Summary of Experimental Dark Matter Searches

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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 □□ annihilation in form of high energy cosmics, neutrinos

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

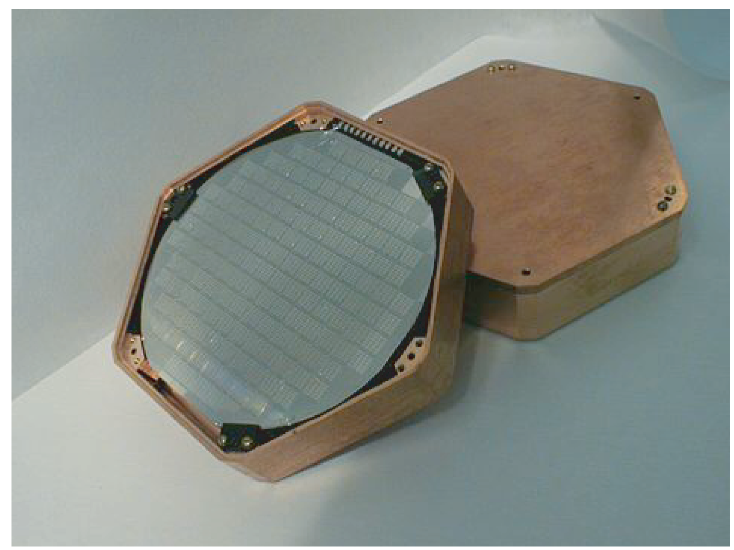
R = N □ < □ v >

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

Key technical challenges:

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

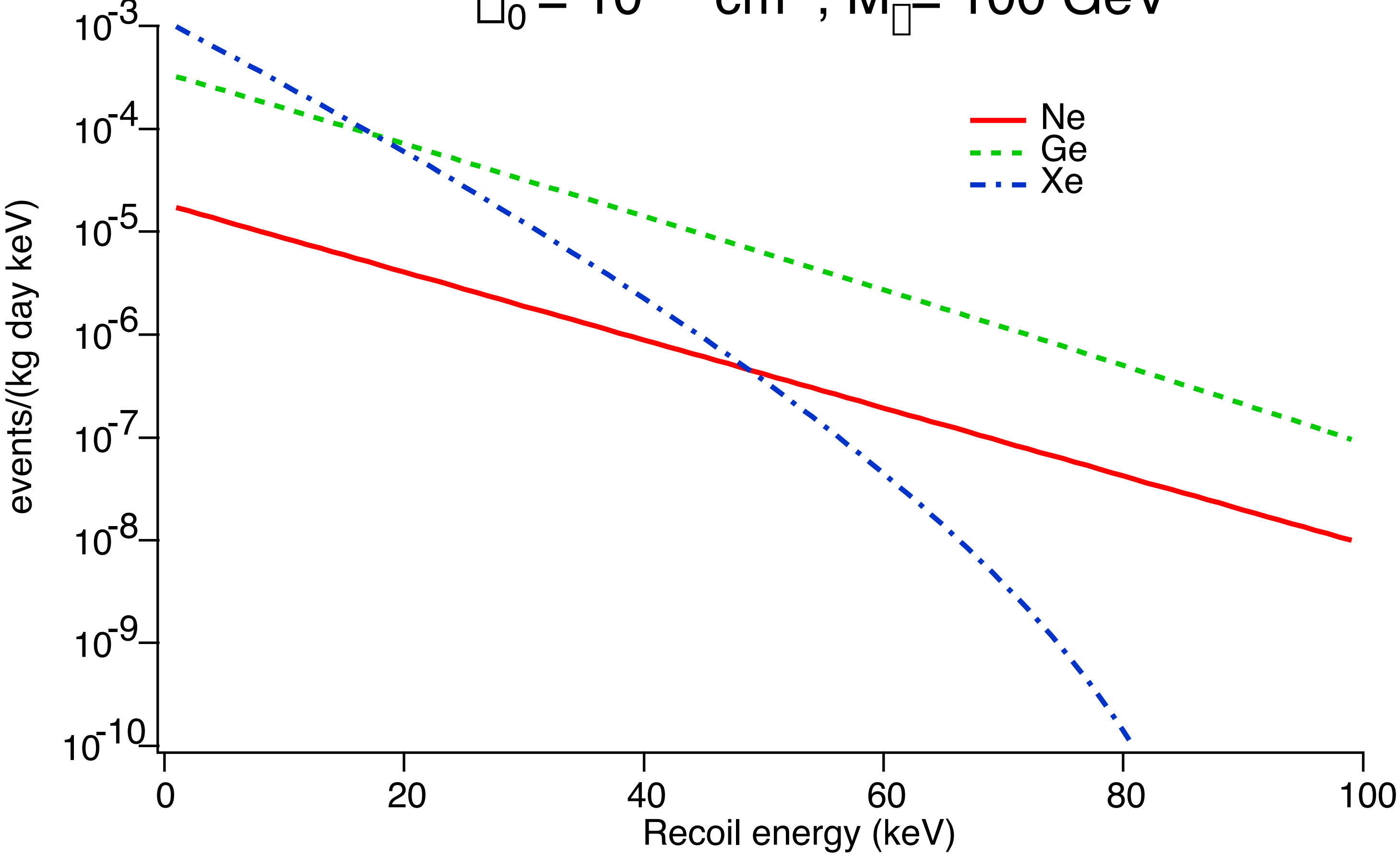
Detect heat, light, or ionization
(or some combination)



Germanium detector
(as in CDMS, Edelweiss)

WIMP recoil spectra

$\sigma_0 = 10^{-44}$ 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

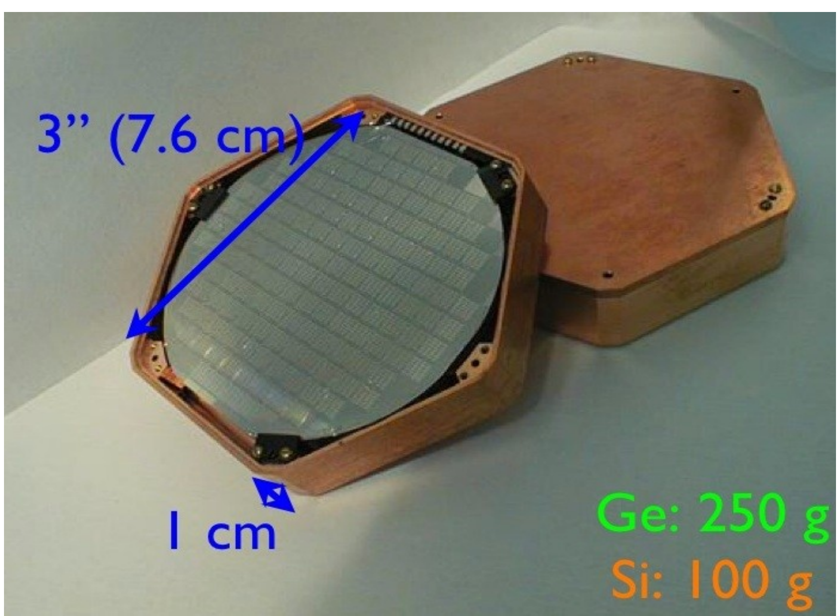
Form factor

World Wide Dark Matter Searches

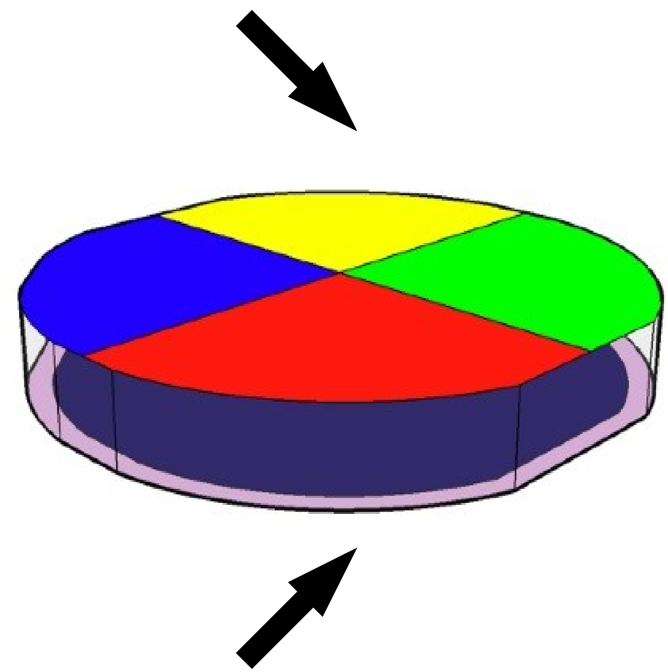
K. Ni

The CDMS ZIP Detectors

- 19 Ge and 11 Si semiconductor detectors
- operated at cryogenic temperatures (~40 mK)
- 2 signals from interaction (ionization and phonon) → event by event discrimination between electron recoils and nuclear recoils
- z-sensitive readout
- xy-position imaging



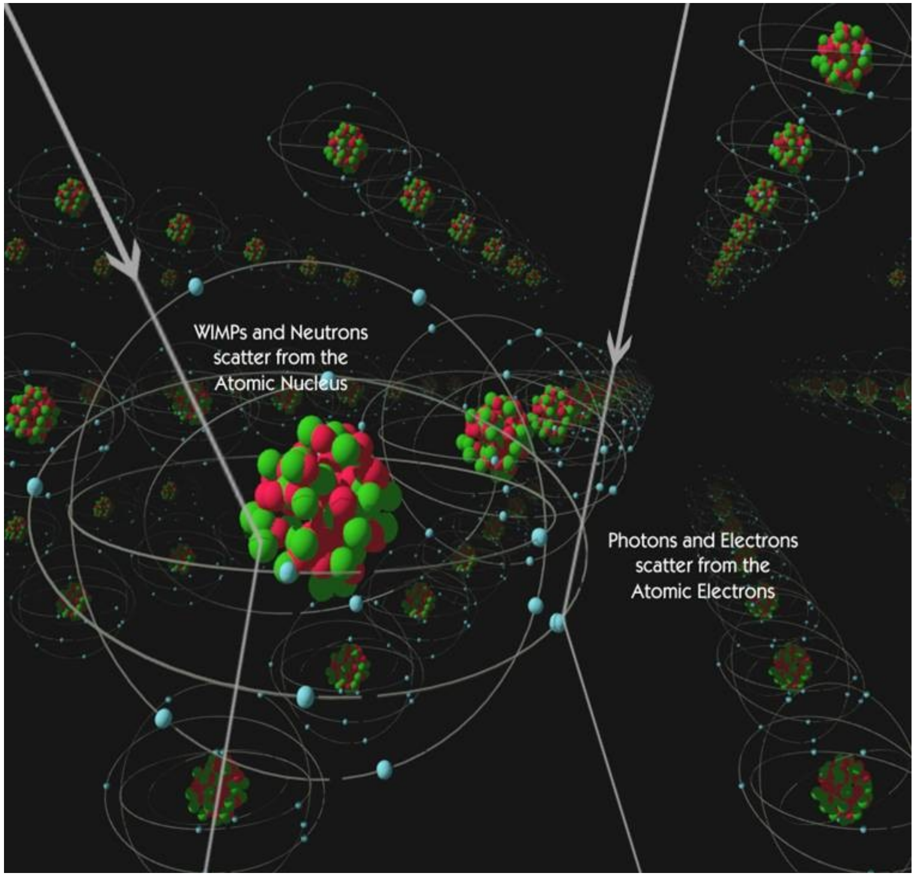
Phonon readout:
4 quadrants of
phonon sensors

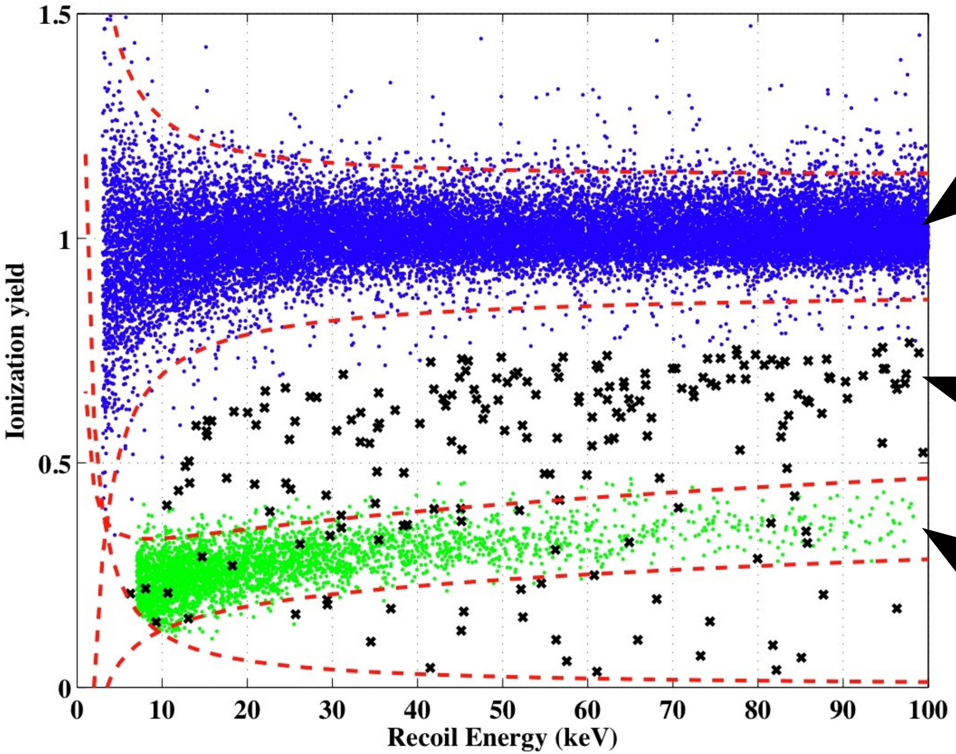


Charge readout:
2 concentric
electrodes

Primary Background Rejection

- most backgrounds (e, γ) produce electron recoils
- neutrons and WIMPs produce nuclear recoils which have a suppressed ionization signal
- define ionization yield as $y = \frac{E_{charge}}{E_{recoil}}$





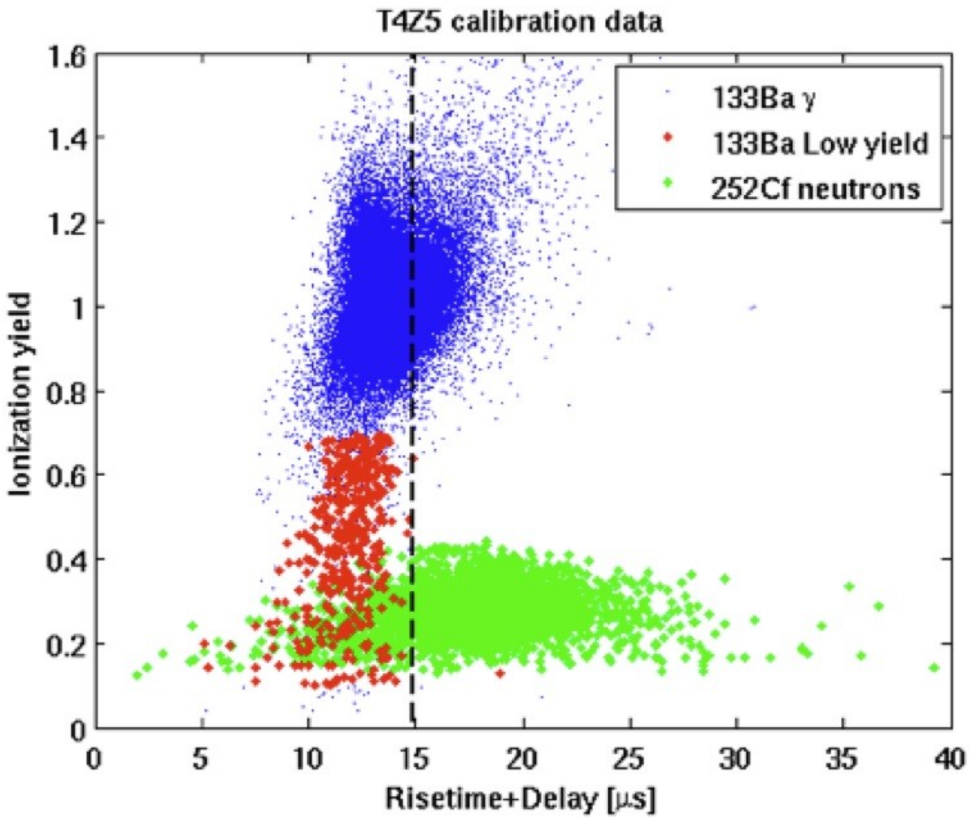
- better than 1:10000 rejection of electron recoils based on ionization yield alone
- dominant remaining background: low-yield surface events

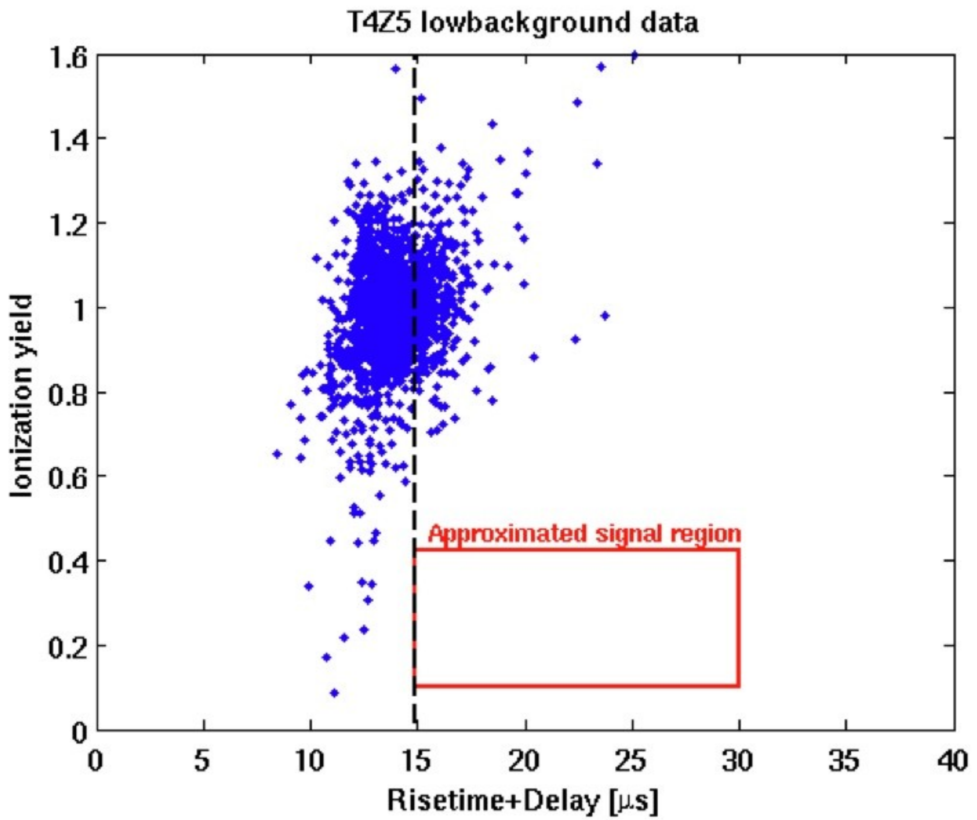
Surface Event Rejection

- use risetime+delaytime to define timing cut on calibration data
- allow ~0.5 events total laekage within WIMP search data

→

- apply cut to lowbackground data
- surface event rejection ~200:1



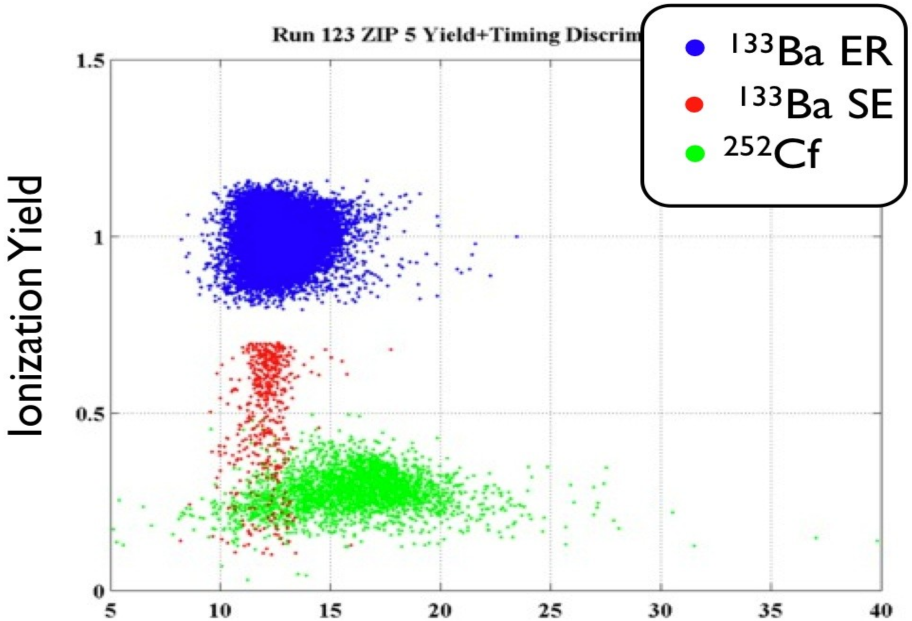


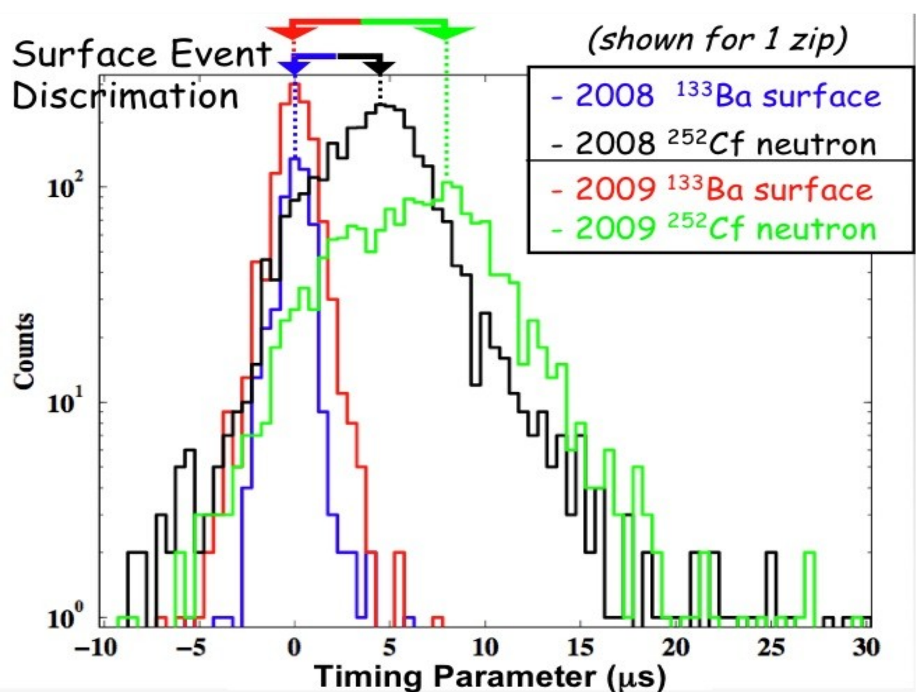
Ongoing Analysis...

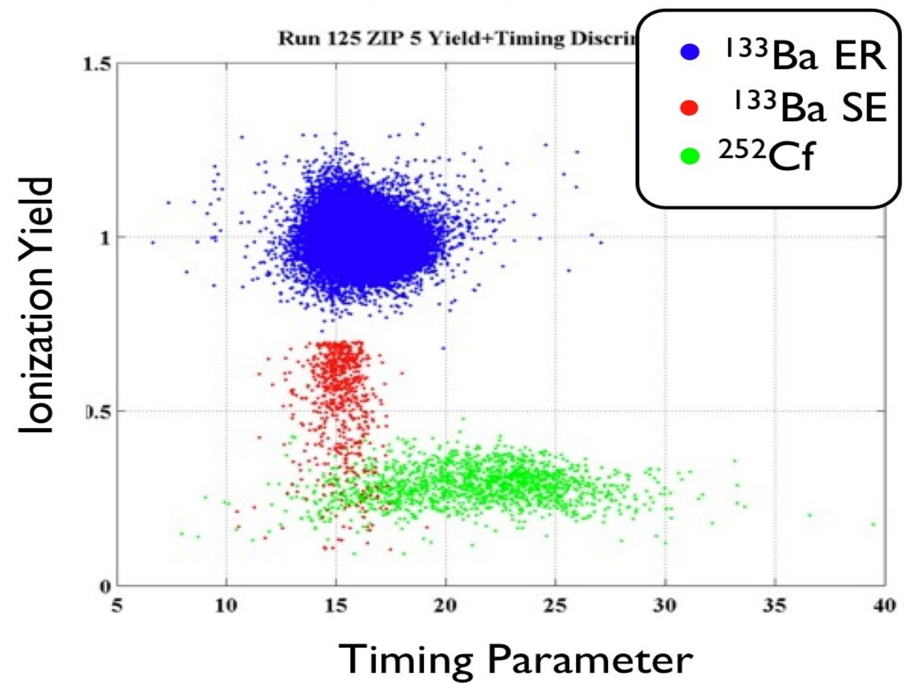
- exposure of ~700 kg-days after basic quality cuts in analysis pipeline

- timing of new data looks promising in obtaining higher detection efficiency

- new results expected in ~1 month





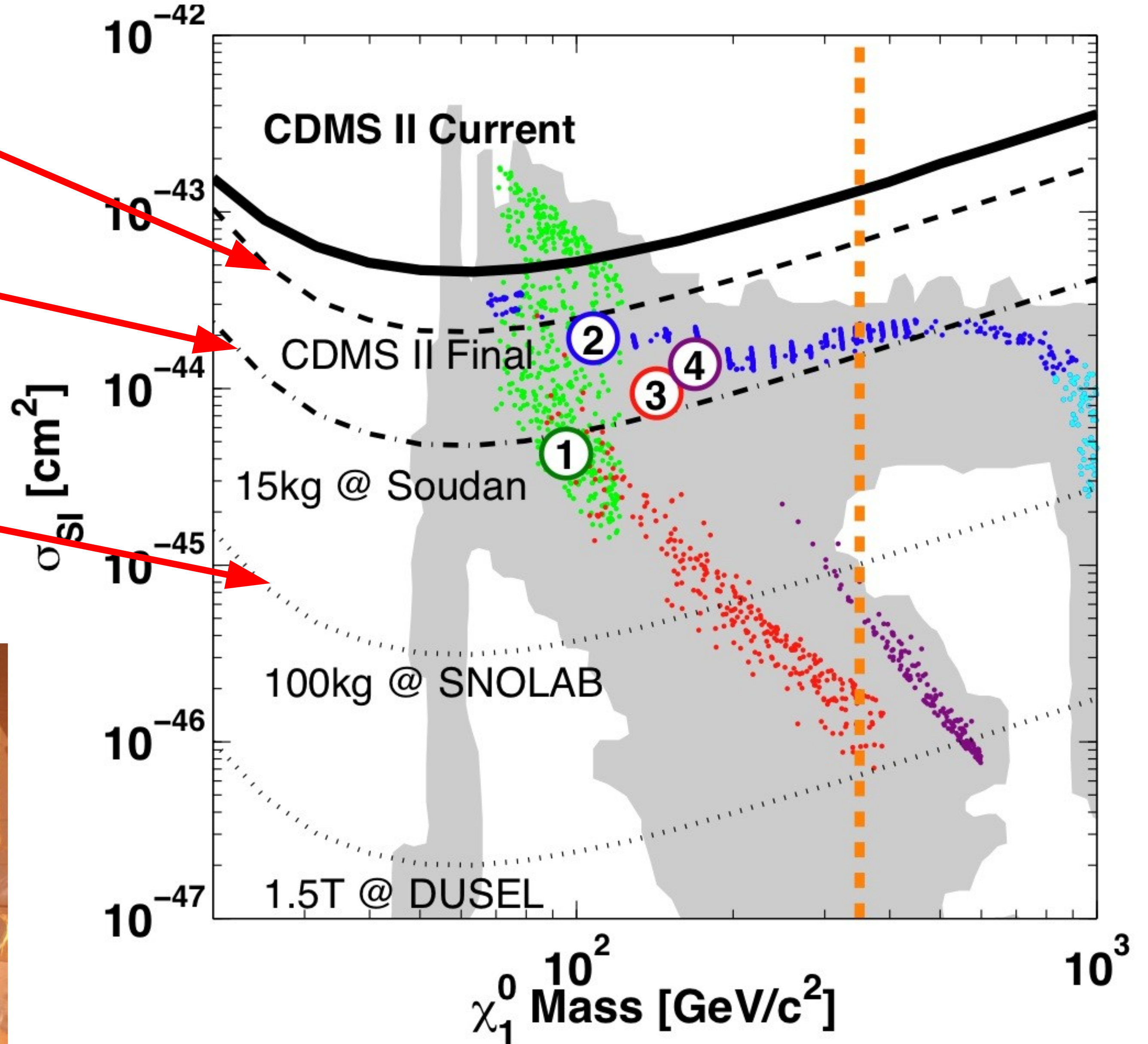


The Future of CDMS

CDMS II @ Soudan
results expected in
~1 month

SuperCDMS @ Soudan
15 kg of Ge
~2 years of operation

SuperCDMS @ SNOLAB
100 kg of Ge
~3 years of operation

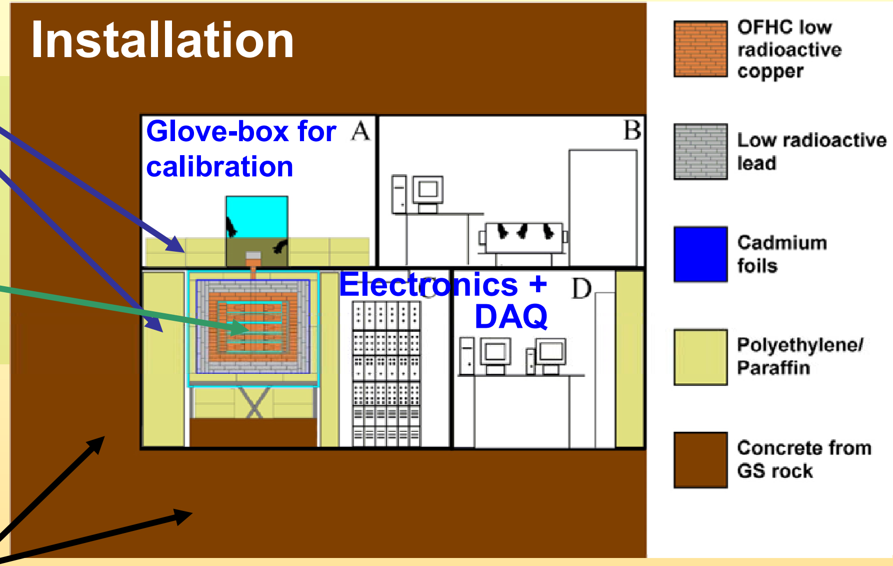


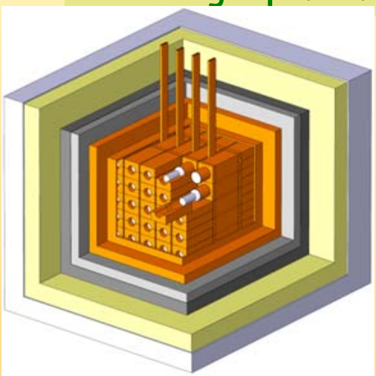
The DAMA/LIBRA set-up

For details, radiopurity, performances, procedures, etc.
NIMA592(2008)297

Polyethylene/
paraffin

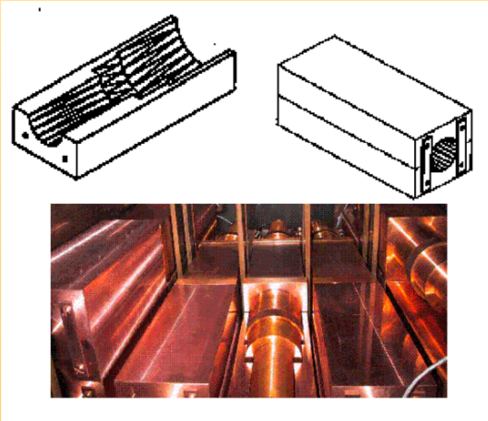
- 25 x 9.7 kg NaI(Tl) in a 5x5 matrix
- two Suprasil-B light guides directly coupled to each bare crystal
- two PMTs working in coincidence at the single ph. el. threshold





~ 1m concrete from GS rock

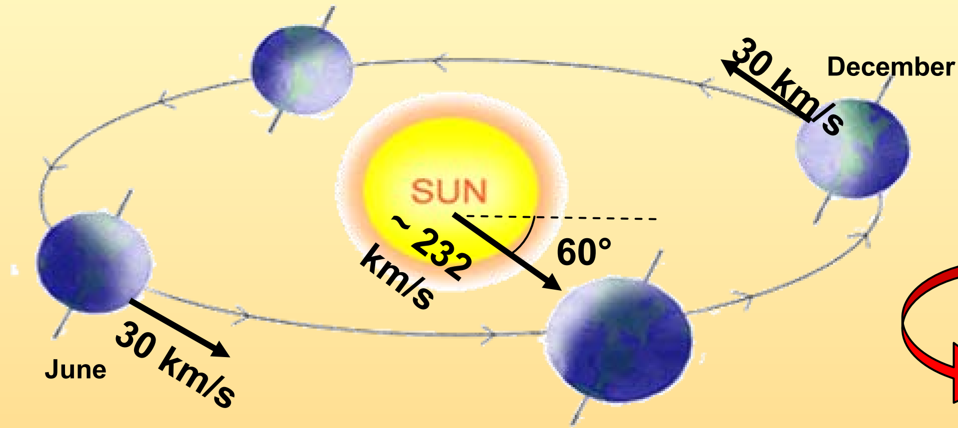
- Dismounting/Installing protocol (with "Scuba" system)
- All the materials selected for low radioactivity
- Multicomponent passive shield (>10 cm of Cu, 15 cm of Pb + Cd foils, 10/40 cm Polyethylene/paraffin, about 1 m concrete, mostly outside the installation)
- Three-level system to exclude Radon from the detectors
- Calibrations in the same running conditions as production runs
- Installation in air conditioning + huge heat capacity of shield
- Monitoring/alarm system; many parameters acquired with the production data
- Pulse shape recorded by Waweform Analyzer *TVS641A* (2chs per detector), 1 *Gsample/s,* 8 bit, bandwidth 250 MHz
- Data collected from low energy up to MeV region, despite the hardware optimization was done for the low energy



The annual modulation: a model independent signature for the investigation of Dark Matter particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small **a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions would point out its presence.**

Drukier, Freese, Spergel PRD86
Freese et al. PRD88



- v_{sun} ~ 232 km/s (Sun velocity in the halo)
- v_{orb} = 30 km/s (Earth velocity around the Sun)
- $\gamma = \pi/3$
- $\omega = 2\pi/T$ T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb}\cos\gamma\cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k}\cos[\omega(t-t_0)]$$

Expected rate in given energy bin changes because the annual motion of the Earth around the Sun moving in the Galaxy

Requirements of the annual modulation

1) **Modulated rate according cosine**
2) **In a definite low energy range**
3) **With a proper period (1 year)**
4) **With proper phase (about 2 June)**
5) **For single hit events in a multi-detector set-up**
6) **With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios**

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

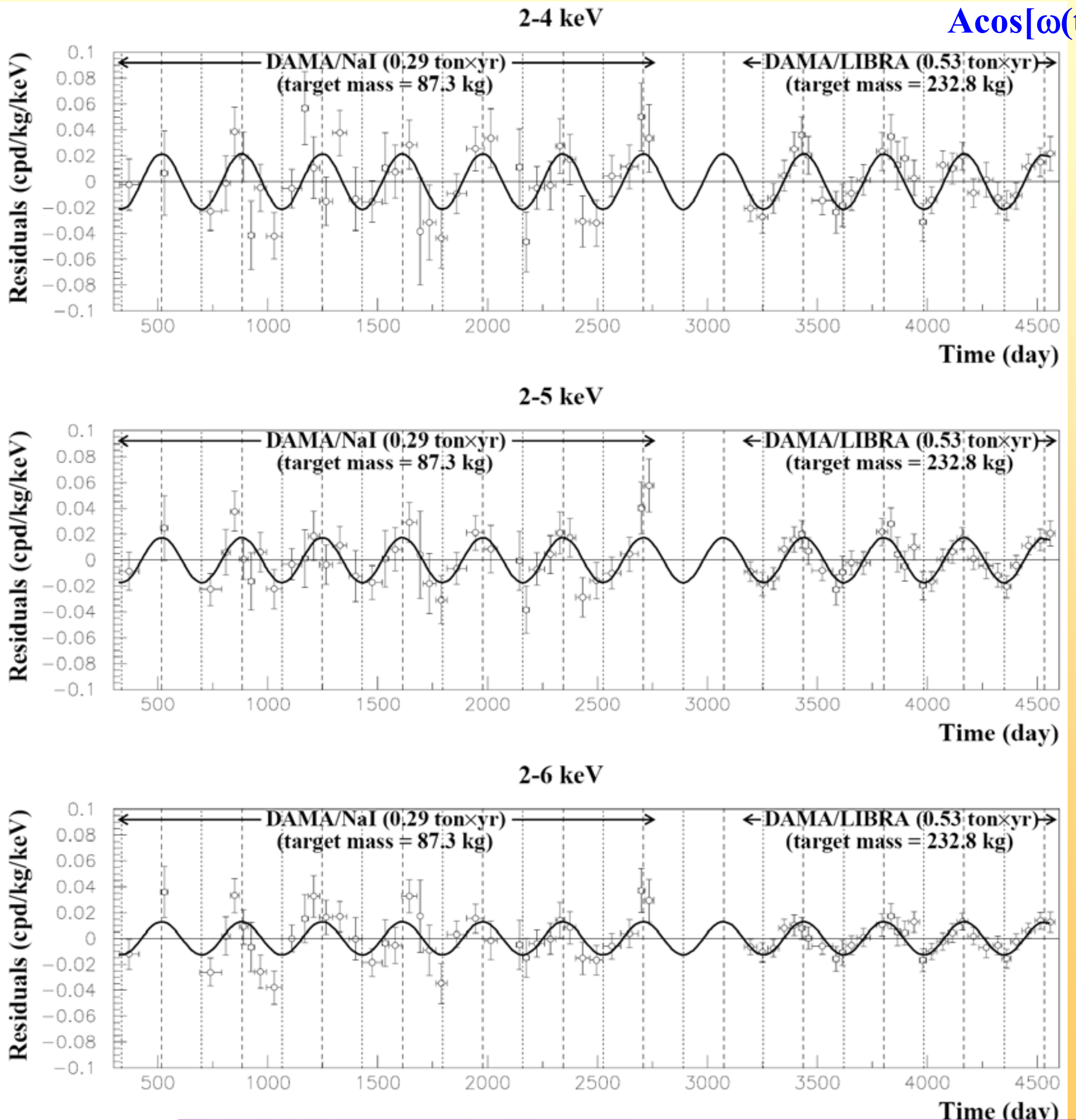
Model Independent Annual Modulation Result

DAMA/NaI (7 years) + DAMA/LIBRA (4 years)   Total exposure: 300555 kg×day = 0.82 ton×yr

EPJC56(2008)333

experimental single-hit residuals rate vs time and energy

$A\cos[\omega(t-t_0)]$; continuous lines: t_0 = 152.5 d, T = 1.00 y



2-4 keV

A=(0.0215±0.0026) cpd/kg/keV

χ^2/dof = 51.9/66   **8.3 σ C.L.**

Absence of modulation? No

χ^2/dof=117.7/67 ⇒ P(A=0) = 1.3×10^{-4}

2-5 keV

A=(0.0176±0.0020) cpd/kg/keV

χ^2/dof = 39.6/66   **8.8 σ C.L.**

Absence of modulation? No

χ^2/dof=116.1/67 ⇒ P(A=0) = 1.9×10^{-4}

2-6 keV

A=(0.0129±0.0016) cpd/kg/keV

χ^2/dof = 54.3/66 **8.2 σ C.L.**

Absence of modulation? No

χ^2/dof=116.4/67 ⇒ P(A=0) = 1.8×10^{-4}

The data favor the presence of a modulated behavior with proper features at 8.2σ C.L.

Princeton NaI Effort

- Radioactive contamination in NaI crystals of DAMA problematic and limiting
  - K level in NaI crystals outstanding: 20 ppb of ^{nat}K is 8 orders of magnitude more than achieved in Borexino!
- R&D program on development of radioclean crystals in the same clean room where Borexino vessels built
- Fact: inclusion of NaI crystals on 4π thick liquid scintillator veto (à la Borexino) would allow redution of ^{40}K background by many orders of magnitude

The Noble Liquid Revolution

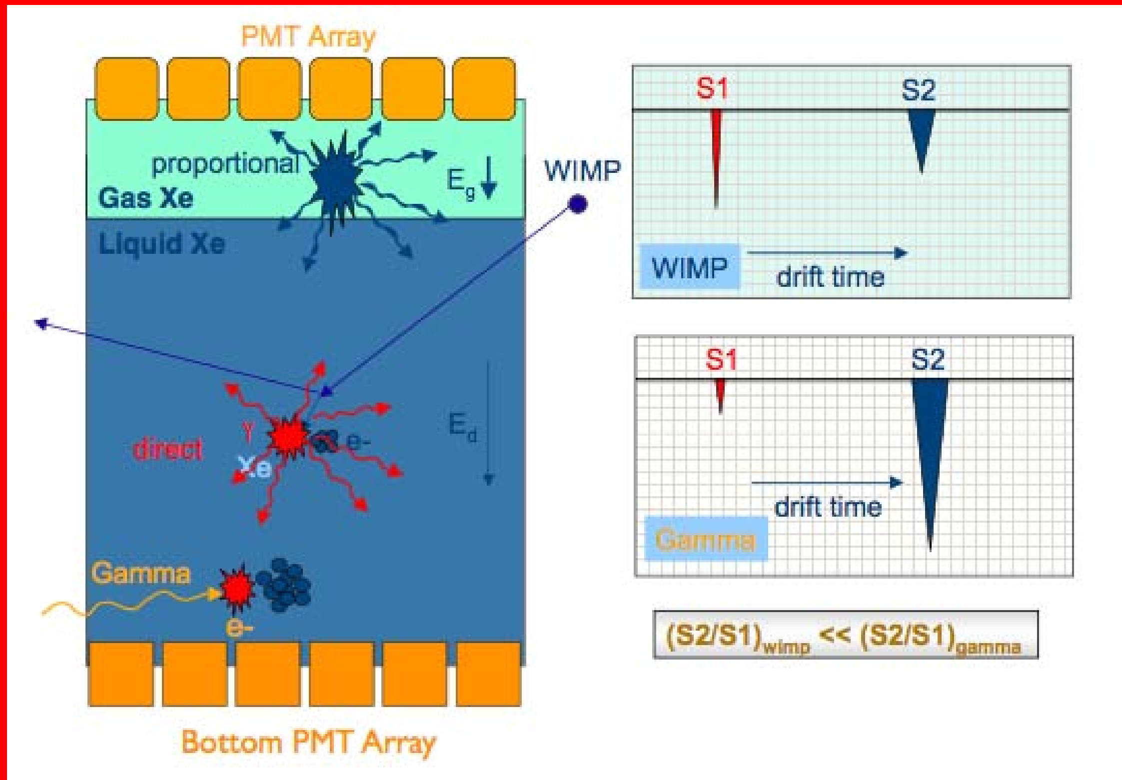
Noble liquids are relatively inexpensive, easy to obtain, and dense.

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



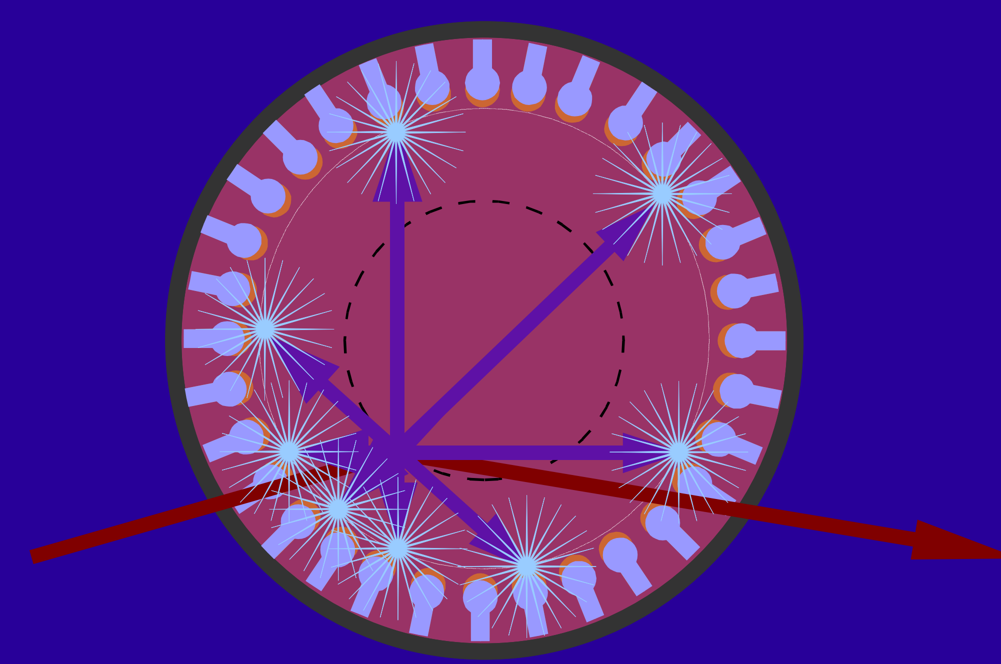
Courtesy E. April

dual phase noble

- Primary scintillation (S1)
- Secondary scintillation (S2)
- Discriminate with S2/S1
- Can also add pulse shape discrimination (PSD) from S1

single phase noble

- Just primary scintillation
- No E-field, no gas/liquid interface
- Excellent light collection ↔ powerful PSD
- Position reconstruction with scintillation light as well.



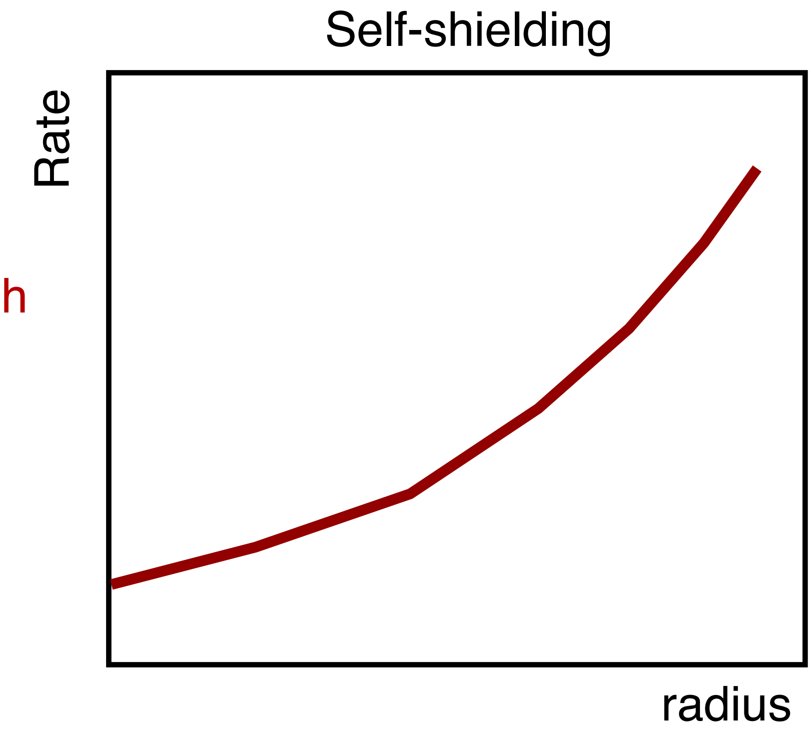
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

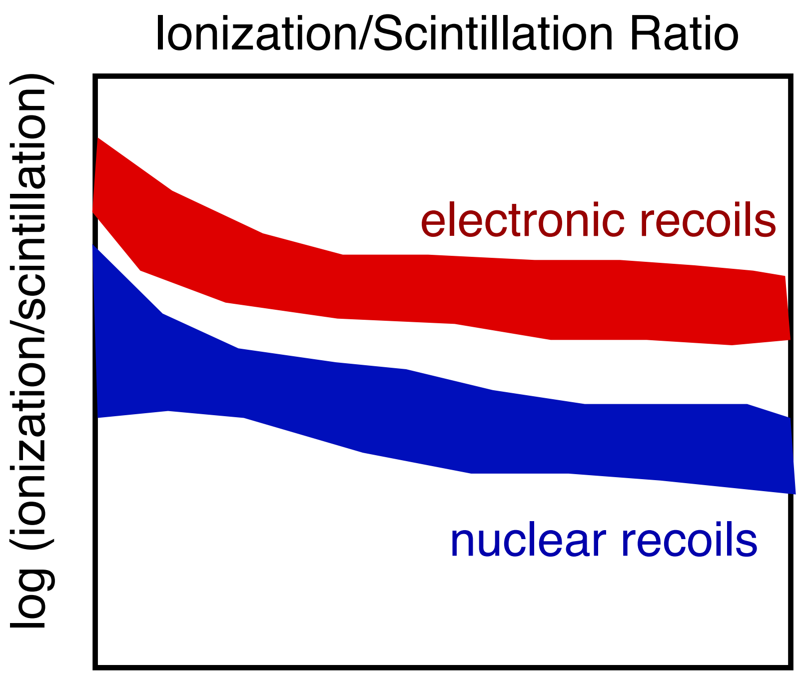
Require < 1 event in signal band during WIMP search

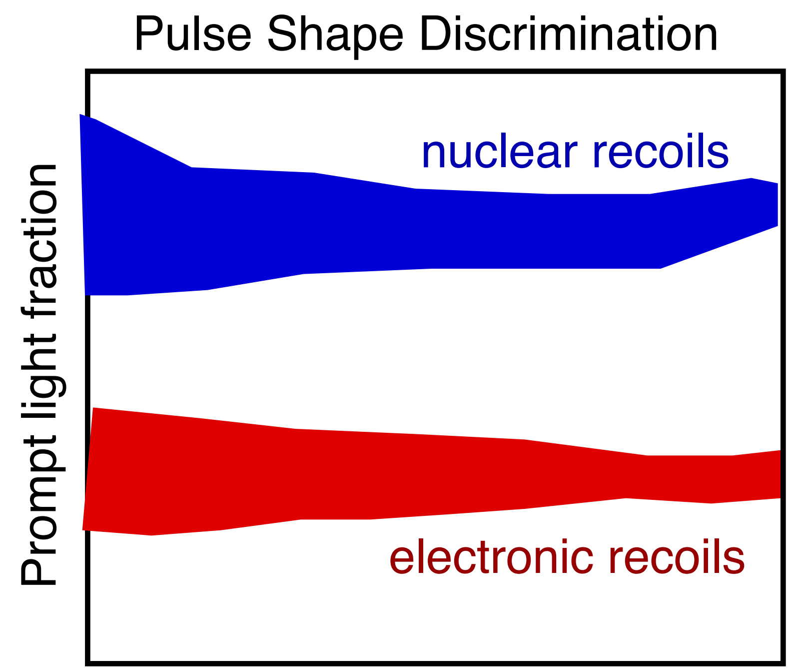
LXe: Self-shielding, Ionization/Scintillation ratio best

LAr: Pulse shape, Ionization/Scintillation ratio best

LNe: Pulse shape, Self-shielding best

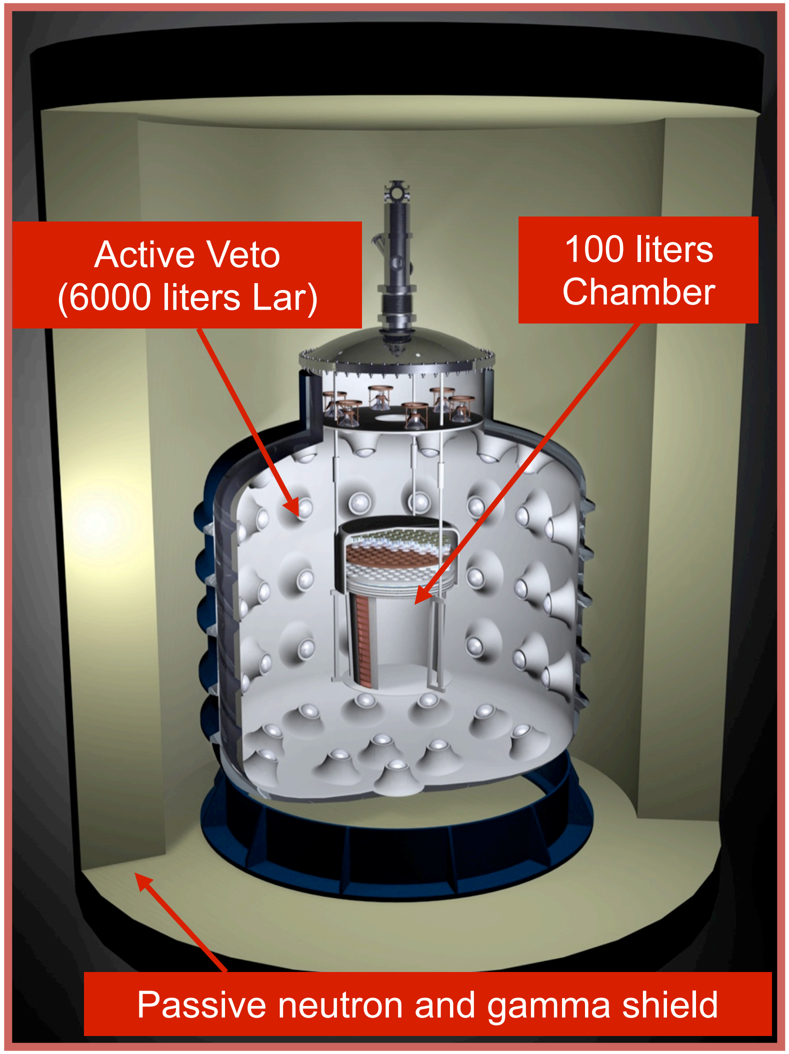




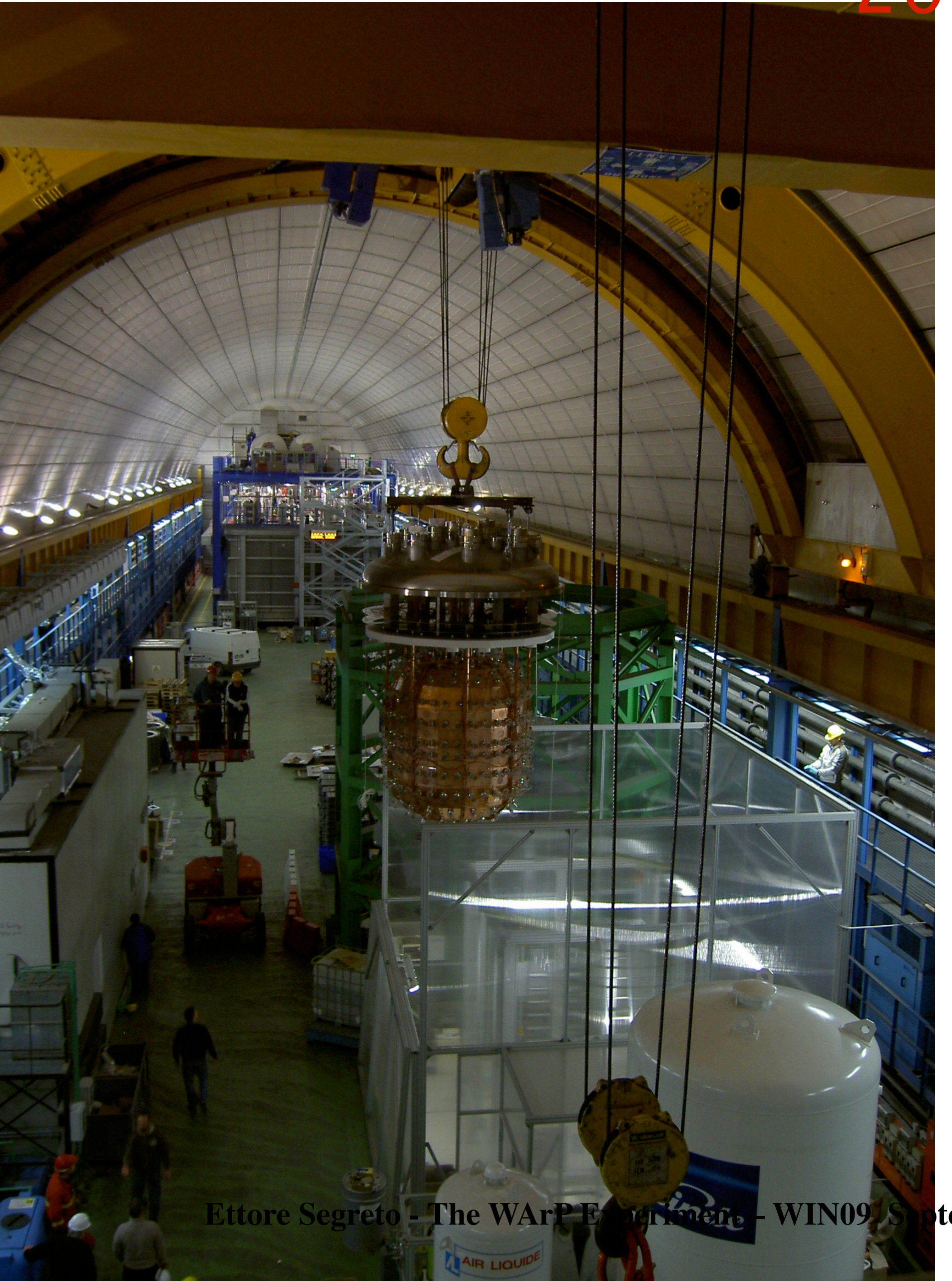


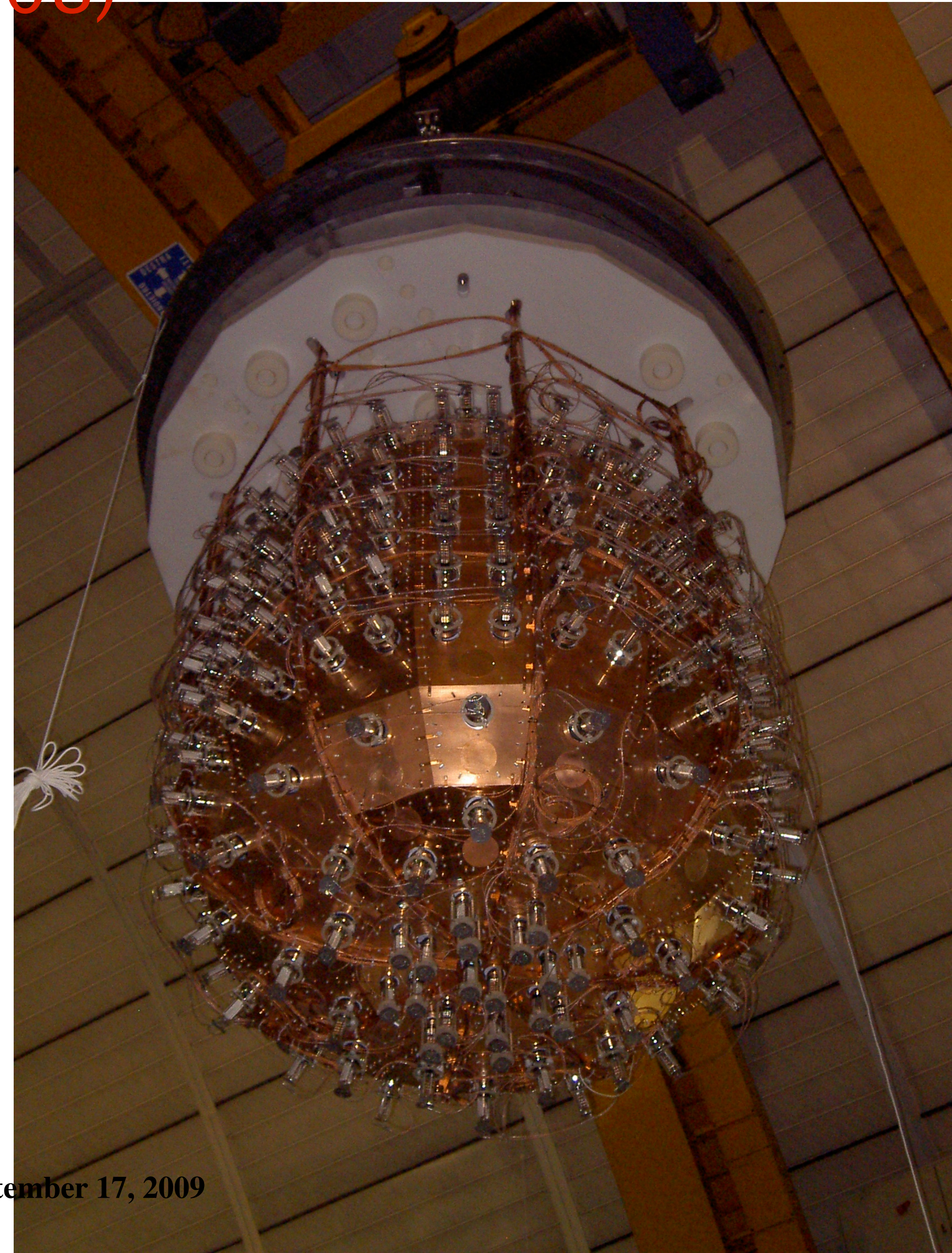
The 100 liters detector

- Sensitive volume = 100 liters (140 kg).
  - 3-D event localization by means of:
    - Drift time recording (vertical axis);
    - Centroid of PM's secondary signal amplitudes (horizontal plane).
- 4π active VETO system:
  - tags and measures the neutron-induced background with an ID-factor ≈ 99.99 %;
- Construction accomplished between mid 2004 and November 2008.
- Detector commissioning: December 2008 to May 2009 (vacuum, cooling and filling with ultra-purified Lar)
- **Designed also to host a 1 ton detector.**



Installation in the main cryostat (December 17th 2008)

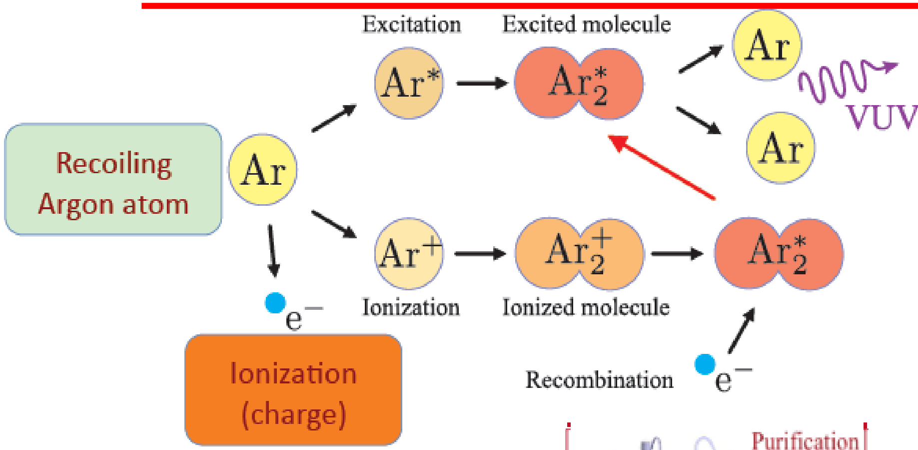




WArP-100 technical Commissioning

- On May 5th (the day after LNGS restart after the earthquake), WArP-100 commissioning (cooling+filling) was started.
- Initial Vacuum level (by pumping): 2÷6 x 10^{-6} mbar
- Cooling: by "low quality" LAr circulation detector cooling down to ~ 200 K has been achieved in ~ 2 days.
- Final Vacuum level (by cryo-pumping): 1÷ 2 x 10^{-6} mbar
- Filling:
  - "good quality" LAr (equiv. 5.5 GAr grade) further purified by in line H_2O and O_2 double stage filter.
  - internal material cooling down to ~ 100 K (~ 3 day)
  - GAr recirculation/reliquifaction ON
  - LAr level rise up to nominal: ~ 3 days
- On May 13th, WArP-100 detector filling was succsessfully completed.
- The technical run of the detector lasted for three months.
- During the three months of operation almost all detector components have been tested and put into operation
- The run was stopped on August 11th because of the breakdown of the HV feedthrough that needs to be substituted.

ArDM experiment

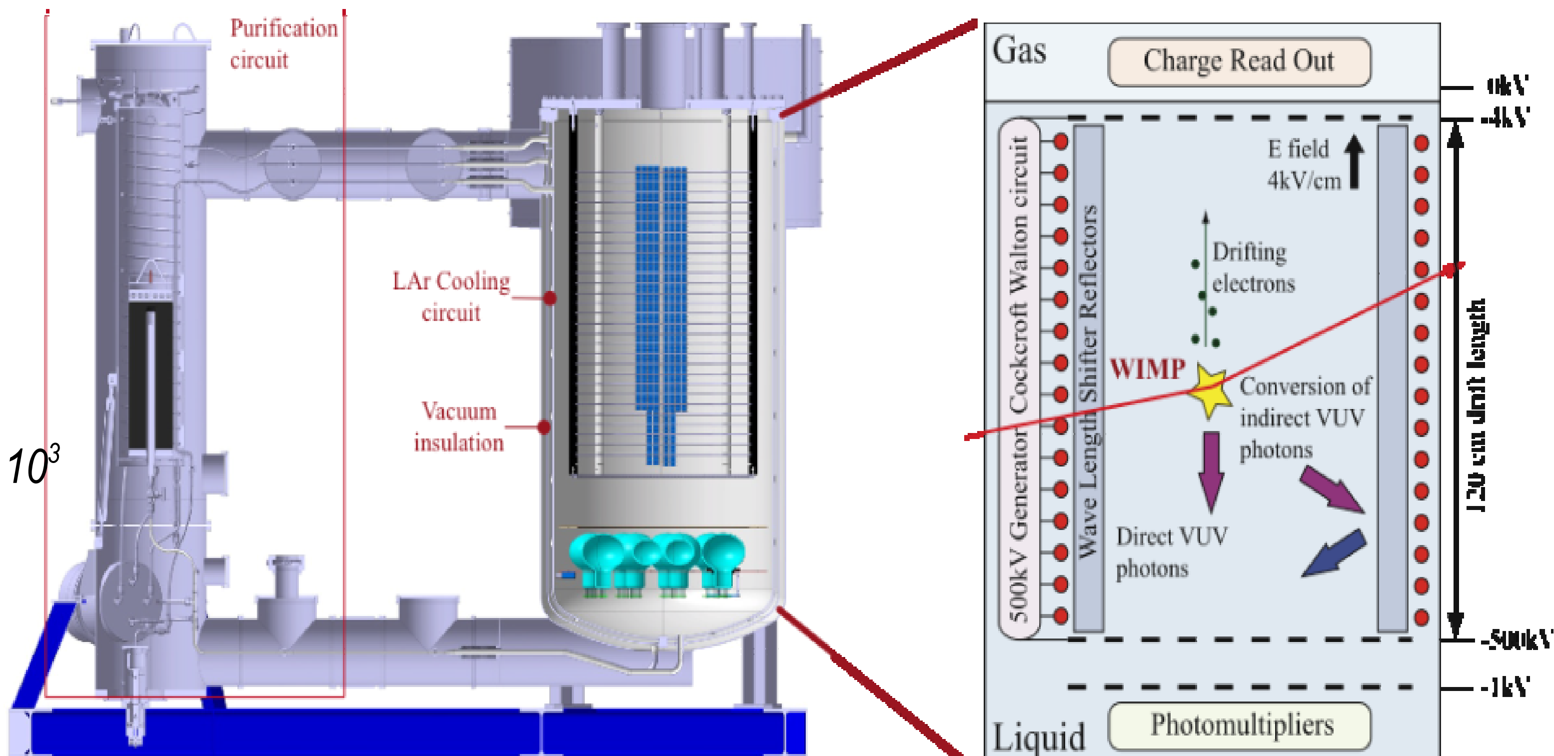


Scintillation and Ionization in LAr

⇓

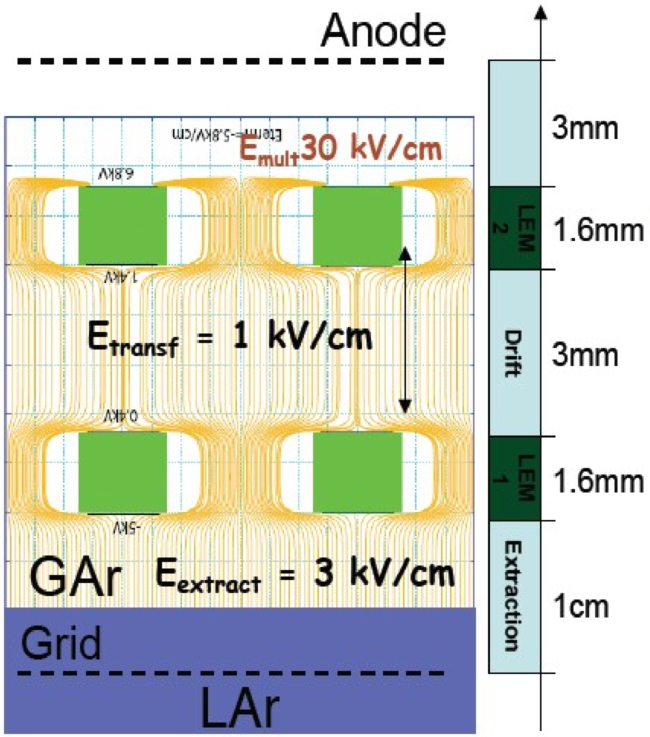
both charge and light are collected in the ArDM experiment

- ✗ *cylindrical volume*
- ✗ *length ≈ 120cm*
- ✗ *drift field: 1 to 4 kV/cm*
- ✗ *850 kg target*
- ✗ *charge readout: LEM, gain 10^3*
- ✗ *light readout: 14 PMT*



A.Rubbia: "ArDM: a Ton-scale liquid Argon experiment for direct detection of dark mater in the universe", J.Phys. Conf.Ser. 39 (2206) 129

Charge readout R&D: LEM



Principles:

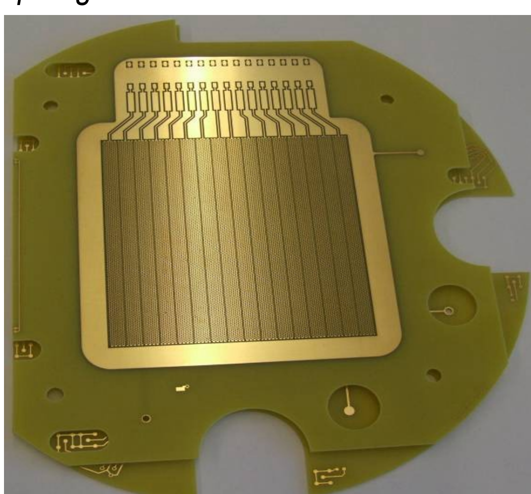
- ✗ *e⁻ drift in LAr towards the surface and are extracted into the vapor phase*
- ✗ *e⁻ are multiplied in the holes in LEM1, then they drift to LEM2, and tthey are again multiplied*
- ✗ *induction of charge on striped anode and on upper LEM2 striped plane*

The device gain depends on the electric field and thickness of the LEM:

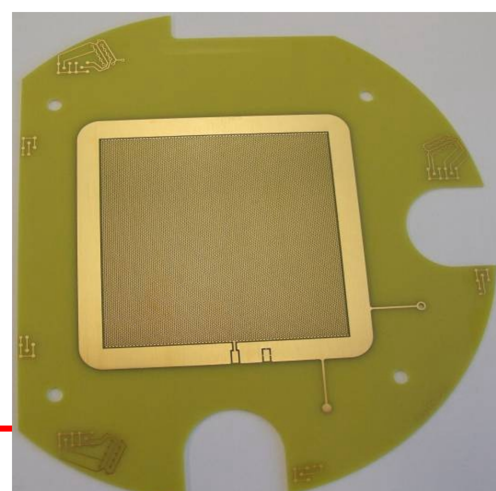
$$G = G_{LEM1} * G_{LEM2} = G^2_{LEM} = e^{(2\alpha x)}$$

x: effective LEM hole length (≈0.8mm)

Top segmented LEM



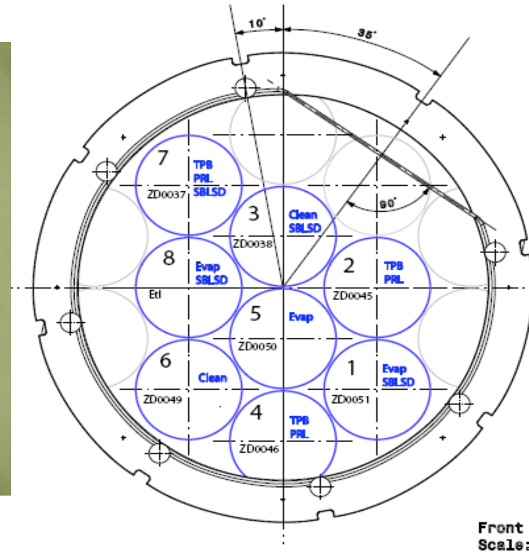
Bottom LEM



- ✗ *produced by standard PCB technique*
- ✗ *precision holes made by drilling (hole diameter 500μm, hole pitch 800μm)*
- ✗ *gold deposition on Cu (<1μm layer) to avoid oxidation*

A. Badertscher et al.: arXiv:0907.2944v1

Cool down test May '09

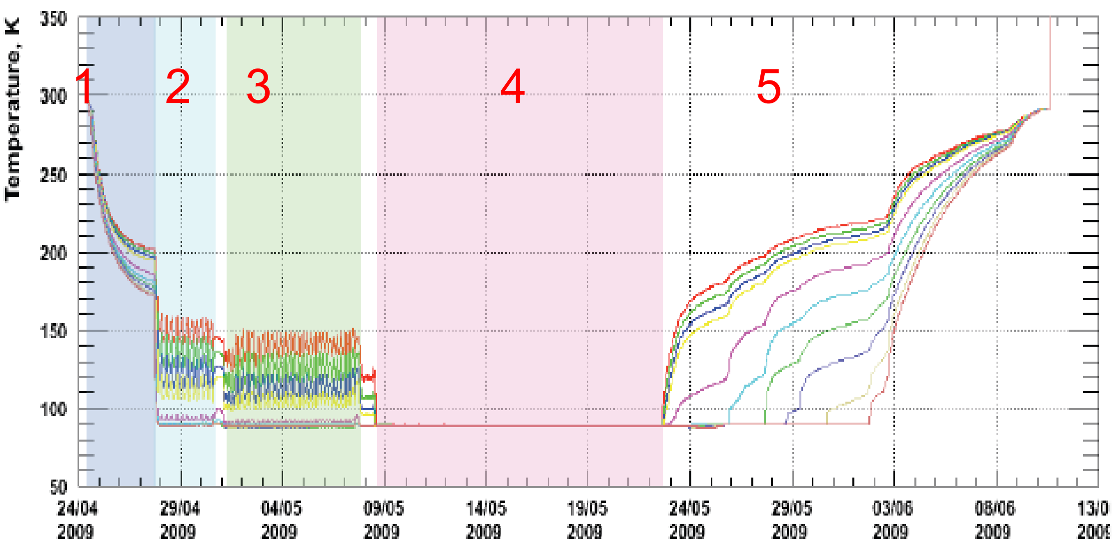


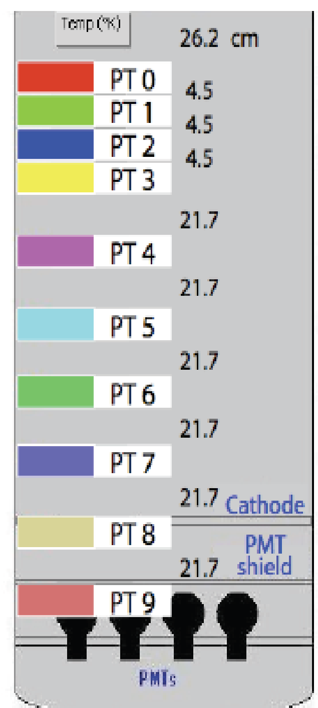
Setup:

8 coated PMT were installed:

products	models	tubes	gain (1500V)
Hamamatsu	R5912/02mod	5	~ 10^9
Hamamatsu	R5912/01mod	2	~ 10^7
ETL	ETL9357	1	~ 10^7

no electric field and charge readout





1.cooling bath filled with LAr

2. filled with pure GAr, test of the light readout system

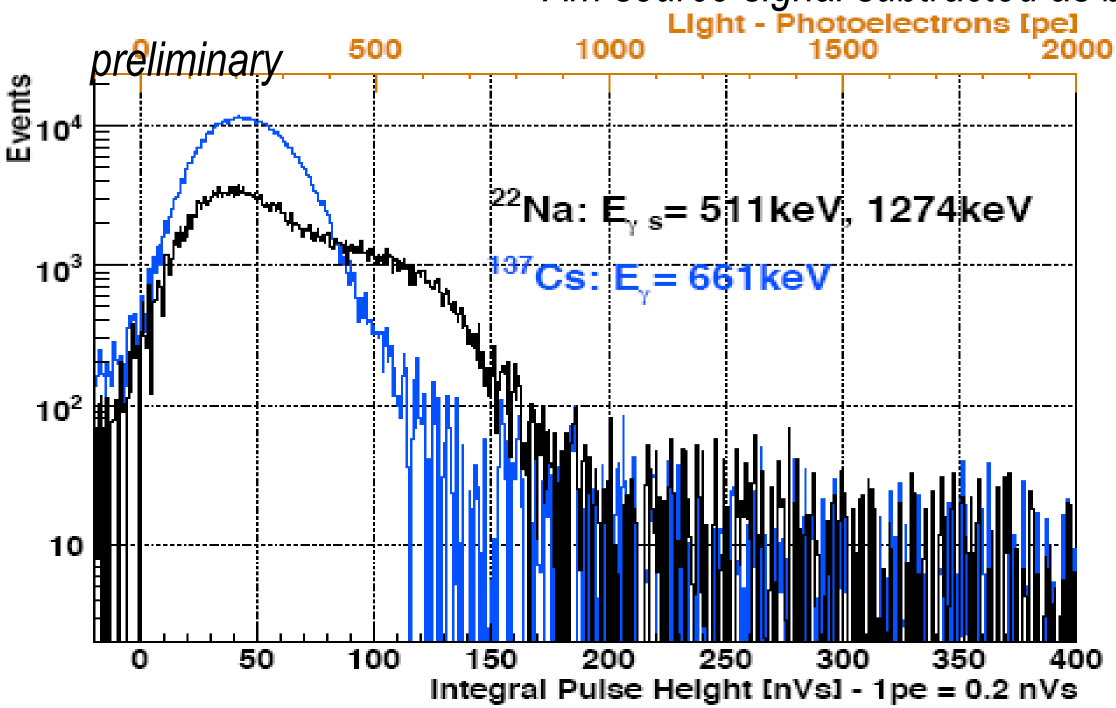
3. half filling 13h, first measurement with immersed PMTs

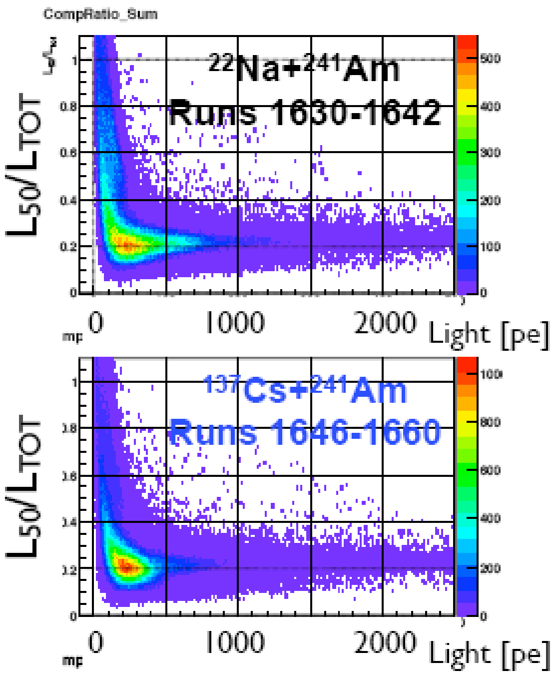
4. full filling in different step, and data taking with internal and external source

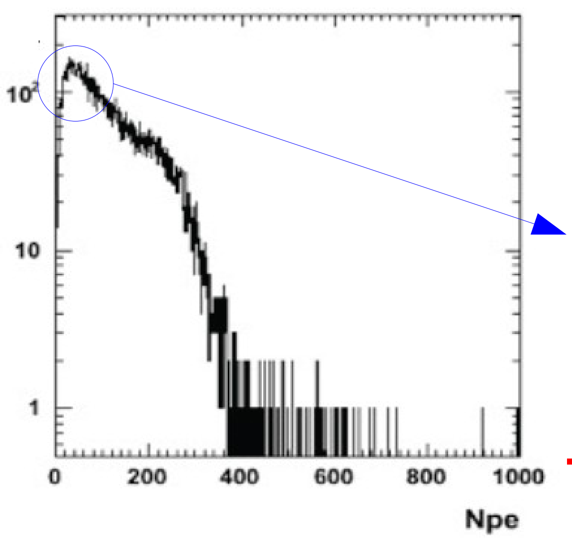
5.warming up

LAr measurement

Am source signal subtracted as background



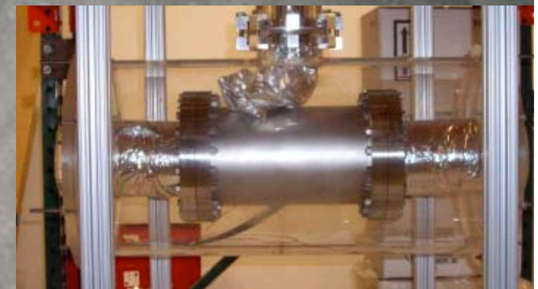




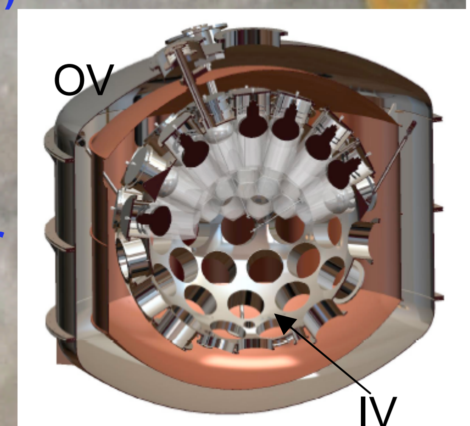
^{22}Na with 511keV in the crystal

preliminary calibration gave 0.5 phe/keVee, 50keV region is visible

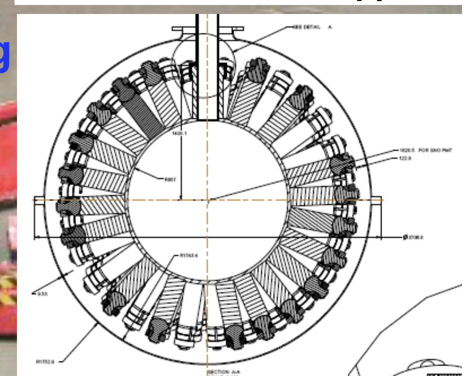
DEAP/CLEAN detectors



- **Existing small prototypes (linear geometry, 2 PMTs)**
  - **DEAP0 and picoCLEAN (initial R&D)**
  - **microCLEAN (4 kg LAr/LNe, cold PMTs)**
    - **Surface tests at Yale (Phys.Rev.C78:035801,2008)**
  - **DEAP-1 (7 kg LAr, warm PMTs, currently running in SNOLAB)**
    - **Discrimination achieved at surface < 6×10^{-8} (arXiv:0904.2930)**



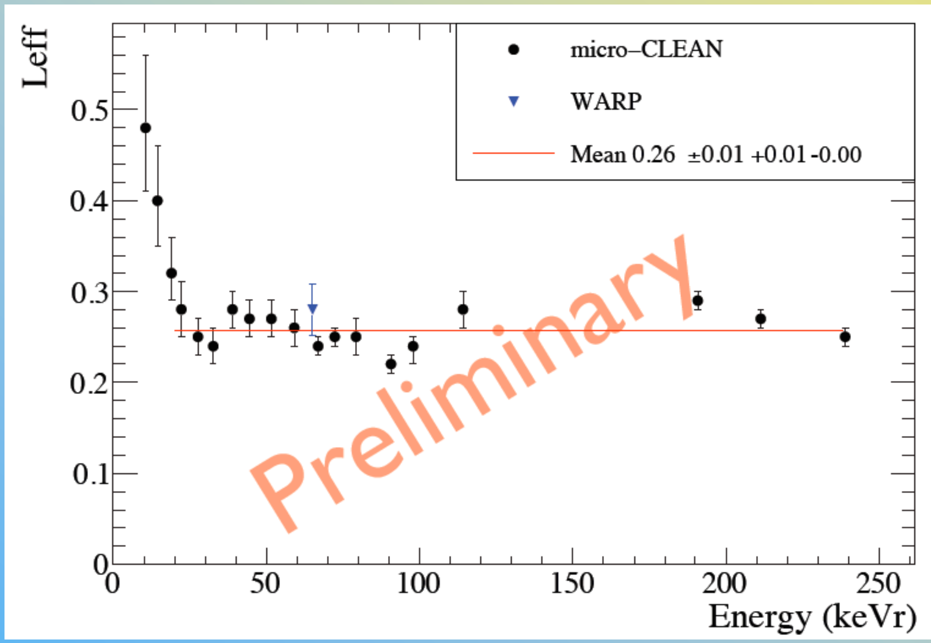
- **Advanced detectors (spherical geometry)**
  - **MiniCLEAN (500 kg LAr, 150 kg fiducial, 92 cold PMTs, under construction, to be commissioned in SNOLAB mid 2010)**
  - **DEAP-3600 (3.6 ton LAr, 1 ton fiducial, 266 warm PMTs, being designed, to be commissioned in SNOLAB in 2011)**

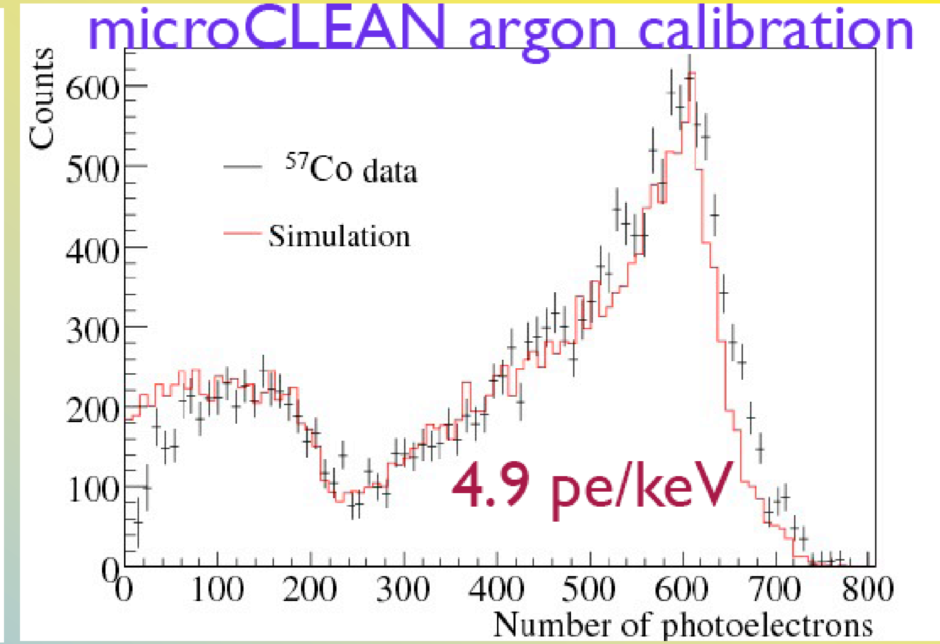


- **Underground location depth (SNOLAB): ~6 km.w.e.**
- **Submitted proposal of CLEAN (50 ton) detector to be run in DUSEL. Construction ~ 2013?**

SNOLAB, Cube Hall

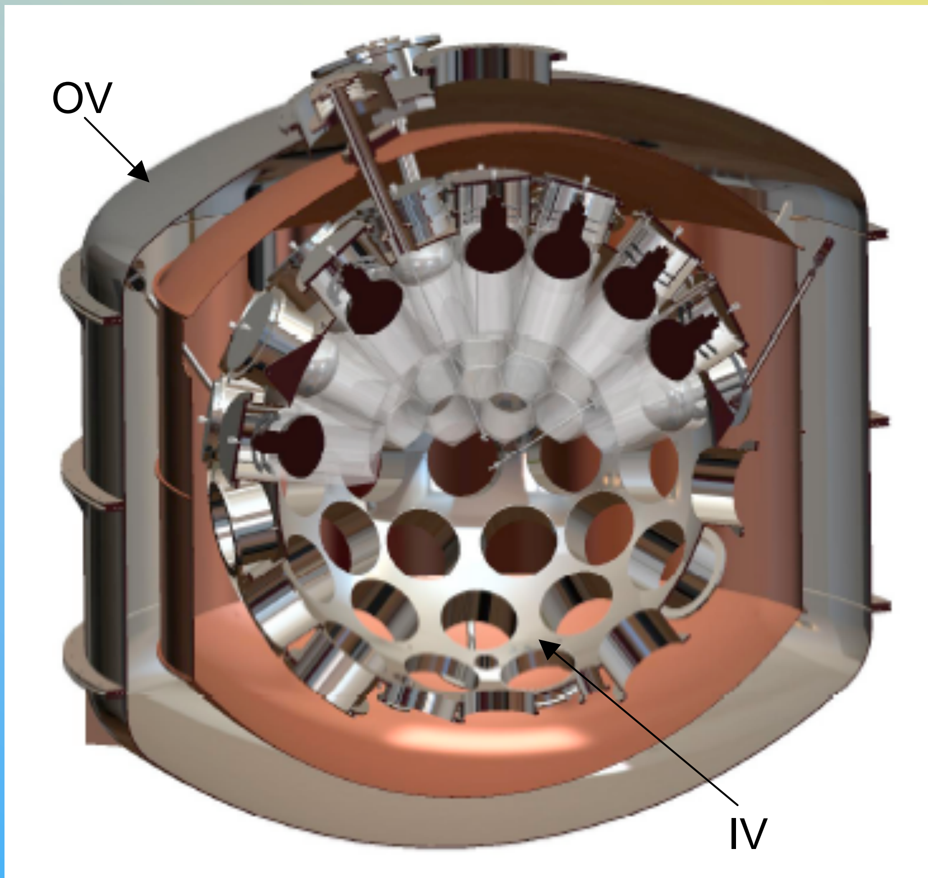
Some LAr R&D results

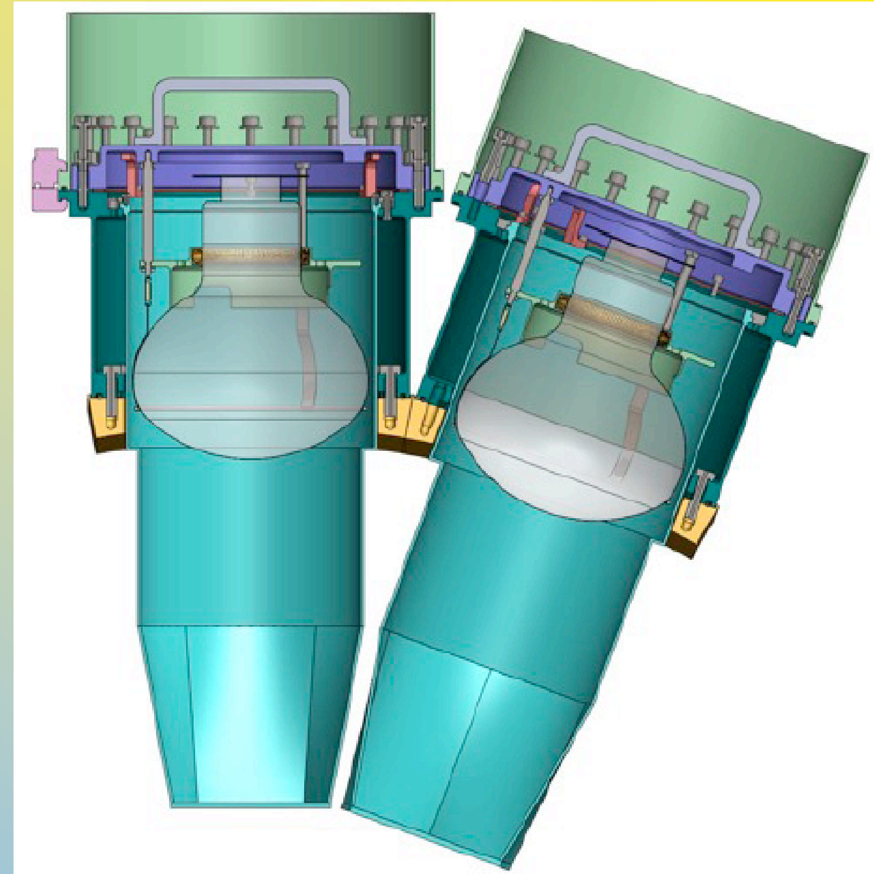




- 4.9 PE/keV experimentally demonstrated
- QF above 20 keV ~0.26

MiniCLEAN structure



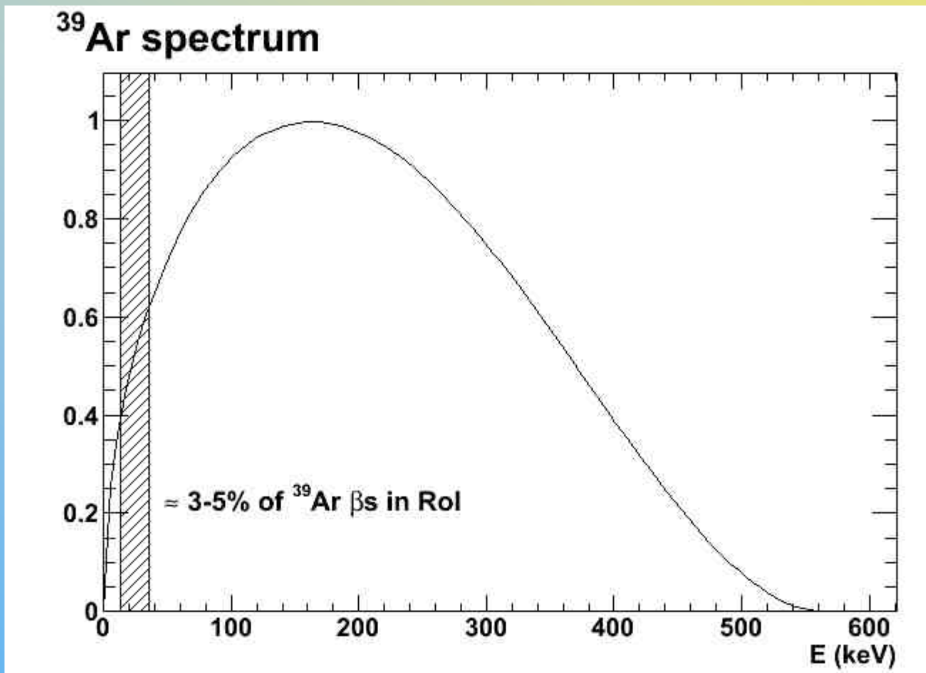


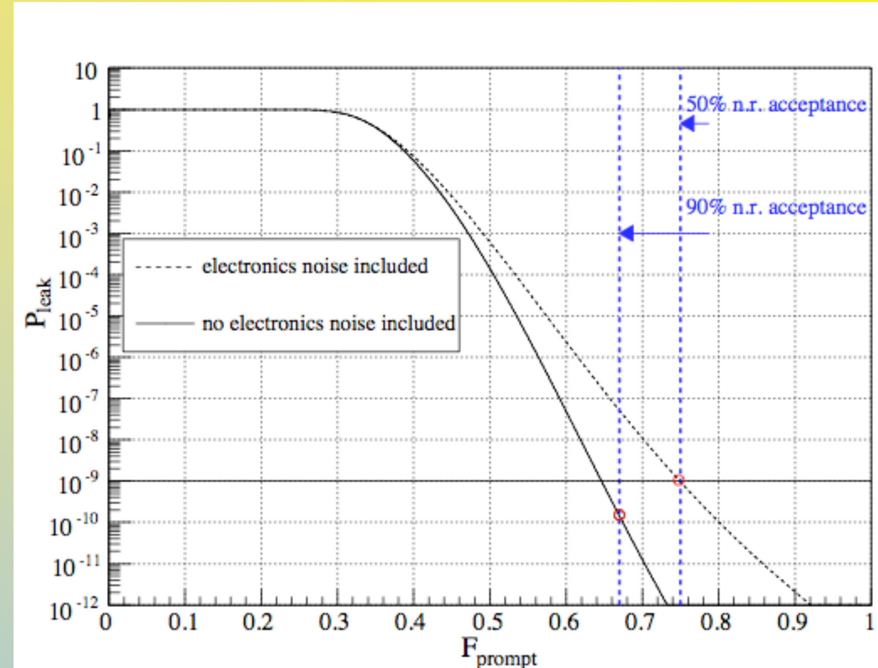
- Modular optics
- In situ (in OV but outside IV) calibration ports

MiniCLEAN status: under construction

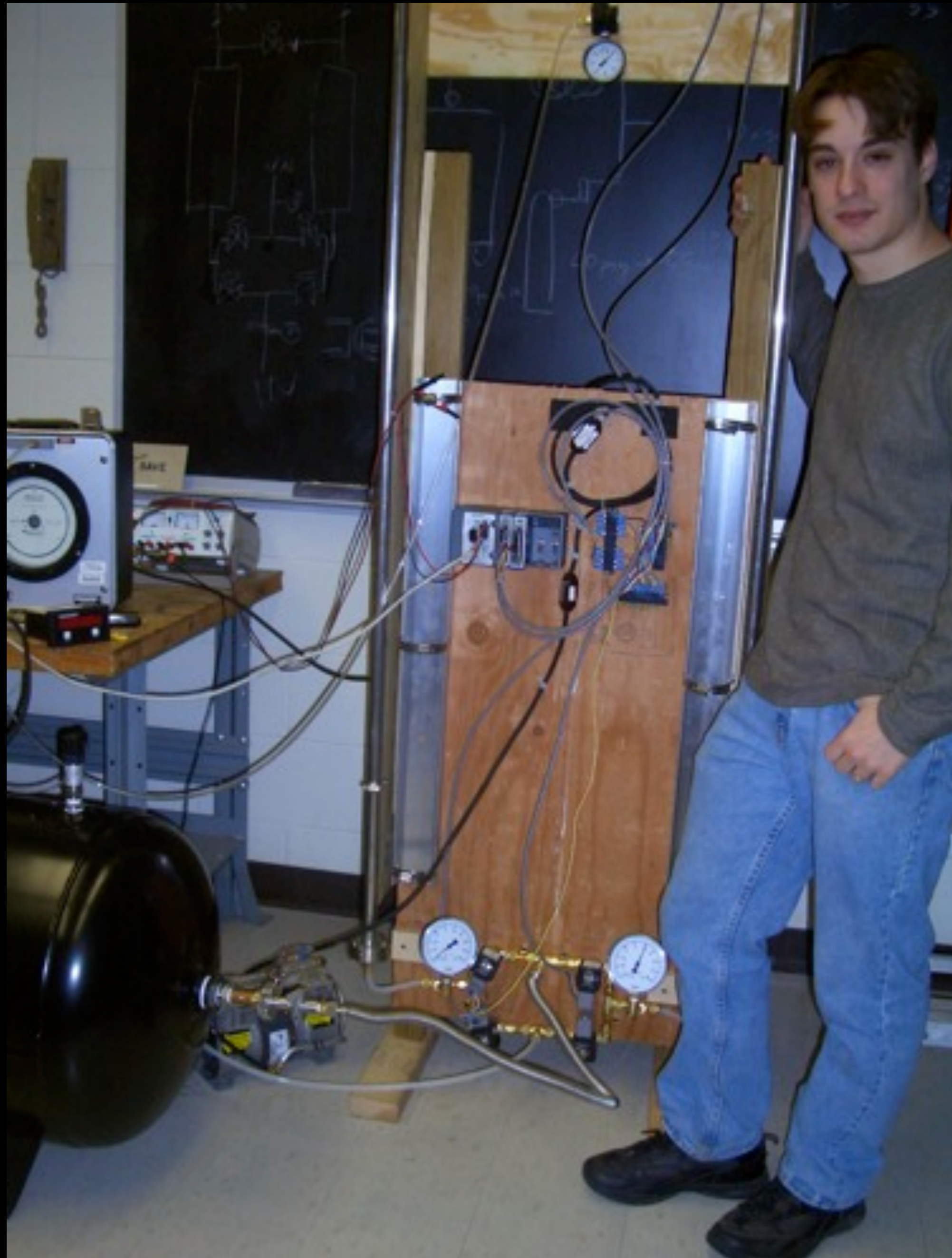
- Outer vessel almost built, delivery to SNOLAB Nov. 09
- Inner vessel construction started, delivery to SNOLAB early 2010
- Estimated construction completion mid 2010

How much do we need to discriminate?





- The full ^{39}Ar ($\tau_{1/2}$ 269 y, Q 565 keV) rate is 1 Bq/kg ~3x10^9 decays/100 kg/y
- ~ 1x10^8 decays/100 kg/y to deal with
- PSD objective (projected for 50% recoil acceptance) for MiniCLEAN is ~ 1x10^{-9} or better
- But the Princeton group has found natural Ar underground reservoir depleted in ^{39}Ar by a factor 20 (Galbiati et al., J. Phys. Conf. Ser. 120 (2008) 042015)



← Prototype Purification Plant at Princeton

Sampling gas field in the West

↓

All across the West: Texas, New Mexico, Colorado, Kansas

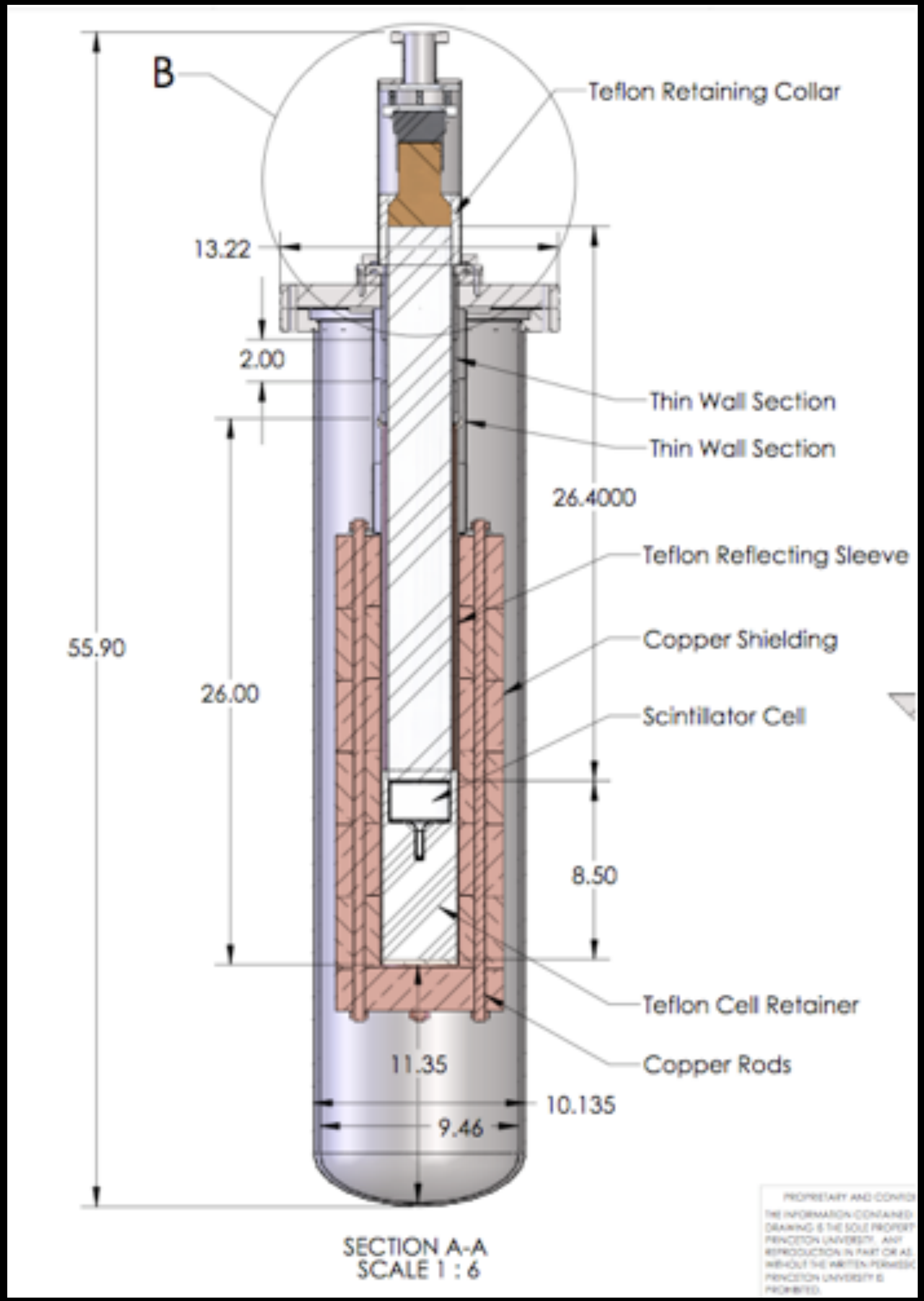
Sources Viable for Large Scale Production

	National Helium Reserve	Doe Canyon Complex
^{39}Ar	<50 mBq/kg	<40 mBq/kg
Depletion	>20	>25
Production capacity	30 tons/yr	>10 tons/yr

Measurements of low levels of ^{39}Ar

- Single phase ~1 kg Ar liquid scintillator
- Long light pipe to Room Temp PMT
- Internal Cu shield. External Pb shielding not shown
- Measure ^{39}Ar spectrum.
- Goal: <1 mB/kg (0.1% atm.)

Inner Tube



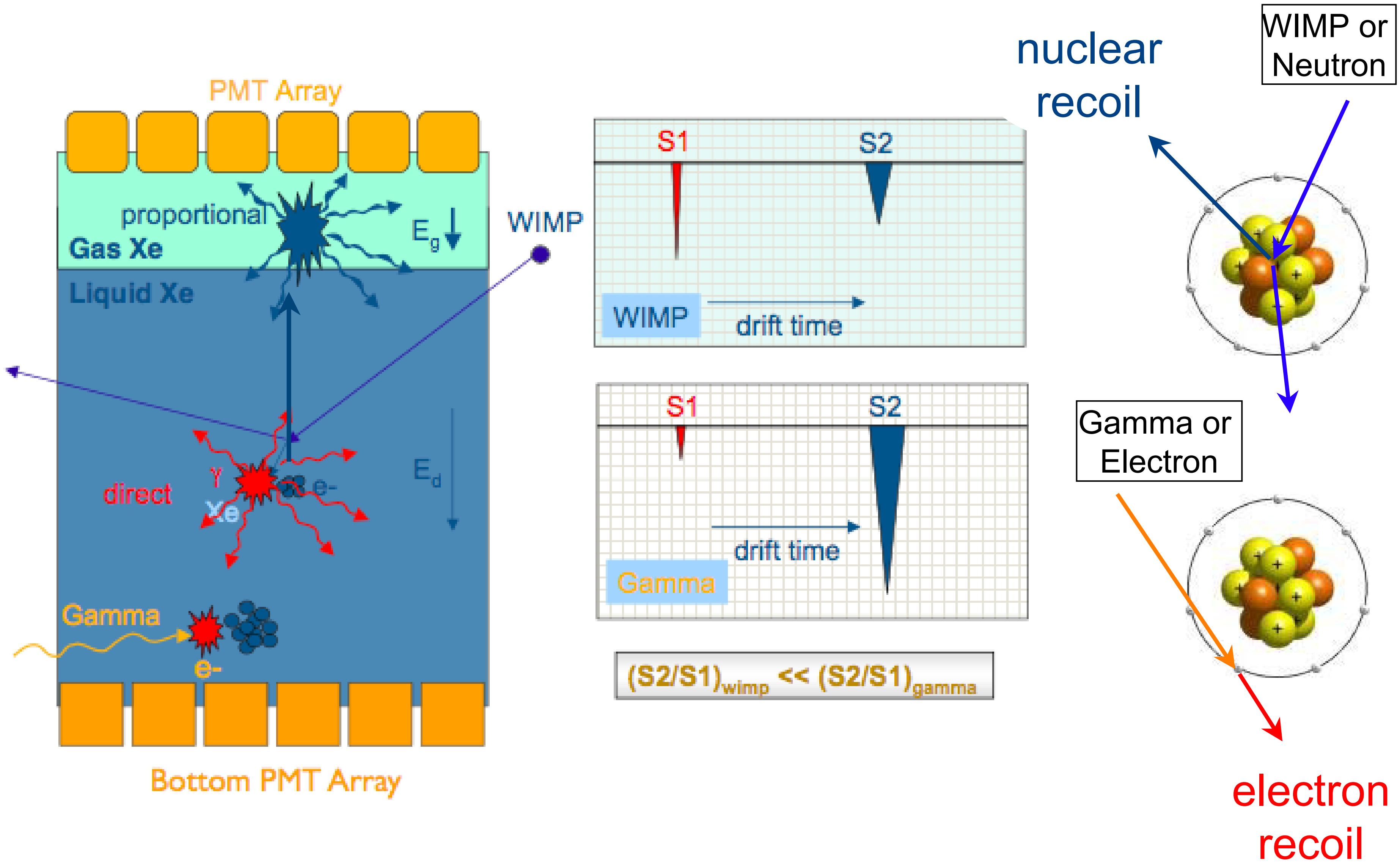
Cryostat with Inner Tube and internal Cu shield

Princeton Prototype Plant for Industrial Scale Production: Achieved 0.5 kg/day

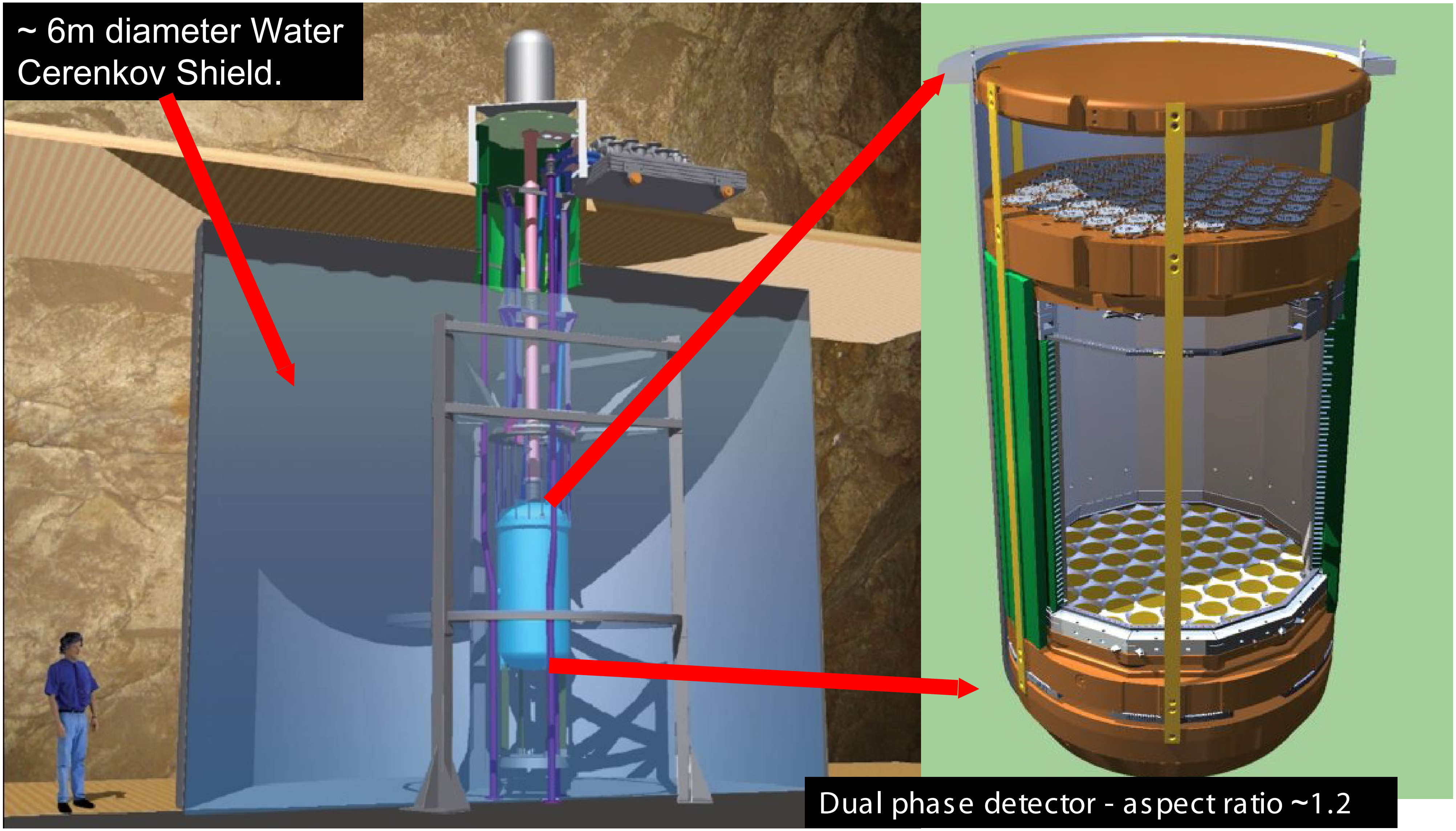
Depleted Ar Prodution Outlook

- R&D completed this summer with deployment of cryogenic distillation
- Upgrade first stage to 2-kg per day in 2009
- Second upgrade to 20-kg per day in 2010
- Production costs below $400/kg
- Share DAr with DEAP-3600
- Cooperation with LNGS group towards 2nd generation 2-phase detectors

Two-phase xenon detectors



The LUX Detector



350 kg Dual Phase Liquid Xenon Time Projection Chamber, fully funded by NSF and DOE
2 kV/cm drift field in liquid, 5 kV/cm for extraction, and 10 kV/cm in gas phase.
122 PMTs (Hamamatsu R8778) in two arrays
3D imaging via TPC eliminates surface events, defines 100 kg fiducial mass

LUX-350 is a background-free experiment

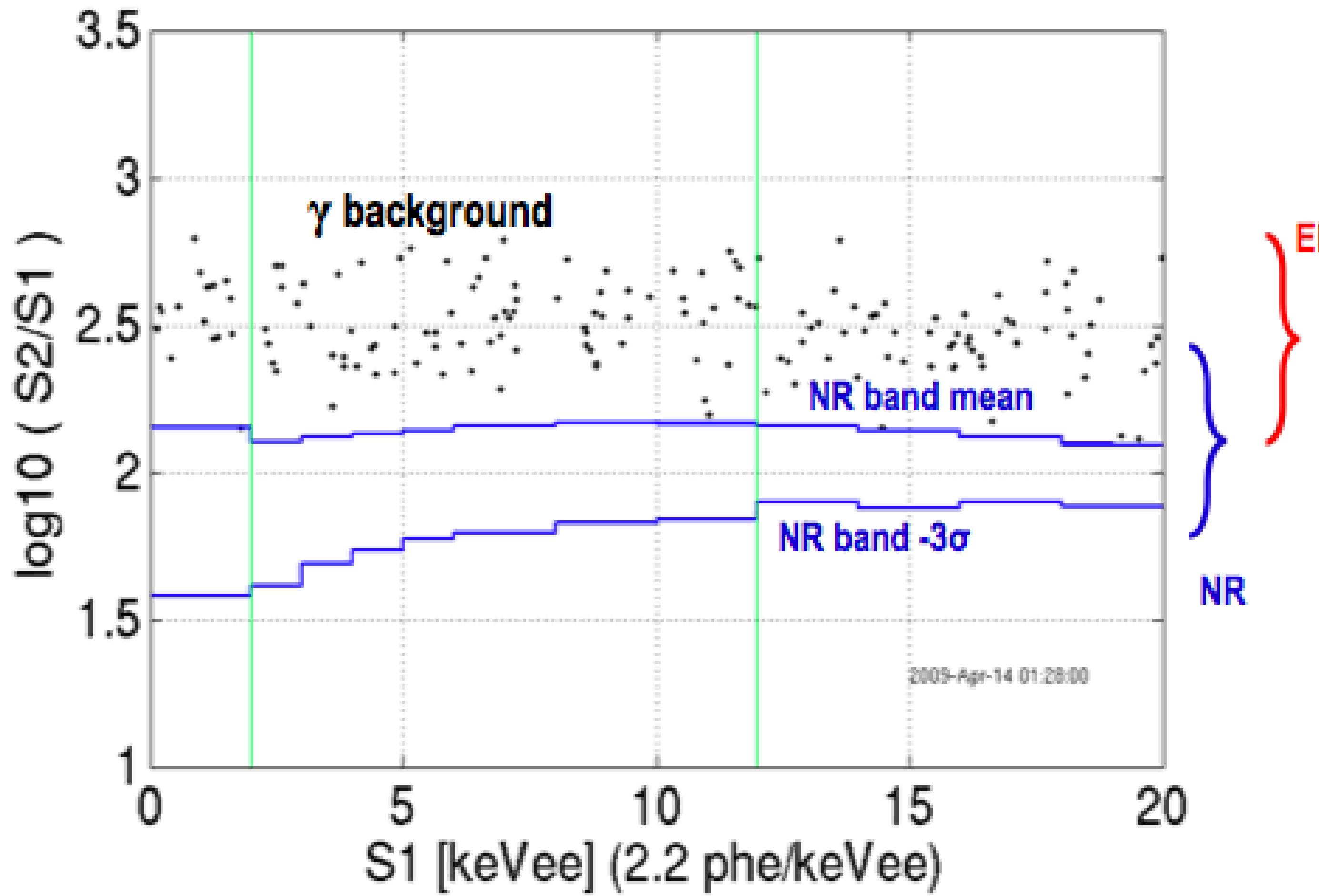
Self-shielding drastically reduces gamma-ray background in the fiducial volume
By defining a fiducial volume, gamma ray backgrounds drop enormously, scaling as exp[-L/Ls], where L is the size of the active volume, and Ls is the gamma ray scattering length. Electron recoil background ~2.6×10^{-4} events/keVee/kg/day (from simulations)

300 days acquisition

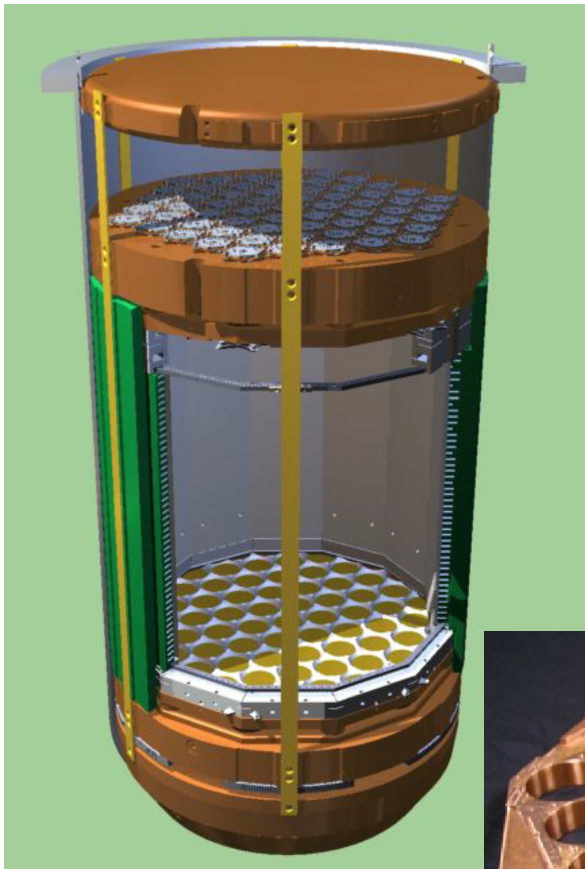
100 kg fiducial mass

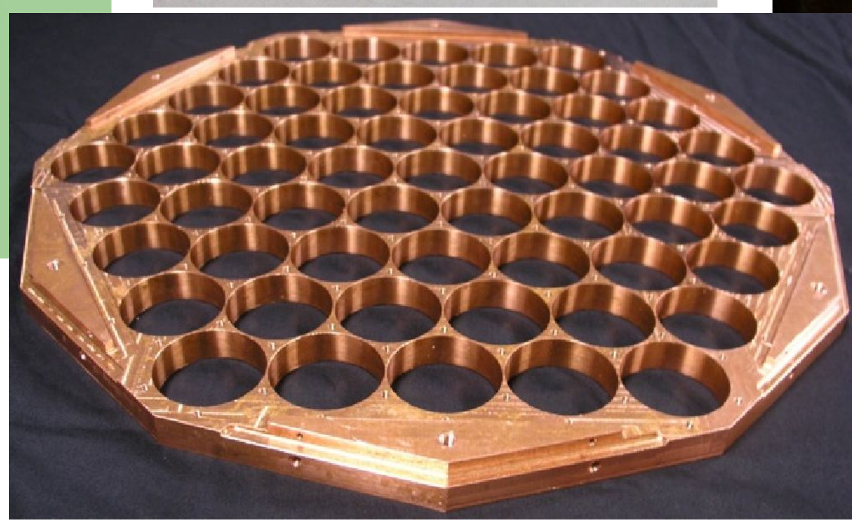
$L_{eff} = 0.19$

Using same
ER and NR bands
as XENON10

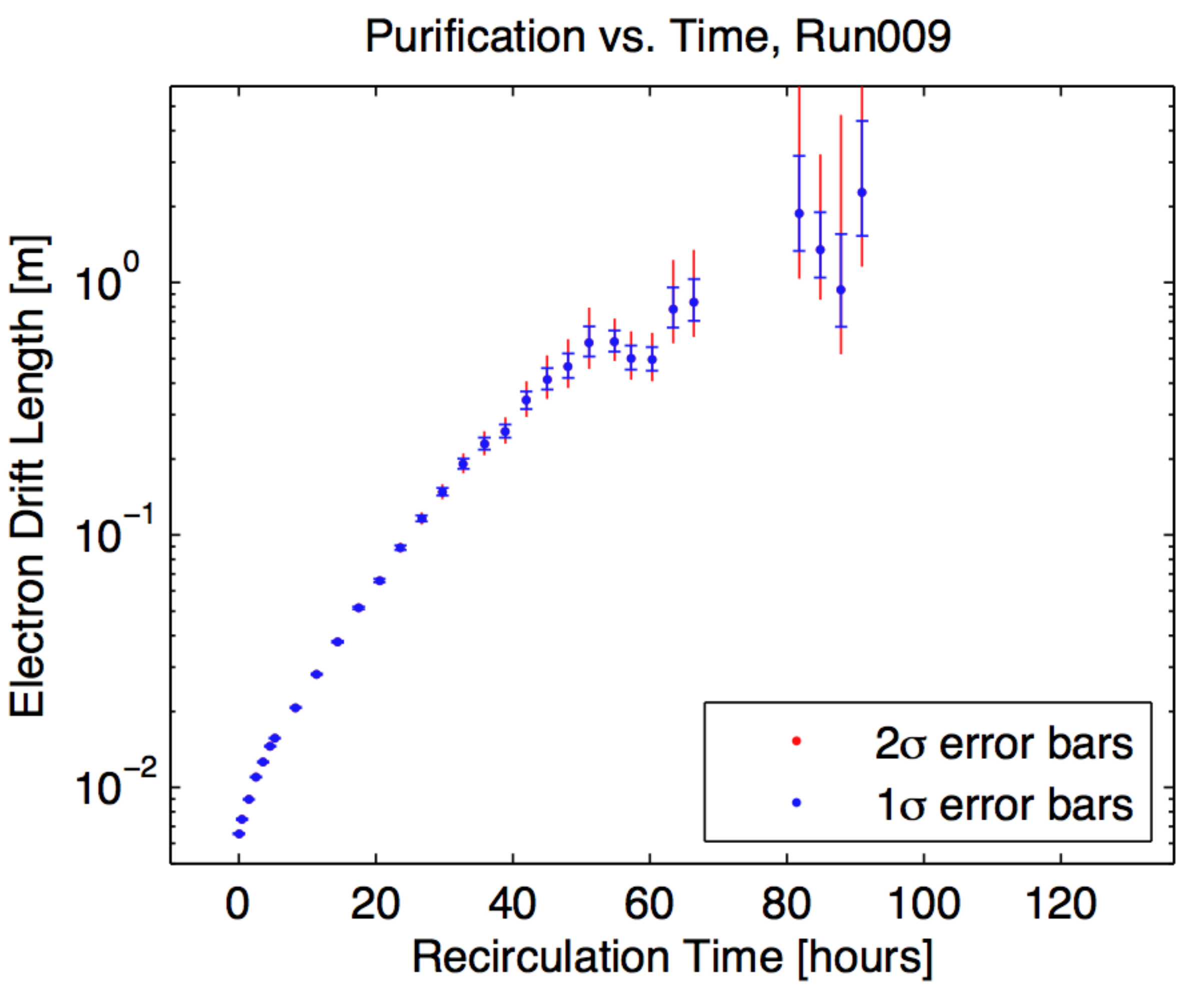


LUX Internals Assembly



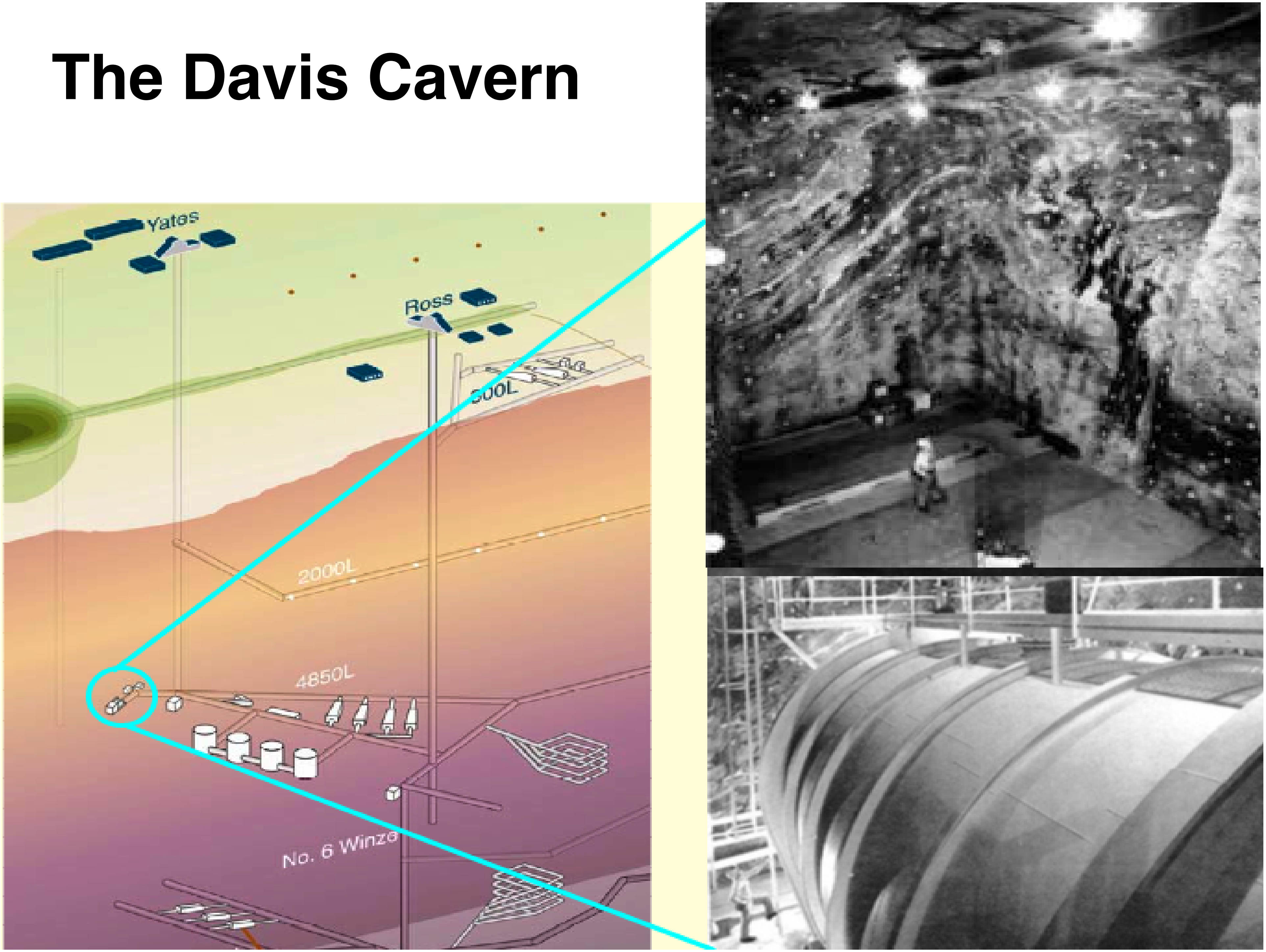


LXe purification tests in LUX 0.1

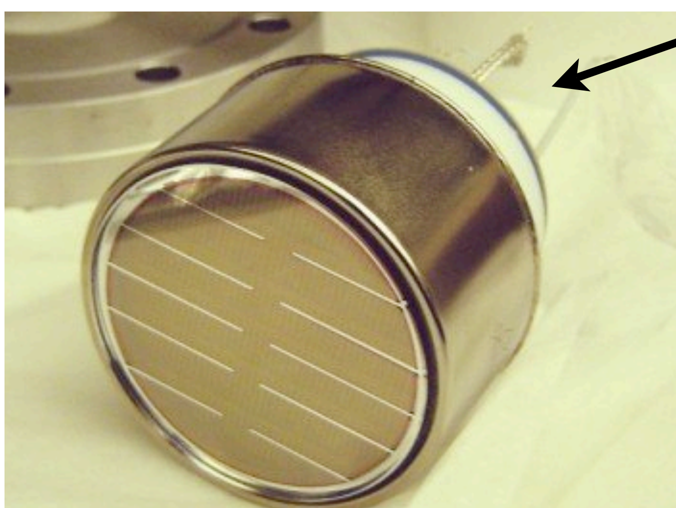


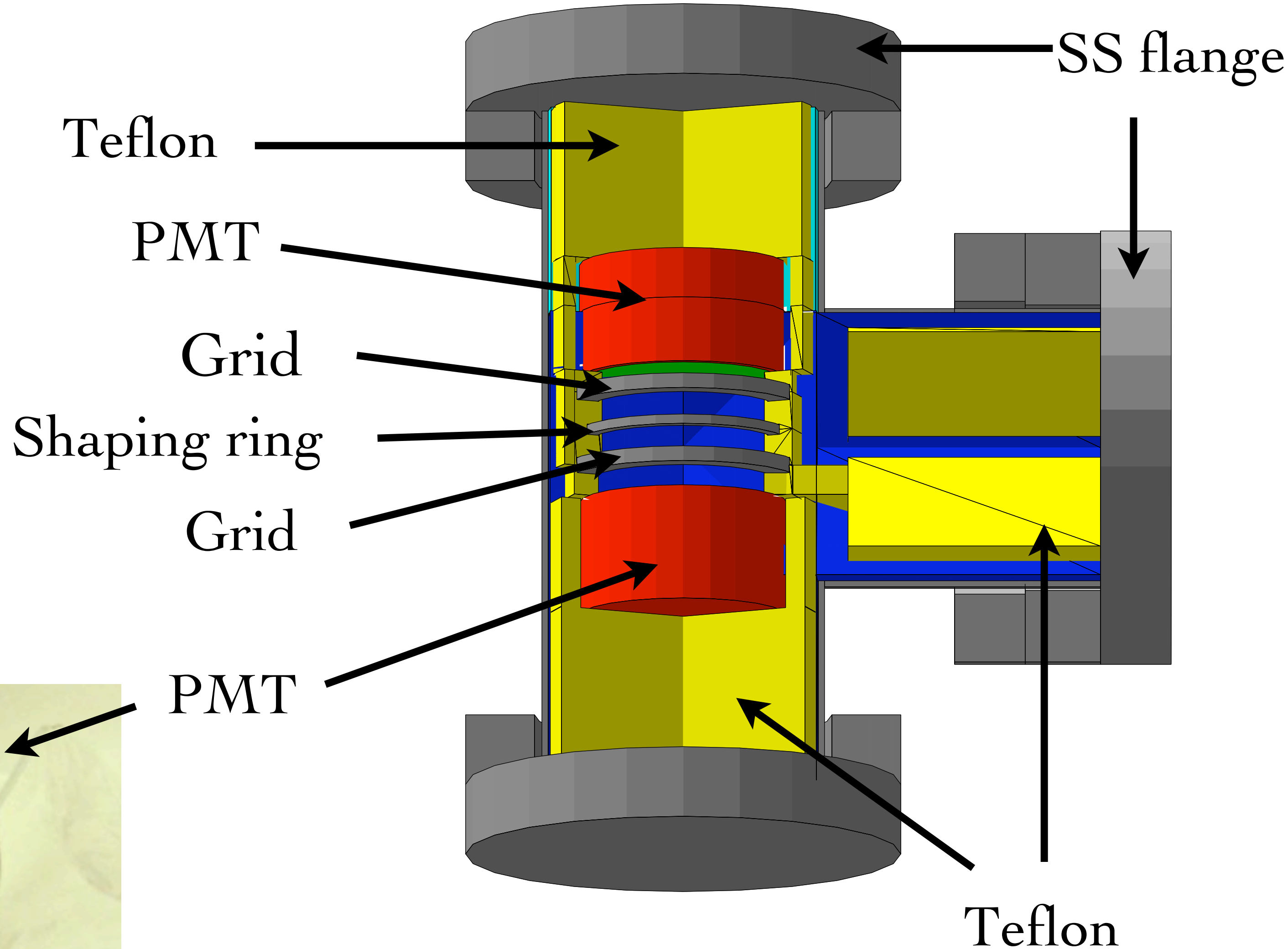
- ~9 hr purification time constant
- > 2 m electron drift length
- This is an order of magnitude faster recirculation than achieved before

The Davis Cavern

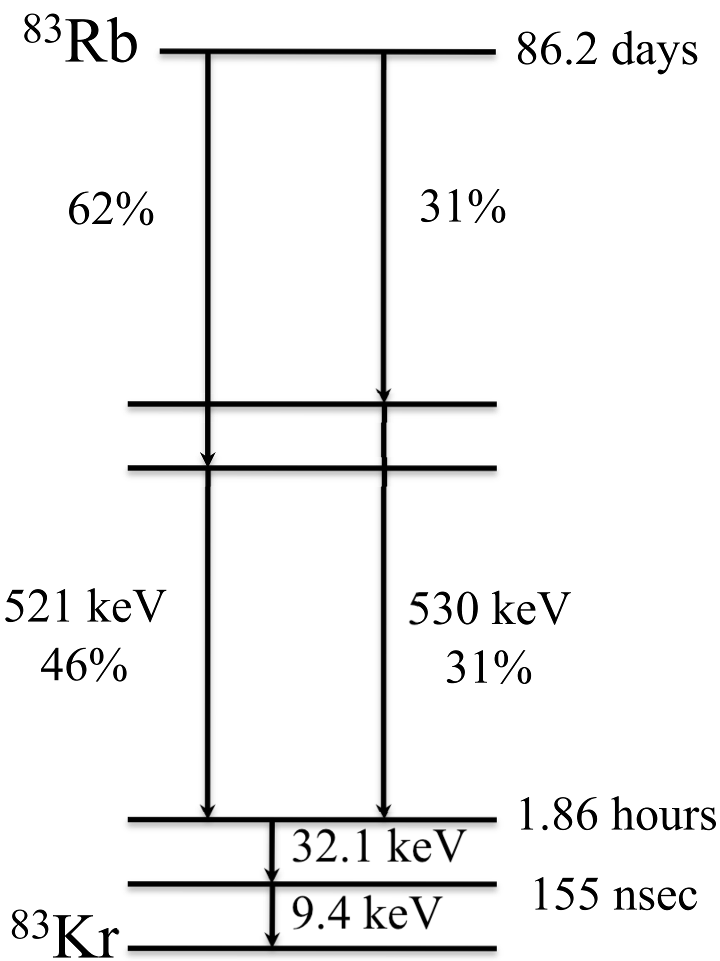


Liquid xenon cell

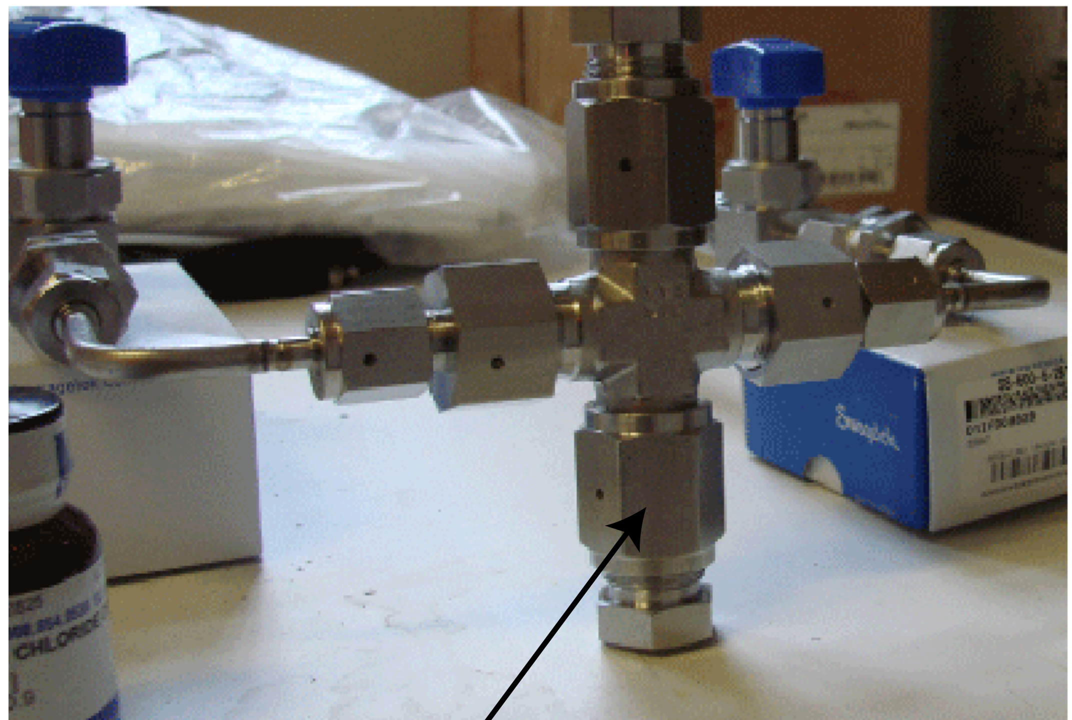




Kr-83m calibration source development at Yale

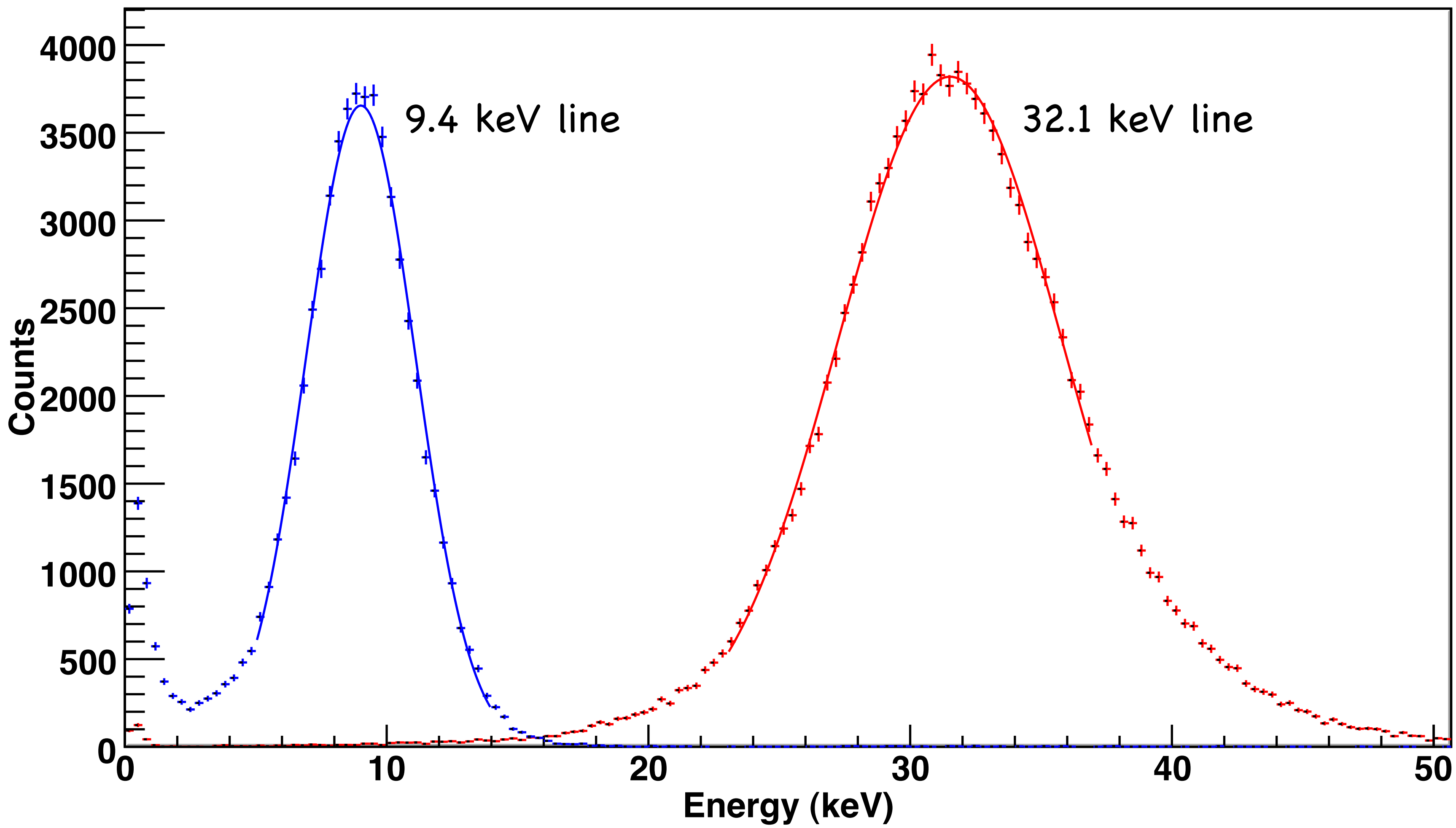


Rb-83 purchased in aqueous solution, then coated on zeolite. Continually emits Kr-83m, which can then be used to calibrate the liquid xenon detector response.



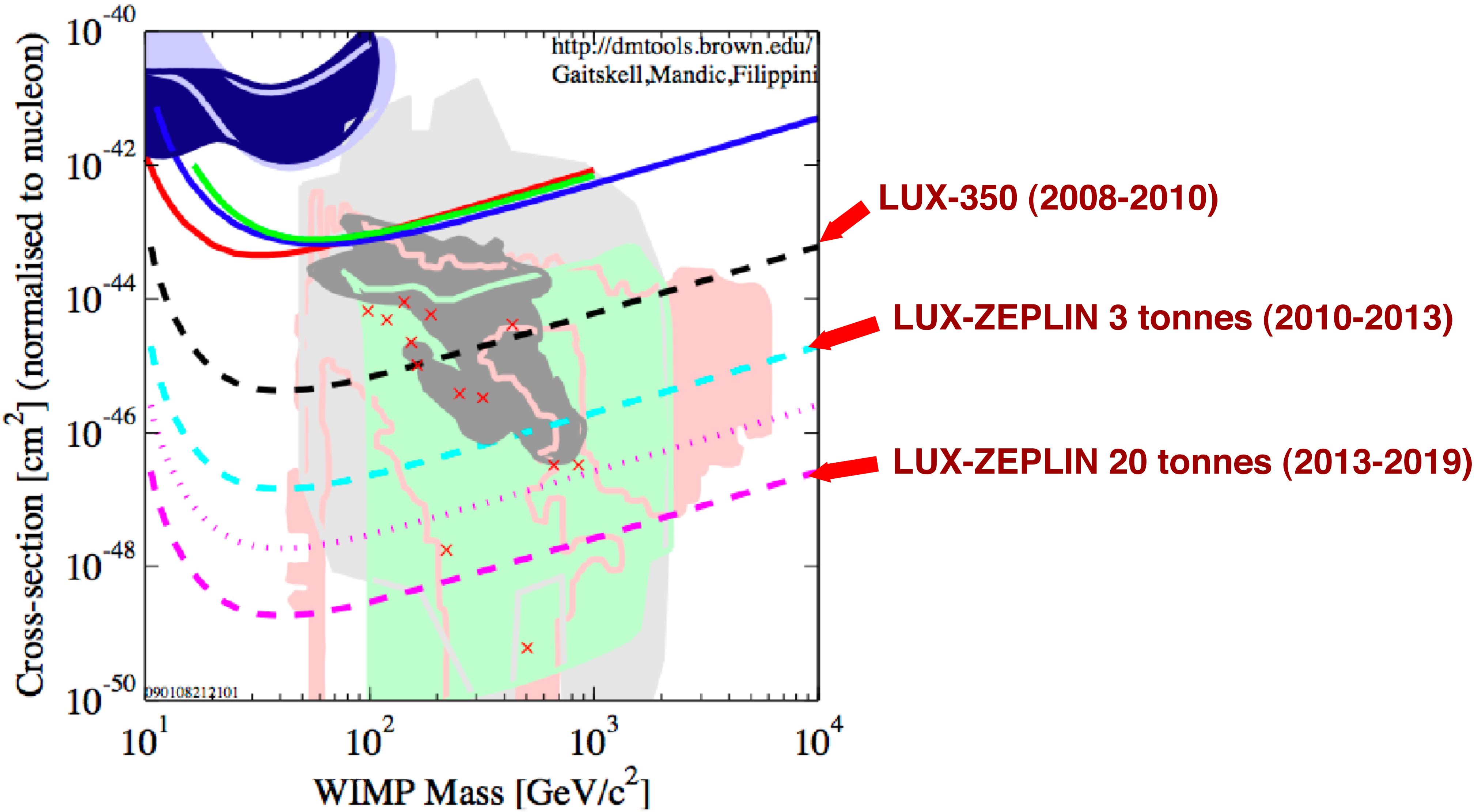
Rb-83 adsorbed on zeolite beads, in vacuum plumbing

LXe scintillation data from Kr-83m dissolved into LXe



L. Kastens et al, arXiv:0905.1766 (accepted to Phys. Rev. C)

Long Term Program

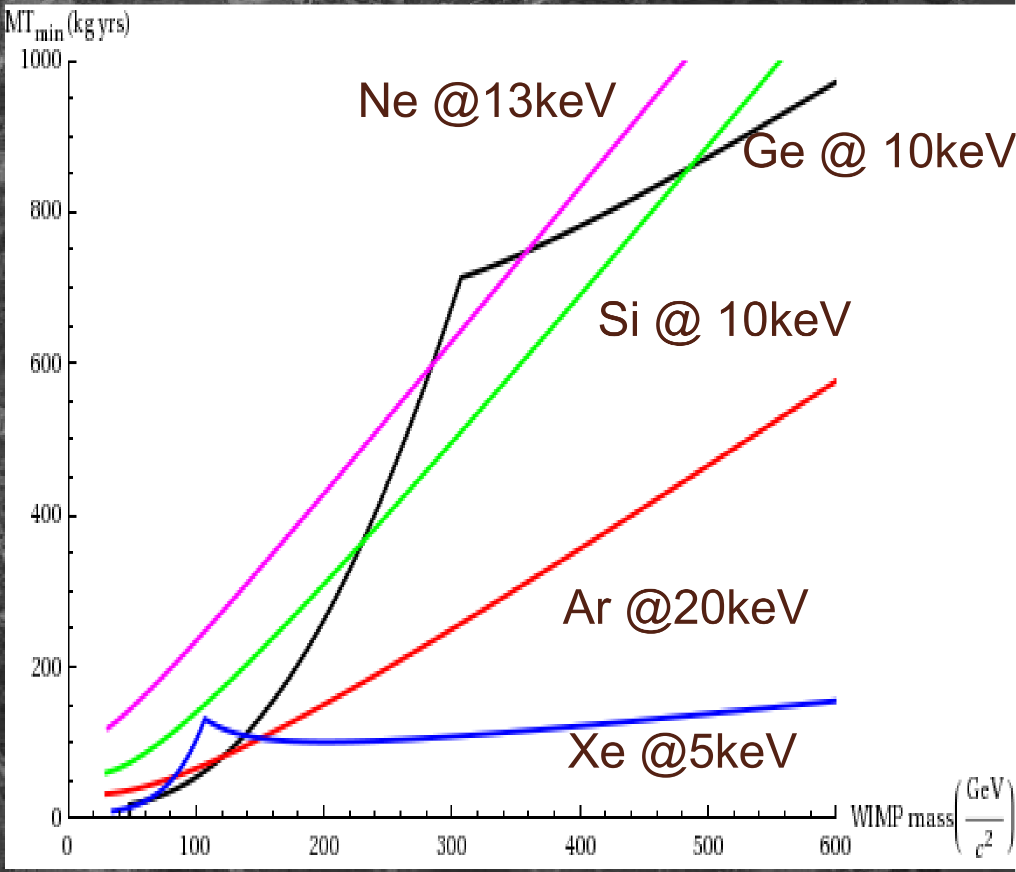


Sensitivity to Annual Modulation

To see the modulation the signal to noise ratio must be high enough (here noise is the constant component of WIMP recoil rate). We can define the s to n ratio as:

$$(s/n) = \frac{S_m(E_i, E_f)}{\sqrt{S_o(E_i, E_f)}}\sqrt{MT},$$

The exposure (Mass x Time) must be large enough to observe the modulation signal.



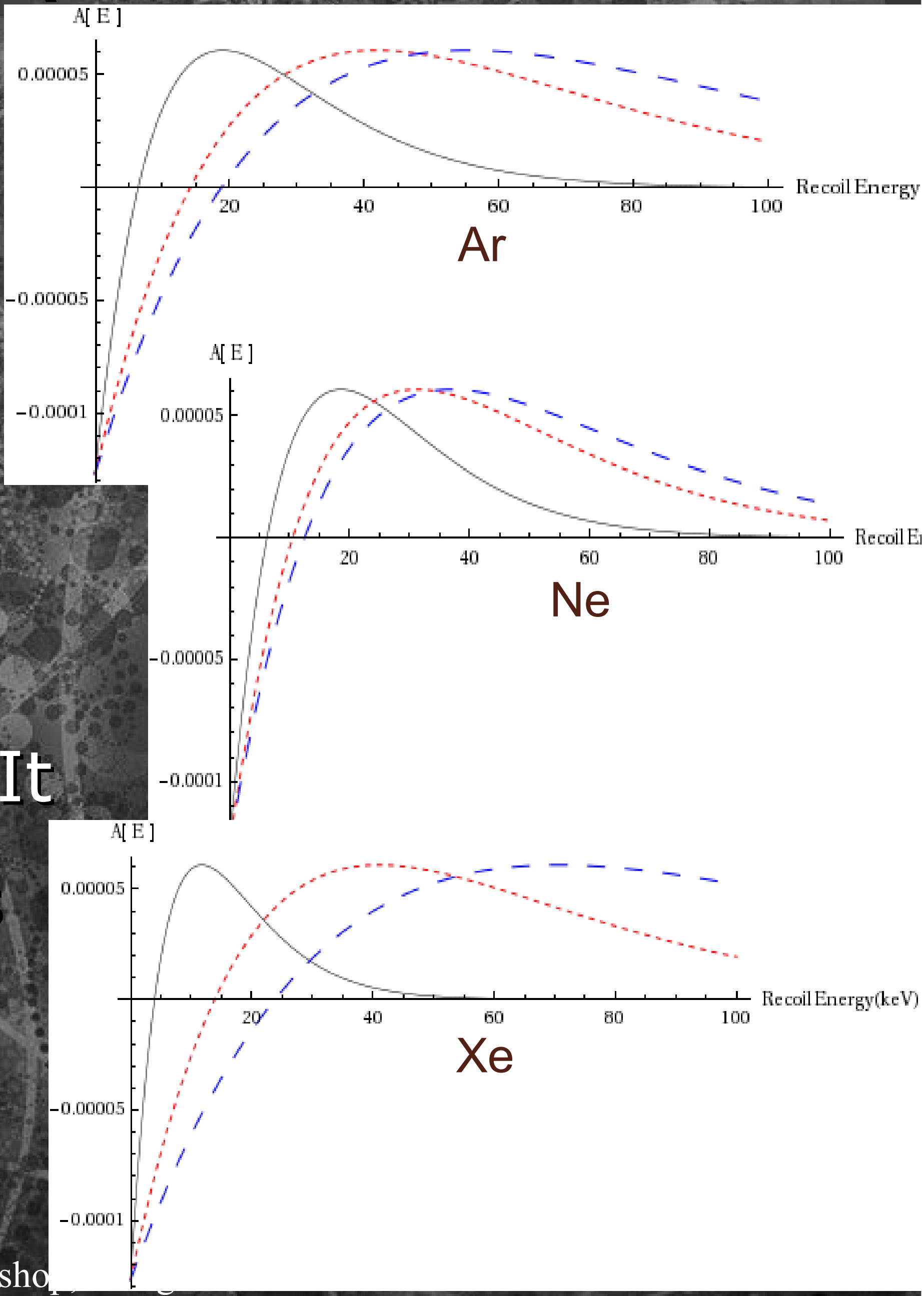
Calculating the Mean Inverse Speed η

Using the v_{obs} defined earlier one can calculate the η . We can assume it has a general form of:

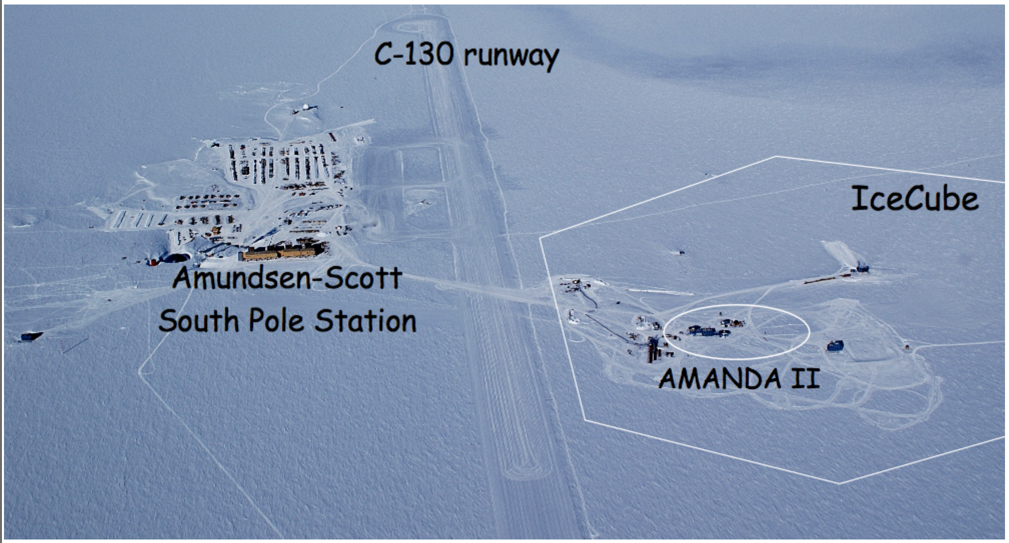
$$\eta(E,t) = B + A\cos(\omega(t - t_c)),$$

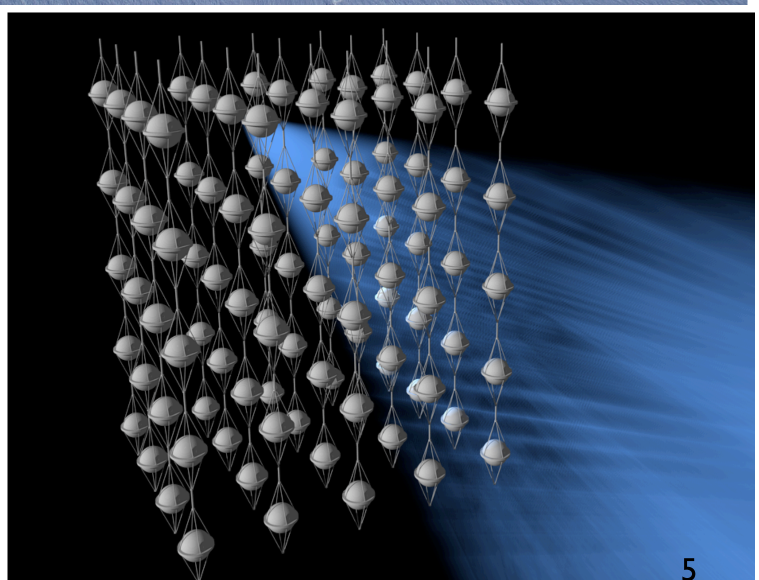
A will affect the amplitude of the annual modulation signal. It depends on E_R and WIMP mass

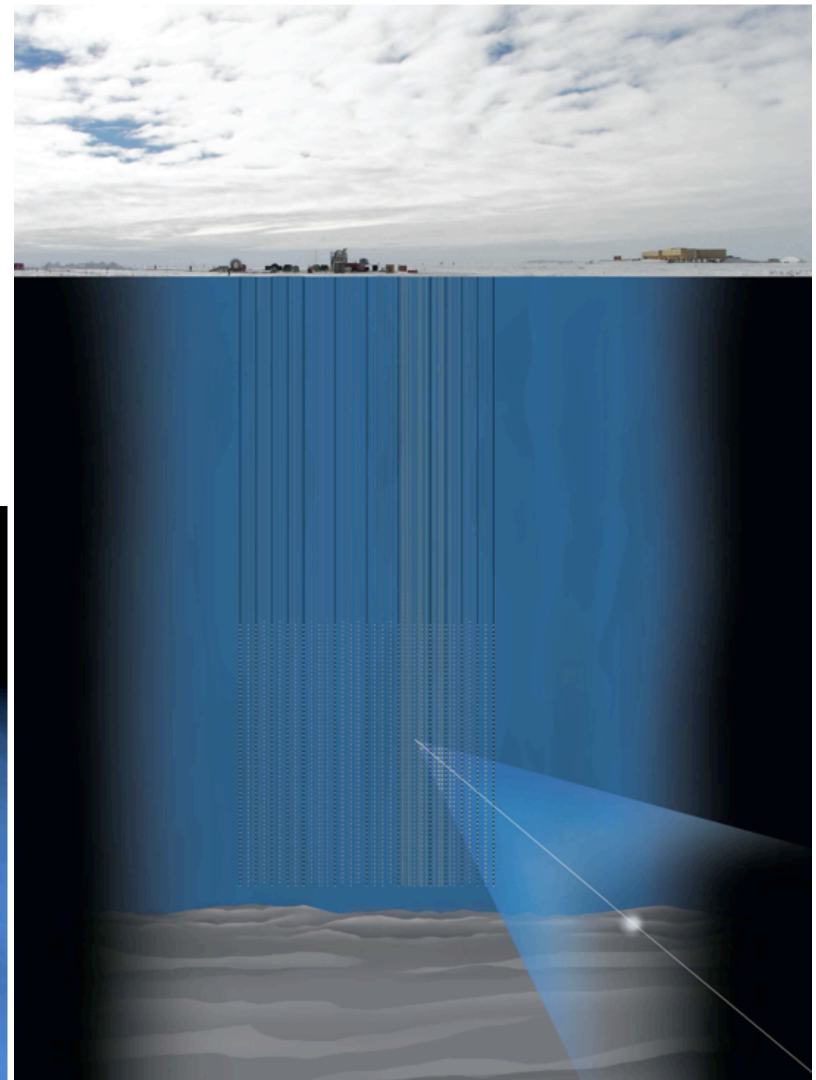
- **There is a critical energy E_c for which A changes sign.**



The IceCube Neutrino Observatory



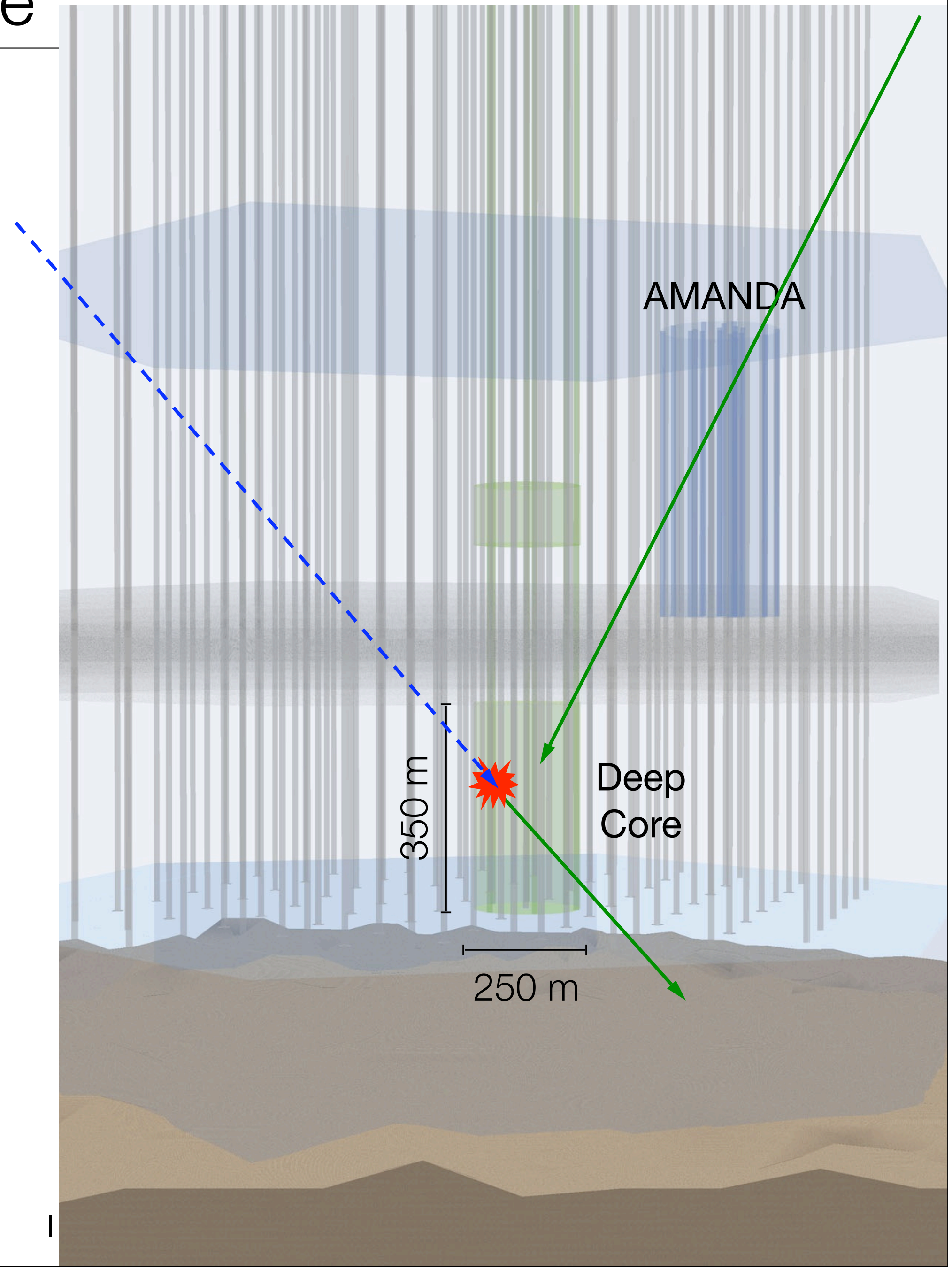




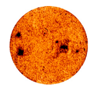
Future Potential - DeepCore

Atmospheric muon veto

- Top and outer layers of IceCube can be used to detect and veto atmospheric muons
- 3 rows of strings on all sides
- Atm. μ/ν trigger ratio is ~10^6
- Try to identify atmospheric muons entering Deep Core
- Down-going neutrinos accessible if they interact in the Deep Core volume
- Development continues, final sensitivities still TBD

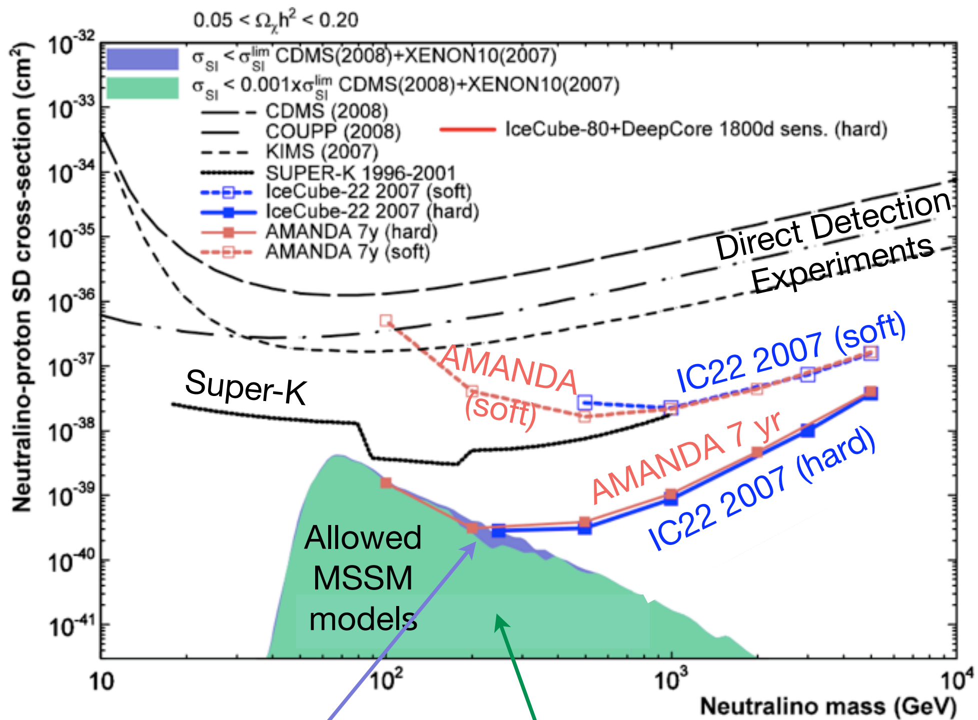


Past and Present Search Results

Solar WIMP search 

- Solar WIMP searches probe SD scattering cross section
    - SI cross section constrained well by direct search experiments
- Requires models of solar dark matter population distributions, annihilation modes
    - hard W^+W^-, soft $b\bar{b}$

Abbasi et al., *Phys. Rev. Lett.* **102**, 201302 (2009)
arXiv:0902.2460



Corresponding σ_{SI} within factor 10^3 of current direct limits

Corresponding σ_{SI} more than factor 10^3 beyond current direct limits

Summary

CDMS has current best spin-independent WIMP cross-section limit
- new limit soon!

DAMA modulated signal remains. New Princeton effort to attempt to duplicate result.

Noble liquids are up-and-coming detector technology - scalable to many tons! Interesting choices: Ar vs Xe, single-phase vs. 2-phase.

Ice-Cube DEEPCORE will have enhanced sensitivity to proton spin-dependent cross-section

Expect rapid progess in next few years.