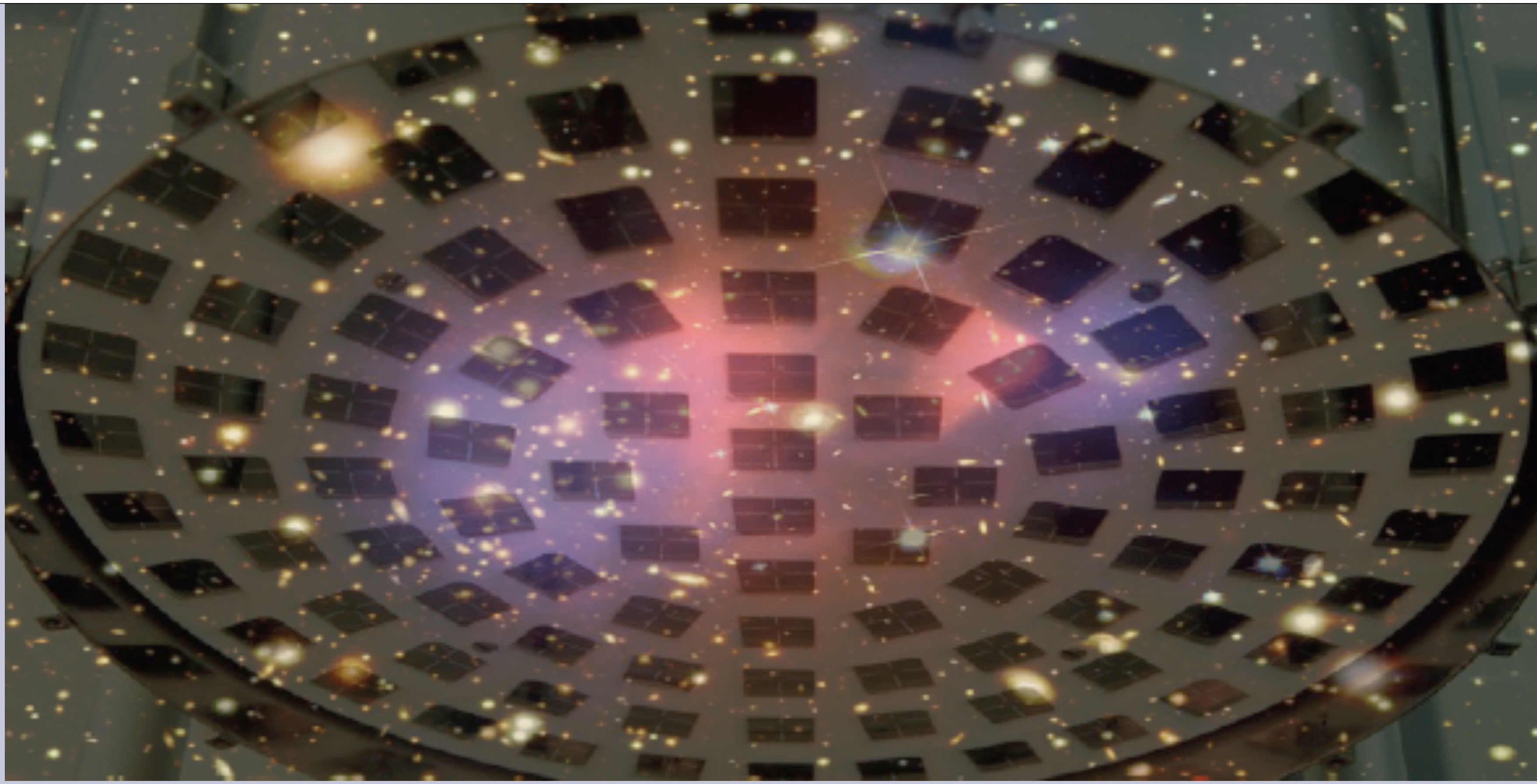


Direct Dark Matter Searches: Lecture 2

Elena Aprile
Columbia University

NIJMEGEN09 Summer School, August 25, 2009

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

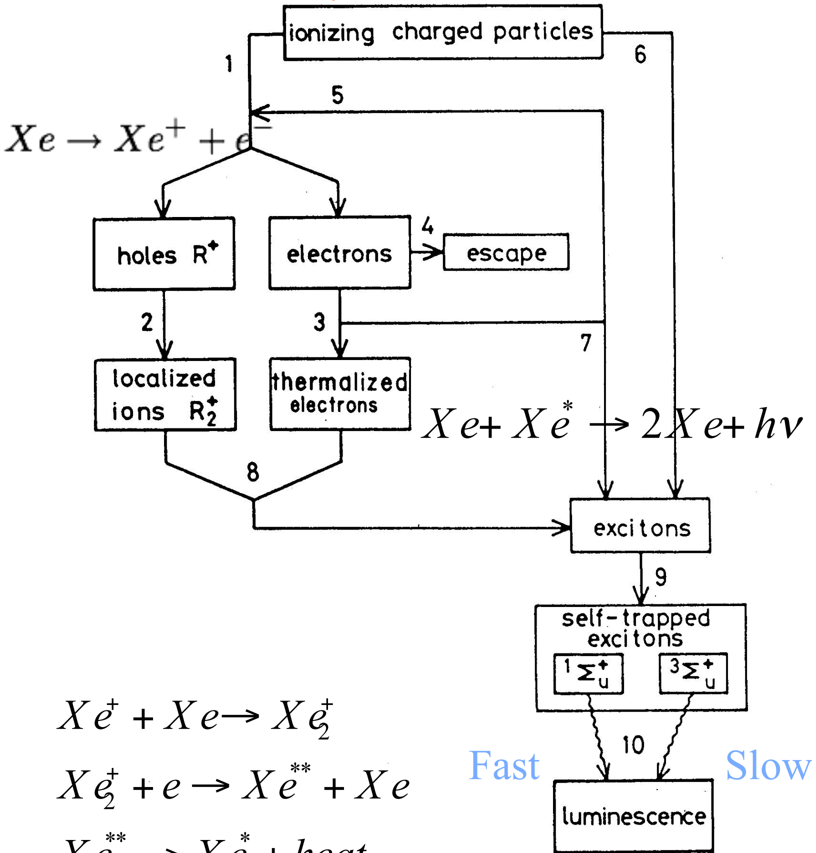
Material	Ar	Kr	Xe
Gas			
Ionization potential I (eV)	15.75	14.00	12.13
W-values (eV)	26.4[a]	24.2[a]	22.0[a]
Liquid			
Gap energy (eV)	14.3	11.7	9.28
W-value (eV)	23.6±0.3[b]	18.4±0.3[c]	15.6±0.3[d]

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

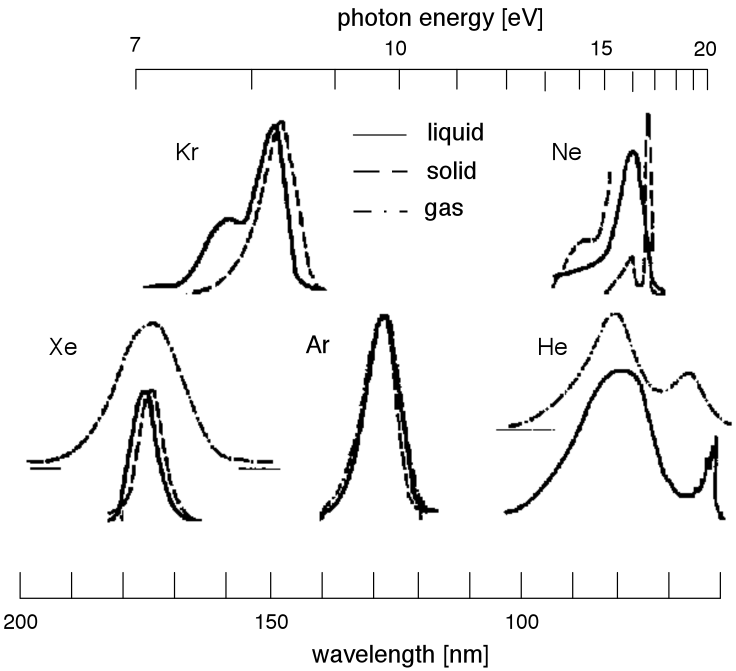


$$Xe^{+} + Xe \rightarrow Xe_2^{+}$$

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

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

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



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

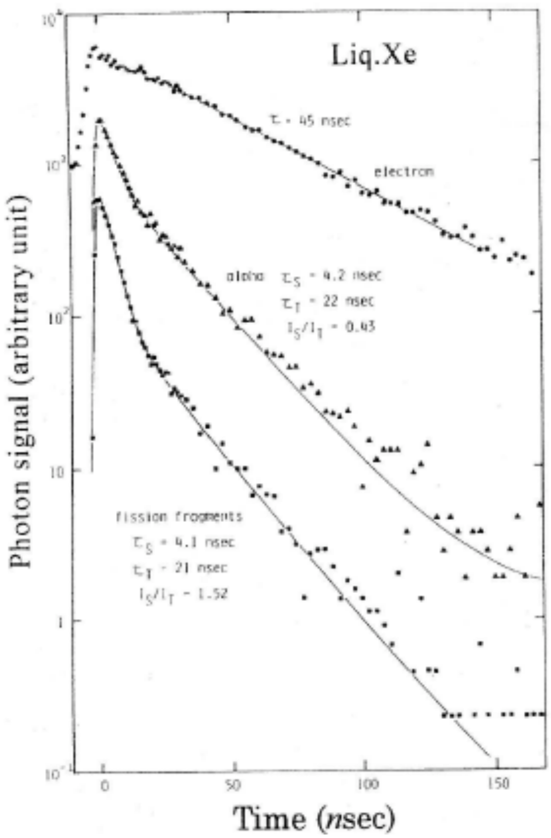
$$\lambda \sim 175_{LXe}$$

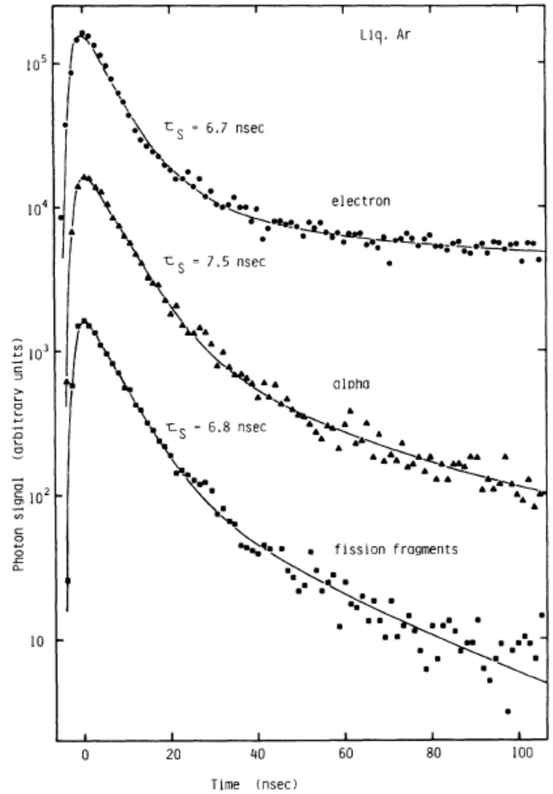
$$\lambda \sim 77.5_{LNe}$$

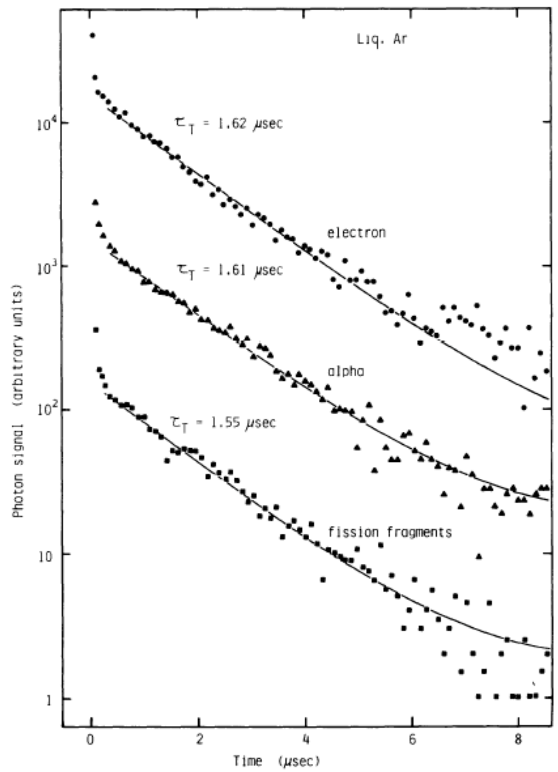
Scintillation Pulse Shape

- 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

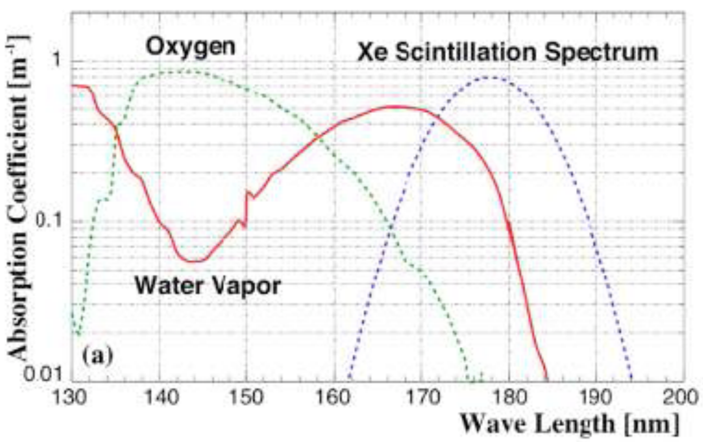


FIG. 25 Absorption coefficient for VUV photons in 1 ppm water vapor and oxygen and superimposed Xe emission spectrum (Ozone, 2005).

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

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

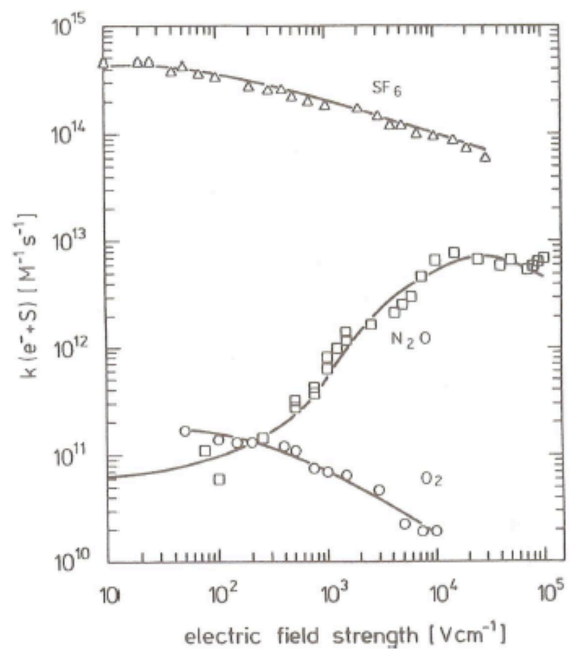
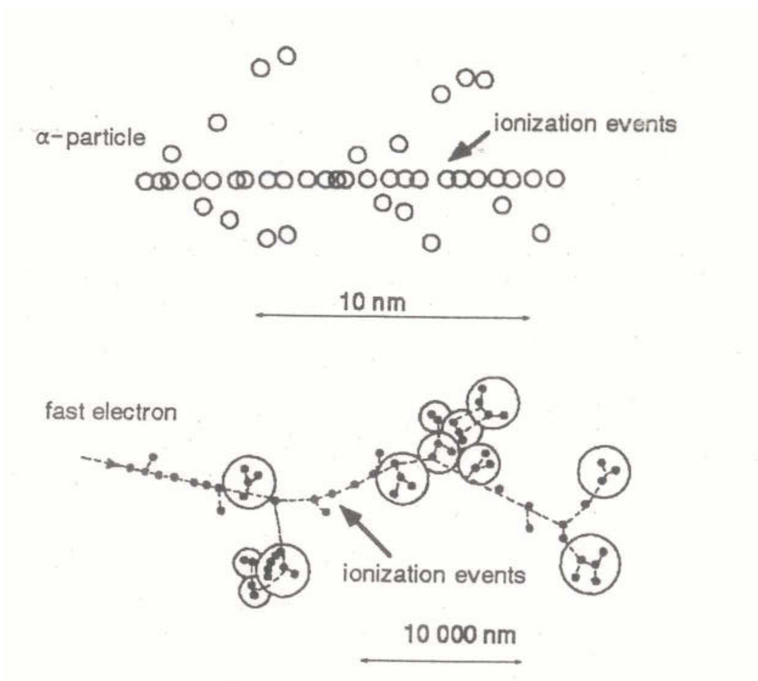


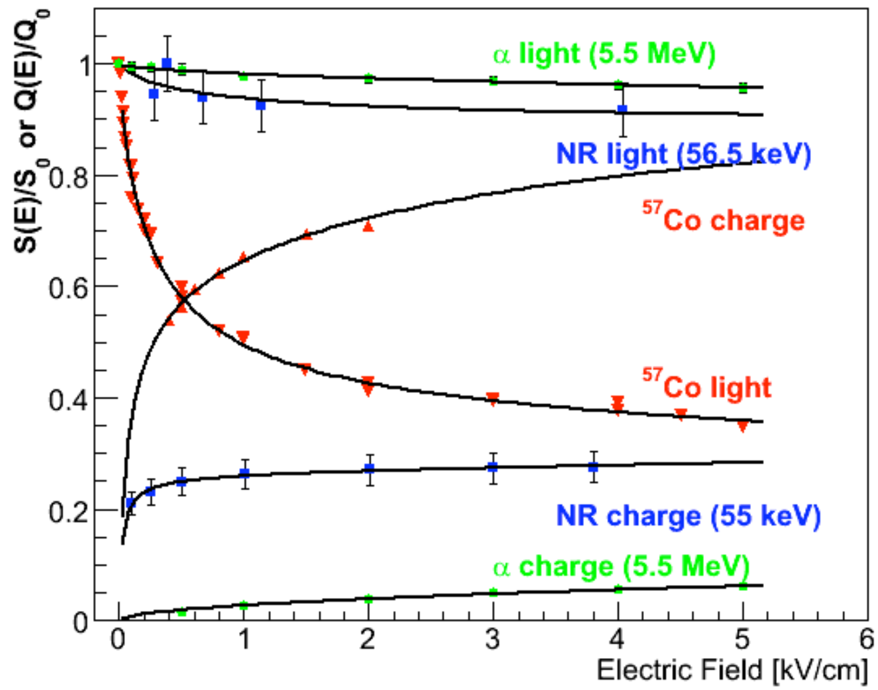
FIG. 15 Rate constant for the attachment of electrons in liquid xenon(T=167°K) to several solutes: (△) SF_6, (□) N_2O, (○) O_2(Bakale, 1976).

Charge and Light response of different particles in LXe

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



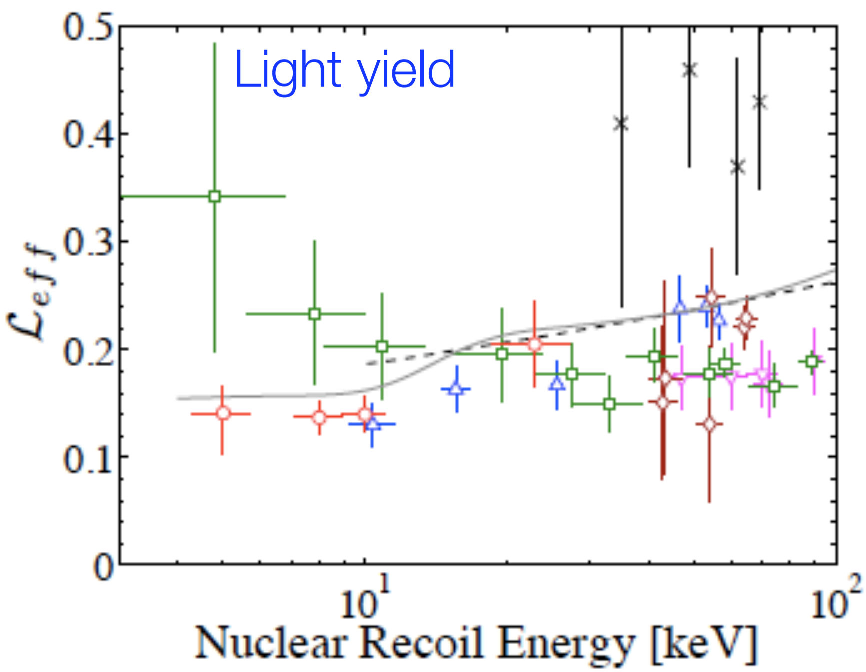
Distribution of ionization around the track of a high energy a-particle or electron



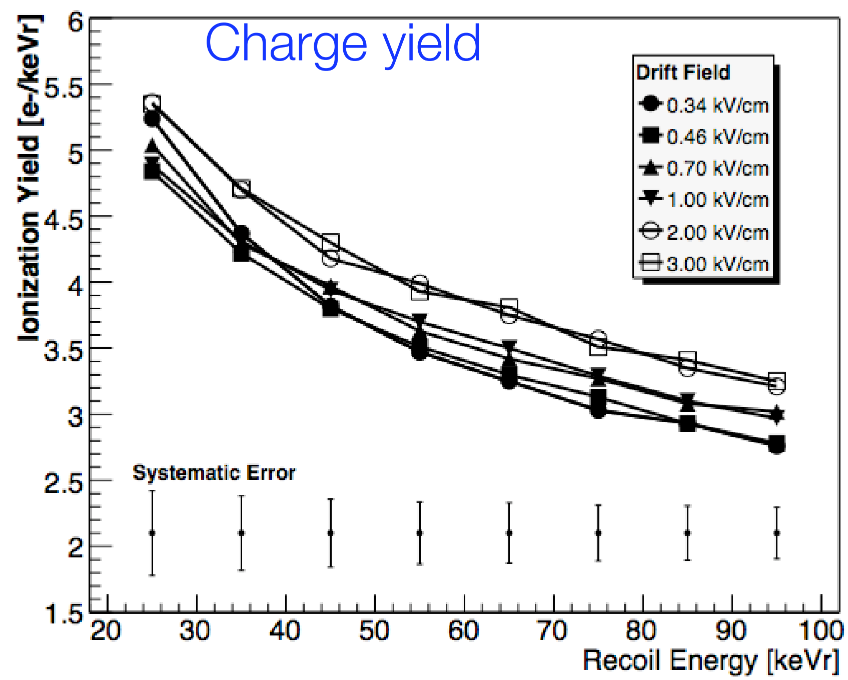
Aprile et al., Phys. Rev. D 72 (2005) 072006

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)

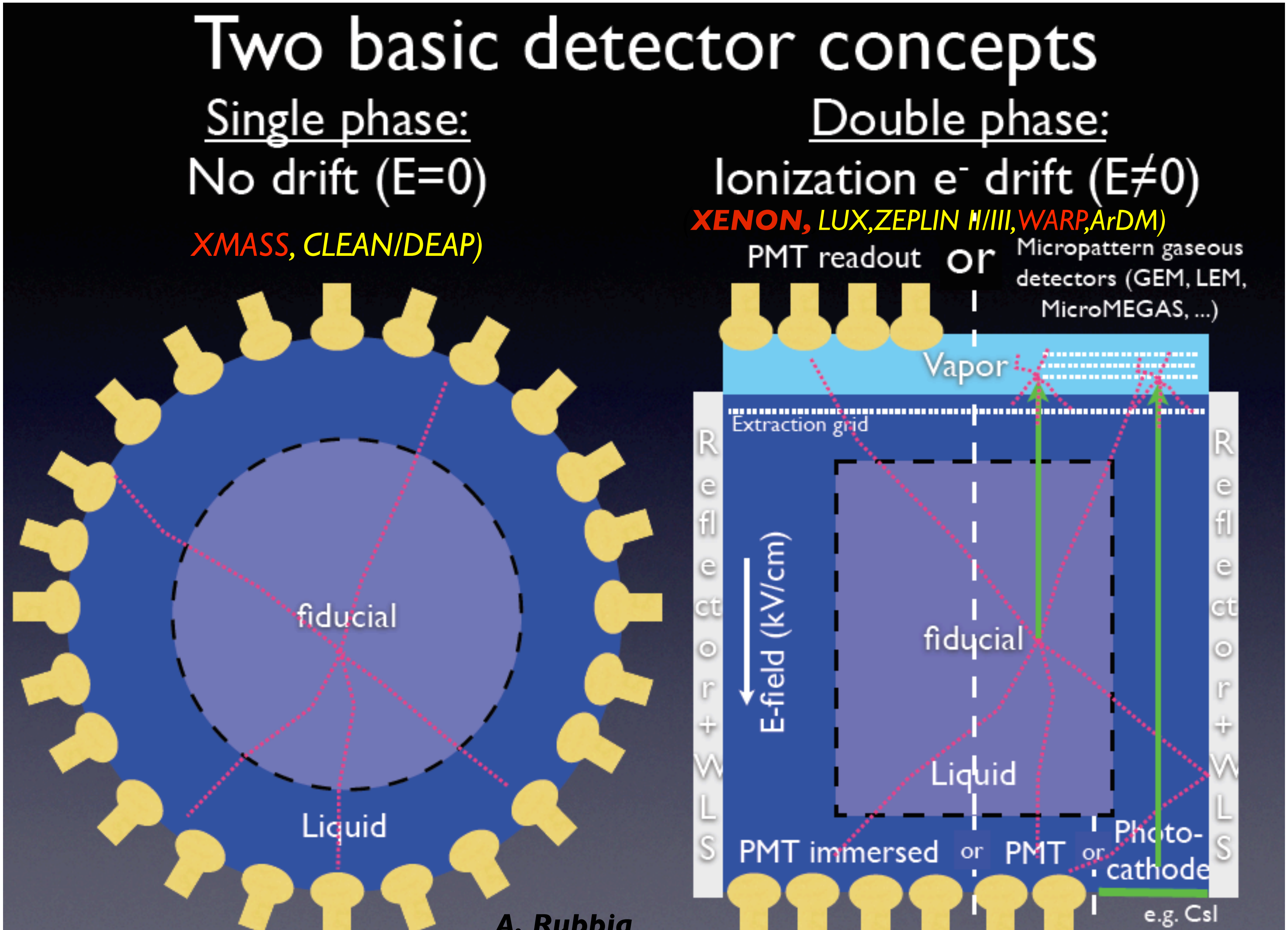


Aprile et al., Phys. Rev. D (2005)
Aprile et al., Phys. Rev. C (2009)



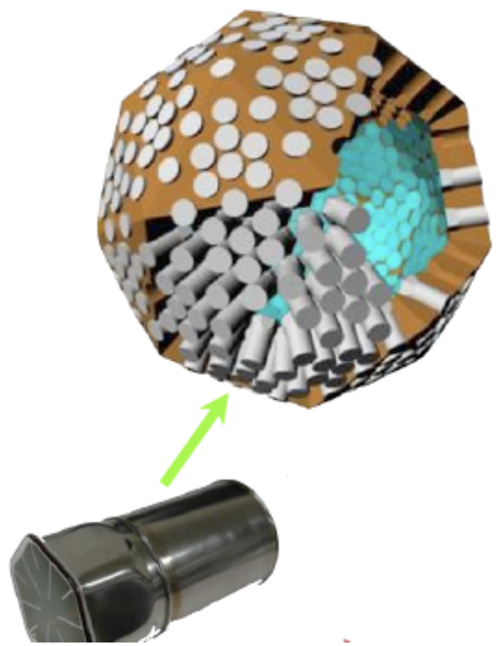
Aprile et al., Phys. Rev. Lett, 97 (2006)

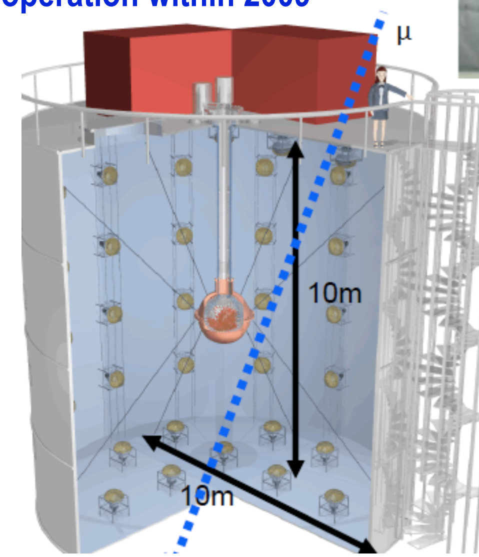
Noble Liquid Experiments for Dark Matter

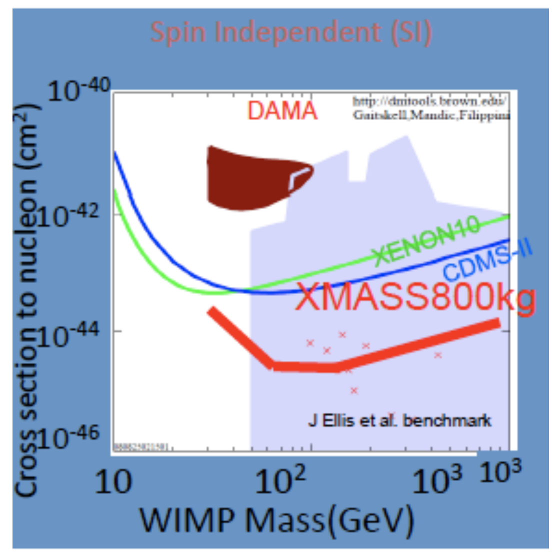


The XMASS Experiment @ Kamioka

- 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
- 5 keVee threshold; PMTs assembly has started; operation within 2009

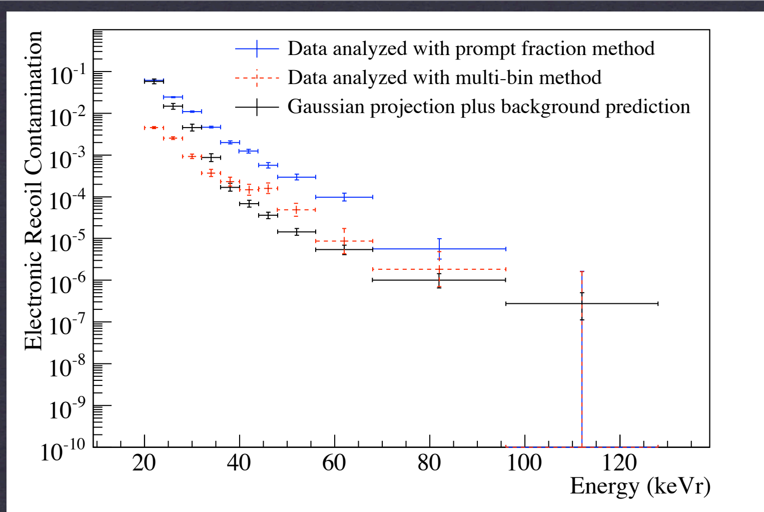






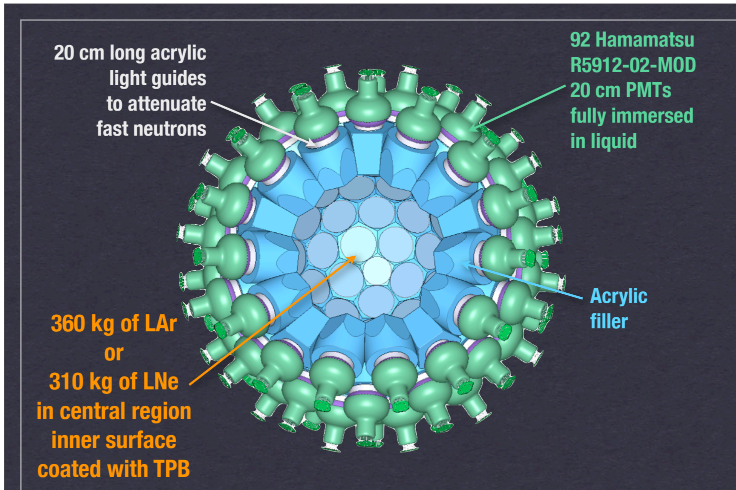
DEAP/CLEAN @ SNOLAB (Canada)

- ton scale DEAP/CLEAN planned for SNOLAB
- proposed first phase: 100 kg mini-CLEAN with WIMP search goal of ~ 5 x 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

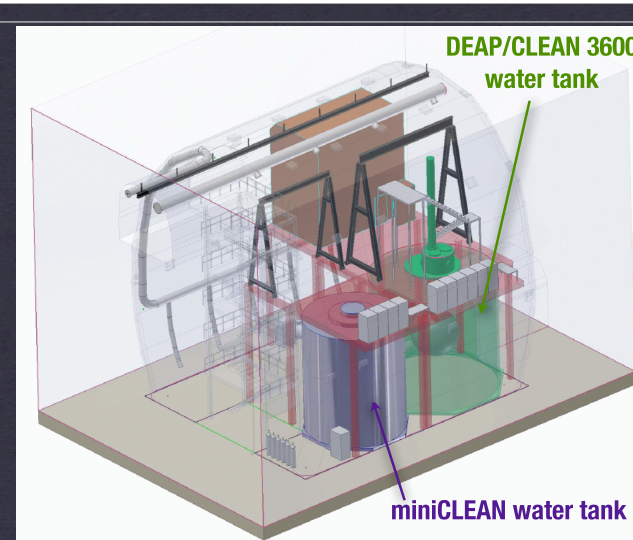


microCLEAN results

pulse shape discrimination of liquid argon, above ground, little shielding



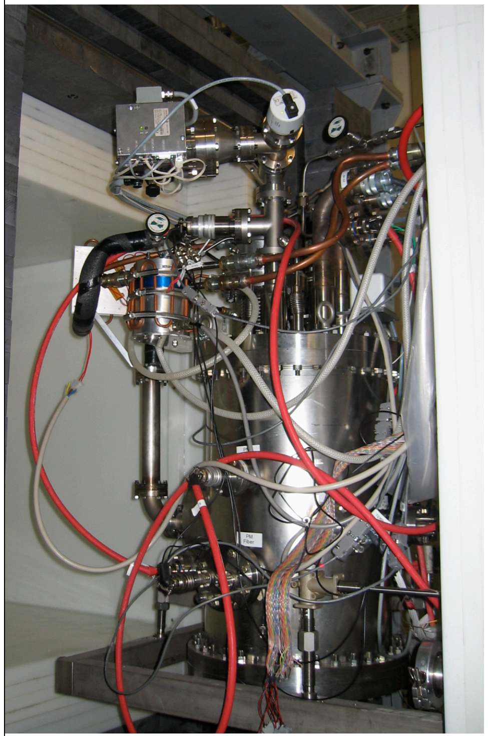
miniCLEAN central detector

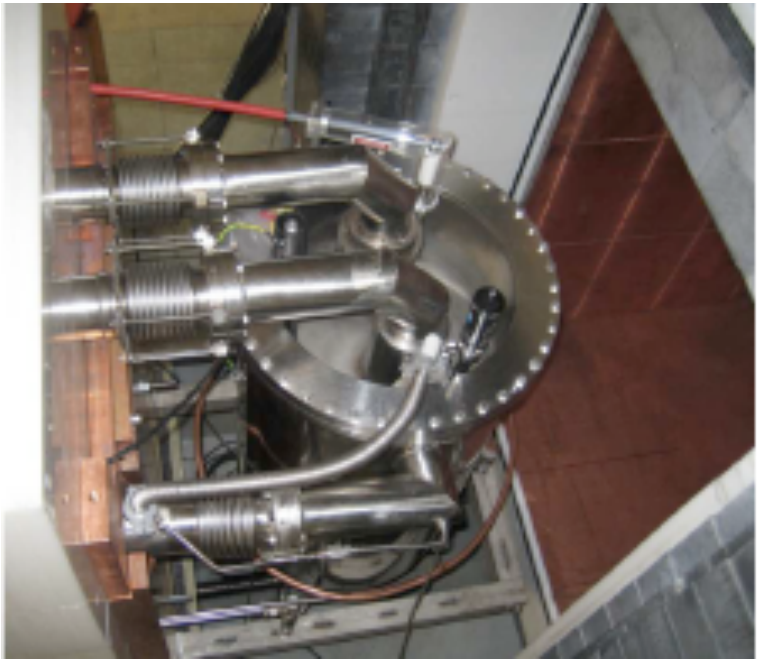


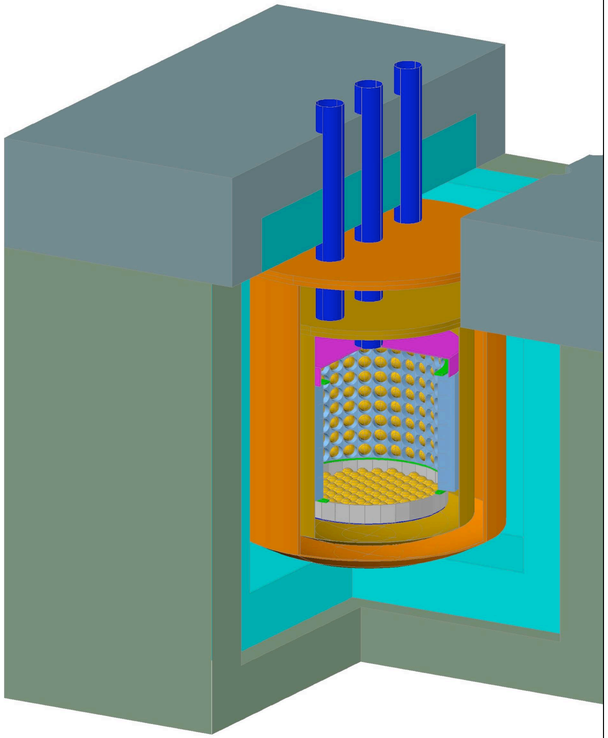
SNOLAB Cube Hall

The XENON Dark Matter Search

past (2005 - 2007)	current (2008-2012)	future (2013-2015)







XENON10

Achieved (2007) σ_{SI}*=8.8 x10*$^{-44}$ *cm*^{2}

XENON100 & 100+

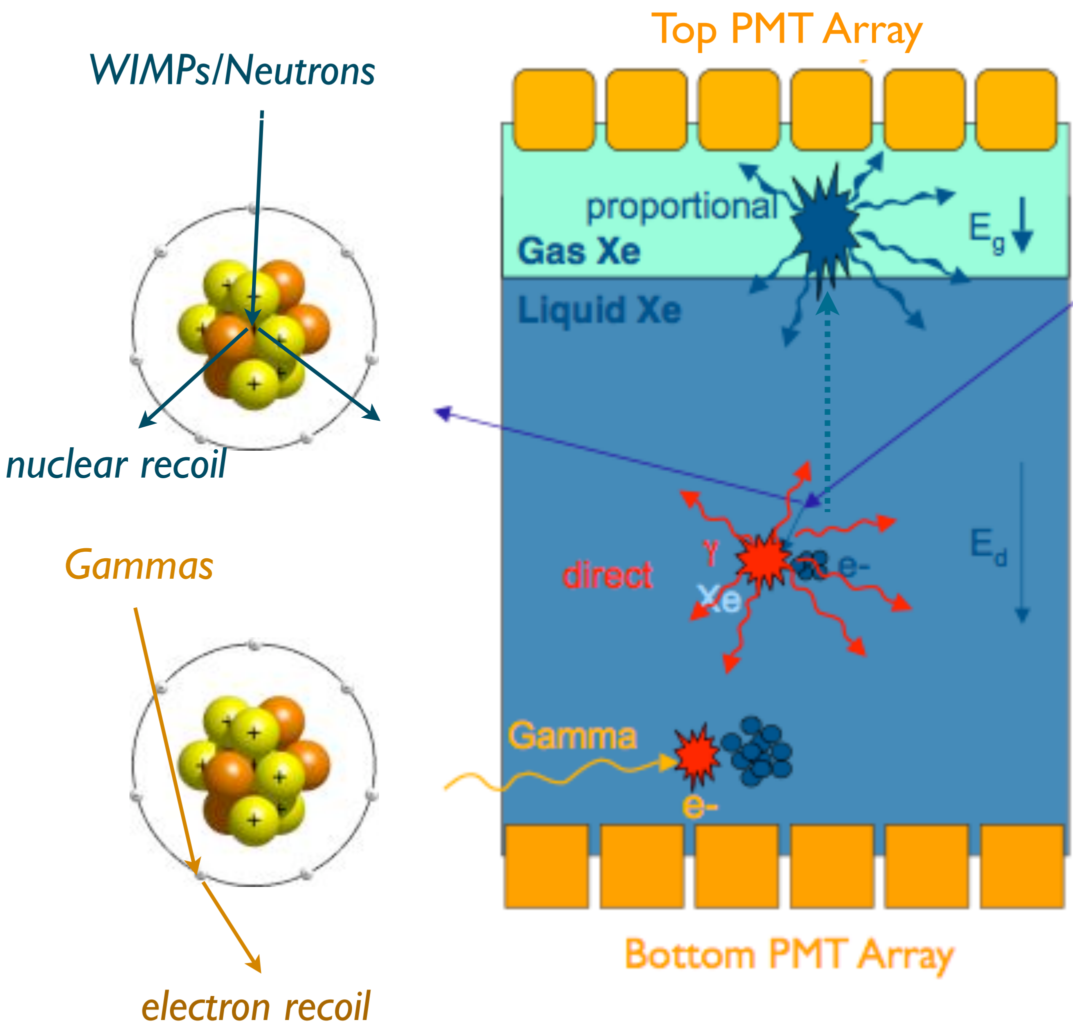
Projected (2010) $\sigma_{SI}\sim 2\times 10^{-45}$ cm^2

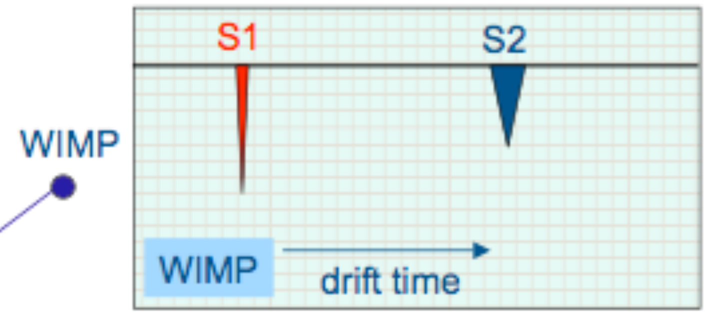
Projected (2012) $\sigma_{SI}\sim 2\times 10^{-46}$ cm^2

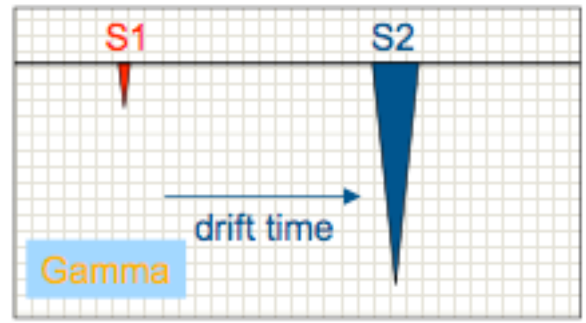
XENON1T

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

Principle of a liquid two-phase TPC





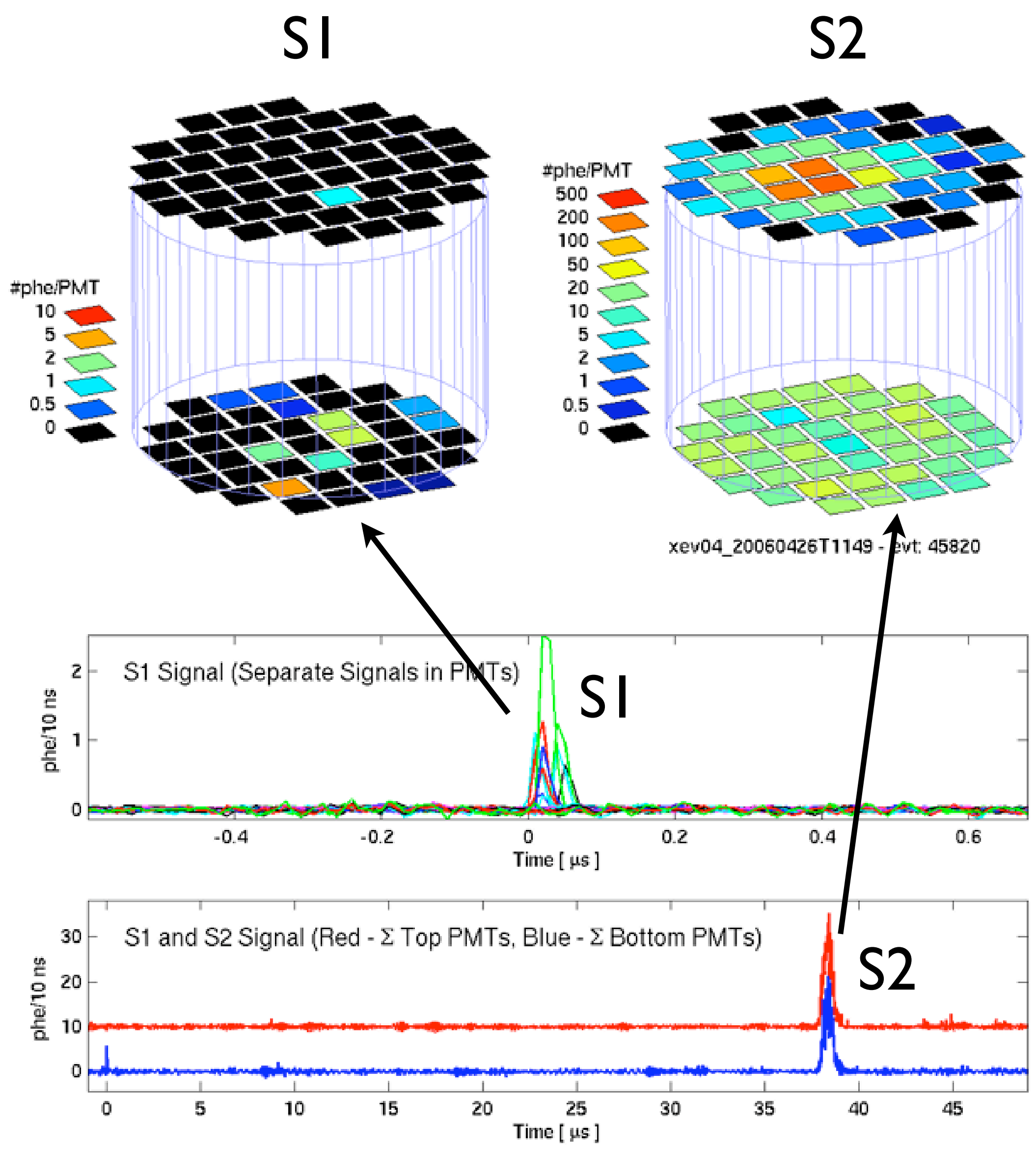


$(S2/S1)_{wimp} << (S2/S1)_{gamma}$

$$G_\gamma \approx \alpha\left(E/p - \varepsilon_{thresh}\right)\cdot x \cdot p$$

$$\alpha_{LXe} = 70\ \gamma / kV \quad \varepsilon_{thresh}^{LXe} = 1.3kV / cm / atm$$

Signals from XENON10

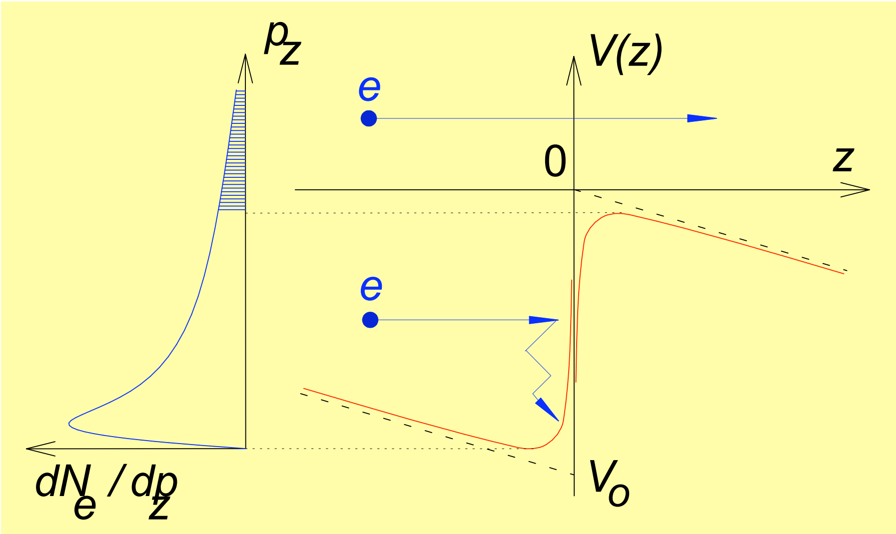


Quasi-free Electron Emission from Noble Liquids

- Excess electrons liberated by ionizing radiation can exist in a quasi-free state.
- The potential energy distribution near the interface of two-phase dielectrics favors emission of excess electrons from the quasi-free state
- In LAr the height of the potential barrier is comparable with the thermal energy of excess electrons. Electrons with $p_z > p_0$ have sufficient energy for emission
- In LXe the potential barrier $|V_0| >> kT$ and spontaneous emission is not easily achieved. However, with a high electric field, electrons are heated and when $p_z > p_0$ they escape from the condensed phase
- Electrons drifting in the gas, under a high electric field (>1kV/(cm bar) in Xe, generate electroluminescence or proportional scintillation. One electron in gas Xe can produce more than 1000 UV photons/cm of drift path

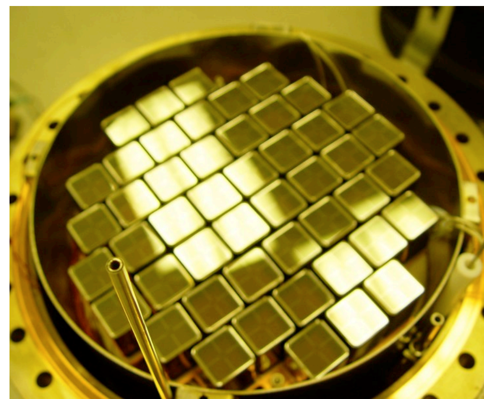
B. Dolgoshein et al. JETP Lett. 11 (1970) 513

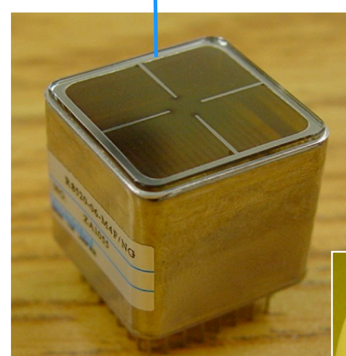
A. Bolozdynya, NIM A422 (1999) 314

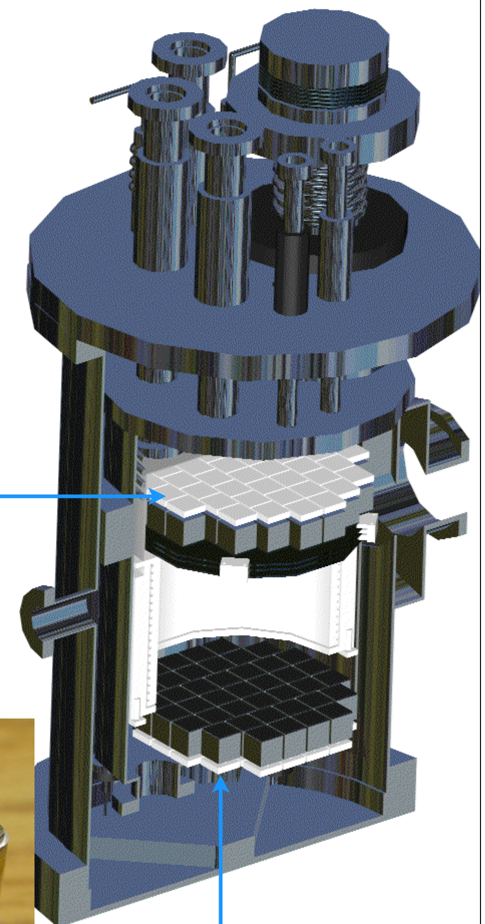


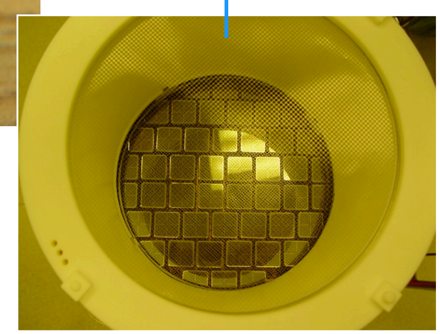
XENON10 @ LNGS

- **22 kg of liquid xenon**
  - ➡15 kg active volume
  - ➡20 cm diameter, 15 cm drift
  - ➡PTFE walls for VUV reflectivity
- **89 Hamamatsu R8520 1”×3.5 cm PMTs**
  bialkali-photocathode Rb-Cs-Sb,
  Quartz window; ok at -100°C and 5 bar
  Quantum efficiency > 20% @ 178 nm
  - ➡x-y position from PMT hit pattern; $\sigma_{x\text{-}y} \approx$ 1 mm
  - ➡z-position from Δt_{drift} ($v_{d,e-} \approx$ 2mm/μs), $\sigma_Z \approx$0.3 mm
- **Cooling: Pulse Tube Refrigerator (PTR),**
  90W, coupled via cold finger (LN_2 for emergency)

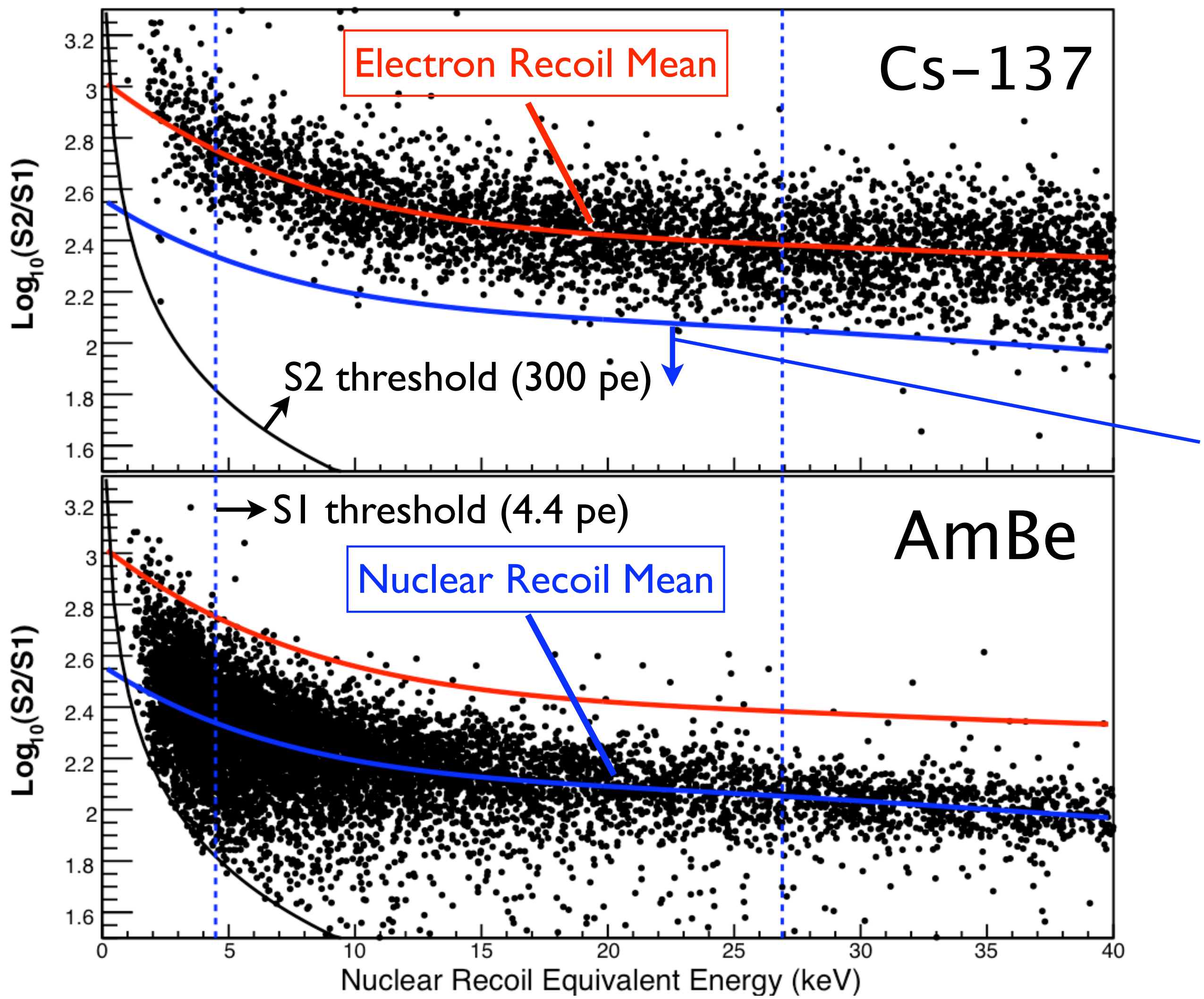








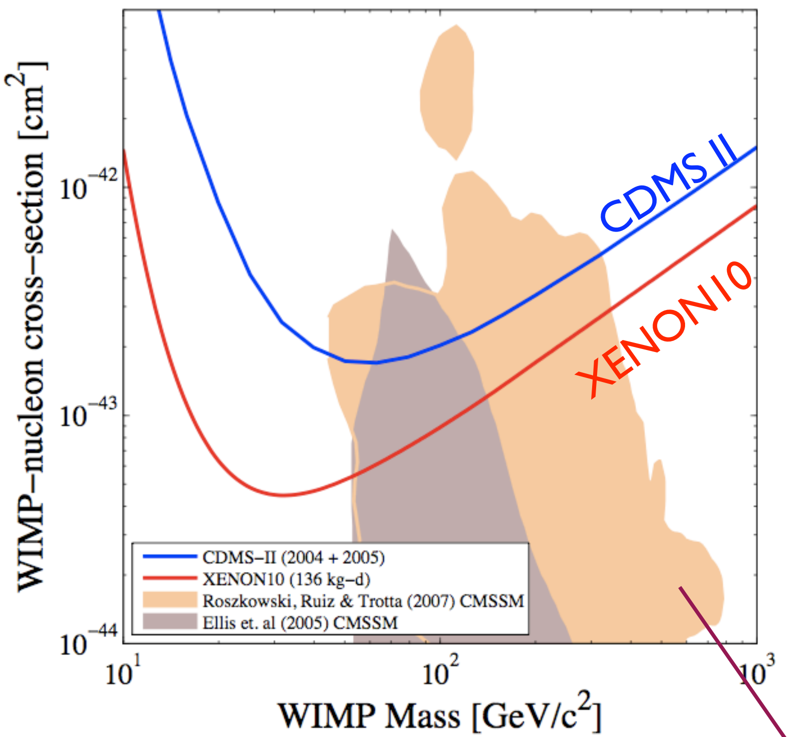
XENON10 Gamma/Neutron calibration



~ 99.5 % gamma events are rejected below the nuclear recoil mean

XENON10 WIMP-Nucleon Cross-Section Upper Limits

Spin-independent
Phys. Rev. Lett. ***100****, 021303 (2008)*



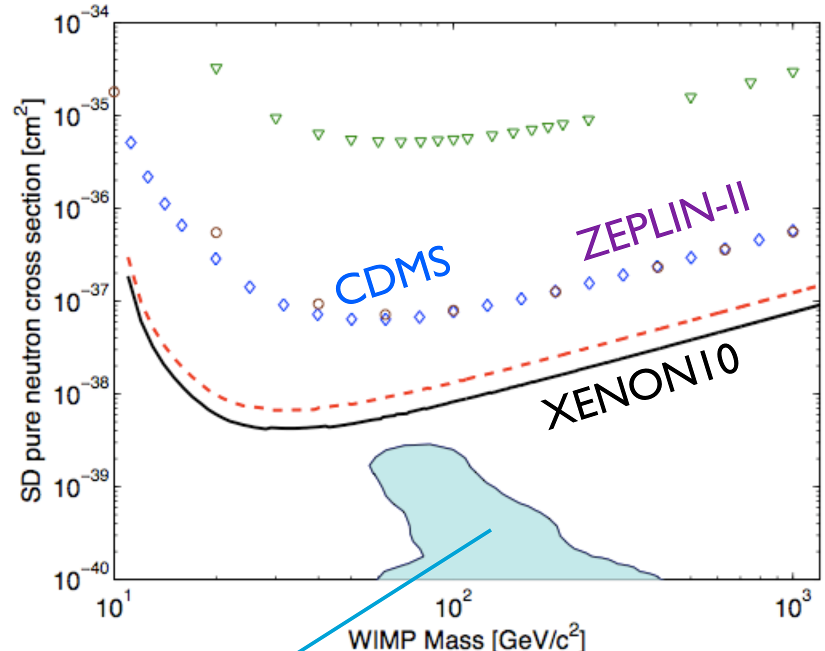
(NO BKG SUBTRACTION)

8.8 x 10^{-44} cm^2 at 100 GeV

4.5 x 10^{-44} cm^2 at 30 GeV

Constrained Minimal Supersymmetric Model

Spin-dependent
Phys. Rev. Lett. ***101****, 091301 (2008)*



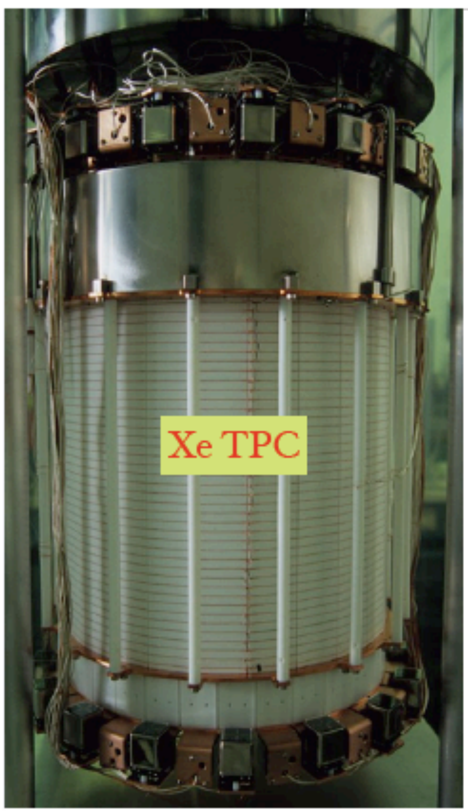
(NO BKG SUBTRACTION)

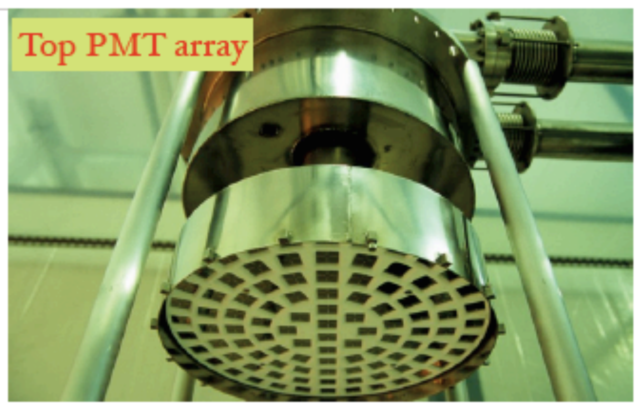
6 x 10^{-39} cm^2 at 30 GeV

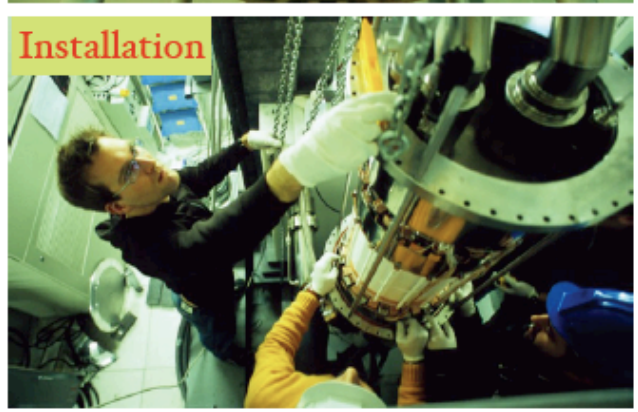
XENON100 @ LNGS

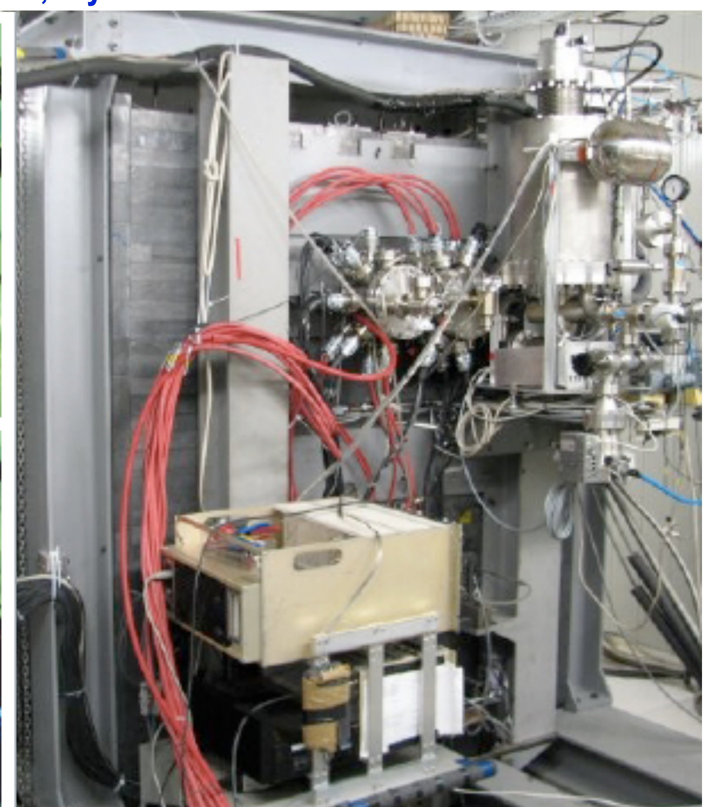
USA, Switzerland, Italy, Portugal, Germany, France, Japan, China

- 170 kg of ultra pure LXe: 70 kg as active target and 100 kg in a 4pi LXe scintillation veto
- 30 cm drift gap TPC (~1 kV/cm) with two PMT arrays to detect both charge and light signals
- 242 x 1 inch square PMTs with < 1mBq/PMT in U/Th) and high QE (25- 33 %) at 178 nm
- 3D event localization with a few millimeter resolution in X-Y and sub-millimeter in Z
- ~100 x less background than XENON10: low activity materials; crycooler outside shield and LXe veto



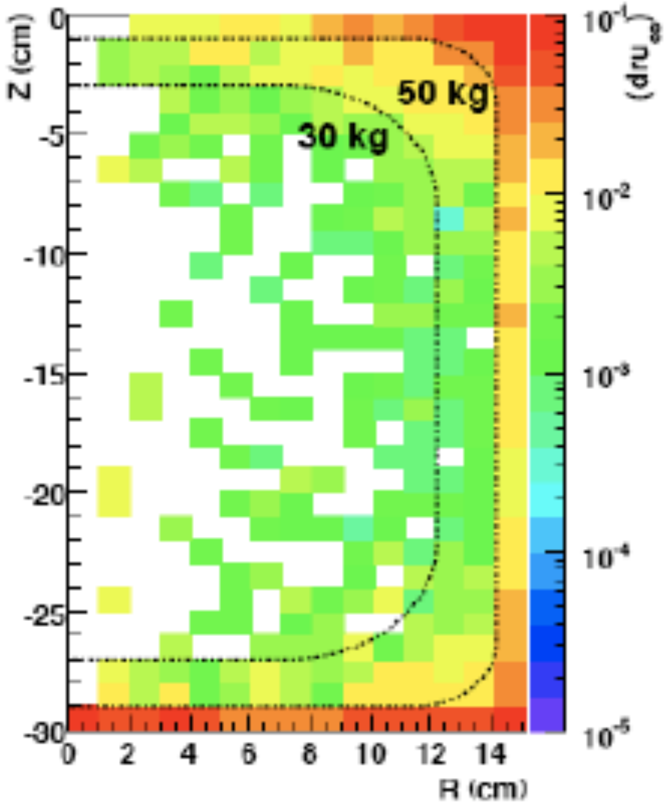






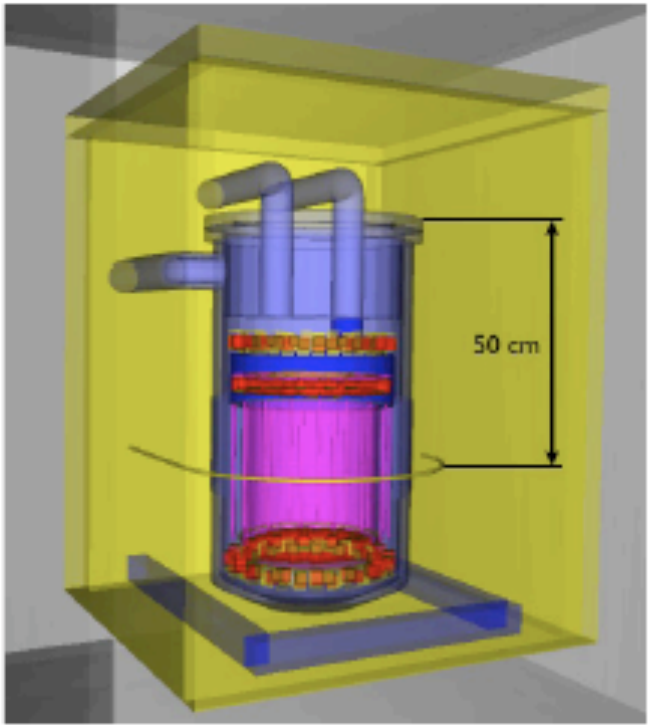
XENON100 Background: Monte Carlo & Data

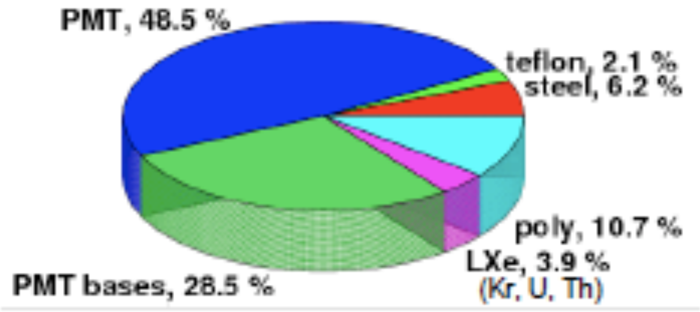
Monte Carlo predicted rate



50 kg: <$1\text{x}10^{-2}$ evts/kg/keV/day
(2000 kg-day, background free)

30kg: <$3\text{x}10^{-3}$ evts/kg/keV/day
(6000 kg-day, background free)

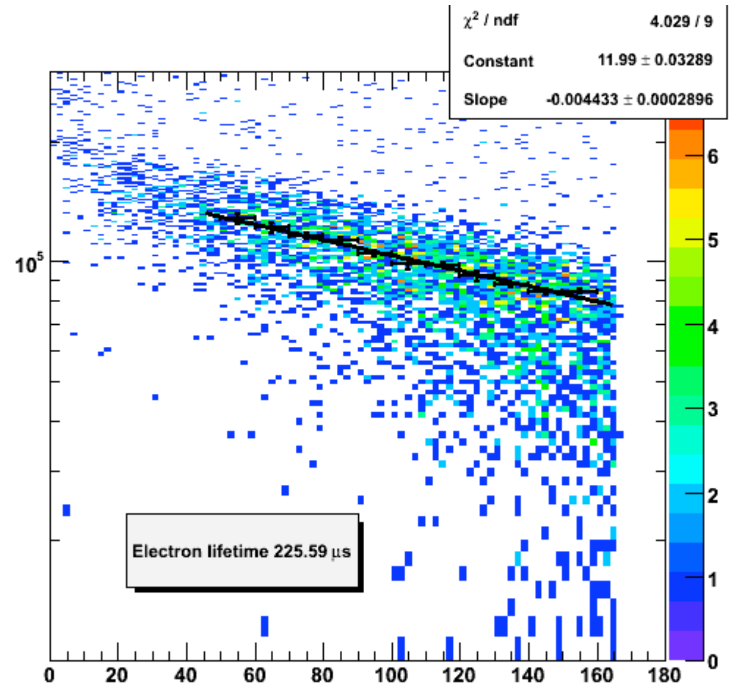


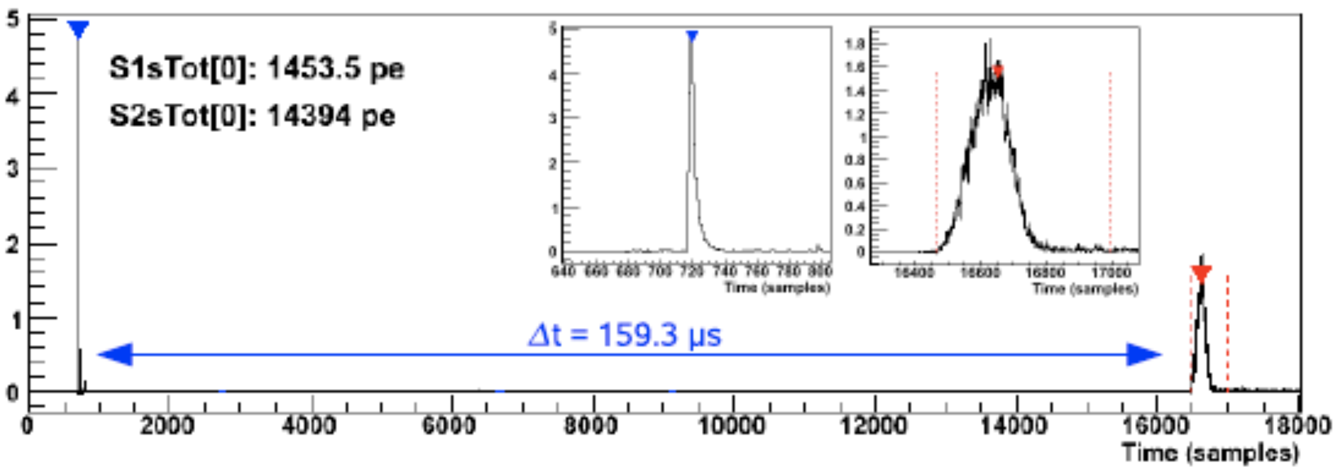


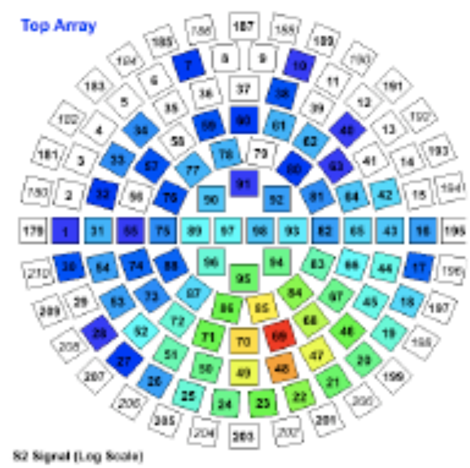
- **rate before S2/S1 discrimination!**

XENON100 Status and Schedule

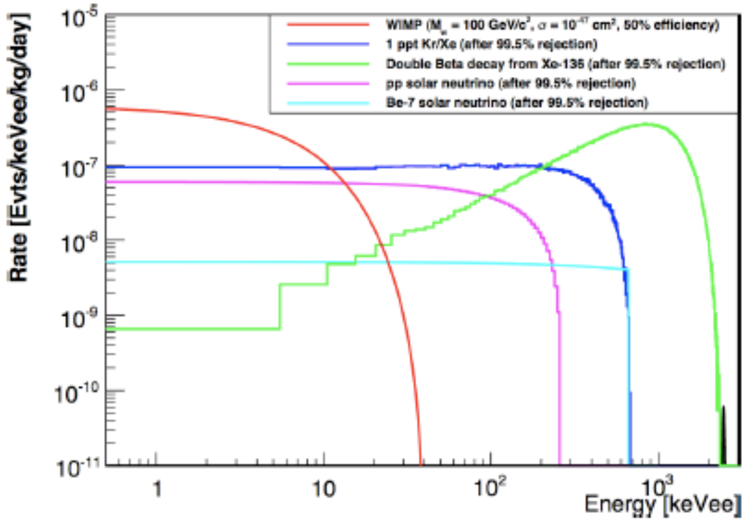
- Detector filled with low-Kr Xe and operational underground
- Taking gamma calibration data to optimize trigger level, energy threshold, overall S1 and S2 response
- Light Yield has reached a maximum value of ~4.5 pe/keVee
- The electron -lifetime increasing with continuous purification
- Initial background data show a level consistent with predicted
- Schedule: finalize Gamma and Neutron Calibration in Fall 09
- Start 1st DM search for ~ 1 month before end of 2009



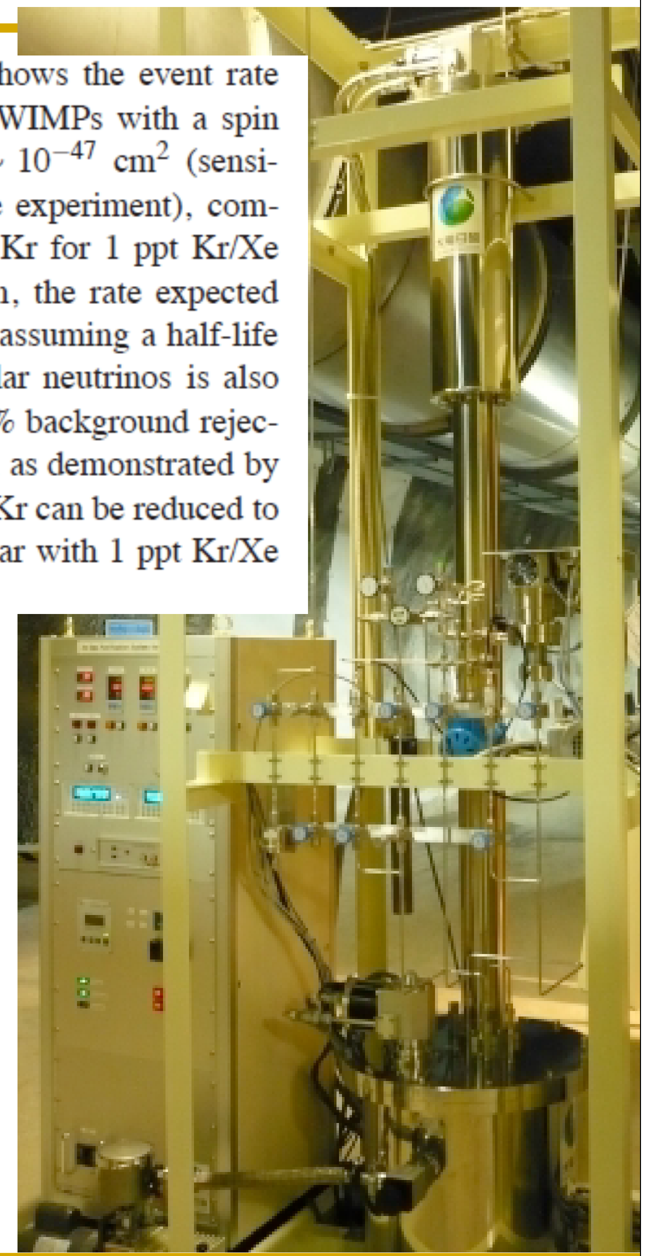




Background from Kr85



As an example, Figure 1 shows the event rate in a Xe target from 100 GeV WIMPs with a spin independent cross section $\sigma \sim 10^{-47}$ cm^2 (sensitivity reach of a ton scale LXe experiment), compared to the event rate from ^{85}Kr for 1 ppt Kr/Xe contamination. For comparison, the rate expected from ^{136}Xe double beta decay (assuming a half-life of 10^{22} years) and from pp solar neutrinos is also shown. With the expected 99.5% background rejection of a two-phase Xe detector, as demonstrated by XENON10 [3], the rate from ^{85}Kr can be reduced to less than 1 event per ton per year with 1 ppt Kr/Xe contamination.



Kr85 (Beta, Emax = 687 keV, t = 10.8 y, br = 99.563%) -> Rb85

Kr85 (Beta, Emax = 173 keV, t = 10.8 y, br = 0.434%)
-> Rb85m (Gamma, E = 514 keV, t = 2.43 us) -> Rb85

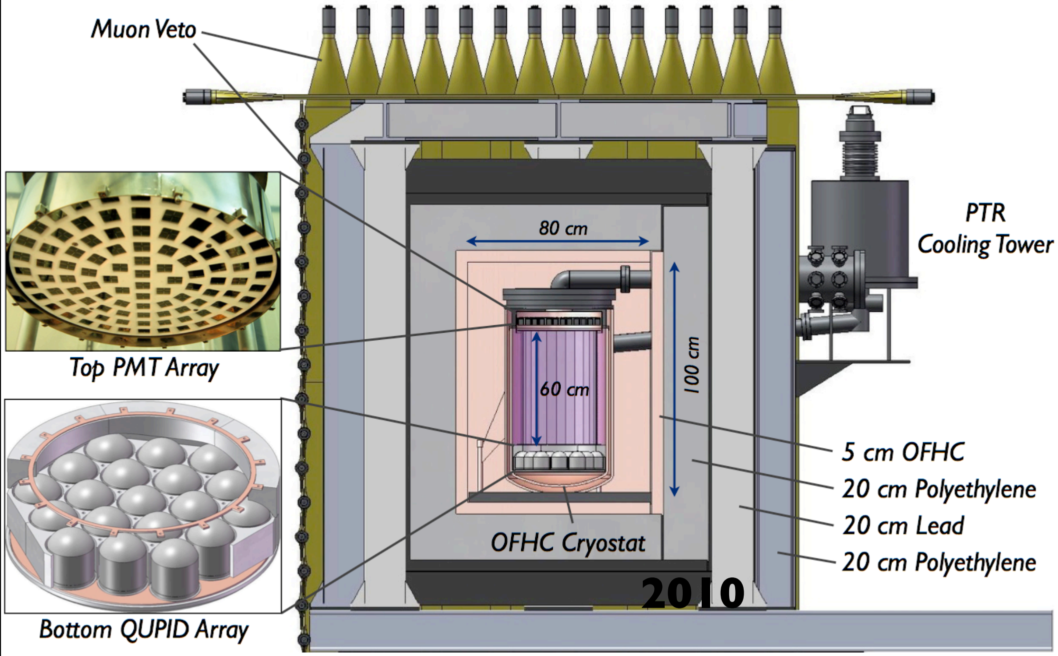
XENON100 science goal requires Kr contamination ~ 50 ppt

We use cryogenic distillation to separate Kr from Xe:

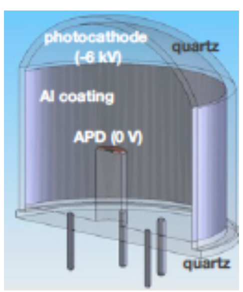
1) distilled by Spectra Gases Industry to < 10 ppb Kr level
verified with XENON100 data by delayed coincidences analysis
Measured Kr contamination = 7+-2 ppb

2) distilled on site by dedicated Cryogenic Distillation Tower
designed to reduce Kr by factor 10^3 at a rate of 0.6 kg/hr

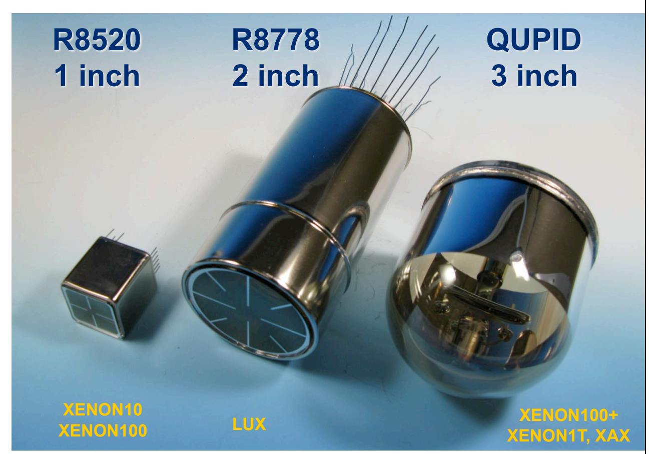
XENON100 Upgrade (2010-12)



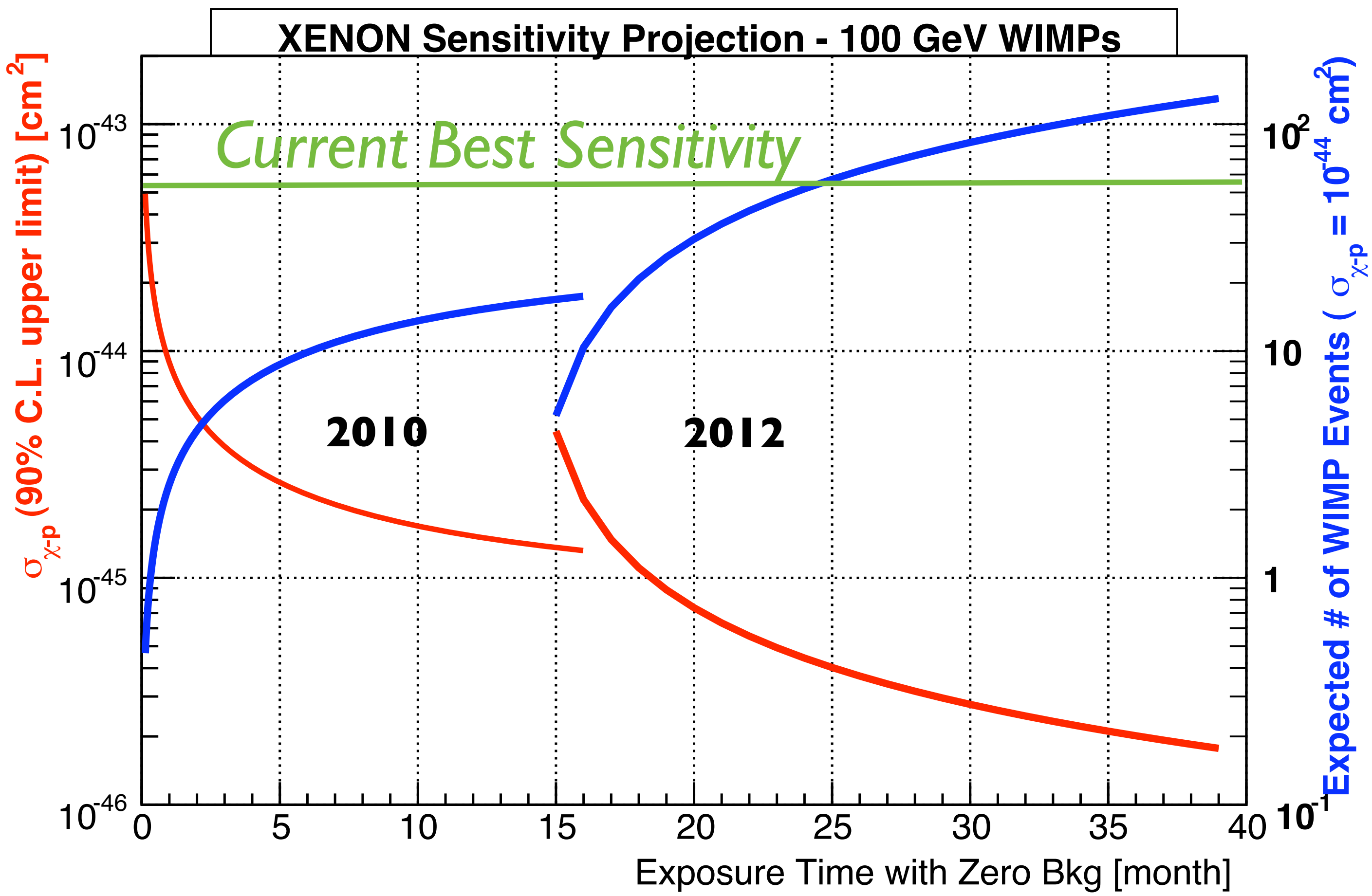
- reduce back from PMTs with QUPIDs
- XENON100+ funded by the NSF
- 300 kg (100kg fiducial) new TPC
- test key technologies for XENON1T



Extremely low radioactivity:	<< 1mBq
Large area:	~ 3 inch
Single photon detection capability	
High QE:	> 30 %
Low temperature operation	
Liquid Xenon:	-108 ^{o}C
Liquid Argon:	-186 ^{o}C



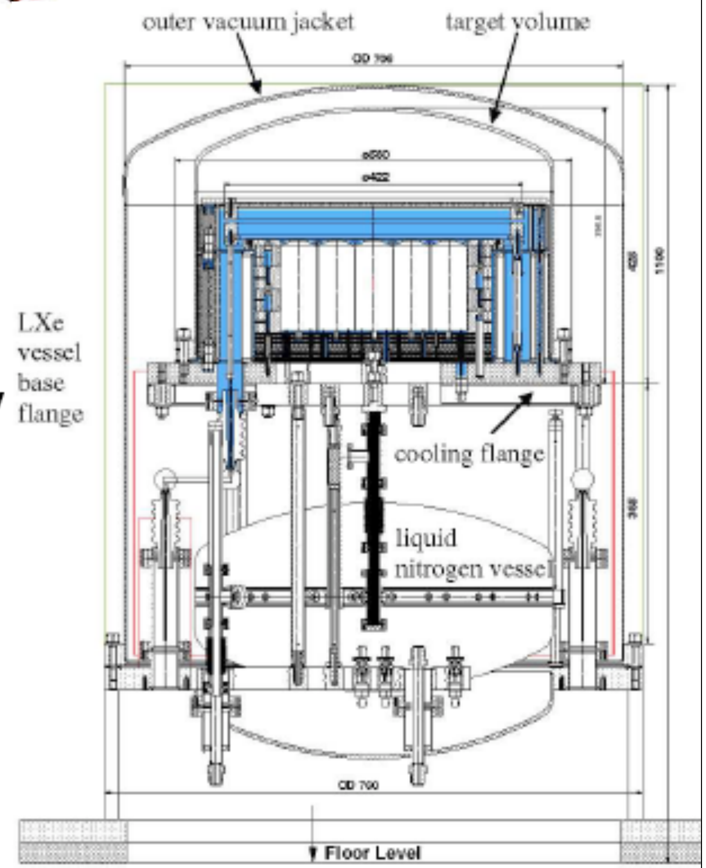
The Discovery Potential of the XENON100 Program



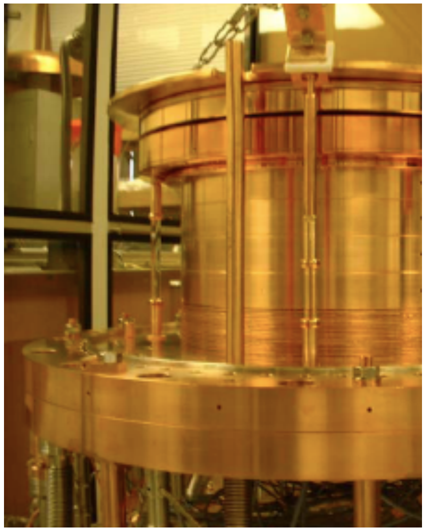
ZEPLIN III @ Boulby Mine

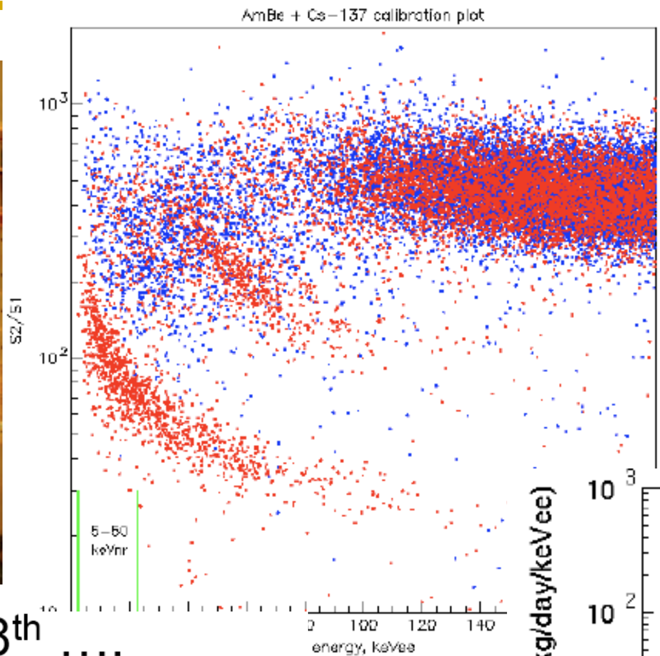
ZEPLIN III Features

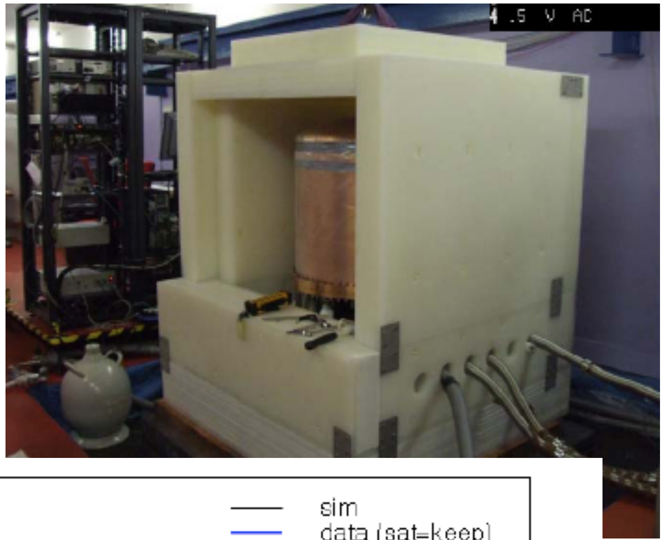
- 8kg fiducial mass
- PMTs in liquid to improve light collection
- 3.5 cm drift depth – higher E-field
- 0.5 cm electroluminescent gap
- 31 small PMTs for fine position sensitivity
- open plan – no surfaces - reduced feedback
- Lower-background PMTs available
- Copper construction
- Low-background xenon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



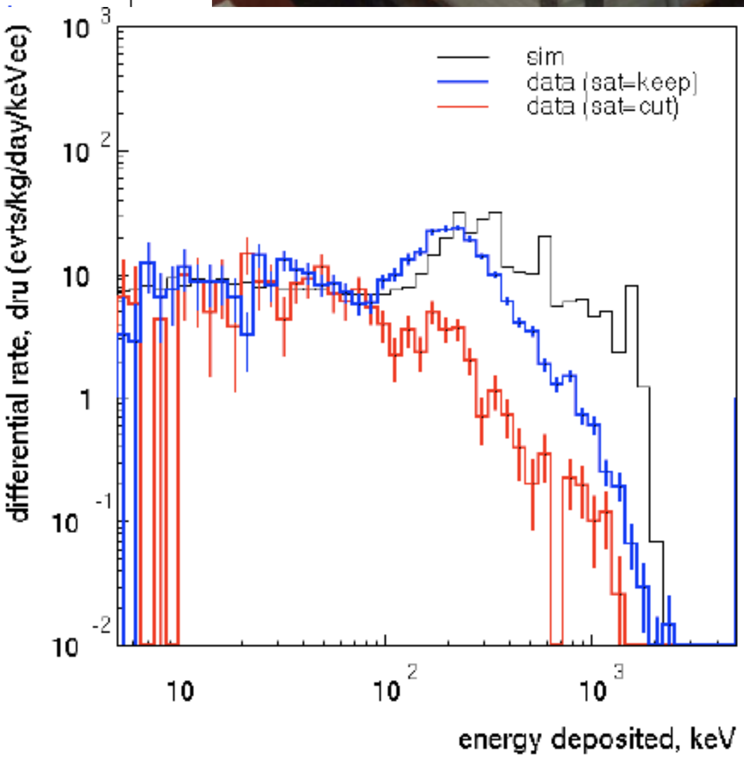
ZEPLIN III: First Data from Boulby



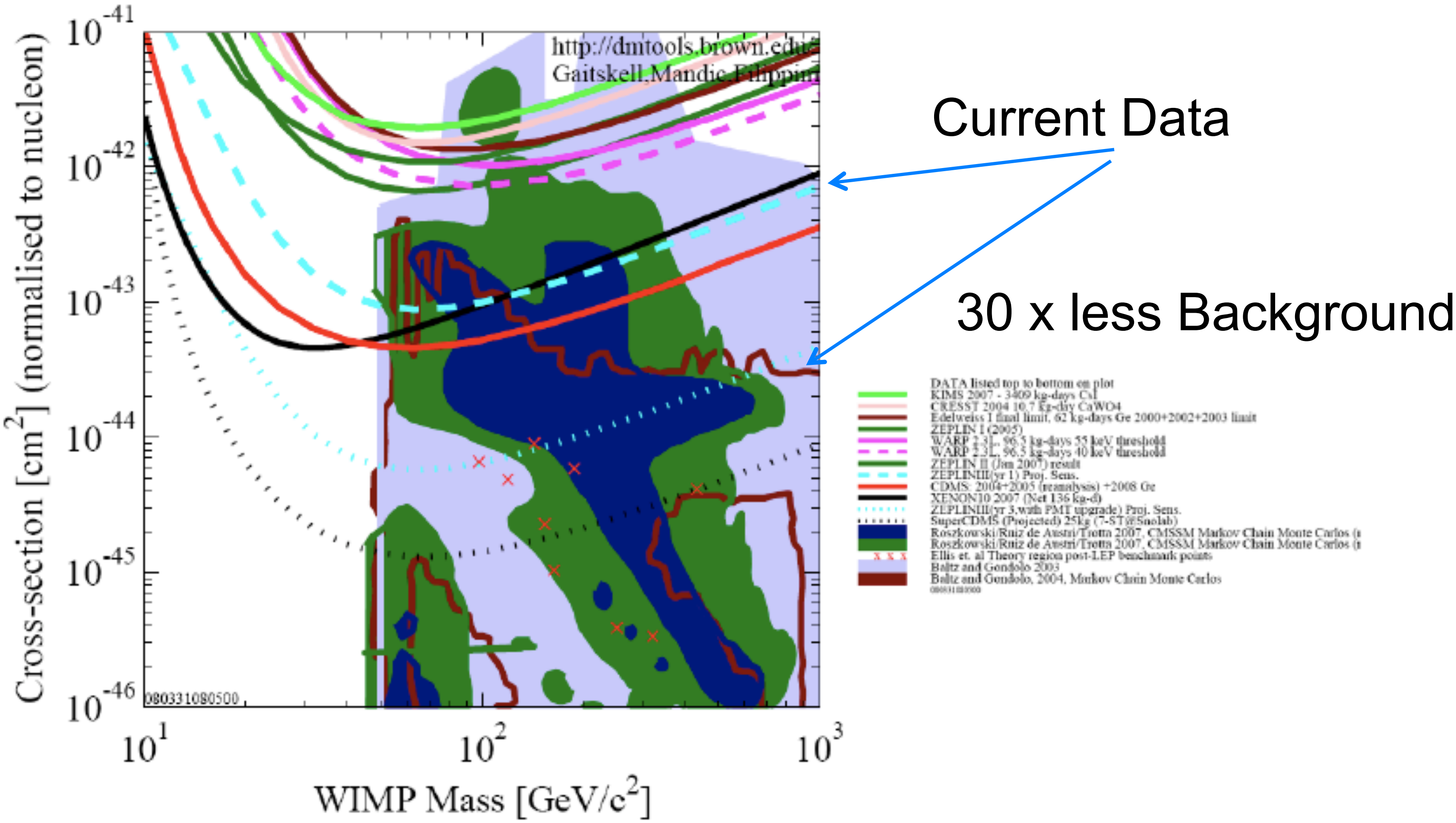




February 28th ….



ZEPLIN III- Sensitivity Projected

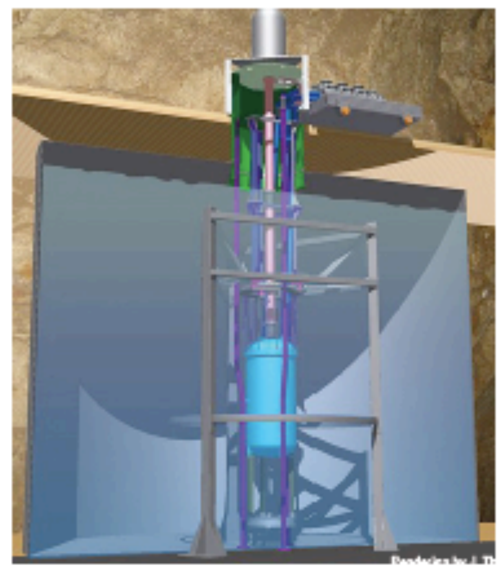


The LUX Experiment @ Homestake

- **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

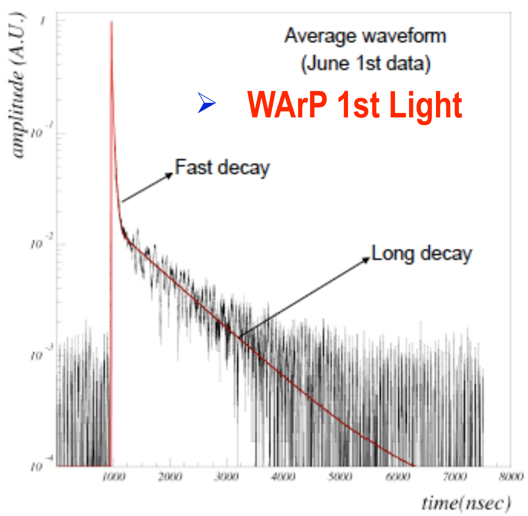


In water shield @ Homestake 4850 ft level

The WArP Experiment @ LNGS

WARP
WIMP ARGON PROGRAMME

- 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



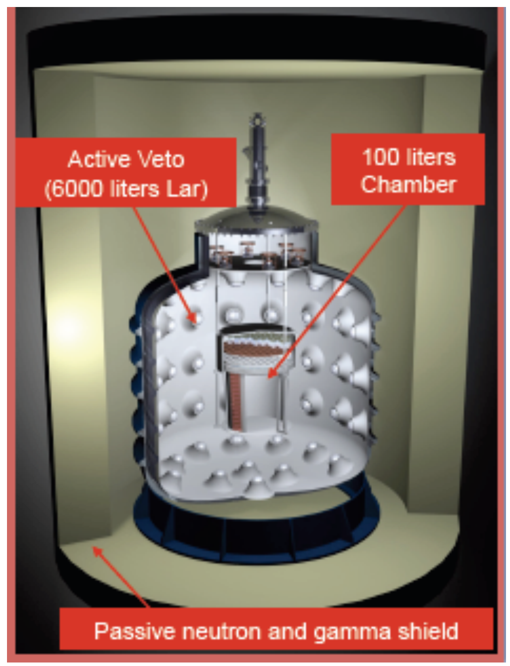
waveform fit (two exp. components).

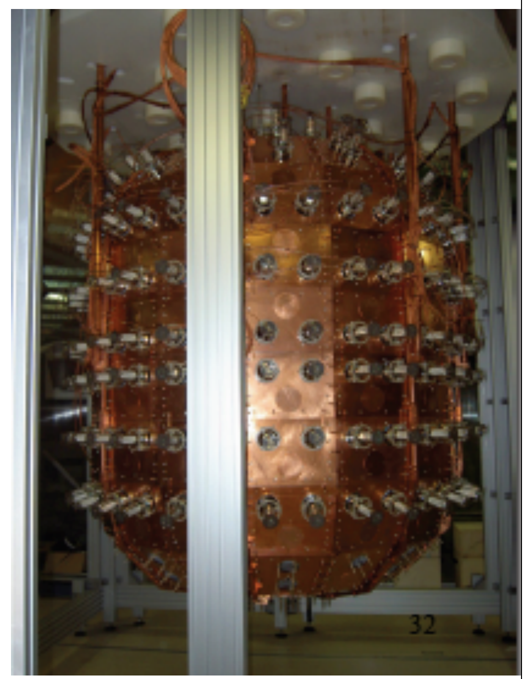
$\tau_{long} \rightarrow$ indication of LAr purity:

τ_{long}(fit) ≈ 1 μs (nominal 1.2 μs)

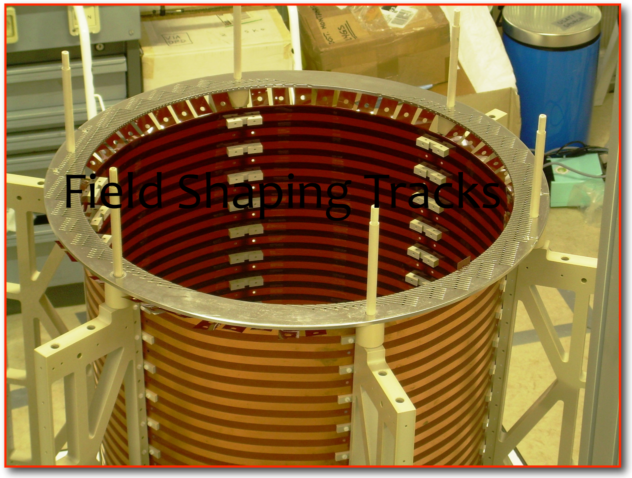
⇓

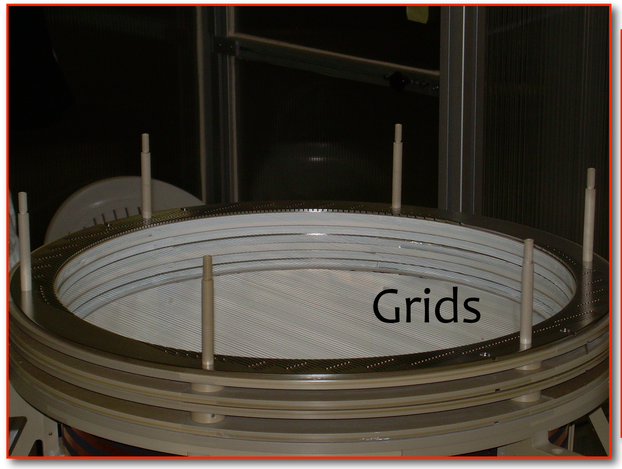
satisfactory LAr purity (after filling)

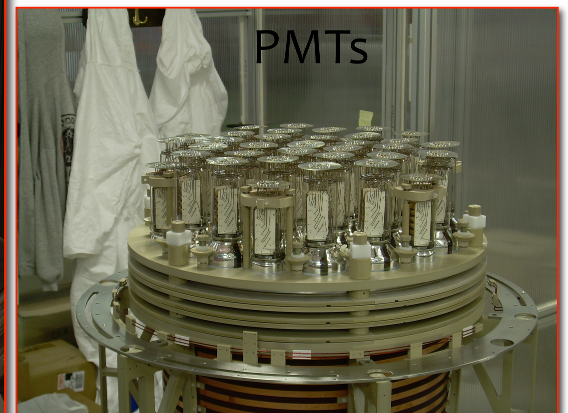


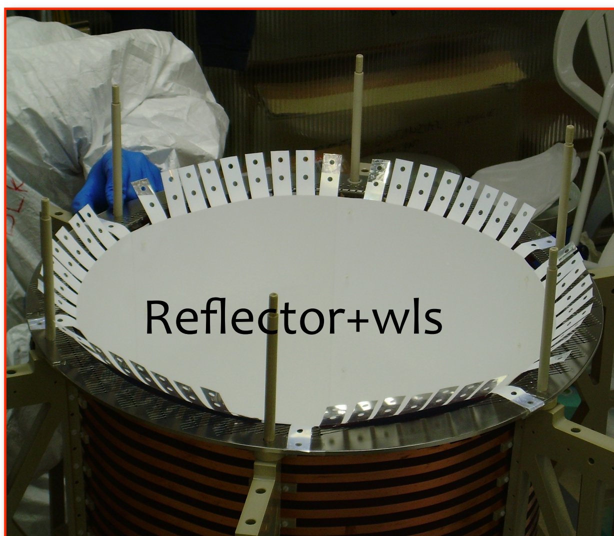


WArP Inner Detector Components

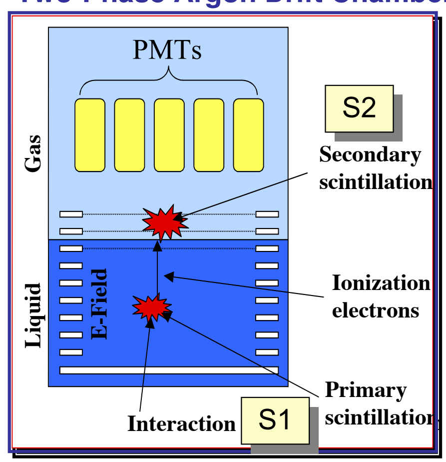






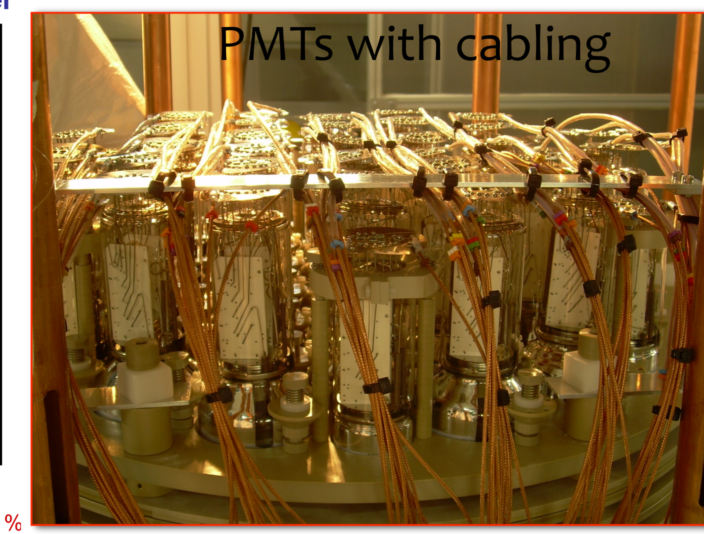


Two-Phase Argon Drift Chamber

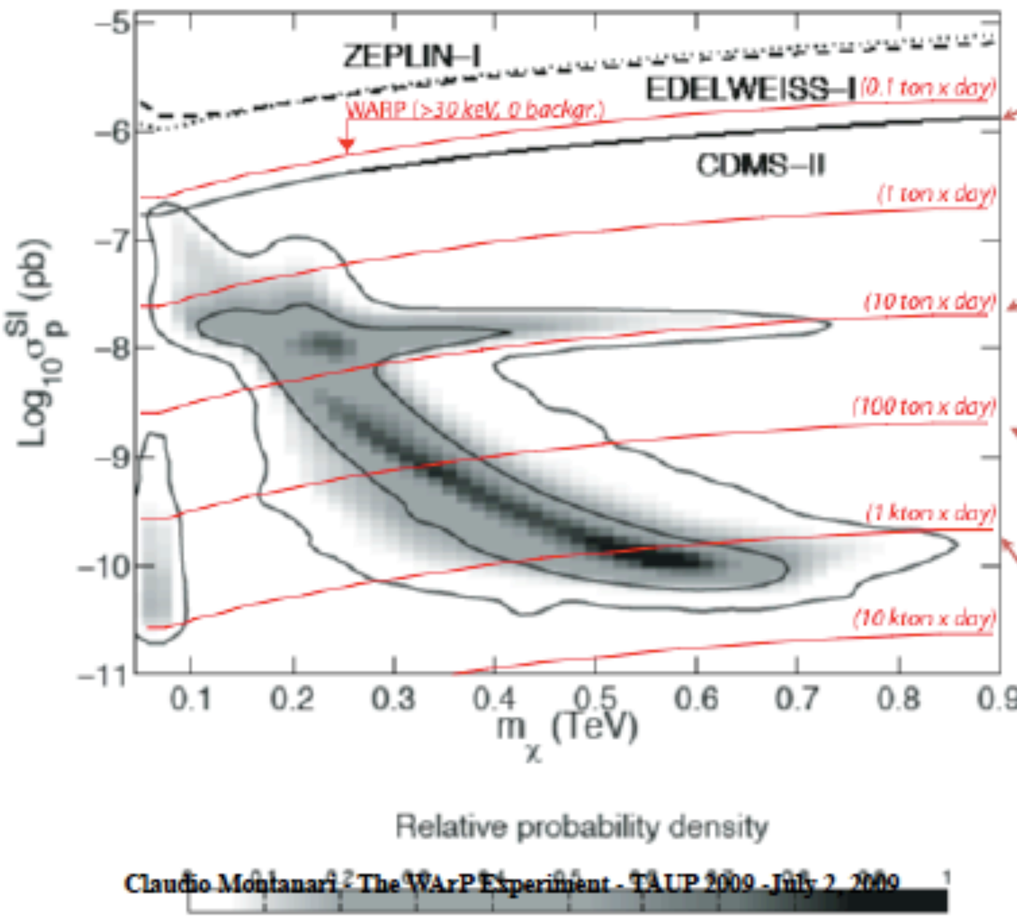


Recoil-like event
Slow component ≈ 10 %

γ-like event
Slow component ≈ 70 %



WArP Discovery Potentials



(2)-WArP 2.3 liters "clean" liquid, no background

(3)-WArP 100 liters 3 months no background (2009÷2010)

(4)-WArP 1 ton 3 months no background (2011÷2012)

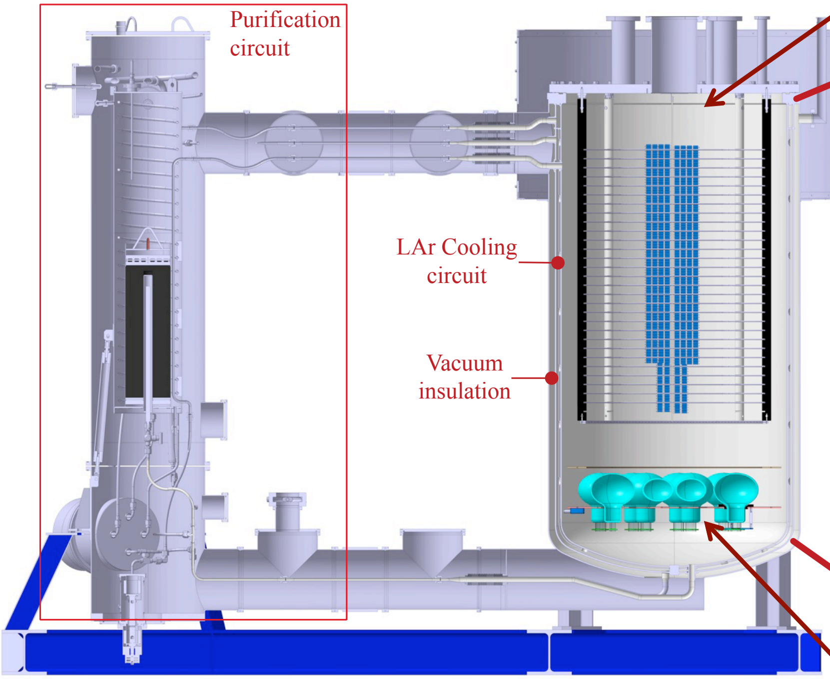
(5)-SuperWArP (10 ton) 3 months no background

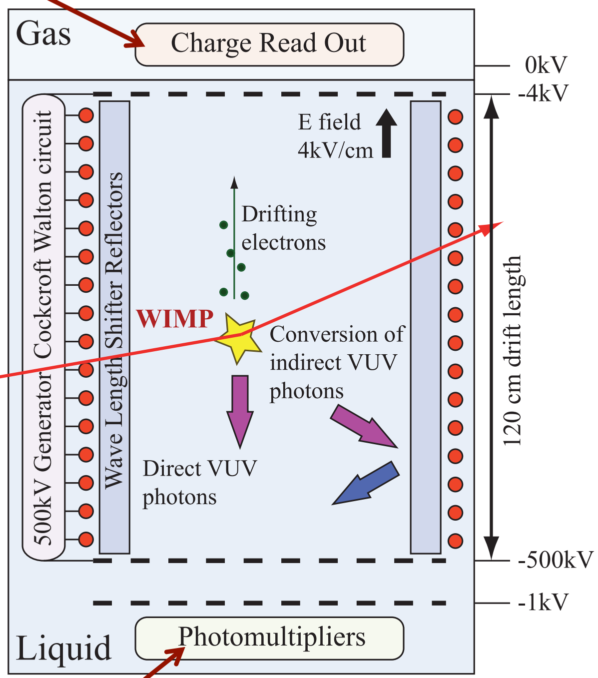
Claudio Montanari - The WArP Experiment - TAUP 2009 - July 2, 2009 44

The ArDM Experiment @ LSC

General Layout of the Experiment

Double stage LEM System

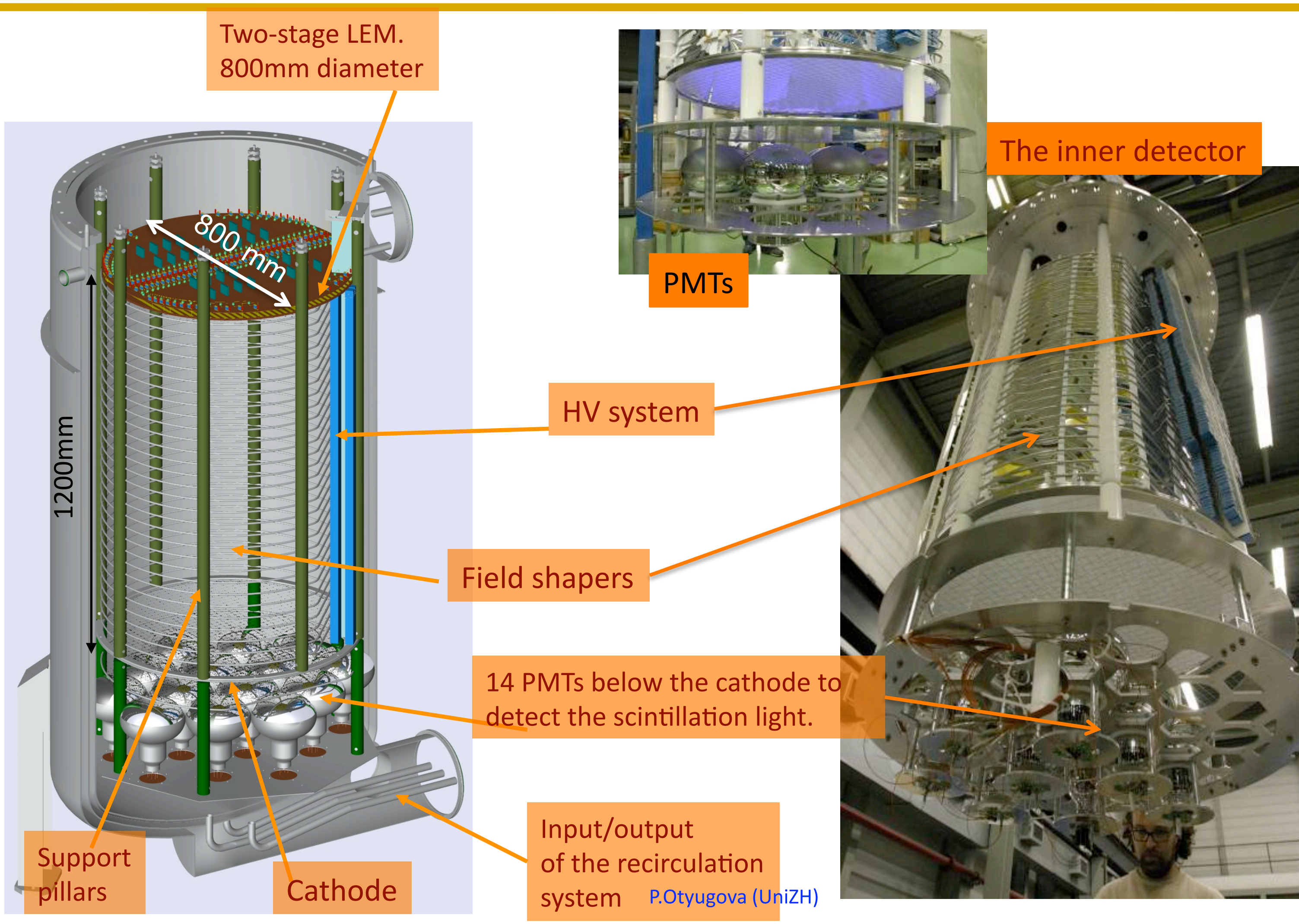




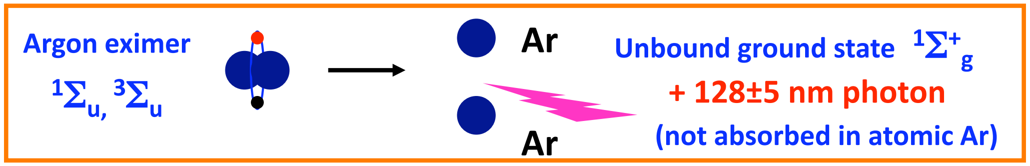
14 Cryogenic PMTs to detect the scintillation light

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

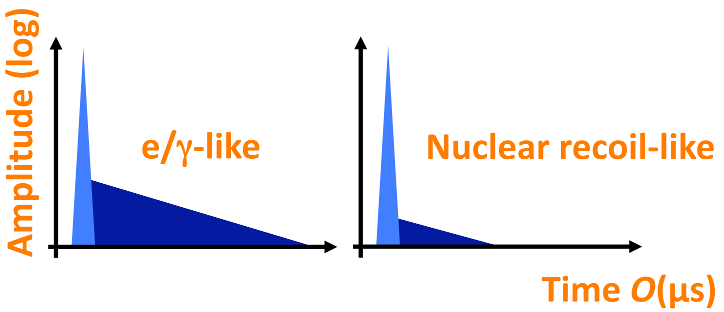
The ArDM design and assembly



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.

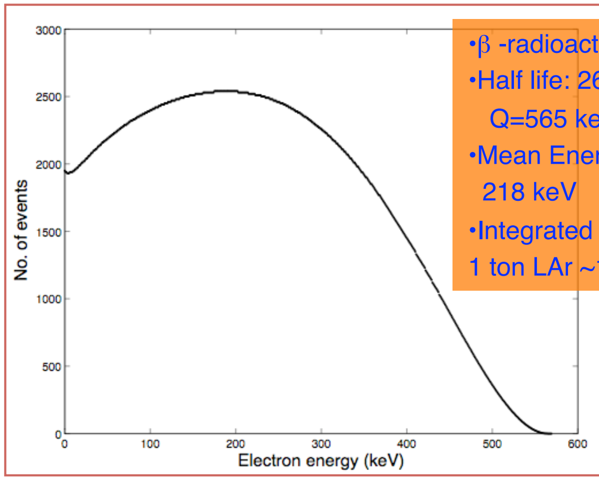
VUV light detection: WLS is required

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

P.Otyugova (UniZH)

Ar^{39} and neutrons backgrounds

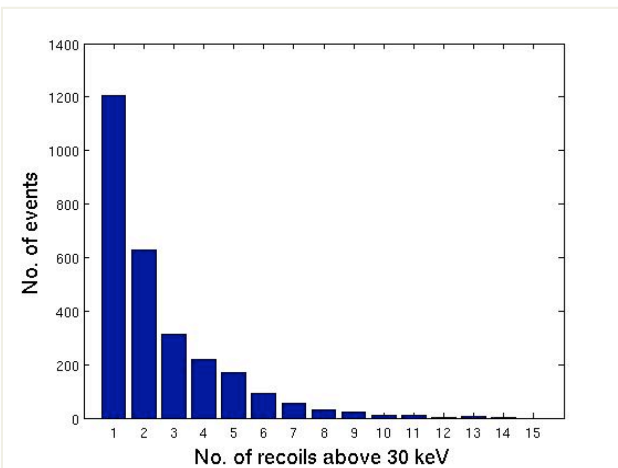
Natural argon from liquefaction of air contains small fractions of ^{39}Ar radioactive isotope.

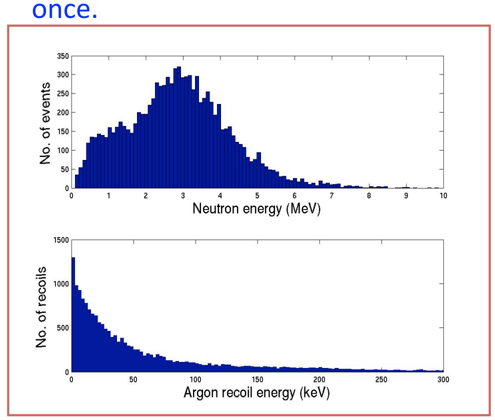


- β -radioactive isotope
- Half life: 269 years
  Q=565 keV
- Mean Energy:
  218 keV
- Integrated rate in
  1 ton LAr ~1kHz

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.

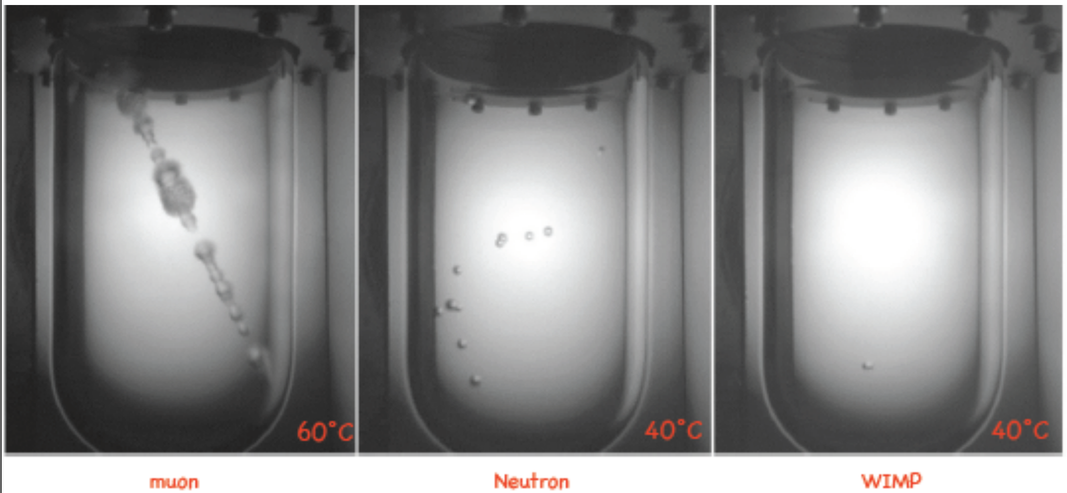


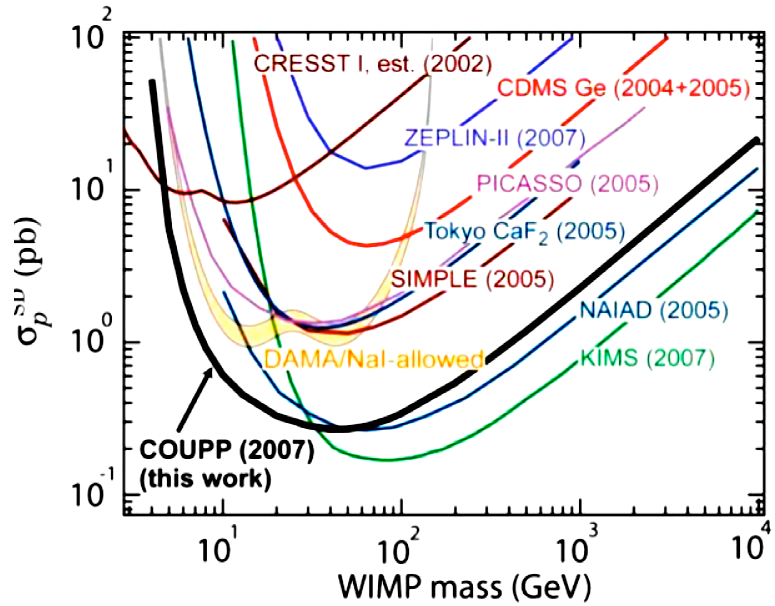


We need:
Rejection power of 10^8
OR
use of ^{39}Ar-depleted argon

P.Otyugova (UniZH)

The COUPP Experiment @ Fermilab



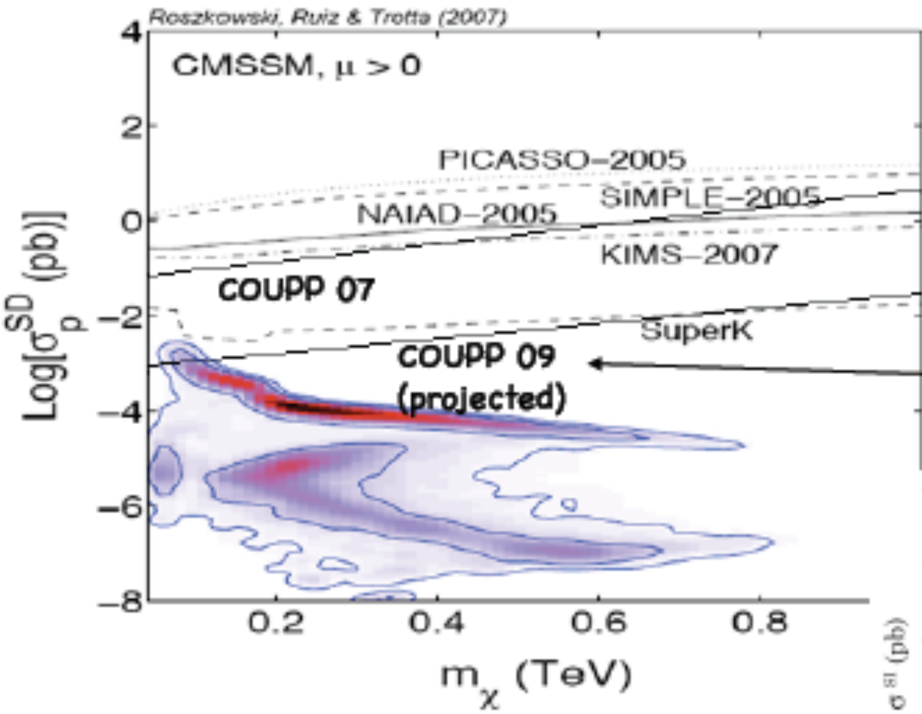


- COUPP approach to WIMP detection: detection of single bubbles induced by high dE/dx nuclear recoils in heavy liquid bubble chamber
- Insensitive to EM background. Large rejection factor for mips $>10^{10}$; High spatial granularity for additional n-rejection
- Scalability to large mass at low cost. Choice of three triggers:pressure, acoustic, motion (video)
- Excellent sensitivity to both SD and SI couplings; different target fluids
- With 2 kg chamber: 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

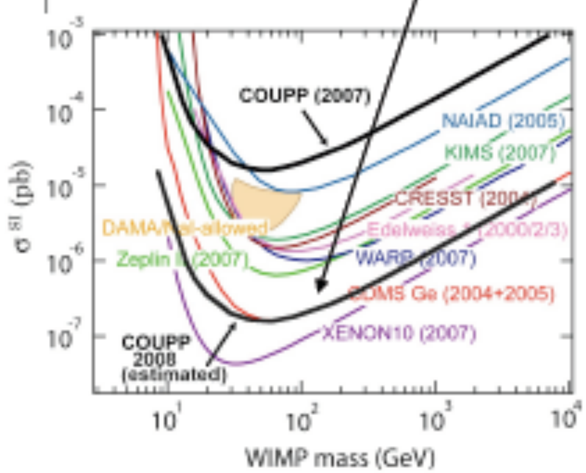
COUPP next step: 60 kg target mass

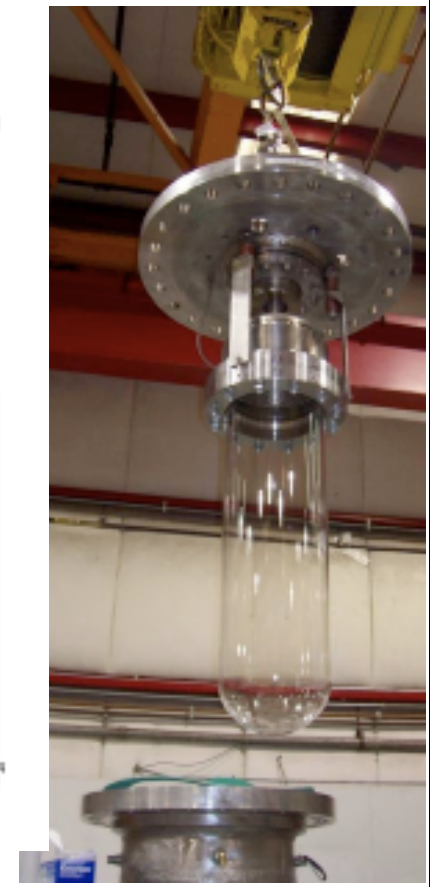
Physics Reach at Fermilab Site

Background goal for E-961: <1 event per kg per day

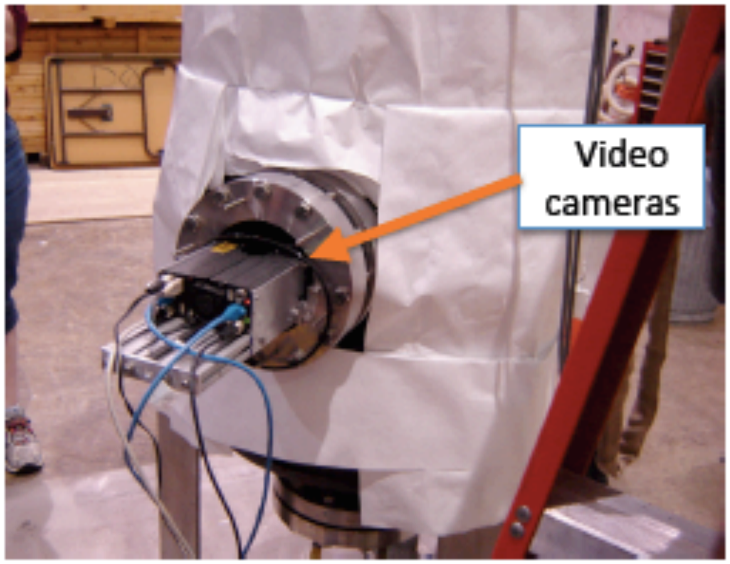


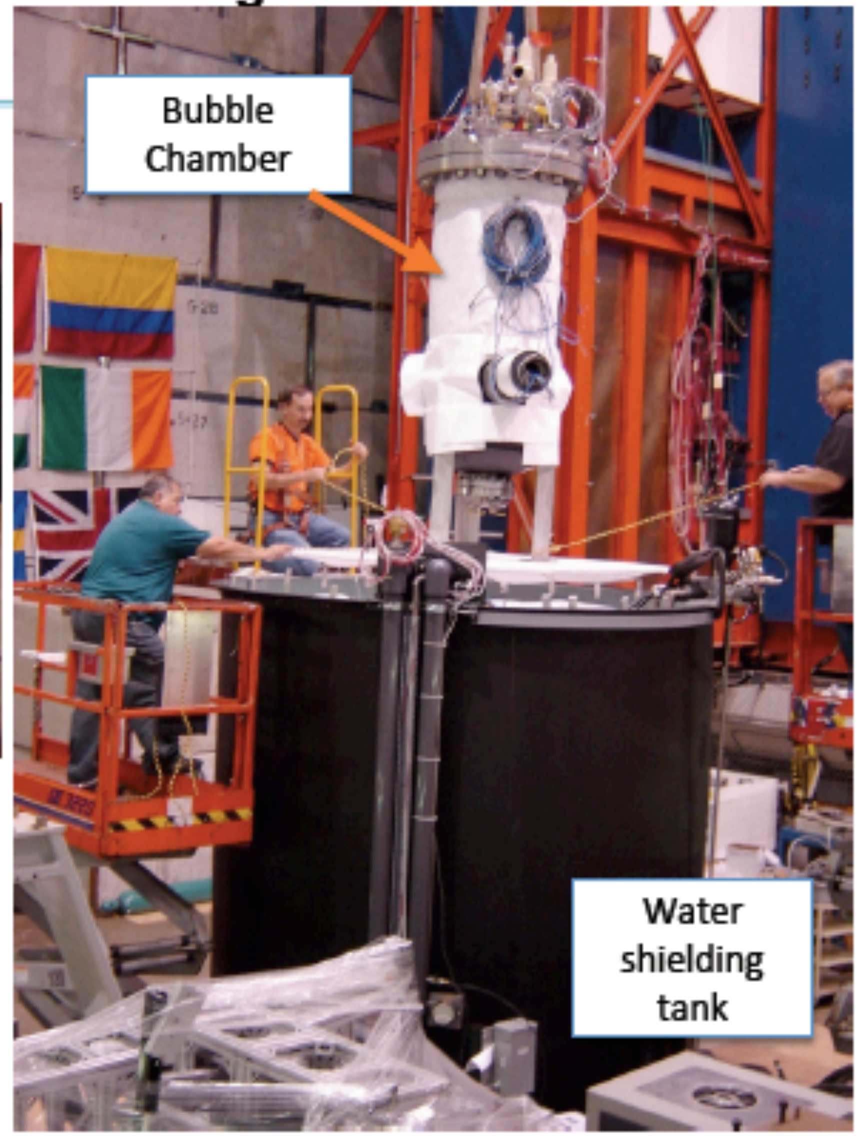
2009 goals: exploring SD favored region for the first time, and competitive SI limits.





COUPP future: 60-kg chamber above ground assembly, June, 2009

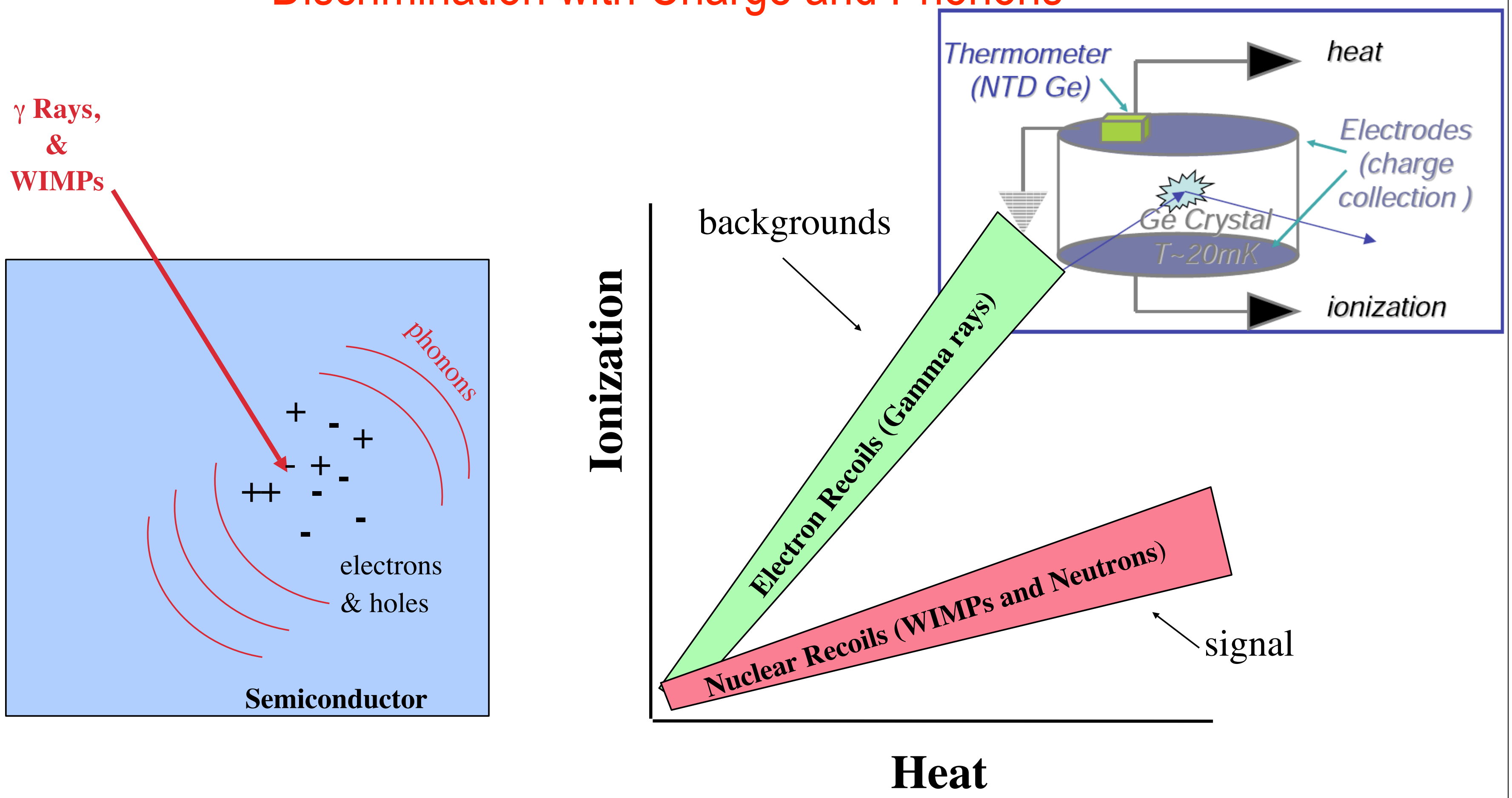




Sonnenschein TAUP2009

Cryogenic Detectors: CDMS and EDELWEISS

Discrimination with Charge and Phonons

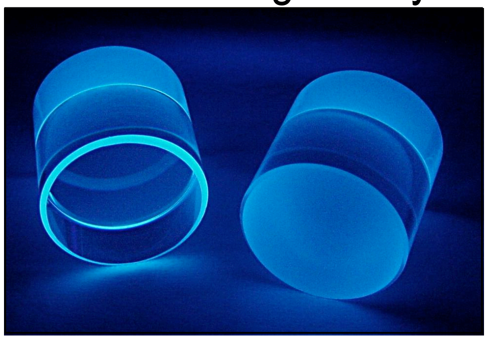


- Gamma and beta rays interact with electrons in target=> **more ionization.**
- WIMPs interact with nucleus, producing a nuclear recoil => **less ionization.**

Cryogenic Detectors: CRESST

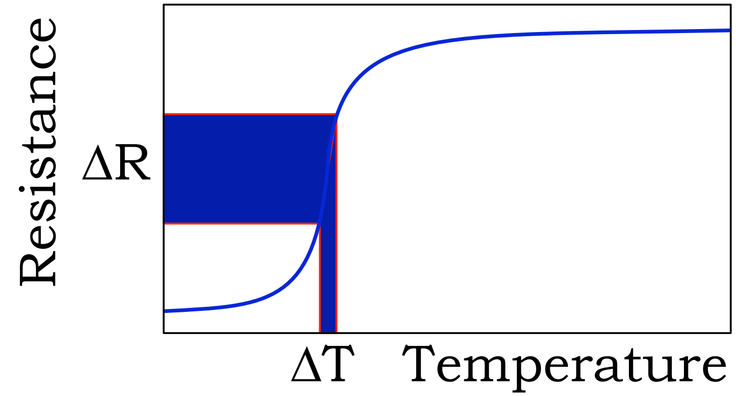
Discrimination with Light and Phonons

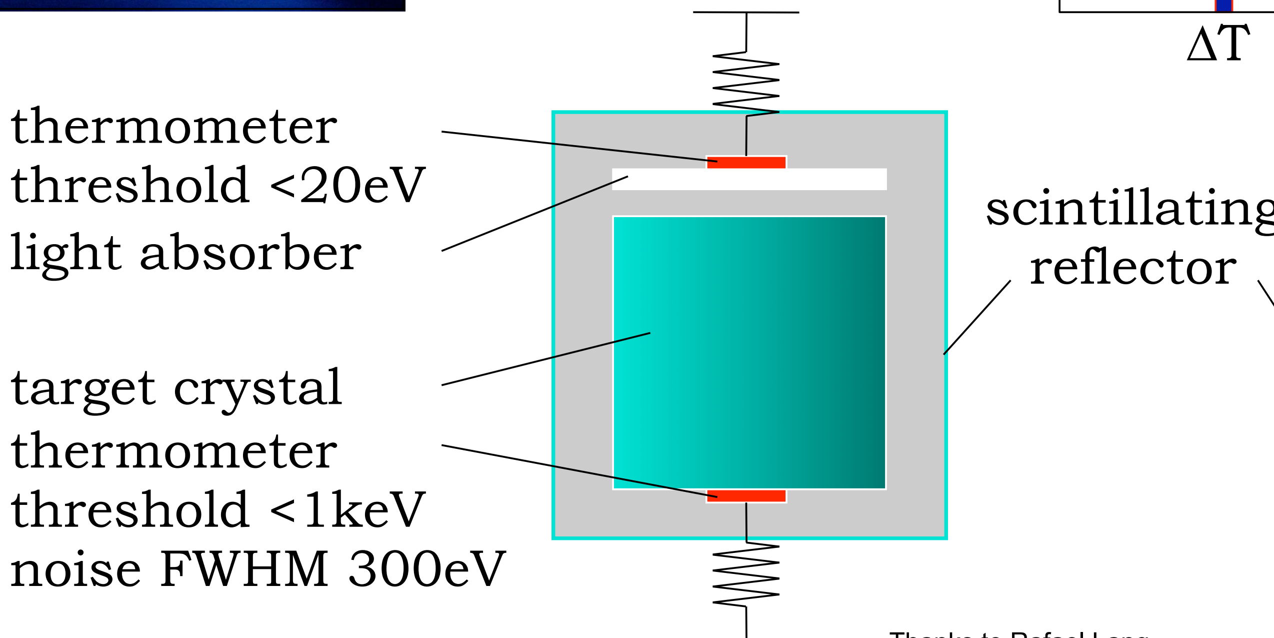
- Scintillating crystals
- ($CaWO_4$, $CaMoO_4$, $ZnWO_4$)
- → multi-target easy



$CaWO_4$,
h=40mm
∅=40mm
m=300g

- Superconducting Phase
- Transition Thermometers
- at T~15mK ± (μK)





Thanks to Rafael Lang

CDMSII @ Soudan

Dark Matter Search data since Oct '03

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

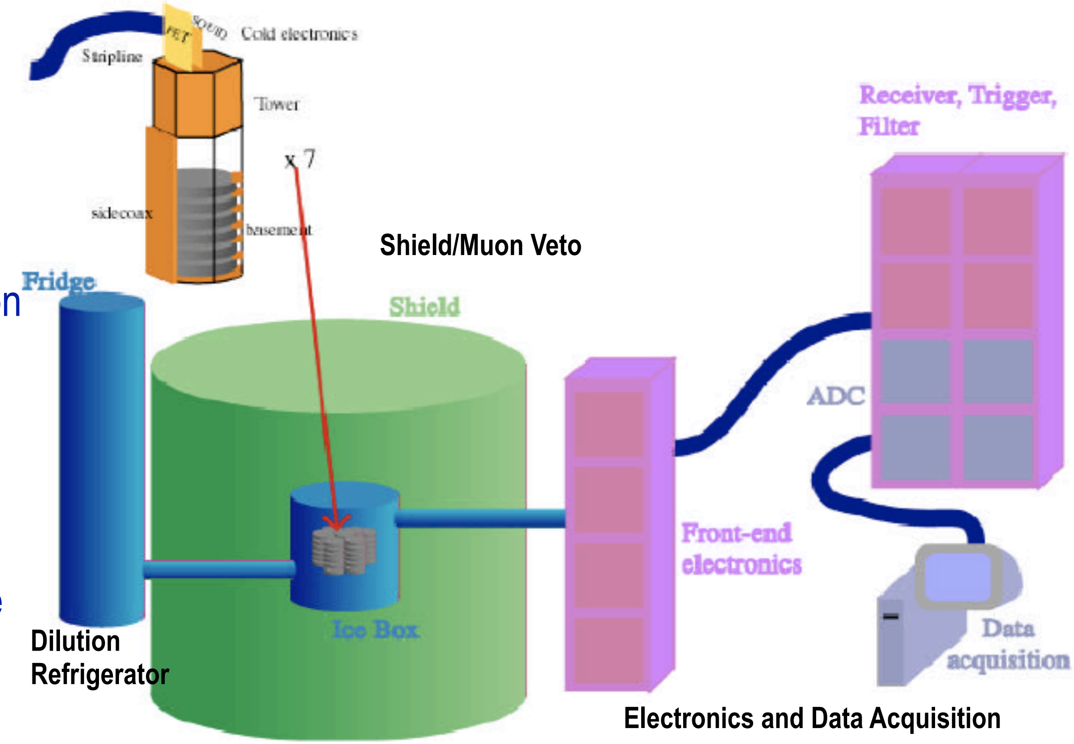
Cryogenic Detectors

- 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).

Cryogenic mK Experiments: near 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: 4×10^{-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: 5×10^{-45} cm^2 with 16 kg Ge

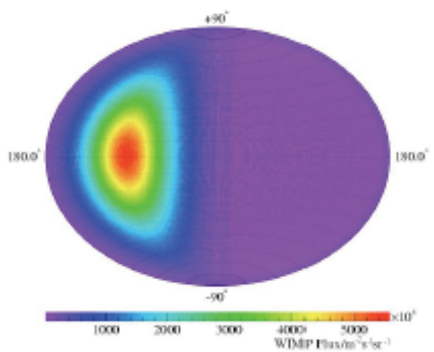
EURECA: joint effort for 100 kg-1t experiment in Europe

Goal: 7 SuperTowers at SNOLAB

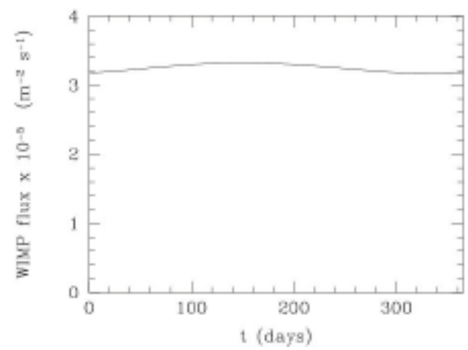
Directional Experiments

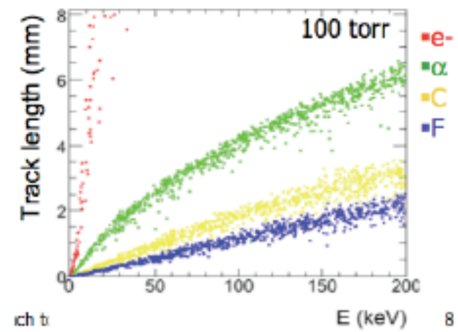
- WIMP events should globally come from Cygnus constellation direction. Strong forward/backward asymmetry
- Powerful signature: hard for background to mimic directional signal; order of 10 events sufficient

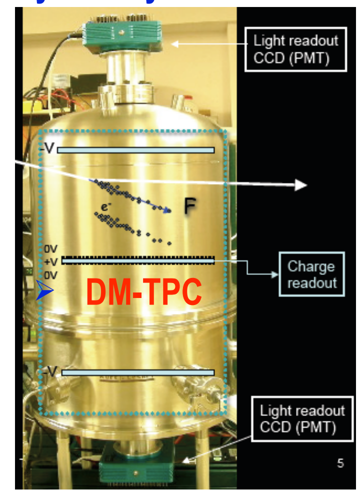
Directional signal



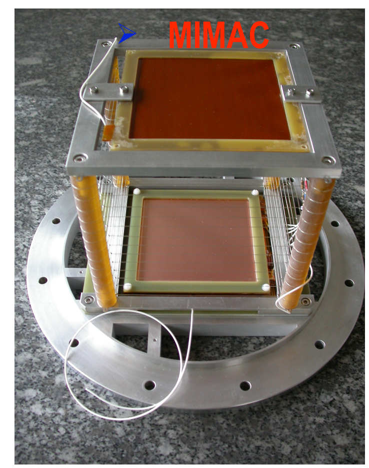
Annual modulation signal







- 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 in the coming decade very likely
- 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 2010.
- On the other hand, 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 and that is very exciting! 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. Ton scale experiments are technically feasible and will follow fast, if 100 kg phase is successful.
- A direct detection signal, from either or both SI and SD interactions, needs to be validated with more than one target and concept: current zoo of experiments vital for field. Directional experiments advancing at good pace. Will provide the ultimate “smoking gun” for DM signal