WIMP Dark Matter Searches with Liquid Xenon and Liquid Argon Detectors

Elena Aprile
Columbia University

TeVPA08
Beijing, September 27, 2008

Principle of Direct Detection

- Elastic collisions with nuclei
- The recoil energy is:

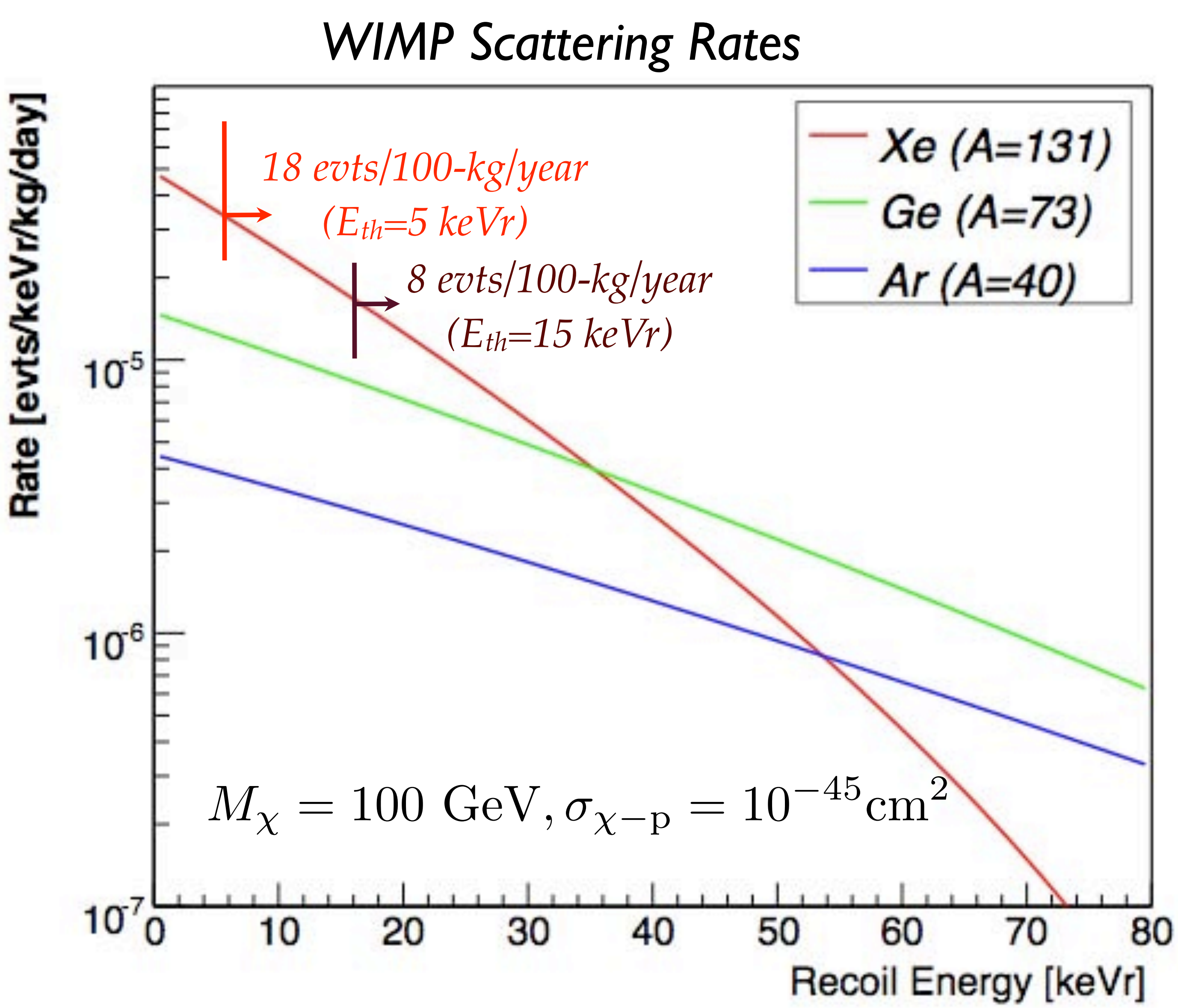
$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1 - \cos\theta) \leq 50\ keV$$

- and the expected rate:

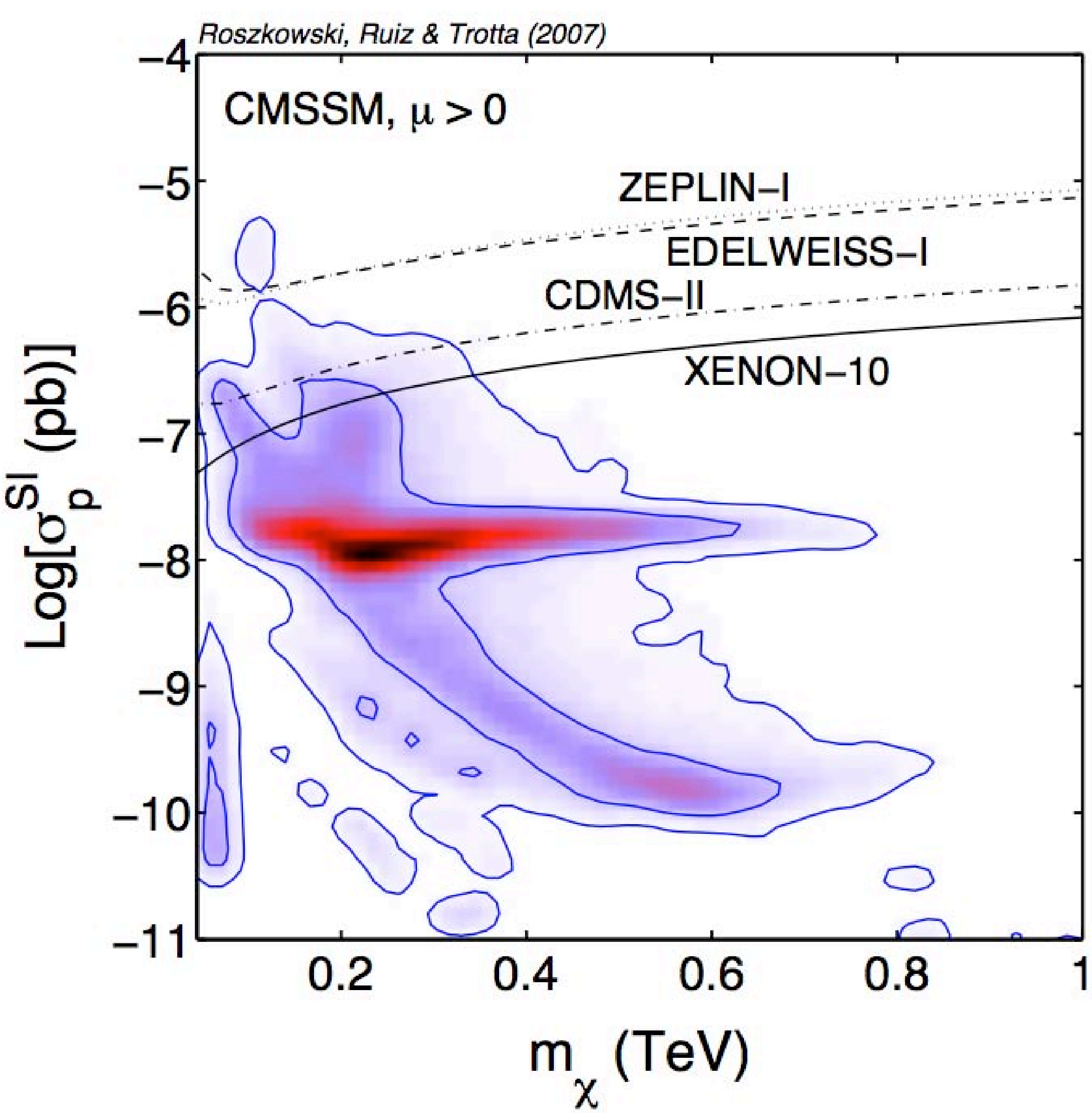
$$R \propto N \frac{\rho_\chi}{m_\chi} \langle \sigma_{\chi N} \rangle \qquad \mu = \frac{m_\chi m_N}{m_\chi + m_N}$$

N = number of target nuclei in detector
ρ_χ = local WIMP density, m_χ = WIMP mass
$\langle\sigma_{\chi N}\rangle$ = scattering cross section

Predicted Rates in Different Targets



Cross sections (normalized to nucleons)



Challenges for Dark Matter Direct Detection

- ➡ *large mass (ton scale)*
- ➡ *low energy threshold (a few keV)*
- ➡ *background suppression*
  - ➡ *deep underground*
  - ➡ *passive/active shielding*
  - ➡ *low intrinsic radioactivity*
  - ➡ *gamma background discrimination*

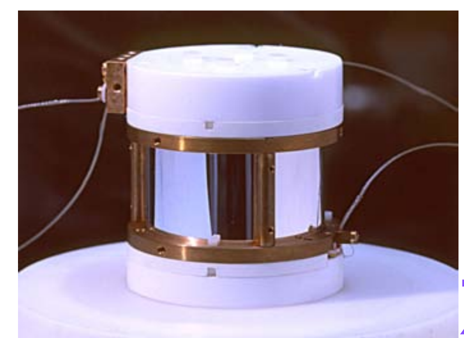
Direct Detection Experiments

COUPP,
PICASSO

Phonons

CDMS
EDELWEISS

Ge, Si



CRESST
ROSEBUD

$CaWO_4$, BGO
$ZnWO_4$, Al_2O_3 ..

E_R

e-h, e-i

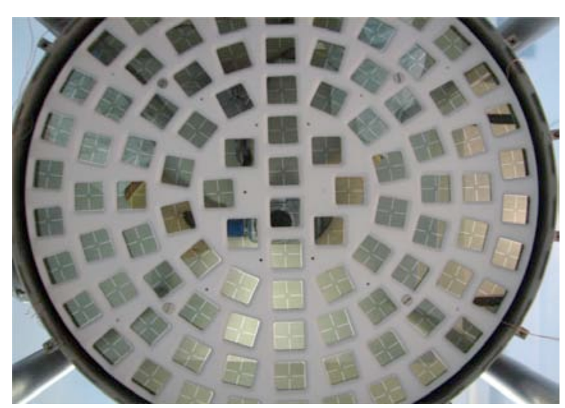
Photons

DAMA/LIBRA,
KIMS, ANAIS,
XMASS, CLEAN

NaI, CsI, Xe, Ar

DRIFT, DM-TPC,
COUPP
NEWAGE, MIMAC

Ge, CS_2, C_3F_8, He3



ZEPLIN, XENON,
WArP, ArDM

Xe, Ar

World Wide Experiments for Dark Matter Direct Detection

The Noble Liquids Revolution

Noble liquids are relatively inexpensive, easy to obtain, and dense

Easily purified
- most impurities freeze out
- low surface binding
- purification easiest for colder liquids

Ionization electrons and scintillation photons provide dual and complementary information on particle energy and ID plus 3D localization when used in TPC

- High ionization (W_{LXe}= 15.6 eV and W_{LAr}= 23.6 eV)
- Very high Scintillation yield (~ 40,000 photons/MeV)
- Transparent to their own scintillation
- modest quenching factors for nuclear recoils
- high electron mobility, low e-diffusion

Well suited for large, homogeneous targets and detectors

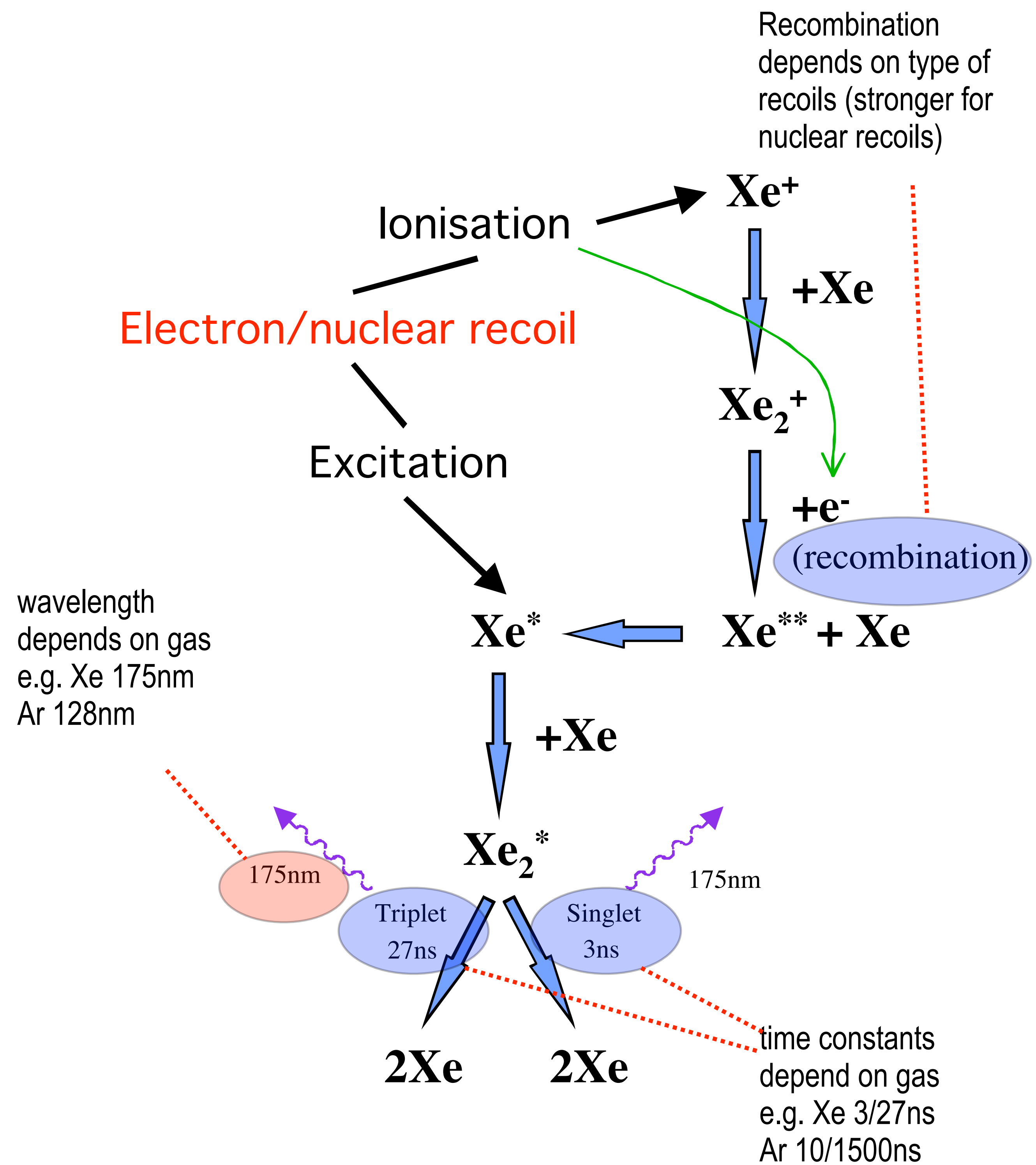
Liquified Noble Gases: Basic Properties

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

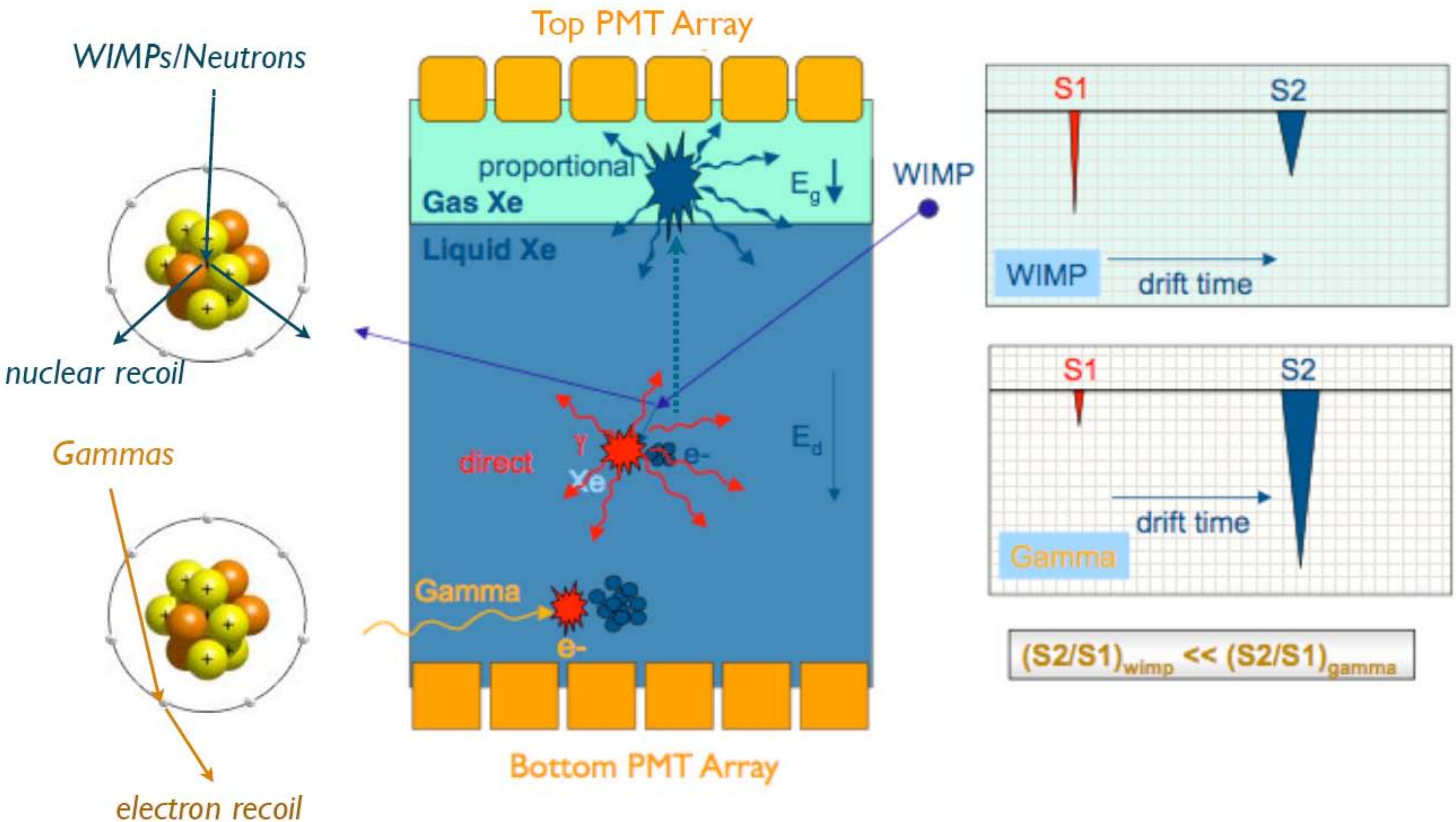
LXe and LAr for Dark Matter Detection

- *complementary nuclei for SI and SD interactions*
- *scalability : large volume detectors at reasonable cost and technical challenge*
- *Multiple and effective Background reduction schemes: liquid self-shielding, event localization in 3D TPC, event topology*
- *intrinsic background: radioactive Kr-85 in Xe can be reduced to ppt level; radioactive Ar-39 in Ar can be reduced by isotope separation and/or extraction from UG wells*
- *recoil energy threshold : high scintillation yields and continuing progress in photosensors with high QE and low back for both LXe and LAr*
- *gamma rejection: via charge/light ratio and via pulse shape discrimination of light pulse(easier for LAr light)*



Two Phase Xe/Ar Time Projection Chamber

(XENON,ZEPLIN,WArP,ArDM)



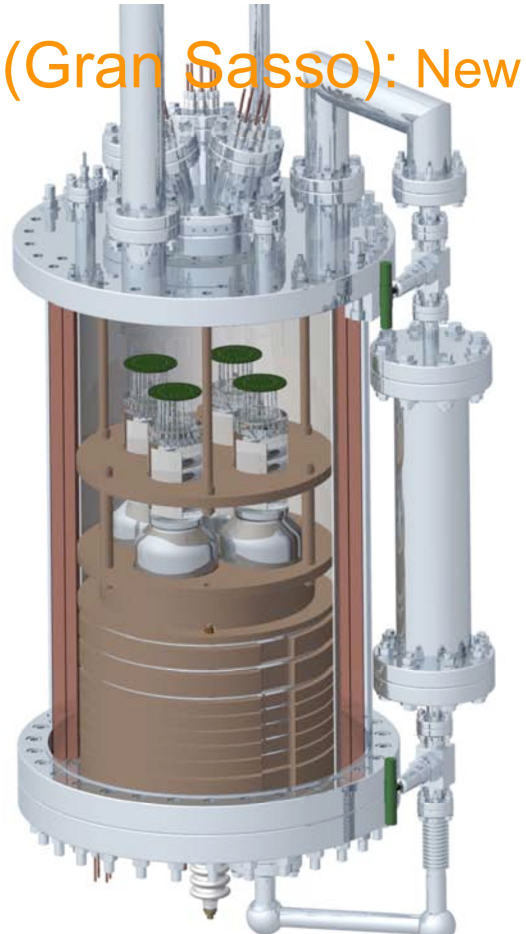
1st Generation Noble Liquid Experiments

- ZEPLIN I, II, III, XENON10, WArP 2l: fiducial mass in the range of ~10 kg.
- Focus review on next generation (2008- 2013): fiducial mass in the range 50 - 1000 kg.

XENON10 (Gran Sasso Lab): 22 kg LXe 2-phase TPC

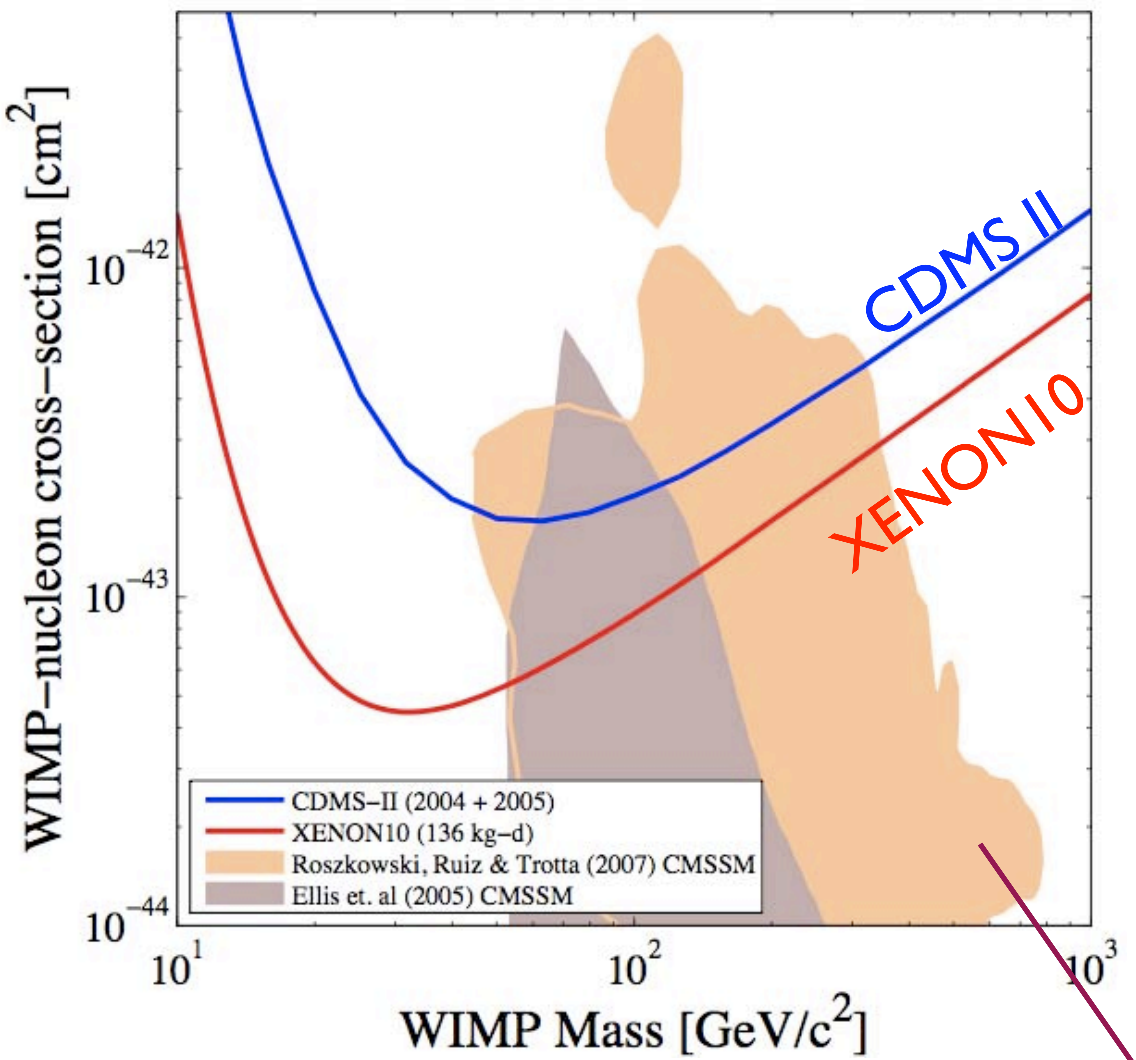
ZEPLIN II (Boulby Mine): 30 kg LXe 2-phase TPC

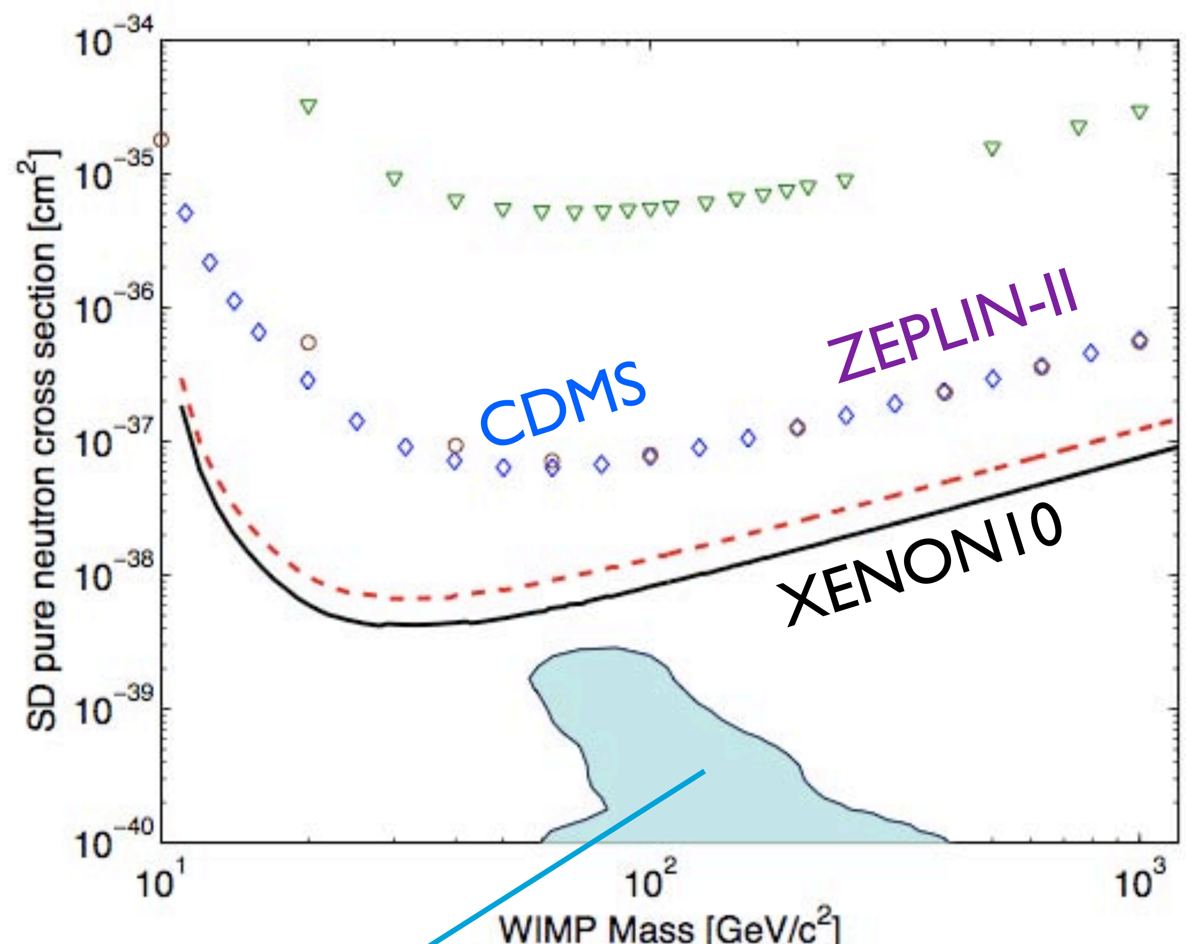
WARP (Gran Sasso): New 2.3l LAr 2-phase TPC



XENON10: Best WIMP-Nucleon Cross Section Upper Limits

Spin-independent	***Spin-dependent, pure neutron coupling***
Phys. Rev. Lett. ***100****, 021303 (2008)*	*Phys. Rev. Lett.* ***101****, 091301 (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

(NO BKG SUBTRACTION)

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

The XENON Dark Matter Phased Program

???

XENON1t

2009-2013
design studies ongoing

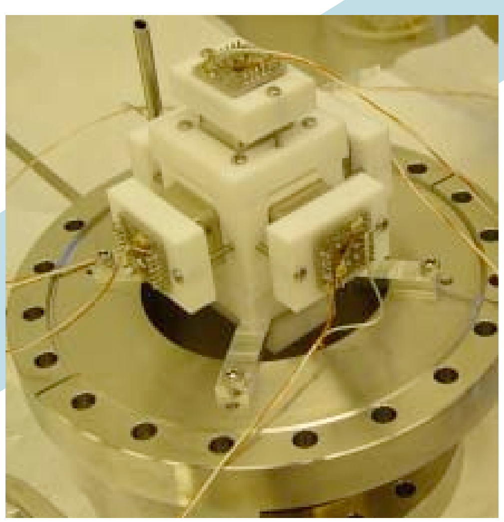
XENON100

2007-2010

XENON10

2006-2007

XENON R&D

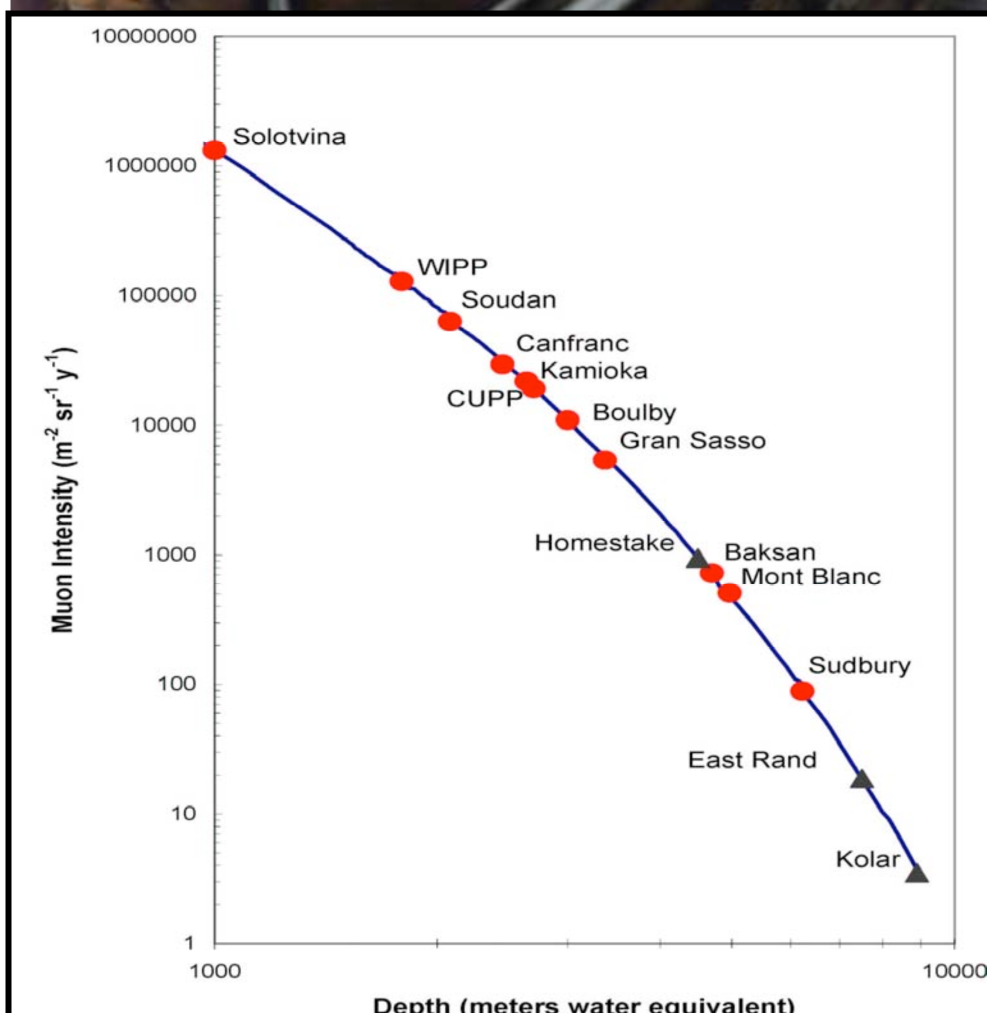


ongoing

XENON100 @ LNGS

1.4 km of rock (3100 mwe)muon intensity is approximately $1/(m^2\ h)$

- *Installed underground in 2008*



The XENON100 Collaboration

LNGS Collaboration Meeting, July 15,2008

Columbia University
Elena Aprile(Spokesperson), Bin Choi, Karl-Ludwig Giboni, Kyungeun Elizabeth Lim, Antonio Jesus Melgarejo, Kaixuan Ni, Guillaume Plante, Taehyun Yoon

Rice University
Uwe Oberlack, Yuan Mei, Marc Schumann, Peter Shagin

University of California, Los Angeles
Katsushi Arisaka, Hanguo Wang, David Cline, Ethan Brown, Artin Teymourian

Gran Sasso National Laboratory, Italy
Francesco Arneodo, Serena Fattori

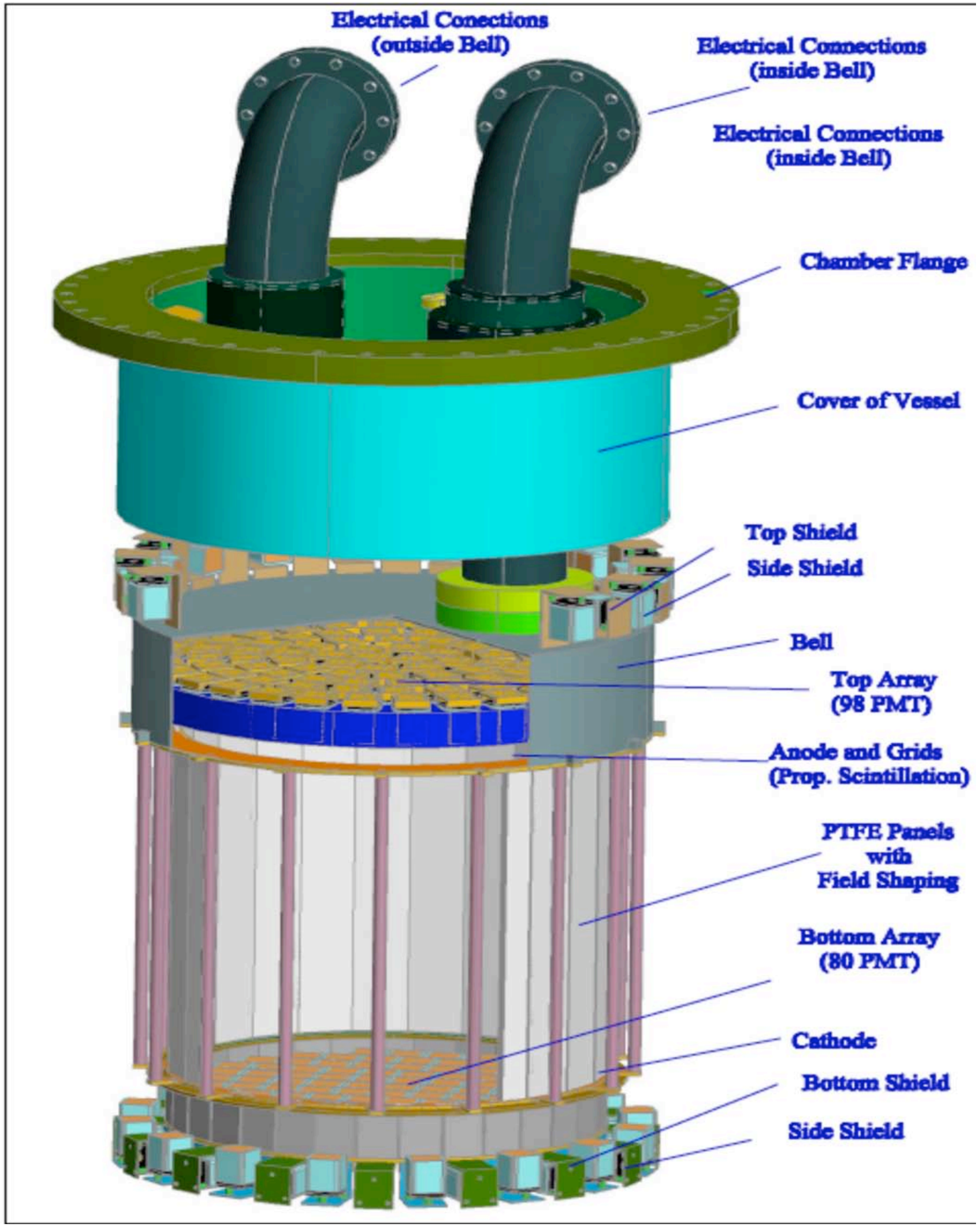
University of Coimbra, Portugal
Jose A Matias Lopes, Joao Cardoso, Luis Coelho, Joaquim Santos

University of Zurich
Laura Baudis, Ali Askin, Alfredo Ferella, Marijke Haffke, Alexander Kish, Roberto Santorelli, Eirini Tziaferi

12 Ph.D. Students and 10 Postdocs

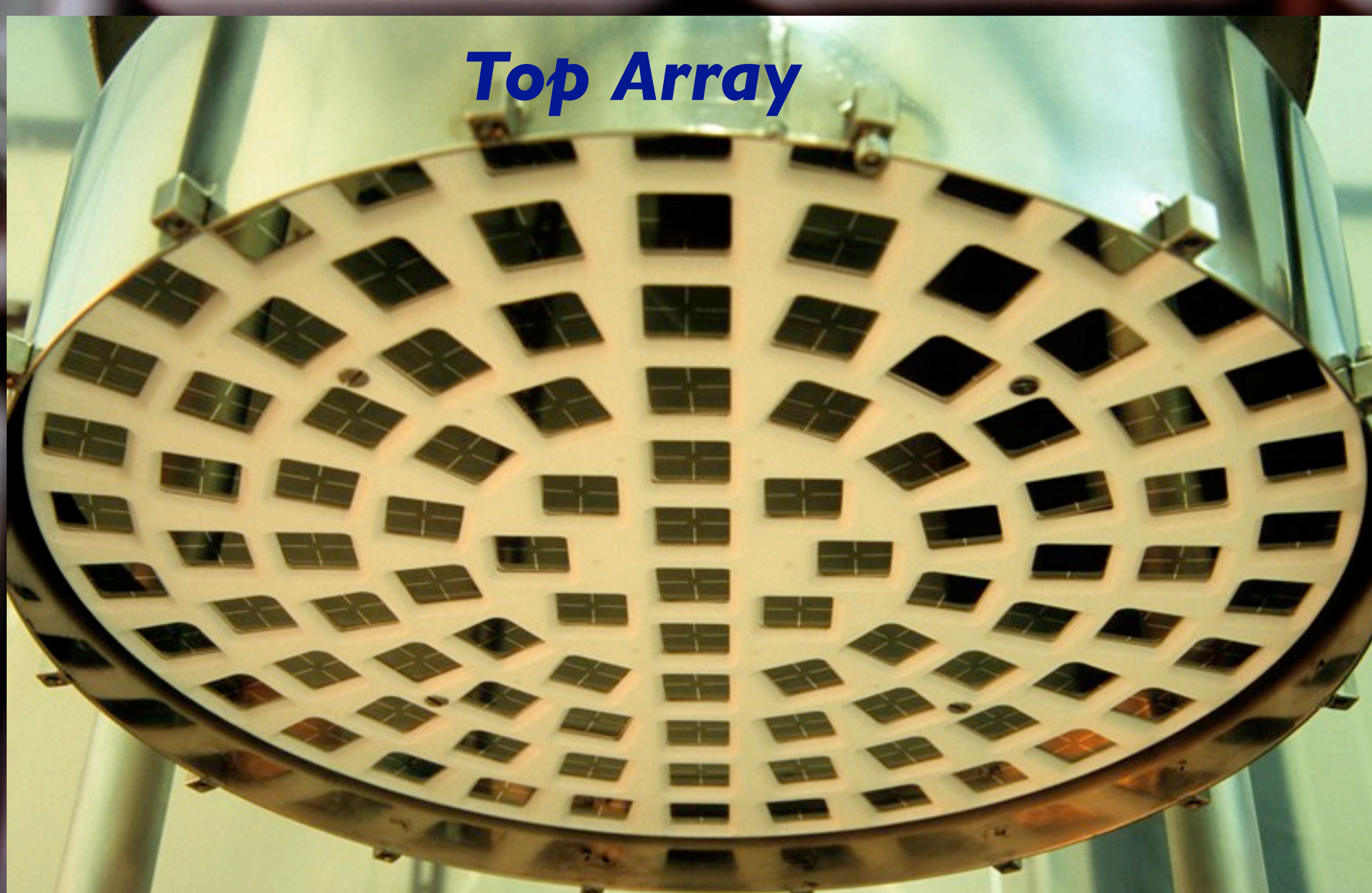
XENON100: The TPC Assembly

- x10 fiducial mass of XENON10
- x100 less back than XENON10



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)



XENON100: Keeping it Clean!

Reduce ^{85}Kr < 50 ppt

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

A Cryogenic Distillation Tower is used to reduce by 10^3 the initial Kr concentration

XENON100 data used to measure initial concentration (7+-2 ppb)

XENON100 science goal: ~50 ppt

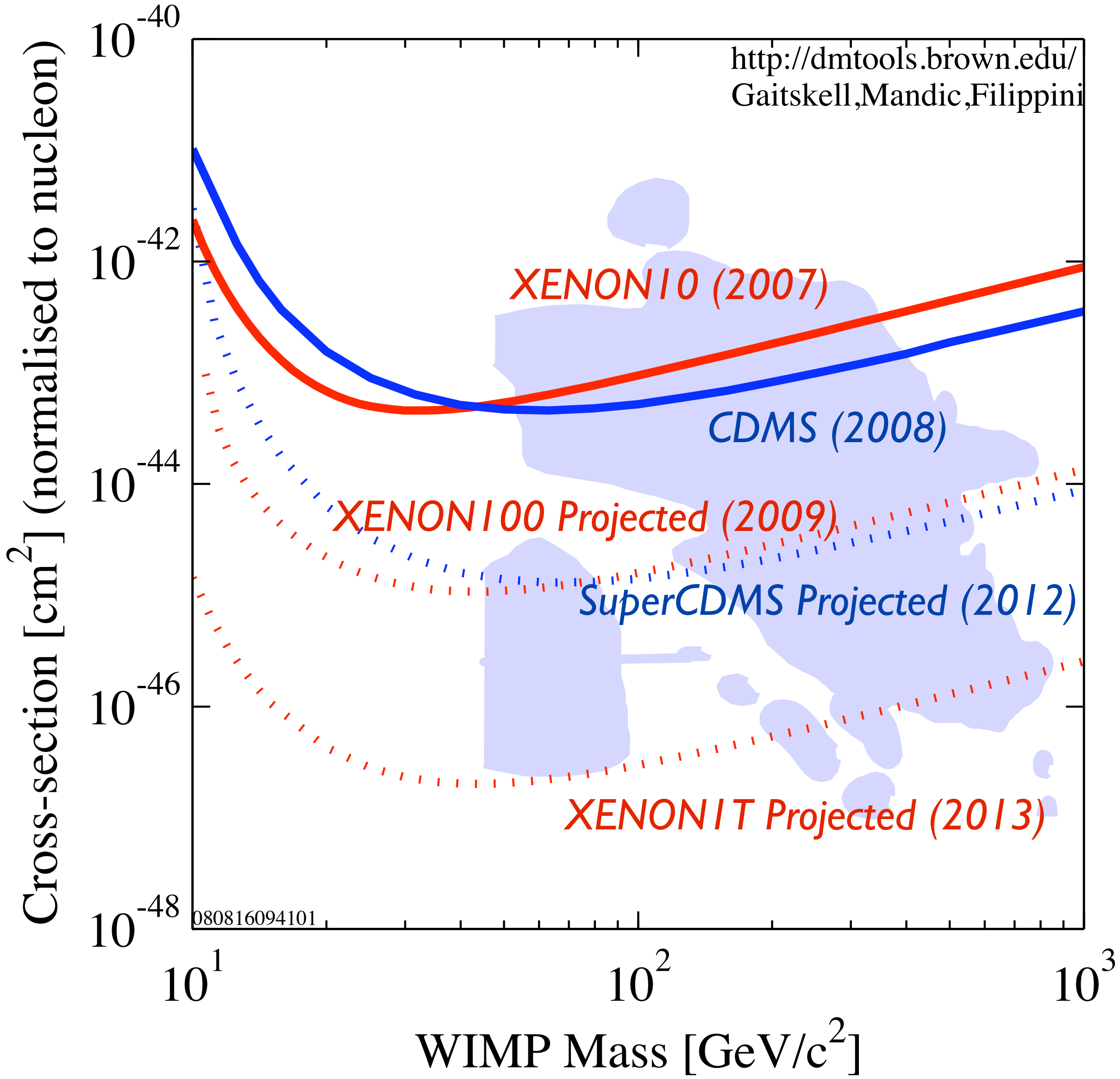
Reduce O_2 < 1 ppb

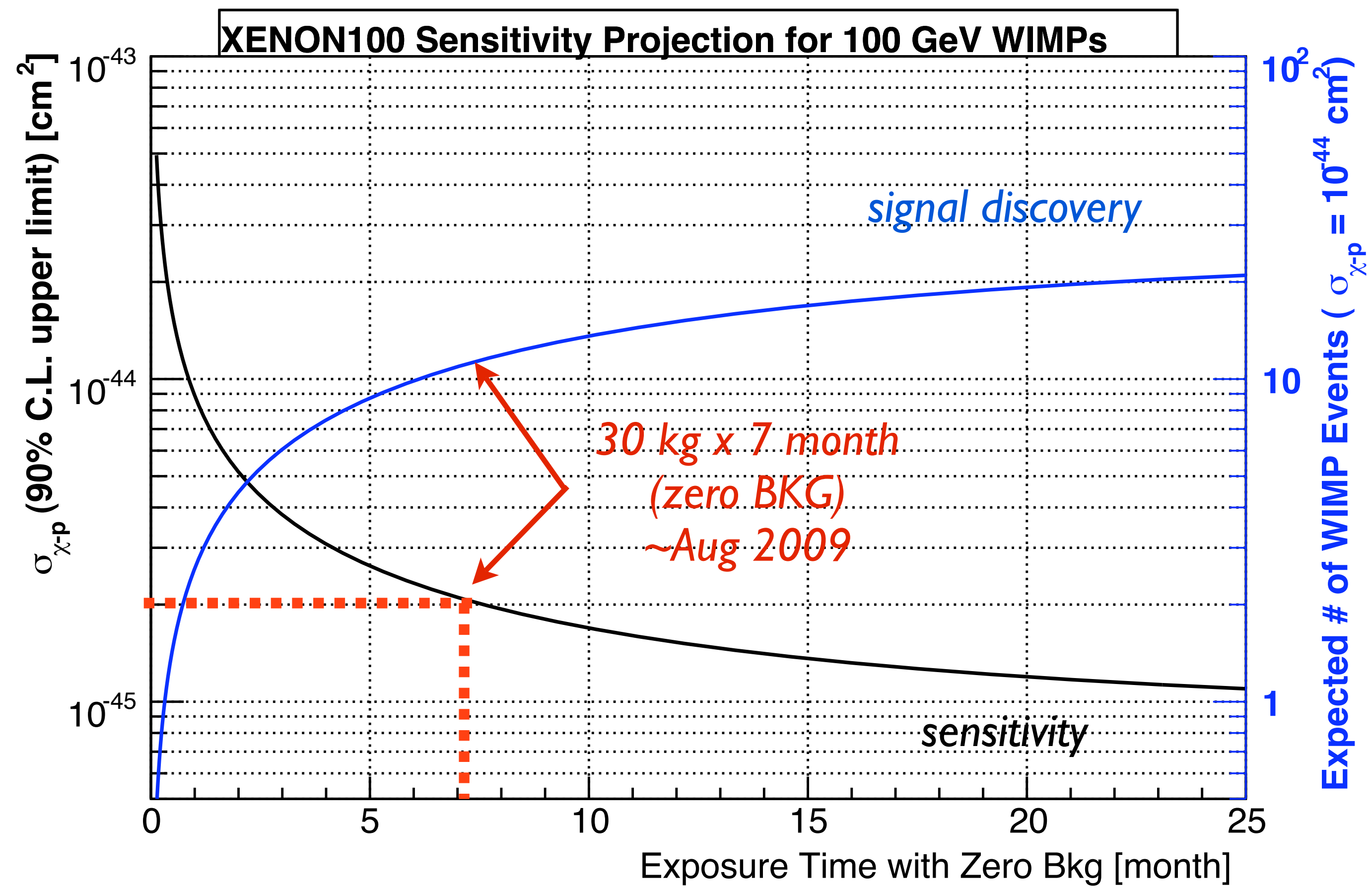
Electronegative impurities reduce charge and light yield.

XENON100 drift is over 30 cm of LXe

Continuous purification by hot getter is used to achieve goal of < 1 ppb O_2

XENON100: Projected Sensitivity

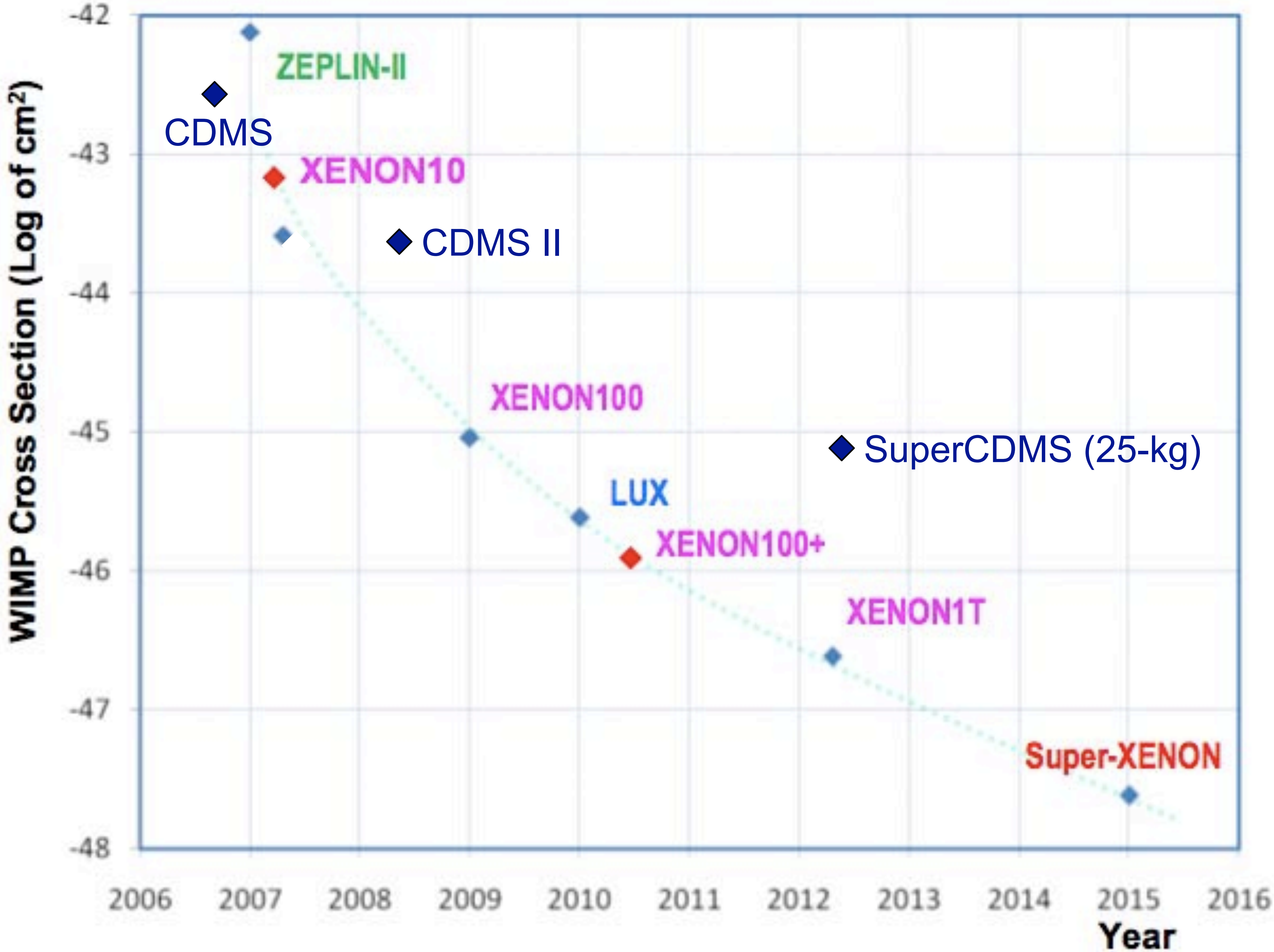




Sensitivity reach is σ_{SI}~$2x10^{-45}$ cm^2 after 7 months data with zero BKG

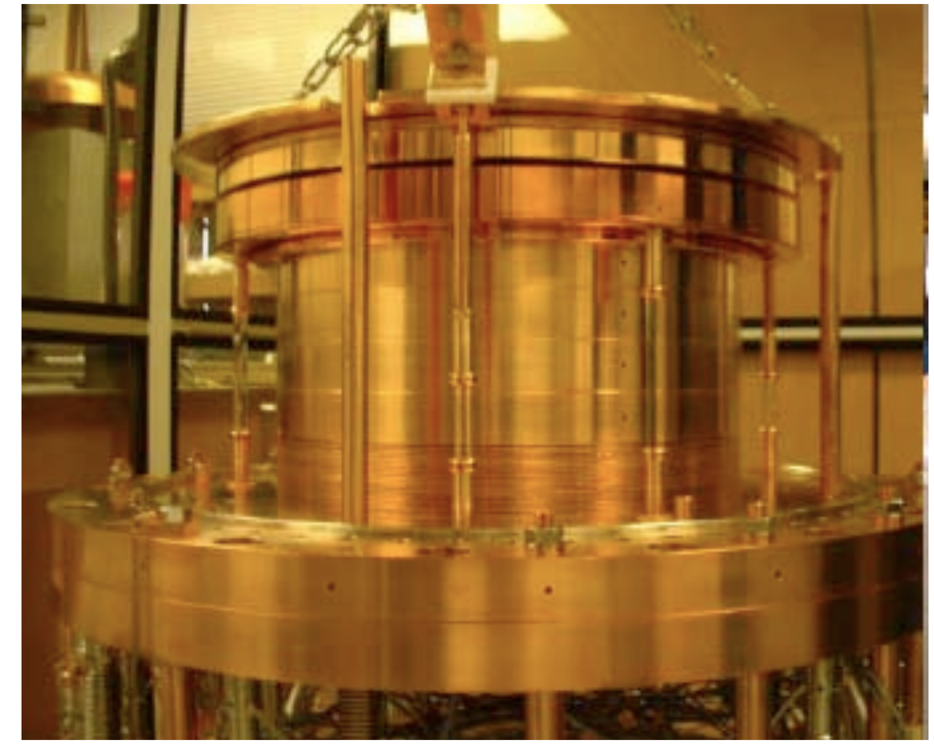
Two years of data would give ~20 WIMP events if σ_{SI}~$2x10^{-44}$ cm^2 for 100 GeV

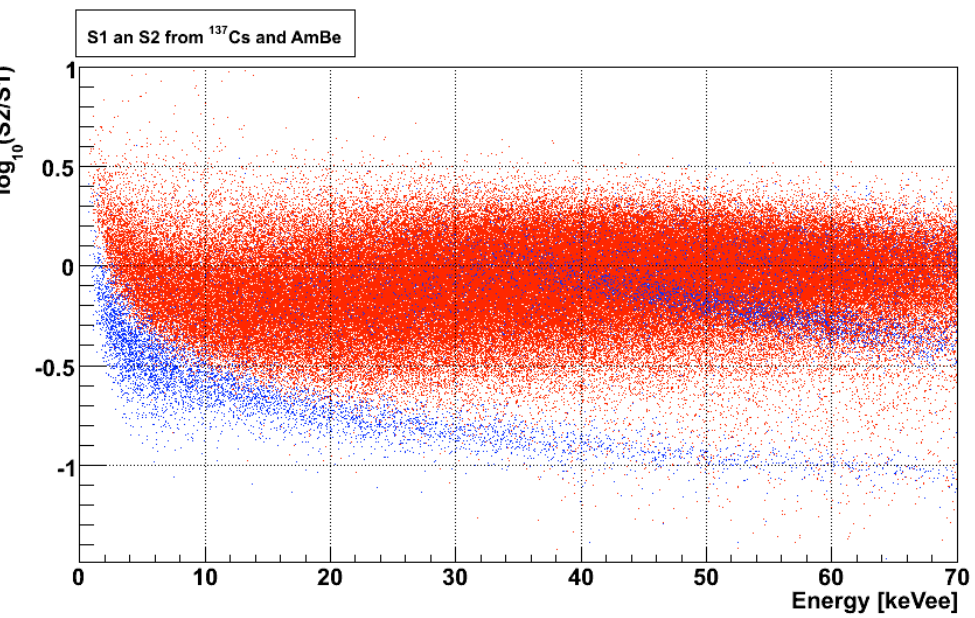
Time Evolution of the XENON Program

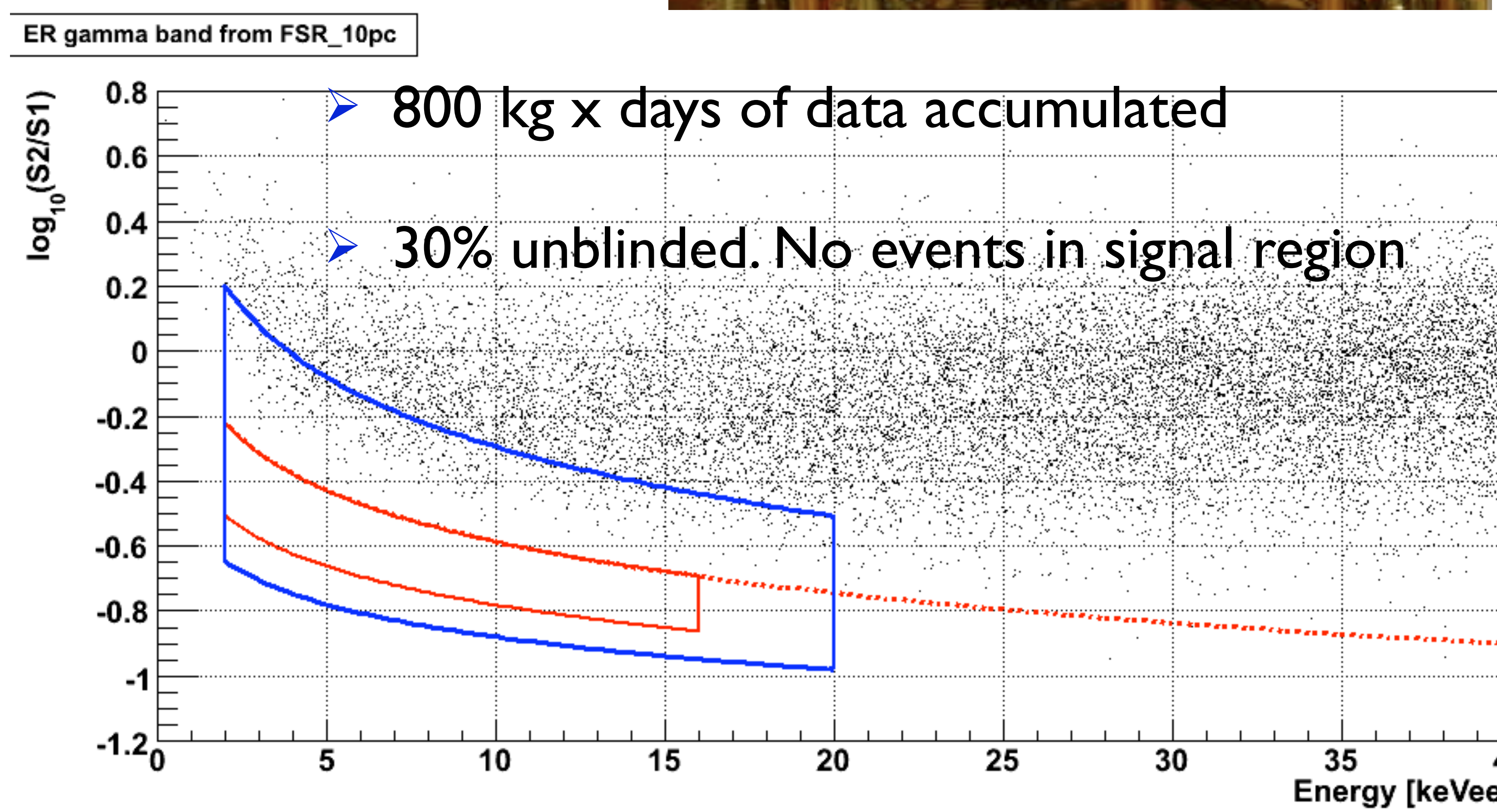


ZEPLIN III @ Boulby

- 14 kg (6.6 kg fiducial) dual-phase XeTPC with 31 PMTs in the liquid
- 3.5 cm drift with high field (4 kV/cm) for better ER/NR
- open plan-no surfaces; all Cu construction



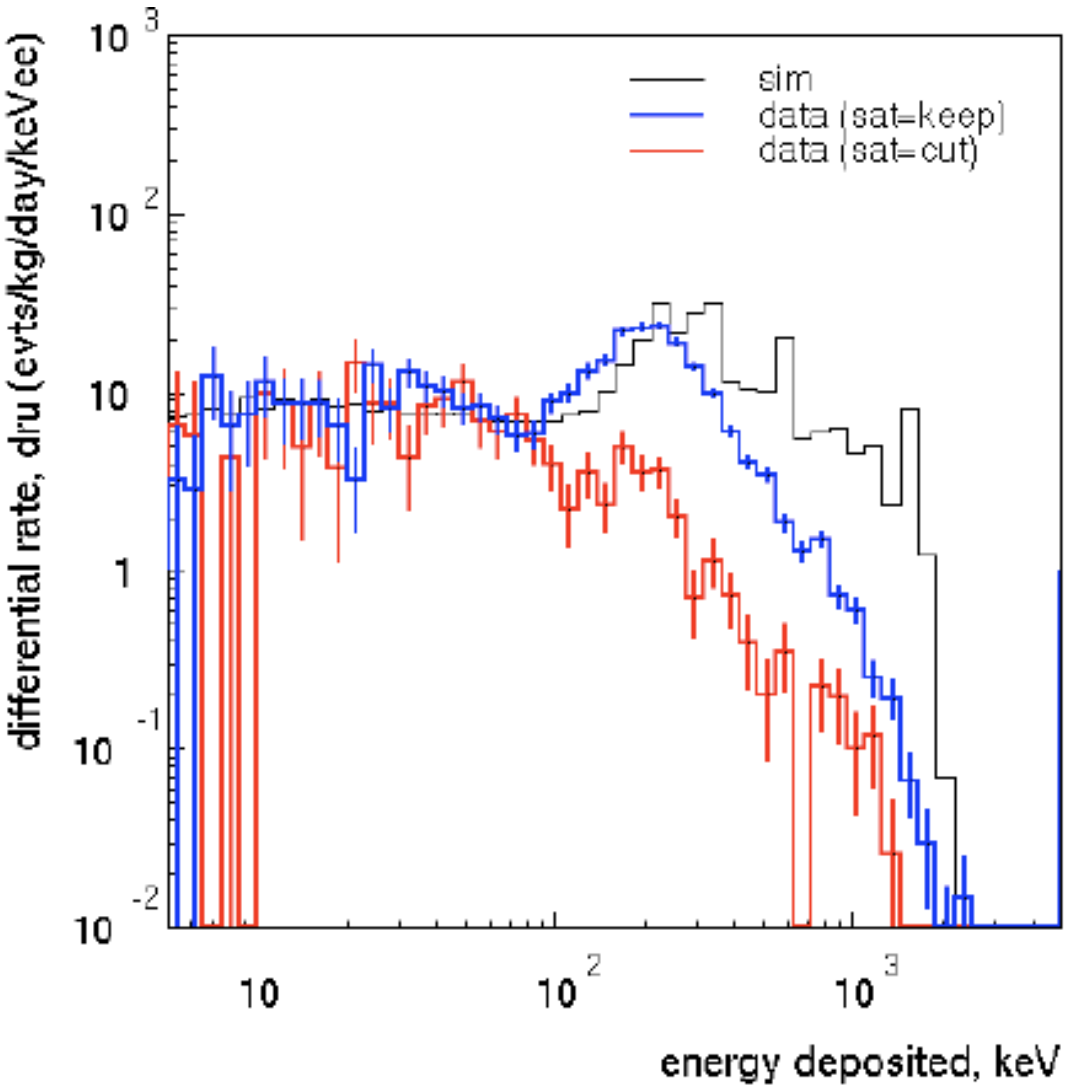


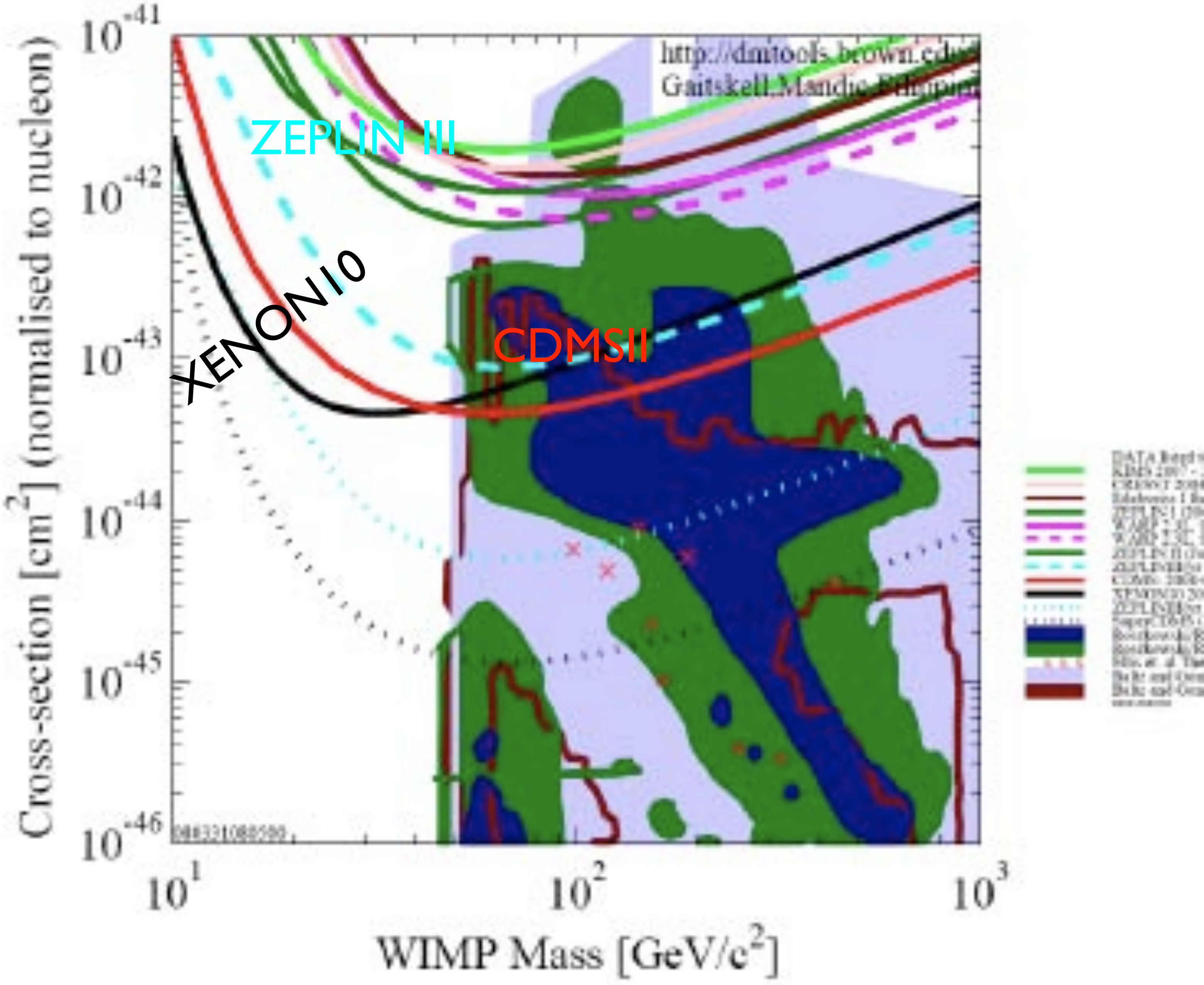


- 800 kg x days of data accumulated
- 30% unblinded. No events in signal region

ZEPLIN III Future Plan

- *Extended gamma calibration run*
- *Repeat neutron calibration*
- *Replace PMTs with low activity type*
- *Predict 30 x background reduction*

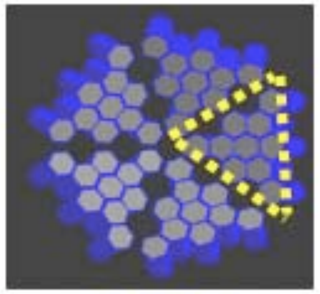


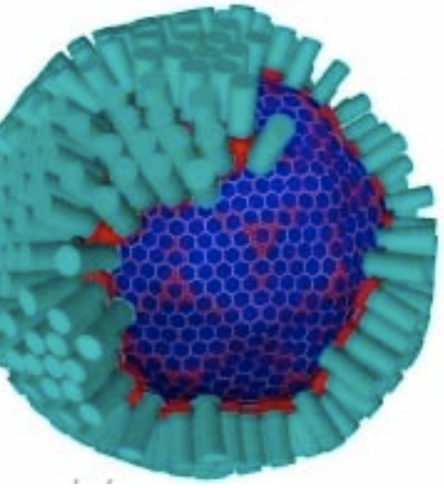


LUX (100 kg)@ Homestake

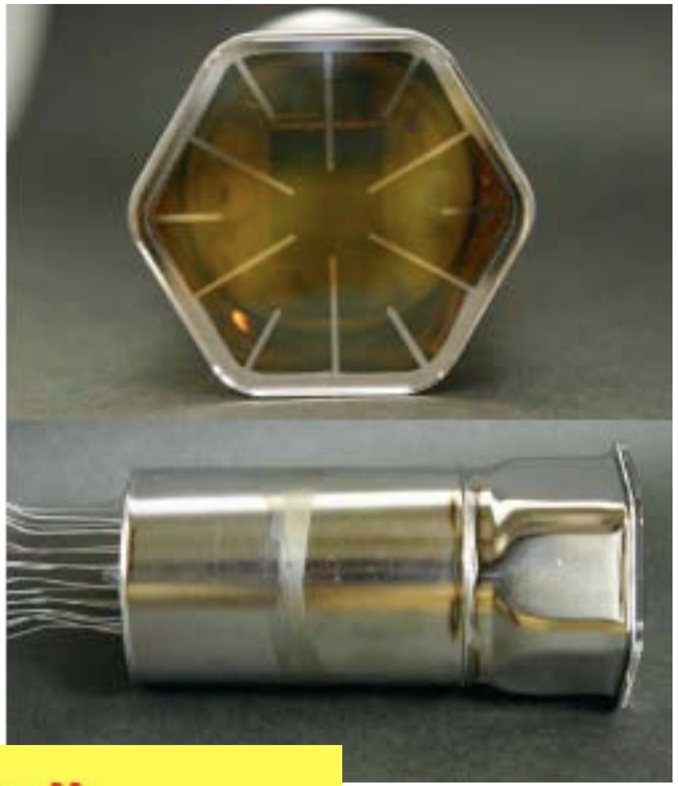
- 300 kg (100 kg fiducial) dual-phase XeTPC with 122 PMTs
- 50 kg prototype with 4 PMTs (R8778) being assembled and tested at CWRU
- plan to move and test full detector above ground at Homestake by end 2008
- water shield to be built in Davis cavern (once water is pumped from that mine)
- aggressive background and sensitivity projections (7 x 10^{-46} cm^2 after 1 yr)

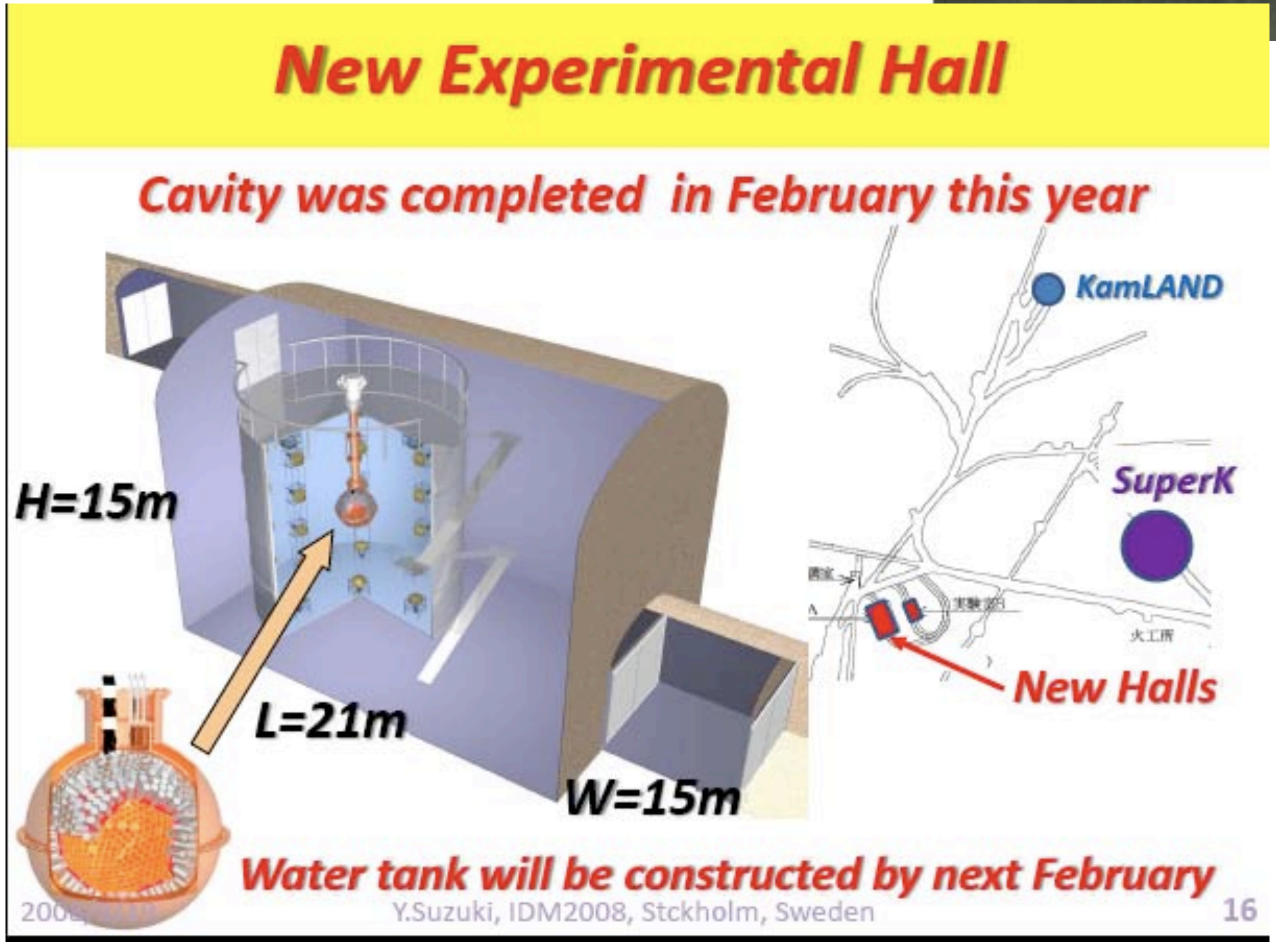
XMASS @ Kamioka





- Single phase liq. Xe
- Pentakis-dodecahedron
  ← 12 pentagonal pyramids
  Each pyramid ← 5 triangles
- Radius: 39~42 cm
- 642 Hex. PMT immersed in liq. Xe
- PMT photo-cathode coverage: 64%
- Inner mass of Xenon: 857kg (~3g/cm^3)





XMASS (100 kg) @ Kamioka

Aim:

– 10^{-4} dru (ev/kg/keV/day) *before any PSD applied*

➔ 10^{-45}cm^2 SI for ~100GeV WIMPs

For the signal detection

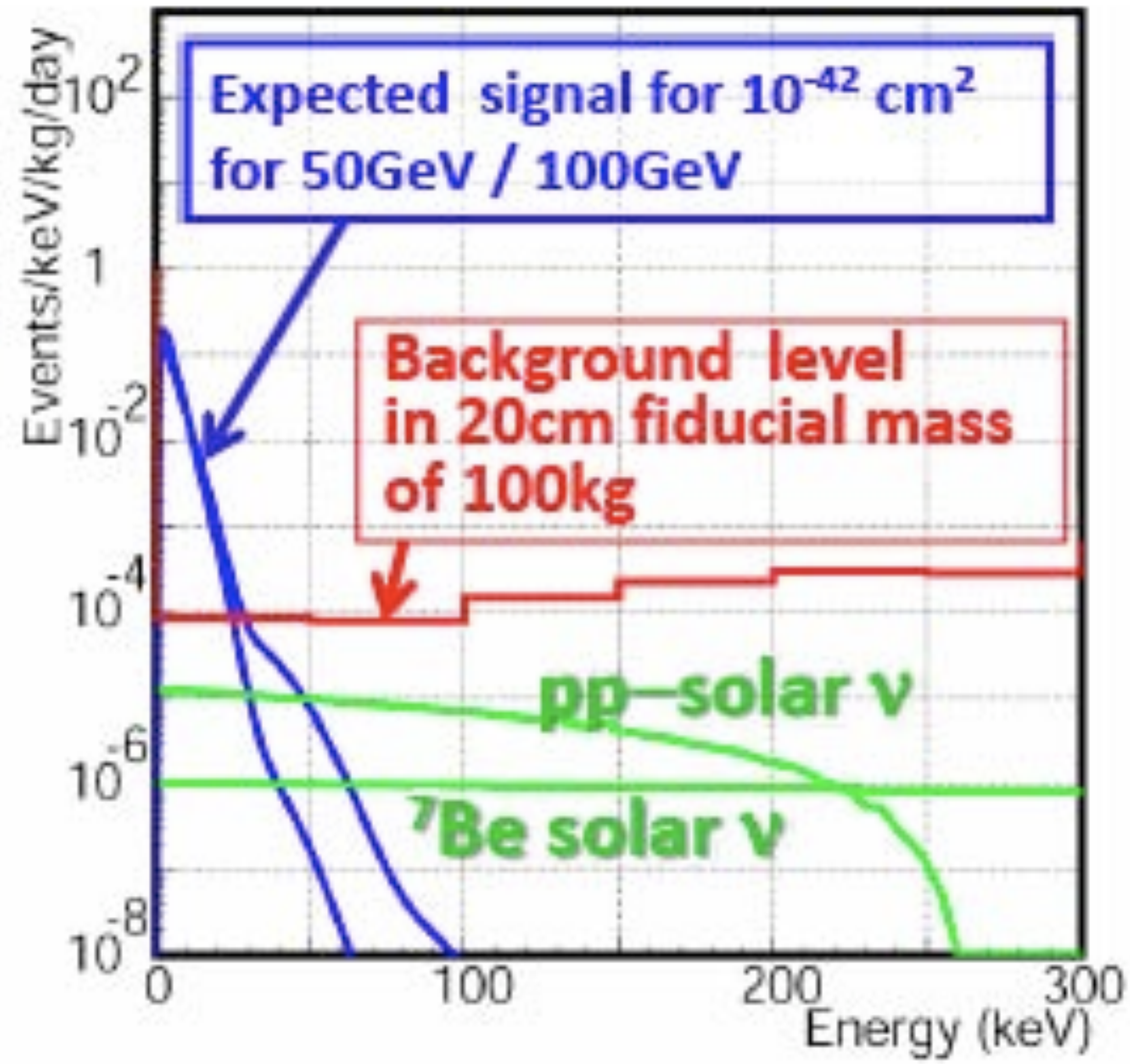
– **Low threshold: ~ 5 keV or less**

🡐 8 pe /keV (64% photo-cov.)

– **Large fiducial volume: 100kg or more**

20cmϕ: 100kg
(20cm self-shield)

25cmϕ: 200kg
(15cm self-shield)

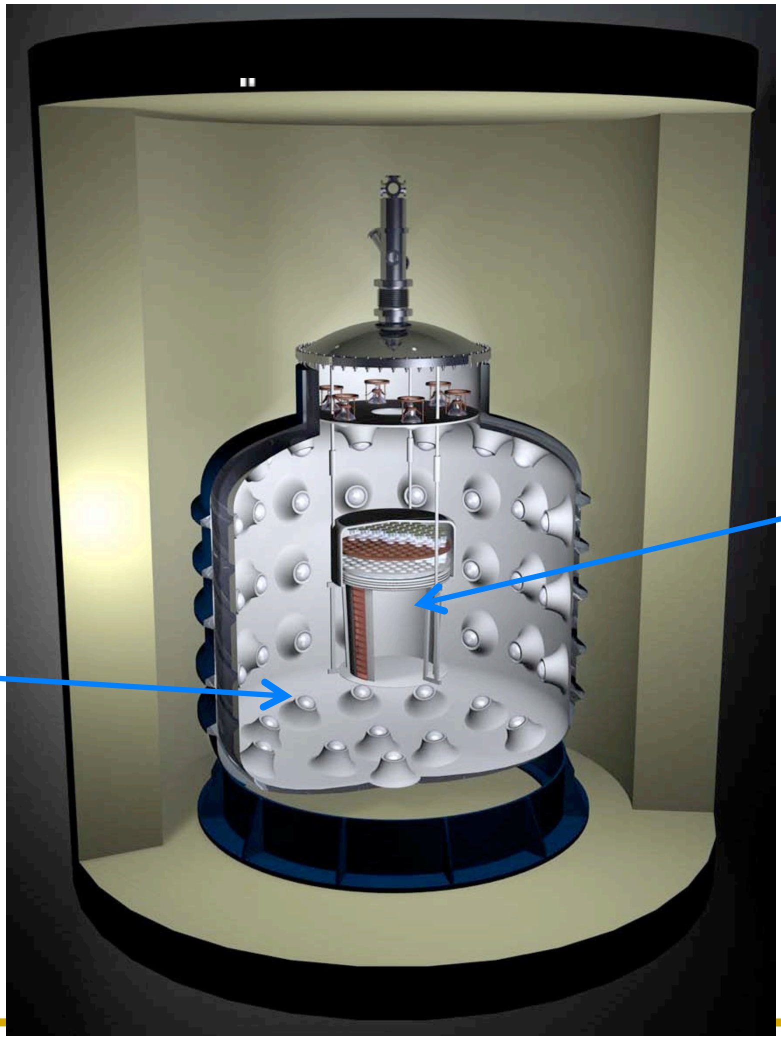


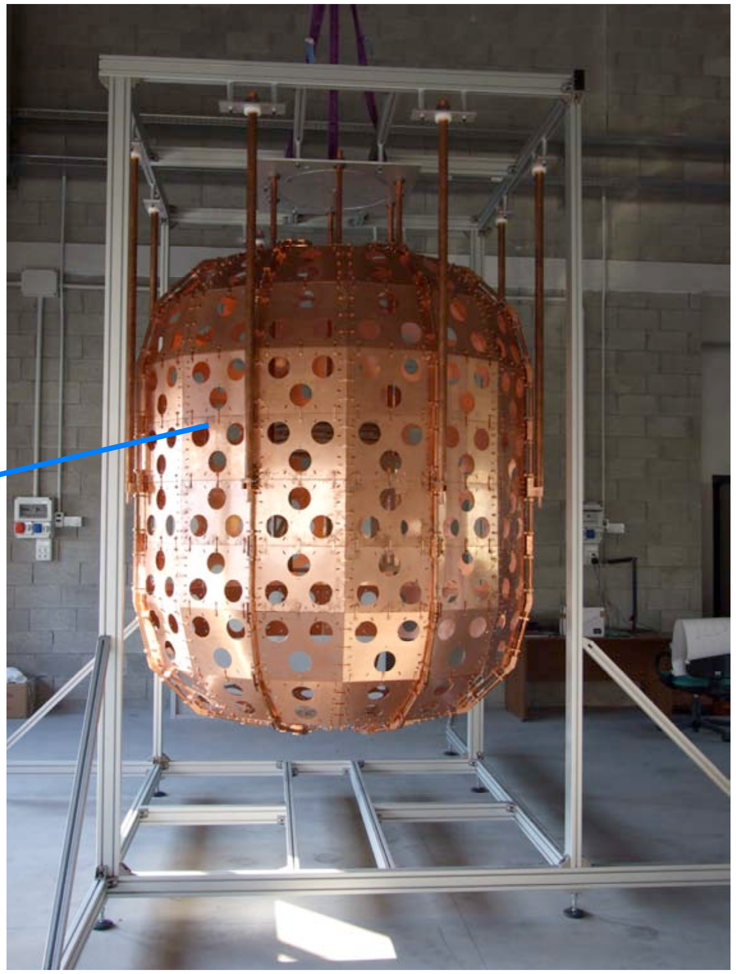
XMASS (100kg, 5yr) *10^{-45}cm^2 (10^{-9}pb) for SI and 10^{-39}cm^2 (10^{-3}pb) for SD*

WArP (100 liter) @ LNGS

- 140 kg dual-phase ArTPC under construction at LNGS with 10^{-45} cm^2 sensitivity reach
- electron recoil discrimination by S2/S1 and by PSD (5ns and 1.6 micros decay times)
- target surrounded by an active LAr shield (9 tons and 300 PMTs)
- electron recoil discrimination by S2/S1 and by PSD of scintillation light , plus event localization
- Ar gas with low level of radioactive ^{39}Ar from US u.g. reservoir promising for multi-ton expt
- Main Cryostat

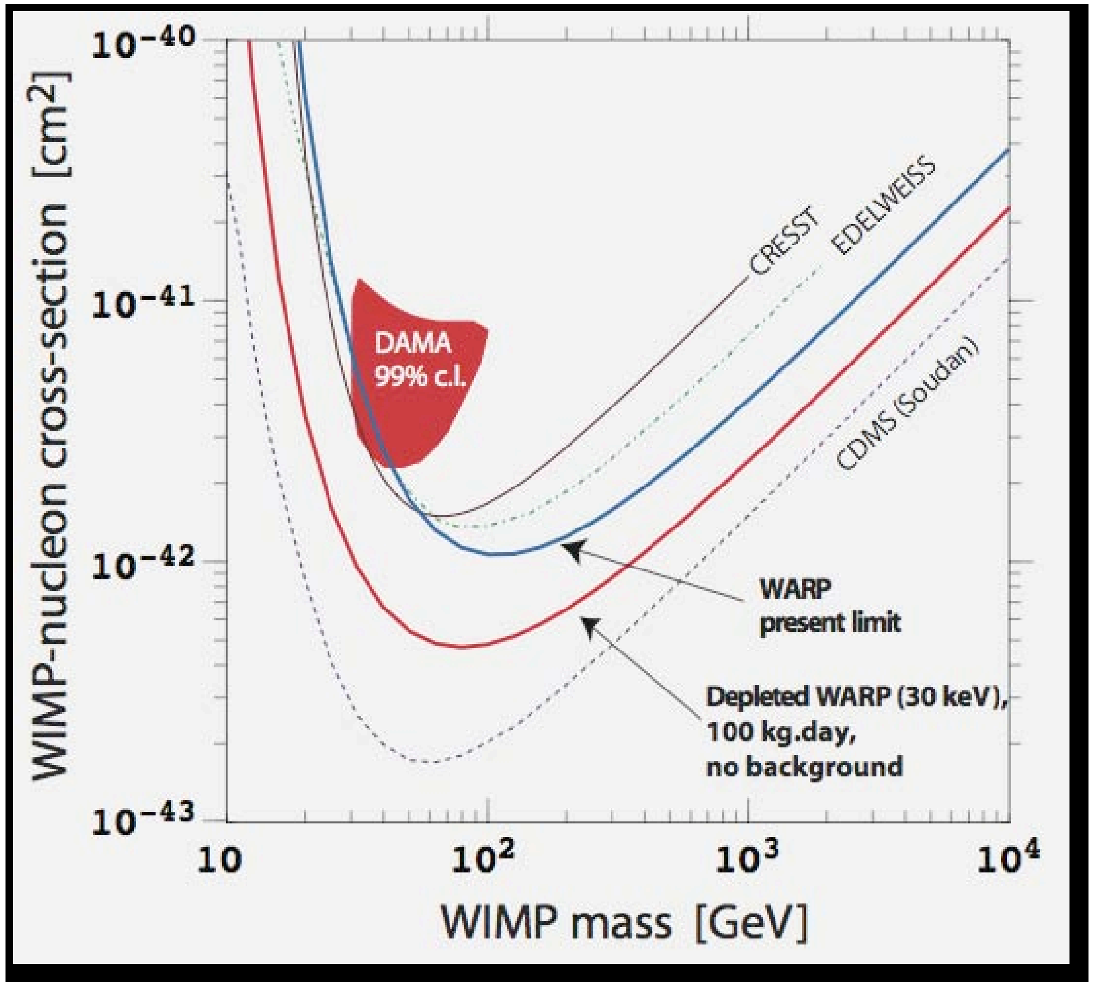
after positioning in Hall-B (Jul.'07) inside sustaining structure



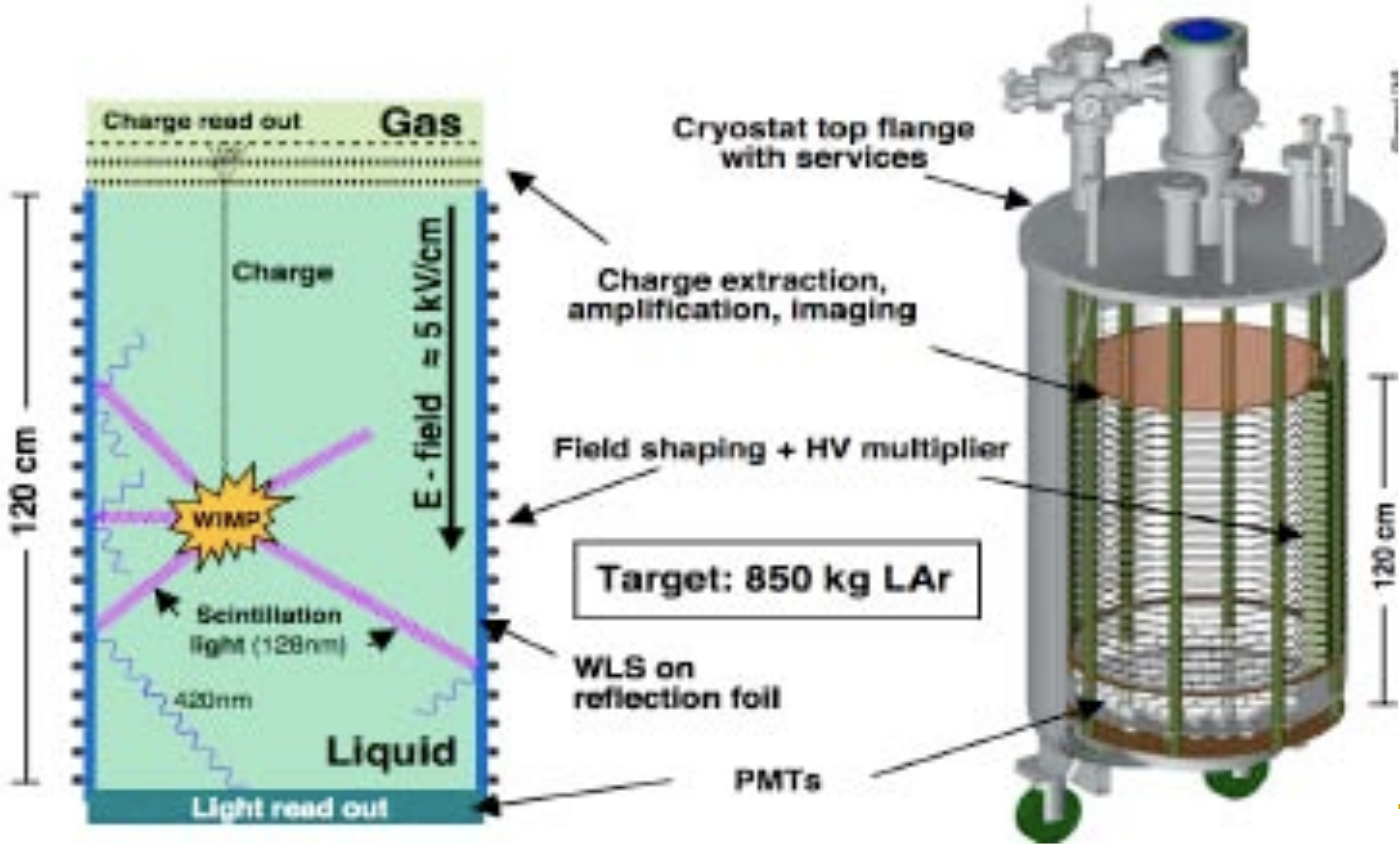


WArP (2 liter Prototype) @ LNGS

- proof of principle demonstration and 1st DM search with LAr
- exposure of 96.5 kg x days (Jan - April 2006): placed a limit at 10^{-42}
- studied discrimination power from PSD at 10^{-8}
- new version of 2.3 liter detector installed underground
- new PMTs, gas recirculation, low activity SS (~ 2 x less back)
- factor of 20 reduction with depleted ^{39}Ar depleted argon

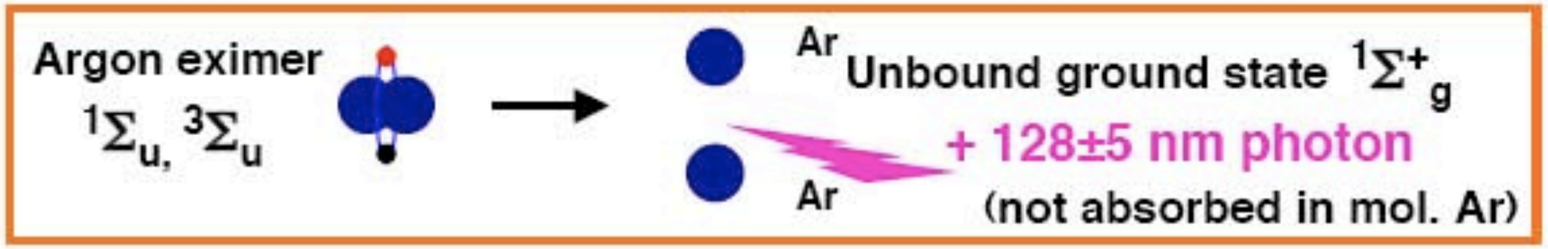


ArDM @ LSM

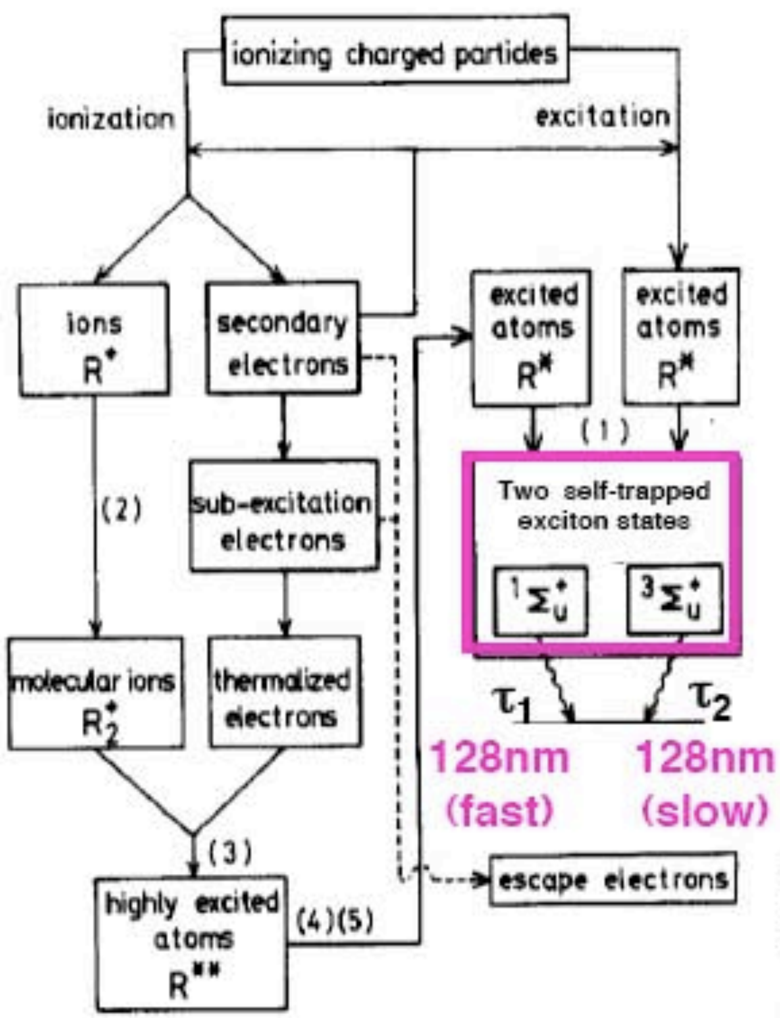
- 850 kg dual-phase ArTPC under construction at CERN for deployment at Canfranc Lab
- electron recoil discrimination by S2/S1 and by PSD of scintillation light , plus event localization
- expected sensitivity: 1 WIMP event/ton/day at 10^{-44} cm^2
- 

Pulse Shape Discrimination in LAr

Scintillation mechanism, light pulse shape

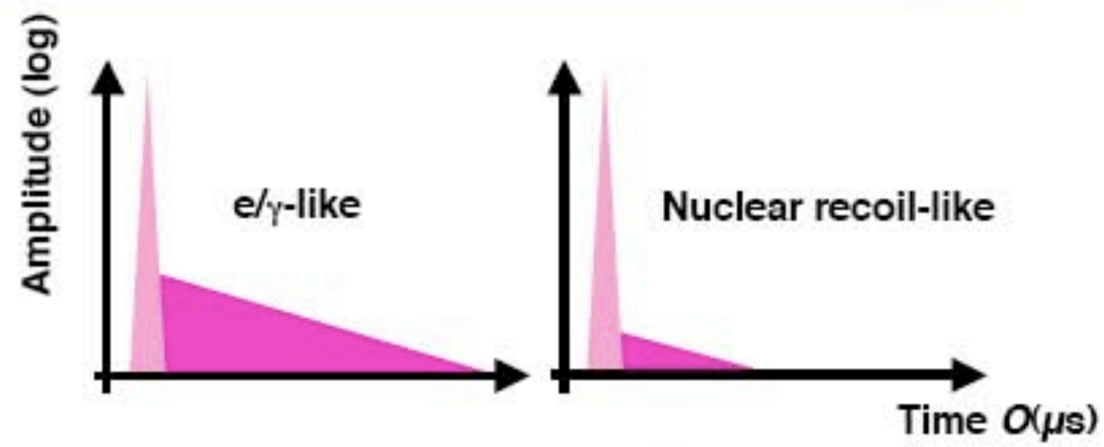


Similar to alkali halide crystals (~40ph/keV)
Complicate production process
Ionisation density dependent ratio (N_{trip} / N_{sing})

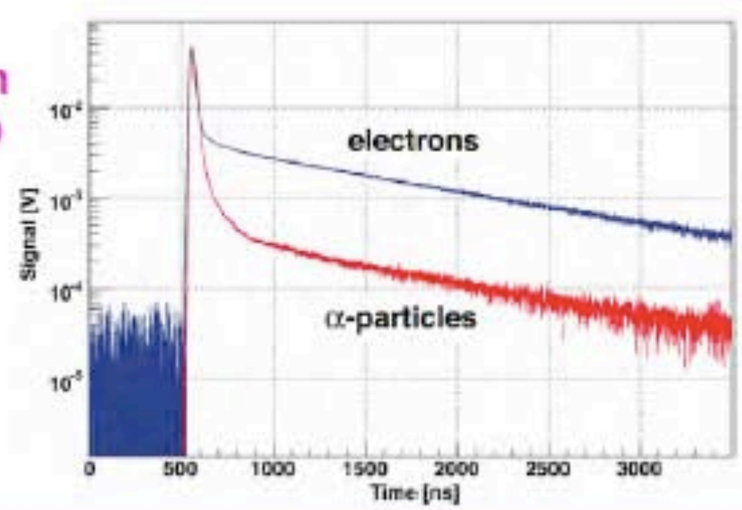


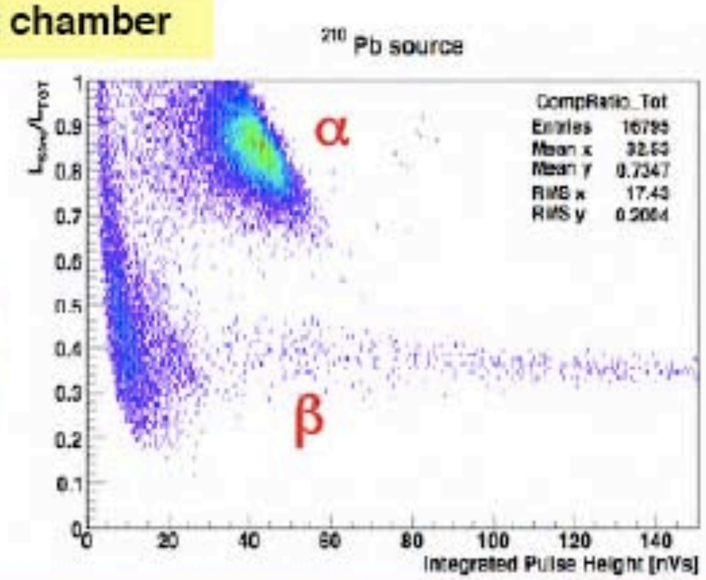
M. SUZUKI, J. RUAN and S. KUBOTA, NIM 192 (1982) 565

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



Ionization density effect in lab test chamber





ArDM Status

Cryostat and liquid purification and recirculation built and tested

HV generator (Greinacher circuit) to reach ≈ 4 kV/cm (V_{tot} = 500 kV) placed in liquid

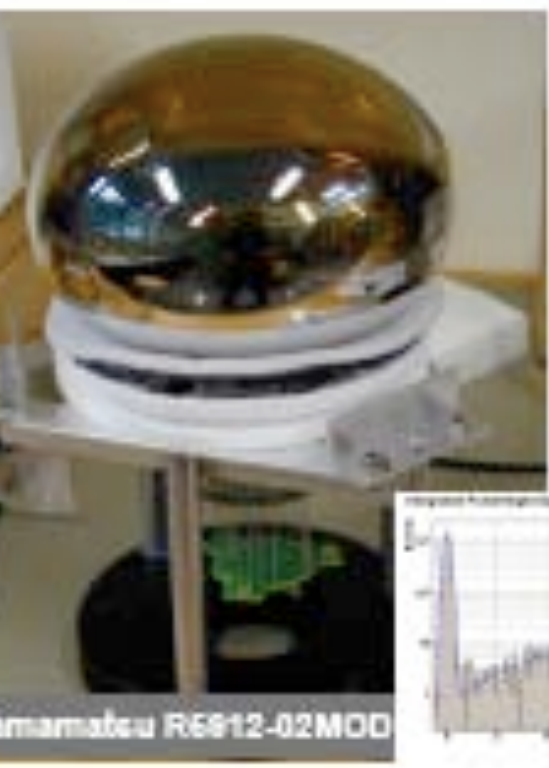
Slow Control has been implemented

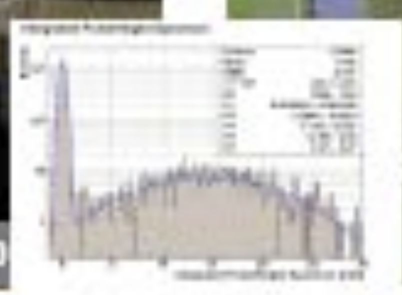
Double phase LEMs successfully operated in double phase Ar mode (stable gain of 10^4); with final LEM charge readout segmented; A/D conversion and DAQ system being developed

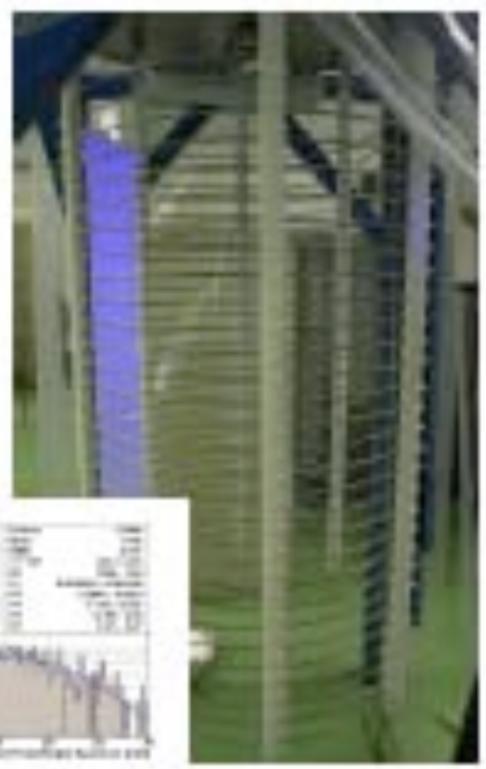
14 bialkali 8" PMTs (TPB coated) installed at the bottom

15 light reflector/shifter foils produced and installed

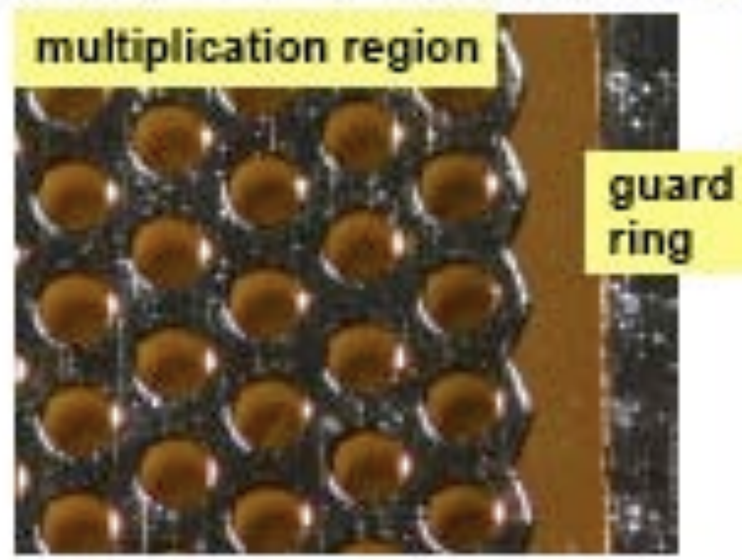
Amsler et al., "Luminescence quenching of the triplet
cimer state by air traces in gaseous argon" arXiv:0708.2621

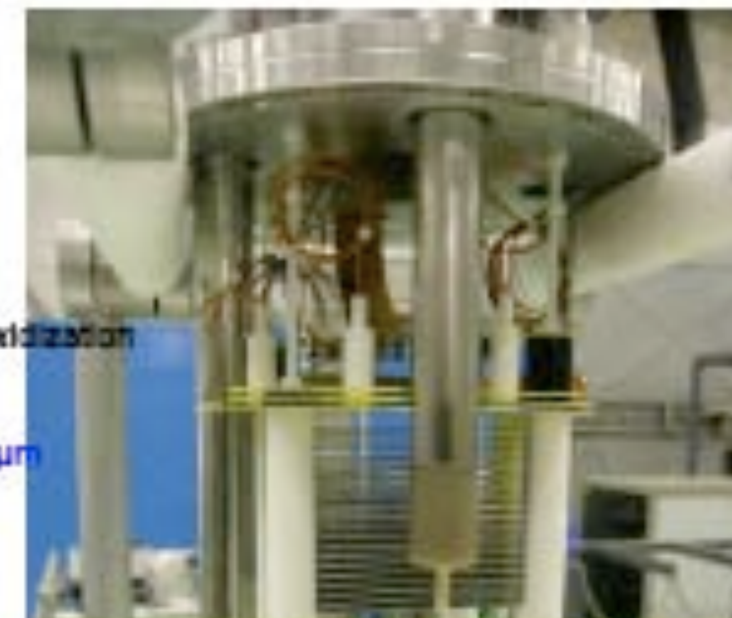






- Double-sided copper-clad (35 µm layer) G-10 plates
- Precision holes by drilling
- Palladium deposition on Cu (<~ 1 µm layer) to avoid oxidization
- Single LEM Thickness: 1.5 mm
- Amplification hole diameter = 500 µm
- Distance between centers of neighboring holes = 800 µm





SUMMARY

- Direct detection experiments with noble liquids have advanced rapidly in past few years . They will play a vital complementary role to indirect and collider searches.
- Sensitivity at the 10^{-45} cm^2 (SI) and 10^{-39} cm^2 (SD) level within the next couple of years. Great discovery potential!
- Systematic effort to lower the backgrounds while simultaneously increasing target mass is paying off quickly. We are currently seeing gamma background rates down from 1 to 10^{-4} cts/keV/kg/day, competitive with the best low background searches!
- The power of a 3D TPC for background identification and suppression and the self shielding property of LXe well established by XENON, ZEPLIN and XMASS prototypes. The larger sensitive volume detectors being deployed or under development today will show a clear advantage for the identification of neutrons by their multiple interactions
- Multiple targets and even same target competition vital for the field at this stage. Natural selection however will occur as scale, cost and complexity increase