The race to detect dark matter with noble liquids.

T. Shutt

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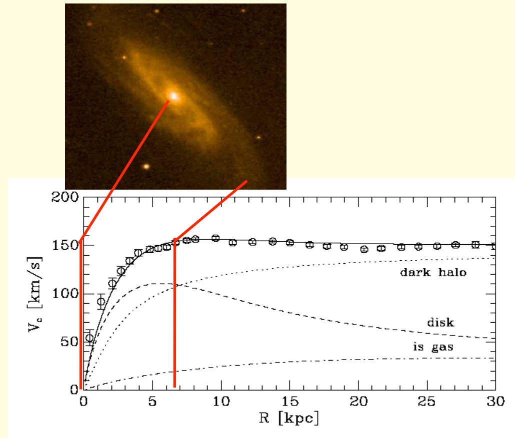
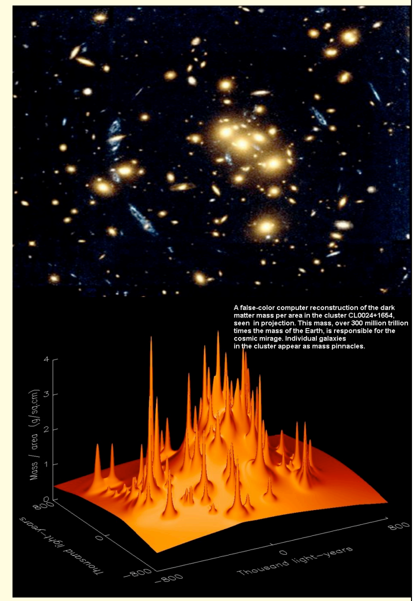
The Fact of Dark Matter

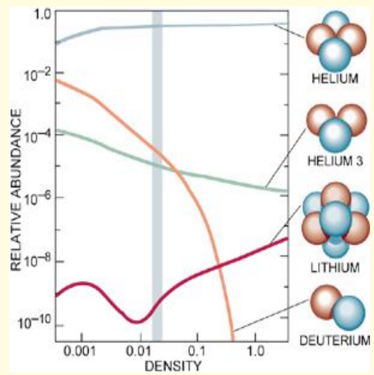
- Galactic rotation curves
- Galaxy clusters
  - Galaxy velocities
  - X-ray Temperature
  - S-Z effect
  - Lensing
- Big bang nucleosynthesis
- CMB anisotropy
- Large-scale structure growth

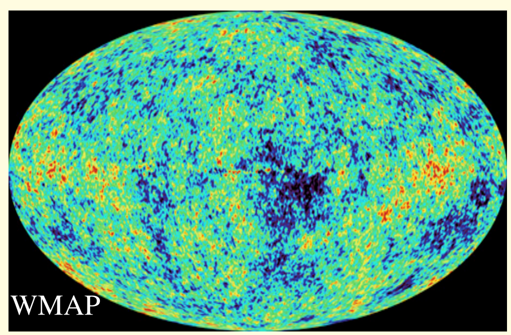
- Fraction of Ω, post WMAP:

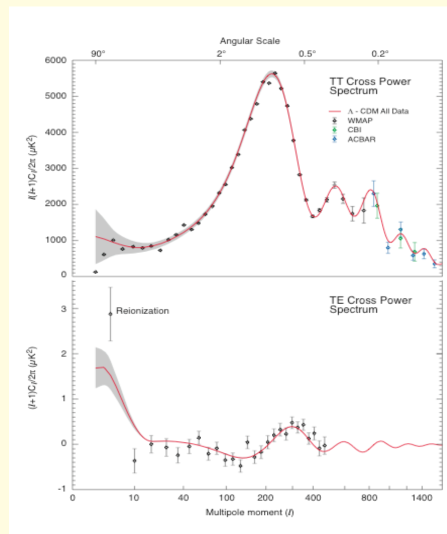
dark energy	≈ 0.73
dark matter	≈ 0.23
baryons	≈ 0.04 (≈ 0.004 in stars)
neutrinos:	$\approx 0.001 < \Omega_\nu < 0.015$
total	1











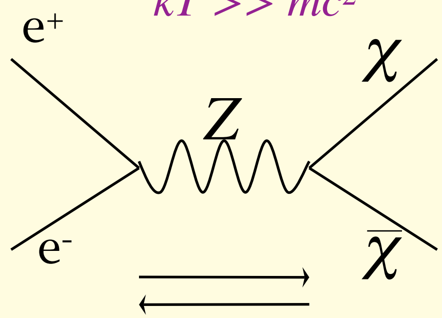
Possible forms of Dark Matter

- Particles:
  - Cold Dark Matter (CDM): non-relativistic in early universe. Rules out *neutrinos*.
  - Some sort of weakly-interacting particle.
  - Non-interacting particle.
- Planets, black holes?
  - How to form them *before* BBN, CMB last-scatter?
- No dark matter - modified gravity. (e.g, MOND)
  - Must match data on huge range of length scales.

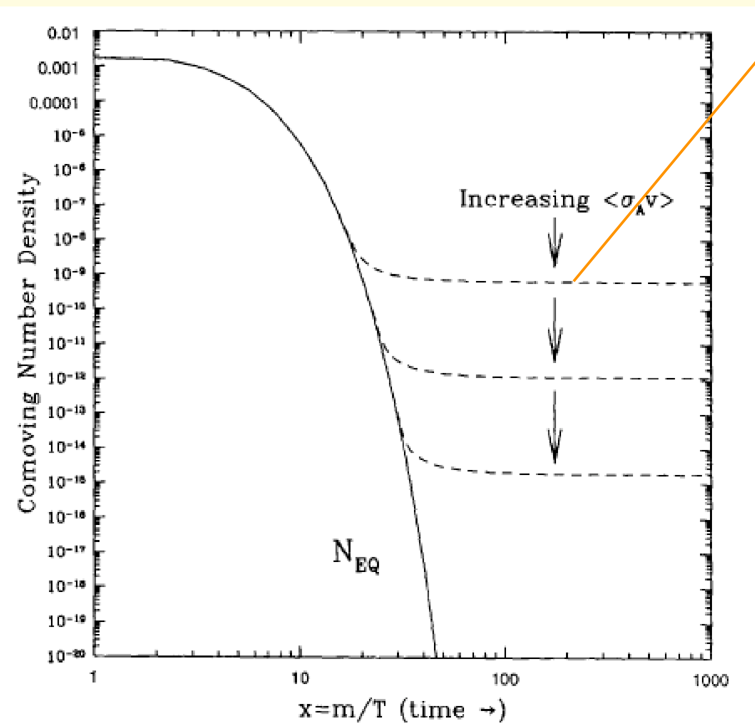
WeaklyInteractingMassiveParticleS

Matter-antimatter plasma,

kT >> mc²



$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_A v \rangle \left[(n_\chi)^2 - (n_\chi{}^{eq})^2 \right]$$



Freezeout:

universe too "thin" for annihilation

$$\Gamma = n_\chi \langle \sigma_A v \rangle = H$$

today:

$$\Omega_\chi h^2 \cong \frac{3 \times 10^{-27} \mathrm{cm}^3 / \mathrm{sec}}{\langle \sigma_A v \rangle}$$

With σ ~ weak

$$\langle \sigma v \rangle \sim \frac{\alpha^2}{m_W^2} \cdot 1 \sim \frac{\left(10^{-2}\right)^2}{(100\mathrm{GeV})^2} \sim 10^{-27}\, \mathrm{cm}^3/\mathrm{s}$$

$\Omega_\chi \sim 1$

New weak physics

=

dark matter!

Supersymmetry and WIMPs

- The lightest particle (LSP) usually taken to be stable (R parity).
- LSP must be weak to have avoided detection
- Neutralino - linear combination of neutral Zino, Bino and Higgsino- is perfect candidate for WIMP
- In big bang, supersymmetry almost guaranteed to generate *some* dark matter.

but WIMPS ≠ Supersymmetry

Detecting galactic WIMP dark matter

Dark matter "Halo" surrounds all galaxies, including ours.

Density at Earth:

$\rho \sim 300\ {}^{m_{\text{proton}}}\!/_{\text{liter}}$

$m_{wimp} \sim 100\ m_{proton}.$

3 WIMPS/liter!

Typical orbital velocity:

$v \approx 230$ km/s

~ 1/1000 speed of light

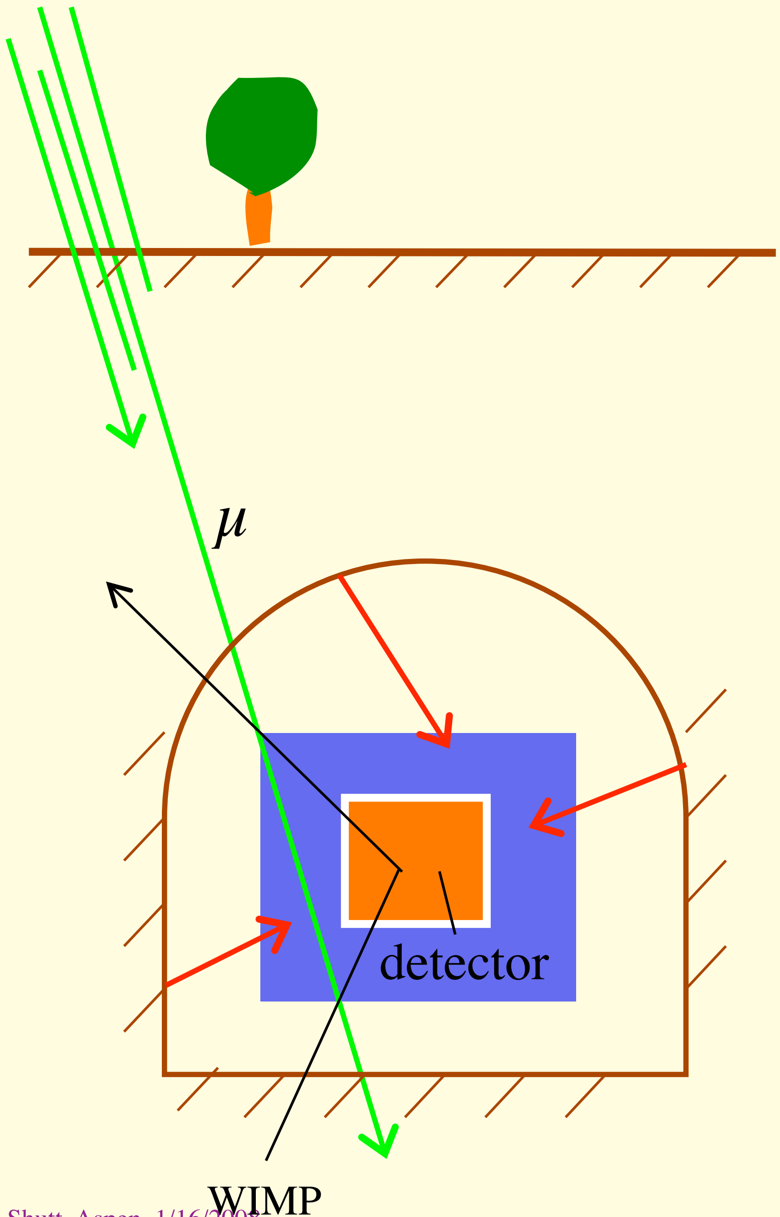
Coherent scalar interactions: A^2

Rate: < 1 event/kg/100day, or much lower

I will not talk about:

- Indirect searches:
  - WIMPs capture in Sun, annihilate to neutrinos, neutrinos detected in next-generation neutrino telescopes.
  - WIMPs annihilate to gammas at galactic center
  - WIMPs annihilate to e^+-e^- or p^+-p^-.
- Axionic dark matter
- Self-interacting, strongly-interacting, warm, fuzzy, other dark matter.

Detecting rare events.



- Problem: radioactivity
  - Ambient: 100 events/kg/sec.
  - Pure materials in detector
- Shield against outside backgrounds
- Underground to avoid muons

Why Roman lead is special.

U, Th in rock: 2 ppm ≈ 10^7 decays/day/kg

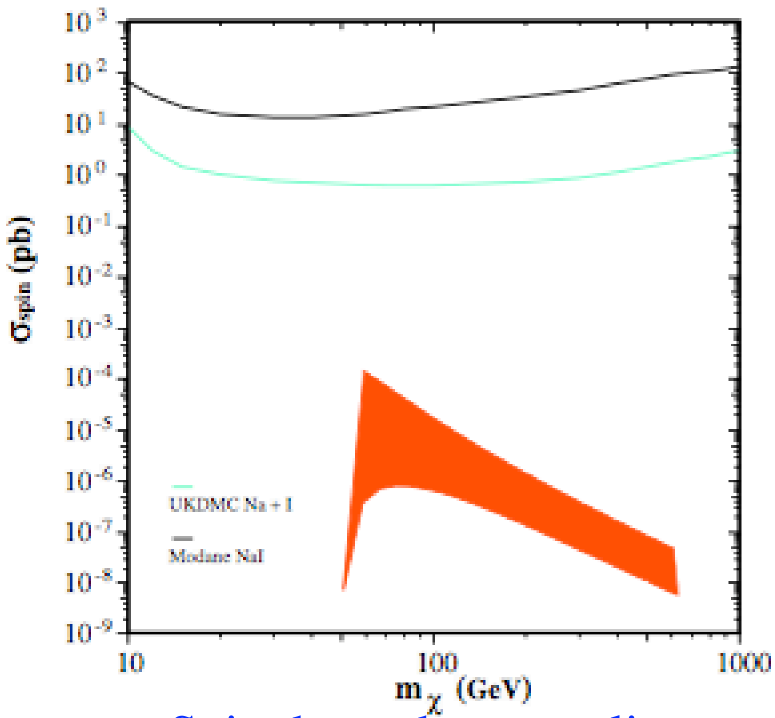
Crude smelting removes U, Th from Pb.

^{210}Pb at bottom of U decay chain remains.

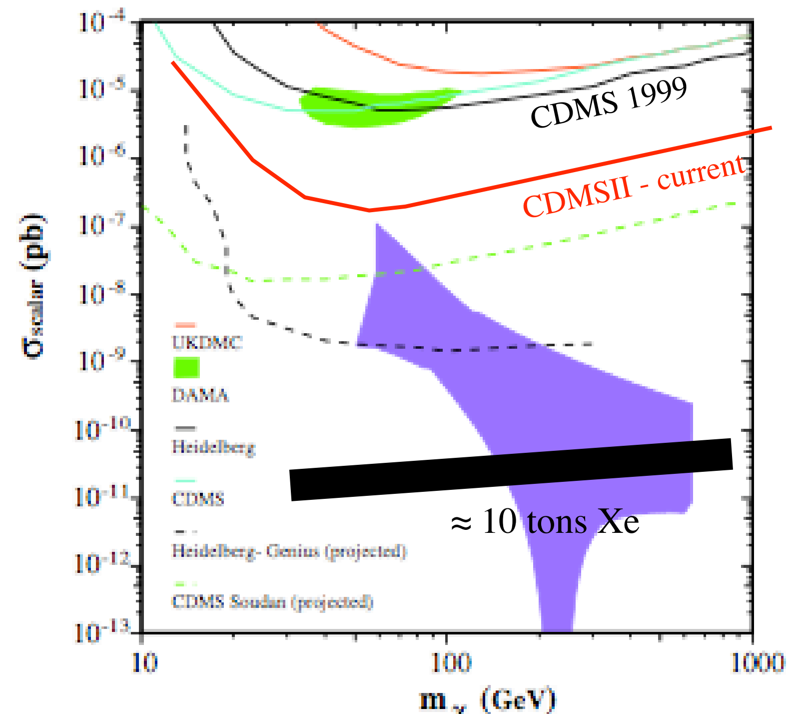
$T_{1/2}$= 22 years

A dose of cold water

J. Ellis, A. Ferstl, K. Olive, *Phys.Lett*. **B**481 (2000) 304-314



Spin dependent couplings

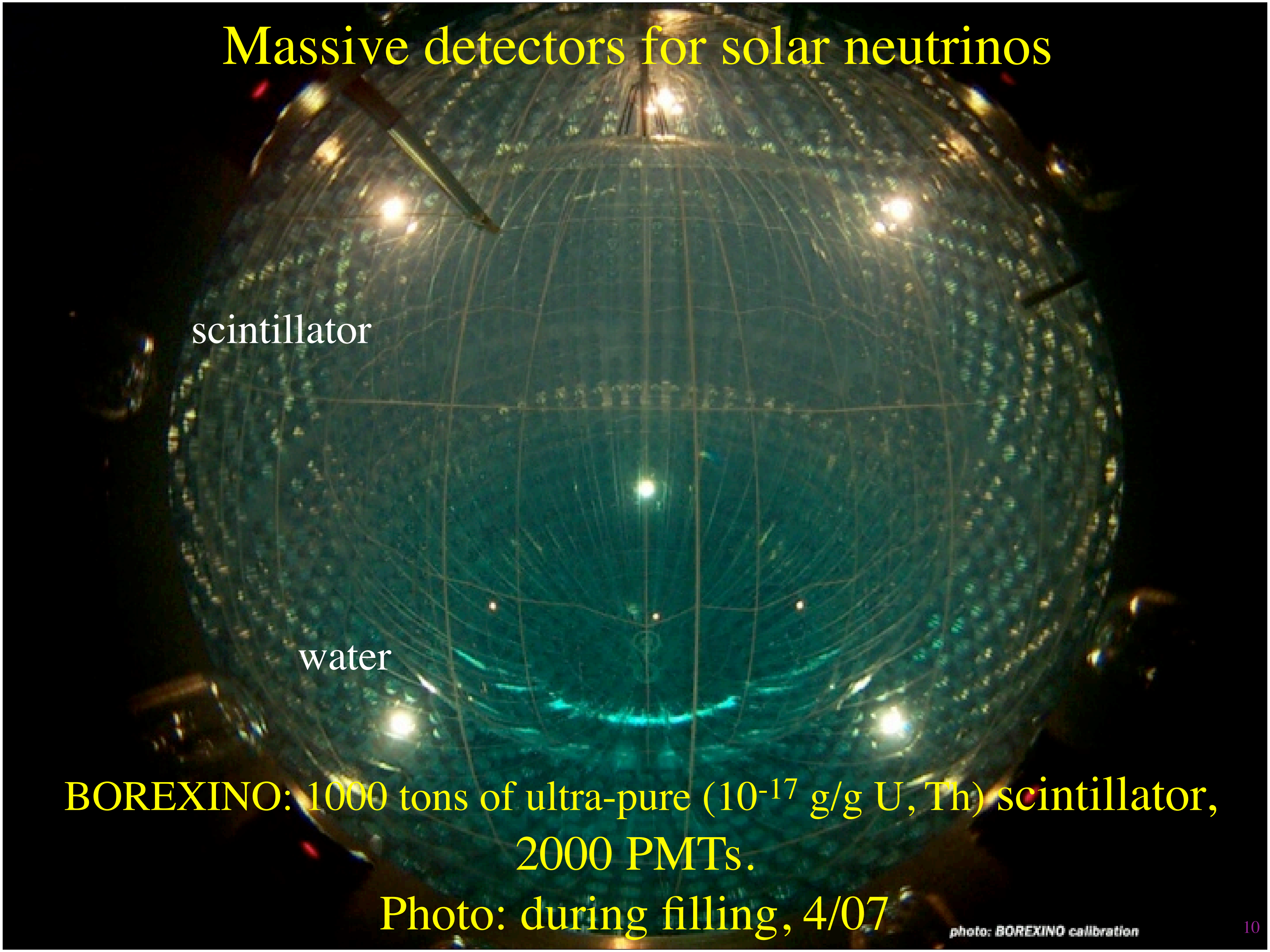


Spin independent couplings

a predominant $U(1)$ gaugino (Bino) composition for the LSP. Our results fall considerably below many of the possible predictions in the literature [10], and may discourage some faint-hearted experimentalists. However, we think they provide a realistic estimate of the target

We should not want our experimental colleagues to be too downcast by the long road they appear to have to cover in order to probe the minimal universal MSSM framework utilized here. For example, there are surely some supersymmetric models that predict larger

Massive detectors for solar neutrinos



BOREXINO: 1000 tons of ultra-pure (10^{-17} g/g U, Th) scintillator, 2000 PMTs.

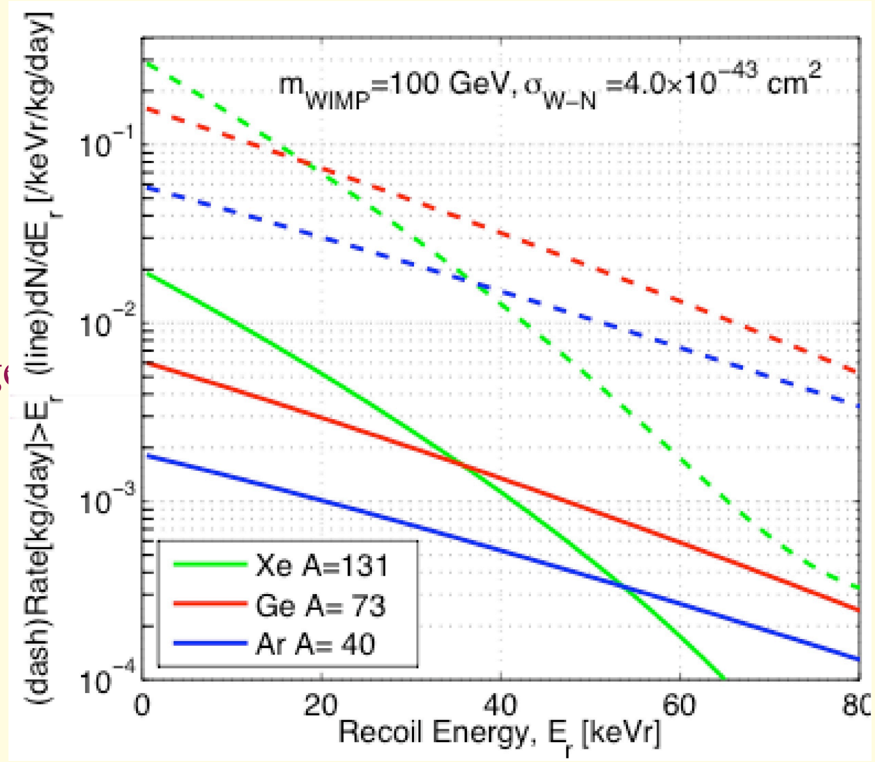
Photo: during filling, 4/07

Two approaches to low backgrounds

- Better living through physics: sophisticated detectors:
  (CDMS)
- Better living through chemistry: pure, large detectors:
  (Borexino)
- Can we get best of both?
  - Mass
  - Highly specific, sophisticated event information.

Liquid Noble Detectors

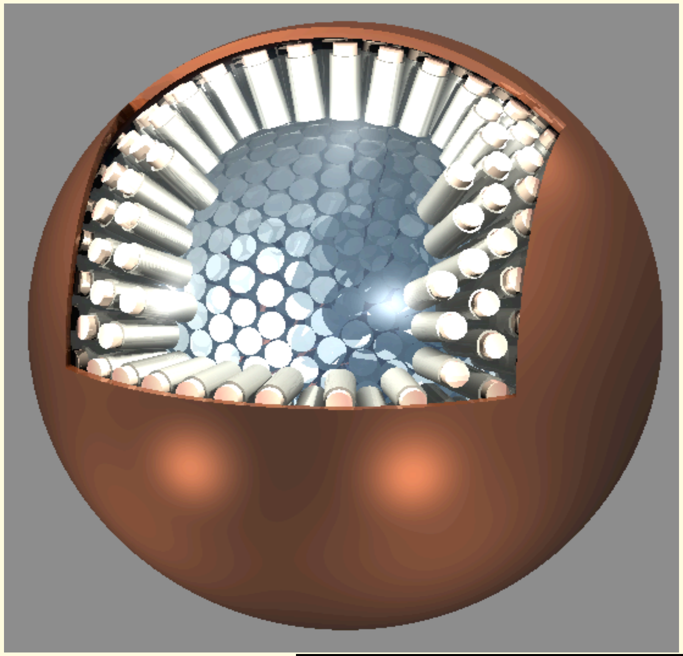
- Liquid target:
  - Readily purified
  - *Scalable to large masses*
- Liquid scintillator: ^{14}C fatal for dark matter
  - Even in petroleum - 10^{-18}
  - ^{14}C: U->*a* + rock -> n -> $^{14}N(n,p)^{14}C$
- Xe, Ar, Ne(?)
  - Xe: 165 K, λ=175 nm
  - Ar: 87.3 K, λ =128 nm, ^{39}Ar - 1 Bq/kg.
  - Ne: 27.1 K, λ =80 nm, bubbles -> slow charge
- Signals: ionization & scintillation
  - Small quanta:
    - $N_{ex}=E/W$, $W_{Ge} \approx 3$ eV, $W_{Xe} \approx 15$ eV
    - Cryogenic: E/kT at $T \sim 20$ mK
    - Rare gasses: High voltage
  - Single photons, electrons readily measured



Single Phase detectors

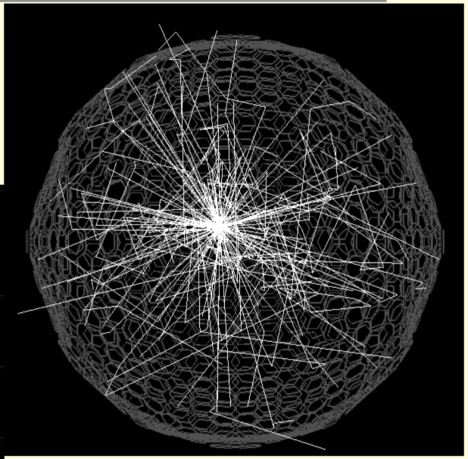
- Scintillation signal.
  - Cryogenic versions of Chooz, Kamland, Borexino.
- Rayleigh scattering:
  - Position reconstruction poor.
  - Need large volume to reject large rate of Rn-daughter background on surface.
  - Multiple-vertex events hard to distinguish.
- PMTs: highly radioactive
  - Self-shielding in large detector
  - LXe best for this

XMASS: 800 kg total, 100 kg fiducial



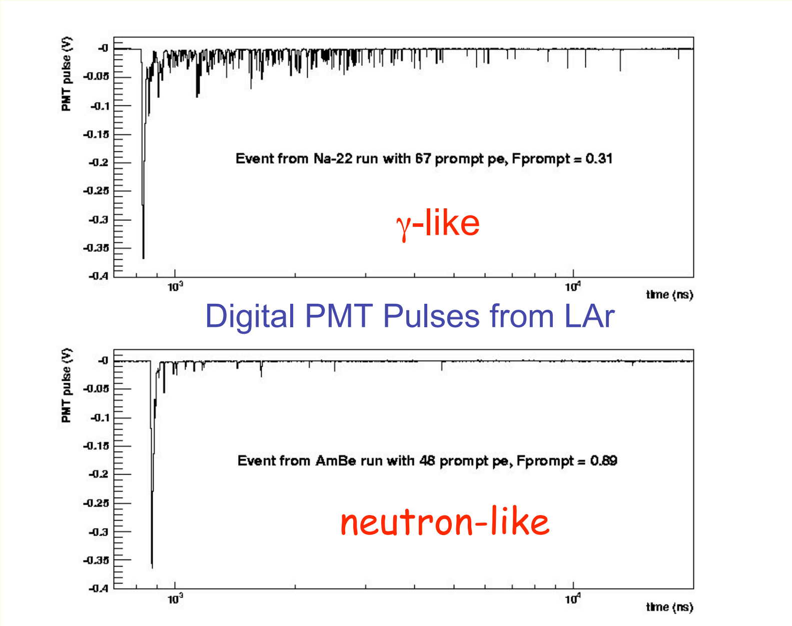
(Seidel, Lanou, Yao, 2002)

	λ (nm)	L theory (cm)	L exp (cm)
Ne	78	60	
Ar	128	90	66
Xe	174	30	30-50



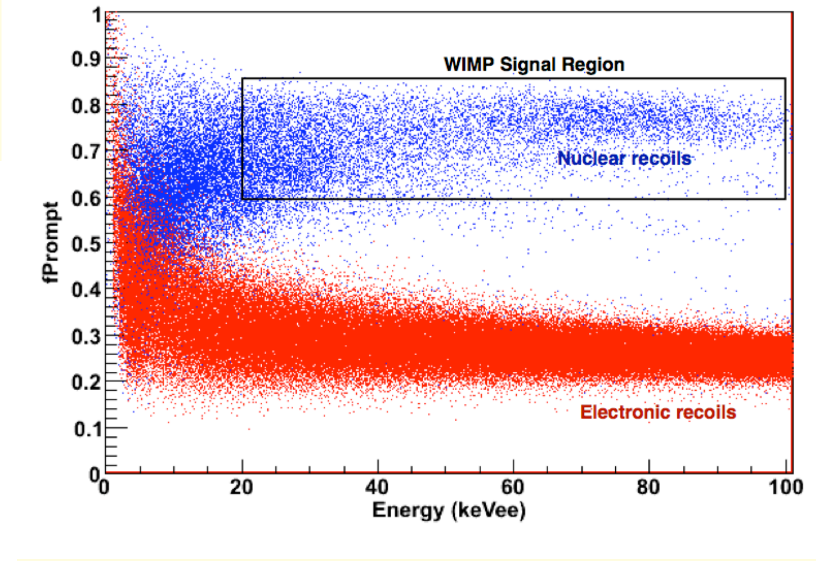
Scintillation pulse shape discrimination

- Scintillation from excimer state:
  - $Ar^* + Ar \rightarrow Ar_2^*$
  - Triplet (long lived)
  - Single (short lived)

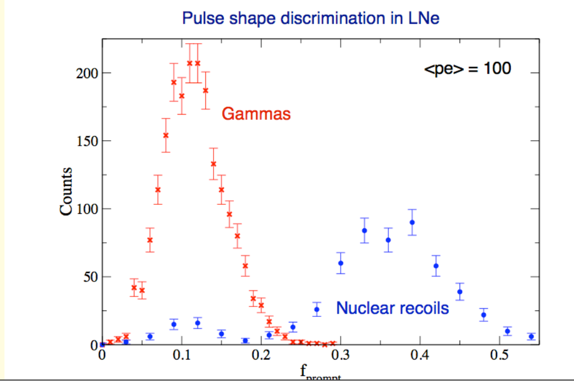


- Discrimination of electron recoil backgrounds:
  - Nuclear recoils don't populate triplet
  - No one knows why

Data: Mini-Clean (McKinsey/Yale)

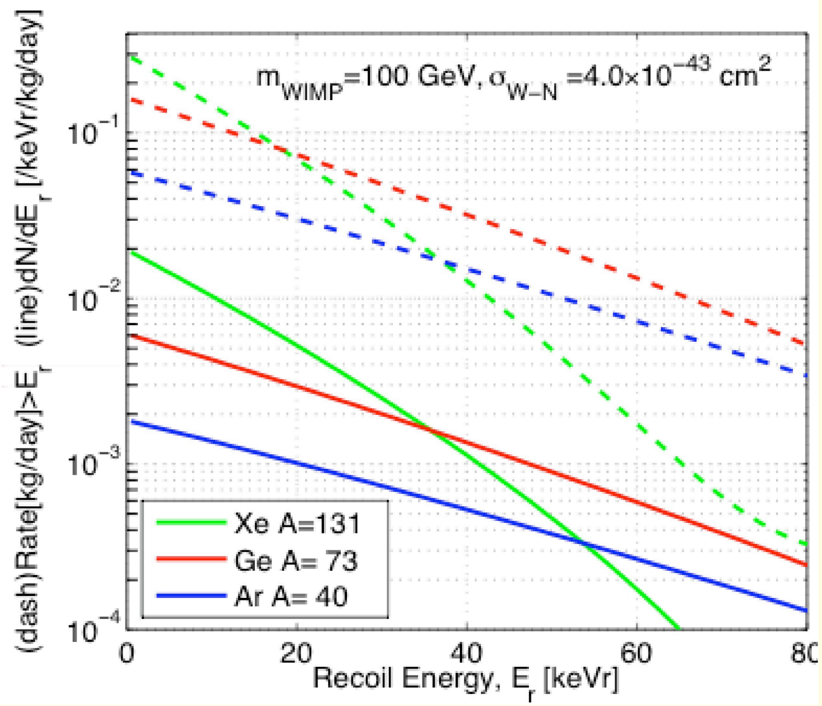


- Ar system by far most favorable



The Ar story

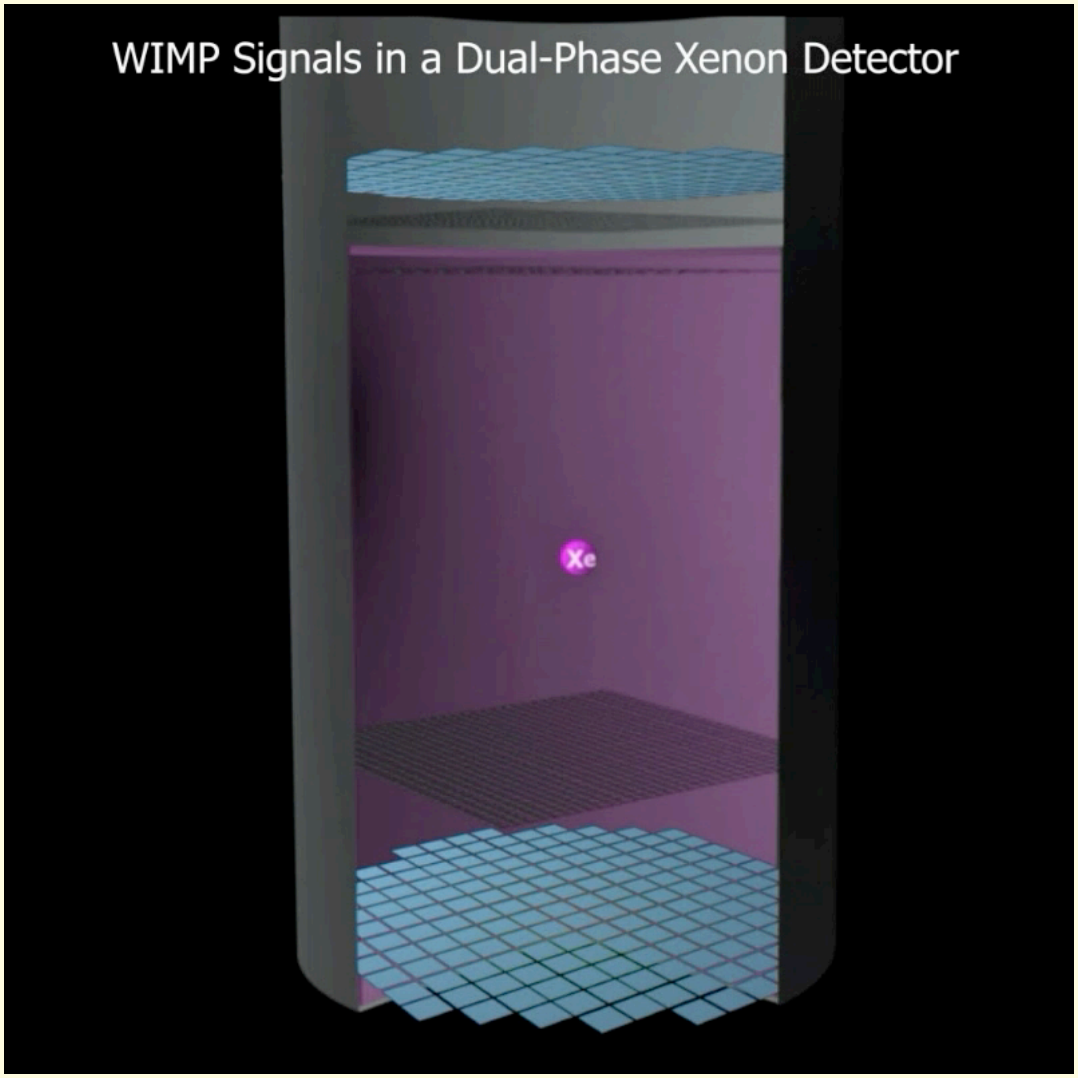
- ^{39}Ar, produced in the atmosphere, gives 1 Bq/kg background.
  - β decay, 269 yr half life, Q=565 keV.
  - On paper, experiment with 60 keVr threshold seems feasible.
  - At 60 keVr, ~ 30 worse than Xe.
- Pulse shape background discrimination from MC, is ~10^9 at 60 keVr.
  - Best measurements (WARP, DEAP/CLEAN) ≥ ~10^7 (WARP, CLEAN) at higher energy
  - Large mass needed.s
- Worldwide hunt for old Ar
  - Issue: ^{39}K(n,p)^{39}Ar
    - All ^{40}Ar from ^{40}K-> ^{40}Ar+e^++ν
  - He reserve
    - 20 reduction recently shown (Galbiati, WARP).
  - Antarctic lakes?



Dual phase time projection chamber

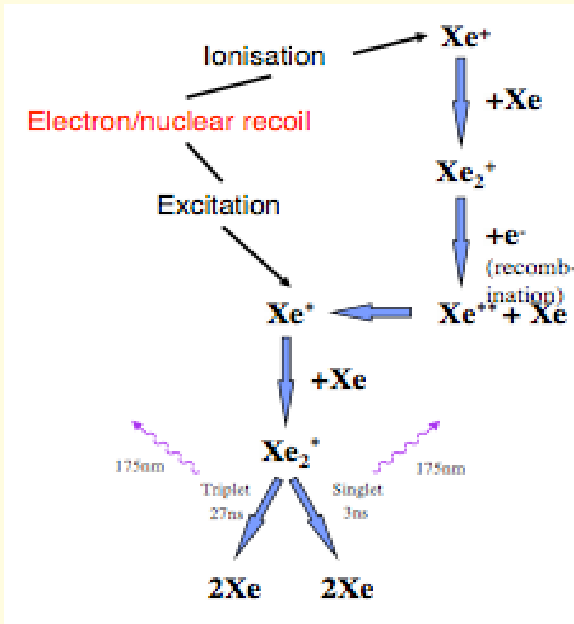
- Can measure single electrons and photons.
- Charge yield reduced for nuclear recoils.
- Good 3D imaging
  - *Eliminating edges crucial.*

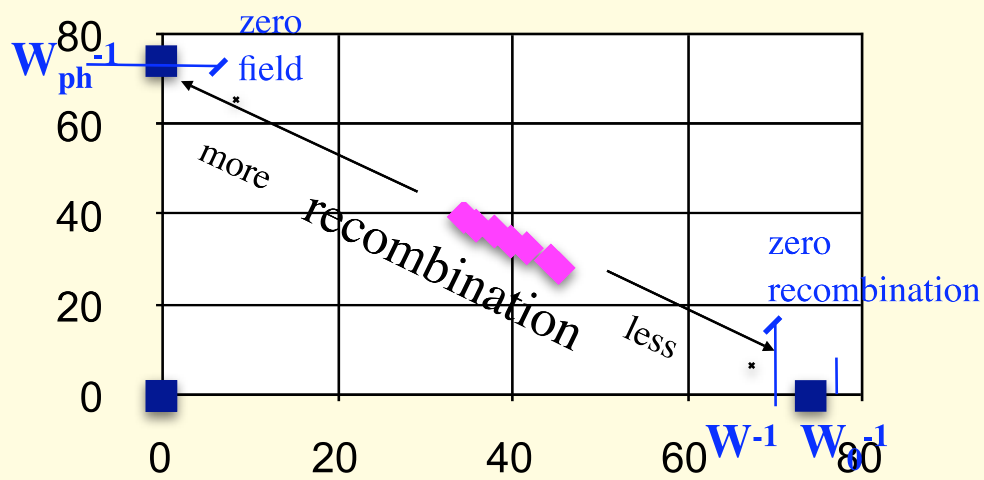
- Current Experiments:
  - XENON10
  - ZEPLIN II
  - WARP
- New
  - XENON100
  - ZEPLIN III
  - LUX
  - WARP 100

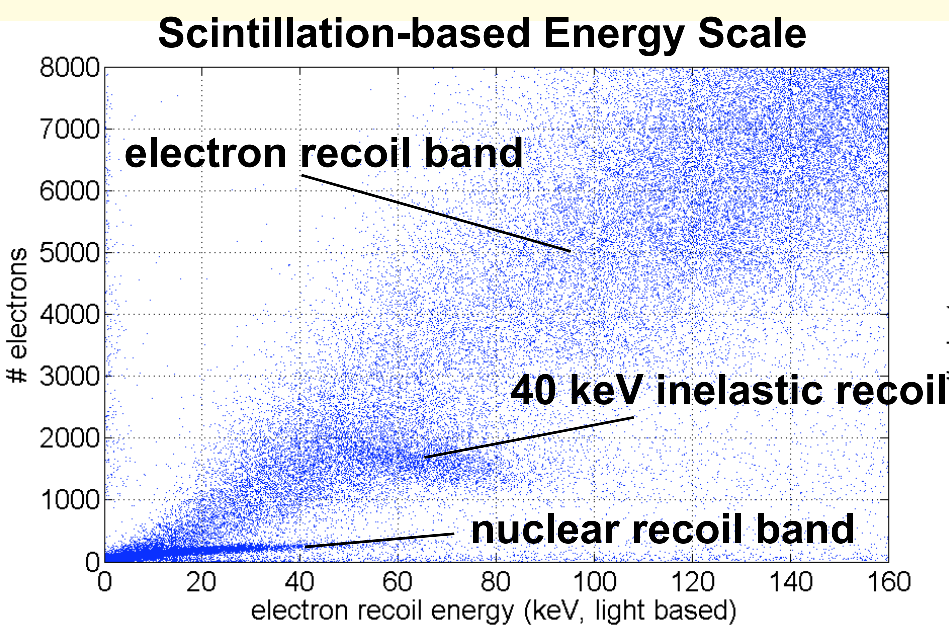


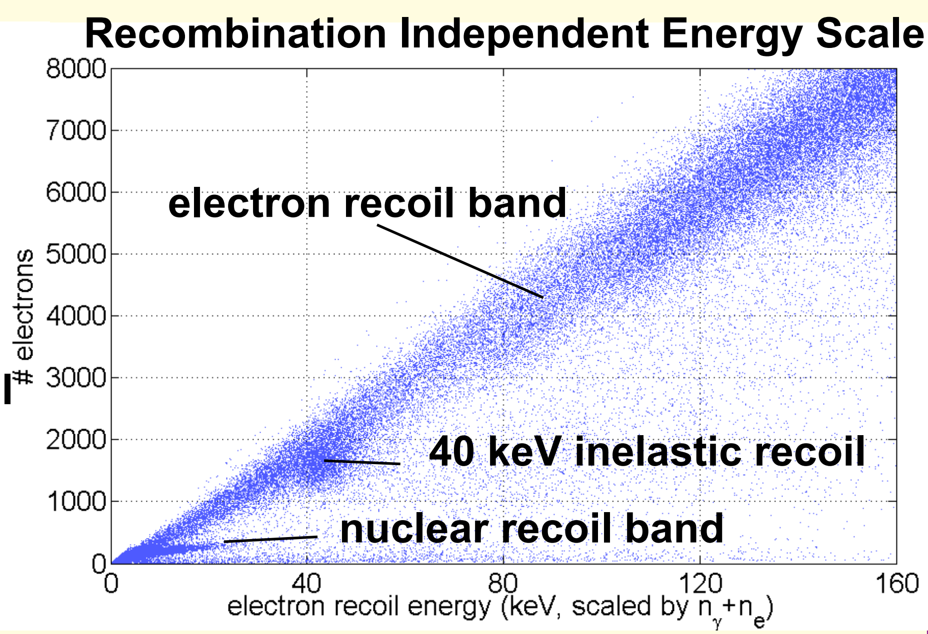
A. Bolozdynya, NIMA 422 p314 (1999).

Recombination - based discrimination









The XENON10 Collaboration

Columbia University Elena Aprile, Karl-Ludwig Giboni, Sharmila Kamat, Maria Elena Monzani, Guillaume Plante, Roberto Santorelli and Masaki Yamashita

Brown University Richard Gaitskell, Simon Fiorucci, Peter Sorensen and Luiz DeViveiros

RWTH Aachen University Laura Baudis, Jesse Angle, Joerg Orboeck, Aaron Manalaysay and Stephan Schulte

Lawrence Livermore National Laboratory Adam Bernstein, Chris Hagmann, Norm Madden and Celeste Winant

Case Western Reserve University Tom Shutt, Peter Brusov, Eric Dahl, John Kwong and Alexander Bolozdynya

Rice University Uwe Oberlack, Roman Gomez, Christopher Olsen and Peter Shagin

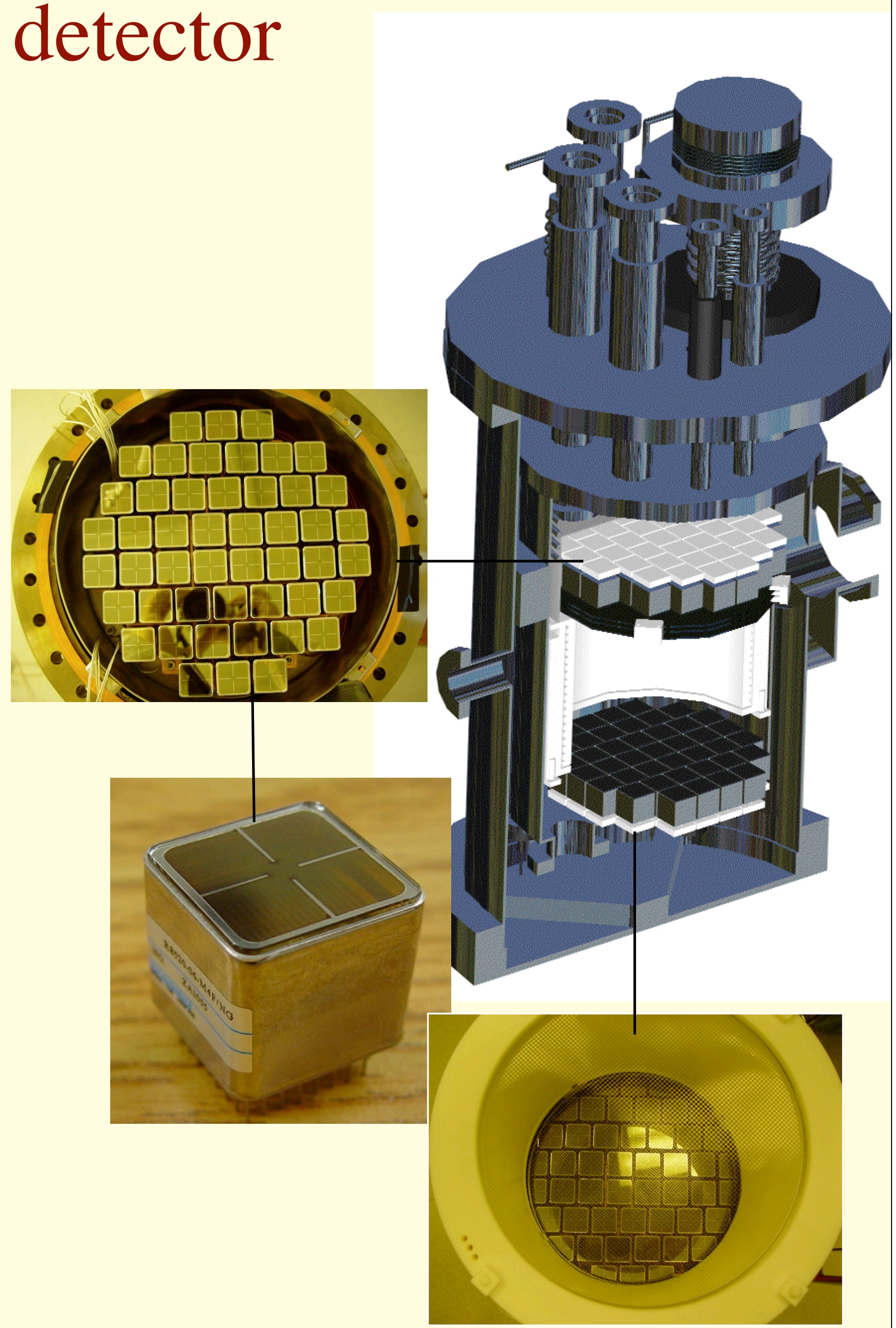
Yale University Daniel McKinsey, Louis Kastens, Angel Manzur and Kaixuan Ni

LNGS Francesco Arneodo and Alfredo Ferella

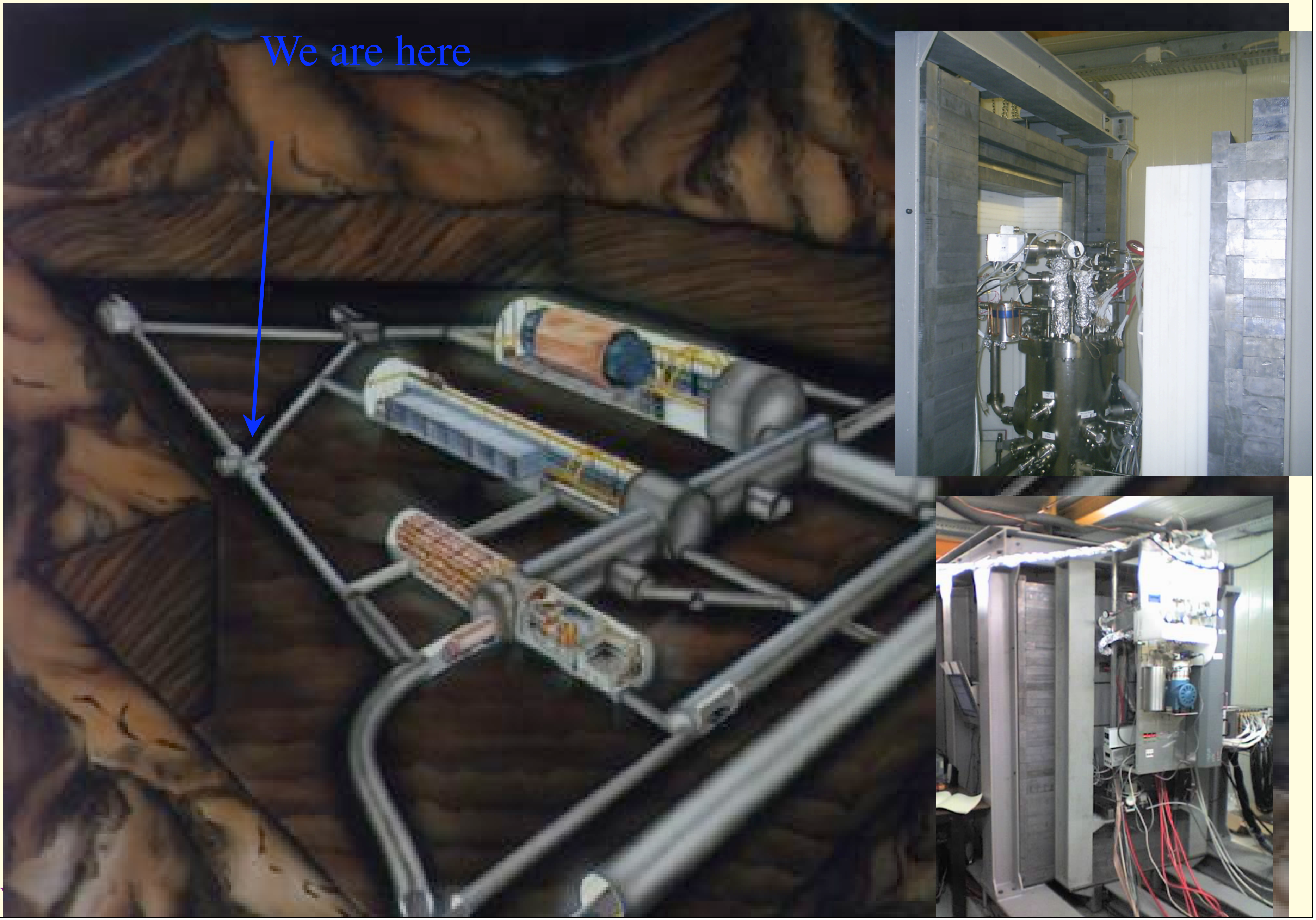
Coimbra University Jose Matias Lopes, Luis Coelho, Luis Fernandes and Joaquin Santos

XENON10 detector

- 22 kg of liquid xenon
  - 15 kg active volume
  - 20 cm diameter, 15 cm drift
- Hamamatsu R8520 1''×3.5 cm PMTs
  - *Quantum efficiency* > 20% @ 178 nm
- 48 PMTs top, 41 PMTs bottom array
  - x-y position from PMT hit pattern; $\sigma_{x-y} \approx 1$ mm
  - z-position from Δtdrift ($v_{d,e-} \approx 2$mm/μs), $\sigma_Z \approx 0.3$ mm
- Cooling: Pulse Tube Refrigerator (PTR),
- 90W, coupled via cold finger (LN2 for emergency)



XENON 10: Underground at LNGS

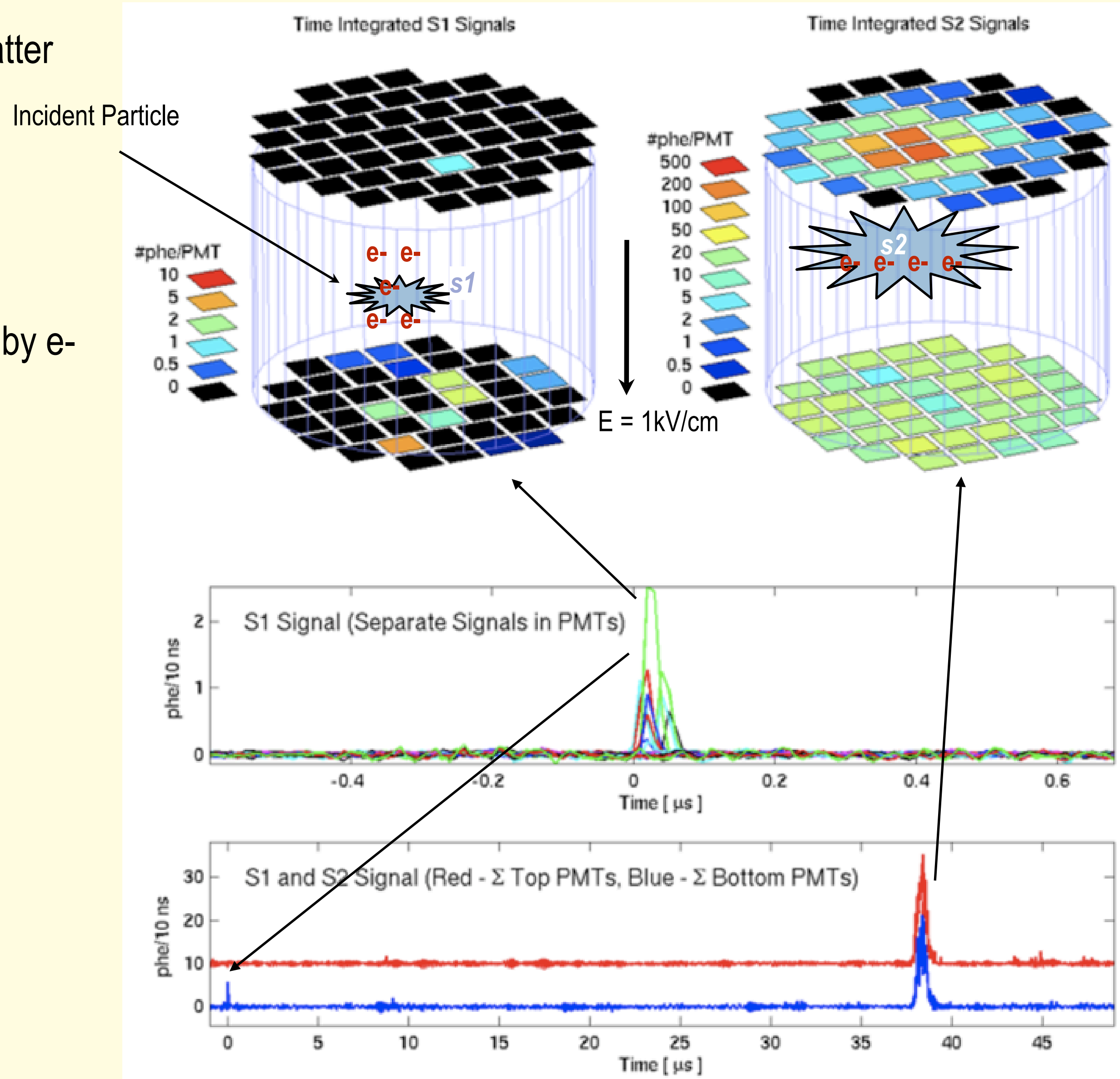


XENON10 Events

Example: Low Energy Compton Scatter
- S1=15.4 phe ~ 6 keVee
- Drift Time ~38 μs => 76 mm

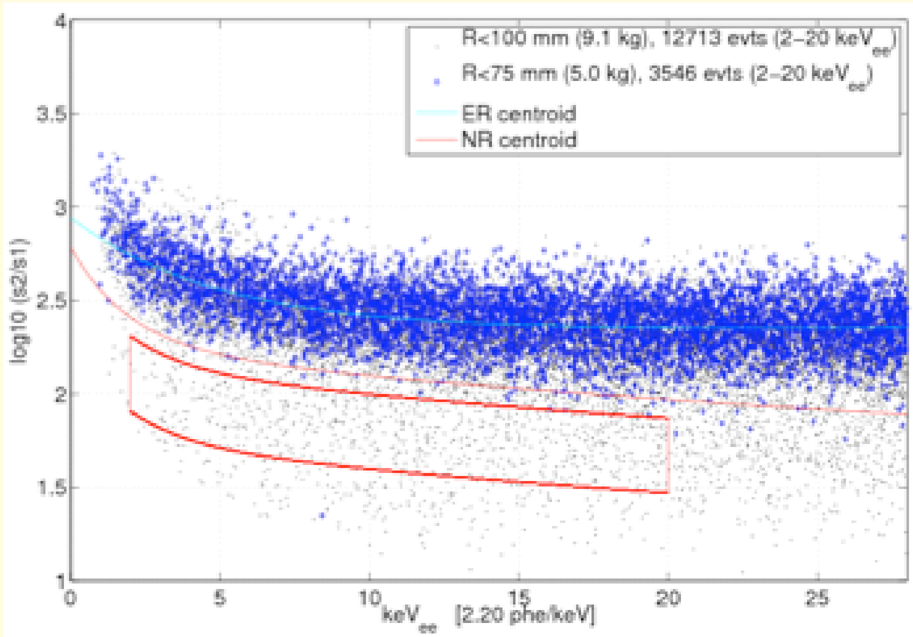
s1: Primary Scintillation Created by Interaction LXe
s2: Secondary Scintillation Created by e- extracted & accelerated in GXe

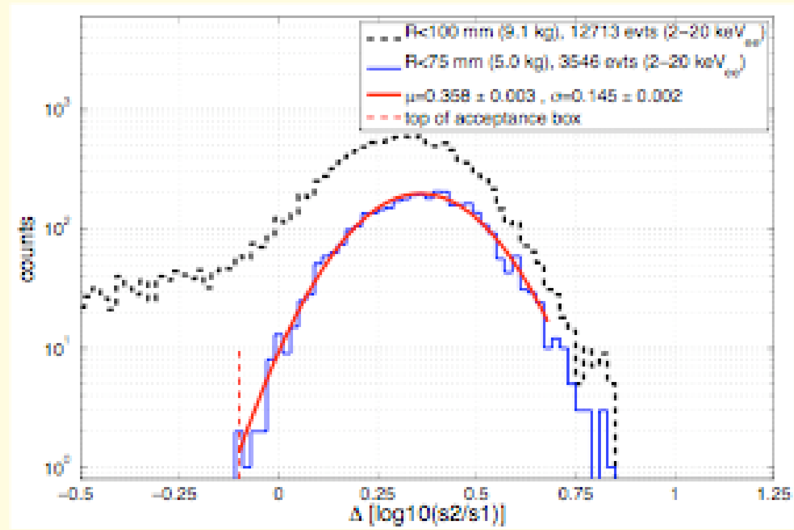
$(s2/s1)_{ER} > (s2/s1)_{NR}$

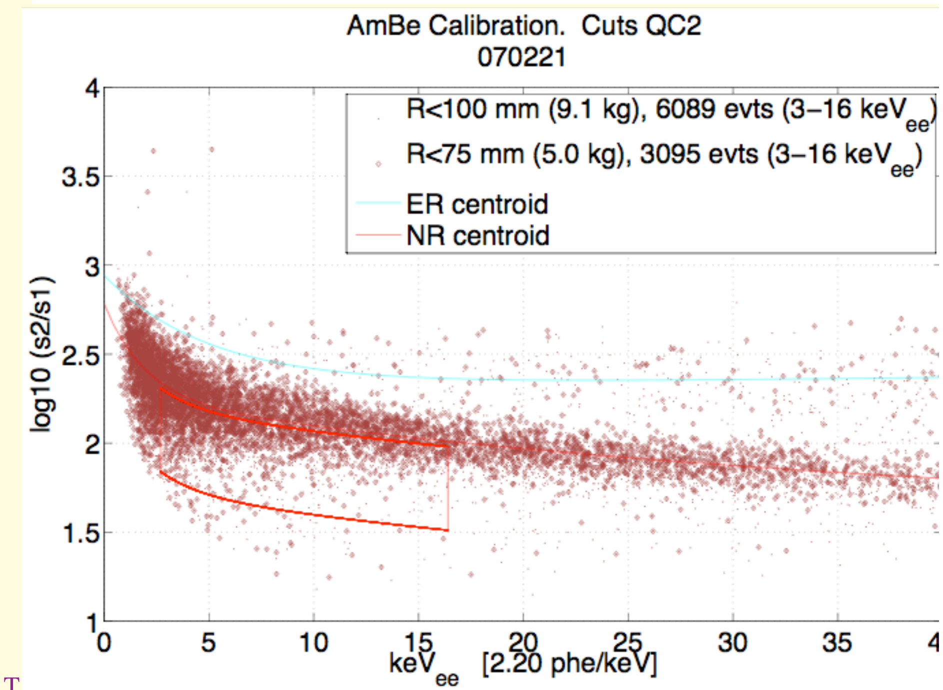


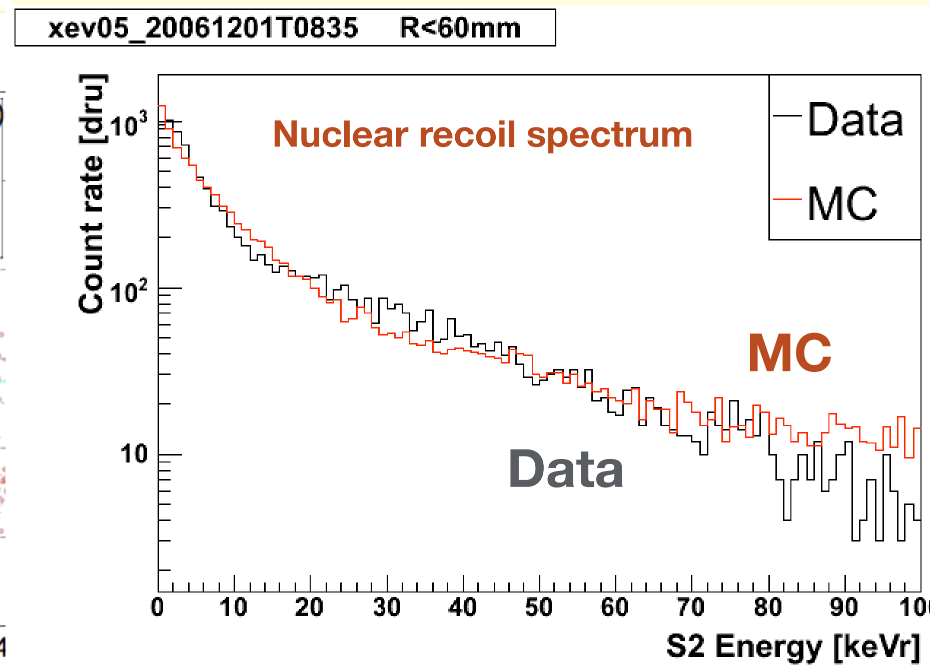
Expect > 99% rejection efficiency of γ/n Recoils…
Reduction of Backgrounds =>
Reduction of Leakage Events

In-situ calibrations





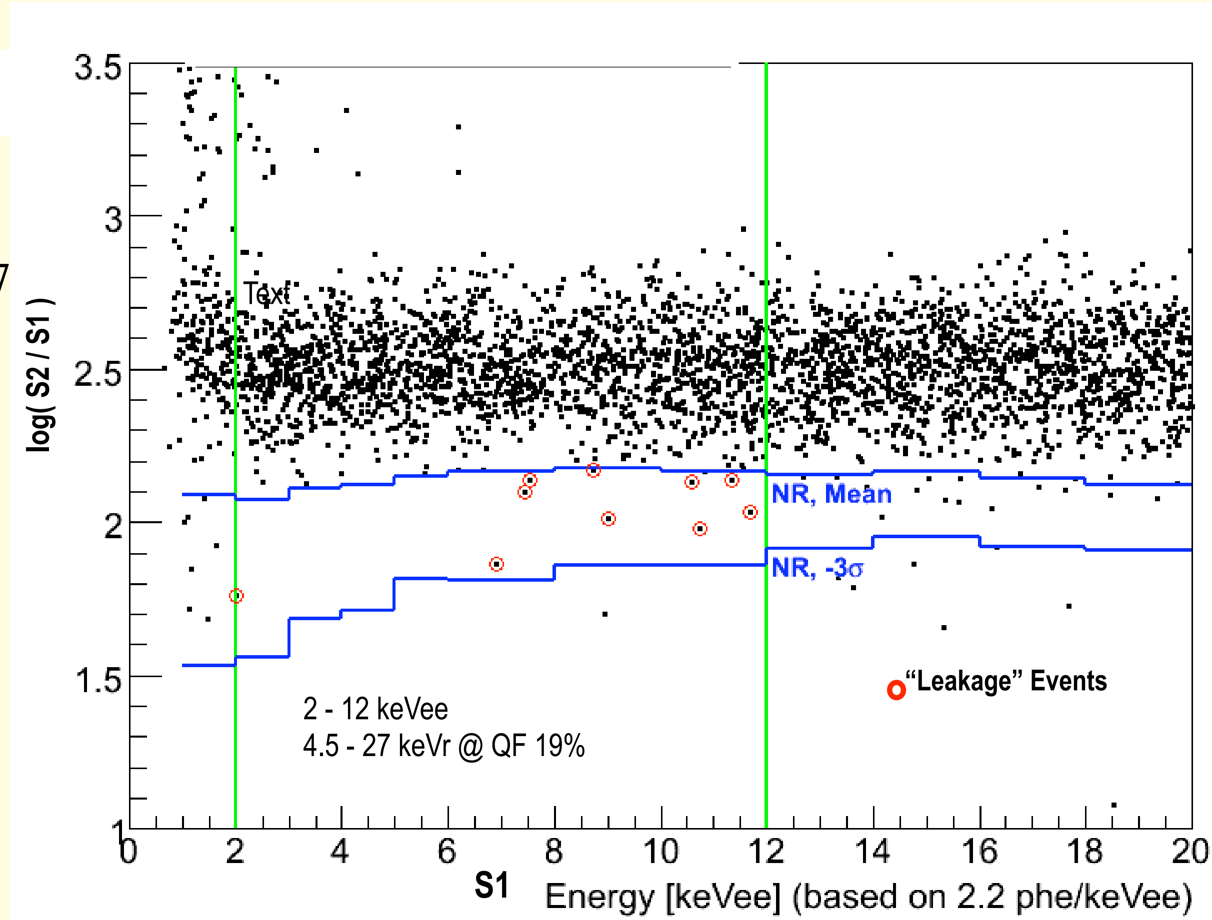




XENON10 WIMP search data

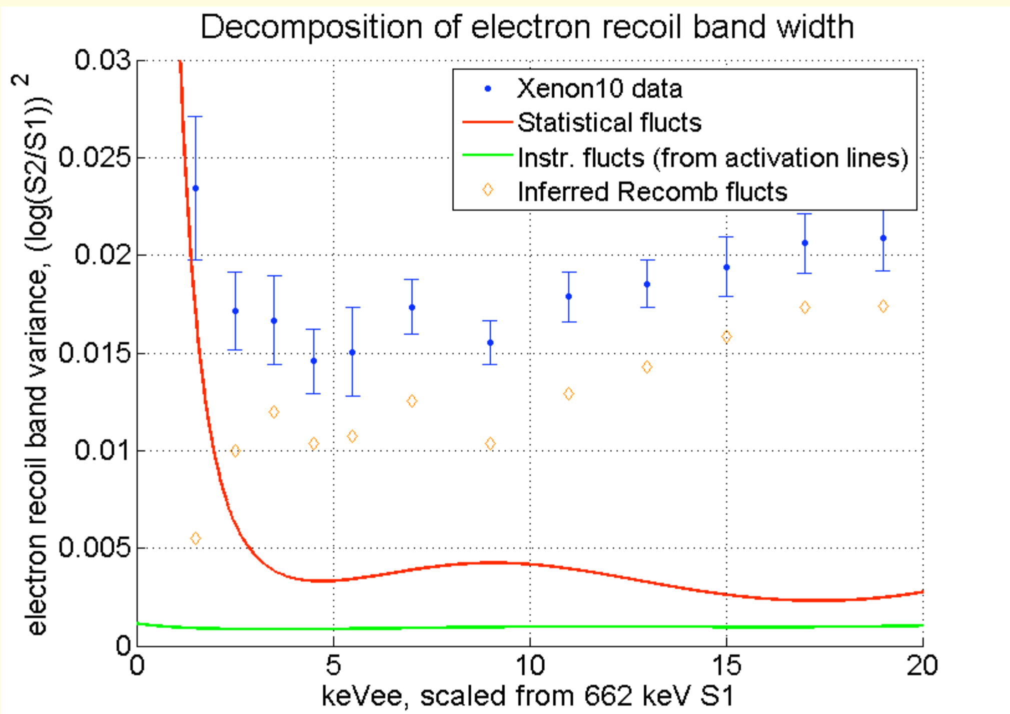
- Blind Analysis
- 58.6 days, 5.4 kg fiducial
- ~50% acceptance of Nuclear Recoils
- 2-12keVee / 4.5-27 keVr
  - Assuming QF 19% 4.5-27 keVr
- 10 events in the "box" after all primary analysis blind cuts
  - Calibration expectation: 7.0 +2.1-1.0 (gaussian)
  - Data: 5 ~gaussian; 5 non-gaussian

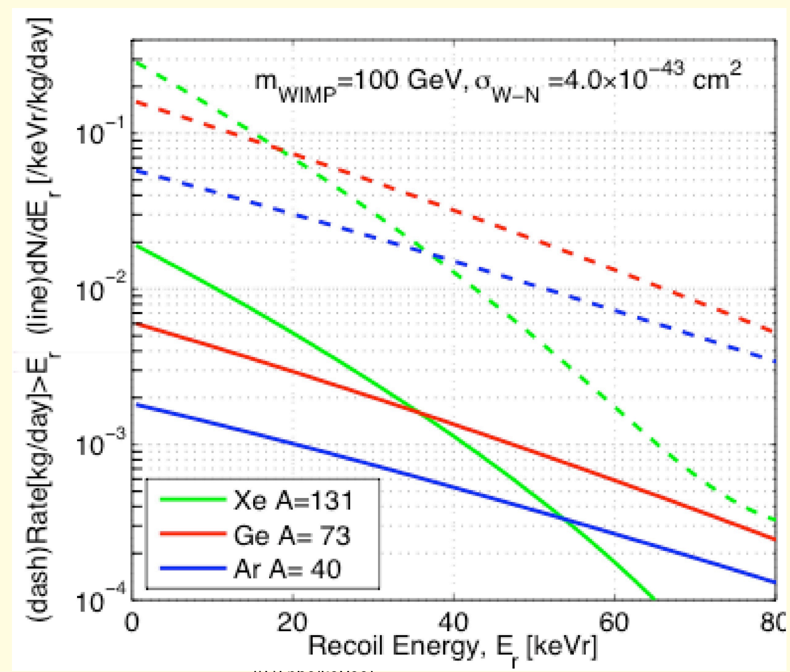
"Straightened ER Scale"



Discrimination robust at low energy

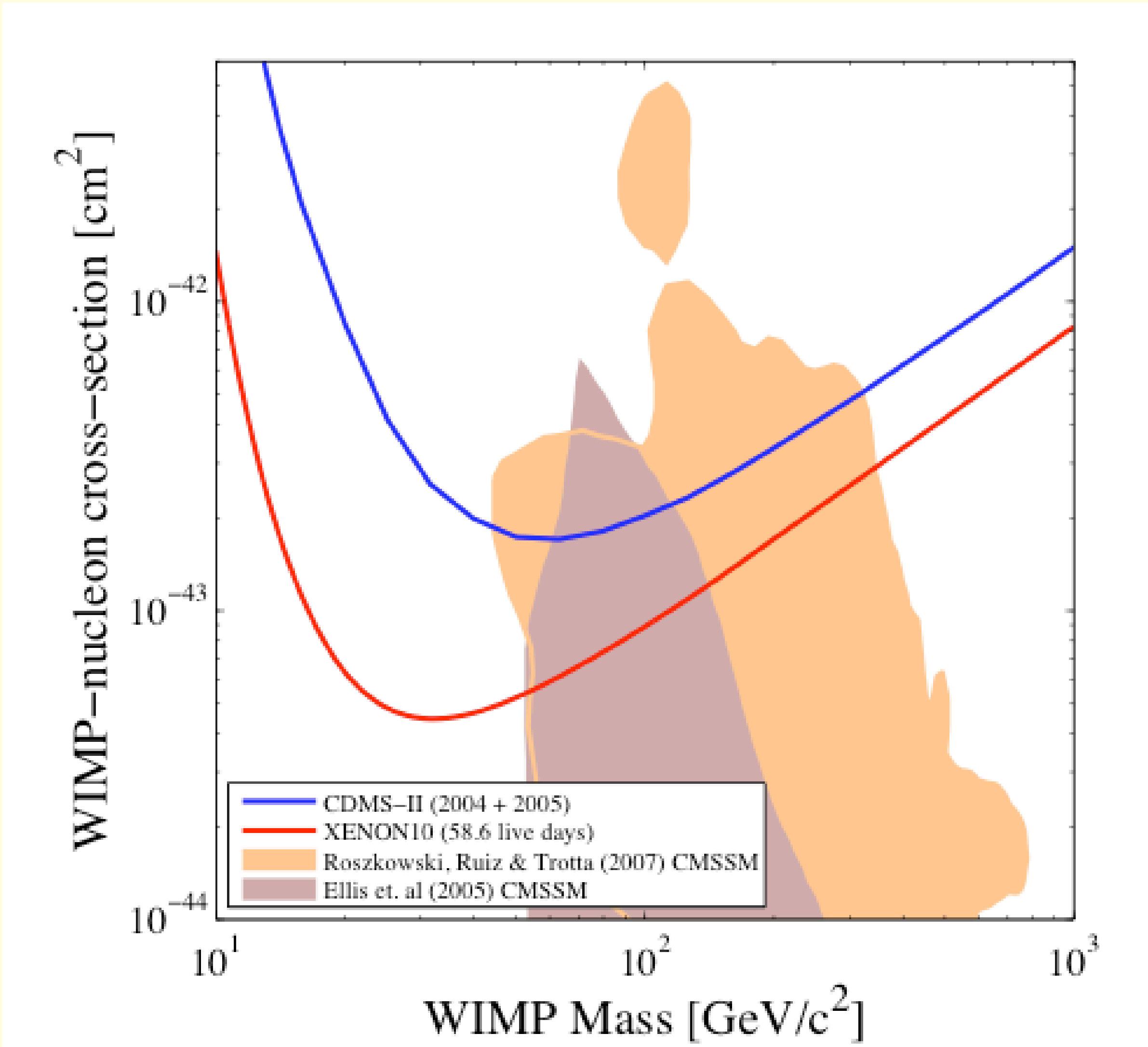
- Limitations understood:
  - Recombination fluctuations
  - Light collection statistics
- ~99.9% at <10 keVr.
- Low threshold gives Xe very high WIMP sensitivity





(2.2 pne/kevee)

XENON10 results



J. Angle, *et al*., accepted for publication in PRL (2008).

So we haven't seen anything.

How do we go to very large scale?

- Current limits ~5×10^{-44} cm^2.
- Goal: 10^{-47} cm^2.

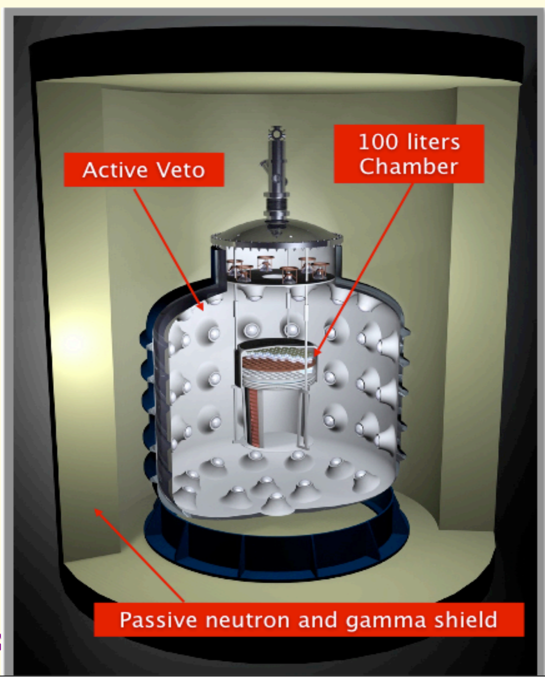
SUSY
Theory
Models

Next phase liquid noble experiments

- XMASS - 800 kg (100 kg fiducial) single-phase Xe
- XENON100 - 100 kg two-phase Xe
- LUX - 300 kg two-phase Xe
- DEAP/MiniCLEAN - 360 and 3600 kg single phase Ar (+Ne?)
- WARP - 100 kg dual phase Ar
- ArDM - large dual phase Ar

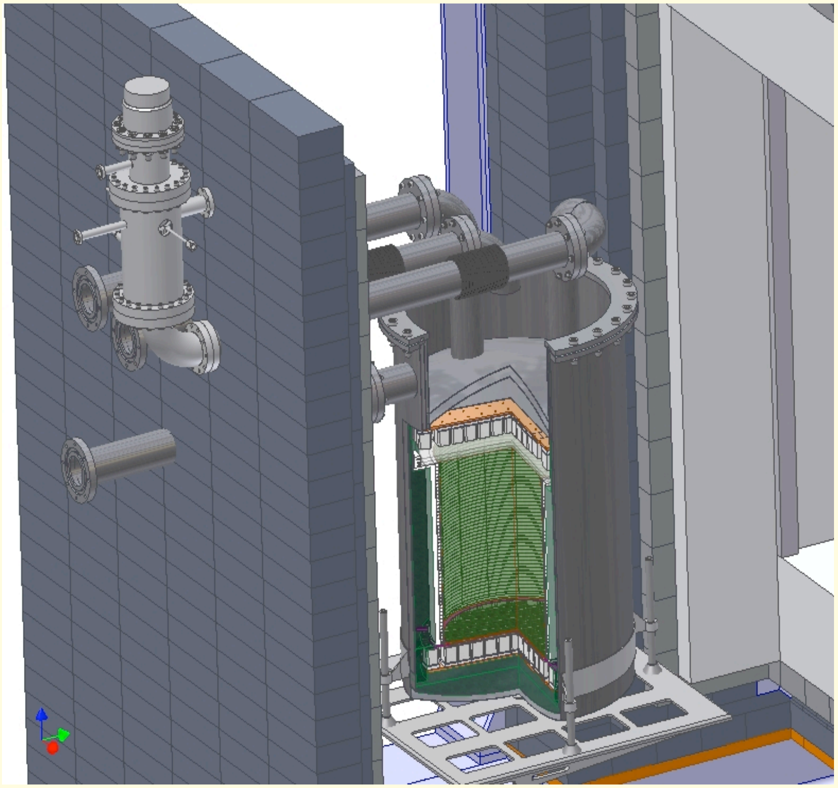
WARP: two-phase LAr

- Icarus spin-off
- 140 kg detector in 800 kg active Ar veto
  - Gran Sasso
  - Opertions start in 2008
- Significant effort on ^{39}Ar depleted Ar. (Princeton)
- ArDM (Zurich, A. Rubbia).



XENON100

- Gran Sasso
- ~100 kg active with ~50 kg active veto.
- Turn on in 2008.
- Projected sensitivity: ~10^{-45} cm^2



LUX Dark Matter Experiment

Brown - Gaitskell

Case - Shutt, Bolozdynya

LLNL - Bernstein

LBNL - Lesko

Rochester - Wolfs

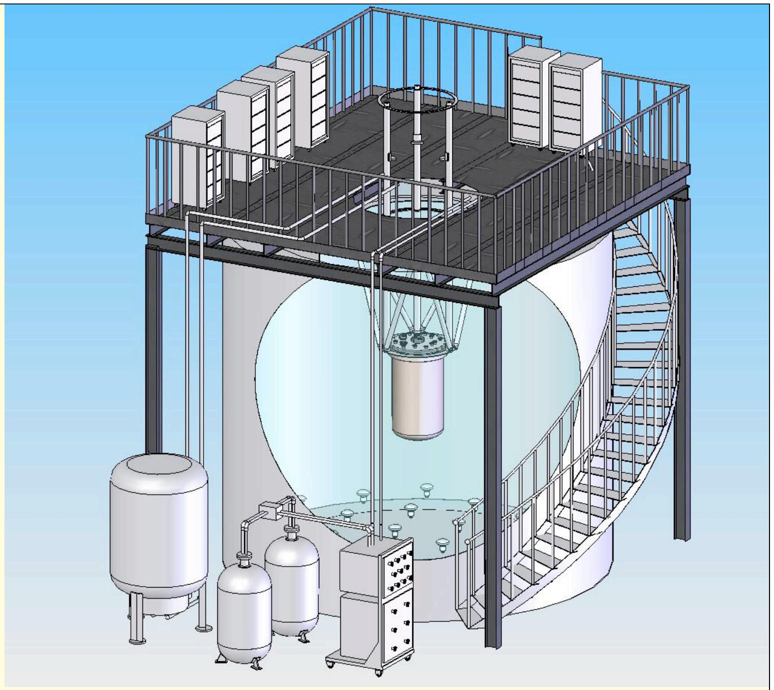
Texas A&M - White

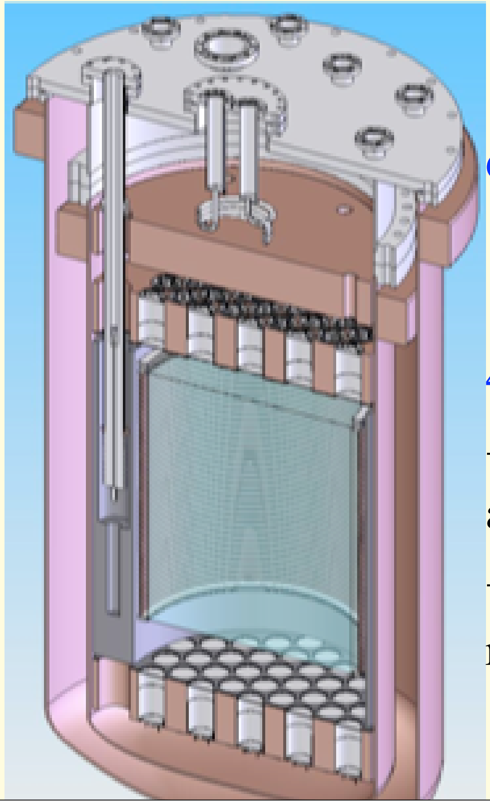
UC Davis - Tripathi, Svoboda

UCLA - Wang, Cline, Arisaka

Yale - McKinsey

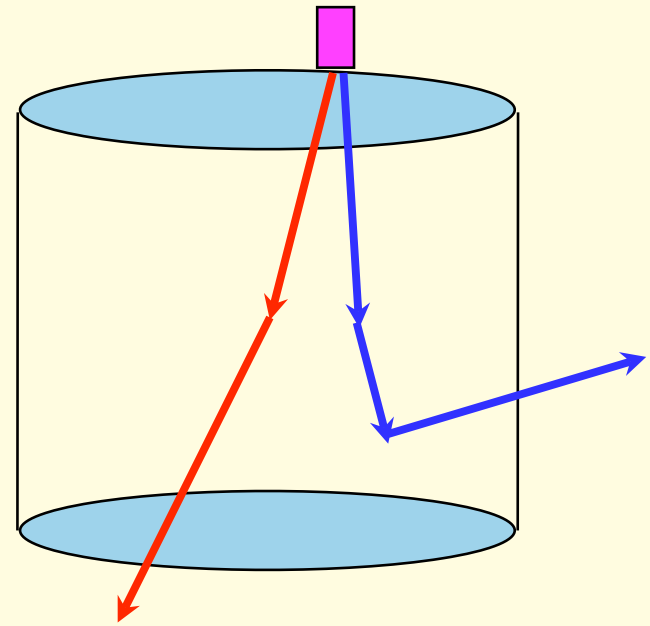
- Dark matter experiments:
  - CDMS, ZEPLIN II, XENON10
- Solar, reactor, atm. neutrinos:
  - SNO, IMB, SuperK, Kamland, Borexino
- High energy physics





- 300 kg total, 100 kg fiducial detector.
- Water shield
- DM reach: $2x10^{-45}$ cm^2 in 4 months
  - Very conservative background assumptions
  - Possibly ~$5x10^{-46}$ cm^2 with longer running.
- Allows *discovery* at $7x10^{-46}$ cm^2.

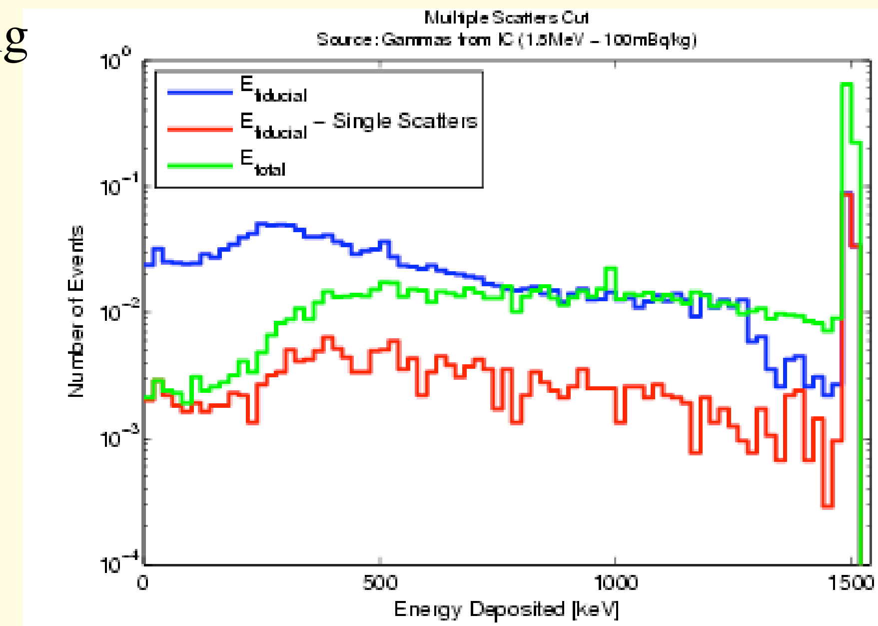
Current dominant background: low-energy photon scatters



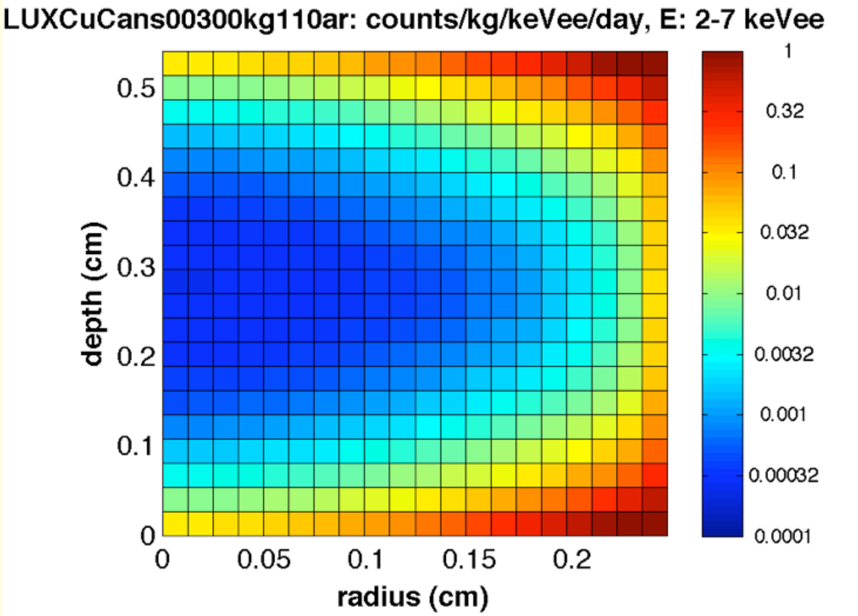
- Simple background problem.
  - Single, low-energy Compton scattering
  - Very forward peaked.
- Rare, because of energetics.
- Can approximate analytically:
  - Probability of *n* scatters while traversing distance *L:*

$$P_n(L) \cong \frac{1}{n!}\left(\frac{L}{\lambda}\right)^n e^{-\frac{L}{\lambda}}$$

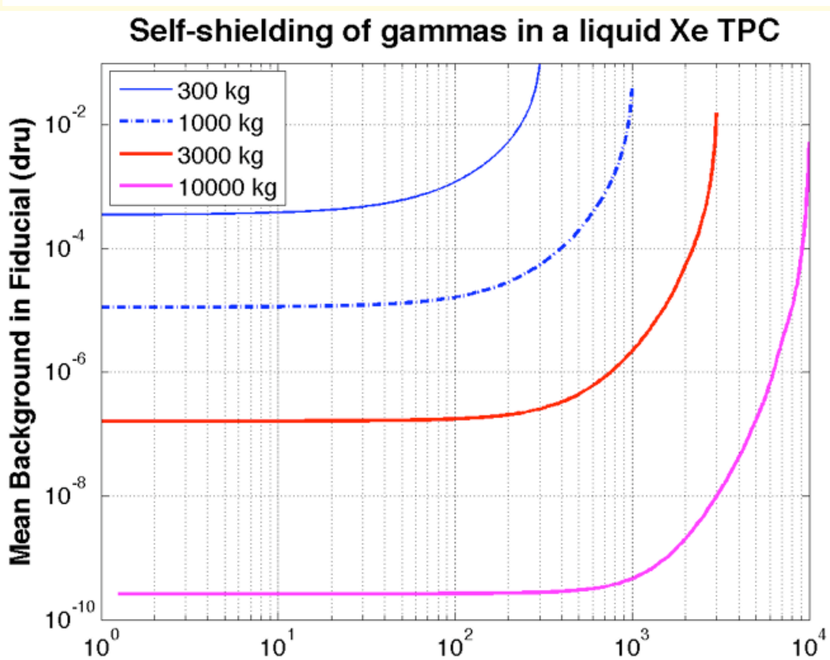
Agrees with Monte Carlo

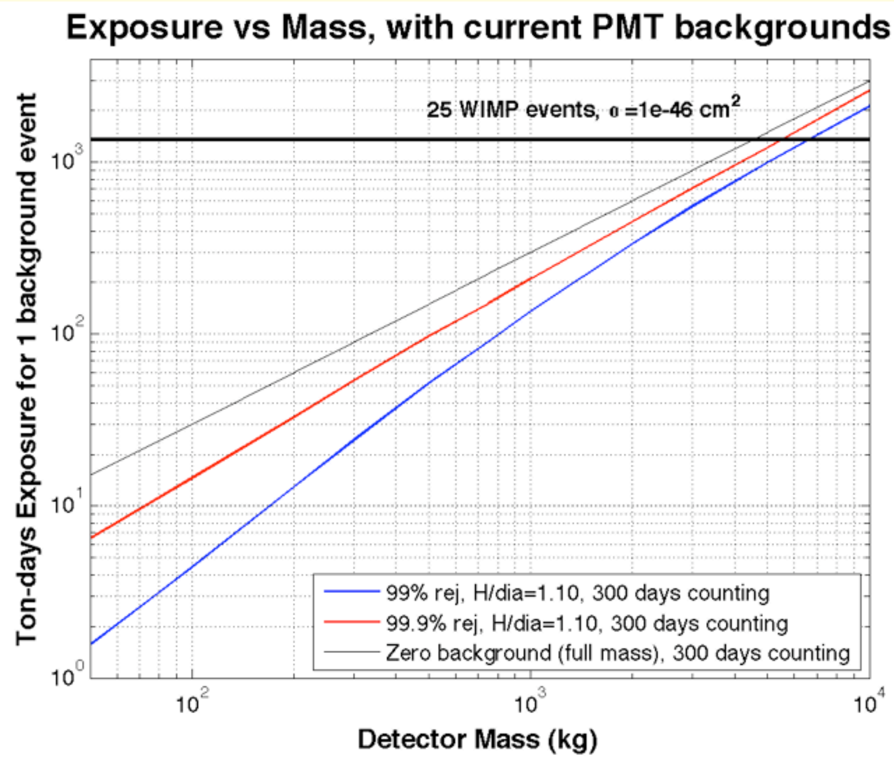


Xe provides very strong self-shielding of gammas



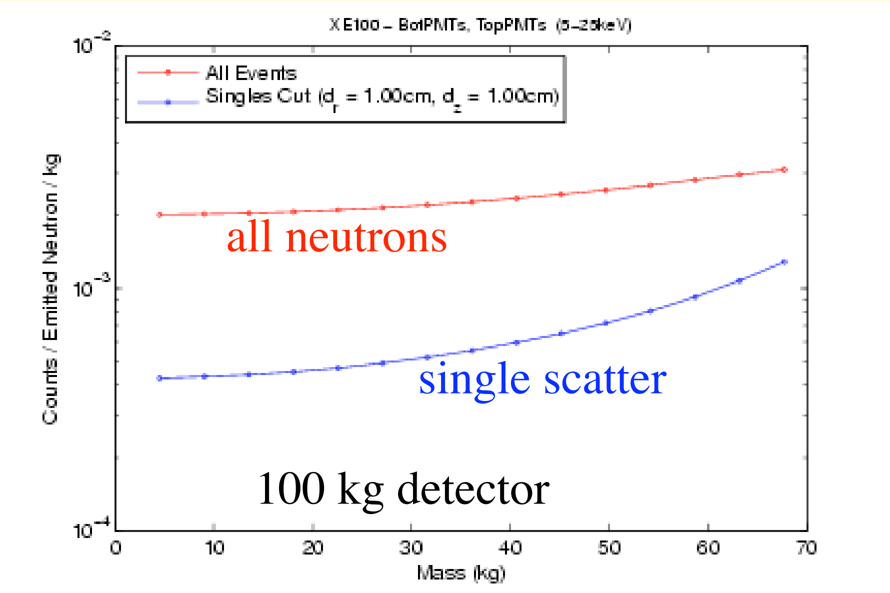
- Effective for detectors large compared to ~10 cm gamma penetration distance: few 100 kg and up.

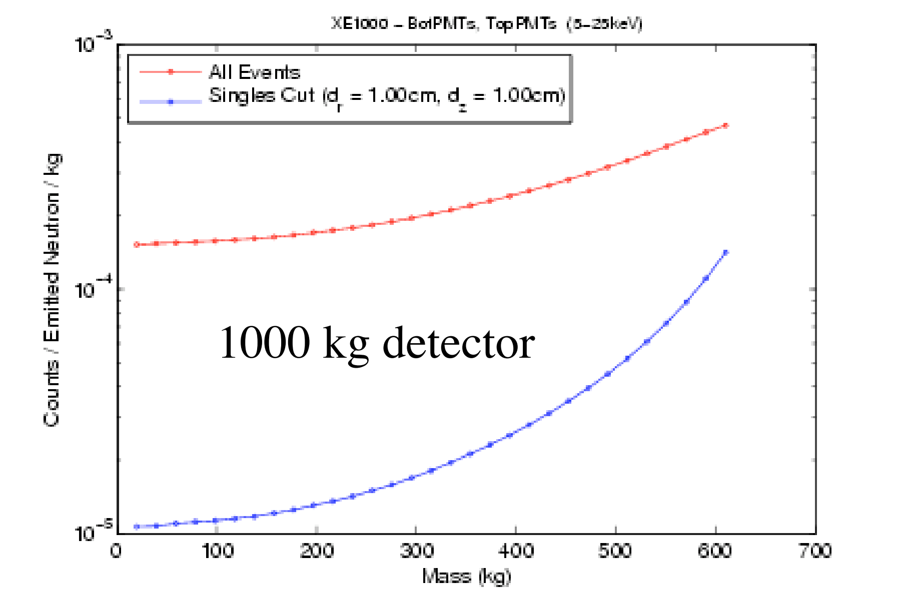




Internal Neutron Backgrounds

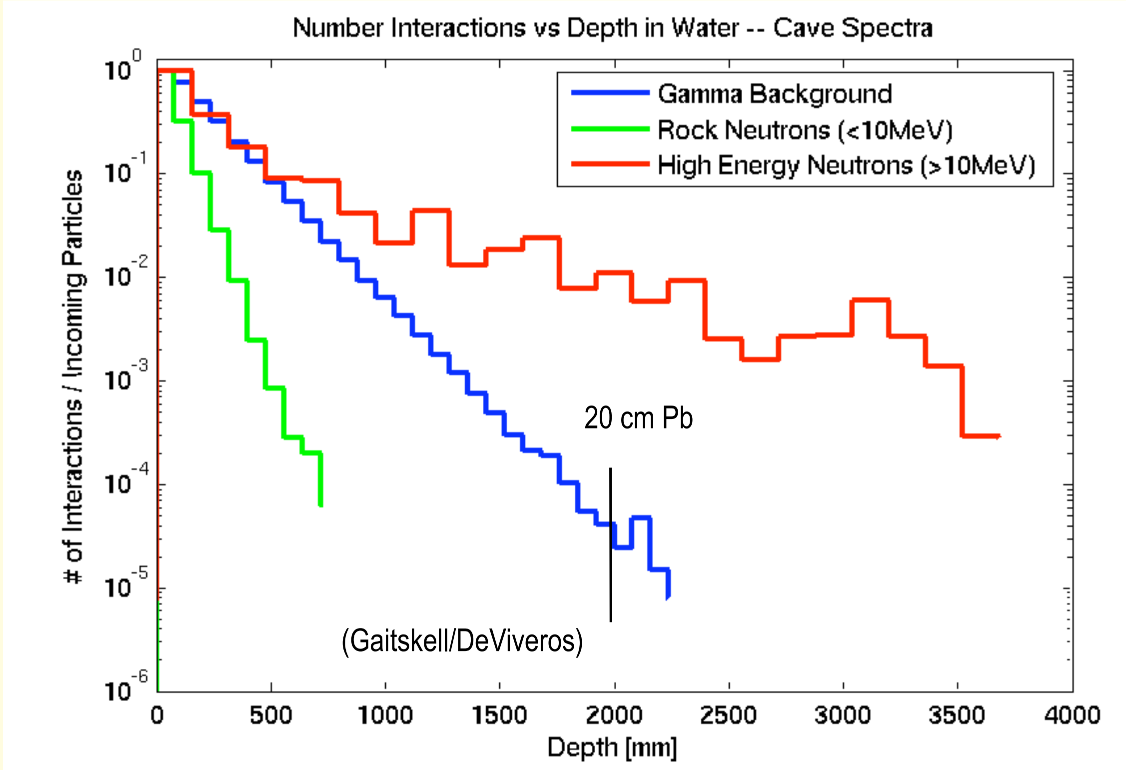
- (alpha,n) and fission neutrons, mostly in PMT
- Multiple scattering rejects these events in TPC
  - But not as effective as for gammas
- At ~10 ton scale, need ~tenfold reduction in PMT activity for efficient shielding.
  - Such PMTs already exist.





Large-scale water shield

- Lowest-known background shielding material
  - Naively ~ 10,000 cleaner than Pb/Cu.
- Very effective for high energy neutrons
  - 1 m: difference betweeen Homestake and SNOLAB
- Very economical
  - 10m, multi-experiment shield:
    - $50 K commerical water purification
    - $100 K for water tank

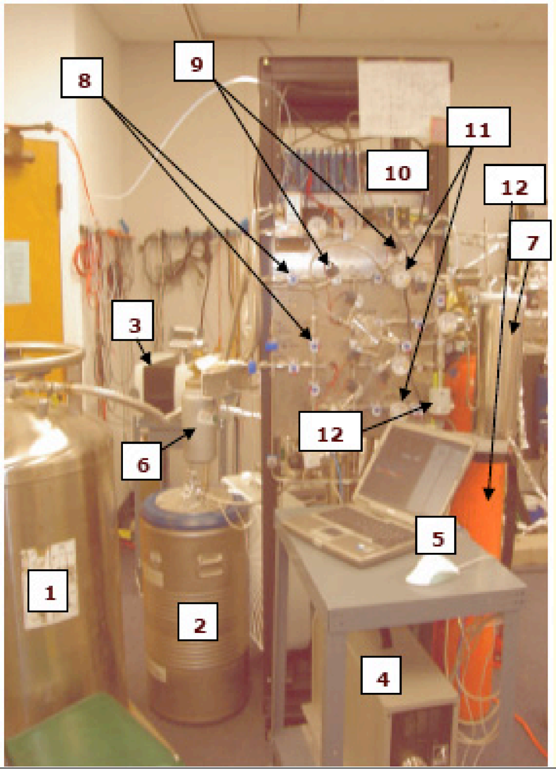


- Possible locations:
  - Homestake "early implementation" DUSEL
  - SNOLAB
  - Other?

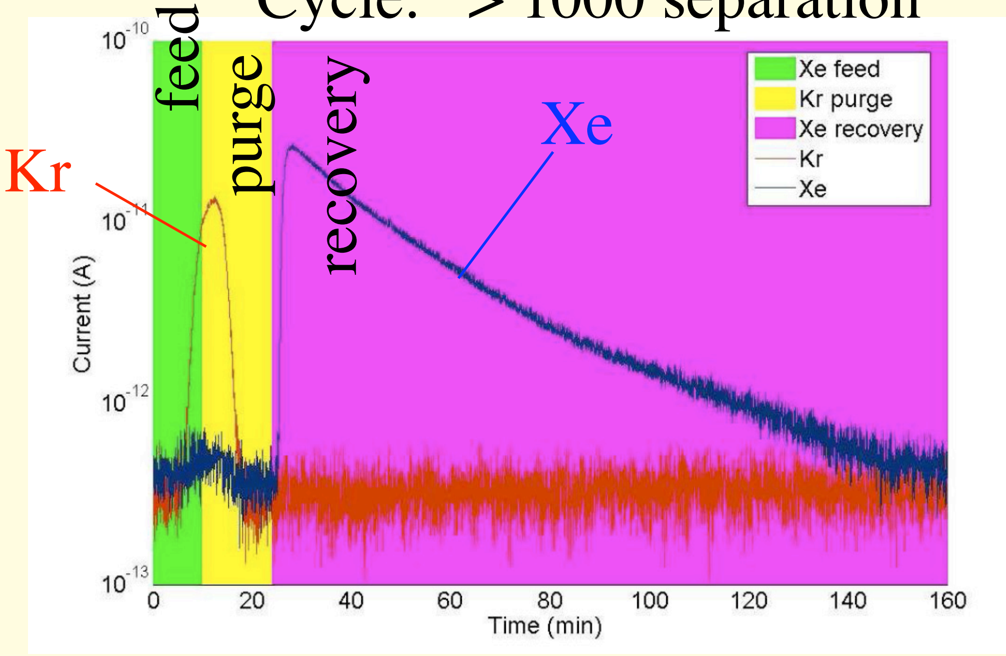
Internal background: ^{85}Kr in Xe

- ^{85}Kr - beta decay, 687 keV endpoint.
  - Goals for 10, 100, 1000 kg detectors: Kr/Xe < 1000, 100, 10 ppt.
  - Commercial Xe (SpectraGas, NJ): ~ 5 ppb (XMASS)
- Chromatographic separation on charcoal column

10 Kg-charocoal column system at Case



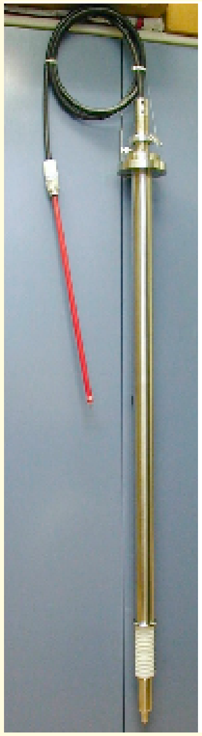
Cycle: > 1000 separation

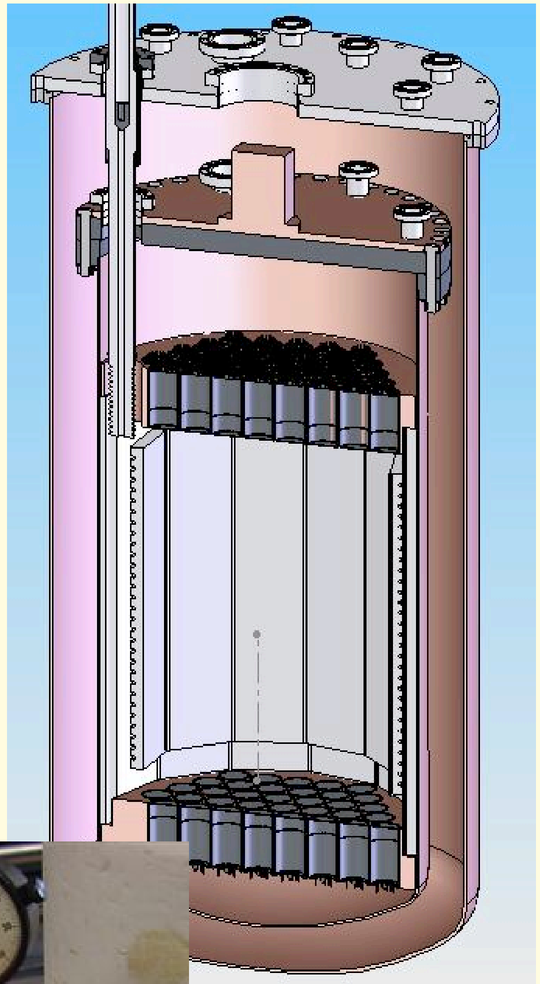


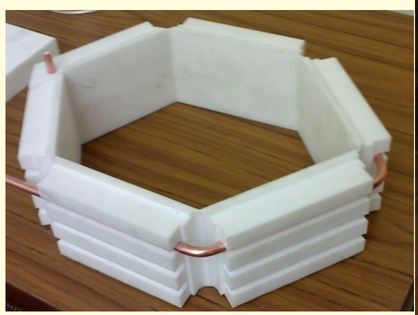
200 g/cycle, 2 kg/day

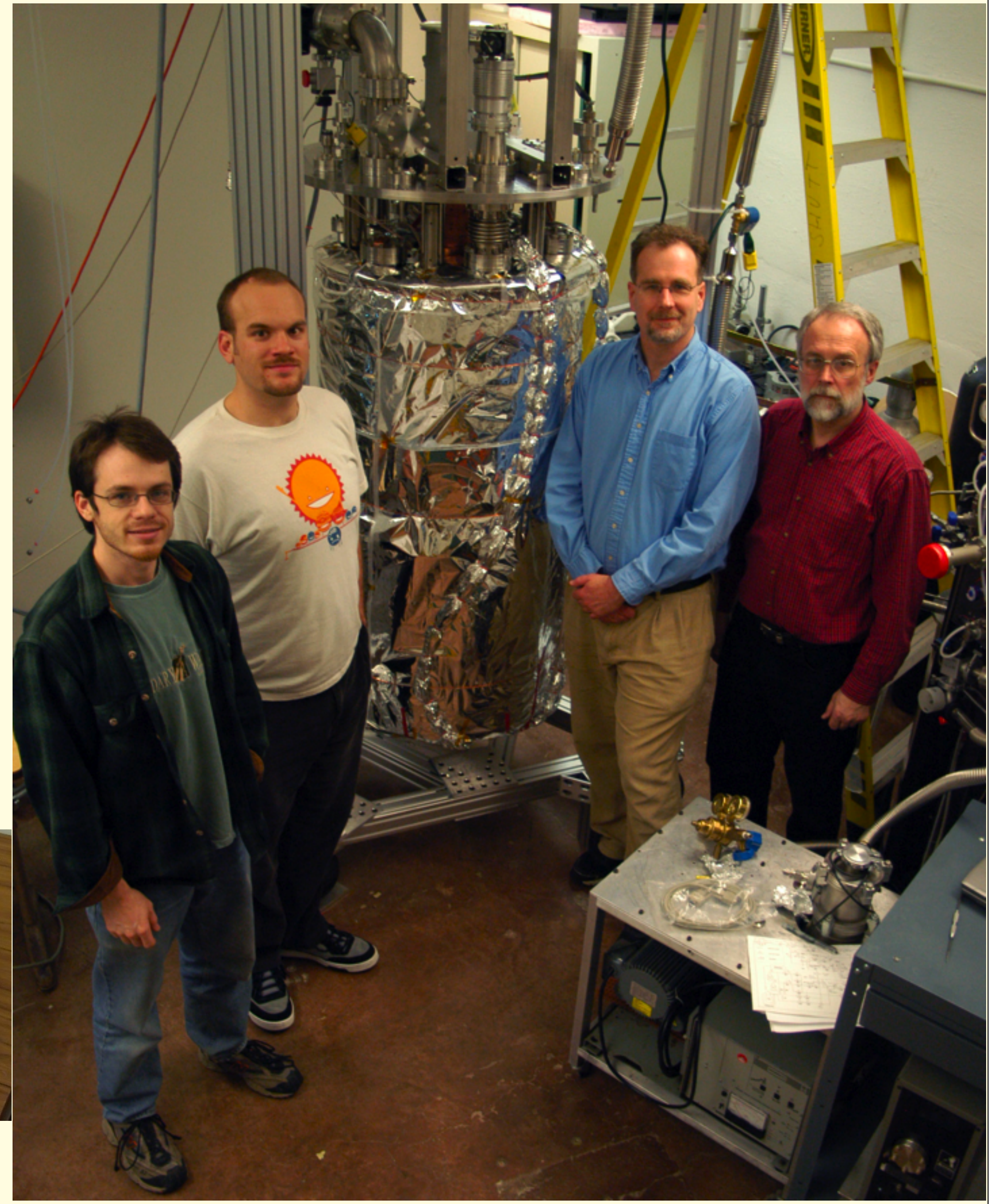
25 Kg purifed to < 10 ppt

LUX Progress prior to funding

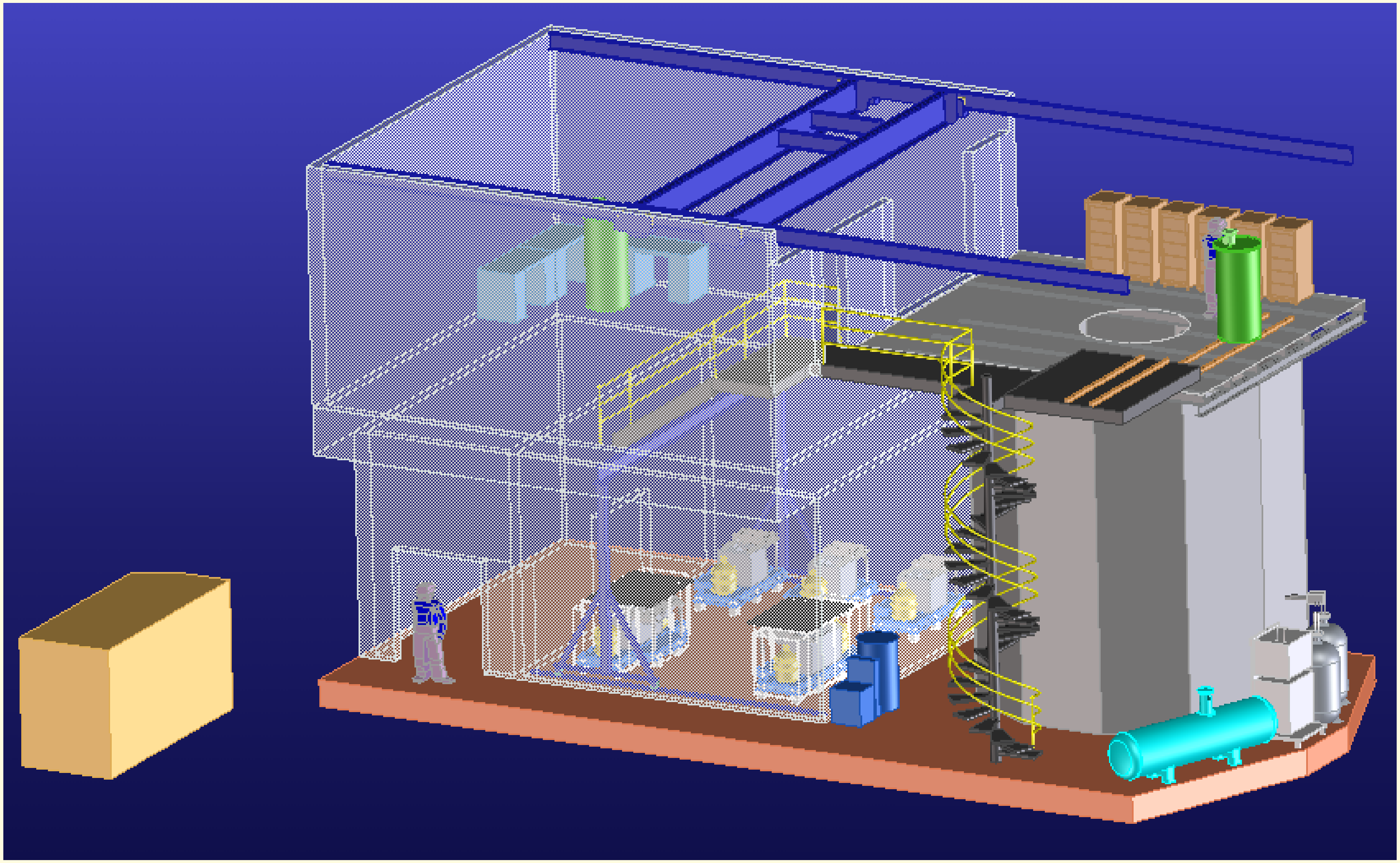




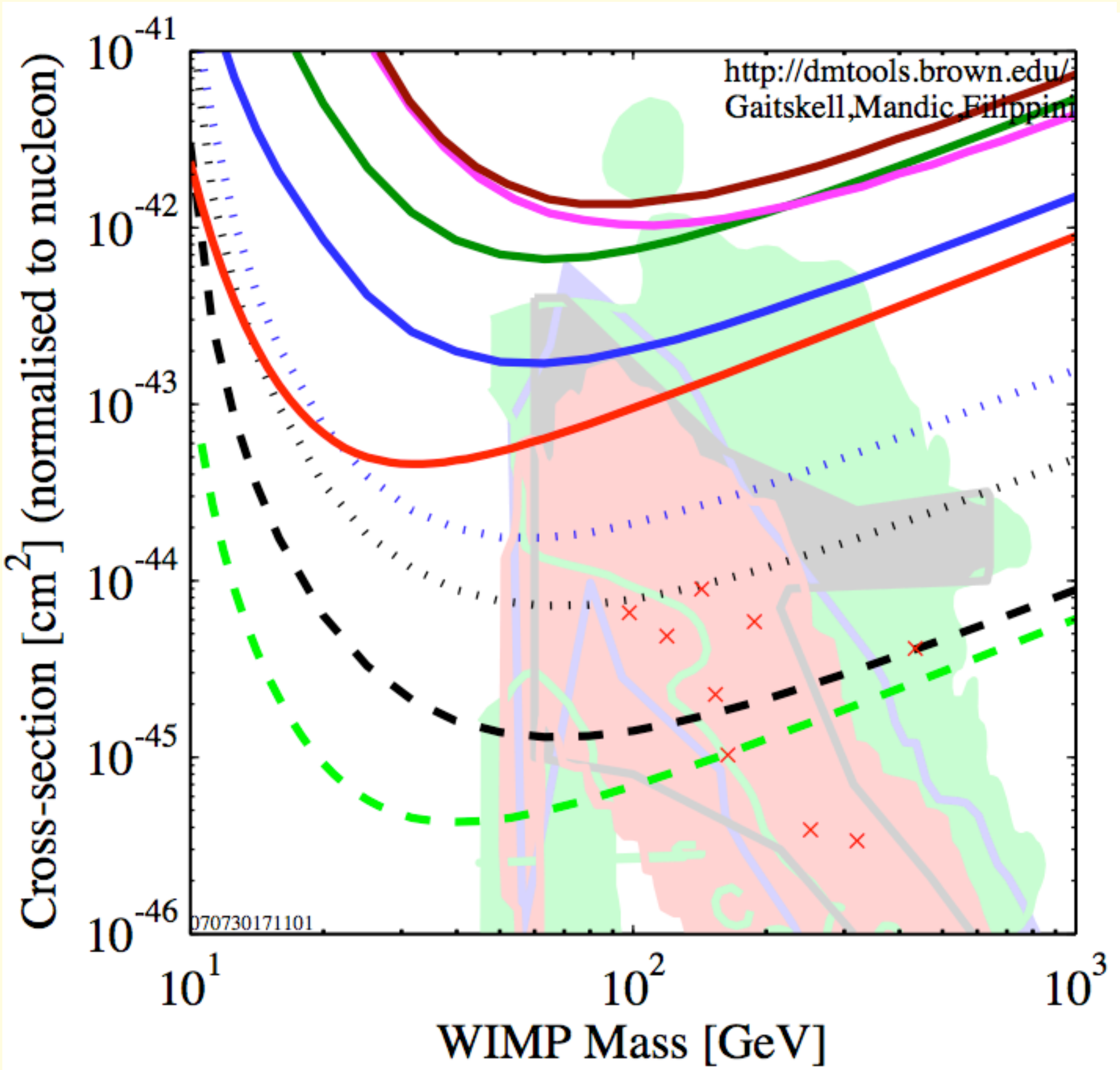




LUX in Davis Cavern at Homestake



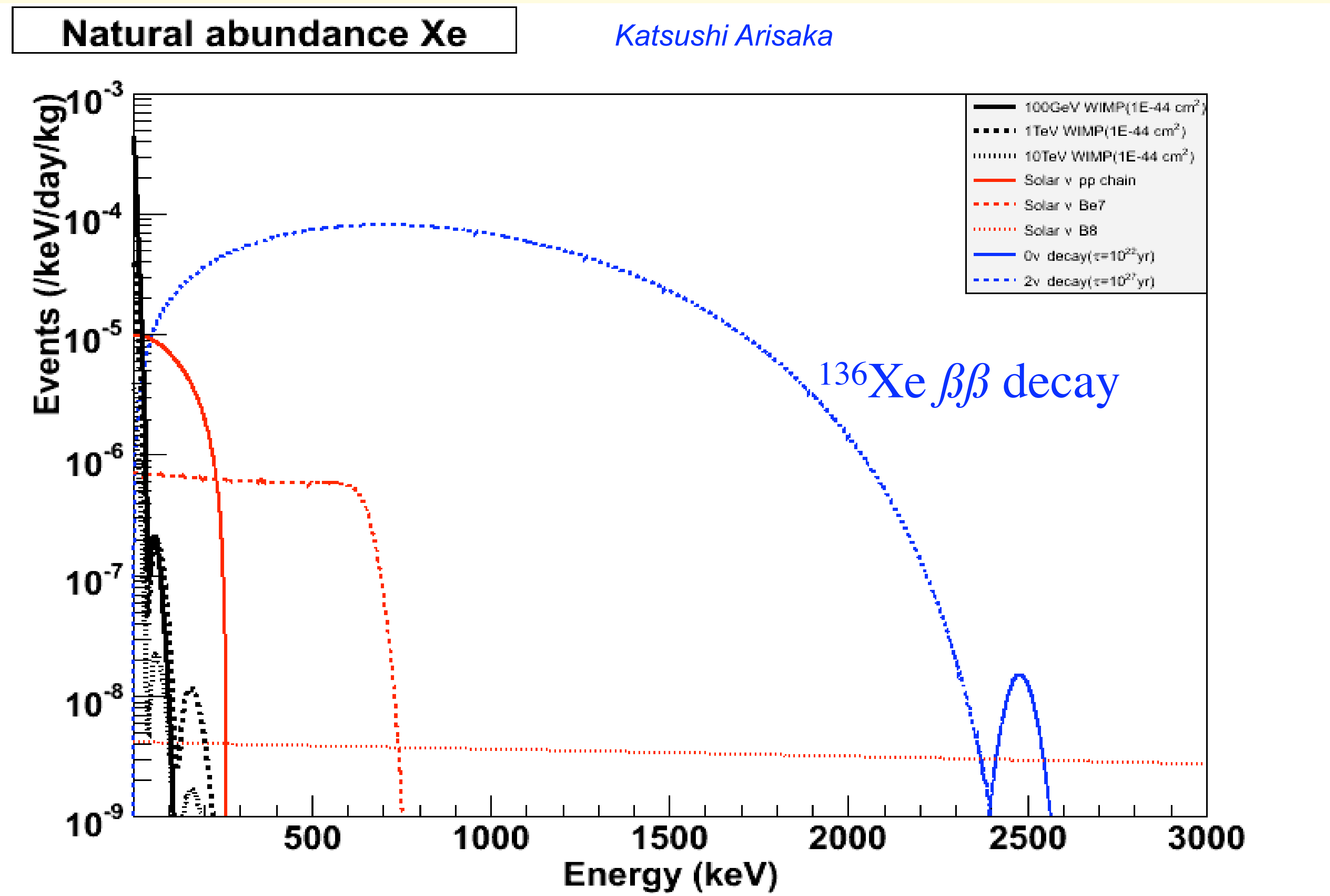
LUX potential



3.9 WIMPs at $7x10^{-46}$ cm^2 (100 GeV) in 1 year

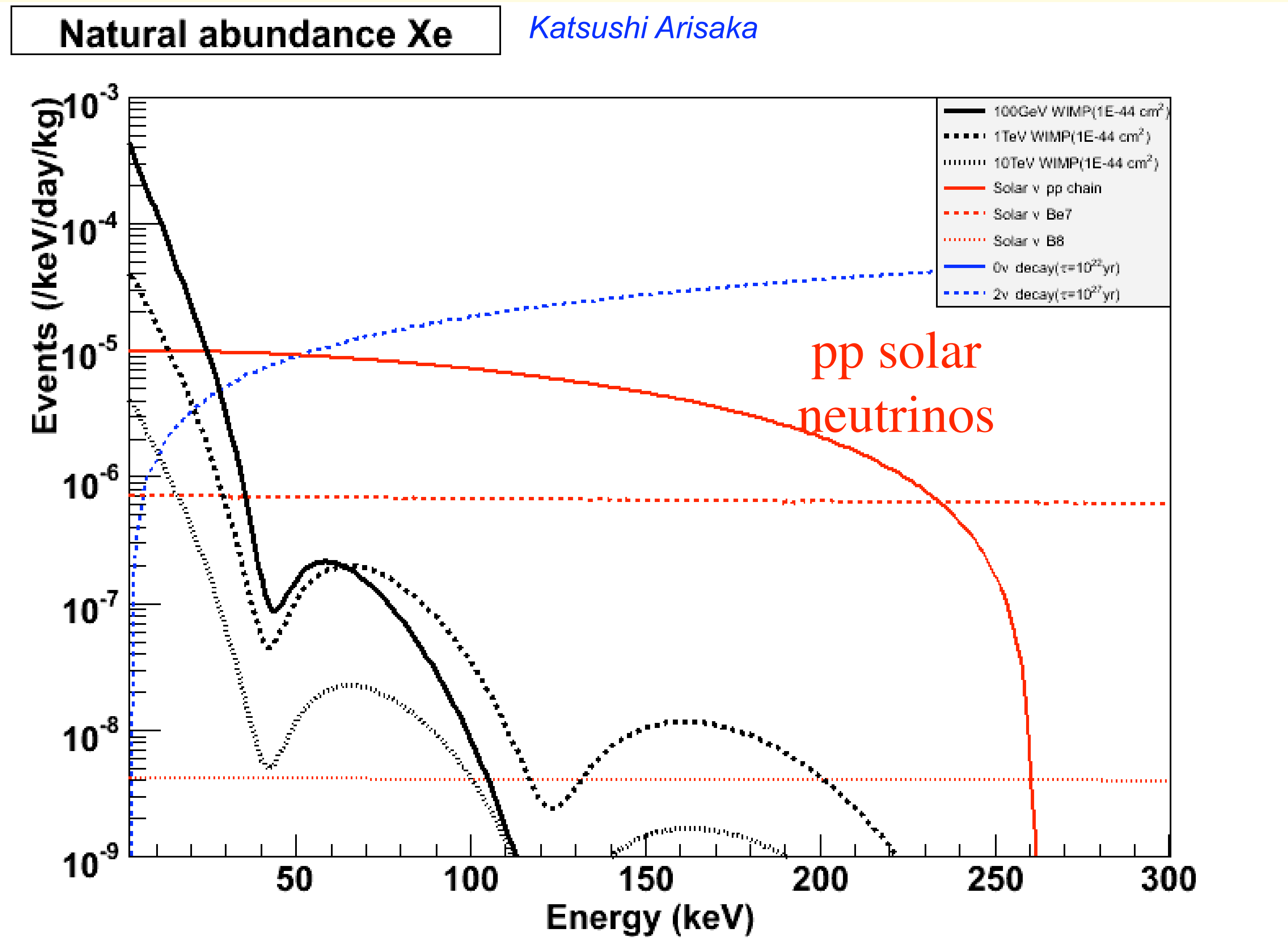
$\beta\beta$ decay, pp solar neutrinos

Grand Unified Dark Matter and neutrino spectrum in Xe



$\beta\beta$ decay, pp solar neutrinos

Grand Unified Dark Matter and neutrino spectrum in Xe

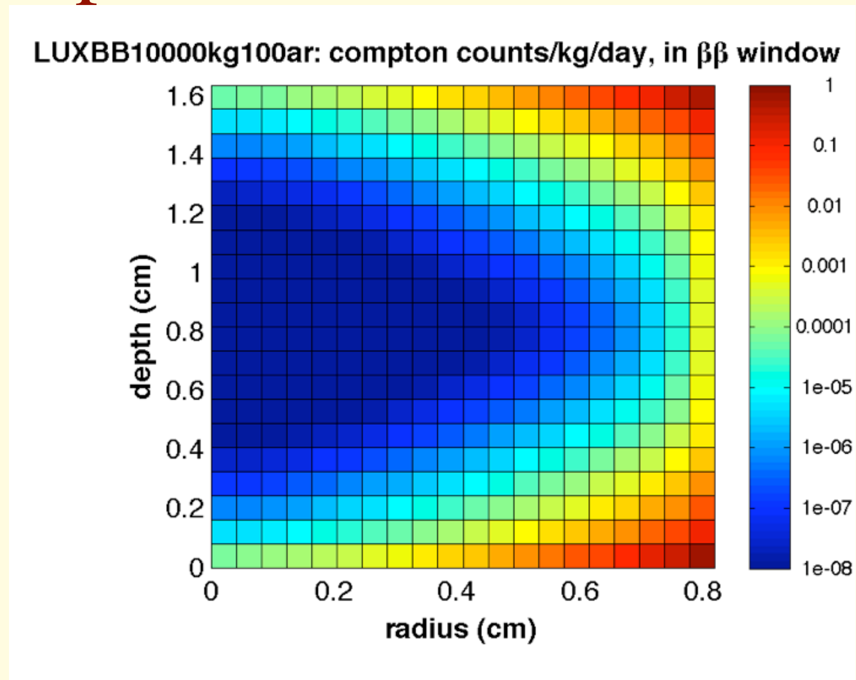


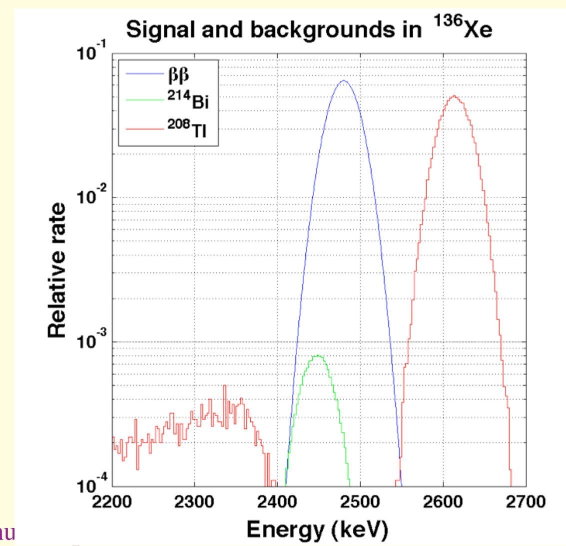
ßß decay, pp solar neutrinos

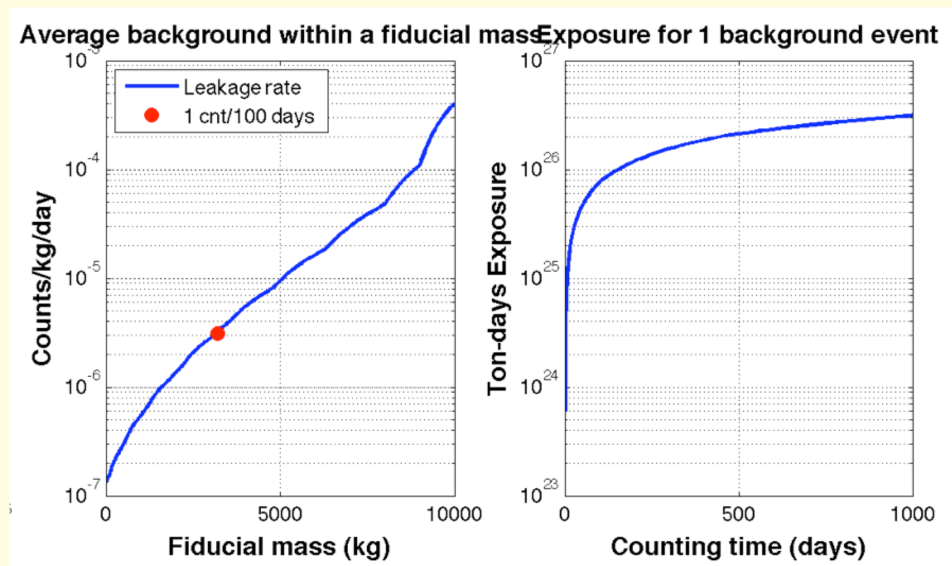
- pp neutrinos possible in Xe, and Ne.
  - Ne - need very large detector: CLEAN
  - Xe - want isotopic separation of 136Xe
  - Two phase Xe detectors ready with current technology
  - Physics goals:
    - Precision test of solar burning
    - Probe for non-standard oscillation scenarios
- Neutrinoless ßß decay of ^{136}Xe is unique opportunity
  - Need modest reduction in PMT radioactivity
    - Already demonstrated by Hamamatsu in small numbers.
  - EXO Ba tagging would provide definitive background rejection
  - 10 ton, isotopically enriched experiment can reach ~10 meV mass.

Reach of $\beta\beta$ experiment

- Highly sensitive to final resolution.
  - Background is single weak line from U decay chain.
  - Reason for optimism
- Isotopically enriched ^{136}Xe, cost ~ \$3-5M/ton (?).
- 10^{28} yr lifetime possible: ~10 meV







Conclusions

- Dark matter experiments now under construction represent a major increase in sensitivity
- Now a horse race to large scale.
- The WIMP hypothesis will be tested soon.
- Sensitive double beta decay and pp-neutrino measurements also coming.
- DUSEL is key opportunity for US to take (or lose) lead in next phase.