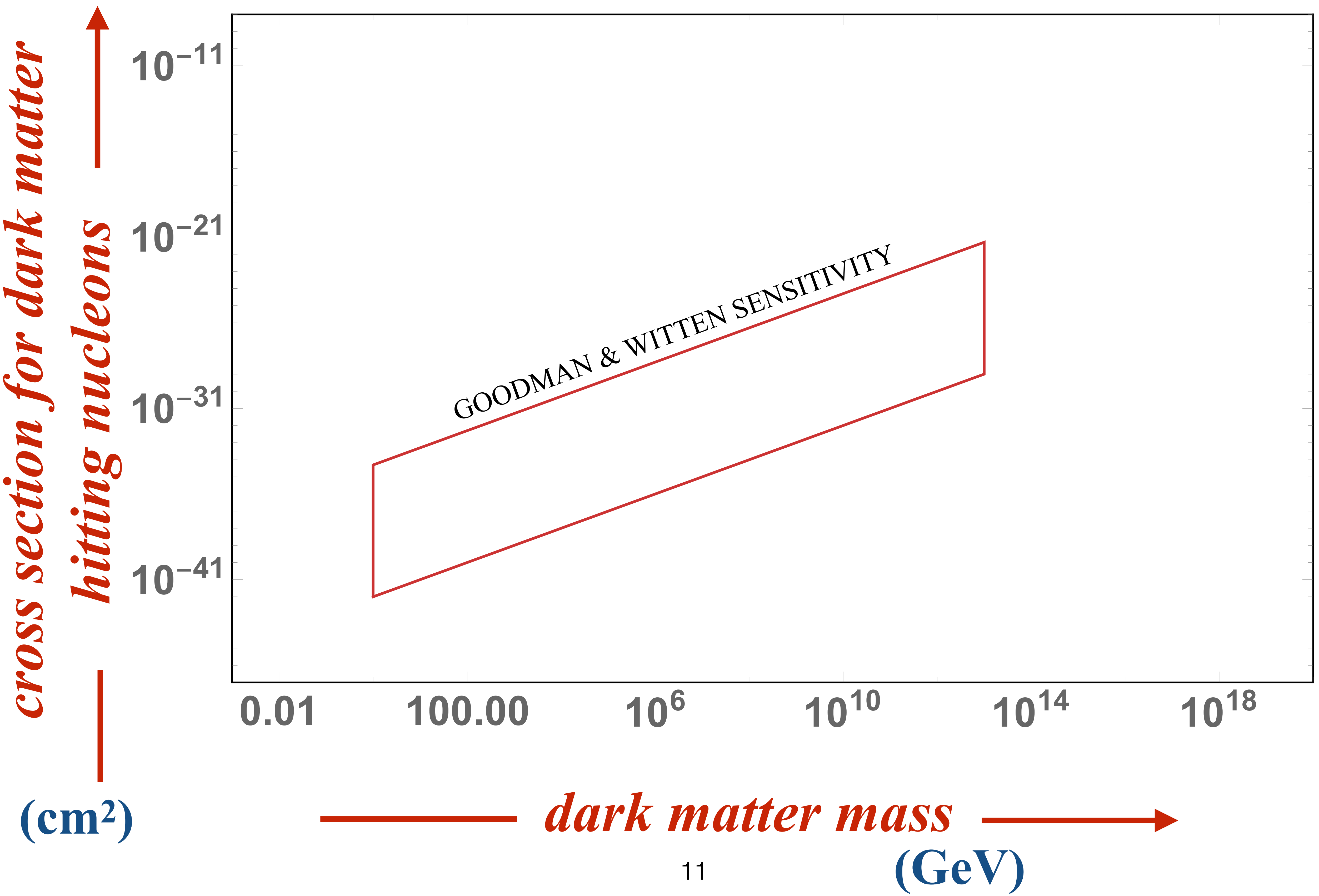
**Detectability of certain dark-matter candidates**

Mark W. Goodman and Edward Witten

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

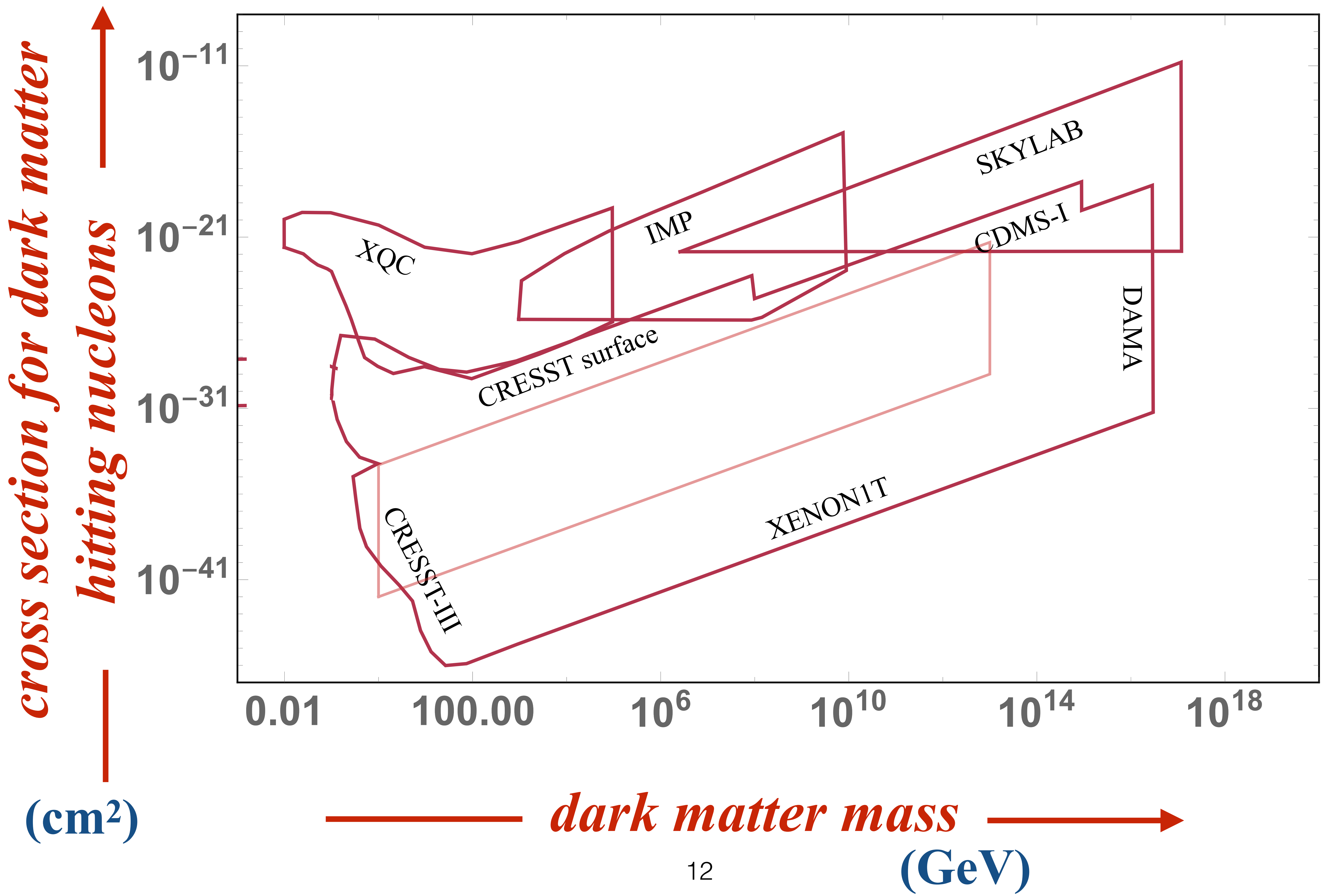


# Status: 1985

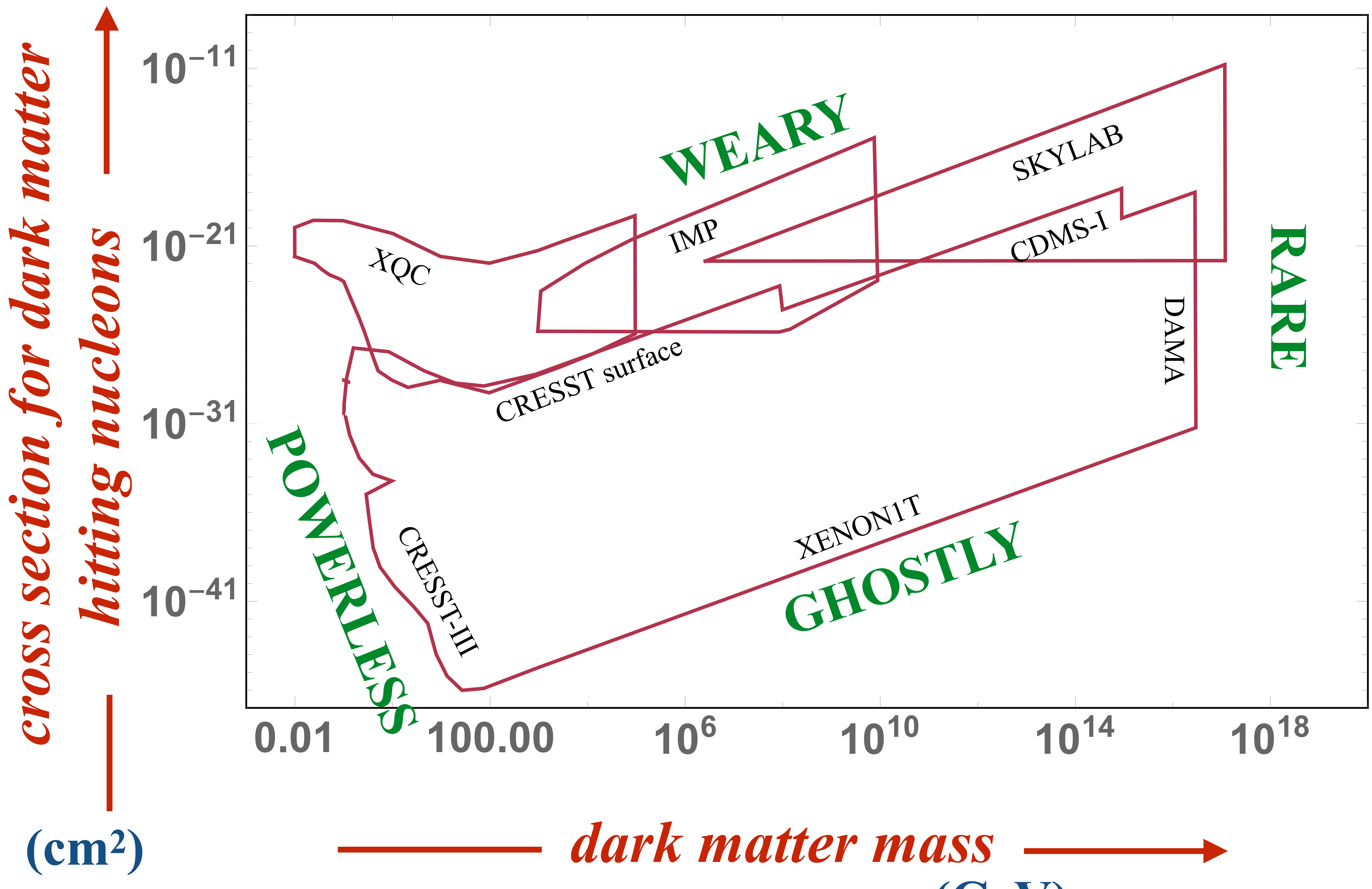


cross section for dark matter
hitting nucleons
(cm²)
10−11
10−21
10−31
10−41
GOODMAN & WITTEN SENSITIVITY
0.01
100.00
10^6
10^10
10^14
10^18
dark matter mass
(GeV)

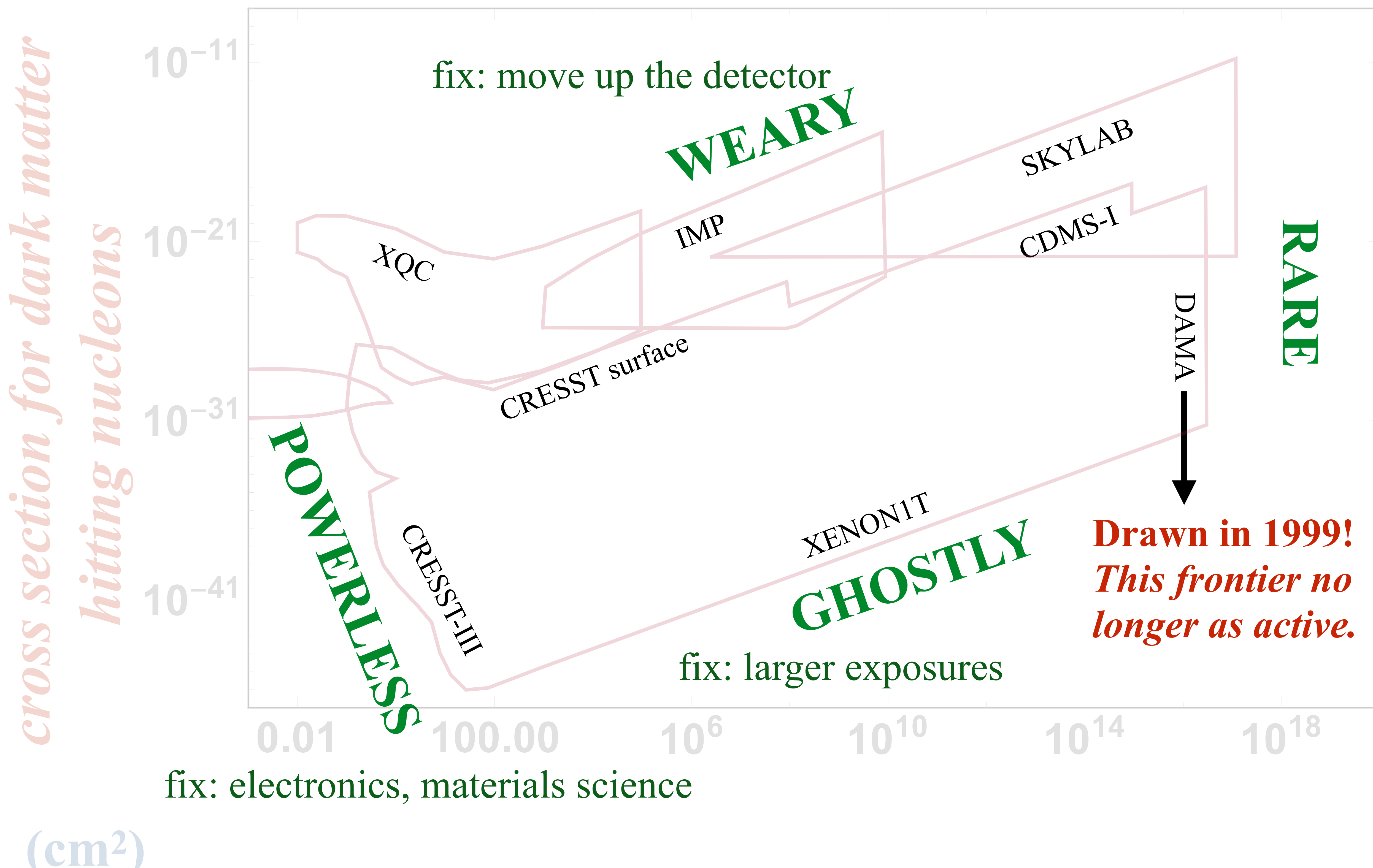
# Status: until Aug 2021



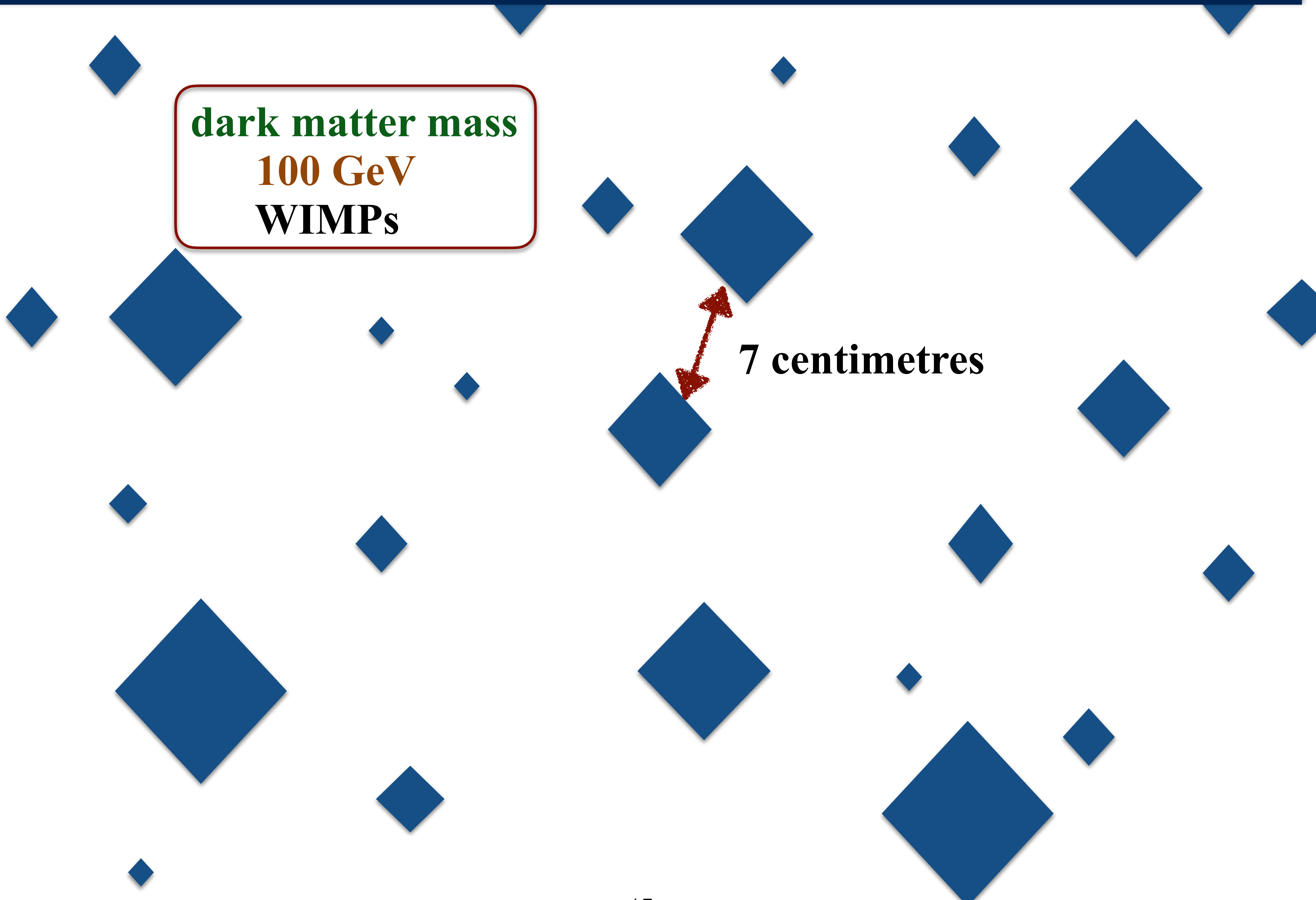
# All the Earth-based constraints



# All the Earth-based constraints

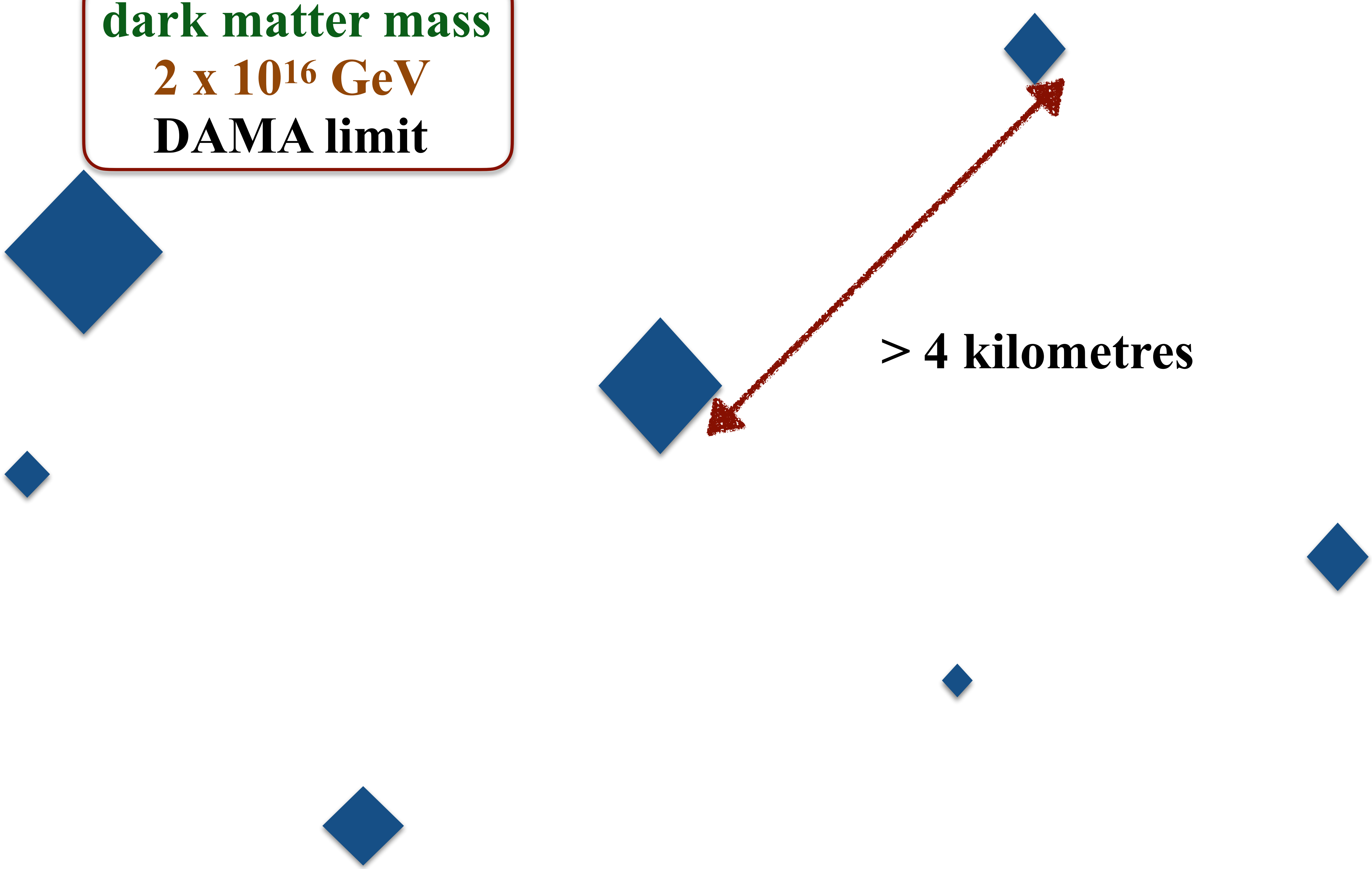


# Profusion

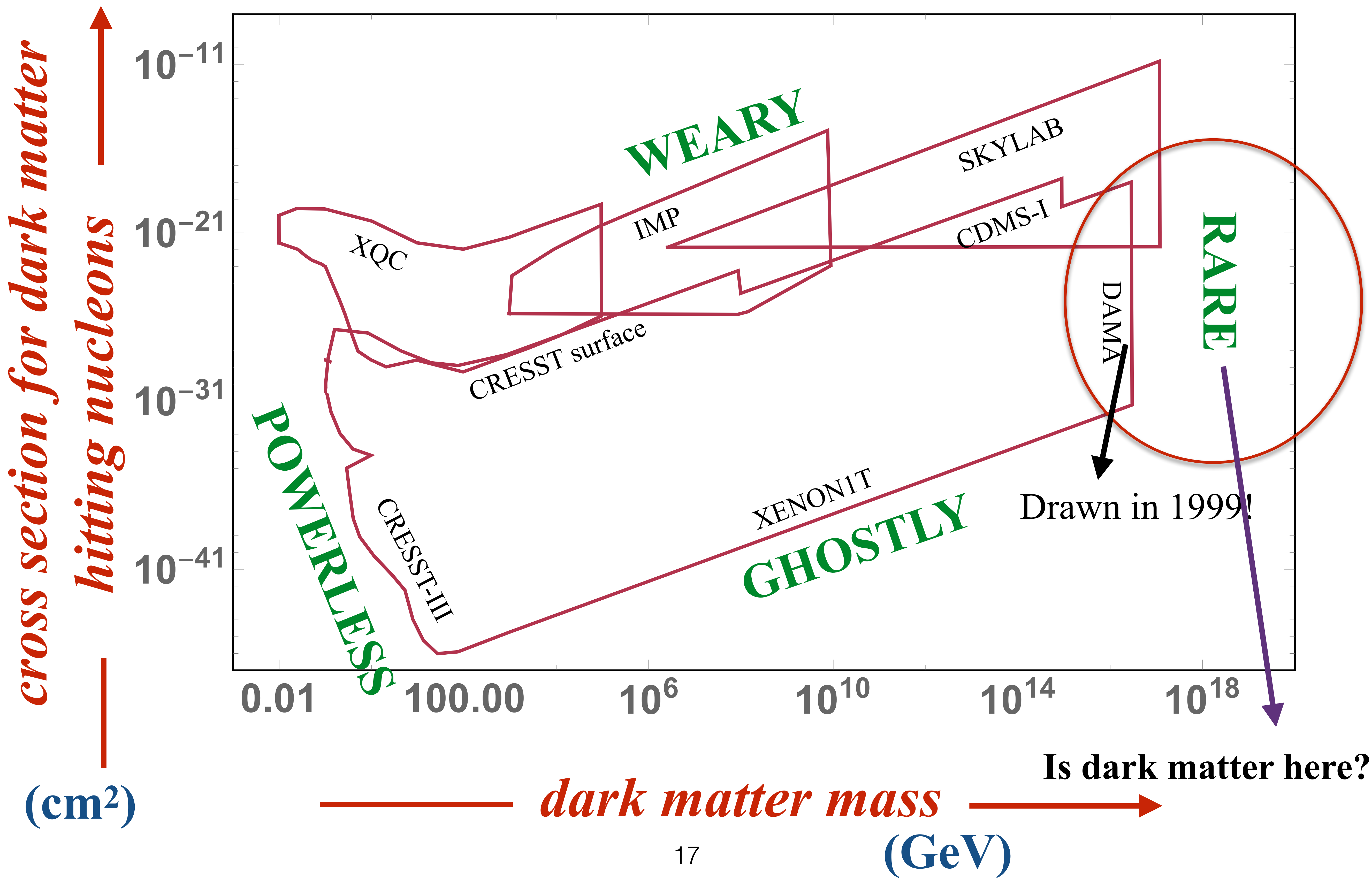


# Rarity

**dark matter mass**
**2 x $10^{16}$ GeV**
**DAMA limit**

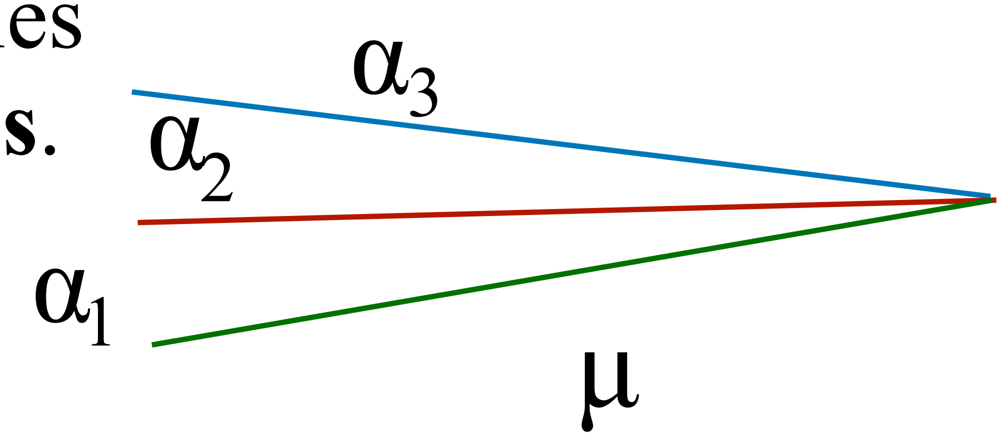


# Hunting even rarer dark matter



# Theoretical appeal

- 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 —> 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

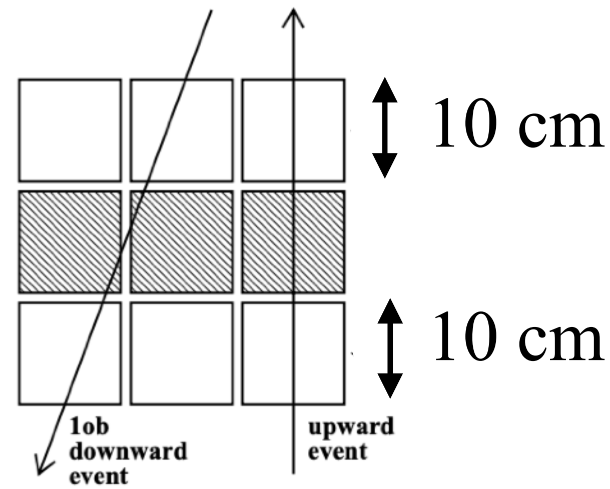
*Heavy dark baryons*
Davoudiasl, Mohlabeng
1809.07768

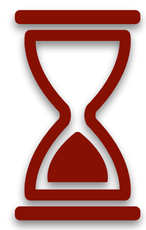
*Heavy dark skyrmions*
Berezowski, Dick
Sep 2019

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

*Snowmass WP @ 2203.06508*

**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*
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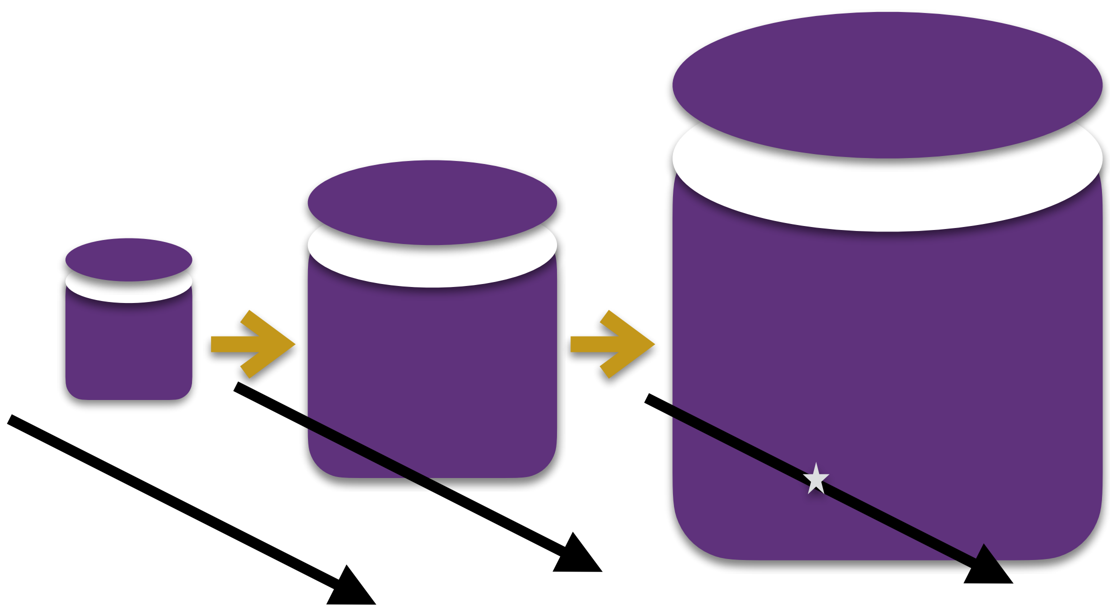
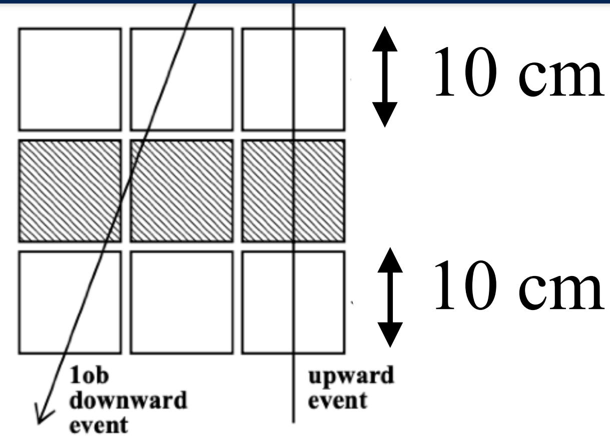
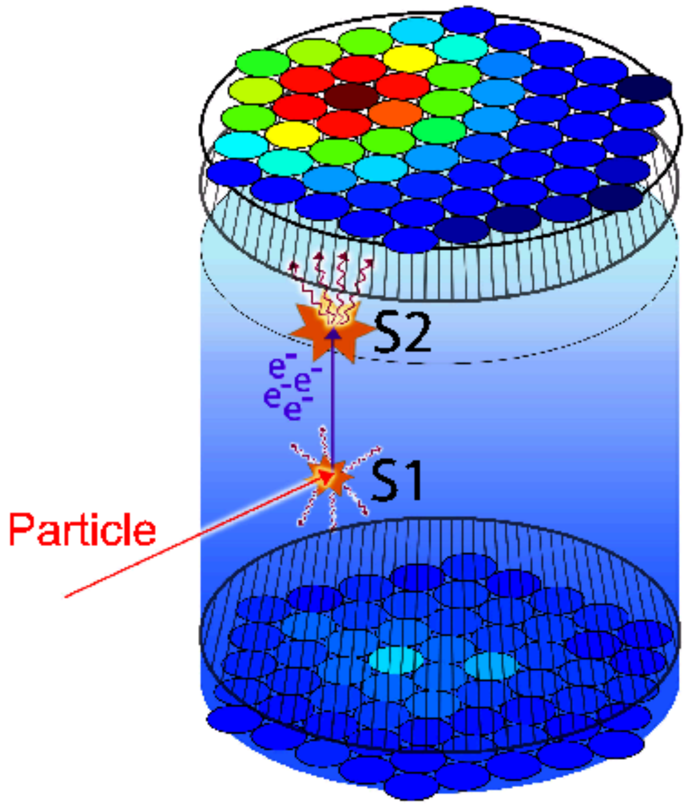


# Today's dark matter detectors

**DAMA 1999 search**

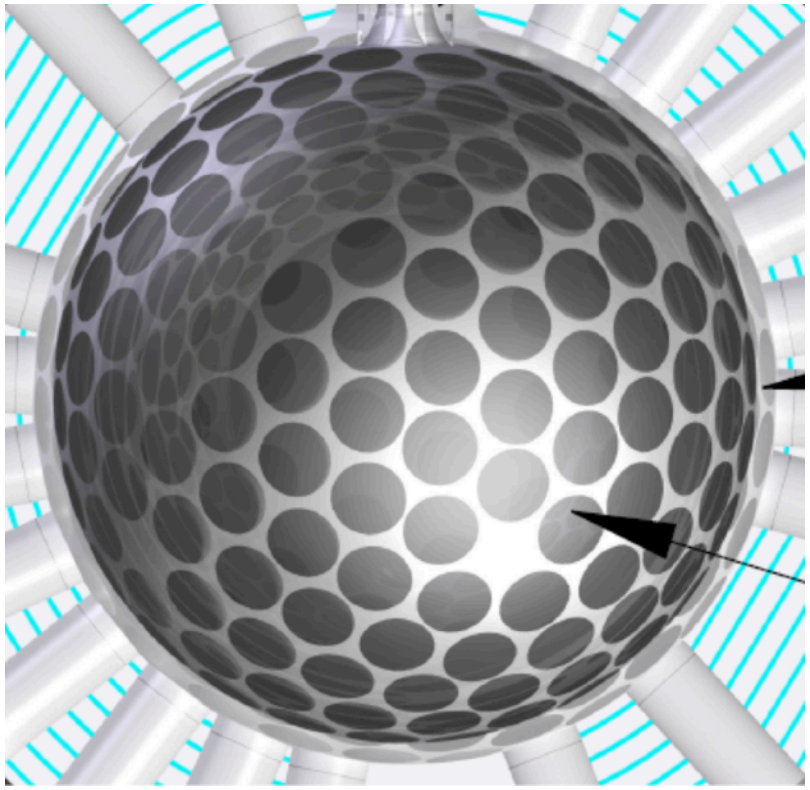



← 100 cm →



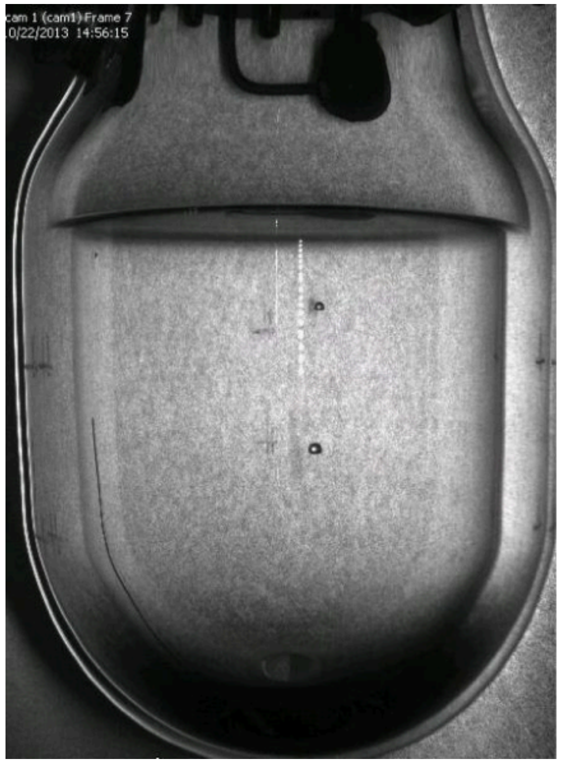

**XENON1T/ LZ/ PANDAX-II**

← 130 cm →

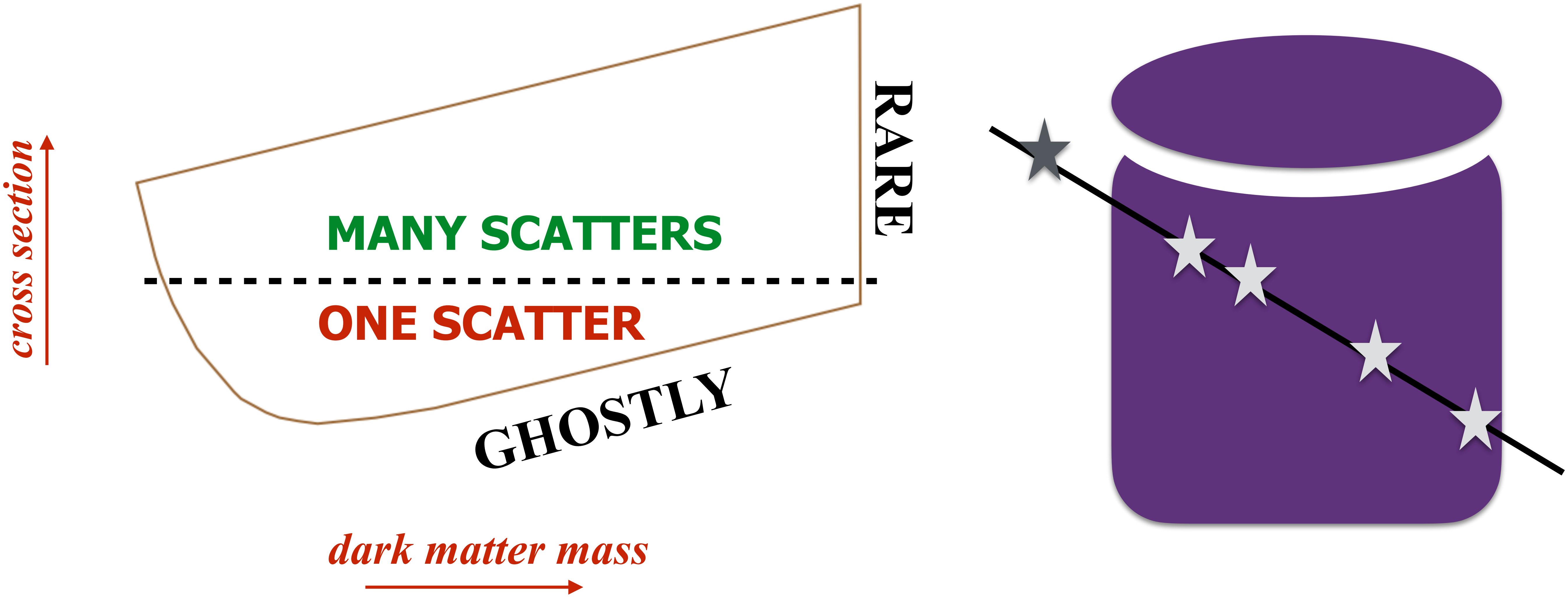


**DEAP-3600**

← 50 cm →



**PICO-40L**




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

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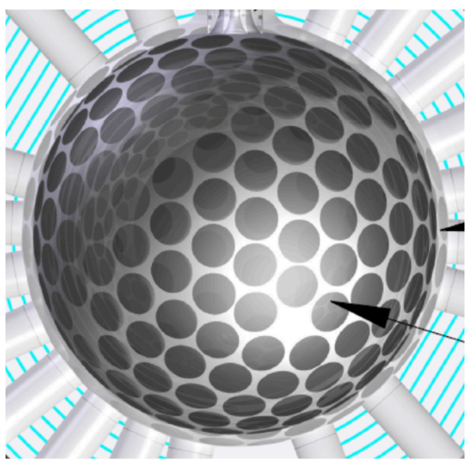
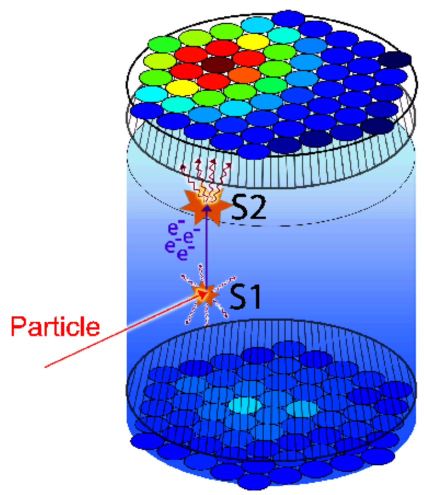
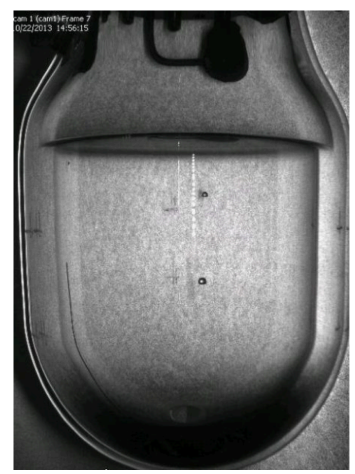
***Phys.Rev.D.*** *(2018)*



DEAP-3600

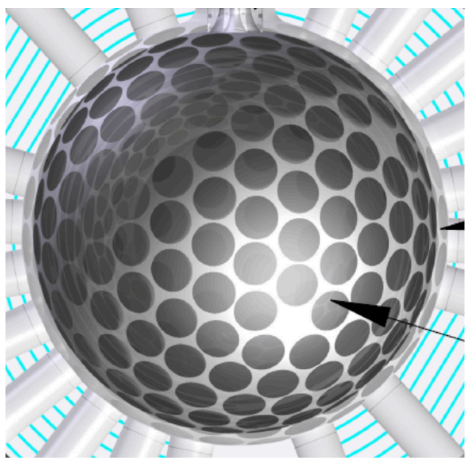


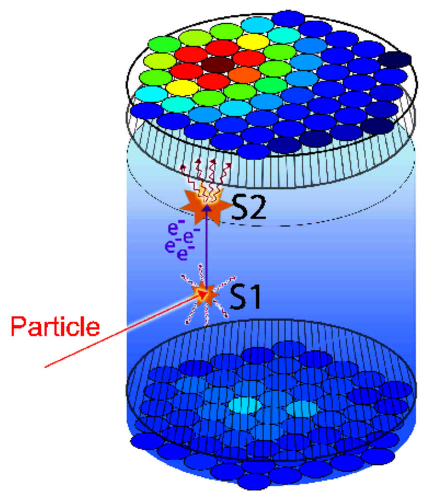

XENON1T & LZ

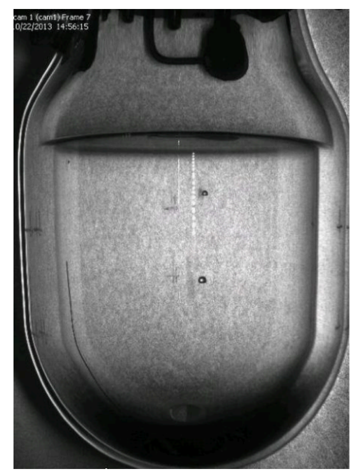


PICO-40L

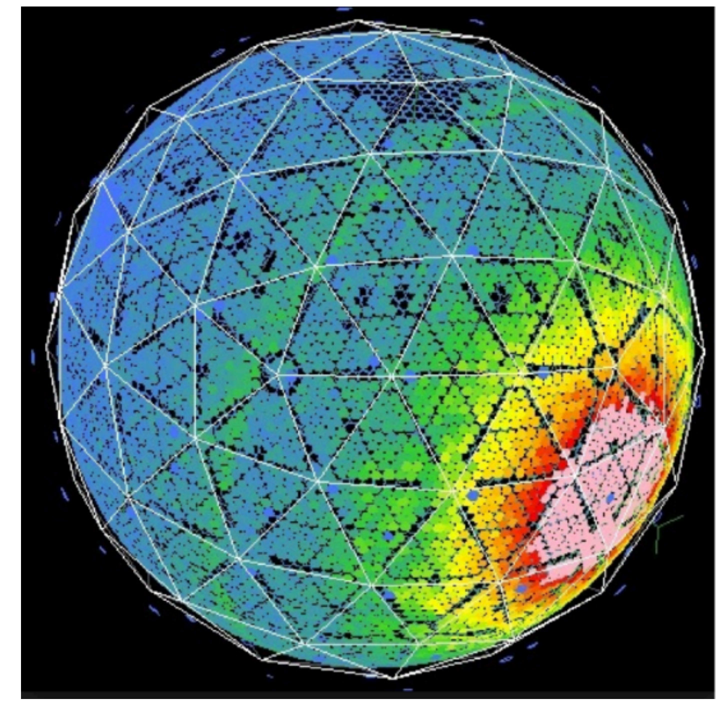
multi-scatter results published





+



DEAP-3600

XENON1T
& LZ

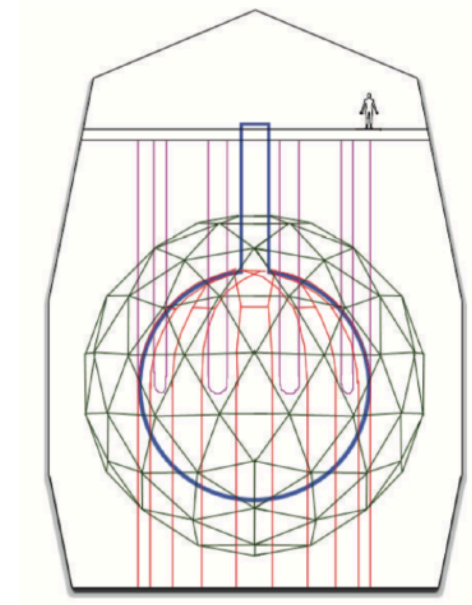
PICO-40L

neutrino detectors

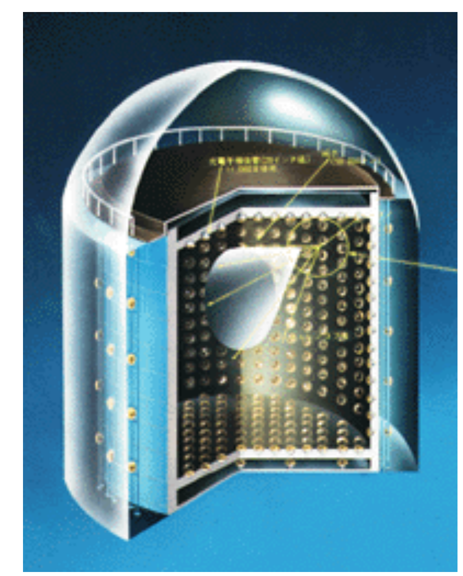
multi-scatter results published

# (Q2) Large volume neutrino detectors?

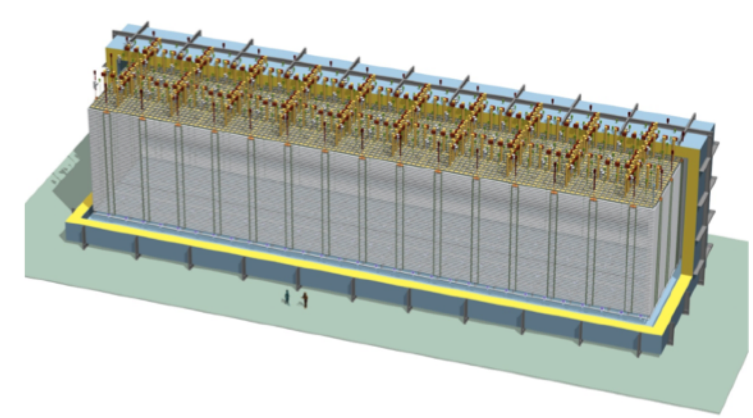
Organic liquid scintillator (SNO+, Borexino, etc.):
**well-suited for dark matter search!**
collect enough light in PMTs => in business



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



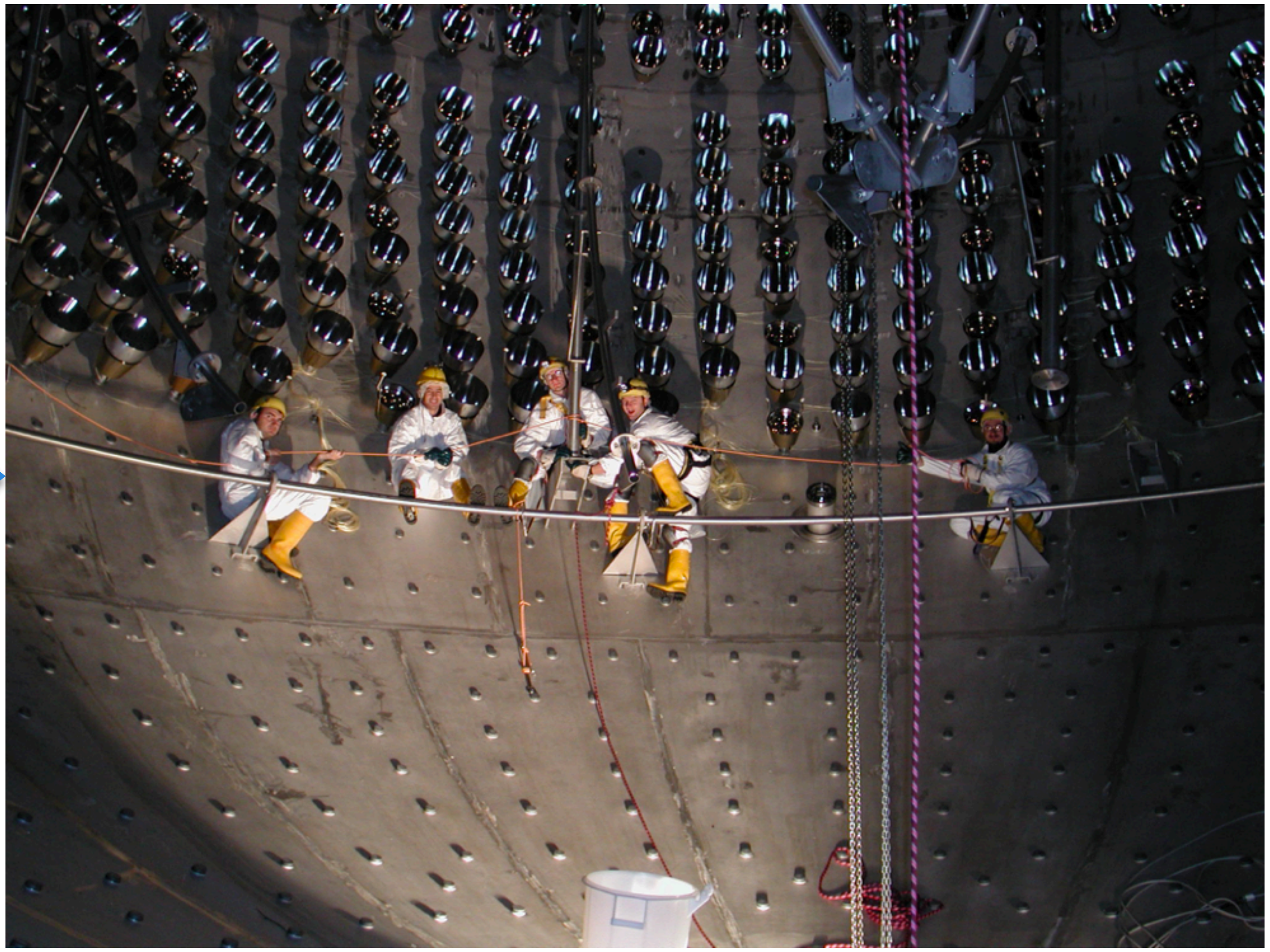
Liquid argon TPCs (DUNE, etc.):
threshold too high



# Liquid scintillator neutrino detectors

**XENON1T, DEAP, PICO, …**

**BOREXINO, SNO+, JUNO**



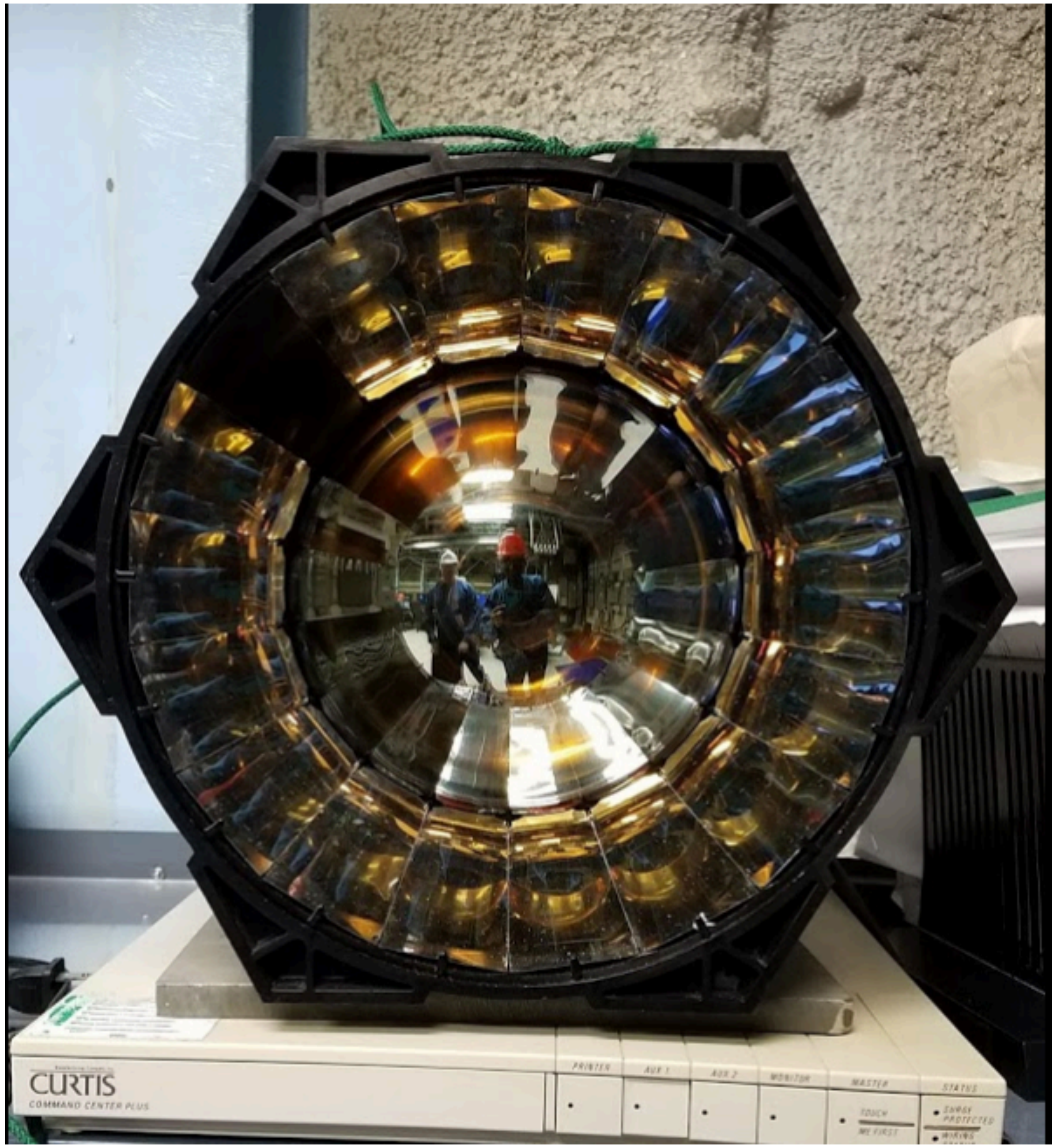
<u>Direct detection @ liq. scint. neutrino detectors</u>

**Mass sensitivity:** dark matter fluxes at least 100 times greater

**Cross section sensitivity:** Satisfy selection trigger

# SNO+

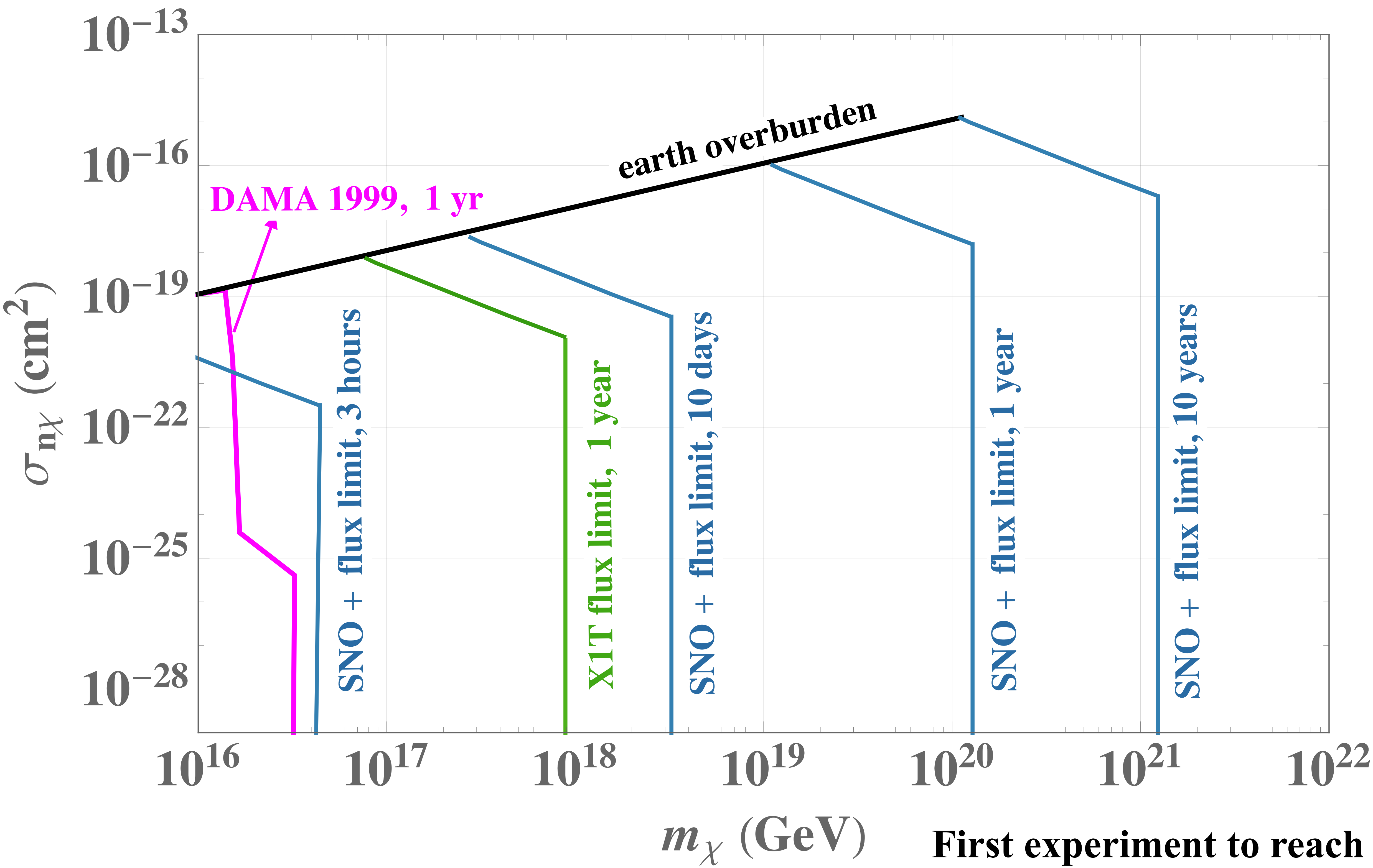
scale model @ SNOLAB




PMT selfie 2 km underground

# SNO+ mass reach

“fiducial area” = $10^6$ cm$^2$




**First experiment to reach Planck mass!**

# SNO+ signal

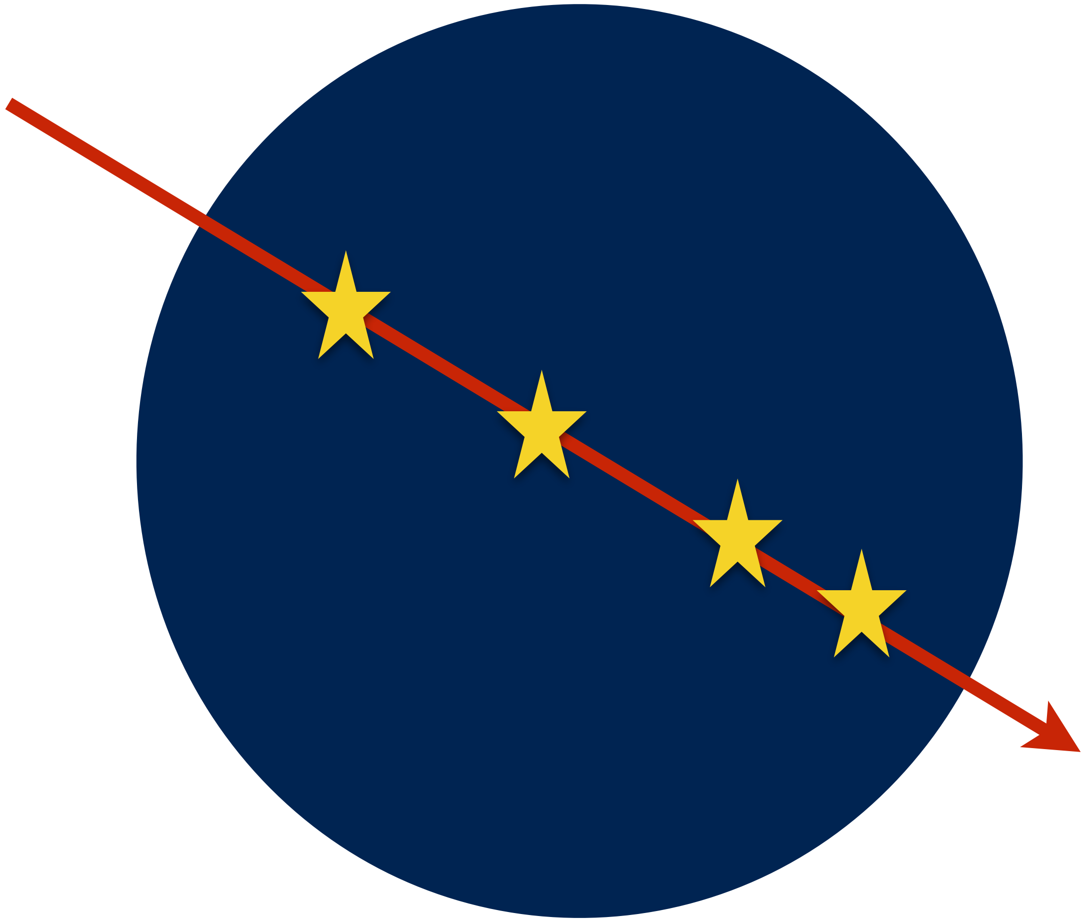
DM transit = 10 μs

- Continuous deposition of photoelectrons over transit time

- Collinearity

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

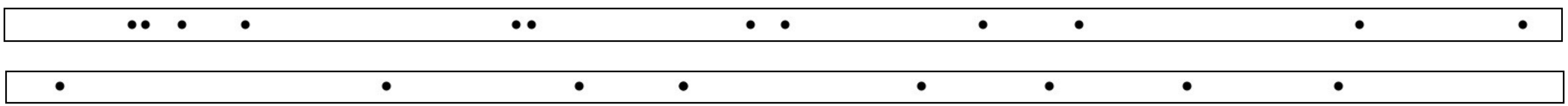
may be exploited with
vertex reconstruction/ timing information



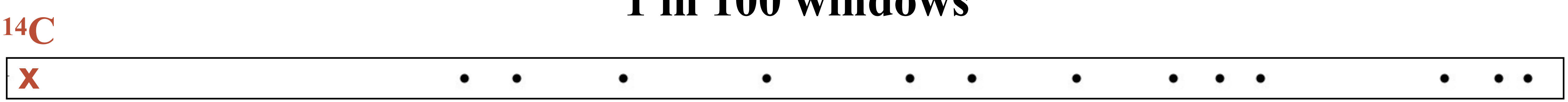
# BOREXINO, 10 μs windows

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

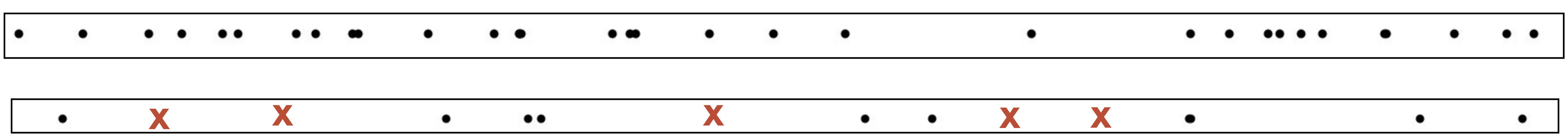
## typical windows with dark counts



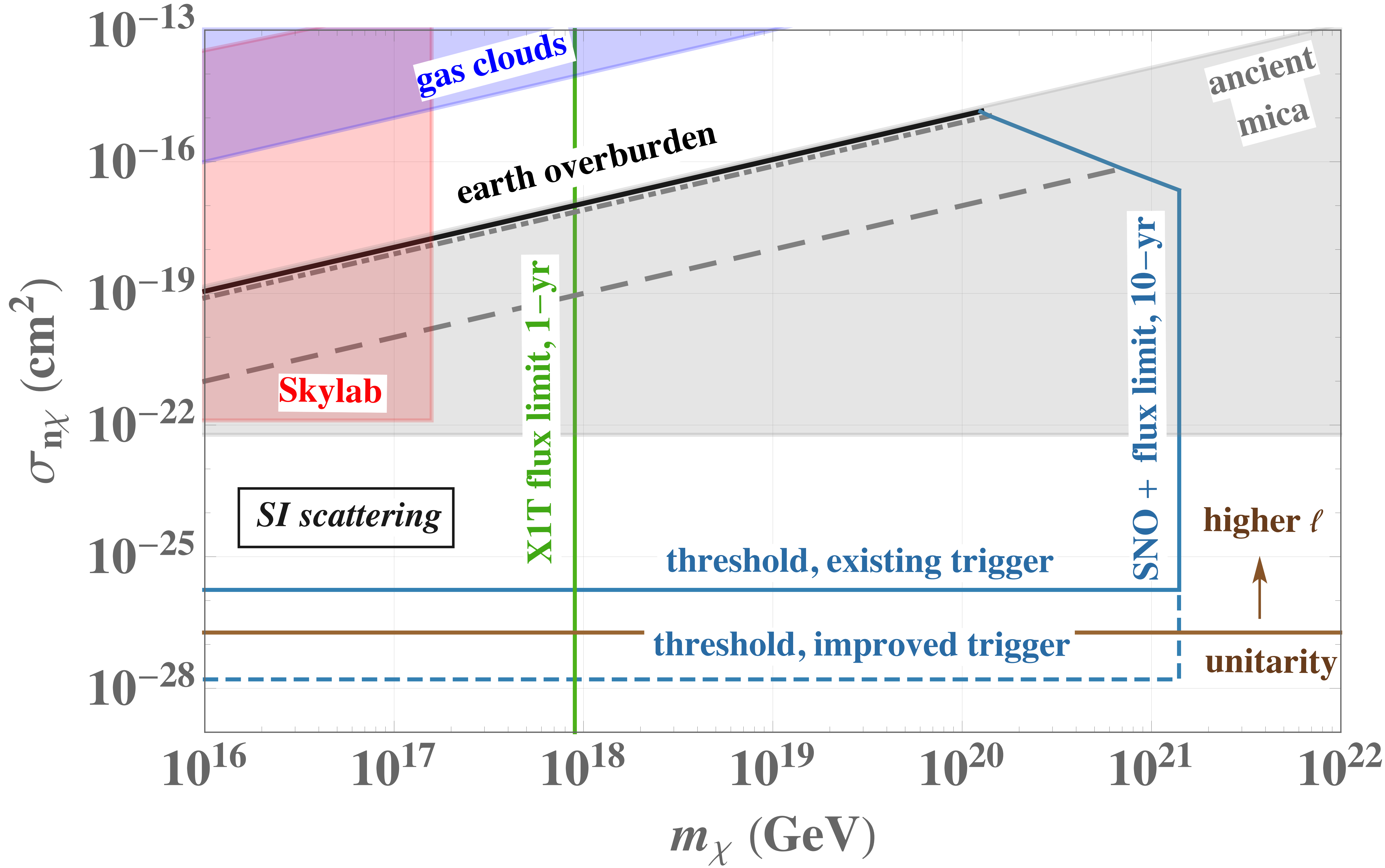
## 1 in 100 windows




## once in 10 years



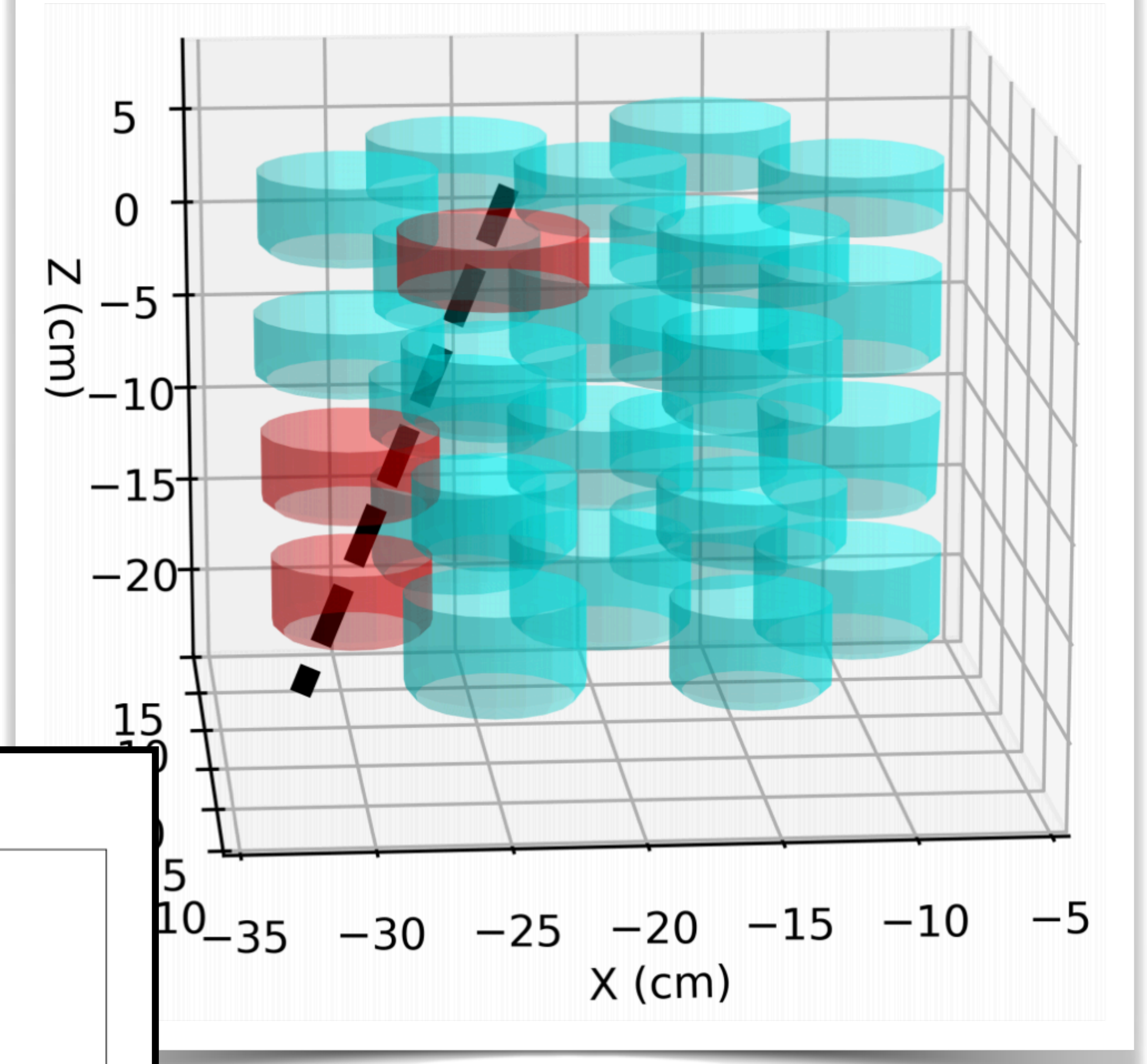
# SNO+ cross section reach

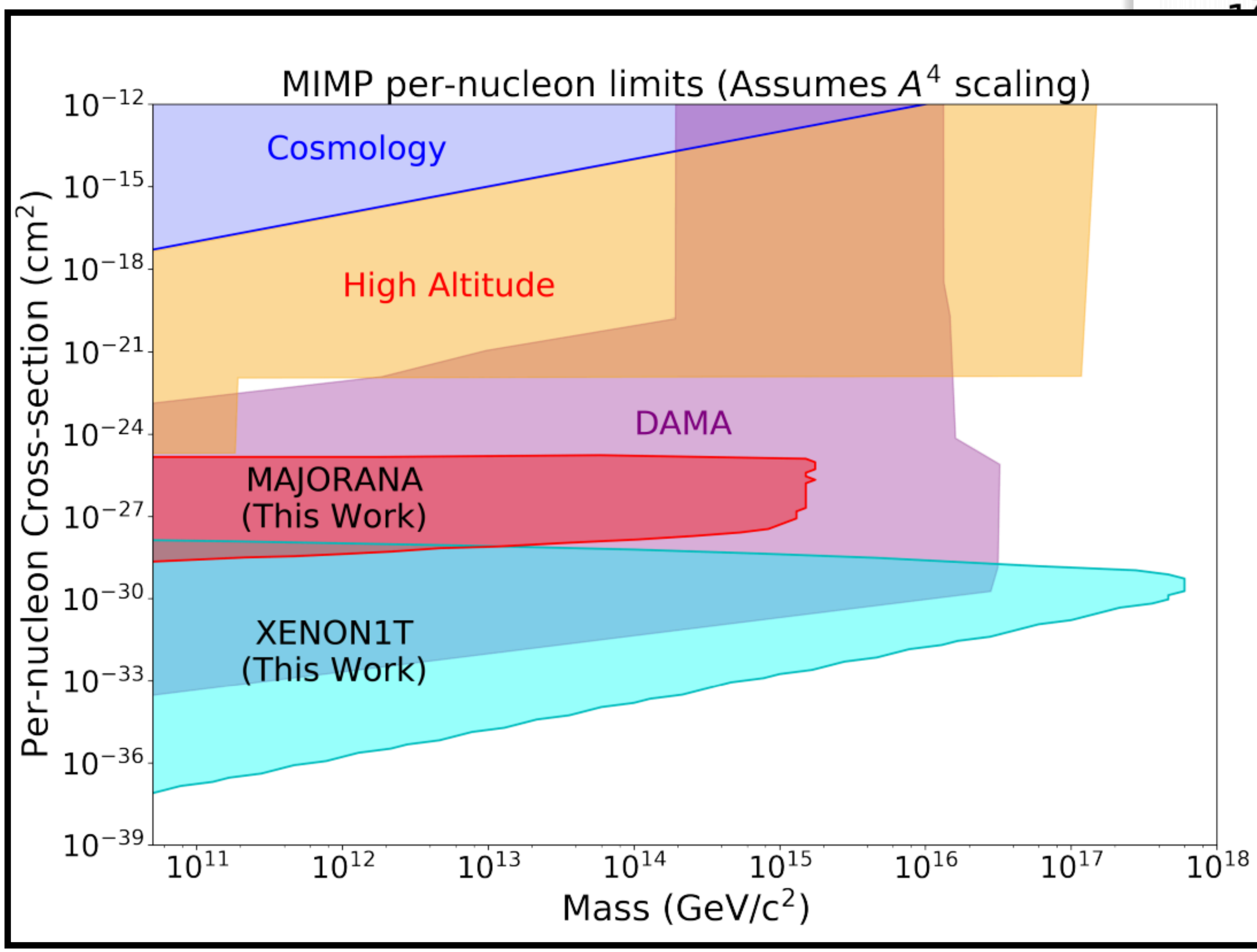


recasting

**MAJORANA DEMONSTRATOR**

search for lightly ionizing particles



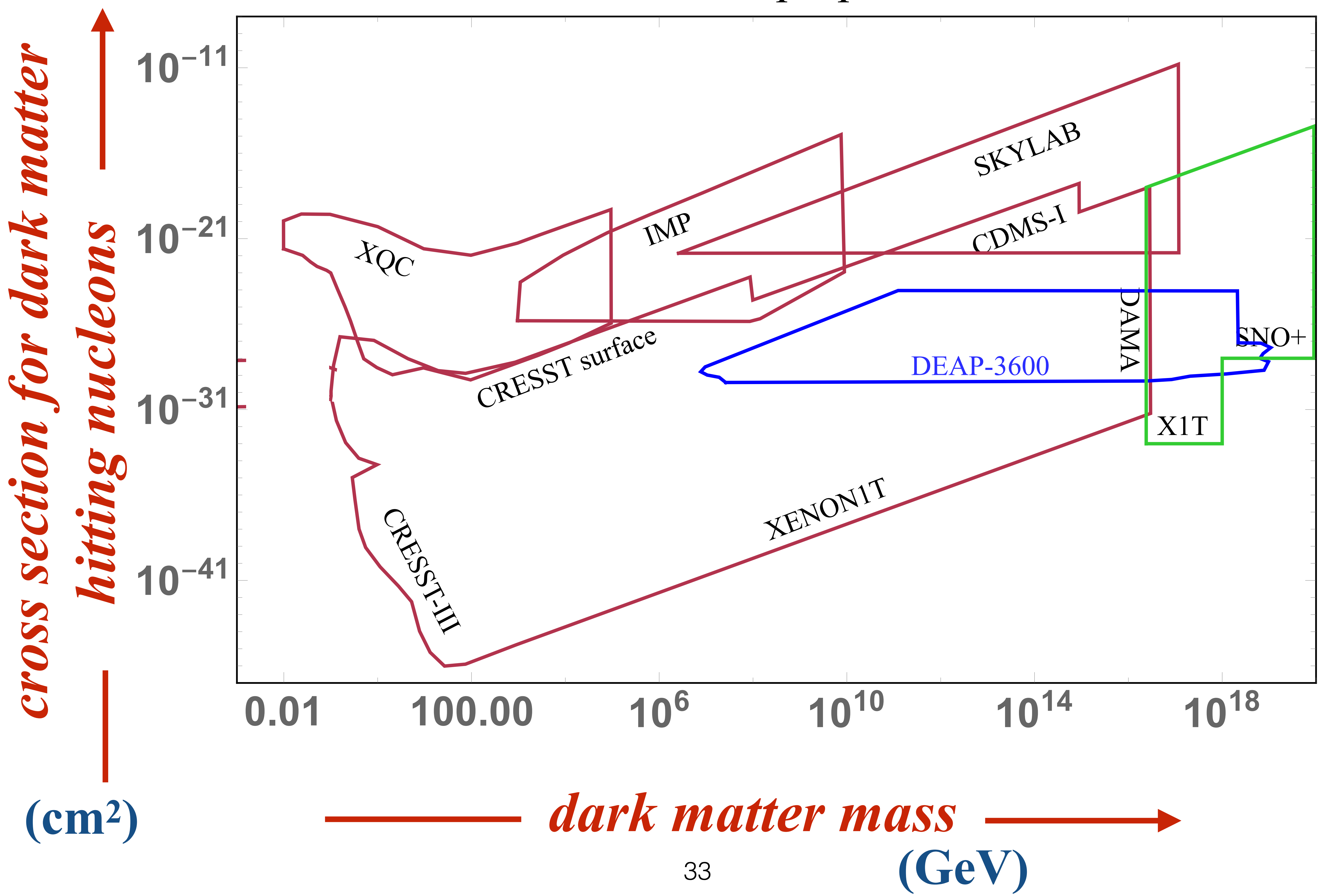




**'Direct Detection Limits on Heavy Dark Matter'**

**2009.07909**

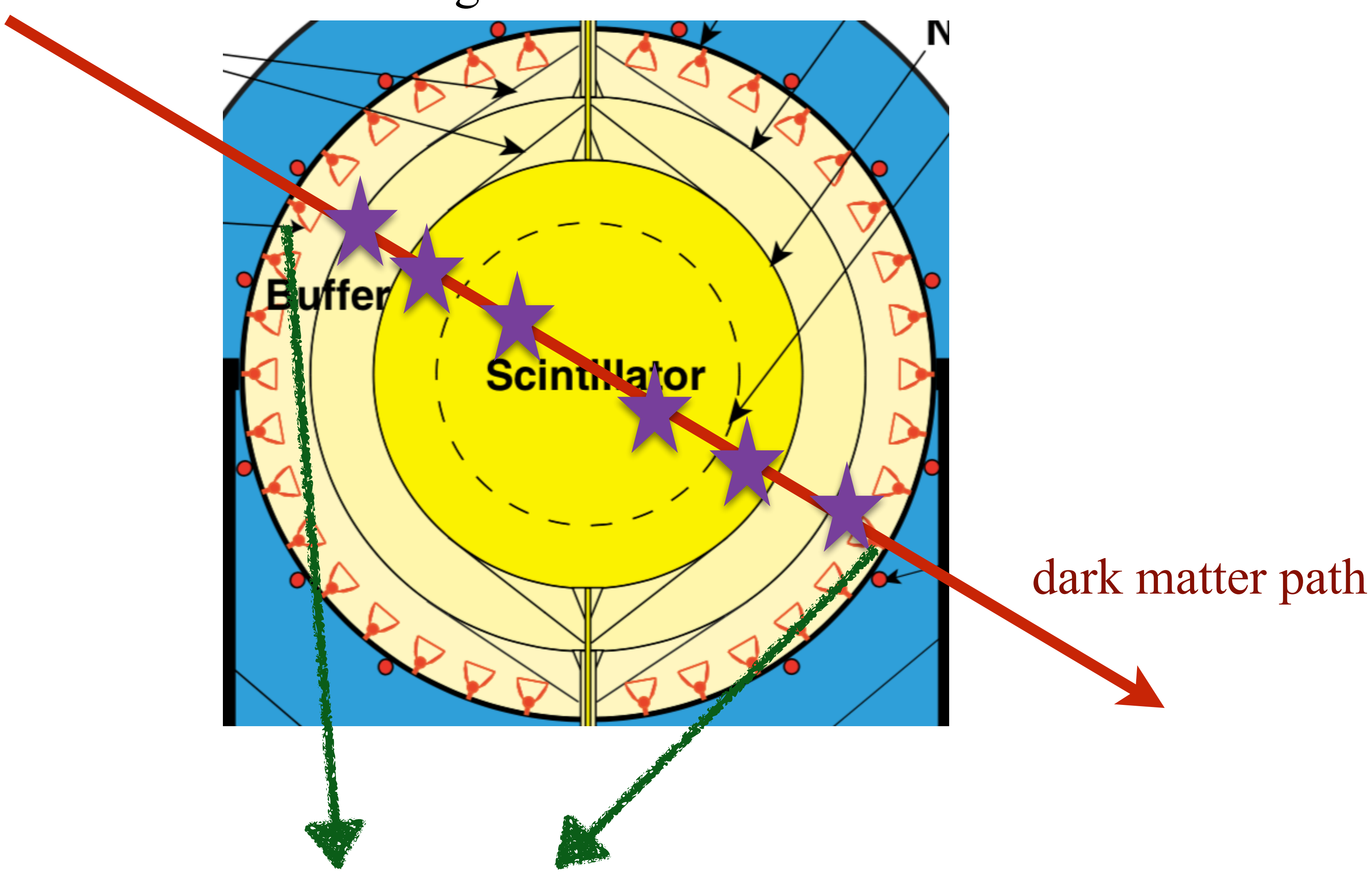
*M. Clark, R. Lang* et al

Near-future: multiscatter + repurposed neutrino detectors



# 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)**

# 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)**

# Testing velocity anisotropies

galactic frame

angular distribution:

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

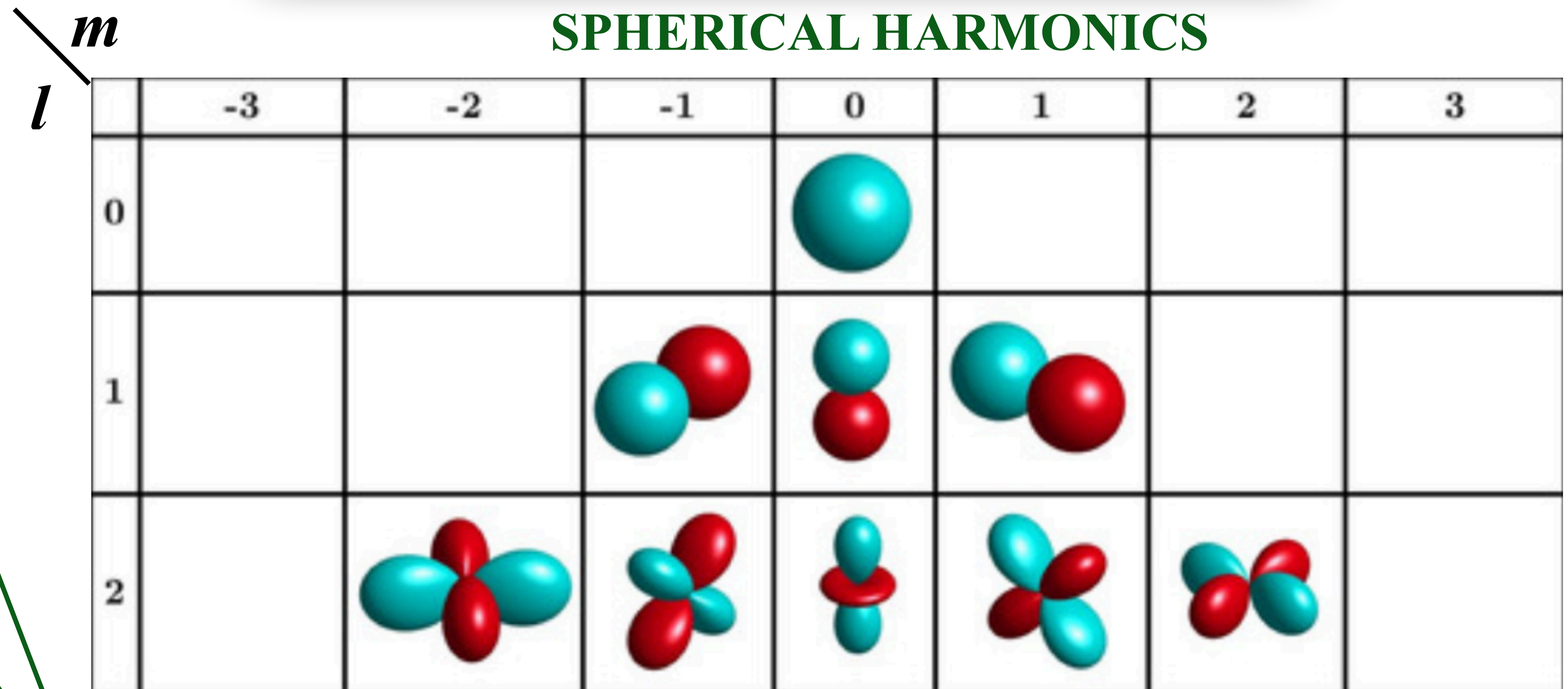
contribution

monopole ~ 1

dipole ~ ε

quadrupole ~ ε

**SPHERICAL HARMONICS**




test anisotropy, ε << 1

Benchmark:

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

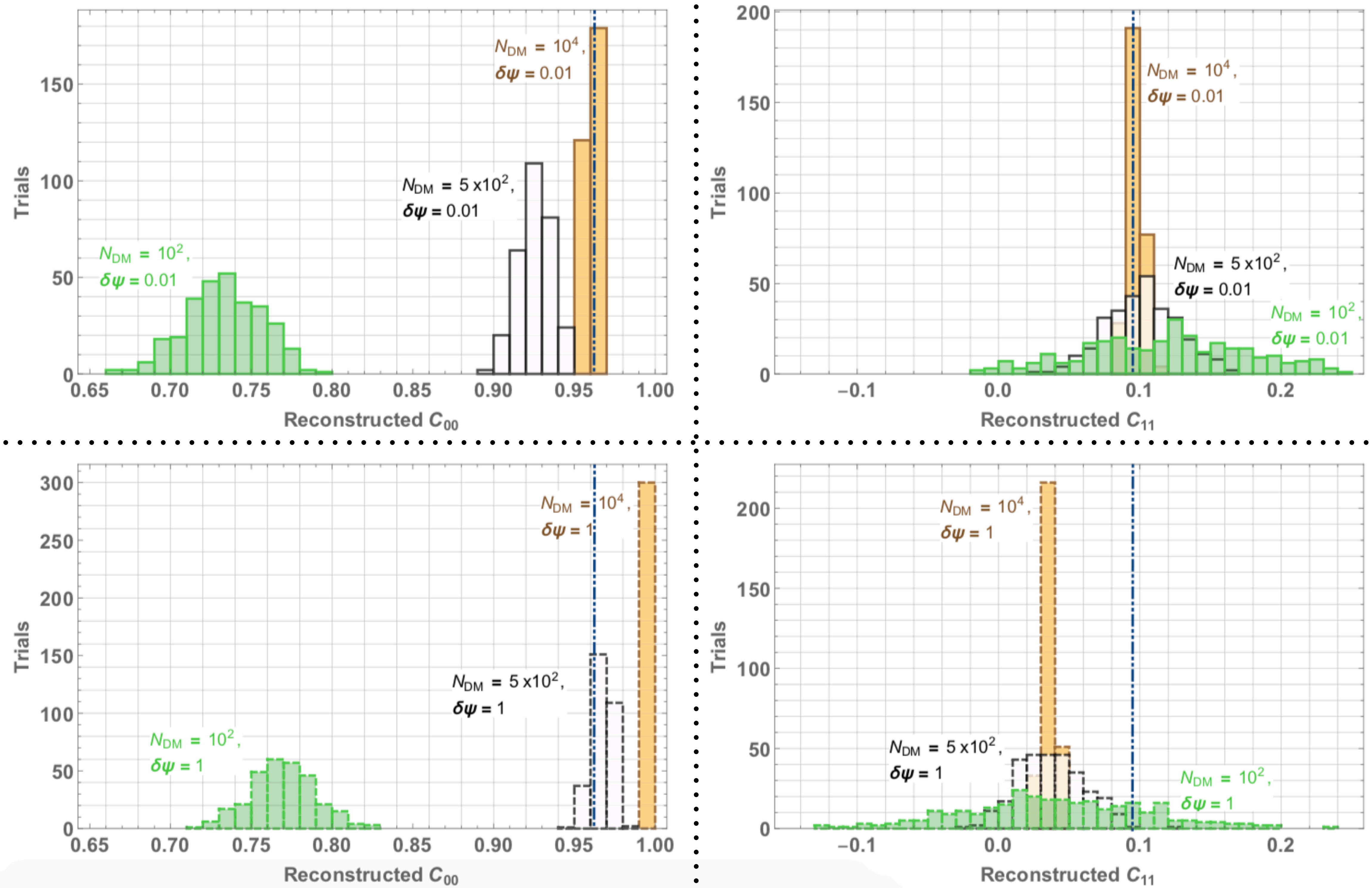
*J. Bramante, J. Kumar,* **N. Raj**
***Phys Rev D* (2019)**

# 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.

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

# Introduction to dark neutrons

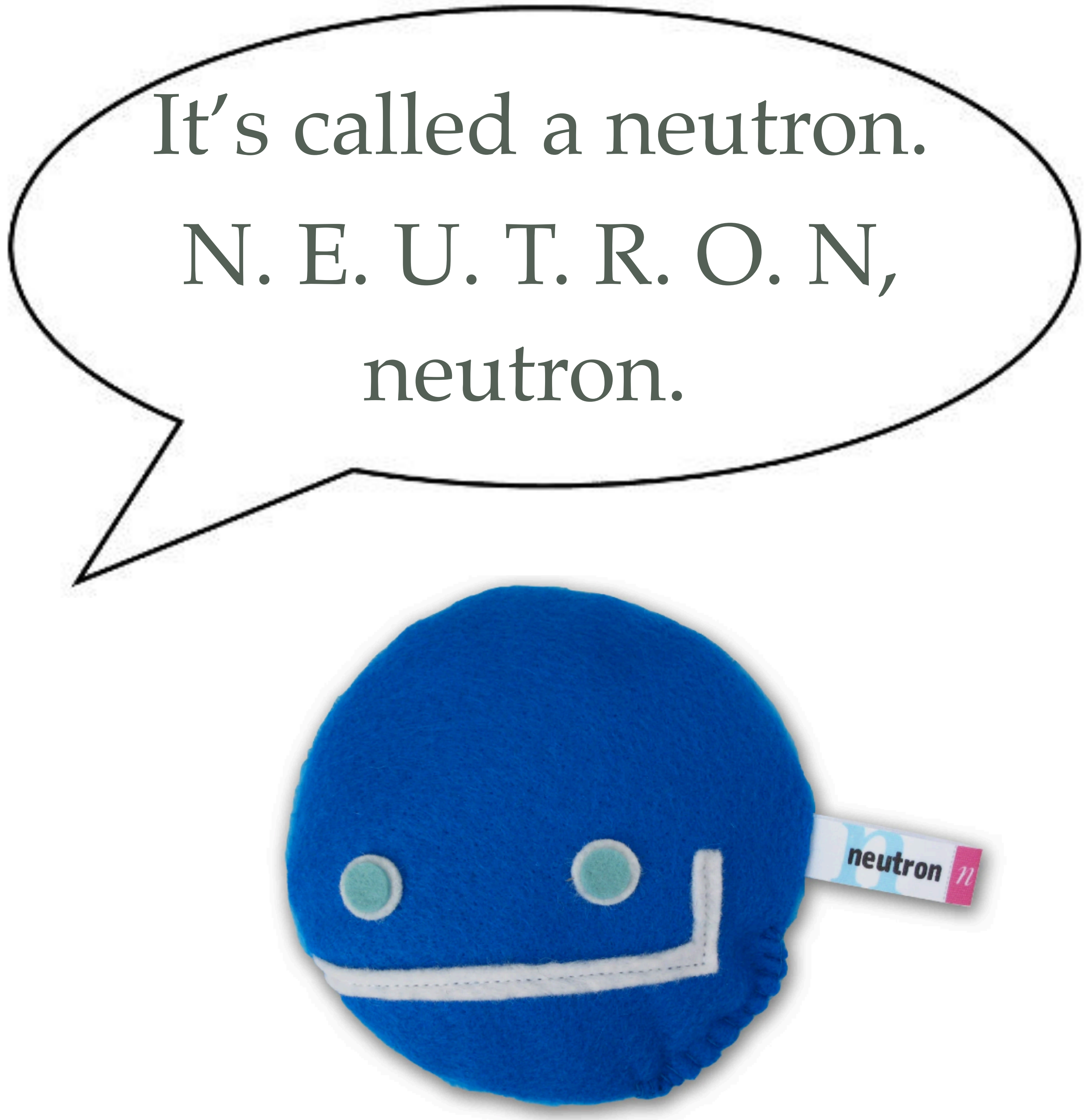
| | |
|---|---|
| hypothesis: | a new particle "$\chi$" |
| its character: | 0 : charge under all fundamental forces |
| | 1/2 : spin |
| | 1 : baryon number |

# Introduction to dark neutrons

hypothesis: a new particle "$\chi$"

its character:
- 0 : charge under all fundamental forces
- 1/2 : spin
- 1 : baryon number

*James Chadwick*




also $\Lambda^0, \Sigma^0, \Delta^0, \ldots$

| neutron | "dark" neutron (hidden) |
| --- | --- |
| $n$ | $\chi$ |
| $m_n$ | $m_\chi$ |
| ↓ | ↓ |
| $939.5654$ MeV/$c^2$ | ? |

neutron — "dark" neutron

$n$ — $\chi$

$m_n$ — $m_\chi$

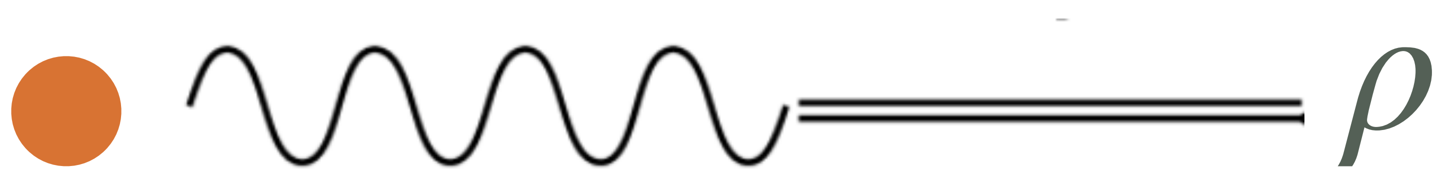
$939.5654\ \mathrm{MeV}/c^2$ — ?

Hamiltonian

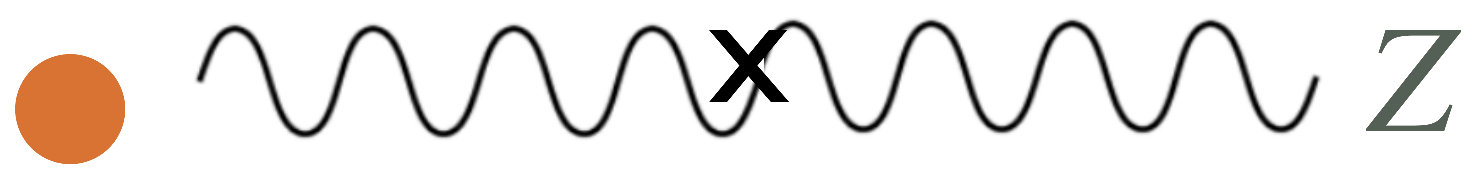
$$\begin{pmatrix} \bar{m}_n & \epsilon_{n\chi} \\ \epsilon_{n\chi} & \bar{m}_\chi \end{pmatrix}$$

$\epsilon_{n\chi}$ nothing forbids it: compulsory! => ***quantum mixing***

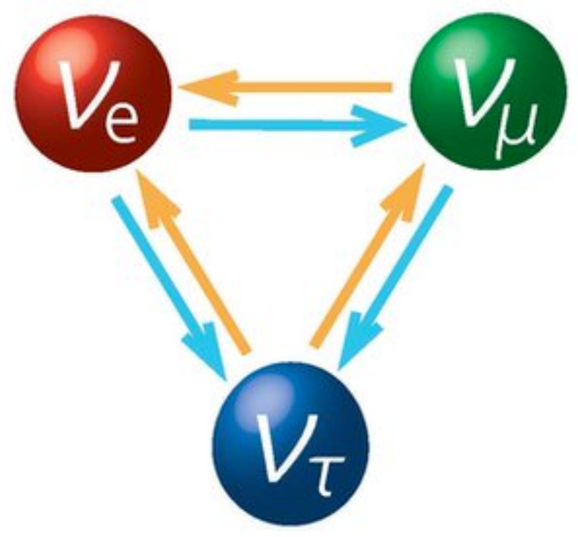
**quantum mixing already seen in Nature:**




photon - rho meson



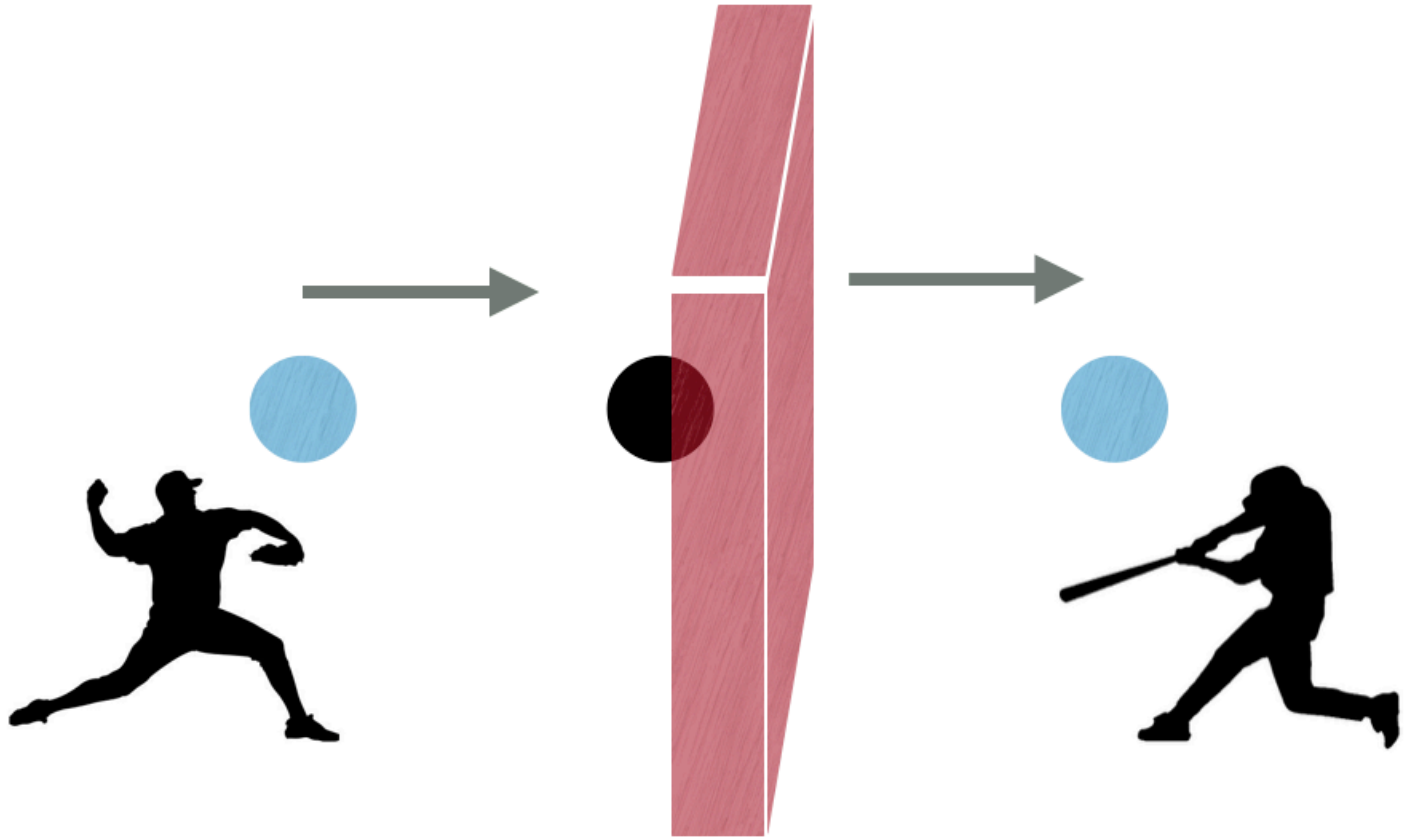

photon - Z boson



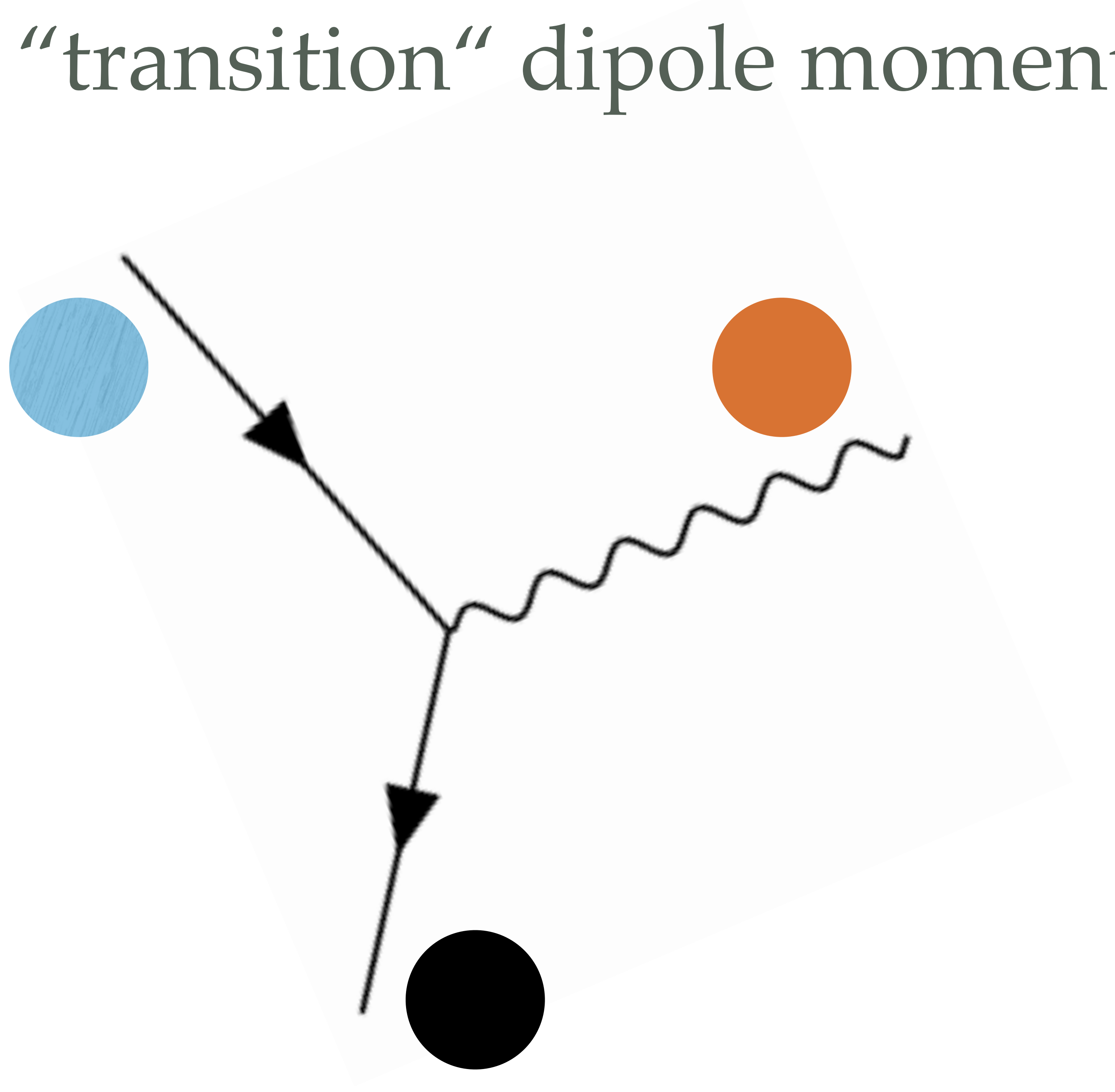

neutrino flavours

# Consequences for neutrons

## oscillations

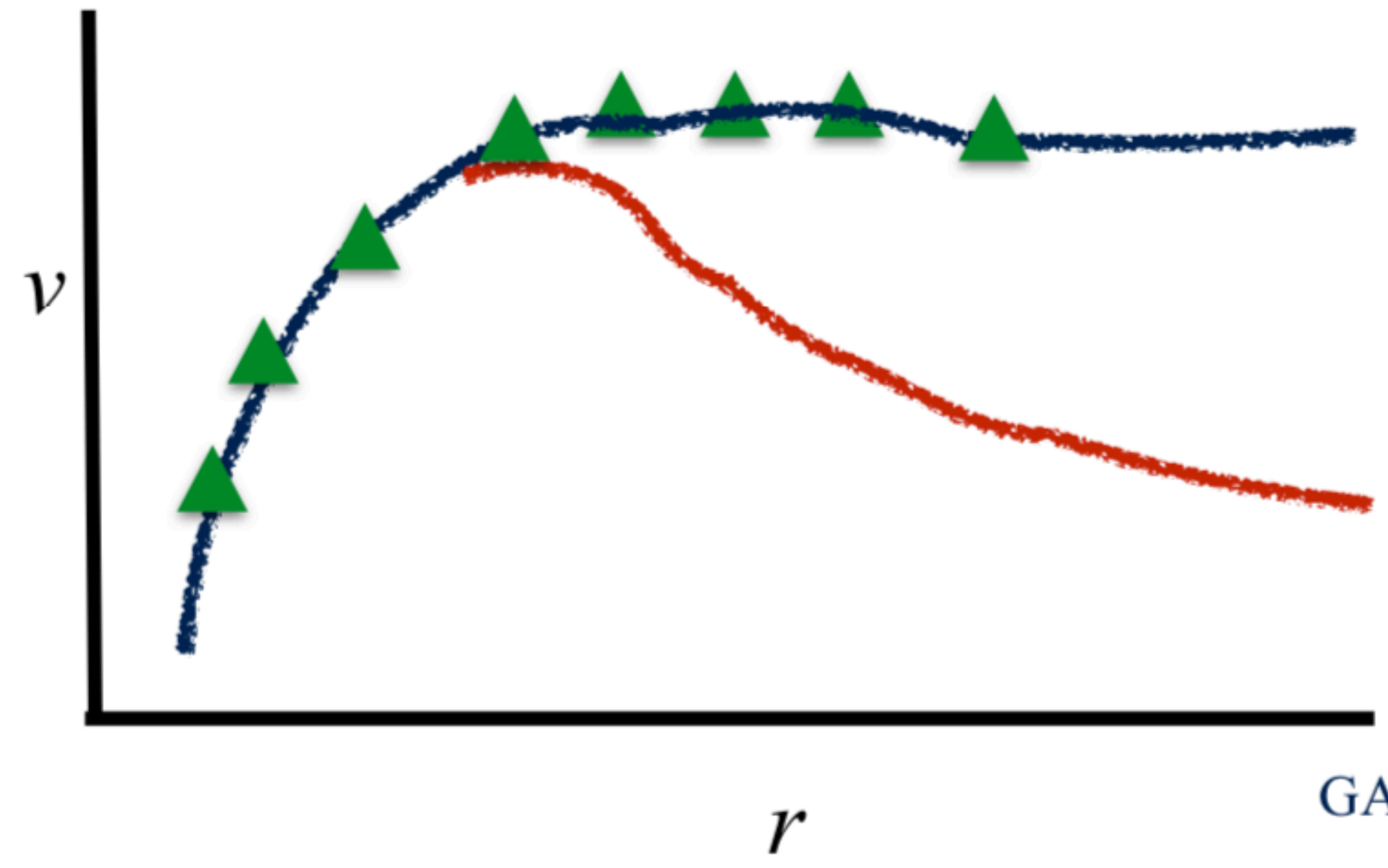


## magnetic “transition“ dipole moment

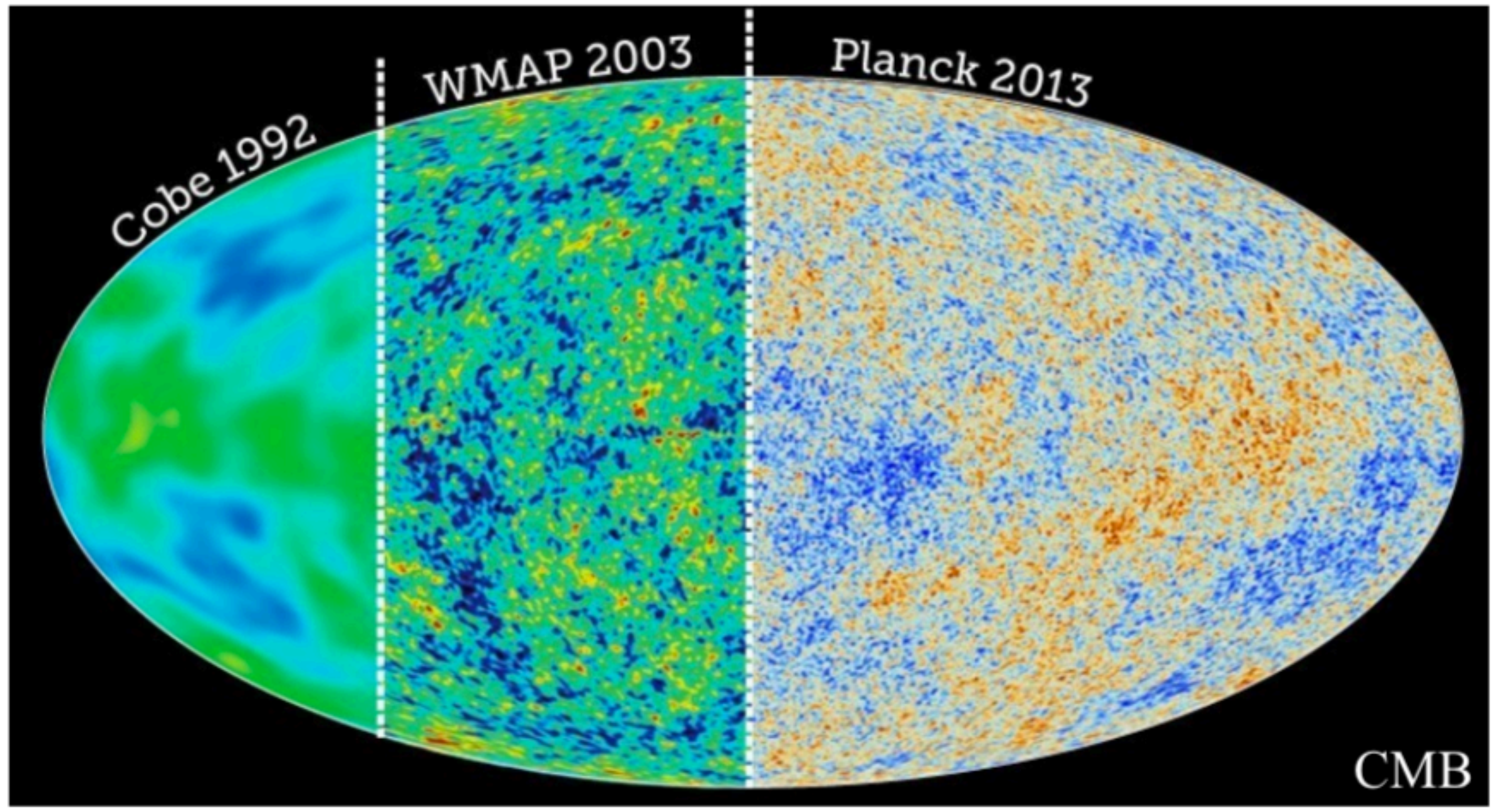


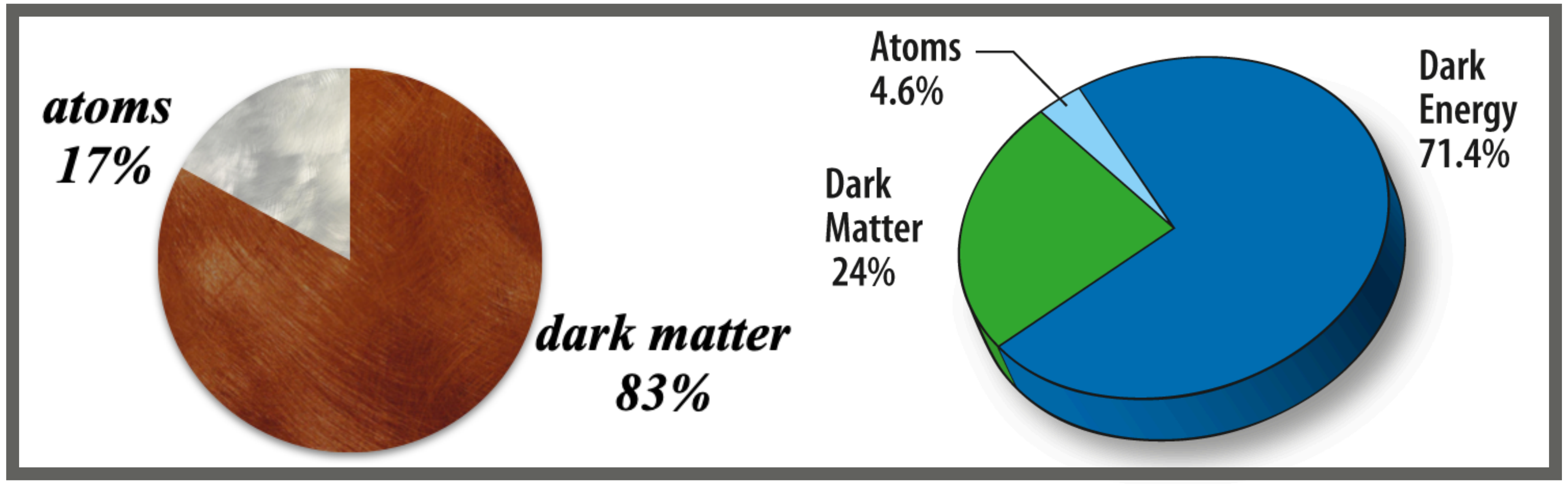
# Why care?

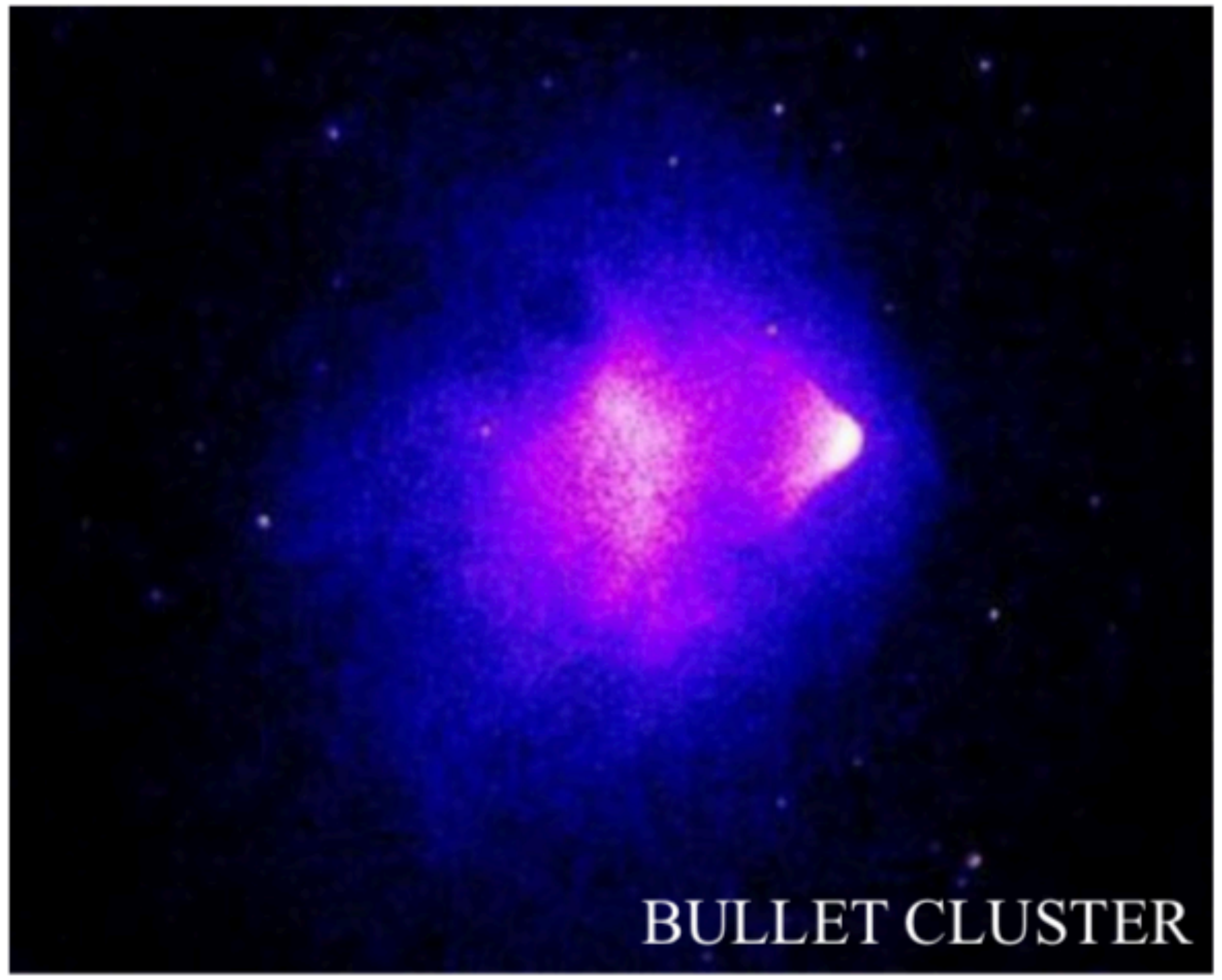
the *dark matter* of the universe




GALACTIC ROTATION



# From where?

elementary

@ hadron level :

$$\mathcal{L} \supset -\delta(\bar{\chi}n + \bar{n}\chi)$$

$$\mathcal{L}_{\text{eff}} \supset \frac{\mu_n}{2}\theta\bar{\chi}\sigma^{\mu\nu}nF_{\mu\nu} + \text{h.c.}$$

$$\mu_n = -1.91\mu_N$$

neutron magnetic moment

$$\delta/(m_n - m_\chi)$$

( $\mu_N = e/(2m_n) \simeq 0.1\ e\,\text{fm}$
nuclear magneton )

# From where?

## elementary

@ hadron level :

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exotic neutron decay

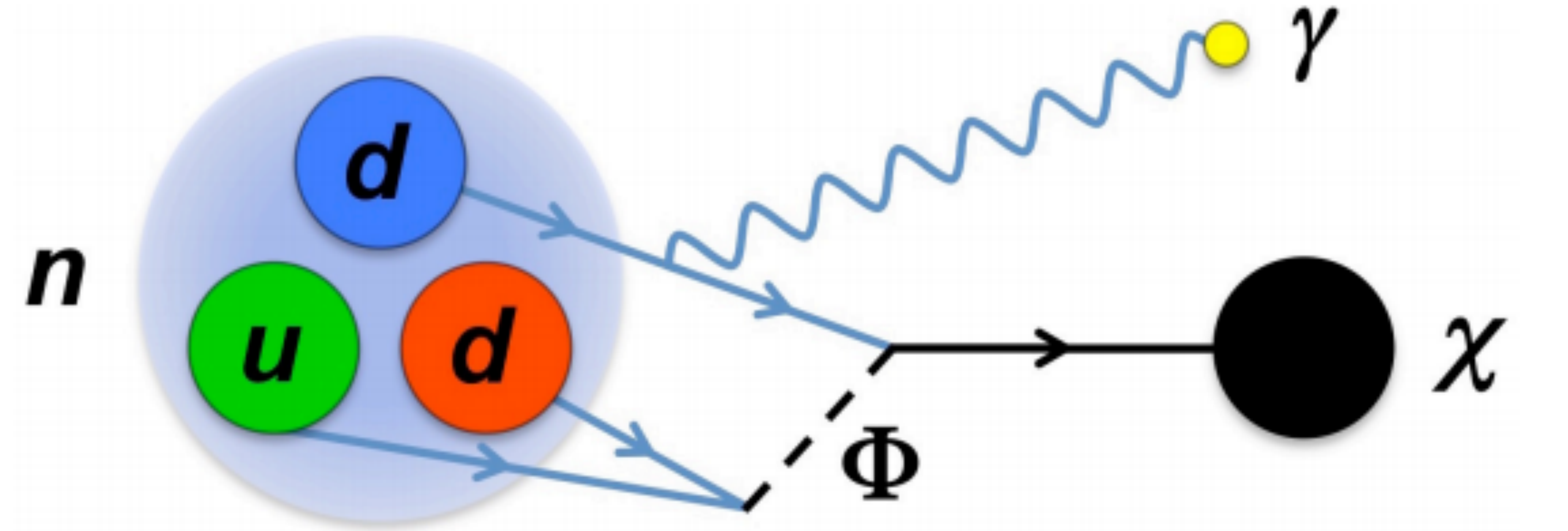



image: Fornal & Grinstein

$n$ lifetime puzzle:

$$\text{Br}_{n\to\chi\gamma} \simeq 0.01\left(\frac{\theta}{5\times10^{-10}}\right)^2\left(\frac{\Delta m}{\text{MeV}}\right)^3$$

$$\Gamma_{\chi\to n\gamma} \simeq \frac{1}{2200\ \text{s}}\left(\frac{\theta}{10^{-10}}\right)^2\left|\frac{\Delta m}{10\ \text{MeV}}\right|^3$$

$$\Gamma_{\chi\to pe^-\bar{\nu}} = \frac{1}{9\times10^{22}\ \text{s}}\left(\frac{\theta}{10^{-10}}\right)^2\frac{F(Q_\chi/m_e)}{F(Q_n/m_e)}$$

# From where?

**composite**

from ***mirror sector***

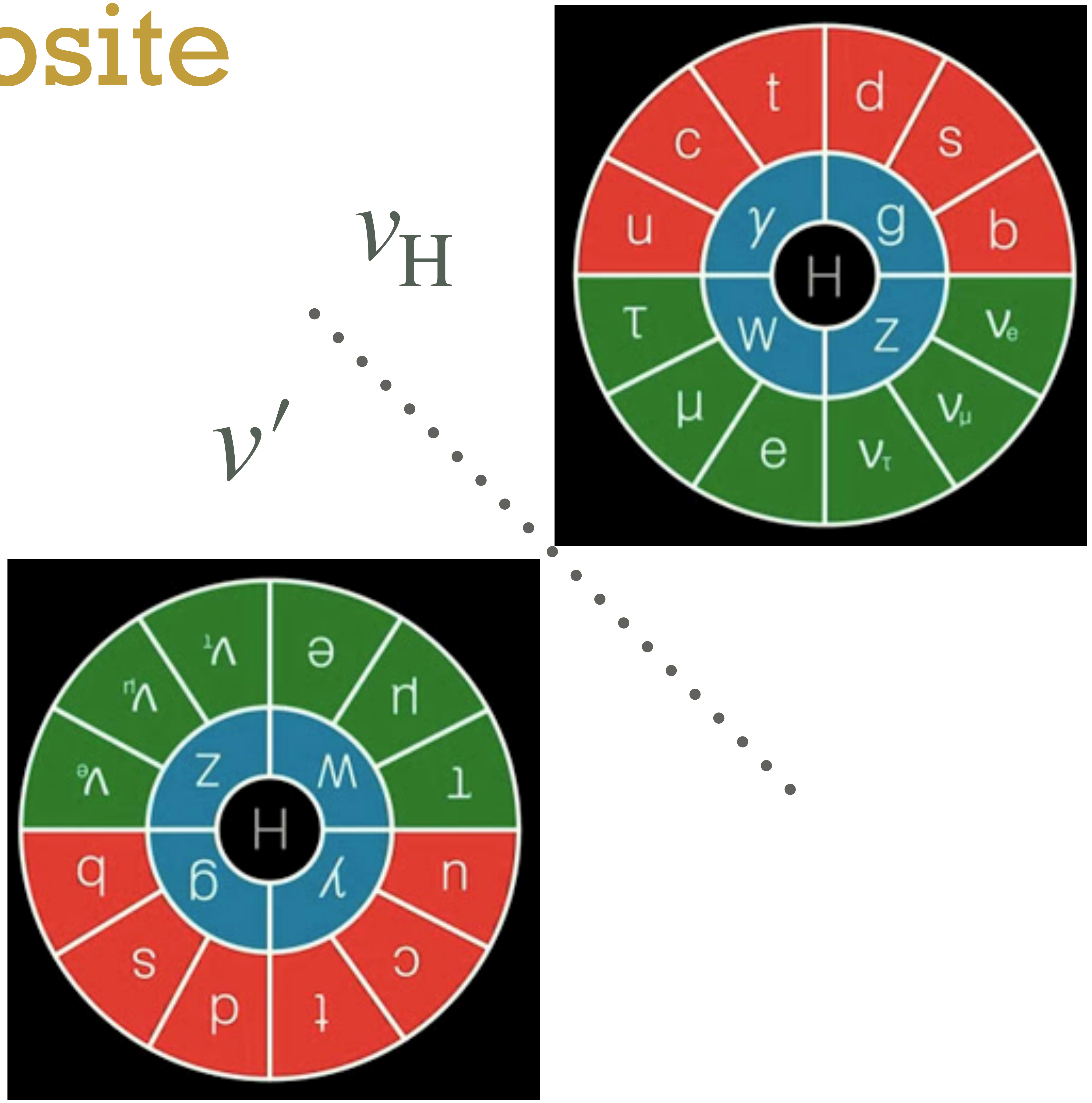
very early idea of “dark sector”,

can address:

+ Why is $v_H \ll M_{\text{Planck}}$?
(Twin Higgs realization)

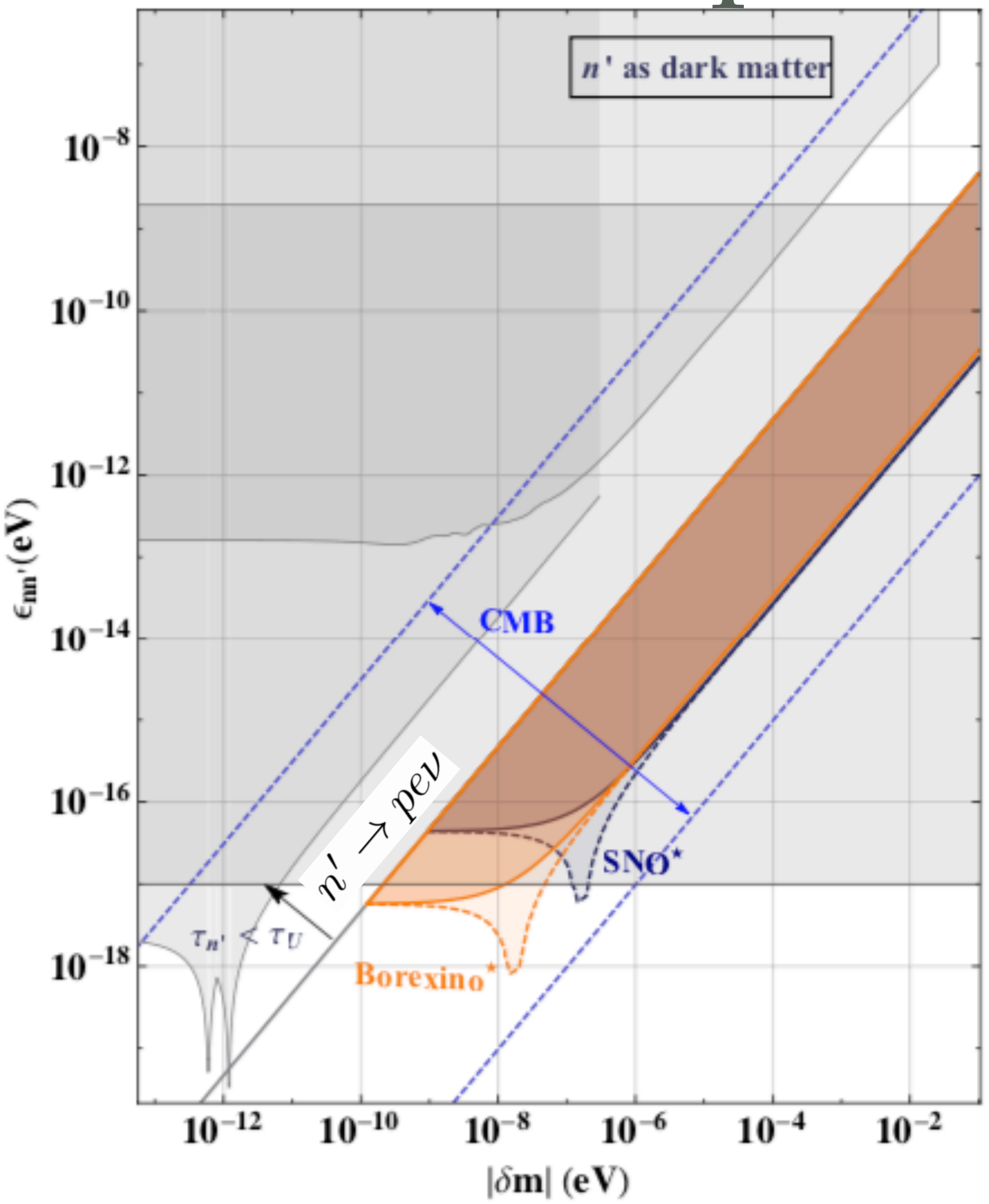
+ dark matter

+ baryogenesis




Kobzarev, Okun, Pomeranchuk 1966

# Nuclear absorption of halo dark matter




DM flux

$$R_{n'/p} = \Phi_\chi \times \theta^2 \sigma_{np} = \theta^2 \times 3.5 \times 10^{-17}\ \mathrm{s}^{-1}$$

neutrons at SNO (solar neutrino data):

$$\nu D \to \nu n p$$

$$R_{\nu/D} = 2.2 \times 10^{-36}\ \mathrm{s}^{-1}$$

neutrons at Borexino
("Pauli exclusion principle violation" search):

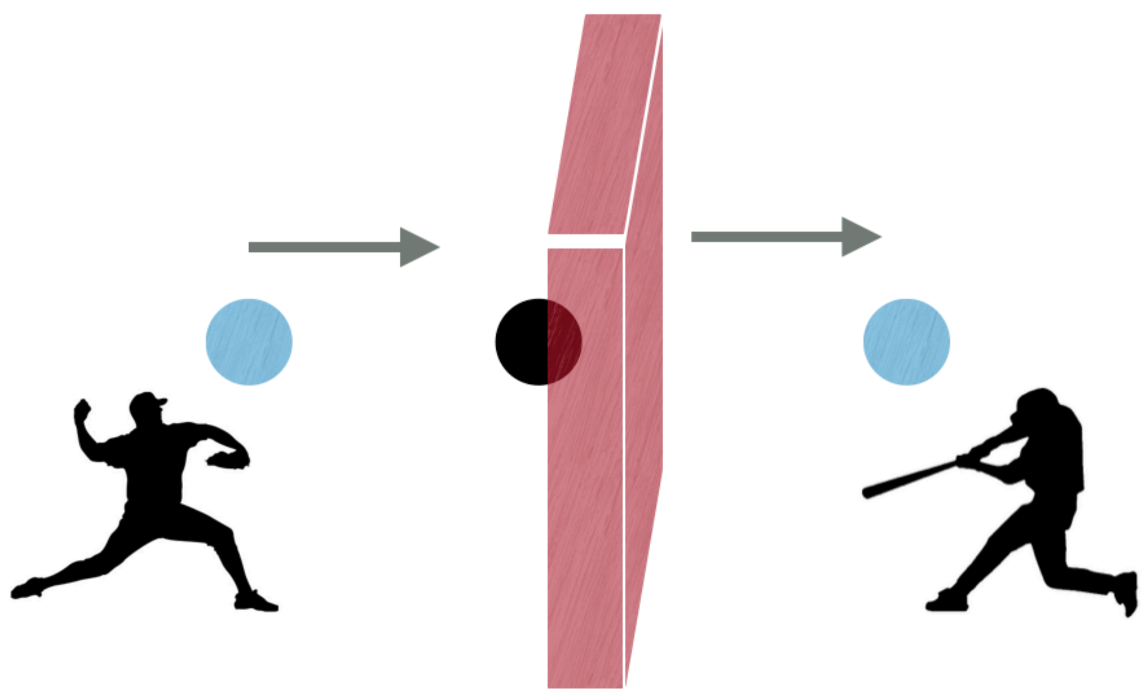
$$^{12}\mathrm{C} \to {}^{11}\widetilde{\mathrm{C}} + n$$

90% C.L.: < 57 events in 128 ton-years

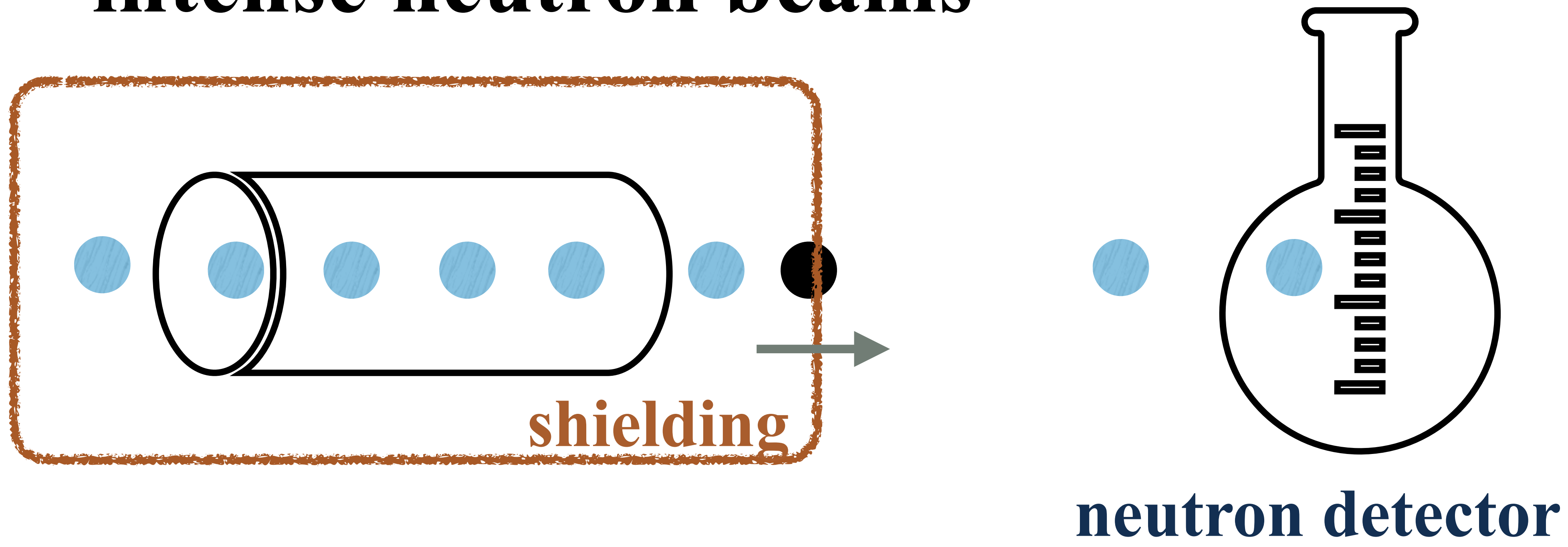
**2201.02603, PRD 2023**

***Hostert, McKeen, Pospelov,* Raj**

# Neutrons shining through a wall



**intense neutron beams**




**e.g. IsoDAR at Yemilab, Korea**

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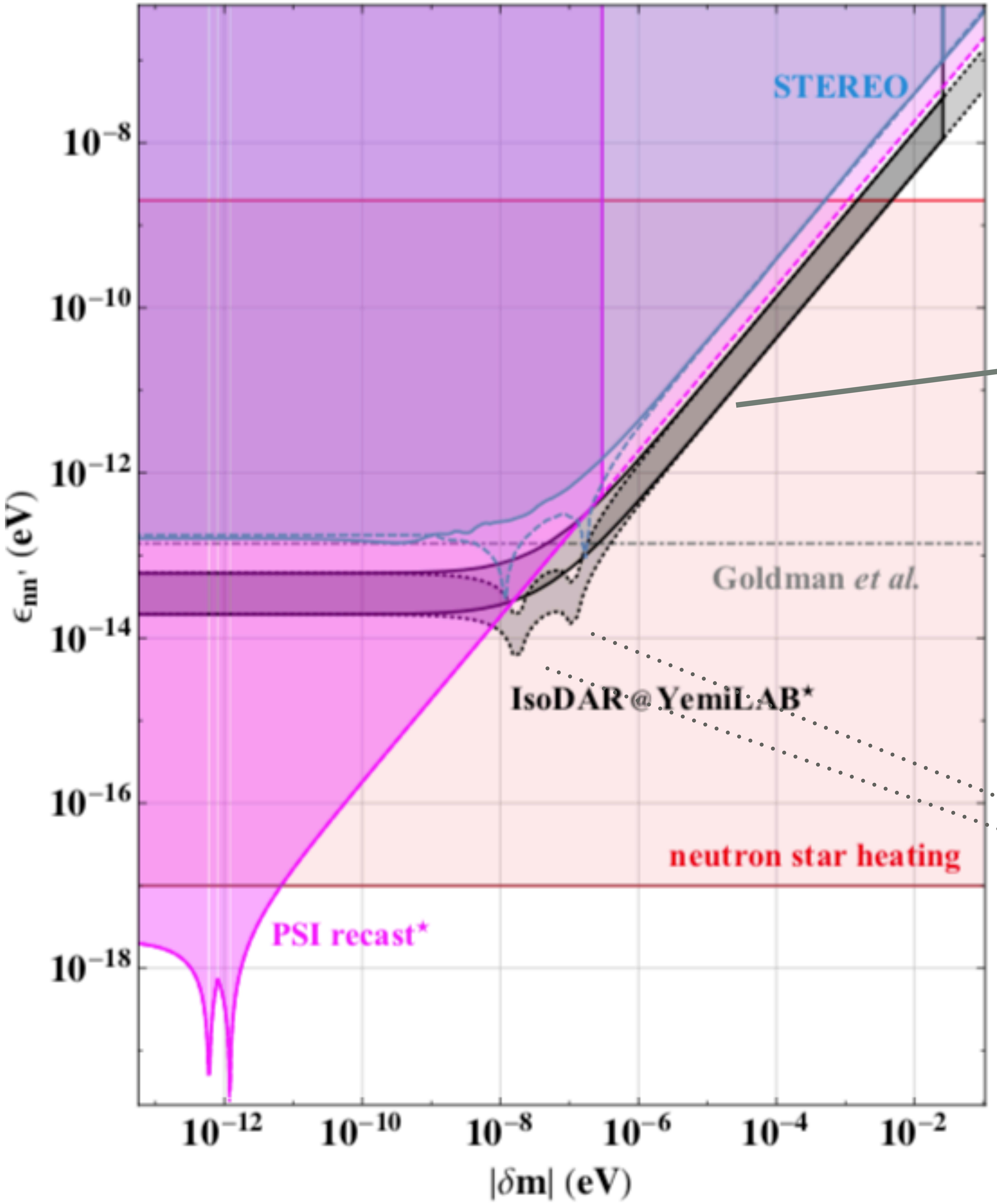
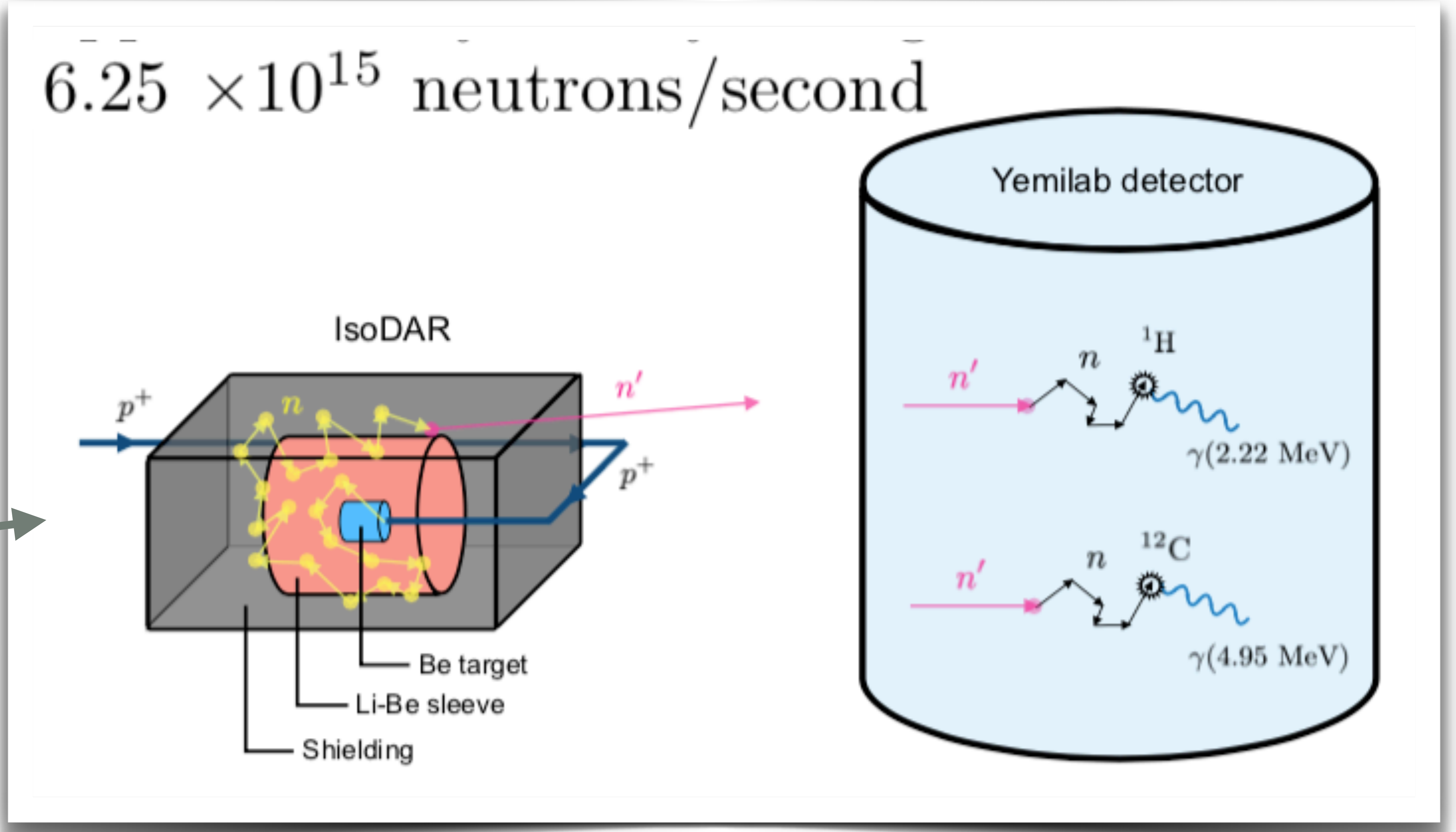
***Hostert, McKeen, Pospelov,* Raj**

# Neutrons shining through a wall




IsoDAR main goal:

$^7\text{Li} + n \to {}^8\text{Li} + \gamma$

$^8\text{Li} \to {}^8\text{Be} + e^- + \bar{\nu}_e$

Look for

$\bar{\nu}_e \to \bar{\nu}_e$

$$H = \begin{pmatrix} m_n + \Delta E & \epsilon_{nn'} \\ \epsilon_{nn'} & m_n + \delta m \end{pmatrix}$$

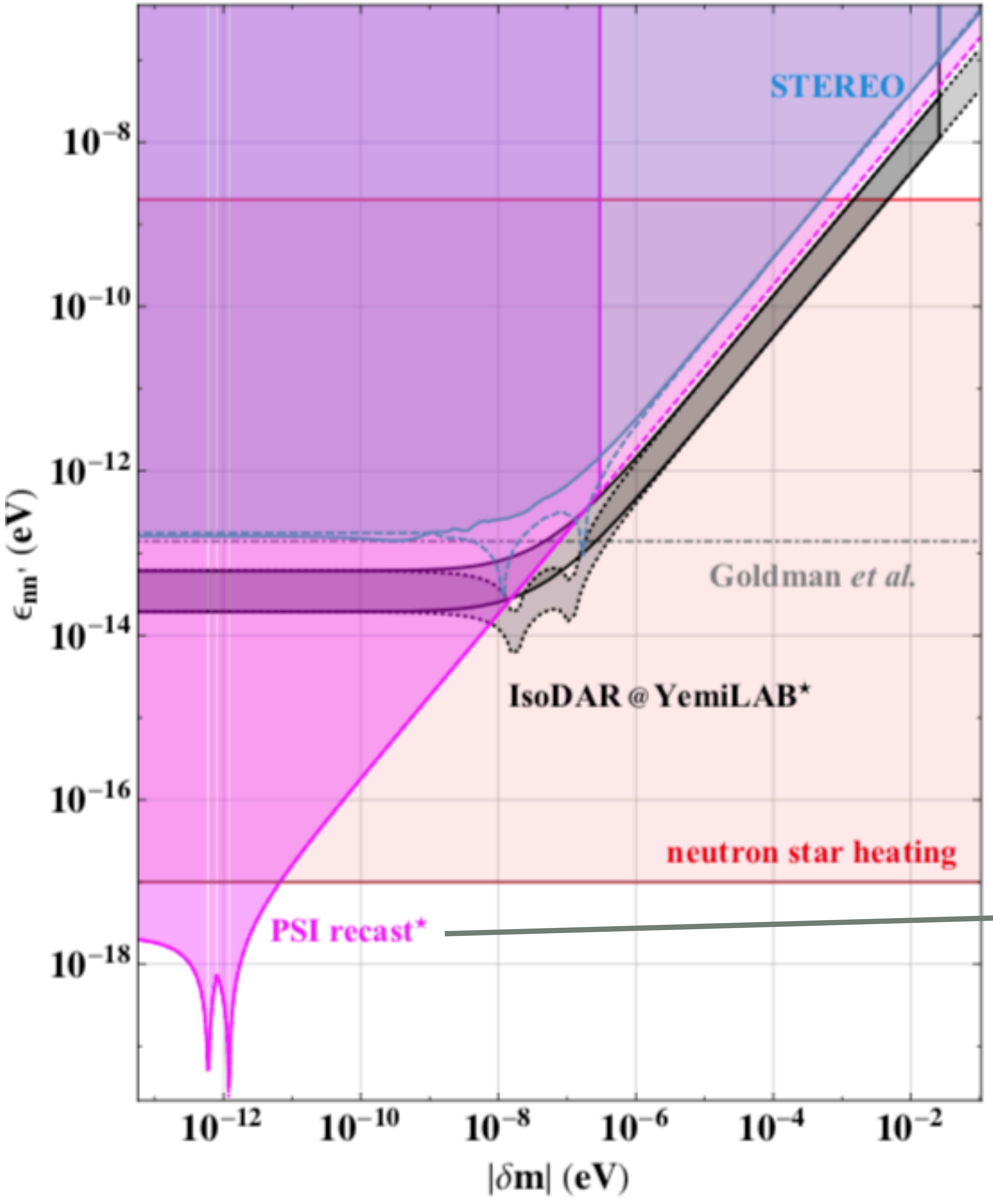
$$\Delta E = \boldsymbol{\mu}_n \cdot \boldsymbol{B} + V_{\text{F}} + \ldots \qquad V_{\text{F}} = \sum_i \frac{2\pi}{m_n} n_{\text{i}} f_{\text{scat},i}$$

$$P_{nn'} \to \frac{t_s}{t_f} \frac{2\epsilon_{nn'}^2}{4\epsilon_{nn'}^2 + (\delta m - \Delta E)^2}$$

**2201.02603, PRD 2023**

***Hostert, McKeen, Pospelov,* Raj**

# Neutron disappearance



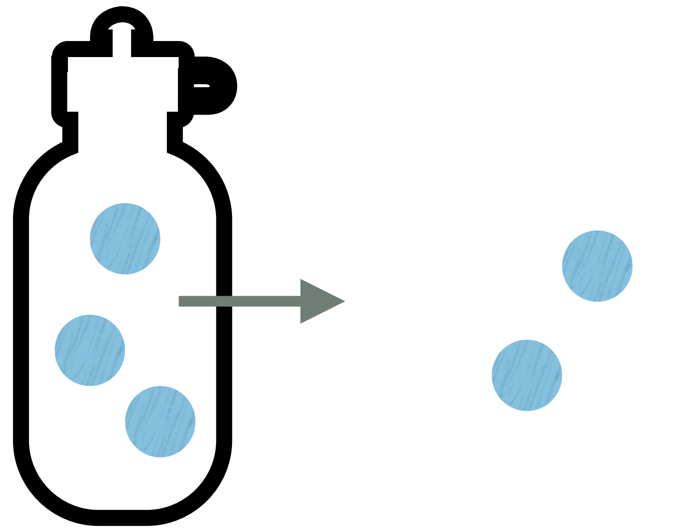

$$P_{nn'} \to \frac{t_s}{t_f} \frac{2\epsilon_{nn'}^2}{4\epsilon_{nn'}^2 + (\delta m - \Delta E)^2}$$ : "fast" oscillations

$$P_{nn'} \to \epsilon_{nn'}^2 t_s t_f$$ : "slow" ditto

recast this limit by equating probabilities:

$$\epsilon_{nn'}^{95\%, \delta m=0} < 1.9 \times 10^{-18} \text{ eV}$$

**UCN disappearance**



**2201.02603, PRD 2023**

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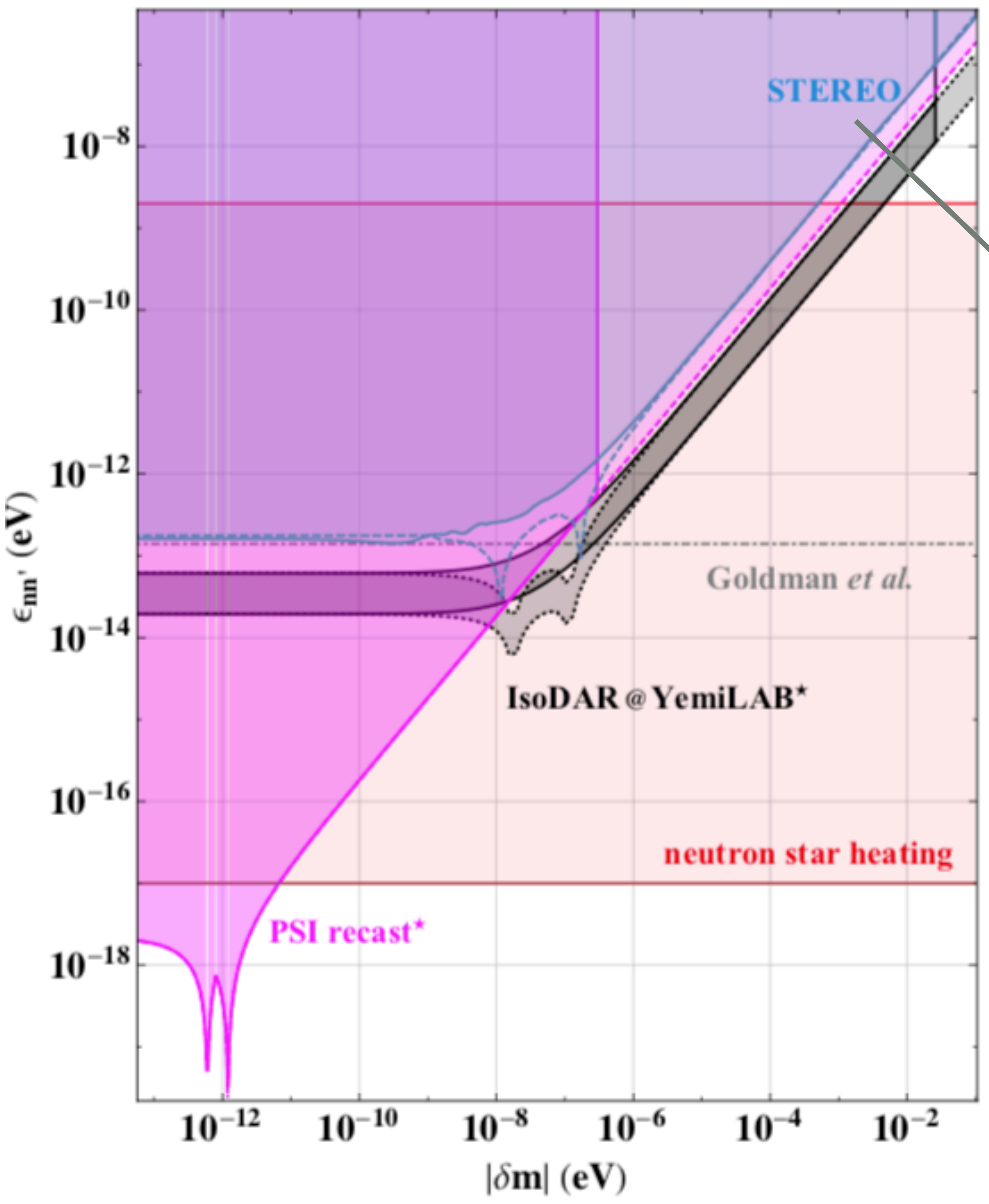
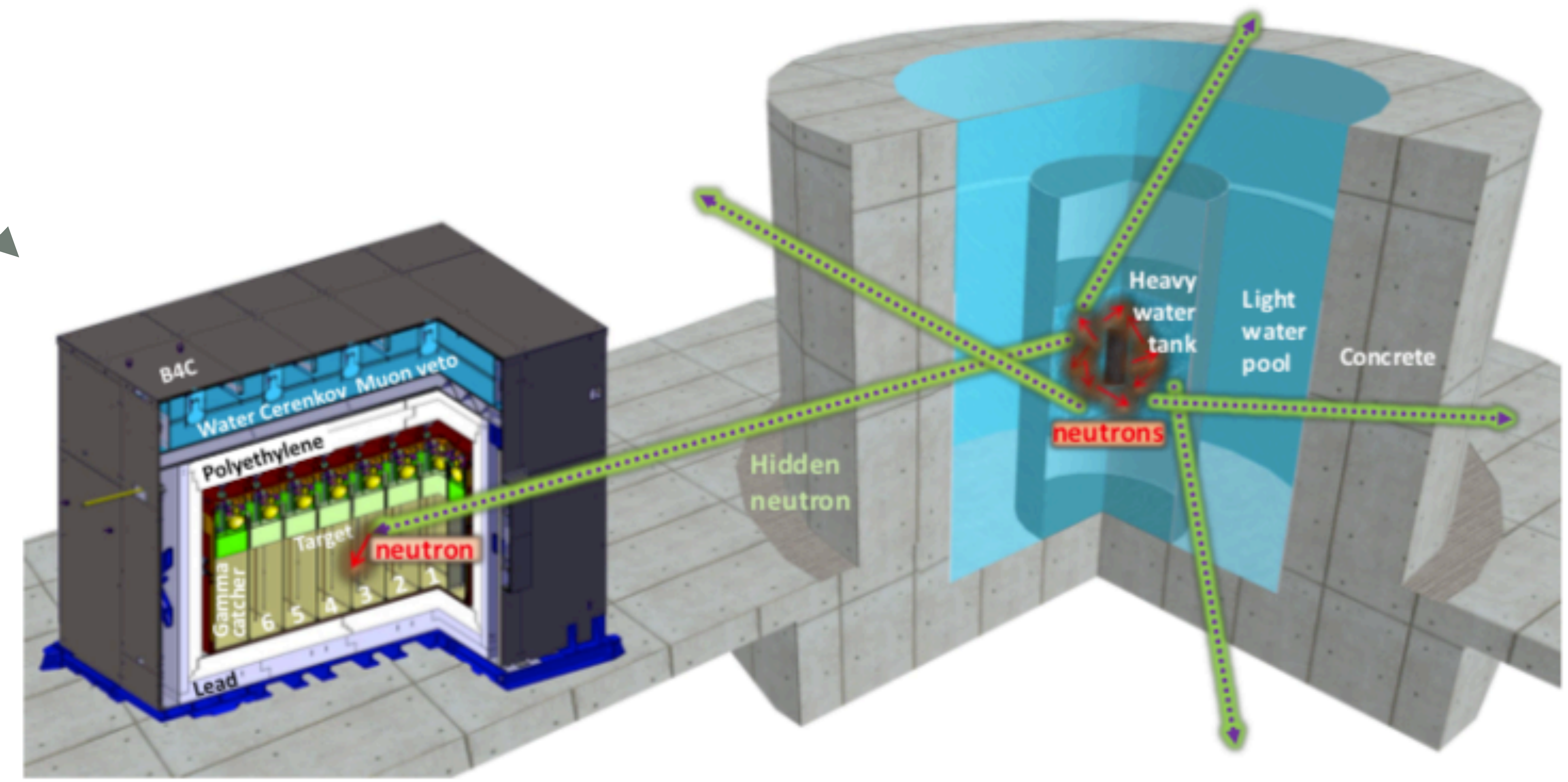
# Neutron regeneration search




**2201.02603, PRD 2023**
***Hostert, McKeen, Pospelov,* Raj**

# Summarizing terrestrial experiments

| Type | Experiment | $\Delta E$ (eV) | Limit on $\theta_{\rm vac} \equiv \theta(\Delta E = 0)$ |
|---|---|---|---|
| shining-through-a-wall | MARS @ SNS [73] | $\sim 10^{-8}$ | $6.3 \times 10^{-5}$ |
| | MURMUR [74] | $\sim 10^{-8} - 10^{-7}$ | $1.4 \times 10^{-5}$ |
| | STEREO [42] | $\sim 10^{-8} - 10^{-7}$ | $3.9 \times 10^{-6}$ |
| | **IsoDAR@YemiLAB** [40, 41] | $\boldsymbol{\sim 10^{-8}}$ | $\mathbf{1.3 \times 10^{-6}}$ (capture on H)<br>$\mathbf{4.0 \times 10^{-7}}$ (capture on C) |
| ultra cold neutron disappearance | nEDM [38] | $\sim \pm 10^{-12}$ | $1.8 \times 10^{-6}$ |
| resonant neutron regeneration | SNS *Broussard et al* [39] | – | $[1, 10] \times 10^{-5}$ [a] |
| | **HFIR** [75, 76] | – | $\boldsymbol{\epsilon_{nn'} < 4.4 \times 10^{-17}}$ **eV** [b] |
| atmospheric neutrons | SNO [77] | $10^{-12}$ | $5.9 \times 10^{-4}$ |
| | Borexino [71] | | $6.0 \times 10^{-4}$ |
| dark neutron dark matter (nuclear absorption) | SNO [77] | $1.7 \times 10^{-7}$ | $2.7 \times 10^{-10}$ |
| | Borexino [71] | $1.7 \times 10^{-8}$ | $3.3 \times 10^{-10}$ |

[a] Valid in the range $\delta m = [50, 400]$ neV.
[b] No information available for the $\delta m \gg \Delta E$ regime.

**2201.02603, PRD 2023**

***Hostert, McKeen, Pospelov,* Raj**

**non-luminous**

**ubiquitous**

**plentiful**

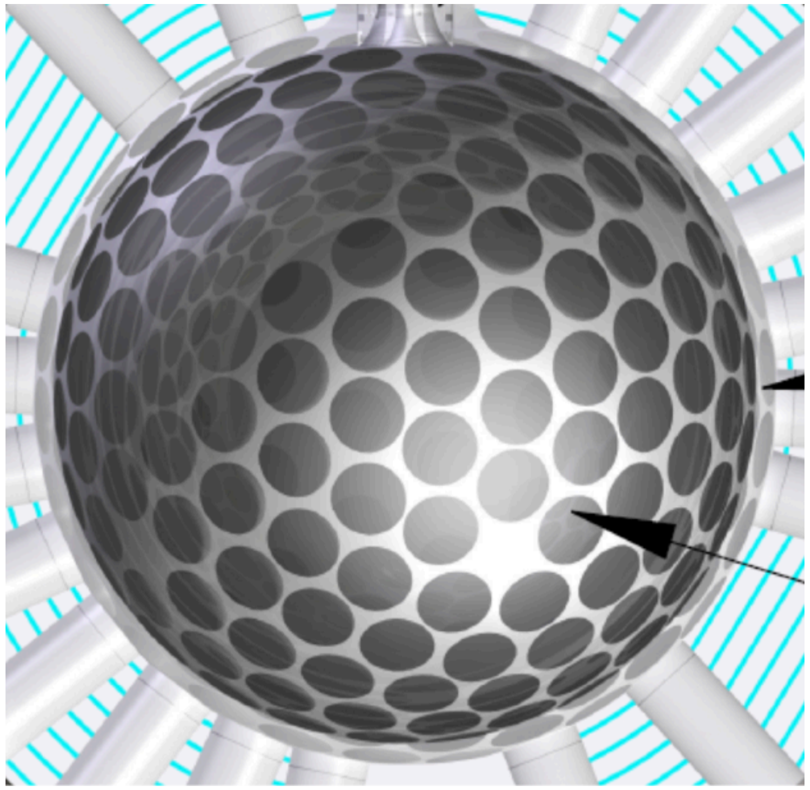
~~**mysterious**~~

# THANK YOU!

# QUESTIONS?

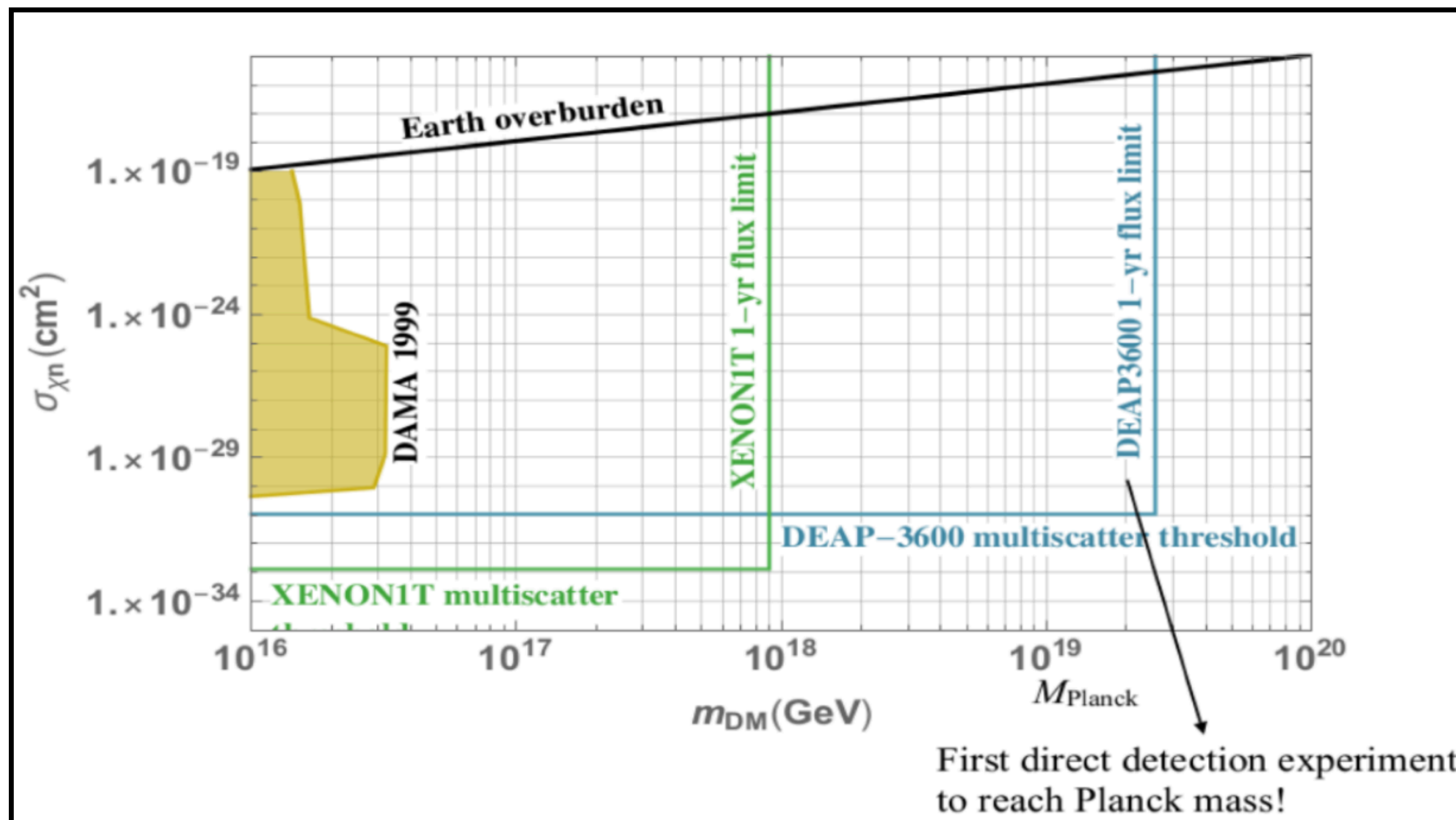
# Back-up slides

## 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

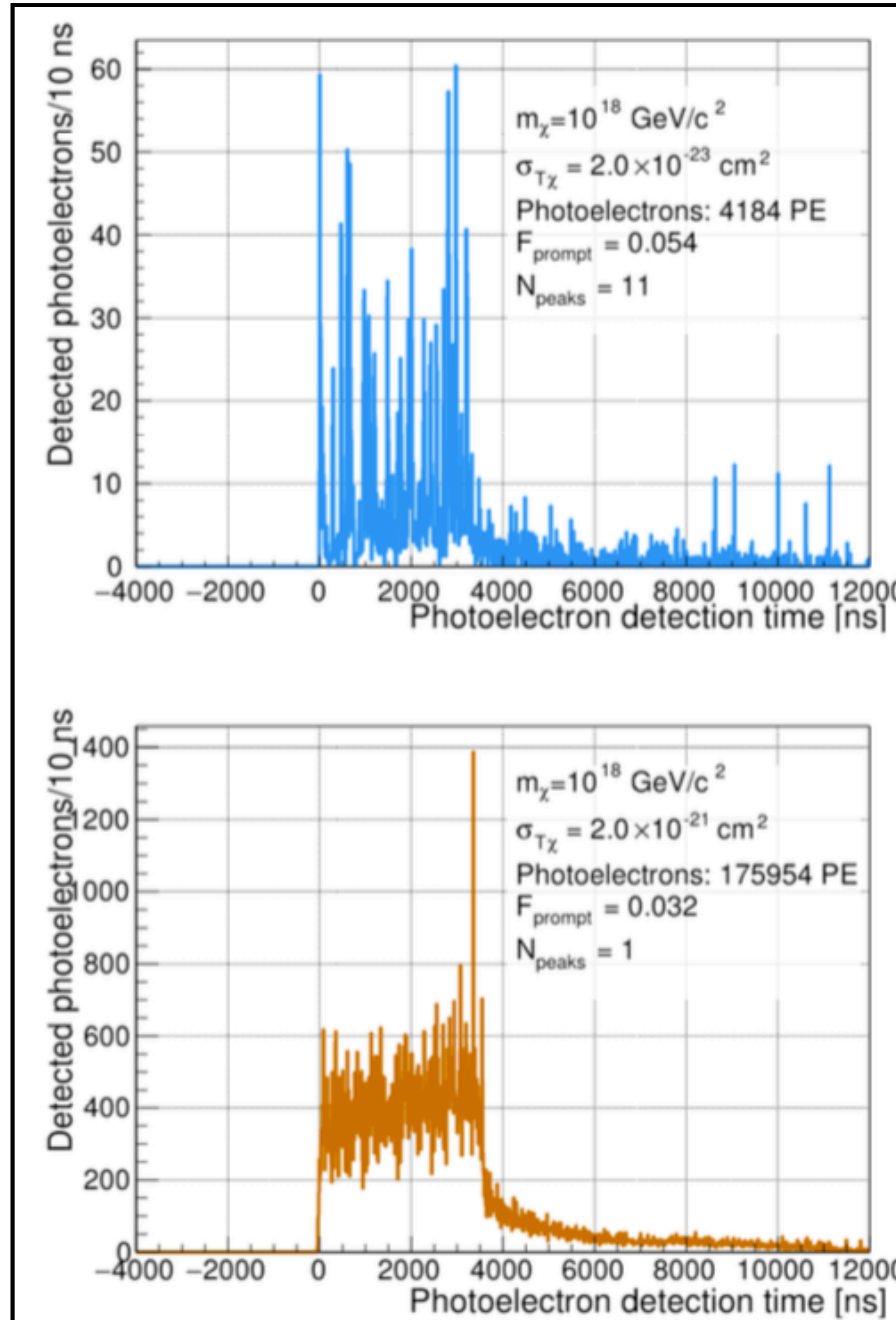
Highlights Recent Accepted Collections Authors Referees Staff

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

working group

*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

**DEAP-3600 @ SNOLAB**

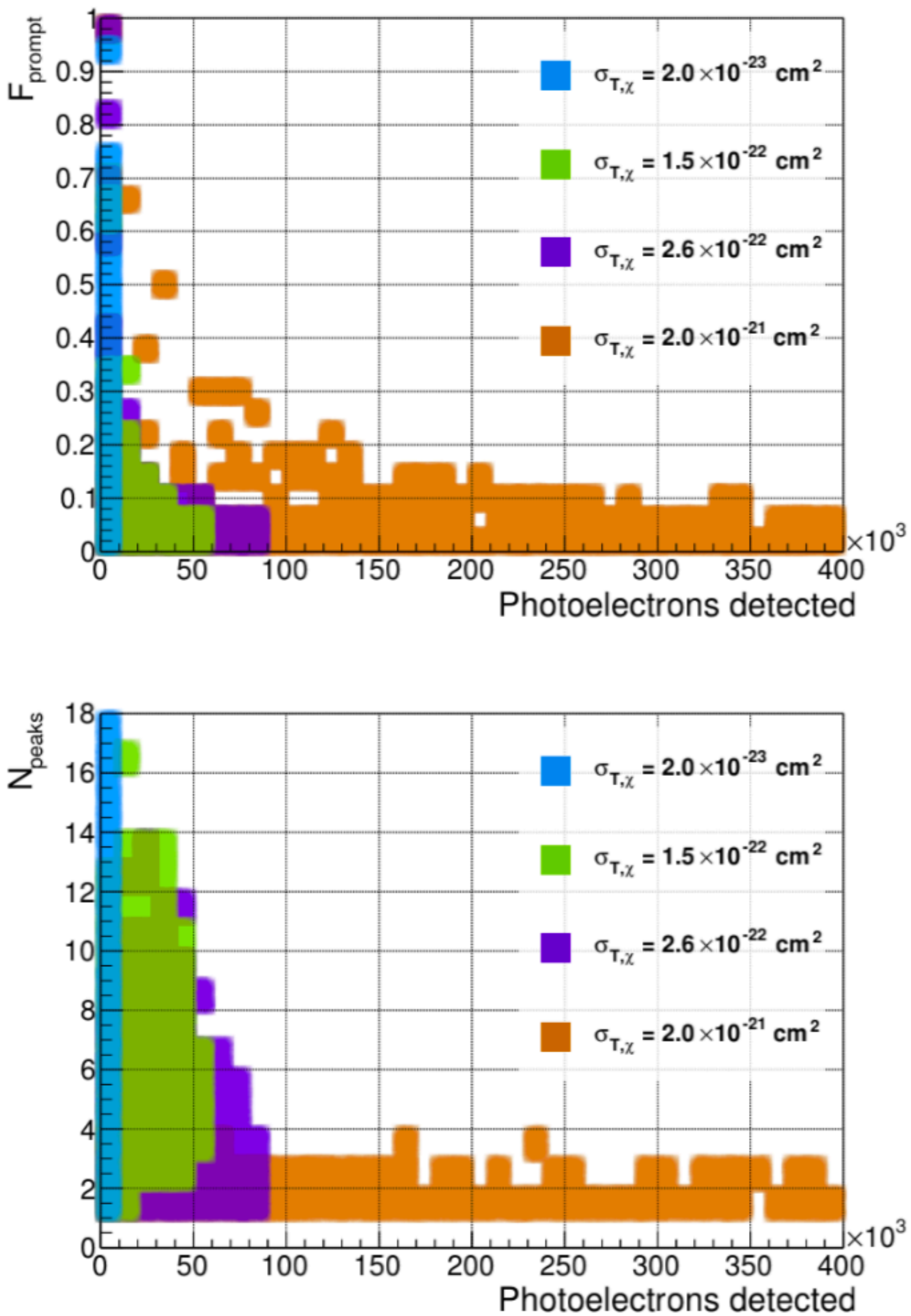



FIG. 2. Simulated $F_{prompt}$ and $N_{peaks}$ distributions for DM with $m_\chi$=$10^{18}$ GeV/$c^2$ for various $\sigma_{T\chi}$.

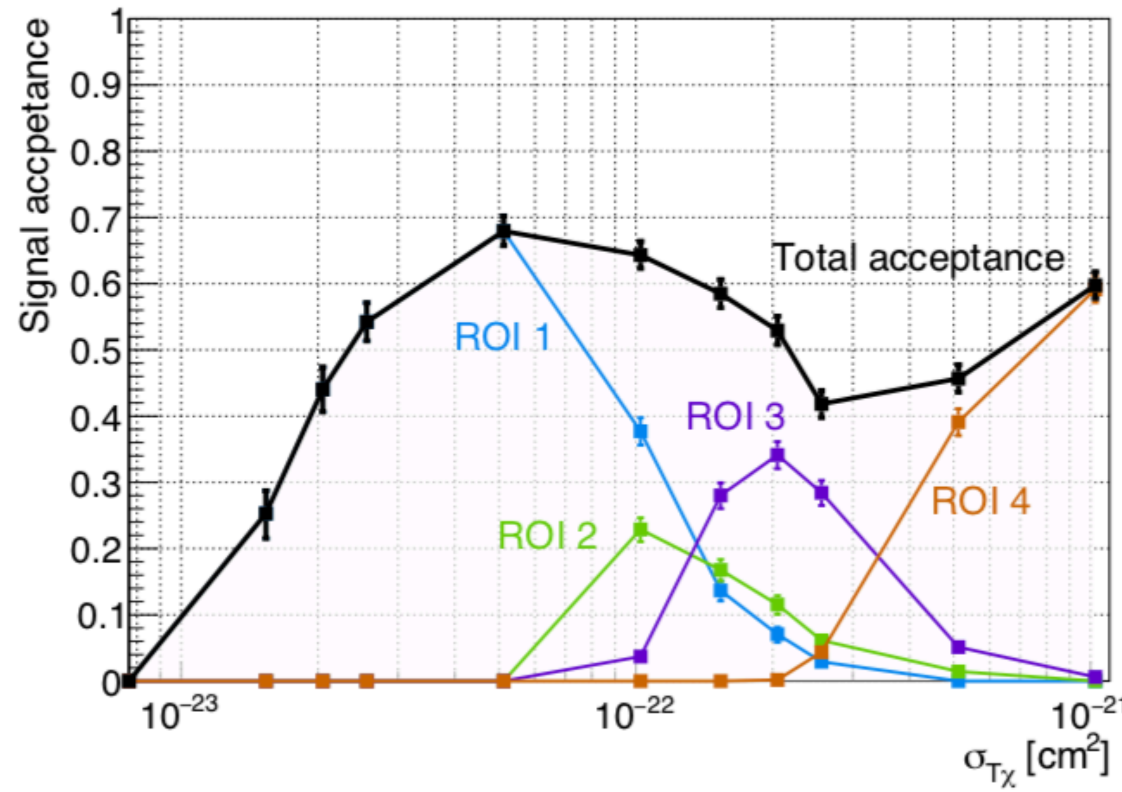
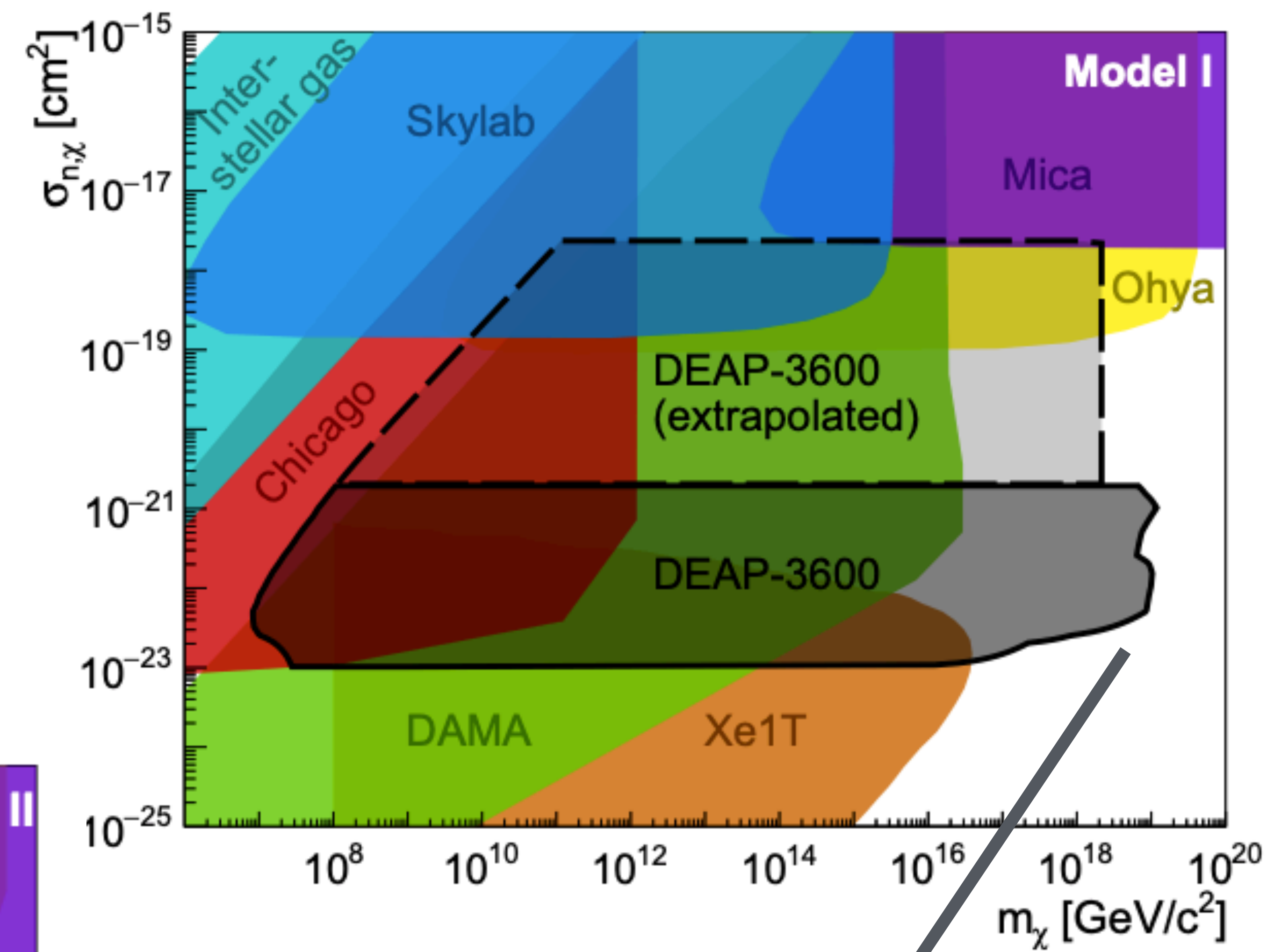


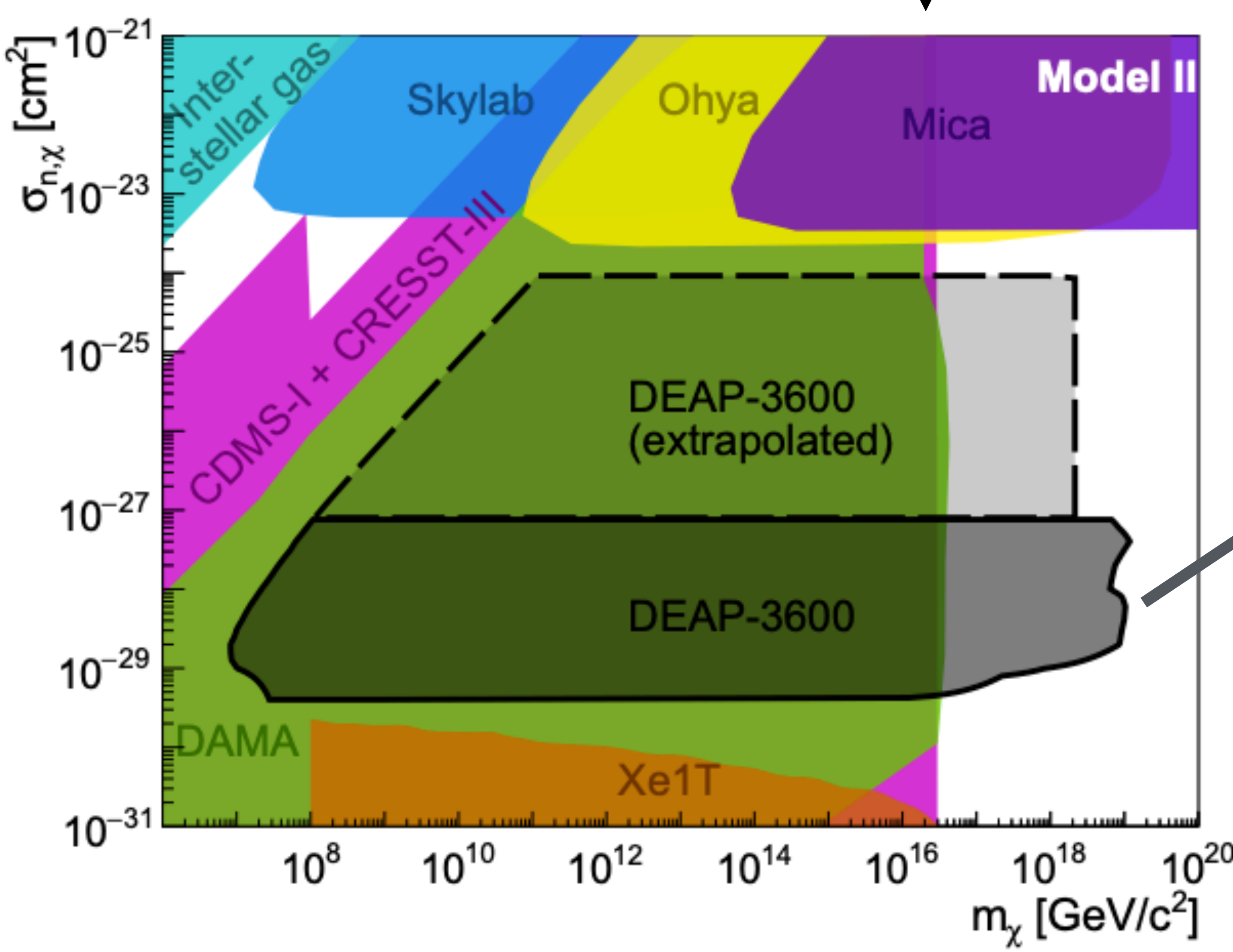

FIG. 3. Probability of DM with $m_\chi$=$10^{18}$ GeV/$c^2$ populating each ROI and surviving all cuts at varying $\sigma_{T\chi}$.

| ROI | PE range | Energy [MeV] | $N_{peaks}^{min}$ | $F_{prompt}^{max}$ | $\mu_b$ | $N_{obs.}$ |
|---|---|---|---|---|---|---|
| 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–$4 \times 10^8$ | 10.4–60 000 | 0 | 0.05 | $(10 \pm 3) \times 10^{-3}$ | 0 |

# (Q1) Going to the Planck mass

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




limit:

$$m_\chi \geq 1.2 \times 10^{19}\ \text{GeV}$$

$$(M_{\text{Planck}})$$

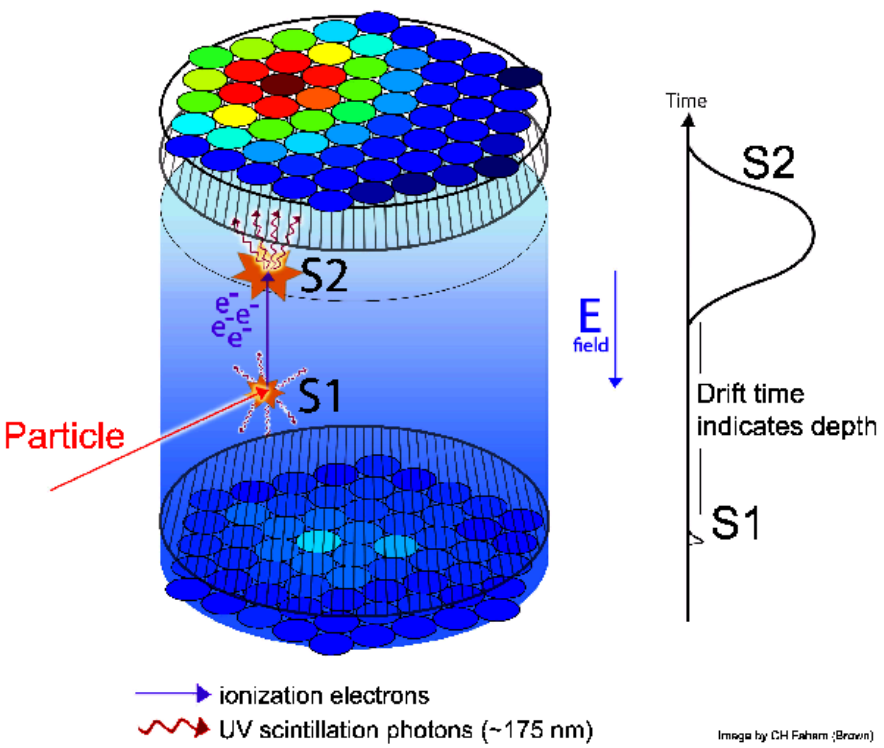
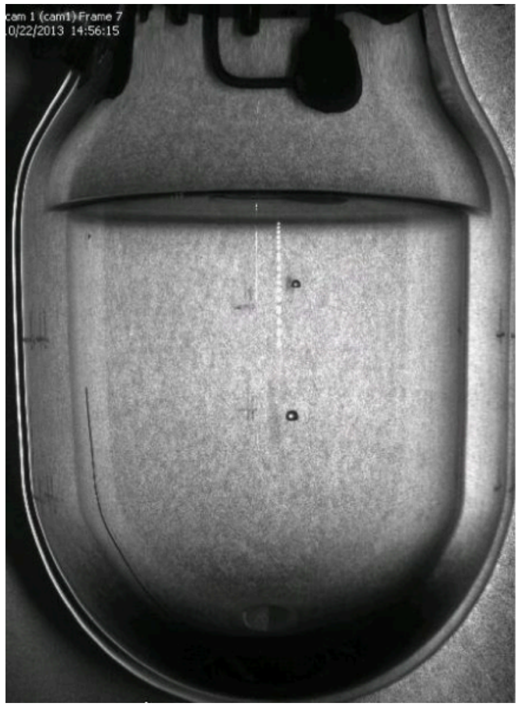
(like hitting the sound barrier)

**N. Raj** & *DEAP-3600*

***Phys.Rev.Lett.*** *(2022)*

# (Q1) Identifying multiscatterers

DM transit = 2.5 μs

| | LUX/PANDAX/XENON1T | PICO-60 |
|---|---|---|
| WIMP: |  |  |
| MIMP: | Train of scintillation pulses + electroluminescence pulses<br><br>For multiplicity > 5 (>500), S2 (S1) pulses merge into elongated pulses | Track of bubbles<br><br>Stereo cameras can image up to 100 bubbles (mm resolution) |

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

# 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 $N_{\rm c}$)

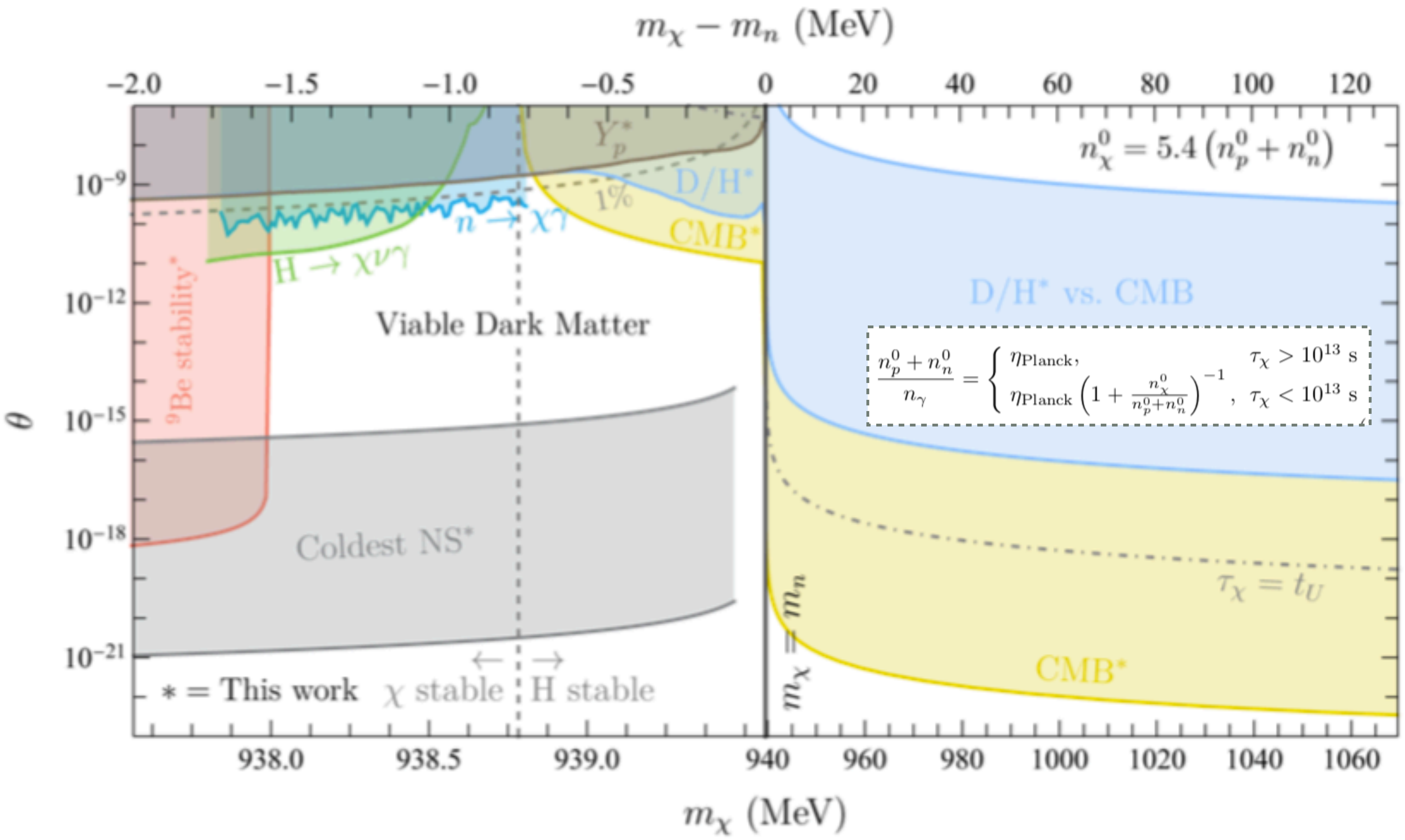
$$\sum_{N_{\rm c}}^{\infty} \frac{(N_{\rm bg})^{N_{\rm c}}}{N_{\rm c}!} e^{-N_{\rm bg}} = \frac{10\ \mu\text{s}}{t_{\rm life}}$$

(10 yr)

— Enhance cross section sensitivity by ~100.

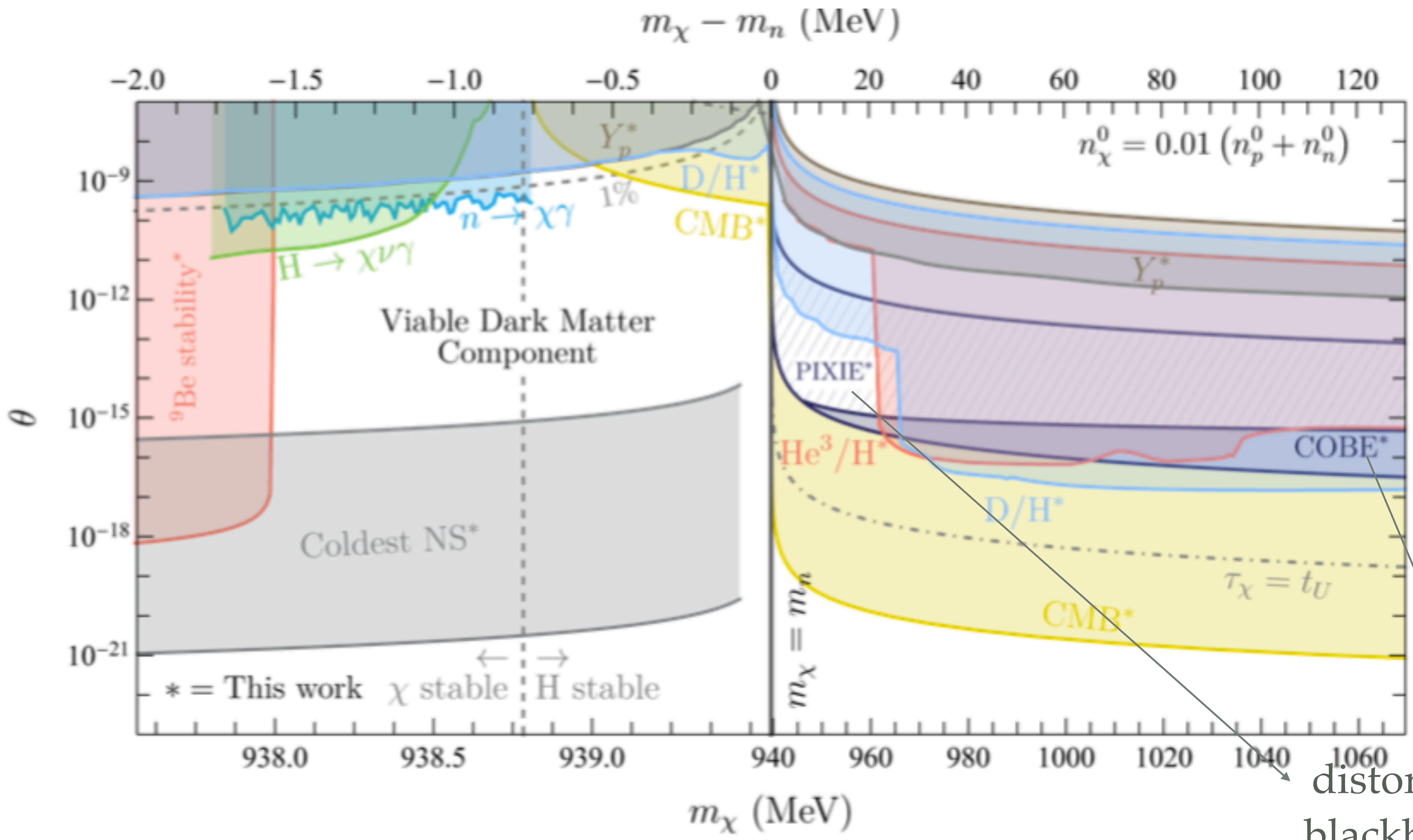
2012.09865 *McKeen, Pospelov, Raj*

# Constraints: $\chi$ all the dark matter



# Constraints: $\chi$ percent-level dark matter

2012.09865 *McKeen, Pospelov,* Raj




distortions of CMB blackbody spectrum