Dark Matter Direct Detection Experimental Summary

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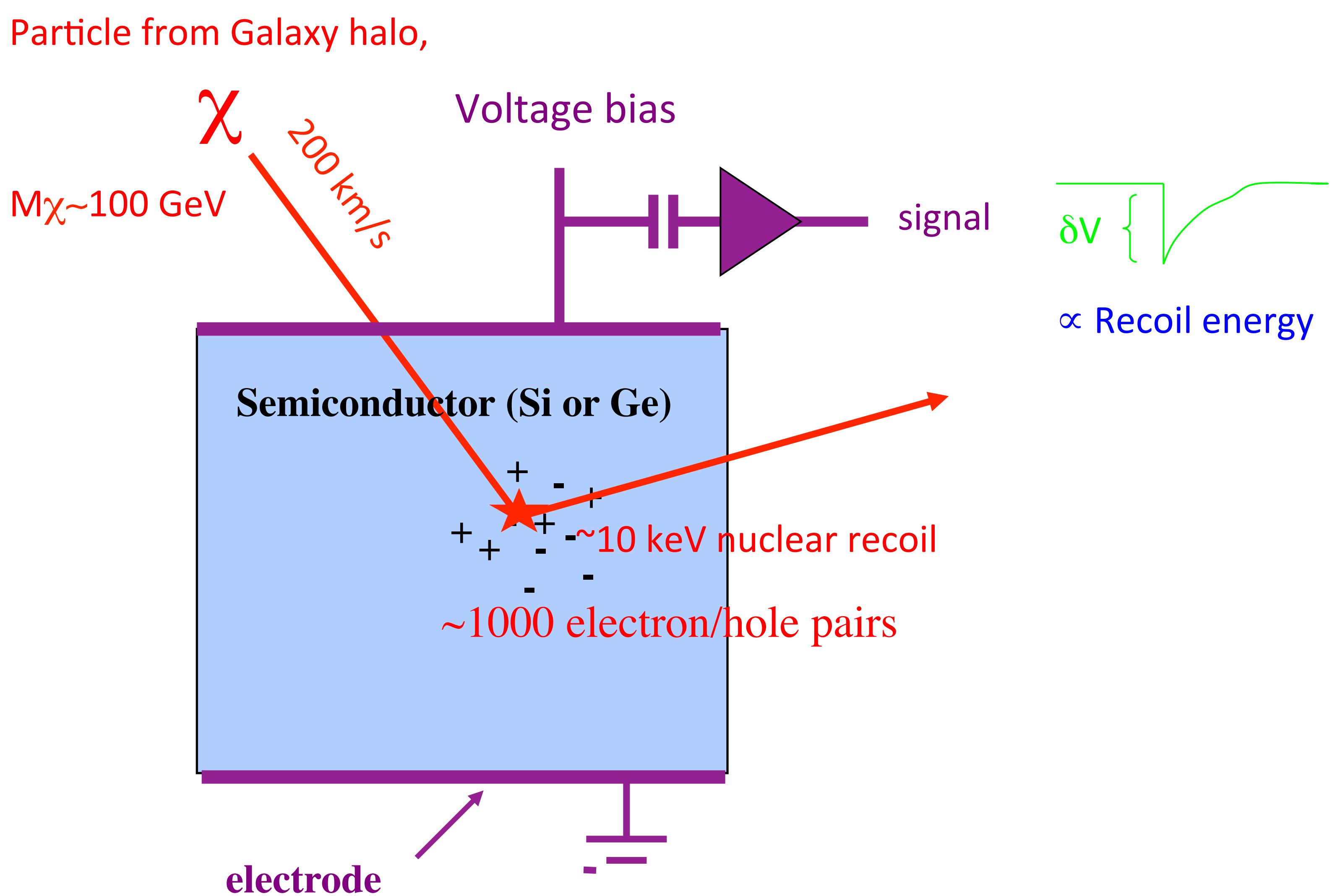
Fermilab

Dec. 4, 2015

Contents

- WIMP detection principles
- Background discrimination techniques
- Noble Liquids: xenon, argon
- Bubble Chambers
- Cryogenic Detectors
- Semiconductors

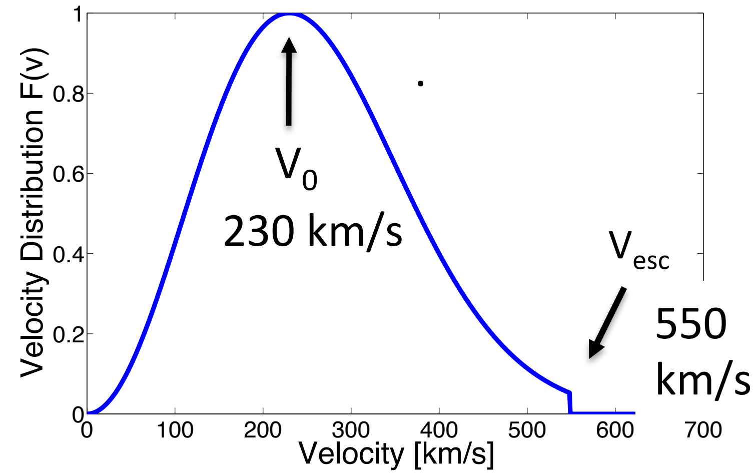
Generic 1st Generation WIMP Detection Experiment ca 1987



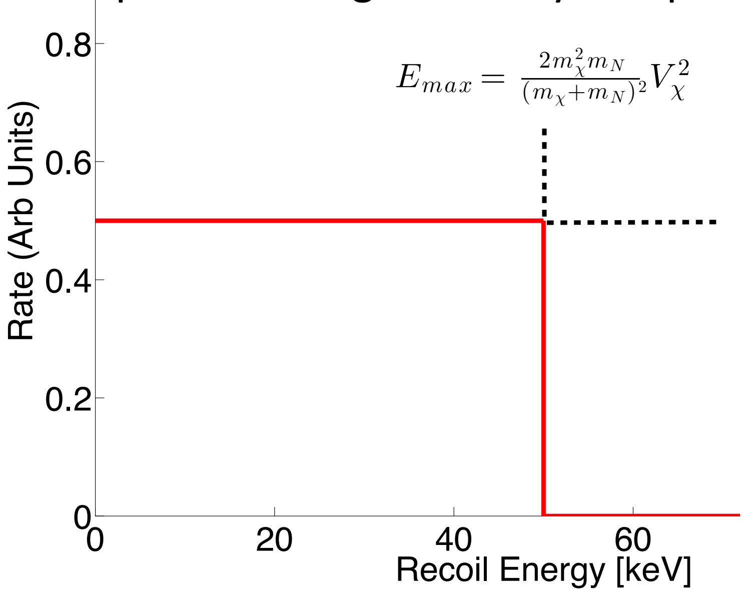
Nuclear Recoil Signal from WIMPs-Ingredients

- WIMP spectrum in a detector is obtained by convolution of monoenergetic detector response with modeled dark matter velocity distribution.
- Standard dark matter density is 0.3 GeV/cm^3

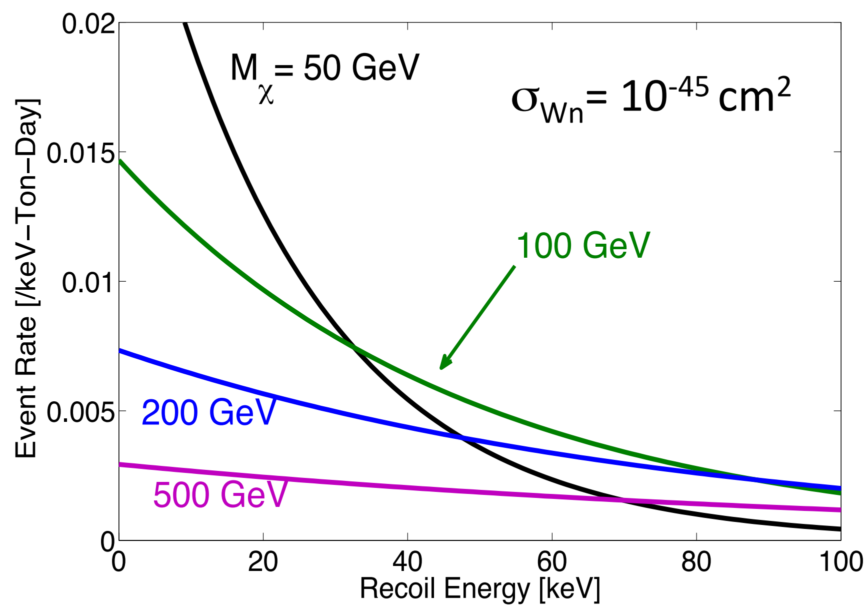
Standard Halo Model WIMP Velocity Distribution



Response to single velocity component

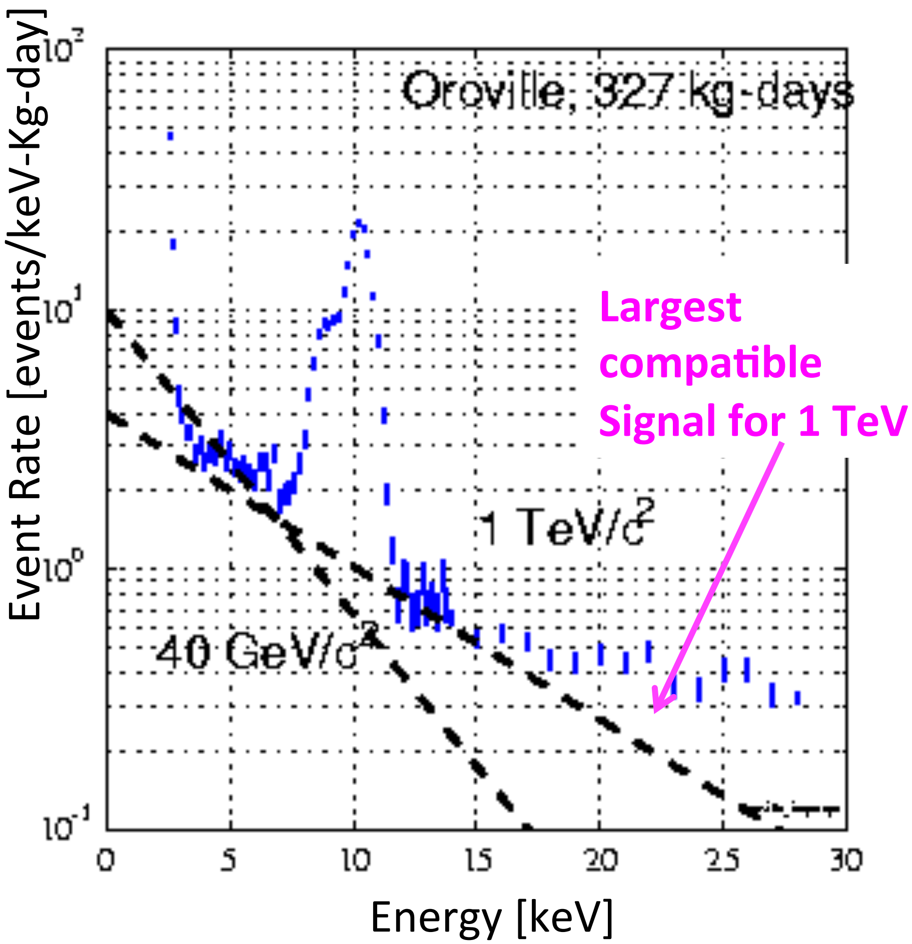


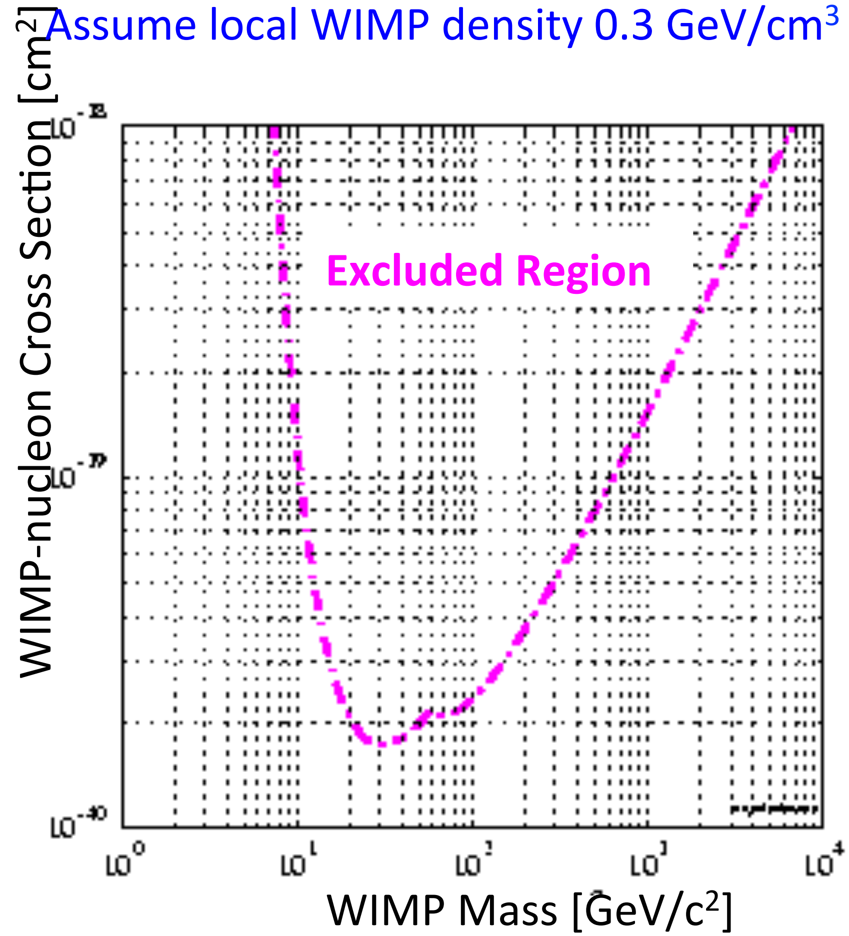
Energy Spectrum for WIMP recoils on Germanium



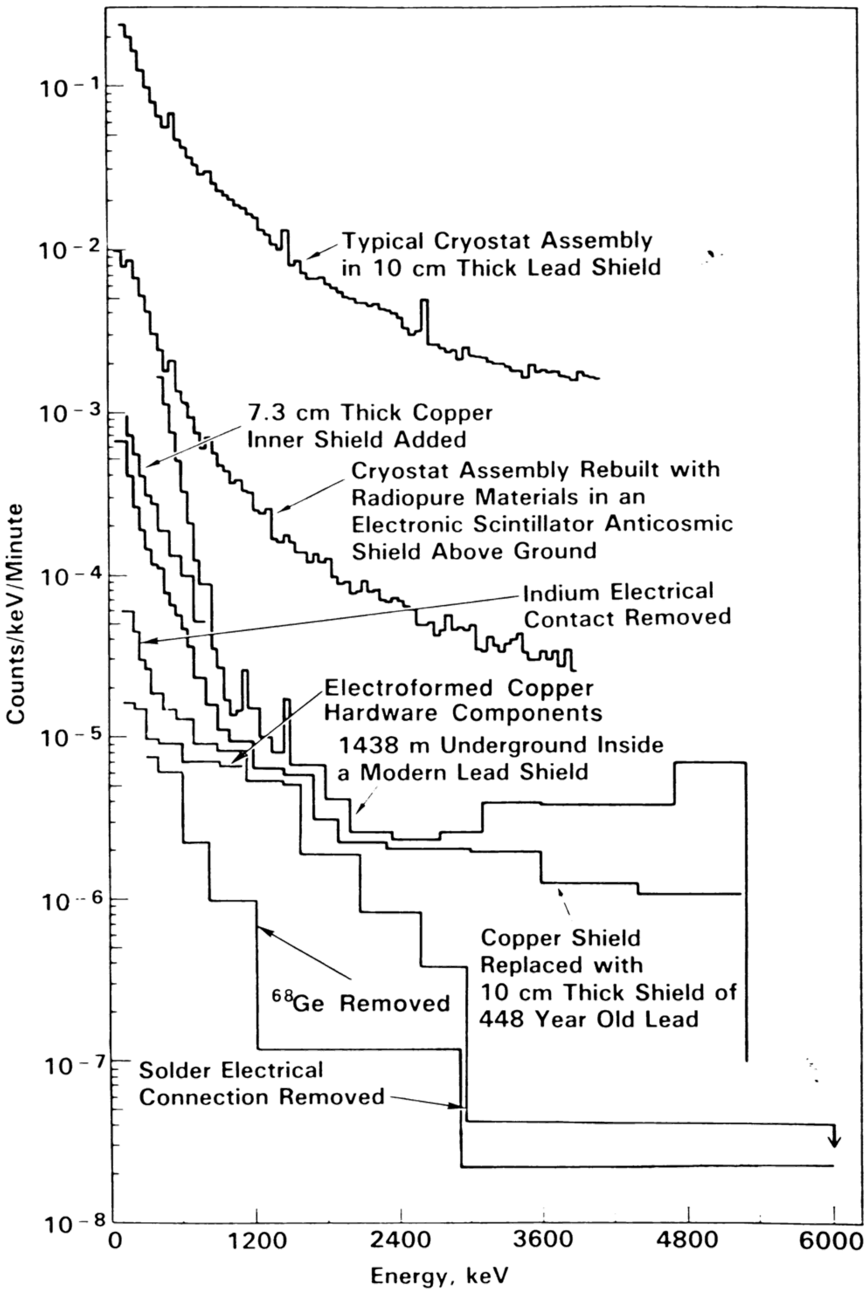
Construction of Sensitivity Plots

- Often in this field backgrounds cannot be accurately modeled and subtracted.
- For any possible WIMP mass, the data allow a maximum possible signal amplitude,
- Excluded region in Mass * Cross Section plane is the envelope of these amplitudes.
- Figures below illustrate trivial case where spectrum is known with high statistical accuracy.
  Other techniques have been developed for the case of a sparse spectrum.





Backgrounds from Radioactivity and Cosmic Rays



- A long history of successful attempts to reduce by choosing special materials and shielding.

Gammas & betas

From primordial, cosmogenic, and manmade nuclei: (not an exhaustive list!)

^{238}U, ^{232}Th + daughters (incl. ^{222}Rn)

^{40}K, ^{14}C

^{85}Kr, ^{137}Cs, ^{3}H - nuclear tests

^{68}Ge, ^{60}Co - cosmogenic in detector setups

Cosmic Rays (p, π , μ, e…)

Can be reduced by going underground.

The μ' s penetrate to great depth.

Neutrons

From μ spallation or (α, n) reactions in rocks, with alphas from U/Th chains. Can be shielded with moderator at low energies.

(figure from Brodzinski et al, Journal of Radioanalytical and Nuclear Chemistry, 193 (1) 1995 pp. 61-70)

WIMP Dark Matter Searches: Experimental Challenge

- Energy transferred by WIMP to a target nucleus is low.
  - ~10 keV, similar to an X-ray
  - Recoil track has a length of only ~100 nm in a solid material

- Event rate is extremely low.
  - < 1 event per ton of target per day

- Backgrounds from environmental radioactivity are high.
  - ~10^5 events/ton-day after careful radiation shielding, limited by trace environmental radioisotopes.
  - Most of these events are due to scattering on electrons (Compton, photoelectric scattering), while the signal is a nuclear recoil.

We need a technology which is <u>scalable</u> to large target mass and has <u>good background rejection for electron-like events.</u>

Coherence and Couplings

- WIMP interactions are coherent over target nucleus due to long wavelength

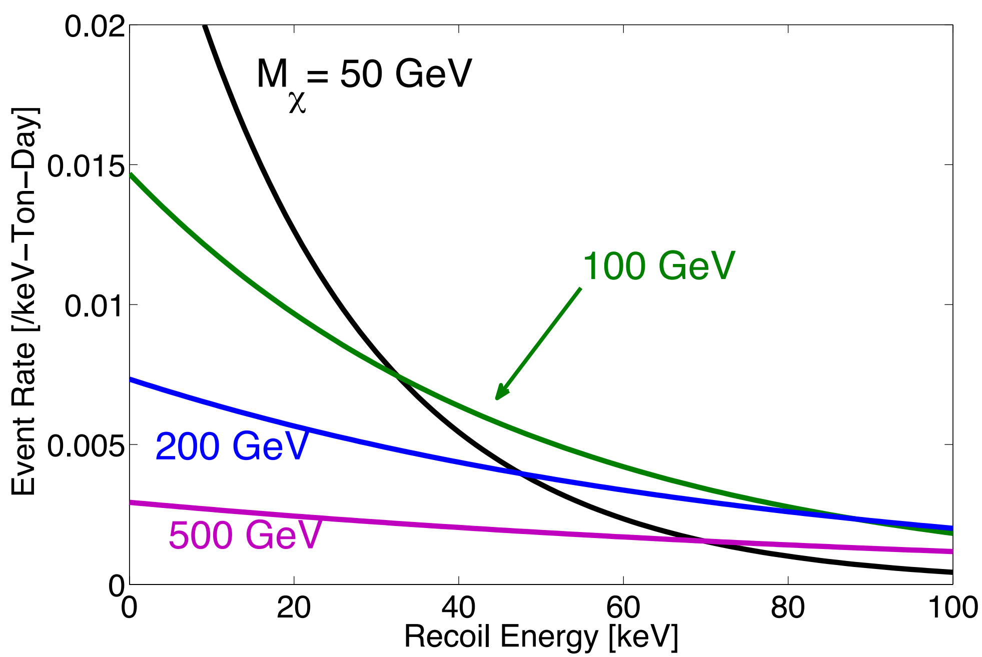
$$\lambda = \frac{h}{m_\chi v_\chi} \simeq 0.9\ \mathrm{fm} \cdot \left(\frac{m_\chi}{100\ \mathrm{GeV}}\right)^{-1} \left(\frac{v_\chi}{220\ \mathrm{km}/s}\right)^{-1}$$

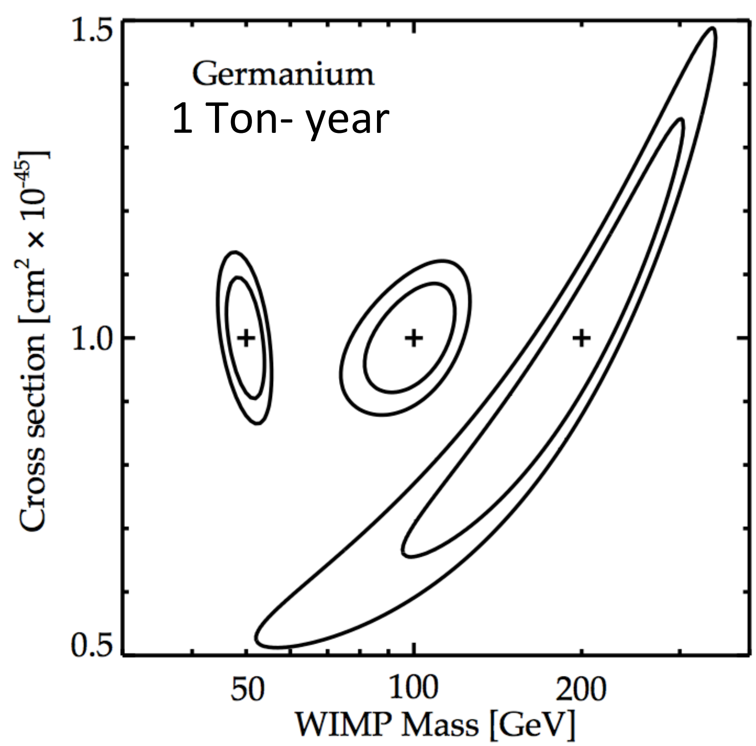
- For "spin-independent" couplings, this typically causes enhancement of cross section by A^2 (A= atomic number) due to summing over nucleons. Strongly favors detection on high-A targets (Germanium, Xenon,…).

- For "Spin-dependent" couplings, opposite spin pairs interfere with net coupling only to any remaining unpaired nucleon– either proton or neutron.

Post Discovery Measurements

- If we see a signal, WIMP mass and cross section for non-relativistic scattering on nucleons may be measured, with some degeneracies.
- When $M_\chi >> M_N$, spectrum becomes flat in energy and nearly independent of WIMP mass.
- Rate decreases as ρ/M_χ making heavy WIMP look like light WIMP with smaller cross section.



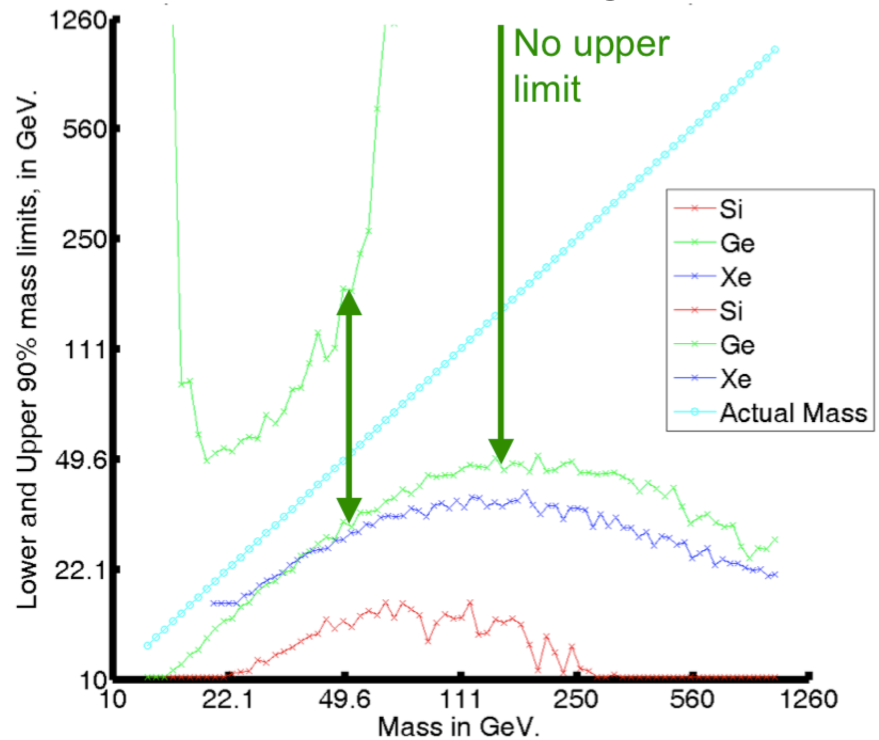


Strigari 2012

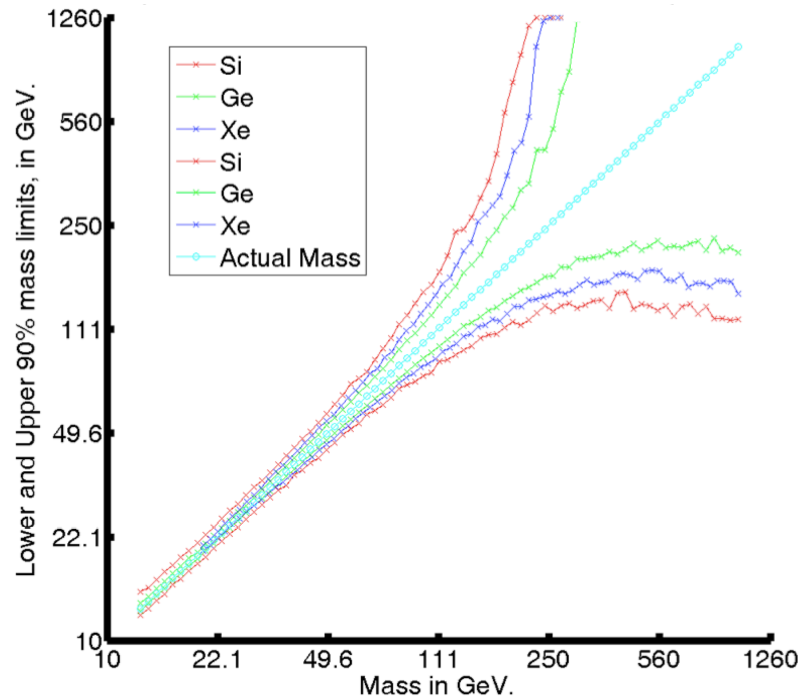
How Many Events Needed to Measure Mass?

- For ~ 10 events, measurements only possible below 50 GeV (lower limit only above 50 GeV).
- For ~1000 events, measurements up to 300 GeV.
- Medium- mass nuclei (Ge) a bit better than heavy (Xe) due to form factors.

10 Events on Ge Target

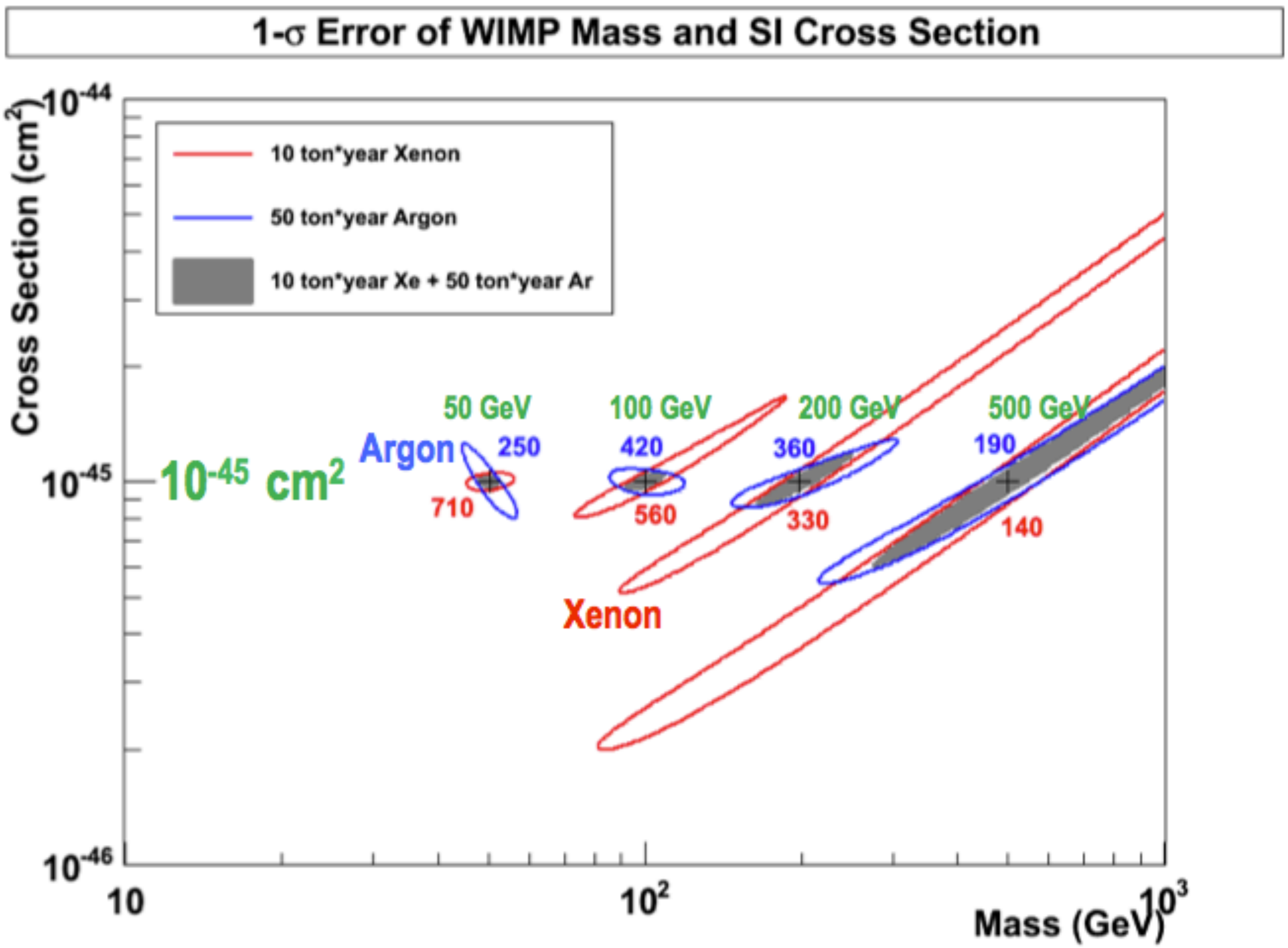


1000 Events on Ge



Jackson, Gaitskell and Schnee, TASI 2009

1-σ Error of WIMP Mass vs SI Cross Section (10 ton*year Xe and 50 ton*year Ar)



Factors Leading to Increased Sensitivity

- **Low backgrounds!**
  - Higher detector material radiopurity.
  - Improvements in background discrimination mechanisms.
- Increased target mass. Up to 20 tons for experiments being planned now.
- Lower energy thresholds.
- More optimal target nuclei
  - Higher A2 for spin-independent
  - Better nuclear form factors for spin-dependent
  - Lighter nuclei for lighter WIMPs.

Background Discrimination: Possible Observables

• Pulse shape differences in scintillation light in noble liquids or crystals. DarkSide, DEAP, KIMS, DAMA.

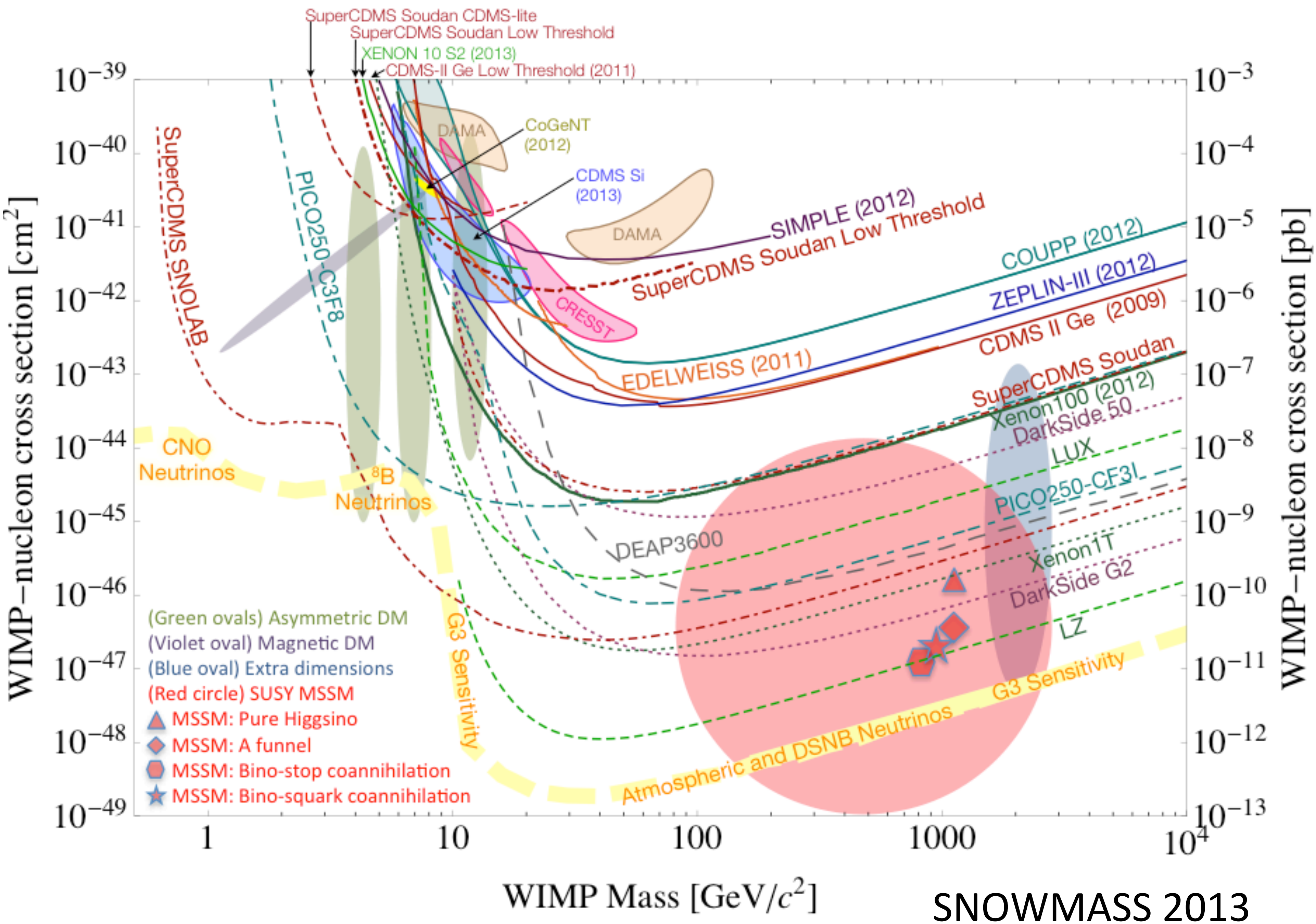
• Ratio of ionization to scintillation in liquid noble gases. LUX, LZ, Xenon, PANDA-X

• Ratio of ionization or scintillation to total deposited heat energy in cryogenic calorimeter. CDMS, EDELWEISS, CRESST.

• Efficiency for bubble formation in superheated liquids. COUPP, PICO, PICASSO, SIMPLE.

•Annual modulation in spectrum due to motion of Earth around the Sun. DAMA

• Track ion charge density in gas drift chamber. Daily modulation in direction of ion tracks. DMTPC, DRIFT



SNOWMASS 2013

Liquified Nobles Gases

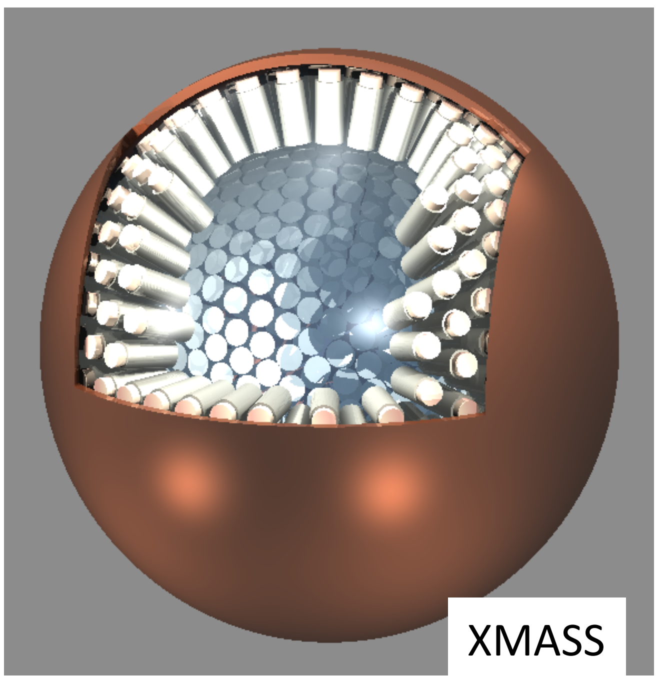
- Available in large quantities with extremely high purity.
- High density- good self- shielding properties in large homogeneous volumes
- High scintillation light yields
- High ionization charge yield.
- High mobility and long drift length for charge

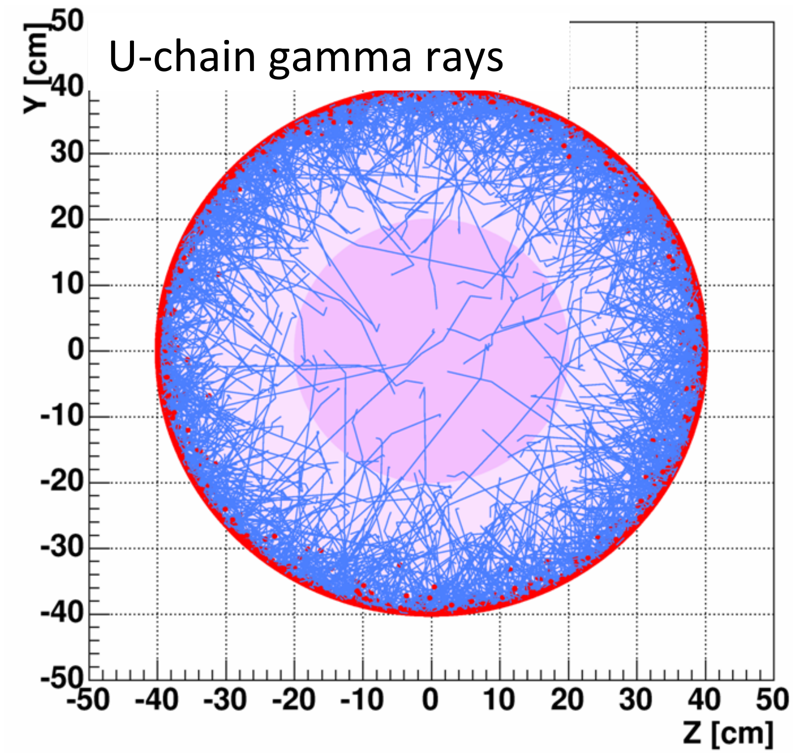
	Liquid density (g/cc)	Boiling point at 1 bar (K)	Electron mobility (cm^2/Vs)	Scintillation wavelength (nm)	Scintillation yield (photons/MeV)	Long-lived radioactive isotopes	Triplet molecule lifetime (μs)
LHe	0.145	4.2	low	80	19,000	none	13,000,000
LNe	1.2	27.1	low	78	30,000	none	15
LAr	1.4	87.3	400	125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

Table from McKinsey, 2013

Single Phase Noble Liquid Detectors

- Simple concept: surround volume of high purity Xenon or Argon with photomultiplier tubes- similar to solar neutrino detectors- SNO, Borexino, Kamland.
- Event position reconstructed from photomultiplier hit pattern.
- Spherical geometry with 4*Pi photocathode coverage is optimal for collection of scintillation light.





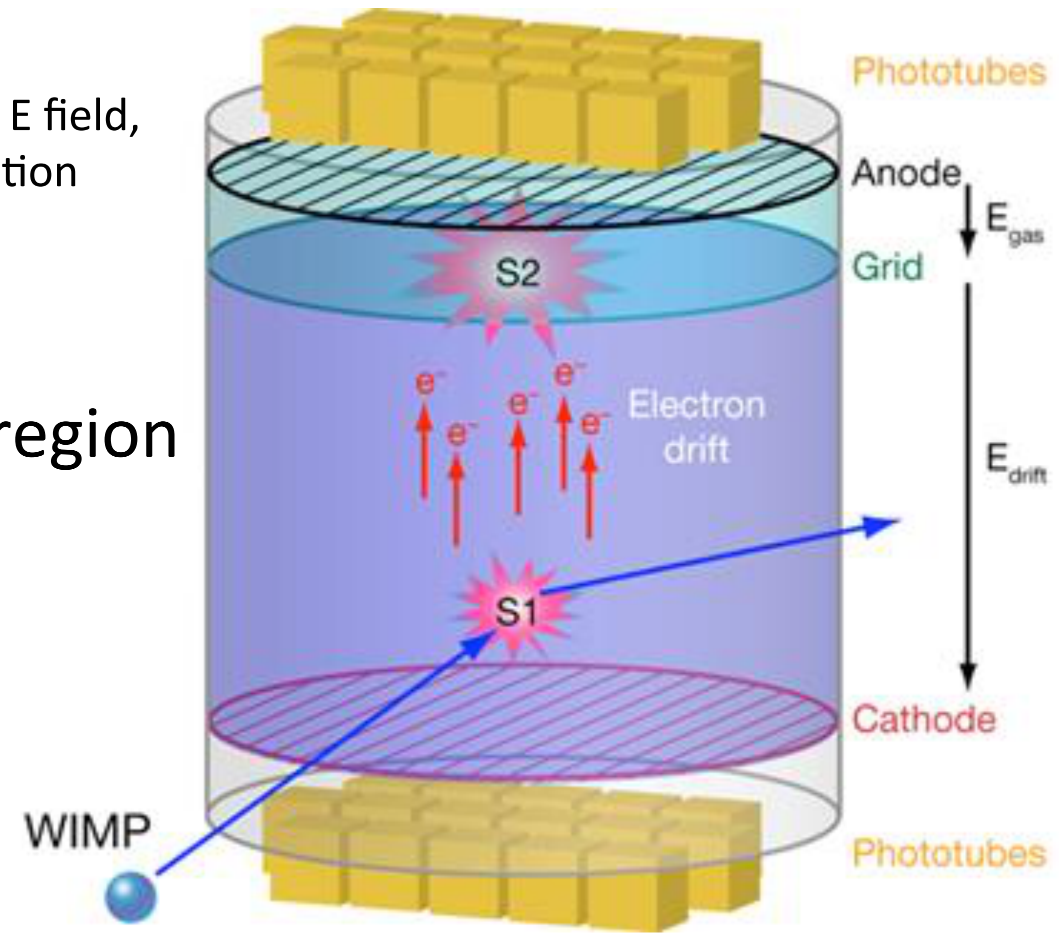
Takeda, IDM2006

Dual Phase Noble Gas TPCs

- Allows simultaneous measurements of charge and light yields in a large, homogeneous liquid volume of xenon or argon.
- Background discrimination from charge/ light ratio.

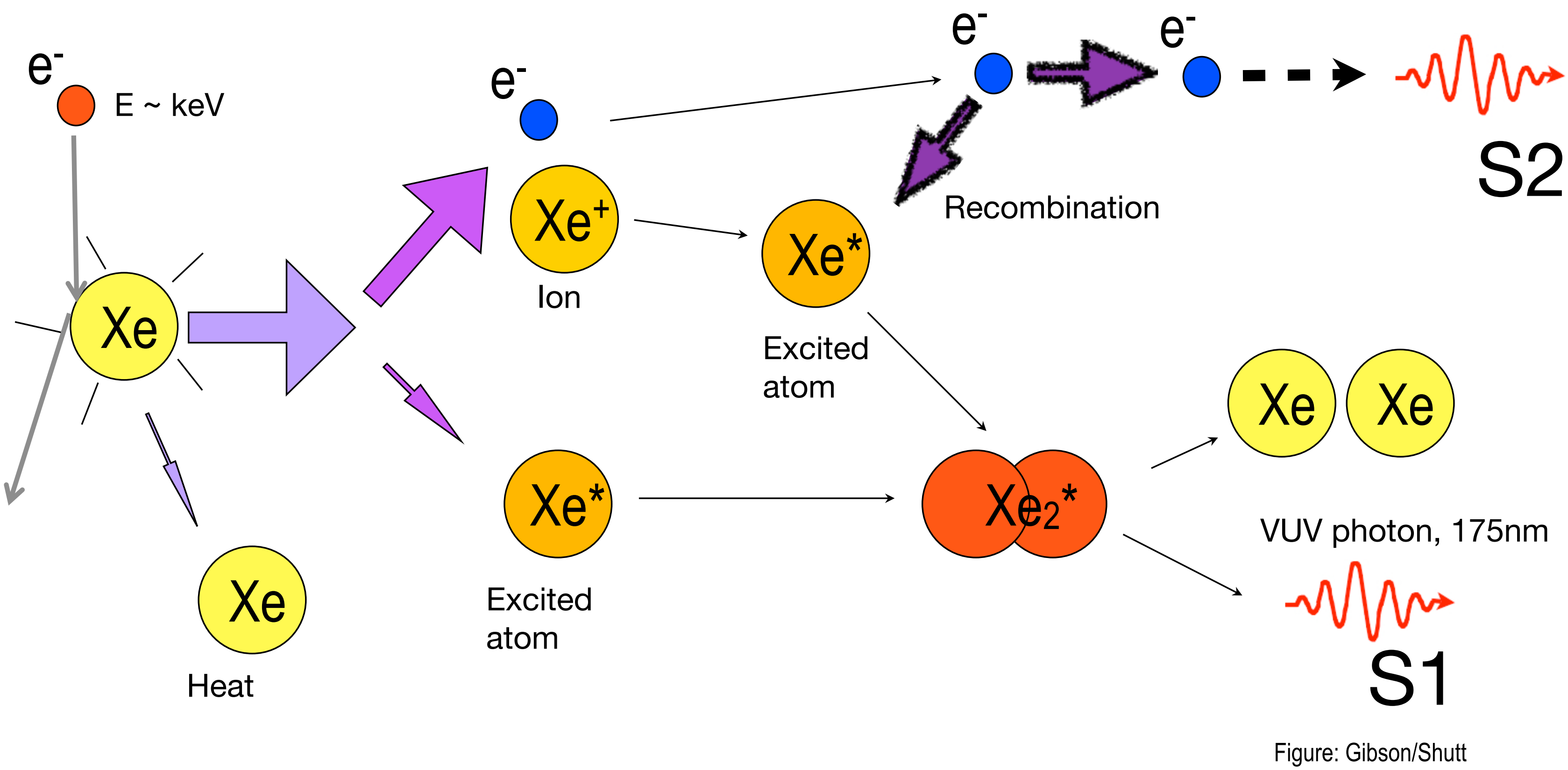
Gas region with high E field,
Proportional scintillation

Liquid target region



Experiments:
LUX/ LZ
Xenon-100/ 1T
Panda-X
DarkSide
ArDM

Signal production in liquid Xe



Electron Recoils

Signal production in liquid Xe

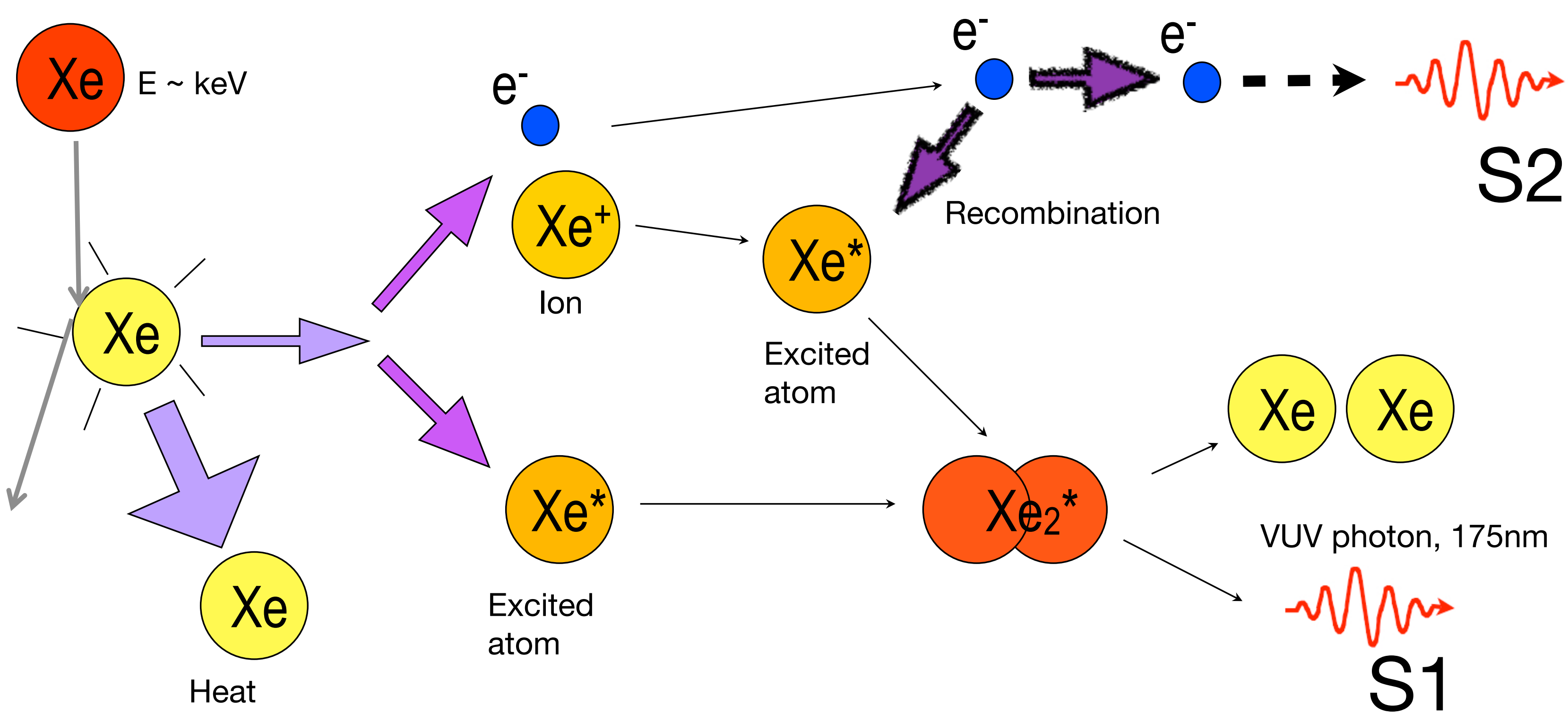
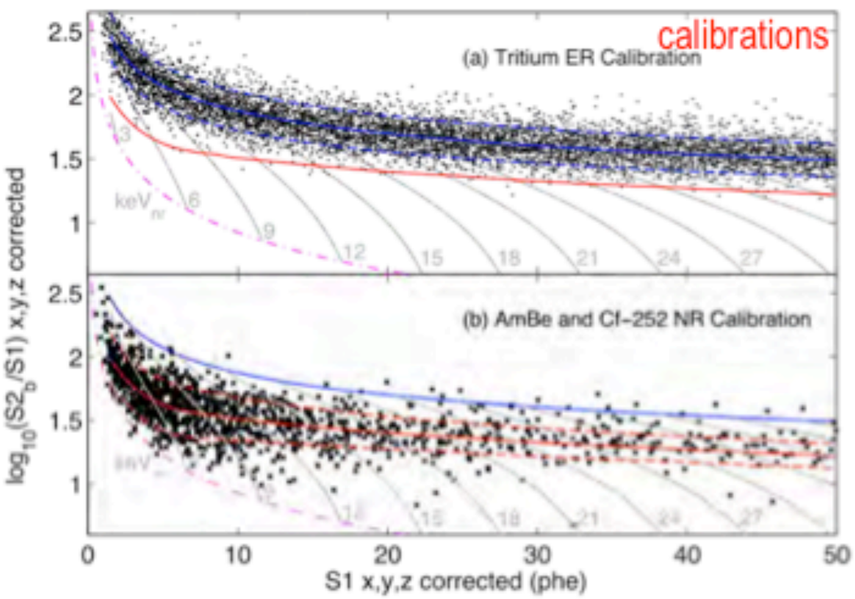
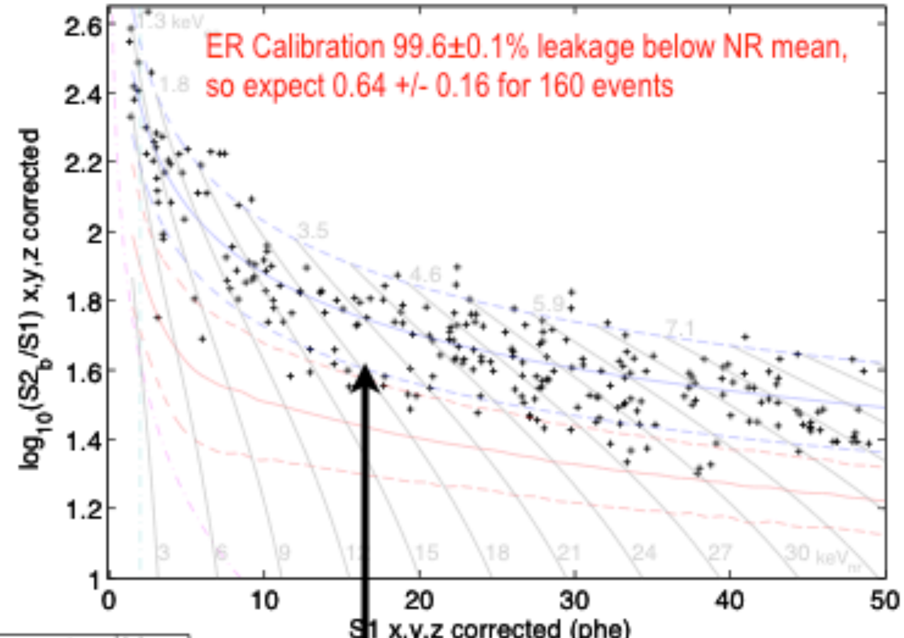


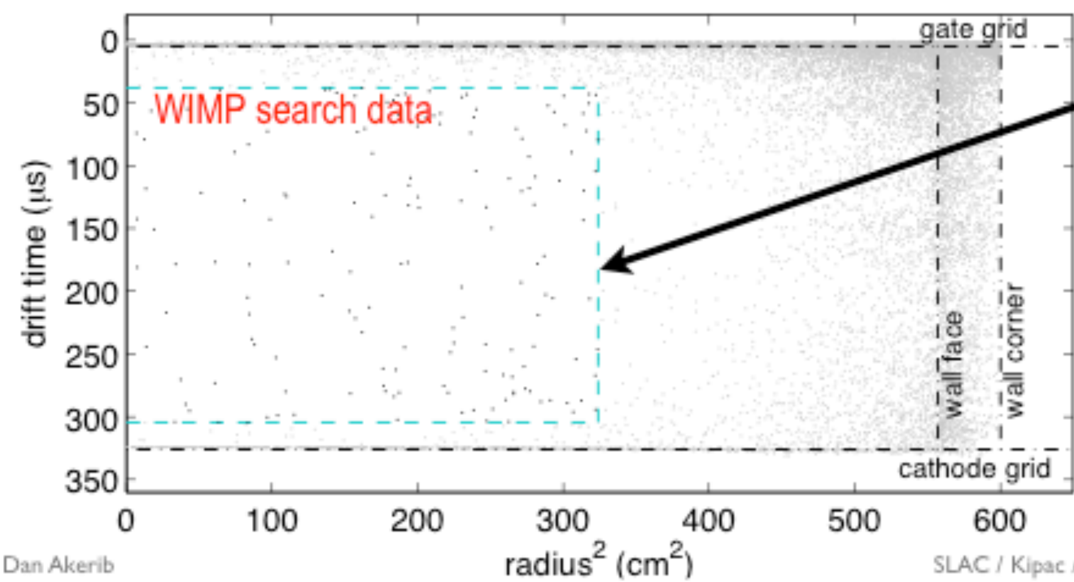
Figure: Gibson/Shutt

Nuclear Recoils

LUX WIMP Search, 85 live-days, 118 kg







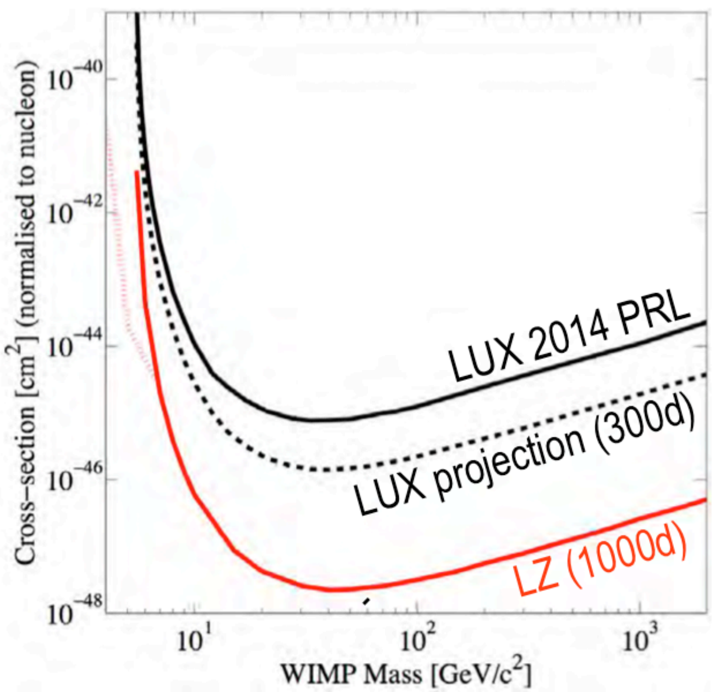
160 events in ER band / 118 kg fiducial

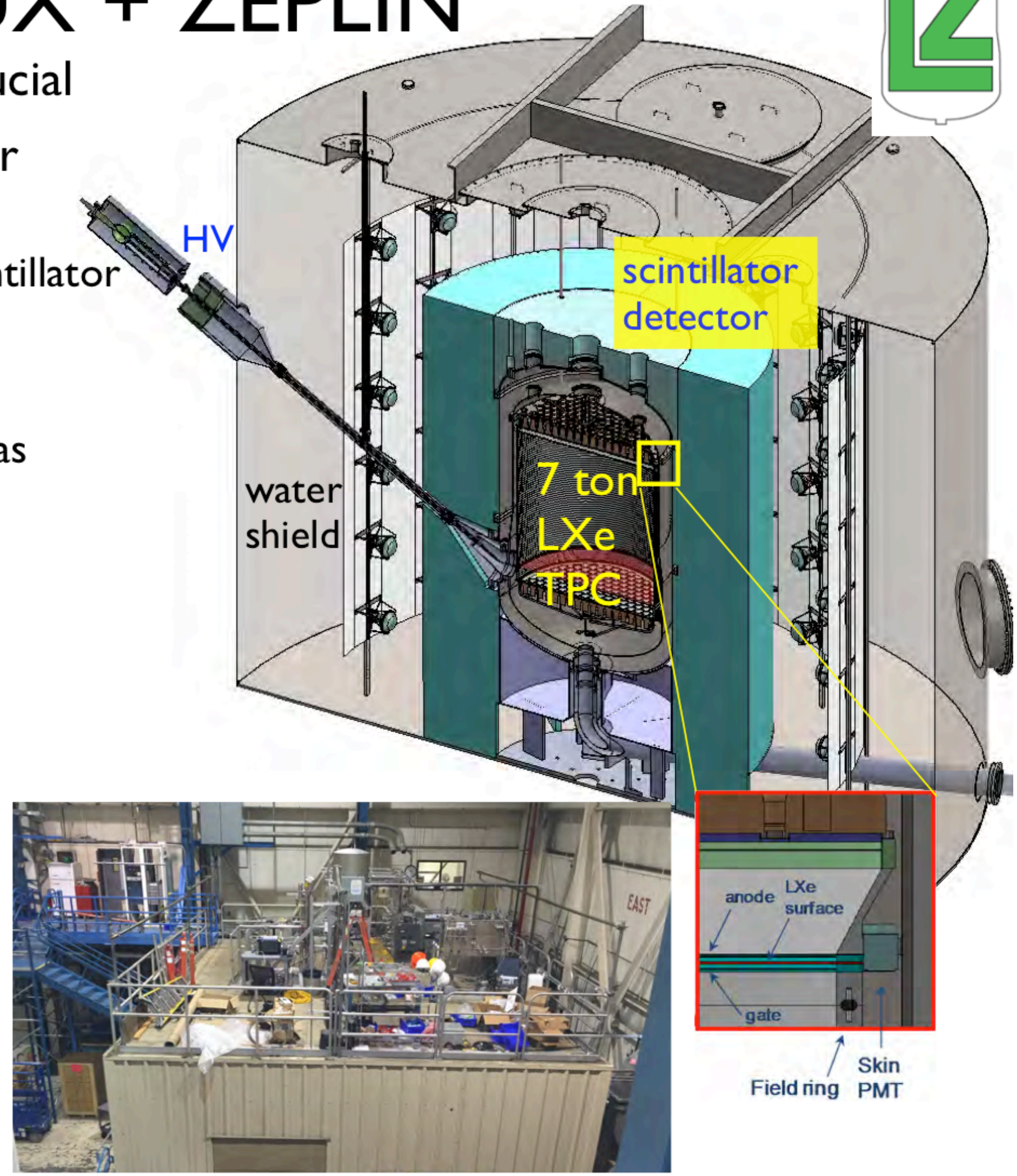
Fit data to combined sig & bkg (^{127}Xe, ^{85}Kr, ^{214}Pb, Compton)

Profile Likelihood Ratio test consistent with all bkg.

LZ: LUX + ZEPLIN

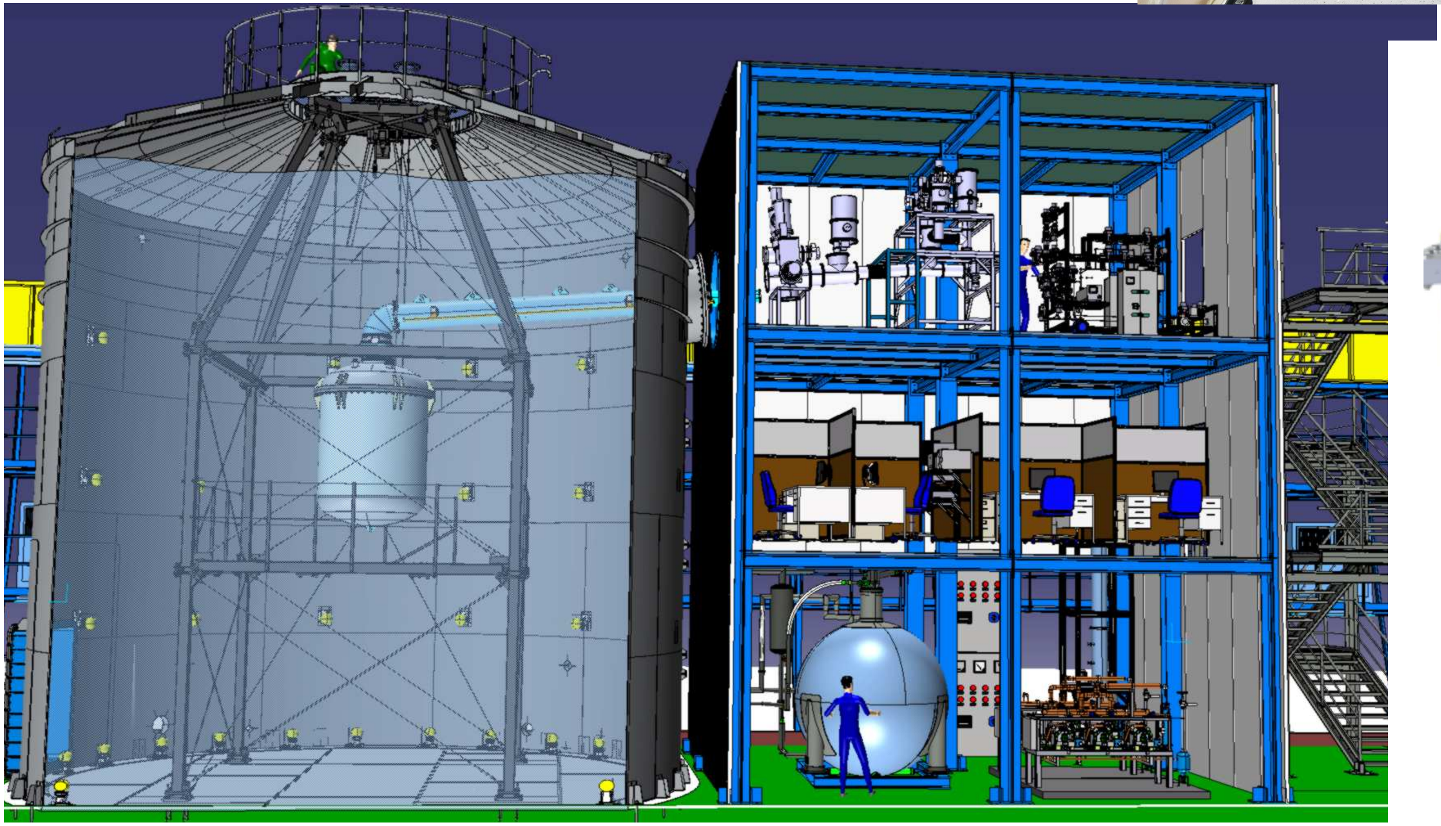
- 10 tons LXe / 7 active / 5.6 fiducial
- Two-component outer detector system
  - 0.75 m thick Gd-loaded LAB scintillator shield (c.f.: Daya Bay)
  - Instrumented Xe "skin"
  - Effective for neutrons and gammas
- System test HV+RFR+grids





Xenon-1Ton Nearing Completion at Gran Sasso

- Scheduled to turn on this year.
- 3.3 Tons of Xenon (2 tons fiducial)
- Will scale to 7 tons beyond 2018

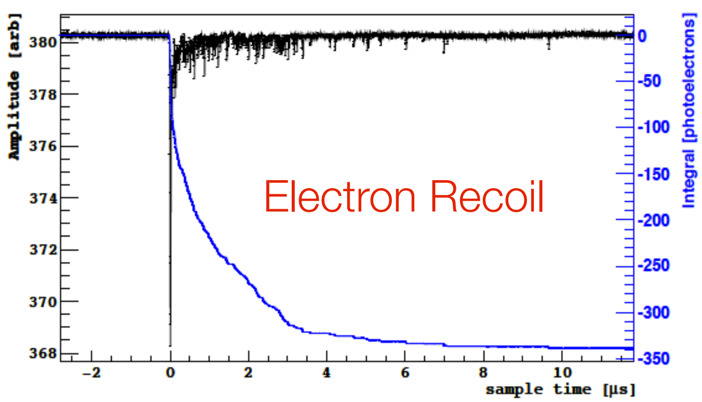


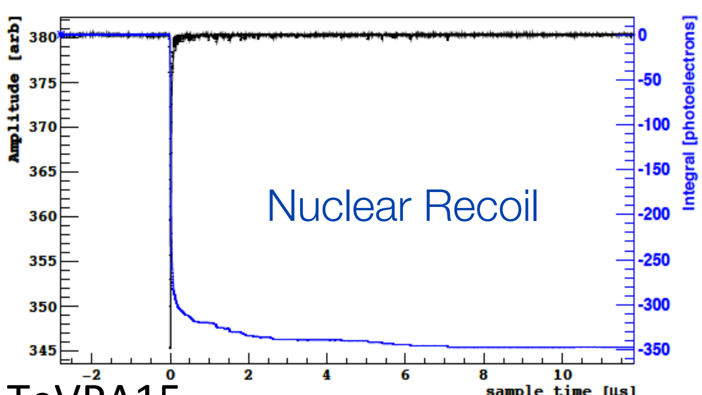
Liquid Argon Dark Matter Detectors

- Single and dual phase operations possible, as for xenon
- Argon has a long-lived radioisotope, ^{39}Ar, with an activity of 10^5 counts/kg-day and 269 y half life. Produced by cosmic rays in atmosphere.
- Large scintillation pulse shape differences for electron recoils vs nuclear recoils.

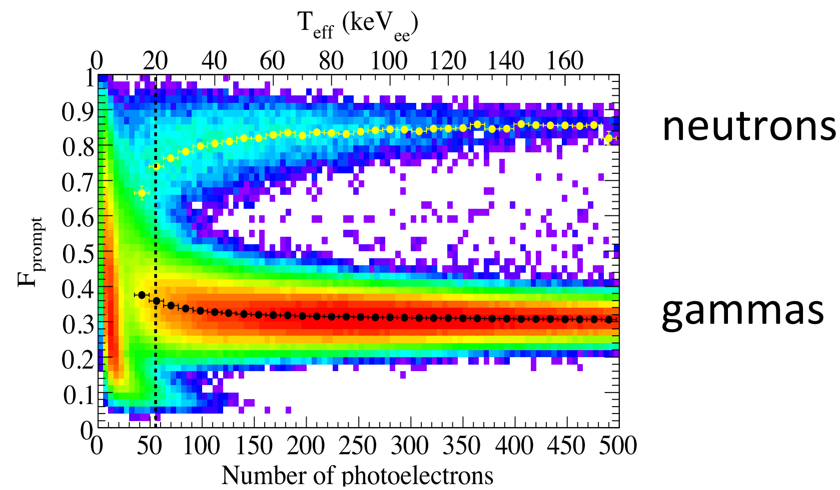
τ singlet ~ 7 ns

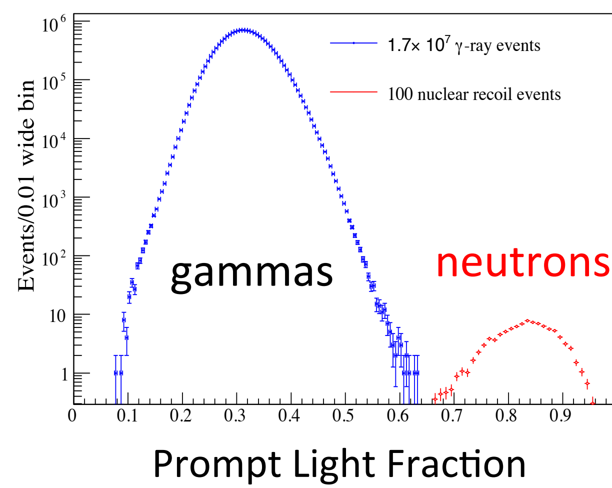
τ triplet ~ 1500 ns





Wada, TeVPA15

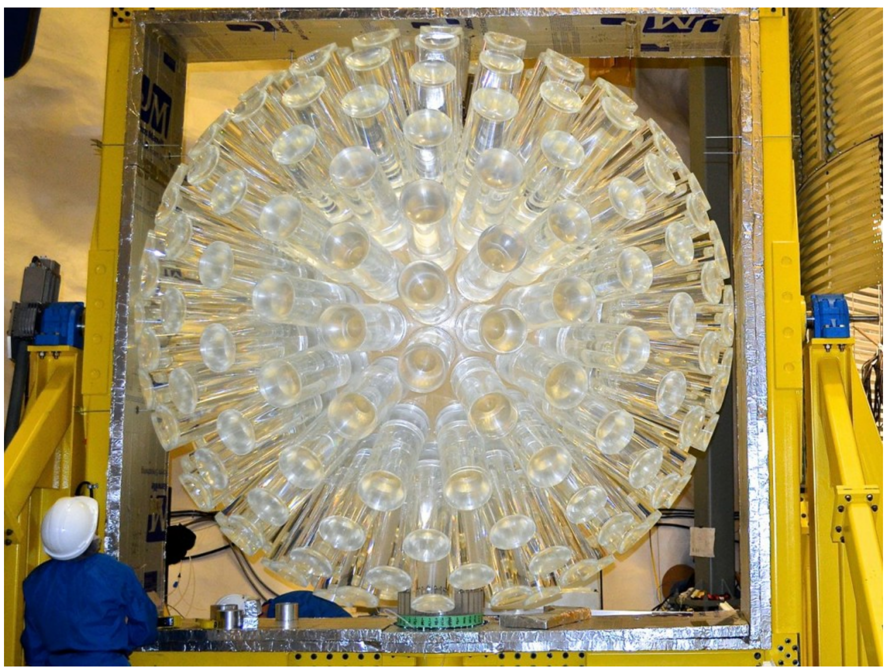


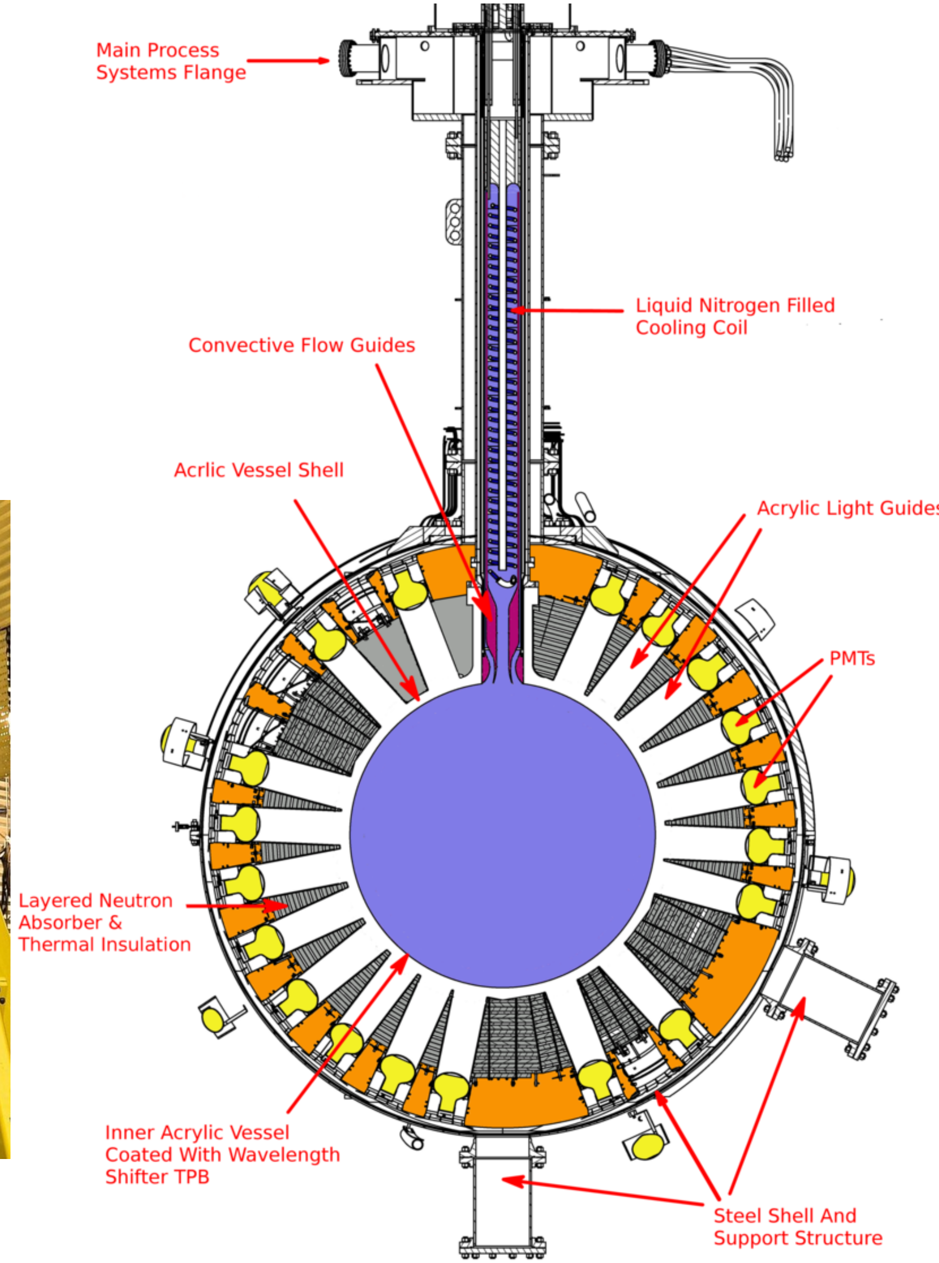


Boulay et al., 0904.2930

DEAP-3600: Liquid Argon Single Phase

- Acrylic vessel-based design descended from Sudbury Neutrino Observatory.
- Nearing completion at SNOLAB.
- Data expected in 2016.





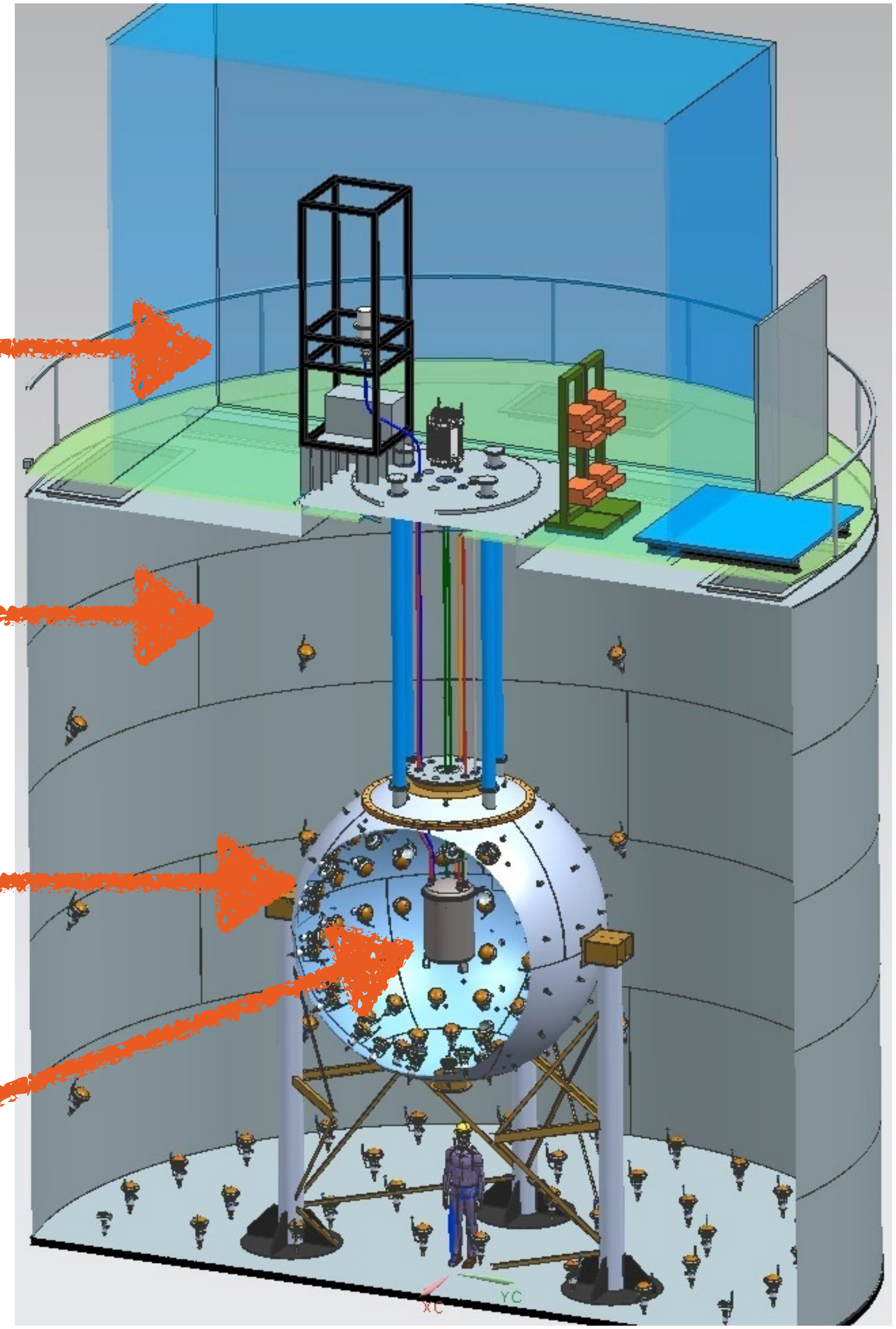
DarkSide 50

Radon-free (Rn levels < 5 mBq/m^3)
Clean Room

1,000-tonne Water-based
Cherenkov **Cosmic Ray Veto**

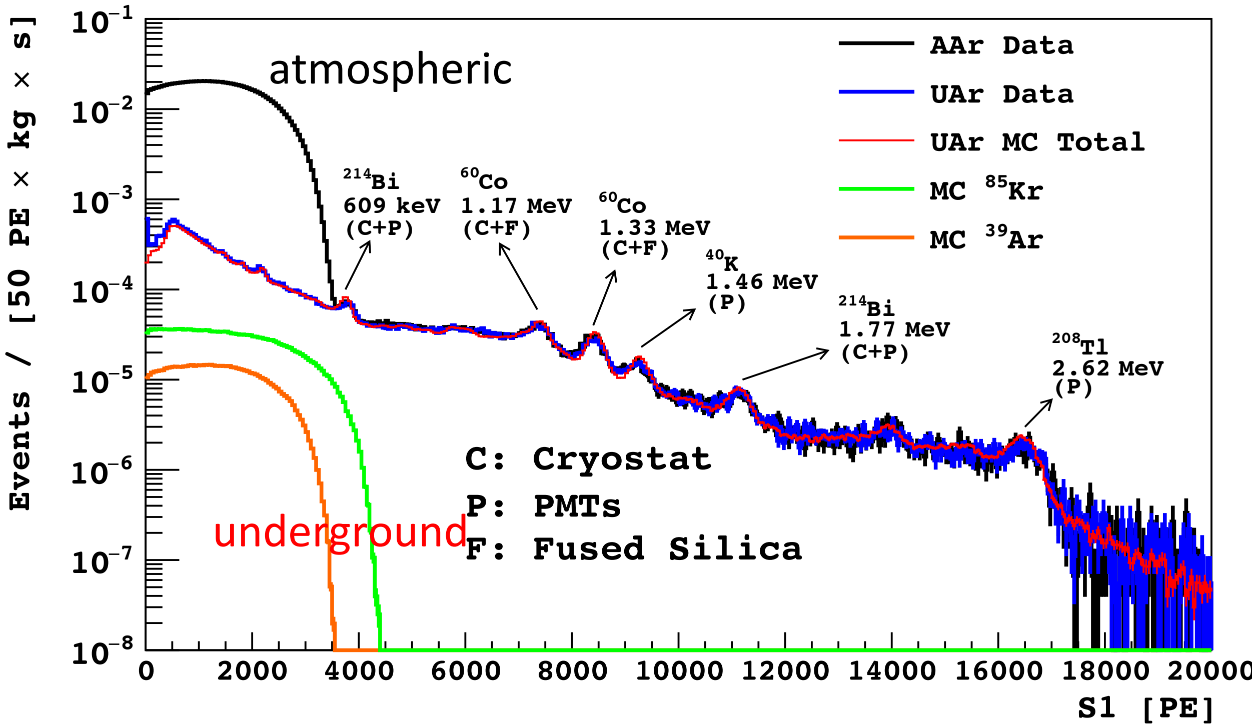
30-tonne Liquid Scintillator
Neutron and γ's Veto

Inner detector **TPC**



DarkSide Underground Argon

- 155 kg of argon extracted from CO_2 gas well in Colorado.
- Depleted in ^{39}Ar by a factor of 1400 with respect to atmospheric argon.

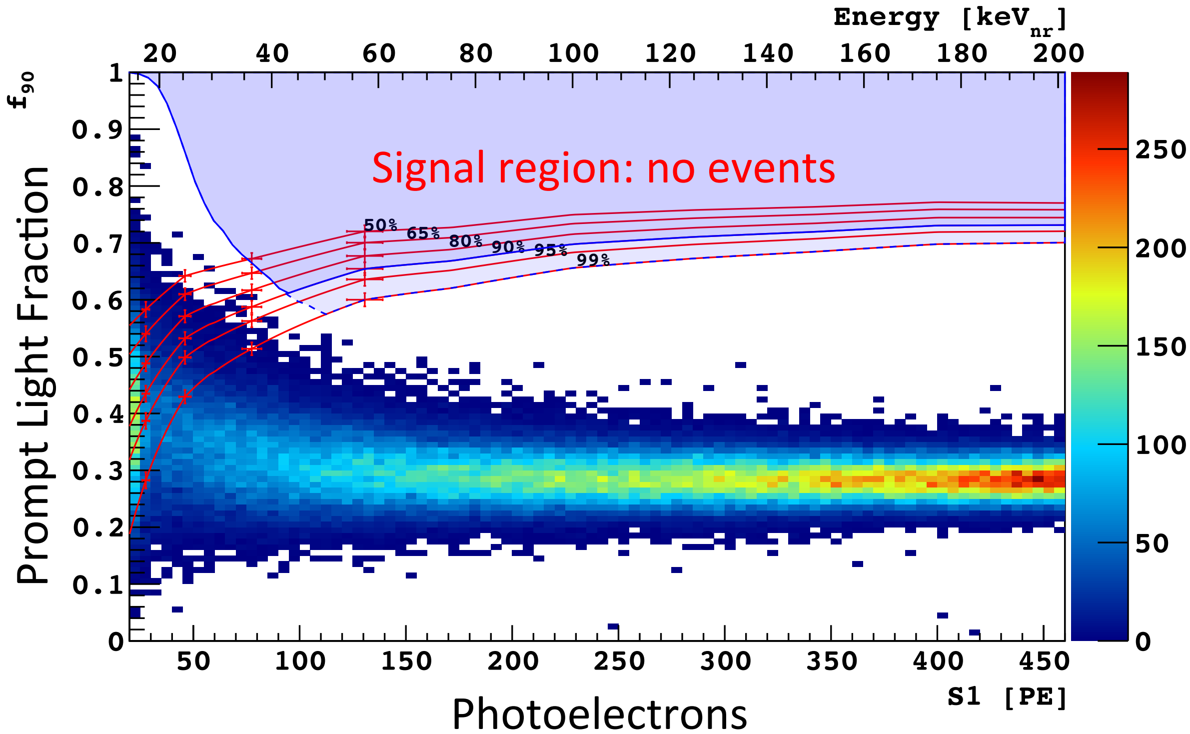


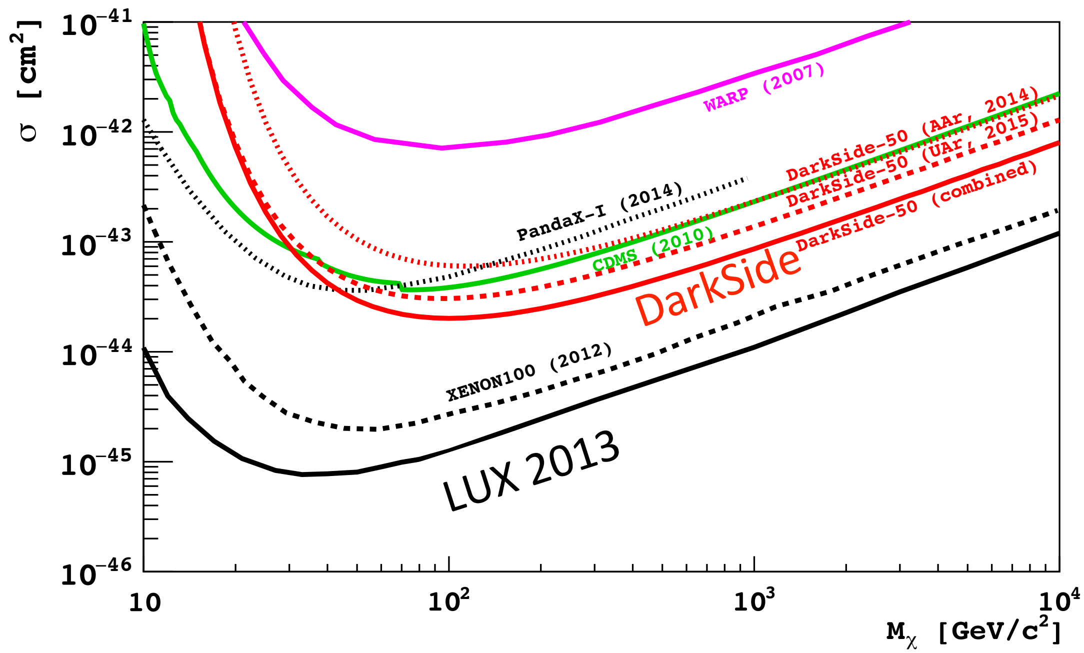
Arxiv 1510.00702

Fermilab Cryo Distillation Syste

DarkSide 2015 Result

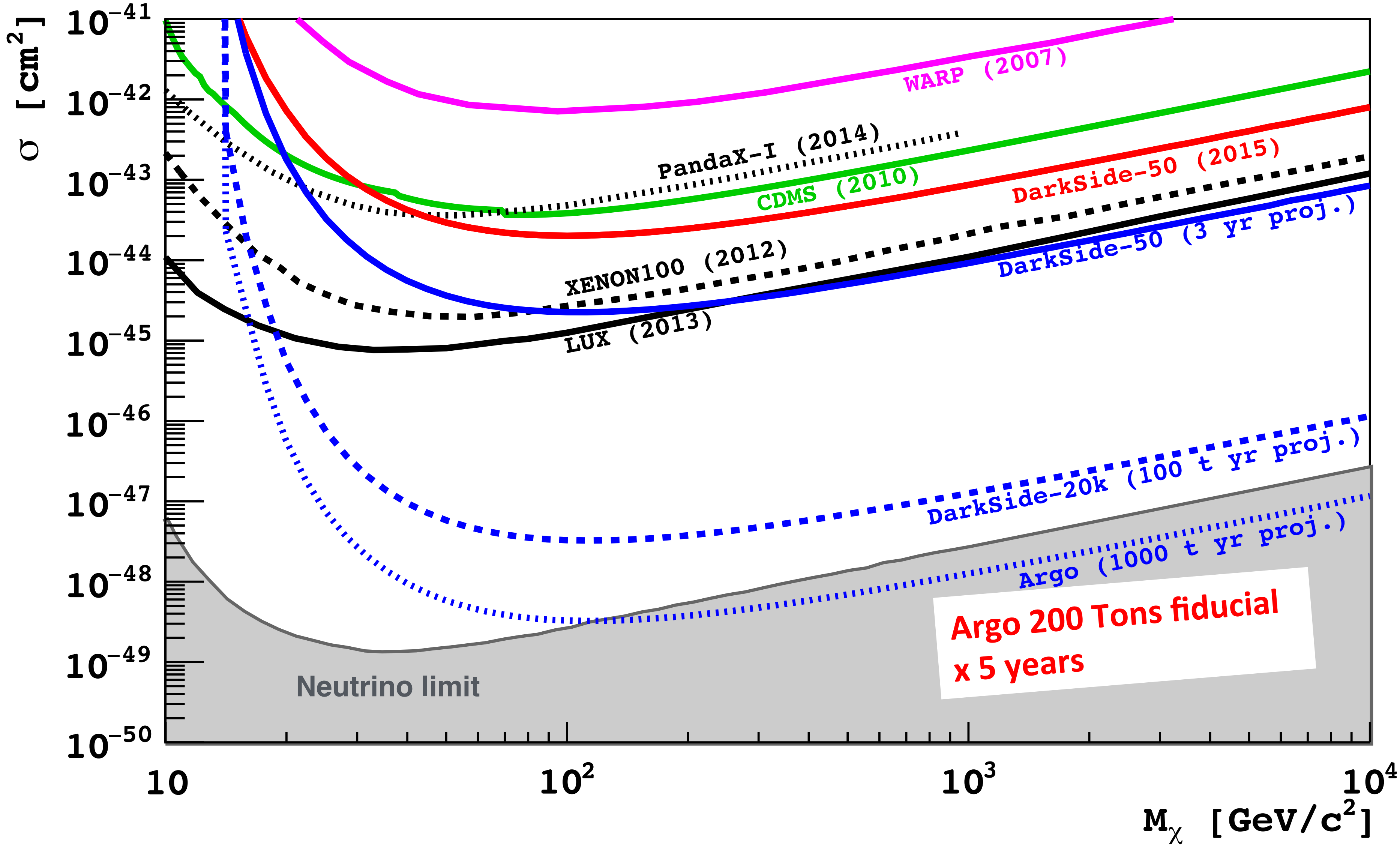
- 2616 Kg- days exposure with underground Argon.
- No background events.
- 3rd best spin-independent limit, behind only LXe TPCs.





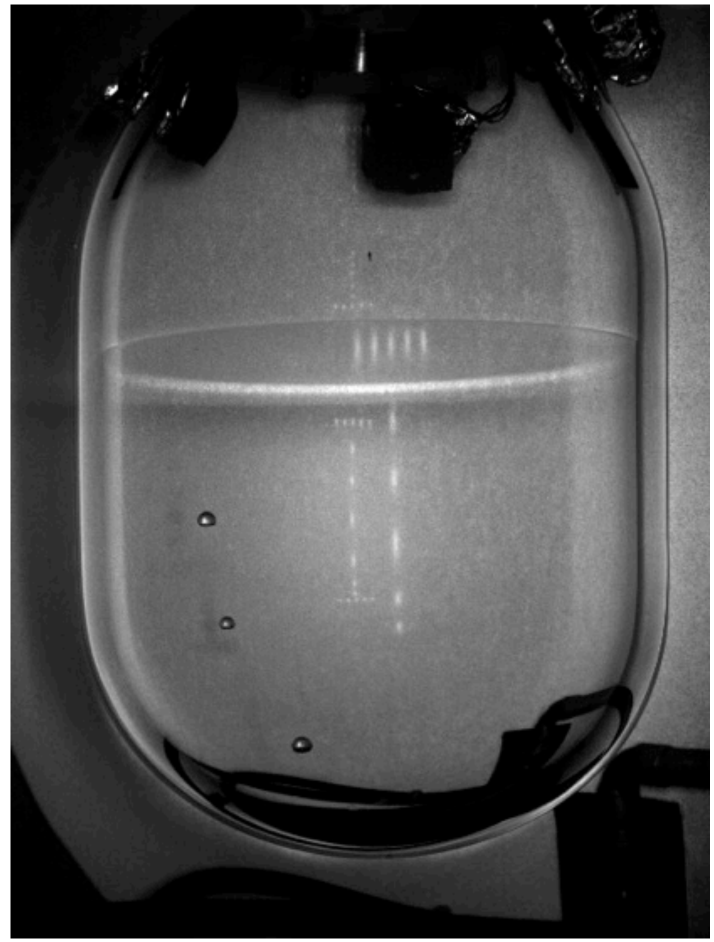
Arxiv 1510.00702

Argon TPC Future– Scaling to Kiloton Exposures



Wada, TeVPA2015

Bubble Chambers: The COUPP/ PICO Program



WIMP Dark Matter Detector Wish List

- Large target mass (>1 ton for next generation)
- Low energy threshold. (~ 10 keV for standard WIMPs, ~ 2 keV for current light WIMP models)
- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin.
- Zero backgrounds from environmental radioactivity.
- Measure nuclear recoil energies.
- Measure nuclear recoil direction.

BUBBLE CHAMBERS

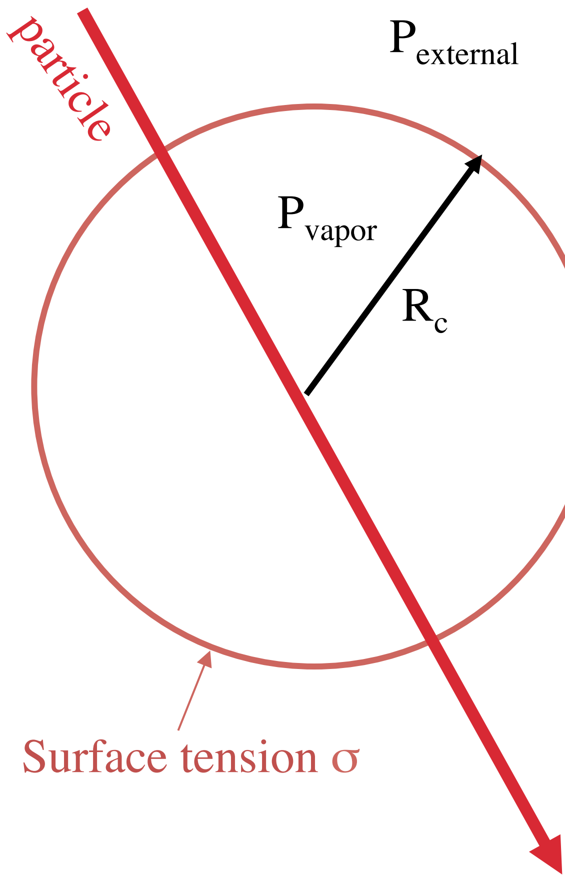
- Large target mass (>1 ton for next generation) ✔
- Low energy threshold. (~ 10 keV for standard WIMPs, ~ 2 keV for current light WIMP models) ✔

Target diversity

- Multiple target nuclei- test expected cross section dependences on atomic number and nuclear spin. ✔
- Zero backgrounds from environmental radioactivity. TBD.
- Measure nuclear recoil energies. By varying threshold
- Measure nuclear recoil direction. No

Bubble Nucleation by Radiation

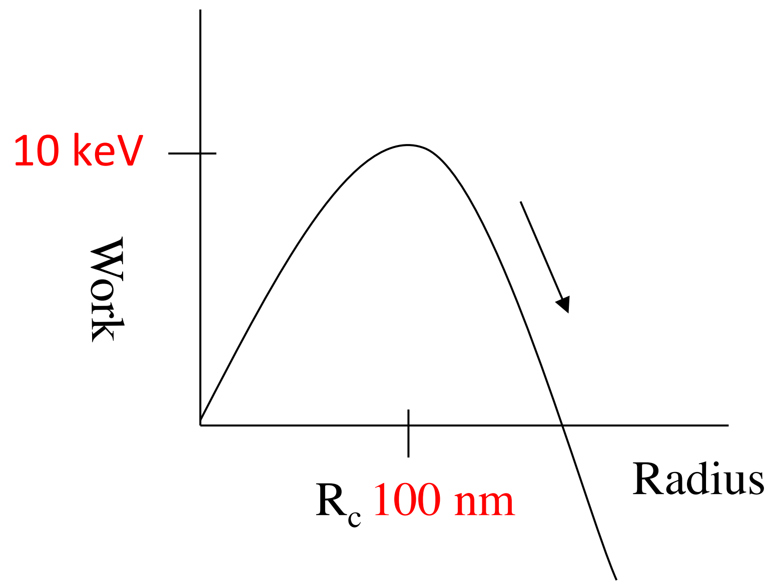
(Seitz, "Thermal Spike Model", 1957)



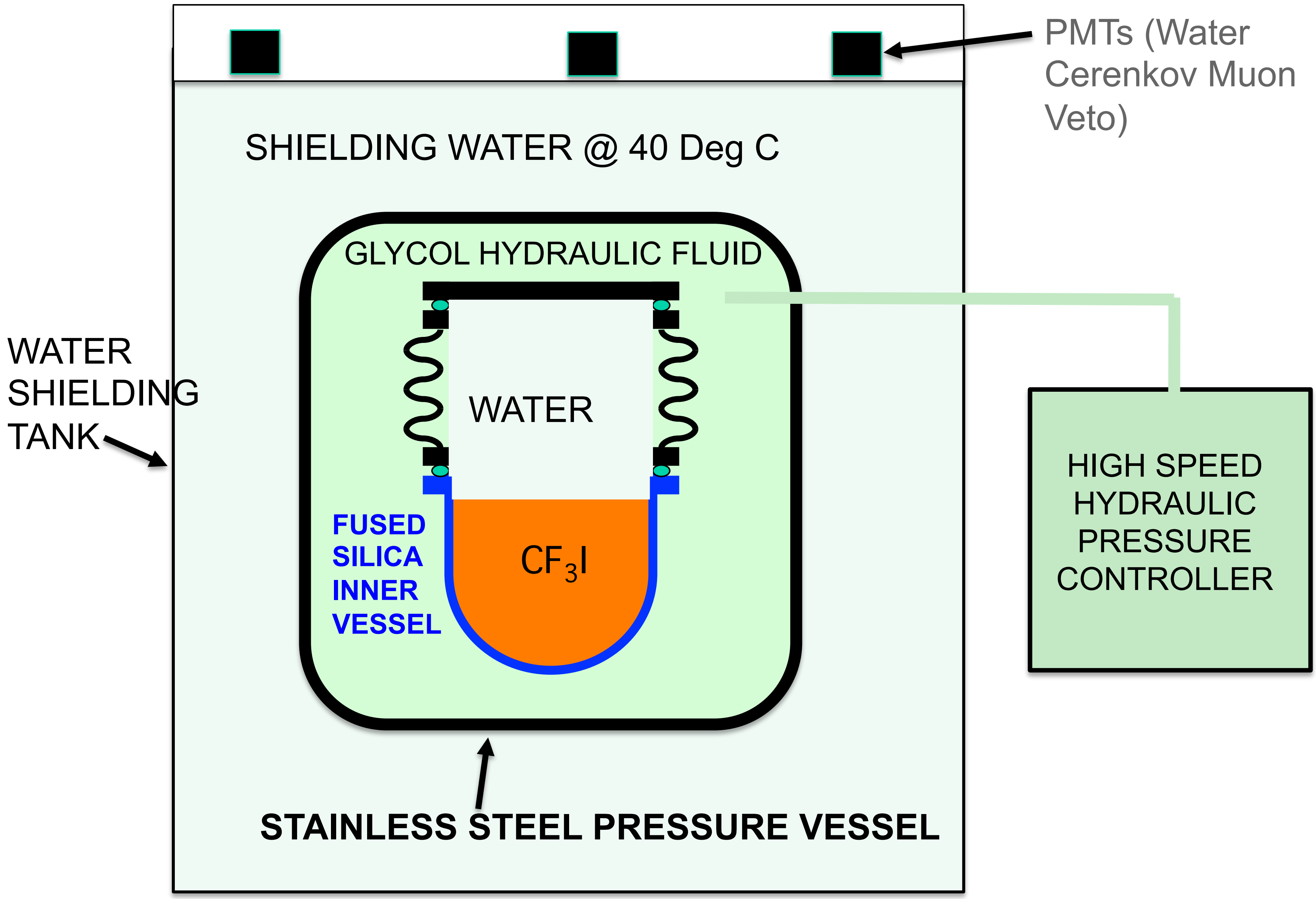
- Pressure inside bubble is equilibrium vapor pressure.
- At critical radius R_c surface tension balances pressure.

$$R_C = \frac{2\sigma}{P_{vapor} - P_{external}}$$

- Bubbles bigger than the critical radius R_c will grow, while smaller bubbles will shrink to zero.
- Boiling occurs when energy loss of throughgoing particle is enough to produce a bubble with radius > R_c



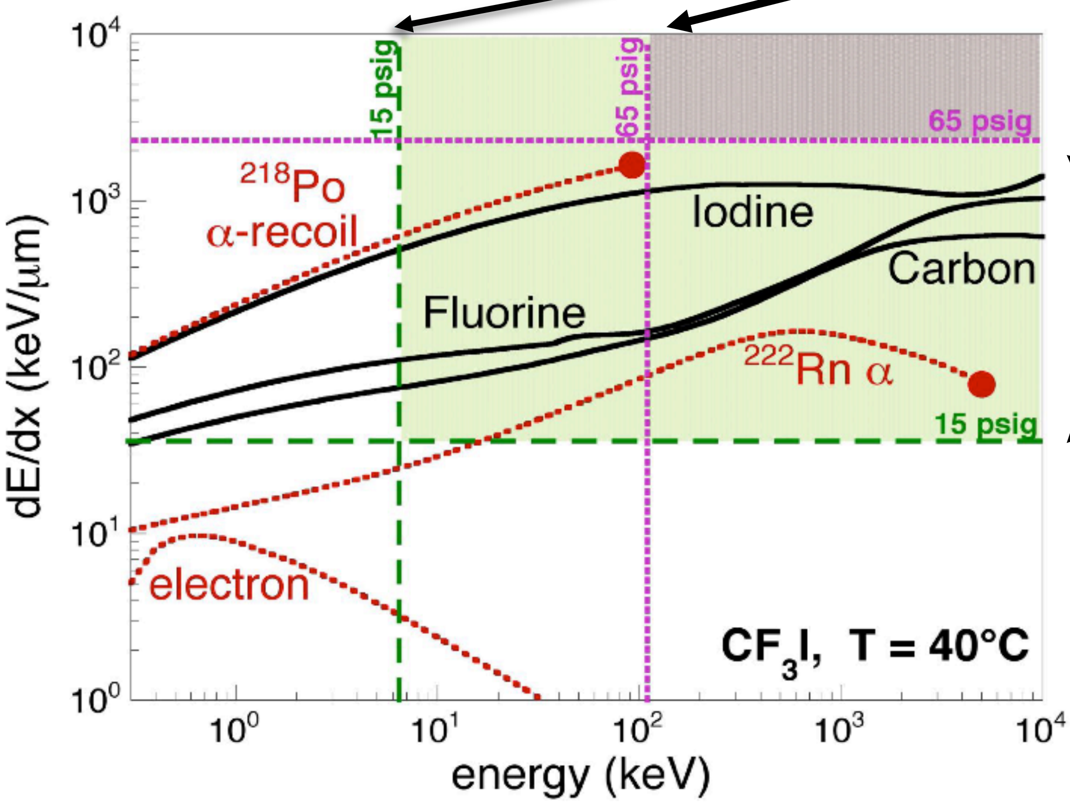
Large Bubble Chamber WIMP Detector Cartoon



Tuning the dE/dX Threshold for Bubble Nucleation

- The bubble chamber operator chooses a pressure and temperature, fixing the minimum size of bubbles that are allowed to grow against surface tension.
- This simultaneously determines minimum deposited energy and energy loss density (dE/dX) that will nucleate bubbles.
- Example below: superheated CF_3I at fixed temperature, two operating pressures.

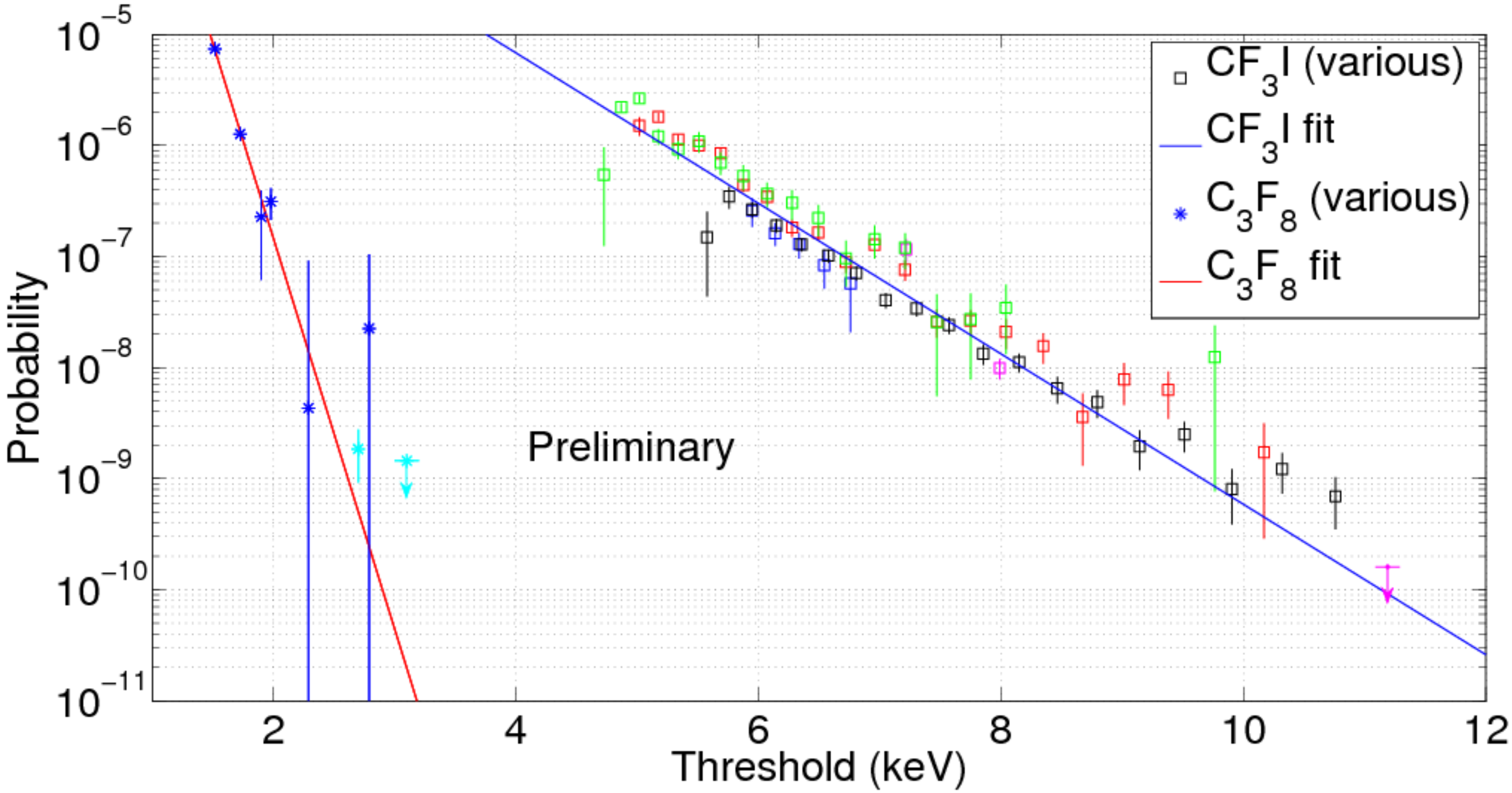
Energy Thresholds



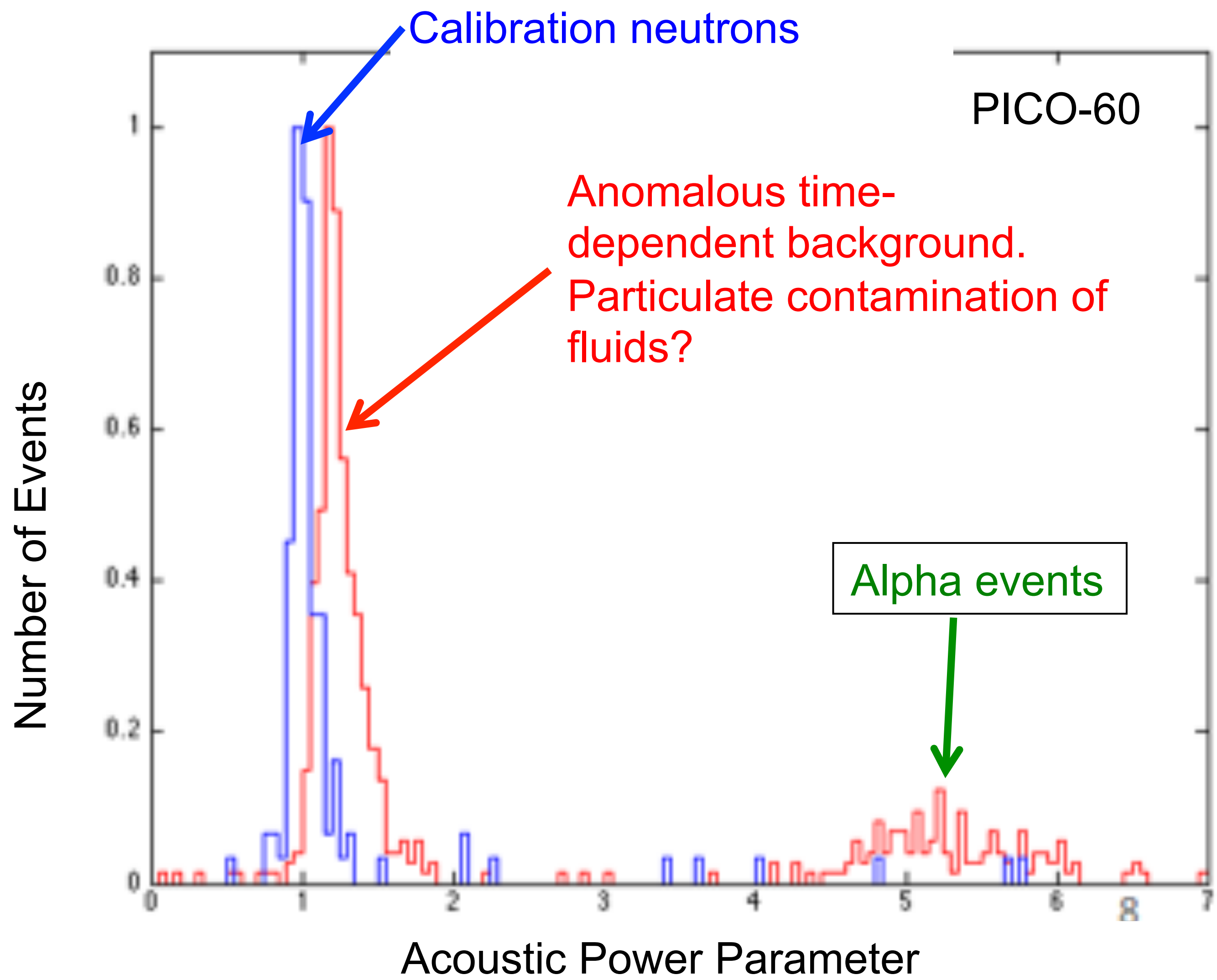
dE/dX threshold at 15 psi and 65 psi

Electron recoil rejection

Bubble nucleation probability from gamma interactions in C_3F_8 and CF_3I

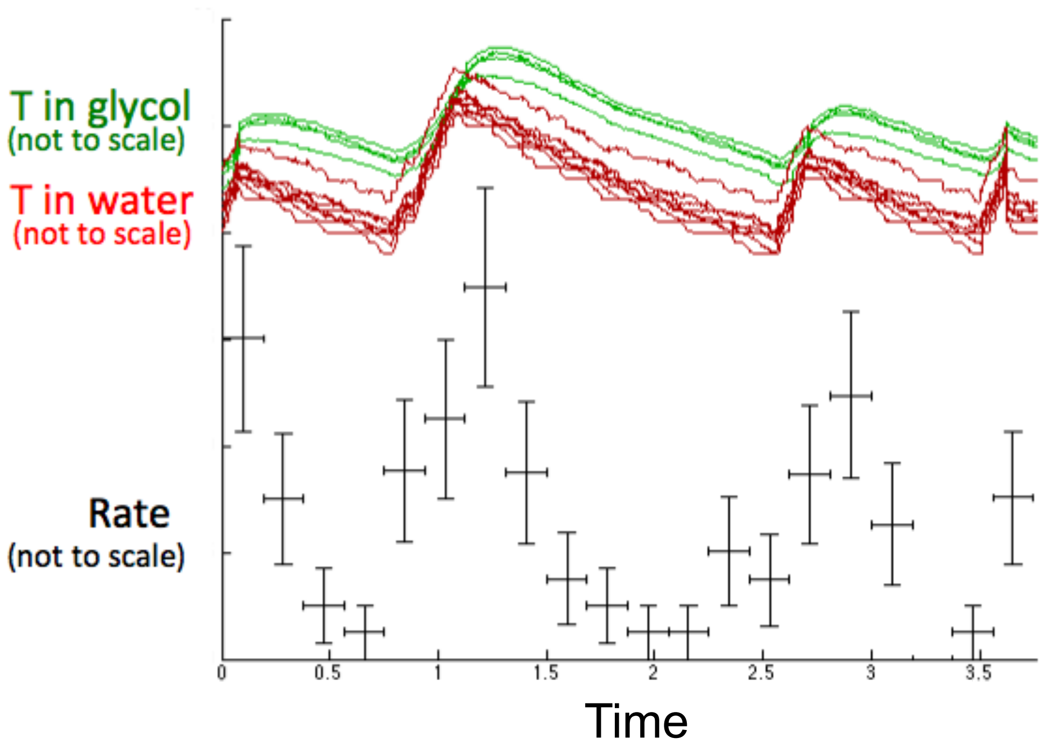


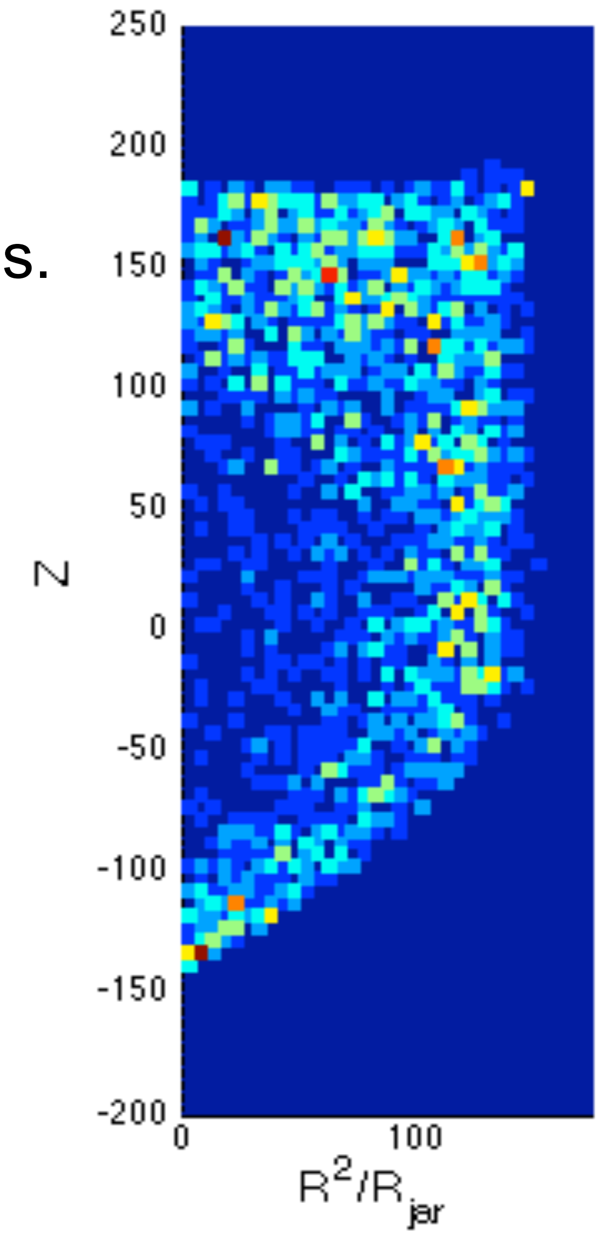
Background Discrimination with Acoustic Signals



Space and Time Distribution of Recoil-Like Events

- Acoustically identified recoil-like events have anomalous spatial and time distributions.
- Correlation with temperature changes.
- This cannot be dark matter.

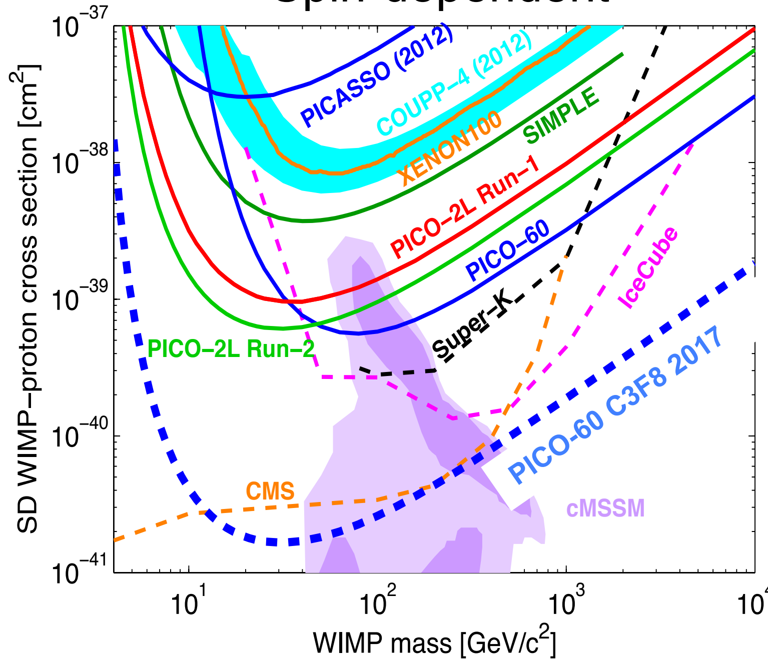




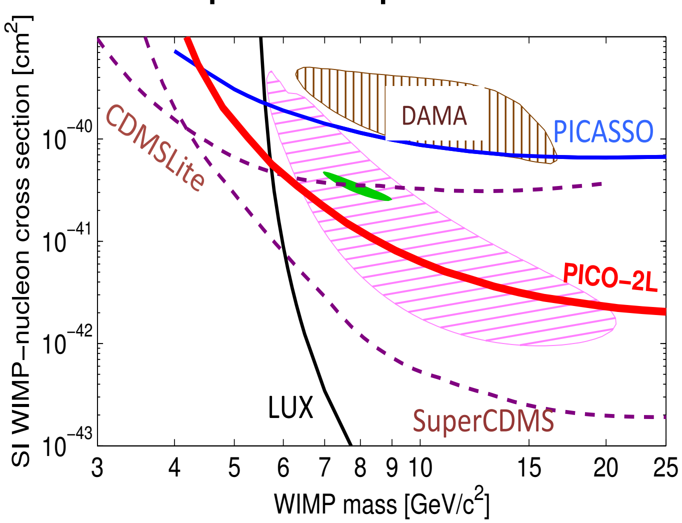
Current PICO Results

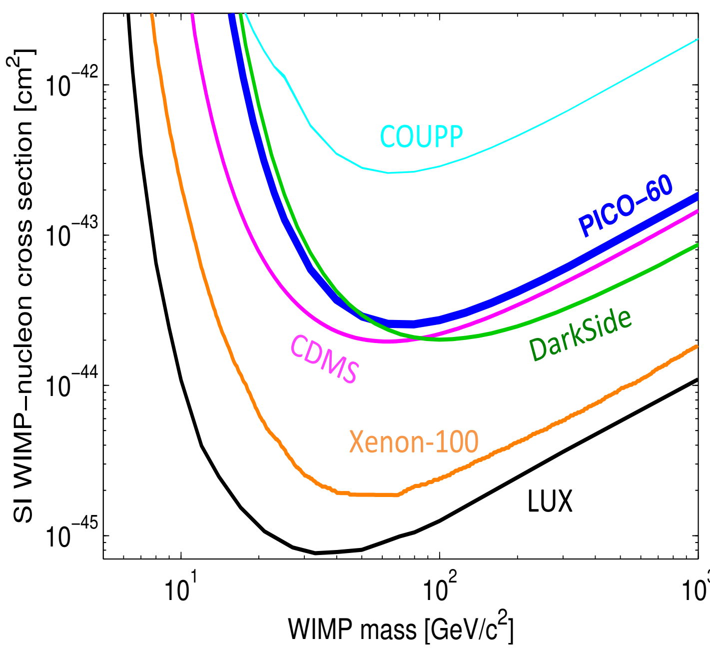
- World's best spin-dependent direct detection limits (Fluorine target with spin carried by proton)
- Competitive for spin-independent, especially at low mass.

Spin-dependent



Spin-independent

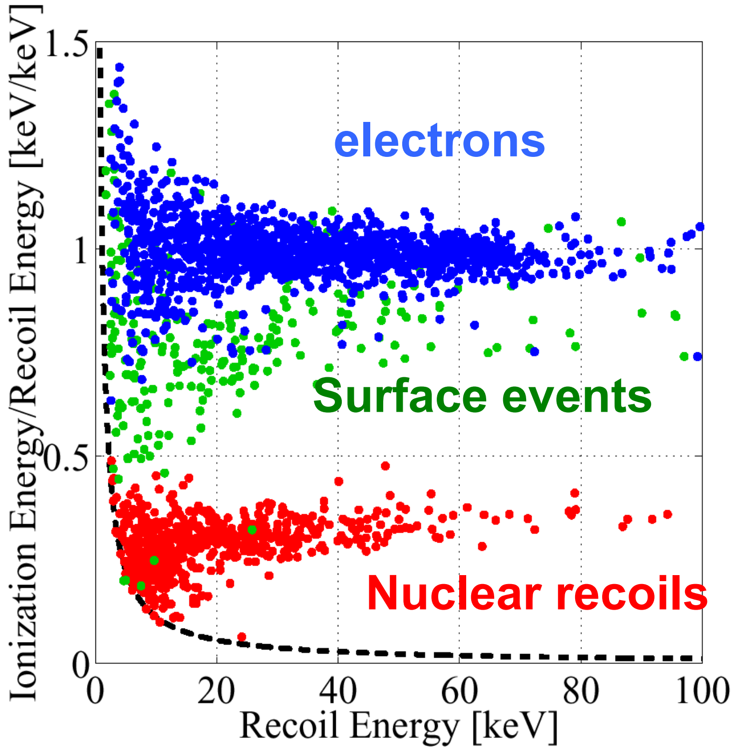




Cryogenic Detectors: SuperCDMS

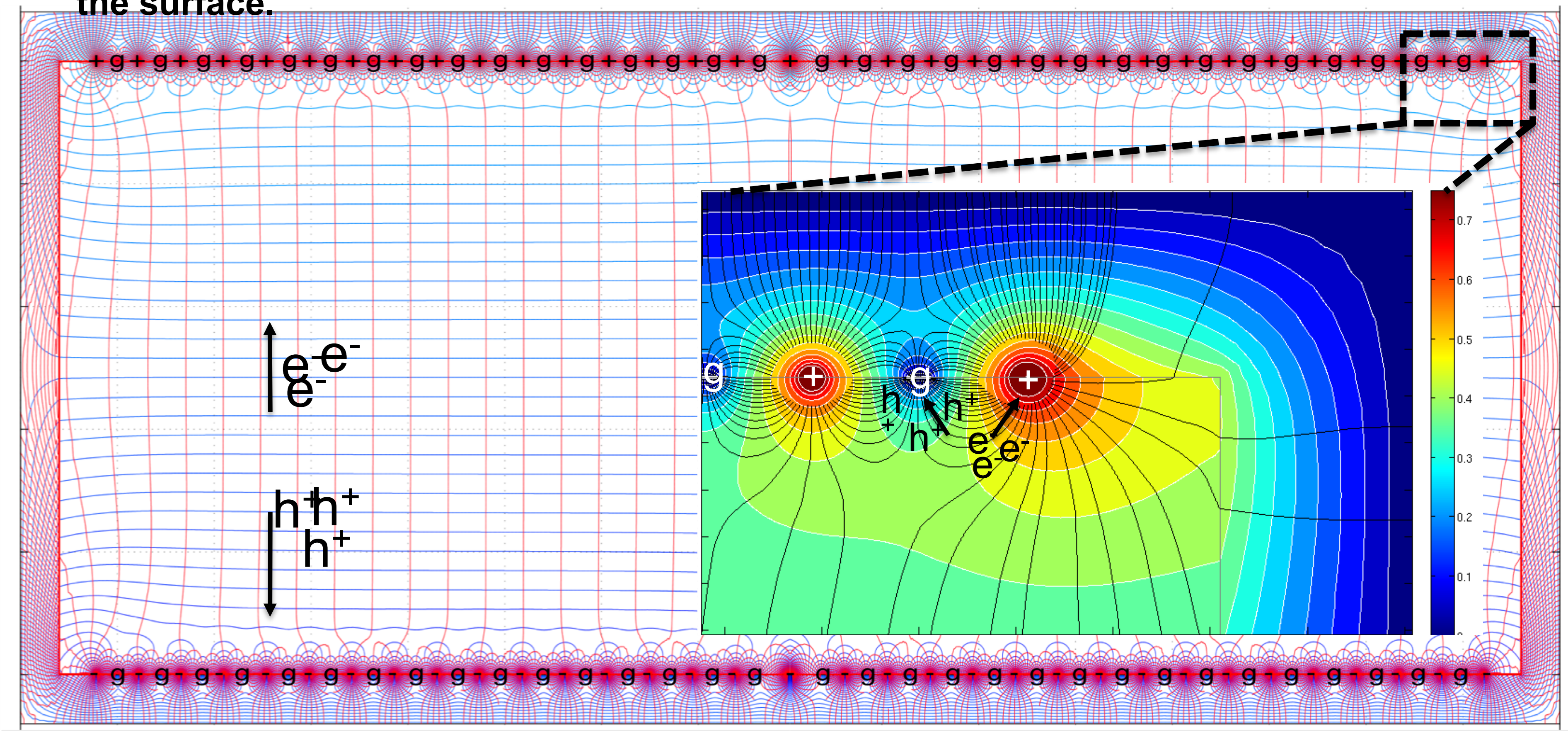
- Germanium and Silicon semiconductors operated at ~50 milliKelvin.
- Readout of ionization and phonons in multiple channels using thin film sensors.
- Many background discrimination handles:
    - Ionization/ phonon ratio
    - Phonon pulse shapes
    - Partition of phonons and ionization between sensors.
    - Time delays between signals.

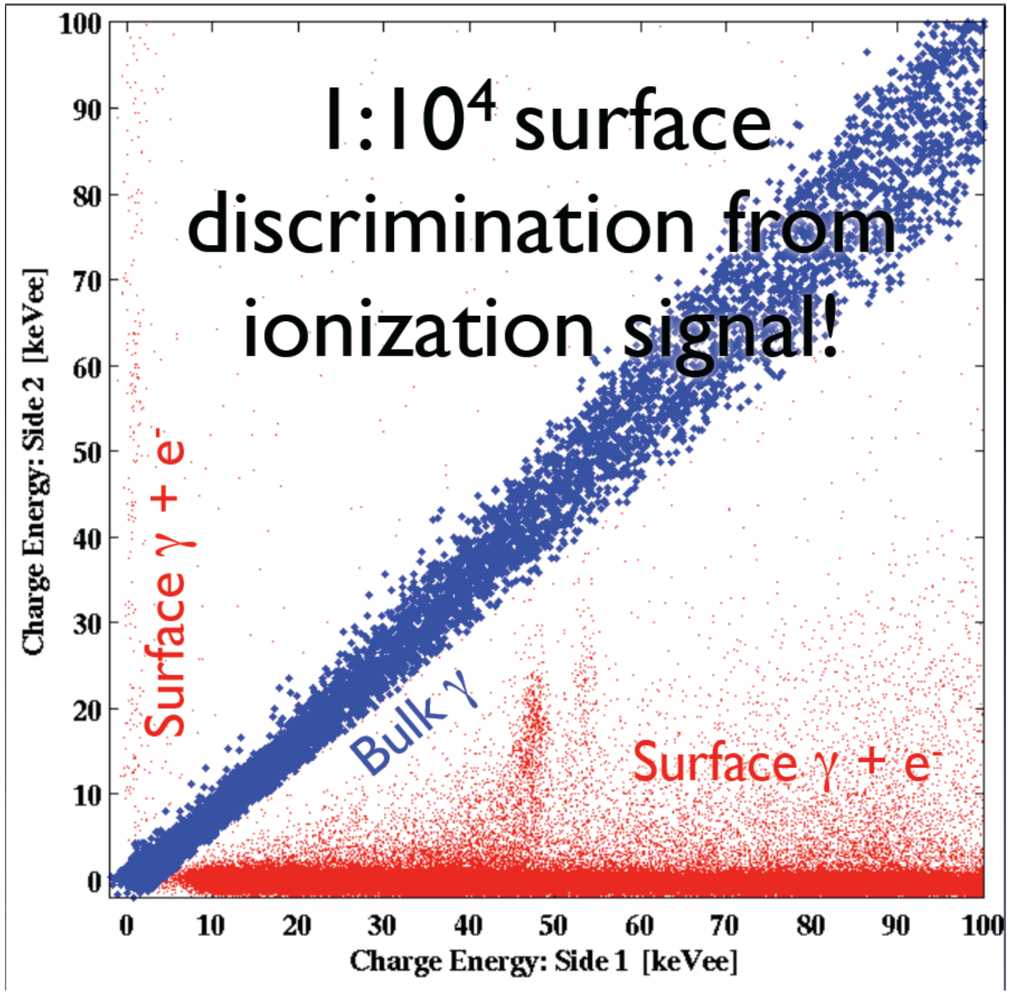
- Energy thresholds now down below 100 eV for some versions of this technology. In principle can go even below 1 eV.



iZIP: A new detector design

- Interleaved electrodes (1 mm pitch) on both sides
- Alternating +V & ground (i.e. phonon sensors) on one side -V & ground on the other side.
- Bulk events see the average Voltage on each side: Uniform Field in the bulk.
- In contrast the problematic Near-surface events sense the big transverse field at the surface.





Mahapatra, Berkeley Workshop on Dark Matter Detection, June 2015

SuperCDMS Soudan

5 Super Towers of Ge iZIPs (9 kg total)

Fully operational since early 2012

WIMP-search strategies

CDMSlite (No discrimination)

Special bias configuration & readout

Light WIMP masses: **< 10 GeV/c^2**

Low-threshold (LT) analysis (with discrimination)

Subset of array w/ best trigger thresholds

Light WIMP masses: **< 20 GeV/c^2**

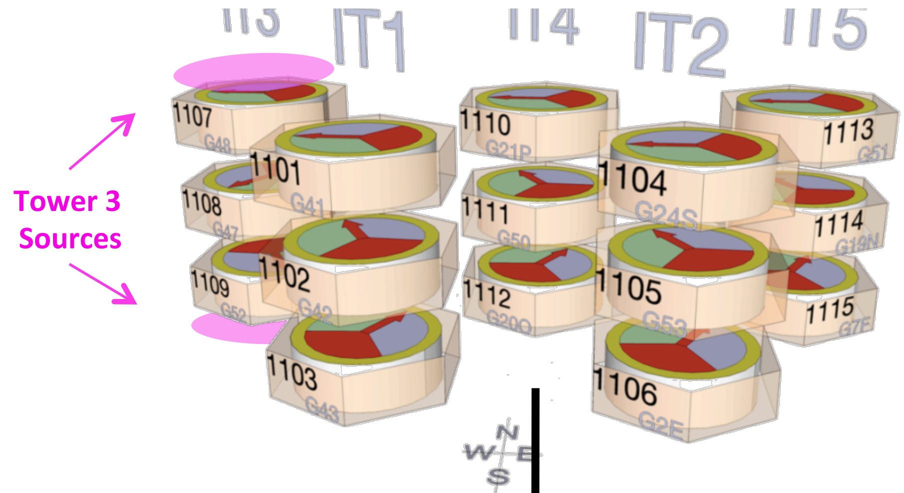
High-threshold Near-zero background analysis

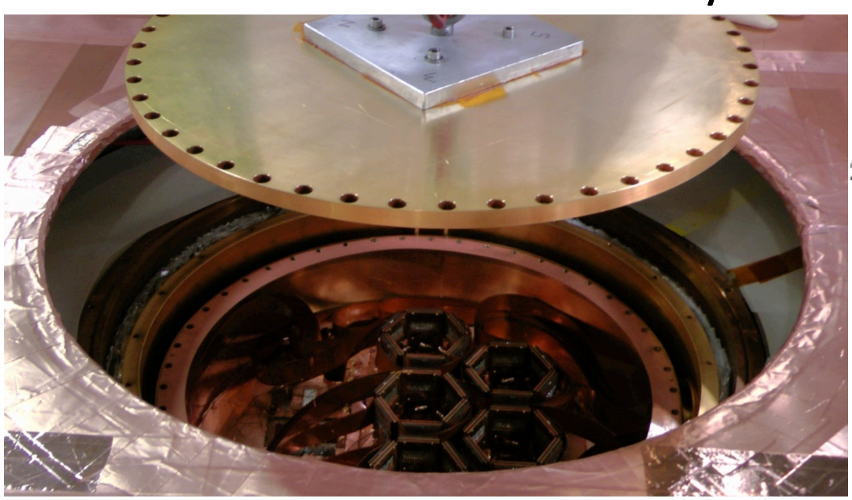
Full detector array & exposure

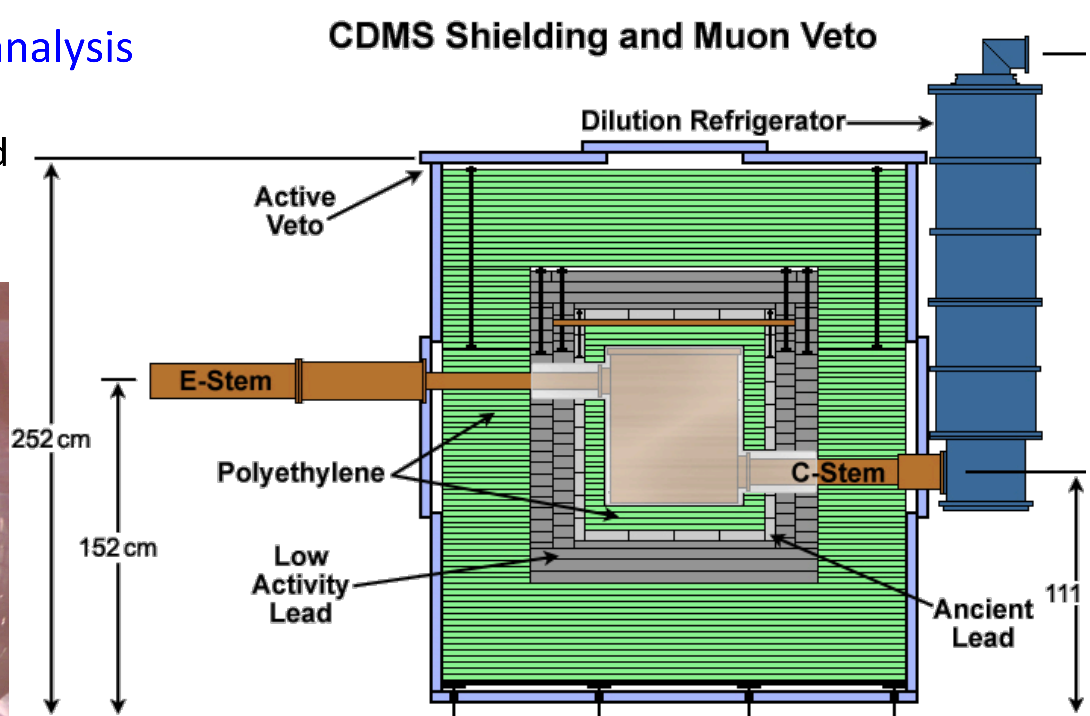
Higher thresholds to prevent background from resolution effects

Heavier WIMP masses: **> 10 GeV/c^2**

Mohapatra, 2015

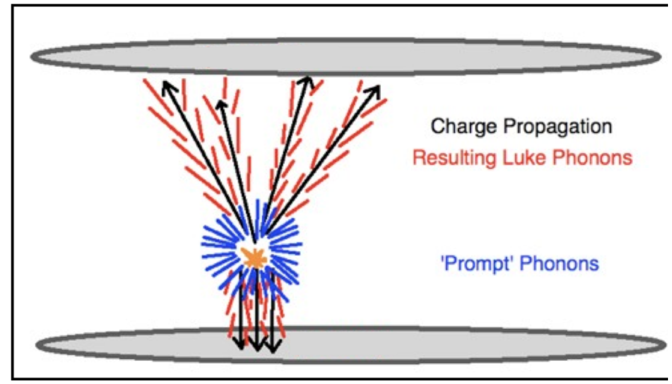






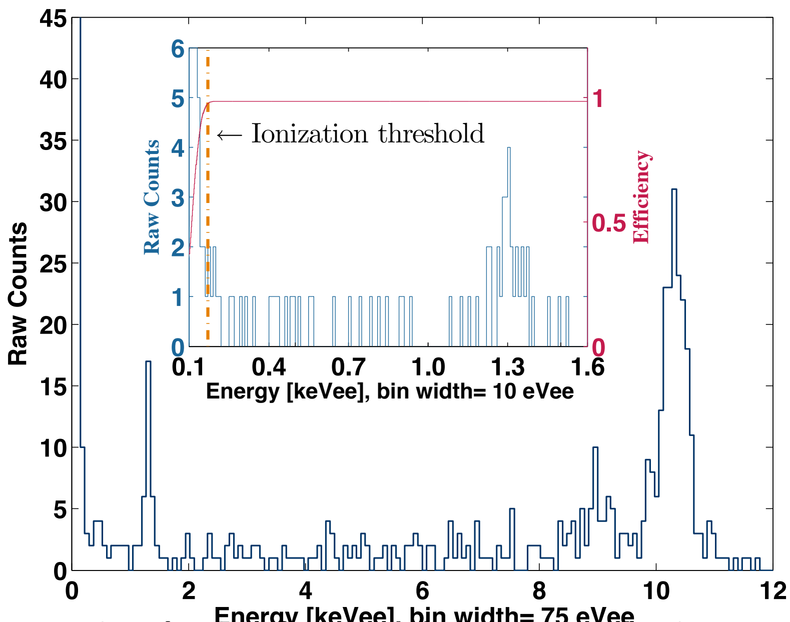
Voltage Assisted Ionization Detection

- Detectors operated for two weeks at 30 V/cm
- World leading limits below 5 GeV
- In principle, increase bias to reach Poisson limit
- In practice, breakdown in Ge limited the bias V
- Huge progress in detector R&D (Berkeley + TAMU) shows promising resolution to few eV!



- **Luke**-Neganov Gain

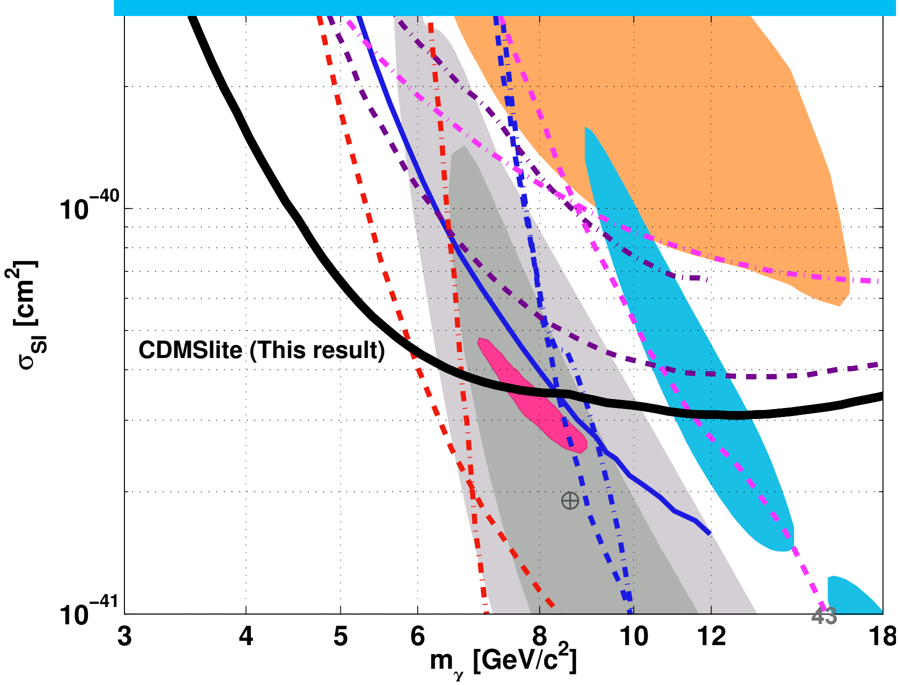
$$\begin{aligned} E_{tot} &= E_r + E_{luke} \\ &= E_r + n_{eh} e V_b \\ &= E_r \left(1 + \frac{e V_b}{\epsilon_{eh}}\right) \end{aligned}$$

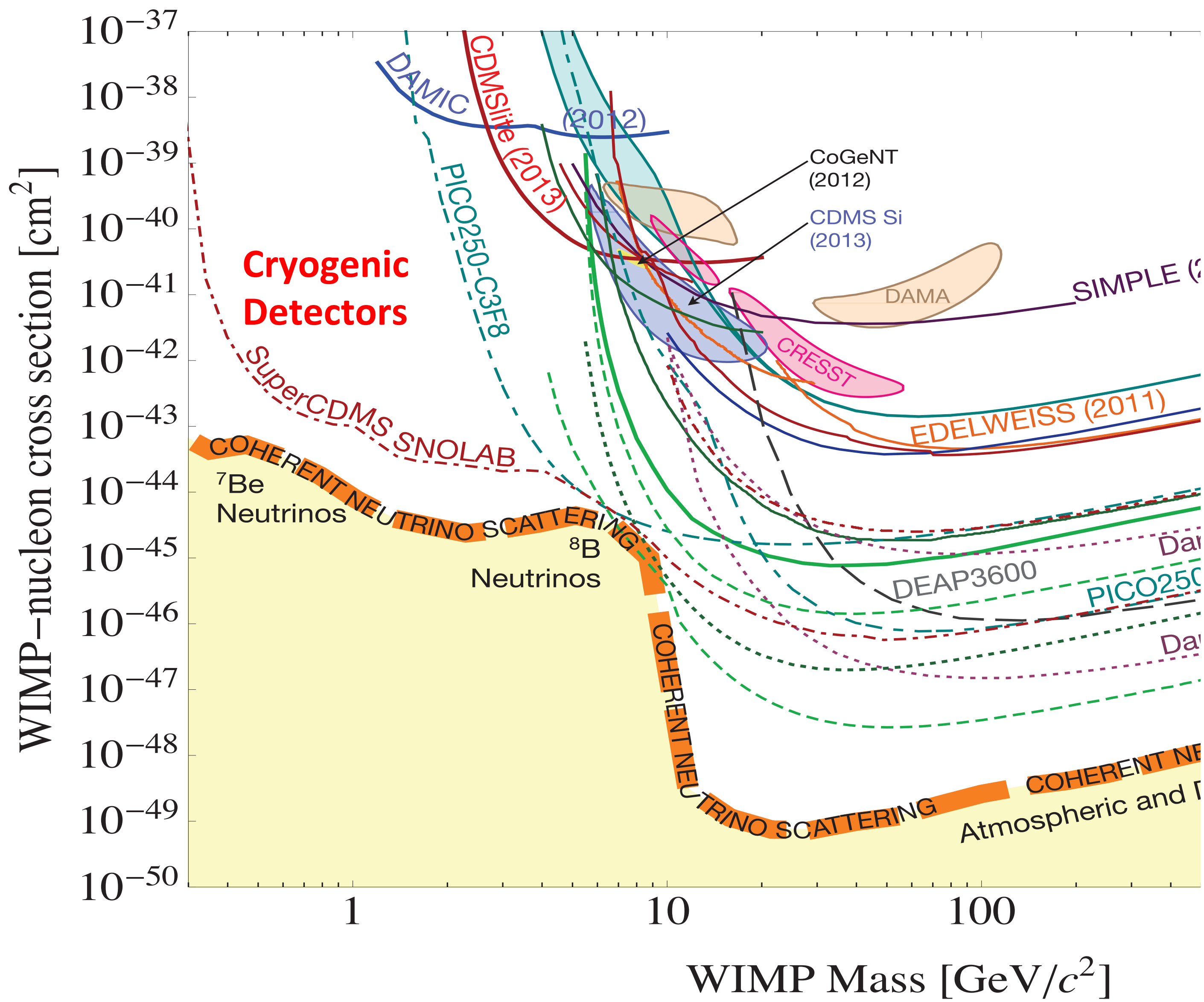


A signal gain of 24 was demonstrated using SuperCDMS iZIPs with alternative electronics. This allowed a lower threshold of 160 eVee.

arXiv:1309.3259; Phys. Rev. Lett. 112, 041302 (2014)

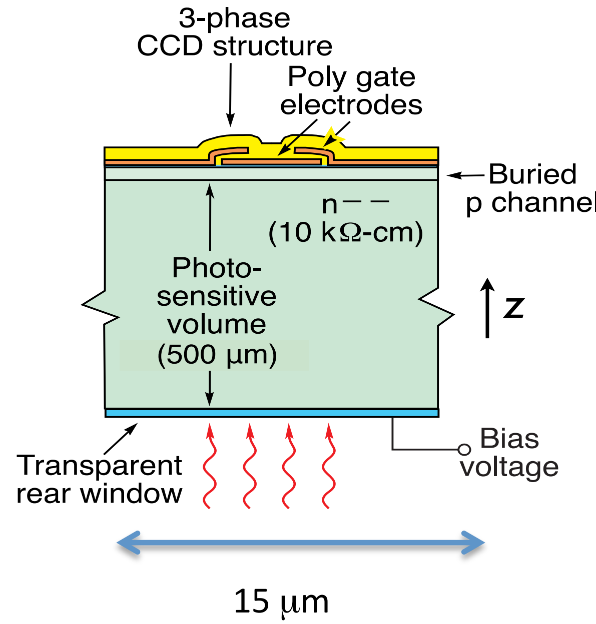
Phonon noise doesn't scale with ionization bias





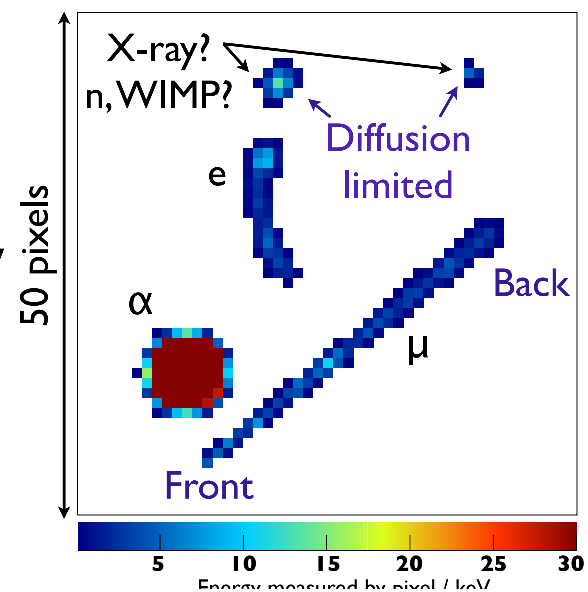
WIMP–nucleon cross section [cm^2]
WIMP Mass [GeV/c^2]
Cryogenic
Detectors
DAMIC
CDMSlite (2013)
(2012)
PICO250-C3F8
CoGeNT
(2012)
CDMS Si
(2013)
DAMA
SIMPLE
CRESST
EDELWEISS (2011)
SuperCDMS SNOLAB
COHERENT NEUTRINO SCATTERING
7Be
Neutrinos
8B
Neutrinos
DEAP3600
PICO250
Atmospheric and

Low Threshold Semiconductors- DAMIC

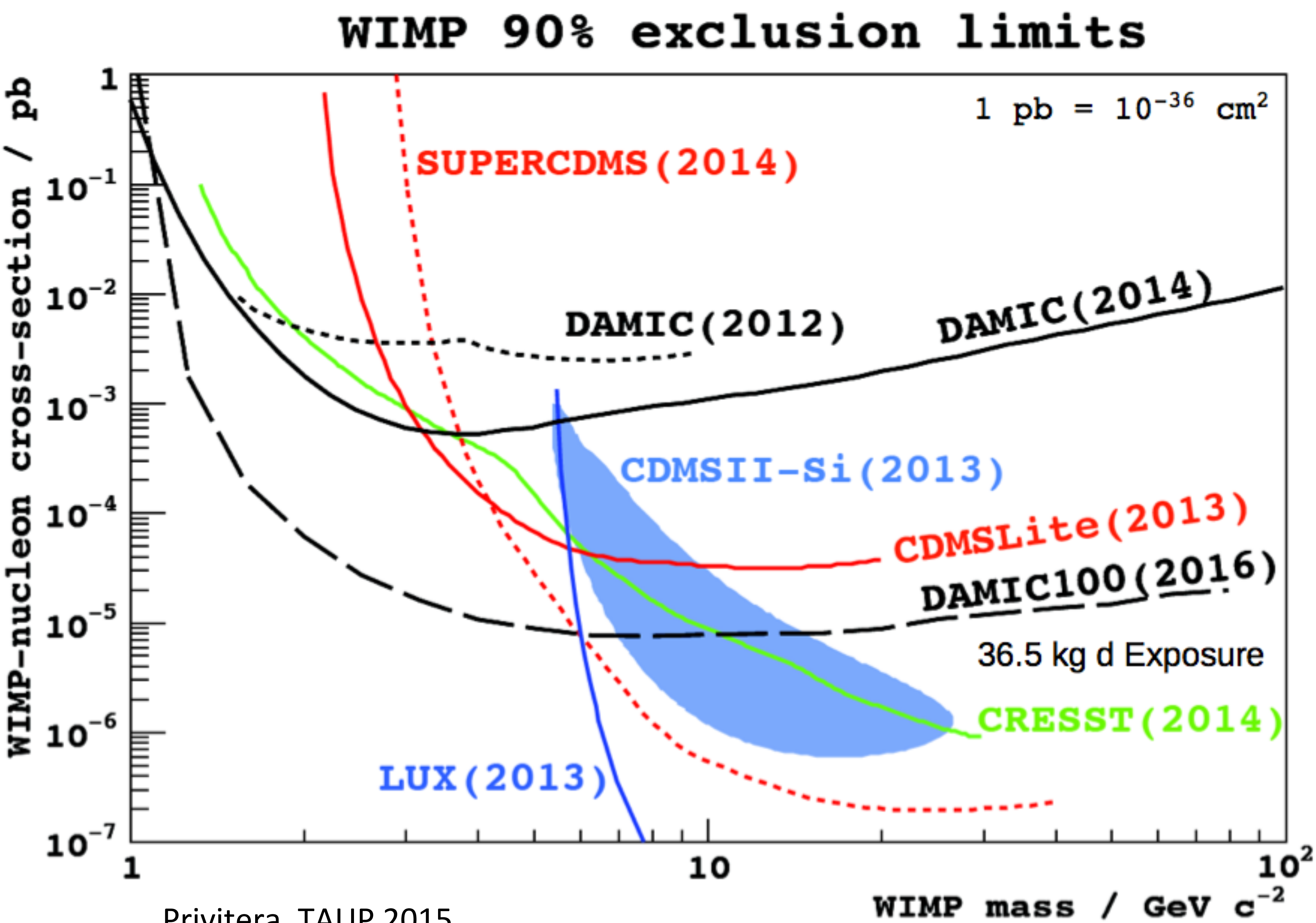


- Charge noise scales with device size (capacitance)
- Array of very small devices such as CCD can have readout noise approaching ~1 electron.

  (0.2 electrons for new proposals!)
- Low threshold comes at expense of low target mass & background discrimination power.
- But imaging allows rejection of many backgrounds.



DAMIC sensitivity



Privitera, TAUP 2015

Summary

- Extraordinarily rapid progress pushing towards "neutrino floor"
- Success of liquid xenon TPC technology driving the field over last ~ 5 years.
- Major recent success with argon TPCs. Could scale to 100s of tons.
- Bubble chambers provide target diversity, may scale to multi ton targets.
- Cryogenic detectors and semiconductors compete at low mass.