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: $v_e < 2v_{WIMP} \rightarrow E_e < \frac{1}{2} m_e v_e^2 = 1$ eV
- Elastic scatter with nuclei: typical $E_{nucleus}$ is 10-100 keV
  (down to the eV range for WIMPs with masses <1 GeV/c^2)

⇒ Search 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)

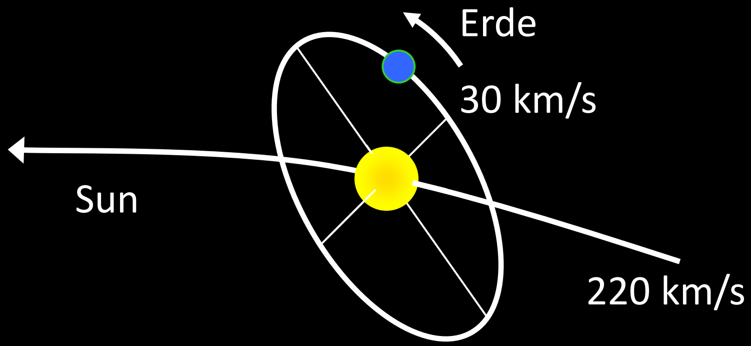
- Typical environmental radiation: kHz/kg (mostly electron recoils, ER)

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

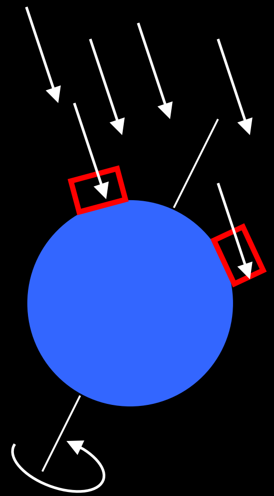
Direct Detection Signatures

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

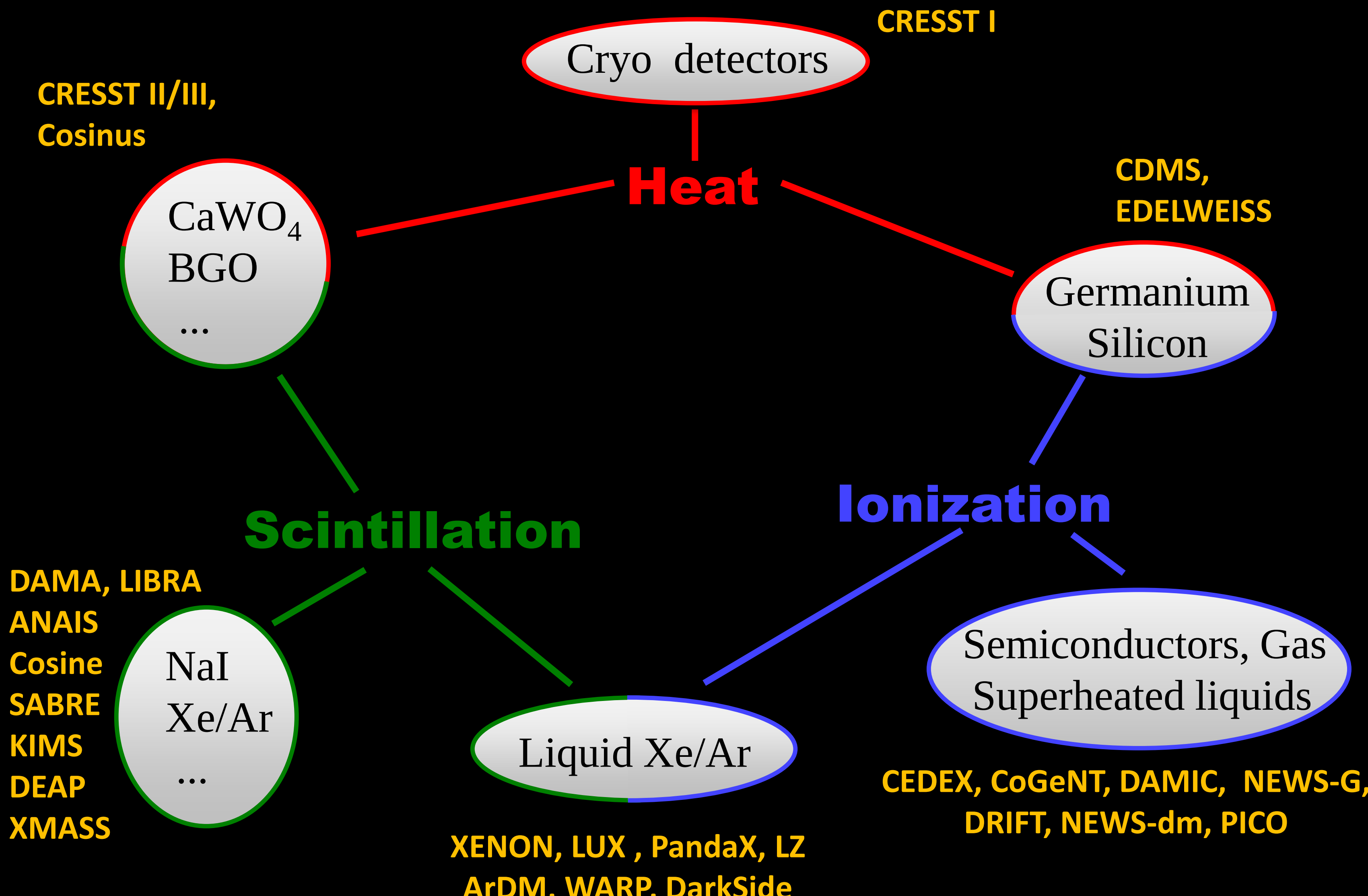
Annual Modulation
- Sun moves about galactic centre
  Earth moves about sun
- Relative velocity between WMPs and detector changes over the year
- Look for (small) periodic variation of signal



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



Ionization Detectors

Ge (77K): CEDEX, CoGeNT
Silicon (RT, CCDs): DAMIC
Gas detectors: NEWS-G

Scintillating Crystals

NaI: DAMA/LIBRA, COSINE, SABRE
CsI: KIMs

Noble Liquid Detectors

Single Phase: DEAP, XMASS
Dual Phase: XENON, PandaX, LZ, DarkSide

Superheated Liquids

PICO

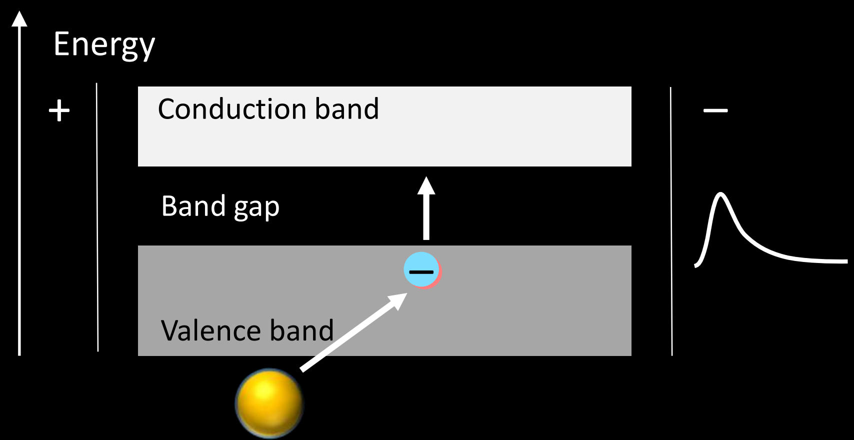
Cryogenic Detectors

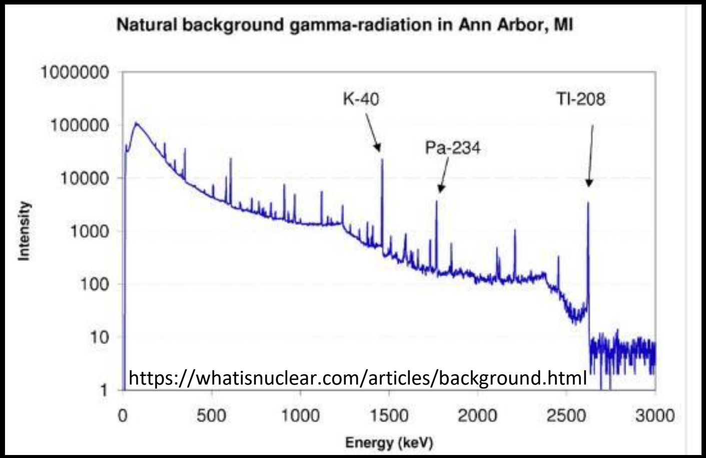
SuperCDMS
EDELWEISS
CRESST
Cosinus

Directional detectors

Drift
NEWS dm

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)

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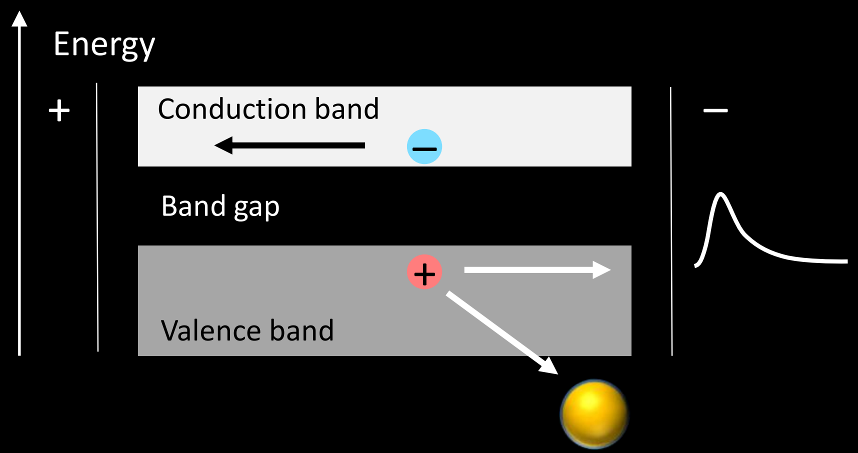

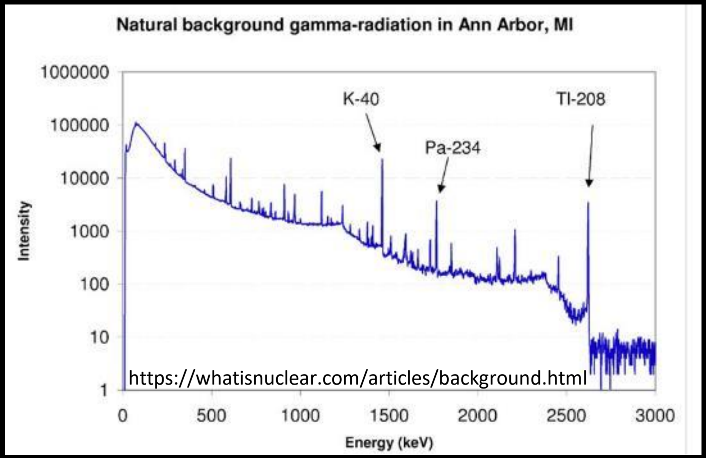

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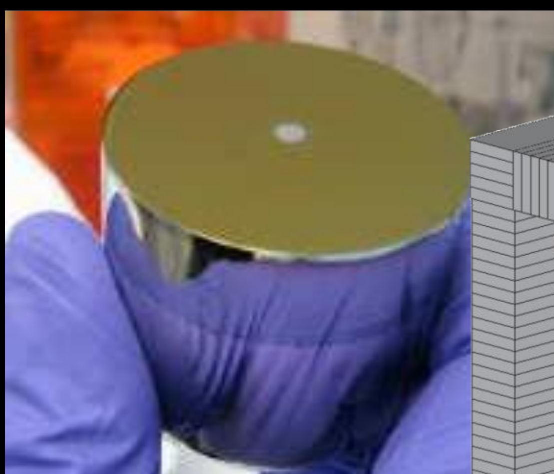
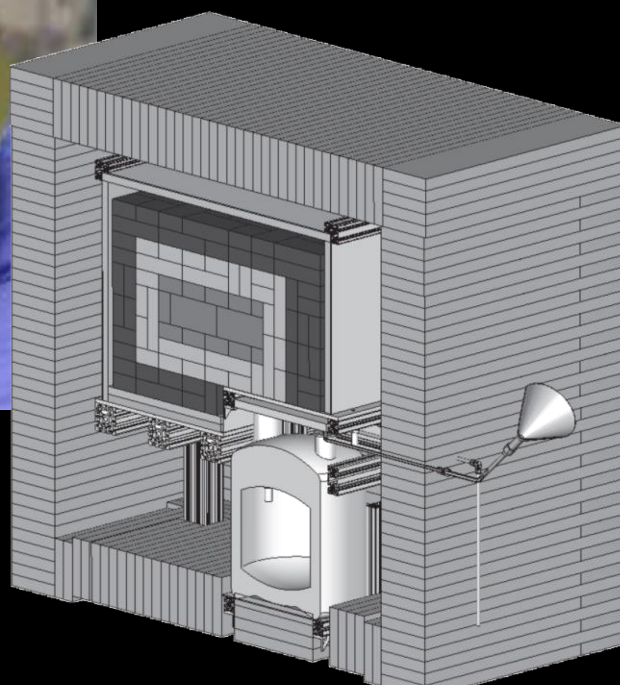
CoGeNT – Germanium Point Contact Detector (Soudan Lab)

- 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))





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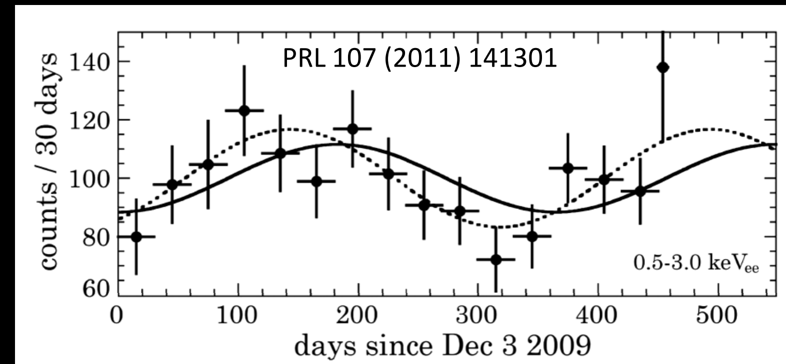
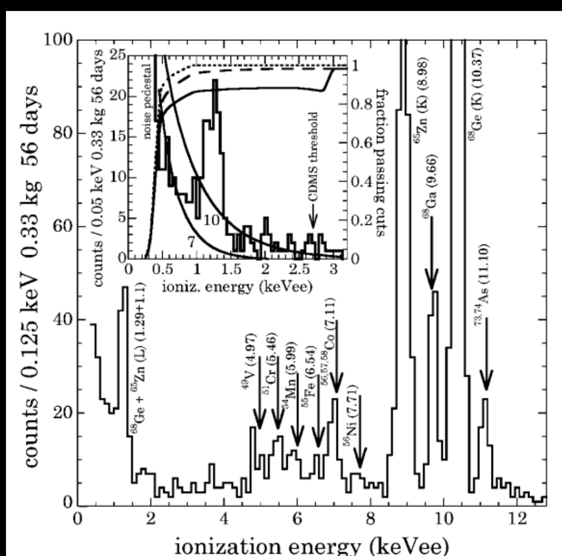
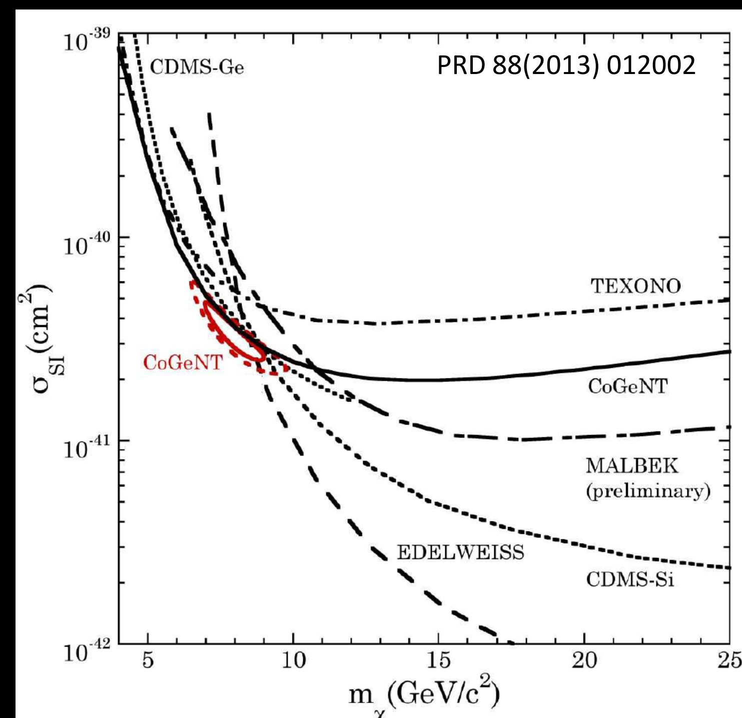
- Observed excess at low energy
- Hint of annual modulation
- Interpretation as indication of dark matter interactions







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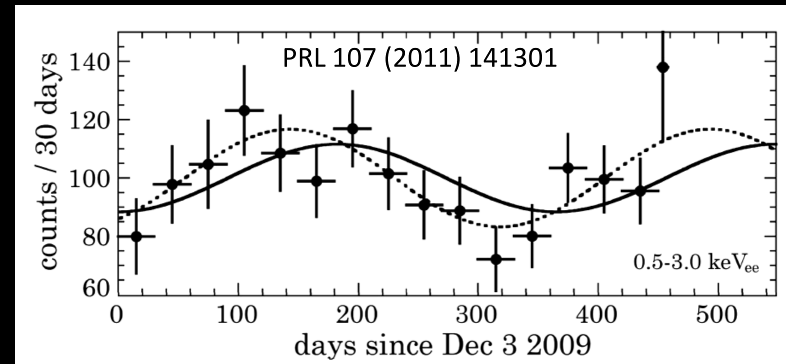
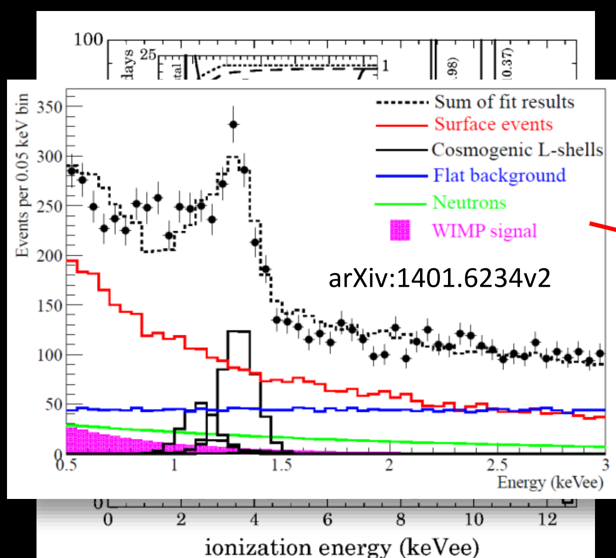
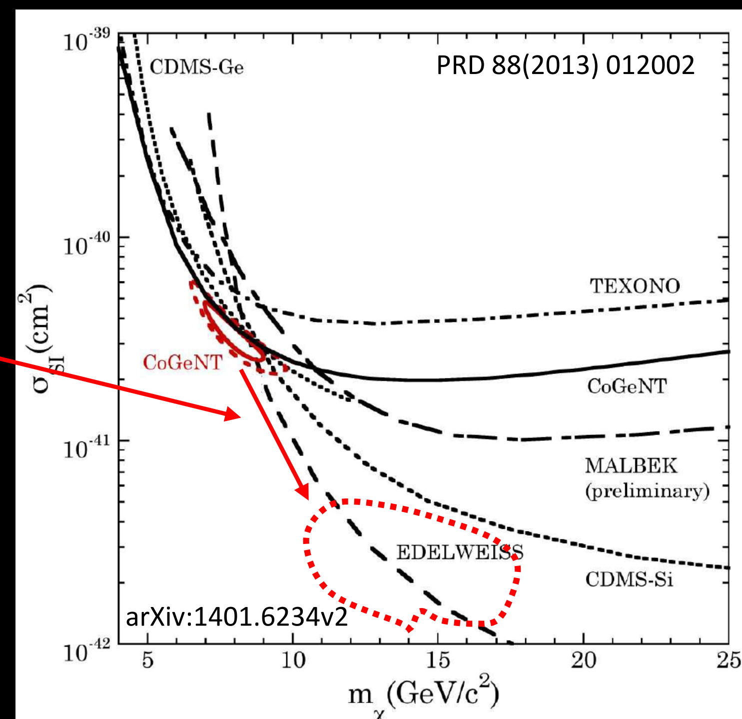
- Hint of annual modulation
- Interpretation as indication of dark matter interactions
- Careful reanalysis: excess is background, no evidence for dark matter

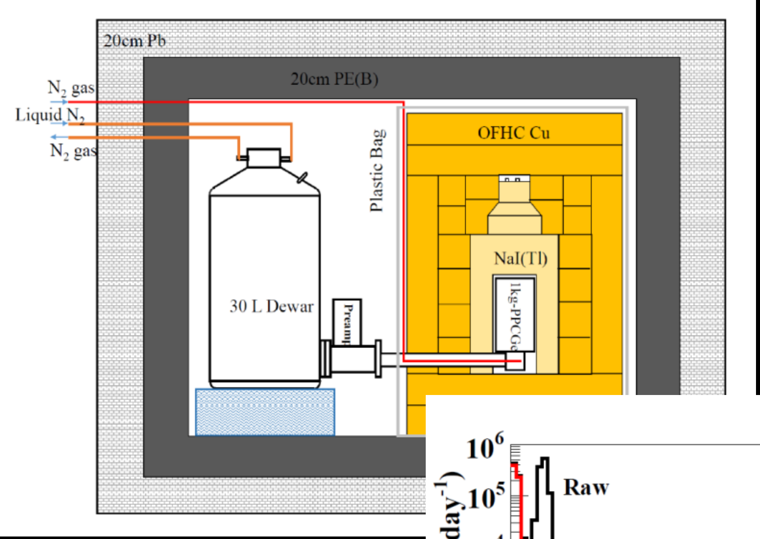


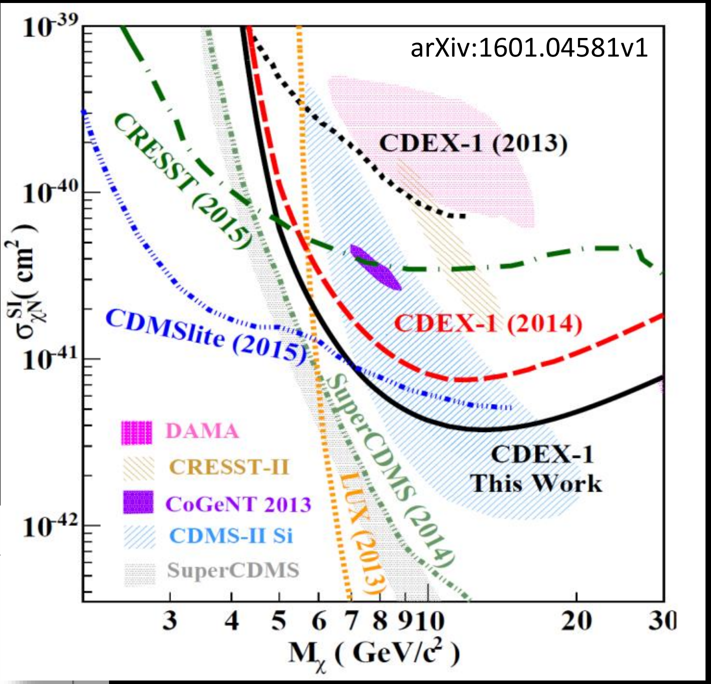


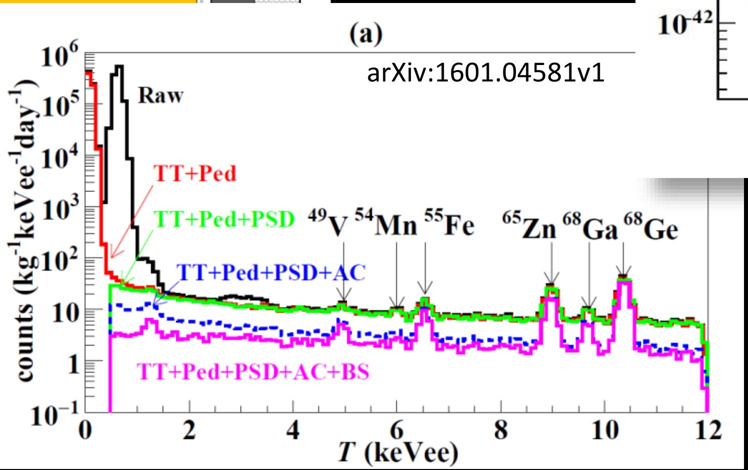


Germanium – CDEX (Jinping Lab)

- Very similar technology to CoGeNT
- Shielding NaI veto, Pb, Cu
- Careful rejection of background in analysis

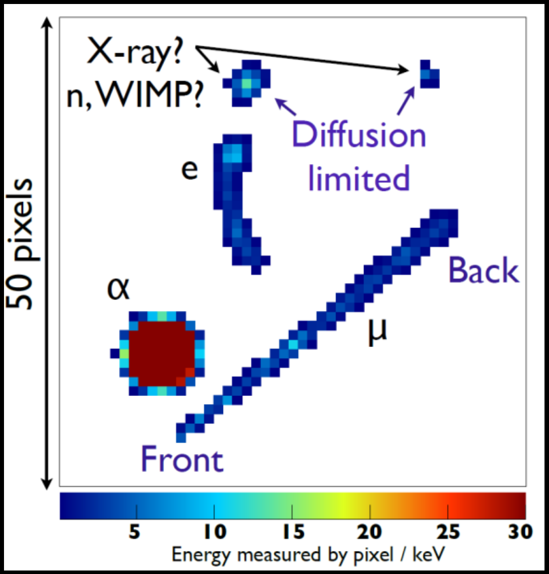


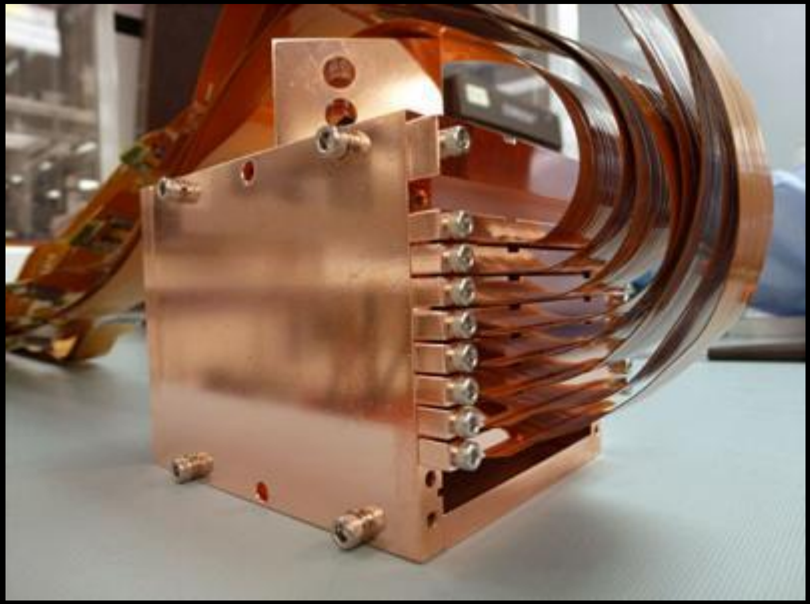


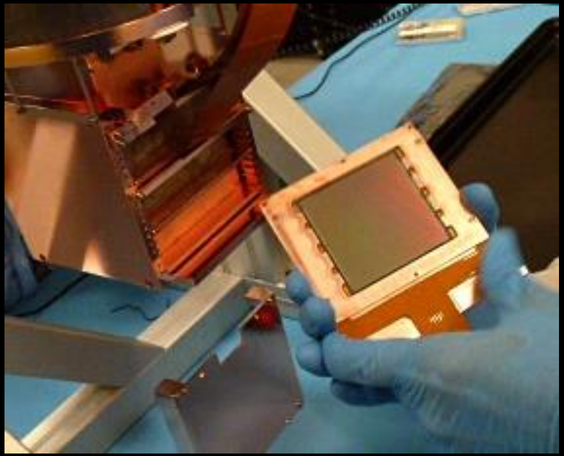


Silicon CCD – DAMIC (SNOLAB)

- Excellent position resolution
- Relatively small target mass
  (2-3 x 2.9 g; next generation: 18 x 5.8 g)
- Silicon: more sensitive to low-mass particles
- Good background understanding
  (good position and energy resolution)







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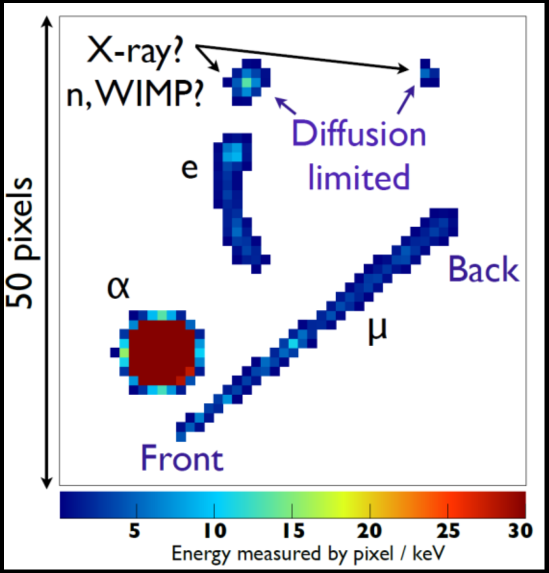
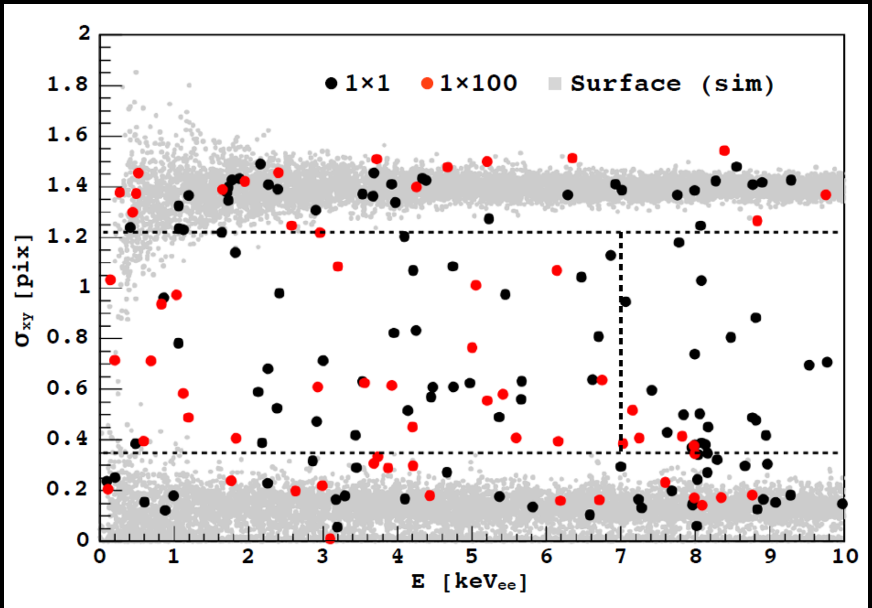
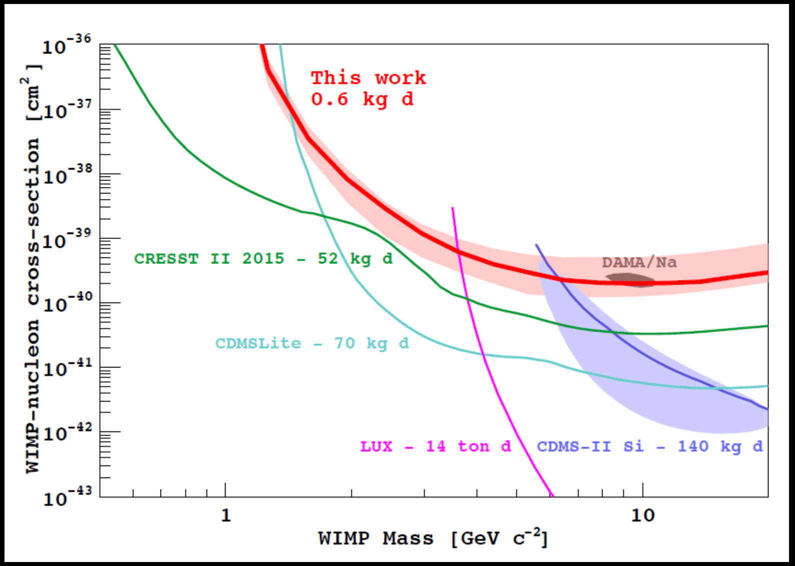
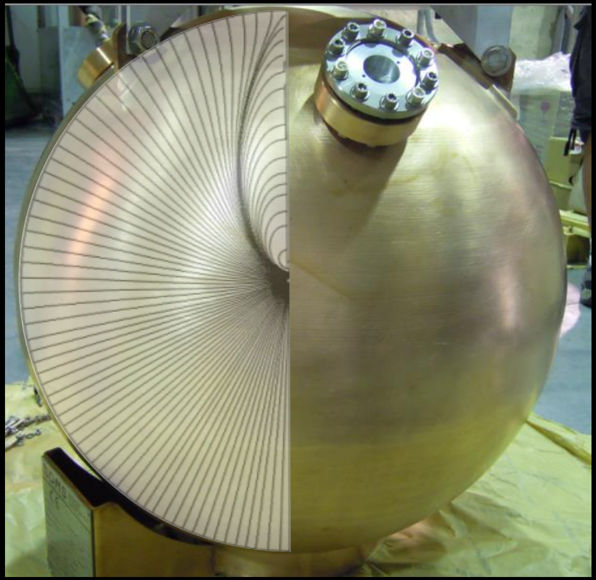


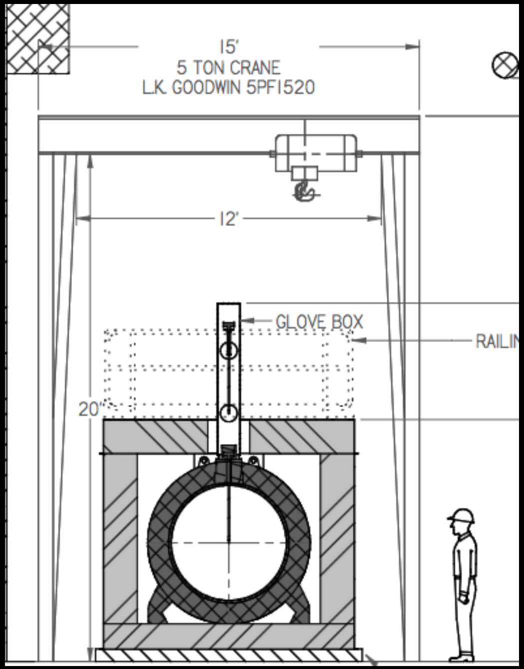


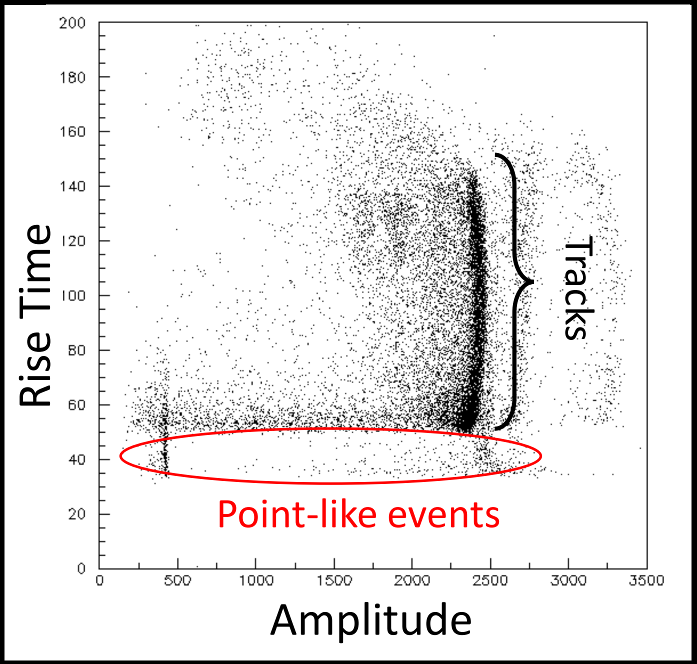


NEWS-G – Spherical gas TPC (Modane (LSM), SNOLAB)

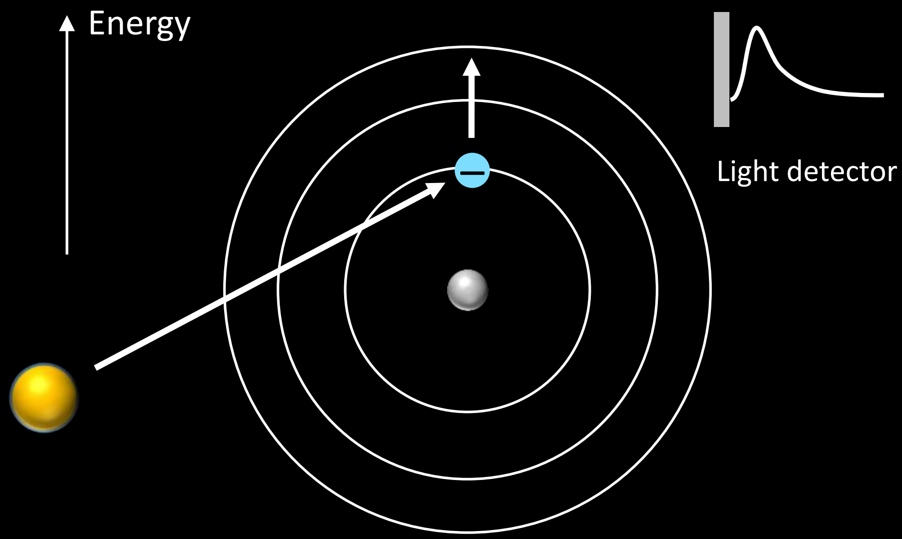
- Low energy threshold (~10 eVee), single electron sensitivity
- Position information from pulse shape
- Different gases: sensitivity to different mass ranges
- First measurements with Ne at LSM (60 cm sphere); data analyzed
- New sphere at SNOLAB under construction (1.4 m sphere)

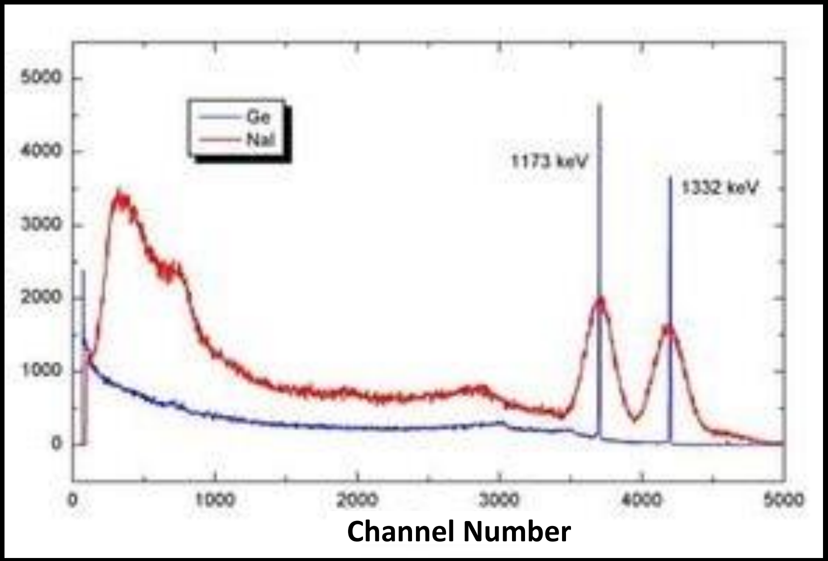






Scintillation Detectors





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)

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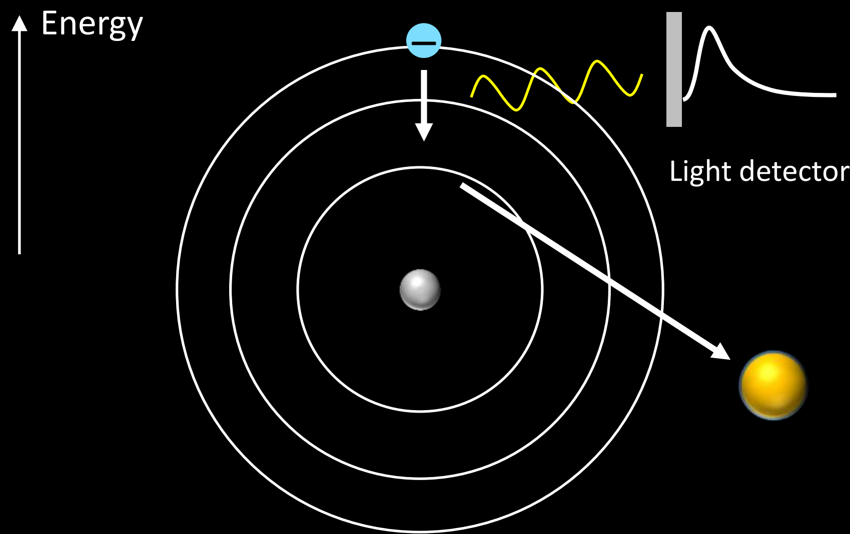

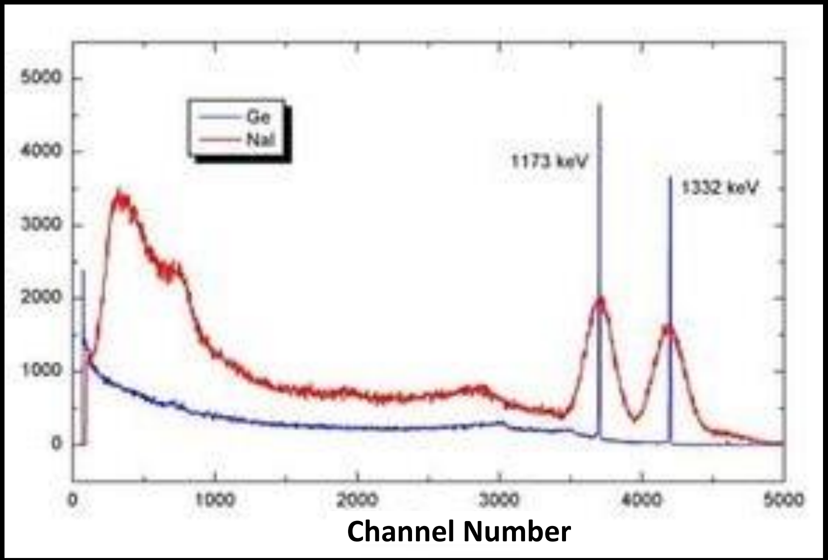

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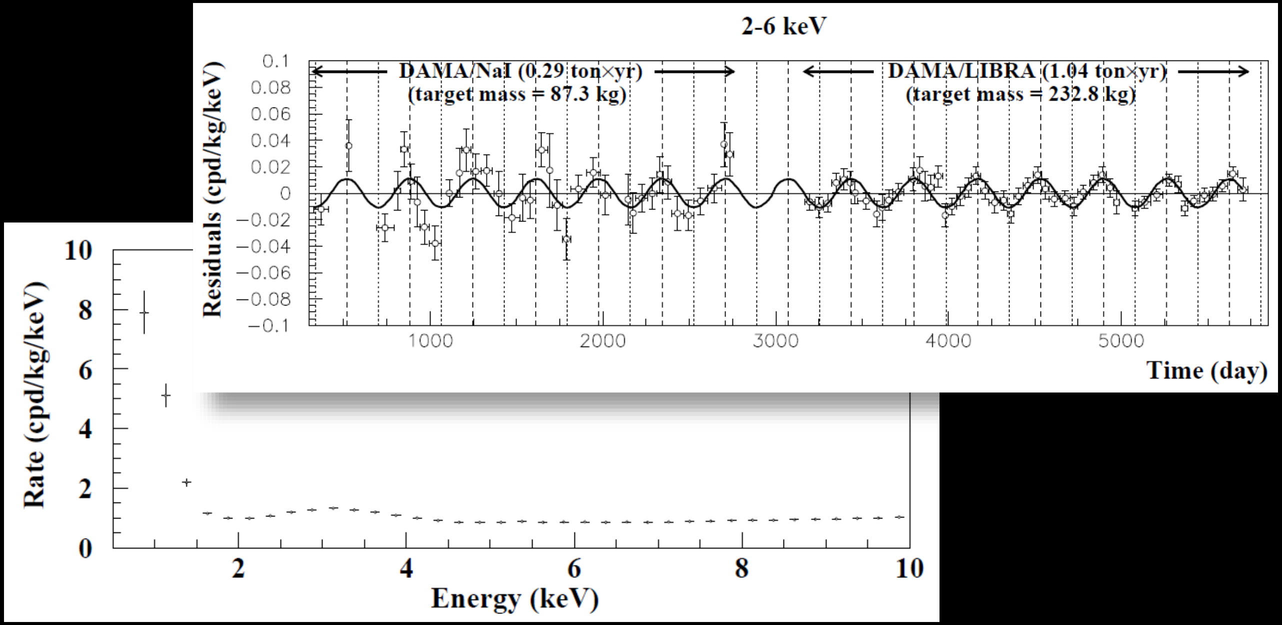
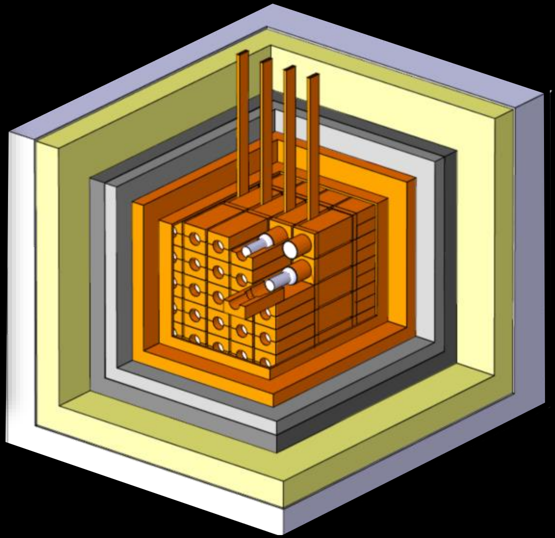
DAMA/LIBRA – NaI (Gran Sasso)

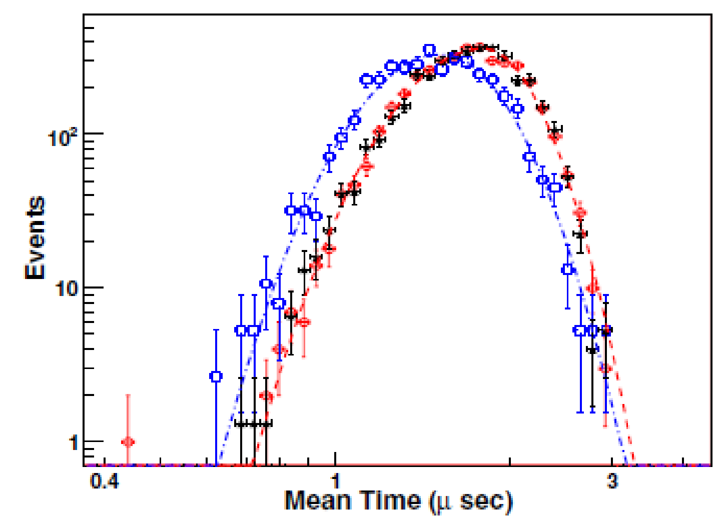
- 100 kg (DAMA/NaI) / 250 kg (DAMA/LIBRA) of NaI
- ~10 kg/crystal, 2 PMTs per crystal
- Shielding: PE, Cd foil, low activity Pb high purity Cu
- Analysis threshold at 2 keV
- Search for annual modulation
- Operating since 1995; 13 annual cycles published, many σ evidence for oscillation; correct phase





KIMS – CsI (Yanyag lab)

- Large CsI detectors (similar to DAMA)
- 9 kg/detector, 103 kg total
- Shielding: Cu, PE, Pb, muon veto
- Pulse shape discrimination
- Total exposure: 24.5 ton days



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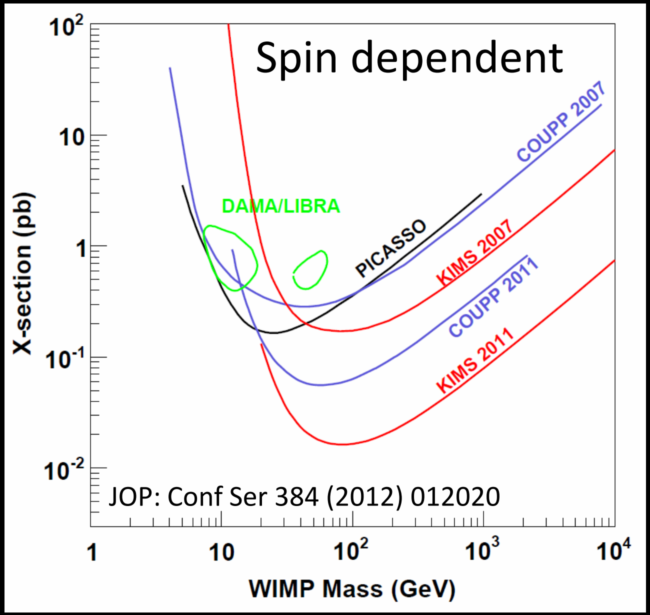
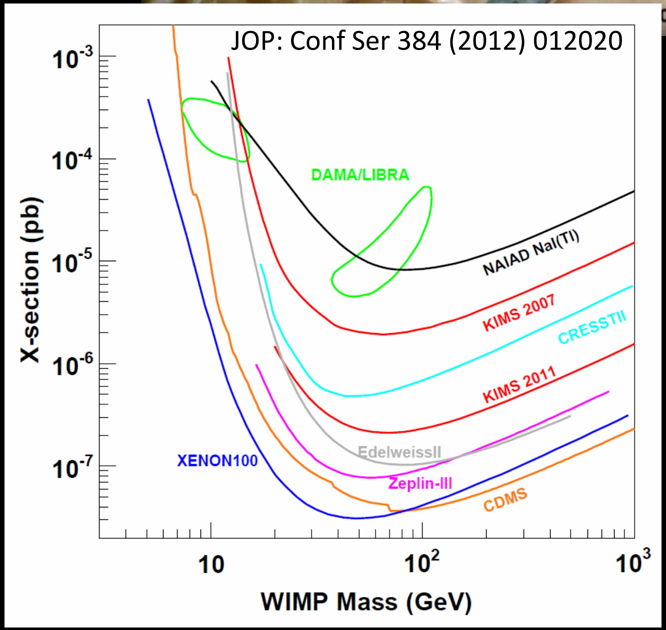
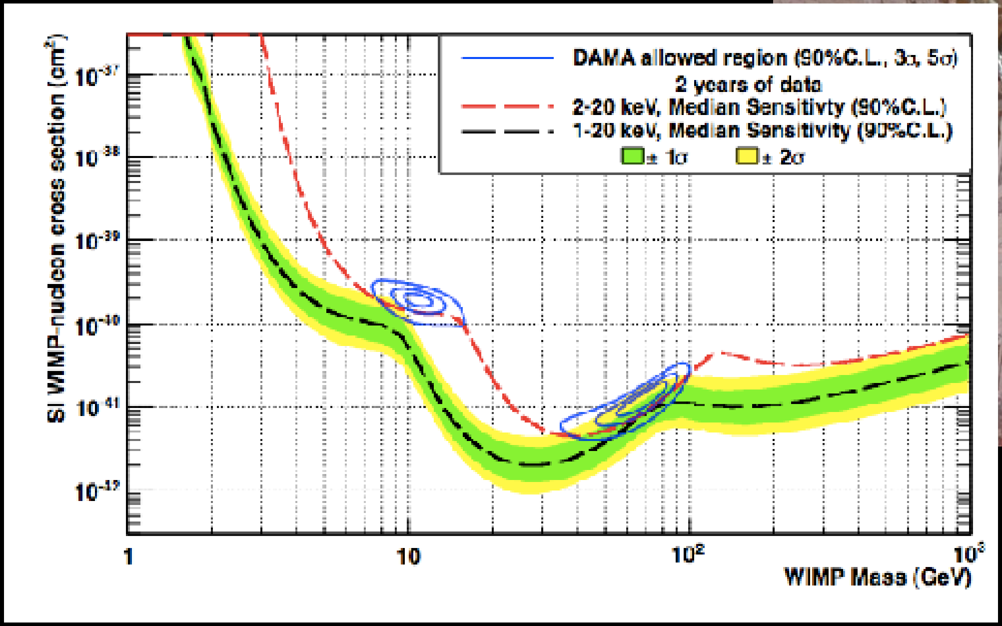




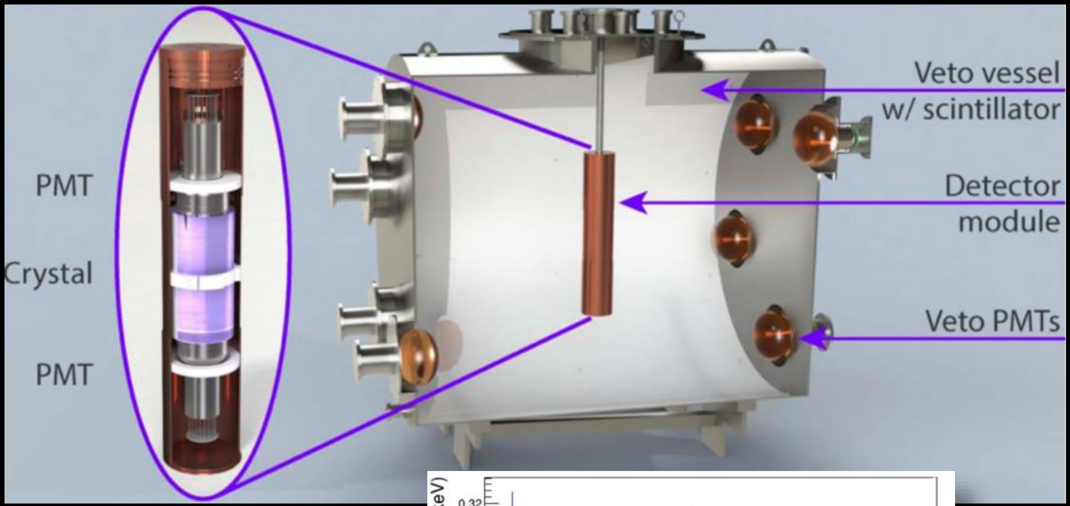
COSINE (DM-ICE & KIMS; Yanyag lab)

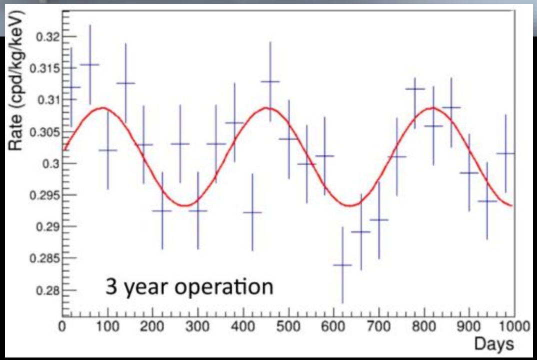
- Ultra pure NaI
- 8-18 kg/detector; 106 kg total
- Shielding: Liquid Scintillator (veto), Cu, Pb, muon veto
- Background still higher than DAMA (x 2-4)
- Projected sensitivity covers DAMA region

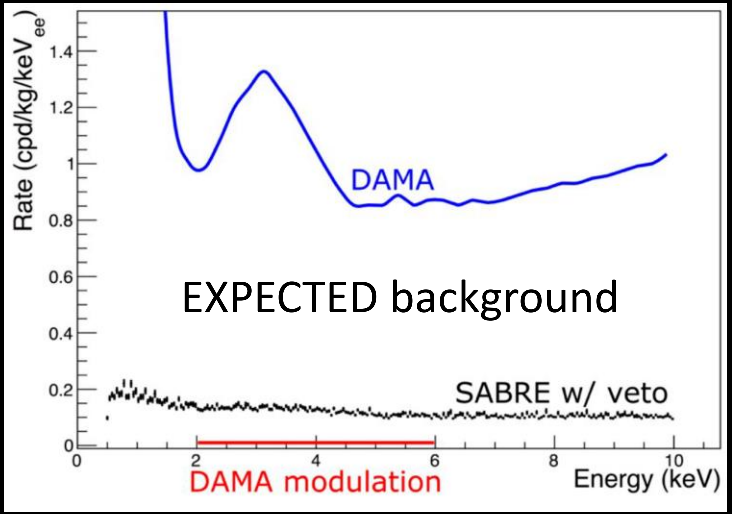


SABRE – NaI with liquid scintillator veto (GS & Stawell Lab)

- Ultra pure NaI detector in liquid scintillator veto tank
- 5 kg/detector, up to 10 detectors per site
- Northern & southern hemisphere: check seasonal effects
- Planned to start this year (2017)

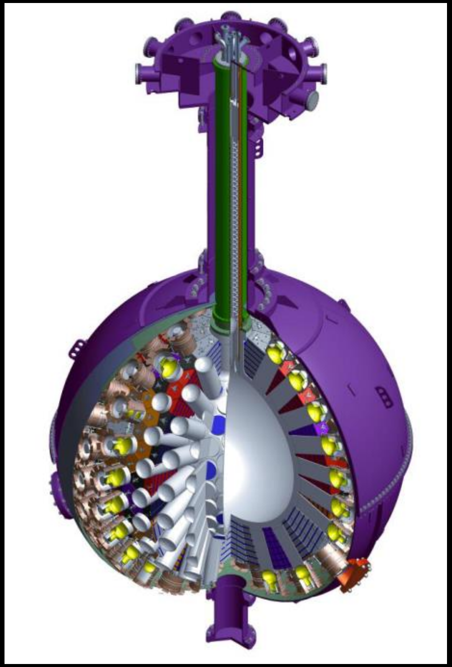


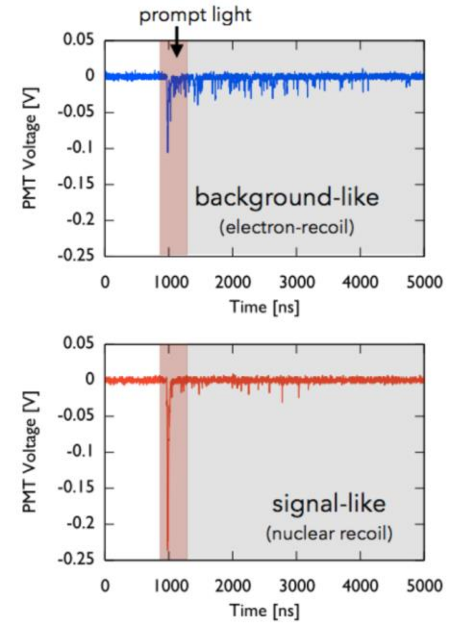


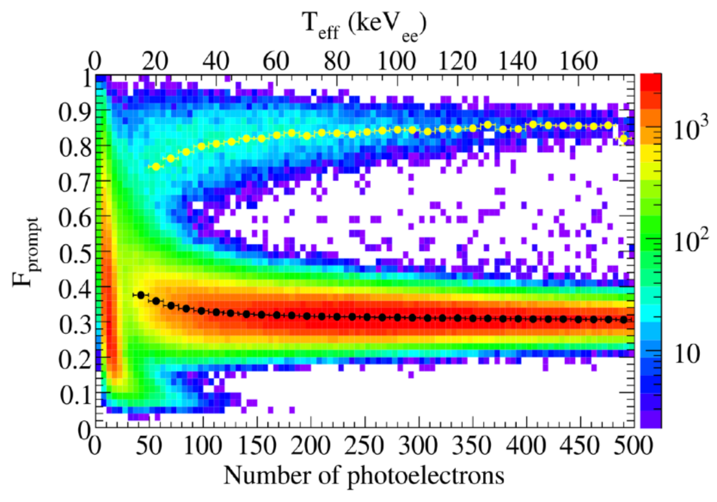


DEAP – Liquid Argon (SNOLAB)

- ~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
- First results expected in July







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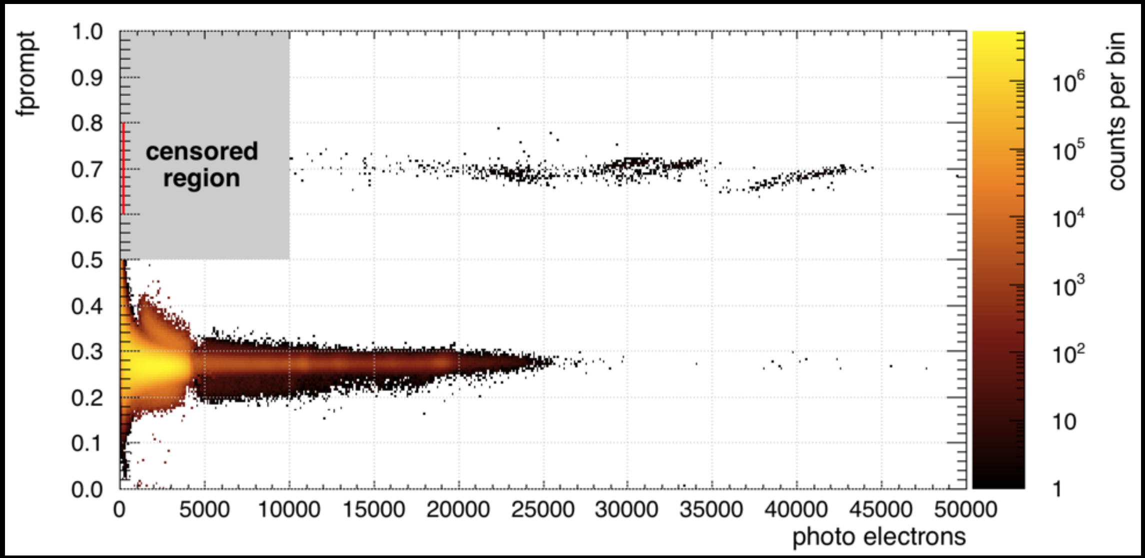
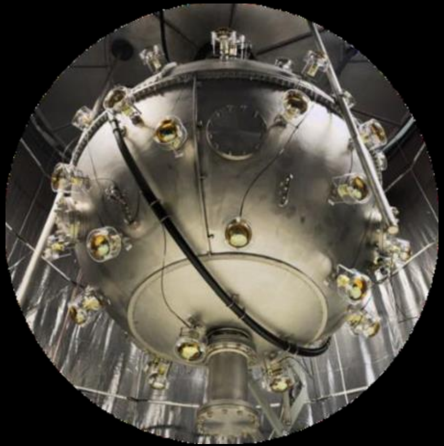
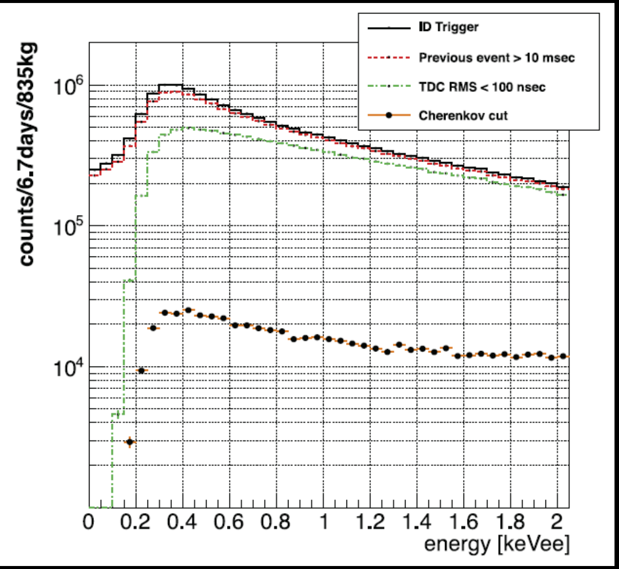
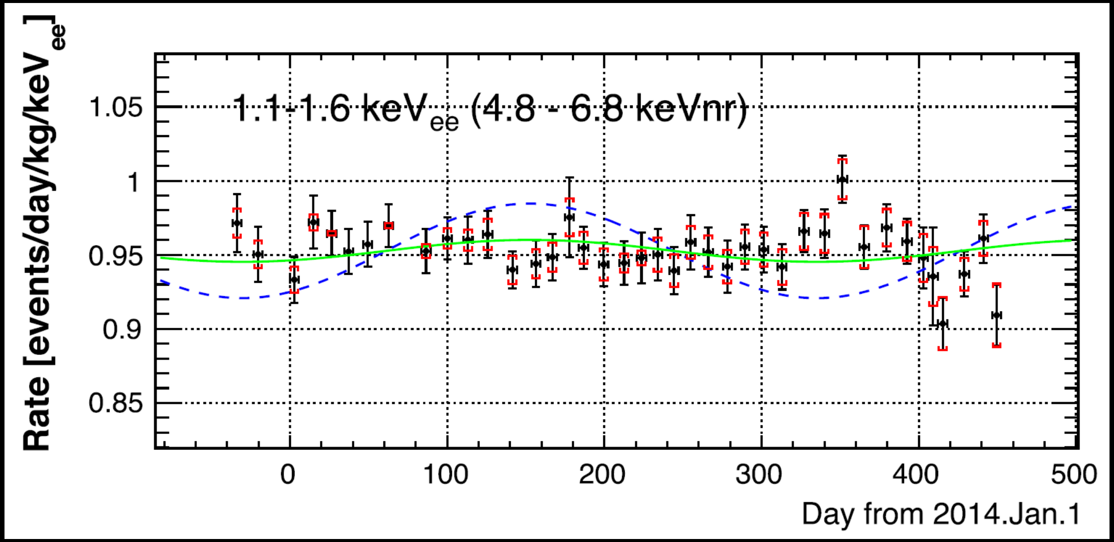




XMASS – Liquid XENON (Kamioka)

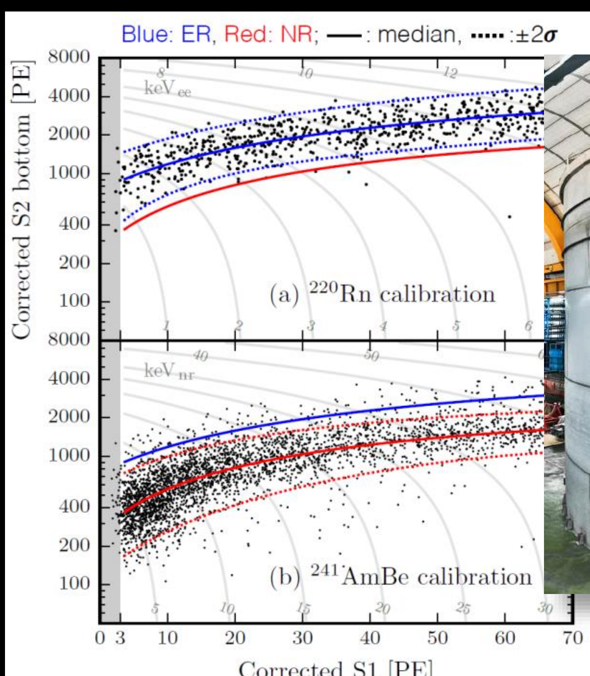
- ~830 kg of LXe surrounded by PMTs
- Copper cryostat, water shield
- Relies on low intrinsic background and self-shielding
- Moderate event rate (3-4 ev/keV kg d) down to threshold (~0.3 keV_{ee})
- Search for annual modulation

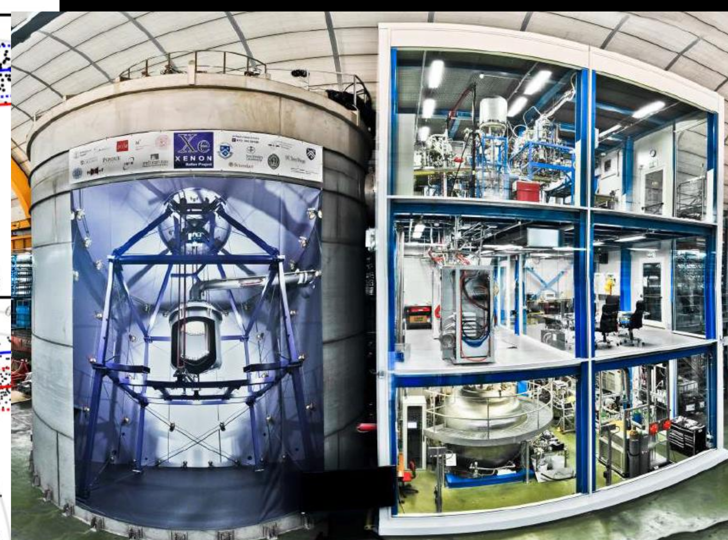


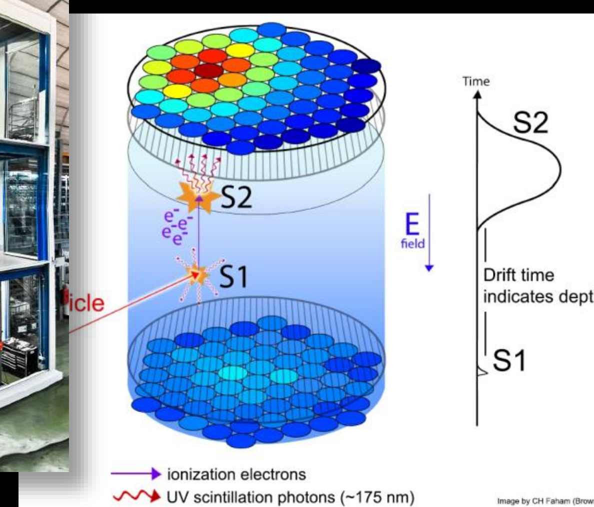


XENON – Liquid Xe TPC (Gran Sasso)

- 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
- More details just before lunch

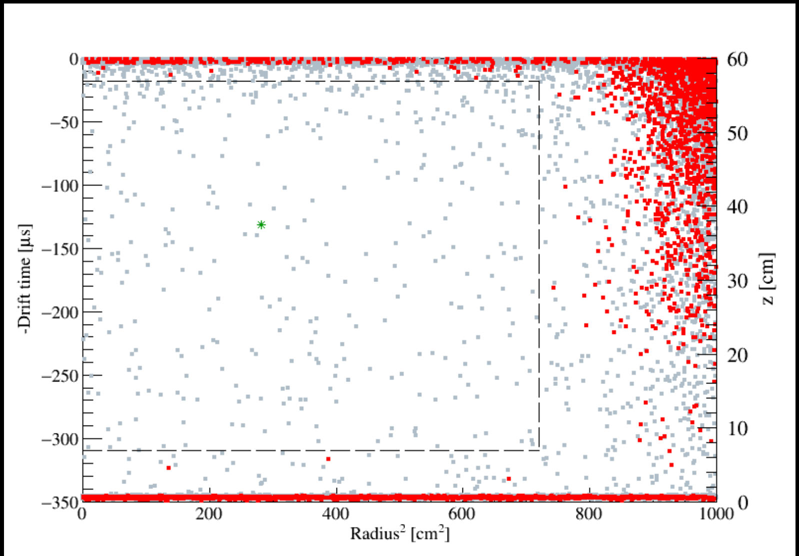


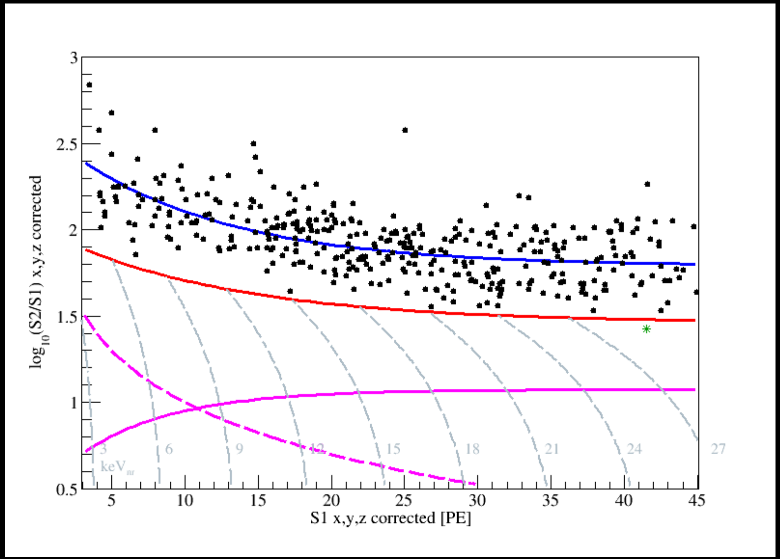




PandaX – Liquid Xe TPC (Jinping)

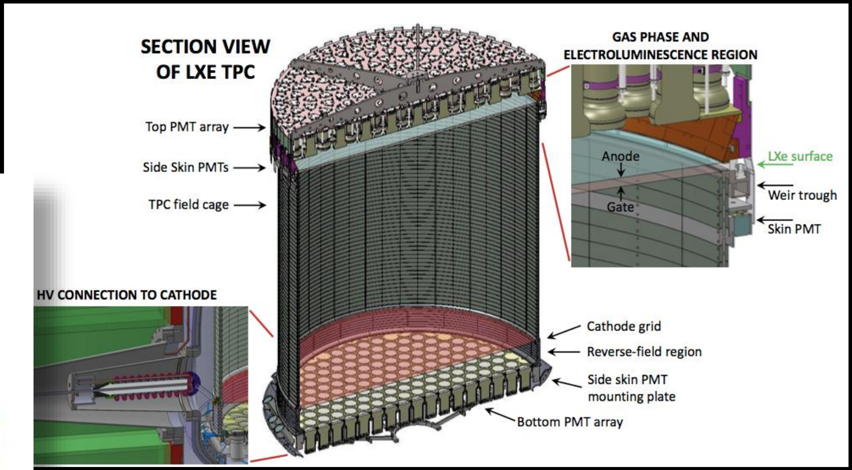
- Exactly the same concept as XENON
- Target: 500 kg LXe (~300 kg fid); exposure 33,000 kgd
- ER background rate: 2e-3 events/keV/kg/d
- Threshold between 1.3 and 8.7 keV_{ee} (varying with detector performance/run conditions)
- Leading sensitivity before XENON1t result came out
- Next generation detectors: several tons for DM and 0.2-1 t for neutrinoless double beta decay of ^{136}Xe

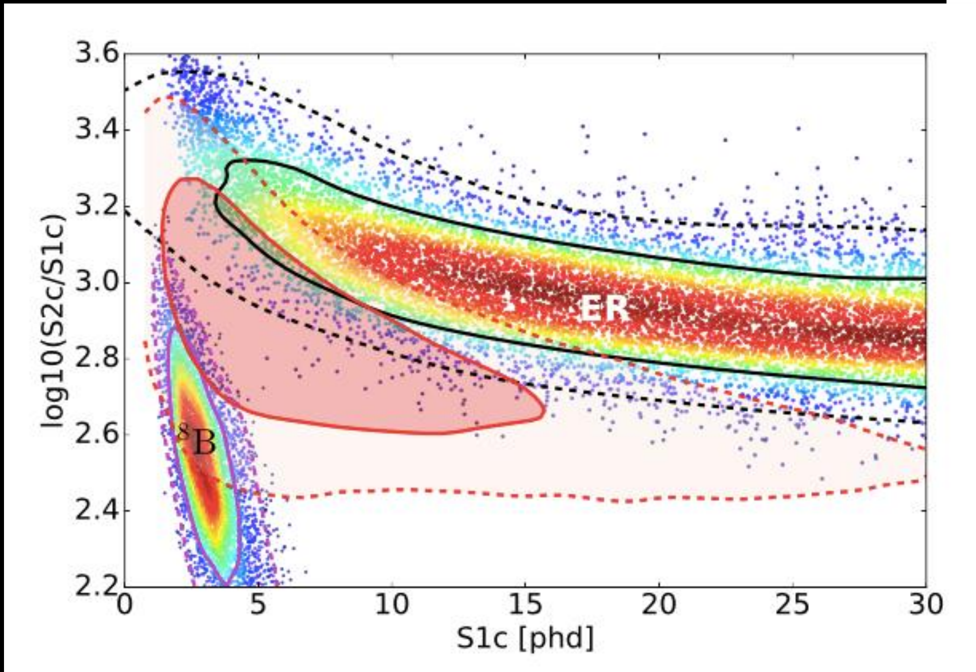




LZ – Liquid Xe TPC (Sanford Underground Lab)

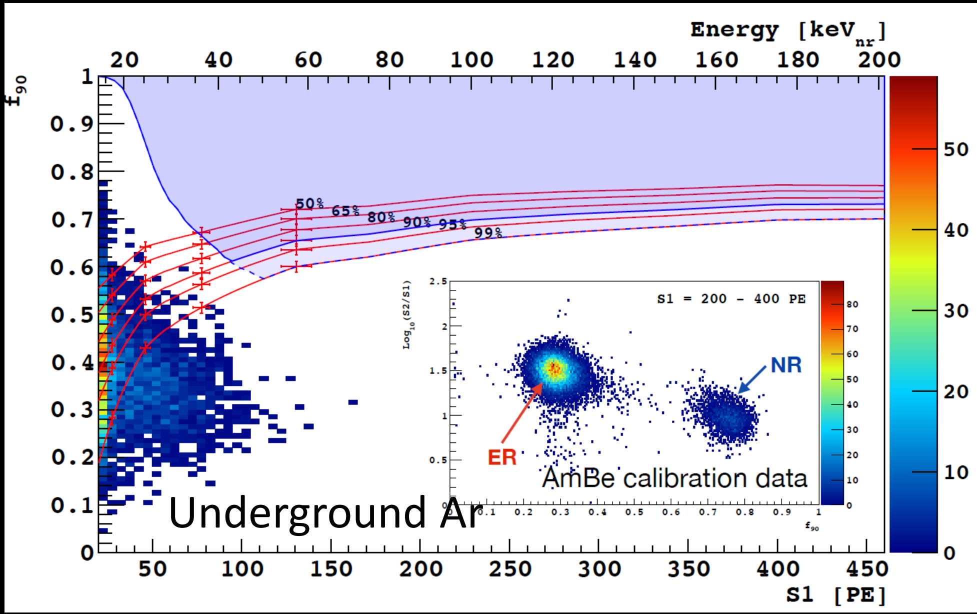
- LZ: LUX (250 kg, US) and ZEPLIN (few kg, UK) joint to build 7 t detector
- Exactly the same concept as XENON,
  EXCEPT: Gd loaded liquid scintillator veto added
- Presently under construction; commissioning in 2019
- Detailed material screening program
- Extensive calibration plans

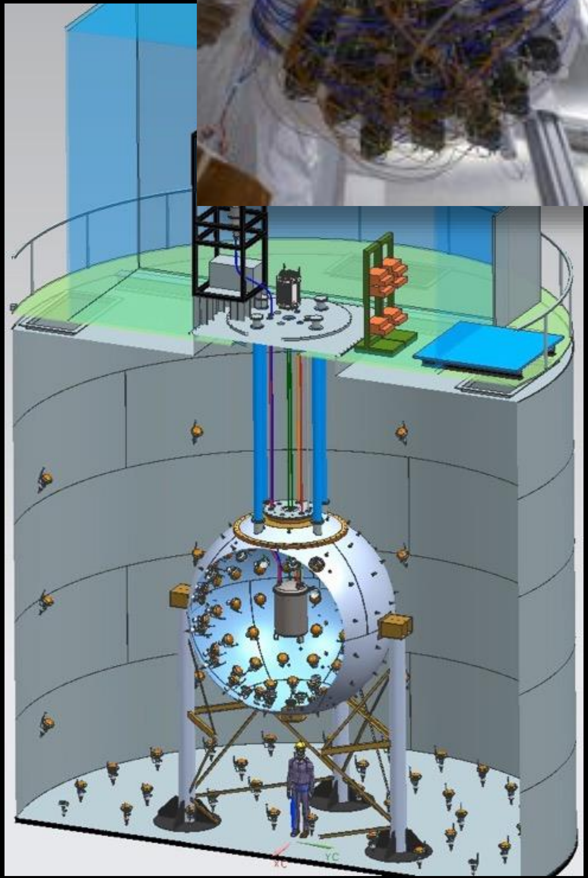




DarkSide – Liquid Ar TPC (Gran Sasso)

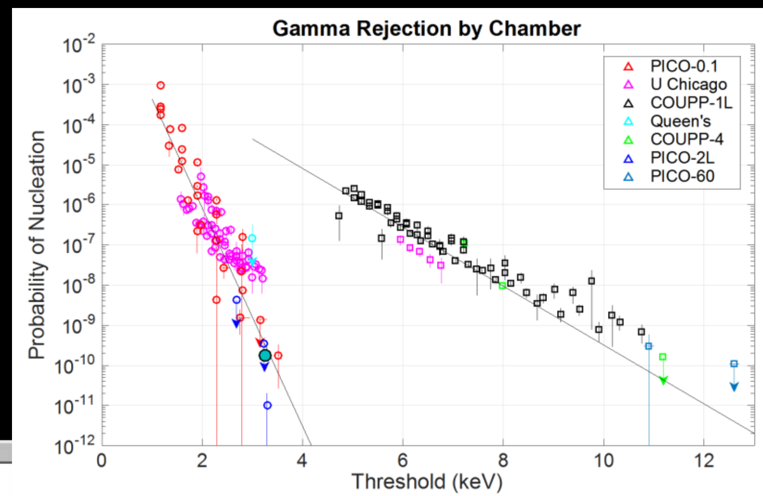
- Concept very similar to LZ, but with Ar as target (50 kg) (Ar TPC, Scintillator veto (Be loaded), Water tank (μ veto)
- Ar from underground sources (1/1400 ^{39}Ar content)
- Advantage compared to Xe: much better ER/NR discrimination
- Disadvantage: higher threshold; less self shielding
- First results (regular Ar) in 2015, UG Ar in 2016
- Future: DS-20k (20 tons, with DEAP?)

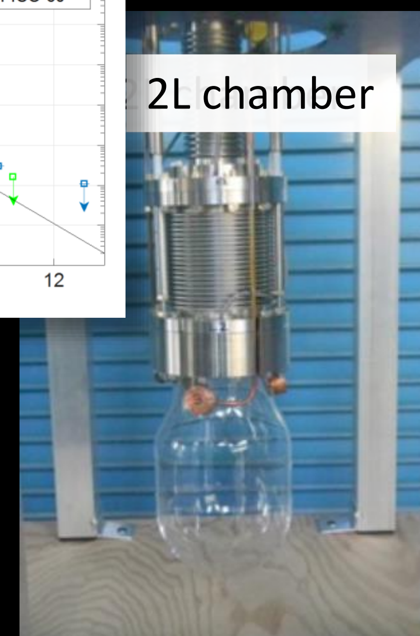


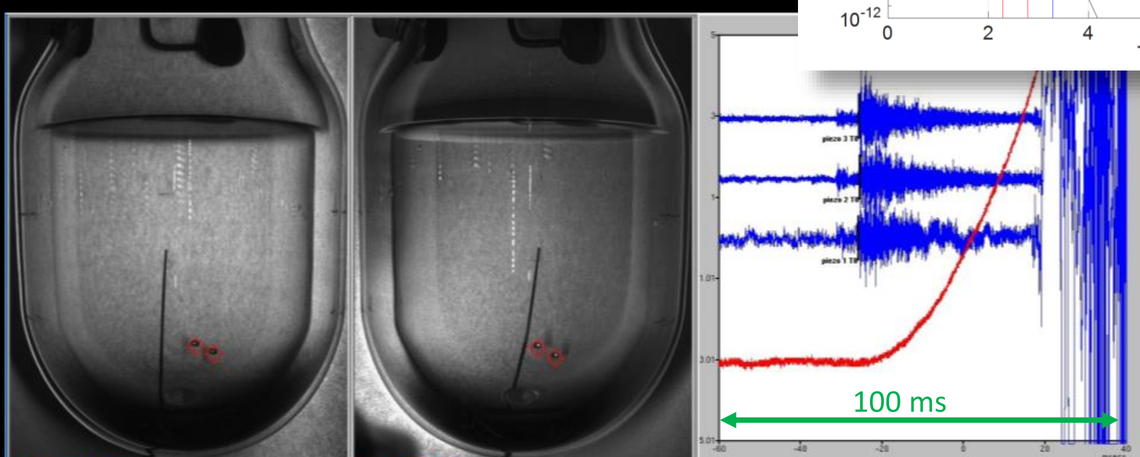


PICO – C_3F_8 Bubble Chamber (SNOLAB)

- 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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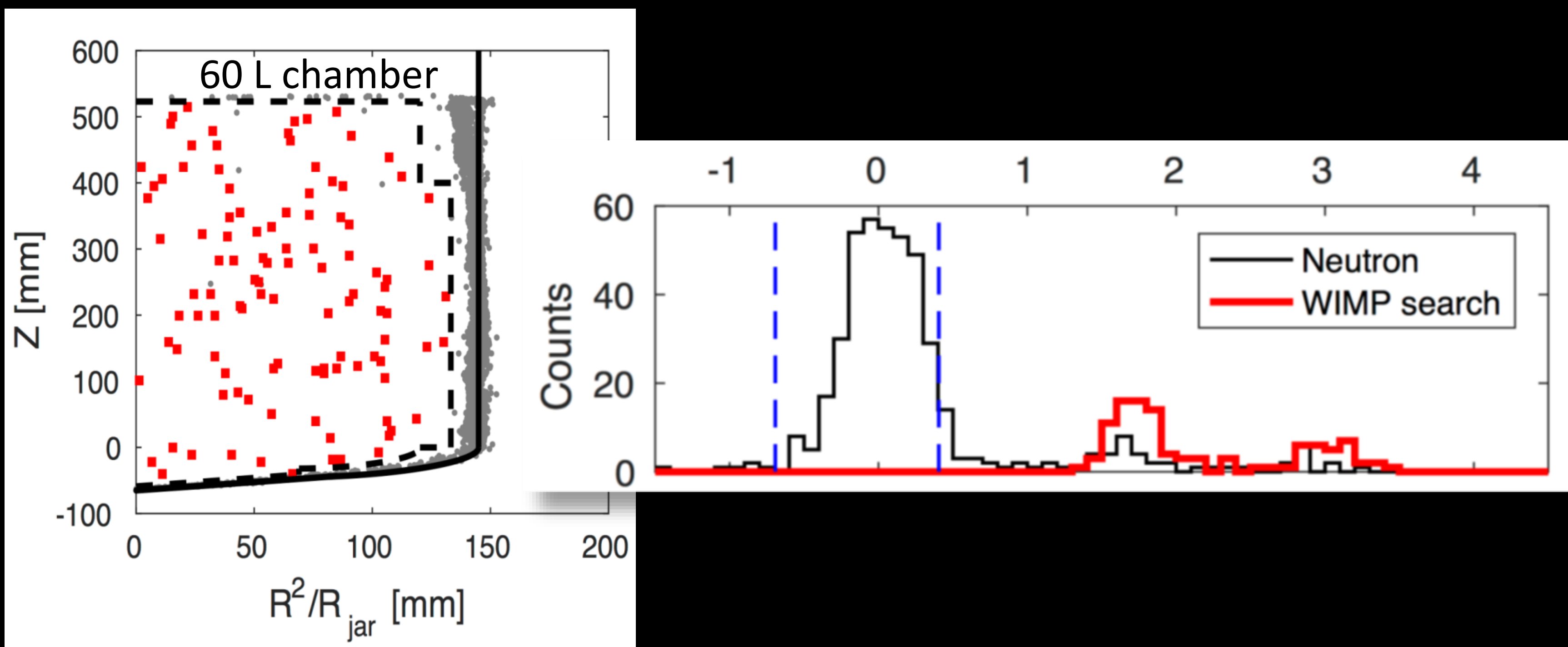
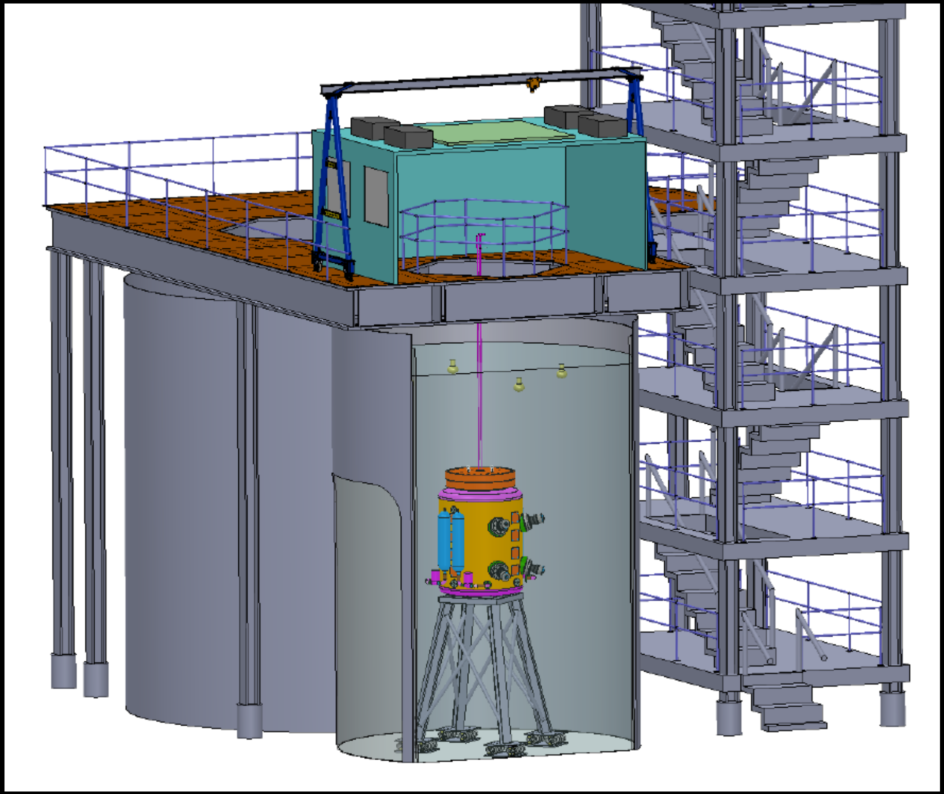
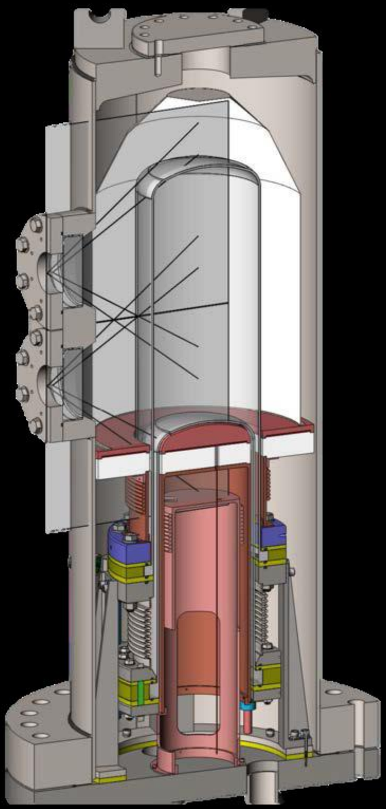


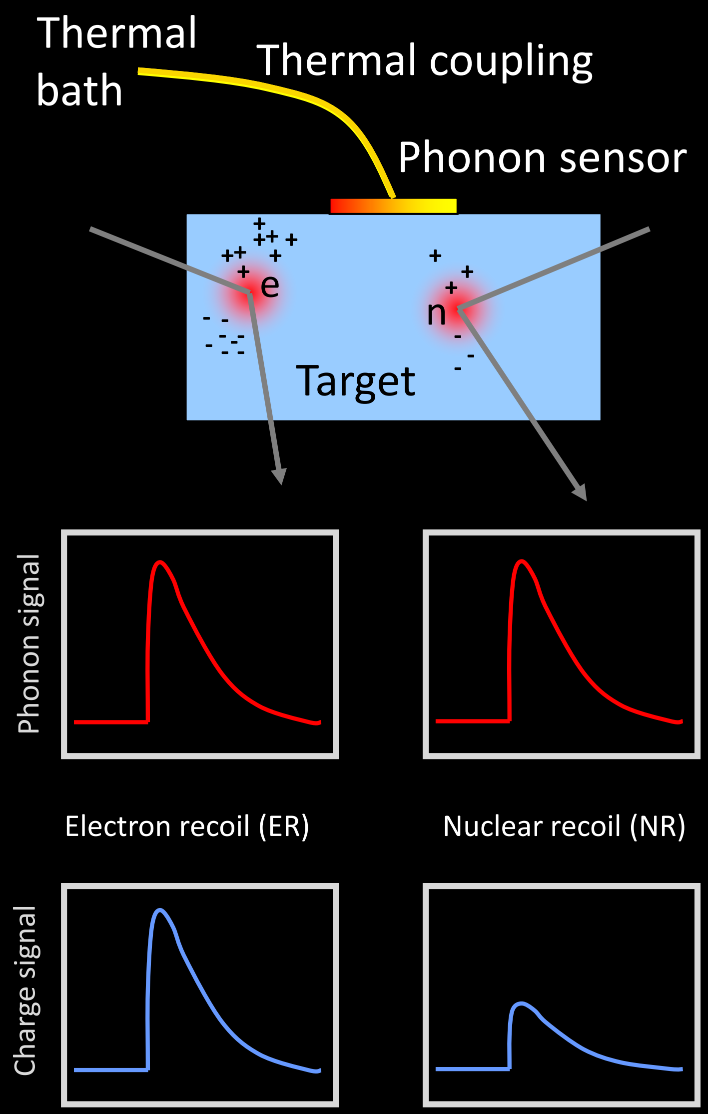
PICO – C_3F_8 Bubble Chamber (SNOLAB)

- 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

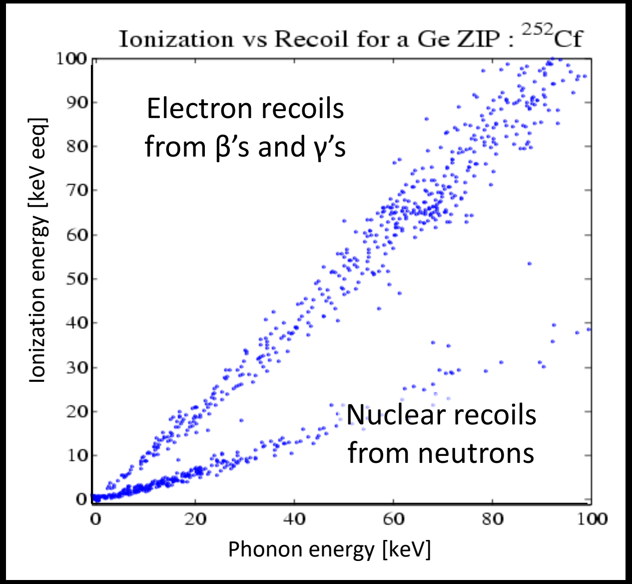




Cryogenic Detectors

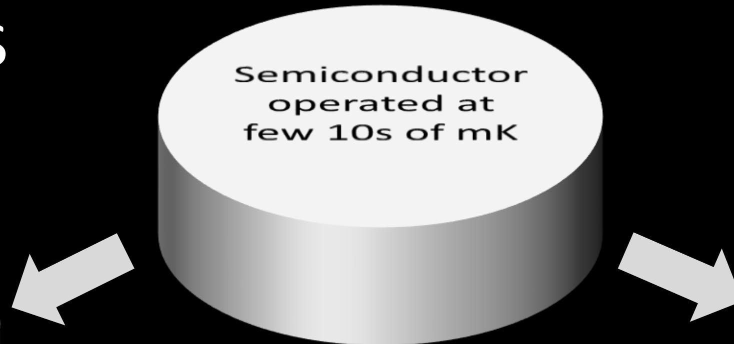


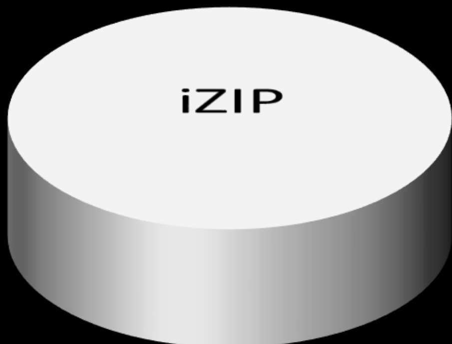
- Phonon signal (single crystal): measures energy deposition
- Ionization/scintillation signal: quenched for nuclear recoils (lower signal efficiency)
- Combination: efficient rejection of electron recoil background

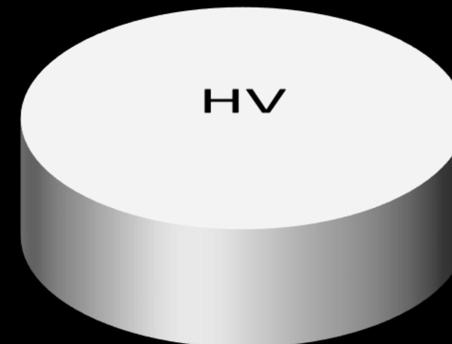


CDMS/SuperCDMS

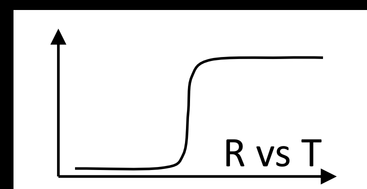
SuperCDMS Soudan



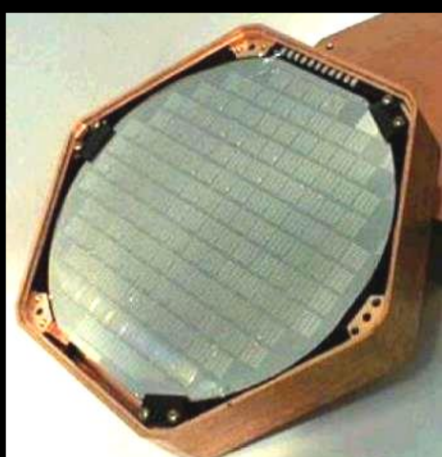


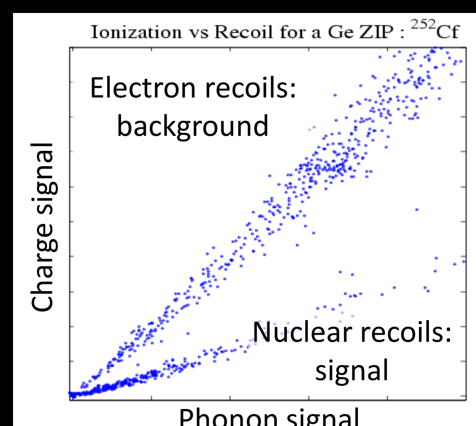


Phonon Readout:
Tungsten TES

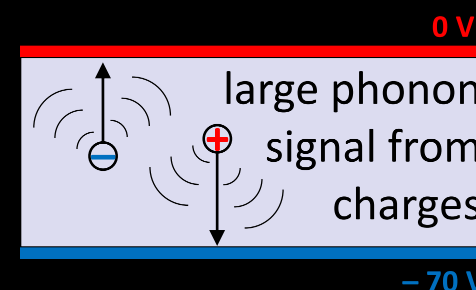


Add: charge readout (few V)
Background discrimination
Threshold < 10 keV





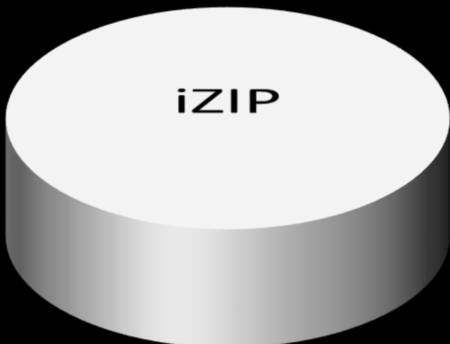
Add: high voltage (~70 V)
Phonons from drifting charges
Threshold 56 eV_{ee} (phonon)

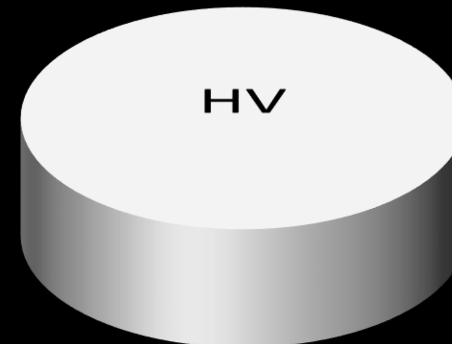


effective threshold:
few hundred eV (NR)

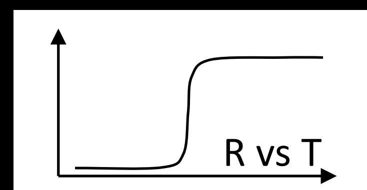
CDMS/SuperCDMS

SuperCDMS
SNOLAB

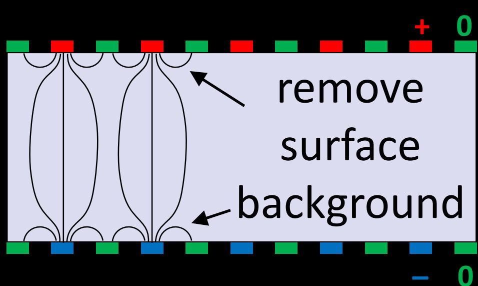




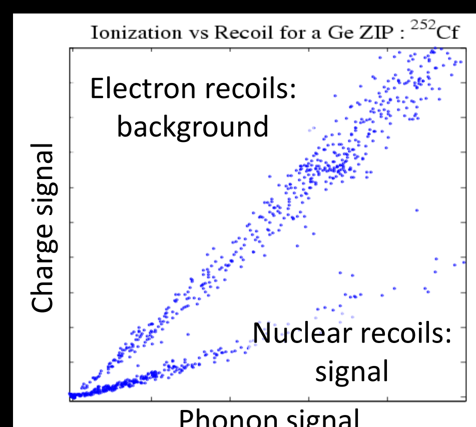
Phonon Readout:
Tungsten TES



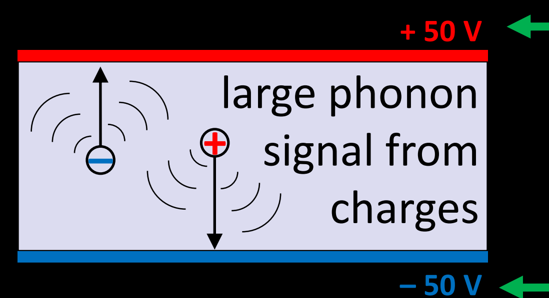
Add: charge readout (few V)
Background discrimination
Threshold < 1 keV



< 1 background event for whole exposure



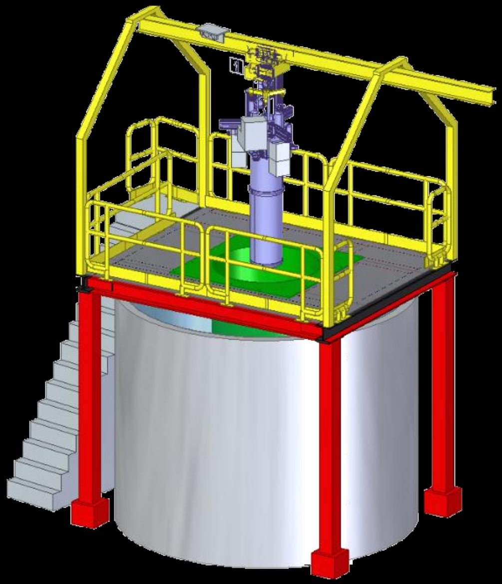
Add: high voltage (~100 V)
Phonons from drifting charges
Threshold < 10 eV_{ee} (phonon)

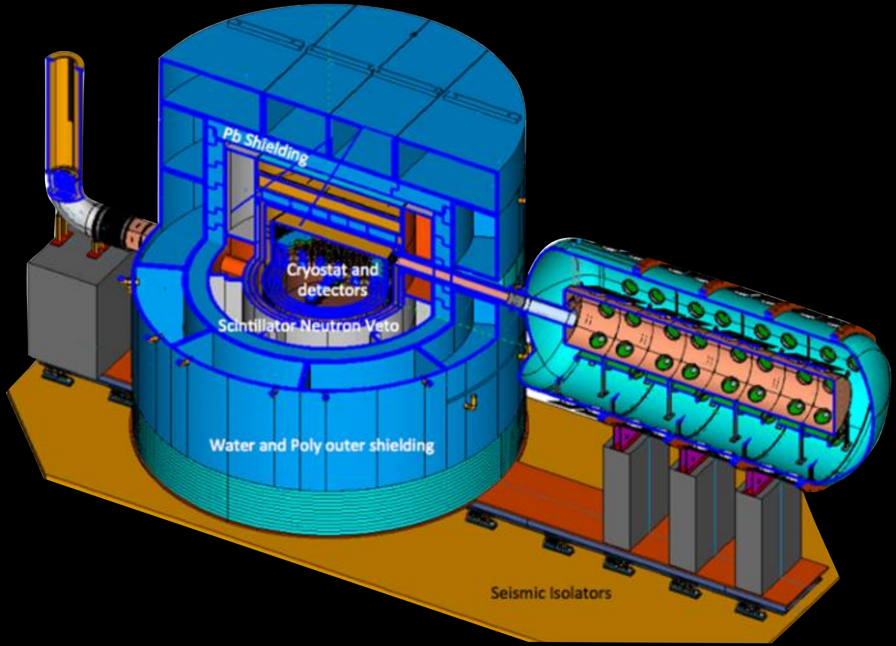


effective threshold: one (or few) electron-hole pairs

SuperCDMS – Cryogenic Ge/Si (SNOLAB)

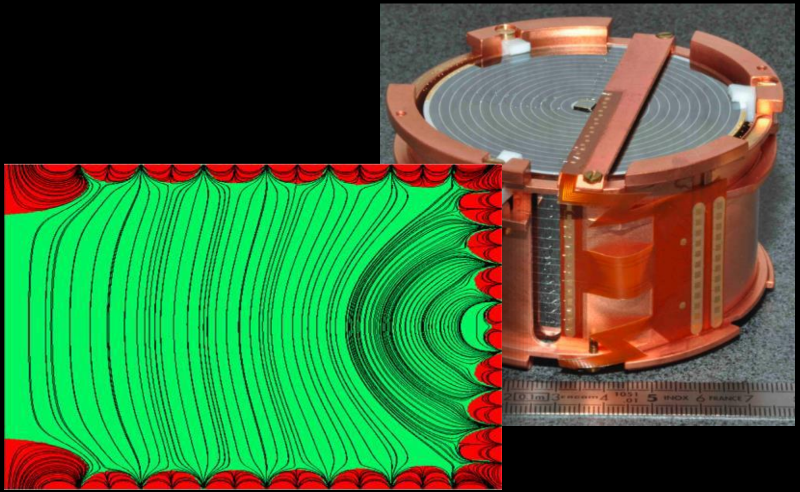
- Ge: 1.4 kg; Si: 600 g; iZIP/HV; initial payload: 24 det
- Shielding: (Cu), PE, Pb, Water/PE
- Threshold goal: <100 eV_t (HV)
- Limiting background (HV): ^3H (^{32}Si)
- Start operation in 2020
- Cryogenic Underground TEst facility (CUTE) being installed at SNOLAB in 2017 ($\rightarrow$ early science?)

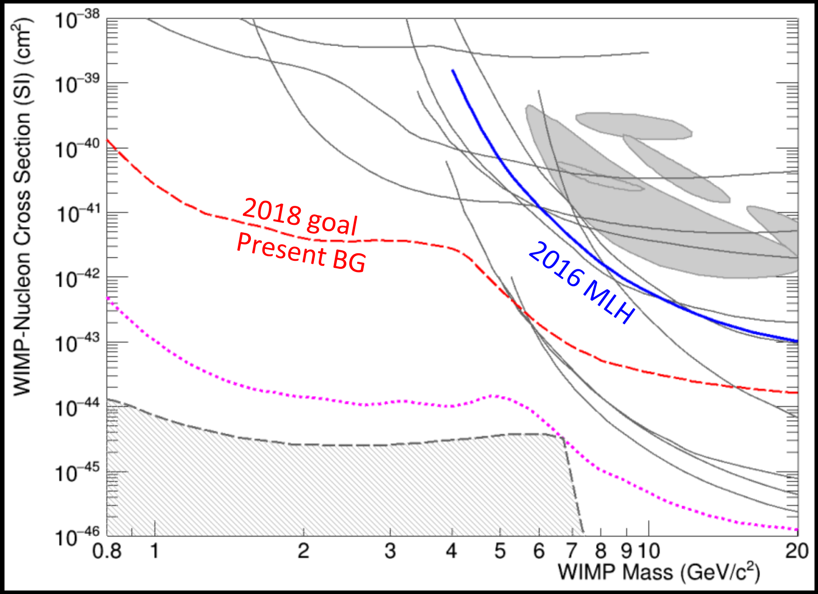


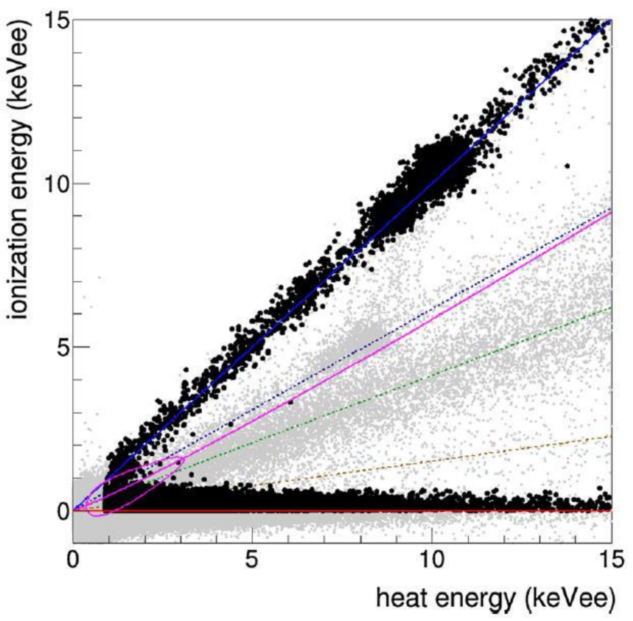


EDELWEISS – Cryogenic germanium (Modane Lab)

- Ge, 870 g modules
- NTD sensors; operation at 18 mK
- Interdigitized electrodes
- Shielding: (Cu), Pb, PE, muon veto
- Cosmogenic BG studies (^{3}H)
- Threshold: 2.5 keV$_{nr}$ (1 keV$_{ee}$)
- Future: HV (140 V); improve sensors; reduce ionization threshold and background

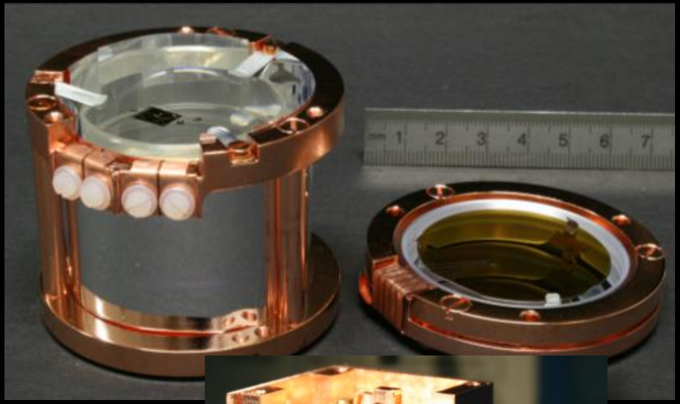


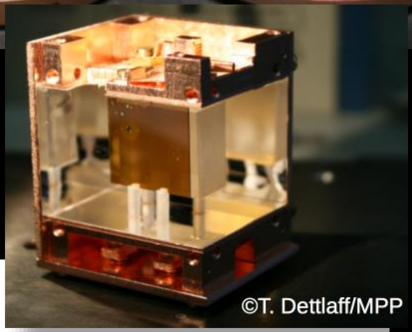


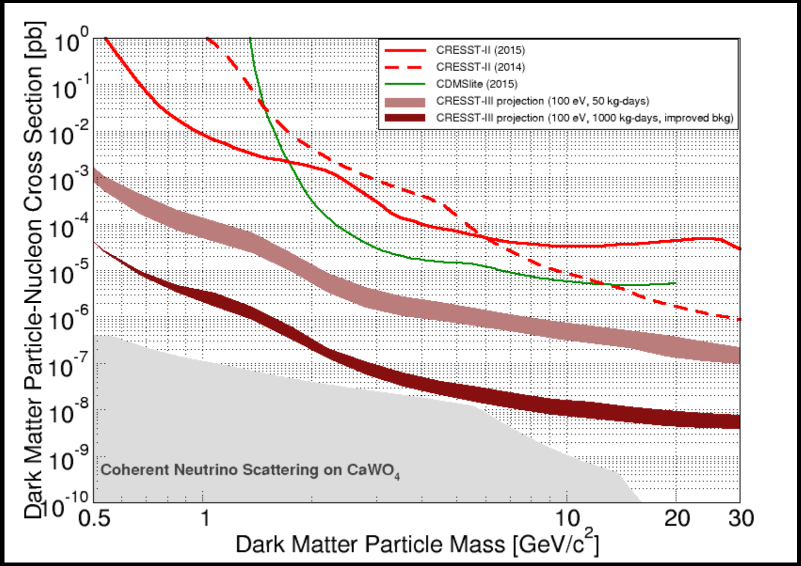


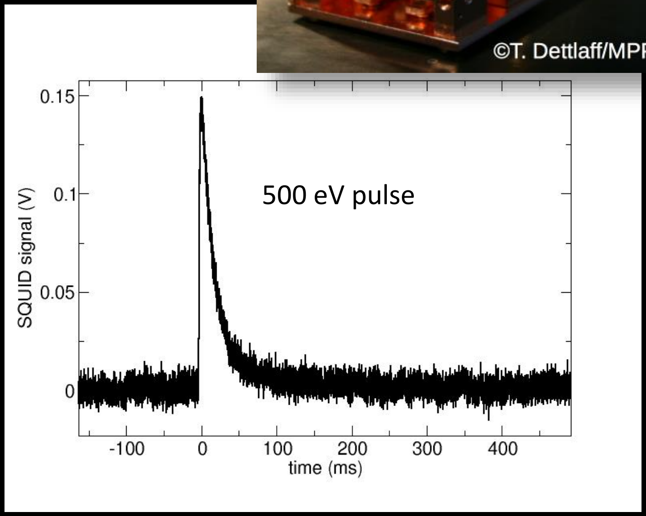
CRESST – Cryogenic Scintillator, $CaWO_4$ (Gran Sasso)

- $CaWO_4$, 300 g (old) / 25 g (new) crystals
- Cryogenic light detector (Si on Al_2O_3)
- TES sensors; operation at ~15 mK
- Shielding: Cu, Pb, muon veto, PE
- Threshold: 307 eV (old) / <100 eV (new)
- 6 new modules operational
- Next phase: 100 modules, reduce background (x100) and threshold: $\mathcal{O}(10\text{ eV})$



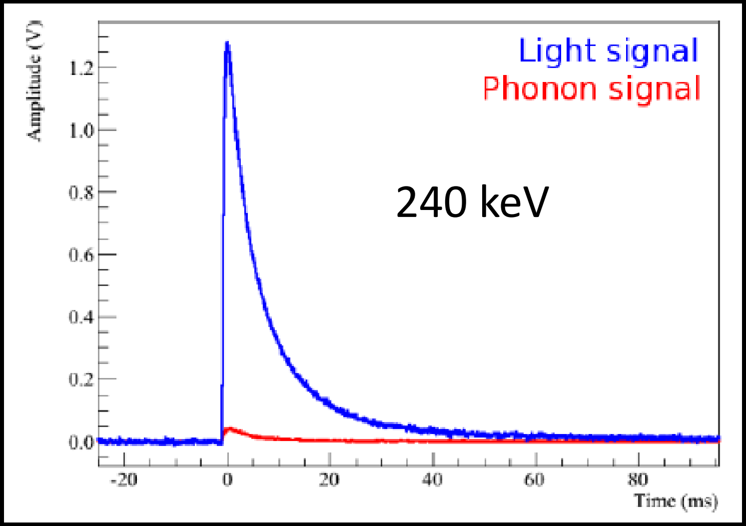






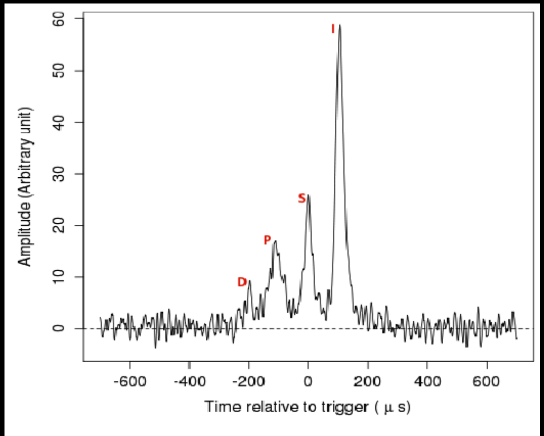
Cosinus – Cryogenic Scintillator, NaI

- Similar to CRESST
- Another attempt to check DAMA
  in this case with good ER/NR discrimination
- So far only R&D – hope to reach low threshold
- Exposure of few 10s of kg-days should be able to check DAMA

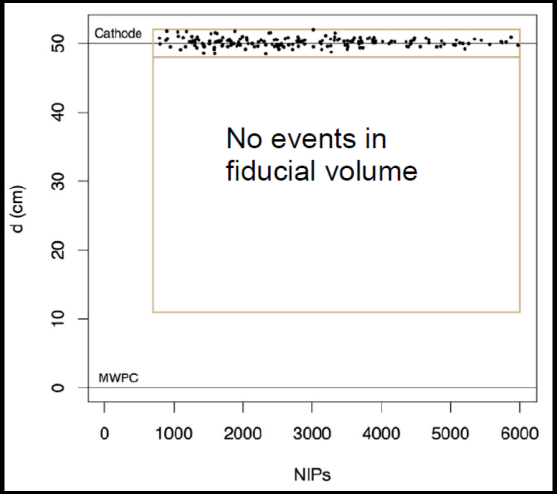


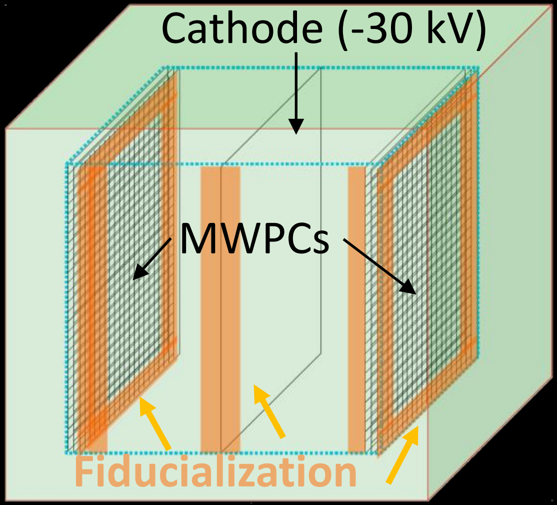
DRIFT – Negative Ion TPC, directional sensitivity (Boulby)

- 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



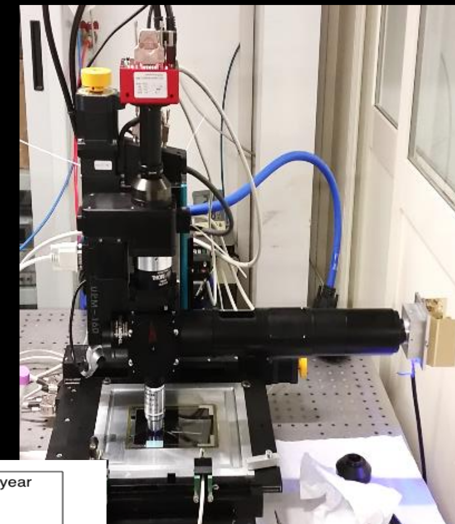
(b) Mid-z event at z = 25.1 cm, NIPs = 1504.

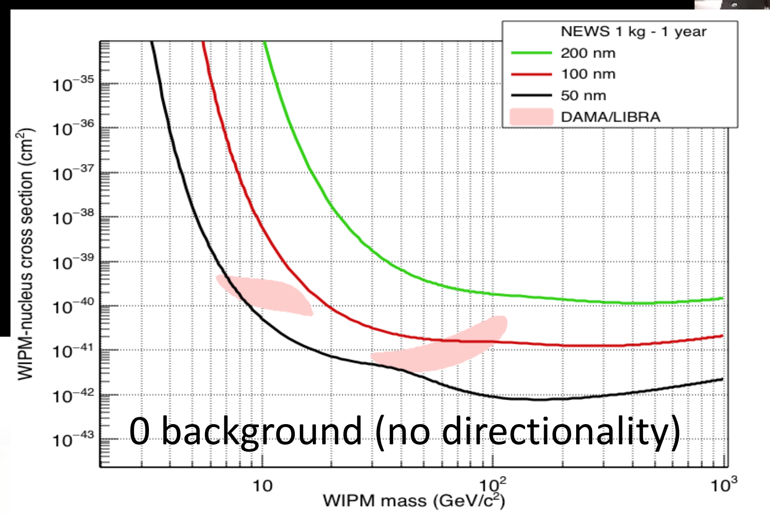


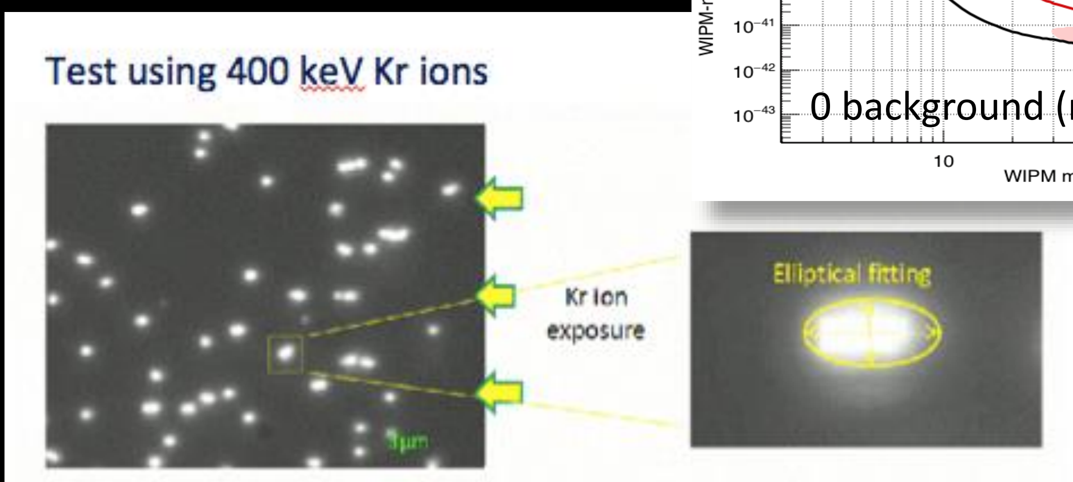


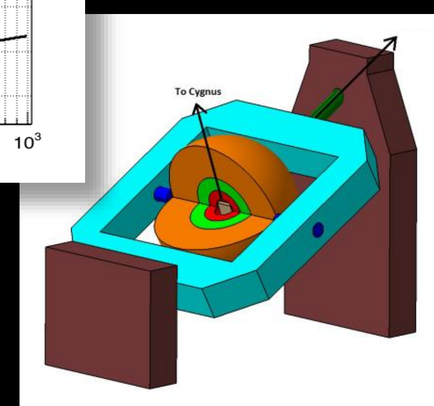
NEWS dm, nuclear emulstion (Gran Sasso)

- Spin-off from OPERA
- Emulsion for directional sensitivity
- Scanning with optical & x-ray microscopes
- Keep orientation constant wrt WIMP wind
- 10 g test exposure under way
- 1 kg exposure for 1 y planned for 2020
- 10 kg y should be possible (given background)

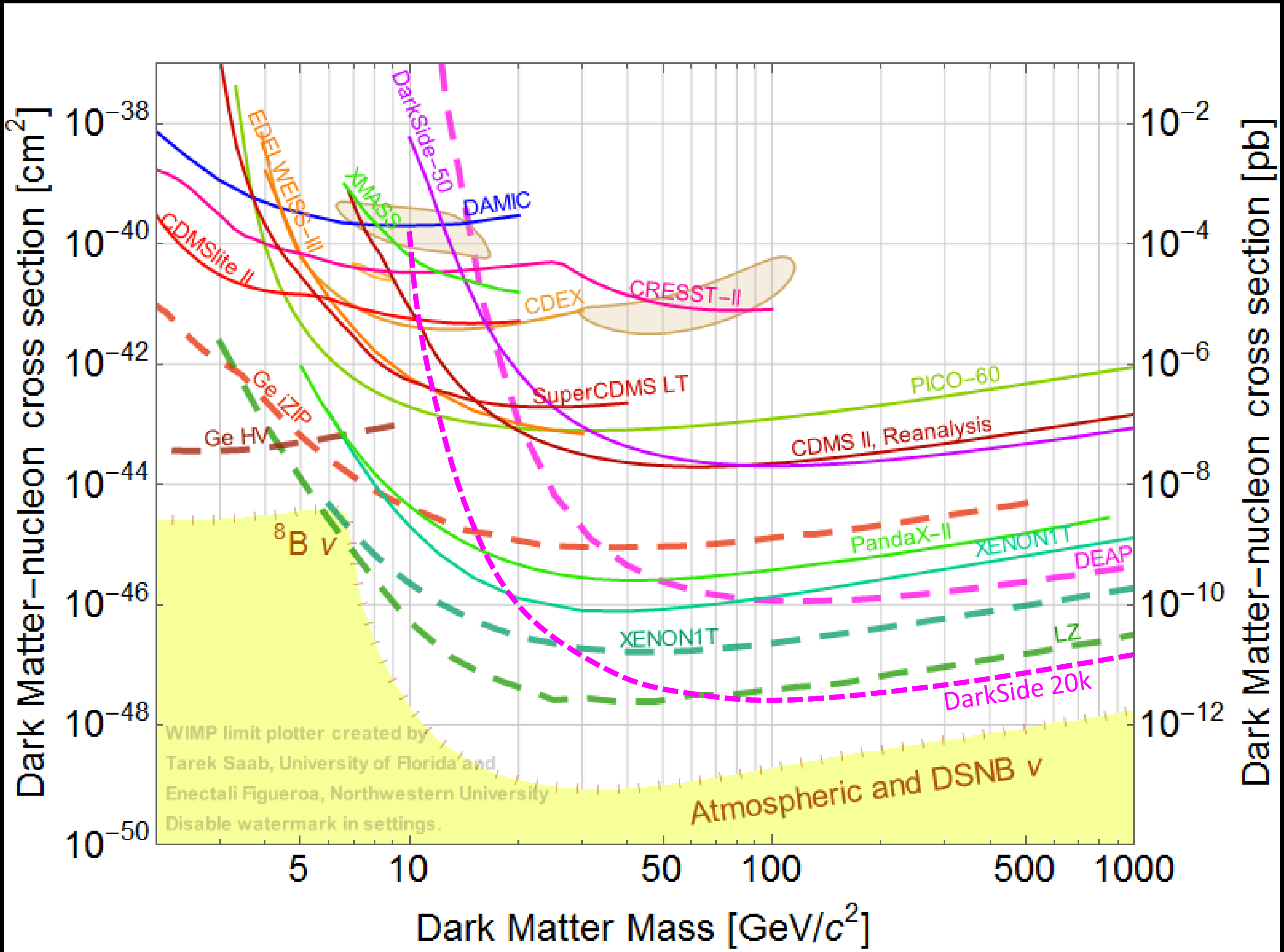




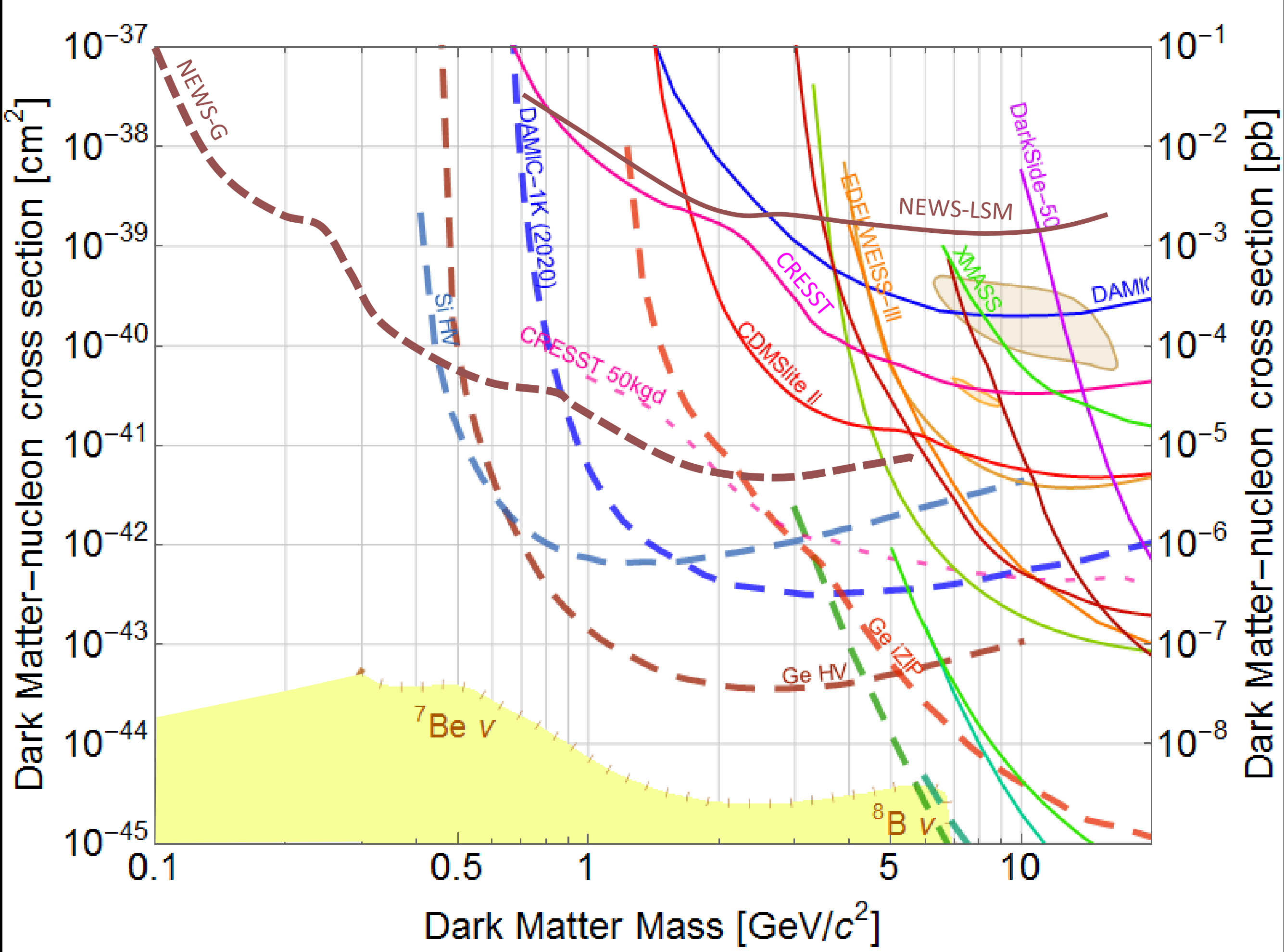




Results and Projections



Results and Projections



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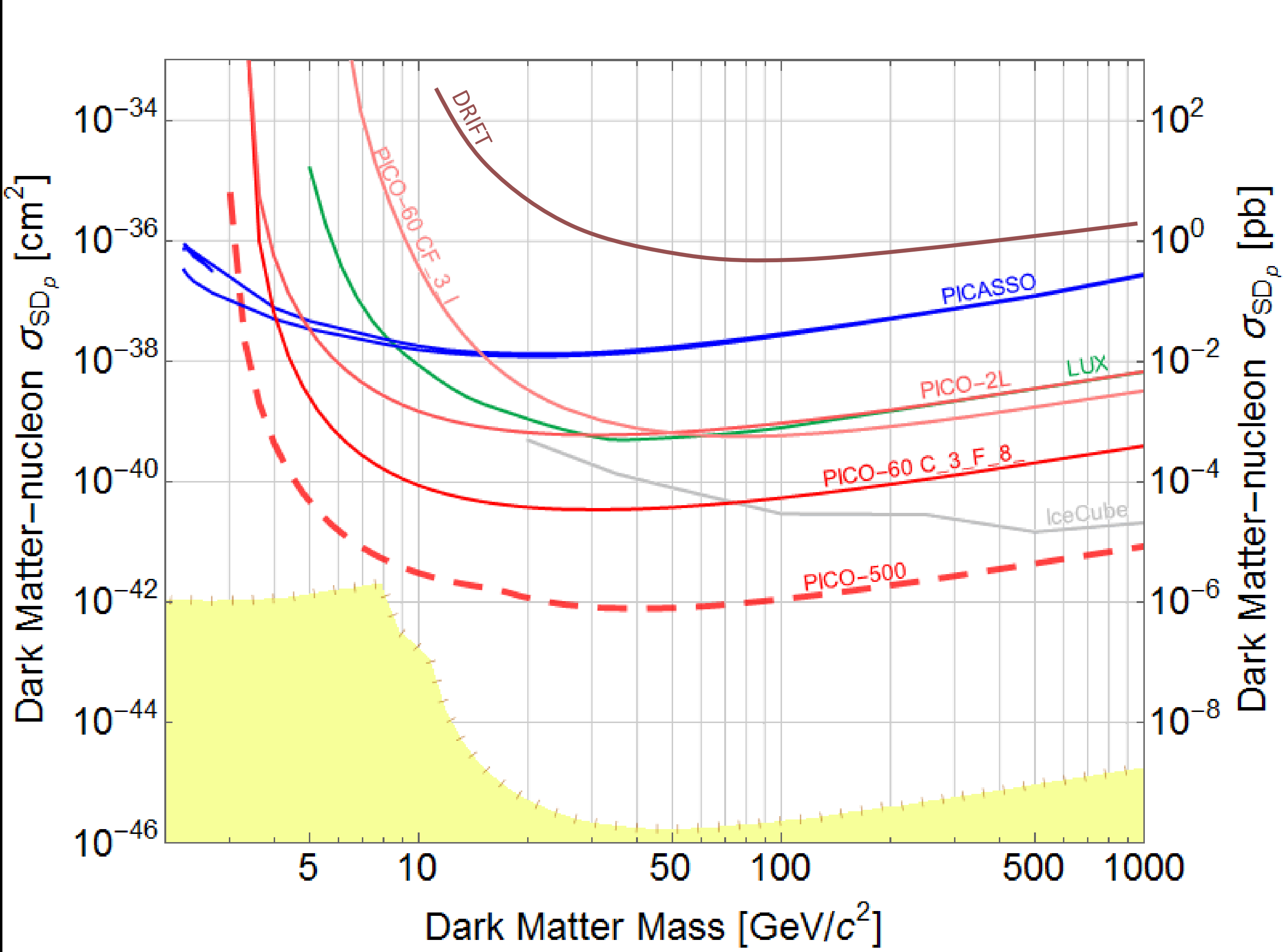
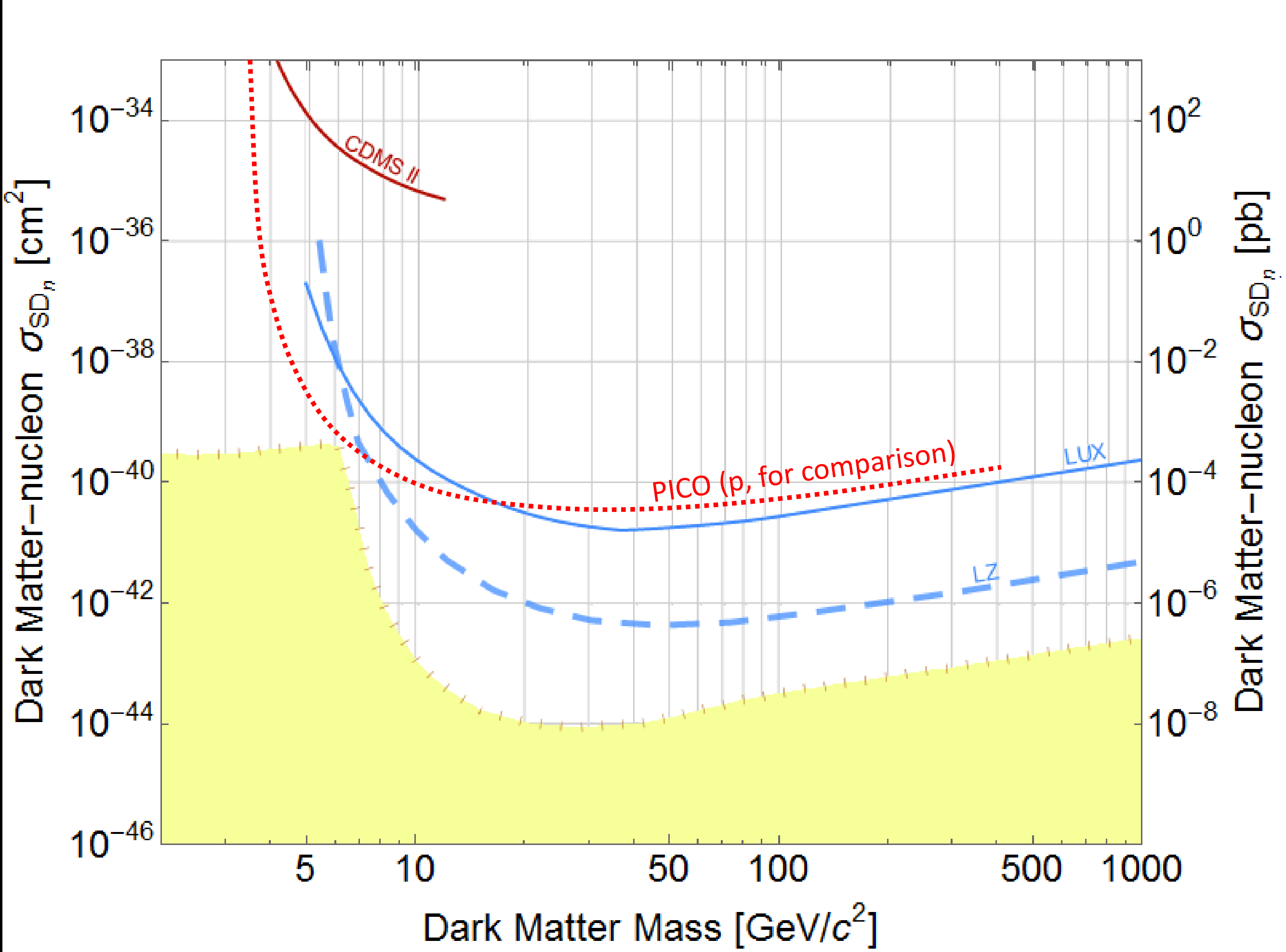


Results and Projections



Conclusions

Status:

- Multiple technologies and multiple targets employed
- Leading in high mass range: noble liquids (presently XENON1t, see later talk)
- Leading in low mass range: cryogenic detectors (CDMSlite, 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
- Leading in directional detection: Low pressure gas TPCs (DRIFT); not yet competitive with rate experiments (small target mass)

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), improved SuperCDMS (low mass); ton-scale directional detector (sub-neutrino floor at low mass)