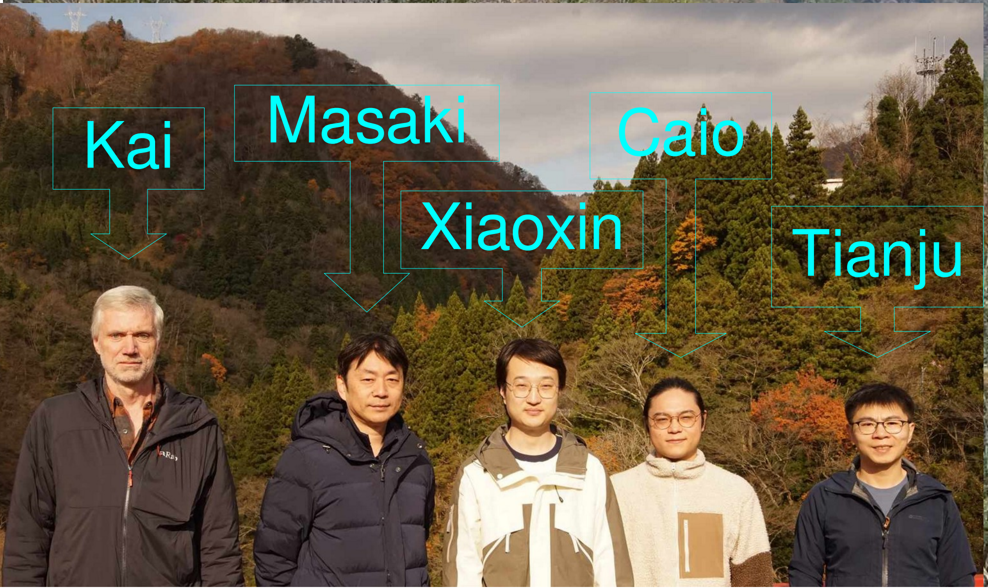
Liquid Xenon @ Kamioka

From **XMASS**, through **XENON**, towards the 3rd Generation **XLZD Detector**



Kai Martens
Kavli IPMU
The University of Tokyo

@ Festa Hitoshi!
2024.12.17

Overview:

XENON

What Dark Matter (DM)

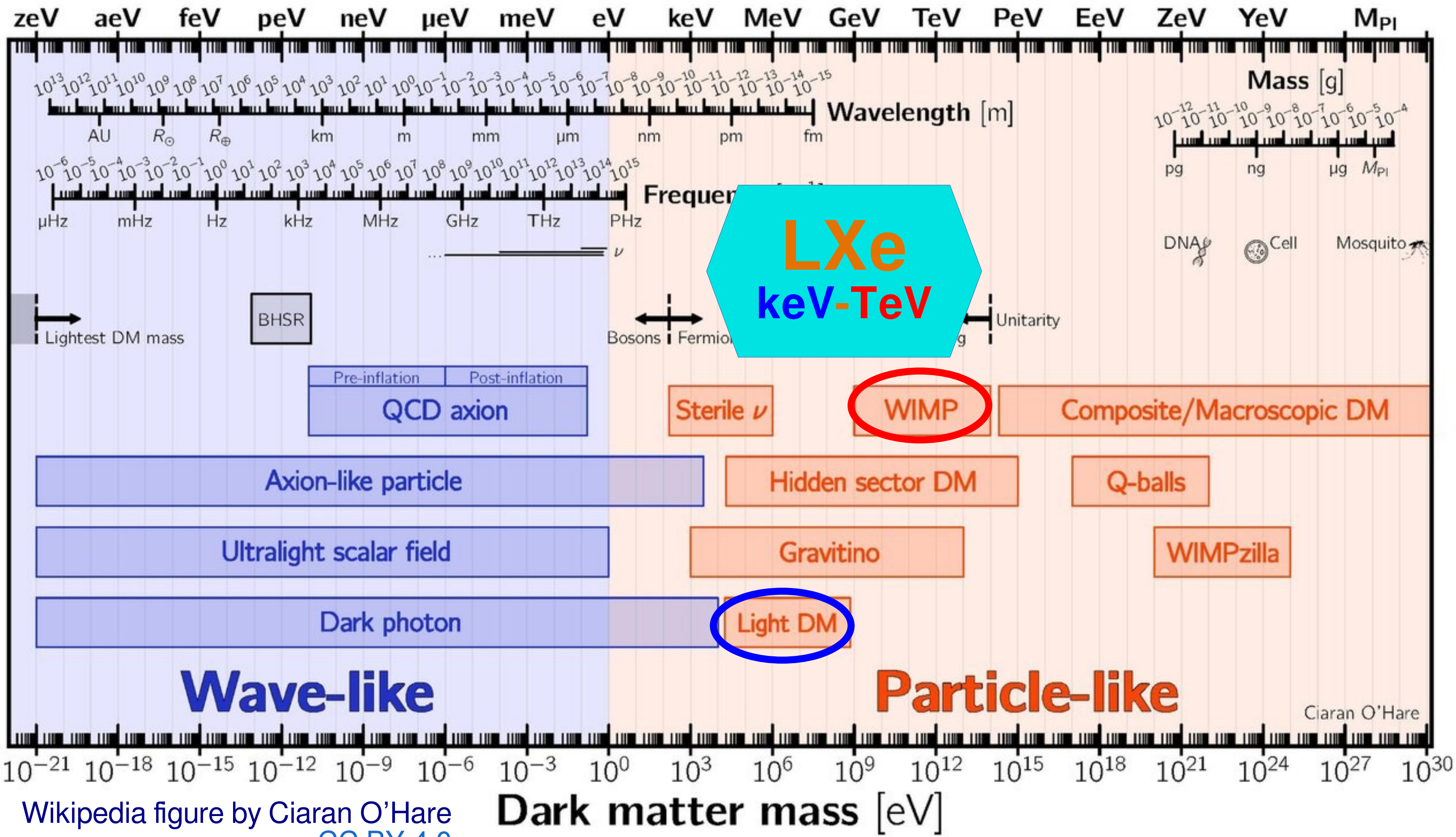
The Why and How of liquid xenon (LXe)

XMASS: **Oct. 2010 – Mar. 2019**, refurbished: Jun. 2012 - Oct. 2013
single phase: scintillation only; highest scintillation light yield

XENONnT: **Jul. 2021 – now**, targeting 20 ton-year exposure
dual-phase: measures both, scintillation & charge yield
lowest background to date

XLZD: **a.s.a.p. *after*** XENONnT (**XnT**) & LUX-ZEPLIN (**LZ**)
"3rd generation" dual-phase LXe: dark matter and CEνNS

What Dark Matter???



Wikipedia figure by Ciaran O'Hare

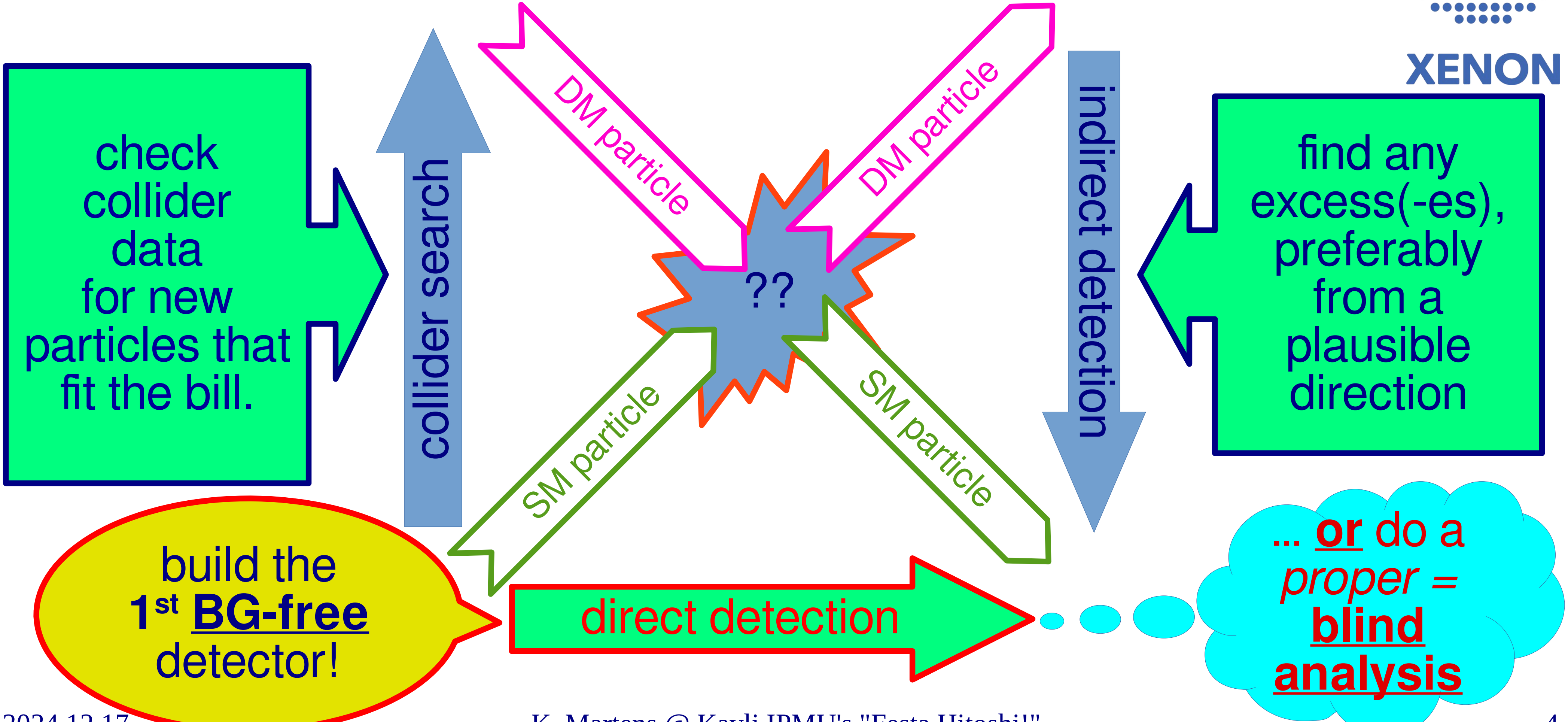
XENON

***That** DM*:
particle
masses
from
a few keV
to
a few hundred TeV

also:
astrophysical
neutrinos !!!

Dark Matter ***particle*** hunting:

XENON



Why LXe?

... many GOOD reasons:

low work function (11.5 eV) → high yield
high density → self-shielding
isotopic composition → spin-dependent analyses
→ nuclear physics
high mass number → high cross section
← spallation bad...
→ go underground !!!

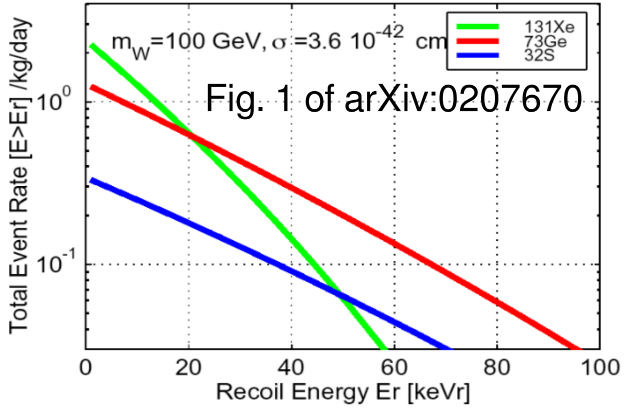


Fig. 1 of arXiv:0207670

liquid state allows to:

use cryogenic distillation → high radio-purity
use getters → high e-lifetime:
build **TPC**s: → mm postion resolution !!!
(Time Projection Chamber)

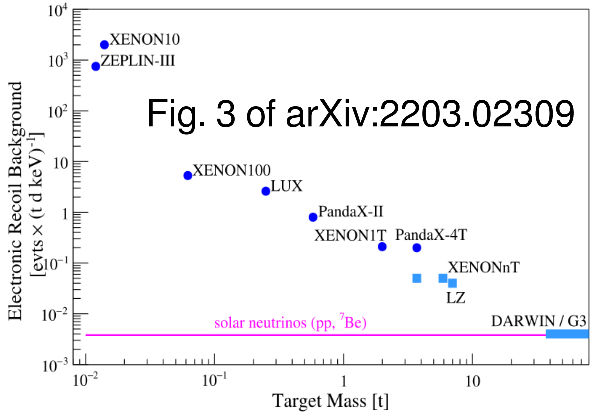


Fig. 3 of arXiv:2203.02309

How to LXe?

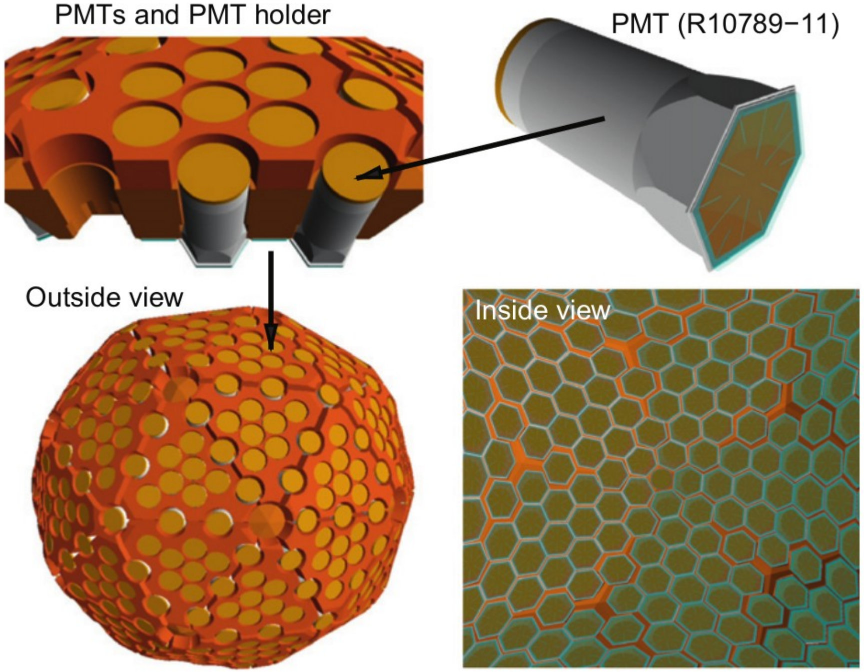
XENON

Single Phase

S1 only → **XMASS**:

maximized photocathode coverage !!!

Figure from NIM A 716 (2013) 78–85



inner diameter ≳ 80 cm: 835 kg LXe

Dual Phase

Time Projection Chamber (TPC):

***S2/S1** ER rejection !!!*

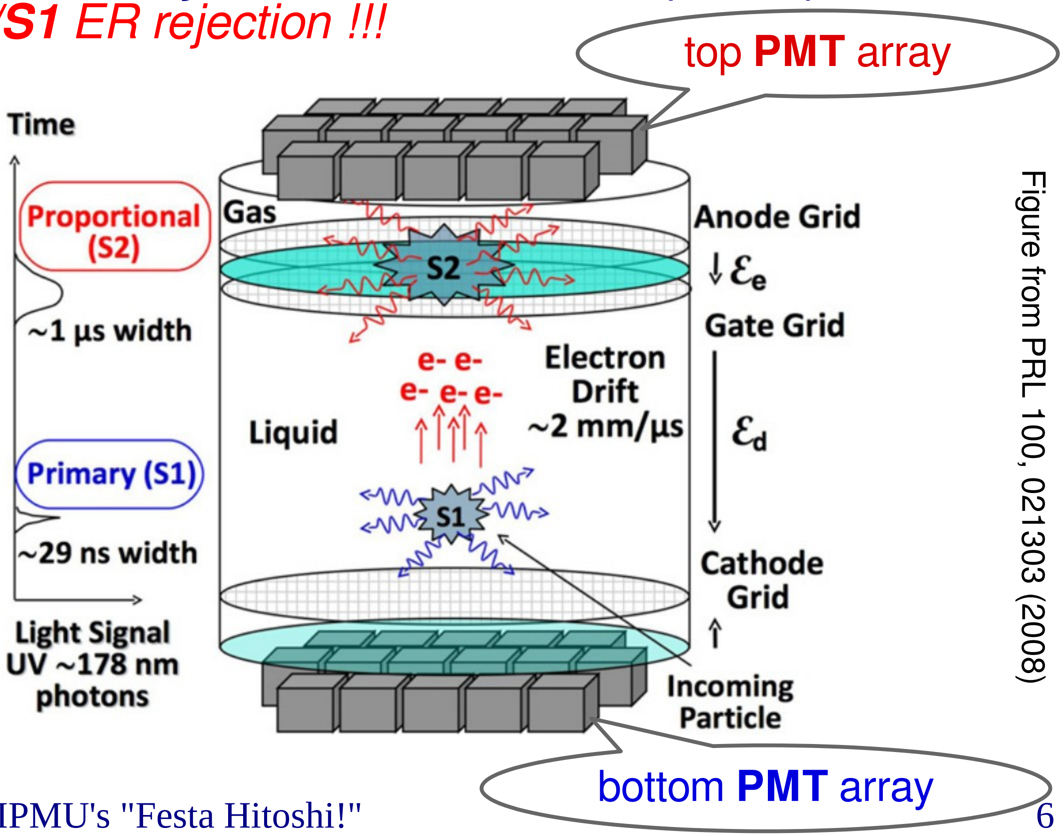


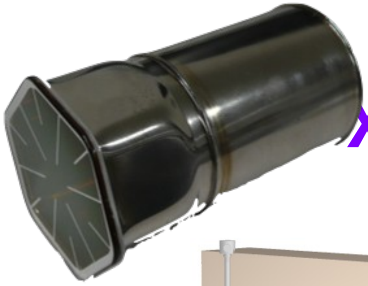
Figure from PRL 100, 021303 (2008)

The XMASS detector at Kamioka

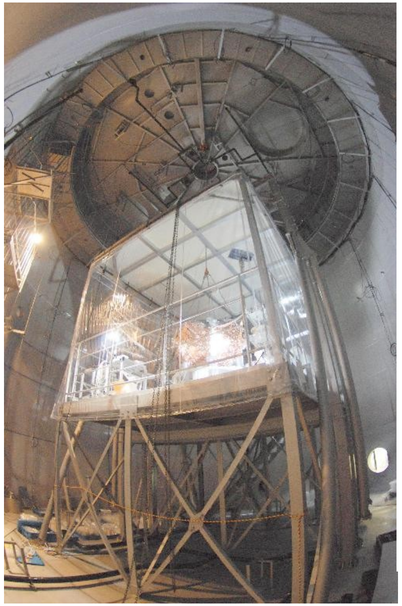
XMASS **proposed** 2000
Kr distillation established 2004
detector **assembly**: 2009+10
commissioning: 2010.12-2012.05
data taking: 2013.11-2019.03

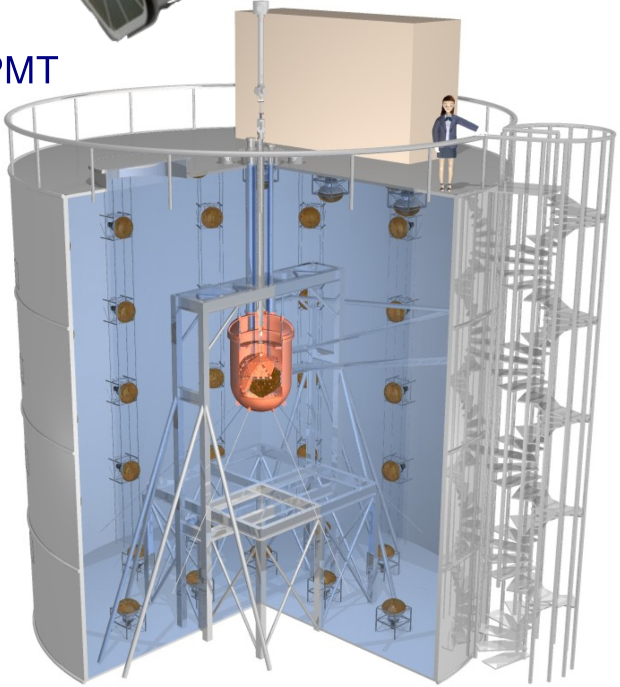
XMASS PMT:
Hamamatsu R10789
QE@175nm = 28-39%

U	< 1 mBq/PMT
Th	< 0.94 mBq/PMT
K	< 9.68 mBq/PMT
Co	= 4.47±0.34 mBq/PMT



XMASS





1st LXe detector with water Cherenkov shield

XMASS-I: 832 kg full, 97 fiducial
(r < 20 cm)

XMASS

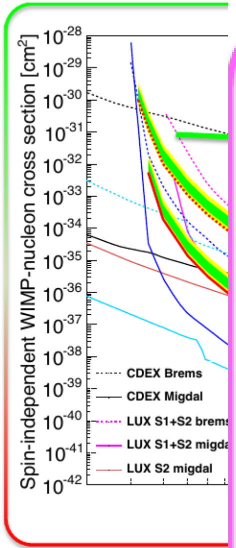
Technical advances:
- Kr distillation demonstrated; 2004: ~1 Bq/kg → < 10 μBq/kg
- 1st water Cherenkov muon veto
- developed lowest BG PMTs w/Hamamatsu

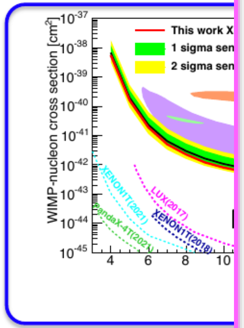
Commissioning phase early results (12.2010 - 05.2012):
- light WIMPs, WIMP-^{129}Xe inelastic
- Solar axions, ^{124}Xe ECEC

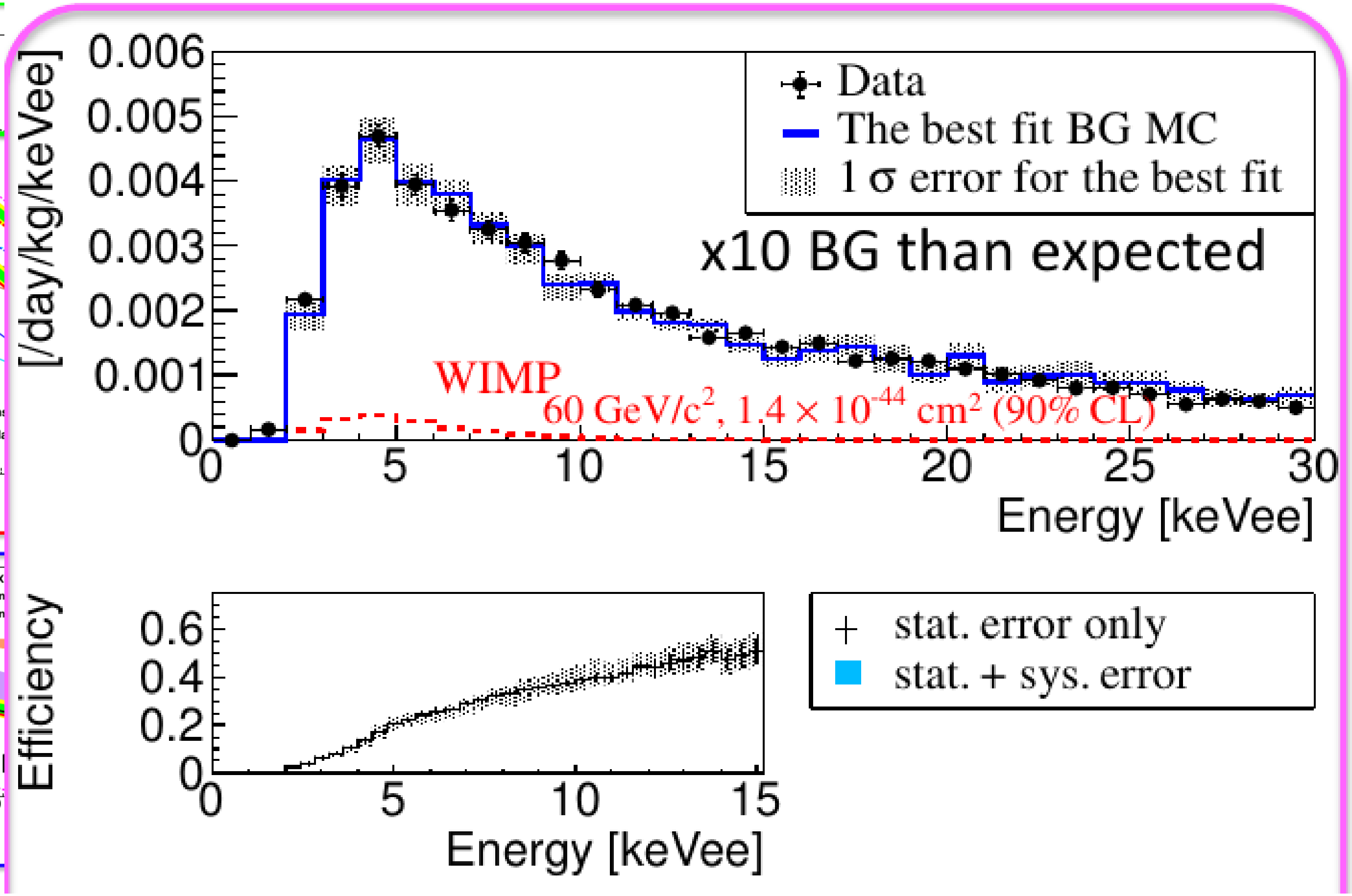
Data taking phase main results (11.2013 - 03.2019):
- annual modulation (also: sub-GeV), WIMPs in fid. vol., WIMP-^{129}Xe inelastic
- Solar axions, ^{124}Xe ECEC, HP/ALPs, exotic ν_{sol} int., ^{136}Xe $0\nu\beta\beta$
- GW associated events

find all XMASS papers at:
https://www-sk.icrr.u-tokyo.ac.jp/xmass/dispatches/publications/index-e.html

Slide by Moriyama (2024.03.05):







XMASS

XMASS-I

pioneered many LXe analyses,

but:

an unexpected beta-emitter contamination produced

BG 10x larger than expected

ultimately limited its reach...

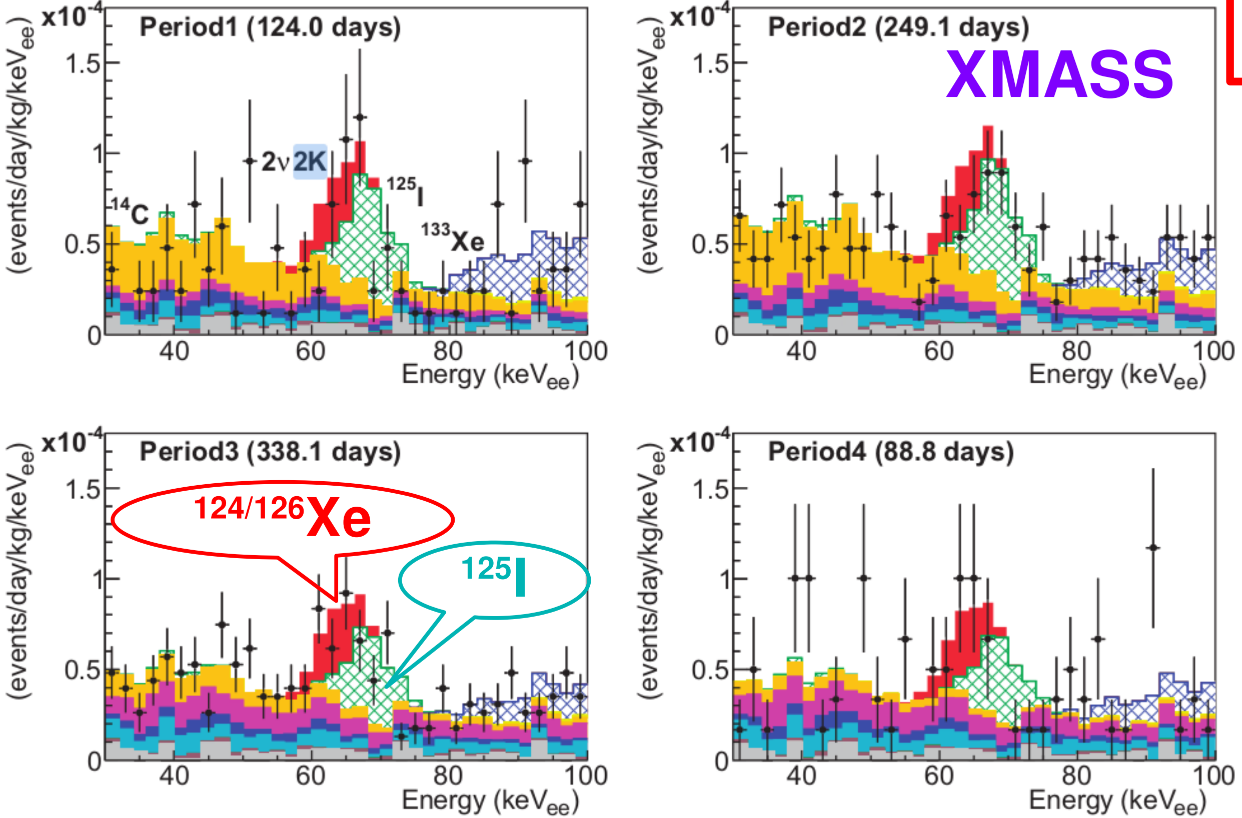
^{124}Xe, ^{126}Xe: 2νECEC; ^{136}Xe: 0νββ

simultaneous capture of 2 K-shell electrons: 2ν2K:
w/β-rejection → ^{124}Xe > 2.1e22 y, ^{126}Xe > 1.9e22 y

natural abundance (Wikipedia):

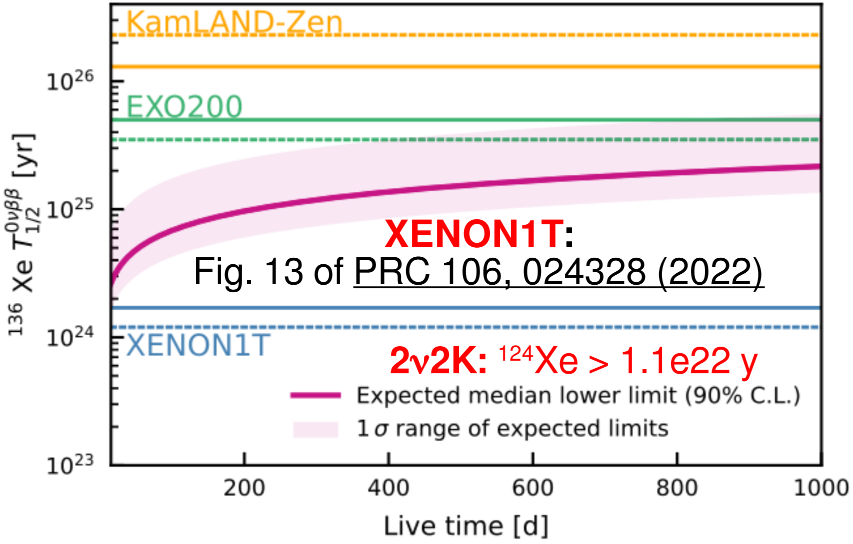
Xe	
	136= 8.9%
	124= 0.9%
	126= 0.9%

XENON
XMASS



XMASS:
Fig. 7 of PTEP 053D03 (2018)

XENON1T ^{136}Xe limit:
w/XENONnT expection
(currently in preparation...)



The XENON Collaboration

191 physicists

THE UNIVERSITY OF CHICAGO — Chicago
COLUMBIA UNIVERSITY — New York City
PURDUE UNIVERSITY — Lafayette

EUROPE

Zurich
KIT Karlsruhe Institute of Technology — Karlsruhe
WWU MÜNSTER — Münster
UNI FREIBURG — Freiburg
JG|U — Mainz
Heidelberg
Nikhef — Amsterdam
Stockholm University — Stockholm
UNIVERSIDADE D COIMBRA — Coimbra
Subatech — Nantes
LPNHE PARIS — Paris
INFN TORINO — Torino
Bologna
UNIVERSITÀ DEGLI STUDI DELL'AQUILA — L'Aquila
INFN LNGS — Assergi
Napoli

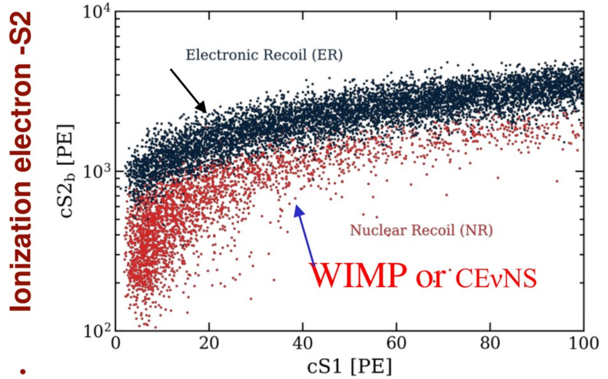
MIDDLE EAST

WEIZMANN INSTITUTE OF SCIENCE — Rehovot
NYU ABU DHABI — Abu Dhabi

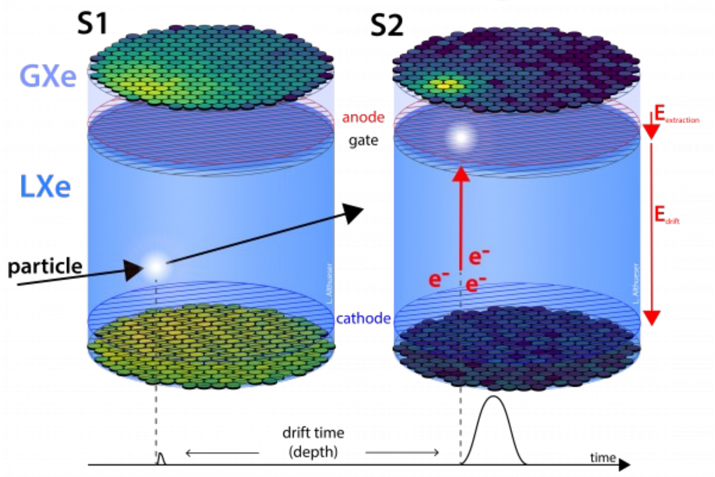
東京大学 — Tokyo
NAGOYA UNIVERSITY — Nagoya
KOBE UNIVERSITY — Kobe

XENONnT (XnT) Genealogy

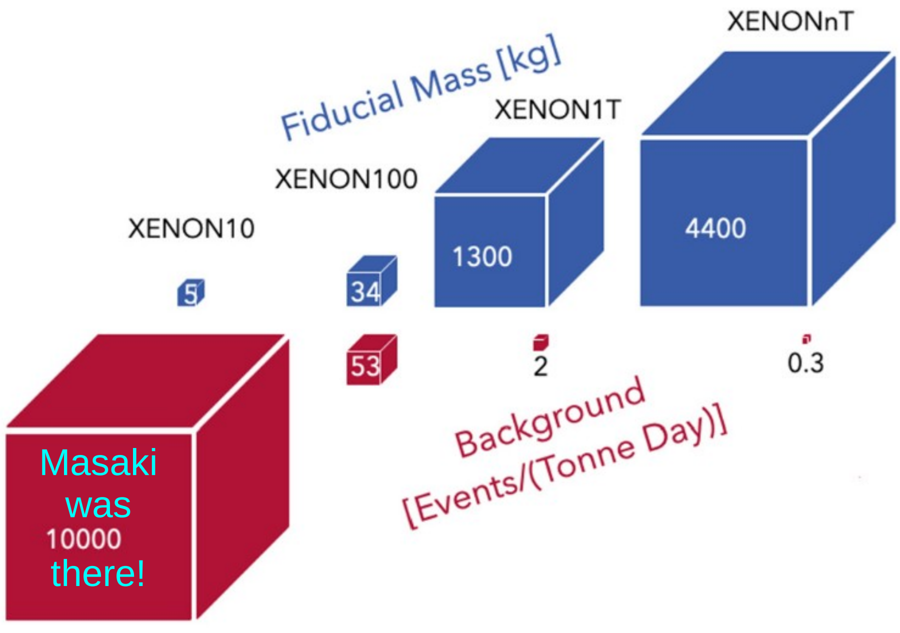
Solar ν (e-scatter) and Background



- Scintillation light - S1



A brief history of **XENON** direct detection Dark Matter detectors:



from: Nucl. Phys. B 1003 (2024) 116463

Now:
XENONnT:
4,370 kg
fiducial
(SR0, ER)
8.5 tonnes
total
background =
battleground:
0.04 / t×d×keV
(ER)

XENONnT: Upgrade of XENON1T

Enlarged dual phase TPC
→ ~4 ton fiducial volume

← to exploit and support this new size, XENONnT needed to:

2 frontiers:
1. SG extraction
2. BG reduction

XENON

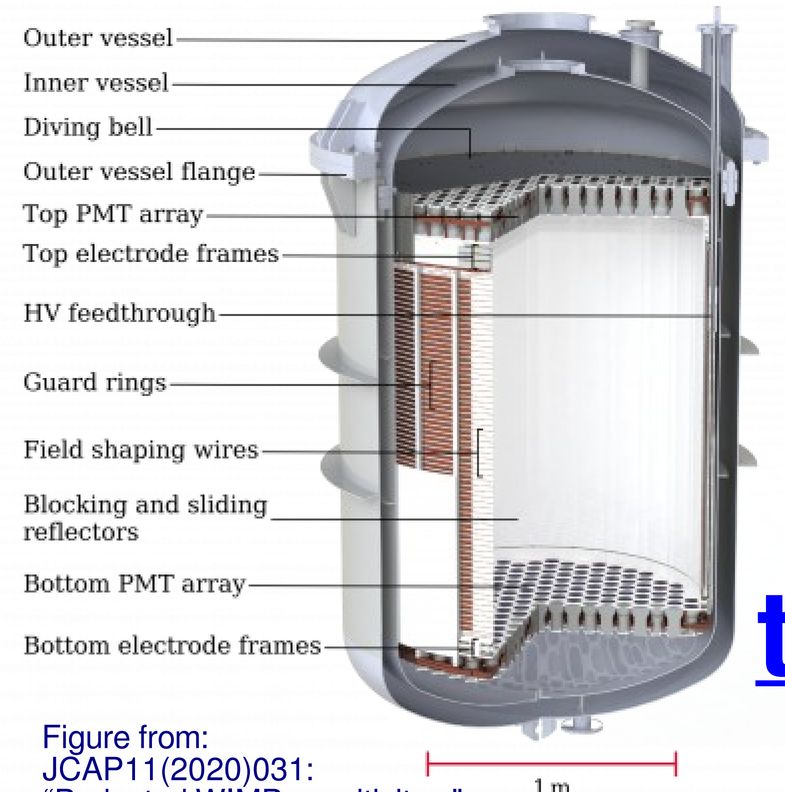
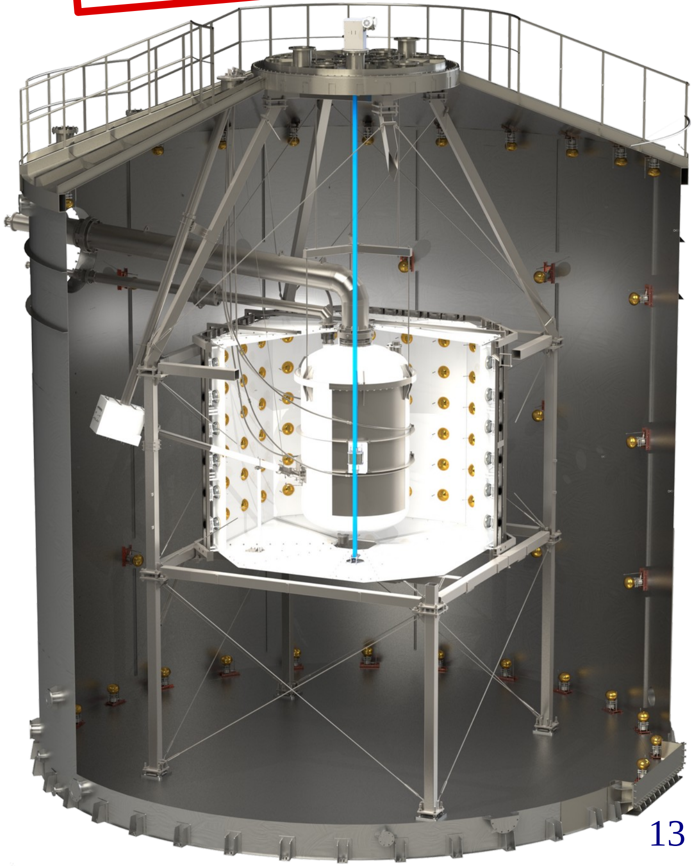


Figure from:
JCAP11(2020)031:
“Projected WIMP sensitivity...”

- suppress electronegative contaminations in LXe:
  → **liquid purification**
- suppress ^{222}Rn (ER BG):
  → **Rn distillation**
- tag radiogenic neutrons
  → **neutron veto**
- LXe emergency storage
  → **new storage**

taking data:
ScienceRun2

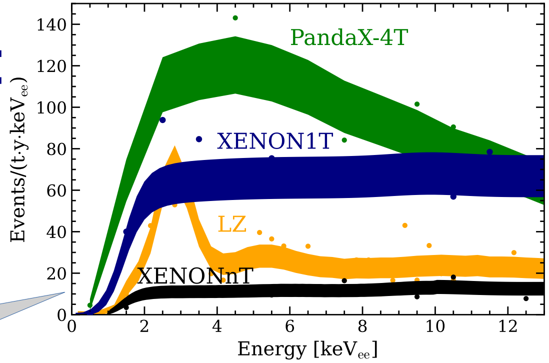


XENONnT: Lowest BG LXe TPC!

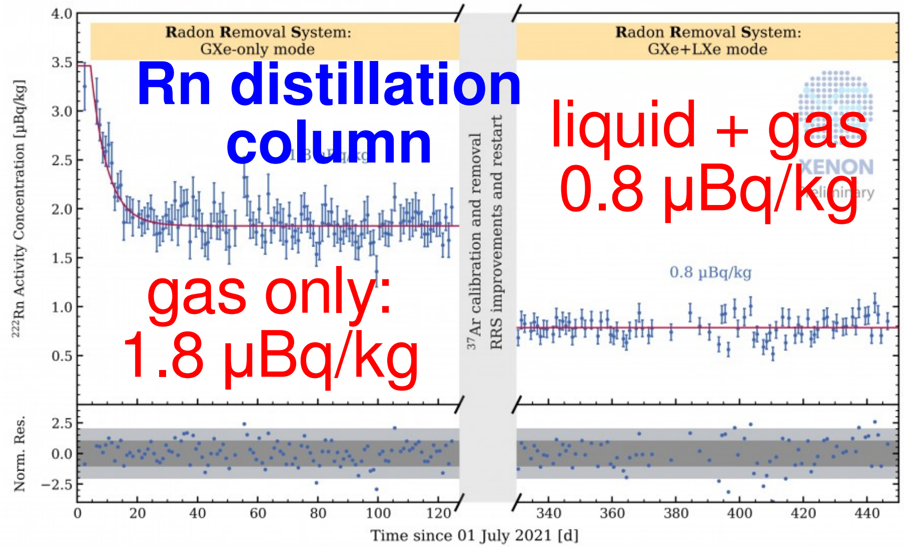
XENON

TPC performance critical upgrade components:

- liquid purification → electron lifetime
- Rn distillation → ^{214}Pb beta BG



results & bragging rights

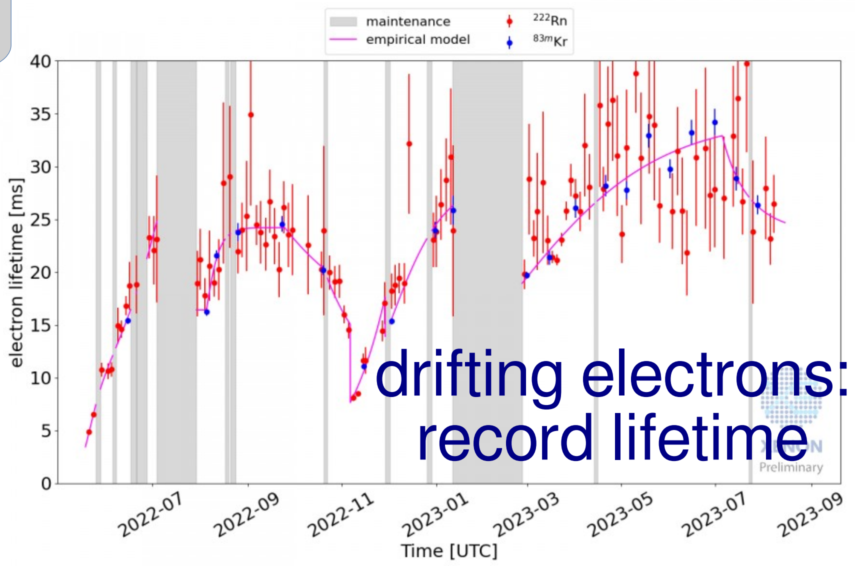


Rn distillation column

gas only: 1.8 µBq/kg

liquid + gas 0.8 µBq/kg

IPMU's Masaki: critical contrib.



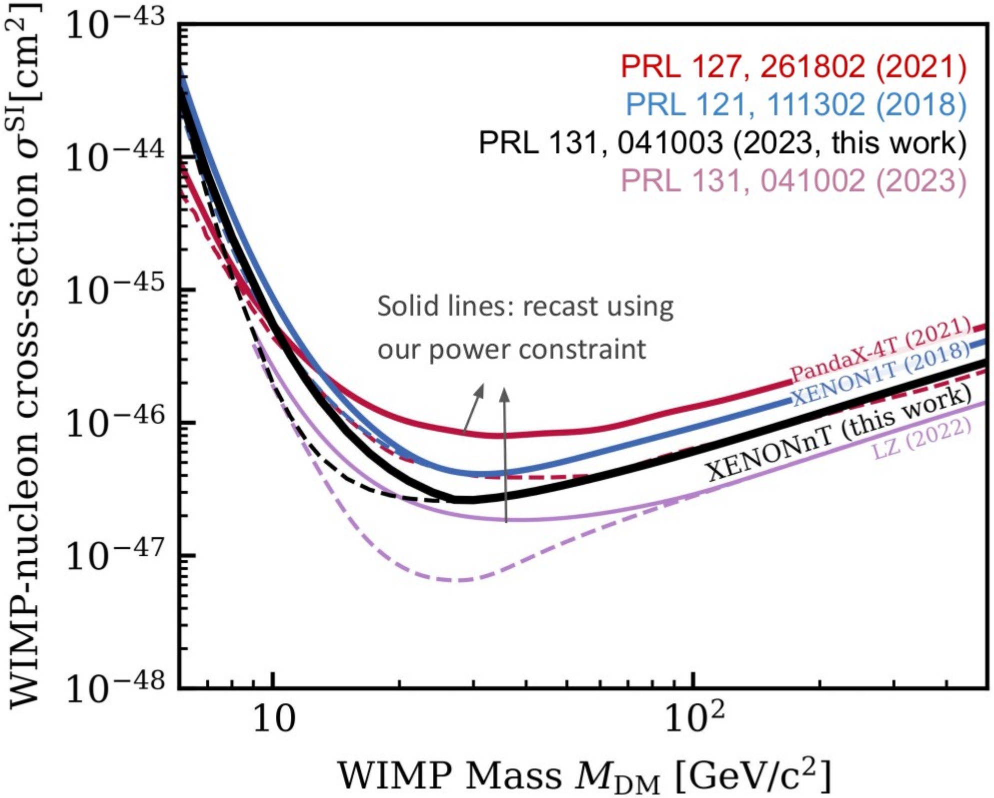
drifting electrons: record lifetime

WIMP nuclear recoil search: SR0

(...currently taking SR2 data)

some comments:

- blind analyses take time...
- both, PandaX-4T & LZ "profited" from statistical under-fluctuations
- PandaX is preparing for a 20 tonne detector
- XENONnT data analyses are proceeding... → *stay tuned*



XENON

key ingredient: proper statistical **inference**: ours is the only **blind analysis**

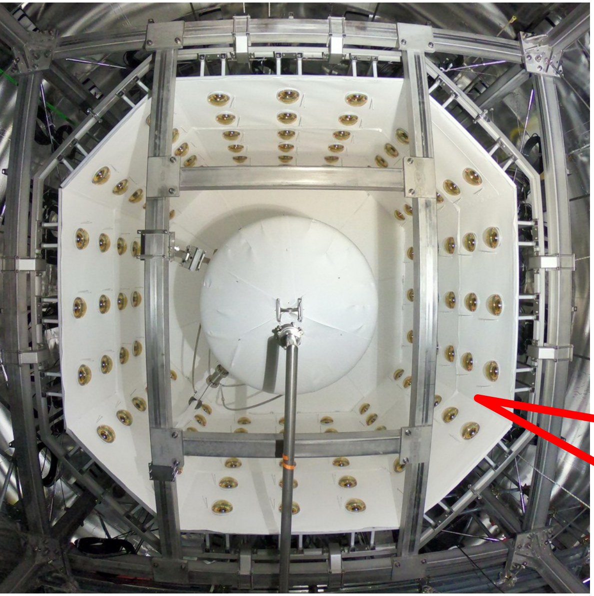
The XnT neutron veto

(NV, **now running with 10% of design Gd-sulfate loading** !!!)

XENON

design success:
world leading ***PURE* water** Cherenkov
neutron tagging efficiency: **(53±3)%**
arXiv 2412.05264 (submitted to EPJC)

EGADS nanofiltration
& SK resin technology:



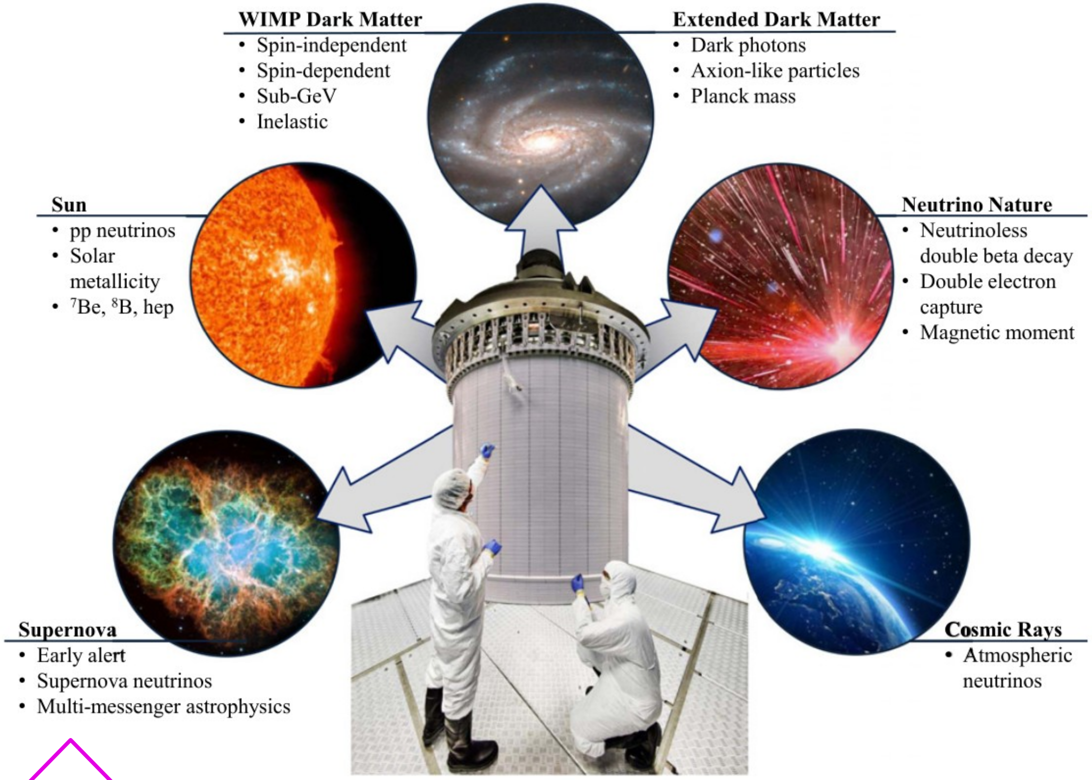
hopper
for salt insertion

2 t mixing tank
with stirrer

unlike Super-K:
few PMTs,
high reflectivity

water shield

XLZD: Towards Discovery (...ies ???):



dual-phase LXe TPCs: XENON

a *proven technology*:
→ the way forward

rare event **discovery** needs:
– confirmation (experiments!)

rare event **interpretation** needs:
– complementarity (targets !!)

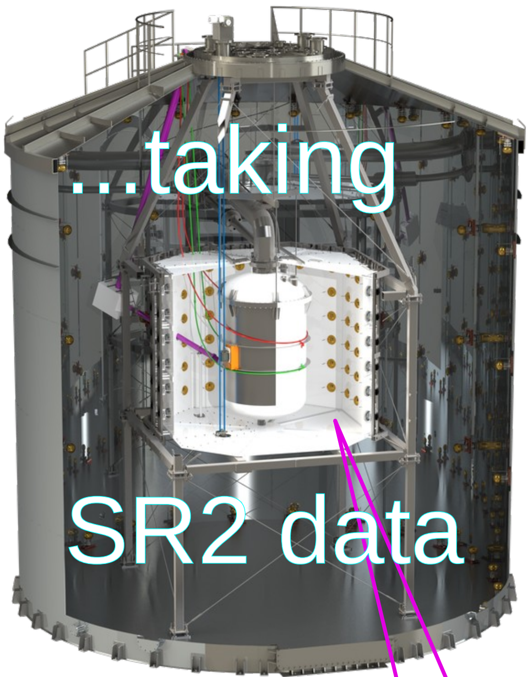
experiments need:
– experienced LXe-scientists !!!

SCJ: *medium size* ! (Ooguri, Masaki)

Fig 2

see our **Whitepaper**:
A next-generation liquid xenon observatory for dark matter and neutrino physics
J Aalbers et al 2023 J. Phys. G: Nucl. Part. Phys. 50 013001 (arXiv: 2203.02309)

Summary:



XENONnT Results:

First Indication of Solar ^{8}B Neutrinos via CEvNS with XENONnT, PRL 133, 191002 (2024)
First Dark Matter Search with Nuclear Recoils from the XENONnT Experiment, PRL 131, 041003 (2023)
Double-weak decays of ^{124}Xe and ^{136}Xe in the XENON1T and XENONnT Experiments, PRC 106, 024328

XENONnT Documentation:

Low-energy calibration of XENON1T with an internal ^{37}Ar source, Eur. Phys. J. C 83 (2023) 542
Design and performance of the field cage for the XENONnT experiment, Eur. Phys. J. C 84 (2024) 138
The triggerless data acquisition system of the XENONnT experiment, JINST 18 (2023)P07054
Detector signal characterization with a Bayesian network in XENONnT, PRD 108, 012016 (2023)
Cosmogenic background simulations for neutrinoless double beta decay with the DARWIN observatory at various underground sites, Eur. Phys. J. C 84 (2024) 88

Kavli IPMU Outreach:

"mono-shiri-shinbun": [物理学]ダークマターを地下で待ち伏せ（Kai Martens、山下雅樹）

XENONnT neutron veto now Gd loaded
to 10% of target concentration; full concentration pending decision about inner detector access;
1st **adaptation** of Super-Kamiokande's EGADS technology **to dark matter direct detection** needs!

DARWIN/XLZD:

Proposal **accepted** by SCJ for
Future Academic Initiative (未来の学術構想)
contact person: Masaki Yamashita (KIPMU)

Yamashita also DARWIN Working Group Leader: **Photosensors**