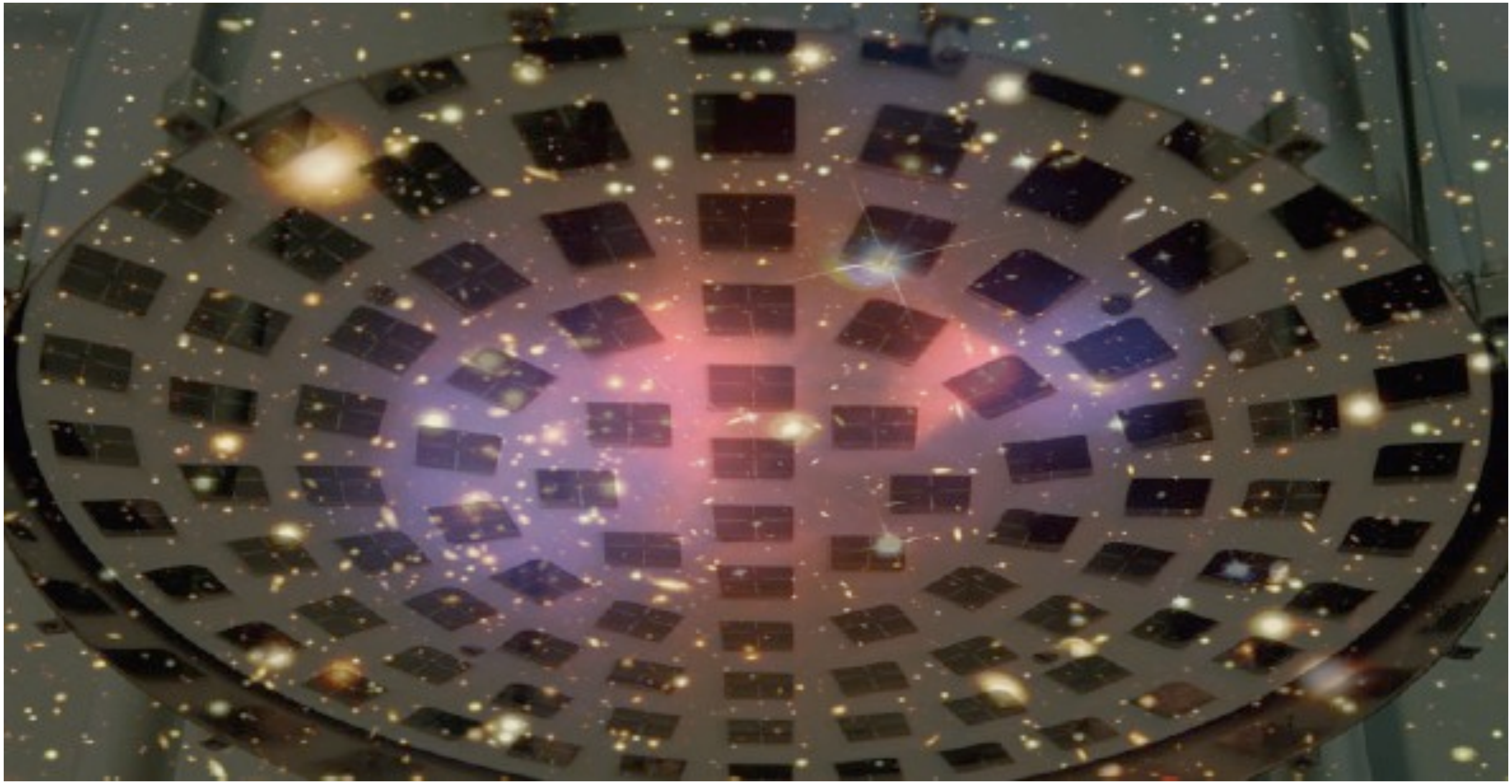
Search for Dark Matter



Elena Aprile
Columbia University

Dublin Summer School on High Energy Astrophysics - July 11, 2011

World Wide Dark Matter Searches: ~50% use Noble Liquids

Liquified Noble Gases: Basic Properties

Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	40,000	^{39}Ar, ^{42}Ar	1.6
LKr	2.4	120	1200	150	25,000	^{81}Kr, ^{85}Kr	0.09
LXe	3.0	165	2200	175	42,000	^{136}Xe	0.03

Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W-values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W-value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

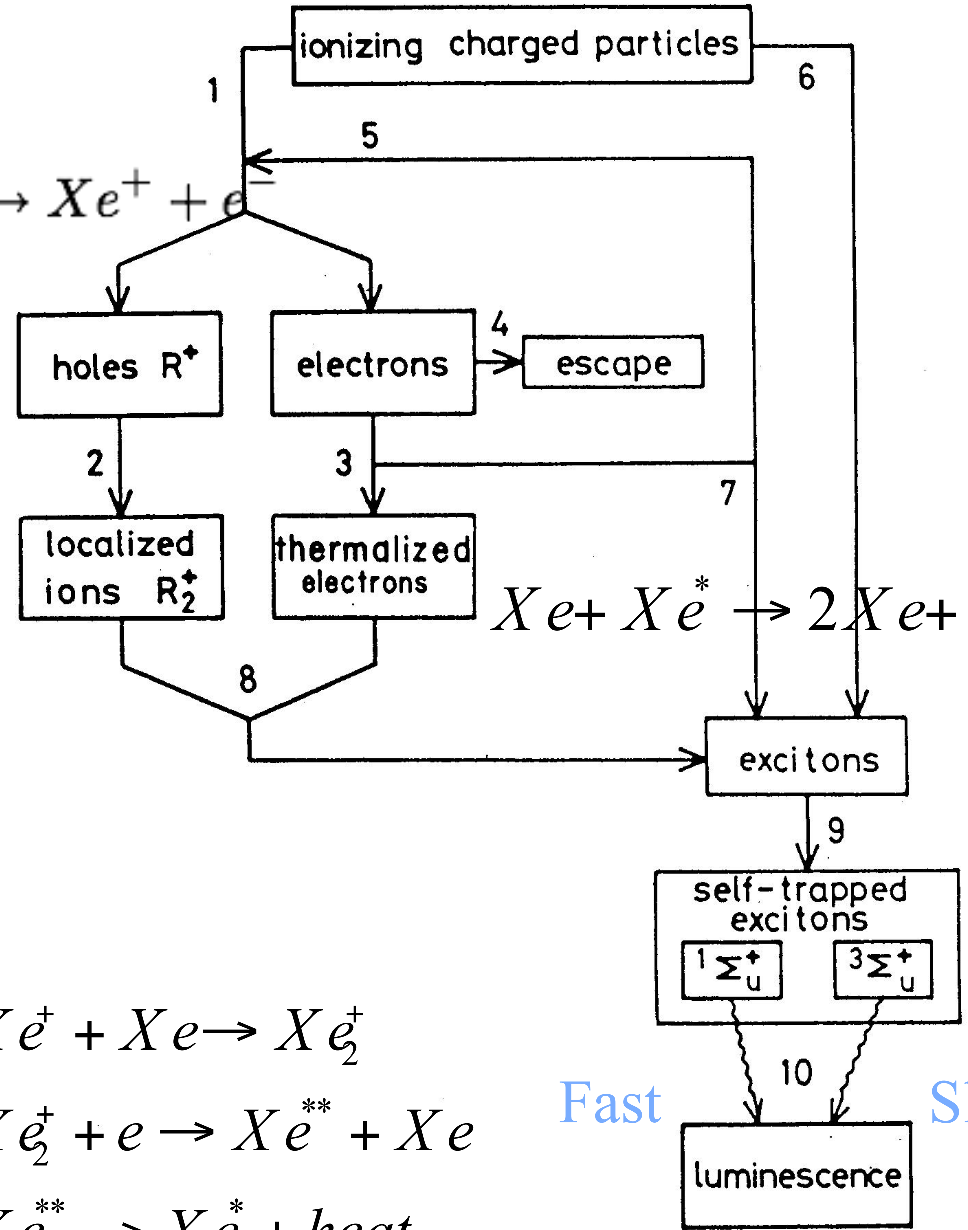
Why Noble Liquids for Dark Matter

- ✦ *scalability : relatively inexpensive for large scale (multi-ton) detectors*
- ✦ *easy cryogenics : 170 K (LXe), 87 K (LAr)*
- ✦ *self-shielding : very effective (especially for LXe case) for external background reduction*
- ✦ *low threshold : high scintillation yield (similar to NaI(Tl) but much faster timing)*
- ✦ *n-recoil discrimination: by charge-to-light ratio and pulse shape discrimination*
- ✦ *Xe nucleus (A~131) : good for SI plus SD sensitivity (~50% odd isotopes)*
- ✦ *For Xe: no long-lived radioactive isotopes (Kr-85 can be removed)*
- ✦ *For Ar: radioactive Ar-39 is an issue but there are ways to overcome it*

Ionization/Scintillation Mechanism in Noble Liquids

Kubota et al. 1979, Phys. Rev.B

$$Xe \rightarrow Xe^{+} + e^{-}$$



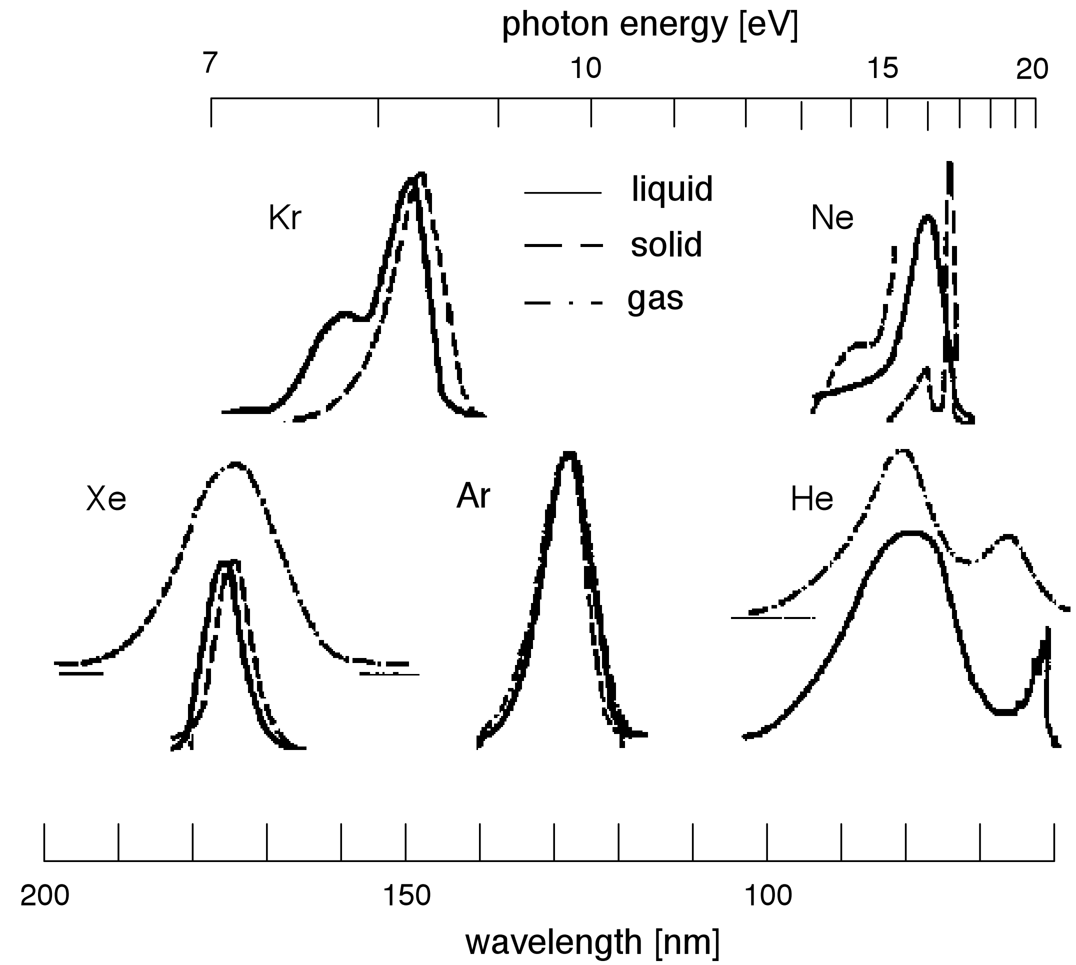
$$Xe + Xe^{*} \rightarrow 2Xe + h\nu$$

$$Xe^{+} + Xe \rightarrow Xe_2^{+}$$

$$Xe_2^{+} + e \rightarrow Xe^{**} + Xe$$

$$Xe^{**} \rightarrow Xe^{*} + heat$$

$$Xe + Xe^{*} \rightarrow Xe_2^{*} \rightarrow 2Xe + h\nu$$



$$\lambda \sim 128_{LAr}$$

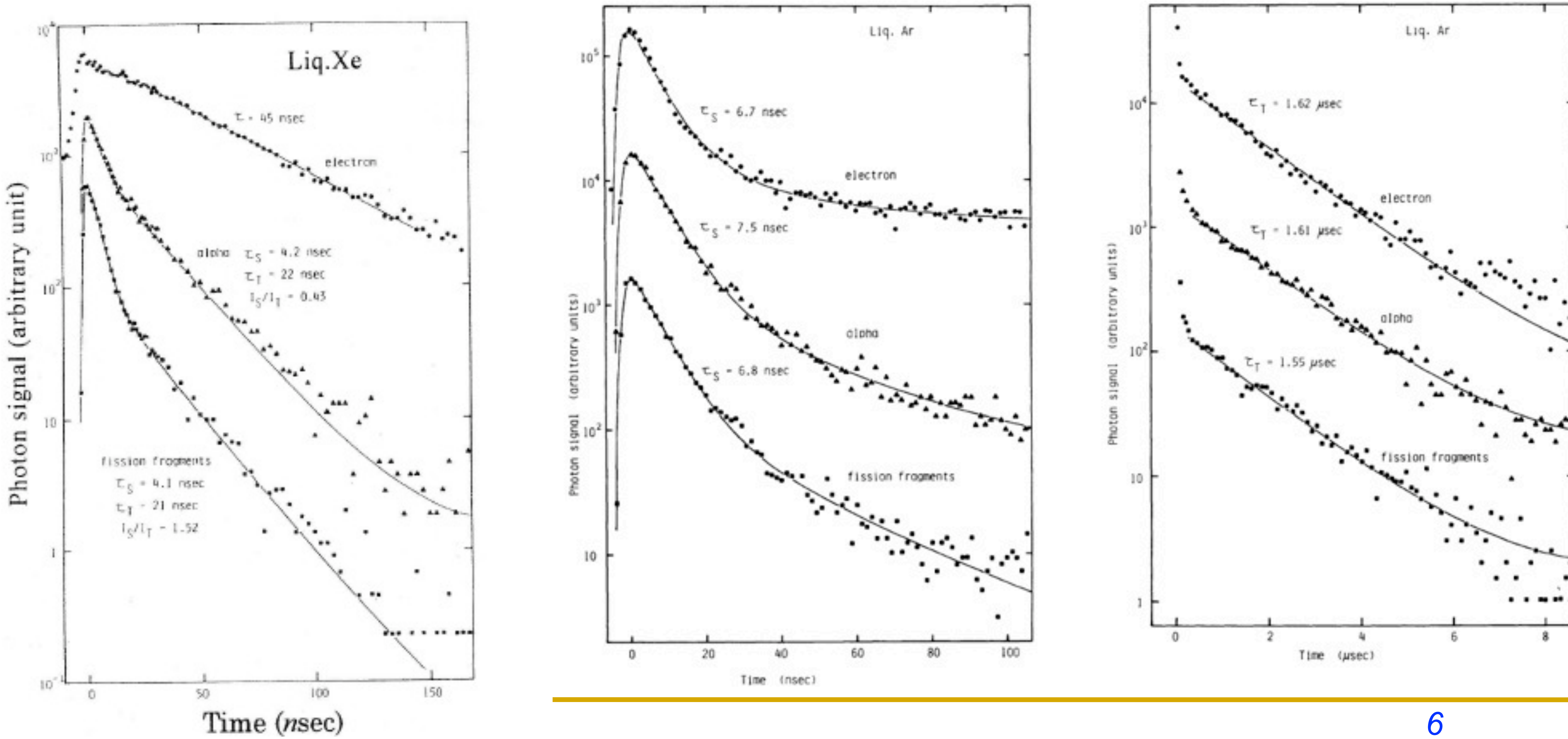
$$\lambda \sim 175_{LXe}$$

$$\lambda \sim 77.5_{LNe}$$

Scintillation Pulse Shape

- Two decay components from de-excitation of singlet and triplet states of dimers
- While the singlet/triplet lifetimes do not depend on the ionization density of particle, their intensity ratio does: it is larger for heavily ionizing particles allowing particle ID
- LXe: the fastest of all noble liquid scintillators (4ns / 22ns)
- LAr: large separation b/w singlet/triplet decay times allow easy PSD

Hitachi, 1983



Light and Charge attenuation by Impurities

Impurities dissolved in the liquid absorb UV photons, reducing the light yield. Light attenuation described as

$$I(x) = I(0)\exp(-x/\lambda_{att})$$

Strong absorption by H2O, even stronger at 128 nm of LAr

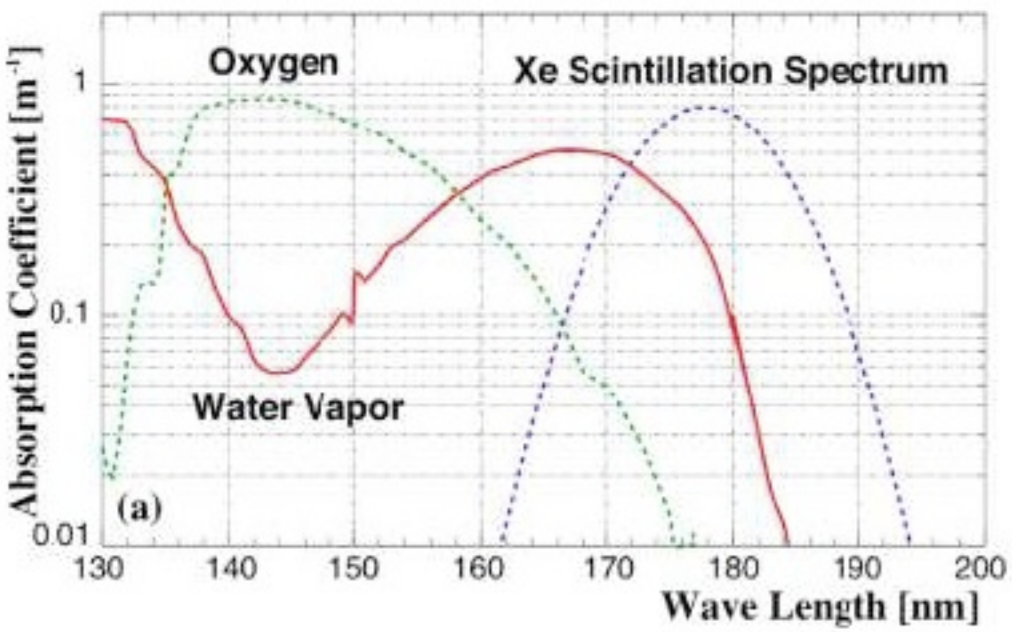


FIG. 25 Absorption coefficient for VUV photons in 1 ppm water vapor and oxygen and superimposed Xe emission spectrum (Ozone, 2005).

Electronegative impurities dissolved in the liquid also trap electrons reducing the charge yield

$$[e(t)] = e(0)exp(-k_S[S]t)$$

We define electron lifetime in terms of the impurity concentration [S] and an attachment rate constant k

$$\tau = (k_S[S])^{-1}$$

The electron attenuation length is related to the lifetime via the electron mobility and the electric field

$$\lambda_{att} = \mu E \tau$$

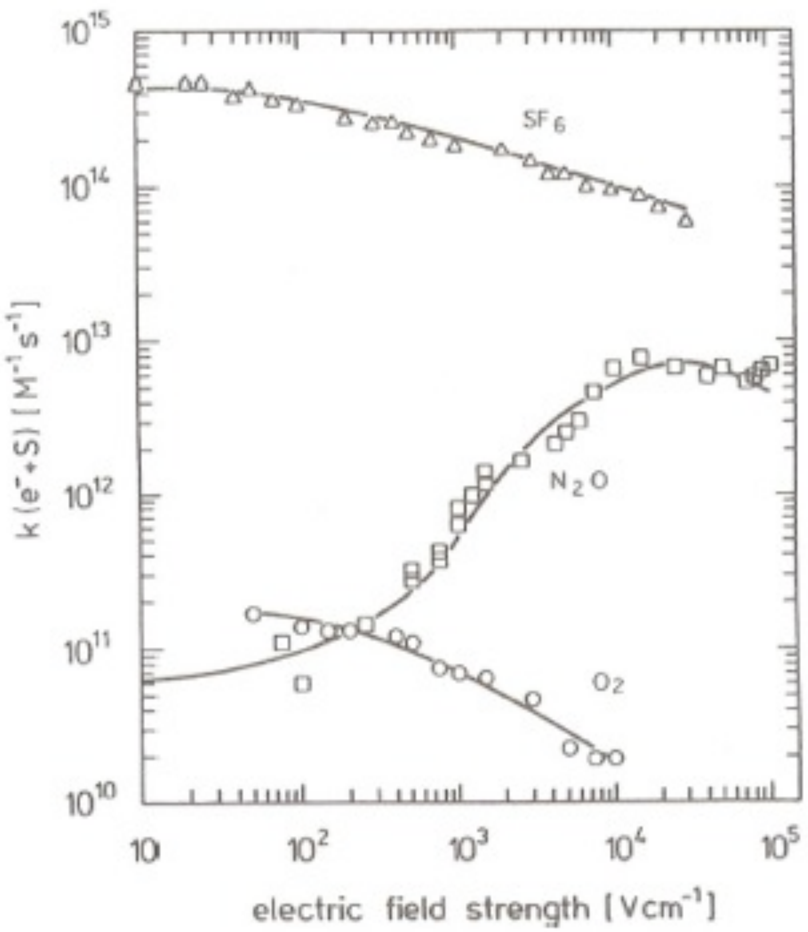
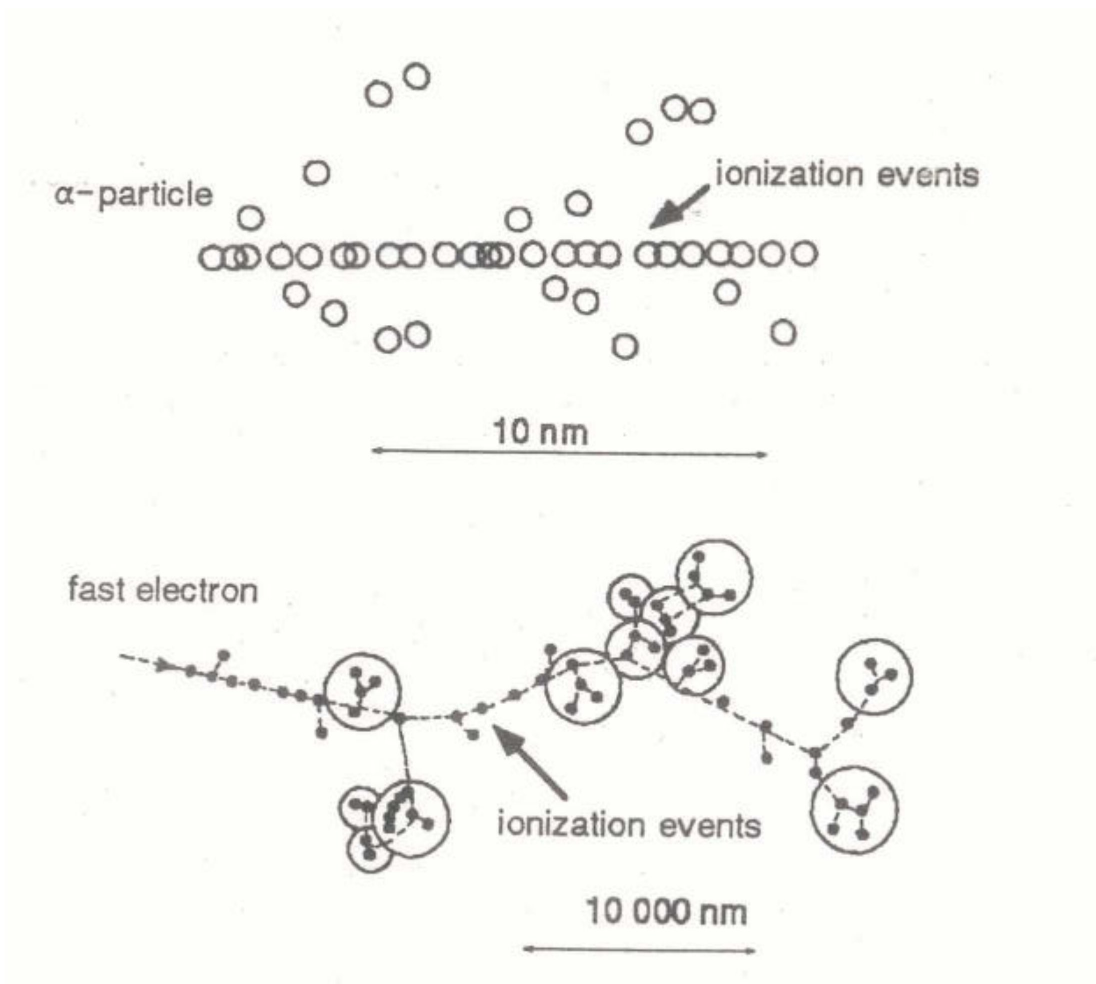


FIG. 15 Rate constant for the attachment of electrons in liquid xenon(T=167°K) to several solutes: (△) SF$_6$, (□) N$_2$O, (○) O$_2$(Bakale, 1976).

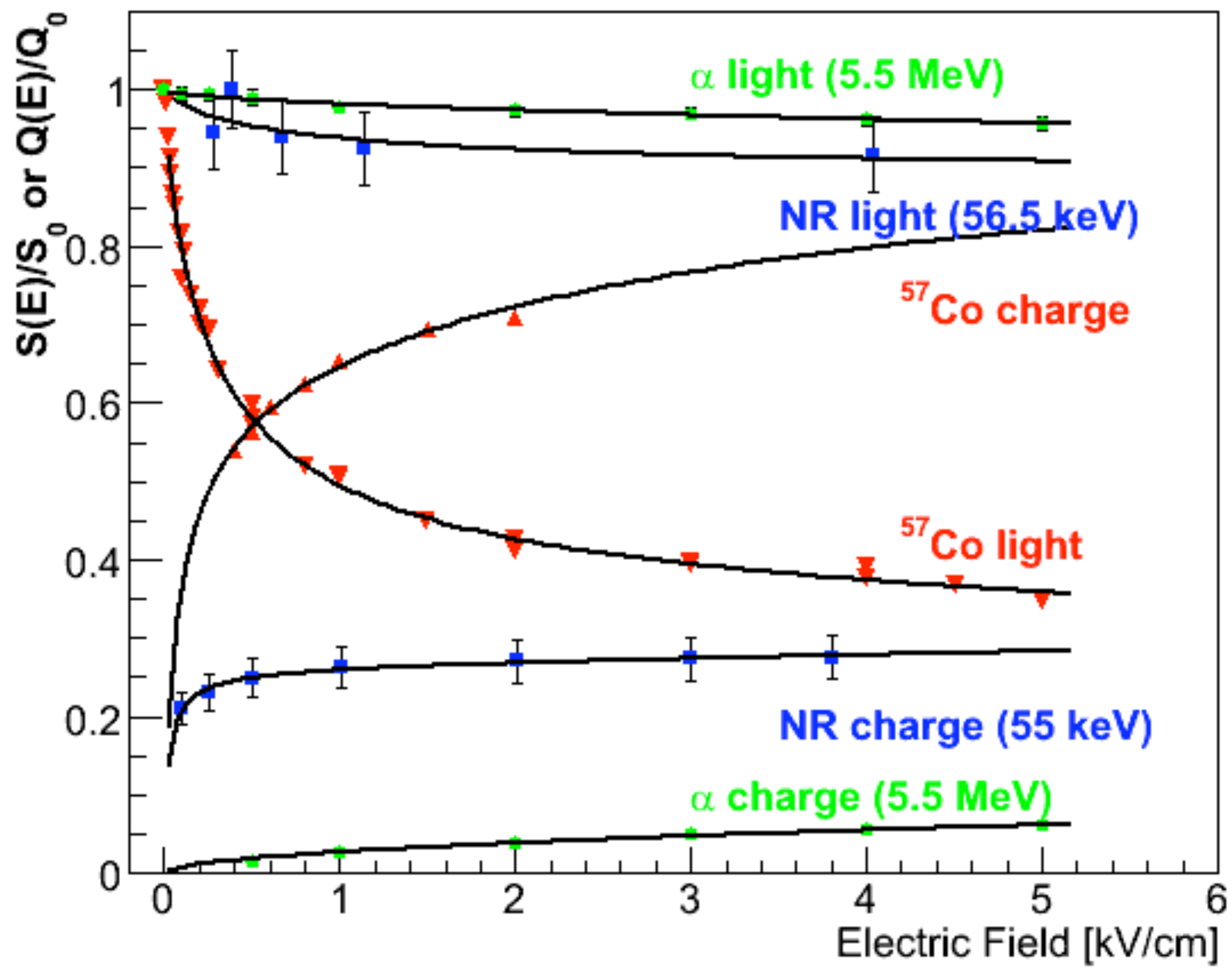
Monday, July 11, 2011

Charge and Light response of different particles in LXe

Charge/Light (electron) >> Charge/Light (non relativistic particle)



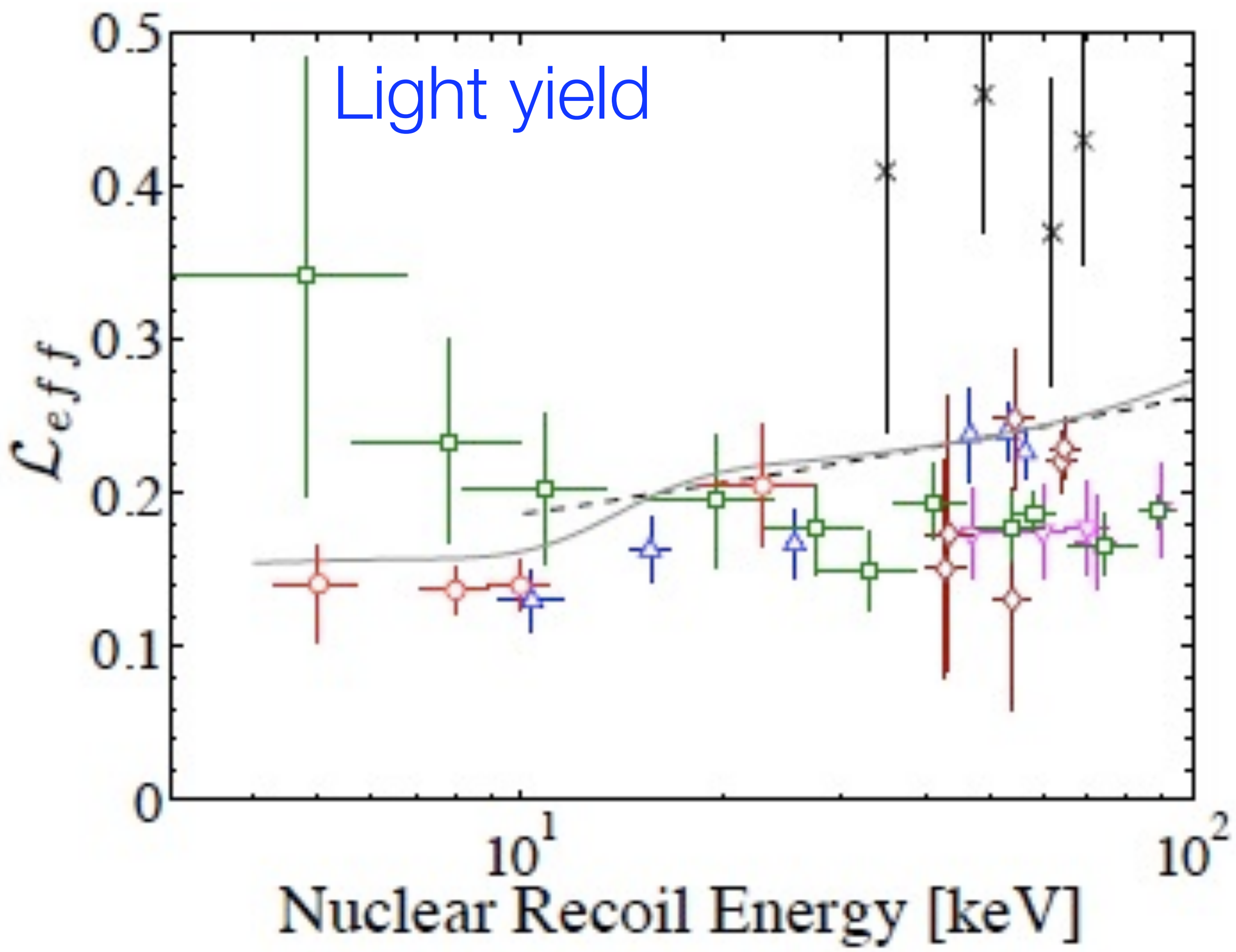
Distribution of ionization around the track of a high energy a-particle or electron



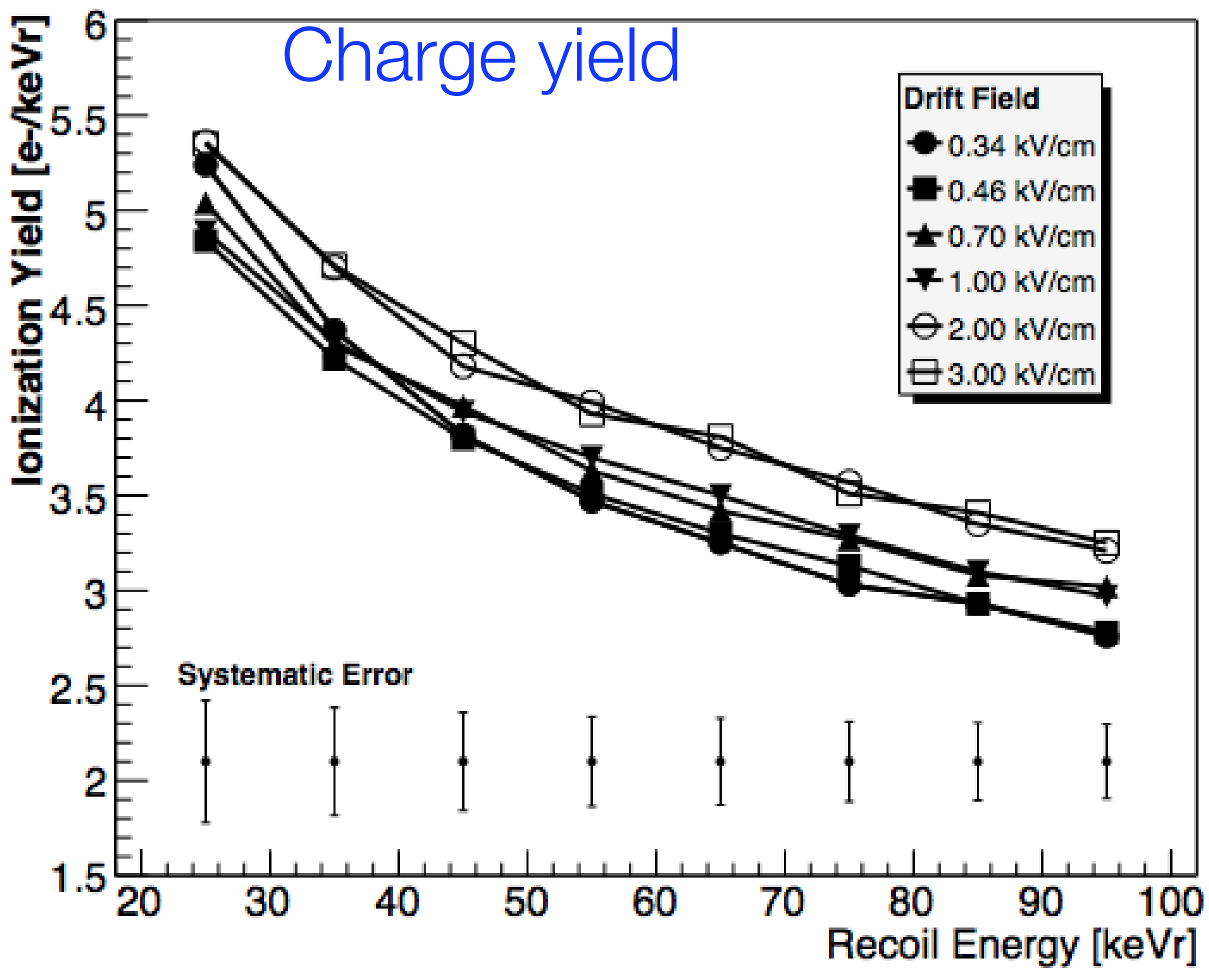
Aprile et al., Phys. Rev. D 72 (2005) 072006

Charge and Light Yield of Nuclear Recoils in LXe

- these quantities are essential for LXe as DM target/detector
- yields measured at **low nuclear recoil energies** for the first time (XENON R&D)

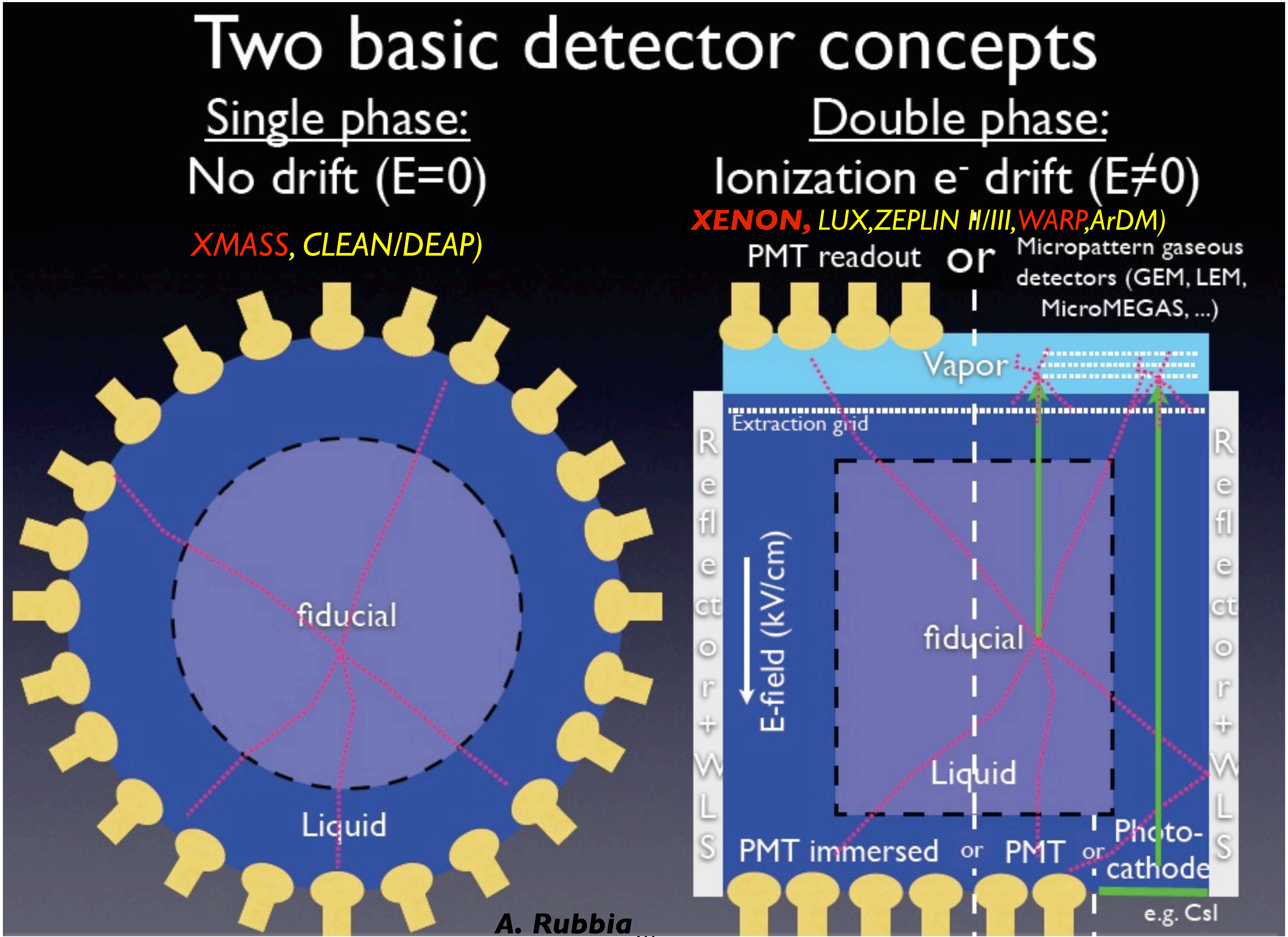


Aprile et al., Phys. Rev. D (2005)
Aprile et al., Phys. Rev. C (2009)



Aprile et al., Phys. Rev. Lett, 97 (2006)

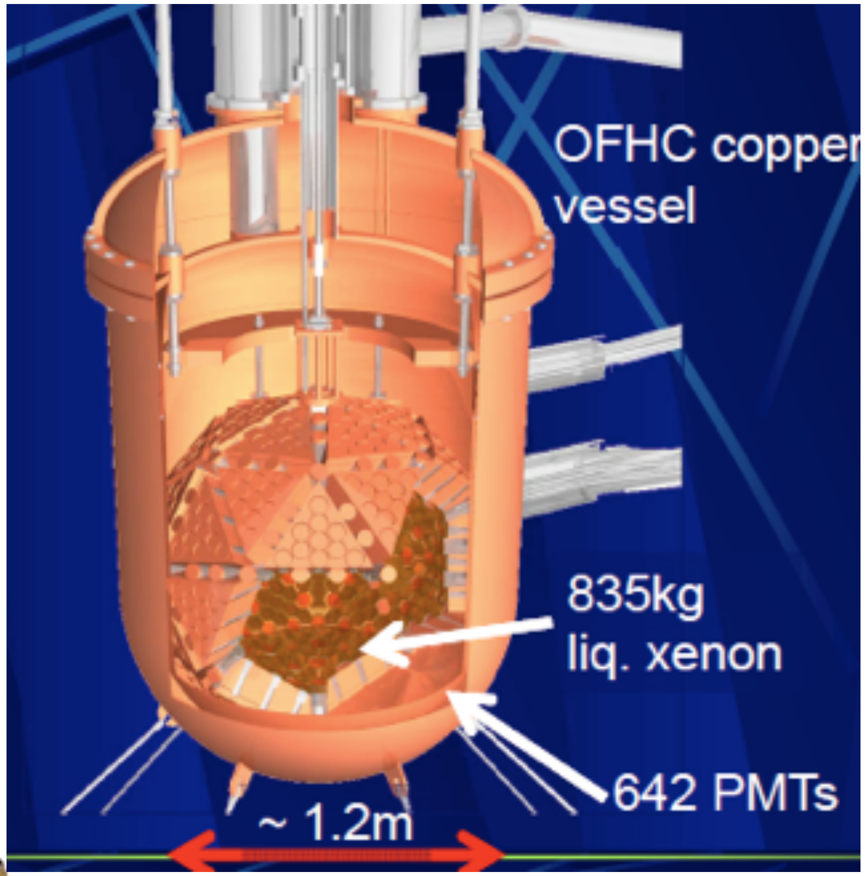
Noble Liquid Experiments for Dark Matter

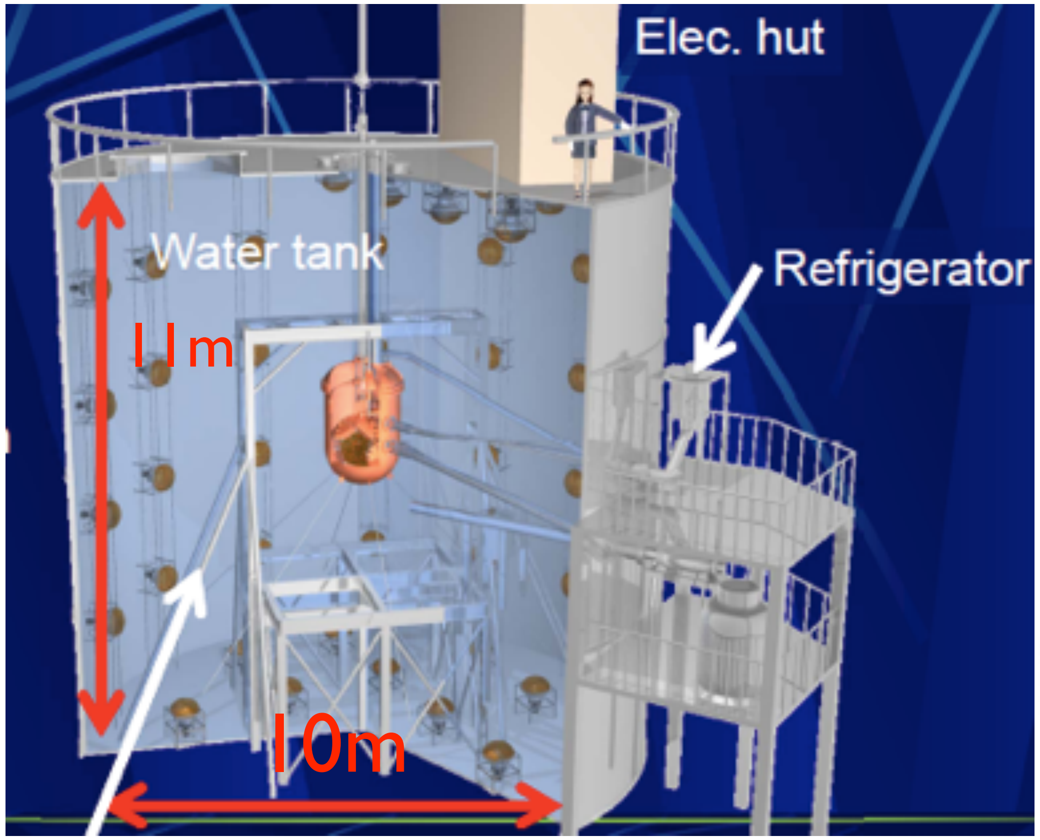


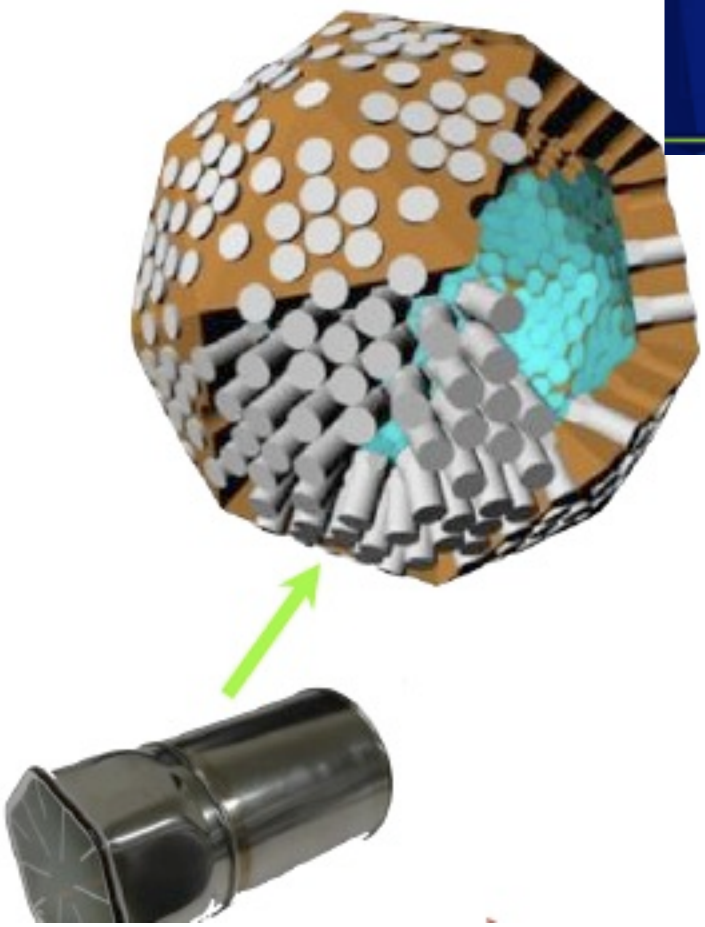
A. Rubbia

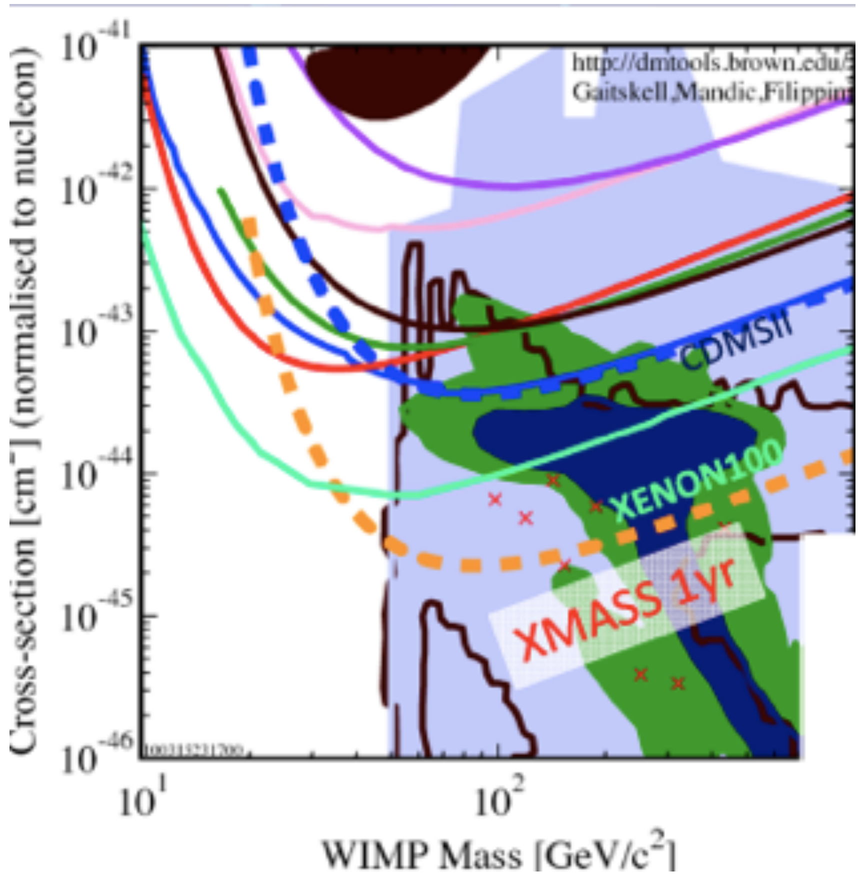
The XMASS Experiment @ Kamioka

- Exploit scintillation signal only, detected by PMTs in the liquid; event localization from light pattern reconstruction ~ a few cm
- low background inner core by self-shielding of LXe (Z=54; 3g/cc)
- active water shield for fast neutron background rejection
- 800 kg (100 kg FV) LXe detector with 642 low activity PMTs
- Commissioning ongoing



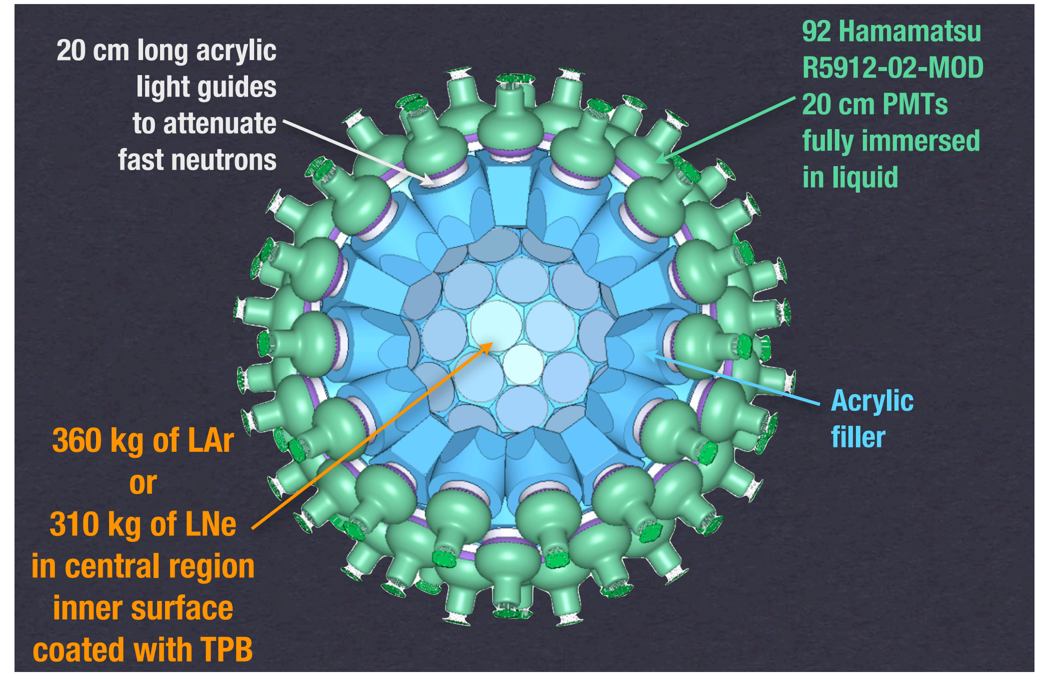


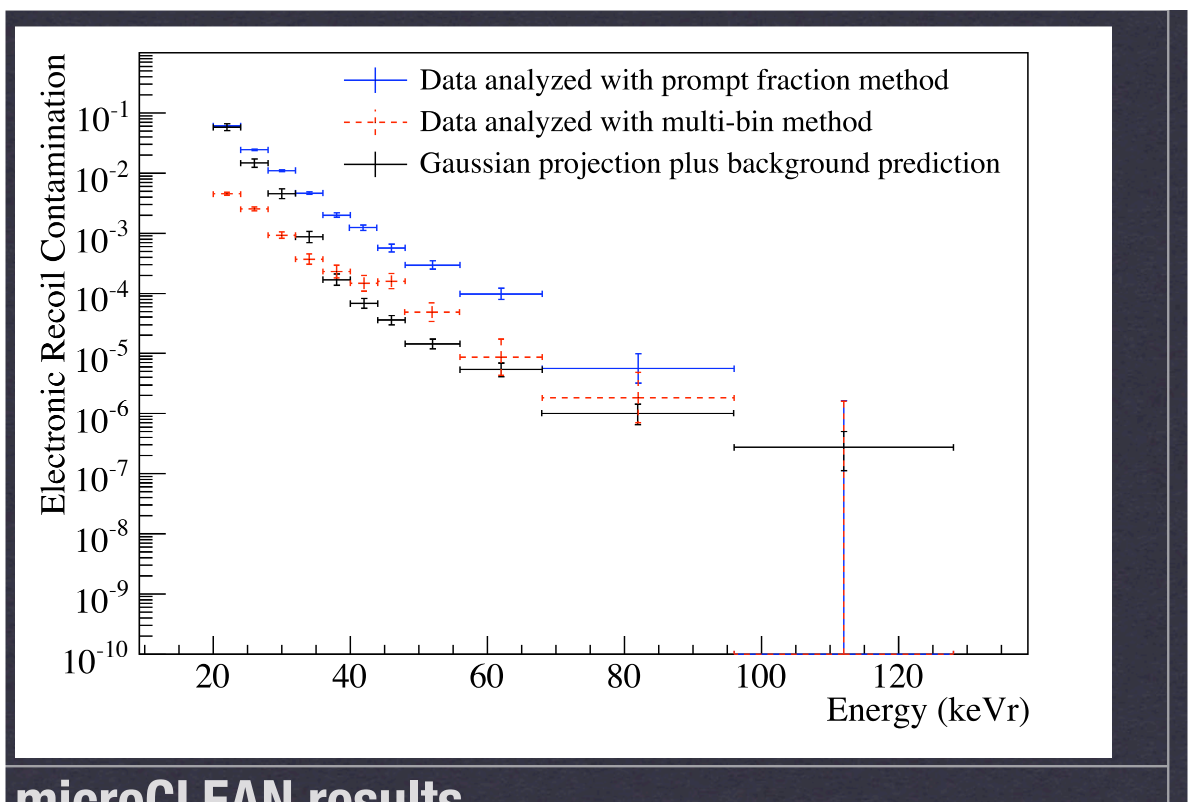


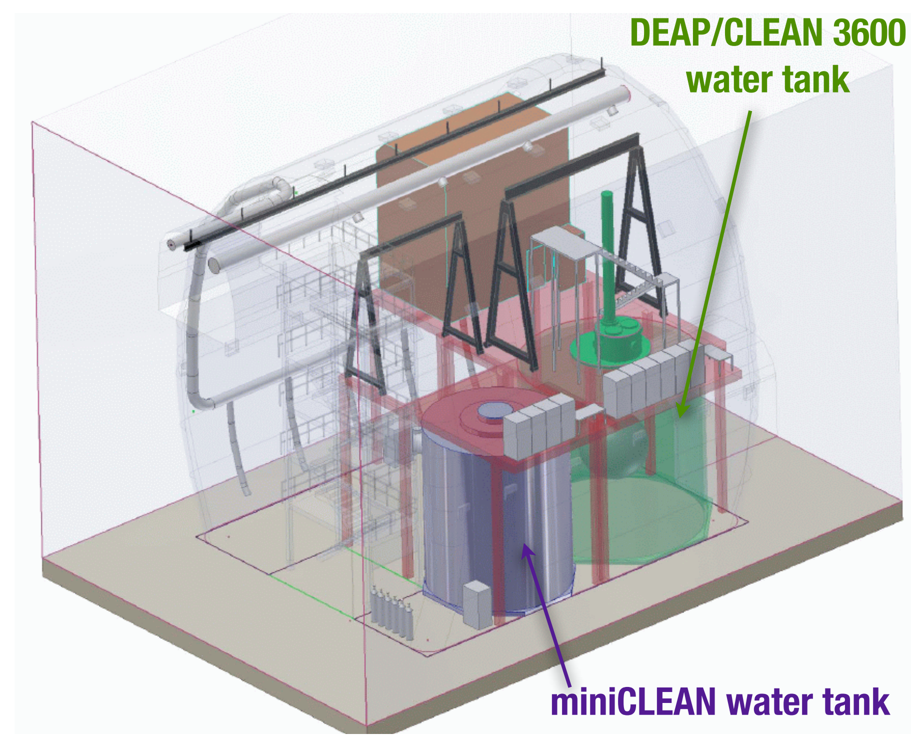


DEAP/CLEAN @ SNOLAB (Canada)

- ton scale DEAP/CLEAN planned for SNOLAB
- proposed first phase: 100 kg mini-CLEAN with WIMP search goal of ~ 5×10^{-45} cm^2 or ~10 events/yr
- To reject gamma background from PMTs and Ar-39 a discrimination better than 10^{-8} for ER> 50keVr is required
- Current data from small (~7 kg) DEAP-1 and micro-CLEAN detectors above ground demonstrate a discrimination of 10^{-5} limited by neutron back in lab

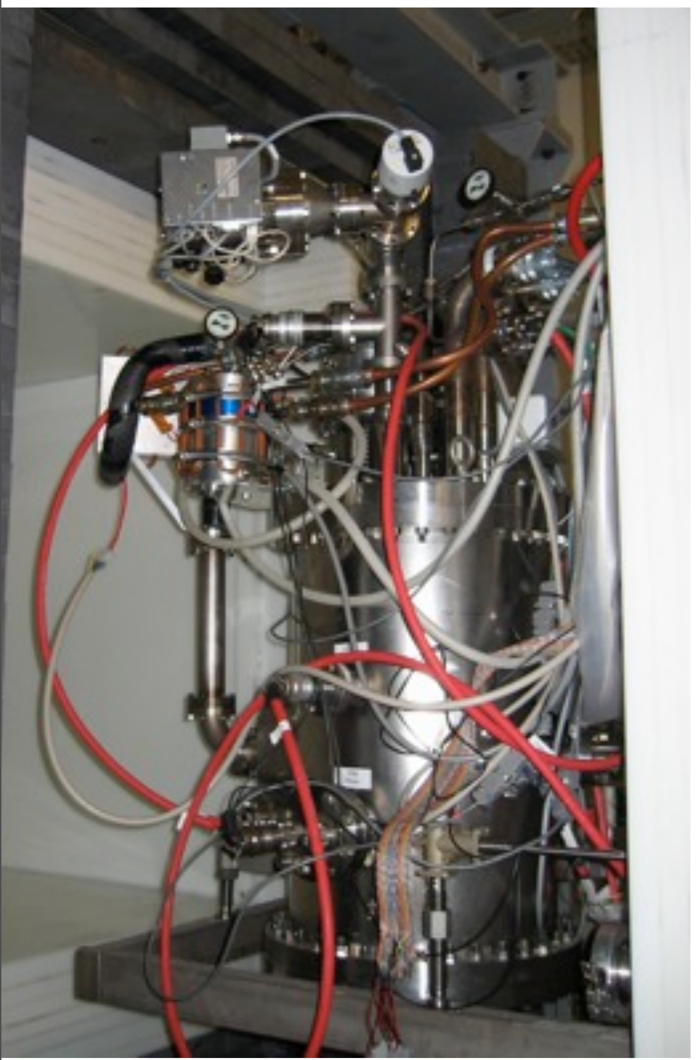


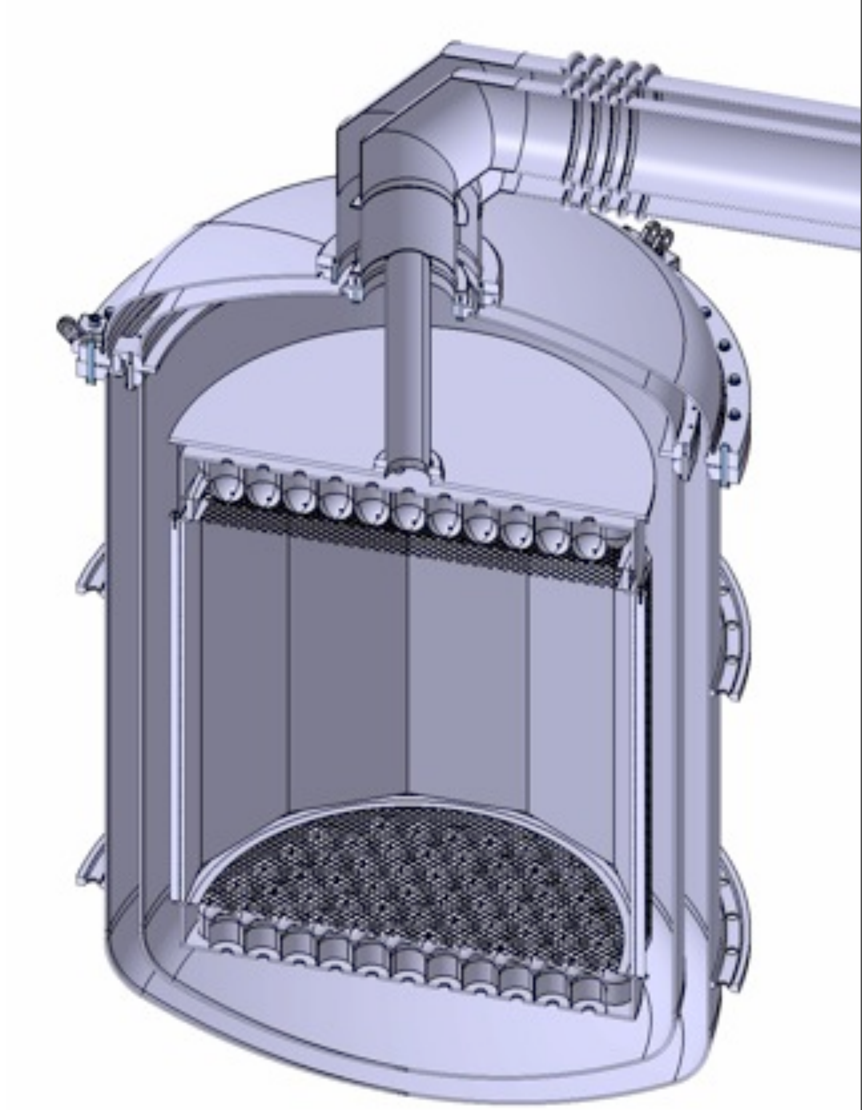




The XENON Dark Matter Search

past (2005 - 2007)	*current* (2007-2011)	*future* (2011-2015)





XENON10

Achieved (2007) $\sigma_{SI}=8.8 \times 10^{-44}$ cm^2

XENON100

Achieved (2011) $\sigma_{SI}=7.0 \times 10^{-45}$ cm^2

Projected (2012) $\sigma_{SI}\sim 2\times 10^{-45}$ cm^2

XENON1T

Projected (2015) $\sigma_{SI} \sim 10^{-47}$ cm^2

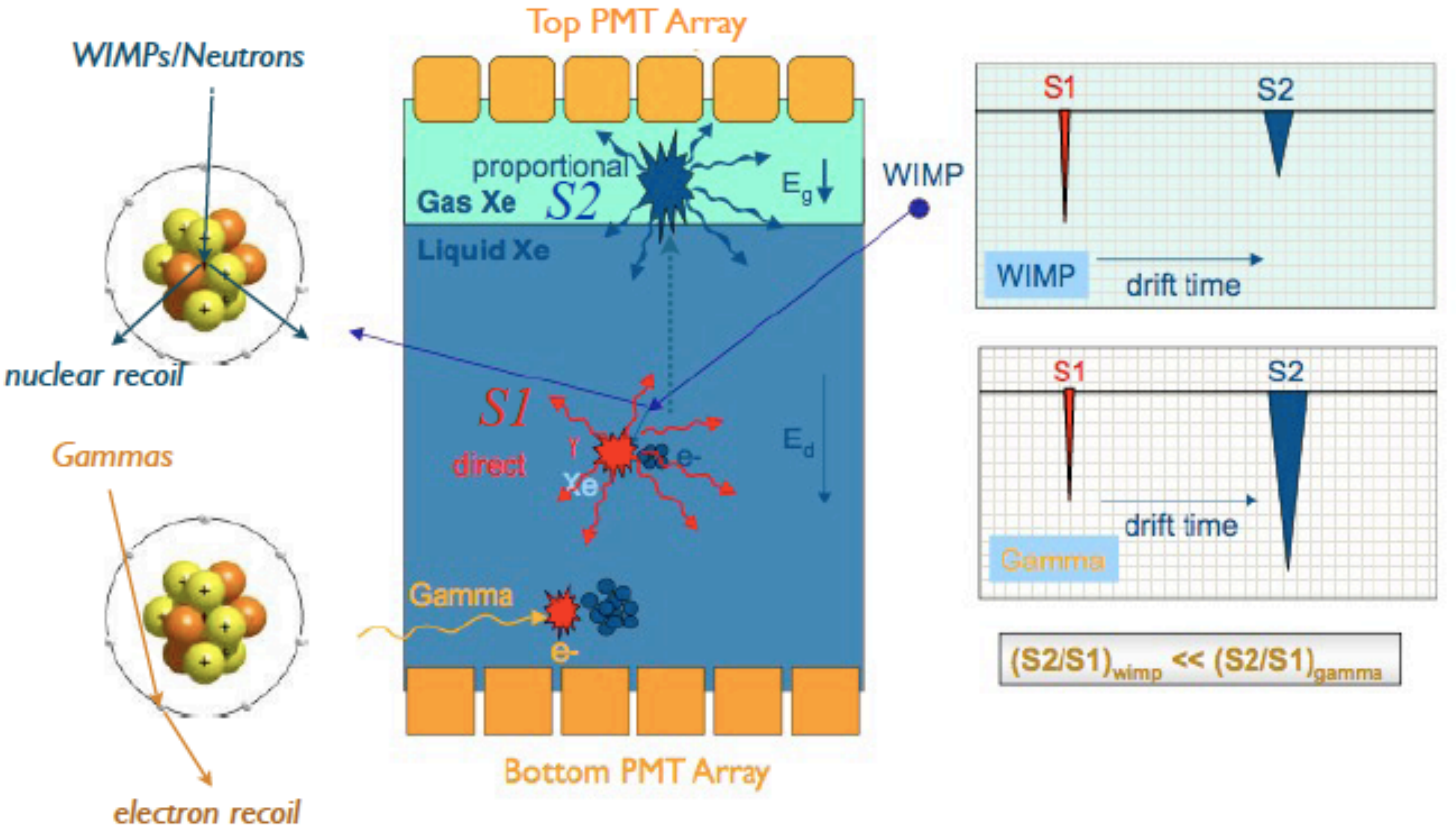
XENON100 Collaboration

Columbia | Rice | UCLA | Zürich | Coimbra | LNGS | SJTU

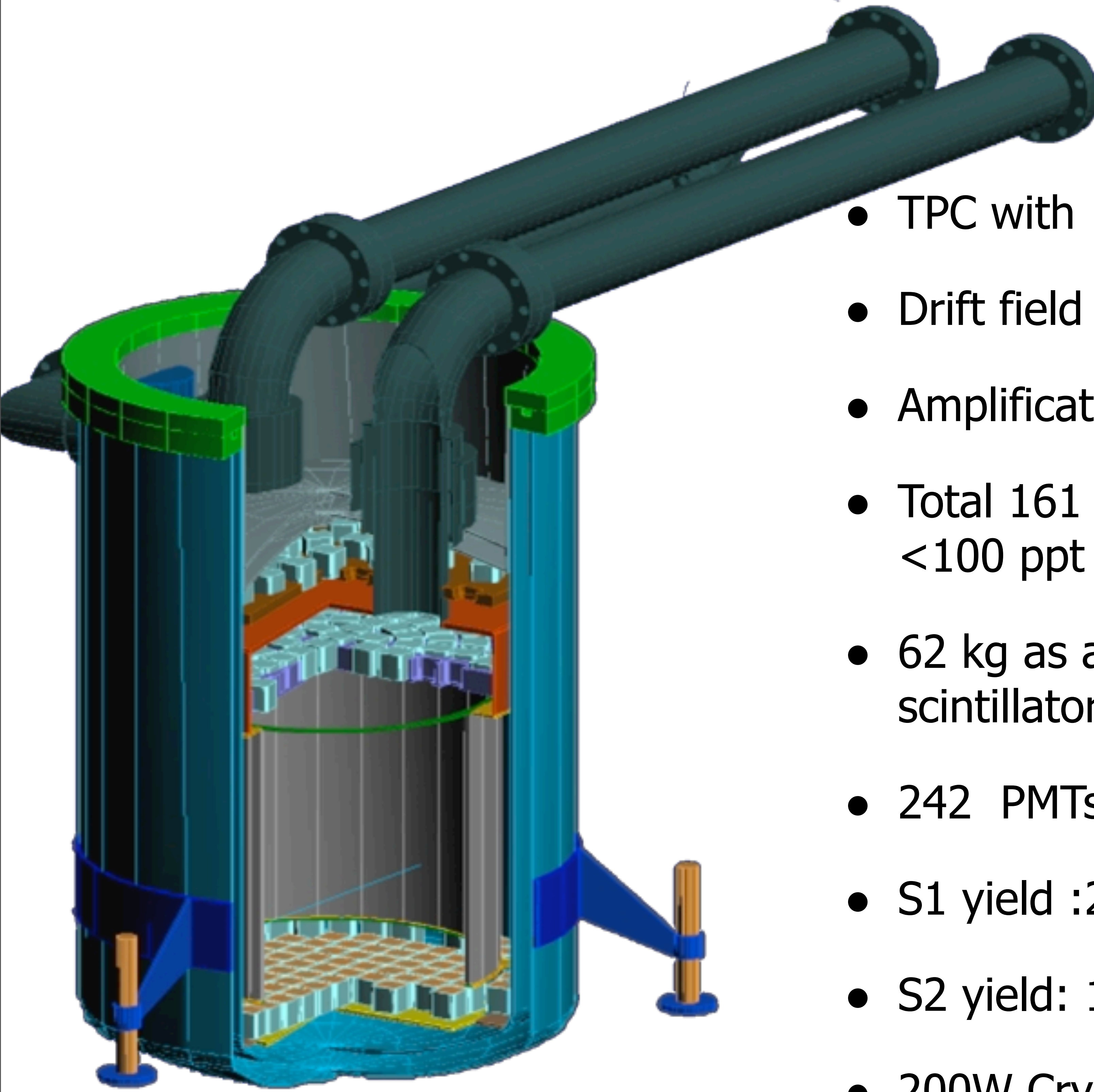
Mainz | Bologna | Subatech | Münster | Nikhef | Heidelberg | Weizman

The XENON Two-Phase TPC

a large, scalable, homogeneous, self-shielding, position-sensitive detector

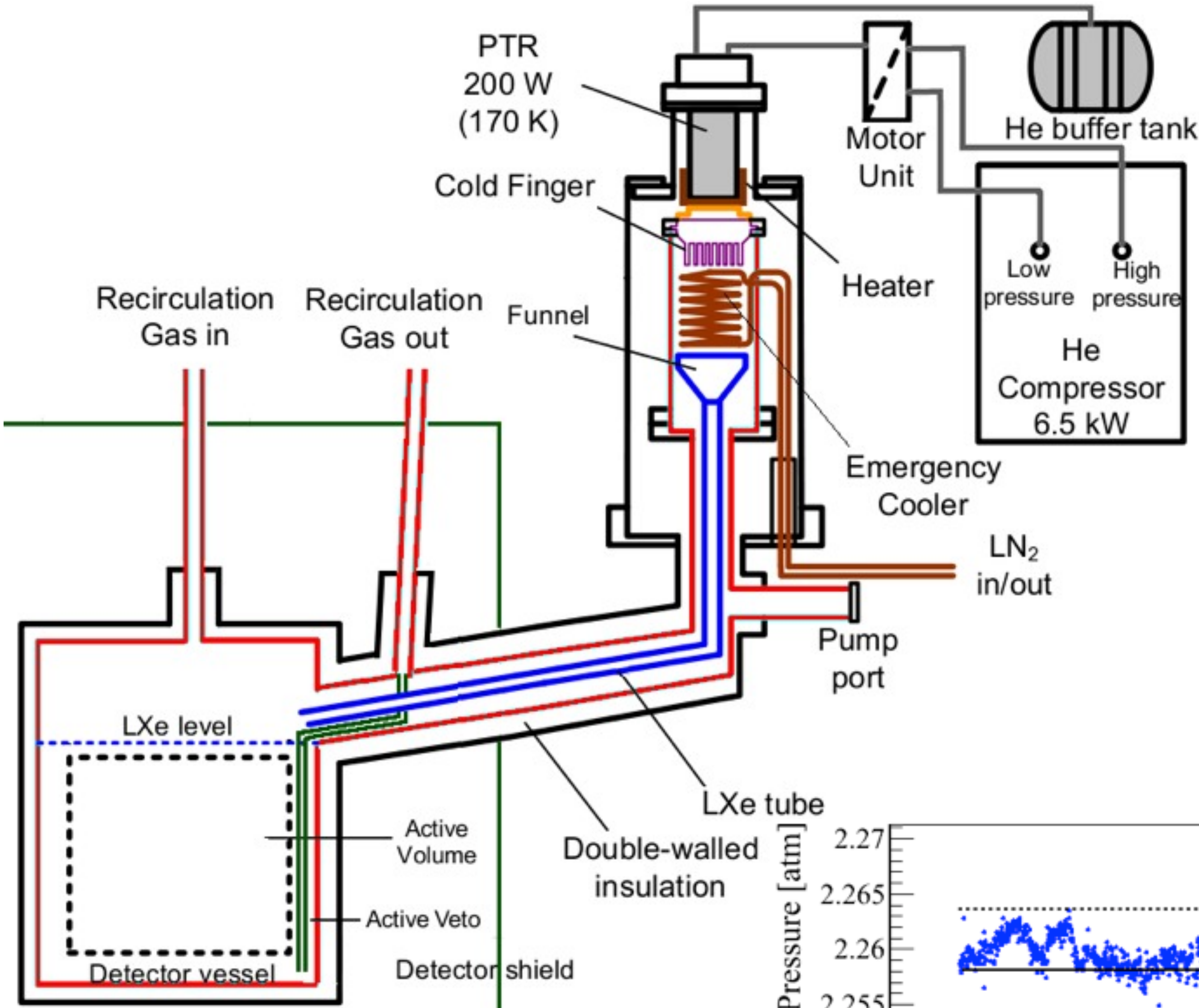


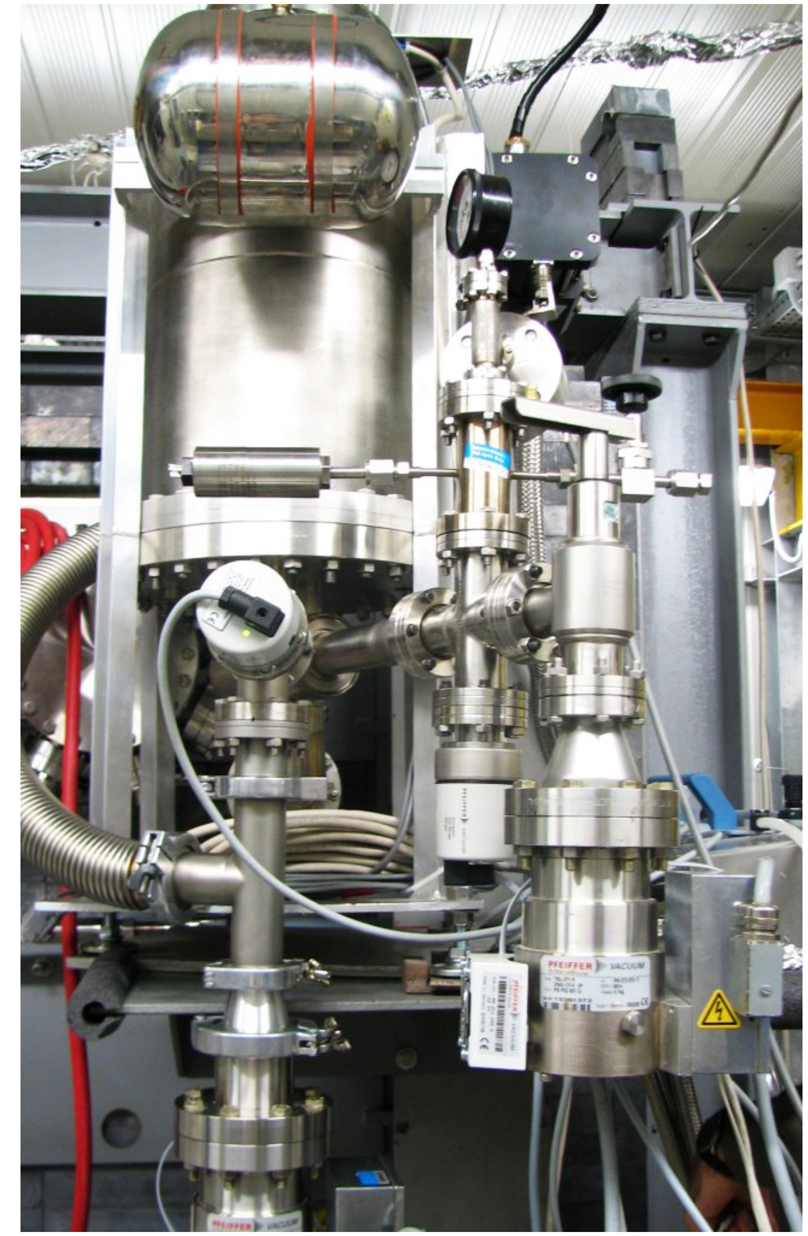
The XENON100 Detector

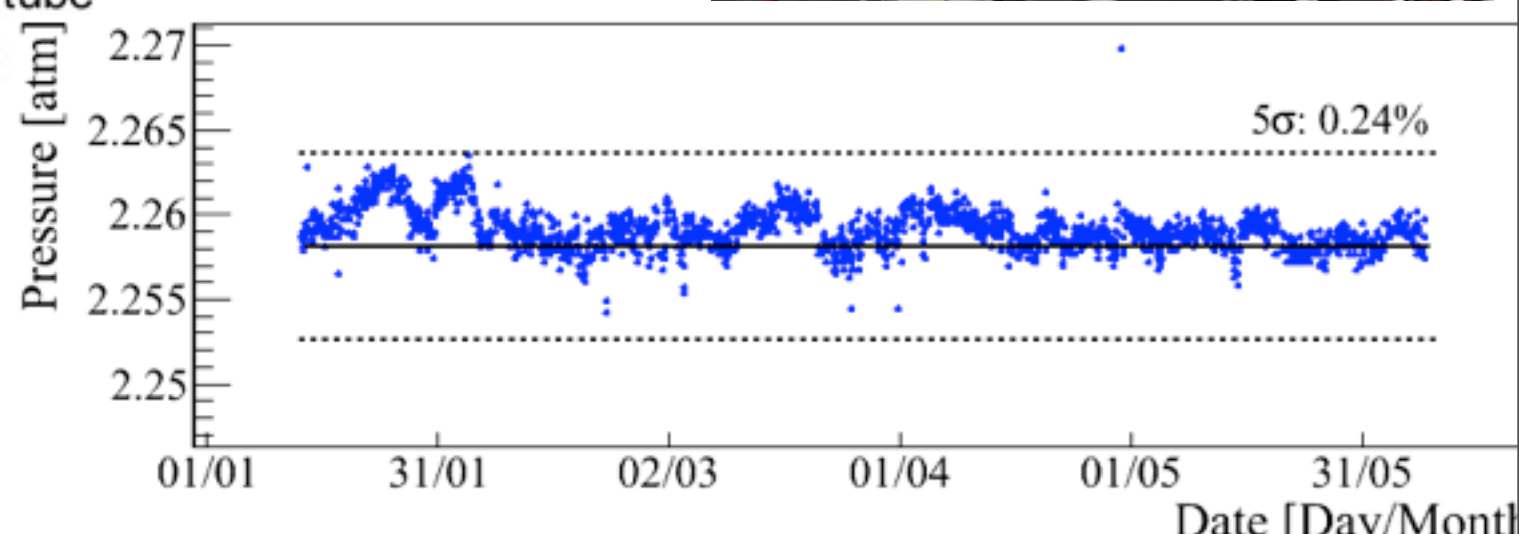


- TPC with 30 cm drift x 30 cm diameter
- Drift field in LXe ~ 0.5 kV/cm
- Amplification field in GXe ~10 kV/cm
- Total 161 kg high-purity Xe: <1ppb O_2/Xe and <100 ppt Kr/Xe contamination
- 62 kg as active target; 99 kg as active LXe scintillator veto
- 242 PMTs with ~1 mBq (U/Th)
- S1 yield :2.2 pe/keV (122 keV and 0.5 kV/cm)
- S2 yield: 18 pe/e (single electron sensitive!)
- 200W Cryocooler and FTs outside shield
- Materials screened for low-radioactivity

The XENON100 Cryogenic System



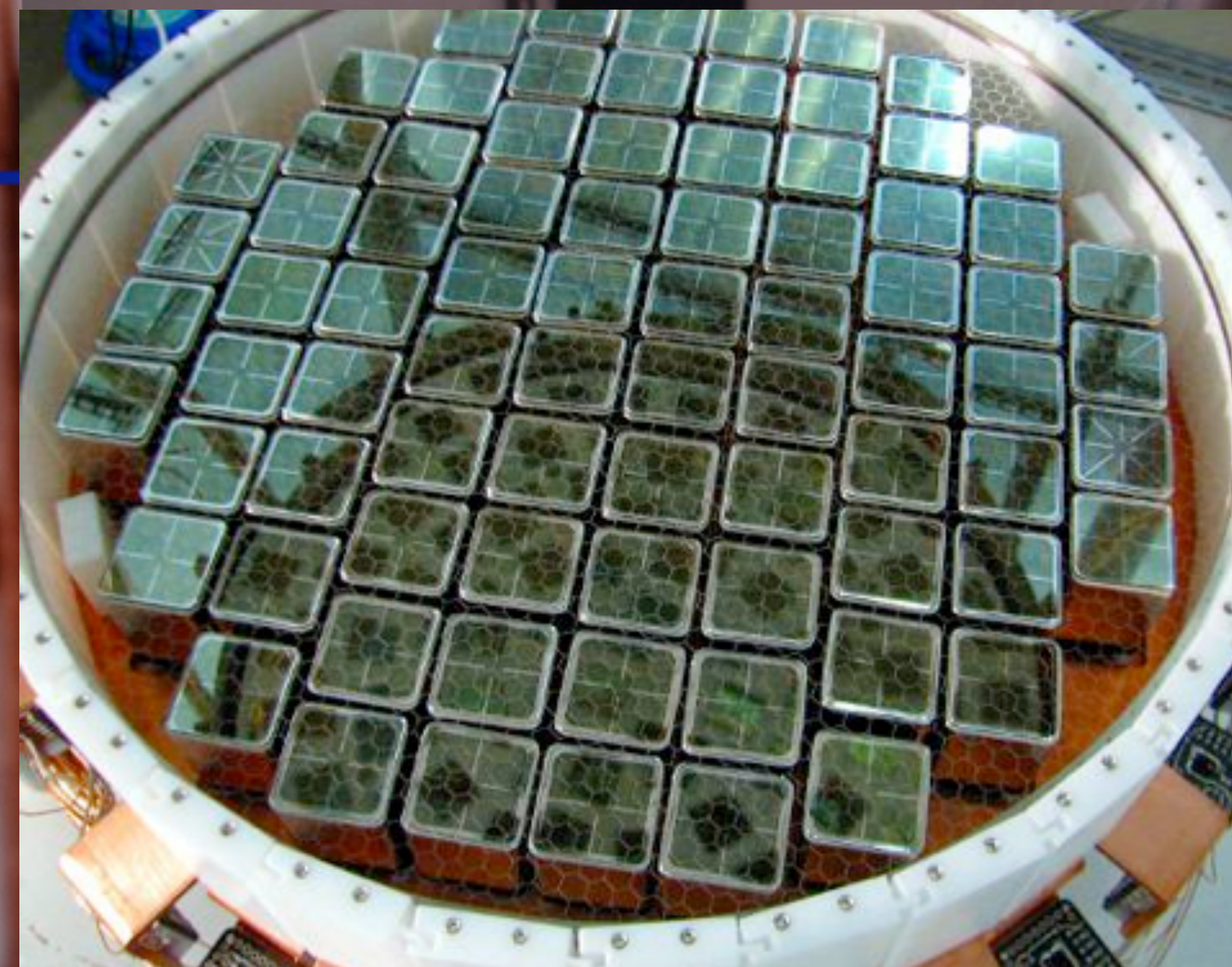


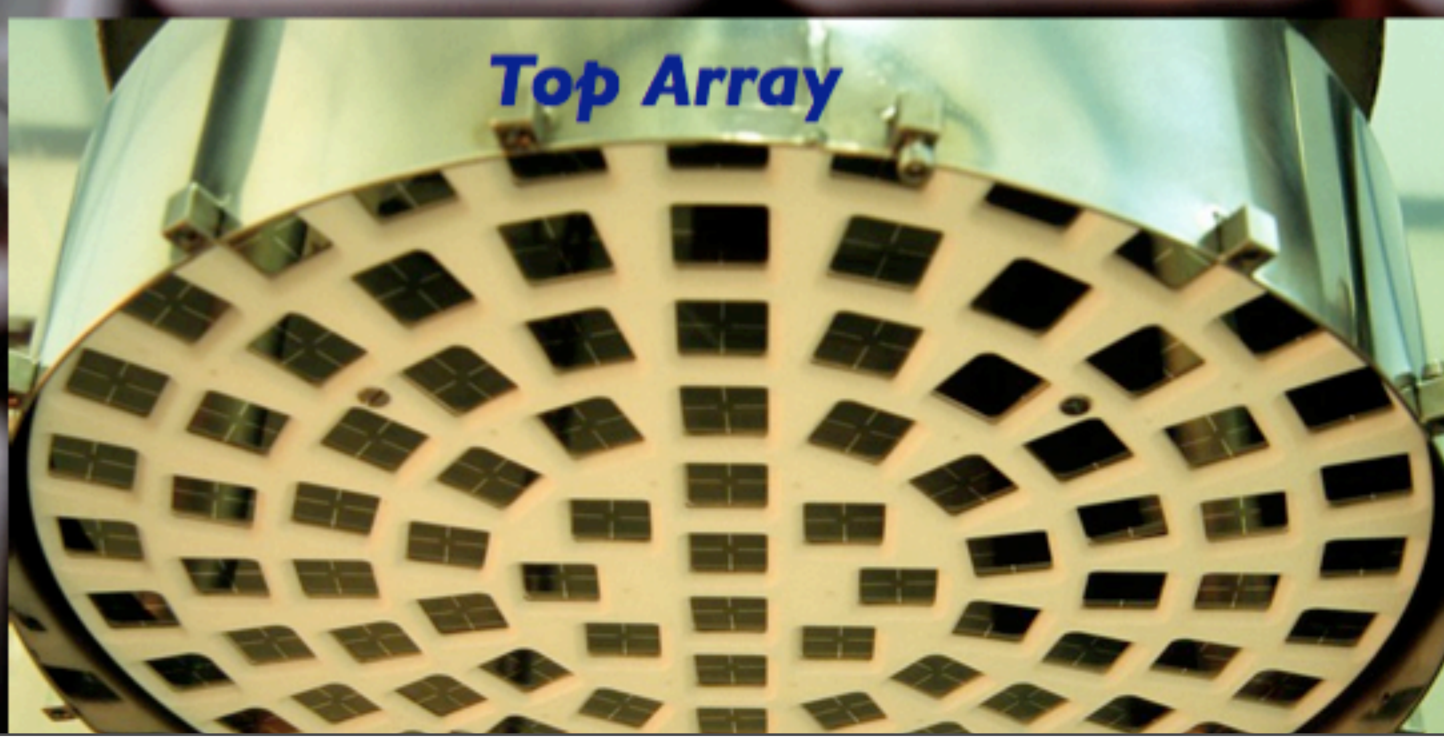


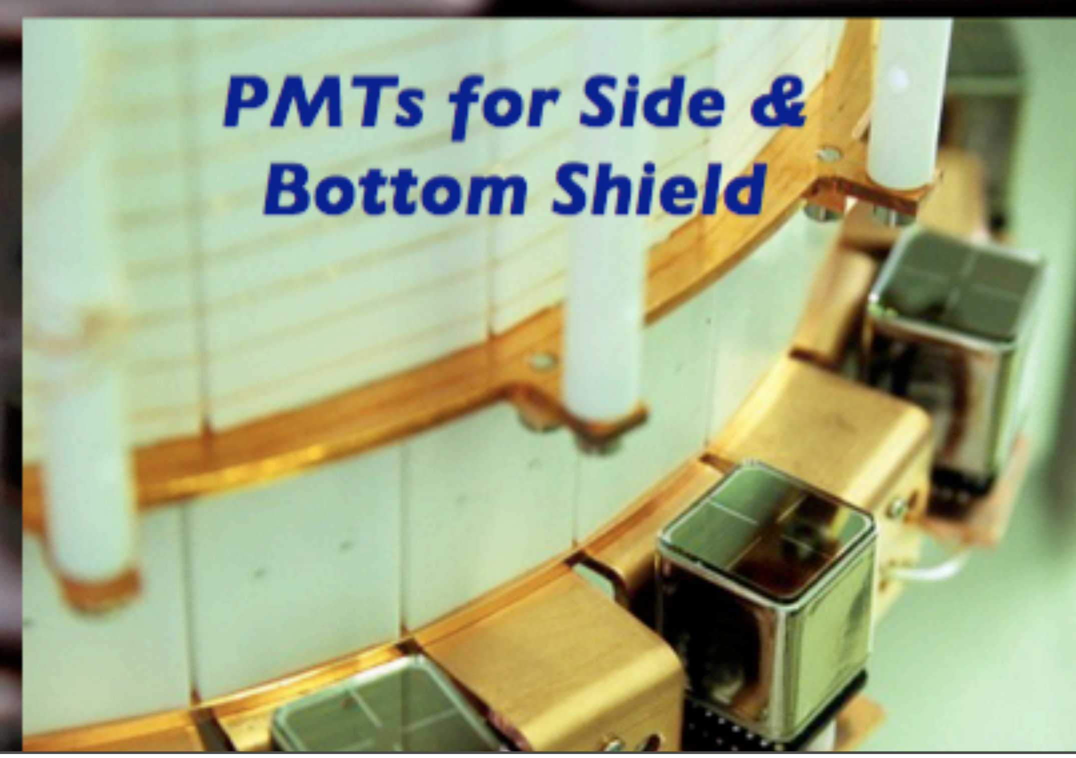
The XENON100 PMTs

XENON100: The PMTs

- 242 PMTs (Hamamatsu R8520-06-Al)
- 1 " square metal channel developed for XENON
- Low radioactivity (<1 mBq U/Th per PMT)
- 80 PMTs for bottom array (33% QE)
- 98 PMTs for top array (23% QE)
- 64 PMTs for top/bottom/side Veto (23% QE)







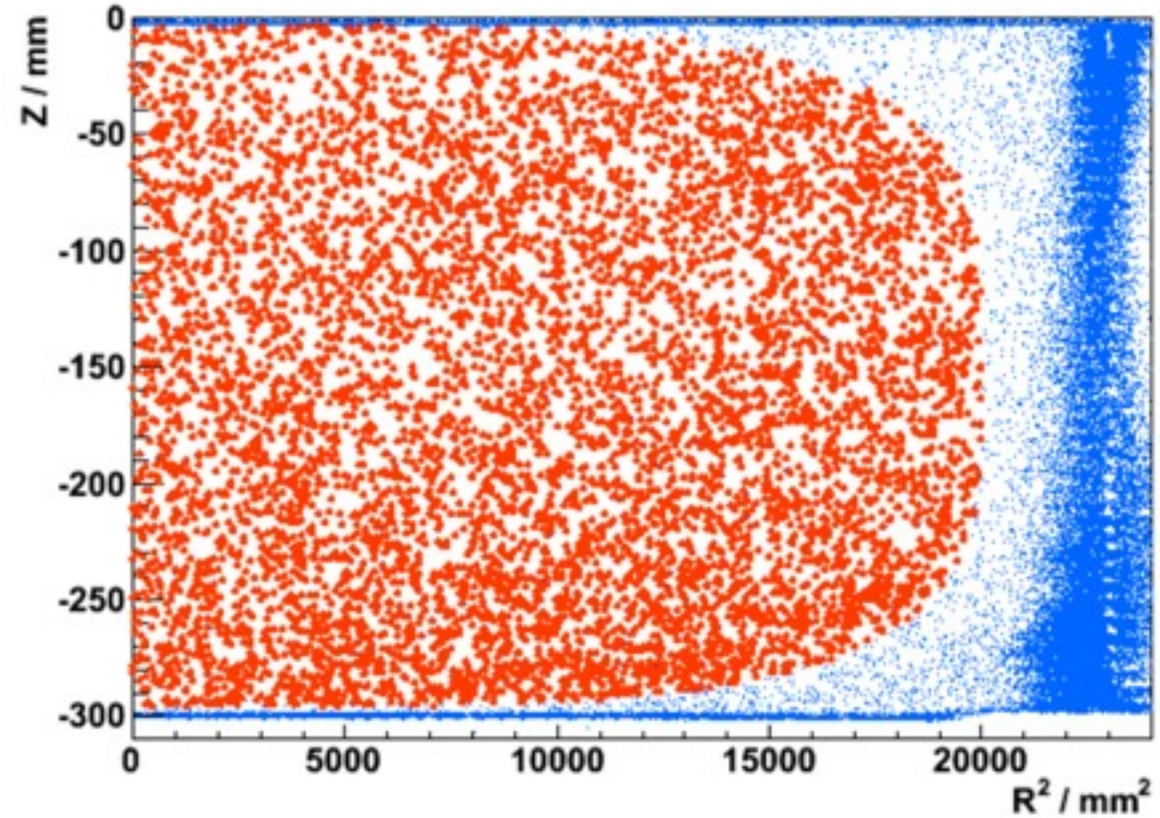
3D Event Localization in XENON100 TPC

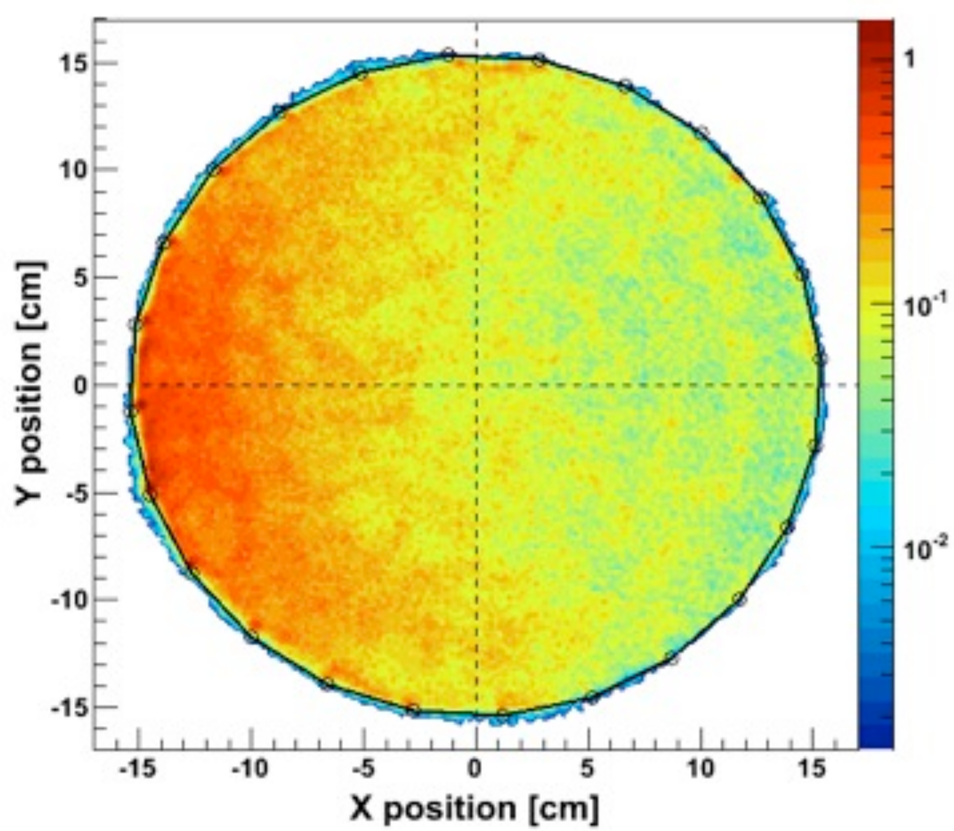
1" PMTs allow event position reconstruction in X-Y (from S2 signals) with millimeter precision

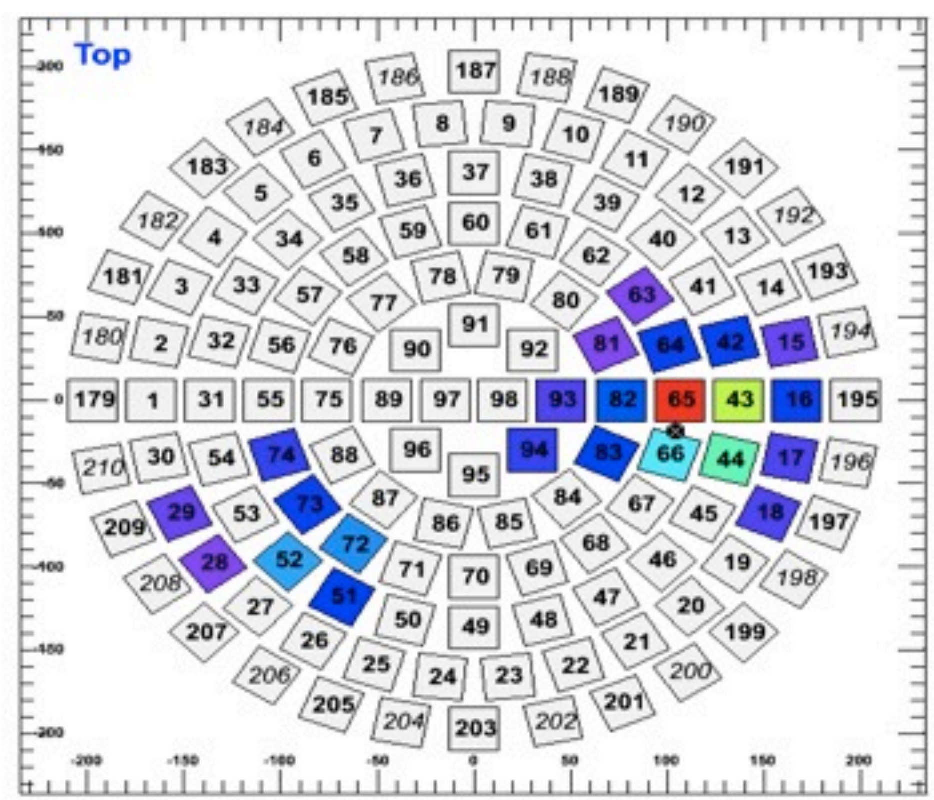
Drift time measurement gives Z coordinate with sub-millimeter precision

3D event localization powerful for background rejection: 1) Fiducial Volume and 2) Single/Multiple Scatters

Fiducialization



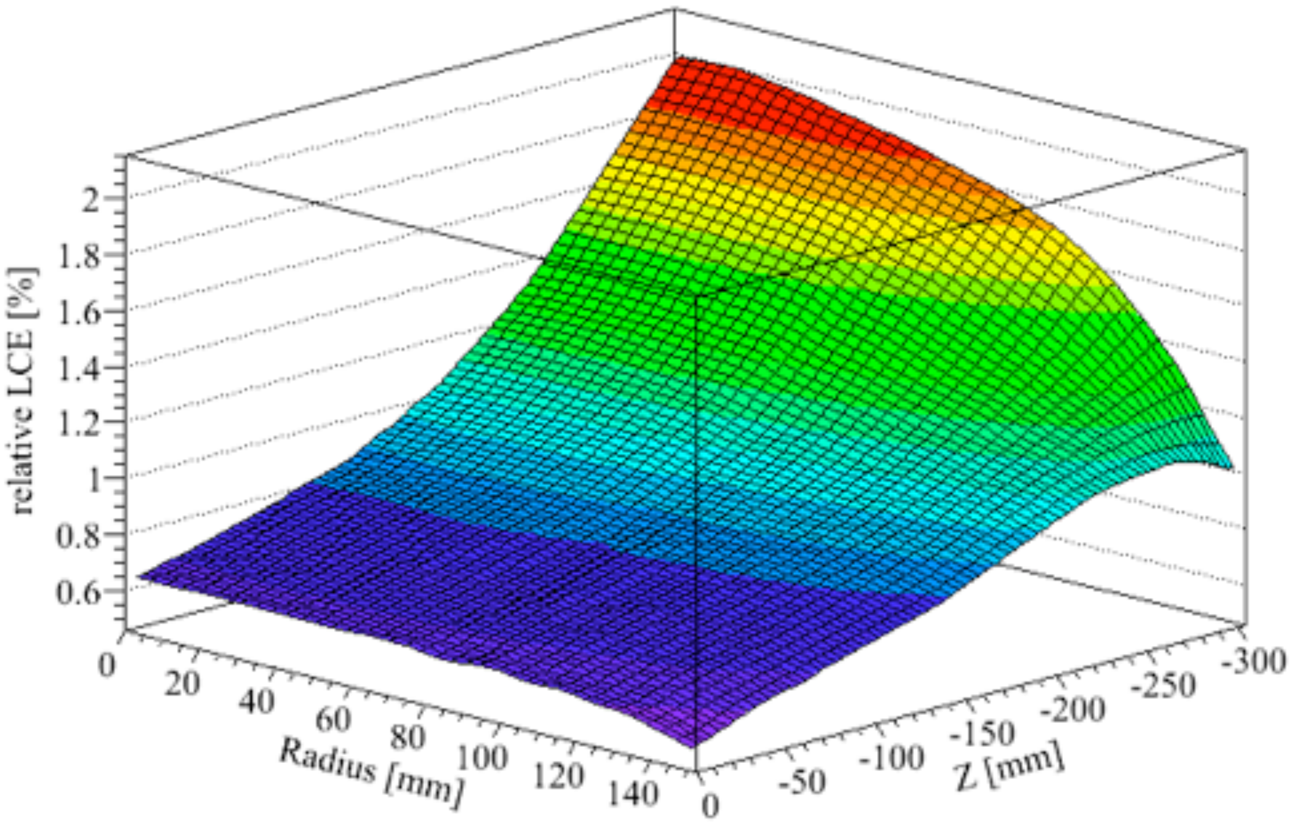




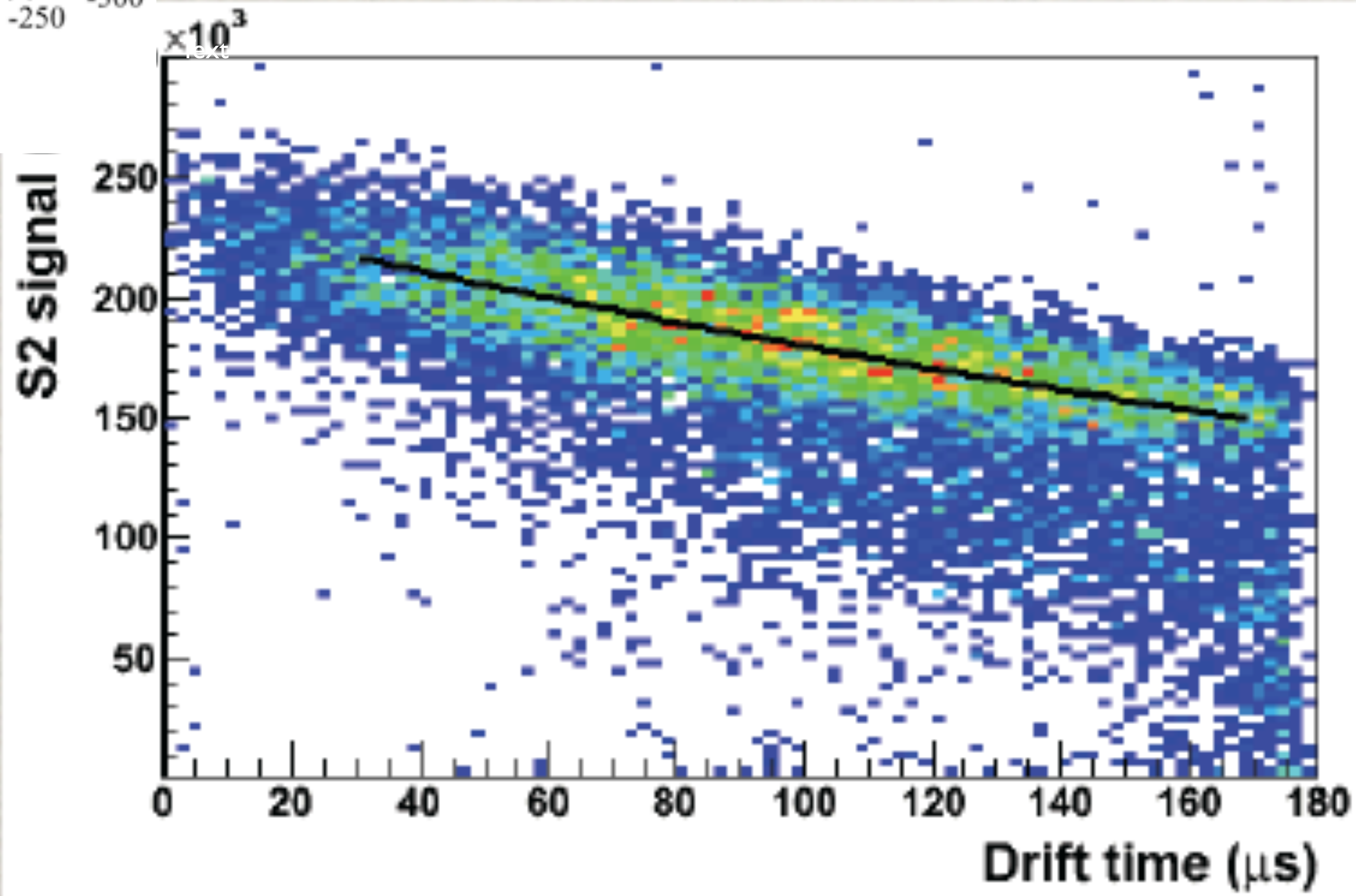
Italic PMTs look inwards

Position-dependent Signals corrections

S1 Light Collection Map



S1 dependence on XYZ
(a factor of 3 difference from bottom to top)

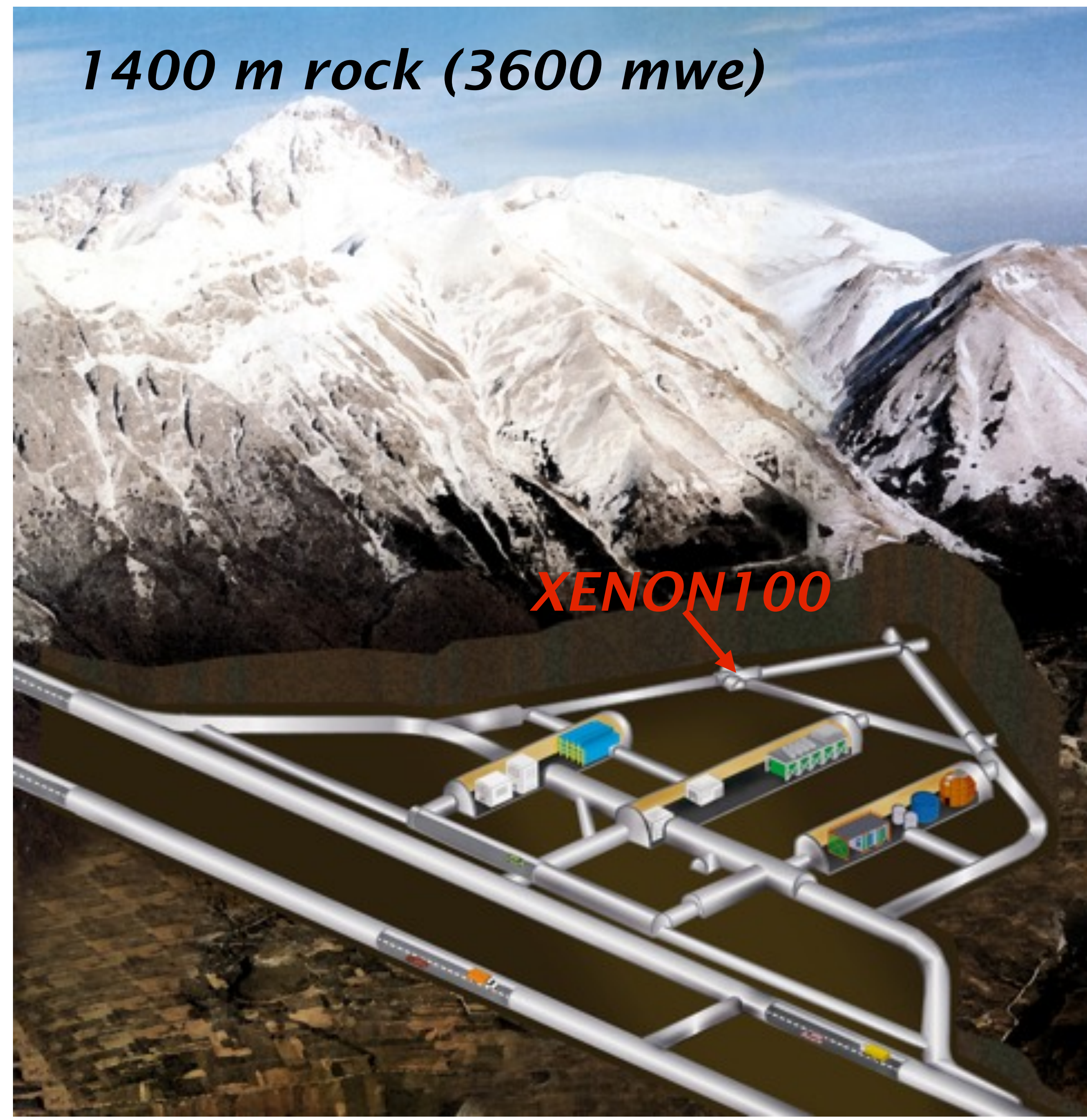


S2 dependence on Z
(depends on the impurity level in Xe)

XENON100 @ LNGS

Shield: 20cm H_2O, 20cm Pb, 20cm PE, 5cm Cu

Shield cavity purged with N_2 to keep Rn level < 0.5 Bq/m^3



Background Sources in XENON100

Neutrons

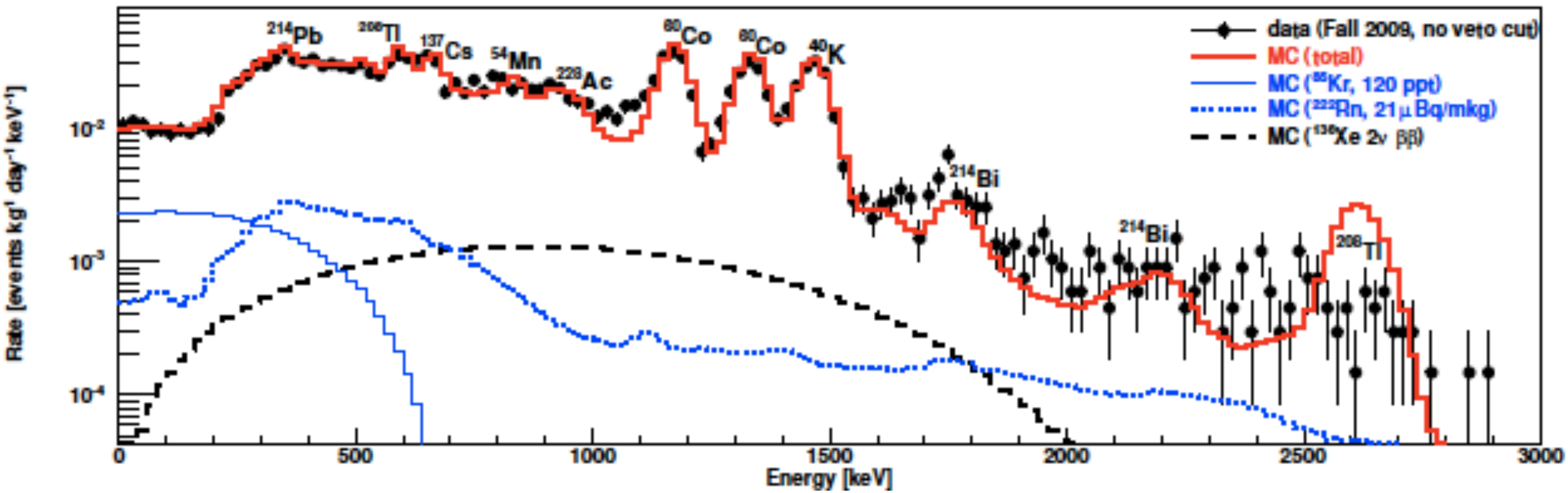
- radiogenic from fission and (a,n) reactions in detector and shield materials
- cosmogenic from spallation of nuclei in materials by high-energy muons

Electromagnetic Radiation

- natural radioactivity in detector and shield materials
- ^{222}Rn in shield cavity
- ^{85}Kr and ^{222}Rn in LXe
- cosmogenic activation of detector materials and of LXe during production and storage on Earth' surface

Measured Background

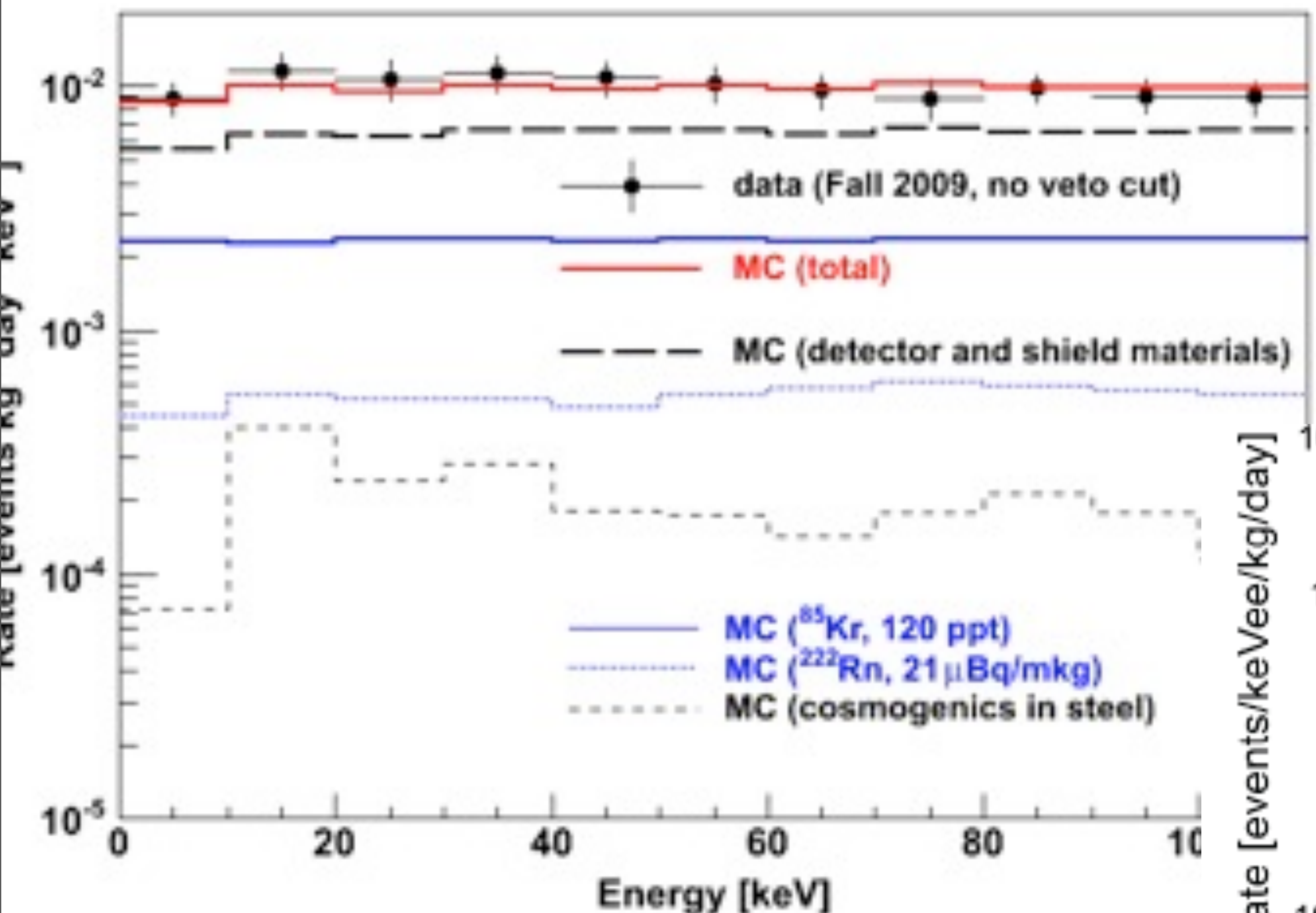
E. Aprile at al. (XENON100), Phys. Rev. D 83, 082001 (2011)

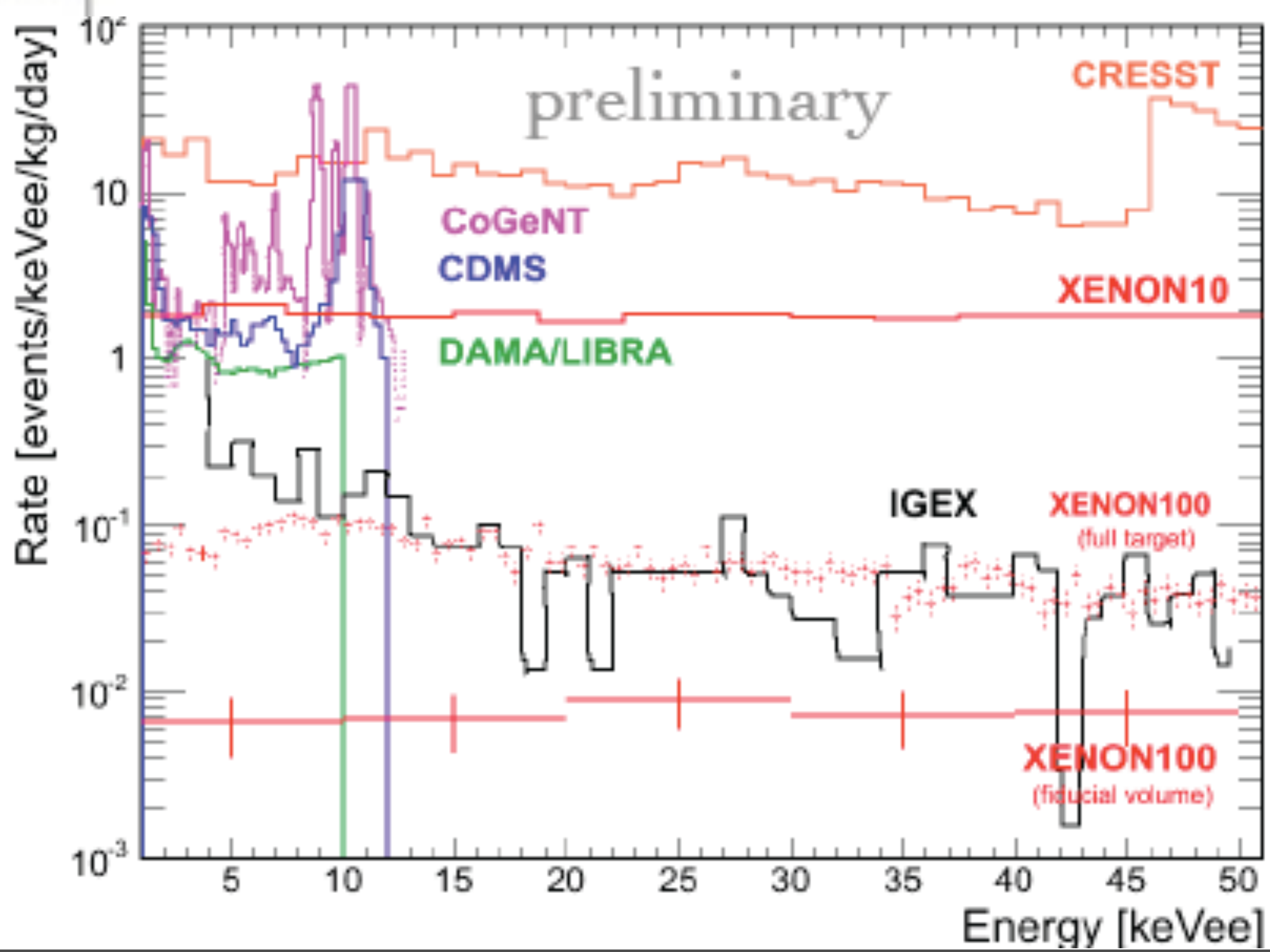


In good agreement with Monte Carlo simulations based on detailed mass model and measured values for U/Th/K/Co/Cs from radioactivity in all screened XENON100 materials. No LXe veto cut

..the lowest of any Dark Matter experiment

- In 30kg fiducial volume background rate is ~10 mdru even before the LXe veto cut
- The LXe veto reduces rate to ~5 mdru, where ^{85}Kr in LXe starts to dominate



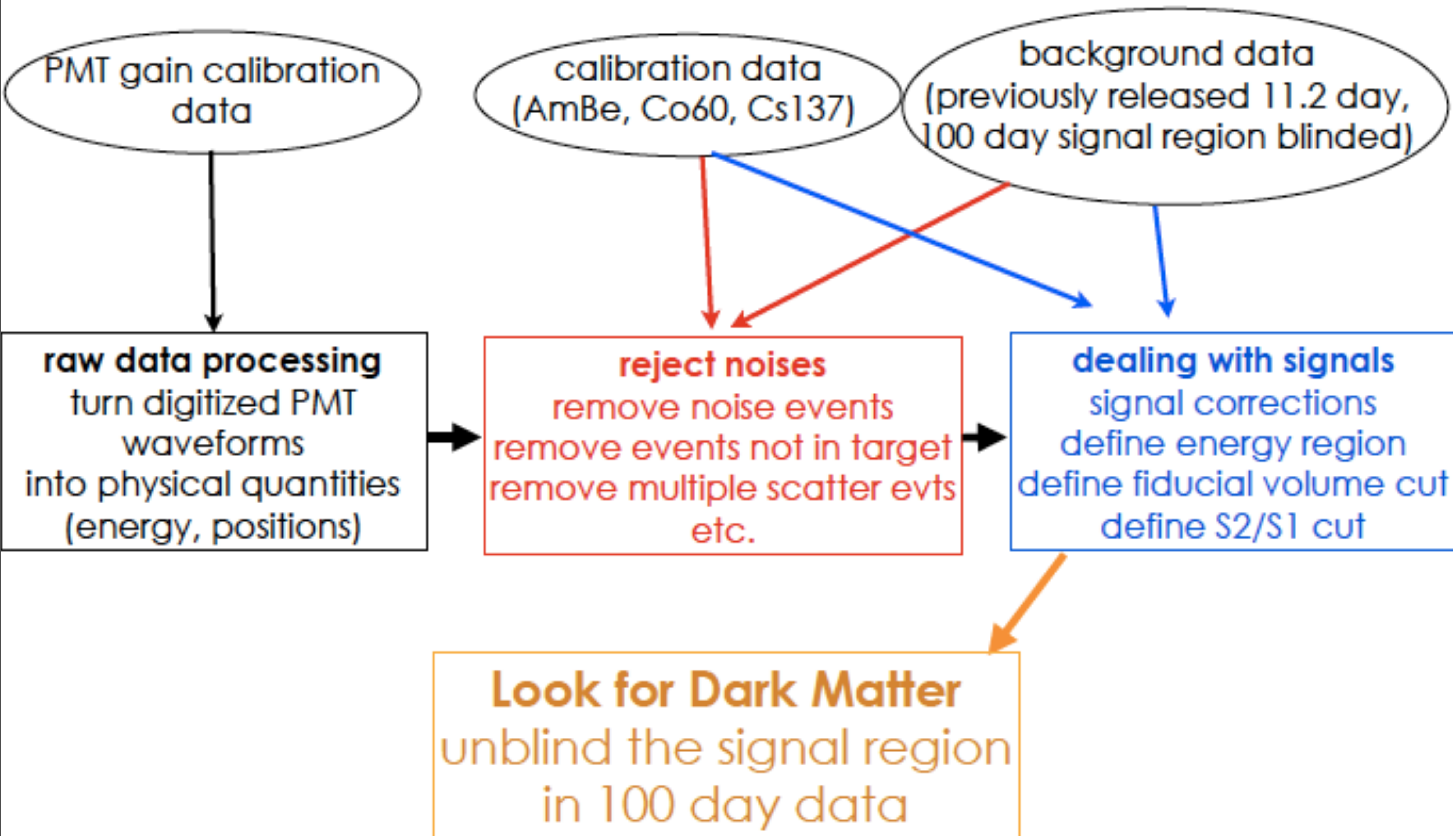


- Factor 100 less than XENON10 and than other DM experiments

XENON100 Dark Matter Search with 100 days of data during 2010

Aprile et al. submitted to Physical Review Letters arxiv:1104.2549

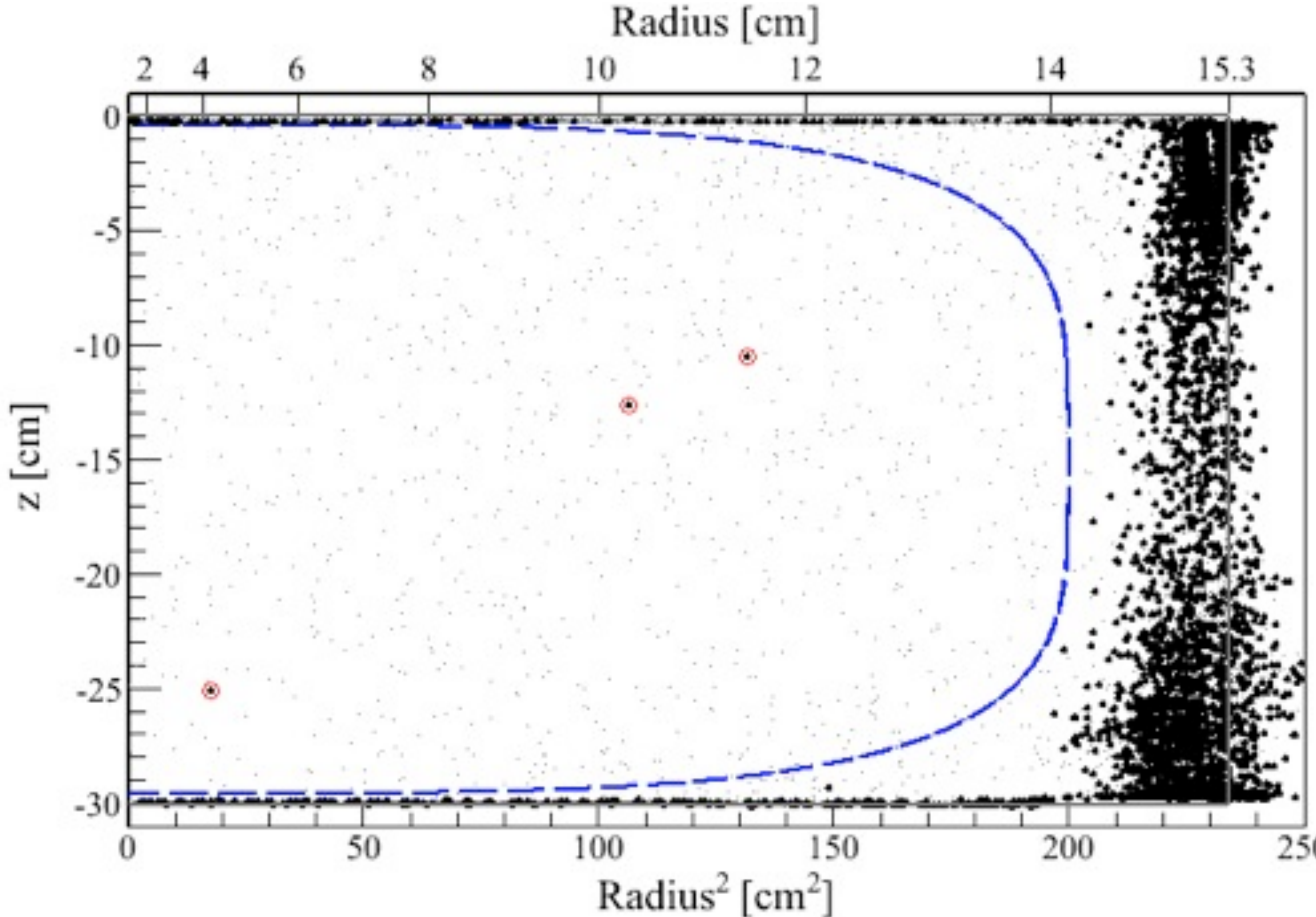
Analysis Steps



Expected Background in Signal Region in 48kg and 100 days

- from radioactivity of detector's materials and estimated 700 ppt Kr in Xe
  - 1.70 electron recoils after 99.75% S2/S1 rejection
  - 0.03 nuclear recoils
- from muon-induced nuclear recoils (Monte Carlo): 0.08
- Total expected background in signal region: 1.8 +- 0.6
- Prediction from data and Monte Carlo; verified on high energy side band

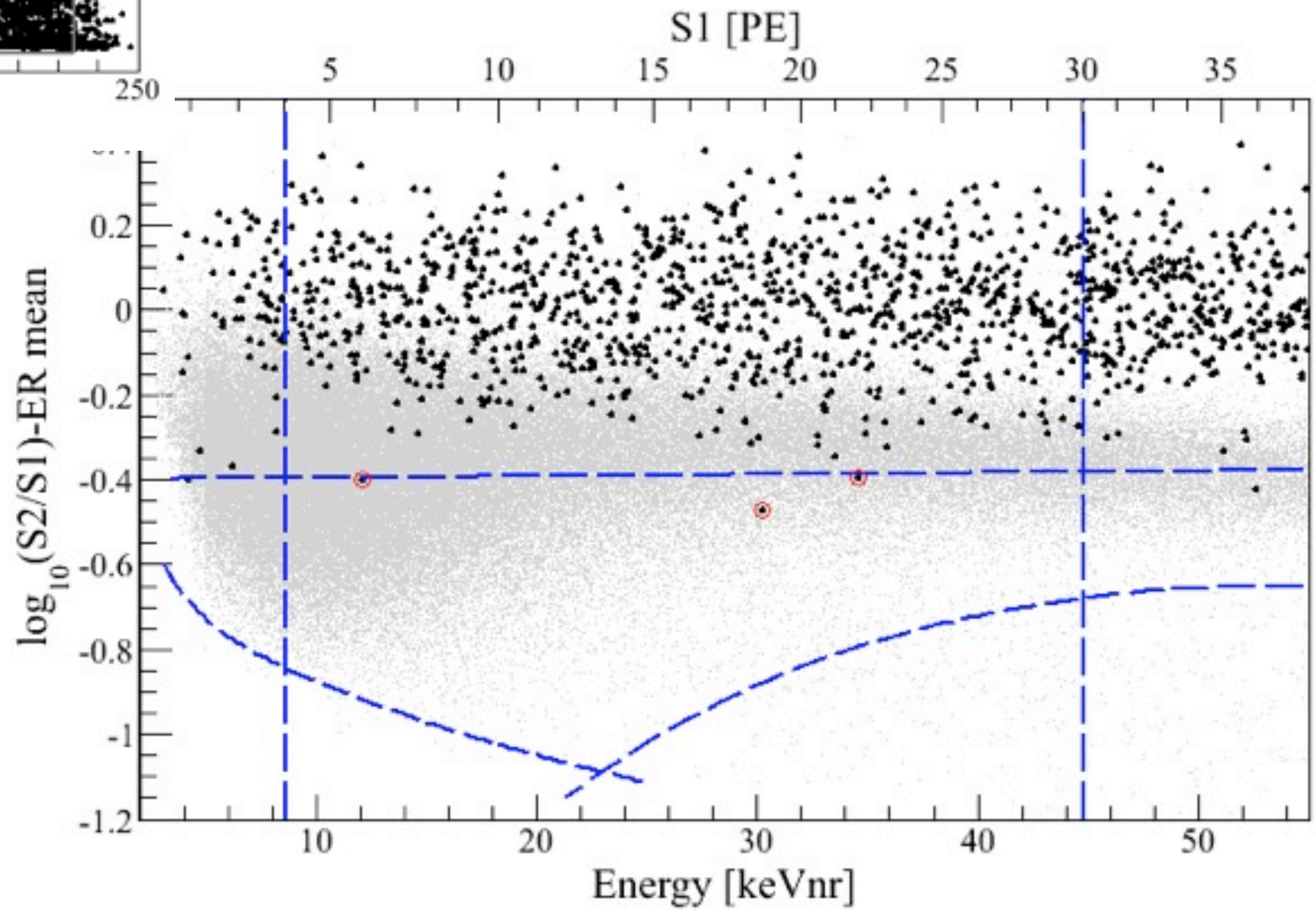
Search Result



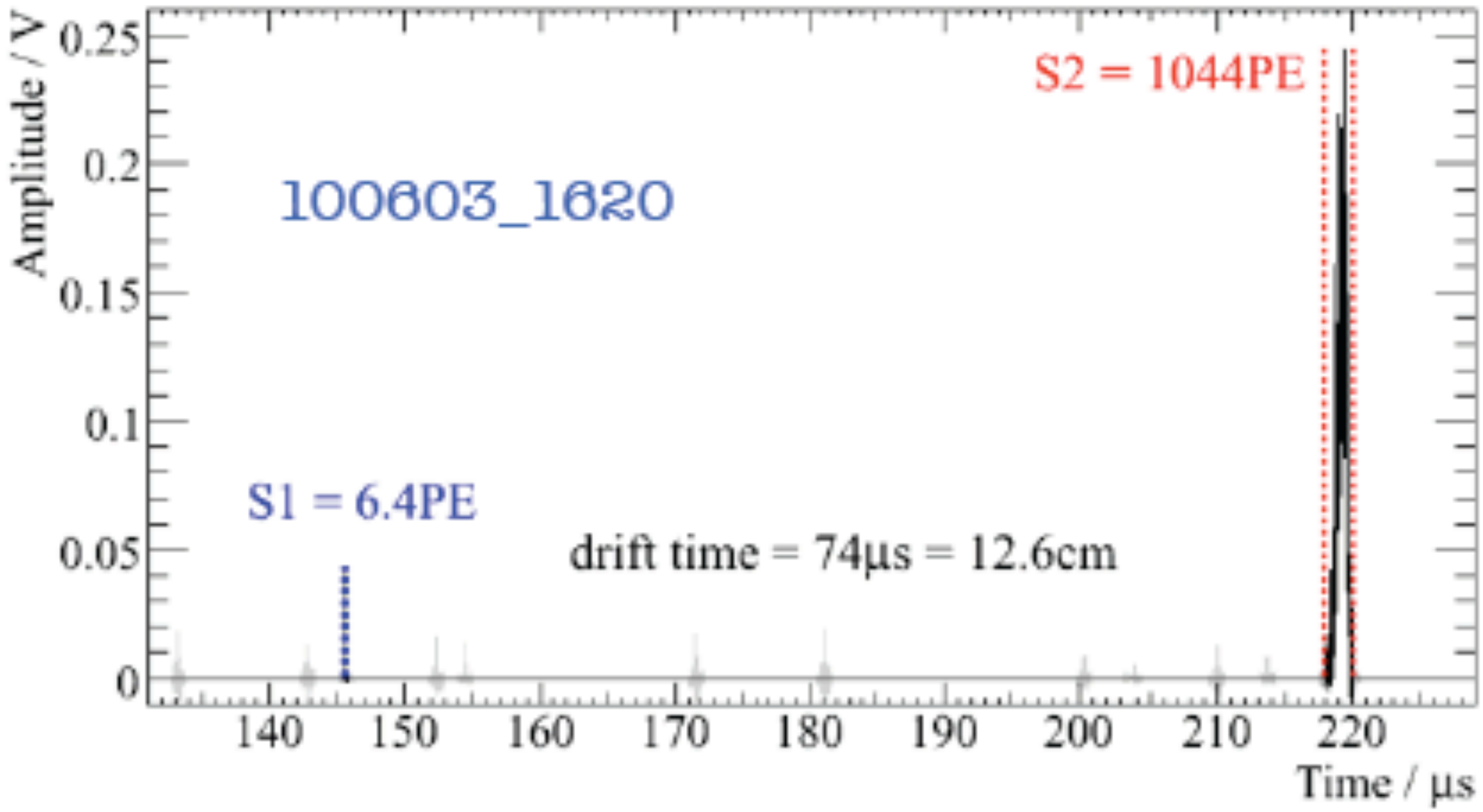
Exposure 1471 kg x days

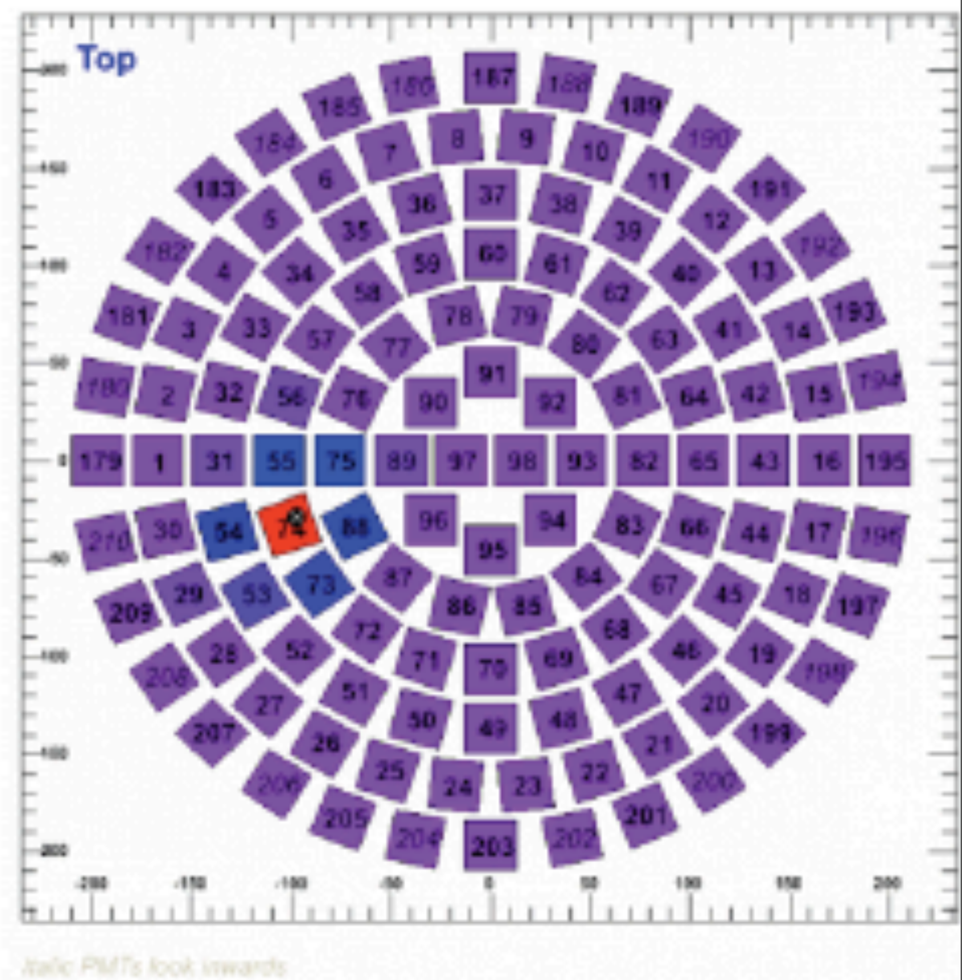
- Total events: 8,311,703
- 4pe < S1 < 30pe: 608,532
- 48 kg Fiducial Volume cut: 898

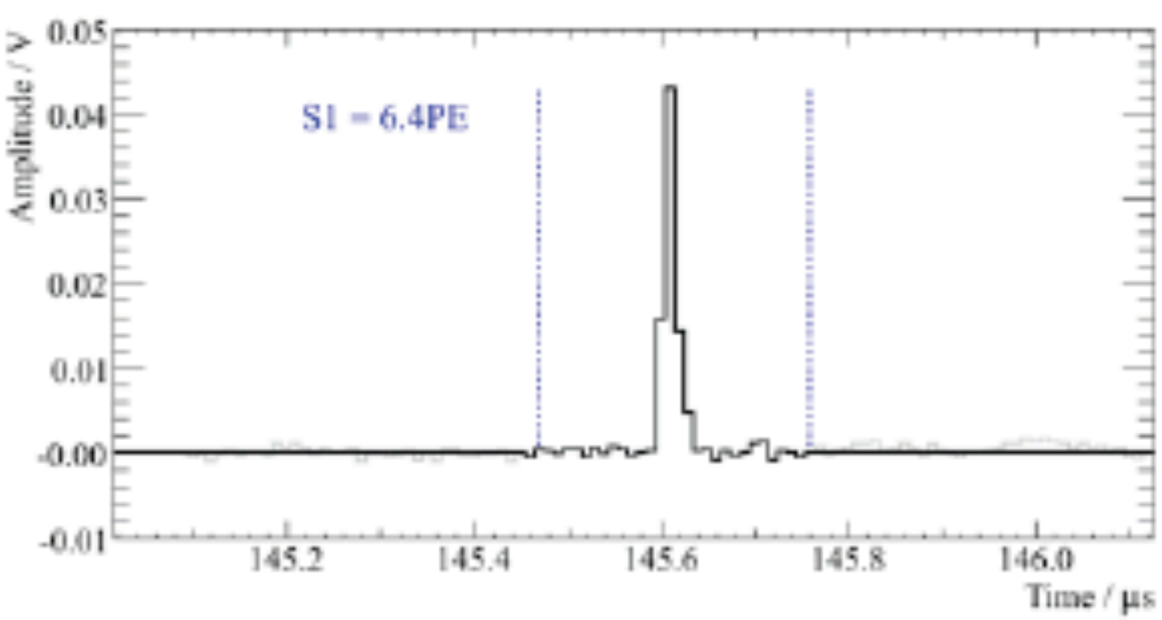
- In signal region (S2/S1): 3 Events
- Expected total background: 1.8 +- 0.6
- 28% probability for 3 or more events
- Profile Likelihood analysis also gives no significant signal

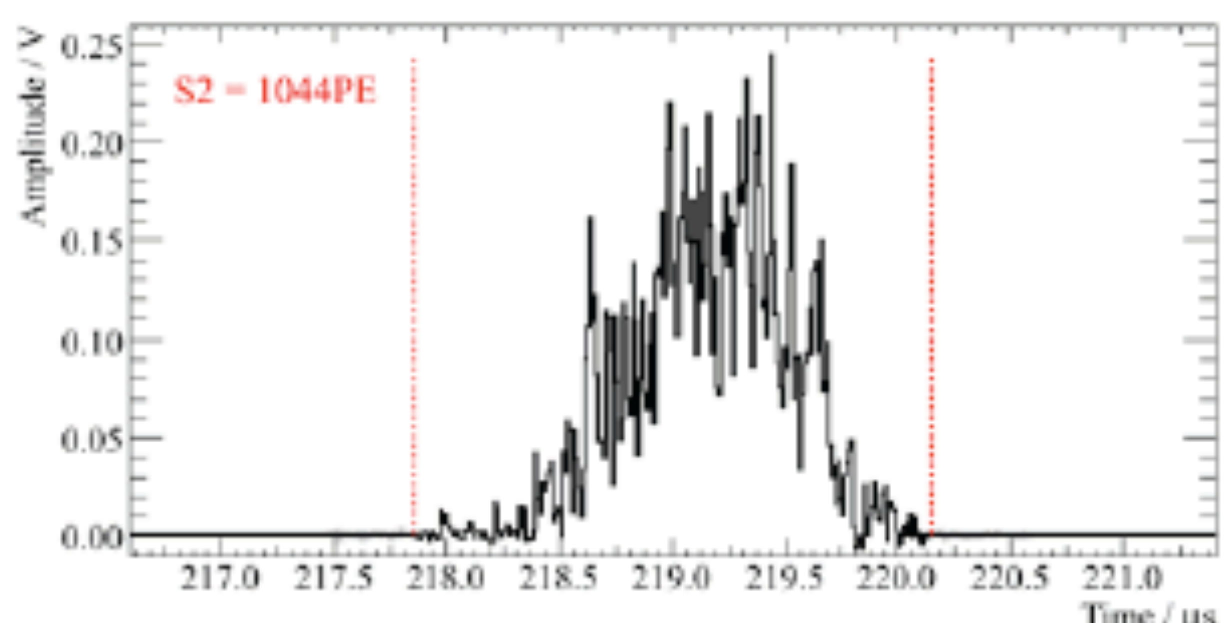


One of the 3 Candidate Events

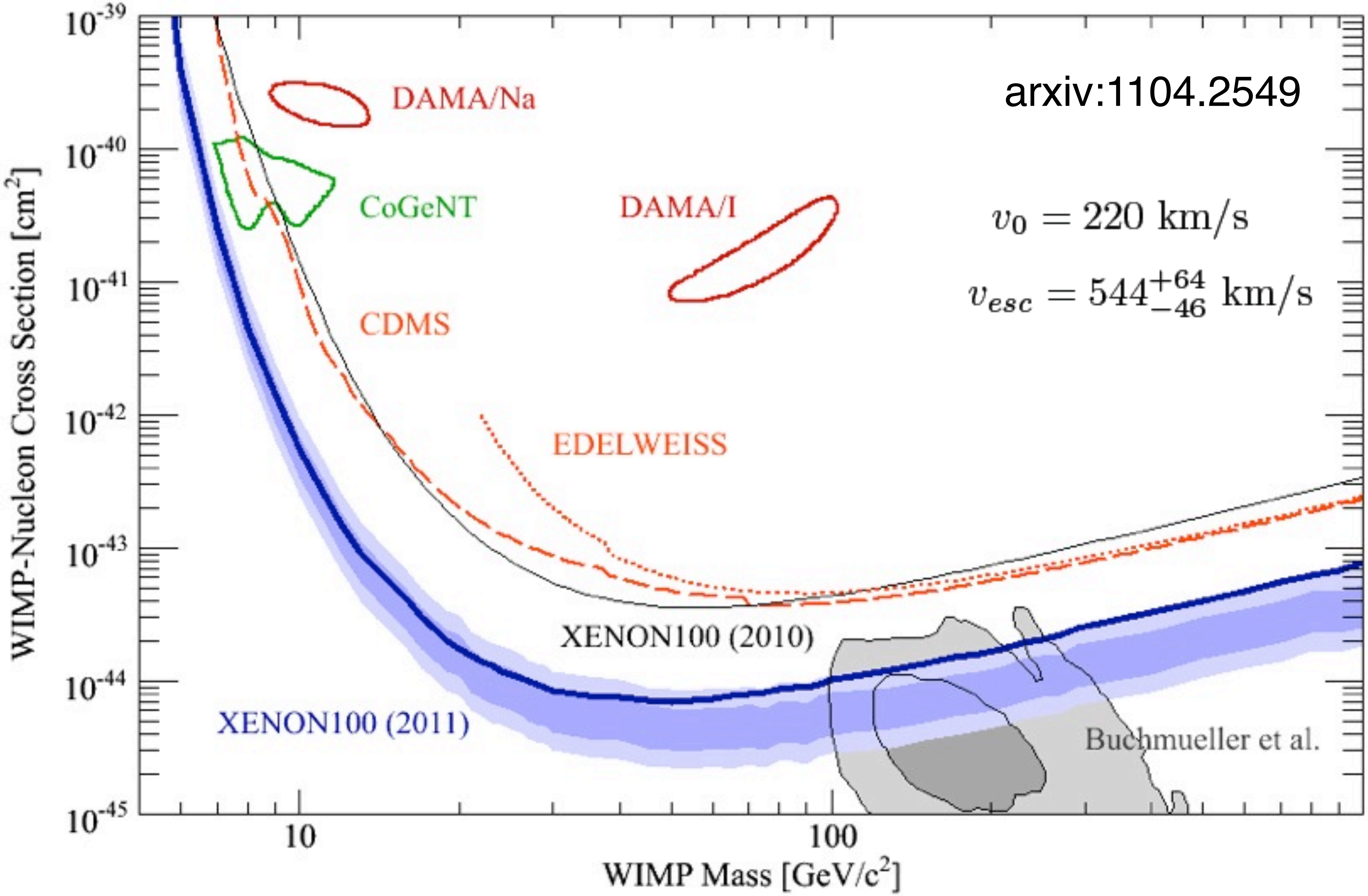








XENON100 Dark Matter Limit (90% CL)

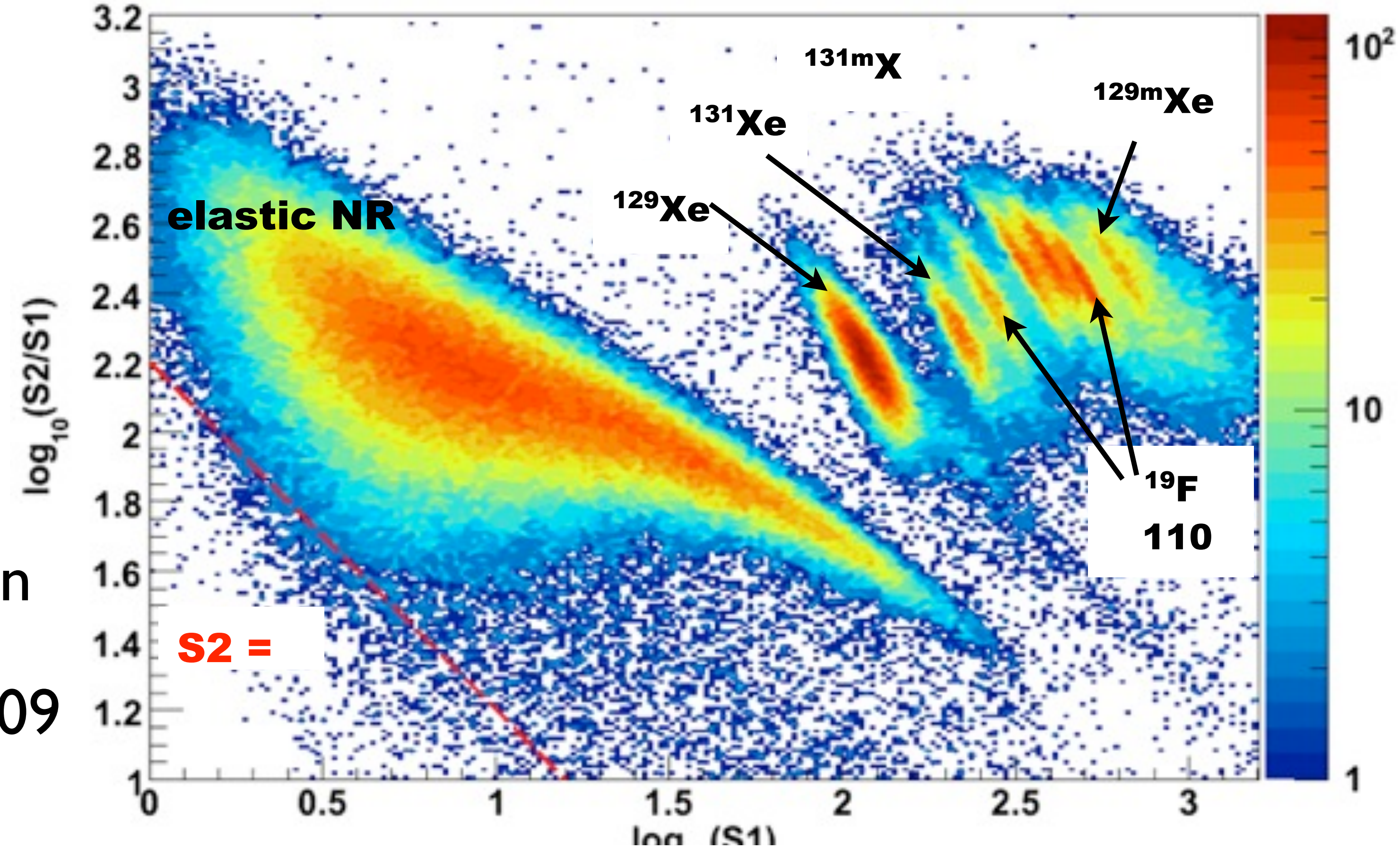


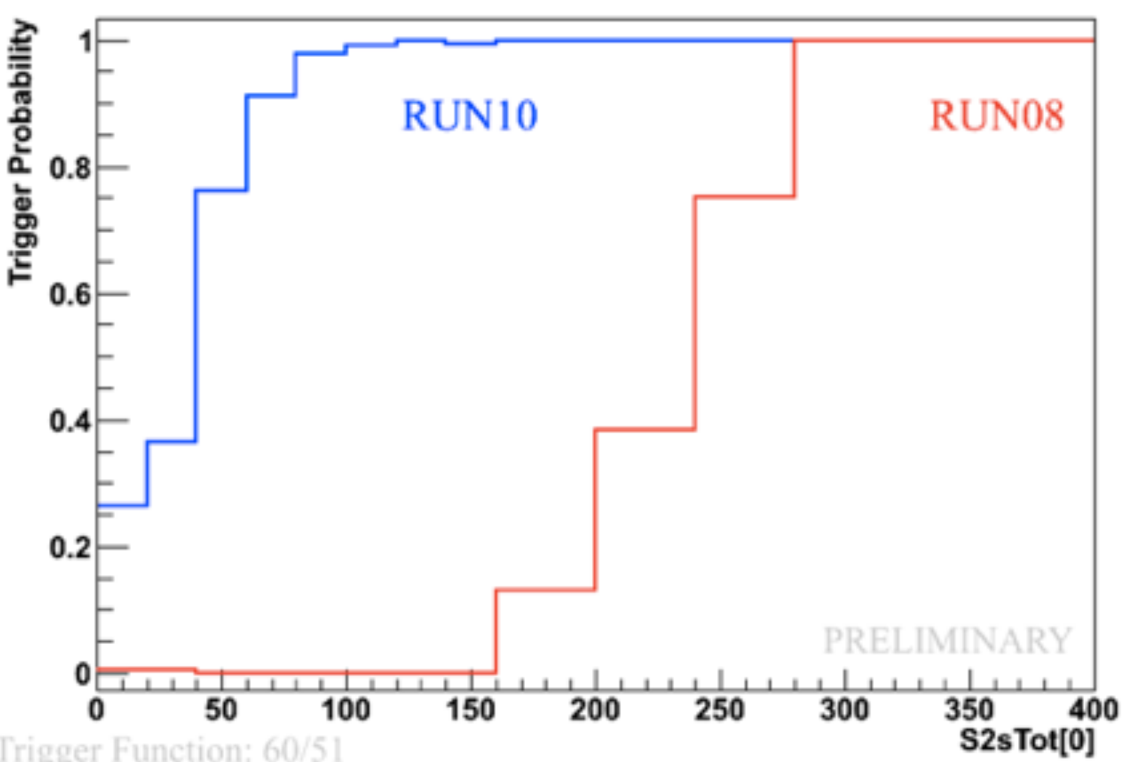
Blue bands are 1 and 2 sigma expectations (PL) based on zero signal

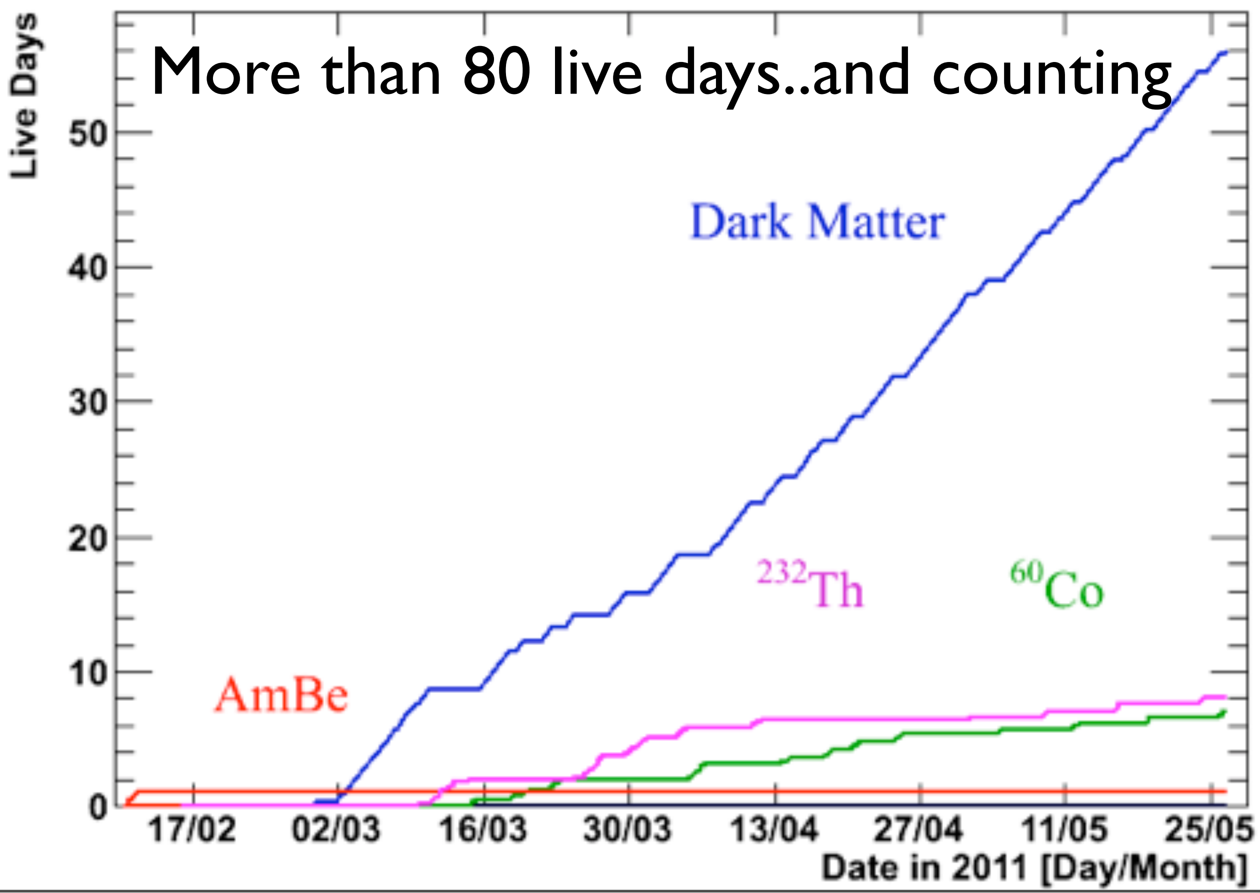
Minimum at 7 x 10^{-45} cm^2 @ 50 GeV

XENON100 Status & Outlook

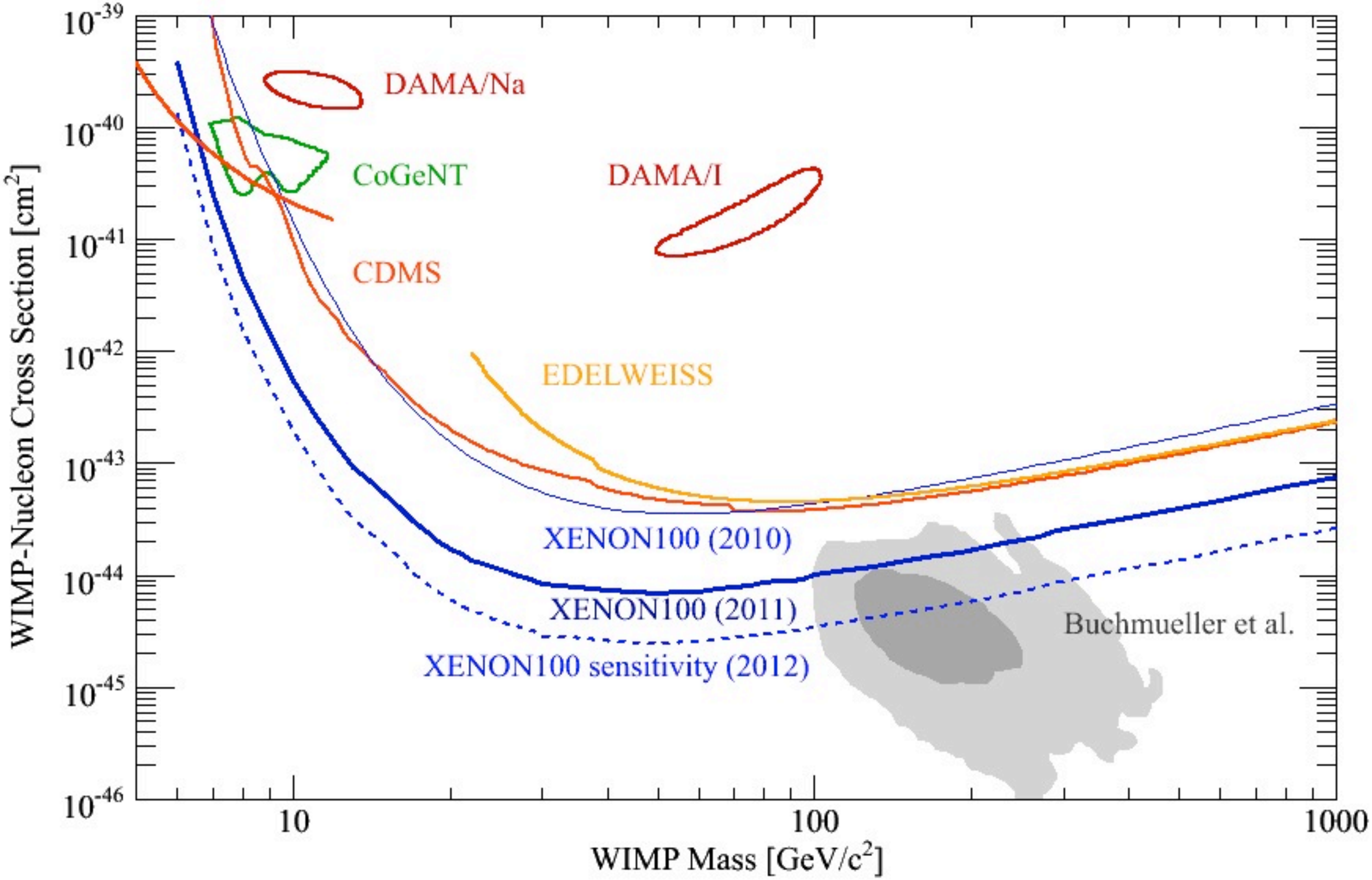
- •Serviced Cryogenic System
- •Run Kr distillation column
- •Lowered S2 Trigger Threshold
- •Completed new AmBe Calibration
- •Taking large Co60 & Th232 Calibration
- •Background at the same level as in 2009
- •Detector Parameters very stable





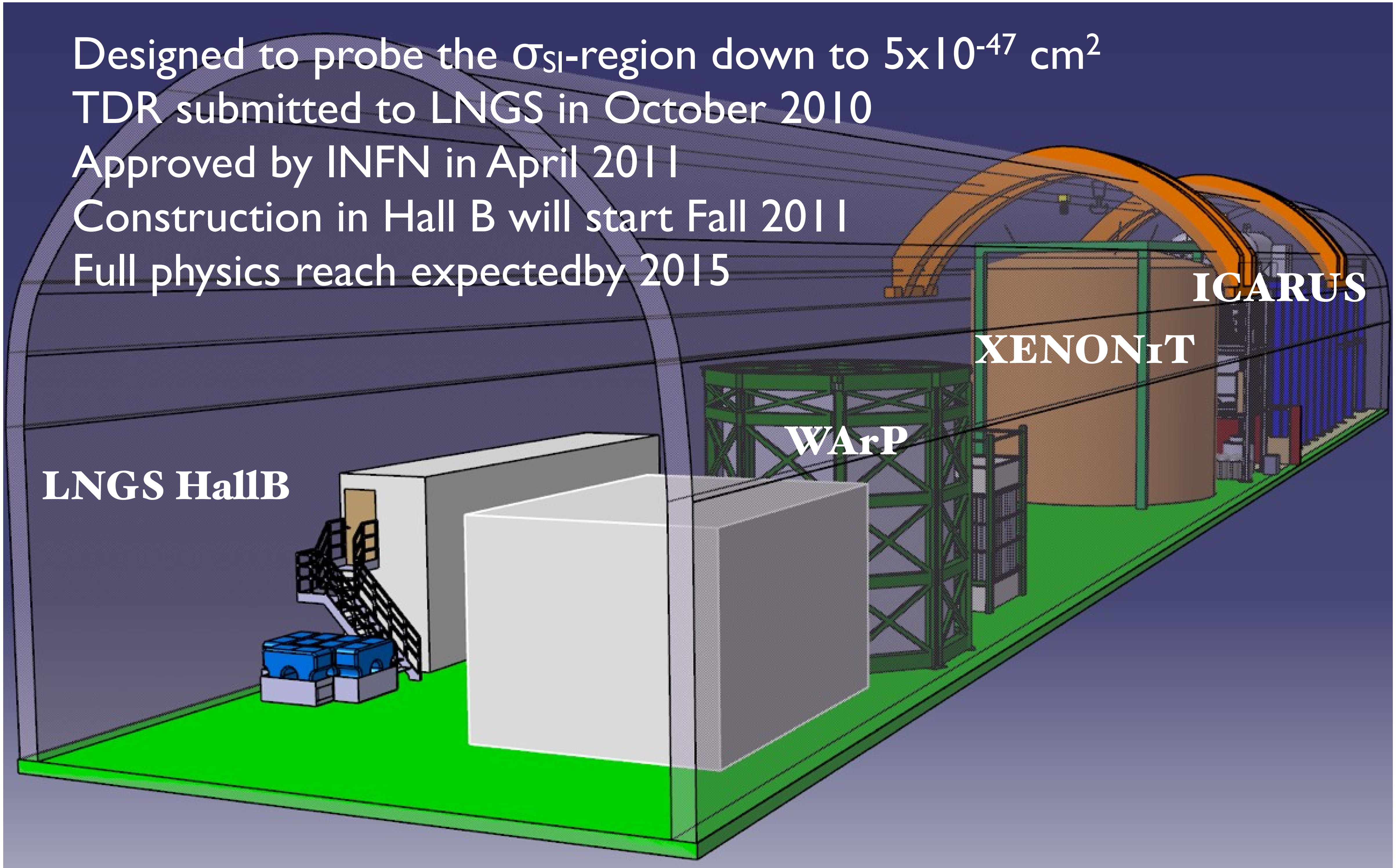


XENON100 by 2012



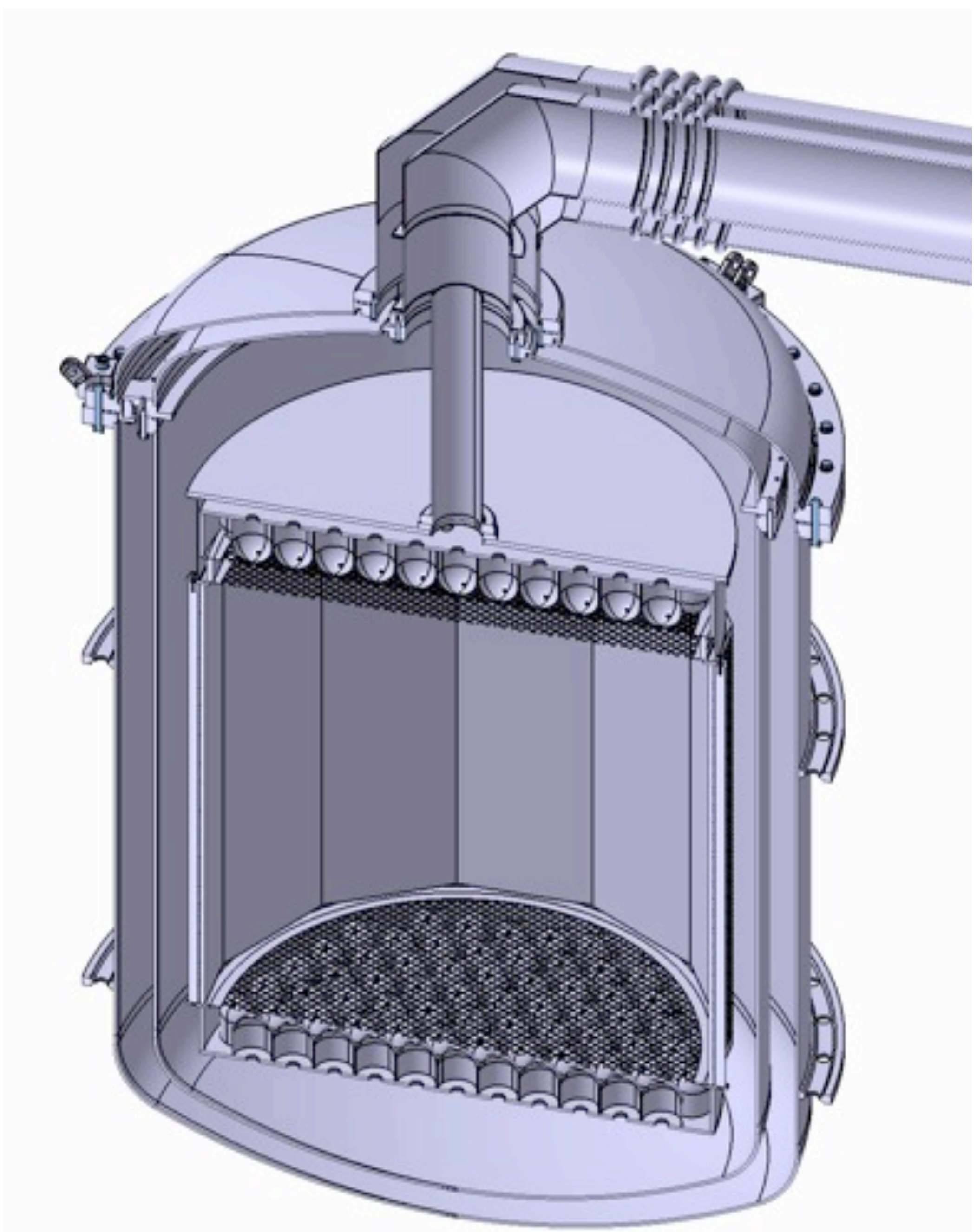
XENON1T @ LNGS

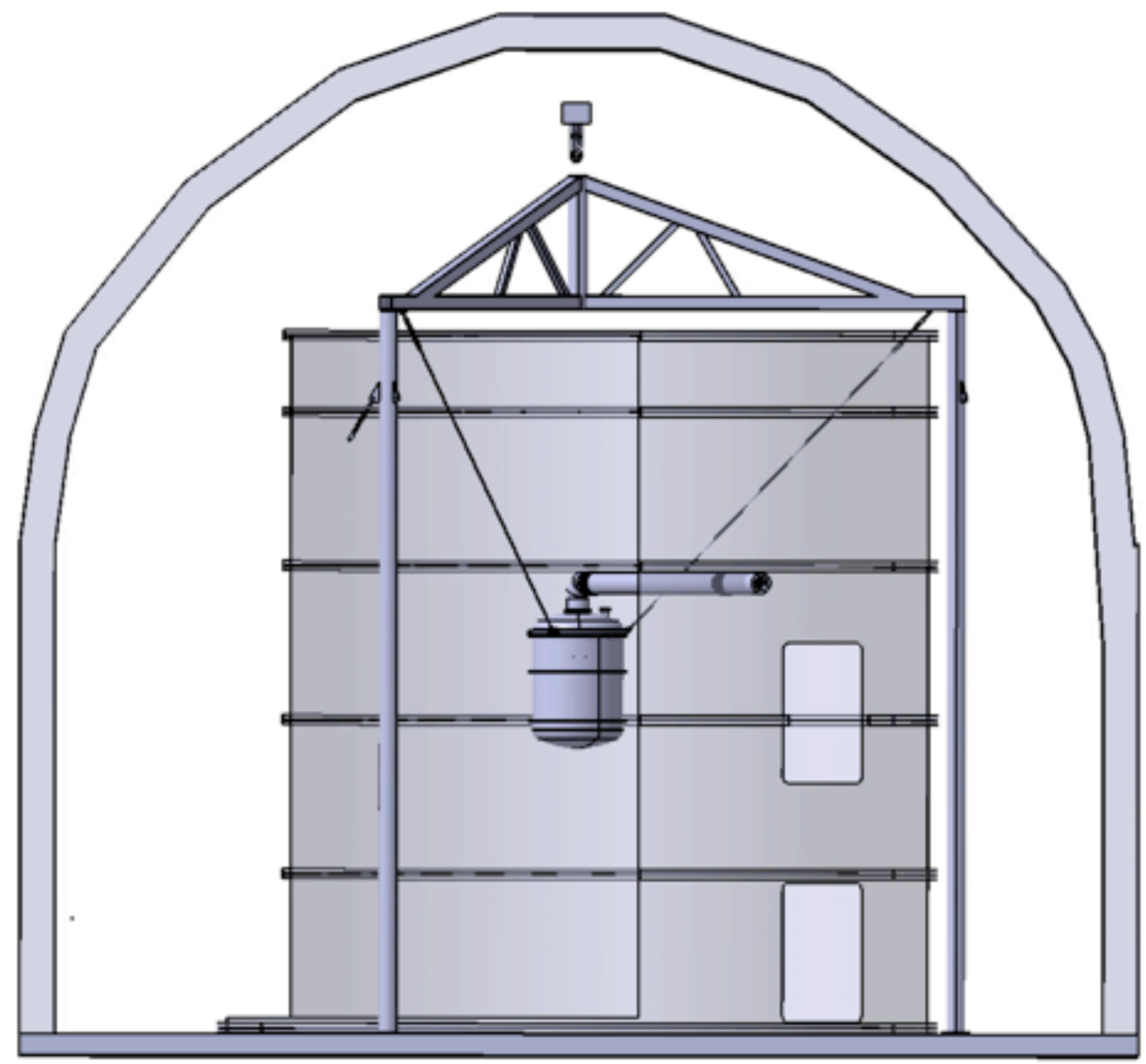
Designed to probe the σ_{SI}-region down to 5×10^{-47} cm^2
TDR submitted to LNGS in October 2010
Approved by INFN in April 2011
Construction in Hall B will start Fall 2011
Full physics reach expectedby 2015



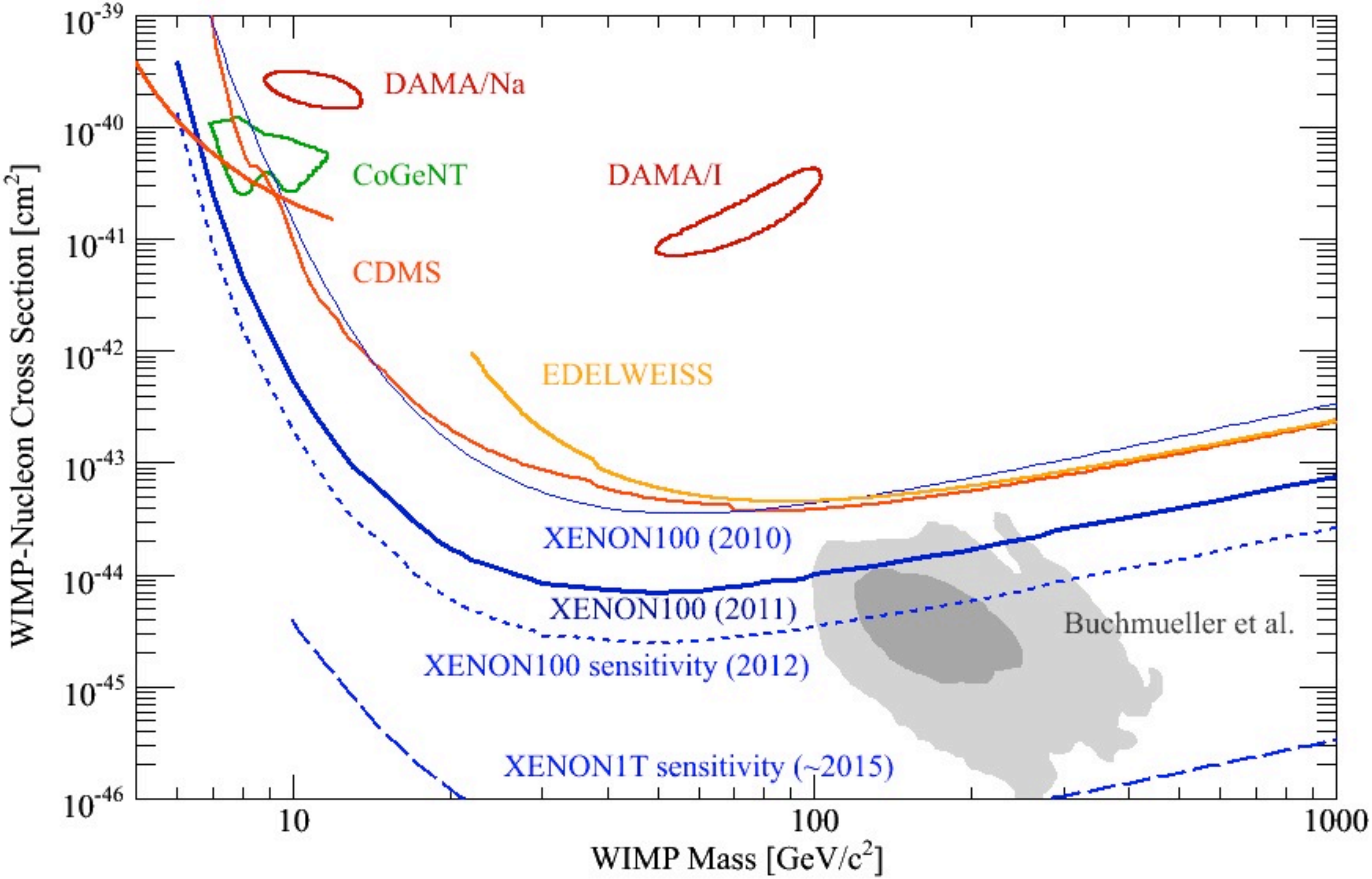
XENON1T

- 2.5 t LXe (1 m^3 TPC) for 1t fiducial target mass
- Goal is 100 x lower background: LXe self-shielding, Ti vessels, low radioactivity PMTs and 10 m x 10 m water shield as active muon veto





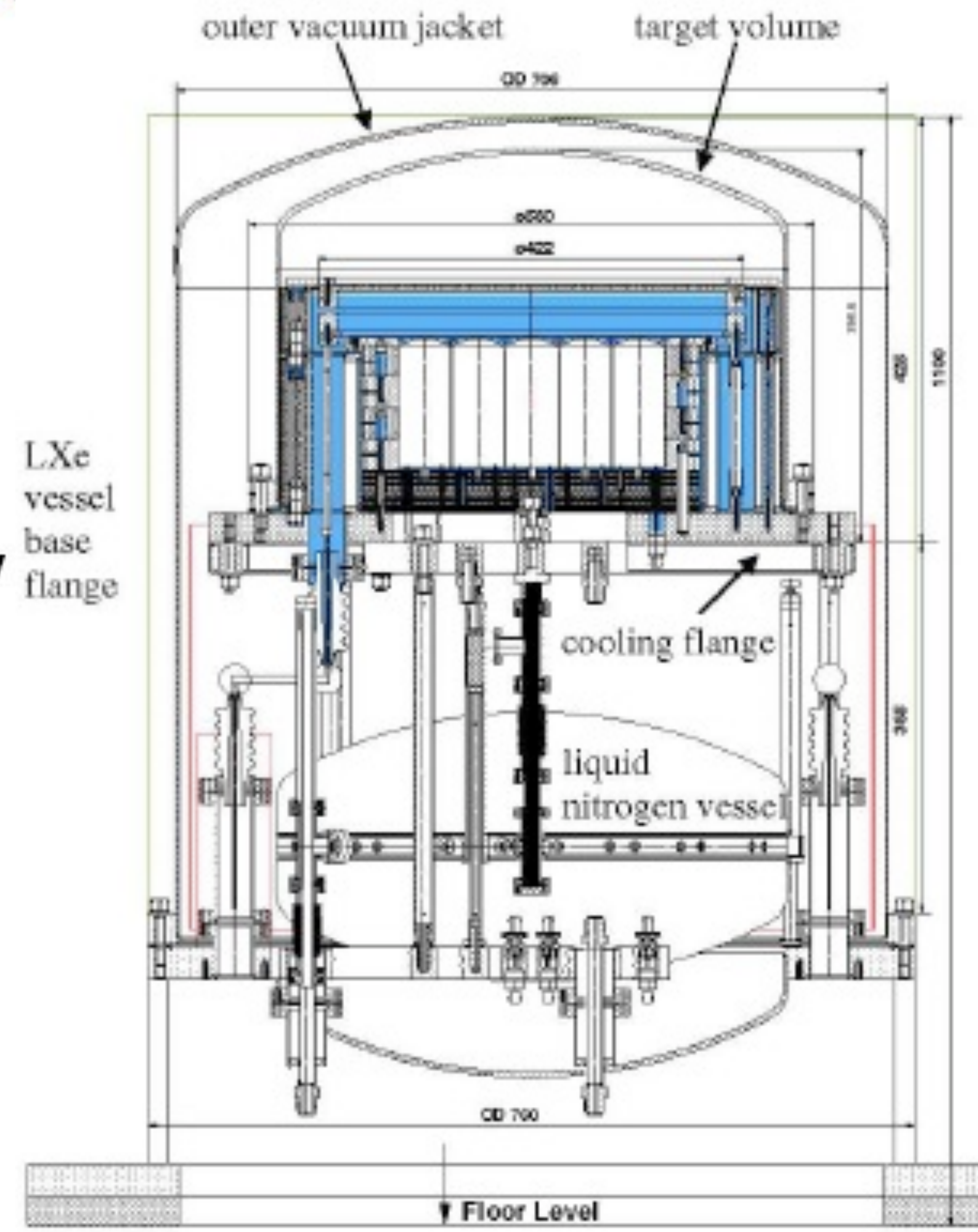
XENON1T by 2015



ZEPLIN III @ Boulby Mine

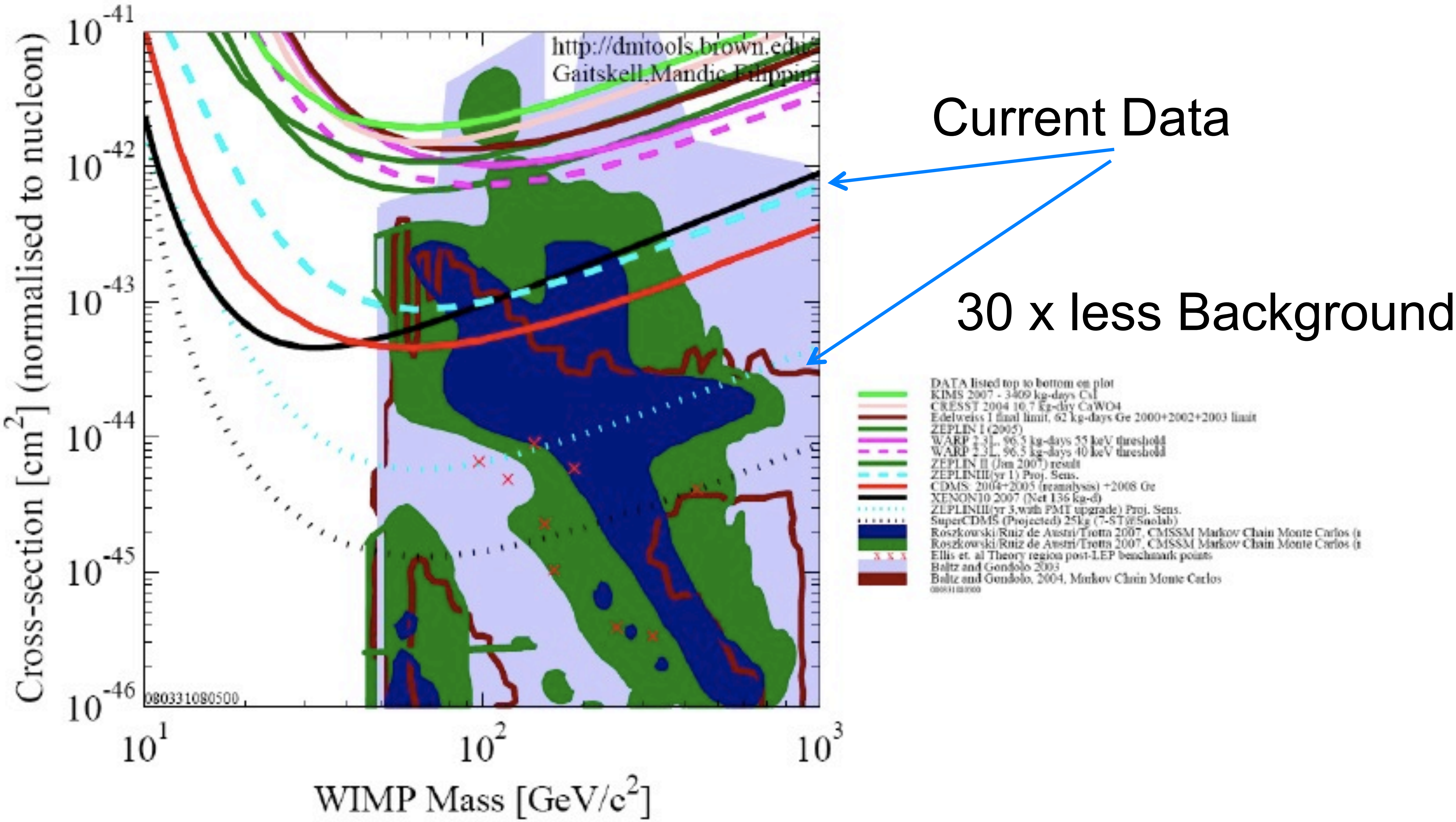
ZEPLIN III Features

- 8kg fiducial mass
- PMTs in liquid to improve light collection
- 3.5 cm drift depth – higher E-field
- 0.5 cm electroluminescent gap
- 31 small PMTs for fine position sensitivity
- open plan – no surfaces - reduced feedback
- Lower-background PMTs available
- Copper construction
- Low-background xenon (from ITEP)



CCLRC LIP CCLRC Imperial College London

ZEPLIN III- Sensitivity Projected

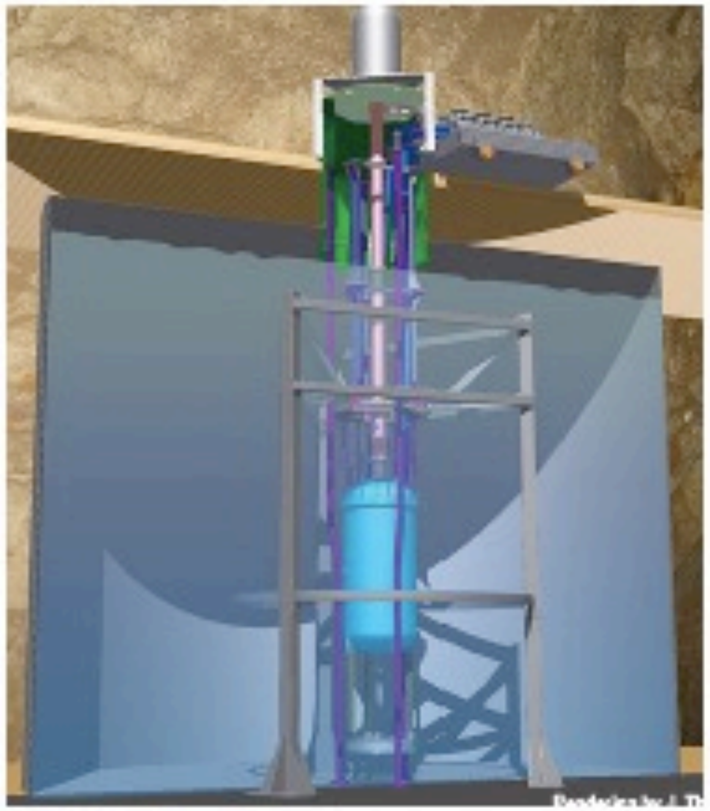


The LUX Experiment @ Homestake

- **350 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto**
- LUX 0.1: 50 kg LXe prototype with 4 R8778 PMTs was assembled and tested at CWRU
- PMTs: 2” diameter, 175 nm > 30% QE; radioactivity: U/Th ~ 9/3 mBq/PMT
- LUX 1.0: full detector to be operated above ground at Homestake in fall 2009
- LUX 1.0: to be installed at Homestake Davis Cavern, 4850 ft in spring 2010 (in 8 m ⌀ water tank)
- **Predicted WIMP sensitivity goal: 7×10^{-10} pb after 10 months**

R8778 PMT

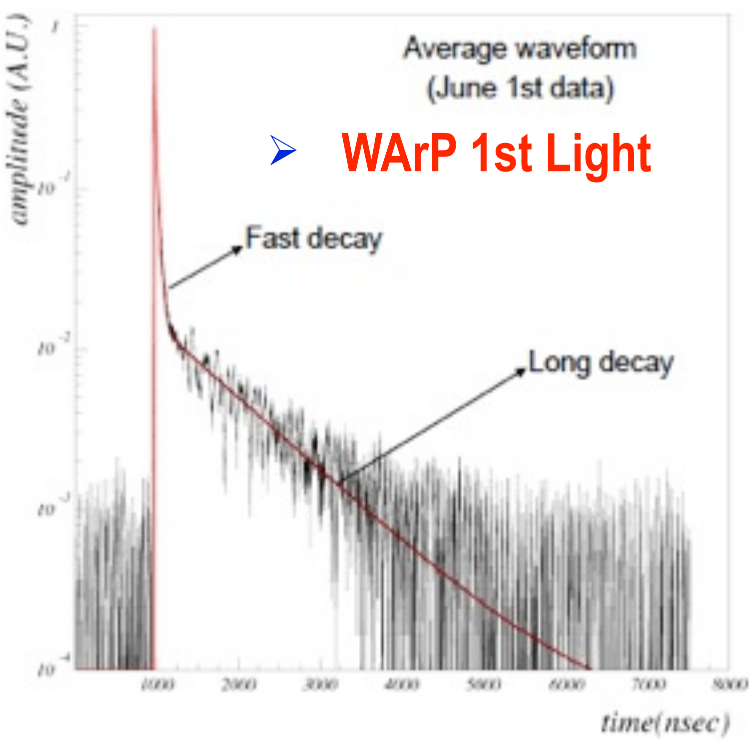
LUX 0.1



In water shield @ Homestake 4850 ft level

The WArP Experiment @ LNGS

- Exploit Ionization/Scintillation plus PSD for background reduction
- **WArP @ LNGS**: 140 kg active LAr volume (20 keVr threshold) surrounded by 8 ton LAr veto for beta/gamma and neutrons
- Detector first filling in May 09; HV feedthrough problem discovered:currently being fixed
- WArP veto system designed for 1 ton scale detector



- WArP 1st Light

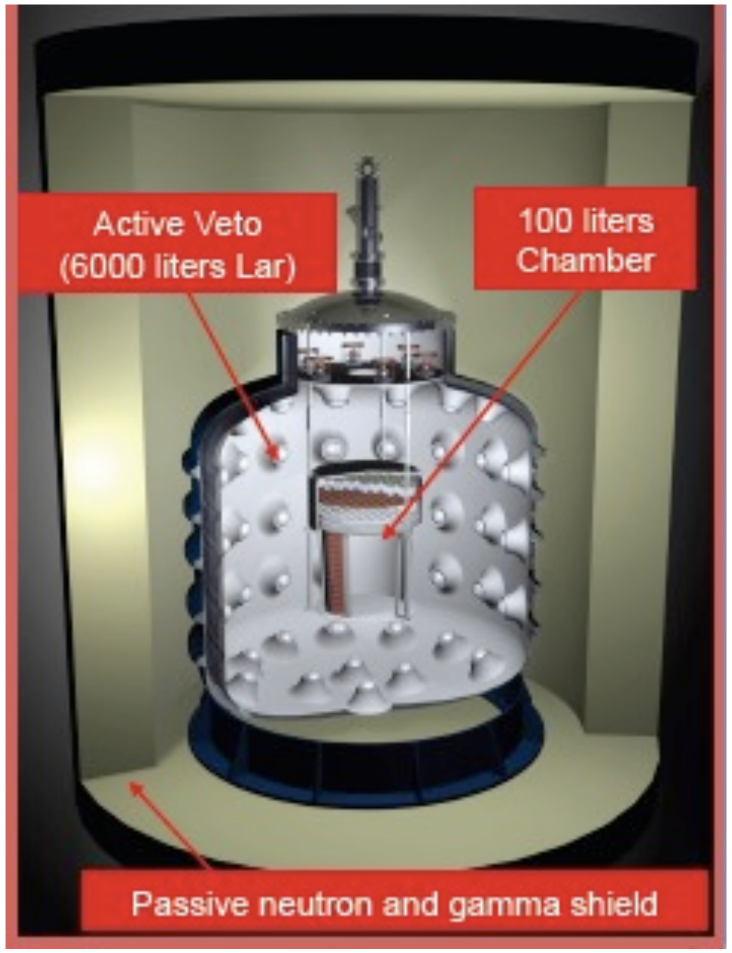
waveform fit (two exp. components).

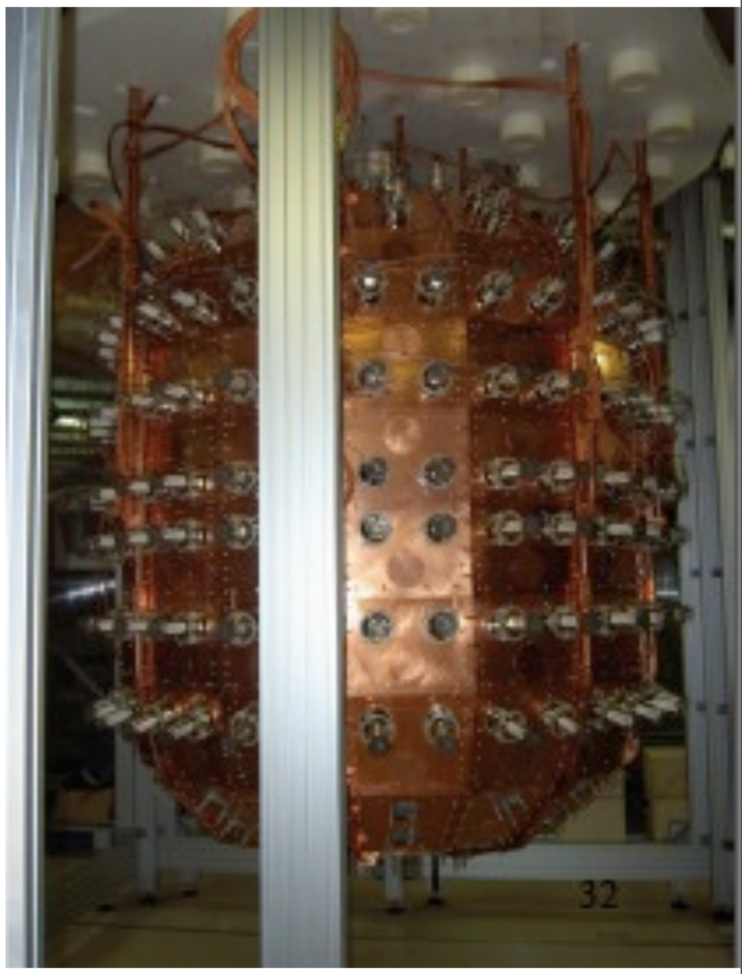
τ_{long} → indication of LAr purity:

τ_{long}(fit) ≈ 1 μs (nominal 1.2 μs)

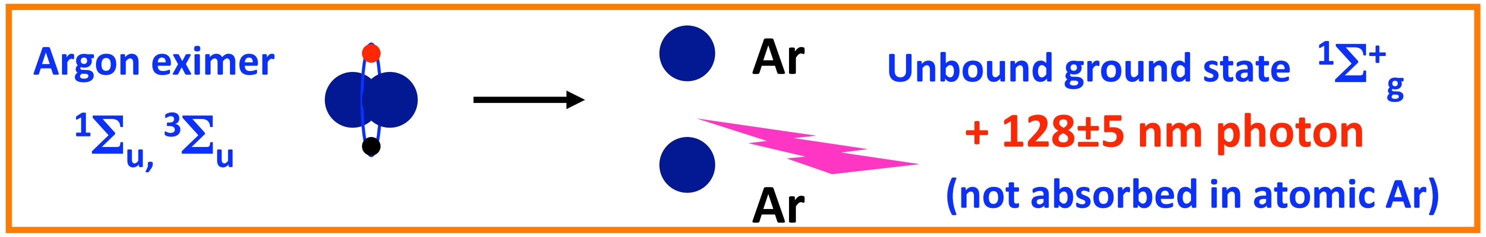
⇓

satisfactory LAr purity (after filling)

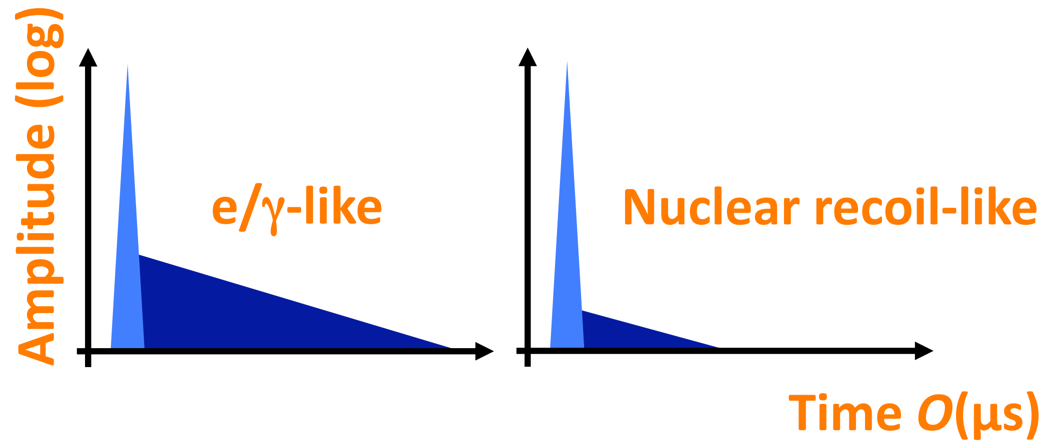




LAr scintillation mechanism



LAr: two characteristic decay times: 5ns, 1.6μs



$^1\Sigma_u$-characteristic decay time: O(ns), strongly allowed

$^3\Sigma_u$ -characteristic decay time: O(μs), allowed due to the spin-orbit coupling in Ar_2, supressed by impurities.

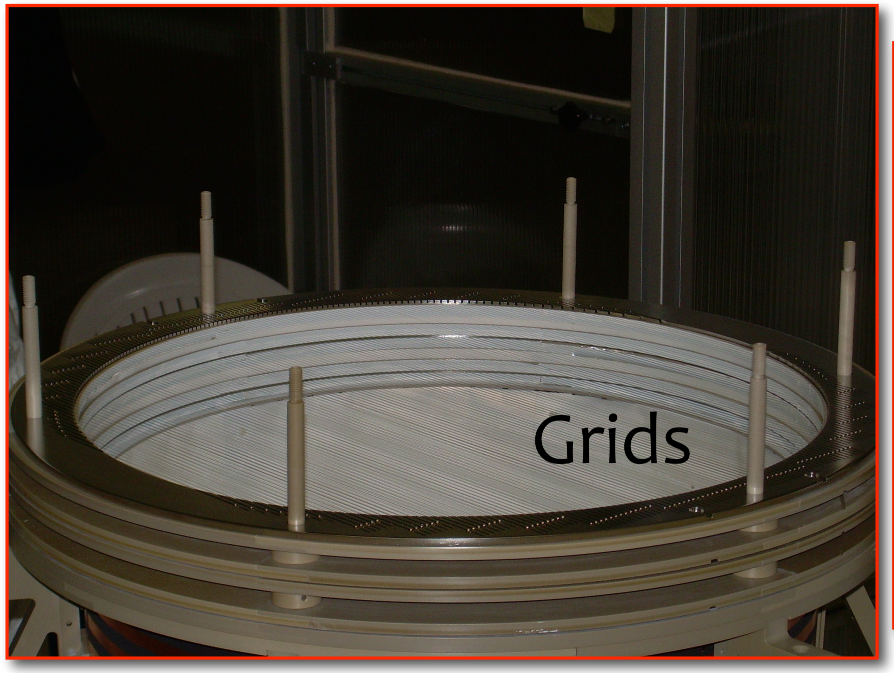
Excitation ratio of the two levels depends on the ionization density.

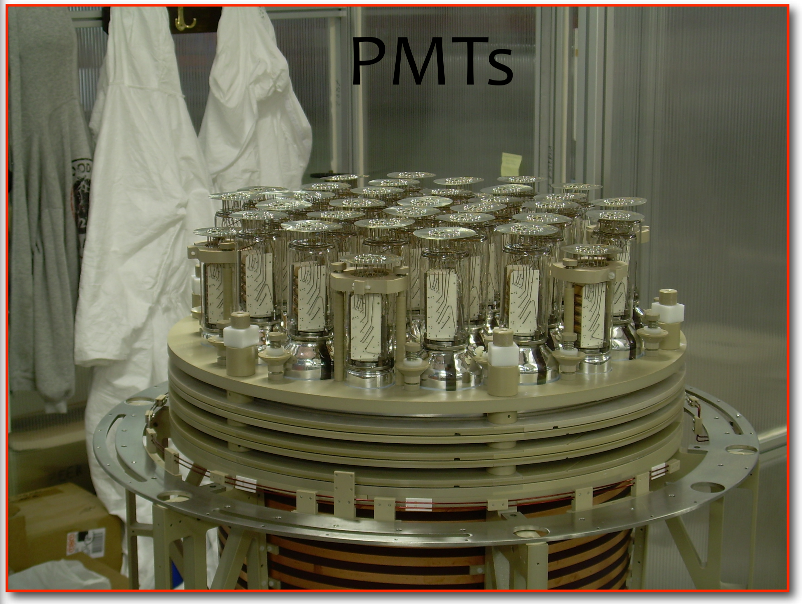
VUV light detection: WLS is required

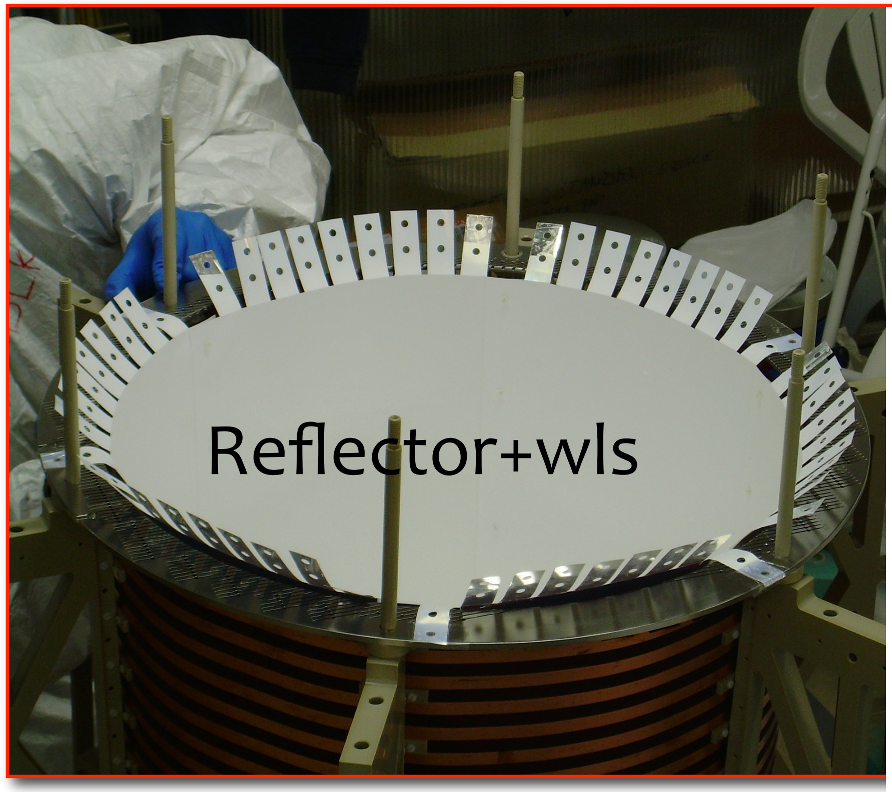
Solution: Tetra-Phenyl-Butadiene (TPB) 128 nm -> 430nm

P.Otyugova (UniZH)

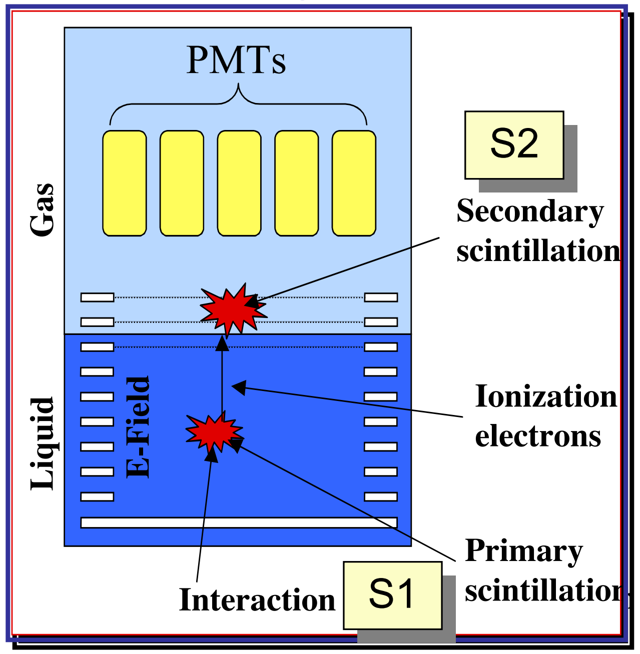
WArP Inner Detector Components





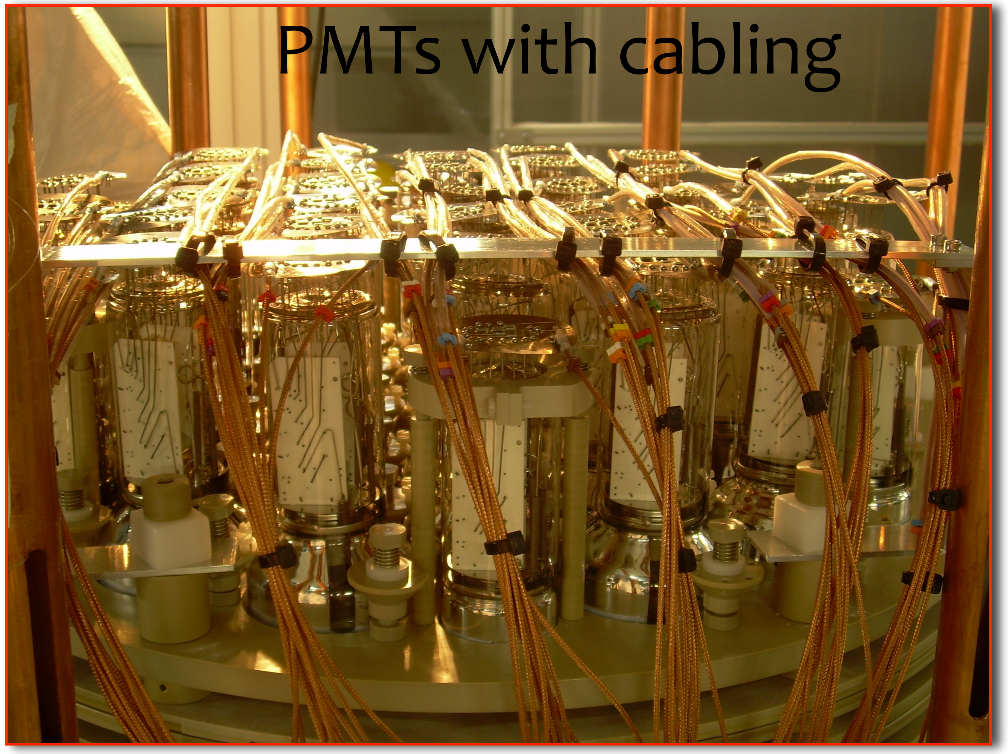


Two-Phase Argon Drift Chamber



Recoil-like event
Slow component ≈ 10 %

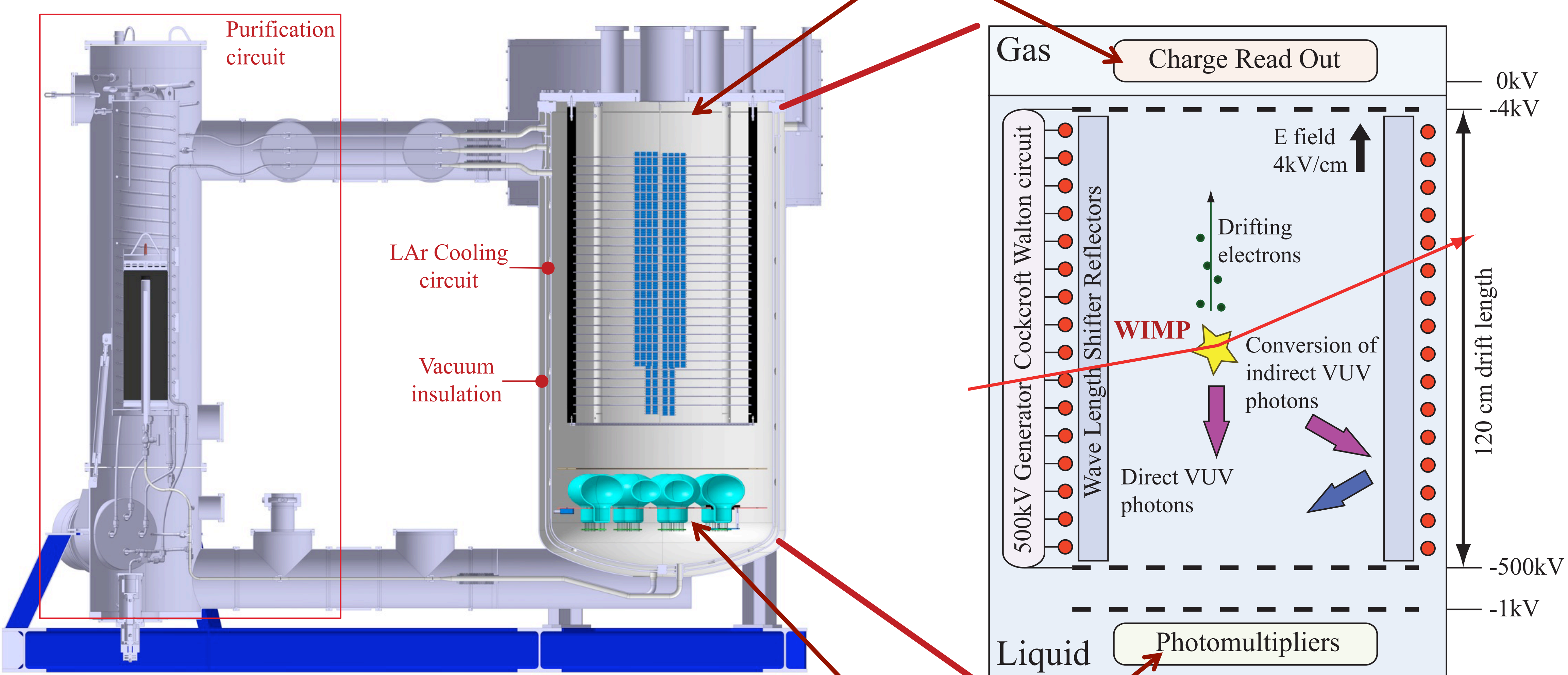
γ-like event
Slow component ≈ 70 %



The ArDM Experiment @ LSC

General Layout of the Experiment

Double stage LEM System

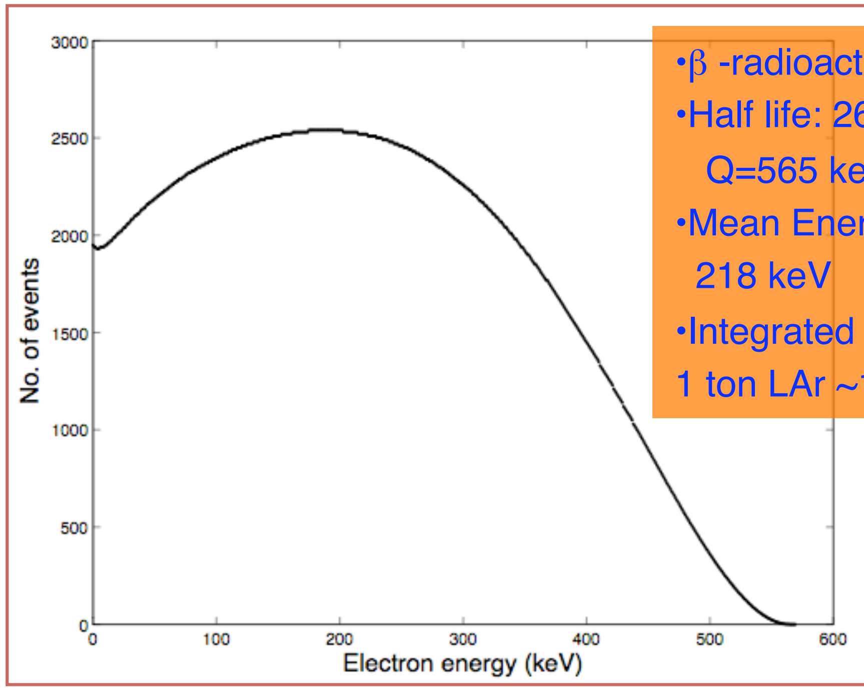


A. Rubbia, "ArDM: a Ton-scale liquid Argon experiment for direct detection of dark matter in the universe", J. Phys. Conf. Ser. 39 (2006) 129

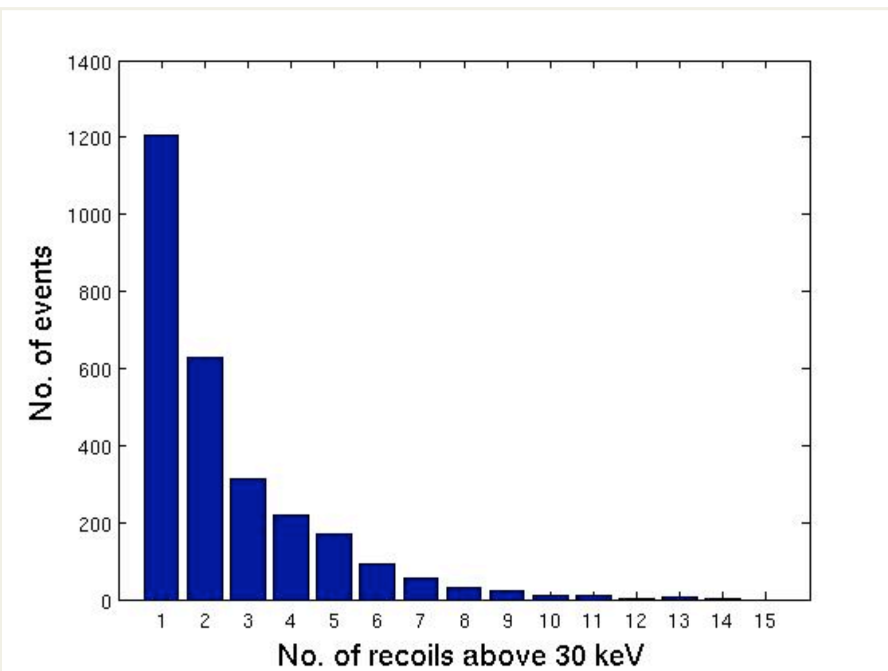
14 Cryogenic PMTs to detect the scintillation light

Ar^{39} and neutrons backgrounds

Natural argon from liquefaction of air contains small fractions of ^{39}Ar radioactive isotope.

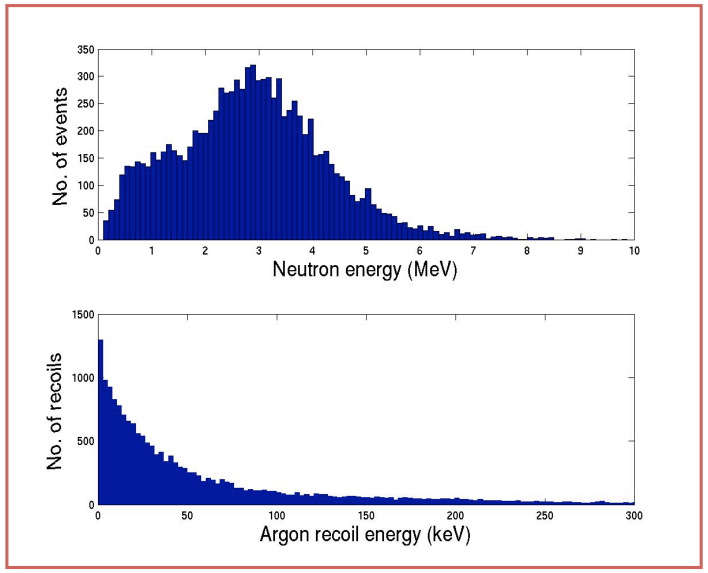


- β -radioactive isotope
- Half life: 269 years
  Q=565 keV
- Mean Energy:
  218 keV
- Integrated rate in
  1 ton LAr ~1kHz



Component	n per year	WIMP-like recoils per year
Container	~ 400	~ 30
LEM (std. mat.)	~ 10000	~ 900
LEM (low bg. mat.)	< 20	< 2
14 PMTs (std. mat.)	~ 12000	~ 1000
14 PMTs (low bg. mat.)	~ 600	~ 50

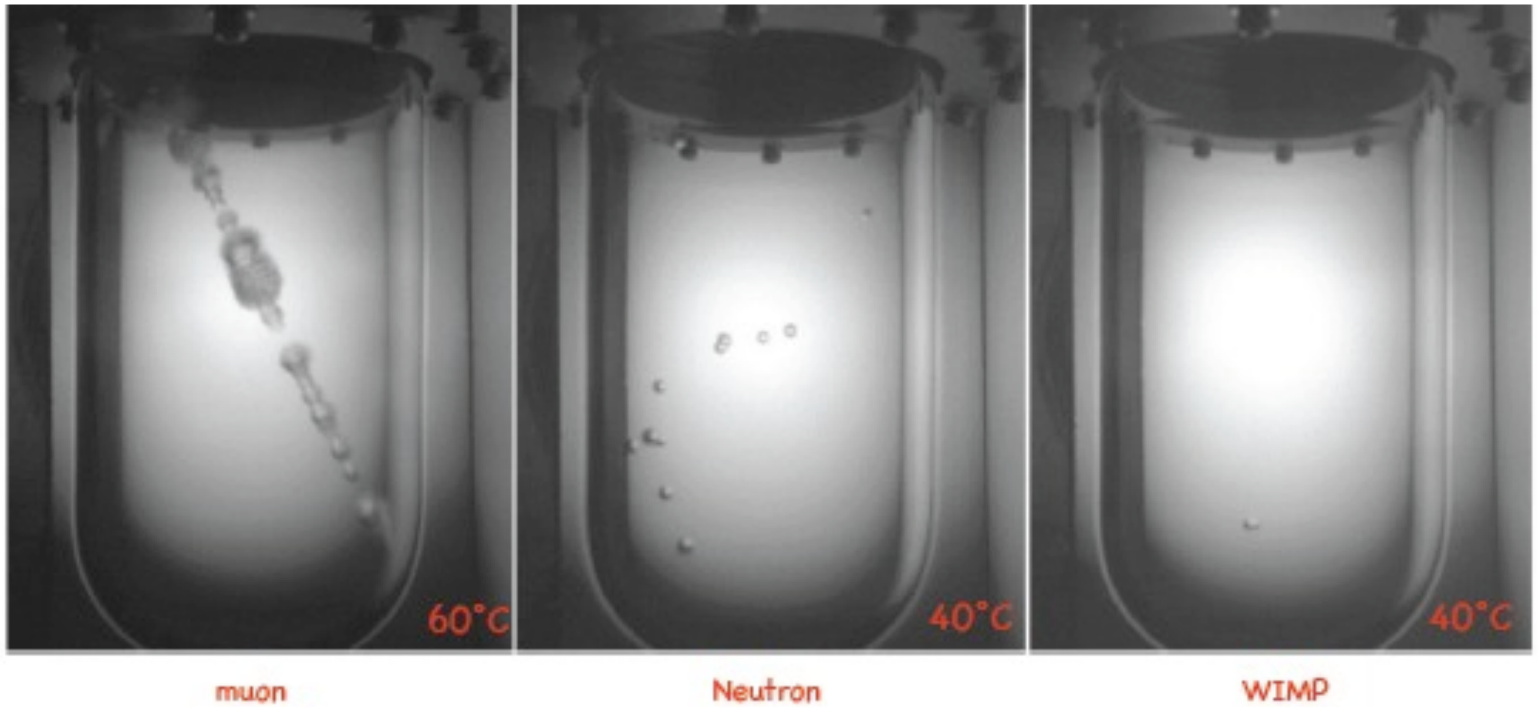
About 55% of the interacting neutrons scatter more than once at the threshold of 30keV.
Less than 10% of the emitted neutrons produce WIMP-like events single recoils, energy ∈ [30,100] keV).
The WIMP cross-section is very low, and it will scatter at most once.

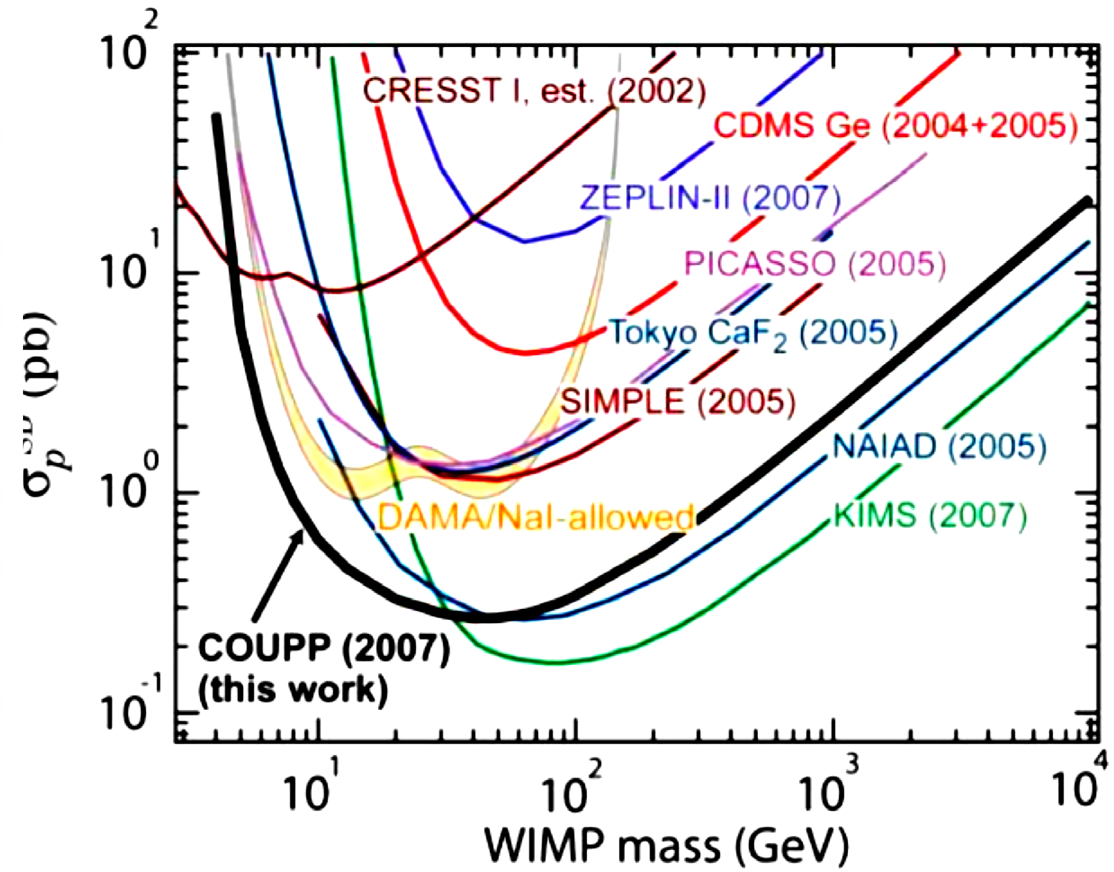


We need:
Rejection power of 10^8
OR
use of ^{39}Ar-depleted argon

P.Otyugova (UniZH)

The COUPP Experiment @ SNOLAB

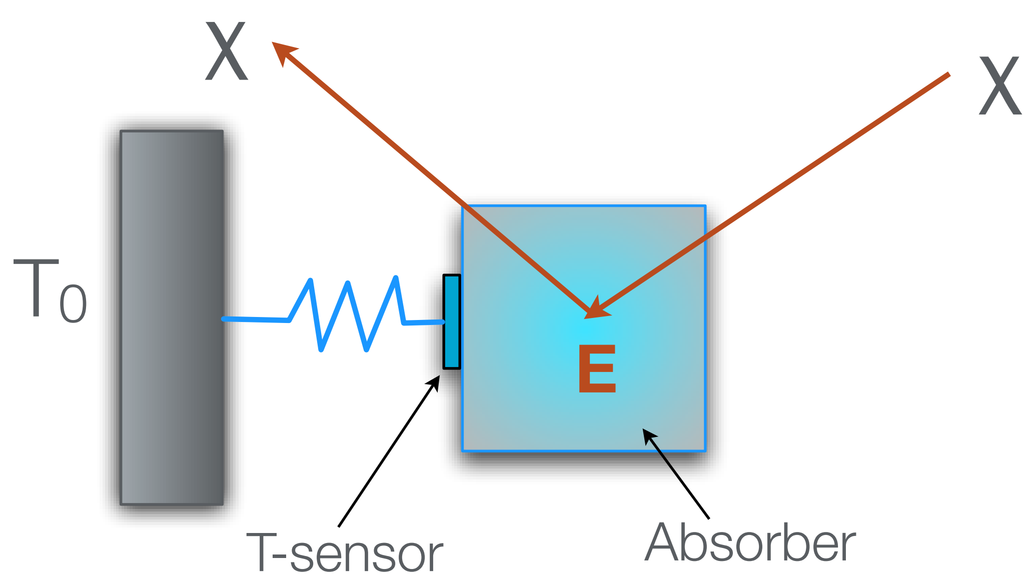




- COUPP approach to WIMP detection: detection of single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chamber
- Insensitive to EM background. Large rejection factor for mips $>10^{10}$; High spatial granularity for additional n-rejection
- Scalability to large mass at low cost. Choice of three triggers:pressure, acoustic, motion (video)
- Excellent sensitivity to both SD and SI couplings; different target fluids
- With 2 kg chamber (Fermilab): most stringent limit on pure proton SD interactions for low mass WIMPs
- 2007 COUPP result excludes low mass region favored by a SD interpretation of DAMA signal
- Next step: 60 kg chamber operated at SNOLAB

Cryogenic Experiments at mK Temperatures

- **Principle:** a deposited energy E produces a temperature rise ΔT



$$\Delta T \propto \frac{E}{C(T)}$$

$$T \ll T_c \Rightarrow C(T) \propto T^3$$

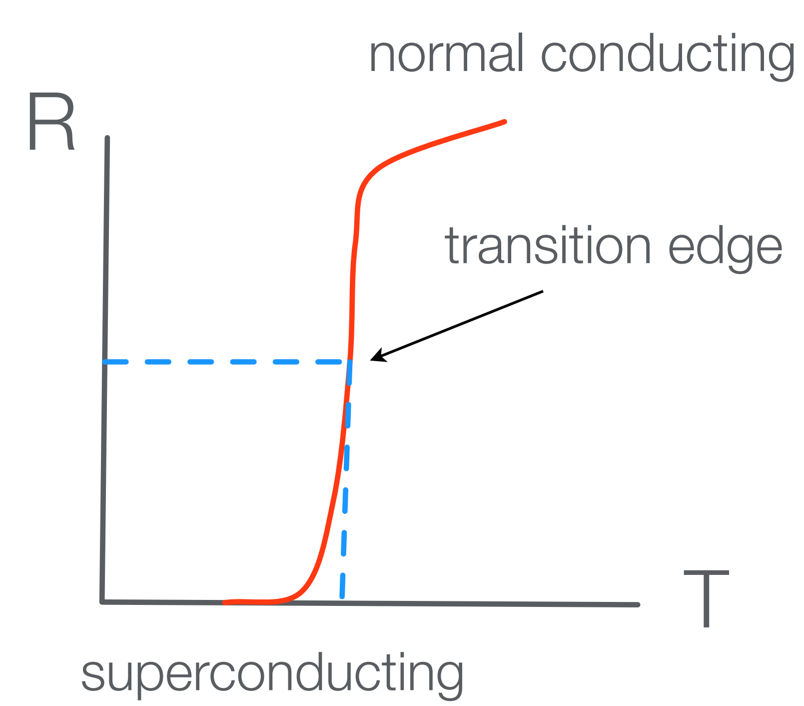
=> the lower T, the larger ΔT per unit of absorbed energy

- **T-sensors:**
  - **superconductor thermistors**

    (highly doped superconductor): NTD Ge → EDELWEISS
  - **superconduction transition sensors**

    (thin films of SC biased near middle of normal/SC transition):

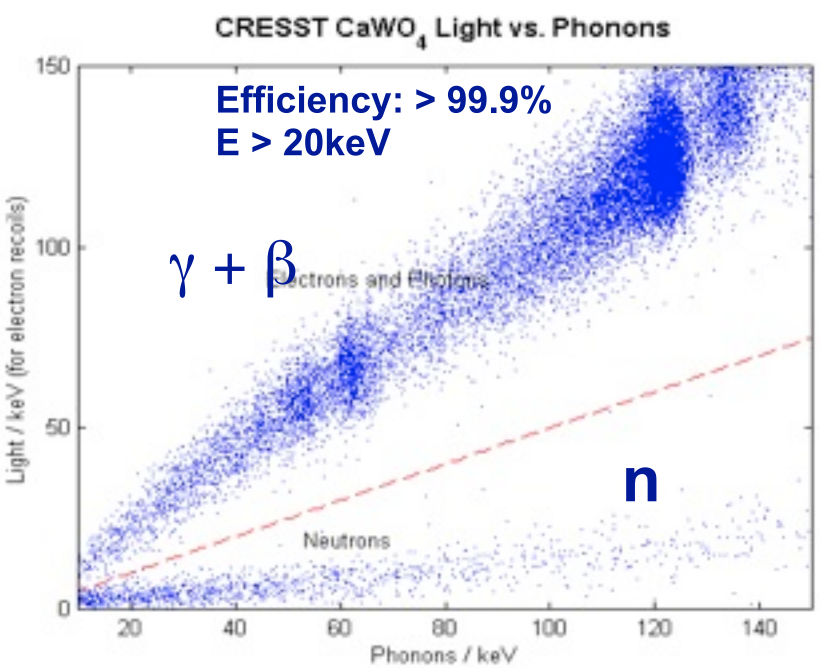
    TES→CDMS, SPT→CRESST



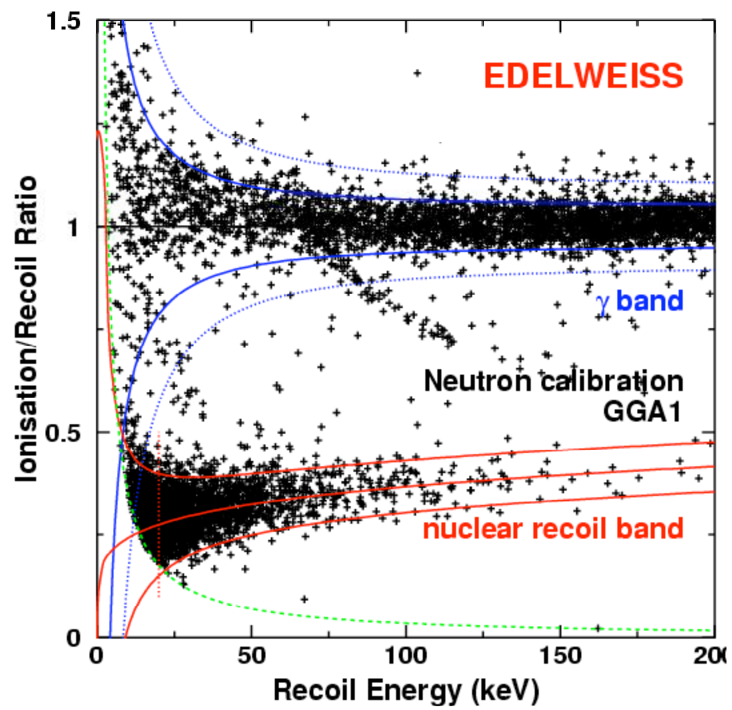
Cryogenic Experiments at mK Temperatures

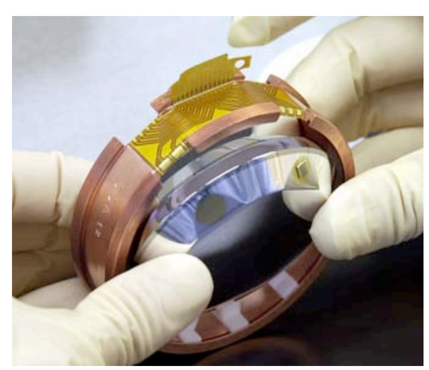
- Advantages: high sensitivity to nuclear recoils
  - measuring the full nuclear recoil energy in the phonon channel
  - low energy threshold (keV to sub-keV), good energy resolution
  - light/phonon and charge/phonon: nuclear vs. electron recoil discrimination

CRESST at LNGS

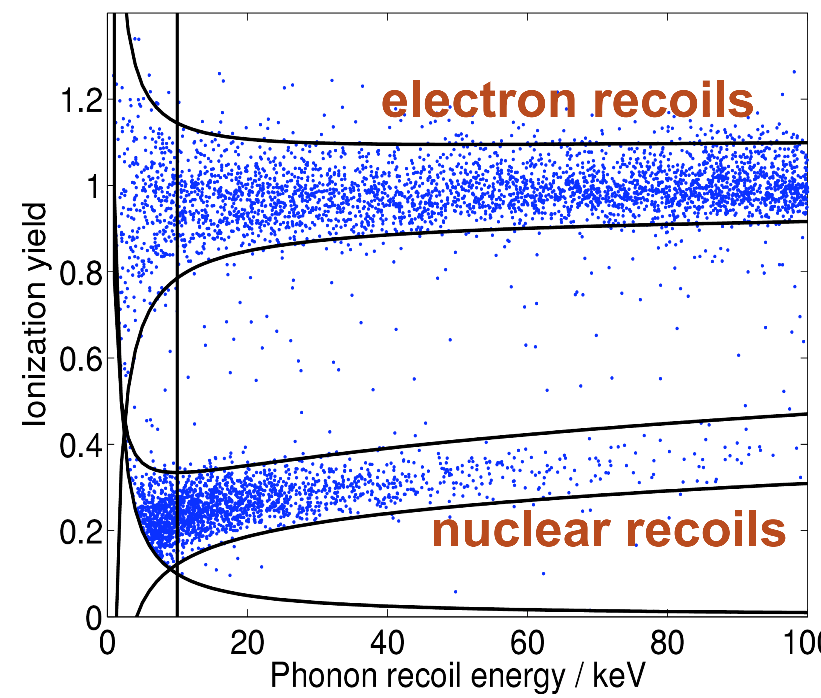


EDELWEISS at LSM





CDMS at Soudan



CDMSII @ Soudan

Dark Matter Search data since Oct '03

- <10 keVr thresh. and excellent resolution→low mass WIMPs

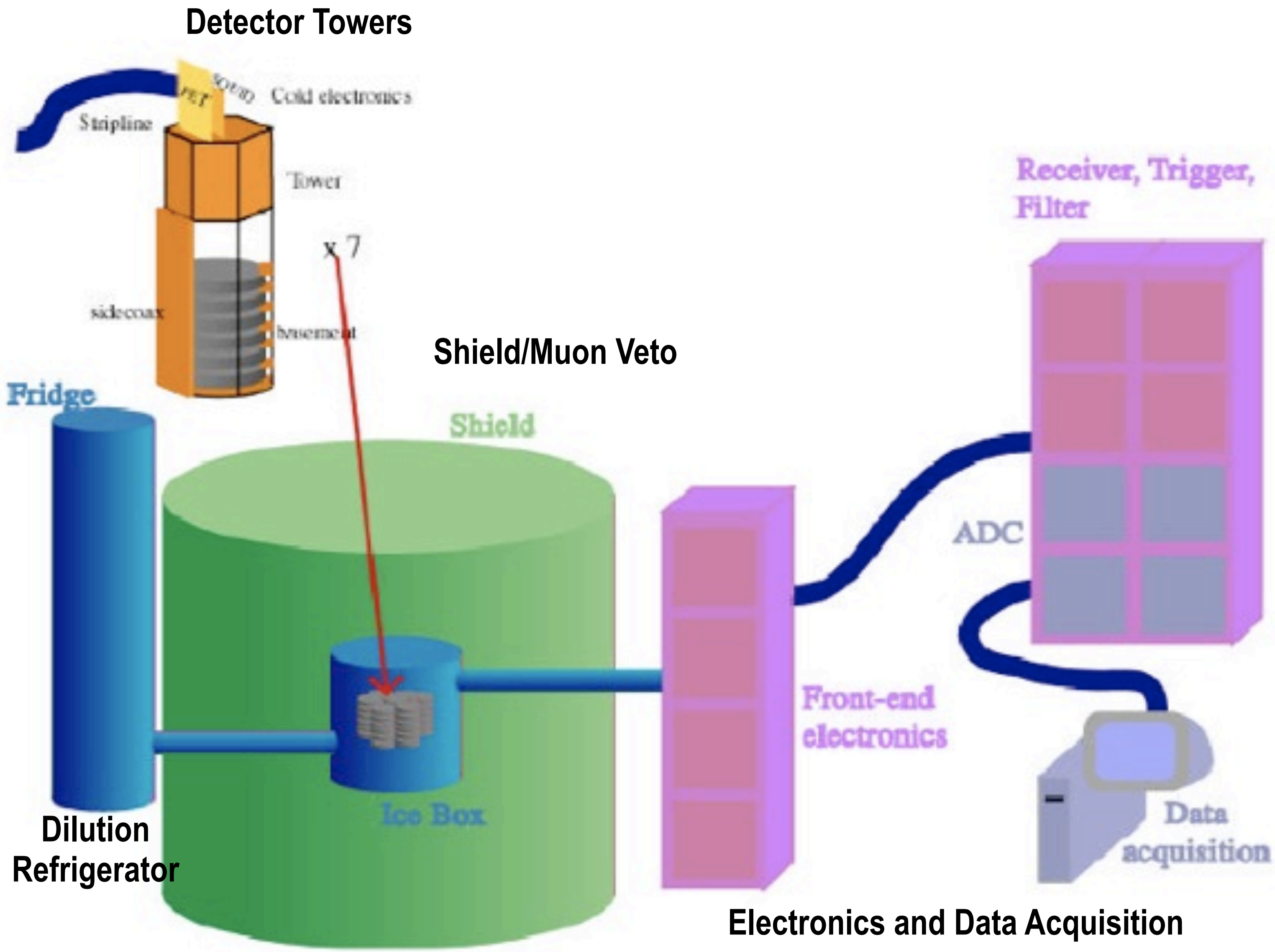
Cryogenic Detectors

- 250g Ge and 100g Si crystals @50 mK using dilution refrigerator

Active Background Rejection

- Ionization Yield (ratio of charge to phonon signal)
- WIMPS, neutrons => nuclear recoils
  - Charge/Phonons ~ 1/3
- EM backgrounds => electron recoils
  - Charge/Phonons = 1
- Rise time (discrimination against surface events)
- Identify neutrons using
  - multiple scattering (not WIMPS)
  - Ge vs Si rates
    - Neutron cross sections similar, but WIMPs x5 higher in Ge

Soon to release new data with 5kg + Work towards SuperCDMS (25 kg) @SNOLAB

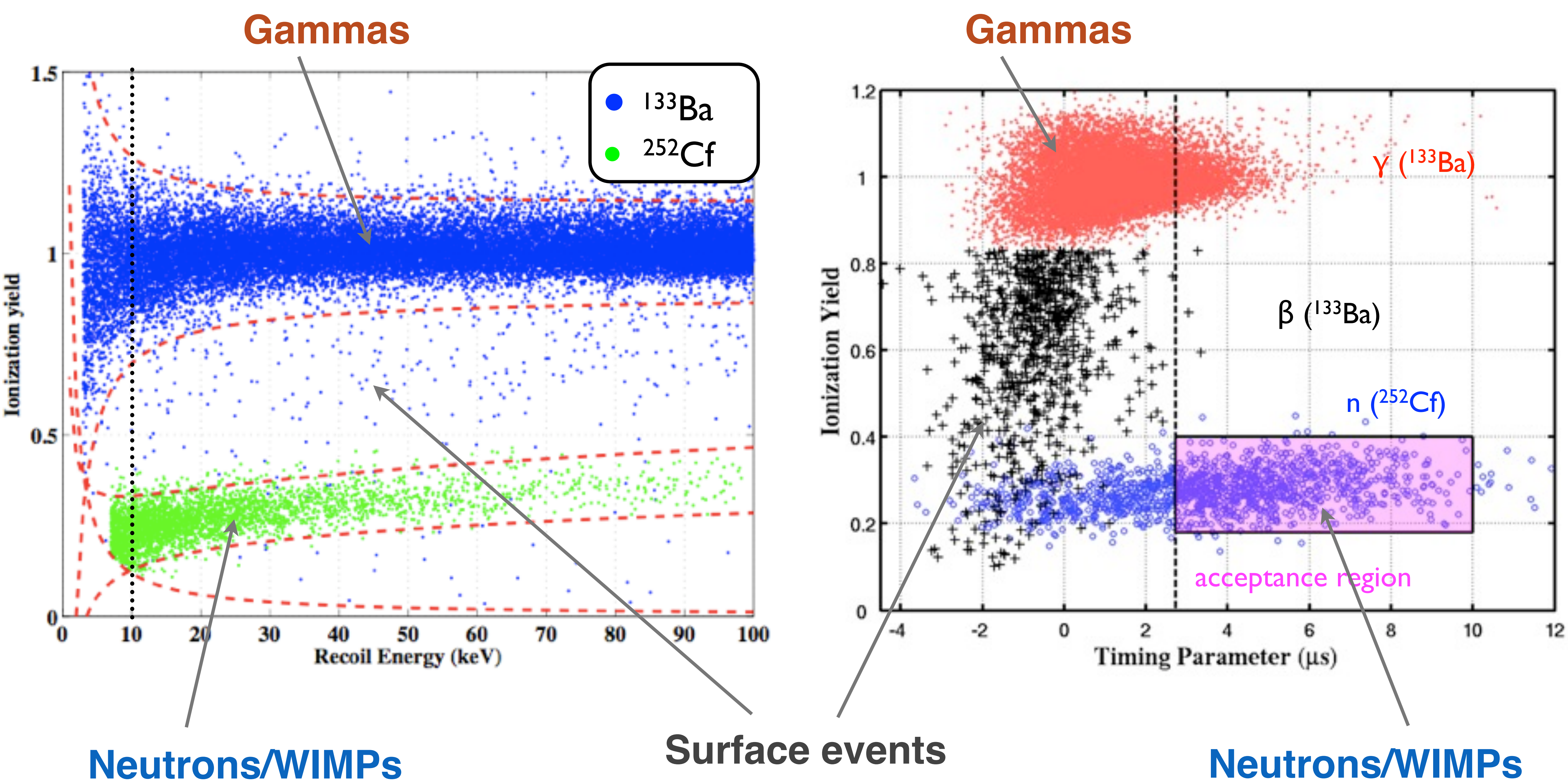


Shielding

Conventional Pb (for γ, β) & Polyethylene (for neutrons) layered shielding and active scintillator veto (>99.9% efficient against cosmic rays).

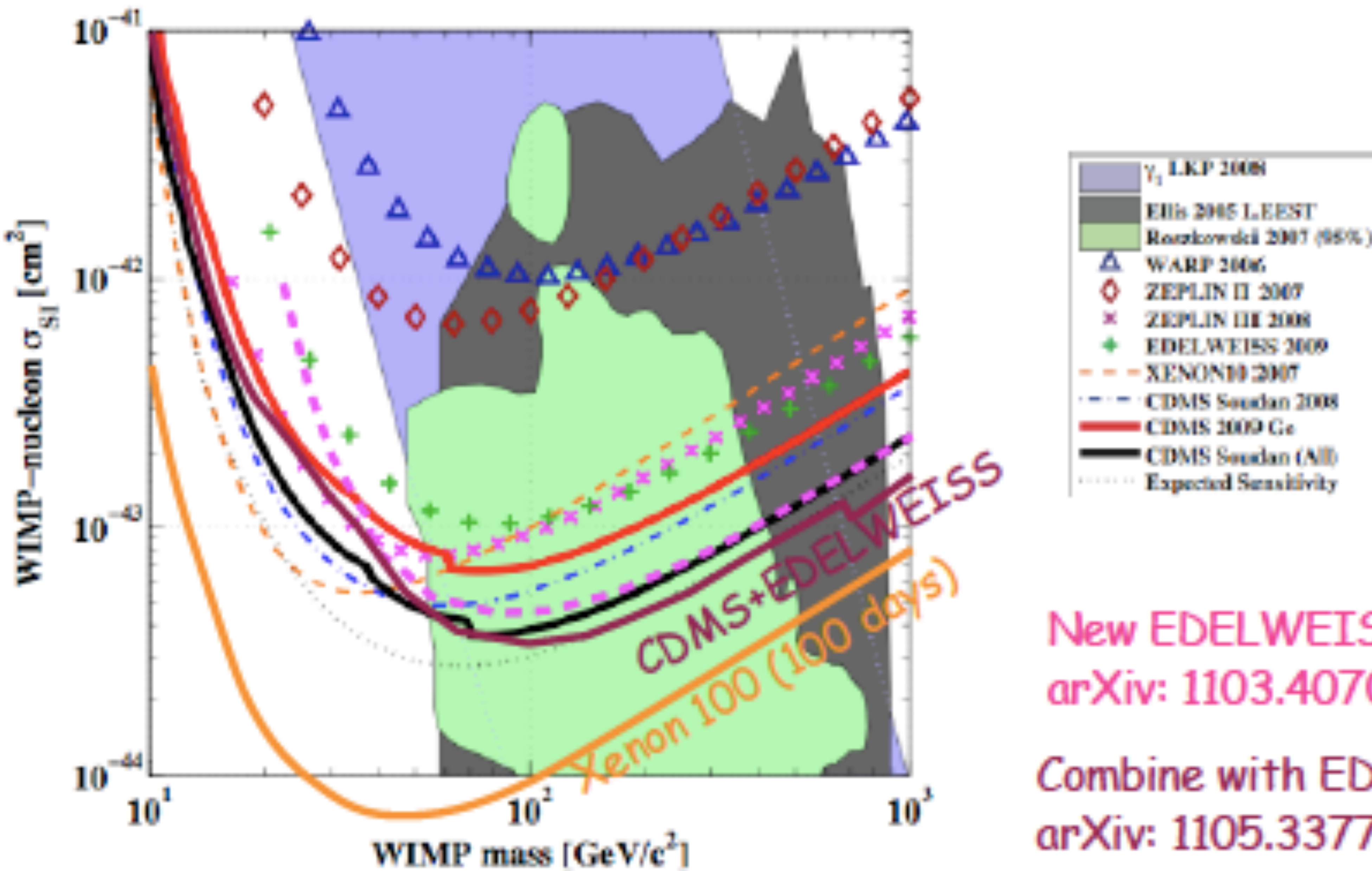
CDMS: Signal versus Background

- Ratio of the charge/phonon-signal and time difference between charge and phonon signals => distinguish signal (WIMPs) from background of electromagnetic origin



Cryogenic mK Experiments: current limits

Science 12 February 2010



Upper limit at the 90% C.L. on the WIMP-nucleon cross section :3.8 x 10^{-44} cm^2 for a WIMP of mass 70 GeV/c^2

Surpassed of course by Xenon 100 (100 days)

New EDELWEISS limit
arXiv: 1103.4070 Johann Gironnet

Combine with EDELWEISS
arXiv: 1105.3377 accepted for publication in PRD

Cryogenic mK Experiments: future

CRESST at LNGS

10 kg array of 33 $CaWO_4$ detectors
new 66 SQUID channel array
- new limit from operating 2 detectors (48 kg d) published in 2008, arXiv:0809.1829v1
- new run in progress

EDELWEISS at LSM

Goal: 10 kg (30 modules) of NTD and ID (new charge electrodes) Ge detectors in new cryostat
- data taking (with 19 detectors) in progress
- reach: 4 x 10^{-44} cm^2

CDMS/SuperCDMS at Soudan

SuperCDMS detectors (1" thick ZIPs, each 650 g of Ge) have been validated

First SuperTower installed at Soudan (3 kg of WIMP target)

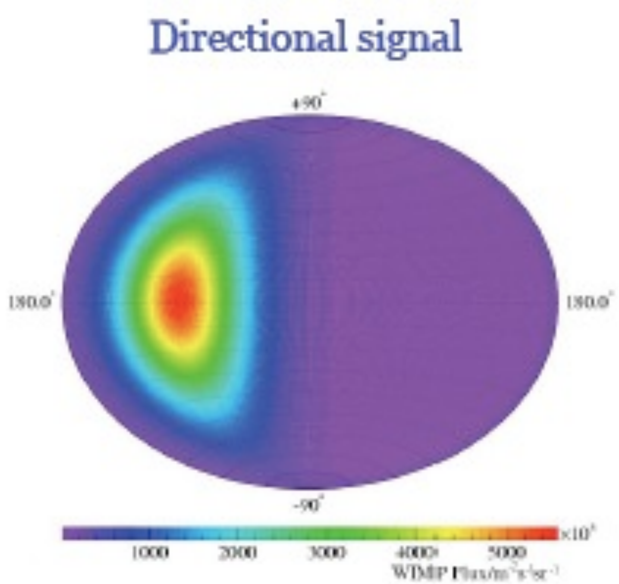
Goal: 5 x 10^{-45} cm^2 with 16 kg Ge

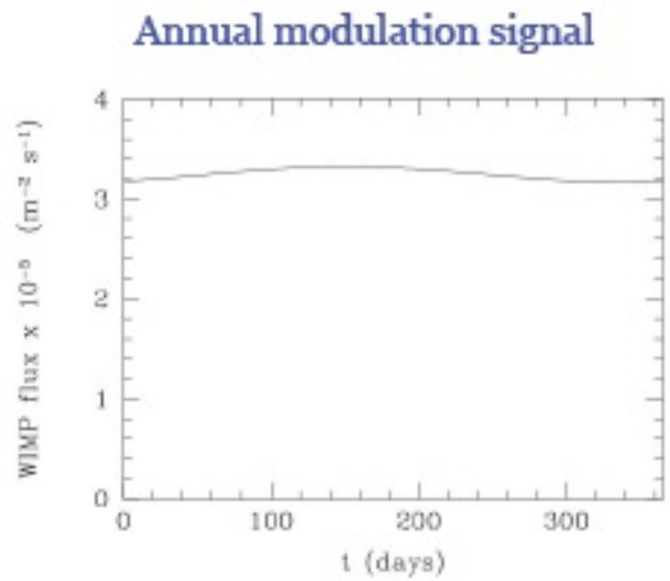
EURECA: joint effort for 100 kg-1t experiment in Europe

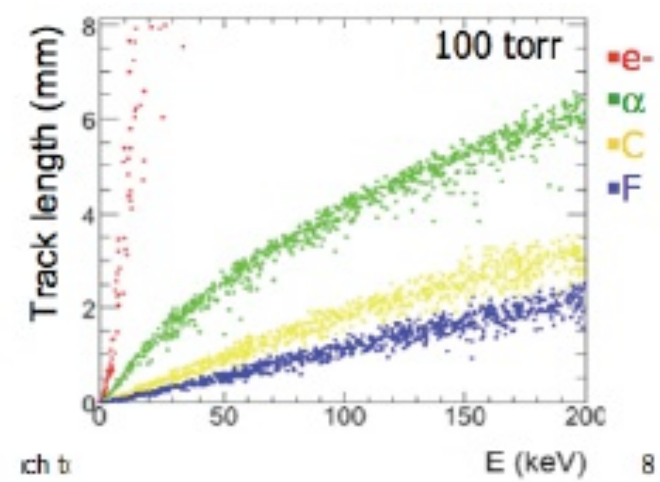
Goal: 7 SuperTowers at SNOLAB

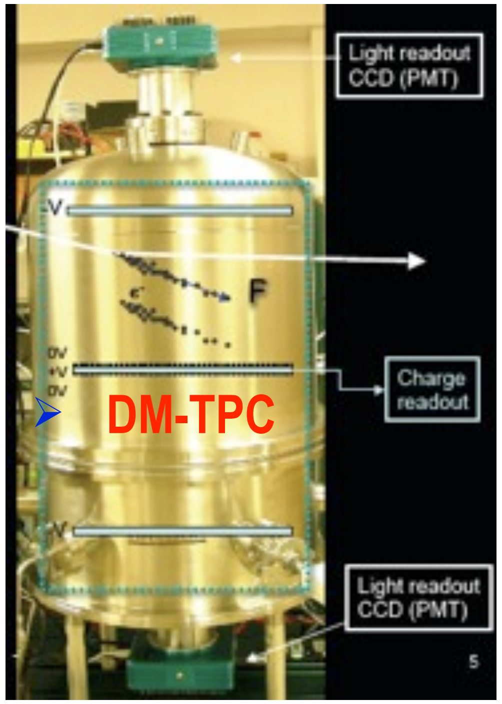
Directional Experiments

- WIMP events should globally come from Cygnus constellation direction. Strong forward/backward asymmetry
- Powerful signature: hard for background to mimic directional signal; order of 10 events sufficient

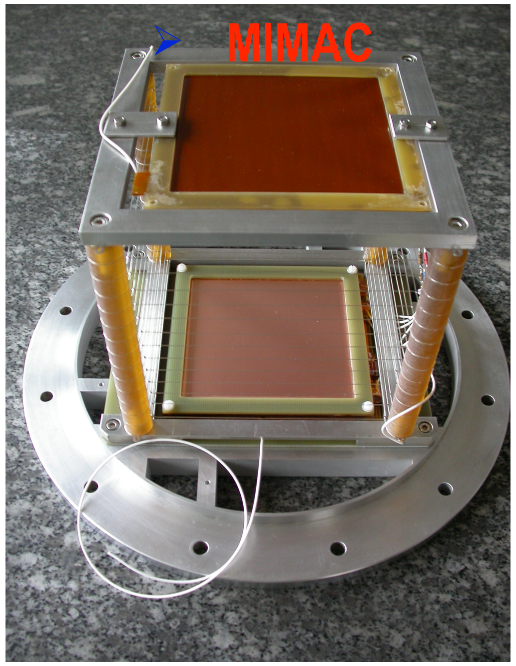








- Directional detectors with low pressure gas (large volume)
- Challenge is to measure 3D tracks of low energy recoils
- DRIFT-II @ Boulby mine: 1 m^3 MWPCs with 40 torr CS_2 (167 g)
- DM-TPC @ MIT: 2x 10^{-2} m^3 with 50 torr CF_4 (PMTs + CCD readout for 3D + E)
- NEWAGE @ Kamioka: 23 x 28 x 30 cm^3 TPC with 150 torr CF_4 and microwell readout
- MIMAC @ Saclay : ^3He & CF_4 TPC modules (3 x 3 cm Micromegas with pixellized anode)



SUMMARY

- The identity of Dark Matter remains a mystery today but potential for breakthrough is in the air
- Direct detection experiments have made significant progress in recent years, driven in part by an aggressive competition worldwide. Complementarity with indirect and collider searches has never felt stronger!
- A few 100 kg scale experiments are now in operation underground or under construction. For XENON100 the 2 x 10^{-9} pb SI sensitivity projection appears well within reach by 2012. XMASS aims at similar goal after 1 yr of data. Exciting time for DM search with LXe detectors.
- If cross-section is at the 10^{-8} pb as in some favored SUSY models, we will start to see a handful of WIMP events! Equally important is that for the first time a low background, massive target, other than NaI, can probe annual modulation
- Increasing mass while keep lowering backgrounds is the rule of the game and noble liquids continue to advance towards this goal. A ton scale experiment such as XENON1T will drive the direct detection scene in the coming years.