Direct Detection of Dark Matter

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Yale University

SUSY 2011
August 31, 2011

Searching for WIMPs

Accelerators: Look for dark matter candidates at the LHC.

Squark and gluino decays result in leptons, jets, and missing energy.

BUT: 1) can't show that dark matter candidate is stable

2) hard to determine couplings/interactions of dark matter candidate

3) can't prove that candidate particle actually makes up the dark matter

Indirect Searches: Look for $\chi\chi$ annihilation in form of high energy cosmics, neutrinos

Direct Searches: Look for anomalous nuclear recoils in a low-background detector

$R = N \rho < \sigma v >$

From $<v> = 220$ km/s, get order of 10 keV

Key technical challenges:

Low radioactivity

Low energy threshold

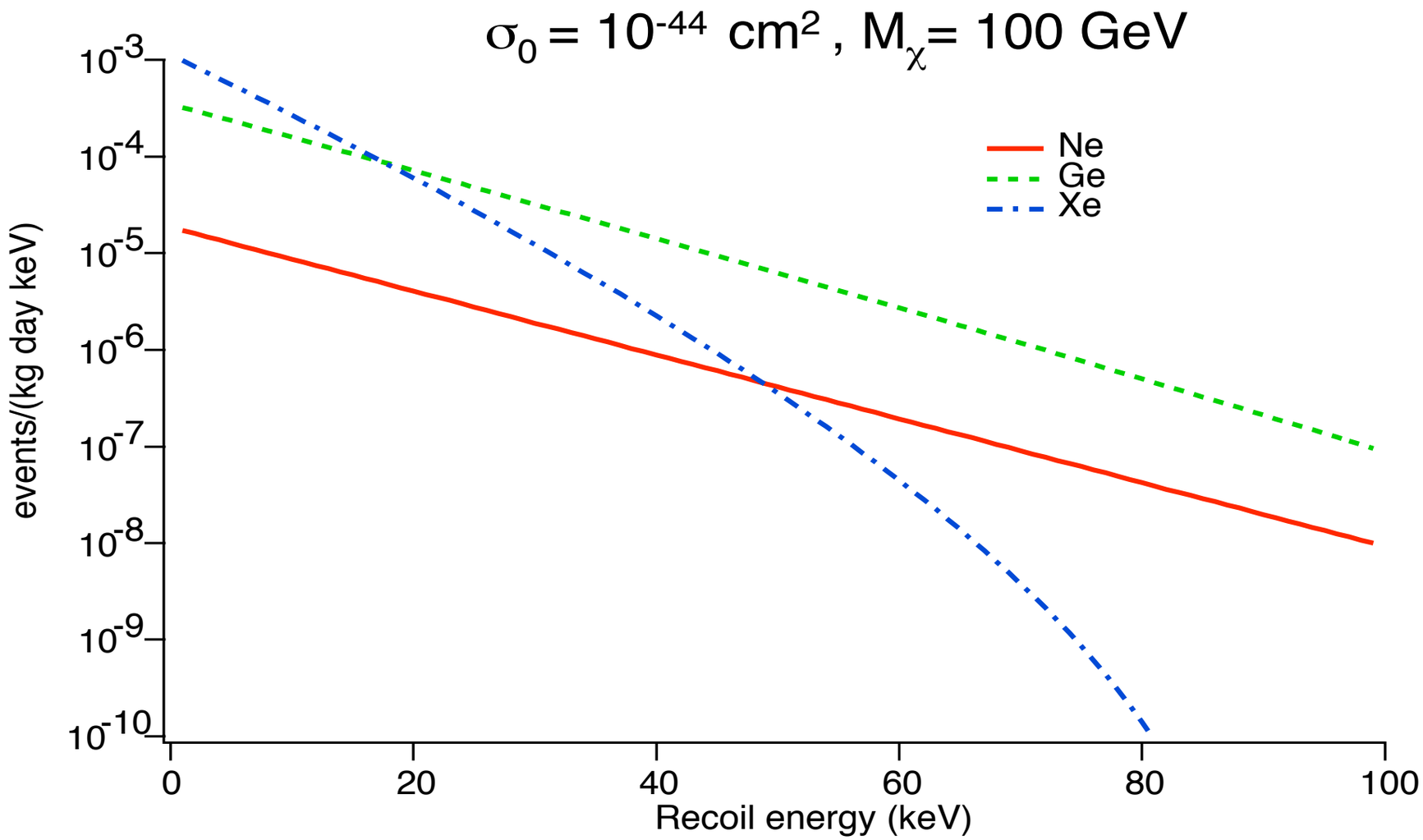
Gamma ray rejection

Scalability

Detect heat, light, or ionization
(or some combination)

Germanium detector
(as in CDMS, Edelweiss)

WIMP recoil spectra



Scattering rate

Sun's velocity around the galaxy

WIMP velocity distribution

$$dR/dQ = (\sigma_0 \rho_0 / \sqrt{\pi}\, v_0\, m_\chi\, m_r^2)\, F^2(Q)\, T(Q)$$

WIMP energy density, 0.3 GeV/cm^3

Form factor

Astrophysical Uncertainties in WIMP Event Rates

During gravitational collapse and subsequent virialization, the collisionless dark matter should form a halo that is roughly spherical. Differences from a spherical isothermal model only affect event rates by order 10% for velocity distributions consistent with galaxy formation models; maximal rotation can change the event rates by roughly 30%.

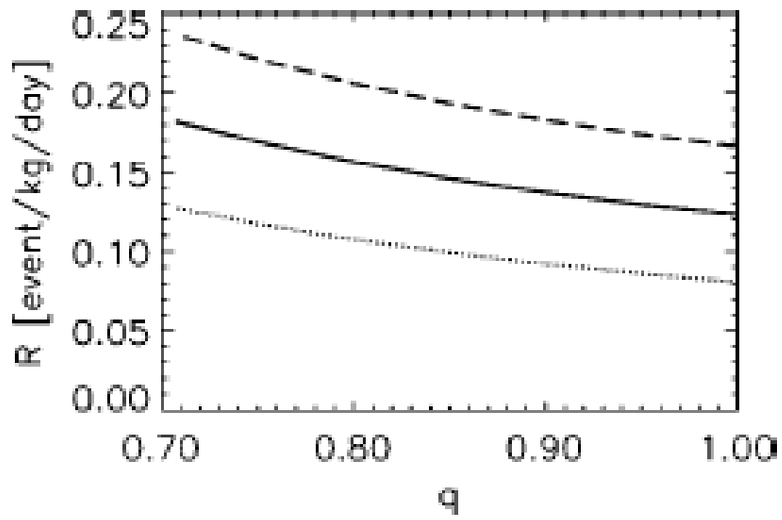


FIG. 4. Total detection rate as a function of halo flattening q for nonrotating (solid), maximally corotating (dashed), and maximally counterrotating (dotted) halos.

Kamionkowski and Kinkhabwala, Phys. Rev. D 57, 3256 (1998).

The local density and distribution of dark matter can be inferred by studying the rotational curve of our galaxy. Clumps in the dark matter should be destroyed through tidal interactions, resulting in a homogeneous distribution (Helmi et al, Phys. Rev. D 66, 063502 (2002)).
The biggest astrophysical uncertainty comes from estimates of the local dark matter density:

$\rho \sim 0.34$ GeV/cm^3 : Bahcall et al, Astrophys. J. 265 (1983) 730.
$\rho \sim 0.23$ GeV/cm^3 : R. R. Caldwell and J. P. Ostriker, Astrophys. J. 251 (1981) 61.
$\rho = 0.34 - 0.73$ GeV/cm^3 : E. I. Gates et al., Astrophys. J. 449 (1995),L123.
$\rho = 0.2 - 0.8$ GeV/cm^3 : L. Bergstrom et al, Astropart. Phys. 9 (1998), 137.

Looking for Dark Matter at Underground Labs

~50% Dark Matter Searches use Noble Liquids

DAMA/LIBRA ~250 kg ULB NaI(Tl)
(Large sodium Iodide Bulk for RAre processes)

As a result of a second generation R&D for more radiopure NaI(Tl)
by exploiting new chemical/physical radiopurification techniques
(all operations involving crystals and PMTs - including photos - in HP Nitrogen atmosphere)

improving installation
and environment

PMT
+HV
divider

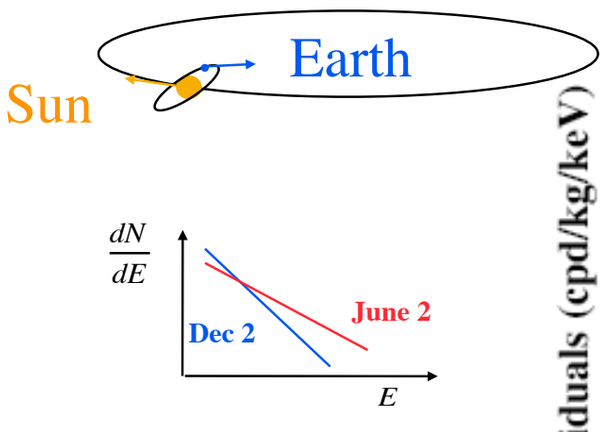
Cu etching with
super- and ultra-
pure HCl solutions,
dried and sealed in
HP N_2

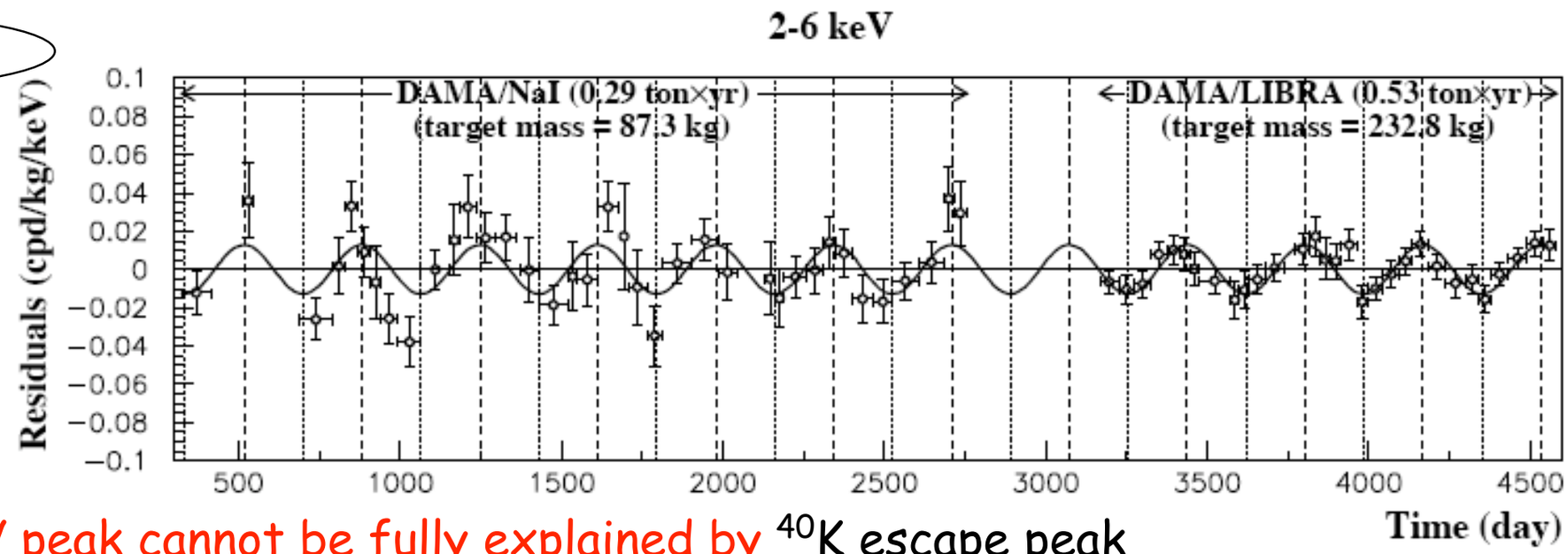
storing new crystals

etching staff at work
in clean room

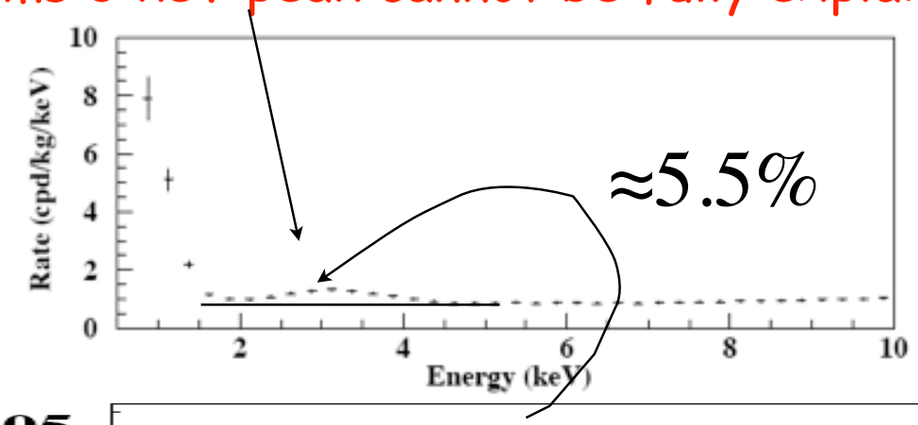
DAMA Claim April 2008

If WIMPs exist, we expect a modulation in event rate

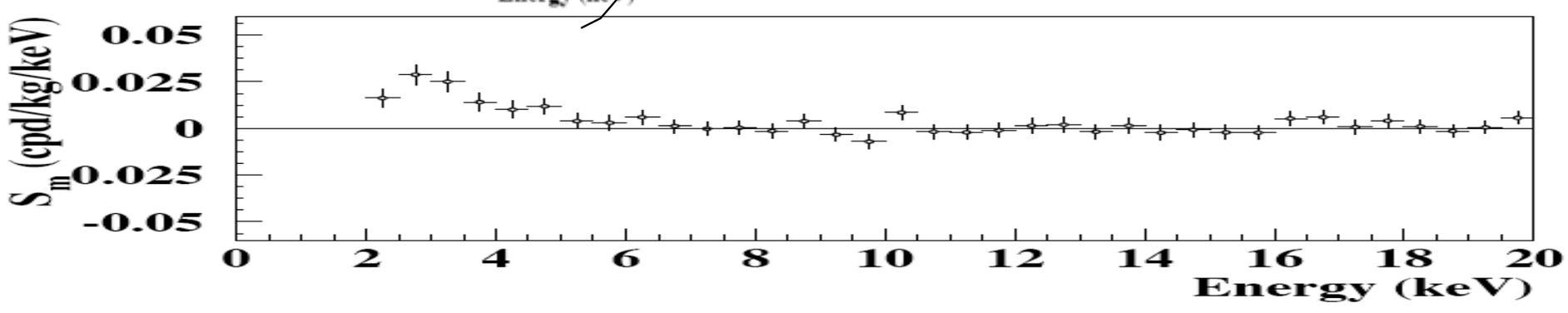




DAMA claims 3 keV peak cannot be fully explained by ^{40}K escape peak



Clearly a modulation



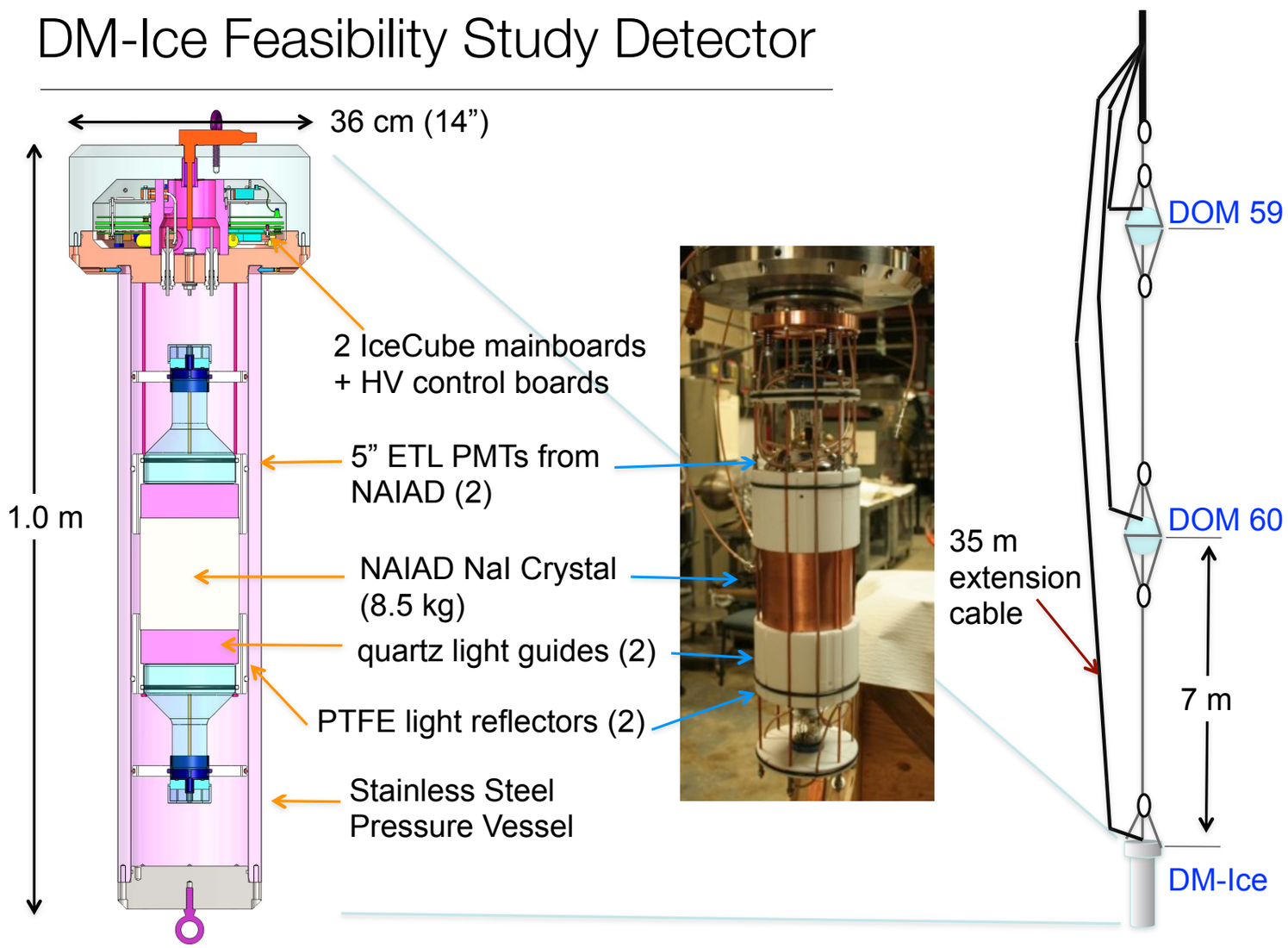
(from B. Cabrera)

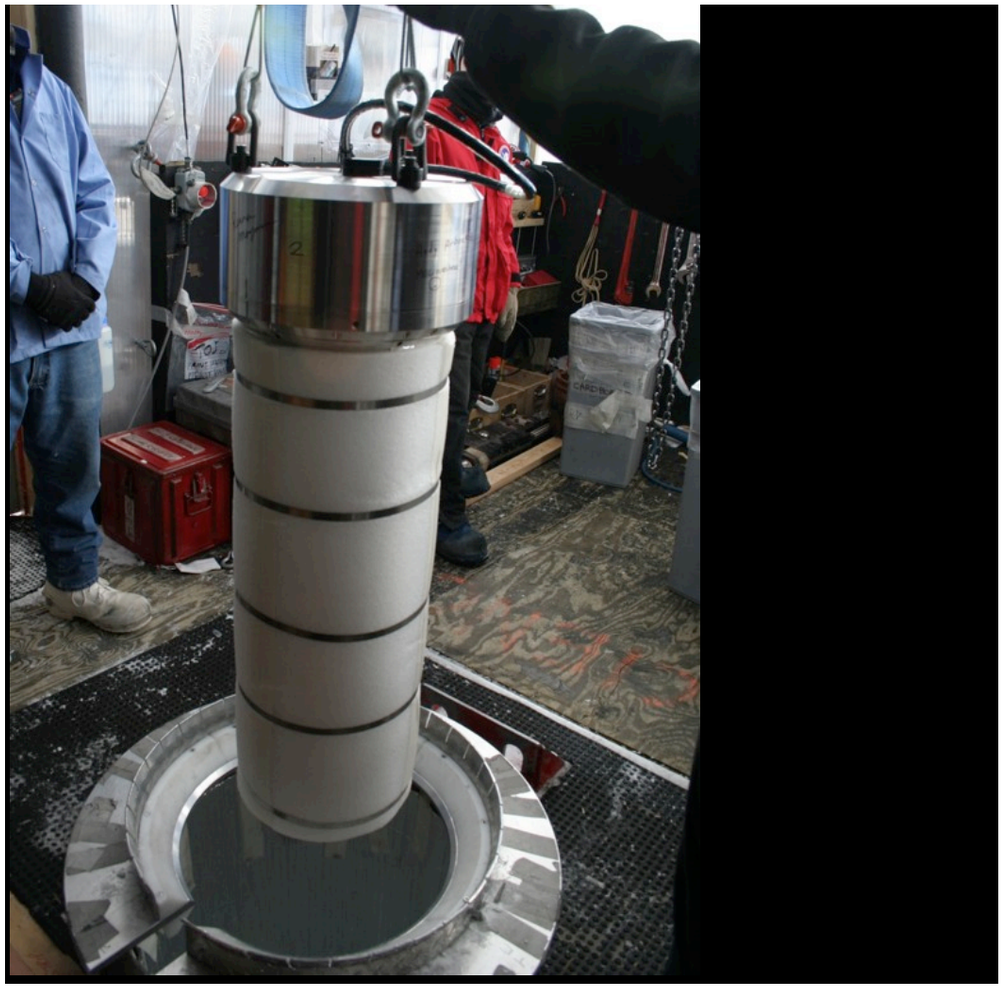
DM-Ice

Goal: Assess the feasibility of deploying NaI crystals in the Antarctic ice, for a dark matter detector to test the DAMA result.

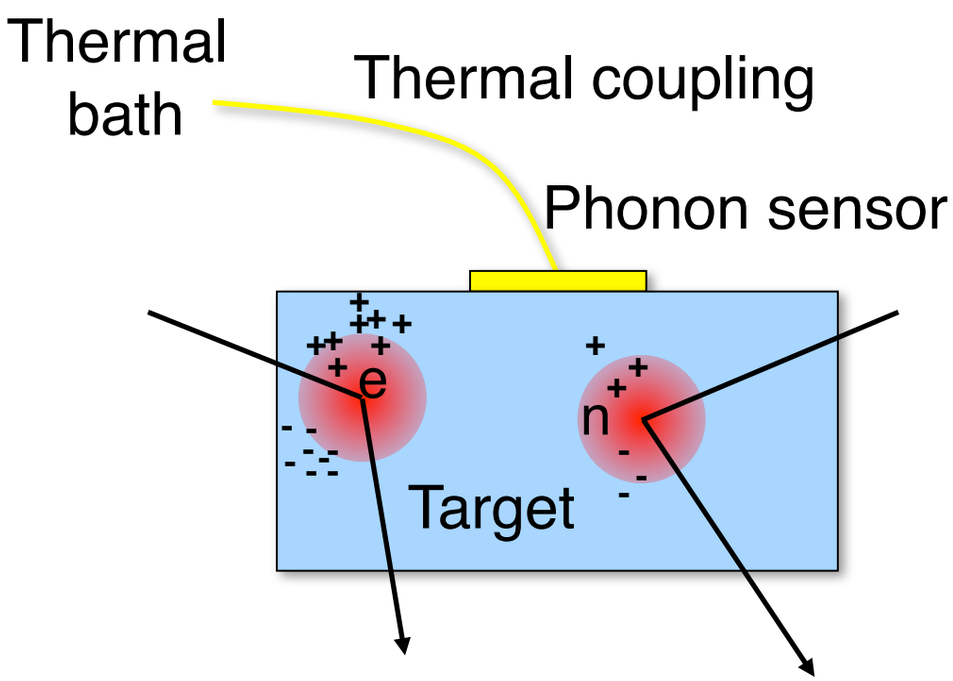
2 crystals (17 kg) from the NAIAD experiment (2000-2003).

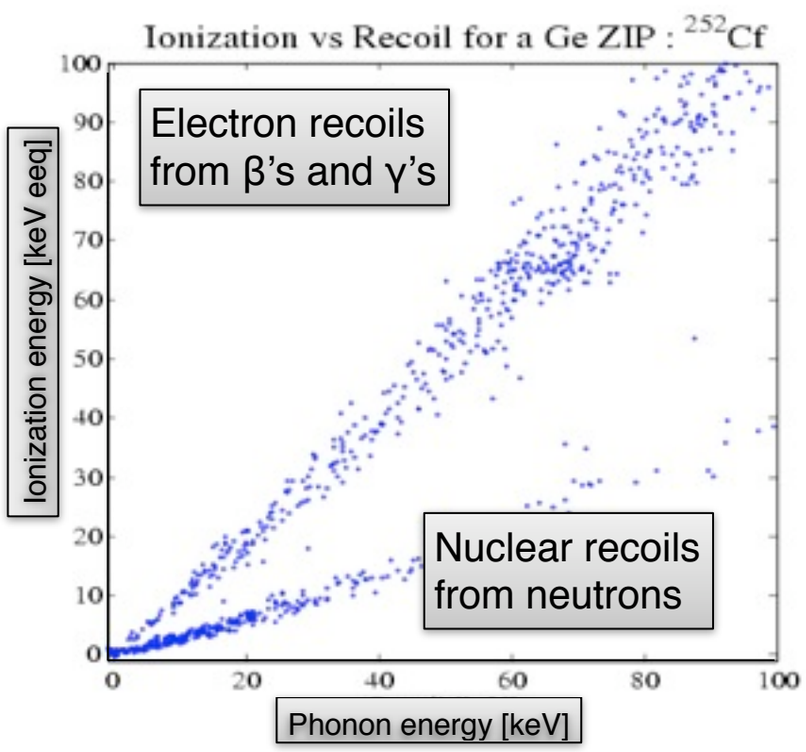
Initial crystals have intrinsic background 5-10 times higher than the reported DAMA background.





CDMS-II



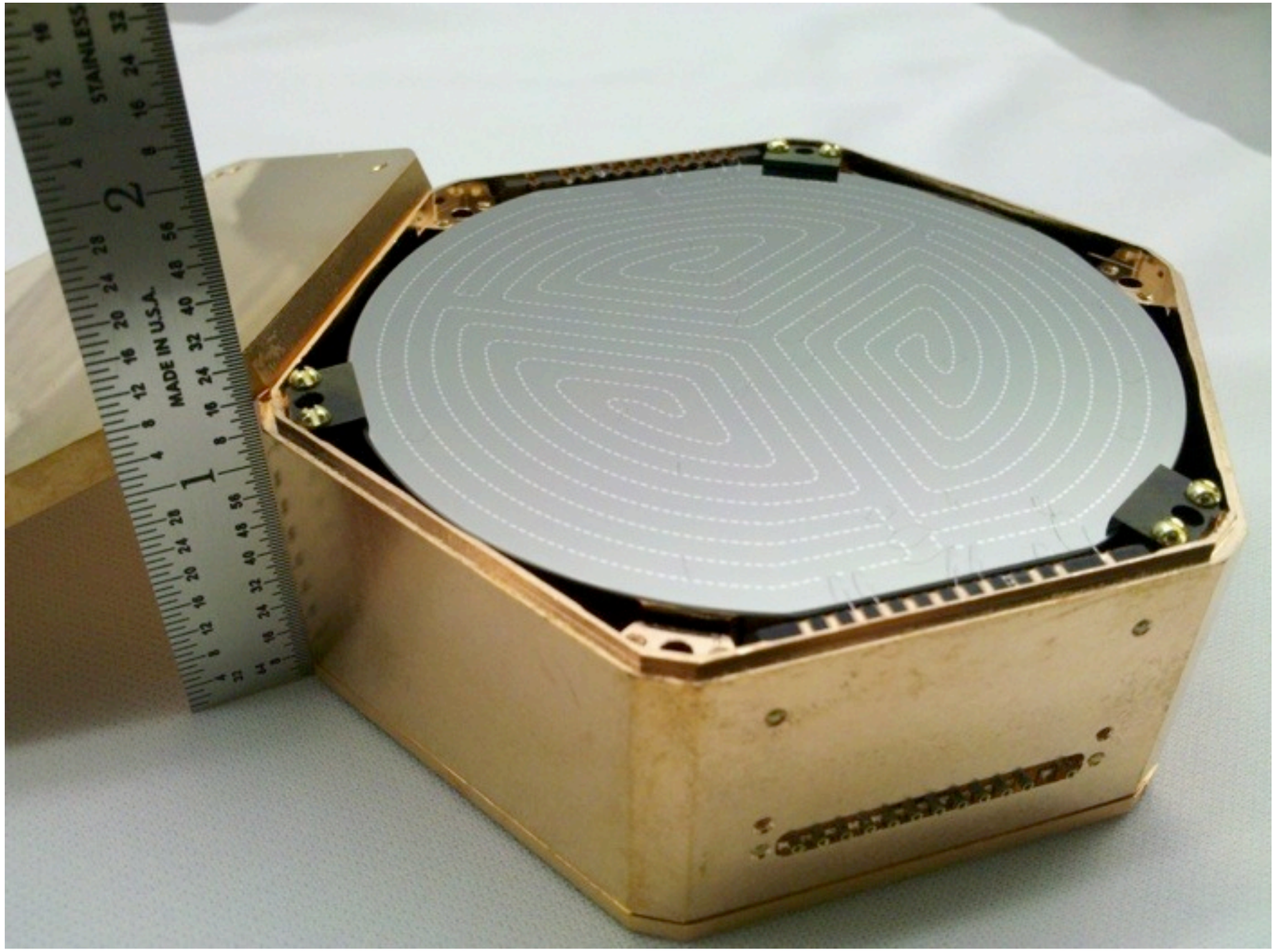


Cryogenic ionization detectors, Ge (Si)

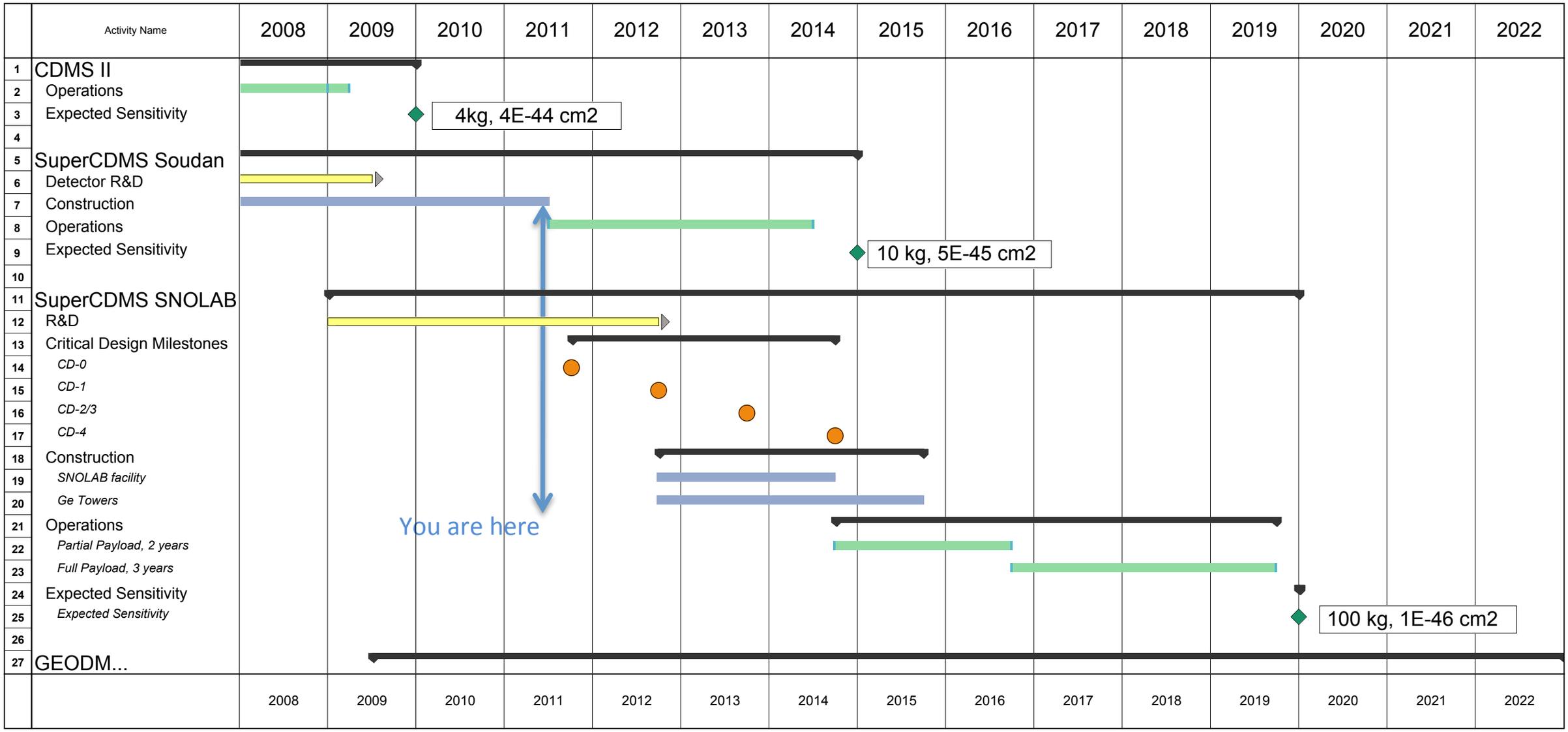
- ∅ = 7 cm, h = 1 cm, m = 250 g (100 g)
- Thermal readout: superconducting phase transition sensor (TES)
- Transition temperature: 50 – 100 mK
- 4 sensors/detector, fast signal (< ms)
- Charge readout: Al electrode, divided

SuperCDMS Soudan iZIP Detectors

- Cool to within 0.05 degrees of absolute zero (-459.6 F)
- For each event simultaneously measure the charge produced and the heat produced.
- Allows us to tell if recoiling particle was an electron (backgrounds) or nucleus (WIMP and neutrons)
- Deep underground to avoid neutrons from cosmic ray activity

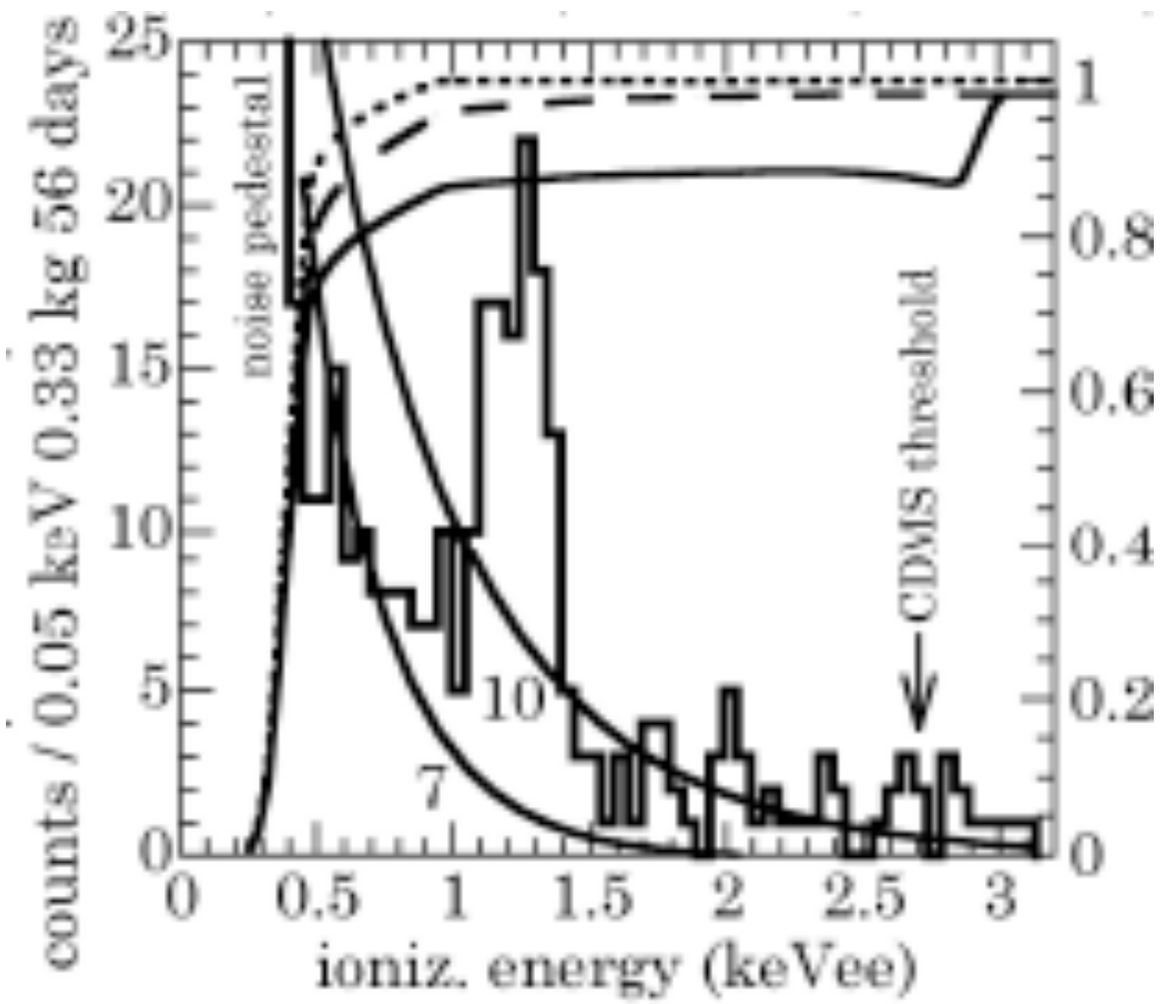


Overview of CDMS

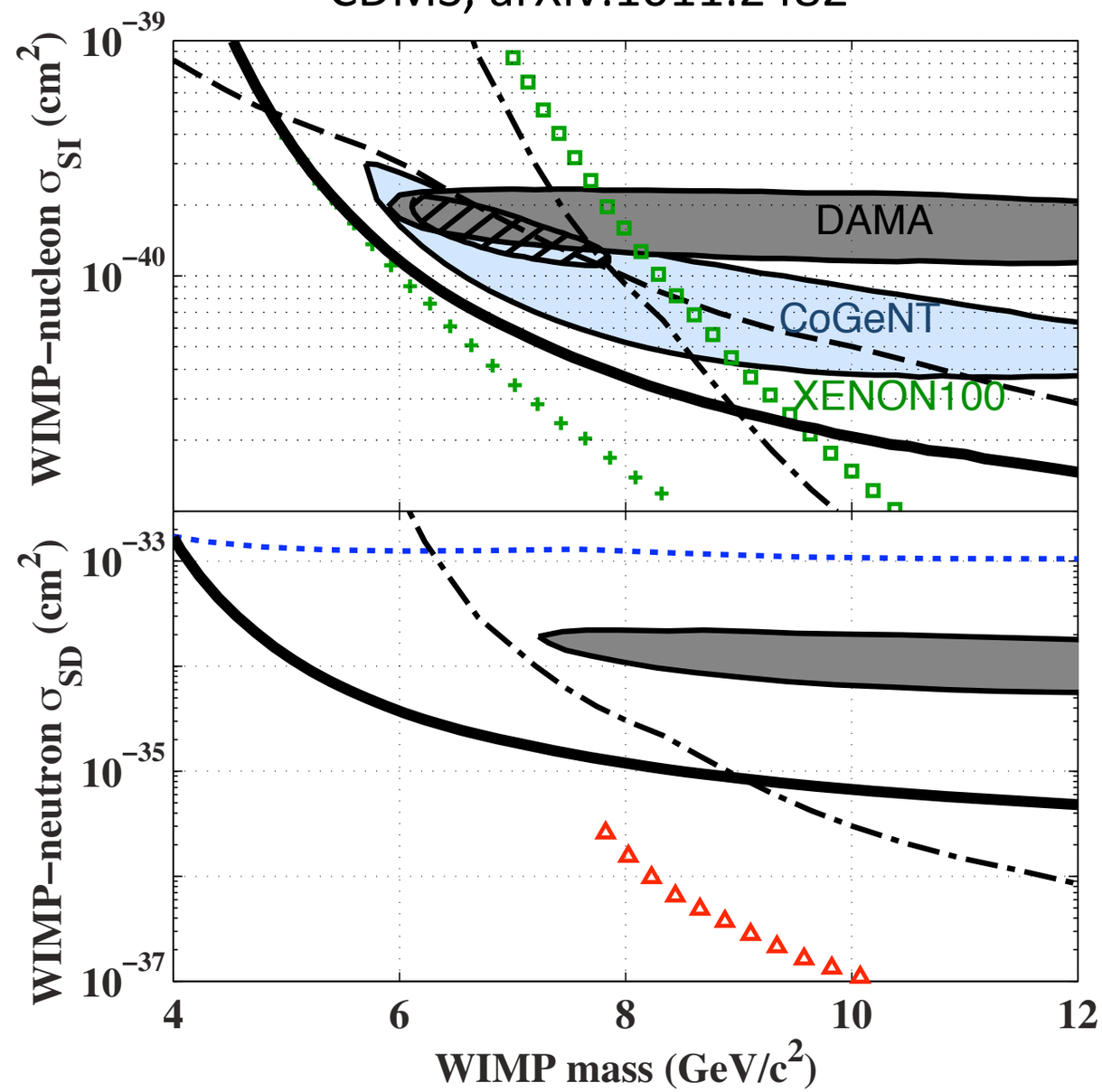


Light WIMPs?

CoGeNT excess: arXiv:1002.4703
P-type point contact Ge detector



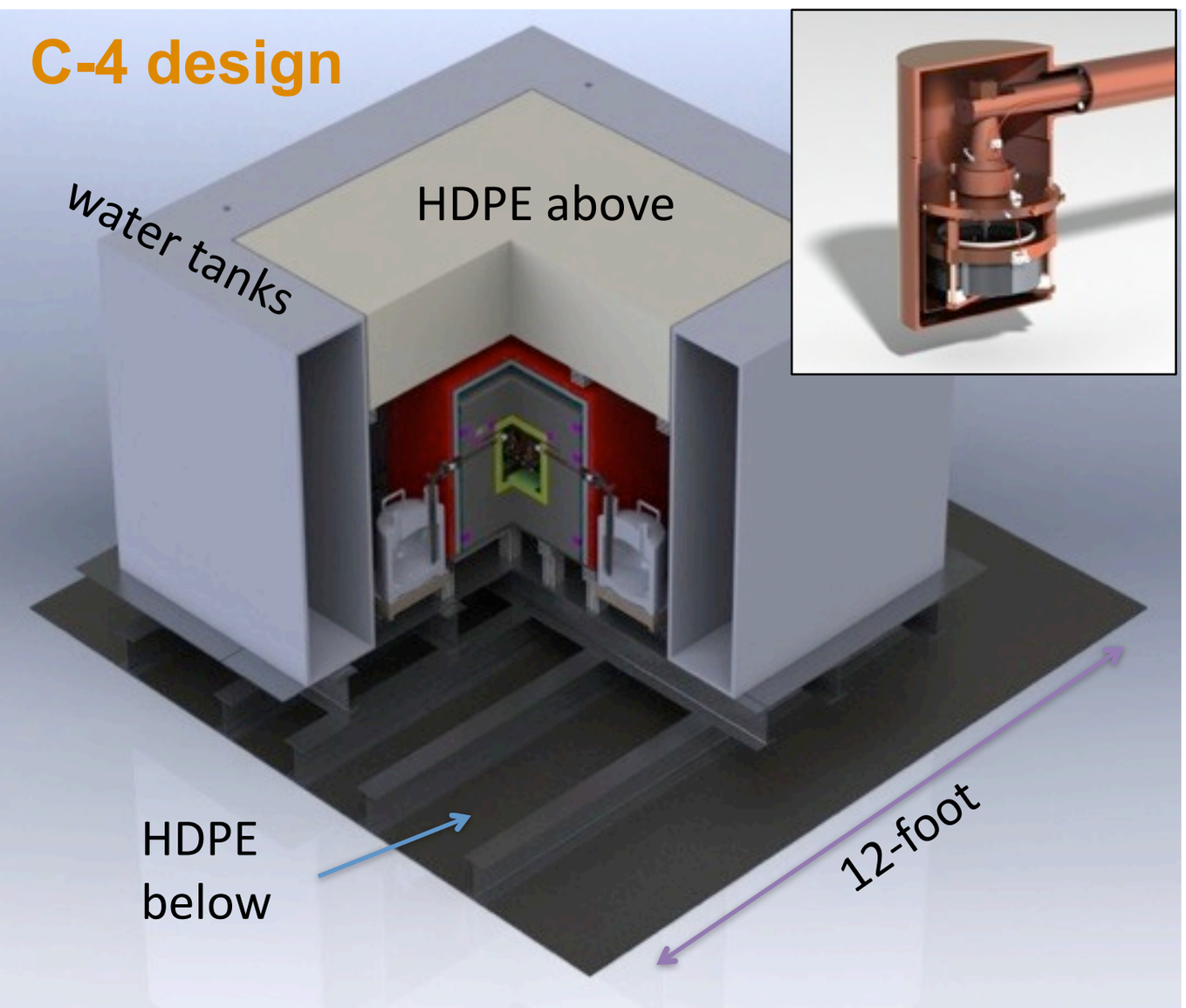
CDMS, arXiv:1011.2482

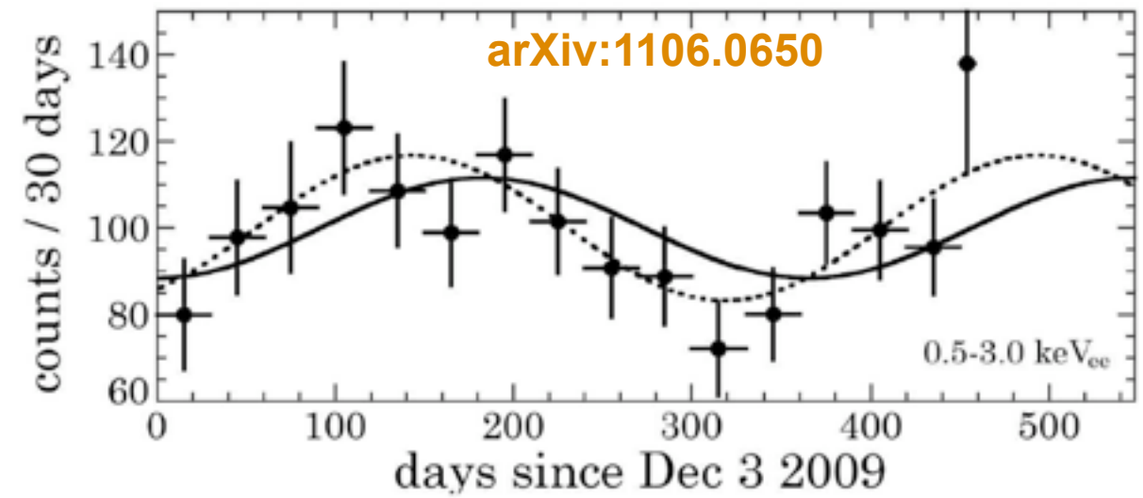


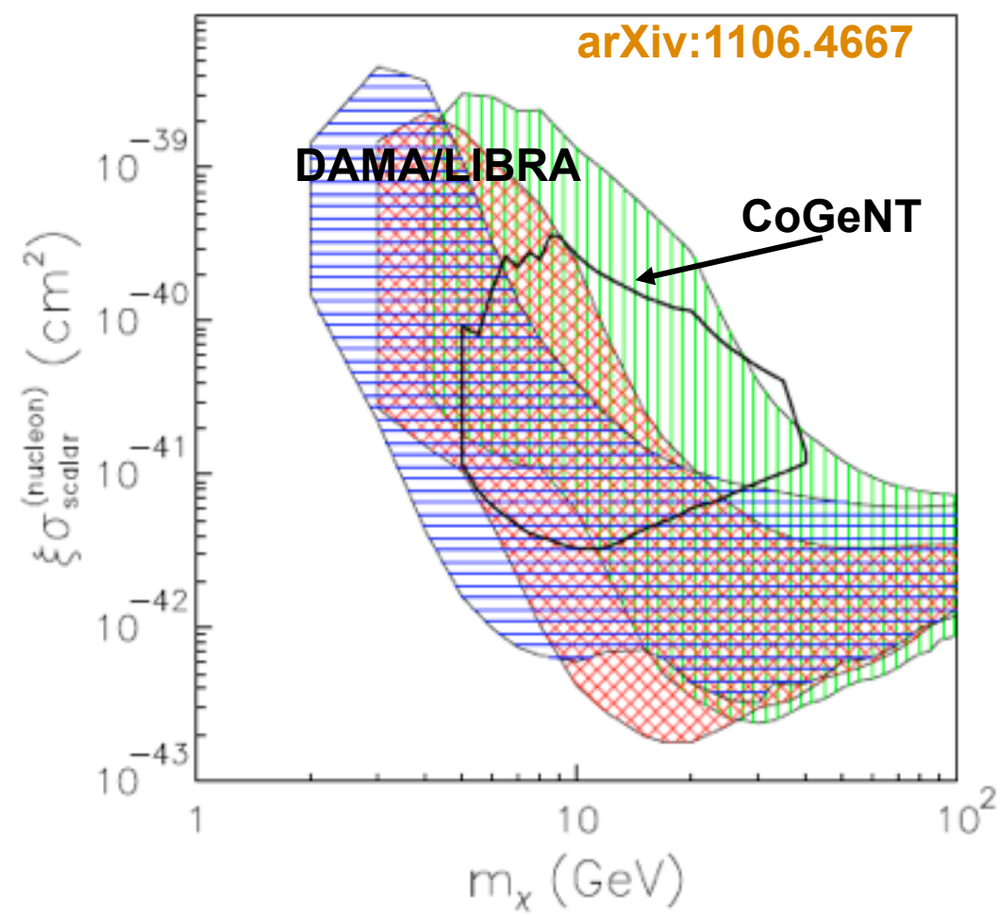
Hatched overlap region: Hooper et al, Phys. Rev. D 82:123509 (2010)

CoGeNT Present Status

- Annual modulation of unknown origin, measured with ~0.4 kg crystal at Soudan, in possible agreement with DAMA/LIBRA.
- C-4 to start end of 2011 in Soudan (x10 present mass, significant reduction in bckg and threshold expected).

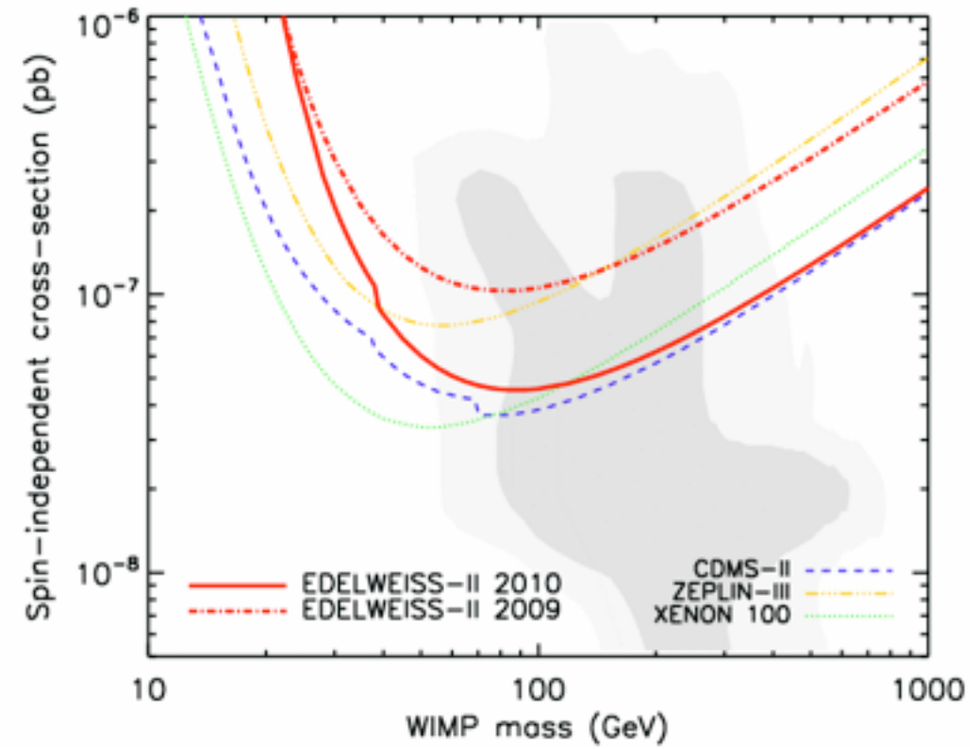


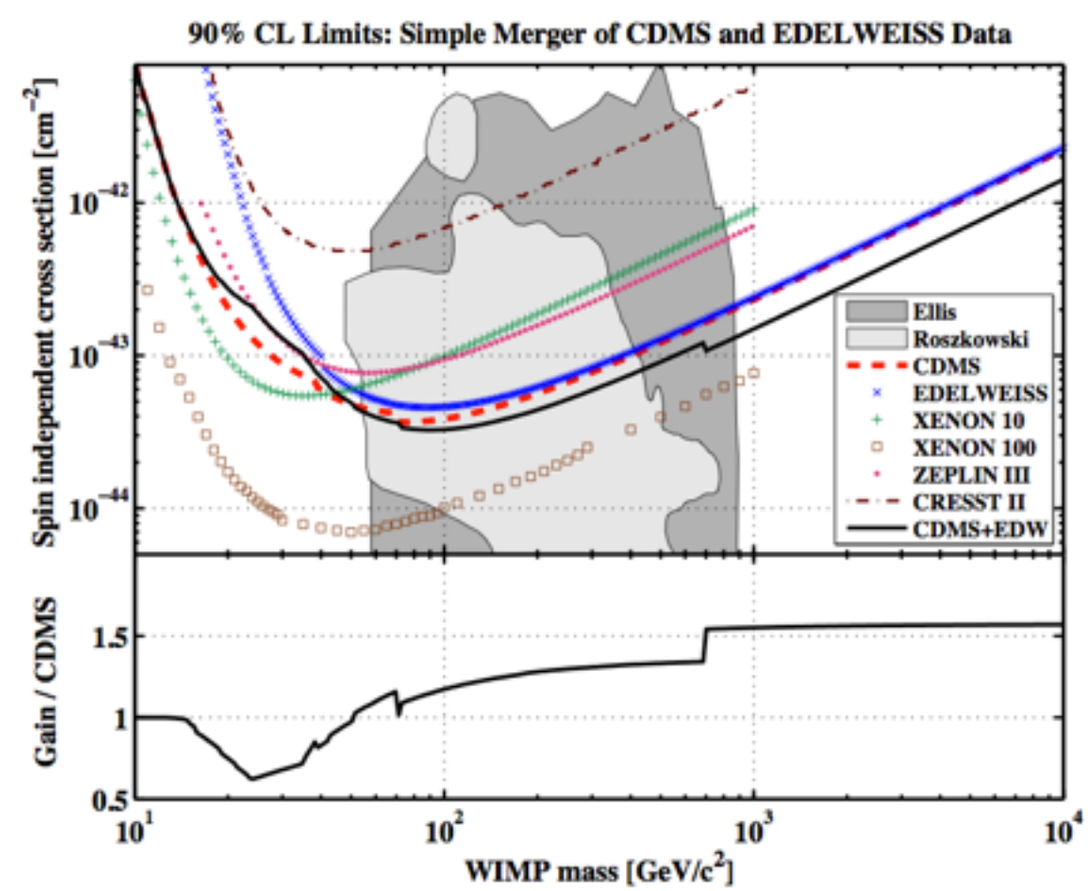




EDELWEISS-II latest WIMP search results

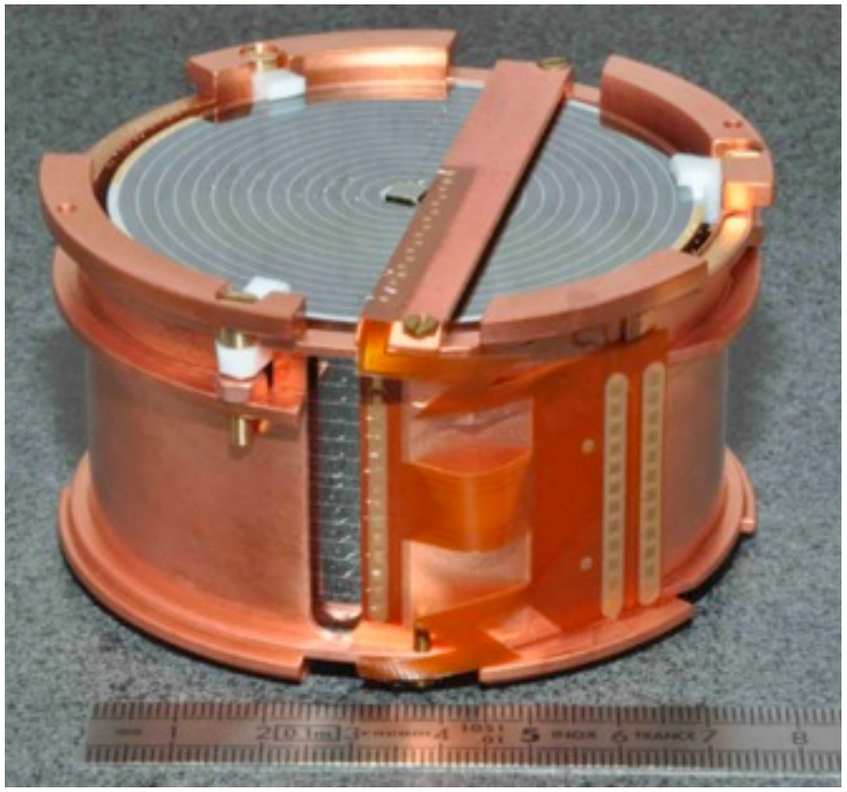
- Interleaved electrode for surface event rejection. PLB 681 (2009) 305.
- Final results with 10 400-g ID detectors (384 kgd): spin dependent limits (4.4×10^{-8}pb at 85 GeV)+ inelastic limits PLB (2011) doi: 10.1016/j.phyletb.2011.07.034, [arXiv:1103.4070v2].
- Joint combination with CDMS - ~50% gain in sensitivity at high masses Phys. Rev. D 84, 011102 (2011).

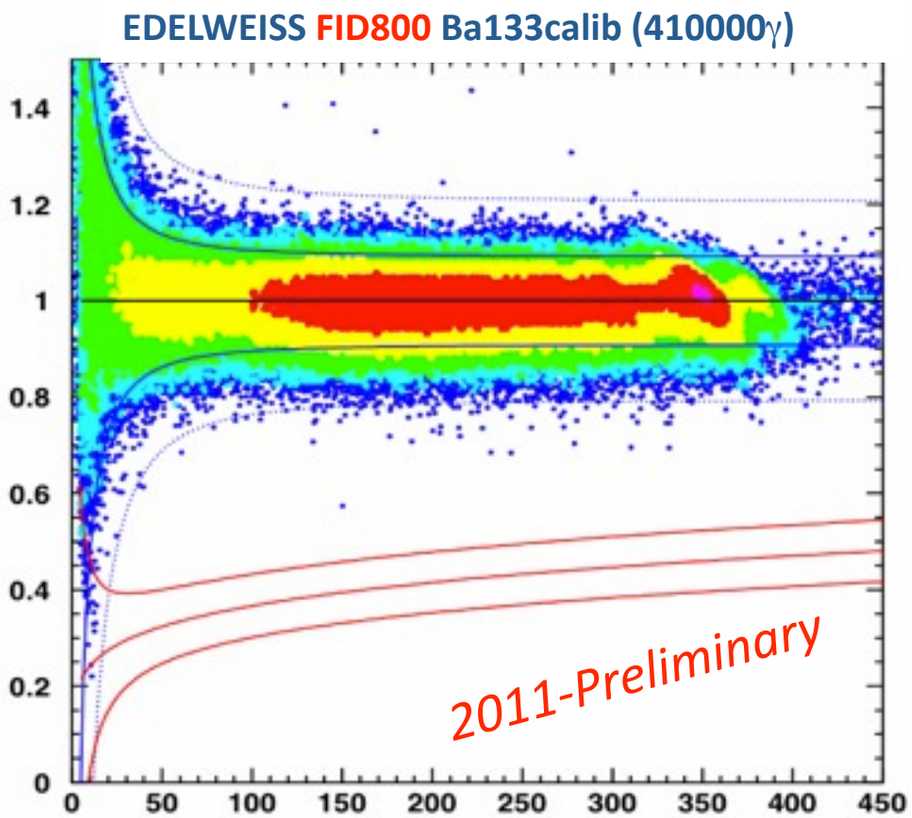




EDELWEISS-III status

- New 800g detectors, fully covered by interleaved electrodes
  - Larger fiducial volume (~X4)
  - Test of first 8 detectors: improved γ-ray rejection wrt EDELWEISS-II
- 40 detectors funded, ready by 2012: 32 kg total mass
  - Reduction of radioactive bkg + improved shielding
  - 3000 kgd in ~6 months, 5×10^{-9} pb sensitivity
- Further plans: EURECA, 0.15 to 1-t scale



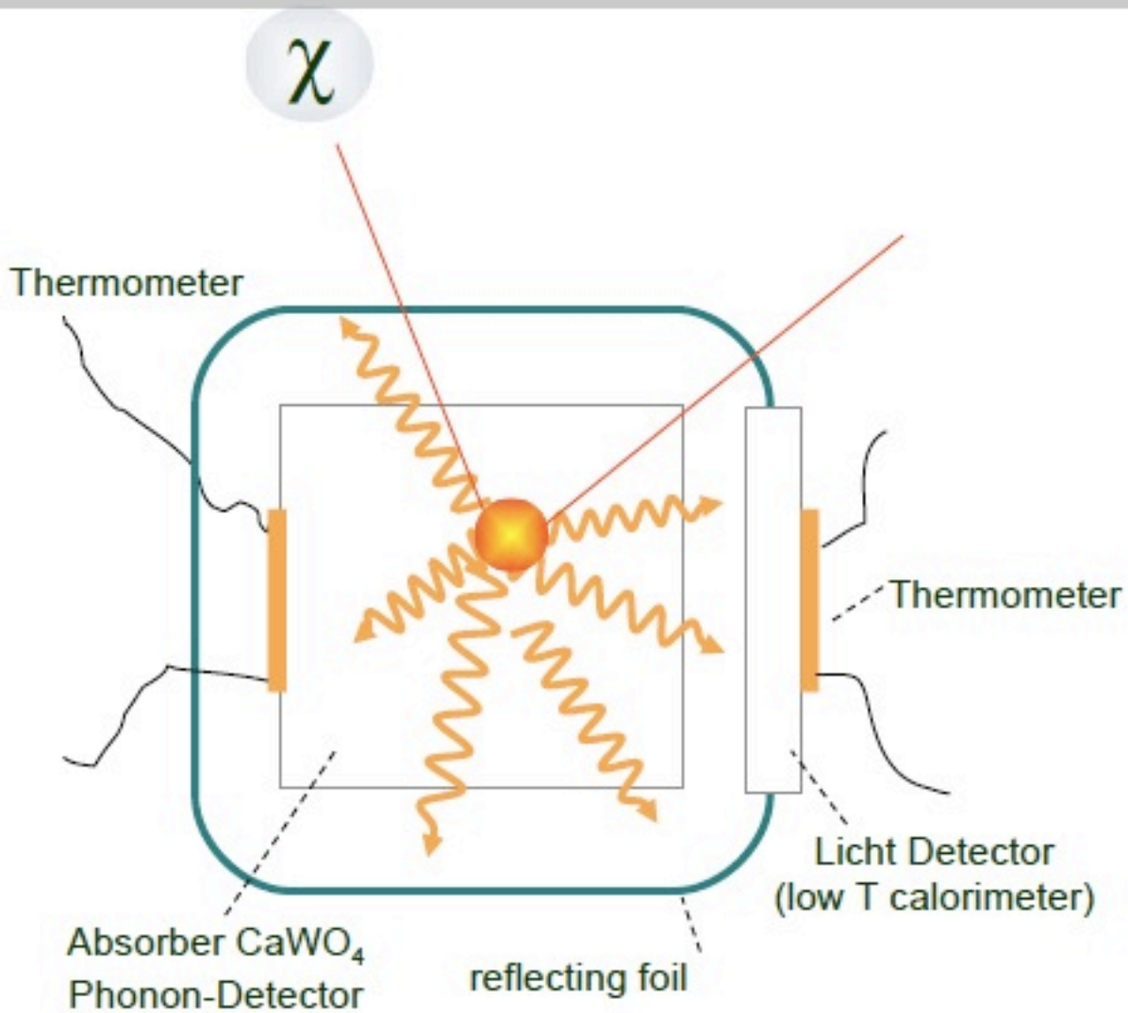


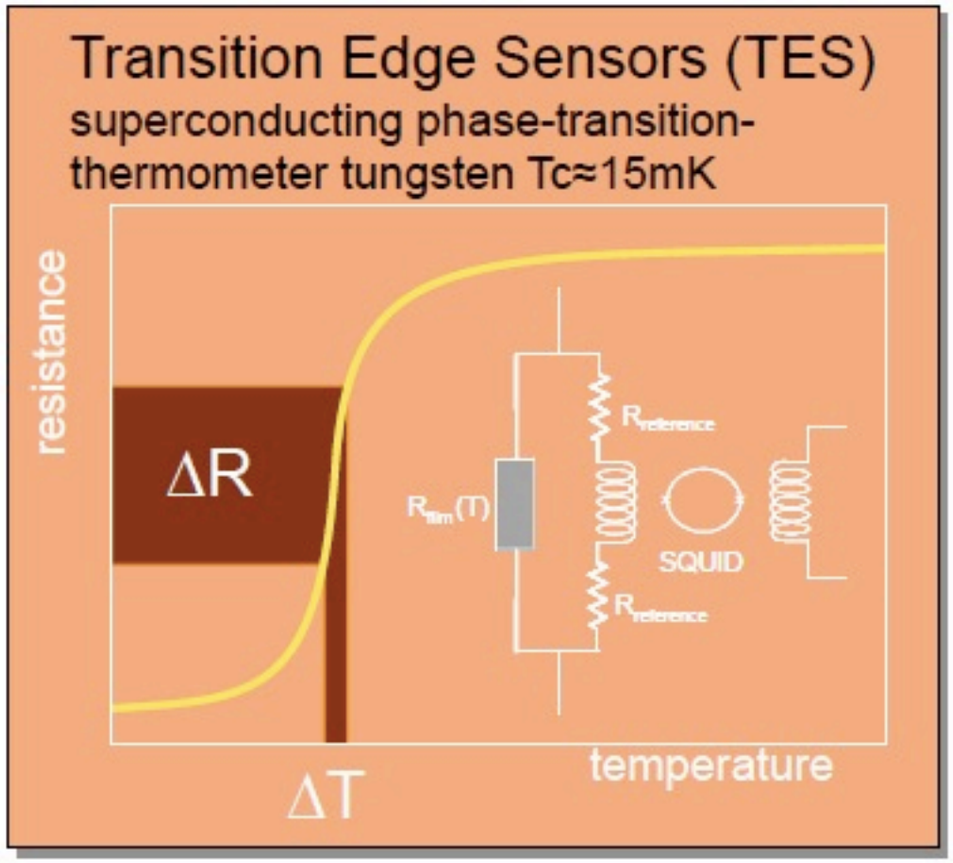
CRESST-II

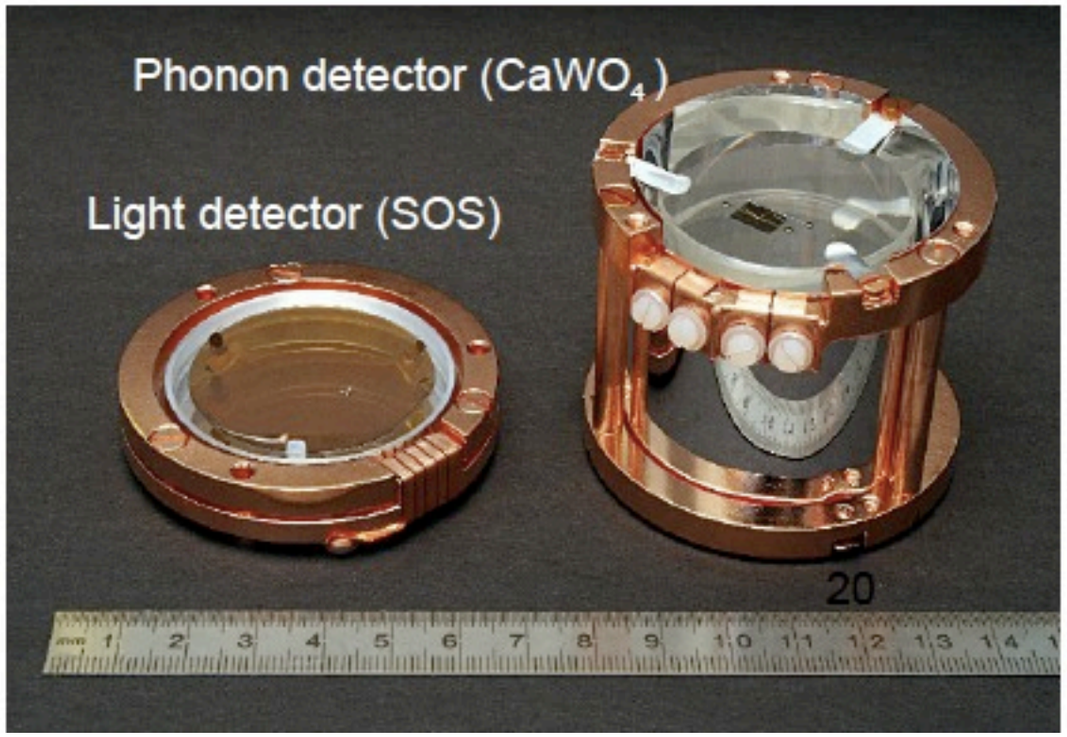
CRESST
Cryogenic Rare Event Search with Superconducting Thermometers

light + phonons (scintillating crystals)

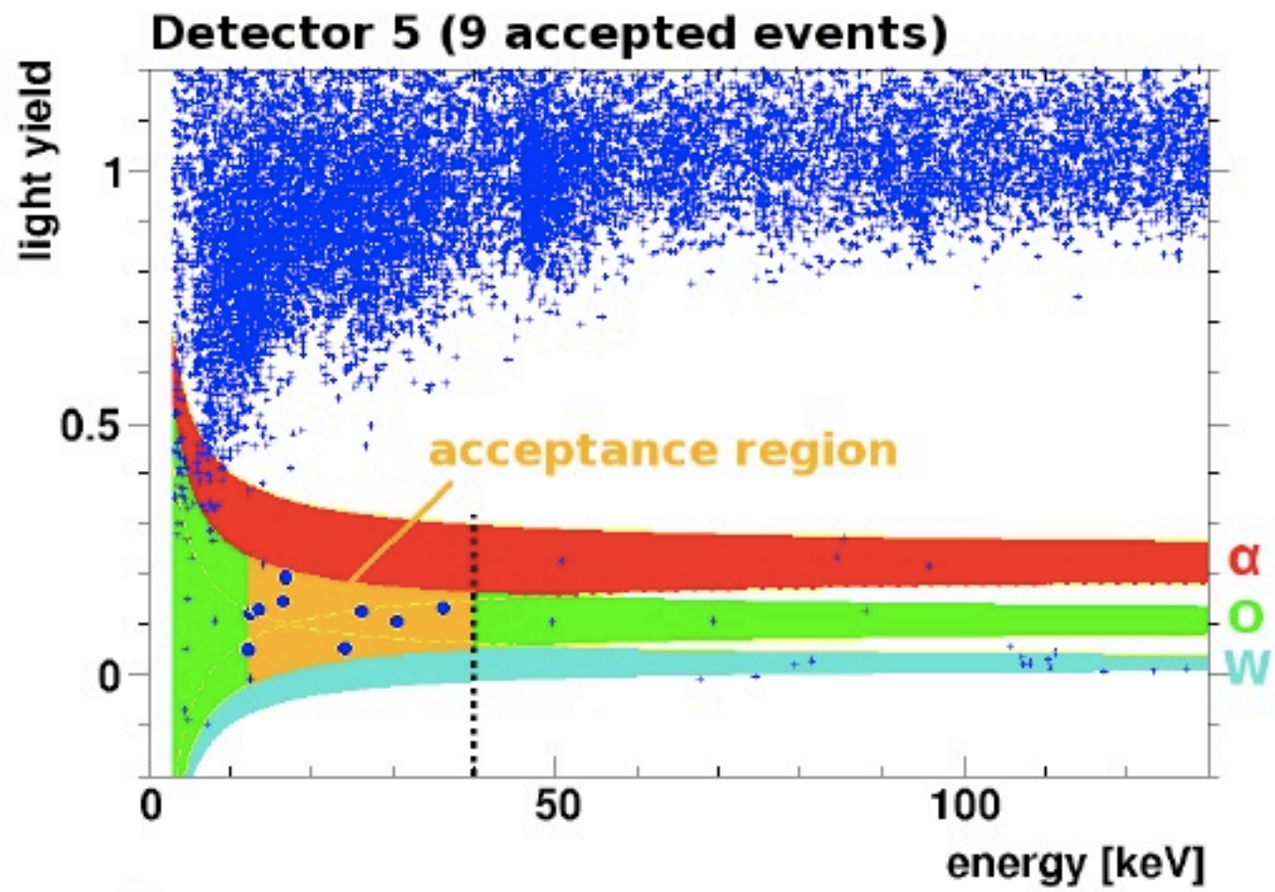
Max-Planck-Institut München, TU München
Universität Tübingen, Oxford University, Gran Sasso

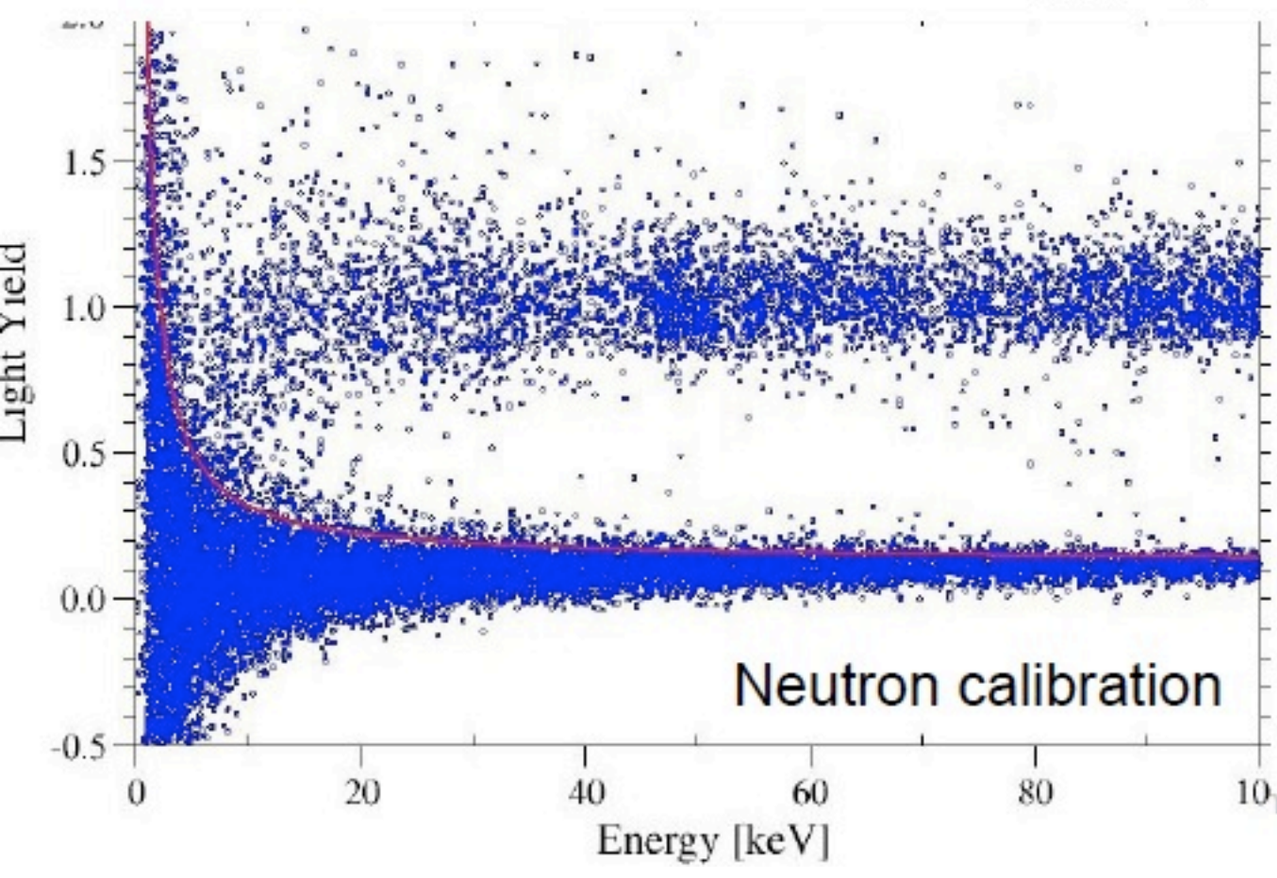






Anomalous events in the CRESST oxygen band





Data from 9 detectors

Exposure: 730 kg d

57 events observed in oxygen band

Background estimated from side bands:

- **9.3 alpha events**
- **17.3 neutrons**
- **9.0 e/gamma leakage**

Excess events not explained by modeled background

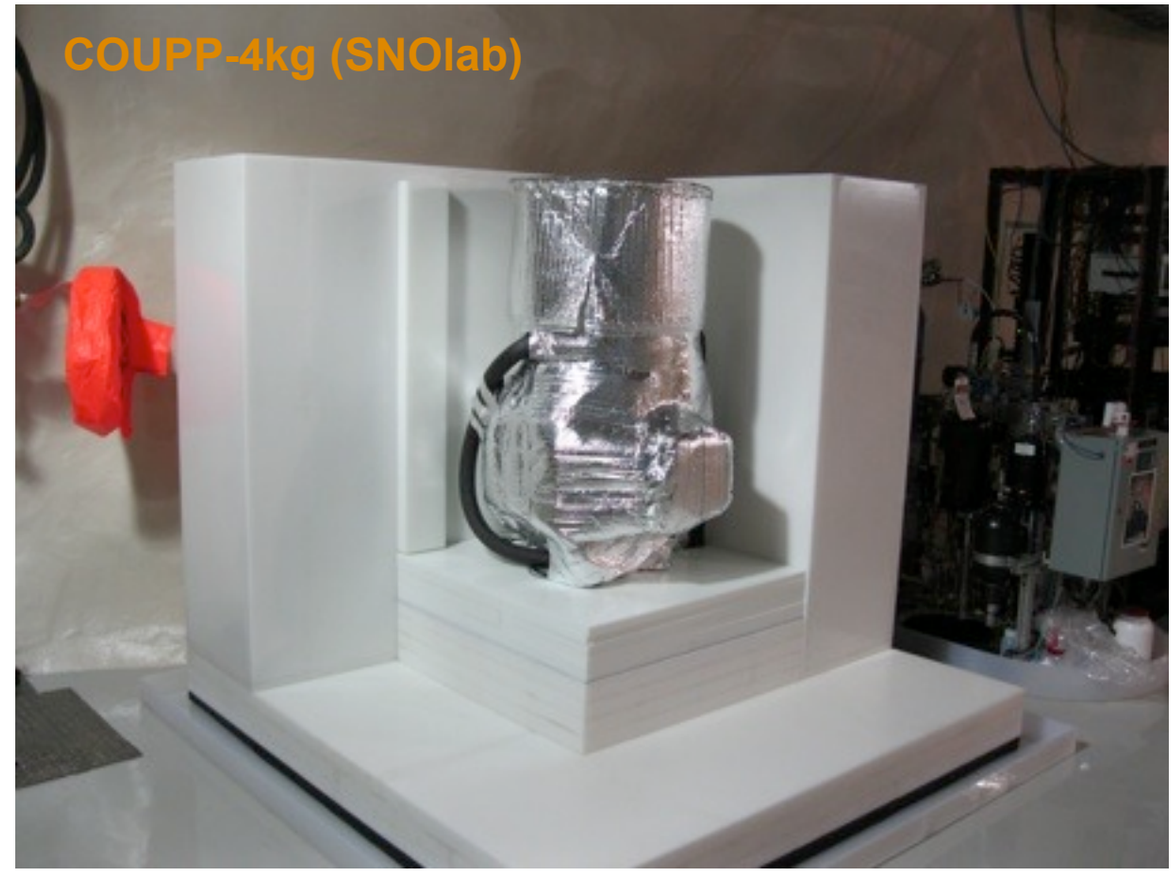
Hint of low-mass WIMPs?

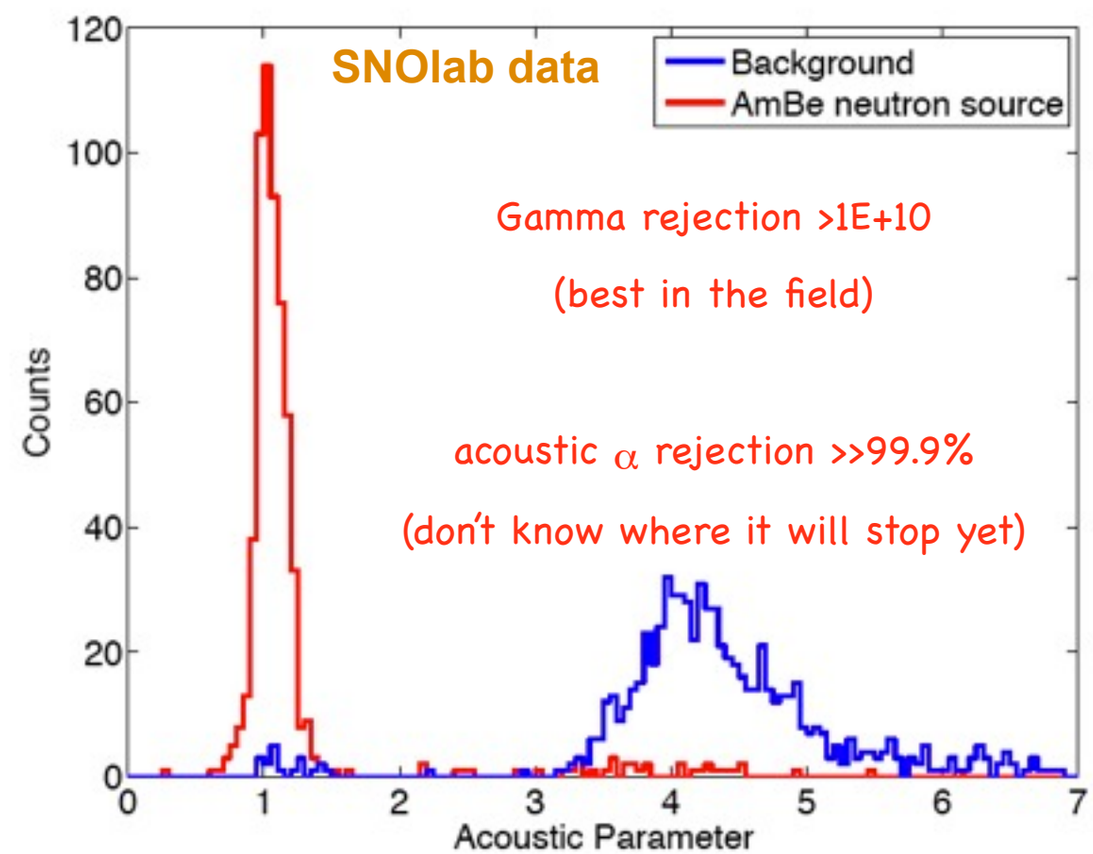
- **13 GeV mass**
- **3e-41 cm^2 cross-section**

CRESST has called a press conference for Sept. 6, coincident with a talk at TAUP. Stay tuned!

COUPP Present Status

- 4 kg chamber taking data at SNOlab.
- Weak (α,n) sources identified and in the process of elimination.
- Excellent acoustic discrimination against alphas demonstrated.
- 60 kg chamber to be installed at SNOlab during 2011.





The Noble Liquid Revolution

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

Easily purified

- low reactivity
- impurities freeze out
- low surface binding
- purification easiest for lighter noble liquids

Ionization electrons may be drifted through the heavier noble liquids

Very high scintillation yields

- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

Easy construction of large, homogeneous detectors

Liquified Noble Gases: Basic Properties

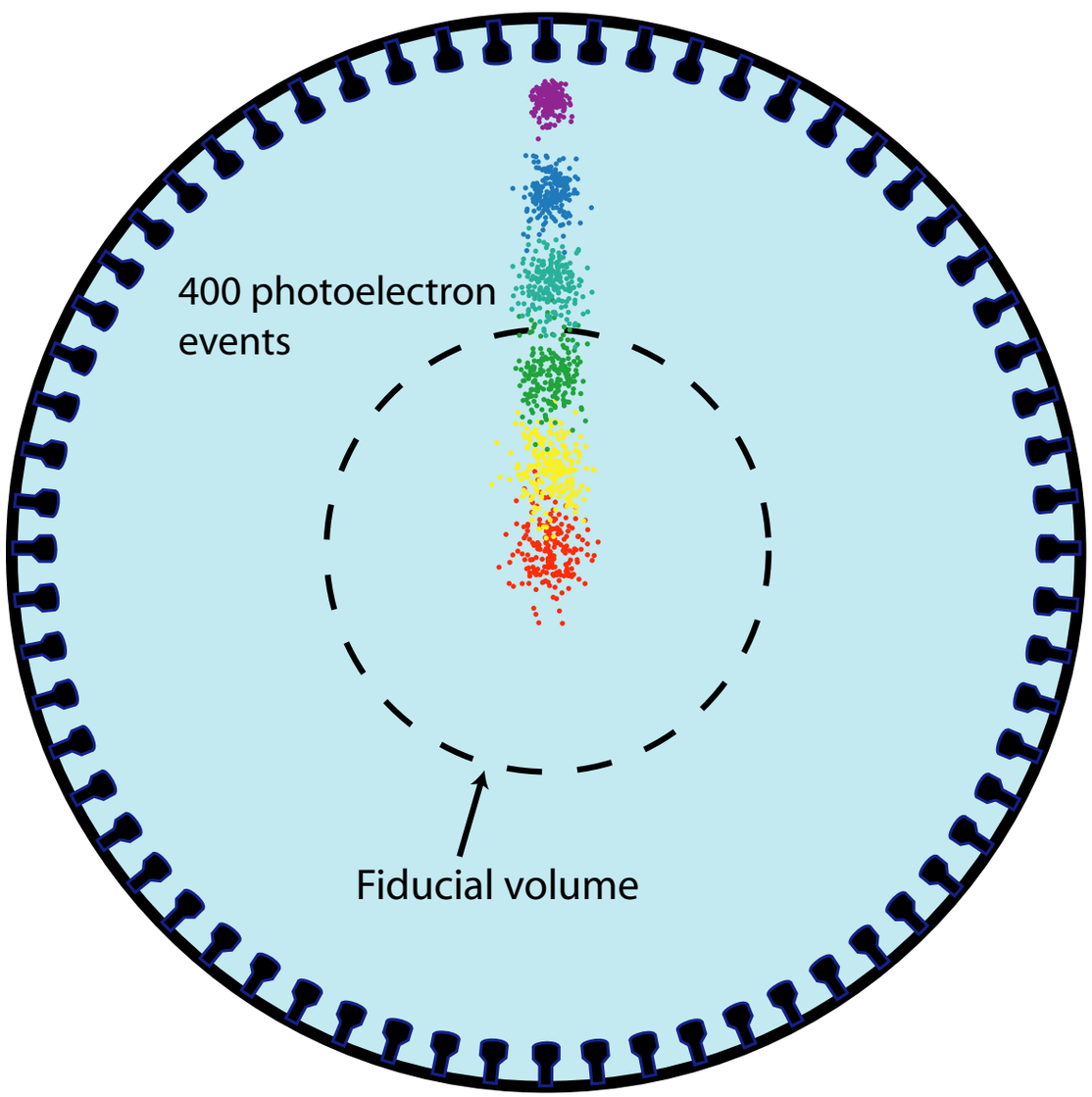
Dense and homogeneous
Do not attach electrons, heavier noble gases give high electron mobility
Easy to purify (especially lighter noble gases)
Inert, not flammable, very good dielectrics
Bright scintillators

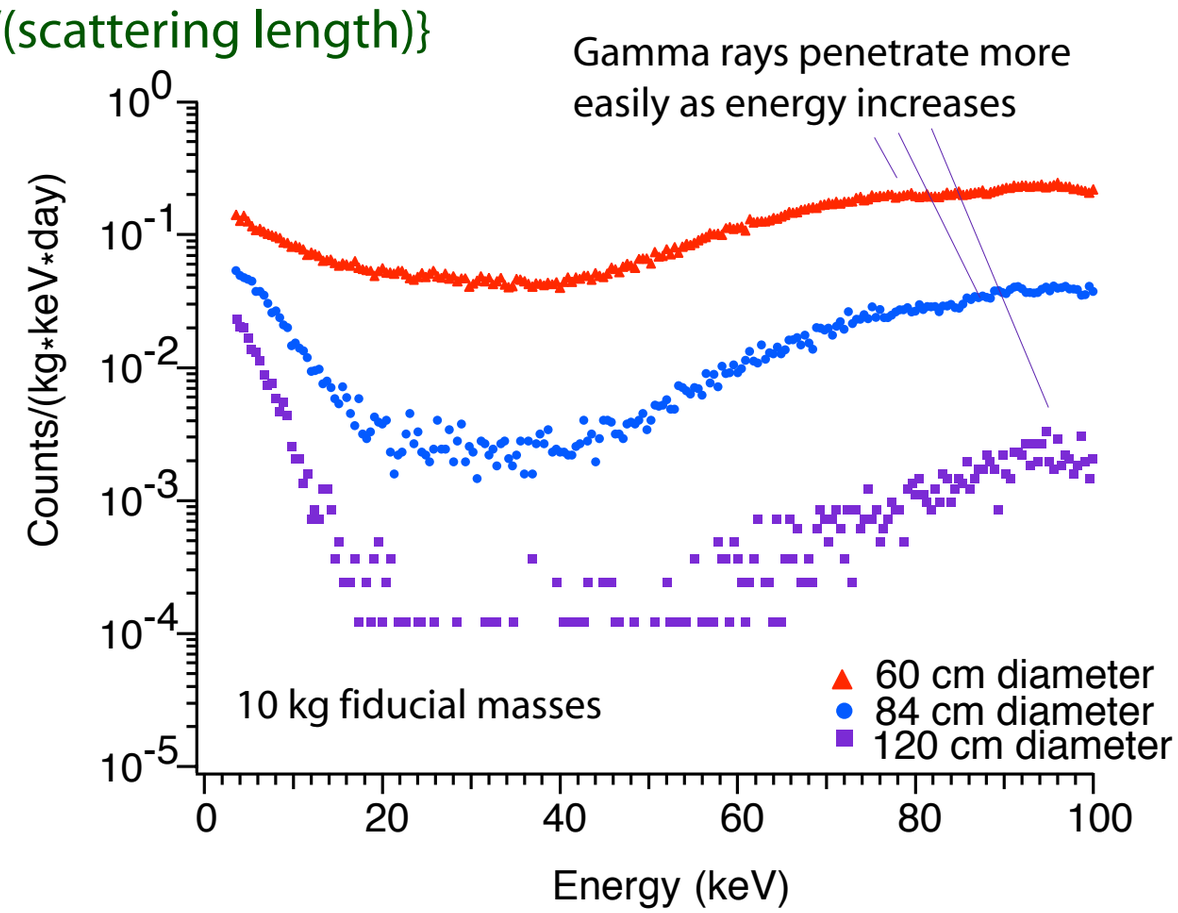
	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125	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

Background reduction through self-shielding and position resolution

There is an energy mismatch between penetrating gamma rays (~MeV) and low energy events of interest. High energy gammas must penetrate fiducial volume, scatter, and escape without depositing too much energy, in order to mimic a WIMP.

Background scales as exp{-(detector diameter)/(scattering length)}





Based on PMT hit pattern
Maximum likelihood algorithm
Incorporates scattering, wavelength shifter

K.J. Coakley and D.N. McKinsey,
Astroparticle Physics 22, 355 (2005).

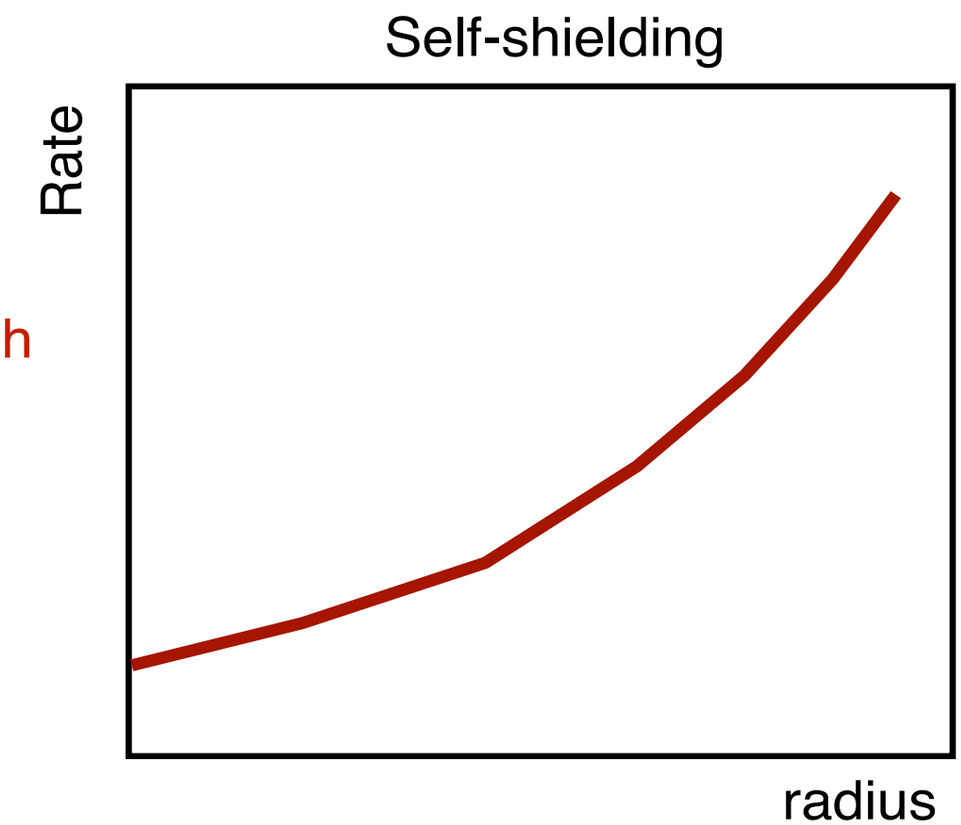
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

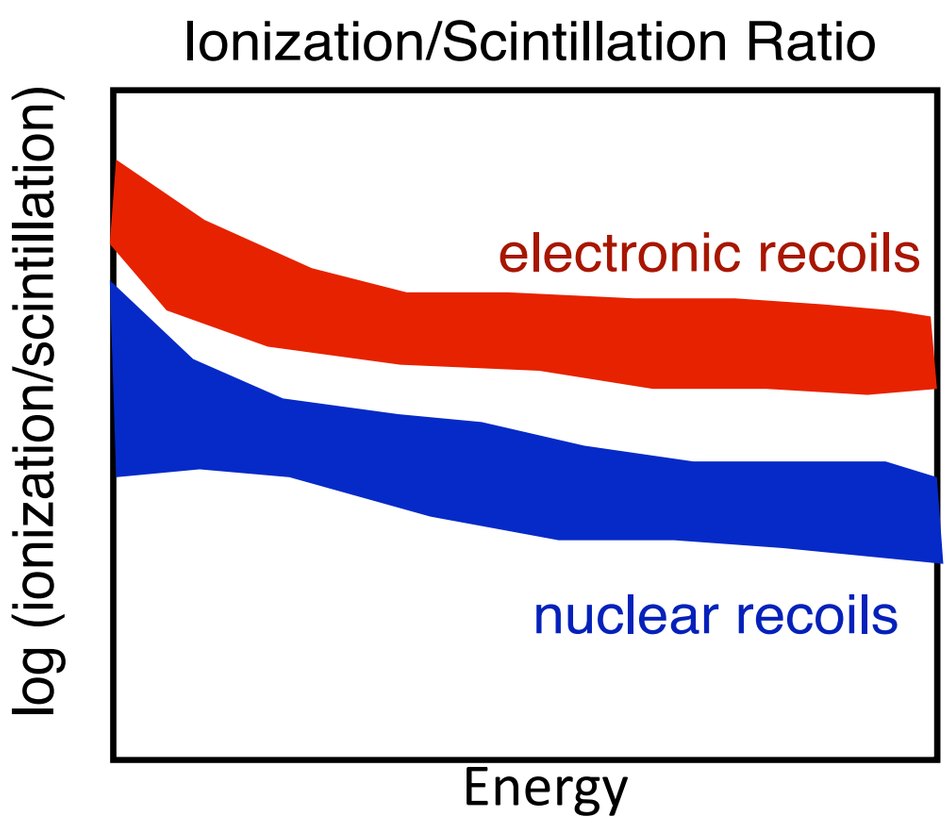
Require < 1 event in signal band during WIMP search

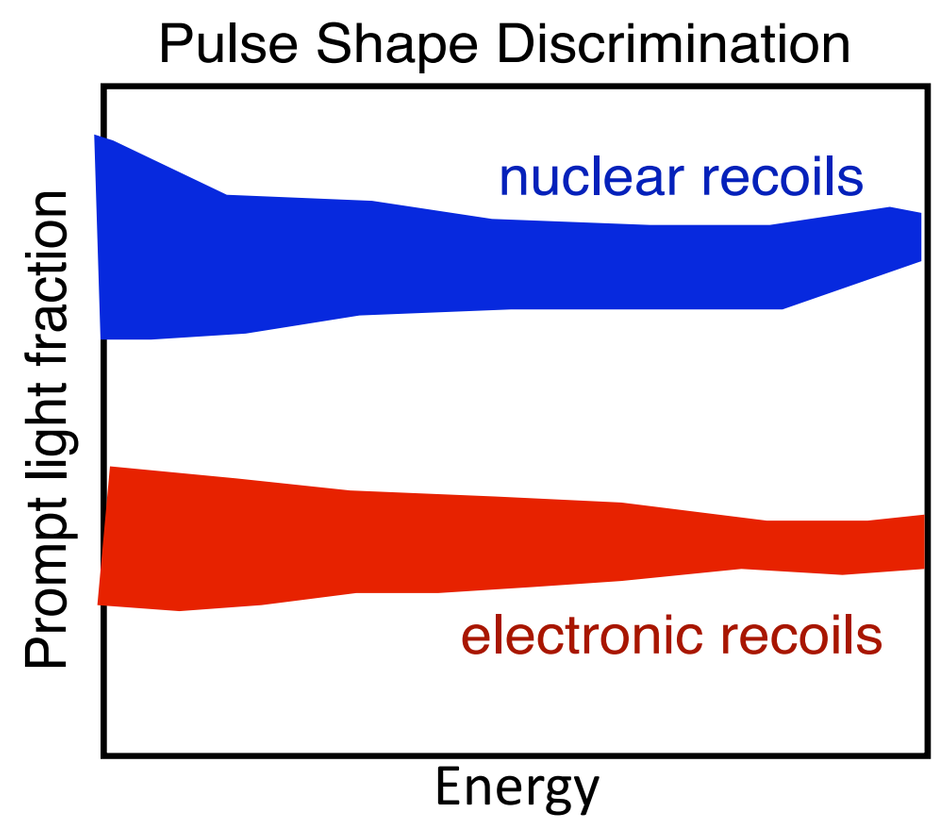
LXe: Self-shielding, Ionization/Scintillation ratio best

LAr: Pulse shape, Ionization/Scintillation ratio best

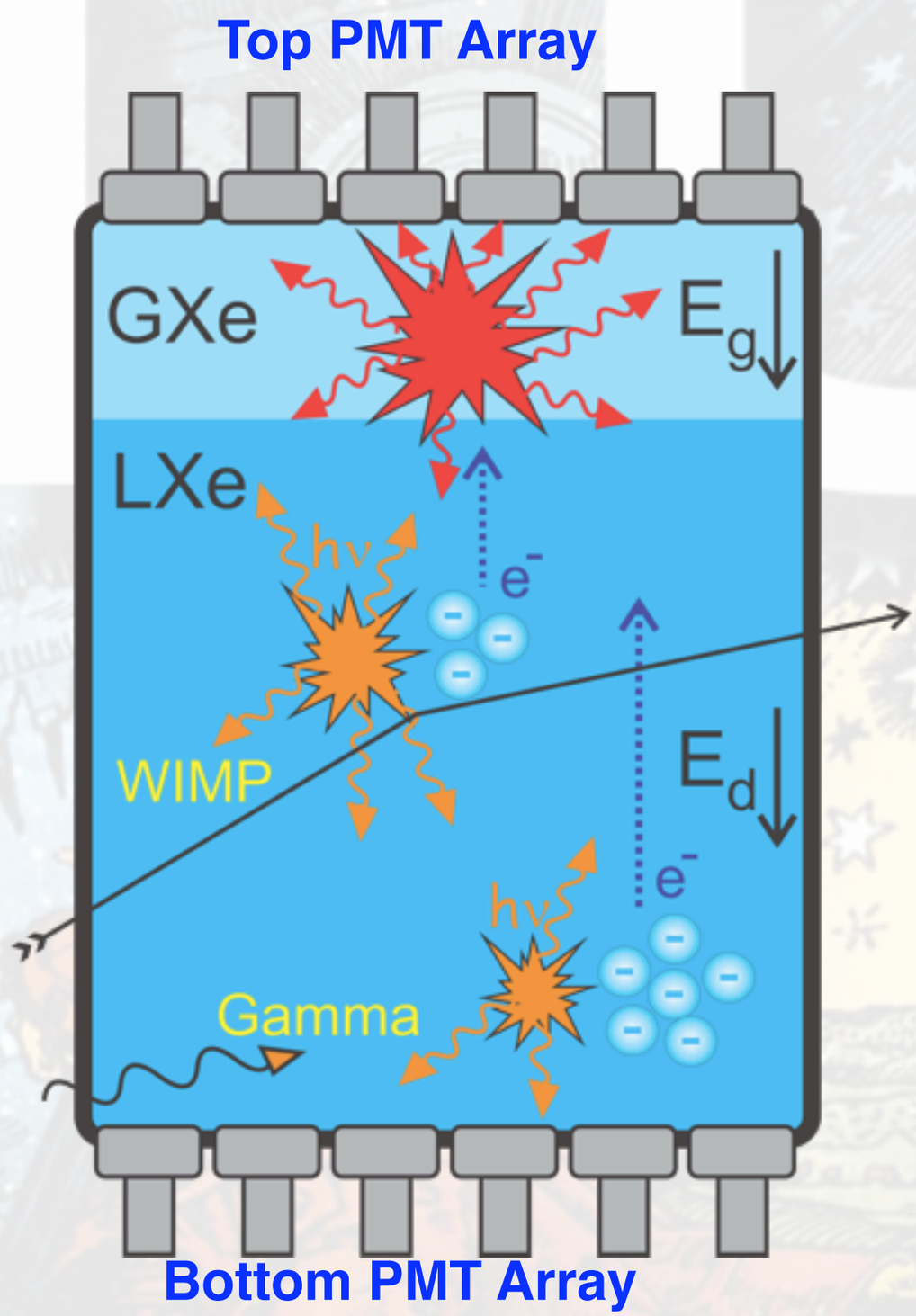
LNe: Pulse shape, Self-shielding best

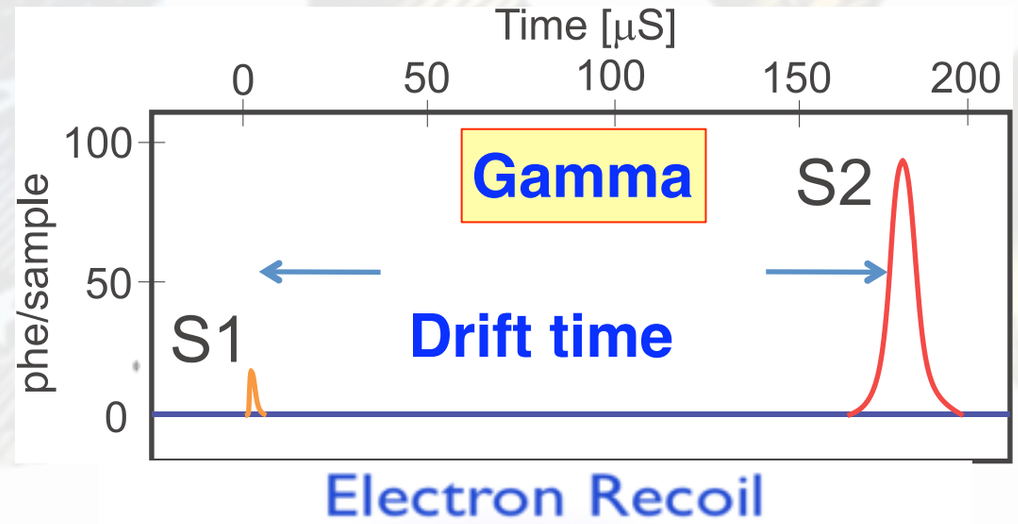


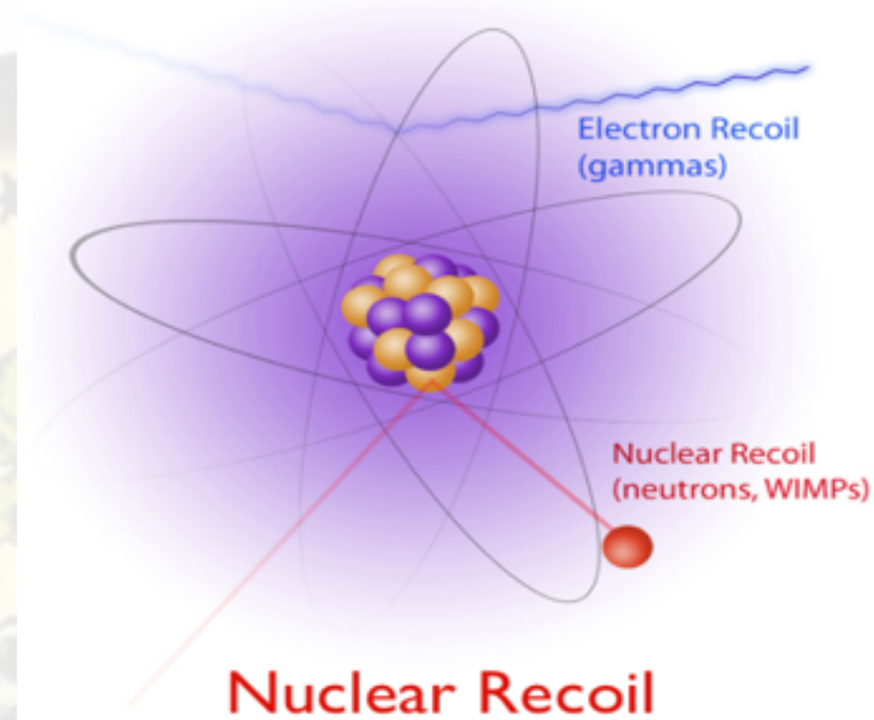


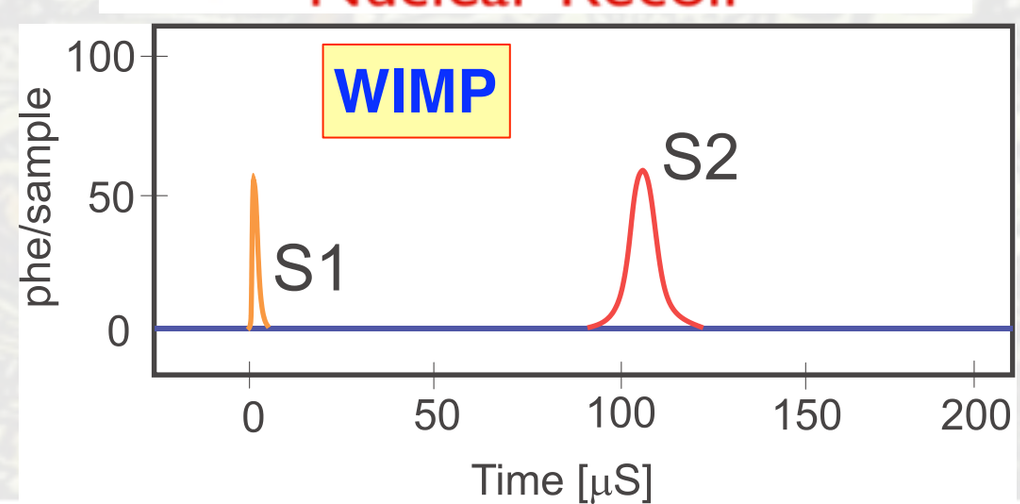


WIMP direct detection: two phase Xe









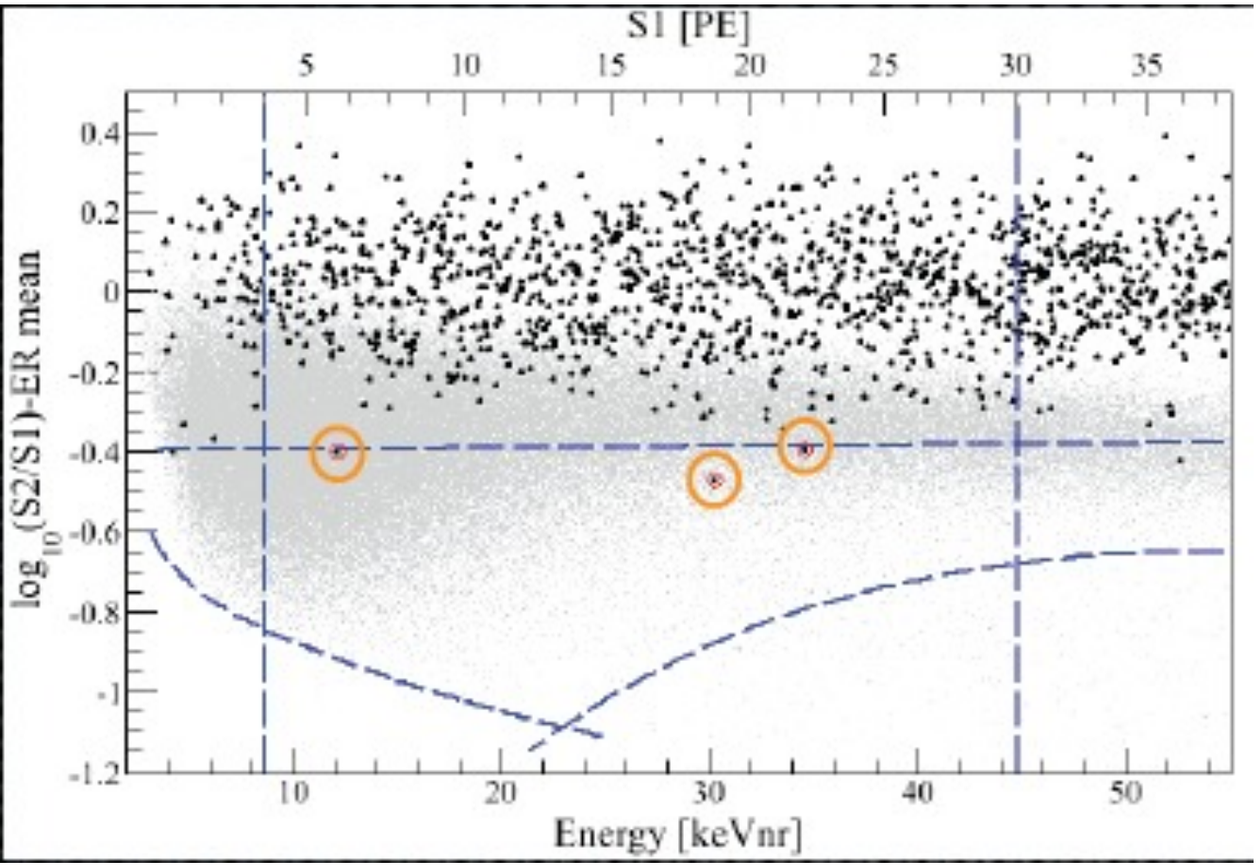
$S2/S1_{Gamma} >> S2/S1_{WIMP}$

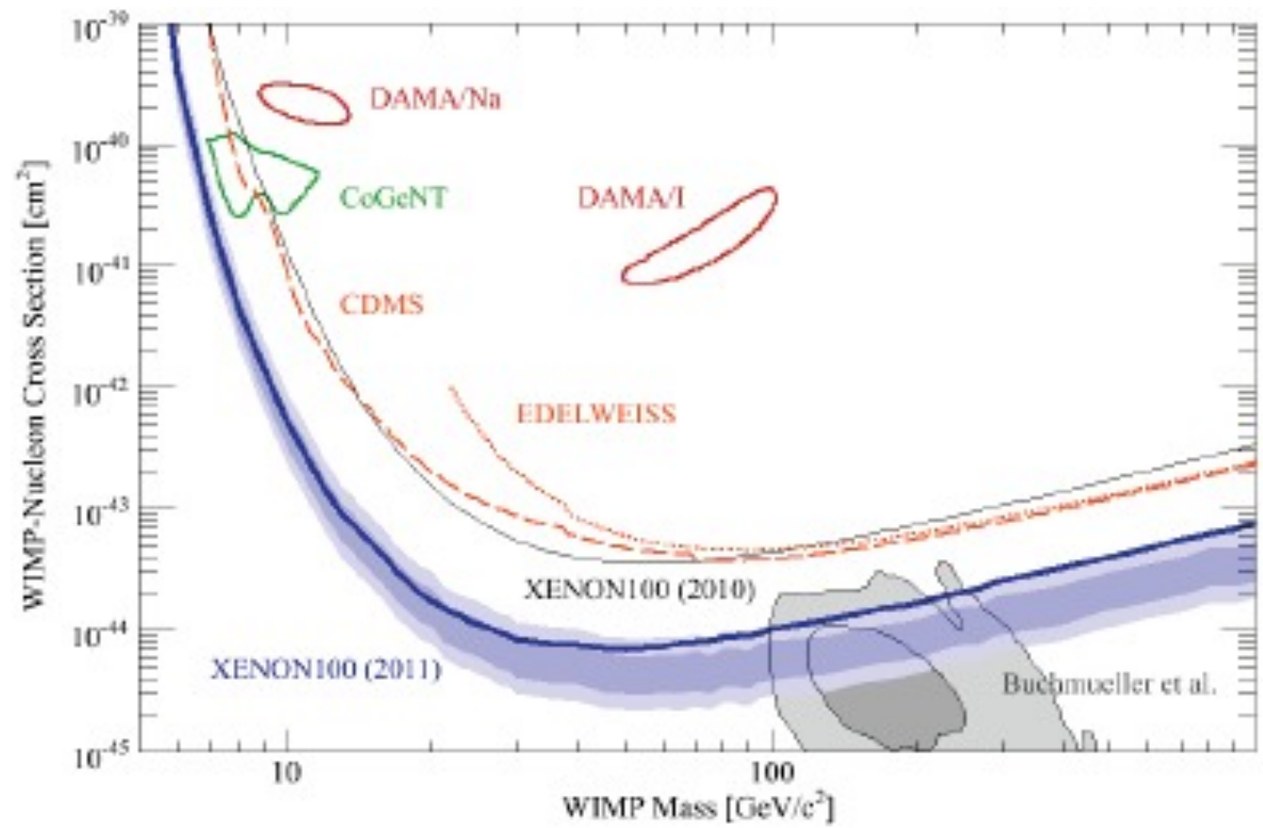
The XENON100 Experiment

- ~100 more sensitive than XENON10
- ~100 x less background and ~10 x more fiducial target than XENON10
- Target: 30 cm drift x 30 cm diameter TPC
- Cryocooler and FTs outside shield
- Materials screened for low radioactivity
- ~1 mBq (U/Th) and ~30% QE PMTs
- LXe veto around target on all sides
- 162 kg ultra pure LXe (target + veto)
- Improved passive shield (Cu,Poly, Pb+Water)

XENON100 Results

1500 kg-days exposure. Jan – June 2010

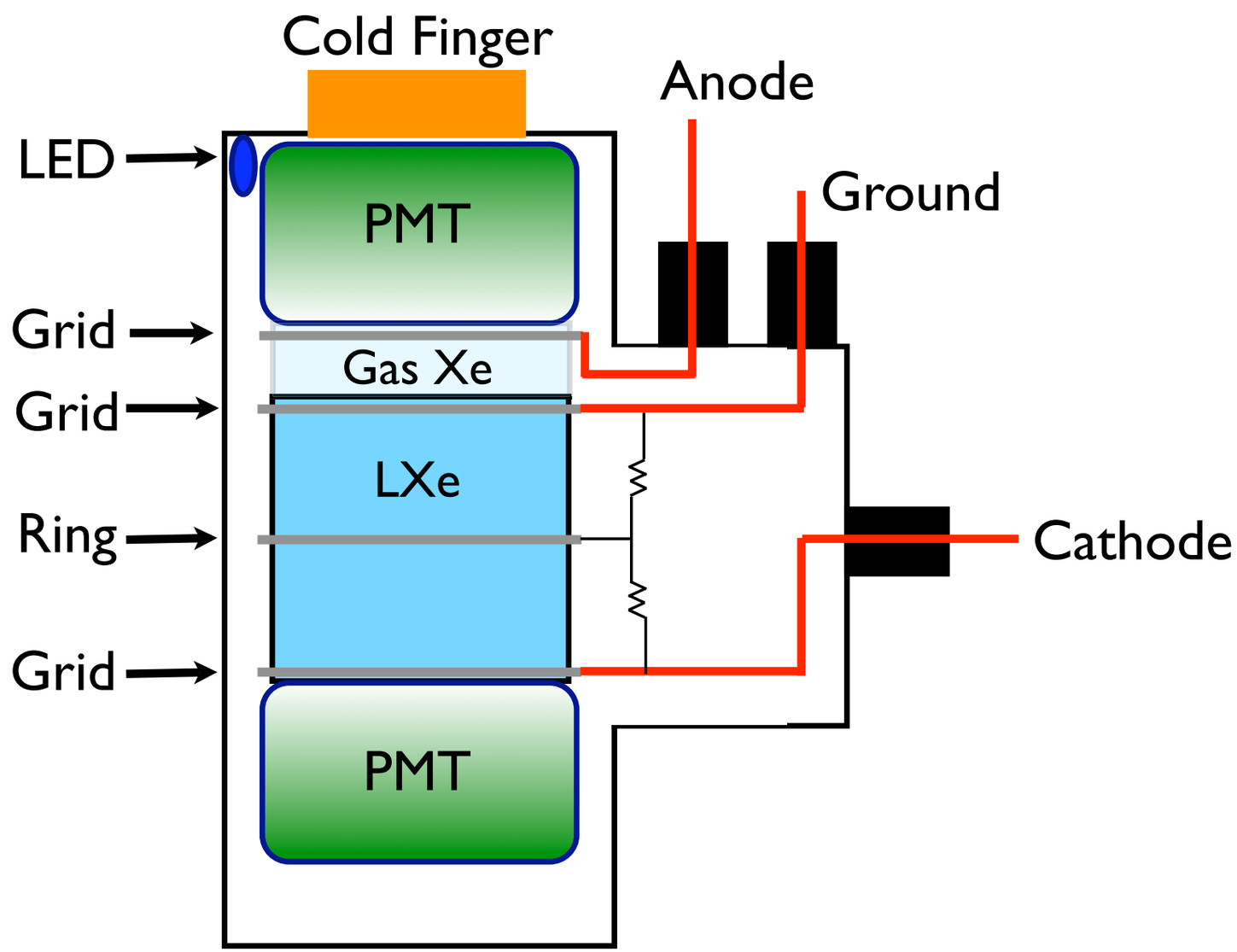




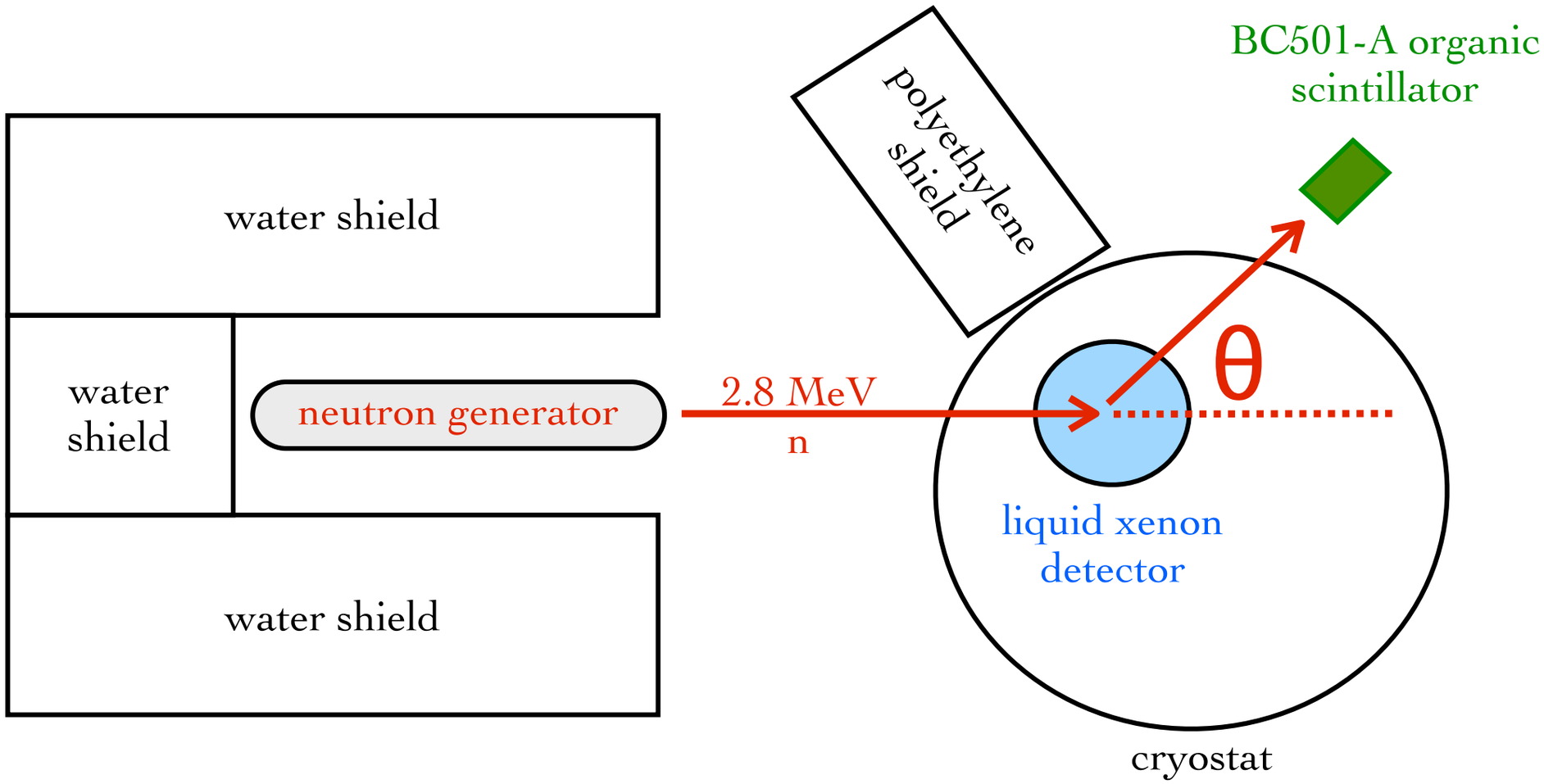
- **6 candidates observed, 3 of which quickly identified as noise**
- **3 remaining candidates on top of 1.8 +/- .6 expected background**
- **Run had Kr problem ~ 700ppt. Aim to be <100ppt in next run**

Two-phase LXe detector at Yale (MAXe)

Variable drift field (1-4 kV/cm)
Variable extraction & proportional scintillation field (6-10 kV/cm)
11 pe/keV at zero field
PMTs have ~35% quantum efficiency



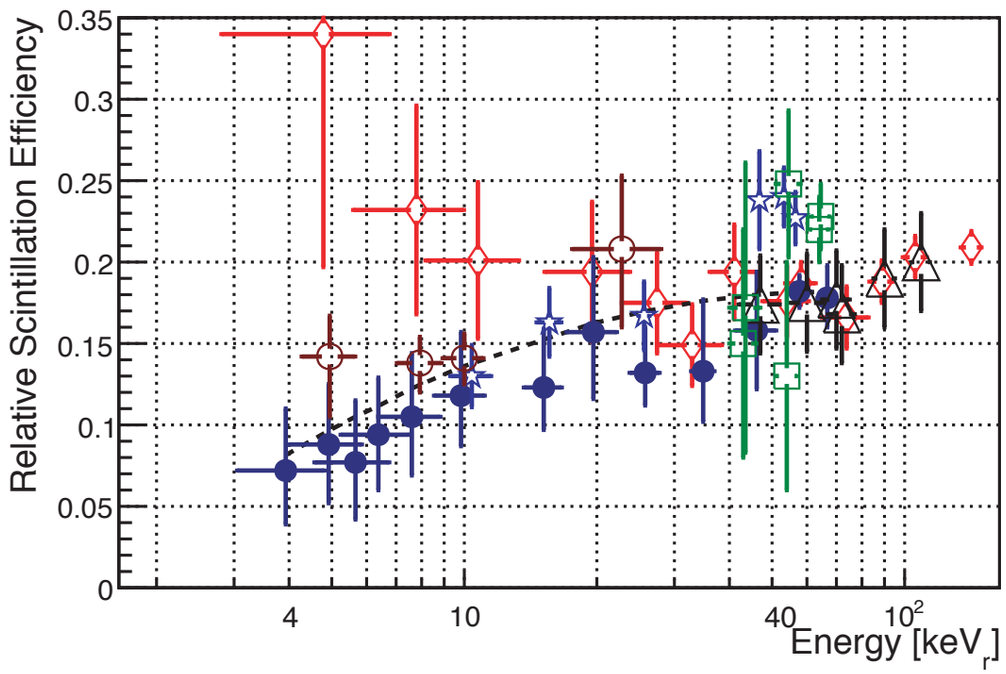
Experimental setup



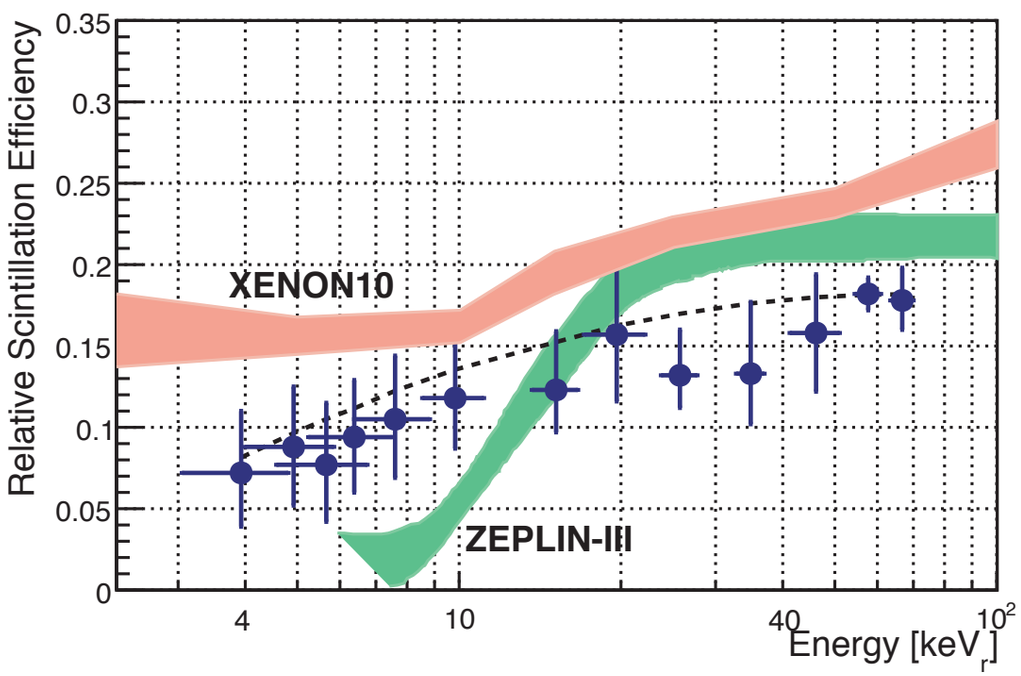
$$E_R = E_n \frac{2 m_n M_{Xe}}{(m_n + M_{Xe})^2} (1 - \cos\theta)$$

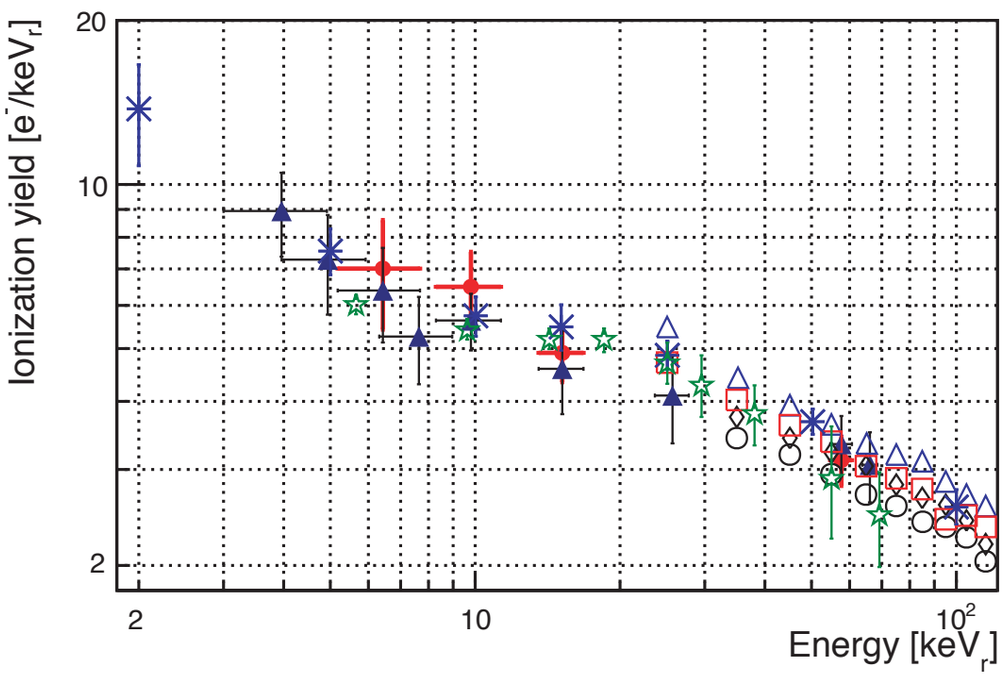
Energies: 4 - 66 keVr

Leff results



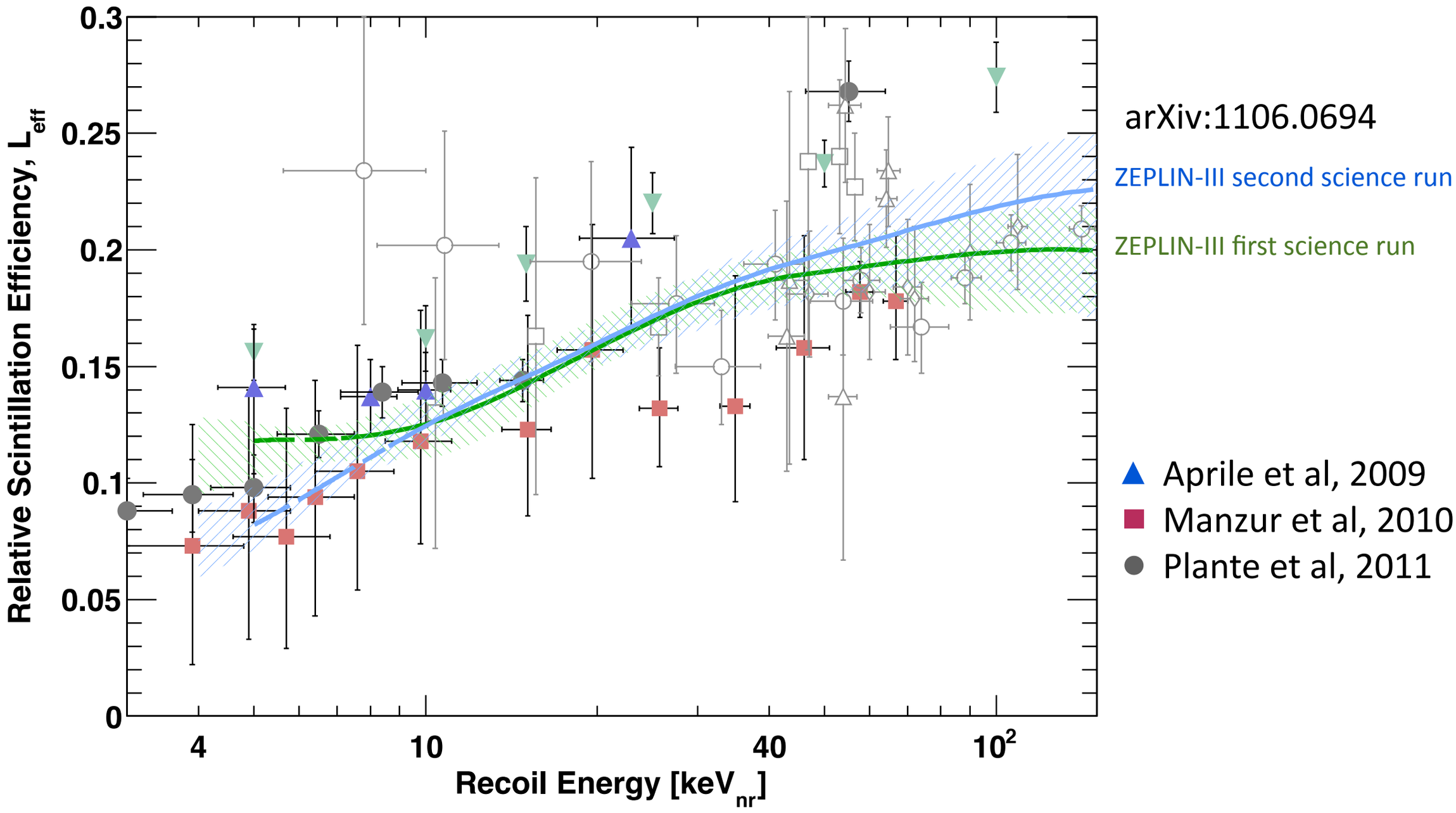
- Manzur et al,, 2009
- Aprile et al, 2009
- Chepel et al, 2006
- Aprile et al, 2005
- Akimov et al, 2002
- Arneodo et al, 2000



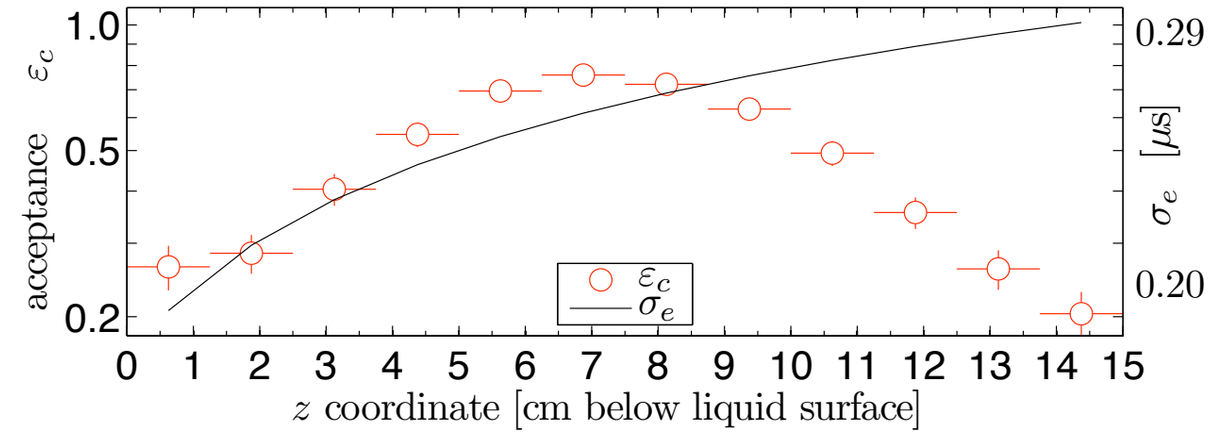


New Leff results from Columbia group and ZEPLIN-III collaboration

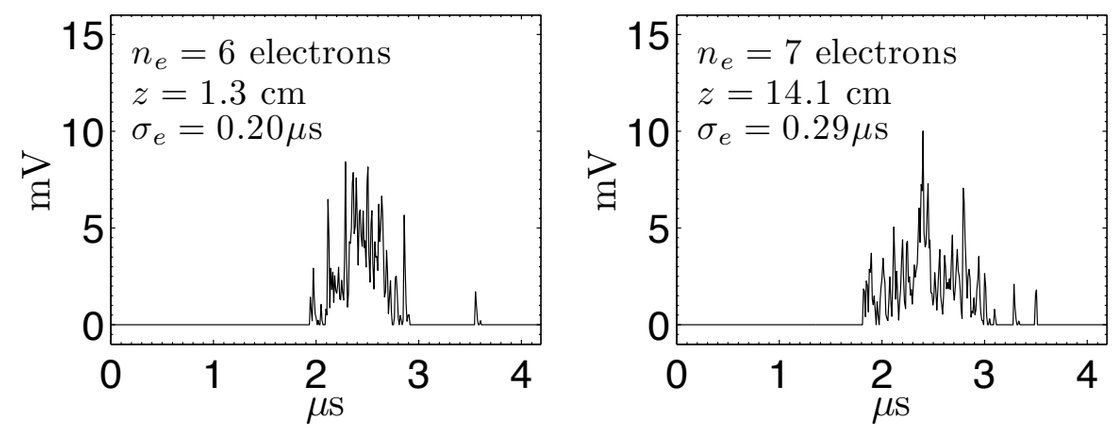
Consensus emerging: Leff drops at lower energies

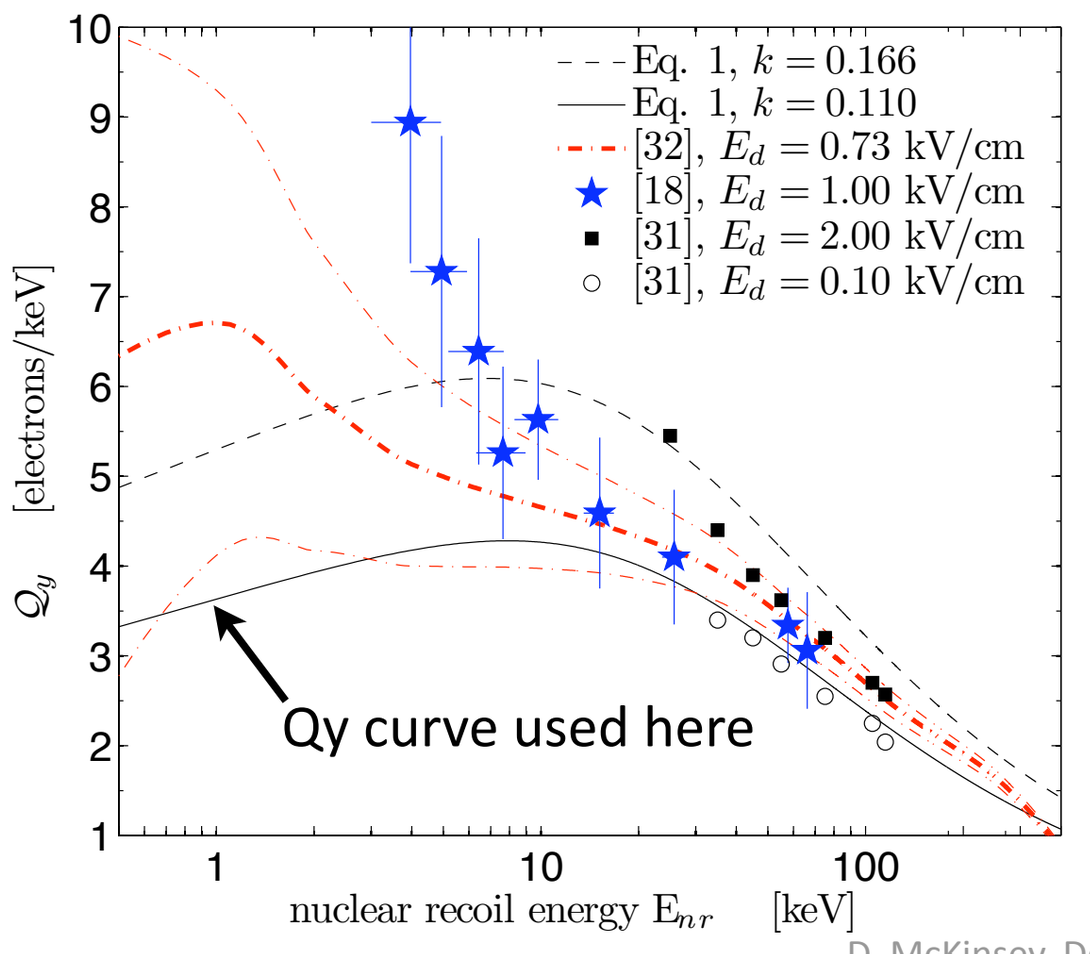


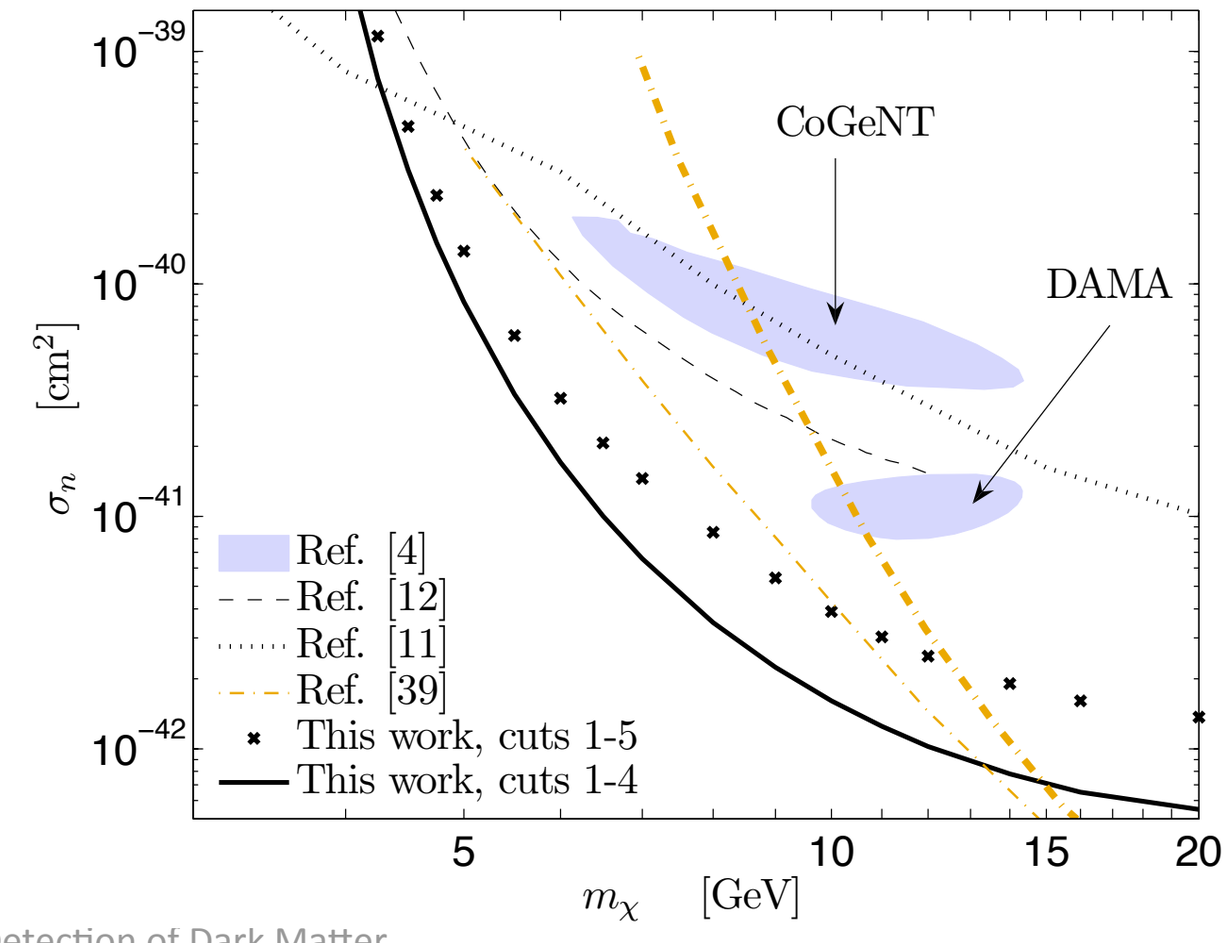
XENON10 charge-only analysis



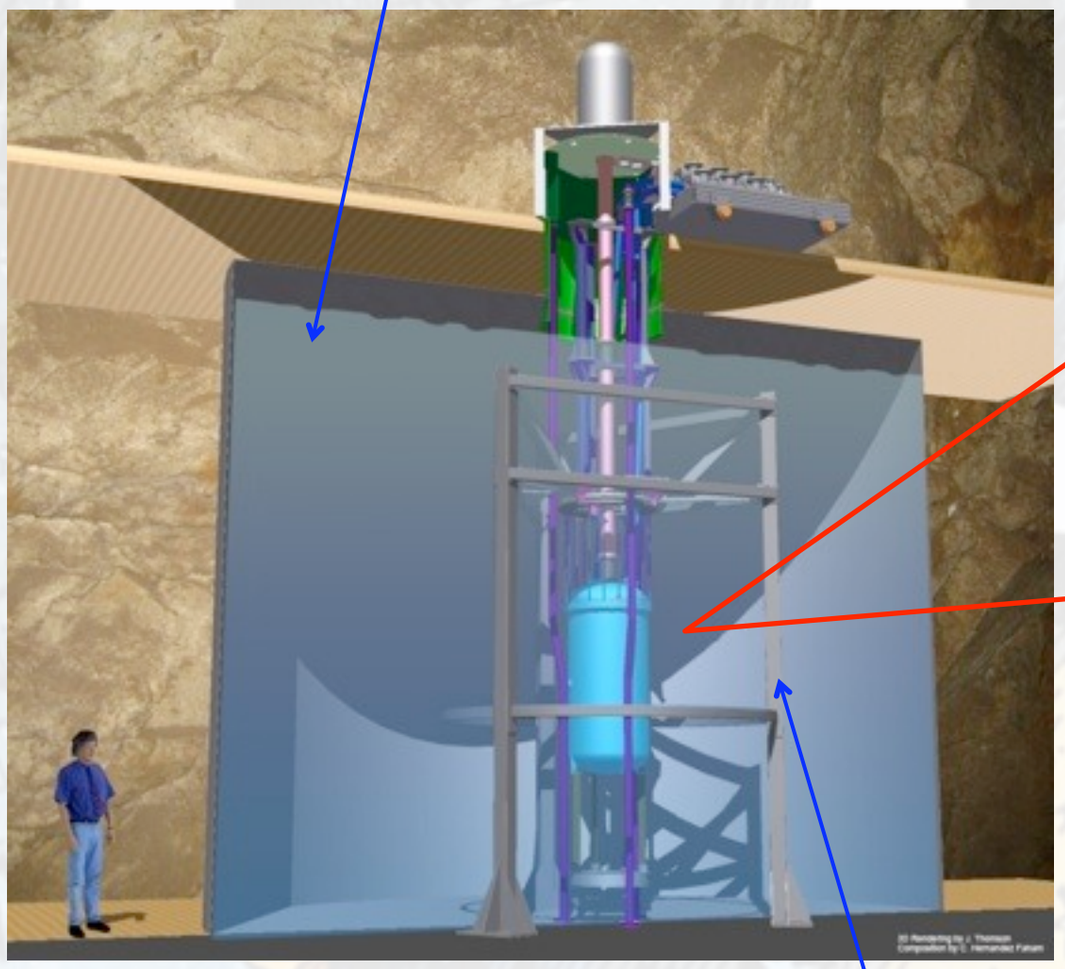
Event depth found by S2 width
Deeper events have more charge diffusion
Assumes a sharp cutoff in Qy at 1.4 keV

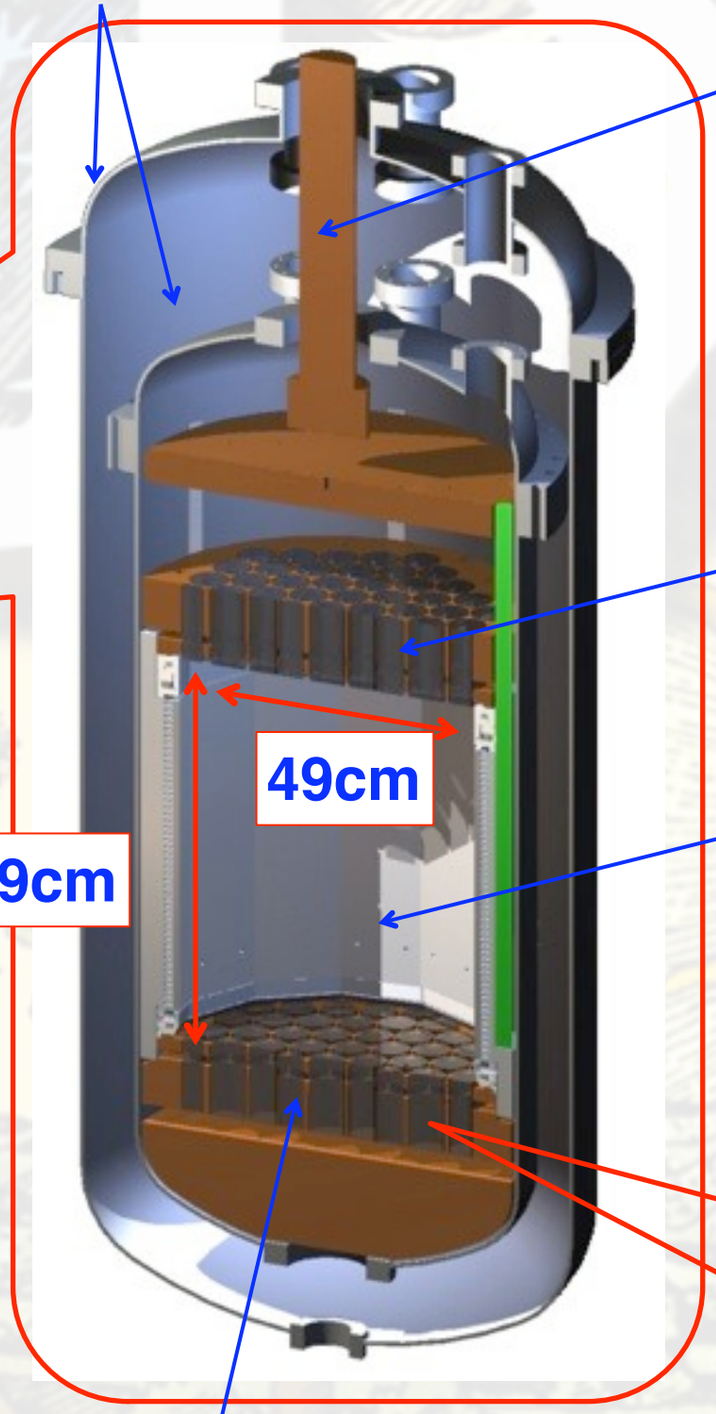






LUX Detector

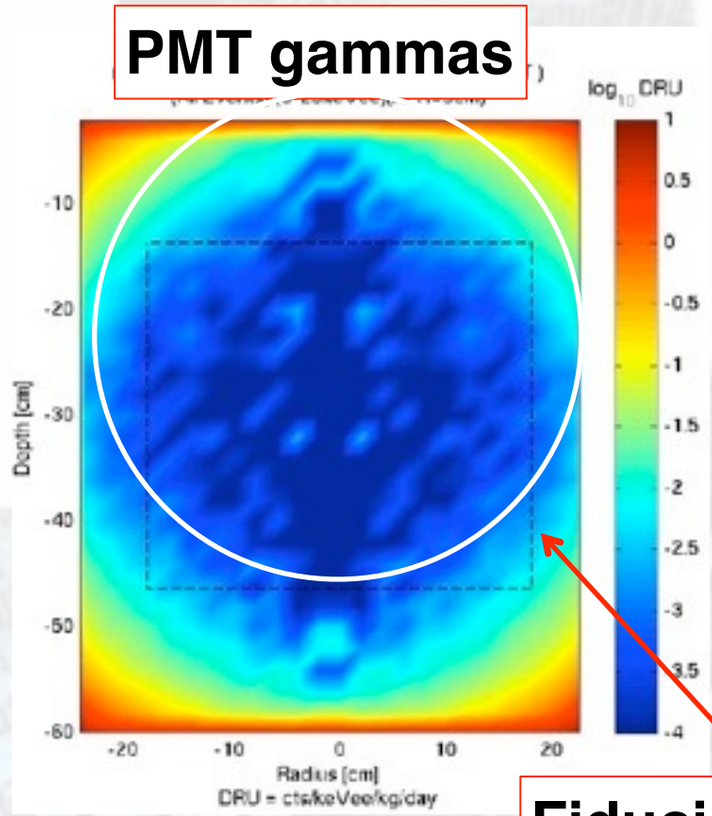




- 350 kg LXe (100 kg fiducial)
- 122 PMTs (QE~30% @ 175nm)
- Low Radioactivity Materials (Ti cryostat)
- Water tank shielding
- >1kW Cooling Power (Thermosyphons)
- 50 liter per minute Xe purification rate

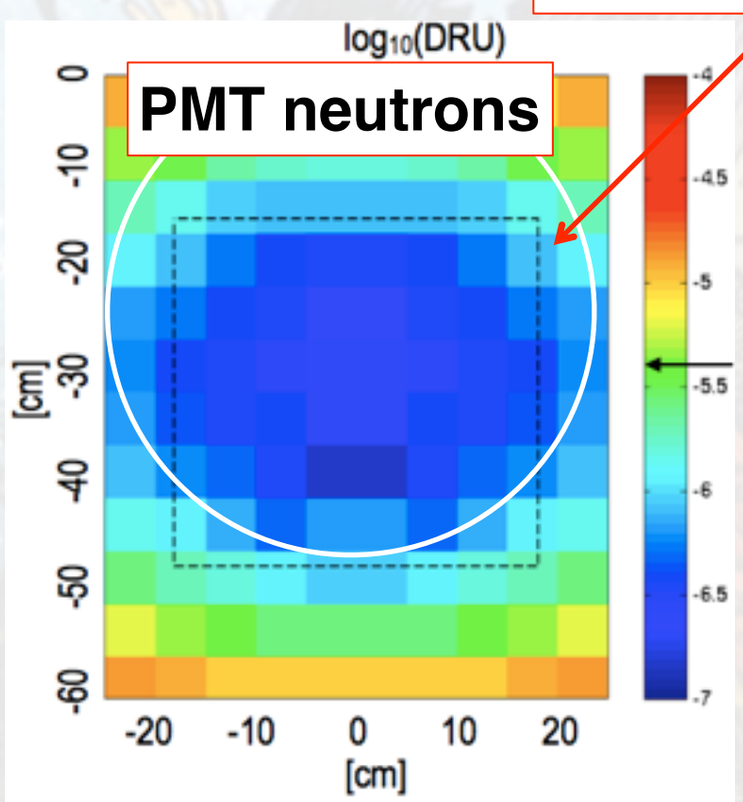
Trickery: Xe self shielding

PMT gammas

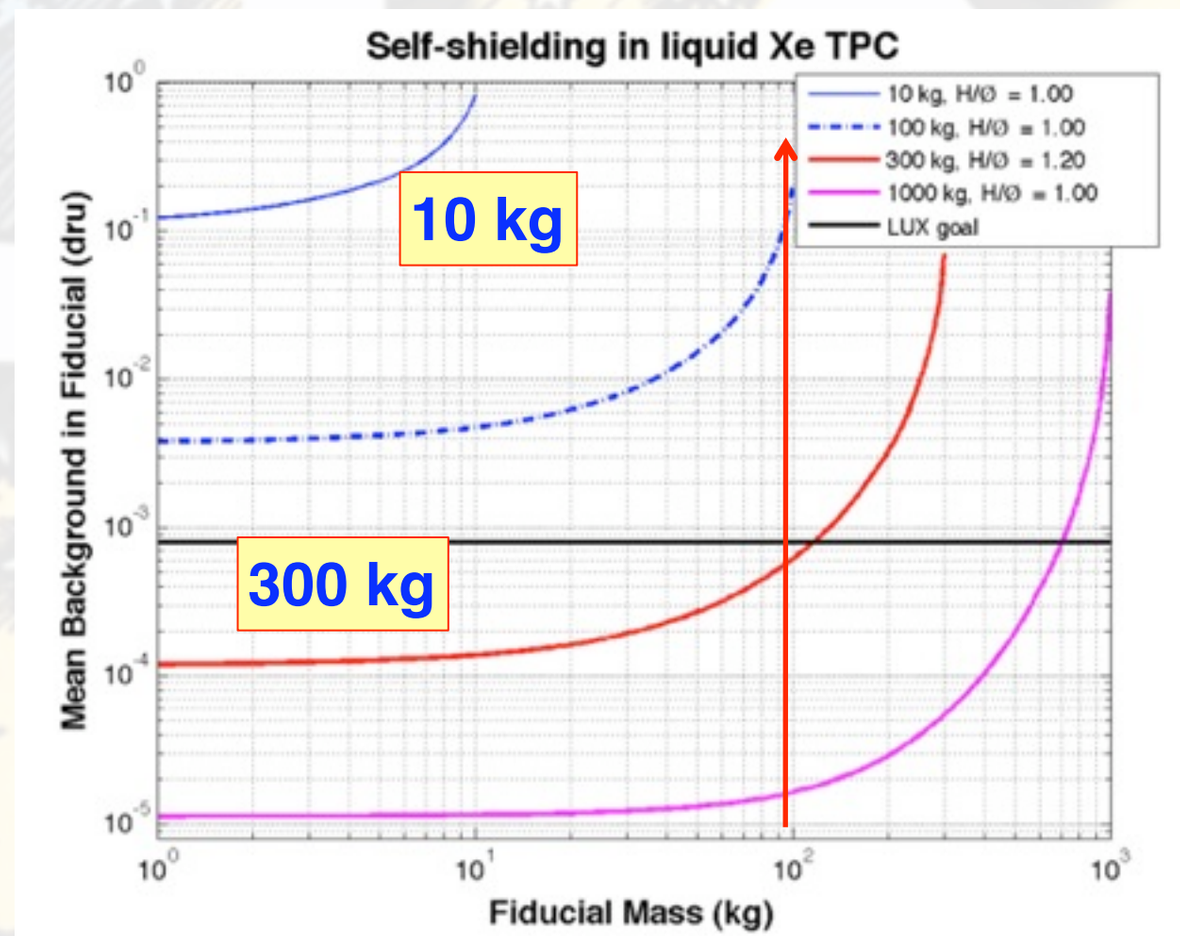


Fiducial volume

PMT neutrons



PMTs are dominant background source



We benefit a lot from scaling up

Expect <0.5 nuclear/electron-recoils in 100 days

The LUX Collaboration

Brown

Richard Gaitskell	PI, Professor
Simon Fiorucci	Research Associate
Monica Pangilinan	Postdoc
Jeremy Chapman	Graduate Student
Carlos Hernandez Faham	Graduate Student
David Malling	Graduate Student
James Verbus	Graduate Student

Case Western

Thomas Shutt	PI, Professor
Dan Akerib	PI, Professor
Mike Dragowsky	Research Associate Professor
Carmen Carmona	Postdoc
Ken Clark	Postdoc
Tom Coffey	Postdoc
Karen Gibson	Postdoc
Adam Bradley	Graduate Student
Patrick Phelps	Graduate Student
Chang Lee	Graduate Student
Kati Pech	Graduate Student

Harvard

Masahiro Morii	PI, Professor
Michal Wlasenko	Postdoc
John Oliver	Electronics Engineer

Lawrence Berkeley + UC Berkeley

Bob Jacobsen	Professor
Jim Siegrist	Professor
Bill Edwards	Engineer
Joseph Rasson	Engineer
Mia ihm	Graduate Student

Lawrence Livermore

Adam Bernstein	PI, Leader of Adv. Detectors Group
Dennis Carr	Mechanical Technician
Kareem Kazkaz	Staff Physicist
Peter Sorensen	Postdoc

University of Maryland

Carter Hall	PI, Professor
Douglas Leonard	Postdoc

Collaboration was formed in 2007 and fully funded by DOE and NSF in 2008.

UC Santa Barbara

Harry Nelson	PI, Professor
Dean White	Engineer
Susanne Kyre	Engineer

LIP Coimbra

Isabel Lopes	PI, Professor
Jose Pinto da Cunha	Assistant Professor
Vladimir Solovov	Senior Researcher
Luiz de Viveiros	Postdoc
Alexander Lindote	Postdoc
Francisco Neves	Postdoc
Claudio Silva	Postdoc

SD School of Mines

Xinhua Bai	PI, Professor, Physics Group Leader
Mark Hanardt	Graduate Student

Texas A&M

James White	PI, Professor
Robert Webb	Professor
Rachel Mannino	Graduate Student
Tyana Stiegler	Graduate Student
Clement Sofka	Graduate Student

UC Davis

Mani Tripathi	PI, Professor
Robert Svoboda	Professor
Richard Lander	Professor
Britt Hollbrook	Senior Engineer
John Thomson	Senior Machinist
Matthew Szydagis	Postdoc
Jeremy Mock	Graduate Student
Melinda Sweany	Graduate Student
Nick Walsh	Graduate Student
Michael Woods	Graduate Student
Sergey Uvarov	Graduate Student

The most recent collaboration meeting was held in Lead, SD in March 2011.

University of Rochester

Frank Wolfs	PI, Professor
Wojtek Skutski	Senior Scientist
Eryk Druszkiewicz	Graduate Student
Mongkol Moongweluwan	Graduate Student

U. South Dakota

Dongming Mei	PI, Professor
Wengchang Xiang	Postdoc
Chao Zhang	Postdoc
Oleg Perevozchikov	Postdoc

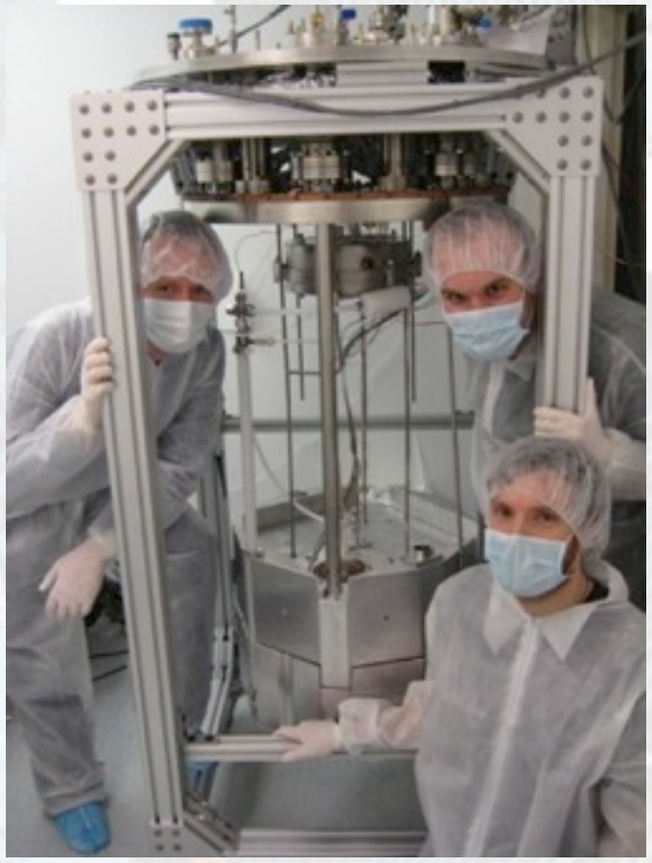
Yale

Daniel McKinsey	PI, Professor
Peter Parker	Professor
James Nikkel	Research Scientist
Sidney Cahn	Lecturer/Research Scientist
Alexey Lyashenko	Postdoc
Ethan Bernard	Postdoc
Blair Edwards	Postdoc
Louis Kastens	Graduate Student
Nicole Larsen	Graduate Student

Sanford Lab Surface Facility

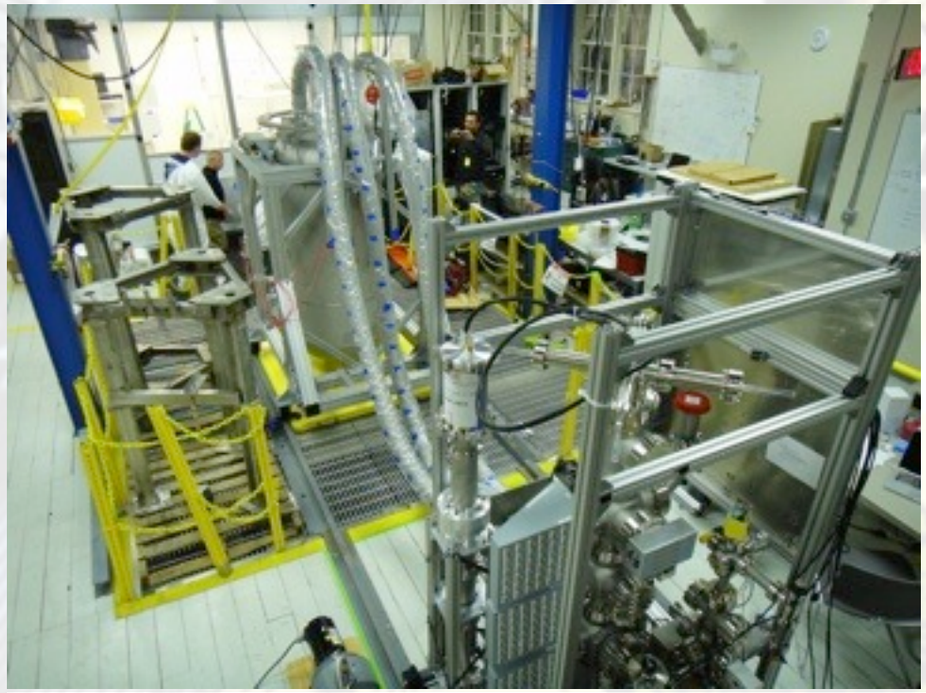
LUX Program Timeline

LUX 0.1



2007 - 2009

LUX Surface Run



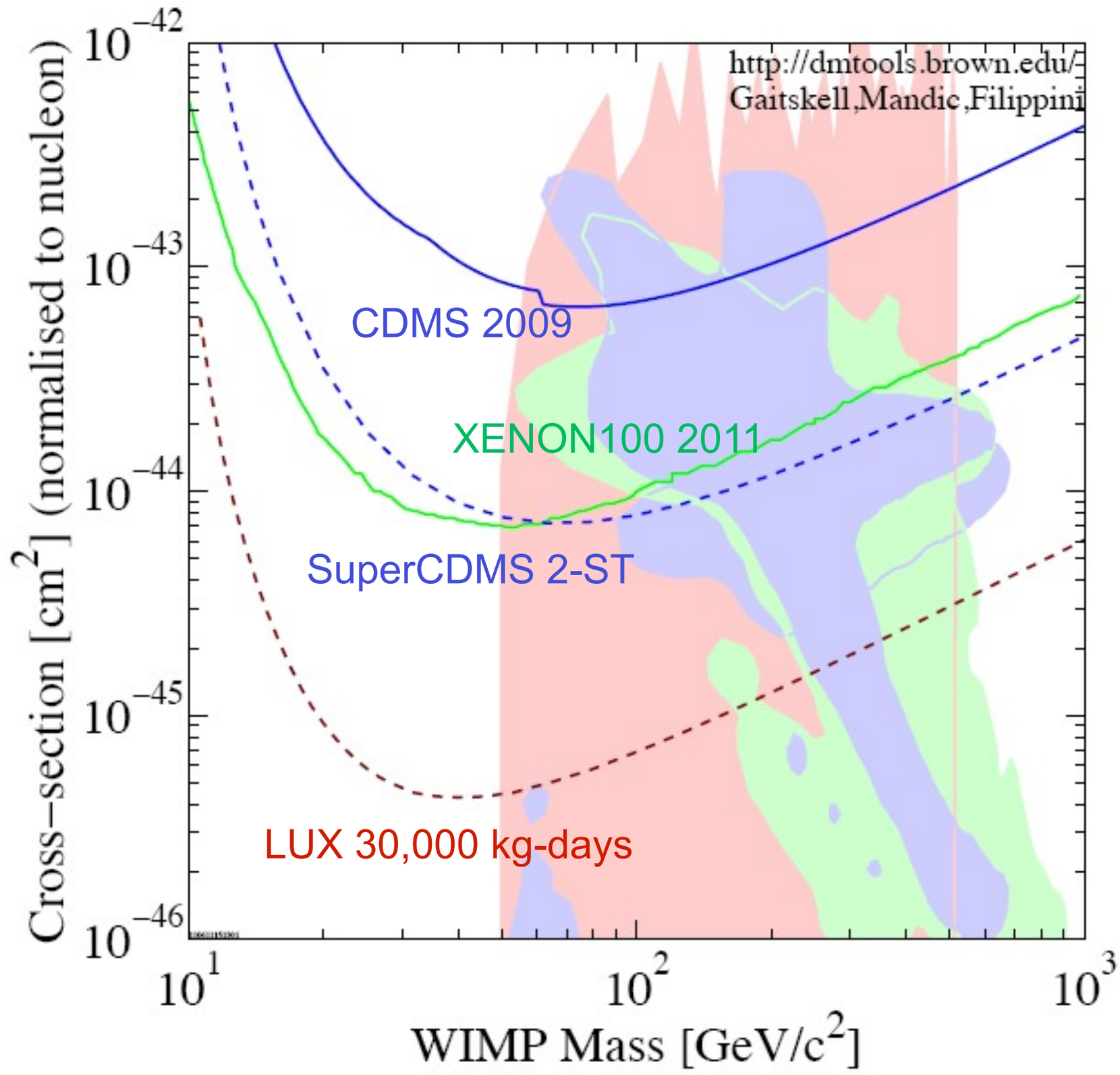
2010 - 2011

NOW!!!

LUX DM Search Run

2012+

LUX dark matter sensitivity

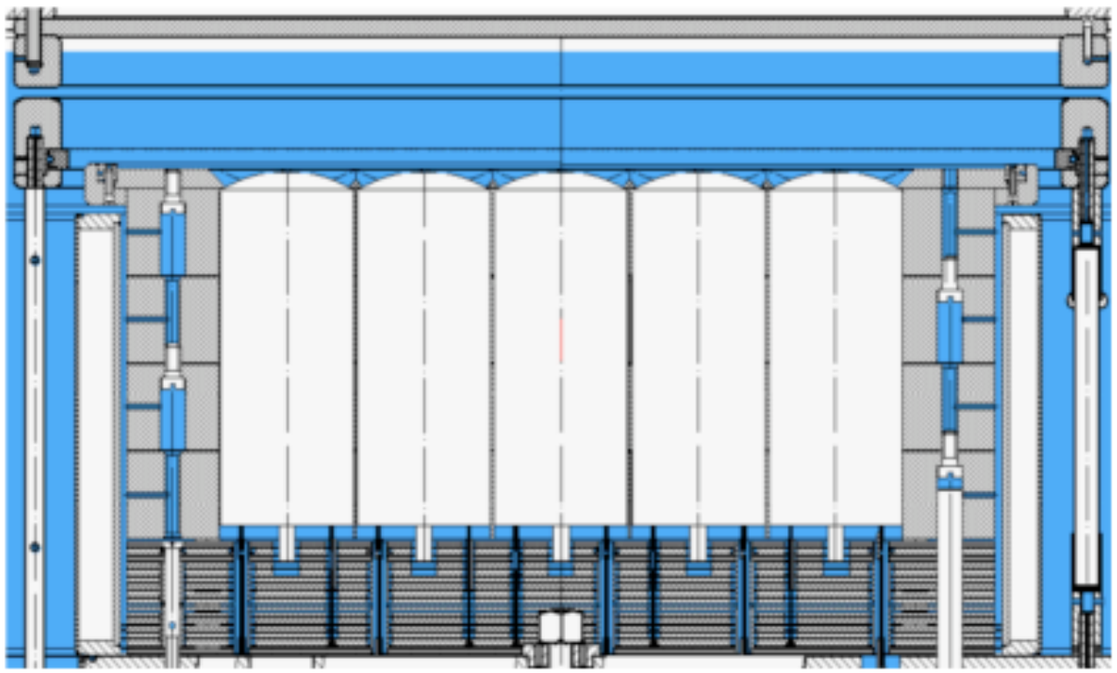


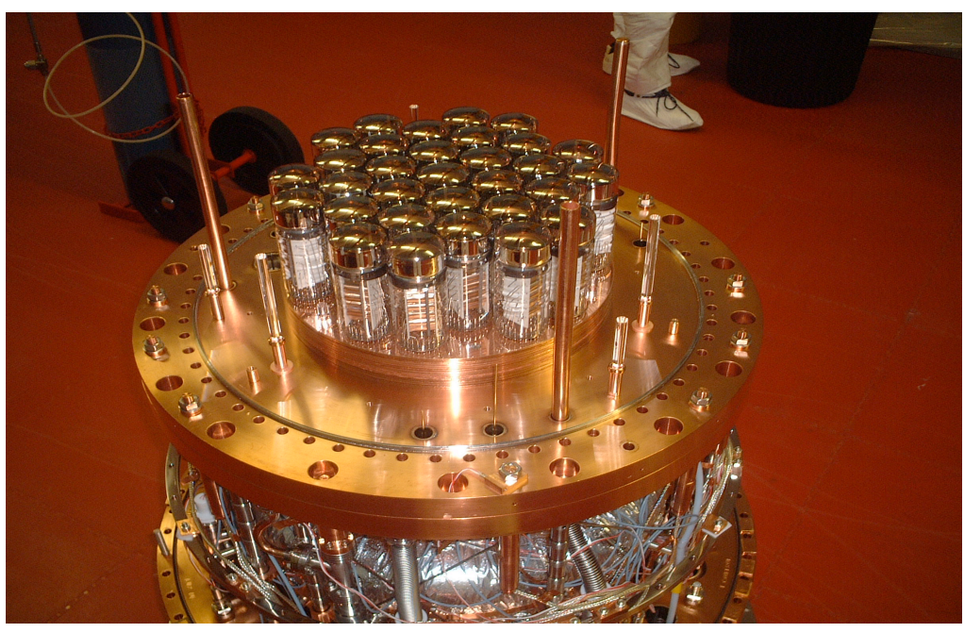
Status: LUX is <u>now</u> being tested on the surface at Homestake.
Moving underground in January 2012.

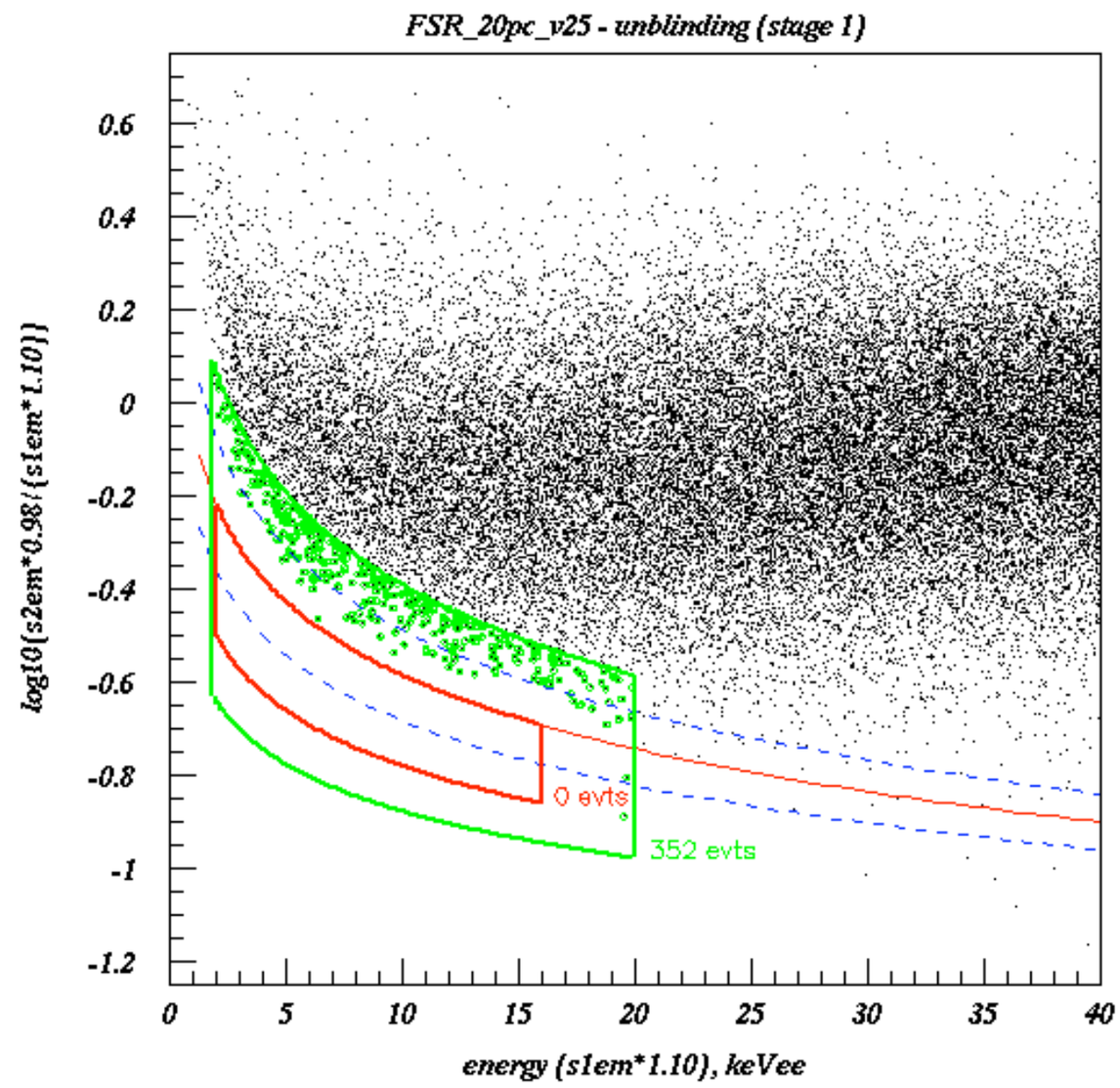
ZEPLIN-III

35 mm fiducial LXe depth;
3.8 kV/cm

31 x 2" PMTs

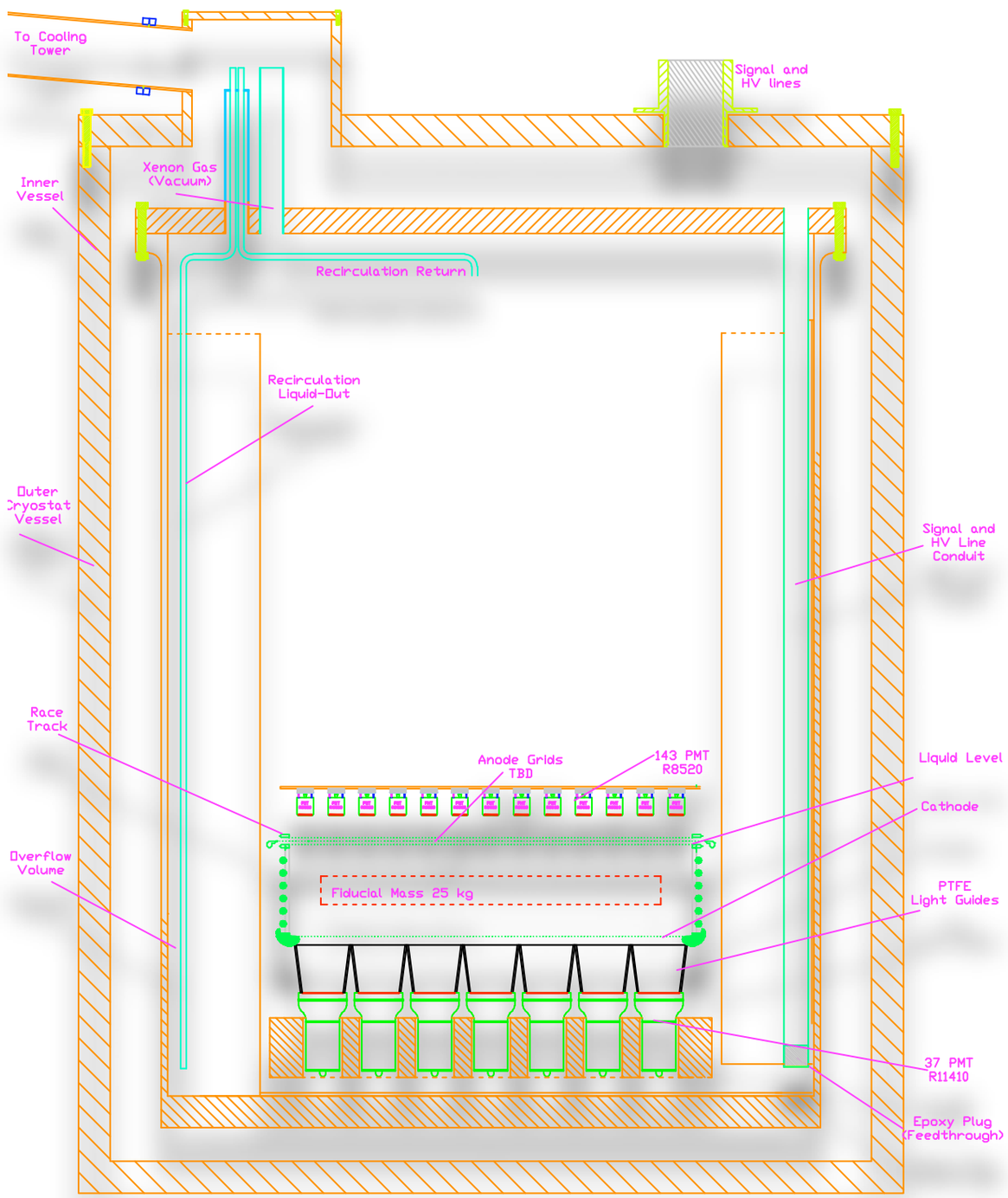






Better discrimination at 4 kV/cm?

PANDA X



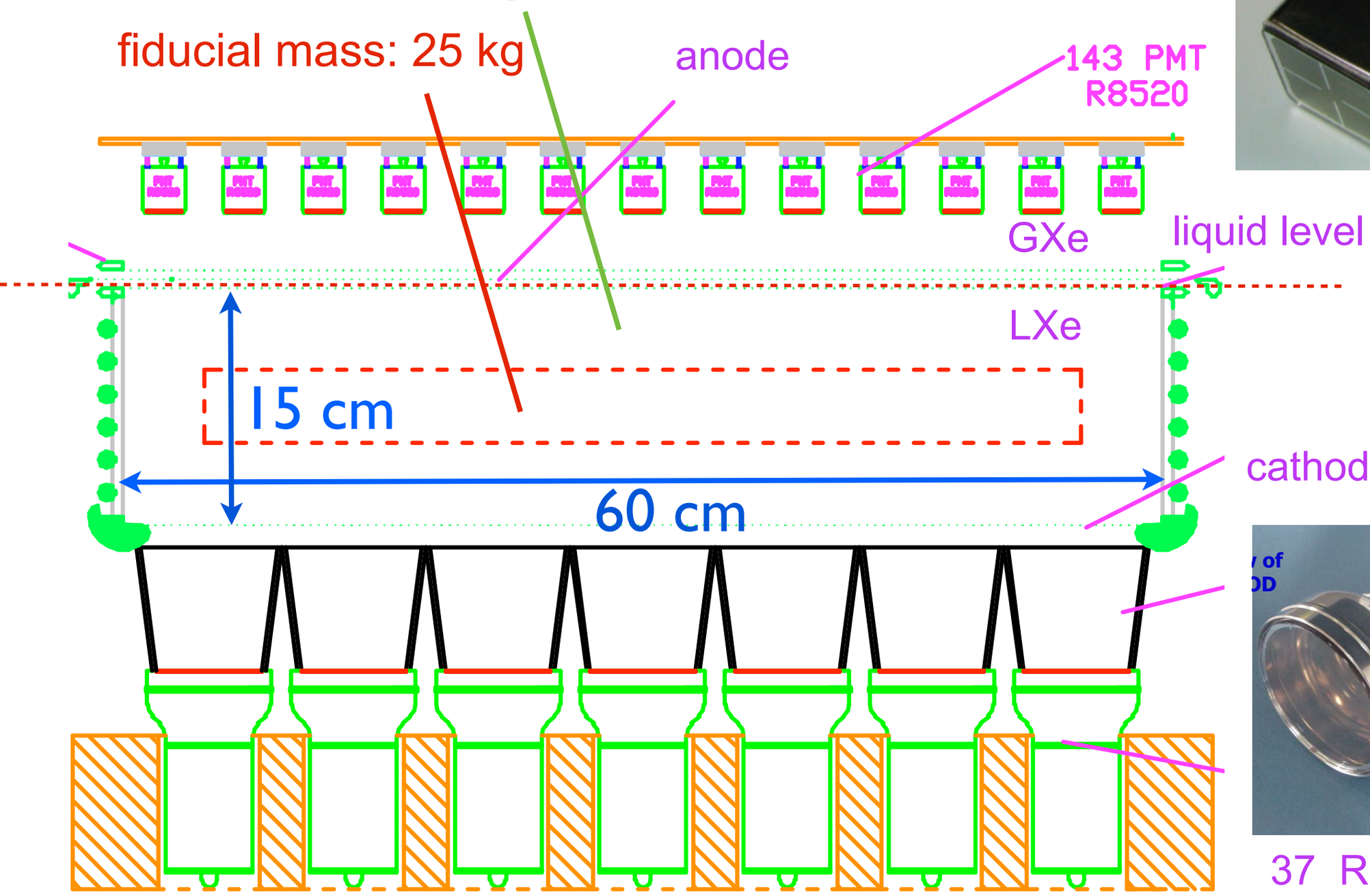
- A multi-stage liquid Xe based dark matter experiment at China Jinping Lab (CJPL)
- PandaX I: TPC design optimized for low mass dark matter with low threshold and high ER bkg rejection (high field operation)
- PandaX II: increase the fiducial mass by an order of magnitude
- Member institutions:
  - Shanghai Jiao Tong University
  - Shanghai Institute of Applied Physics
  - Shandong University
  - Peking University
  - University of Michigan

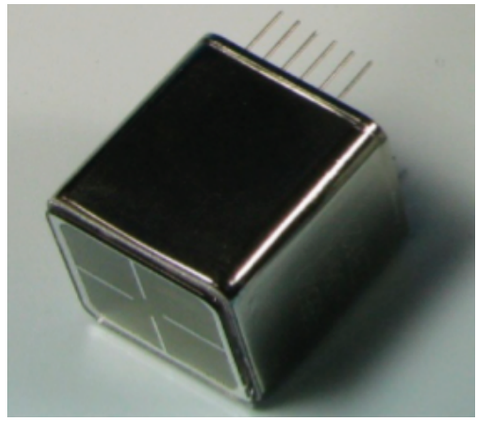
PandaX I: TPC Design

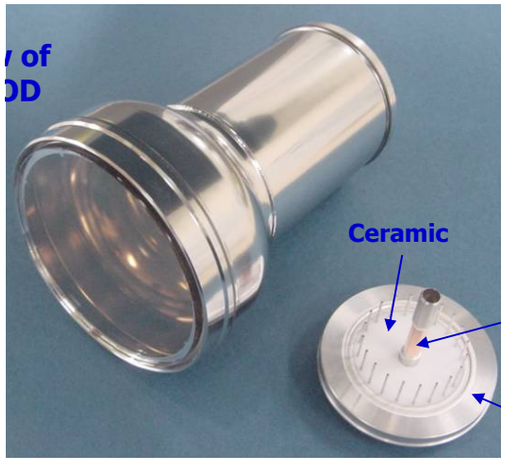
total Xe mass：300 kg

sensitive mass：123 kg

fiducial mass: 25 kg



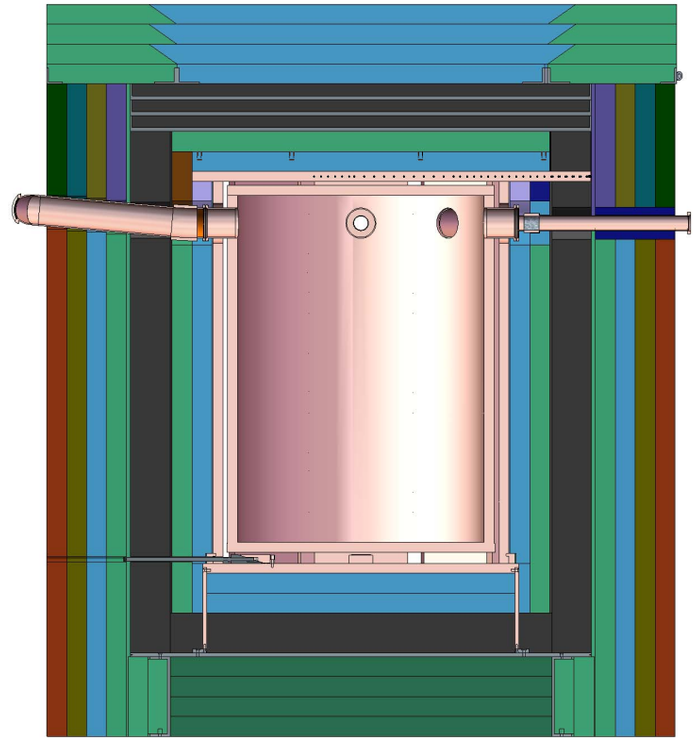




37 R11410 PMT

PandaX under construction
(expected to move underground in 2012)

CJPL

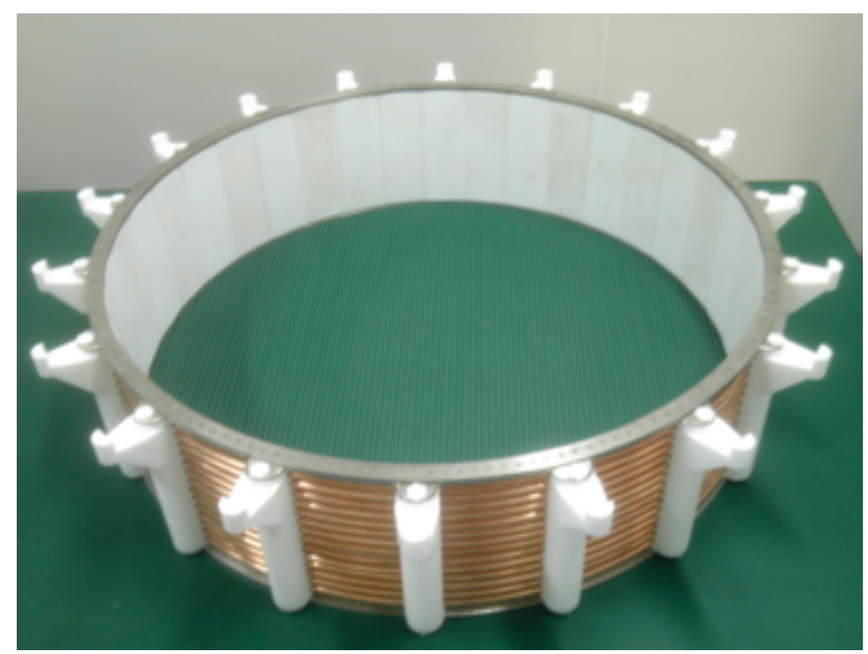


shield design

Cu vessel

Kr removal

cooling system



TPC

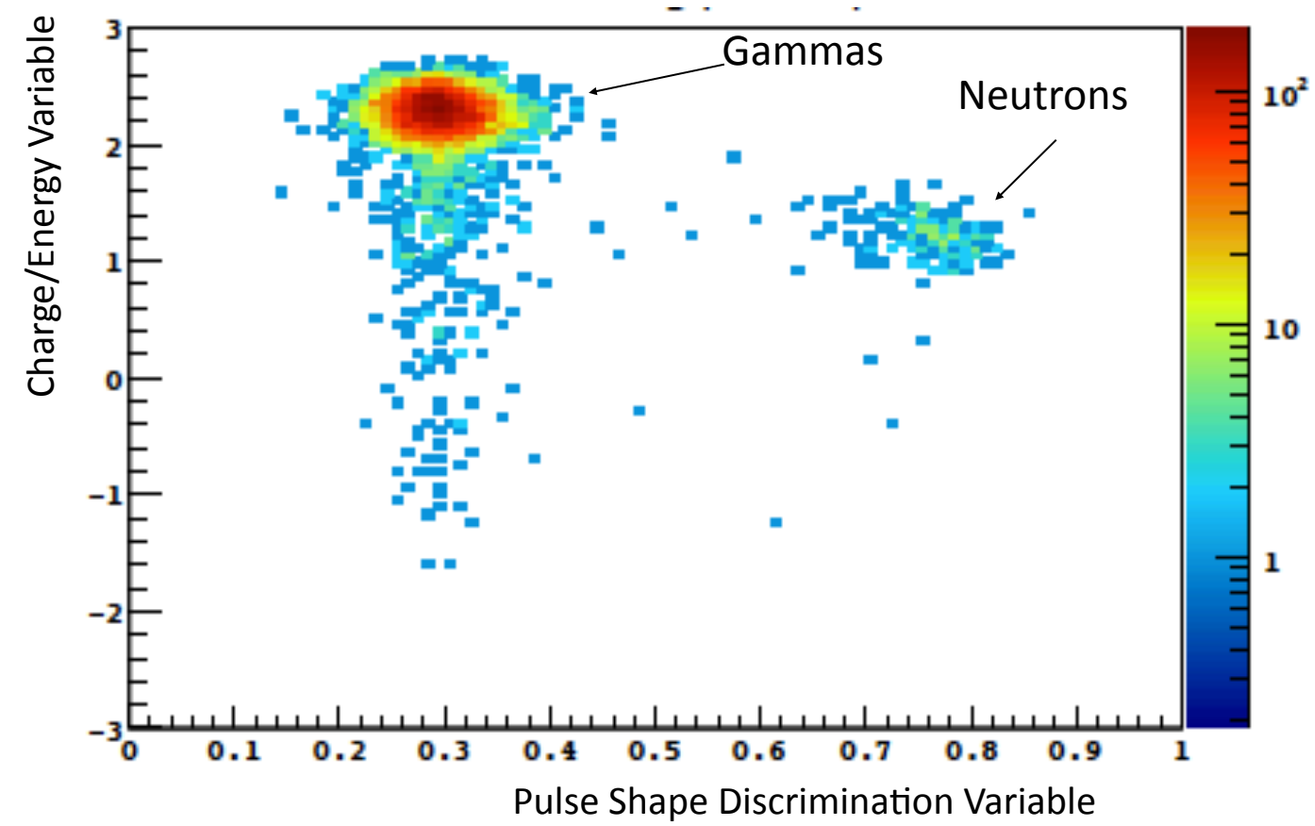
XMASS Single Phase Xenon Detector @

- 800kg of liquid xenon
- 100kg fiducial
- 630 PMTs
- PMT Cover > 62% inner surface
- Interaction position reconstruction
- ~25keV NR threshold
- Commissioning run in 2011

DARK SIDE

Two phase argon TPCs at LNGS

Maintain powerful argon pulse shape discrimination + add charge/energy discrimination from TPC



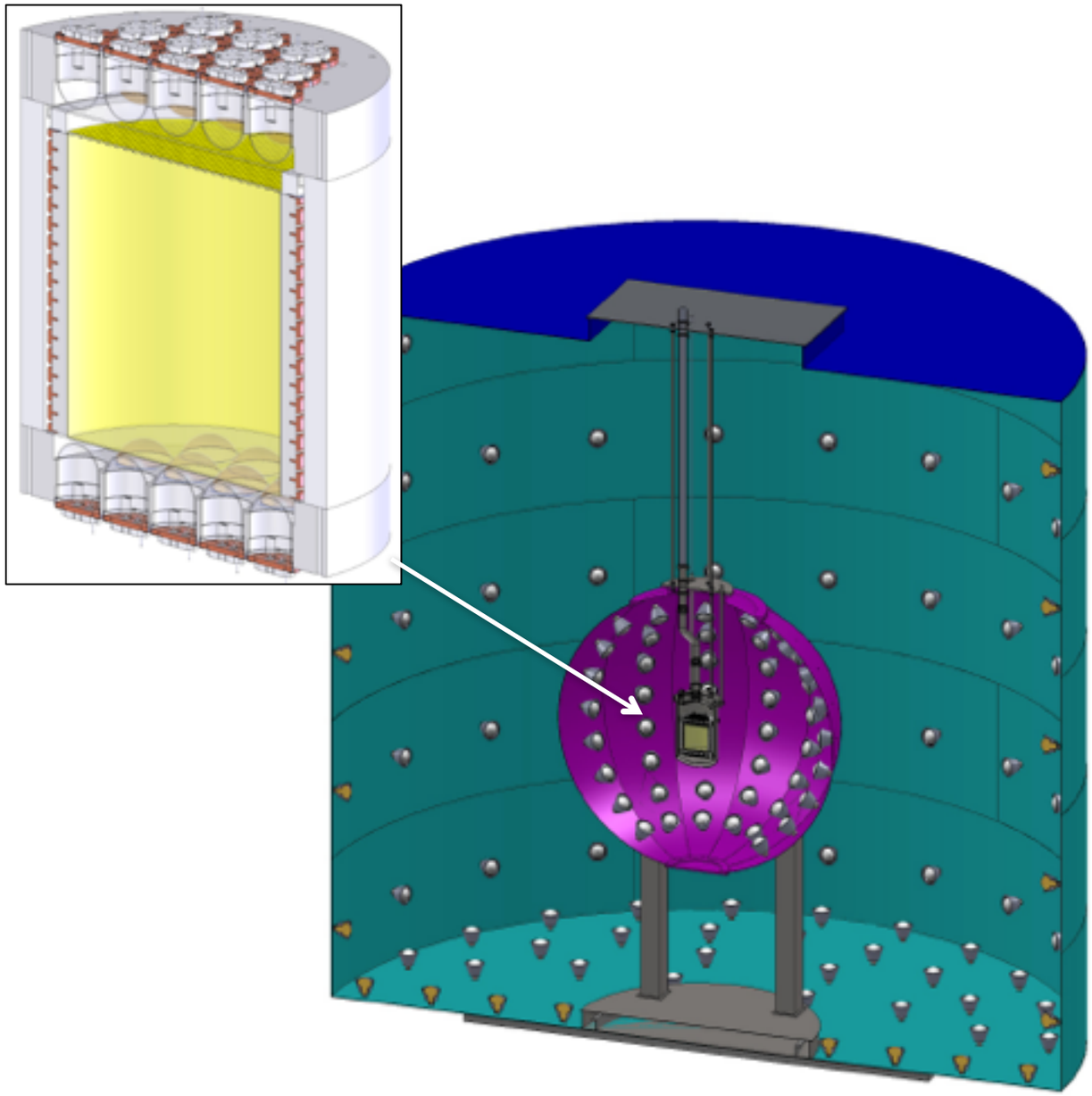
Naturally depleted argon reduces electron recoil rate (^{39}Ar activity <2% of atmospheric)

~45 kg collected so far

← Extraction plant in Cortez, CO

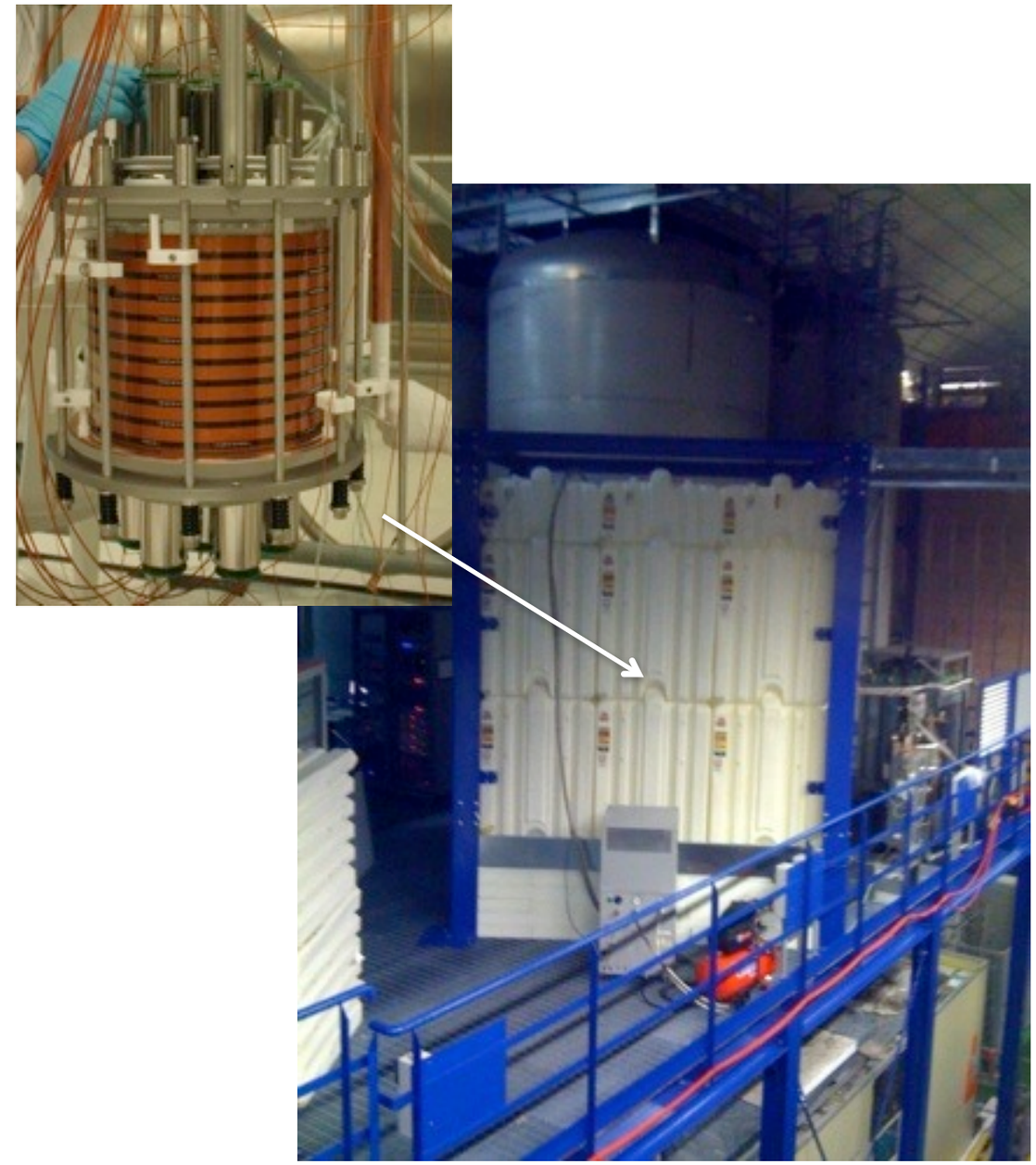
Argon distillation column at FNAL →

DarkSide-50



- 50kg physics detector, deploy late 2012
- Active shielding from scintillator-based neutron veto + CTF tank
  - <0.05 expected background events in 0.1 T-yr
  - Ability to measure background levels *in situ*
- Capable of detection at $<10^{-45}$ cm^2

DarkSide-10



- 10 kg prototype, currently installed at LNGS
- Study backgrounds and background rejection in DarkSide

ArDM-1t

ArDM goal: 1-ton two-phase (gas & liquid) LAr detector with *independent* charge and light readout optimized for direct DM searches [high discrimination power against background, few keV energy threshold]

- Time projection chamber [TPC] readout for the charge produced by ionizing radiation using Large Electron Multipliers [LEM]. Fine segmentation helps background rejection: accurate fiducialization, detection of multiple interactions within the same event.
- Light readout of the prompt scintillation light using cryogenic photomultipliers in LAr. Rejection of beta/gamma background from charge/light ratio and pulse shape discrimination.

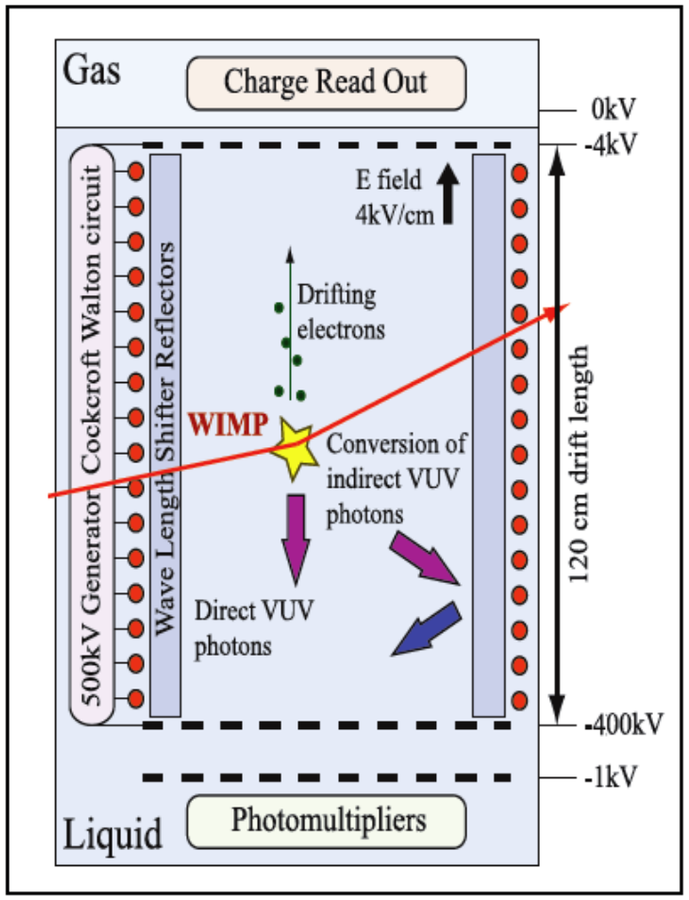
Phased approach:

a. Surface operation: build and commission1-ton two-phase LArTPC at CERN, while pursuing separate R&D activities on specific topics[completed: ArDM-1t works as dual phase LAr TPC with low energy threshold, ready for an underground phase.]

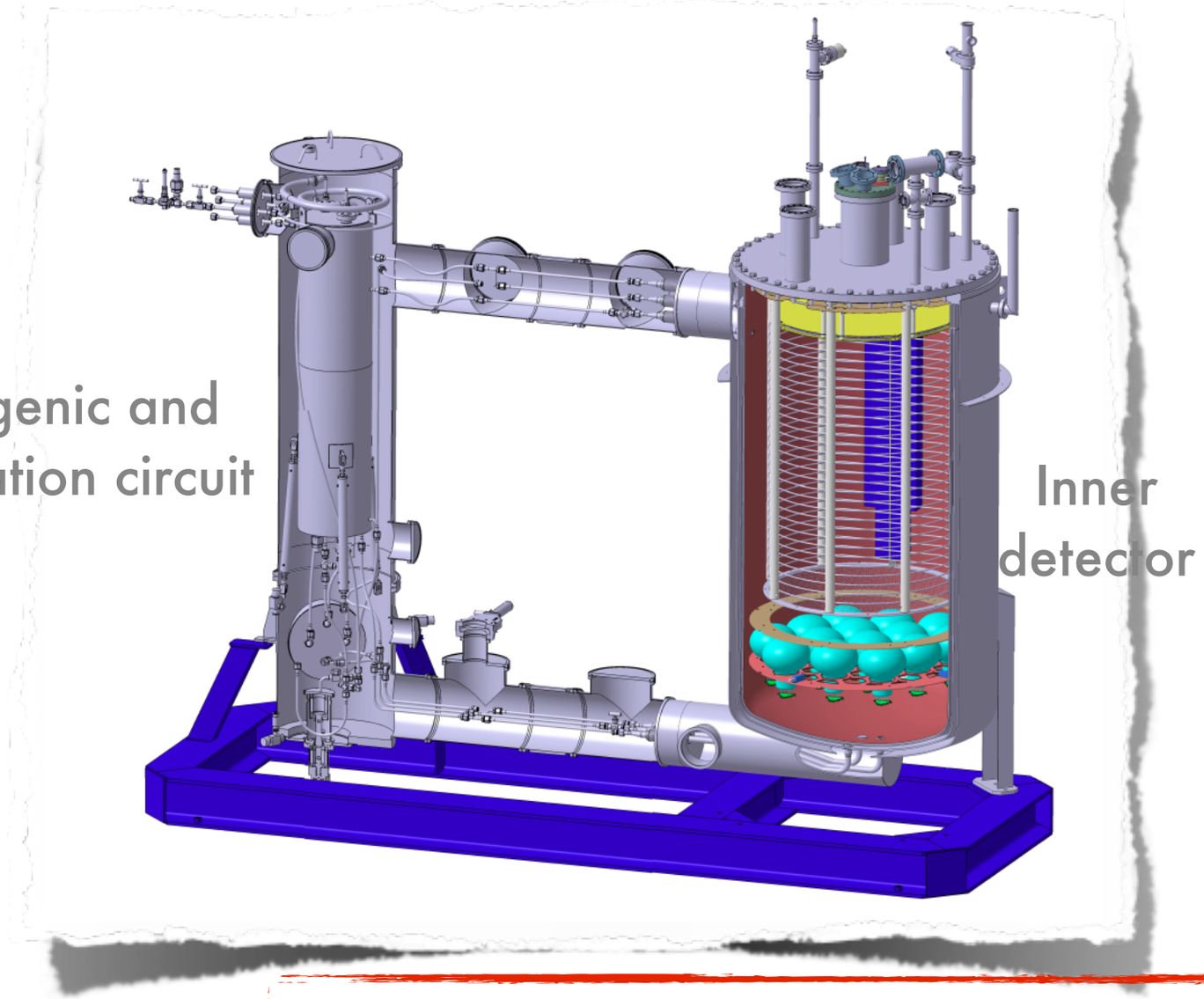
b. Underground operation in Canfranc: Phase I: development of underground infrastructure, including shield system [on going - underground installation started], science run using natural Ar [2012]

c. Underground operation Phase II: science run using depleted Ar [starts when sensitivity of science run with natural Ar is "^{39}Ar limited" AND a sufficient amount of ^{39}Ar depleted Ar is available. 2014?]

Working principle



A.Rubbia, J.Phys.Conf.Ser.39 (2006) 129



Inner detector: 14 8"cryogenic PMTs R5912-02MOD coated with TPB, sensitive volume defined by TPB coated reflectors, 120 cm drift, Greinacher [Cockcroft-Walton] high voltage generator, R&D for final charge readout on-going with substantial progress, possible temporary charge readout for first underground operations.

Cryogenics and LAr purification: 600 W cooling power closed loop system using commercial GM cryocoolers, Ar can be recirculated and purified both in gas and liquid phase.

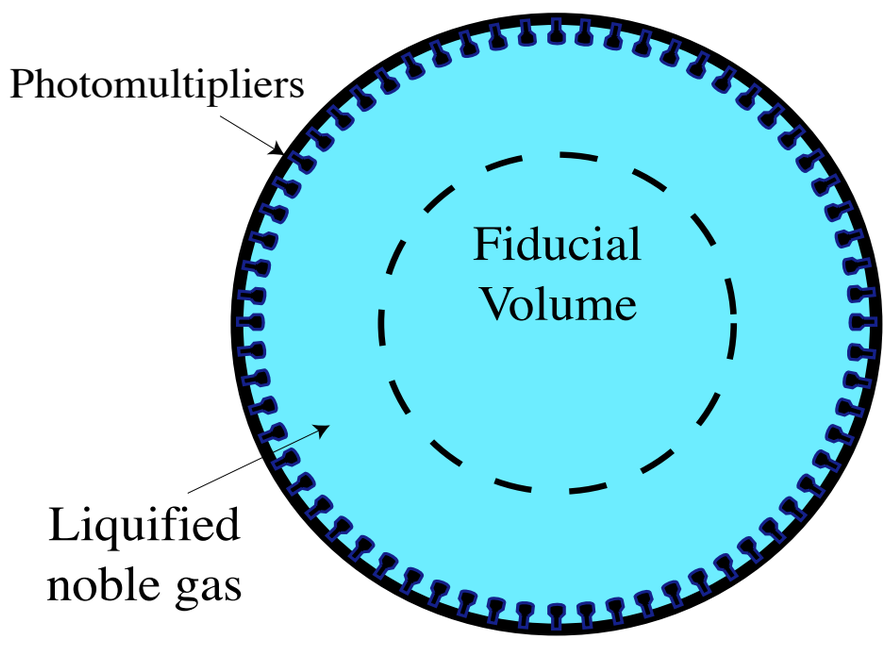
Hermetic 17 ton polyethylene neutron shield is being prepared for the underground installation

The Mini-CLEAN Approach

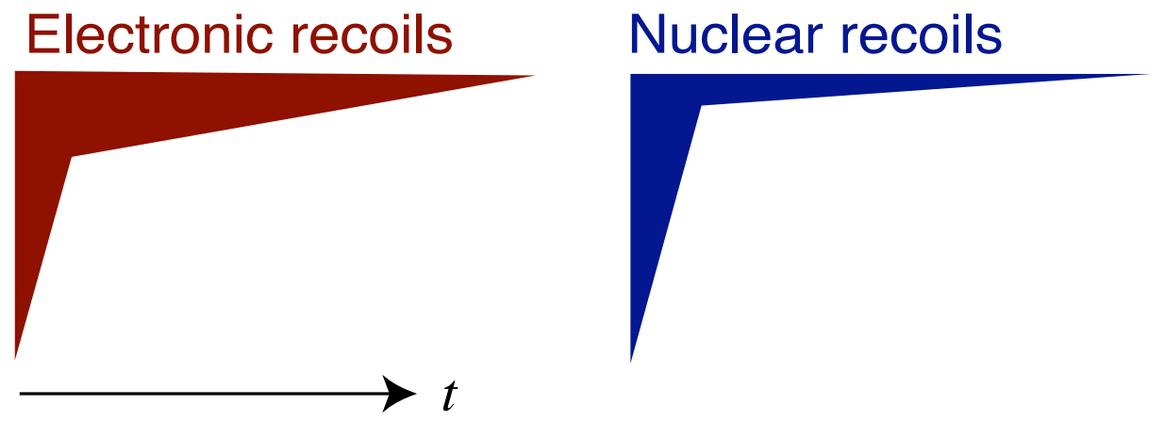
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

Liquid neon and liquid argon are bright scintillators (30,000 - 40,000 photons/MeV).
Do not absorb their own scintillation.
Are inexpensive (Ar: $2k/ton, Ne: $60k/ton).
Are easily purified underground.
Exhibit effective pulse shape discrimination.
Exchange of targets allows direct testing of A^2 dependence of WIMP scattering rate

Self-shielding



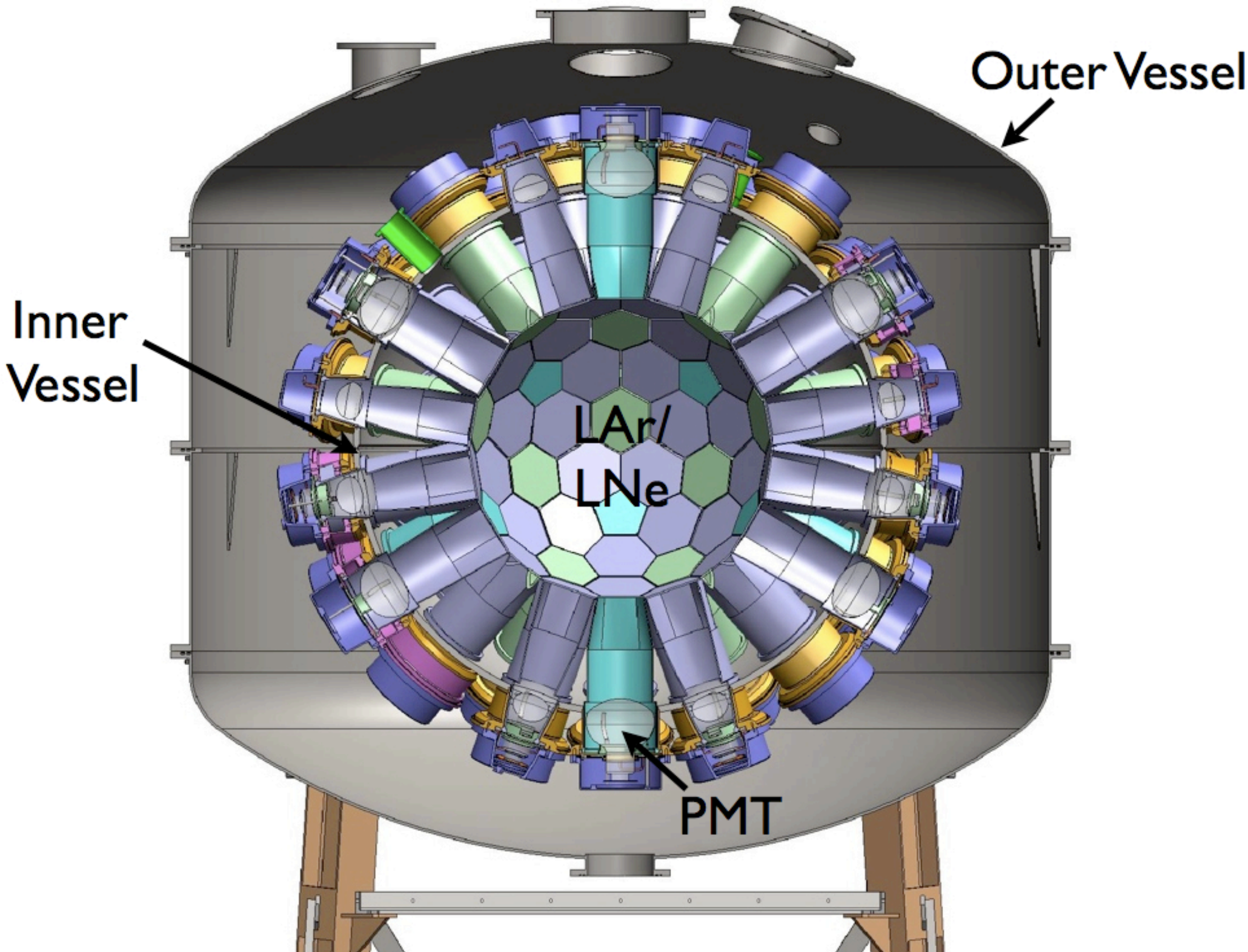
Pulse-shape discrimination



Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

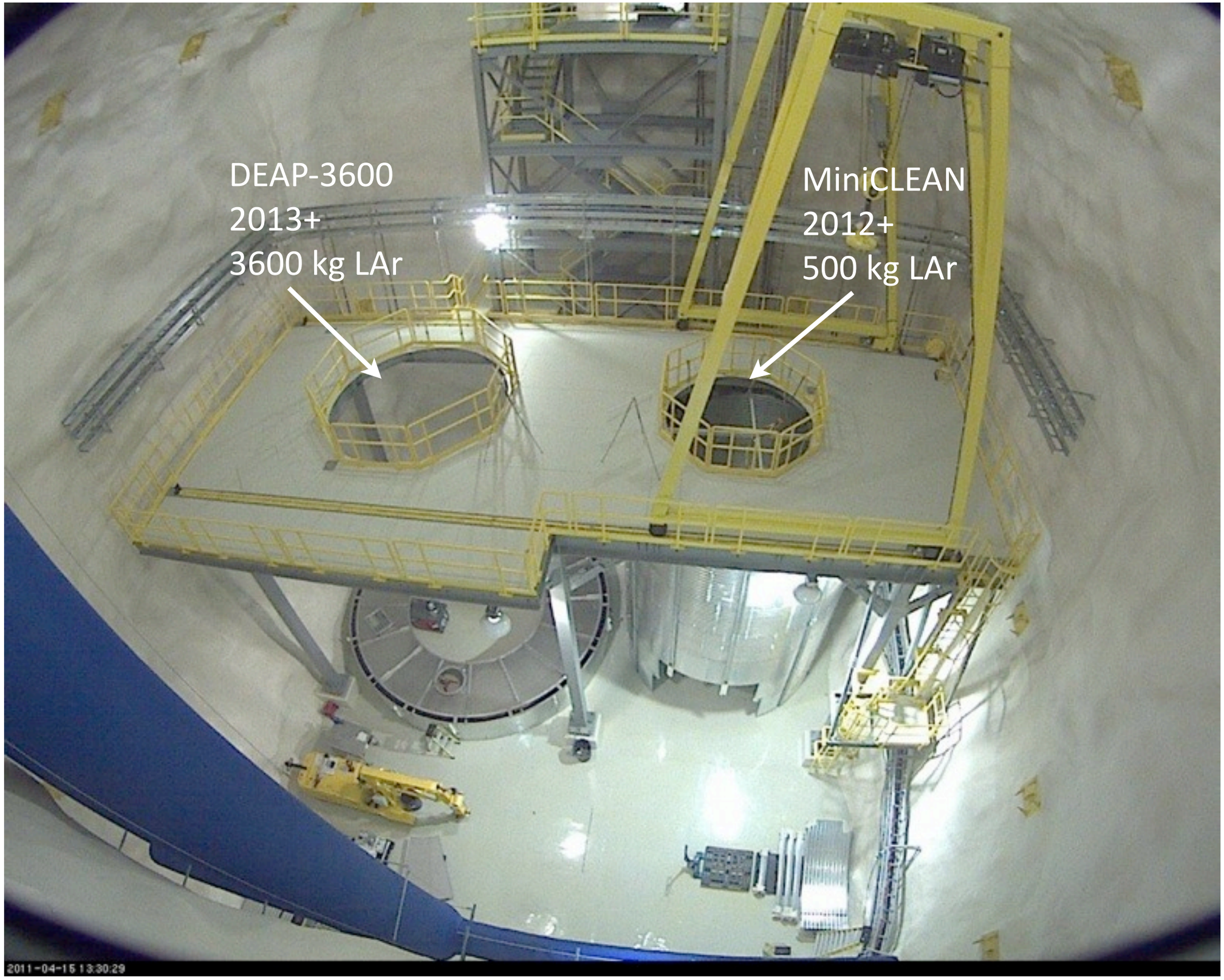
MiniCLEAN detector



The MiniCLEAN Outer Vacuum Vessel

MiniCLEAN construction

The Cube Hall at SNOLAB



DRIFT progress and status 2010/11

US: Occidental, UNM, CSU; UK: Sheffield, Edinburgh, RAL

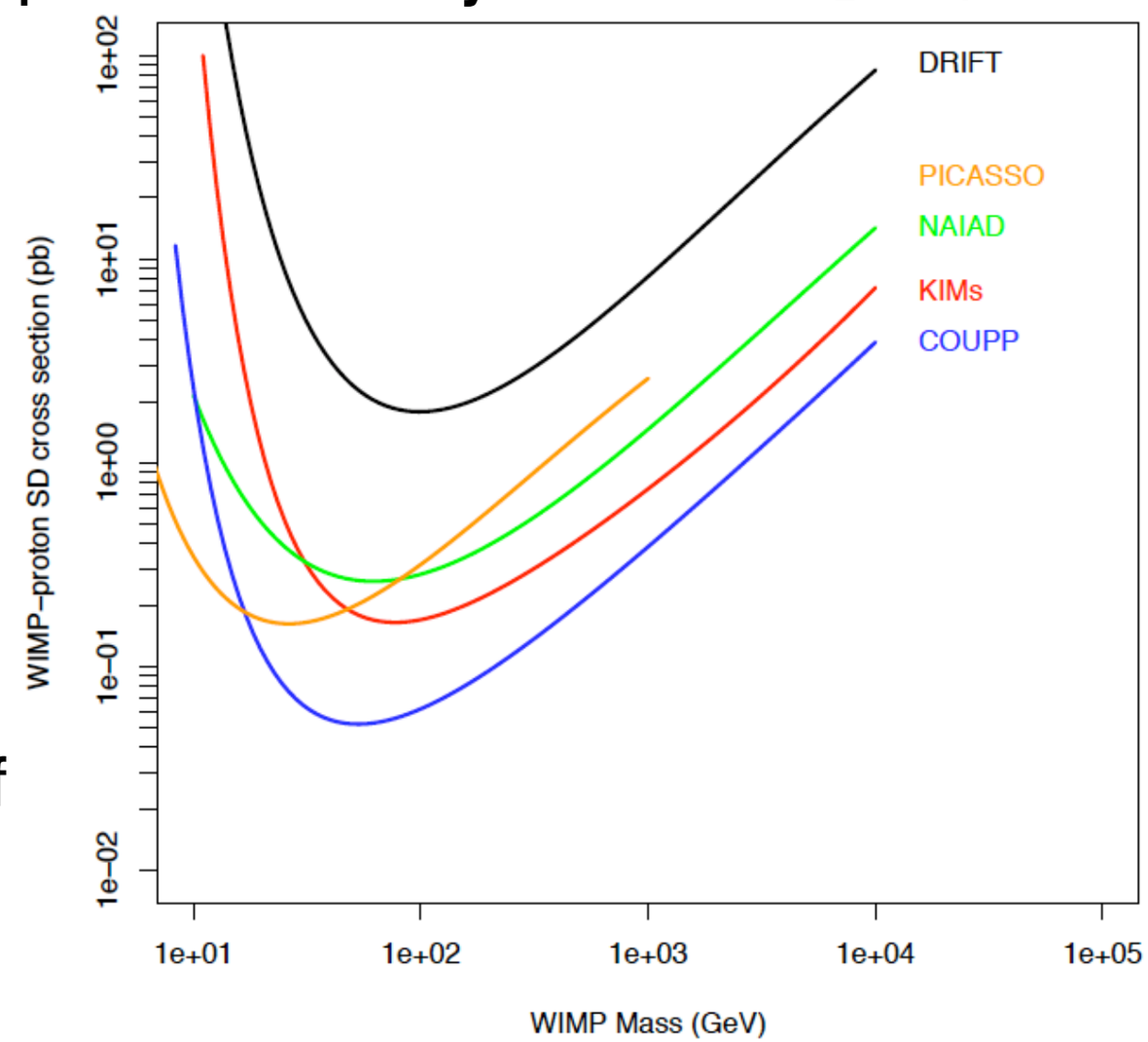
Introduction to DRIFT

- Goal: Directional Detection of WIMP Dark Matter - Identify a Galactic Signal
- DRIFT is a proven directional detector
- Operational in the Boulby Mine since 2001

Recent progress: DRIFT-IId

- Built and installed new gas system for CF_4 (SI sensitivity)
- Built and installed new DAQ
- New publications including world's best limit with direction sensitivity: **arXiv:1012.5967**
- Thin-film cathode installed for reduction of dominant source of backgrounds from radon progeny recoils (RPRs)

47 day run with CS_2/CF_4

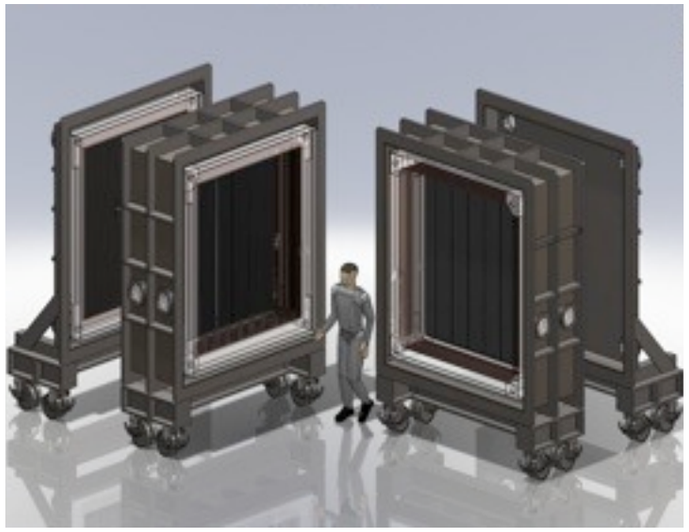


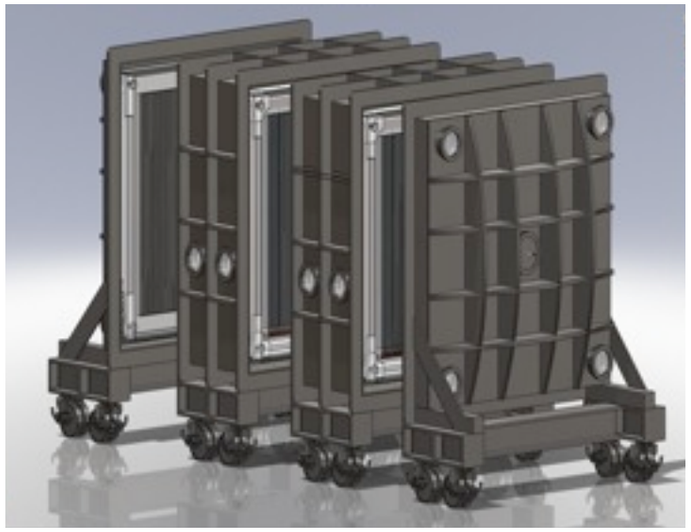
Current status: DRIFT-IId

- Factor ~30 reduction in radon progeny recoil backgrounds, from 130/day down to 4/day: thin-film cathode works!
- Dark matter run with thin-film cathode of ~50 days of data undergoing blind analysis
- Operational in the Boulby Mine since 2001

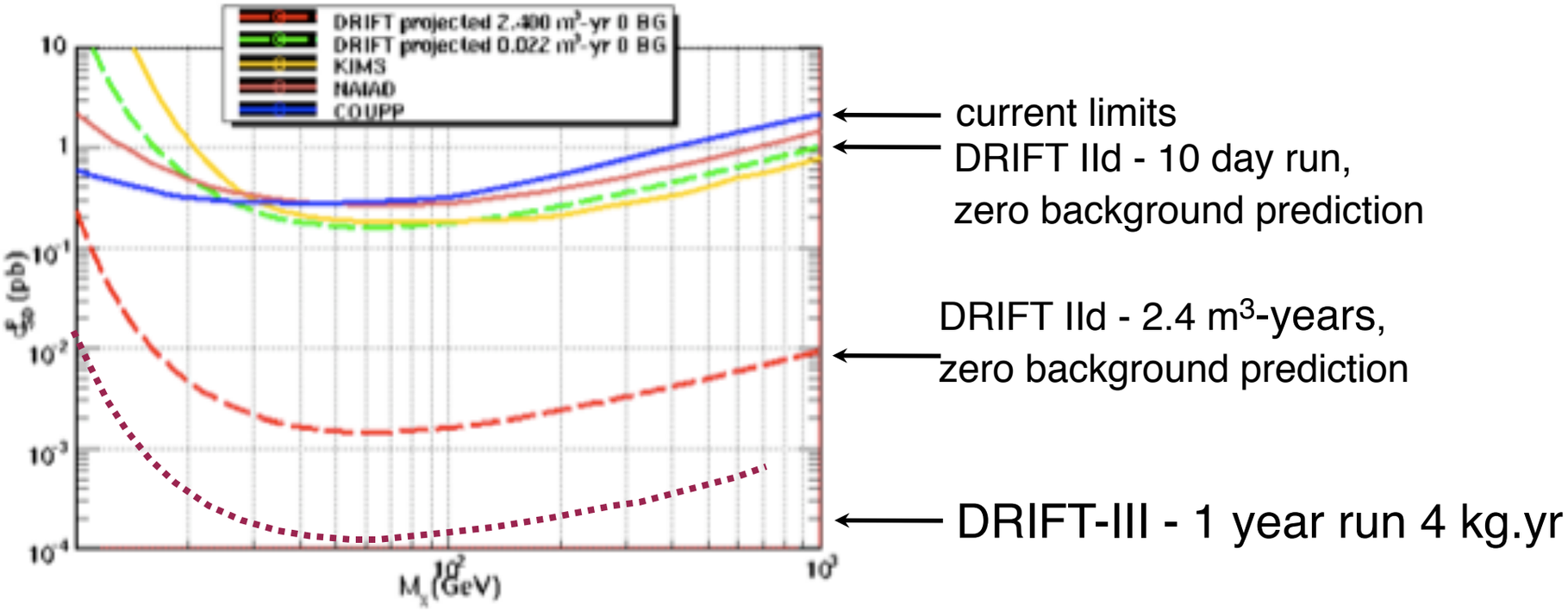
Future plans: DRIFT-III

DRIFT-II is now Volume × Time limited: scale up to a 24 m^3, 4 kg target mass, DRIFT-III detector planned





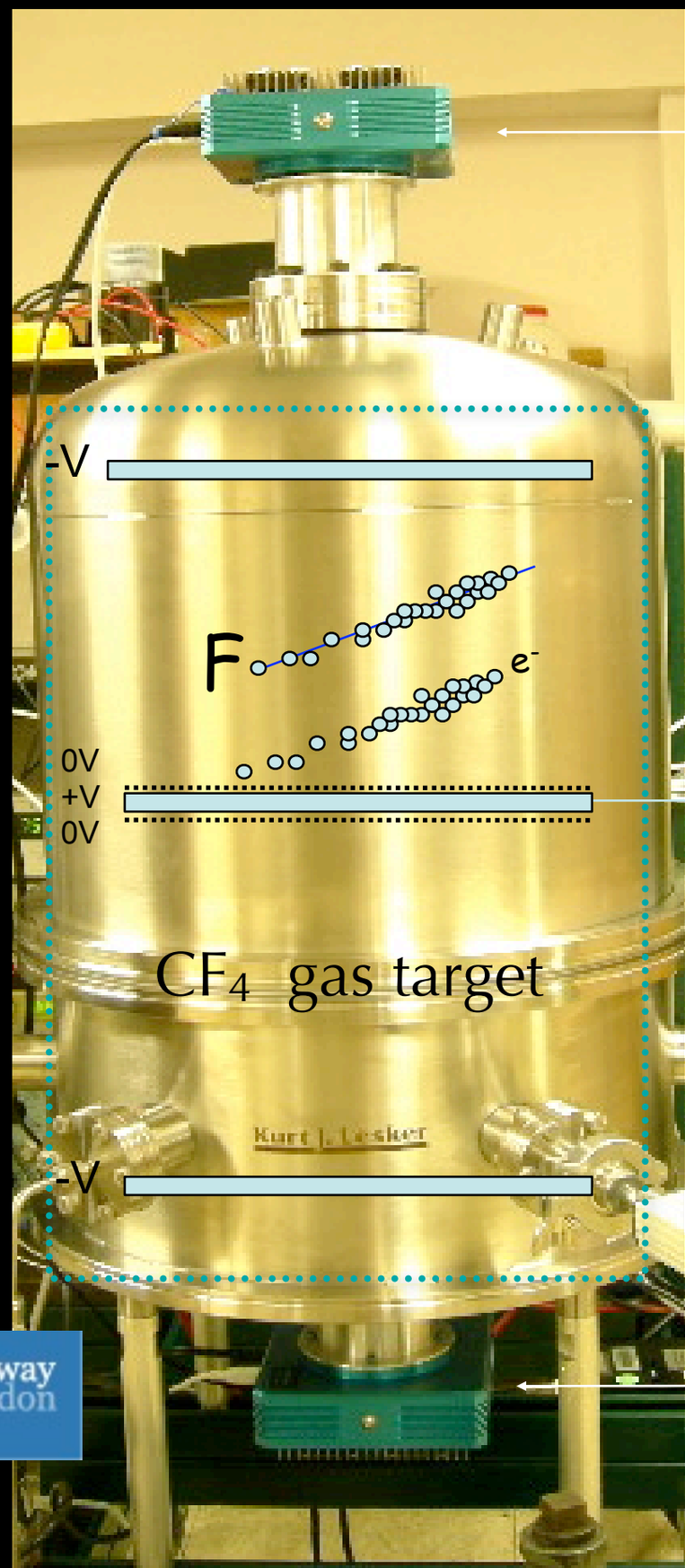
Sensitivity Estimates (SD)

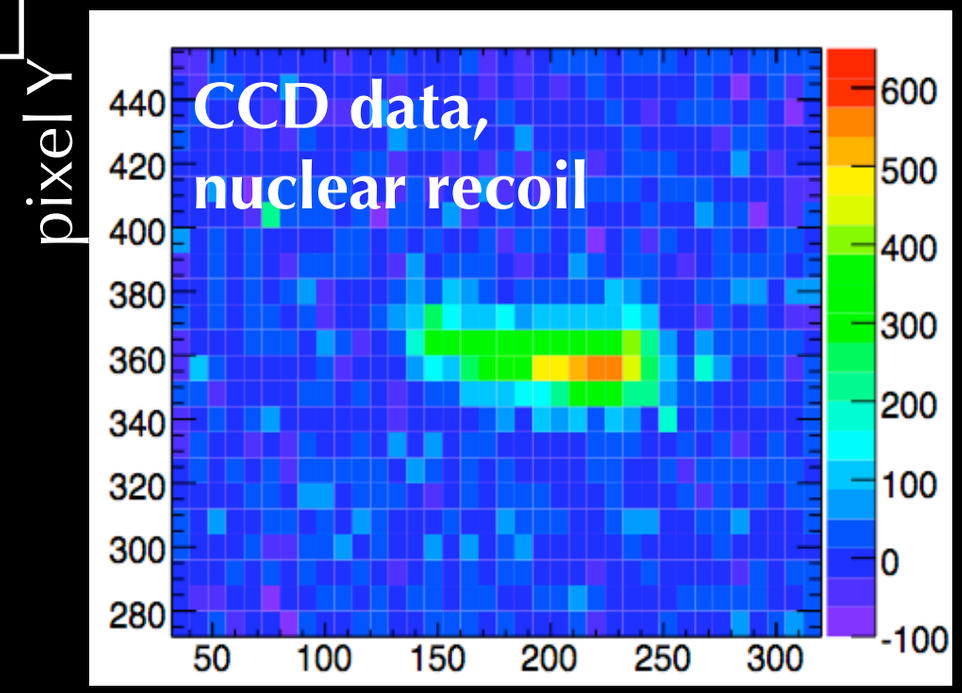


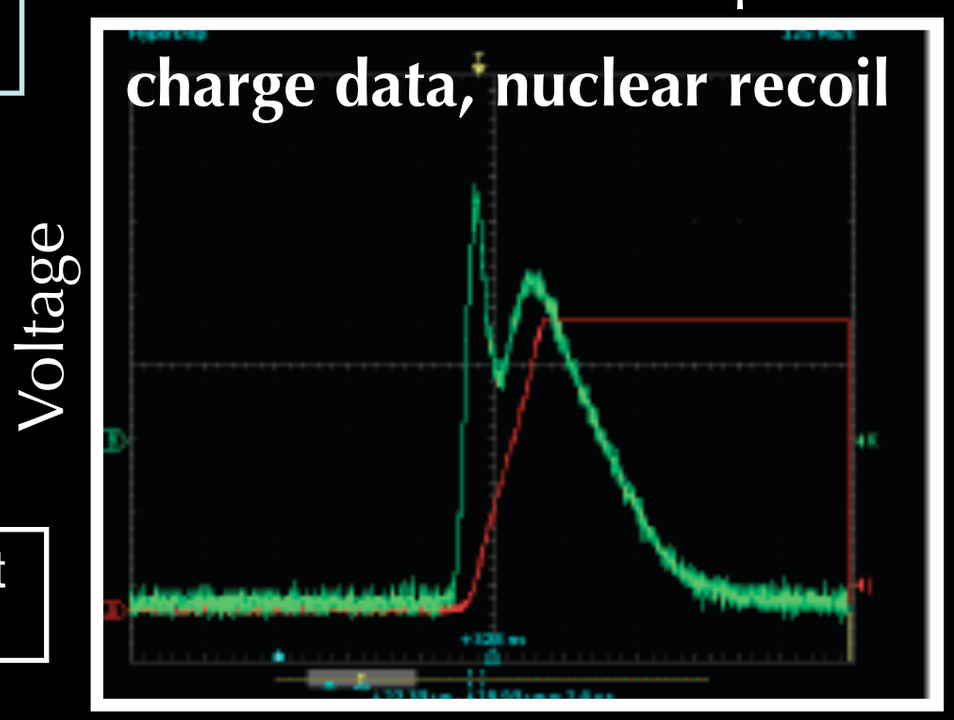
DMTPC Directional Dark Matter Search

(Dark Matter Time Projection Chamber)

Goal: correlate WIMP-induced recoil signal with galactic motion







Directional Detection Spin-Dependent Sensitivity

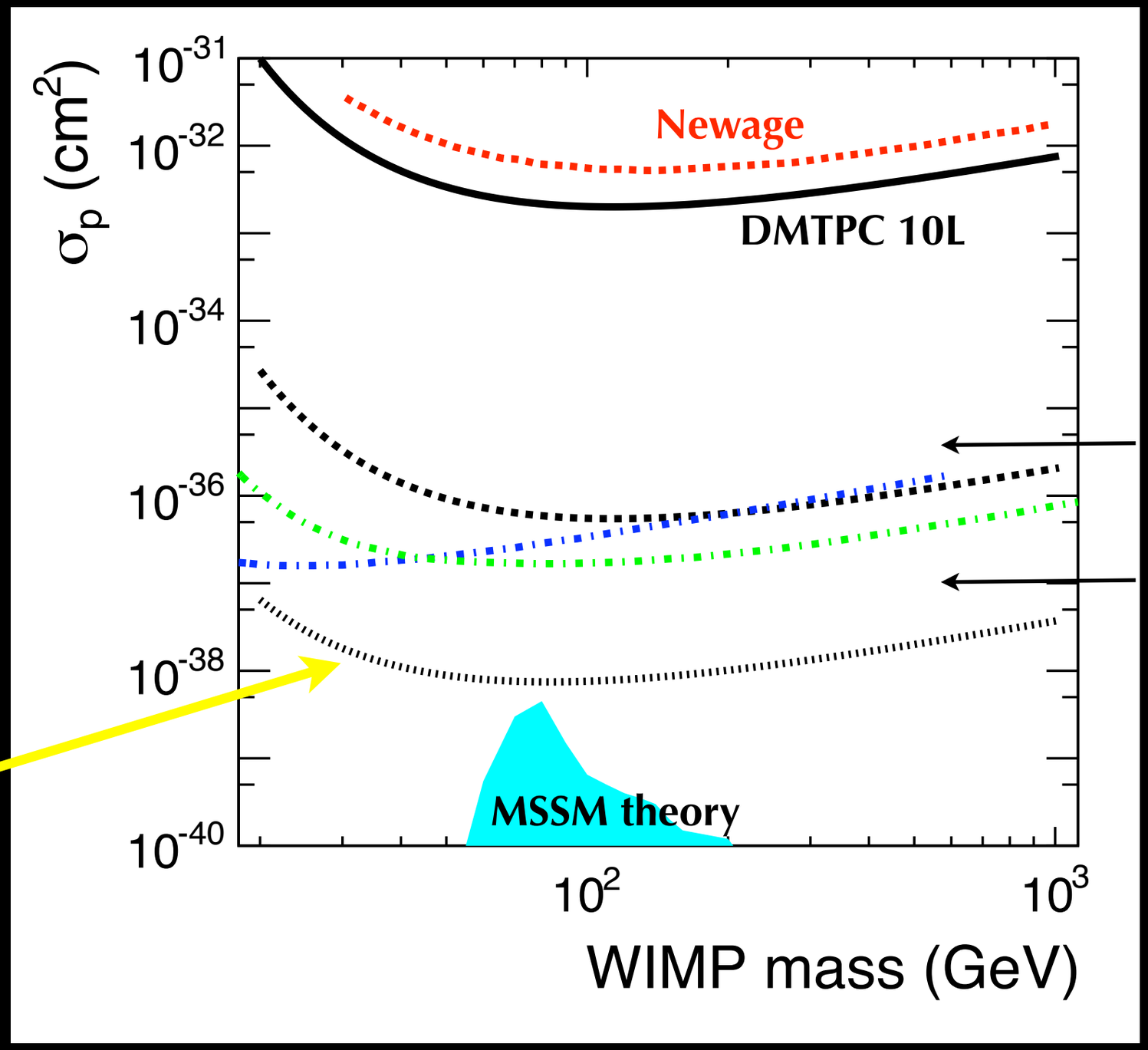
NEWAGE limit (Kamioka)

K. Miuchi et al., Phys.Lett.B686:11-17 (2010)

DMTPC 10L limit (at surface, 38 gm-day)

S. Ahlen et al., Phys. Lett. B 695 (2011)

1m^3 at WIPP (DMTPCino) projected sensitivity (1 year)



directional results

DRIFT, *arXiv: 1010.3027*

1D results

COUPP, IDM2010

DMTPC now operating 1.6 km.w.e. underground at WIPP, since Fall 2010

Next steps: low-background detector R&D, DMTPCino at WIPP (1m^3 detector)

Summary

1) WIMPs might be detected by direct searches, indirect searches, or the LHC
If Nature is kind, WIMPs will be detectable by all three!

2) Interesting new results from DAMA, CDMS, COUPP, and CoGeNT.

3) Experiments based on liquefied noble gases are scalable and allow background reduction based on ionization/scintillation ratio, pulse shape, and/or self-shielding.

3) New results from liquefied noble gas experiments illustrate their promise as WIMP detection materials.

4) Future experiments will reach deep into WIMP parameter space in the very near future.