Dark Matter Direct Detection Experiments

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Direct Detection

- Search for interactions of WIMPs in terrestrial detectors
  $\rightarrow$ WIMPs gravitationally bound to galaxy ("galactic WIMPs"):
  $v_{WIMP} < v_{escape} \approx 600\, km/s = 2 \times 10^{-3}\, c$
- Elastic scatter with electrons: eV-range energies
- Elastic scatter with nuclei: 10s of keV range
  (below keV for WIMPs with masses $\lesssim$1 GeV/c^2)

⇒ Default DM Search: look for nuclear recoils (NR)

- Dark Matter density (here): ~0.3 GeV/c^2
- Typical cross section with nucleons: <10^{-45} cm^2

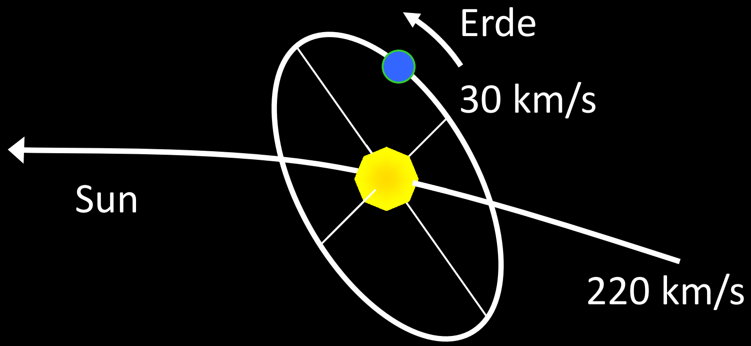
⇒ Expected interaction rate very small (experimental limit: < few/ton/year)

- Typical environmental radiation: kHz/kg (mostly electron recoils, ER)

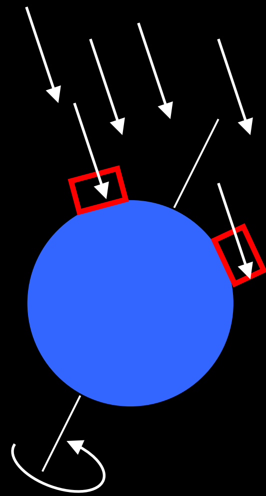
⇒ Shielding (cosmogenic radiation, environmental radioactivity);
material selection, cleaning; ER/NR discrimination

Direct Detection Signatures

Nuclear recoils
- Eliminate other sources of nuclear recoils (mostly neutrons)
- Discriminate against electron recoils

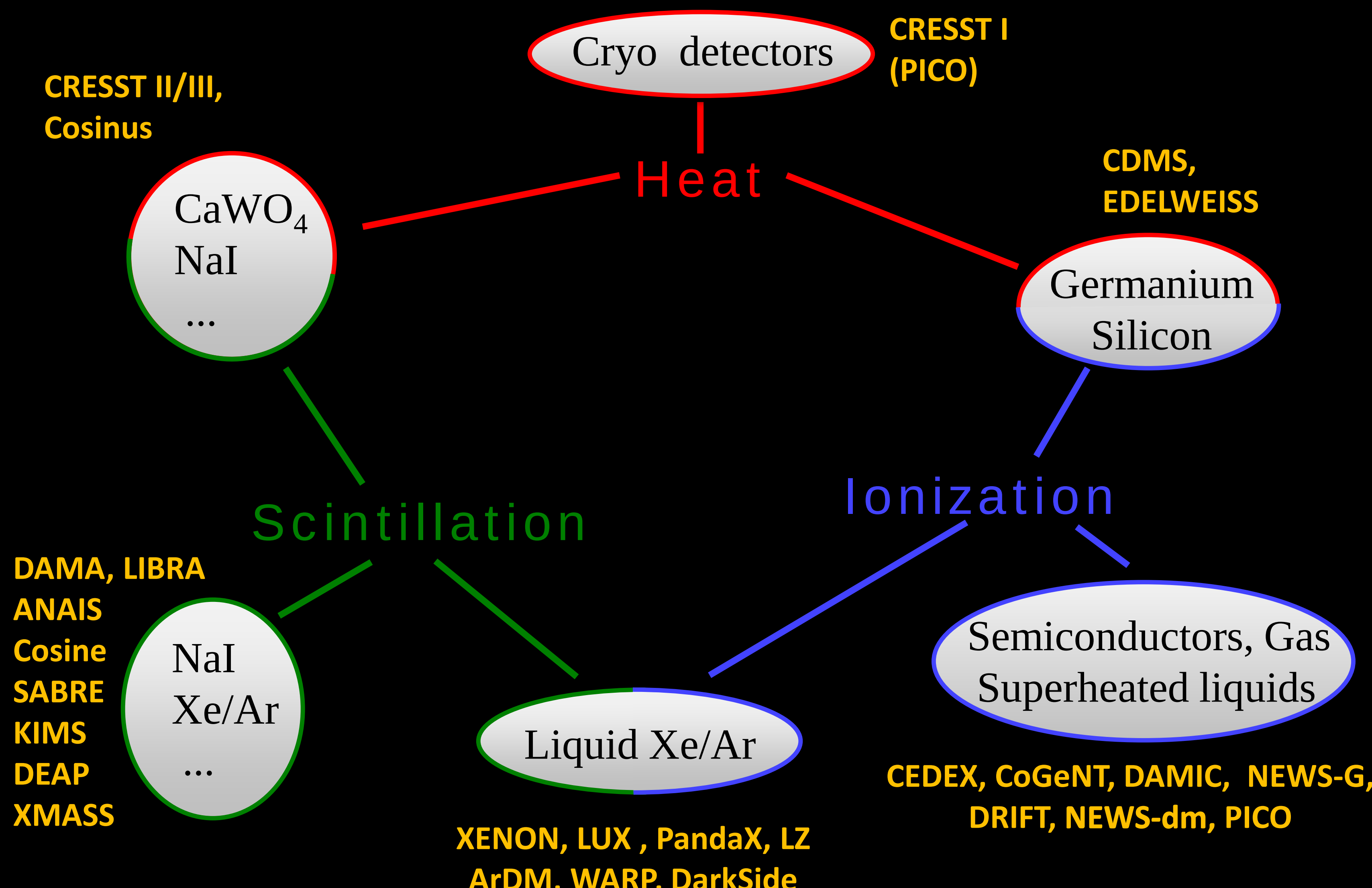


Annual Modulation
- Sun moves about galactic centre
  Earth moves about sun
- Relative velocity between WMPs and detector changes over the year
- Look for (small) periodic variation of signal

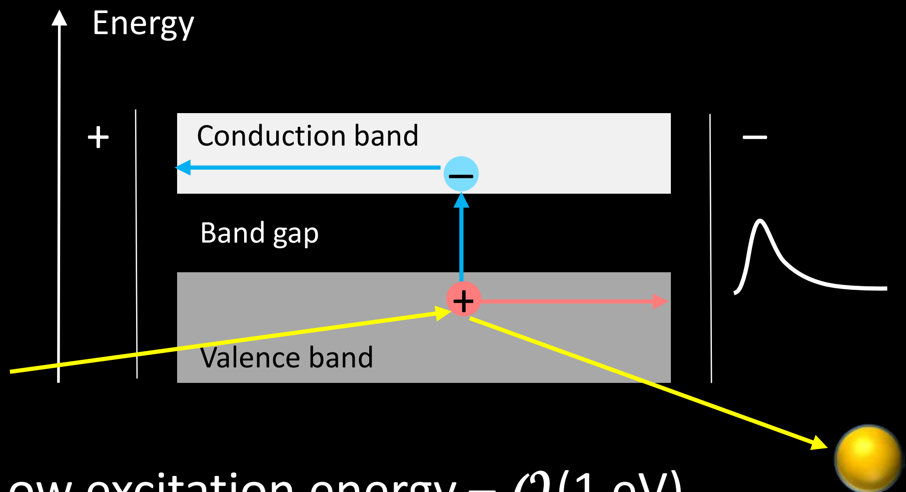


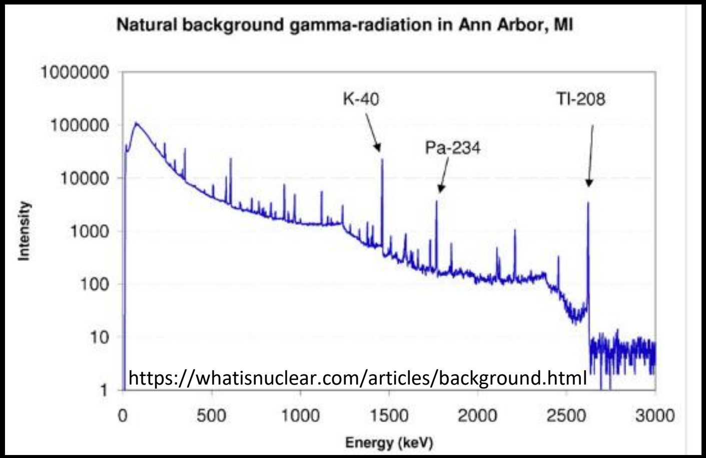
Diurnal modulation of direction
- Earth moves through WIMP cloud
- From earth point of view: ‘WIMP wind’
- Direction relative to detector changes over course of the day
- Look for preferred direction of WIMP interaction

Direct Detection Triangle



Semiconductor Detectors





Low excitation energy – $\mathcal{O}$(1 eV)
→ many charge carriers (~300 / keV)
→ good energy resolution
→ low energy threshold

Raw material (Ge, Si) very pure
→ low intrinsic contamination
→ low background

Well established detector technology

Germanium:

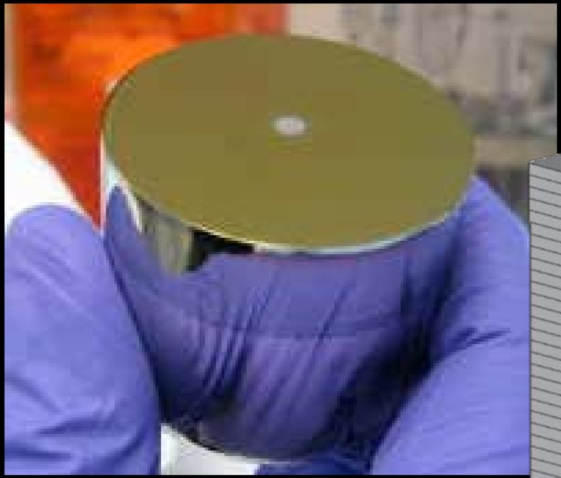
- Requires low temperature (77 K)
- High voltage (typically ~2kV)
- Typically large mass

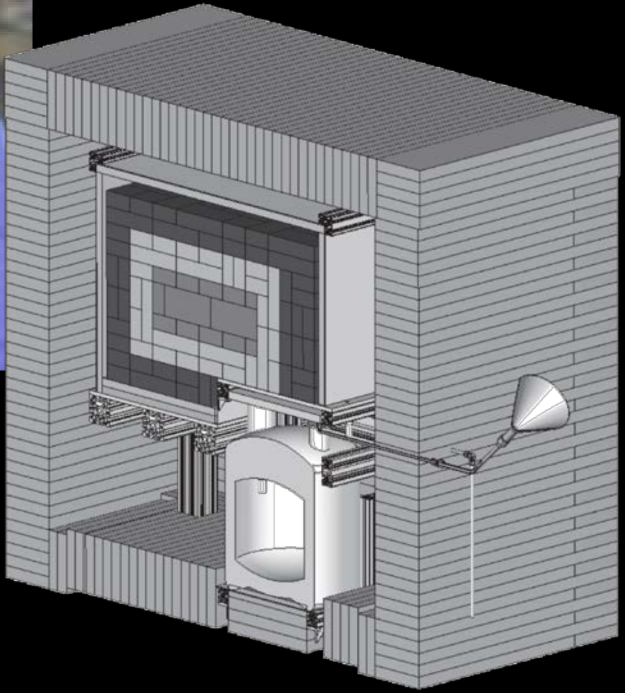
Silicon:

- Operation at room temperature (or with moderate cooling)
- Works with low voltage
- Typically low volume (wafers)

CoGeNT – Germanium Point Contact Detector (Soudan Lab)

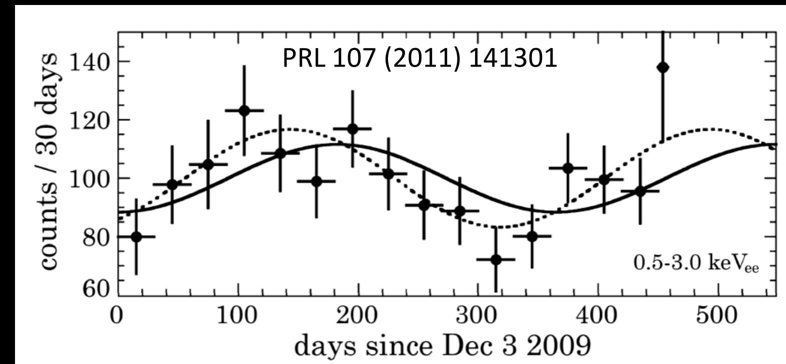
- Spin-off from Majorana (double beta decay experiment)
- Point-contact Ge detector (440 g)
- Optimized for low threshold (0.4 keV)
- Layered shield (PE, borated PE, 3 layers of Pb (innermost: ancient Pb))

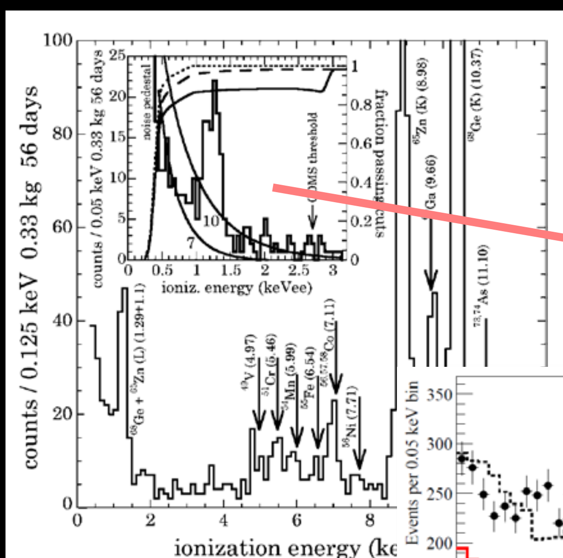


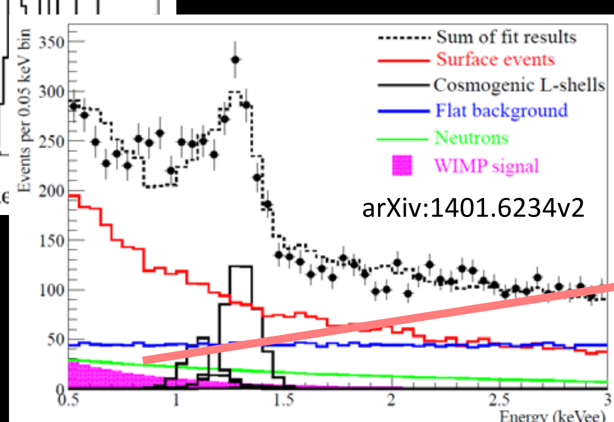


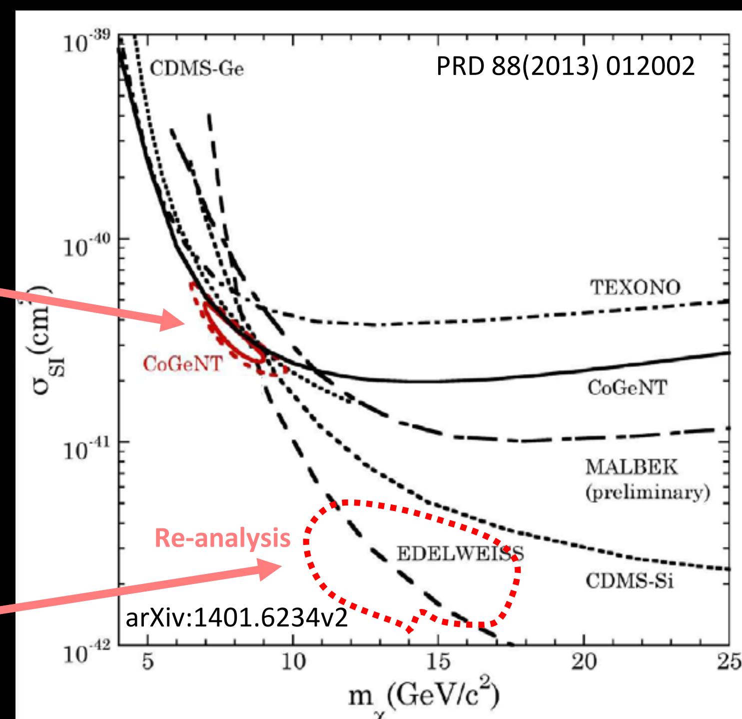
CoGeNT – Germanium Point Contact Detector (Soudan Lab)

- Observed excess at low energy
- Hint of annual modulation
- Interpretation as indication of dark matter interactions
- Careful reanalysis: excess is background



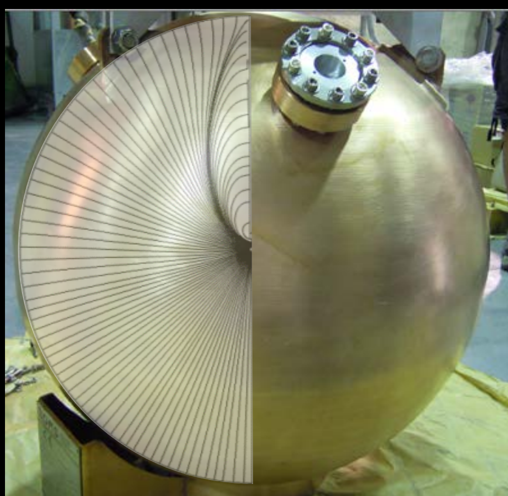


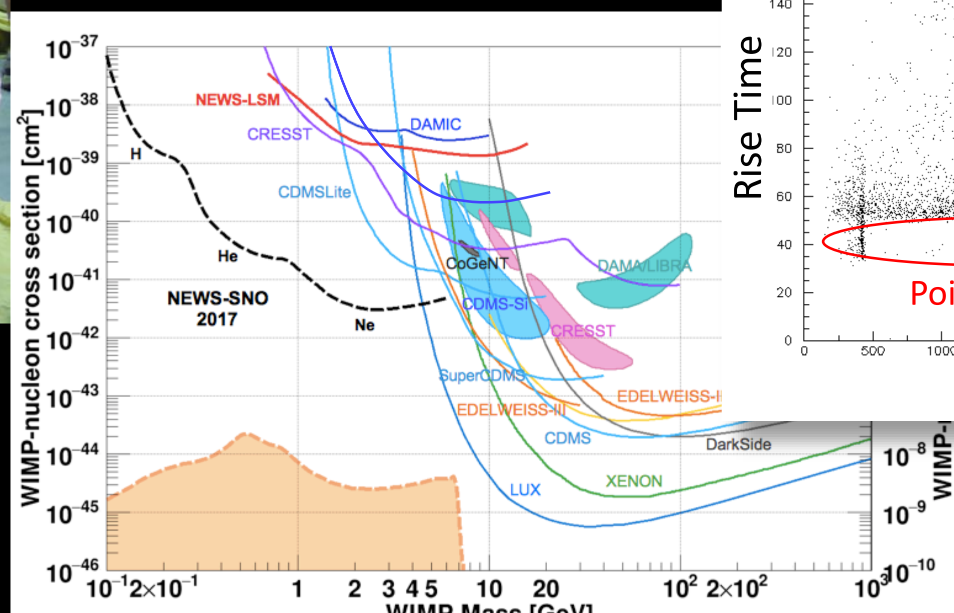


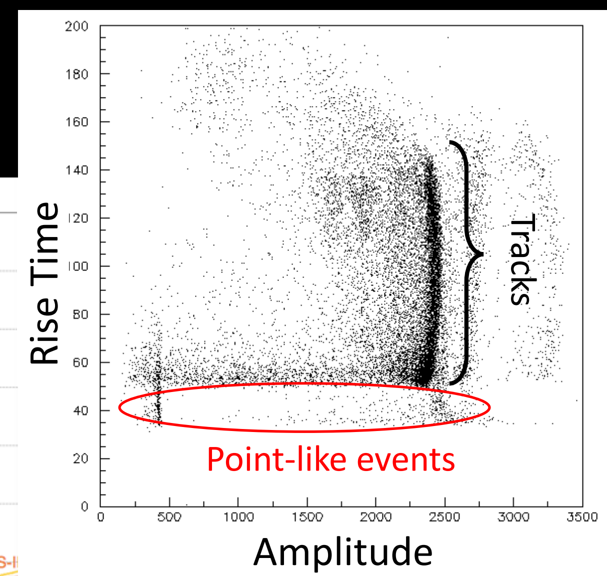


NEWS-G – Spherical gas TPC (Modane (LSM), SNOLAB)

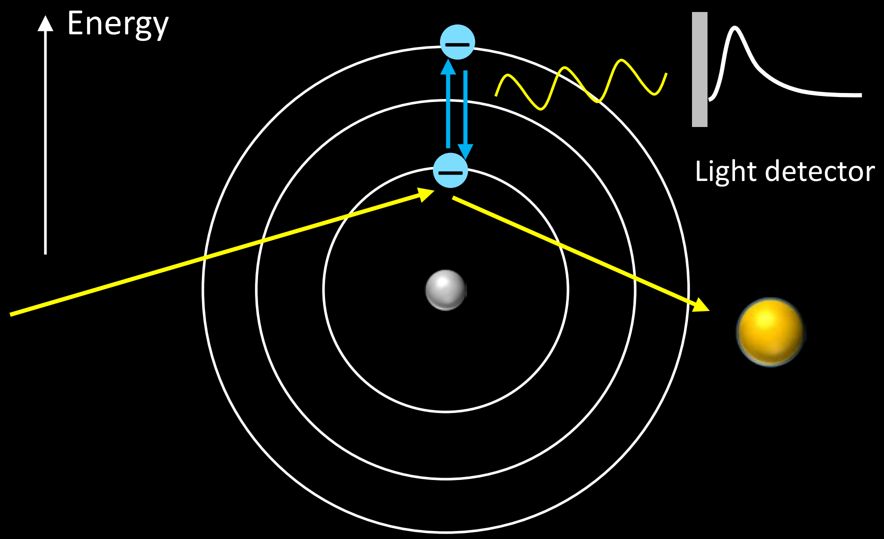
- Low energy threshold (~10 eVee), single electron sensitivity
- Position information from pulse shape
- Different gases: sensitivity to different mass ranges
- First measurements with Ne at LSM (60 cm sphere); data analyzed
- New sphere at SNOLAB under construction (1.4 m sphere)

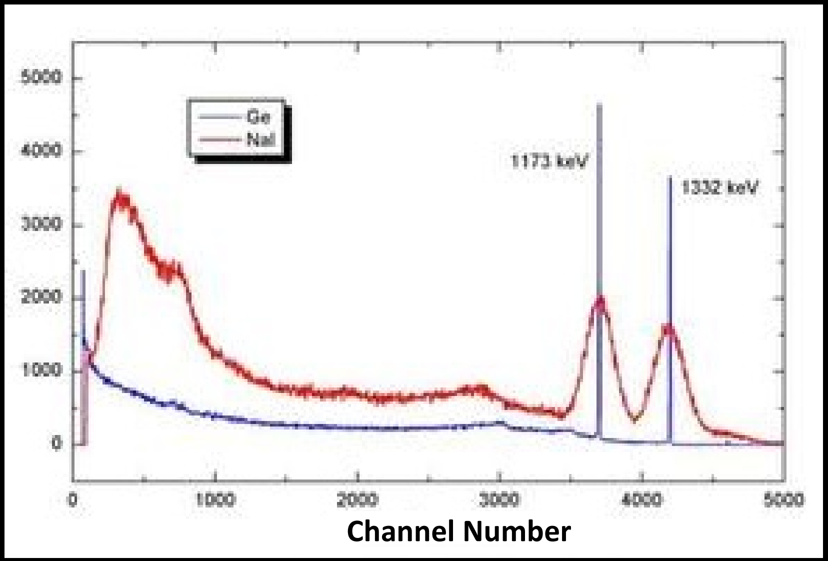






Scintillation Detectors





Excitation energy: few eV

Inefficient process (few % of energy)

- Moderate number of photons: $\mathcal{O}(50/\text{keV})$
- Worse energy resolution than semiconductor
- More difficult to purify than Ge/Si
- Light detectors often contribute background
- Cheaper than semiconductors
- Easier to operate (room temperature)

NaI(Tl)

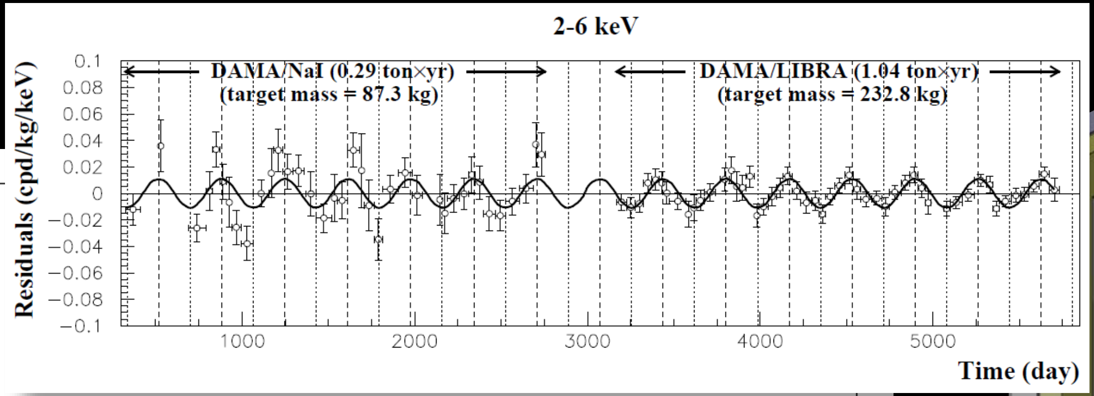
- Very good scintillator
- Spin target (^{23}Na, ^{129}I)

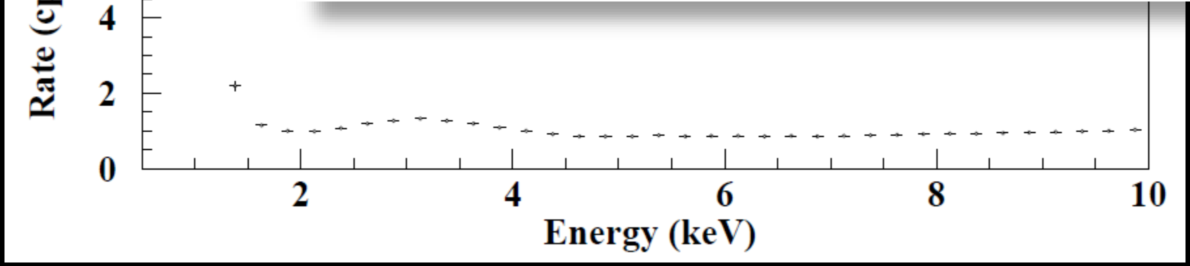
CsI

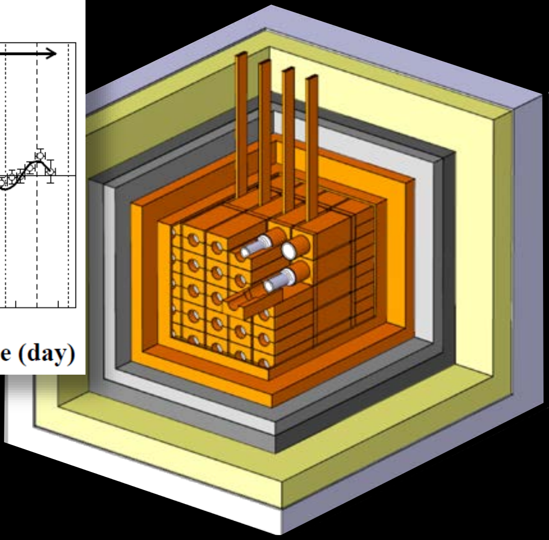
- ~20 % less light than NaI
- High Z (good spin-independent sensitivity)

DAMA/LIBRA – NaI (Gran Sasso)

- 100 kg (DAMA/NaI) / 250 kg (DAMA/LIBRA) of NaI
- ~10 kg/crystal, 2 PMTs per crystal
- Shielding: PE, Cd foil, low activity Pb high purity Cu
- Analysis threshold at 2 keV
- Search for annual modulation
- Operating since 1995; 13 annual cycles published, many σ evidence for oscillation; correct phase

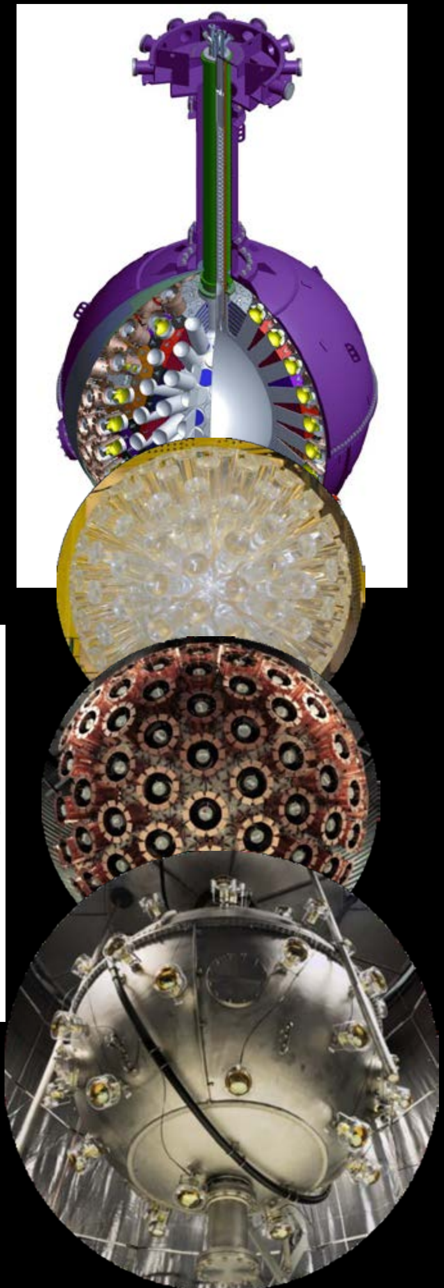


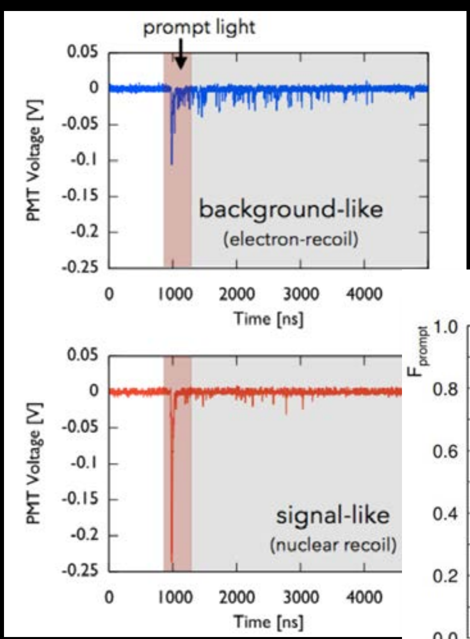


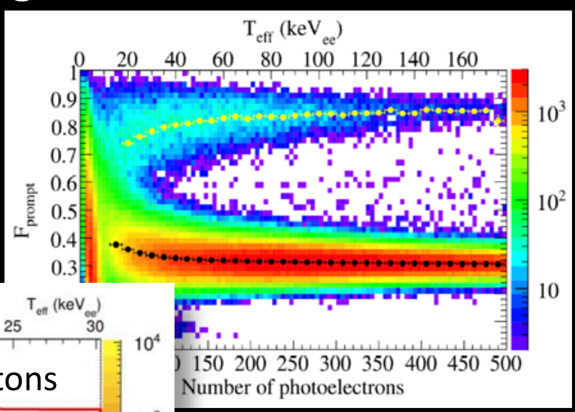


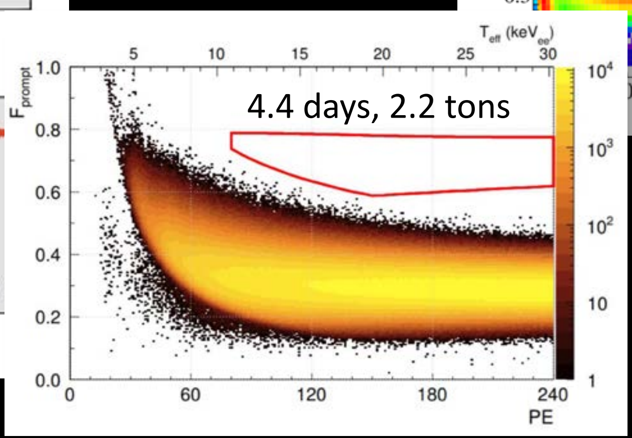
DEAP – Liquid Argon (SNOLAB)

- ~3300 kg of LAr in acrylic sphere
- Acrylic light guides, 255 PMTs, Steel shell, water shield
- Pulse shape discrimination ($<10^{-10}$)
  removes ER (dominated by ~3kHz of ^{39}Ar)
- Fiducialization (1 t) removes surface background
- Expected background: $\mathcal{O}$(1 event) in 3 years
- BG limit: n from PMTs, Radon daughters



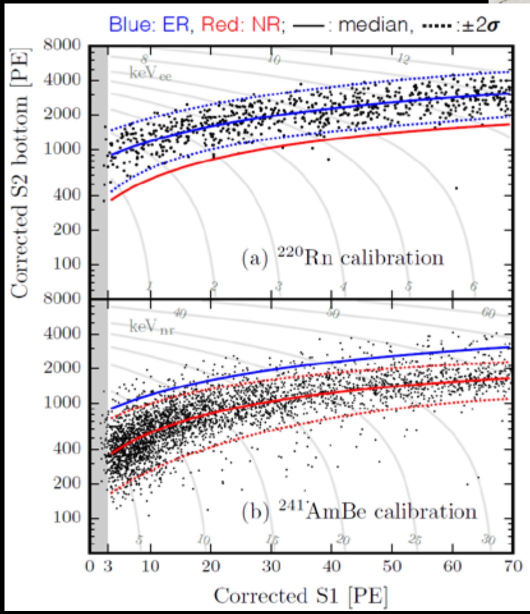


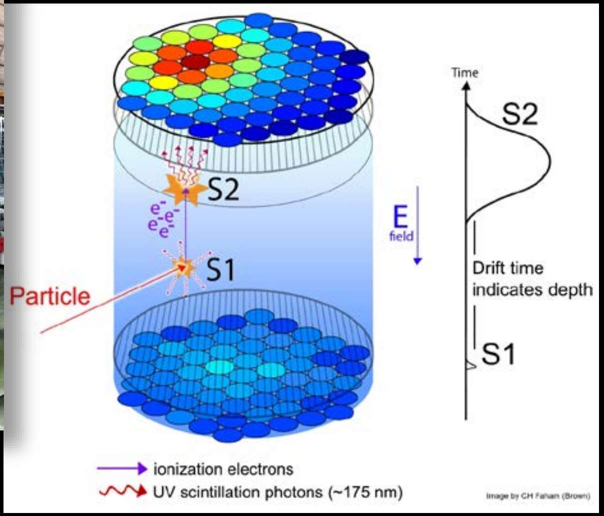




XENON – Liquid Xe TPC (Gran Sasso)

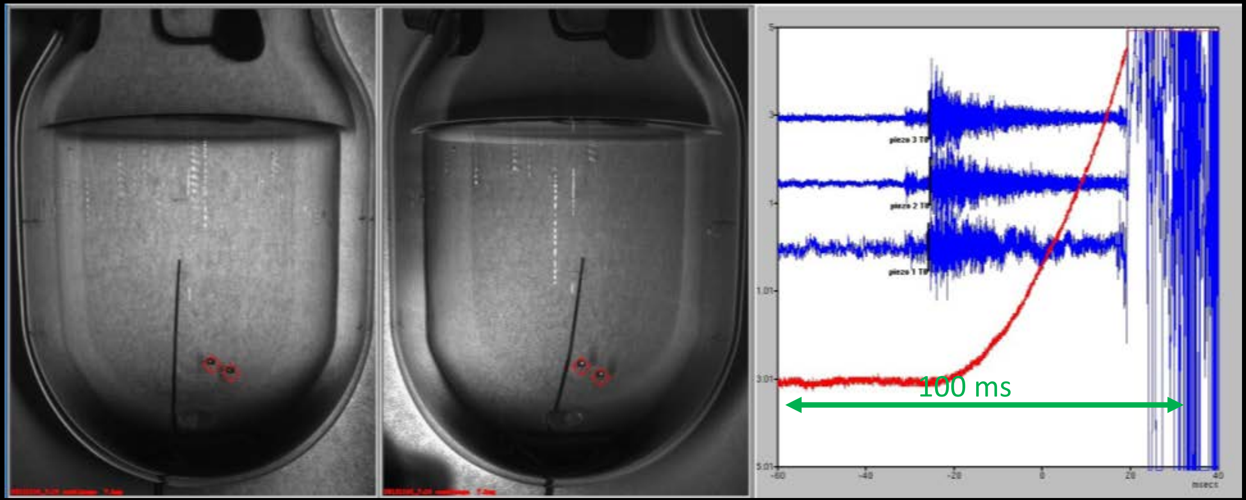
- Family of 2-phase Xe TPCs (10 kg, 100 kg, 1 t, 6 t (future))
- Cylindrical vessel with PMTs on top & bottom
- E-field to drift electrons, extract to gas phase and amplify
- Measure primary scintillation (S1) and gas scintillation (S2)
- Ratio of signals discriminates between ER and NR
- Xenon veto, water shield surrounding main detector





PICO – C_3F_8 Bubble Chamber (SNOLAB)

- Target: C_3F_8 – ^{19}F has unpaired p; sensitive to spin dependent interaction
- Superheated liquid: small energy deposition triggers phase transition
- Readout: optical (bubbles), acoustic (pressure waves)
- Need ionization density above threshold: sensitive to NR, αs; NOT βs, γs
- Acoustic discrimination against αs (are louder)
- Data: 2 L chamber, 60 kg (40 L) chamber (C_3F_8 and CF_3I)



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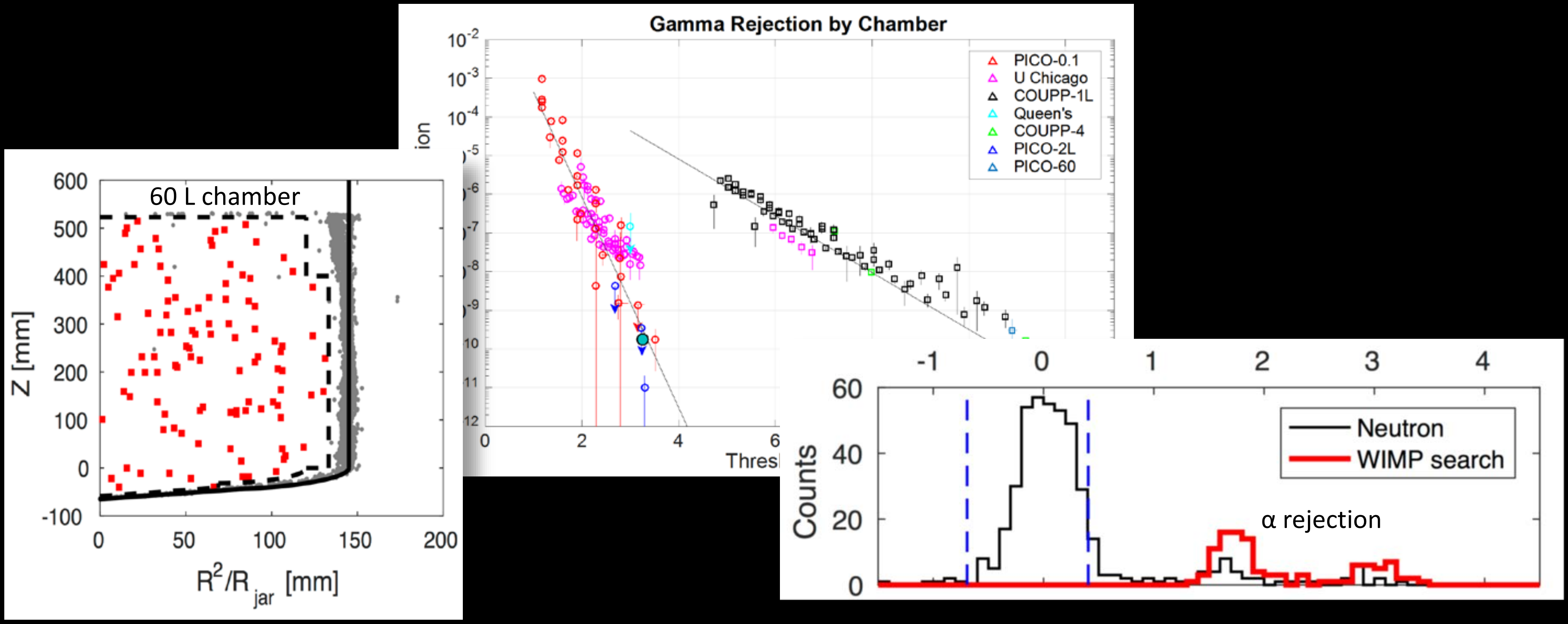
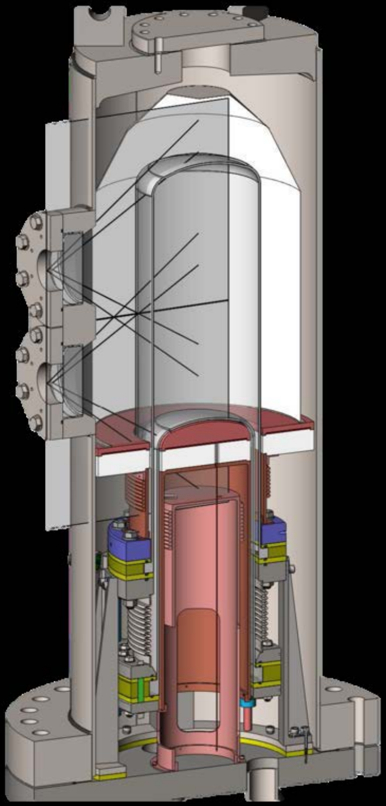
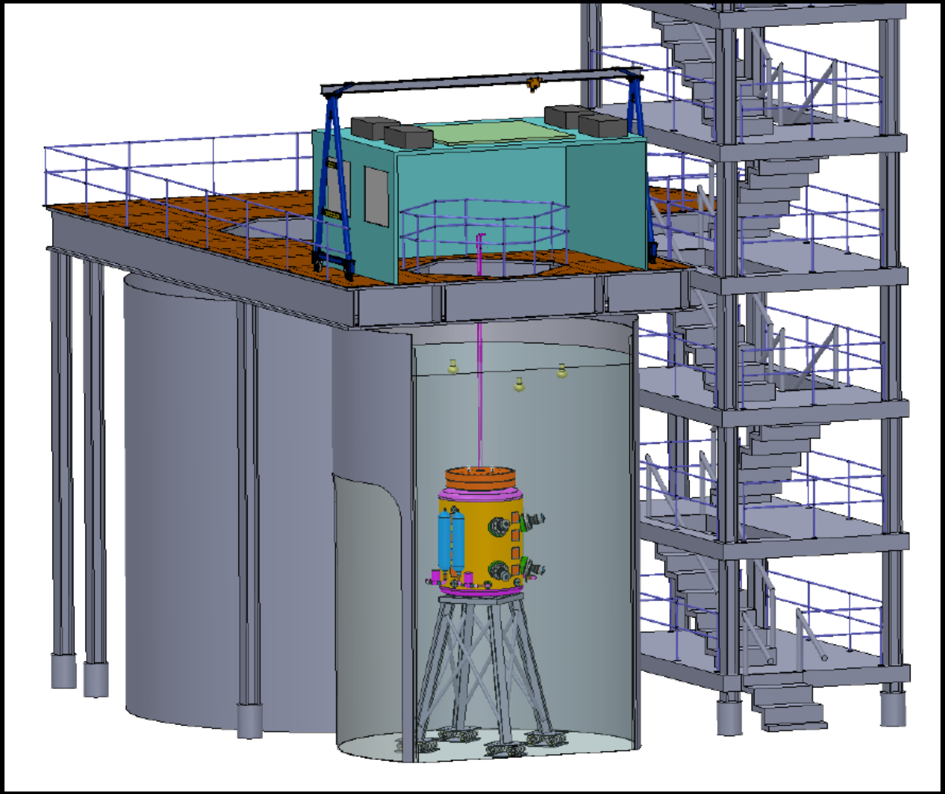


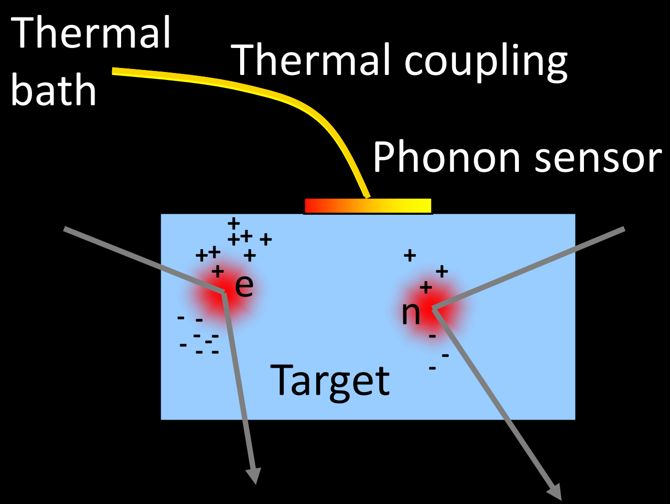
PICO – C_3F_8 Bubble Chamber (SNOLAB)

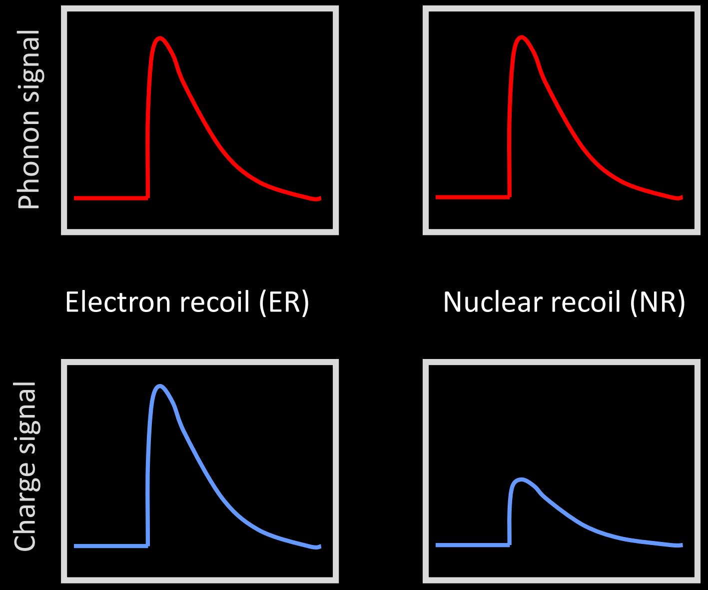
- Leading sensitivity to (proton-)spin dependent interaction reached with 60 kg chamber (and 2 L chamber, at time of publication)
- Next phase under construction: 40 L chamber with inverted geometry (avoiding interfaces, instrumental backgrounds)
- Longer term: 500 L chamber (in preparation)



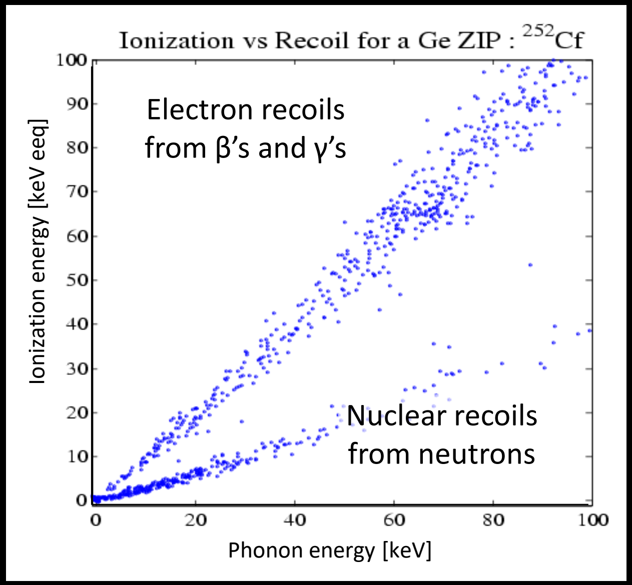


Cryogenic Detectors



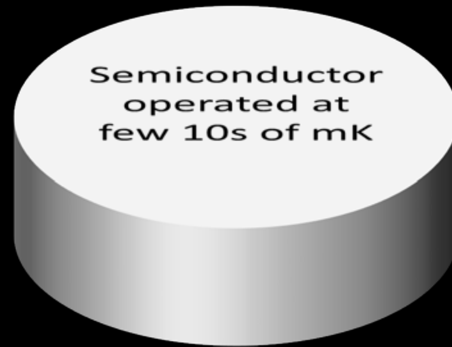


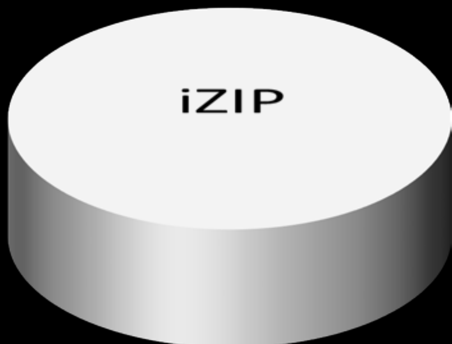
- Phonon signal (single crystal): measures energy deposition
- Ionization/scintillation signal: quenched for nuclear recoils (lower signal efficiency)
- Combination: efficient rejection of electron recoil background

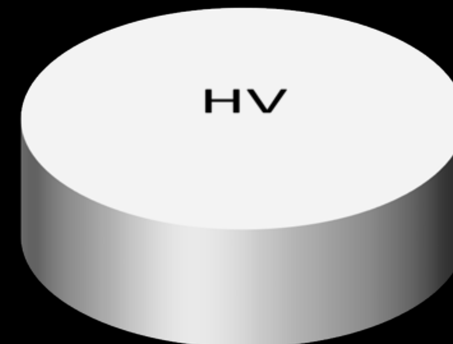


SuperCDMS

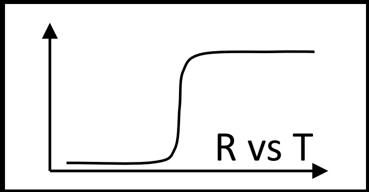
SuperCDMS Soudan



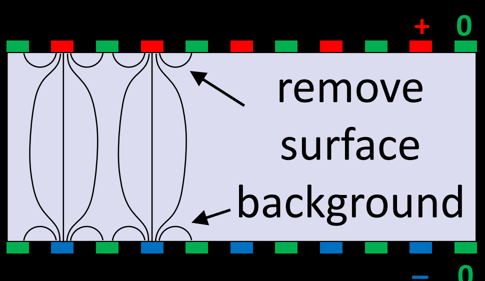




Phonon Readout:
Tungsten TES

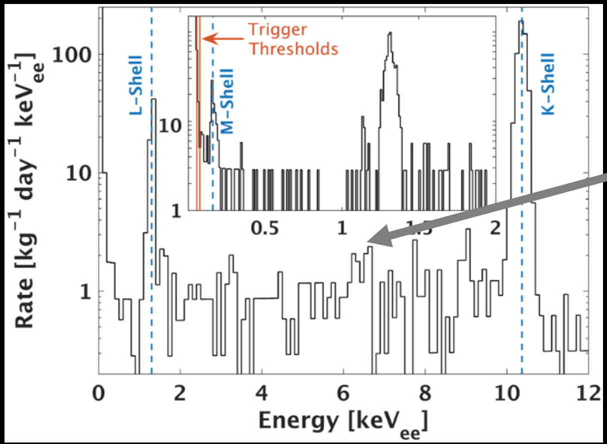


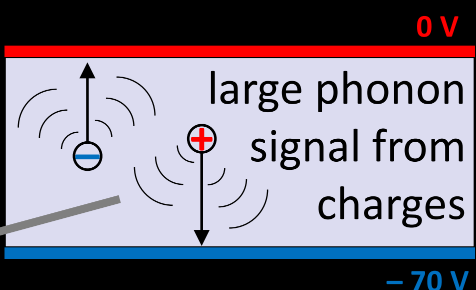
Add: charge readout (few V)
Background discrimination
Threshold < 10 keV



< 1 background event for whole exposure

Add: high voltage (~70 V)
Phonons from drifting charges
Threshold 56 eV_{ee} (phonon)

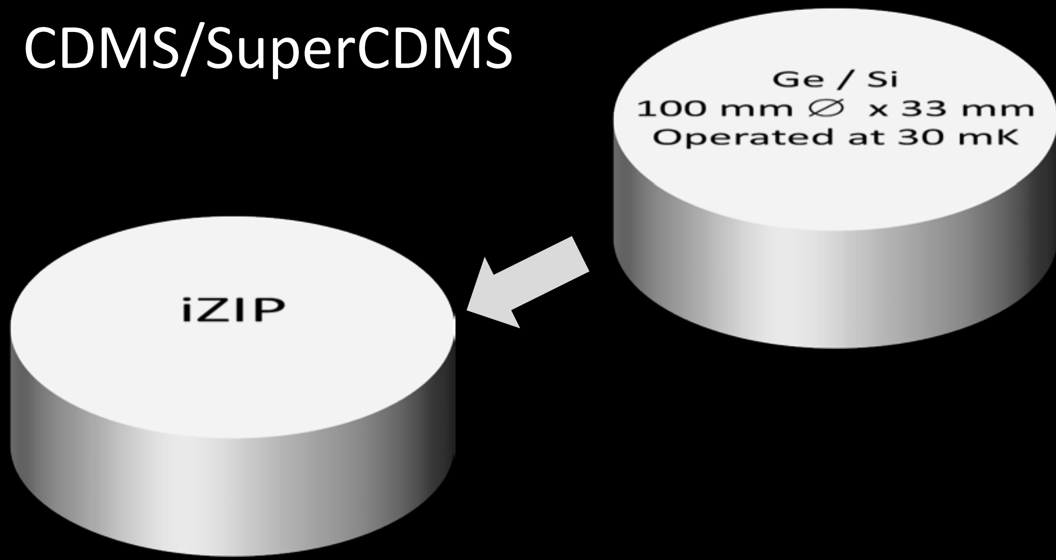




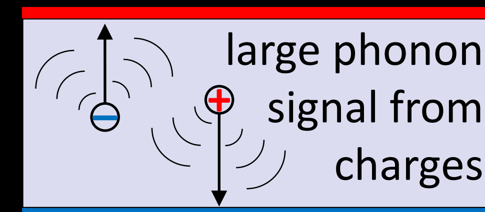
effective threshold:
few hundred eV (NR)

CDMS/SuperCDMS

SuperCDMS
SNOLAB



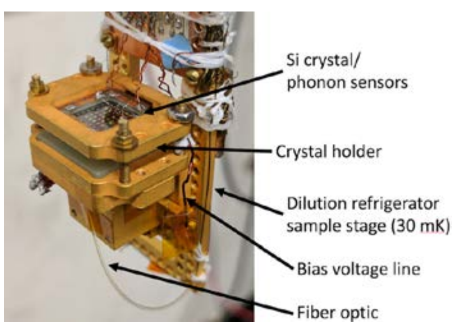
Add: high voltage (~100 V)
Phonons from drifting charges
Threshold < 10 eV_{ee} (phonon)

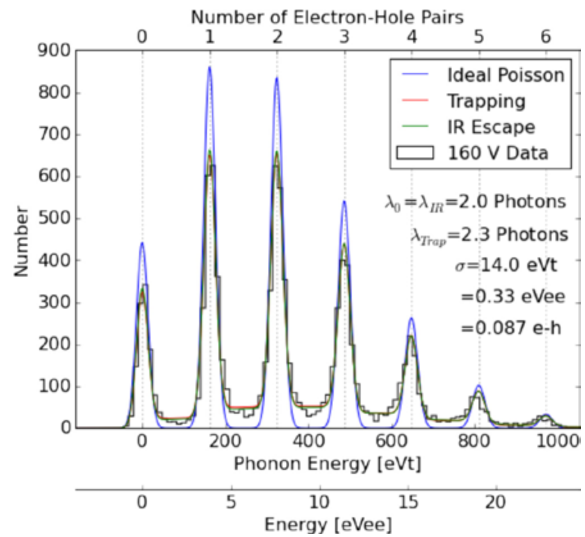


effective threshold: one (or few) electron-hole pairs

Potential of the HV approach

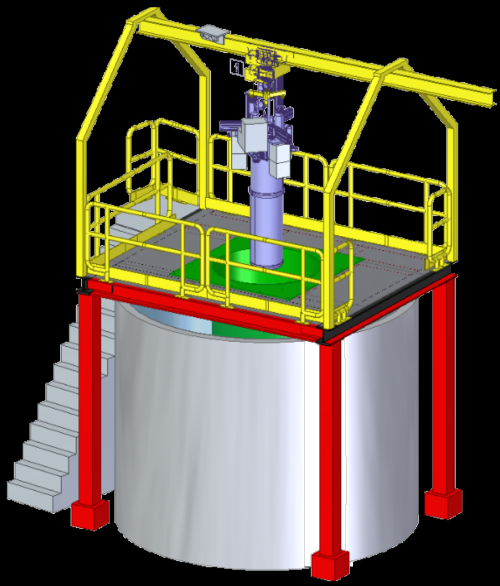
Si detector
1 cm x 1 cm x 4 mm (0.9 g)
Sensors like SuperCDMS detectors

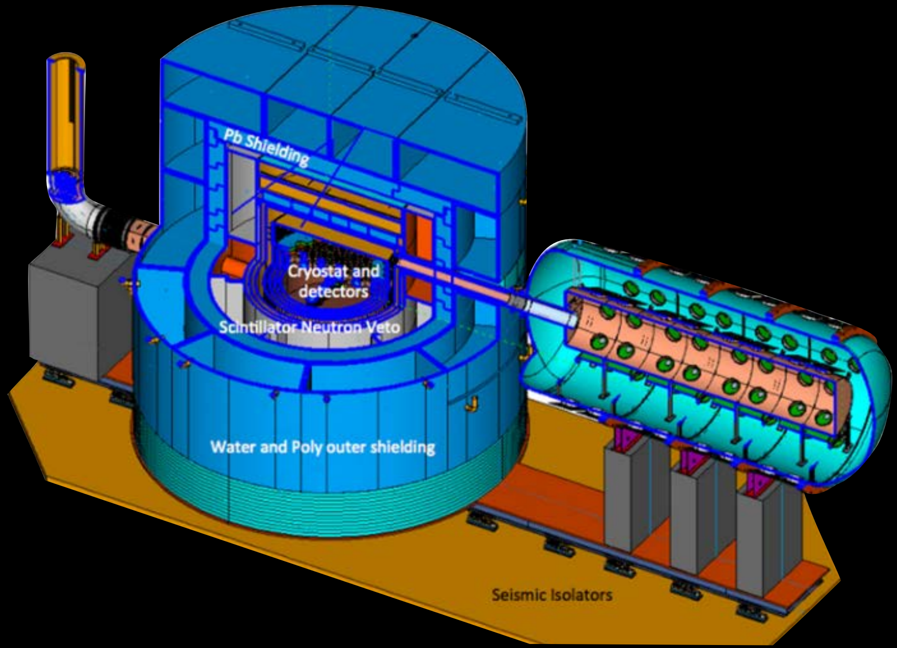




SuperCDMS – Cryogenic Ge/Si (SNOLAB)

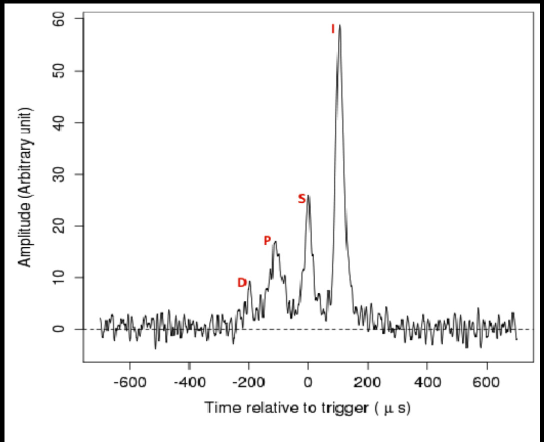
- Ge: 1.4 kg; Si: 600 g; iZIP/HV; initial payload: 24 det
- Shielding: (Cu), PE, Pb, Water/PE
- Threshold goal: <100 eV_t (HV)
- Limiting background (HV): ^3H (^{32}Si)
- Start operation in 2020
- Cryogenic Underground TEst facility (CUTE) being installed at SNOLAB in 2018 (→ early science?)



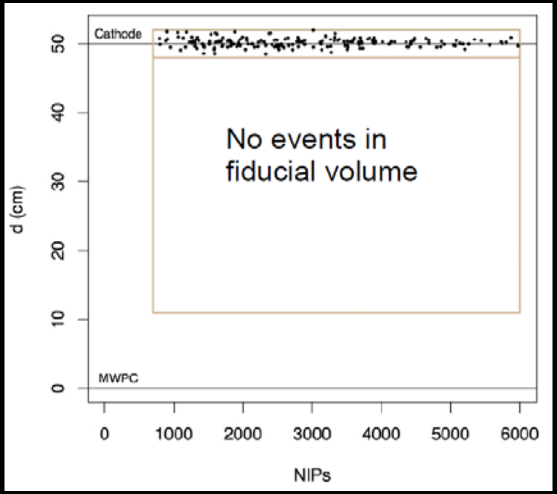


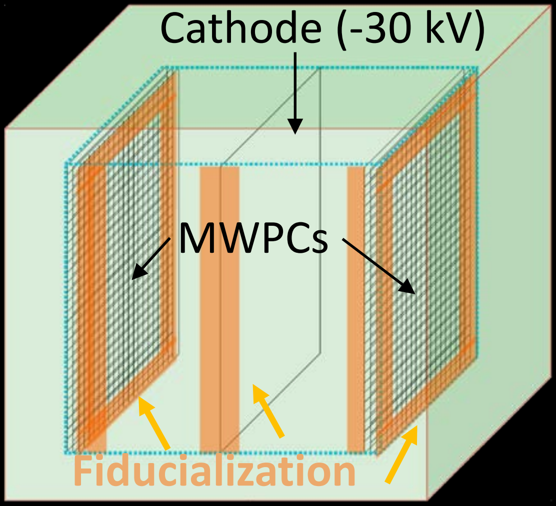
DRIFT – Negative Ion TPC, directional sensitivity (Boulby)

- Negative ion TPC, 1 m3 (2 back-to-back chambers)
- 30 kV at central cathode (field: 550 V/cm)
- Anode: MWPC (2 mm spacing)
- $CS_2 + CF_4 + O_2$ (30-10-1 Torr) (O for z-fiducialization)
- Head-tail discrimination on a statistical basis (z-axis)
- ER/NR discrimination: track geometry – threshold
- Background free data: 55 days, 1.87 kg d (F)
- Future: Cygnus (with other TPC experiments), SF_6, modular setup; multi-ton, multi-site

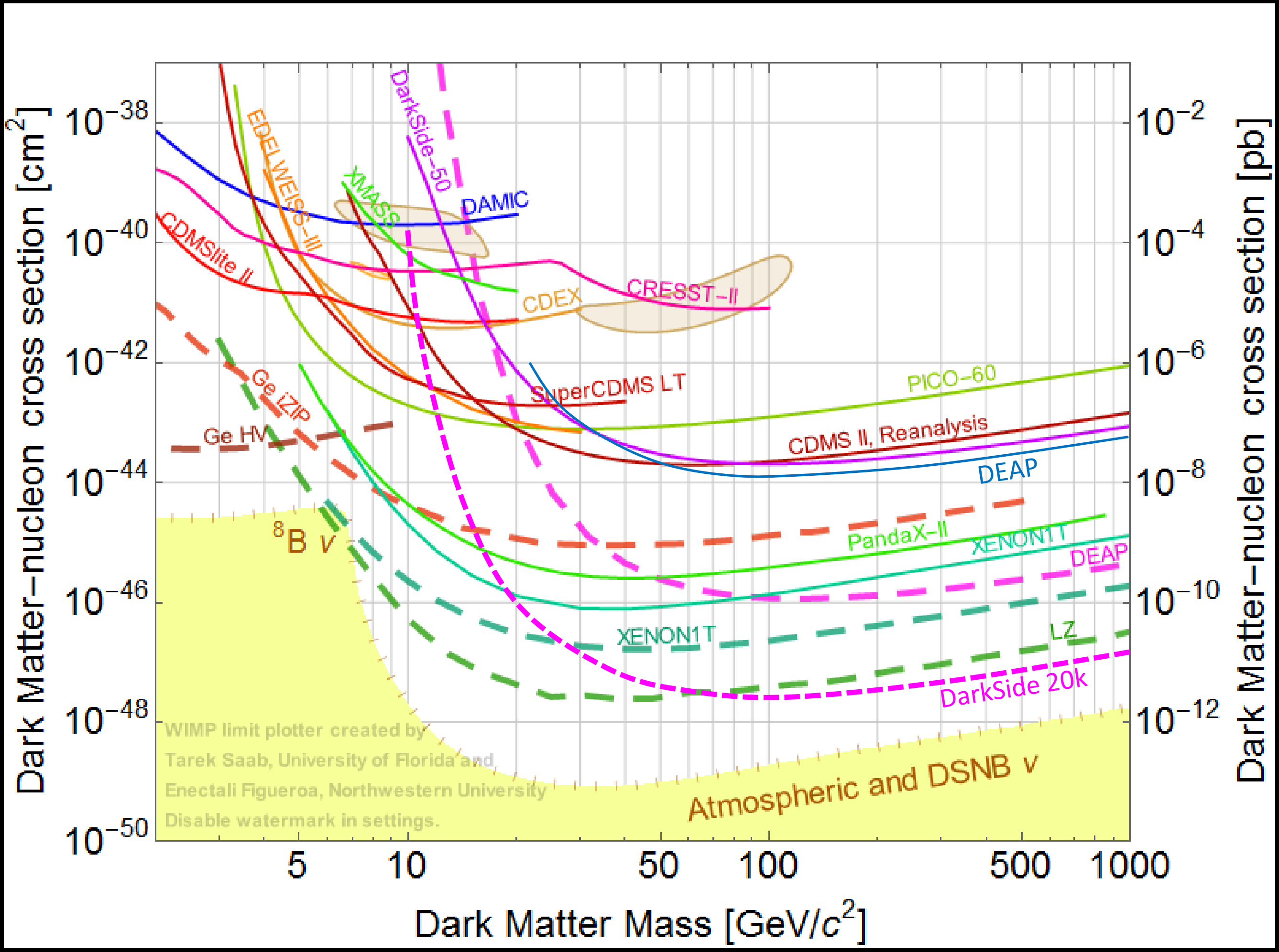


(b) Mid-z event at z = 25.1 cm, NIPs = 1504.

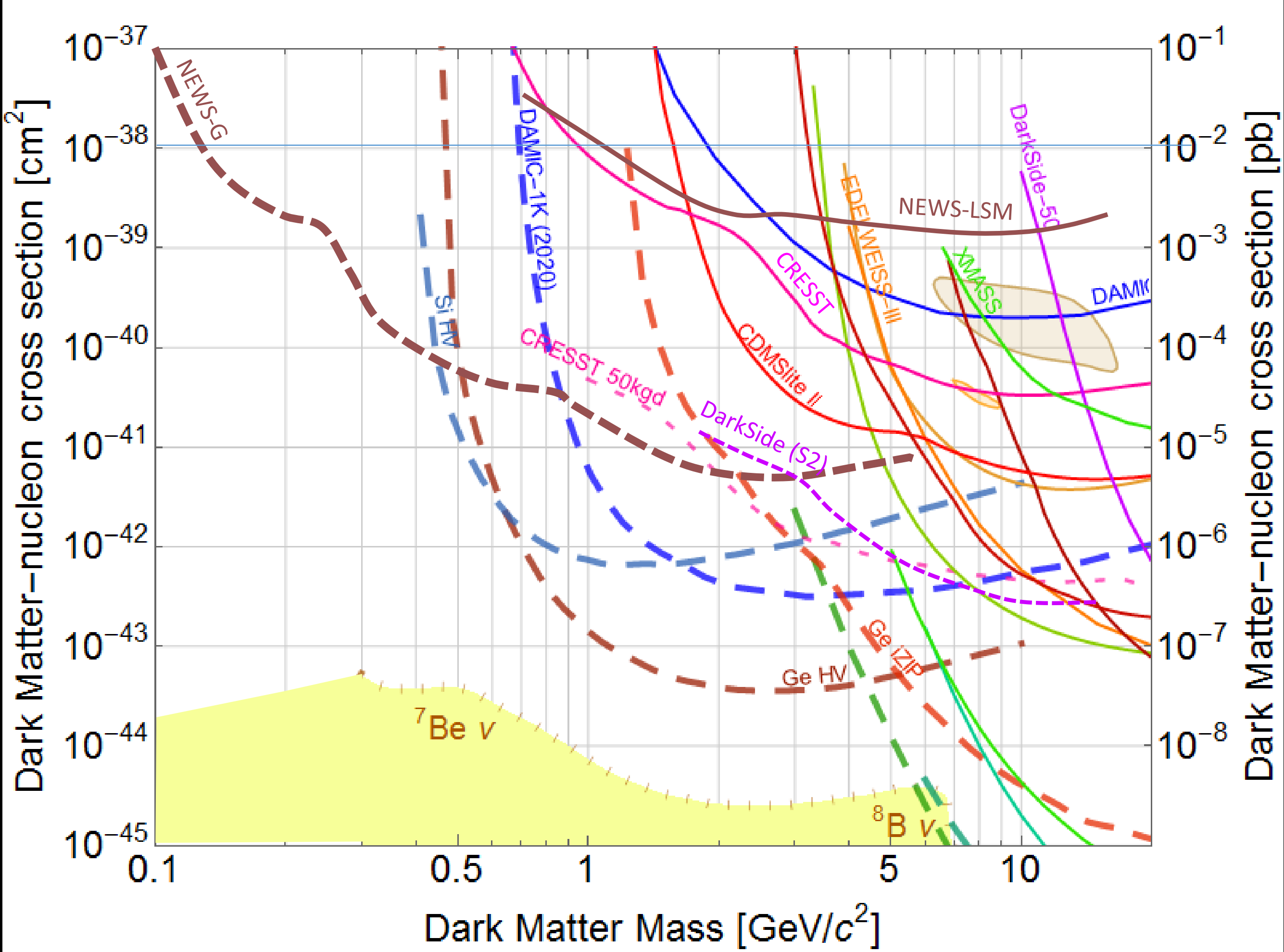




Results and Projections



Results and Projections



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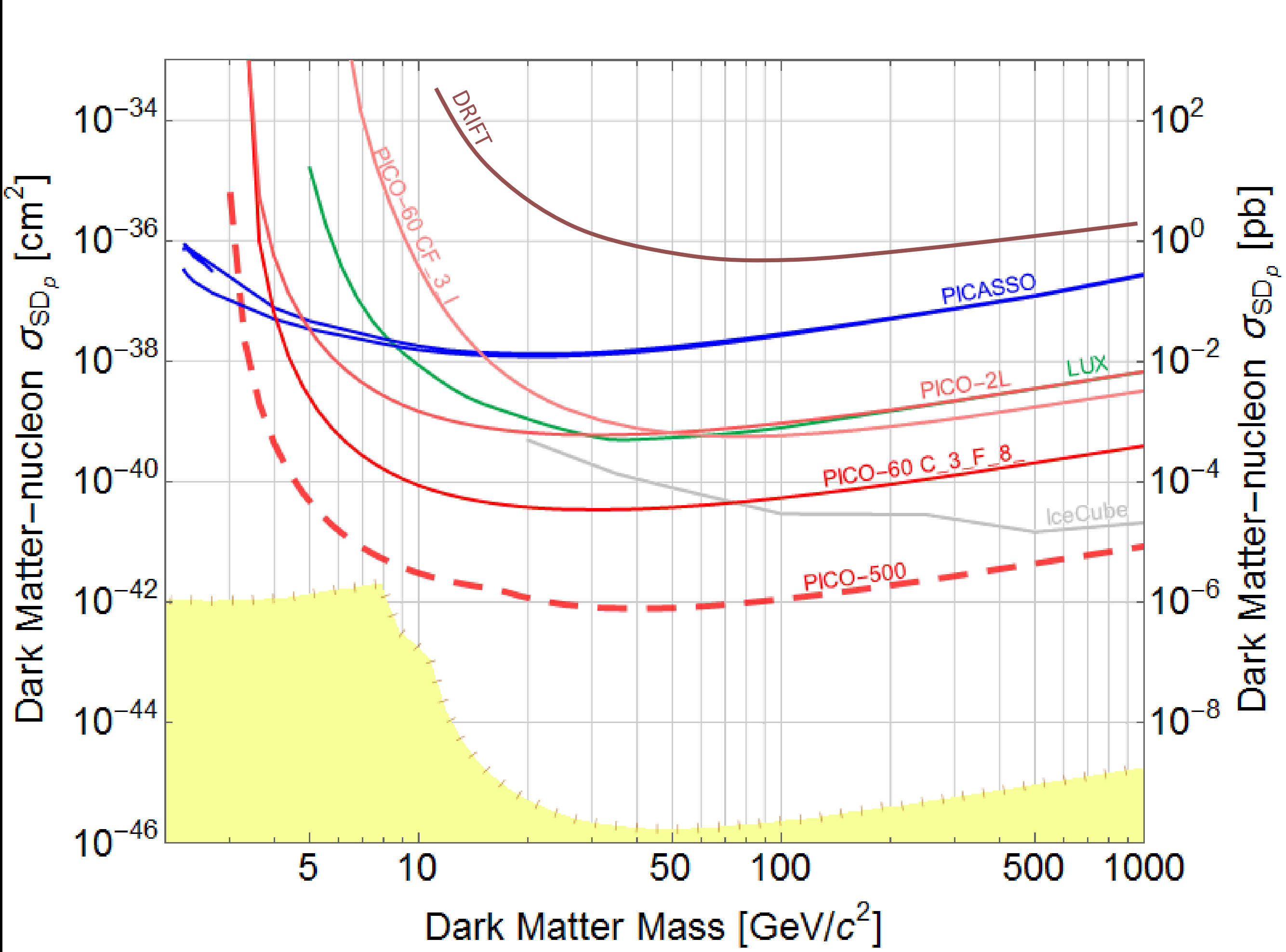

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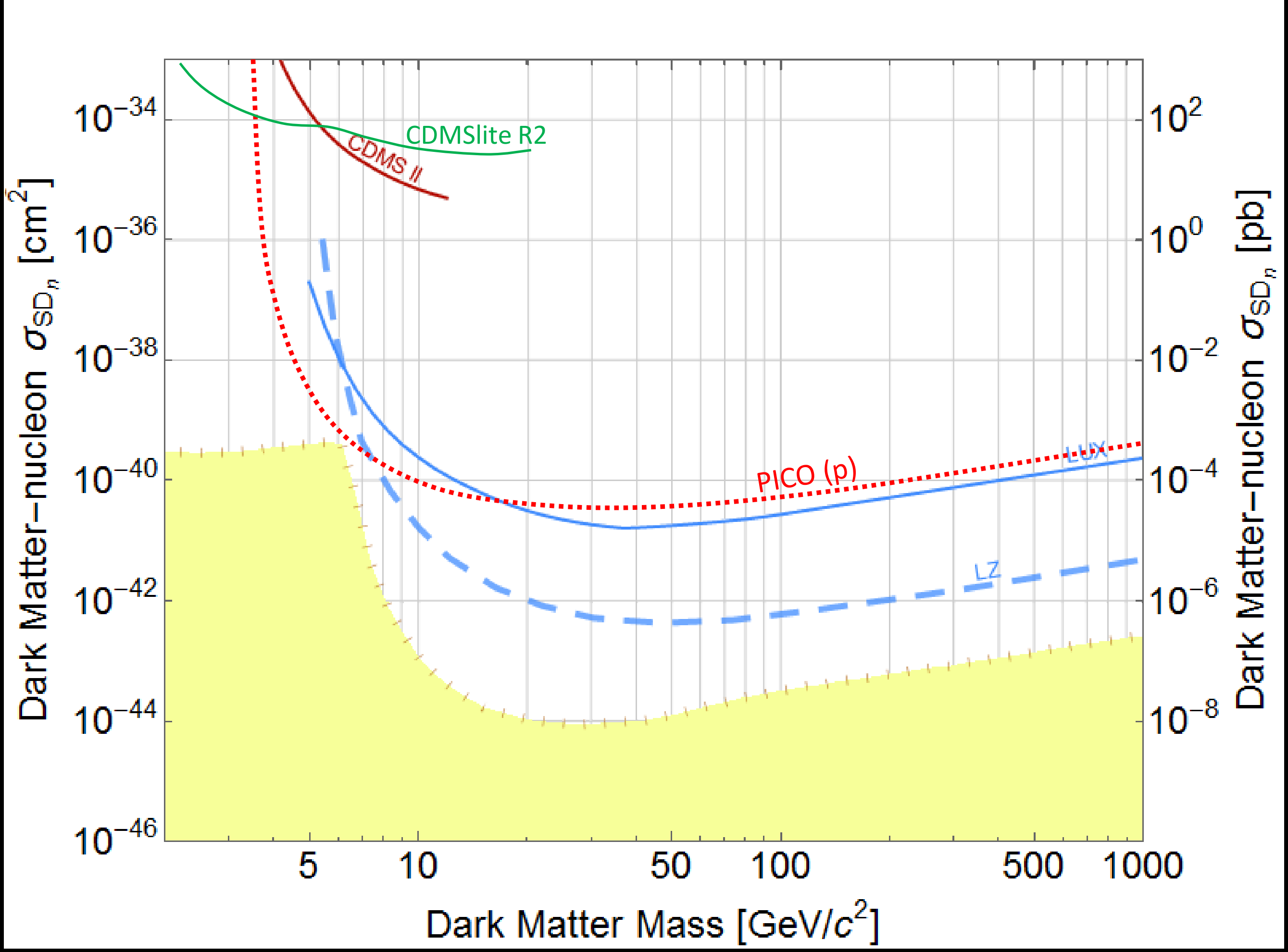
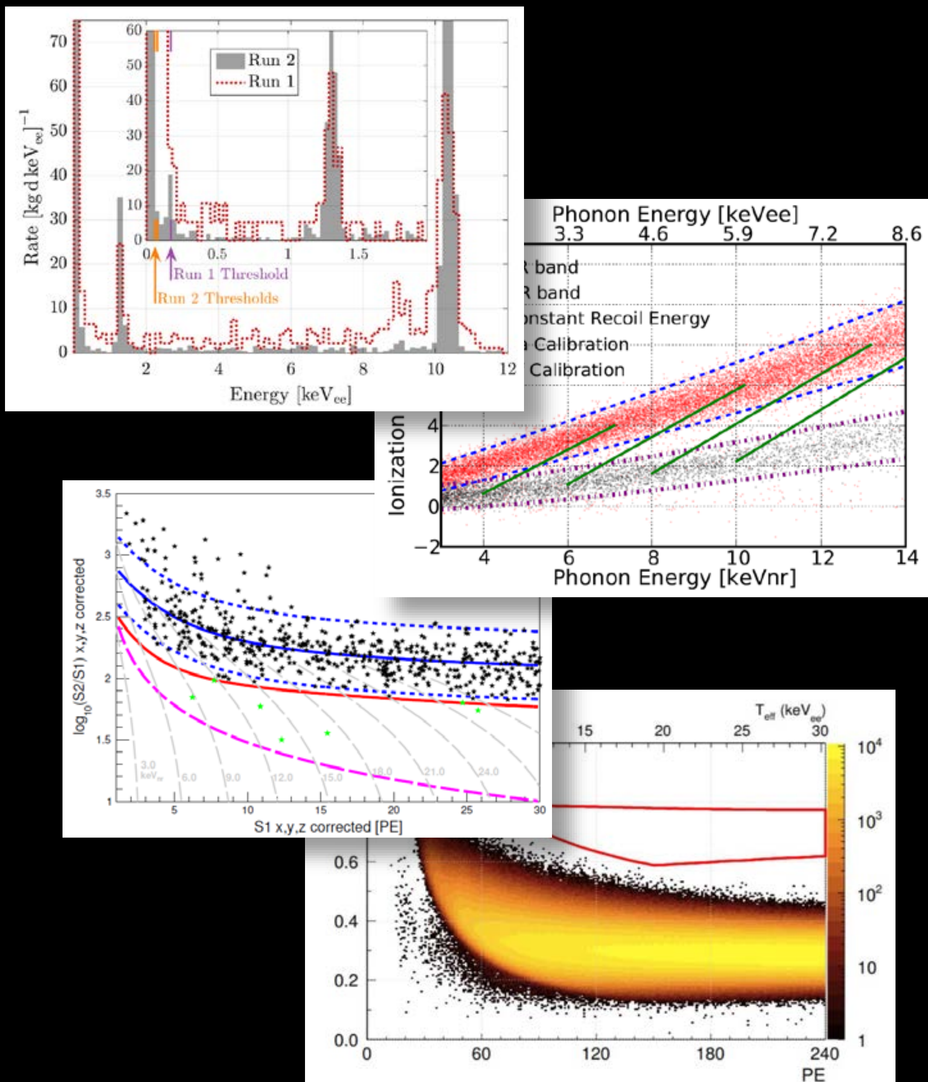
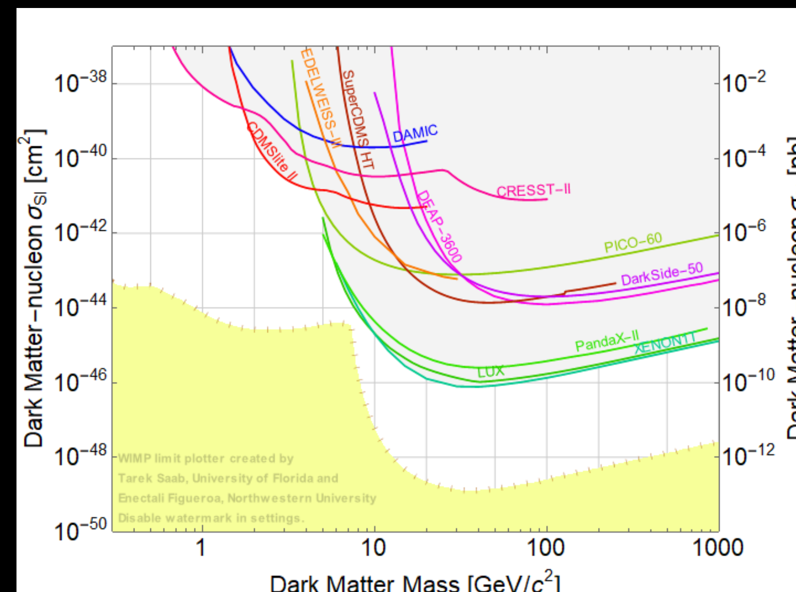


How do we get

from here … … to here?

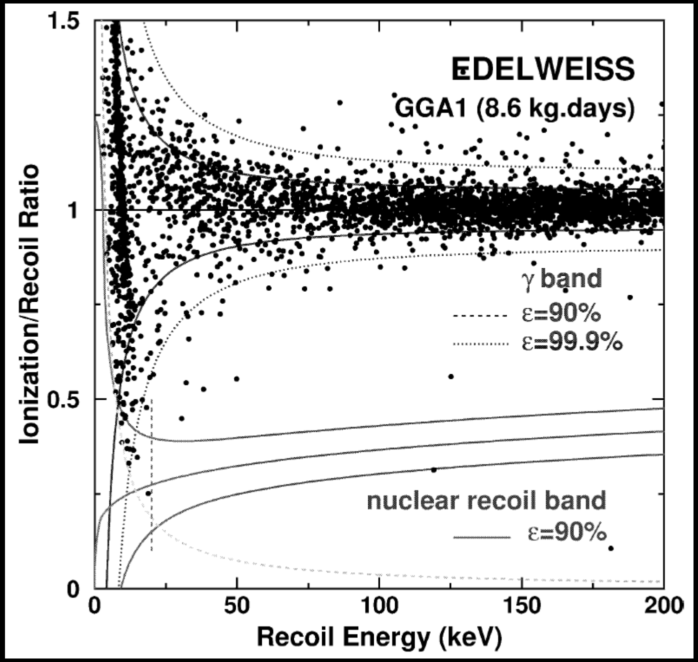




And how do we know it's right?

EDELWEISS 2002

A "Background-free Experiment"



Several events close to ROI but none inside.

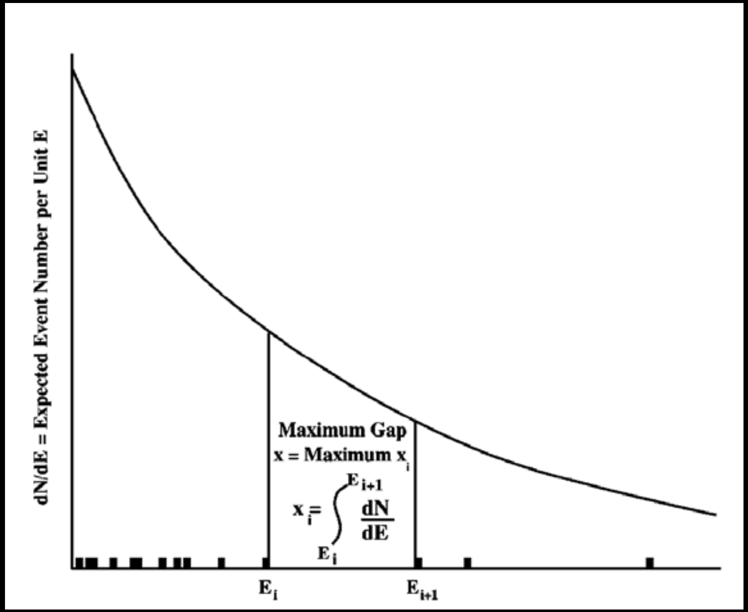
Once the 1st event appears inside, the DM limit gets worse.

"Should we stop the measurement before the 1st BG event appears in the ROI, so we don't ruin our result?"

Is there a way perform the analysis that would be free of this problem?

Maximum Gap (Yellin, PRD 2002)

Example: measured event distribution



May be mix of signal and background

Goal: find maximum possible signal rate compatible with data (e.g. at 90 % CL)

Approach:

- Locate *Maximum Gap*
- Perform Monte Carlo for different expected rates
- Reject rates that would 'in most cases' produce a smaller 'max gap'

X-axis can be any quantity for which the expected signal distribution is known

If signal distribution is not constant in x, define gap size as $\int (expected\ distribution)$

Equivalent: rescale x-axis so the distribution becomes constant

Optimum Interval

Same as Maximum Gap, but also allow intervals with finite numbers of events

- Maximum Gap and Optimum Interval methods can only ever produce limits.
- Limits are conservative since no assumption is made with regards to the origin of any of the events.
- I believe this method gives you the best limit under these conditions

Optimum Interval with Known Background

Replace “Signal” by “Signal plus known background”

Once total ‘rate’ is determined, subtract known background

Is a multi-dimensional Optimum “Interval” analysis possible?

Likelihood Analysis

If background distributions are well known:

- You can do a likelihood fit using signal and background distributions
- Or you can do a likelihood ratio test (BG+signal/BG only)
- Allows for discovery (not just limit)
- Requires very high confidence in background model
- Possible compromise: cut out regions of parameter space where you have unknown background (or background with unknown distribution) and apply likelihood fit to remaining region where BG is well understood
[may need to determine leakage of unknown background past cut]

Combining Results

Example 1: different detectors / data sets from the same experiment

- Each detector / data set has different background performance
- E.g.: aim for 'background free': <0.5 expected events in total exposure
- Same cut value produces very different leakage in each detector / data set
- What is the best strategy to set cuts for each detector / data set?
- Is there a way to smartly combine data from detectors, so one bad one doesn't ruin the sensitivity overall?
- Is it worth the effort?

Example 2: different experiments

- Same technology/systematics: similar to above example
- Different technology/target/systematics: can we get a more stringent limit?
- How to find out if an allowed signal from one experiment is compatible with a limit from another?

Conclusions

Status:

- Multiple technologies and multiple targets employed
- Leading in high mass range: noble liquids (presently PandaX, but very close competition)
- Leading in low mass range: cryogenic detectors (~~CDMSlite~~ DarkSide, CRESST) and NEWS-LSM
- Leading in spin-dependent sector:
  protons: PICO (Superheated liquid with F); neutrons: LUX (XENON1t)
- Annual modulation signature: DAMA/LIBRA claims signal, controversial

Short term future

- SI: Upcoming experiments will get to about a factor of 10 above the neutrino floor (low mass: SuperCDMS, CRESST, NEWS-G; high mass: LZ, XENONnT) first signal from coherent solar neutrino scattering expected
- SD: order of magnitude improvement from PICO

Long term future: neutrino floor

- Very large LAr detector (high mass), perhaps multi-ton Xe, improved SuperCDMS (low mass) [sub-neutrino floor: ton-scale directional detector ?]