Direct Dark Matter Detection Using Scintillation

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The Hunt For Dark Matter
A Symposium on Collider, Direct and Indirect Searches
Fermilab

Searching for WIMPs

Accelerators: Look for dark matter candidates at the LHC (lifetime limit < 1 ms)

Indirect Searches: Look for □□ annihilation in form of high energy cosmics, neutrinos

Direct Searches:

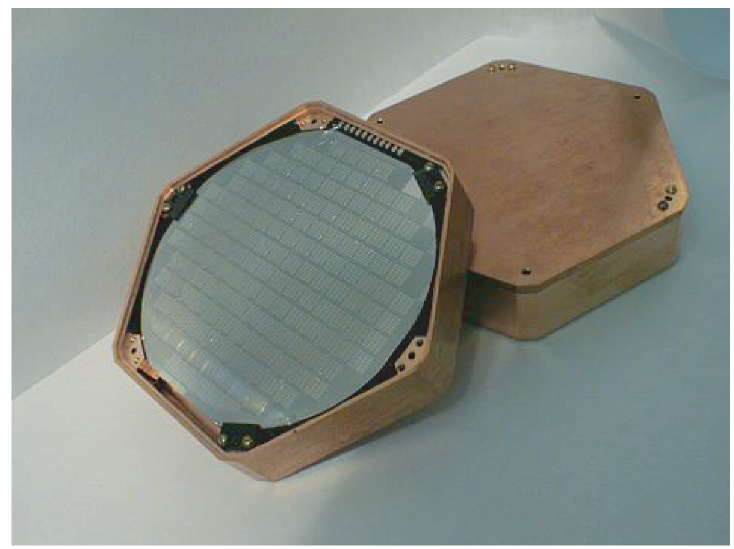
R = N □ □ <v>

From <v> = 220 km/s, get order of 10 keV deposited per nuclear recoil event

Key technical challenges:

- Low radioactivity
- Low energy threshold
- Gamma ray rejection
- Scalability

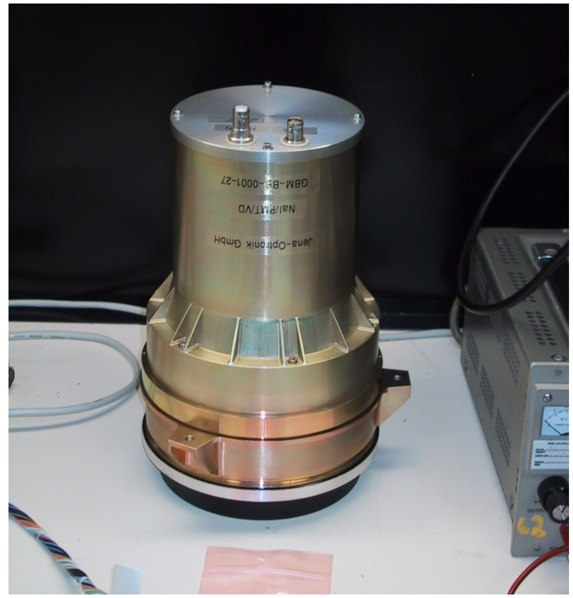
Detect heat, light, or ionization
(or some combination)



Germanium detector
(as in CDMS, Edelweiss)

Some standard radiation detectors

Geiger counter



Sodium iodide crystal

Germanium

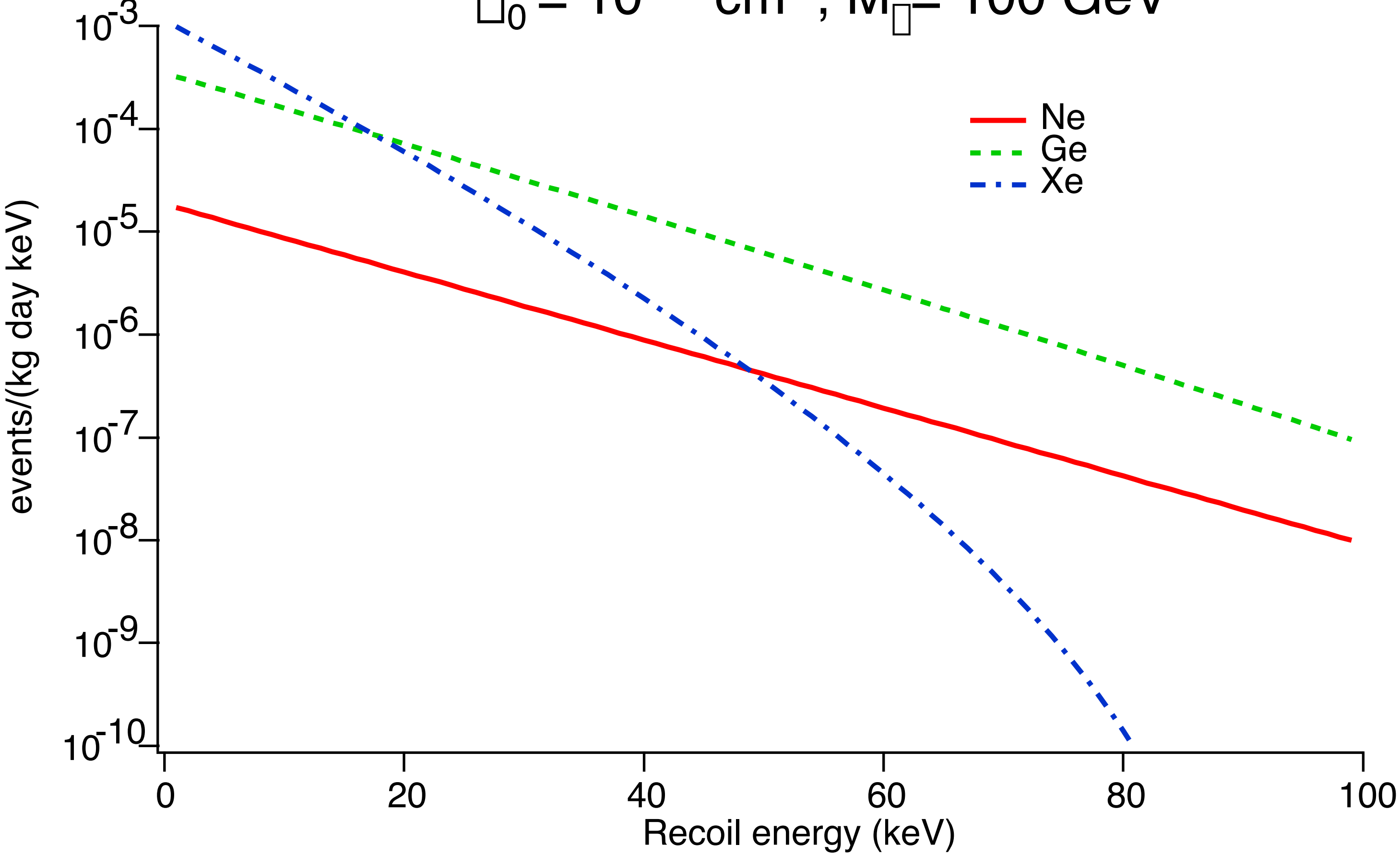
Gamma ray interaction rate is proportional to
(# of electrons in detector) x (gamma ray flux)

Typical count rate = 100 events/second/kg = 10,000,000 events/day/kg
put it in a good lead shield ---> rate drops to 100 events/day/kg.

State-of-the-art dark matter detectors ---> sensitive to 0.01 events/kg/day

WIMP recoil spectra

$\sigma_0 = 10^{-44}$ cm^2, $M_\chi = 100$ GeV



Scattering rate

Sun's velocity around the galaxy

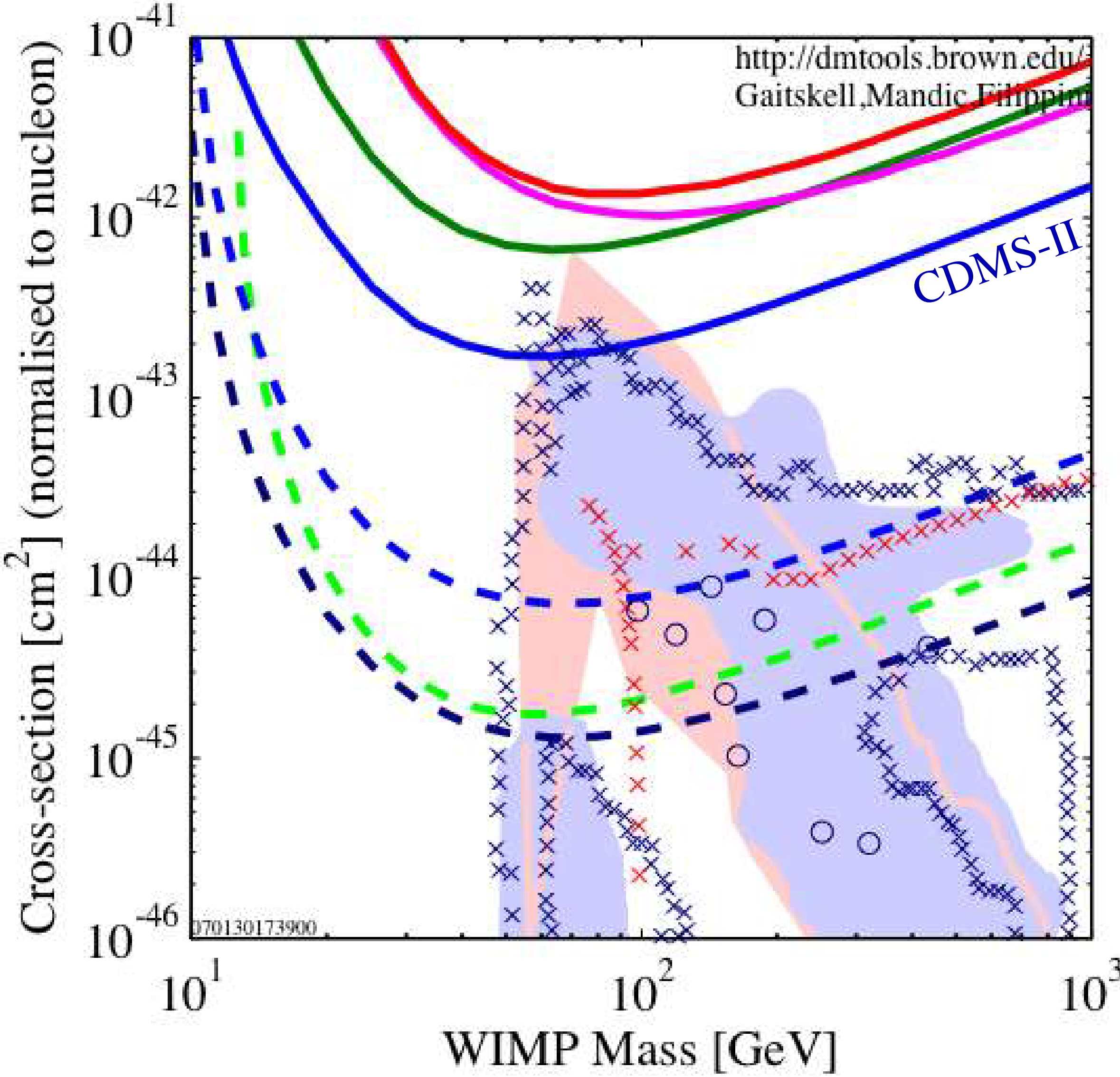
WIMP velocity distribution

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

WIMP energy density, 0.3 GeV/cm^3

Form factor

Direct Dark Matter Searches and SUSY Theory



[solid lines] Published experimental limits

[dashed lines] Experiments planned for the near future

[blue] T. Baltz and P. Gondolo, Markov Chain Monte Carlos. JHEP 0410 (2004) 052.

[red] J. Ellis et al. CMSSM, Phys. Rev. D71 (2005) 095007.

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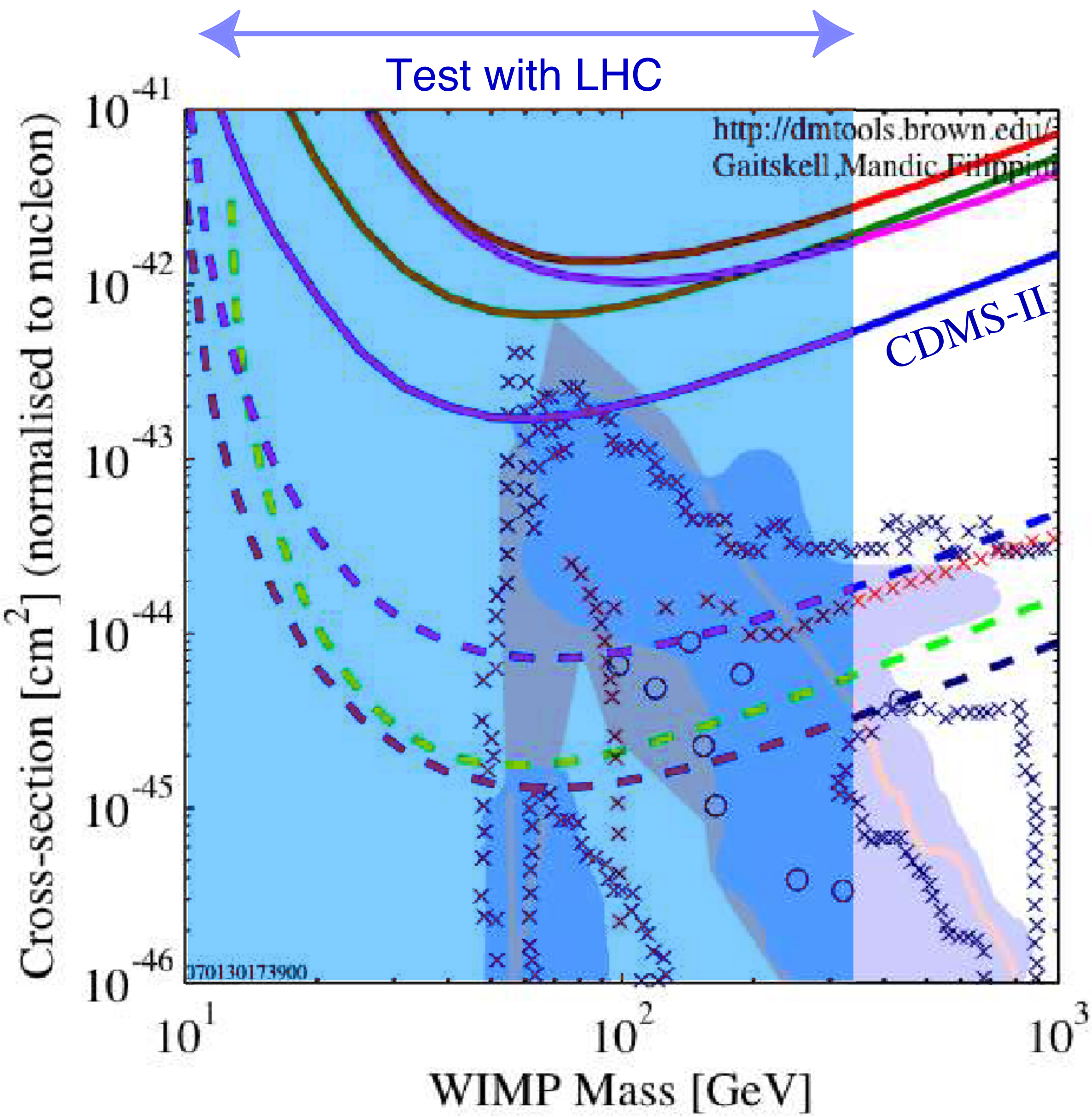
Direct Dark Matter Searches and SUSY Theory



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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

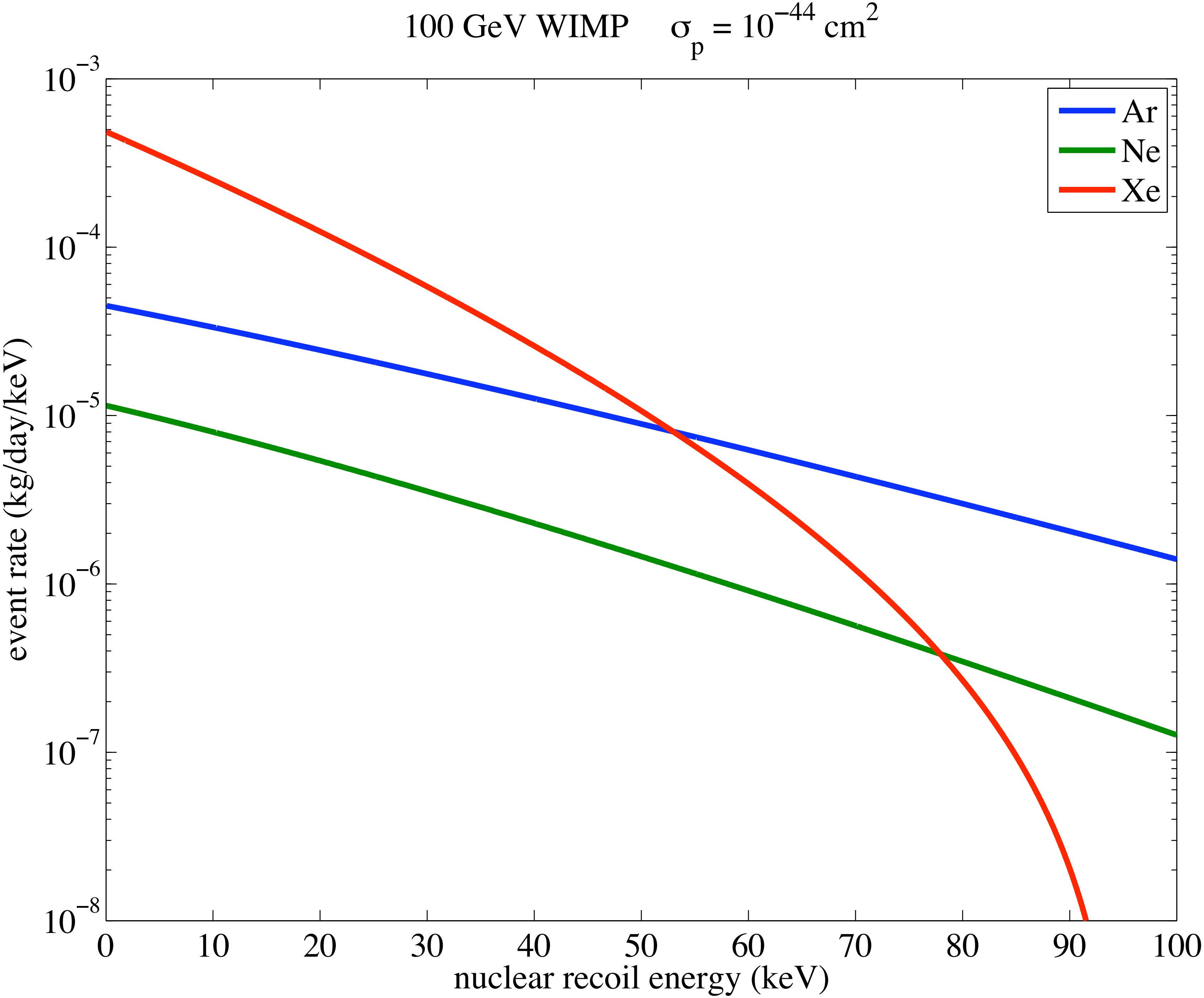
- noble liquids do not absorb their own scintillation
- 30,000 to 40,000 photons/MeV
- modest quenching factors for nuclear recoils

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


100 GeV WIMP σ_p = 10^−44 cm^2
event rate (kg/day/keV)
10^−3
10^−4
10^−5
10^−6
10^−7
10^−8
0
10
20
30
40
50
60
70
80
90
100
nuclear recoil energy (keV)
Ar
Ne
Xe

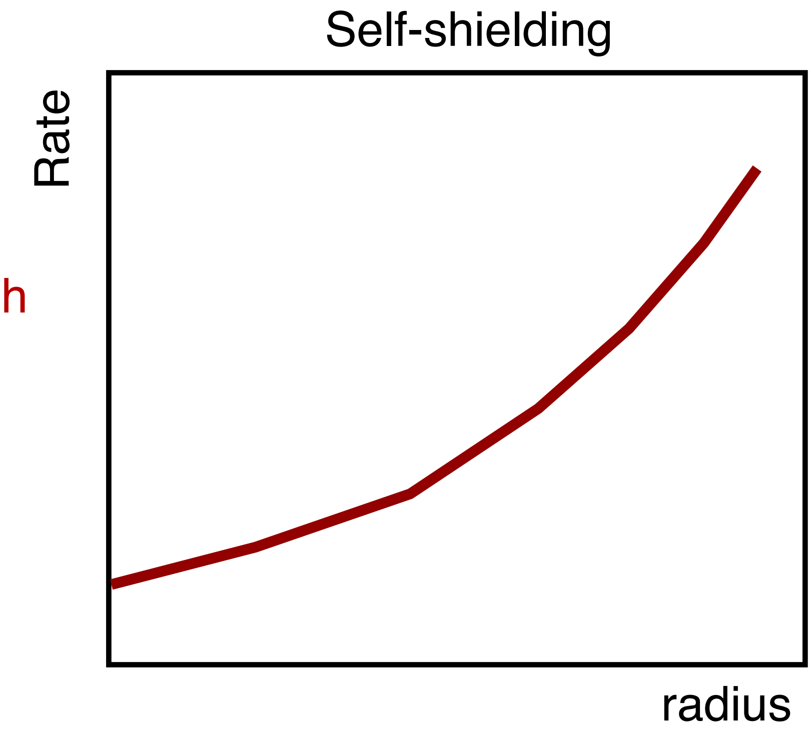
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

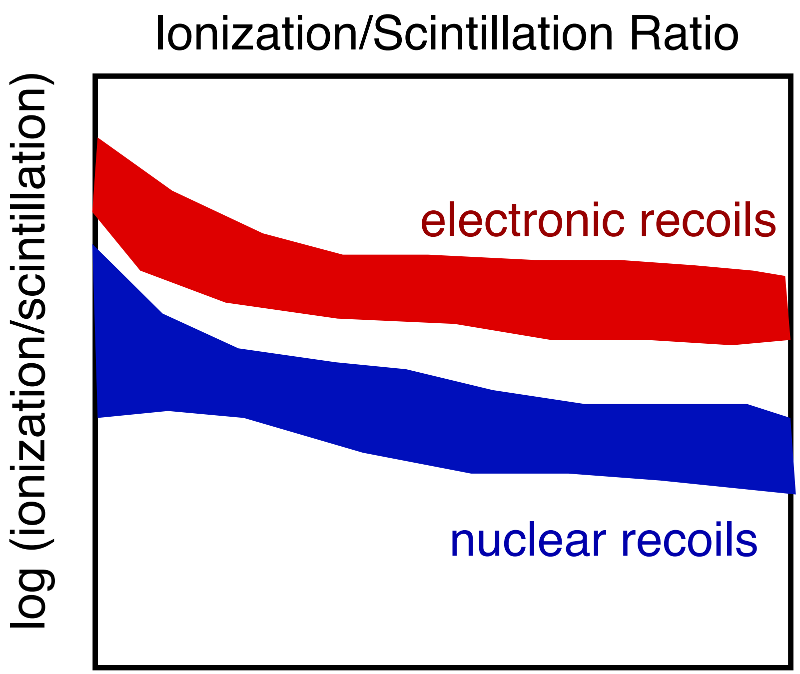
Require < 1 event in signal band during WIMP search

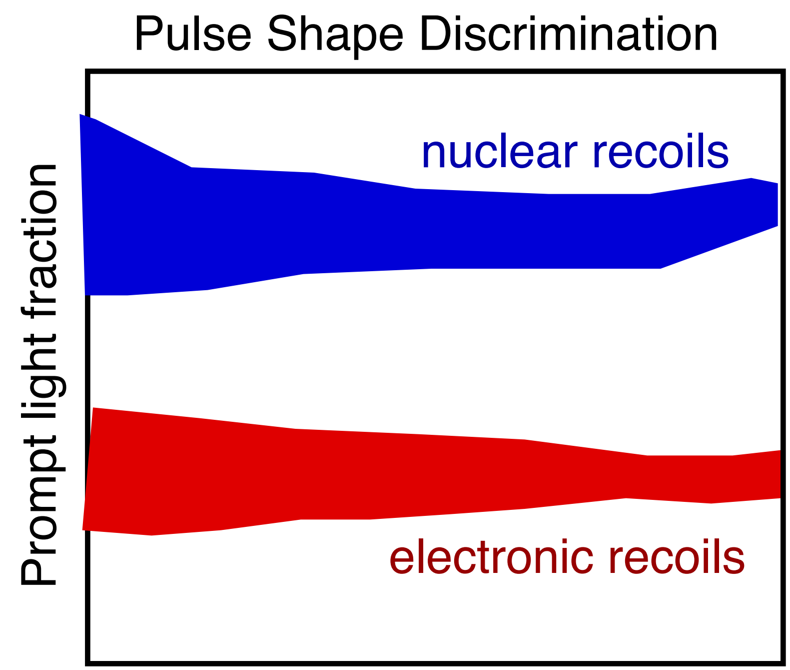
LXe: Self-shielding, Ionization/Scintillation ratio best

LAr: Pulse shape, Ionization/Scintillation ratio best

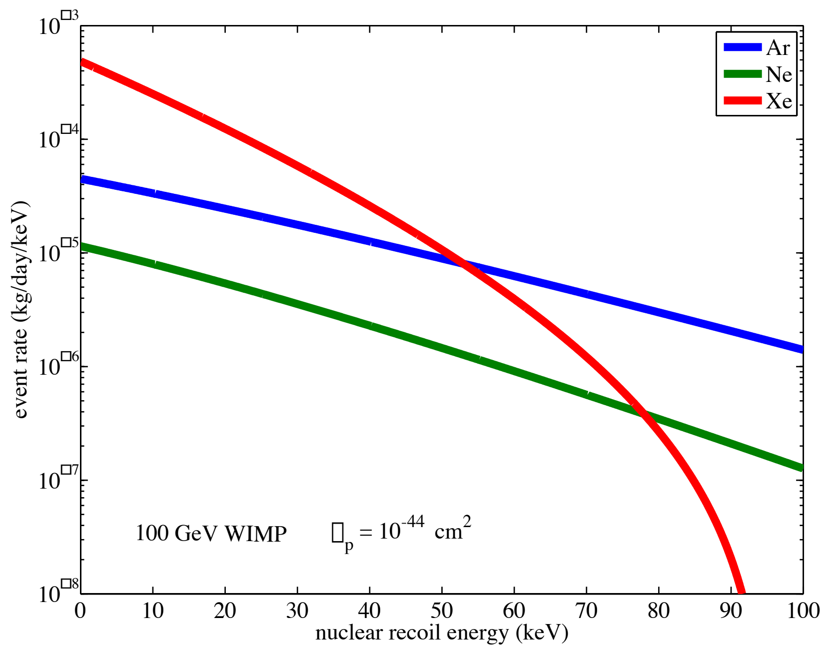
LNe: Pulse shape, Self-shielding best



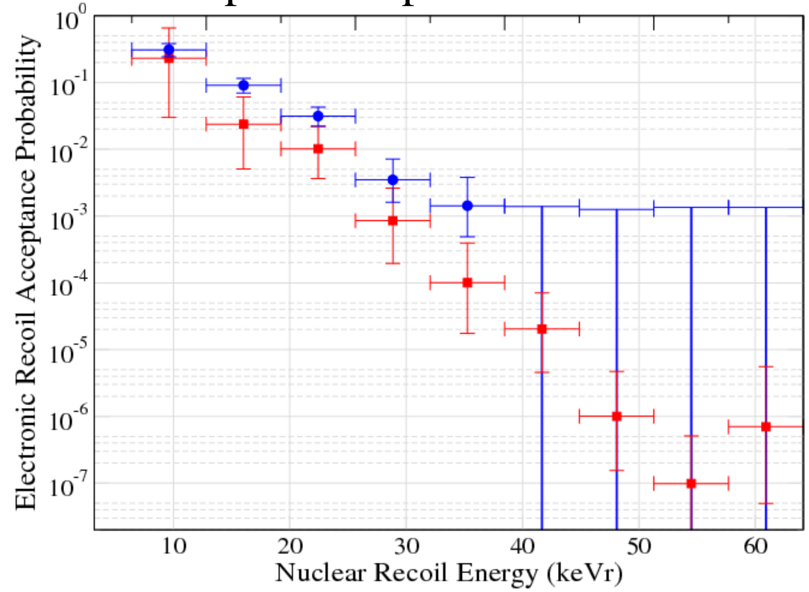




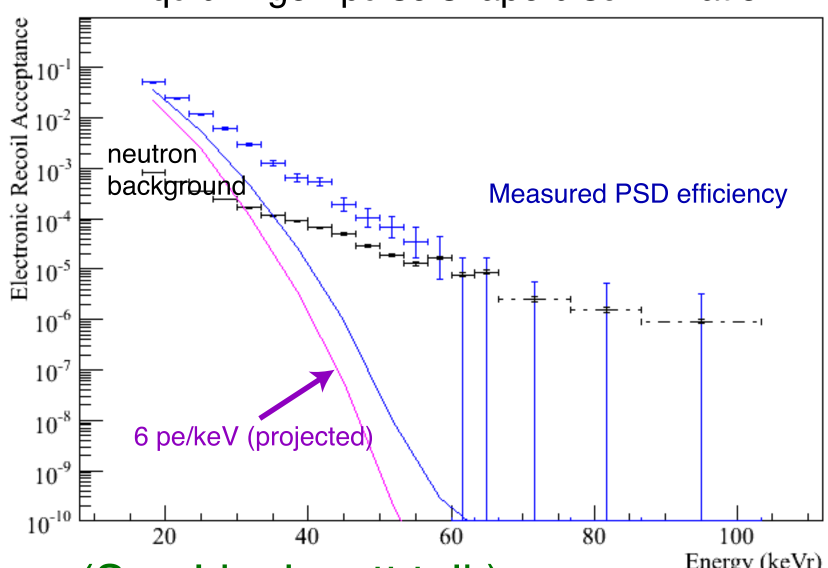
Electronic Recoil Discrimination



LNe pulse shape discrimination

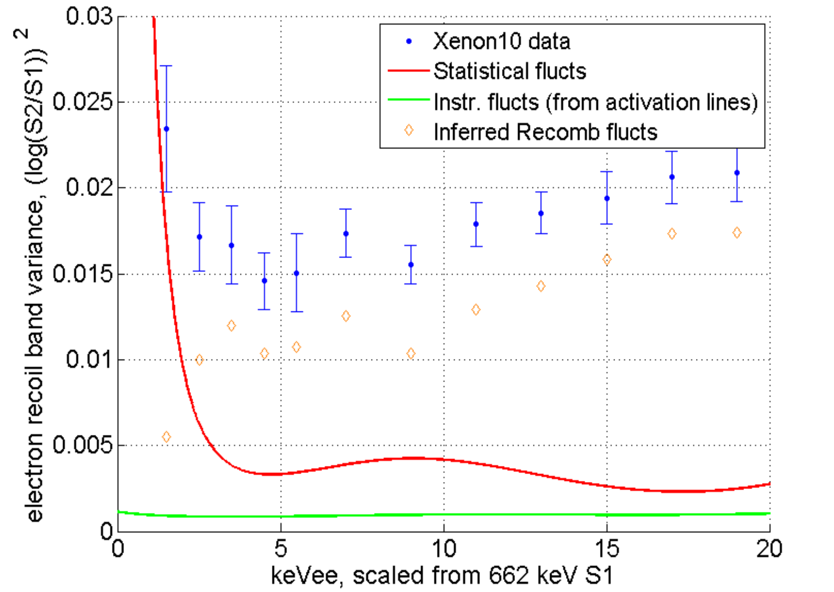


Liquid Argon pulse shape discrimination



(See Lippincott talk)

Liquid Xenon ionization/scintillation discrimination



(See Dahl talk)

Other Backgrounds

(currently subdominant, but a concern fo future experiments)

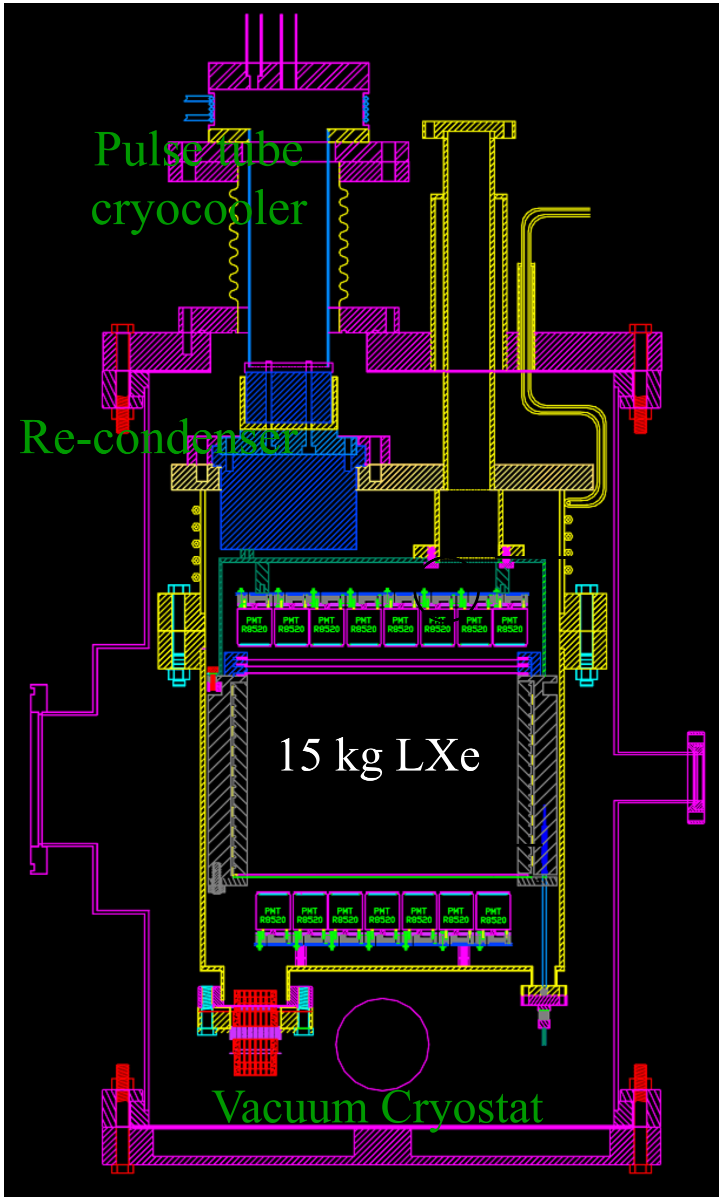
Fast neutrons:

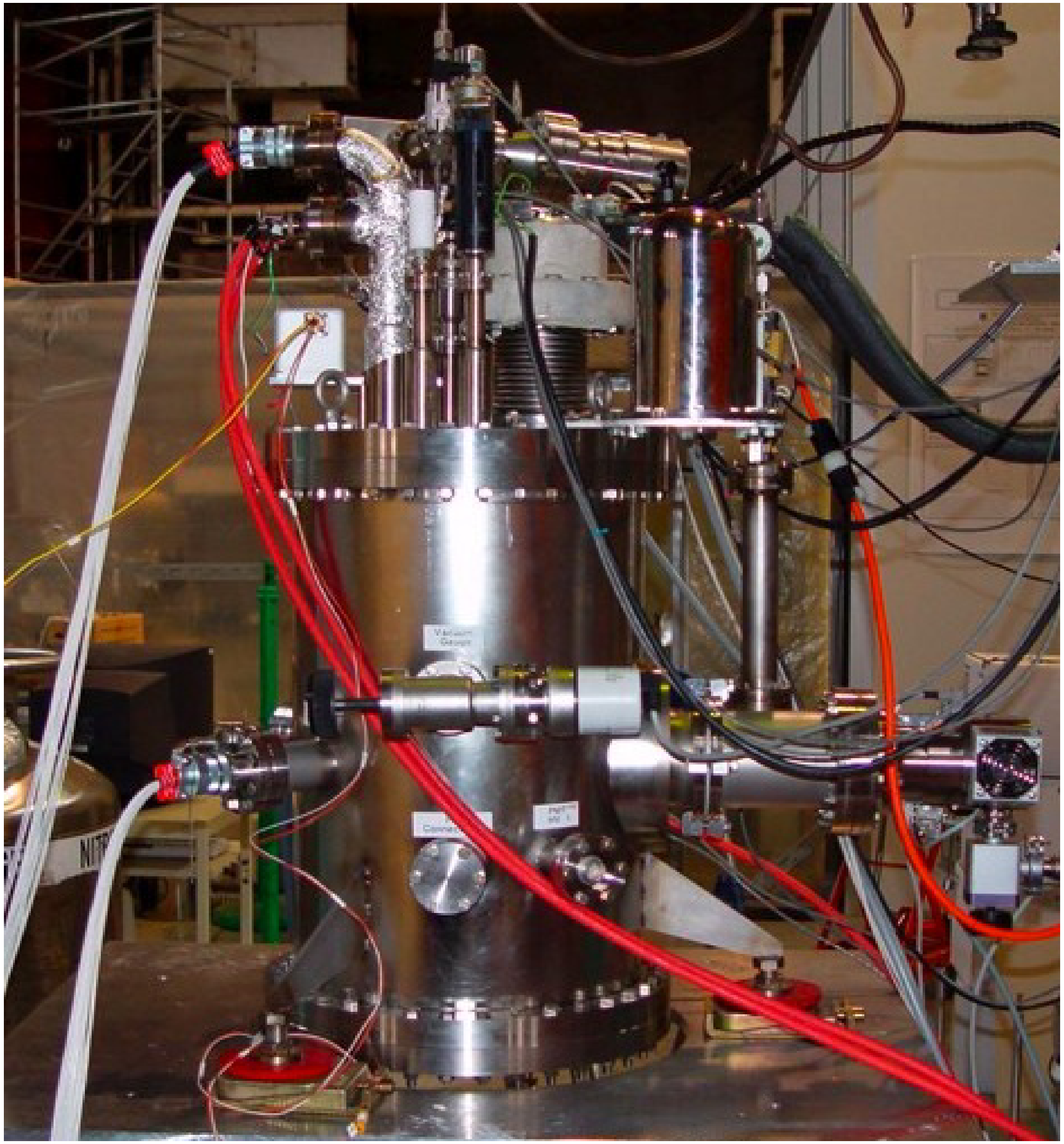
Can elastically scatter from nuclei; these events look just like WIMPs
Come from surrounding rock, muon spallation, detector materials
Need depth to mitigate muon-produced neutrons
Hydrogenous material (polyethylene or water) to moderate fast neutrons
Large detectors can look for multiple scattering, or shield out the fast neutrons

Radon daughters:

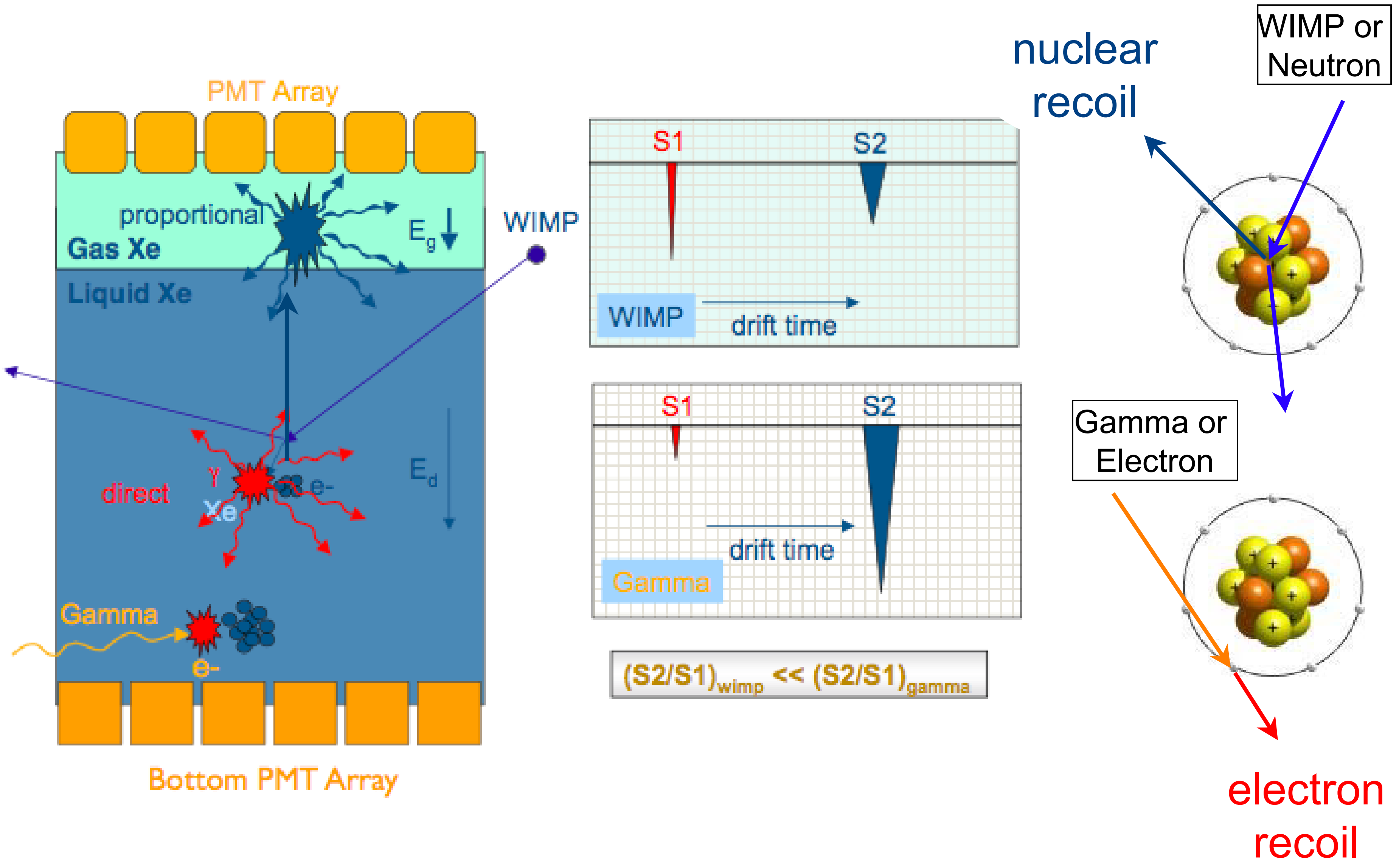
Can decay on the detector surfaces
Produce nuclear recoils that can mimic the WIMP signal
Mitigate using careful surface preparation, radon control,
Can also reduce using position resolution
Active tagging of radon daughters, if the detector surfaces are active

XENON10 (See talk by R. Gaitskell)





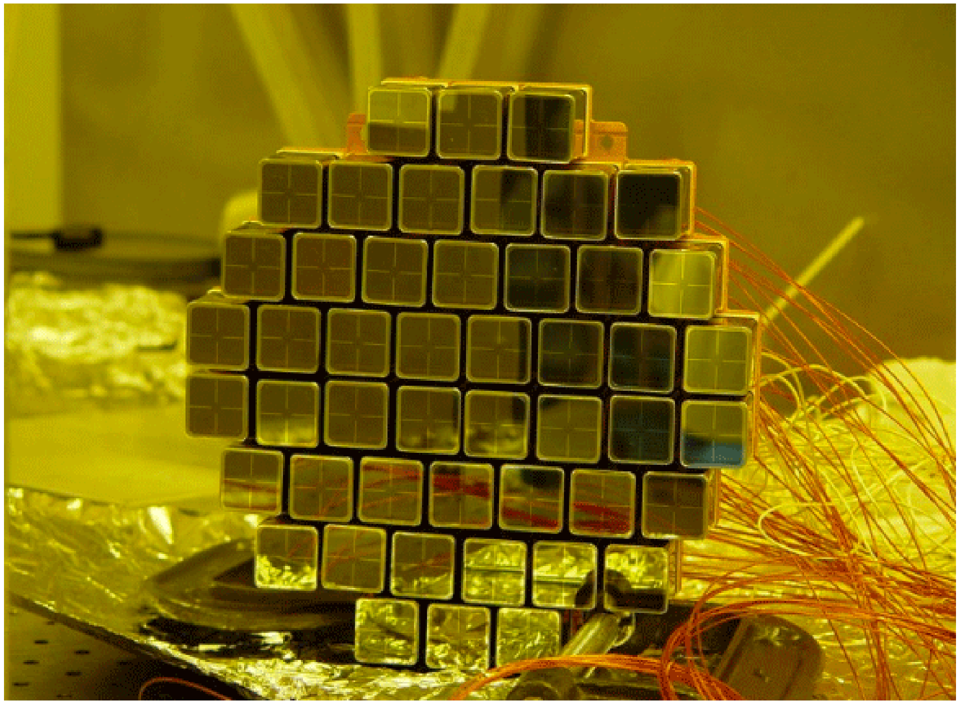
The XENON Detector: How It Works



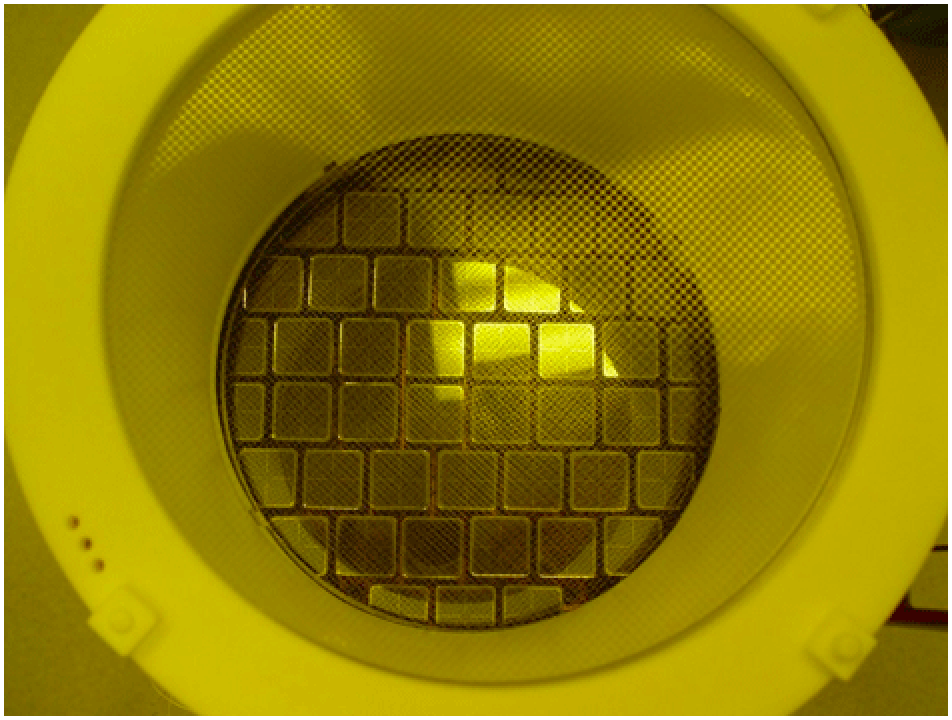
The XENON10 Photomultipliers

Hamamatsu 8520-06-AL 2.5 cm x 3.5 cm
Bialkali photocathode Rb-Cs-Sb
10 dynodes
Quartz window
U/Th/K/Co = 0.17/0.20/0.09/0.56 mBq/PMT
Quantum efficiency > 20% at 178 nm

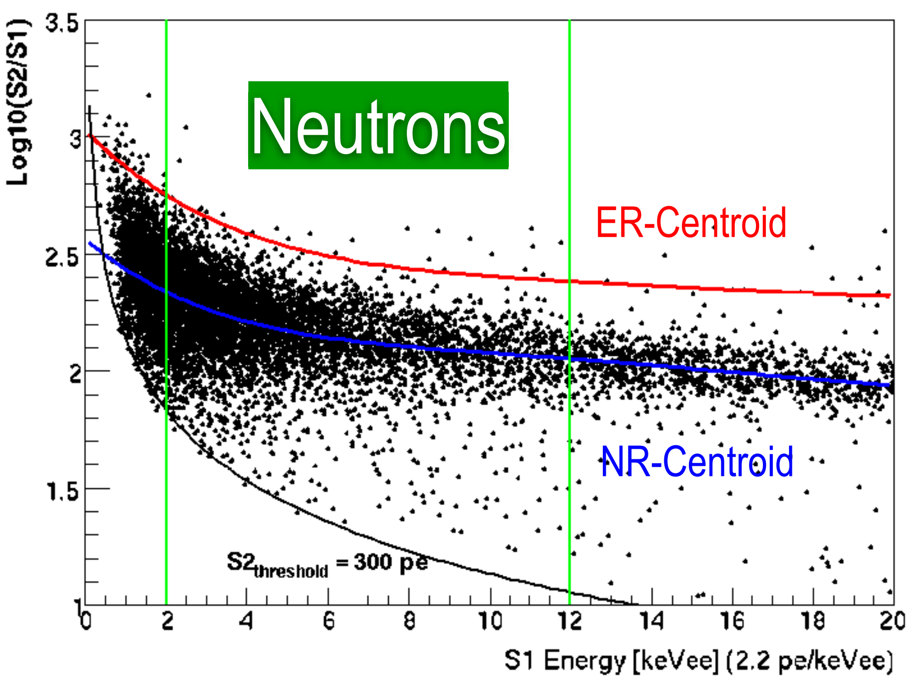
Double PMT arrays --> 3.0 pe/keV w/field
4.9 pe/keV without

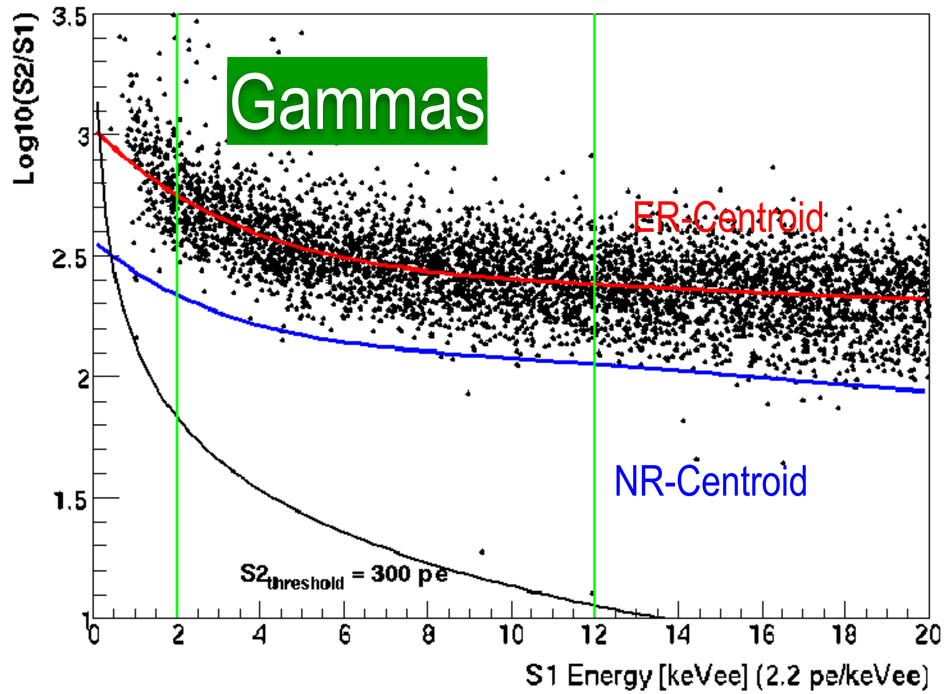


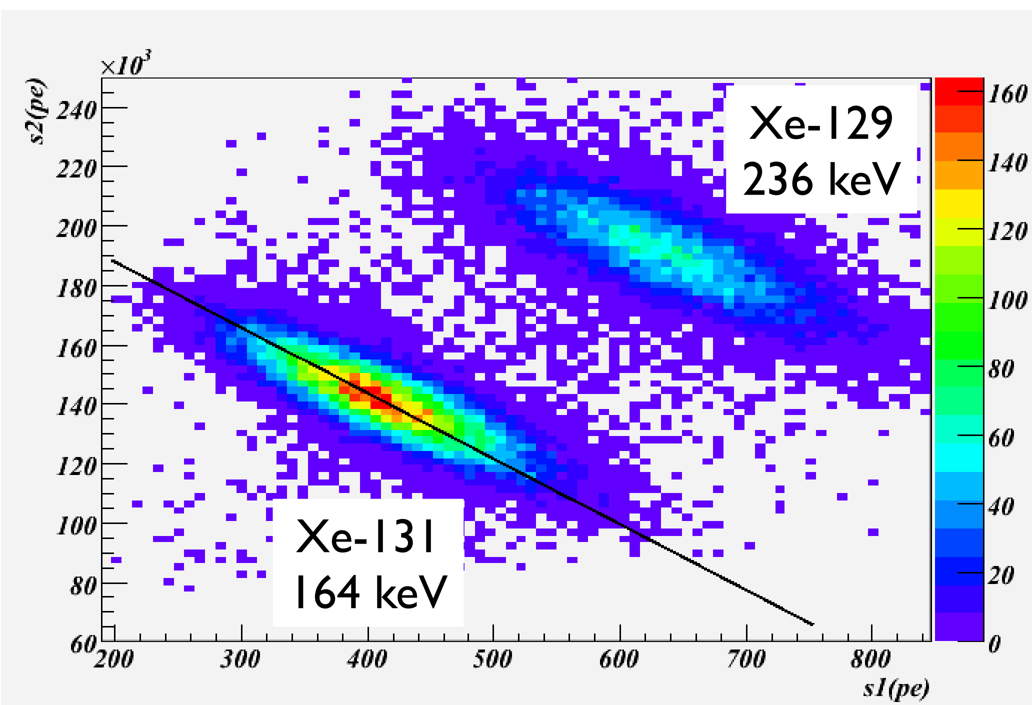
Angel Manzur (Yale) individually testing PMTs

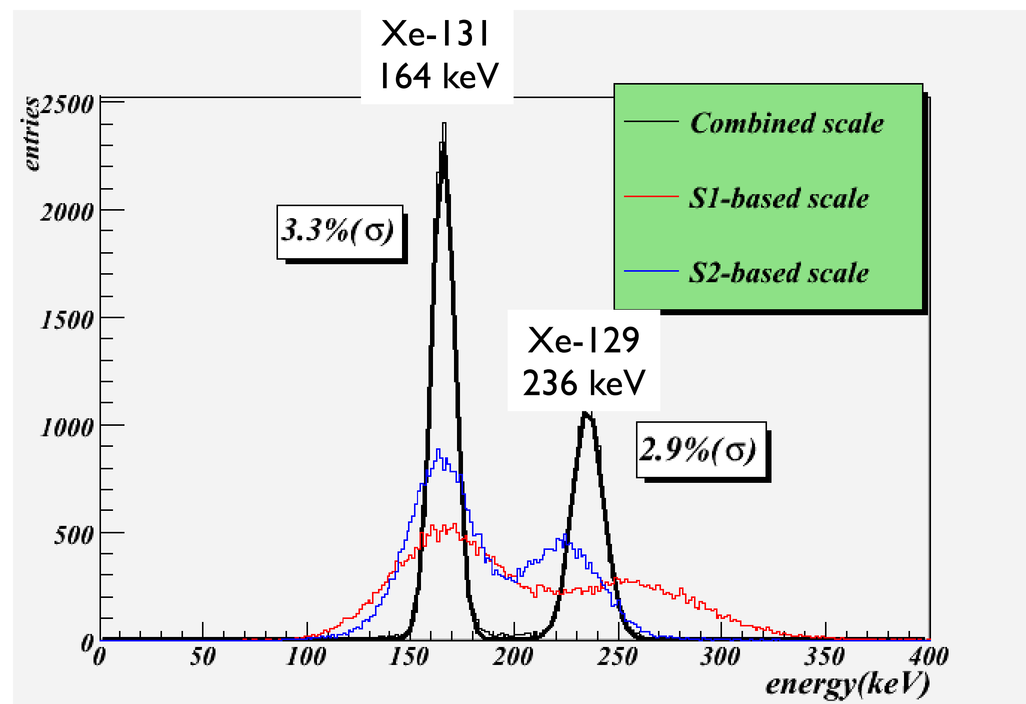


XENON10 Calibration (see Manzur talk)



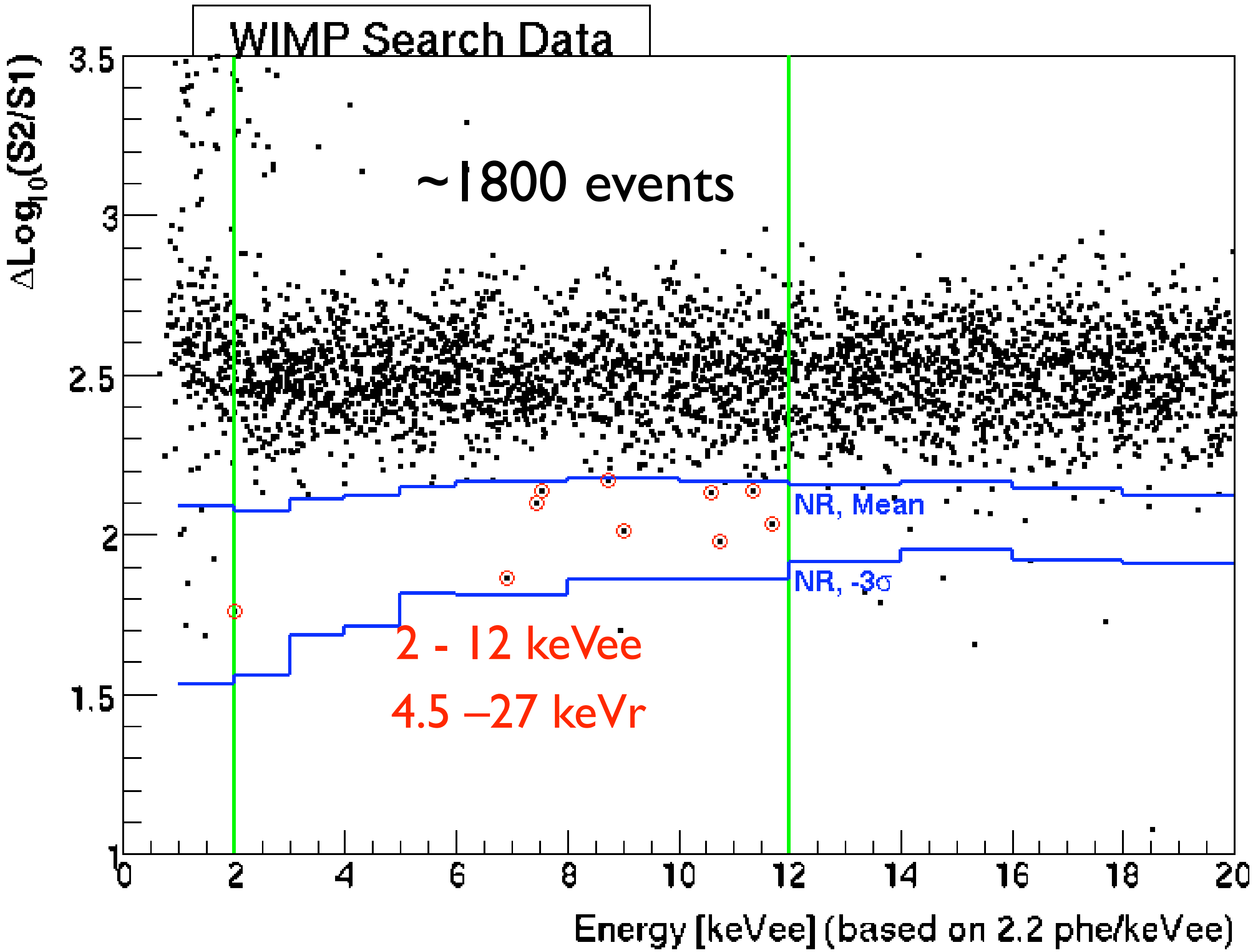






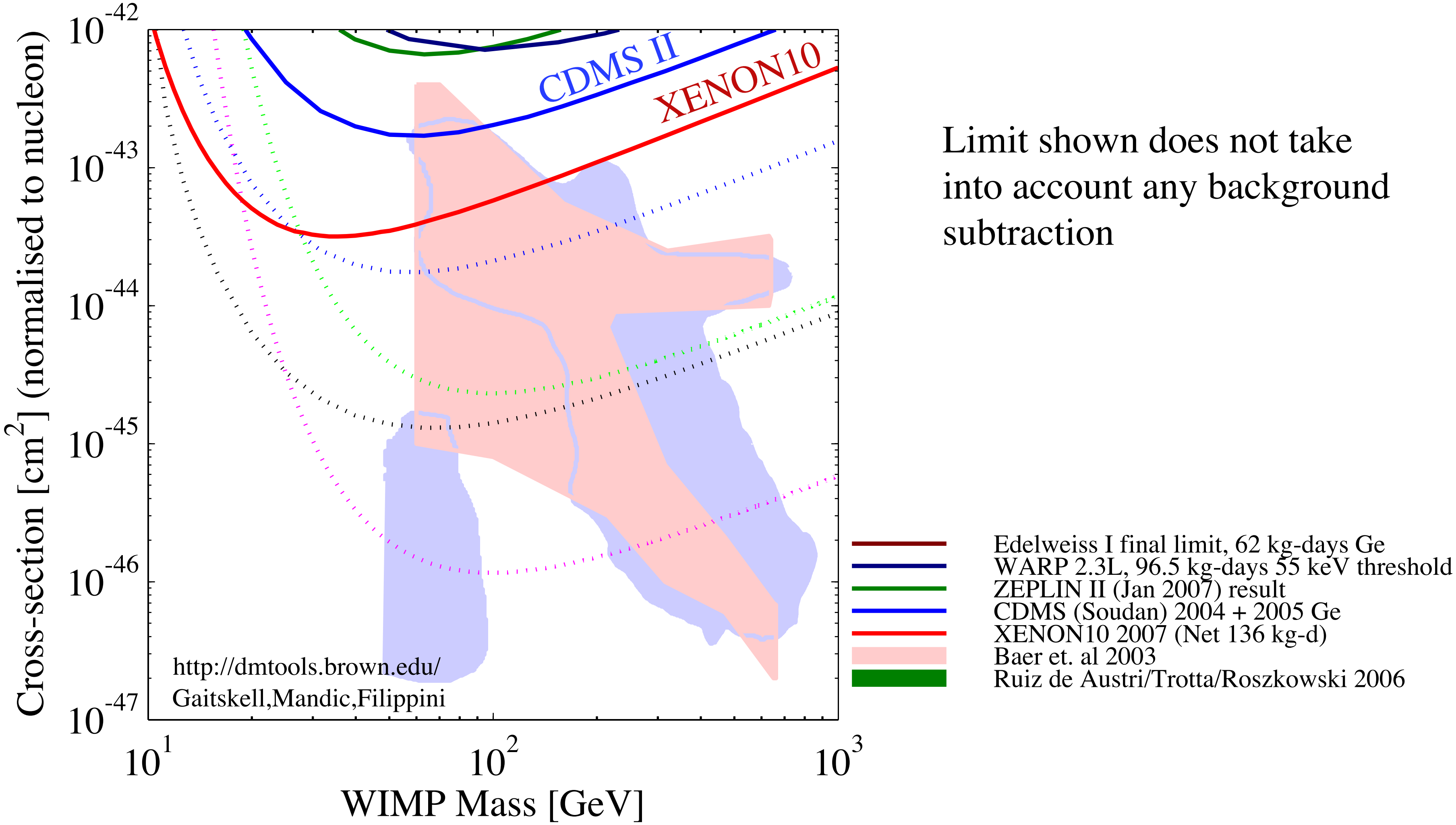
XENON10 WIMP Search Data

136 kg-days Exposure= 58.6 live days x 5.4 kg x 0.86 (ε) x 0.50 (50% NR)



- WIMP "Box" defined at ~50% acceptance of Nuclear Recoils (blue lines): [Mean, -3σ]
- 10 events in the "box" after all cuts in Primary Analysis
- 6.9 statistical leakage events expected from ER band
- NR energy scale based on 19% constant QF

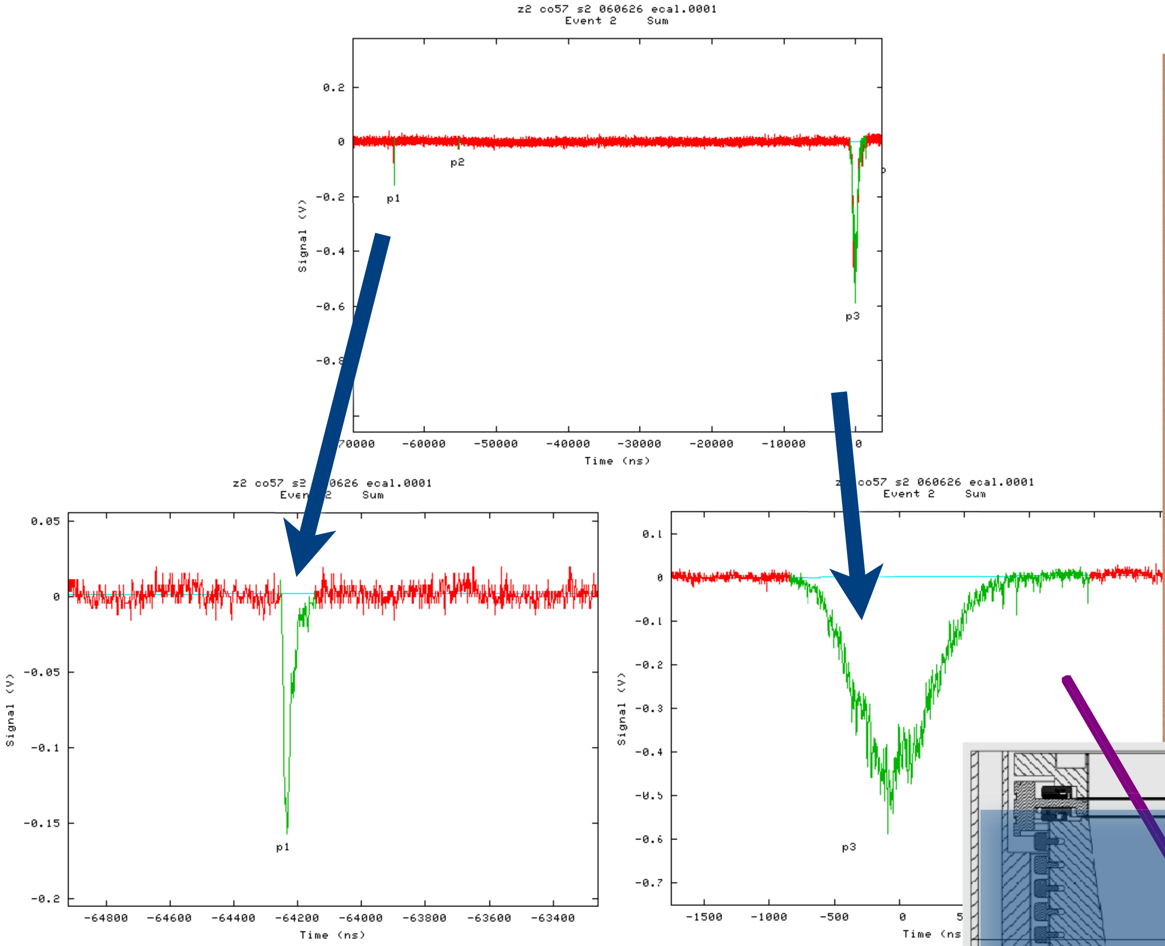
New XENON10 WIMP dark matter limit, announced at April APS meeting

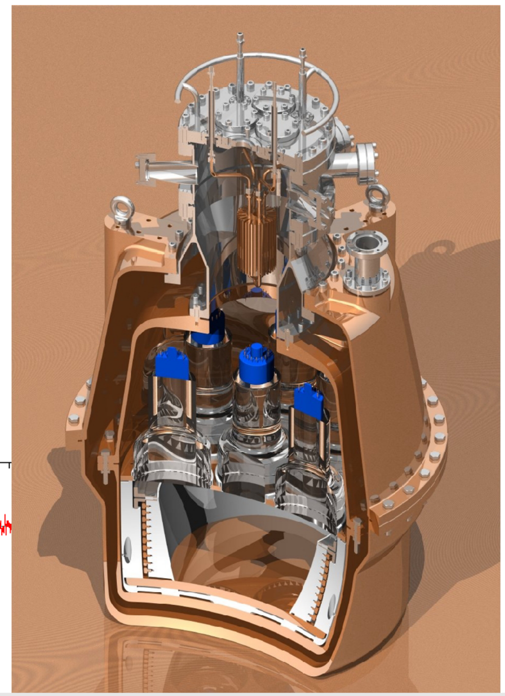


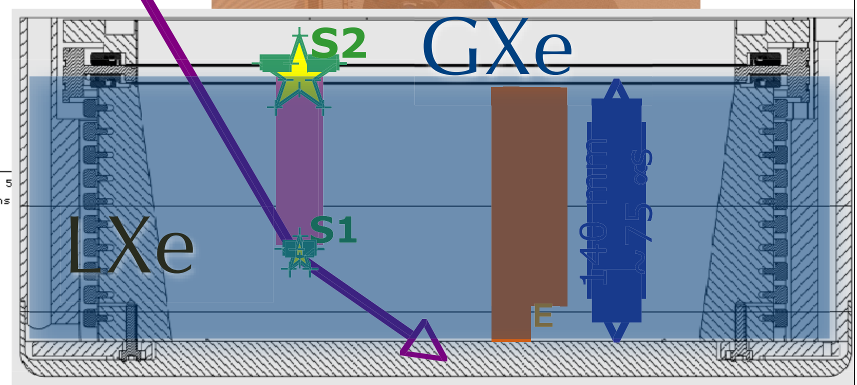
Limit shown does not take into account any background subtraction

ZEPLIN-II Detector

(See N. Smith talk)

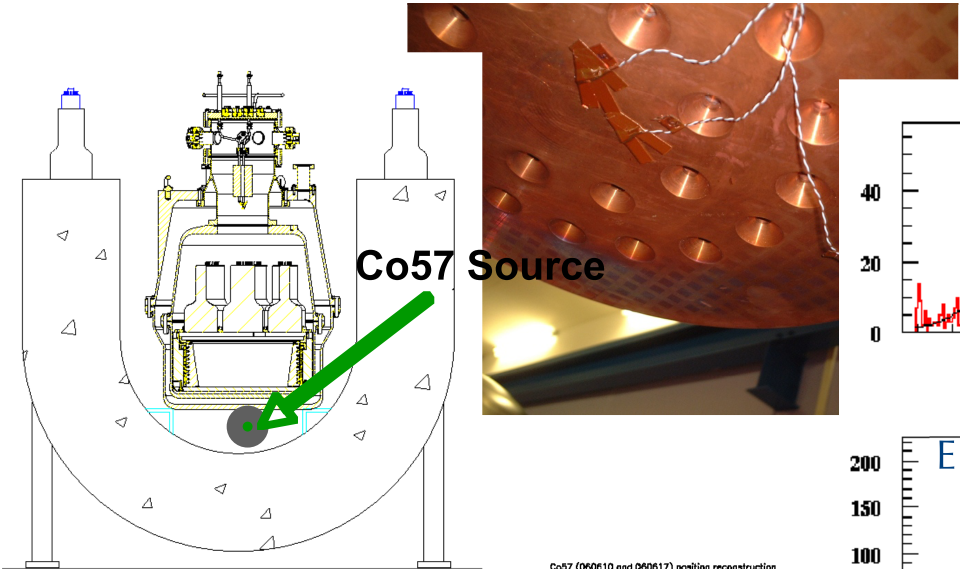


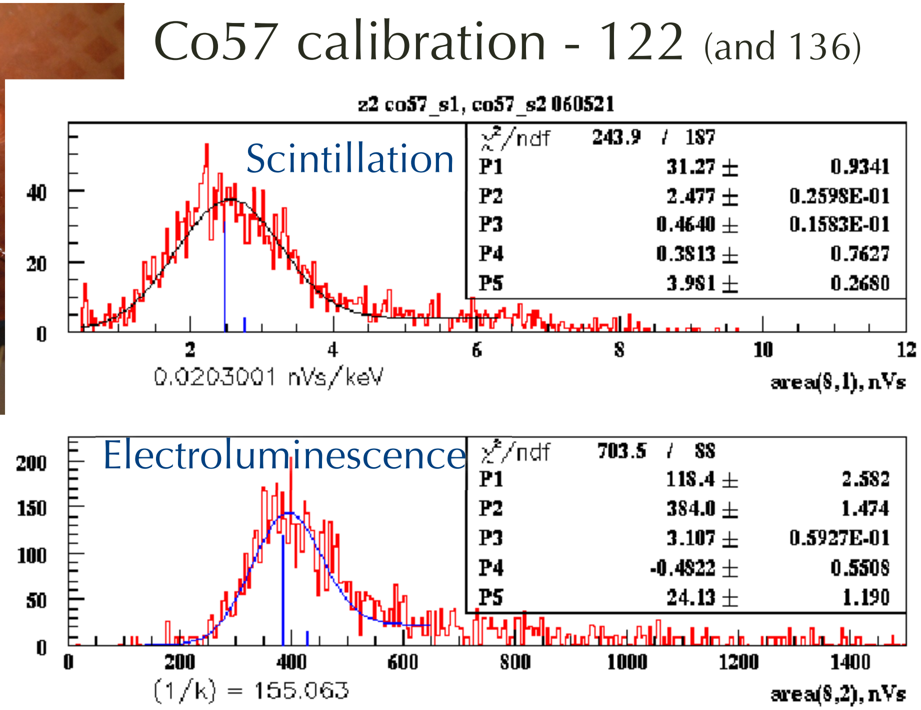


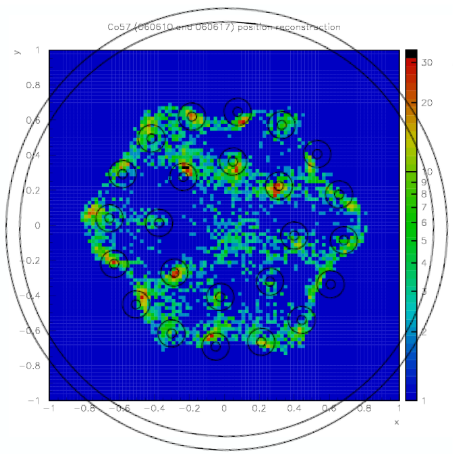


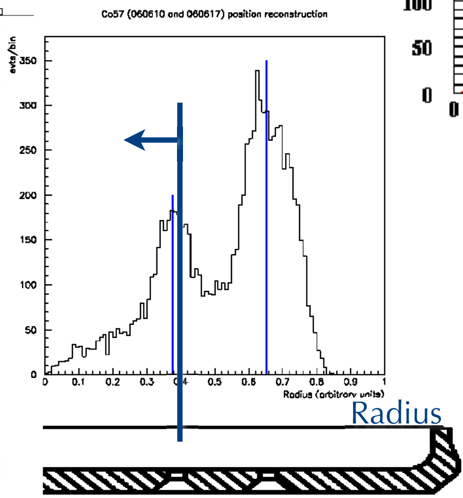
- 5 months continuous operation
- 1.0t*day of raw DM data

Detector response: ^{57}Co calibration





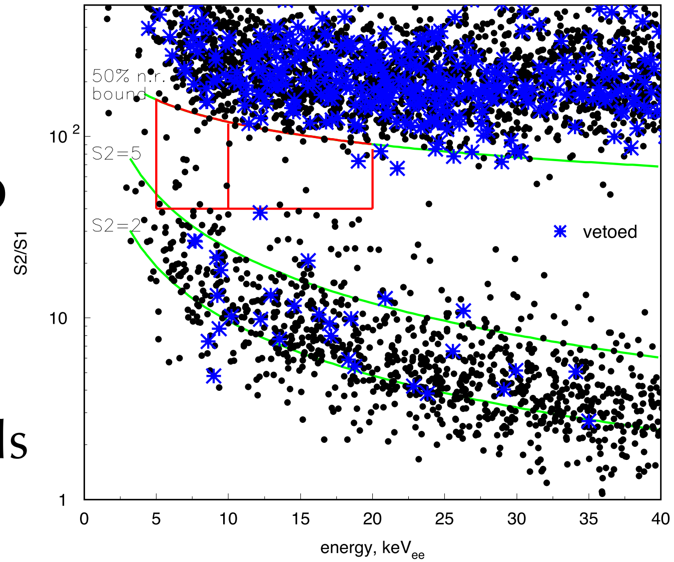


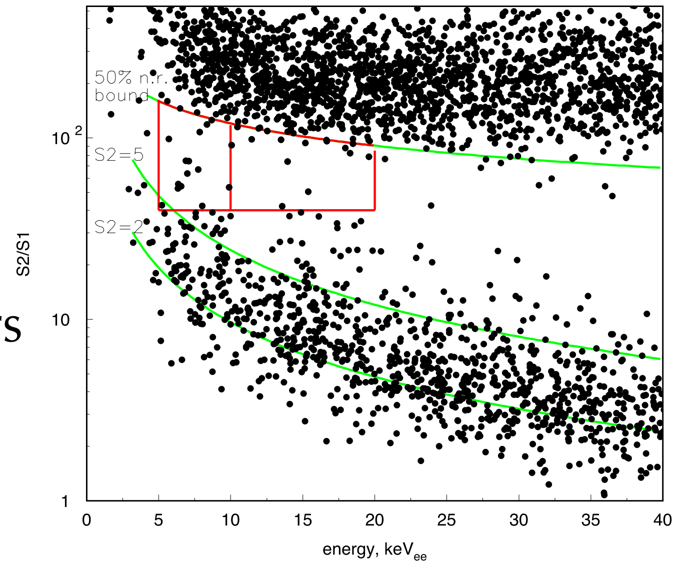


- 0.55 phe/keV (with field)
- Spatial resolution ~1cm
- Fiducial volume ~7.2kg

Science runs

- Top plot shows events with veto
- Lower plot has them removed
  - Second population seen
  - Due to radon-progeny events on walls
  - Acceptance window as before
  - Also shown constant S2 contours
- Second run in preparation
  - Remove radon events to remove second population
  - Emission confirmed from SAES getters



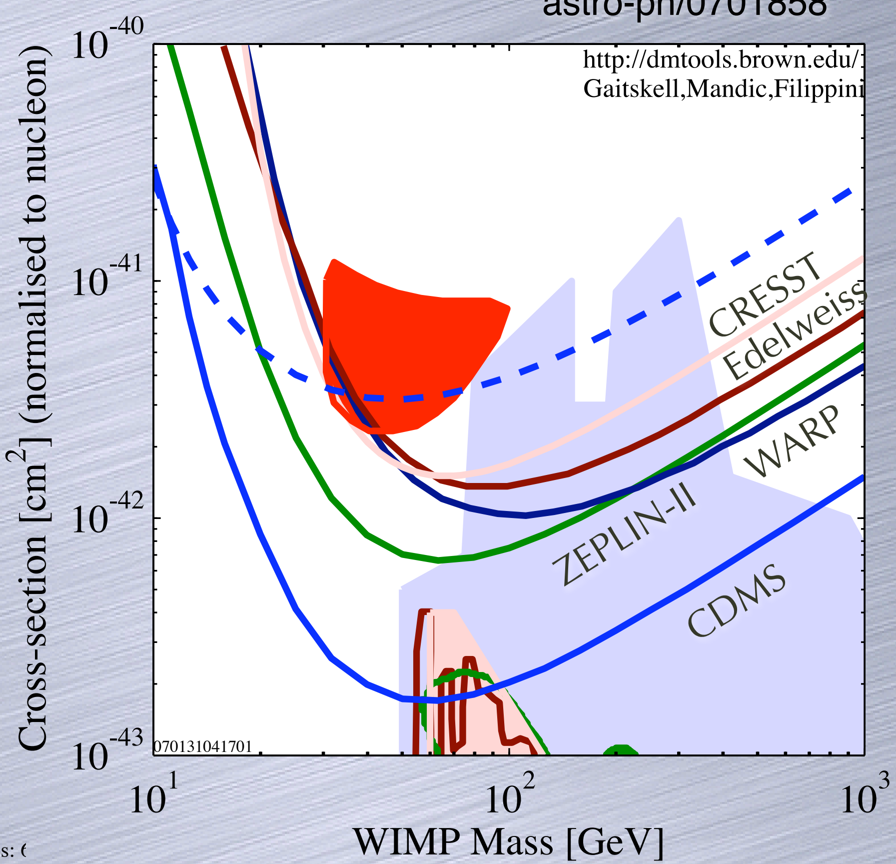


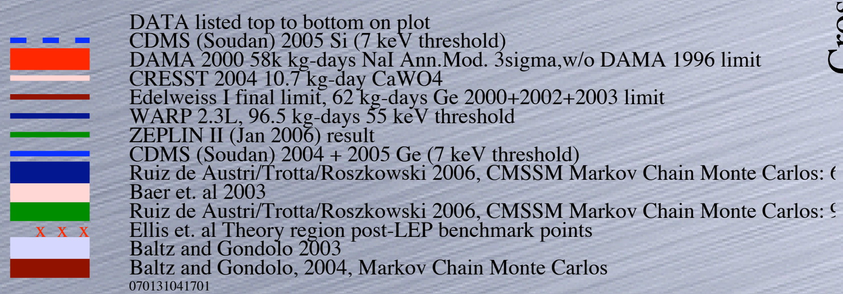
Cross-section result, first run

In review: Submitted to Astropart. Phys.

astro-ph/0701858

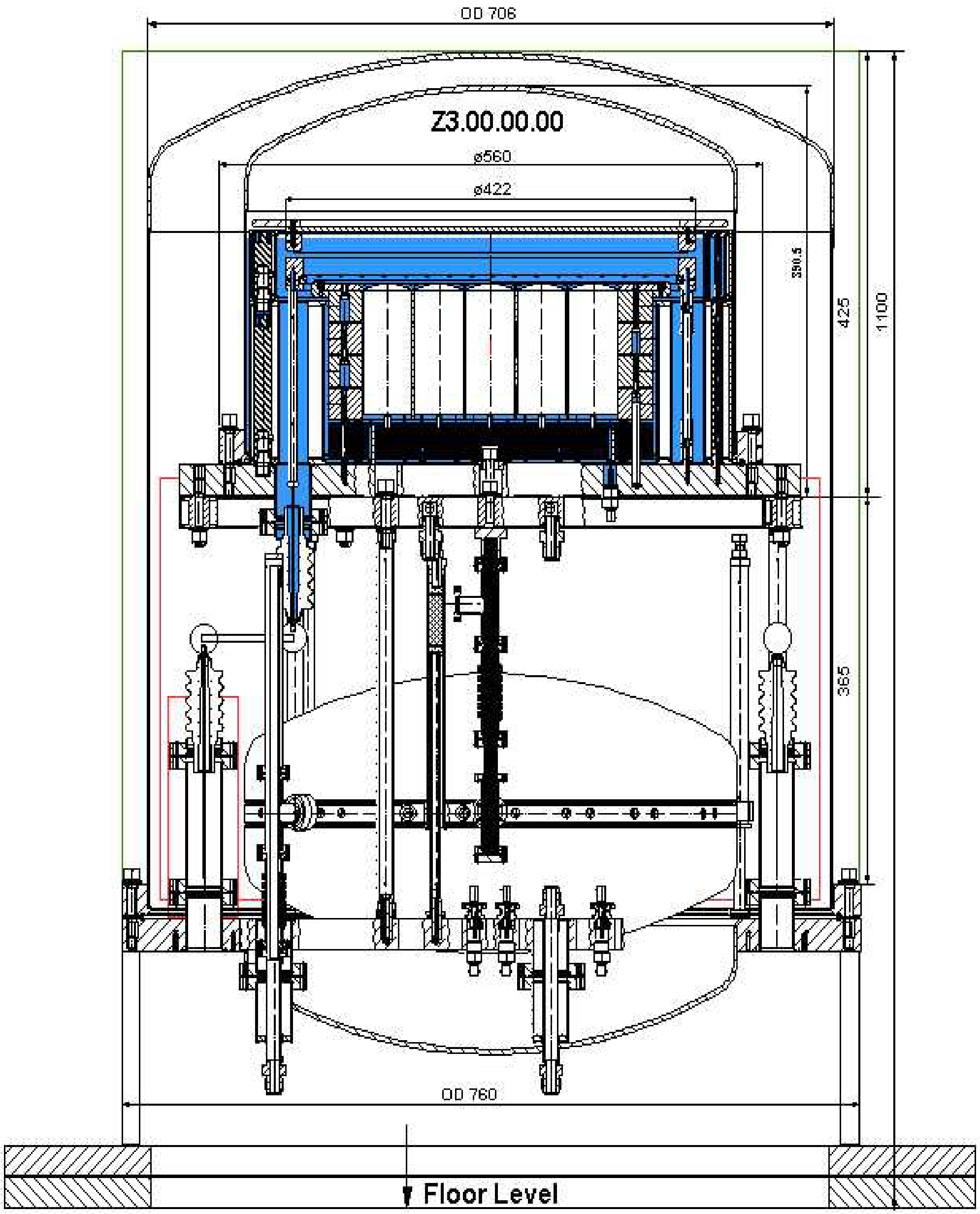
- 29 events seen in box
- 28.6±4.3 expected (total)
- 10.4 upper limit to n.r
- Translates to limit shown
  - 'canonical' halo model

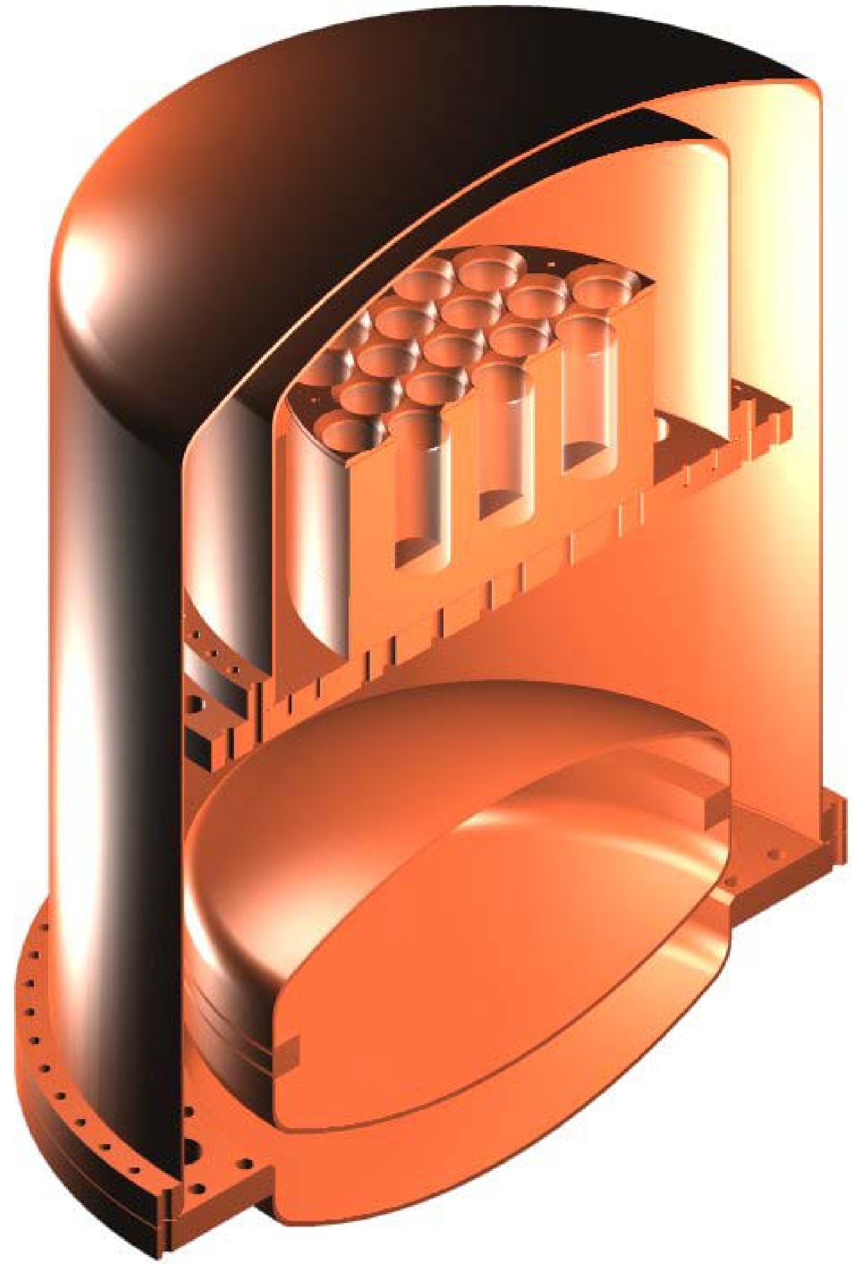




ZEPLIN III Features

- 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)





Imperial College London
CCLRC
LIP

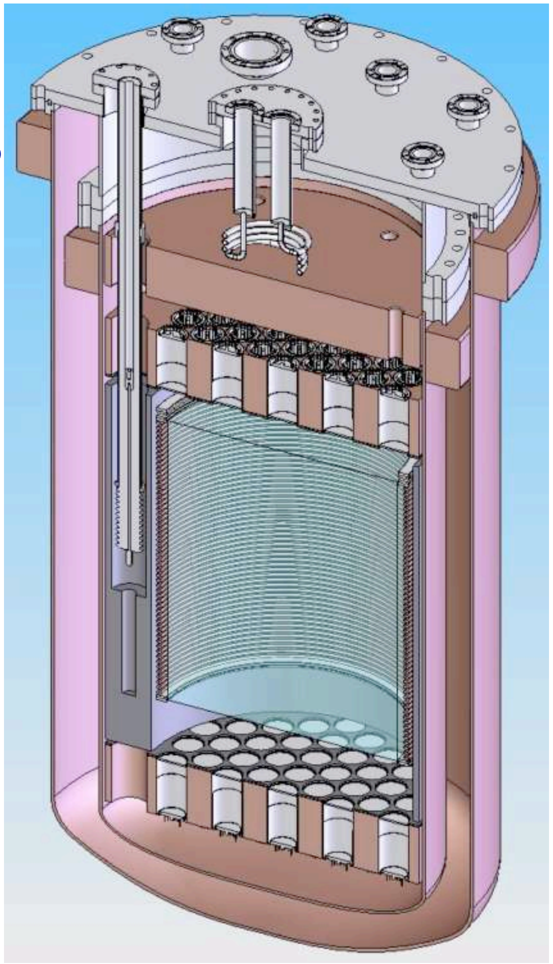
CCLRC
Imperial College London

ZEPLIN III Status: Funding approved in full for both operations and upgrade

LUX Dark Matter Experiment - Summary

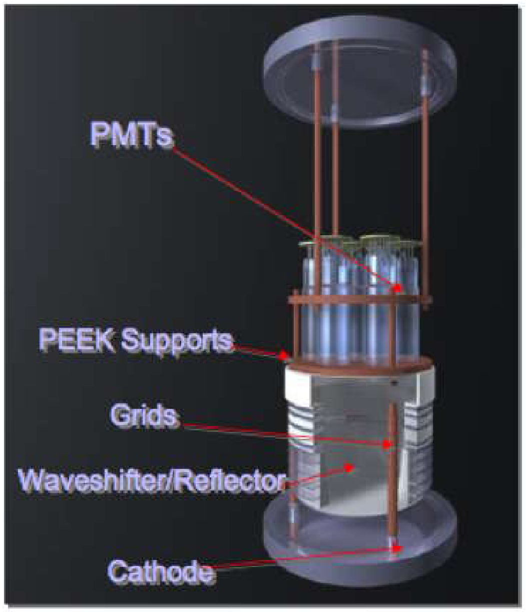
- Brown [Gaitskell], Case [Shutt], LBNL [Lesko] , LLNL [Bernstein], Rochester [Wolfs], Texas A&M [White], UC Davis [Svoboda/Tripathi], UCLA [Wang/Arisaka/Cline]
  - XENON10, ZEPLIN II (US) and CDMS; ν Detectors (Kamland/SuperK/SNO/Borexino); HEP/γ-ray astro
  - (Also ZEPLIN III Groups after their current program trajectory is established)
  - Co-spokespersons: Shutt (Case)/Gaitskell (Brown)
- 300 kg Dual Phase liquid Xe TPC with 100 kg fiducial
  - Using conservative assumptions: >99% ER background rejection for 50% NR acceptance, E>10 keVr

    (Case+Columbia/Brown Prototypes + XENON10 + ZEPLIN II)
  - 3D-imaging TPC eliminates surface activity, defines fiducial
- Backgrounds:
  - Internal: strong self-shielding of PMT activity
    - Can achieve BG $\gamma+\beta < 7\times10^{-4}$ /keVee/kg/day, dominated by PMTs (Hamamatsu R8778 or R8520).
    - Neutrons (α,n) & fission subdominant
  - External: large water shield with muon veto.
    - Very effective for cavern γ+n, and HE n from muons
    - Very low gamma backgrouns with readily achievable $<10^{-11}$ g/g purity.
- DM reach: 2×10^{-45} cm^2 in 4 months
  - Possible $<5\times10^{-46}$ cm^2 reach with recent PMT activity reductions, longer running.

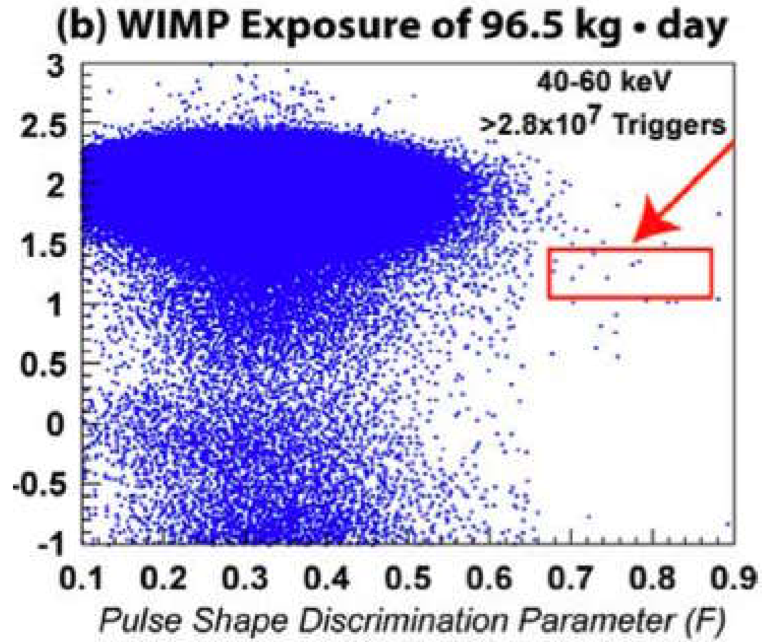


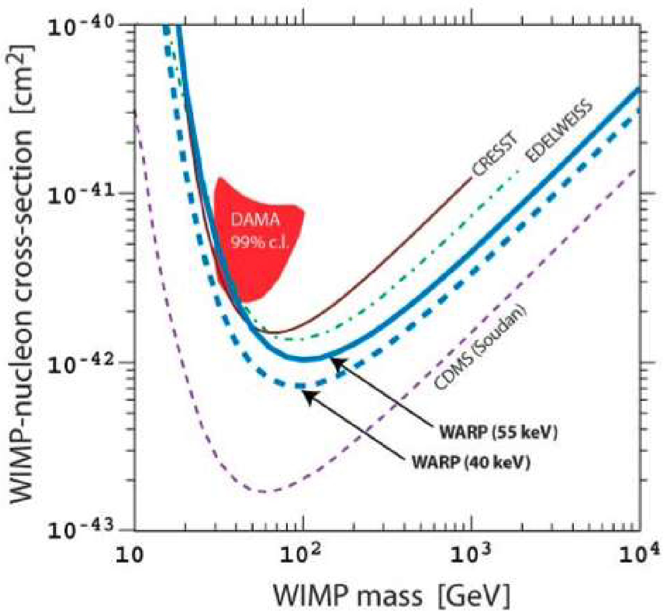
http://www.luxdarkmatter.org

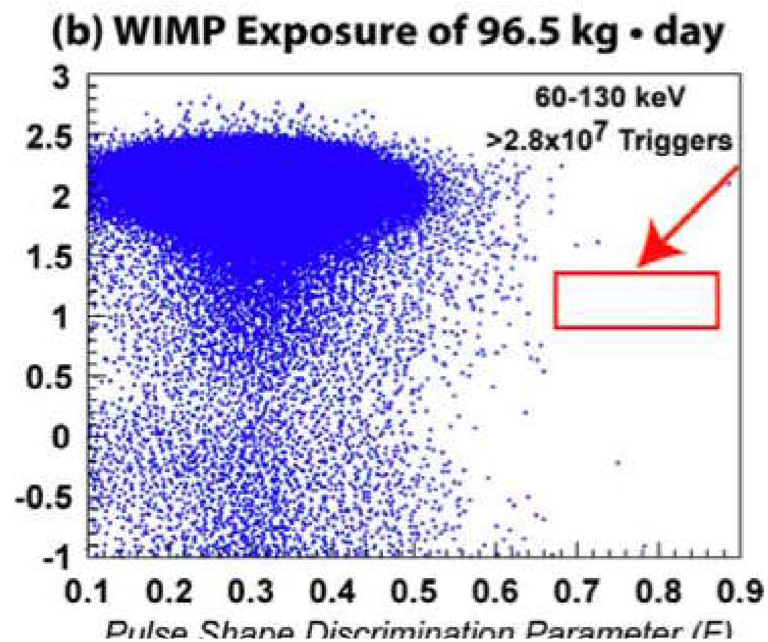
Recent results from WARP 3.2 kg prototype at Gran Sasso
Next step: construction of 100-liter detector



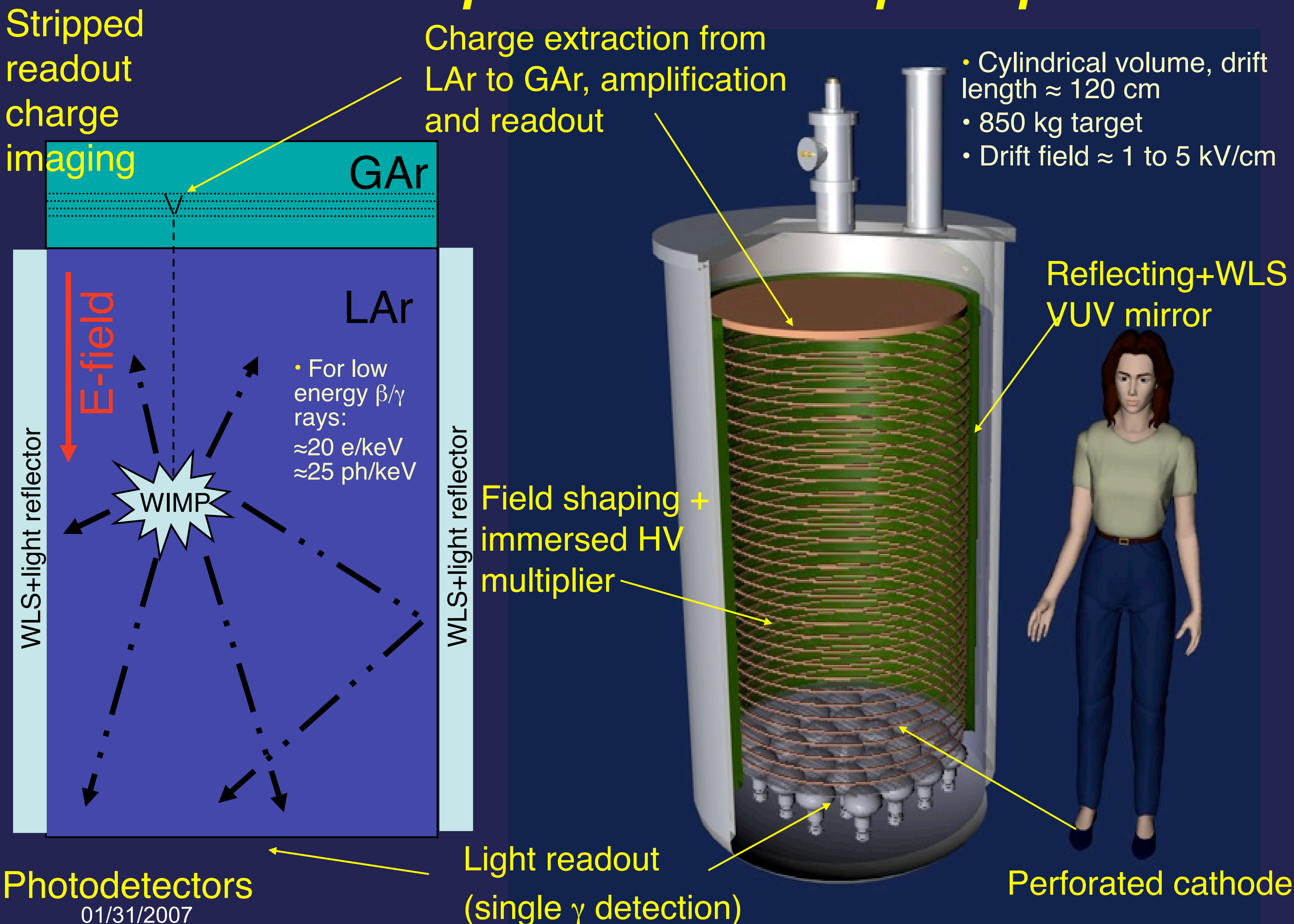
Schematic view of the 2.3 liters chamber







ArDM bi-phase detection principle



01/31/2007

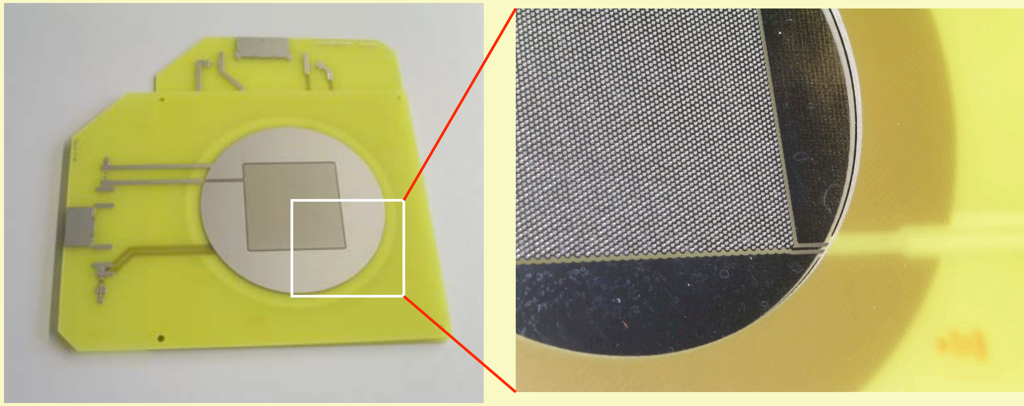
Charge readout: Thick Large Electron Multiplier (LEM)

Thick-LEM: Vetronite with holes, coated with copper

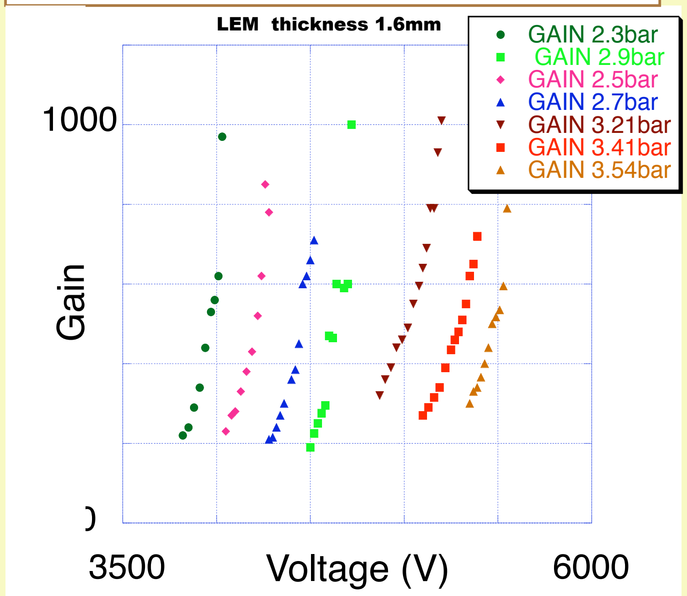
→ macroscopic GEM

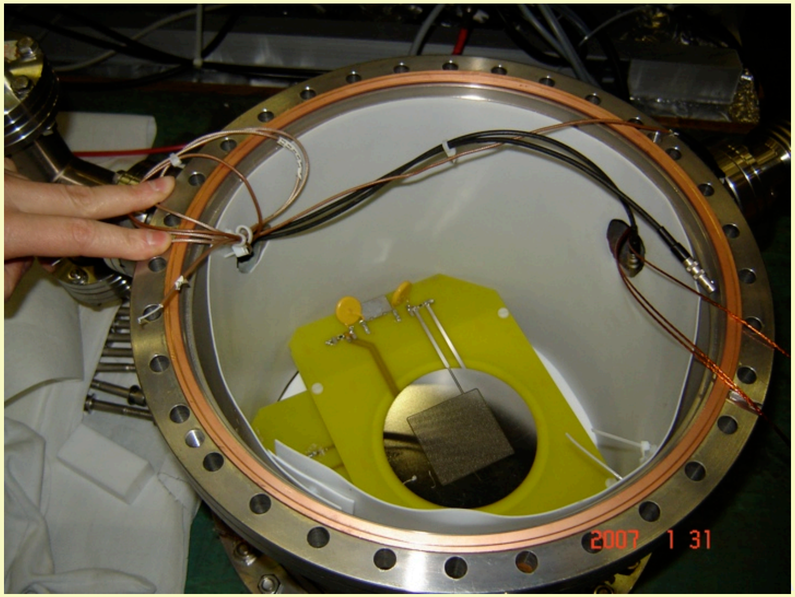
✳ easier to operate at cryogenic temperatures

✳ hole dimensions: 500 μm diameter, 800 μm distance



High gain operation of LEM in pure argon at high pressure





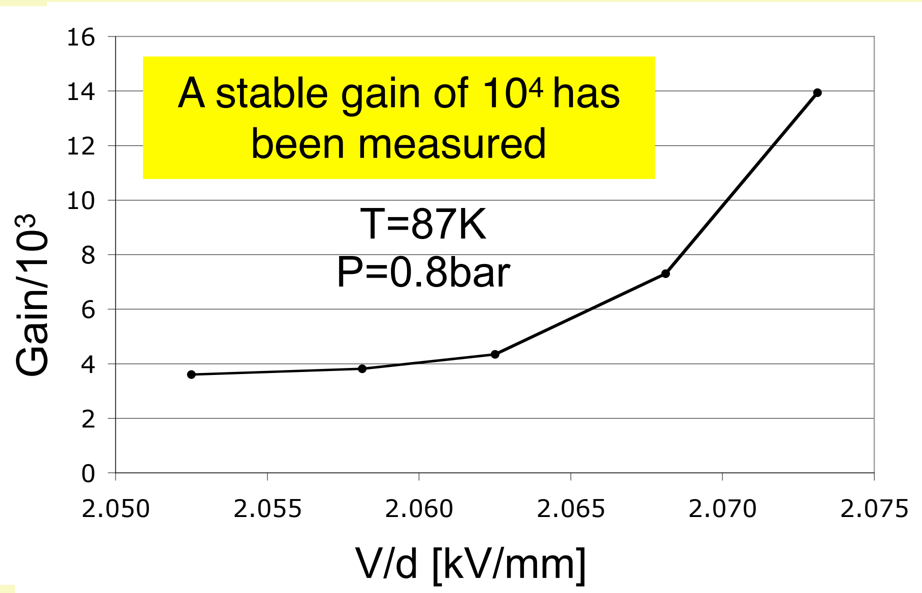
➡ The level of the liquid argon is placed just below a LEM readout system

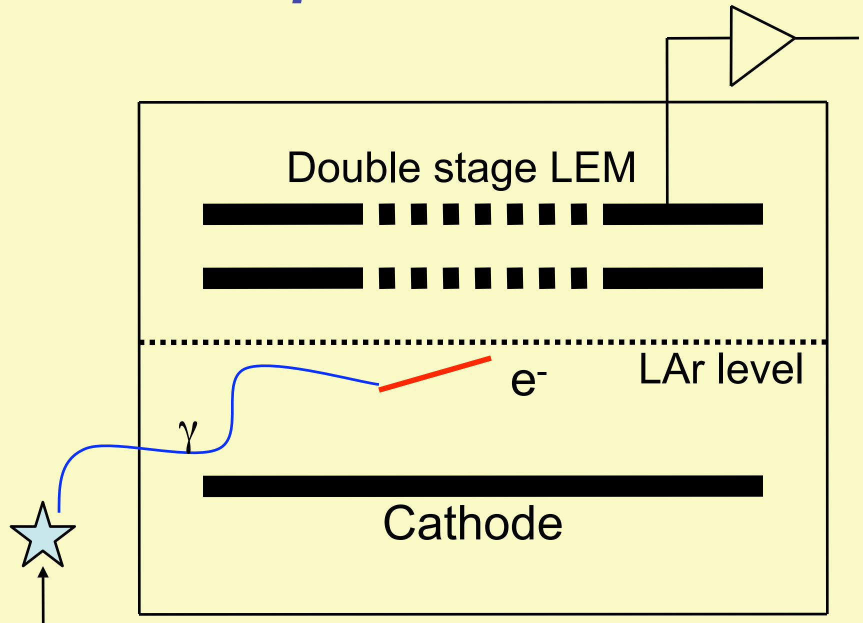
➡ Each extracted electron creates an avalanche which is detected on the anode.

➡ Gain of up to 800 possible even at high pressure (good prospects for operation in cold)

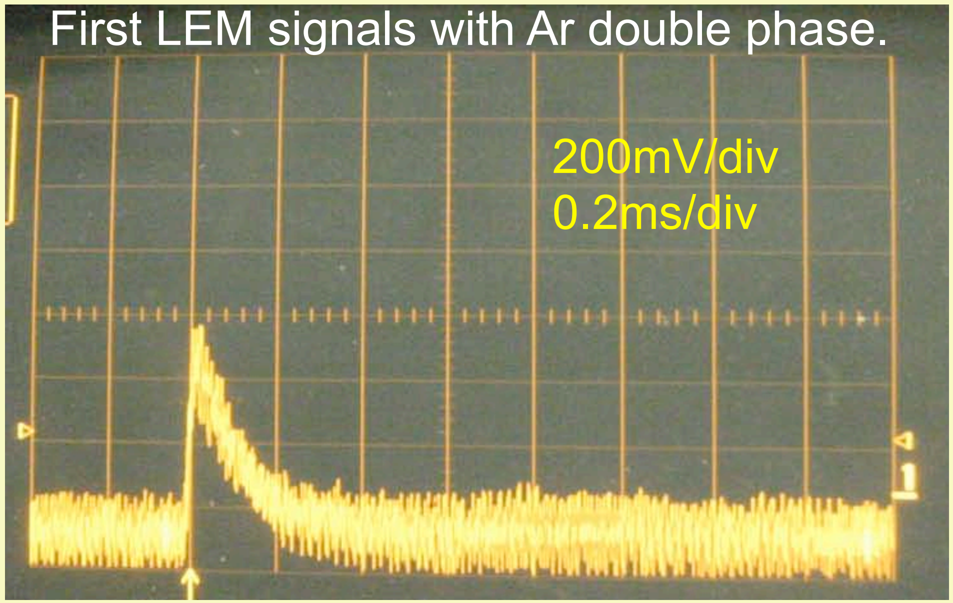
➡ A segmented LEM readout allows event localization

Two-stage LEM with Ar double phase



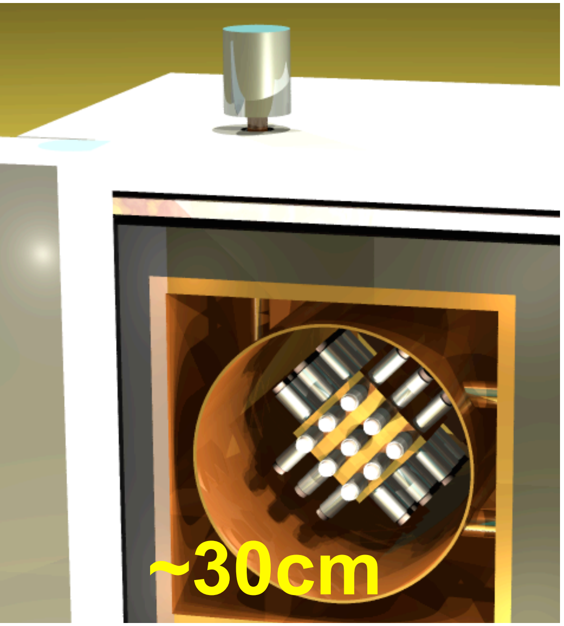


External γ sources. (511keV,1275keV and 662keV)



XMASS project

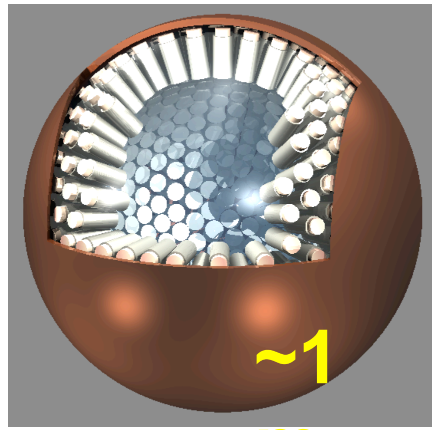
(See Abe Ko talk)



Prototype detector
(FV 3kg) R&D

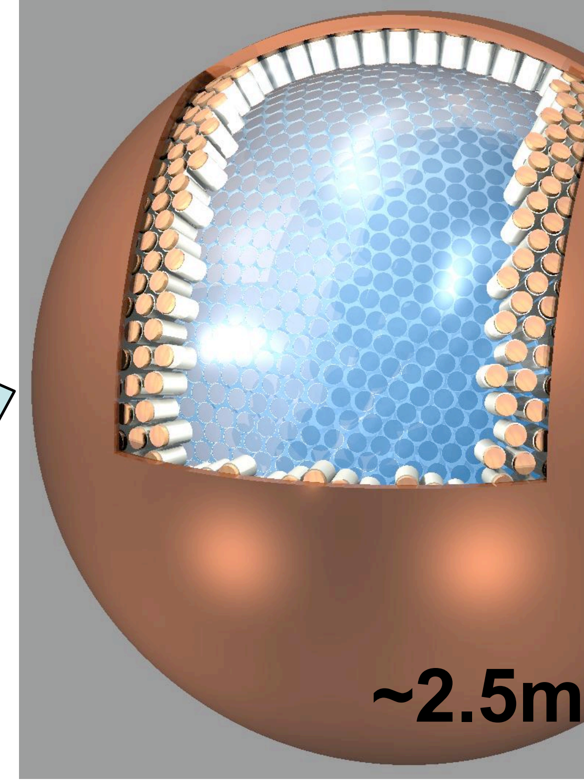
Developed :
- Test self-shield of liq. Xe
- Vertex reconstruction method
- Kr removal by distillation

Feasibility confirmed



800kg detector
(FV 100kg)
Dark matter search

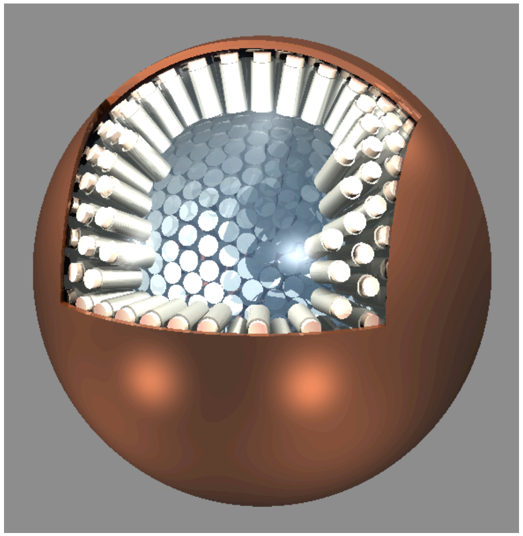
Budget funded in this year.
Construction will start soon.



~20 ton detector
(FV 10ton)
Solar neutrinos
Dark matter search
Double beta decay

Background level of the 800kg detector

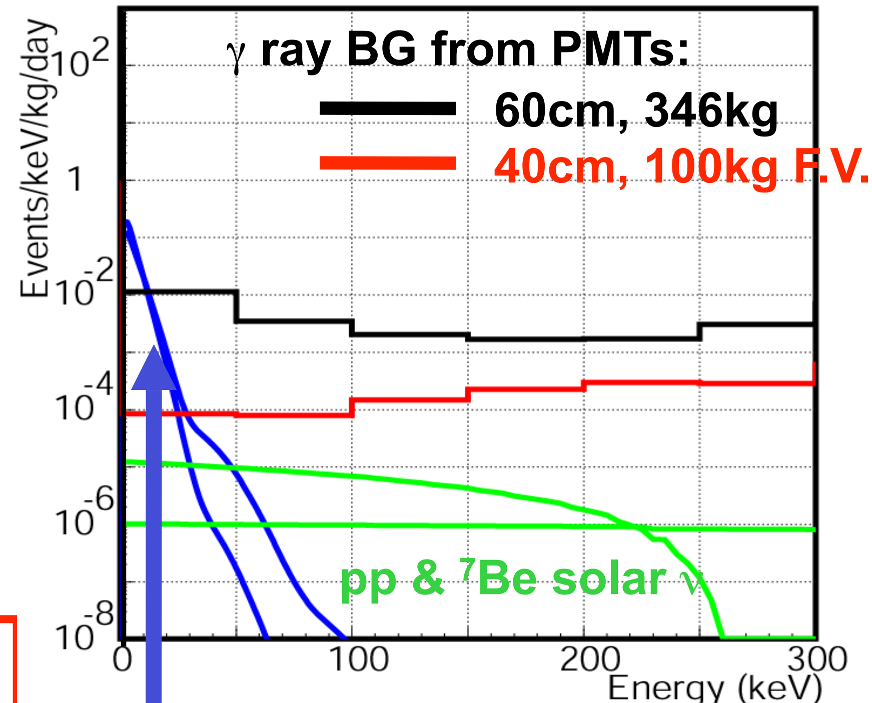
Detector



80cm diameter

812-hex low BG PMTs immersed in liq. Xe.
70% photo-coverage gives ~5p.e./keVee

Estimated background from PMTs

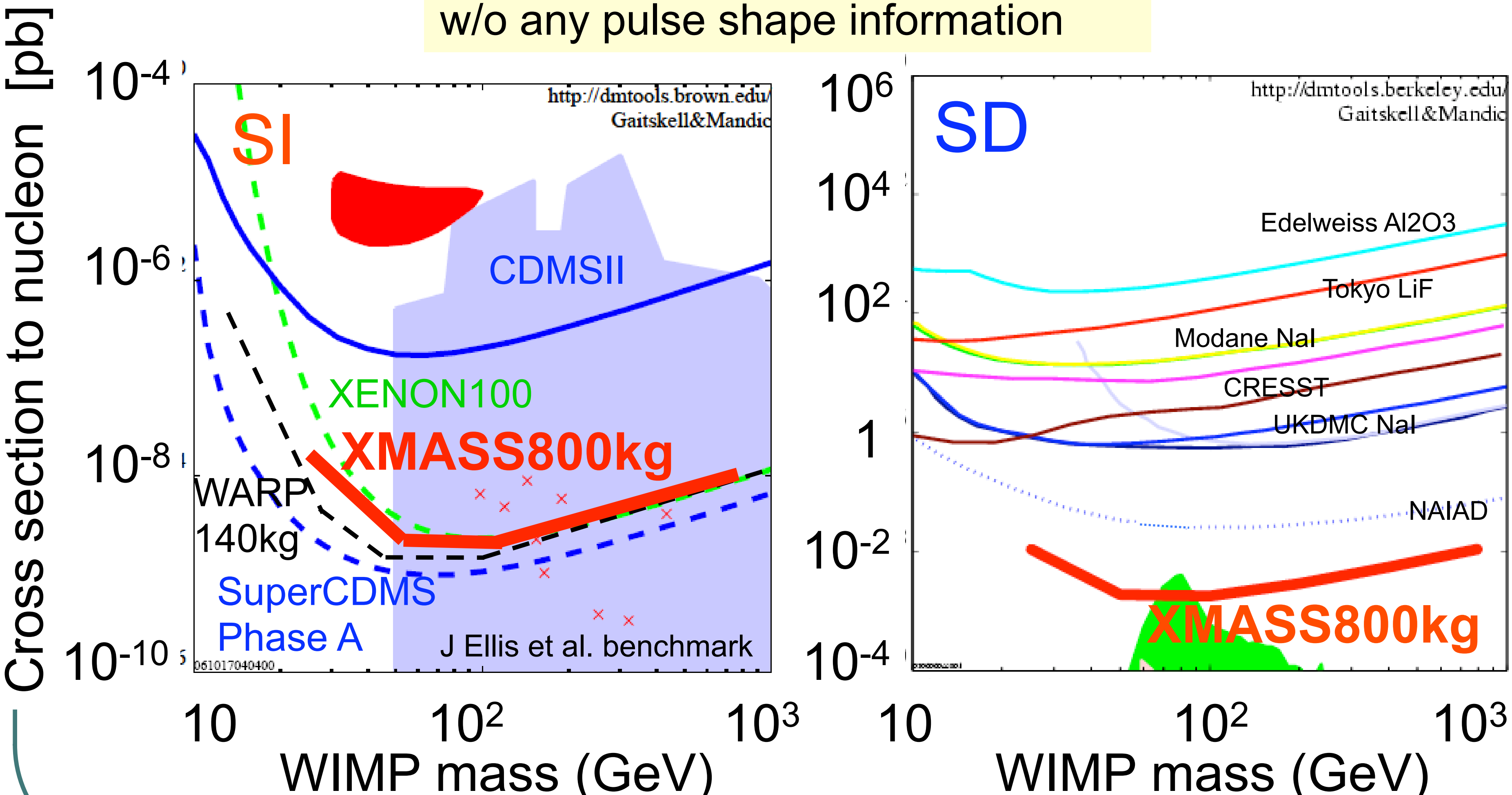


Expected dark matter signal (assuming 10^{-42} cm^2, Q.F.=0.2 50,100GeV)

10^{-4} /keV/kg/day can be achieved in the 40cm diameter fiducial volume (100kg).

Expected sensitivity

XMASS FV 0.5ton year (100kg, 5yr)
3σ discovery
w/o any pulse shape information



Large improvements ~10² expected.

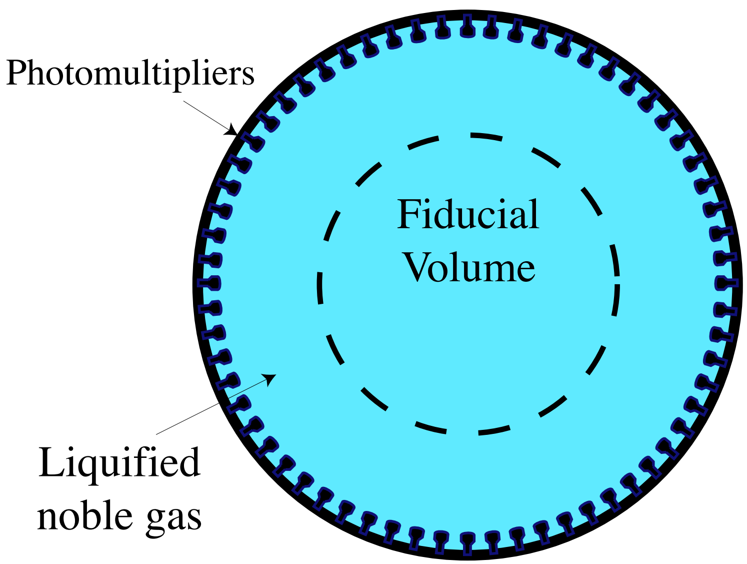
Plots except for XMASS:
http://dmtools.berkeley.edu
Gaitskell & Mandic

The Mini-CLEAN Approach

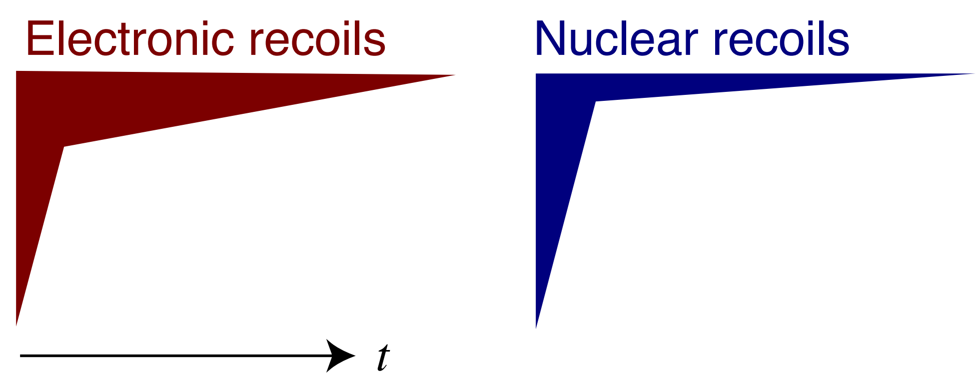
Scaleable technology based on detection of scintillation in liquified noble gases. No E field.
Ultraviolet scintillation light is converted to visible light with a wavelength-shifting film.

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 better characterization of radioactive backgrounds

Self-shielding



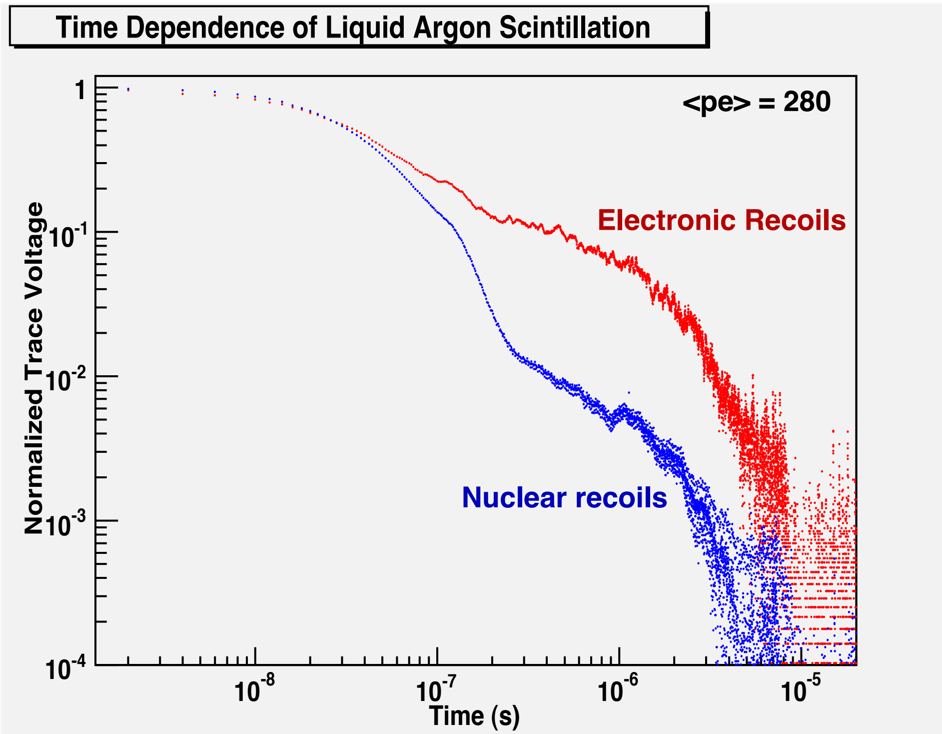
Pulse-shape discrimination

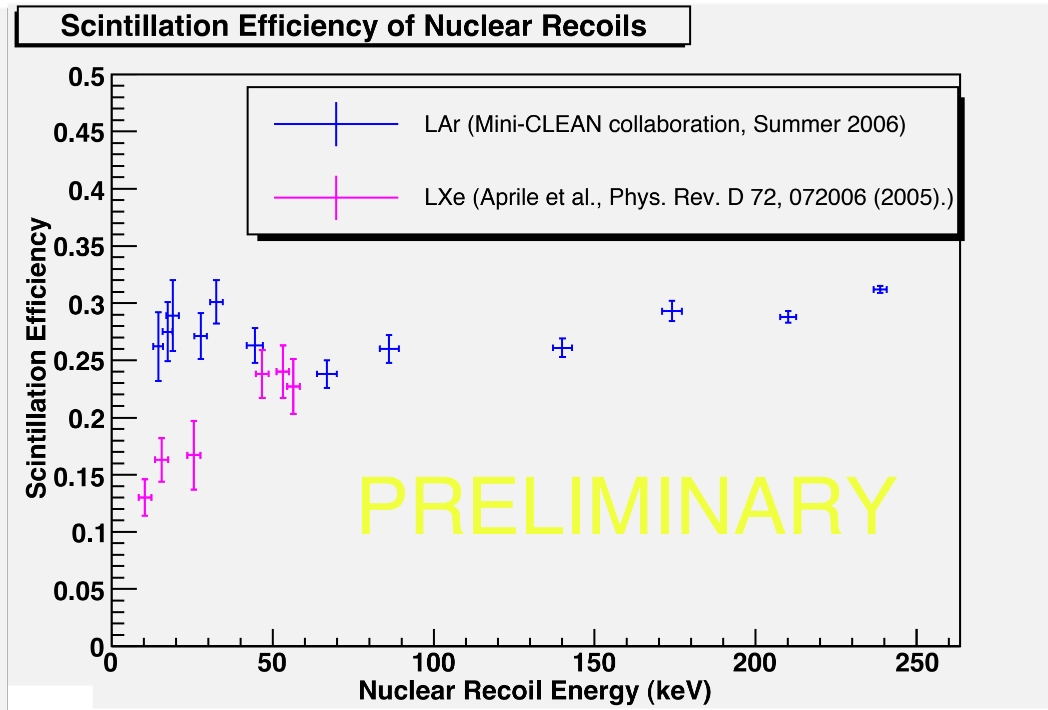


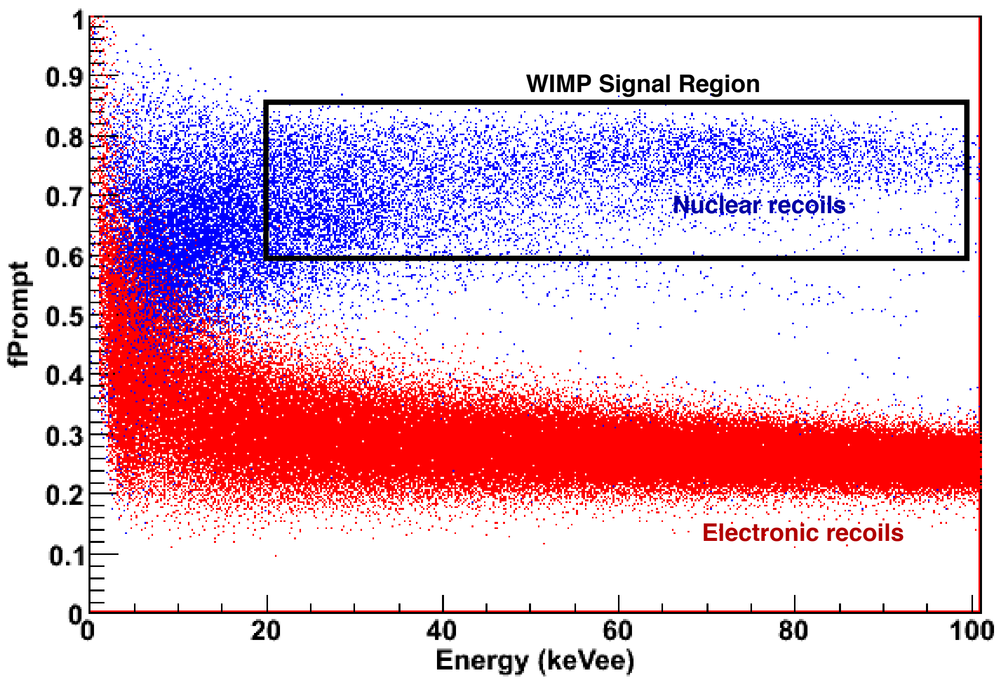
Fast component: < 10 ns
Slow component: 1.6 μs (LAr), 15 μs (LNe)
Discriminate based on fraction of light in first 100 ns (Fprompt)

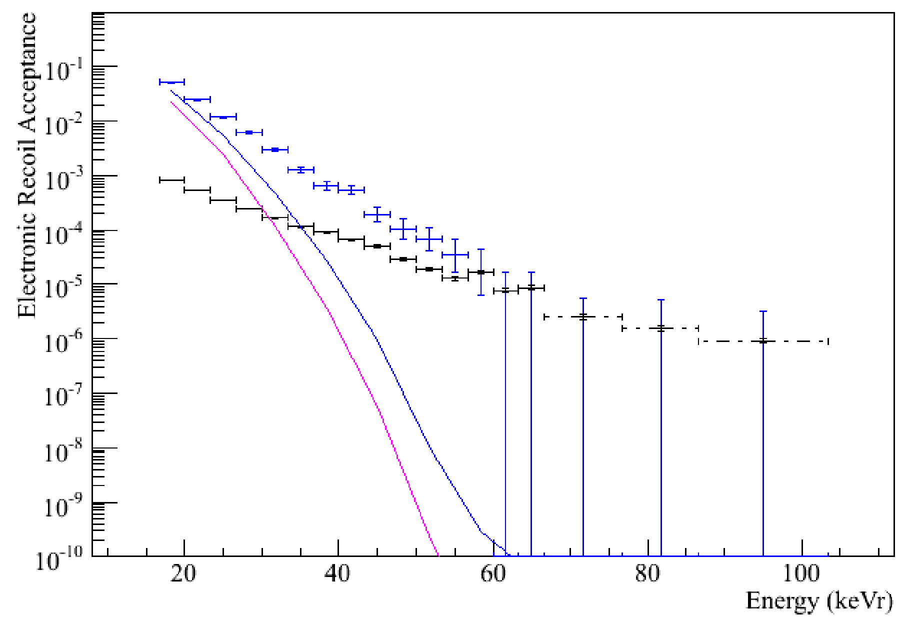
D. N. McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000).
D. N. McKinsey and K. J. Coakley, Astropart. Phys. 22, 355 (2005).
M. Boulay, J. Lidgard, and A. Hime, nucl-ex/0410025
M. Boulay and A. Hime, Astropart. Phys. 25, 179 (2006).

Micro-CLEAN LAr R&D data (see Lippincott talk)



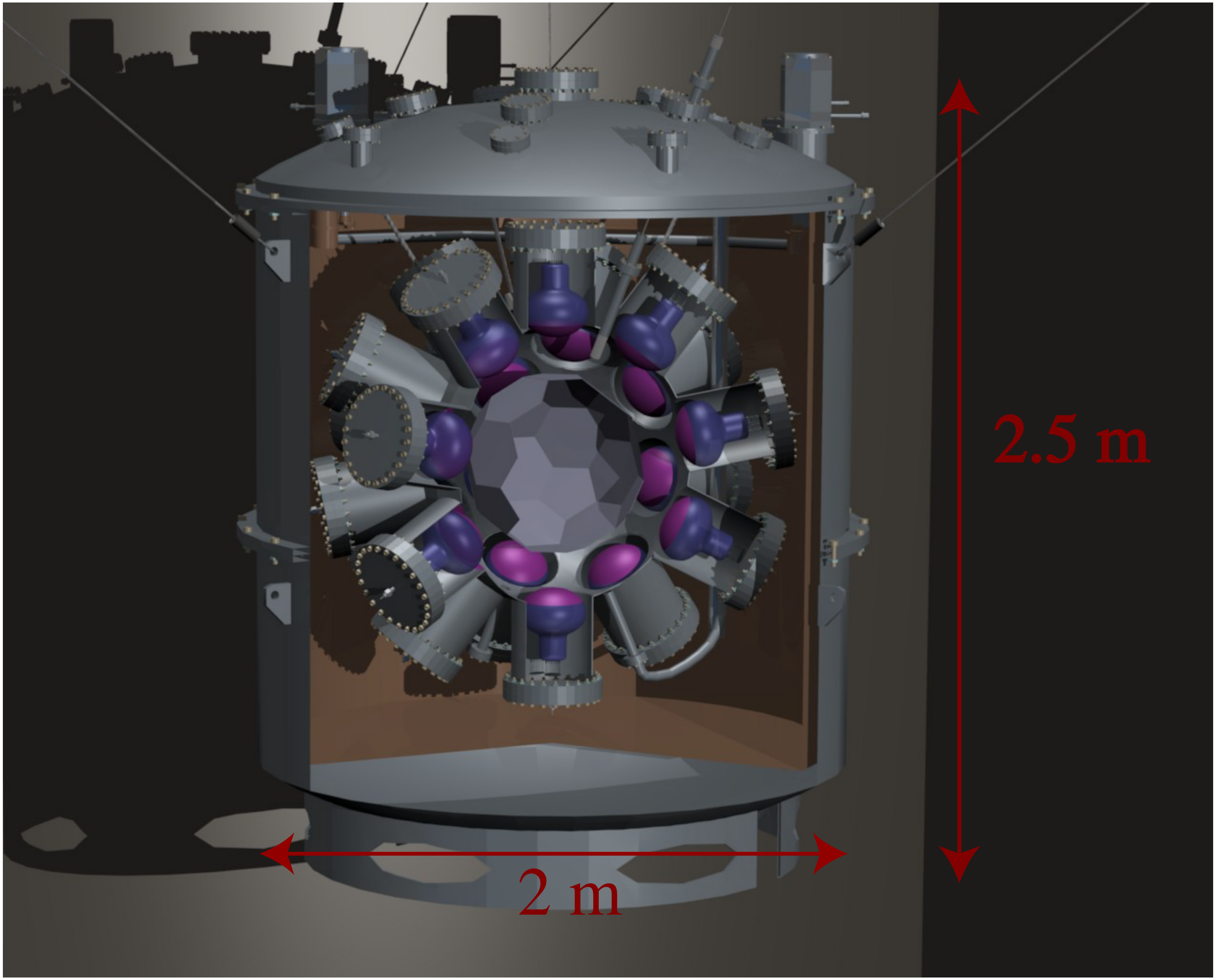






Mini-CLEAN-100 (See Nikkel talk)

Fiducial (total) mass: □ 25 (~ 100) kg of LAr or LNe.   Expected signal yield > 6 pe/keV



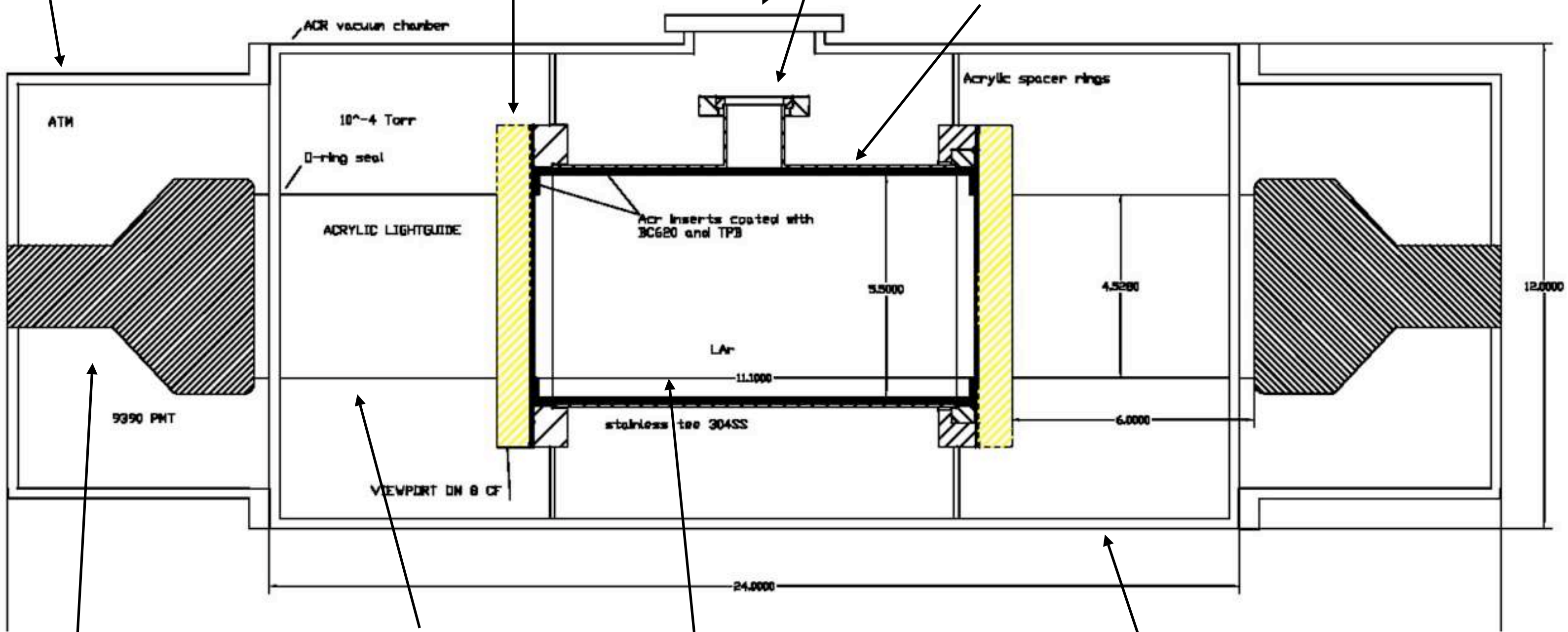
DEAP-1 design

Quartz windows

Neck connects to vacuum and Gas/liquid lines

11” x 6” (8” CF) tee

poly PMT supports



6” acrylic guide

Acrylic vacuum chamber

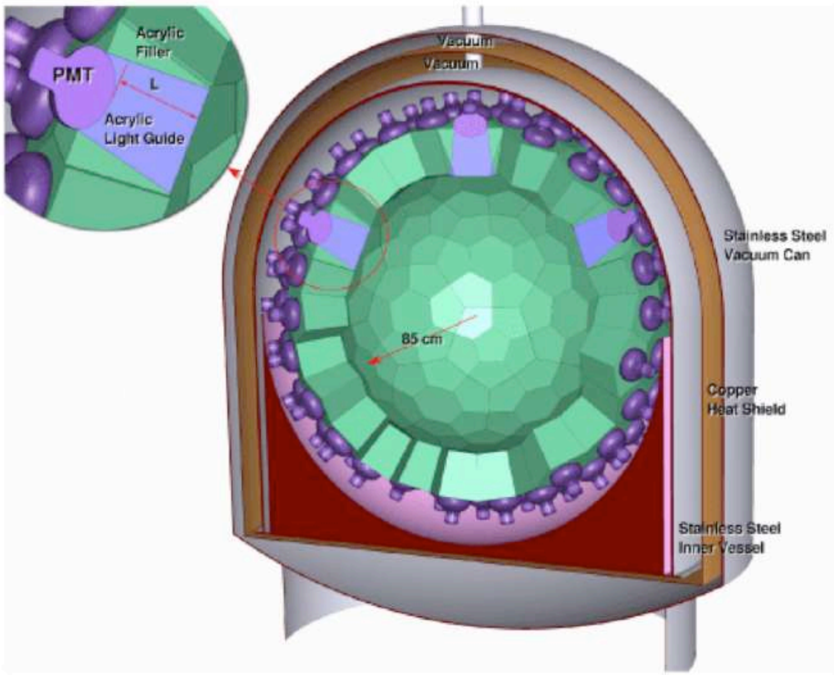
ET 9390 PMT 5”

inner surface 97% diffuse reflector,
Covered with TPB wavelength shifter

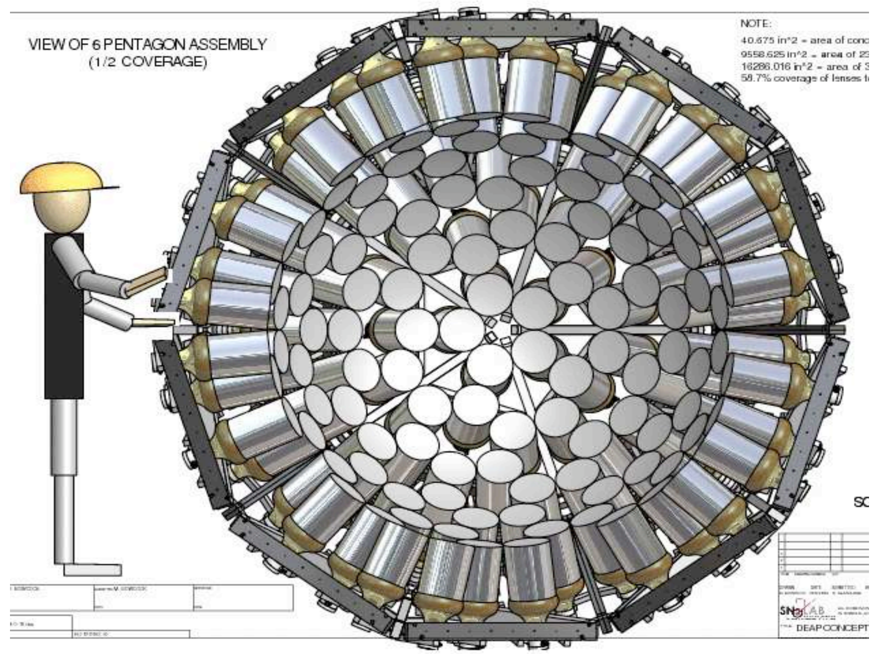
Mark Boulay

DEAP & CLEAN "ULTIMATE" designs

"miniCLEAN" 1000 kg

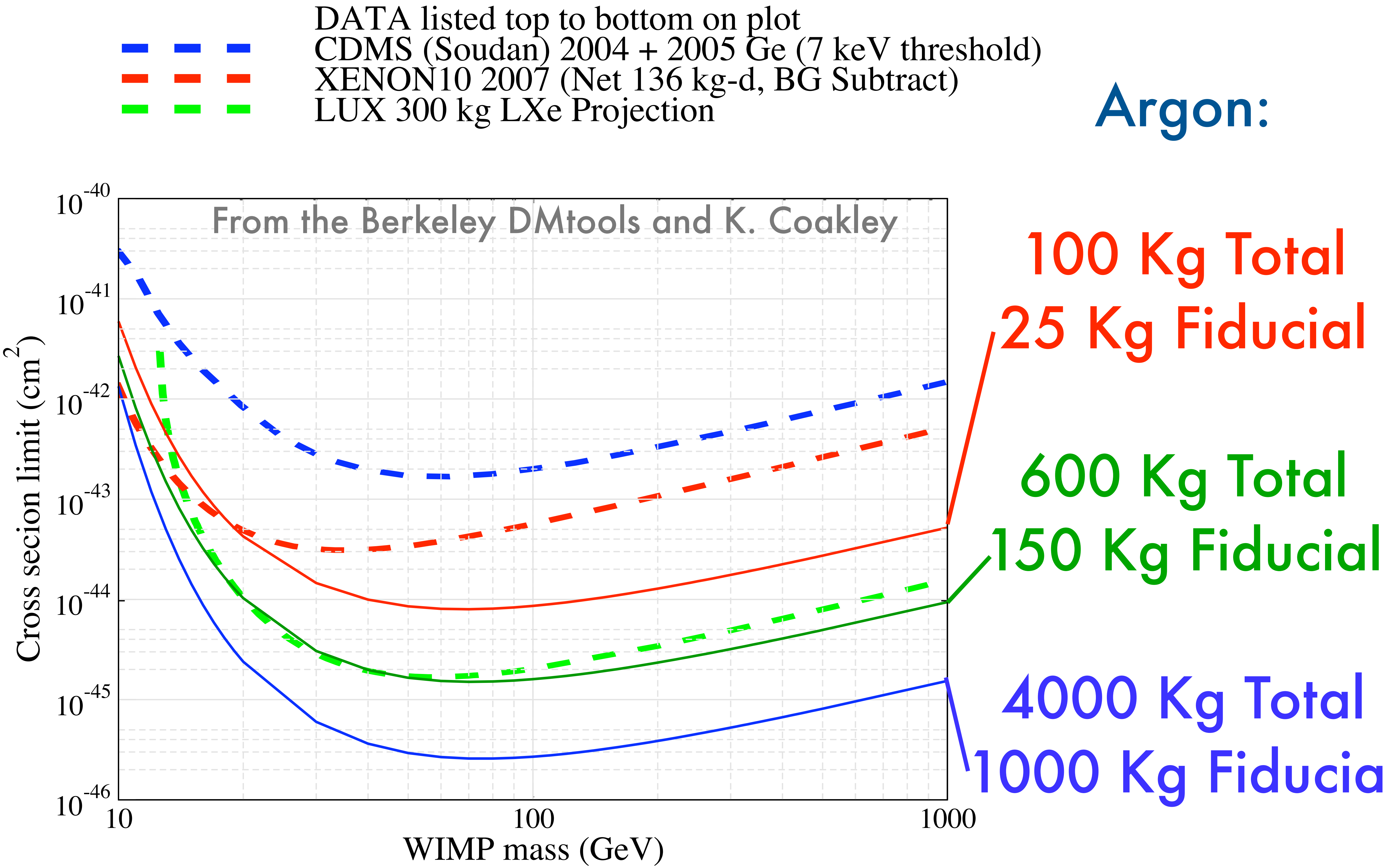


DEAP-3



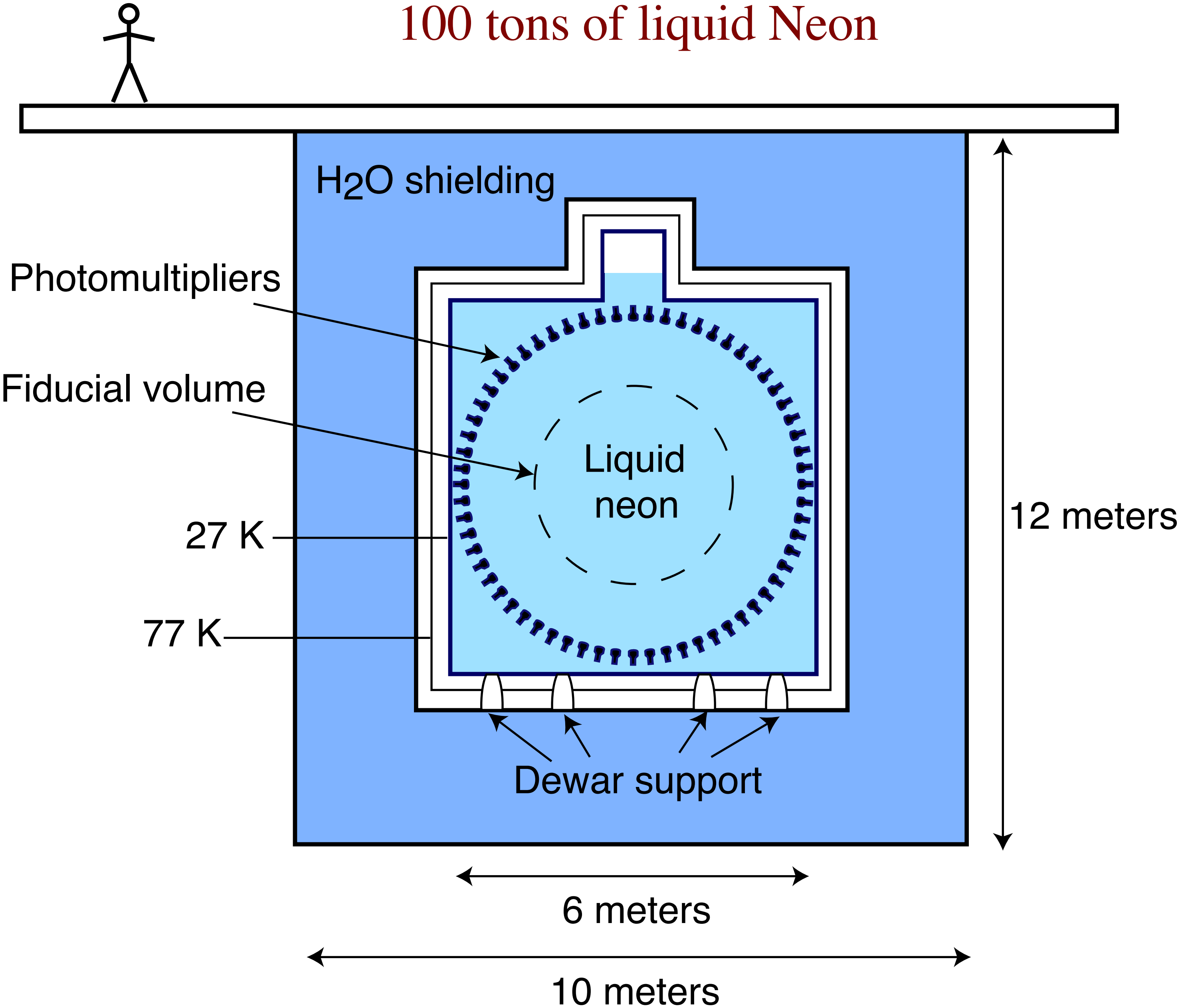
- Design is driven by need for neutron reduction via hydrogenous material
- Vacuum thermal insulation versus ice thermal insulation
- Ice insulation not the preferred design for neon due to heat loads

- Liquid Argon 87 K (greater than LN2), Liquid Neon (27 K)


DATA listed top to bottom on plot
CDMS (Soudan) 2004 + 2005 Ge (7 keV threshold)
XENON10 2007 (Net 136 kg-d, BG Subtract)
LUX 300 kg LXe Projection
Argon:
From the Berkeley DMtools and K. Coakley
100 Kg Total
25 Kg Fiducial
600 Kg Total
150 Kg Fiducial
4000 Kg Total
1000 Kg Fiducial
Cross secion limit (cm^2)
10^{-40}
10^{-41}
10^{-42}
10^{-43}
10^{-44}
10^{-45}
10^{-46}
10
100
1000
WIMP mass (GeV)

CLEAN

100 tons of liquid Neon

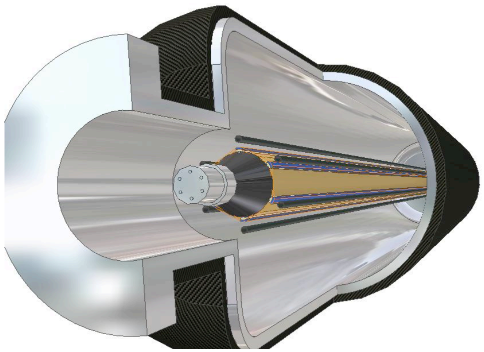


DM and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2000)
DM and K. J. Coakley, Astropart. Phys. 22, 355 (2005)

Requires > 6000 m.w.e.

SIGN: Scintillation and Ionization in Gaseous Nobles

J. T. White, TAMU
H. Wang, UCLA



Concept:

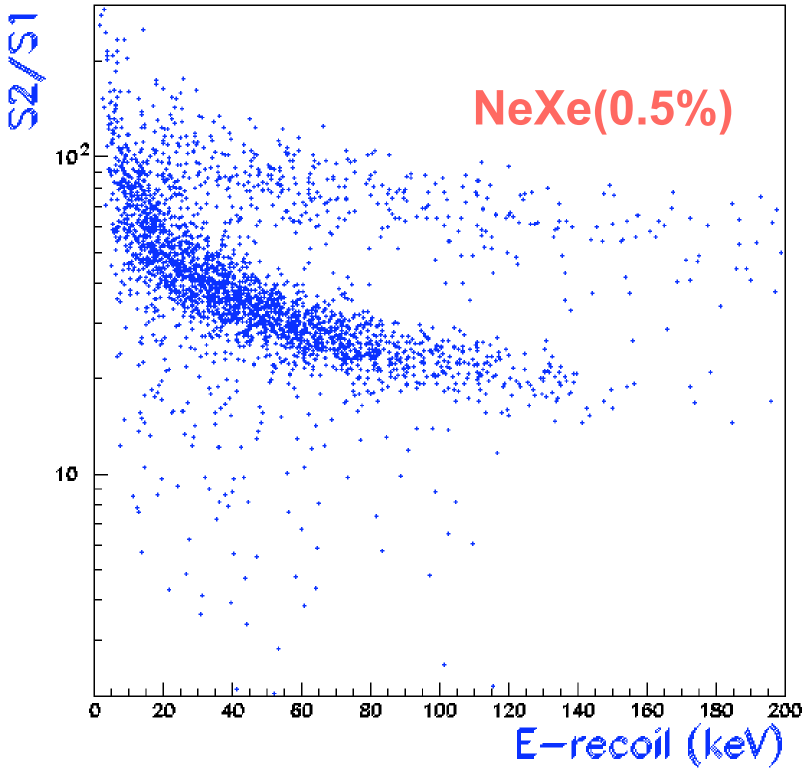
WIMP Detector employing S2/S1 discrimination in modular, room temperature, pressurized gas cylinders with CsI internal photocathode and WLS fiber readout.

Status:

Completed preliminary investigation of light yield, charge yield and S2/S1 discrimination for selection of gasses / mixtures including neon, argon and xenon at pressures up to 100 atm.

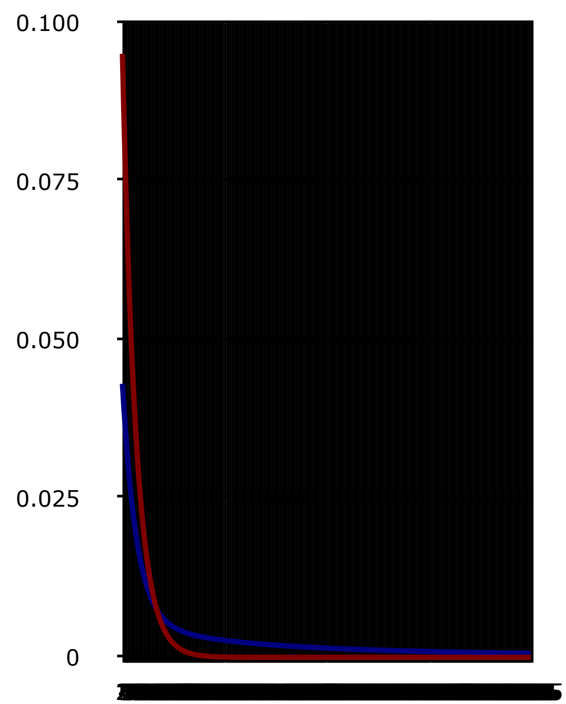
Plans:

Preparing proposal for proto-experiment for DUSEL. Phased program to start with Xe @ ~20 atm and increase pressure to Ne @ 200 atm.



HPGS - high pressure gas scintillation

C J Martoff (Temple), P F Smith (Temple, RAL)

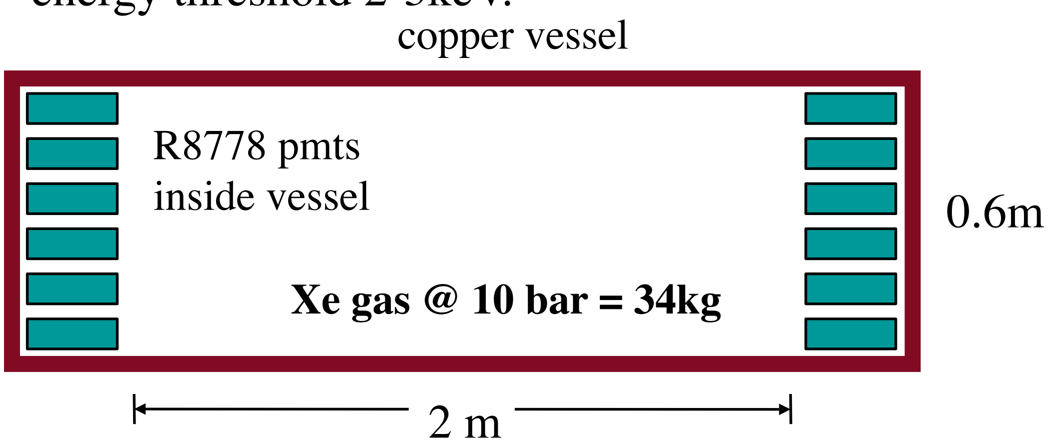


High dark matter sensitivity with simple room temperature detector using scintillation only

Published scintillation pulses from Xe gas show large pulse shape difference between □s and □s (representative of nuclear recoils).

Gives significant signal for 10 nuclear recoil events in background of 1E6 gammas.

Size reasonable at 5-10 bar - 2m x 0.6m module gives 34kg Xe gas. Internal PMTs give energy threshold 2-3keV.

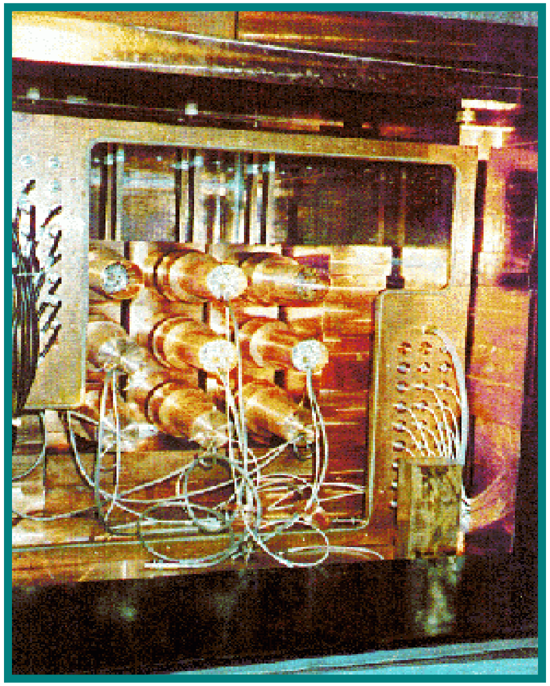


Backgrounds with water shielding, Cu vessel, R8778 PMTs, allow sensitivity 3E-9pb in 360 days running for single 34kg module.

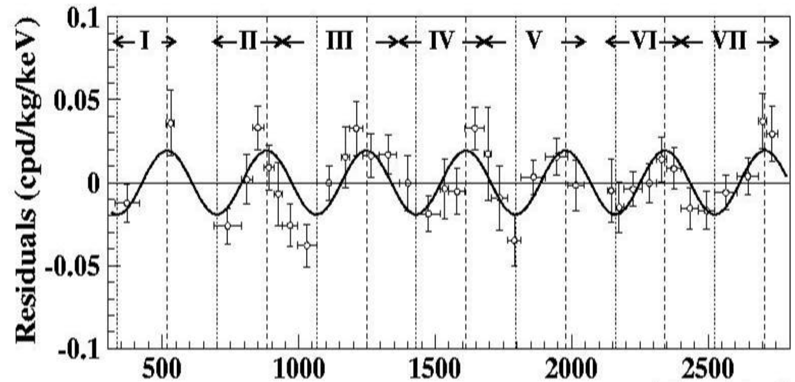
24 modules (1000kg) gives sensitivity 1-2E-10pb in 360 days running

Ambient temperature operation simpler & cheaper than cryogenic techniques.

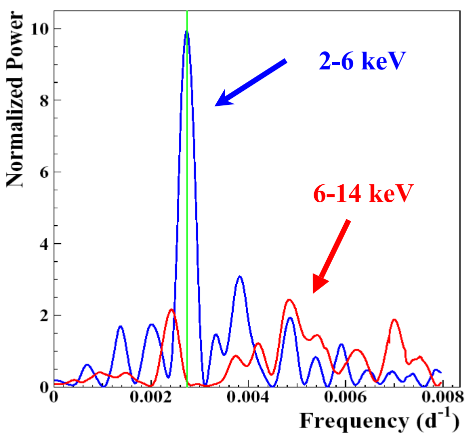
DAMA/NaI(Tl)~100 kg

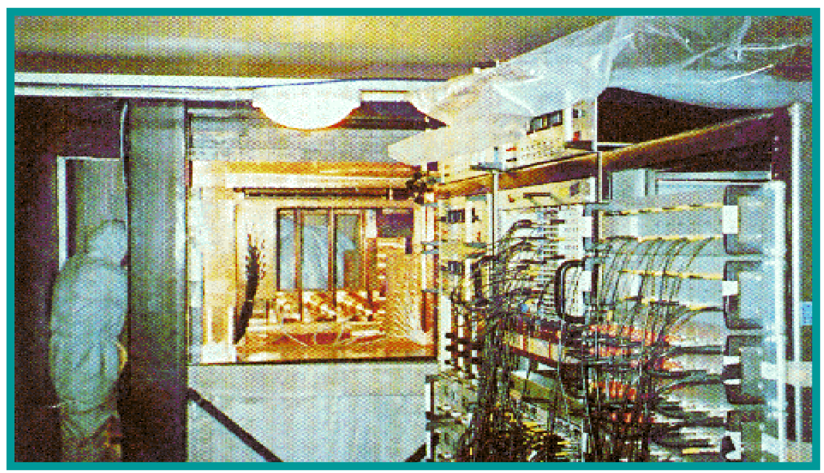


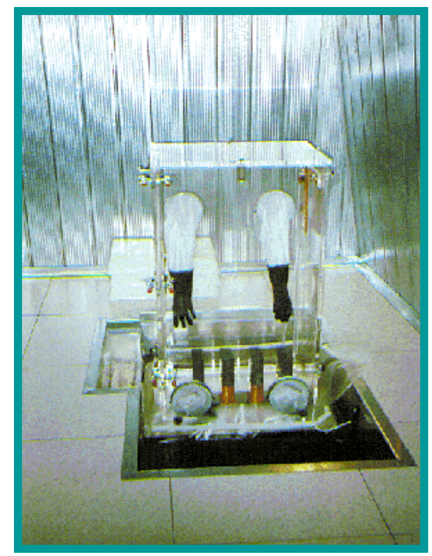
Annual modulation signal at 6.3σ



Principal mode = 2.737 x 10^{-3} d^{-1} = 1 yr^{-1}







DAMA/LIBRA

- Continuous data taking since March 2003

e.g. up to March 2007:

collected exposure: of order of 1.5 x 10^5 kg x d

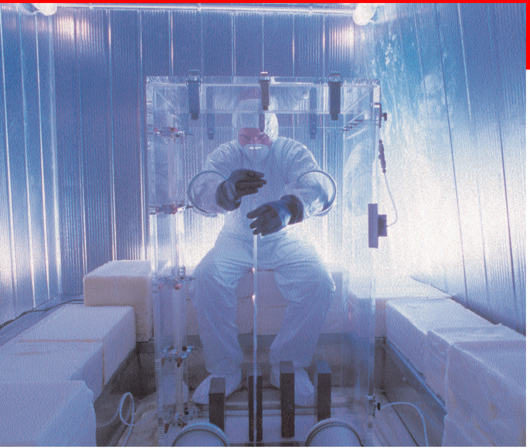
calibrations: acquired 40 M events of sources

acceptance window eff: acquired 2 M ev/keV

- <u>Model independent data analysis in progress:</u>

already almost completed in all the aspects on a partial exposure of

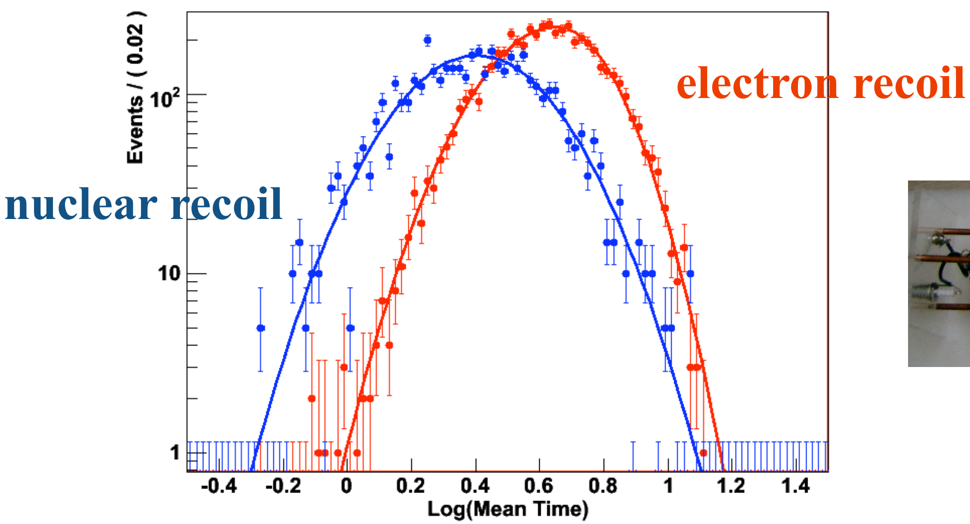
0.255 ton year

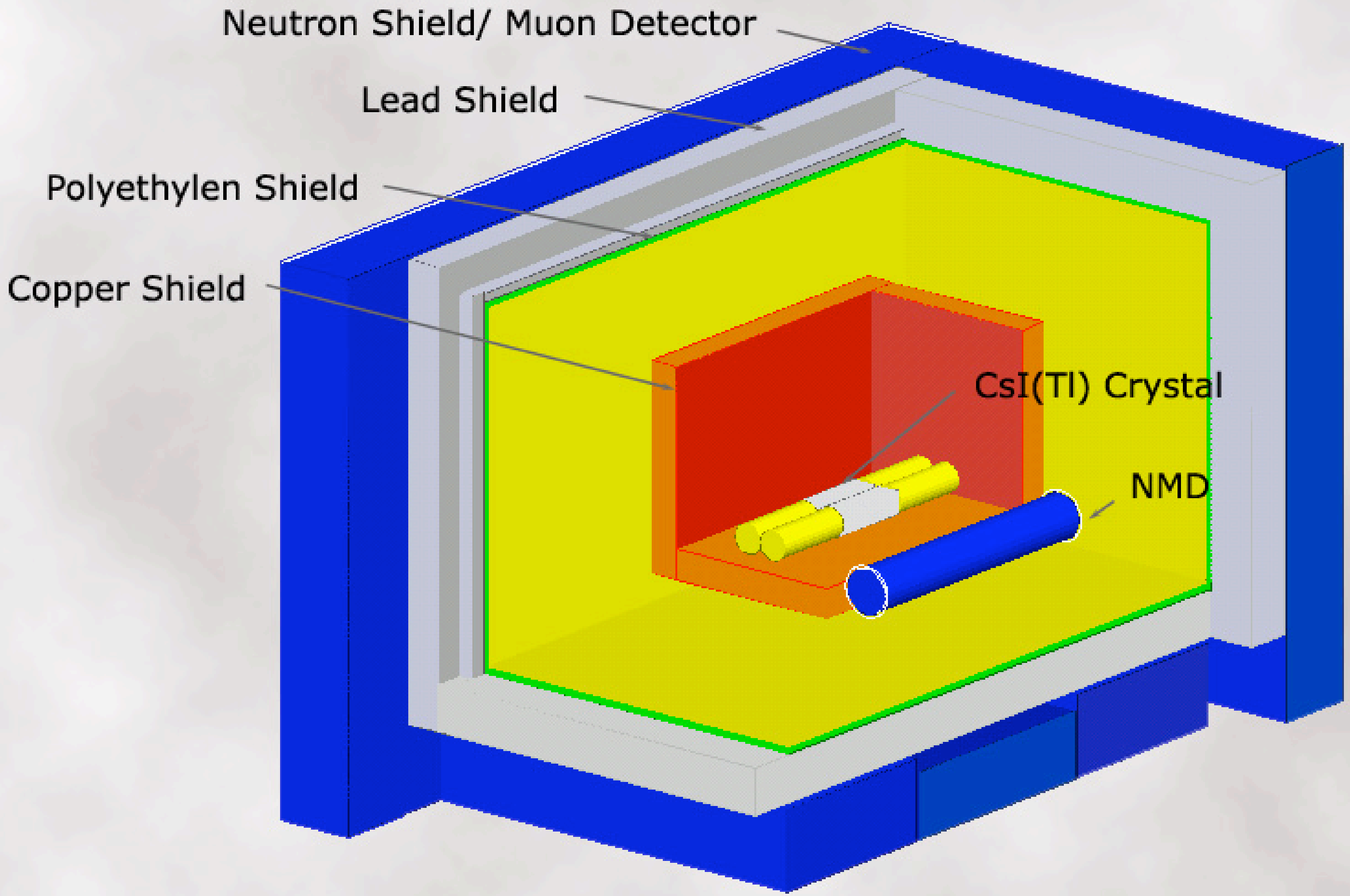


First data release foreseen not later than the end of 2008

KIMS Dark Matter Search, Using CsI Crystals

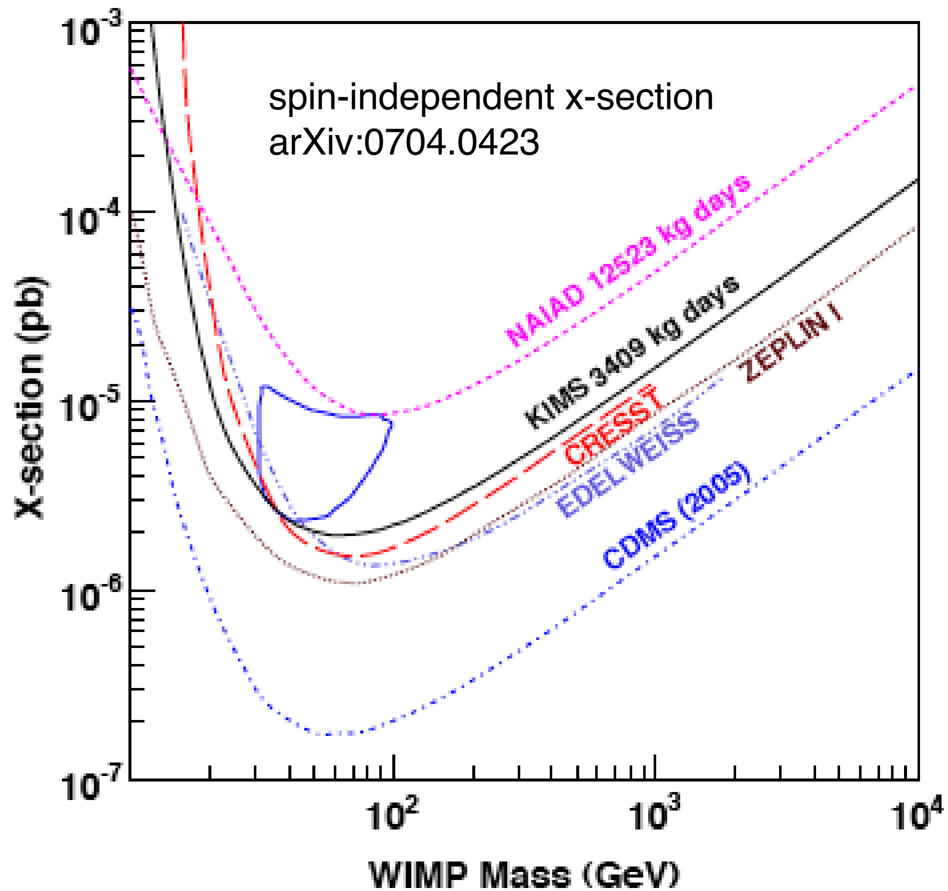
Easy to get large mass with an affordable cost
  ➔ Good for AM study
High light yield ~60,000/MeV
Pulse shape discrimination
  ➔ Moderate background rejection
Easy fabrication and handling
Cs-133, I-127 (SI cross section ~ A^2)
Both Cs-133, I-127 are sensitive to SD interaction




Neutron Shield/ Muon Detector
Lead Shield
Polyethylen Shield
Copper Shield
CsI(Tl) Crystal
NMD

Current status of the KIMS experiment:
Now installing 12 crystals (~ 100kg mass in total) at Yangyang underground laboratory.
Will probably start to take data from this month
and we will take data more than a year with a stable condition.
Will test the annual modulation of DAMA directly.

,



Summary

1) In some cases, WIMPs can be detected by direct searches but not by the LHC (and vice versa). If Nature is kind, it will be detectable by both.

2) Technologies based on scintillation are highly sensitive to WIMP-nucleus scattering.

3) Experiments based on noble liquids (LXe, LAr, LNe) are scalable and allow background reduction based on ionization/scintillation ratio, pulse shape, and/or self-shielding.

4) New results from WARP, ZEPLIN II, and XENON10 illustrate the promise of noble liquids as WIMP detection materials.

5) Future experiments such as XMASS, Mini-CLEAN, DEAP, ArDM, WARP, ZEPLIN-III, and LUX/XENON-100 will reach deep into WIMP parameter space in the very near future.

6) Proposed experiments based on room-temperature noble gases (SIGN, HPGS) may allow sensitive WIMP searches without cryogenics.

7) The DAMA/LIBRA collaboration will release new data in 2008, should shed new light on a previous 6.3σ detection of an annual modulation signal. The KIMS experiment will also soon have enough data to directly search for annual modulation.