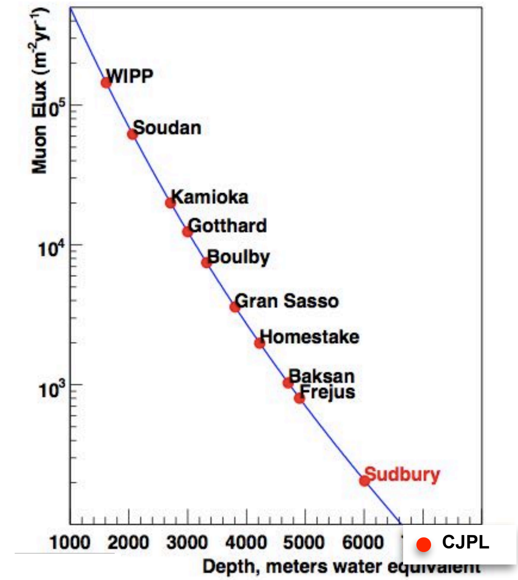
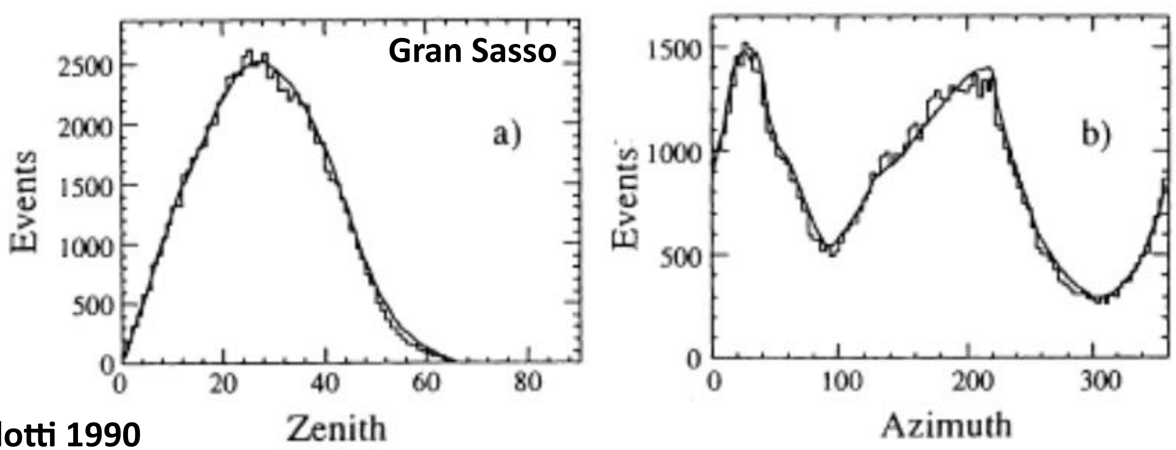
WIMP Direct Search Challenges

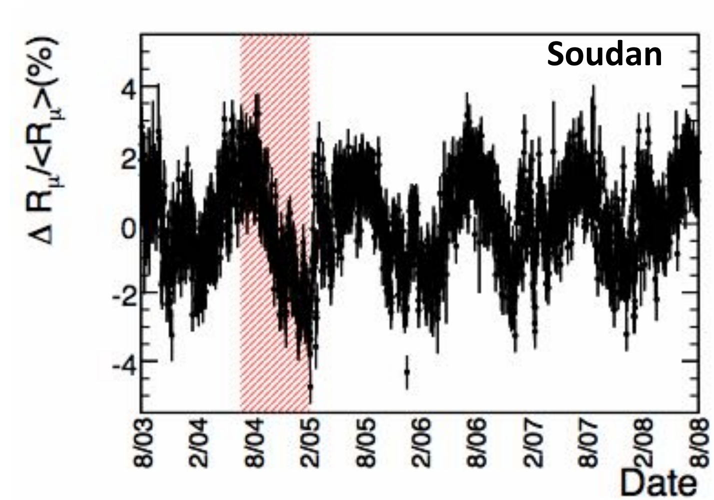
- WIMP nuclear recoil signal is:
  - Low rate (<~events/tonne/year)
  - Small energy (1-100 keV actual: observed is less)
- Detection technique must be:
  - Low background
    - Gamma, beta: from U/Th/Co/Pb/etc radio-impurities
    - Neutron: from U/Th radio-impurities and c.r. μ spallation
    - Radon daughters: environment and emanation
  - Low energy threshold
    - To minimise form factor, maximise energy spectrum
  - Discriminating & Position sensitivity
    - Discriminate between WIMPs/n and γ/β/α
    - Background rejection, neutron multiplicity calibrations
    - Directionality
  - Large mass

Effect of over-burden

- Deep underground facilities provide significant rock overburden and commensurate reduction in c.r. flux, and c.r.-spallation induced products (neutrons)
- Muons can be veto'd in anti-coincidence shield; secondary products may be an issue
- Cosmogenics may require underground material production or purification
  - May also contribute to b/grounds (e.g. ^{11}C)
- Muon flux depends on
  - overburden
  - overburden profile
  - seasonal effects







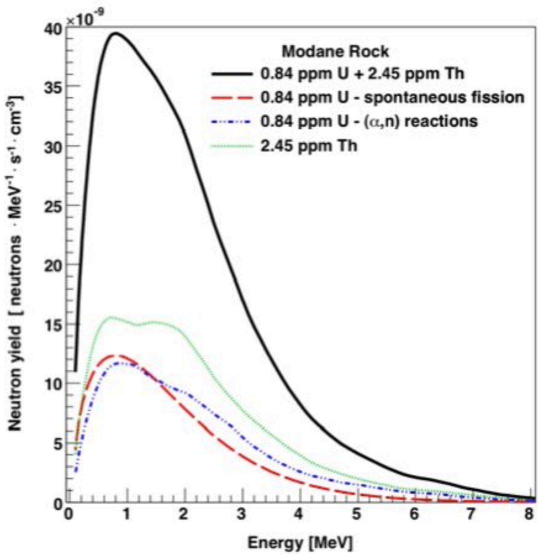
Bellotti 1990

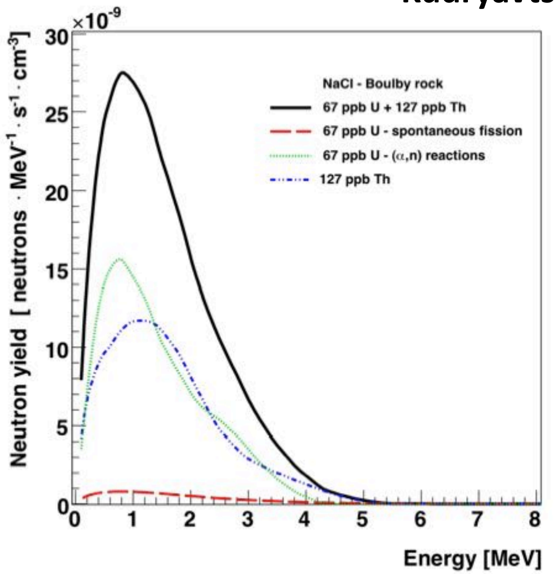
Adamson 2010

Neutron backgrounds

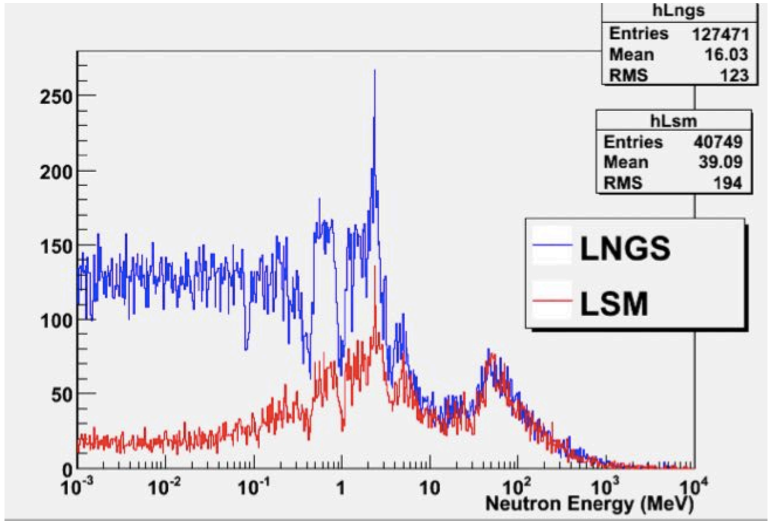
- Neutron production from
  - c.r. muon spallation
  - U/Th fission
  - α, n reactions
  - radon reactions

Kudryavtsev





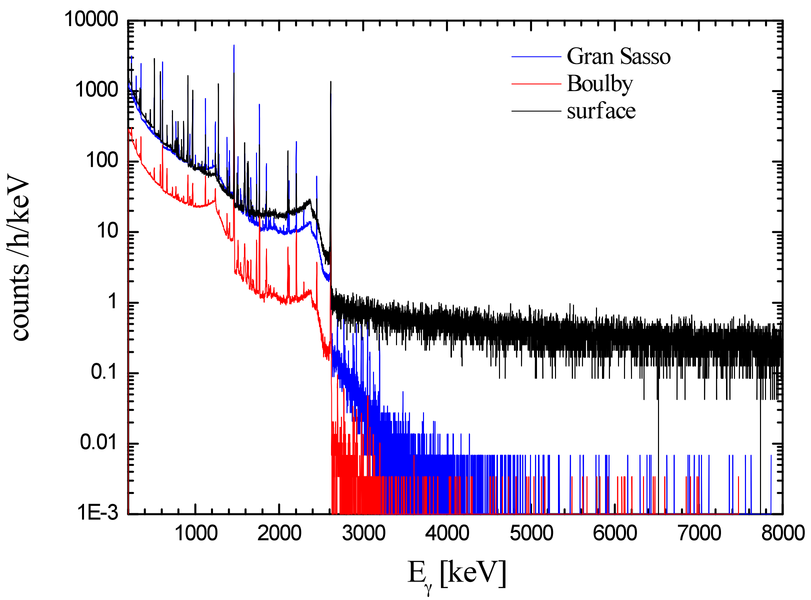
- Spectrum in laboratory depends on local geology (rock composition)
  - both for fast and thermal neutrons
  - U/Th + moderators
  - muons + moderators
  - small levels of high neutron cross-section contaminants make a big difference



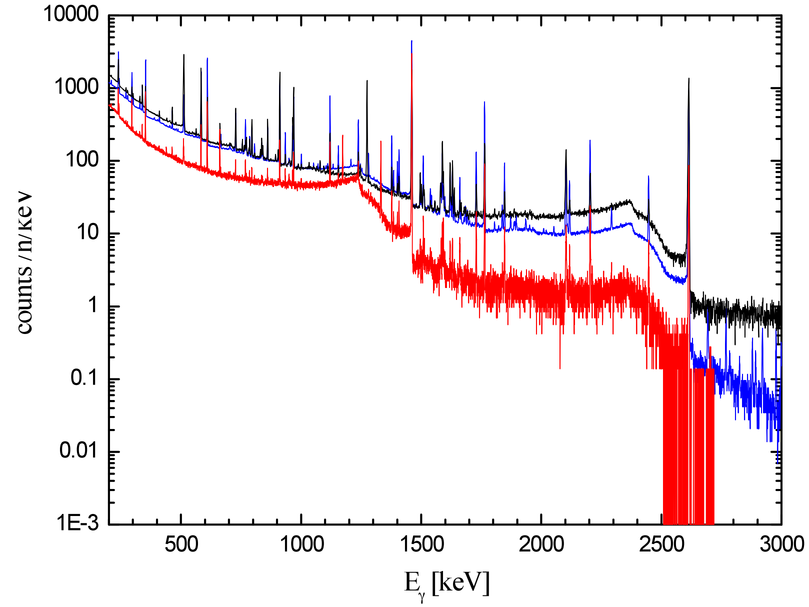
Persiani / Selvi

γ-ray Backgrounds

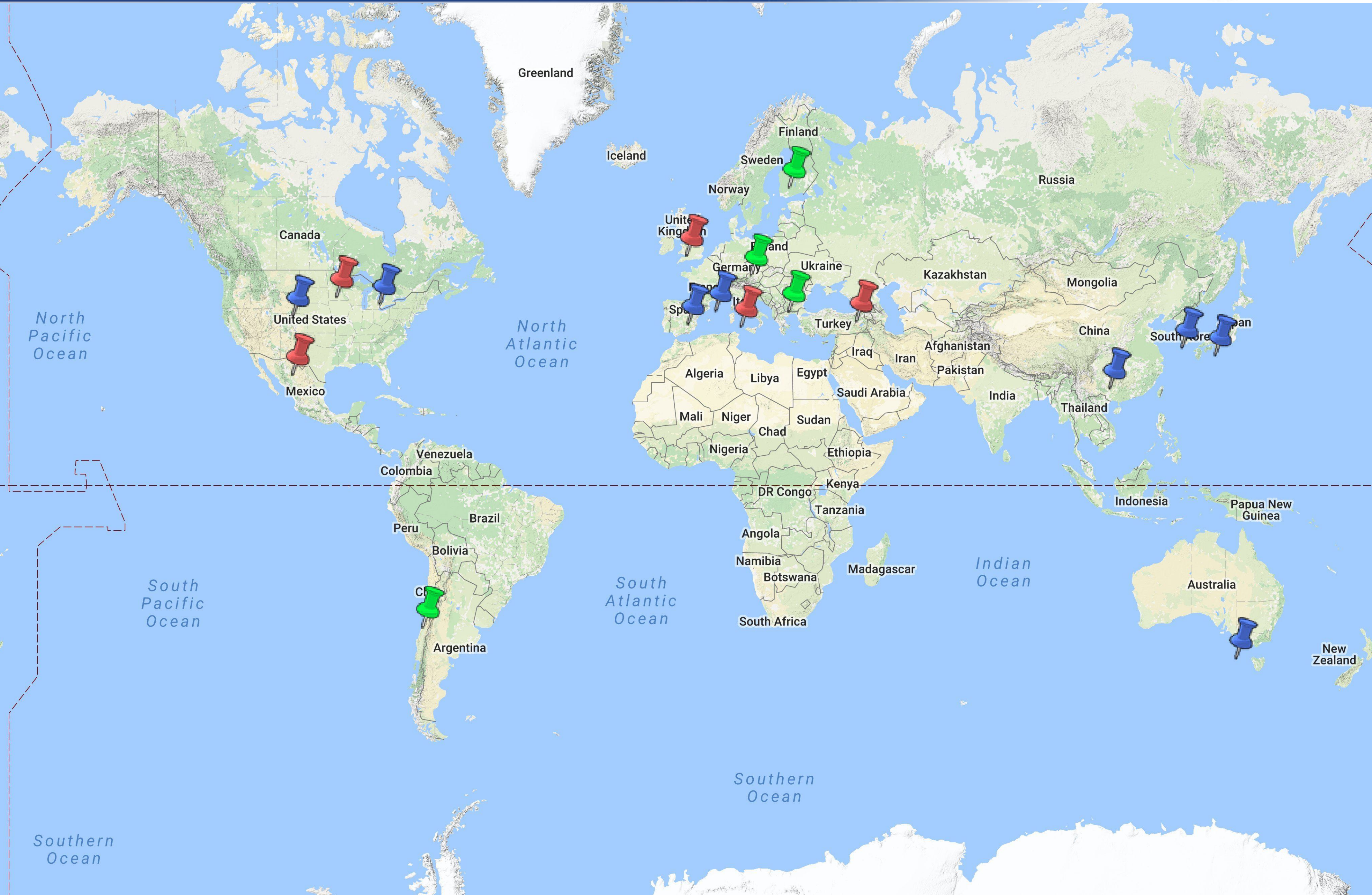
- Reduction in γ-ray background at higher energies from c.r. and neutron reduction
  - important for nuclear astrophysics dedicated beam experiments, and some $0\nu\beta\beta$ isotopes



- Below 3.5MeV dependent on local geology and rock material
  - Boulby (red)
  - Gran Sasso (blue)
  - surface (black)



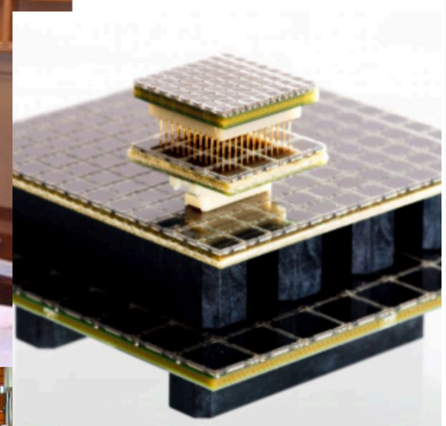
Underground Facilities



Intrinsic Backgrounds

- Removal of external backgrounds by depth and shielding
- Challenge is now control of internal backgrounds:

Intrinsic activity and assay



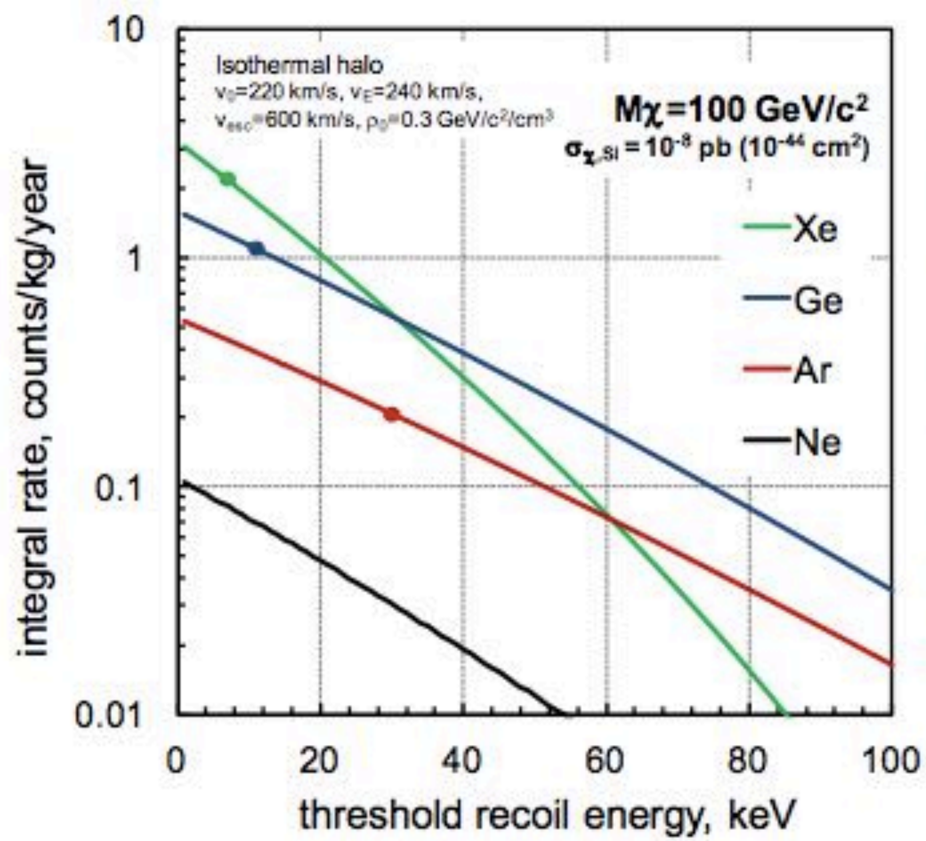
Low background material production and assay

Target radionuclide reduction

Radon mitigation

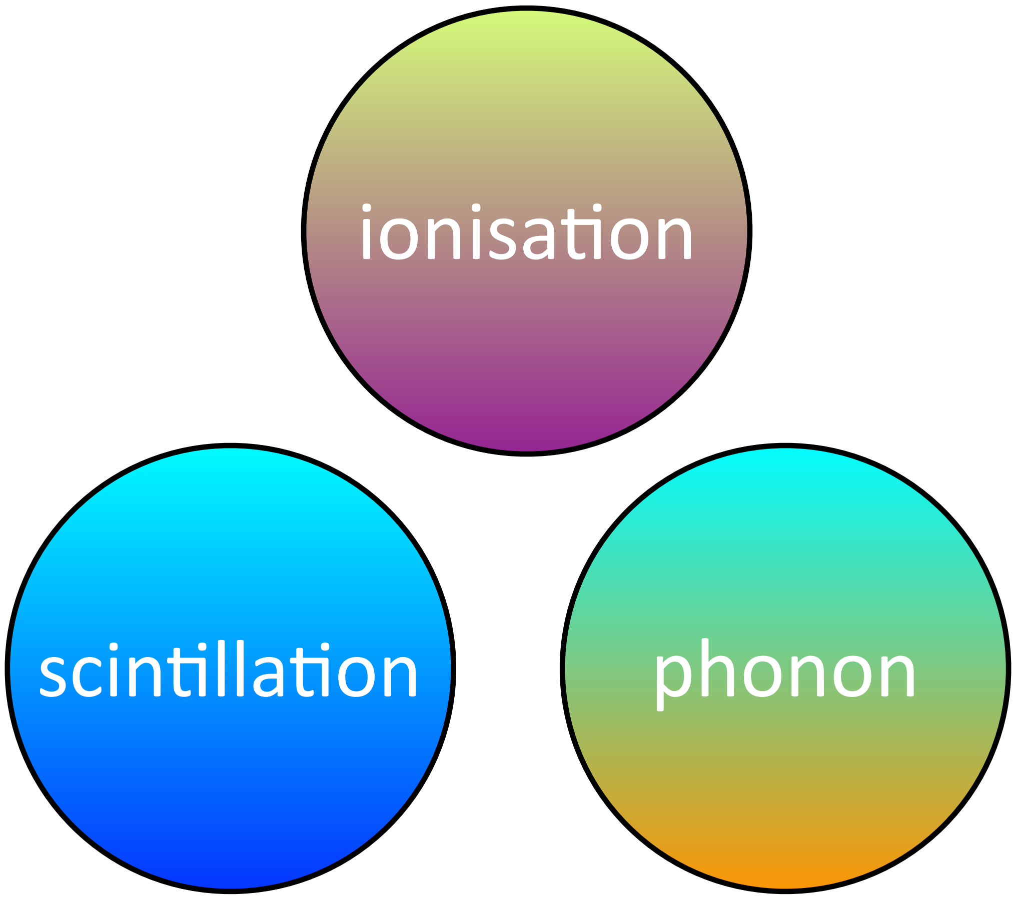
Response to elastic scattering

- Principle technique for WIMPs and neutrino detection is coherent elastic scattering off target nucleii
- For WIMP detection
  - low threshold required in xenon to maximise signal
  - higher threshold in argon for discrimination



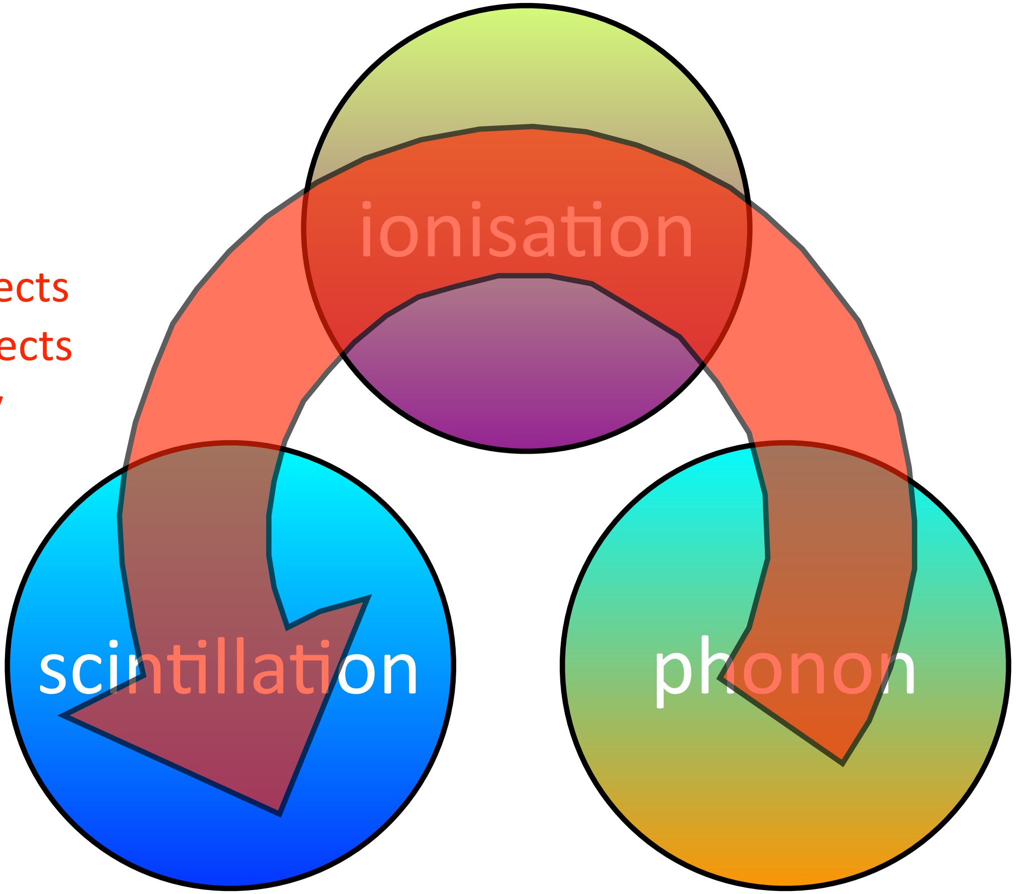
Chepel/Araújo

Detection techniques



Following Araujo

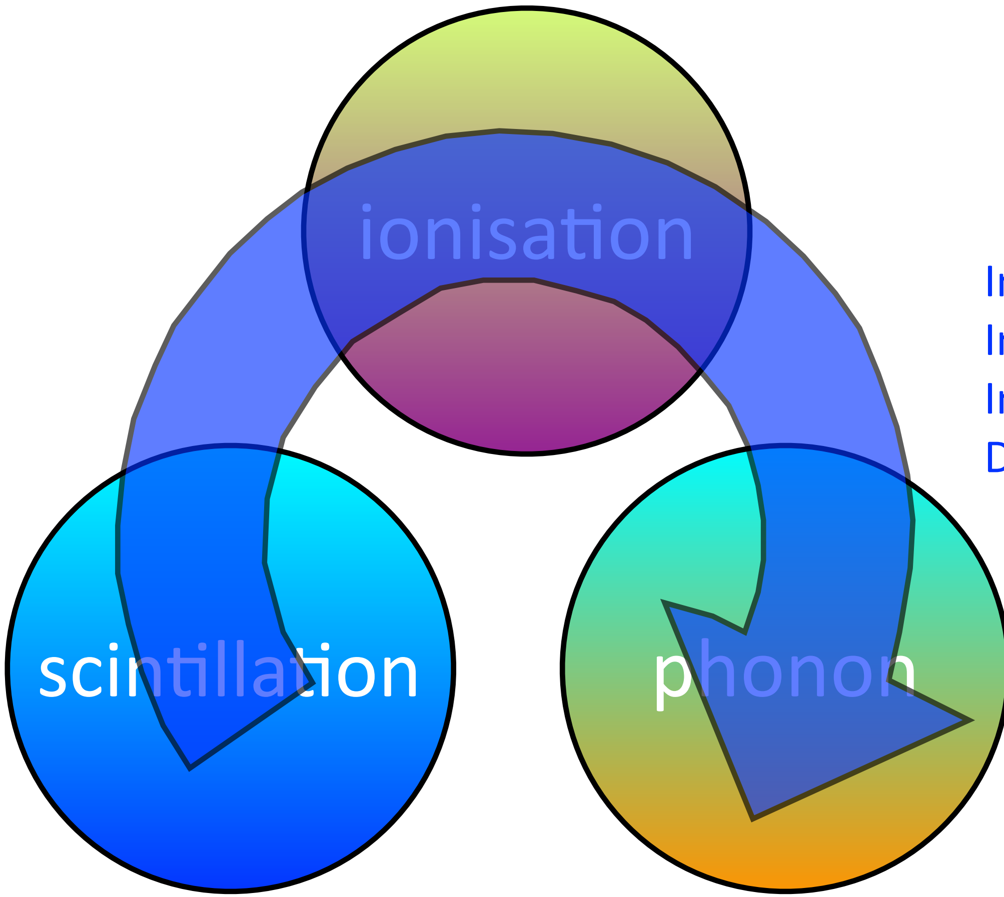
Detection techniques



Improve surface effects
Improve volume effects
Improve scaleability

Following Araujo

Detection techniques

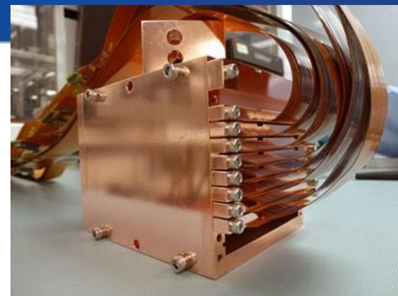


Improve resolution
Improve threshold
Improve noise
Decrease temperature

Following Araujo

Detection techniques

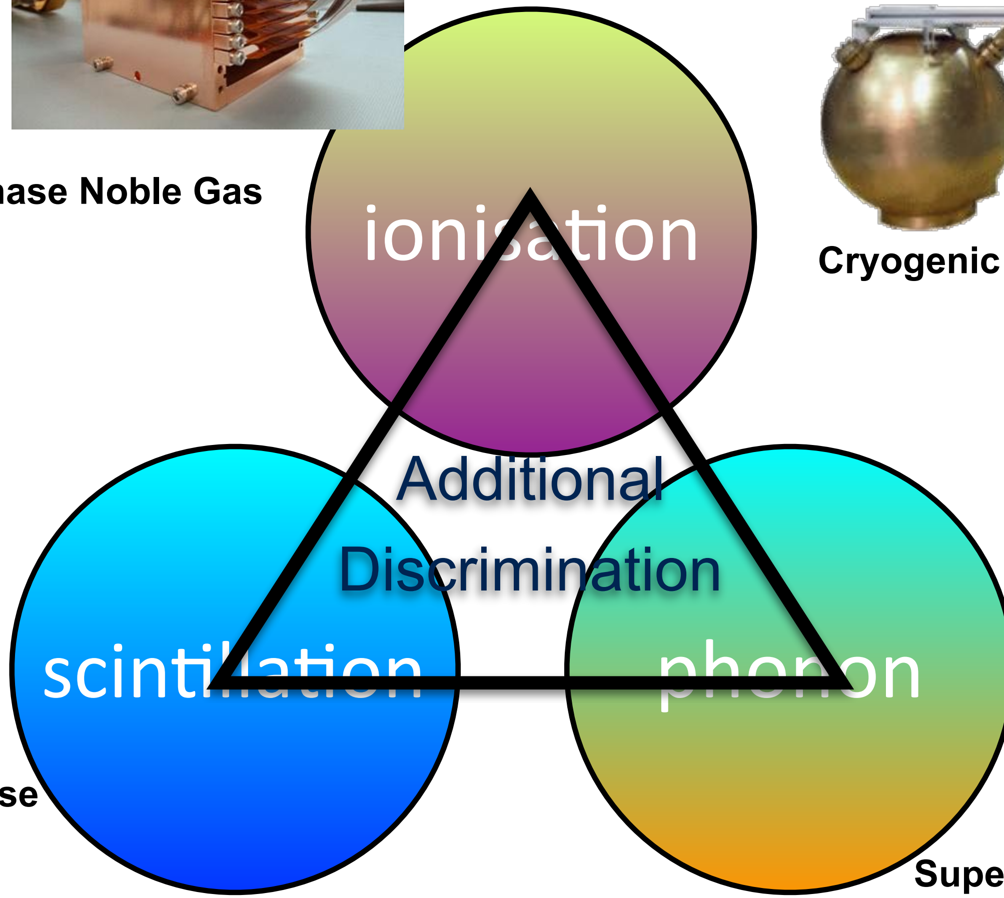
Two Phase Noble Gas

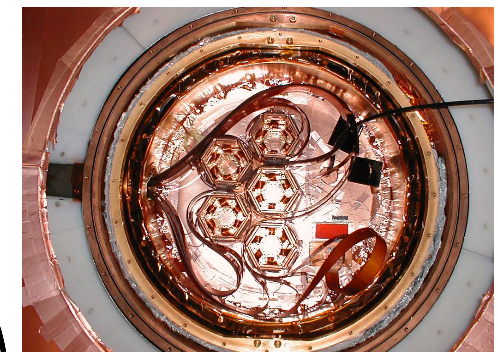


CCD

TPC / Directional

Cryogenic Ionisation





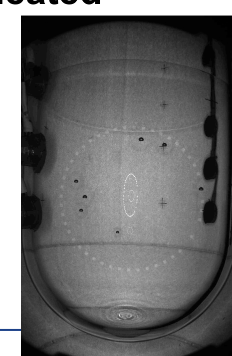
Cryogenic Bolometers

Single Phase
Noble Gas

Inorganic
Scintillators

Cryogenic Scintillators

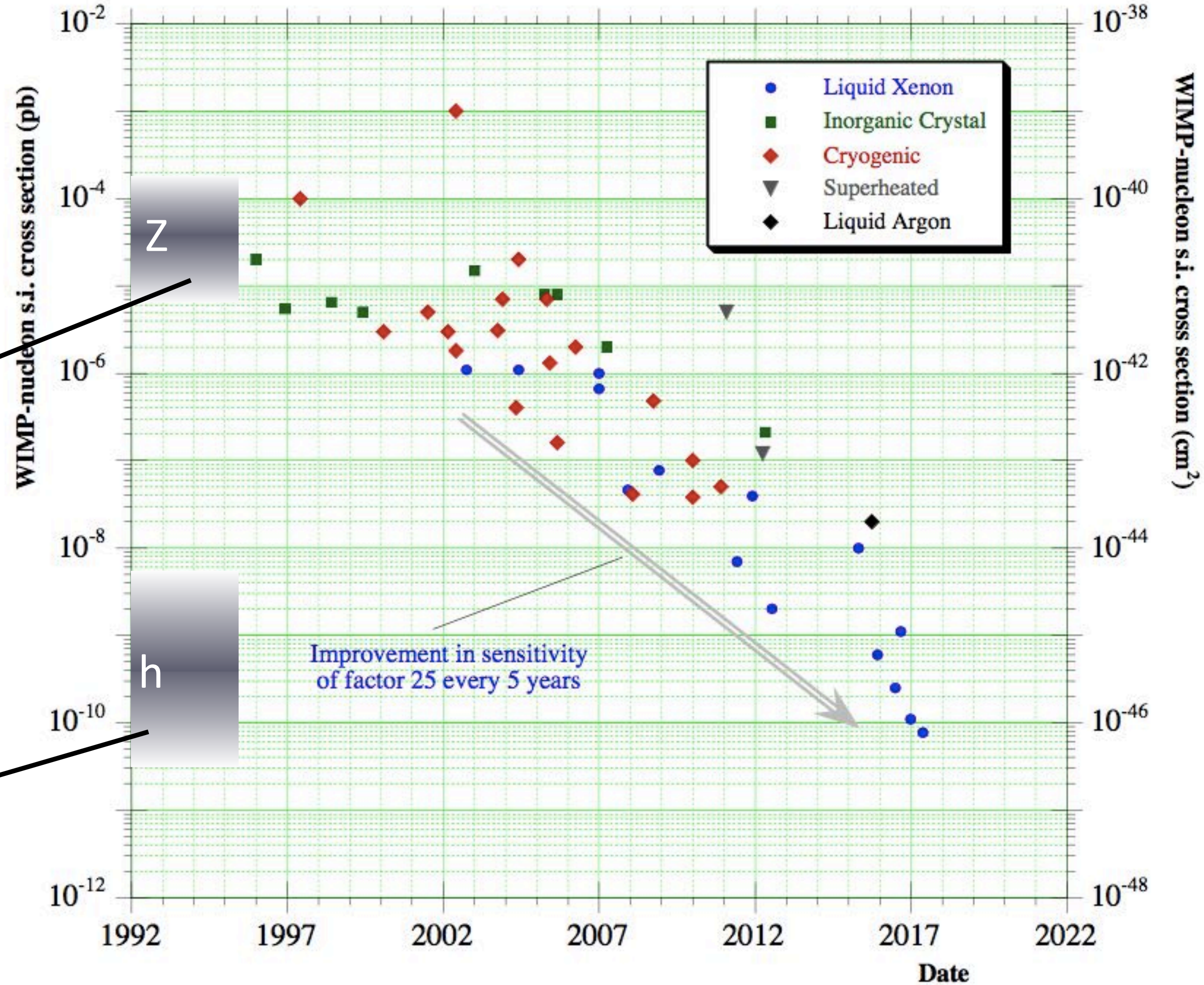
Superheated
Fluid



Following Araujo

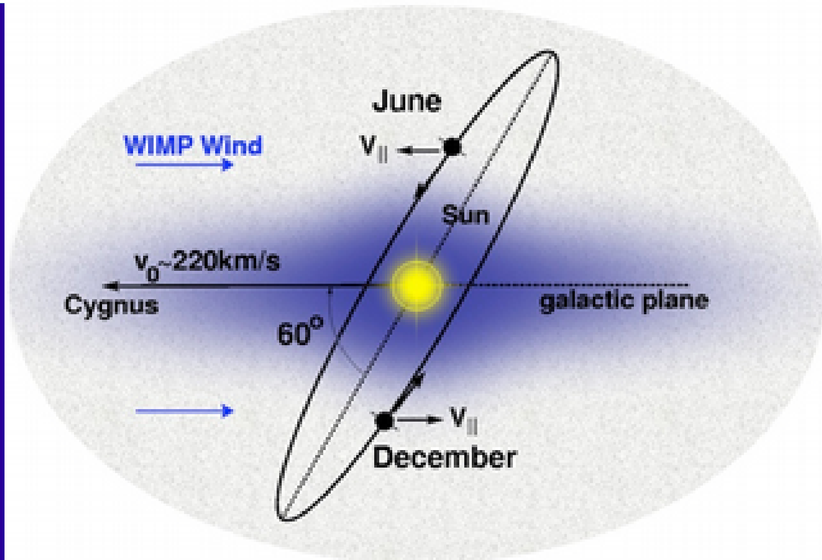
Strong and steady progress made

- Direct detection sensitivities improving factor 25 every 5 years
- Already (1990's) excluded Z-mediated exchanges (e.g. heavy neutrinos)
- Now into higgs-mediated cross sections



After Gaitskell

Particles from the HALO



DM particles (whatever they are) interact in detectors producing low energy events (keV) with two characteristic **signatures**:

Annual Modulation

$$R(t) = Background + S_0 + S_m \cos\left(\frac{2\pi}{T}(t - t_0)\right)$$

Directionality

DAMA-LIBRA

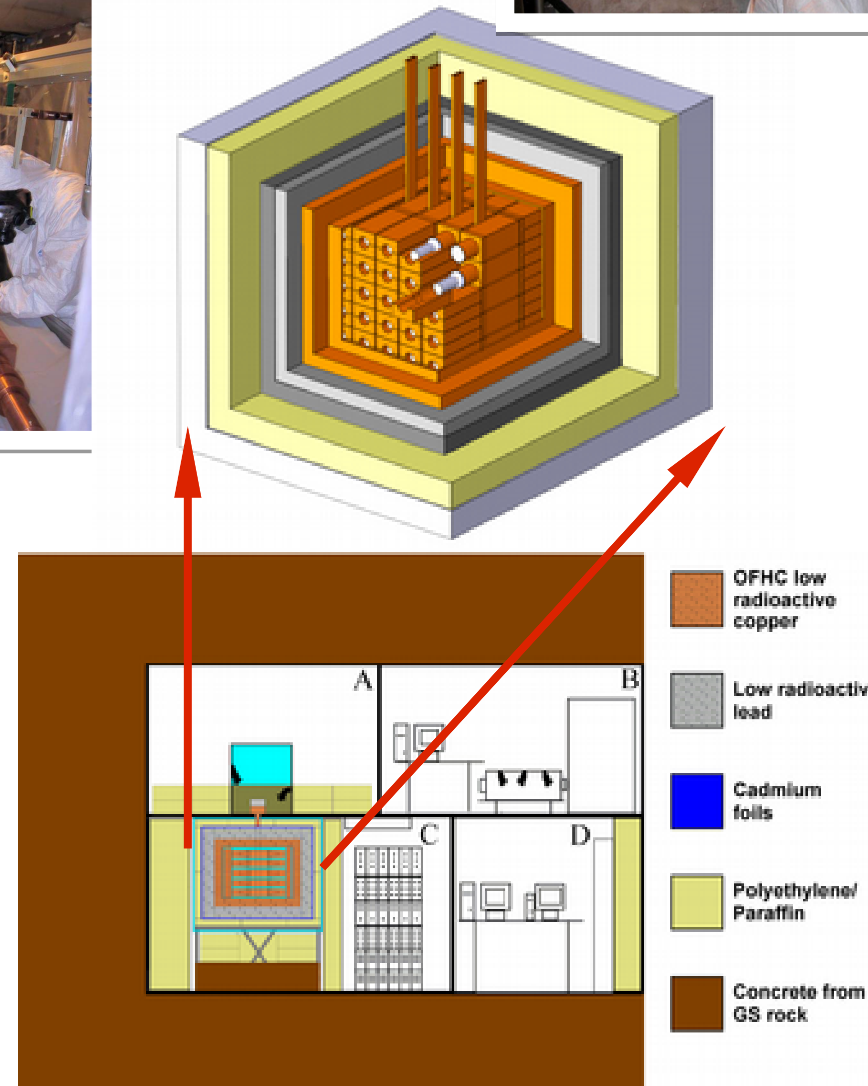
DAMA

- pioneering experiment with ultra-low background 1996-2002

LIBRA

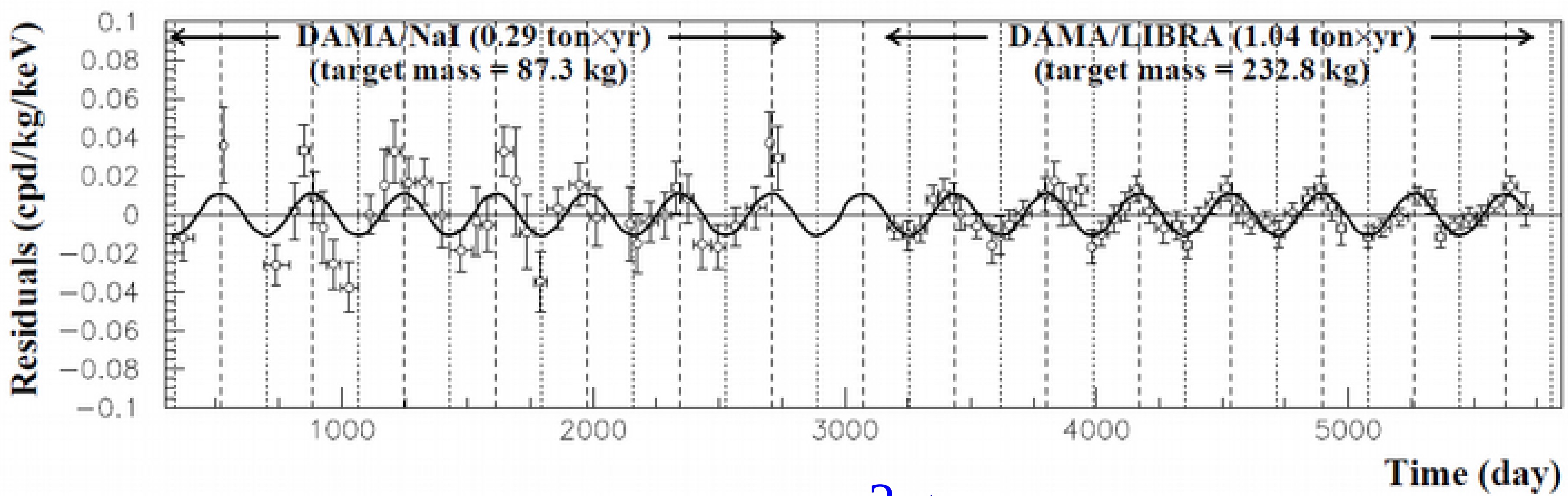
- **25 NaI(Tl) ~1 kg ultrapure crystals**

  (residual contam. ~10^{-12} g/g in Th/U/K)
- **two low radioactivity PM for each crystal**
- **heavy shielded:** Cu+Pb+Cd+polyethylene/paraffin
- three level **anti Rn system**
- **PHASE II (PM upgrade) running**



Dama/Libra – annual modulation

ANY EVENT in 2-6 keV: Electron Recoils & Nuclear Recoils



Single-hit residuals *vs* time: $S_m \cos\left(\frac{2\pi}{T}(t-t_0)\right)$

EPJC 56(2008)333
EPJC 67(2010)39
EPJC 73(2013)2648

Fit with all the parameters free:

S_m = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d
T = (0.998±0.002) y

Significance: 9.3 σ

Expectations:
t_0 = 152.5 d (2nd June)
T = 1 y

Dama/Libra – cross checks

PHASE I: results pubblished

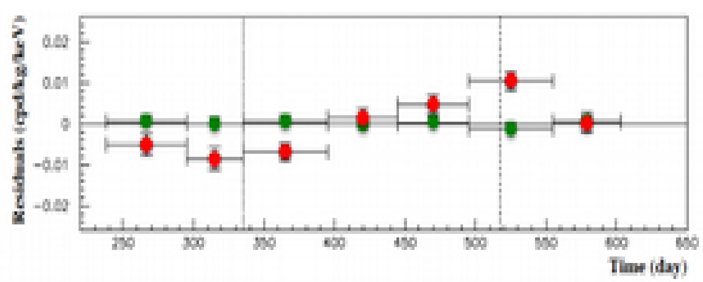
several cross checks:

1) reliability of the result

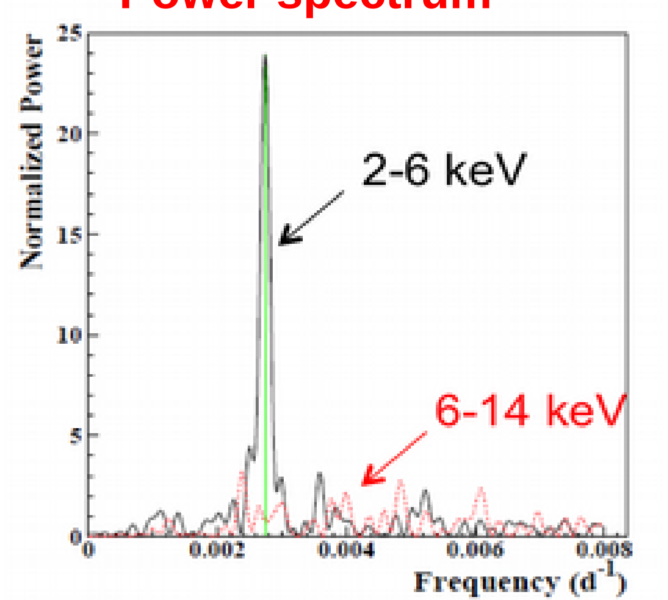
2) alternative sources of modulation done

Single-hit residuals vs. multi hit residuals

S_m =-(0.0005±0.0004) cpd/kg/keV



Power spectrum



- No modulation above 6 keV
- No modulation in the whole energy spectrum
- No modulation in the 2-6 keV multiple-hit events

PHASE II ongoing

all PMTs replaced with new ones of higher Q.E. (2010)

Previous PMTs: 5.5-7.5 ph.e./keV
New PMTs: up to 10 ph.e./keV

PHASE III possible

DISCOVERY ?

How can this result be confirmed ?

identical technique → **SABRE** **(ANAIS, IDM-Ice)**

SABRE

scrutinize DAMA signal: identical technique + improved set-up

NaI(Tl) scintillating crystals:

- very low background via crystal purity
- active rejection through liquid scintillator veto

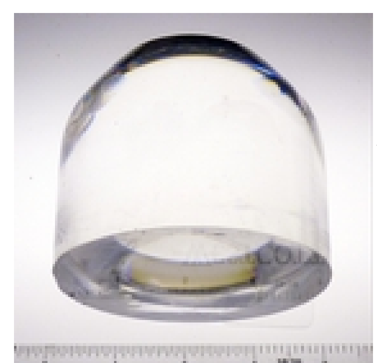
twin detectors:

- underground at LNGS
- Stawell (Australia) gold mine → Seasons have opposite phases !!

key issue: control of ^{40}K

^{40}K → (EC 10%)

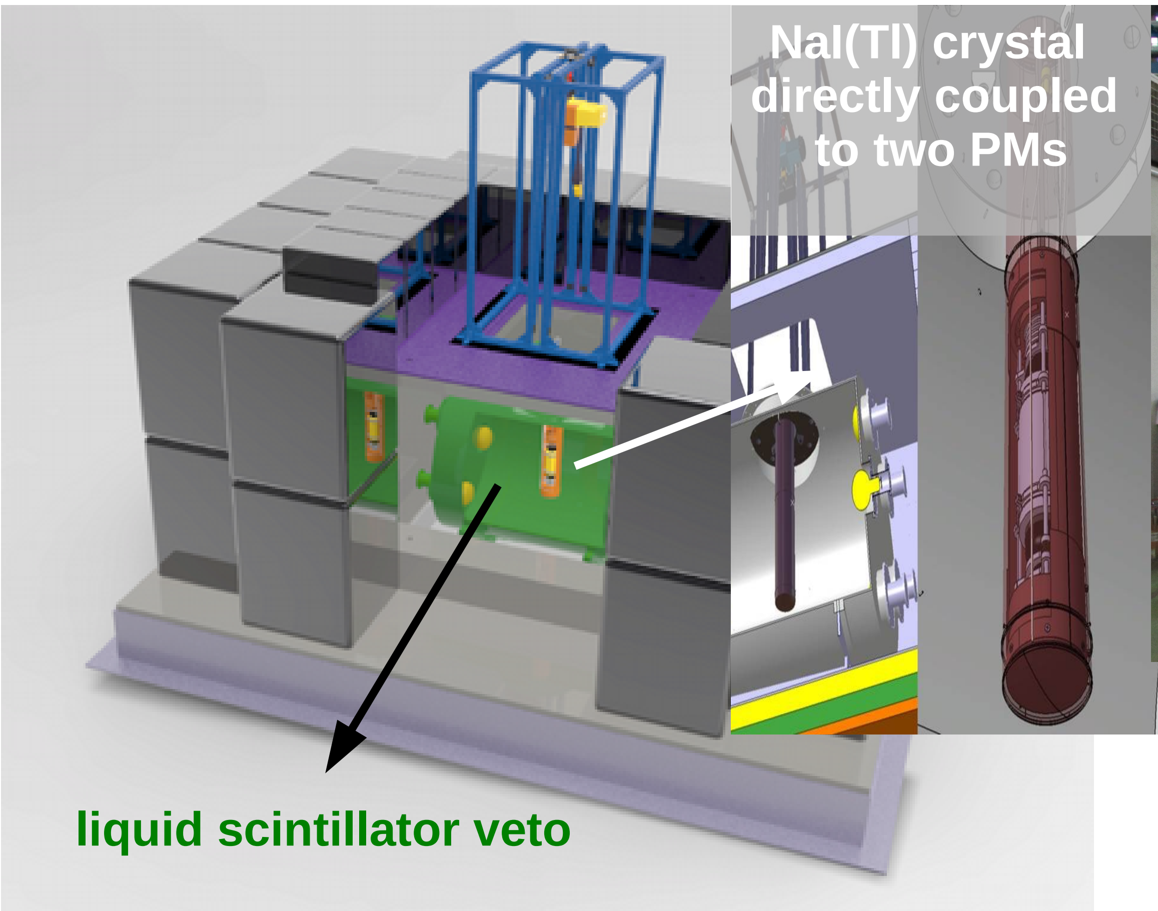
→ 1460 keV + 3 keV (X/Auger)



2kg crystal grown from SA Astrograde powder
^{39}K in crystal:
11-15 ppb ^{40}K in crystal
→ at DAMA level

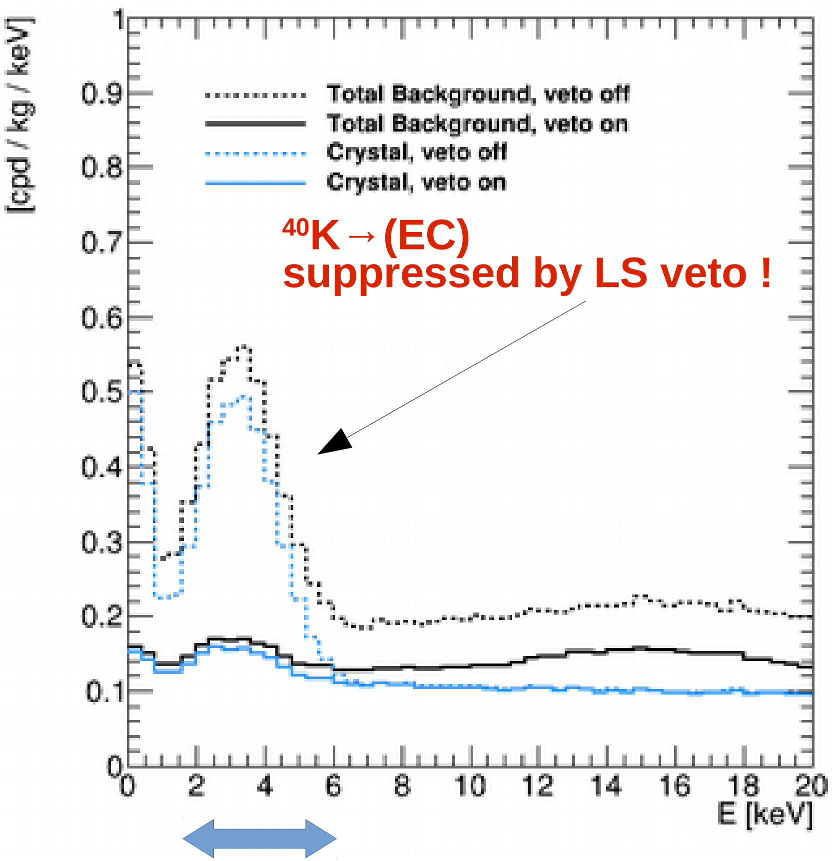
SABRE – Prove of Principle (PoP)

PoP under construction at LNGS



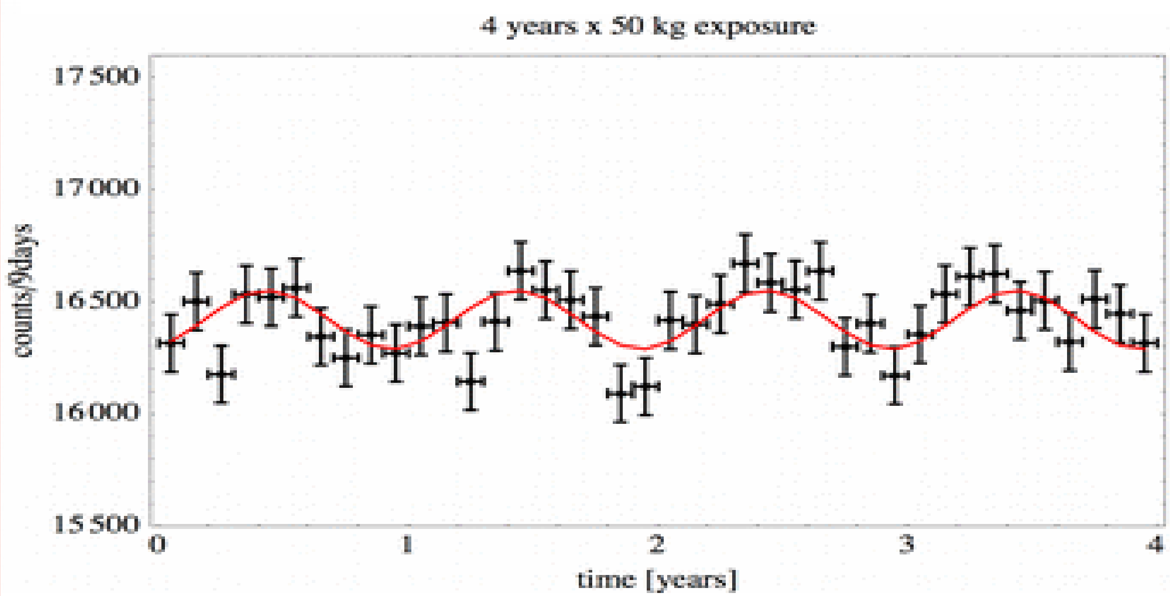
SABRE – Sensitivity

MC simulations of background contributions in PoP



Expected Sensitivity

Exposure = 4 years x 50 kg
Background in ROI = 0.53 dru (conservative)
Three free parameters



DISCOVERY ?

How can this result be confirmed ?

identical technique → **SABRE** **(ANAIS, IDM-Ice)**

similar approach (ER+NR) → **CoGENT** - **Xenon – XMASS ....**

assuming NR interaction → **many other**

hypotheses on interaction and detector response

Cryogenic Solid State detectors

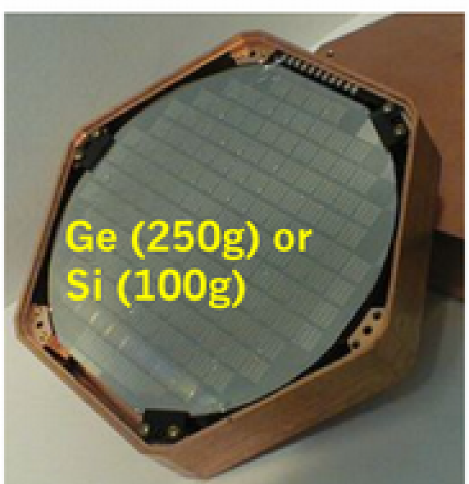
CDMS II (Soudan)	EDELWEISS (Modane)	CRESST II (Gran Sasso)
Phonon	*Bolometric*	*Phonon*
Photolithography W-TES sensors w/Al fins SQUID readout	(NTD-Ge) sensor FET	Superconducting thin W-film TES SQUID readout

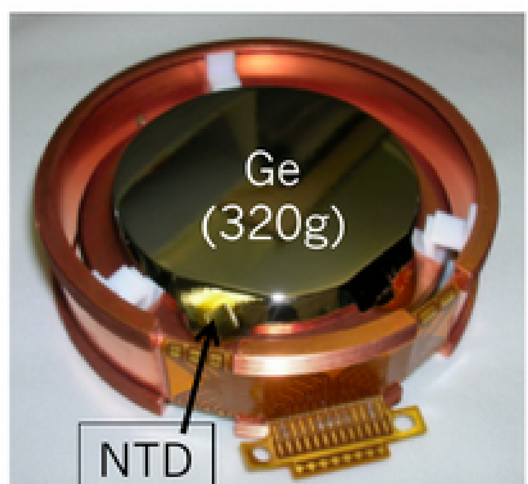
Ionization

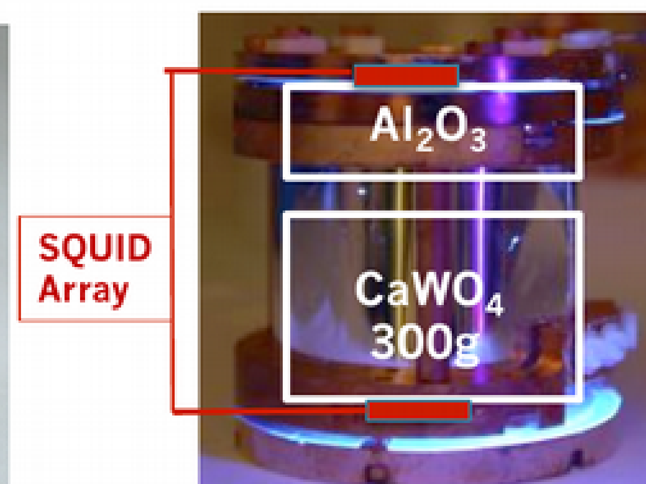
Apply voltage across crystal
Read out drifted charge from FET

Scintillation

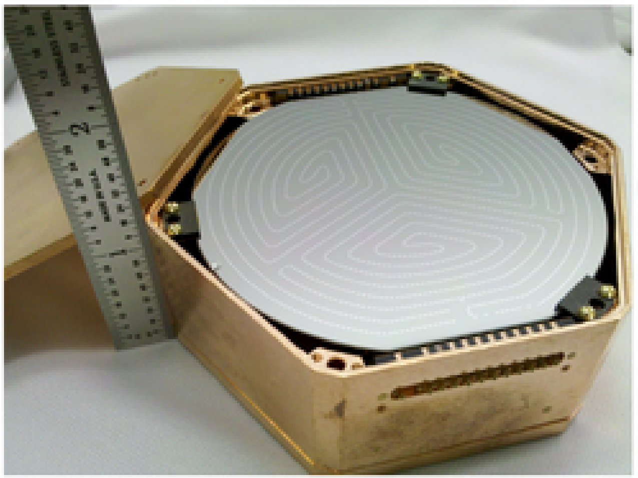
light from $CaWO_4$

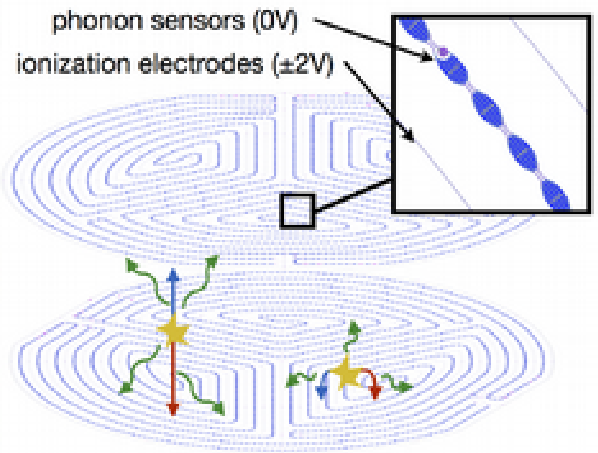


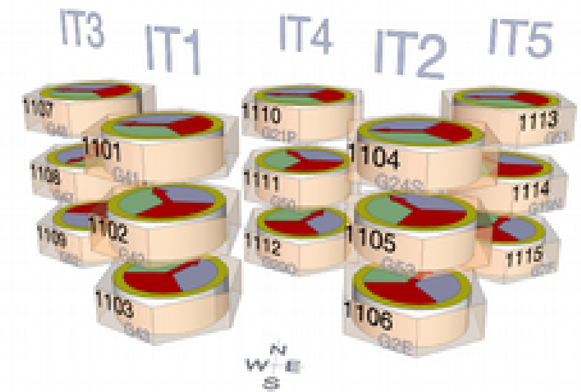




SuperCDMS & CDMSLite







- 2 km w. e. Soudan
- CDMS II infrastructure
- **0.6 kg Ge x 15** detectors
- **ionization + phonon** (Luke-Neganov)
- **iZIP** fiducial volume definition

SuperCDMS

- 577 kg y (7 detectors)
- 11 events survive cuts (compatible with bkg)

CDMSlite

10.1 day x 1 detector

specially operated in high V Luke-Neganov to reach a **0.8 keV$_{NR}$**

move to SNOLAB + operate iZIP and HV (no ionization)

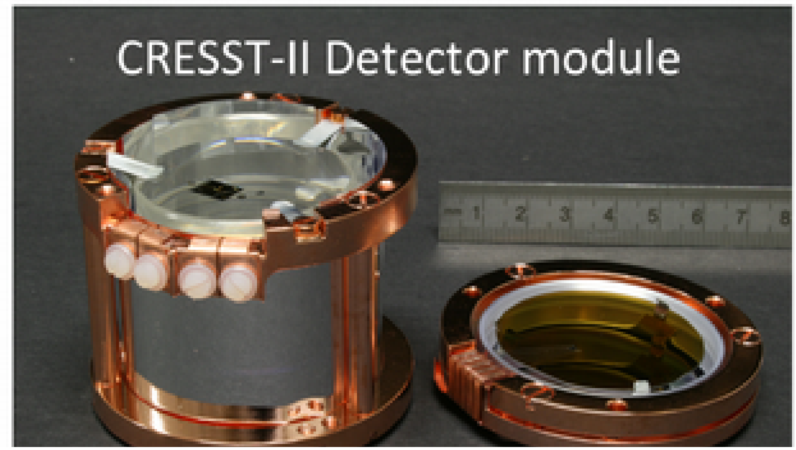
CRESST

Cryogenic Rare Event Search with Superconducting Thermometers

Scintillating $CaWO_4$ crystals as target

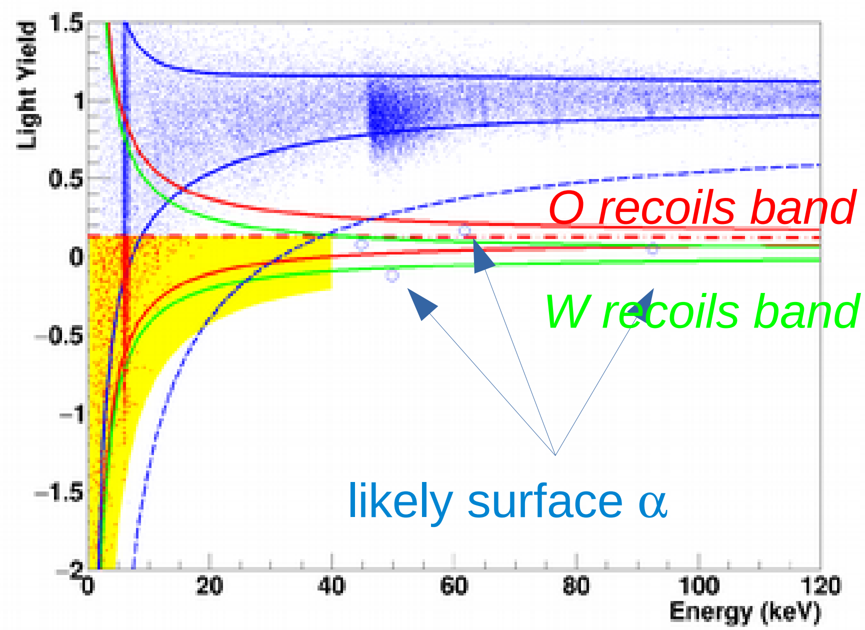
Target crystals operated as **cryogenic calorimeters** (~15mK)

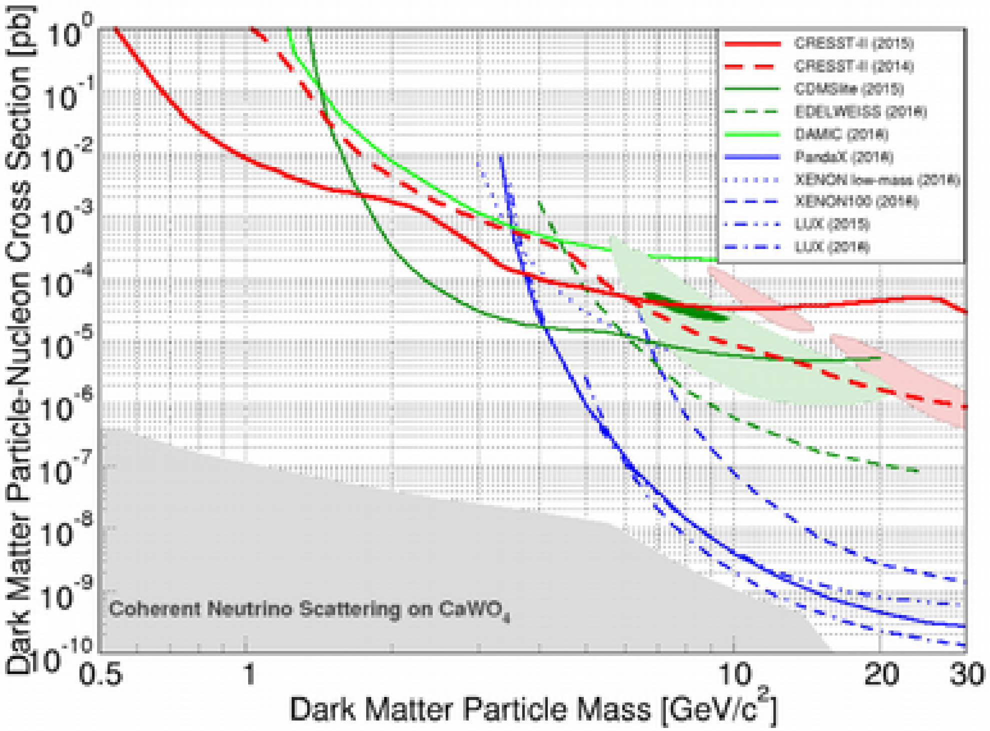
Separate **cryogenic light detector** to



CRESST II- phase 1 (2014)
re-analyzed no more signal

CRESST II- phase 2 (2015)
LISA 300 g → 0.307 keV NR threshold





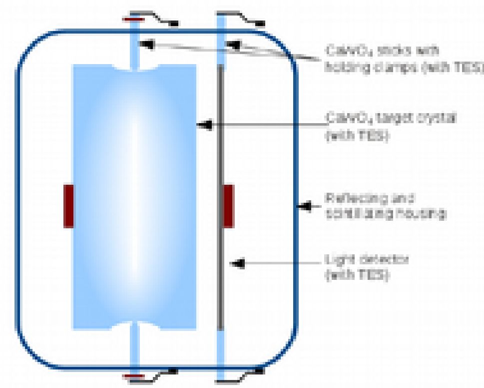
- 300g crystal
- 307eV nuclear recoil threshold
- world-leading result below 1.7GeV/c^2
- first experiment to explore masses in the sub-GeV/c^2 range

Searching for light dark matter requires a low threshold!

Change of strategy to improve sensitivity to low masses

Detector layout optimized for low-mass dark matter

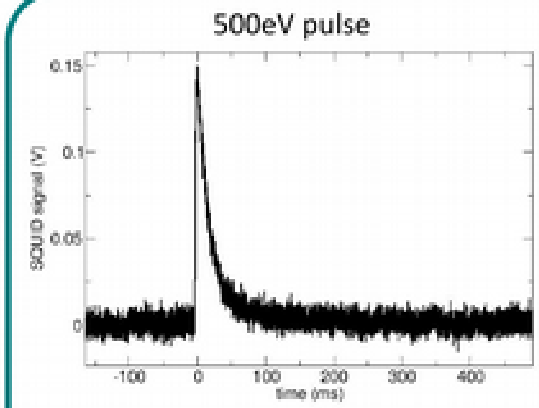
- clean self-grown crystals
- small crystal of (20×20×10)mm^3 (25g)
- 100eV threshold design goal
- small light detector (20×20)mm^2



6 modules with threshold <100eV running at LNGS

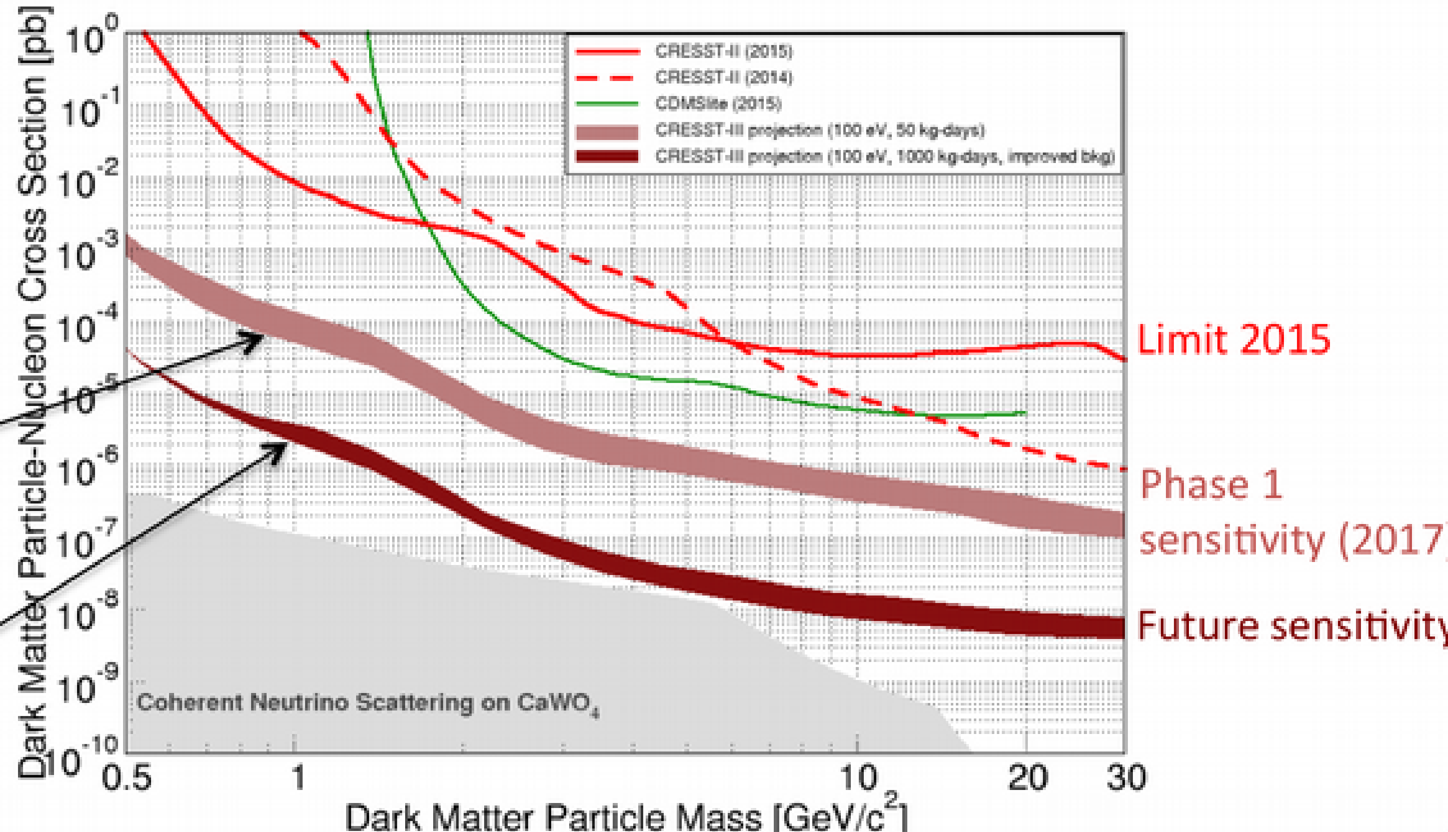
Threshold design goal exceeded

CRESST III – data taking ongoing since Summer



Projected sensitivity for 50kg days (1 year) with design goal threshold (100eV)

Projected sensitivity for 1000kg days (2 year with 100 detectors) with design goal threshold (100eV)

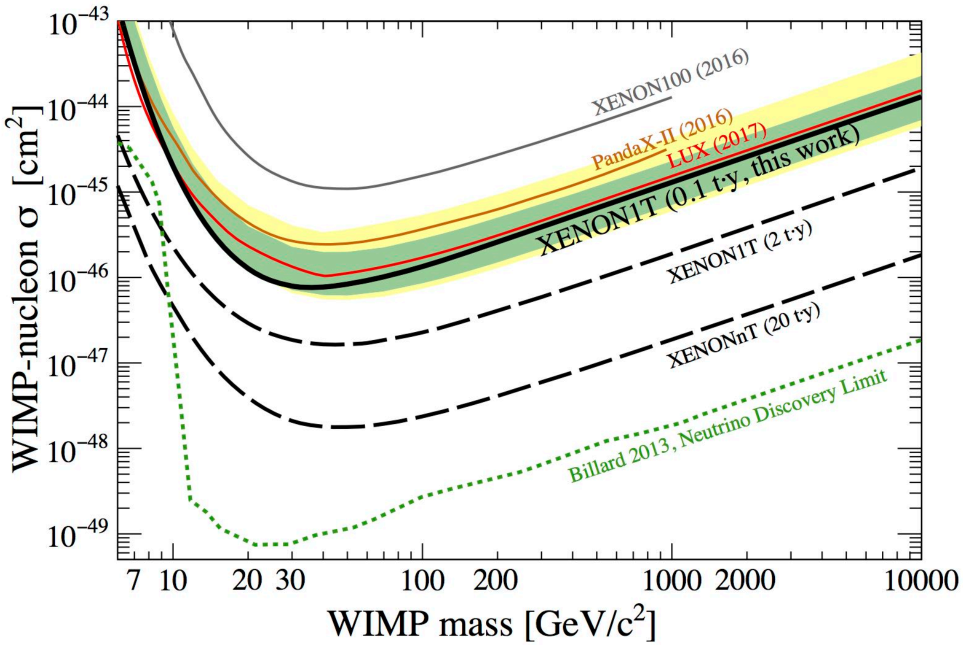


Extreme low mass sensitivity ideal for direct dark matter search and identification

Future: approach the neutrino floor

- material screening and purification of raw material for crystal production
  - factor of 100 reduction of background
- upgrade of LNGS facility to operate 100 detectors
  - 1000 kg days in 2 years

XENON1T



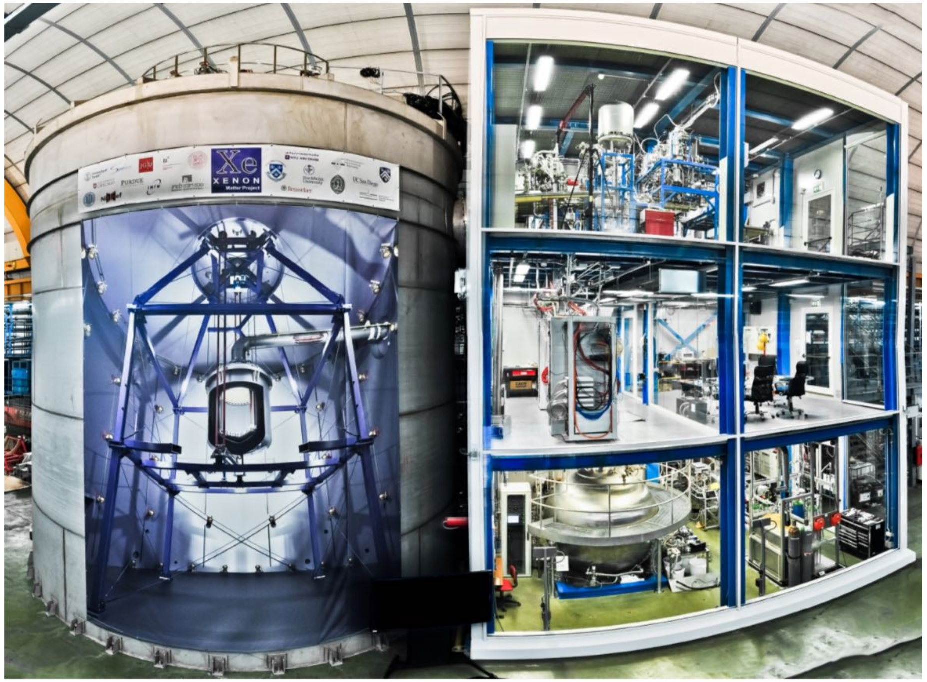
First science run: 34.2 live-days

- Largest ever Xe fiducial mass: 1042 kg
- Lowest ever low-E ER bg.: (0.193 ± 0.025) mDRU
- Most stringent SI-WIMP limit

Still running, >100 live-days taken

XENONnT upgrade planned for 2019

The first ton-scale LXe TPC

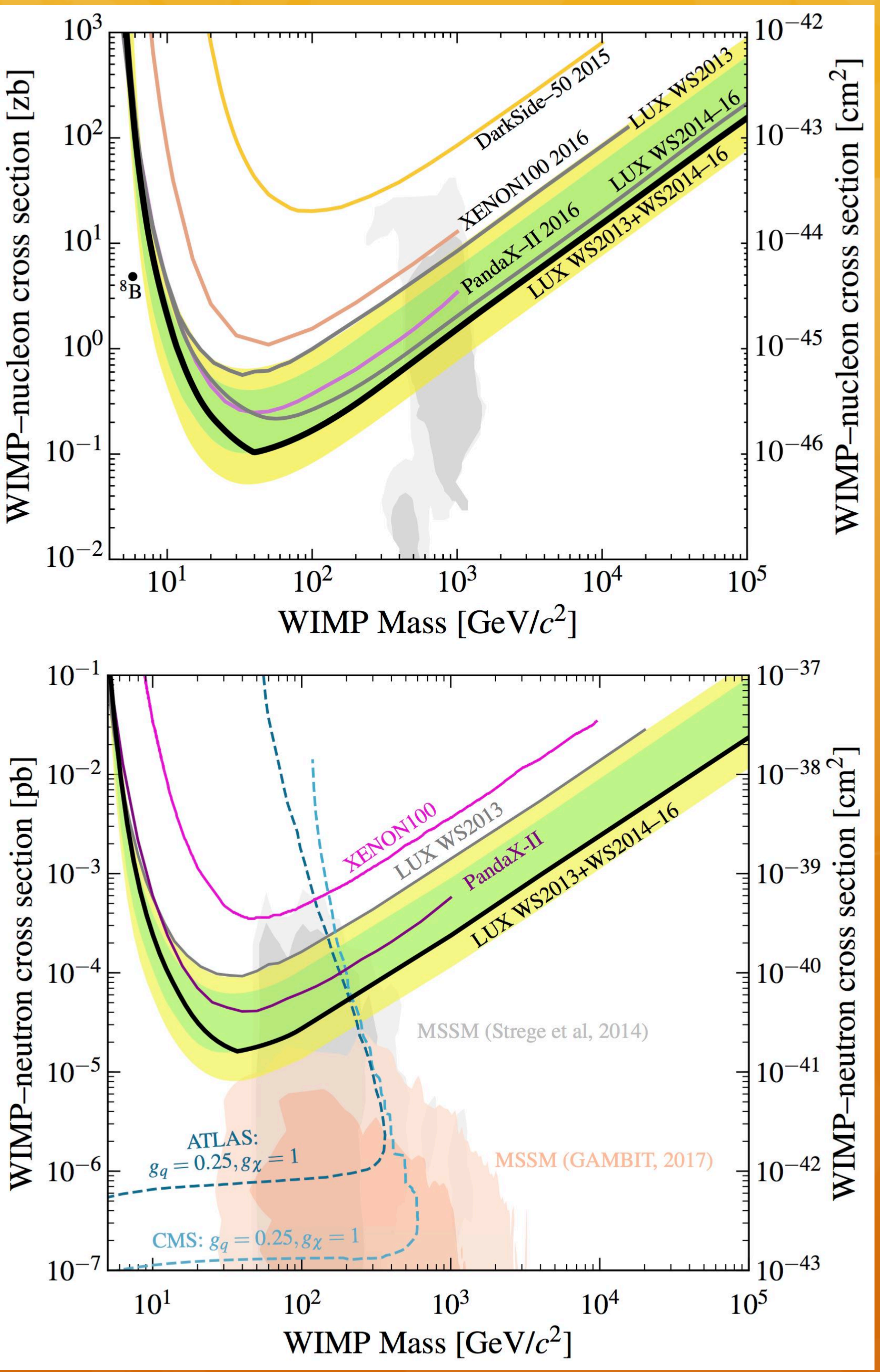


More information:

- Manfred Lindner's talk (Thursday)
- Paper preprint: arxiv:1705.06655
- http://xenon1t.org/
- https://twitter.com/Xenon1T

Xe XENON Dark Matter Project

LUX Impact 2013/17



- LUX First Science Run in 2013
  Second Science Run 2014-2016
  Full exposure: 47,500 kg.days
  (427 live-days)

- Improved Spin-Indep. WIMP Sensitivity by Factor 20x since state prior to 2013. Also Neutron Spin-Dep. Sensitivity.

- Axion/ALP Search

- Full self-consistent models for all backgrounds events and detector response

- In parallel: Major program improving LXe ER and NR calibration over wide energy range (including sub keV) with high statistics and low systematics. Allowed significant improvement in accuracy of Xe response models. Also clearly establishes sensitivity to 8B coh. scattering.

- LZ: Kim Palladino Tues 15:30
  LZ: Christine Ignarra, Tues 15:45
  LUX: Rick Gaitskell Wed 14:00

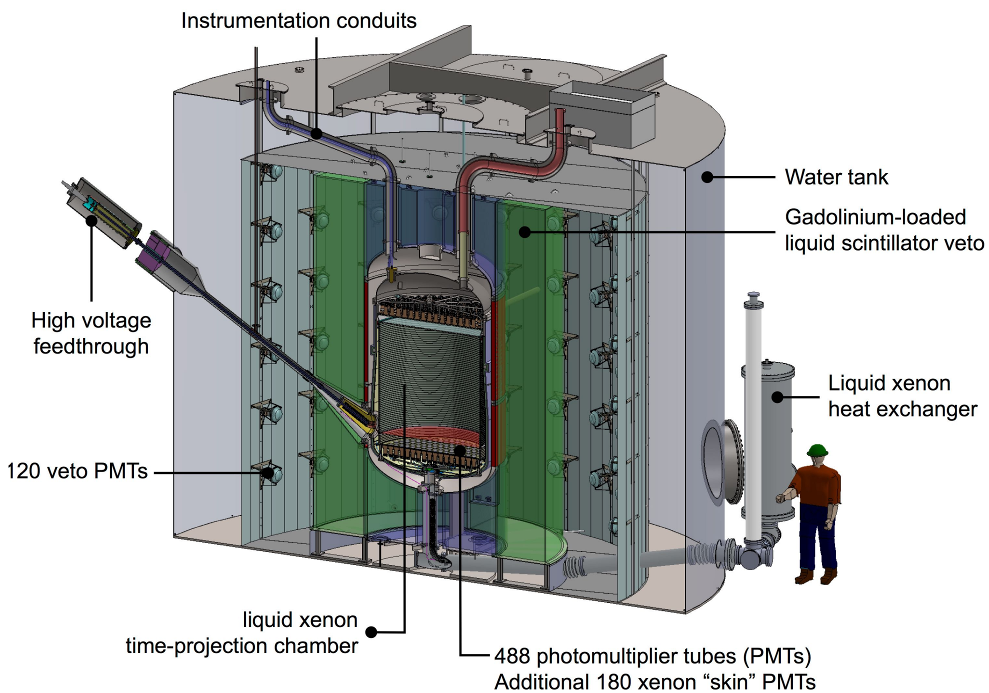
LZ Detector - 10 tonnes Xe

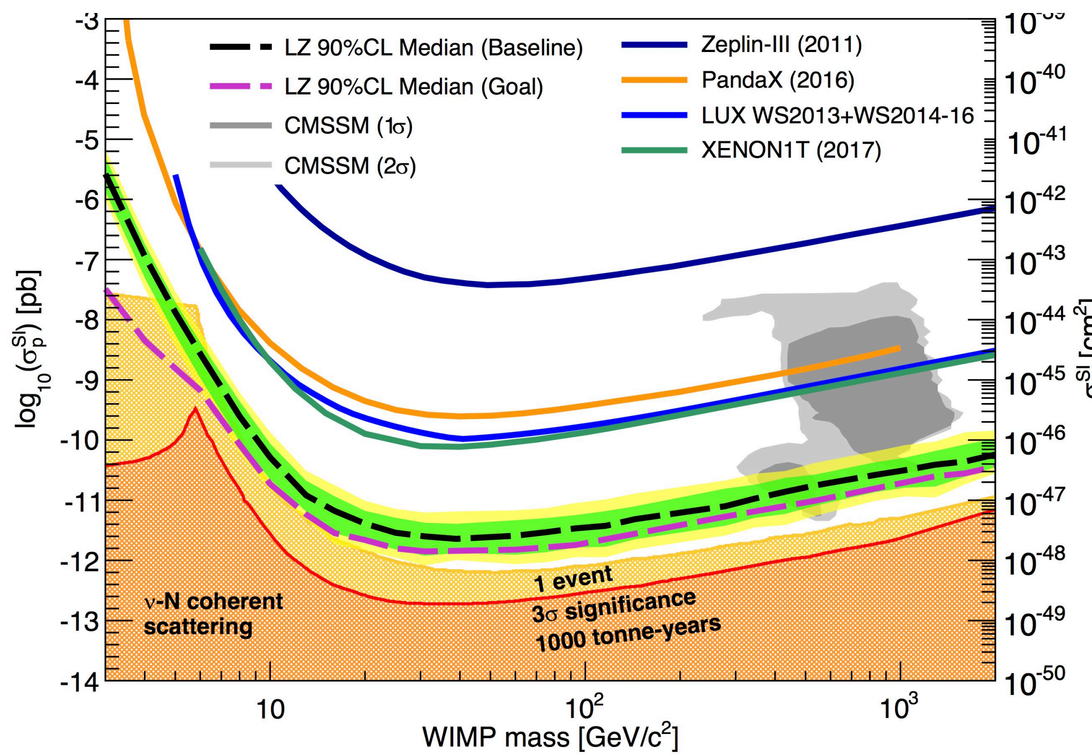
Replacing LUX at the Sanford Underground Research Facility (SURF)

Technical Design Report arXiv:1703.09144 260 Authors, 400 Pages

DOE Project, Construction Fully Underway > CD4
Commissioning April 2020, Physics in 2021, Goal 1000 days

Baseline WIMP sensitivity @ 40 GeV is 2.3 x 10^{-48} cm^2
Other promising science targets:
ββ0n, pp & 8B solar neutrinos,
coherent neutrino scattering





✿ LZ: Kim Palladino Tues 15:30
LZ: Christine Ignarra, Tues 15:45
LUX: Rick Gaitskell Wed 14:00

DEAP-3600

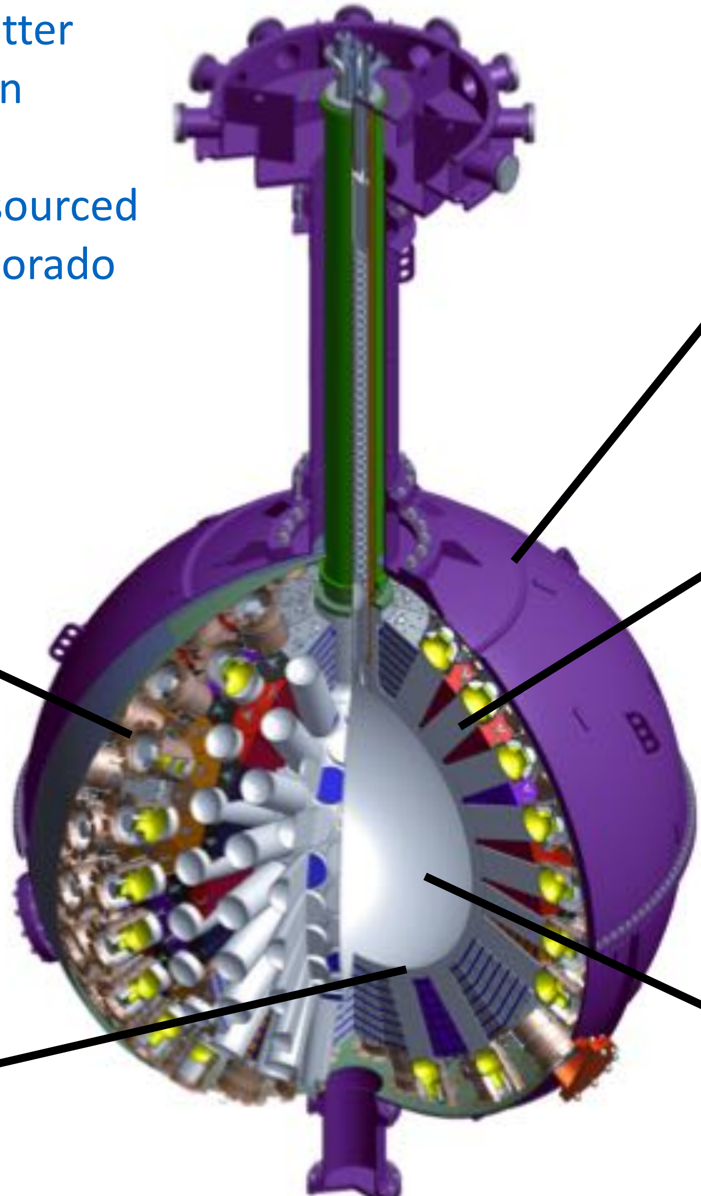
Uses liquid argon as a dark matter target with good discrimination

Low background argon being sourced from underground wells in Colorado

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

Steel Shell immersed in 8 m water shield at SNOLAB

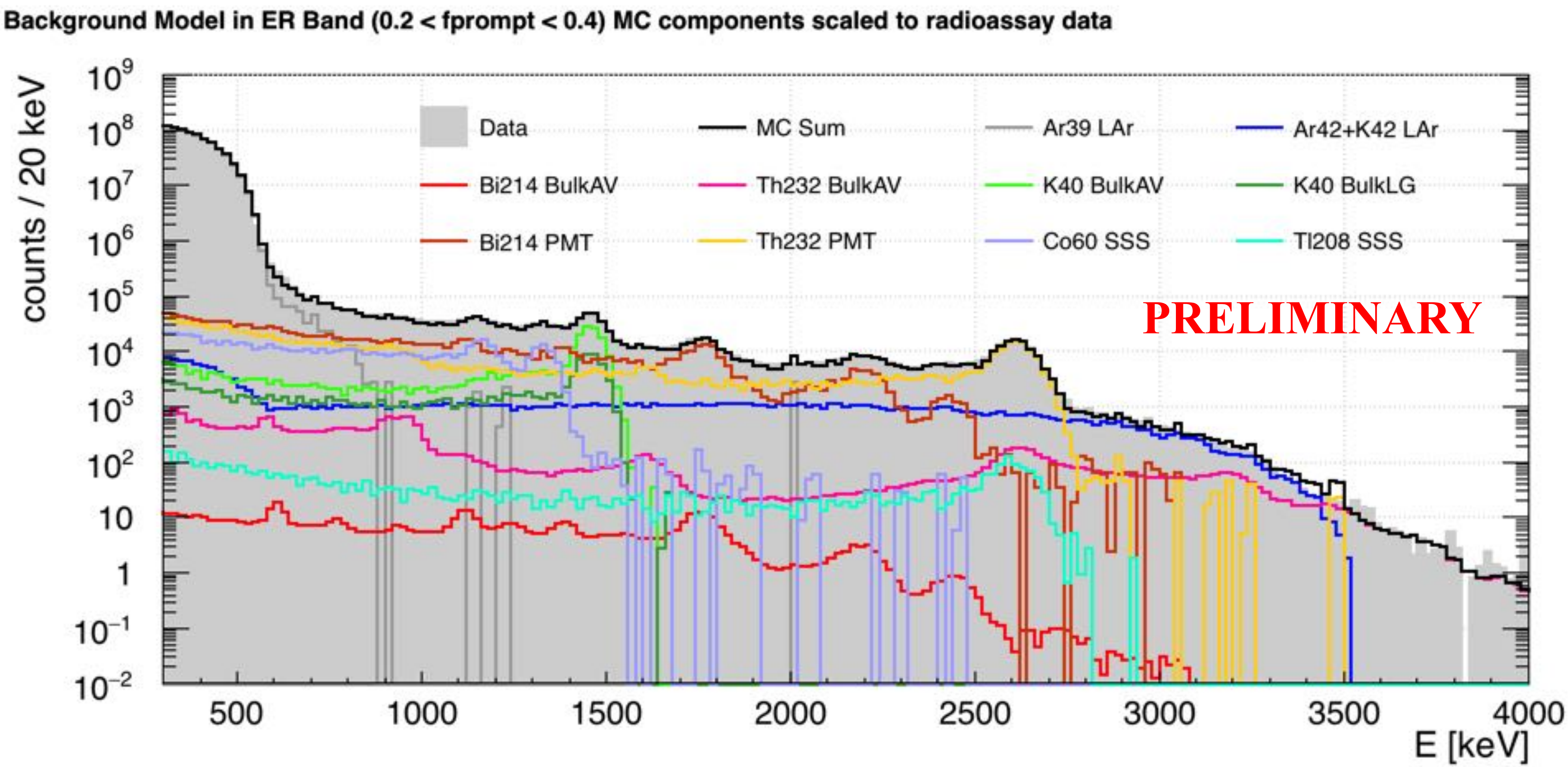
50 cm light guides + polyethylene shielding provide neutron moderation



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

3600 kg argon target (1000 kg fiducial) in sealed ultra-clean Acrylic Vessel

Electron Recoil Band Background Model



- Empiric energy calibration based on 1460 keV (^{40}K) and 2614 keV (^{208}Tl) peak
- Scaling of MC simulations to known screening / literature values (this is not a fit)
- Low energy region (< 0.5 MeV) dominated by ^{39}Ar
- Mid energy region (0.5 - 2.6 MeV) dominated by gamma from outside components (mainly PMT glass)
- High energy region (> 2.6 MeV) dominated by ^{42}K and beta components from very close ^{208}Tl sources

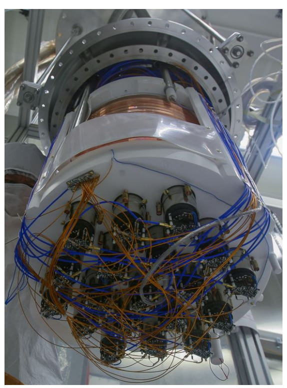
- **Gamma line measurements can be used to constrain (α,n) neutron production**

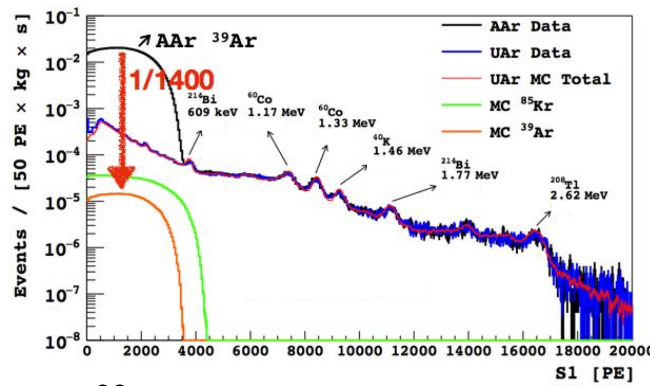
DarkSide: direct WIMP searches with two-phase argon TPCs

- High light yield: LAr Pulse Shape Discrimination $>10^7$
- Underground Argon: low ^{39}Ar
- TPC 3D event reconstruction
- High-efficiency neutron vetoing

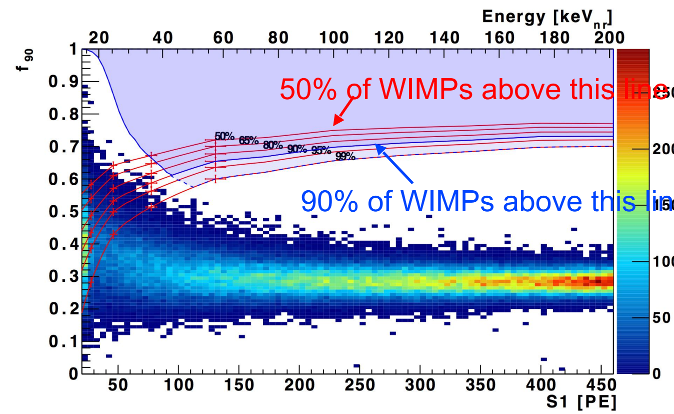
DarkSide-50

150/50/30 kg
total/active/fiducial
Sensitivity$<10^{-44}$ cm^2
Data: 2013-present





^{39}Ar reduced by 1400

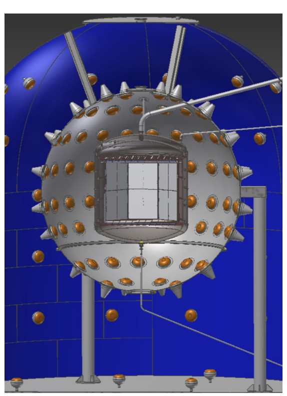


70-d of Underground Ar

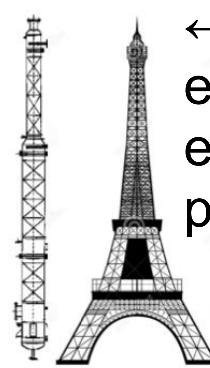
Blind analysis of 500-d underway

DarkSide-20k

30/23/20 T
tot/act/fiducial
Sensitivity$<10^{-47}$ cm^2
Data: ~2021

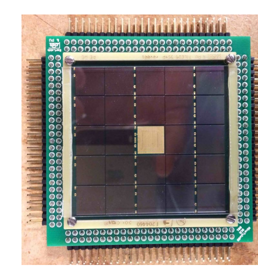


New Argon Collaboration
DarkSide
DEAP
MiniCLEAN
ArDM
} DS-20k⟶ Multi-100 ton



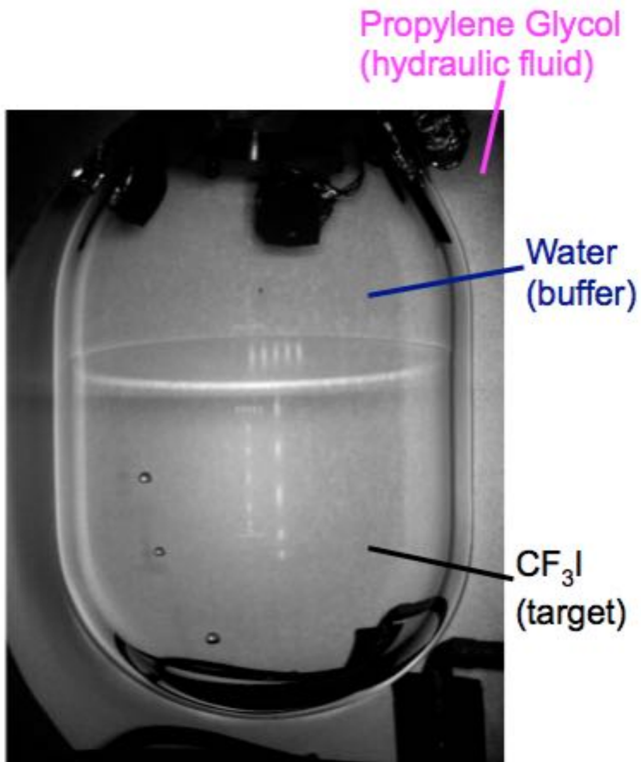
← Massive effort to extract and purify UAr

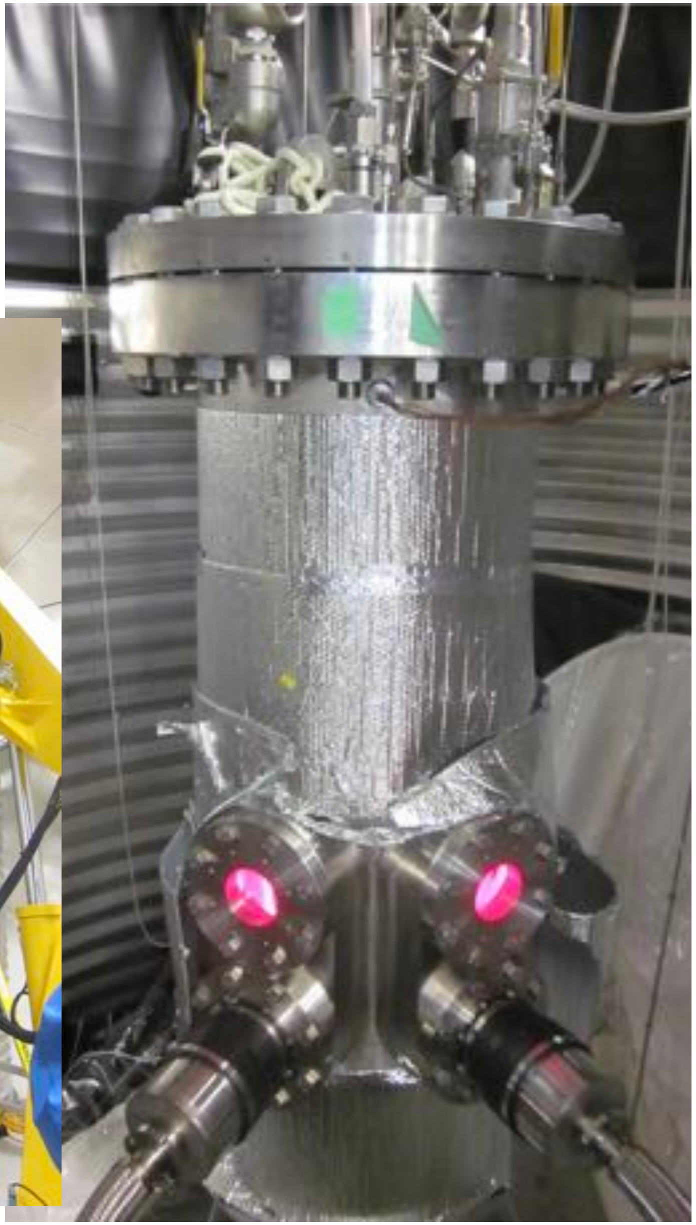
SiPMs replace → PMTs



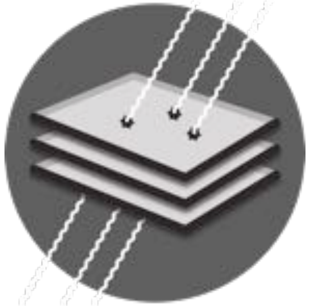
PICO Programme

- Superheated fluid bubble chambers
- Particle interactions nucleate bubbles
  - Good discrimination against backgrounds
  - Alphas ’louder’
  - Gammas do not nucleate
- Visual and acoustic sensors

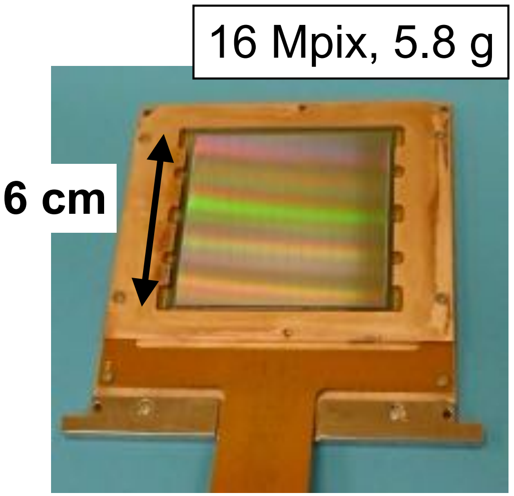


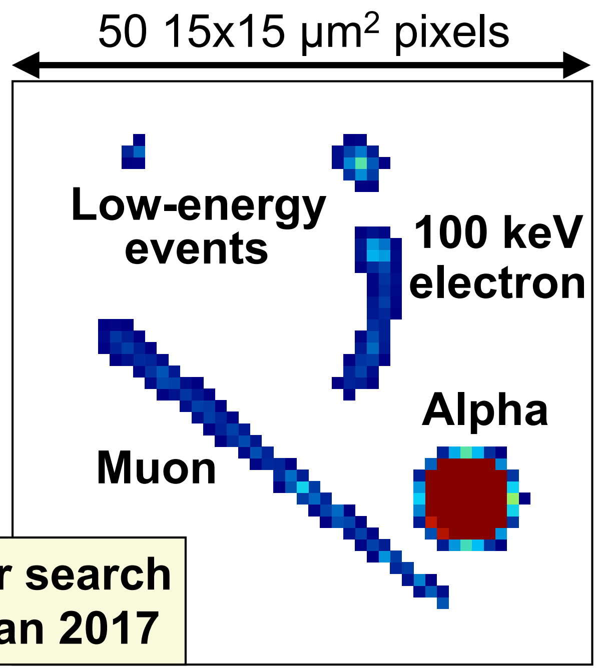


DAMIC at SNOLAB



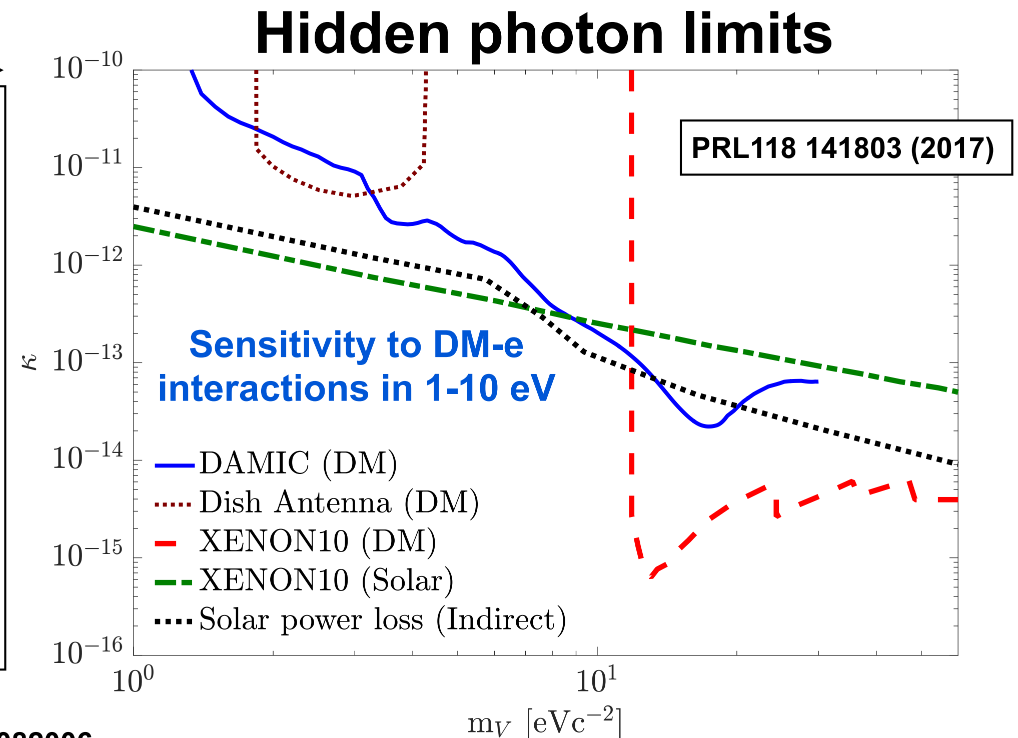
Charge-coupled devices (CCDs) to search for faint (few e^-) ionization signals from dark matter particles in the Galactic halo.



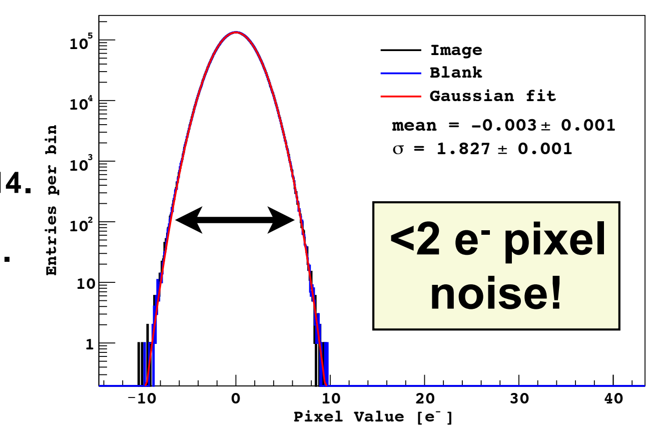


On-going dark matter search with 7 CCDs since Jan 2017

Hidden photon limits

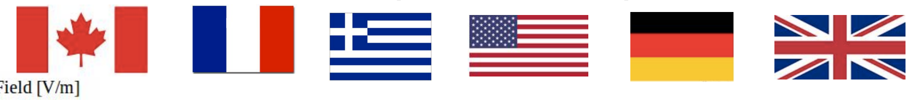


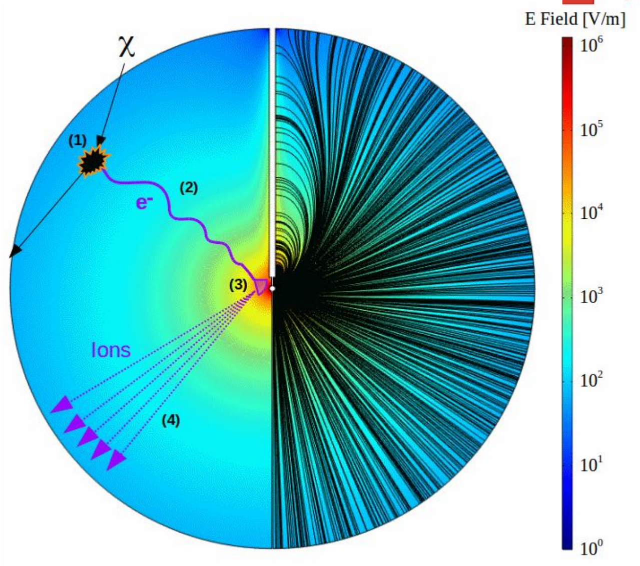
- Low-mass WIMP limits with 0.6 kg d exposure **PRD94 082006.**
- Nuclear / electron recoil response characterized down to 60 eV_{ee} threshold **PRD94 082007, JINST12 P06014, arXiv:1706.06053.**
- High-spatial resolution for powerful background rejection **JINST 10 P08014.**
- Lowest leakage current ever achieved in a silicon device **PRL118 141803.**
- Demonstrated single e^- detection with “skipper” technology for next generation **arXiv:1706.00028.**

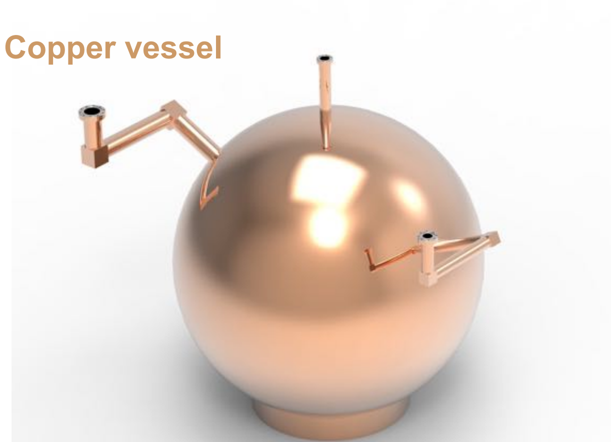


New Experiment With Spheres-Gas

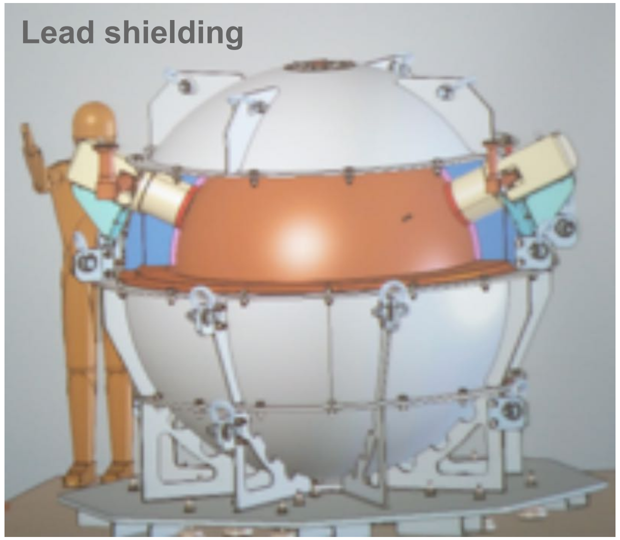
Search for low-mass WIMPs with Spherical Proportional Counters (SPCs)







140 cm Ø detector to be operated @ 10 bars



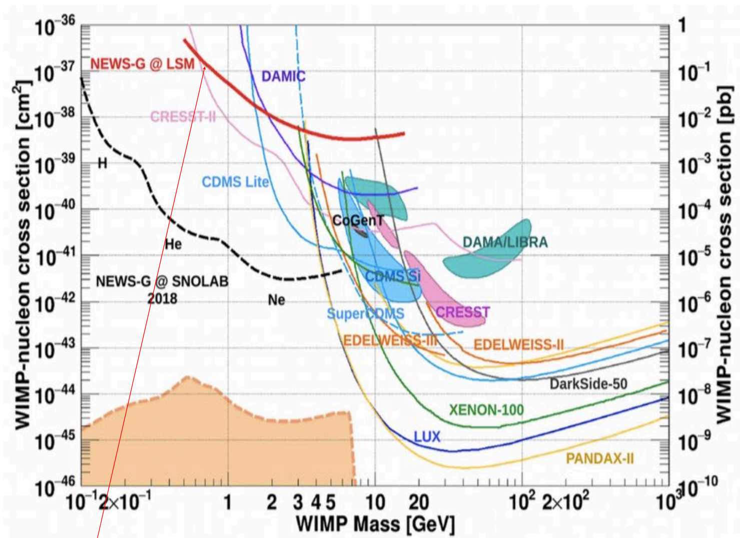
to be installed @ SNOLAB by summer 2018

Designed to search for low-mass WIMPs down to 0.1 GeV/c^2

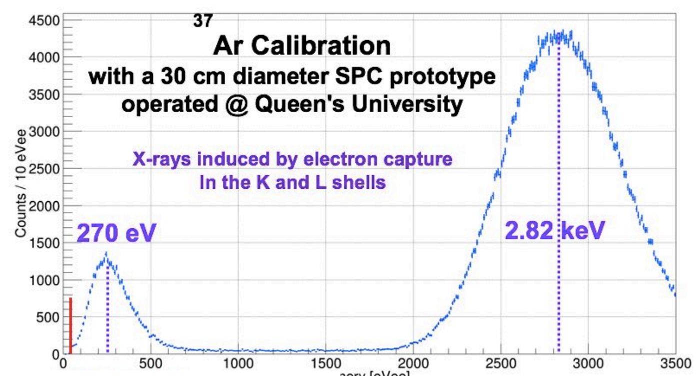
Low capacitance of the sensor & High amplification gain :
 => detection thresholds of 10 to 40 eVee

Light target gases (H, He, Ne) :
 => optimization of momentum transfers for low-mass particles

Rise-time based pulse-shape discrimination:
 => surface event rejection



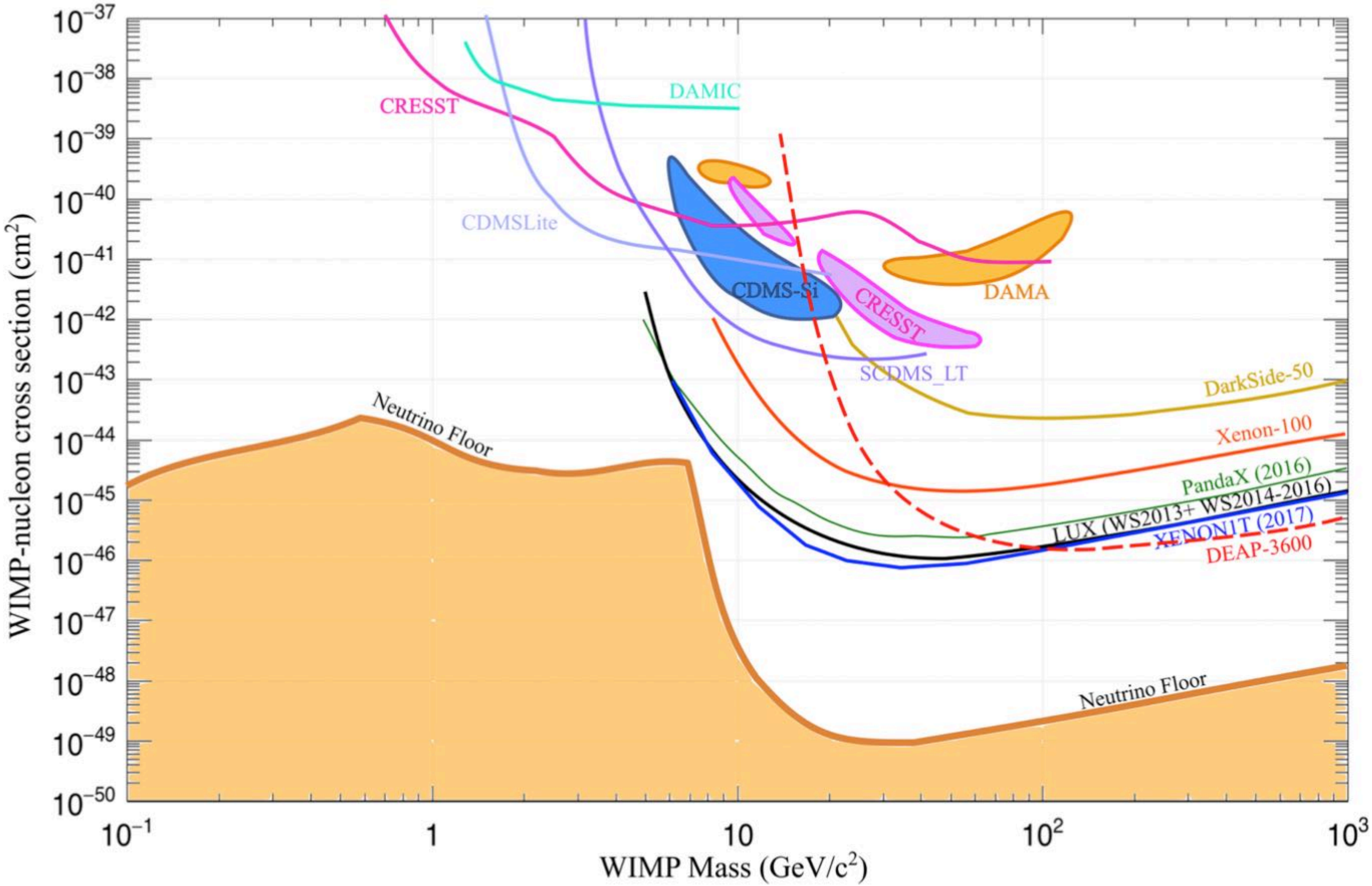
Results with Neon @ LSM :Q. Arnaud et al. [NEWS-G Collaboration], (2017) submitted to Astropart. Phys. (arXiv:1706.04934)



40 eV threshold

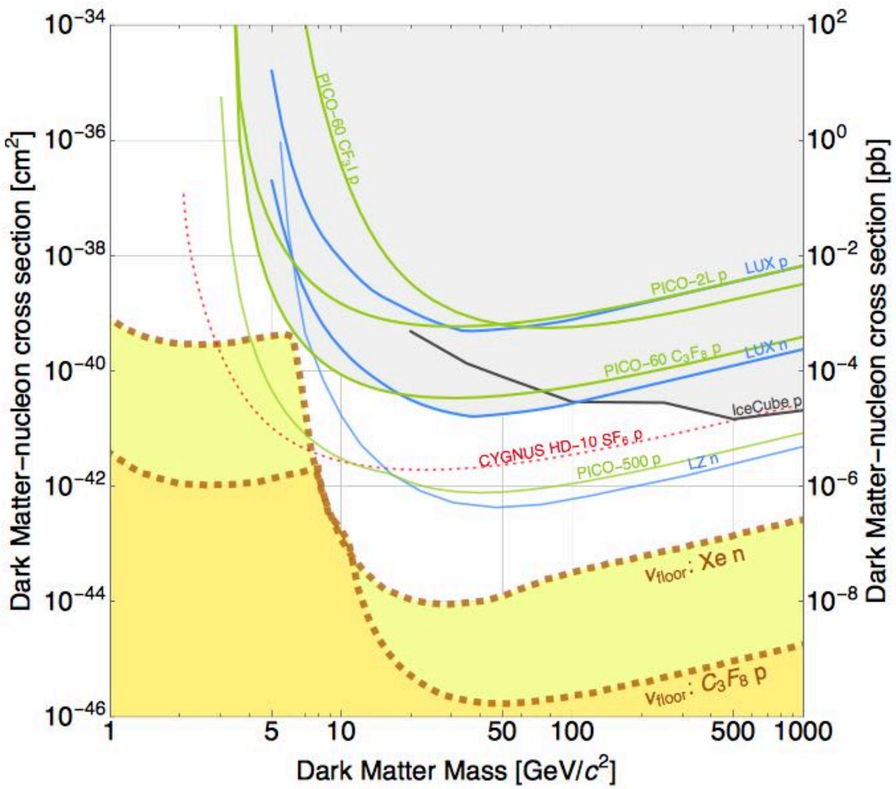
Optimisation of sensor to obtain low threshold and homogeneity of response

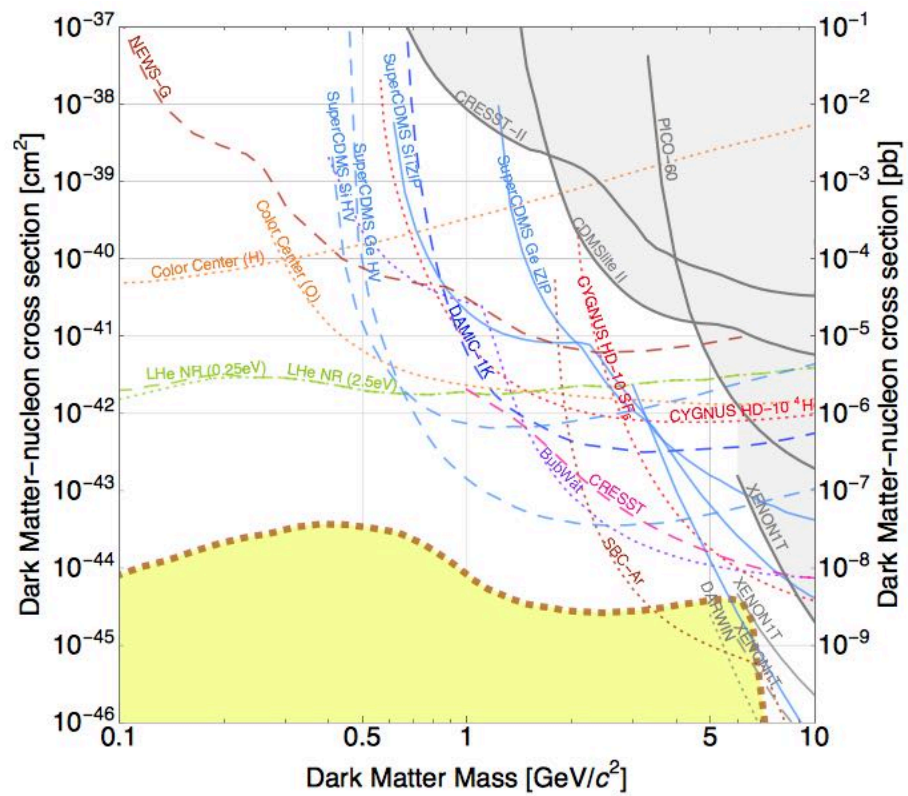
Current Status



P. Gorel

Current status and projections





Spin-dependent
WIMP-nucleon (p or n) cross section

Spin-independent, low mass,
WIMP-nucleon cross section

US Cosmic Visions Report: arxiv.org/1707.04591