

The Future with Noble Liquid Detectors

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Closing in on Dark Matter
Aspen Center for Physics
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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

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

Direct WIMP Detection with Liquid Xenon

Goal: observe recoils
between a WIMP and a
target nucleus

Equation for WIMP
interaction cross section

$$\frac{dN}{dE_R} \propto \left(\frac{e^{-E_R I(E_0 r)}}{E_0 r} \right) \cdot (F^2(E_R) \cdot I)$$

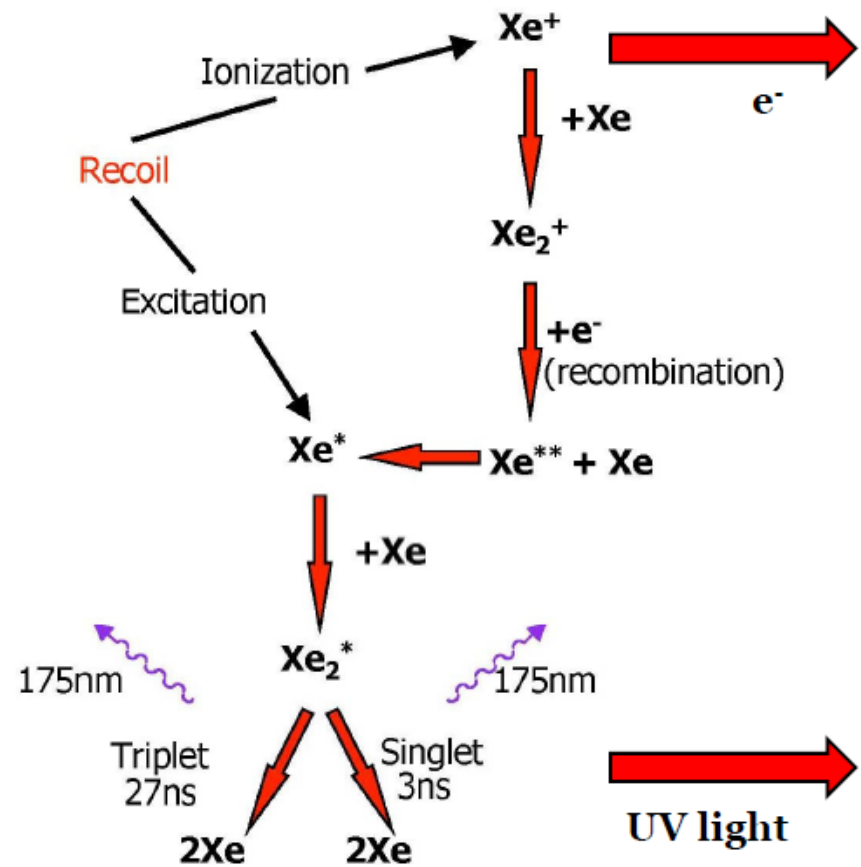
$$I \propto A^2 \quad (\text{for S.I. interactions})$$

Recoil energy deposited in
three channels:

Scintillation (photons)

Ionization (charge)

Heat (phonons)



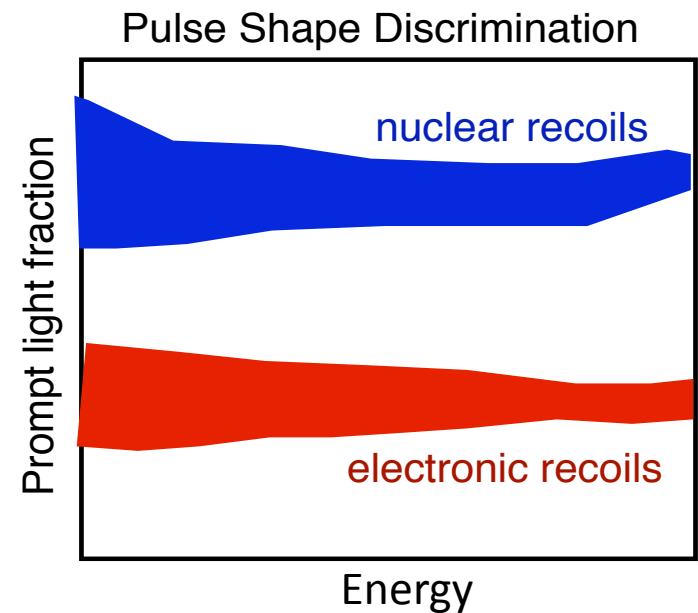
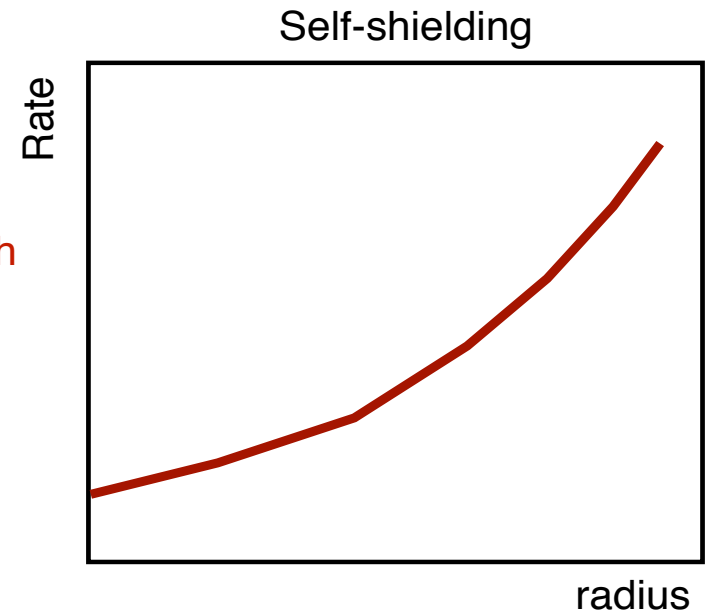
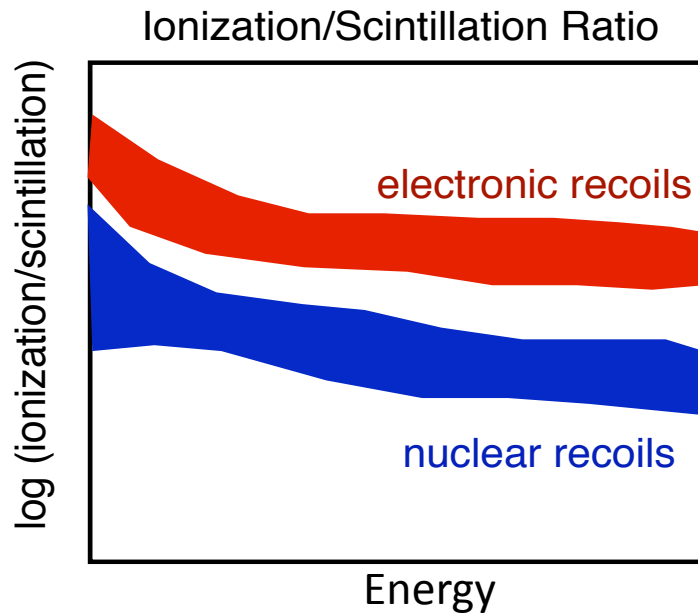
Strategies for Electronic Recoil Background Reduction in Scintillation Experiments

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

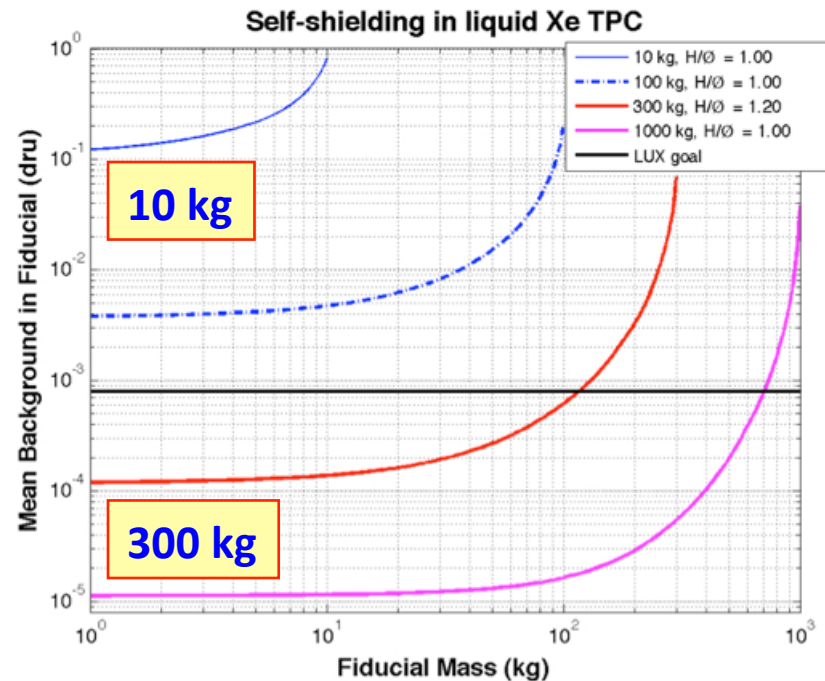
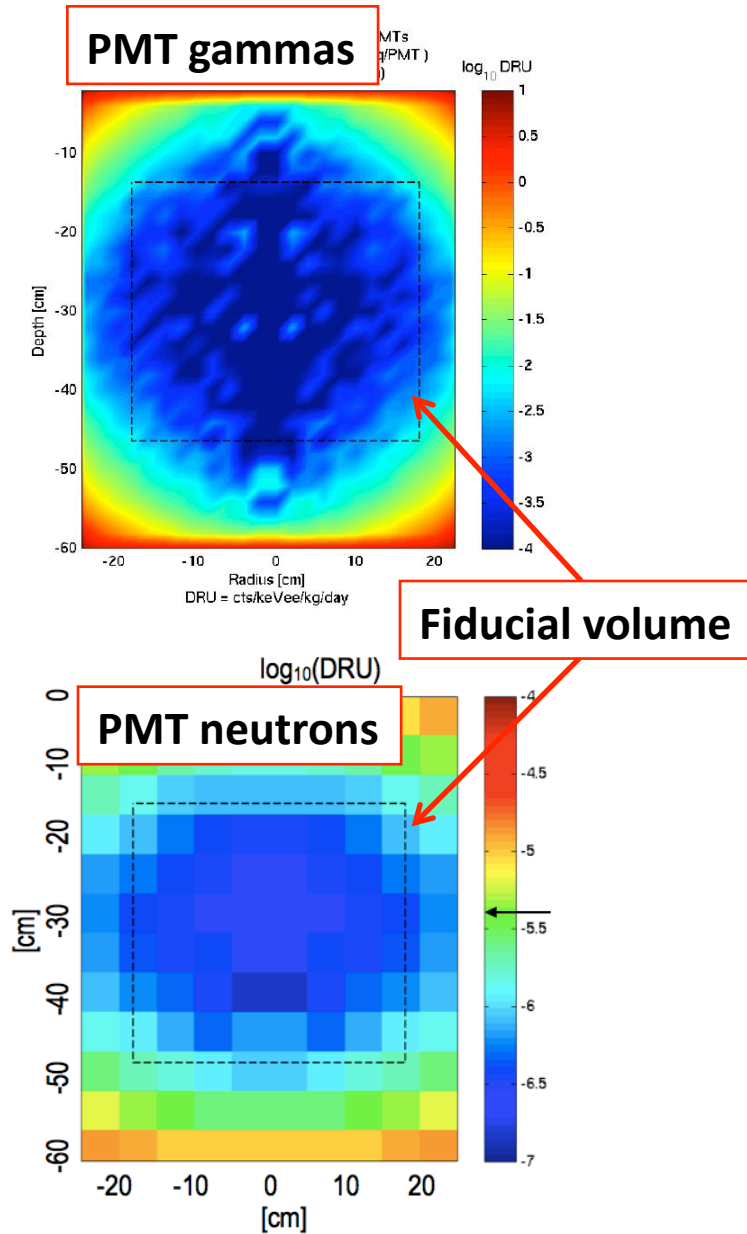


Xe Self-Shielding

Liquid xenon density = 3 g/cm^3 .

To cause a background event, gamma rays and neutrons must penetrate into the fiducial volume, scatter once, and then escape without scattering again.

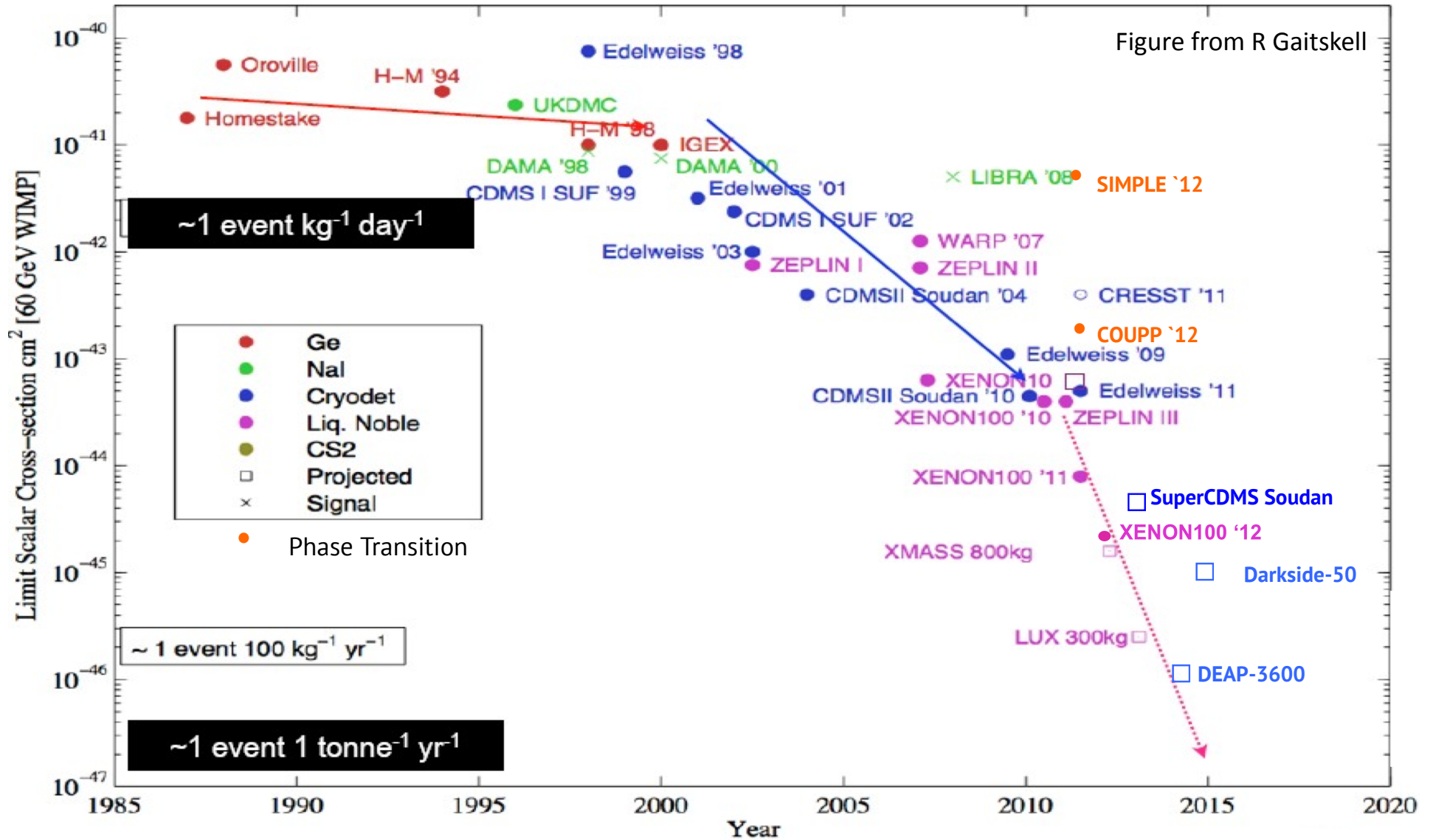
Gamma ray, neutron backgrounds drop exponentially with detector size.



Historical Trend

Dark Matter Searches: Past, Present & Future

Figure from R Gaiatskell



Lots of Noble Liquid Experiments

I won't talk about:

- MiniCLEAN, DEAP, CLEAN – K. Palladino talk.
- LUX – R. Gaitskell talk, projected sensitivity $2 \times 10^{-46} \text{ cm}^2$ by 2015.
- XENON1T – R. Lang talk, projected sensitivity $2 \times 10^{-47} \text{ cm}^2$ by 2017.
- PandaX – S. Stephenson talk, projected stage II sensitivity $\sim 3 \times 10^{-47} \text{ cm}^2$.

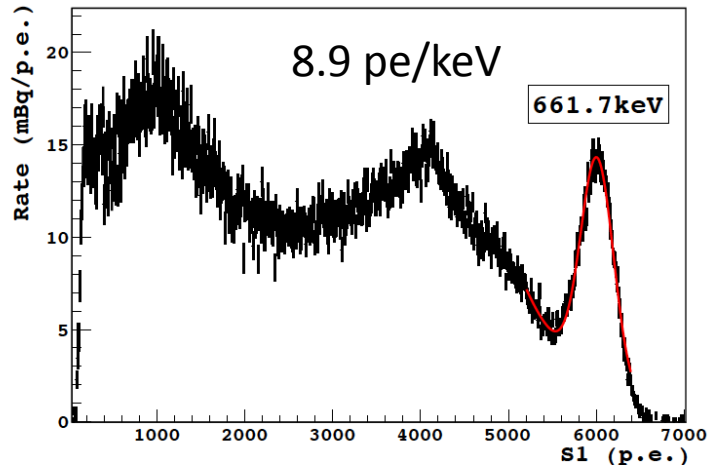
I will talk about:

- DarkSide – two phase argon
- ArDM – two phase argon
- XMASS –single phase xenon
- LZ – two phase Xe
- Liquid Helium-4 for light WIMPs

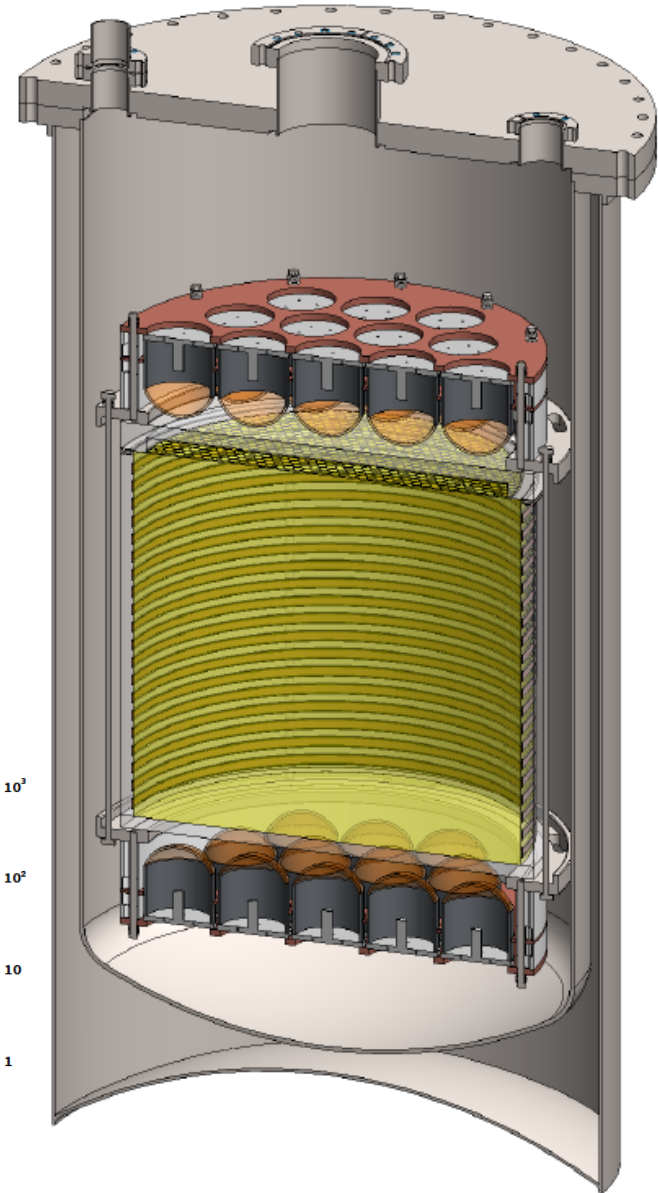
DarkSide-50

- A two-phase Argon detector.
- Funded by NSF, DOE, INFN.
- Uses both pulse shape and S2/S1 discrimination to reduce electron recoil backgrounds.
- Underground Ar, with ^{39}Ar reduced by factor > 100 . Collected 125 of 150 kg needed, production at 0.5 kg/day.
- Located in Gran Sasso
- Projected sensitivity $2 \times 10^{-45} \text{ cm}^2$.

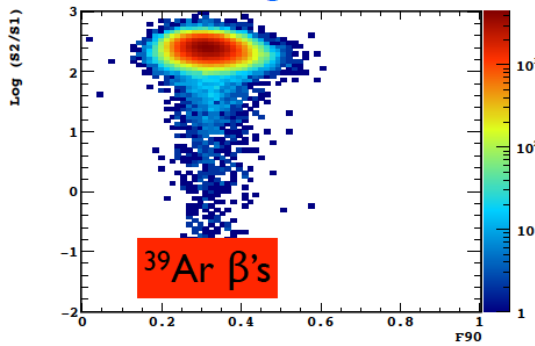
DS-10 data



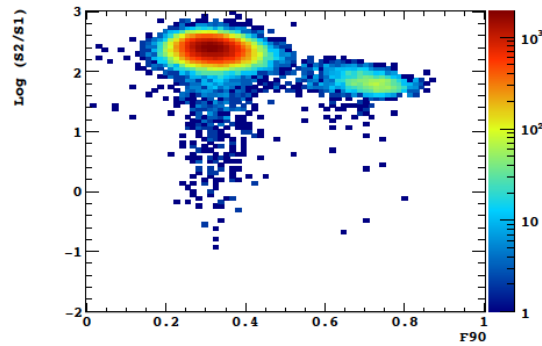
DS-50 model



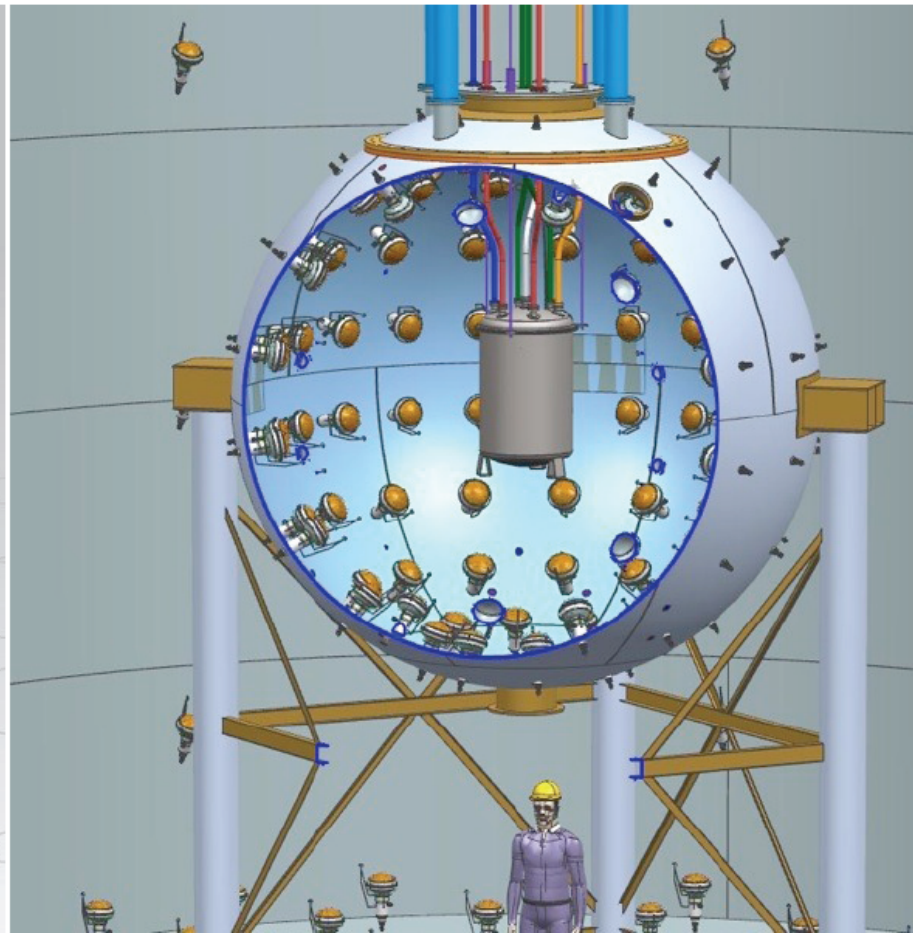
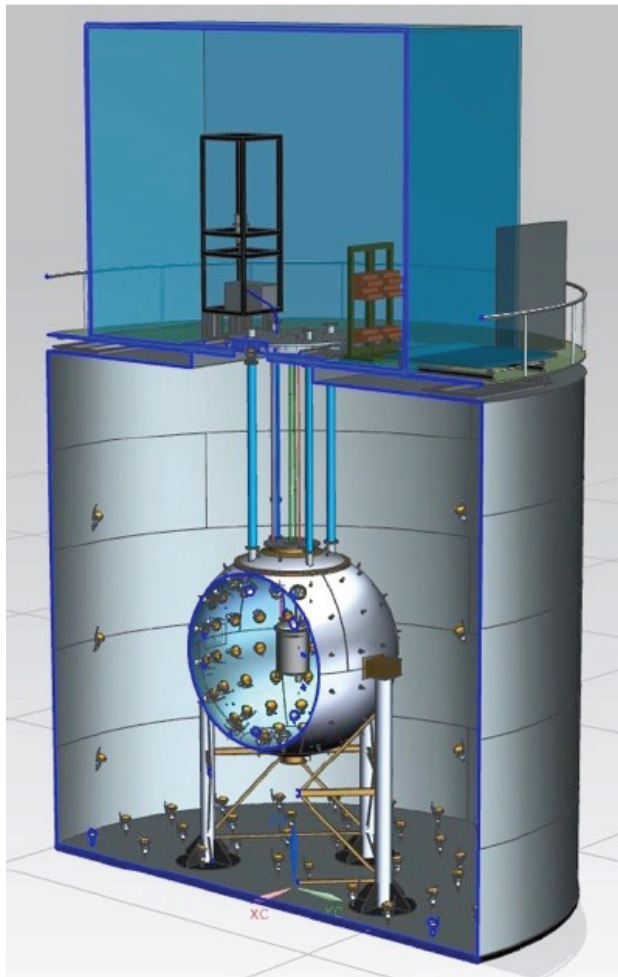
Background



Am-Be Source



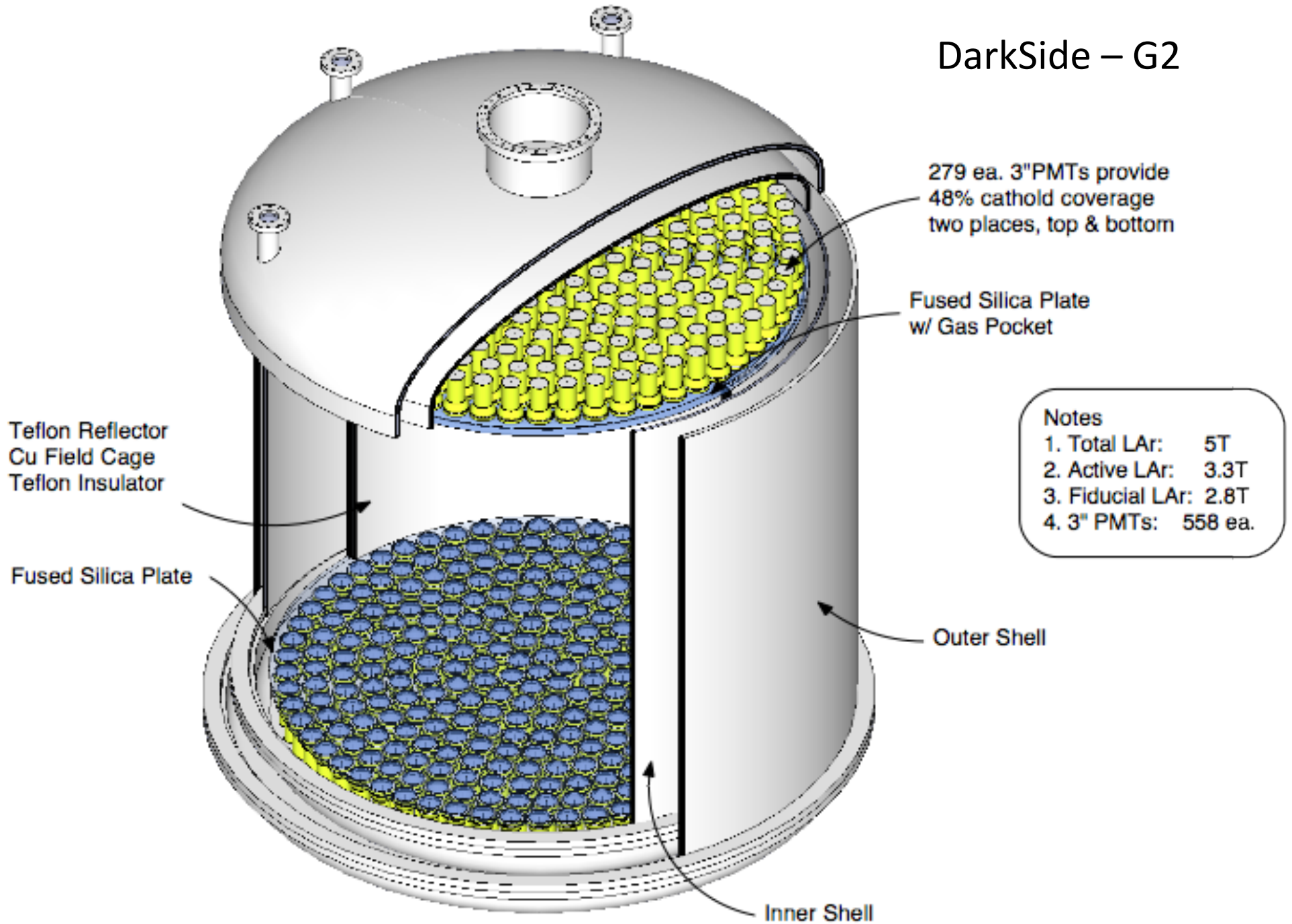
3D model of full detector



DarkSide-G2

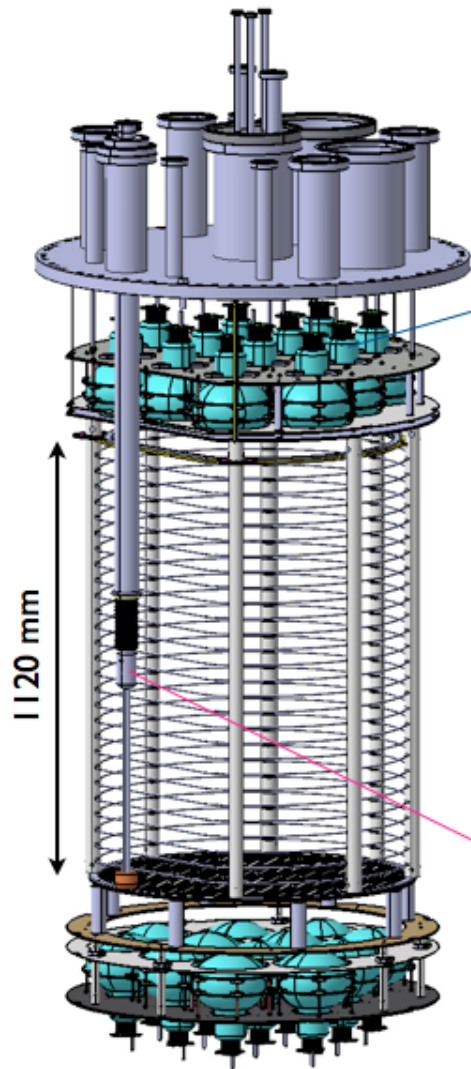
- 5 ton underground two-phase argon detector
- To be installed inside liquid scintillator neutron veto and water Čerenkov muon veto already built for DarkSide-50
- Sensitivity reach 10^{-47} cm²

DarkSide – G2



ArDM

Slide from A. Rubbia



Fully PMT-based readout
(initial configuration)

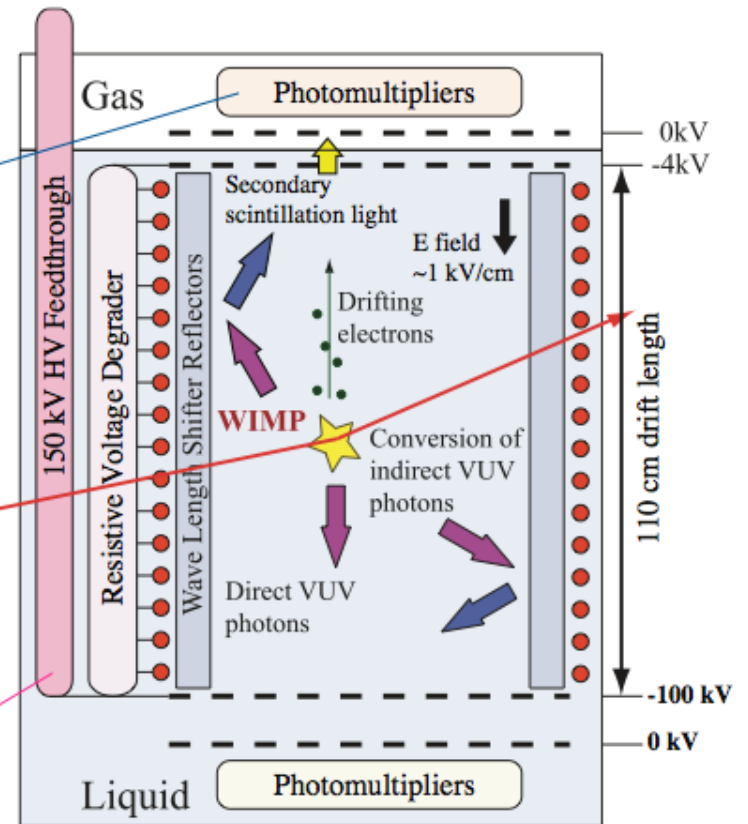
Top PMT array in gas phase
and bottom array in liquid,

both will be newly built :

- ▶ new PMT supporting structure
- ▶ new layout with 12 PMTs
- ▶ fresh coating with wave-length shifting TPB

HV feedthrough
for drift field

Modified field cage



Canfranc Underground Laboratory (LSC)

- Location: Somport tunnel in the Pyrenees
- 850 m below „El Tobazo“:
 - 2450 meters water equivalent of shielding from cosmic rays
 - μ flux $\approx 2 \cdot 10^{-7} \mu/(\text{cm}^2 \cdot \text{s})$
- Low background environment
 - n flux $\approx 3.8 \cdot 10^{-6} \text{ n}/(\text{cm}^2 \cdot \text{s})$
- The cryogenic system and the control system of ArDM have been installed at LSC in February 2012.
- A neutron shield (50 cm thick PE blocks) reduces the expected neutron events, originating from the rock, in the region of interest to 0.08 n/day.

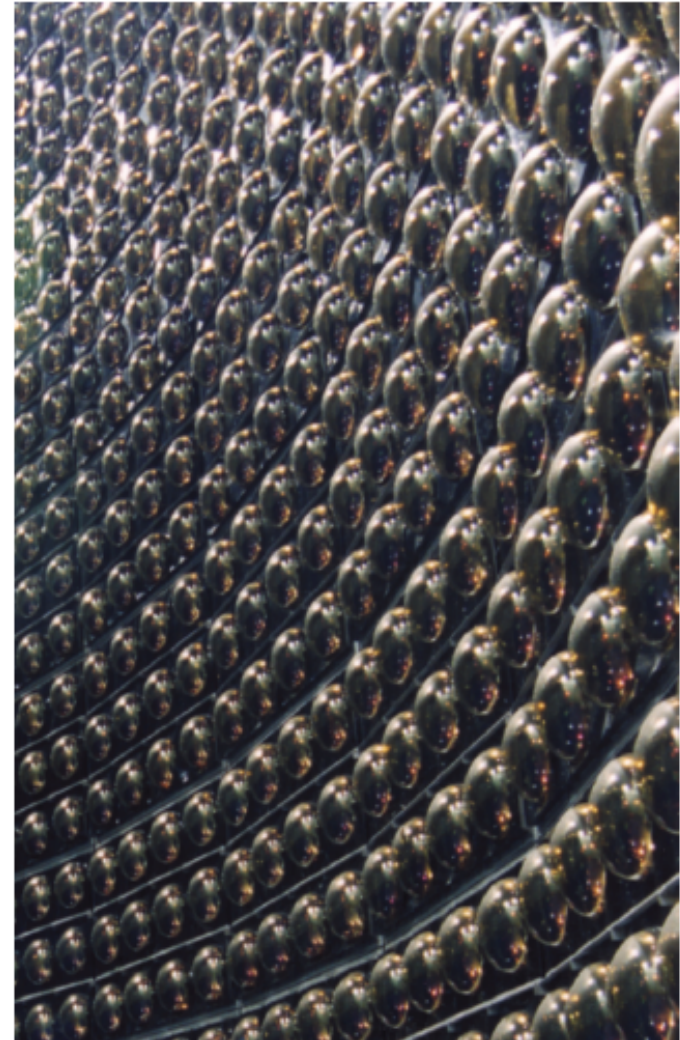


XMASS 1.5

(Slide from Y. Suzuki)

XMASS 1.5

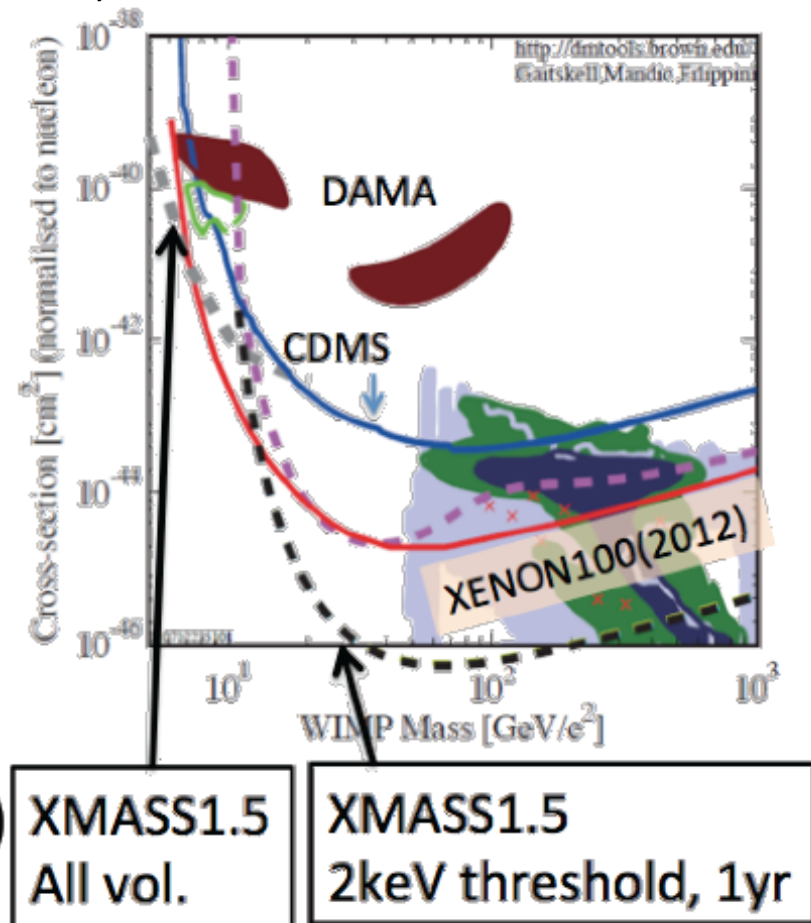
- Total mass: 5 tons
- Fiducial mass: 1 ton ← 100kg
- Backgrounds
 - No dirty aluminum
 - No GORETEX
 - Less surface ^{210}Pb
- Identify surface BG
- → PMT w/ round shape windows



Sensitivity of XMASS1.5

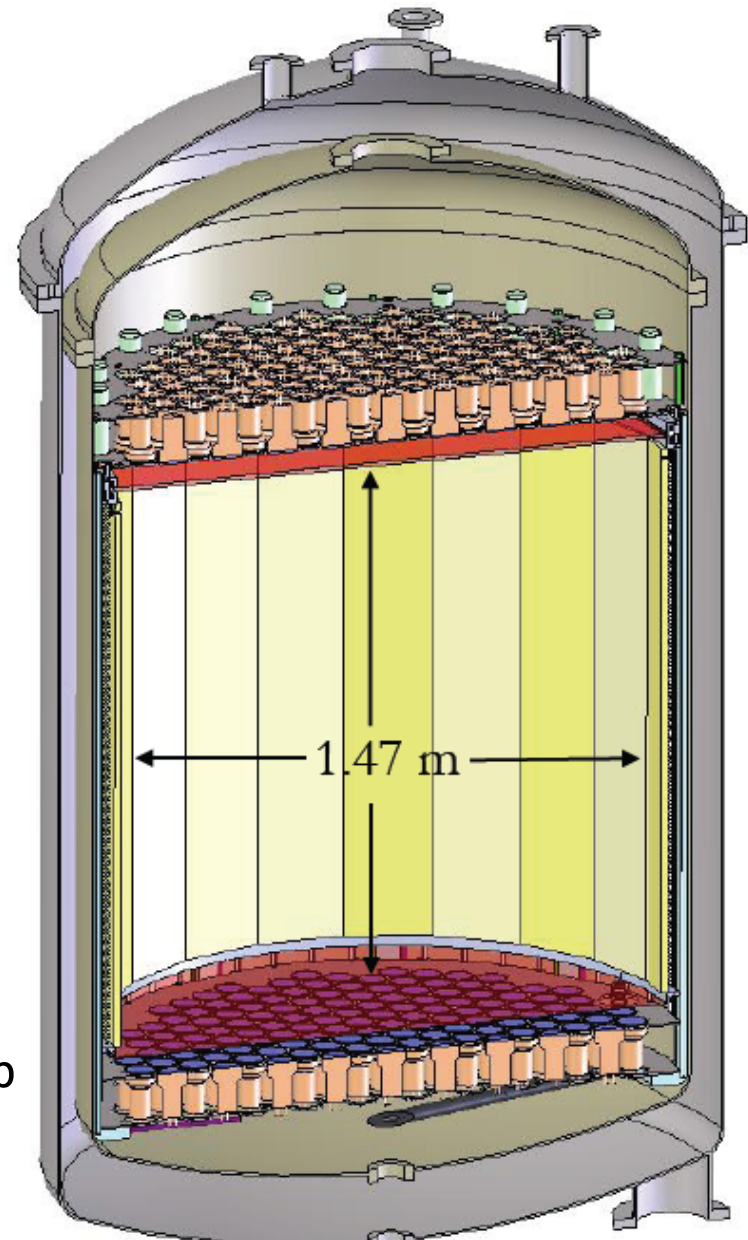
(Slide from Y. Suzuki)

- BG level: 10^{-5} dru
- sensitivity: $\sigma_{SI} < 10^{-46} \text{ cm}^2$ (> 5 keV)
- Low mass sensitivity:
 - \rightarrow a few $\times 10^{-42} \text{ cm}^2$ (a few GeV region)
- ALP search : improve O(2):
(DM axions, Solar axions
[Bremsstrahlung and Compton])



LZ Dark Matter Detector

- LZ = LUX + ZEPLIN
- Currently in development phase
 - NSF, DOE, and SDSTA funding
- Two-component veto system
 - 75-cm thick Gd-doped LAB scintillator shield
 - Instrumented LXe “skin”
 - Effective for both neutrons and gammas
- 20-fold scale-up from LUX mass
- Ultralow background Ti cryostat
- Low background R11410 PMT readout
- Thermosyphon cryogenics
- Fits in existing Davis cavern water shield
- DOE project organization, with LBL lead lab
- Projected sensitivity $\sim 2 \times 10^{-48} \text{ cm}^2$



S2/S1 Discrimination in LXe

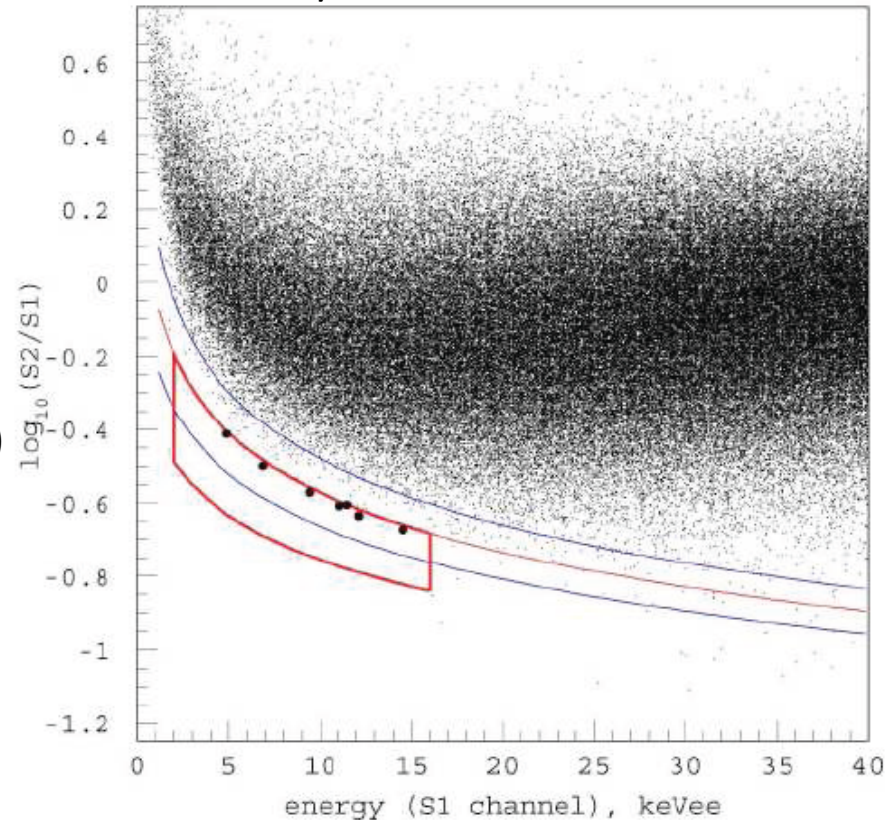
Neutrinos produces an electron recoil
background of $1.2e-5$ events/keVee/kg/day

In LZ, 99.5% baseline assumption predicts
3.6 events from pp solar neutrino electron
scattering in 1000 days.

Also, have two-neutrino double beta decay
of Xe-136 (though subdominant to
pp solar neutrinos for WIMP recoil energies)

Reduce these backgrounds through
higher field, to reject these electron recoils
via S2/S1 ratio?

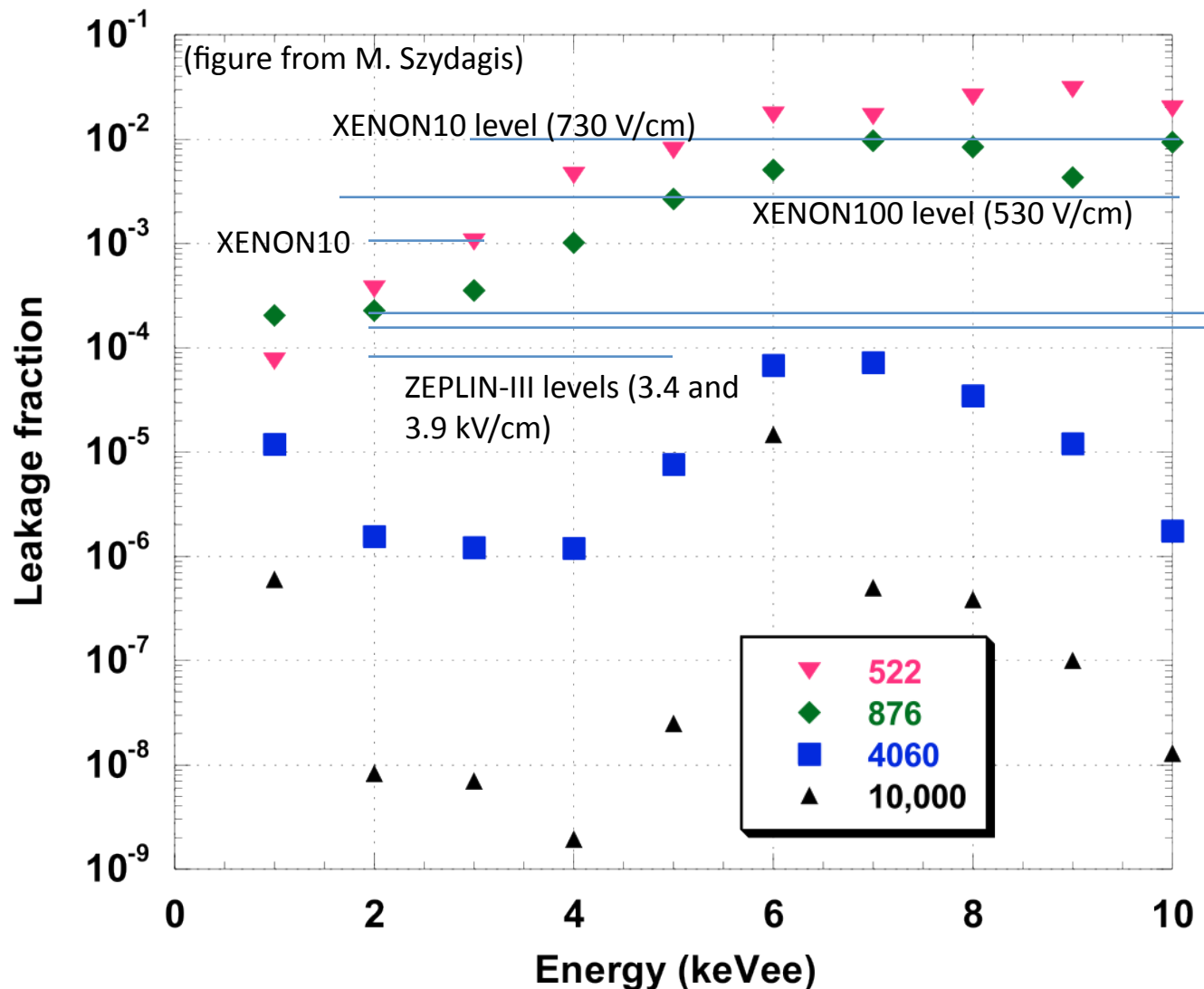
ZEPLIN-III saw 99.99% discrimination
at 3.9 kV/cm



Discrimination vs. Electric Field

500 kV on the LZ cathode should allow ZEPLIN-III levels of discrimination ($\sim 99.99\%$)
ZEPLIN-III is an existence proof that such fields can be reached without a cathode electroluminescence problem.

- The $\log_{10}(S_2/S_1)$ ER and NR bands are getting thinner with field AND pulling away from each other, even in the Thomas-Imel regime (low energies) where they are essentially parallel curves
- As field increases, the number of electrons pulled out increases, but it increases MORE for ER than for NR, which changes slowly



Two-phase Xe beyond XENON1T and LZ

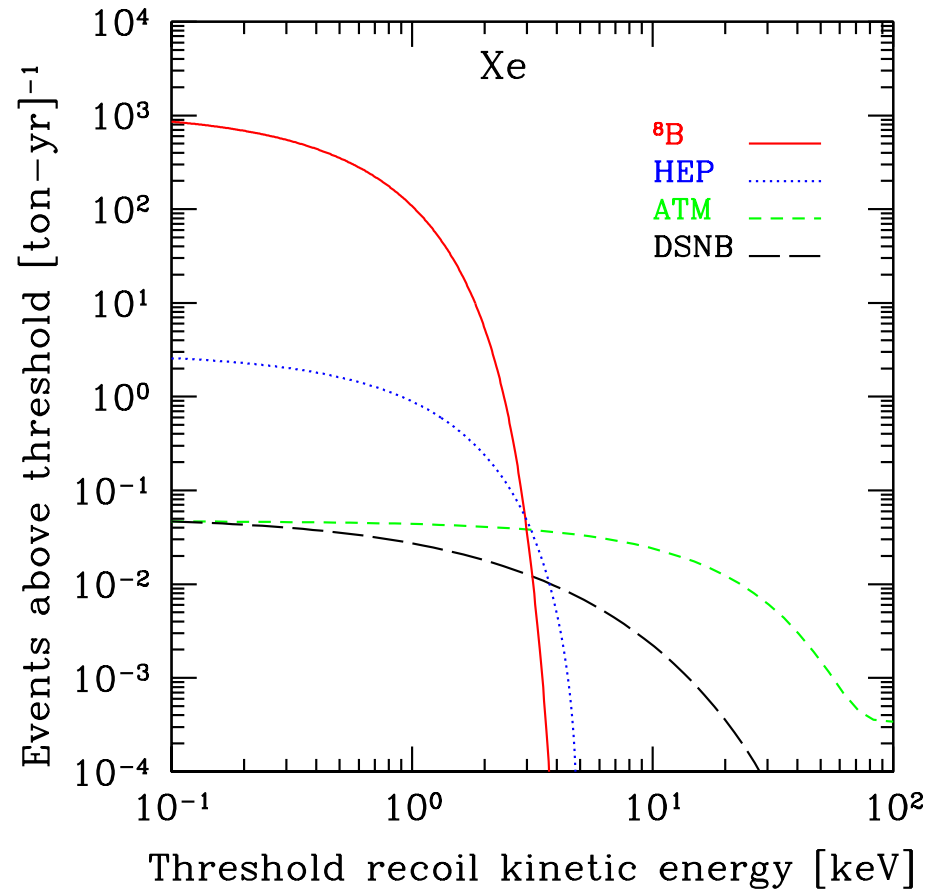
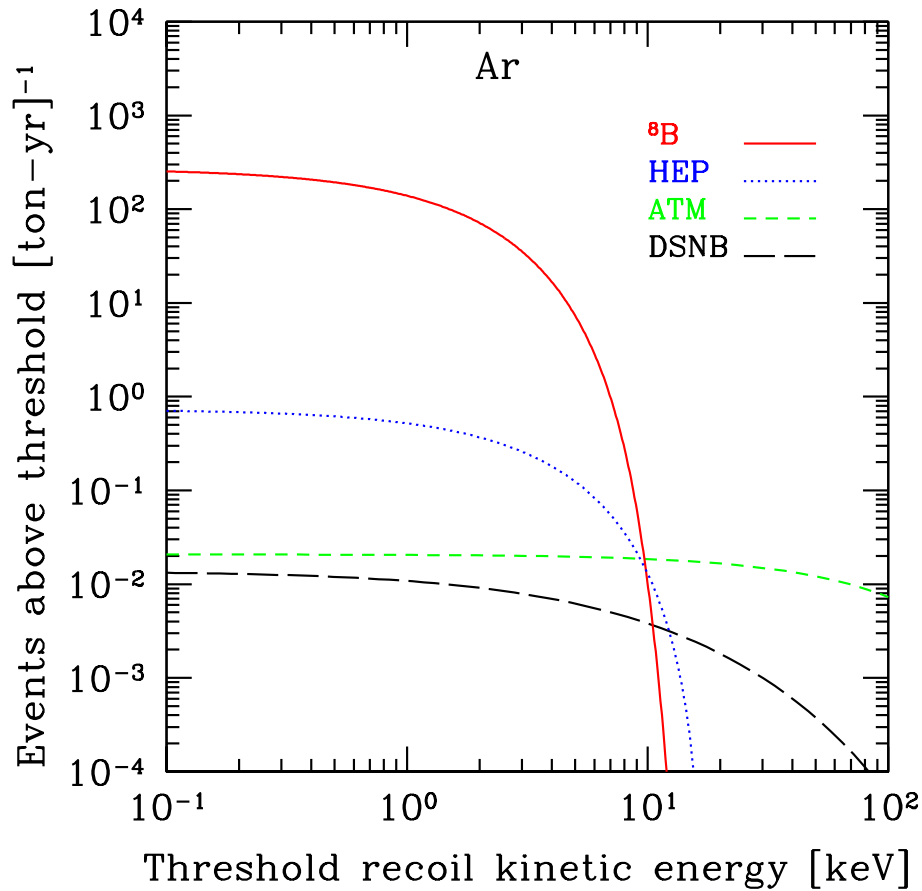
Option 1: Keep scaling bigger

- Optimize cost per kg, since readout cost scales with surface area.
- Neutron and gamma ray backgrounds will drop further with self-shielding.
- Favorable for ^{136}Xe neutrinoless double beta decay, where main background is 2.5 MeV gamma rays?
- But main dark matter background is neutrinos, which cannot be shielded.

Option 2: Many modules (7-10 tonnes each)

- Dark matter background dominated by neutrinos, so why keep scaling up?
- Solar neutrino and $2\nu\text{BB}$ backgrounds minimized with higher drift fields, so if cathode voltage is limitation then smaller detectors may have smaller neutrino backgrounds.
- Cost savings from not having to keep redesigning – just build more modules.
- Different modules could have different isotope compositions (high Xe isotope masses 134 and 136 for $0\nu\text{BB}$ and spin-independent dark matter, while low 129 and 131 masses used for spin-dependent dark matter, solar neutrinos).

Ultimate limits from neutrino-nucleus coherent scattering (L. Strigari, New J. Phys. 11 (2009) 105011)



Superfluid helium as a detector material

- **Used to produce, store, and detect ultracold neutrons.** Detection based on scintillation light (S1)
 - Measurement of neutron lifetime: P.R. Huffman et al, Nature **403**, 62-64 (2000).
 - Search for the neutron electric dipole moment: R. Golub and S.K. Lamoreaux, Phys. Rep. **237**, 1-62 (1994).
- Proposed for **measurement of pp solar neutrino flux** using roton detection (HERON): R.E. Lanou, H.J. Maris, and G.M. Seidel, Phys. Rev. Lett. **58**, 2498 (1987).
- Proposed for **WIMP detection** with superfluid He-3 at 100 microK (MACHe3): F. Mayet et al, Phys. Lett. **B 538**, 257C265 (2002)

Light WIMP Detector Kinematic Figure of Merit

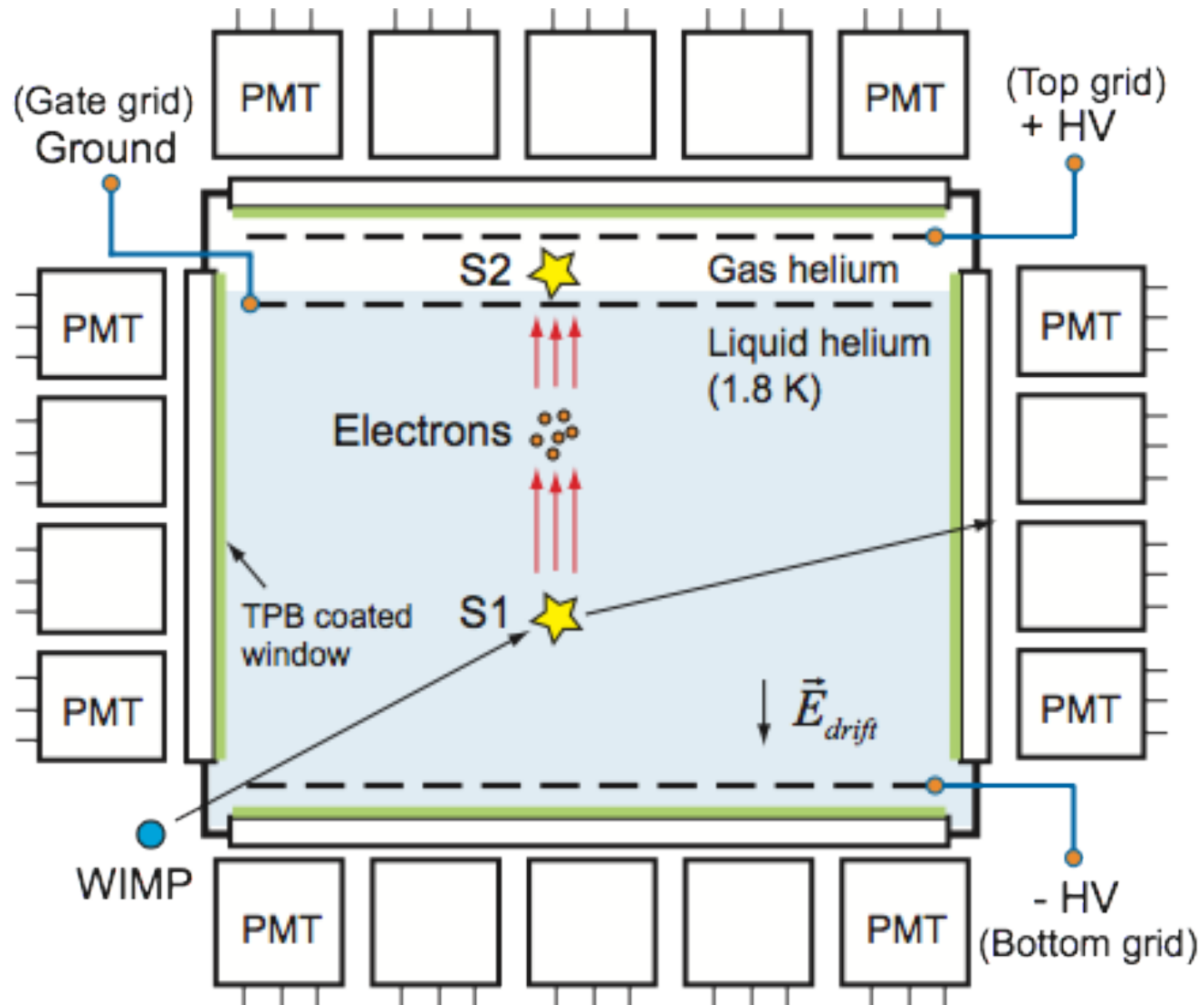
It is more difficult for heavy targets to be sensitive to light WIMPs, since for typical energy thresholds they are only sensitive to a small part of the WIMP velocity distribution. The lower limit of the WIMP-target reduced mass at which a detector can be sensitive is given by

$$r_{\text{limit}} = 1/v_{\text{esc}} * \text{sqrt}\{E_t M_T/2\}$$

where v_{esc} is the Galactic escape velocity of 544 km/s, E_t is the energy threshold, and M_T is the mass of the target nucleus. In the limit of small dark matter mass, the reduced mass is the mass of the dark matter particle.

So for reaching sensitivity to small dark matter masses, the kinematic figure of merit is the **product of the energy threshold and the target mass**, which should be minimized.

Light WIMP Detector Concept

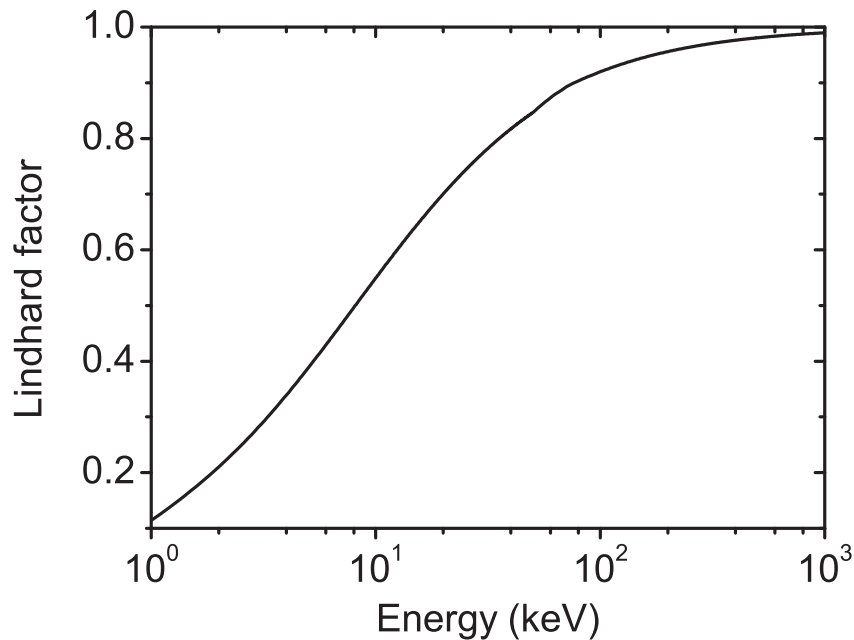


How to detect the charge signal?

Many options:

- Proportional scintillation and PMTs (like in 2-phase Xe, Ar detectors)
- Gas Electron Multipliers (GEMs) or Thick GEMs, detect light produced in avalanche.
- Micromegas, detect avalanche light.
- Thin wires in liquid helium. This should generate electroluminescence at fields $\sim 1-10$ MV/cm near wire, and is known to happen in LAr and LXe.
- Roton emission by drifting electrons (should be very effective at low helium temperature, analogous to Luke phonons in CDMS).

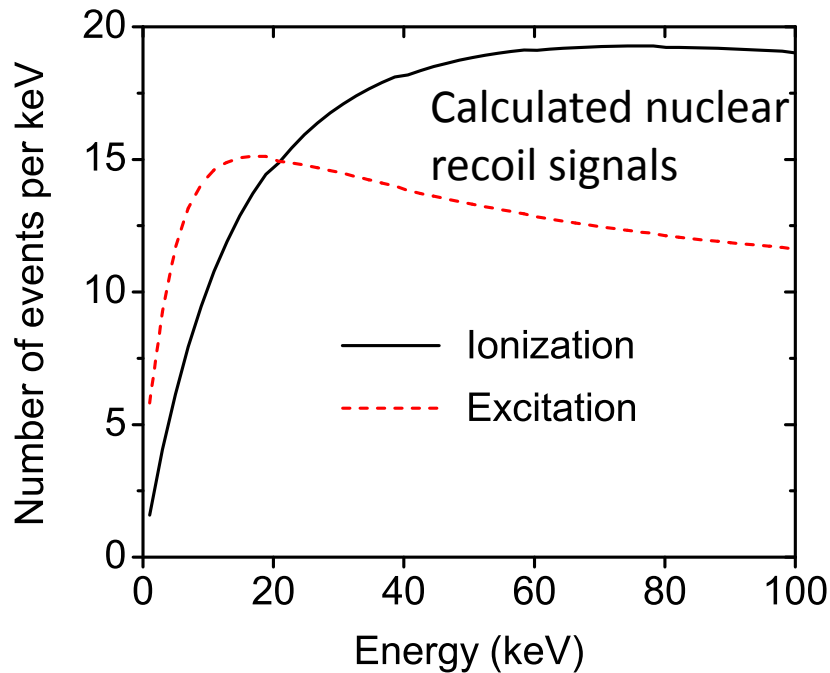
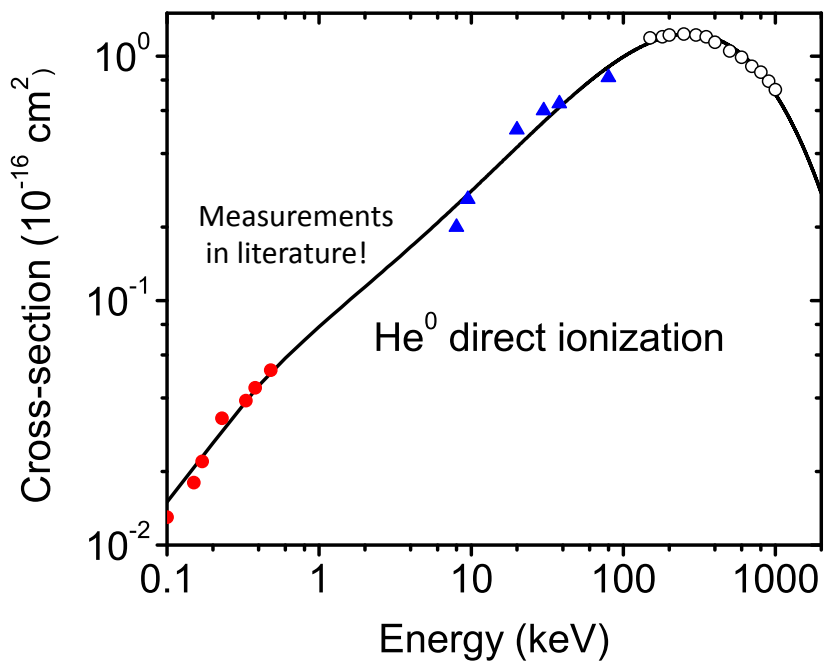
Charge will drift at ~ 1 cm/ms velocities. Slower than LAr/LXe, but pileup manageable for low background rates.



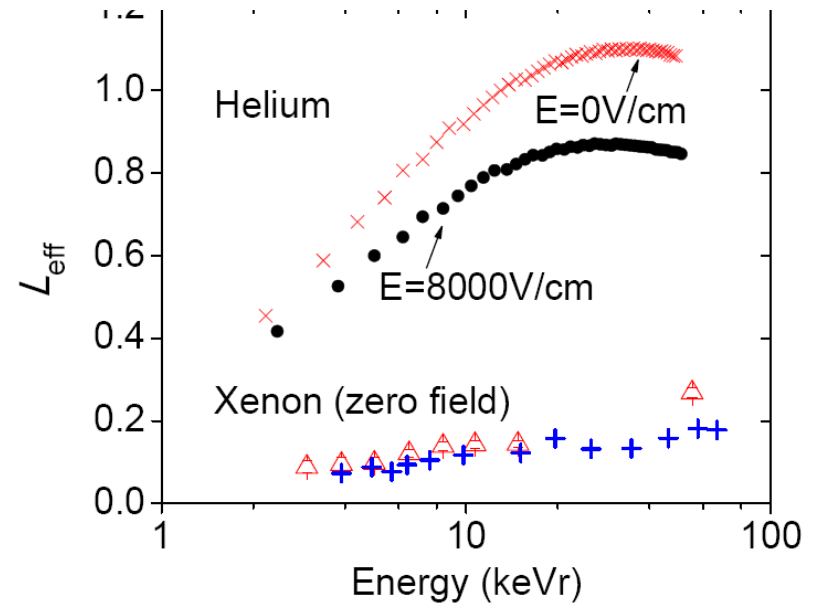
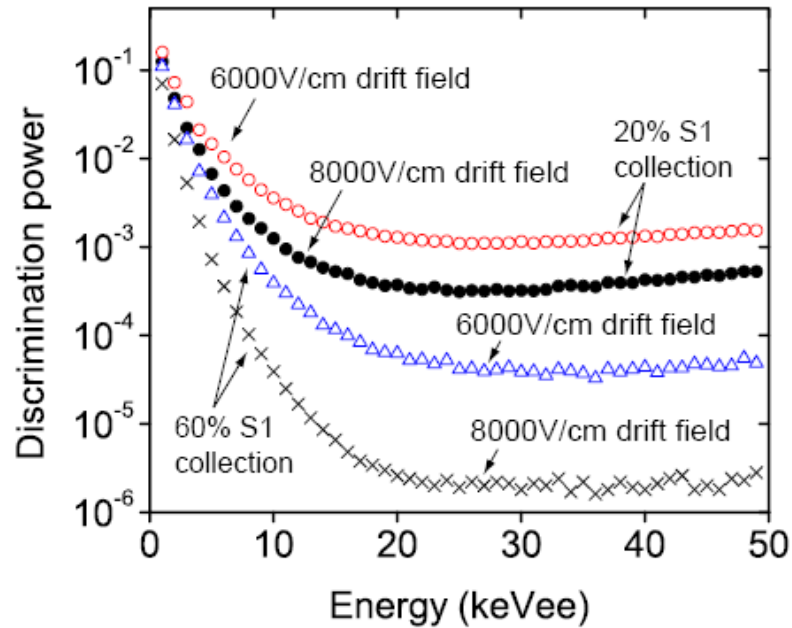
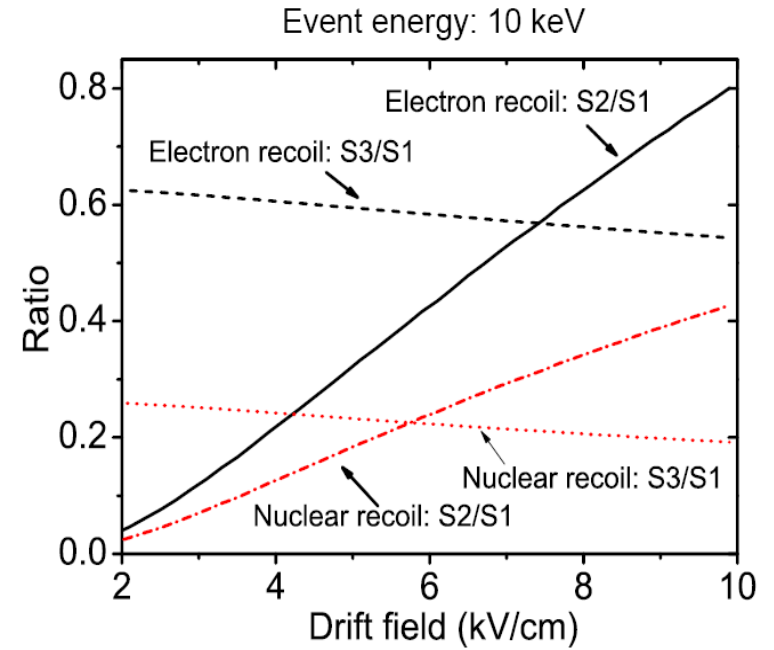
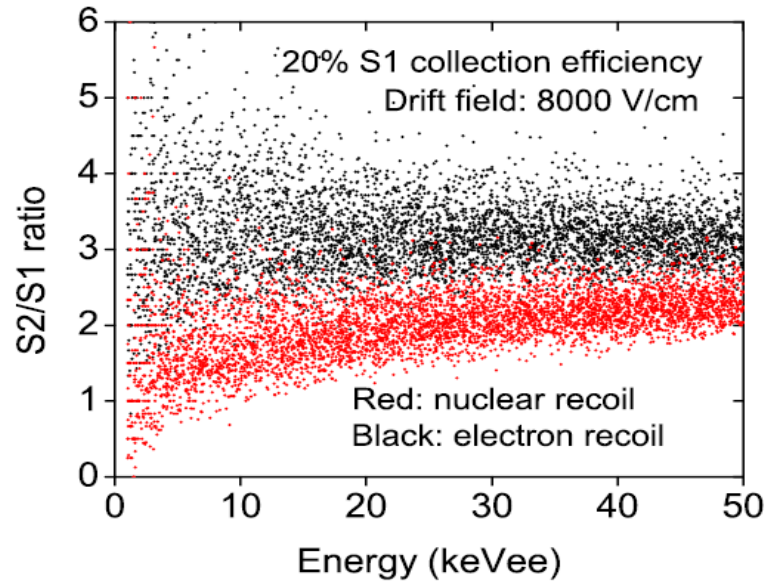
Liquid helium-4 predicted response
(Guo and McKinsey, just submitted to arXiv)

Lower electron scintillation yield (19 photons/keV)

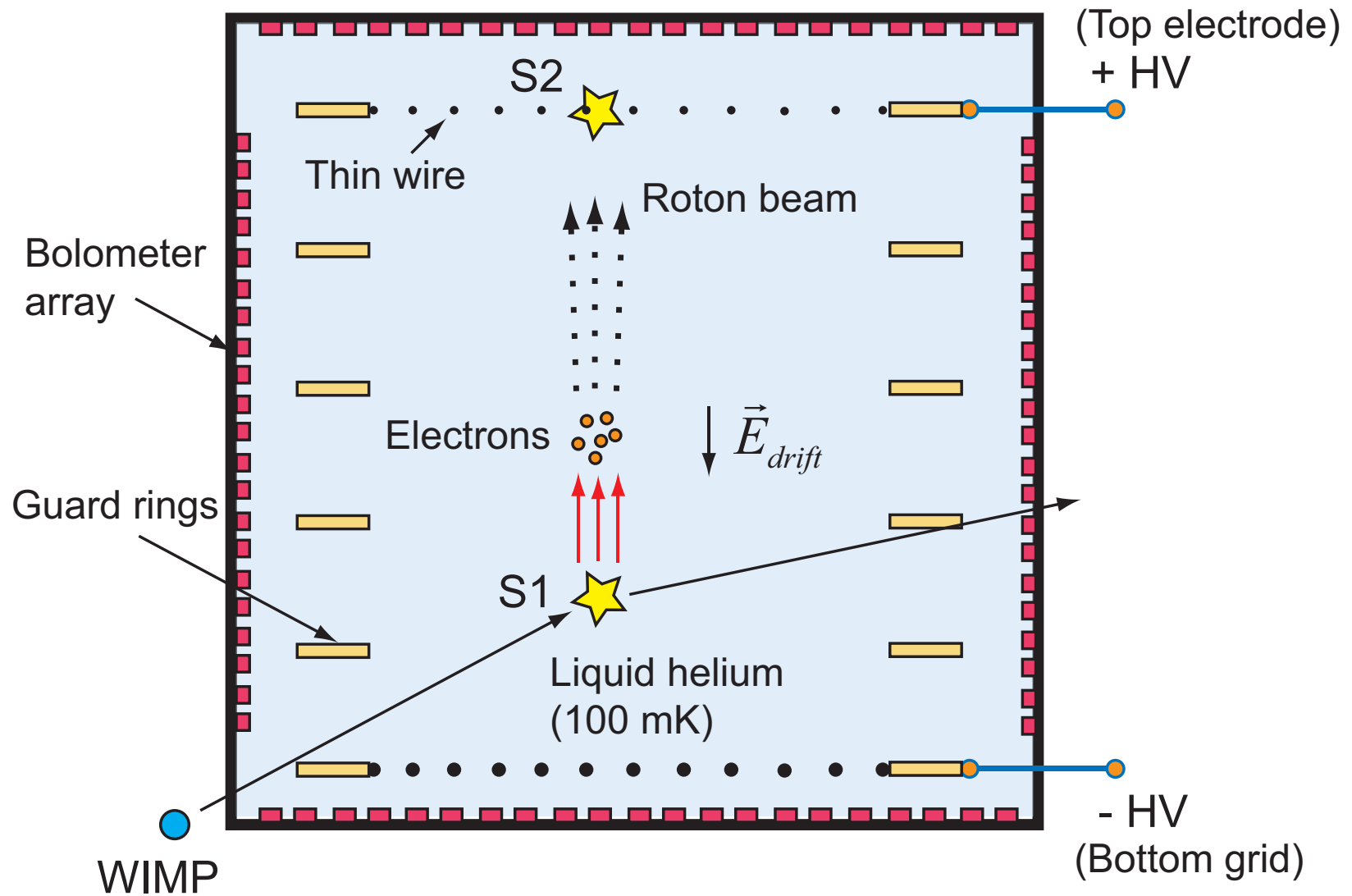
But, extremely high L_{eff} , good charge/light discrimination and low nuclear mass for excellent predicted light WIMP sensitivity



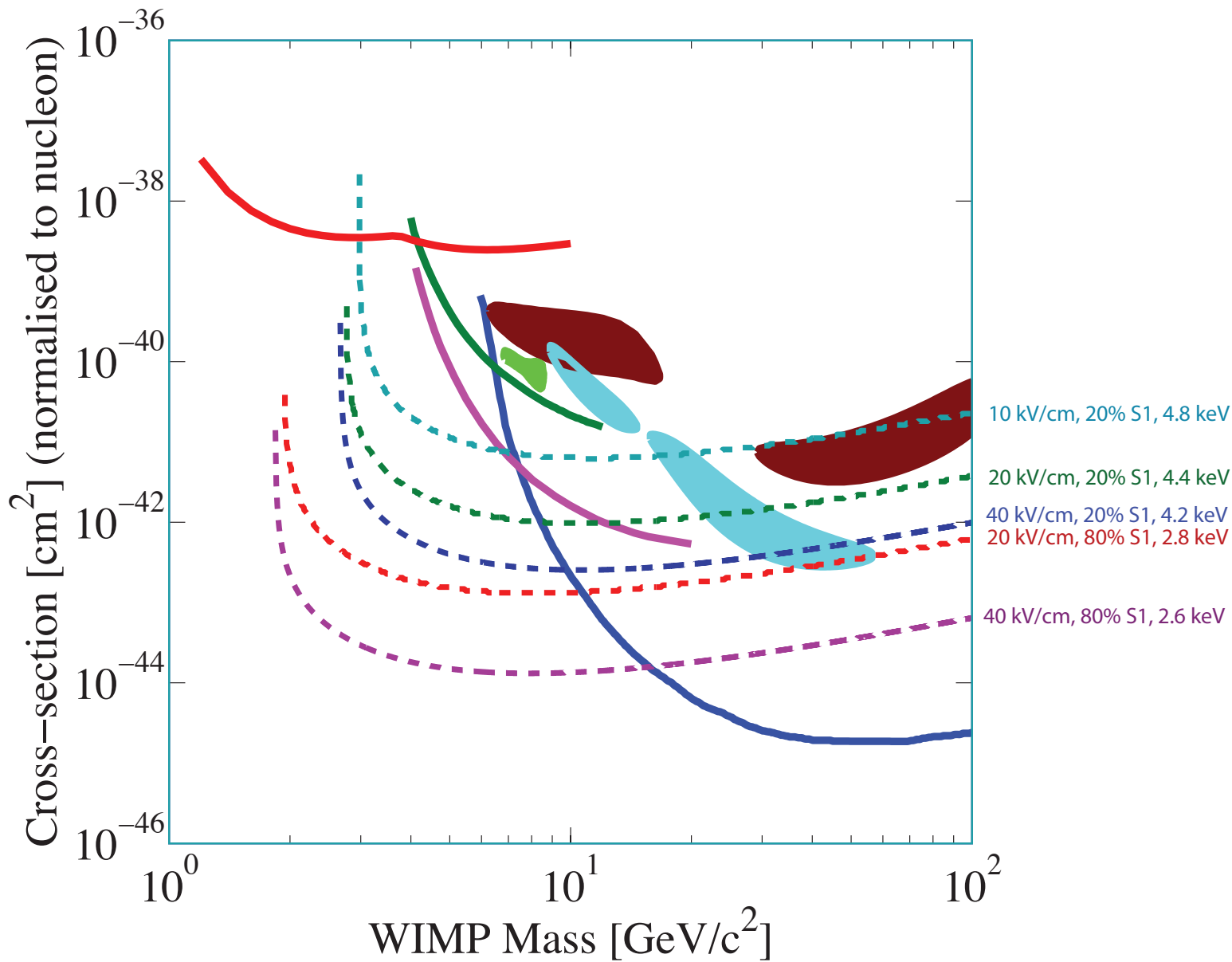
Predicted nuclear recoil discrimination and signal strengths in liquid helium



Concept for a Light WIMP Detector at ~ 100 mK



Projected Sensitivity for Liquid Helium



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Very high scintillation yields

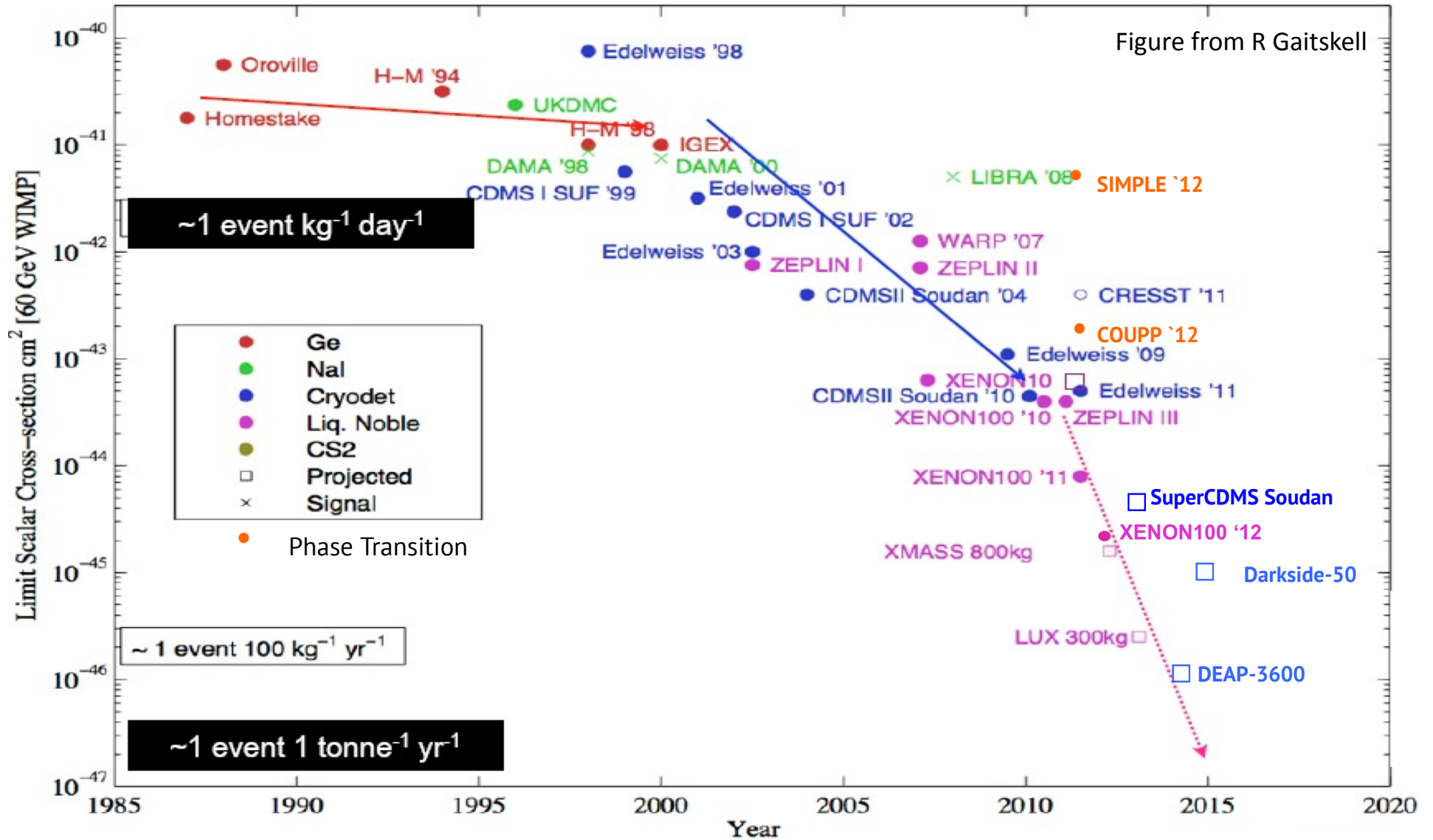
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Dark Matter Searches: Past, Present & Future

Figure from R Gaiatskell



Vive la Revolution!

