Review of Dark Matter Searches with Noble Liquid Detectors and Recent Results from XMASS

Hiroyuki Sekiya

ICRR & Kavli-IPMU, University of Tokyo

for the XMASS collaboration

Feb. 7 2014

Kavli IPMU Seminar

Contents

- Principle of direct detection
  - Direction insensitive searches
- Detection technologies with liquid noble gasses = noble liquids
  - Review of double phase detectors
  - Review of single phase detectors
    - XMASS
    - Liquid Xe TPC
- Future noble liquid detectors

Total 61 pages

Principle of WIMP Direct Detection

- Particle physics × Astrophysics
  (cross section) (flux)

$$
\begin{aligned}
R &= \sigma_{\chi-\mathrm{N}} \times n\langle v \rangle \\
&= \sigma_{\chi-\mathrm{N}} \times \rho \int \vec{v} f(\vec{v}) d\vec{v}
\end{aligned}
$$

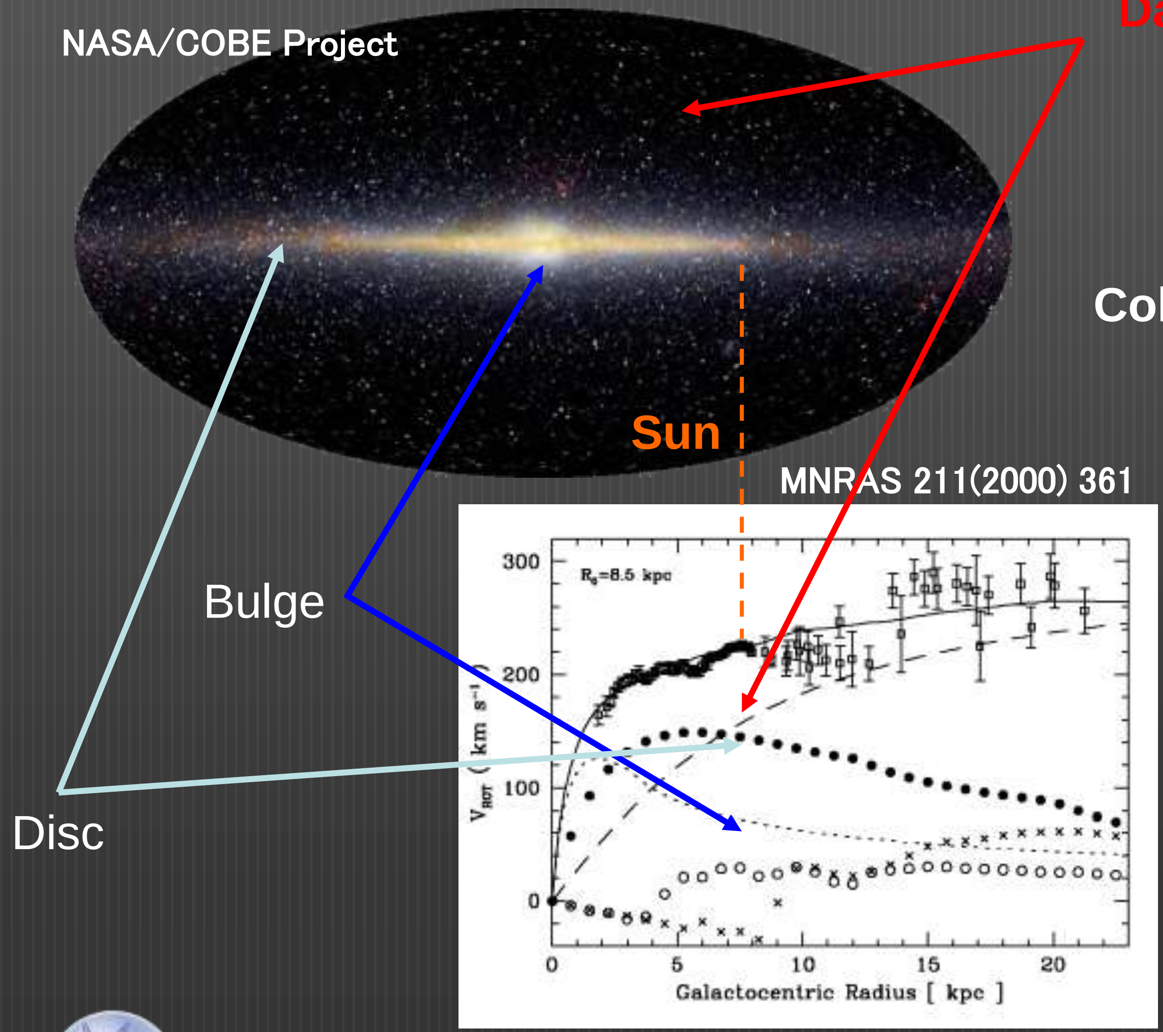
$\sigma_{\chi-\mathrm{N}}$: **WIMP-nucleus cross section**

ρ : **WIMP density**

$f(\vec{v})$: **WIMP velocity distribution**

Both the WIMP cross section and flux must be studied, but…

Astrophysics -The model-



Dark Halo $$\rho(r) \propto \frac{1}{r^2}$$

$$\rho(r_{\mathrm{Sun}}) = 0.3\mathrm{GeV/cm^3}$$

⬇

Collision-less Boltzmann equation

⬇

Maxwell distribution

$$f(\vec{v}) = \frac{1}{\pi^{3/2}\sigma^3} e^{-|\vec{v}|^2/\sigma^2}$$

$$\sigma = \sqrt{3/2}\, v_{\mathrm{ROT}}$$

$$v_{\mathrm{ROT}} = 220\ \mathrm{km/s}$$

$$v_{\mathrm{esc}} = 544\ \mathrm{km/s}$$

“Standard halo model”

Astrophysics -Recent N-body simulations-

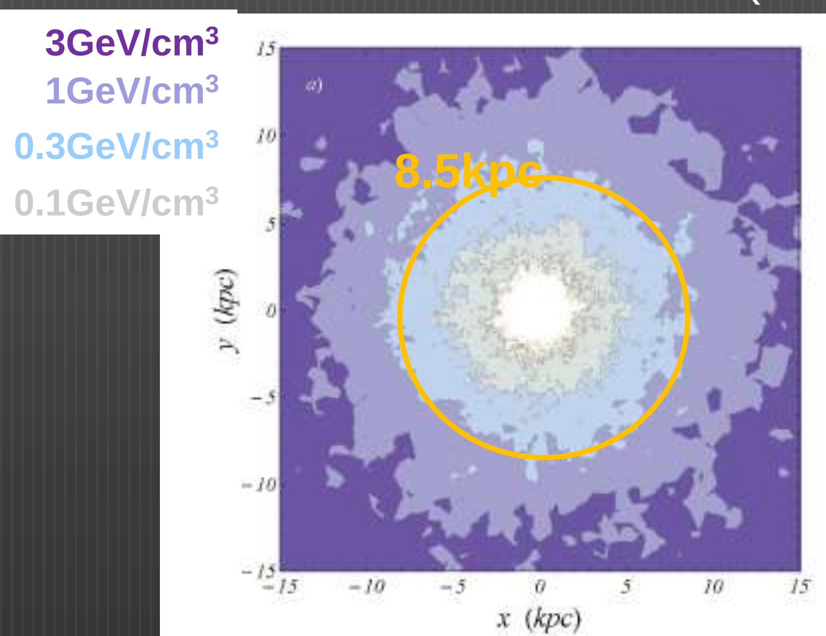
- Density

$$\rho = 0.39\mathrm{GeV/cm^3}$$

arXiv:0907.0018

$$\rho = 0.37\mathrm{GeV/cm^3}$$

JCAP 02(2010) 012



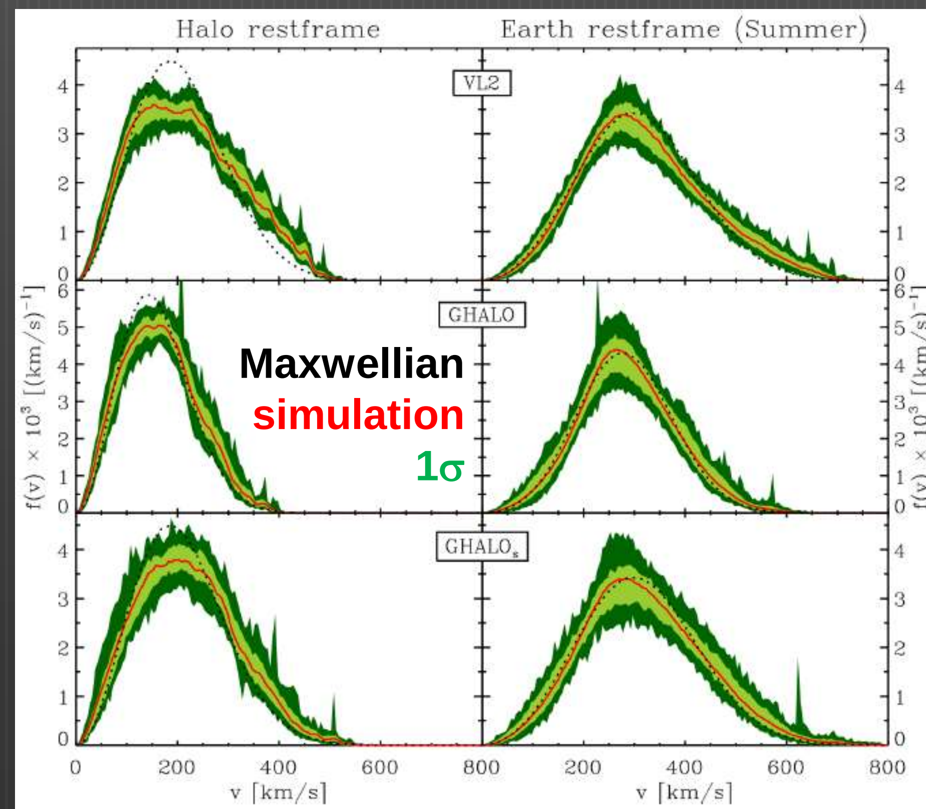
Halo density profile
in the galactic plane

- Velocity distribution

Indications of deviations from Maxwell distribution, particularly at high velocities.

→Impact on Light WIMPs
Direction sensitive search

JCAP 02(2010) 030



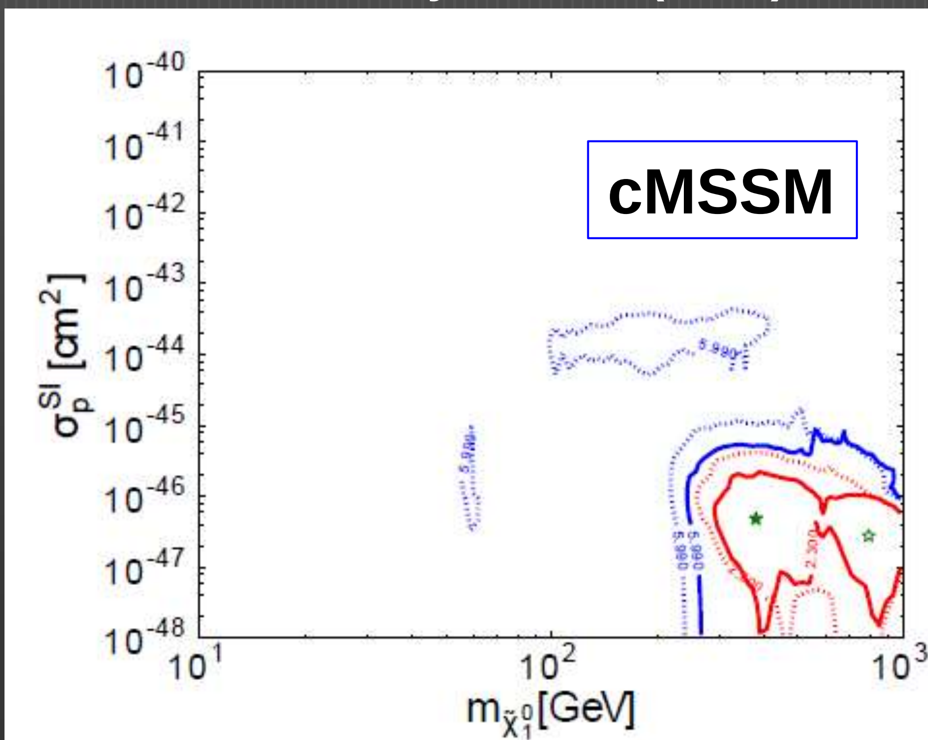
Recent Halo models

- Tidal streams
  - C. Savage, K. Freese, P. Gondolo, Phys. Rev. D74,043531 (2006).
  - A. Natarajan, C. Savage, K. Freese, Phys. Rev. D84,103005 (2011).
  - C.W. Purcell, A.R. Zentner, M.Y. Wang, JCAP 08, 027(2012).
- Debris flow
  - M. Kuhlen, M. Lisanti, D.N. Spergel, Phys. Rev. D86, 063505 (2012).
- Extra galactic components
  - K. Freese, P. Gondolo, L. Stodolsky, Phys. Rev. D64,123502 (2001).
  - A.N. Baushev, Astrophys. J. 771, 117 (2013).
- Dark disk
  - T. Bruch et al., Astrophys. J. 696, 920 (2009).
- etc,….
  - P. Belli et al. Phys. Rev. D66, 043503 (2002).
  - A.M. Green, JCAP 10, 034 (2010).PRD 74 043531(2006)
  - …

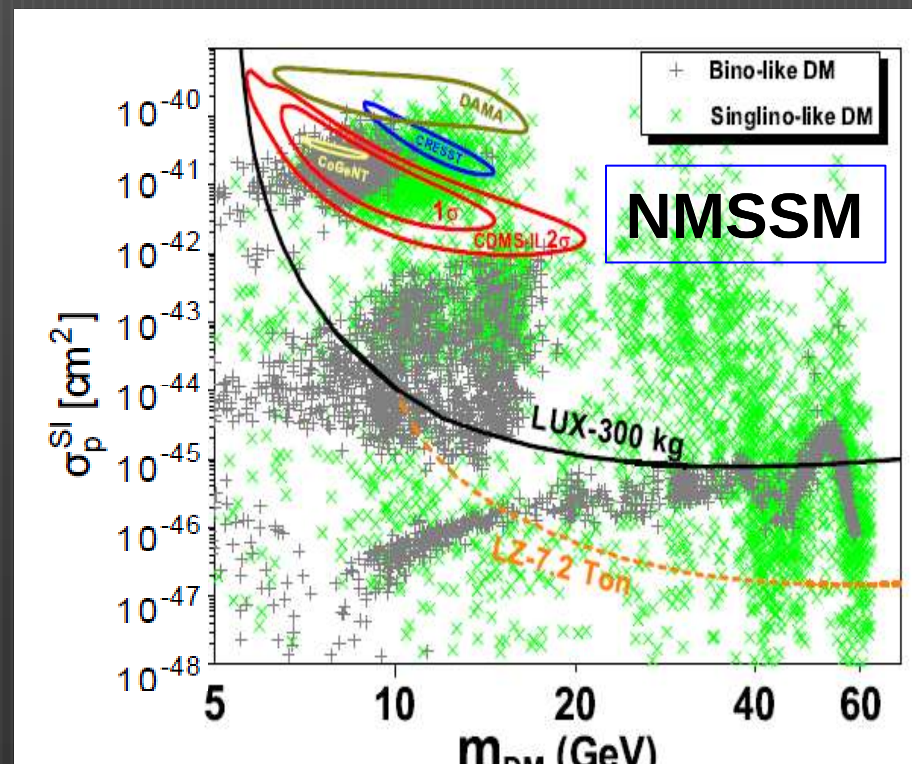
Particle physics after LHC

- SUSY $\tilde{\chi}_0^1$ is still attractive, but it goes far…
  - Nucleon scattering cross section, $\sigma_{\chi\text{-}n}$, is now down to ~ 10^{-48} cm^2

Eur. Phys. J. C72(2012) 2243



arXiv:1311.0678



WIMP-Nucleus elastic scattering

- Recoil energy

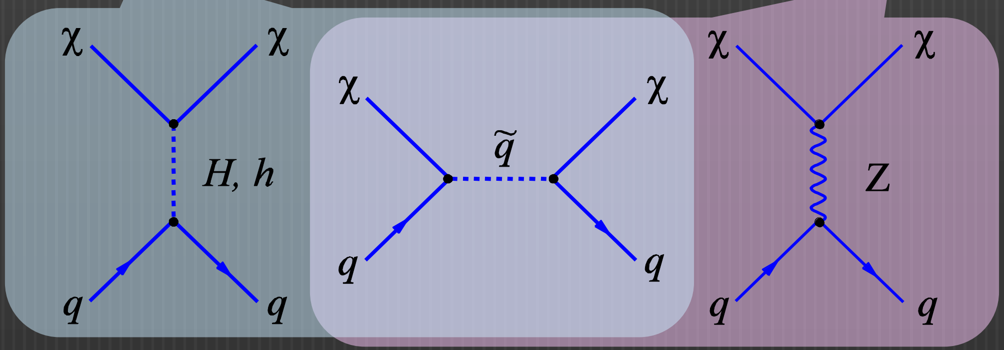
$$E_R = \frac{M_N M_\chi^2}{(M_N + M_\chi)^2} v^2 (1 - \cos\eta)$$

η : scattering angle in CM

- Cross section

$$\sigma_{\chi-\mathrm{N}} = 4 G_\mathrm{F}^2 \left(\frac{M_\chi M_N}{M_\chi + M_N} \right)^2 (C_\mathrm{N}^\mathrm{SI} + C_\mathrm{N}^\mathrm{SD})$$

$$C_N^{SI} \propto A^2 \sigma_{\chi\text{-}n} \qquad C_\mathrm{N}^\mathrm{SD} \propto \left(a_\mathrm{p} \langle S_\mathrm{p} \rangle_N + a_\mathrm{n} \langle S_n \rangle_N \right)^2 \frac{J+1}{J}$$



In this talk I will focus on only SI
(but I love Fluorine!)

Digression: ^{19}F

$$\sigma_{\chi-N} = 4G_F^2 \mu_{\chi-N}^2 C_N$$

$$\mu_{\chi-N} = \frac{M_\chi M_N}{M_\chi + M_N}$$ Reduced mass

G_F Fermi coupling constant

Enhancement factor

$$C_N = C_N^{SD} + C_N^{SI} \qquad (C_N^{SI} \propto A^2)$$

$$C_N^{SD} \propto \left(a_p \langle S_p \rangle_N + a_n \langle S_n \rangle_N\right)^2 \frac{J+1}{J}$$

$<S_p>_N$, $<S_n>_N$ nucleon spin in the nucleus

a_p, a_n : χ-nucleon coupling

Since the signs of $<Sp>_N$ and $<Sn>_N$ are opposite.

^{19}F can play a unique role in

setting limits on a_p & a_n

Materials used so far;

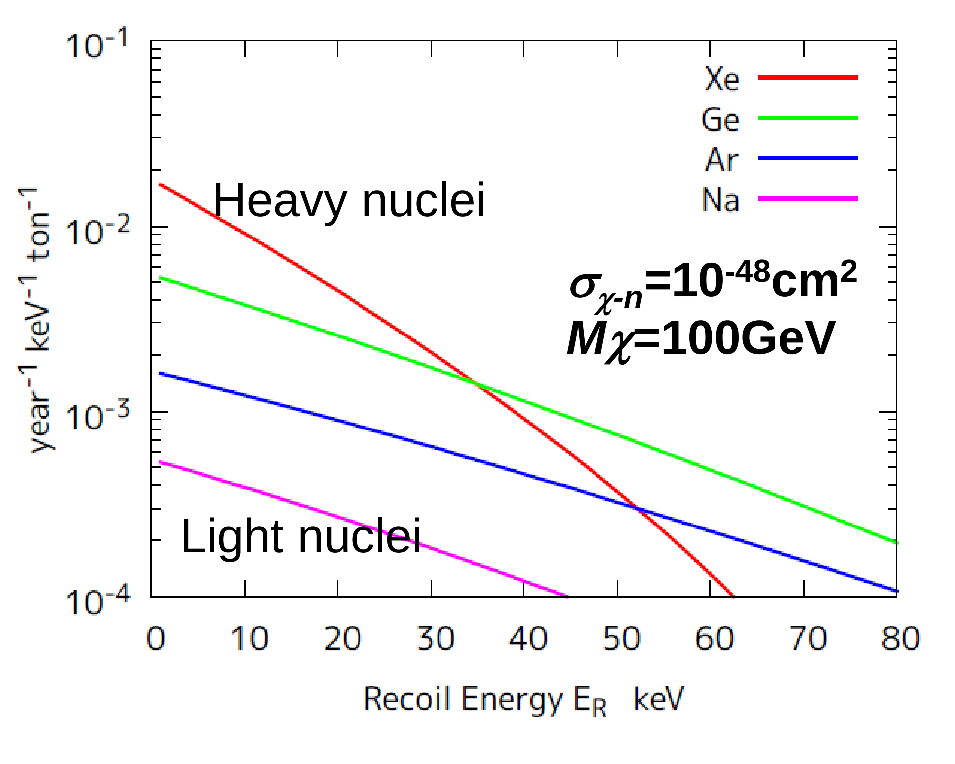
Solid: LiF/NaF
Liquid: CF_3I, C_4F_{10}
Gas: CF_4

Isotope	J	$<S_P>_N$	$<S_n>_N$
^{19}F	1/2	0.441	-0.109
^{7}Li	3/2	0.497	0.004
^{23}Na	3/2	0.248	0.020
^{73}Ge	9/2	0.009	0.372
^{127}I	5/2	0.309	0.075
^{129}Xe	1/2	0.028	0.359
^{131}Xe	3/2	-0.009	-0.227

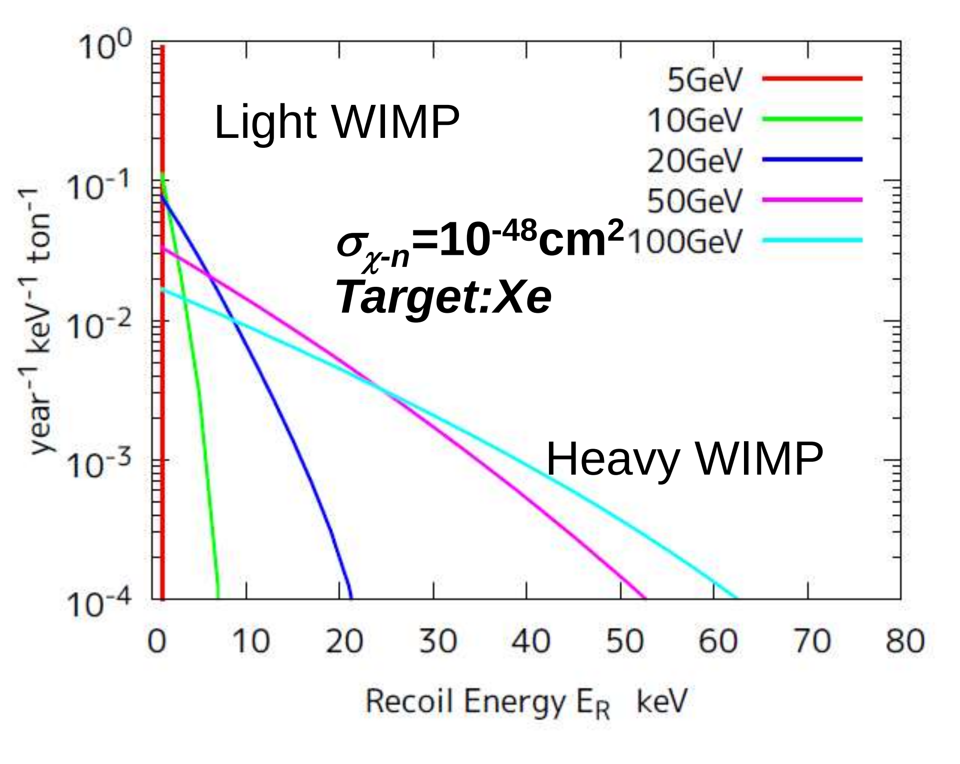
Expected detection rate

- Integrated over the velocity distribution (SI)

For different Nuclei



For different WIMP mass



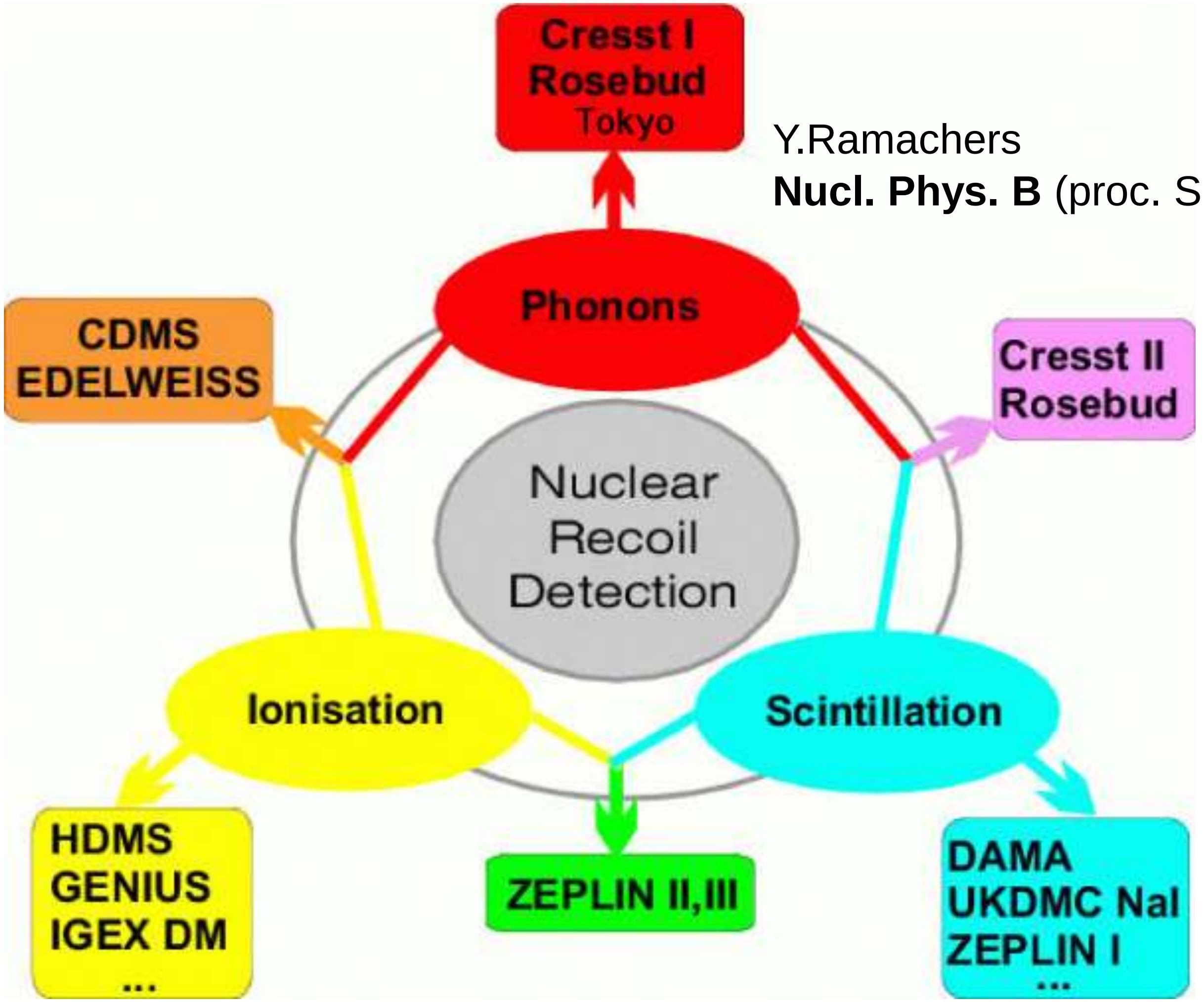
- Ton scale experiments are necessary.
- Heavy nuclei and Light WIMPs are easier for experimentalists

Direct Search Experimental Challenge

As we have seen

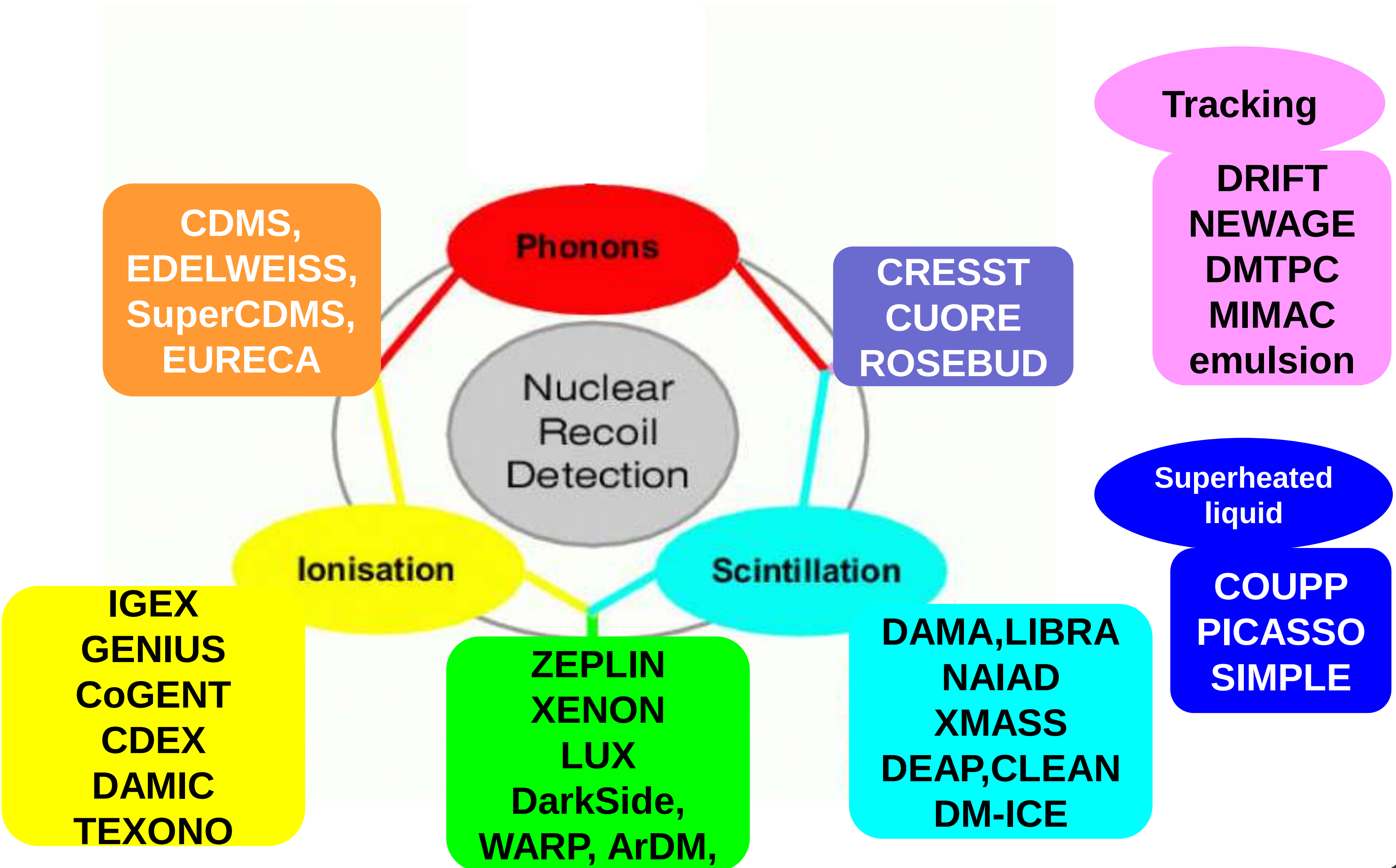
- WIMP nuclear recoil signal is:
  - Low rate (<1 events/ton/year)
  - Low energy (<10keV, actual visible energy is even lower)
  - Expected exponential spectrum is similar to many background signals
- Detection technique must be:
  - Extremely low background
  - Low threshold
  - Large mass
- It's better to be
  - Position sensitive to allow fiducialization
  - Discriminating between WIMPs/n and γ/β
  - Directional

Technologies in 2003



Y.Ramachers
Nucl. Phys. B (proc. Suppl**.) 118(2003)373**

Technologies in 2013



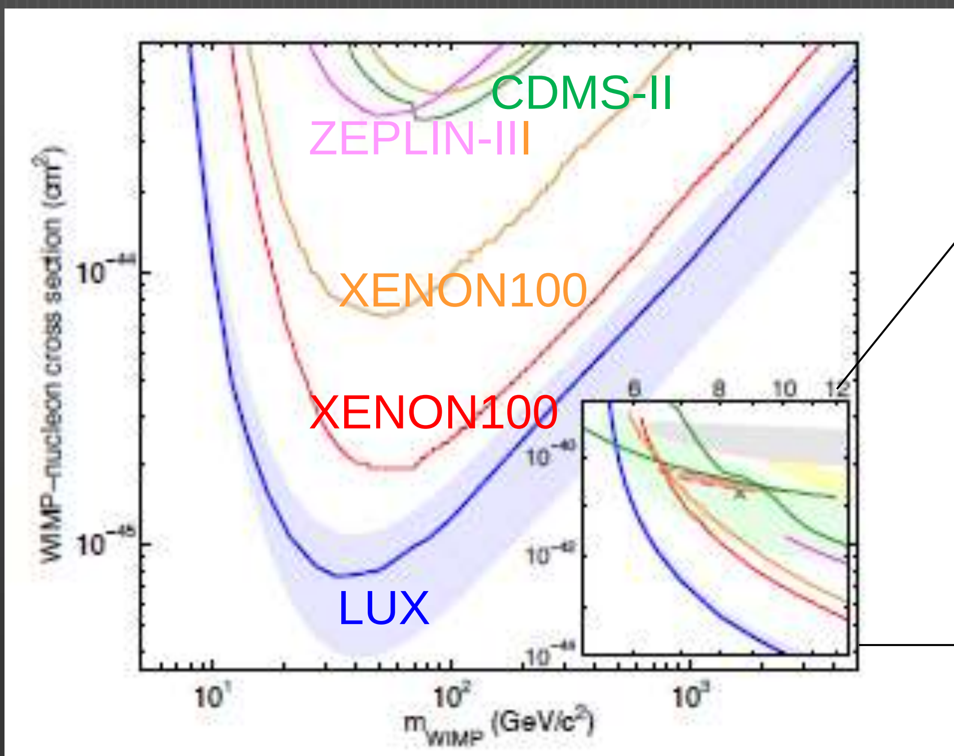
Direct searches on Earth

Baudis SUSY2013

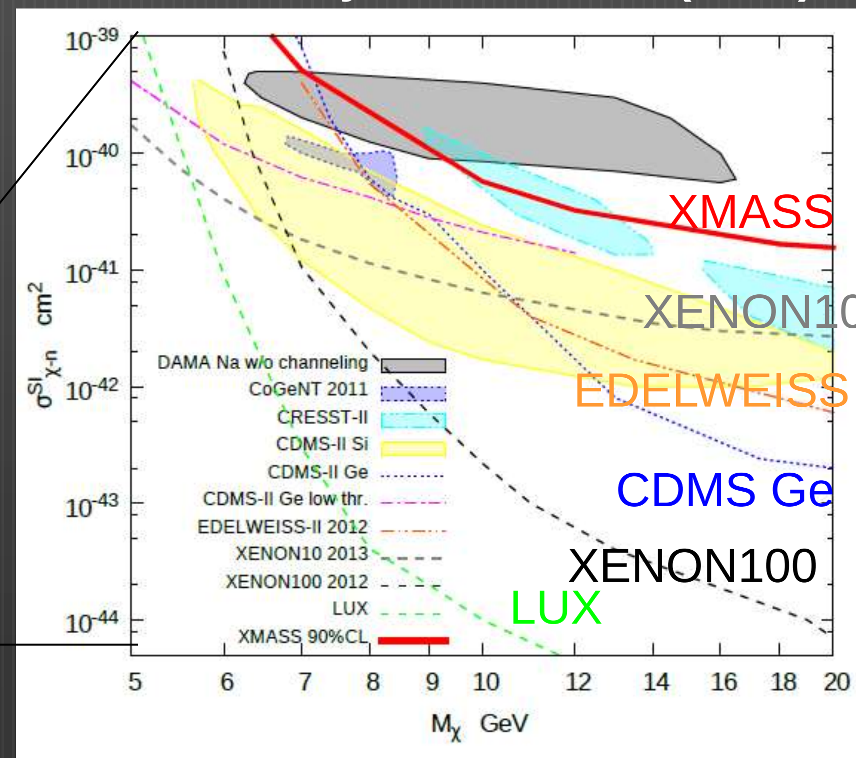
Current Status

- SI WIMP-nucleon cross section limits as of Nov 2013
  - The best is LUX, reaches 10^{-46} cm^2.
  - Top 3 limits are all from double-phase Xe detectors

arXiv:1310.8214



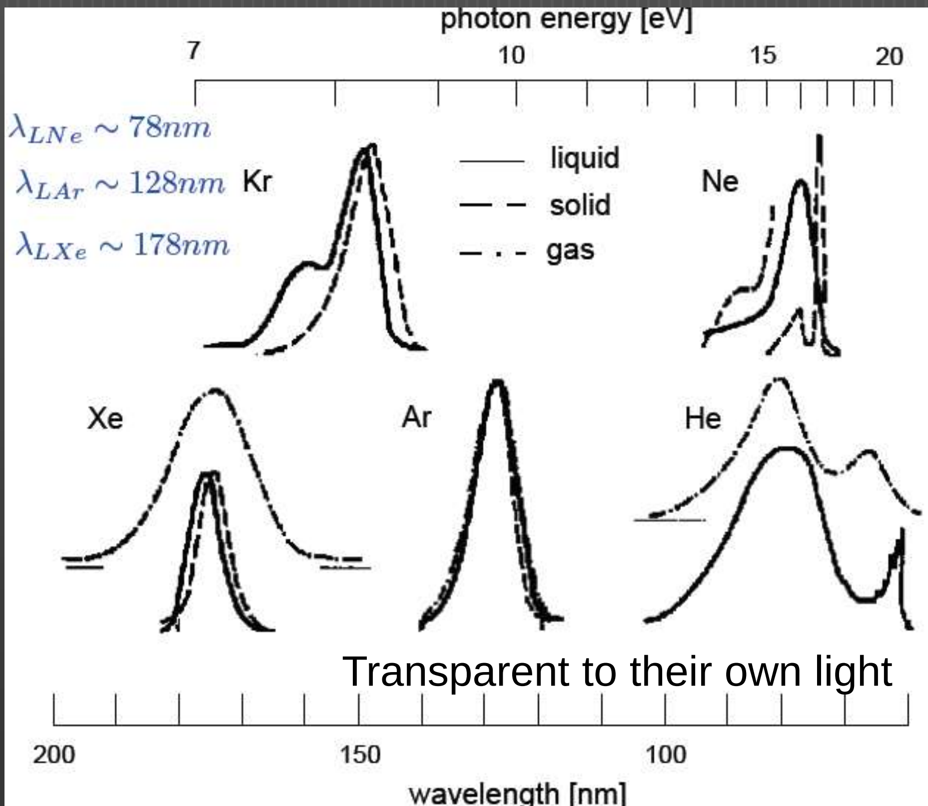
Phys. Lett. B 719 (2013) 78



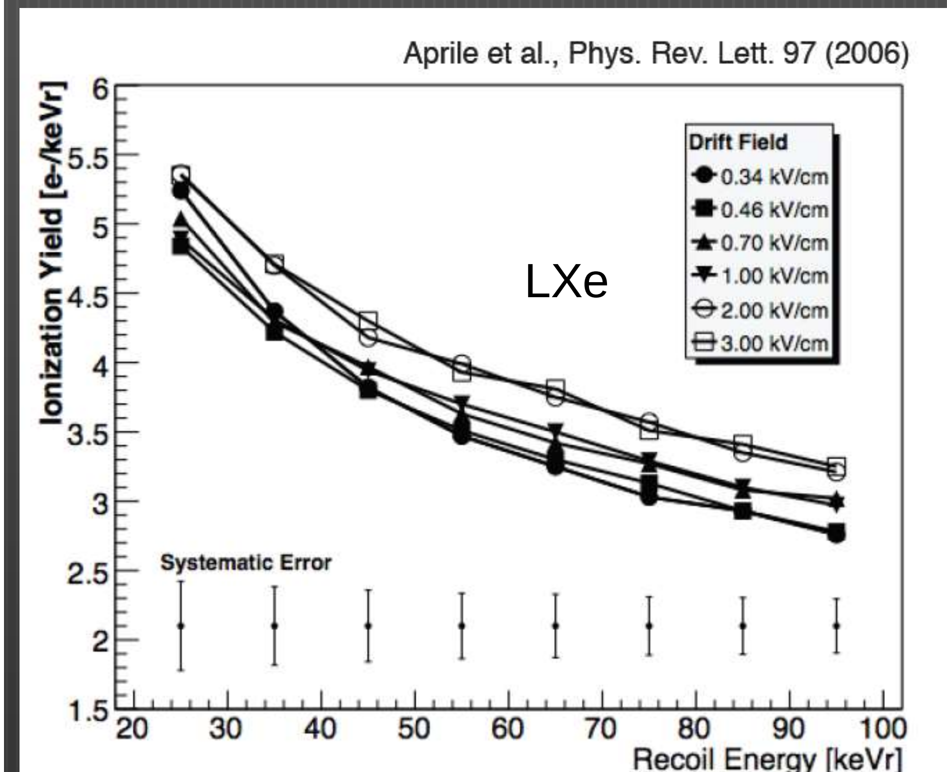
Noble liquid detector

- scintillation detector / ionization detector

Baudis SUSY2013



Aprile Phys. Rev. Lett 97(2006)



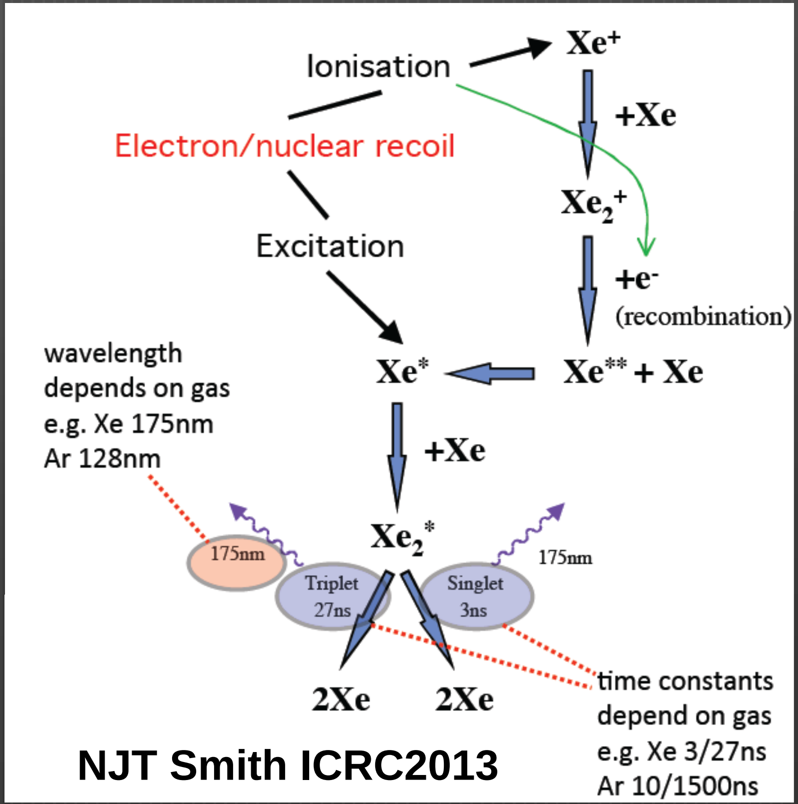
Why are noble liquids good for WIMP searches?

- Large mass/scalability especially Ar ←cost
- Large mass number especially Xe

→Passive BG rejection: self shielding by fiducialization

- Large light yields→low threshold
- Purification→low BG

Noble gas interaction process



NJT Smith ICRC2013

- Both scintillation and ionization signals are detectable.
- Excitation/ionization ratio provides electron/nuclear recoil separation

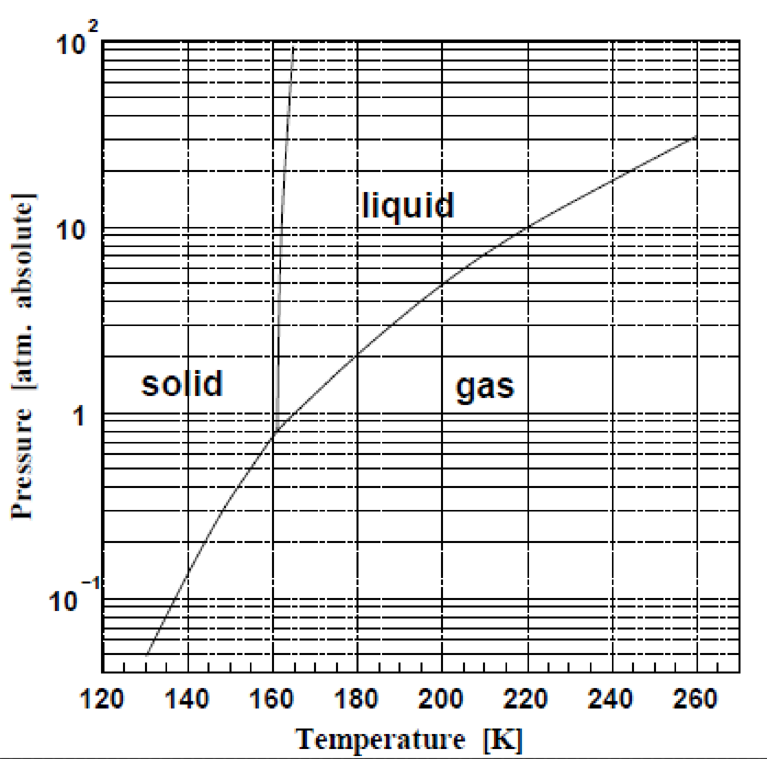
→Active BG rejection

How to use noble liquids

3 concepts has been considered.

- Single-phase (liquid)
  - Just as scintillators
  - TPC to measure ionization directly
- double-phase (liquid+gas)
  - TPC same as single-phase, but this is easier.

Xenon phase diagram



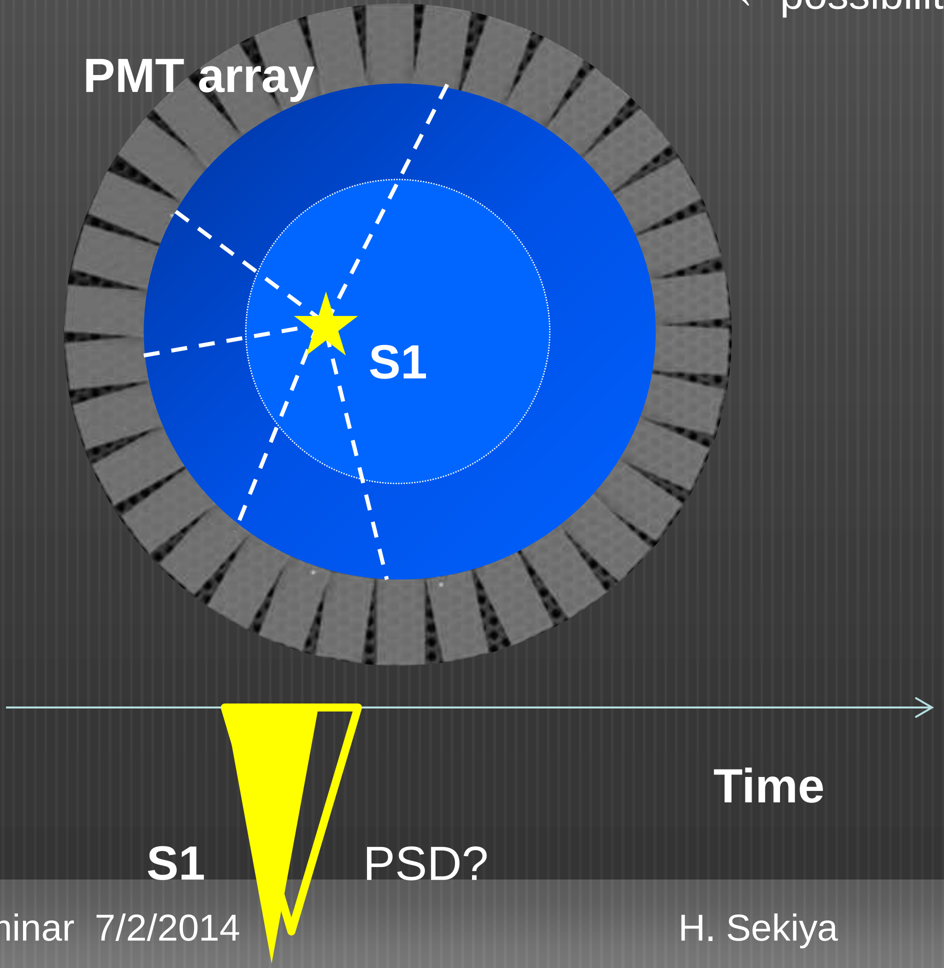
How to use noble solids (R&D@ UCLA, Fermilab,…)

- Single-phase (solid)
  - Just as scintillators
  - TPC to measure ionization directly
- double-phase (solid+gas)
  - TPC same as single-phase, but this is easier.

Single-phase scintillator

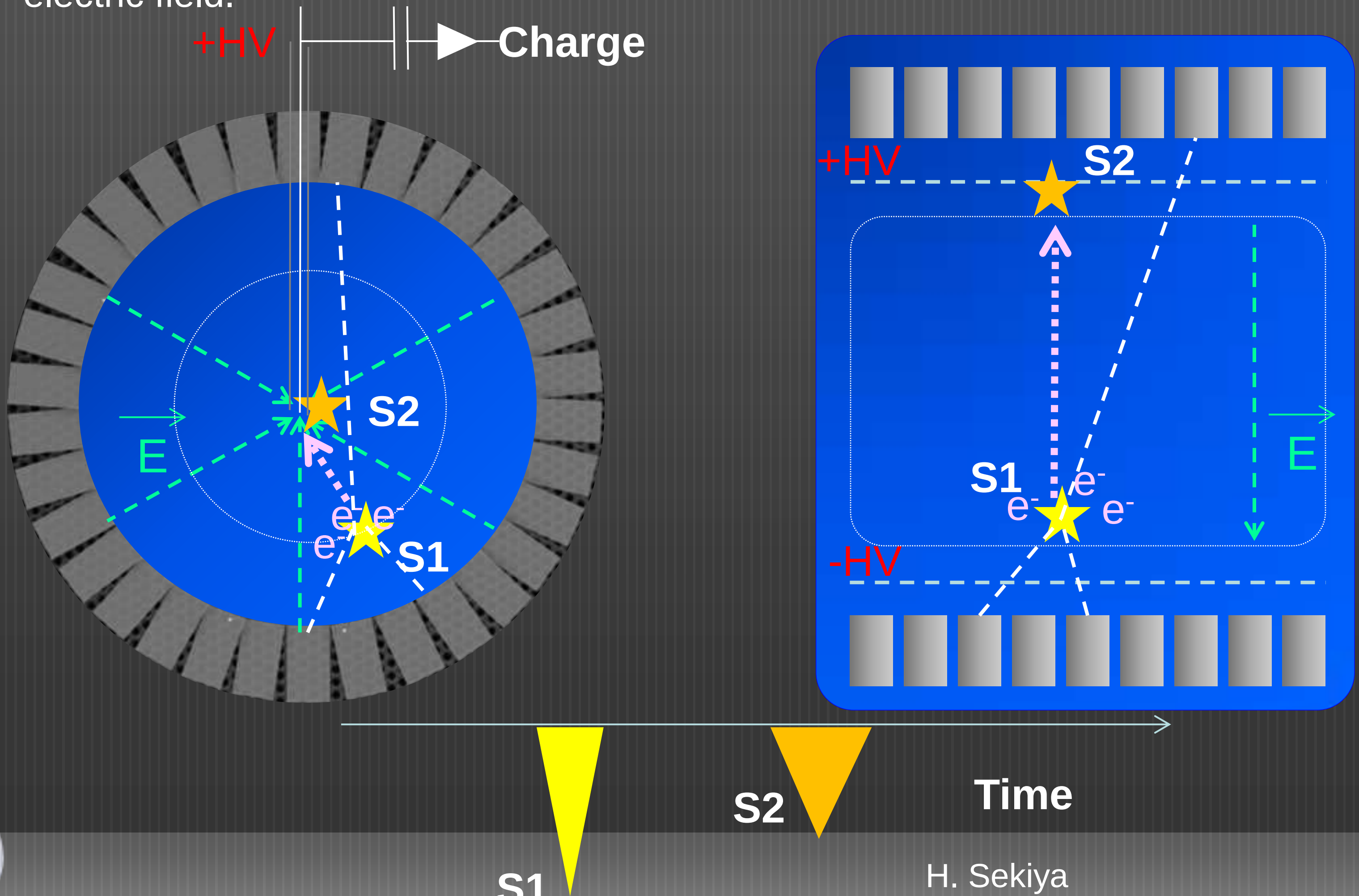
- This concept has been realized recently
  - Also sensitive to ionization, in a sense, through the recombination process
  - Singlet/triplet ratio differs between nuclear/electron recoil events

←possibility of PSD



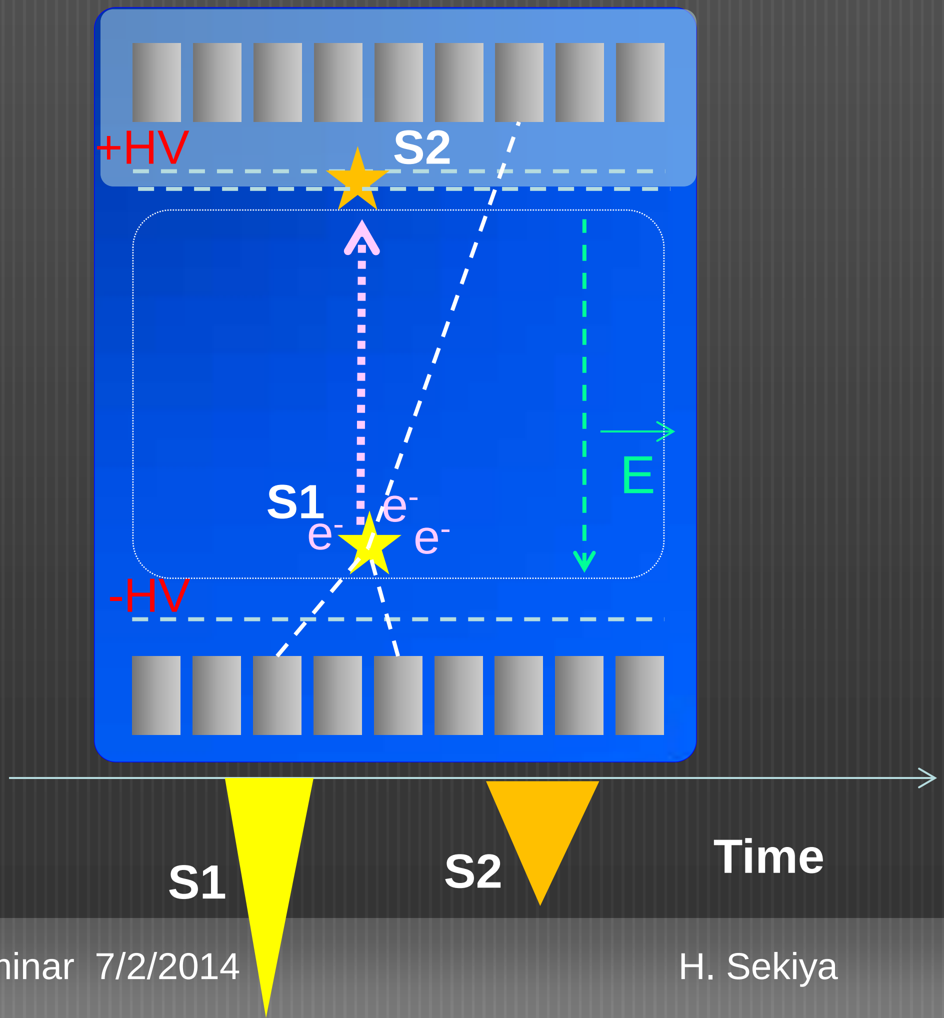
Single-phase TPC

- The original concept, but has not been realized yet.
  - By applying an electric field, electrons produced by ionization can be collected. These can be observed via charge amplification or proportional scintillation with a strong electric field.



double-phase TPC

- Realized first. Now well-established with several successful implementations
  - Same as single phase TPC, but if electrons are extracted from liquid phase to gas phase, charge amplification / proportional scintillation become easier with a strong electric field



Liquid Xe/Ar TPCs

Based on
N.J.T. Smith ICRC2013
L. Baudis SUSY2013

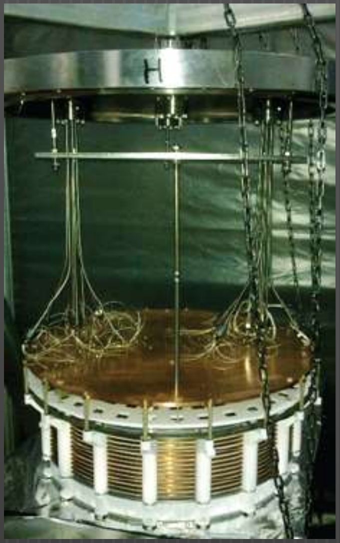
LUX@SURF

350kg total
118kg FV
122 2” PMTs
Data taking will continue until 2015

XENON100@LNGS

161kg total
50kg FV
242 1” PMTs
Data taking on-going

PANDA-X @CJPL



125kg total
25kg FV
143 1” PMTs
37 3” PMTs
Started data taking

ArDM @Canfranc

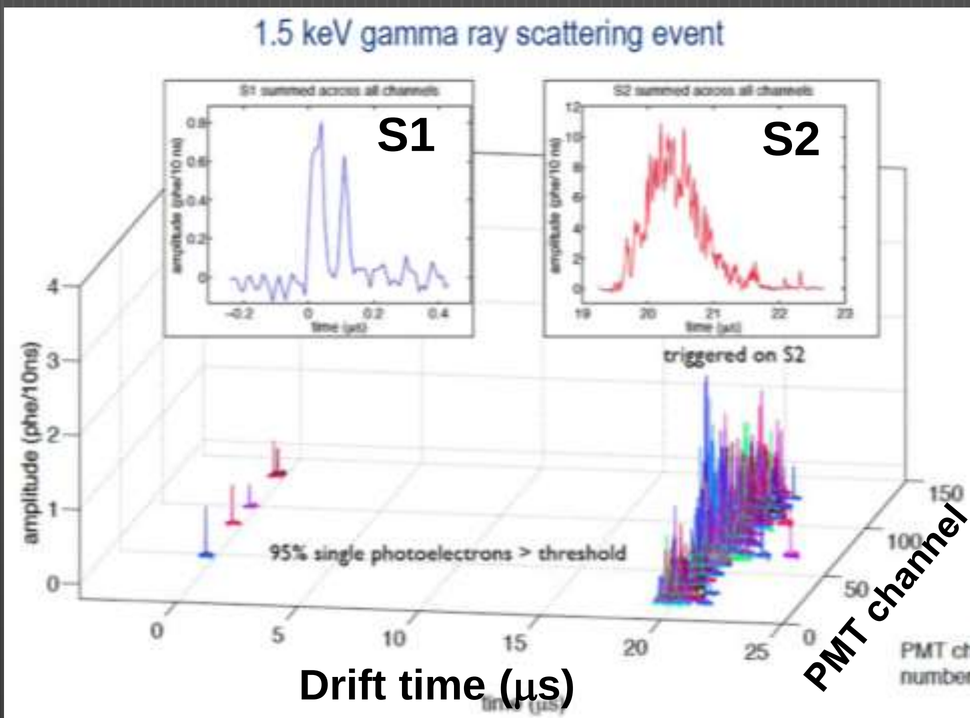
850kg total
100kg FV
28 3” PMTs
Commissioning
Will start taking data in 2014

Darkside @LNGS

50kg total
33kg FV
^{39}Ar (depleted)
38 3” PMTs
Started data taking

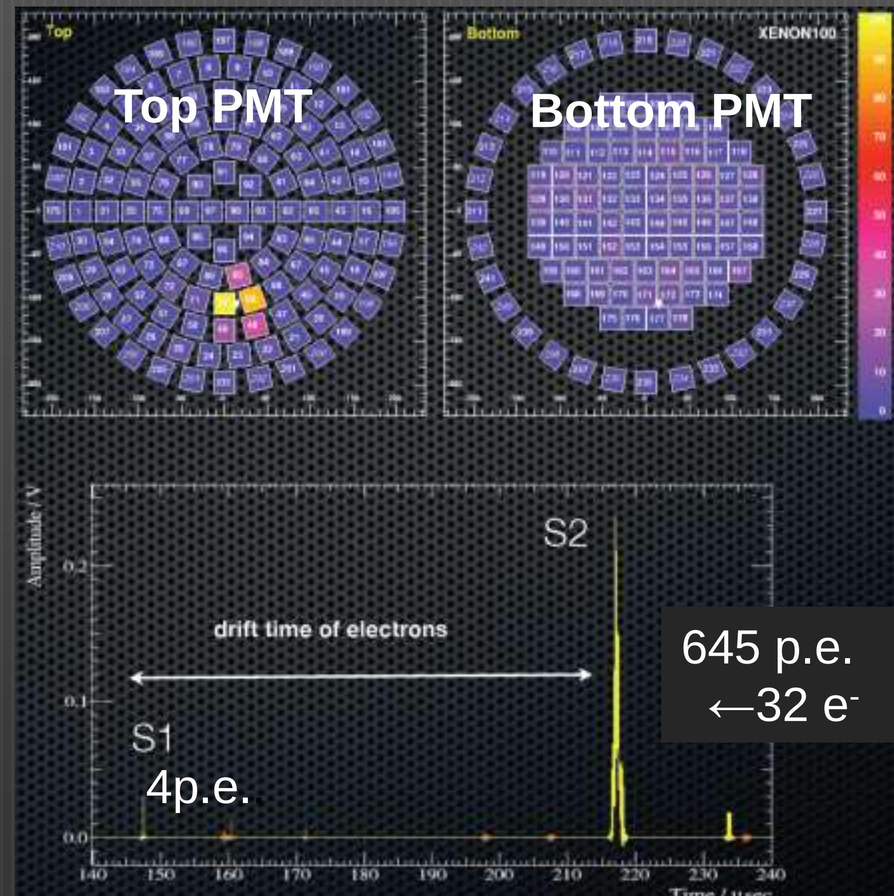
Example events in double-phase detectors

- 1.5keV gamma in LUX



D. McKinsey, R. Gaitskell Oct30 2013

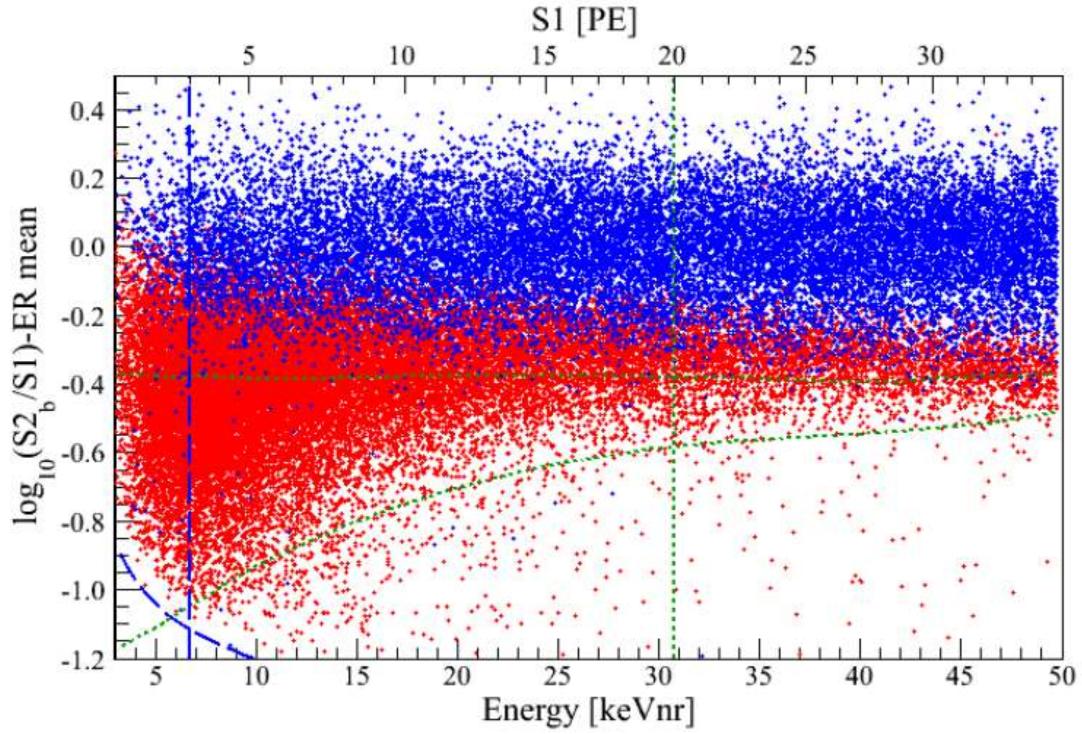
- 9keV recoil in XENON100



L. Baudis SUSY 2013

Electron/nuclear recoil separation power

- XENON100's performance

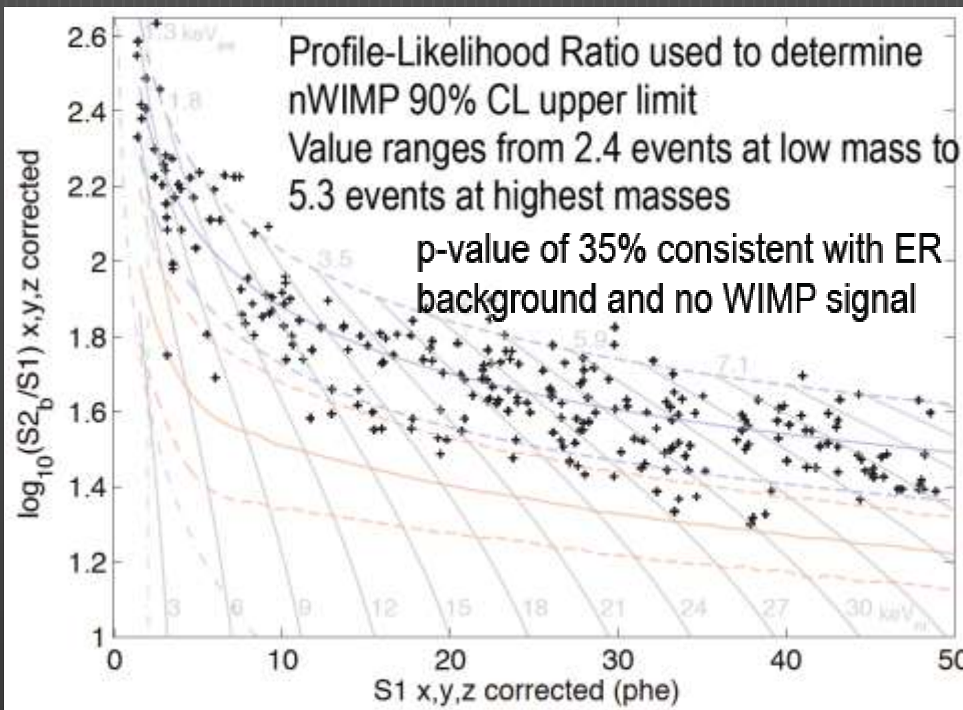


- ER calibration: ^{60}Co and ^{232}Th, NR Calibration: AmBe
- 99.75% ER rejection for 50% efficiency loss on NRs

N. Priel SUSY2013

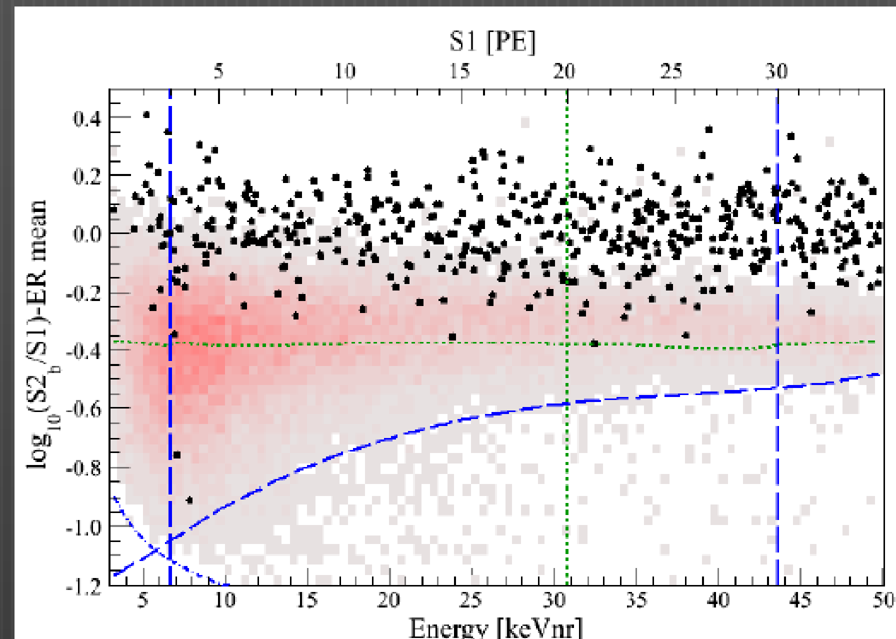
DM search results

- LUX 85 days



D. McKinsey, R. Gaitskell Oct30 2013

- XENON100 225 days



- Expected background of 1 +/- 0.2 events
- 2 events observed
- Compatible with the background hypothesis

N. Priel SUSY2013

Liquid Xe/Ar scintillators

XMASS-1@Kamioka

835kg total
100kg FV
642 2'' PMTs
Refurbished
Restarted data taking

miniCLEAN@SNOLab

500kg total
180kg FV
LNe for solar neutrino
Under construction
Will start taking data in 2014

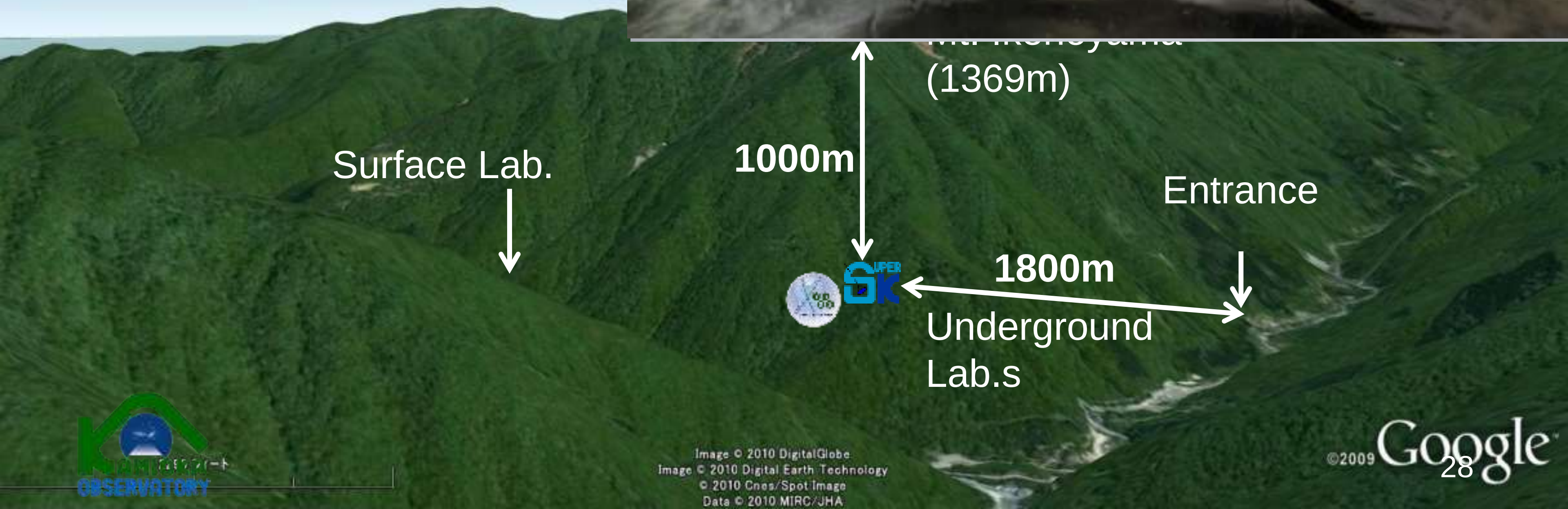
DEAP3600@SNOLab

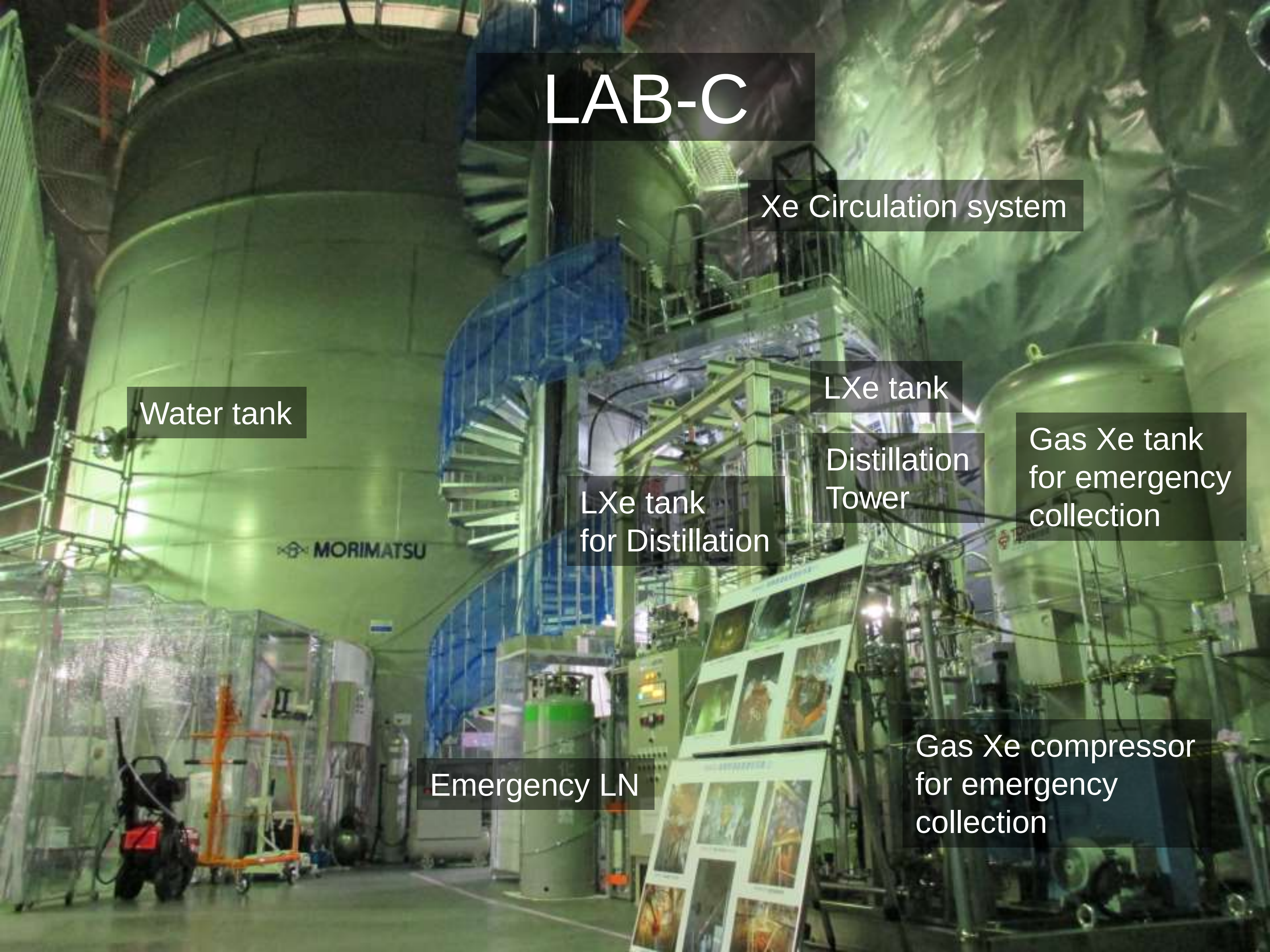
3.6 ton total
1 ton FV
255 8'' PMTs
Under construction
Will start data taking in 2014

XMASS

Where?

- Located underground Mozumi zinc mine at 2700 m.w.e. depth.
- 2km horizontal access cars

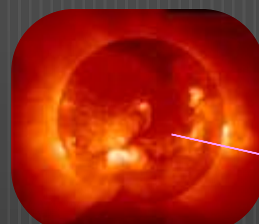



LAB-C
Xe Circulation system
LXe tank
Water tank
Distillation Tower
Gas Xe tank for emergency collection
LXe tank for Distillation
MORIMATSU
Emergency LN
Gas Xe compressor for emergency collection

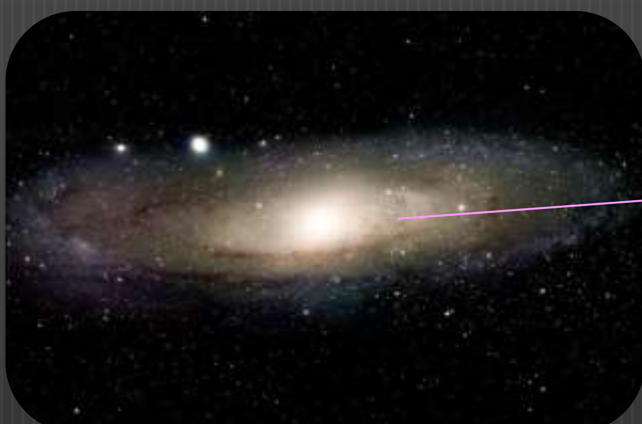
XMASS Projects

Multipurpose low BG experiment with single phase (liquid) Xe

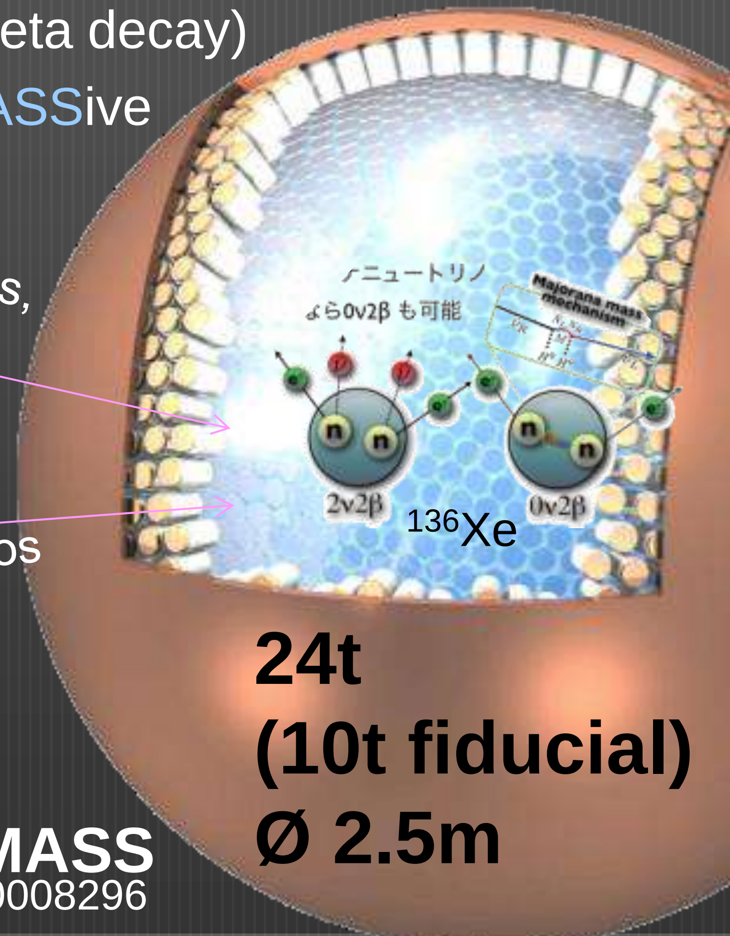
- Xenon MASSive detector for Solar neutrino (pp/^{7}Be)
- Xenon neutrino MASS detector (double beta decay)
- Xenon detector for Weakly Interacting MASSive Particles(DM)



neutrinos, axions



dark matters, neutrinos



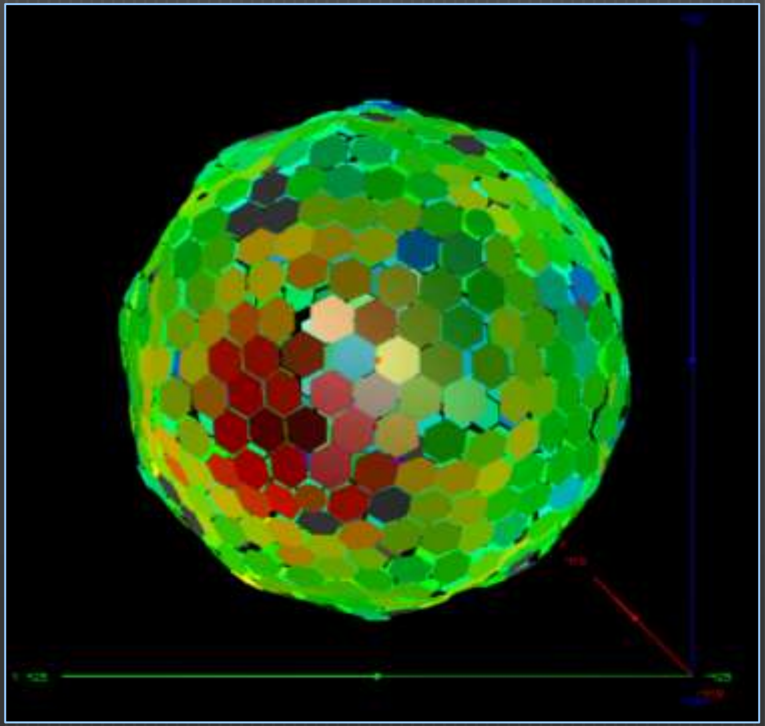
24t
(10t fiducial)
Ø 2.5m

The ultimate XMASS
Y. Suzuki, hep-ph/0008296

XMASS-1

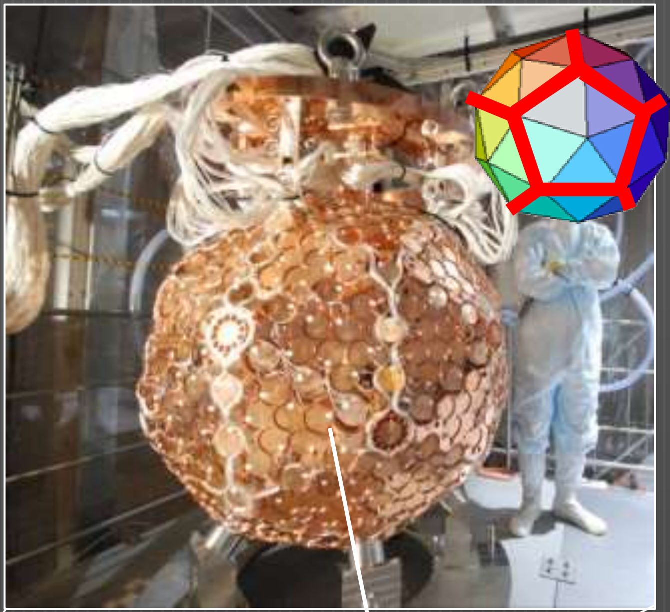
- 835kg LXe detector for Dark Matter search

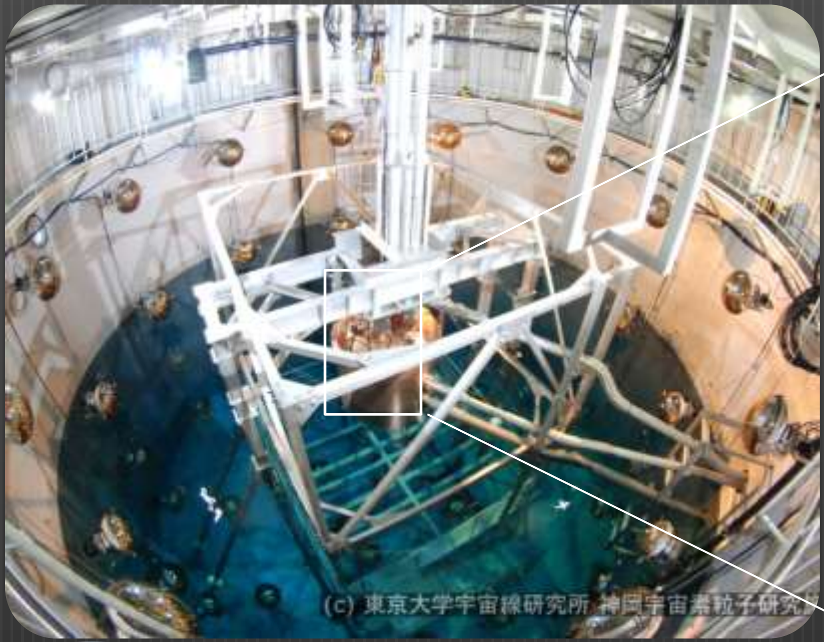
80cm

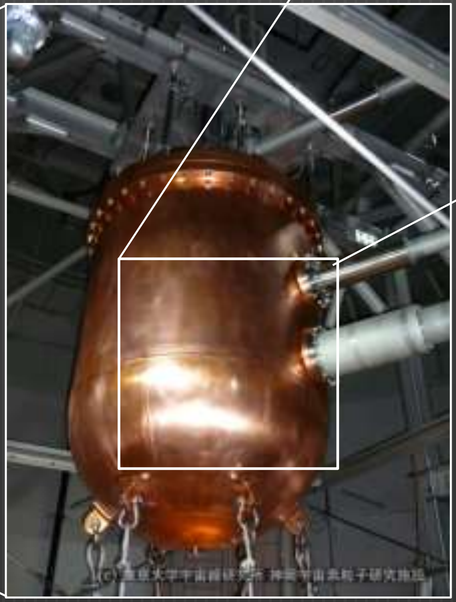


XMASS must be extremely clean

- 10m x ϕ10m water shield for external BG
- Made of pure materials
  - Development of low BG PMTs
- Xe purification technologies
  - Distillation system







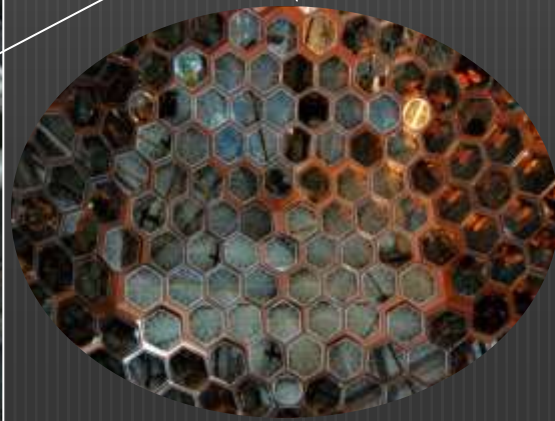


Photo coverage 62.4%

Radiopure PMT

HAMAMATSU

XMASS PMT HISTORY

→LUX

YEAR	2000	2002	2009
Model	Prototype	R8778	R10789
Material:Body	glass	Kovar	Kovar
QE	25%	25%	**27-39%**
RI:			w/ PMT base
U [mBq/PMT]	*50*	*18±2*	*0.70±0.28*
Th [mBq/PMT]	*13*	*6.9±1.3*	*1.51±0.31*
^{40}K [mBq/PMT]	*610*	*140±20*	*9.10±2.15*
^{60}Co [mBq/PMT]	*<1.8*	*5.5±0.9*	*2.92±1.61*

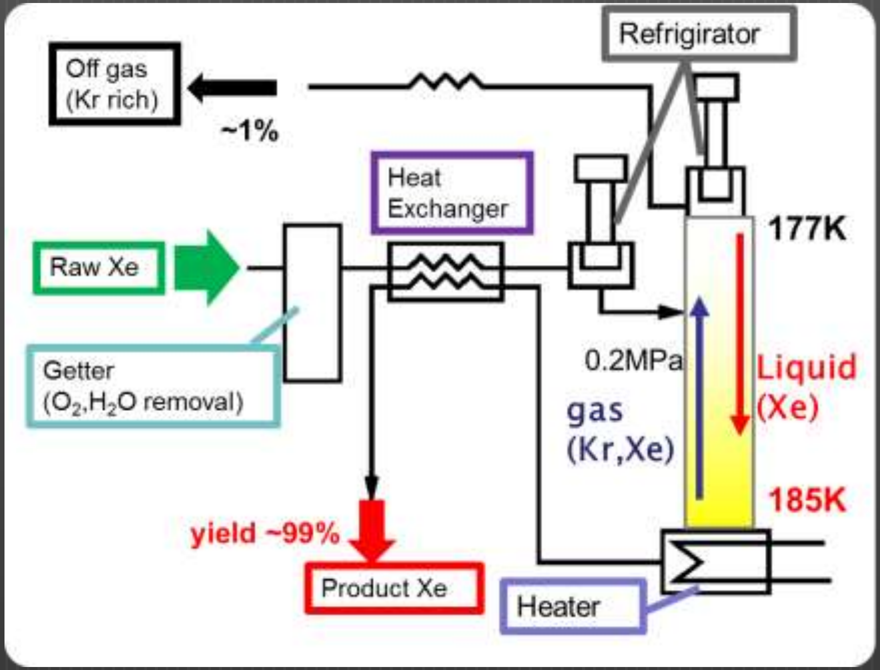
- A radiopure PMT Base has also been developed

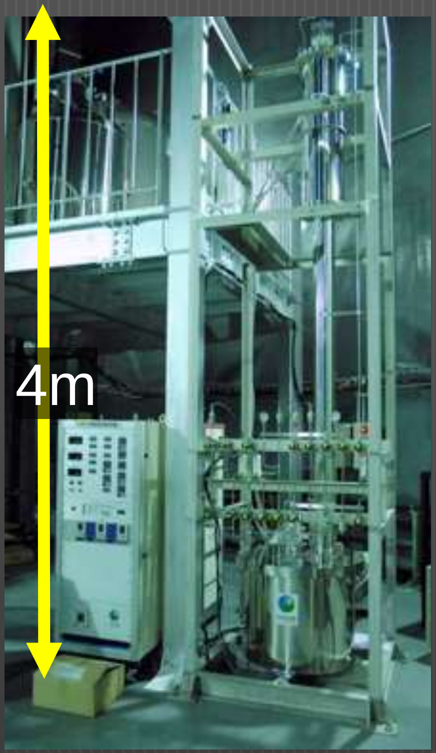
Xe Distillation System

- Commercial "pure Xe" contains ~0.1ppm Kr
  - $^{85}K / K = 1.2 \times 10^{-11}$ τ =10.8 year, Q_β = 687keV
  - 5 order reduction was essential .

	Boiling point (@0.2MPa)
Xe	178K
Kr	140K~150K

We established Xe purifiaction using distillation



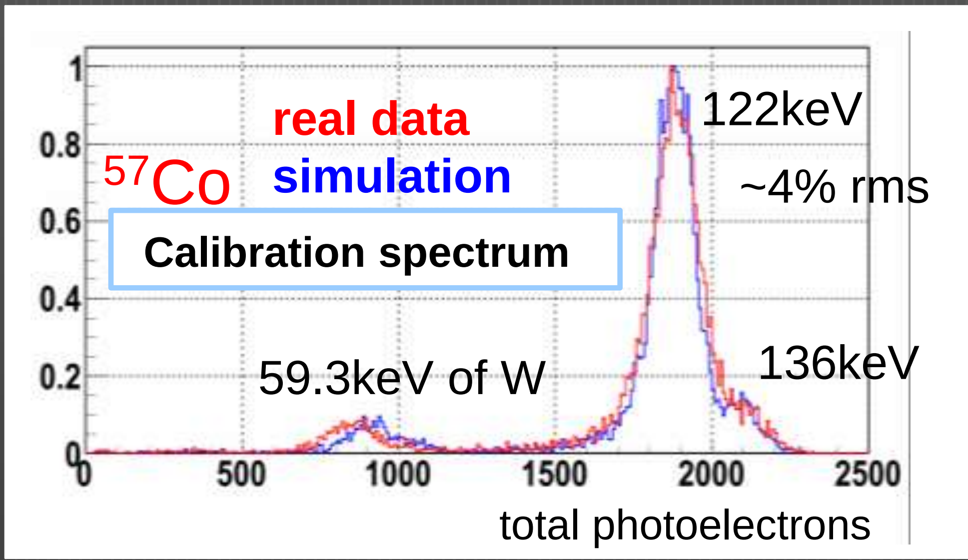


- 1 ton LXe = 170 m^3 gas Xe Process speed: 4.7kg/hr → 10 days
- Confirmed Kr < 2.7ppt by API-MS

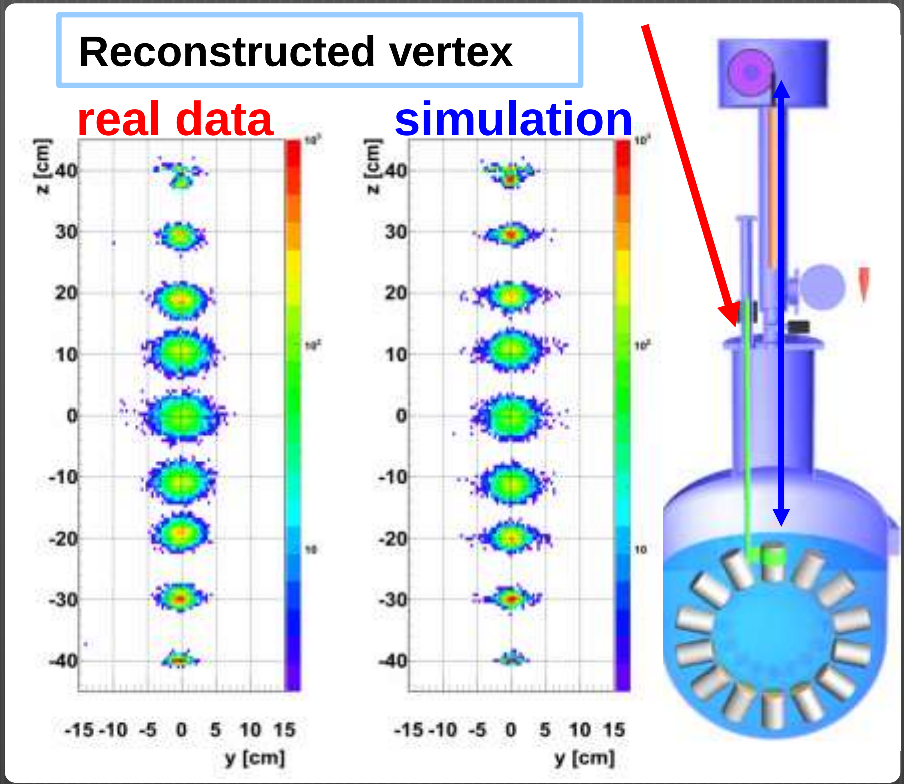
→XENON

NIM A 716 (2013) 78

Detector Response



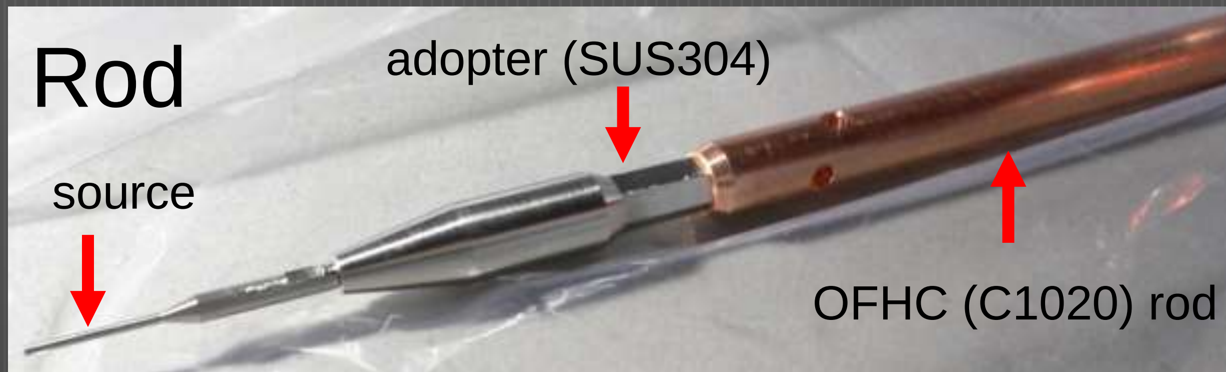
Top PMT manipulator

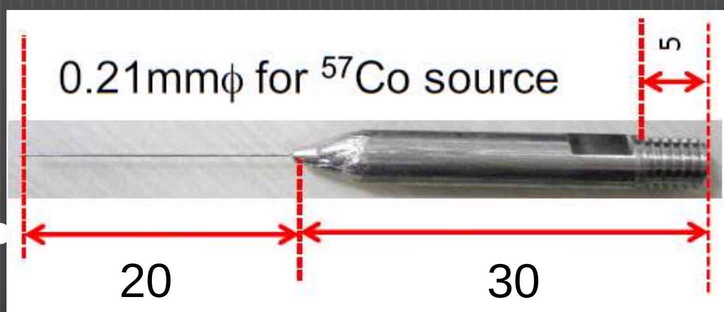


- Highest LXe scintillation yields:
  14.7p.e./keVee
- Lowest threshold: 4hits→0.3keVee

-1.4 cm r.m.s. @ z = 0
-1.0 cm r.m.s. @ z = ±20 cm

(extremely tiny) Calibration sources

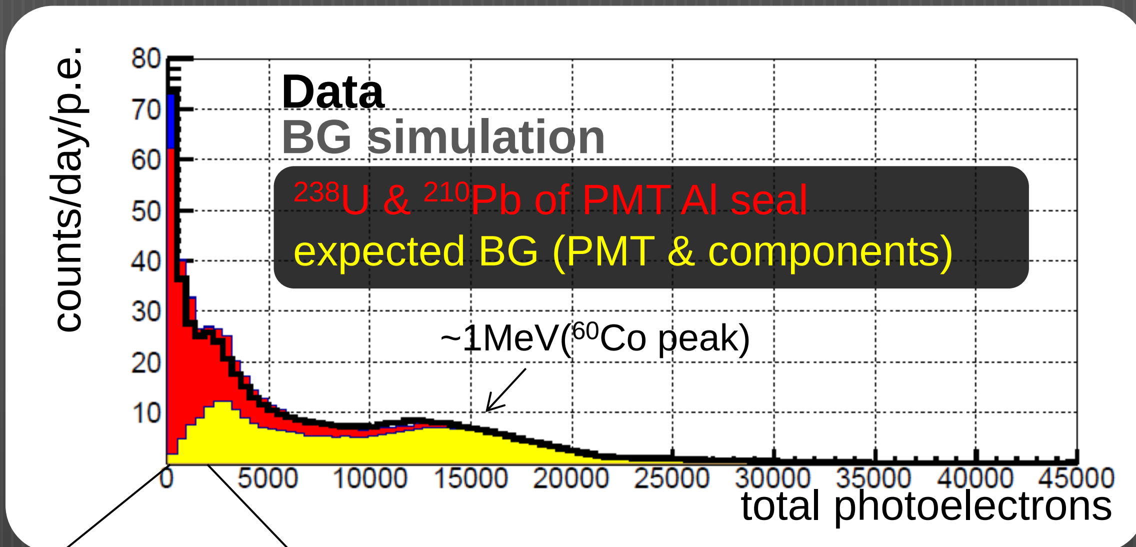


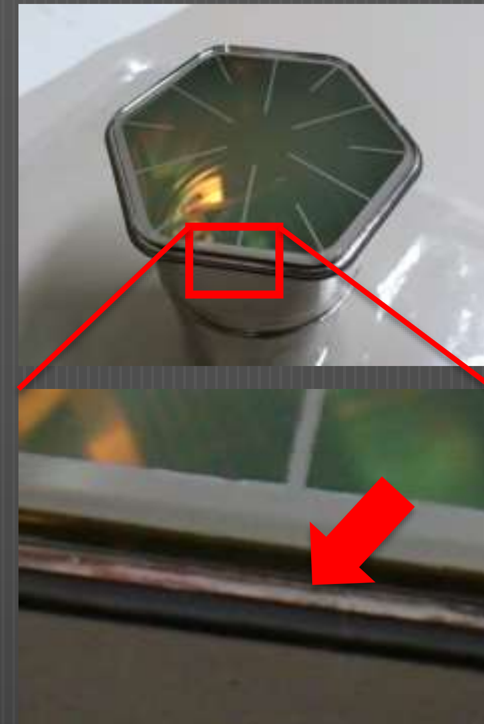


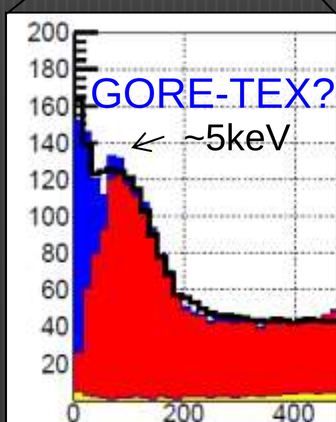
Isotopes	Energy [keV]
^{55}Fe	5.9
^{109}Cd	8(*1), 22, 58, 88
^{241}Am	17.8, 59.5
^{57}Co	59.3(*2), 122
^{137}Cs	662

Unexpected BG

- BG is 2 orders of magnitude higher than expected.



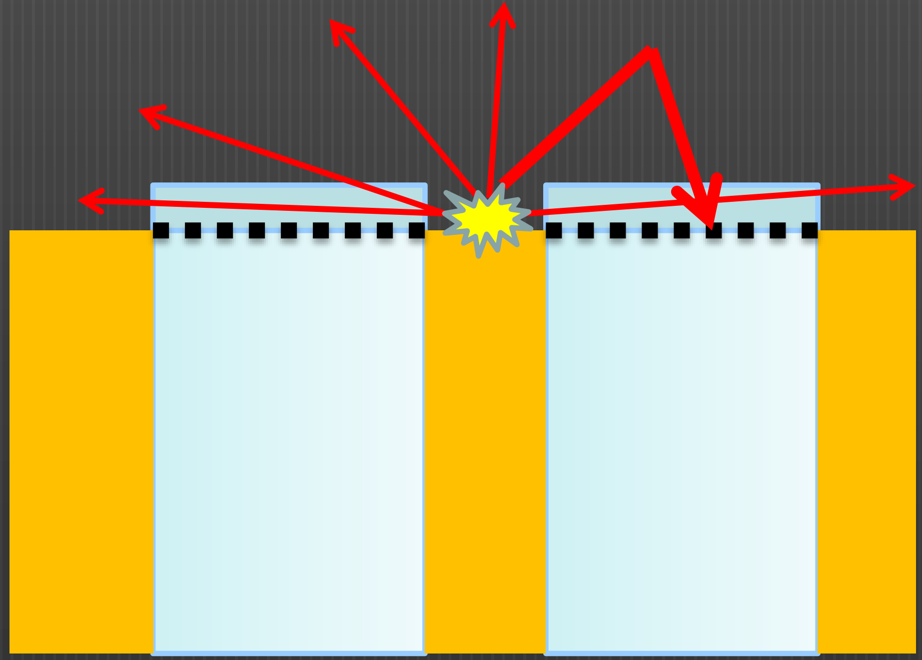




- Major BG source was thoughts to be γ from PMTs, but the observed data seemed to indicate additional surface contamination.
  - Aluminum sealing parts for the PMT (btw metal body and quartz glass) contains ^{238}U and ^{210}Pb (>5keV)
  - GORE-TEX between PMT and holder is suspicious below 5keV.

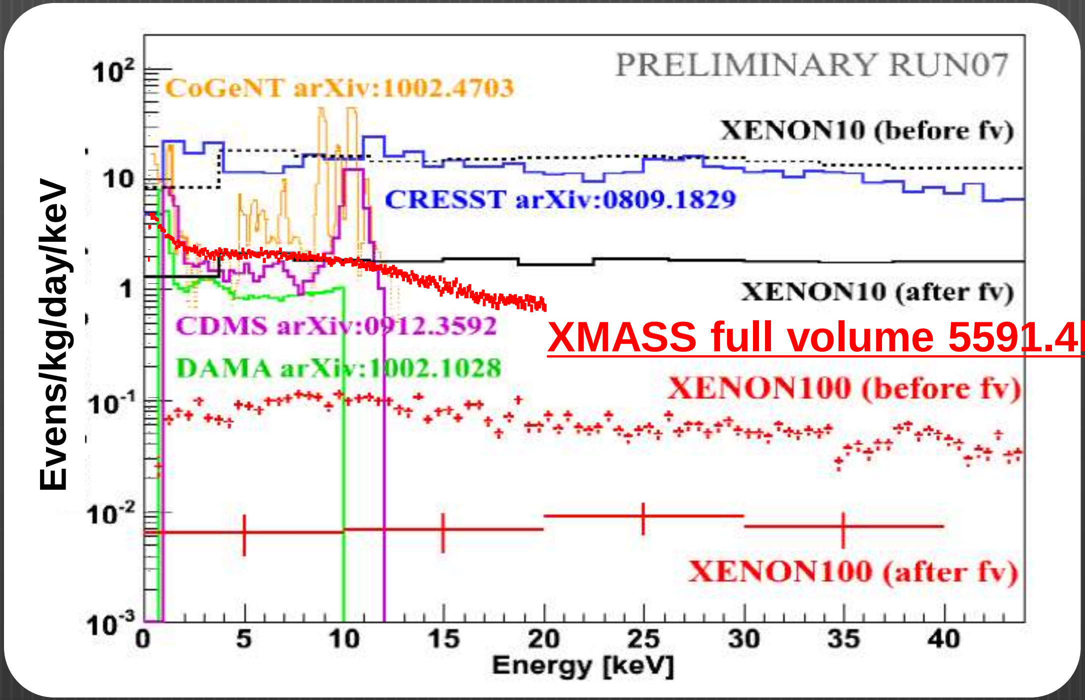
To make matters worse

- Those backgrounds deposit energy on "dead zones" and make position reconstruction difficult
  - Could not conduct a FV analysis.



XMASS Full Volume: Low BG w/o PID

- Although extra BG sources were found, XMASS BG level is still competitive.
  - w/o rejecting electron recoil events.
- XMASS has a competitive sensitivity to Light WIMPs

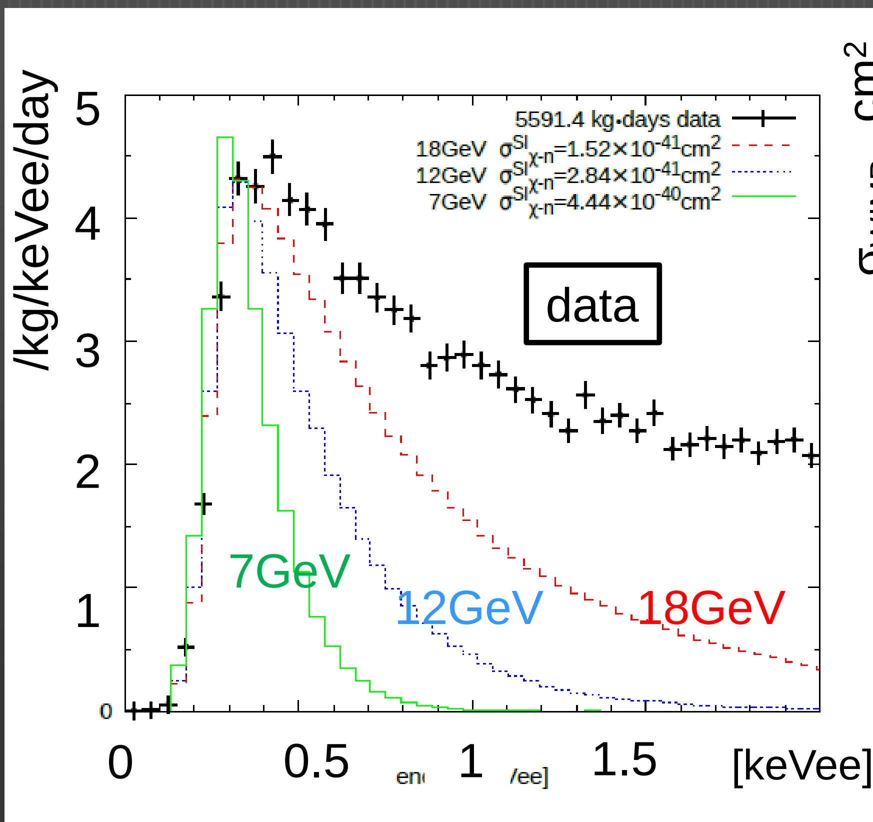


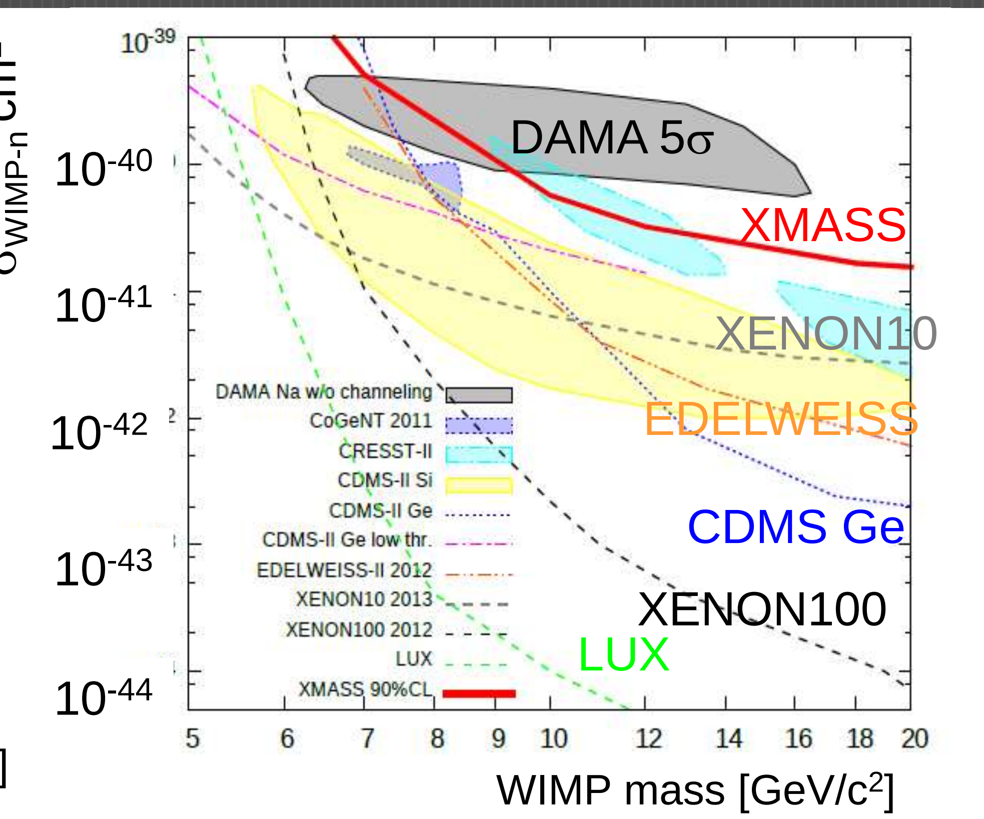
E. Aprile, 2010
Princeton

Light WIMPs

- XMASS set an upper limit on the WIMP-nucleon cross section for WIMPs with masses below 20GeV w/o PID and excluded part of the parameter space allowed by DAMA

Phys. Lett. B719 (2013) 78

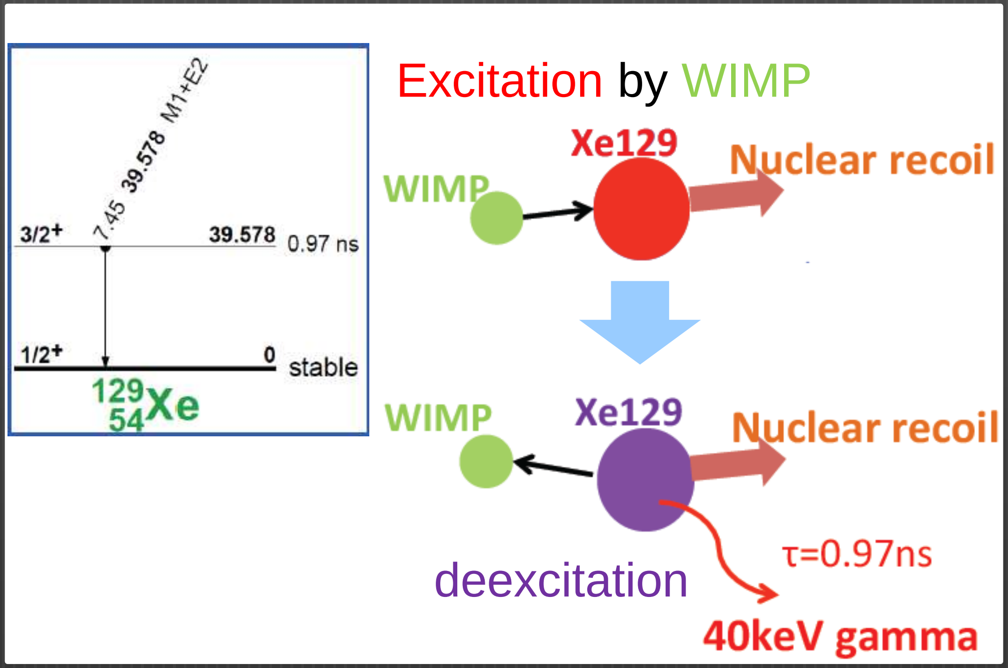




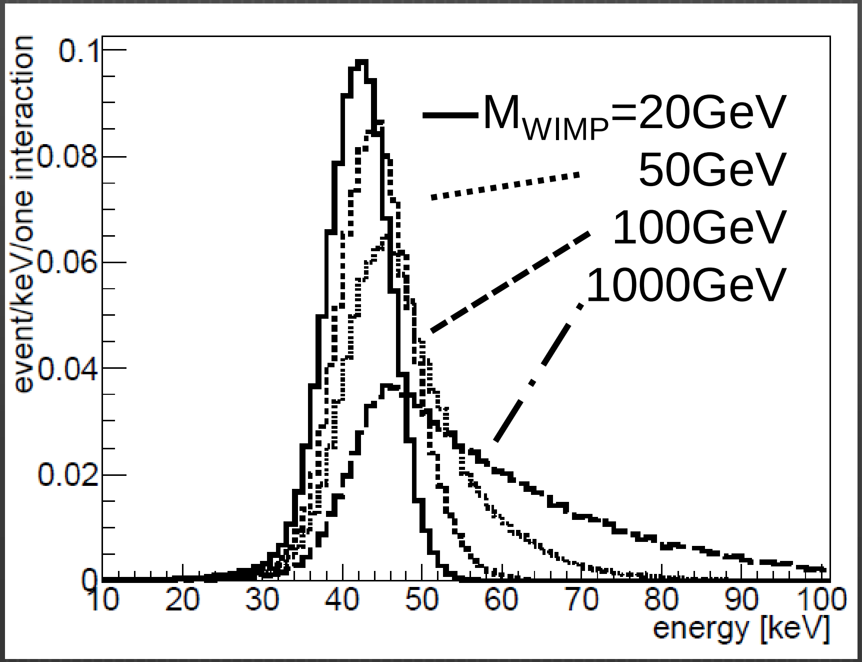
Search via inelastic scattering

arXiv:1401.4737

- XMASS can probe WIMP energy deposition through inelastic scattering using electronic events
- ^{129}Xe (NA 26.4%) has an excited state at 39.578keV

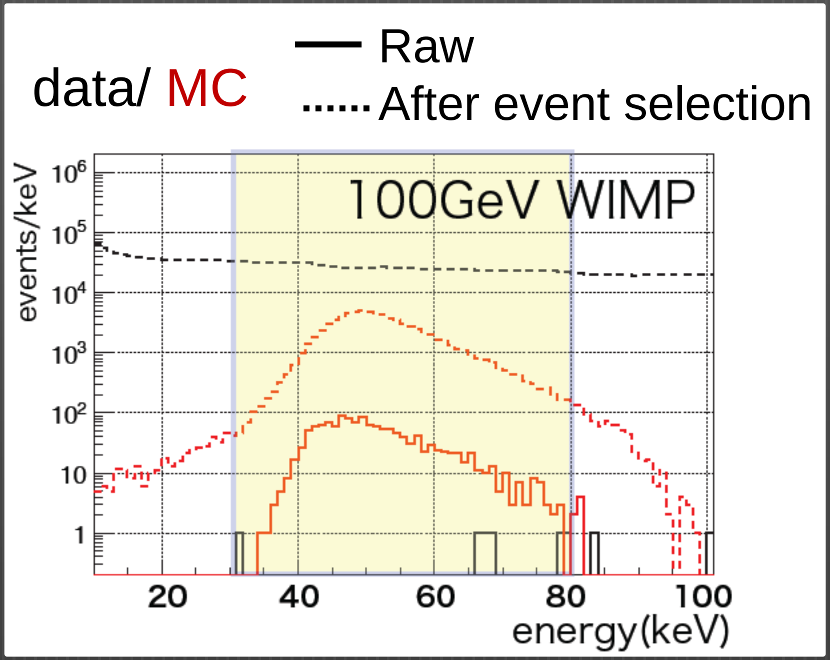


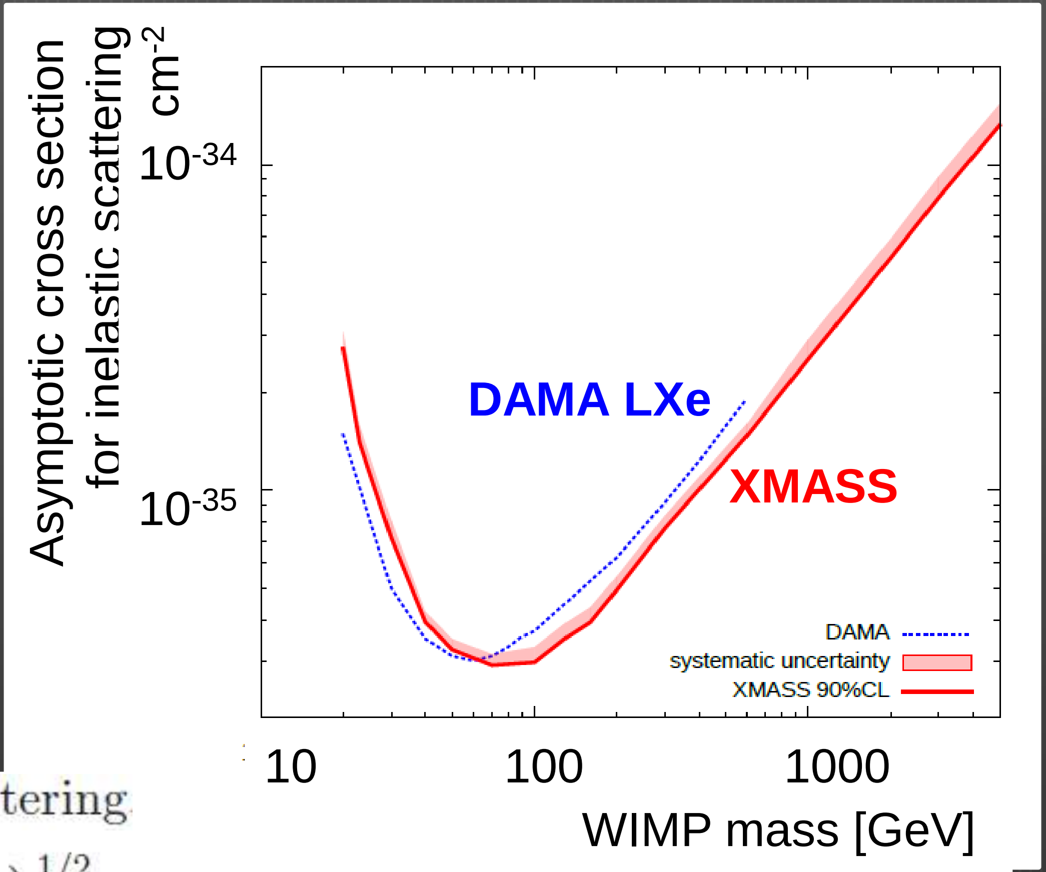
Simulated signal in XMASS



Limits on ^{129}Xe inelastic scattering cross section

arXiv:1401.4737,submitted to PTEP





- Asymptotic means…

the matrix element for inelastic scattering

$$\sigma_I(v) = \frac{\mu^2}{\pi M_N}|\langle N^*|M|N\rangle|^2\left(1-\frac{v_{thr}^2}{v^2}\right)^{1/2}$$

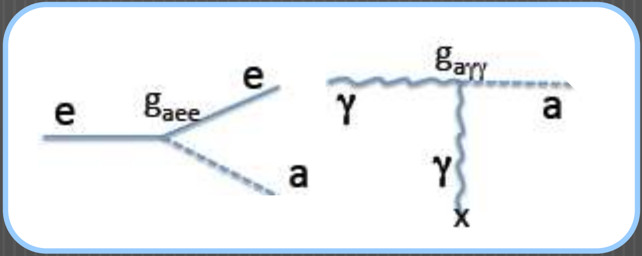
$$= \sigma_I^{as}\left(1-\frac{v_{thr}^2}{v^2}\right)^{1/2} \qquad v_{thr}^2 = 2\Delta E c^2/\mu,$$

The threshold velocity needed to excite ^{129}Xe

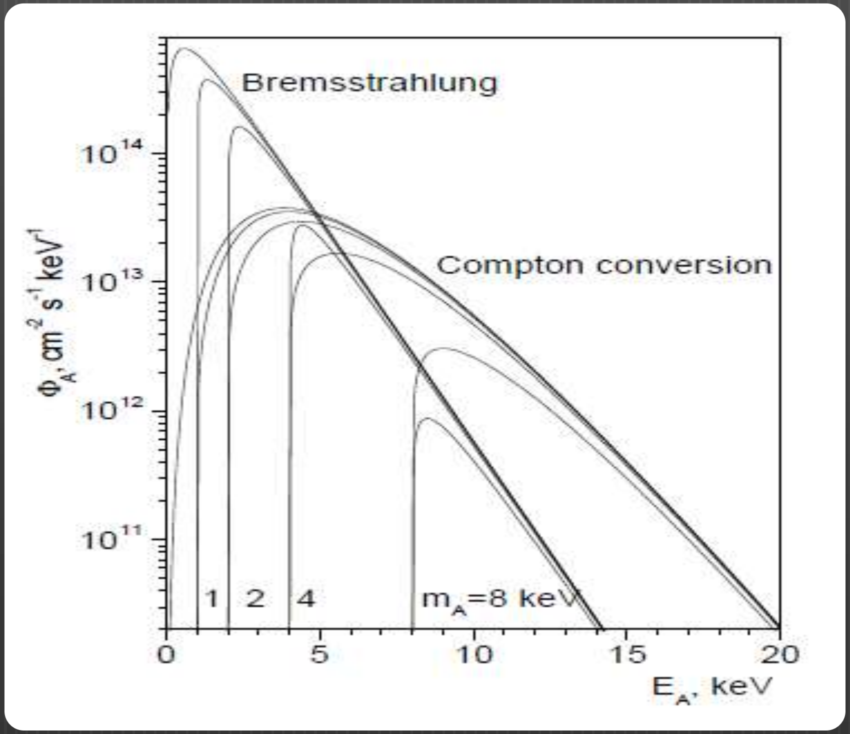
Solar Axions

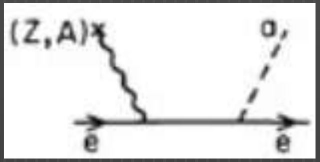
JETP Lett., 95, 379 (2012)
A. V. Derbin et al.,arXiv:1206.4142

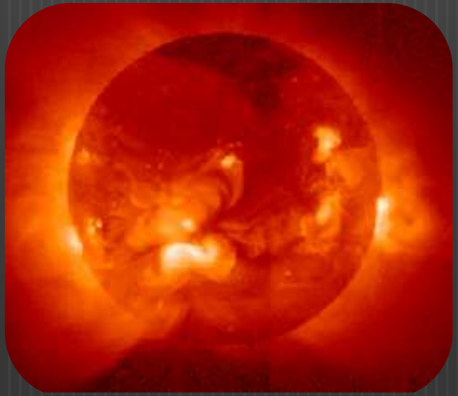
- Through the axio-electric effect in Xe, XMASS also has sensitivity to solar axions, which may be produced by Bremsstrahlung and Compton effects (g_{aee}) in the Sun
  - N.B. Not $g_{a\gamma\gamma}$ through Primakoff effect



Expected flux $g_{aee}=10^{-10}$



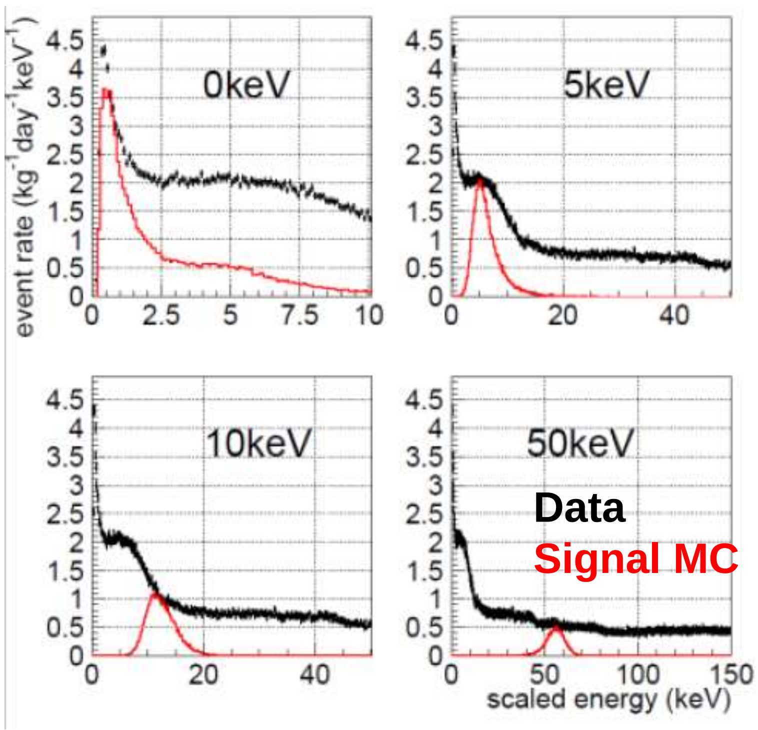


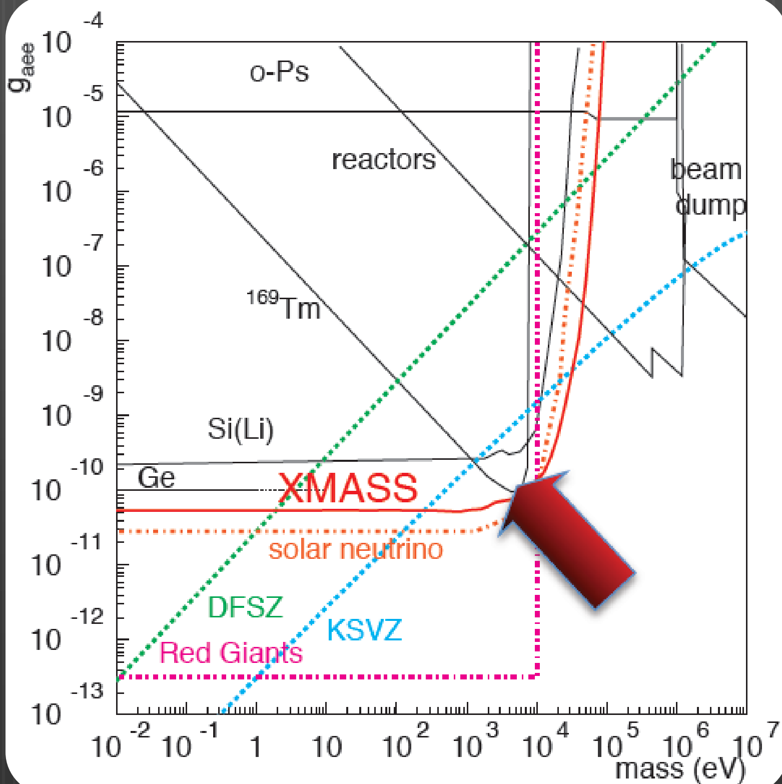


Phys. Lett. B724 (2013) 46

Solar Axions

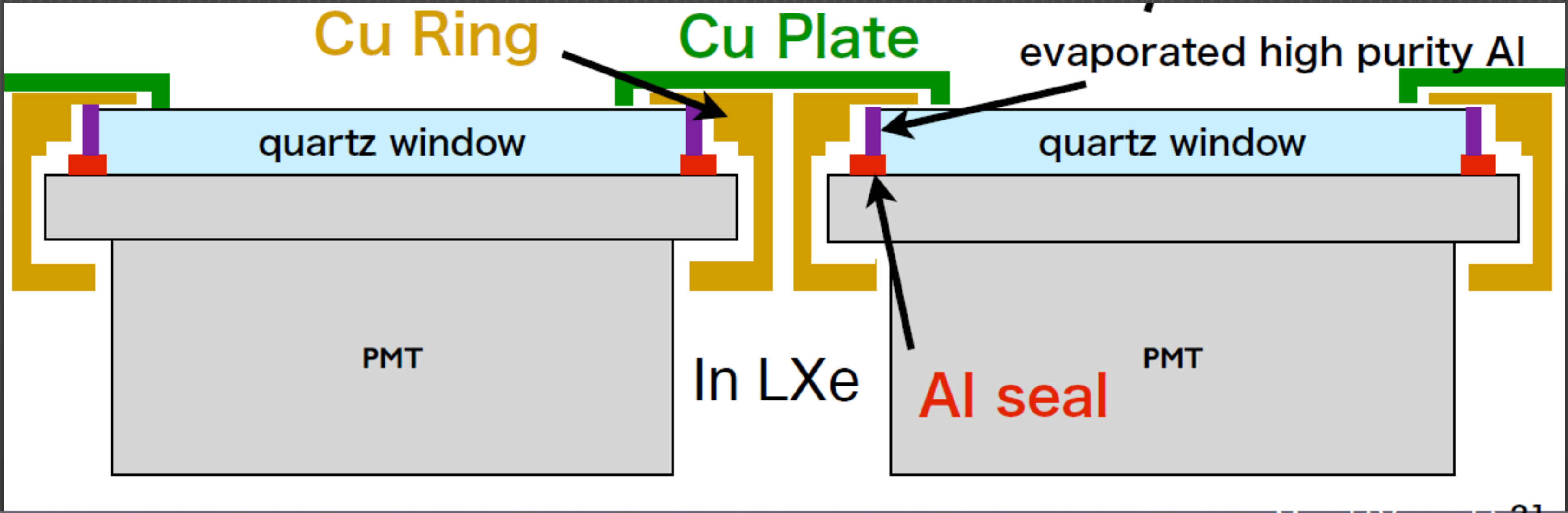
- Same data set as Light WIMP search
- No indication of signals. Bound in gaee vs. mass.
- Better than any other constraint in 10-40keV.
- Better than any other experimental constraint





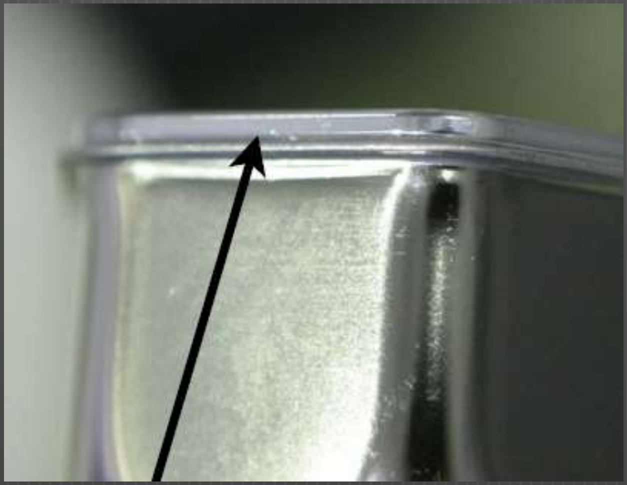
XMASS-1 Refurbishment
for Background reduction

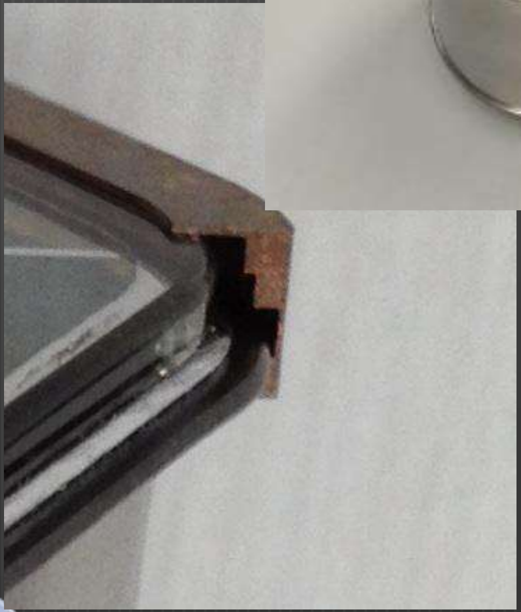
- Countermeasures
  - PMT+Cu surfaces were cleaned and GORE-TEX was removed.
  - High purity Al was deposited on the side of PMT window to prevent light leakage from dead zone
  - PMT Aluminum seal was covered
    - Cu ring around aluminum seal
    - Electro-polished Cu plate above Cu rings



XMASS-1 **Refurbishment**
for Background reduction

- Countermeasures





Refurbishment

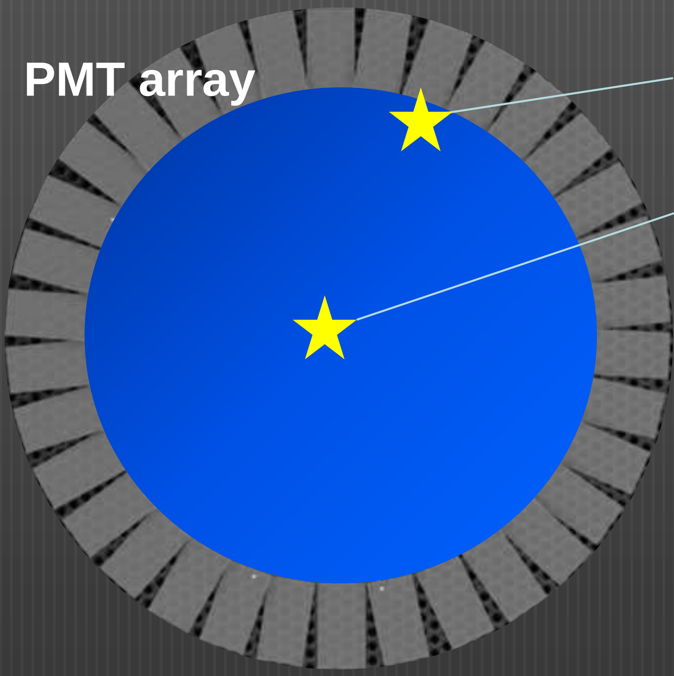
before

after

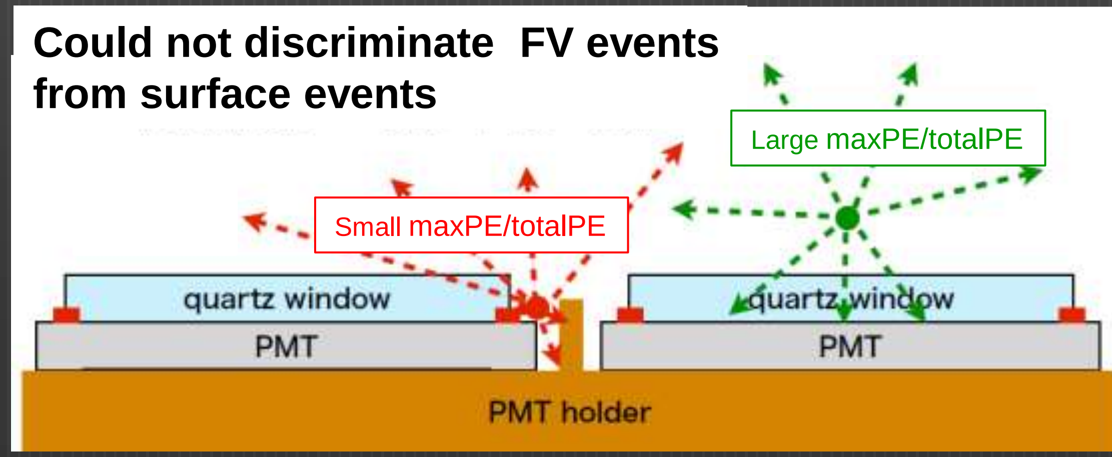
- Resumed data taking in November 2013
  - First data looks… improved!

Quick look at the data after RFB

- maxPE/totalPE = $\dfrac{\text{Maximum photoelectrons in one PMT}}{\text{Total photoelectrons}}$

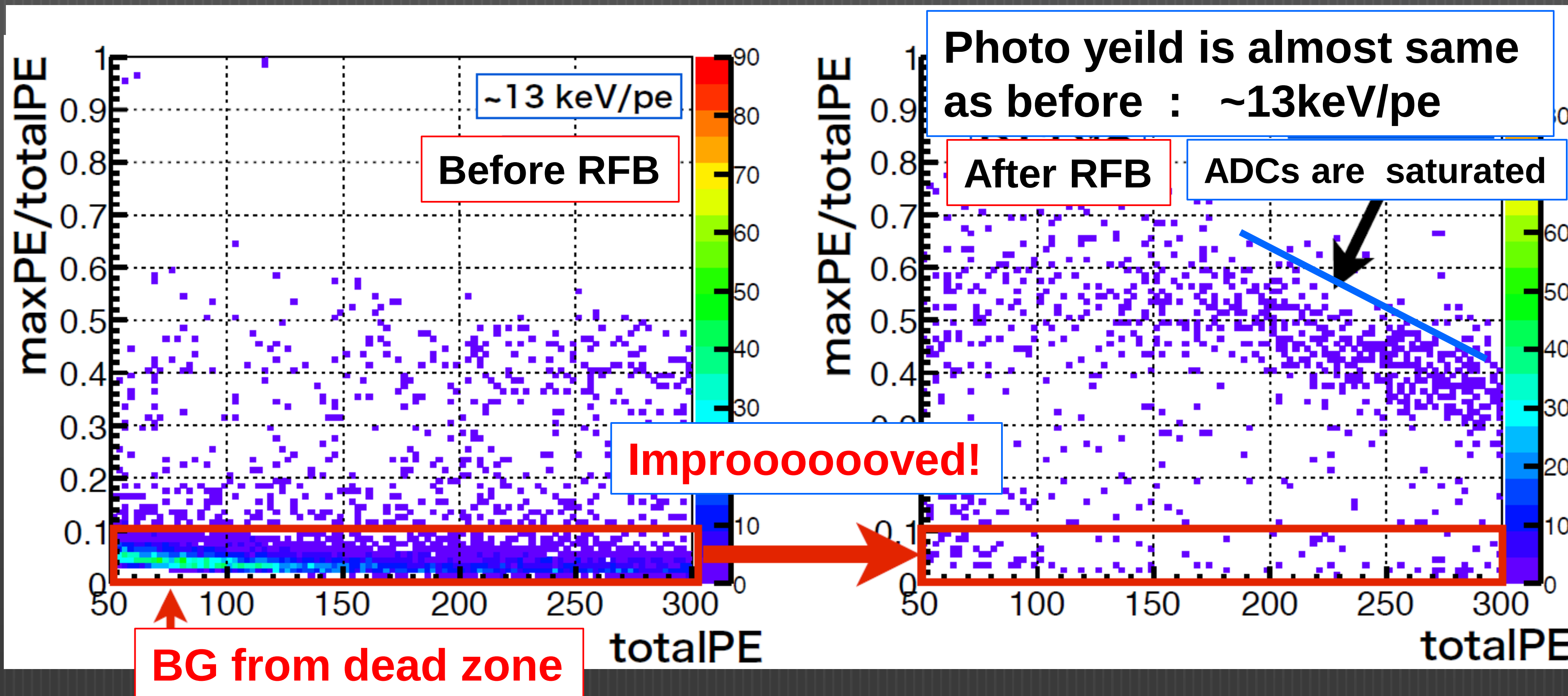


The larger R, the larger maxPE/totalPE
EXCEPT events in the dead zone



Quick look at the data after RFB

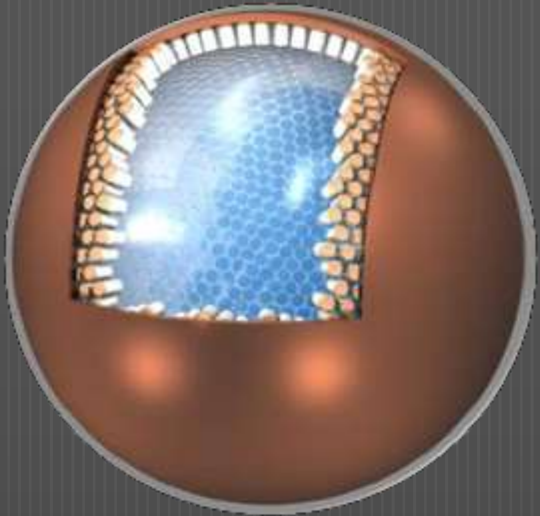
Normalized by live time



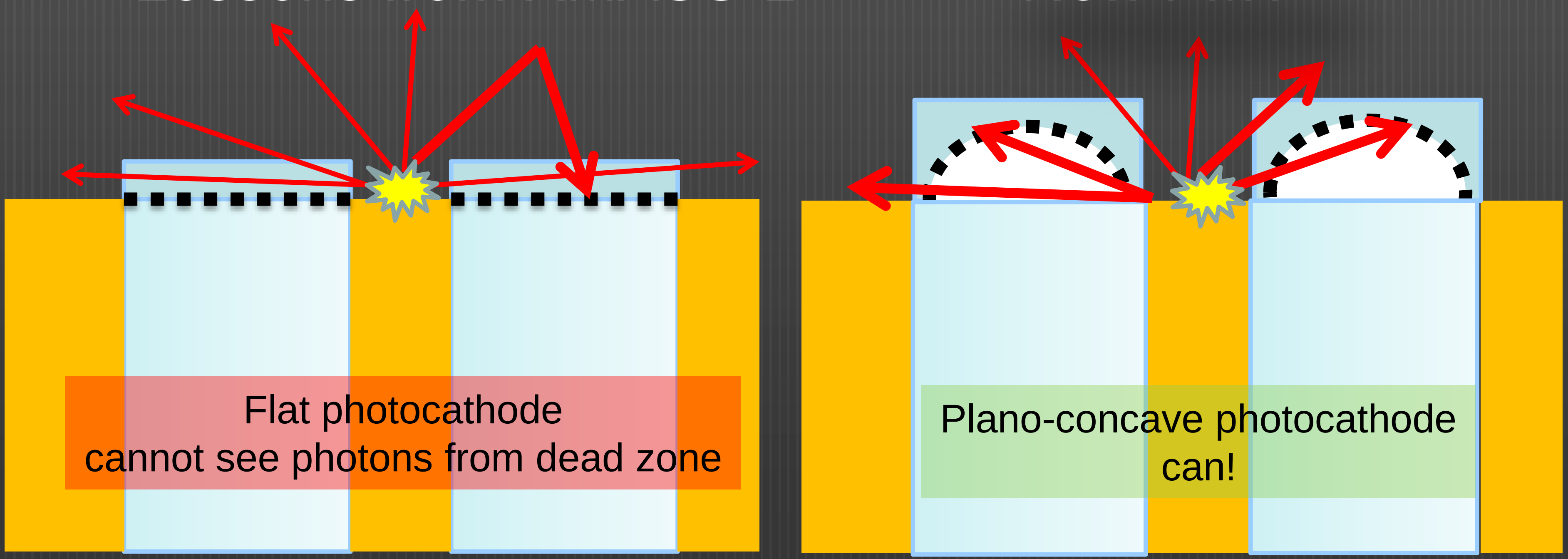
- At least 1/10 BG reduction
  - Another 1/10 reduction is expected through the position reconstruction (PE,timing) New results coming soon!

Next step: XMASS-1.5

- Inner Ø: 1.5 m
  - contains 5 tons of LXe
  - fiducial mass 1 ton
- Lessons from XMASS-1

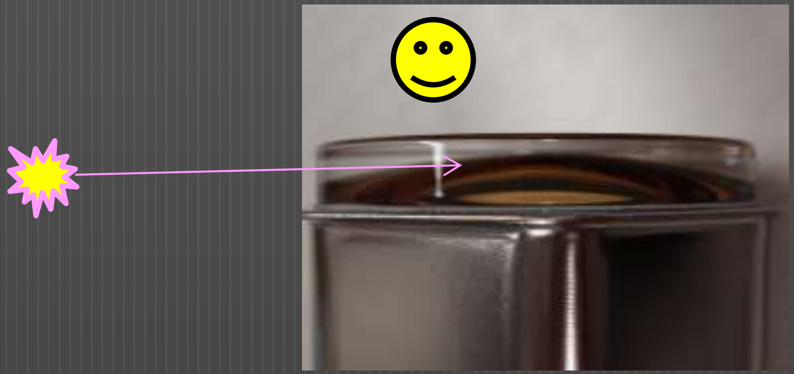


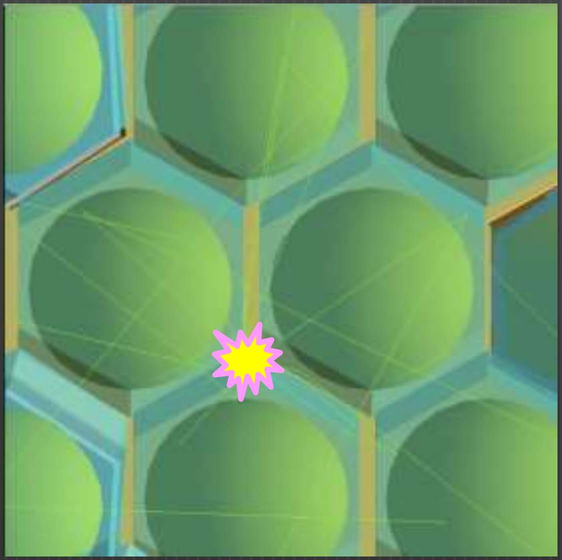
New PMT



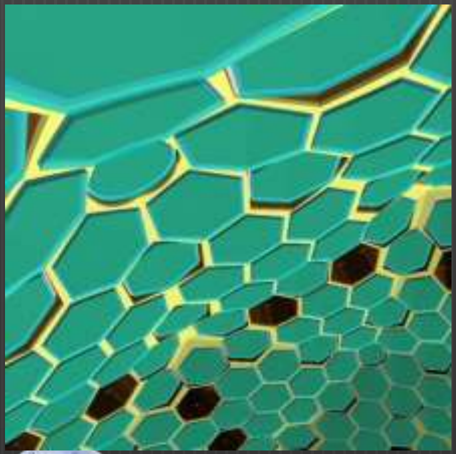
XMASS-1.5

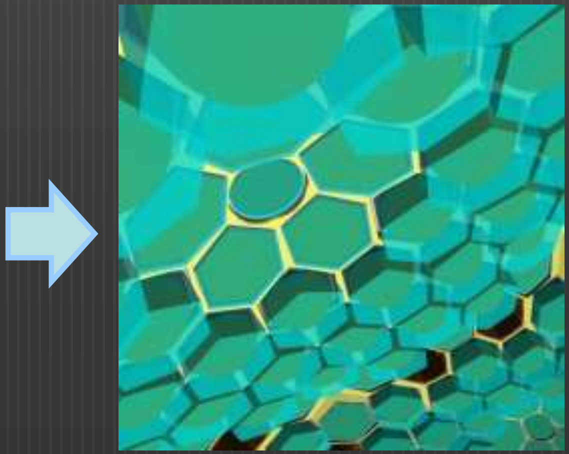
- Actively being developed w/ Hamamatsu





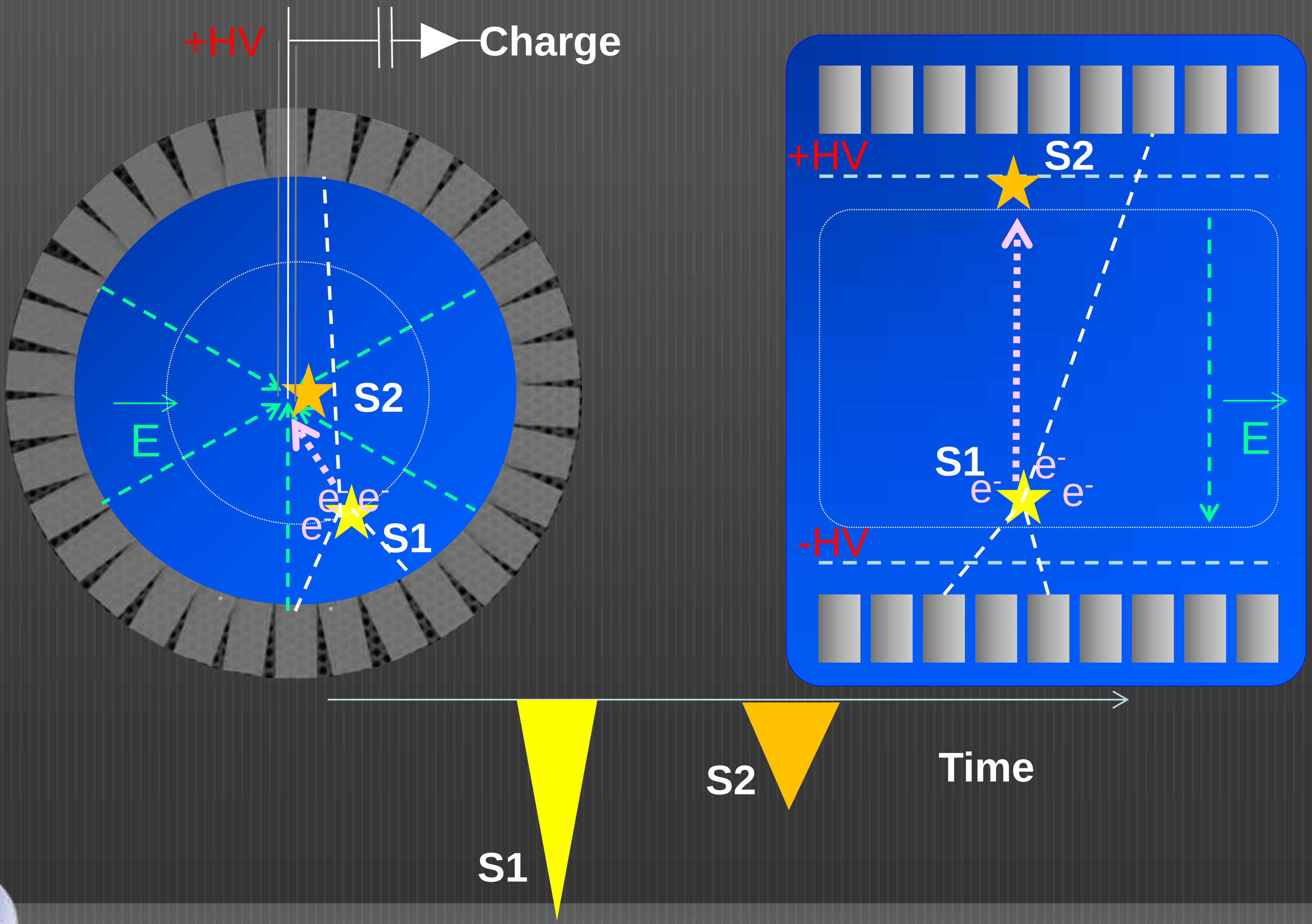
- Effectiveness is verified with MC





Single-phase TPC

- The original concept, but has not realized yet.

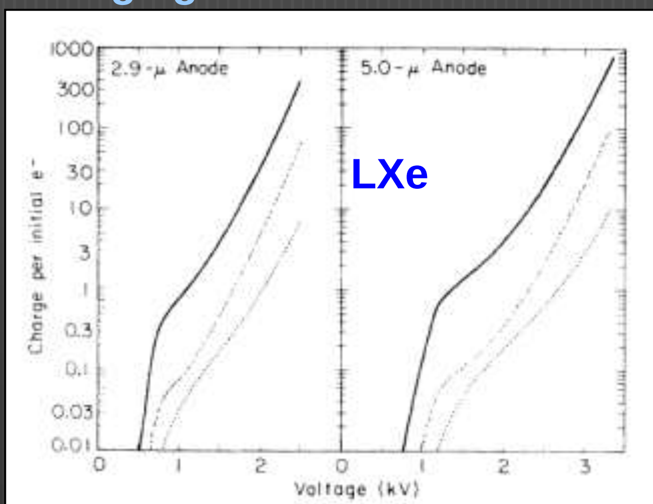


Single-phase TPC

Before the realization of two-phase detectors, there were many studies focused on charge amplification and proportional scintillation in single-phase LXe.

Derenzo , Phys. Rev. A 9 (1974) 2582

Charge gain ~400



Miyajima NIM 134 (1976) 403

Charge gain ~100

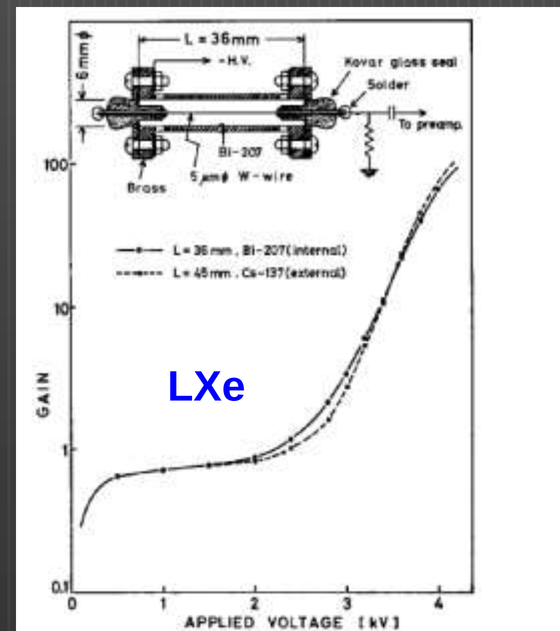


Fig. 1. Gain vs voltage for single-wire proportional chambers having an anode of 5 μm in diameter. Solid line represents the gain for internal ^{207}Bi source and dashed line for external irradiation of collimated ^{137}Cs gamma rays. Inserted figure shows a schematic diagram of single wire proportional chamber.

S2 in LXe

Masuda NIM 160 (1979) 247

Charge gain & proportional scintillation

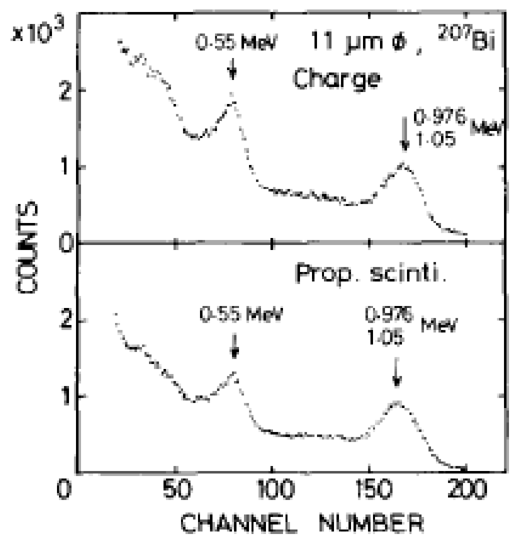
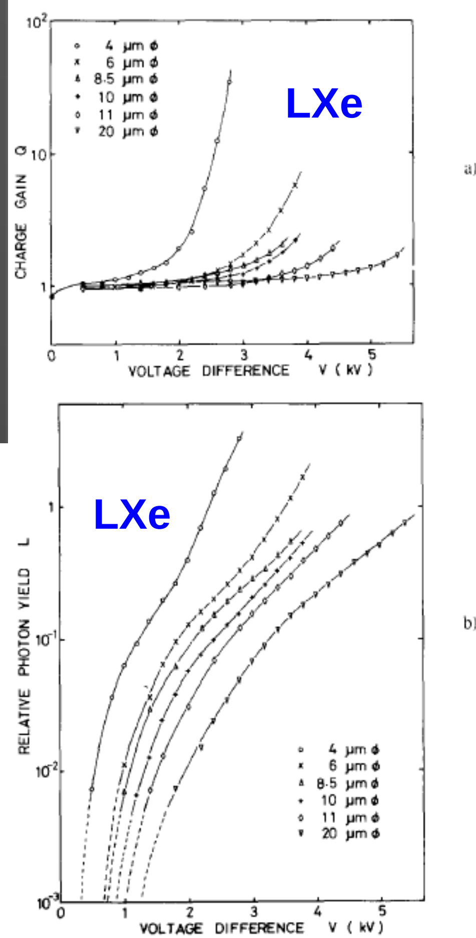


Fig. 5. Energy spectra of ^{207}Bi for the center wire of 11 μm in diameter at $V = 4.0$ kV which is the optimum voltage for this wire. The upper spectrum is for the charge and the lower for the proportional scintillation. The peak positions in both spectra are laid at the same channel.



Benetti NIMA 327 (1993) 203

^{109}Cd 22keV was observed

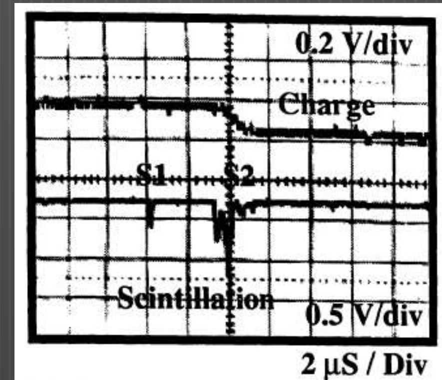


Fig. 5. Charge avalanche signal from preamplifier of 22 keV gamma rays from ^{109}Cd (top) together with the nonintegrated scintillation signal.

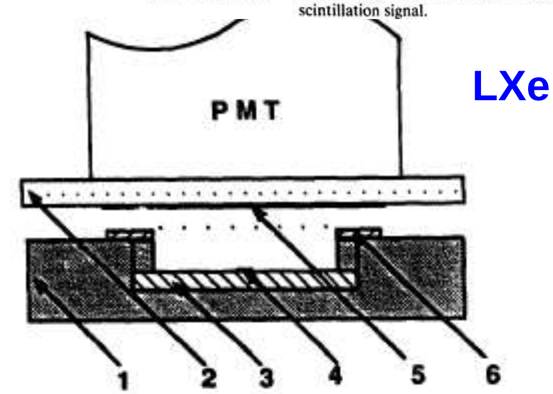
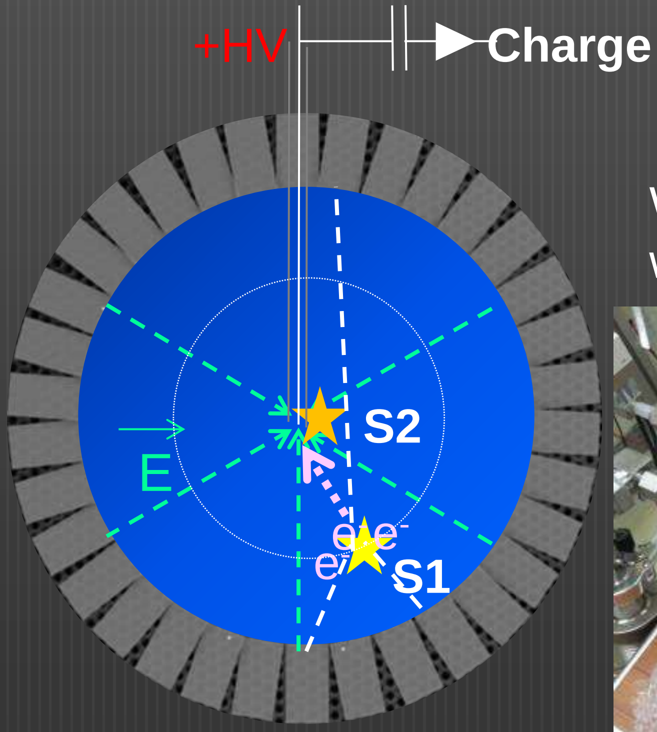


Fig. 1. Schematic drawing of the test chamber (1) HV insulator (Macor), (2) UV quartz window, (3) Cathode (stainless steel), (4) Source, (5) Grid (grounded), (6) Anode.

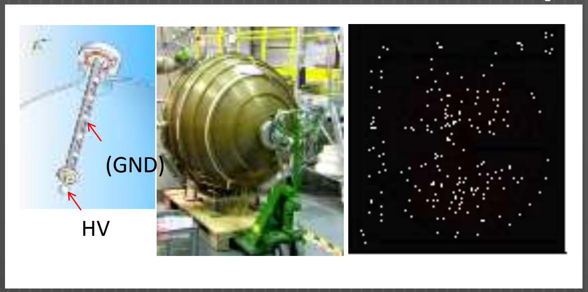
Single-phase TPC

Masuda,Itow and HS
ParisTPC conf (2012)

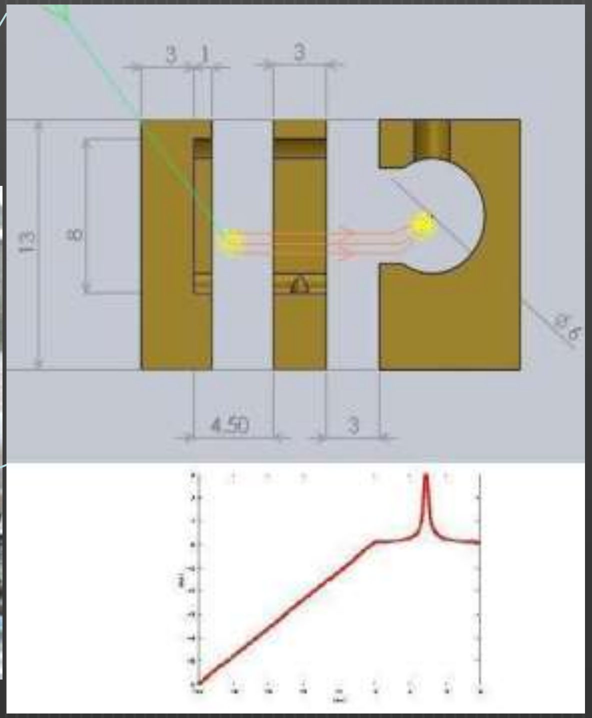
- Spherical LXe TPC
  - High electric field in XMASS
    20kV at the center



Gas spherical TPC
Giomataris JINST 3:P09007(2008)



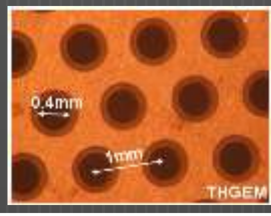
Will be tested with single wire in this chamber



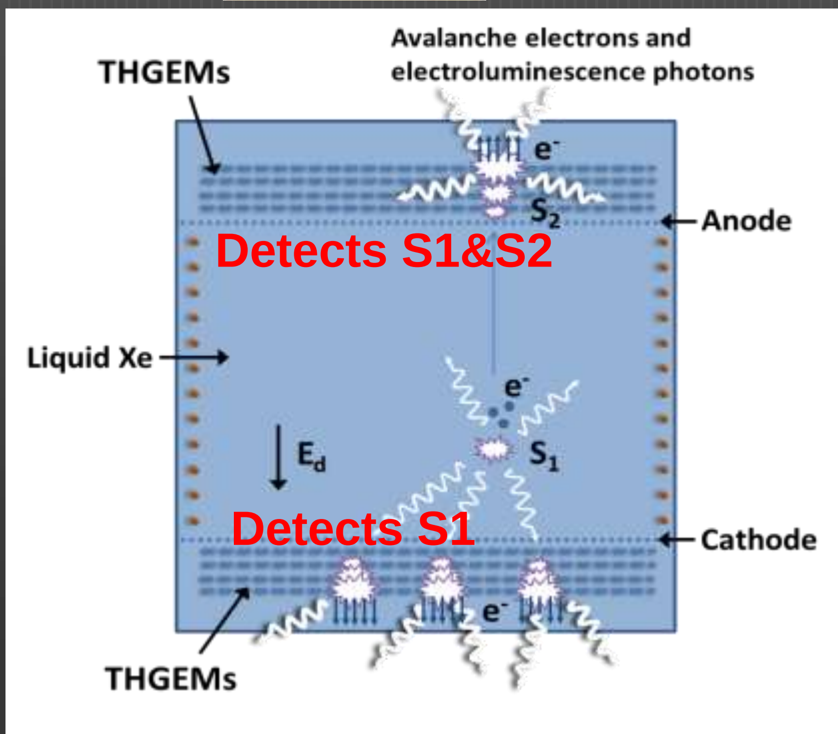
Single-phase TPC

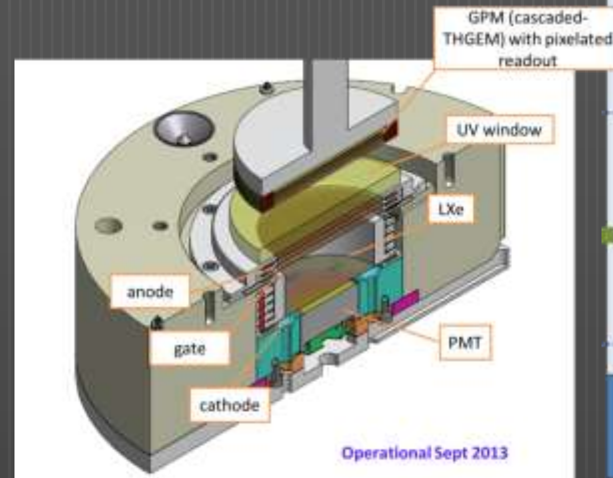
Breskin
ParisTPC conf (2012)

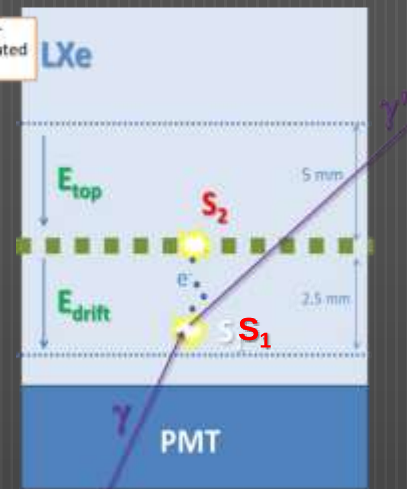
- Thick GEM in LXe



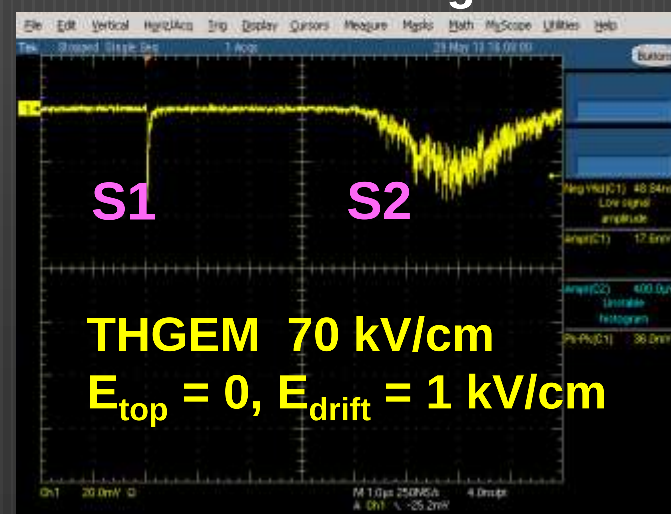
Thickness 0.4mm







RD51 Aug 2013

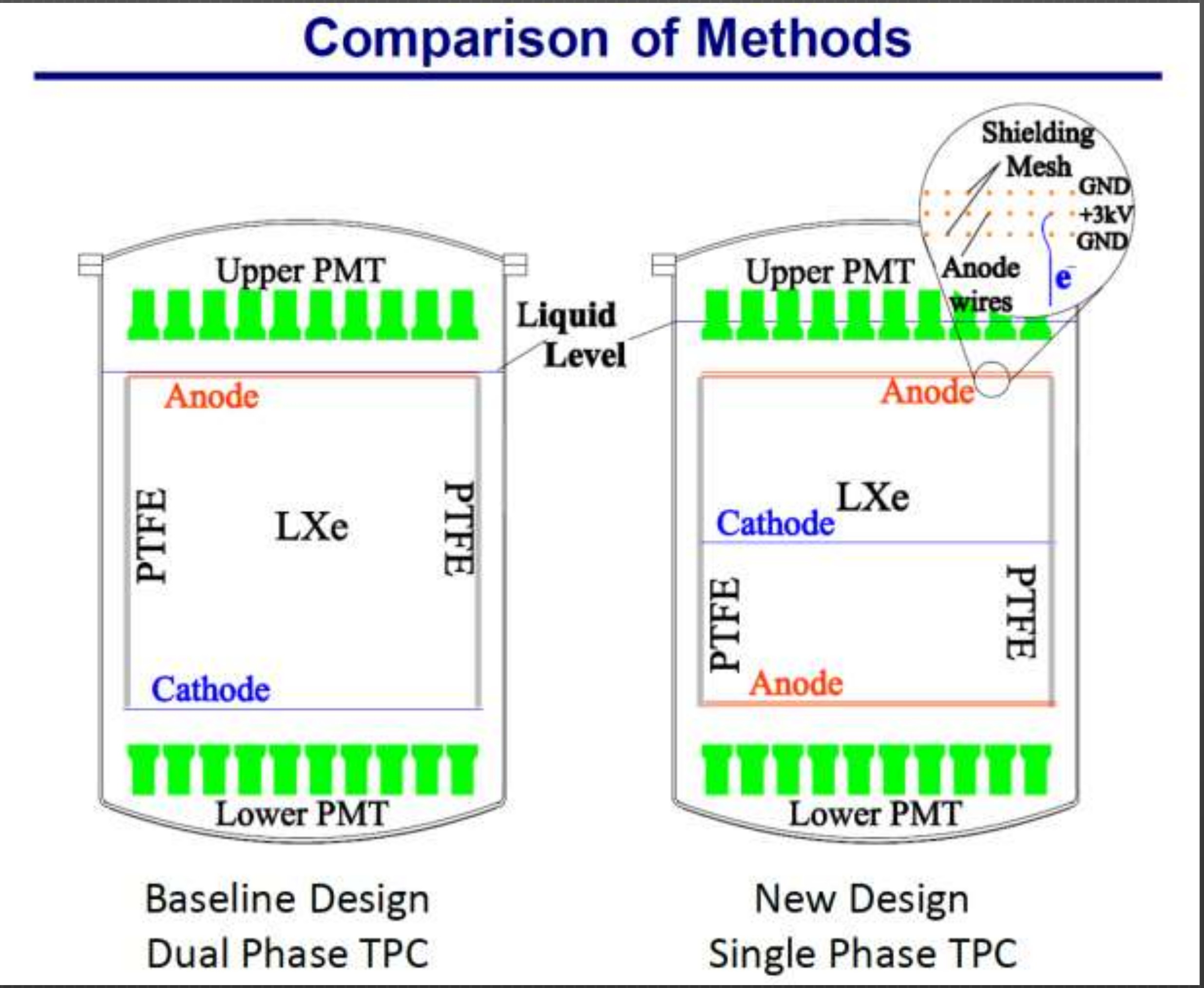


Single-Phase TPC

Karl Giboni
WPAS2014 conf.

- Panda-X

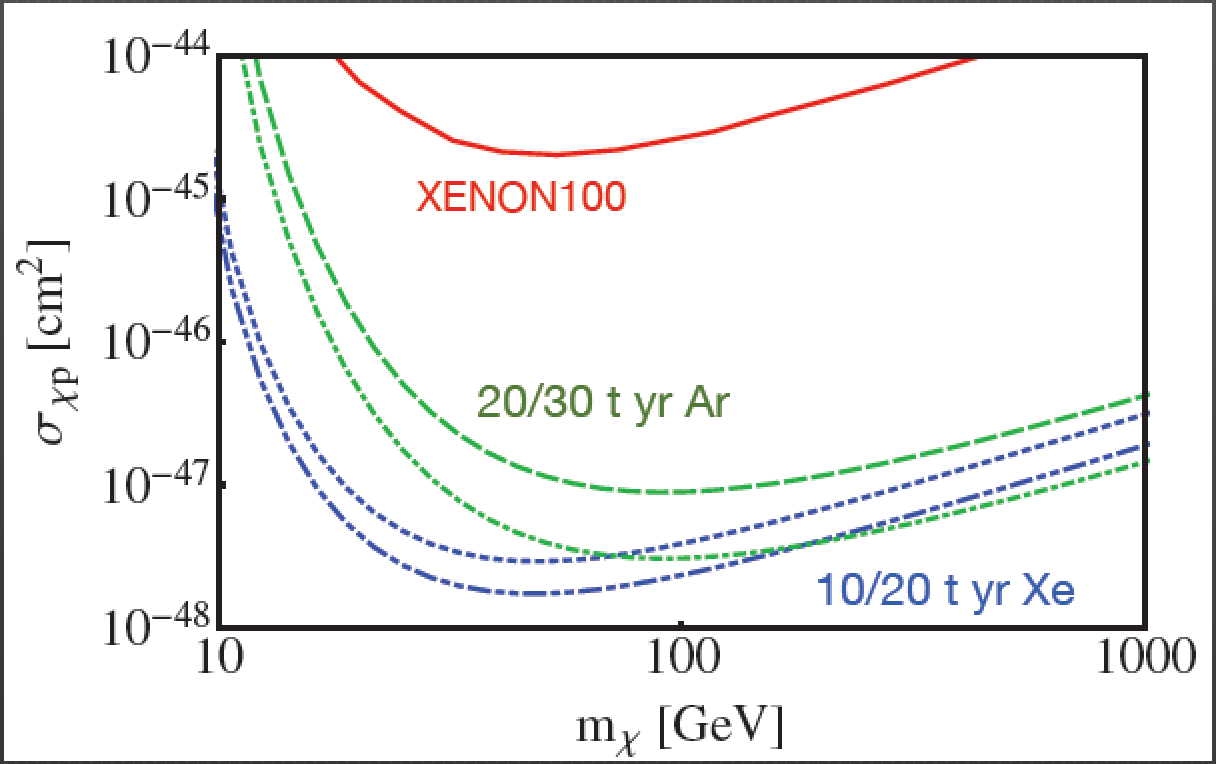
Double phase TPC has Leveling problem!



Future Projects
How much noble liquid do we need?

- To reach ～10^{-48} cm^2

arXiv:1306.3244



Future Projects (all in water)

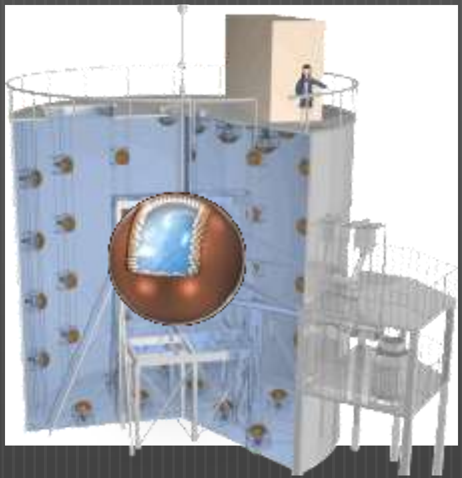
Time →

XENON1t

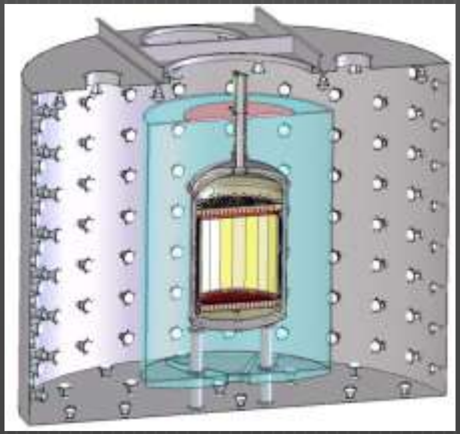
3.5t total
248 3" PMTs
In 2015?

XMASS1.5

5t total
New 3" PMTs



LZ = LUX+ZEPLIN



7t total
500 3" PMTs

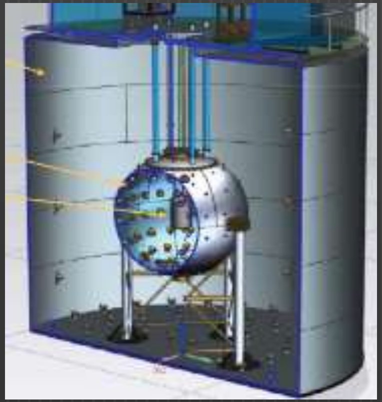
XMASS 2

24t total

XENON nt

DarkSide G2

5t total



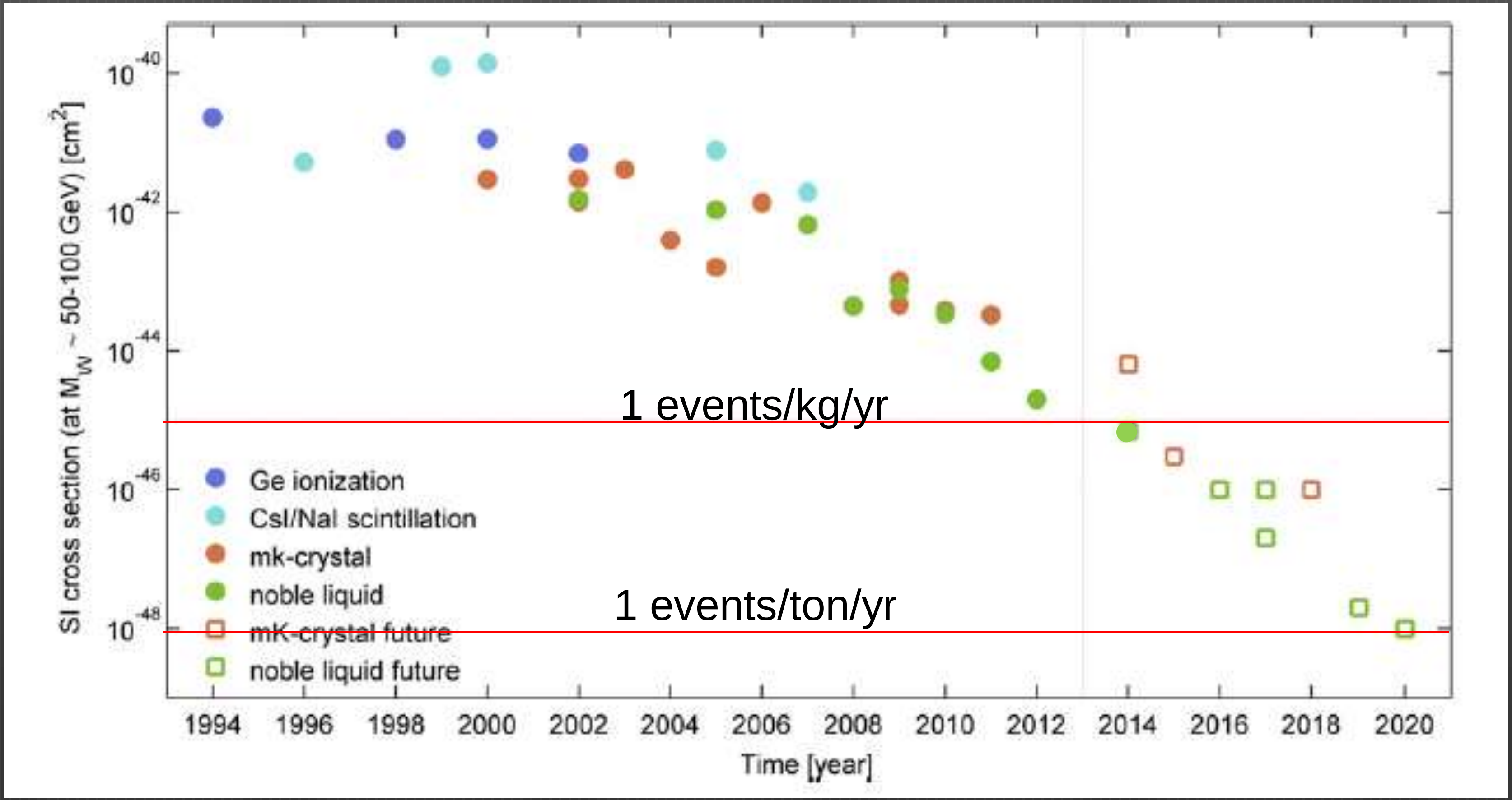
DARWIN

20t LAr
10t LXe

Evolution of Direct Dark Matter Search

- Can we push to such low BG levels?

L.Baudis Phys Dark Univ.1(2012) 94



Conclusion

- Direct detection experiments have reached sensitivity to WIMP cross sections down to ~10^{-46}cm^2 with noble liquid technologies.
- Detectors coming online in the next 5 years will aim for <10^{-47}cm^2 and all will use noble liquids.
  - Can noble liquids catch Dark Matter?
  - Beyond noble liquids, completely new technology will be required?
  - SUSY? After LHC upgrade, we may have to go further…or…