Direct Dark Matter Searches

Hans Kraus

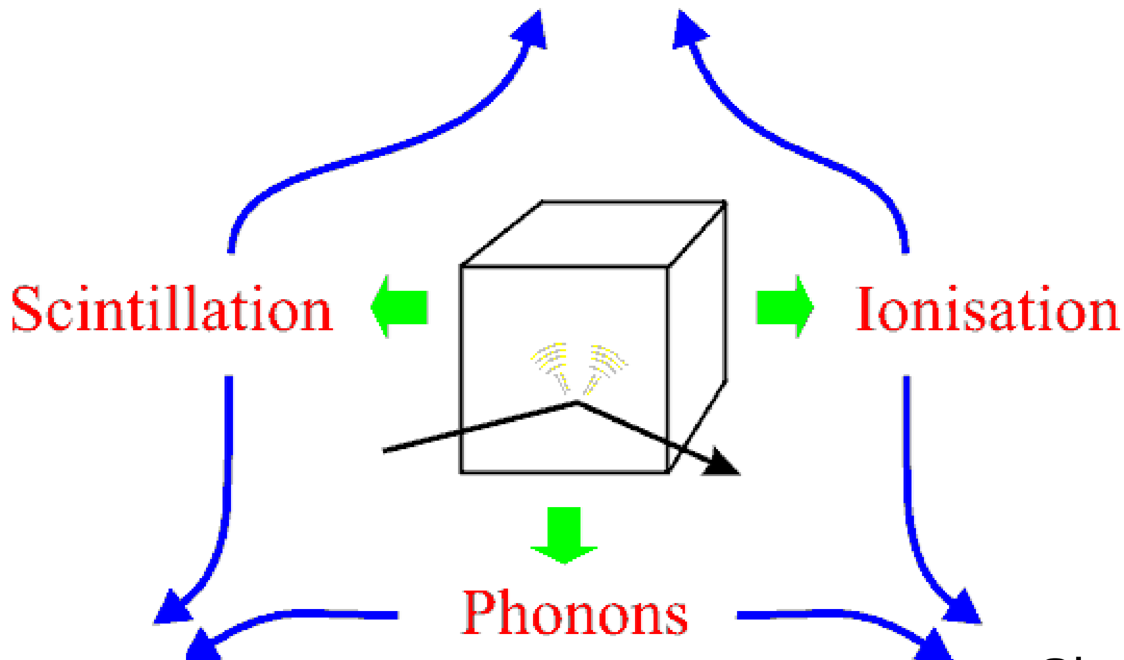
- Detector Technologies / Historic
- Cryogenic
- Noble Liquids

A rather selective summary of dark matter search experiments

Direct Detection Techniques

Ar, Xe
ArDM, DarkSide, XENON, ZEPLIN-II/III, LUX, Panda-X, LUX-ZEPLIN

NaI, Ar, Xe
DAMA/LIBRA
ANAIS
NAIAD
KIMS
XMASS
DEAP/CLEAN
ZEPLIN-I



Ge
CoGENT
GERDA
MAJORANA
IGEX

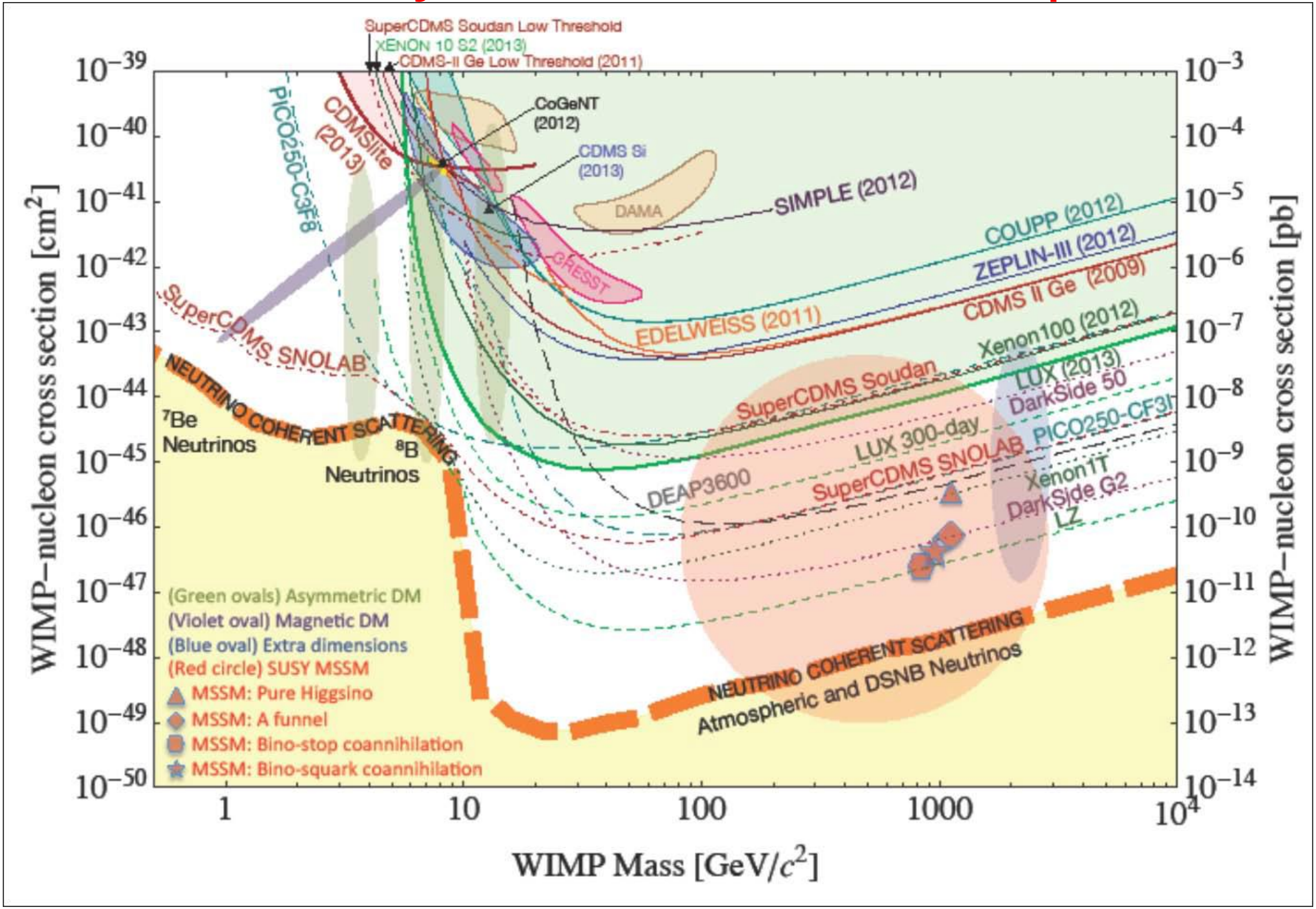
$CaWO_4$, $ZnWO_4$
CRESST II
ROSEBUD
EURECA

Al_2O_3 and others
CRESST I
CUOPP
SIMPLE
PICASSO

Si, Ge
CDMS
EDELWEISS
EURECA

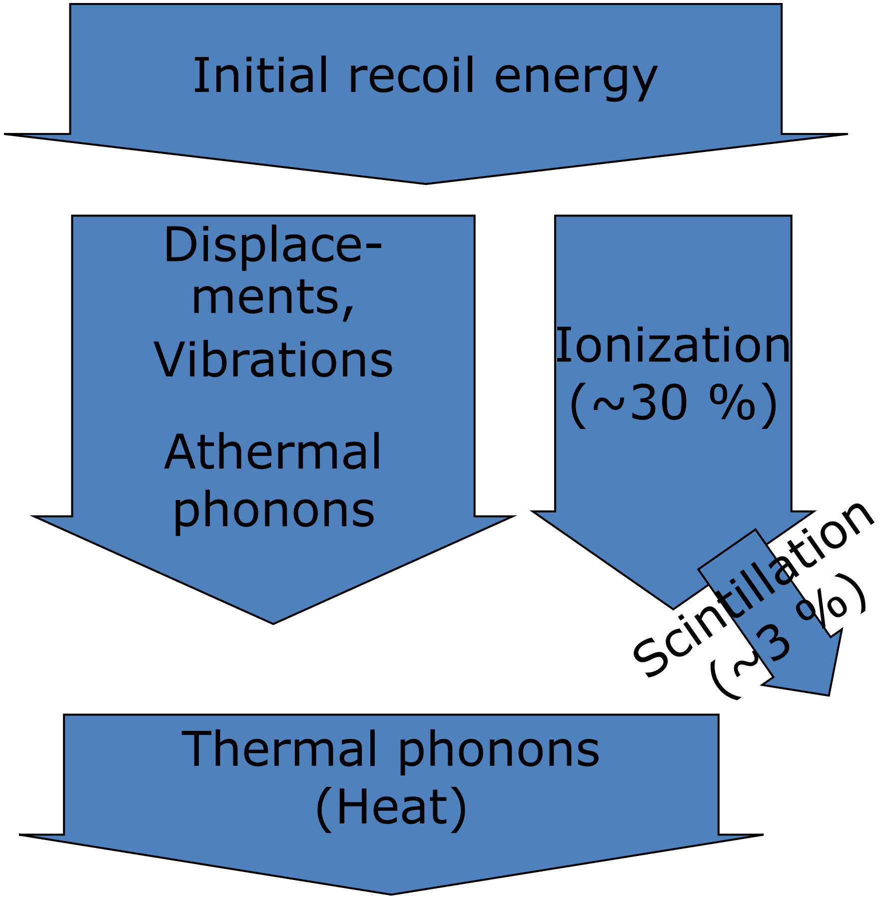
Displacement / tracking: DRIFT, Newage, MIMAC, DM-TPC

The Physics Result Landscape



Cryogenic detectors

Phonon-ionization / phonon-scintillation

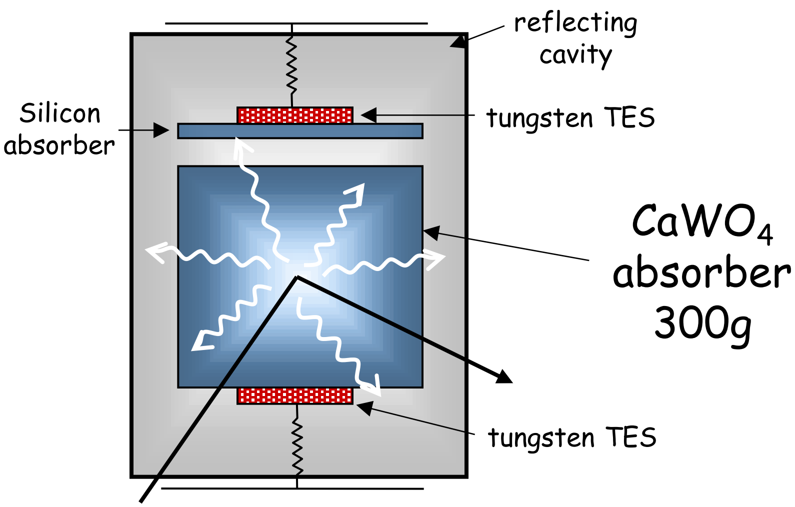


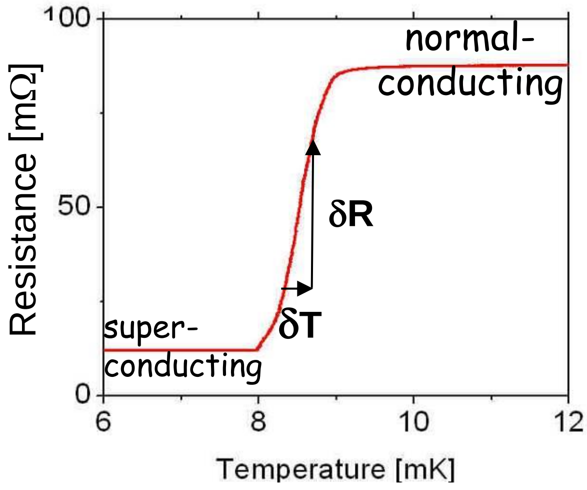
Phonon: most precise total energy measurement

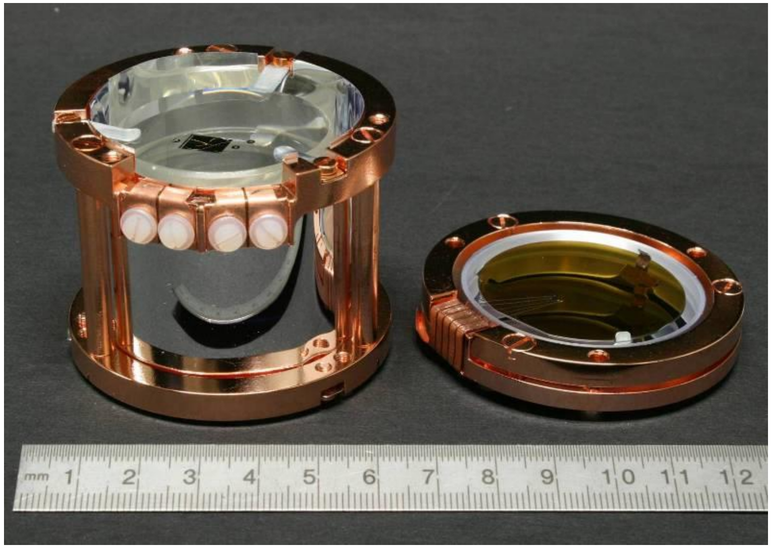
Ionization / Scintillation: yield depends on recoiling particle

Nuclear / electron recoil discrimination.

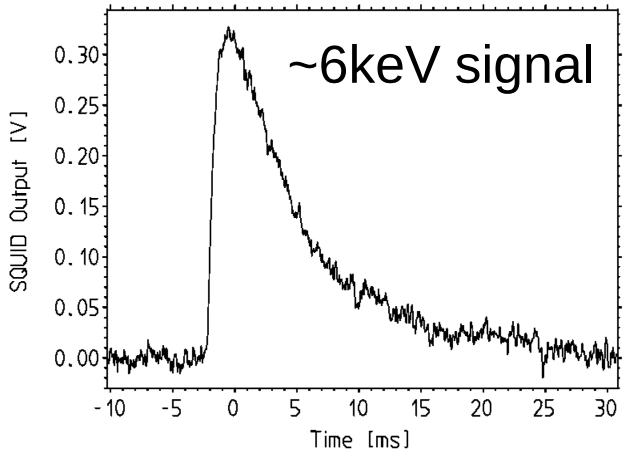
CRESST Detectors



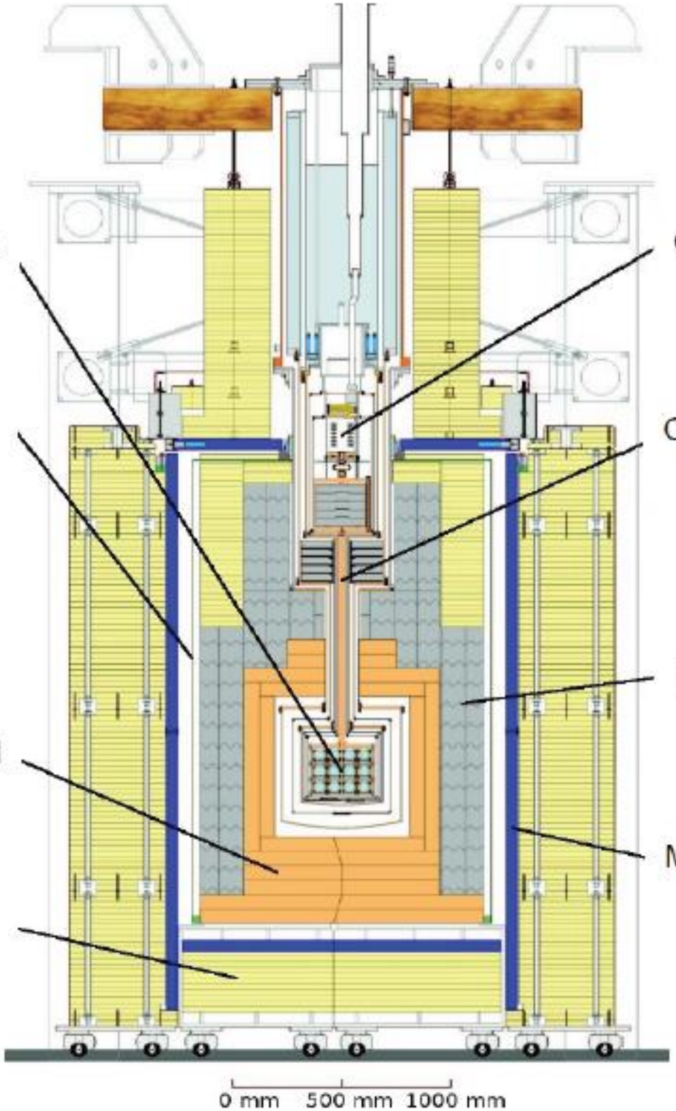




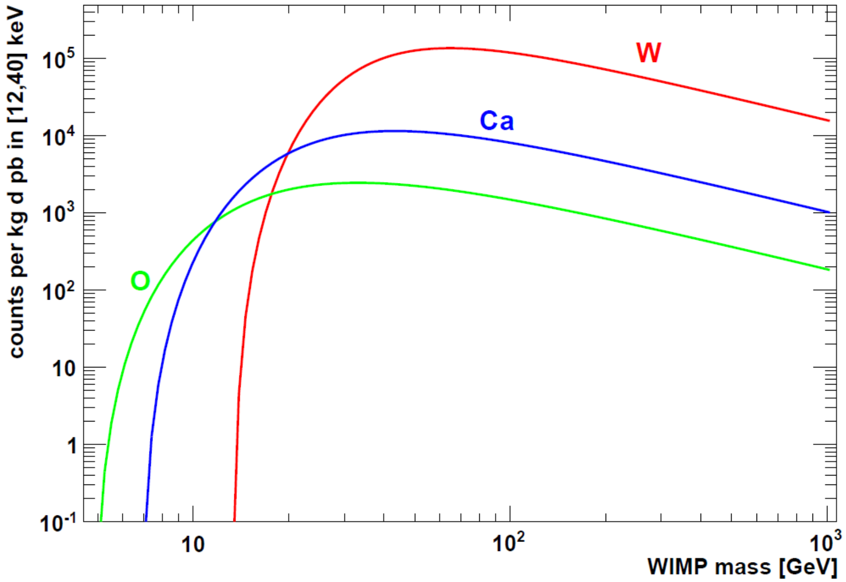
Width of transition: ~1mK
Signals: few μ K
Stablity: ~ μ K

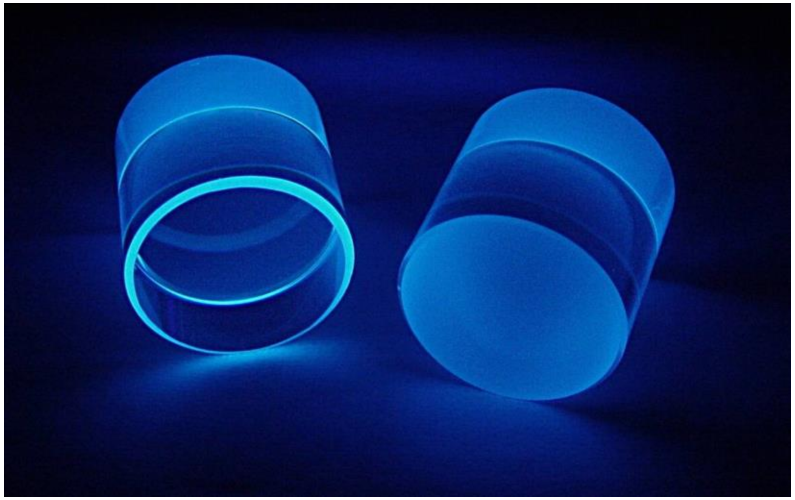


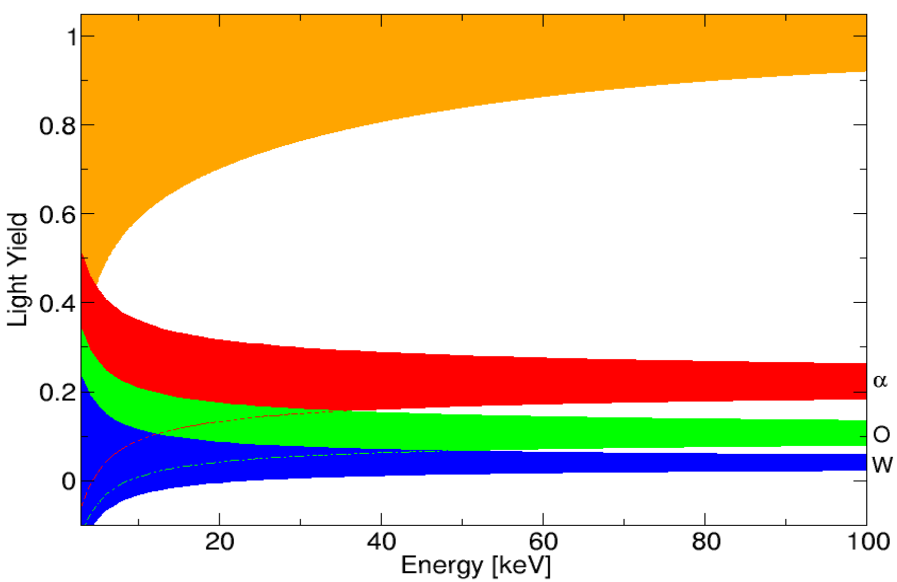
CRESST in Gran Sasso

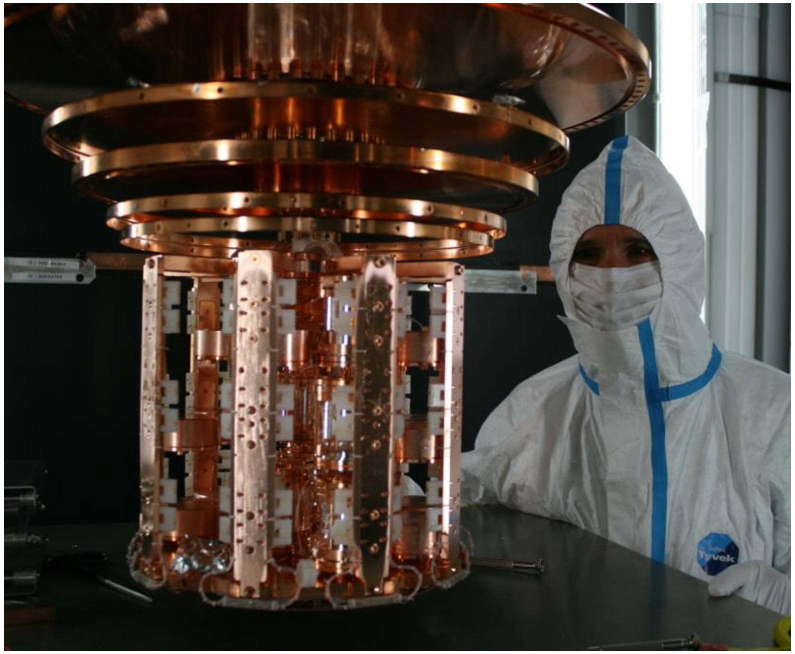


CRESST

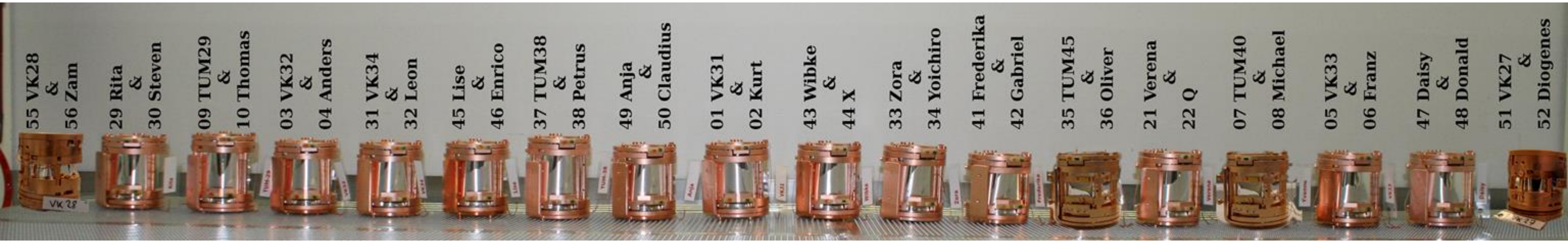

counts per kg d pb in [12,40] keV
WIMP mass [GeV]
W
Ca
O
10
10^2
10^3
10^{-1}
1
10
10^2
10^3
10^4
10^5




Light Yield
Energy [keV]
α
O
W
20
40
60
80
100
0
0.2
0.4
0.6
0.8
1

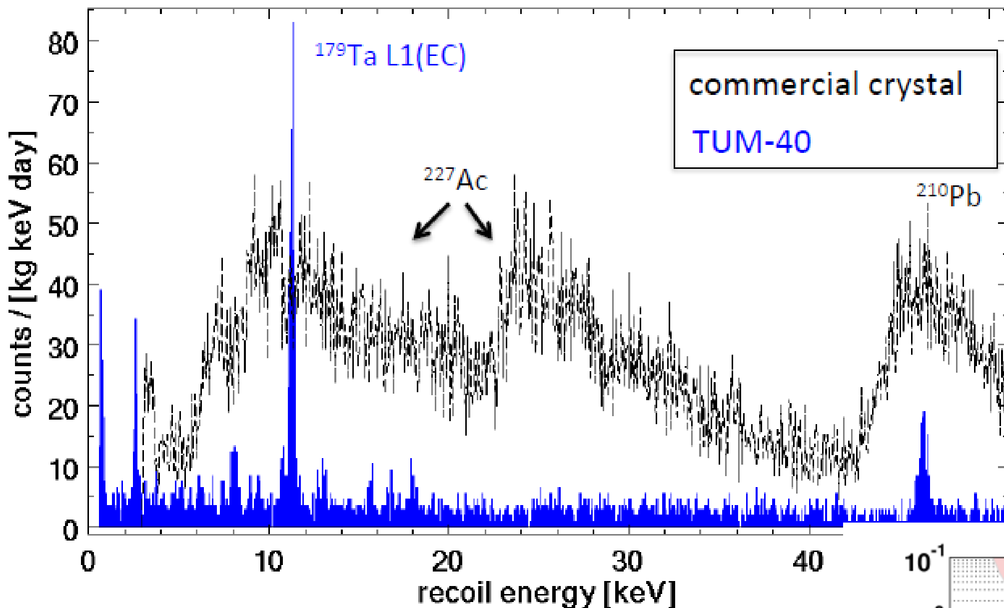


CRESST Status (Run 33)



- 18 detector modules mounted (12 standard design, 6 with active veto for ^{206}Pb recoils)
- Non-blind data set (Aug ’13 to 7th Jan ’14), 377 kg.day to evaluate performance and define / adjust cuts.
- Data since 7th Jan ’14 to be used in blind analysis.
- Smooth running conditions (>90% duty cycle), 5% removed due to instabilities (from heavy works in the tunnel).

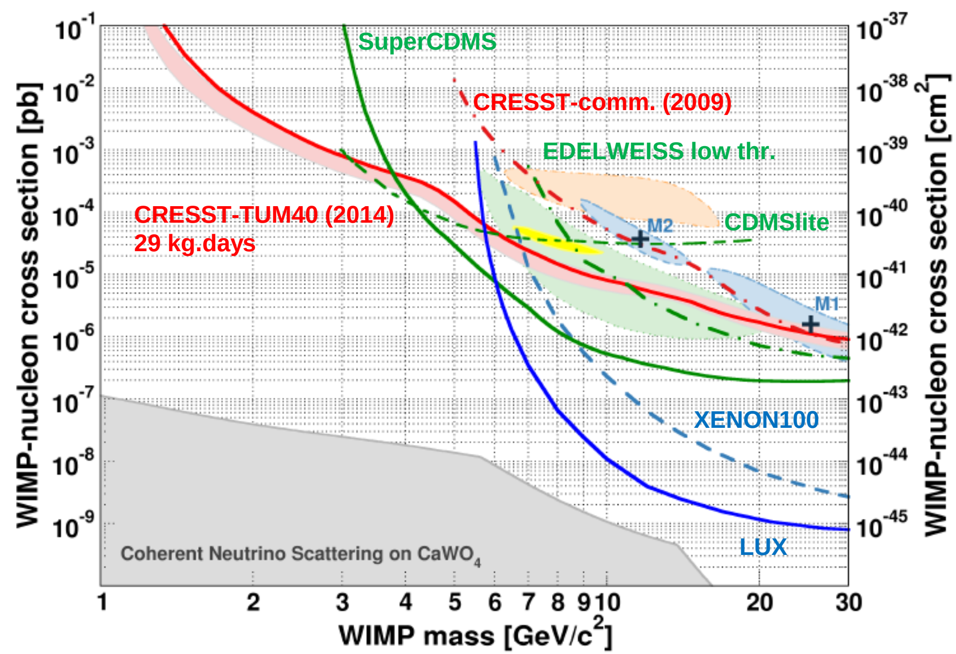
CRESST Status (crystals and latest result)



Average rate:
~3.5 counts / [kg keV day]

Gamma lines from cosmogenic activation

Excellent resolution: σ ≈ 100eV



Expérience pour **DE**tecter **L**es **W**imps **E**n **SI**te **S**outerrain

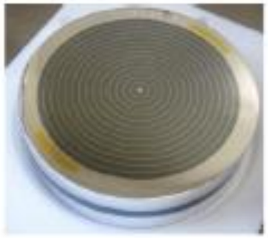
- Search for WIMP dark matter (scattering: ~10keV nuclear recoil with <0.01 events/kg/day)
- Need:
  - Sensitive Detectors (cryogenic germanium phonon-ionization detectors)
  - Low background (passive shielding and ultra-low background materials)
  - Excellent background discrimination (active rejection by muon vetoing and surface event identification)
  - Extended running periods / stability (good cryostat performance and calibrations)
- Laboratoire Souterrain de Modane

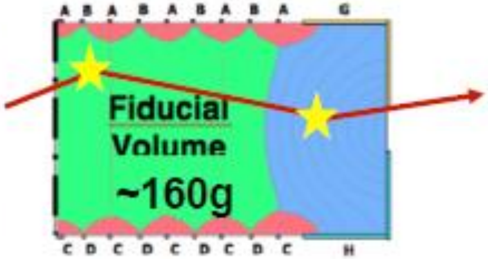
EDELWEISS-III Detectors

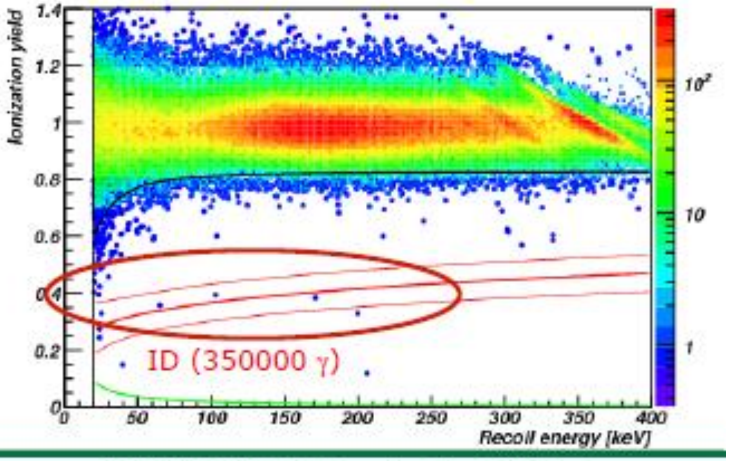
From ID detectors to FID detectors

EDELWEISS-II

ID 400g with 10x **160g** fiducial mass

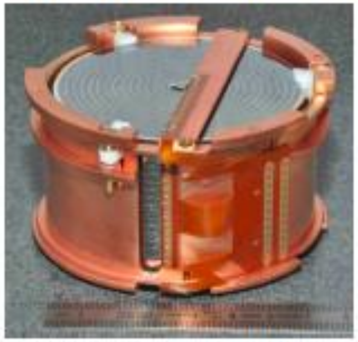


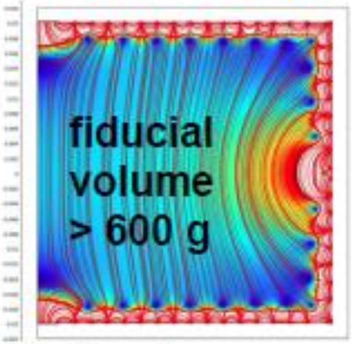


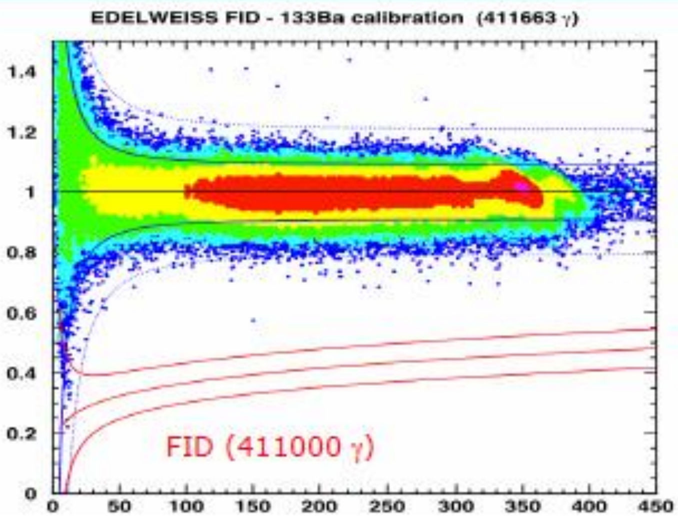


EDELWEISS-III

FID 800g with 40x **~600g** fiducial mass







« **F**ull **I**nter**D**igitised »

Towards a few × 10^{-9} pb: EDELWEISS III

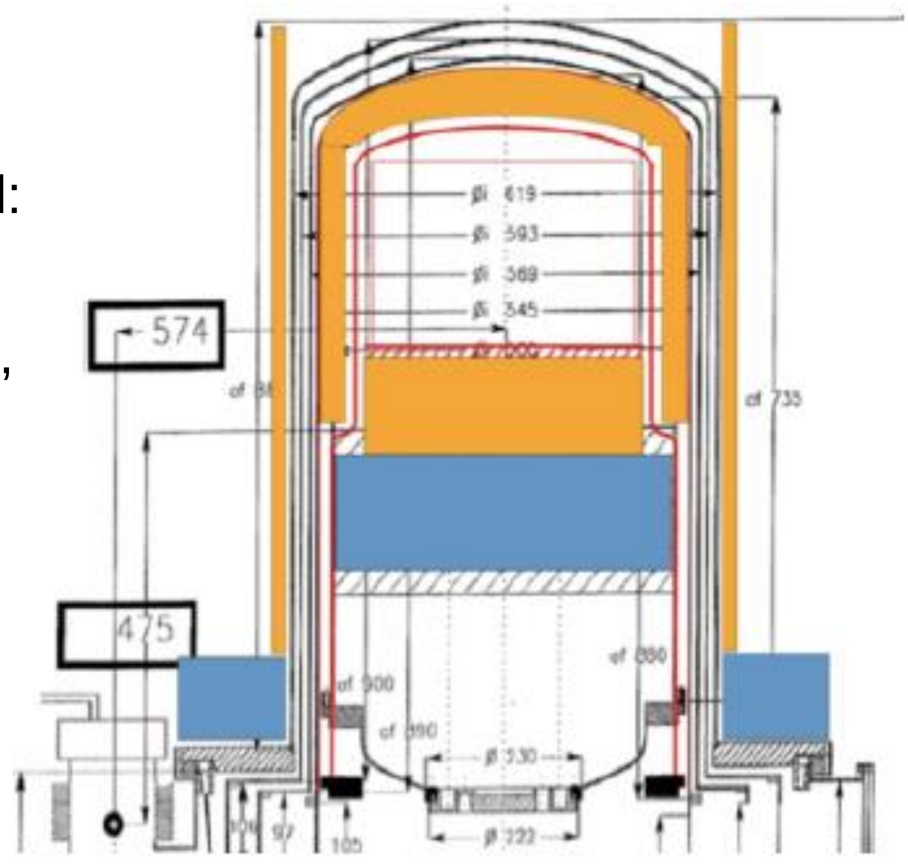
Programme under way, funded.

Detector improvements:

- ~40 FID800 detectors to be installed: 24kg fiducial
- 2 NTD heat sensors (better heat ch), 4 ionization channels, instead of 6.

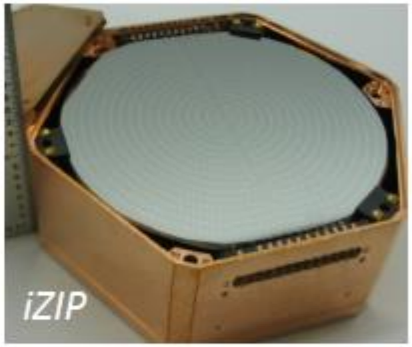
Infrastructure improvements:

- **Within the Edelweiss-II setup** – upgrades of cryogenics, cabling, DAQ, shielding.
- Extra internal PE shield.

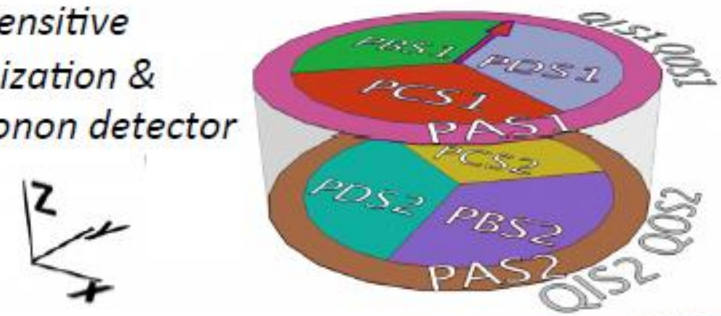


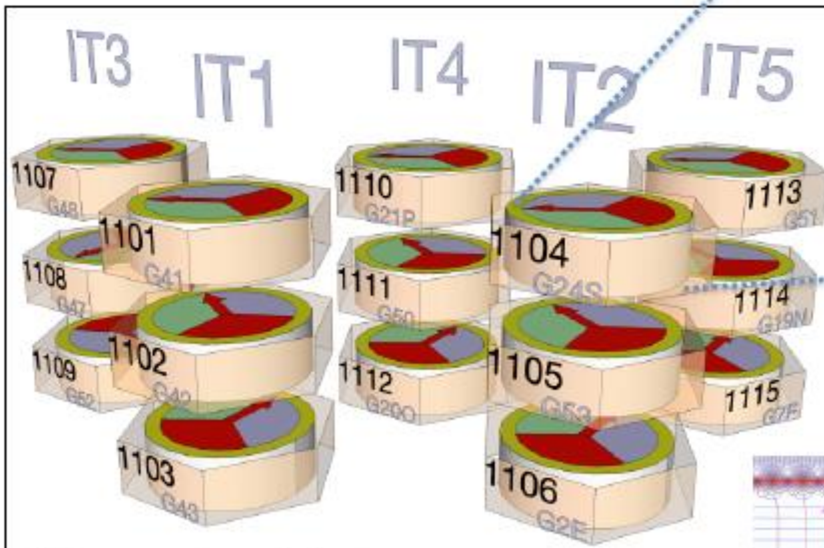
EDELWEISS Infrastructure

SuperCDMS Soudan



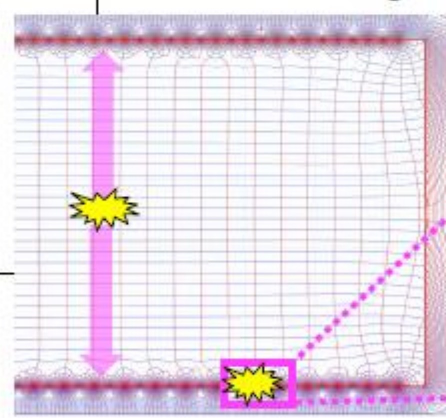
interleaved
Z-sensitive
Ionization &
Phonon detector



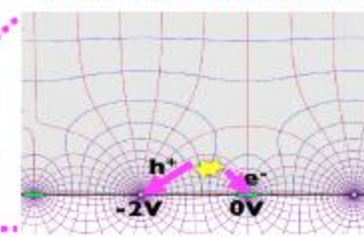


15 germanium detectors
0.6 kg each
Operational since March of 2012

Improved fiducialization from measurement of z-symmetric ionization response
Phonon guard and z-symmetric phonon response helps too!



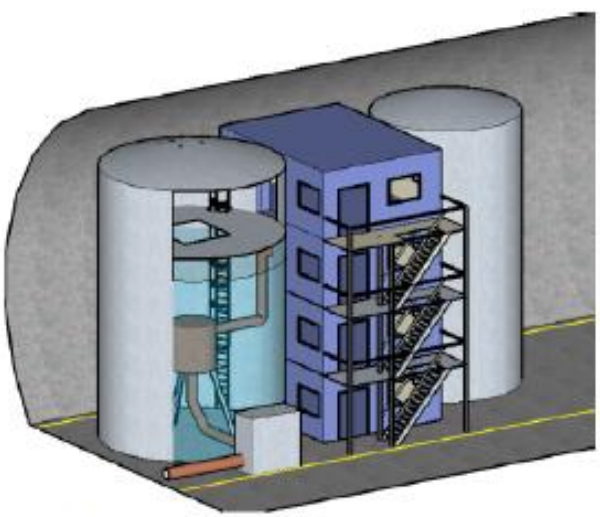
APL 103, 164105(2013)



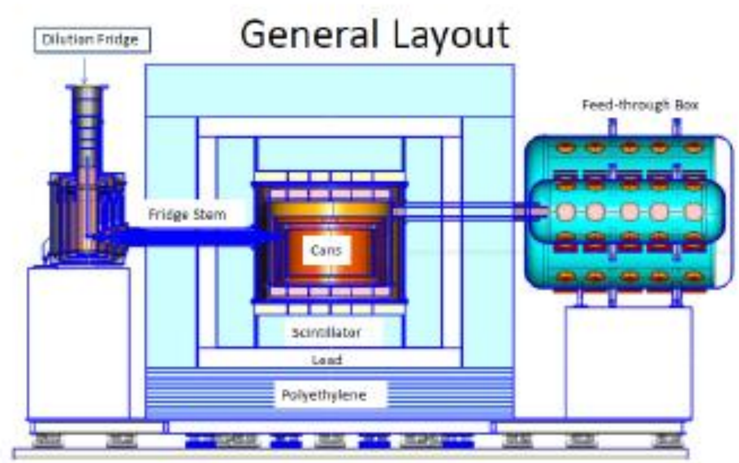
Data for this analysis: *577 kg-days*
taken from Mar 2012 – July 2013
7 iZIPs w/ lowest trigger thresh

EURECA

- Further investment into Germanium (EDELWEISS) and CaWO4 (CRESST) detectors.
- Together with Super-CDMS: target especially low-mass WIMP window.
- CRESST: background removal, increased scintillation yield.
- EDELWEISS: HEMT readout – lower threshold.

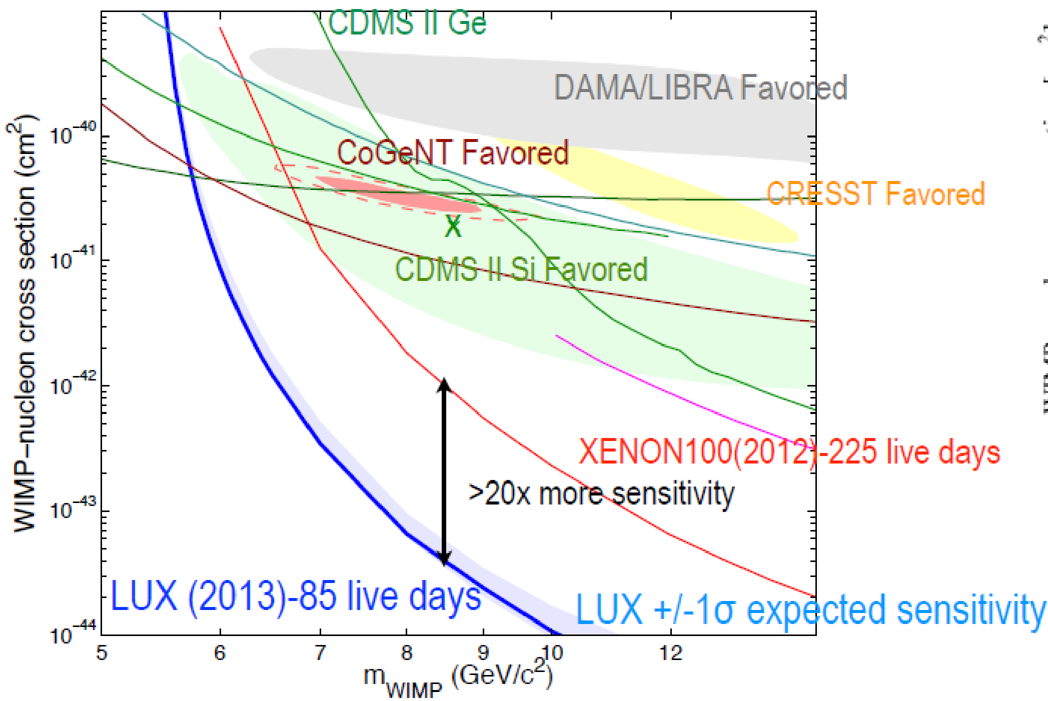


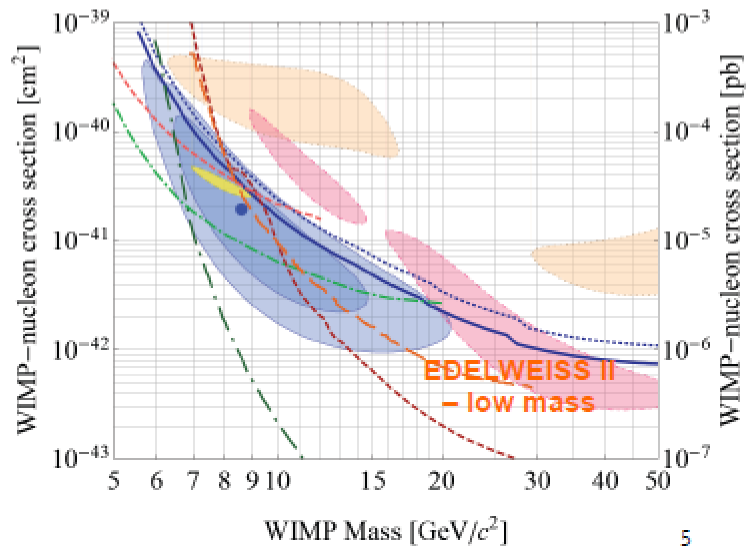
from EURECA conceptual design report (2013)

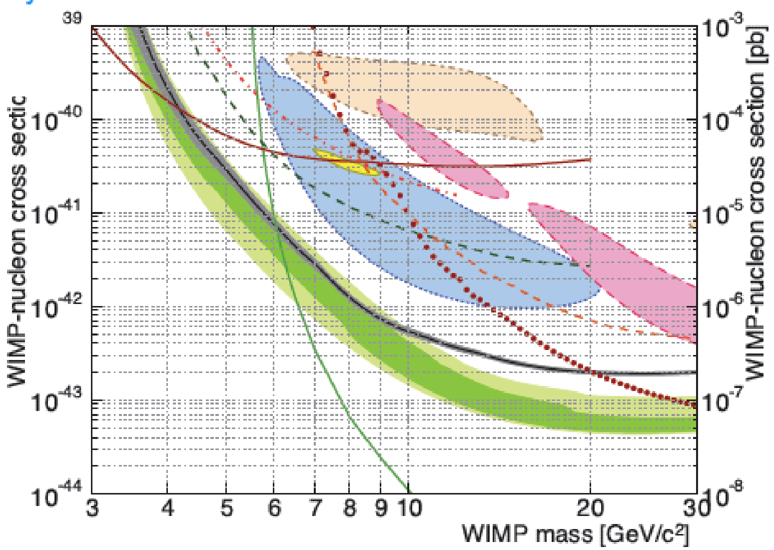


SuperCDMS design for SNOLAB

The low-mass WIMP scenario







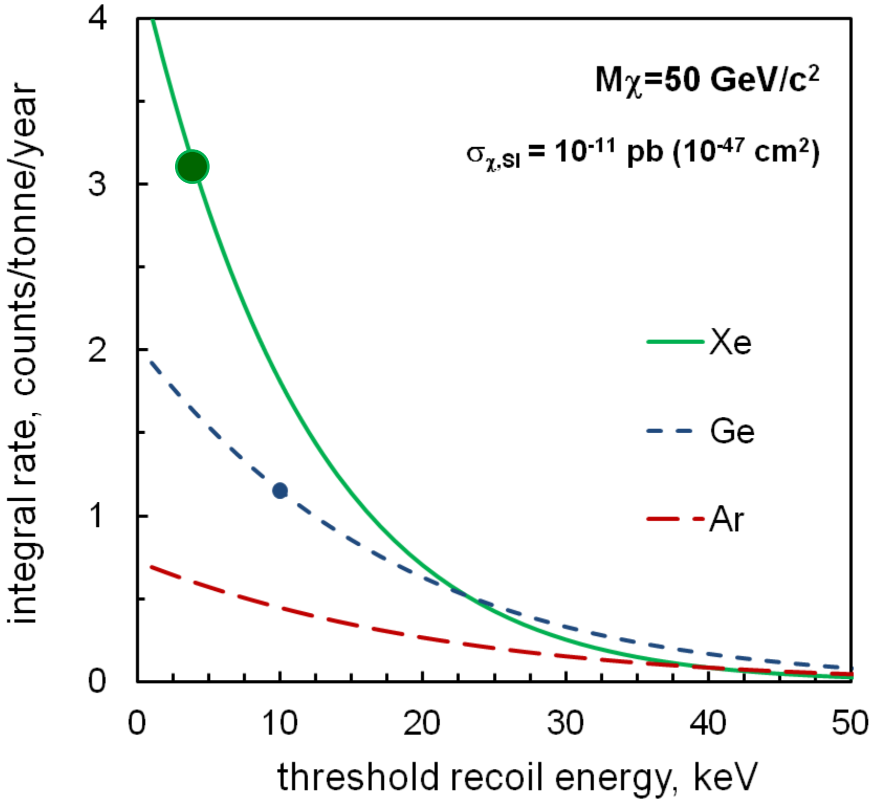
Low-mass WIMPs:
focus of cryogenic experiments (EURECA – SuperCDMS).
[but also sensitivity for medium – high mass WIMPs]

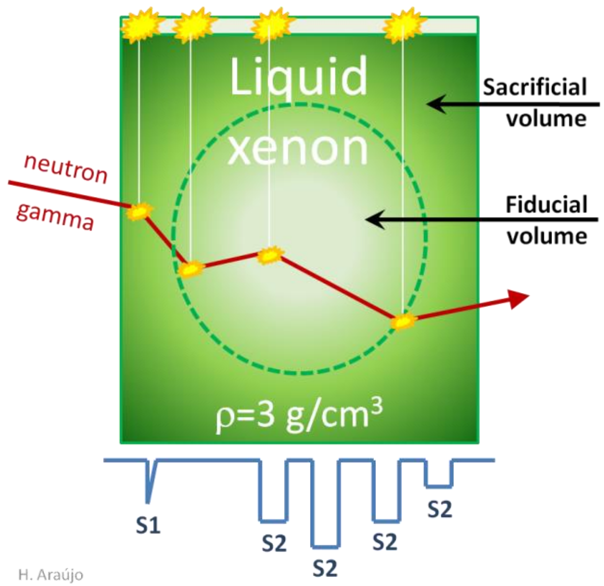
Simple But Important Statements:

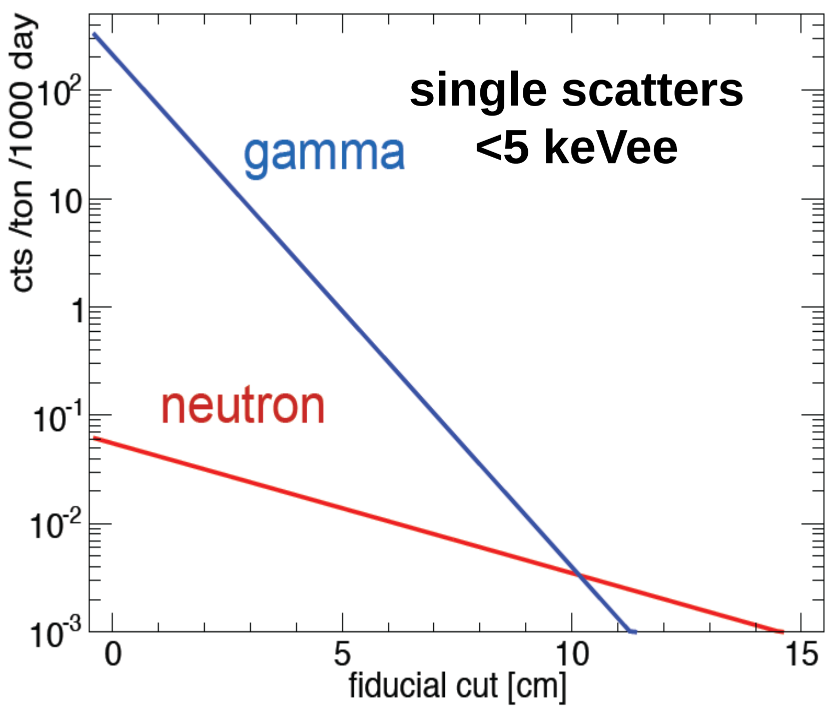
"The Sensitivity of a Dark Matter Experiment Scales as its Mass"

"The problems scale as its Surface Area"

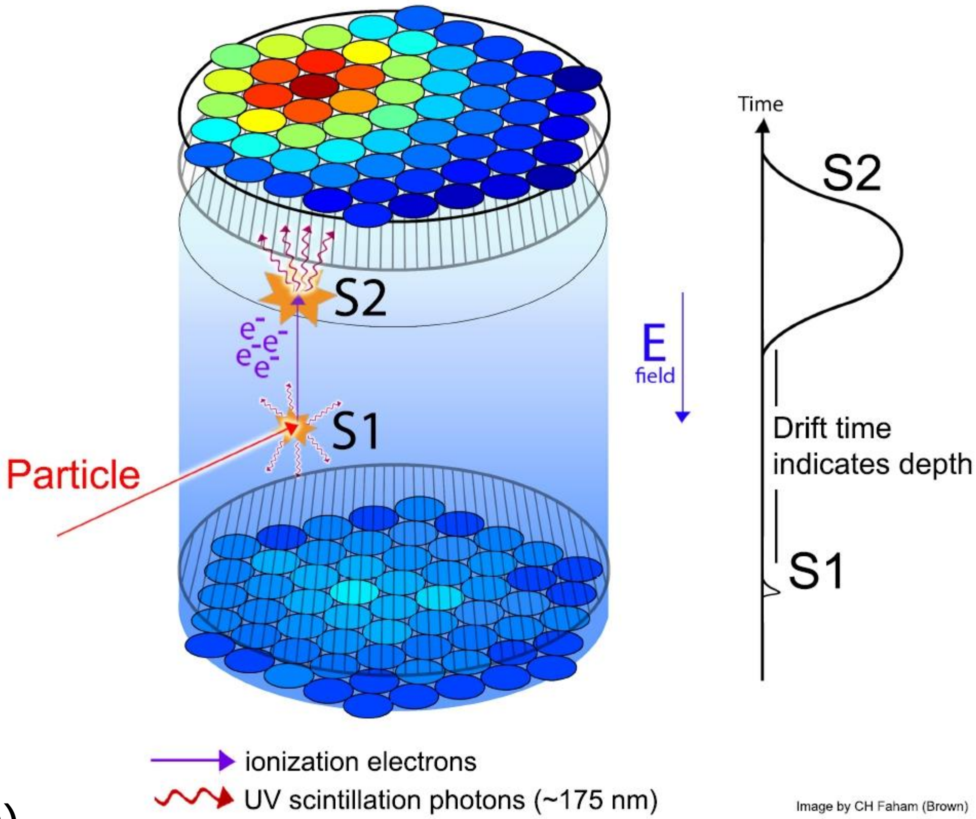
The Noble Liquid Xenon







Two-phase Xenon TPC Principle



S1: prompt scintillation signal

- Light yield: ~60 ph/keV (ER, 0 field)
- Scintillation light: 178 nm (VUV)
- Nuclear recoil threshold ~5 keV

S2: delayed ionisation signal

- Electroluminescence in vapour phase
- Sensitive to single ionisation electrons
- Nuclear recoil threshold ~1 keV

S1+S2 event by event

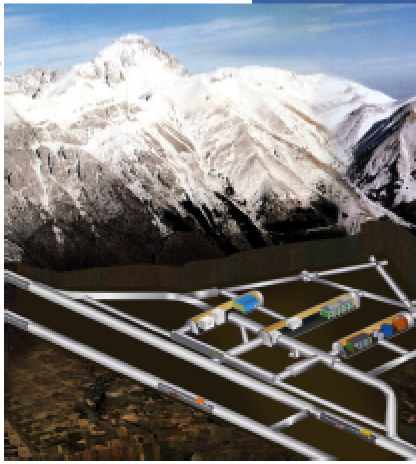
- ER/NR discrimination (>99.5% rejection)
- mm vertex resolution + high density: self-shielding of radioactive backgrounds

LXe is the leading WIMP target:

- Scalar WIMP-nucleon scattering rate dR/dE ~A^2, broad mass coverage (> 5 GeV)
- Odd-neutron isotopes (^{129}Xe, ^{131}Xe) enable SD sensitivity; target exchange possible
- No damaging intrinsic nasties (^{127}Xe short-lived, ^{85}Kr removable, ^{136}Xe $2\nu\beta\beta$ ok)

The XENON Program

GOAL: Explore WIMP Dark Matter to a sensitivity of $\sigma_{SI} \sim 10^{-48}$ cm^2.



Location: LNGS

CONCEPT:

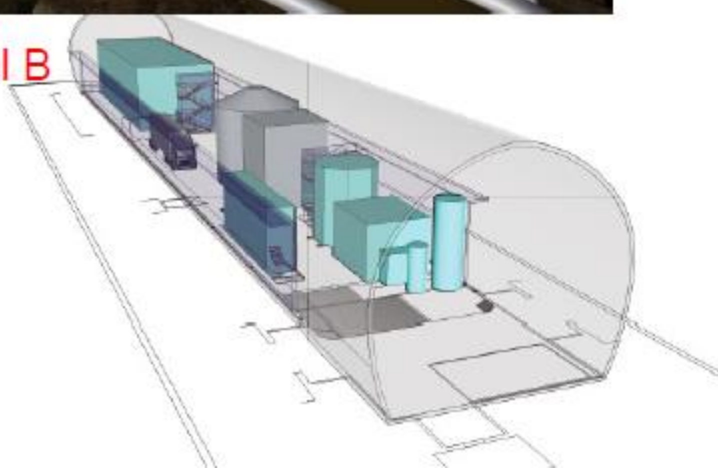
- Target LXe: excellent for DM WIMPs scattering.
  Sensitive to both axial and scalar coupling.
- Detector: two-phase LXeTPC: 3D position sensitive calorimeter.
- Background discrimination:
  - simultaneous charge & light detection
  - single site interactions, fiducialization, self shielding
- High light yield + proportional scintillation
  → low energy threshold for nuclear recoils (~ 5 keV).

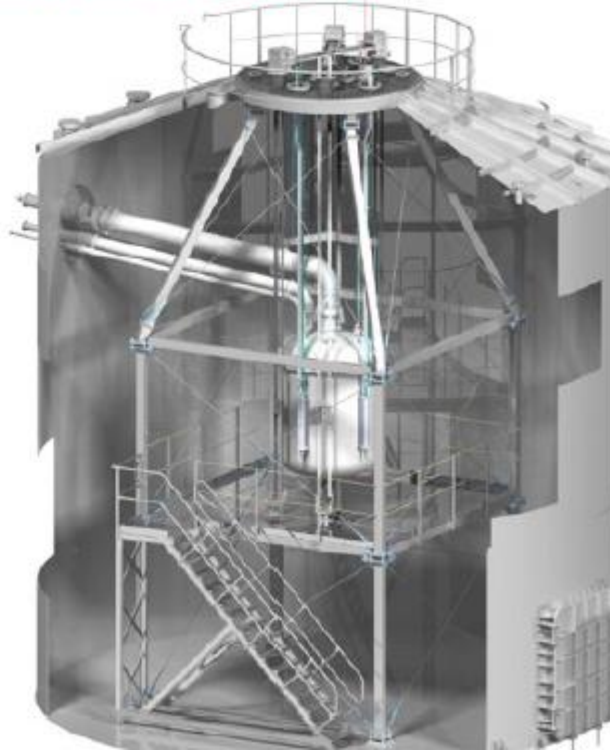
PHASES:

R&D	XENON10	XENON100	XENON1T	XENONnT
Start: 2002	2005-2007	2007 → ...	2011 → DM search '15	2018 →
	Proof of concept. Total mass: 14 kg 15 cm drift. Best limit in '07: $\sigma_{SI} \sim 10^{-43}$ cm^2	Ongoing DM search. Total mass: 161 kg 30 cm drift. Best limits in '11, '12: $\sigma_{SI} \sim 2 \times 10^{-45}$ cm^2	Construction ongoing. Total mass: ~ 3.3 t 1 m drift. Goal: $\sigma_{SI} \sim 2 \times 10^{-47}$ cm^2	Goal: $\sigma_{SI} \sim 10^{-48}$ cm^2

XENON1T

- ~ 1 m^3, ~ 3 t LXe, ~ 1 t fiducial mass
- Water Cherenkov Muon Veto ~10 m x 9.6 r
- ER background < 5 x 10^{-5} ev / kg / keV / da
- Kr/Xe < 0.5 ppt & Rn/Xe < 1 µBq/kg
- Project approved and funded (~50% NSF, ~50% Europe + Israel)
- Design of major systems completed
- Construction ongoing.

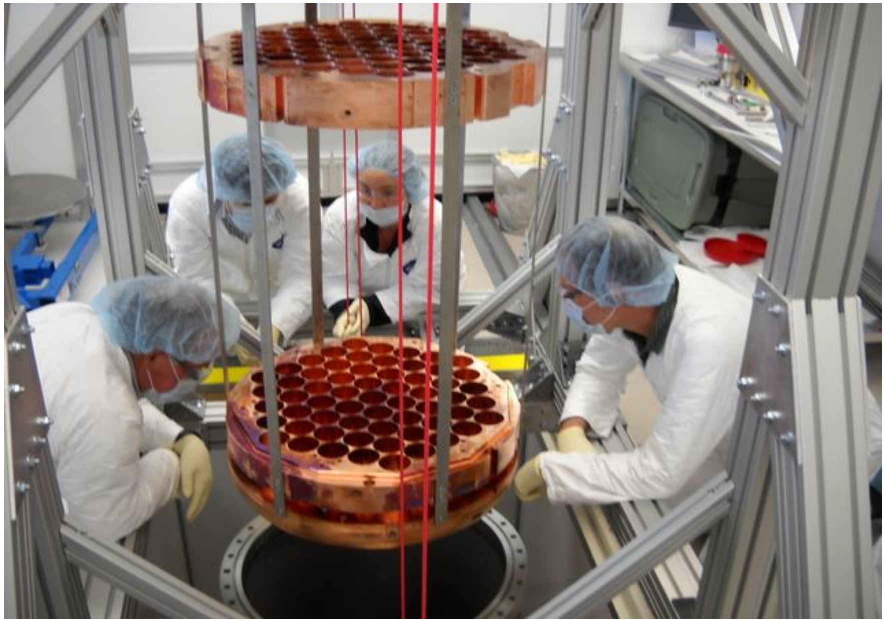


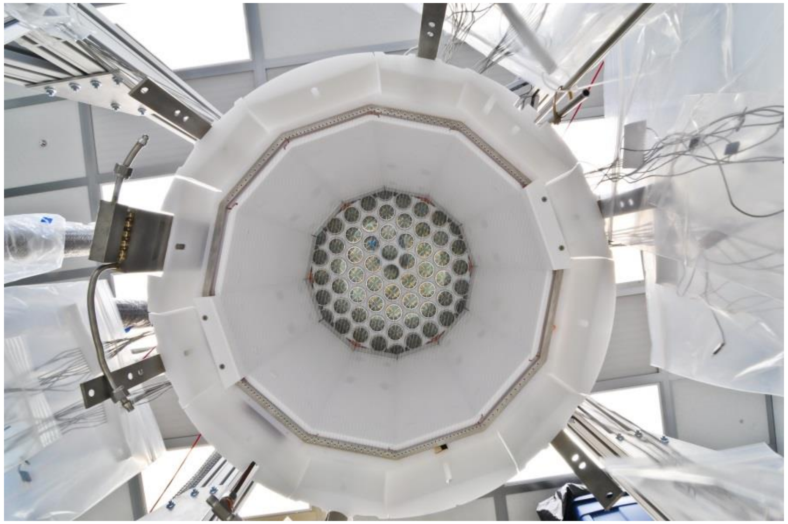


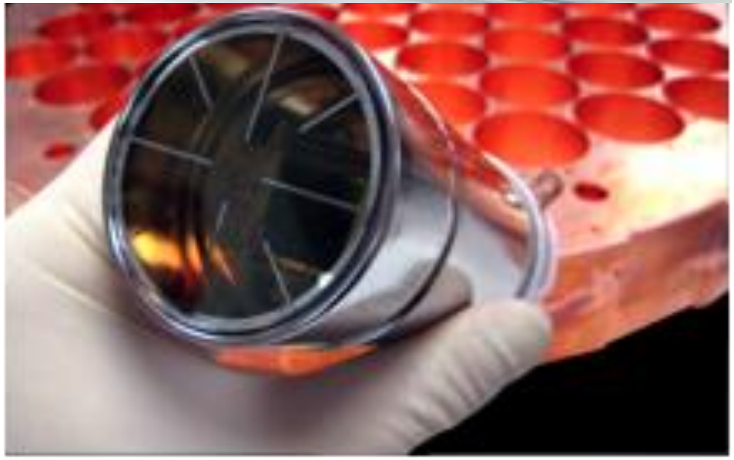
LUX - LUX-ZEPLIN (LZ)

Currently running LUX
LUX-ZEPLIN to use LUX infrastructure
Two-phase Xenon detector

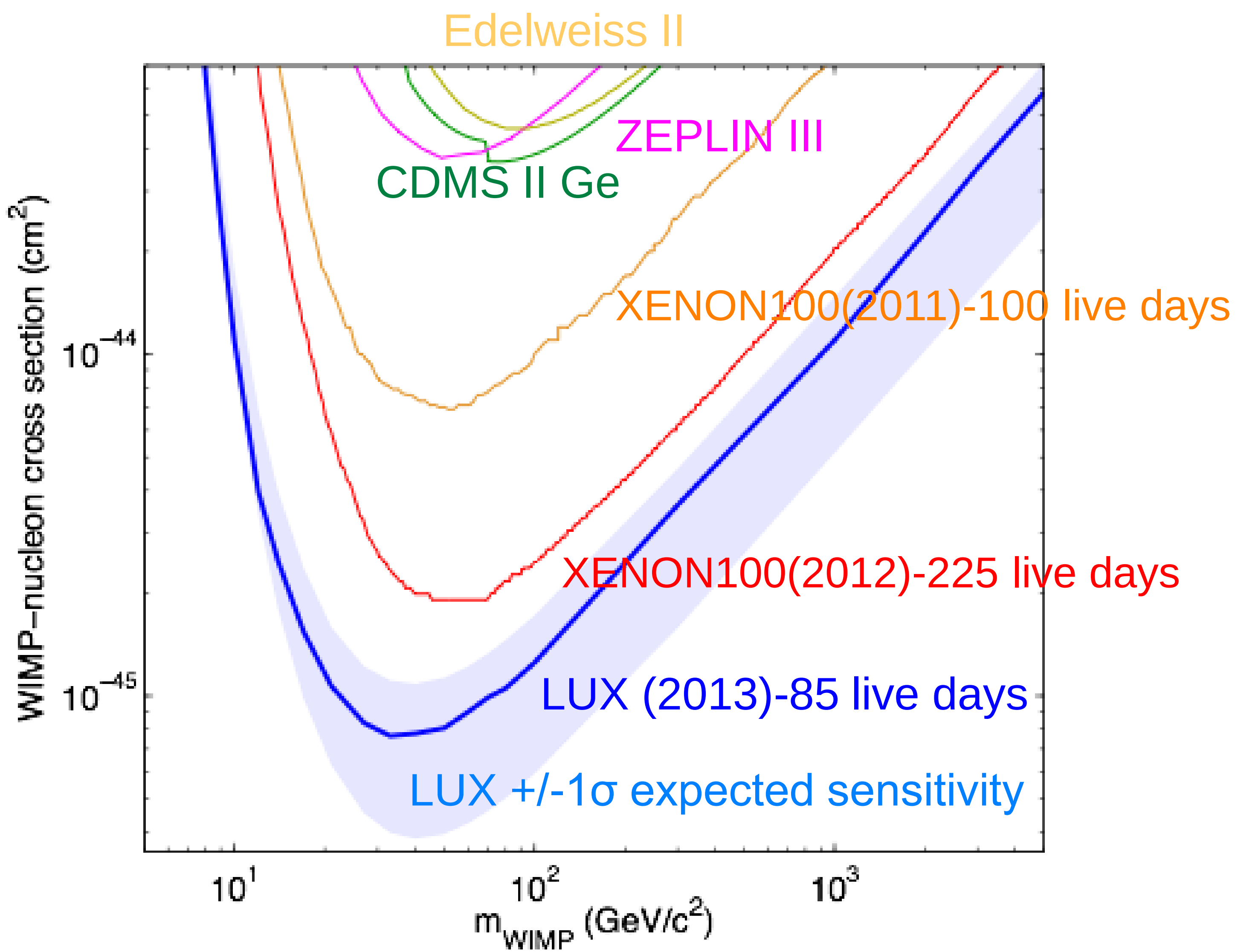
LUX as it was built



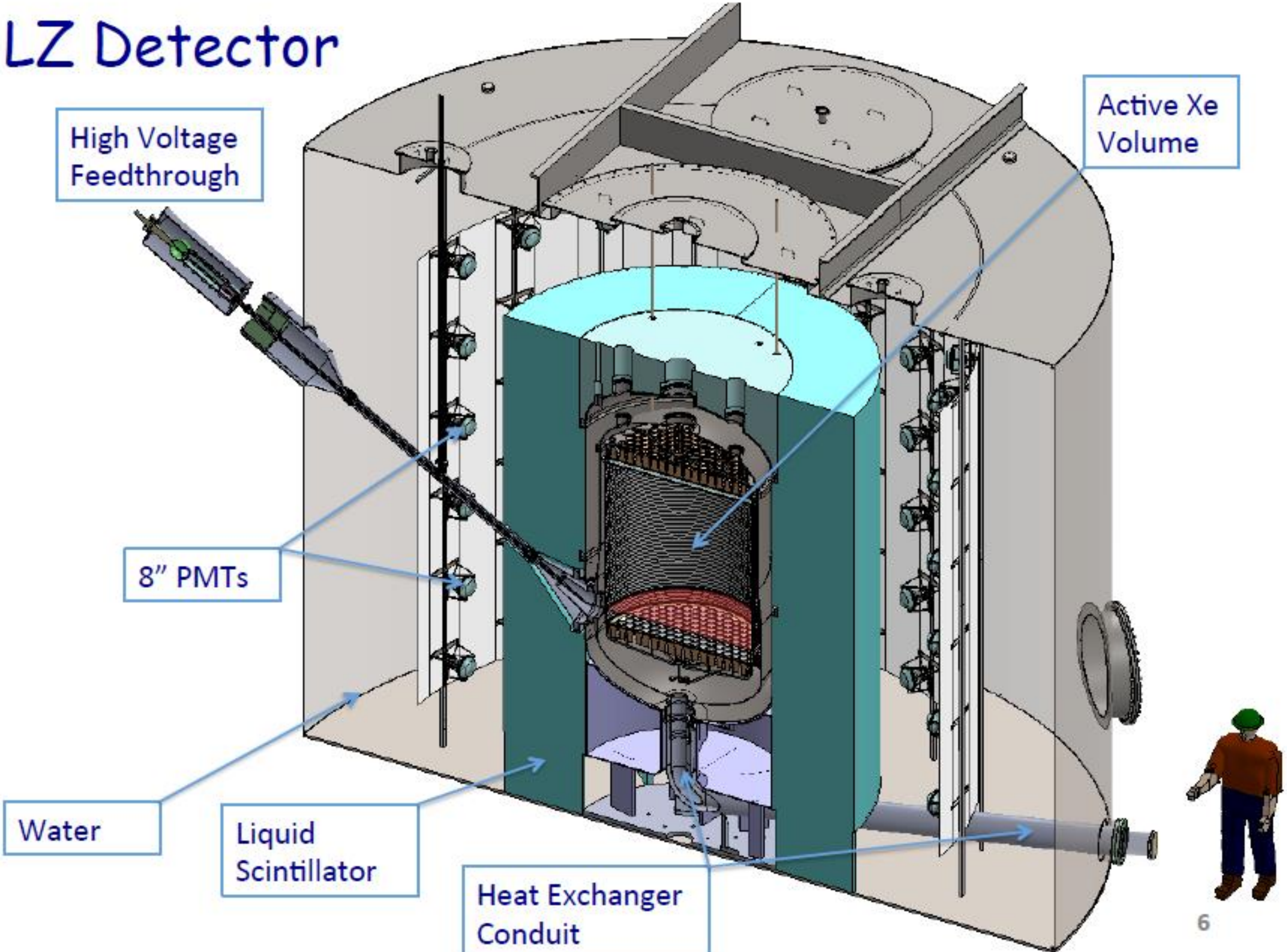




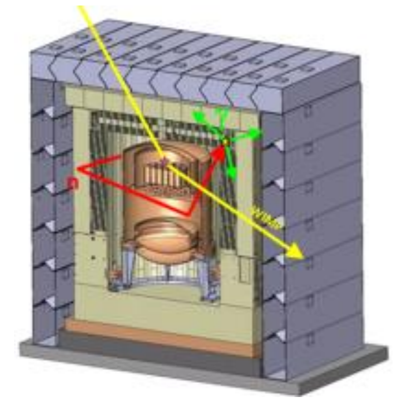
The LUX Result (and sensitivity progress)



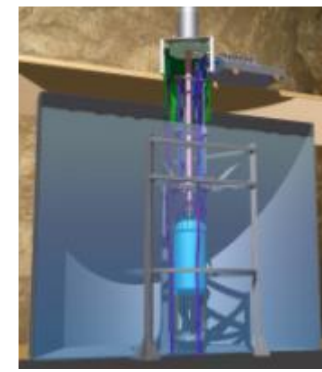
LZ Detector


High Voltage
Feedthrough
Active Xe
Volume
8" PMTs
Water
Liquid
Scintillator
Heat Exchanger
Conduit

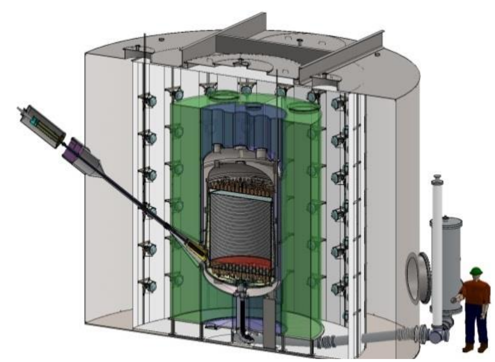
ZEPLIN → LUX → LUX-ZEPLIN



- **UK-led ZEPLIN programme at Boulby (2001-2011)**
  - Pioneered two-phase xenon technology
  - World class results from 3 xenon experiments
  - Fiducial mass ~6 kg



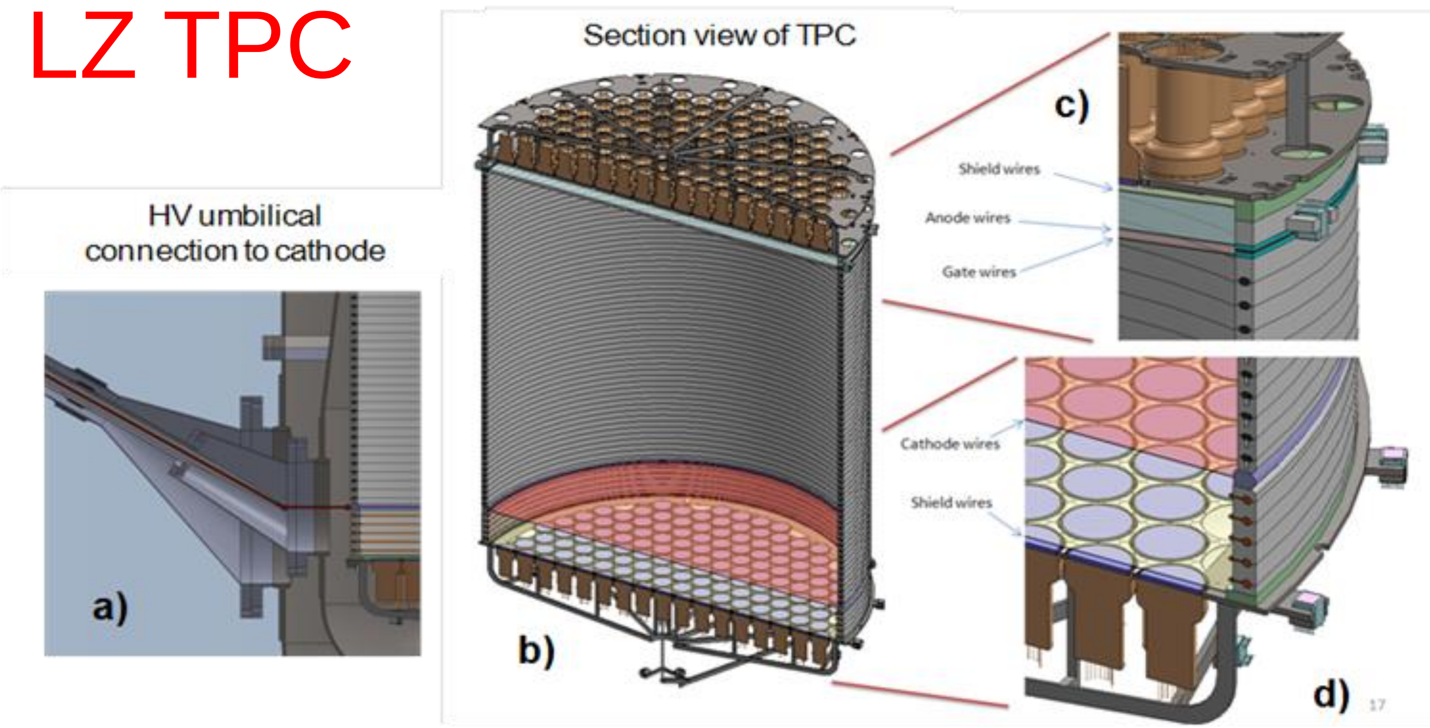
- **LUX operating at Sanford Underground Laboratory**
  - Imperial, Edinburgh and UCL joined after ZEPLIN-III
  - Present world-leading experiment
  - Fiducial mass ~100 kg



- **LZ: next-generation experiment**
  - LZ formed with MOU between LUX and ZEPLIN-III in 2008
  - Selected by DMUK for construction proposal to STFC
  - Fiducial mass ~5,600kg (~10^{-48} cm^2 sensitivity)
  - Conceptual design nearly completed, construction f. 2015

The University of Edinburgh · Imperial College London · University of Liverpool · University of Oxford · Science & Technology Facilities Council · The University Of Sheffield. · UCL

The LZ TPC



- **TPC PARAMETERS**
  - **1.5 m diameter/length (3x LUX)**
  - **7 tonne active LXe mass (28x LUX)**
  - **2x 241 3-inch PMTs (4x LUX)**
  - **Highly reflective PTFE field cage**
  - **100 kV cathode HV (10x LUX)**
  - **Electron lifetime 3 ms (3x LUX)**

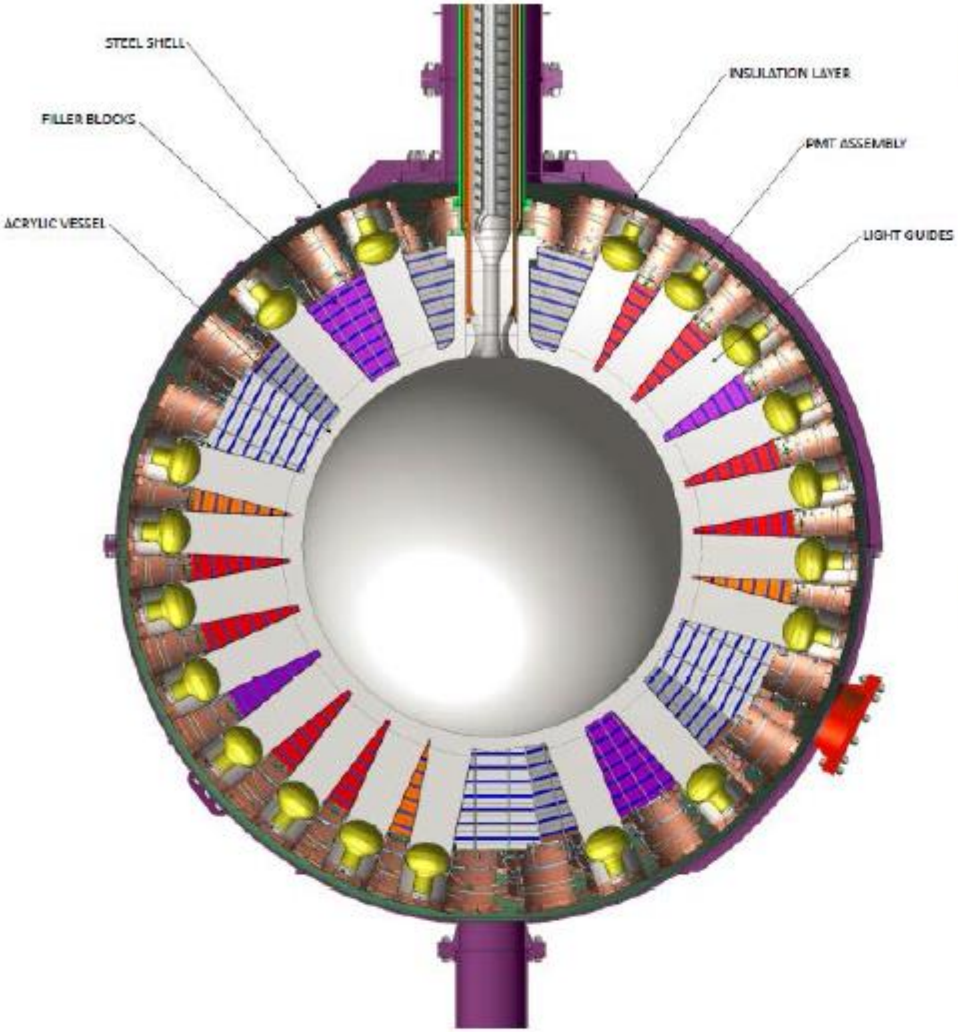
PHYSICS PARAMETERS

- **5.8 keVr S1 threshold (4.5 keVr LUX)**
- **0.7 kV/cm drift field, 99.5% ER/NR disc. (already surpassed in LUX at 0.2 kV/cm)**

TPC CALIBRATION

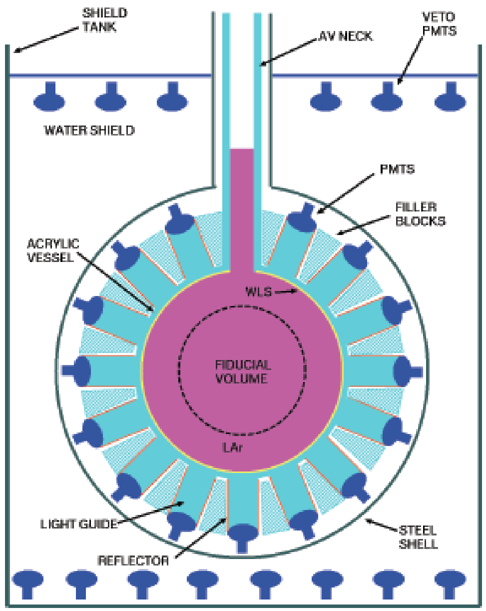
- **ER: Dispersed sources: Kr-83m, CH3T**
- **NR: AmBe, YBe, D-D generator**

Argon: DEAP-3600 Concept



- **3.6 tonnes of liquid Argon**
  - Enclosed in 85 cm radius acrylic ball
  - 1 tonne fiducial
    - Excluding surface events
- **Scintillation only**
  - Aka single phase
  - Light viewed by 255 photo-multiplier tubes

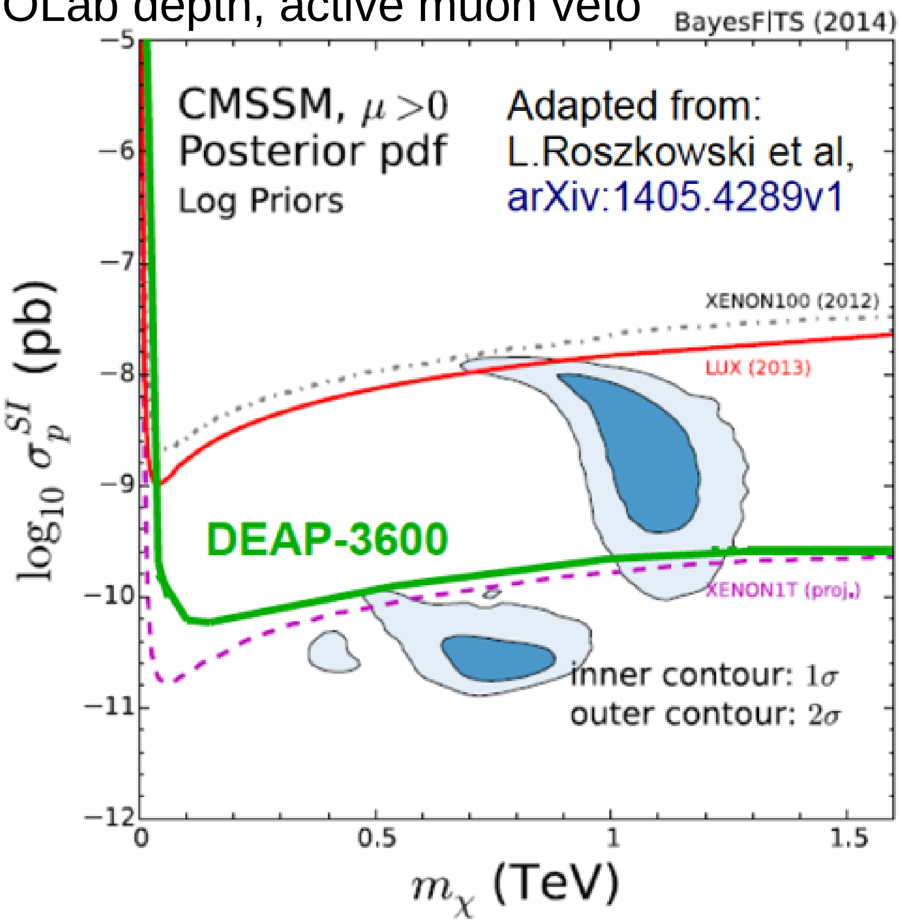
DEAP/CLEAN Single Phase Detectors



McKinsey and J. M. Doyle, J. Low Temp. Phys. 118, 153 (2

Open volume of cryogen, surrounded by PMTs in 4**π**, no electric field, to maximize detected PE per keV

Background strategy: pulse shape discrimination using fast/slow scintillation to ID recoils and reject ^{39}Ar, self-shielding of LAr target to mitigate alphas, gammas, neutrons, + SNOLab depth, active muon veto



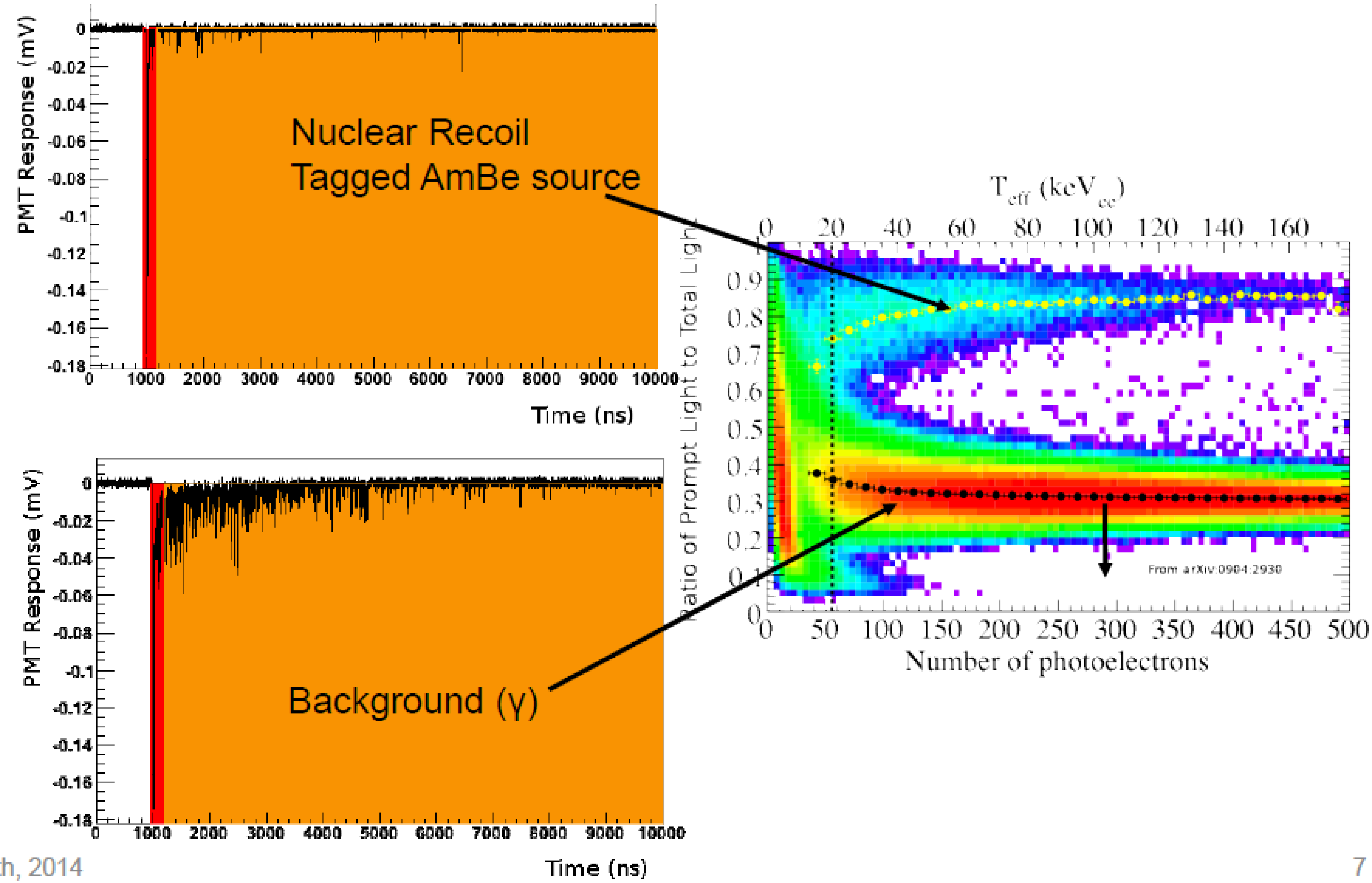
Staged detector development programme:

MiniCLEAN: measure PSD, prototype LAr/LNe target exchange to test A^2 scaling

DEAP3600: dark matter discovery reach of 10^{-46} cm^2 in 3 tonne-yrs exposure, at conservative 60 keVr threshold

UK: Calibration, Refrigeration, Veto systems

DEAP-3600 Pulse Shape Discrimination



Summary

Noble liquid detectors (Xe) clearly geared for exploring very low WIMP-nucleon cross sections.

Cryogenic detectors focus on low-mass WIMPs.