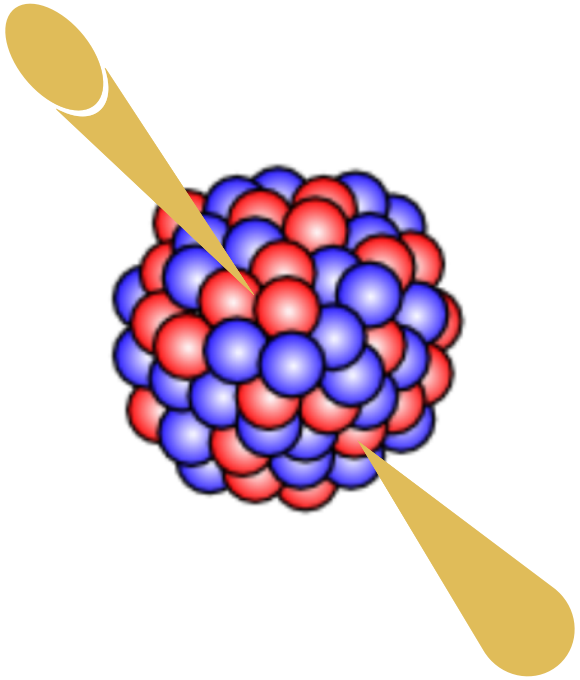
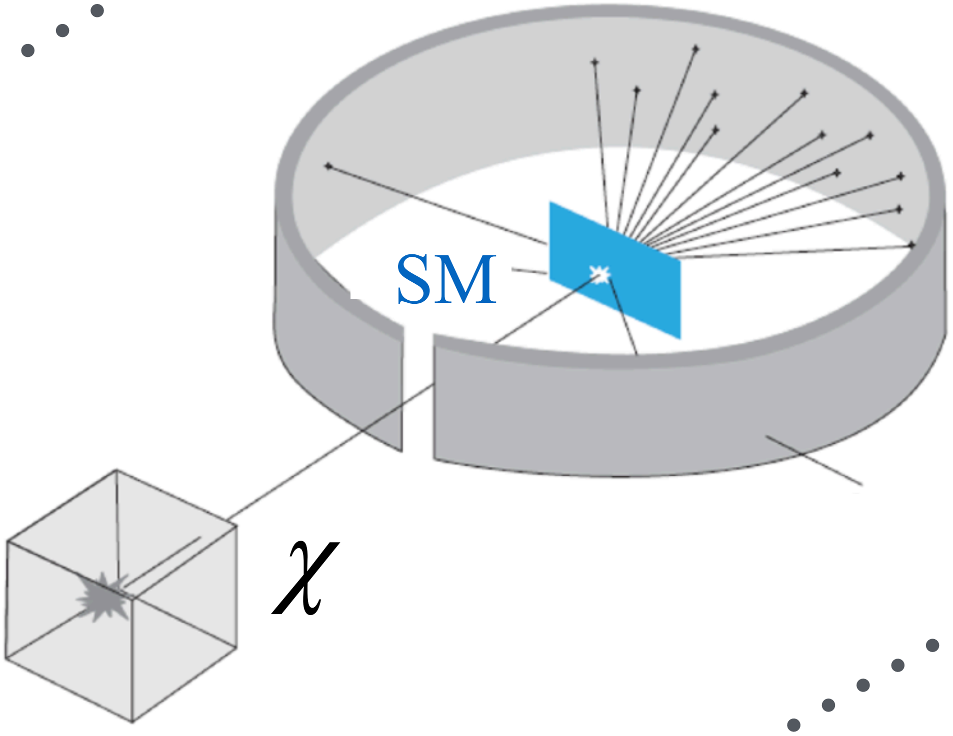
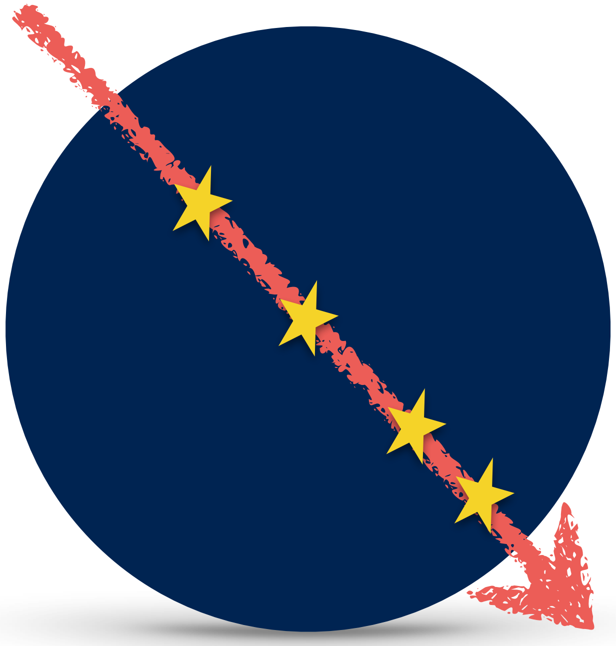
The Reverse Rutherford Era of Dark Matter

NIRMAL RAJ

TRIUMF





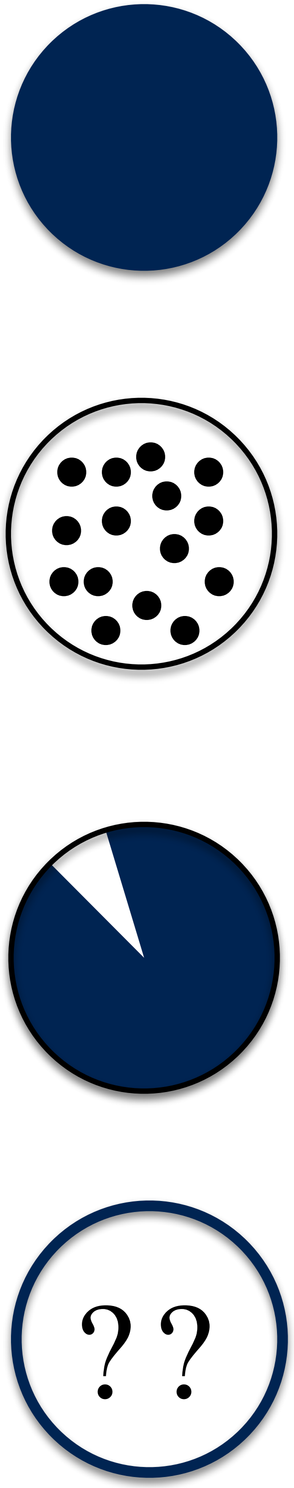


HEP Colloquium

INFN Cagliari

02/10/2021

Dark matter



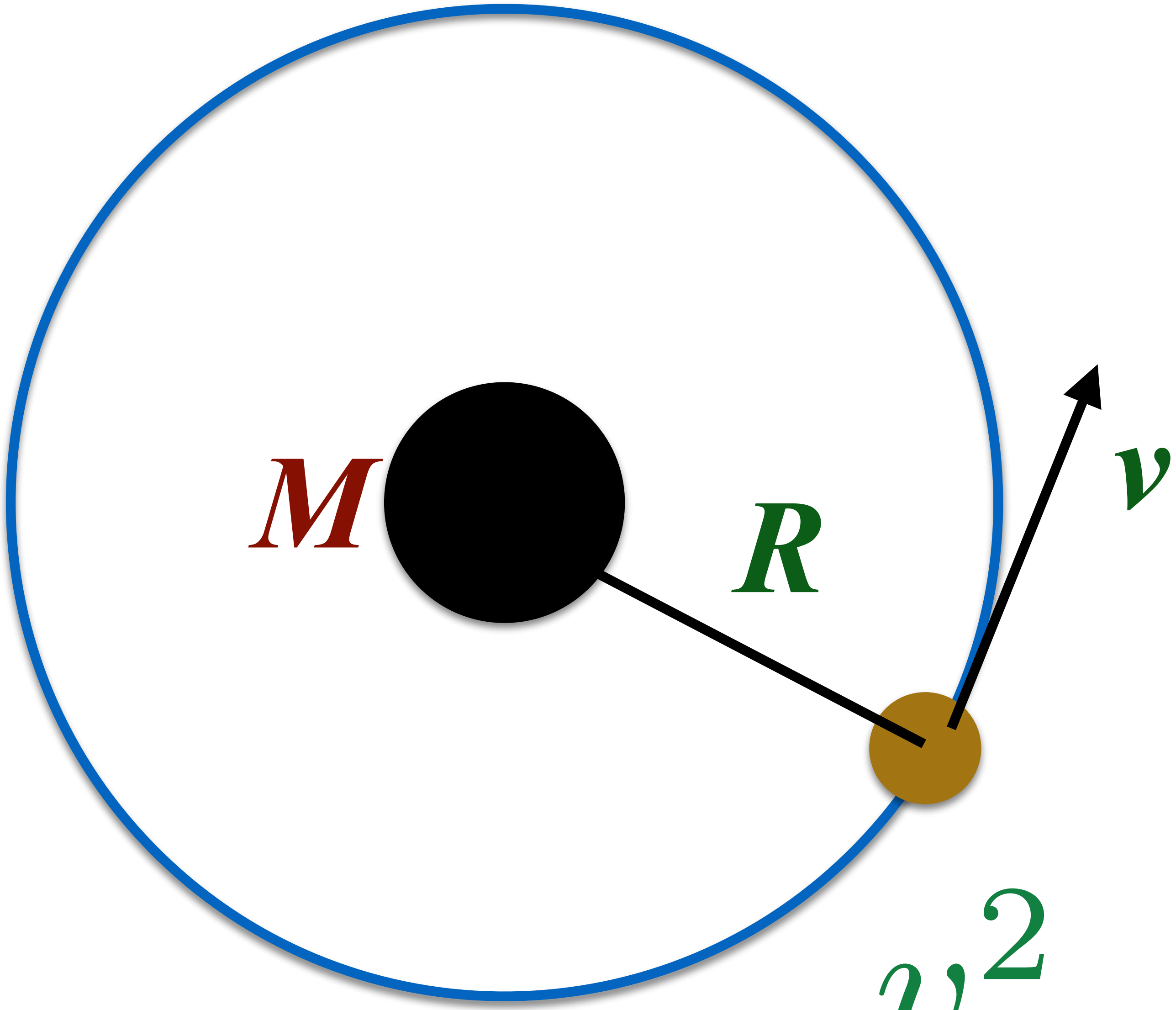
non-luminous

ubiquitous

plentiful

mysterious

How we know it's there: effects of gravity



$$\frac{v^2}{R} = G\,\frac{M}{R^2}$$

This is how we weighed the Sun!

Dark matter: 1930s

Fritz Zwicky

+

Coma Cluster

+

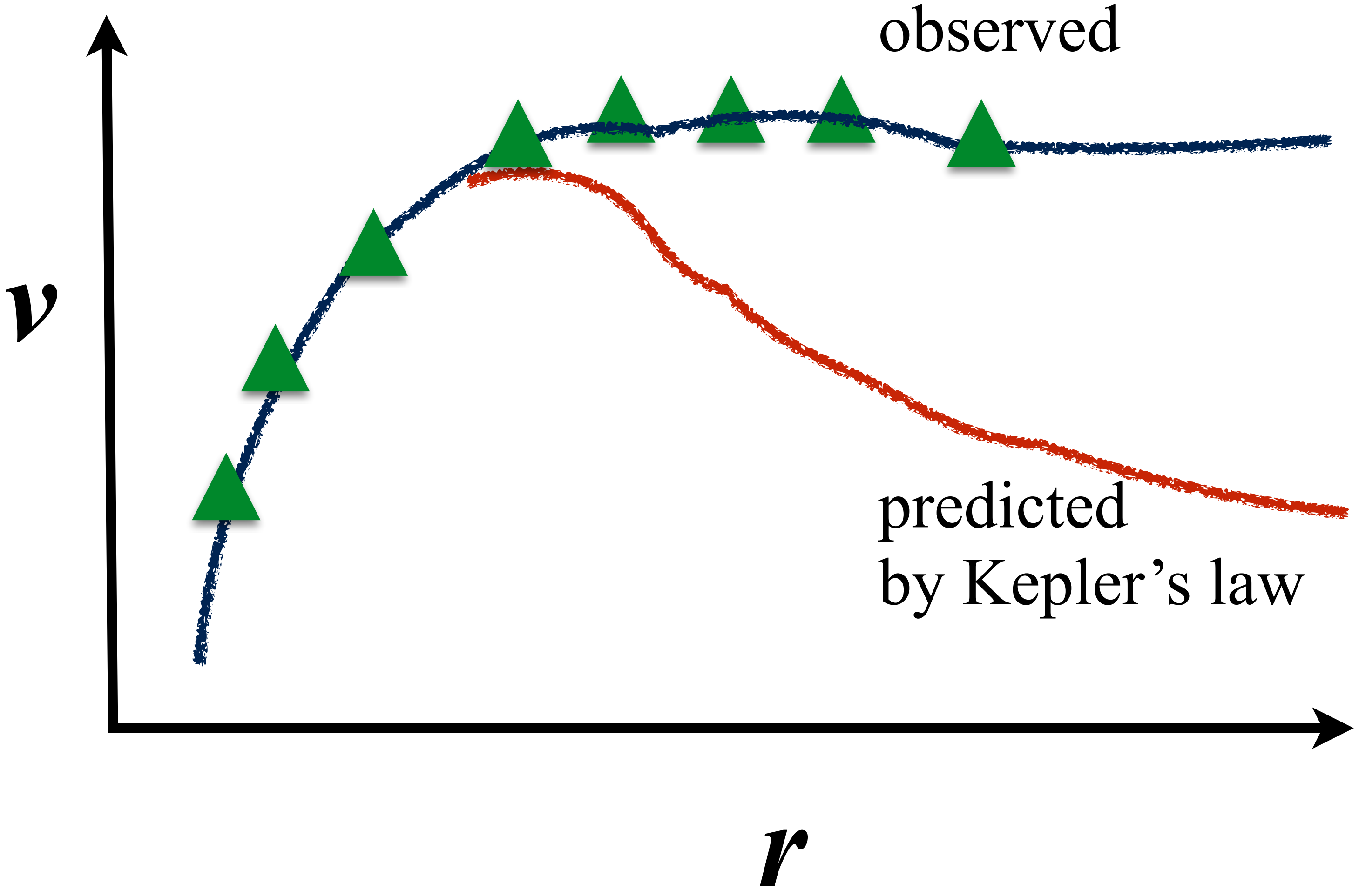
$$\boxed{\frac{3}{5}\frac{GM}{R} = \frac{3}{2}\frac{k_{\mathrm{B}}T}{m_{\mathrm{p}}} = \frac{1}{2}v^2}$$

virial theorem

"If this would be confirmed, we would get the surprising result that ***dark matter*** *is present*
in much greater amount than luminous matter."

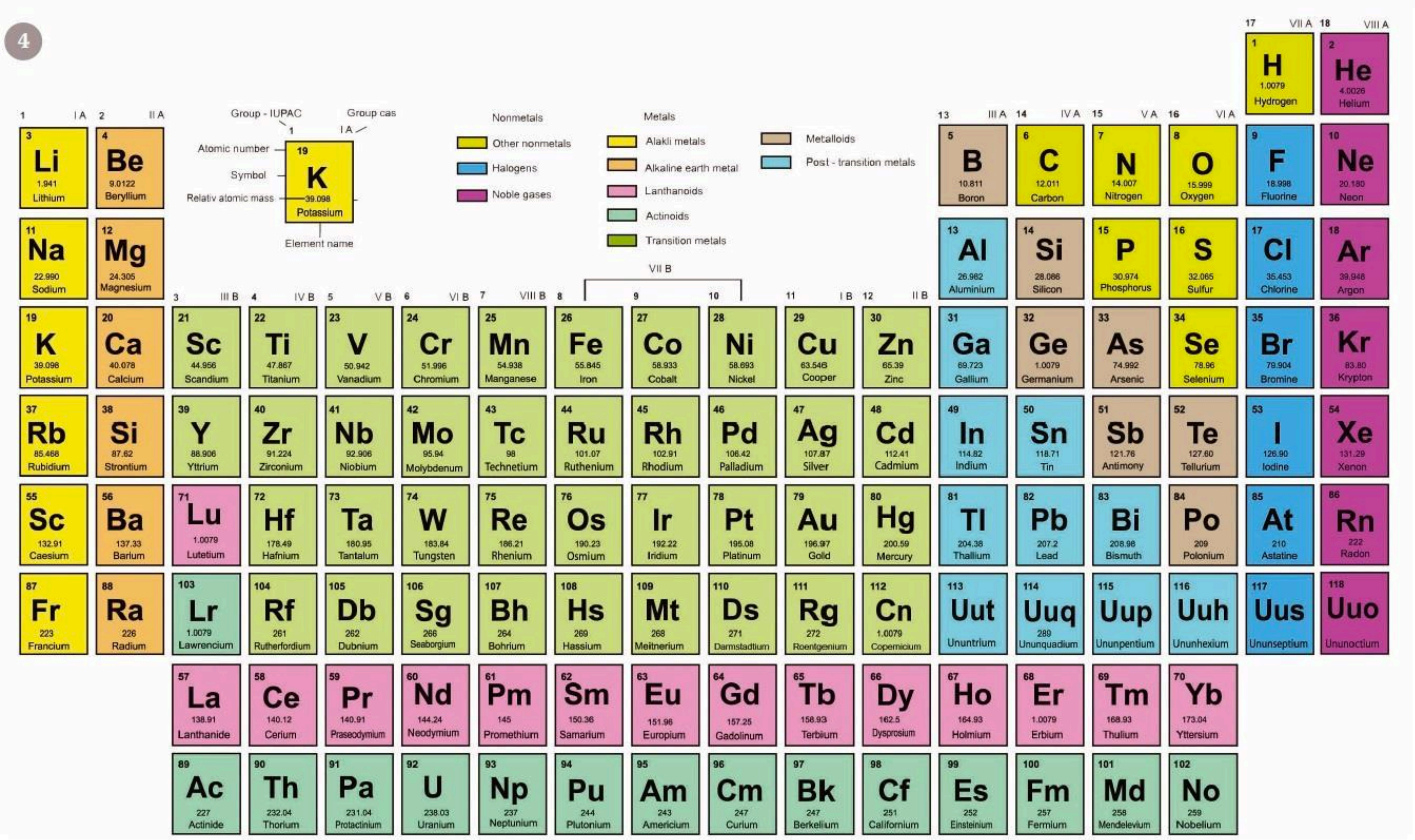
Dark matter: 1970s

Vera Rubin
(+Kent Ford)



What is dark matter made of?

Until 1980s:



4

Group - IUPAC
Group cas
Atomic number
Symbol
Relativ atomic mass
Element name

19 K 39.098 Potassium

Nonmetals
- Other nonmetals
- Halogens
- Noble gases

Metals
- Alakli metals
- Alkaline earth metal
- Lanthanoids
- Actinoids
- Transition metals

- Metalloids
- Post - transition metals

1 I A	2 II A	3 III B	4 IV B	5 V B	6 VI B	7 VIII B	8	9	10	11 I B	12 II B	13 III A	14 IV A	15 V A	16 VI A	17 VII A	18 VIII A
							VII B									1 H 1.0079 Hydrogen	2 He 4.0026 Helium
3 Li 1.941 Lithium	4 Be 9.0122 Beryllium											5 B 10.811 Boron	6 C 12.011 Carbon	7 N 14.007 Nitrogen	8 O 15.999 Oxygen	9 F 18.998 Fluorine	10 Ne 20.180 Neon
11 Na 22.990 Sodium	12 Mg 24.305 Magnesium											13 Al 26.982 Aluminium	14 Si 28.086 Silicon	15 P 30.974 Phosphorus	16 S 32.065 Sulfur	17 Cl 35.453 Chlorine	18 Ar 39.948 Argon
19 K 39.098 Potassium	20 Ca 40.078 Calcium	21 Sc 44.956 Scandium	22 Ti 47.867 Titanium	23 V 50.942 Vanadium	24 Cr 51.996 Chromium	25 Mn 54.938 Manganese	26 Fe 55.845 Iron	27 Co 58.933 Cobalt	28 Ni 58.693 Nickel	29 Cu 63.546 Cooper	30 Zn 65.39 Zinc	31 Ga 69.723 Gallium	32 Ge 1.0079 Germanium	33 As 74.992 Arsenic	34 Se 78.96 Selenium	35 Br 79.904 Bromine	36 Kr 83.80 Krypton
37 Rb 85.468 Rubidium	38 Si 87.62 Strontium	39 Y 88.906 Yttrium	40 Zr 91.224 Zirconium	41 Nb 92.906 Niobium	42 Mo 95.94 Molybdenum	43 Tc 98 Technetium	44 Ru 101.07 Ruthenium	45 Rh 102.91 Rhodium	46 Pd 106.42 Palladium	47 Ag 107.87 Silver	48 Cd 112.41 Cadmium	49 In 114.82 Indium	50 Sn 118.71 Tin	51 Sb 121.76 Antimony	52 Te 127.60 Tellurium	53 I 126.90 Iodine	54 Xe 131.29 Xenon
55 Sc 132.91 Caesium	56 Ba 137.33 Barium	71 Lu 1.0079 Lutetium	72 Hf 178.49 Hafnium	73 Ta 180.95 Tantalum	74 W 183.84 Tungsten	75 Re 186.21 Rhenium	76 Os 190.23 Osmium	77 Ir 192.22 Iridium	78 Pt 195.08 Platinum	79 Au 196.97 Gold	80 Hg 200.59 Mercury	81 Tl 204.38 Thallium	82 Pb 207.2 Lead	83 Bi 208.98 Bismuth	84 Po 209 Polonium	85 At 210 Astatine	86 Rn 222 Radon
87 Fr 223 Francium	88 Ra 226 Radium	103 Lr 1.0079 Lawrencium	104 Rf 261 Rutherfordium	105 Db 262 Dubnium	106 Sg 266 Seaborgium	107 Bh 264 Bohrium	108 Hs 269 Hassium	109 Mt 268 Meitnerium	110 Ds 271 Darmstadtium	111 Rg 272 Roentgenium	112 Cn 1.0079 Copernicium	113 Uut Ununtrium	114 Uuq 289 Ununquadium	115 Uup Ununpentium	116 Uuh Ununhexium	117 Uus Ununseptium	118 Uuo Ununoctium
		57 La 138.91 Lanthanide	58 Ce 140.12 Cerium	59 Pr 140.91 Praseodymium	60 Nd 144.24 Neodymium	61 Pm 145 Promethium	62 Sm 150.36 Samarium	63 Eu 151.96 Europium	64 Gd 157.25 Gadolinum	65 Tb 158.93 Terbium	66 Dy 162.5 Dysprosium	67 Ho 164.93 Holmium	68 Er 1.0079 Erbium	69 Tm 168.93 Thulium	70 Yb 173.04 Yttersium		
		89 Ac 227 Actinide	90 Th 232.04 Thorium	91 Pa 231.04 Protactinium	92 U 238.03 Uranium	93 Np 237 Neptunium	94 Pu 244 Plutonium	95 Am 243 Americium	96 Cm 247 Curium	97 Bk 247 Berkelium	98 Cf 251 Californium	99 Es 252 Einsteinium	100 Fm 257 Fermium	101 Md 258 Mendelevium	102 No 259 Nobelium		

Stuff too faint to see:
planets, white/brown/red dwarfs, neutron stars, black holes

What is dark matter made of?

1990s — present

planets, white/brown/red dwarfs, neutron stars, black holes

missing in gravitational (micro)lensing surveys

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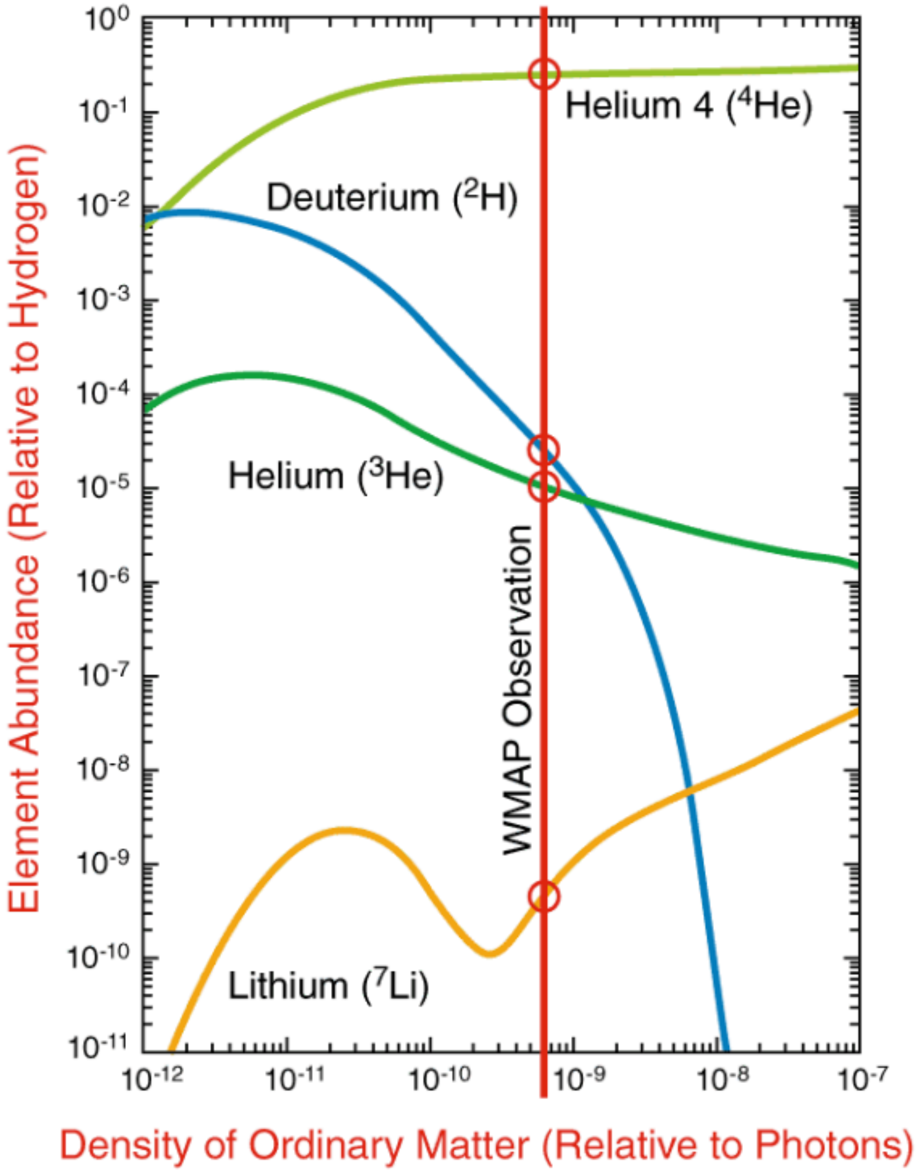
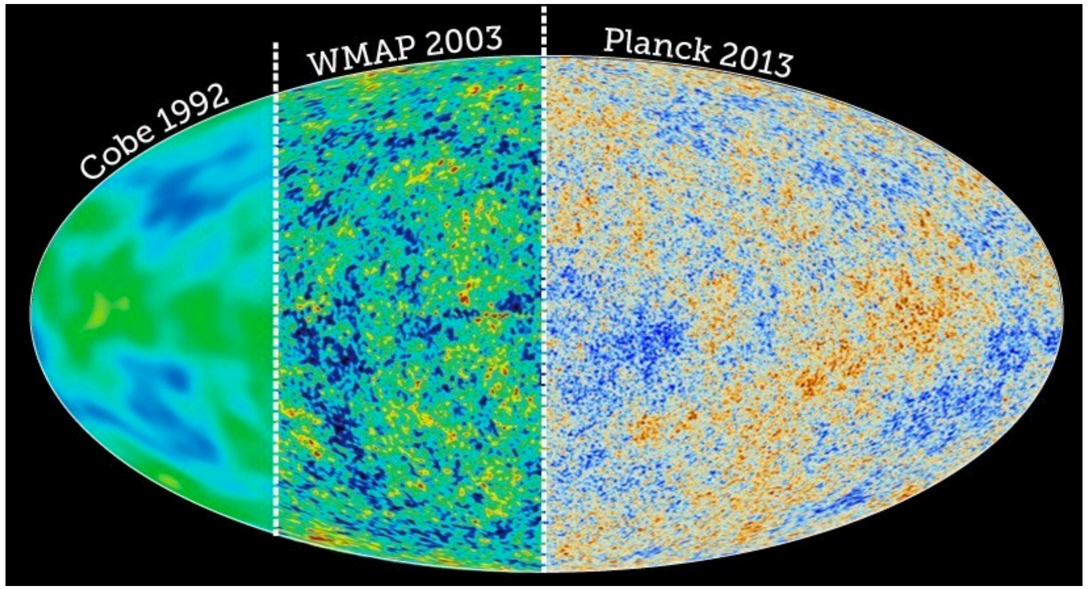




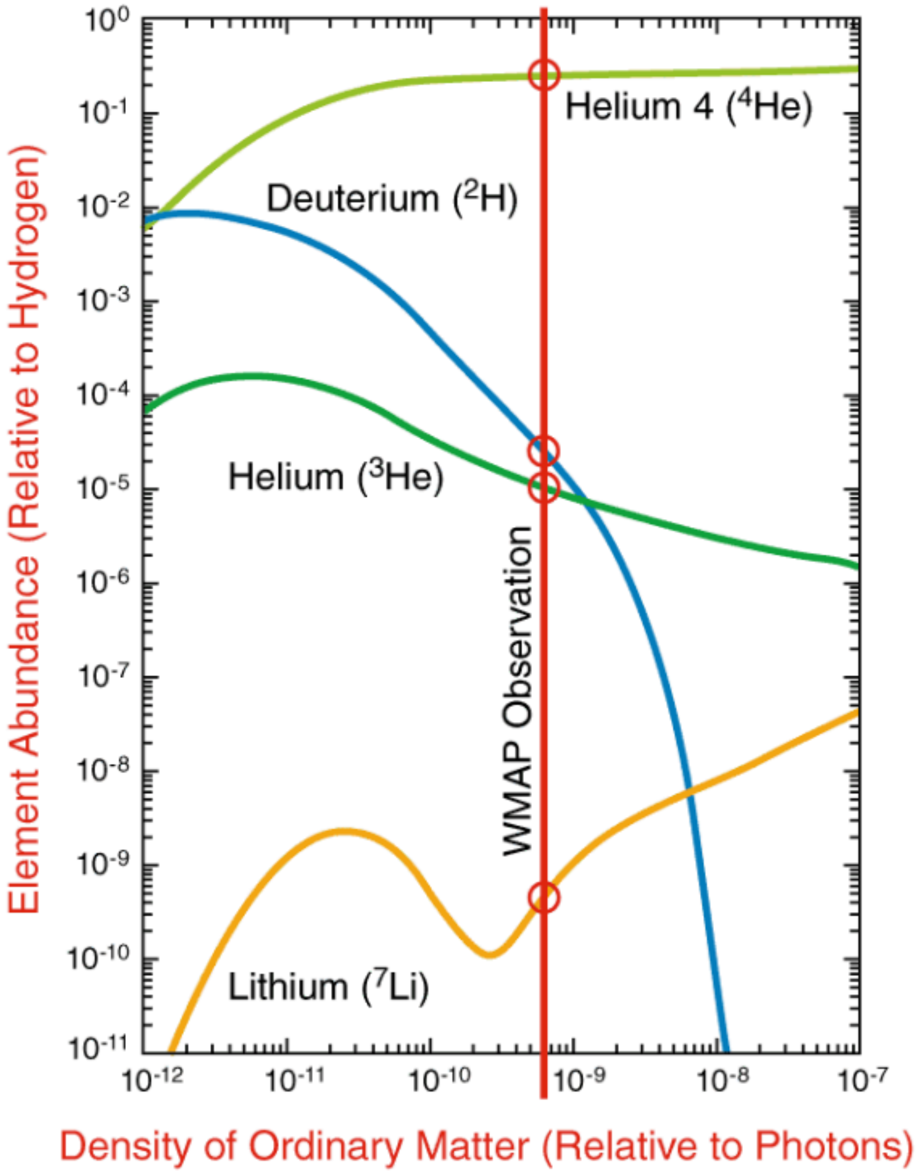
cosmic microwaves

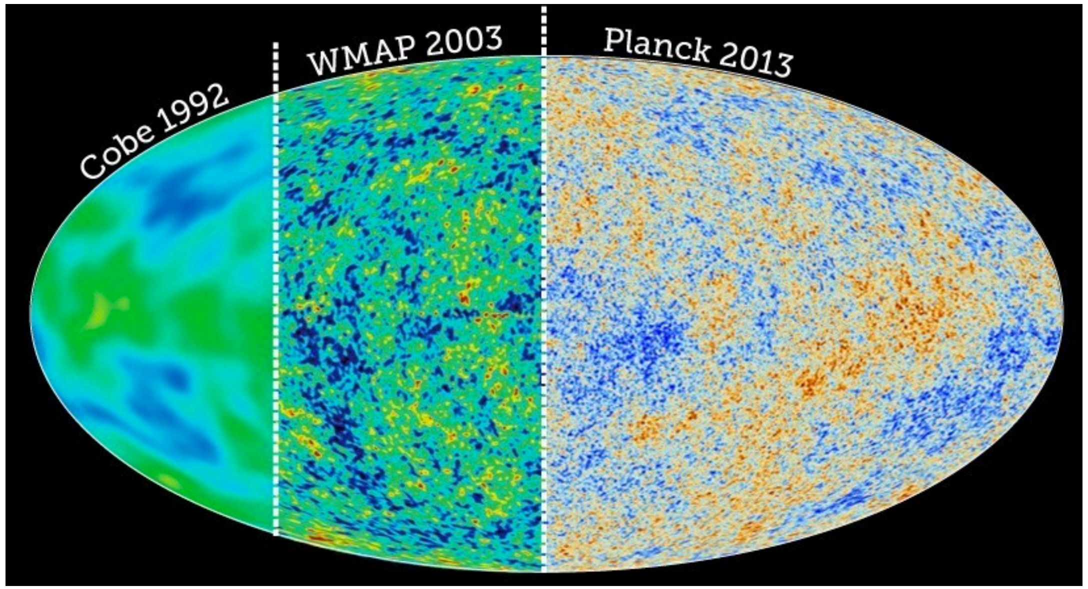
What is dark matter made of?

1990s — present

planets, white/brown/red dwarfs, neutron stars, black holes

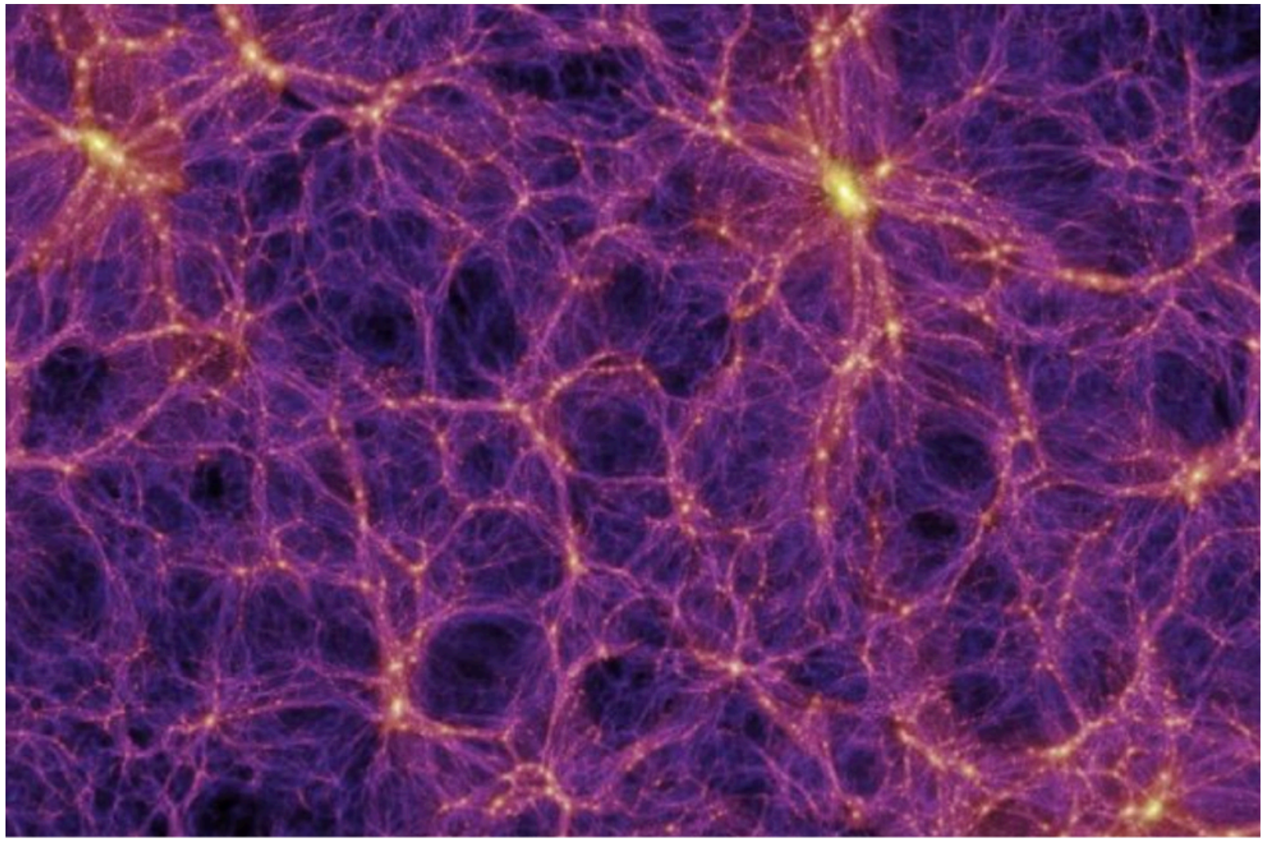
missing in gravitational (micro)lensing surveys



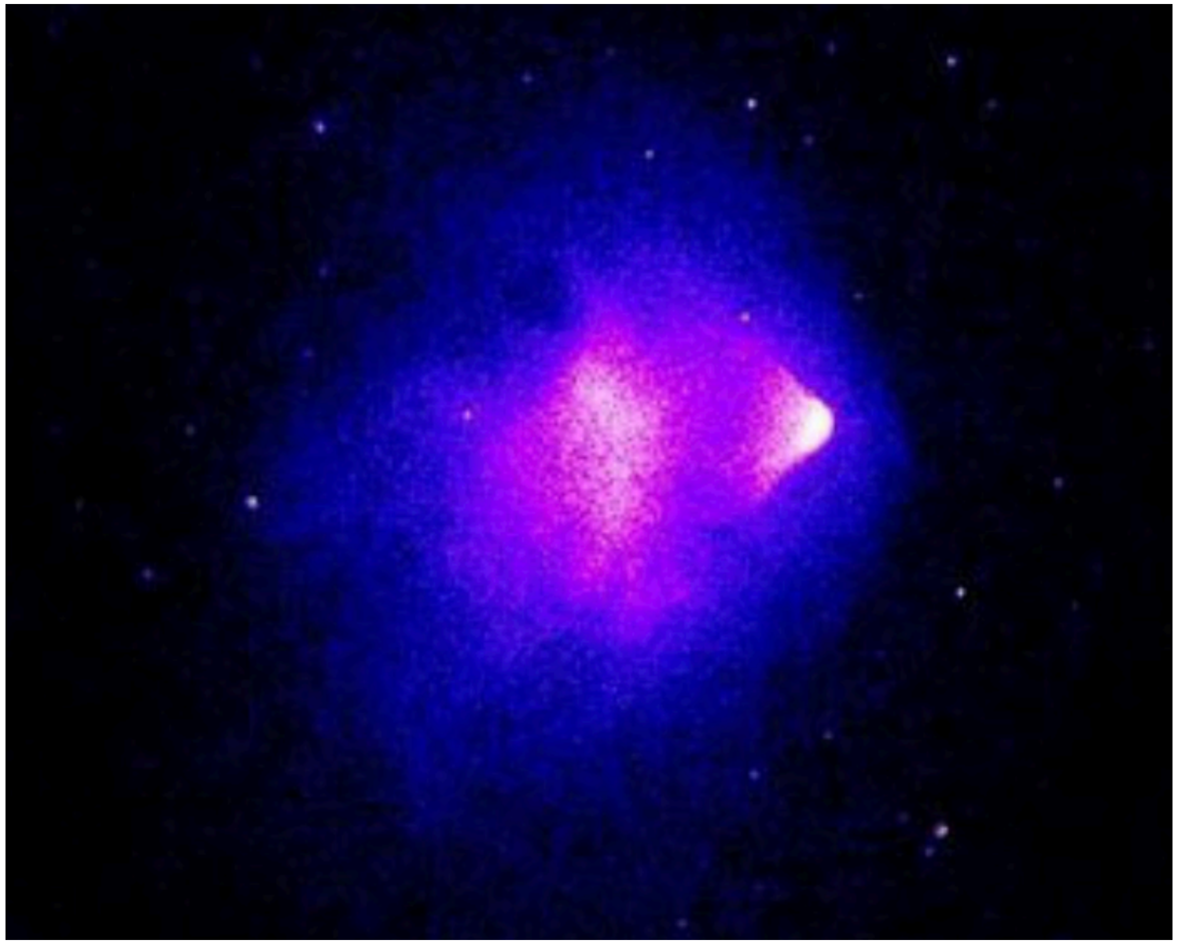


cosmic microwaves

More evidence



large scale structure

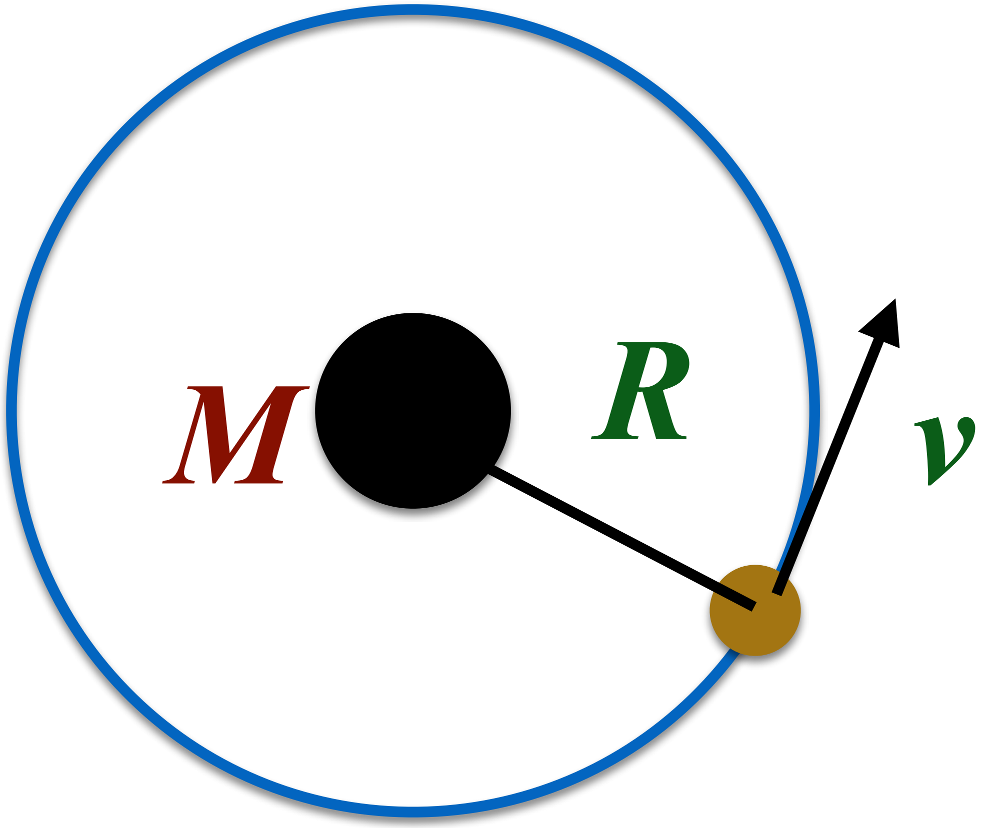


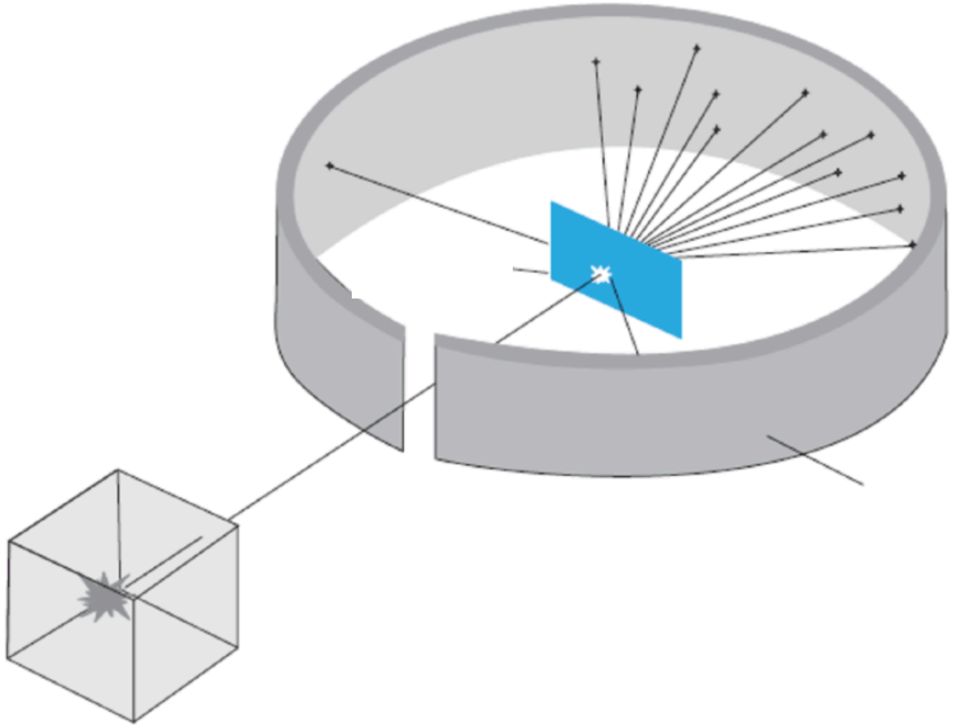
Bullet Cluster

✔ gravitational evidence

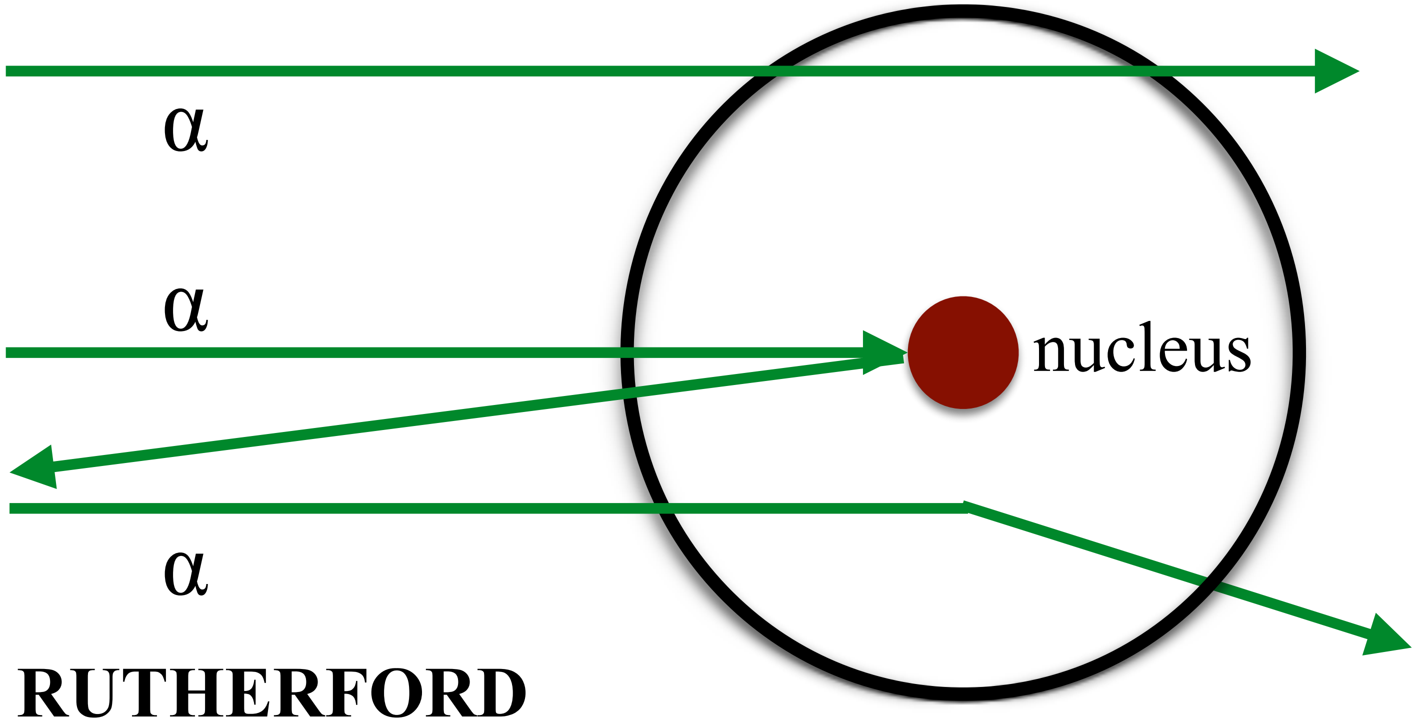
↓

? particle physics knowledge



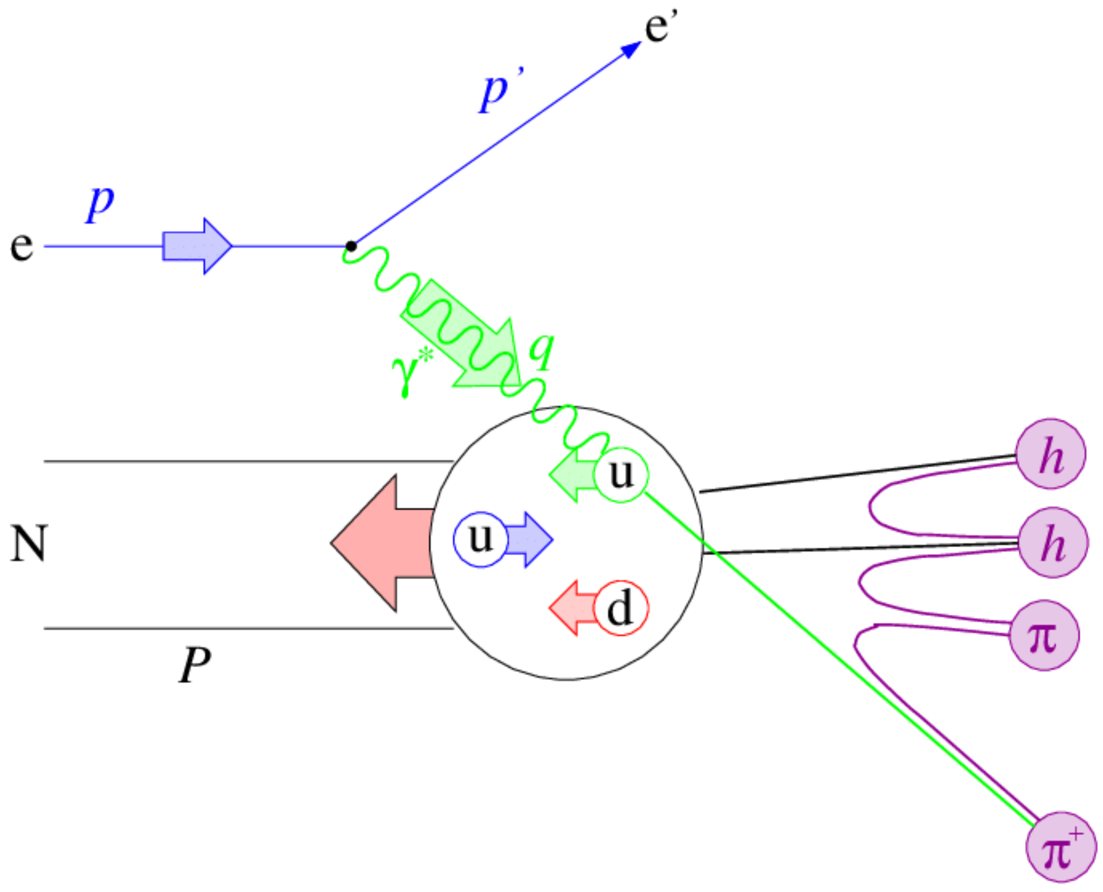


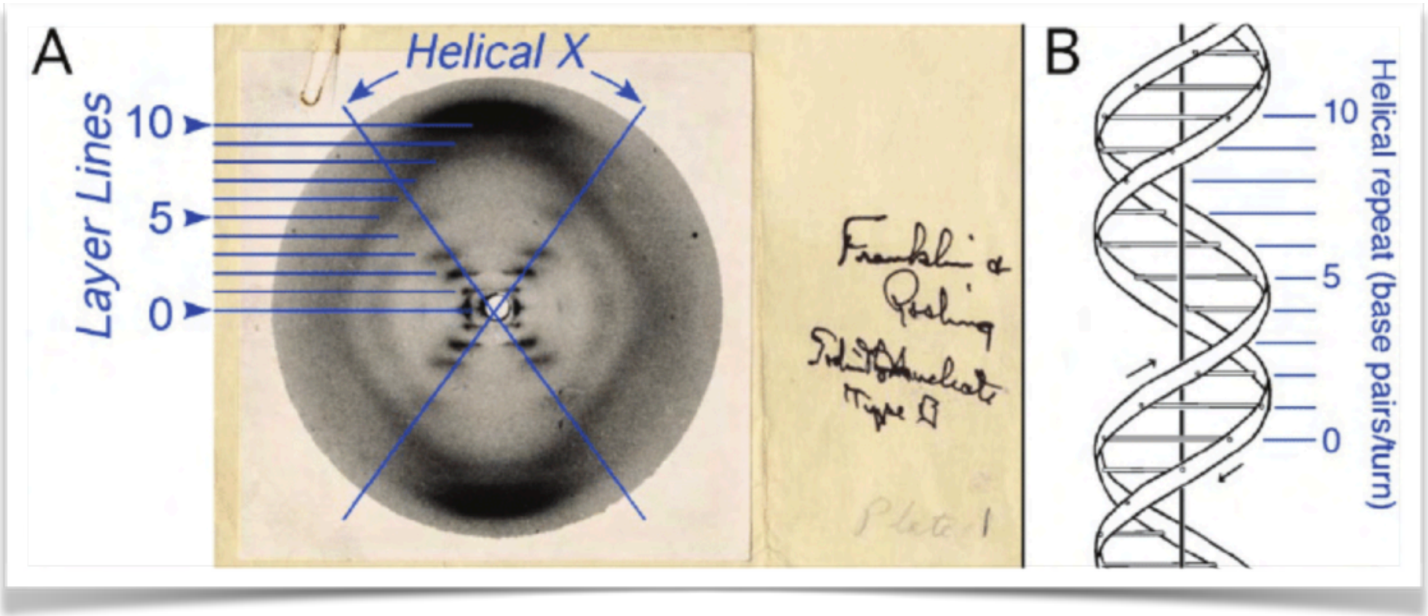
Scattering!



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

<u>Intrinsic quantity</u>: helps identify dark matter

strategy

Reverse Rutherford scattering

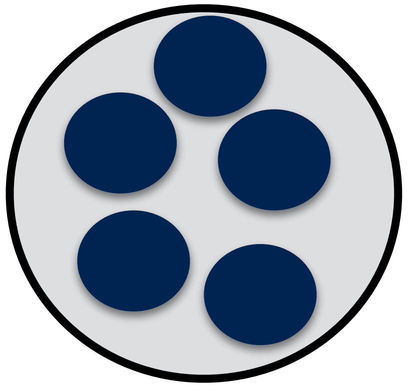
Beam of ambient dark matter (unknown species) hits target of nuclei (well-understood species).

Energy and momentum transferred => study changes in target.

inputs

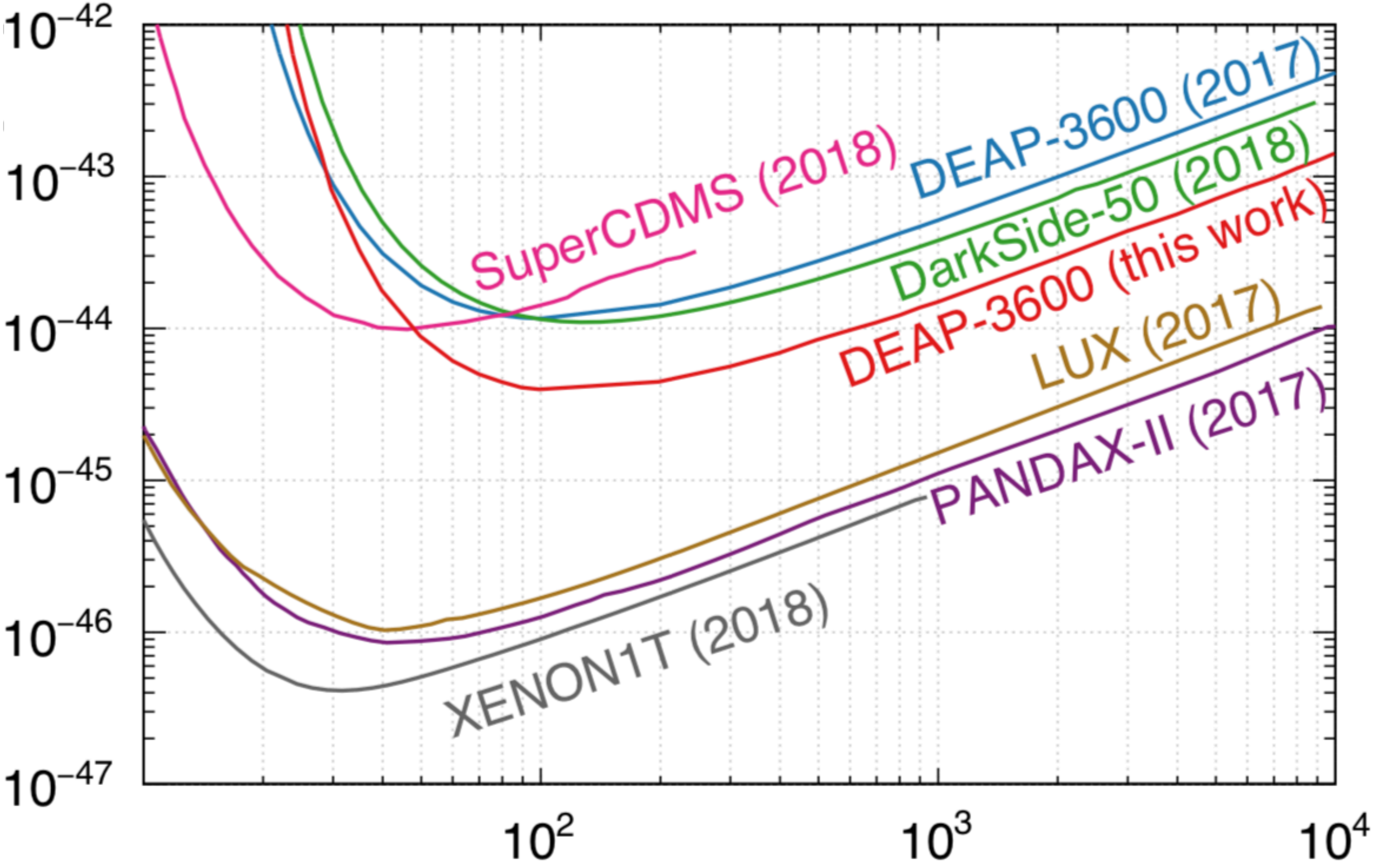
[inferred from star motion]

300 km/s



0.3 GeV/cm^3

Preview: modern searches



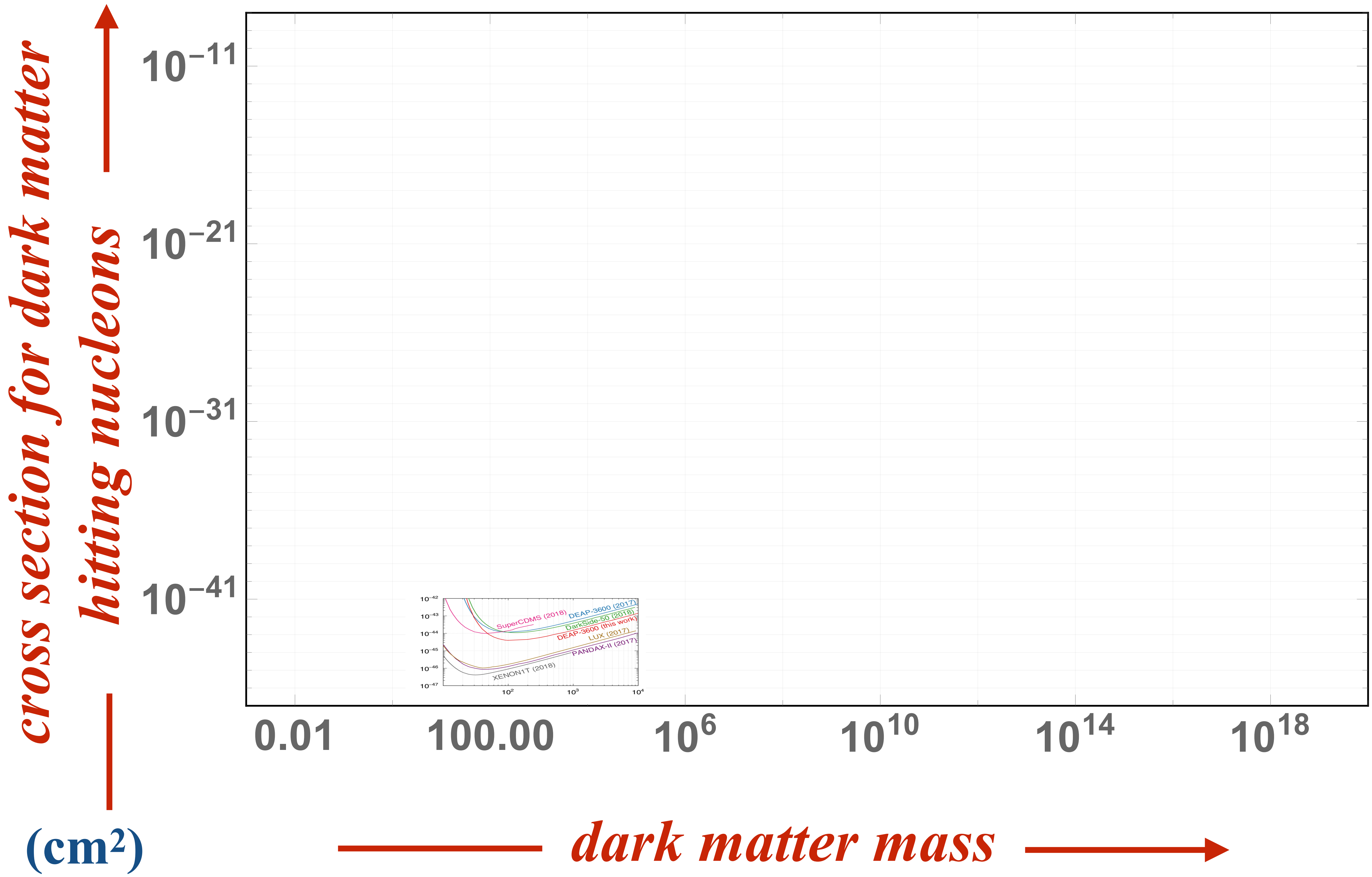
cross section for dark matter hitting nucleons

(cm²)

dark matter mass

(GeV)

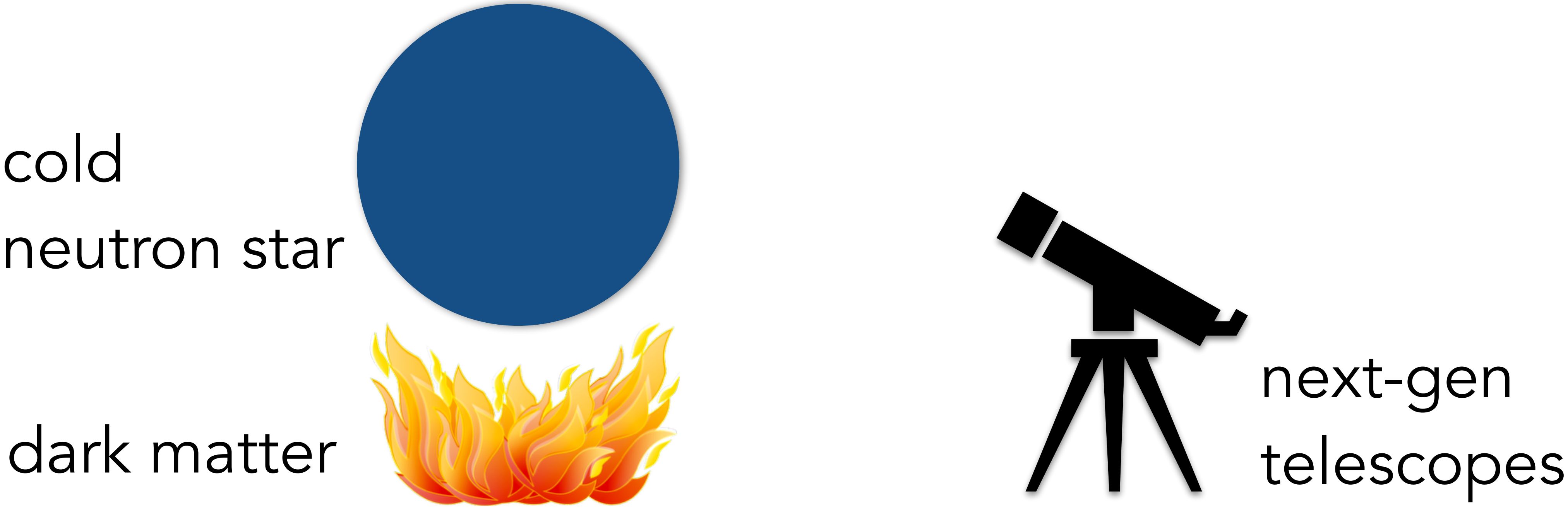
Bird's-eye view



(GeV)

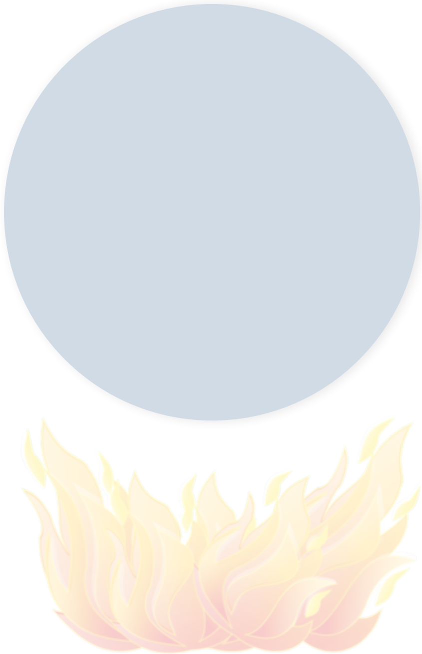
Reverse Rutherford experiments

Experiment 1: in space



Reverse Rutherford experiments

Experiment 1: in space



cold

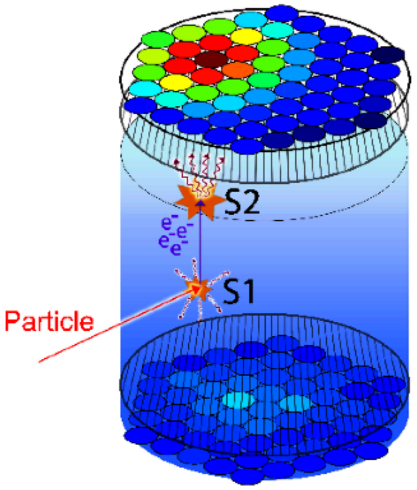
neutron star

dark matter

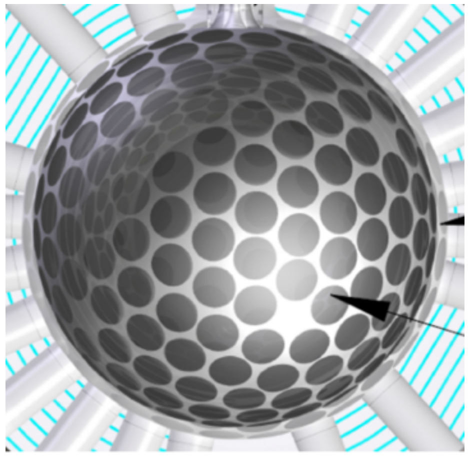
next-gen

telescopes

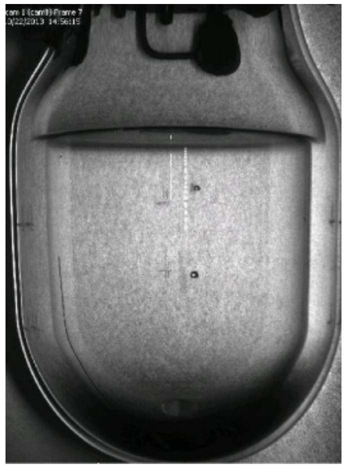
Experiment 2: Earth-based



XENON1T

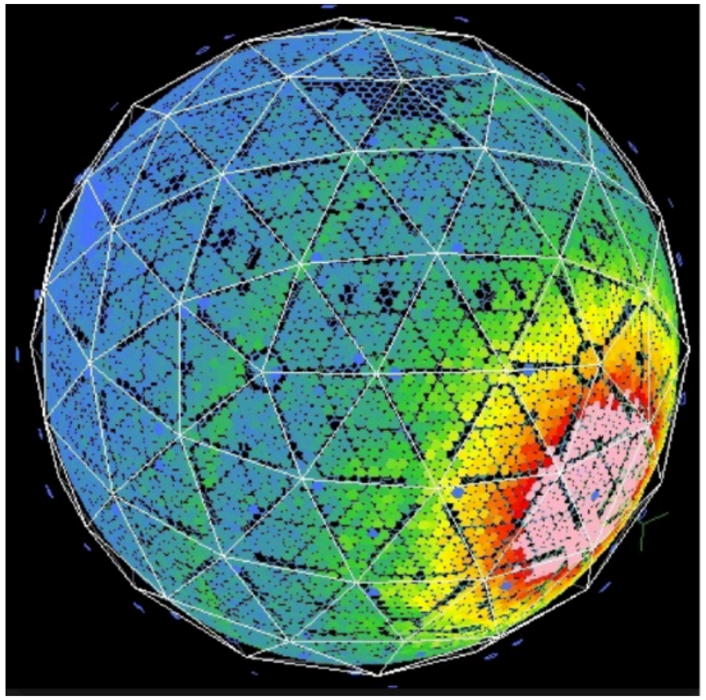


DEAP-3600



PICO-40L

+

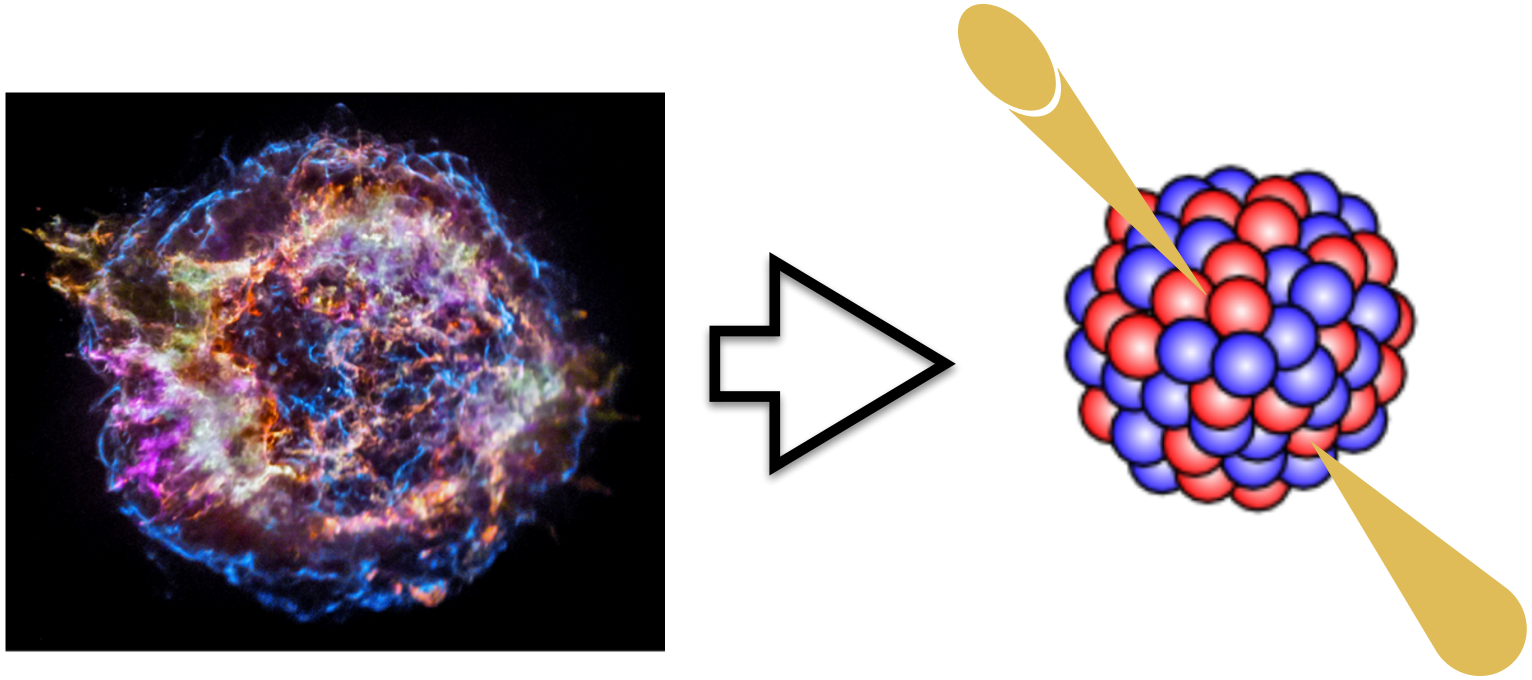


Enter SNO+

Experiment 1: a proposal

Use **neutron stars** as scattering targets

M Baryakhtar, J Bramante,
S Li, T Linden, **N Raj**
Phys.Rev.Lett. *(2017)*



core-collapse supernova

neutron star

<u>“detector” properties</u>

diameter: 20 km

density: 10^{15} g/cm^3

temperature:
100-1000 K
(if 10^9 yr old)

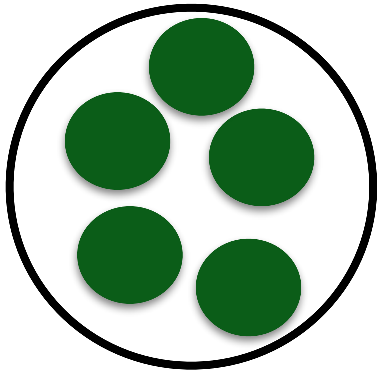
luminosity = kinetic power

(out) (in)

Zwicky misses the party

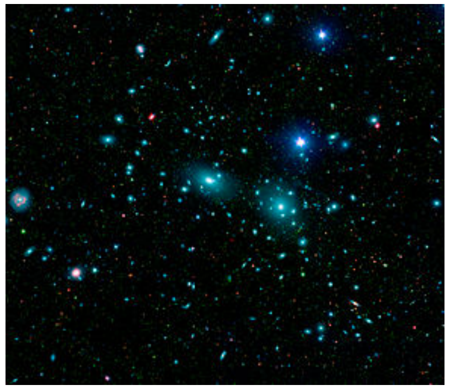
FROM LOCAL MEASUREMENTS

300 km/s



$0.3\ \mathrm{GeV/cm^3}$

unknown to Zwicky

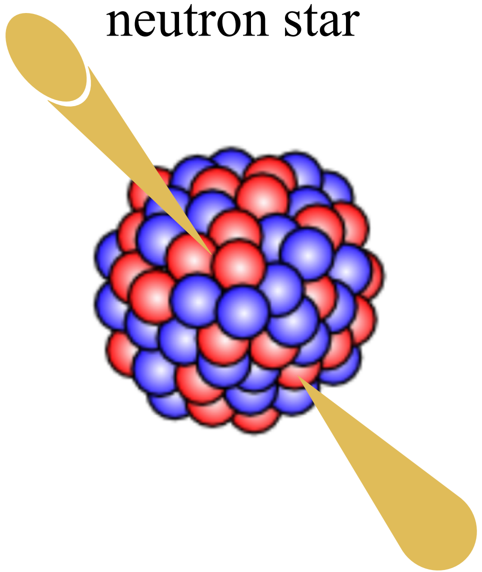


dark matter

1933

$$\mathrm{KE}_{\mathrm{DM}} \times \frac{dN_{\mathrm{DM}}}{dt}$$

neutron star



1934

density: $7 \times 10^{14}\ \mathrm{g/cm^3}$

radius: 10 km

$T_{\mathrm{effective}} \sim 100\ \mathrm{K}$

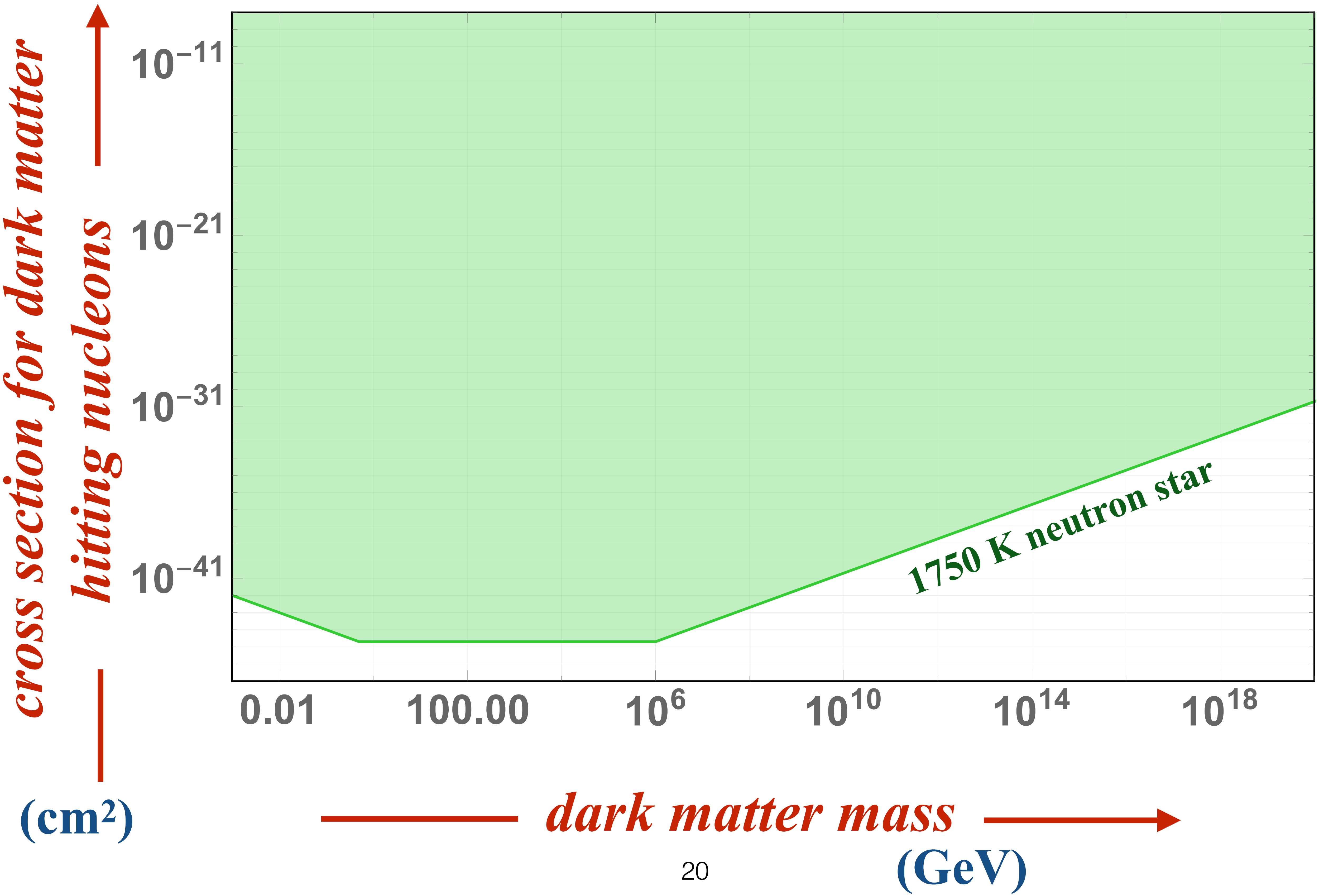
estimable by Zwicky

How hot can dark matter keep my neutron star?

Dark matter coverage

M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj**
Phys.Rev.Lett. *(2017)*

N. Raj*, P Tanedo, H-B Yu*
Phys.Rev.D. *(2017)*



Observation prospects

Radio telescopes (design: pulsar discovery)

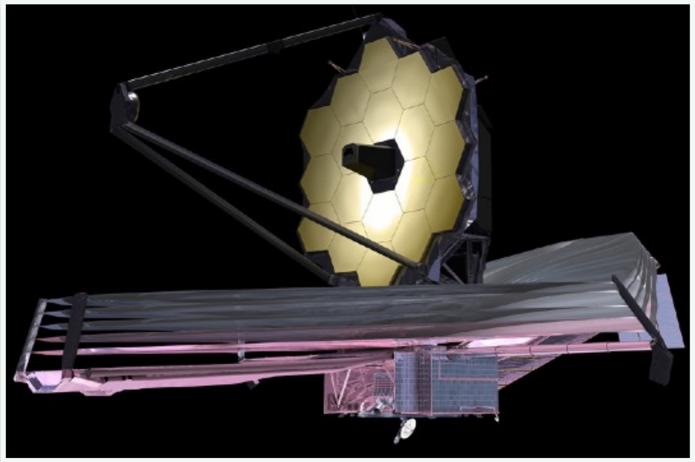
CHIME

FAST

100 old, cold neutron stars
in the local 50 pc.

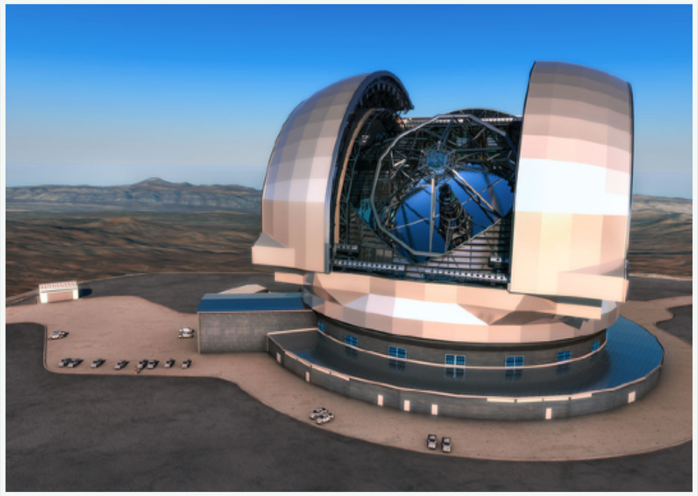
O. Blaes, P. Madau (1993)

Infrared telescopes (design: exoplanet atmosphere study)



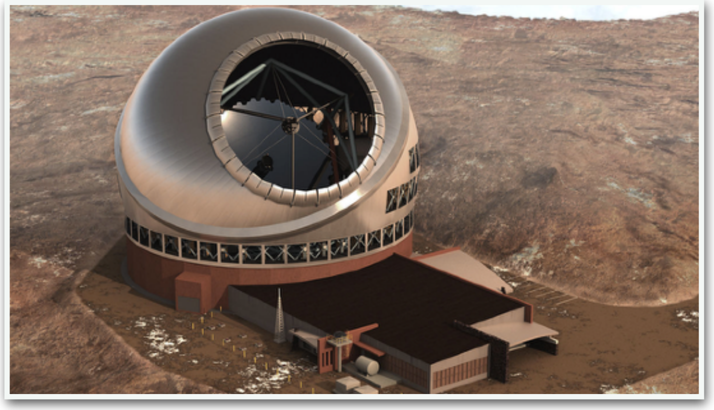
James Webb

2021



Extremely Large

2025



Thirty Meter

2027

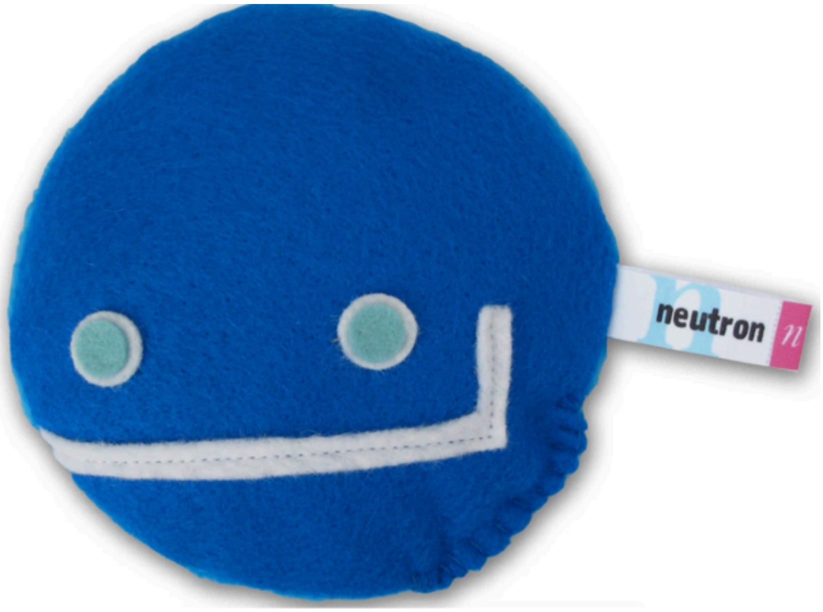
M Baryakhtar, J Bramante, S Li, T Linden, **N. Raj** ***Phys.Rev.Lett.*** *(2017)*

Important variations on a theme

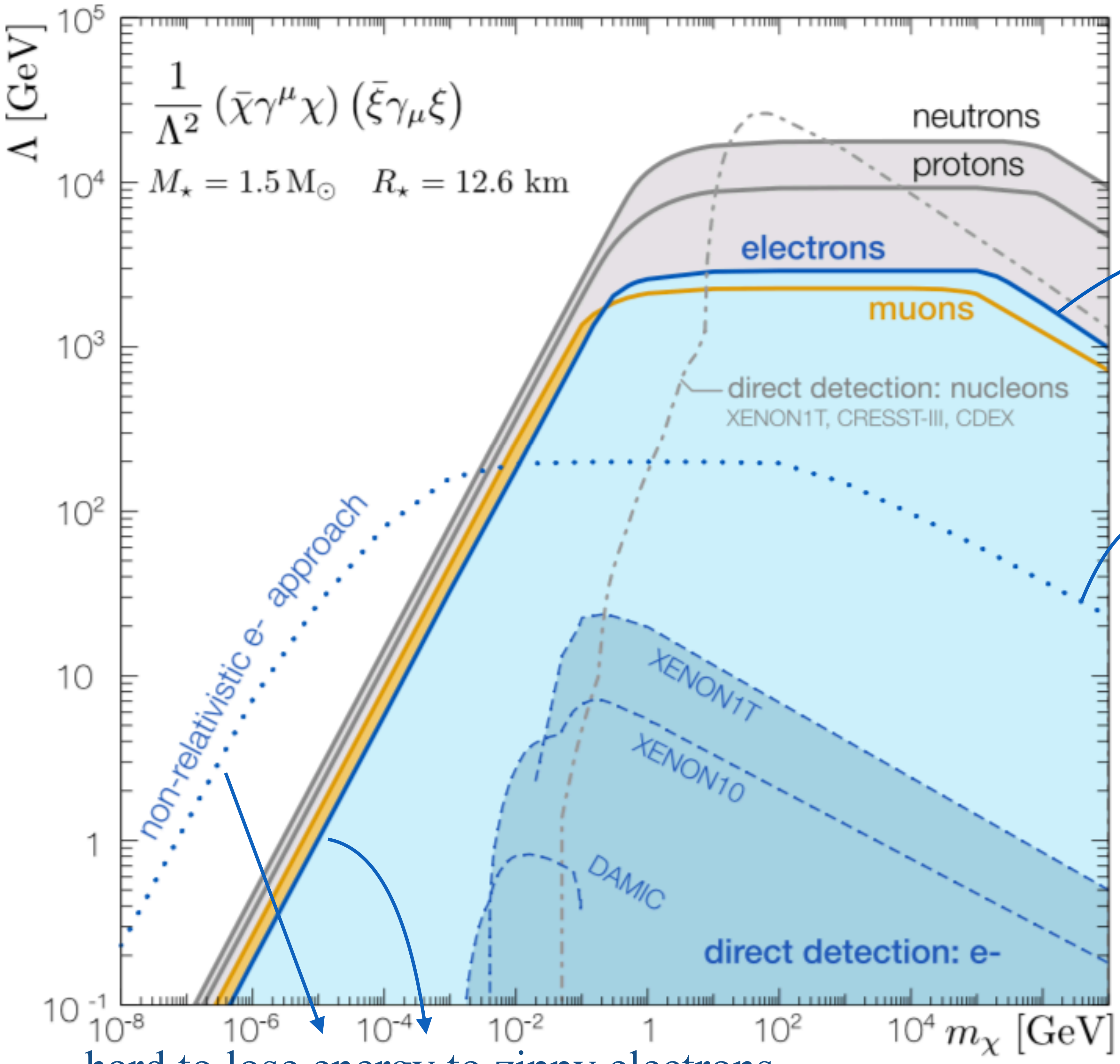
_#1_

Are we barking down the wrong scattering target?

A Joglekar, **N Raj**, *P Tanedo, H-B. Yu*
PLB (2020) & 2004.09539



“Electron star” dark matter detection



cross section ∝ Fermi energy^2
[(150 MeV)^2]

cross section ∝ electron mass^2
[(0.5 MeV)^2]

hard to lose energy to zippy electrons

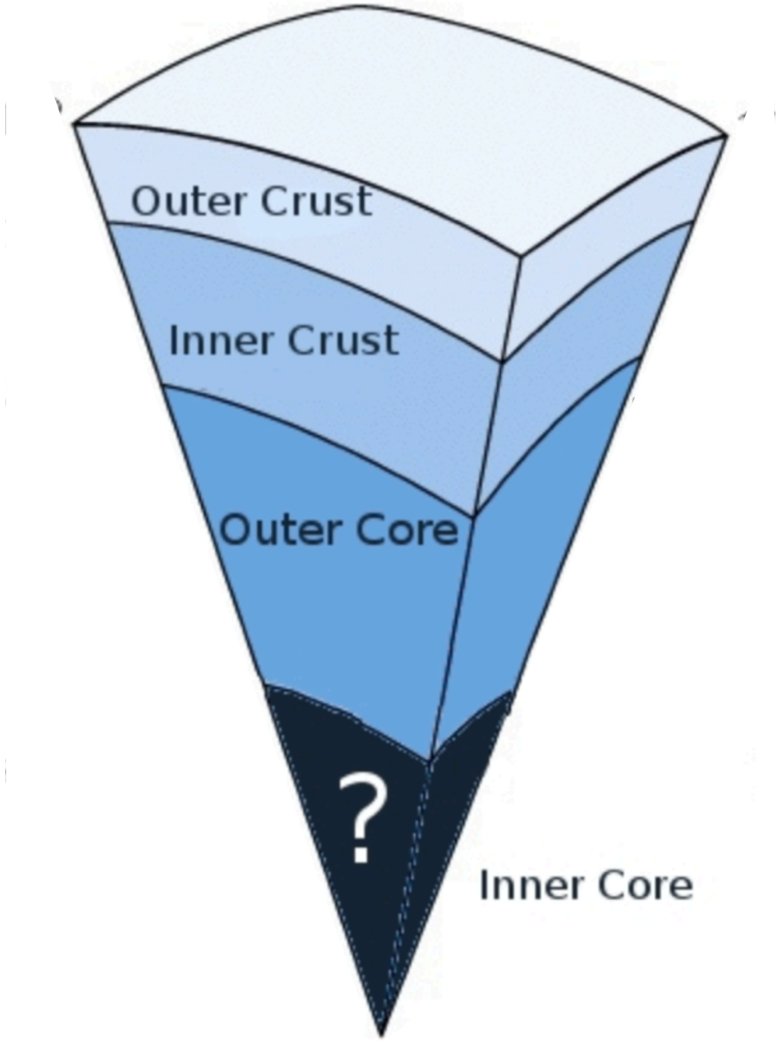
A Joglekar, **N Raj**, *P Tanedo, H-B. Yu*
PLB (2020) & 2004.09539

Important variations on a theme

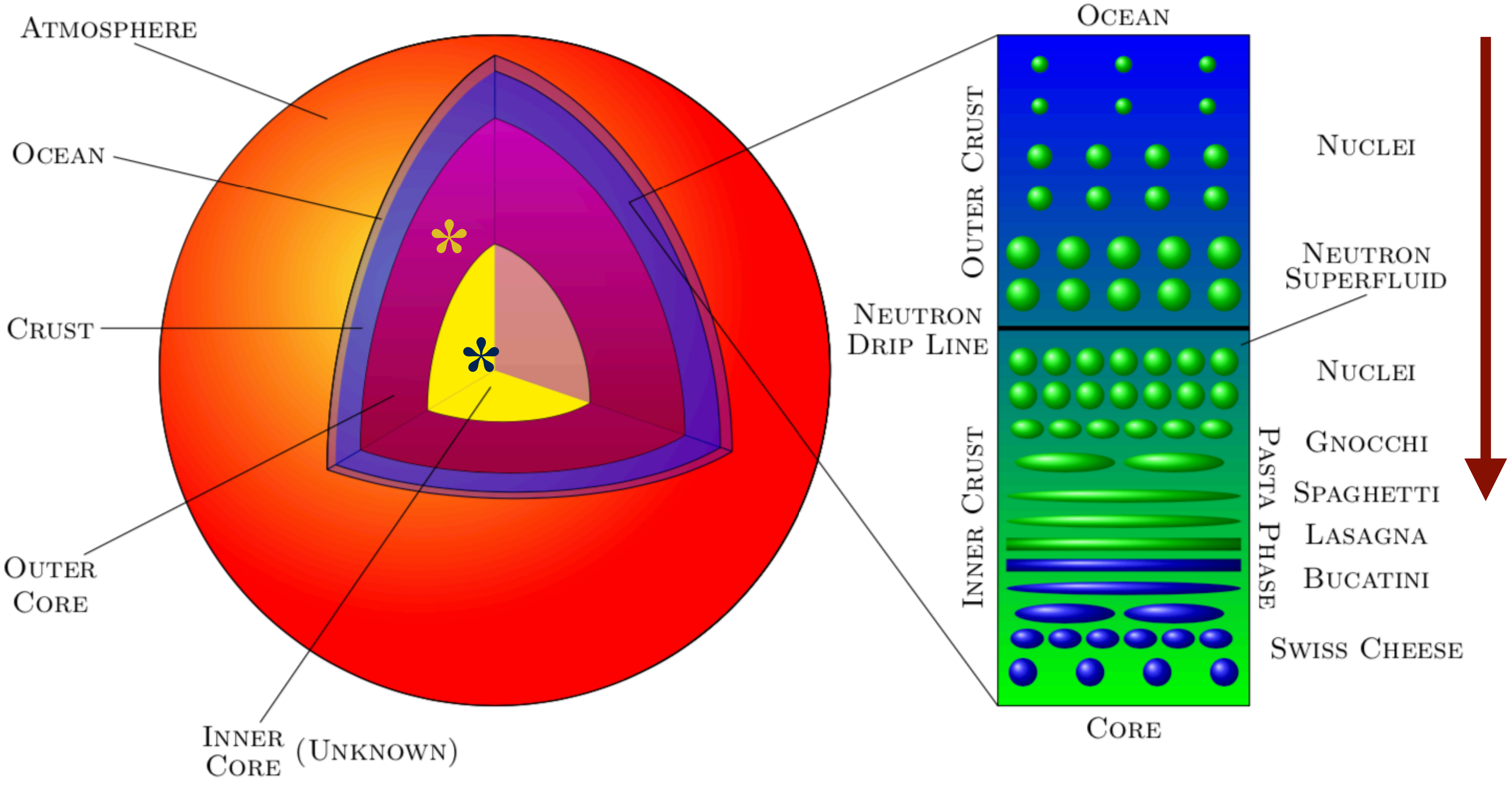
#2

Are we barking down the wrong stellar region?

J Acevedo, J Bramante, R Leane, **N Raj**
JCAP (2020)



Neutron star structure



deeper =>
knowledge of structure
more uncertain

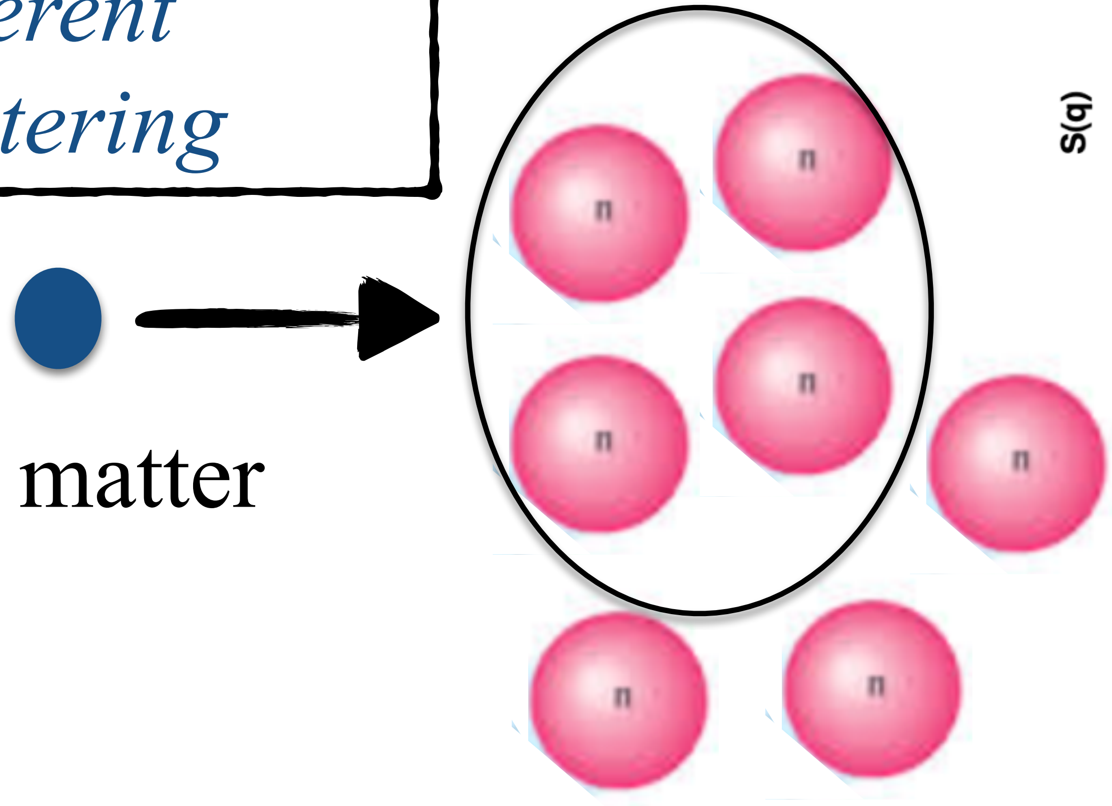
better capture,
more dubious

* may not be neutrons
(maybe quark matter, meson condensates, etc.)

J Acevedo, J Bramante, R Leane, **N Raj**
JCAP (2020)

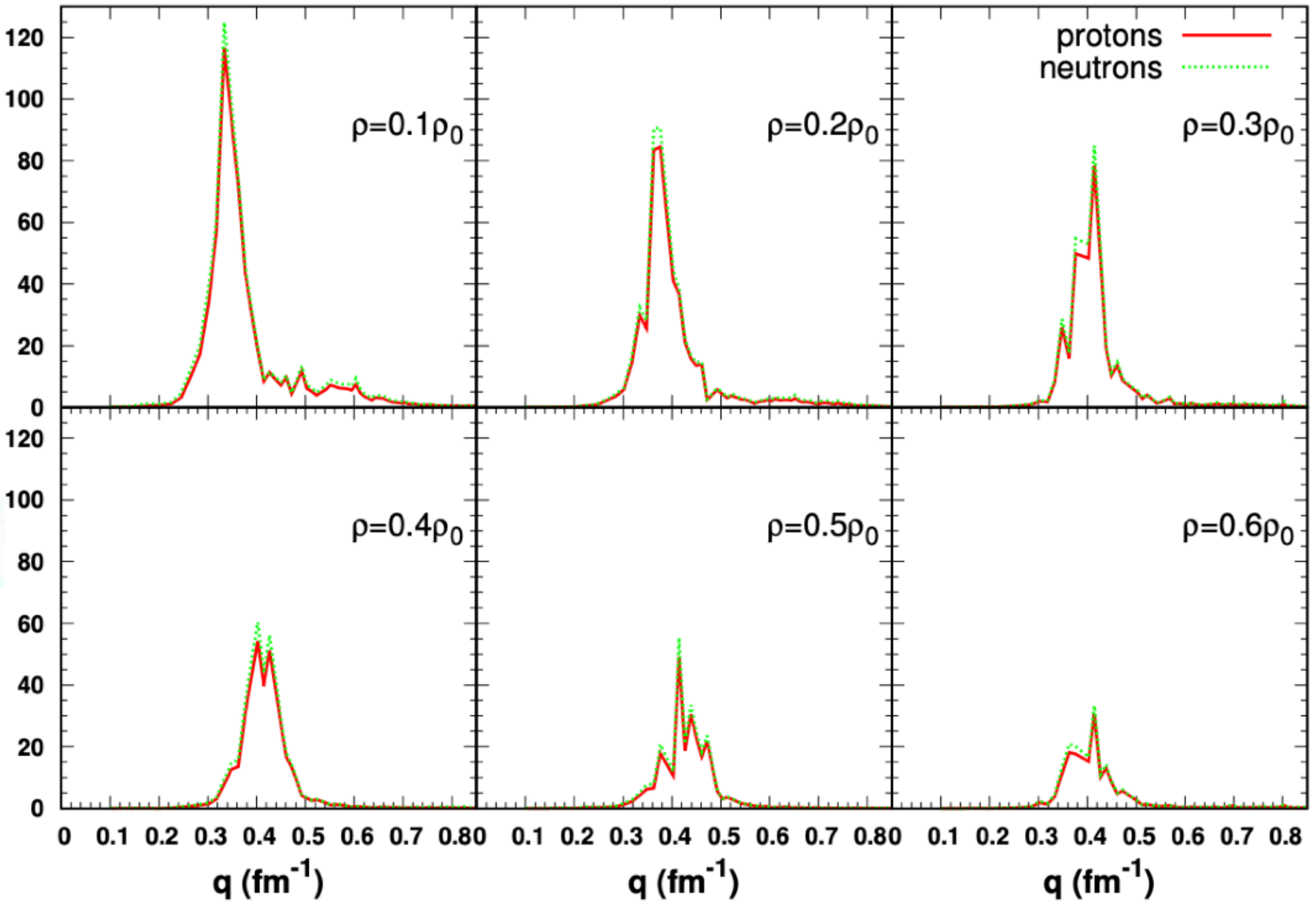
Scattering on pasta

low momenta: coherent scattering



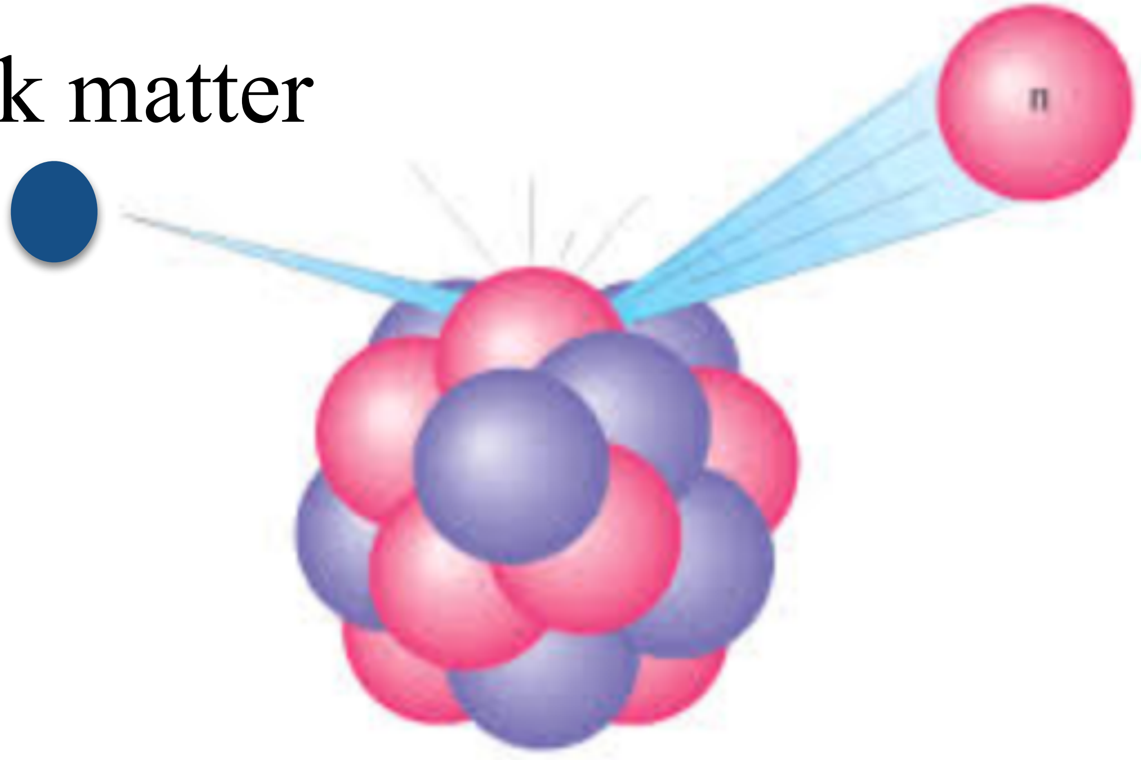
dark matter

response functions Nandi & Schramm (2017)



$$\boxed{\sigma_{\text{pasta}}(q) = S_{\text{pasta}}(q)\ \sigma_{n\chi}}$$

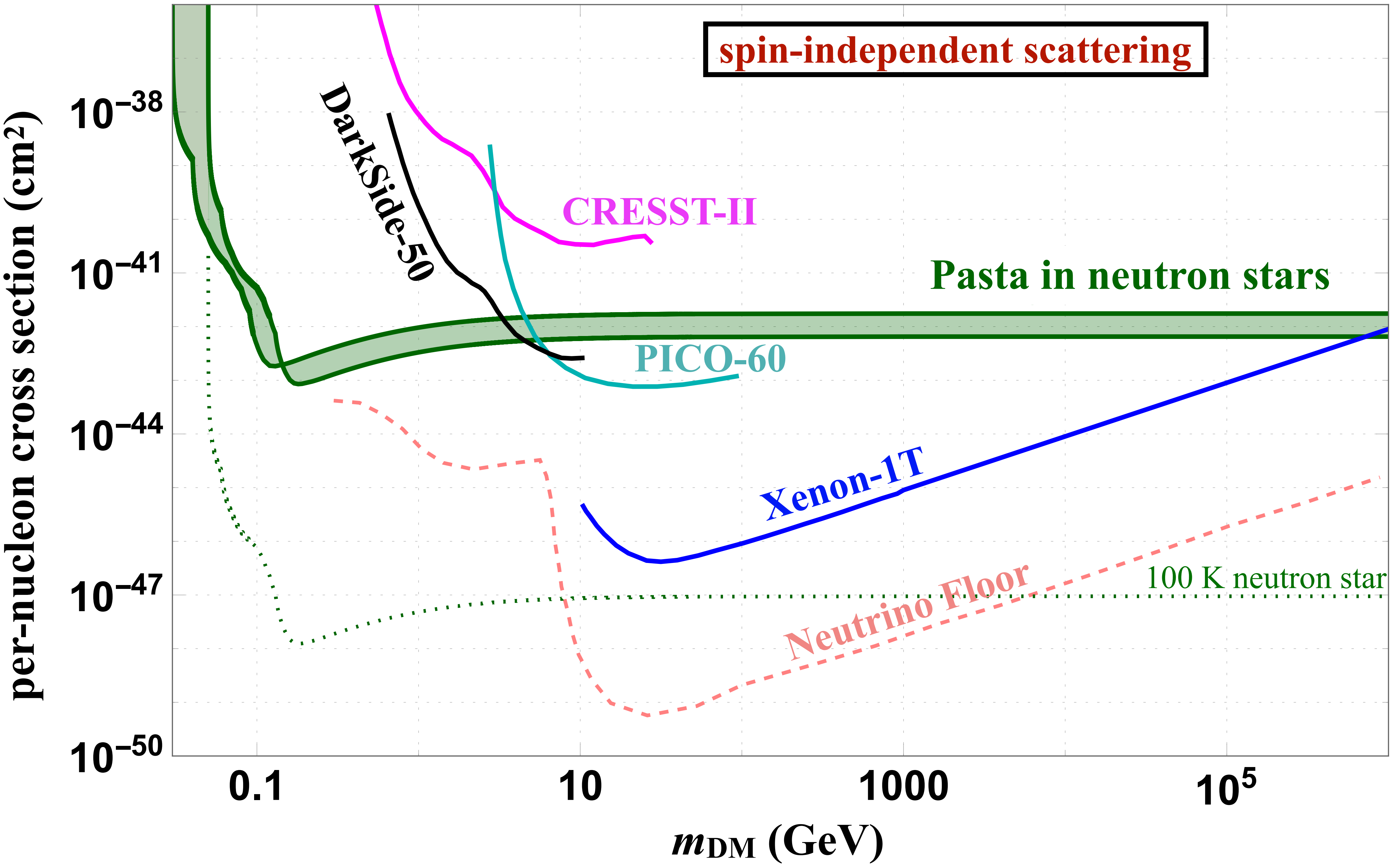
dark matter



high momenta: quasi-elastic scattering

J Acevedo, J Bramante, R Leane, **N Raj**
JCAP (2020)

Sensitivities



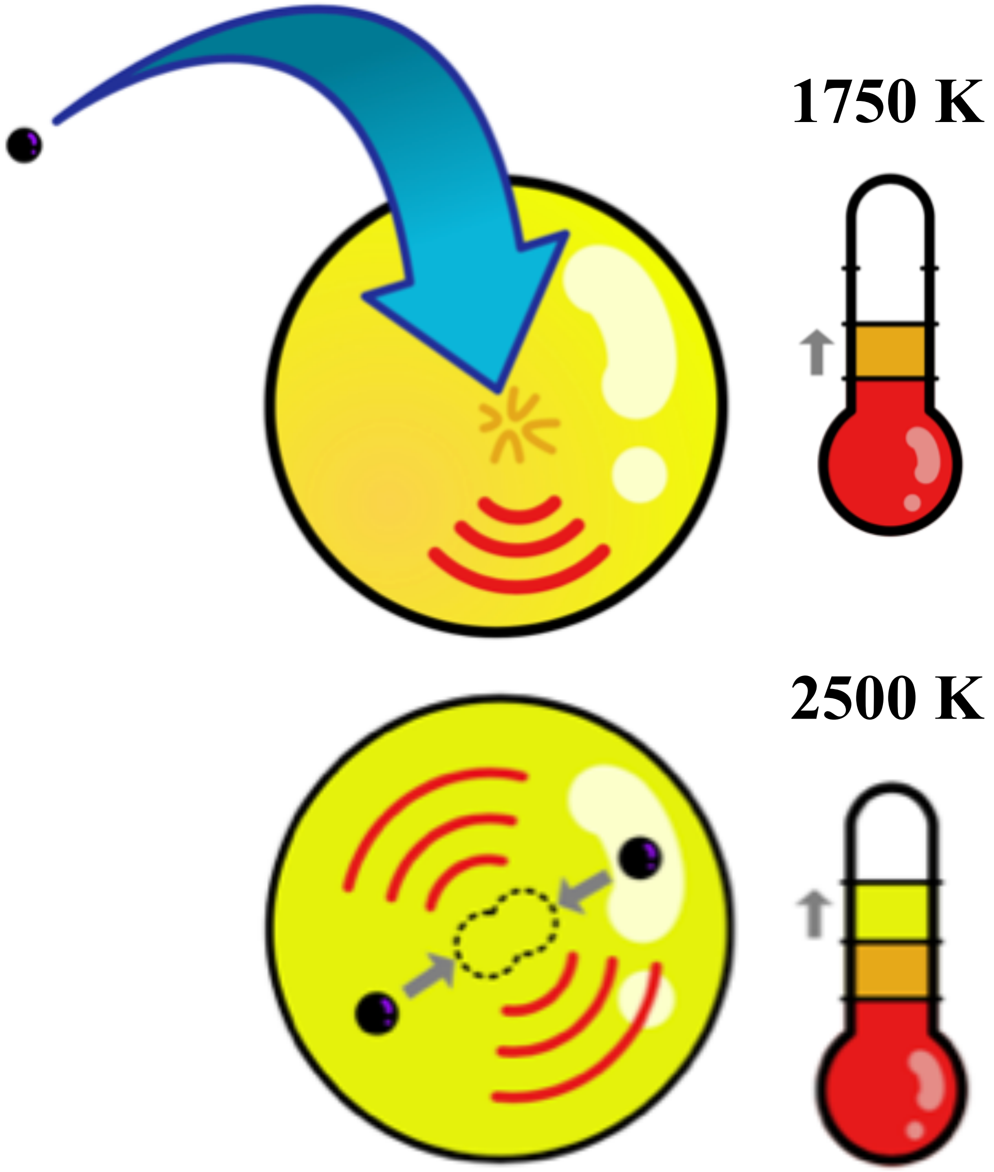
J Acevedo, J Bramante, R Leane, **N Raj**
JCAP (2020)

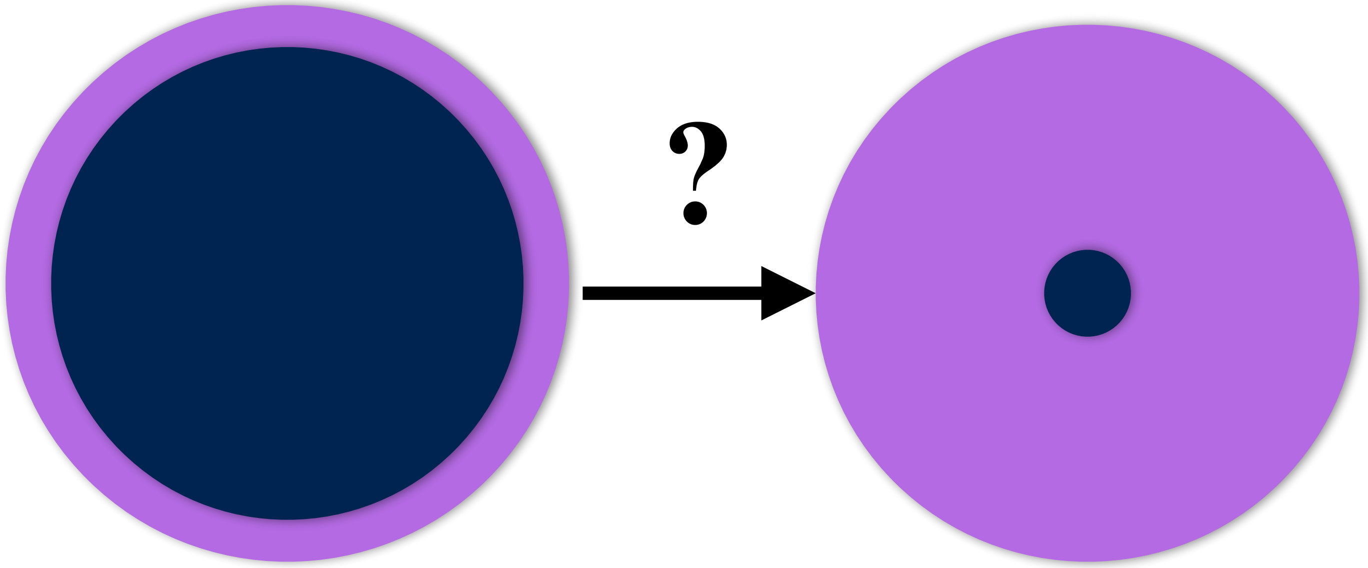
Important variations on a theme

#3

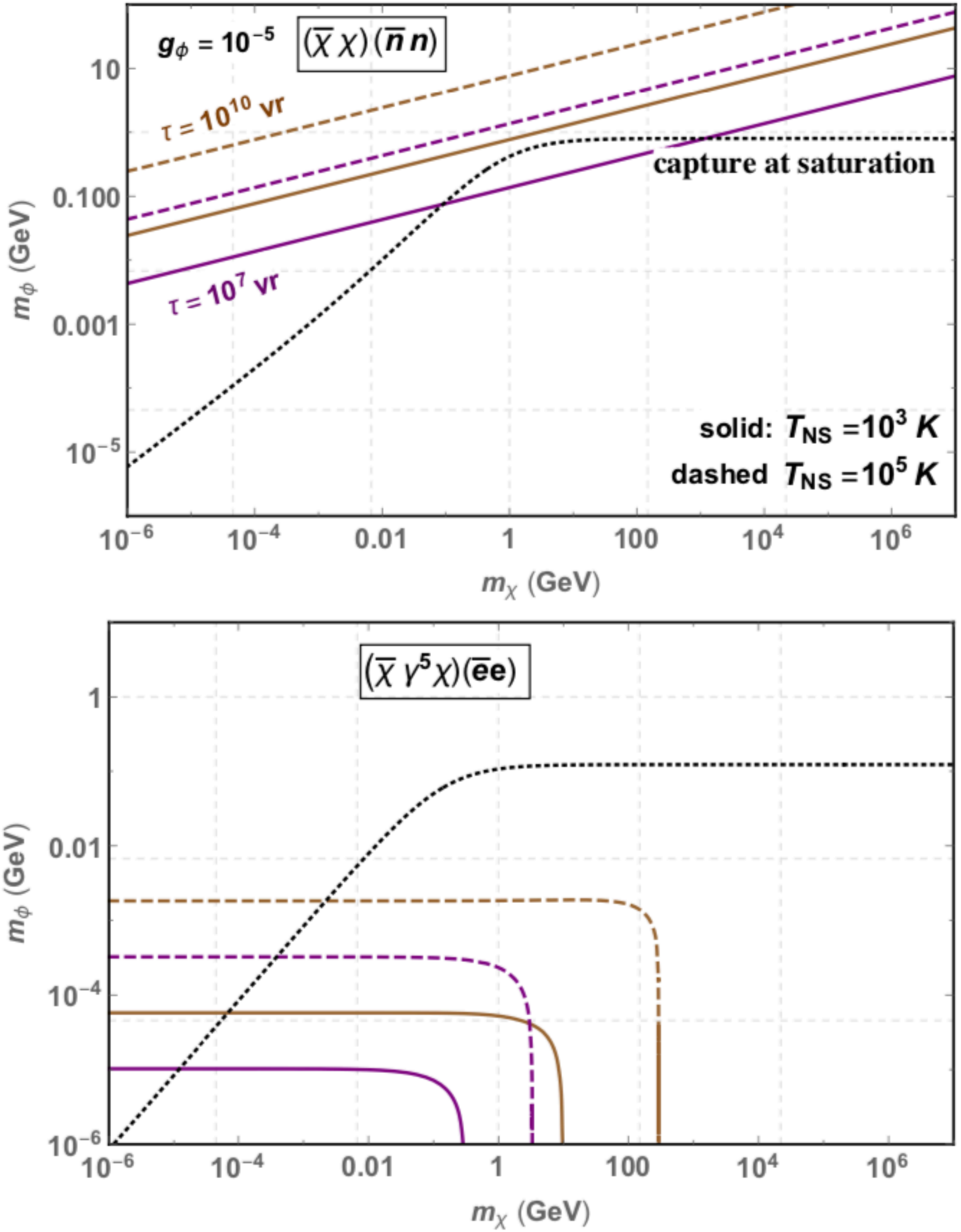
Must we refrigerate dark matter to see its effects?

R Garani, A Gupta,, **N Raj**
2009.10728



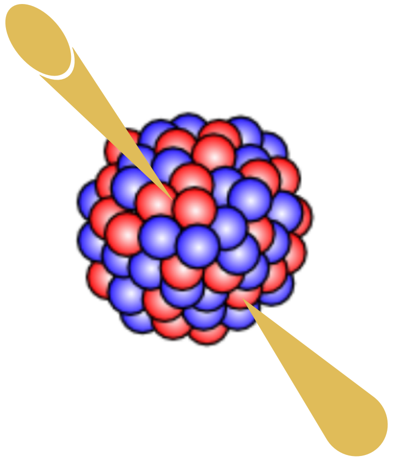


Thermalization vs capture



R Garani, A Gupta,, **N Raj**
2009.10728

Future promise



JWST	2021
EELT	2025
TMT	2027

dark matter search

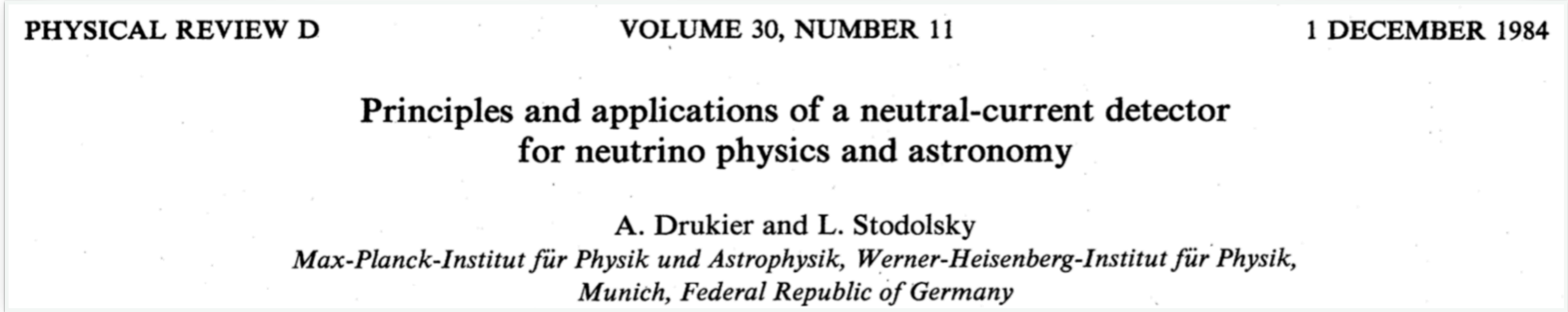
\+ 5 - 10 yrs

Past and present probes

— since 1985

— great swathes of
cross section vs mass space
already constrained

How it began

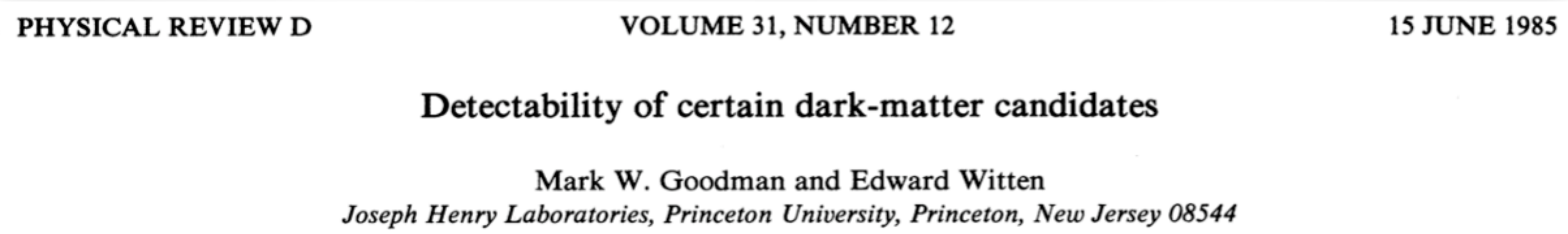


PHYSICAL REVIEW D VOLUME 30, NUMBER 11 1 DECEMBER 1984

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

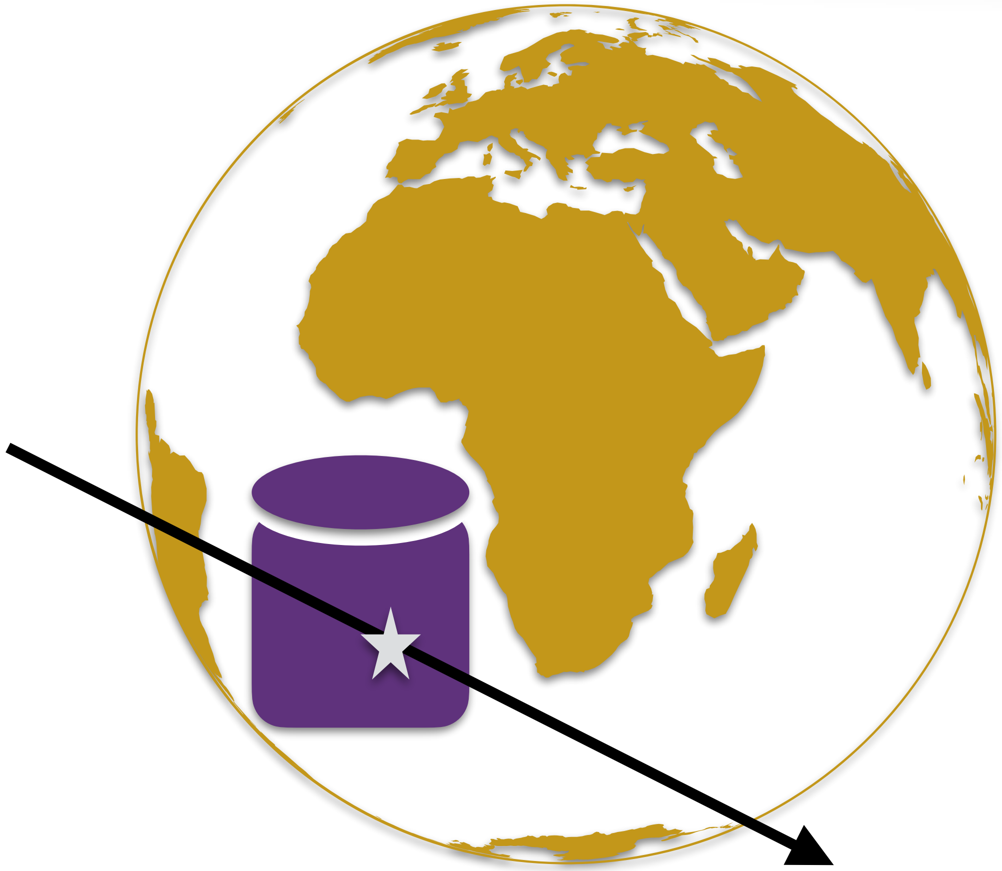


PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

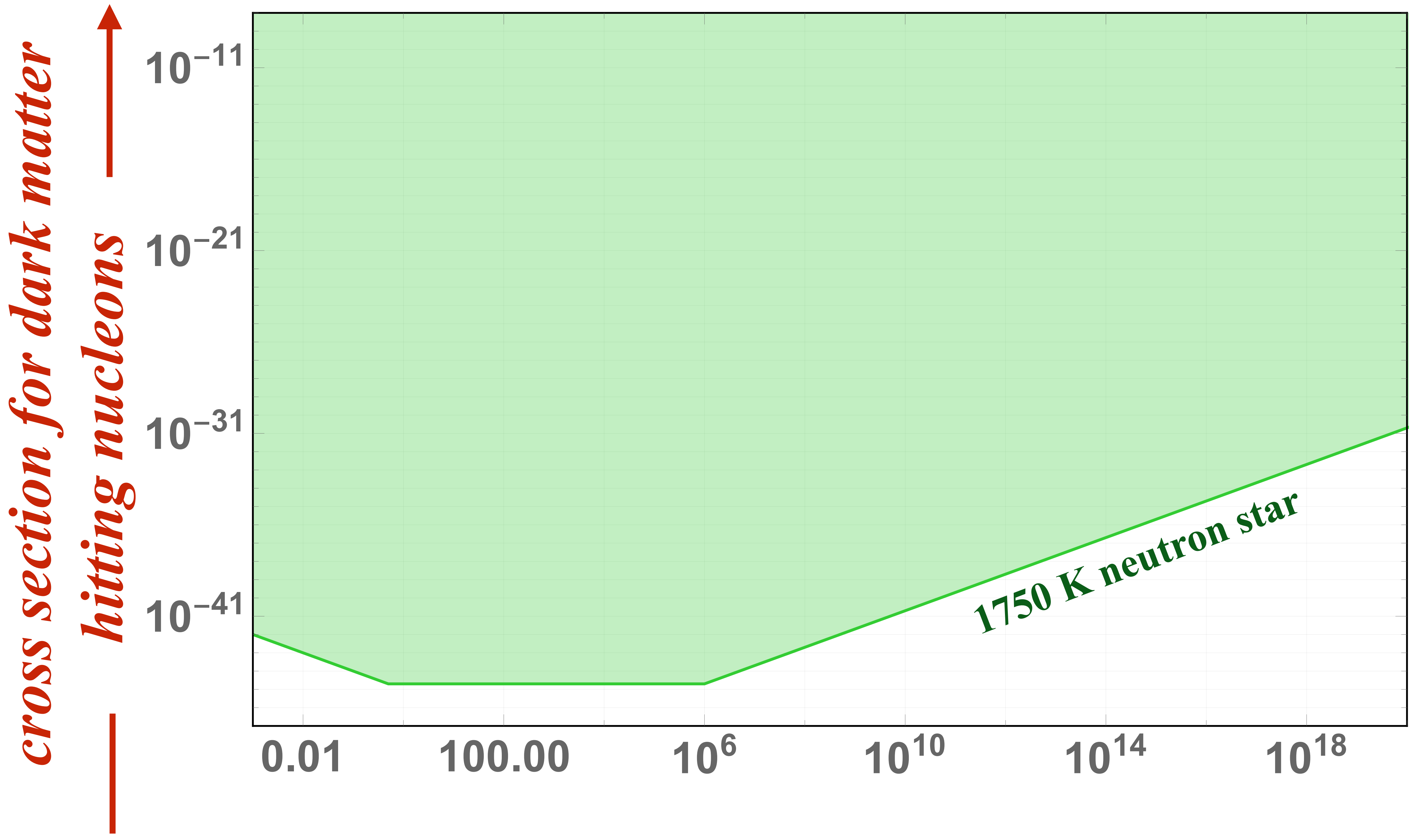
Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten

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



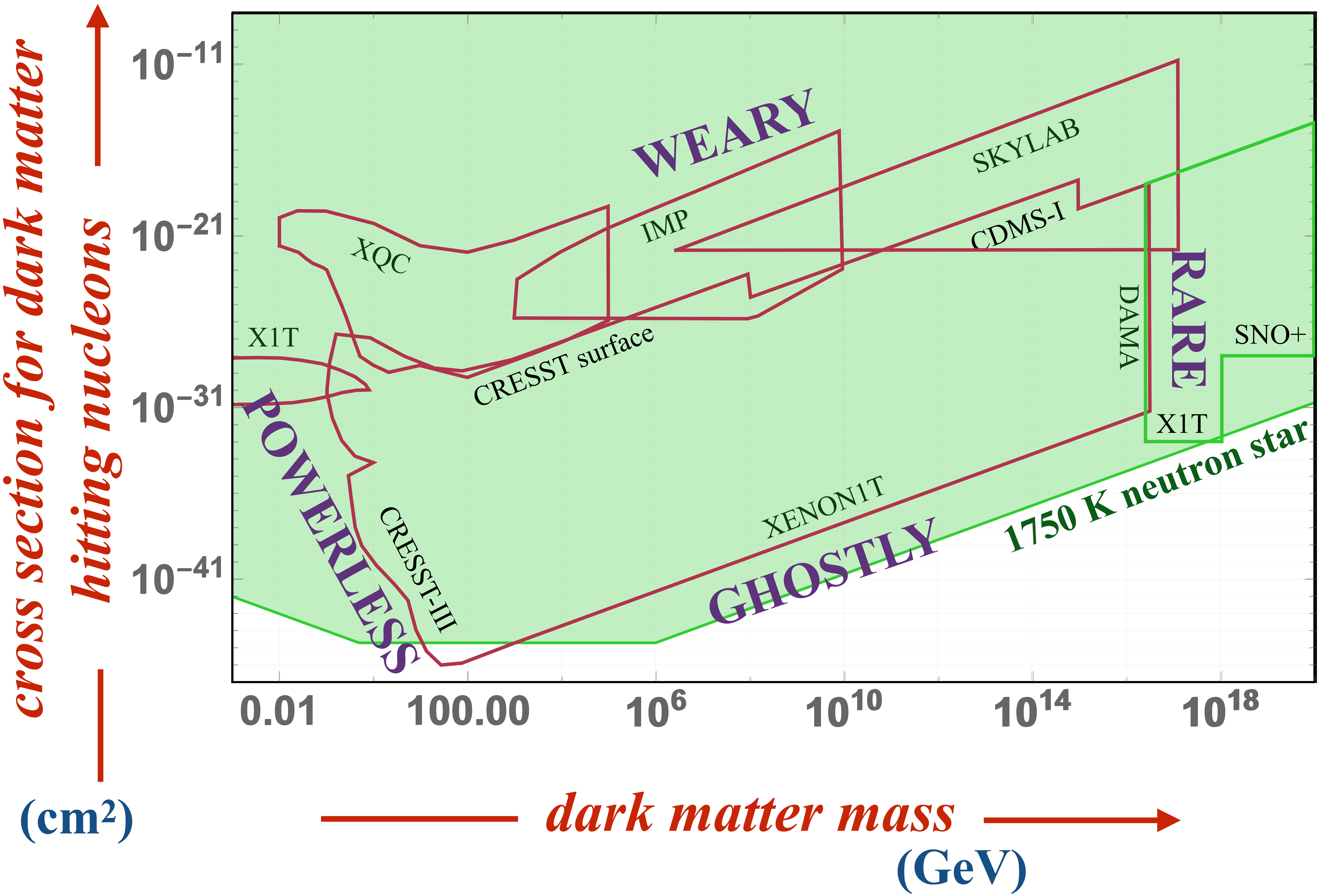
Where are we now on this?



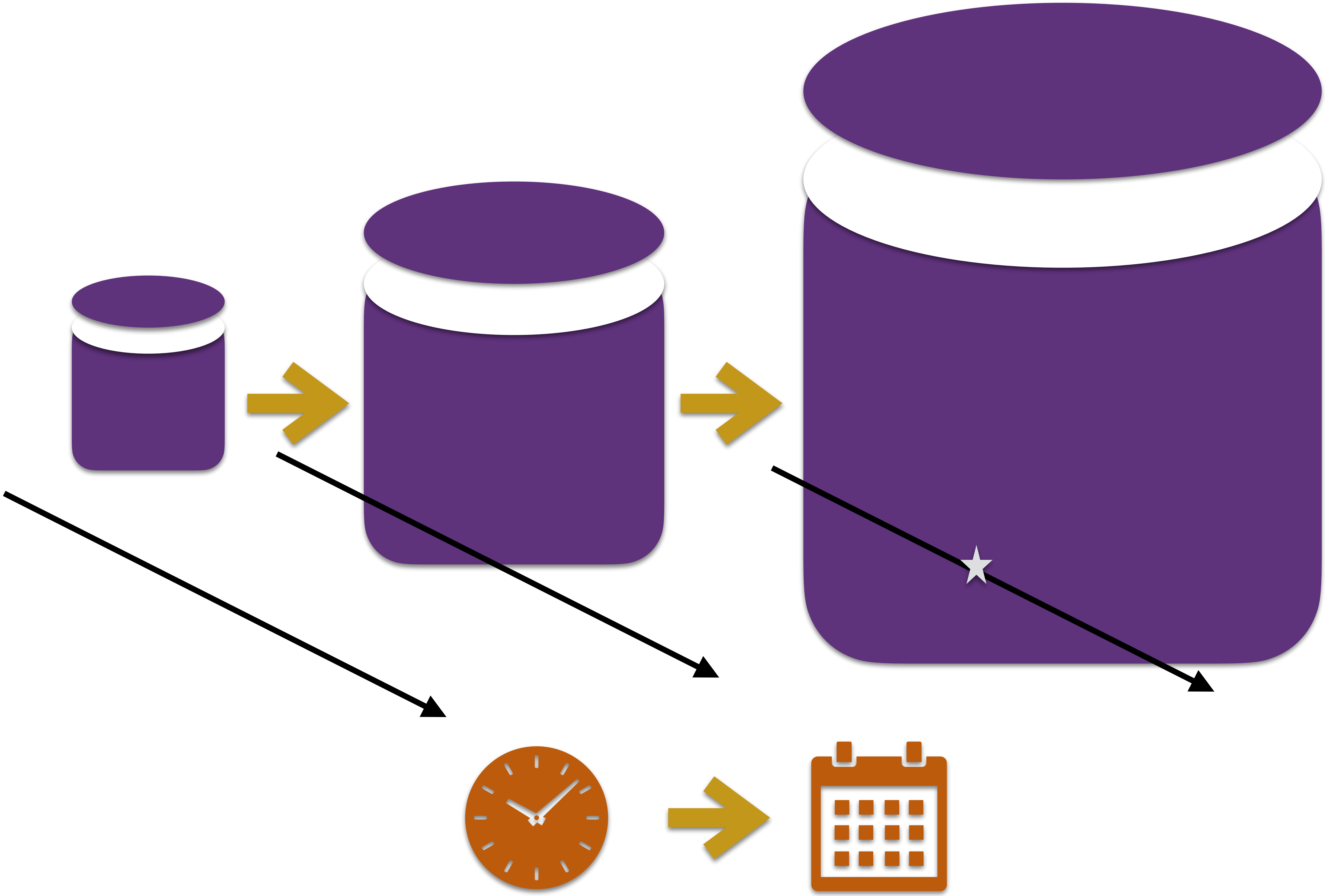
dark matter mass

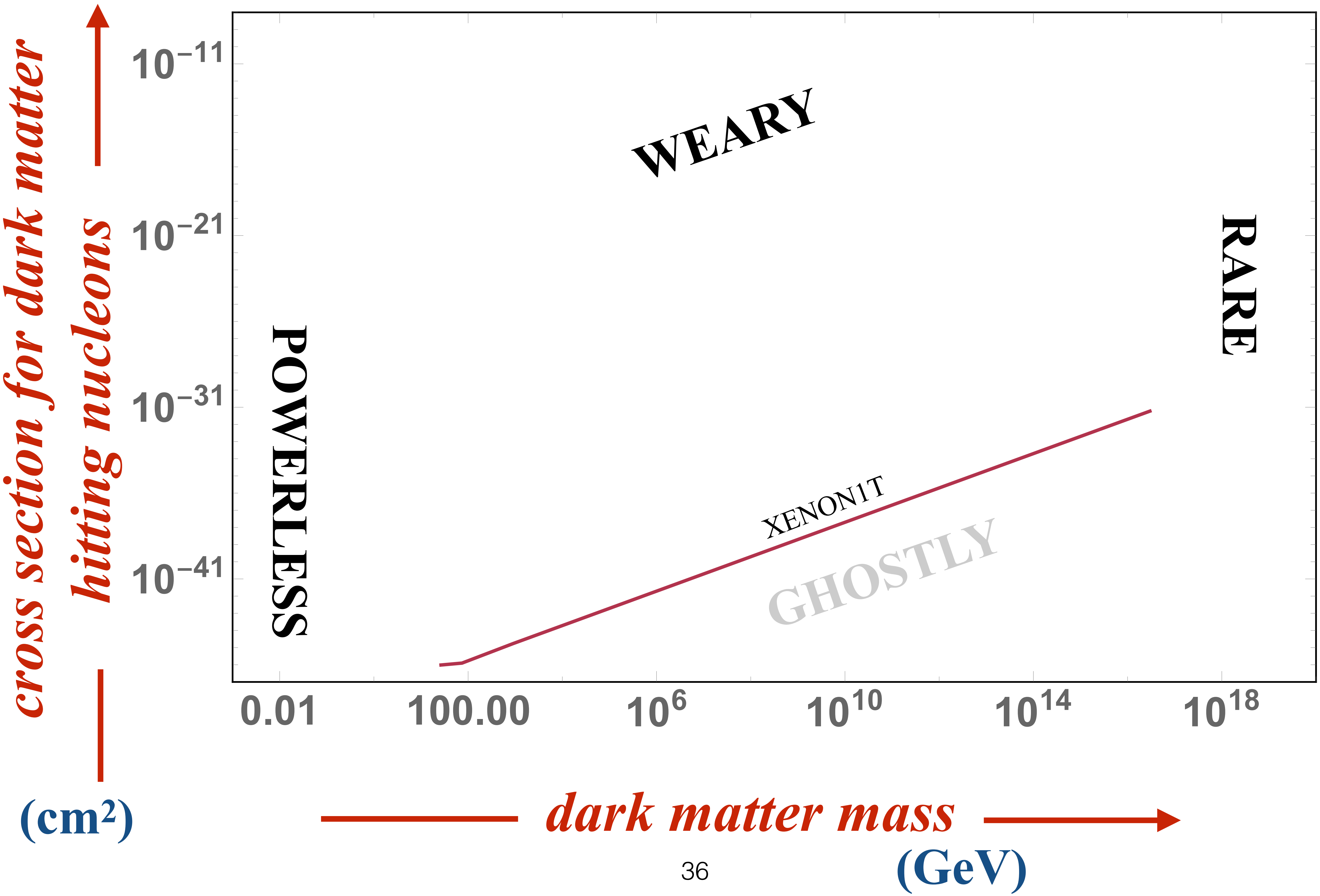
(GeV)

All Earth-based constraints



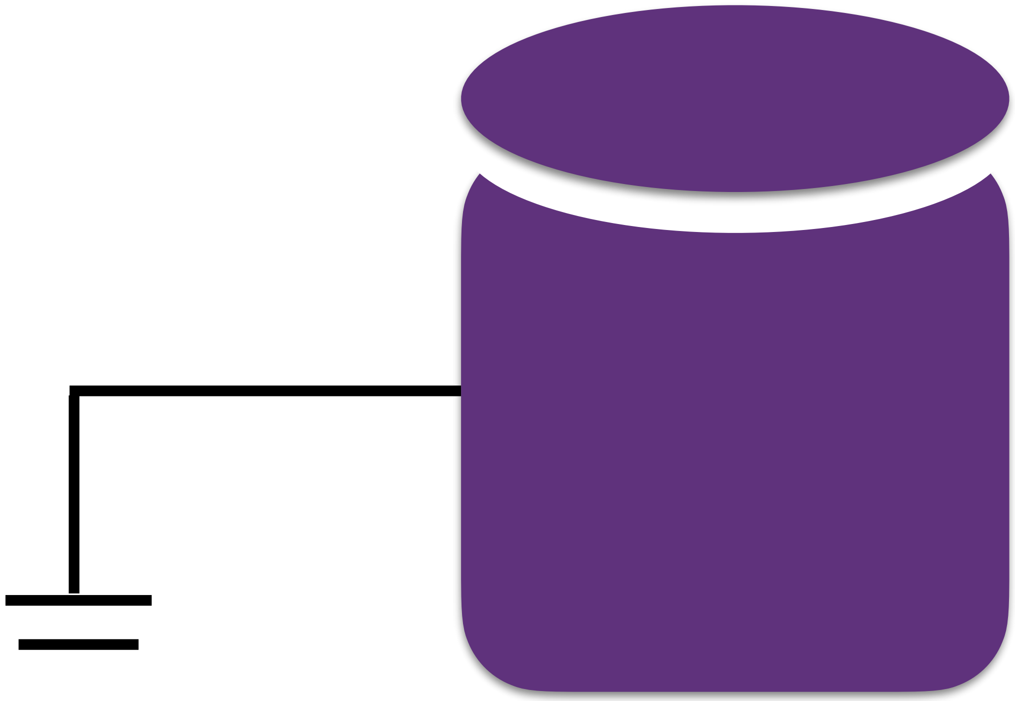
Hunting ghostlier dark matter




cross section for dark matter hitting nucleons
(cm²)
10^{-11}
10^{-21}
10^{-31}
10^{-41}
WEARY
RARE
POWERLESS
XENON1T
GHOSTLY
0.01
100.00
10^{6}
10^{10}
10^{14}
10^{18}
dark matter mass
(GeV)

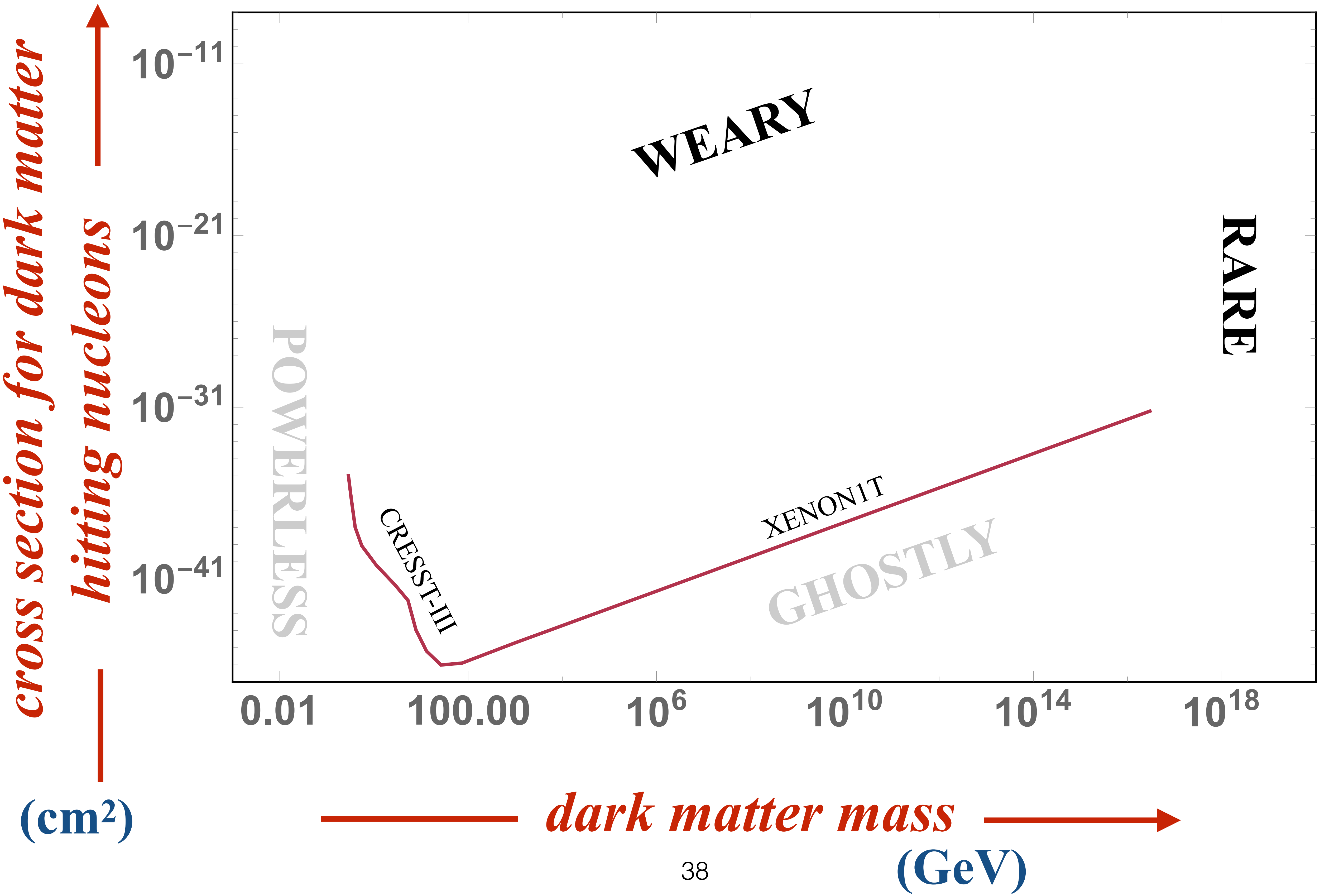
Hunting lighter dark matter

Reduce energy threshold of experiment

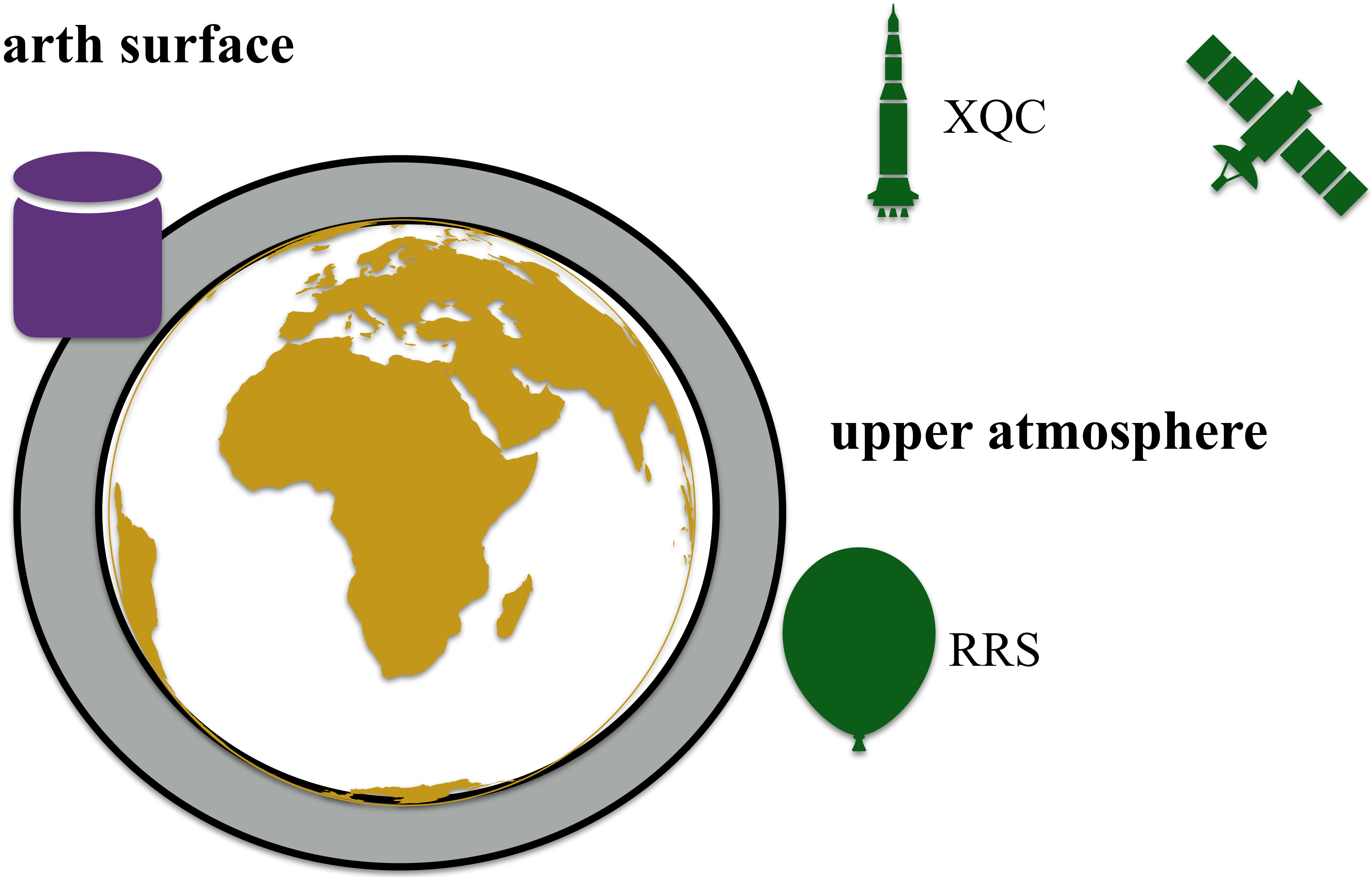


- Light elements
- Small detectors
- Sensitive readout

CRESST, SuperCDMS, SENSEI, DAMIC, …


cross section for dark matter hitting nucleons
(cm^2)
10^{-11}
10^{-21}
10^{-31}
10^{-41}
WEARY
RARE
POWERLESS
CRESST-III
XENON1T
GHOSTLY
0.01
100.00
10^{6}
10^{10}
10^{14}
10^{18}
dark matter mass
(GeV)

Detector location



Earth surface

space

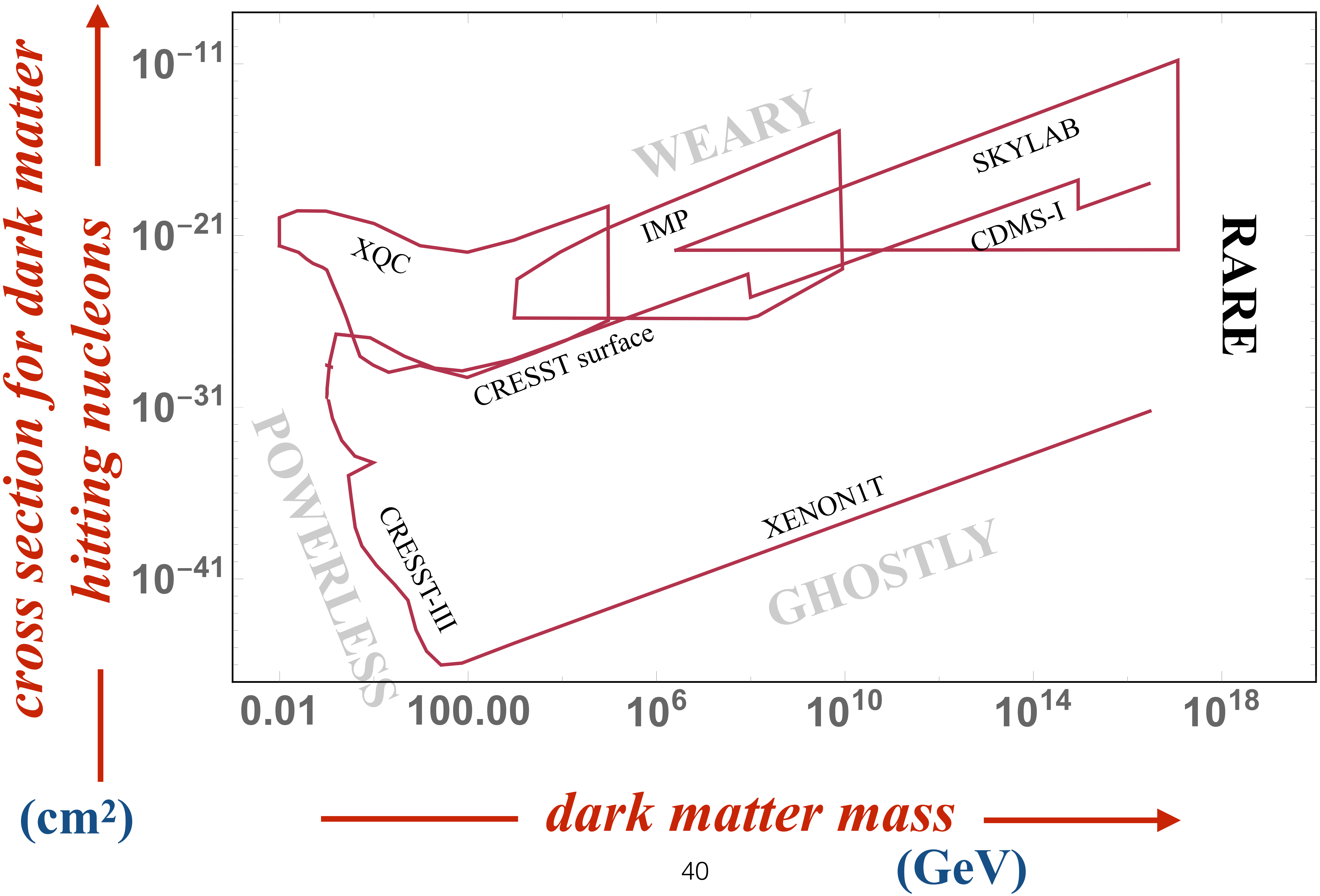
XQC

IMP-8

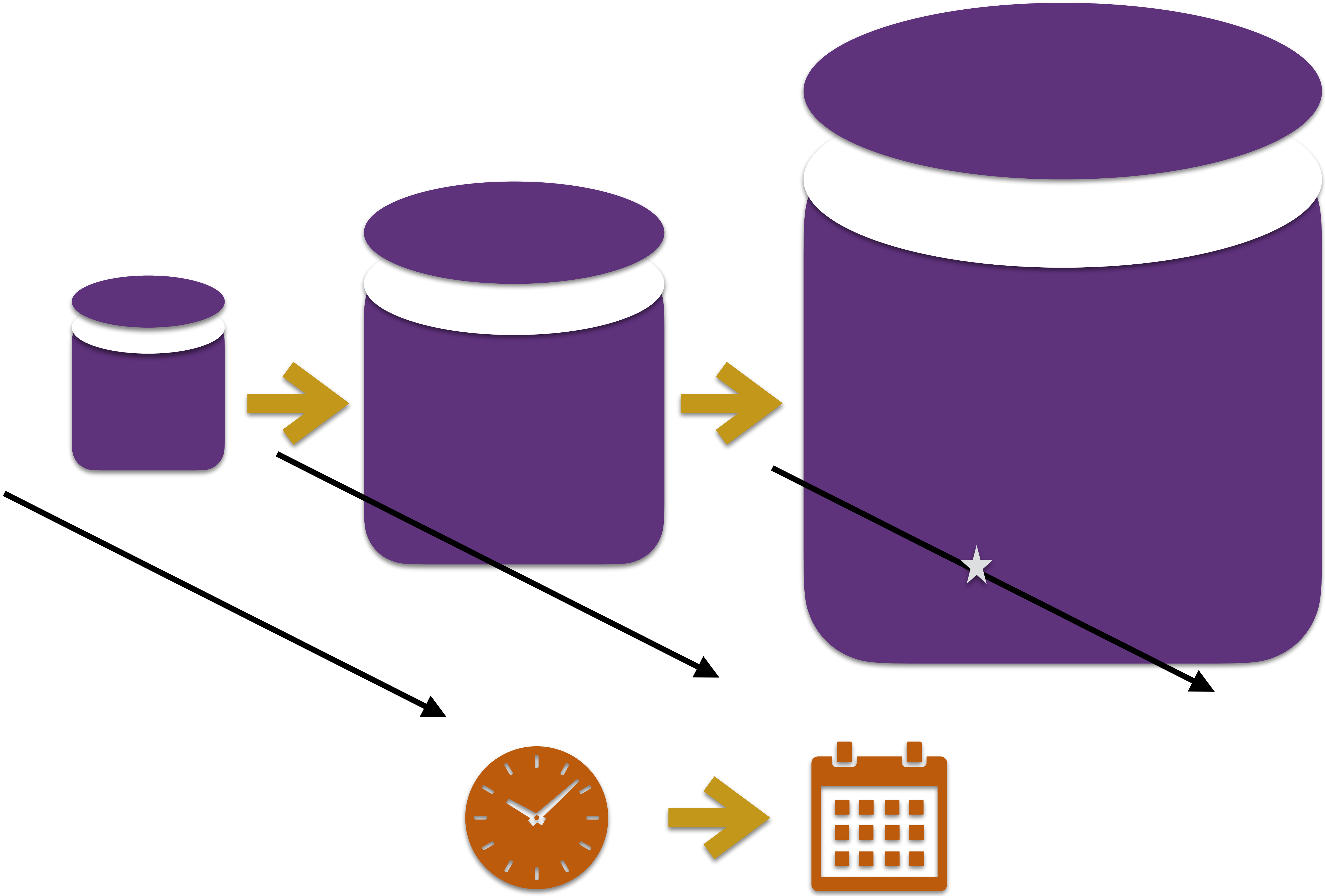
SKYLAB

upper atmosphere

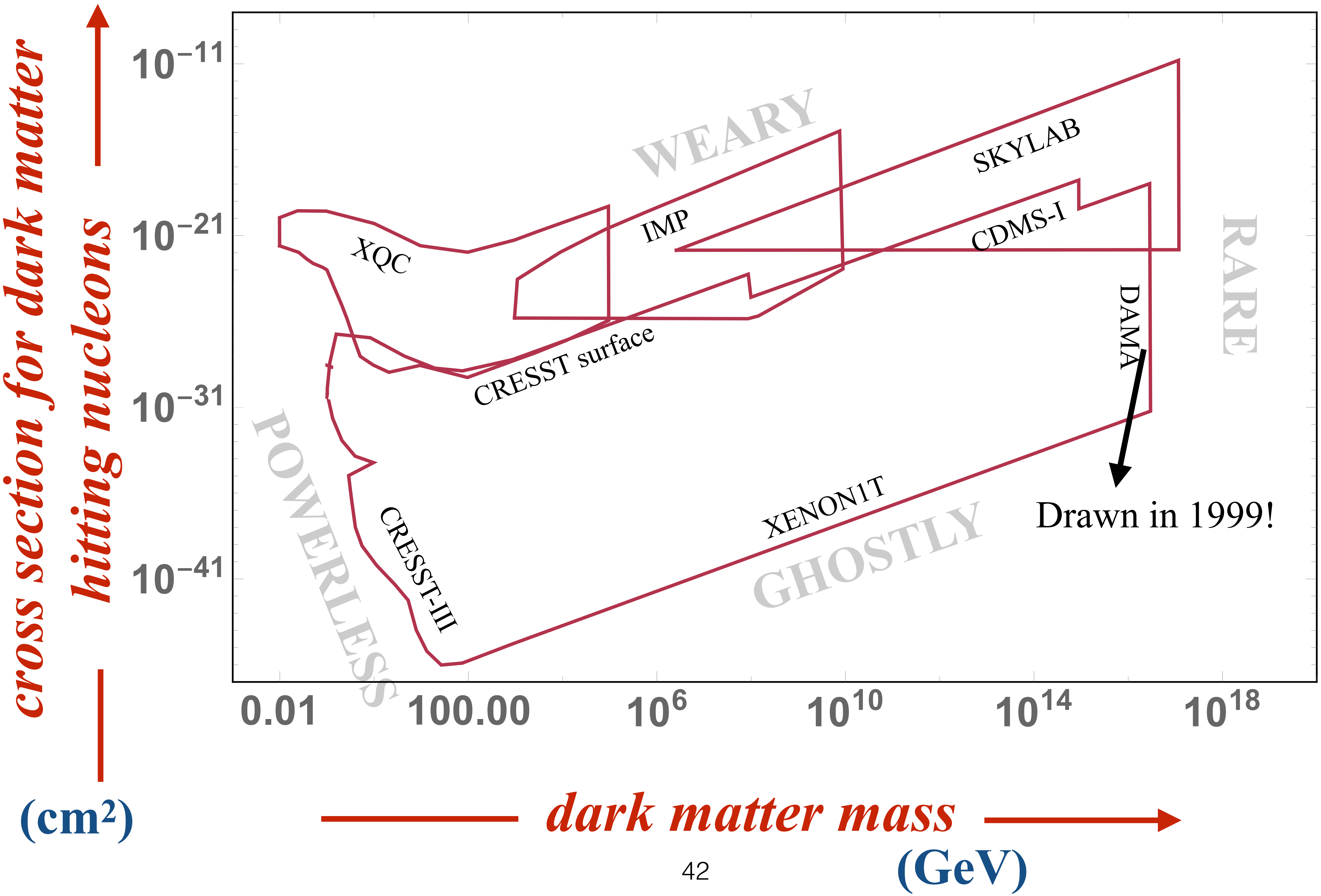
RRS


cross section for dark matter hitting nucleons
(cm²)
dark matter mass
(GeV)
10−11
10−21
10−31
10−41
0.01
100.00
10^6
10^10
10^14
10^18
WEARY
SKYLAB
IMP
XQC
CDMS-I
RARE
CRESST surface
POWERLESS
CRESST-III
XENON1T
GHOSTLY

Hunting rarer dark matter

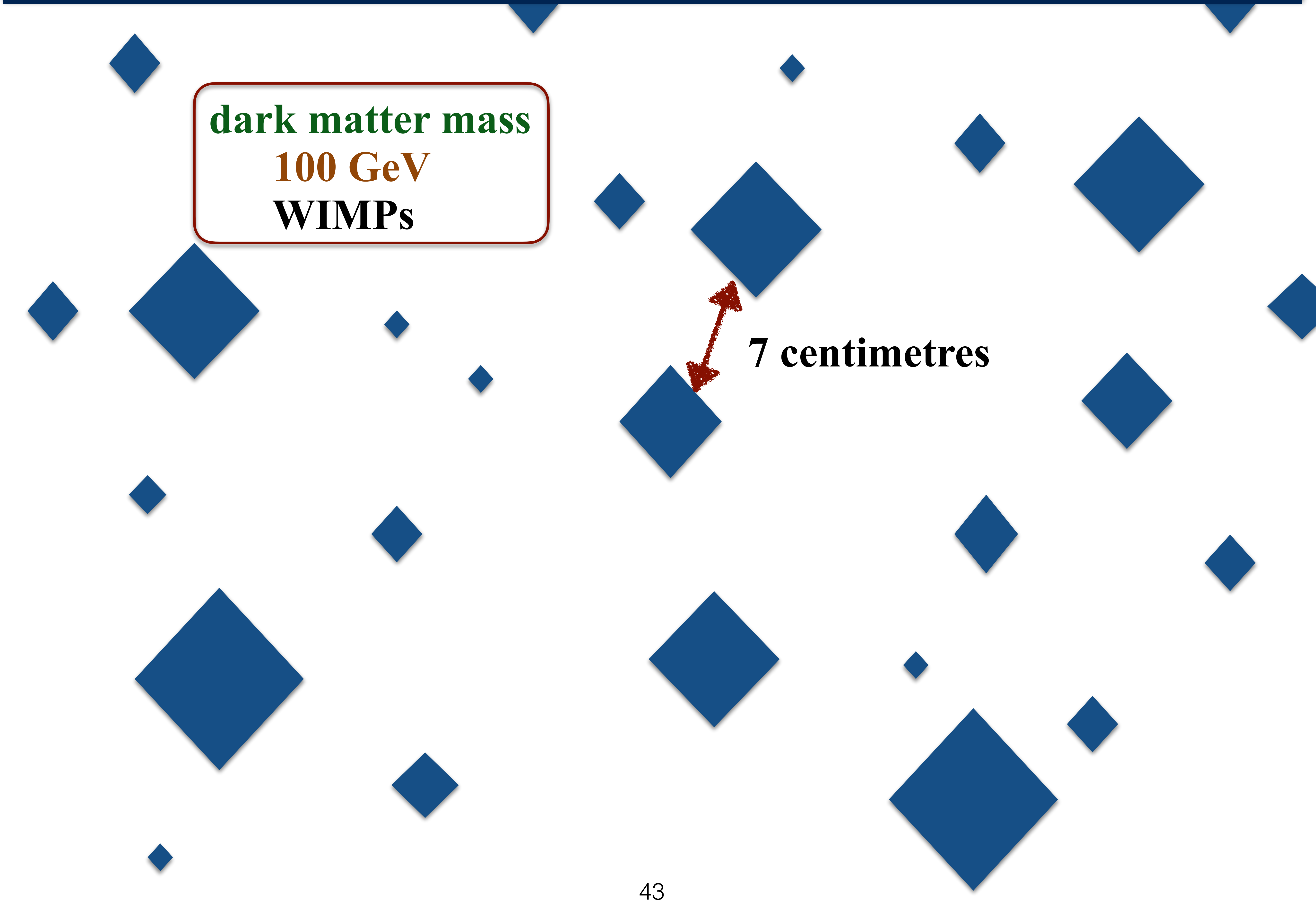


All the Earth-based constraints



Drawn in 1999!

Profusion



dark matter mass
100 GeV
WIMPs

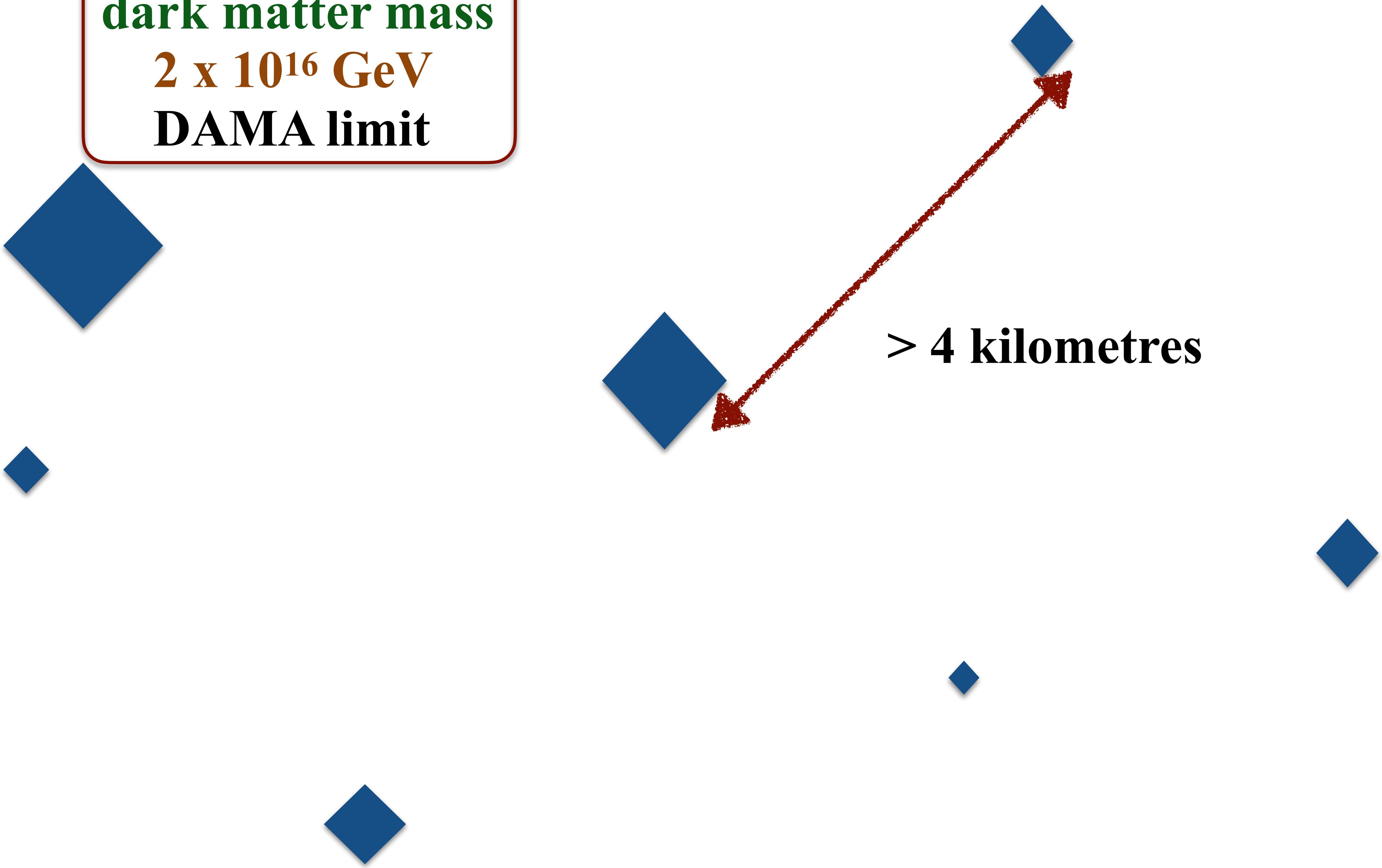
7 centimetres

Rarity

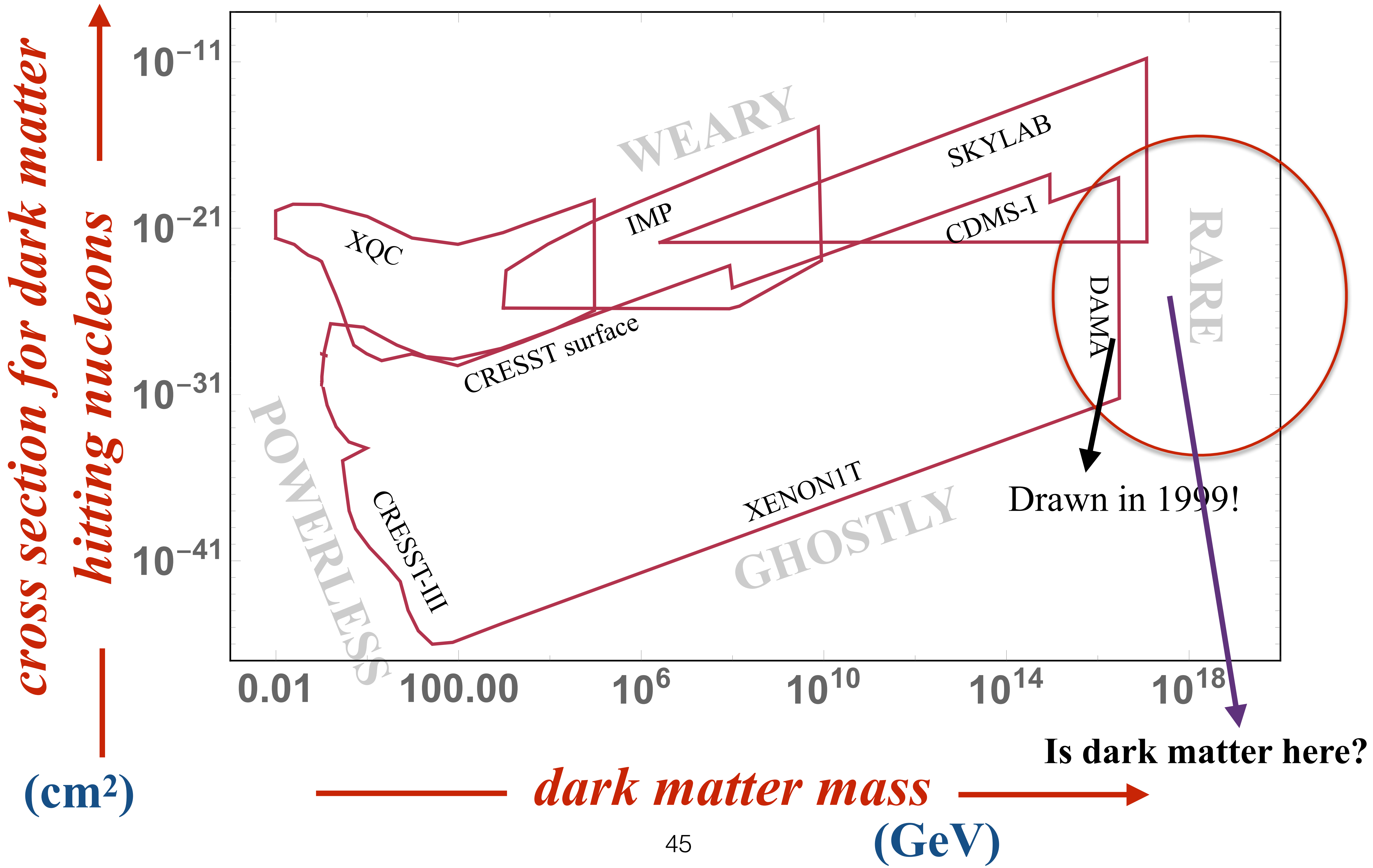
dark matter mass

2 x 10^{16} GeV

DAMA limit



Hunting even rarer dark matter

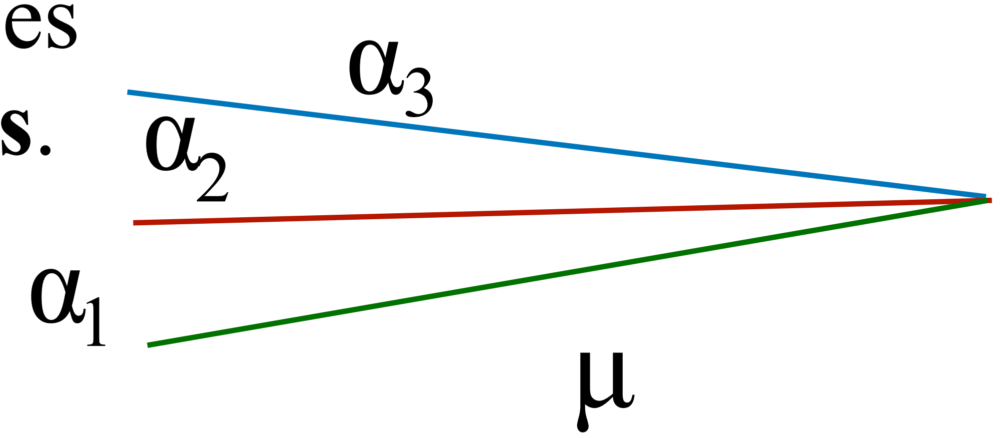


Drawn in 1999!

Is dark matter here?

Theoretical appeal

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



- Can make them in early universe:

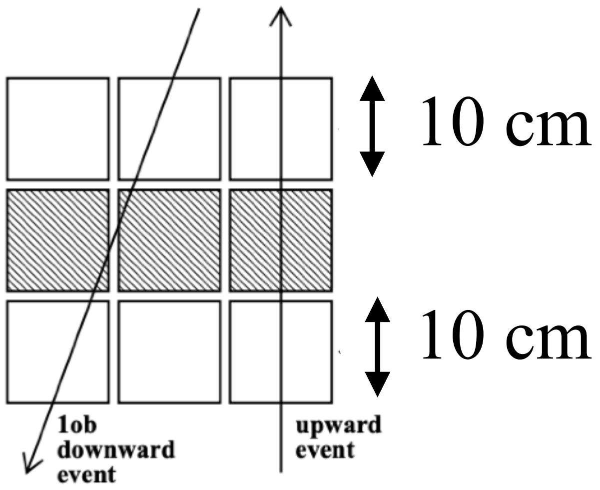
* Hawking radiation from primordial black holes
Hooper, Krnjaic, McDermott (2019)

* 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)

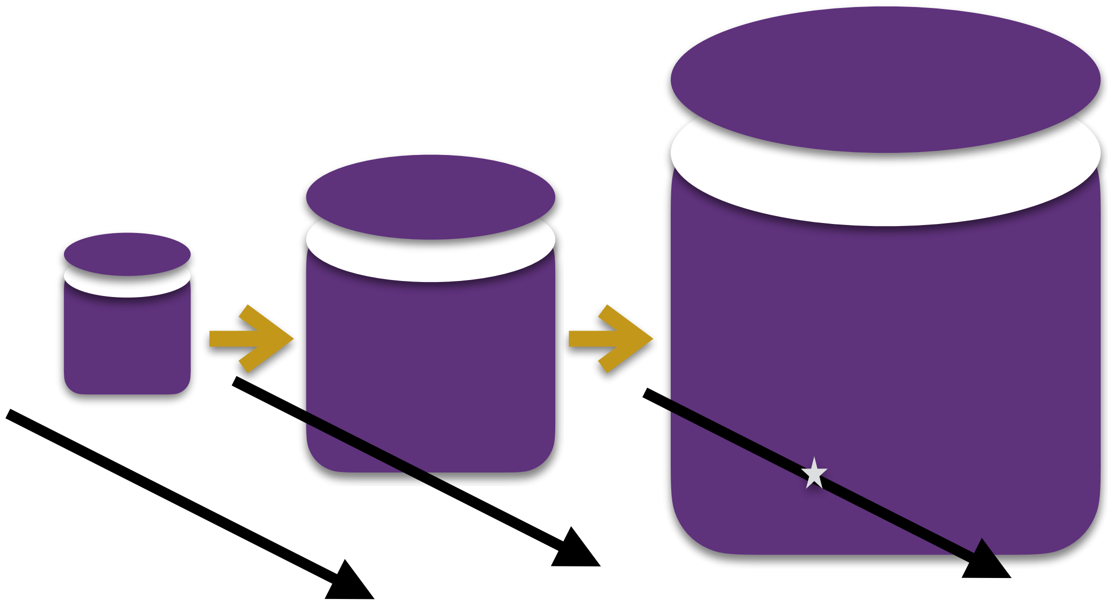
* Thermally!
Kim, Kuflik (2019)

DAMA
1999
search



350 days

TODAY



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

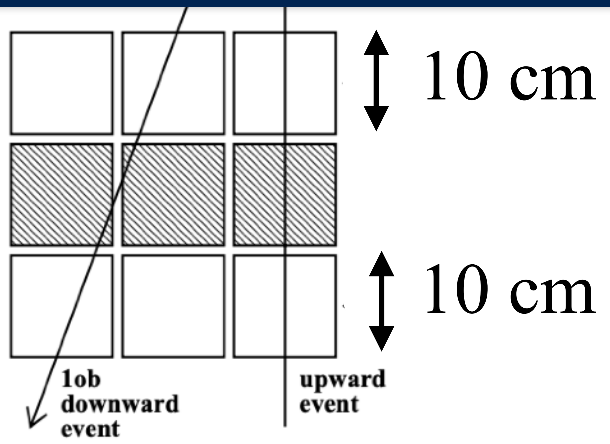
B. Broerman, J. Bramante, R. Lang, **N. Raj**
Phys.Rev.D. *(2018)*

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

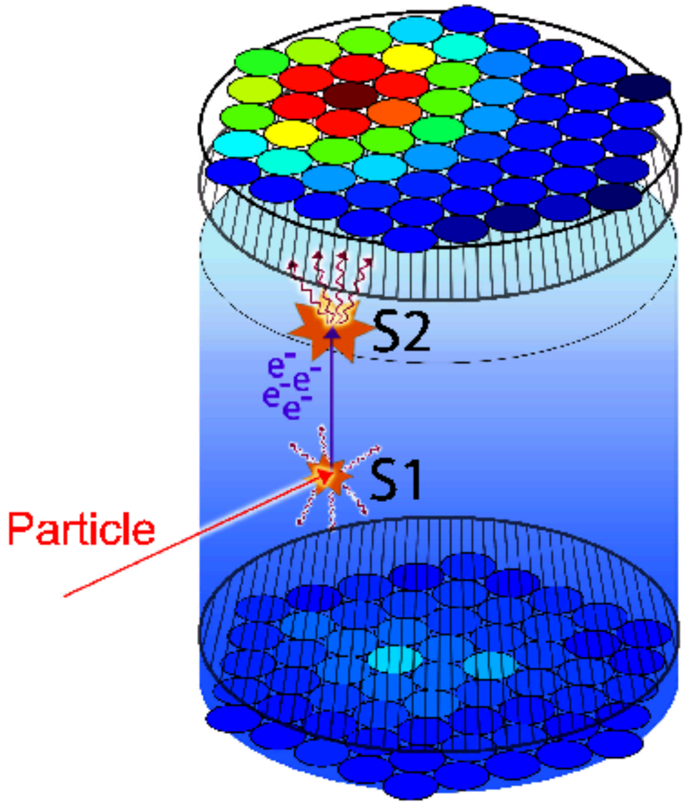
B. Broerman, J. Bramante, J. Kumar,
R. Lang, M. Pospelov, **N. Raj**
Phys.Rev.D. *(2018)*
J. Bramante, J. Kumar, **N. Raj**
Phys.Rev.D. *(2019)*

Today's dark matter detectors

DAMA 1999 search

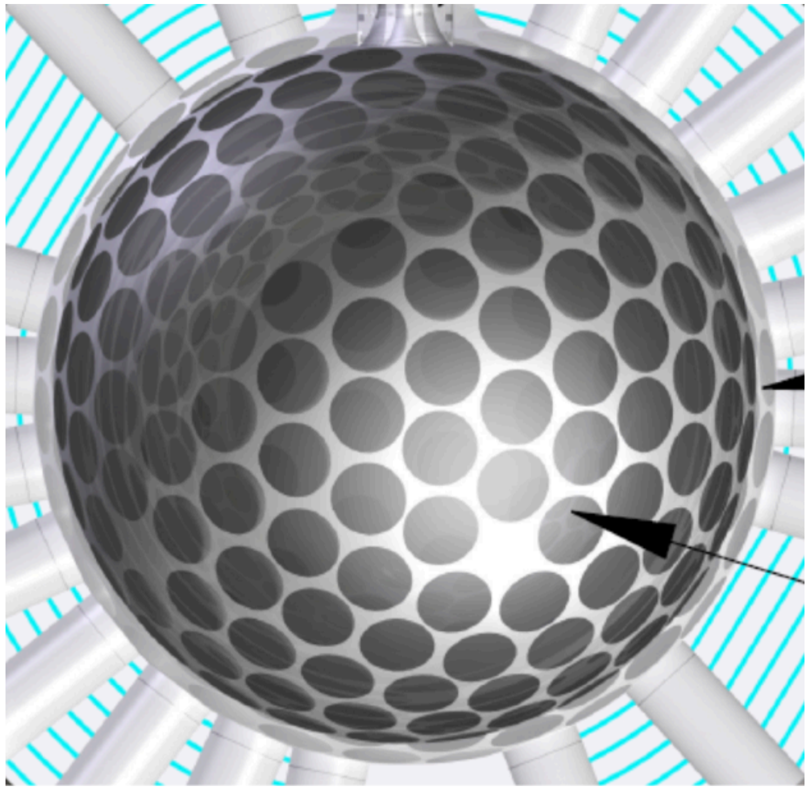


← 100 cm →



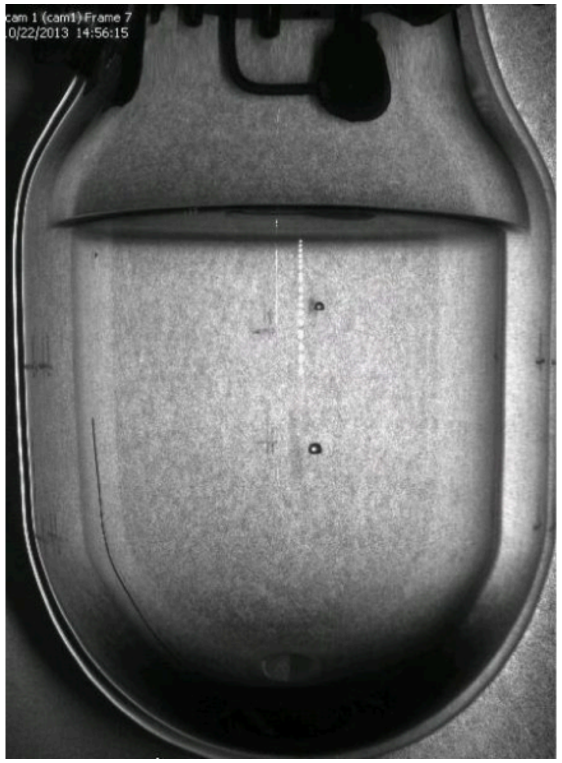
XENON1T/ LUX/ PANDAX-II

← 130 cm →



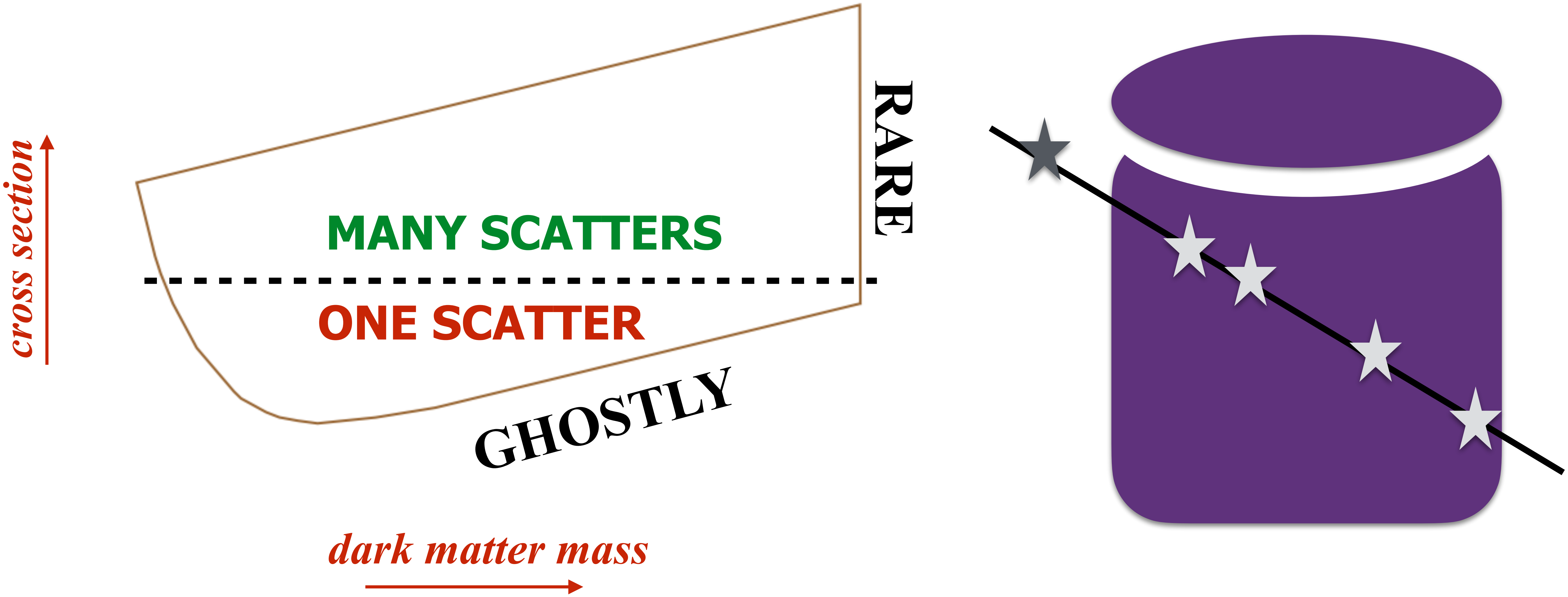
DEAP-3600

← 50 cm →



PICO-40L

Multiscatter signatures essential



MANY SCATTERS

ONE SCATTER

RARE

GHOSTLY

cross section

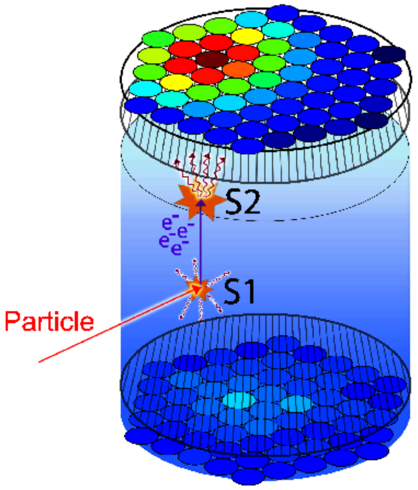
dark matter mass

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

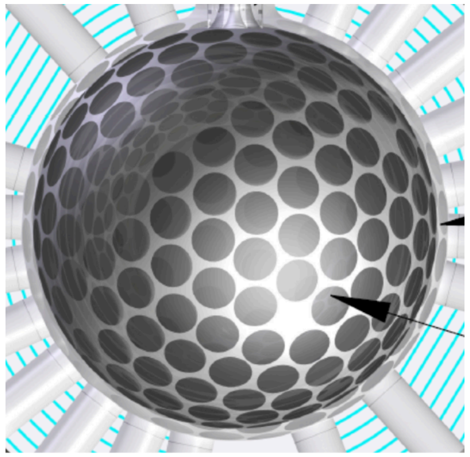
Phys.Rev.D. *(2018)*

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

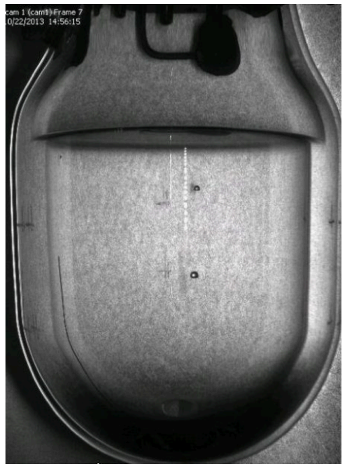
B. Broerman, J. Bramante, J. Kumar,
R. Lang, M. Pospelov, **N. Raj**
Phys.Rev.D. *(2018)*



XENON1T



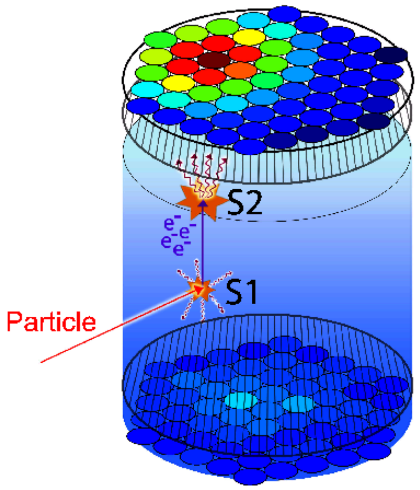
DEAP-3600



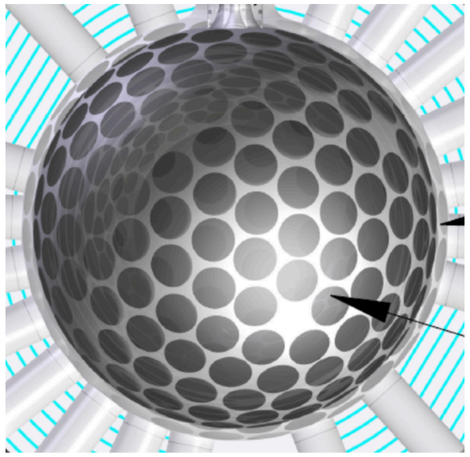
PICO-40L

Reverse Rutherford

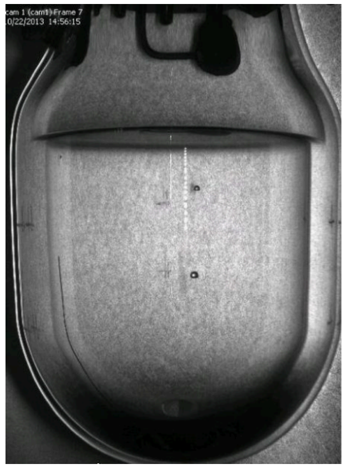
Experiment 2



XENON1T

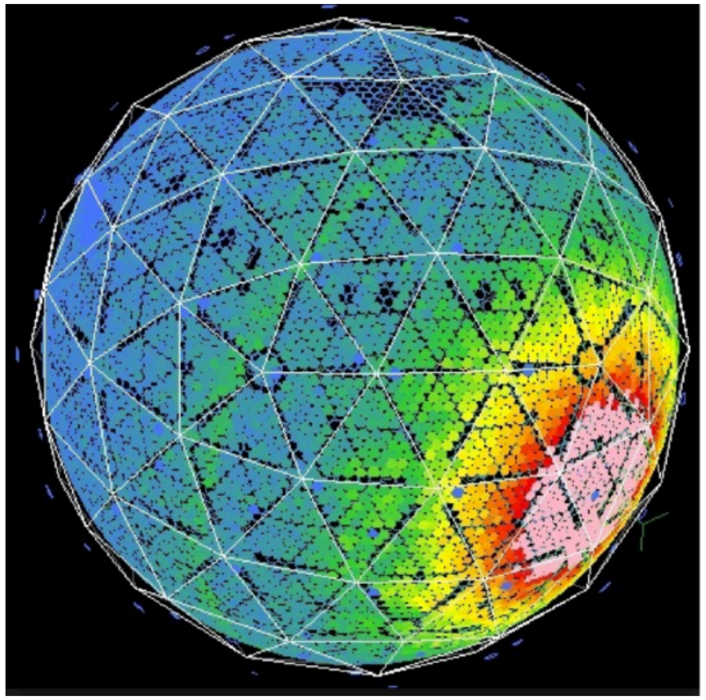


DEAP-3600



PICO-40L

+

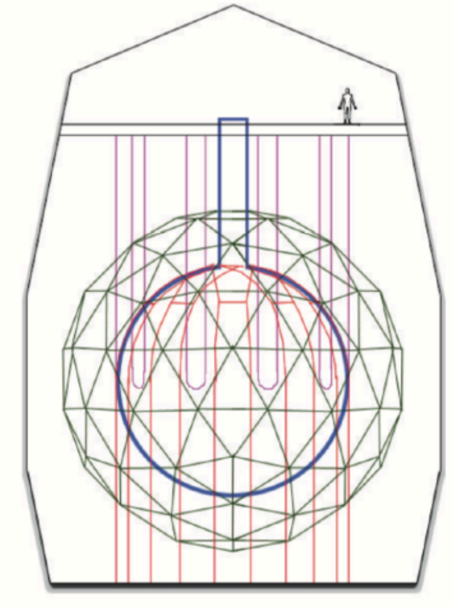


neutrino detectors

(Q2) Large volume neutrino detectors?

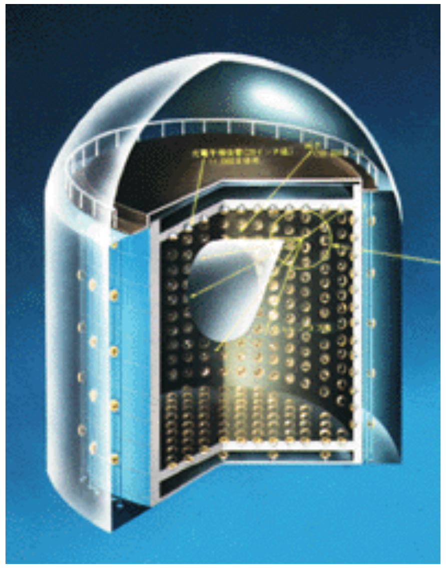
Organic liquid scintillator (SNO+, Borexino, etc.):
well-suited for dark matter search!
collect enough light in PMTs => in business

✓



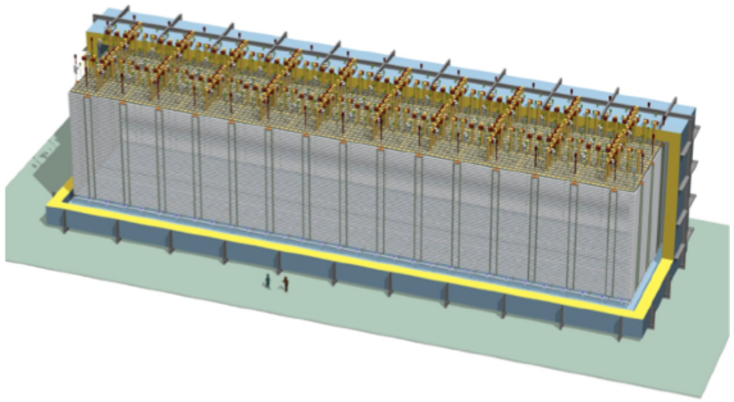
Water Cerenkov (Super-K, SNO, etc.) unsuitable:
non-relativistic scattering

⛔



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

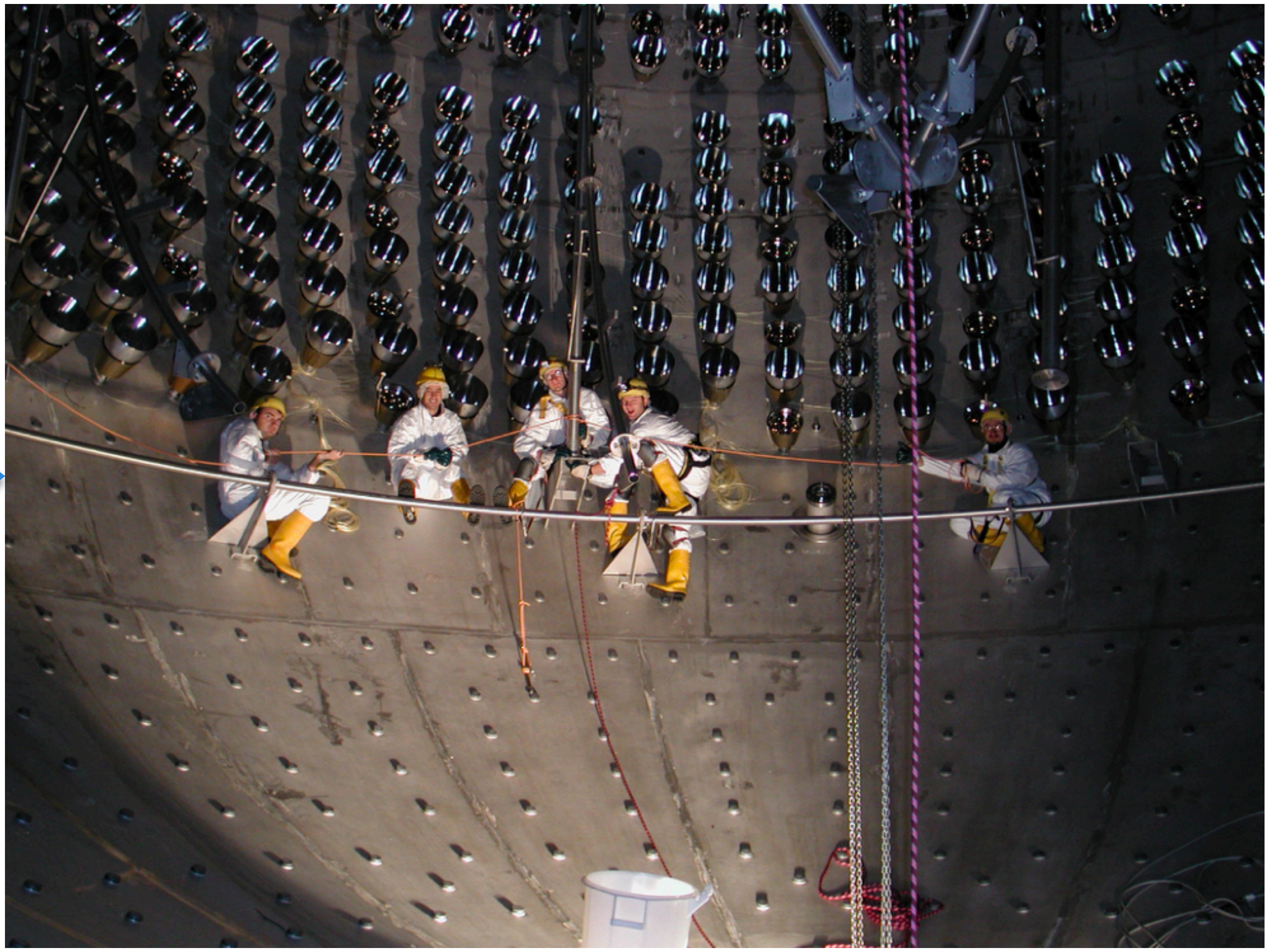
⛔



Liquid scintillator neutrino detectors

XENON1T, DEAP, PICO, …

BOREXINO, SNO+, JUNO



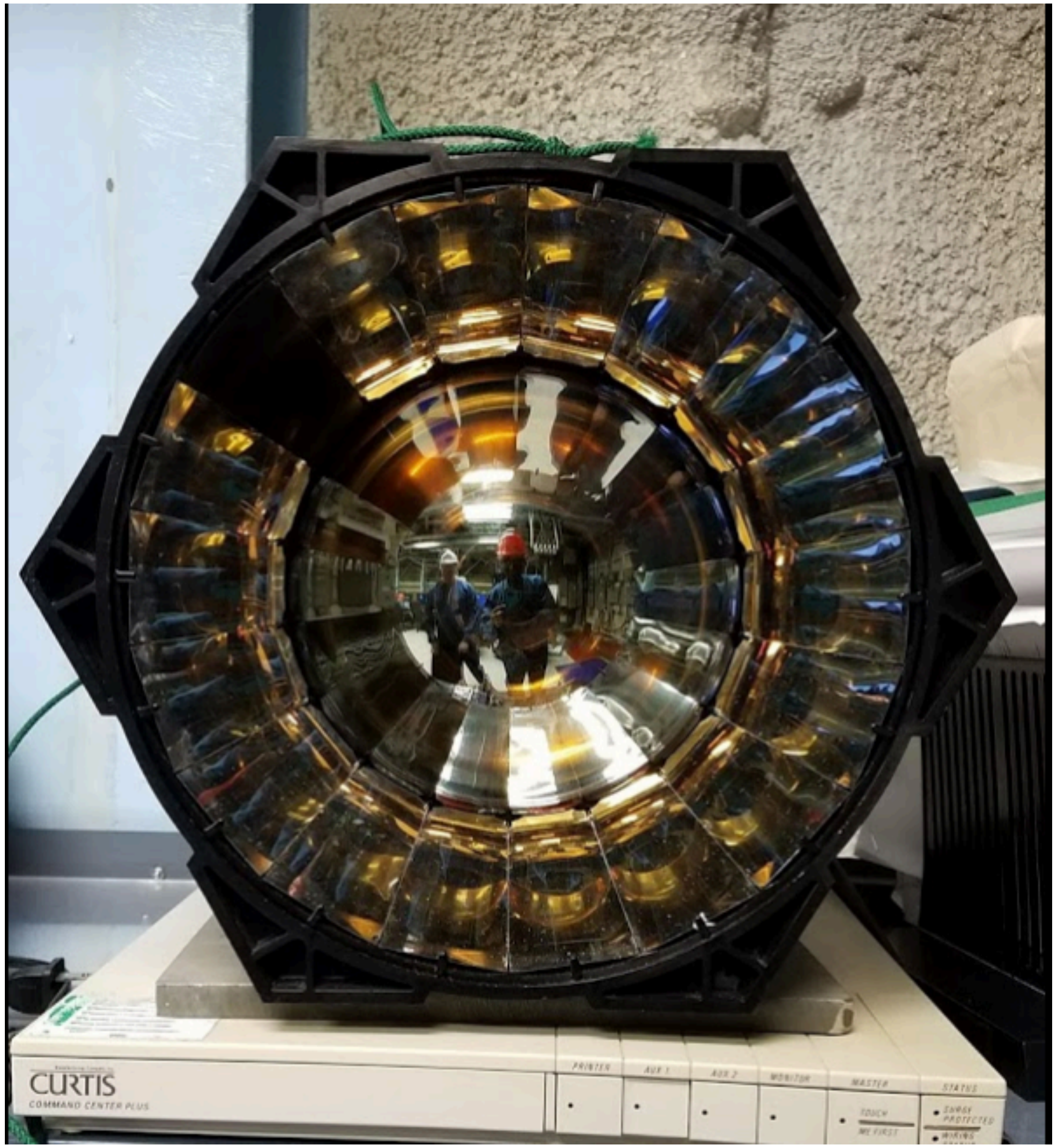
<u>Direct detection @ liq. scint. neutrino detectors</u>

Mass sensitivity: dark matter fluxes at least 100 times greater

Cross section sensitivity: Satisfy selection trigger

SNO+

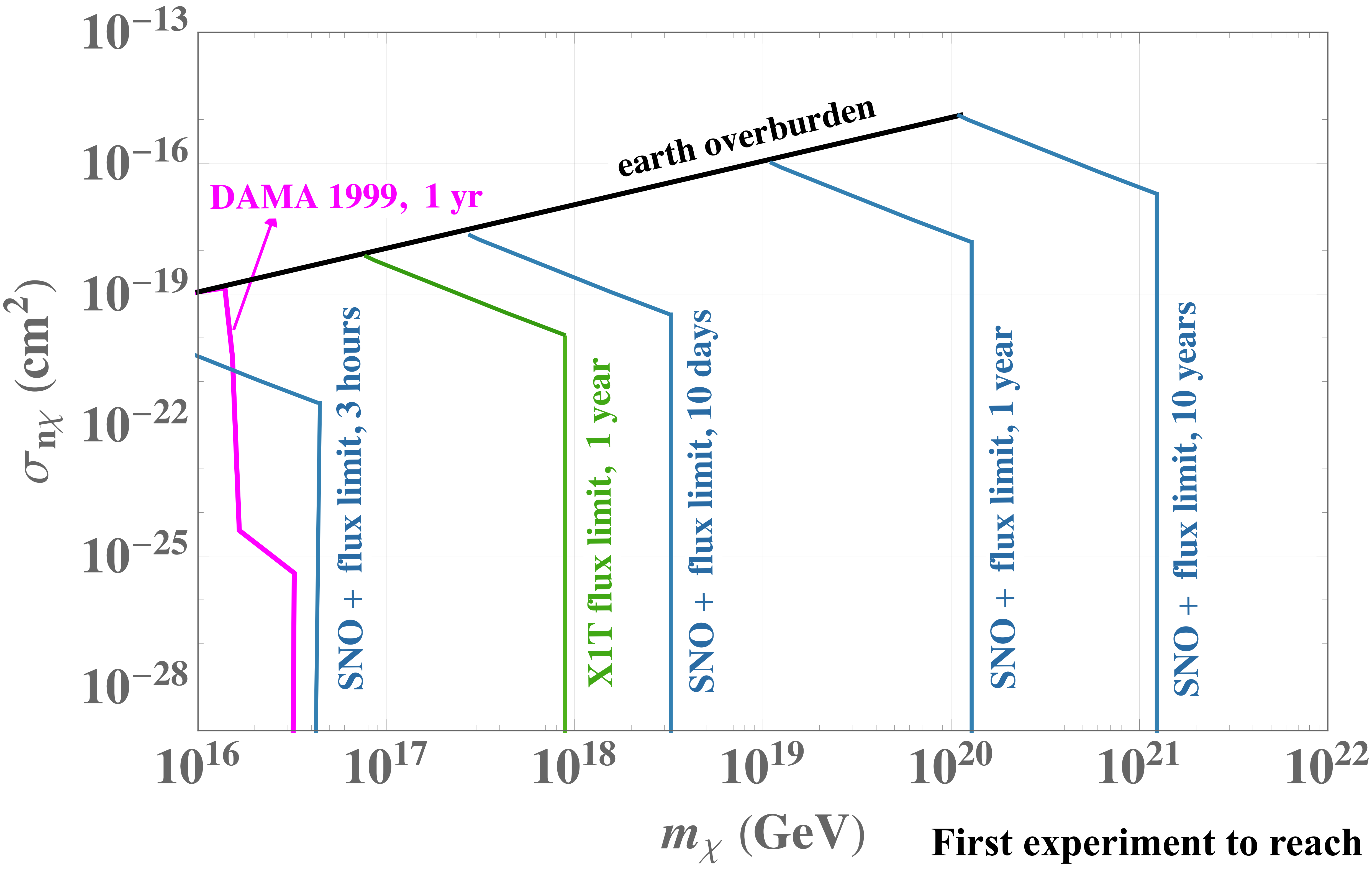
scale model @ SNOLAB



PMT selfie 2 km underground

SNO+ mass reach

“fiducial area” = 10^6 cm^2



First experiment to reach Planck mass!

SNO+ signal

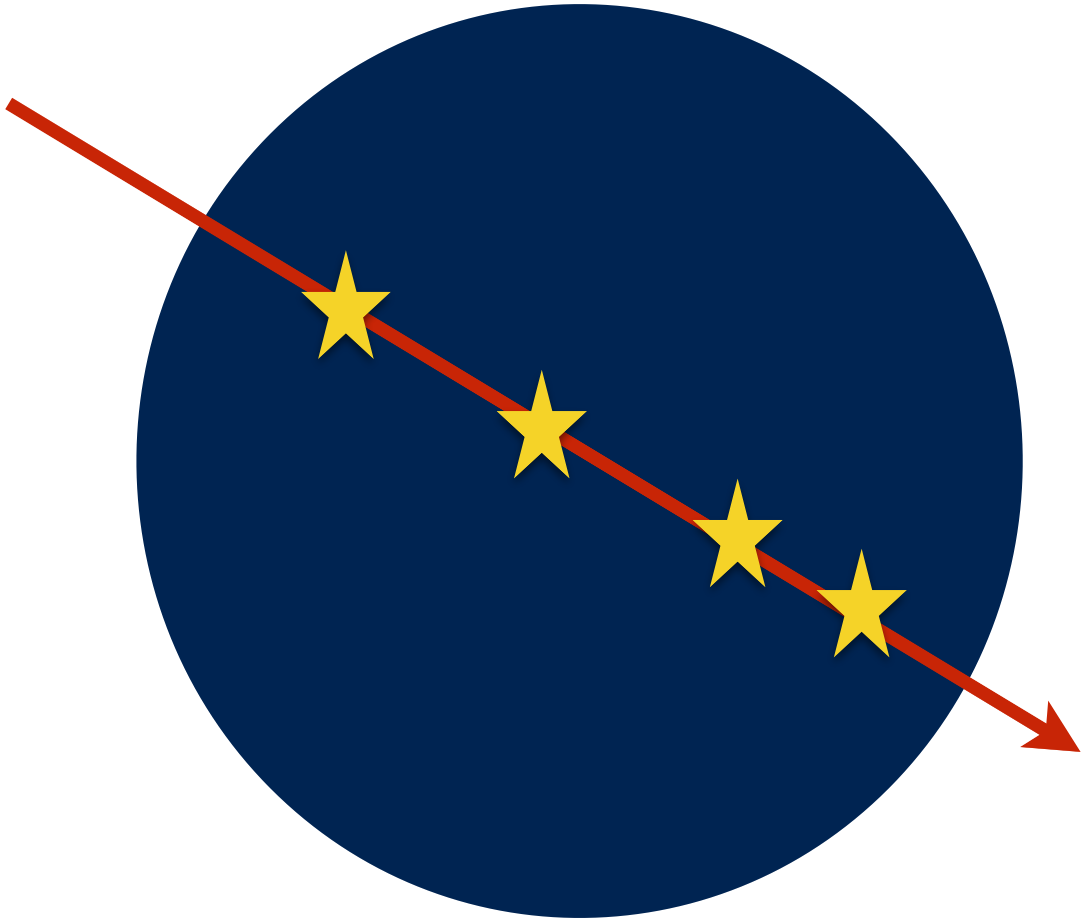
DM transit = 10 μs

- Continuous deposition of photoelectrons over transit time

- Collinearity

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

may be exploited with
vertex reconstruction/ timing information

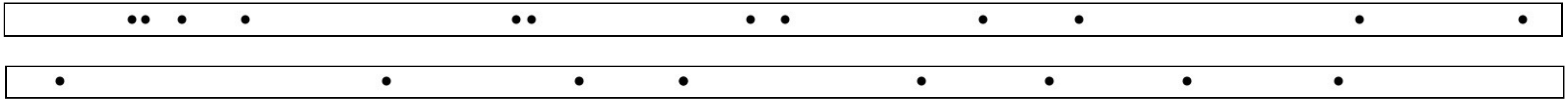


Signal vs background windows

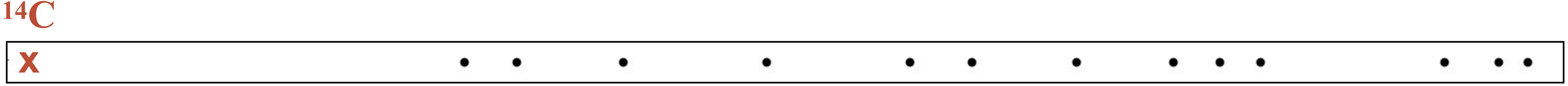
BOREXINO, 10 μs windows

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

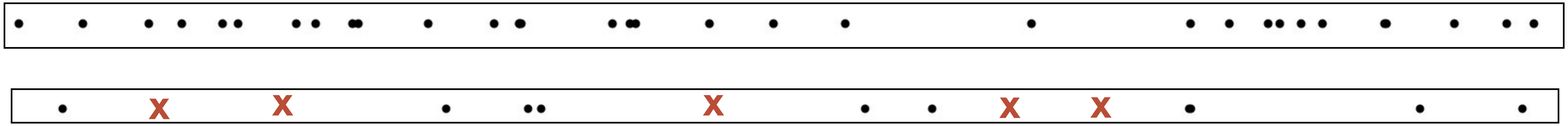
typical windows with dark counts



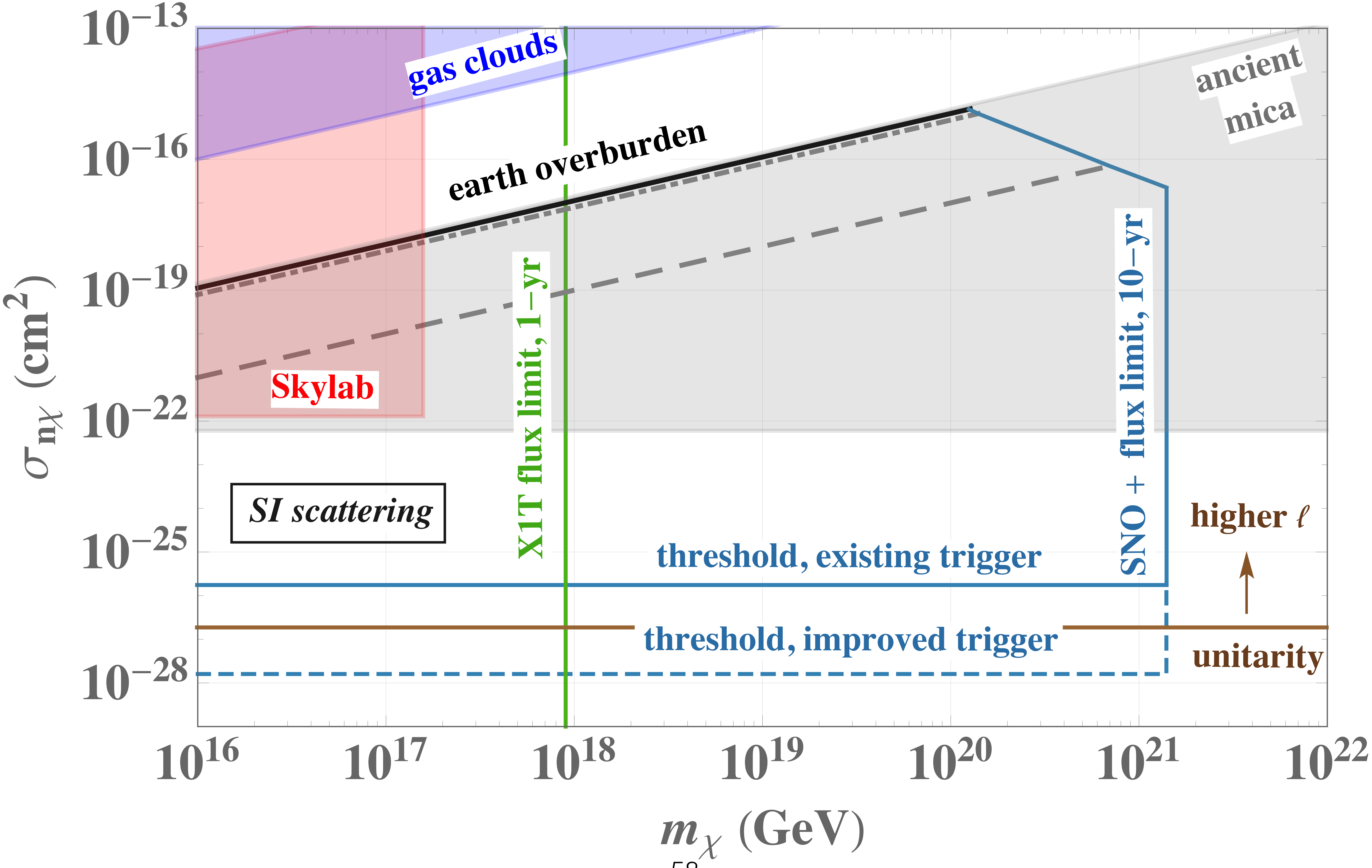
1 in 100 windows



once in 10 years

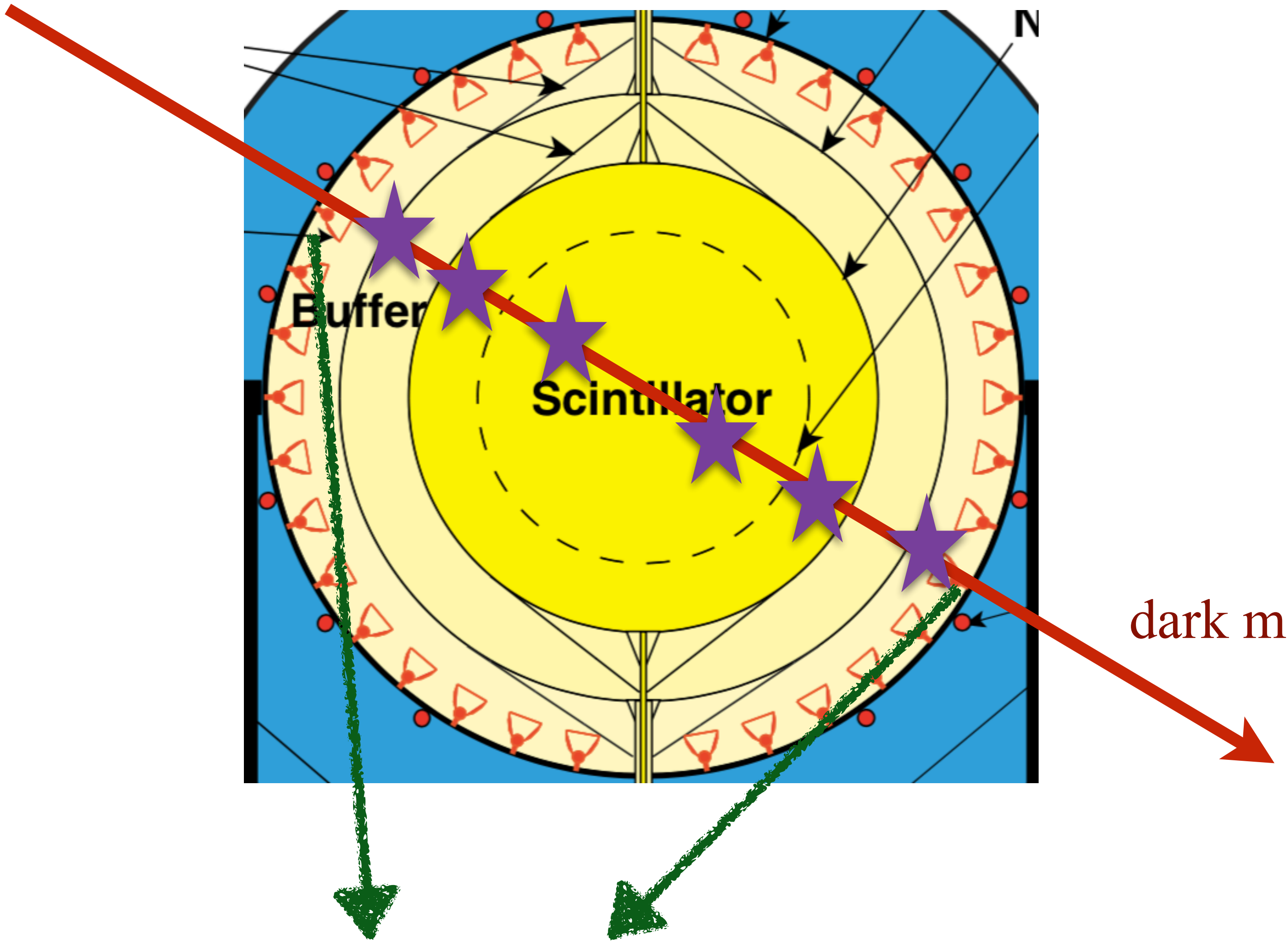


SNO+ cross section reach



Reconstructing dark matter velocity vector

Image: Borexino 1308.0443



PMT "hot spots"
with numerous illuminations

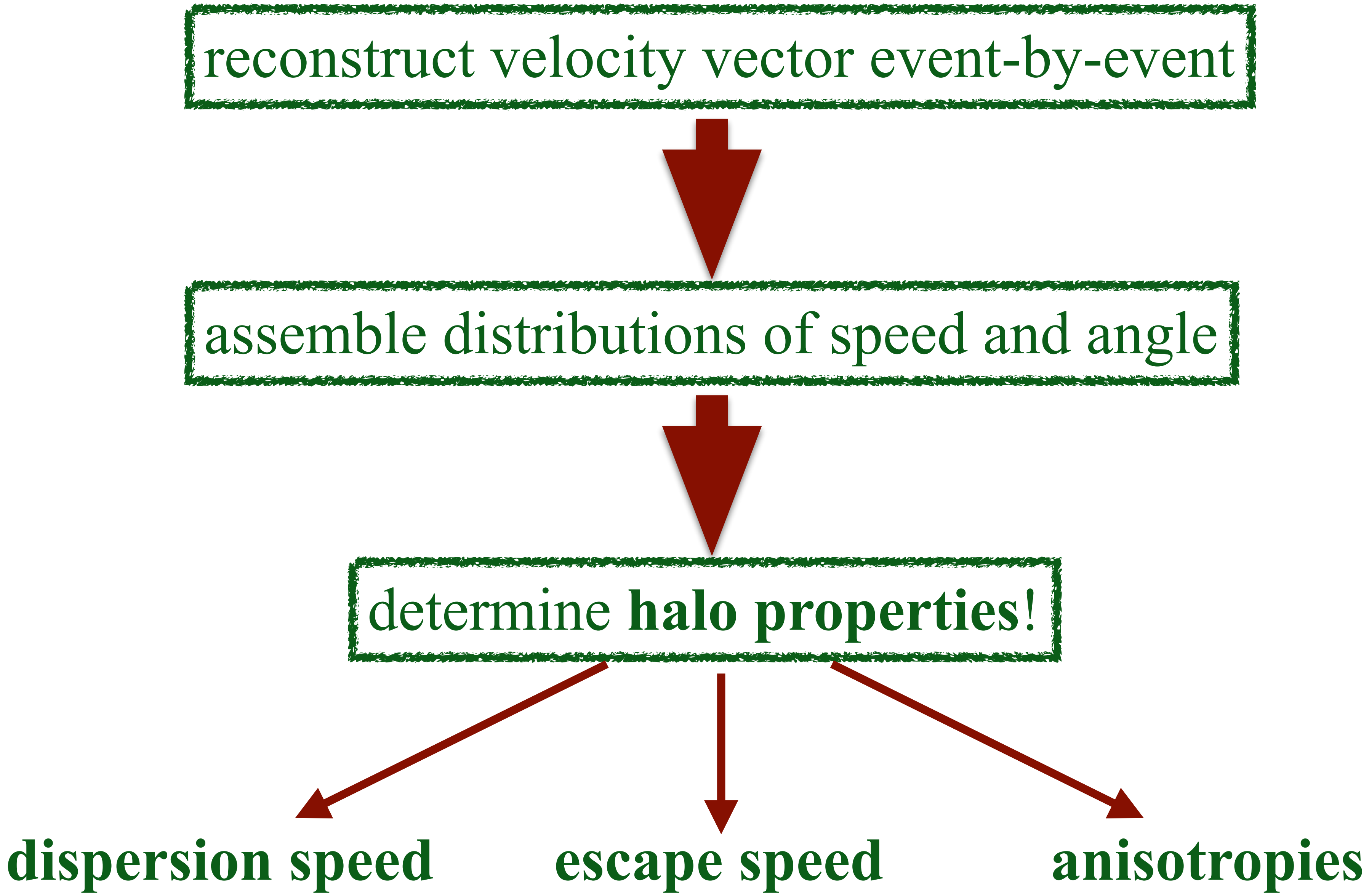
=> **dark matter direction & path length**

\+ timestamps

=> **dark matter speed**

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

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:

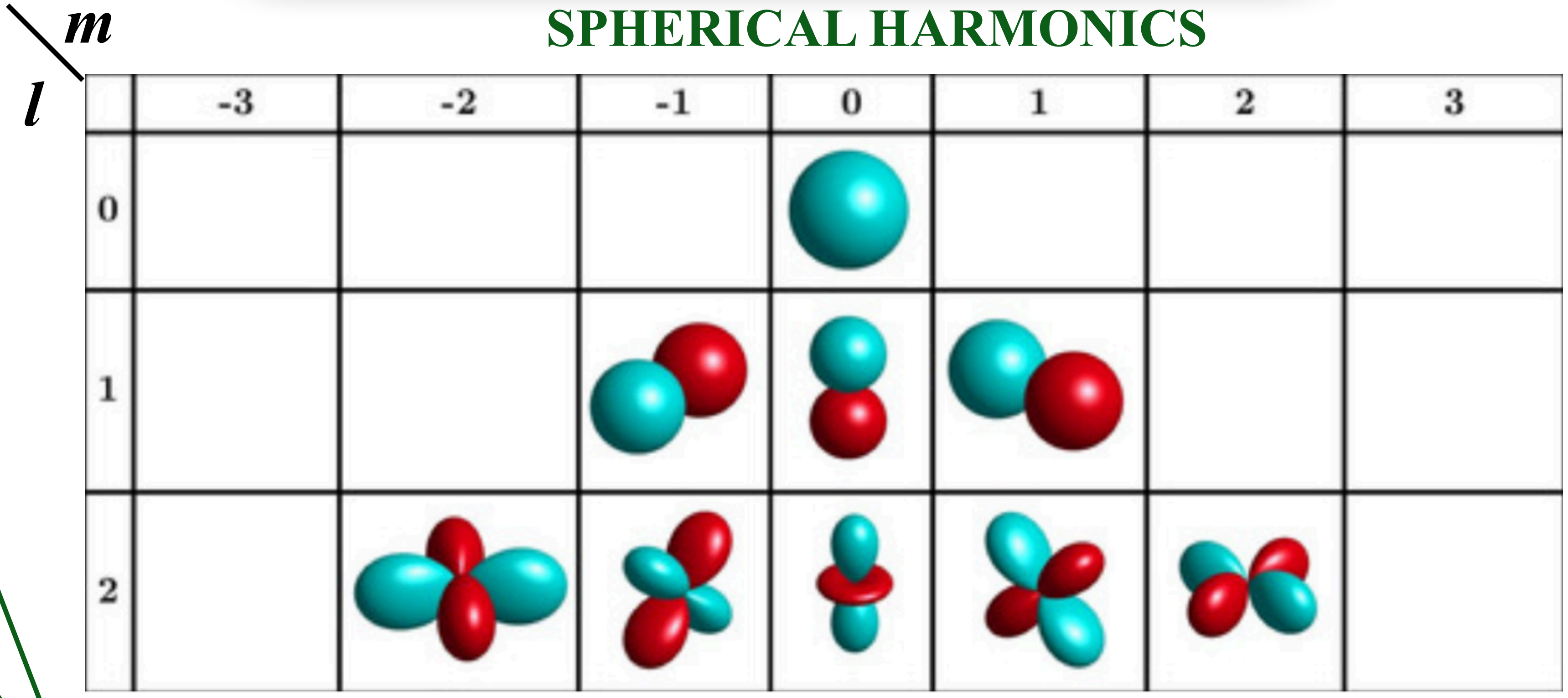
$$g(\theta, \phi) = c_{00} Y_{00} + c_{\ell m} \sum_{\ell=1,2} Y_{\ell m}$$

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

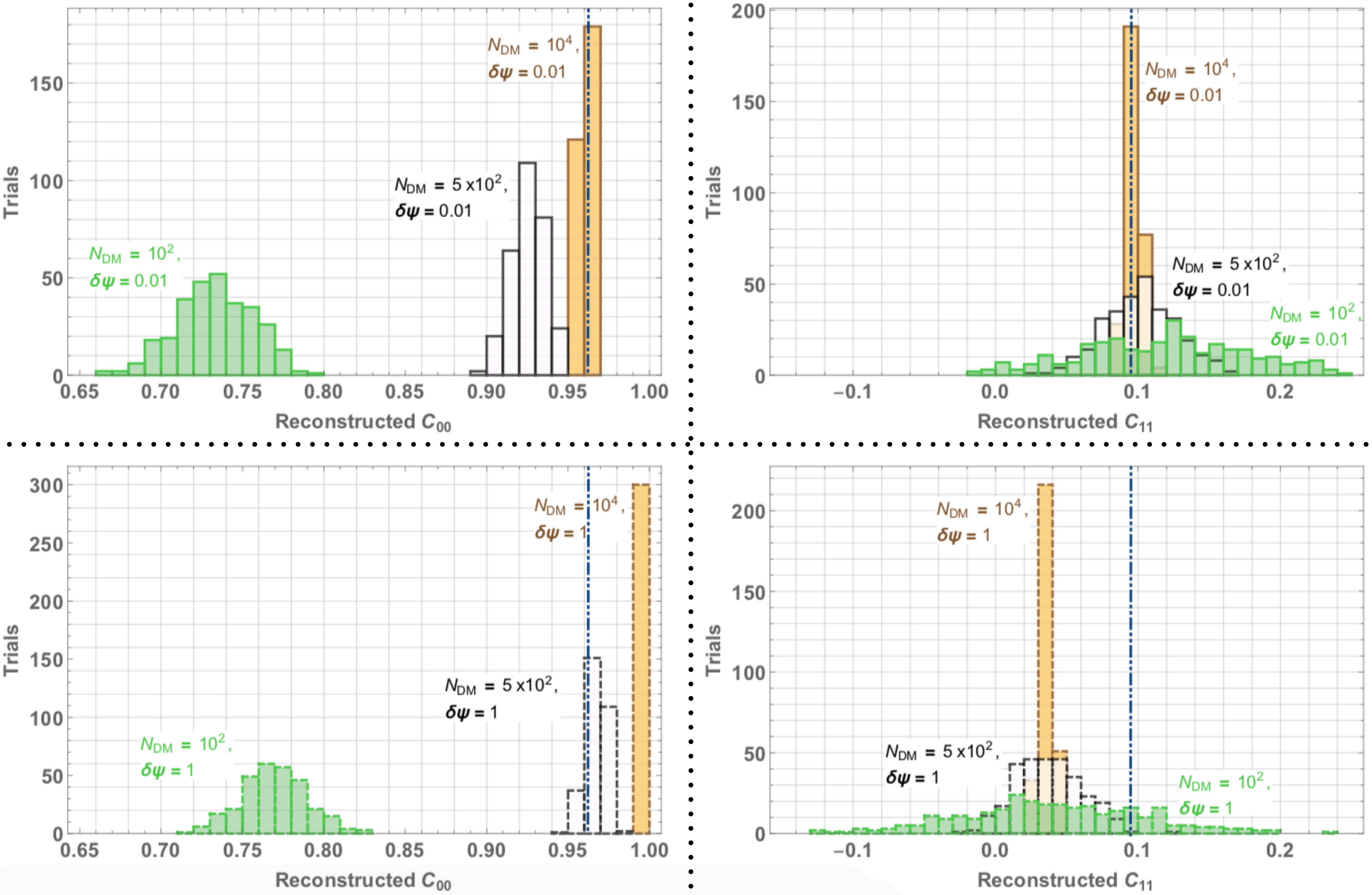
dipole coefficient

good angular resolution

(smearing negligible)

poor angular resolution

(smearing significant)

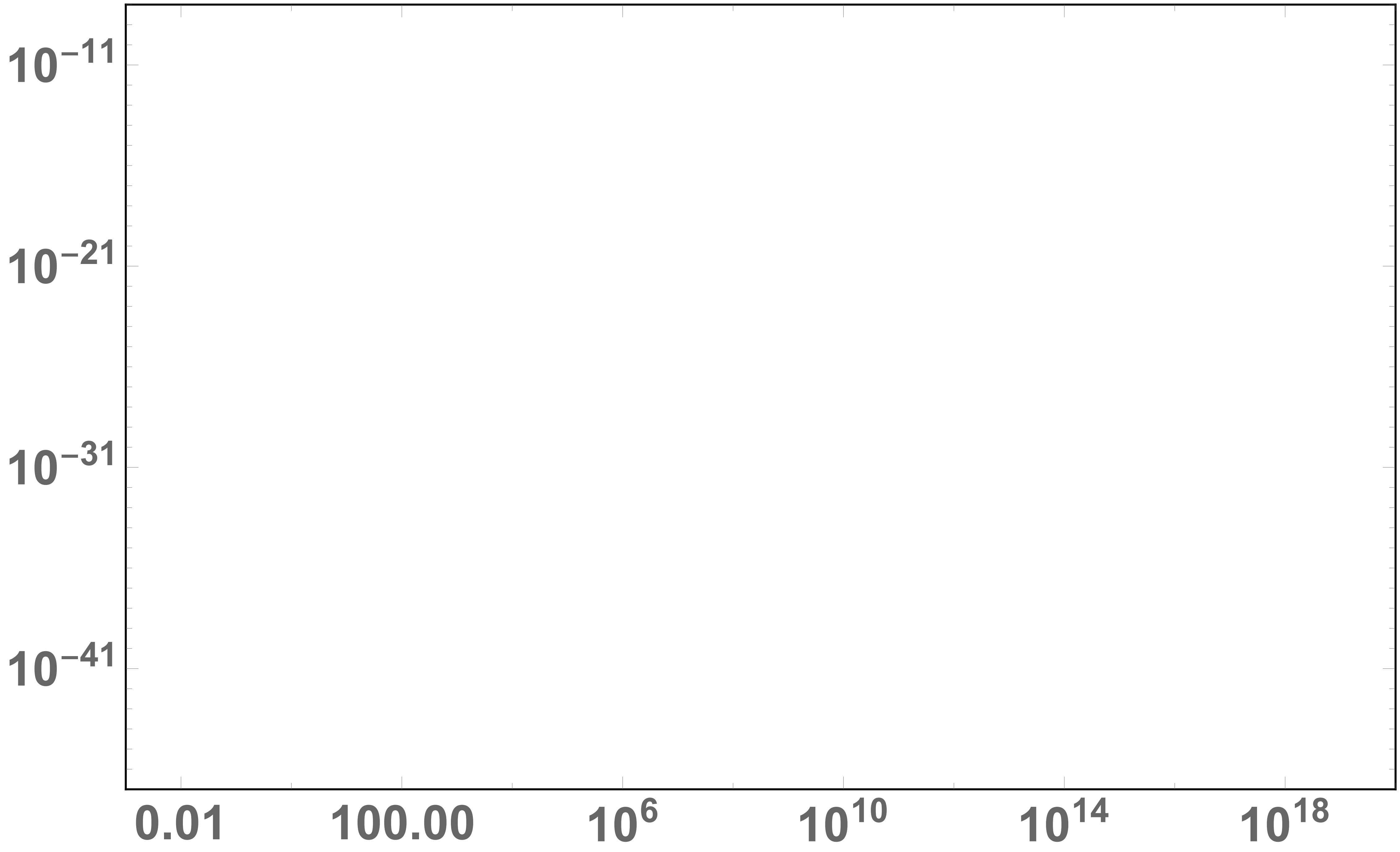


LESSONS: good statistics => accuracy & precision,
smearing => anisotropies wash out.

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

Summary

in the beginning…



cross section for dark matter hitting nucleons

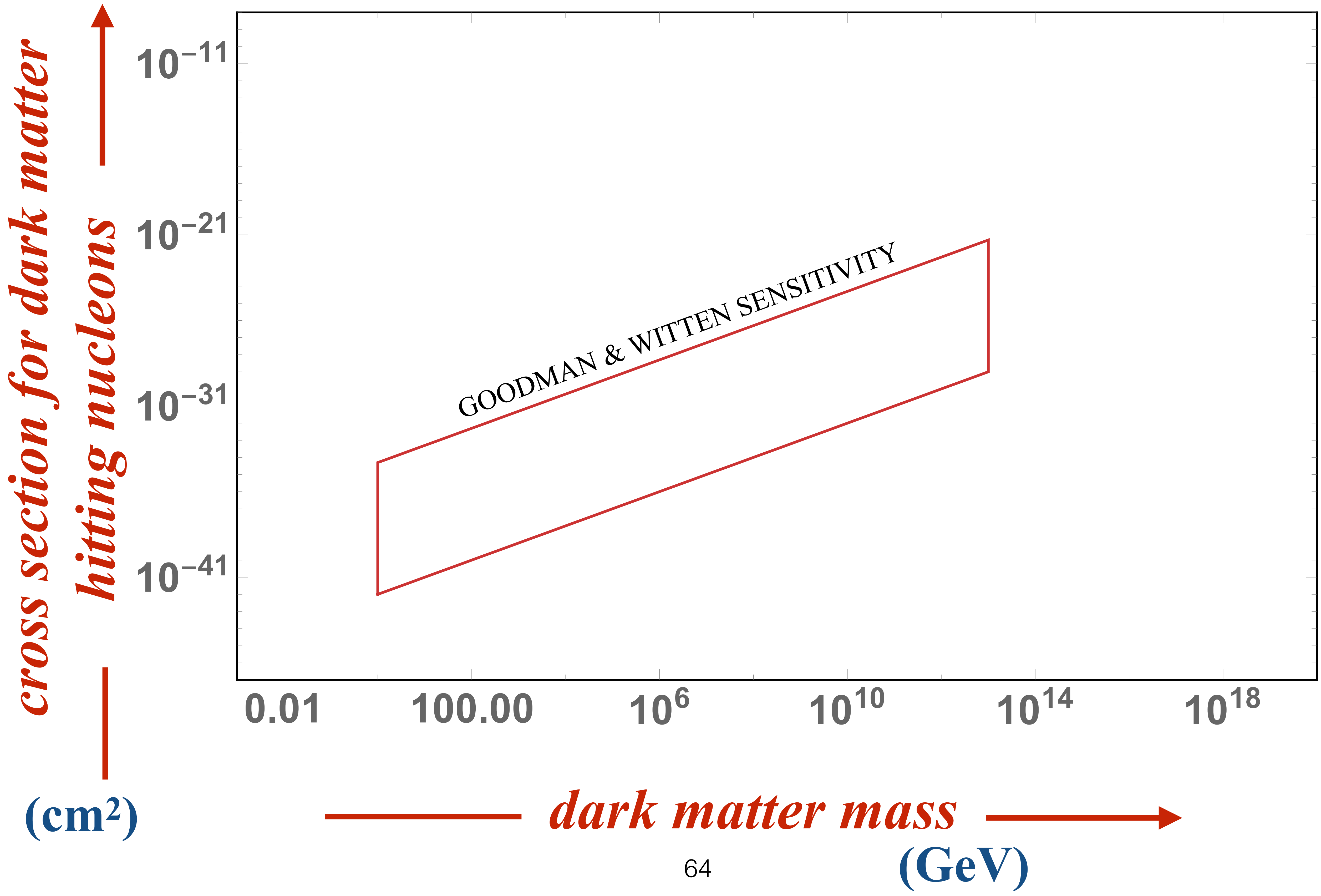
(cm²)

dark matter mass

(GeV)

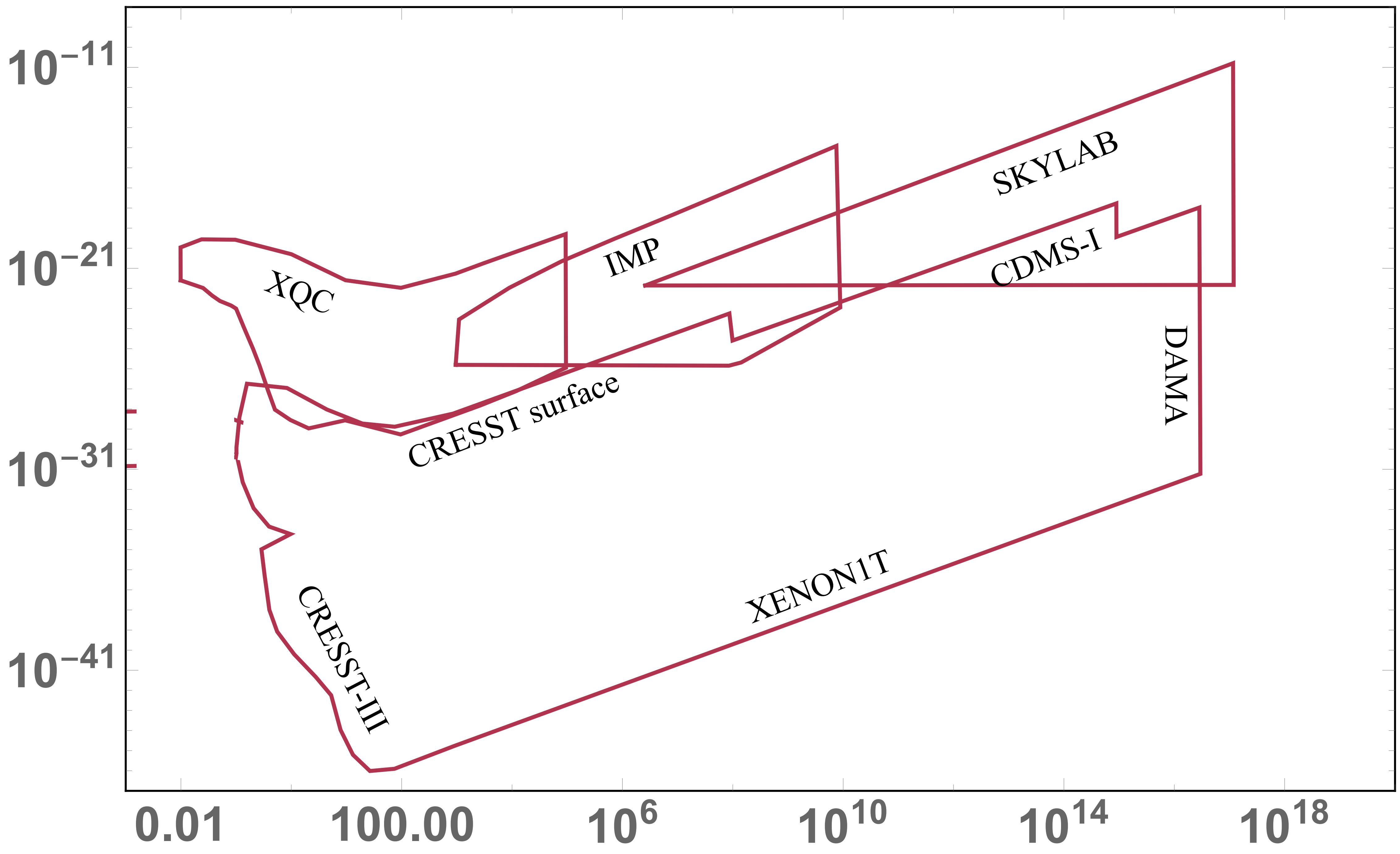
Summary

1985: enter Reverse Rutherford era of dark matter



Summary

Today: thick of the Reverse Rutherford era



cross section for dark matter hitting nucleons

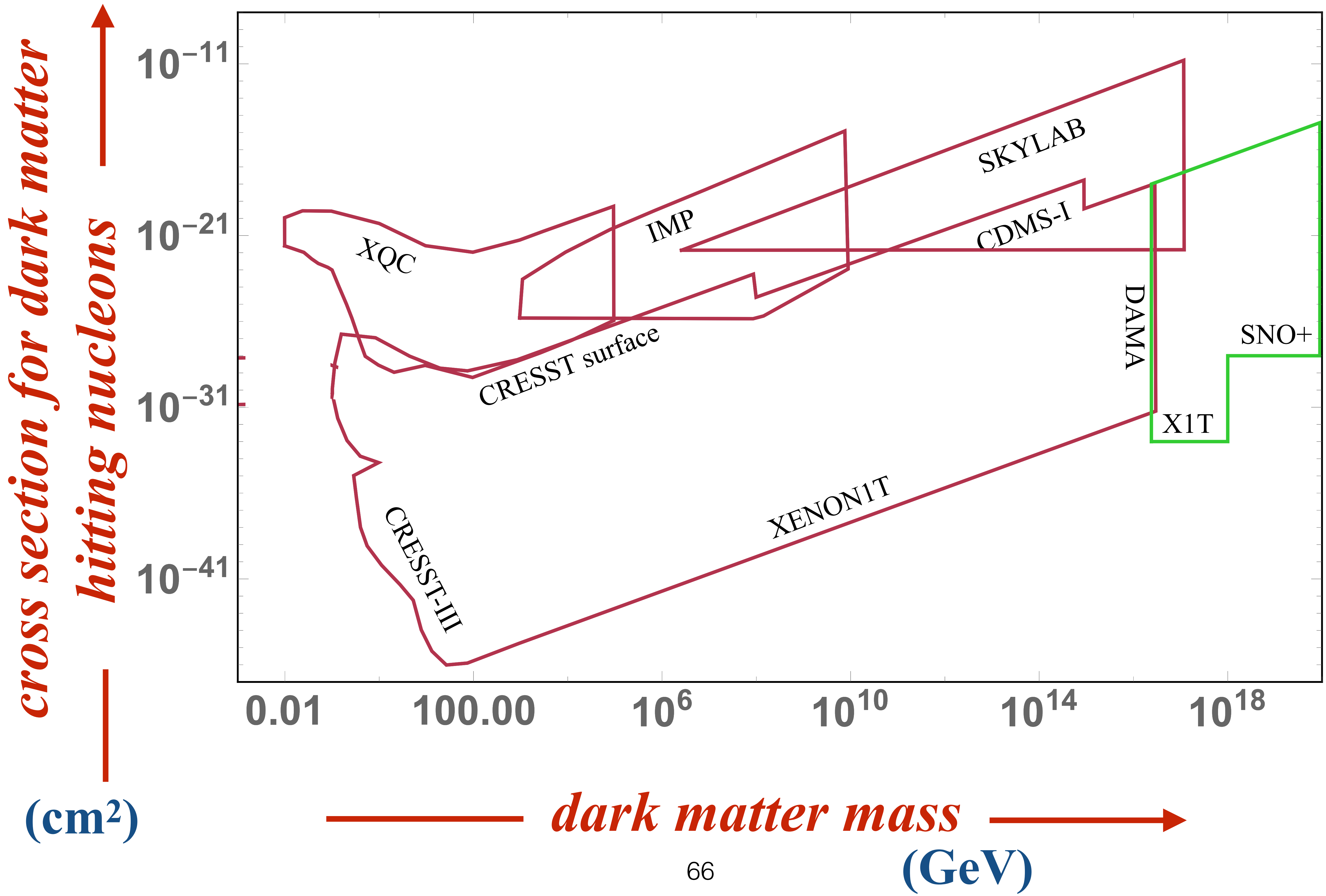
(cm²)

dark matter mass

(GeV)

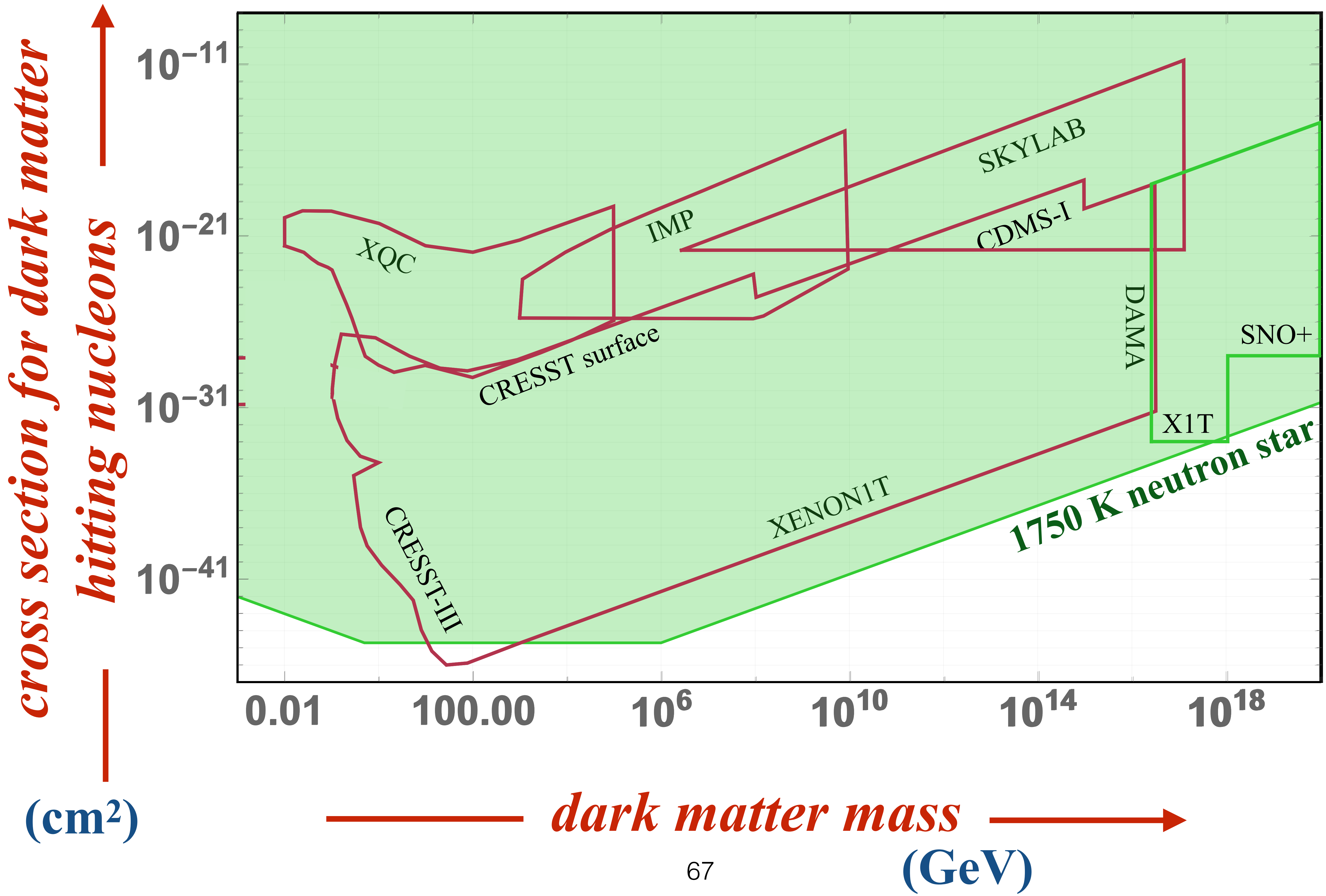
Summary

Near-future: multiscatter + repurposed neutrino detectors



Summary

Middle future: neutron star detectors



non-luminous

ubiquitous

plentiful

~~mysterious~~

THANK YOU!

QUESTIONS?

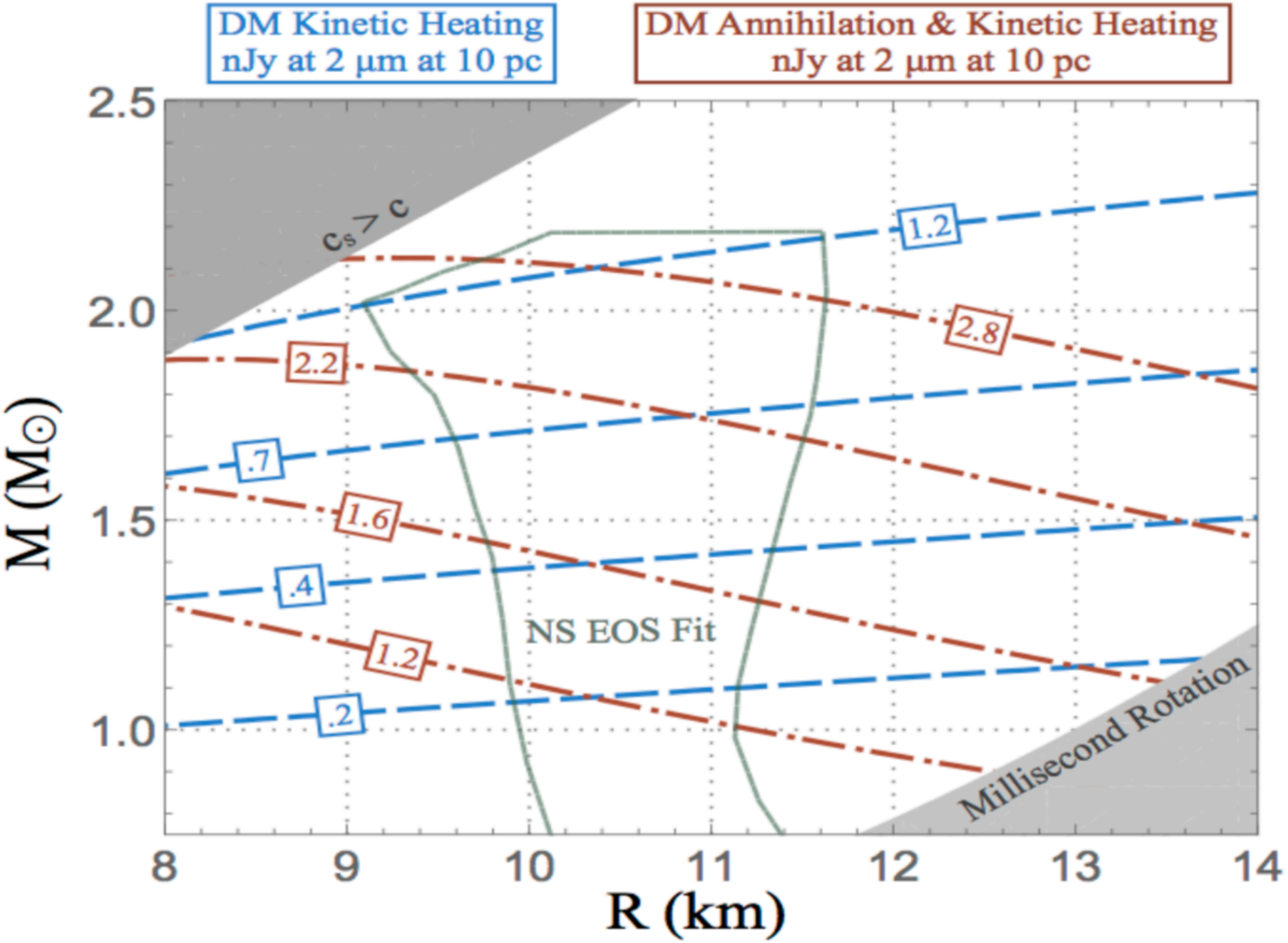
Detection: star brightness

$$L \propto \boxed{\boxed{(\gamma - 1)m_{\mathrm{DM}}} + m_{\mathrm{DM}}}$$

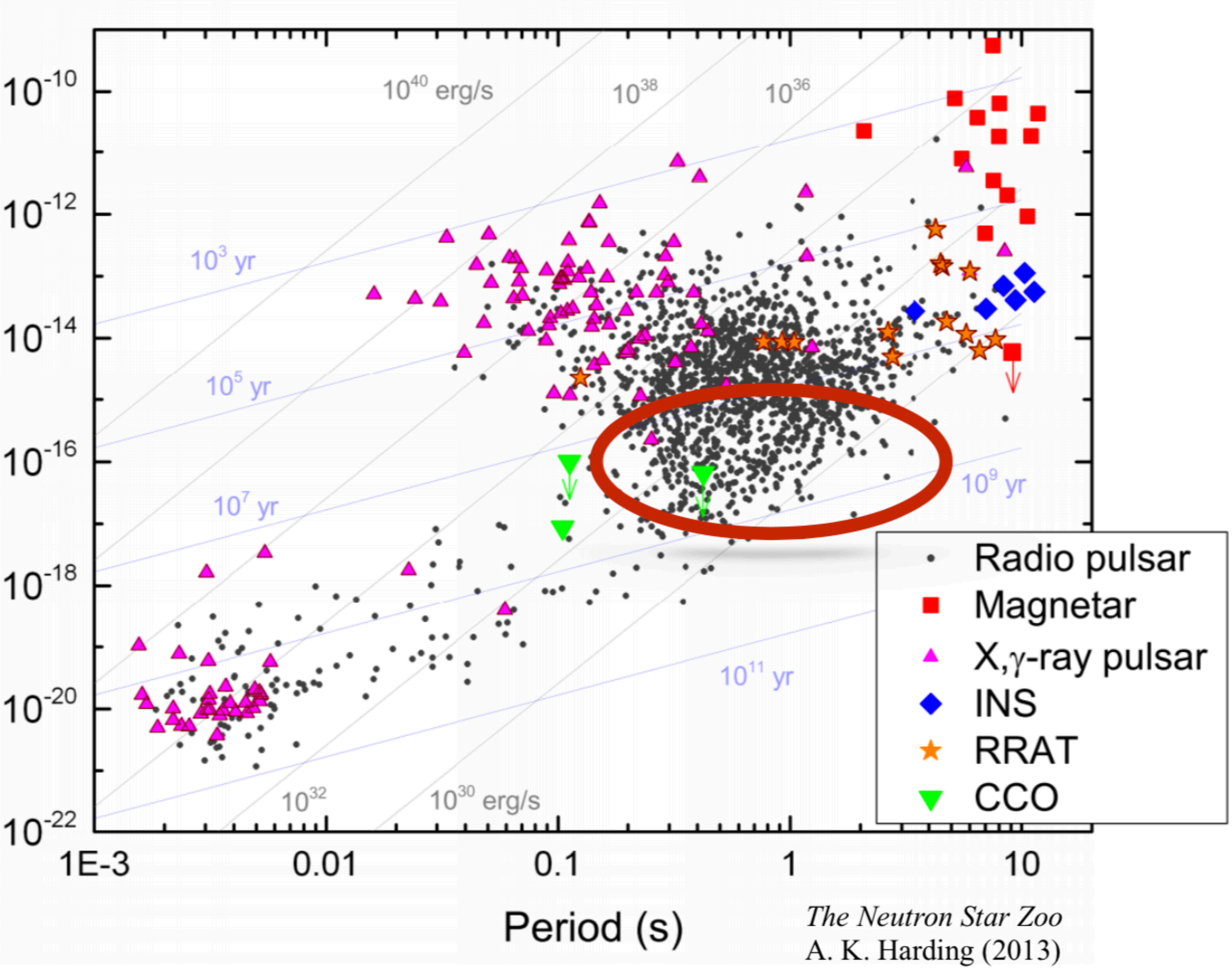
$$\left(\gamma = \frac{1}{\sqrt{1 - 2GM/R}}\right)$$

kinetic heating

+ annihilation



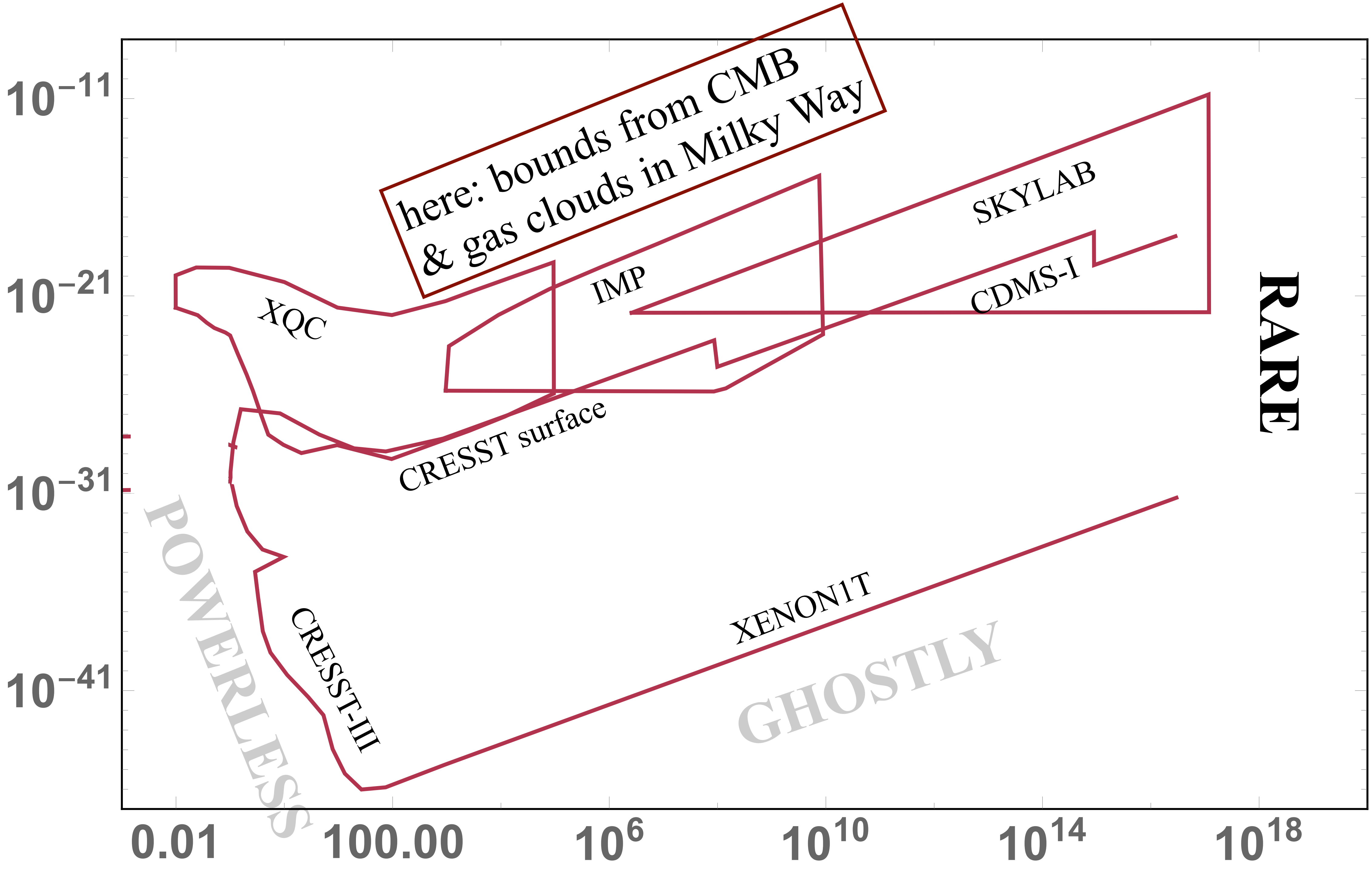
Detection: radio pulsing



The Neutron Star Zoo
A. K. Harding (2013)

cross section for dark matter hitting nucleons

(sq cm)



here: bounds from CMB & gas clouds in Milky Way

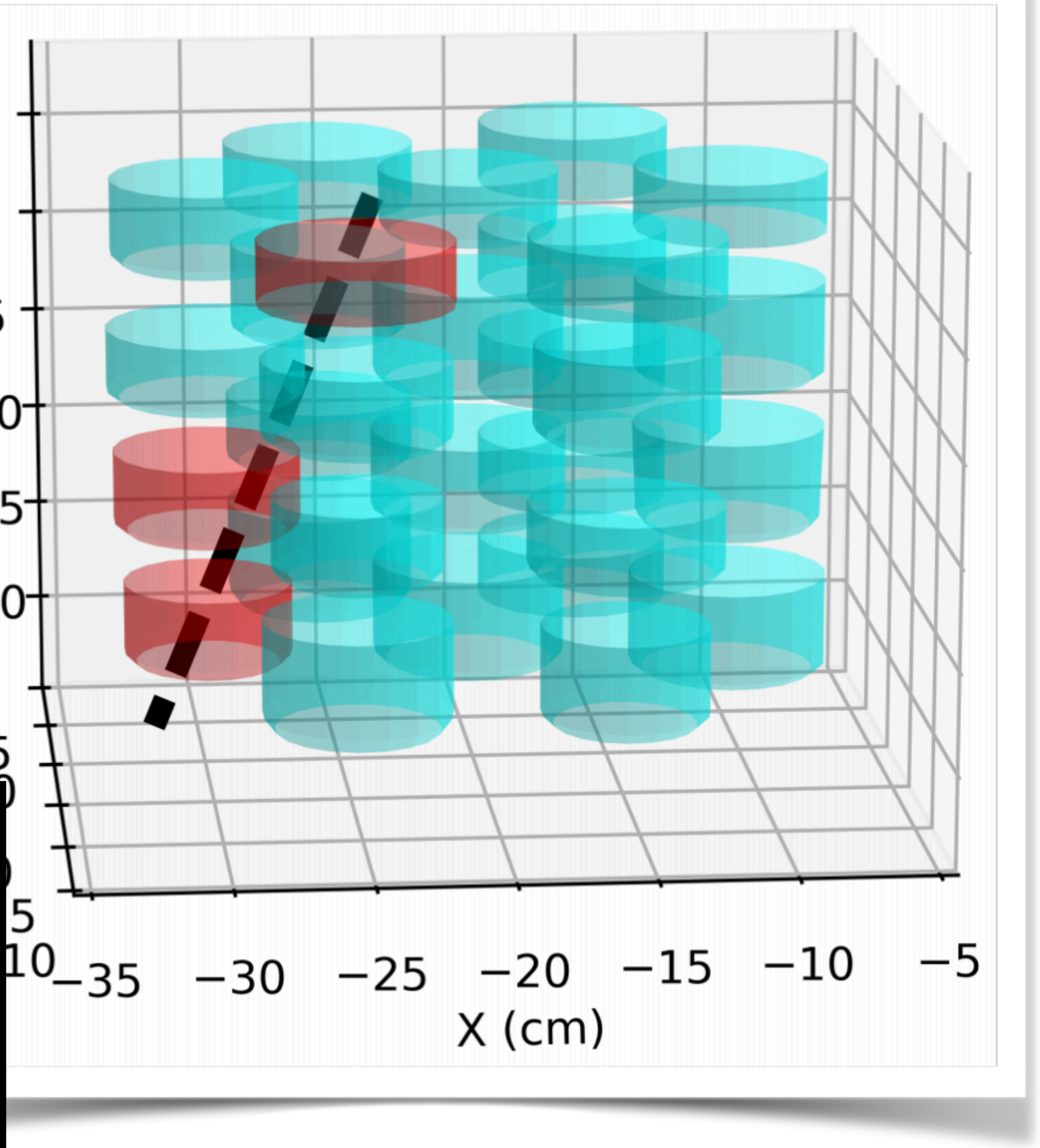
dark matter mass

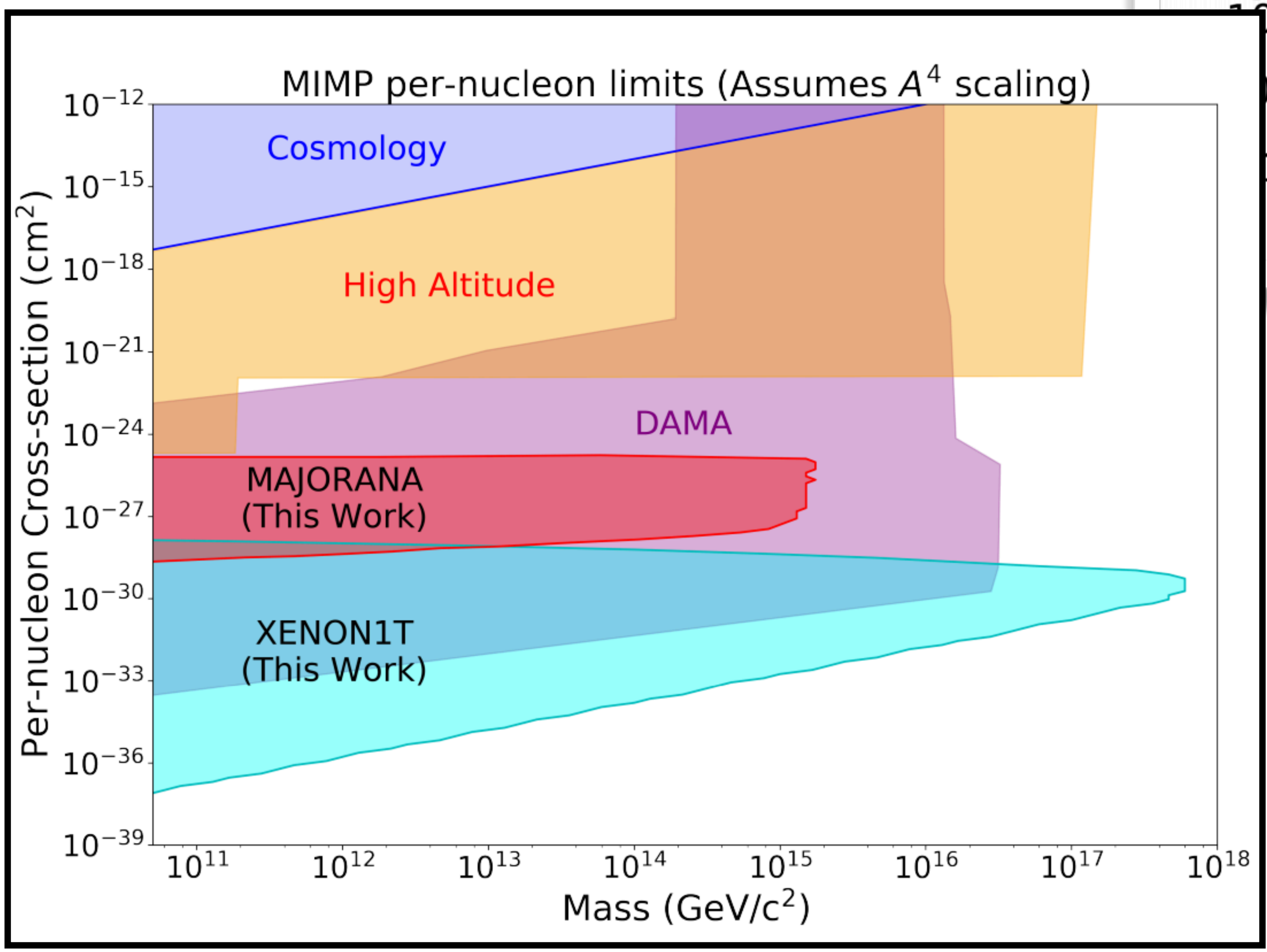
(GeV)

recasting

MAJORANA DEMONSTRATOR

search for lightly ionizing particles





‘Direct Detection Limits on Heavy Dark Matter’

2009.07909

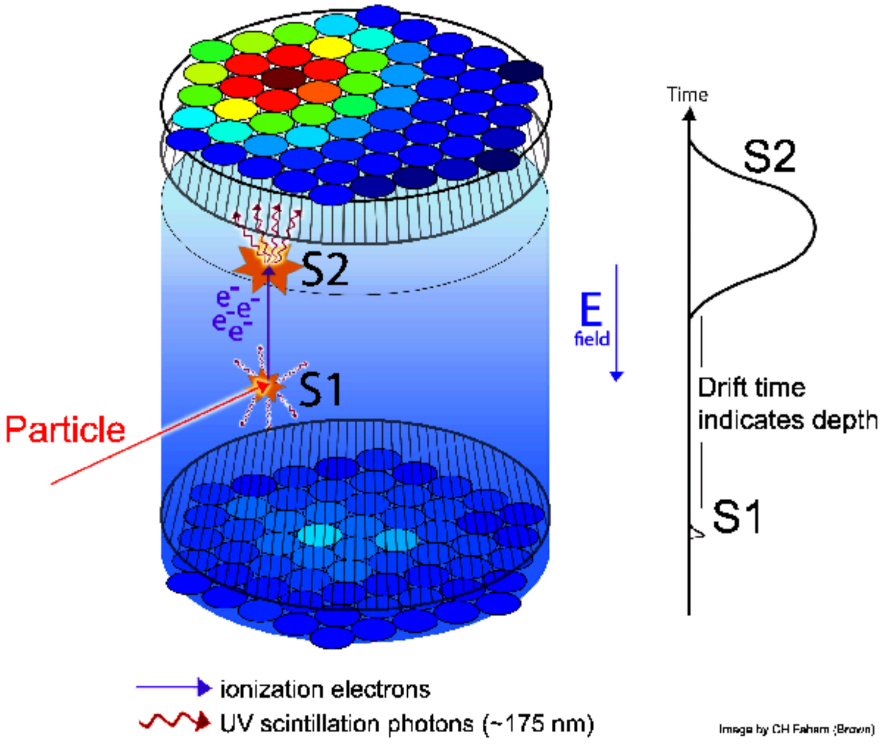
M. Clark, R. Lang et al

(Q1) Identifying multiscatterers

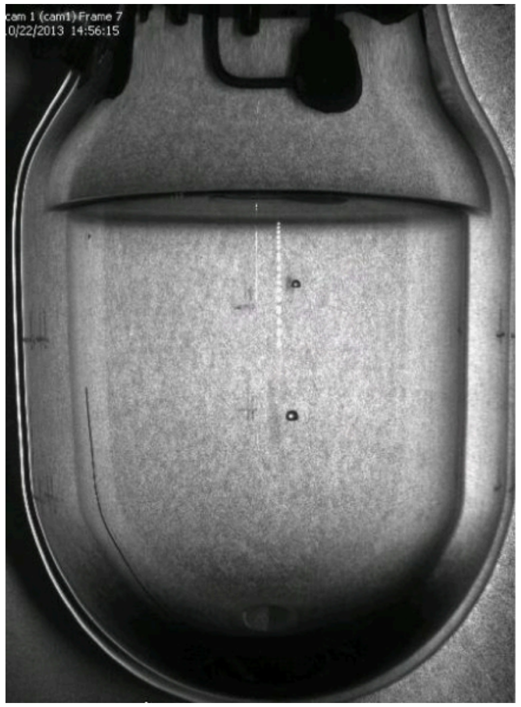
DM transit = 2.5 μs

LUX/PANDAX/XENON1T

WIMP:



PICO-60



MIMP:

Train of scintillation pulses + electroluminescence pulses

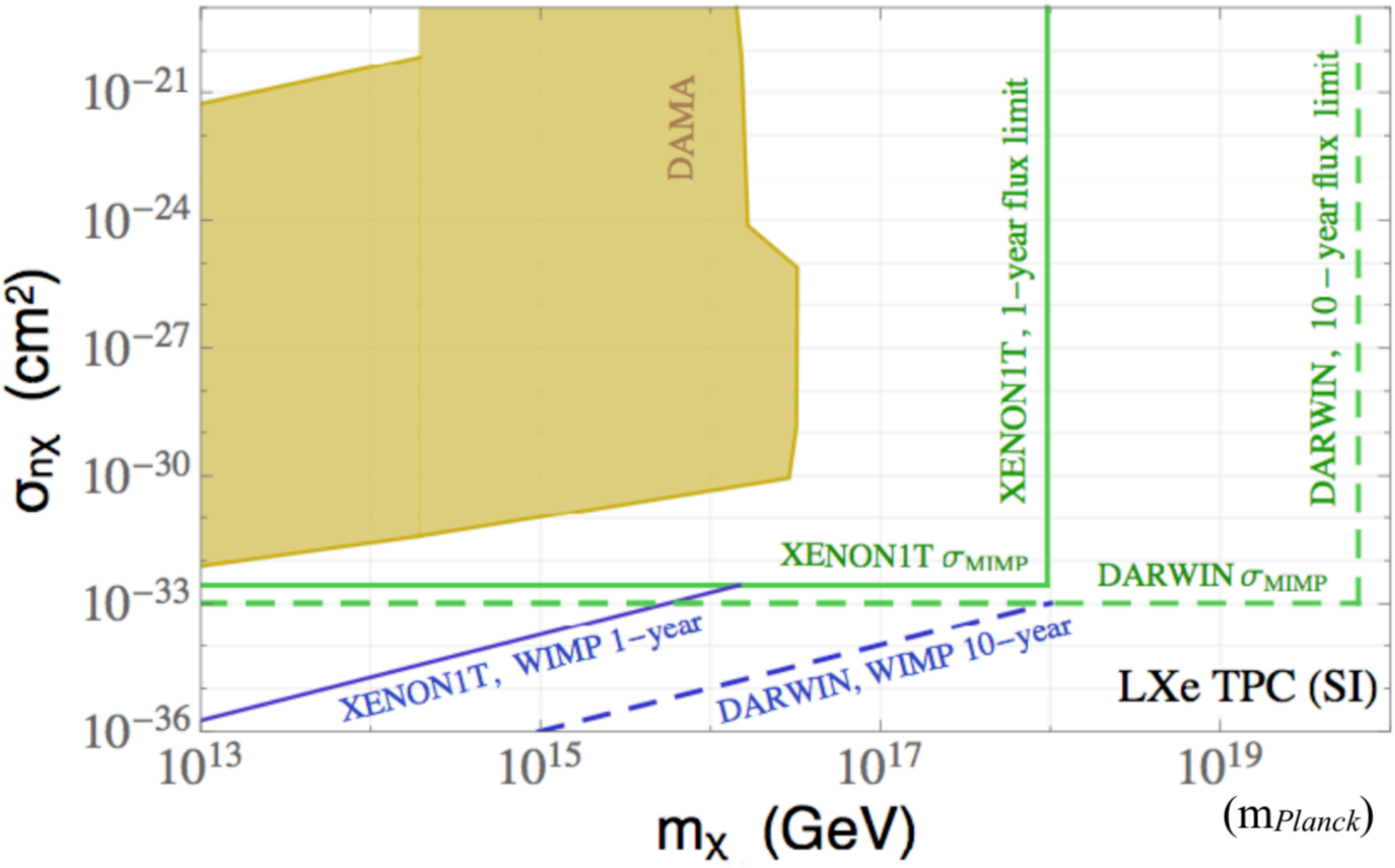
For multiplicity > 5 (>500), S2 (S1) pulses merge into elongated pulses

Track of bubbles

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

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

Multsicatter search in direct detection



Overburden

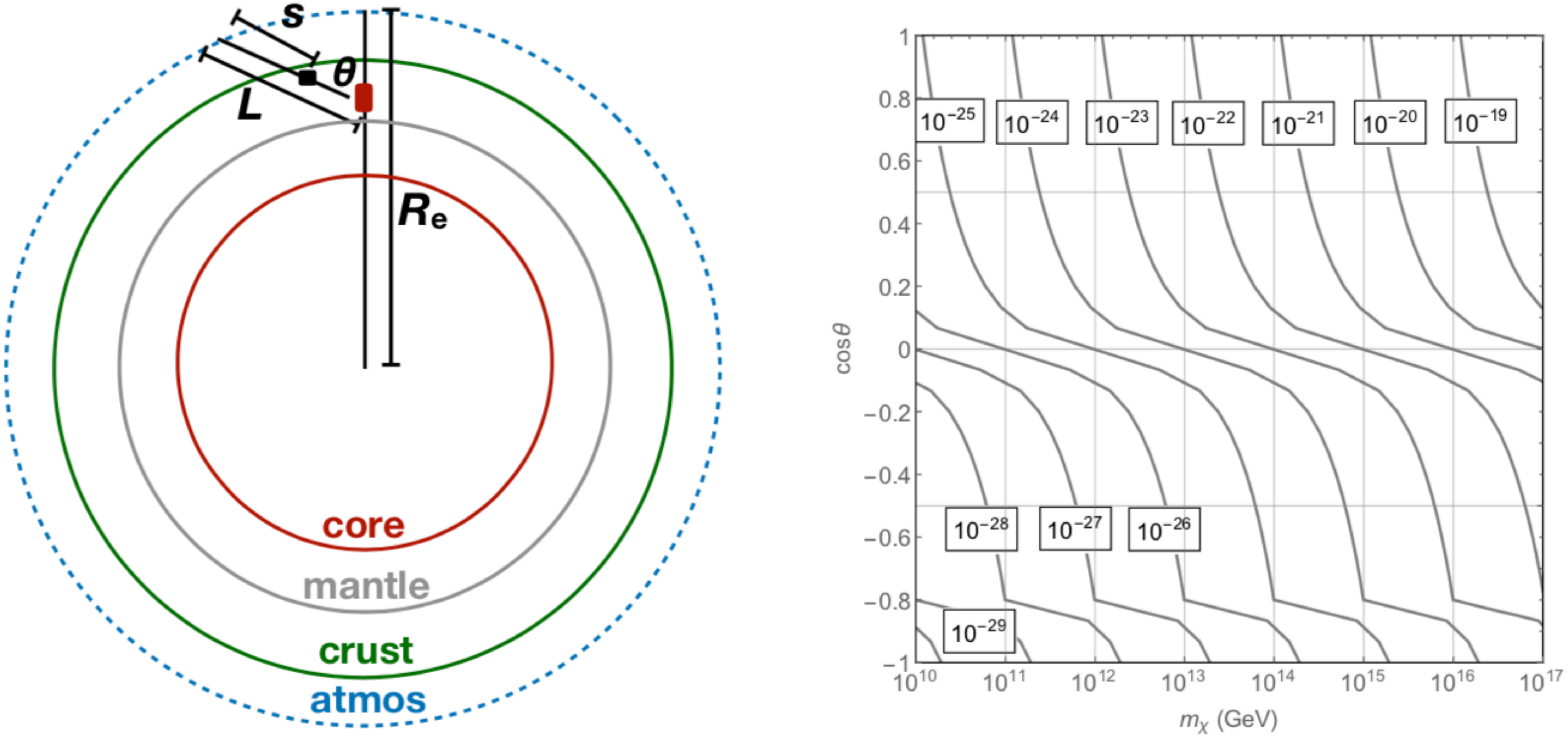


Figure 2. ***Left.*** Geometric schematic of a dark matter particle traveling along a straight path to a dark matter detector through the Earth's atmosphere and rock. This diagram is not to scale. ***Right.*** Contours in the $\cos\theta$-m_χ plane, of the spin-independent per-nucleon cross sections (in cm^2) required for the Earth overburden to slow down dark matter below detector thresholds. This illustrative calculation assumes an isotropic dark matter distribution with a uniform speed = 220 km/s.

SNO+ cross section reach: triggers

Existing @ BOREXINO

50 keV/ 100 ns =>

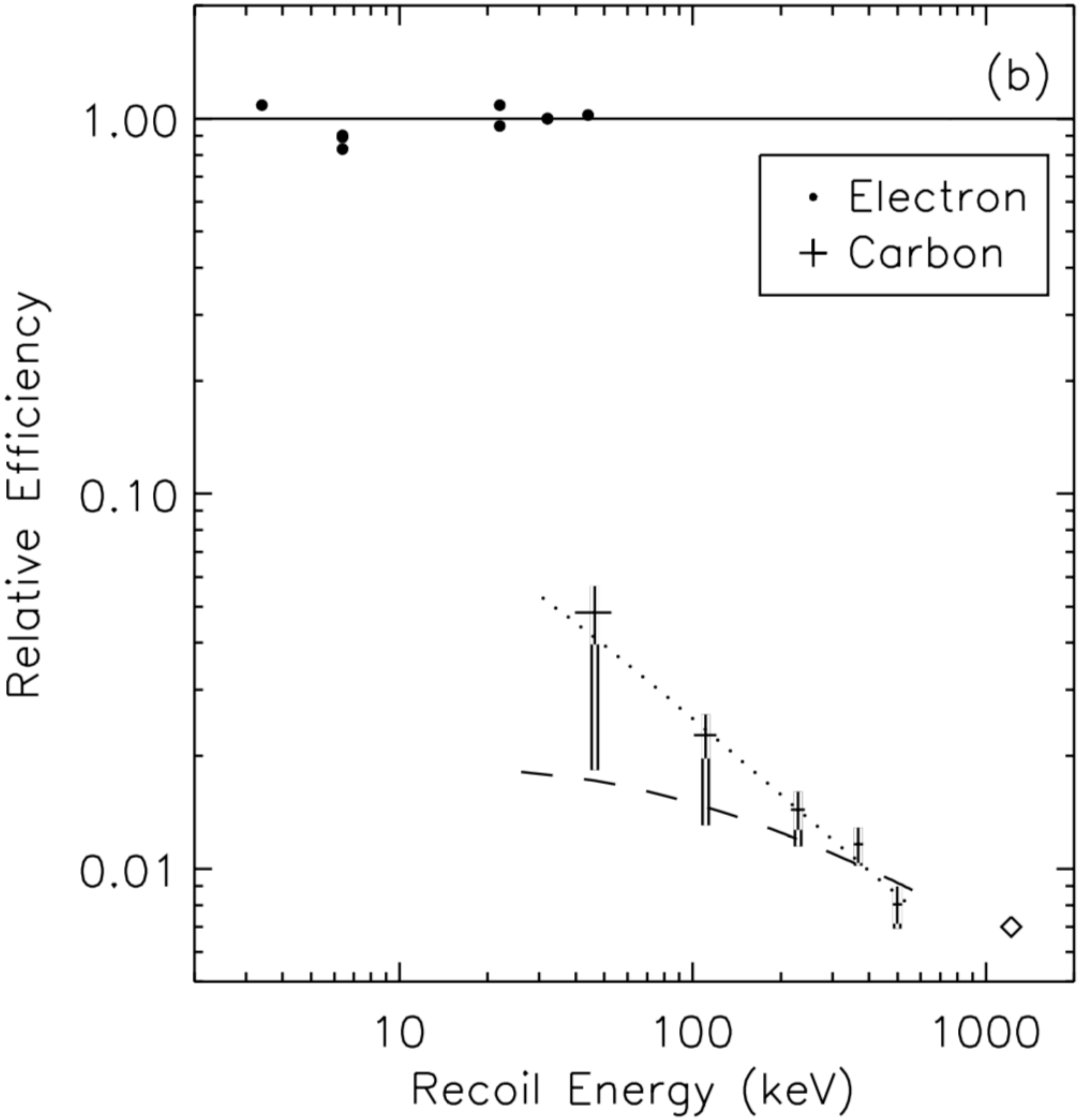
50 PE /100 ns, or

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_{bg} = **10 PE/ 10 μs.**

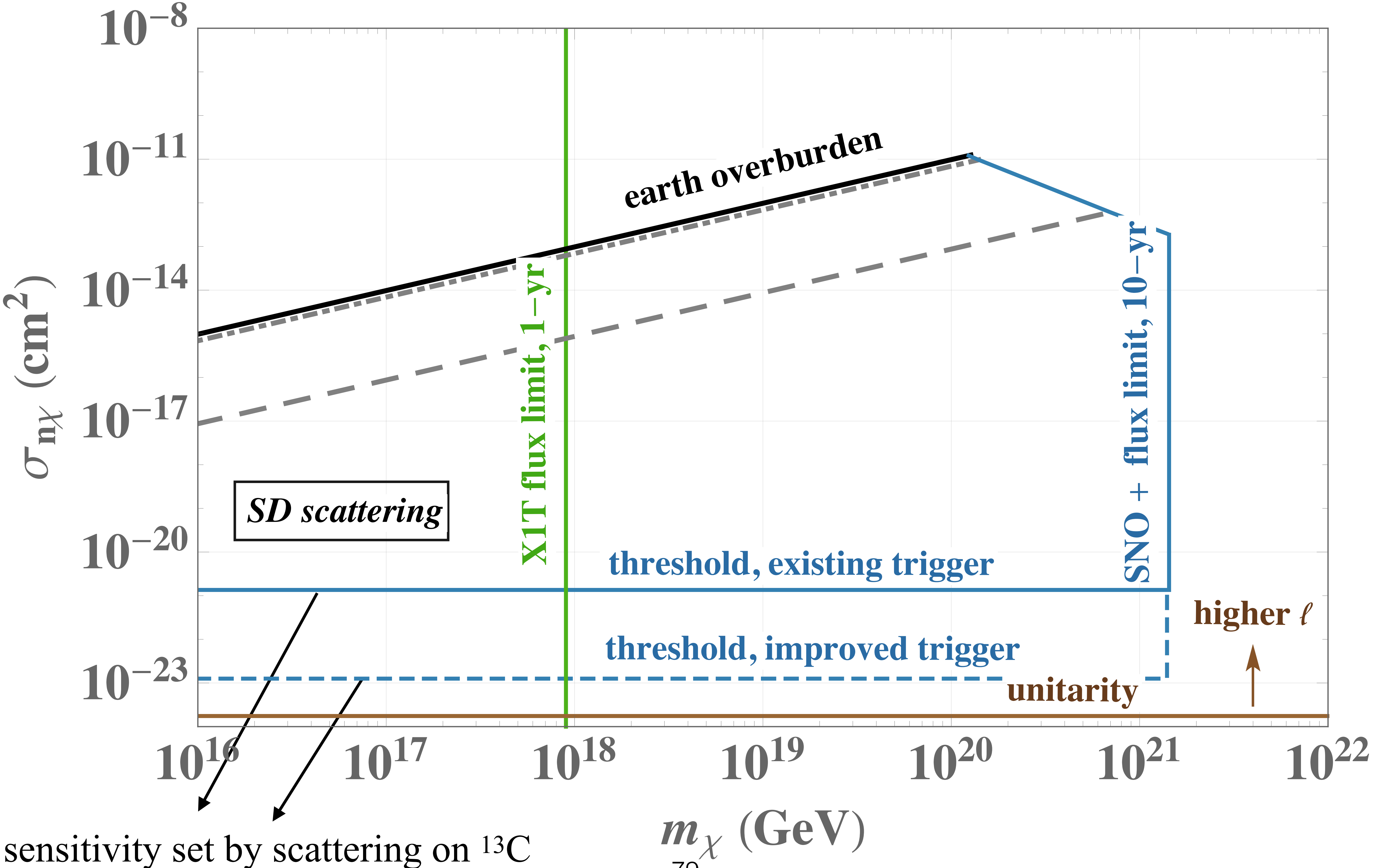
— Get required trigger from trial factors (solve for N_{c})

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

(10 yr)

— Enhance cross section sensitivity by ~100.

SNO+ cross section reach



sensitivity set by scattering on ^{13}C