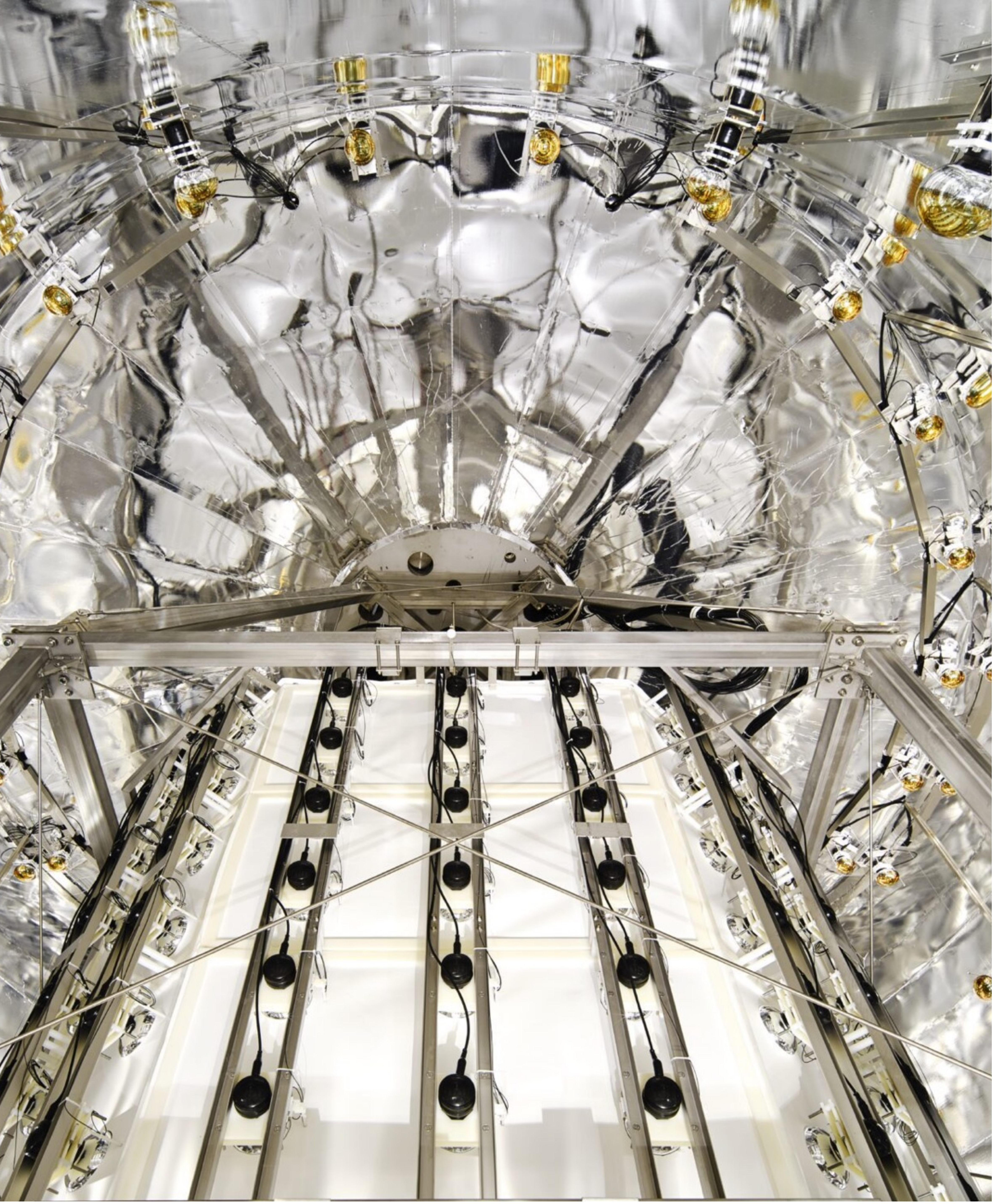


XENON

暗黒物質直接探索検出器を用いた超新星ニュートリノの観測

計画研究 B02：
超大型液体キセノン検出器で解明する宇宙暗黒物質の謎

KAVLI IPMU
Kavli IPMU, UTokyo
Masaki Yamashita
on behalf of the XENON Collaboration

第11回超新星ニュートリノ研究会2025/03/03, 04 @東大駒場キャンパス

KAVLI IPMU

SNEWS 2.0

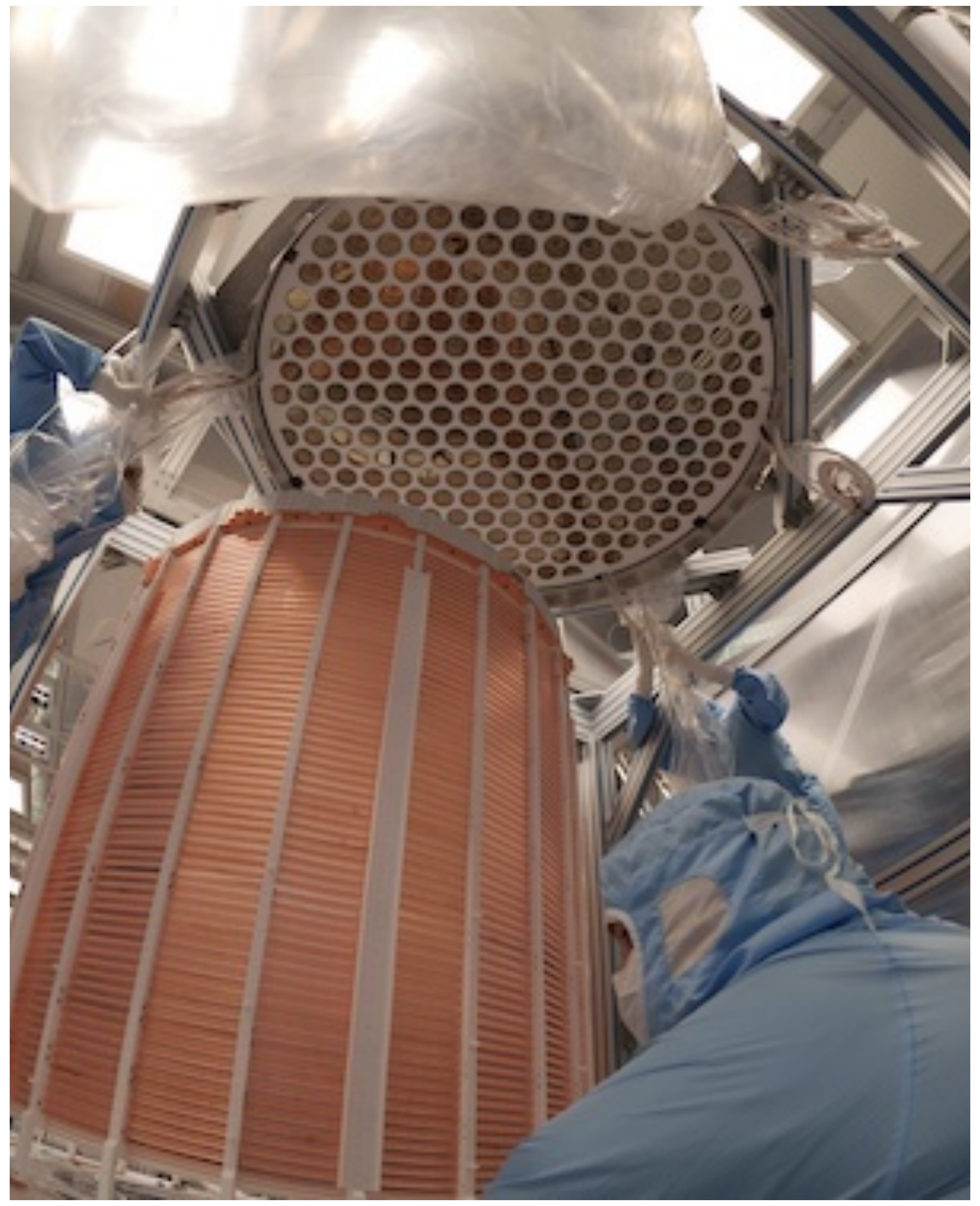
SNEWS SUPERNOVA EARLY WARNING SYSTEM

XENON

https://snews2.org

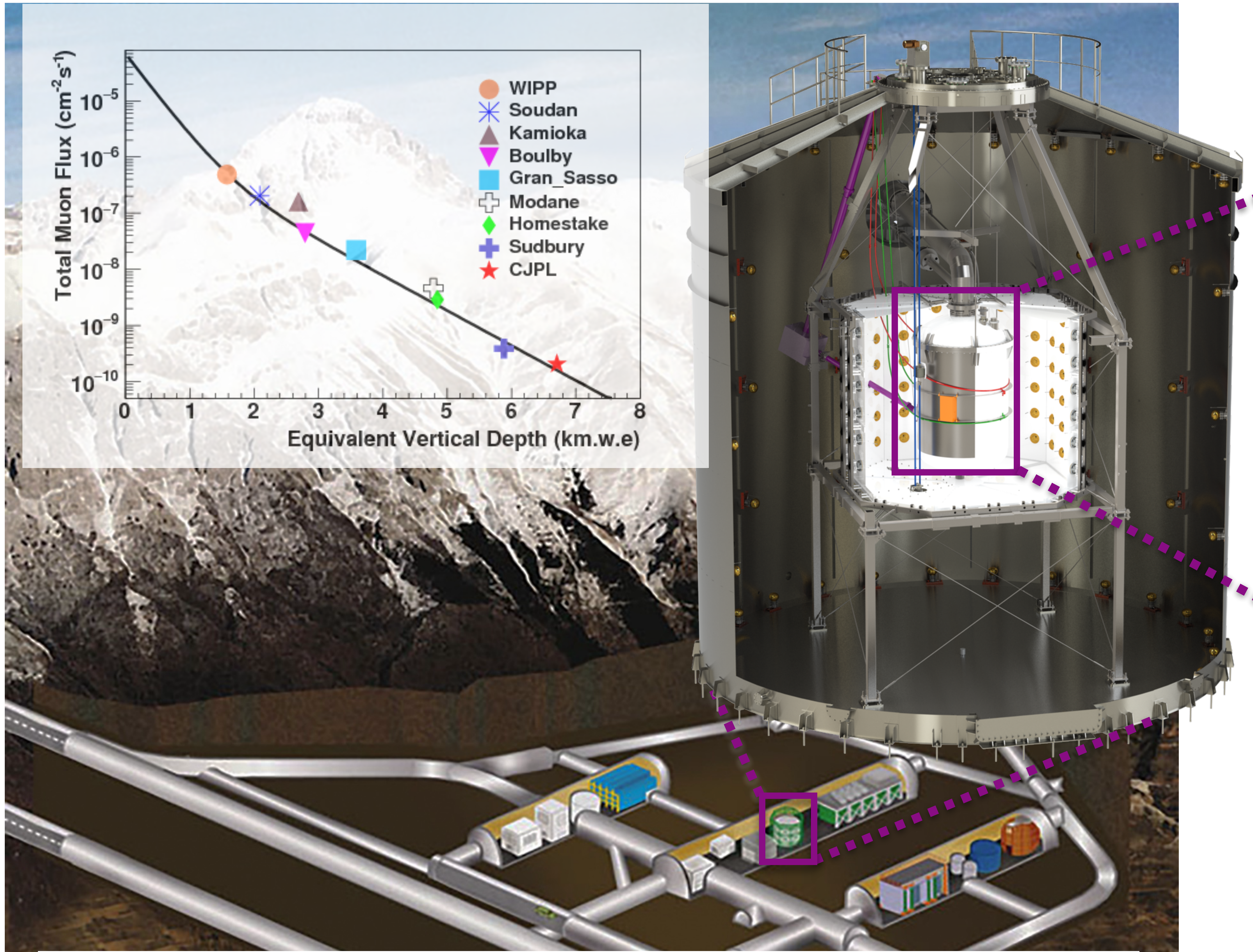
S Al Kharusi et al 2021 New J. Phys. 23 031201

Experiment	Type	Mass (kt)	Location	11.2 $M_\odot$	27.0 $M_\odot$	40.0 $M_\odot$
Super-K	$H_2O/\bar{\nu}_e$	32	Japan	4000/4100	7800/7600	7600/4900
Hyper-K	$H_2O/\bar{\nu}_e$	220	Japan	28K/28K	53K/52K	52K/34K
IceCube	String/$\bar{\nu}_e$	2500∗	South Pole	320K/330K	660K/660K	820K/630K
KM3NeT	String/$\bar{\nu}_e$	150∗	Italy/France	17K/18K	37K/38K	47K/38K
LVD	$C_nH_{2n}/\bar{\nu}_e$	1	Italy	190/190	360/350	340/240
KamLAND	$C_nH_{2n}/\bar{\nu}_e$	1	Japan	190/190	360/350	340/240
Borexino	$C_nH_{2n}/\bar{\nu}_e$	0.278	Italy	52/52	100/97	96/65
JUNO	$C_nH_{2n}/\bar{\nu}_e$	20	China	3800/3800	7200/7000	6900/4700
SNO+	$C_nH_{2n}/\bar{\nu}_e$	0.78	Canada	150/150	280/270	270/180
NOνA	$C_nH_{2n}/\bar{\nu}_e$	14	USA	1900/2000	3700/3600	3600/2500
Baksan	$C_nH_{2n}/\bar{\nu}_e$	0.24	Russia	45/45	86/84	82/56
HALO	Lead/ν_e	0.079	Canada	4/3	9/8	9/9
HALO-1kT	Lead/ν_e	1	Italy	53/47	120/100	120/120
DUNE	Ar/ν_e	40	USA	2700/2500	5500/5200	5800/6000
MicroBooNe	Ar/ν_e	0.09	USA	6/5	12/11	13/13
SBND	Ar/ν_e	0.12	USA	8/7	16/15	17/18
DarkSide-20k	Ar/any ν	0.0386	Italy	—	250	—
XENONnT	Xe/any ν	0.006	Italy	56	106	—
LZ	Xe/any ν	0.007	USA	65	123	—
PandaX-4T	Xe/any ν	0.004	China	37	70	—

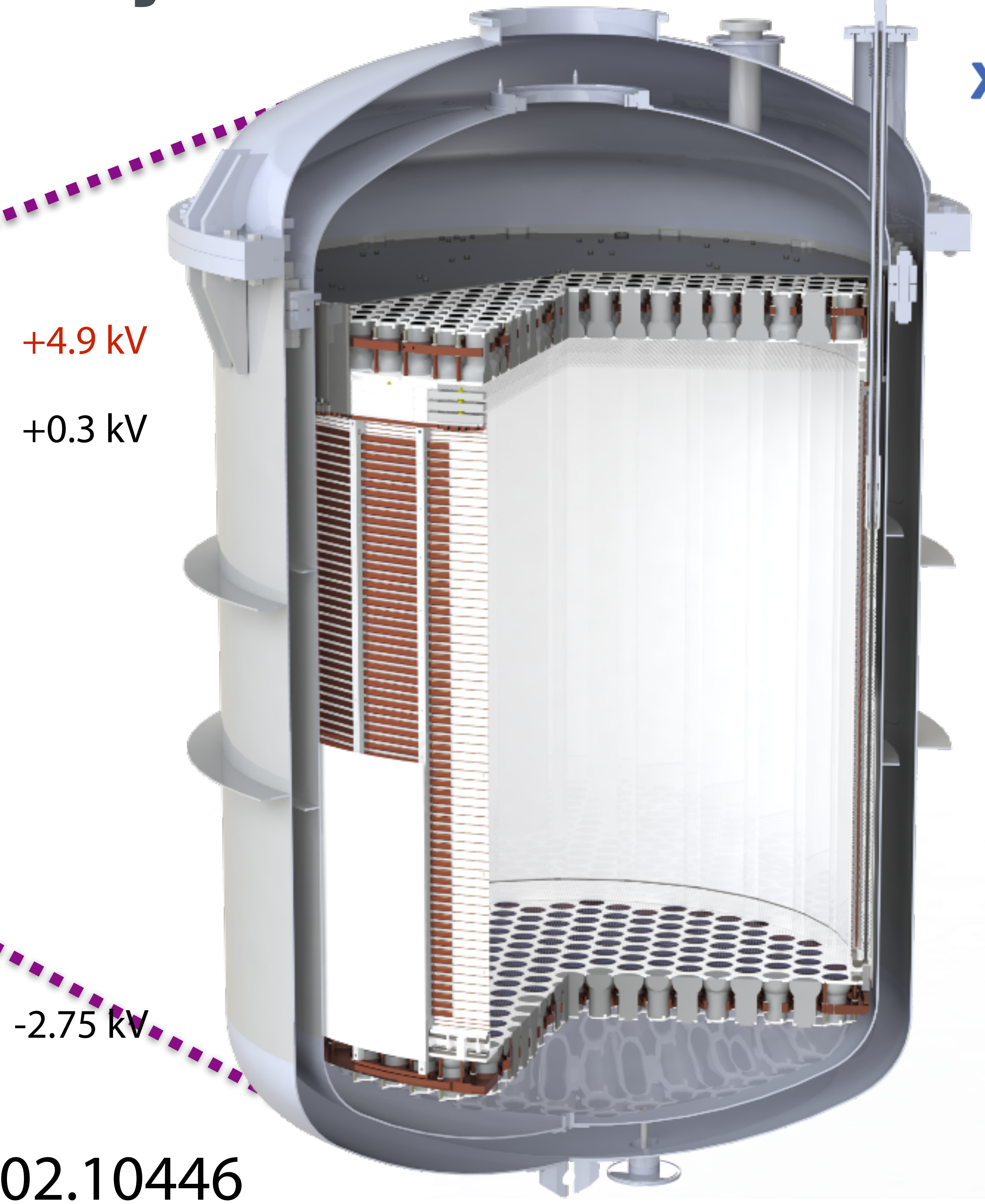


XENON

XENONnT@Gran Sasso in Italy



WIMP dark matter
Neutrino
Rare Decay （double electron capture, double beta decay)



arXiv: 2402.10446

Drift Length	Diameter	Sensitive Target	Drift Field
1.5m	1.32m	5.9 tonne	23 V/cm

XENON Collaboration

KAVLI IPMU

XENON

- •200+ scientists
- •30 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

ASIA

- 清華大學 Tsinghua University — Beijing
- 西湖大學 Westlake University — Hangzhou
- Shenzhen
- 東京大学 The University of Tokyo — Tokyo
- Nagoya University — Nagoya
- Kobe University — Kobe

EUROPE / MIDDLE EAST

- Zurich
- KIT Karlsruhe Institute of Technology — Karlsruhe
- WWU Münster — Münster
- Uni Freiburg — Freiburg
- JG|U — 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
- מכון ויצמן למדע Weizmann Institute of Science — Rehovot
- جامعة نيويورك أبوظبي NYU Abu Dhabi — Abu Dhabi

Neutrino detectors and XENONnT

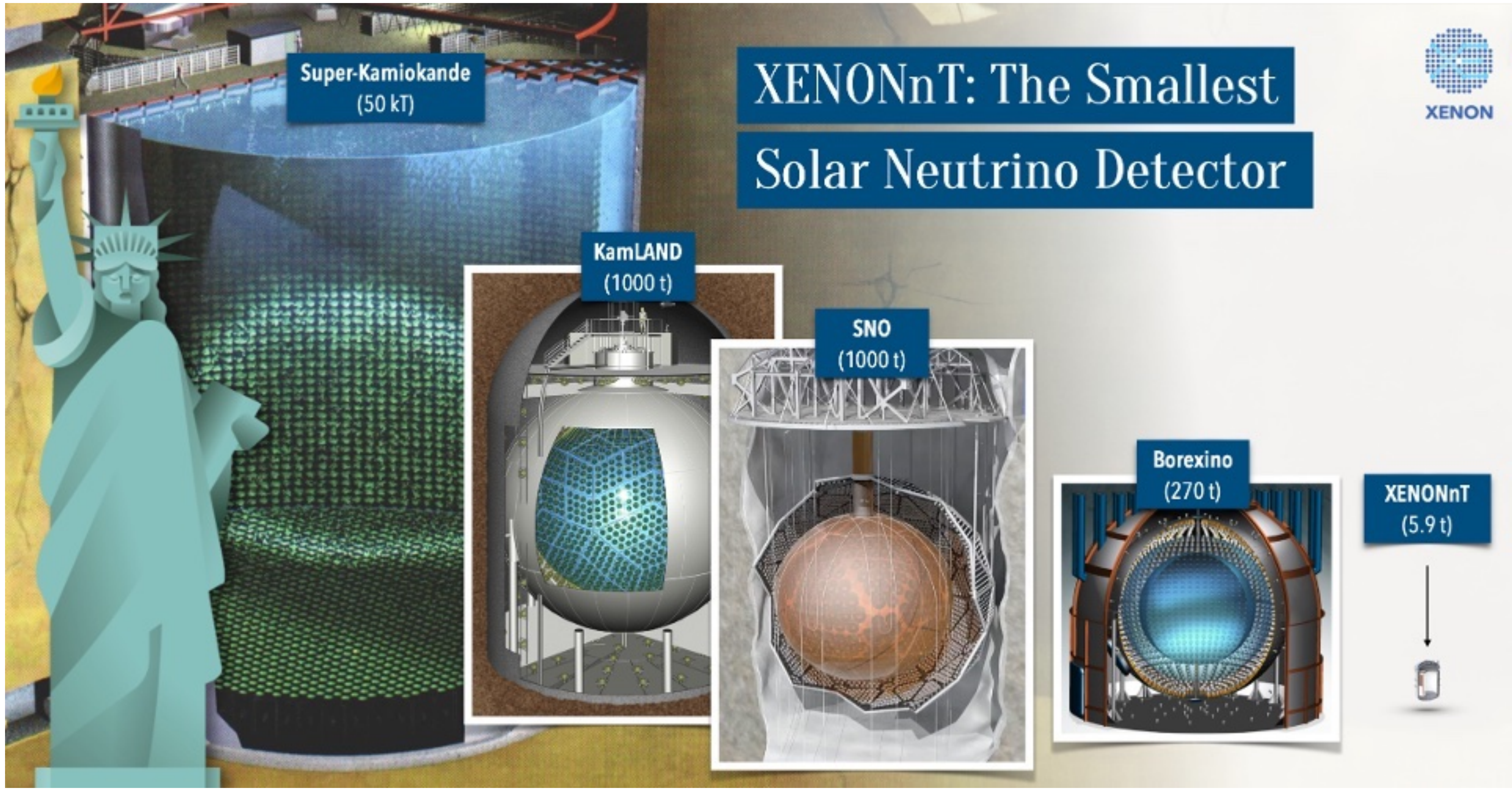
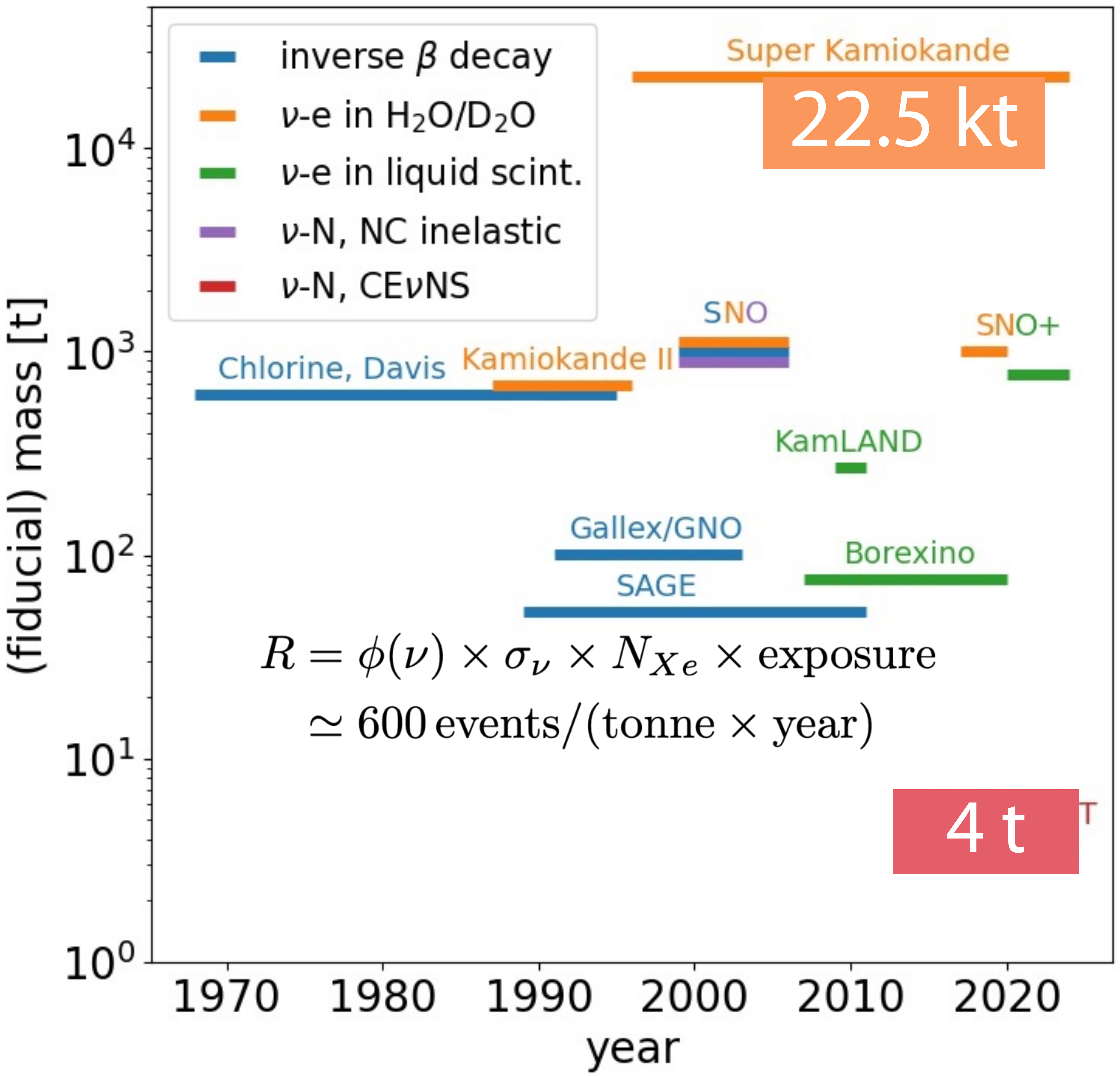


Figure: Detection of solar neutrinos. Compilation courtesy R. Hammann.



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

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)

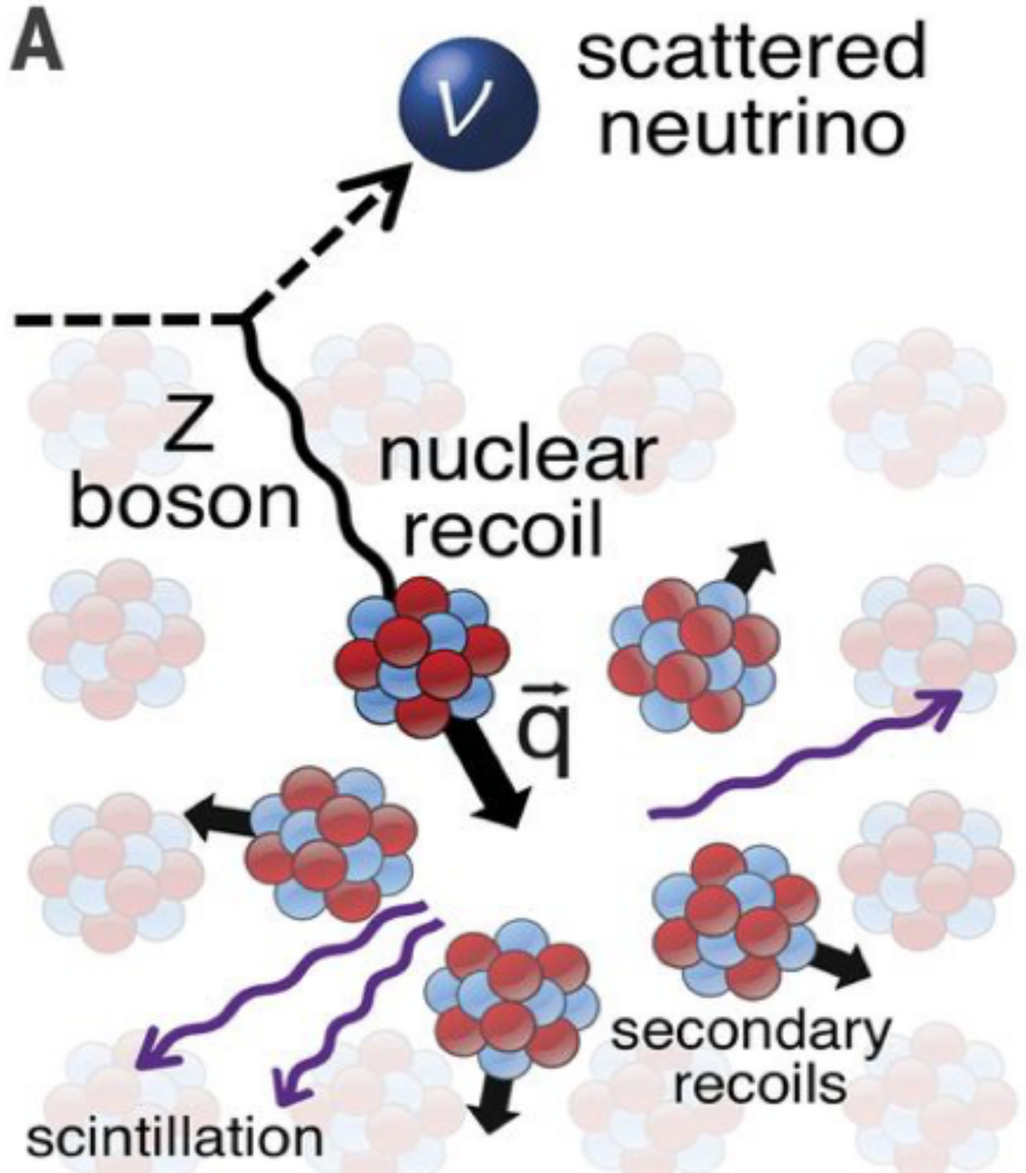
If there is a weak neutral current, then the elastic scattering process $\nu + A \to \nu + A$ should have a sharp coherent forward peak just as $e + A \to e + A$ does. Experiments to observe this peak can give important information on the isospin structure of the neutral current. The experiments are 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.

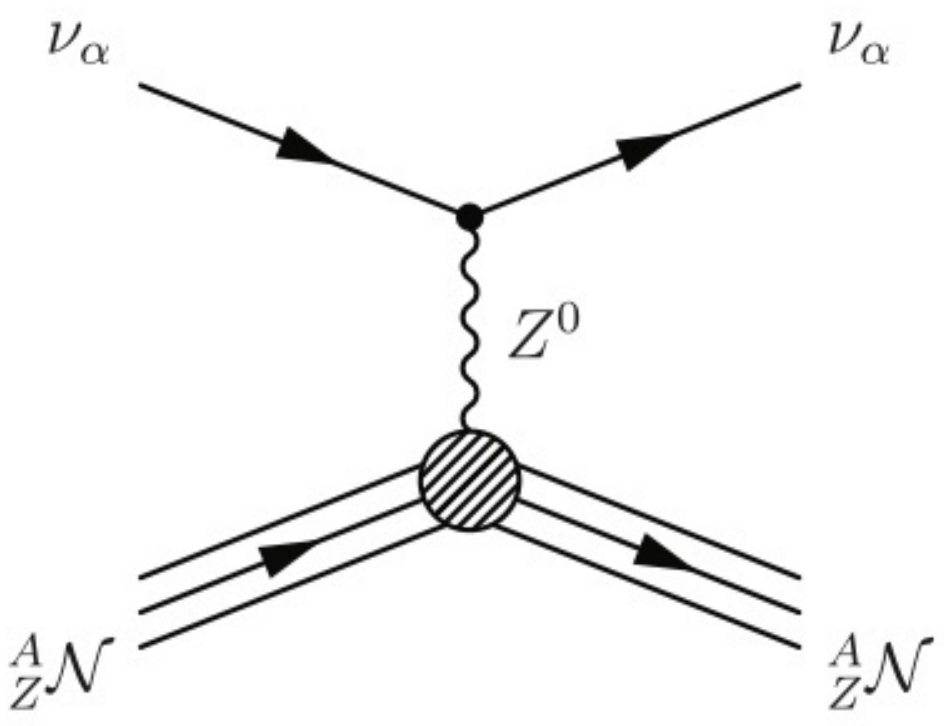
1974 Coherent elastic neutrino-nucleus scattering (CEvNS) was predicted theoretically by D.Z. Freedman.

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.

ν





D. Akimov et al, Science 357 (2017)

It took ~40 years to observe it. Why?

Coherent Elastic Neutrino Nucleus Scattering

XENON

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

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:

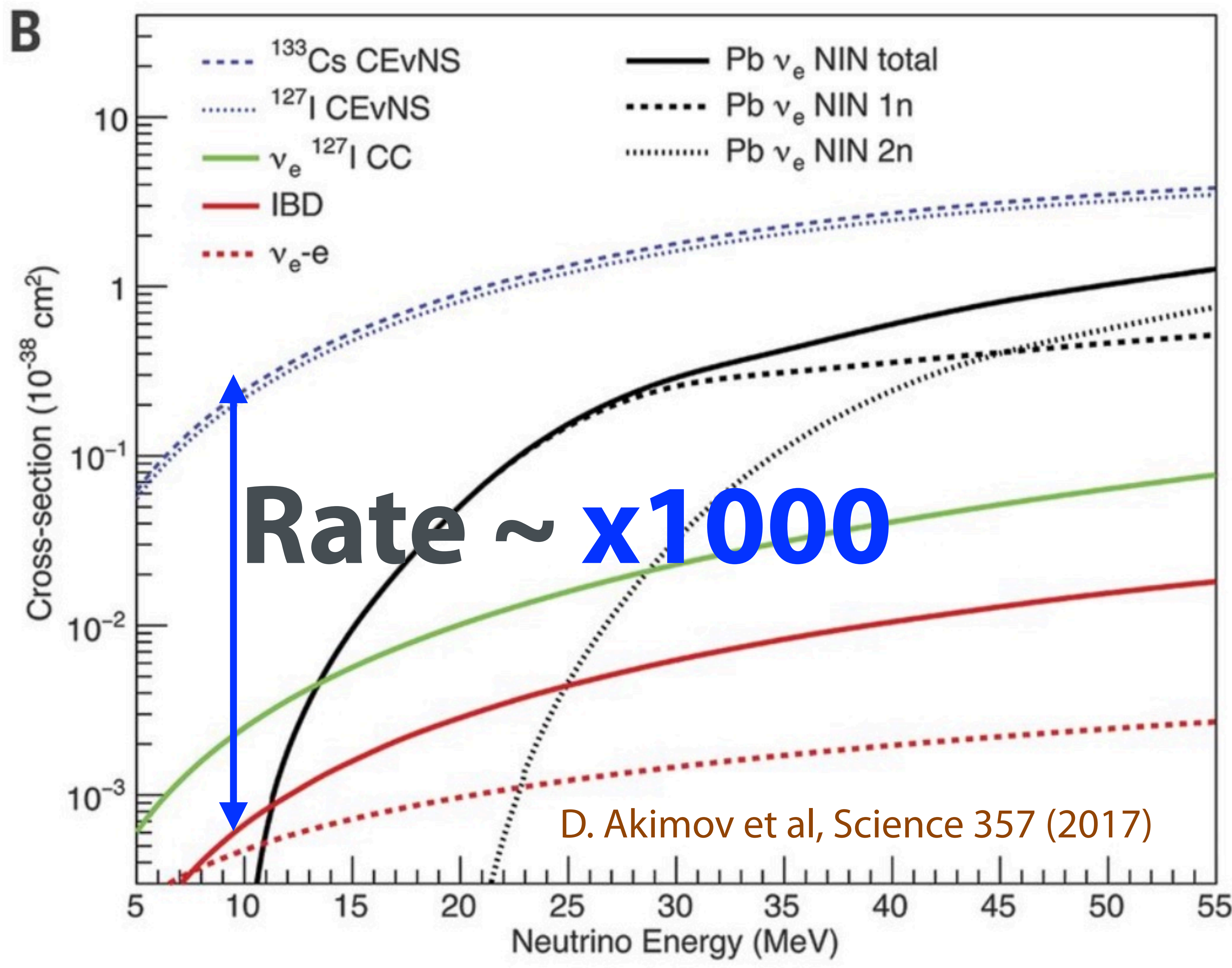
Proton

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

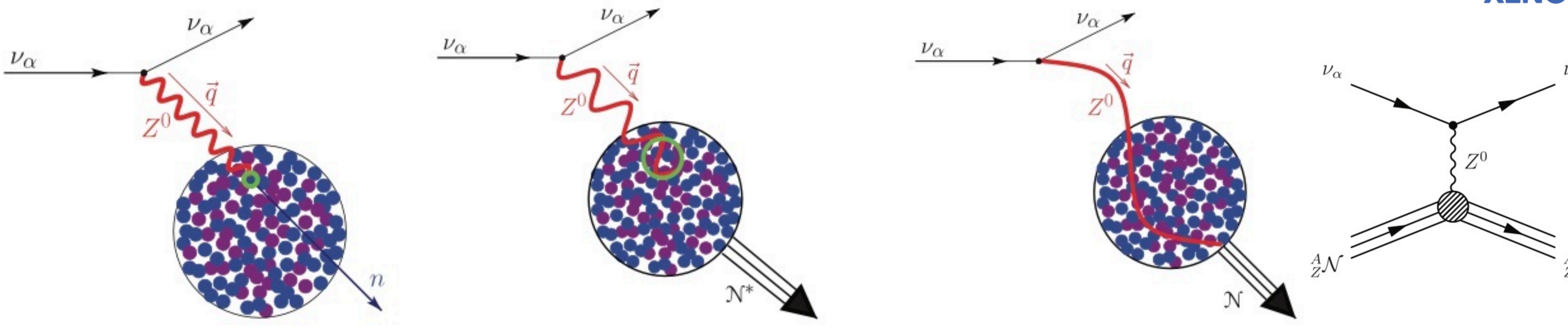
Neutron

$\sin^2\theta_W \sim 0.239$

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



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

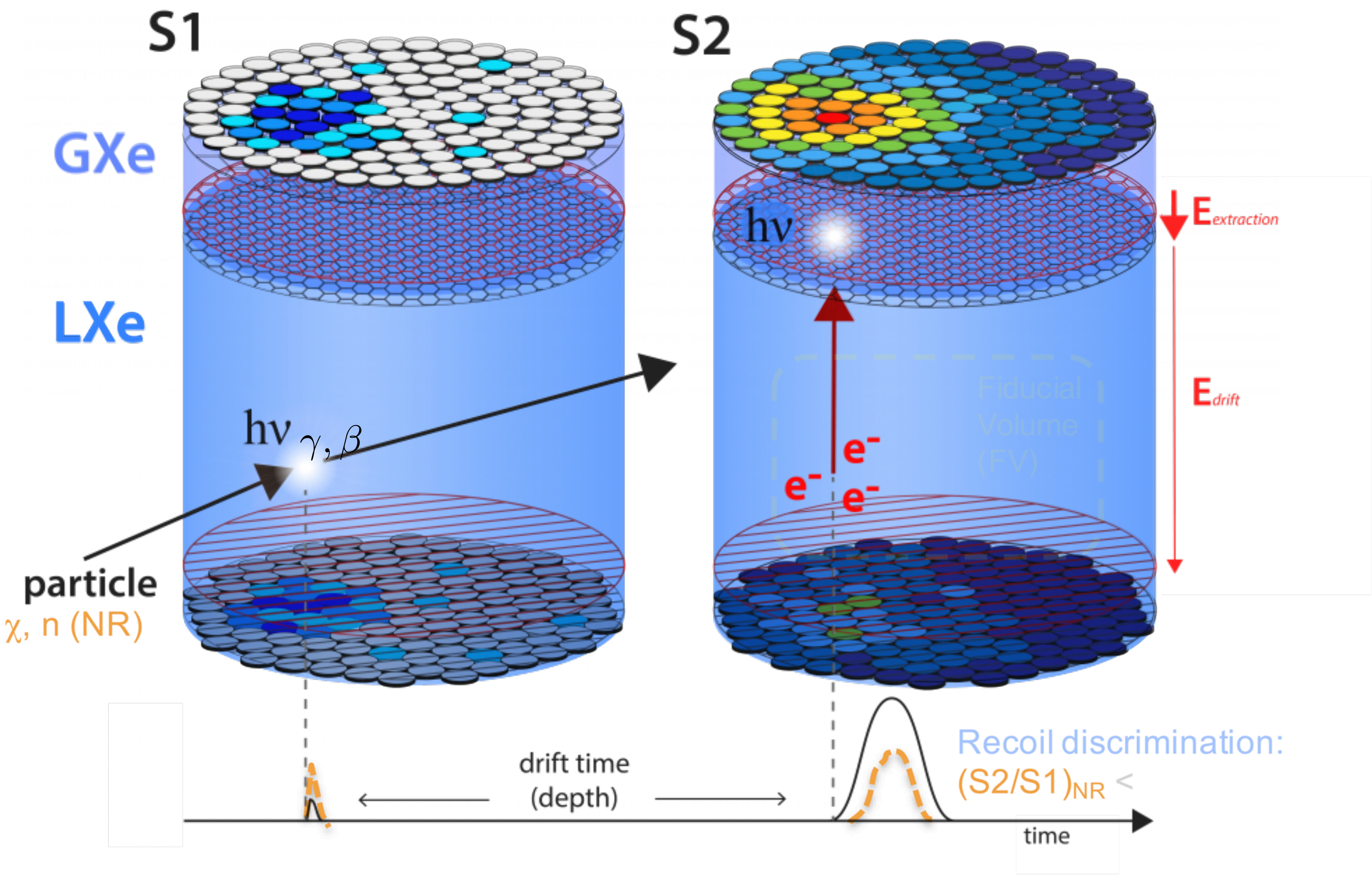
E_{max}: $\frac{2E_\nu^2}{M}$ ~ 1.5 keV

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

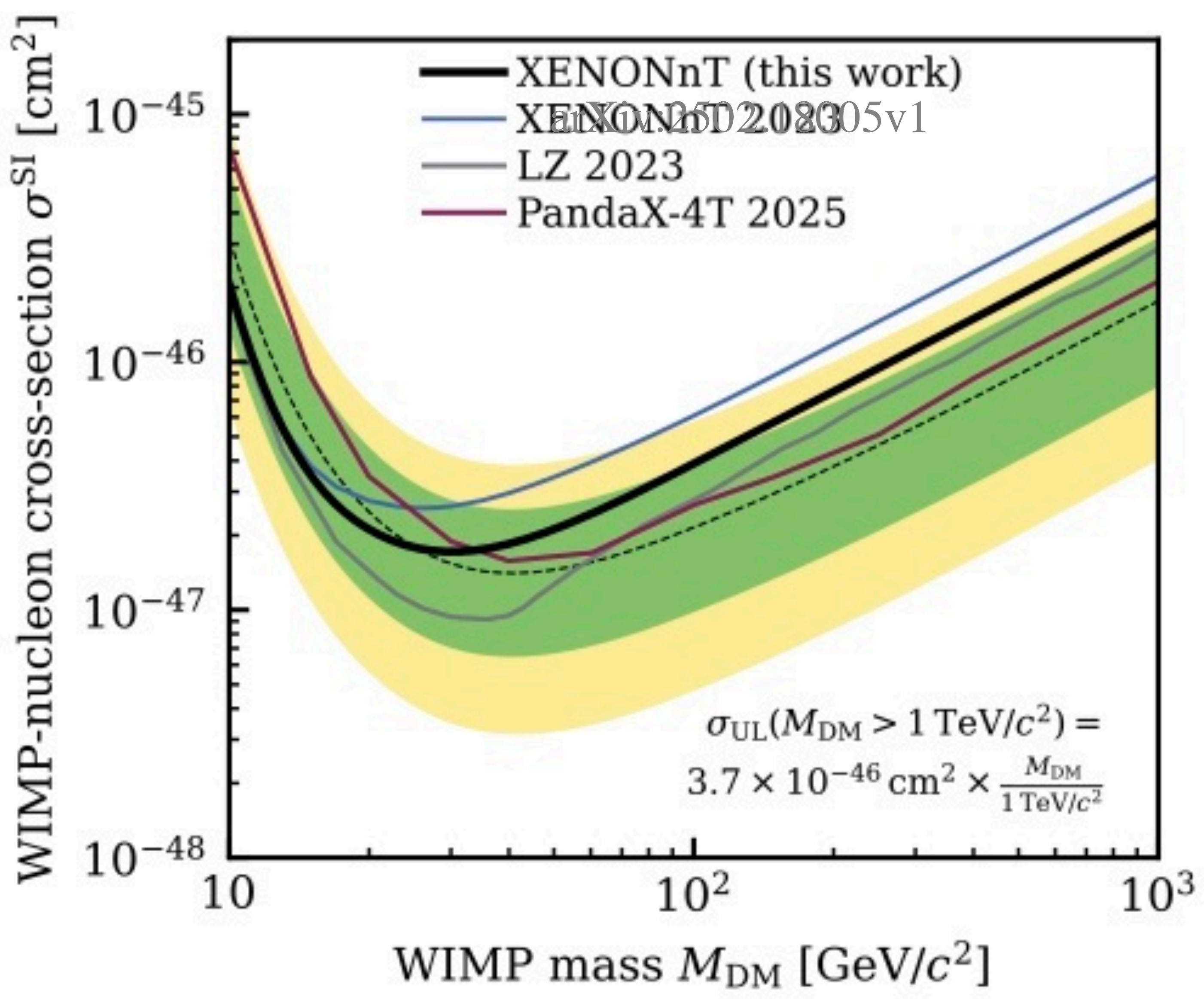
Two-phase Xe Time Projection Chamber

XENON

- **Target Liquid Xenon (-100°C, 3 g/cm^{-3})**
- **S1: Scintillation**
- **S2: electron （->proportional light）**



- simultaneously observe both S1 and S2
- 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)



Two-phase Xe Time Projection Chamber

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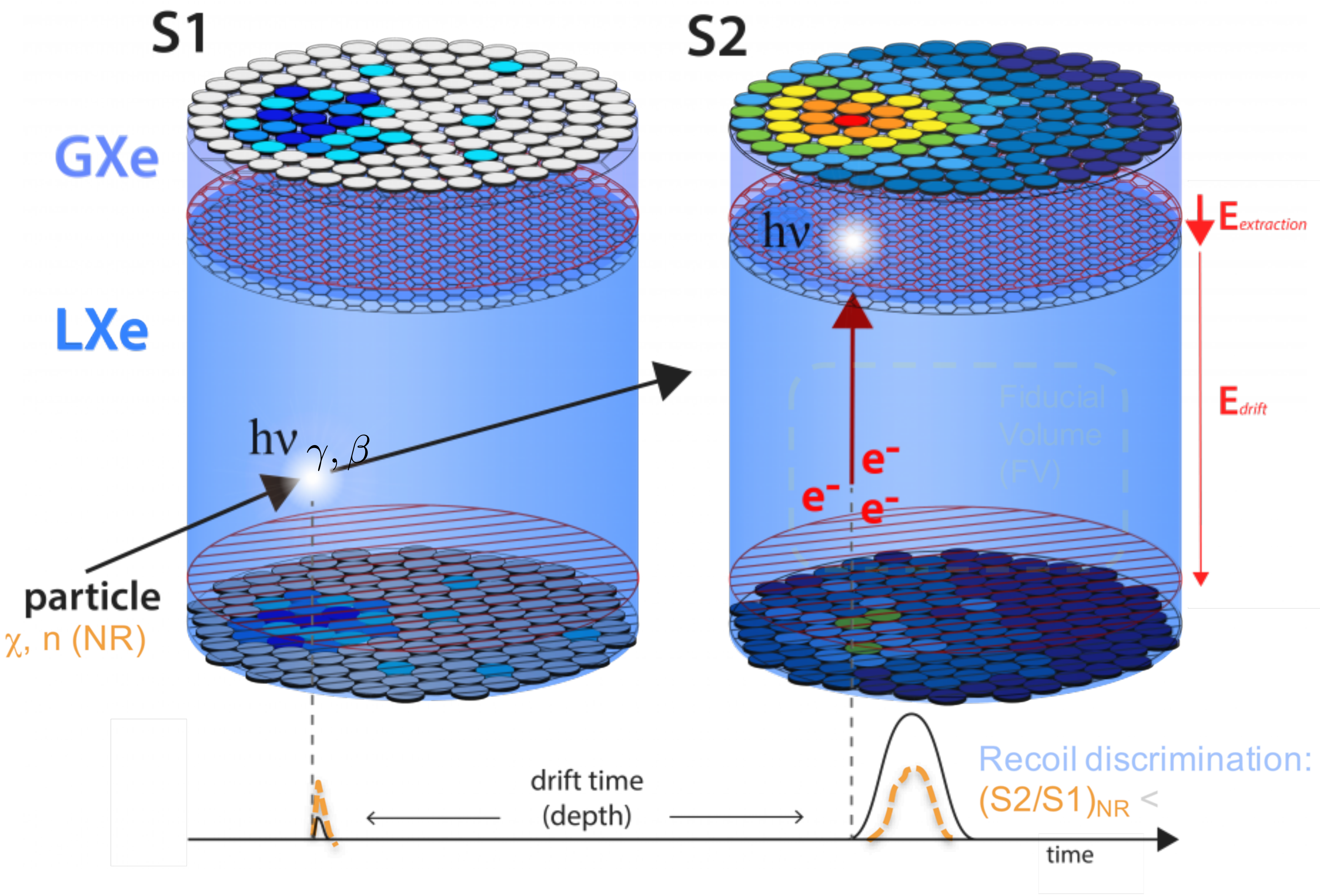

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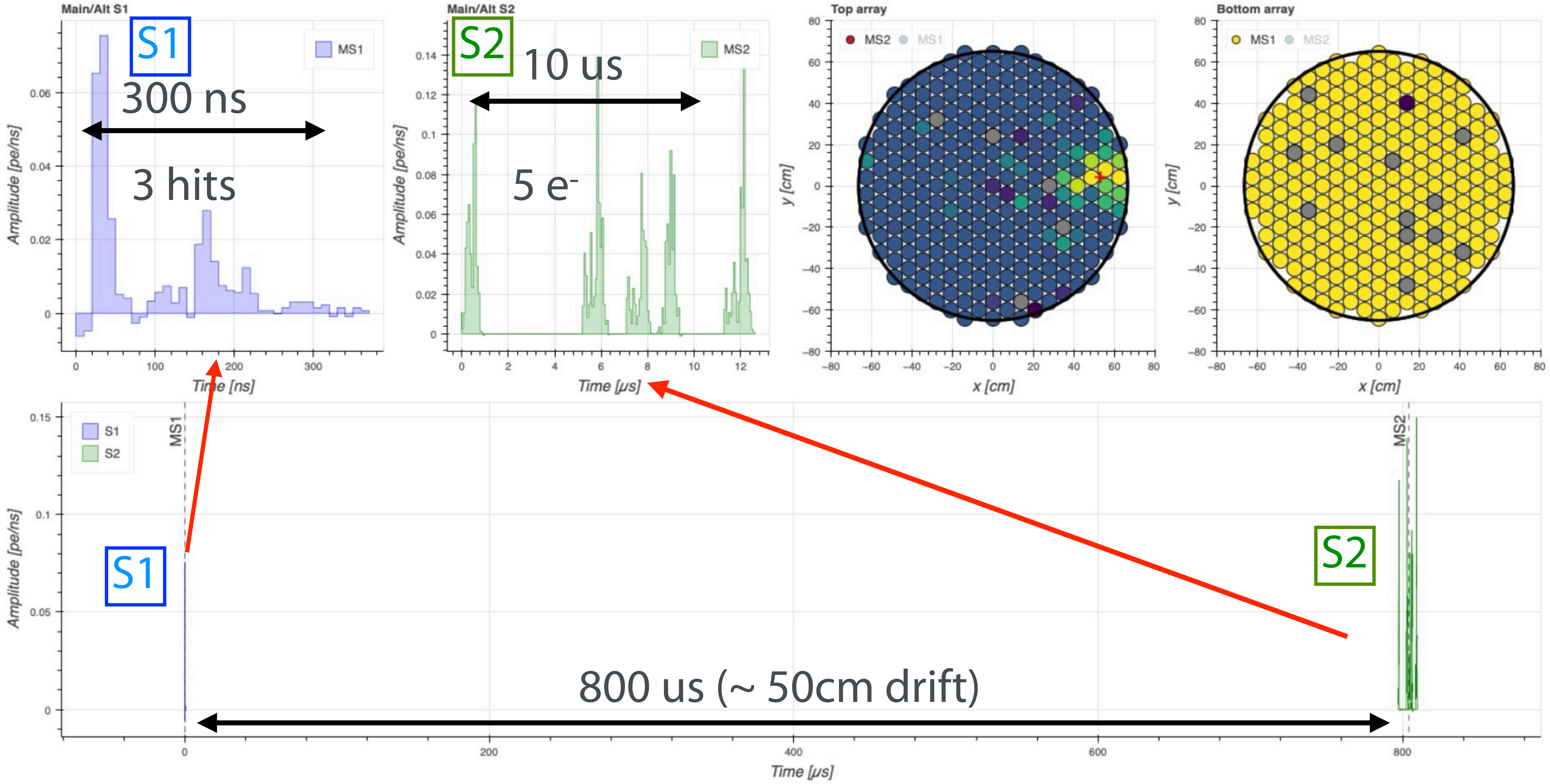
- 3D event imaging: x-y (S2) and z (drift time)
- Self-shielding, surface event rejection, single vs multiple scatter events
- Particle identification using S2/S1 ratio (nuclear recoil vs beta, gamma)

one drifted electron produces ~ 200 photon
-> ~30 Photoelectron/electron

Improve Energy threshold by usin S2-only for SN search :
S2 only < 1keV (E threshold)

Signal (S1, S2)



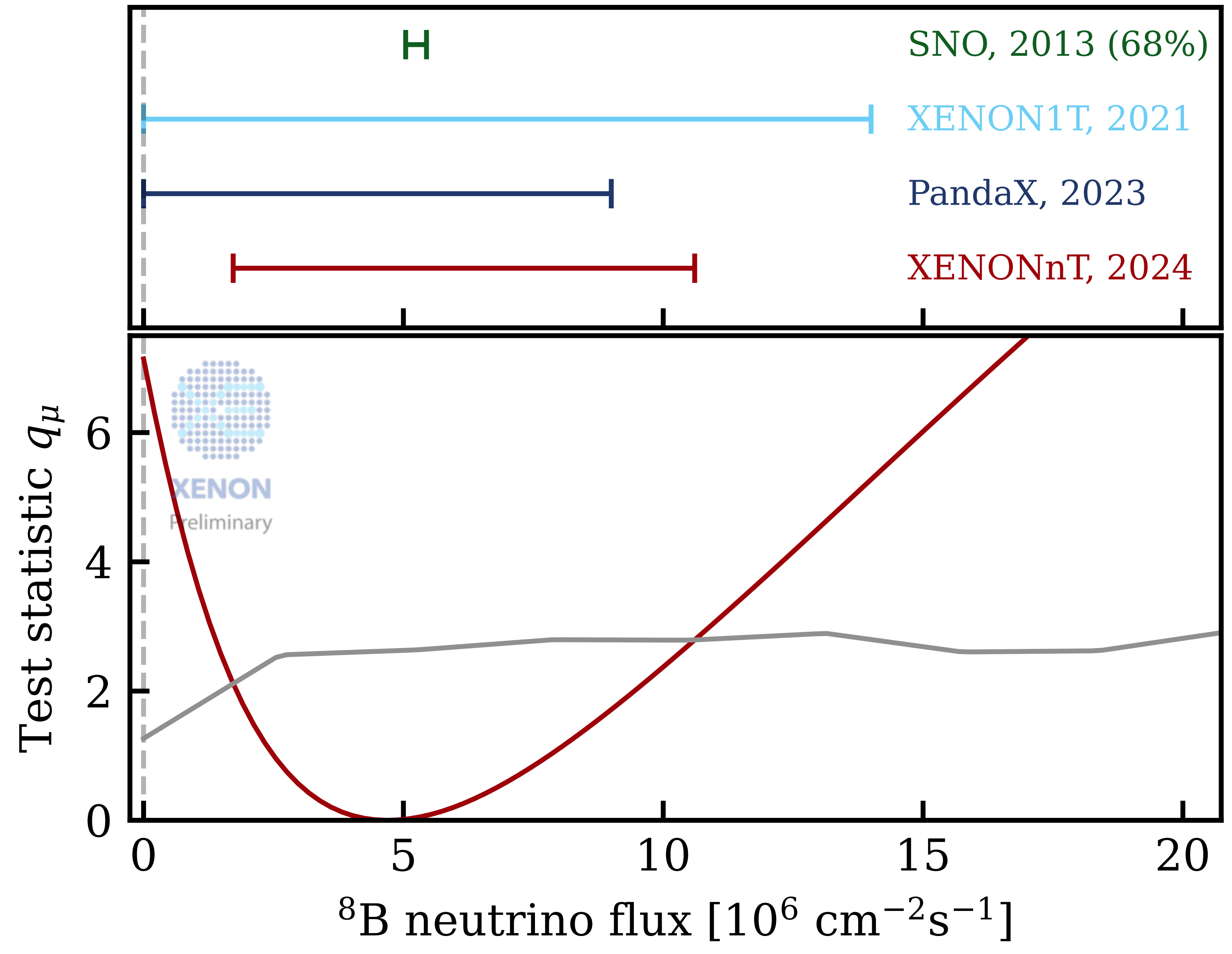
Main/Alt S1
S1
MS1
300 ns
3 hits
Amplitude [pe/ns]
Time [ns]
Main/Alt S2
S2
MS2
10 us
5 e-
Amplitude [pe/ns]
Time [μs]
Top array
MS2
MS1
y [cm]
x [cm]
Bottom array
MS1
MS2
y [cm]
x [cm]
S1
S2
MS1
MS2
S1
S2
Amplitude [pe/ns]
800 us (~ 50cm drift)
Time [μs]

Solar Neutrino (^{8}B) Result

PHYSICAL REVIEW LETTERS **133,** 191002 (2024)

Editors' Suggestion **Featured in Physics**

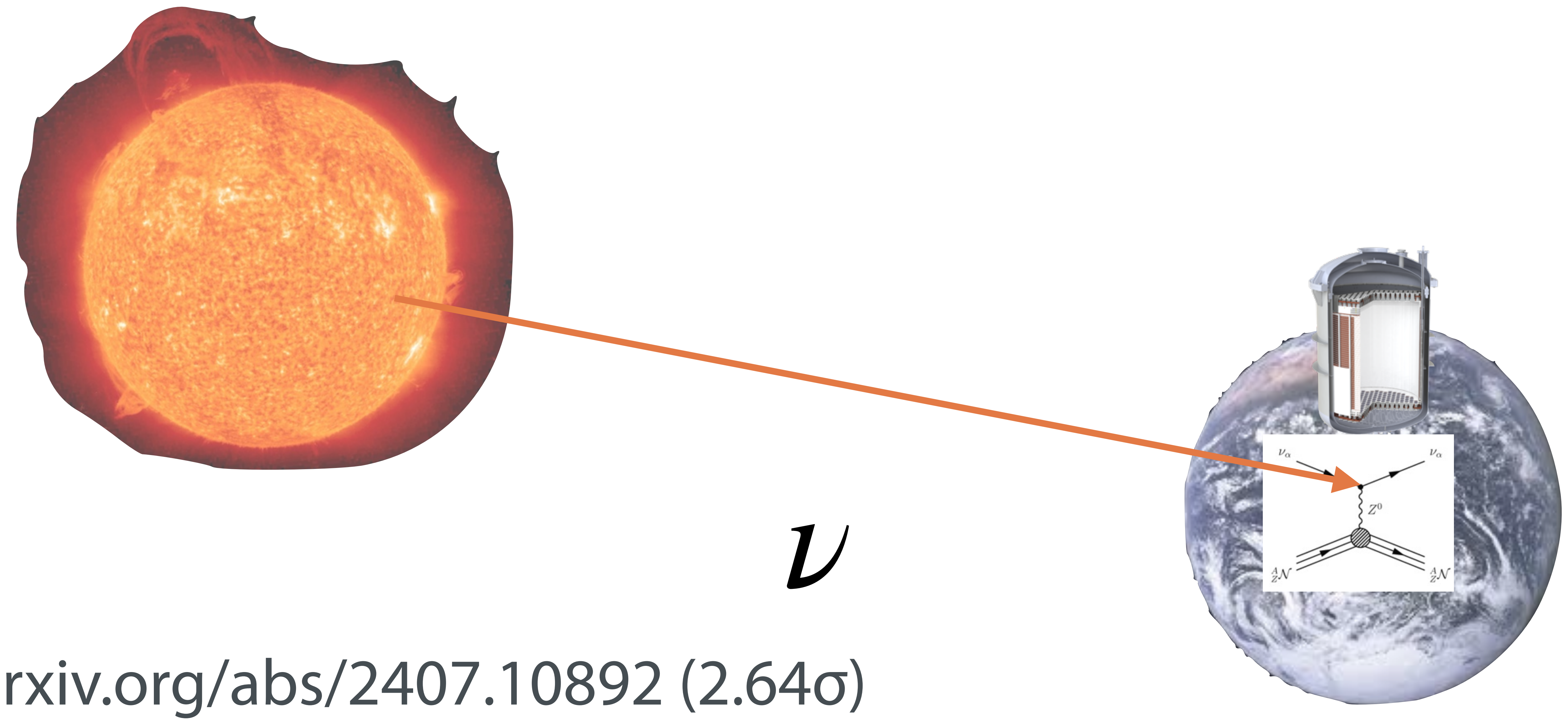
First Indication of Solar ^{8}B Neutrinos via Coherent Elastic Neutrino-Nucleus Scattering with XENONnT



The background-only hypothesis is disfavored at 2.73σ

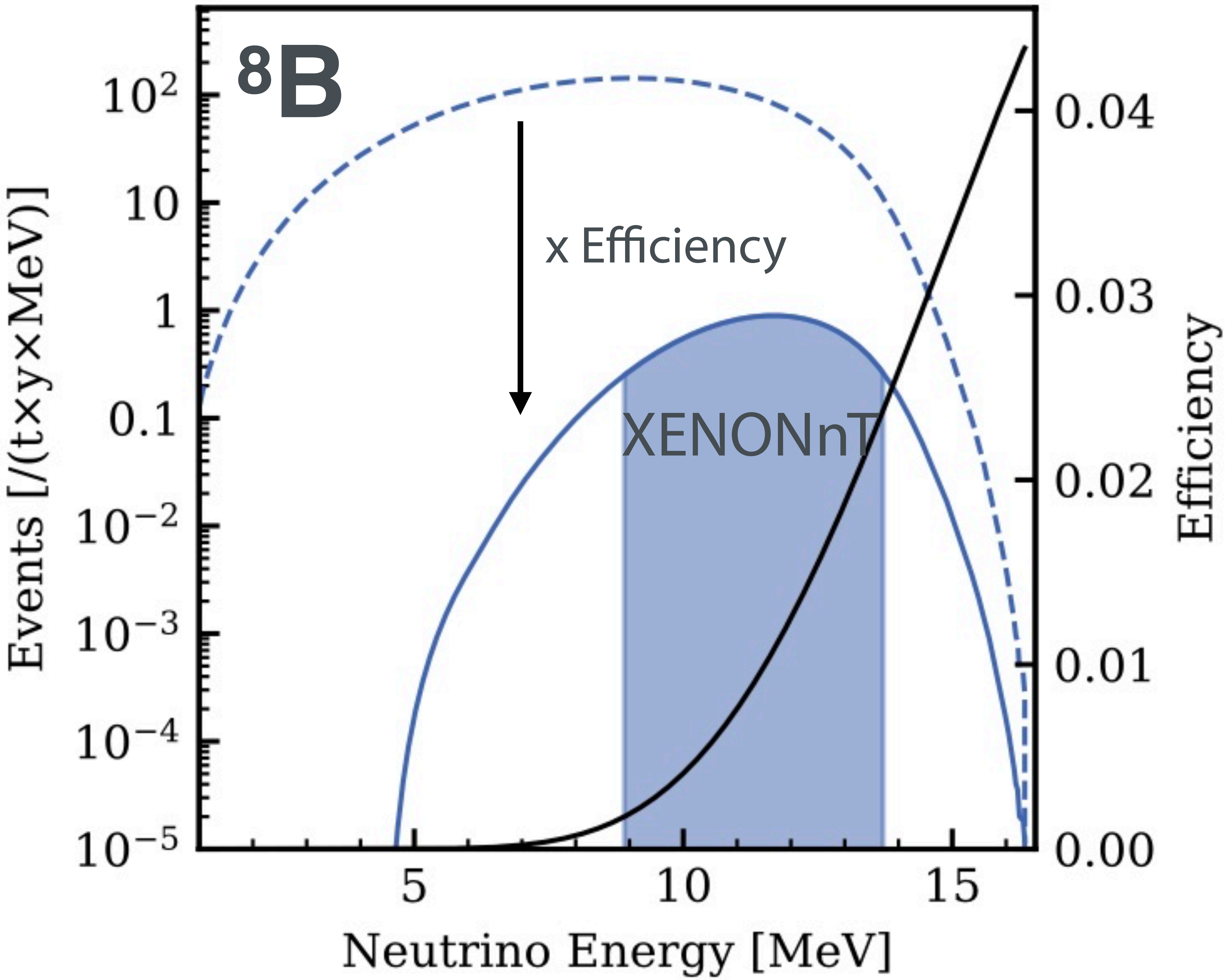
First solar ^{8}B flux measurement via CEvNS as

$(4.7^{+3.6}_{-2.3}) \times 10^6$ cm^{-2} s^{-1} cm^{-2} s^{-1} at 90% C.L.

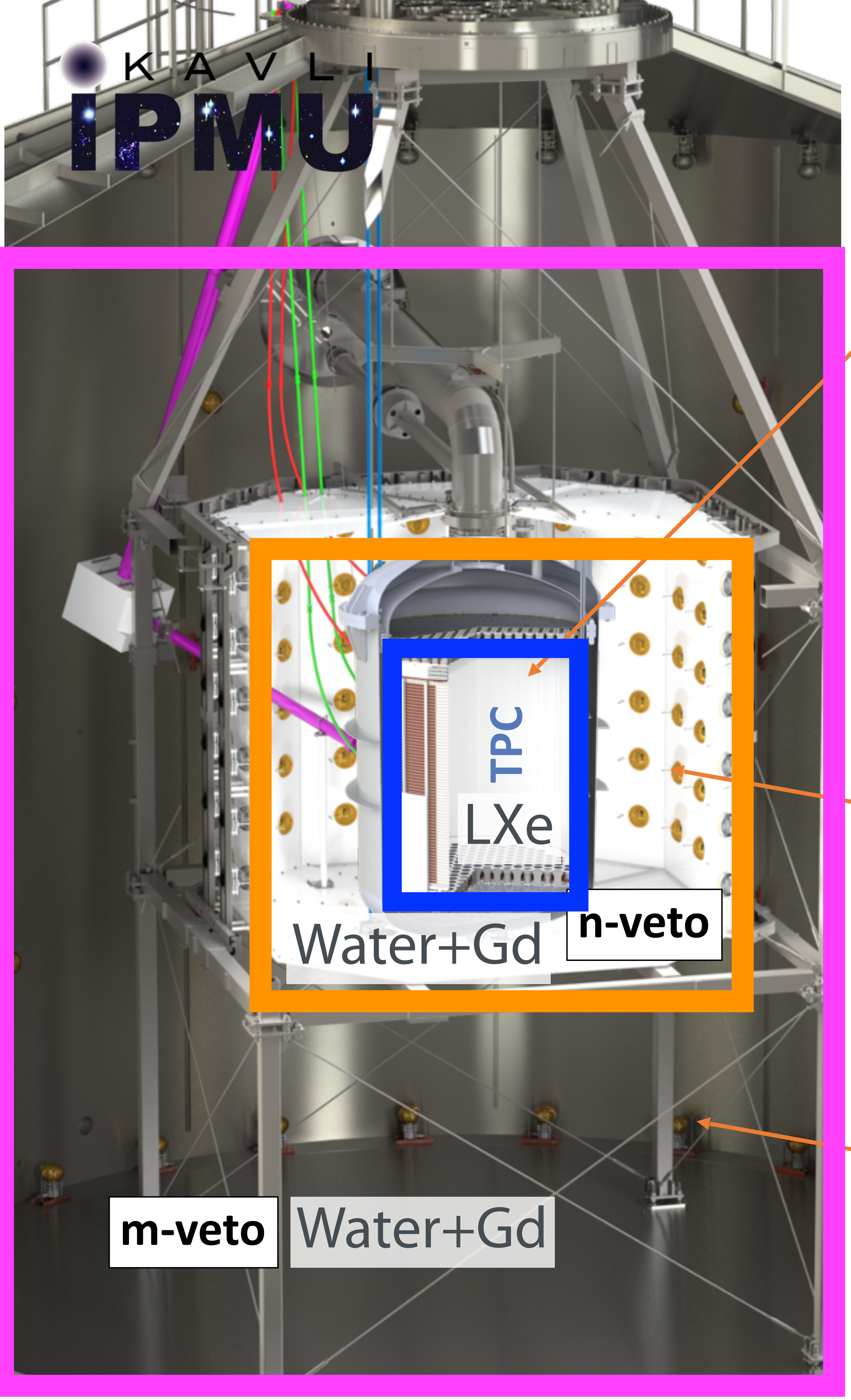


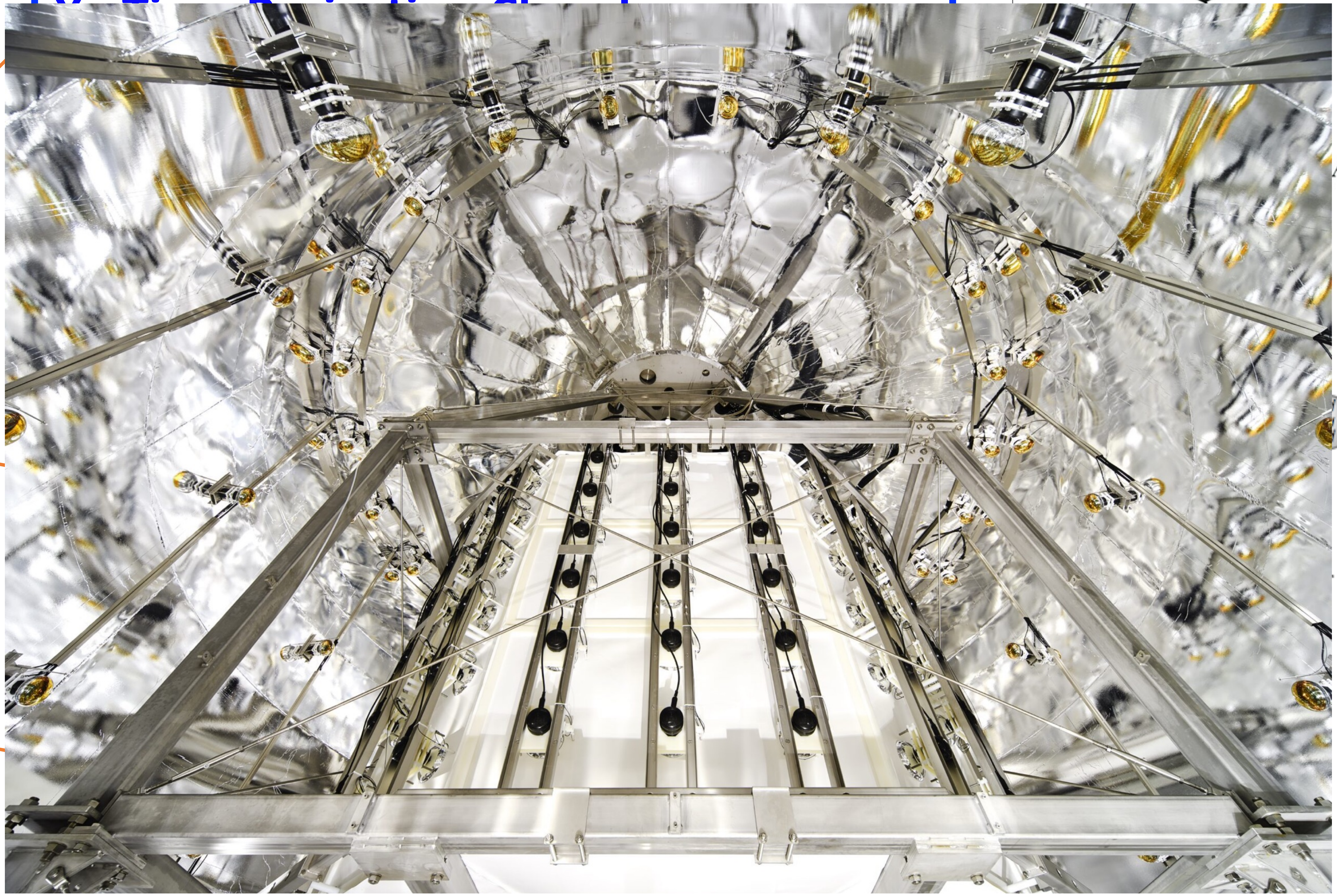
* Panda-X https://arxiv.org/abs/2407.10892 (2.64σ)

8B solar neutrino, which energy range?



XENONnT: 3 detectors



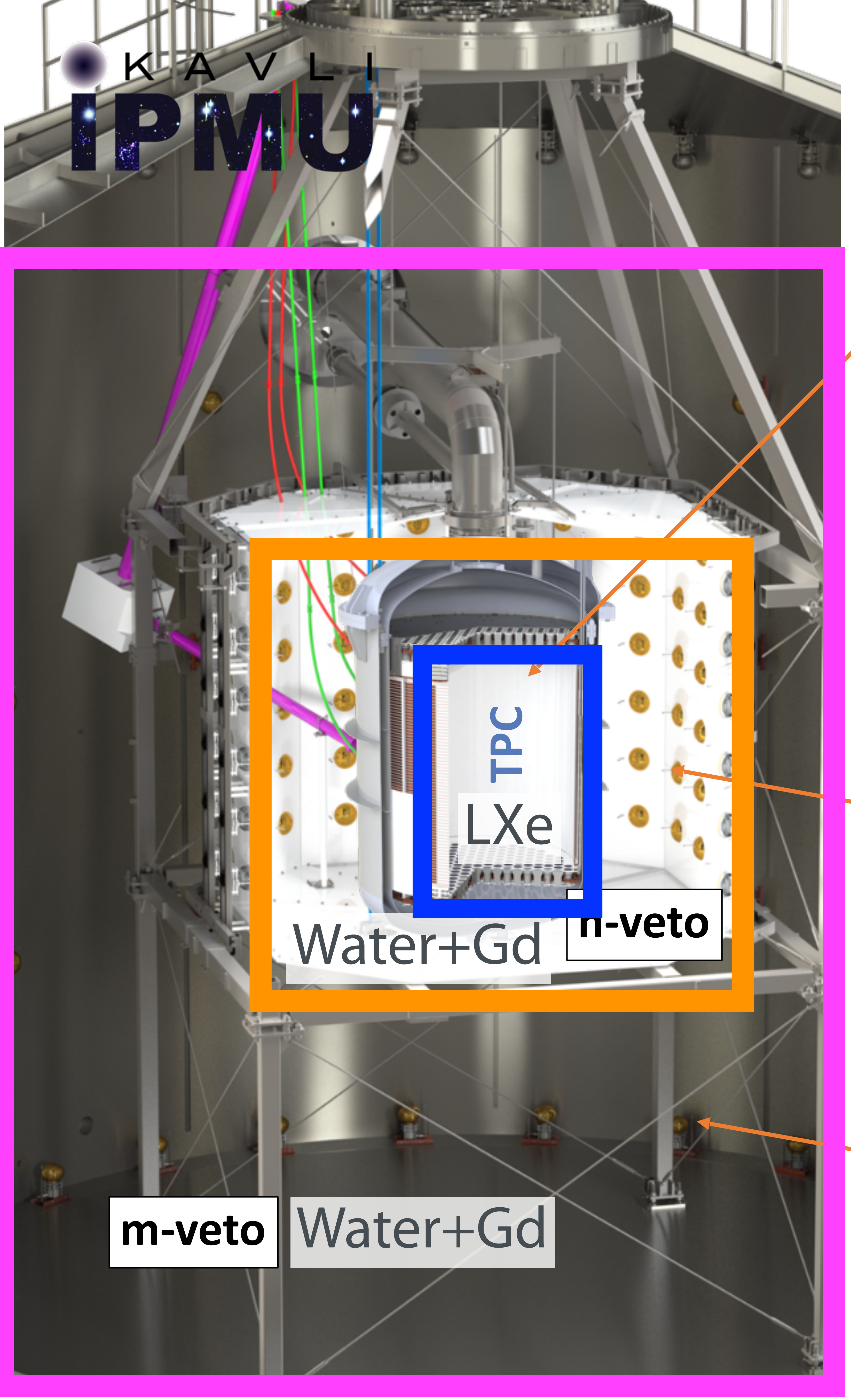


CEvNS

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

Supernova Neutrino Detection through inverse-beta decay channel

XENONnT: 3 detectors

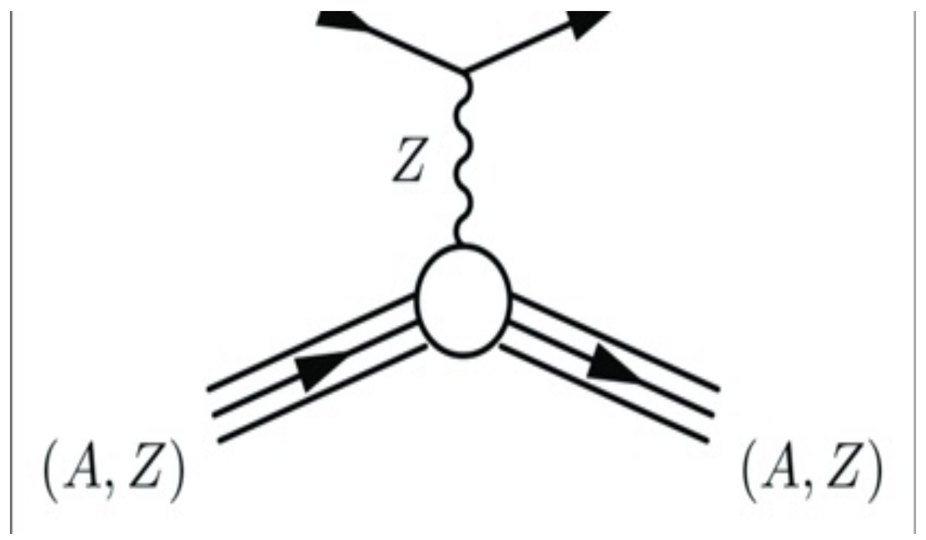


Xe Time Projection Chamber

- 5.9 t LXe target (WIMP detector)

~100events

CEvNS

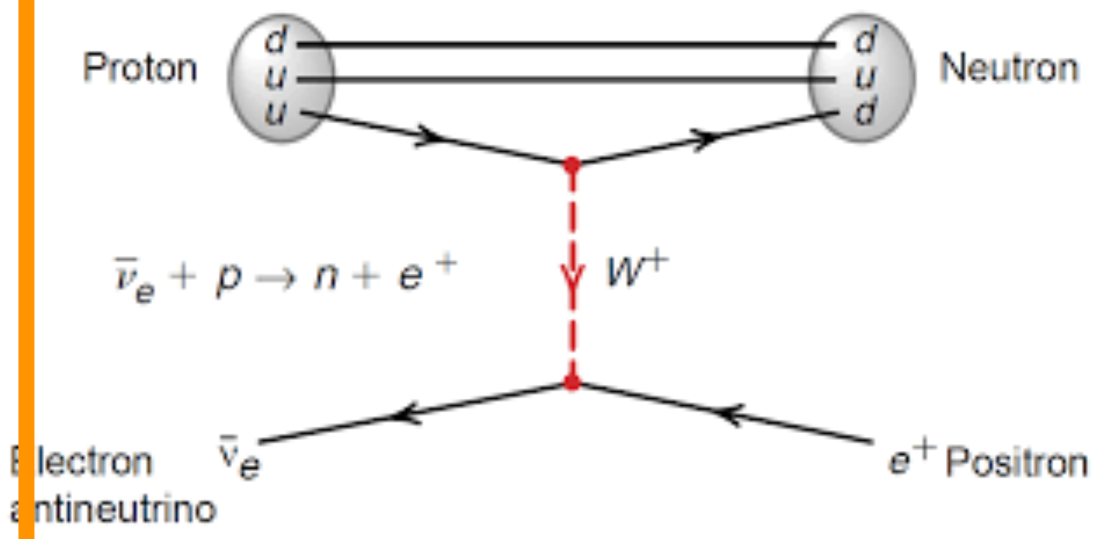


Neutron Veto System: Gd-loaded Water

- 45 t (out of 700 t water tank)
- 120 PMTs in nVETO
- Highly reflective ePTFE and ultra-pure water to maximize light-collection efficiency
- Tag neutrons through the neutron capture on hydrogen which releases a 2.22 MeV γ-ray

~10 events

IBD



Muon Veto System: Gd-loaded Water

- 655 t (out of 700 t water tank)
- 84 PMTs in μVETO

~60 events

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

Supernova Neutrino Detection through inverse-beta decay channel

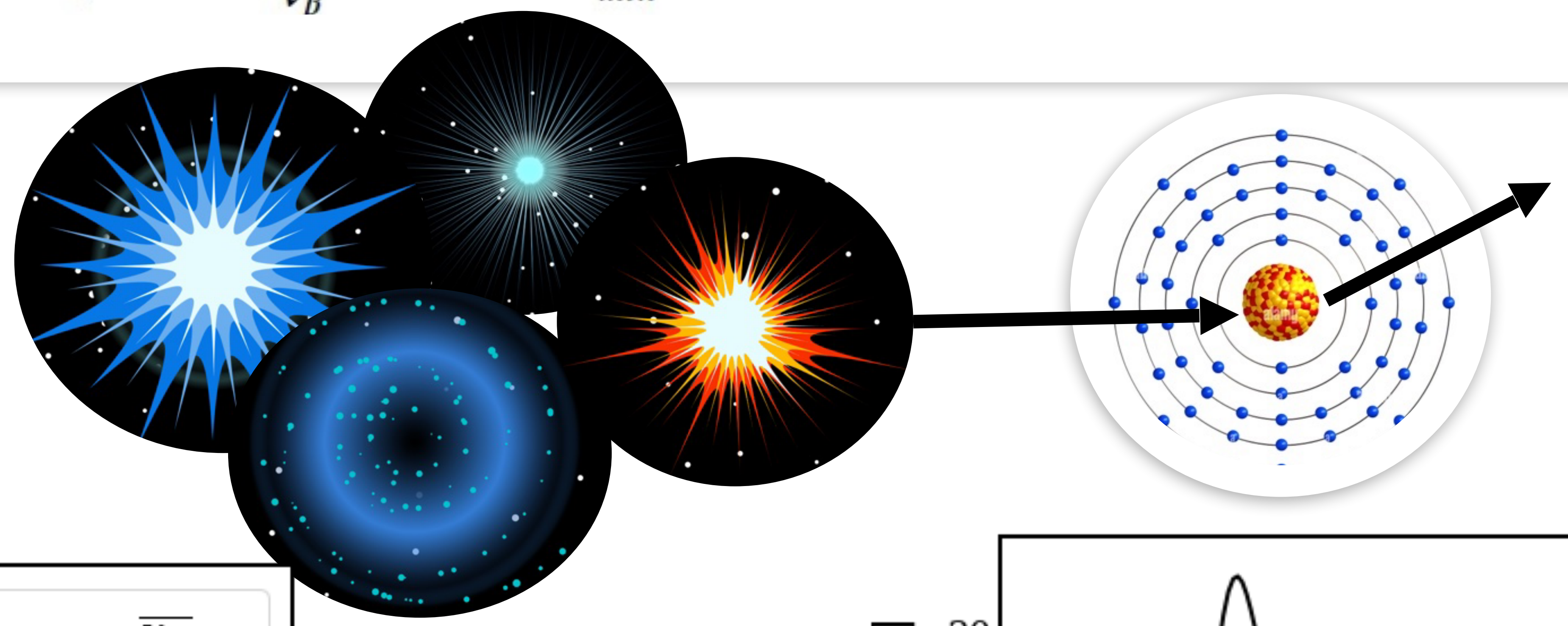
CEvNS: Coherent Elastic Neutrino-Nucleus Scattering

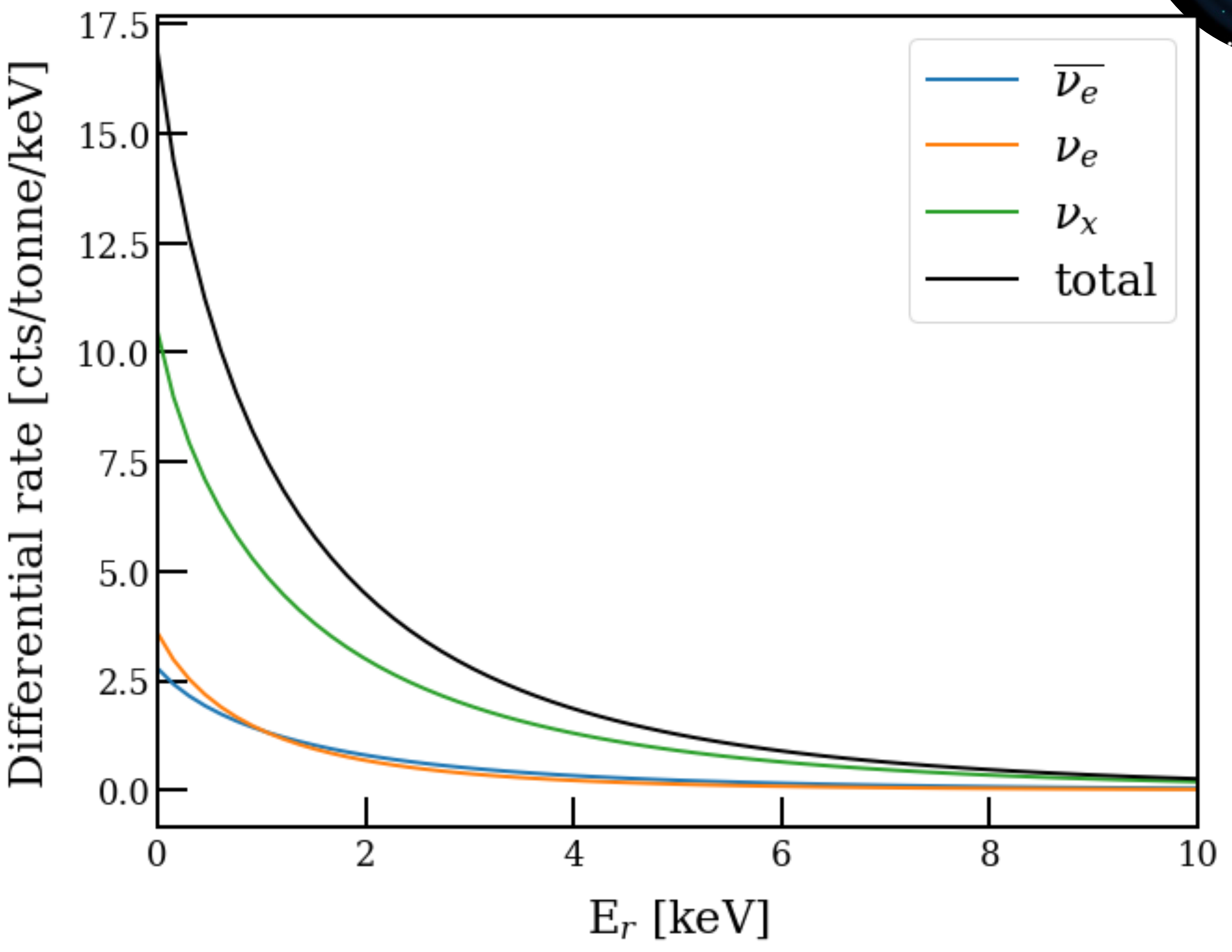
Melih Kara@SNvD

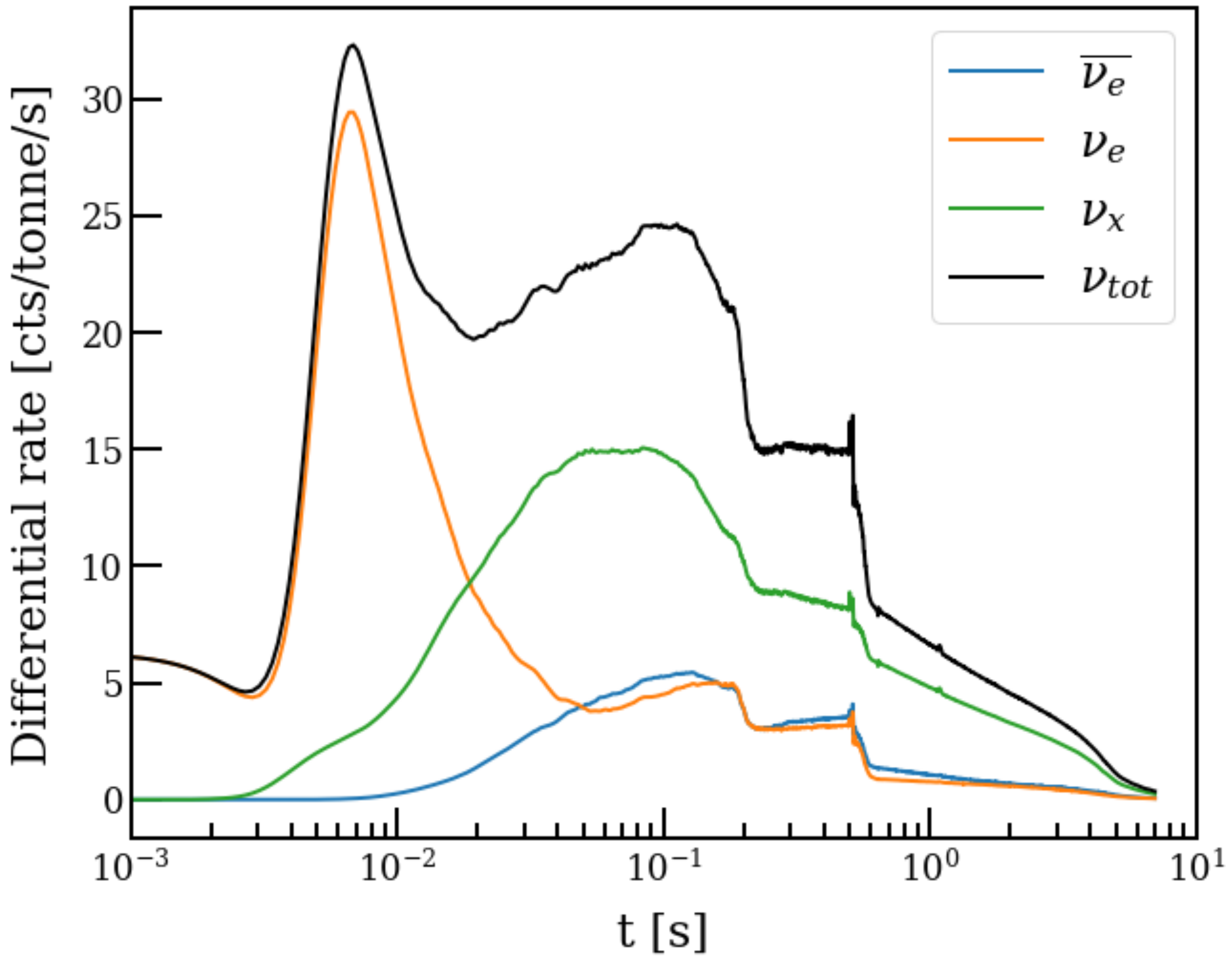
Differential CEνNS rates

$$\frac{d^2R}{dE_R dt_{pb}} = \sum_{\nu_\beta} N_{Xe} \int_{E_{min}^{\nu}} dE_\nu \, f_\nu(E_\nu, t, d) \, \frac{d\sigma}{dE_R}(E_\nu, E_r)$$

GitHub
SNAX

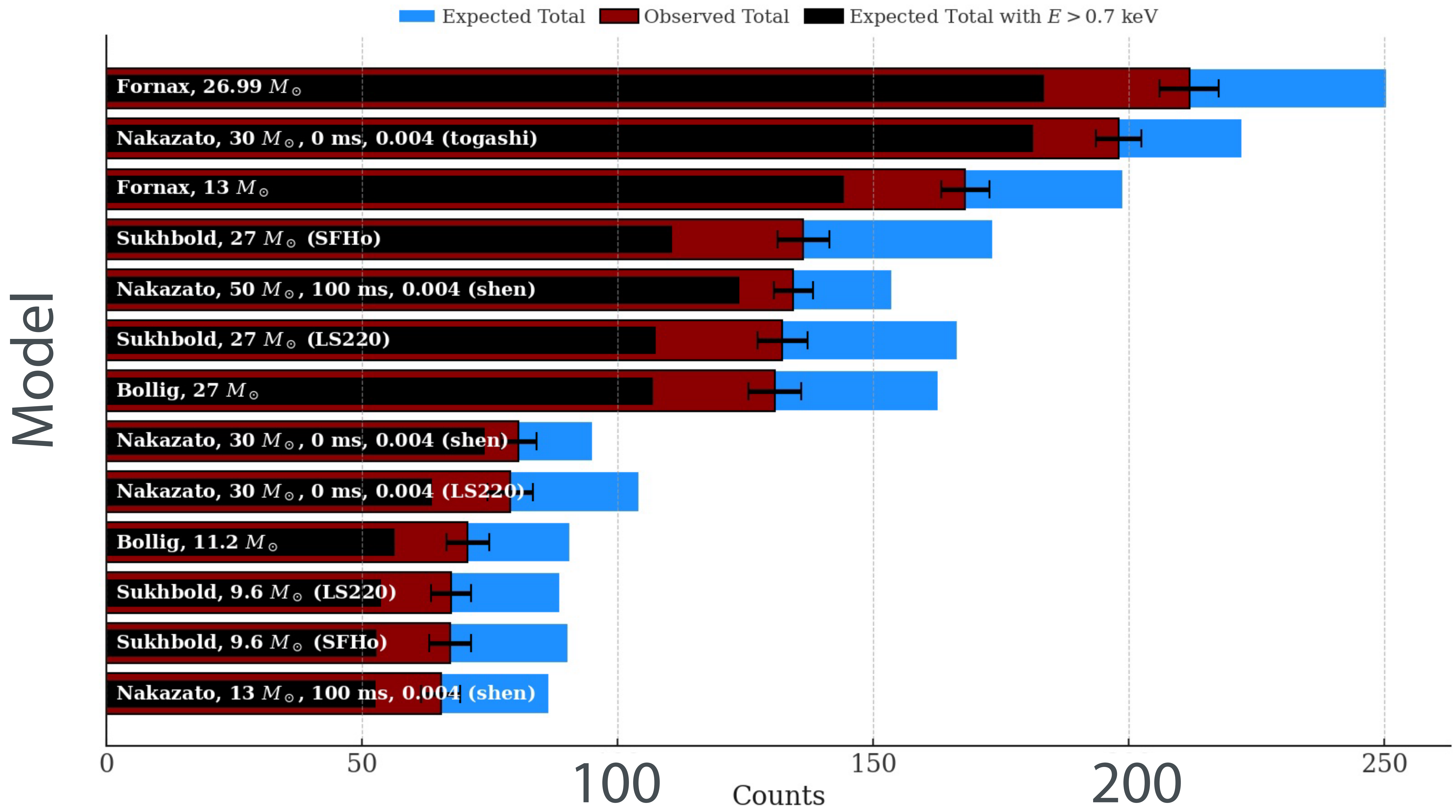




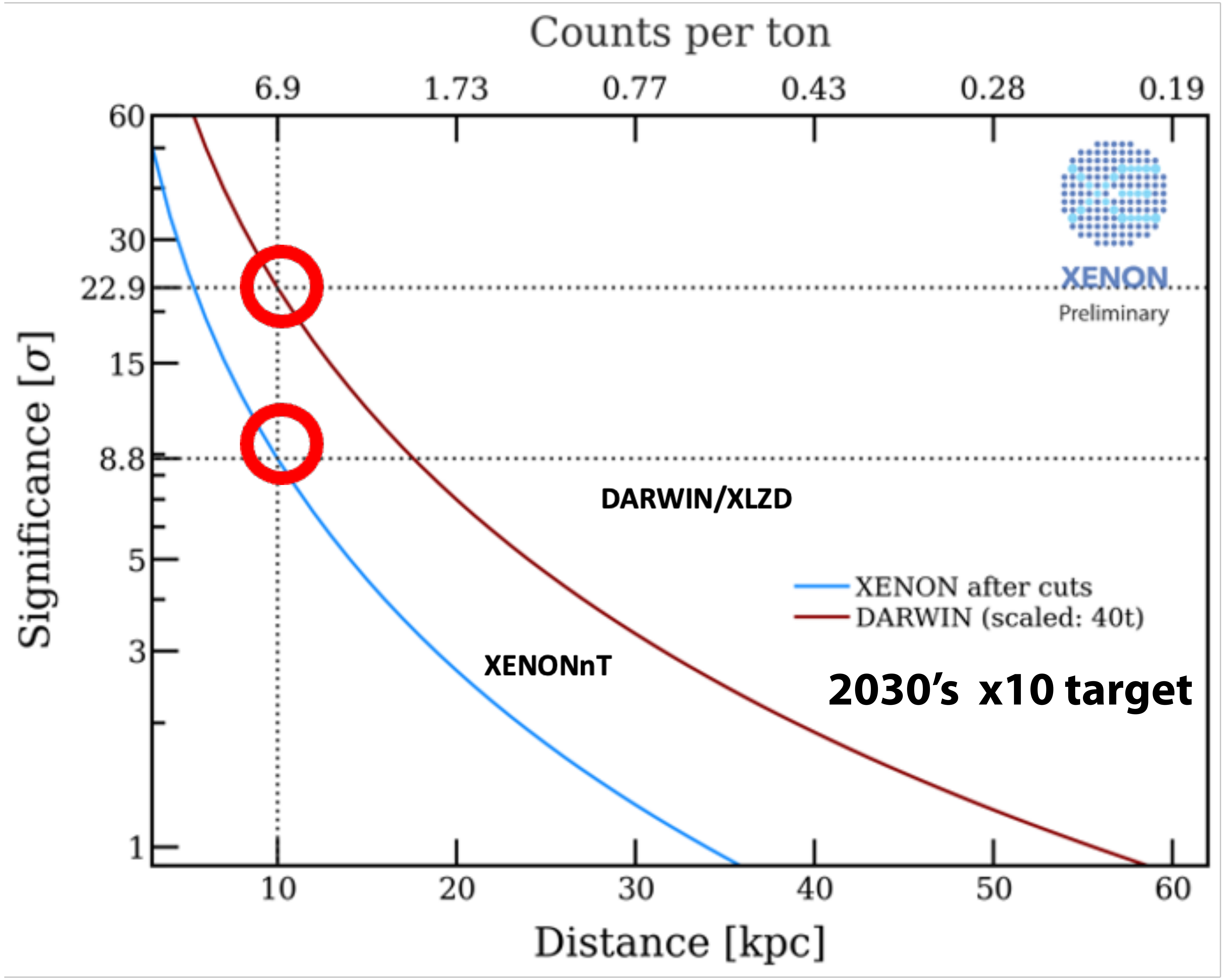


@10 kpc ~ 50-100 interactions

XENONnT LXe TPC



XENONnT and XLZD Sensitivity



snewpy: Astrophys.J. 925 (2022) 2, 107

Summary and Outlook

- Dual phase dark matter LXe detectors can detect supernova neutrinos.
- Large atomic number of xenon (A~131) dominant signal in CEvNS.
- XENONnT is ready to participate in Supernova Early Warning System.
- More than 8σ significance within 10 kpc.
- DARWIN/XLZD is the ultimate dark matter detector at least 10x larger target mass.

XENON-LZ-Darwin (XLZD)