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Summer School in Cosmology

21 July - 1 August, 2008

Dark Matter
Lecture 4: Direct detection techniques and experiments, II

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Lecture 4: Direct detection techniques and experiments, II

July 24th, 2008

Laura Baudis, Universität Zürich

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- Liquid Noble Elements Experiments
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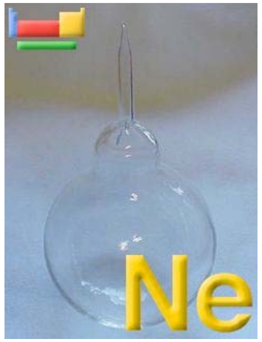
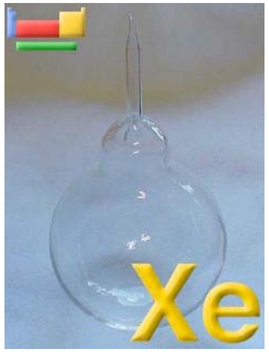
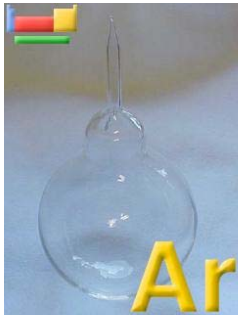
- Directional detectors:
  - ➡ DRIFT







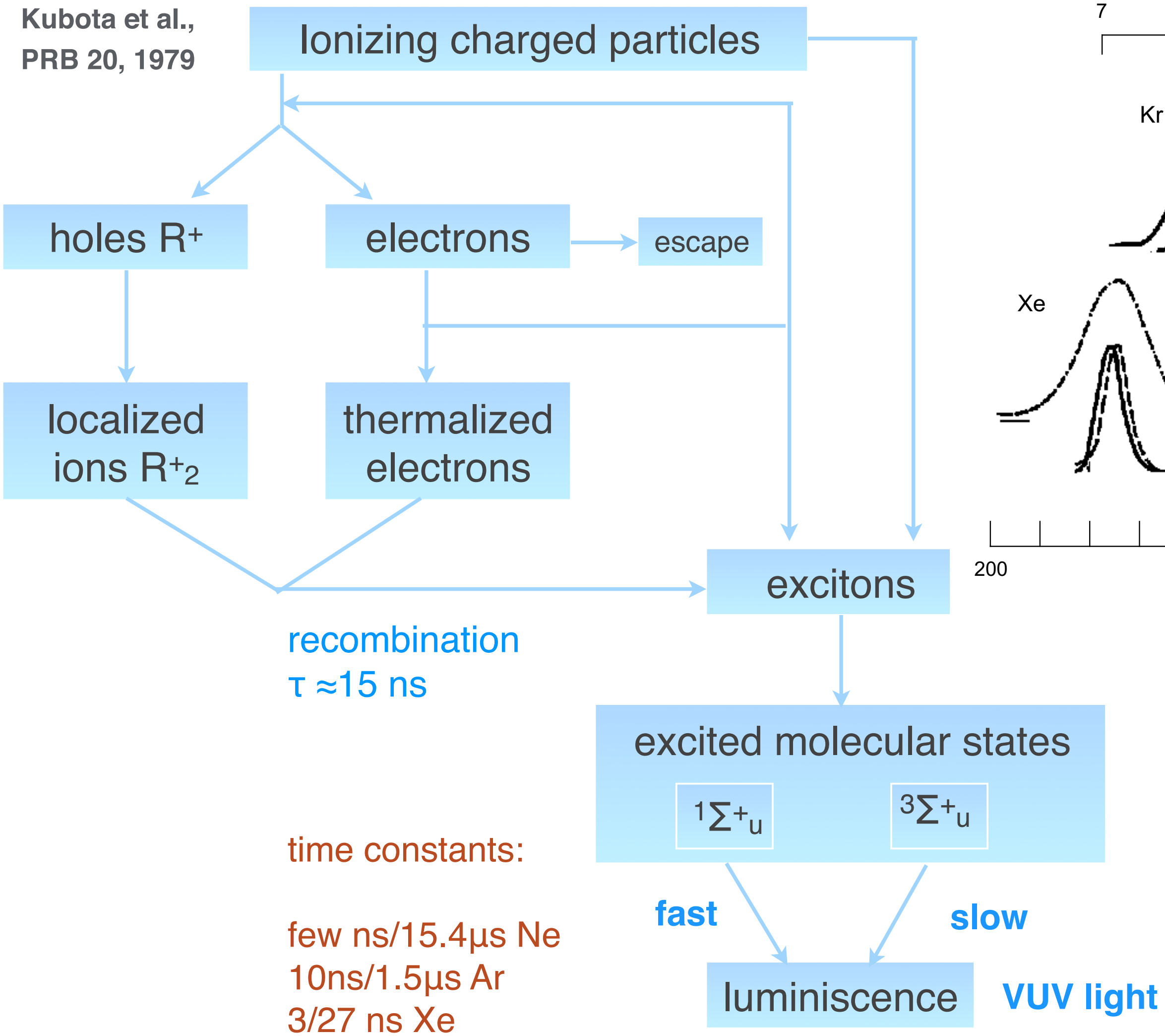
Cryogenic Noble Liquids: some properties

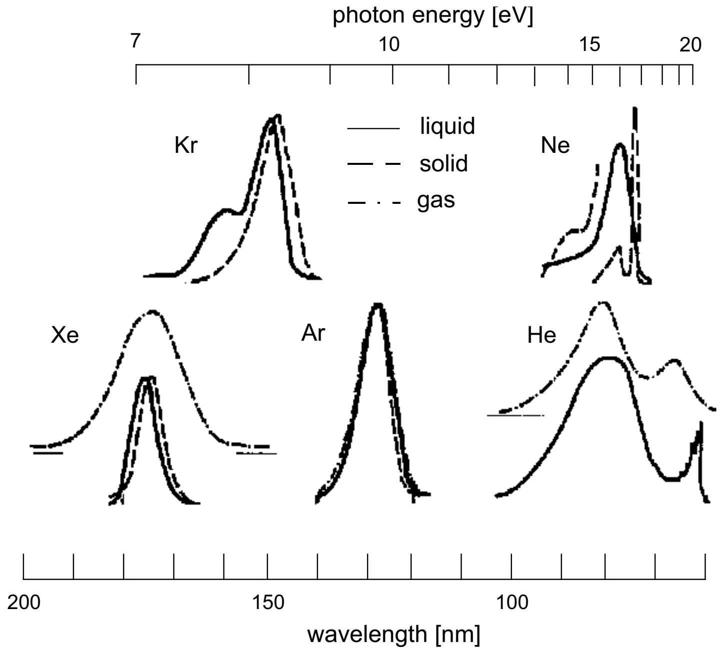
- Suitable materials for detection of ionizing tracks:
  - ➡ dense, homogeneous target and also detectors (scintillation and ionization)
  - ➡ do not attach electrons; inert not flammable, very good dielectrics
  - ➡ commercially easy to obtain and purify
- Large detector masses are feasible; self-shielding + good position resolution in TPC mode

Element	Z (A)	BP (T_b) at 1 atm [K]	liquid density at T_b [g/cc]	ionization [e^-/keV]	scintillation [photon/keV]
He	2 (4)	4.2	0.13	39	15
Ne	10 (20)	27.1	1.21	46	7
Ar	18 (40)	87.3	1.40	42	40
Kr	36 (84)	119.8	2.41	49	25
Xe	54 (131)	165.0	3.06	64	46

Charge and Light in Noble Liquids

Kubota et al.,
PRB 20, 1979

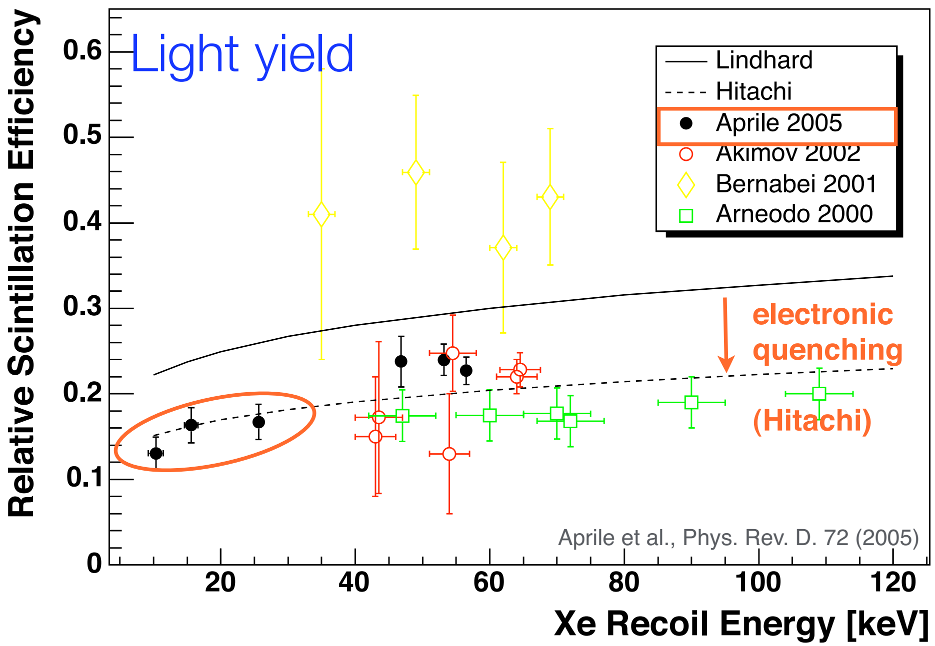




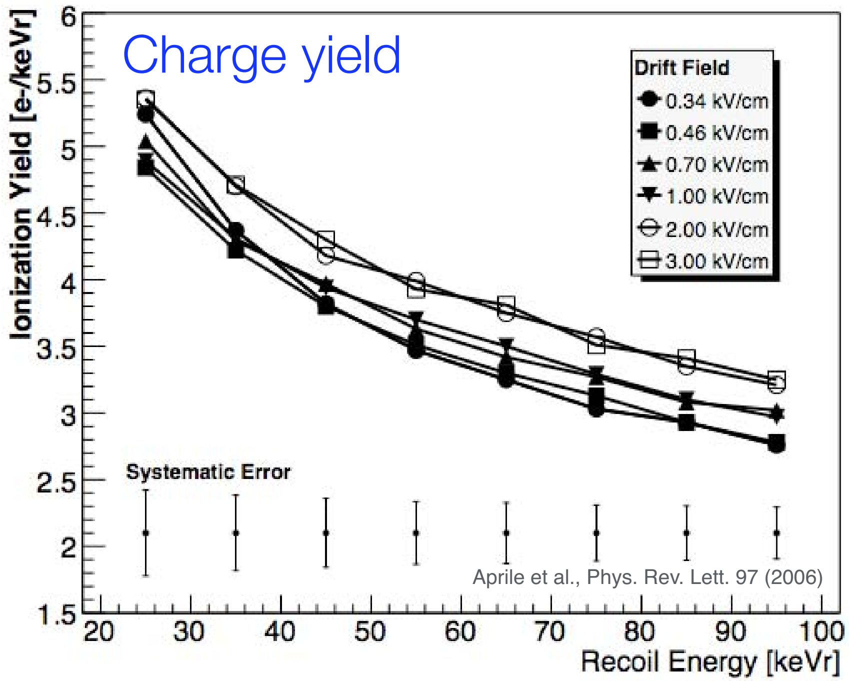
$$\lambda_{LNe} \sim 77.5\ nm$$
$$\lambda_{LAr} \sim 128\ nm$$
$$\lambda_{LXe} \sim 175\ nm$$

Light and Charge Yield in Noble Liquids

- the light and charge yield needs to be measured at **low nuclear recoil energies**
- **here an example: liquid xenon**



Data down to 10 keVr; yield: 13% - 20% from 10 keVr to 60 keVr. Good agreement with prediction by Hitachi (Astrop. Phys. 24, 2005) at low recoil energies



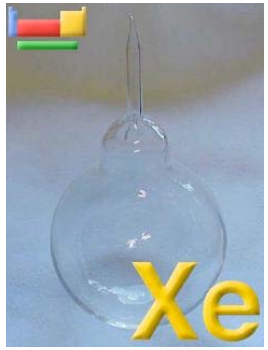
Weak dependence on electric field
Yield increases at low recoil energies

Existing Experiments and Proposed Projects

	Single Phase (liquid only) pulse shape discrimination (PSD)	**Double Phase (liquid and gas) PSD and Charge/Light**
Neon (A=20)	miniCLEAN (100 kg) CLEAN (10-100 t)	SIGN
Argon (A=40)	DEAP-I (7 kg) miniCLEAN (100 kg) CLEAN (10-100 t)	ArDM (1 ton) WARP (3.2 kg) WARP (140 kg)
Xenon (A=131)	ZEPLIN I XMASS (100 kg) XMASS (800 kg) XMASS (23 t)	ZEPLIN II + III (31 kg, 8 kg) XENON10, XENON100 LUX (300 kg), ELIXIR (1t)

- **Single phase:** e^--ion recombination occurs; singlet/triplet ratio is 10/1 for NR/ER
- **Double phase:** ionization and scintillation; electrons are drifted in ~ 1kV/cm E-field

Liquid Xenon Detectors: why Liquid Xenon?



Large A (~131) good for SI interactions, requires low energy threshold E_{th}

^{129}Xe (26.4%, spin 1/2) and ^{131}Xe (21.2%, spin 3/2) for SD interactions

No radioactive isotopes (^{85}Kr reduced to ppt levels, ^{136}Xe: $T_{1/2} > 10^{20}$ yr)

High stopping power (Z=54, ρ=3 g/cm^3) for compact, self-shielding geometry

Efficient and fast scintillator (yield ~ 80% NaI), transparent to its own light

Good ionization yield (W=15.6 eV: energy required to produce an e^--ion pair)

Modest quenching factor (QF) for nuclear recoils (QF ~ 0.2)

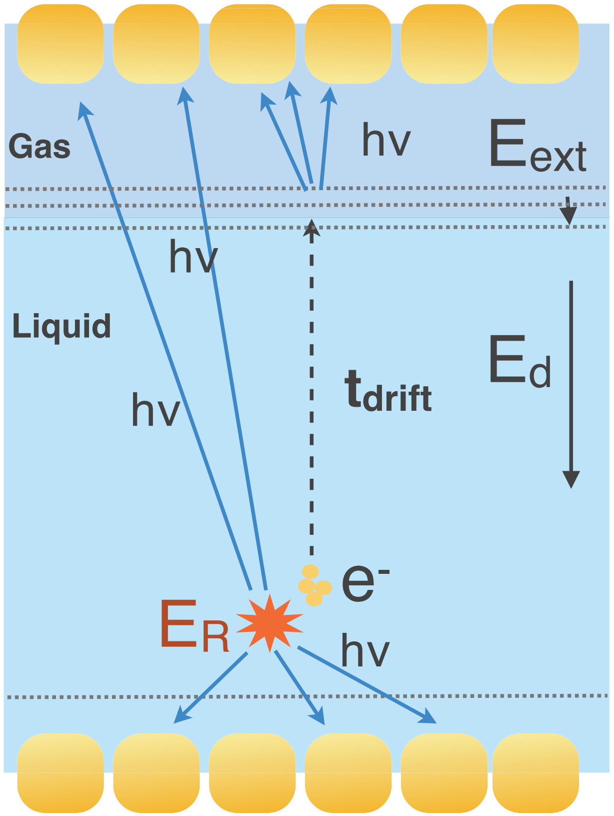
'Easy' cryogenics at ~ 165 K

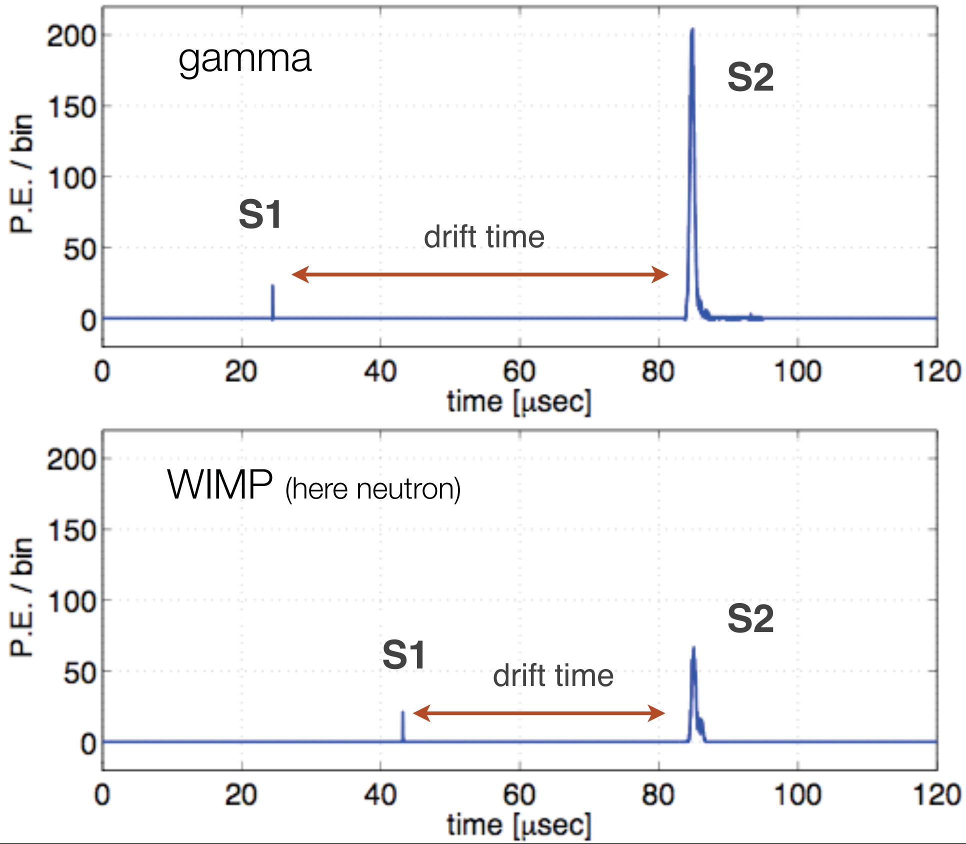
Background rejection: > 99.5% by simultaneous light and charge detection

3D event localization and LXe shelf-shielding => large, homogeneous detectors

The Double-Phase Detector Concept

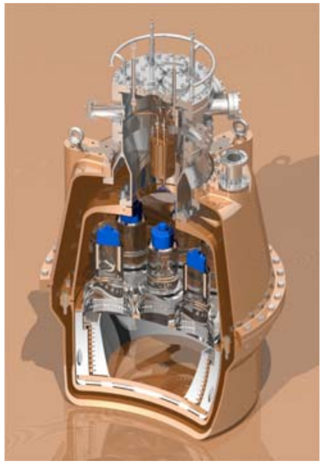
- **Prompt (S1) light signal** after interaction in active volume; charge is drifted, extracted into the gas phase and detected as **proportional light (S2)**
- **Challenge:** ultra-pure liquid + high drift field; efficient extraction + detection of e^-





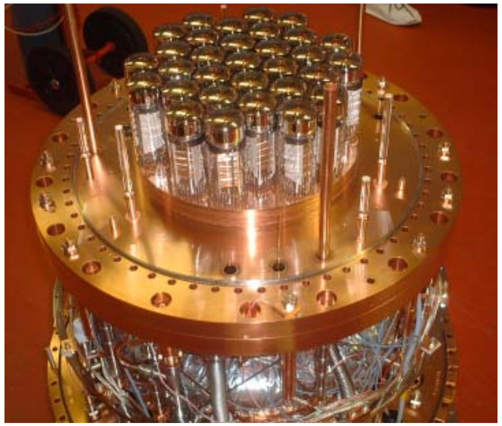
Two-phase (liquid/gas) Xenon Detectors

ZEPLIN II at Boulby/UK



31 kg (7.2 fiducial),
7 x 13 cm PMTs
for 1 t day raw data
29 events is WIMP
signal region, all
background

ZEPLIN III at Boulby/UK



8 kg LXe
31 x 2'' PMTs
WIMP search run
calibrations and
data analysis in
progress

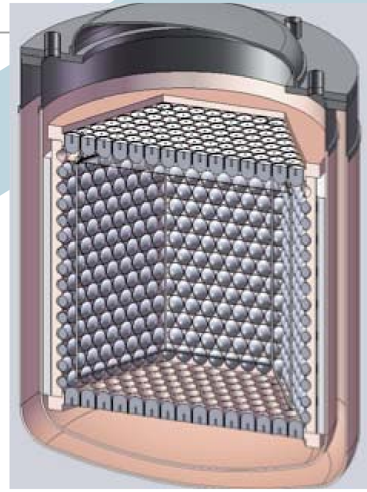
XENON10 at Gran Sasso

15 kg (5.4 fiducial),
89 2'' PMTs
136 kg d (after all cuts)
of WIMP search data, 10
events, all compatible
with background

The XENON Program

???

XENON1t



2009-2011 ?

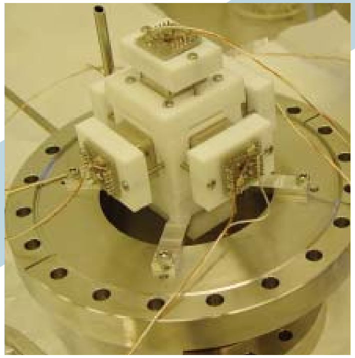
XENON100

in progress

XENON10

2006-2007

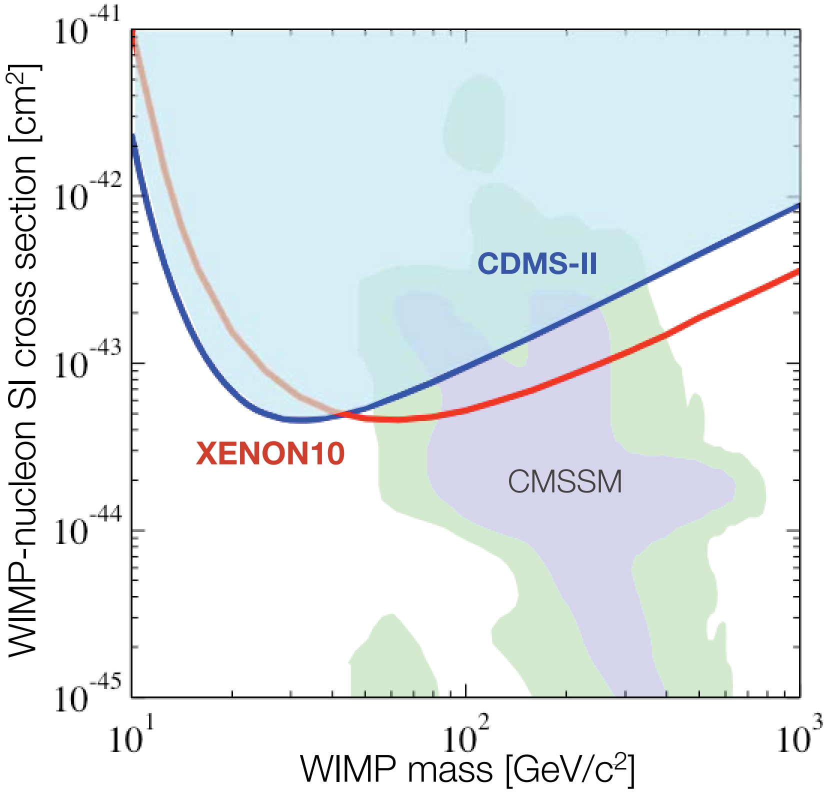
XENON R&D



ongoing

XENON10 Results for SI and SD Interactions

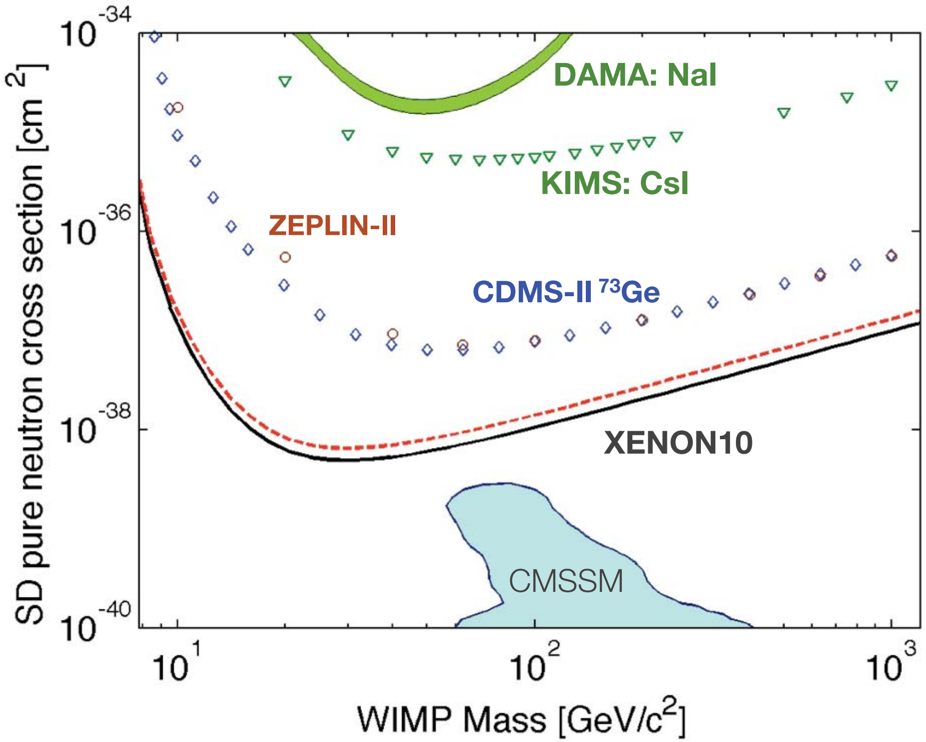
Spin-Independent WIMP interactions



Phys. Rev. Lett. **100**, 021303 (2008)

SD: pure neutron couplings

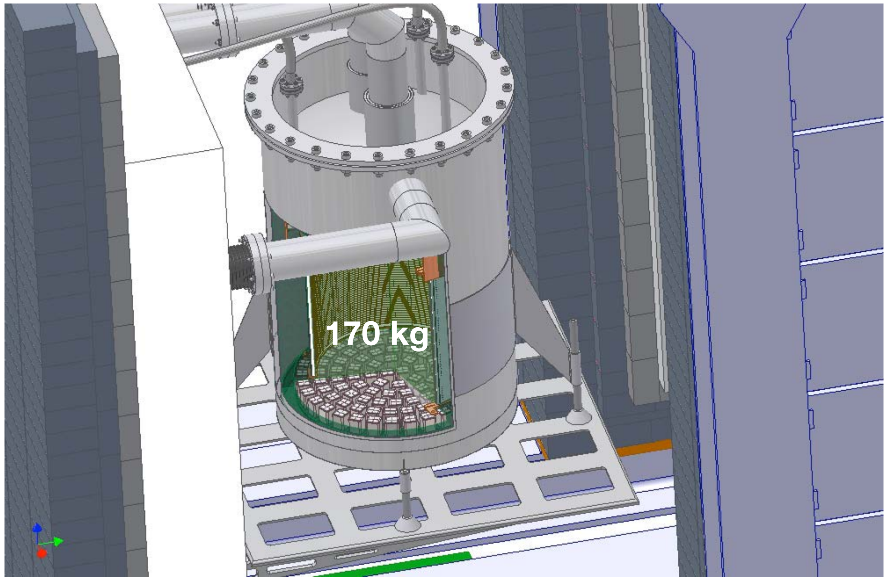
^{129}Xe, 26.4 %, spin 1/2, ^{131}Xe, 21.2%, spin 3/2



arXiv:0805.2939 (accepted in PRL)

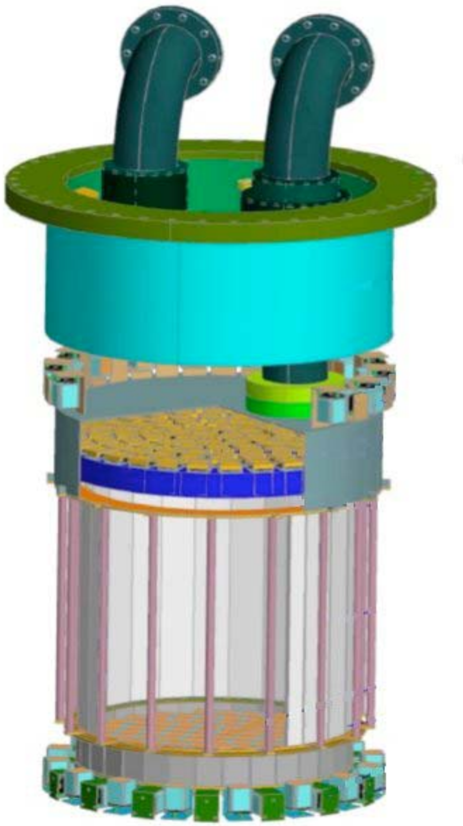
The XENON100 Experiment

- **Goals:**
  - ➡target mass of ~ 100 kg
  - ➡decrease backgrounds by x 100 (rel. to Xenon10)
  - \- through strong material selection + screening
  - \- active veto shield and detector design
- Status: under commissioning at LNGS



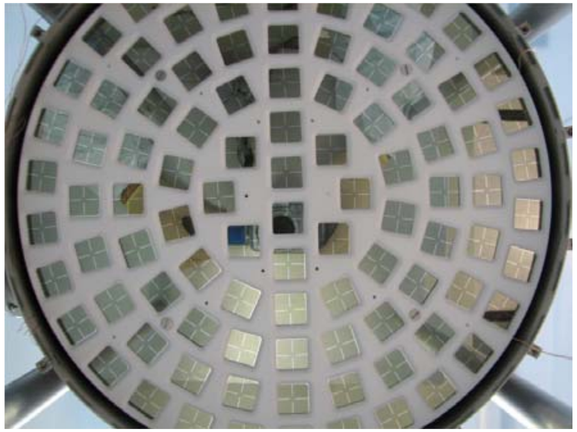
The XENON100 Time Projection Chamber

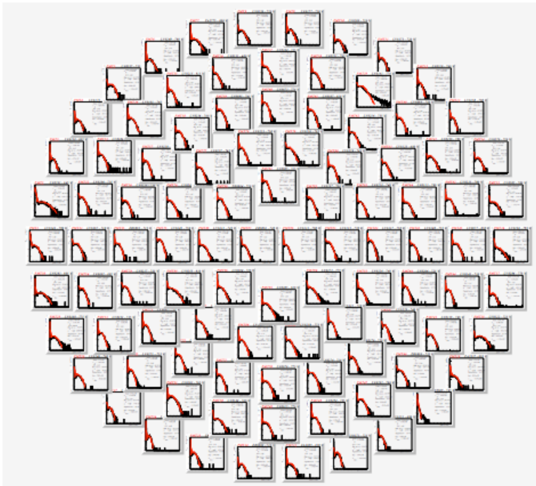
- TPC (total of 170 kg LXe) with active veto (100 kg LXe) installed underground since February 2008
- Xe purified to ppt ^{85}Kr-levels ($T_{1/2}$ = 10.7 y, β^- 678 keV); expected to start WIMP search run in fall 08



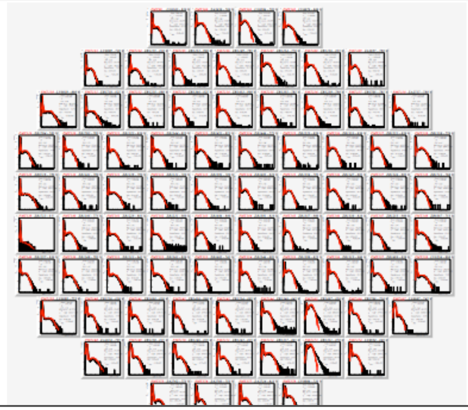
XENON100 PMTs

- 242 (Hamamatsu R8520) 1”x1”, low radioactivity PMTs; 80 with high QE of 33%
- 98 top: for good fiducial volume cut efficiency
- 80 bottom: for optimal S1 collection efficiency (thus low threshold); 64 in active LXe shield
- PMT gain calibration with blue LEDs; the SPE response is measured



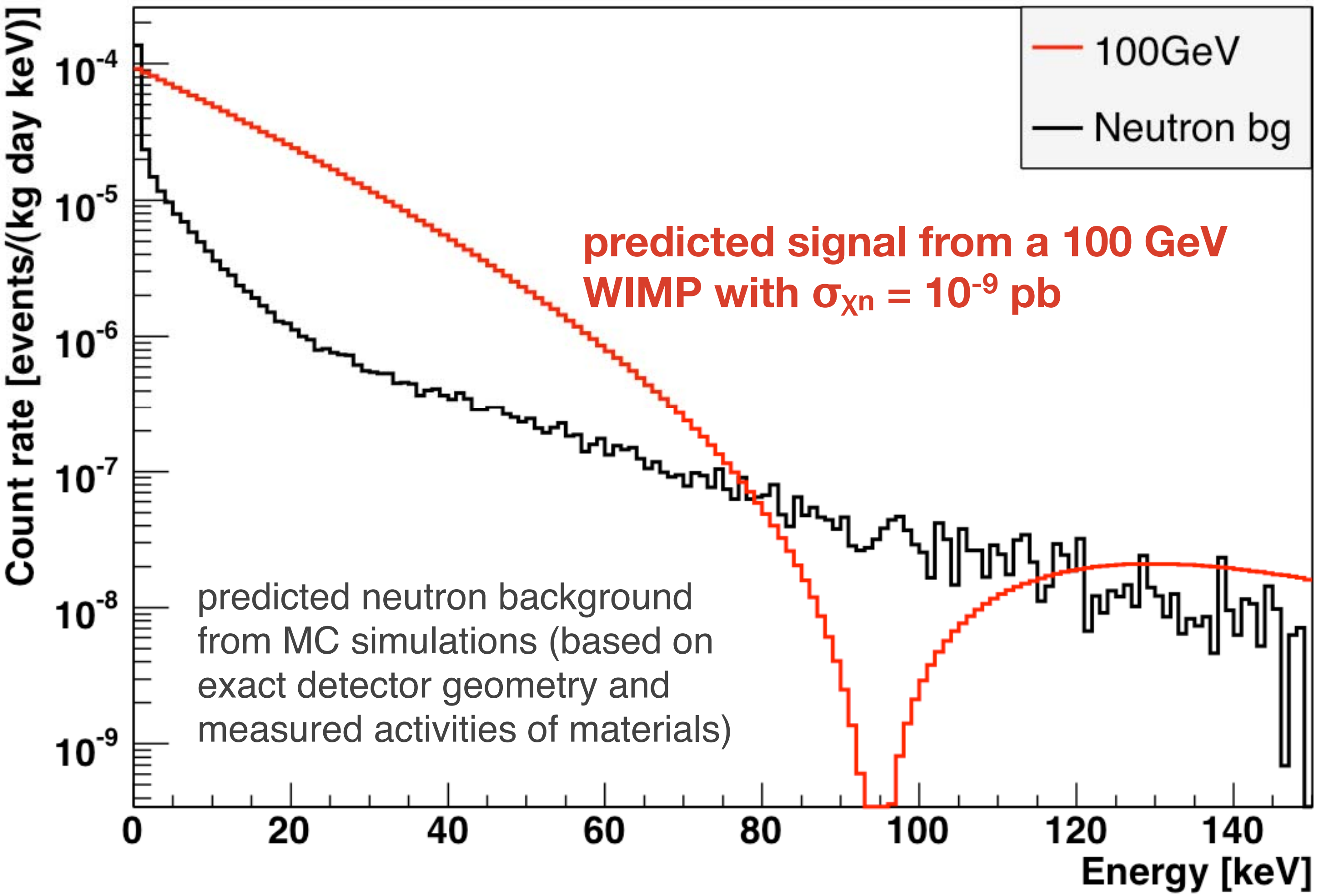


top PMT array
(gain equalized to $2x10^6$)



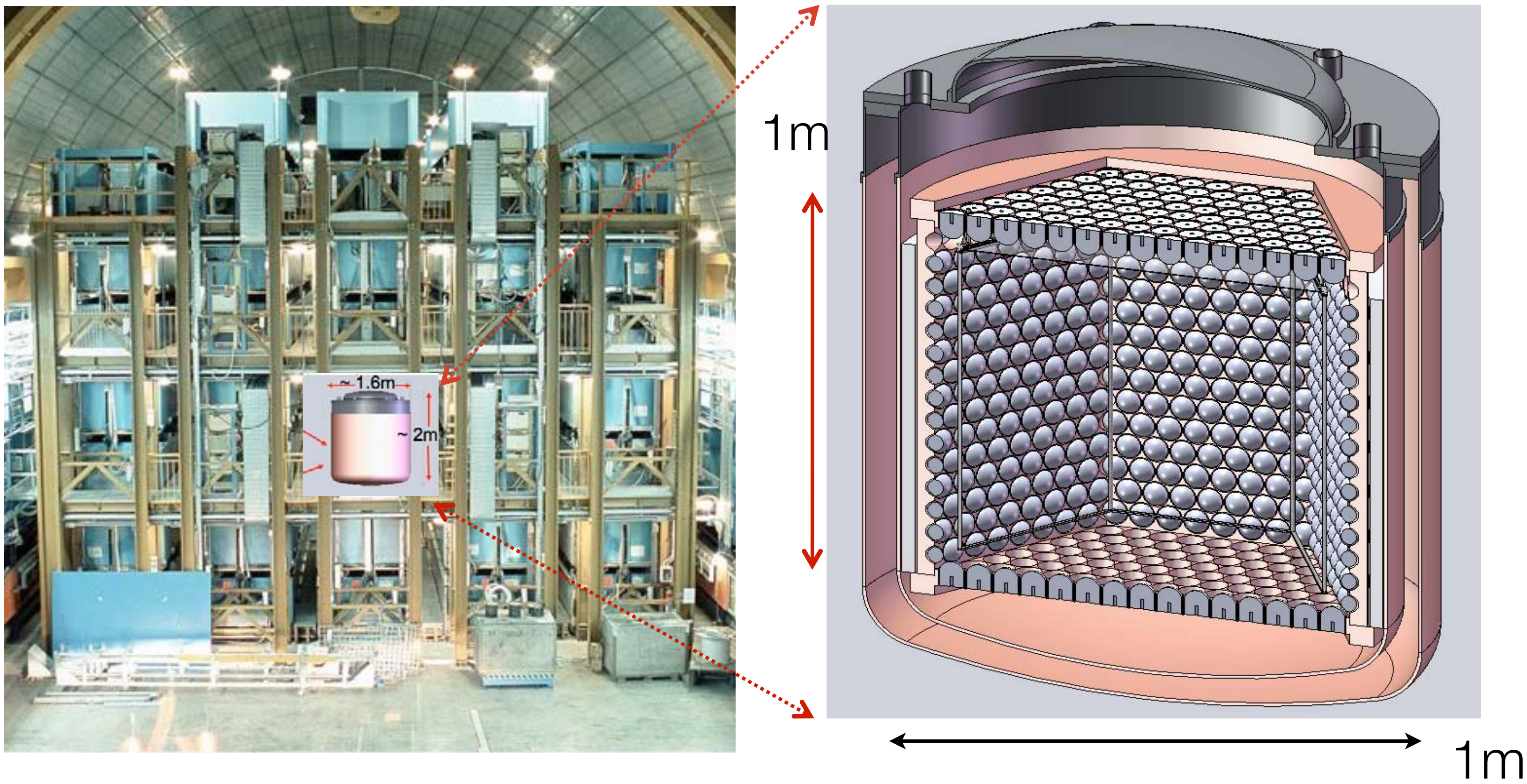
bottom PMT array
(gain equalized to $2x10^6$)

XENON100 Neutron BG and WIMP Signal



Next Phase: XENON1t

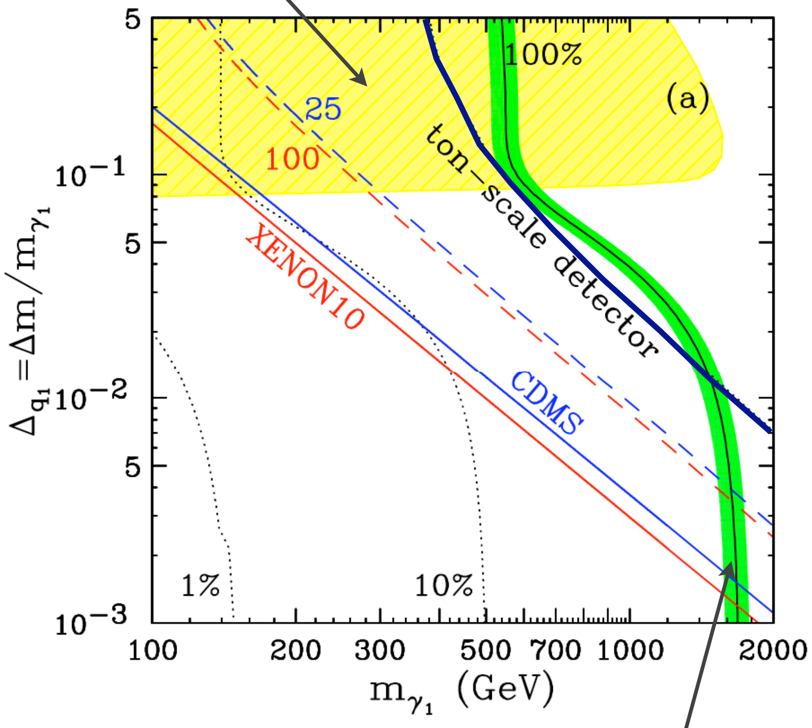
- Studies are in progress for 3 t (1t fiducial) LXe detector
- Possible location: inside a supernova neutrino detector (LVD) at the Gran Sasso Laboratory
    - ➡ active, ~ 4π veto for μ-induced neutrons



Ton Scale Detector: Predicted Sensitivity

UED

LHC reach in 4l+$\not{E}_T$ channel

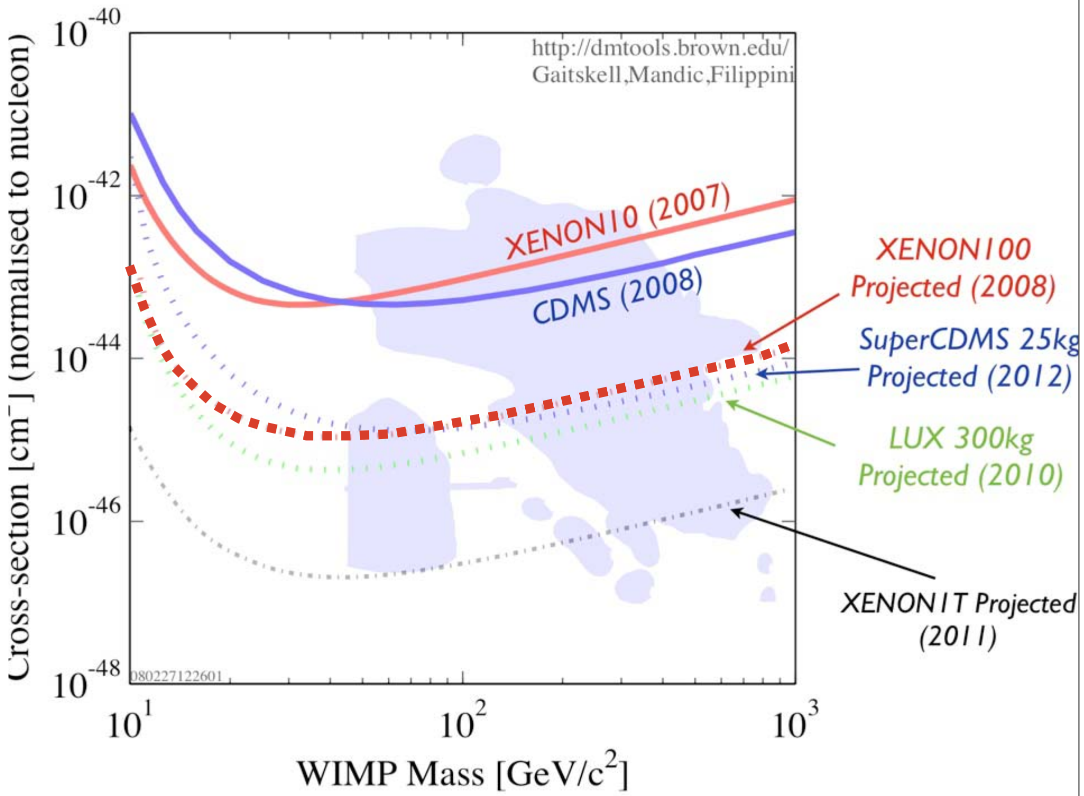


arXiv:0805.4210

WMAP5 region

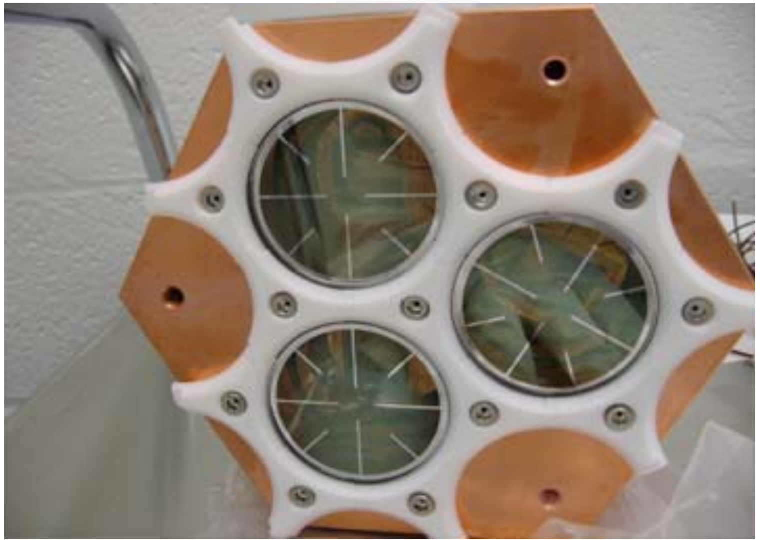
(WIMPs are 100% of the dark matter)

SUSY



The LUX Experiment

- 300 kg dual phase LXe TPC (100 kg fiducial), with 122 PMTs in large water shield with muon veto
- 50 kg LXe prototype with 4 R8778 PMTs being assembled and tested at CWRU
- full detector to be installed at Homestake Davis Cavern, 4850 ft in 2008-2009 (in 8 m ∅ water tank)
- WIMP sensitivity goal: 7×10^{-10} pb after 10 months

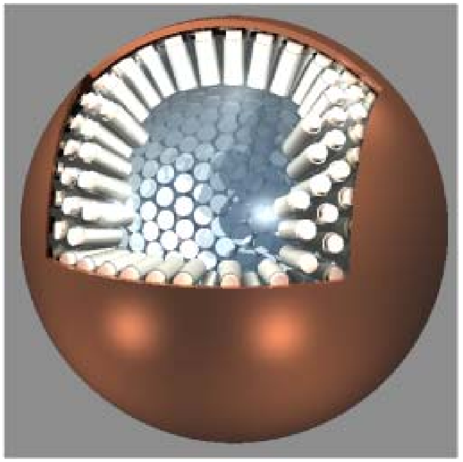


Single-phase Xenon: XMASS

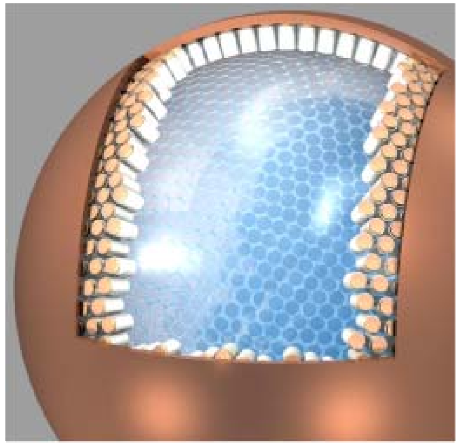
- 100 kg (3 kg fiducial mass) prototype operated (52 2” Hamamatsu R8778 PMTs)
    - the PMT coverage was limited, thus also the position reconstruction of edge events
- **next step:** 800 kg with 812 PMTs (67% photo coverage)
    - basic performance confirmed with prototype
    - vertex reconstruction, self-shielding, BG level studied with MCs
- **detector is being designed, excavations started**

S. Moriyama, KEKPH07, March 07

100 kg (3 kg fiducial)



800 kg (100 kg fiducial)

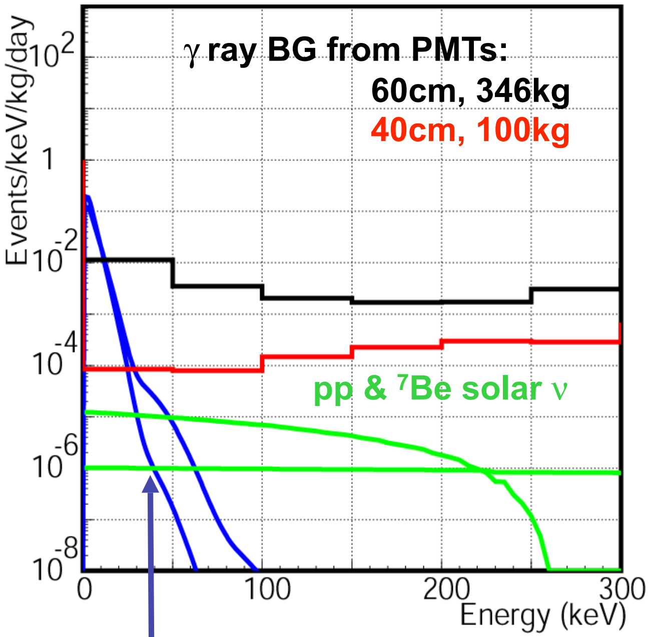


23 t (10 t fiducial)

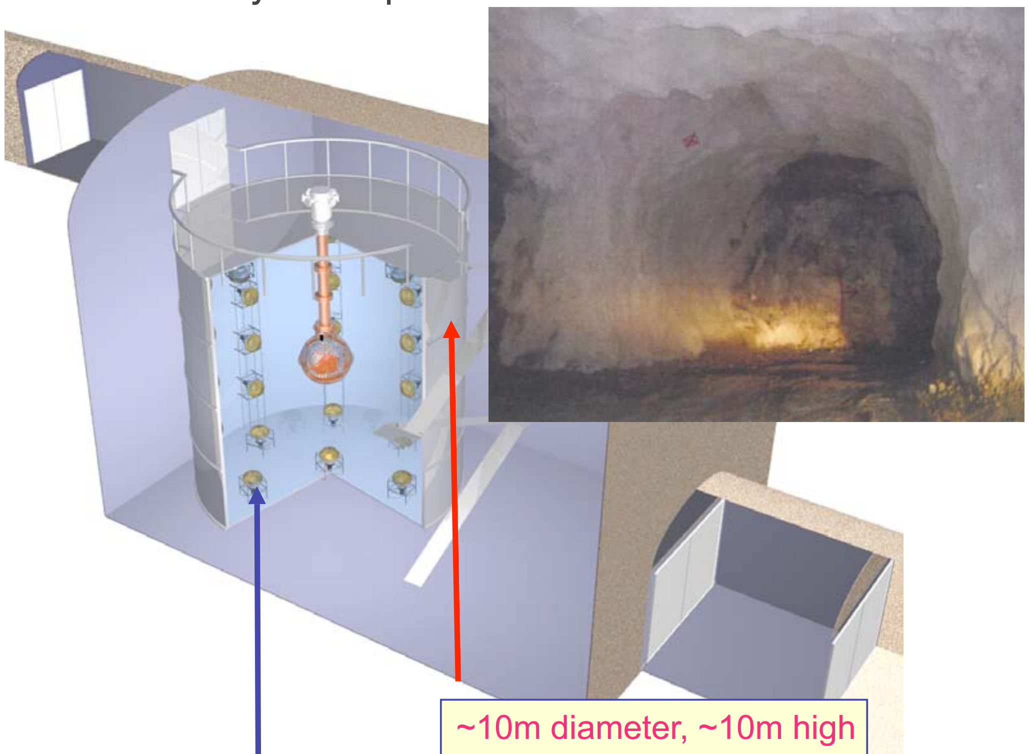
XMASS: BG and expected signal

Active and passive water shield in new experimental hall at KAMIOKA - almost ready
Construction of 10 m x 10 m water tank will start this summer

Expected WIMP sensitivity: 1×10^{-45} cm^2 for 0.5 ton × year exposure



Expected dark matter signal
(assuming 10^{-42} cm^2, Q.F.=0.2, Mχ=50,100GeV)



~10m diameter, ~10m high pure water tank.

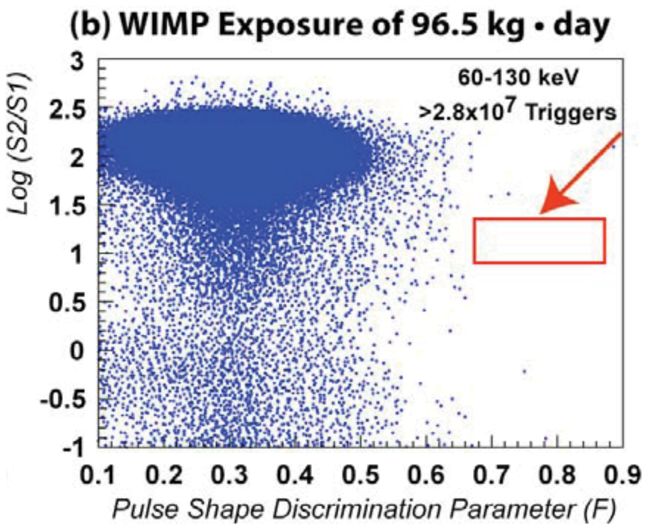
20-inch PMTs for veto counter.

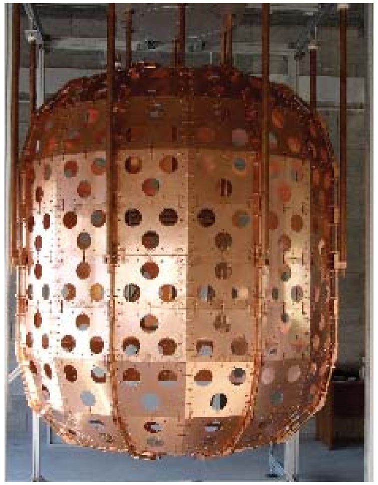
M. Nakahata, DARK2007, Sept 07
M. Yamashita, July 2008

Two-phase Argon Detectors

WARP at LNGS

3.2 kg LAr operated at LNGS; results from zero events > 55 keVr

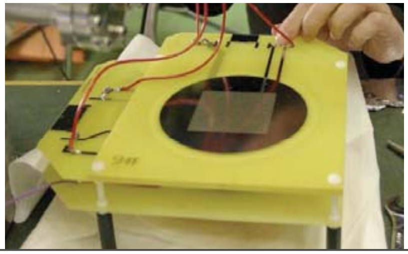




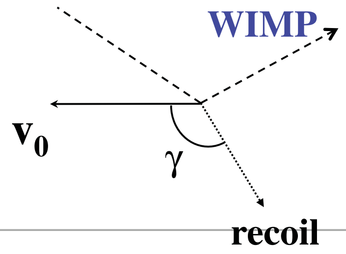
140 kg LAr, 41 3” PMTs under construction
active LAr shield: ~ 8t, viewed by 300 PMTs

ArDM at CERN

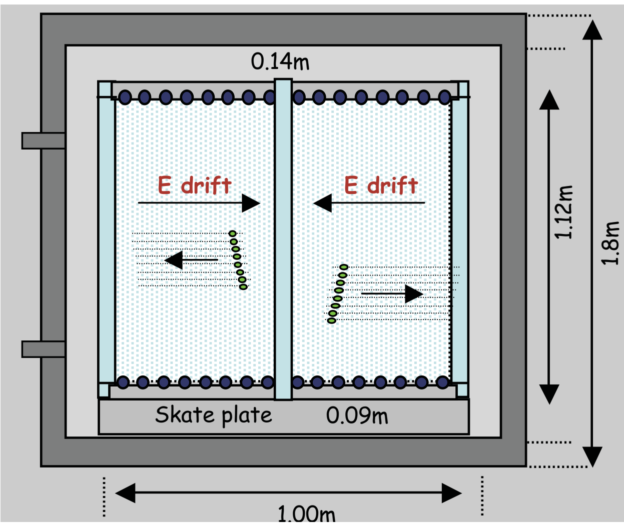
1 t LAr prototype under construction
direct electron readout via LEMs (thick macroscopic GEM)
S1 with 14 x 8” PMTs

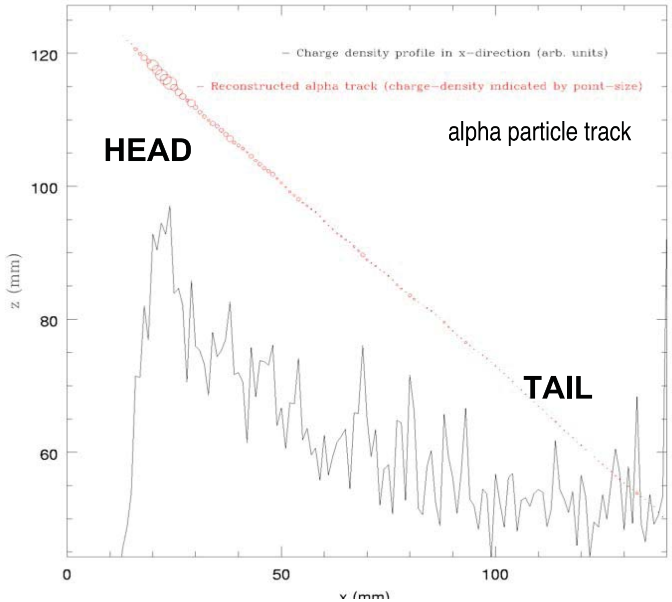


Directional Detector: DRIFT



- **Negative ion (CS_2) TPC**: 1 m^3 40 Torr CS_2 gas (0.17 kg); 2 mm pitch anode + crossed MWPC grid->2D
- NR discrimination via track morphology in gas (gamma misidentification probability < 5 x 10^{-6})
- **3D track reconstruction** for recoil direction: find head-tail of recoil based on dE/dx
- DRIFT IIa operated at Boulby in 2005: background from Rn emanation of detector components (recoiling nuclei from alpha-decays on cathode wires); 6 kd-d of data being analyzed
- **DRIFT IIb: installed in 2006/07, new run with strongly reduced Rn backgrounds**
- **WIMP Telescope!**





Summary and Conclusions

- Strong evidence for Cold Dark Matter (galaxies, clusters, LSS, CMB, etc)
- Cold Dark Matter: likely new, long-lived particles produced in the early Universe
- Neutral, massive and weakly interacting particles are independently predicted by physics beyond the standard model, needed to stabilize the weak scale
- Dark matter particles of galactic origin can elastically scatter from nuclei in ultra-low background, low energy threshold terrestrial detectors
- The energy of the recoiling nucleus is transformed into a charge, light or phonon signal and could be detected with ultra-sensitive devices operated in underground laboratories
- A possible signal has to be consistent with a series of predicted ‘signatures’ in order to qualify as WIMP dark matter
- So far there is one claim for a signal, not confirmed by other, independent experiments
- Existing experiments can probe WIMP-nucleon cross sections down to ~ 10^{-7} pb
- Experiments under construction and future, ton-scale detectors should probe most of the theoretically interesting parameter space

End

Cryogenic Noble Liquids: some challenges

- Cryogenics: efficient, reliable and cost effective cooling systems
- Detector materials: compatible with low-radioactivity and purity requirements
- Intrinsic radioactivity: ^{39}Ar and ^{42}Ar in LAr, ^{85}Kr in LXe
- **Light detection:**
  - ➡ efficient VUV PMTs, directly coupled to liquid (low T and high P capability, high purity), effective VUV reflectors
  - ➡ light can be absorbed by H_2O and O: continuous purification
- **Charge detection:**
  - ➡ requires << 1ppb (O_2 equivalent) for e^--lifetime > 1 ms (commercial purifiers and continuous circulation)
  - ➡ electric fields ≥ 1 kV/cm required for maximum yield for MIPs; for alphas and NRs the field dependence is much weaker, challenge to detect a small charge in presence of HV

The XENON100 Shield and Status

- Shielding modifications: cryogenics, feed-throughs, cables etc outside shield (+ 5 cm Cu)
- Detector is filled with LXe; calibration runs in progress.
- Plan to start WIMP search: ~ fall 2008