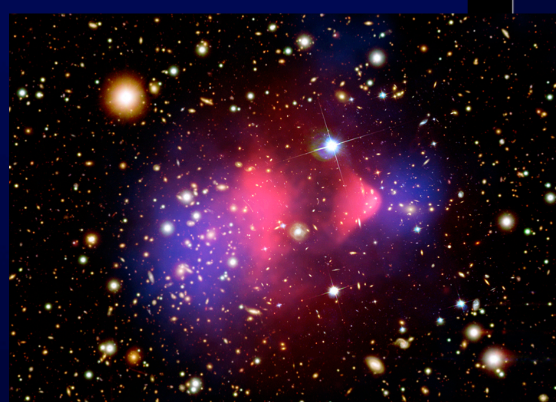
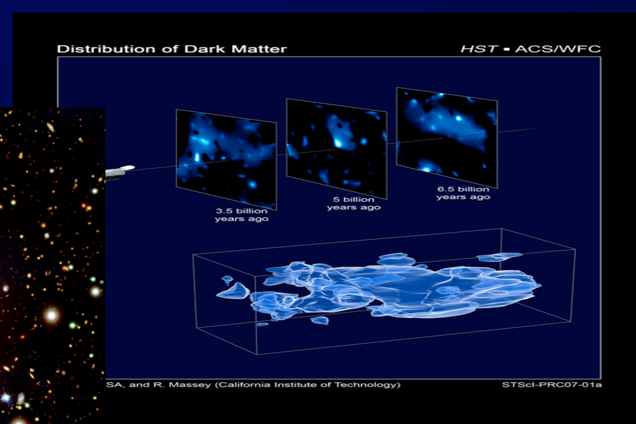
Status of Dark Matter Direct Detection Searches

Bruno Serfass - UC Berkeley

CGI Workshop, Oct. 2012

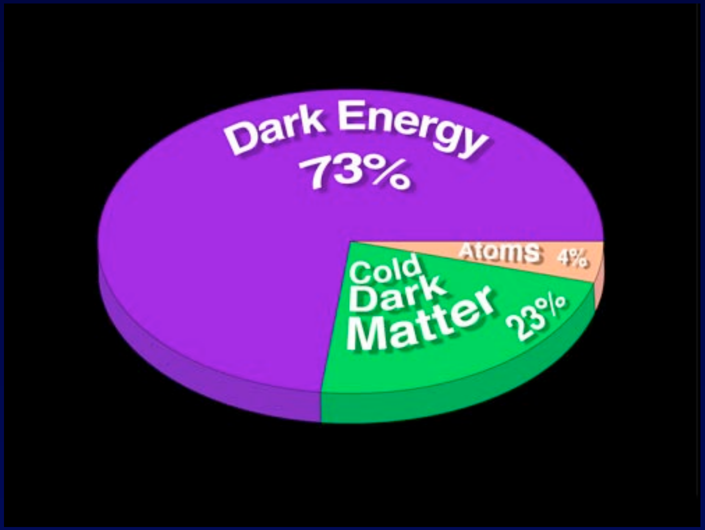




Dark Matter Halo

Evidence of Dark Matter at various galactic scales

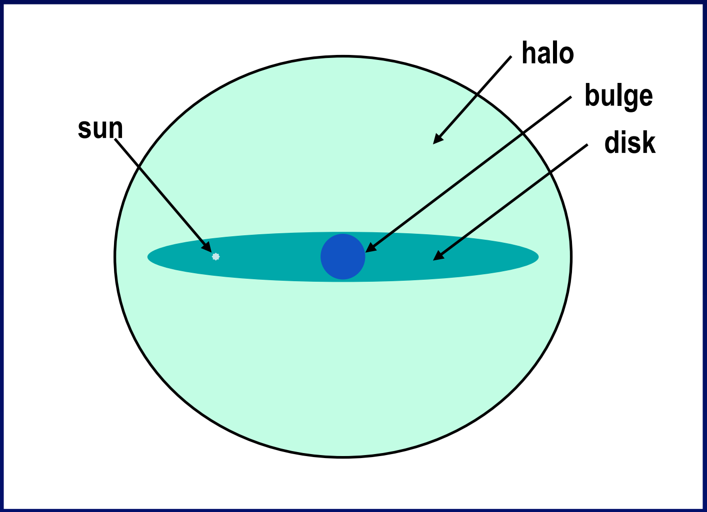
- In particular, rotation curve of spiral galaxies imply the presence of dark matter halo
- Many candidates: WIMPs (SUSY, etc), axions,…



Standard DM halo assumptions:

- Isothermal and spherical
- Maxwell- Boltzmann velocity distribution
  $\langle V \rangle$= 270 km/s, ρ = 0.3 GeV / cm^3

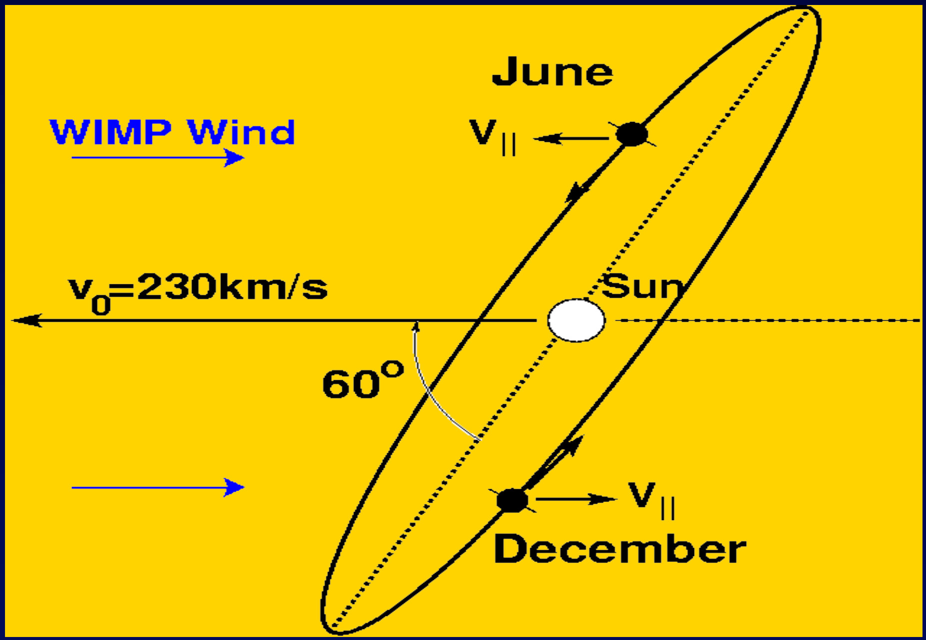
But large uncertainties…

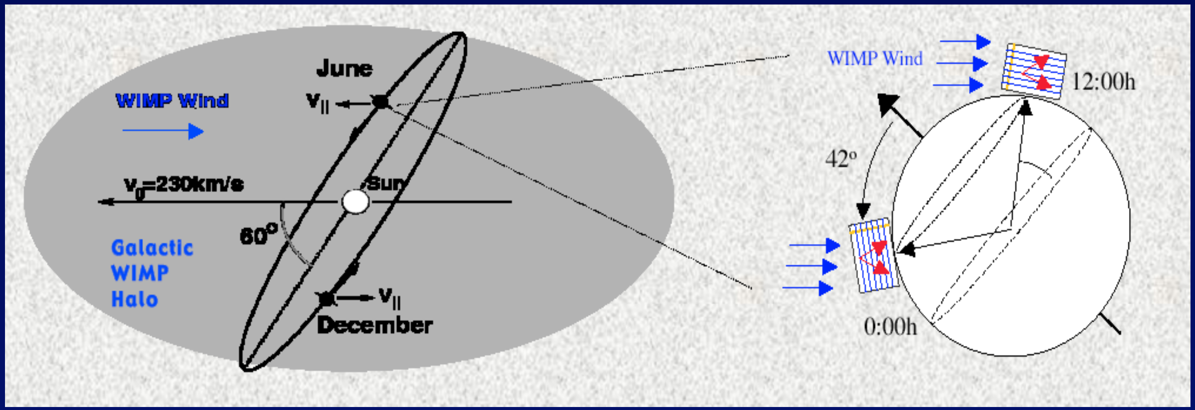


Dark Matter Wind on Earth

- **Annual modulation**
  - Sun travels through the DM cloud at 230 km/s
  - Earth adds or subtracts 15 km/s to solar velocity

Expect a few ± 1 % annual modulation in rate



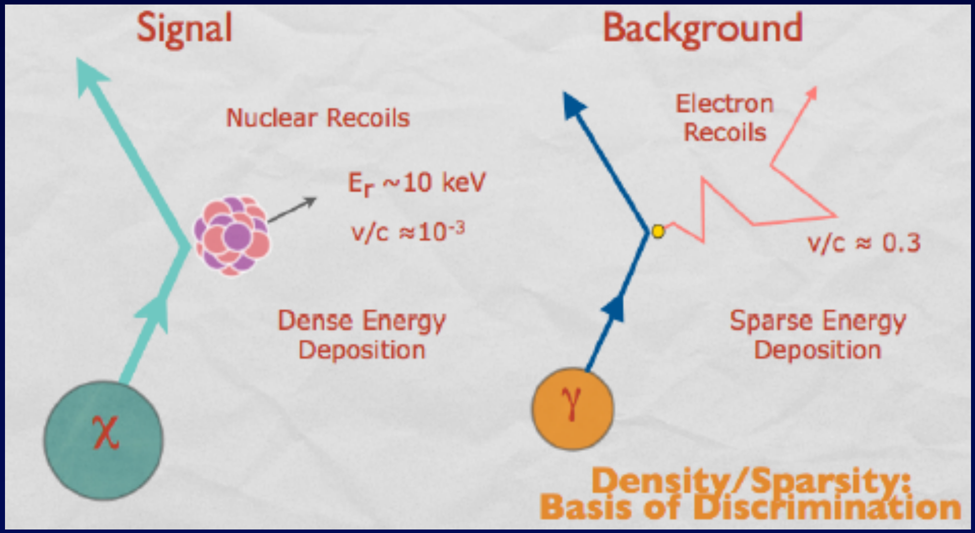


- **Diurnal modulation**
  - 90° change of direction
  - But short track length in detectors
    ➔ difficult measurement

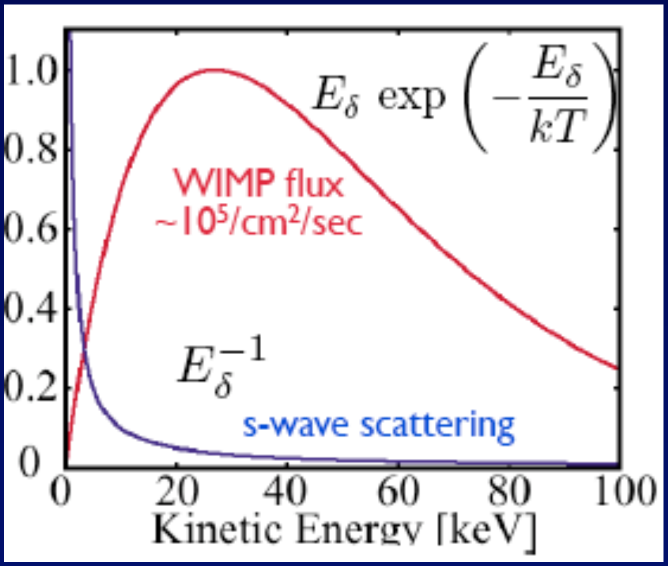
Direct Detection of WIMPs

If WIMPs are the halo, detect them via **elastic scattering** on target nuclei **(nuclear recoils)**

Energy spectrum and rate depend on target nucleus masses and WIMP distribution in Dark Matter Halo



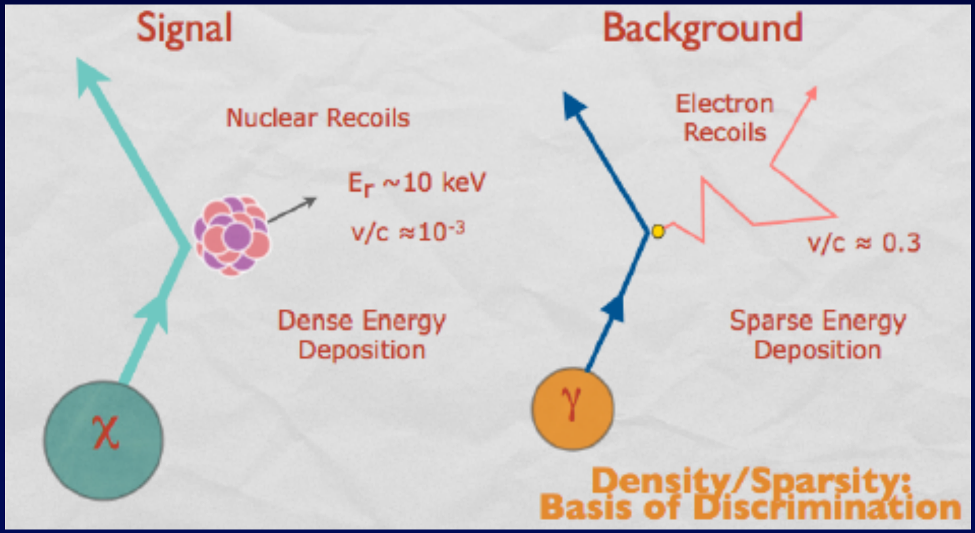
(For Standard DM halo)



- **Energy spectrum of recoils**
  ~ falling exponential with <E> ~ 15 keV
- **Rate (based on $\sigma_{n\chi}$ and ρ) << 1 event /kg/day**

Direct Detection of WIMPs

If WIMPs are the halo, detect them via **elastic scattering** on target nuclei **(nuclear recoils)**



Energy spectrum and rate depend on target nucleus masses and WIMP distribution in Dark Matter Halo

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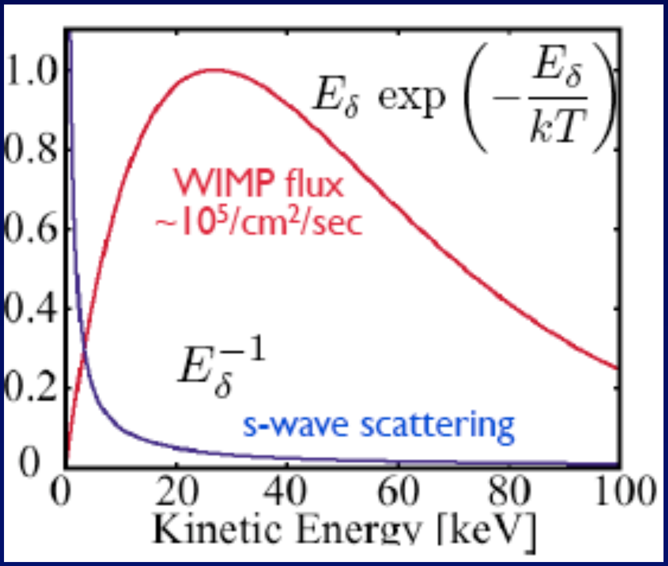


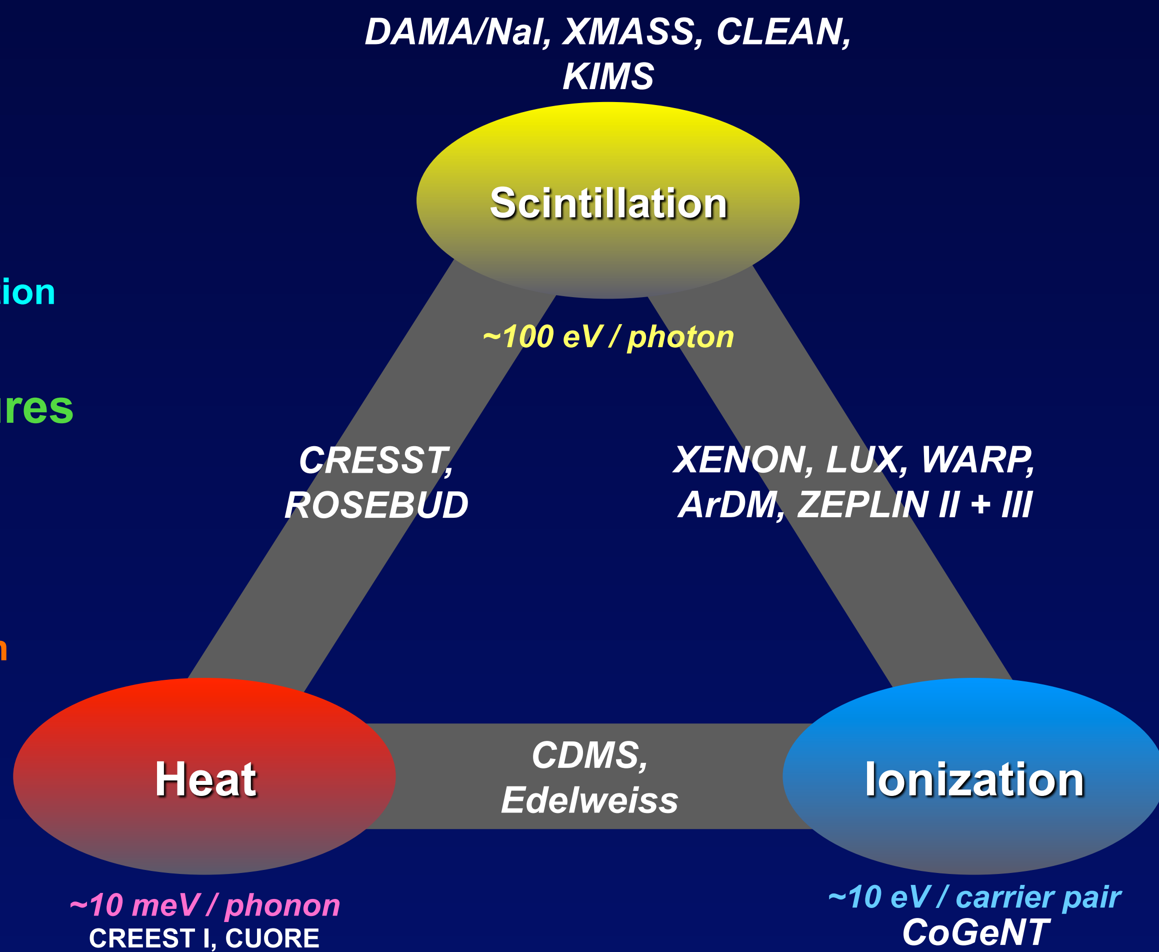
- Low Energy threshold needed (~ keV)
- Good background rejection
- Large exposure (high target mass)

Direct Detection Strategies

Goal: find a very small WIMP signal in presence of many other background particles interacting in detectors

Techniques:

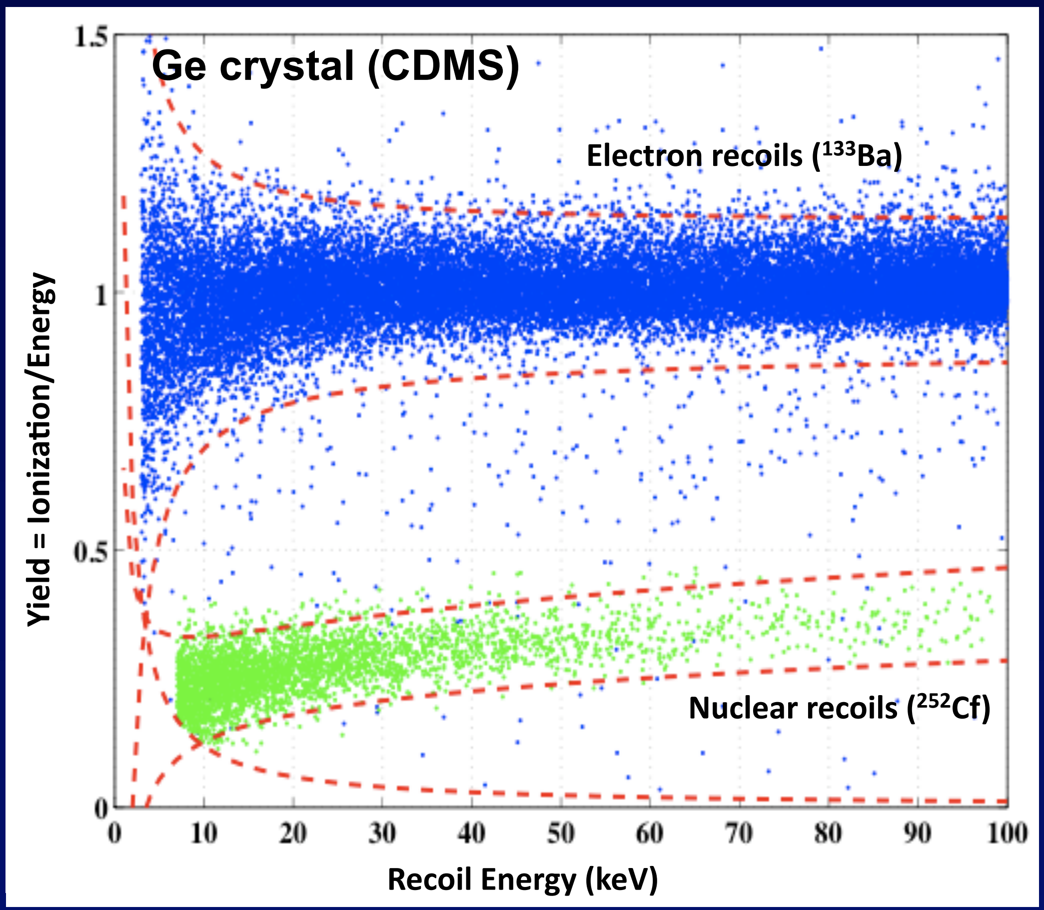
- Statistical signature
  - annual modulation
  - diurnal direction modulation
- Event by event signatures
  - Nuclear recoils: dense energy deposition
  - Electron recoils (α, β, γ): sparse energy deposition



Direct Detection Strategies

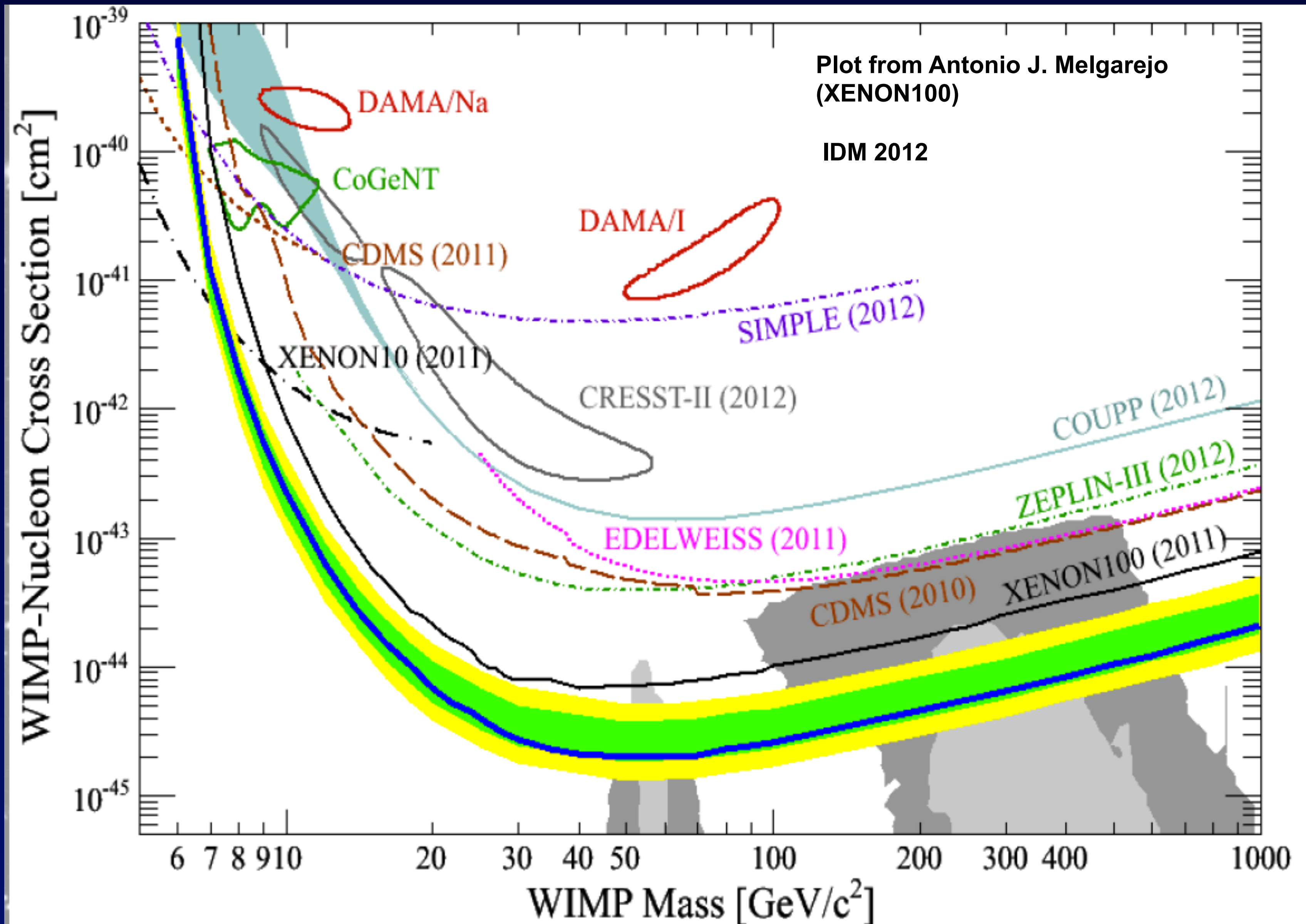
Nuclear/Electron Recoils (NR / ER):

Amount of charge or light created after an event depends on the type of interaction = "Quenching factor" (Q)



Energies calibrated with gamma sources are called "electron equivalent energies" ("keVee")

Direct Detection Sensitivity



Lots of Experiments

May experiments around the word. Deep underground to avoid cosmic rays

Sensitivity for a ~50 GeV WIMP:

- Current Generation (or soon):

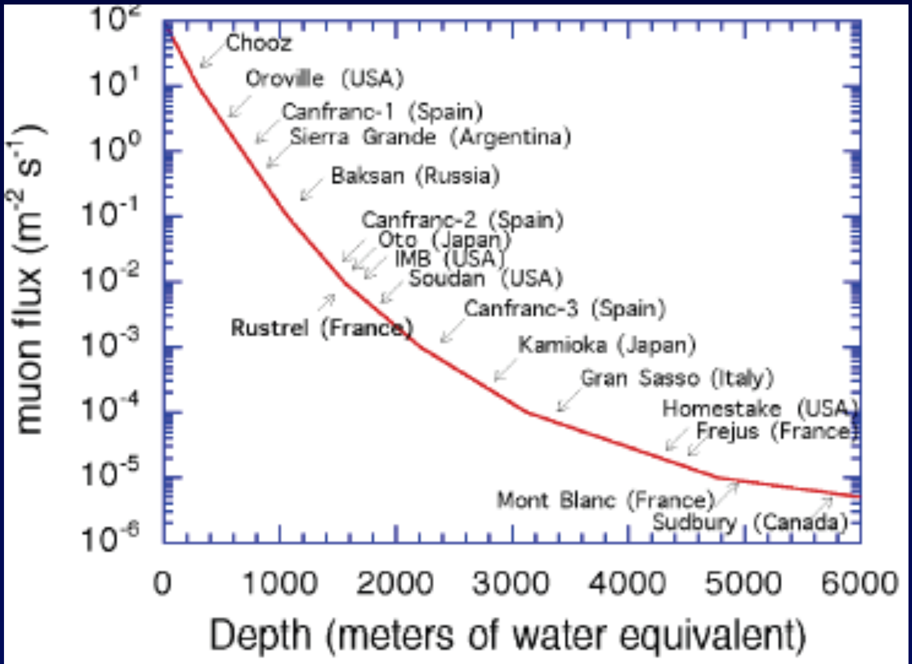
  $\sigma_{SI} \sim 10^{-45} cm^2$

- Next step ~1 Ton Exp. (under construction / development):

  $\sigma_{SI} \sim 10^{-46}$, few $x10^{-47}$ cm^2

- Plans for multi-ton Exp. (>5 years)

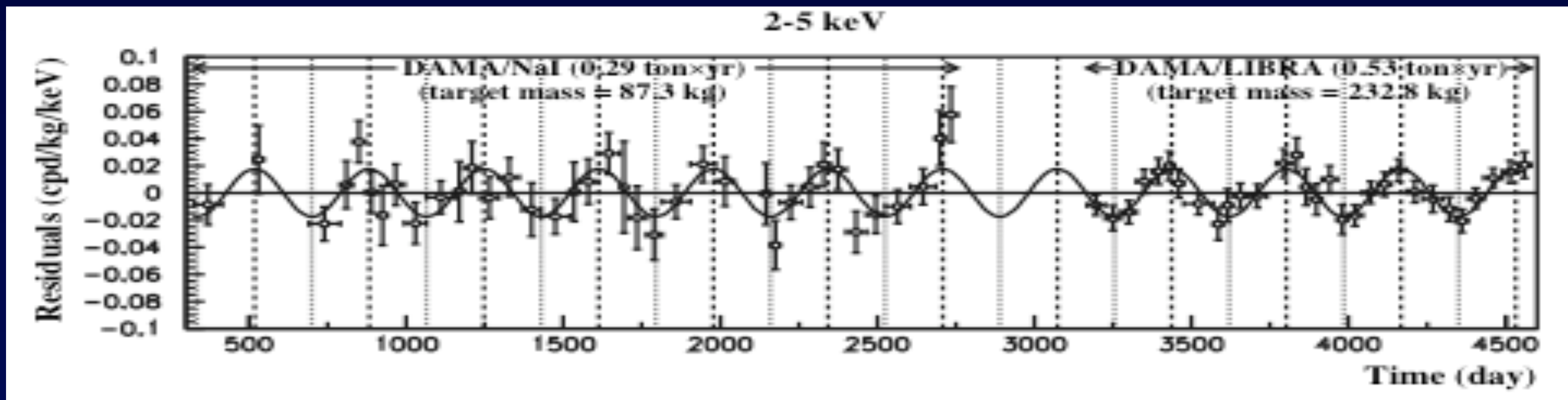
  $\sigma_{SI} \sim$ few $x10^{-48}$ cm^2



End of the road? Not so far away from being limited by backgrounds from low energy solar neutrinos

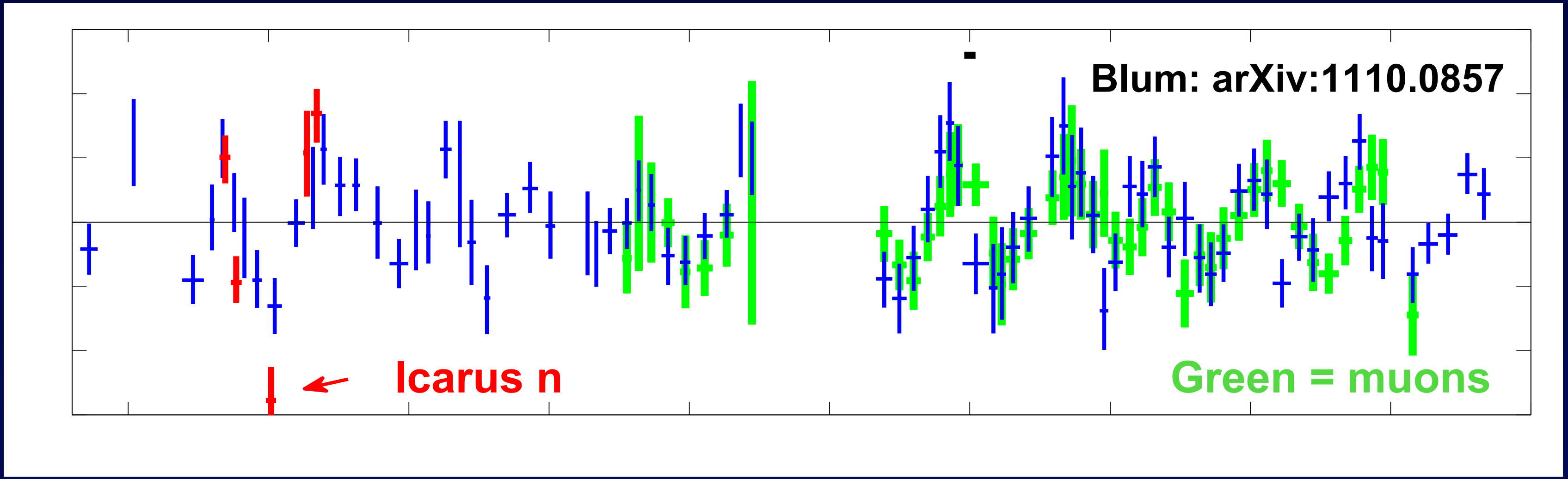
DAMA / LIBRA

Time Dependence of Residual Singles Rate in 2-4 keVee bin



- 25 NaI(Tl) scintillating crystals in 5x5 grid (9.7 kg each) = 243 kg
- Two light guides + two PMTs on each crystal
- 8.9 sigma CL evidence of signal. But is it Dark Matter?
- ‘Natural’ WIMP candidate in contradiction with CDMSII, Xenon10 S2 Only, Xenon100

DAMA: DM Signal?



- The number of environmental conditions which have annual modulation is too big to count!
  - Muons
  - Neutrons
  - Temperature
  - Humidity
  - Human activity

Blum, arXiv:1110.0857
Nygren, arXiv:1102.0815
Ralston, arXiv:1006.5255

→ DAMA, arXiv:1202.4179

$$f_{osc} = \frac{R_{osc}}{R_{DC}} \sim 2\%$$

$$= \frac{R_{osc}(\mu)}{R_{DC}(\mu) + R_{DC}(\text{other})} < \frac{R_{osc}(\mu)}{R_{DC}(\mu)} \sim 2\%$$

$$R_{DC}(\text{other}) \sim 0$$

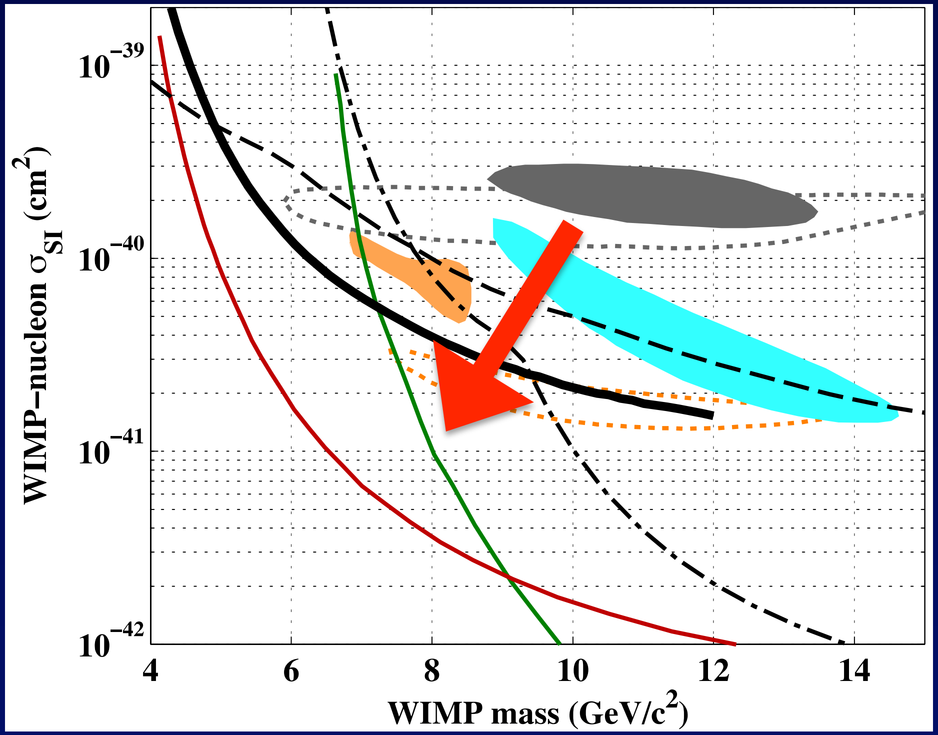
Muon? DAMA oscillation too large…

DAMA: Reconciling discrepancies

Blum: arXiv:1110.0857

- **Astrophysics:**
  - Non-Maxwellian velocity distributions (Chaudhury et al, arXiv:1006.5588)
  - WIMP streams (Gondolo et al, arXiv:0504010 & Kelso et al, arXiv:1110.5338)

  ➔ By itself, still incompatible with CDMS and Xenon results (Fox et al, arXiv:1107.0717)

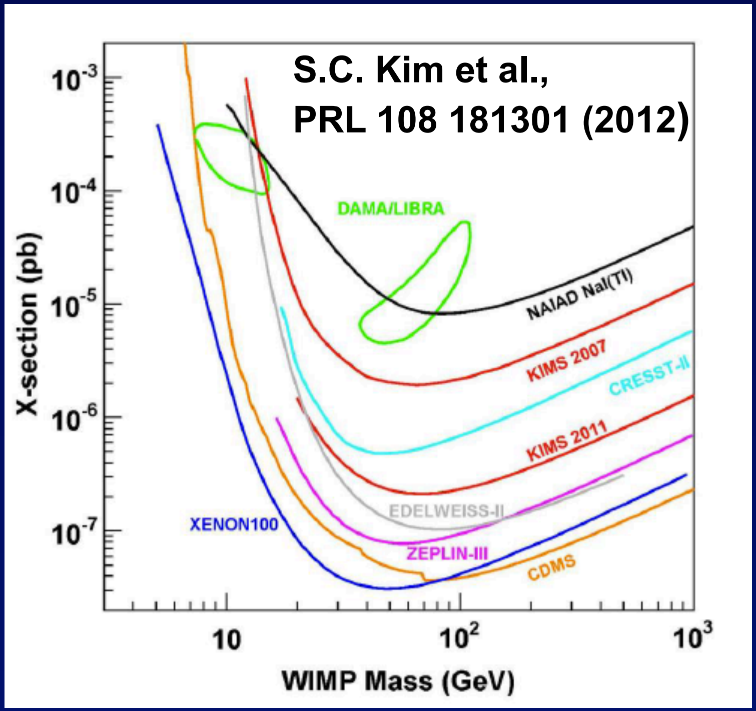


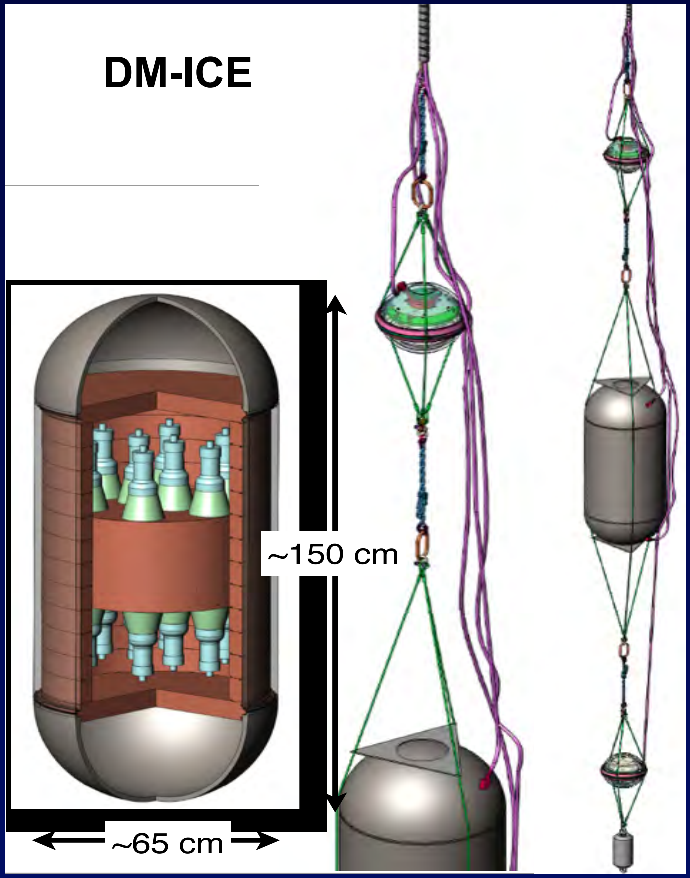
- **Other possible explanations:**
  - Material-dependent scattering cross sections
    - Isospin-violating DM
    - Inelastic scattering
  - Experimental Problems:
    - Threshold, energy calibration

DAMA: Reconciling discrepancies

Need to reproduce DAMA results:

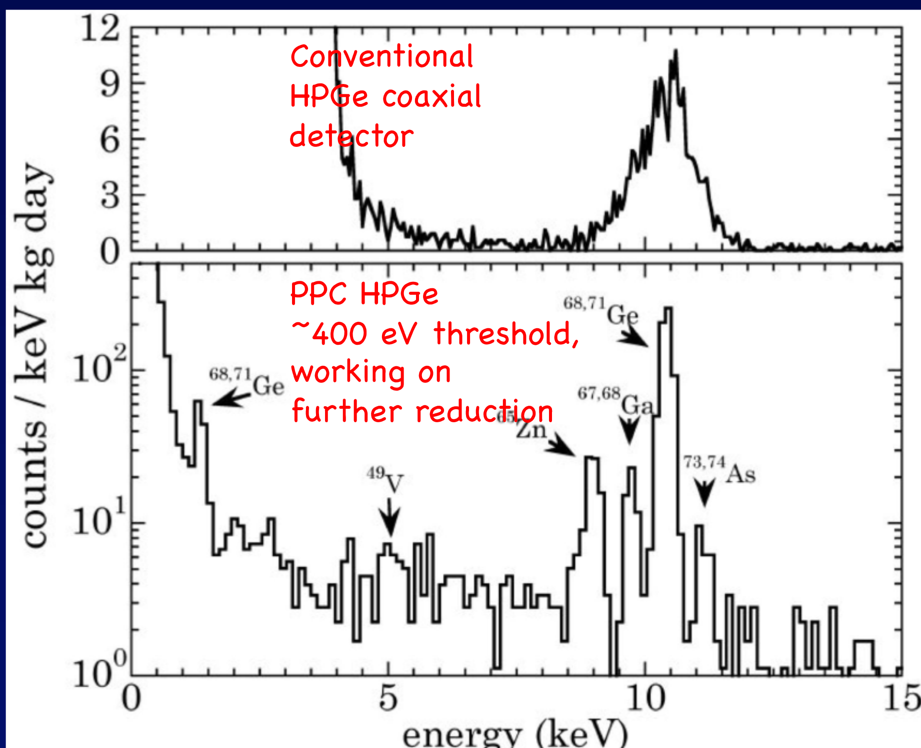
- **DM-ICE: NaI at South Pole**
  - Under development, data available with prototype
- **KIMS - Korea Invisible Mass Search (Yangyang), CsI scintillators**

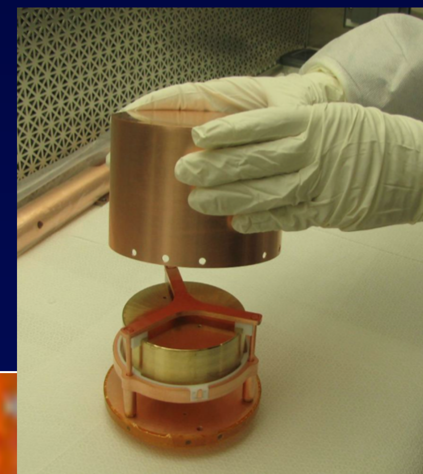


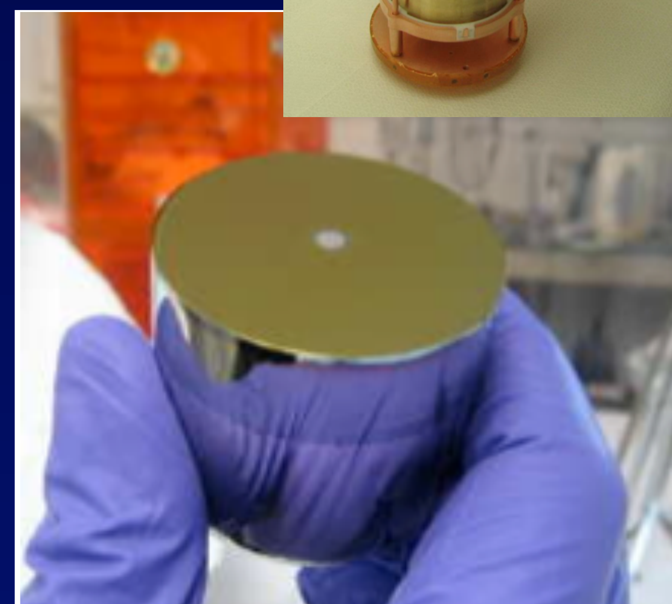


CoGENT

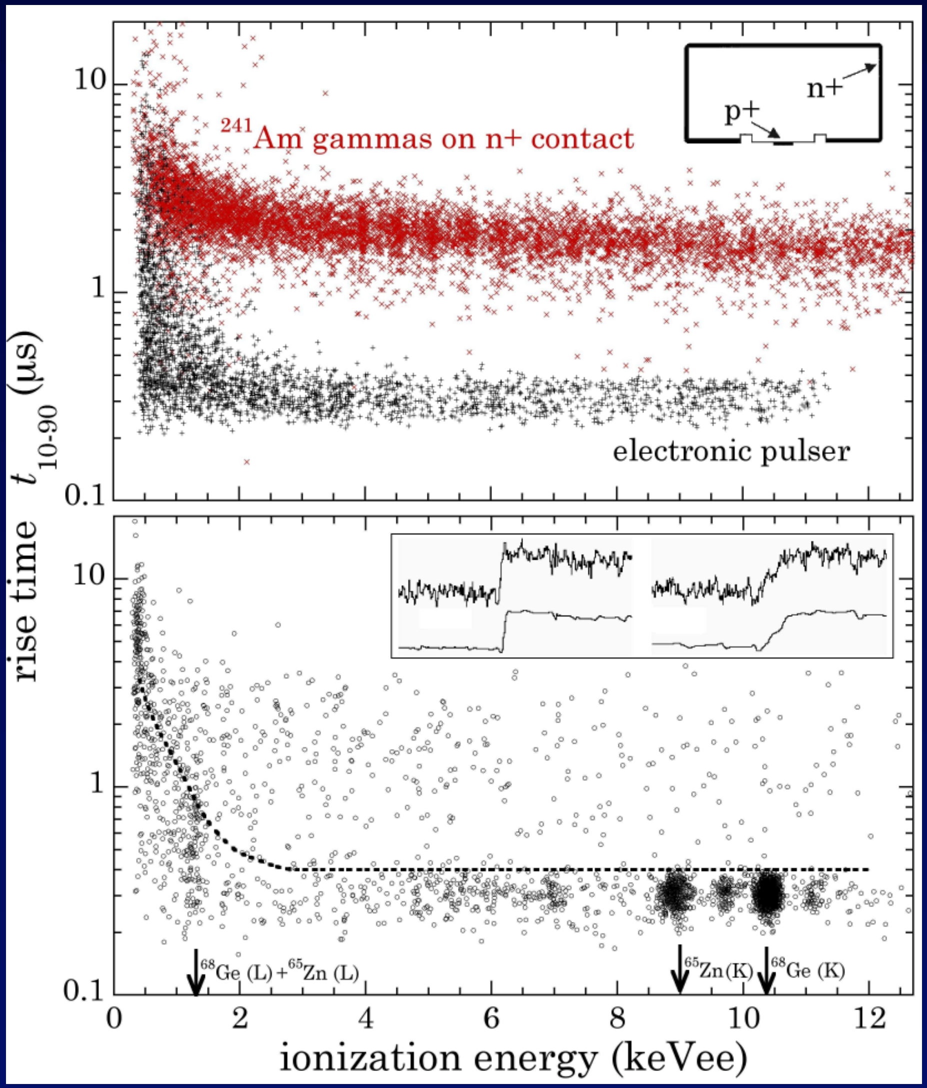
- **440g p-type Point Contact Ge Detector**
  (ionization only)
- **$E_{threshold}$ ~ 0.4 keVee**
- **Next step: PNNL/UC/Canberra C-4 expansion (x10 mass, lower bckg and threshold)**







CoGENT Timing information

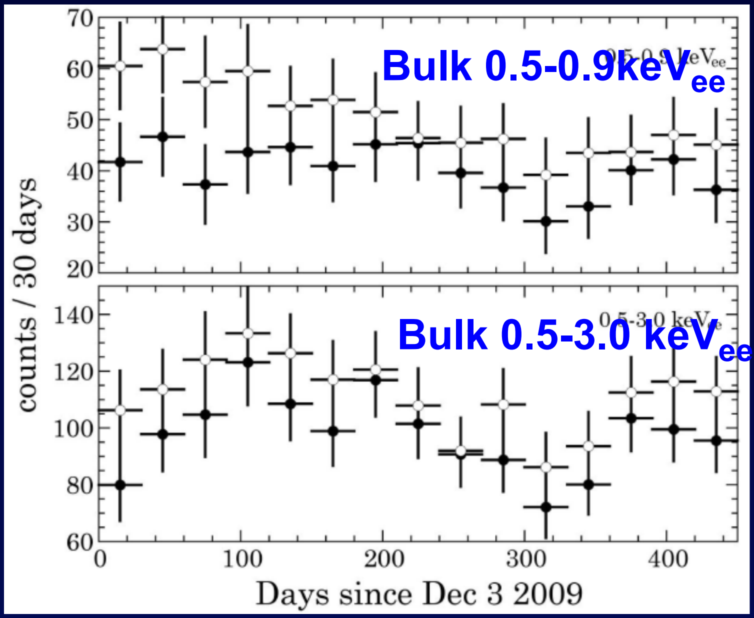


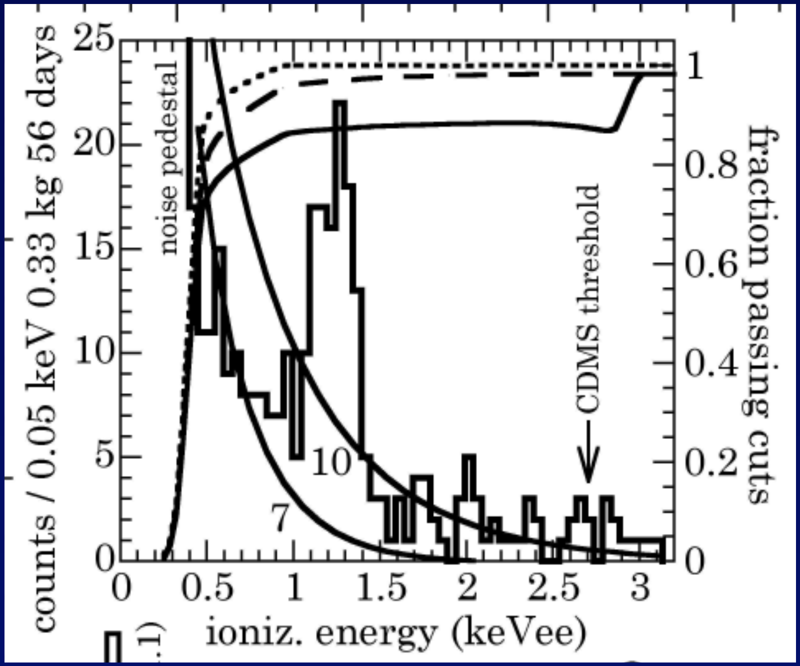
- slow carrier transport near n^+ electrode means slow risetimes
- 1002.4703: Surface Event Leakage ~0 for E>1keV$_{ee}$
- Potential Problems:
  - Quasi Collimated Source position dependence
  - Between band events in background data?

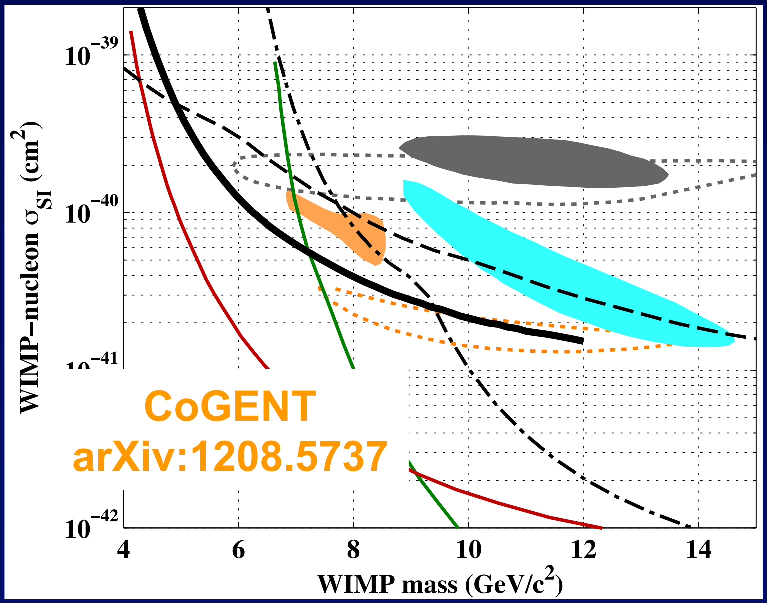
CoGENT Results

- Unexplained Excess below 3keV$_{ee}$
Enormous Modulation

- Enormous Modulation
  - DAMA: 2% vs CoGENT: >20%
  - 2.8σ statistical significance

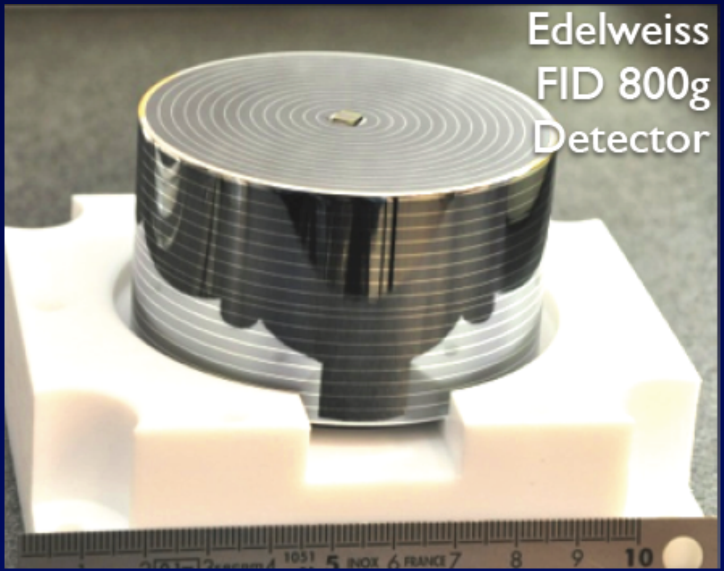






(Very) Low Temperature Detectors

- Array of small dielectric crystal (Al_2O_3, Ge, Si, $CaWO_4$, etc) cooled to <50 mK



- Measure phonon +
  ionization (CDMS, Edelweiss)
  or light (CRESST)

Advantages:

- after an interaction (event), all excitations transform to heat ➔Good resolution
- Phonon excitation ~10-6 eV compare to few eV for conventional semiconductor detectorr ➔Low threshold

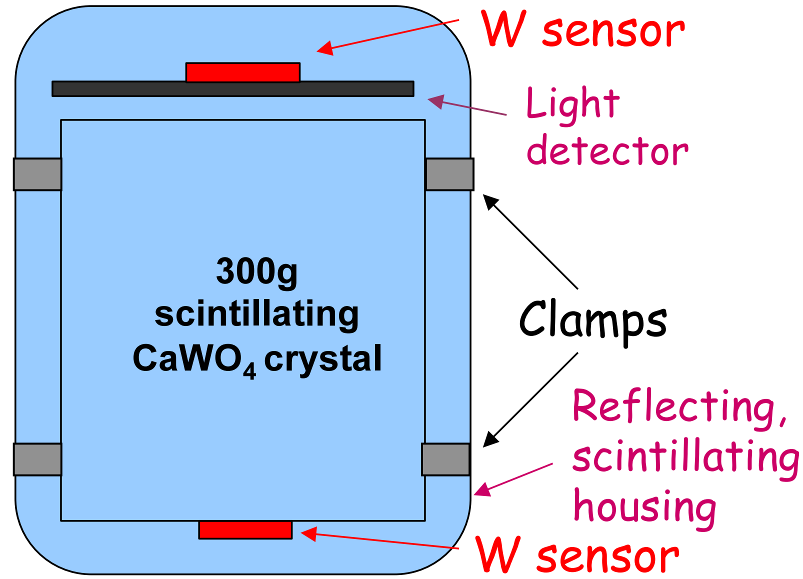
CRESST

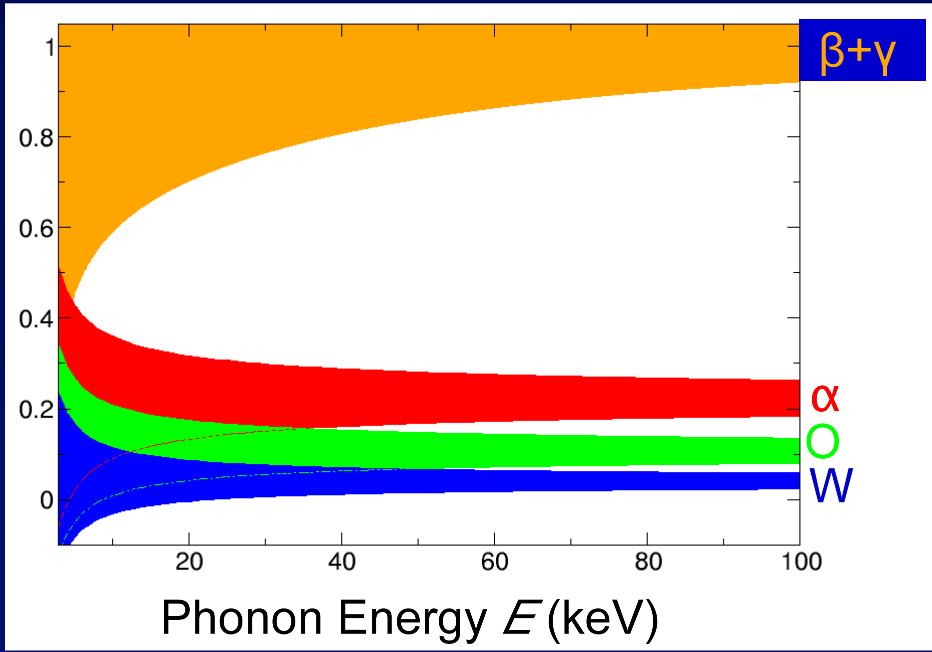
- CaWO$_4$ Crystals, measure phonon and Scintillation
- 8 detectors, 730kg-d
- Multiple Nuclei: Multiple Q

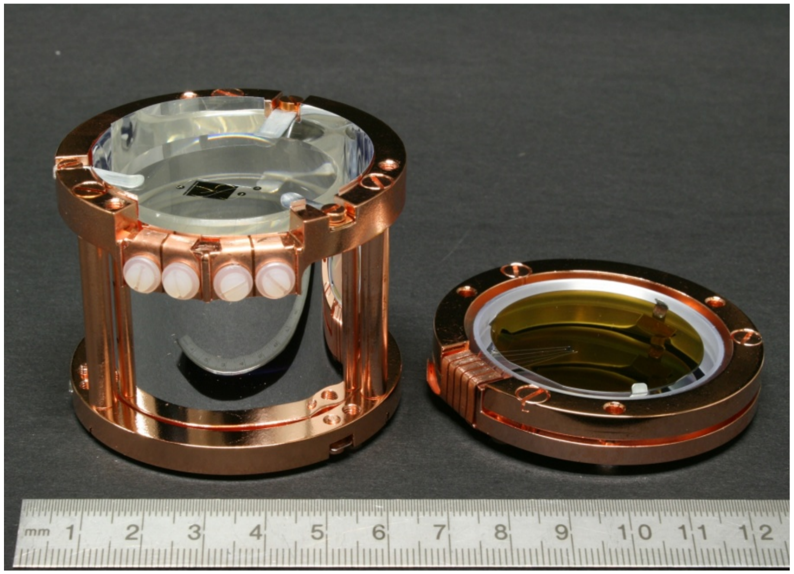
  Q_O~0.1

  Q_{Ca}~0.06

  Q_W~0.04

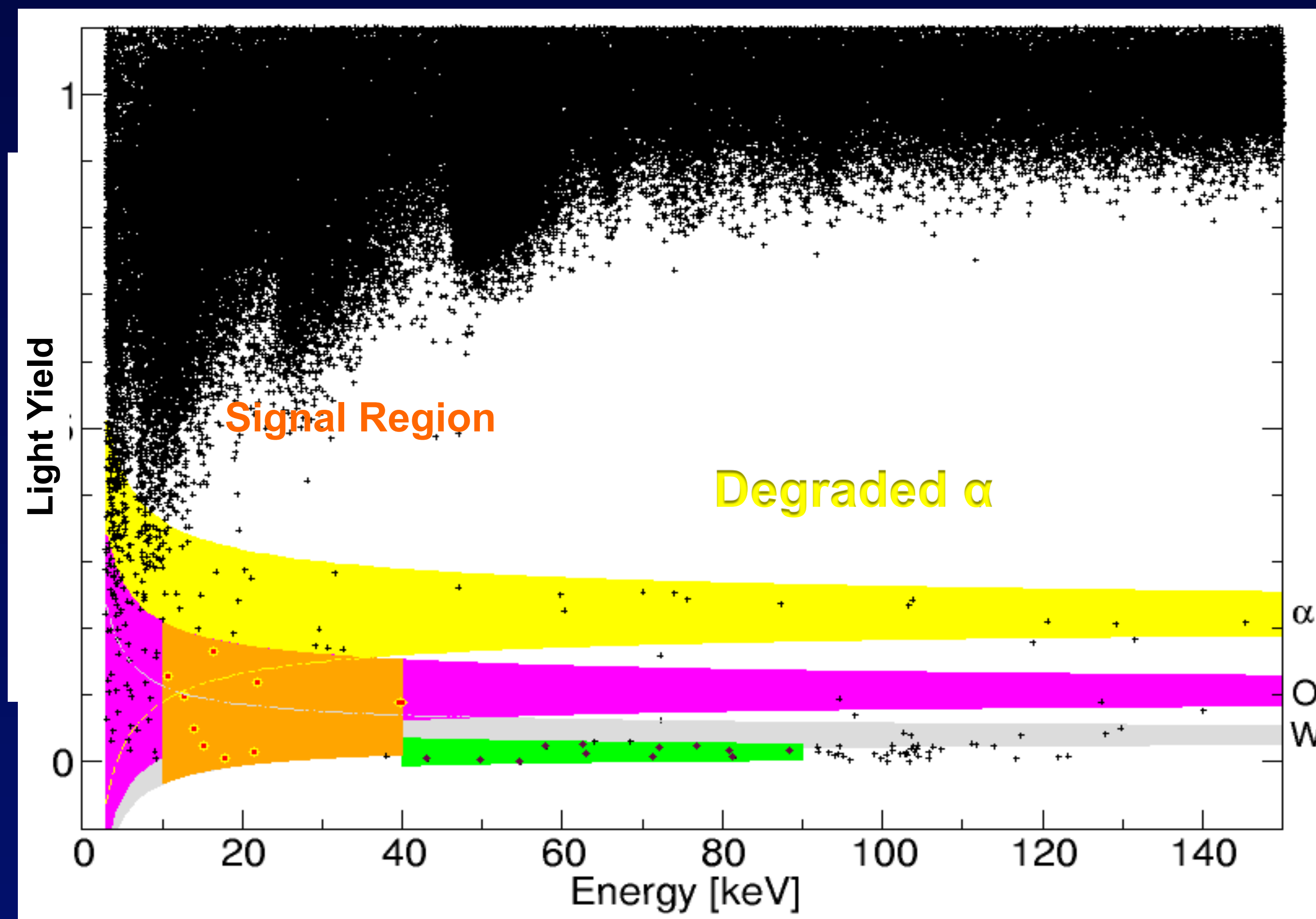






CRESST Results

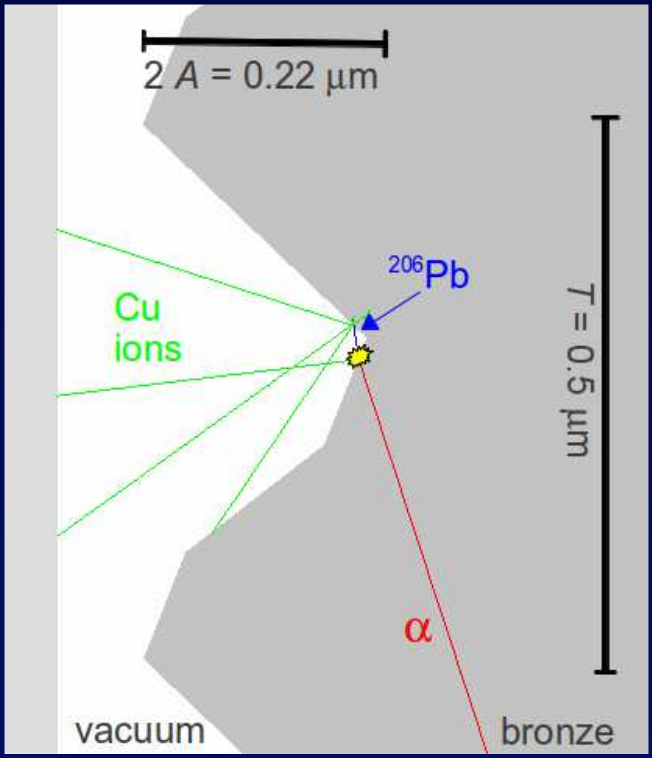
- 67 events at low energy observed “in the O, Ca, and W box”
- E_{max} = 40 keV, E_{min} = 10-19 keV depending module



Eur. Phys. J. C (2012) 72:1971

CRESST Results

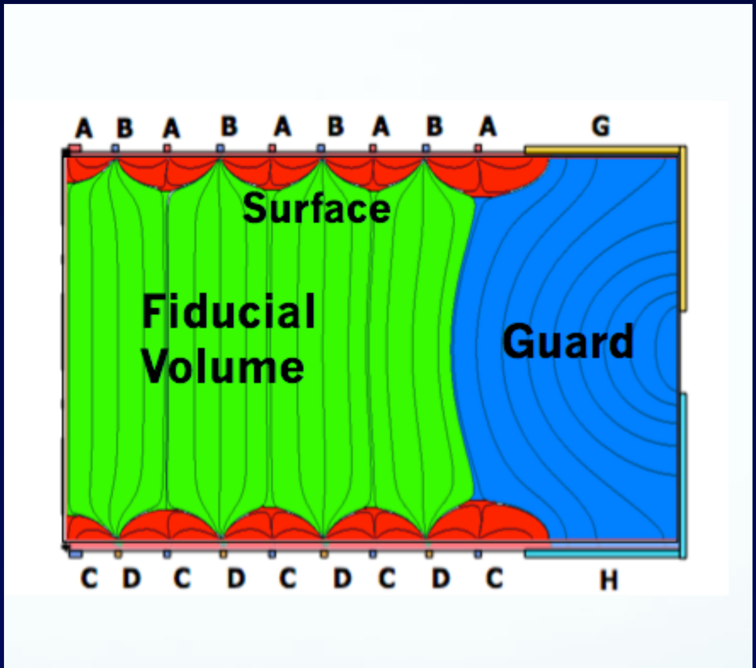
- CRESST: Assumed flat surfaces in monte carlo
- M. Kuzniak et al (1203.1576): Spectral shape varies significantly with surface roughness
- Maximal likelihood analysis overconstrained

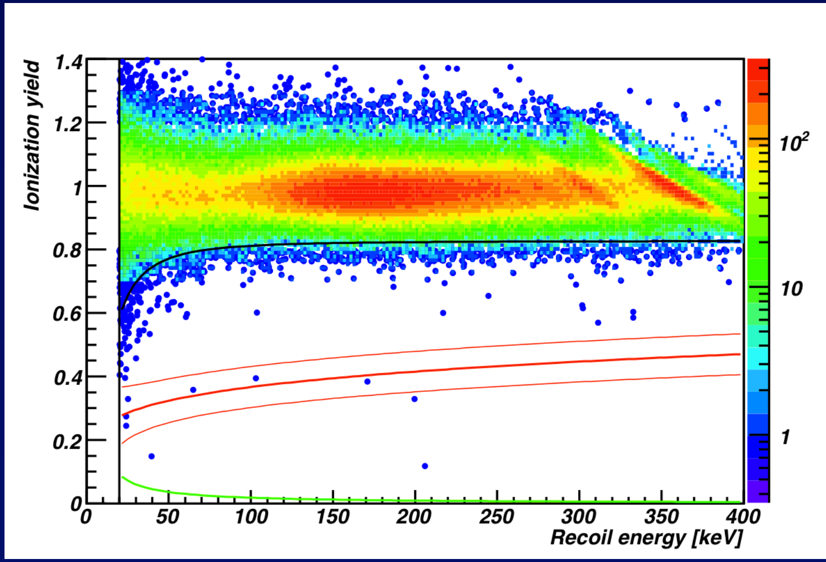


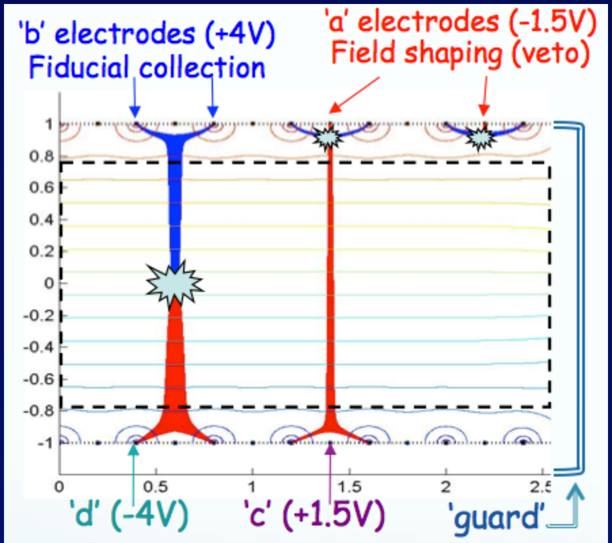
- Next steps:
  - Decrease Clam Radioactivity
  - additional internal neutron shielding
  - increase of target mass
  - Next run schedule end of year

Edelweiss

- Ge Crystals, measure charge and total phonon signal
- Interdigitated design provides excellent Surface rejection
- Fiducial volume 53% for 400g design





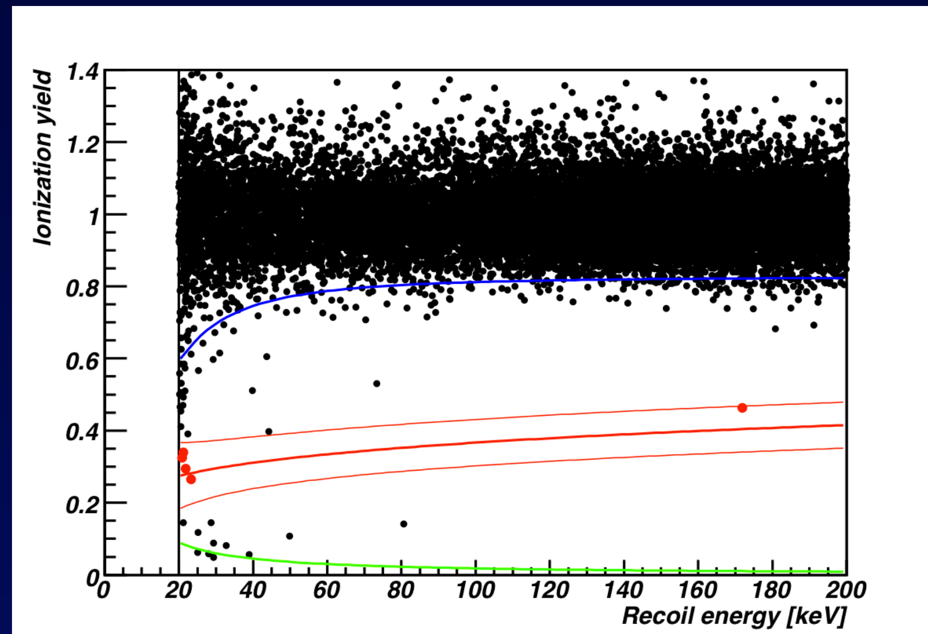


Edelweiss II Results

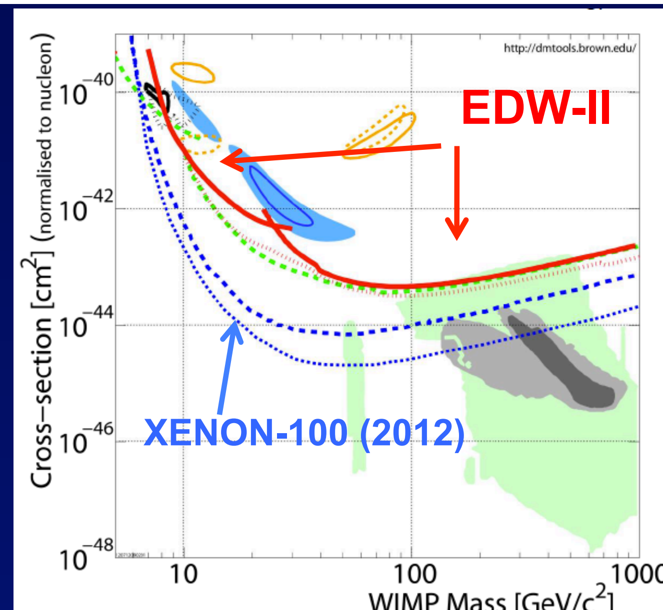
- Data from 2008 – 2010 using 10 x 400g detectors

- 384 kg days in the energy range of [20,200] keV

  - 5 events observed in NR
  - 3 evts bg expected

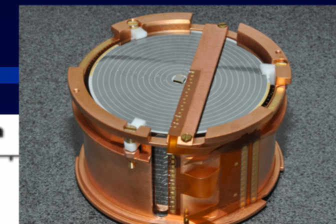


- Low-E investigation [5-20 keV] using 113 kg-day exposure (3 evts obs, <3 bgd)



- Phys. Lett. B 702 (2011) 335–329.
- arXiv:1207.1815v1 (Low E)

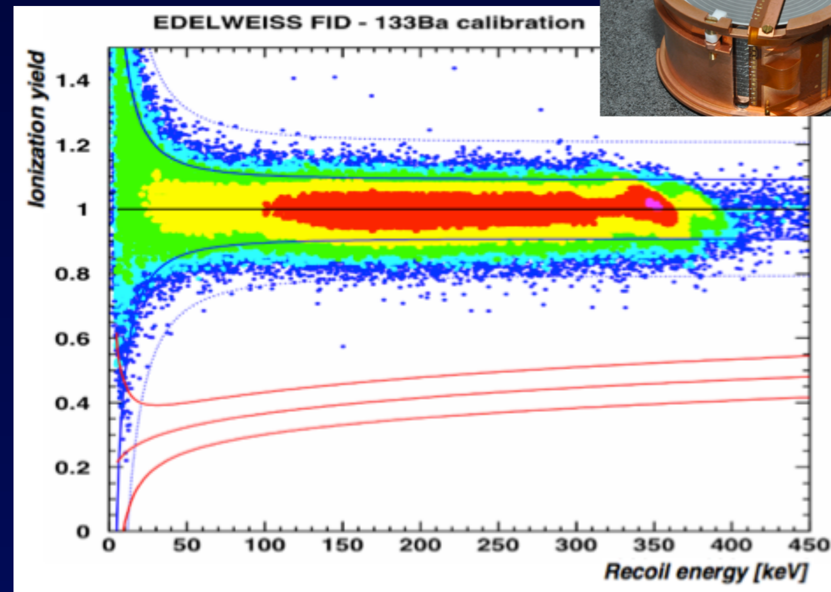
Edelweiss Next Steps

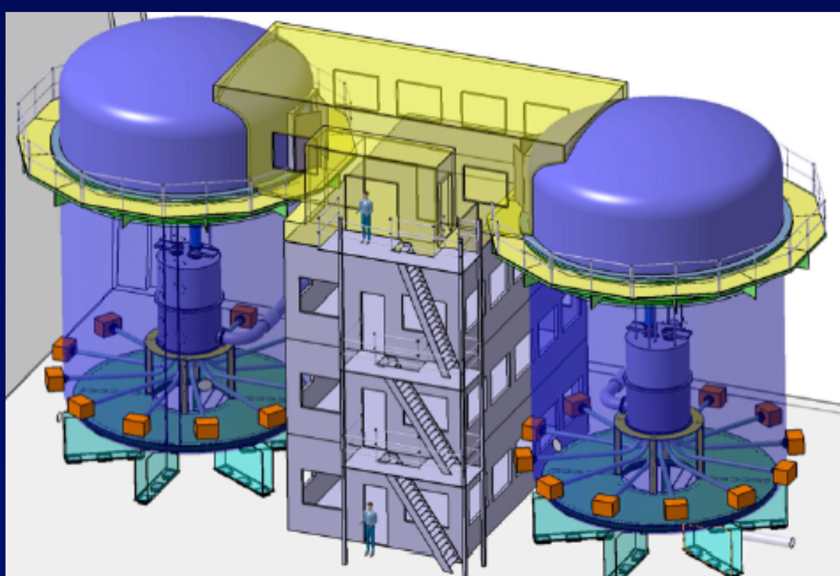


- **Edelweiss III:**

40 x 800g bolometers installed in 2012 : 24 kg fiducial

⇒ 3000 kg.d ($5x10^{-45}$ cm^2)





- **Eureka:** (Edelweiss, CRESST)

  - Multi-target (Ge, CaWO4)
  - Phase 1 (2015): 150 kg
  - Full Scale: 500 - 1000 kg

⇒ 10^{-10} pb (10^{-46} cm^2) sensitivity

CDMS / SuperCDMS

- Ge/Si Crystals. Measure charge and athermal phonons
- CDMSII
  - 7.6cm x 1cm detectors, 4 phonon + 2 charge channels
  - use timing information of the athermal phonons for surface events discrimination
  - data taken with 5 Towers (30 det.) between Oct. 2006 to Sept. 2008

WIMP search 10-100 keV recoil Analysis:

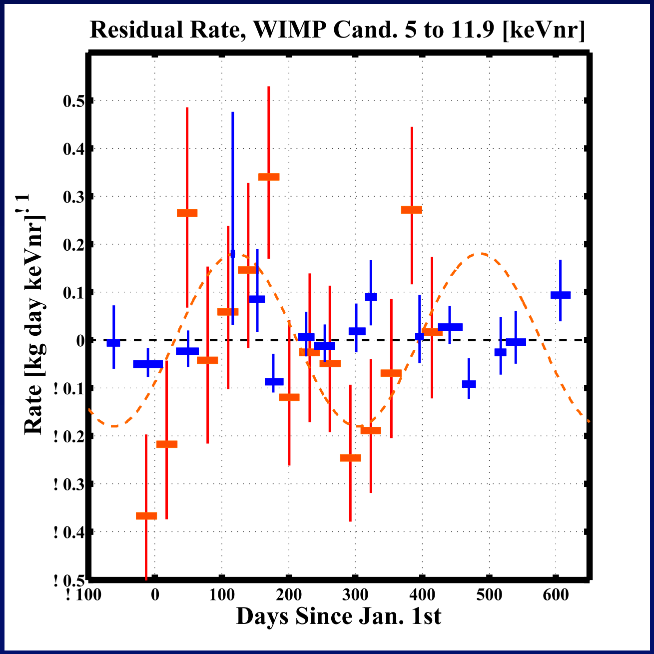
Ahmed et al., Science 327:1619-1621,2010

Low Threshold Analysis:

Ahmed et al., PRL 106, 131302 (2011)

Modulation Analysis:

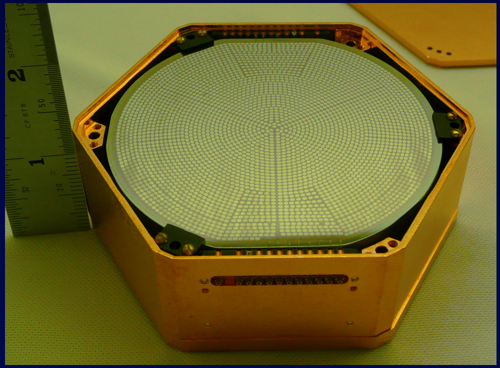
No significant evidence for annual modulation
in NR singles (WIMPs) In the energy range [5, 11.9] keV

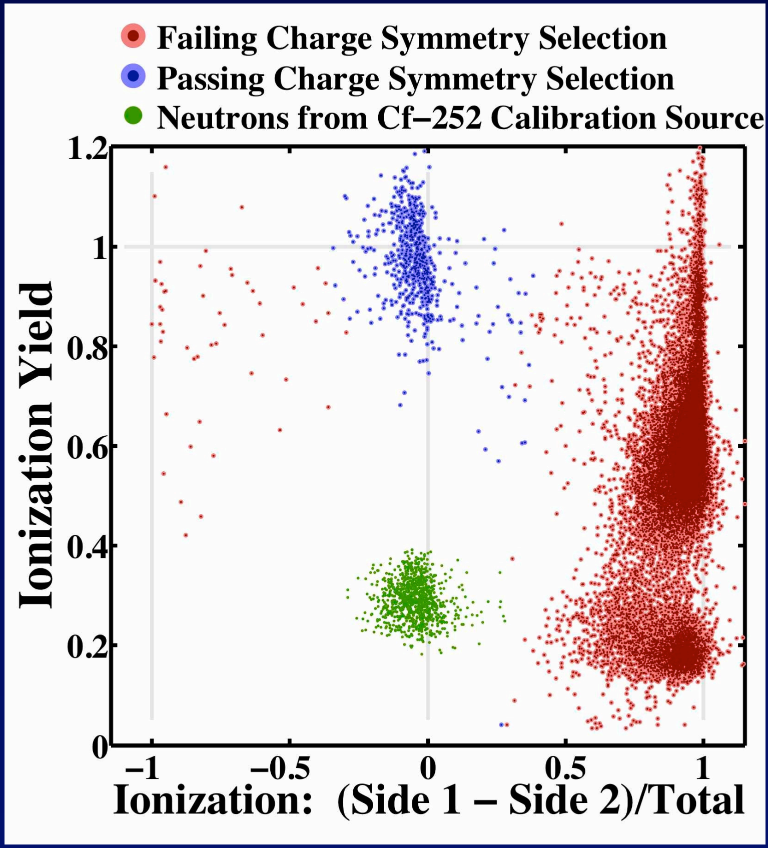


CDMS / SuperCDMS

➢ SuperCDMS Soudan (2011-2013)

- 7.6cm x 2.5 cm detectors
- 12 phonon + 4 charge channels, interleaved
- use charge and phonon partition for surface events discrimination

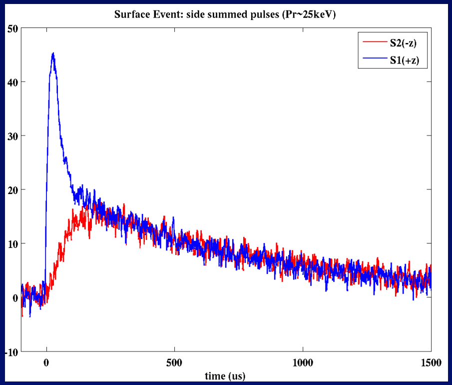


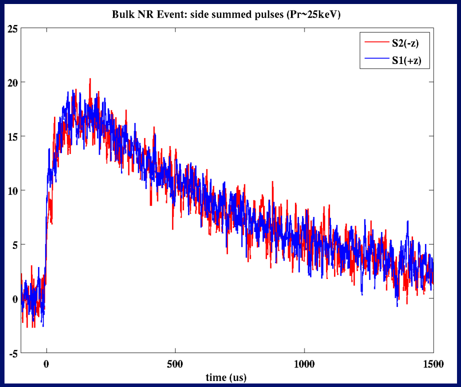


➢ 15 detectors (total mass ~9kg) in operation

➢ Surface electron rejection exceed what's needed for Soudan, 1 event at 930 kg-years raw.

➢ Expect between 5 and 8e-^{45} cm^2 sensitivity with 10 keV threshold





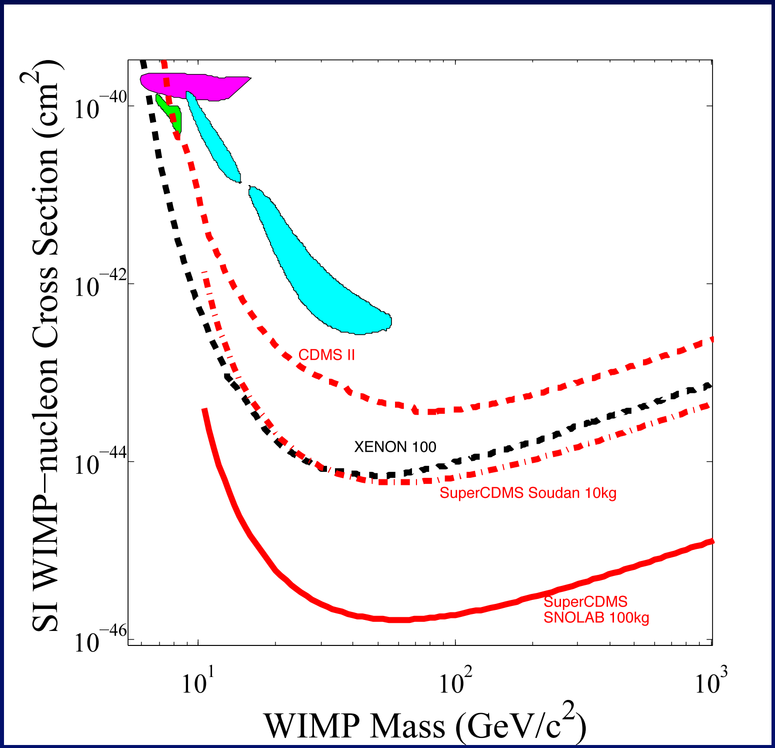
SuperCDMS SNOLAB

150 kg-scale Ge target, expected reach 0.2 zepto-barnes (2 x 10^{-46} cm^2)

- Use iZIP SuperCDMS Soudan design, with bigger detectors (1.38 kg) to reduce fabrication costs

- Surface events rejection demonstrated with iZIP Soudan

- Aiming for construction start in 2014



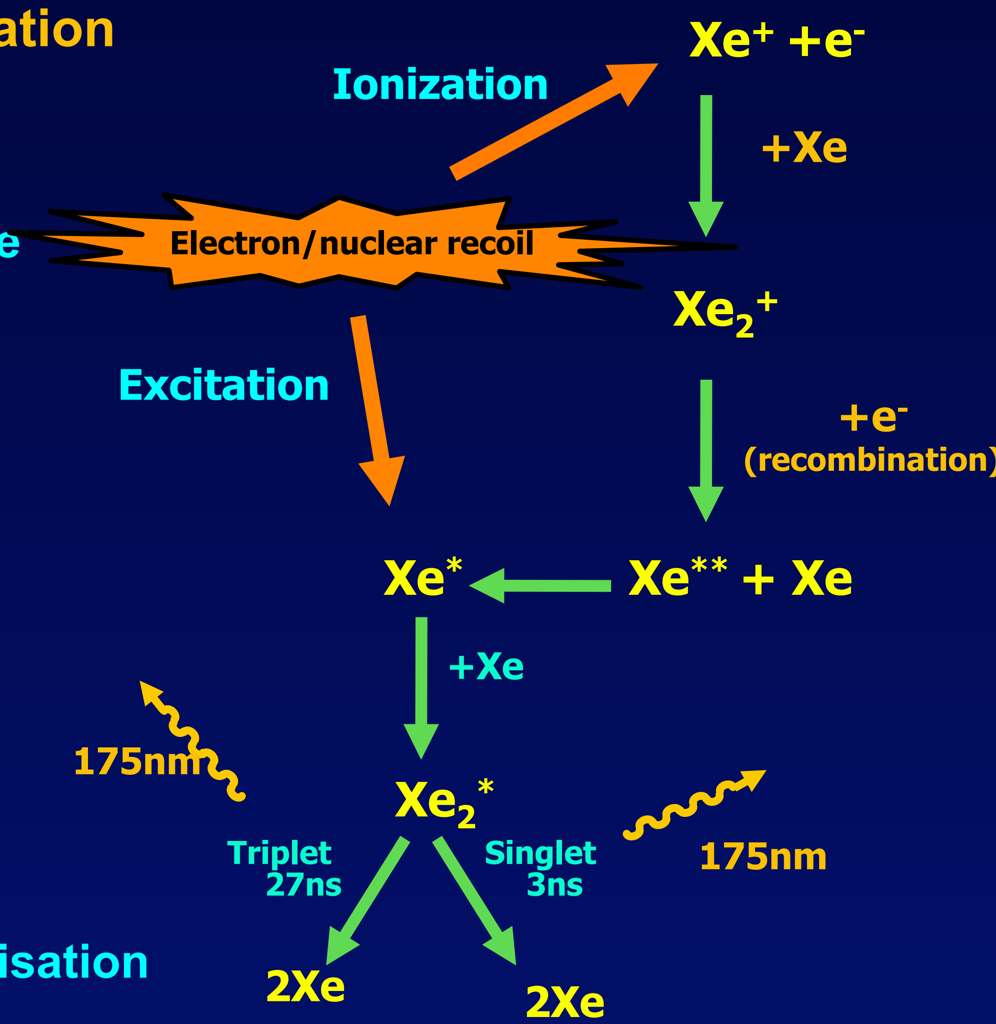
(Liquid) Noble Gas Detectors (Xe, Ar, Ne)

Nuclear/electron recoil discrimination methods:

- singlet/triplet ratio 10:1 nuclear recoil:electron recoil (pulse shape discrimination)

  Time constants (singlet/triplet):
  Xe: 3ns/27ns, Ar 10/1500ns

- Ionization and direct excitation ratio



Implementation:

- Single phase: measure scintillation only
- Double phase: measure also ionisation through electroluminescense

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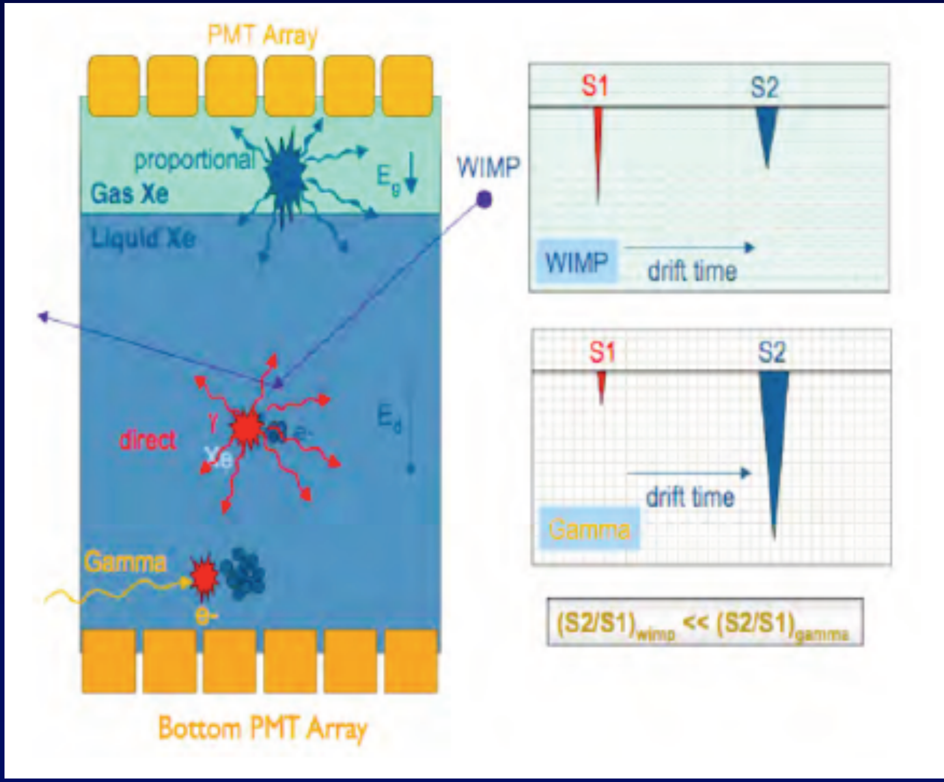

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GAS	Single Phase	Double Phase
Xenon	ZEPLIN I, XMASS	ZEPLIN, XENON LUX
Argon	DEAP, CLEAN	WARP/ DarkSide, ArDM
Neon	CLEAN	SIGN

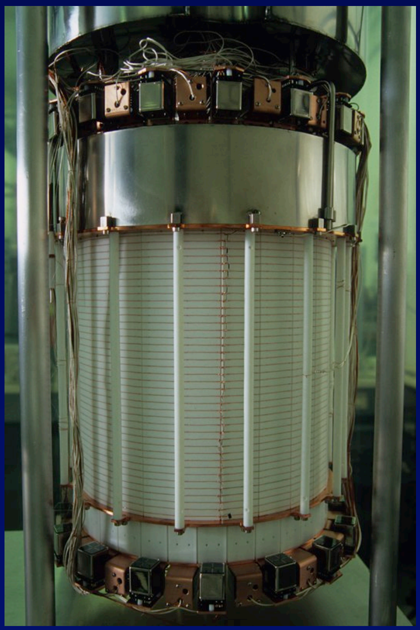
Liquid Xenon: XENON10/100/1T

XENON10

- 2005-2007
- Total Xe: 22 kg
- Fiducial: 5.4 kg
  - PRL 100, 101, 107
  - PRD 80
  - NIM A 601

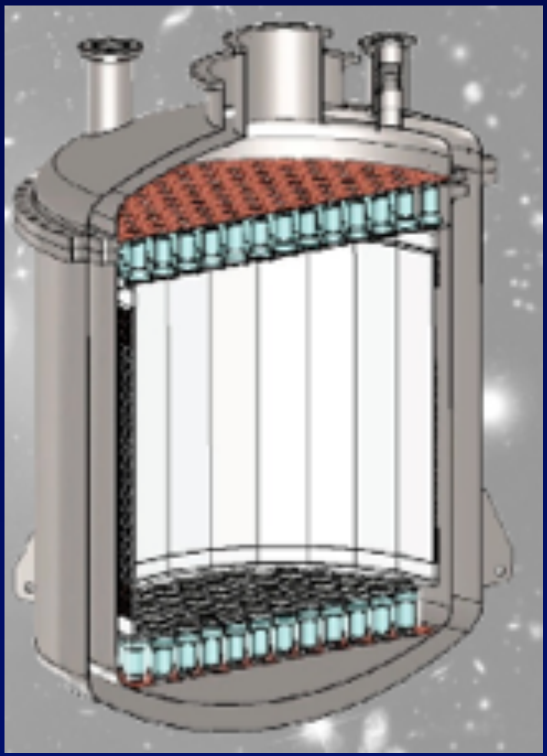
XENON100

- 2008-2013
- Total Xe: 170 kg
- Fiducial: 65 kg
  - PRL 105, 107
  - PRD 84
  - More to come..



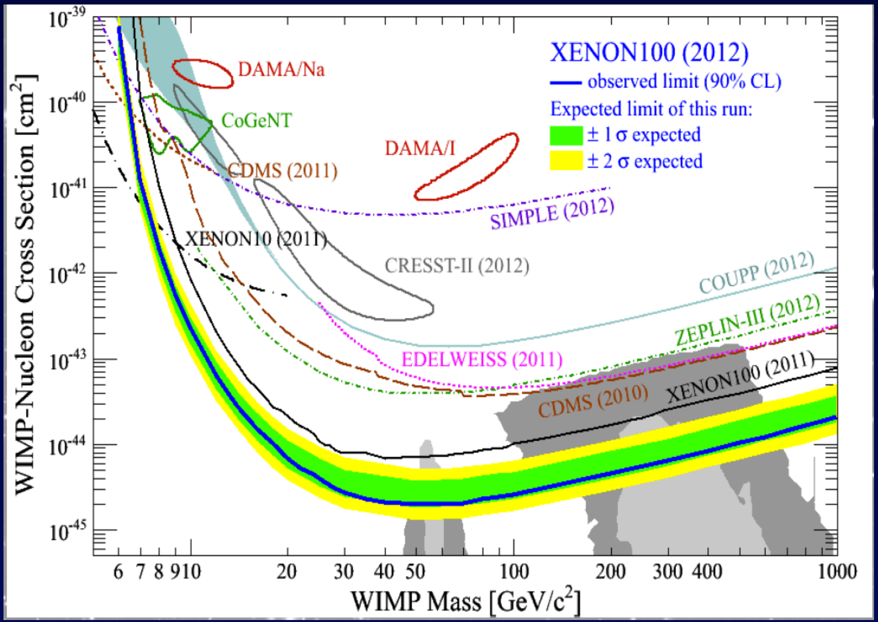
XENON1T

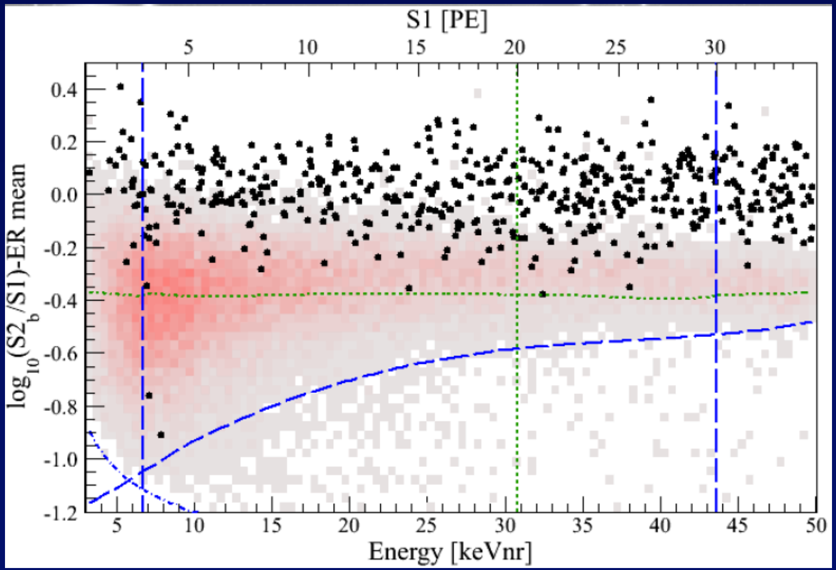
- Construction start fall 2012
- Total Xe: 2.2 T
- Fiducial: ~1.1T
- Projection 2×10^{-47} cm^2

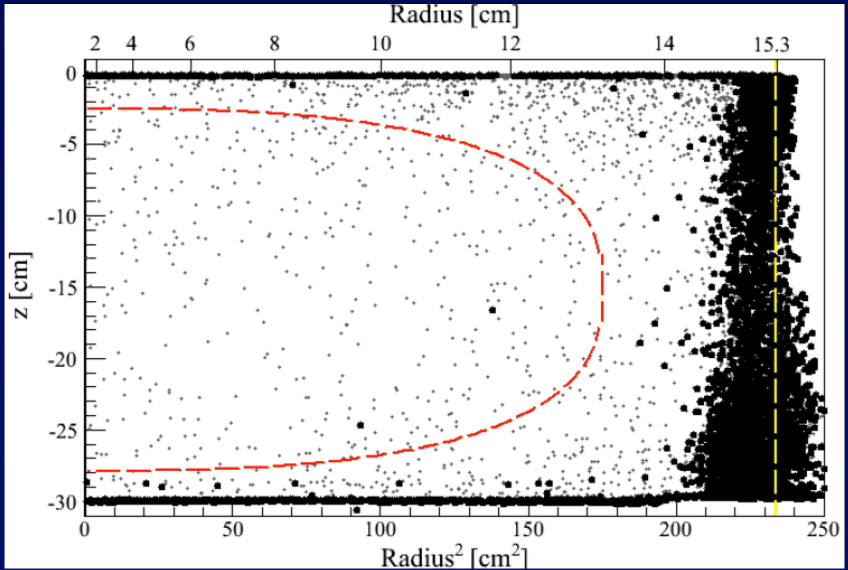


Liquid Xenon: XENON100 latest result

- Data taken between February 2011 and March 2012 (reduced background)
- 2 events observed with a background expectation of 1 ± 0.2
- $\sigma_{SI} = 2.0\times10^{-45}\text{cm}^2$ for a 50 GeV WIMP (90% CL)



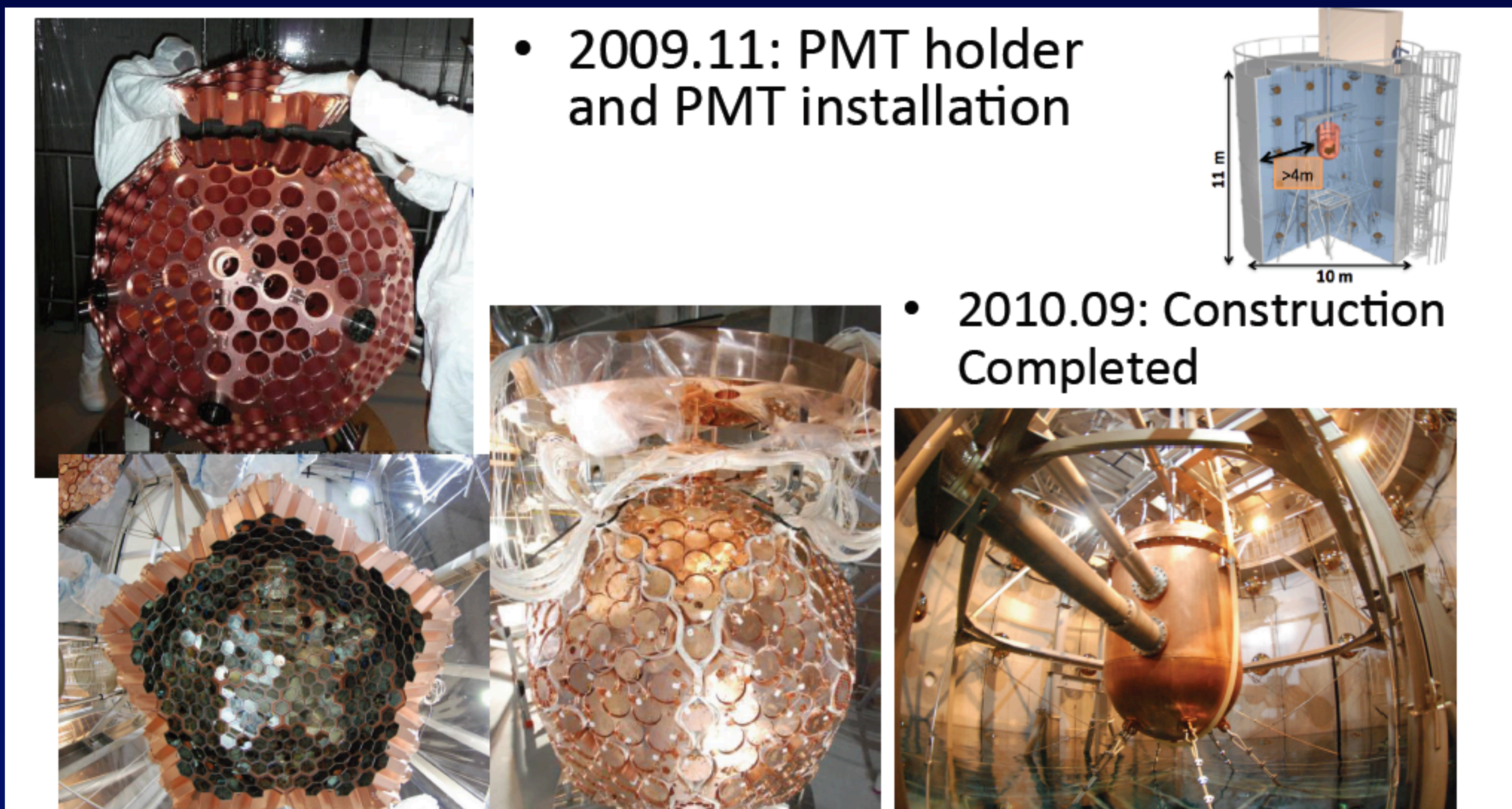




Plots from A. J. Melgarejo Fernandez, IDM 2012

Liquid Xenon: XMASS

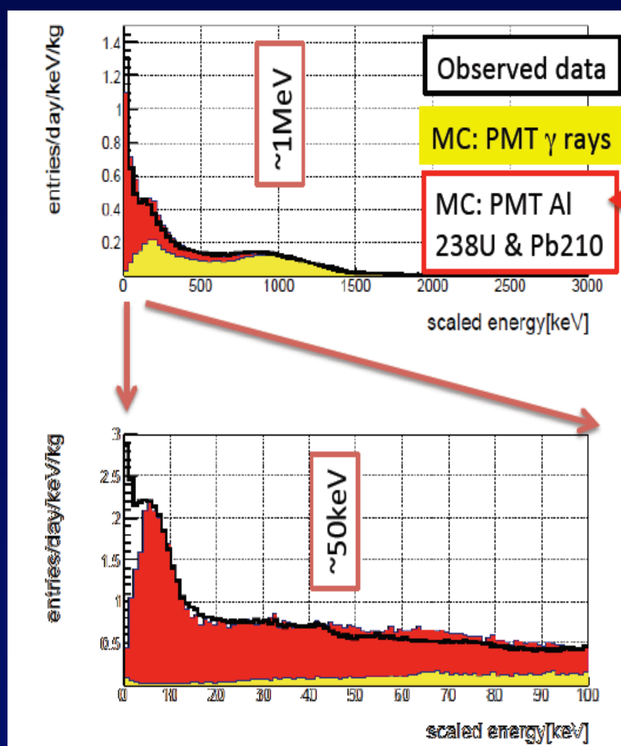
- Single phase detector (scintillation readout), self-shielding only
- 800 Kg total, 100 Kg fiducial
- Search down to σ_{SI} ~ a few x 10^{-45} cm^2

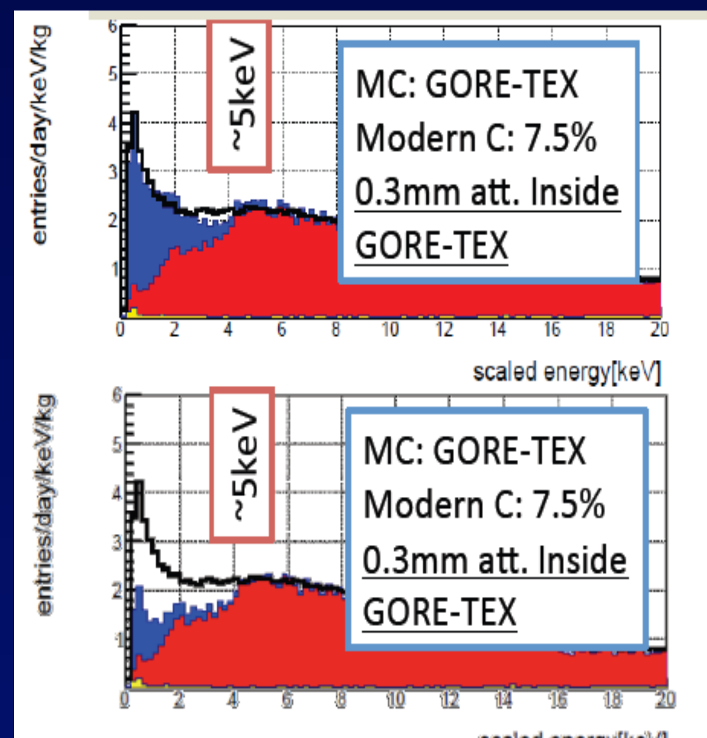


Slide from Y. Suzuki, IDM 2012

Liquid Xenon: XMASS

- **XMASS completed first commissioning phase:**
  - **Light yield: 14.7 PE/keVee (x4 XENON100) -> possible light-WIMP search**
  - **Backgrounds (will be reduced in the near future):**
    - **Above 5 keV: γ from PMTs, ^{210}Pb PMT Al seal and Cu surface**
    - **Below 5keV: not quite understood (^{14}C contaminated in GORE-TEX?)**

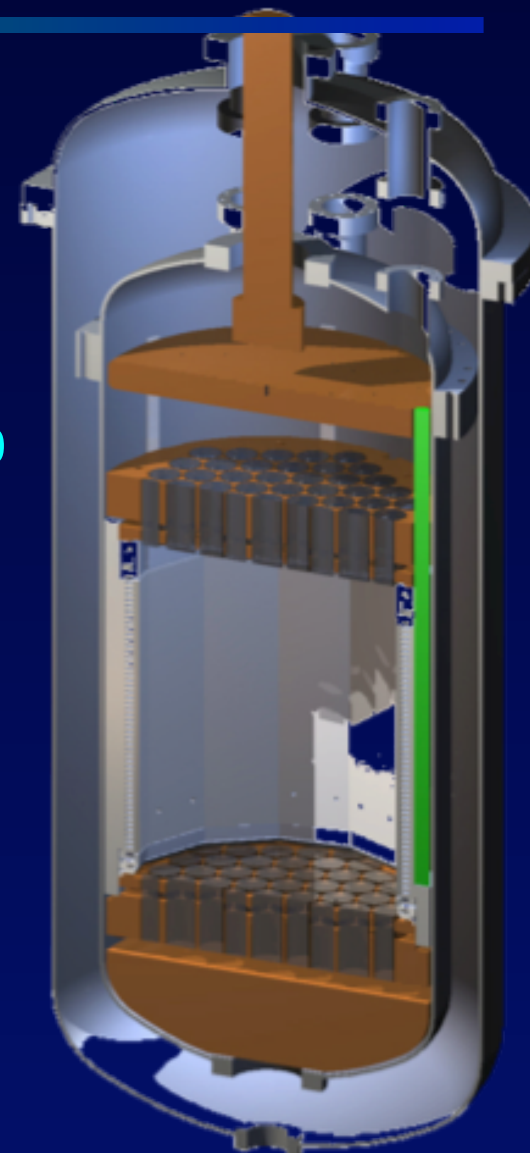




Plots from Y. Suzuki, IDM 2012

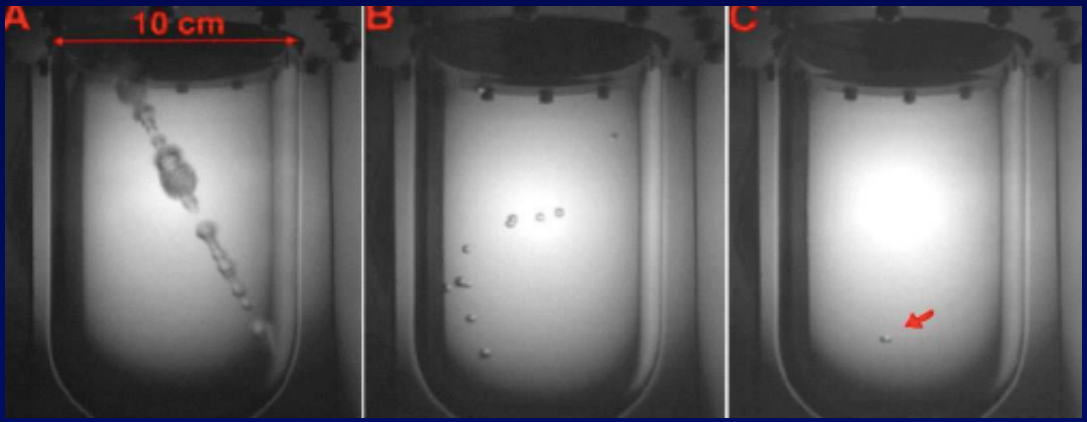
Liquid Xenon: LUX

- Dual-phase xenon TPC, 350 kg (100 kg fiducial)
- Located at the Sanford Underground Research Facility in Lead, SD (4850 feet)
- Science run starts this year
- Projected sensitivity of a few $\times 10^{-46}$ cm^2 after 300 days



Metastable Bubble Chamber Detectors

- Superheated fluid (bulk or droplets)
- Energy density effect: min. ionizing and low energy ER deposition density too small to nucleate bubbles (intrinsic rejection, no data cuts needed)
- Threshold, controlled by temperature, pressure
- Readout:
  - acoustic (ultrasound)
  - motion sensing(video)



COUPP

- inexpensive, easily scalable
- Assorted nuclei: spin dep. (F) or indep. (I and Br)

COUPP

- Bubble chamber, filled with CF_3I target
- Instrumented with transducers for: temperature, pressure, acoustic transients, as well as machine vision cameras

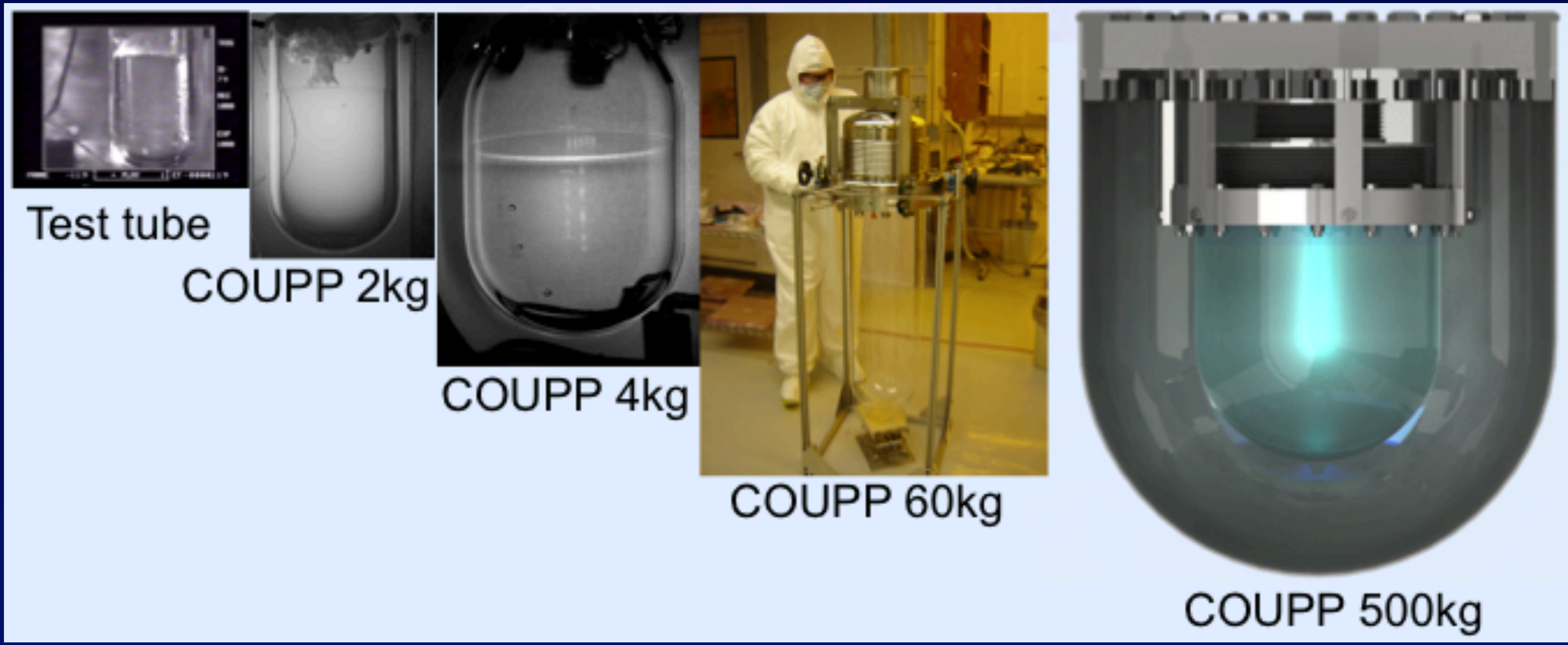
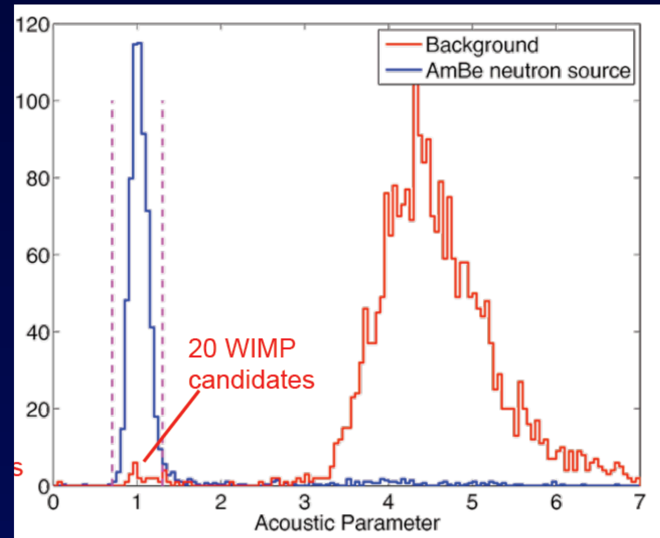


Figure from M. Crisler, IDM 2012

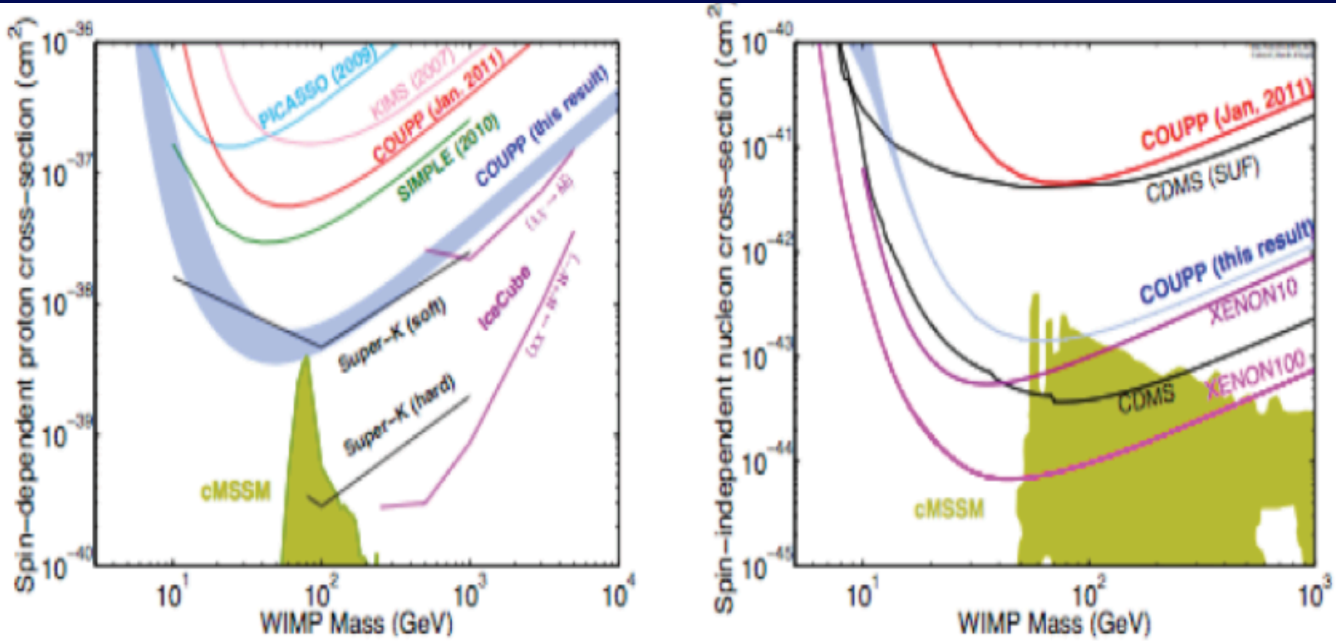
COUPP 4Kg Results

- Bubble chamber, filled with CF_3I target
- 20 WIMP candidates
- “Almost certainly not WIMPs”, background under investigation



COUPP

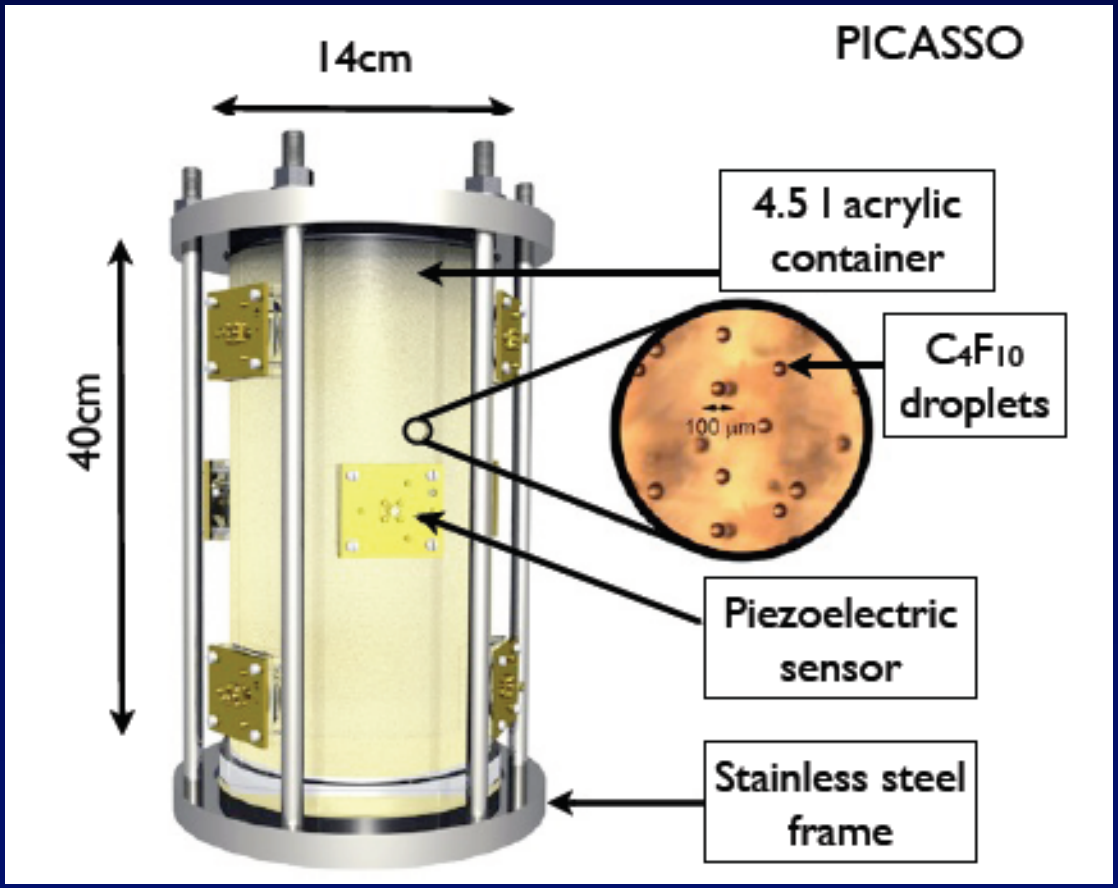
astro-ph/1202.3094



IDM 2012

PICASSO

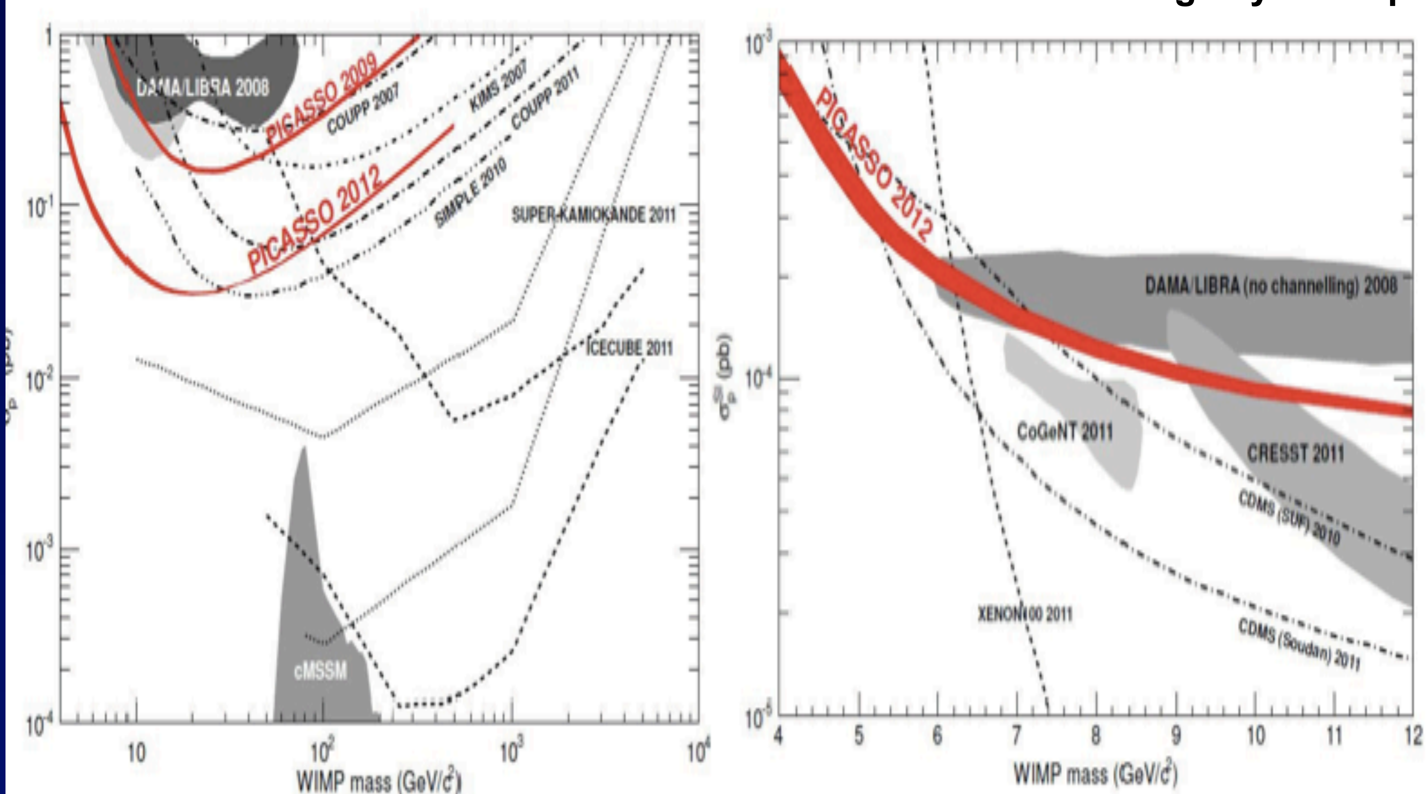
- Super-heated freon (C_4F_{10}) droplets suspended in gel
- Exploding bubbles are detected acoustically (piezoelectric device)
- Triangulation between multiple sensors allows for position reconstruction



PICASSO

- Super-heated freon (C_4F_{10}) droplets suspended in gel
- Exploding bubbles are detected acoustically (piezoelectric device)
- Triangulation between multiple sensors allows for position reconstruction

Data set of 115kg days of exposure



PICASSO

hep-ex/1202.1240

CONCLUSIONS

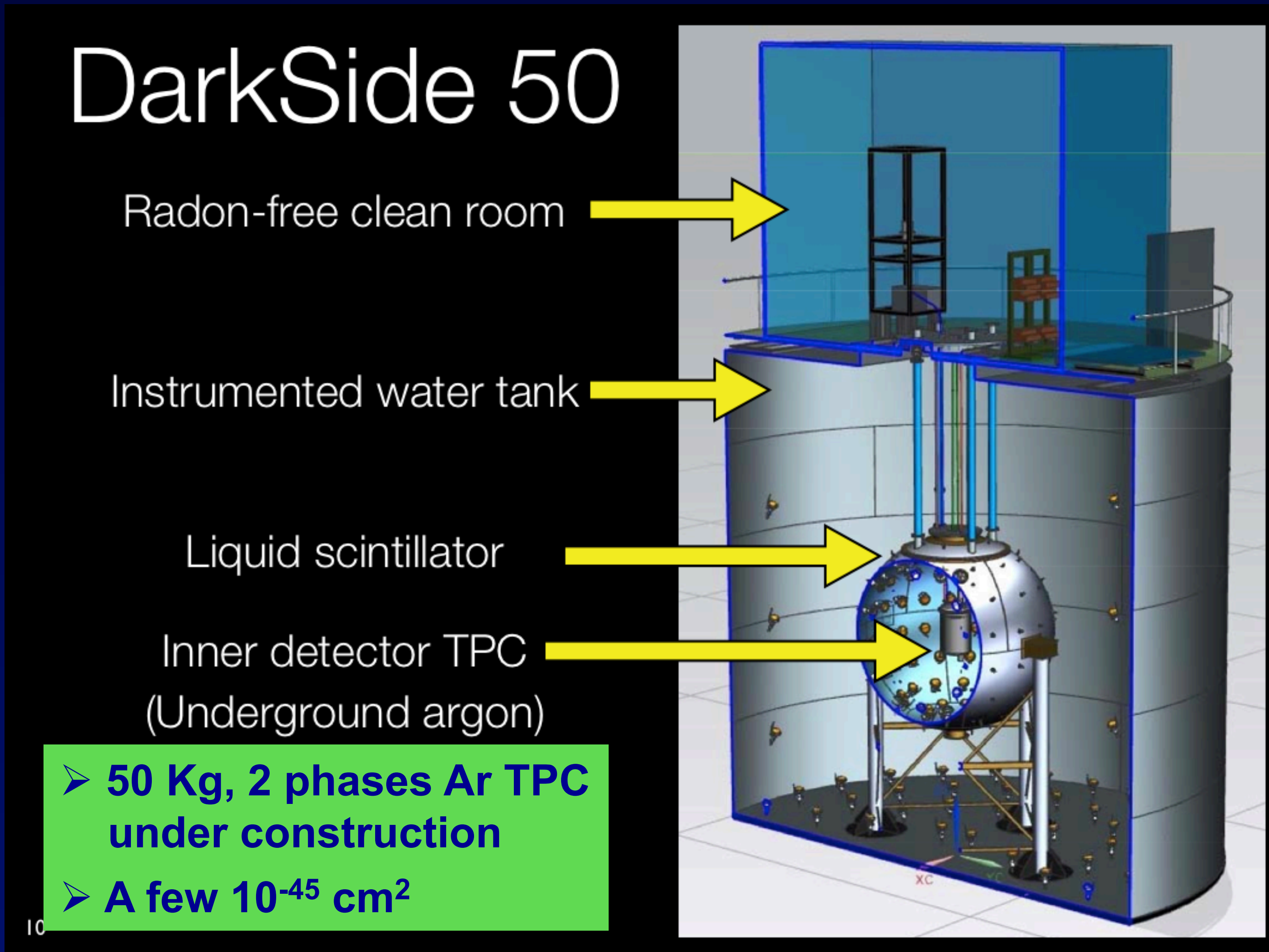
- **Light WIMPs:**
  - No conclusion, lots of confusion
  - More data needed !

- **High Mass WIMPs:**
  - XENON100 reached $2x10^{-45}$ cm^2
  - Will be soon joined by other experiments

➔ **Stay tuned, more data coming!**

Extra Slides

Liquid Argon: DarkSide



- **50 Kg, 2 phases Ar TPC under construction**
- **A few 10^{-45} cm^2**

Slide from R. Saldanha, IDM 2012

Liquid Argon: ArDM

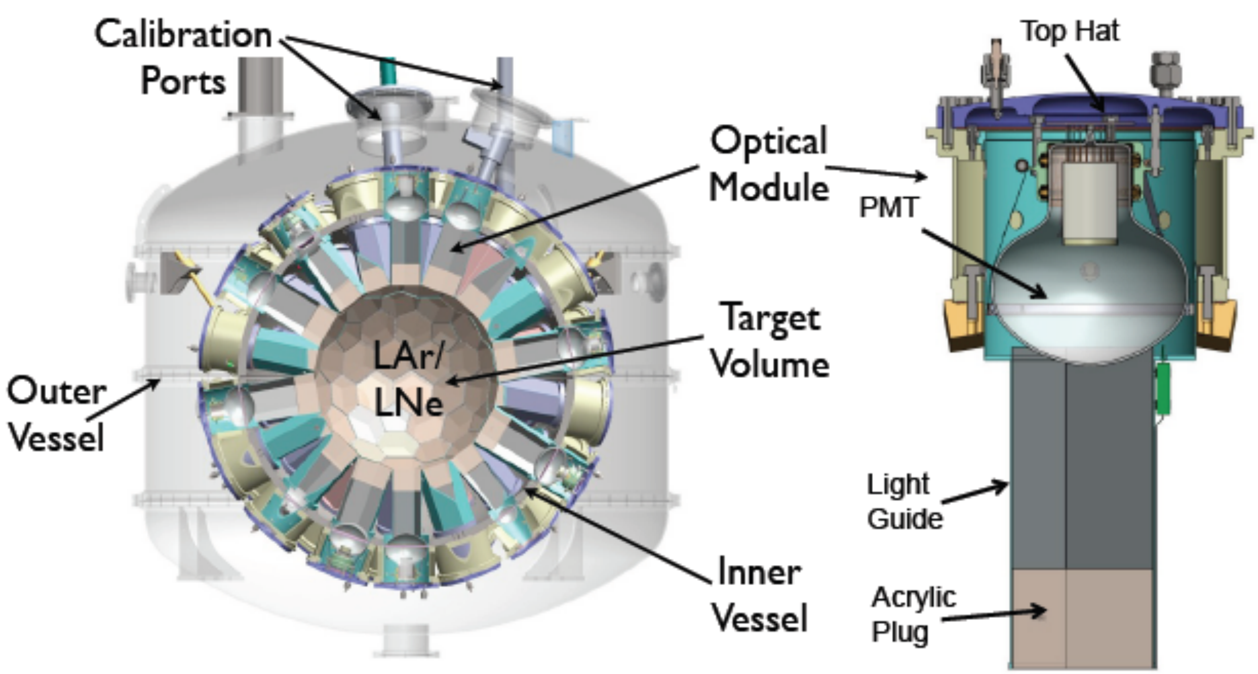
- 850 kg two-phase LAr target: 120cm drift length, 25cm diameter

- PMT array on bottom, LEMs on top for charge readout

- Deployment at Canfranc 2012

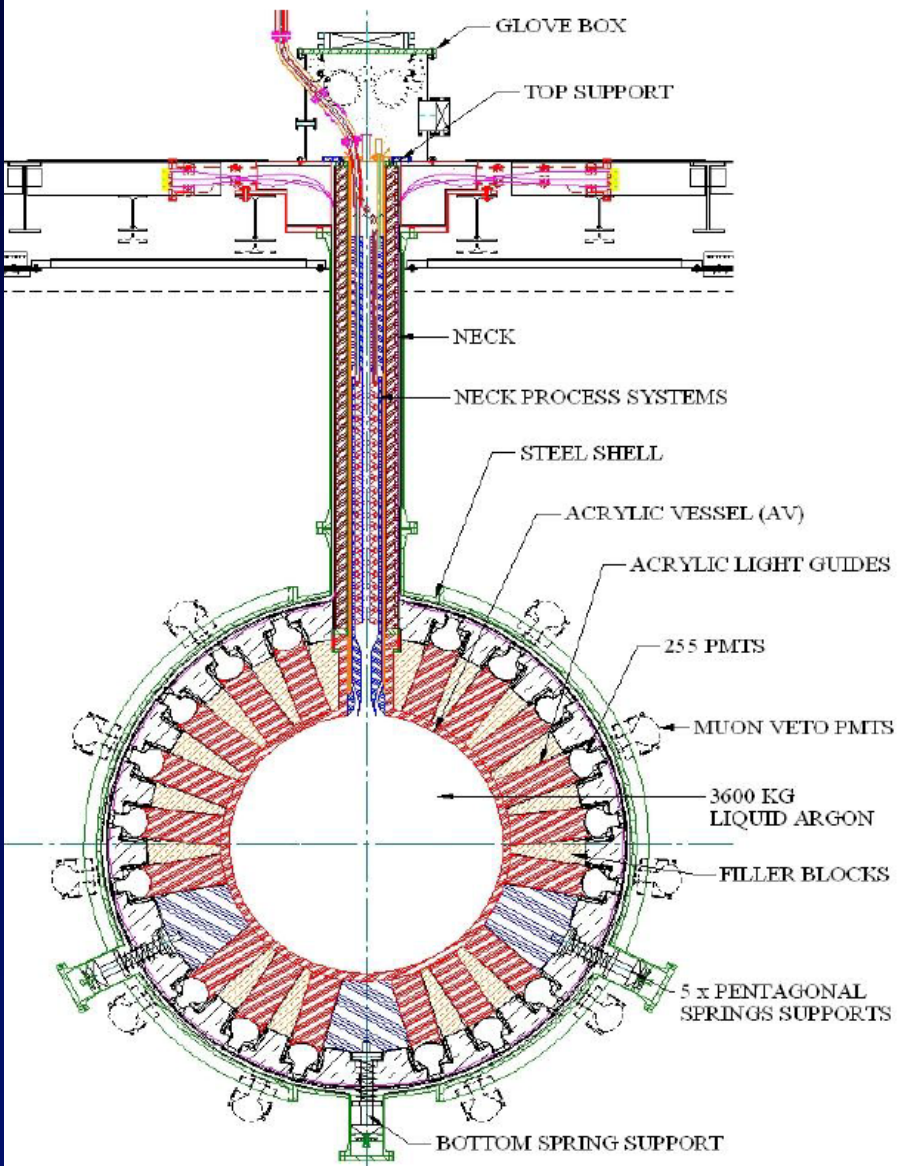
Liquid Argon: MiniClean

- 4π coverage to maximize light-yield at threshold …
  - 3D Position Reconstruction
  - Particle-ID via Pulse-shape discrimination
- Radon-free assembly …
- "Cold" design allows both LAr & LNe …
- No electric fields … PMTs only active component …
- Fast signals (τ_3 = 1.6 μs) avoid pulse-pileup in LAr …



Slide from A. Hime, IDM 2012

Liquid Argon: DEAP- 3600



DEAP-3600 Detector

3600 kg argon target (1000 kg fiducial) in sealed ultraclean Acrylic Vessel

Vessel is "resurfaced" in-situ to remove deposited Rn daughters after construction

Large area vacuum deposition source for TPB wavelength shifter deposition

255 Hamamatsu R5912 HQE PMTs 8-inch (32% QE, 75% coverage)

50 cm light guides + PE shielding provide neutron moderation

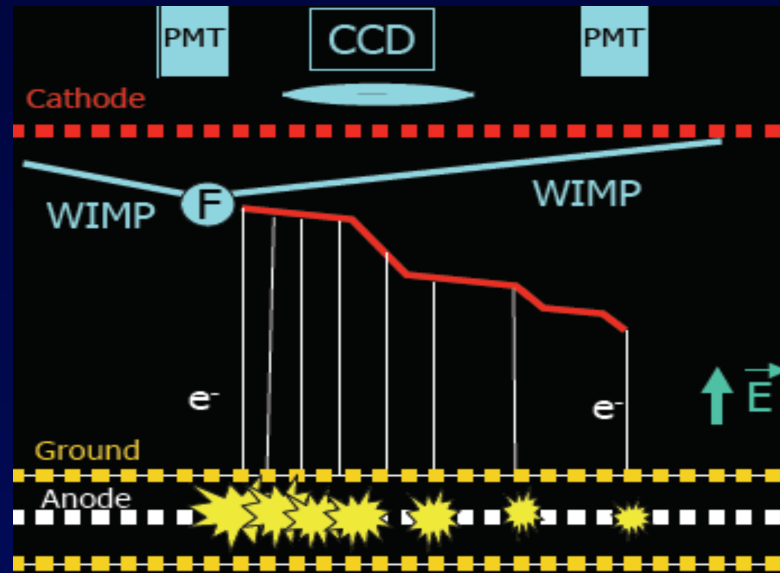
Detector in 8 m water shield at SNOLAB

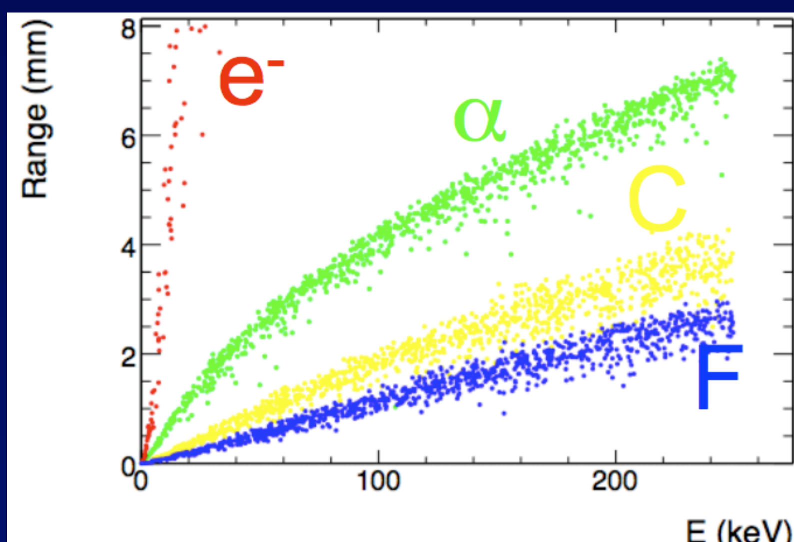
Slide from M. Boulay, IDM 2012

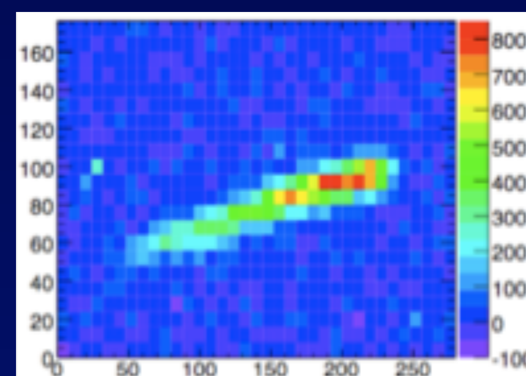
Directionality: Time Projected Chambers

➢ DMTPC

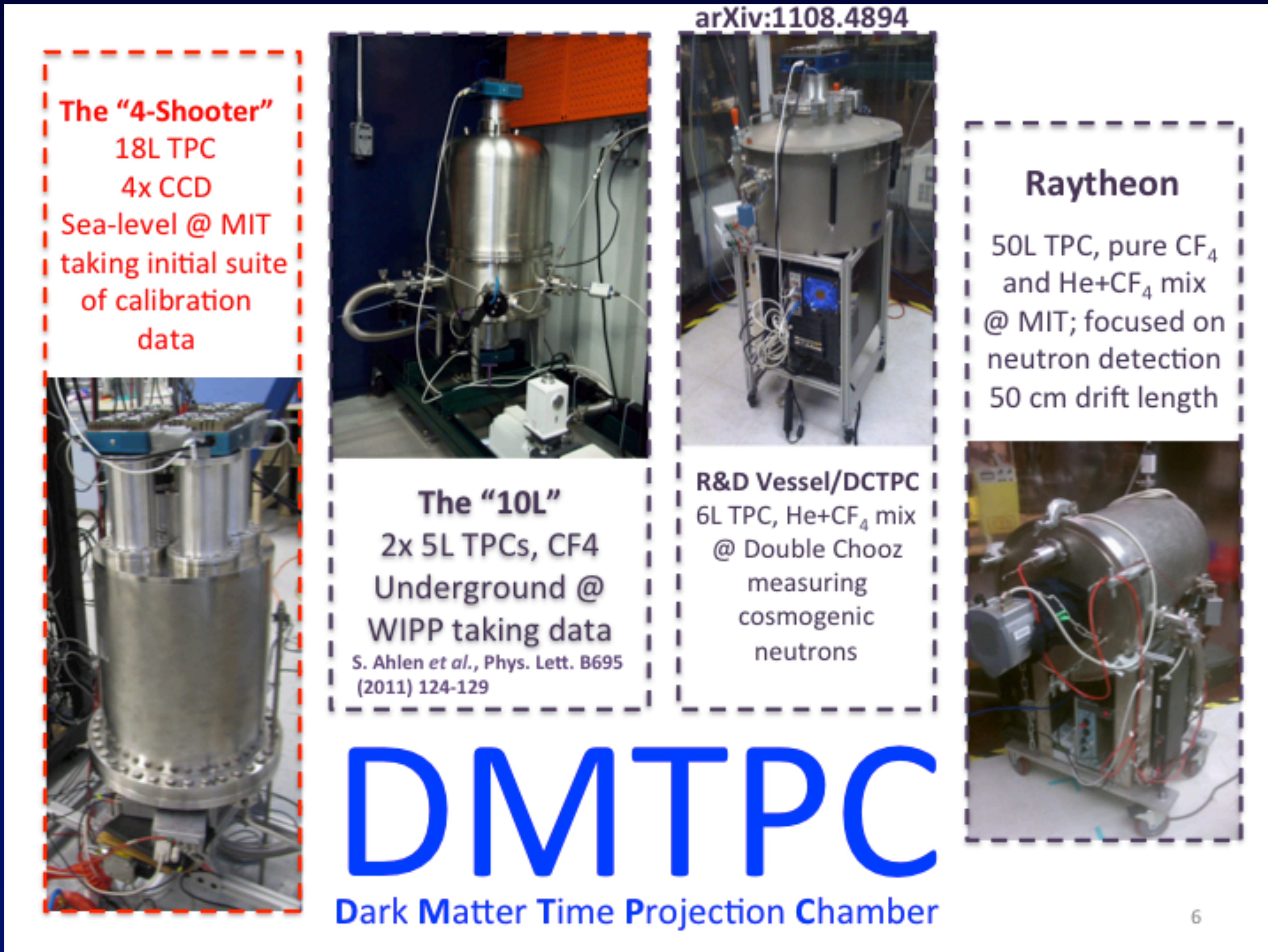
- CCD based detector with directional sensitivity
- Total energy is given by amount of light deposited
- PMTs for trigger, Z information
- Excellent gamma/beta rejection base on track size







- surface run background data at MIT (3.3kg, exposure 44 kg.days)
- $1m^3$ in fabrication, plan for underground operation at WIPP

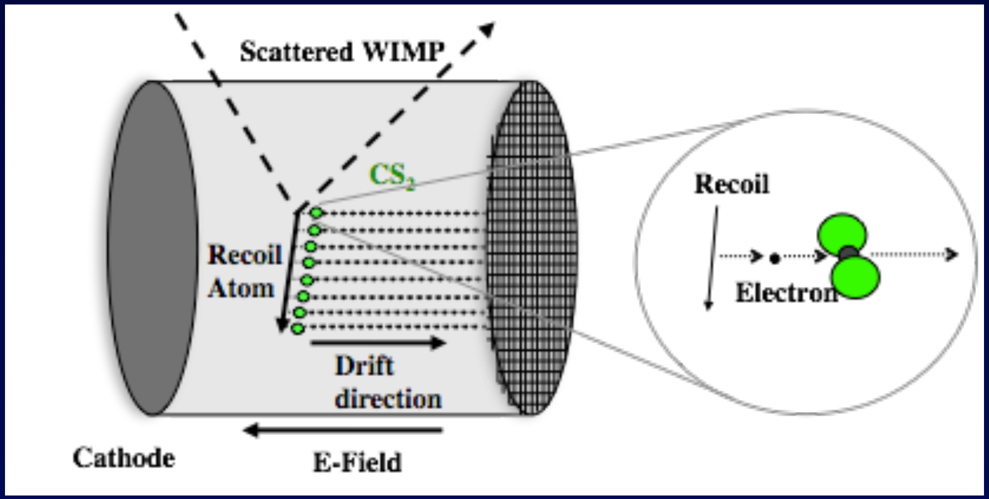


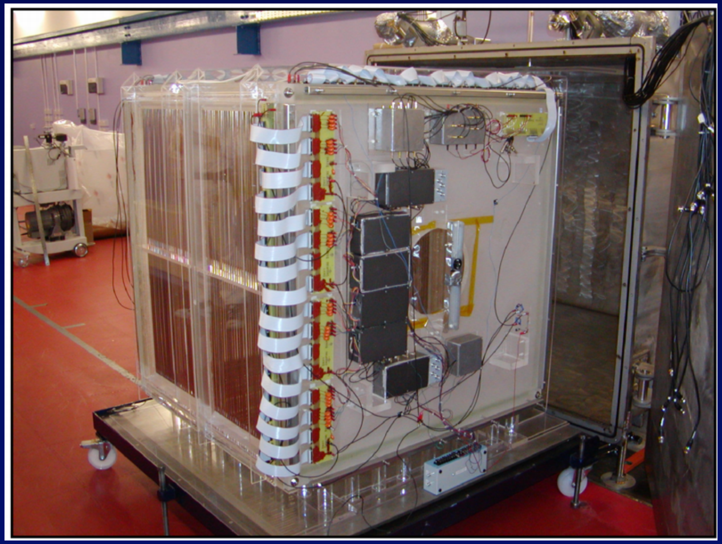
Slide from S. Henderson, IDM 2012

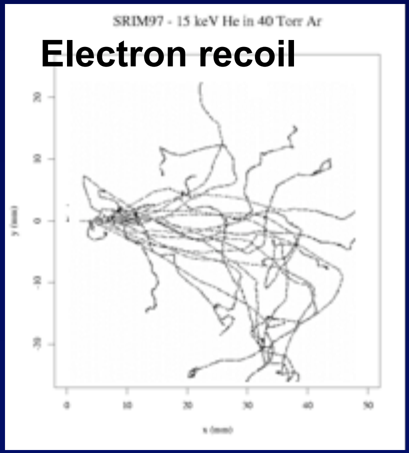
Directionality: Time Projected Chambers

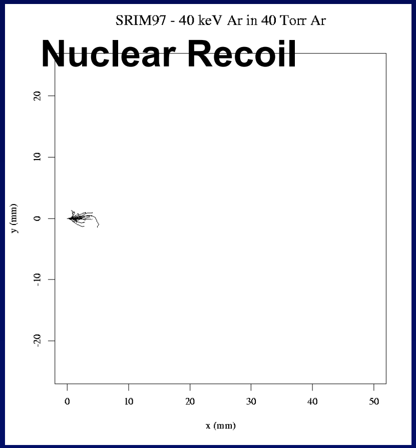
➢ DRIFT (Boulby)

- Sensitive to direction of recoiling nucleus
- Drift negative ions (CS_2 molecule) in TPC
  - remove magnetic field
  - reduces diffusion
- Excellent gamma/beta rejection base on track size









Searching for Axions

- Light pseudoscalar particle
  - introduced to solve strong CP problem
  - weak couplings
  - born non-relativistic (cold dark matter)
- Detection rely on induced coupling to photons
- Techniques:
  - **CAST:** conversion of solar axions to photons in magnetic field (using LHC prototype magnet B~10T)
  - **ADMX:** high-Q resonance cavity in an external B field