Looking for a needle in a haystack: Direct Searches for Dark Matter

"The existence of this matter may seriously affect all previous estimates concerning the distribution of matter in the Universe."
Fritz Zwicky 1957

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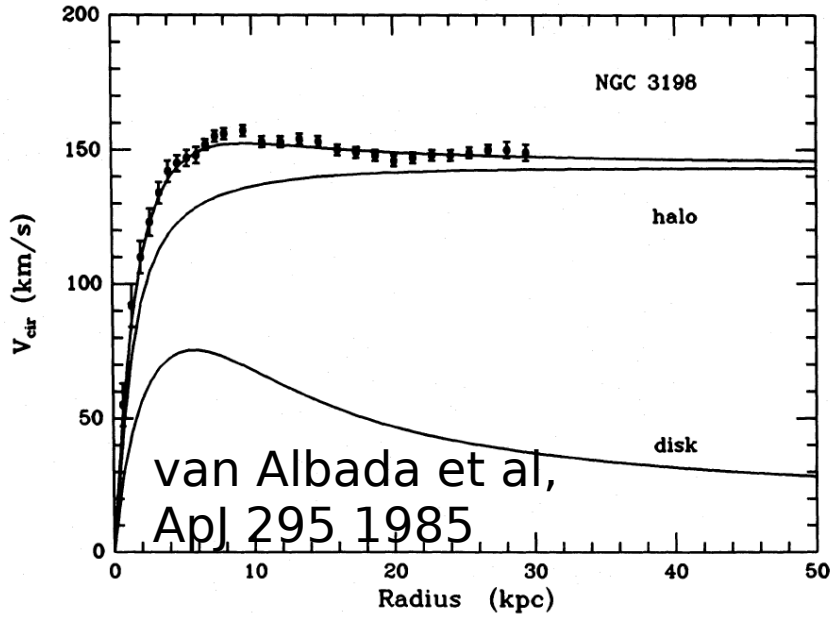
- Dark matter: underground astrophysics
- Experimental efforts:
  - Clarifying the situation at low-masses
  - Forging ahead at high-mass
- How to confirm a signal, and investigating DAMA claim

Matter in the Universe

- Most matter appears only through gravitational effects
- Dark Matter at all Scales
  - Galaxies (rotation curves)
  - Clusters
  - Large-scale structure
  - Cosmic Microwave Background



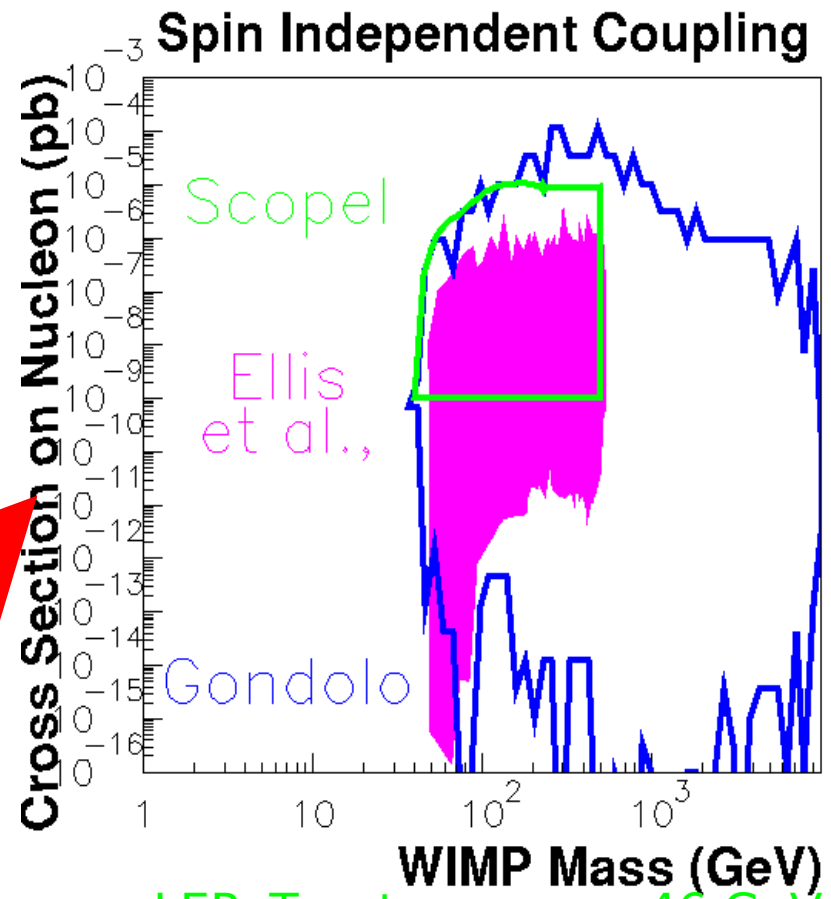
van Albada et al, ApJ 295 1985

- Big Bang Nucleosynthesis: most of the dark matter is non-baryonic
- Possible explanations?
  - Gravity wrong? MoND??
  - Massive Compact Halo Objects (MACHOs)? Microlensing?
  - Neutrinos? Structure Formation?
  - New Particles: Weakly Interacting Massive Particles (WIMPs)?
  - … ?

Solution to Dark Matter: SUSY WIMPs?

Pagels & Primack PRL 48 223 1982

- Supersymmetry (SUSY):
  - So far undetected extension of standard model that may solve some of its riddles
  - Fermions ↔ Bosons
  - Broken at usual energies
- LSP (χ): Lightest SUSY Particle
  - Probably neutralino (mix of photino, zino and higgsinos)
  - Stable if R-parity conserved*
  - $m_\chi \sim$ GeV-TeV ($\sim 1\text{-}10^3\ m_{proton}$)
- Relevant relic abundance:
  - $\Omega_c \sim 0.1$
- Coupling to matter:
  - Spin independent: $\sigma \propto A^2 m^2 \sigma_p$
  - Spin dependent: $\sigma = C\ J(J+1)\ m^2 \sigma_p$

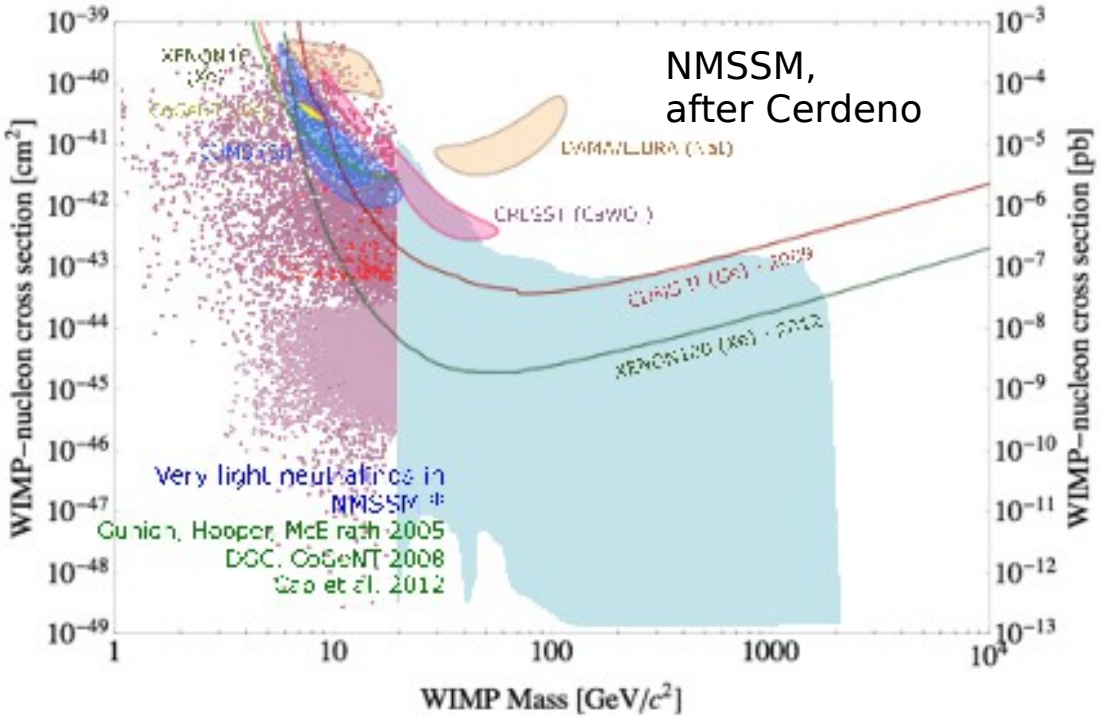


LEP, Tevatron⇒ m > 46 GeV
(J. Ellis et al., hep-ph/0004169)

SUSY and WIMPs in light of LHC

- Certain of the simplest (most appealing?) SUSY models favoring O(100 GeV) WIMPs now seem excluded (cf arXiv:1207.3185)
  - Remaing SUSY models allow O(1-1000 GeV) WIMPs (eg NMSSM Albornoz-Vasquez arXiv:1110.4817)
- WIMPs aren't necessarily SUSY → new interest in other extensions of Std Model:
  - Asymmetric Dark Matter (Zurek arXiv:1308.0338)
  - Isospin-Violating Dark Matt
  - Inelastic Dark Matter
  - Composite Goldstone Dark Matter (Hietanen arXiv:1308.4130)

- Experiments need to consider larger range of masses O(1 GeV) → O(1 TeV)



Physics Theory
Predicting Particles into Existence?

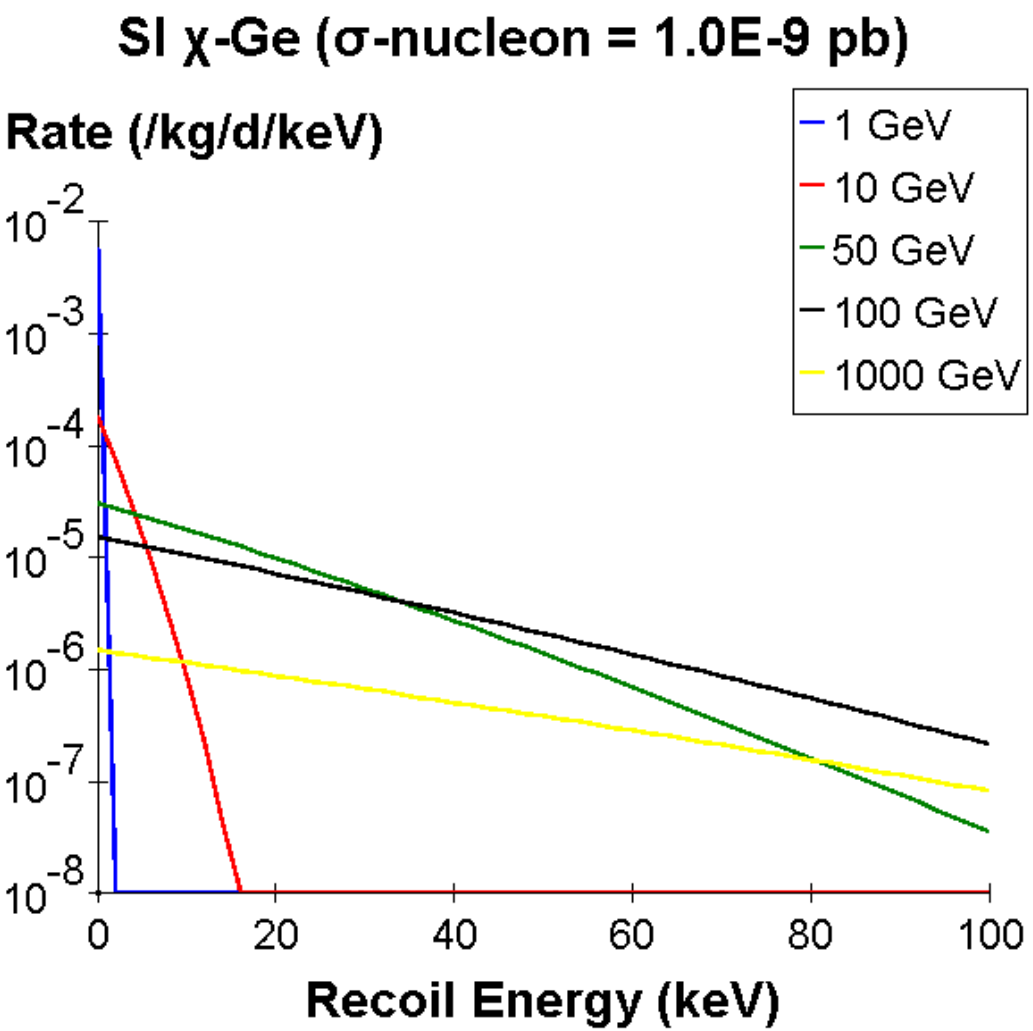
- Many hits, eg:
  - Positron: predicted by Dirac 1931, discovered by Andersen 1932
  - So far, Standard Model (SM) has not been wrong, at worst incomplete
    - W^{+-}, Z_0: predicted Glashow, Weinberg, Salam 1960s, discovered UA1/UA2 1983
    - Tau neutrino; predicted 1970s, discovered by DONUT 2000
    - BEH boson: predicted 1960s, discovered by ATLAS/CMS 2012
- Some theoretical misses (hopefully useful), eg:
  - Nuclear democracy: 1960s
  - Early Technicolor: 1970s
  - Cosmion: 1980s
- ... jury still out on many extensions of SM

Direct Detection of WIMPs

- Seek elastic scattering of WIMPs themselves in detector (Drukier and Stodolsky Phys. Rev. D 30(11)22951984, Goodman & Witten Phys. Rev. D31(12)3059 1985)
- Counting experiments: build it and they will come ?
- Theoretical ingredients:
  - WIMP local astrophysical distribution: speeds v_{rms}~250 km/s, $v_{Earth/Galaxy}$ ~230 km/s (10% modulation over year), density~0.3 GeV/cm^3...) Some uncertainties (graininess: Zemp et al 2008; non-Maxwellian: Stiff & Widrow 2003)

    RAVE latest results (arXiv:1406.6896): Density=0.54±0.04 g/cm^3
  - Cross-section (SI, SD)
  - Kinematics (elastic scattering)
  - Nuclear form-factor (loss of coherence)
- Recoil spectrum: $$\frac{dR}{dE} \approx \frac{\sigma n_0}{v_0 \mu^2} F^2(E) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

Spectra: Effect of WIMP Mass

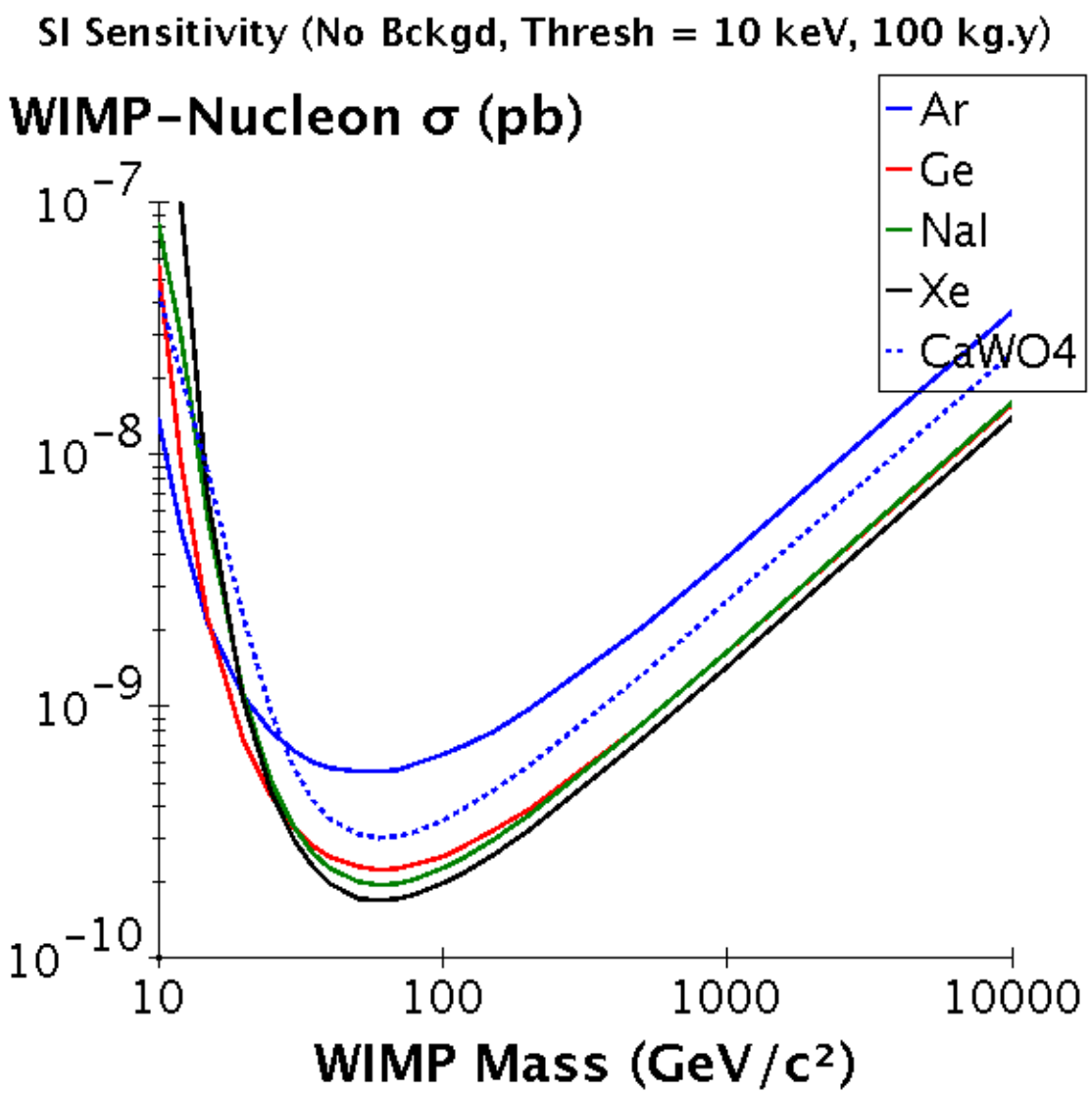


- Exponential-ish shape
- Few counts: <1 /kg/month

The needle

- The lighter the WIMP, the faster the fall
- Detector threshold effect
- Effects for different targets:
  - $\sigma \propto \mu^2 A^2$
  - Scattering kinematics

Ideal Experiments (No Background)



- Same **exposure** (MT), **threshold**: sensitivities similar
- No background:

$$sensitivity \propto MT$$

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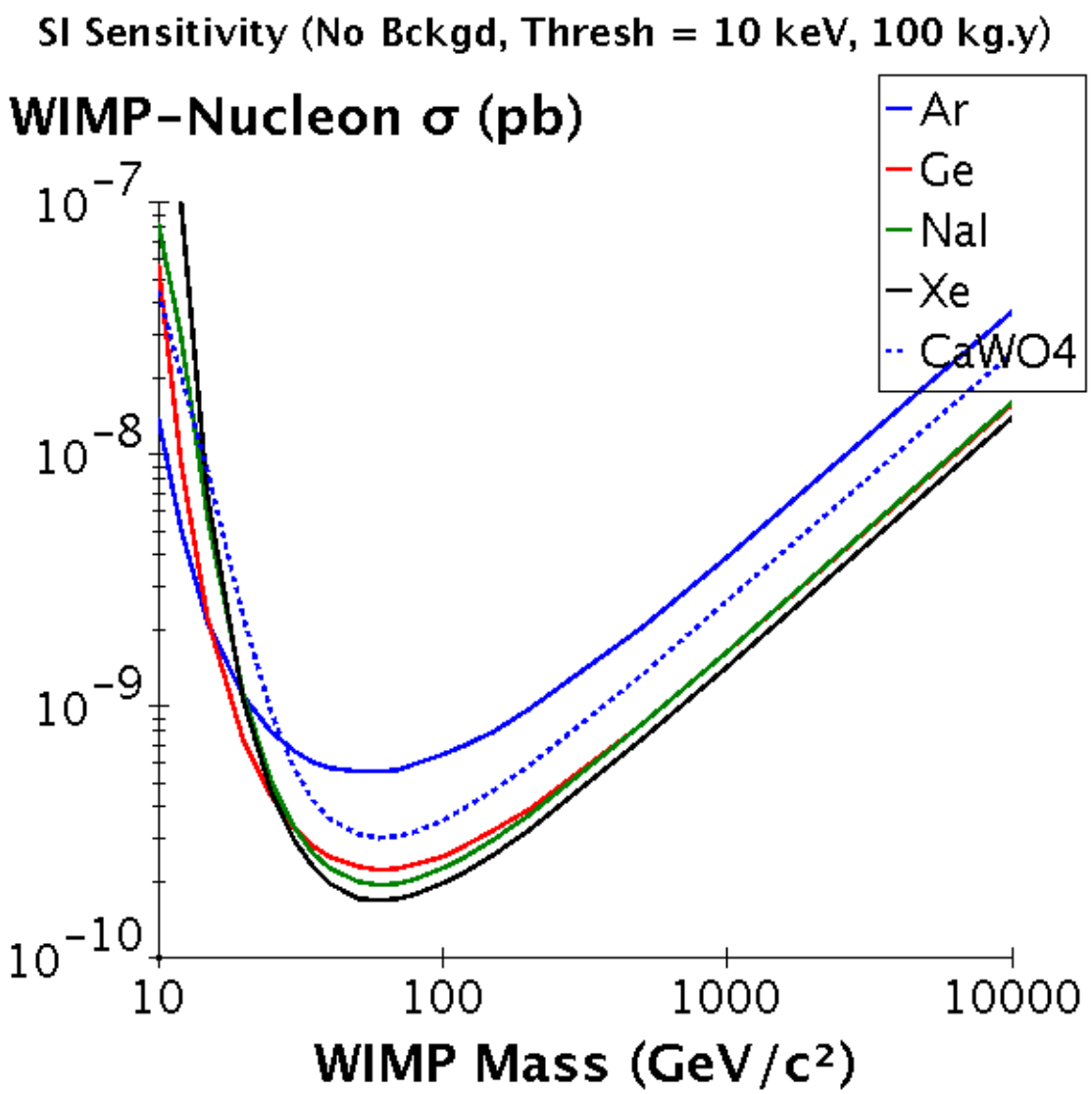

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- Real experiment: bckgd !.
  - No rejection: sensitivity limited by background
  - Partial **bckgd rejection**:

$$sensitivity \propto \sqrt{MT}$$

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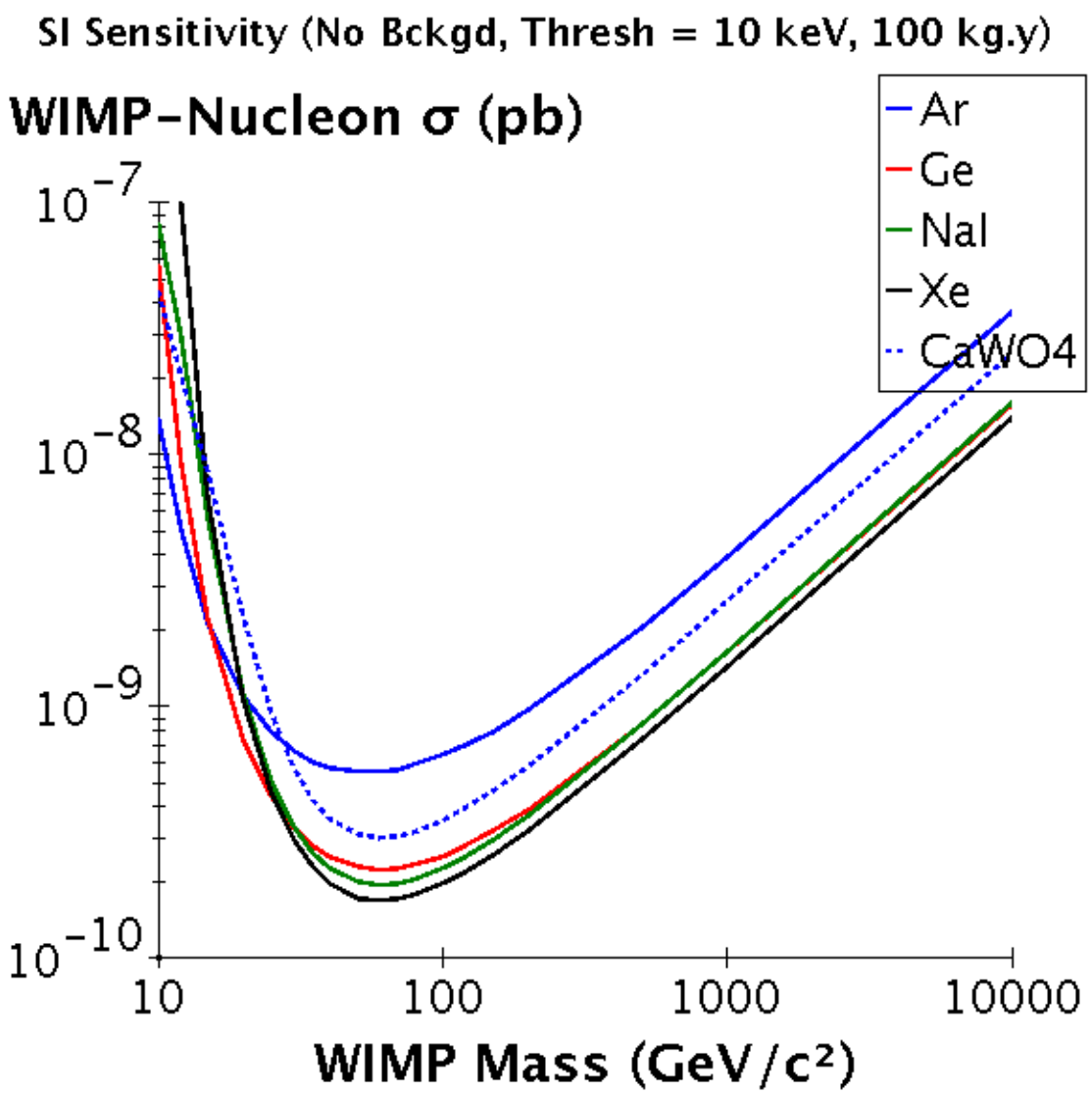

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- No background:

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- Real experiment: bckgd !.
  - No rejection: sensitivity limited by background
  - Partial **bckgd rejection**:

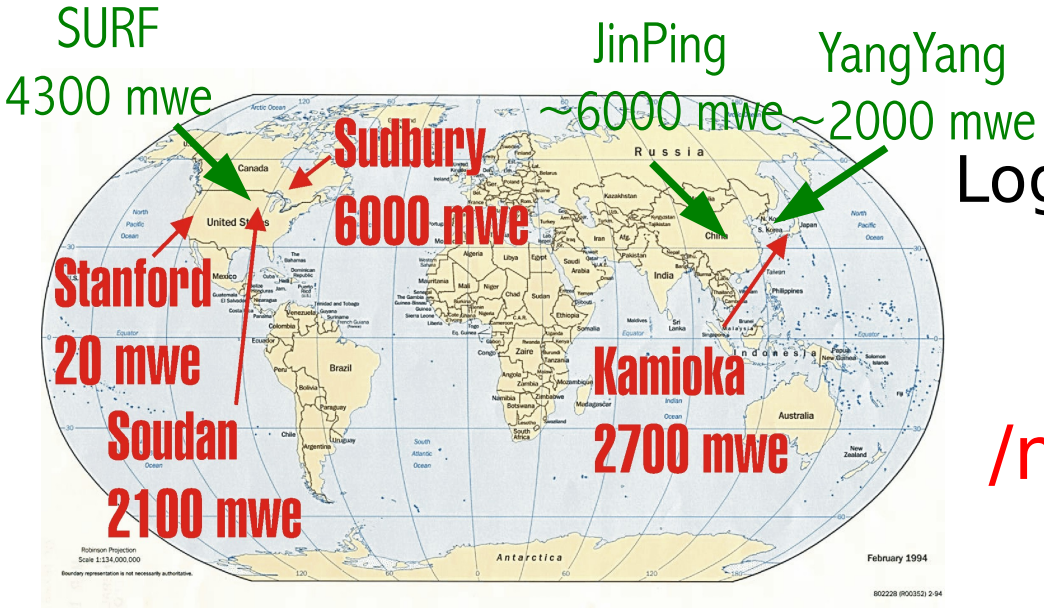
$$sensitivity \propto \sqrt{MT}$$

  - Total rejection:

$$sensitivity \propto MT$$

Escaping the Haystack in Mines and Tunnels:

Going Underground to Reduce Background

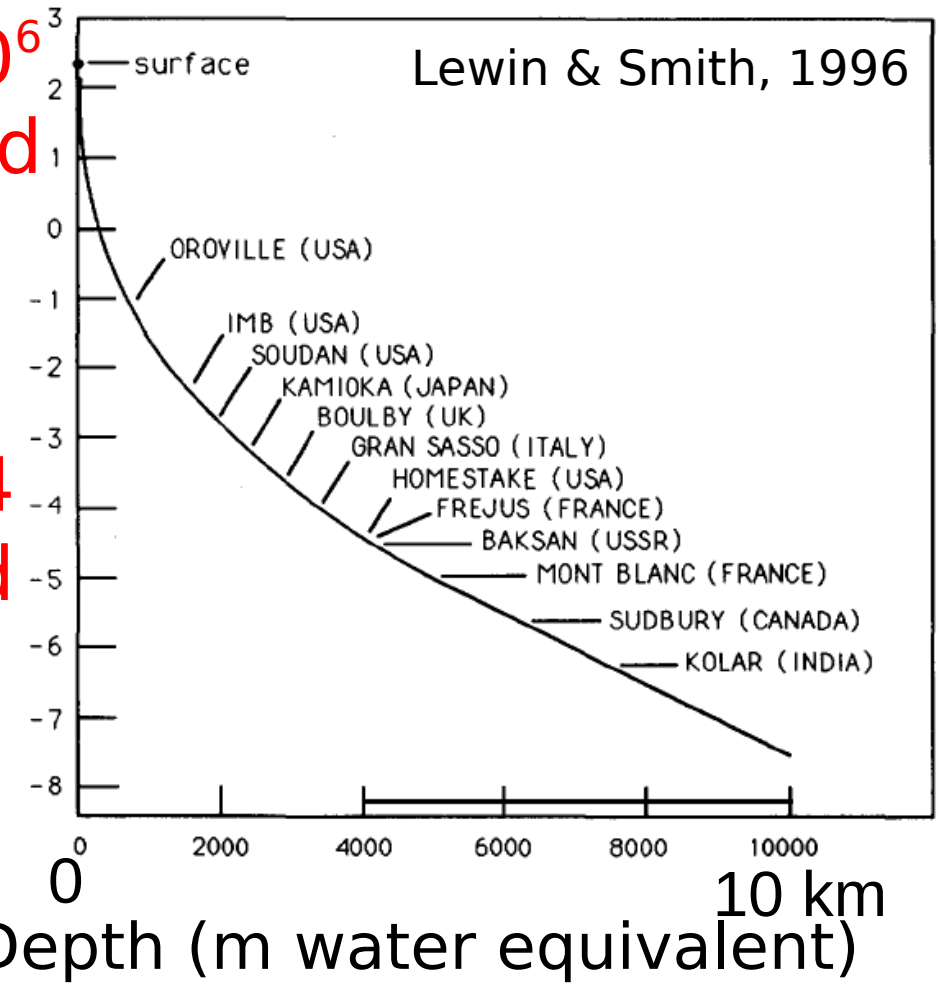


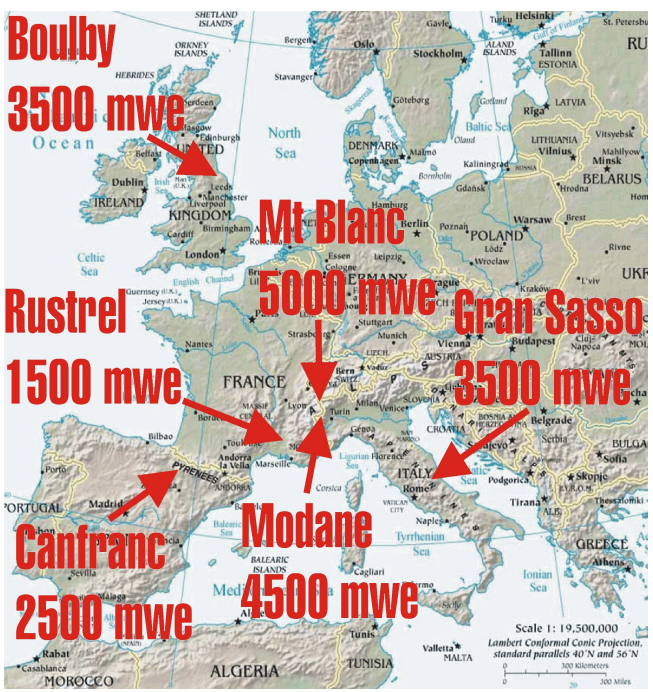
Cosmic muon flux reduced

Log(μ flux) (/m²/s)

10^6 /m²/d

4 /m²/d





Fast neutron flux

≈ 10^{-6}/cm²/s

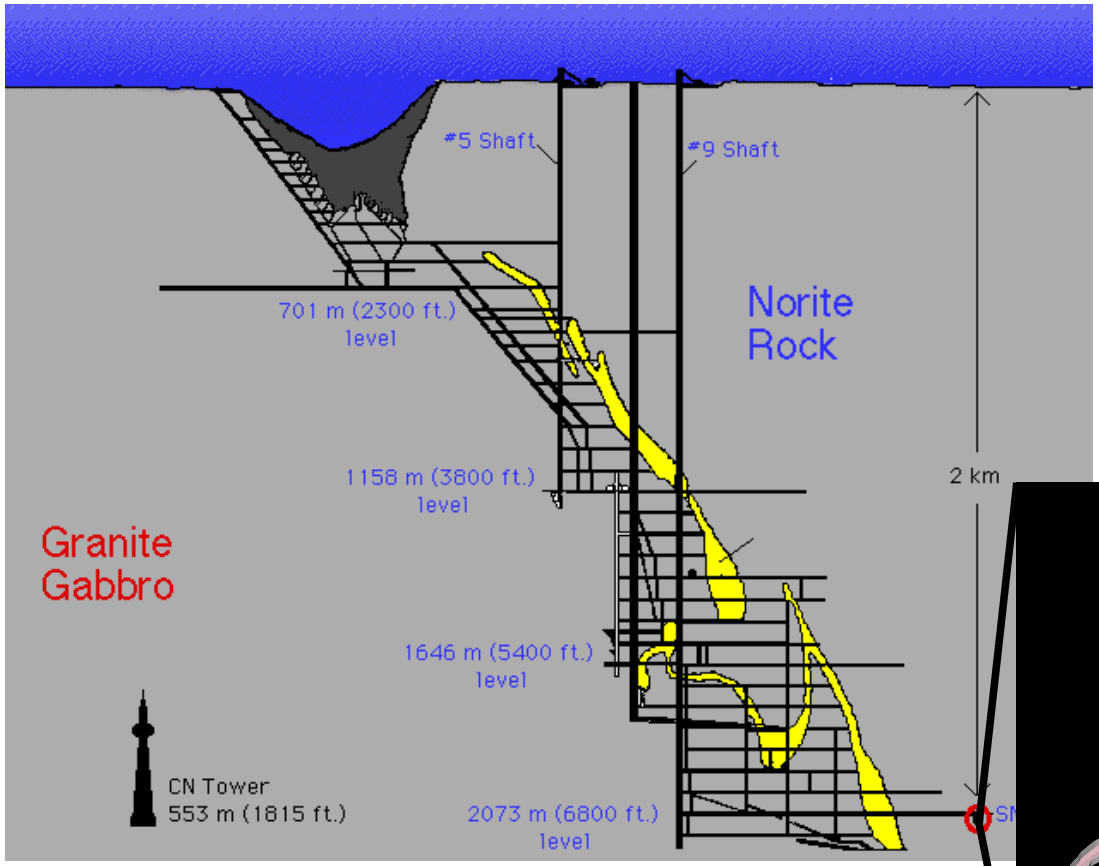
(Gran Sasso)

Soudan, MN

- Old mine converted to National Park
- Rock overburden: 2900 mwe

SNOLAB, Sudbury ON: ~6 kmwe

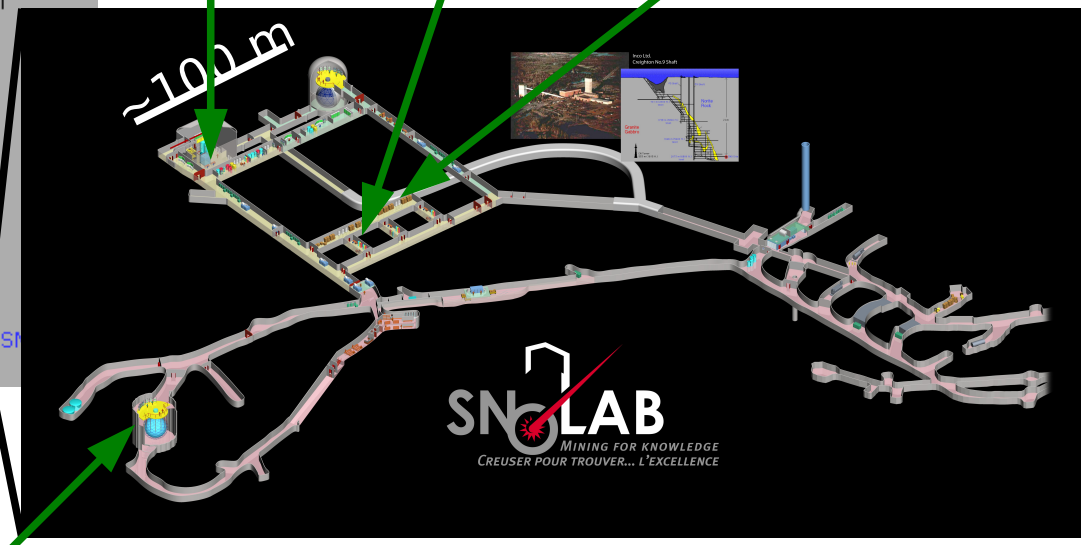
One of the deepest and cleanest labs



DEAP (Dark Matter)

PICO (DM)

CDMS ? (DM)



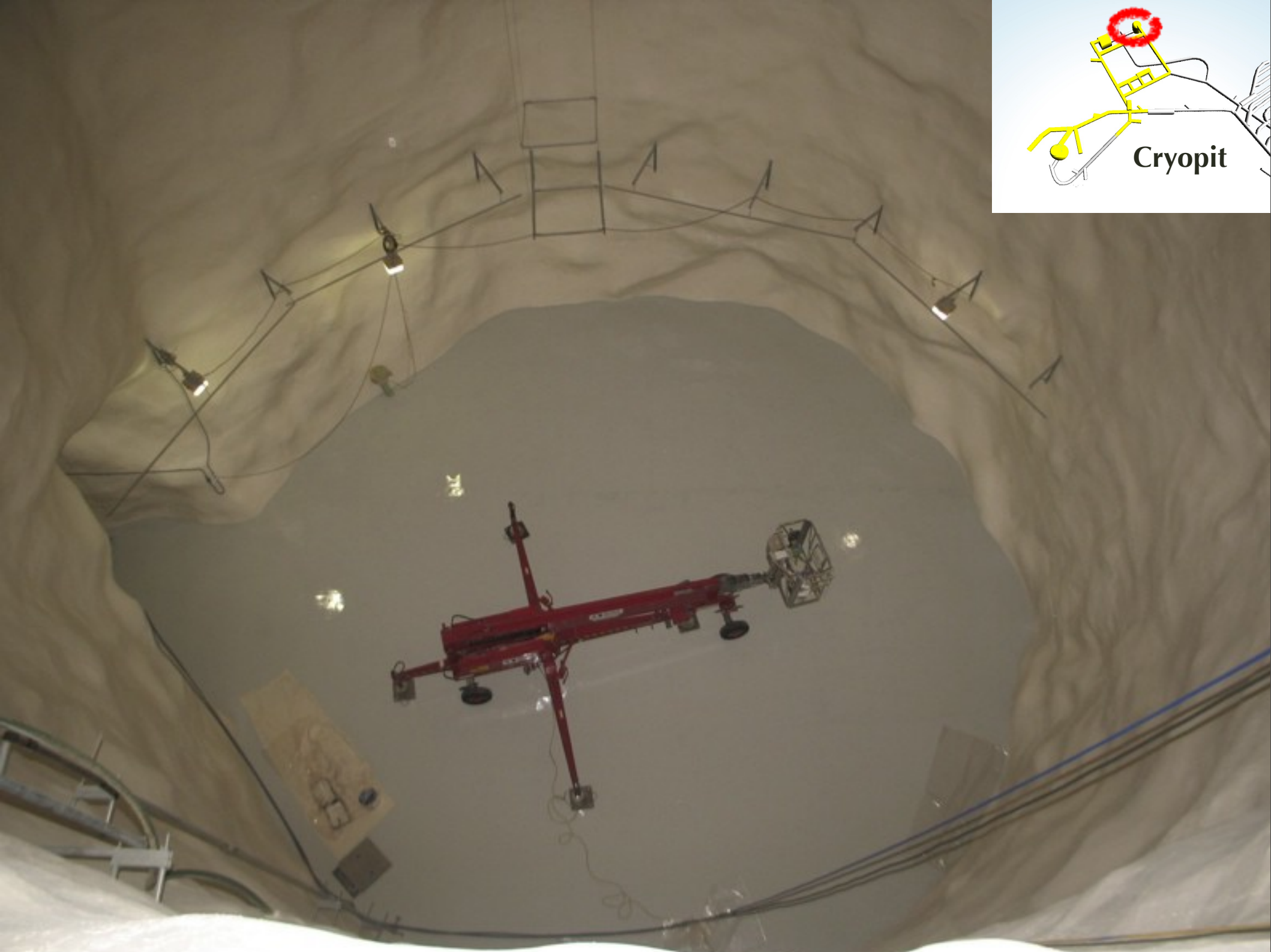
SNO+ (neutrinos)

Also: HALO (SN neutrinos), DAMIC (DM), PUPS (seismology) ...


6800
Lab Entry


Lab Entry


Personnel
Facility


Cryopit

More haystack: human radioactivity

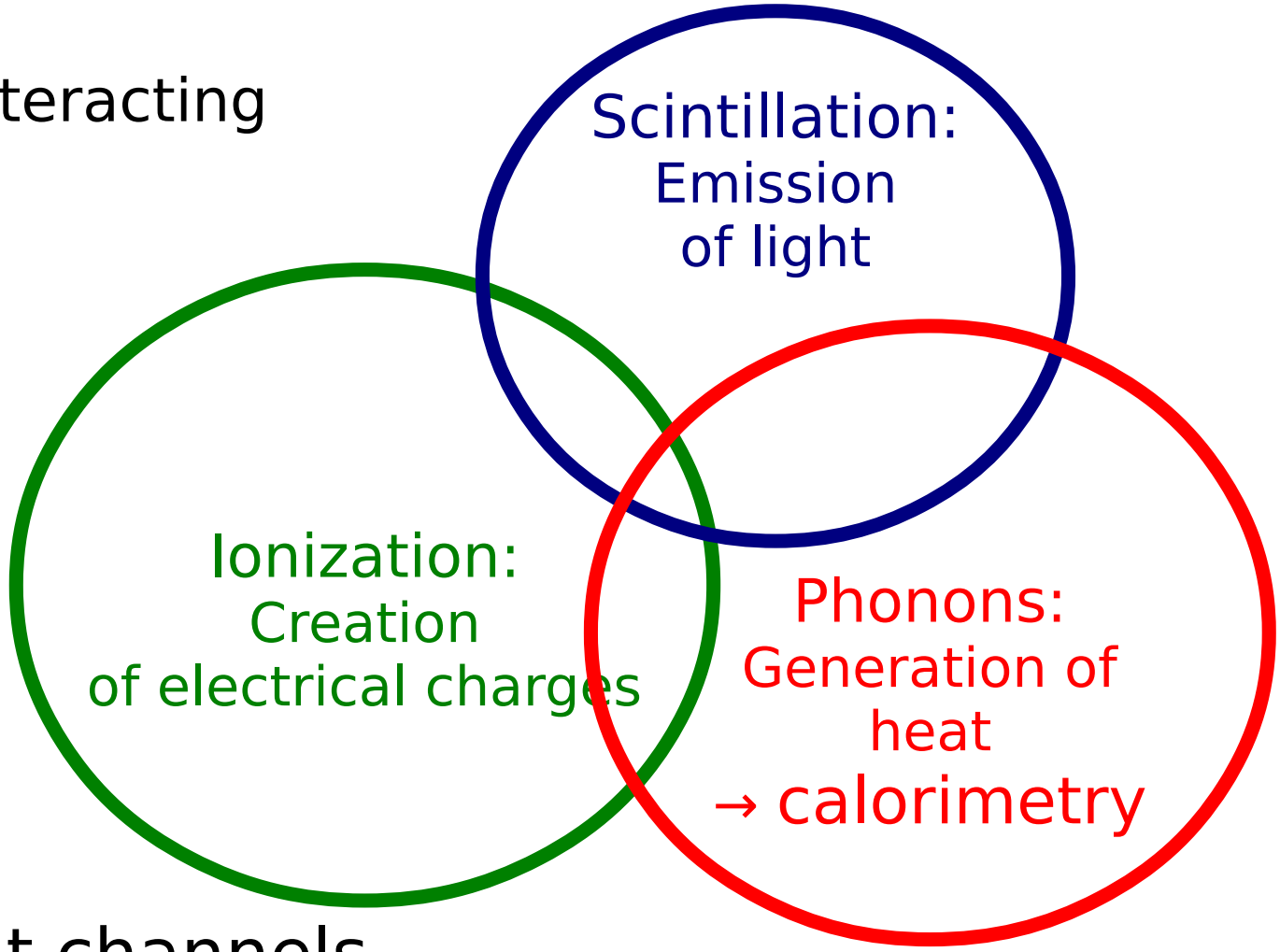
- Typical human radioactivity: 8 kBq

- Main contributions:
  - ^{40}K: $T_{1/2} = 1{,}3*10^9$ y
    - 89% b^-: E < 1,3 MeV
    - 11% g: E = 1,5 MeV
      (and 3 keV X-ray: cf DAMA)
  - ^{14}C: $T_{1/2} = 5730$ y
    - 100% b^-:
      E < 156 keV

8 kBq/80 kg = 100 disintegrations /s/kg

How to detect WIMPs?

A particle interacting in matter can create:



- 3 different channels
- Combinations → particle identification
  - Dominant radioactive background (β, γ) highly ionizing (interacts with e^- in matter)
  - WIMPs, and fast neutrons, scatter elastically off nuclei

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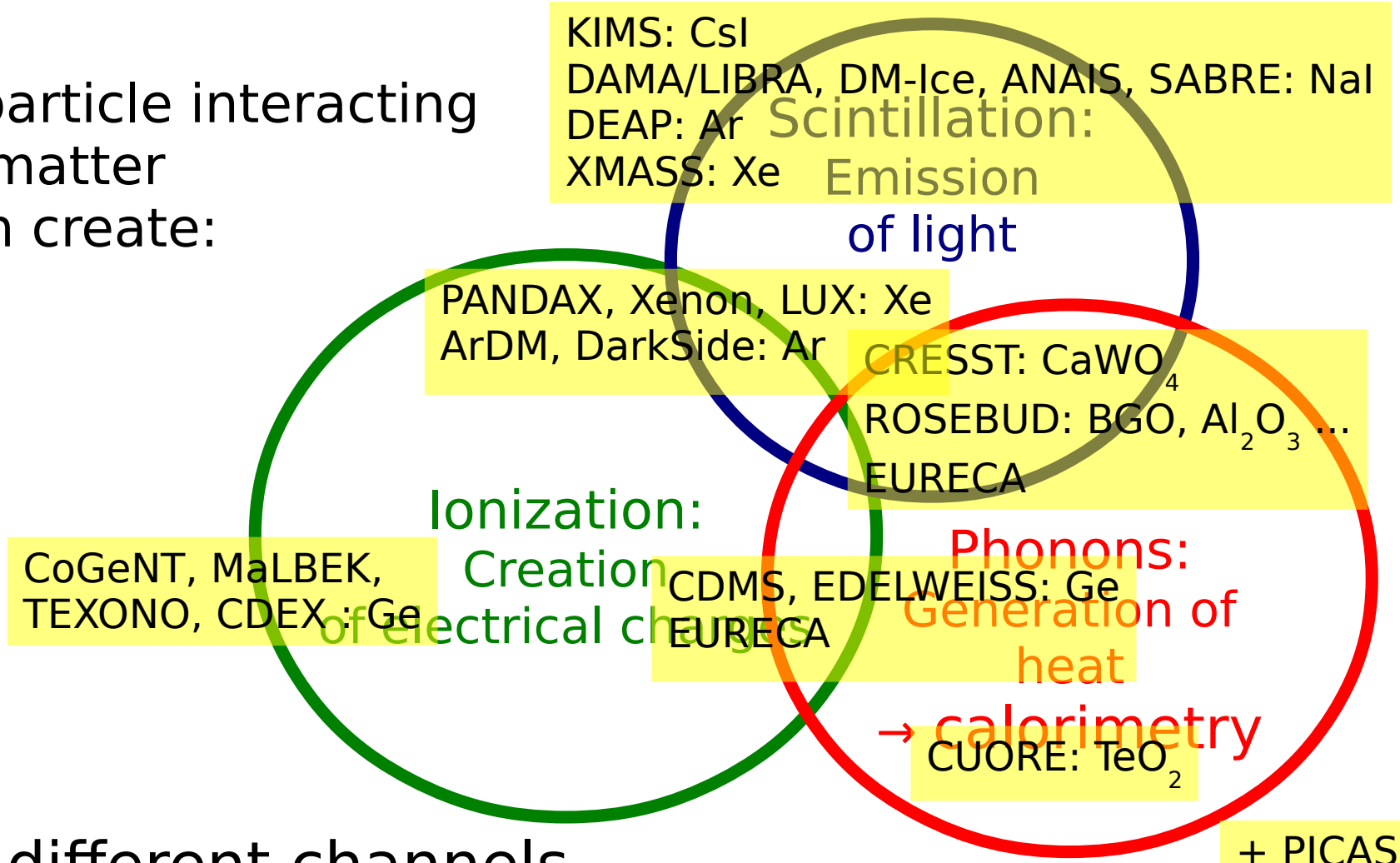
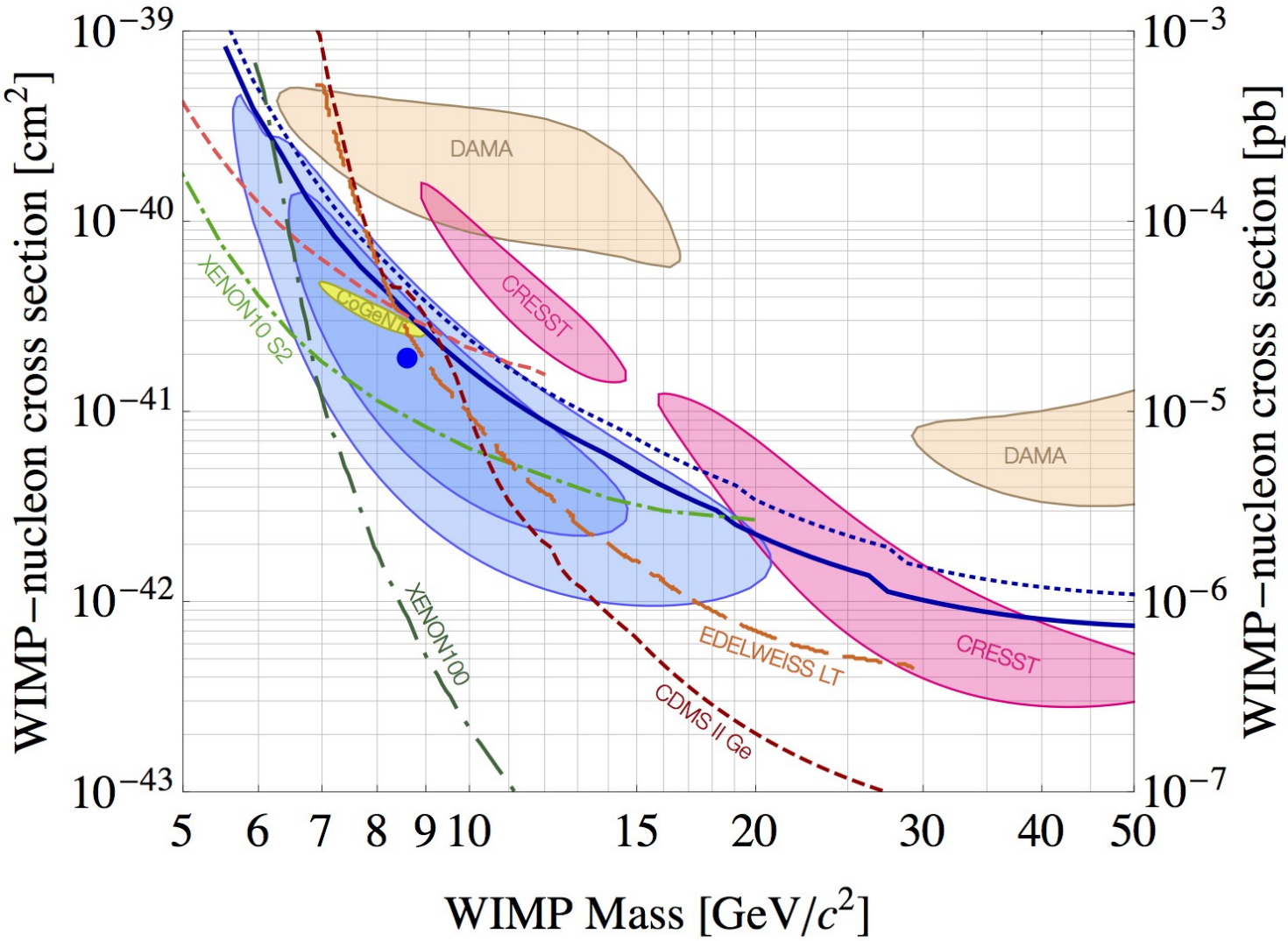


+ PICASSO, COUPP, PICO, SIMPLE, MOSCAB, MIMAC, DRIFT, DMTPC, DAMIC ...

- 3 different channels
- Combinations → particle identification
  - Dominant radioactive background (β, γ) highly ionizing (interacts with e^- in matter)
  - WIMPs, and fast neutrons, scatter elastically off nuclei

2010-2013: The Low-Mass Mess

- 4 independent experiments observe “hints” of signal, at low masses
- Different statistical strengths
- Under standard astro and particle assumptions:
  - Not all compatible with one another
  - Already tension with XENON (and CDMS, EDELWEISS)

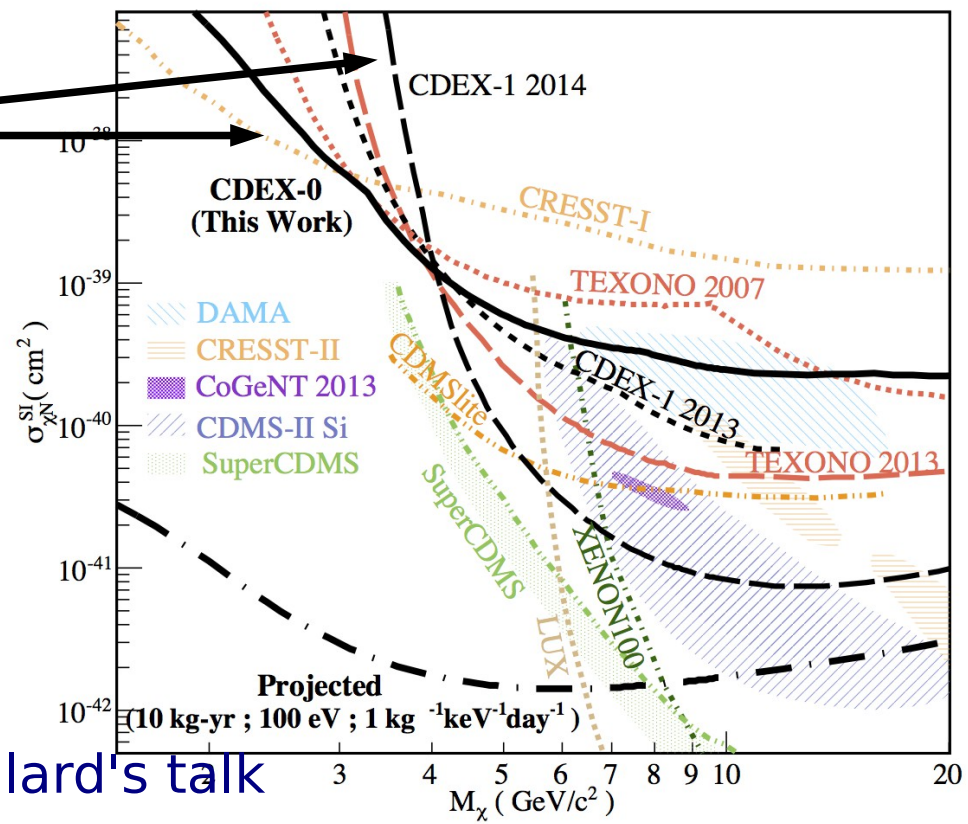


Clarifying low-masses

No background rejection

- Spherical gaseous TPC:
  - SEDINE → see I. Giomataris' talk
- CCD:
  - DAMIC 100: 18x5.5=110 g of Si CCDs, threshold 50 eVee ~ 0.5 keVr, to SNOLAB 2014, goal: to test CDMS-Si in 1 year exposure
- Semiconductor, ionization-only detector:
  - CoGeNT, MALBEK
  - TEXONO, CDEX:
    - 170 eVee threshold
    - 20 g, 0.8 kg.d
- Cryogenic
  - CRESST
  - ROSEBUD
  - EDELWEISS
  - CDMS, CDMSLite → see J. Billard's talk

Background rejection

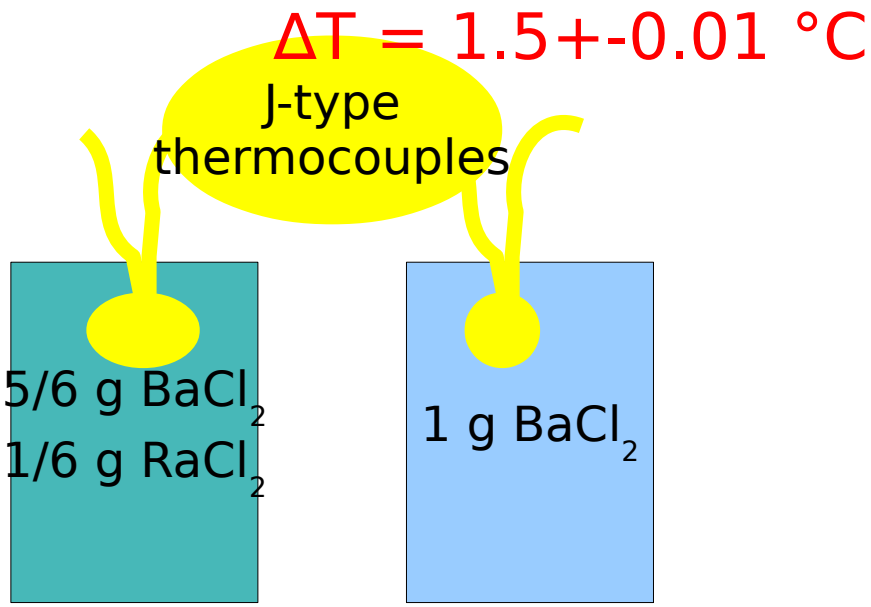


An ancestor of cryogenic detectors: calorimetry to measure radioactivity

C. R., 1903, 1er Semestre. (T. CXXXVI, N° 11.)

RADIOACTIVITÉ. — *Sur la chaleur dégagée spontanément par les sels de radium.*
Note de MM. **P. Curie** et **A. Laborde**, présentée par M. Lippmann.

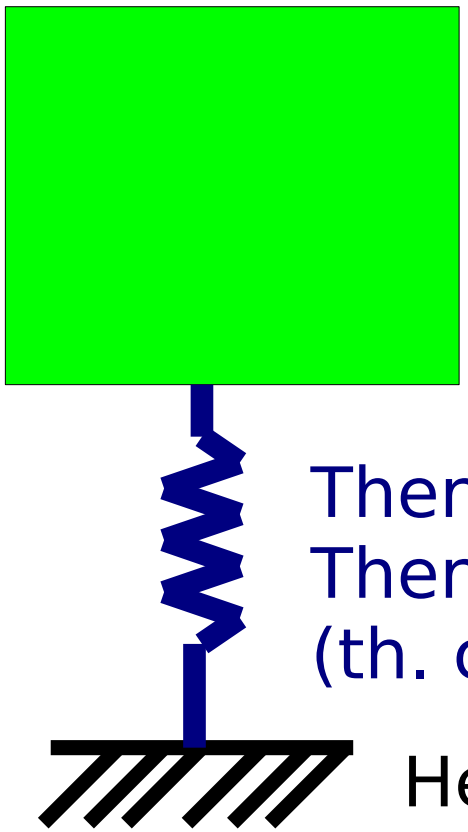
« Nous avons constaté que les sels de radium dégagent de la chaleur d'une manière continue.



- Large heat released by Ra:
  - Not compatible with chemical processes
  - Evidence for radioactivity
- Calorimetry: use temperature to measure energy: $\Delta T = E/C$

Sensitivity:
P = 14 *petites calories/h* = 60 J/h = 16 mW

Basic Principle of Cryogenic Calorimetry

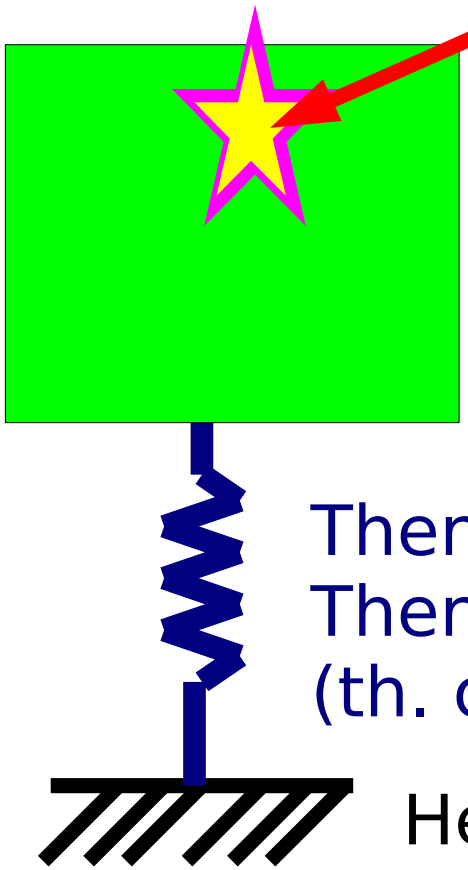


Absorber:
Heat capacity C
Temperature T

Thermal link
Thermal resistance R
(th. conductance G)

Heat sink, T_0

Basic Principle of Cryogenic Calorimetry



A particle deposits energy E in absorber

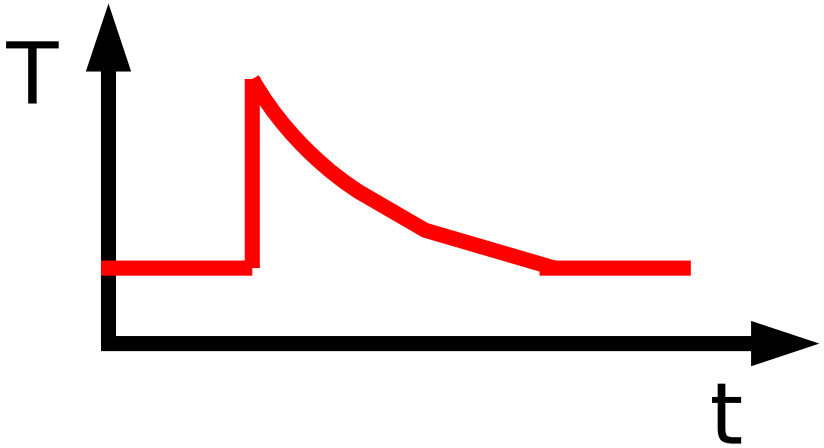
Absorber:
Heat capacity C
Temperature T

Thermal link
Thermal resistance R
(th. conductance G)

Heat sink, T_0

- If no thermal link, T steps up by E/C
- Thermal link allows relaxation back to T_0:

$$T(t)-T_0 = E/C\ e^{-t/RC}$$

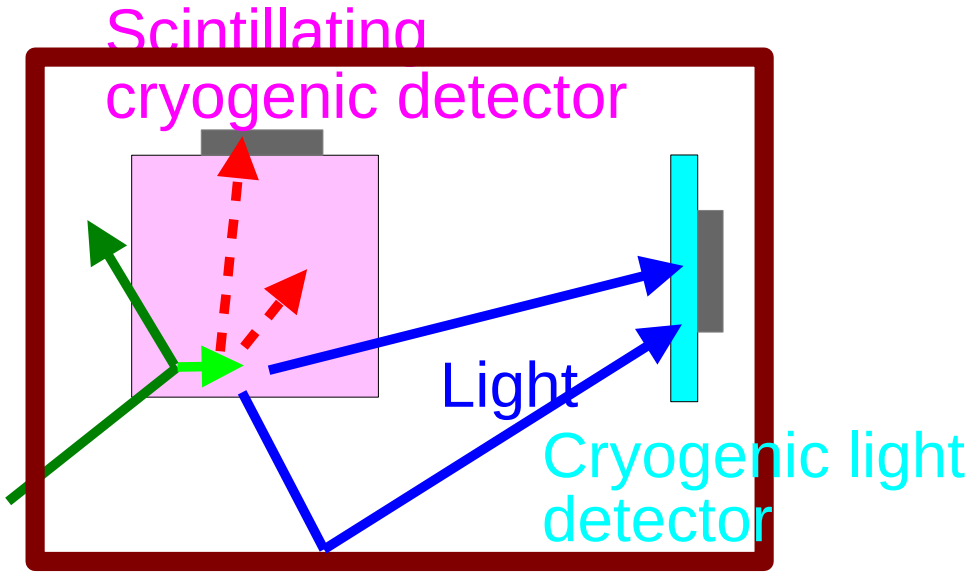


→ Excellent threshold and resolution ...
at O(10 mK) temperatures

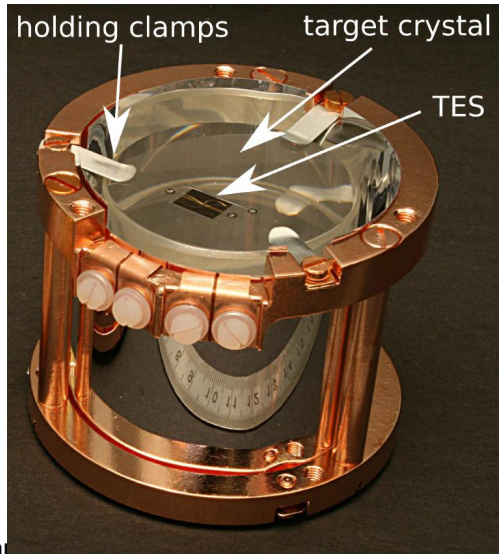
Reducing the Haystack:

Cryogenic Scintillation: CRESST/ROSEBUD/EURECA

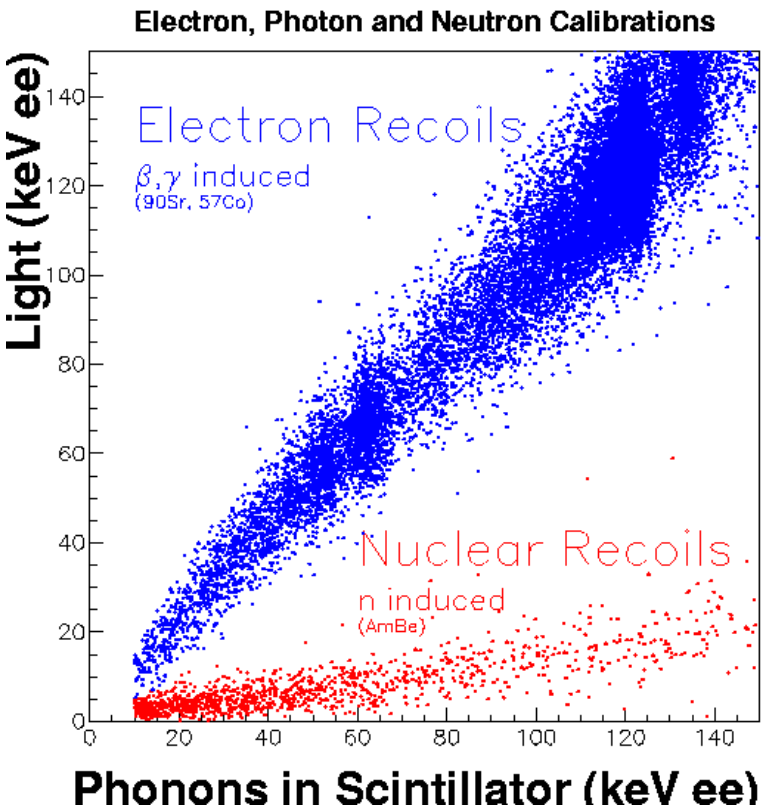
- Phonon-scintillation detectors



Light collector



- **Particle identification!**

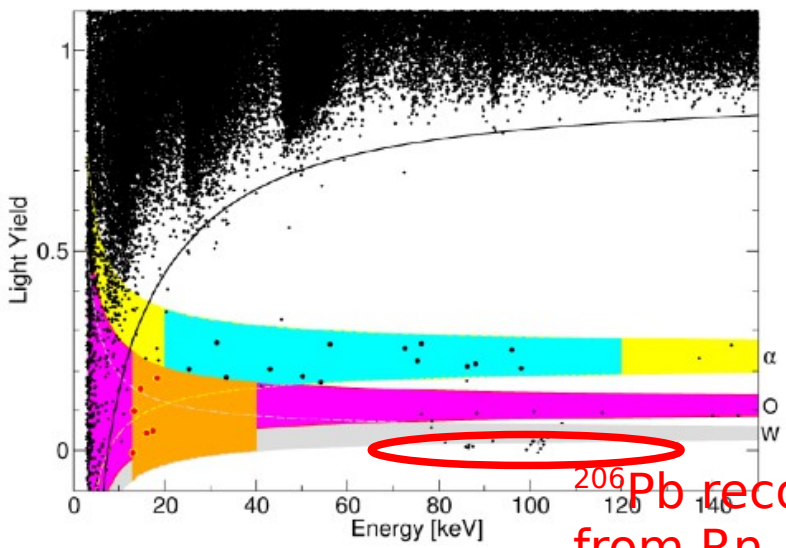


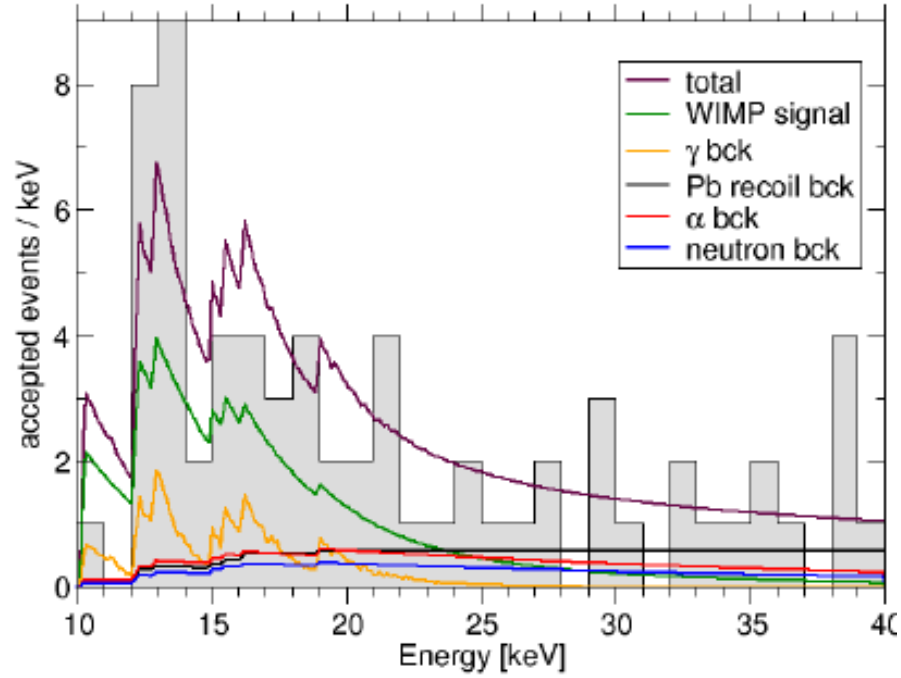
✔ Choice of nuclei ($CaWO_4$, BGO, CaF_2 ...)

CRESST 2012

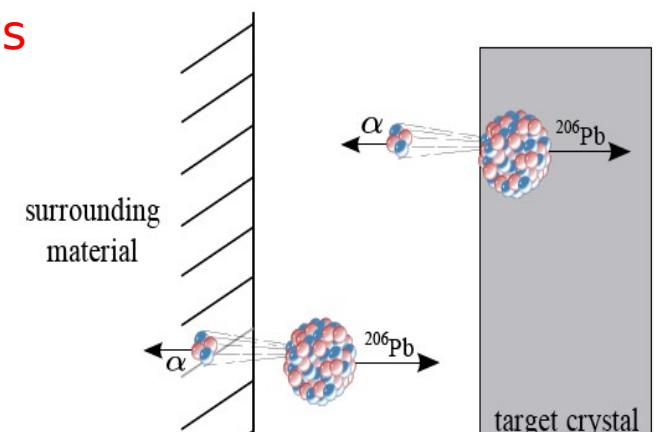
Eur. Phys. J. C (2012) 72:1971

- Detector modules: $CaWO_4$, 300 g
- 8 modules → 730 kg.d





- ^{206}Pb recoils from Rn, clamps holding crystal
- 67 events remain in signal region
- **Known** backgrounds account for ~40
- Contribution from WIMPs could explain spectrum
- Clamps suspected as a source of BG (see also Kuzniak et al, Astropart Phys 36 77 2012)



Not a factor

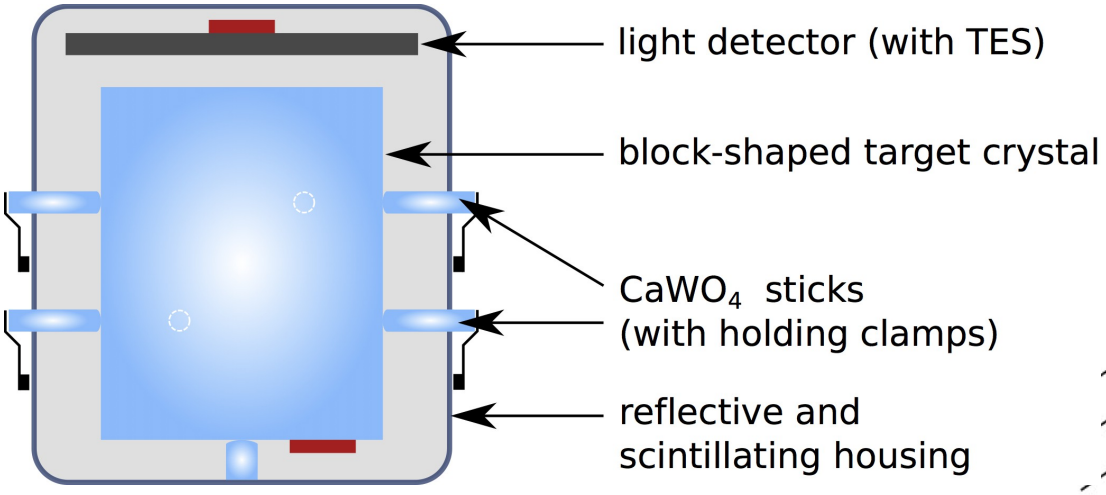
$E_{dep} \geq 103$ keV

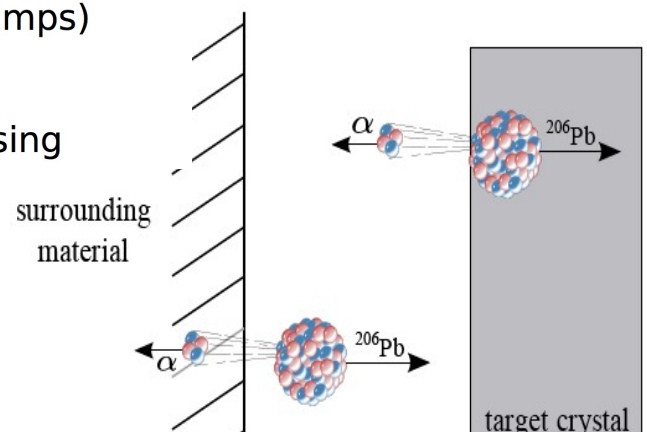
$E_{dep} \leq 103$ keV

Detector surrounded by scintillating foil (except for clamps)

CRESST 2014: arXiv:1407.3146

- One 249 g, $CaWO_4$ module, lower BG crystal, new clamps





Not a factor

$E_{dep} \geq 103\,keV$

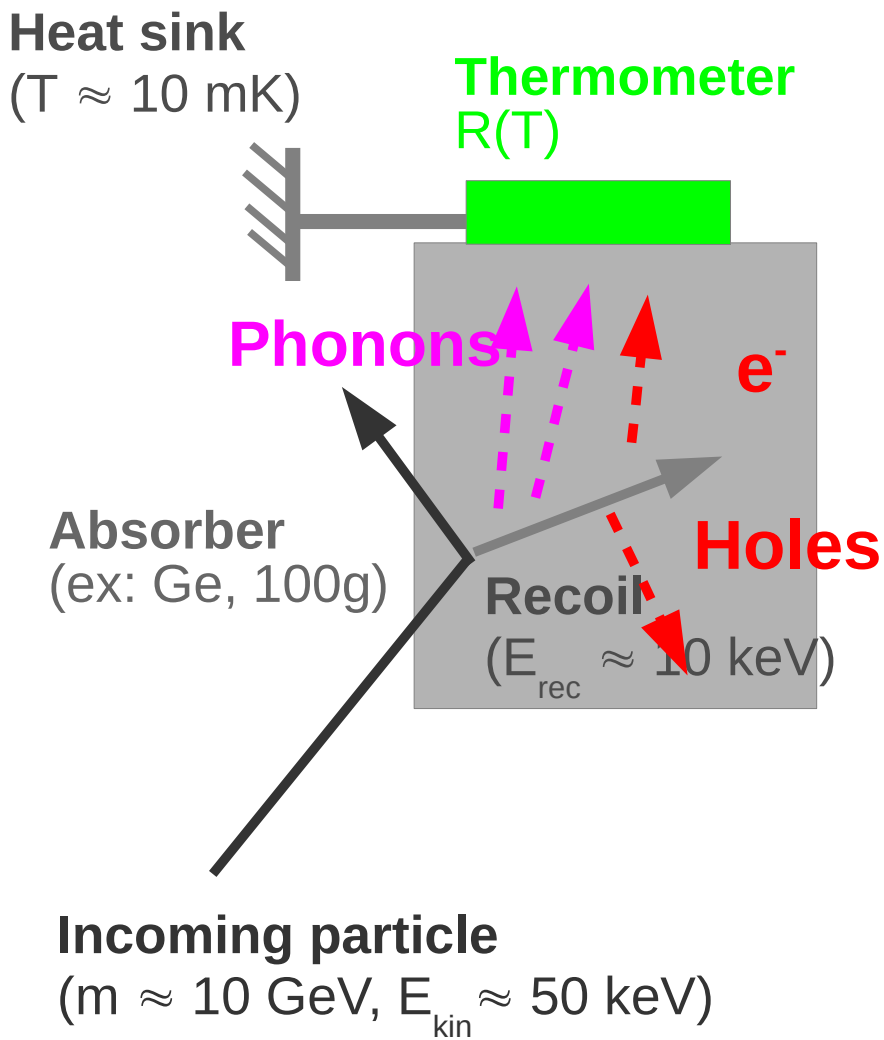
$E_{dep} \leq 103\,keV$

Detector surrounded by scintillating foil ~~(except for clamps)~~

- 29 kg.d exposure: rules out all of O-claim, most of Ca-claim
- Total of 18 modules of various designs running currently

Reducing the Haystack: Ionization-Phonon Detectors

(T. Shutt et al. PRL 69 3425 1992, L. Bergé et al. NPB 70 69 1999)



- Phonon signal: $\Delta T/T \approx$ 0.1% over ms

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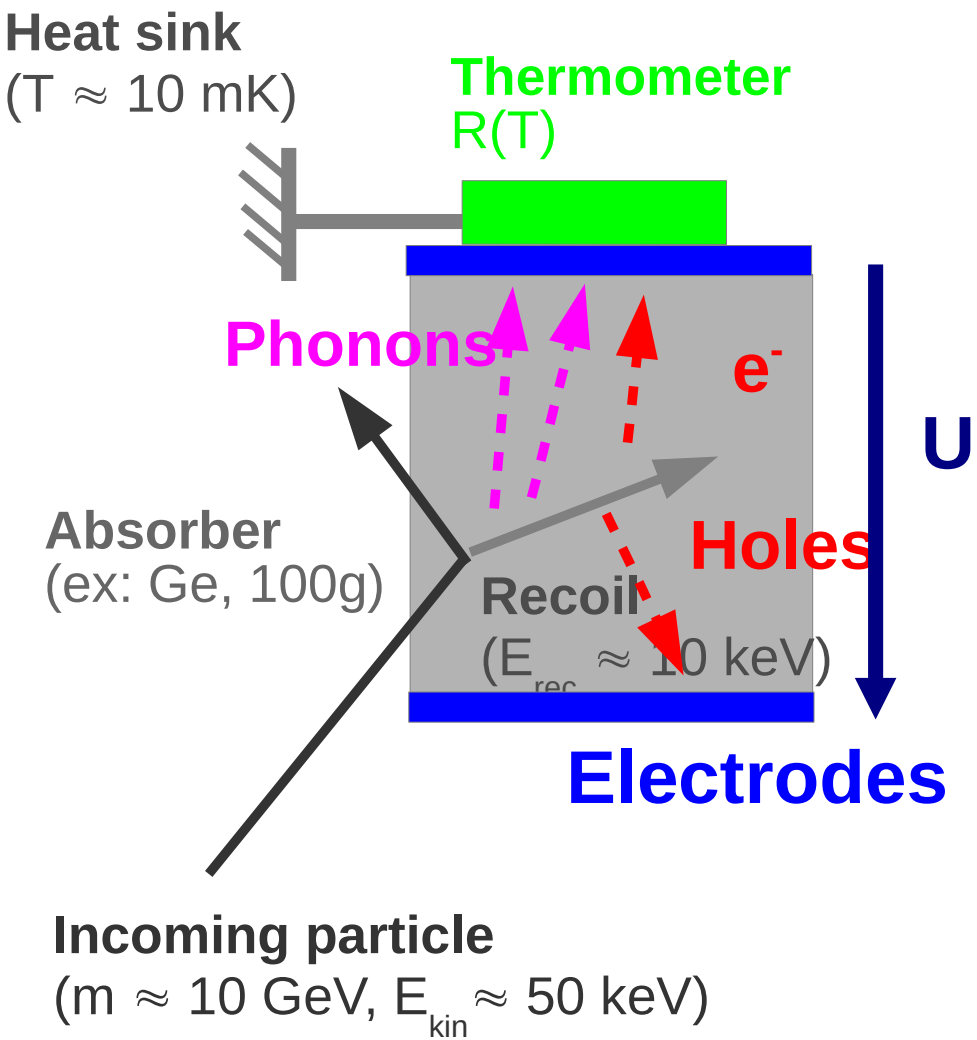

- Phonon signal: $\Delta T/T \approx$ 0.1% over ms
- Charge signal: $\approx$ 1000 pairs over μs

Reducing the Haystack: Ionization-Phonon Detectors

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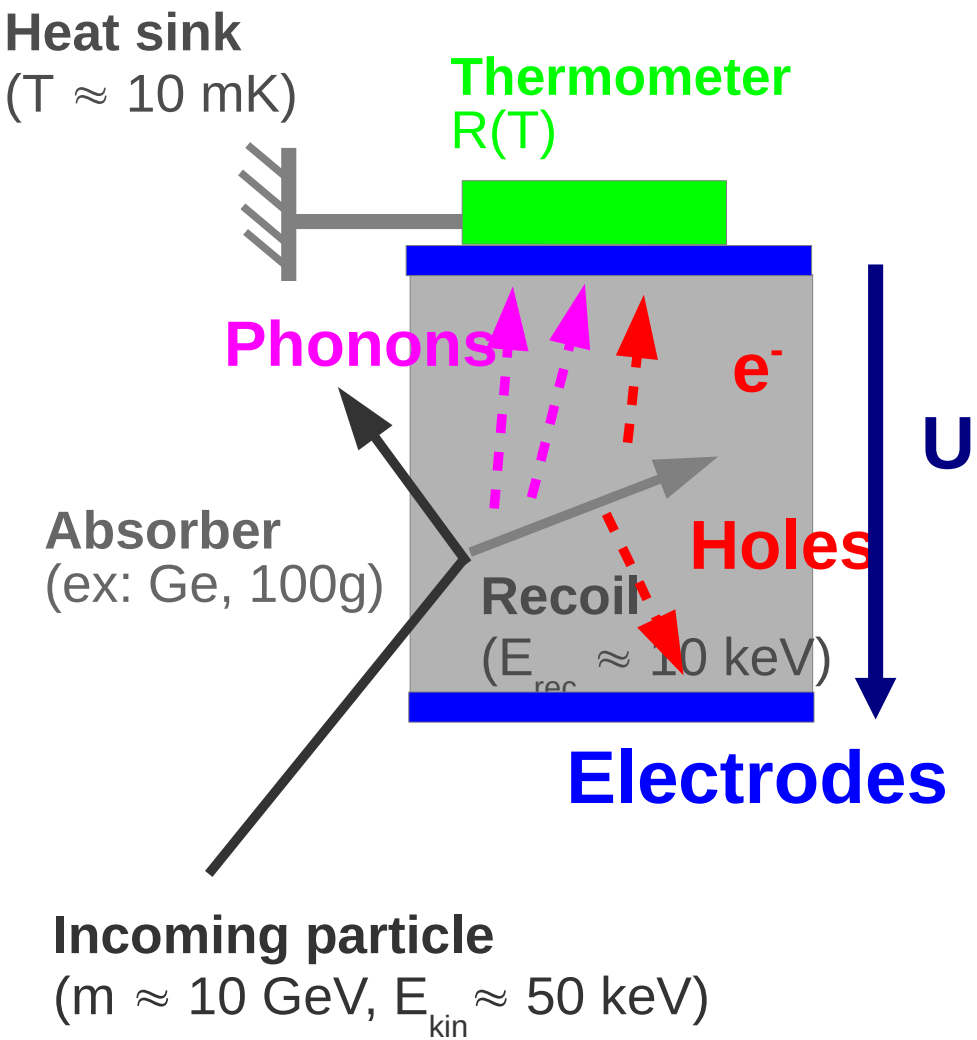


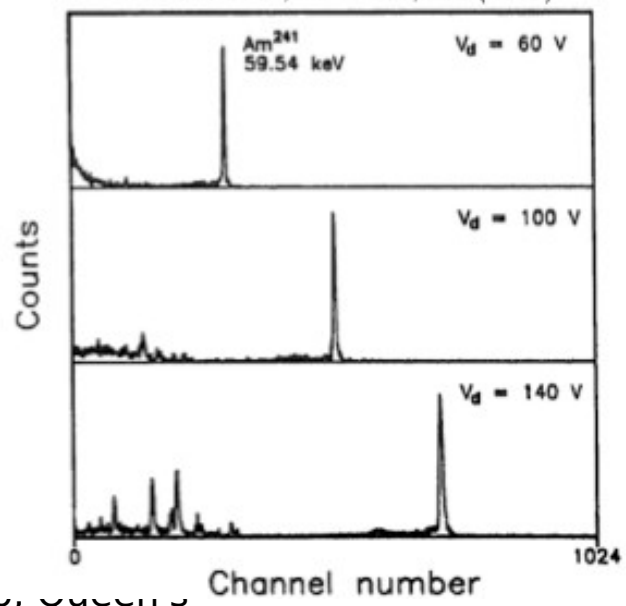
- Phonon signal: $\Delta T/T \approx$ 0.1% over ms
- Charge signal: ≈ 1000 pairs over μs
- β,γ particles ionize more than WIMPs, neutrons

➔ Event by event background rejection

Luke-Neganov effect in CDMSLite: Use phonons to read charge

- Bias a standard SuperCDMS 600 g iZIP detector at 69 V (rather than 4 V)
- As charges drift in electric field, work done on them by electric field leads to spontaneous emission of ballistic phonons
- Phonon amplification proportional to charge, bias voltage (CDMSLite: x24 for gammas)

P.N. Luke et al., NIM A289, 406 (1990)

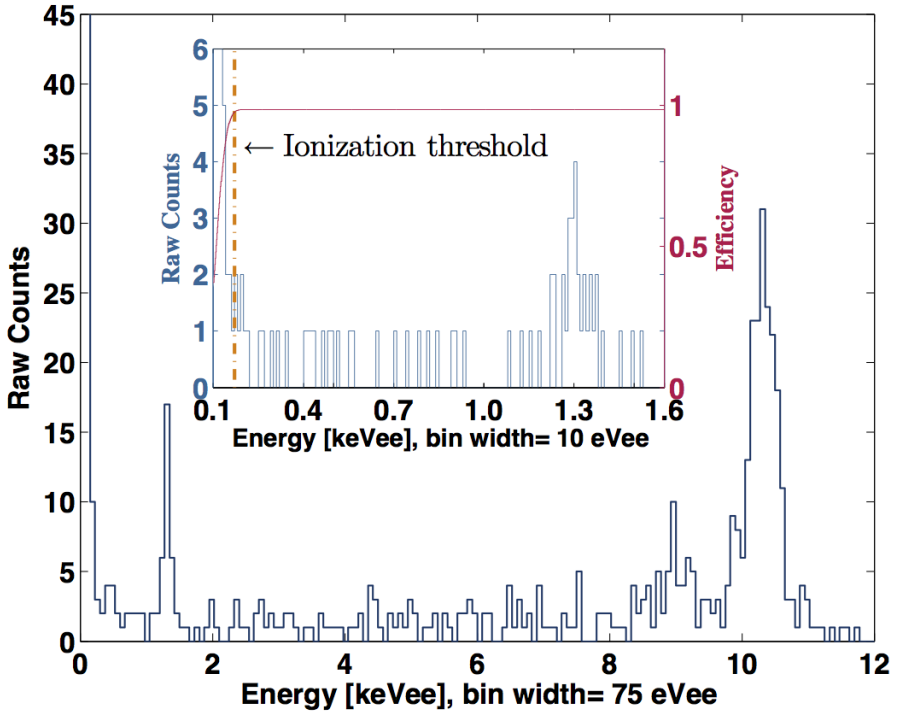


- Exposure 6.3 kg.d

✔ Excellent threshold (170 eVee ie 840 eVnr on Ge), resolution (1σ 43 eVee @ 1.3 keVee)

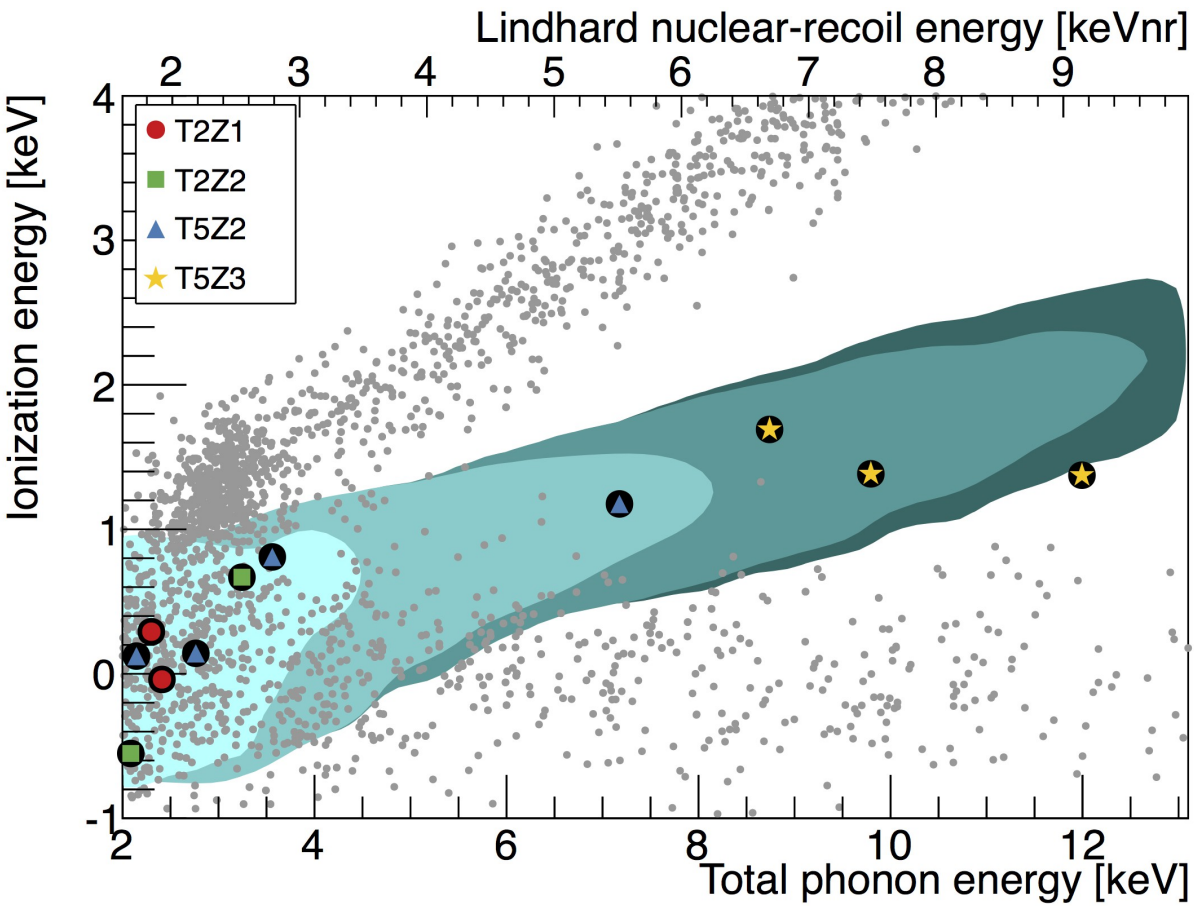
✗ Loss of background discrimination

✔ BG diluted with respect to signal



(n activation → K and L shell captures of ^{71}Ge visible)

Low-threshold unblinded results

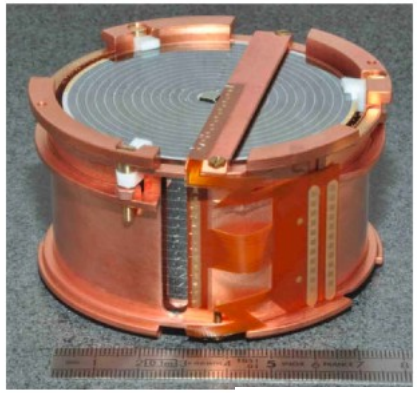


95% confidence contours for expected signal from **5**, **7**, **10** & **15** GeV/c^2 WIMPs

- $6.1^{+1.1}_{-0.8}$ evts expected
- 11 observed, including 3 at high energy from T5Z3 (with malfunctioning guard electrode)

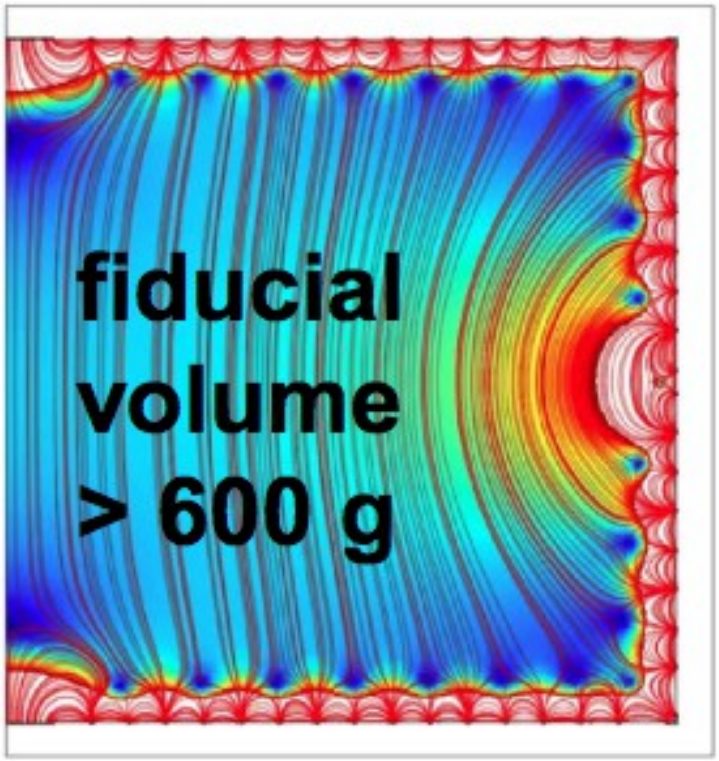
EDELWEISS III @ LSM

arXiv:1207.1815v1, Scorza AP 2014



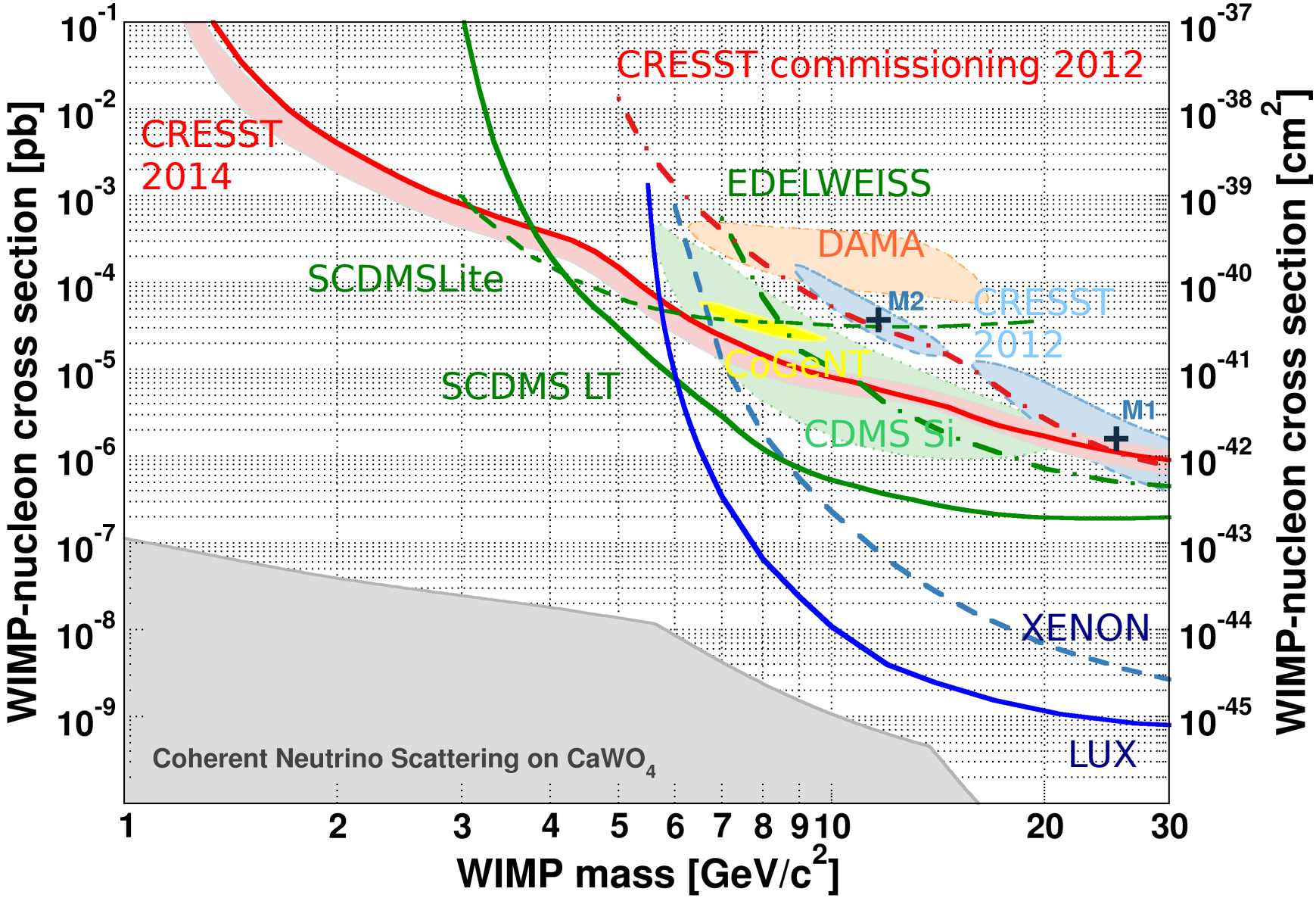
Interleaved electrodes on all surfaces
→ ID of surface events
+ good fiducial volume

Radial slice of detector



- Ionization-phonon technology similar to CDMS
  - Phonons: NTD vs TES
  - Charge: fuller interleaved electrode coverage
- Currently running:
  - 36 modules, 800 g each
  - Improved cryogenics, shielding, DAQ
- 500 kg.d and counting

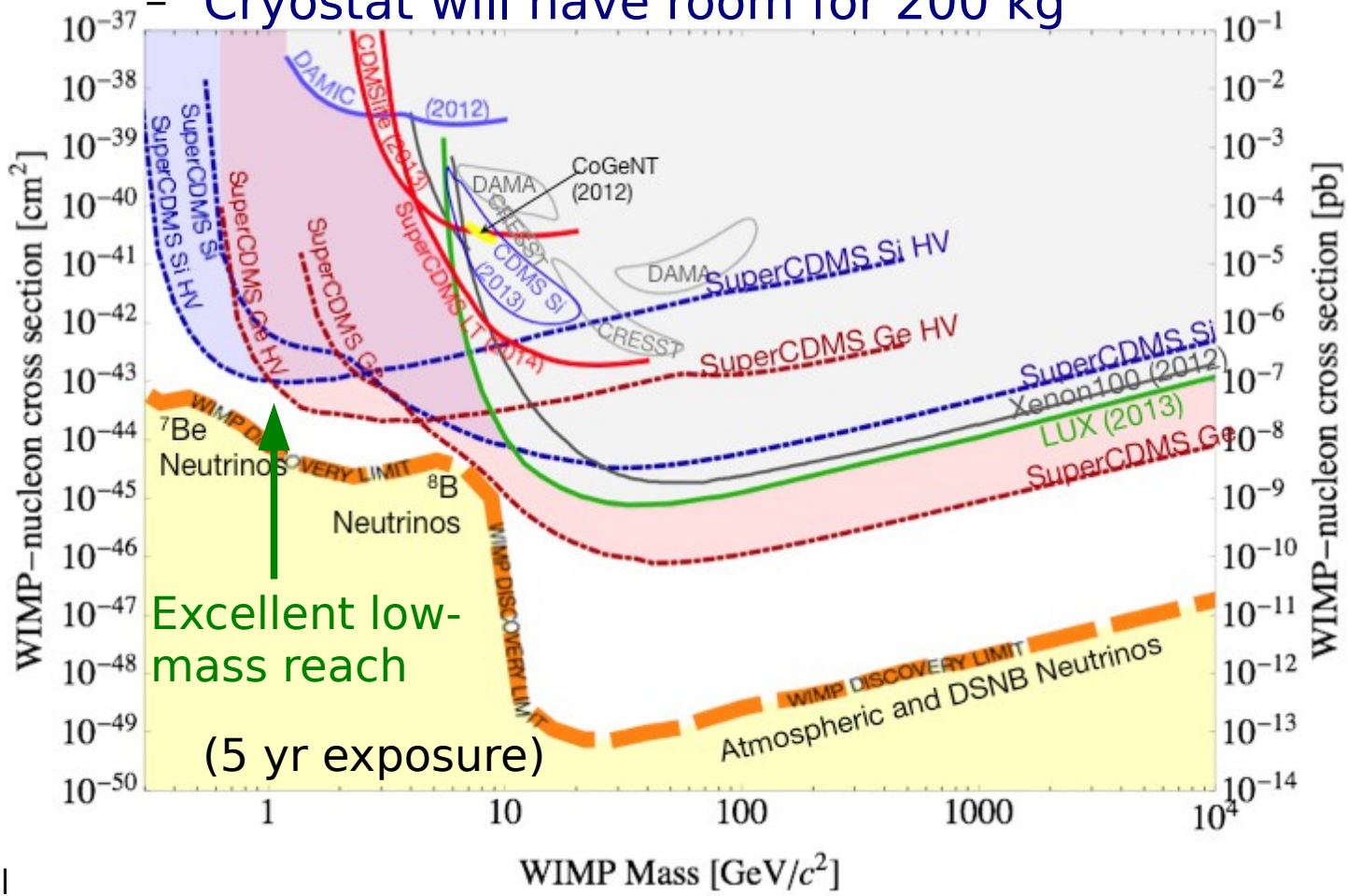
After the dust has settled: exploring towards lower masses



- Hints all but ruled out by new constraints (with little or no model-dependence in the case of CDMS-CoGeNT and CRESST-CRESST)
- Note also XENON, LUX

SuperCDMS @ SNOLAB

- Deeper, cleaner site to reduce BG
- Larger, cleaner experiment
  - 110 kg payload of improved detectors
    - Std: 92 kg Ge, 11 kg Si
    - Lite: 5 kg Ge, 1.2 kg Si
  - Cryostat will have room for 200 kg



- 3.4 M$ CDN received from CFI, contingent on US funding...
- Selected by DOE G2 process ... waiting for ~20 M$
- Discussions with EURECA (CRESST+EDELWEISS) for collaboration
- Data-taking could start 2018

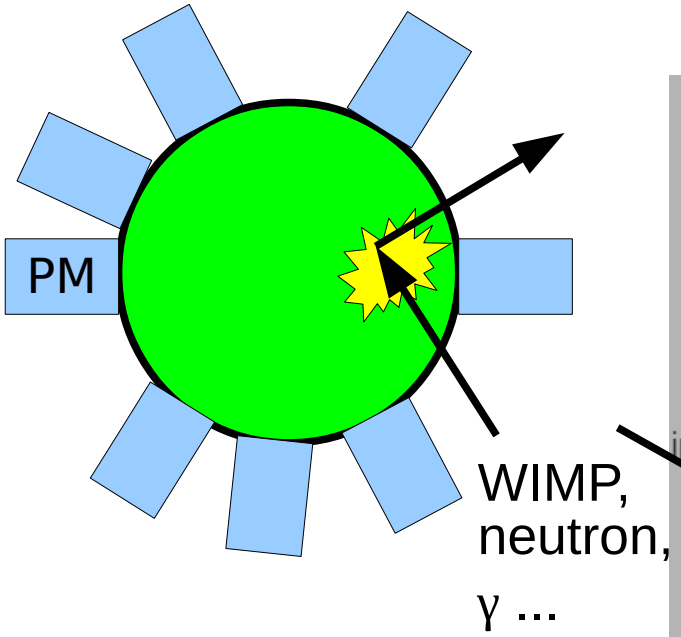
High-mass searches

- Xe
  - XENON → E. Aprile's talk
  - PANDA → K. Giboni's talk
  - LUX
  - XMASS
- Ar
  - DARKSIDE → P. Agnes' talk
  - DEAP
  - ArDM
  - WArP

Noble Liquids: Discrimination & Mass

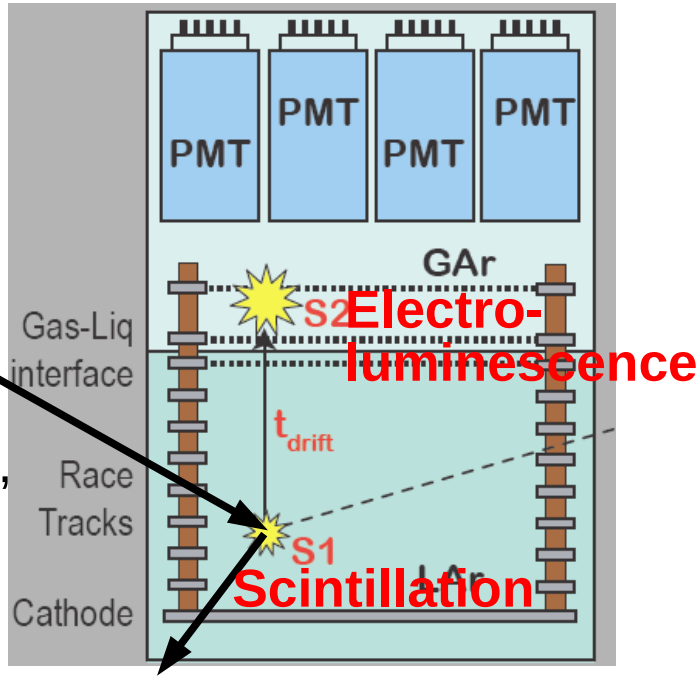
A	39.9	131.3
Boiling point (K)	87	165
Density (g/cm3)	1.4	2.9
Discrimination	S1/S2, S1 PSD	S1/S2
Radioactive isotopes	39Ar	
DM projects & experiments	WArP, ArDM, DEAP, CLEAN ...	XENON, XMASS, LUX, PANDAX ...

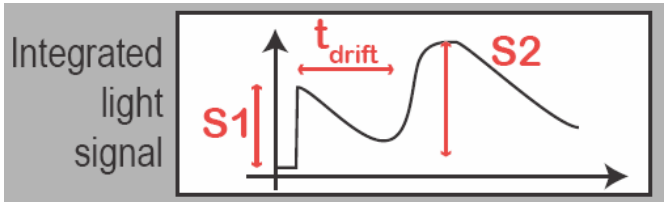
Single phase
(XMASS, DEAP, CLEAN)



S1 only, + PSD

Dual phase TPC
(XENON, LUX, PANDAX, ArDM, DarkSide)





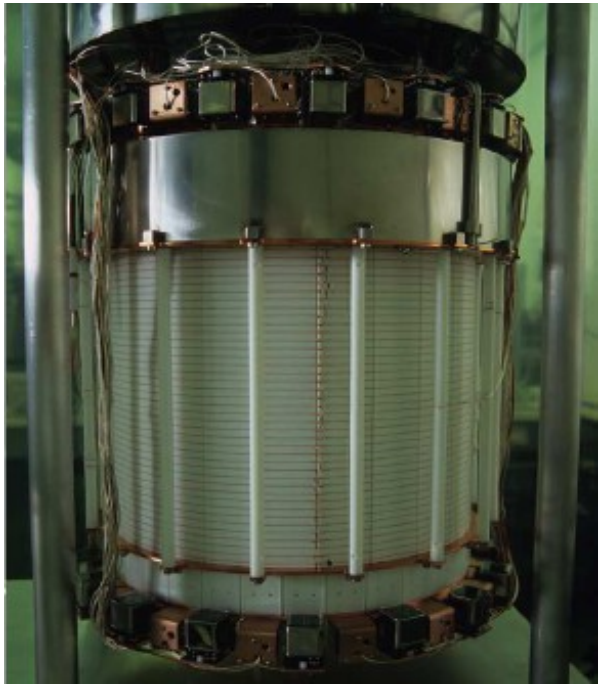
Figs. L Grandi, INFN Pavia (WArP)

- PSD **much** better in Ar ($>10^8$) than Xe
- Position reconstruction better in dual phase (~mm) than single phase (~cm)

XENON 100 @ Gran Sasso

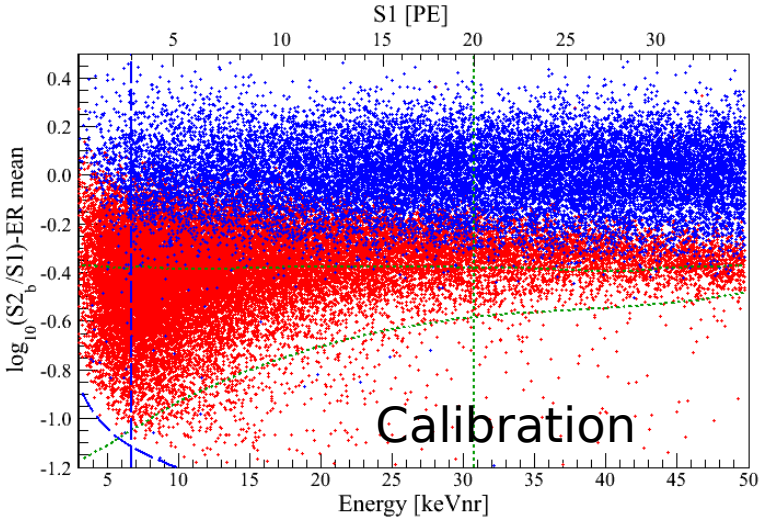
(Aprile, arXiv:1207.3458)

- Dual-phase, 165 kg (35 kg fiducial) Xenon TPC

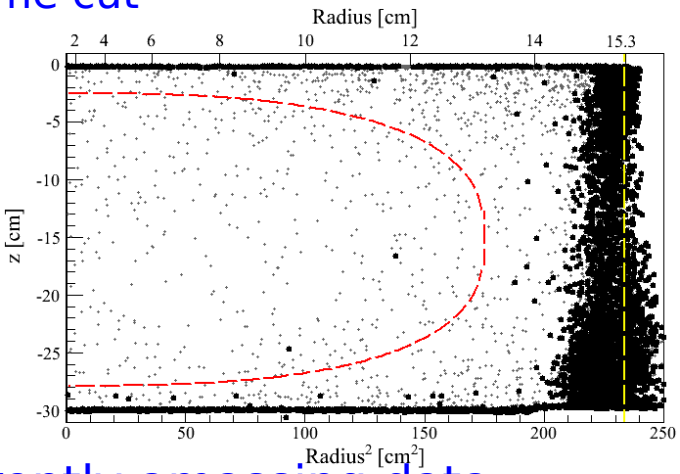


- Rapid progress and impressive **world-leading** (until 2013) results...

- ...despite mundane gamma, beta BG rejection ("only" 98.75% for acceptance 20-60%)



- Clean, and powerful self-shielding, fiducial volume cut



- Currently amassing data:
  - Lower masses
  - Modulation study
  - Demo for 1T: BG, calibrations...

XENON1T: overview

1 m- drift dual-phase XeTPC filled with ~3.3 tonnes of ultra-pure LXe

Designed to enable a fast detector's upgrade to ~7 tonnes Xe target in 2018

Detector& support systems based largely on proven (XENON100) technologies

New 3 inch low-activity PMTs developed for XENON1T: average QE~34%

Detector shielded by water Cherenkov muon veto

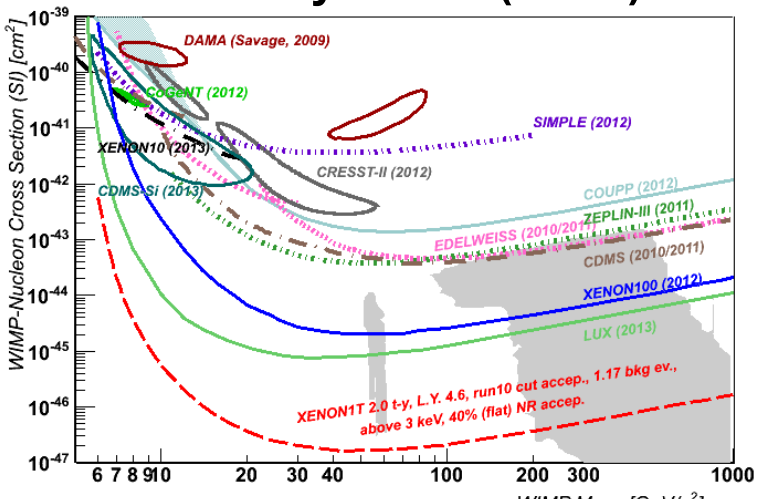
Background goal:*100 x lower than XENON100, ~5 x 10-2 events/(t-d-keV)*

Under construction in Hall B - commissioning of cryogenic plants ongoing

TPC commissioning in late Spring 2015. Expect first science run by Fall 2015

Science Goal: 2 x 10-47 cm2 for 50 GeV WIMP with 2 ton x yr data (2017)

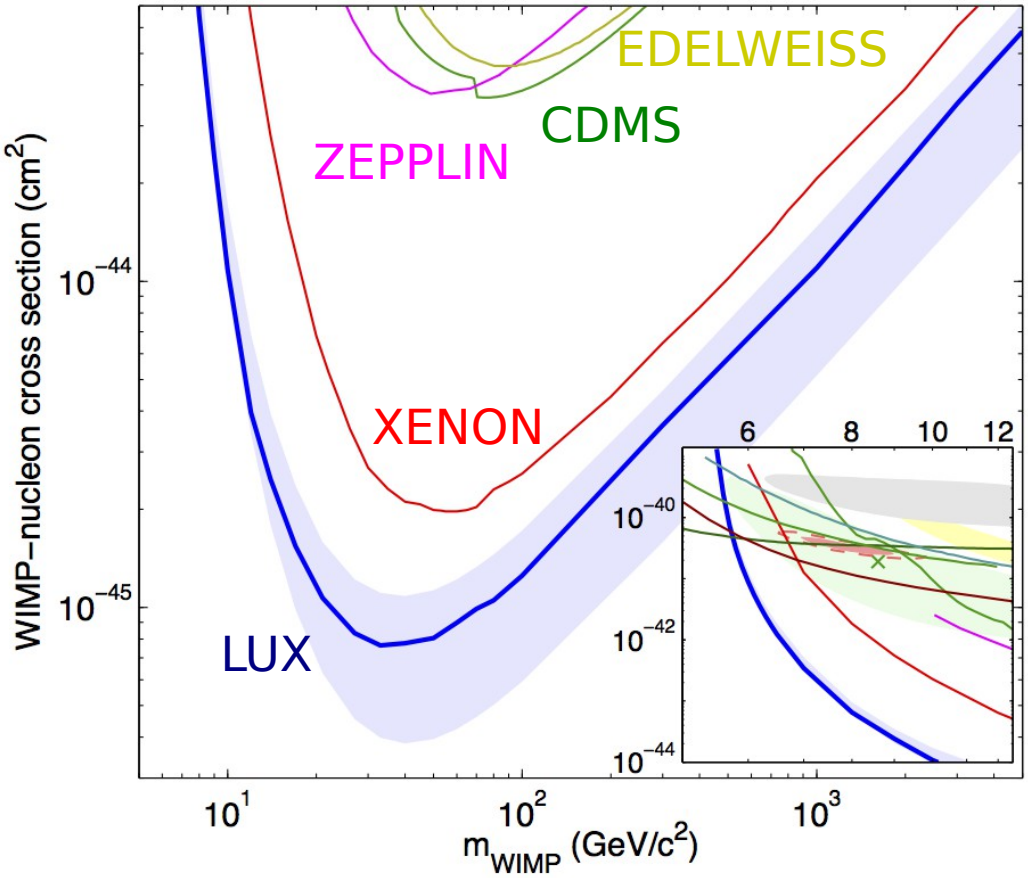
Courtesy E. Aprile



LUX @ SURF* (2013)

(D. Akerib et al., Phys. Rev. Lett. 112, 091303 (2014))

- Fiducial mass: 118 kg
- Livetime: 83 d
- After BG rejection:
  - 160 evts (!)
  - Compatible with leakage from electron recoils
- **Leading field**
- Exploring new parameter space
- Status:
  - Calibrating at low E to reduce threshold in 2013 data
  - Starting a low BG 300 d run improve sensitivity by factor <4
  - LZ, 7-ton fiducial, DOE G2 approved



- **<u>Incompatible with all hints for signal from other expt</u>** (under std assumptions)

*Sanford Underground Research Facility

DEAP-3600 Dark Matter Search at SNOLAB

Project Overview

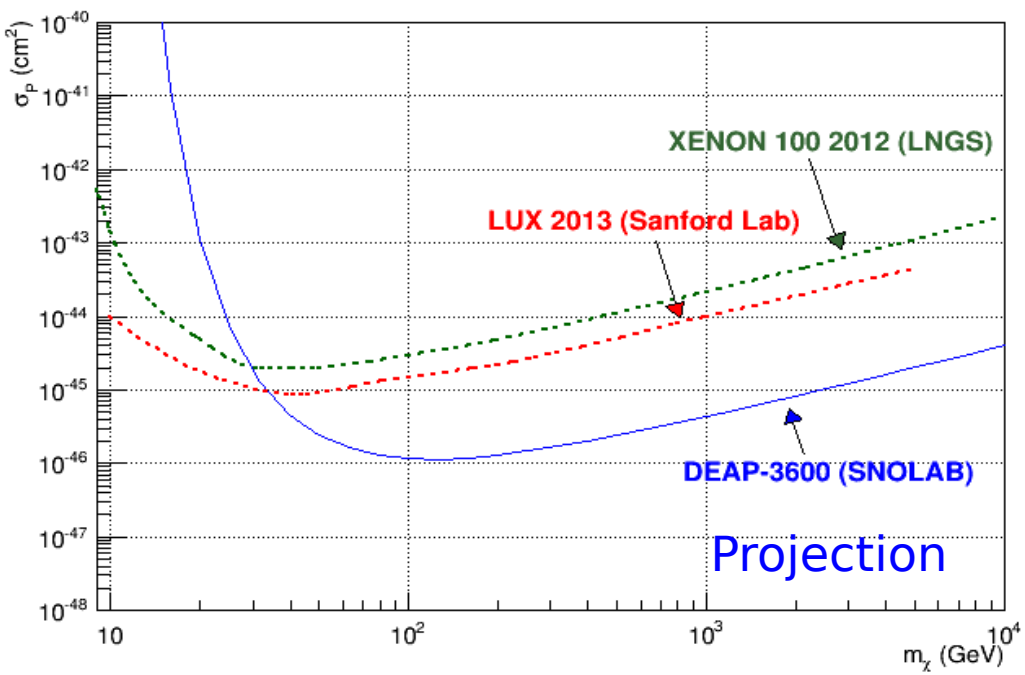
3.6 tonnes liquid argon in ultraclean acrylic vessel, 255 8-inch HQE PMTs

1 tonne fiducial mass designed for < 0.2 background events/year

10-46 cm2 sensitivity for ~100-GeV WIMP with 3-year exposure

Project Timeline

Turn-on PMT systems	Nov/Dec '14
Argon gas runs and in-situ background measurements, commissioning	Dec '14/ Jan '15
Physics Data start	Early 2015

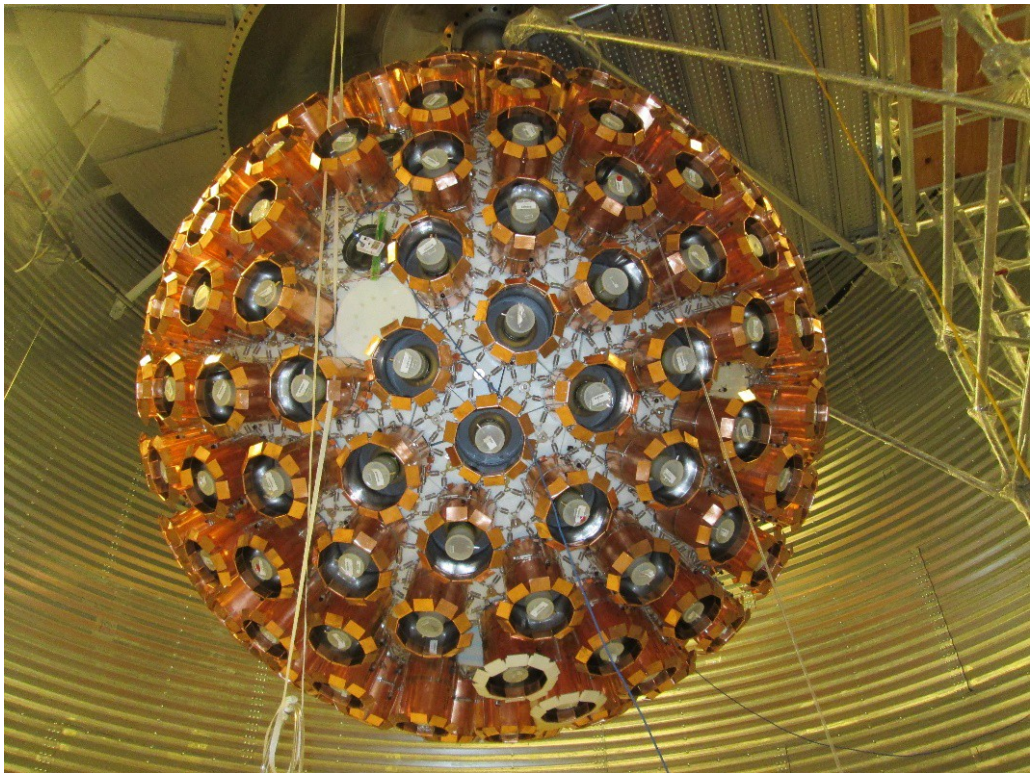


Future Project

Planning for development of future 50-tonne argon experiment (photo-detector development, low-background argon and engineering proposal)

Courtesy M Boulay

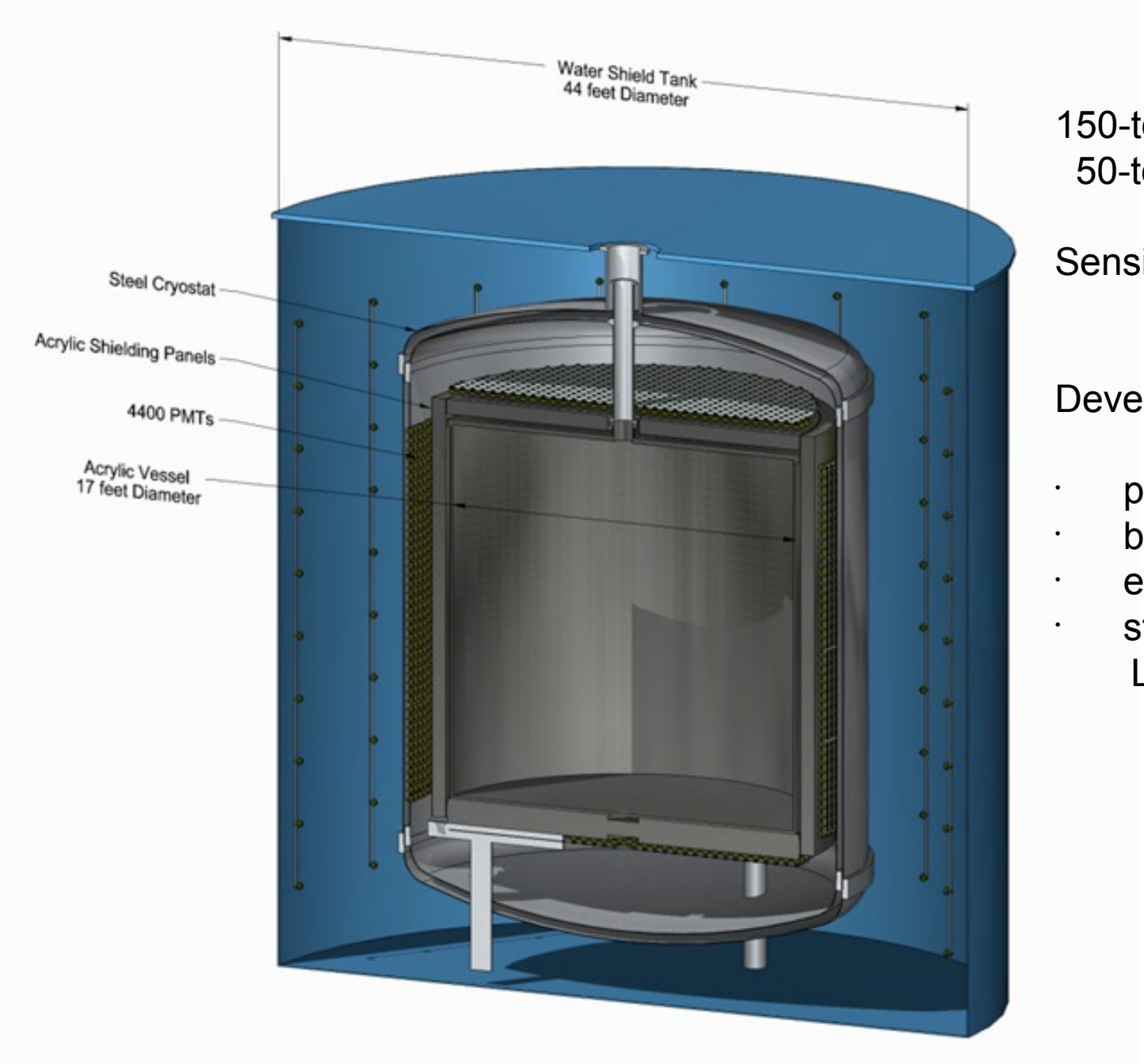
DEAP-3600 Detector at SNOLAB



Completed inner detector
255 8” R5912HQE PMTs
installed in water shield tank

Steel Containment Sphere
in 8m diameter water shield tank

DEAP-50T: Follow-up with 50-tonnes of liquid argon (Development Proposal)



150-tonnes DAr in AV
50-tonne fiducial

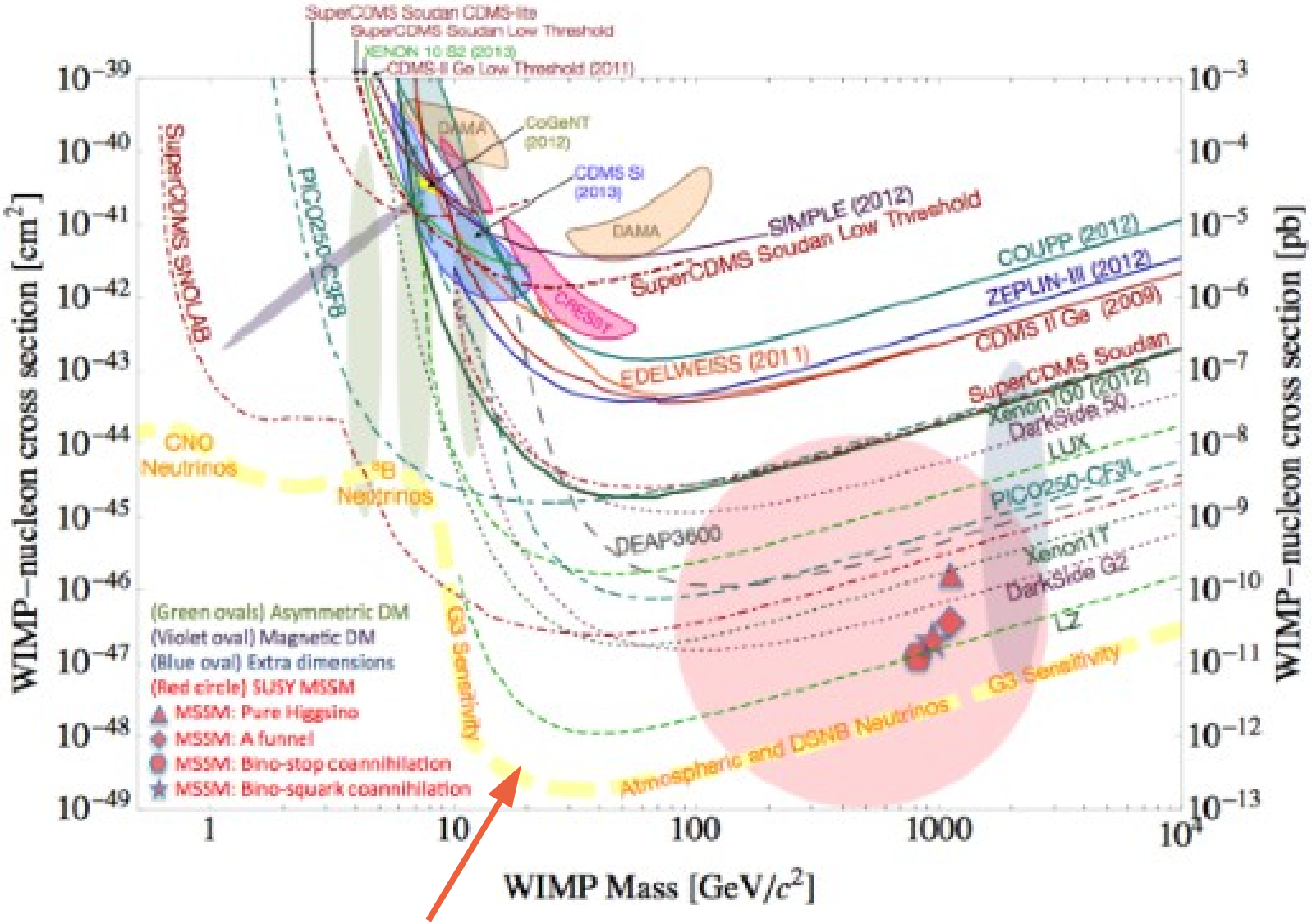
Sensitivity 10-48 cm2

Development

- photodetector development
- background reduction
- engineering and safety
- storage and screening of Low-Radioactivity Argon

Prospects for the Field

"Toute action de l'esprit est aisée si elle n'est pas soumise au réel" M. Proust



Coherent neutrino scattering background from Sun, atmosphere, SN

Fig Cushman/Snowmass

How to convincingly discover WIMPs?

- Large detector mass seems necessary to see hints of WIMPs
- Annual/diurnal modulation signatures not water-tight, especially if there is background, but useful (MIMAC → Q. Riffard, T-REX → F. J. Iguaz Gutierrez, NEWAGE → K. Miuchi, DRIFT, DMTPC ...)
- Need particle identification (not necessary for a limit)
- WIMP conundrum:
  - Most signal expected near threshold...
  - ... but threshold is where particle identification usually falters and where new backgrounds appear
  - ➔ Good understanding of threshold is paramount
- Mix targets, technologies and sites to understand backgrounds and systematics
- Too much fine-tuning of astrophysical and particle assumptions detrimental to credibility
- Now-discredited low-mass hints shows nothing will be easy
- Be open with data and in discussions

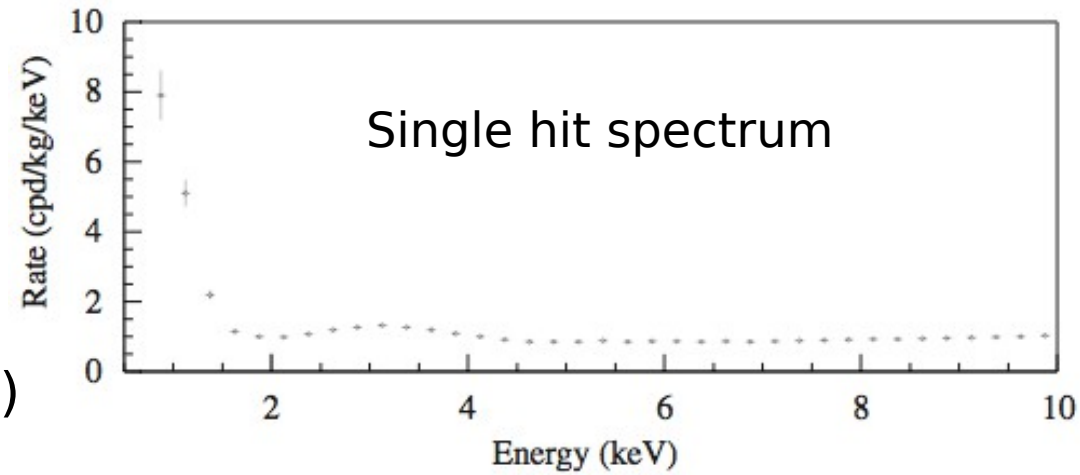
Misc

- SD Sector: PICO, SIMPLE
- Proposals/projects to investigate DAMA:
  - DM-Ice
  - SABRE
  - KIMS-NaI
  - ANAIS
  - Cryogenic detectors?

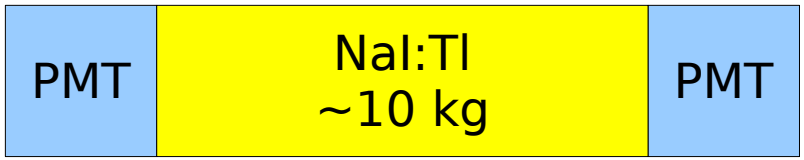
DAMA/LIBRA NIMA 592 (2008) 297

- At Gran Sasso, since mid-1990s
- From 100 to 250 kg of NaI:Tl, over a dozen years
- Ultra-pure detectors and environment
- Total exposure ~1.2 T.y

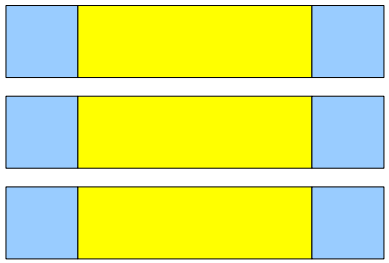
- Threshold 2 keVee, ie:
  - ~6 keV recoil for Na
  - ~20 keV recoil for I



Module: trigger on coincidence between PMTs (see ~ 6 pe/keVee)

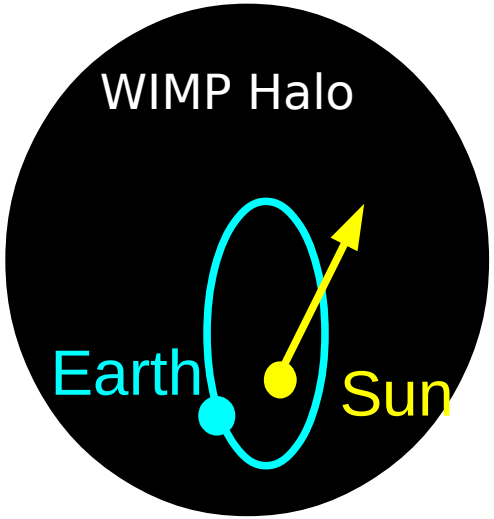


Self-shielding: reject coincidences between modules



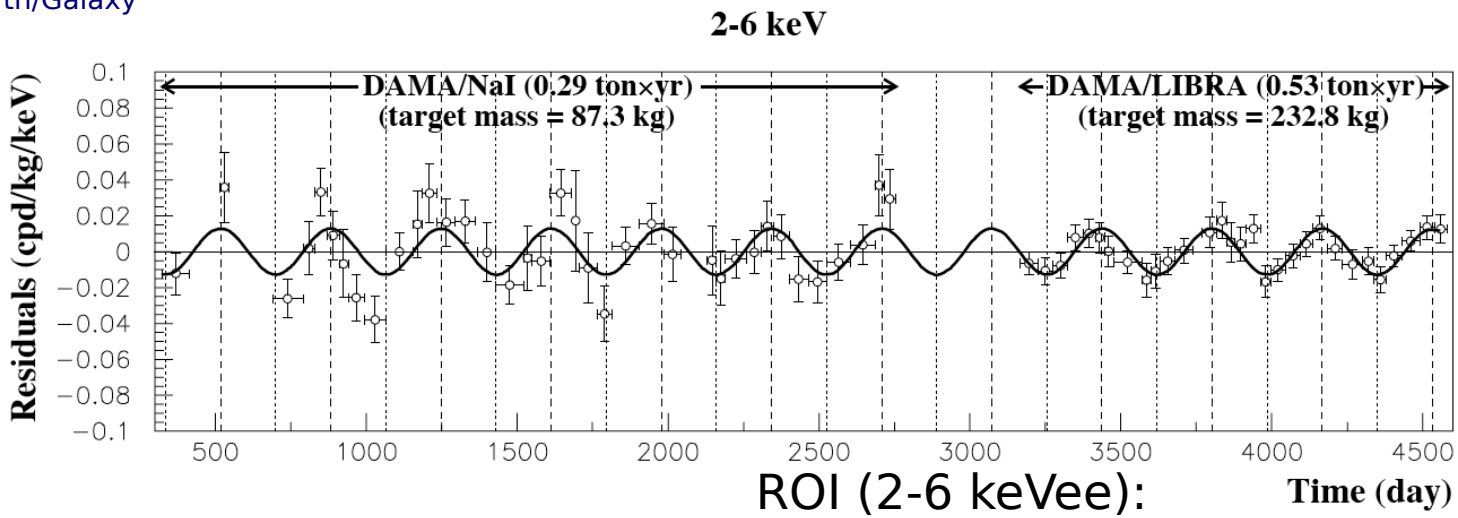
DAMA Results

- Significant annual modulation observed (>7σ)



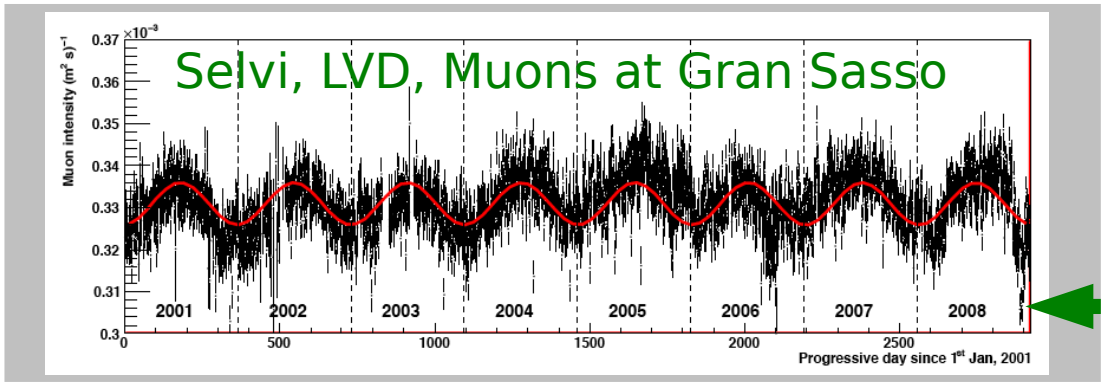
December - June

$V_{Earth/Galaxy}$ ~ 220 – 250 km/s → recoil spectrum modulated:



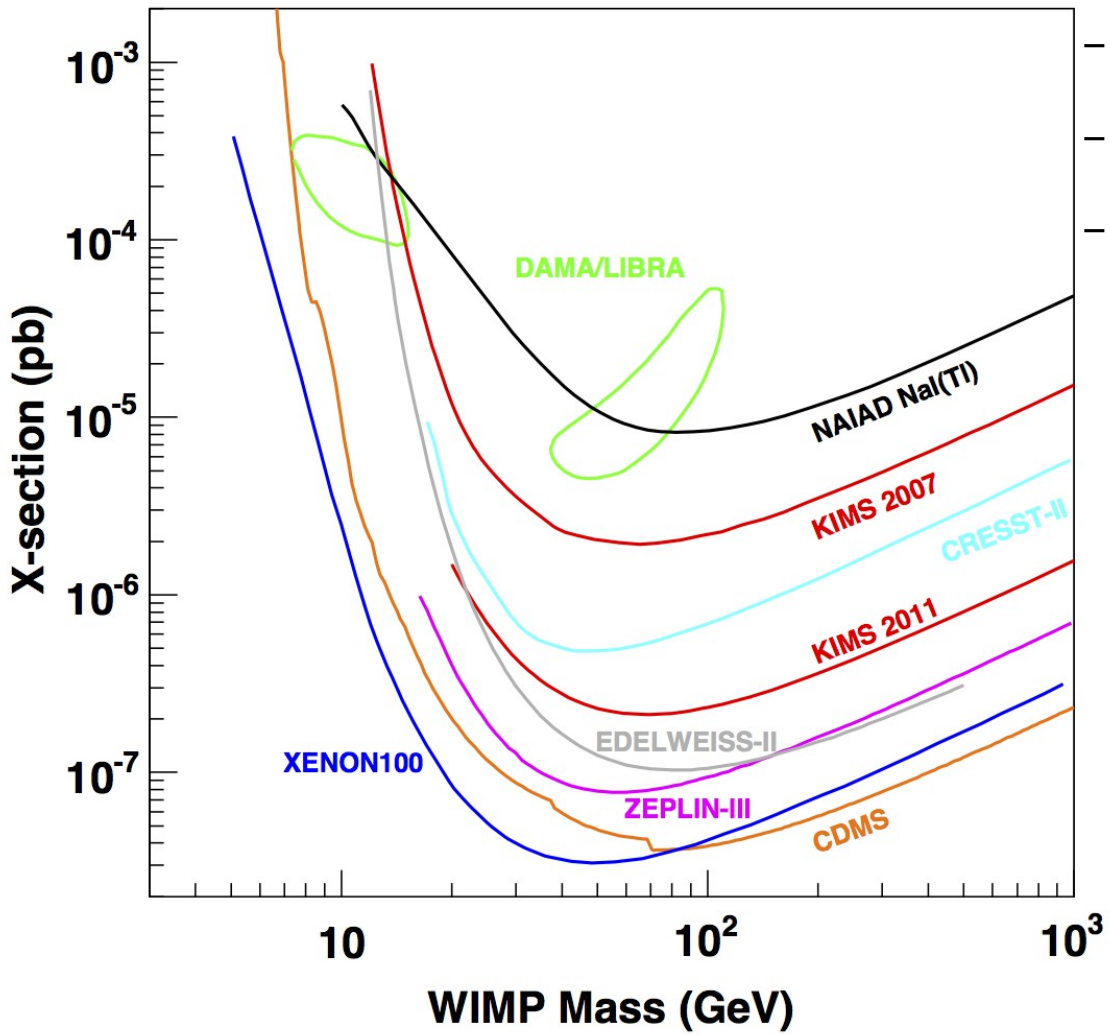
ROI (2-6 keVee):
AC: 0.045 /d/kg
DC: 1.0 /d/kg/keV

- Interpretation not straightforward:
  - No particle identification (no pulse shape discrimination at low energies)
  - Many things have an annual modulation, eg:



Many things have annual modulation → μ-induced fluorescence (Nygren 2011) ?

“Standard” interpretation of DAMA results in conflict with many other experiments



Similar scintillation-only expts:

- KIMS (CsI:Tl)
- NaIAD, ANAIS, SABRE … (NaI:Tl)
- DM-Ice (NaI:Tl at South Pole)
  - Southern hemisphere → WIMPs would have same phase, season would have opposite
  - Leverage shielding, know-how and DAQ from IceCube
  - Tests with 2 old crystals from NAIAD (total m 17 kg)
  - Bonus: light yield of NaI:Tl increases around -30 °
  - Extra challenge: procuring radiopure NaI

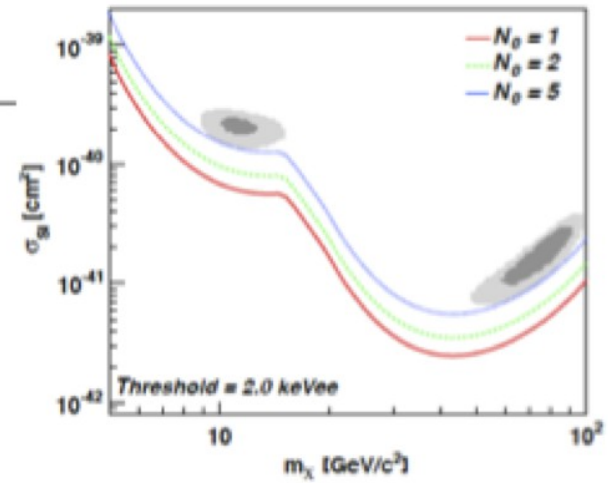
DM-Ice

Objectives

- **Directly test DAMA's observation, definitive probe of longest standing DM claim**
- **Test assertion that the observed signal is due to dark matter & understand its origin**

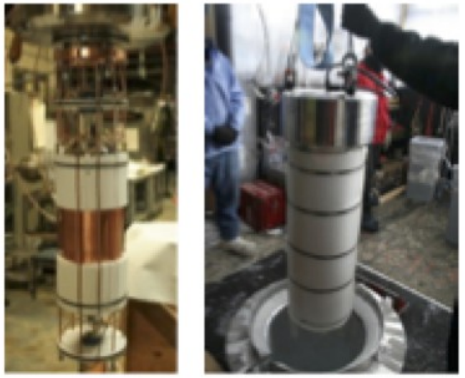
Key Features

- NaI(Tl) target
- only experiment with access to both Northern & Southern Hemispheres



500 kg·years
(2 - 4 keV) with 1, 2, and 5 dru background (DAMA has ~1 dru)

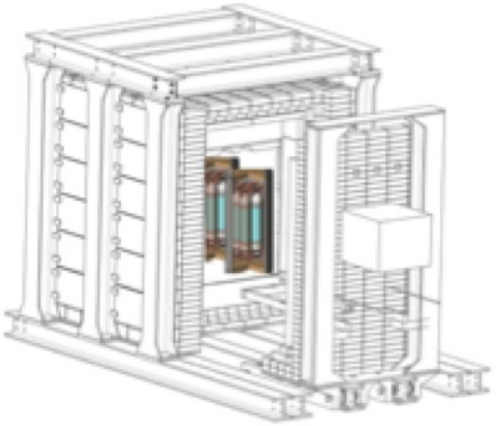
DM-Ice17



Operating continuously since 2011
17 kg of NaI(Tl) at 2450m depth at South Pole, analysis ongoing

PRD 90 (2014) 092005

DM-Ice 250 North



Northern Hemisphere Run
Portable 250 kg NaI(Tl) detector
Tests the null hypothesis & study possible sources of modulation

DM-Ice 250 South

Deployment at South Pole
Definitive testing if signal observed independently from DAMA.

Astropart.Phys. 35 (2012) 749-754

Reina Maruyama

Current BG in ROI 30 times > DAMA (more ^{40}K, no veto)

Courtesy R Maruyama

Courtesy Princeton group: Calaprice, Froborg, Xu

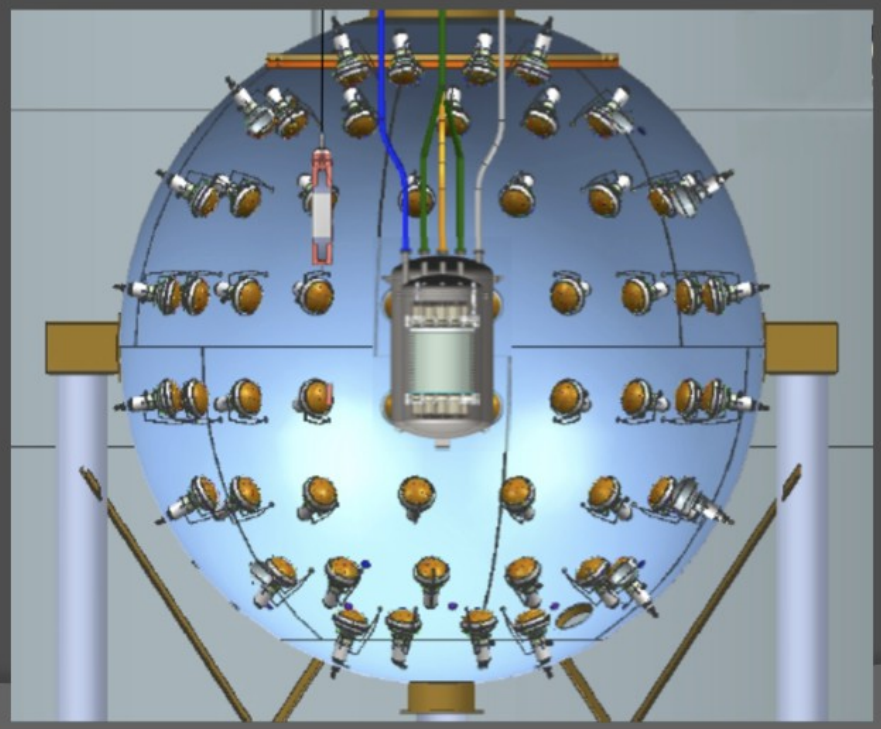
SABRE: Sodium Iodide with Active Background REjection

Goal: Definitive test of DAMA by using

- Ultra high purity powder and clean growing methods to obtain ultra pure NaI(Tl) crystals
- Low radioactive high Q.E. PMTs without light guide to achieve high light yield and low energy threshold
- Active liquid scintillator veto to reject ^{40}K and other backgrounds

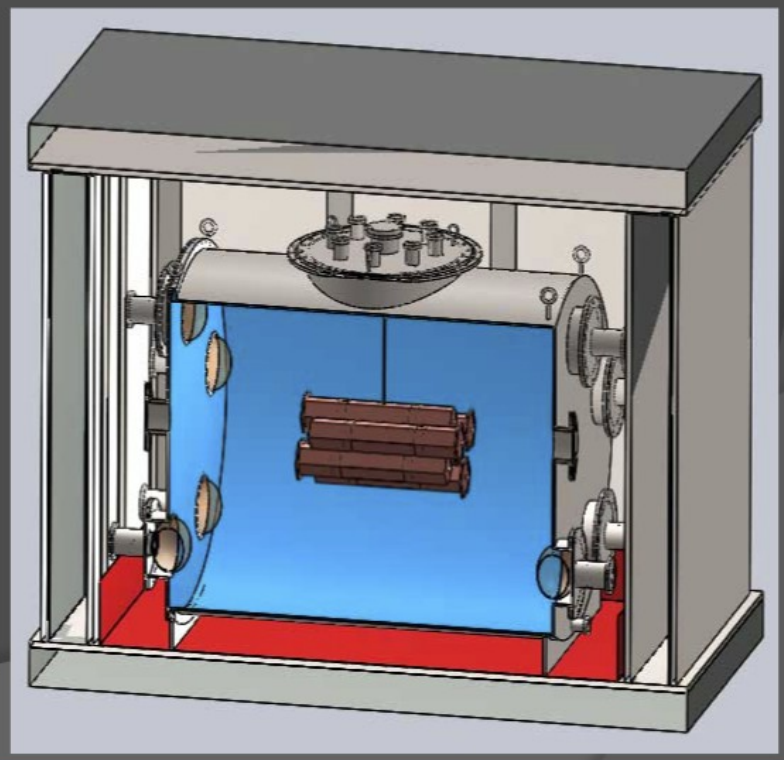
DarkSide veto (LNGS)

- 4m diameter liquid scintillator veto shielded by >3-4 m of water
- 1st NaI(Tl) detector background test in prep



Portable SABRE veto

- 1.5m x 1.5m cylinder
- Currently under construction
- Possible locations: SNOlab, LNGS, Australia



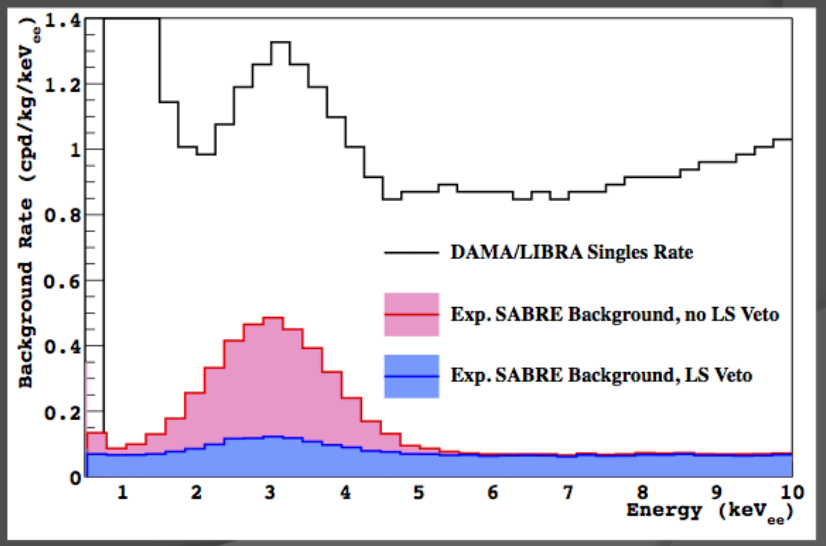
SABRE: Sodium Iodide with Active Background REjection

Status:

- NaI powder: K ~10 ppb; U, Th <1 ppt; Rb ~0.2 ppb
- NaI(Tl) crystals:
  - Small high purity crystal grown (impurity levels same as powder)
  - Large (3" dia.) standard purity crystal grown using high purity techniques
  - Large high purity crystal growth in preparation
- NaI(Tl) property study:
  - Measurement of Na quenching factor down to 6 keV nuclear recoil
  - Pulse shape discrimination down to ~6 keV nuclear recoil

Outlook:

- Improve NaI powder purity by zone refining and improved production technique
- Improve NaI(Tl) crystal growth and processing
- Improve detector packaging with optimized optical coupling, lower humidity levels and lower contamination
- 50-kg array with background of 0.1 cpd/kg/keV, indicated by current powder/crystal tests, provides 4-sigma evidence for or against the DAMA dark matter claim in 3-year run.

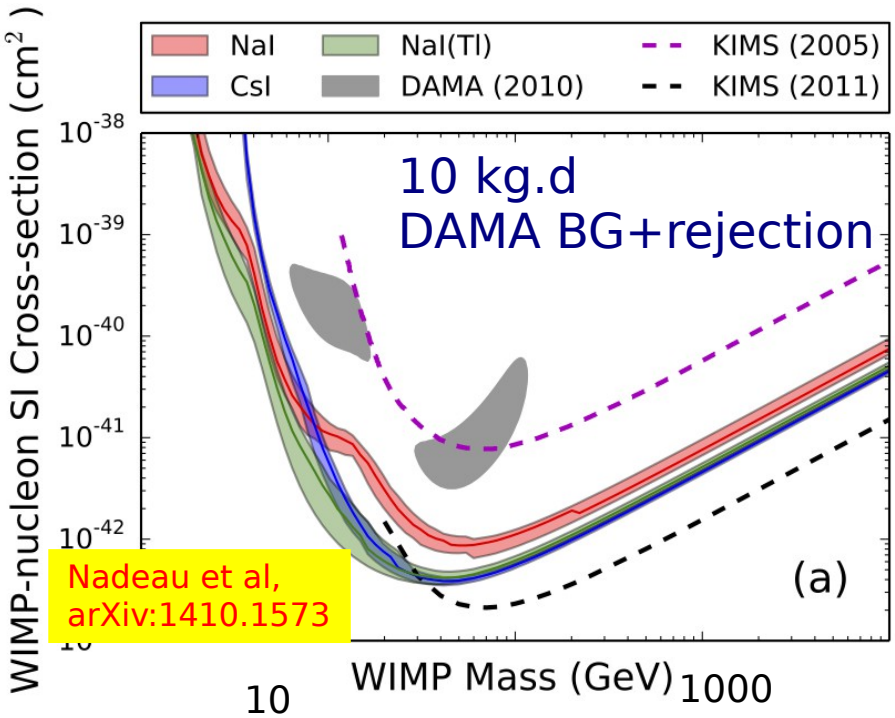


Expected SABRE background
Assuming same impurity levels as in powder

Cryogenic Detectors to Test DAMA?

- mK phonon + scintillation readout à la CRESST
- R&D on NaI at low T:
  - Spectra, coatings vs hygroscopicity: Coron et al, EPJ Web of Conferences 65, 02001 (2014)
  - Alpha light Yield: Sailer al, Eur. Phys. J. C (2012) 72:2061
  - Alpha, gamma light yields: Nadeau PhD, in preparation
- Phonon channel a challenge (Schäffner et al, J Low Temp Phys (2012) 167:1075–1080 10 keV resolution in CsI)
  - Low Debye T
  - Hygroscopicity
- Potential payoff:
  - Less astro, particle dependence
  - Particle identification

- Sensitivity assuming phonon performance improved to current CRESST level:

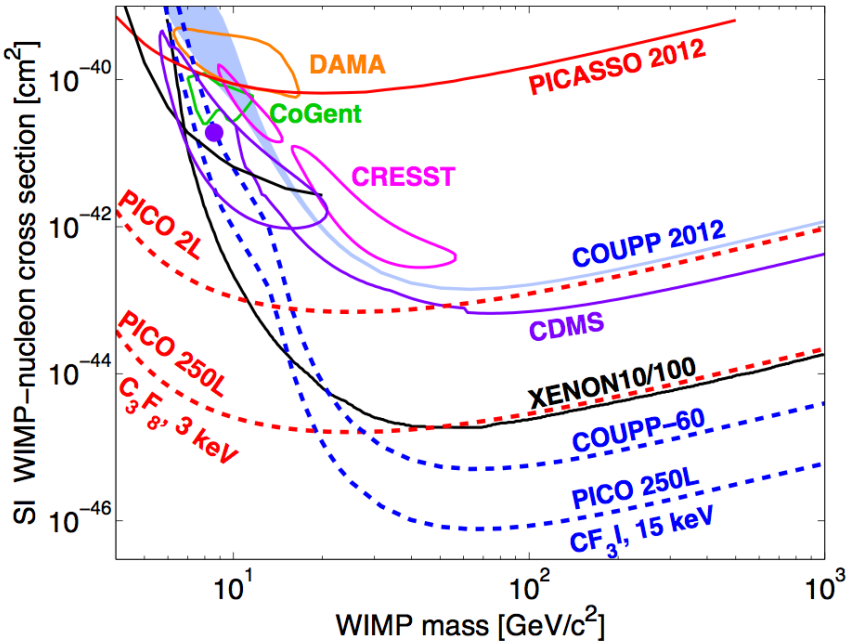


- With BG rejection
  - Small mass sufficient
  - Modulation analysis also goes faster (for a given mass)

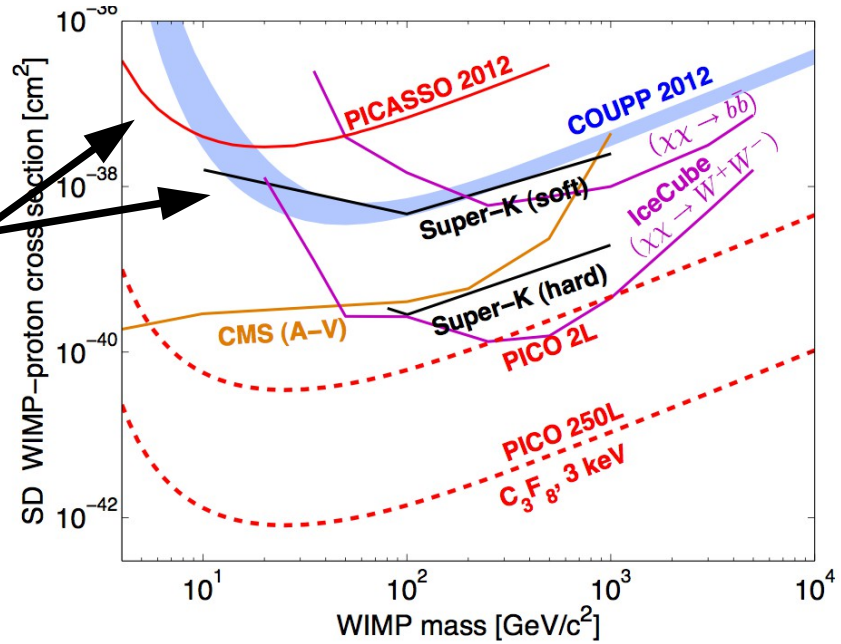
PICASSO + COUPP = PICO

PLB 711 (2012) 153 PRD 86 052001 (2012)

- Superheated detectors at SNOLAB
  - PICASSO (114 kg.d): C_4F_{10} droplets
  - COUPP (553 kg.d): CF_3I bubble chamber
- Also MOSCAB condensation chamber
- Detect bubbles with piezoelectric sensors (and cameras for COUPP)
- Insensitive to β, γ
- Identification of α also possible thanks to acoustic signature (Aubin NJP 2008)
- Geared towards SD, light WIMPs
- PICO 2L:
  - Similar to COUPP, but with C_3F_8
  - Being installed at SNOLAB
- Future: PICO 250L



Leading sensitivity



Direct Dark Matter Searches

- Post-Higgs, astrophysics and particle physics still faced with dual challenge
  - Dark matter?
  - Physics beyond standard model?
- Significant progress over past decade (sensitivity $x10^3$), fueled by improvements in detector technology
- As SUSY has waned, interest has expanded to low masses *(though full GeV-TeV range still possible)*:
  - **No confirmed signal!**
- Complementary mix of targets and technologies required to validate any discovery