KMI/NITEP School

Dark Matter

From Ultra Light to Super Massive

March 9-11, 2026

KMI Science Symposia (ES635), Nagoya University

Lecture 4-2

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deposit energy in a detector

$$E_R = r\frac{(1-\cos\theta)}{2}E_W$$

$$r = \frac{4M_\chi M_N}{(M_\chi + M_N)^2},$$

Let's assume:

Mw = 100 GeV/c2 , MT = 100 GeV/c2 (Xe :A ~130)

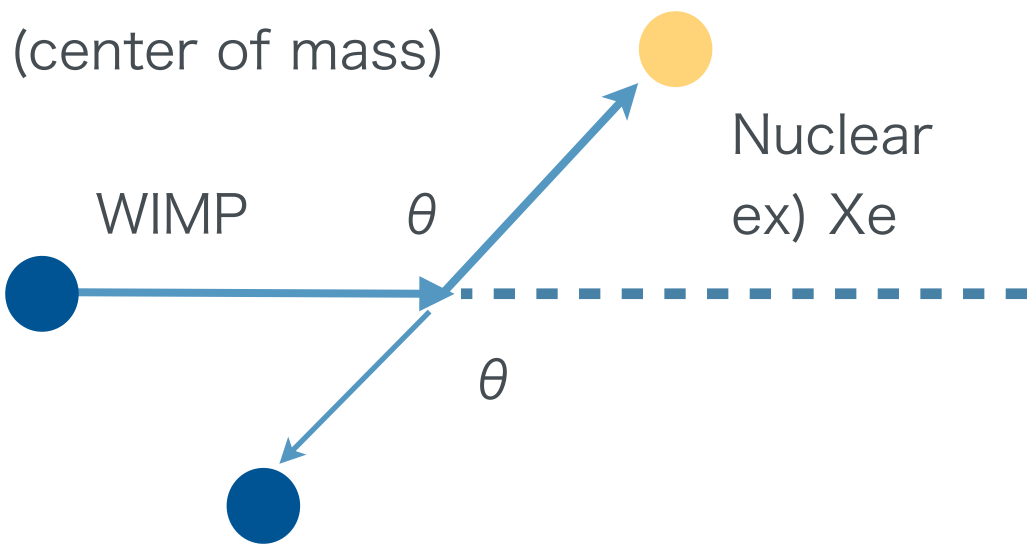
, r = 1

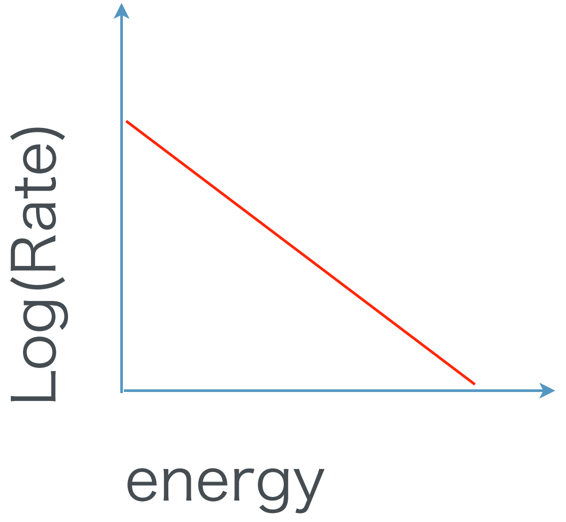
WIMP velocity: v= 220 km/sec ~ 0.75 X 10^{-3} c

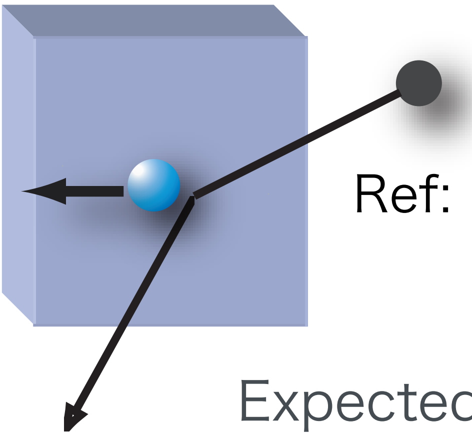
$$E_R = \frac{1}{2}M_w\beta^2c^2$$

$$= 1/2 \times 100\mathrm{GeV/c^2} \times (0.75 \times 10^{-3})^2$$

$$\approx 28\mathrm{keV}$$







Energy spectrum

Ref: PRD 74, 043531 (2006) C. Savage et al. が良い。

Expected spectrum:

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

detector

motion dynamics

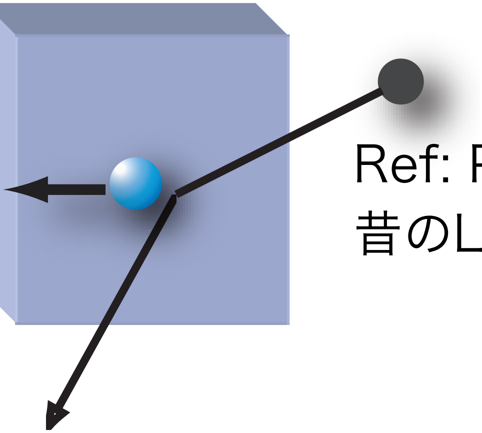
R0: Event rate

F: Form Factor
(depends on atomic nuclei)

Maxwellian distribution for DM velocity is assumed.
V :velocity onto target,
VE: Earth's motion around the Sun

=> annual modulation

Energy spectrum



Ref: PRD 74, 043531 (2006) C. Savage et al. が良い。
昔のLewin&Smithも良いがバグがある。

Expected spectrum:

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \boxed{\int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}}$$

Rate:

$$R_0 = \frac{377}{M_\chi M_N} \left(\frac{\sigma_0}{1\text{pb}}\right) \left(\frac{\rho_D}{0.3\text{GeVc}^{-2}\text{cm}^{-3}}\right) \left(\frac{v_0}{230\text{km s}^{-1}}\right) \text{kg d}^{-1}$$

Cross Section (Spin independent)

$$\frac{d\sigma(E_{\mathrm{nr}})}{dE_{\mathrm{nr}}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_{\mathrm{SI}} F_{\mathrm{SI}}^2(E_{\mathrm{nr}}) + \sigma_{\mathrm{SD}} F_{\mathrm{SD}}^2(E_{\mathrm{nr}})\right],$$

$$\sigma_{\mathrm{SI}} = \sigma_n \frac{\mu^2}{\mu_n^2} \frac{(f_p Z + f_n(A-Z))^2}{f_n^2} = \sigma_n \frac{\mu^2}{\mu_n^2} A^2$$

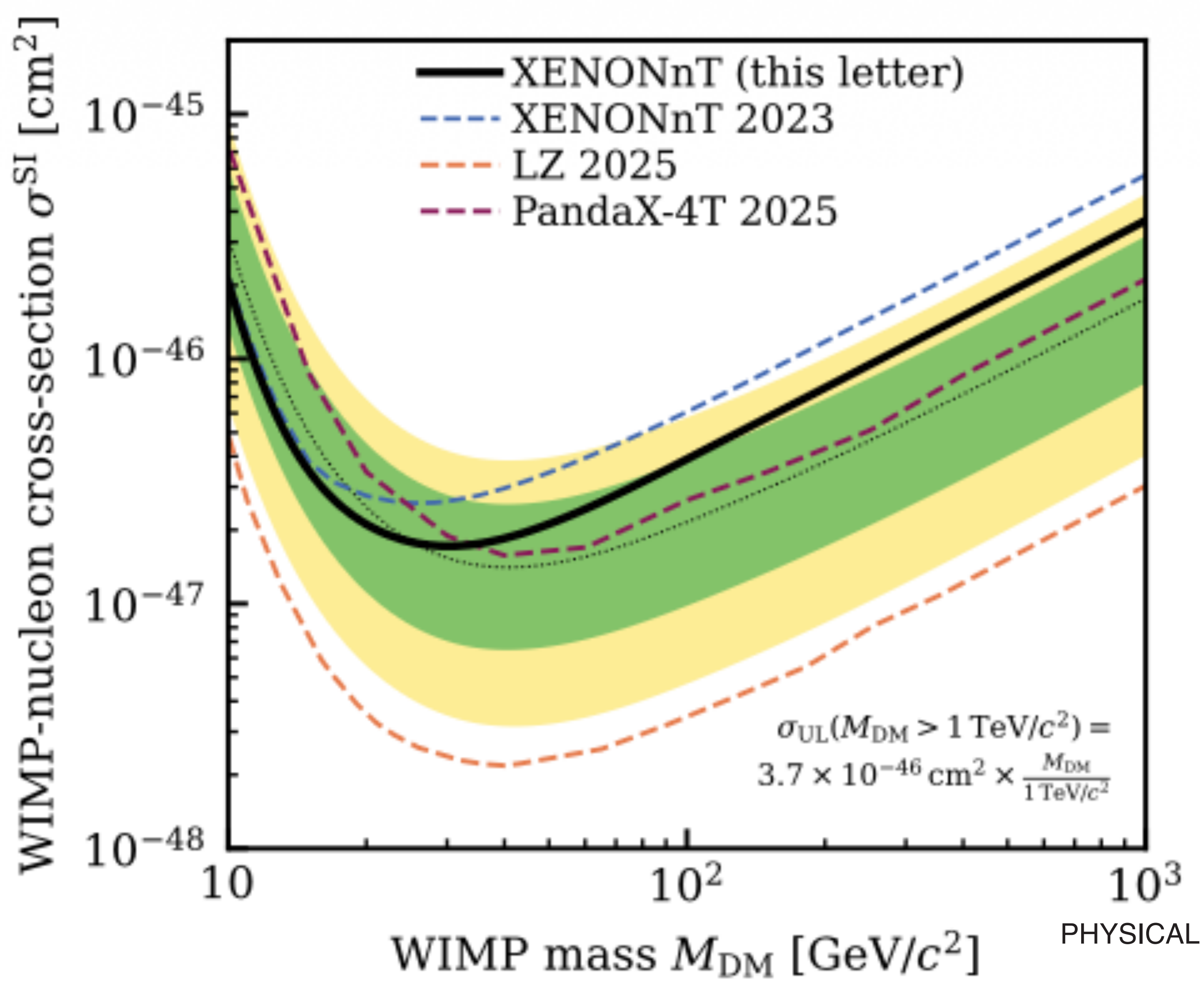
Cross Section (Spin dependent)

$$\frac{d\sigma(E_{\rm nr})}{dE_{\rm nr}} = \frac{m_N}{2v^2\mu^2}\left[\sigma_{\rm SI}F^2_{\rm SI}(E_{\rm nr}) + \sigma_{\rm SD}F^2_{\rm SD}(E_{\rm nr})\right],$$

$$\frac{d\sigma_{\rm SD}}{d|\vec{q}|^2} = \frac{8G_F^2}{\pi v^2}\left[a_p\langle S_p\rangle + a_n\langle S_n\rangle\right]^2 \frac{J+1}{J}\frac{S(|\vec{q}|)}{S(0)}.$$

Nucleus	J	Odd Nucleon	$\langle S_p\rangle$	$\langle S_n\rangle$	$\lambda^2_{p,Z}J(J+1)$
^{7}Li	3/2	p	0.497	0.004	0.406
^{19}F	1/2	p	0.441	-0.109	0.855
^{23}Na	3/2	p	0.248	0.020	0.089
^{73}Ge	9/2	n	0.009	0.372	0.105
^{125}Te	1/2	n	0.001	0.287	0.178
^{127}I	5/2	n	0.309	0.075	0.084
^{129}Xe	1/2	n	0.028	0.359	0.232
^{131}Xe	3/2	n	-0.009	-0.227	0.057

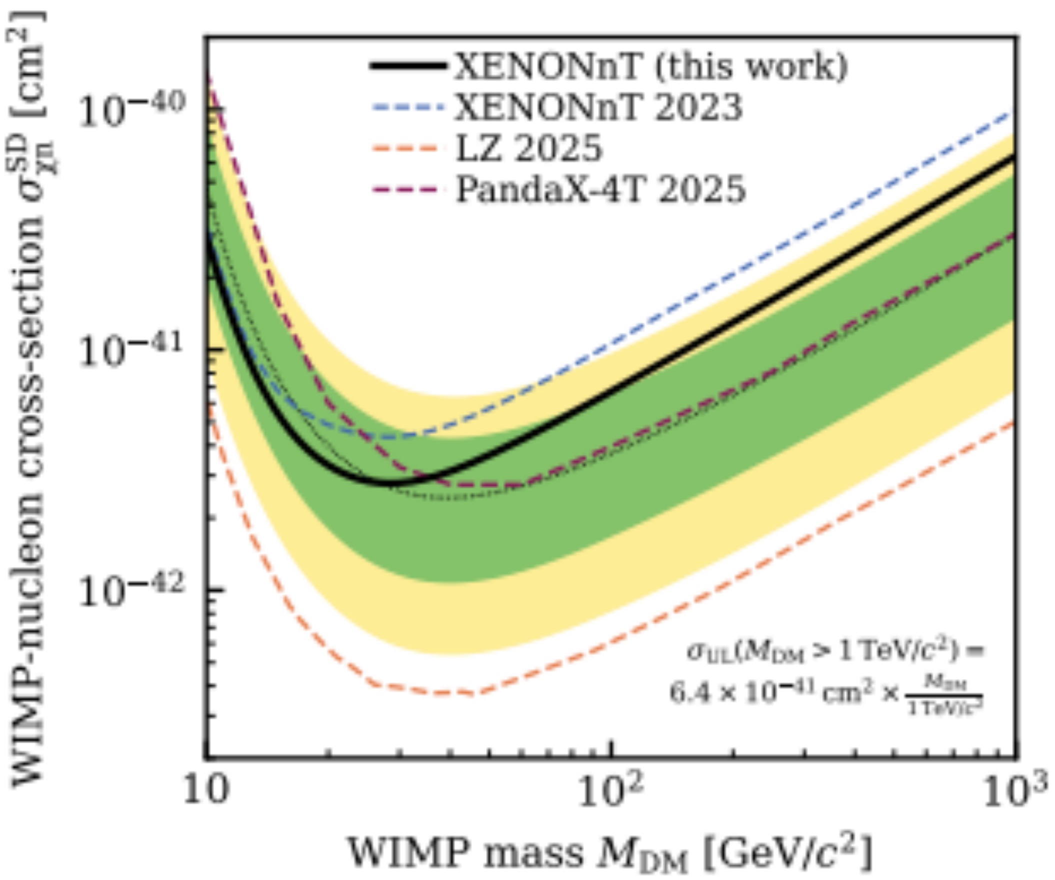
Spin Independent



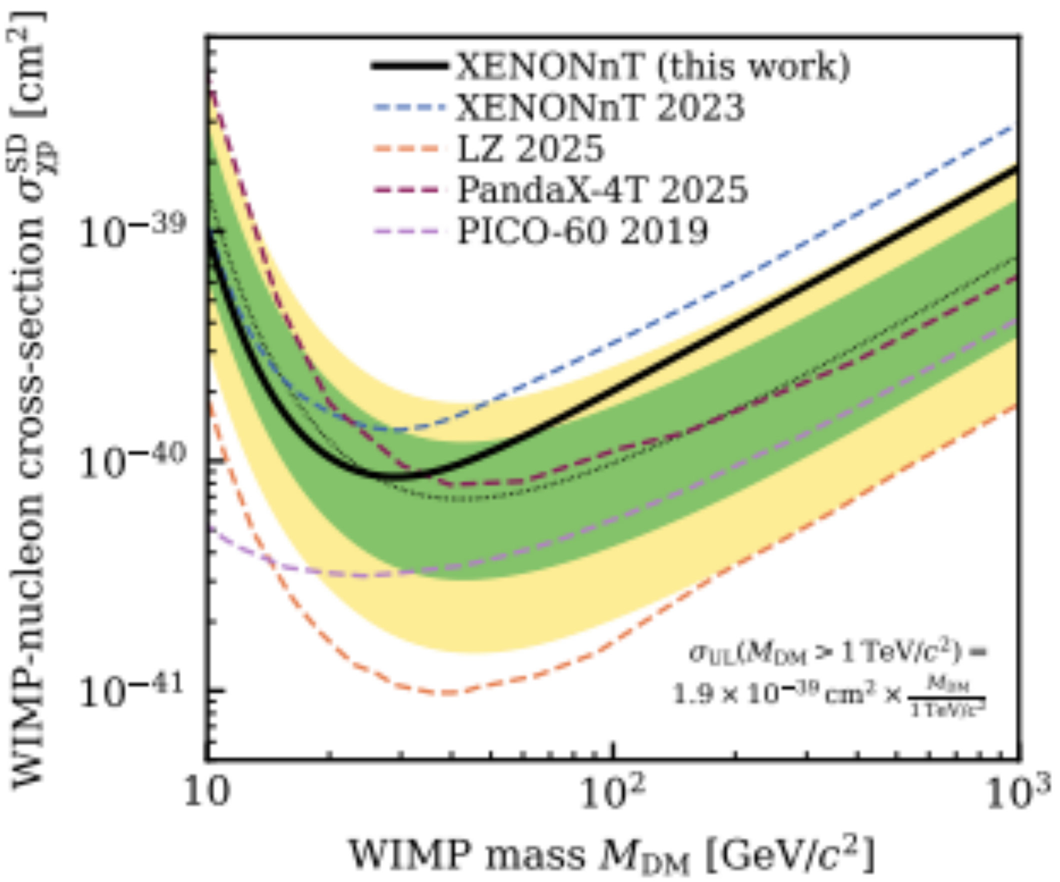
PHYSICAL REVIEW LETTERS 135, 221003 (2025)

Spin dependent

Coupling to unpaired neutron



Coupling to unpaired proton



PICO-60 C_3F_8

Form Factor

Lewin&Smith
1996, Astro. Phys.

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

1. Why does a form factor appear?

DM scatters off **atomic nuclei** in the detector.

However, a nucleus is **not a point particle**; it has a **finite size**.

- **Small momentum transfer** (low recoil energy):
  The DM wavelength is larger than the nucleus
  → the entire nucleus scatters **coherently**
  → F(q) ~ 1
- **Large momentum transfer** (high recoil energy):
  The DM wavelength becomes comparable to or smaller than the nuclear size
  → loss of coherence inside the nucleus
  → scattering is **suppressed** (F(q)<1)

•Helm approximation:

Fourier transform of ρ (r) $F(\mathbf{q}) = \frac{1}{A}\int d^3r\, \rho(\mathbf{r})\, e^{i\mathbf{q}\cdot\mathbf{r}}$

$$F(q) = 3\frac{j_1(qr_n)}{qr_n}e^{-(qs)^2/2}$$

·effective nuclear radius $r_n{}^2 = c^2 + \frac{7}{3}\pi^2 a^2 - 5s^2.$

·nuclear skin thickness $c \simeq 1.23A^{1/3} - 0.60$ fm;

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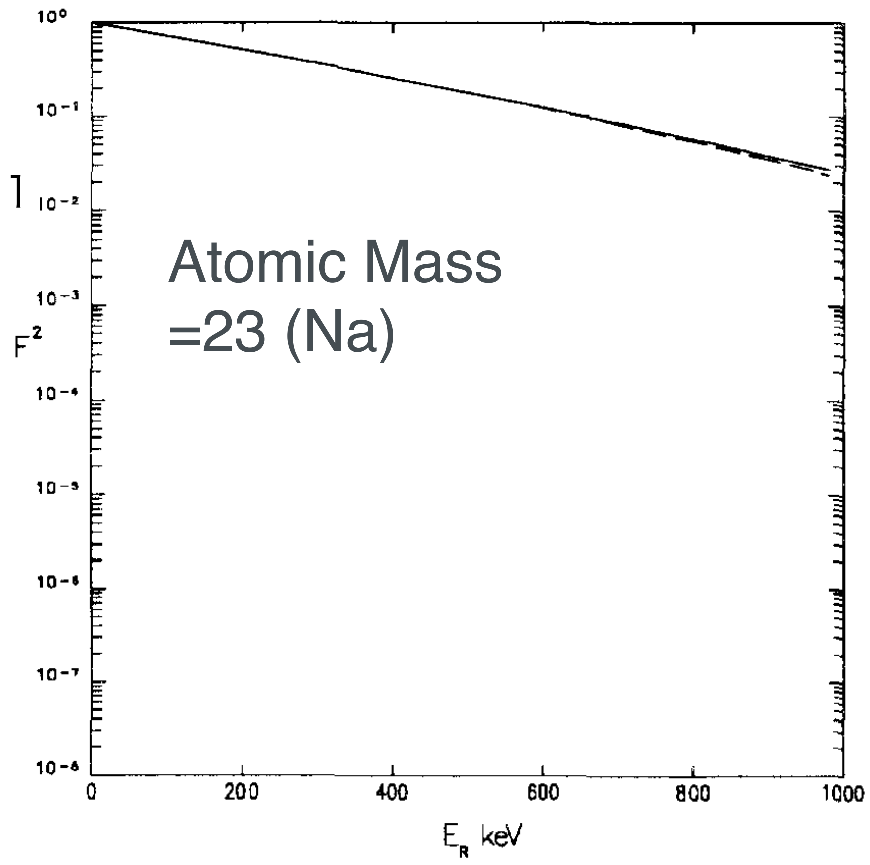
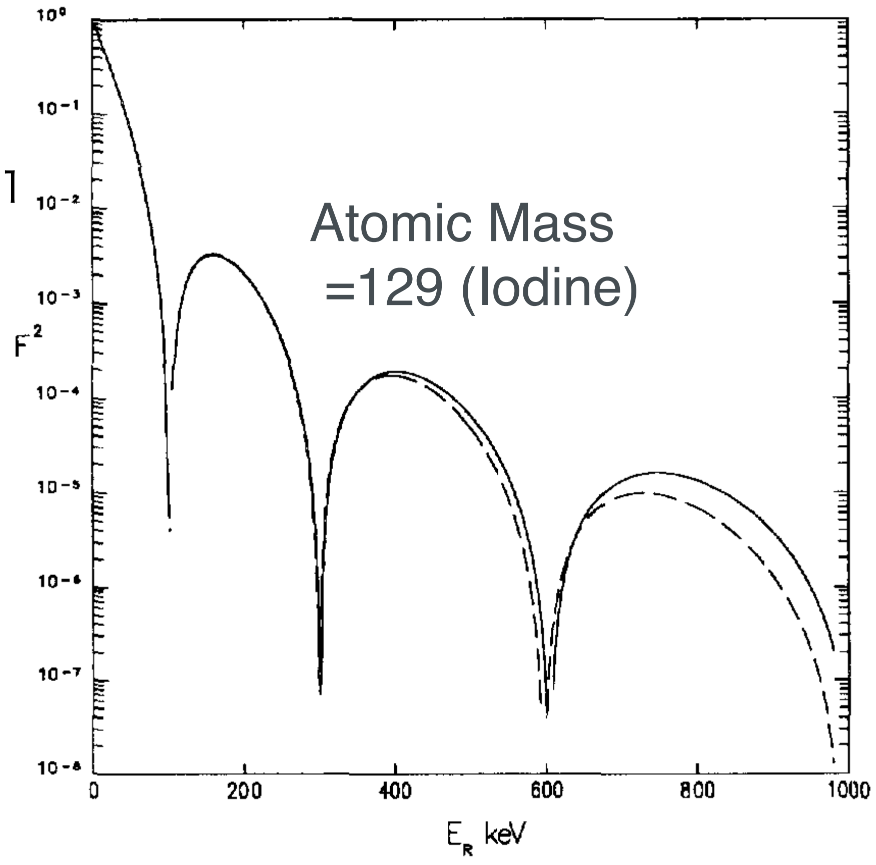
Form Factor





Form Factor

Lewin&Smith
1996, Astro. Phys.

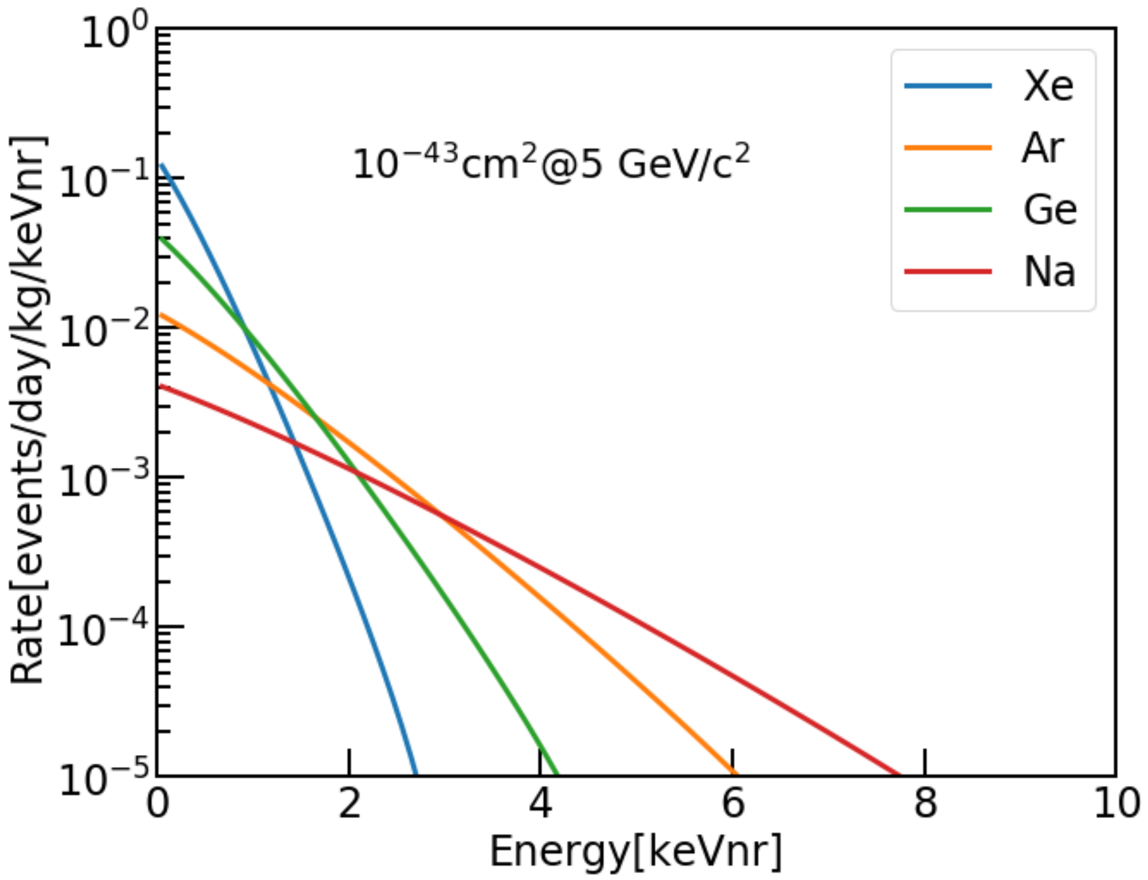
- the nucleus acts as a finite-size scattering object
- waves scattered from different parts of the nucleus interfere
- at certain momentum transfers the interference is destructive.

Differential Rate

ρ_{dm} = 0.3 GeV/cm³,
V_0 = 220 km/s
V_{esc} = 544 km/s

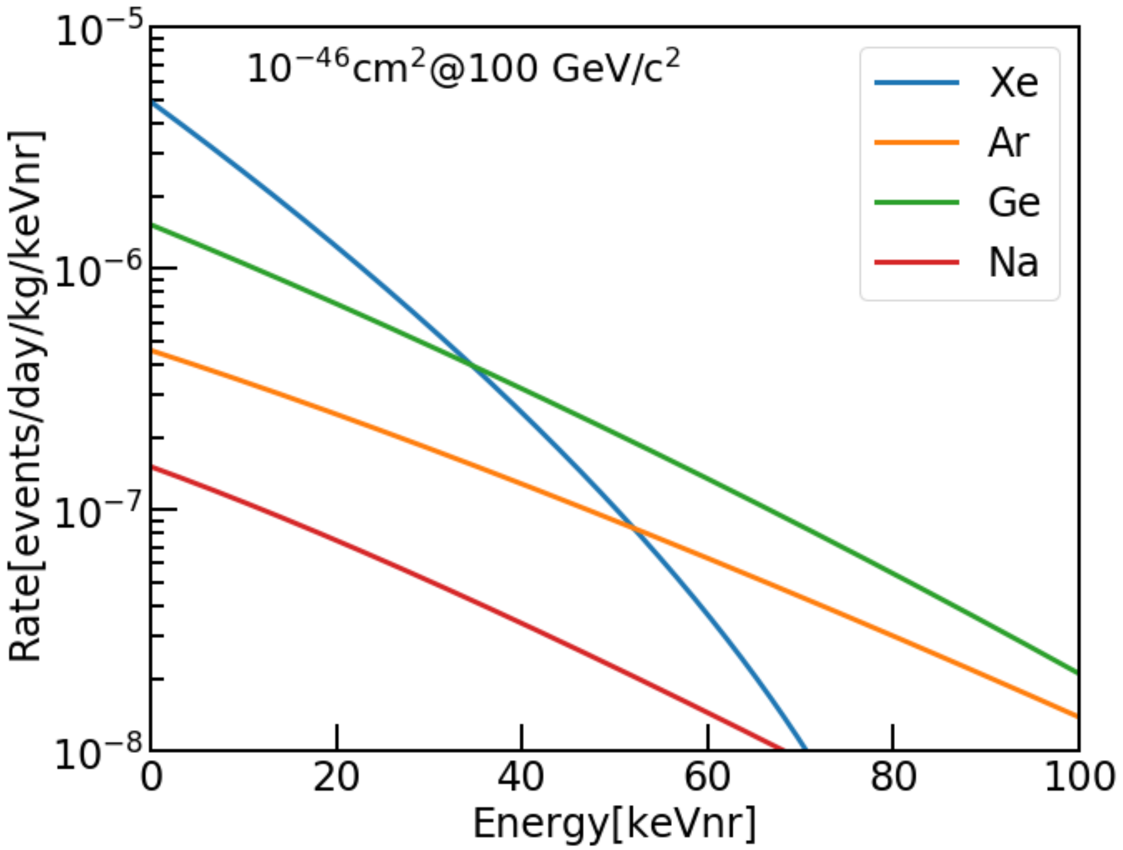
+ Standard Halo Model

5GeV Mass



low energy threshold

100GeV Mass



Large Mass Target

Uncertainty DM Count rate

$$\frac{dR}{dE_R} = \frac{R_0 F^2(E_R)}{E_0 r} \frac{k_0}{k} \frac{1}{2\pi v_0} \int_{v_{min}}^{v_{max}} \frac{1}{v} f(\mathbf{v}, \mathbf{v_E}) d^3\mathbf{v}$$

Type	Signal Parameter	impact on signal
Particle physics	• DM mass (GeV-TeV) • Couplings	• rate, shape
Nuclear physics	• Form factor	• shape
Astrophysics	• Local DM density • DM velocity distribution	• rate (0.3 GeV/cm3) • shape (Standard Halo Model)

DM velocity distribution

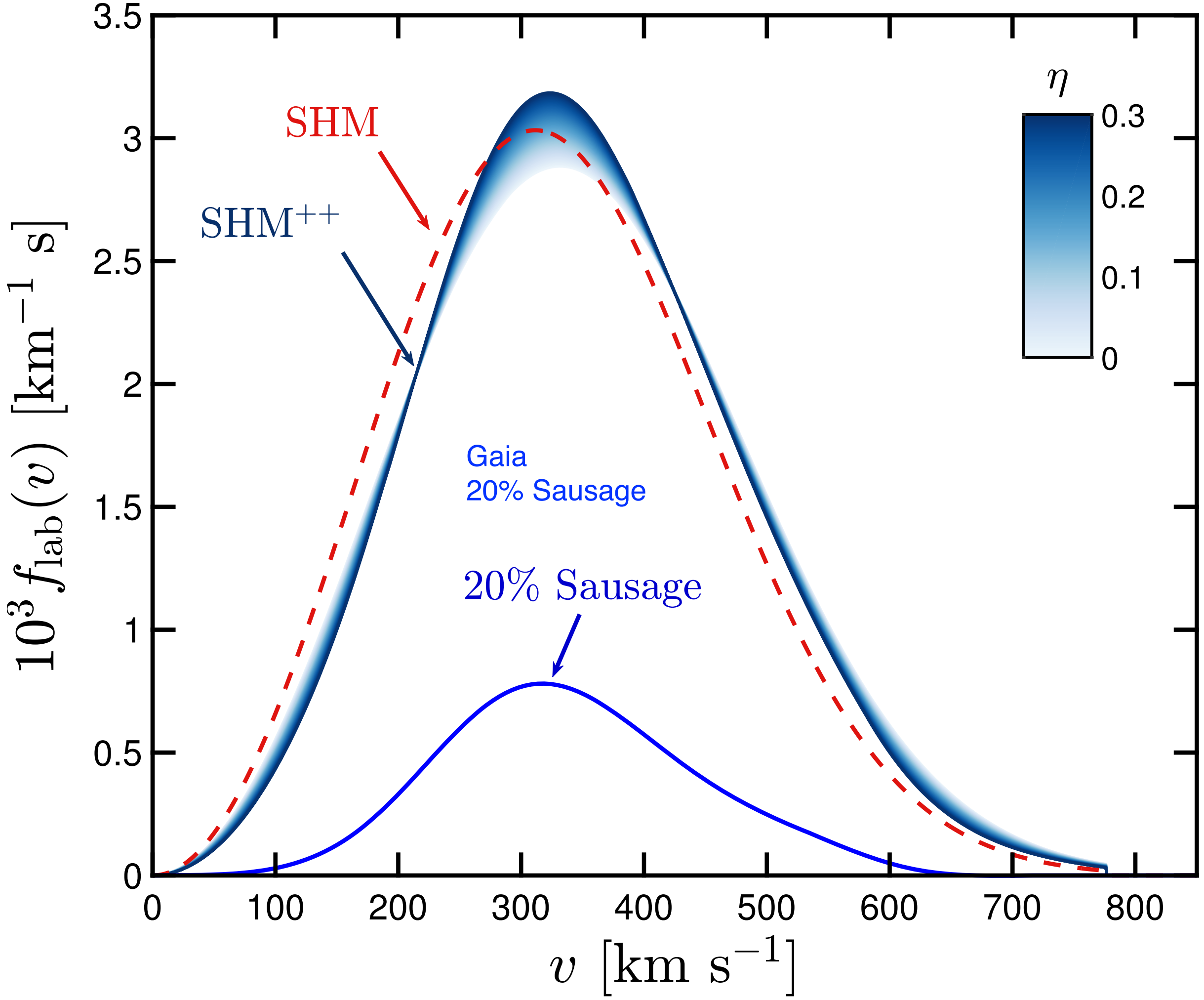
N. Wyn Evans et al., PRD99, 023012 (2019)

Gaia Sausage

Gaia–Sausage is the debris of an ancient dwarf galaxy that merged with the Milky Way, revealed by stars on radial orbits observed by Gaia.

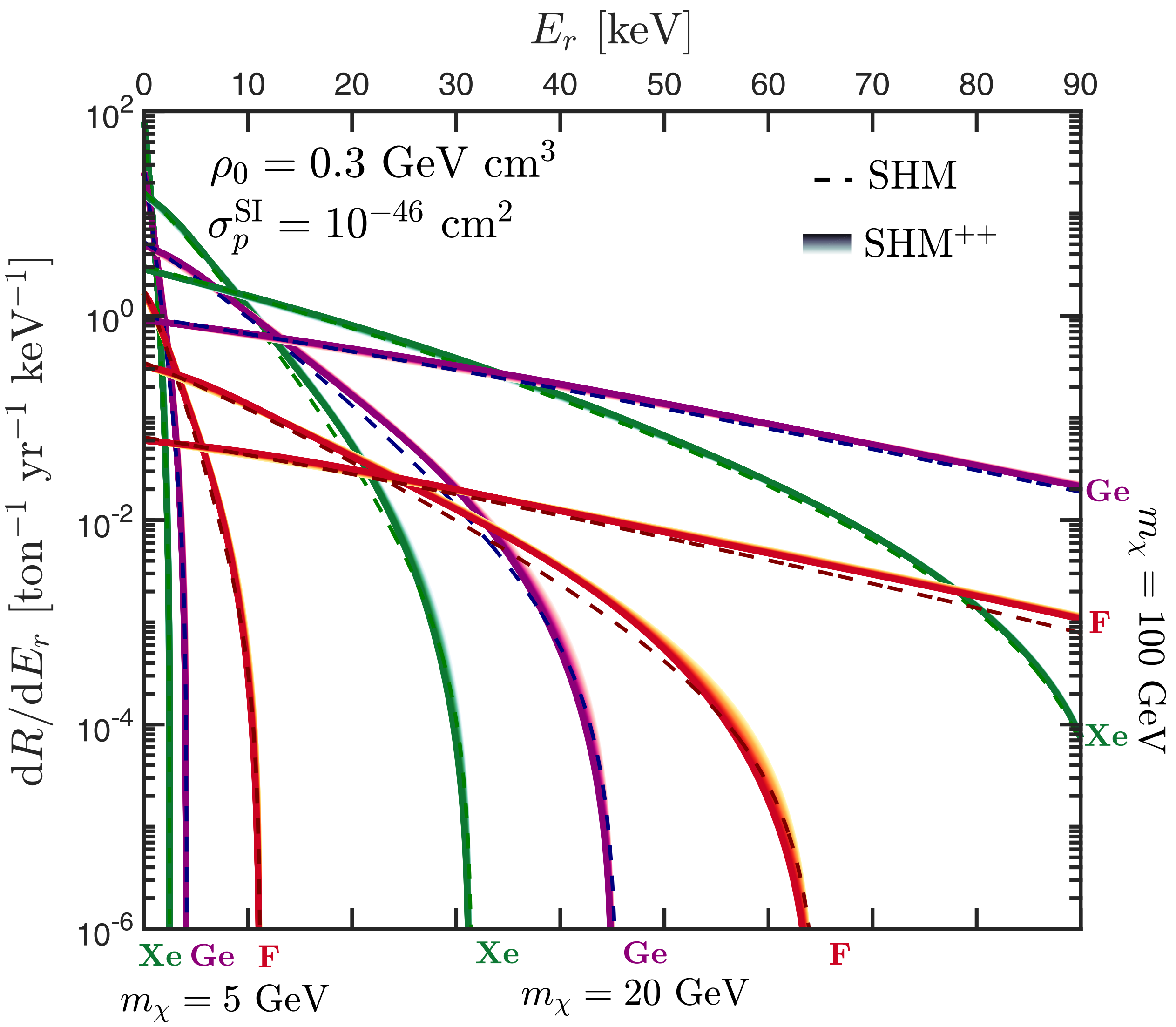
SHM	Local DM density	ρ_0	$0.3\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$220\ \mathrm{km\,s^{-1}}$
	Escape speed	v_{esc}	$544\ \mathrm{km\,s^{-1}}$
	Velocity distribution	$f_{\mathrm{R}}(\mathbf{v})$	Eq. (1)
SHM^{++}	Local DM density	ρ_0	$0.55 \pm 0.17\ \mathrm{GeV\,cm^{-3}}$
	Circular rotation speed	v_0	$233 \pm 3\ \mathrm{km\,s^{-1}}$
	Escape speed	v_{esc}	528^{+24}_{-25}
	Sausage anisotropy	β	0.9 ± 0.05
	Sausage fraction	η	0.2 ± 0.1
	Velocity distribution	$f(\mathbf{v})$	Eq. (3)

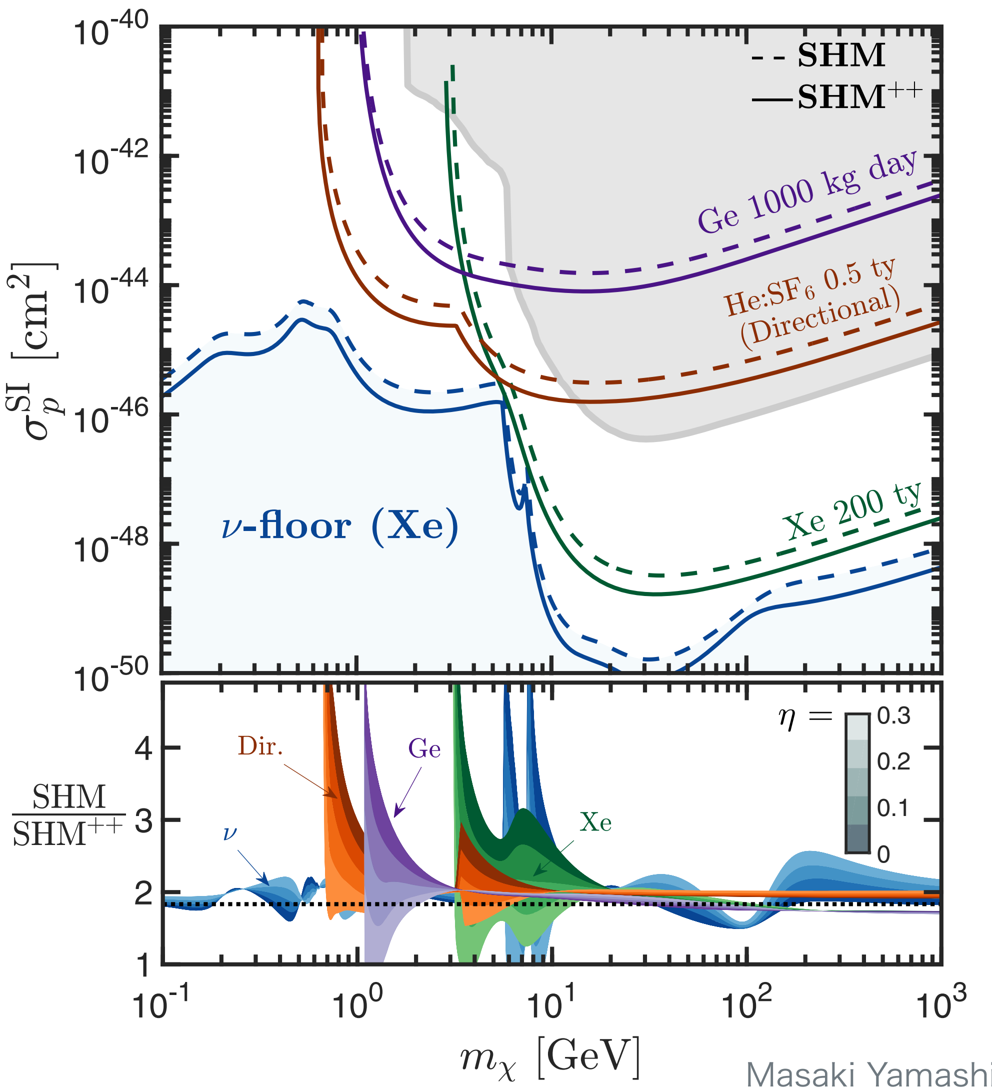
#The local dark matter velocity distribution is affected not only by the Gaia–Sausage merger but also by the gravitational perturbation from the Large Magellanic Cloud and smaller tidal streams.



DM velocity distribution

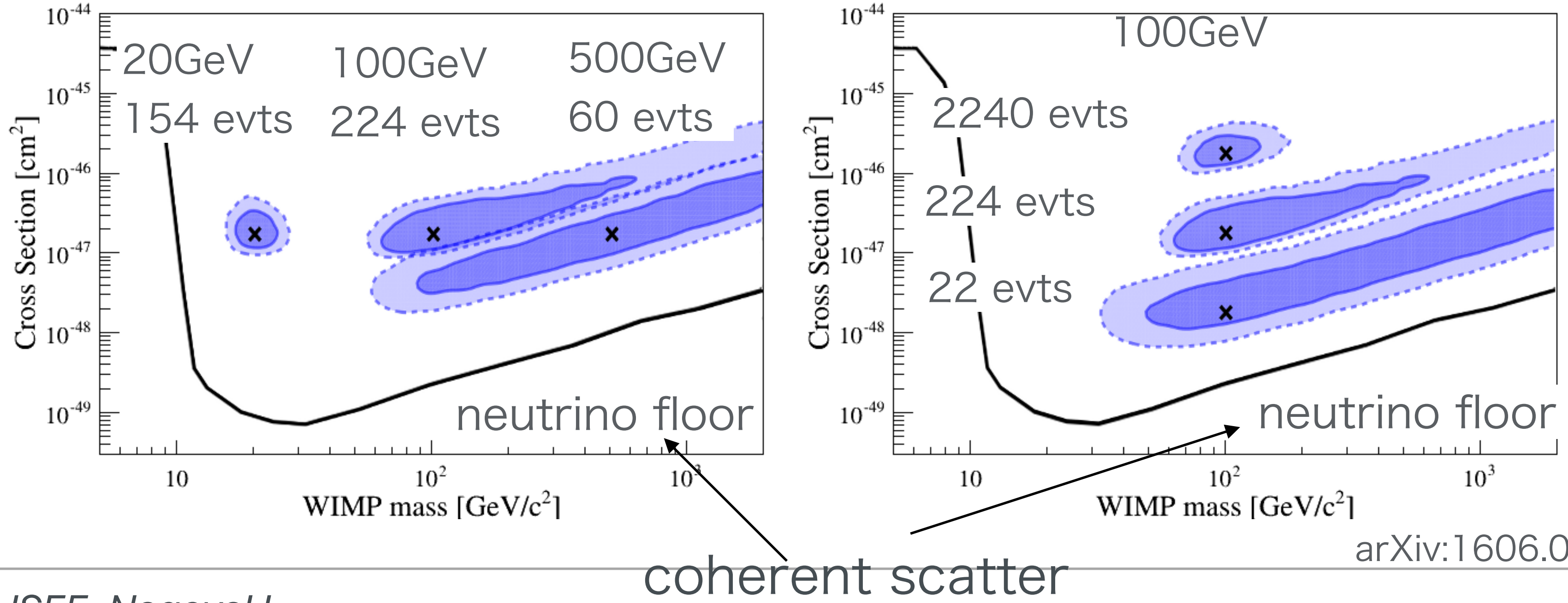
N. Wyn Evans et al., PRD99, 023012 (2019)





What we (will) get from Direct Search?

- DM exists around us in nature
- DM mass
- DM-SM cross section
- higher than100 GeV, harder to determine mass. (spectrum shape is similar)



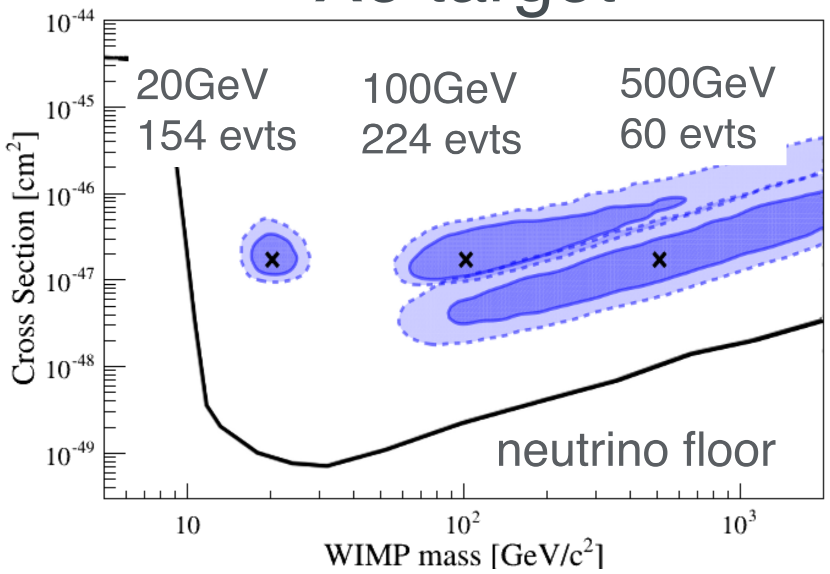
arXiv:1606.07001

What we get from Direct Detection?

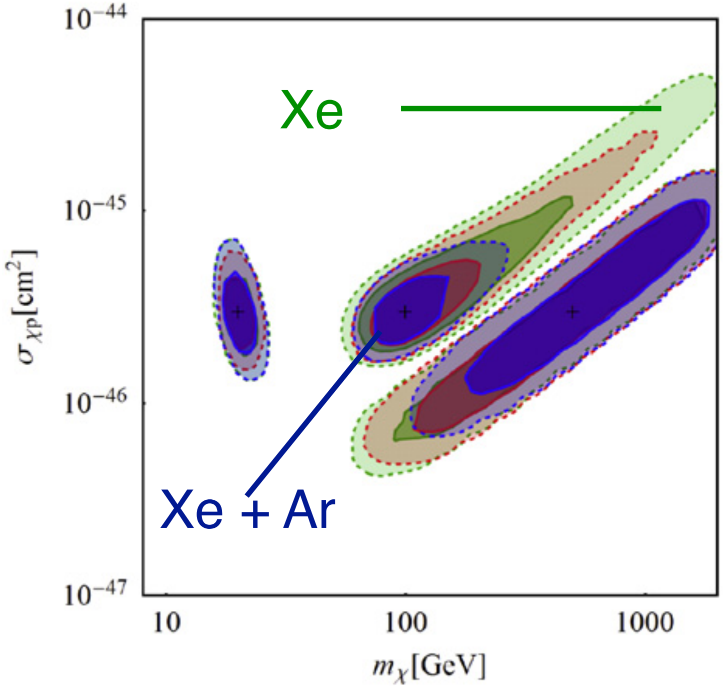
once we detect dark matter….

- DM particles are moving around us.
- Mass of DM particles
- DM-nucleus scattering cross section ⇒ **Complementarity of targets**
- It will rely on ρ_{dm} (= 0.3 GeV/cm^3), Velocity distribution (= > Maxwellian, DM stream?)

Xe target



J. Aalbers *et al* JCAP11(2016)017

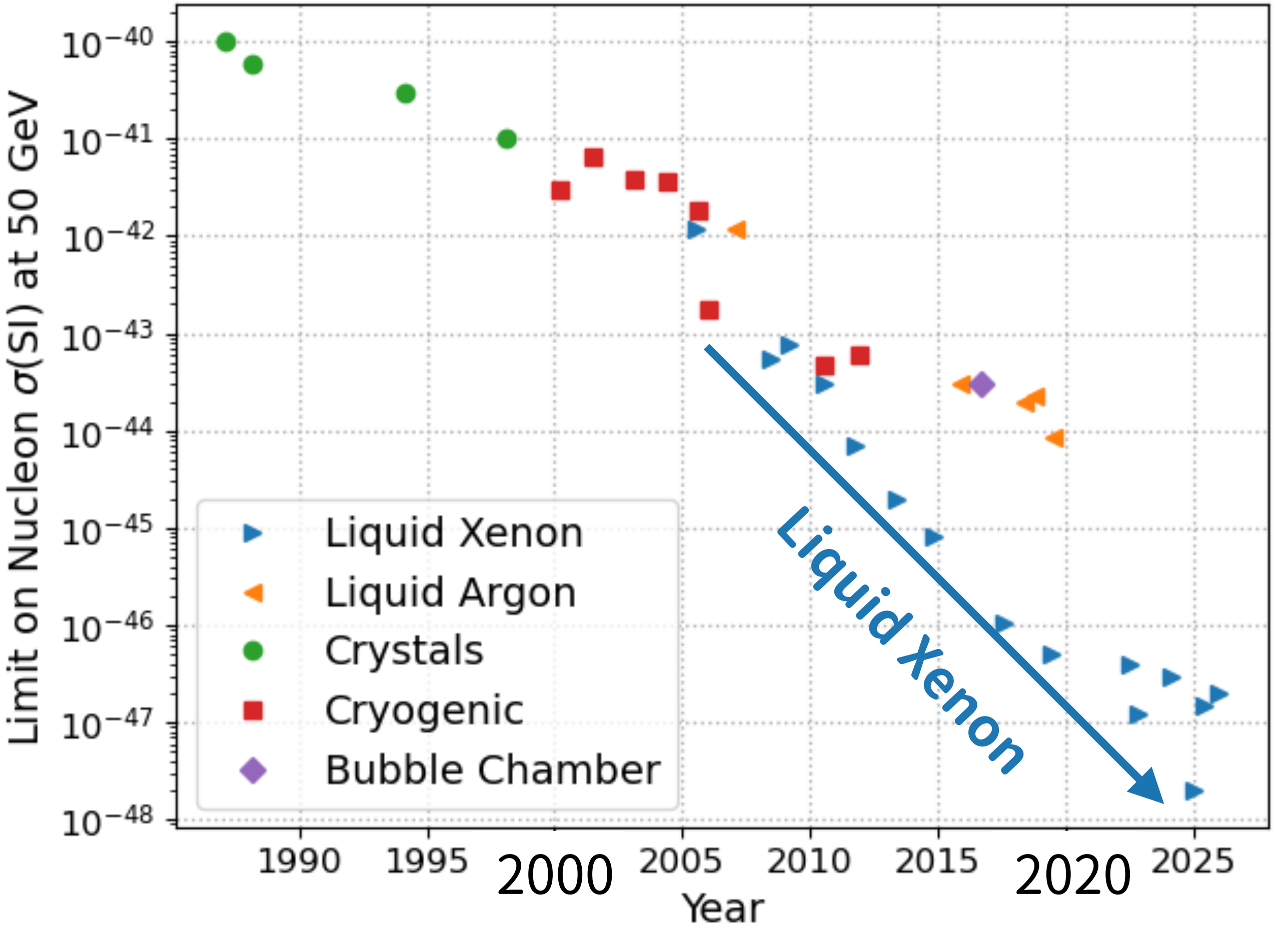


J. Newstead et al , PRD 88, 076011 (2013)

History of Direct WIMP Dark Matter Search

Liquid-gas double phase Xe Time Projection Chamber

- Scalability, large mass (tonne scale)
- Self-shielding: High Z(=54) and density (~3g/cm^3)
- Easy purification in gas and liquid phase, even during science run
- Particle identification of electronic recoils and nuclear recoils
- Low energy threshold
- Liquid Xenon Detectors: World leading since 2007



D. Akerib@IDM 2025

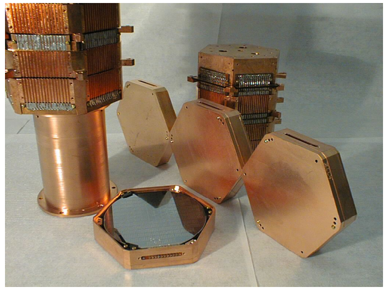
Direct Dark Matter Search Experiments

Detectors

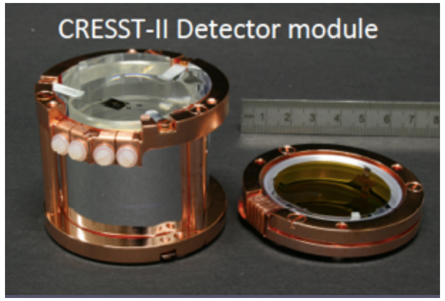
Keys:
- **low energy threshold < 10 keV**
- **Large target mass (> tonne)**
- **low background**

Phonon

SuperCDMS
EDELWEISS



CRESST



bubble

PICO

E_{recoil}

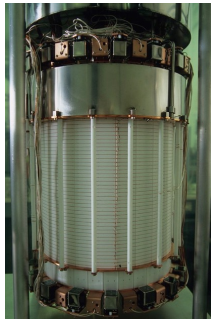
CoGENT Ge

$CaWO_4$

ionization

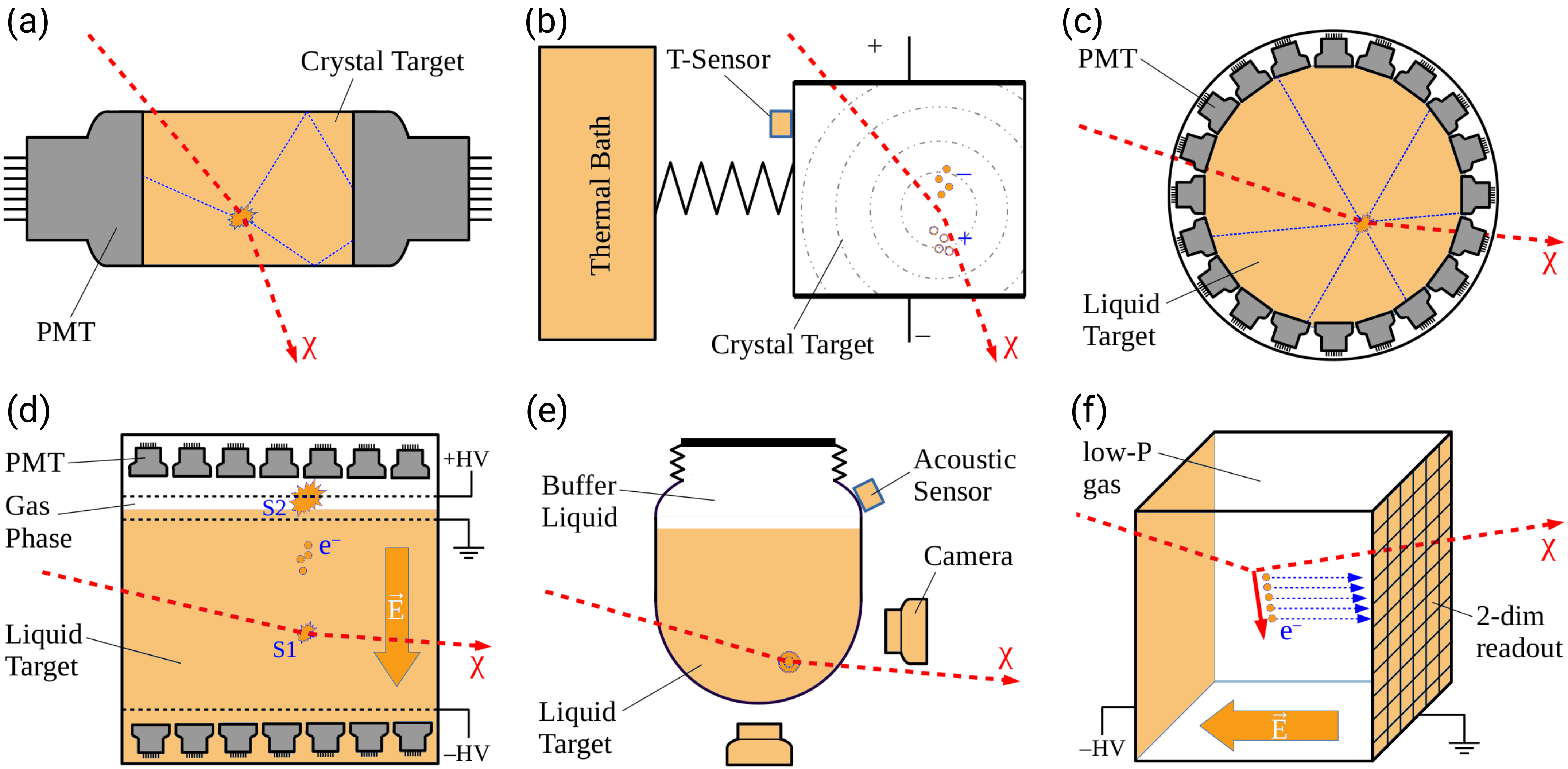
Scintillation

XENON, LZ, Panda-X
DarkSide



DAMA, NAIAD, XMASS,
DEEP-CLEAN

LXe, LAr, NaI …



arXiv:2104.07634v1

How to Detect?

Underground Lab

↓

Radiation Shield

↓

Material Selection

↓

Particle Identification

↓

Fiducial volume

↓

Neutron veto

How to Detect?

Underground Lab

↓

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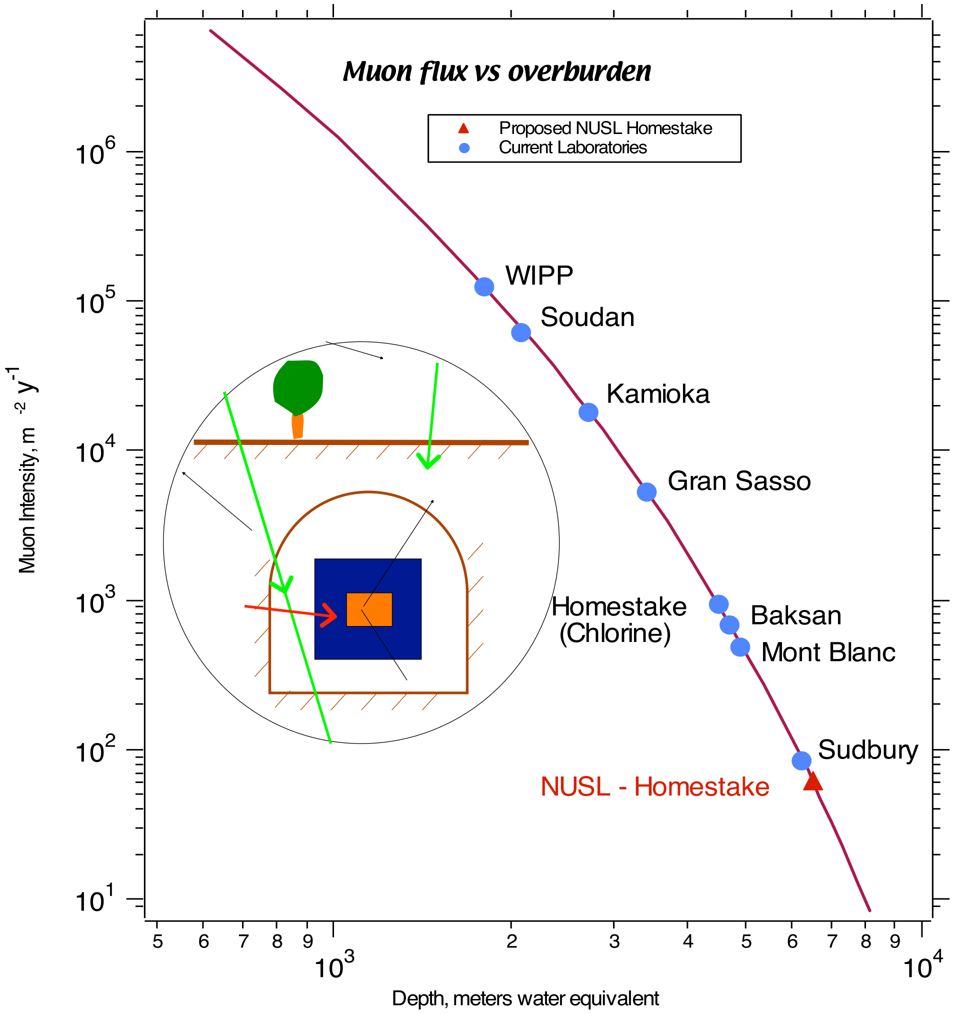
Neutron veto

cosmic ray flux -> 1/10^5



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Radiation Shild

Underground Lab

↓

Radiation Shield

↓

Material Selection

↓

Particle Identification

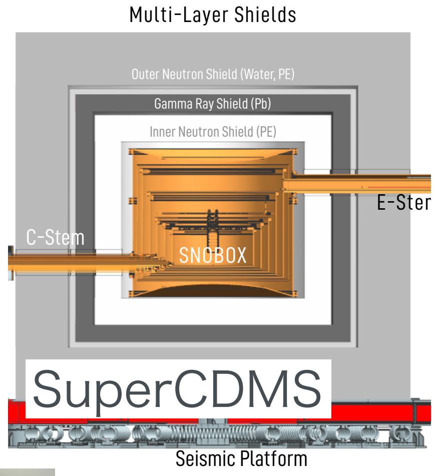
↓

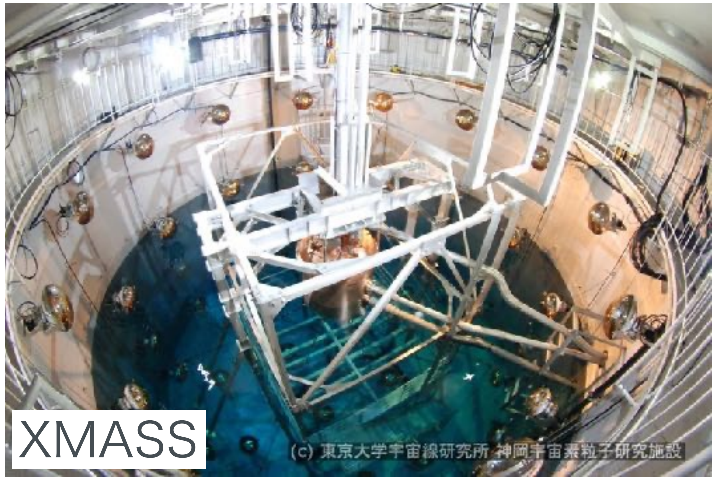
Fiducial volume

↓

Neutron veto

- ~20cm of Copper, Lead, Polyethylene (for neutron)
- Tonne scale detector -> Water shield
  - XMASS, LUX, XENON, LZ, (DarkSide(LAr)
  - => muon veto: tagging neutron

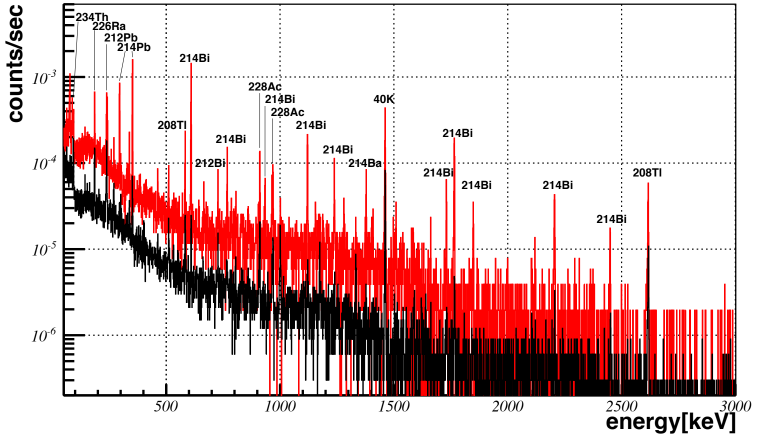


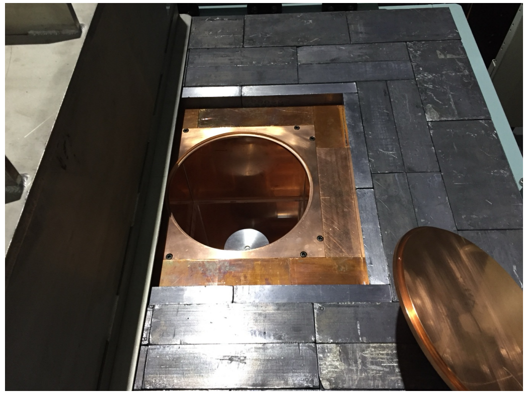


Material Selection (radioactivity)

- Underground Lab
- Radiation Shield
- **Material Selection**
- Particle Identification
- Fiducial volume
- Neutron veto

- All materials used in the detector are screened for radioactivity using high-purity germanium (HPGe) detectors, ICP-MS, and surface alpha counters.
- The required sensitivity is typically at the ppt–ppb level, mainly for the U/Th decay chains, as well as ^{40}K and ^{60}Co.
- Components such as photomultiplier tubes (PMTs) are disassembled and measured part by part.





PMT in HPGe

Table 3: Results of measurements for the developed R10789 parts measured in mBq/PMT for ^{226}Ra, ^{228}Ra, ^{40}K and ^{60}Co with HPGe, and for ^{238}U and ^{232}Th with HPGe, GDMS and ICPMS. Measuring methods for ^{238}U and ^{232}Th are also listed. Details of the calculation of upper limit and summation are explained in the text.

Samples	^{226}Ra	^{228}Ra	^{40}K	^{60}Co	^{238}U	^{232}Th	Method for ^{238}U & ^{232}Th
PMT(R10789)							
Dynodes	<0.10	<0.27	<0.95	0.11±0.04	$<2.8\cdot10^{-2}$	0.15	GDMS
Electrode	<0.20	<0.17	<0.63	$<8.8\cdot10^{-2}$	$<1.0\cdot10^{-2}$	$<3.3\cdot10^{-3}$	GDMS
Body, hex part	<0.16	<0.35	<1.6	1.0±0.1	$<4.2\cdot10^{-2}$	$<1.4\cdot10^{-2}$	GDMS
Body, cylinder part	<0.18	<0.33	<1.6	1.14±0.08	$<6.2\cdot10^{-2}$	$<2.0\cdot10^{-2}$	GDMS
Stem	<0.14	<0.24	<1.2	1.08±0.07	$<3.3\cdot10^{-2}$	$<1.1\cdot10^{-3}$	GDMS
Glass beads	1.61±0.02	0.28±0.02	3.3±0.2	$<6.7\cdot10^{-3}$	0.43±0.16		HPGe
Lead wires	$<9.4\cdot10^{-3}$	$<2.3\cdot10^{-2}$	$<8.2\cdot10^{-2}$	$<4.0\cdot10^{-3}$	$<2.2\cdot10^{-3}$	$<7.2\cdot10^{-4}$	GDMS
Quartz	<0.18	<0.19	<2.9	$<7.5\cdot10^{-2}$	$<6.0\cdot10^{-3}$	$<1.9\cdot10^{-3}$	ICPMS
Sealing	$<1.2\cdot10^{-2}$	$(3.5\pm0.9)\cdot10^{-2}$	<0.238	$<6.0\cdot10^{-3}$	1.3	$2.5\cdot10^{-2}$	ICPMS
Getter	$<6.1\cdot10^{-2}$	0.10±0.04	<0.53	$<2.2\cdot10^{-2}$			
Sum of the PMT (R10789) parts	1.6±0.3	1.1±0.3	<3.2	3.4±0.2			

arXiv:1808.03617v1

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History of low radioactive PMTs(XMASS)

XMASS PMT HISTORY

PMT

YEAR	2000	2002	2008	2015-
Size	2inch	2inch	2inch	3inch
Model	Prototype	R8778	R10789	R13111
Material:Body	glass	Kovar	Kovar	goal is 1/10 of R10780
QE	25%	25%	27-39%	
U [mBq/PMT]	50	18±2	0.70 +/- 0.28	
Th [mBq/PMT]	13	6.9±1.3	1.5 +/- 0.31	
^{40}K [mBq/PMT]	610	140±20	< 5.1	
^{60}Co [mBq/PMT]	<1.8	5.5±0.9	2.9 +/- 0.16	

Exercise: Radioactivity of ^{40}K in the Human Body

Estimate the total radioactivity (in Bq) of ^{40}K in a human body with a mass of 70 kg.

Use the following information:

- Mass fraction of potassium in the human body: 0.20%
- Natural abundance of ^{40}K in potassium: 0.0117%
- Half-life of ^{40}K: 1.25×10^9 years
- Molar mass of potassium: 39.1 g/mol
- Avogadro constant: $6.02 \times 10^{23}\,\mathrm{mol}^{-1}$

Hint:

decay constant

$$\lambda = \frac{\ln 2}{T_{1/2}}$$

radioactivity:

$$A = \lambda N$$

Solution

1. Total mass of potassium in the body

For a 70 kg person:

$$m_K = 70 \times 0.002 = 0.14\,\text{kg} = 140\,\text{g}$$

2. Mass of ^{40}K

The abundance of ^{40}K is

$$0.0117\% = 1.17 \times 10^{-4}$$

Thus,

$$m_{40} = 140 \times 1.17 \times 10^{-4} = 1.64 \times 10^{-2}\,\text{g}$$

3. Number of ^{40}K atoms

$$n = \frac{m_{40}}{39.1} = 4.19 \times 10^{-4}\,\text{mol}$$

$$N = nN_A = 4.19 \times 10^{-4} \times 6.02 \times 10^{23} = 2.52 \times 10^{20}$$

4. Decay constant

Convert the half-life to seconds:

$$T_{1/2} = 1.25 \times 10^9 \times 365 \times 24 \times 3600 = 3.94 \times 10^{16}\,\text{s}$$

$$\lambda = \frac{\ln 2}{T_{1/2}} = \frac{0.693}{3.94 \times 10^{16}} = 1.76 \times 10^{-17}\,\text{s}^{-1}$$

5. Activity

$$A = \lambda N$$

$$A = 1.76 \times 10^{-17} \times 2.52 \times 10^{20} \approx 4.4 \times 10^3\,\text{Bq}$$

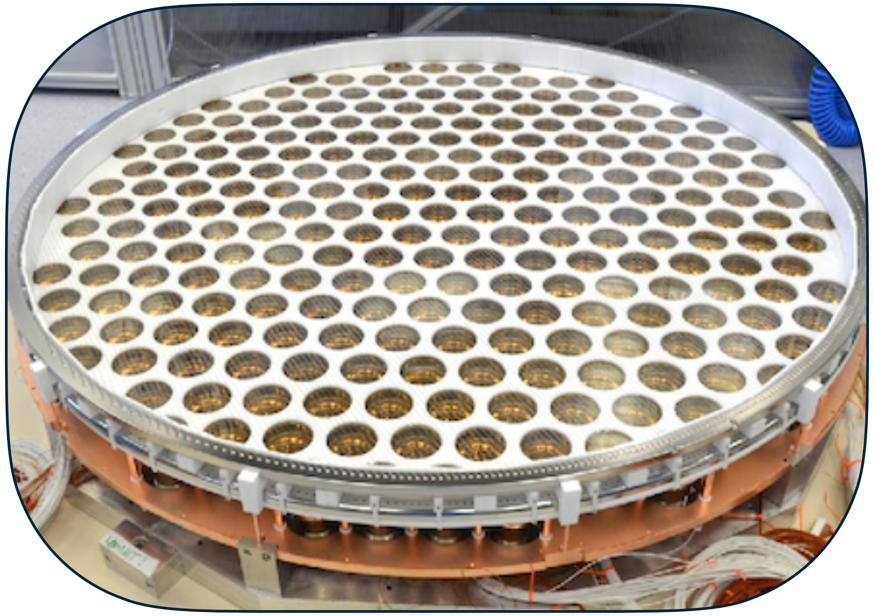
XENONnT uses about 500 light sensors.

How low in radioactivity do these sensors need to be?

1 Bq：1 radioactive decay/second

4000 Bq/person

^{40}K



less than 1/1000 than usual one

XENONnT uses about 500 light sensors.

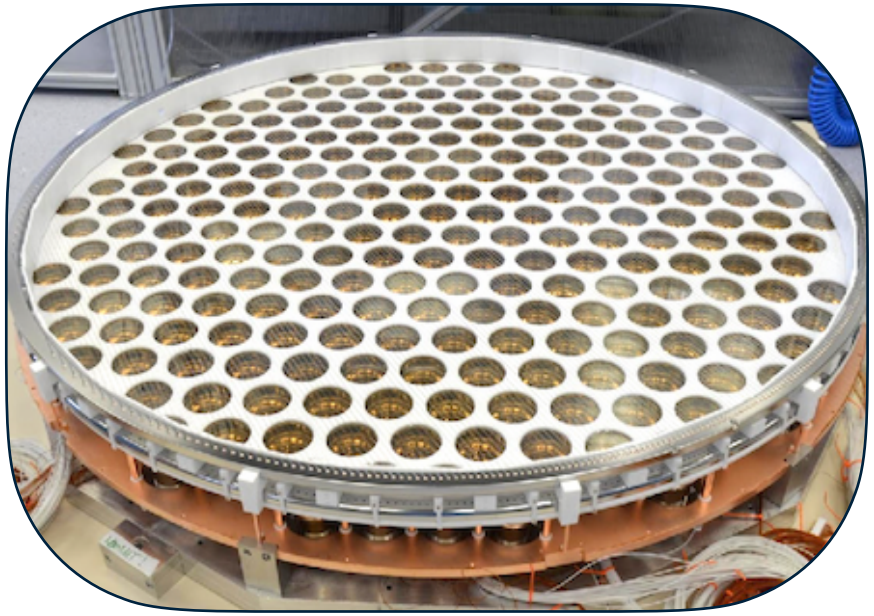
How low in radioactivity do these sensors need to be?

1 Bq：1 radioactive decay/second

4000 Bq/person

^{40}K

15 Bq/Banana



less than 1/1000 than usual one

XENONnT uses about 500 light sensors.

How low in radioactivity do these sensors need to be?

1 Bq：1 radioactive decay/second

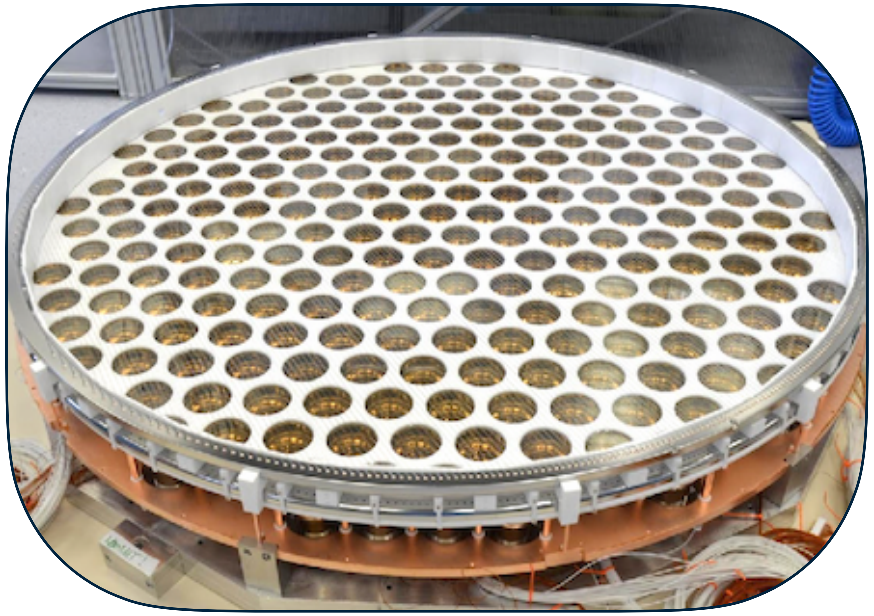
4000 Bq/person

^{40}K

15 Bq/Banana

0.01 Bq/Sensor

5 Bq/500 sensors



less than 1/1000 than usual one

Particle Identification

Underground Lab

Radiation Shield

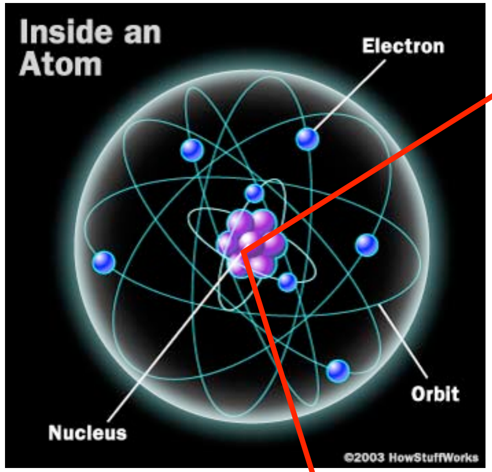
Material Selection

Particle Identification

Fiducial volume

Neutron veto

nuclear recoil

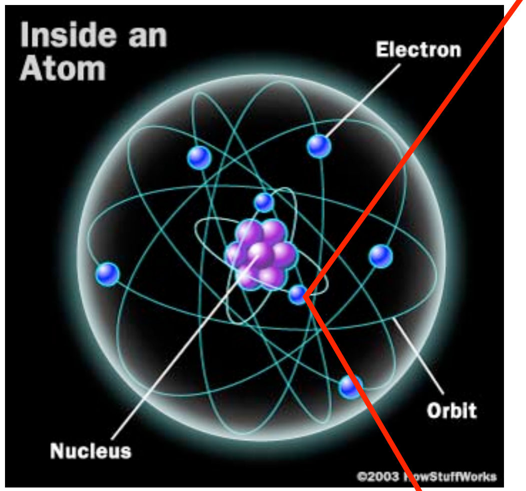


fast neutron

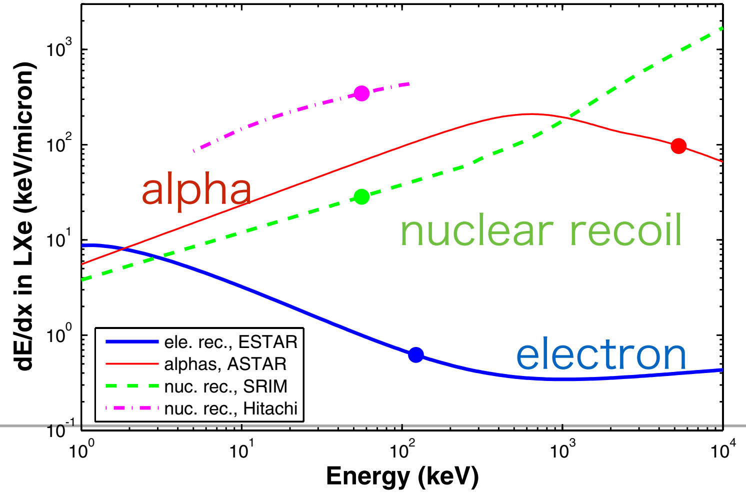
Neutrino

WIMP

electronic recoil



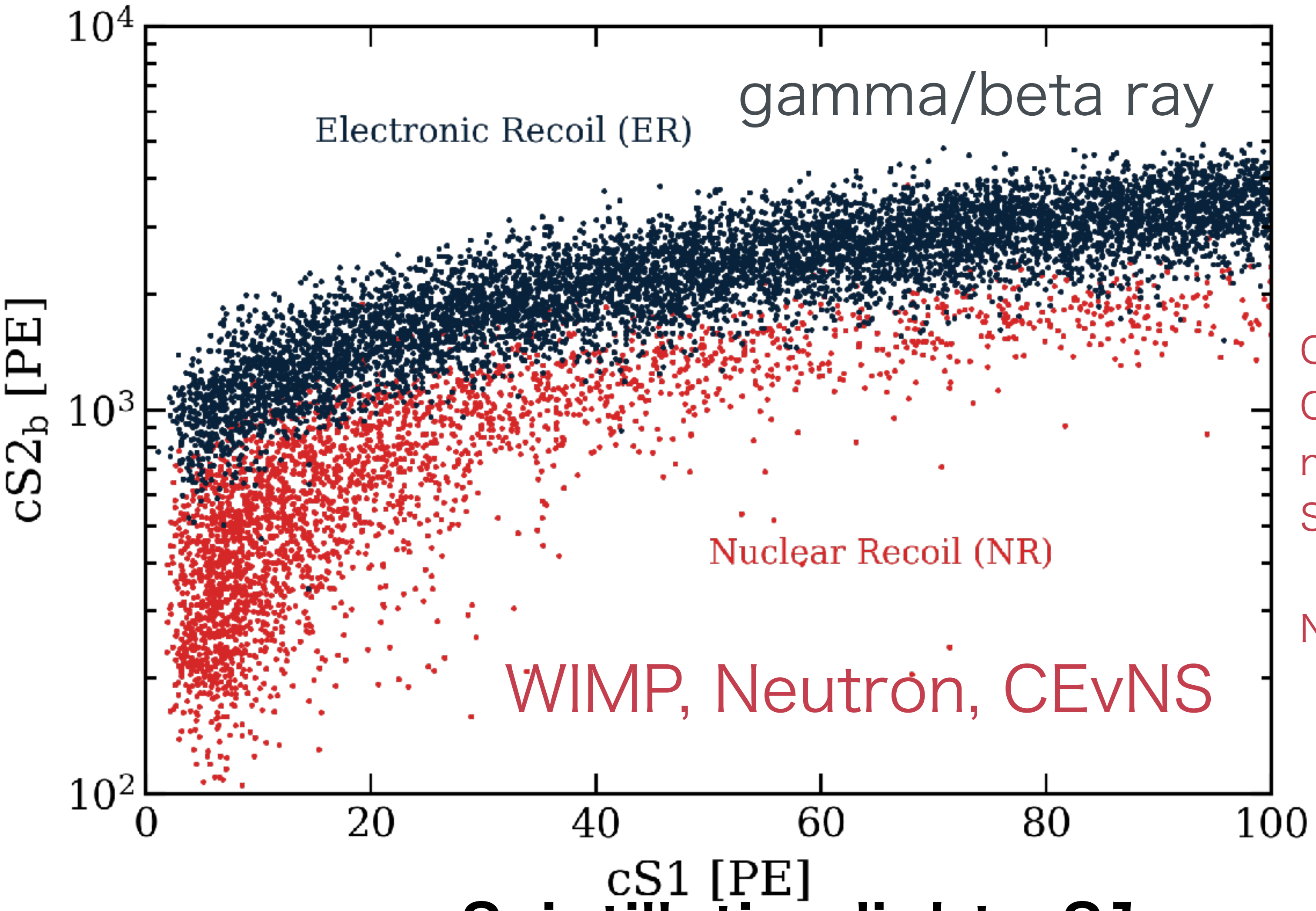
-U/Th/^{40}K etc background



Two-phase Xe Time Projection Chamber

- Recoil type discrimination from ratio of charge (S2) to light (S1)

- Ionization electron -S2



CEvNS=
Coherent Elastic
neutrino-Nucleus
Scattering

N + ν -> N + ν

- Scintillation light - S1

Fiducial volume cut

Underground Lab

Radiation Shield

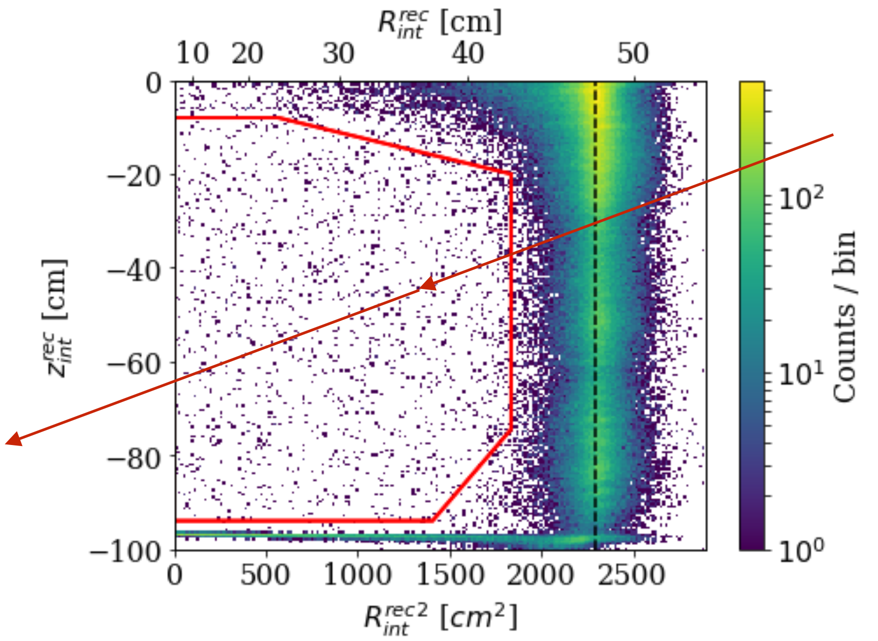
Material Selection

Particle Identification

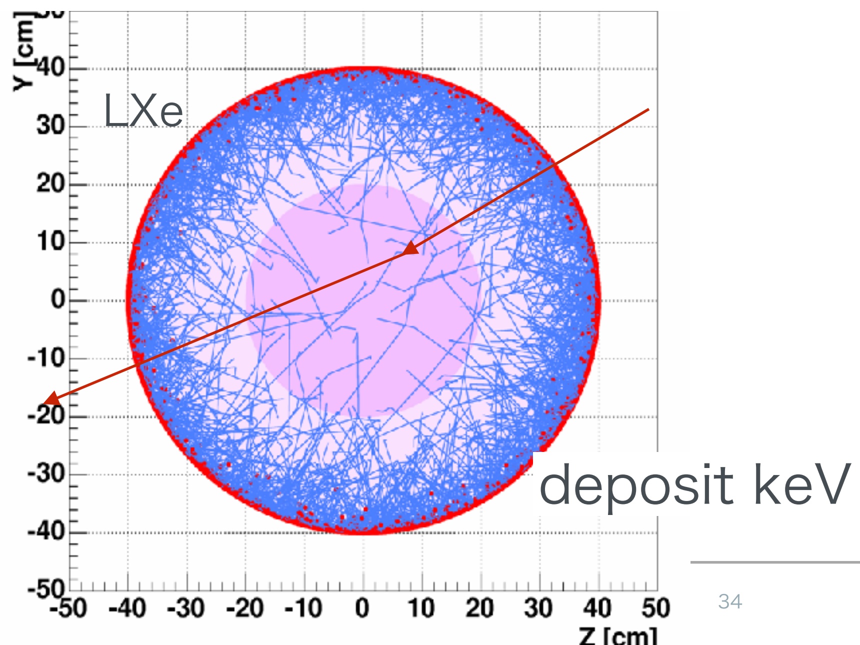
Fiducial volume

Neutron veto

Xe	
High	Z(=54)
High Density 3g/cc	



- It is essentially impossible for an MeV gamma ray to deposit energy only in the few-keV fiducial volume and then escape the detector without further interactions.
- This leads to a background suppression of order 10^5.
- Therefore, reducing internal backgrounds —such as ^{85}Kr and radon (^{222}Rn)— is crucial.



Neutron Veto

Underground Lab

Radiation Shield

Material Selection

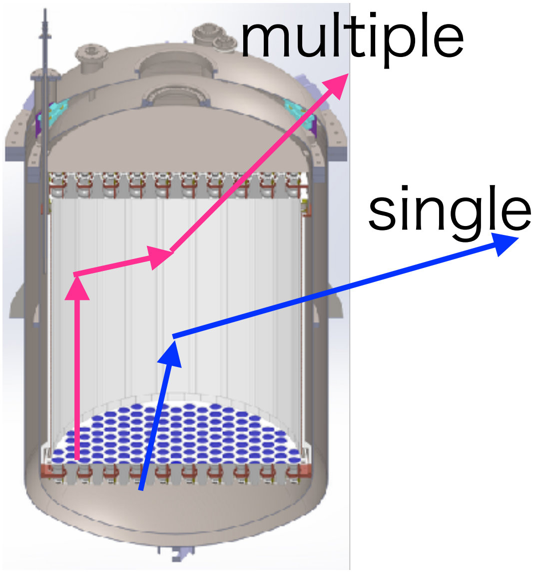
Particle Identification

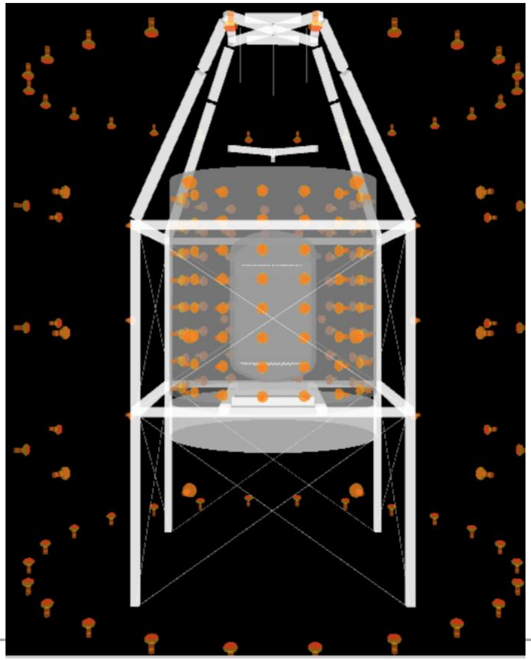
Fiducial volume

Neutron veto

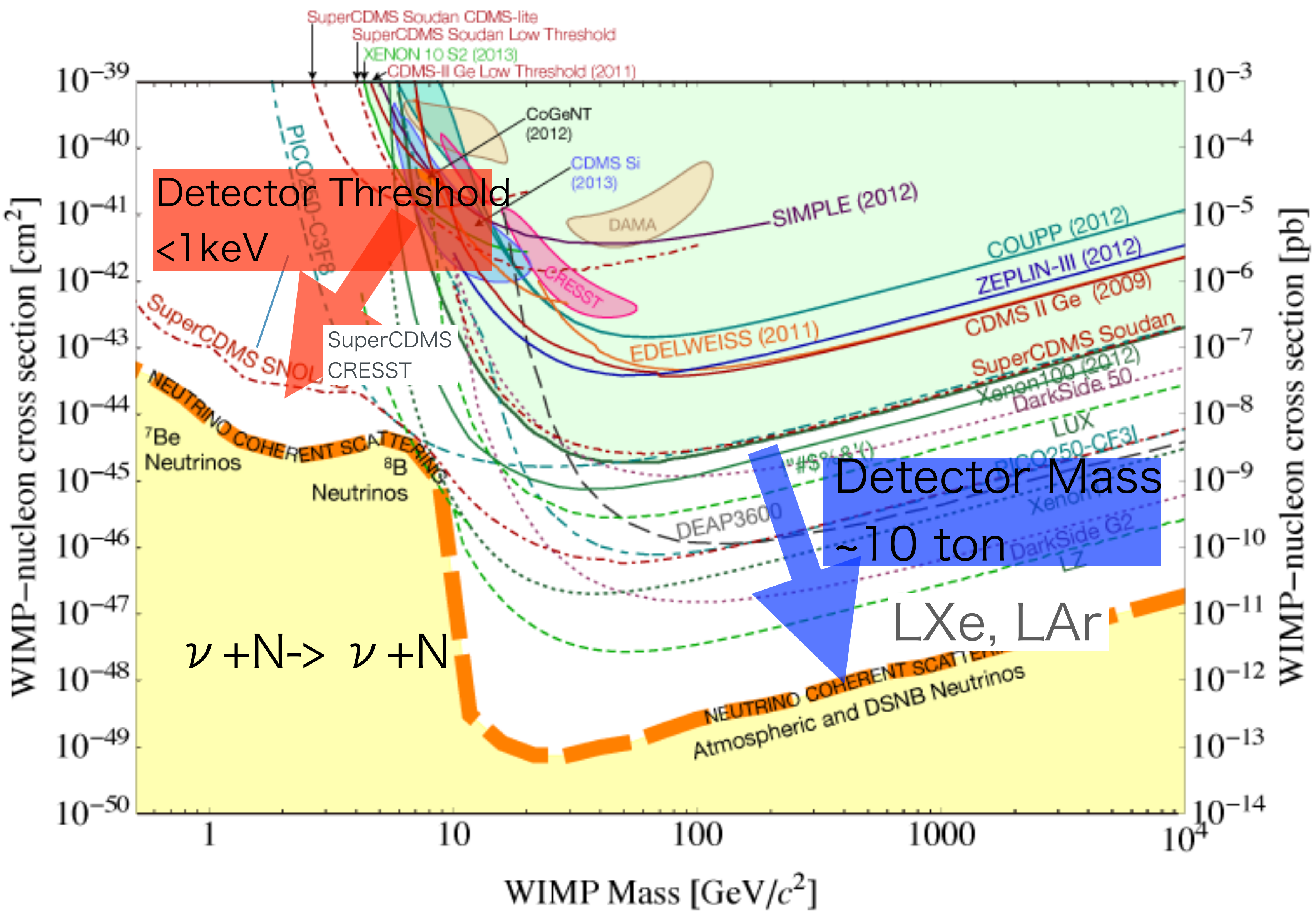
current generation (XENONnT, LZ, Panda-X)

- About **a few neutrons** single-scatter events per ton per year are expected over a 4-year exposure.
- Such neutron events are i**ndistinguishable from dark-matter signals** using the TPC alone.
- These neutrons originate mainly from fission and **(α,n) reactions** induced by U/Th contamination in detector materials such as the cryostat, PMTs, and PTFE.
- To enable a dark-matter discovery, **a neutron tagging efficiency exceeding 80%** is required.
- XENONnT: neutron tagging using **water Cherenkov detector with gadolinium**, based on technologies developed in EGADS and Super-Kamiokande-Gd
    - LZ: neutron tagging using a liquid scintillator veto





Underground lab and DM searches


SuperCDMS Soudan CDMS-lite
SuperCDMS Soudan Low Threshold
XENON 10 S2 (2013)
CDMS-II Ge Low Threshold (2011)
CoGeNT (2012)
CDMS Si (2013)
DAMA
SIMPLE (2012)
CRESST
COUPP (2012)
ZEPLIN-III (2012)
CDMS II Ge (2009)
EDELWEISS (2011)
SuperCDMS Soudan
Xenon100 (2012)
DarkSide 50
LUX
PICO250-CF3I
DEAP3600
Xenon
DarkSide G2
LZ
PICO2L-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
^{7}Be Neutrinos
^{8}B Neutrinos
Atmospheric and DSNB Neutrinos
Detector Threshold
<1keV
SuperCDMS
CRESST
Detector Mass
~10 ton
LXe, LAr
ν+N-> ν+N
WIMP–nucleon cross section [cm^2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c^2]

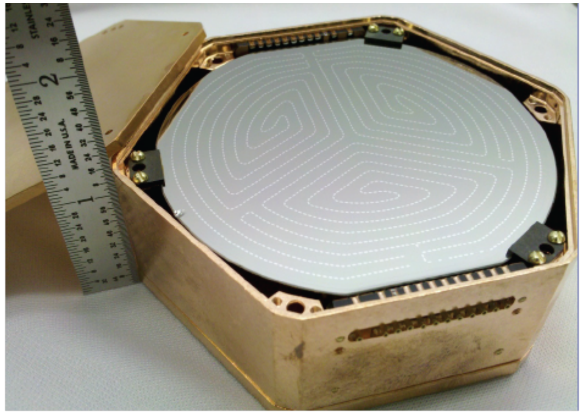
Low Mass by cryogenic detectors

SuperCDMS

CDMSlite
E threshold = 56 eV

=> SNOLAB
4 towers x 6 detectors
about 30 kg total

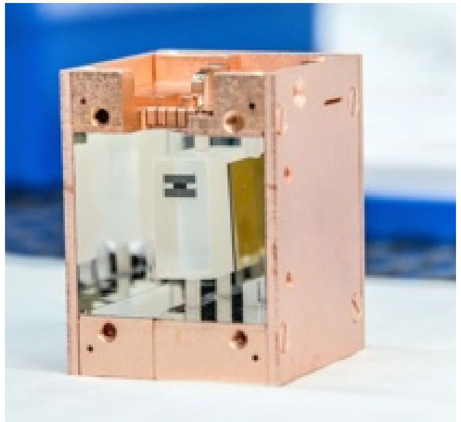
Phys. Rev. D **99**, 062001



CRESST-III

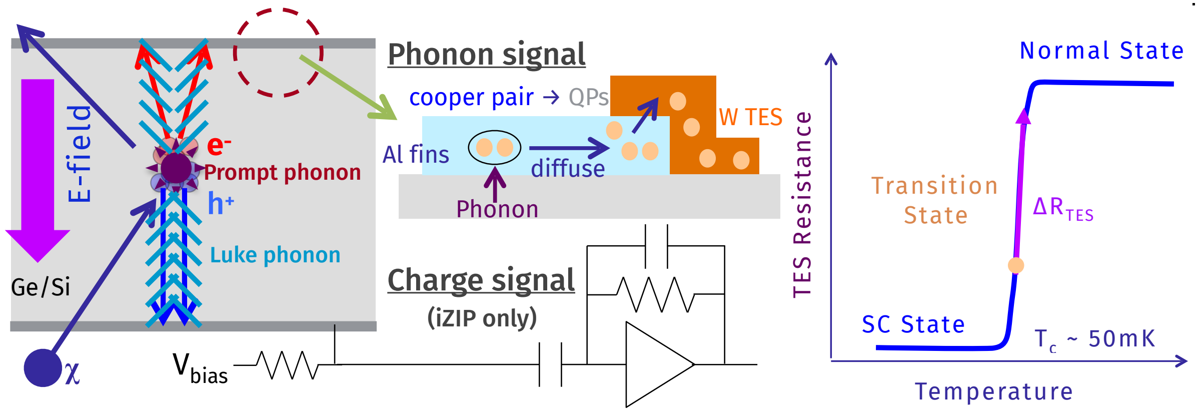
$CaWO_4$ @LNGS
Mass: 23.6 g
E threshold = 30.1 eV

arXiv:1711.07692



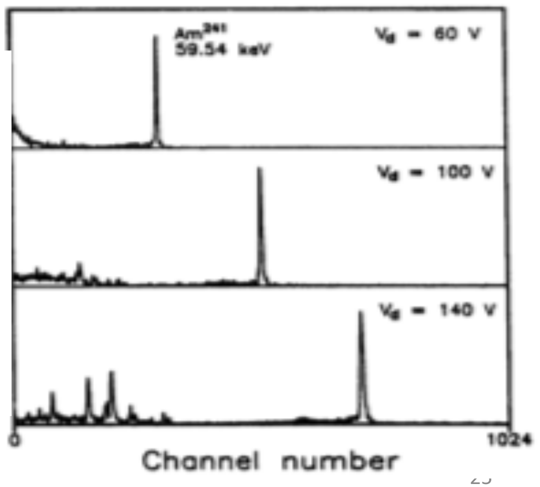
Super-CDMS

Luke-Neganov Ionization Amplification



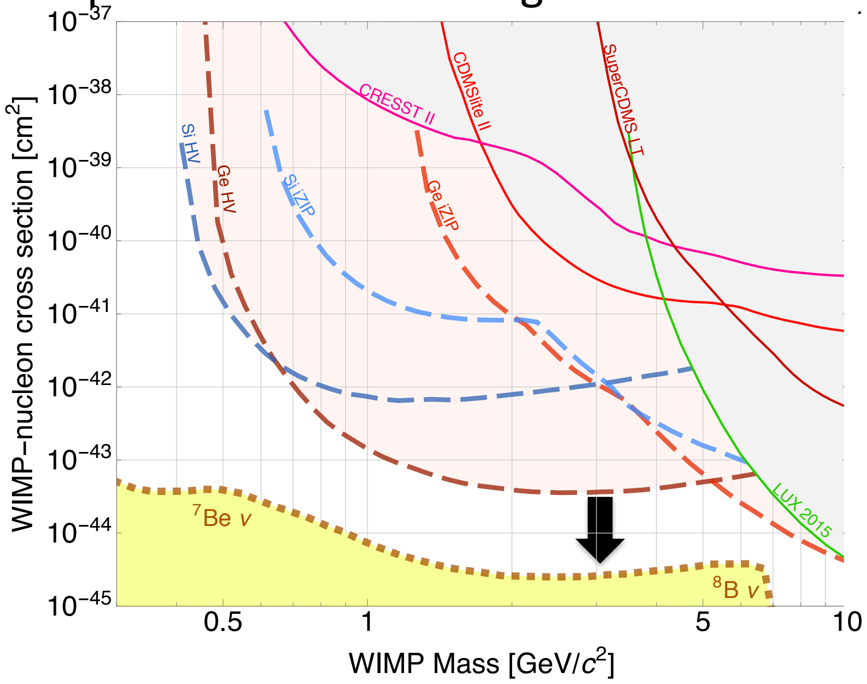
$$E_{total} = E_{recoil} + E_{luke}$$
$$= E_{recoil} + Qe\Delta V$$
$$\lim_{\Delta V \to \infty} E_{total} \propto Q$$

Eth << 1keV



P.N. Luke et al. NIM A289, 405 (1990)

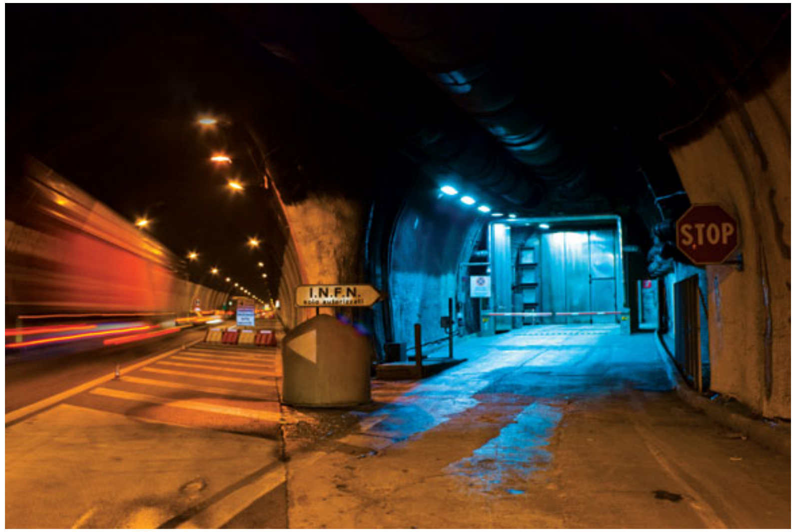
SuperCDMS G2+: Hitting the Neutrino Floor



XENON Experiment

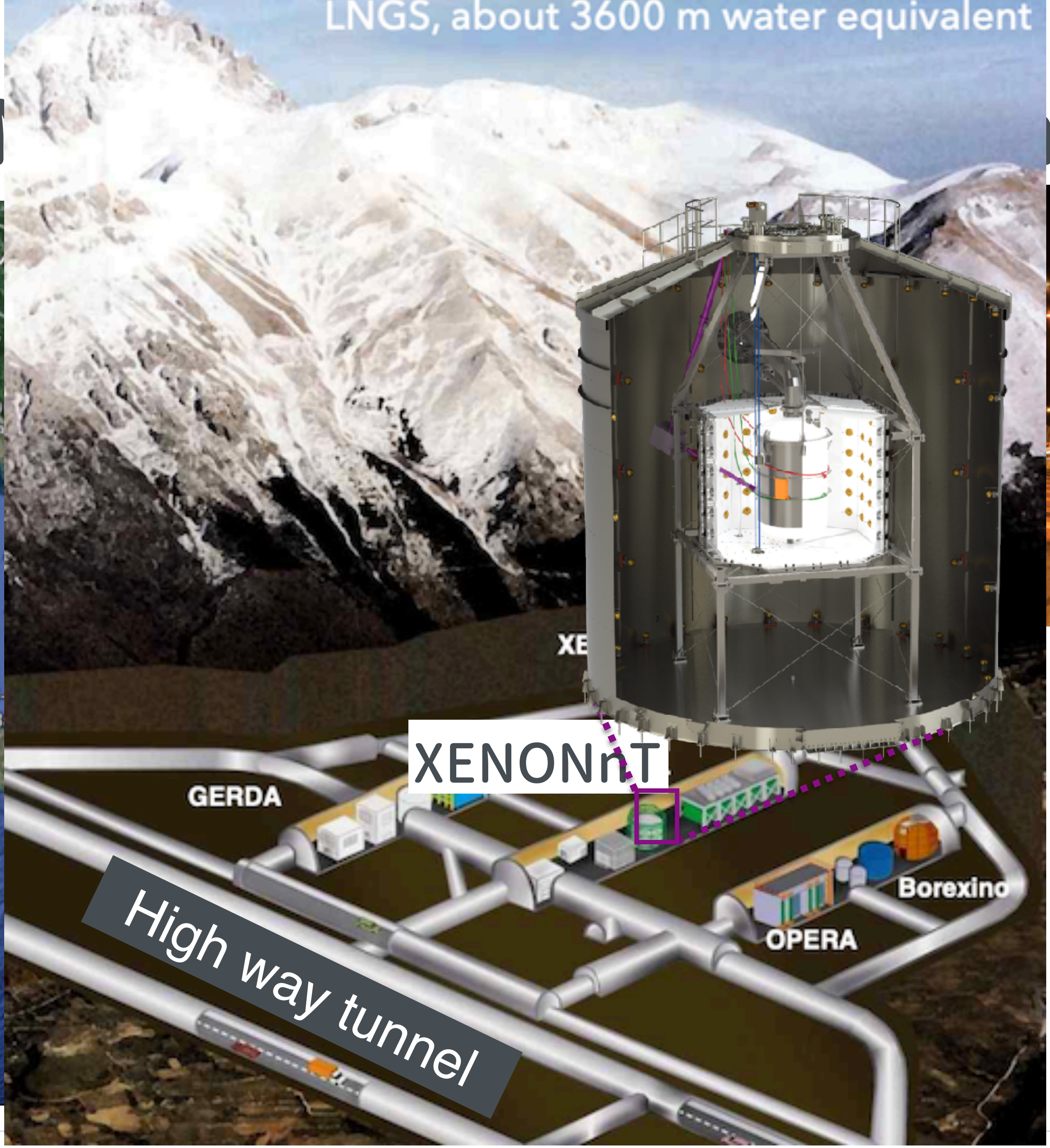
Masaki Yamashita, ISEE NagoyaU

Gran Sasso Laboratory



- 120 km from Rome (Abruzzo)
- Gran Sasso (2,914 m)
- Underground Lab 1, 400 m
  - Cosmic Rays flux **$1/10^6$**
- Middle of 10 km high way tunnel

XE… Sasso in Ital…



ISEE Institute for Space-Earth Environmental Research

XENON Collaboration

- 200+ scientists
- 29 institutions
- 12 countries

AMERICA

- UC San Diego — San Diego
- Houston
- The University of Chicago — Chicago
- Columbia University in the City of New York — New York City
- Purdue University — Lafayette

Europe

- Zurich
- KIT Karlsruhe Institute of Technology — Karlsruhe
- WWU Münster — Münster
- Uni Freiburg — Freiburg
- JGU — Mainz
- Max Planck Institut für Kernphysik — Heidelberg
- Nikhef — Amsterdam
- Stockholm University — Stockholm
- Coimbra
- Subatech — Nantes
- LPNHE Paris — Paris
- INFN Torino — Torino
- Bologna
- Università degli Studi dell'Aquila — L'Aquila
- INFN LNGS — Assergi
- Napoli

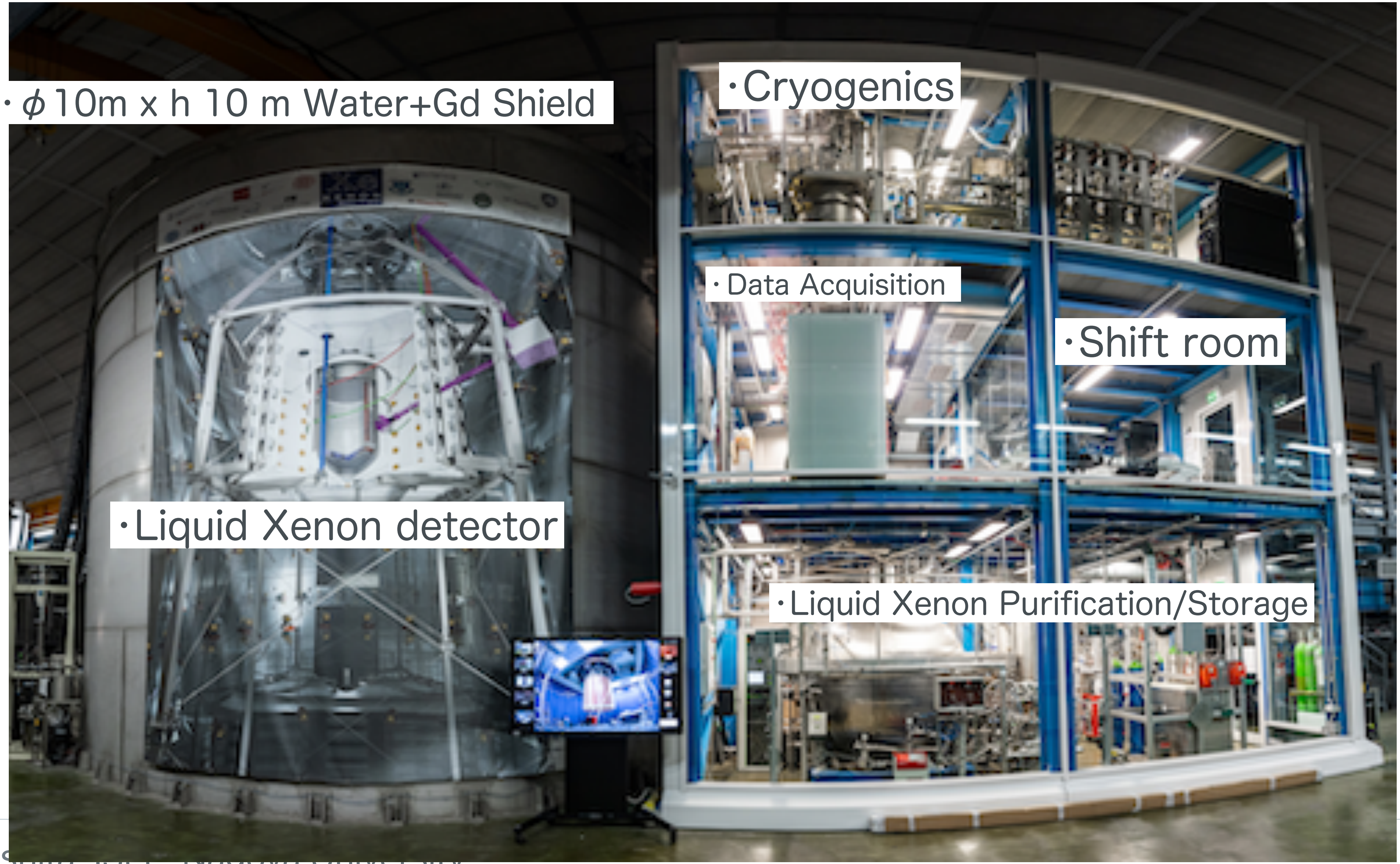
Middle East

- מכון ויצמן למדע Weizmann Institute of Science — Rehovot
- جامعة نيويورك أبوظبي NYU Abu Dhabi — Abu Dhabi

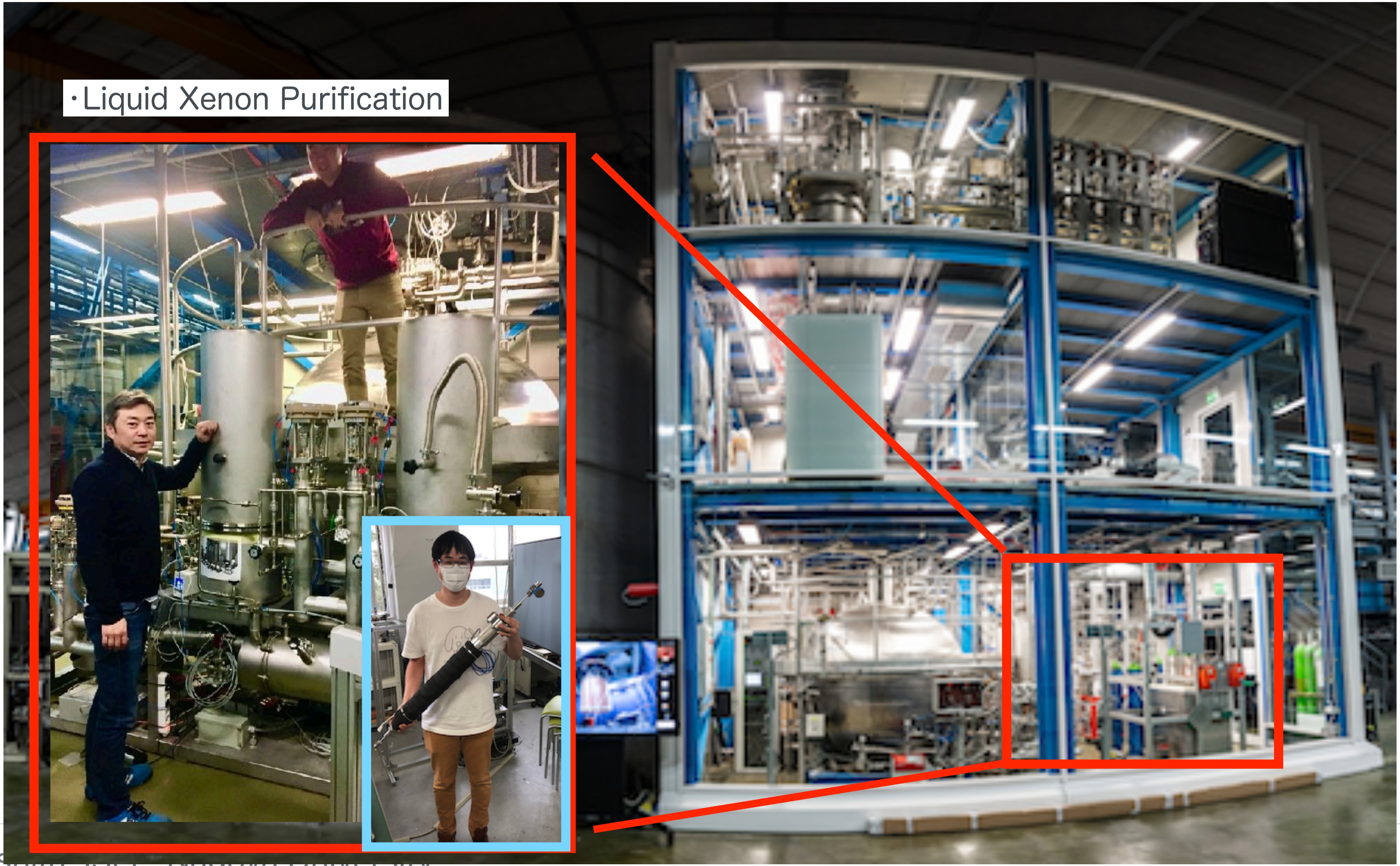
ASIA

- 清华大学 Tsinghua University — Beijing
- 西湖大学 Westlake University — Hangzhou
- Shenzhen
- 東京大学 The University of Tokyo — Tokyo
- Nagoya University — Nagoya
- Kobe University — Kobe

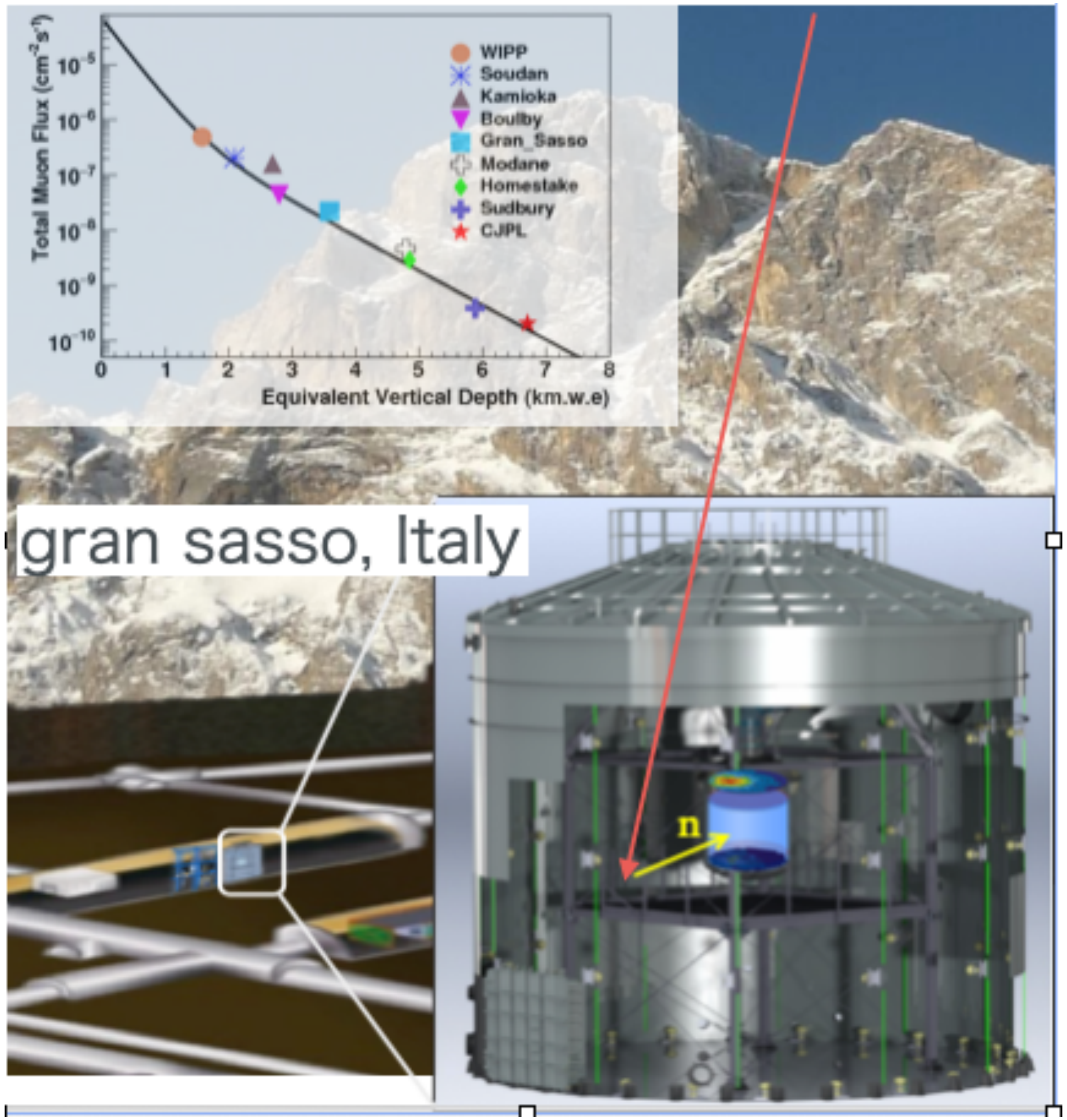
XENONnT Detector

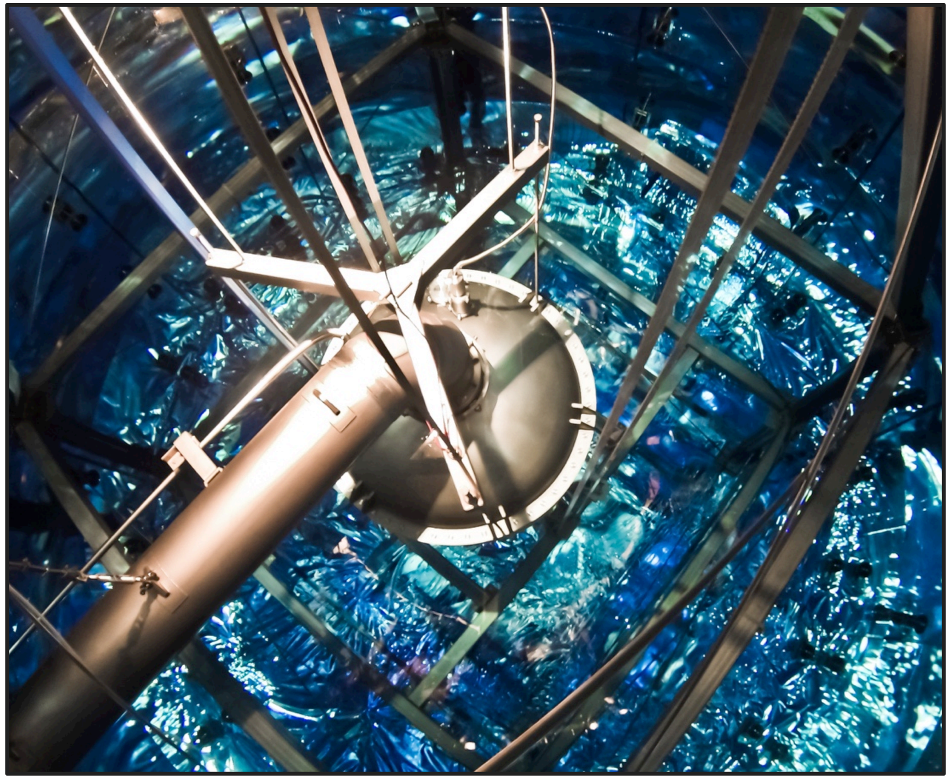


Liquid Xenon Purification

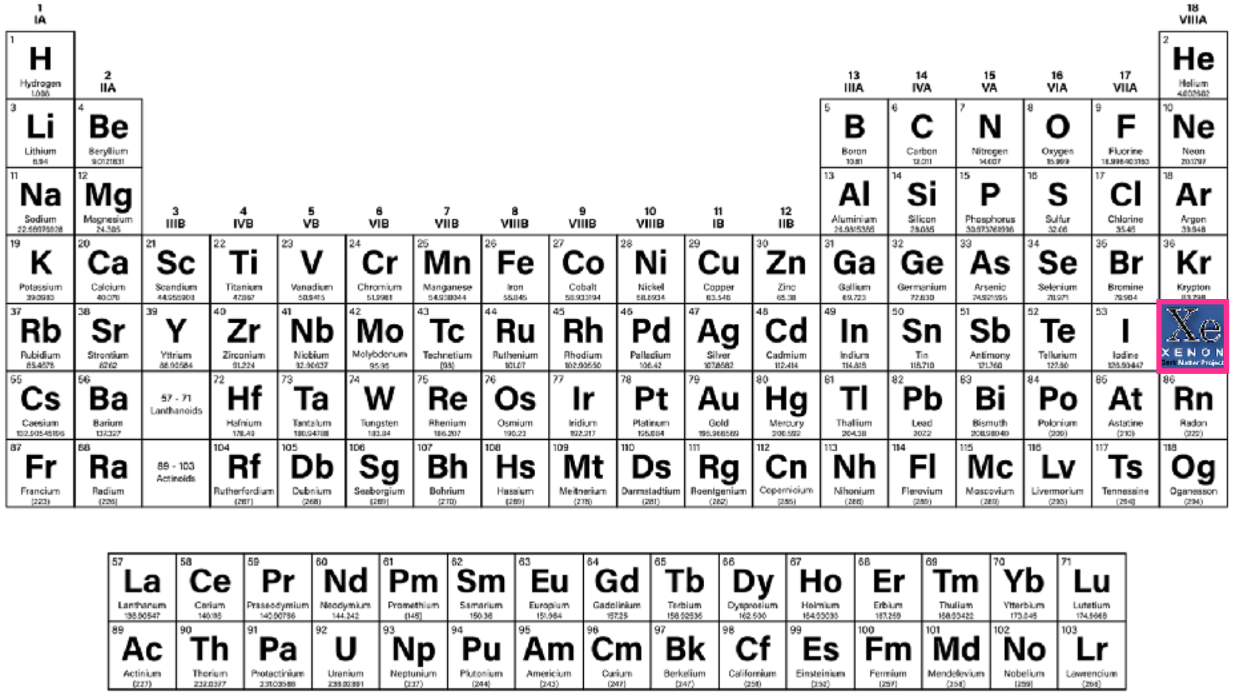


XENON1T at Gran Sasso, Italy

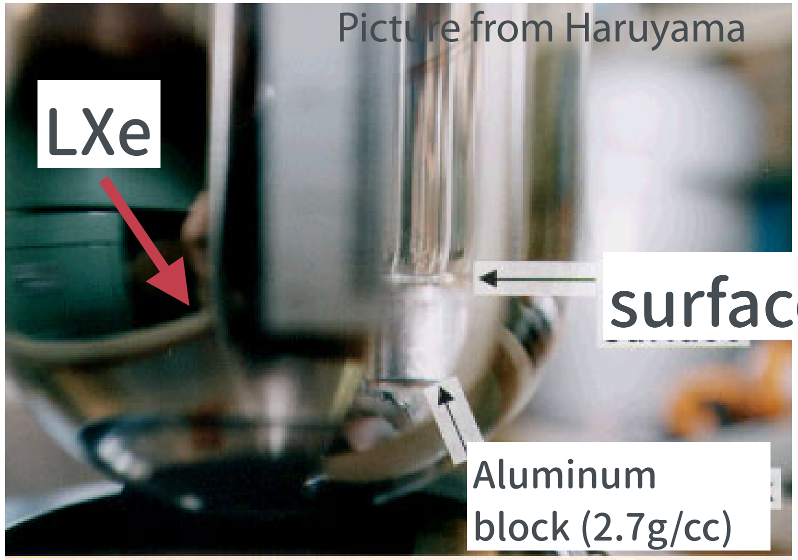




Why Liquid Xenon?



Aluminum block floating in liquid xenon (picture)



Heavy liquid => large mass

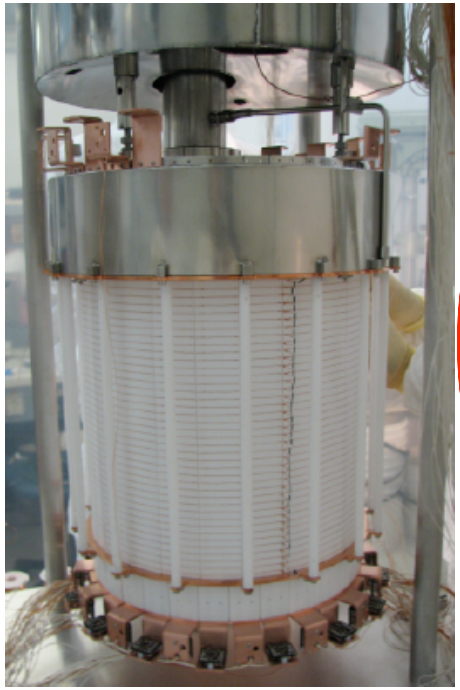
Xenon	
Atomic Number	54
Atomic Mass	131

Large Dark Matter cross section

T	−100°C
Density	3g/cc

Shape-flexible
Liq/gas purificaton

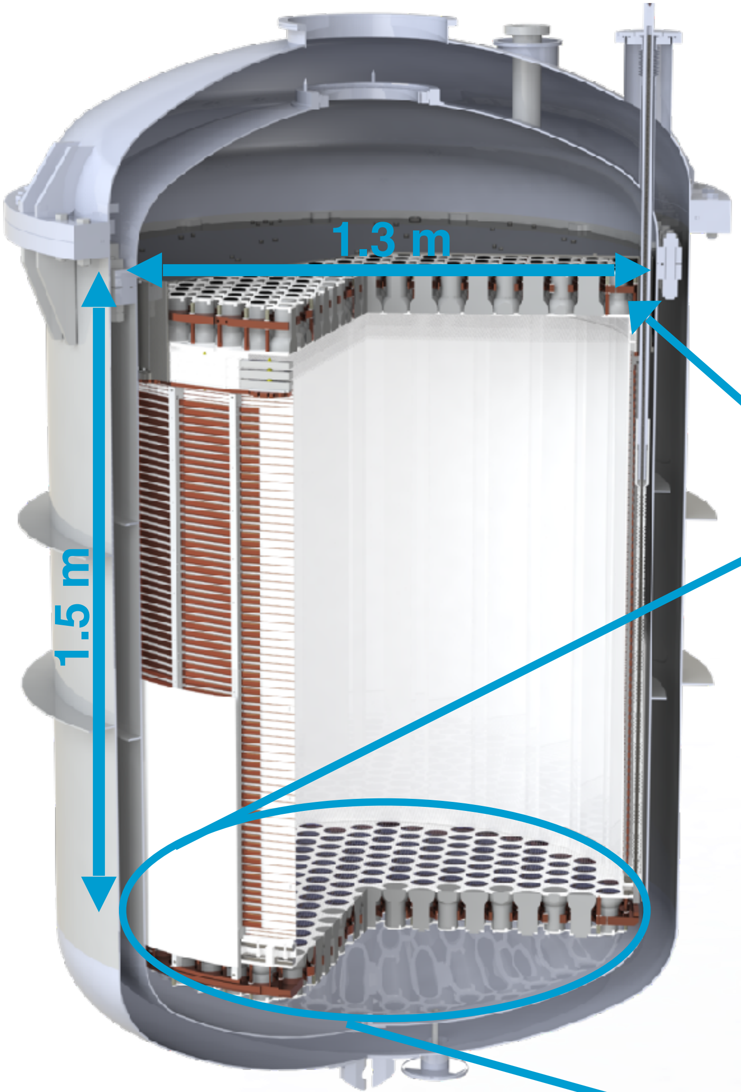
Development of XENON Program

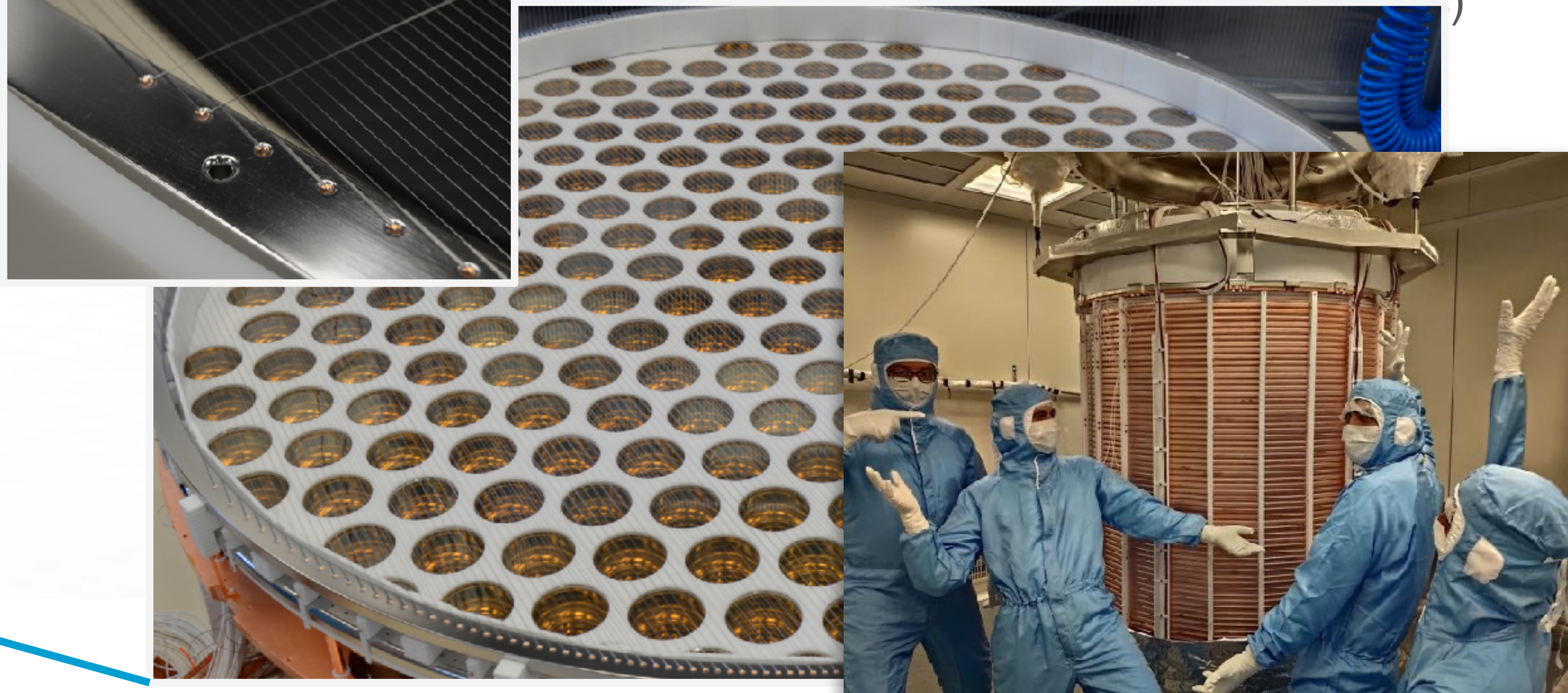
XENON10	XENON100	XENON1T	XENONnT
			
2005-2007	2008-2016	2012-2018	2019-202x
25 kg - 15cm drift	161 kg - 30 cm drift	3.2 ton - 1 m drift	8 ton - 1.5 m drift
~10^{-43} cm^2	~10^{-45} cm^2	~10^{-47} cm^2	~10^{-48} cm^2

Dual phase xenon time projection chamber (TPC)

- Cylindrical PTFE walls for high reflectivity,
  all materials carefully screened and selected
- 494 3” PMTs (R11410-21)
- Inside TPC: 5.9 t of liquid xenon (> 4 t fiducial volume)
- 5 meshes and a field cage to define electric fields and protect PMTs
  cathode, gate and anode + 2 screening meshes to shield PMT arrays
  …de reinforced by additional perpendicular wires)

XENONnT

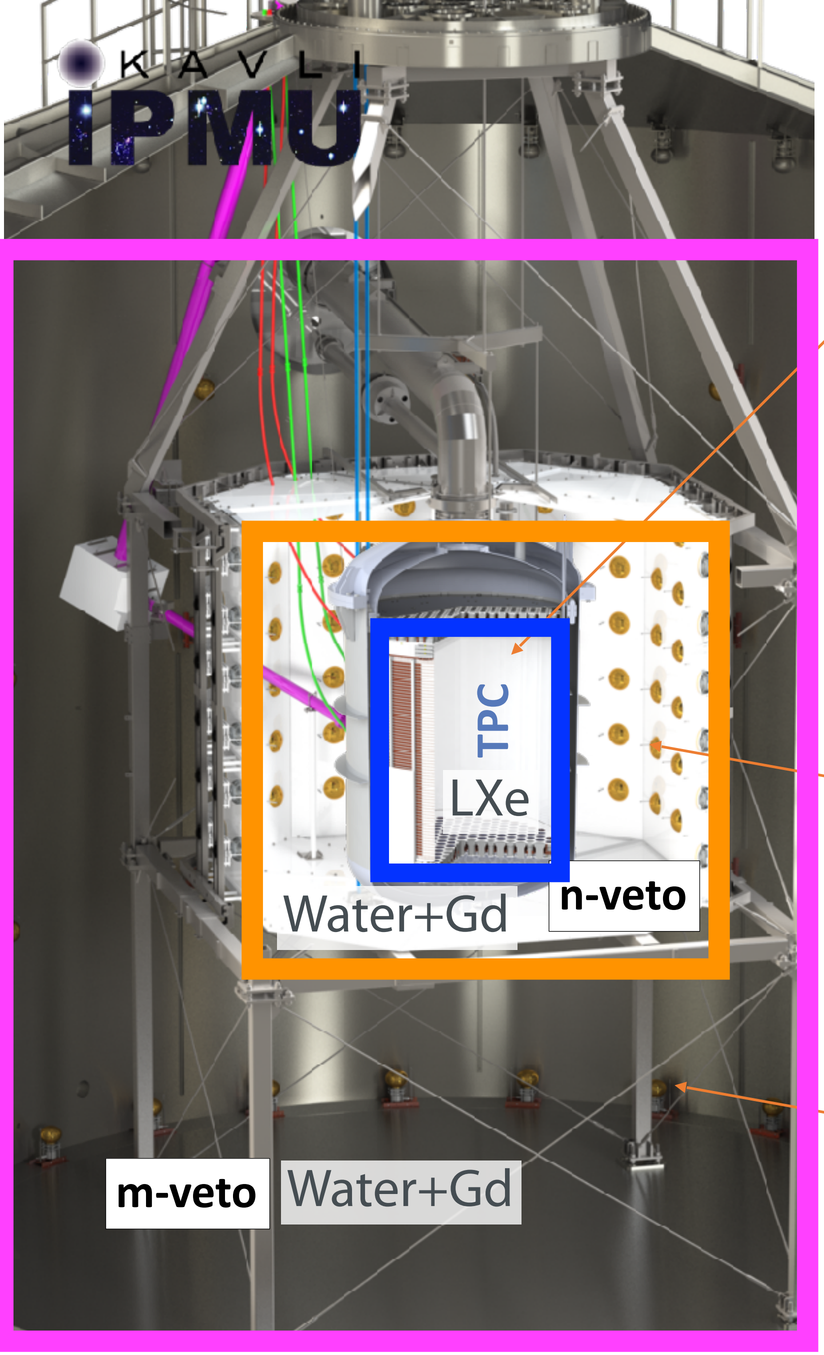


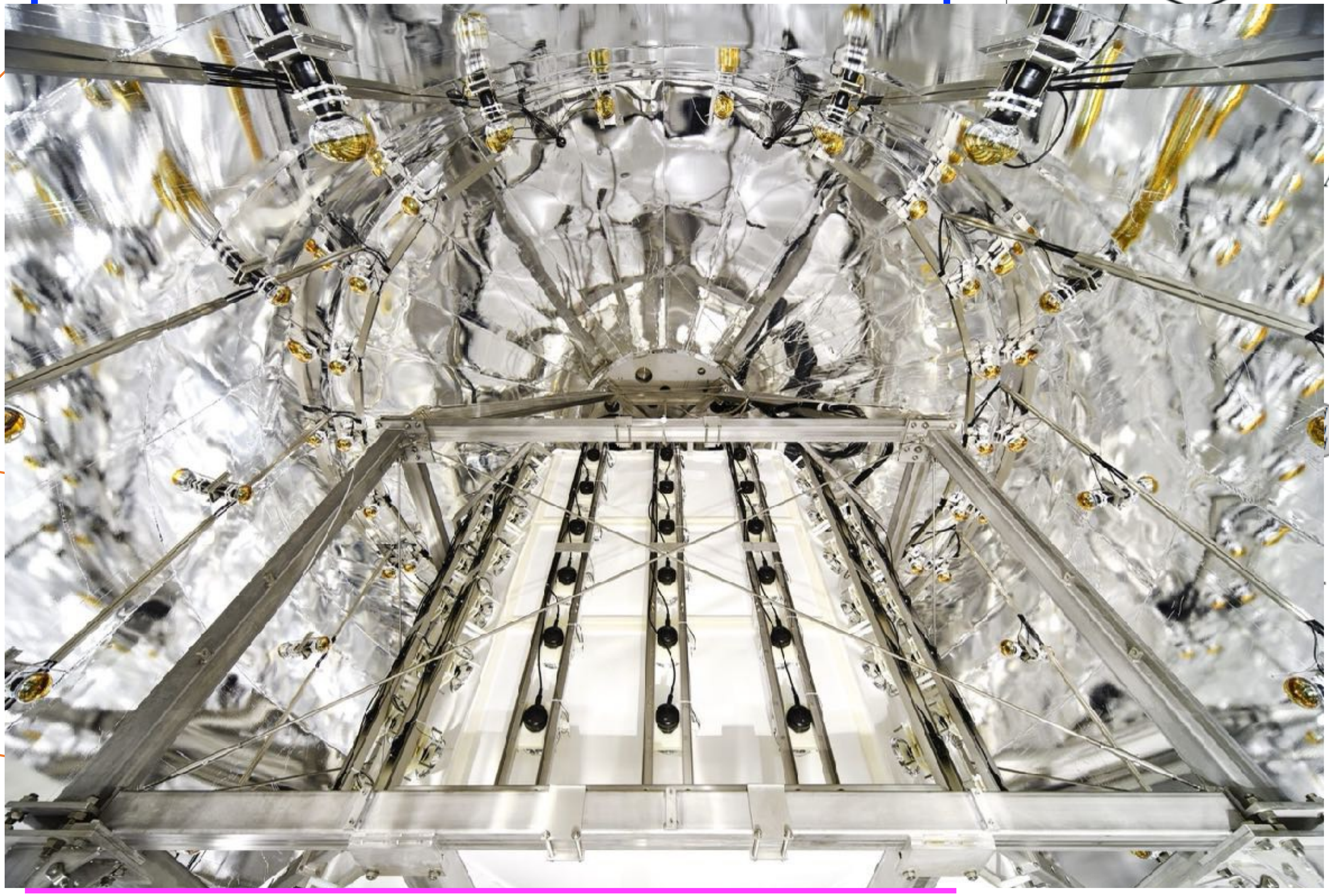


Masaki Yamashita, ISEE NagoyaU

XENONnT: 3 detectors

CEvNS



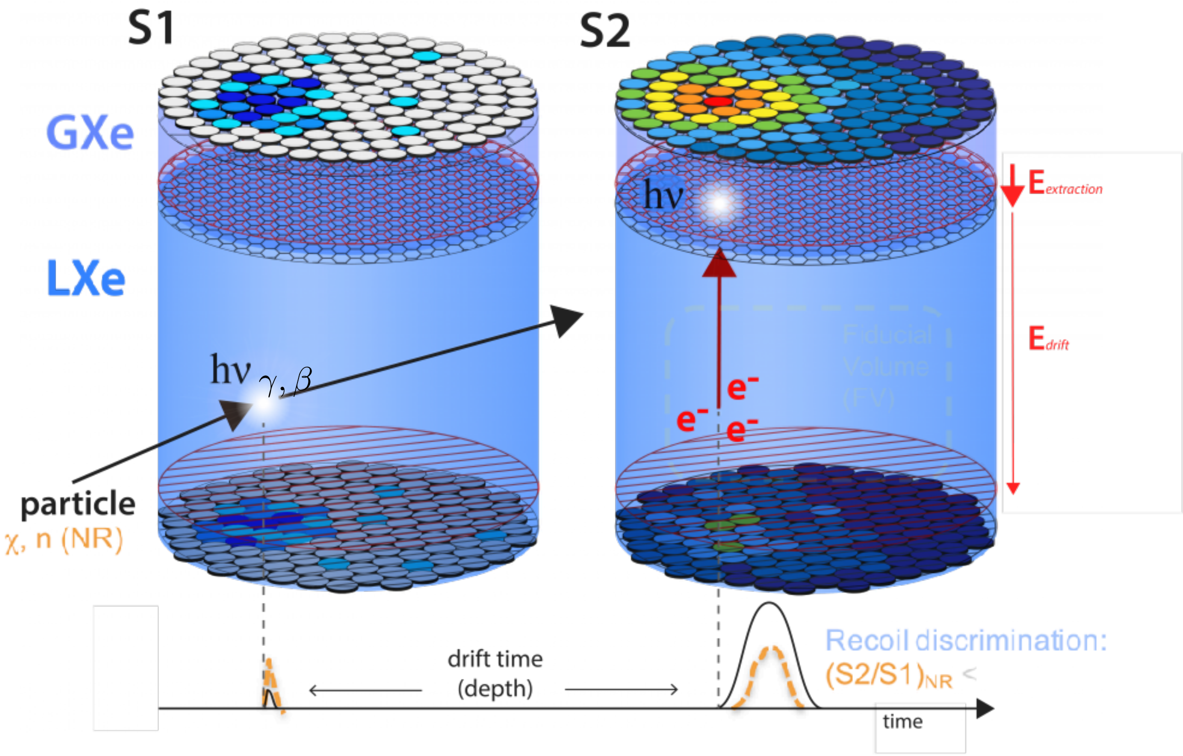


Gd-loaded water (EGADS, SK-Gd technology)

Supernova Neutrino Detection through inverse-beta decay channel

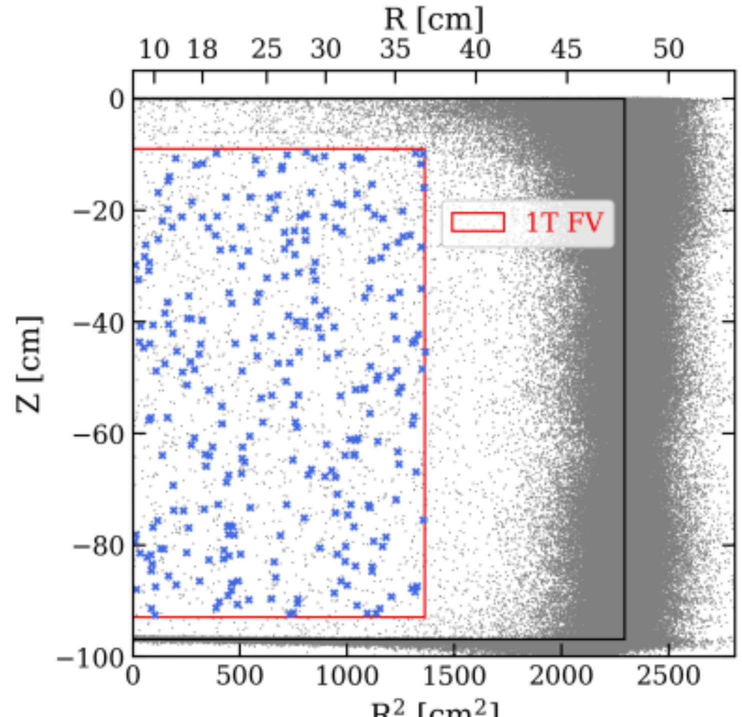
Two-phase Xe Time Projection Chamber

- **Scintillation light - S1**
- **Ionization electron -S2**

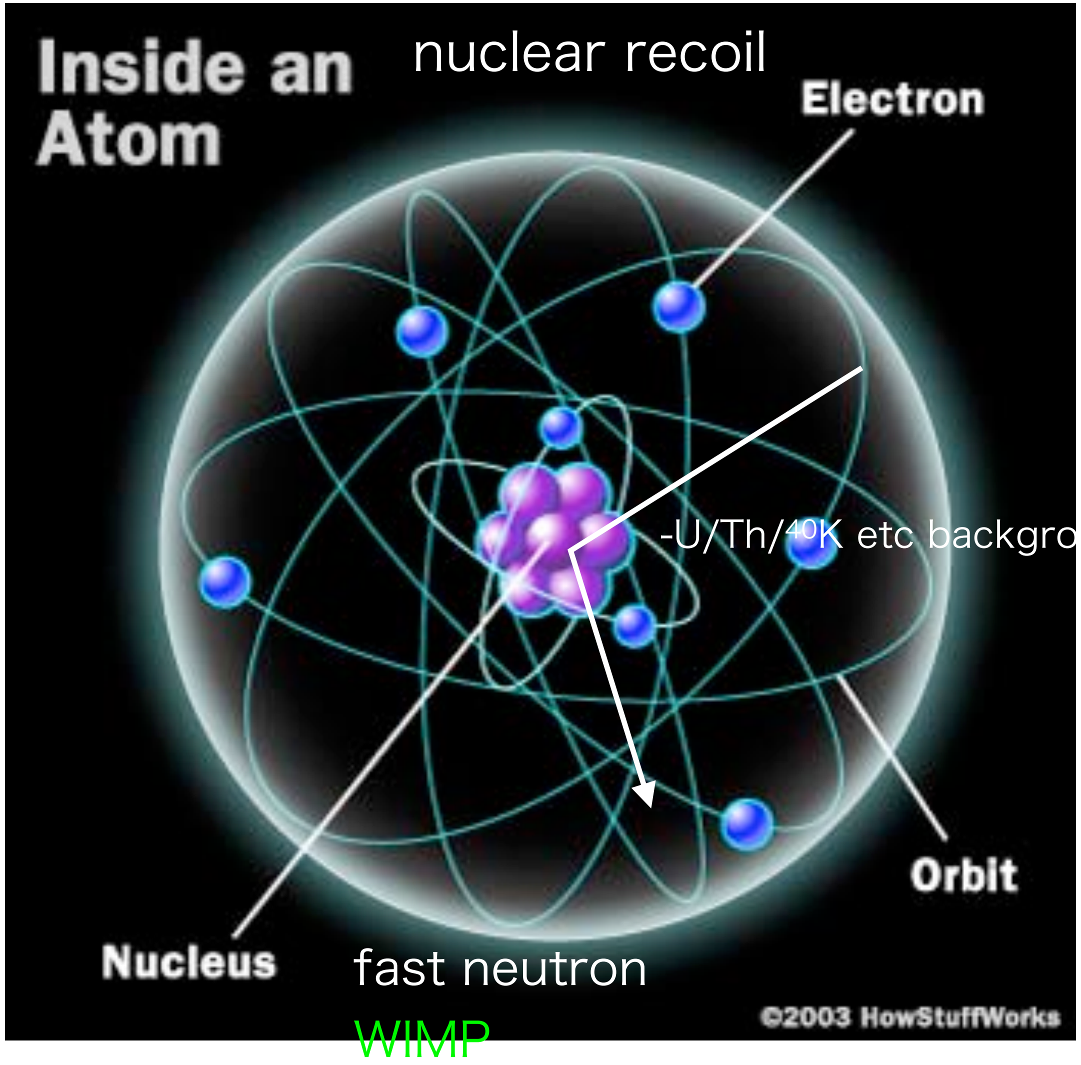


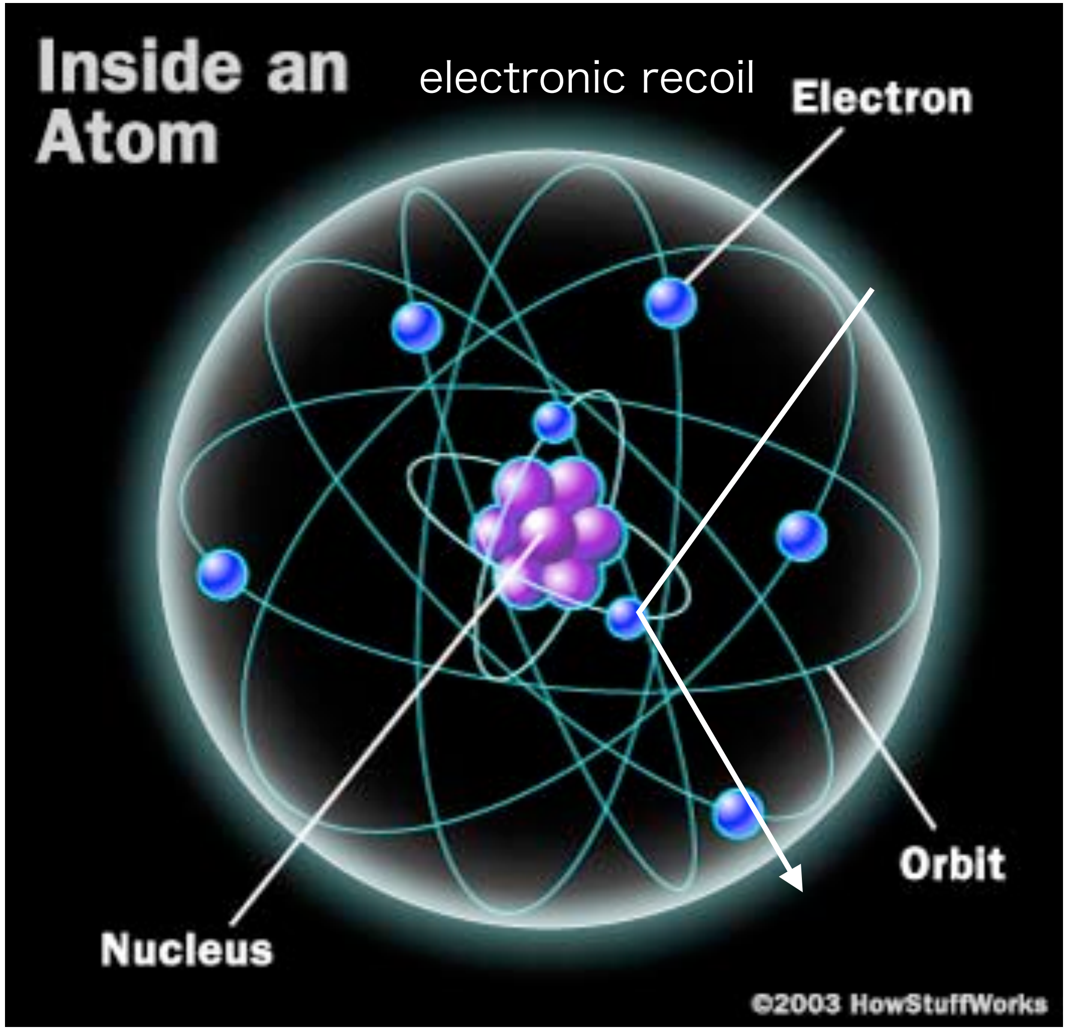
- two signals for each event:
  - 3D event imaging: x-y (S2) and z (drift time)
  - self-shielding, surface event rejection, single vs multiple scatter events
  - Particle identification using S2/S1 ratio (nuclear recoil vs beta, gamma)

ER



Interaction with dark matter

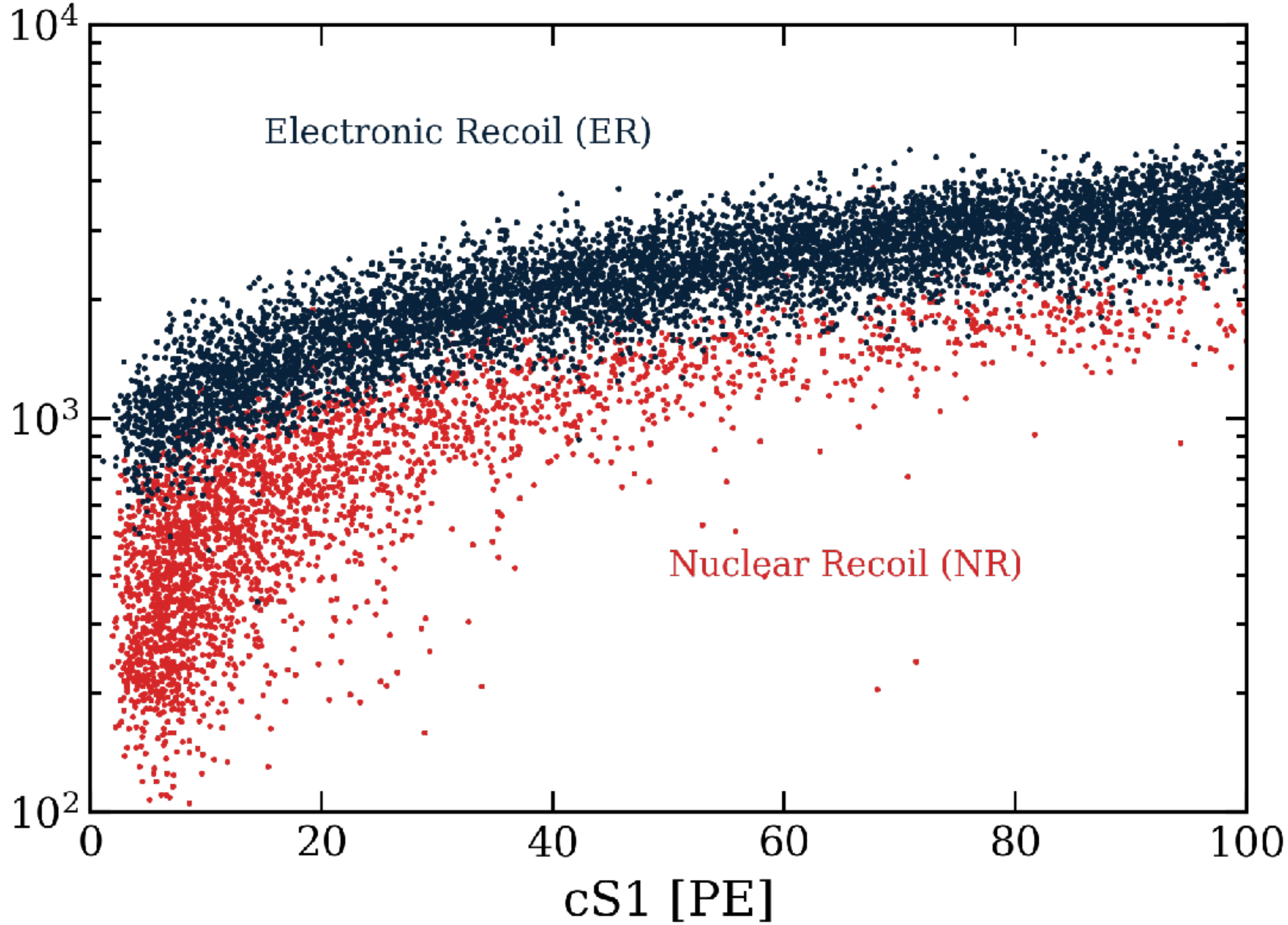




Two-phase Xe Time Projection Chamber

- Recoil type discrimination from ratio of charge (S2) to light (S1)

· Ionization electron -S2

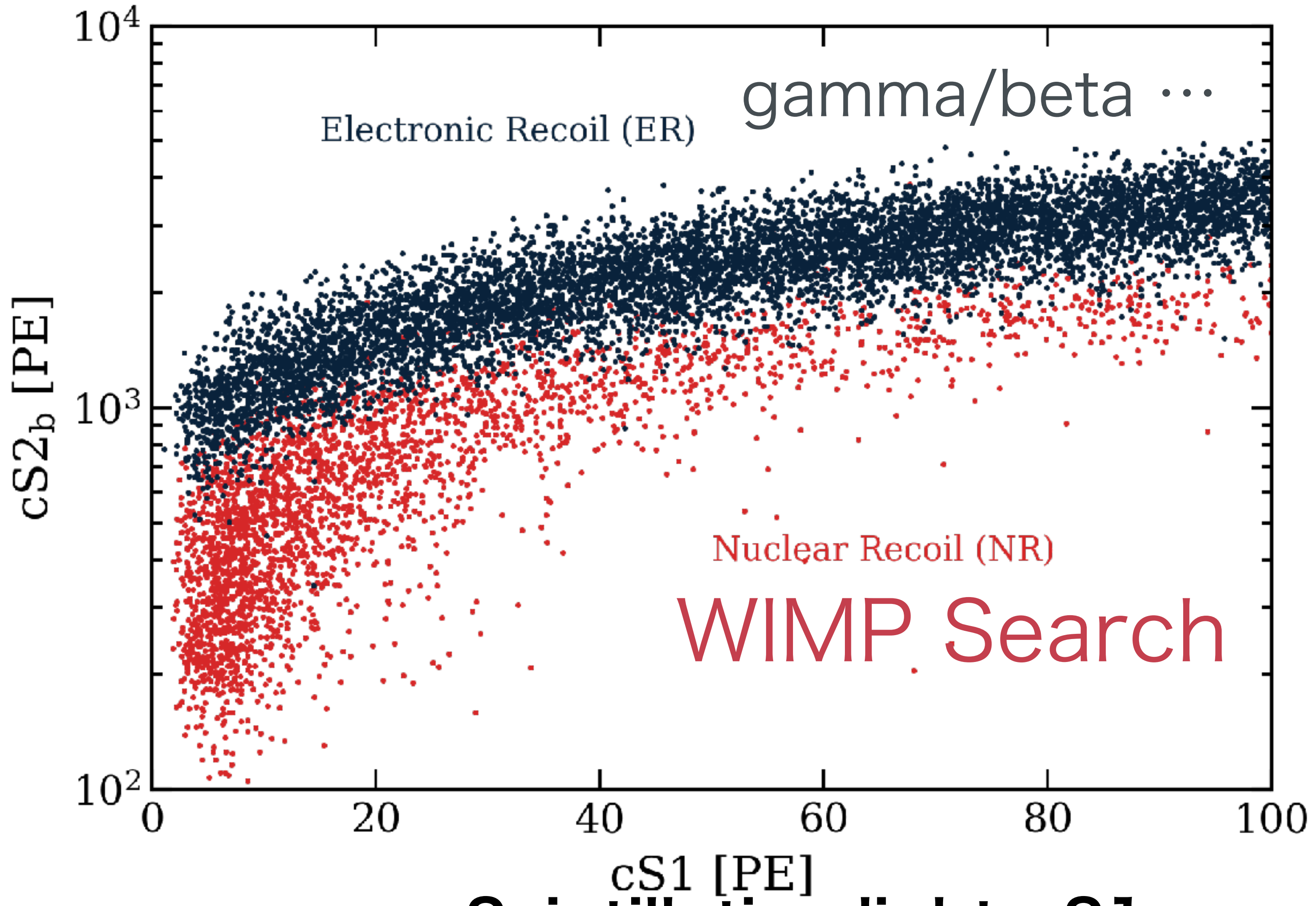


· Scintillation light - S1

Two-phase Xe Time Projection Chamber

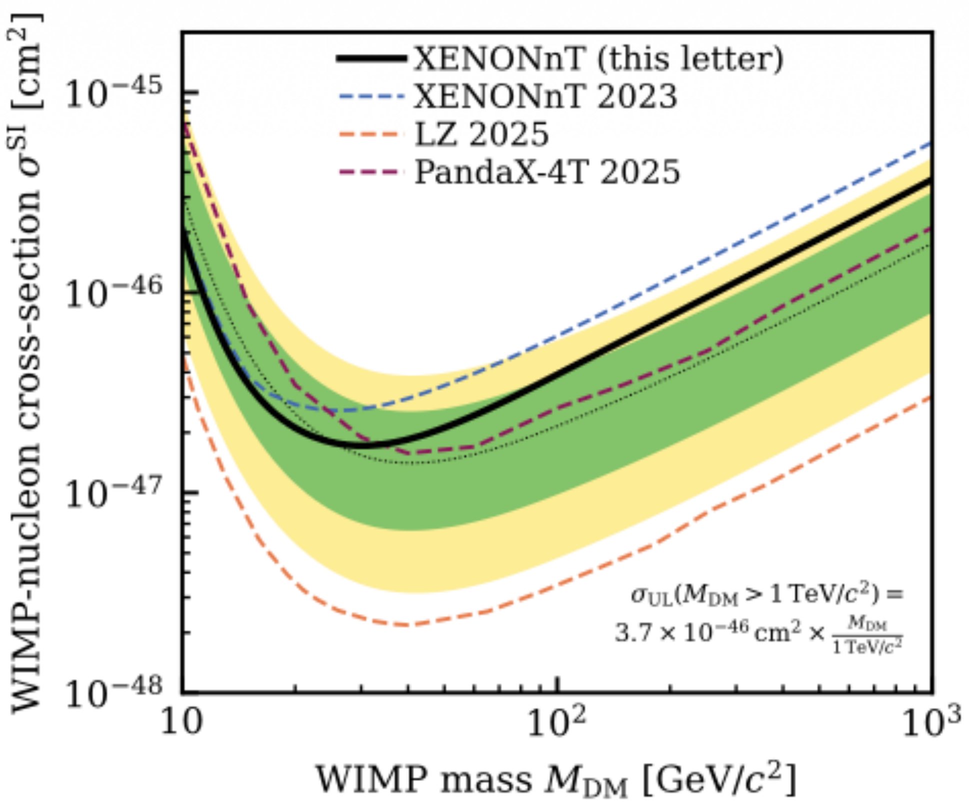
- Recoil type discrimination from ratio of charge (S2) to light (S1)

- Ionization electron -S2

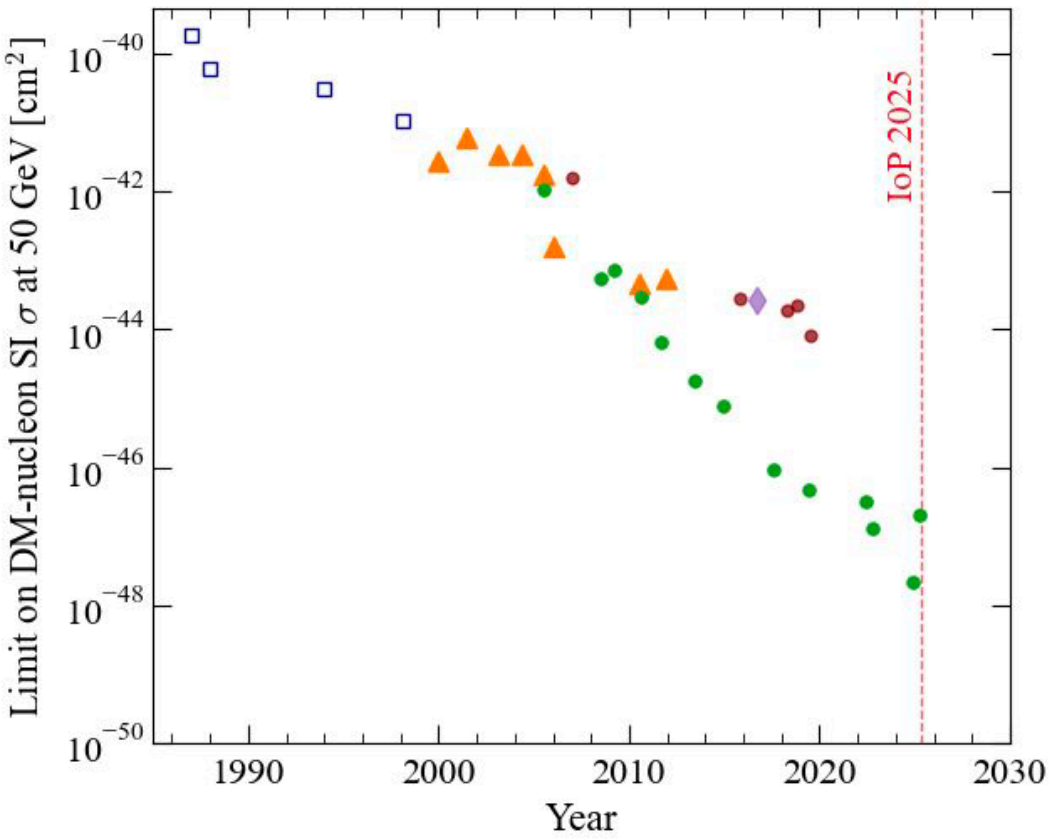


- Scintillation light - S1

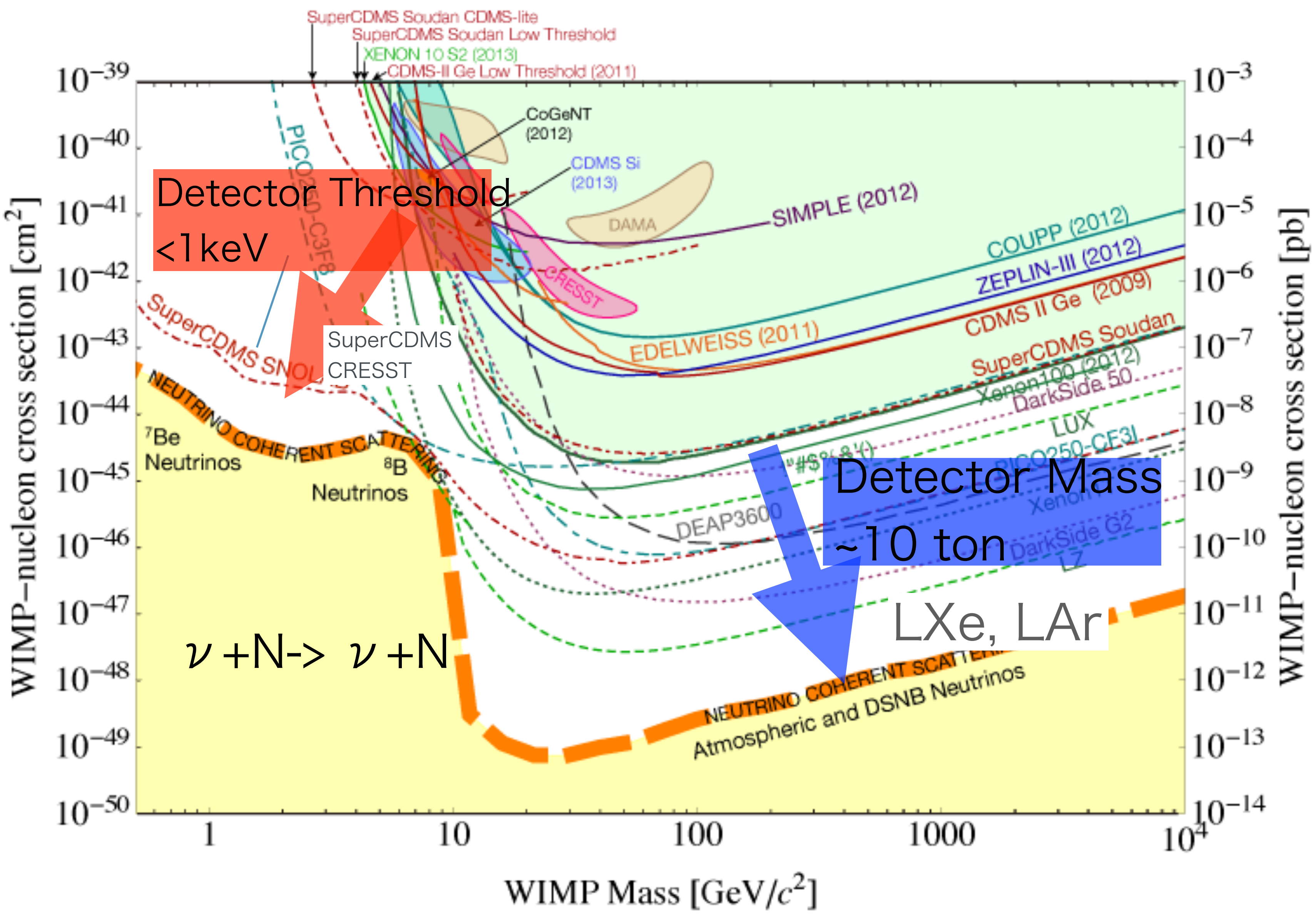
Status of xenon-based dark matter search experiments



PHYSICAL REVIEW LETTERS 135, 221003 (2025)



- XENON, PandaX in China, and LZ in US use the two phase Xe TPC


SuperCDMS Soudan CDMS-lite
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PICO250-C3F8
SuperCDMS SNOLAB
NEUTRINO COHERENT SCATTERING
7Be Neutrinos
8B Neutrinos
Atmospheric and DSNB Neutrinos
Detector Threshold
<1keV
SuperCDMS
CRESST
Detector Mass
~10 ton
LXe, LAr
ν+N-> ν+N
WIMP–nucleon cross section [cm2]
WIMP–nucleon cross section [pb]
WIMP Mass [GeV/c2]

Coherent Elastic Scattering of Neutrinos (CEvNS)

PHYSICAL REVIEW D VOLUME 9, NUMBER 5 1 MARCH 1974

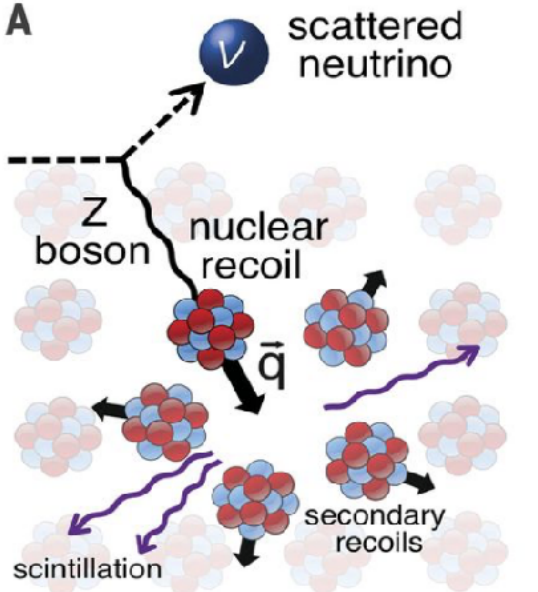
Coherent effects of a weak neutral current

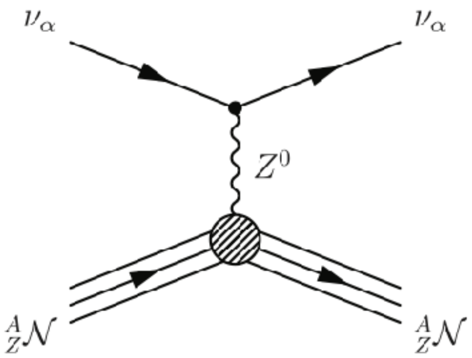
Daniel Z. Freedman†
National Accelerator Laboratory, Batavia, Illinois 60510
and Institute for Theoretical Physics, State University of New York, Stony Brook, New York 11790

(Received 15 October 1973; revised manuscript received 19 November 1973)

If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are very difficult, although the estimated cross sections (about 10^{-38} cm^2 on carbon) are favorable. The coherent cross sections (in contrast to incoherent) are almost energy-independent. Therefore, energies as low as 100 MeV may be suitable. Quasi-coherent nuclear excitation processes $\nu + A \to \nu + A^*$ provide possible tests of the conservation of the weak neutral current. Because of strong coherent effects at very low energies, the nuclear elastic scattering process may be important in inhibiting cooling by neutrino emission in stellar collapse and neutron stars.

ν





D. Akimov et al, Science 357 (2017)

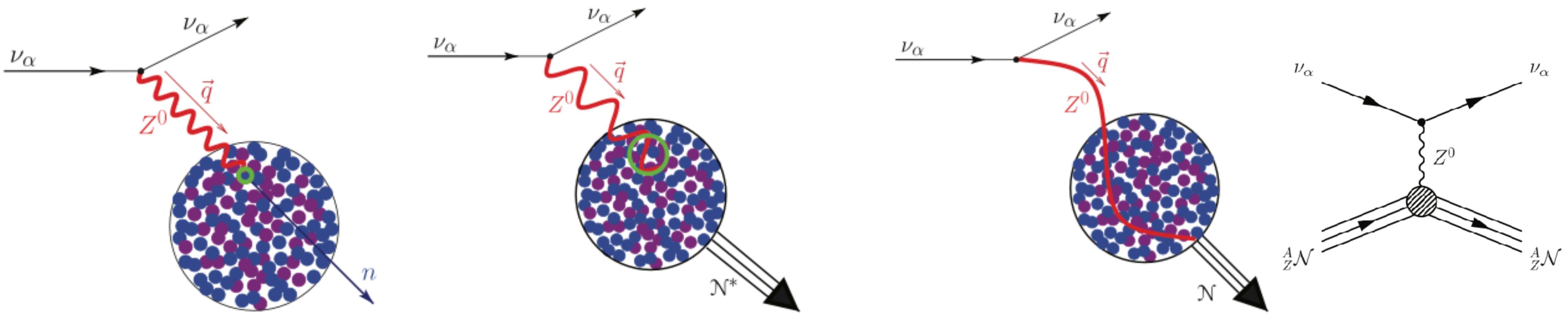
1973 Coherent elastic neutrino-nucleus scattering (CEvNS) was predicted theoretically by D.Z. Freedman.

1985 Drukier&Stodolsky and Goodman&Witten showed the possibility for the detection of astrophysical neutrino or dark matter through coherent elastic scattering

2017 It was observed experimentally for the first time only in 2017 in the COHERENT experiment with neutrinos produced by the Spallation Neutron Source.

It took ~40 years to observe it. Why?

Neutrino-Nucleus Interactions



Inelastic incoherent	Elastic incoherent	Elastic coherent (CEνNS)
$\lambda_{Z^0} \ll 2R$	$\lambda_{Z^0} \lesssim 2R$	$\lambda_{Z^0} \gtrsim 2R$
~ 100 GeV	~ GeV	~MeV

λ~R (~ 5fm), $E_\nu \lesssim$ 50 MeV,

M. Cadeddu et al. EPL, 143 (2023) 34001

Emax: $\frac{2E_\nu^2}{M}$ ~ 1.5 keV

E ~ x 1/1000 w.r.t. neutrino detector

Coherent Elastic Neutrino Nucleus Scattering

$$\nu + A \rightarrow \nu + A$$

nuclear mass | weak nuclear charge | nuclear recoil energy

$$\frac{d\sigma}{dE} \sim \frac{G_F^2 \cdot M}{2\pi} \cdot \frac{Q_W^2}{4} \cdot F^2(Q) \cdot \left(2 - \frac{M \cdot E}{E_\nu^2}\right)$$

form factor | incident ν energy

In the Standard Model:

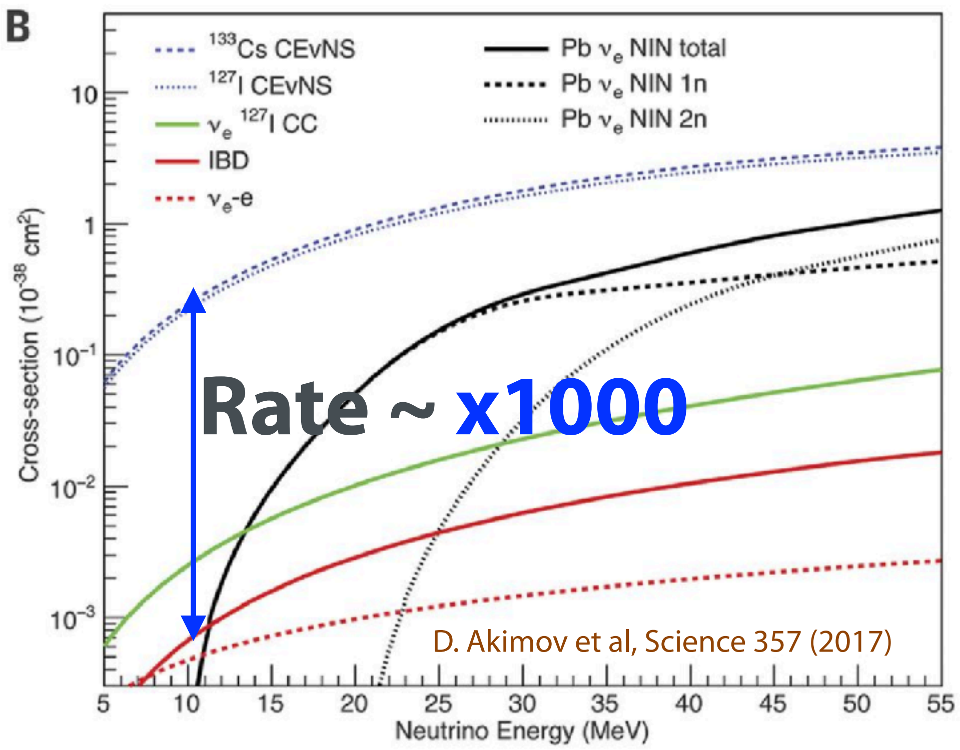
Proton

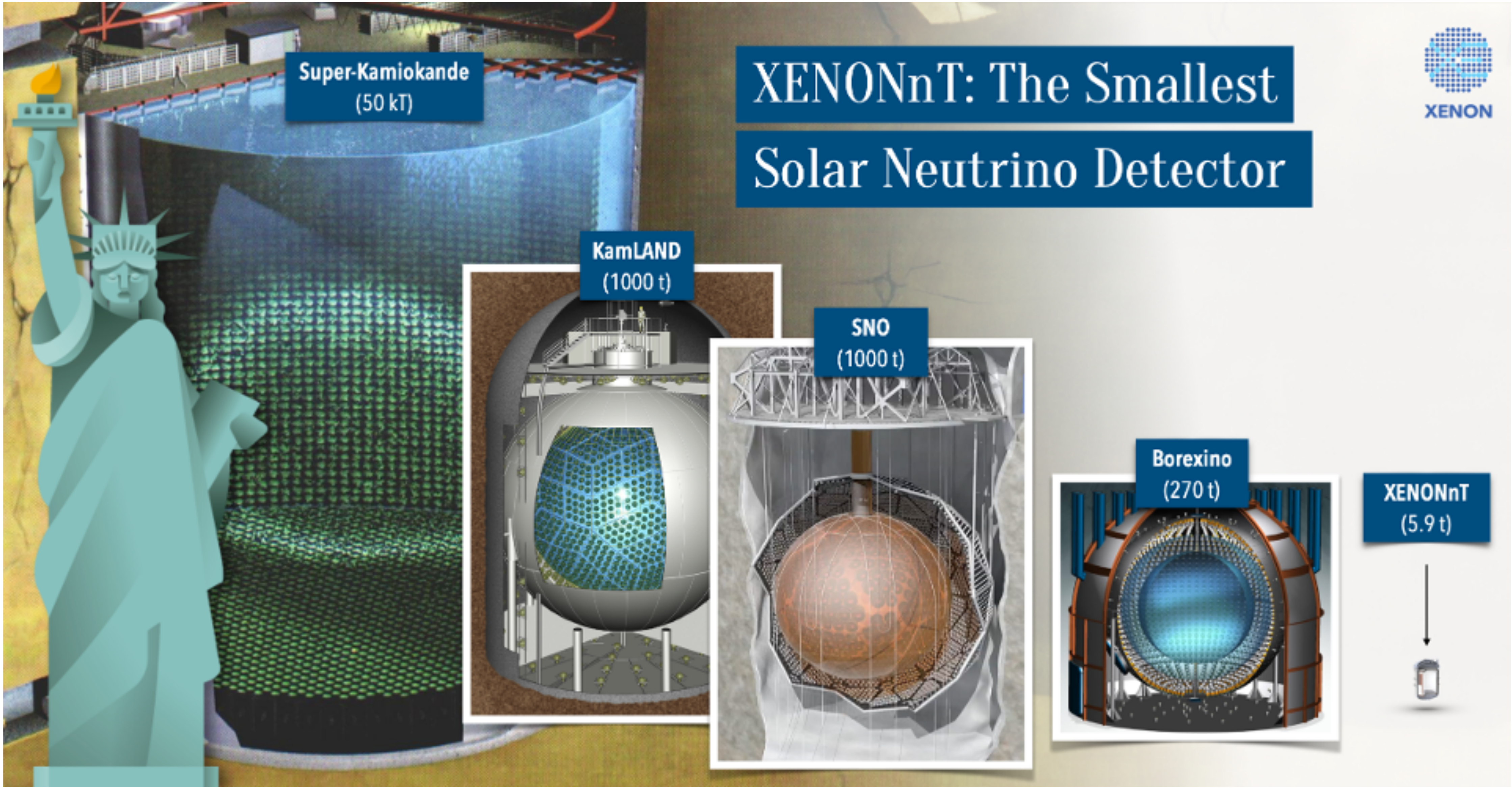
$$\sigma \propto Q_W^2 \propto (N - (1 - 4 \cdot \sin^2\theta_W) Z)^2 \sim N^2$$

Neutron

$$\sin^2\theta_W \sim 0.239$$

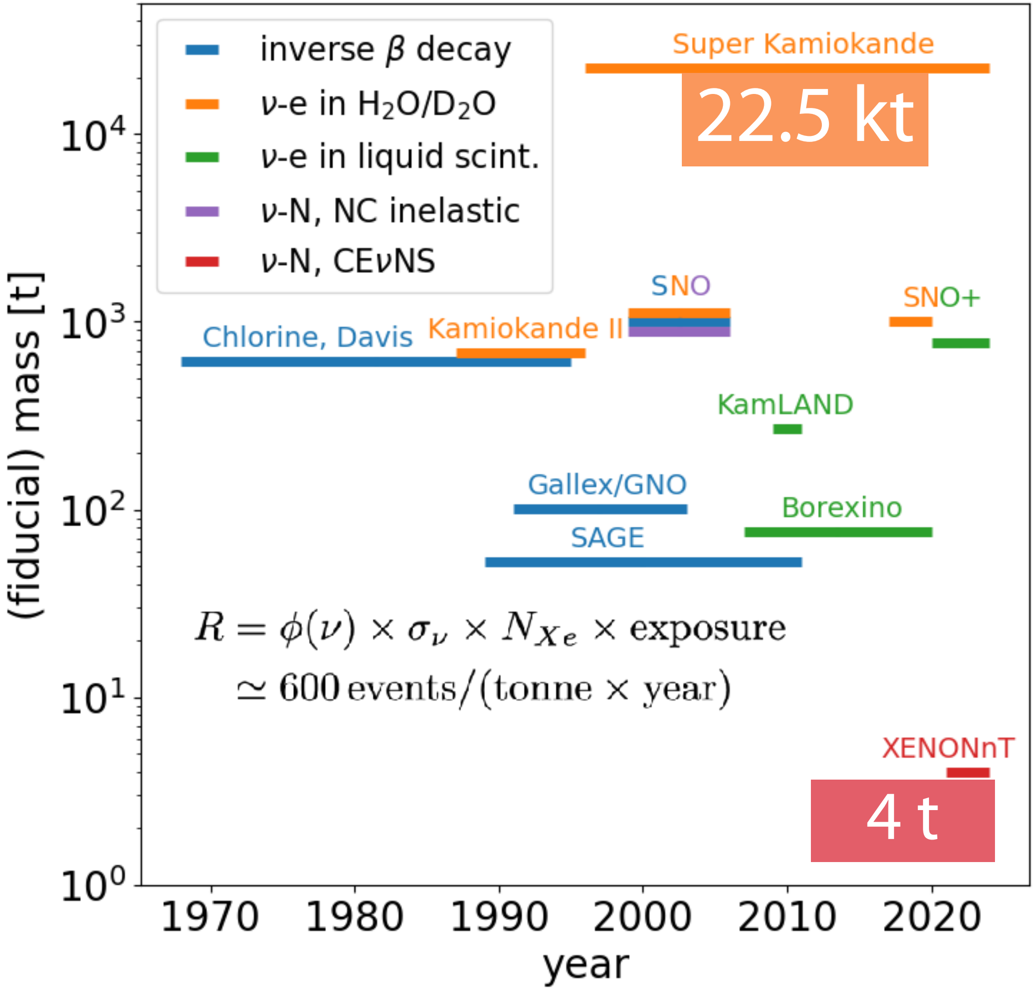
#Spin-independent Dark Matter case: $\sigma \propto A^2$



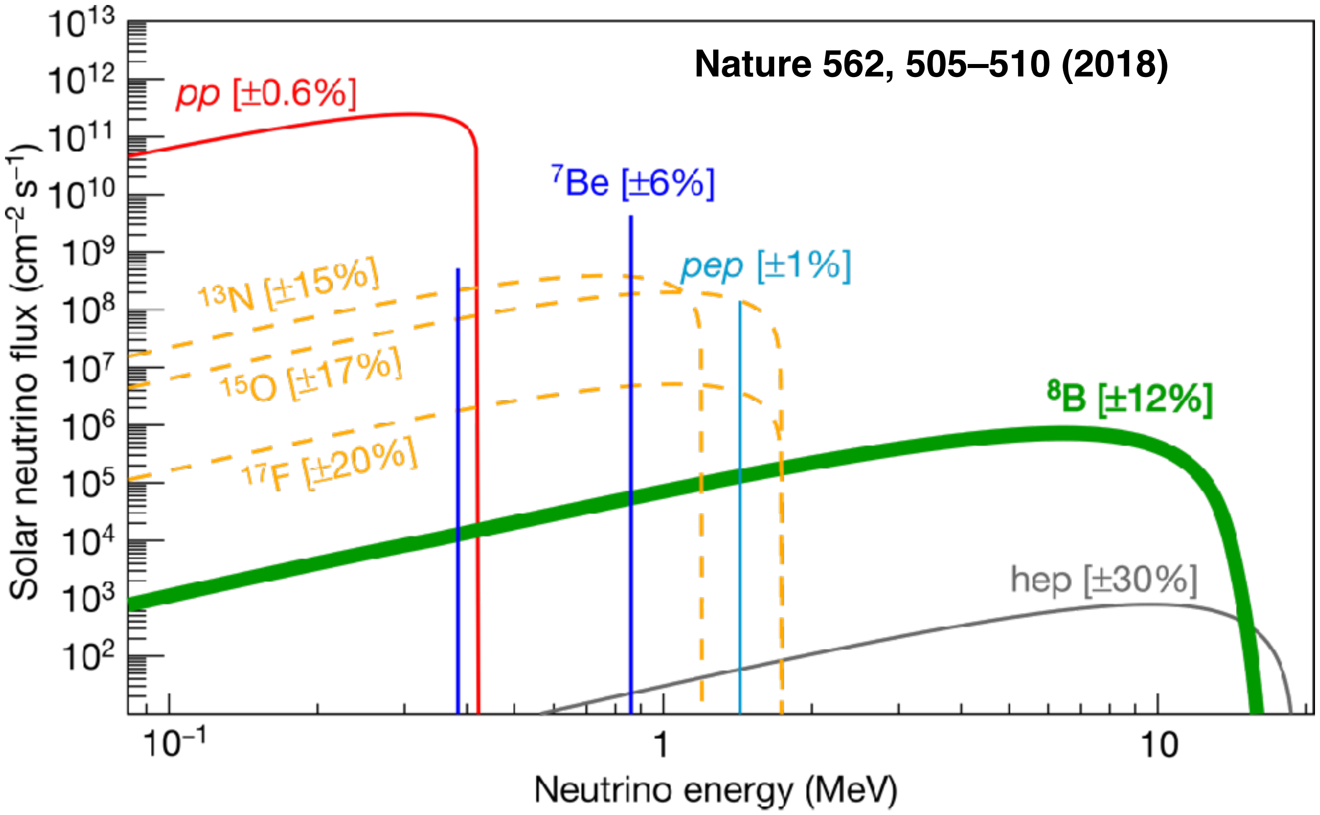

XENONnT: The Smallest
Solar Neutrino Detector
XENON
Super-Kamiokande
(50 kT)
KamLAND
(1000 t)
SNO
(1000 t)
Borexino
(270 t)
XENONnT
(5.9 t)

R. Hammann.

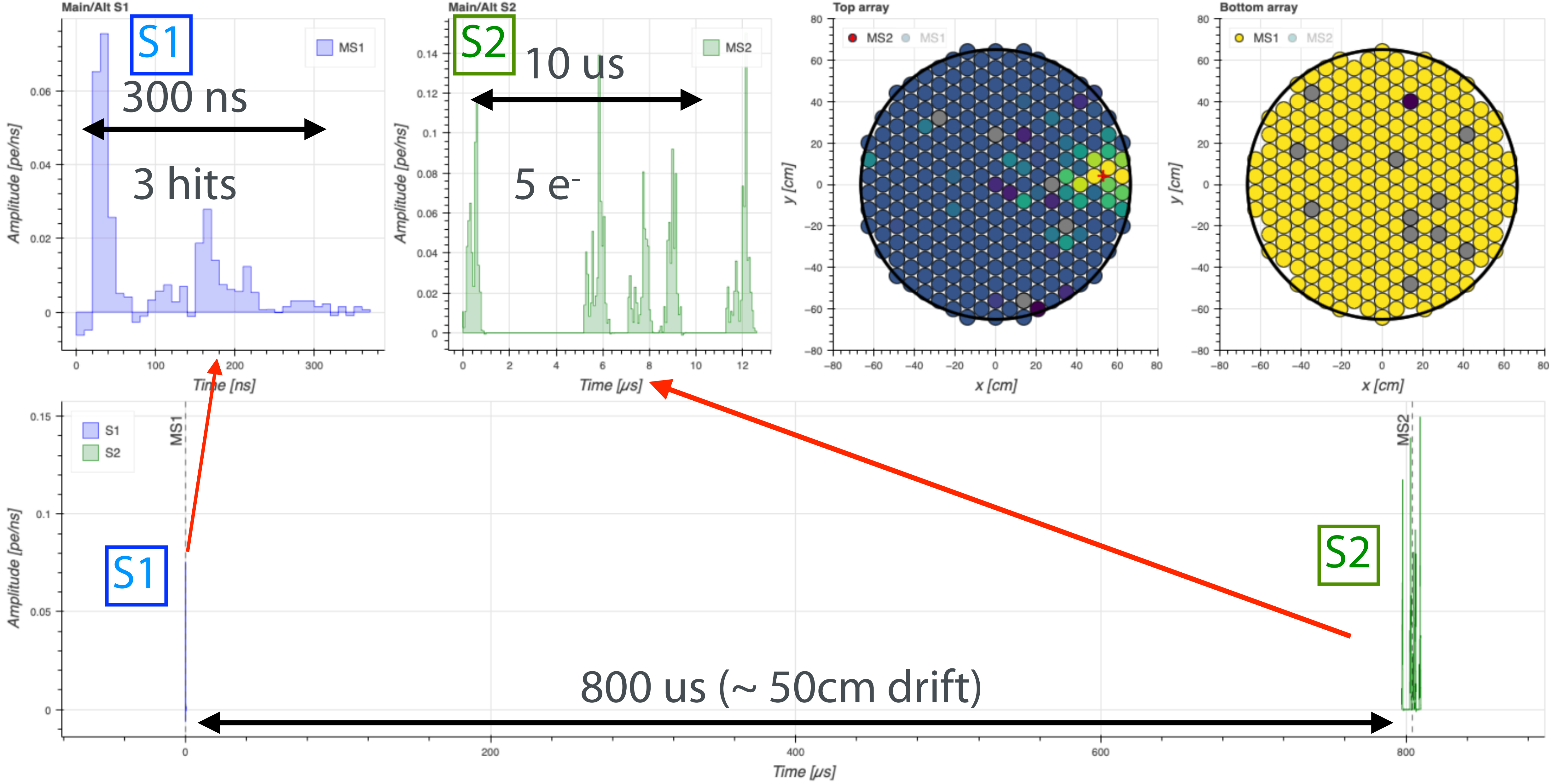
XENONnT as a Solar Neutrino Detector via CEvNS



$$R = \phi(\nu) \times \sigma_\nu \times N_{Xe} \times \text{exposure}$$
$$\simeq 600\,\text{events}/(\text{tonne} \times \text{year})$$

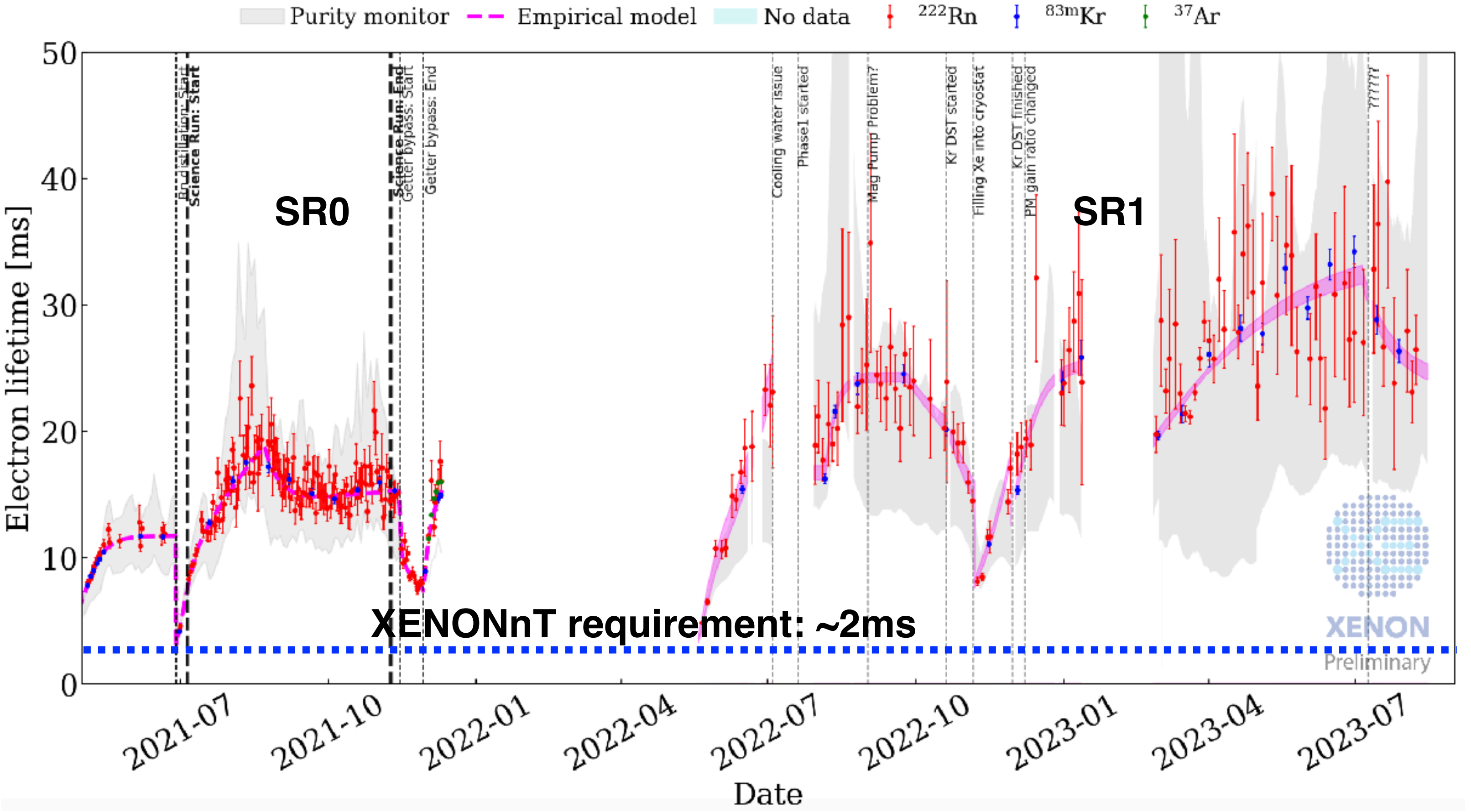


Signal (S1, S2)


Main/Alt S1
S1
MS1
300 ns
3 hits
Amplitude [pe/ns]
Time [ns]
Main/Alt S2
S2
MS2
10 us
5 e-
Amplitude [pe/ns]
Time [μs]
Top array
MS2 MS1
y [cm]
x [cm]
Bottom array
MS1 MS2
y [cm]
x [cm]
S1
S2
MS1
MS2
S1
S2
Amplitude [pe/ns]
800 us (~ 50cm drift)
Time [μs]

Liquid Xenon Purity During Science Runs

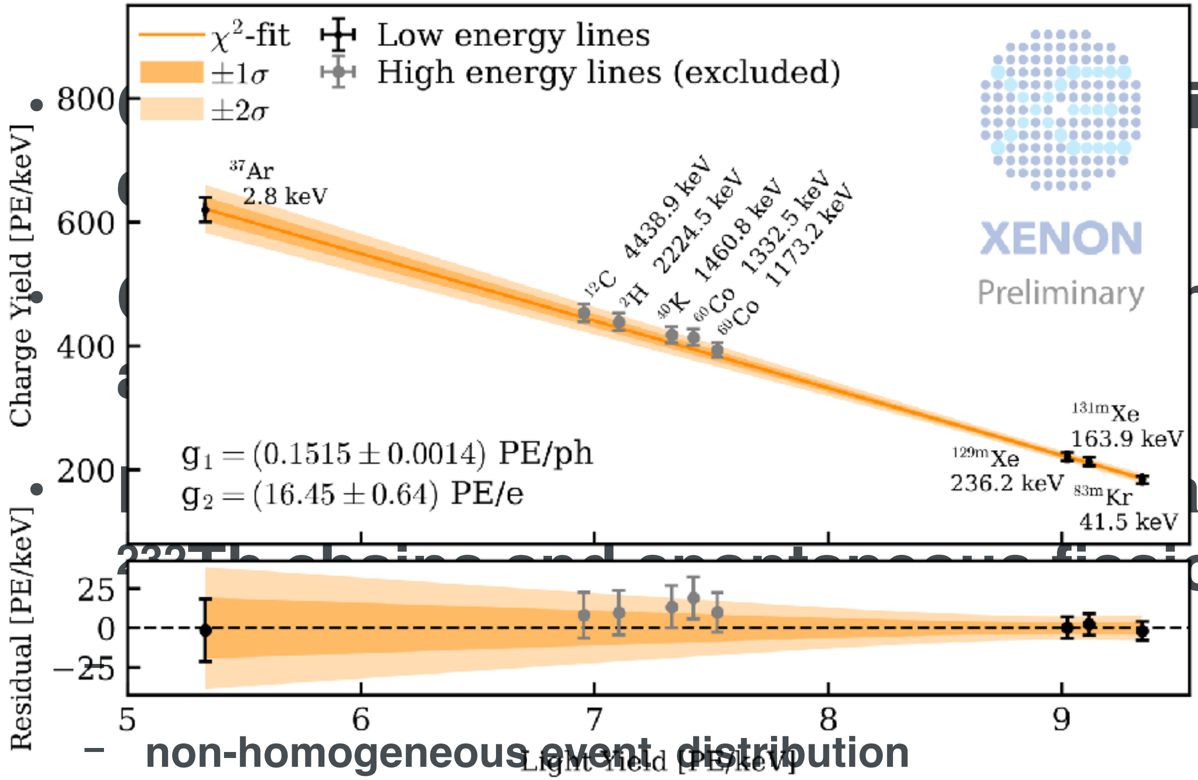
Liquid phase purification



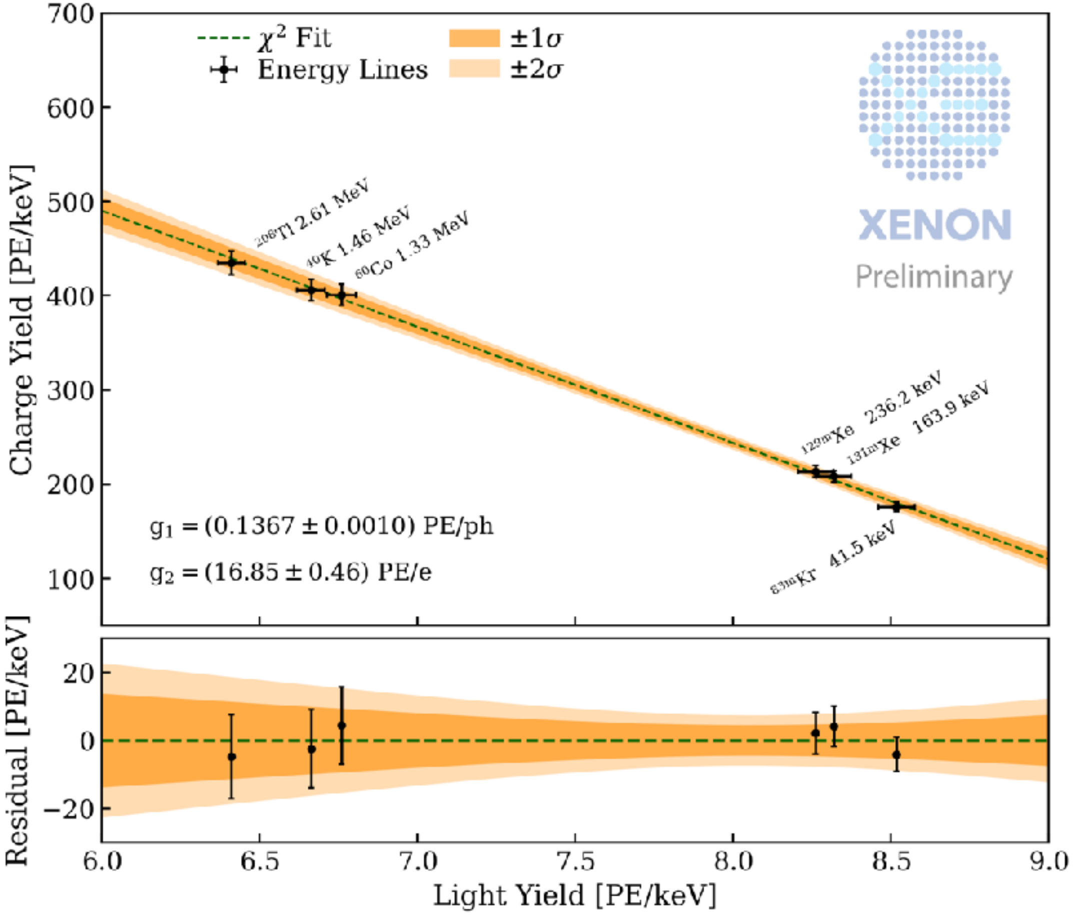
- S2 (Charge) signals depend on the purity of LXe. (e.g. O_2 impurity)
- XENONnT maintains high electron lifetime thanks to its novel liquid phase purification

Calibration with Mono-energetic Electronic Recoils

SR0



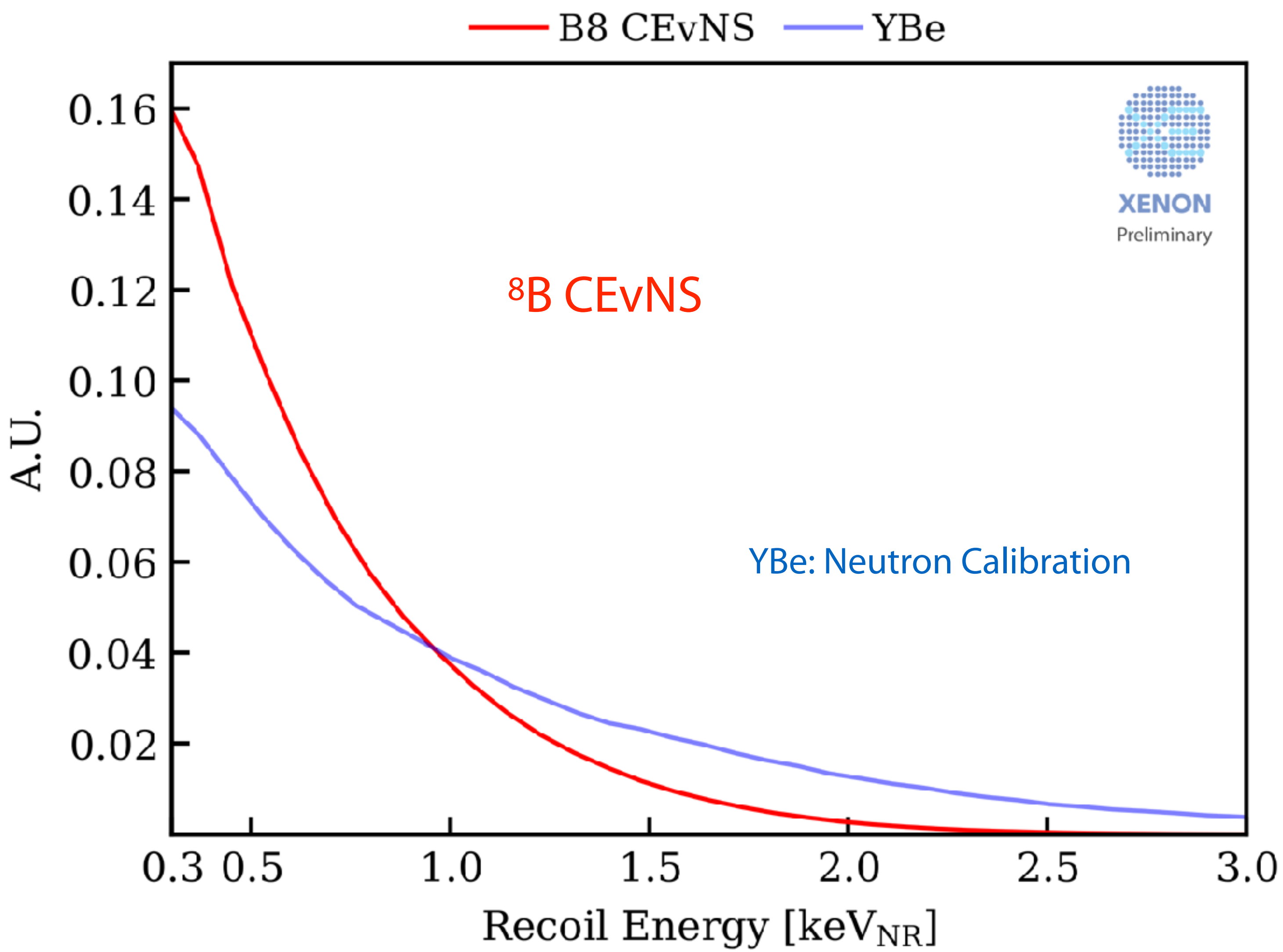
SR1

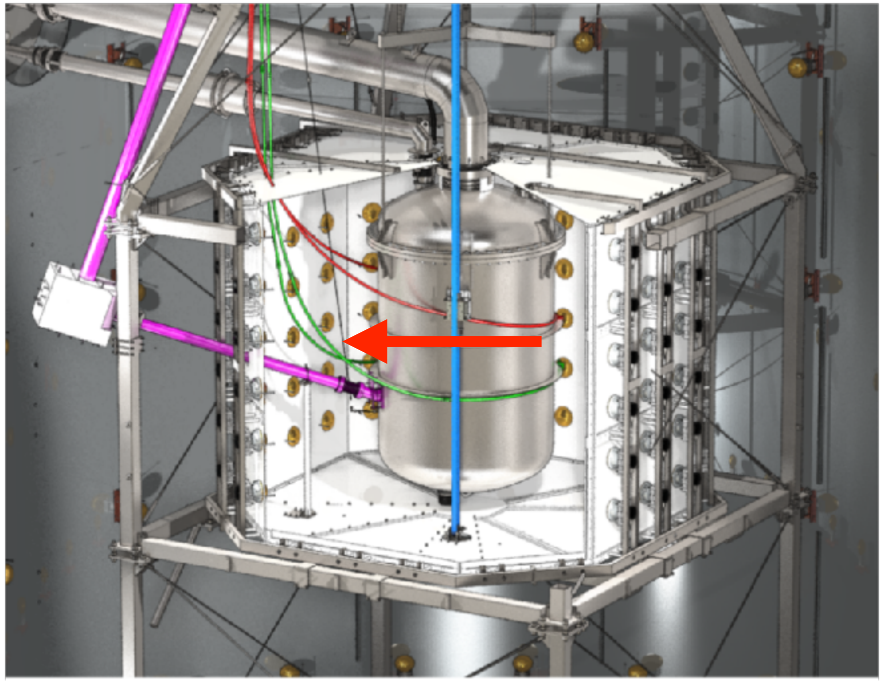


– non-homogeneous event distribution

Science Run	g1 [PE/ph]	g2 [PE/e]
SR0	0.1515 ± 0.0014	16.45 ± 0.64
SR1	0.1367 ± 0.0010	16.85 ± 0.46

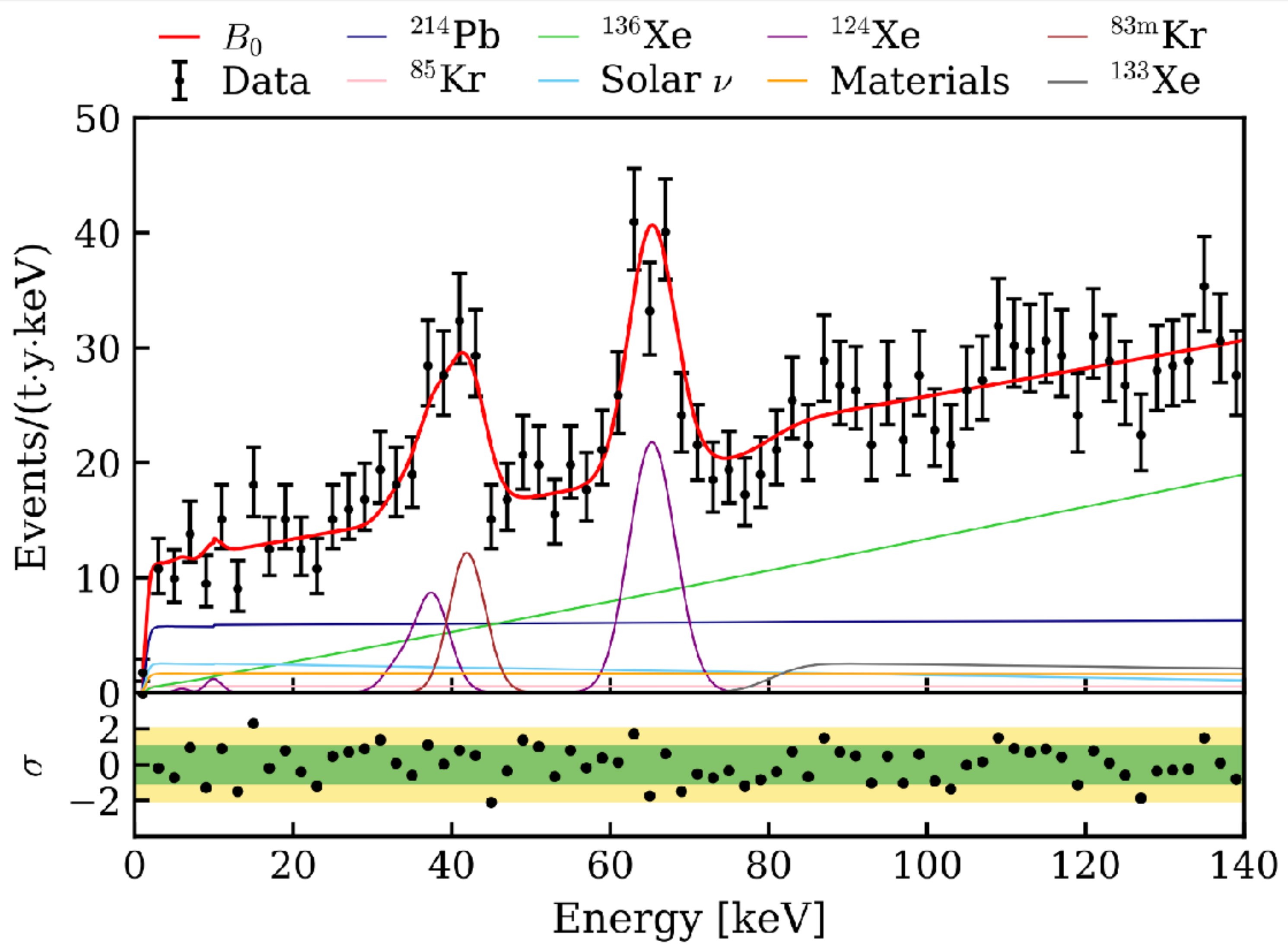
^{88}YBe neutron calibration





neutron energy 152keV
(γ, n) reaction, ~ 20 n/s

Electronic Recoil Background



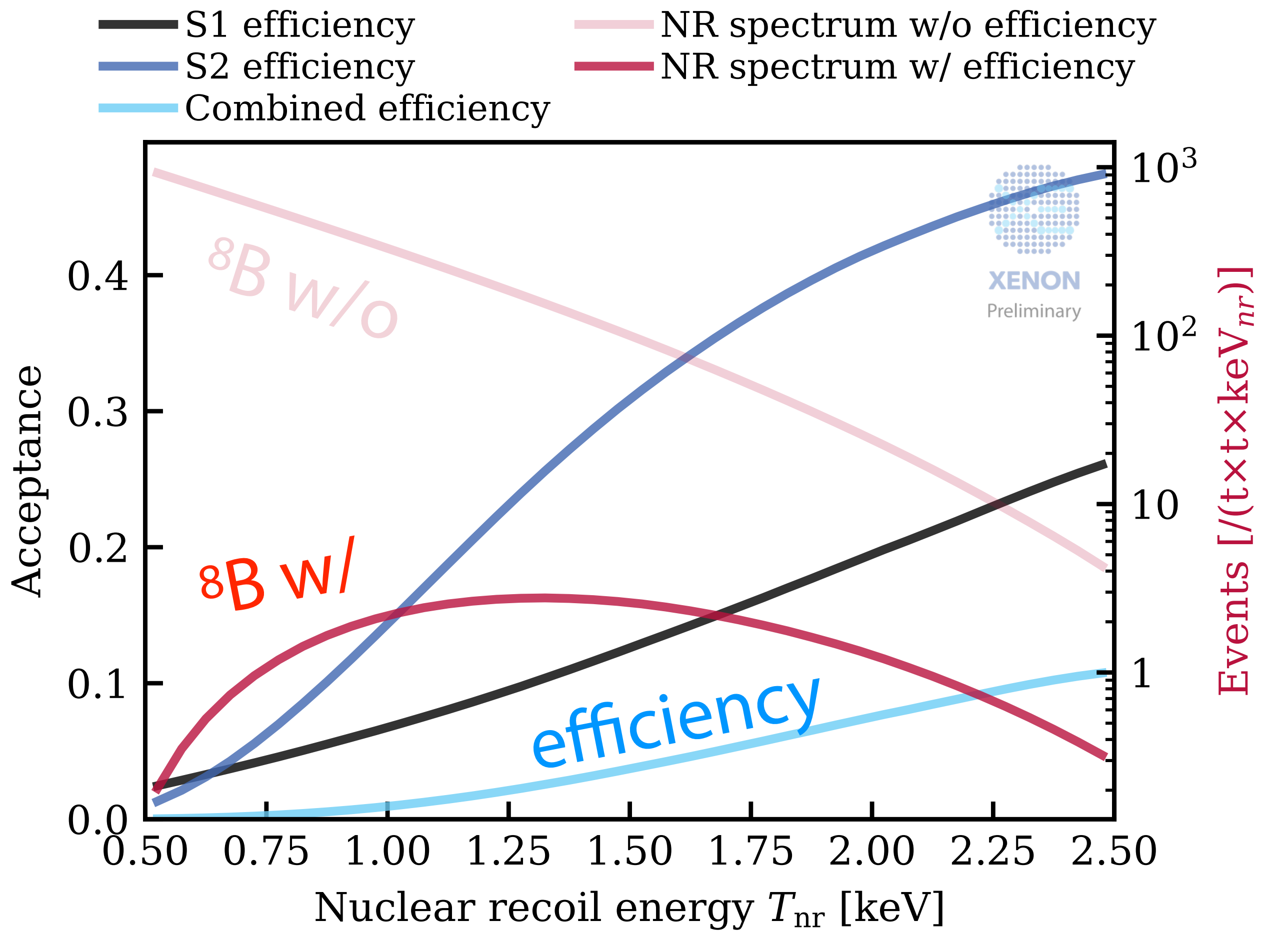
Final ER background prediction

- SR0: 0.13 ± 0.13 Events
- SR1: 0.56 ± 0.56 Events

Final Prediction of ^{8}B Signal and Background

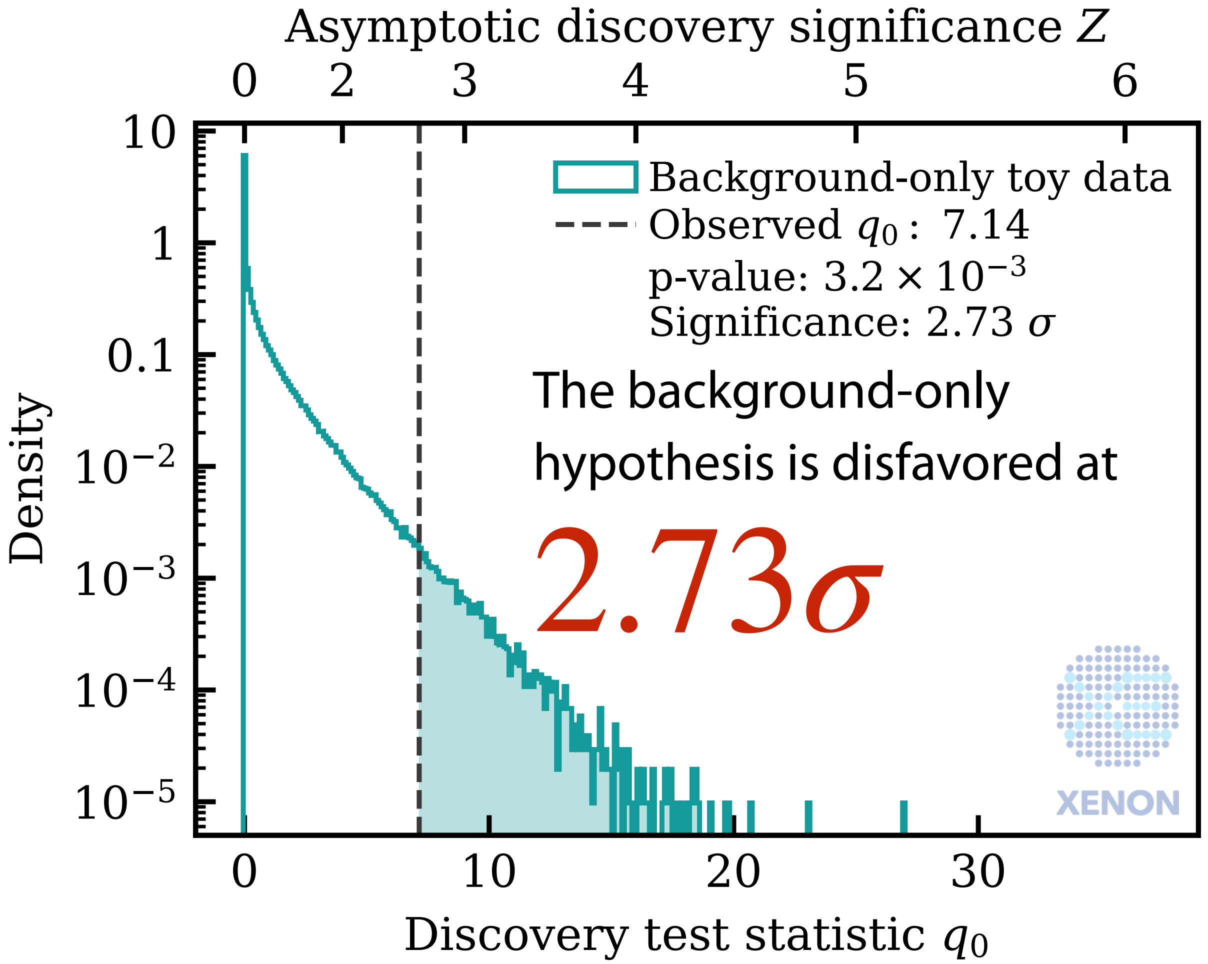
Final Prediction

Component	Rate [Events]
AC - SR0	7.48 ± 0.52
AC - SR1	17.77 ± 1.23
ER	0.68 ± 0.68
NR	0.47 ± 0.32
Total Background	26.4 ± 1.5
^{8}B	11.93 ± 3.1



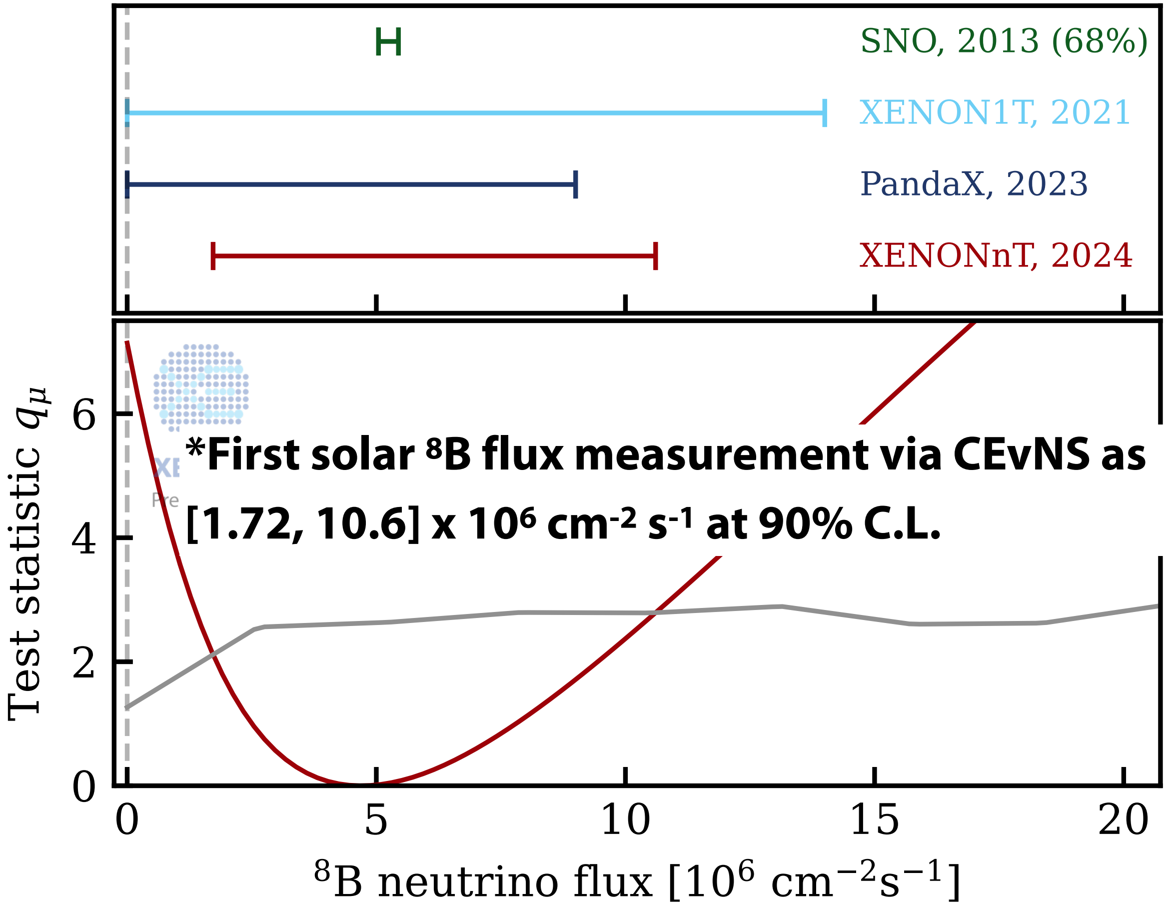
We expect solar ^{8}B neutrinos at a median significance of ~2σ, with a counting-only analysis

Results from Unblinding



The background-only hypothesis is disfavored at

2.73σ

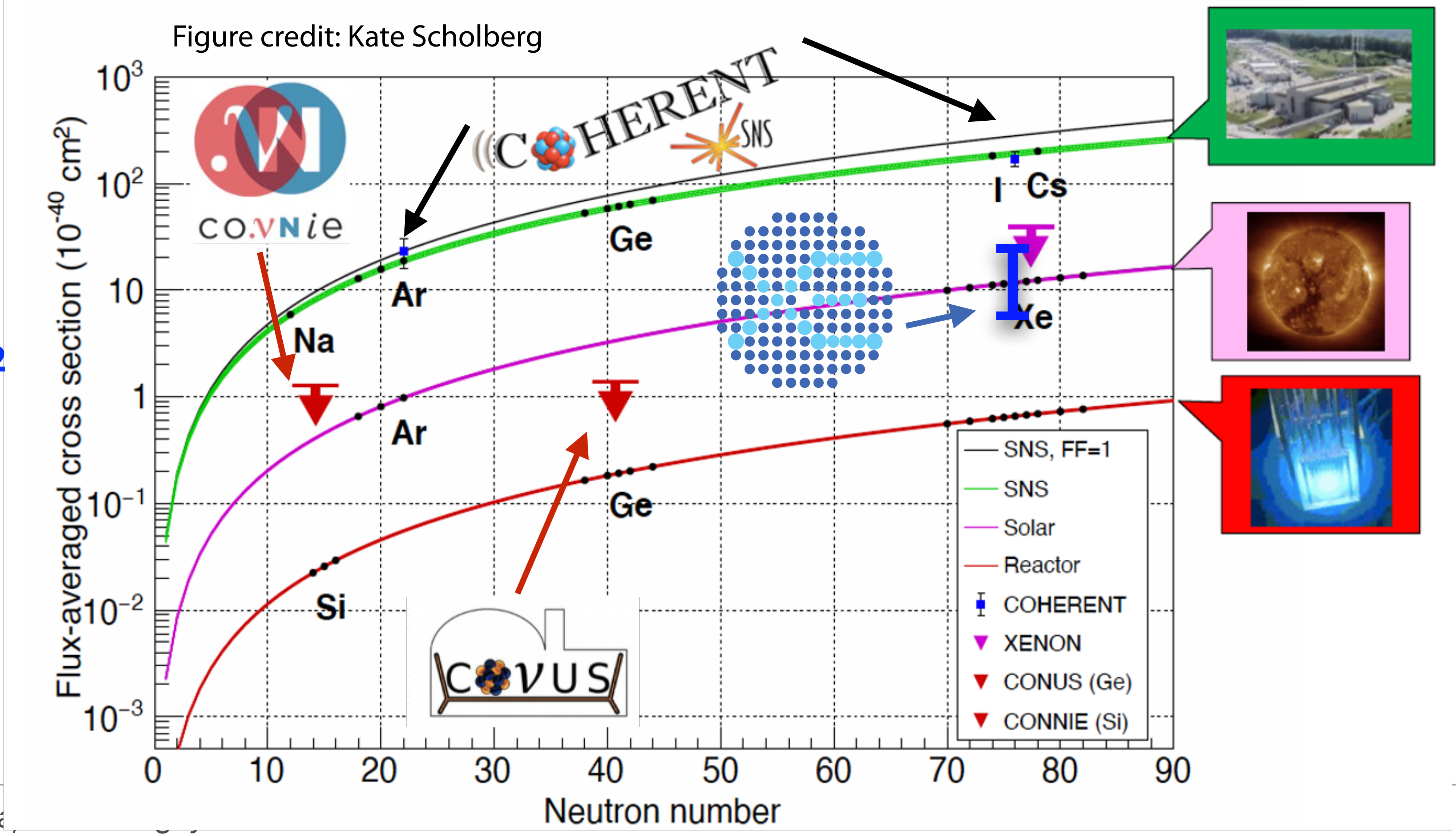


***First solar ^{8}B flux measurement via CEvNS as [1.72, 10.6] x 10^6 cm^{-2} s^{-1} at 90% C.L.**

* Panda-X https://arxiv.org/abs/2407.10892 (2.64σ)

First Measurement of CEvNS with a Xe Target

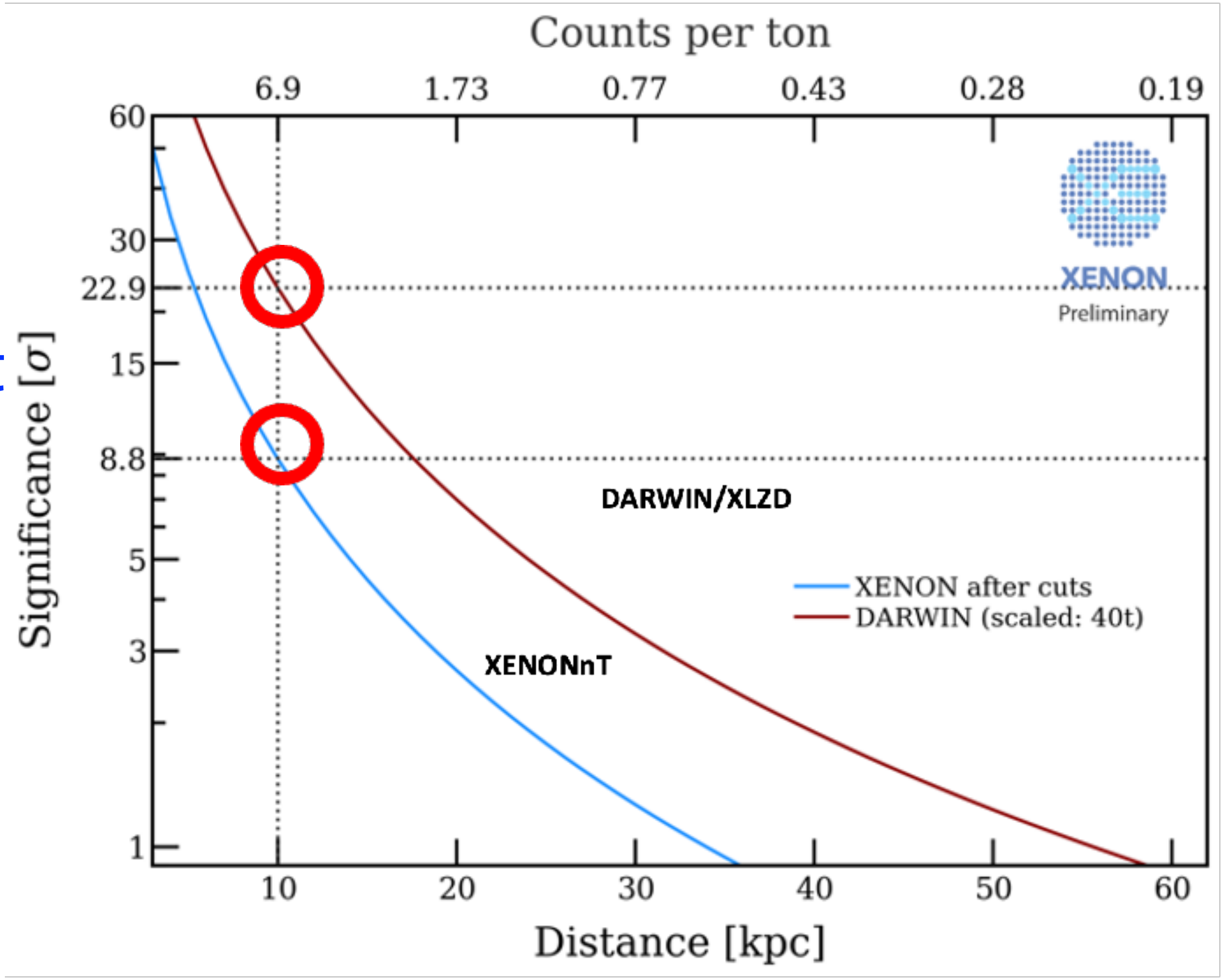
$\sigma \sim$ **N^2**



Summary and Outlook

- First 8B solar neutrinos measurement by the coherent neutrinos-nucleus scattering.

  #Recently, LZ report > 4 sigma
- Demonstration of Supernova burst neutrino detection. (flavor independent, multi-messenger)



And more...

PHYSICAL REVIEW LETTERS 129, 161805 (2022)

Inelastic scattering

(Higgsino e.g. CAP04(2023)026)

Migdal effect

(Nature　649，580 (2026))

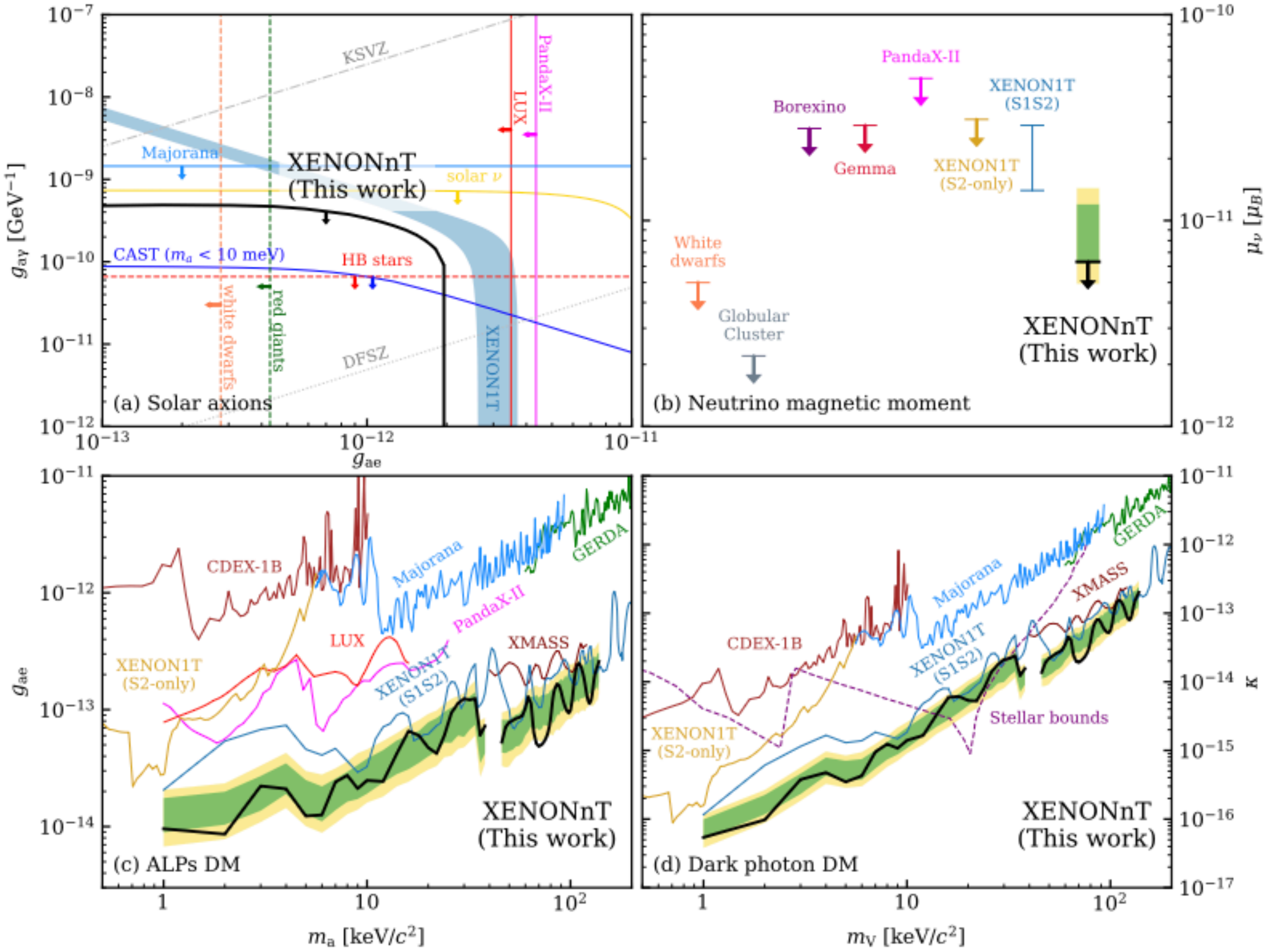
Electronic Signal

-Solar Axions

-ALPs

-Dark Photon

-ν magnetic moment

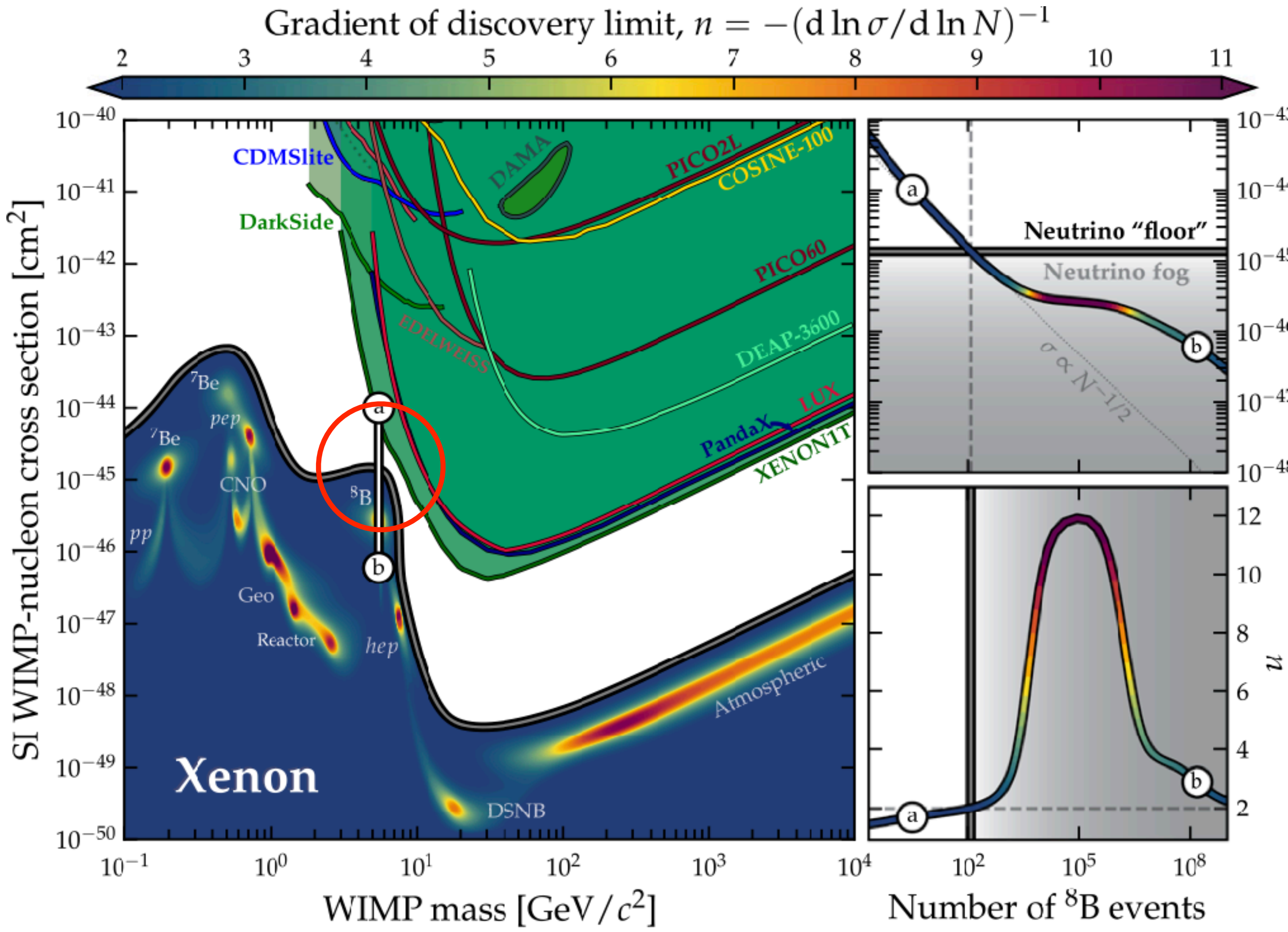


Summary and Outlook

- First 8B solar neutrinos measurement by the coherent neutrinos-nucleus scattering.

- Demonstration of Supernova burst neutrino detection. (flavor independent, multimessenger)

- Dawn of Neutrino Fog Era for Dark Matter Search (~ 6 GeV WIMP)



2021 PRL Ciaran A. J. O'Hare

The XLZD Collaboration

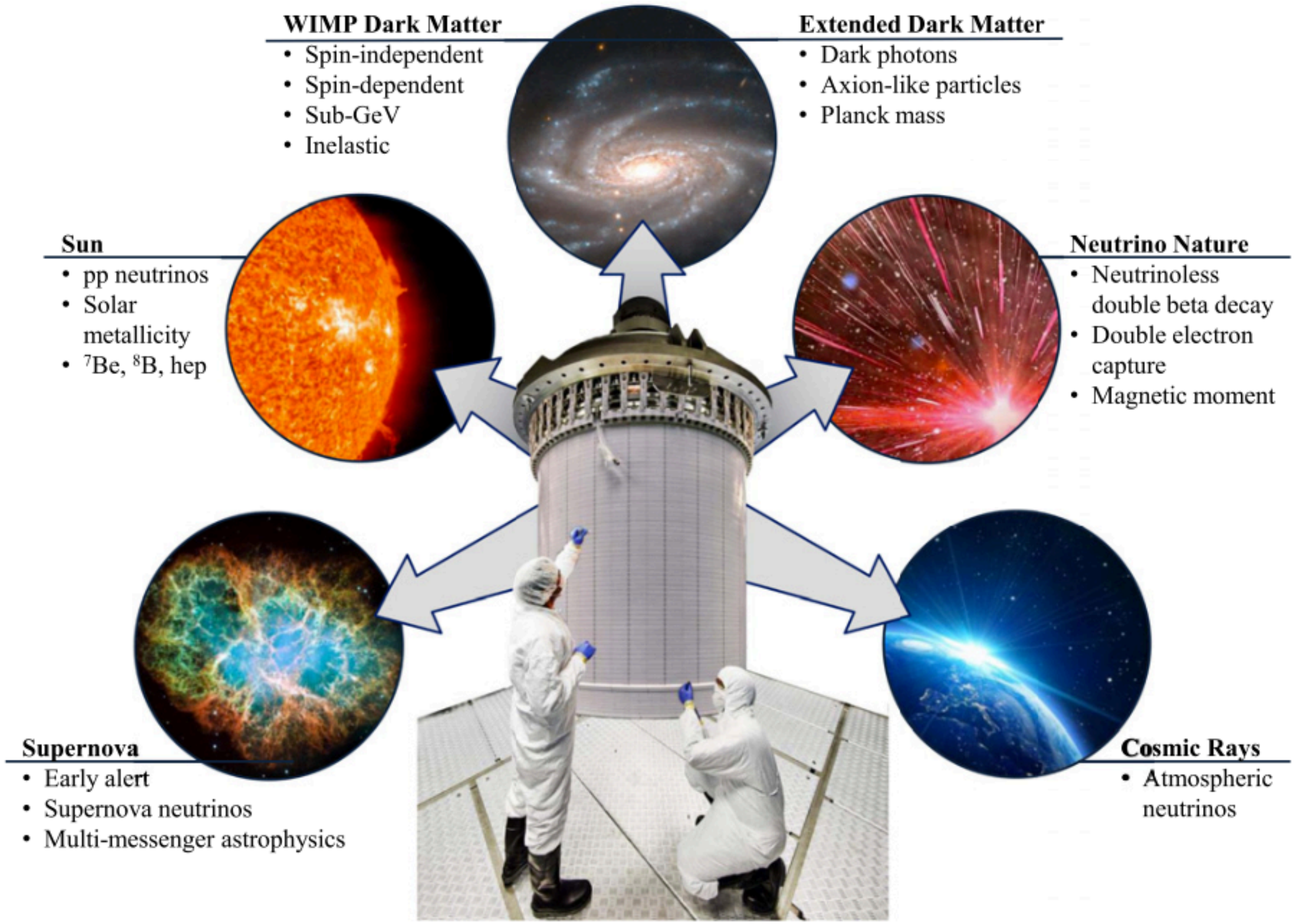
XENONnT + LUX-ZEPLIN + DARWIN

Countries: 17
Institutions: 76
Members: 440+

+active discussion with nEXO members

XLZD Meeting - LNGS, July 2025

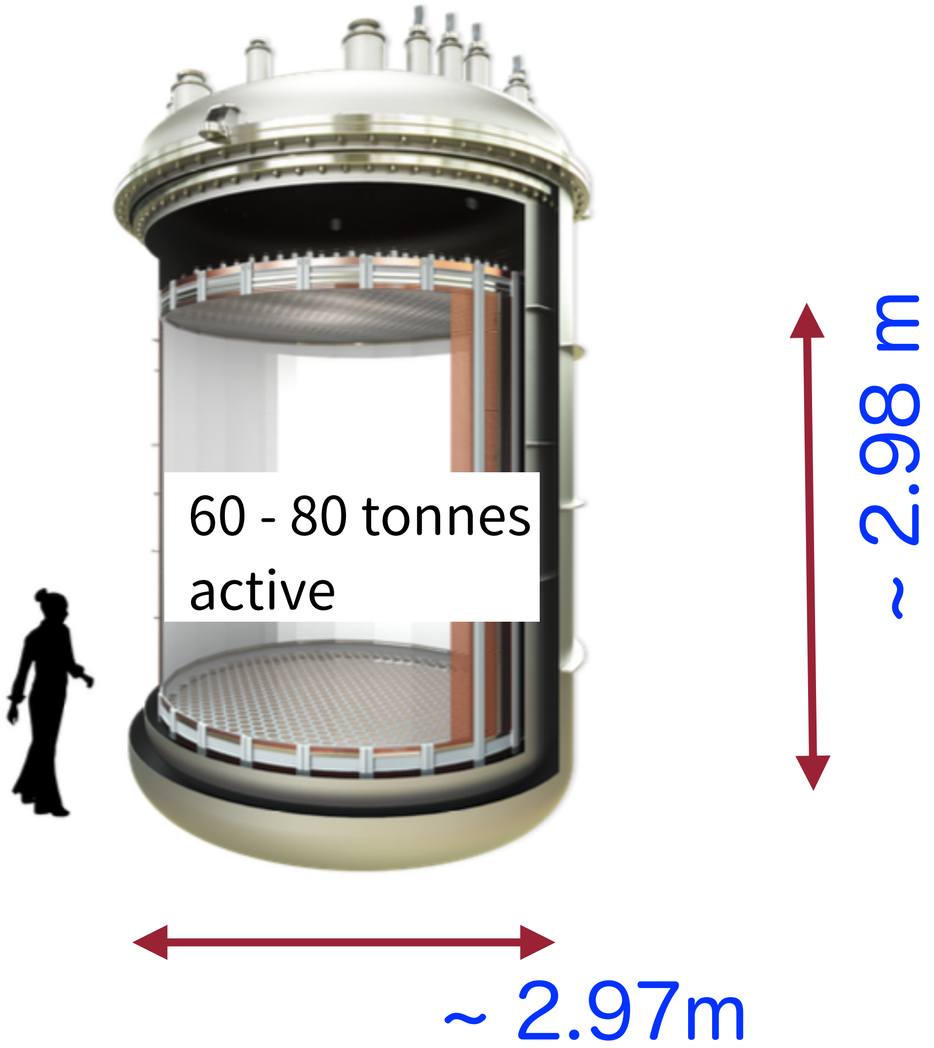
Science: Multi-purpose observatory



- WIMP search is the primary goal
- Opportunity to be competitive in $0\nu\beta\beta$
- Other DM candidates
  (Light WIMPs, Axions, ALPs, Dark Photons, etc)
- Neutrino physics
  - Solar neutrinos (model, properties)
  - Supernovae

Detector: Liquid Xenon Time Projection Chamber

- **Largest xenon observatory for rare events**
  - The design is based on the mature technology of current-generation LXe TPC and will have opportunities for further optimization of the individual detector components.
  - ~ 3 m diameter and drift length
  - Target Mass: 60-80 tonnes LXe



Xenon Isotopes

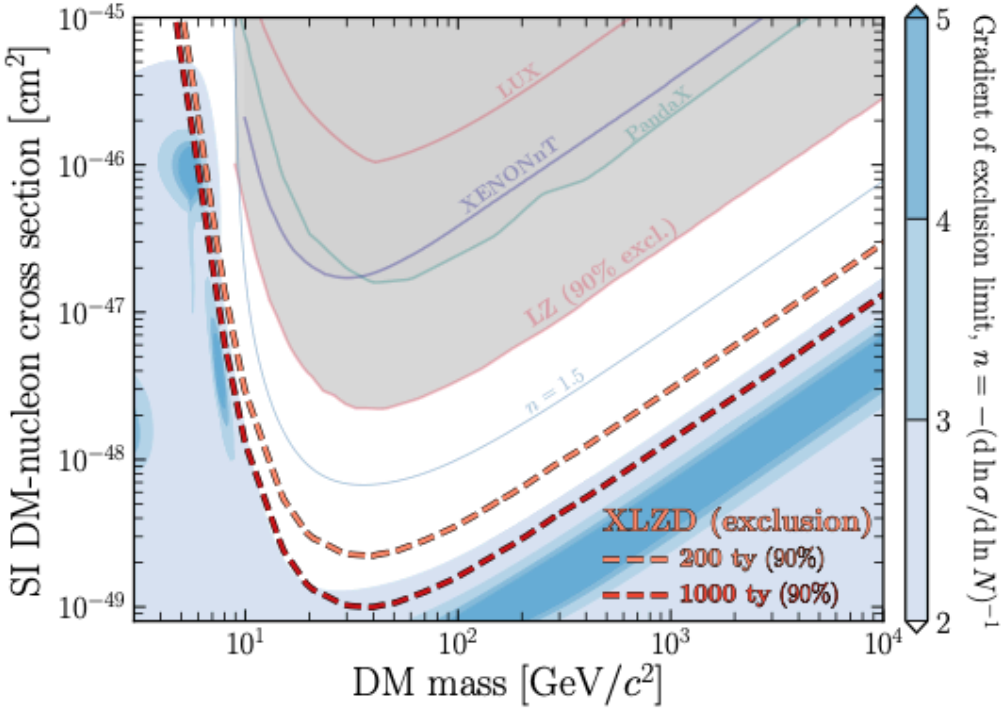
^{124}Xe	^{126}Xe	^{128}Xe	^{129}Xe	^{130}Xe	^{131}Xe	^{132}Xe	^{134}Xe	^{136}Xe
0.10%	0.09%	1.92%	26.4%	4.07%	21.2%	26.9%	10.4%	8.87%

- Both spin-independent and spin-dependent WIMP DM search (half-half)
- No long-lived isotopes except ^{124}Xe and ^{136}Xe
  - ^{124}Xe double electron capture isotope ($T_{1/2} \sim 10^{22}$ y)
    - the longest half-life ever measured directly
  - ^{136}Xe $0\nu\beta\beta$ decay
- Enrich or depleted gases are possible.
  - e.g. Y. Suzuki arXiv:0008296

XLZD: WIMP Sensitivity

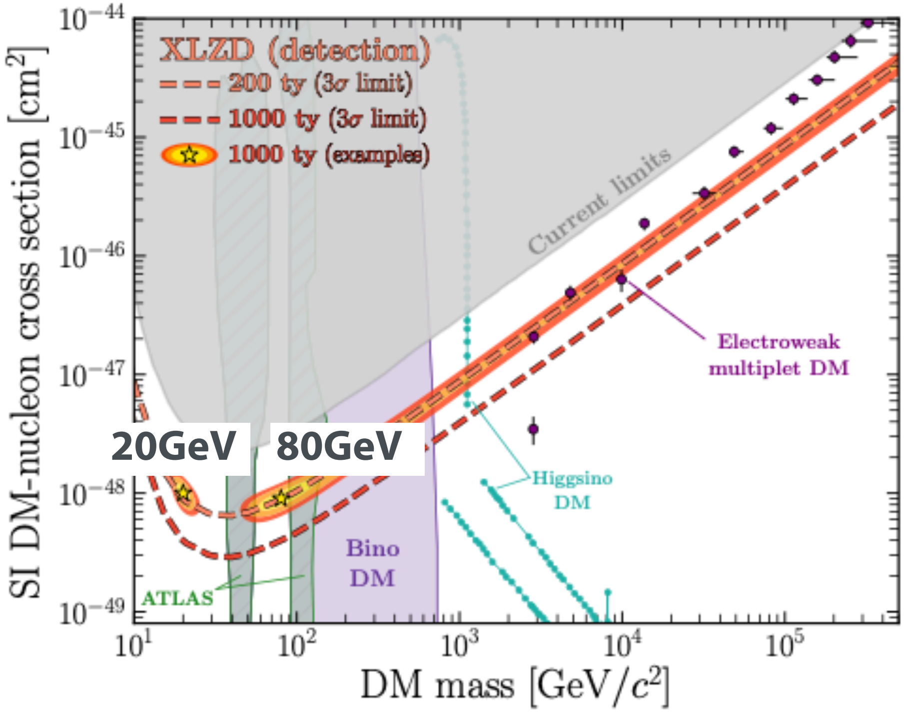
The XLZD Design Book: Towards the Next-Generation Liquid Xenon Observatory for Dark Matter and Neutrino Physics
arXiv:2410.17137v1

Projected sensitivity and current limits



- **Searching for WIMPs down to the neutrino "fog"**
  - Indistinguishable background from astrophysical neutrinos
  - Limited sensitivity improvement (20% flux uncertainly)
  - Systematic uncertainty limit (1000 t·yr)
  - 90% C.L. exclusion 2.5x10^{-49} cm^2 (at 40 GeV, 200 t·yr)

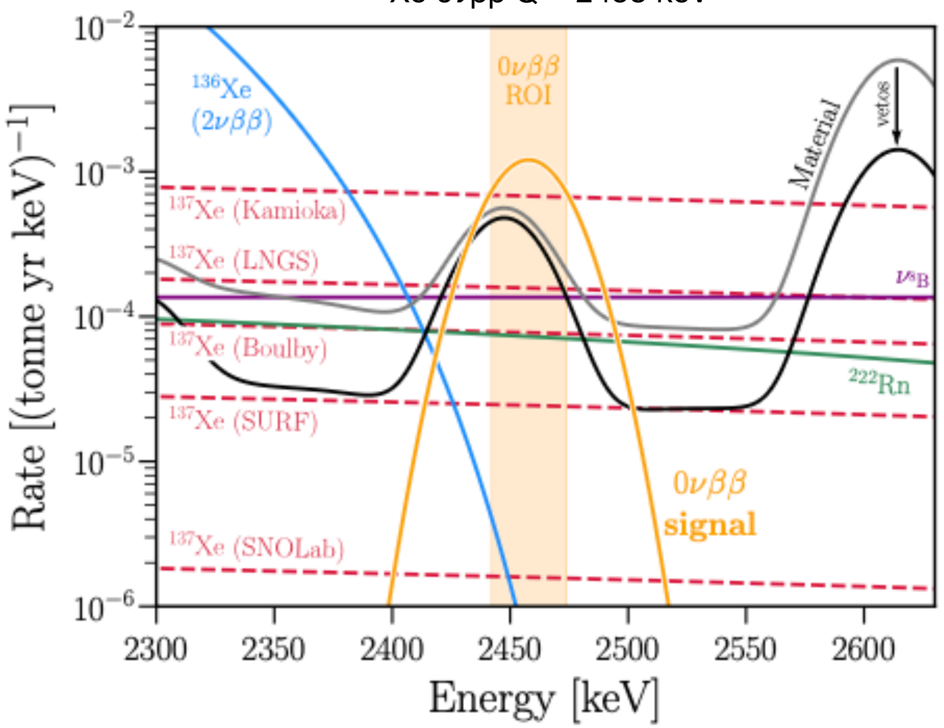
Detection capability of benchmark candidates

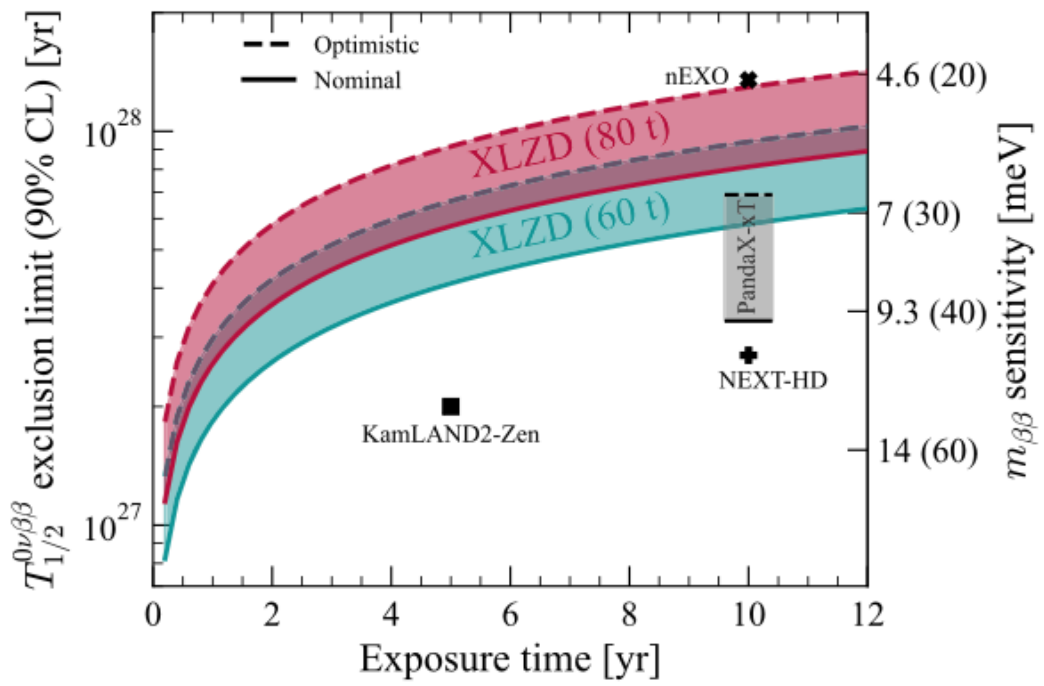


- **Constraining dark matter properties**
  - evidence contours for 20 GeV and 80 GeV WIMPs (1000 t・y)
  - covering most of the cases for Electroweak multiplet DM
  - Higgsino and Bino DM: highly complementary to that of collider

XLZD: ^{136}Xe $0\nu\beta\beta$ Search

^{136}Xe $0\nu\beta\beta$ Q = 2458 keV

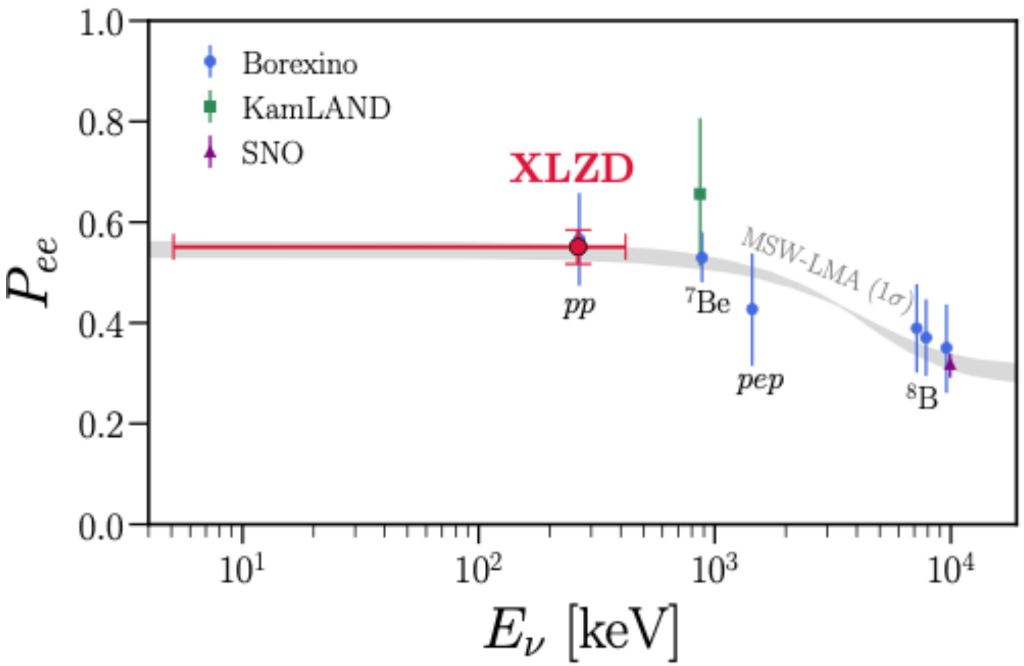


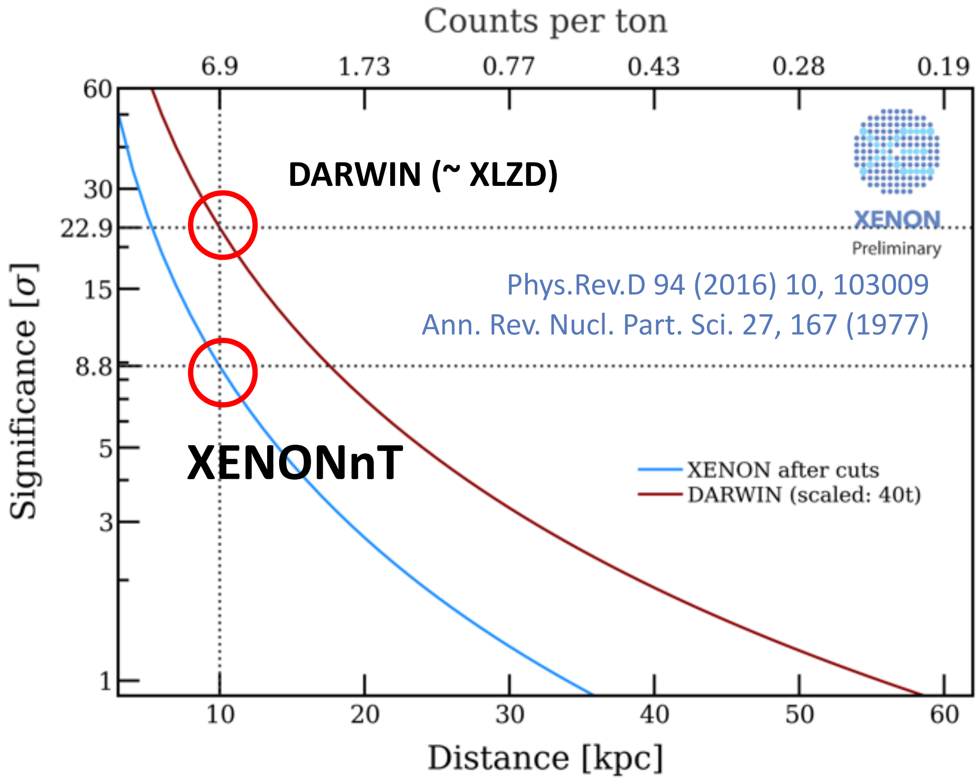


- ^{136}Xe is 8.9% of natural xenon
  - With 80 t target mass, XLZD will contain >7 t of ^{136}Xe
- Xenon TPCs have excellent resolution
  - 0.67% demonstrated in LZ, 0.8% in XENON1T

- **Internal and intrinsic backgrounds**
  - ^{214}Bi β from ^{222}Rn in the xenon (Q = 3270 keV)
    - We assume 0.1 μBq/kg ^{222}Rn rate and >99.95% BiPo tagging
  - ^{137}Xe β (Q = 4170 keV), neutron activation of ^{136}Xe
    - Mostly by muon-induced neutrons, depending on the installation site
  - Electron recoils from ν-e^- scattering (^{8}B), irreducible

Neutrino



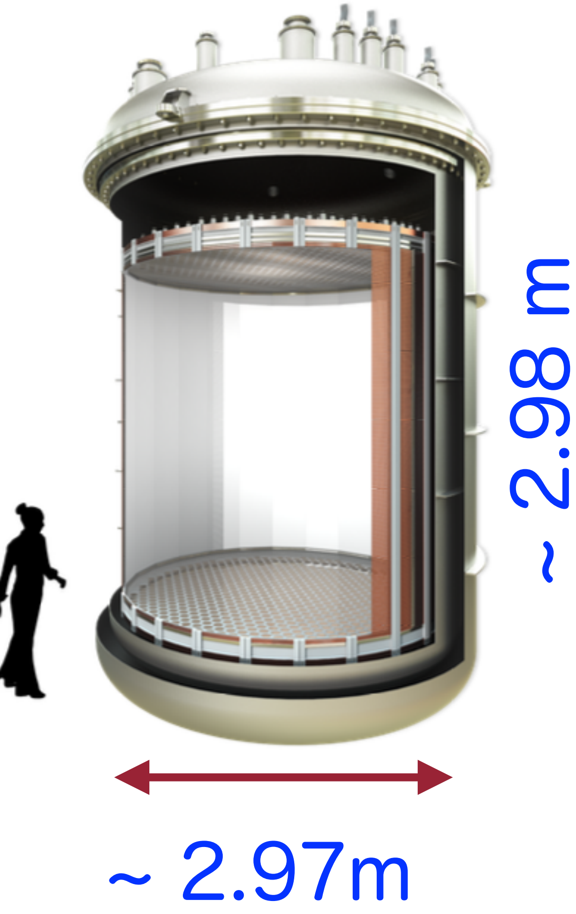


- Neutrinos (solar model, neutrino properties)
  - **High statistics pp neutrino measurement**
  - **Neutrino survival probability** (5.1-420 keV)
    - lowest energy threshold
    - Test the LMA-MSW solution to neutrino oscillations
  - **Neutrino magnetic moment**

- Flavor independent detection via CEvNS
- A few 100s events @ 10kpc

R&D Activities: TPC and Electrodes/HV

Full height and diameter test facility for DARWIN/XLZD

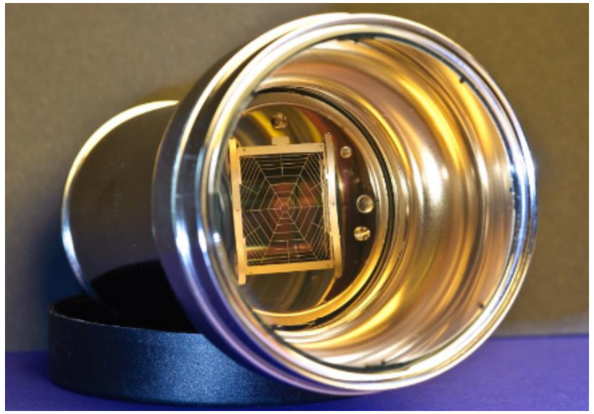


JINST 16 P08052(2021)

High voltage, Purity …

Electrode and other detector components

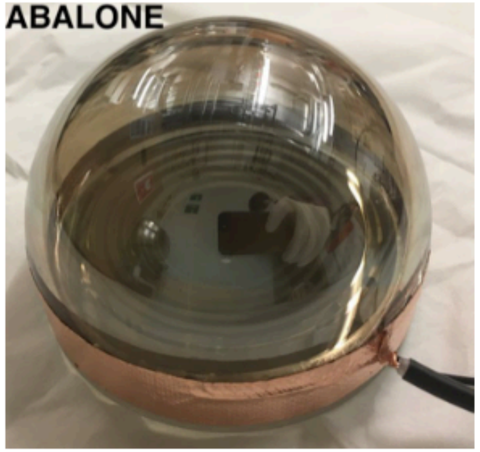
Photosensors



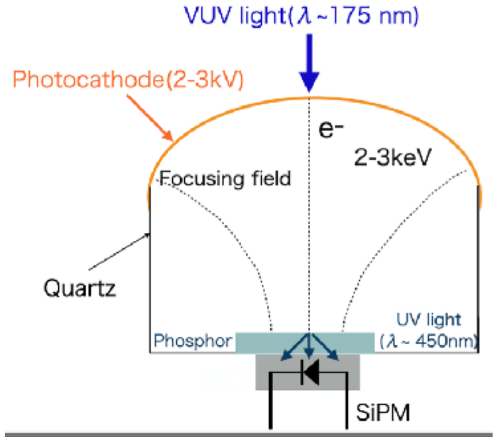
R11410 (LZ, XENONnT, PandaX)

K. Abe et al. JINST 15 P09027

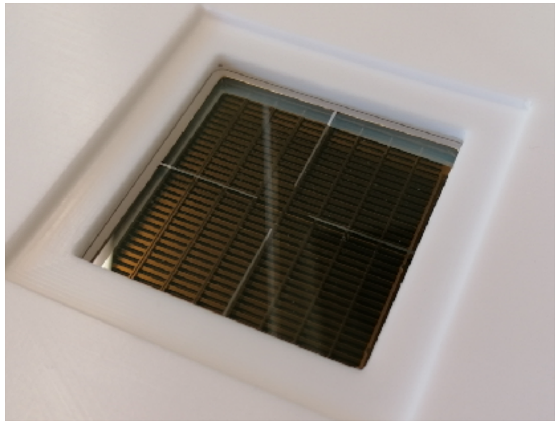
R13111 (XMASS)
Lowest radioactivity



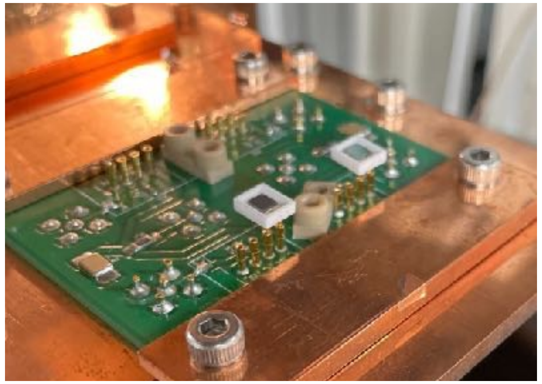
JINST **17** C01038 (2022)



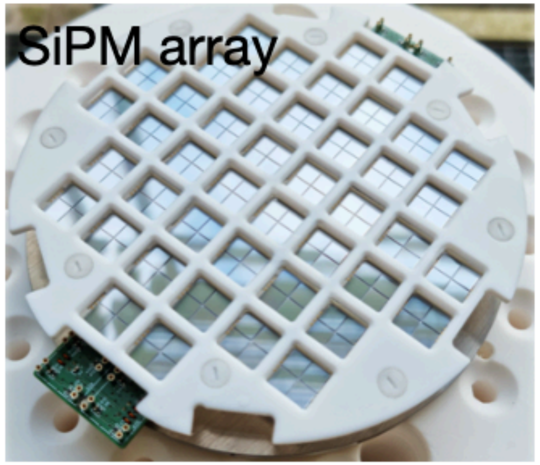
Hybrid



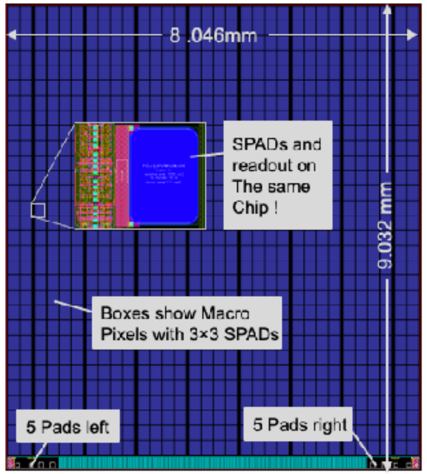
2inch square



Low Dark Current SiPM



JINST **18** C03027 (2023)



Digital SiPM

Conclusion

- The **XLZD** collaboration was formed in 2024 by
  - **XENONnT + LUX-ZEPLIN + DARWIN**

·XLZD will be a successor to the state-of-the-art liquid xenon dark matter detector.

·Ultimate detector for WIMP search (neutrino fog)

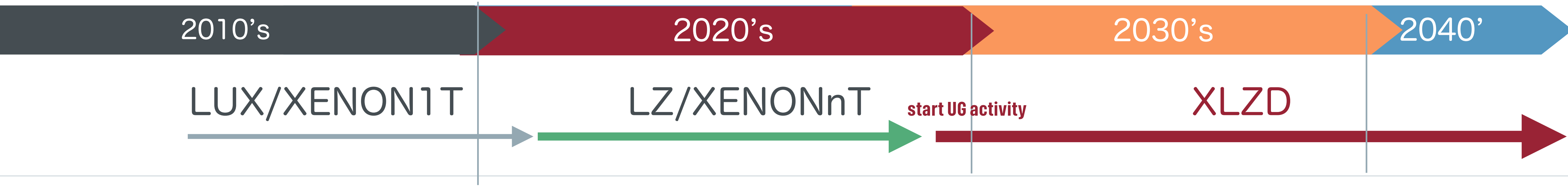
-Solar Neutrino

-Double Beta Decay

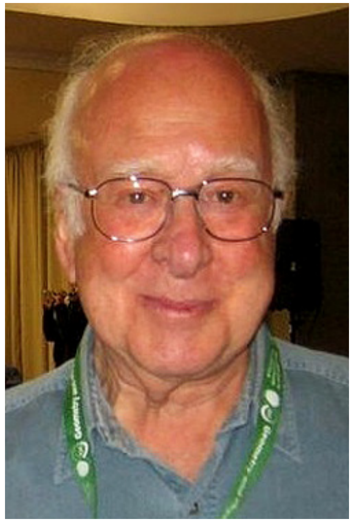
-SuperNova …etc

· start observation in 2030’

LNGS visit during the XLZD meeting

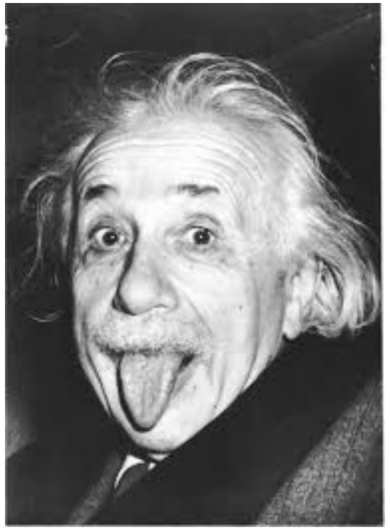


Higgs



50 yrs

GW

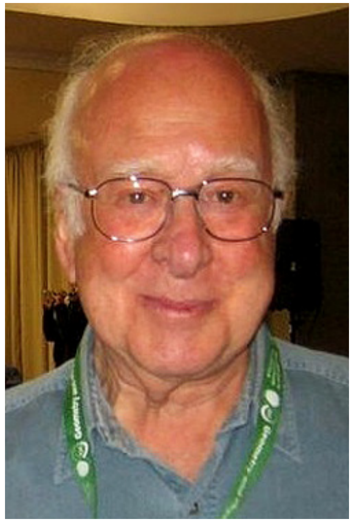


100 yrs

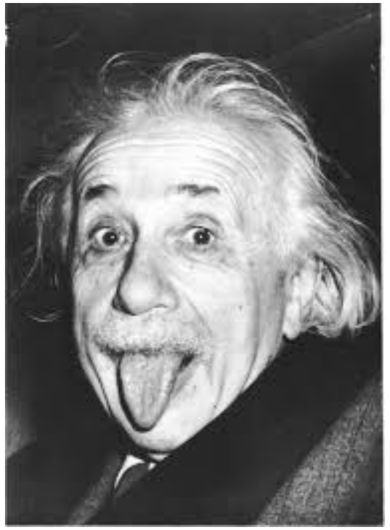
Higgs

GW

Dark Matter



50 yrs



100 yrs

90yrs

50yrs

MACRO (1988-2002) at LNGS

NuclearInstruments andMethodsinPhysicsResearchA486(2002)663–707

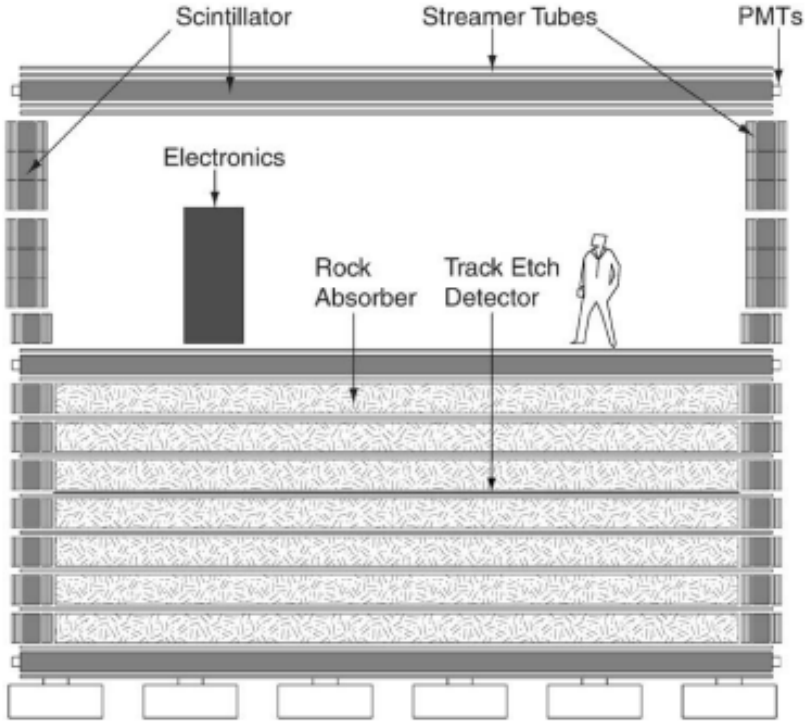
Scintillator + Trach Etch Detector (CR39)

Search for

magnetic monopole,

nuclearite (u + d + s)

charged Q-ball



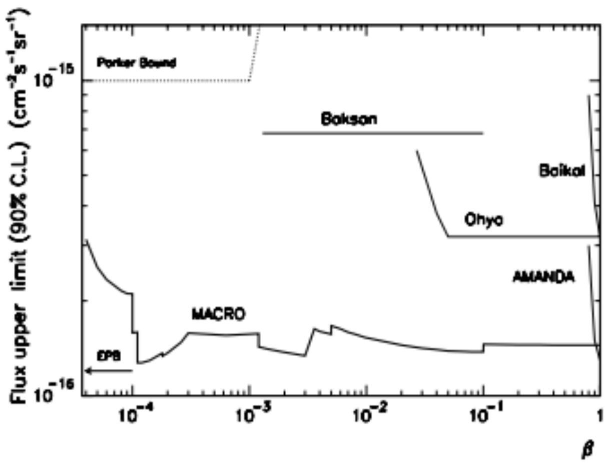


Fig. 9. The global MACRO limit for an isotropic flux of bare magnetic monopoles, with $m \geq 10^{17}$ GeV/c^2, $g = g_D$ and σ_{cat} < few mb. For comparison, we present also the flux limits from other experiments [31]