Direct Detection of Dark Matter and XENONnT

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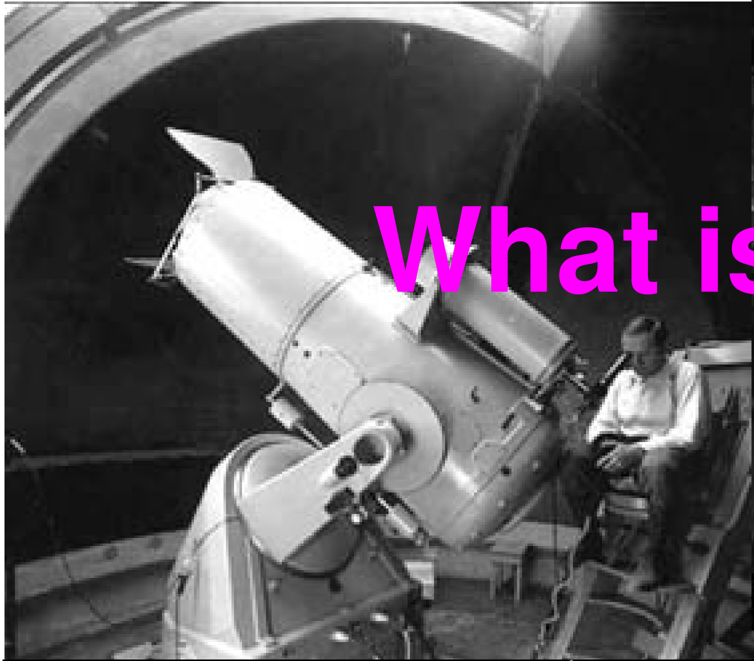
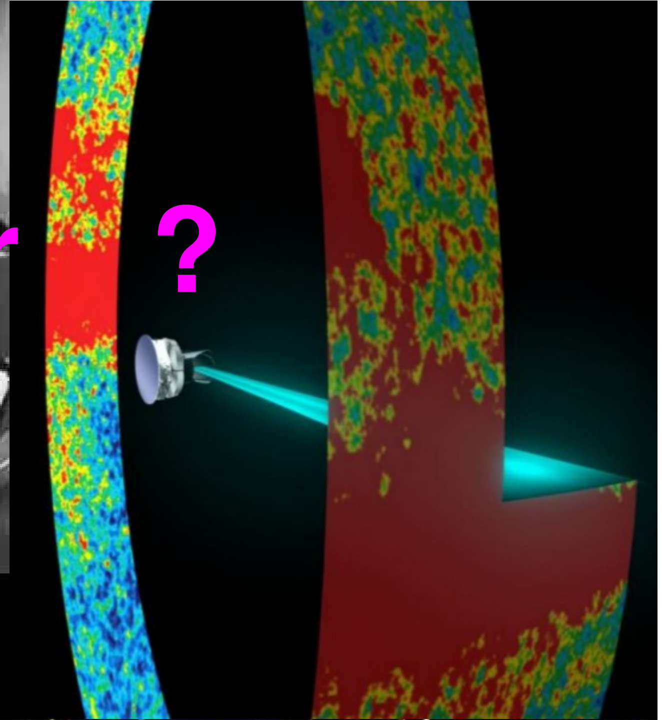
Kavli IPMU, The University of Tokyo
at the
John Hopkins Workshop 2019

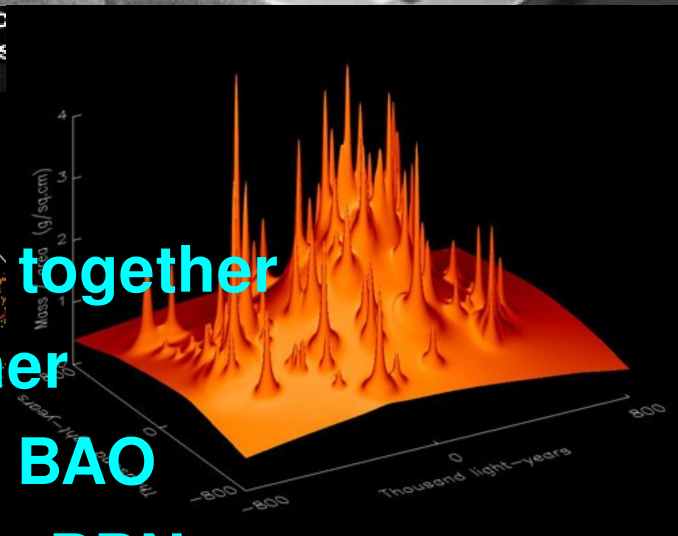
Overview

- What is Dark Matter (DM)?
- What is DM Direct Detection?
- How to directly detect DM?
- The XENON way of detecting DM
- Upgrading XENON1T to XENONnT
- Beyond XENONnT: Completing the XMASS physics program

What is Dark Matter ?







Dark Matter is what:

– holds galaxy clusters together
– holds galaxies together
– shaped the Universe: BAO
– bred the fuel for stars: BBN
– explains the CMB measurements
– keeps theorists puzzled
– keeps experimentalists busy: LHC, (in-)direct detection

What we know:

Dark Matter (DM) gravitates, and is:

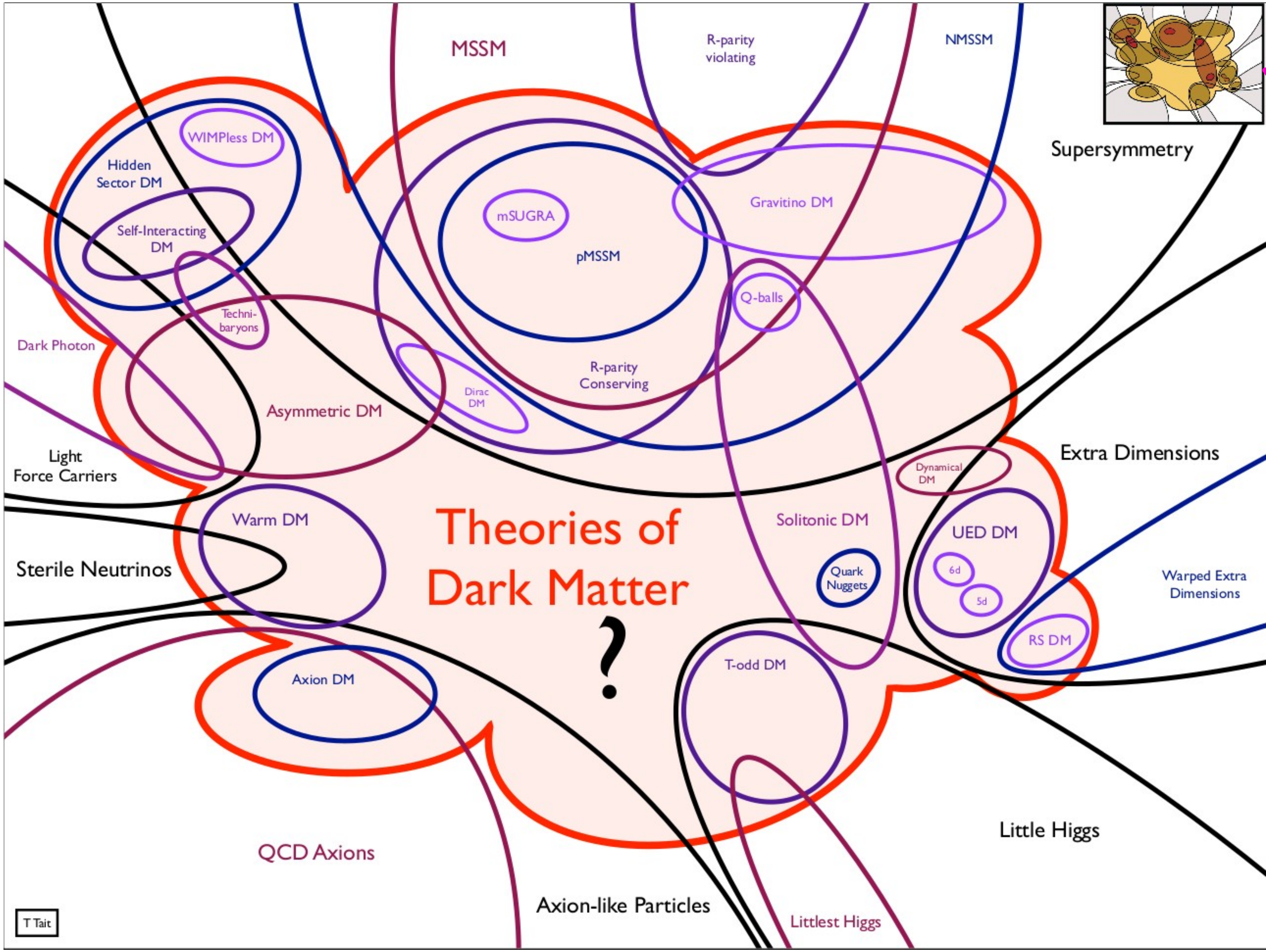
long lived:	still around, since the Big Bang
neutral:	dark
collisionless:	bullet cluster
non-relativistic:	heavy and cold (freeze out) light and axionic (misalignment)

What we hope for:

... that it also *interacts* with OUR baryonic world in some way
OTHER than gravitationally ...

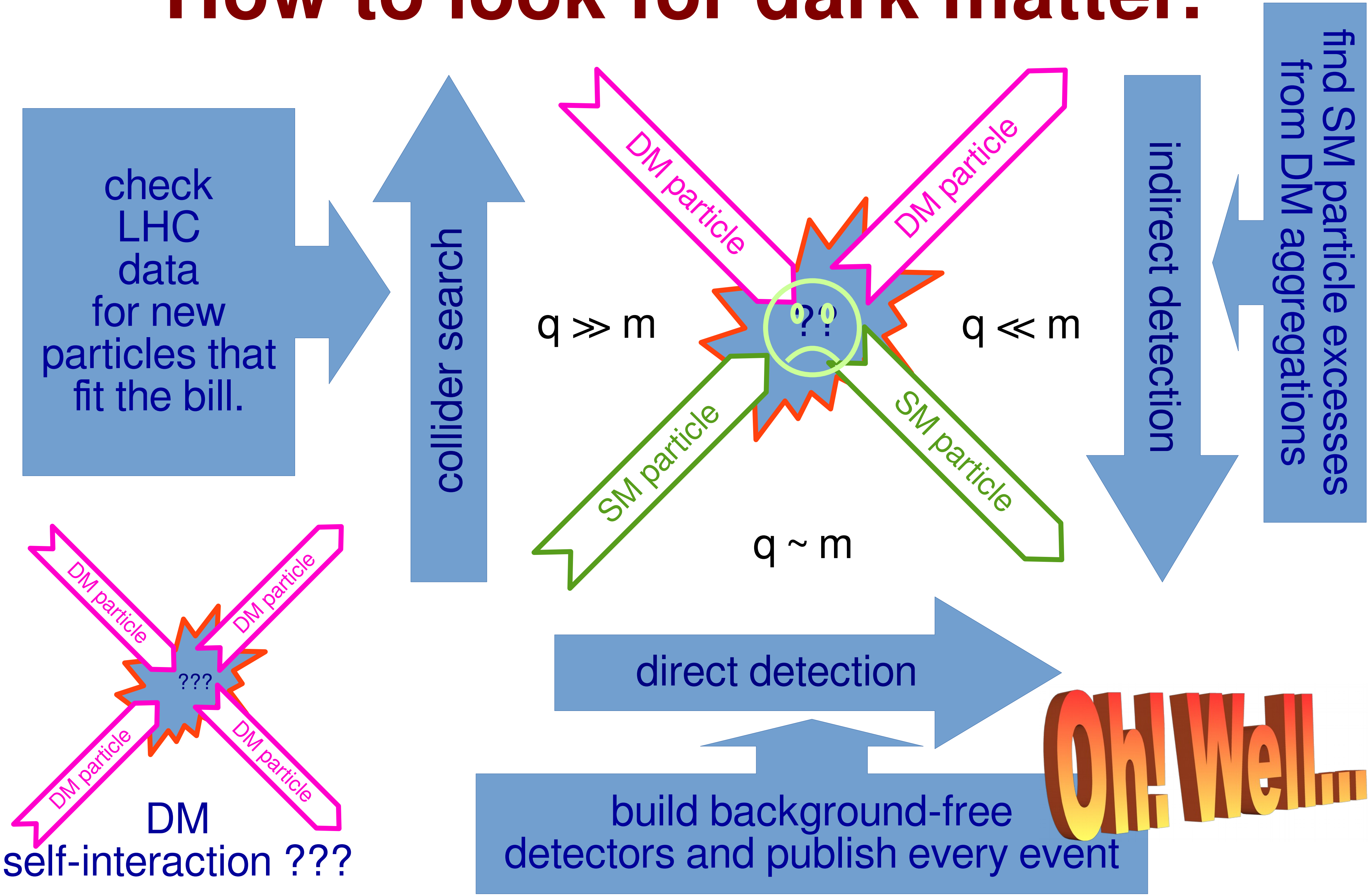
If – and only if – it does can we *maybe* "see" or even probe Dark Matter.

Theoretical “”””””Guidance?



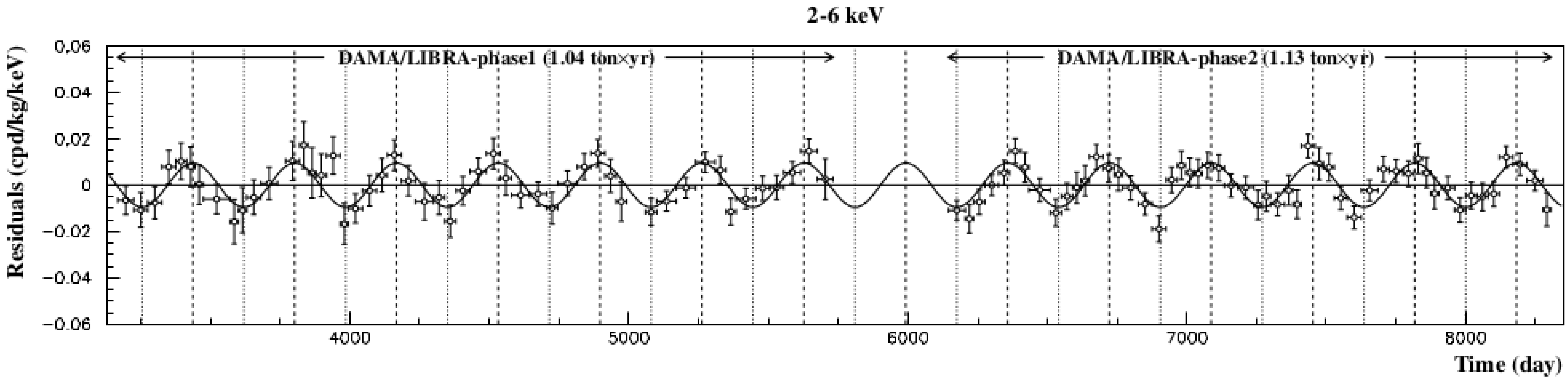
What to do depends on **who** you ask, who your “favorite” theorist is ☹☹☹

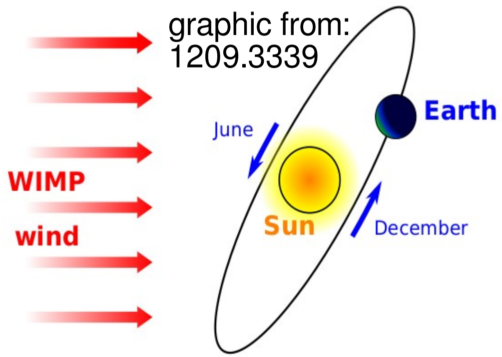
How to look for dark matter:



DM Direct Detection Signals?

Most persistent: **DAMA/Libra** annual modulation (1805.10486: 12.9σ)





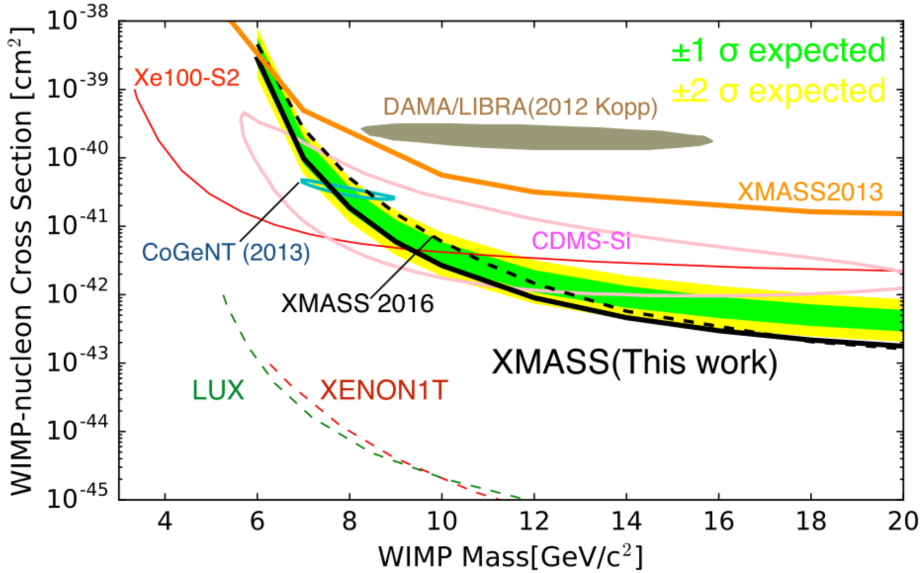
Notes:

- CoGeNT now <2σ
- CDMS-Si 3σ, but: not observed in Ge
- DAMA/Libra: tension with others!

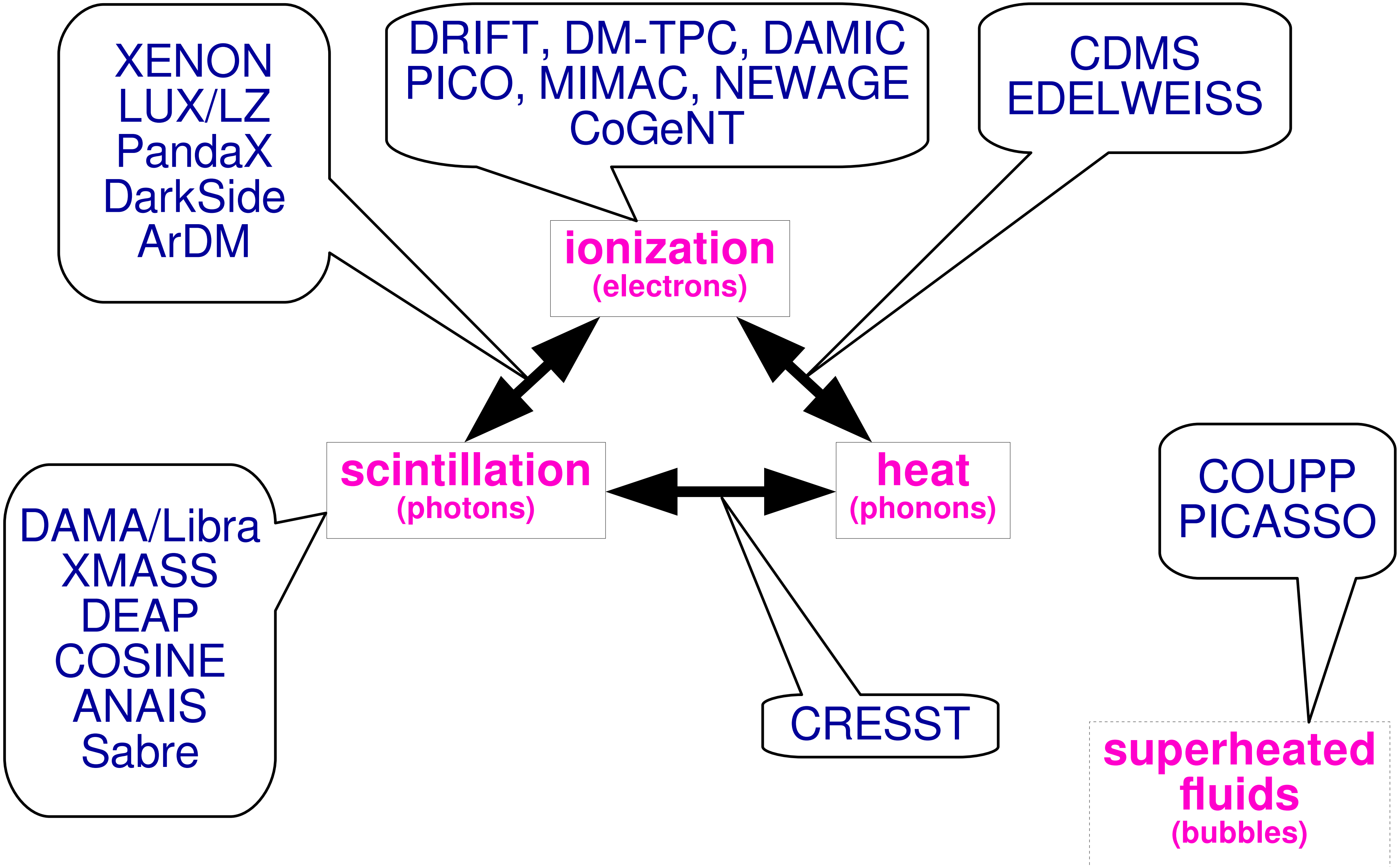
<u>worldwide NaI(Tl) verification efforts</u>:

- ANAIS (Canfranc, Spain)
- Cosine (Yangyang, Korea)
- DM-Ice (Antarctica)
- Sabre (LNGS, Italy)

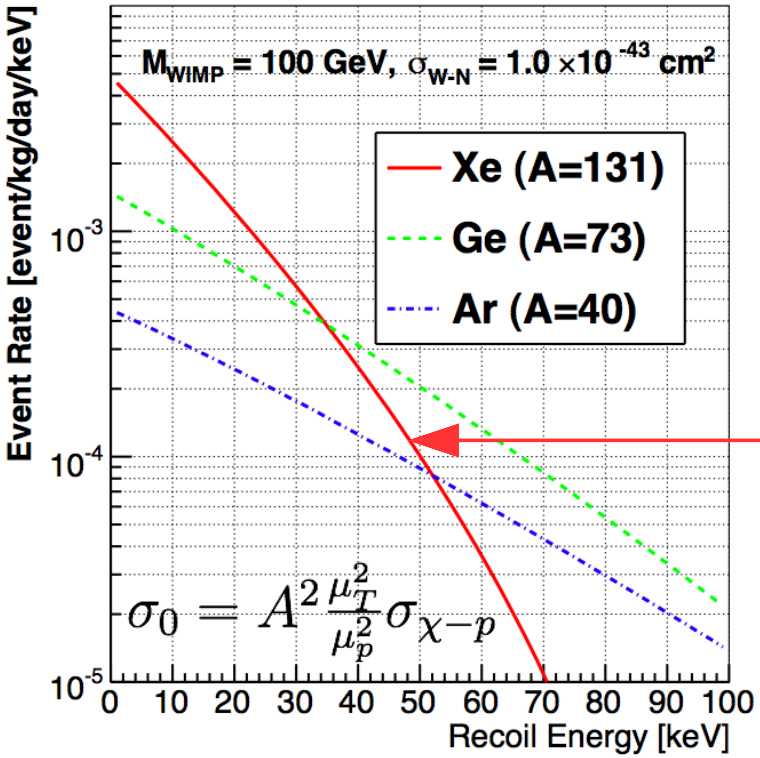
XMASS 2.7 year modulation analysis 1801.10096:



Direct Detection Technologies



Why (Liquid) Xenon?



SI cross-section:

coherent on whole nucleus $\propto A^2$
but: suppressed by form factor
$\rightarrow$ advantage diminishes with momentum transfer...

- **high mass number** → **high SI cross section**
- **no long-lived radioactive isotope** → **no intrinsic background**
- **high density (liquid): 3g/cm³** → **self-shielding**
- **48% odd isotopes (natural)** → **SD cross section**
- **ββ candidate** — $^{136}Xe \rightarrow {}^{136}Ba + 2e^- + 2.48$ MeV
- **good scintillation yield** — ~ **46ph/keV**

The XENON Collaboration

@LNGS:
April 2019
Technical
Meeting

155
scientists
from
27
institutions

XENON

The next step in the **XENON program**:

dual phase **liquid xenon detectors** for

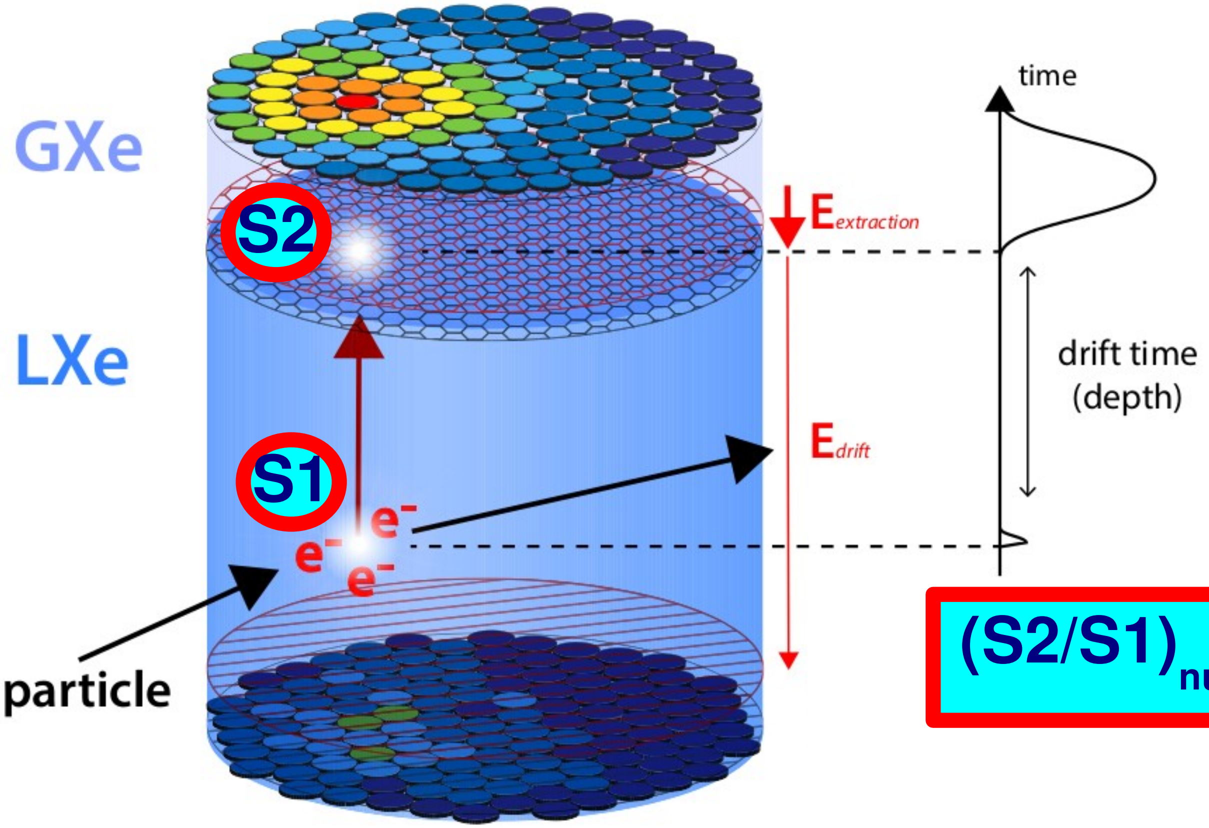
- the discovery of dark matter particle interactions
- a precision measurement of pp-solar neutrinos
- the observation of SN explosions through coherent scattering
- the search for double beta decay (^{136}Xe)

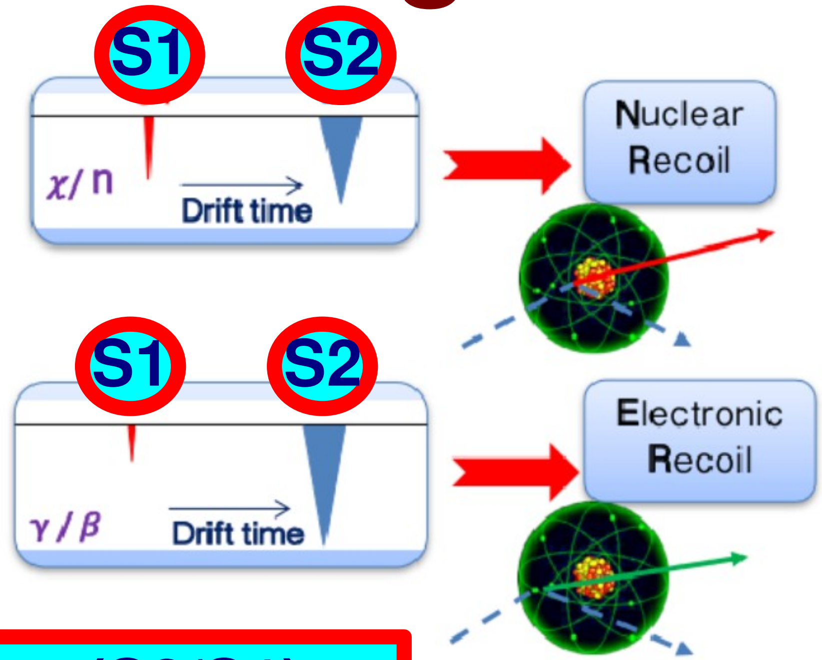
→ the goals are the same as they were for *single phase* **XMASS**!

XENON timeline: (3rd line: total Xe / length of drift)

XENON10	XENON100	XENON1T	XENONnT
2005 – 2007	2008 – 2016	2011 – 2018	2019 – 2023
14 kg / 15 cm	161 kg / 30 cm	3.2 t / 100 cm	8 t / 150 cm
10^{-43} cm^2	**10^{-45} cm^2**	**$4*10^{-47}$ cm^2**	**→ $2*10^{-48}$ cm^2**

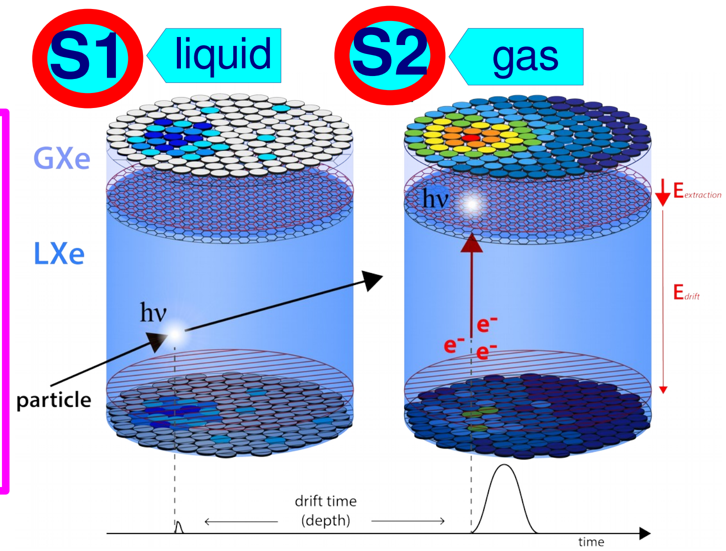
Dual Phase TPC Advantages





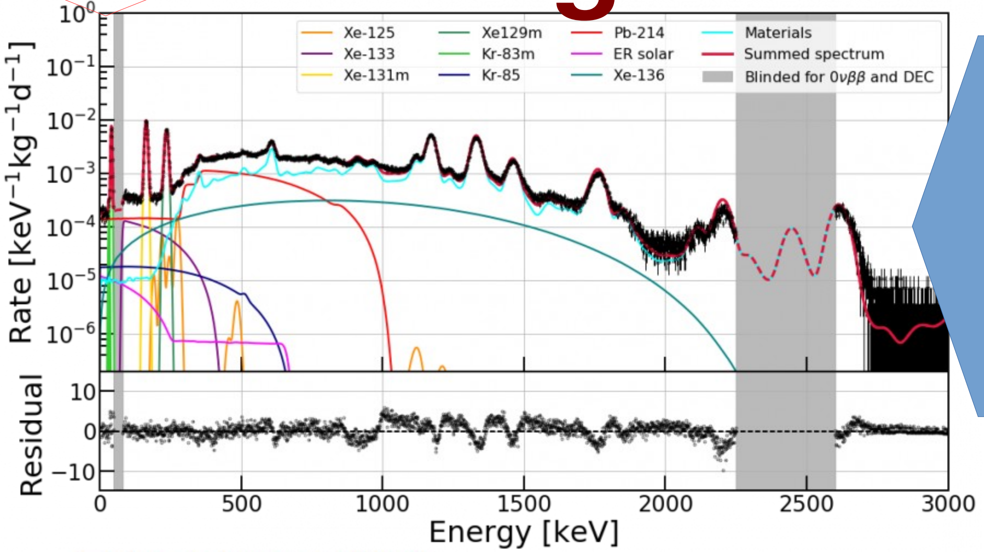
$(S2/S1)_{nucl} < (S2/S1)_{elec}$

- discriminates nuclear/electron recoil ≳ 5 keV
- better fiducialization:
- S2 amplification → low threshold



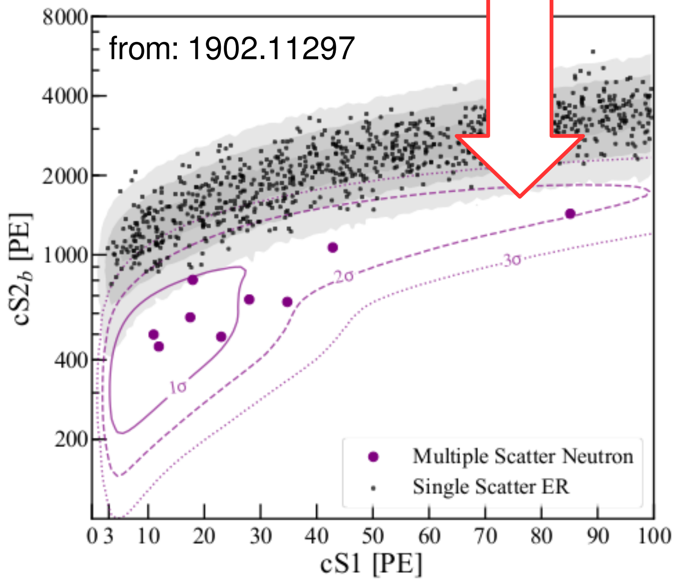
WIMPS

Background is the *Enemy!*

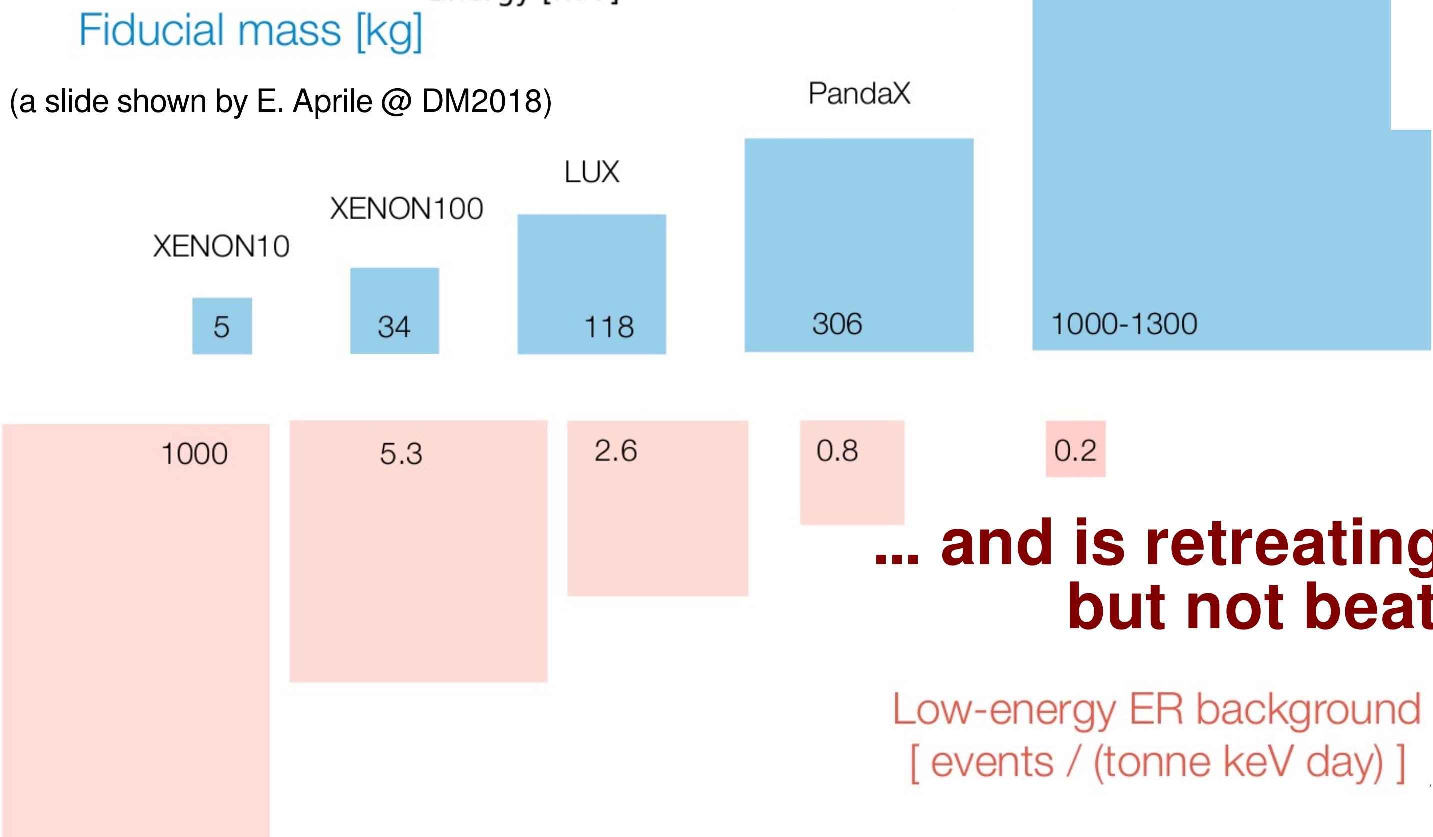


XENON1T matched BG spectrum at low energies: $^{222}Rn \rightarrow {}^{214}Pb$

more BG = "better" chance to populate the signal region ☹



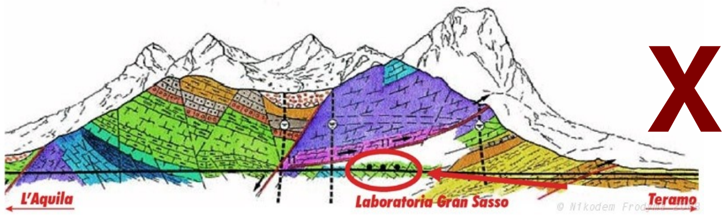
(a slide shown by E. Aprile @ DM2018)



... and is retreating, but not beaten.

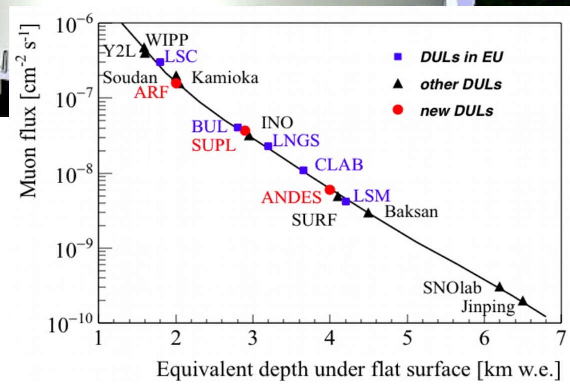
who will be better?

LZ ?
PandaX-4T ?
XENONnT (!)
(TBD...)



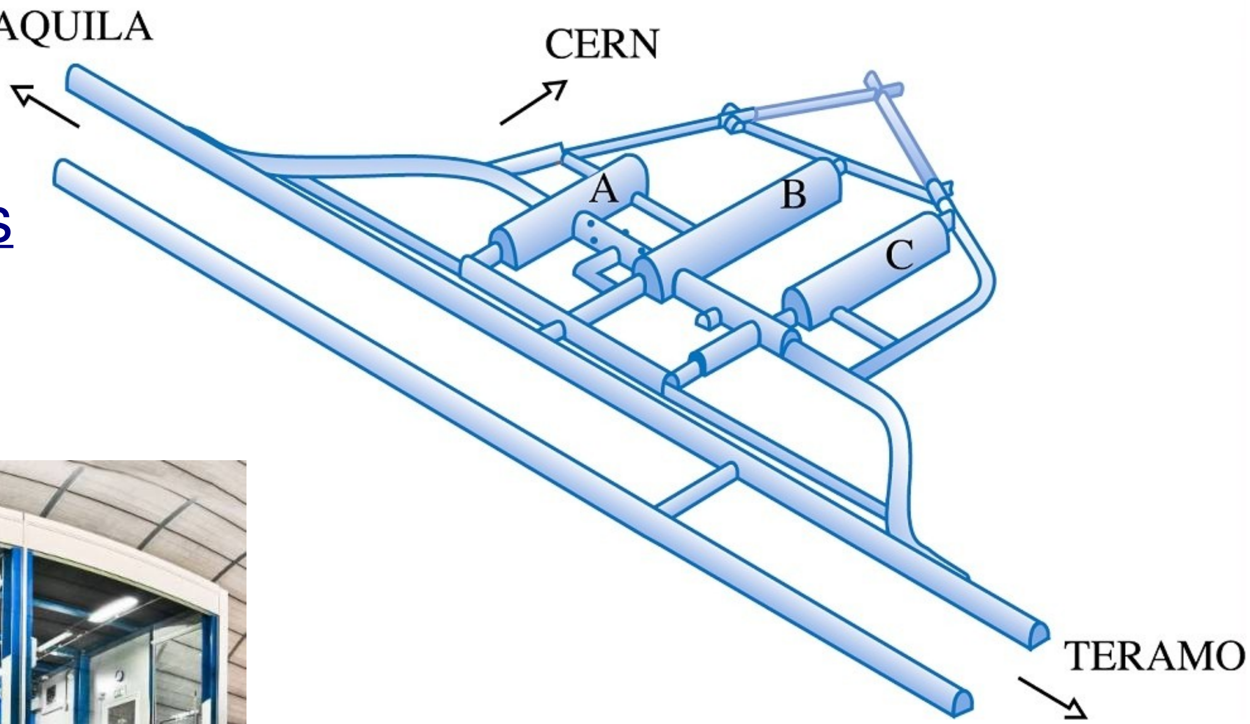
XENON @ LNGS

some
guy crouching



pictures above of XENON1T:
→ proven infrastructure in place → upgrade !!!

Hall B: XENON1T → XENONnT



XENON1T:

(current holder of heavy WIMP world bragging rights)

infrastructure and sub-systems
proven in action !!!
→ *ready, upgrade, go...*

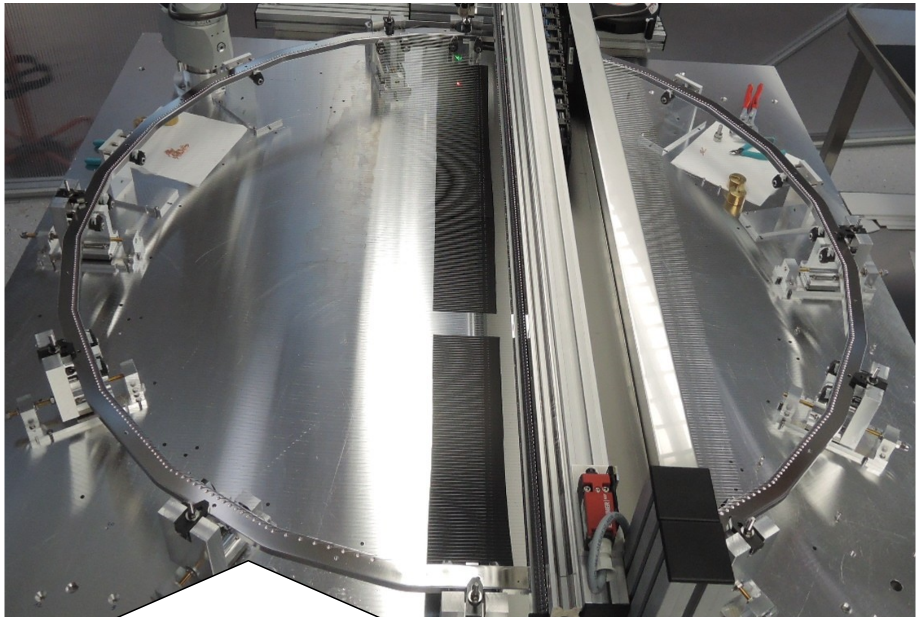
the upgrades are underway:

- larger, cleaner **TPC**
- Xe liquid phase **purification**
- continuous **Rn distillation**
- add a **neutron veto**

(underlined: w/Kamioka expertise)

TPC upgrade: TPC & Cryostat

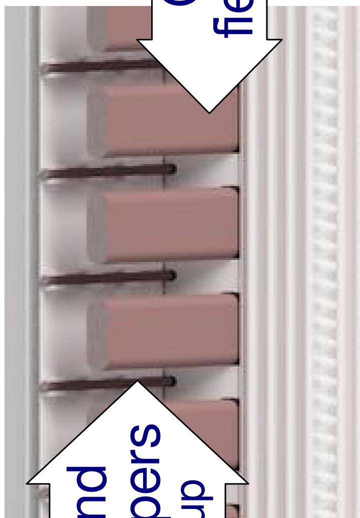
- 2.0 → **5.9 tonne active LXe volume**
  ⌀ 133 cm, 148 cm drift
- **494 PMTs** (3” Hamamatsu R11410-21)
  127 → 253 in gas, 121 → 241 in liquid
- **200 V/cm drift field** (design)



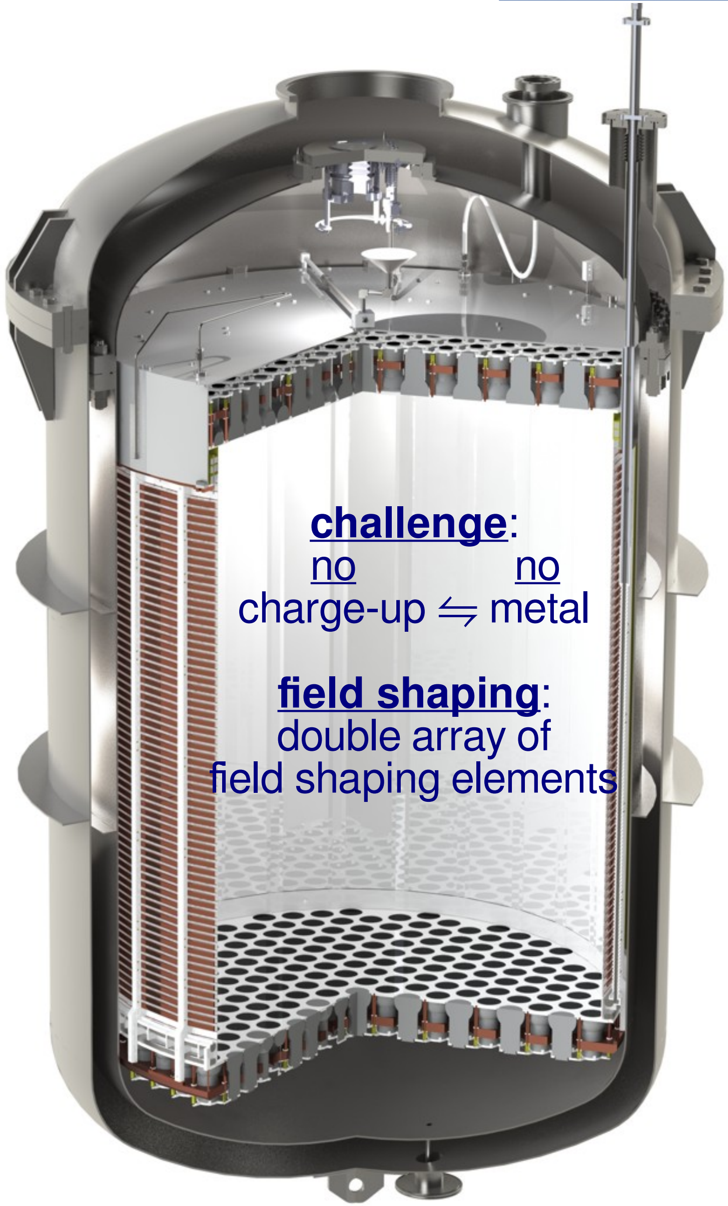
quality verification on a TPC electrode

field configuration:
experience ⊕ simulation

Cu rings: field guards



Cu wires behind PTFE: field shapers
to avoid charge-up

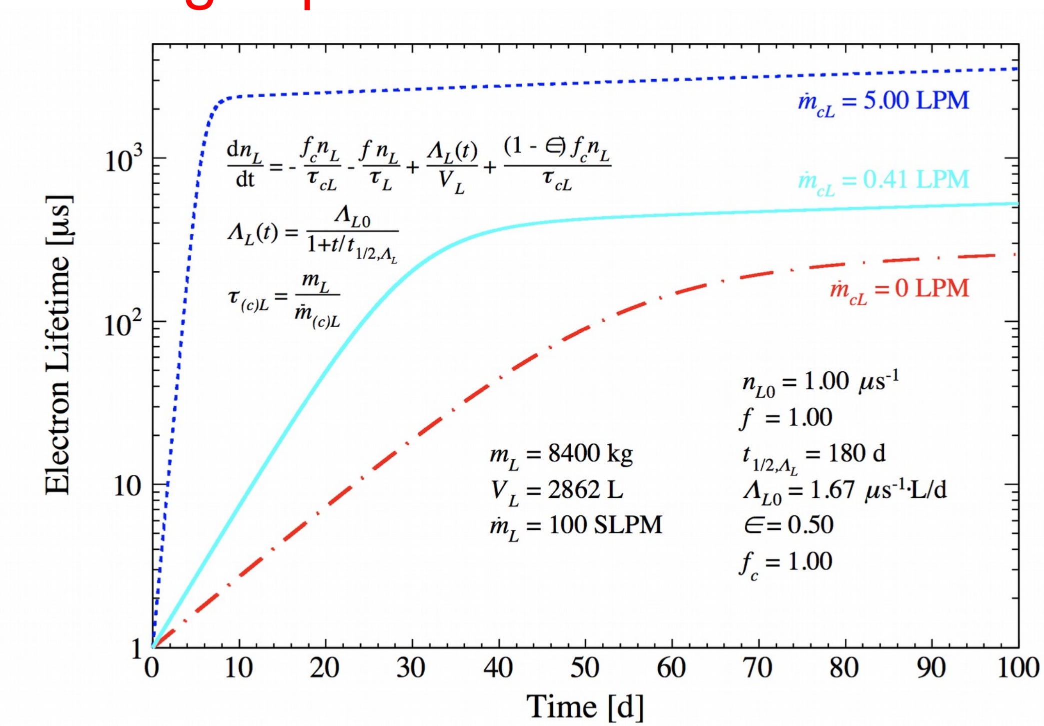


New: Liquid Phase Purification

electronegative contaminants:
– limit the electron lifetime → limit S2 for long drift
– continually re-supplied from detector materials...
→ **need to be removed continually!**

1.5 m drift, ~10^{-48} cm^2
→ > 1 ms required !

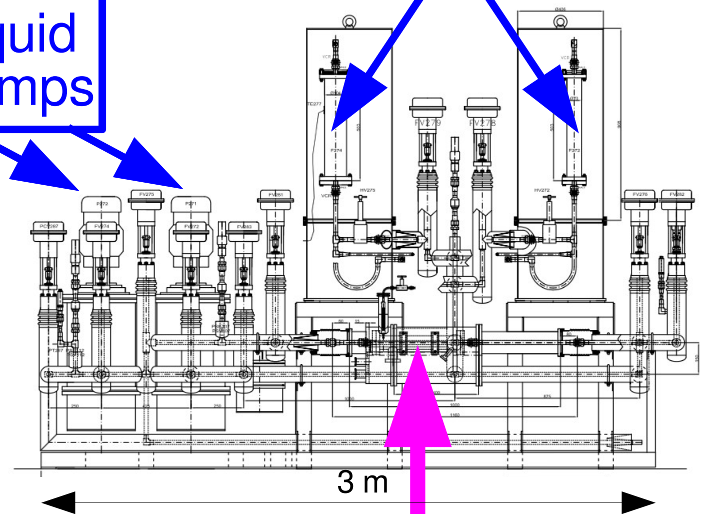
XENON up to 1T, XMASS, ... so far all used *hot* zirconium getters
→ gas phase: too slow



liquid purification:
(installed at XENONnT)

adsorbant containers

liquid pumps



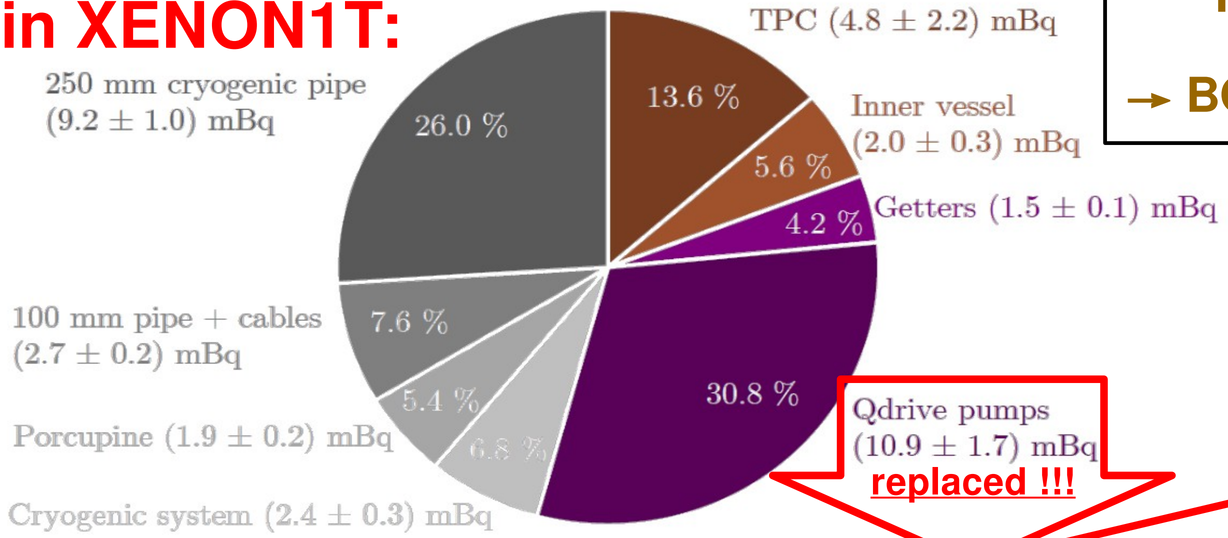
Made in Kamioka

we have an 80% – 90% efficient Cu adsobant ✓

Continuous Rn Distillation

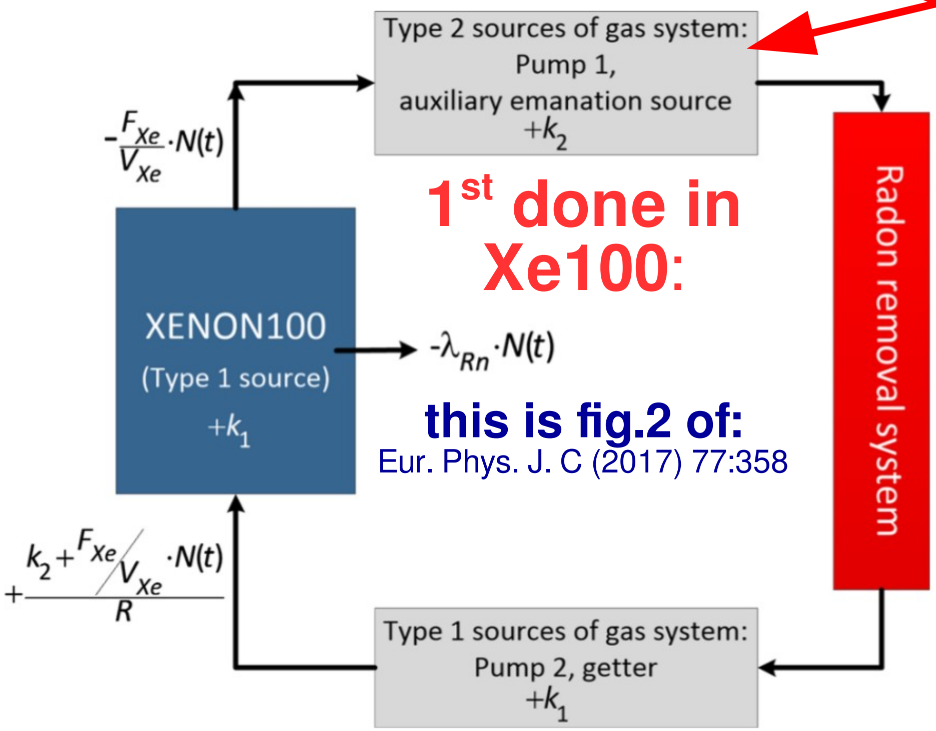
XENON Dark Matter Project

Rn sources in XENON1T:



replaced !!!

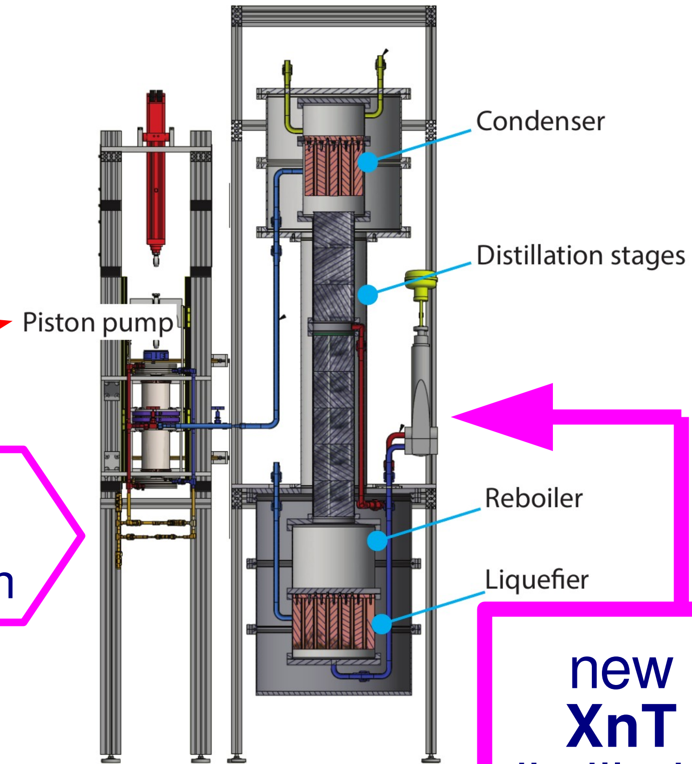
^{214}Pb: low energy β-decay in ^{222}Rn decay chain → BG in WIMP search region

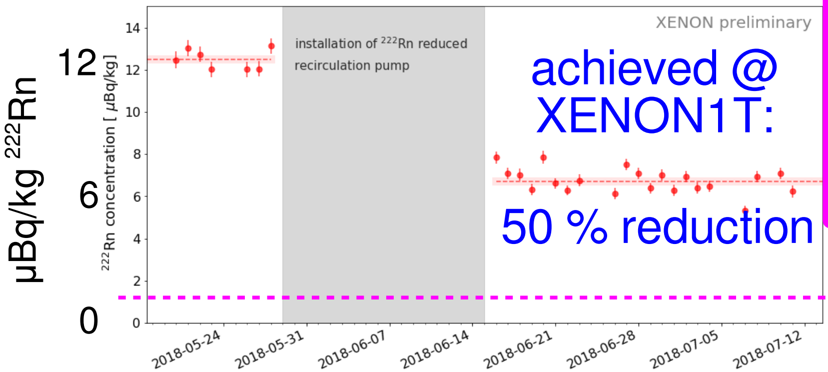


1st done in Xe100:

this is fig.2 of:
Eur. Phys. J. C (2017) 77:358

all a part of liquid purification





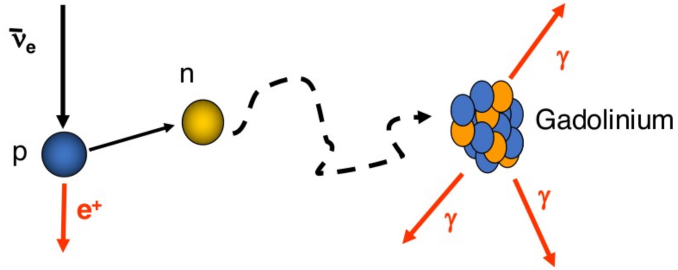
achieved @ XENON1T:
50 % reduction

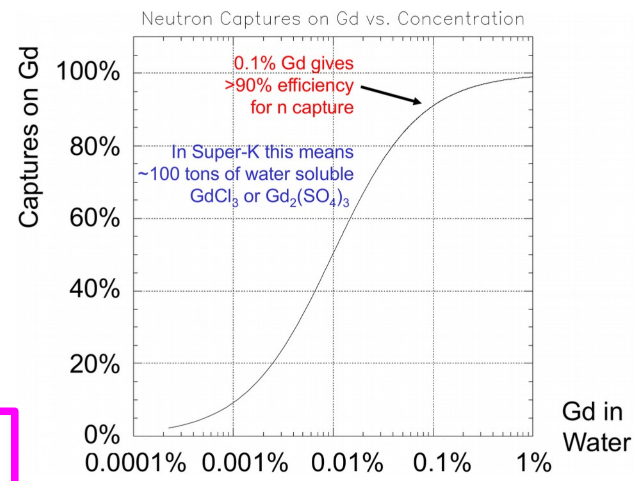
new **XnT** distillation column
target: 1 µBq/kg

XnT Neutron Veto: à la Japonaise

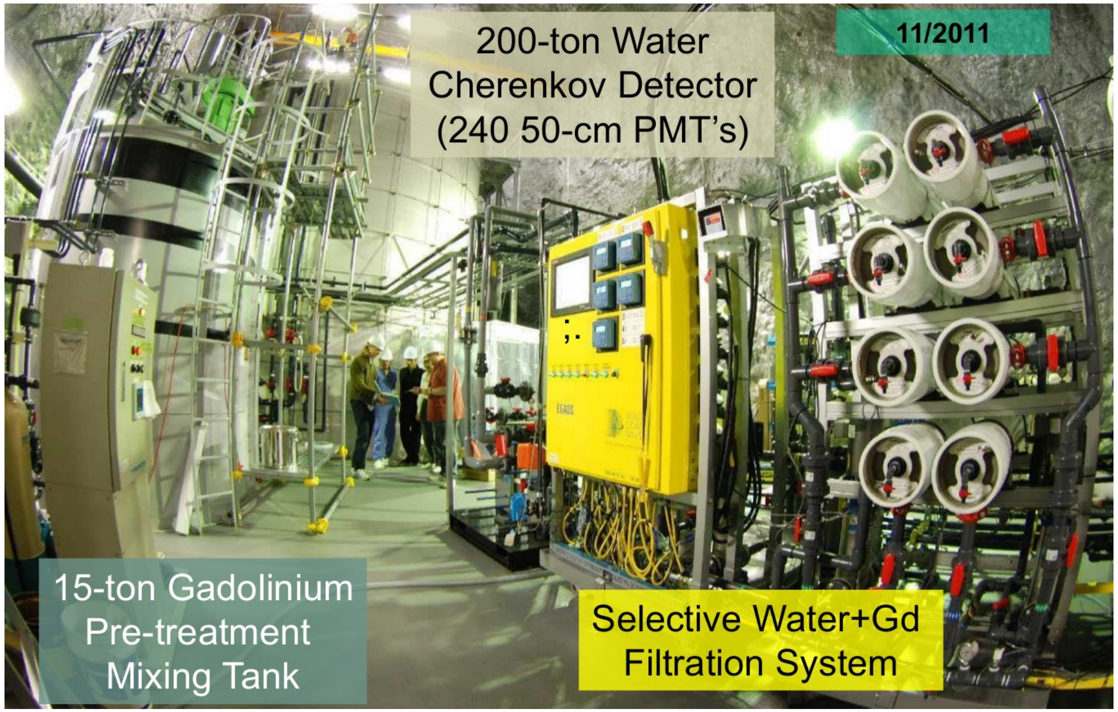
Mark Vagins (K-IPMU)
& John Beacom (Ohio)
PRL 93 (2004) 171101
(sketch by Mark)

put Gd into SK to tag antineutrinos:

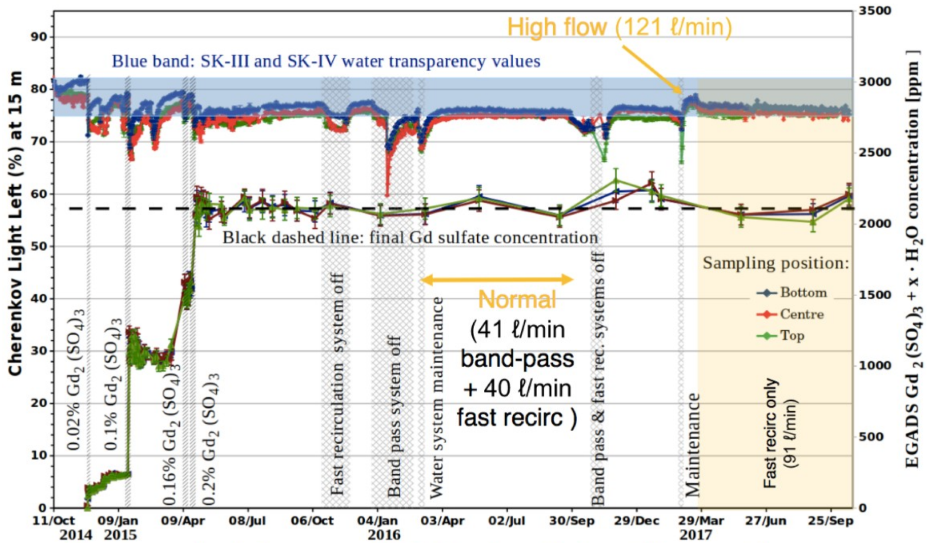




EGADS: technology demonstration
→ SK-Gd starts JP-FY 2019 !!!



Light @ 15 meters and Gd conc. in the 200-ton EGADS tank



After two and a half years at full Gd loading, during stable operations EGADS water transparency remains within the SK ultrapure range.

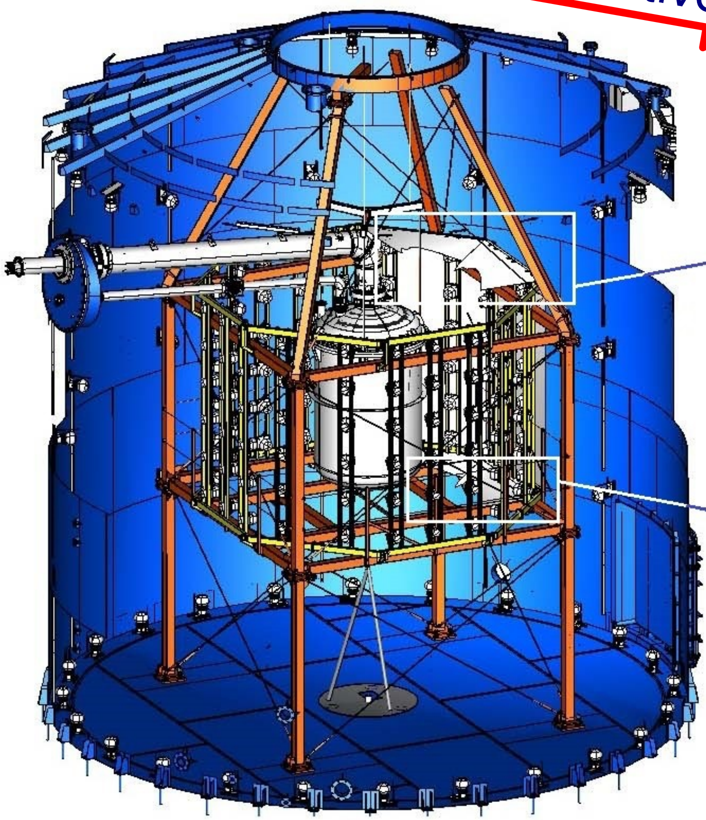
→ No detectable loss of Gd after more than 650 complete turnovers. ←

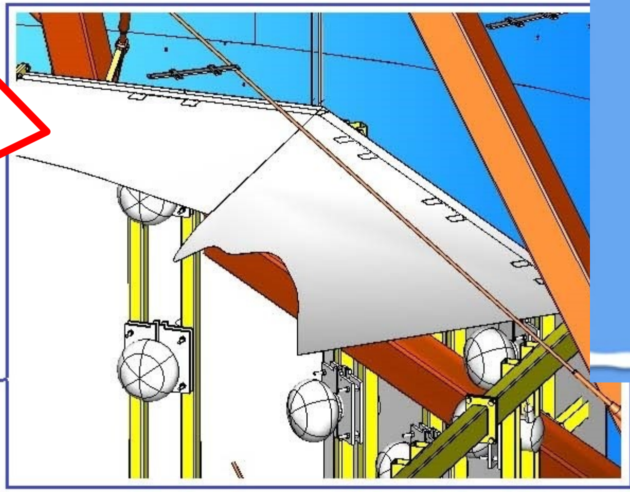
Slide credit: Mark Vagins

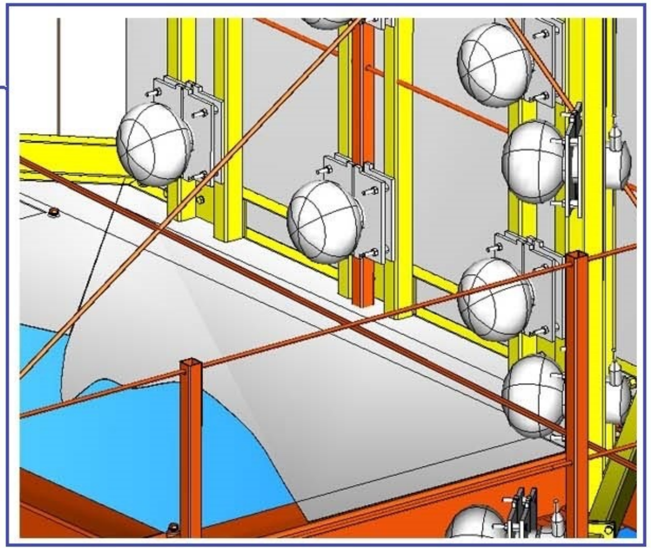
Neutron Veto for XENONnT

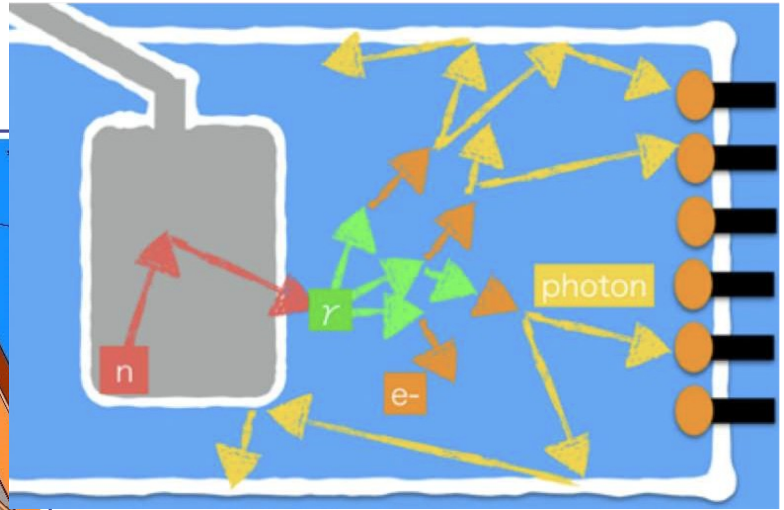
different optimization from EGADS/SK-Gd:
low coverage (PMT = RI...), high efficiency

99% reflective

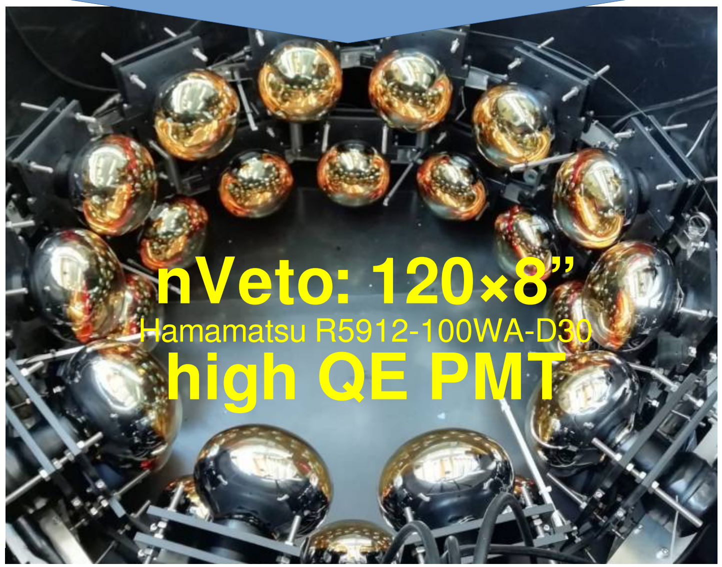








ongoing @ LNGS:
nVeto PMT testing



n-tagging efficiency estimate:
65% w/pure water
85% w/0.2% Gd loading
→ < 1 n in 20 t×y

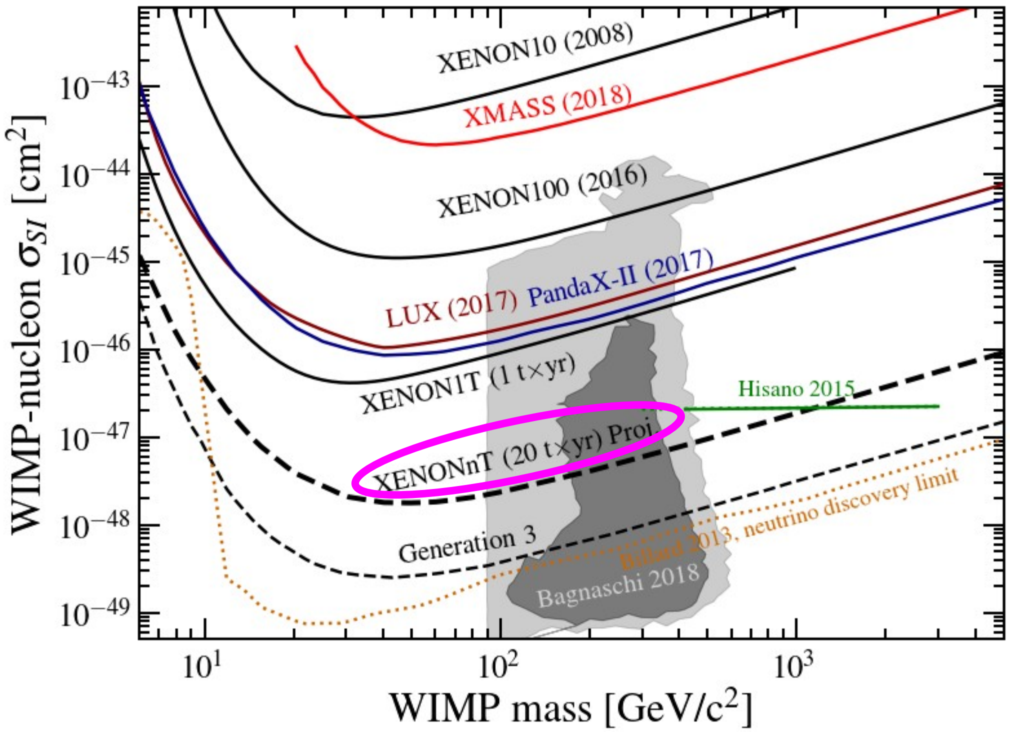
XENONnT Sensitivity Projection

a <u>discovery experiment</u> *is being built* at LNGS:

– <u>using the cumulative **experience**</u> of:
- ► many individual **people** !!!
- ► three successful generations of **XENON** detectors !!!
- ► **XMASS**
- ► Kamioka Gd efforts **EGADS** and **SK-Gd**
- ► lab staff at **LNGS** and **Kamioka**

– setting out <u>to detect dark matter</u>:
- ► heavy WIMPs
- ► nimble Axions
- ► YOUR favorite ?
- ► anything that leaves a discernible trace...

Hisano 2015:
example of a next-to-leading order QCD cross-section calculation for wino-DM



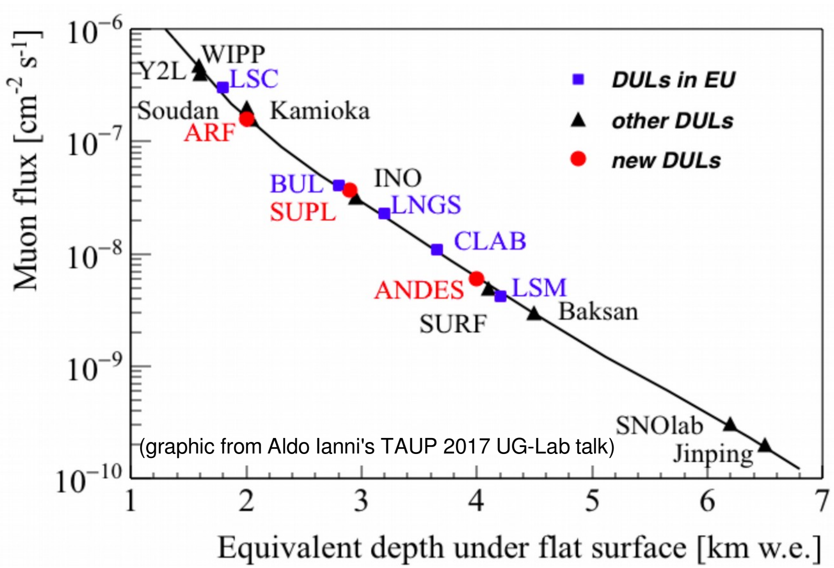
Please see Shingo Kazama's talk on XENON1T results later today!

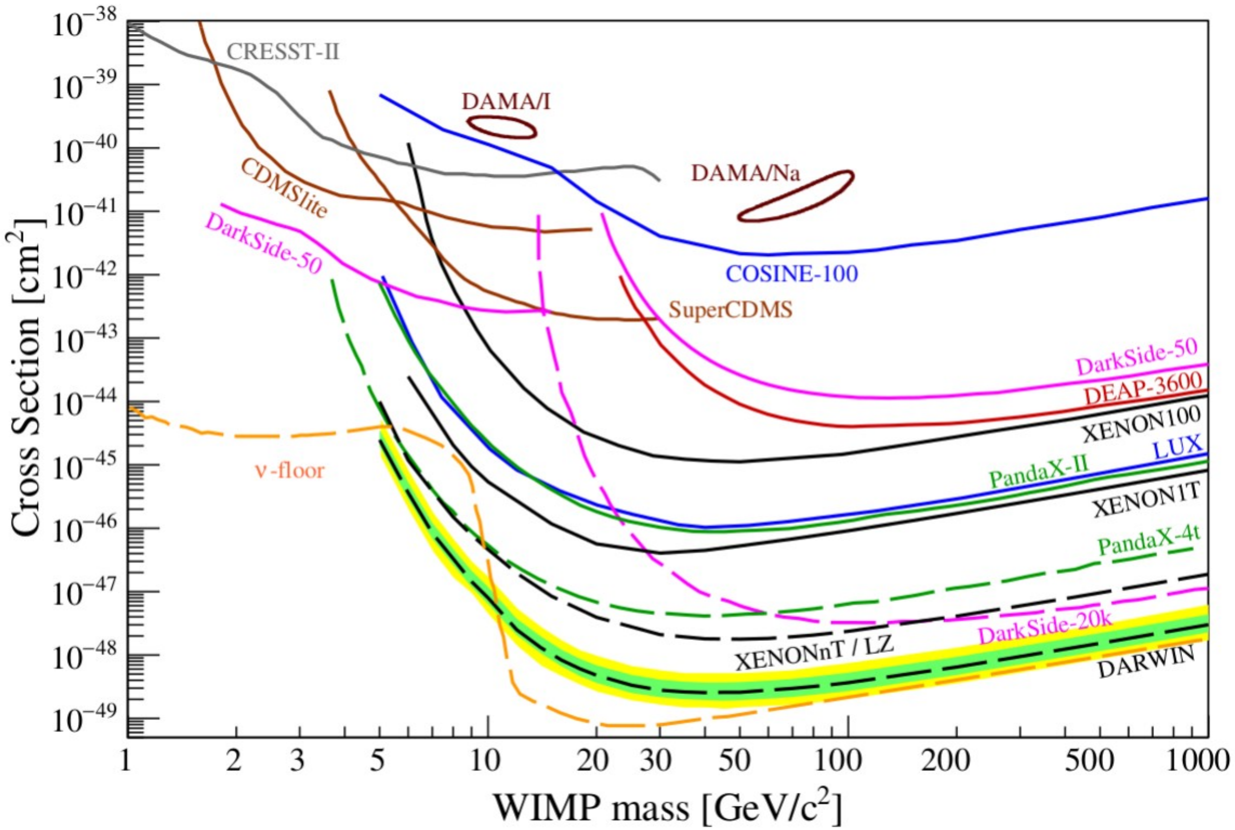
<u>After</u> XENONnT, LZ, PandaX-4T

30 tonnes fiducial volume means **50 tonnes of Xe** ~ yearly world production
$\rightarrow$ 40 tonnes in TPC, 200 tonne$*$year exposure

continue the LXe experimental program:
- dark matter (spectroscopy???)
- solar neutrinos
- $0\nu\beta\beta$
- SN neutrino detection

<u>best environment needed</u>:
- overburden
- cleanliness
- access

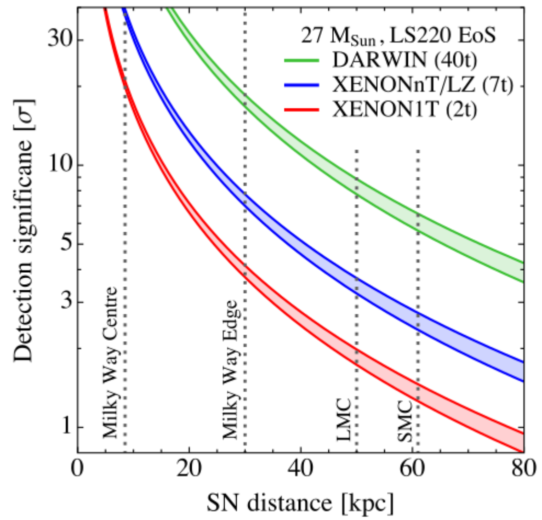


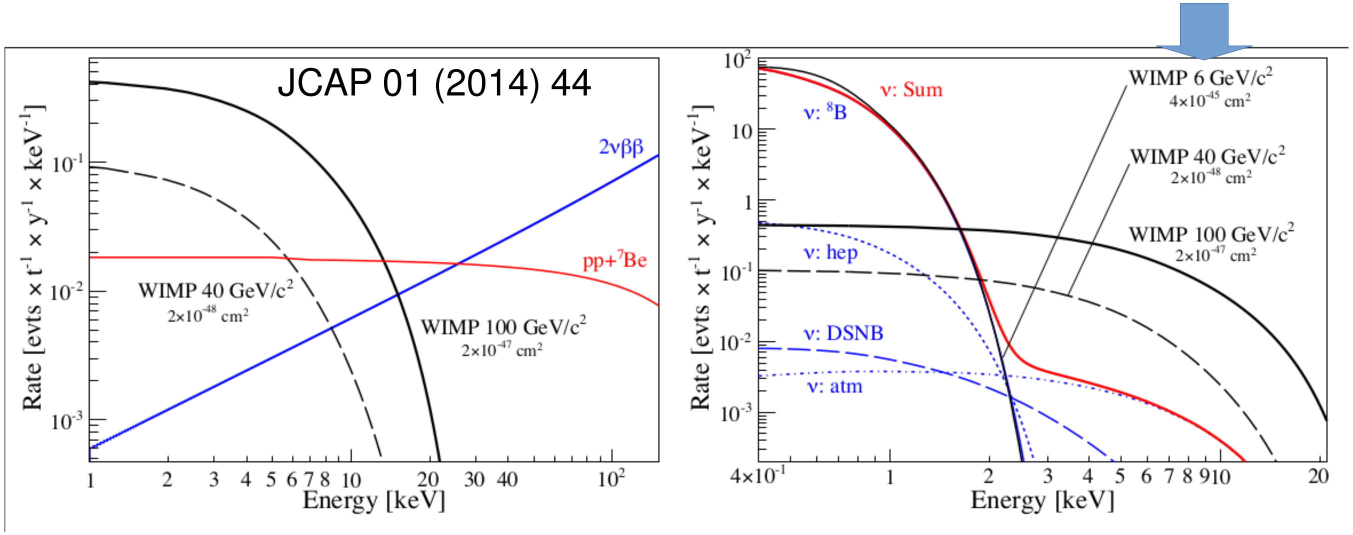


G3 LXe Experiment: The Vision

still pushing the WIMP DM boundary – or measuring WIMP DM spectrum?

PRD 94 (2016) 103009





solar neutrinos:

– measure ER spectrum of pp- and ^{7}Be neutrinos

– **CEνNS** for ^{8}B neutrinos (+ direct SN neutrinos…) ← ER suppression

Q: ^{136}Xe enrichment (→ ββ ER background…) ???

(heard of someone dreaming of a 1km high distillation column…)

40 tonnes natural Xe = 4.4 tonnes of ^{136}Xe

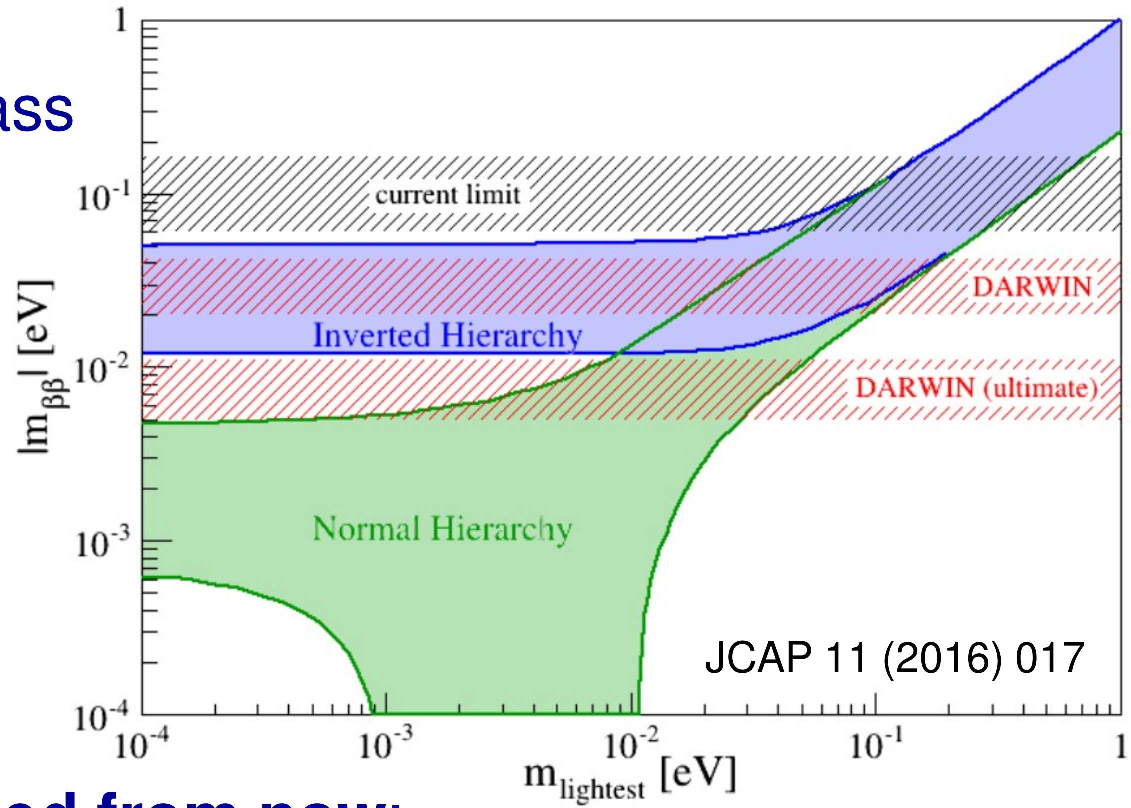
case study (for live development project): DARWIN → JCAP 11, 017 (2016)

0νββ with 30 tonne LXe Detector

IH region of effective Majorana mass will be covered.

special HE readout to improve energy resolution at endpoint.

high sensitivity to half live due to high ^{136}Xe mass.



<u>The effort is being organized from now</u>:

- G3C consortium here in Japan
- DARWIN mainly in Europa:
  preliminary timeline: TDR by 2024, construction 2024/25, data 2025–35
- PandaX XY (?)

→ can Japan/Kamioka play a role? Do we want to? **(I DO !)**

HK starts 20XY → water shielded high pressure Xe TPC inside SK tank ???

Outlook

– we, the Japanese groups, are playing an important role, and contribute important knowledge and technology in **XENONnT**

– **XENONnT** and its competitors are built as discovery machines: push deep into the 10^{-48} cm^2 scale for WIMP SI interactions

– this physics program of both XENON and XMASS will be realized by one world-wide **G3 liquid xenon detector consortium**

– personal remark:
  Hall-C (ICRR) and **Lab-1** (Kavli-IPMU) are a unique asset:
  – *underground* cleanroom environment with screening facilities
  – operational **800 ton water shield** and up to X 1ns FADC ch.
  – timely:

national:	**G3C** (G3 consortium)
Kamioka Observatory:	effort to "internationalize"
worldwide:	LXe effort needs testbed

what do YOU see:

mere coincidence, or a chance to take a central role and leadership ?!?