Title: Direct Searches for Dark Matter

Date: May 05, 2015 01:00 PM

URL: http://pirsa.org/15050112

Abstract: <p>Astrophysical observations suggest that the majority of matter in the Universe is made up of novel Weakly Interacting Massive Particles (WIMPs). Such WIMPs are often predicted by extensions to the Standard Model. Efforts have been underway for more than two decades to detect WIMPs directly in detectors on earth. The challenge is great because of the small energies involved and the low interaction rates. The field has been driven by progress in detectors able to identify radioactive backgrounds. I will review how recent enthusiasm for low-mass WIMPs, which was generated by tantalizing hints seen in several experiments, has waned. Lastly, I will discuss various ideas to check the longstanding DAMA WIMP-detection claim, including the feasibility of alkali-halide cryogenic detectors.</p>

~~63 64 65 66 67 68 69 70~~ 71 78

A 6~~2~~ Year Old Problem

Fritz Zwicky and the Coma galaxy cluster

Helv. Phys. Acta, 6, N° 2, p 110, 1933

Die Rotverschiebung von extragalaktischen Nebeln

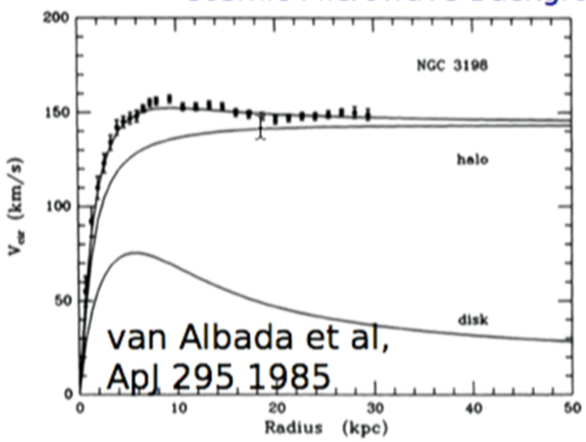
Um, wie beobachtet, einen mittleren Dopplereffekt von 1000 km/sek oder mehr zu erhalten, müsste also die mittlere Dichte im Comasystem mindestens 400 mal grösser sein als die auf Grund von Beobachtungen an leuchtender Materie abgeleitete[1]). Falls sich dies bewahrheiten sollte, würde sich also das überraschende Resultat ergeben, dass dunkle Materie in sehr viel grösserer Dichte

$$\rho_{gravitation} > 400\ \rho_{luminous}$$

Dark Matter ?

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



- 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)?

–... ?

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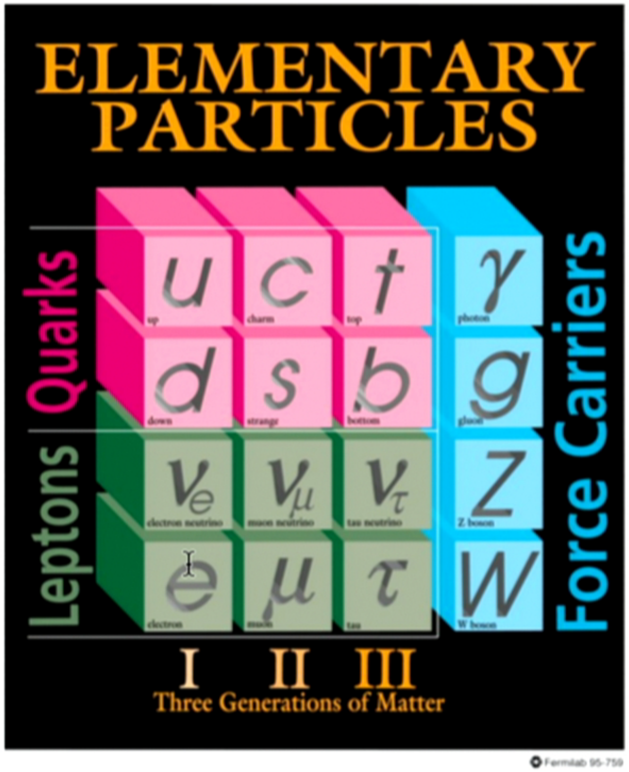
The Standard Model of Particle Physics

- Fermions and bosons



- Several particles predicted before they were discovered
- Strong evidence for all particles ...
- ... including Higgs boson (thanks to ATLAS & CMS @ LHC)

✗ Many parameters (>18) ?

✗ Gravity ?

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

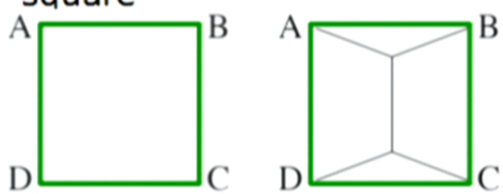
Symmetries in (Particle) Physics

Emmy Noether (1882-1935)

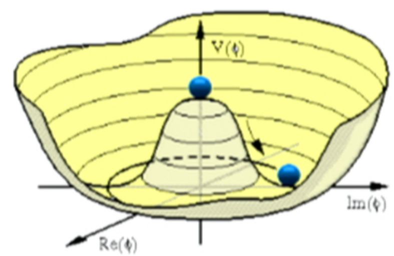
Spherical symmetry

- Continuous symmetries linked to conserved quantities, eg:
  - Equations invariant by translation in time → energy conserved
  - Quantum electrodynamics invariant by (local) rotations in a plane (U(1) group) → electrical charge conserved (+ massless gauge boson)
- Broken symmetries, eg:

Shortest set of lines between summits of a square does not have all the symmetries of the square



Equilibrium can have different symmetries than the potential



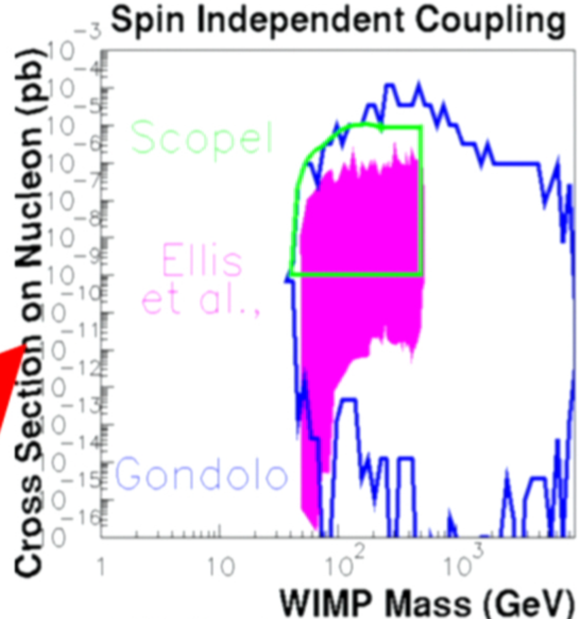
- Much cross-pollination with other branches of physics, eg phase-transitions, superconductivity

Pre ~2012:

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_χ ~ GeV-TeV (~ $1\text{-}10^3\ m_{proton}$)
- Relevant relic abundance:
  - $\Omega_c \sim 0.1$
- Coupling to matter:
  - Spin independent: σ a $A^2\, m^2\, \sigma_p$
  - Spin dependent: $\sigma = C\, J(J+1)\, m^2\, \sigma_p$



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

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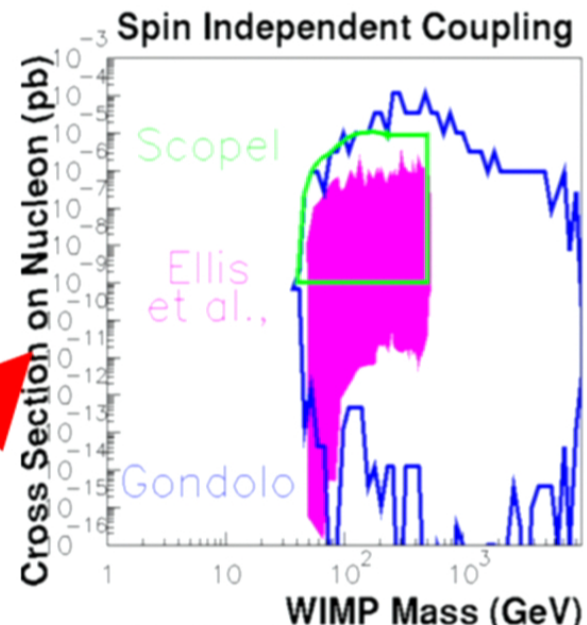
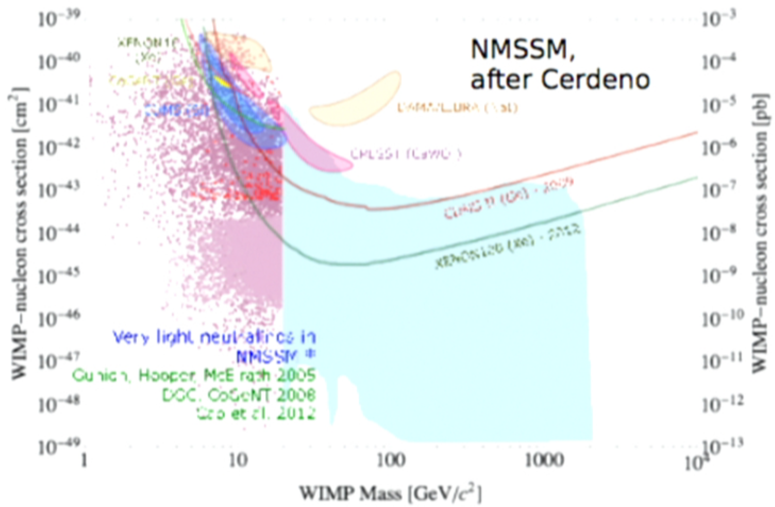


LEP, Tevatron⇒ m > 46 GeV
(J. Ellis et al., hep-ph/0004169)

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)



DARK MATTER CAVEAT

Remember that:

- Dark matter is a huge scientific mystery
- Most of the competing solutions proposed so far must be false
- In fact, all could be false
- The solution could be something we have not yet imagined

→ Are we dealing with

- the discovery of Neptune precisely predicted (to within 1°) from discrepancies between the theoretical and observed orbit of Uranus (Le Verrier/Galle 1846),
- or with aether (displaced by special relativity 1905)?

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)
  - Cross-section (SI, SD)
  - Kinematics (elastic scattering)
  - Nuclear form-factor (loss of coherence)

RAVE latest results (arXiv:1406.6896): Density=0.54±0.04 g/cm^3

- Recoil spectrum: $$\frac{dR}{dE} \approx \frac{\sigma n_0}{v_0 \mu^2} F^2(E) \int_{v_{min}}^{v_{max}} \frac{f(v)}{v} dv$$

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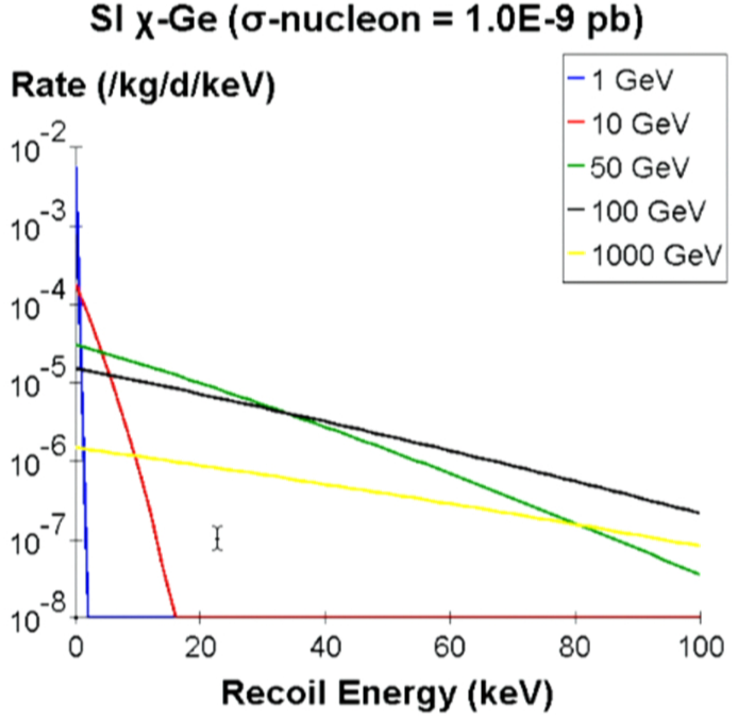
Spectra: Effect of WIMP Mass



- 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

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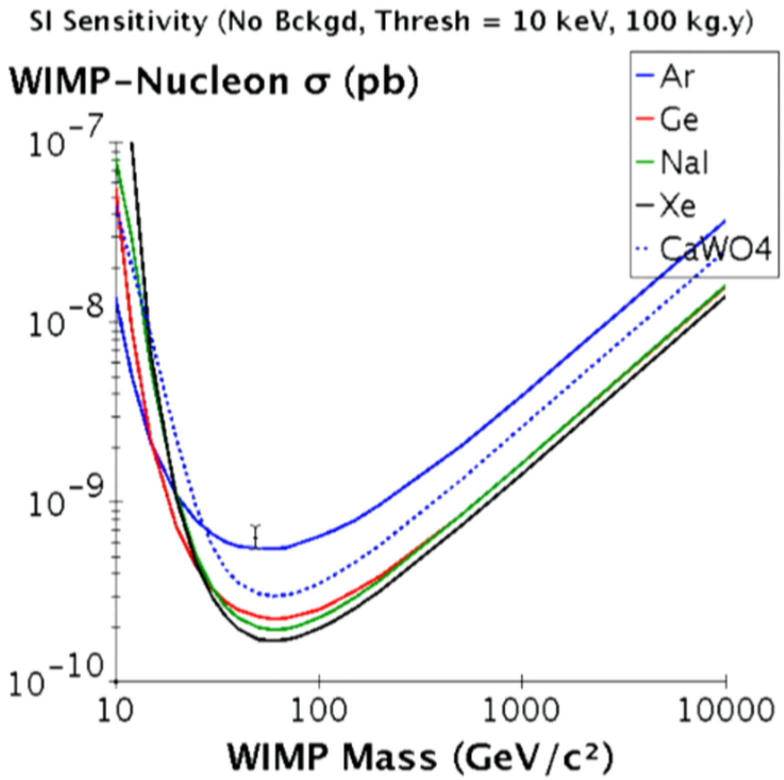
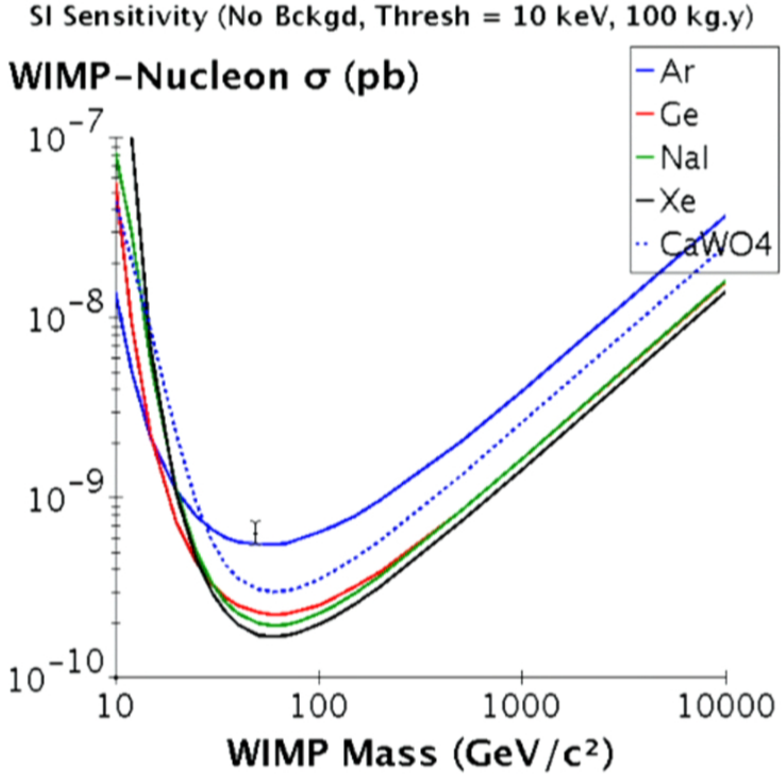
Ideal Experiments (No Background)



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

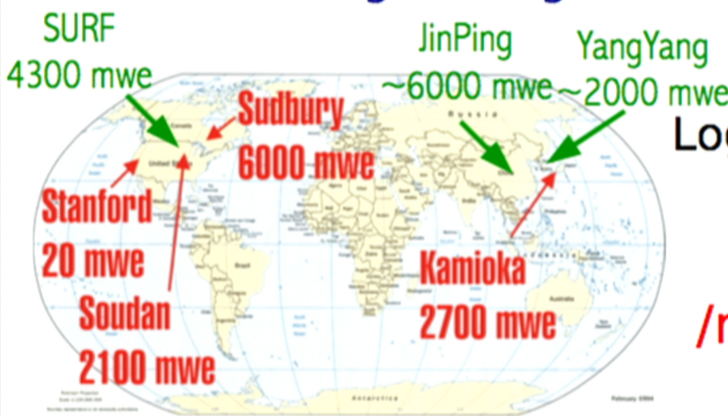
$$sensitivity \propto MT$$

Experiments (Background)

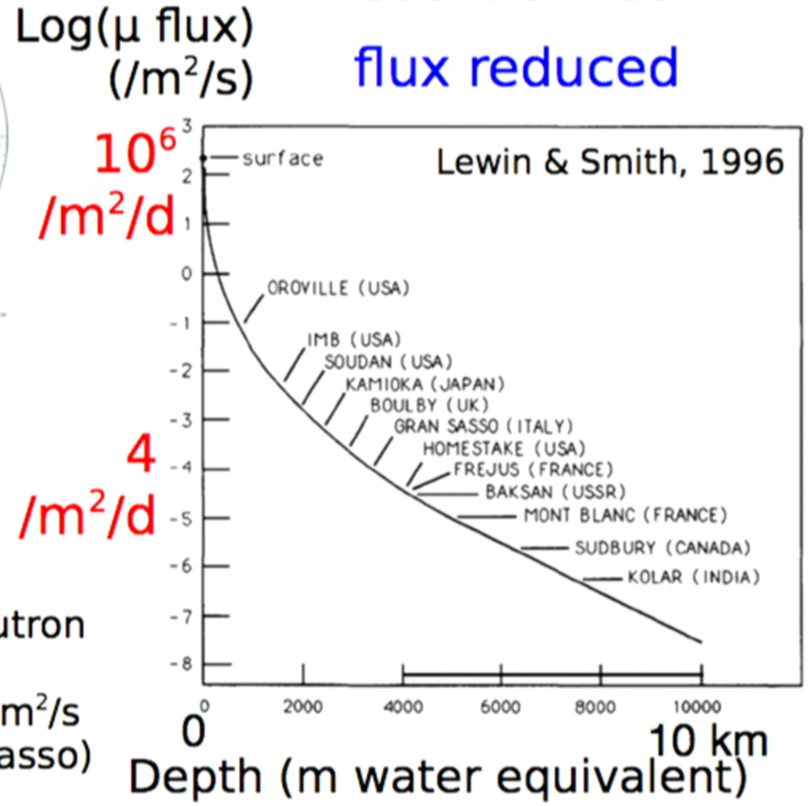


- Same **exposure** (MT), **threshold**: sensitivities similar
- No background:
  $$sensitivity \propto MT$$
- Real experiment: bckgd !.
  - No rejection: sensitivity limited by background
  - Partial **bckgd rejection**:
    $$sensitivity \propto \sqrt{MT}$$

Escaping the Haystack in Mines and Tunnels:
Going Underground to Reduce Background



Cosmic muon flux reduced



Fast neutron flux $\approx 10^{-6}/cm^2/s$ (Gran Sasso)

Soudan, MN

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

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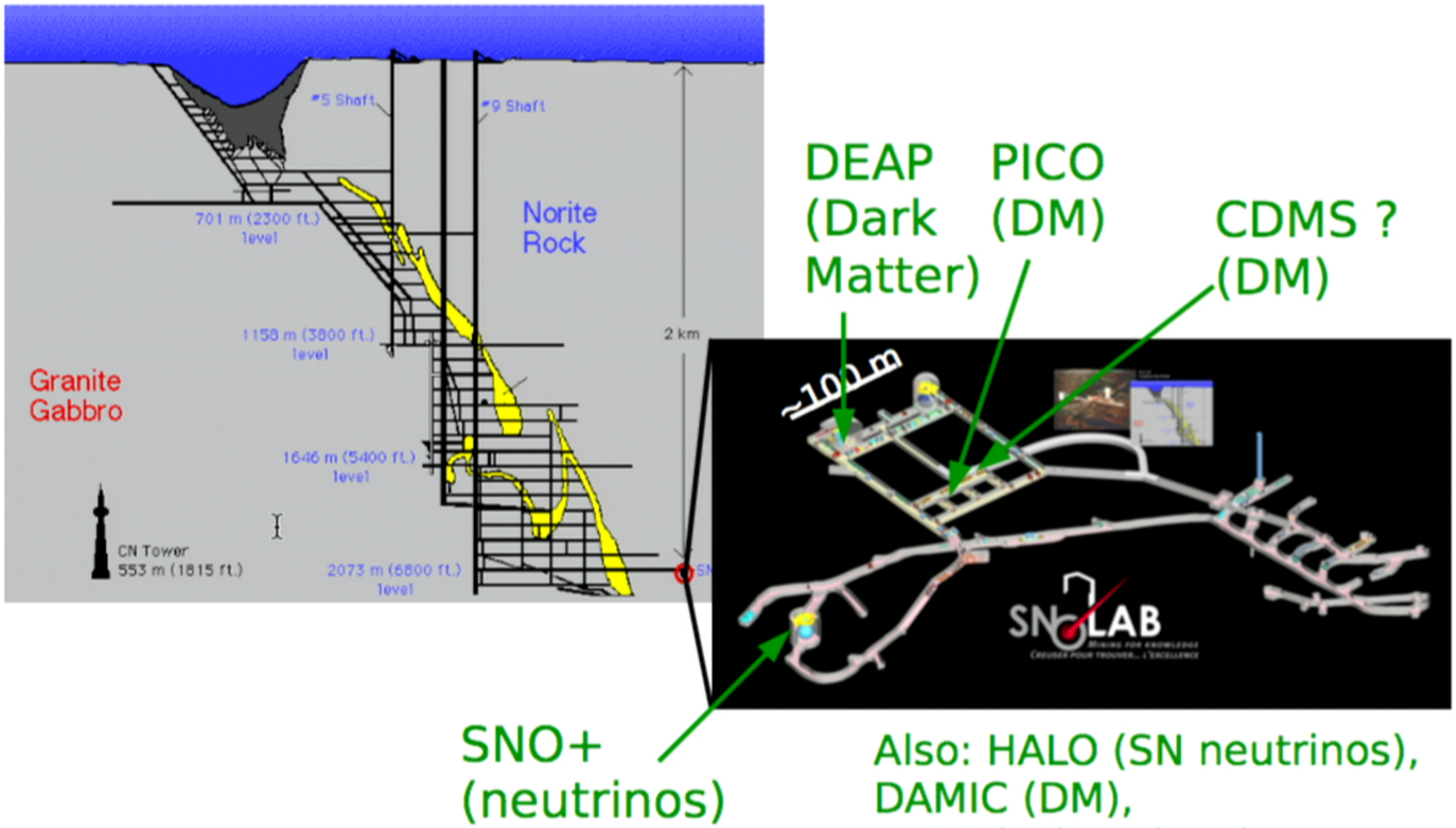
SNOLAB, Sudbury ON: ~6 kmwe

One of the deepest and cleanest labs



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


Lab Entry
6800


Lab Entry


Personnel
Facility
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Cryopit
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More haystack: human radioactivity

- Typical human radioactivity: 8 kBq

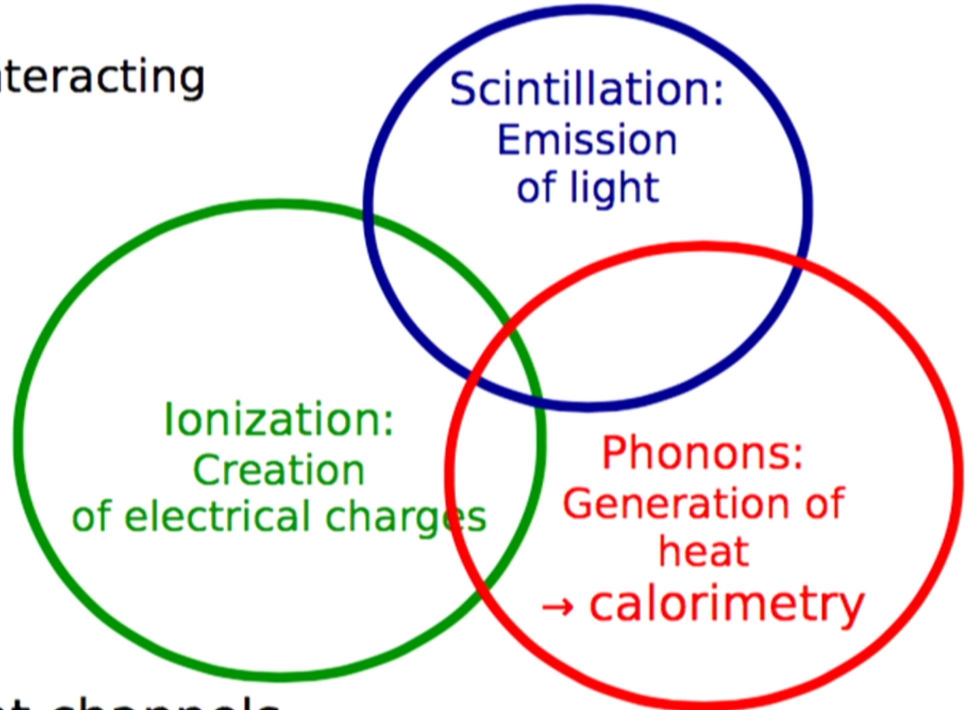
8 kBq/80 kg
= 100 disintegrations /s/kg

- Main contributions:
  - ^{40}K: $T_{1/2} = 1,3*10^9$ y
    - 89% β^-: E < 1,3 MeV
    - 11% γ: E = 1,46 MeV + E = 3 keV (EC*: ^{40}K →^{40}Ar* → ^{40}Ar)
    - ~0.2%? γ: E=3.2 keV (EC: ^{40}K → ^{40}Ar)

    Important for DAMA (Pradler, Singh, Yavin 2013)
  - ^{14}C: $T_{1/2}$ = 5730 y
    - 100% β^-: E < 156 keV

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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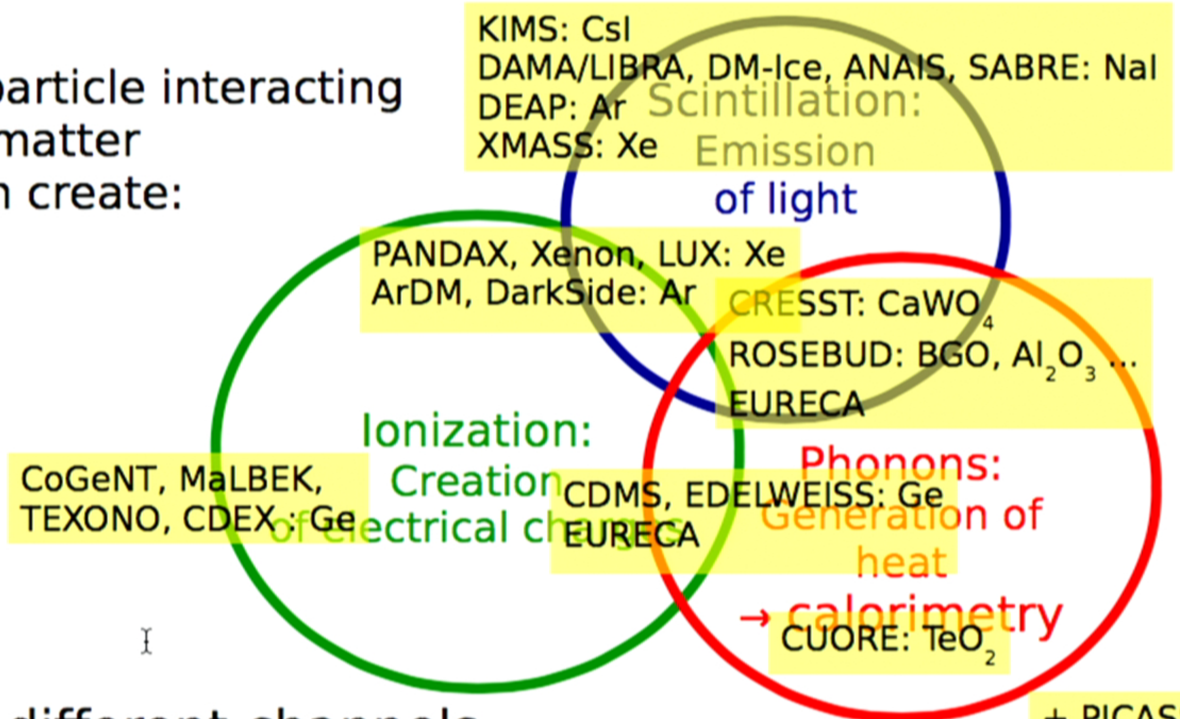
A particle interacting in matter can create:



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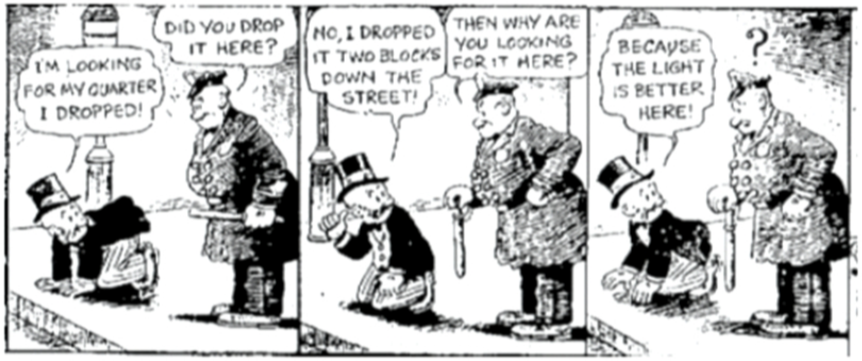
+ PICASSO, COUPP, PICO, SIMPLE, MOSCAB, MIMAC, DRIFT, DMTPC, DAMIC ...

The evolution of the species: specialization of experiments

- High (> 100 GeV) masses now dominated by large noble liquid detectors
- Other technologies, with lower thresholds, specializing in low masses
- Are experimentalists looking for keys under the lamp-post? Some guidance from theorists would be welcome.



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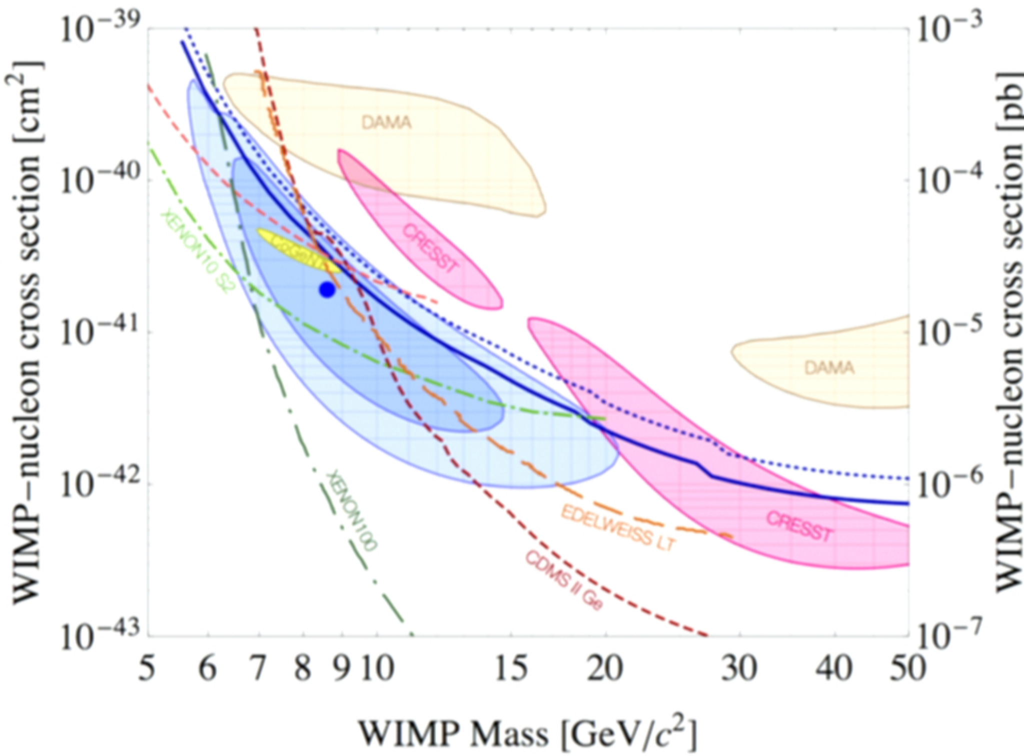
2010-2013: The Low-Mass Mess

- 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)



ATTENTION

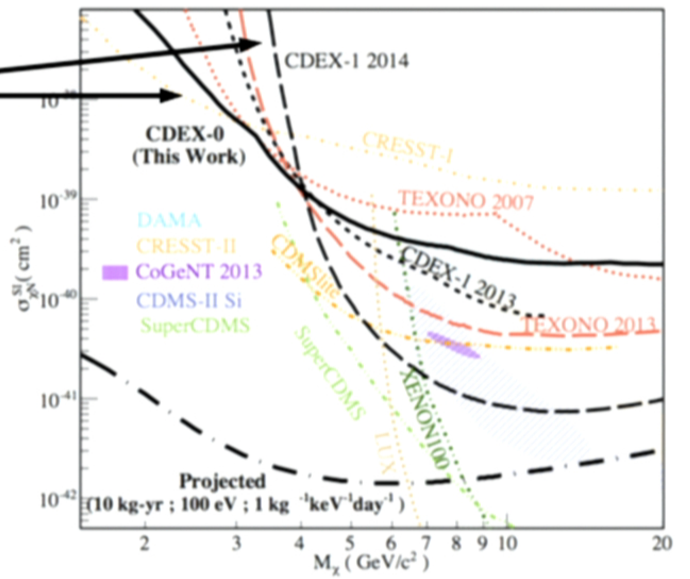
Your mother doesn't work here.

Please clean up your <u>own</u> mess!

Clarifying low-masses

No background rejection

- Spherical gaseous TPC:
  - SEDINE/NEWS
- 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



Background rejection

- Cryogenic
  - CRESST
  - ROSEBUD
  - EDELWEISS
  - CDMS, CDMSLite

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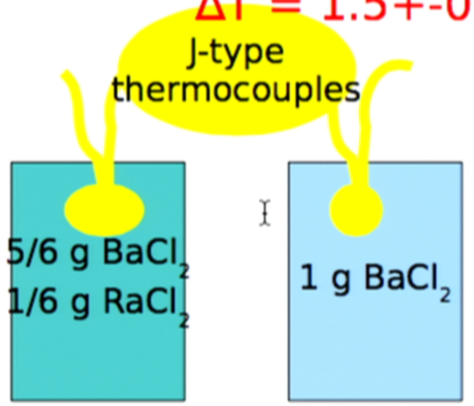
An ancestor of cryogenic detectors: calorimetry to measure radioactivity

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.

$\Delta T = 1.5 \pm 0.01$ °C



- 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

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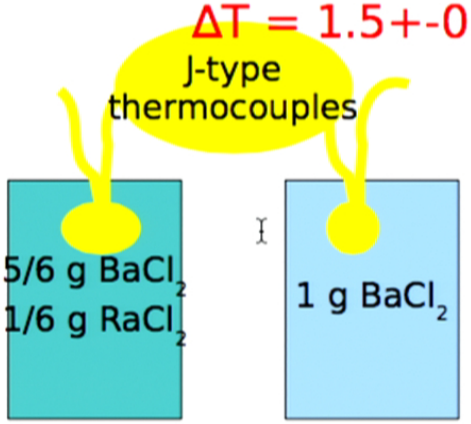

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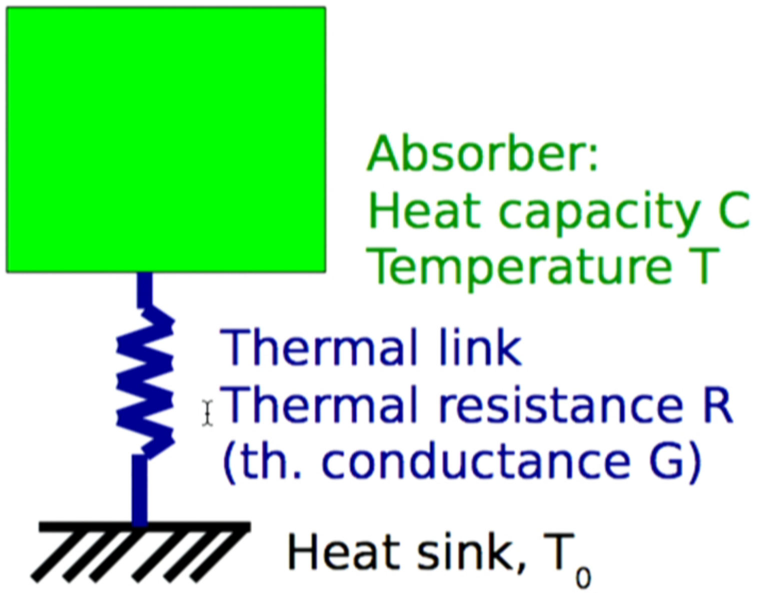
Basic Principle of Cryogenic Calorimetry



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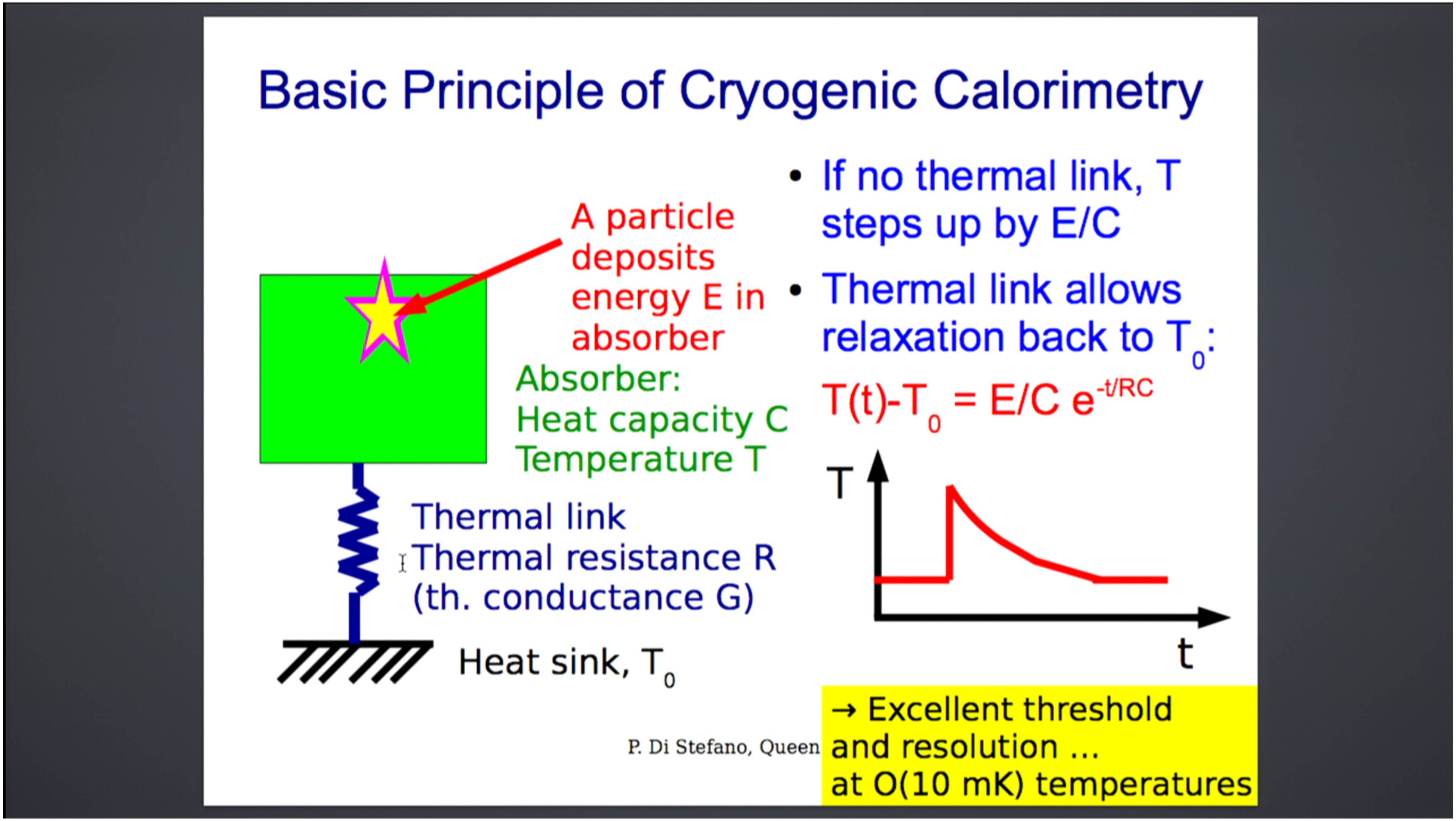
Basic Principle of Cryogenic Calorimetry
A particle deposits energy E in absorber
Absorber:
Heat capacity C
Temperature T
Thermal link
Thermal resistance R
(th. conductance G)
Heat sink, T_0
• If no thermal link, T steps up by E/C
• Thermal link allows relaxation back to T_0:
$T(t)-T_0 = E/C\ e^{-t/RC}$
T
t
→ Excellent threshold and resolution ...
at O(10 mK) temperatures
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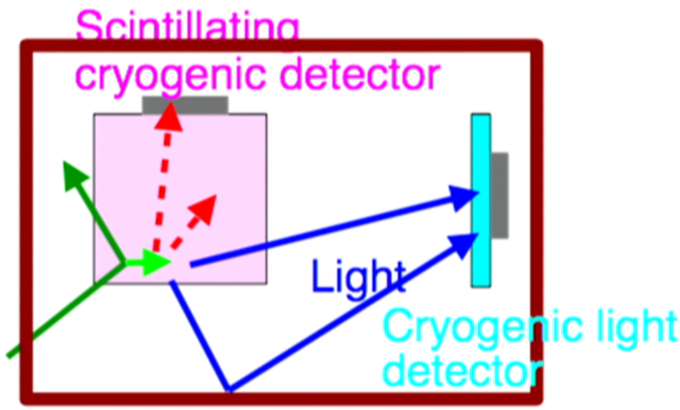
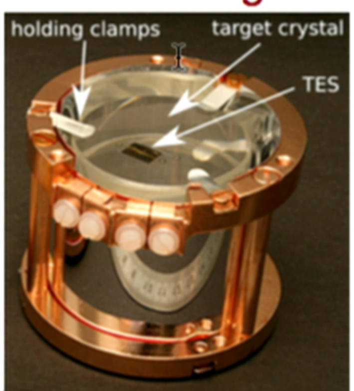
Reducing the Haystack:

Cryogenic Scintillation: CRESST/ROSEBUD/EURECA

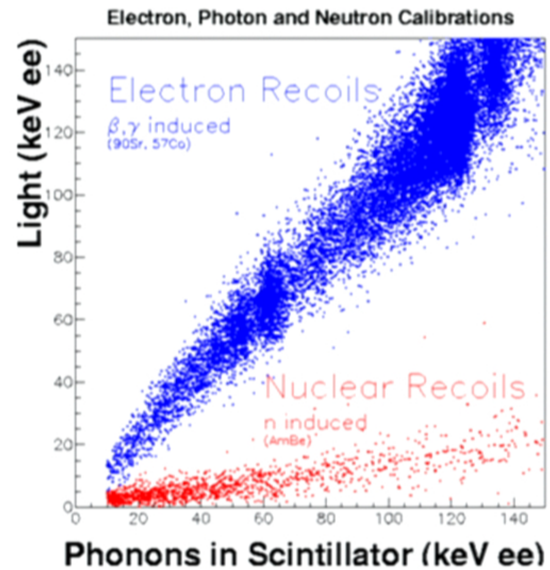
- Phonon-scintillation detectors



Light collector



- **Particle identification!**

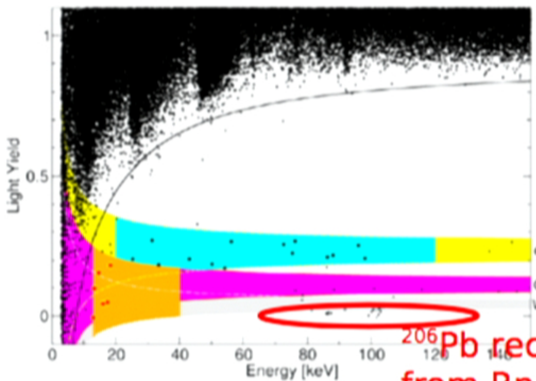


✔ Choice of nuclei ($CaWO_4$, BGO, CaF_2 ...)

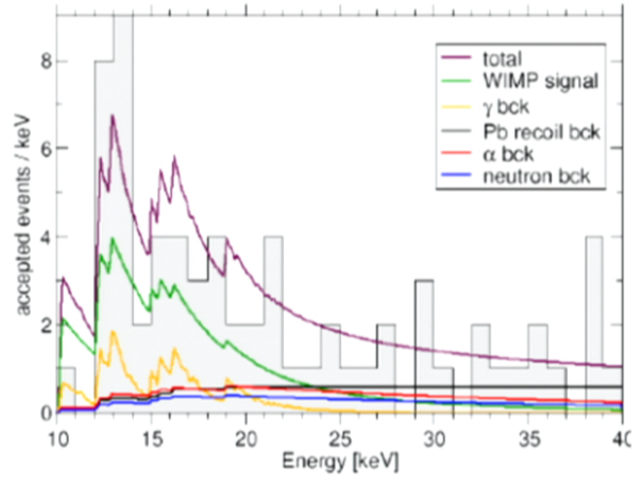
CRESST 2012

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

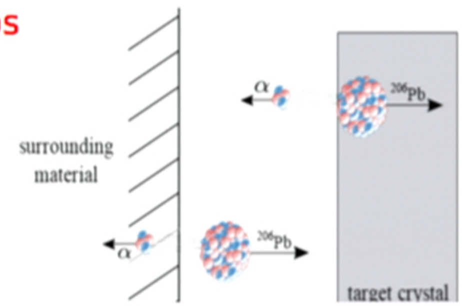
- Detector modules: $CaWO_4$, 300 g
- 8 modules → 730 kg.d



^{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)

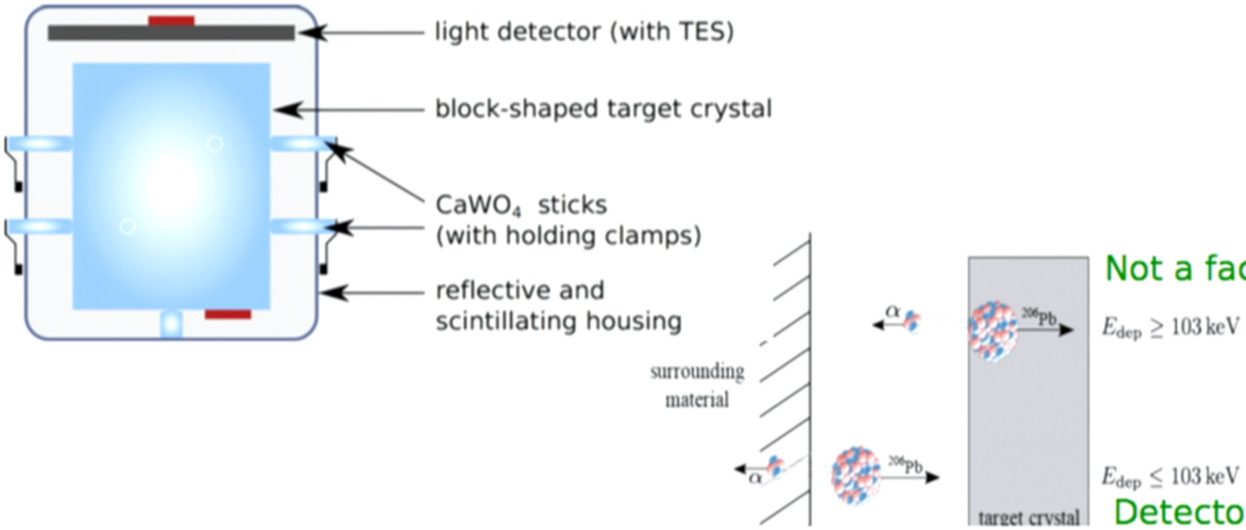


Not a factor

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

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

Retro-Interlude (circa 1999):
CRESST and the 12 Sapphire Bearings

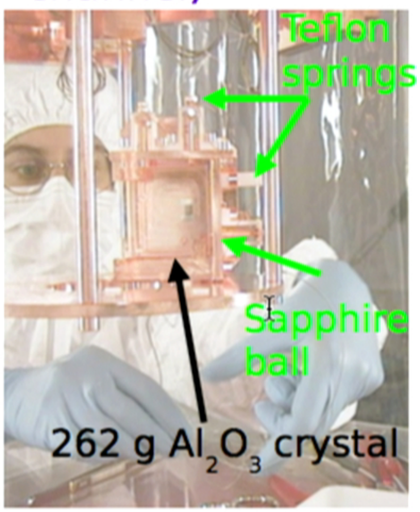
Shards of crystals !

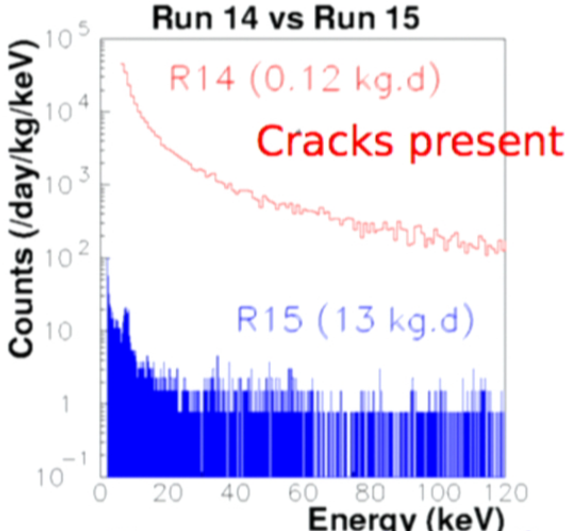
Tintin et le 7 boules de cristal

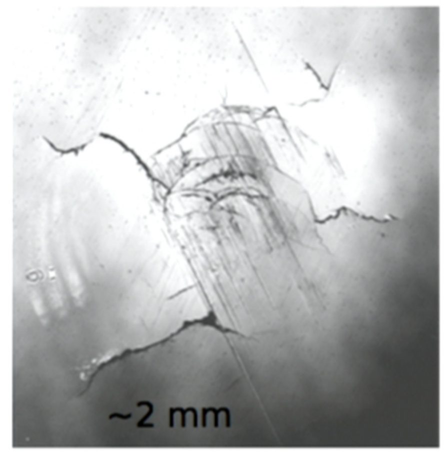
Brittle fracture and the mysterious CRESST background (circa 1999)

Sapphire cryogenic detectors (phonon-only measurement, no light channel)

A very high background caused by brittle fracture







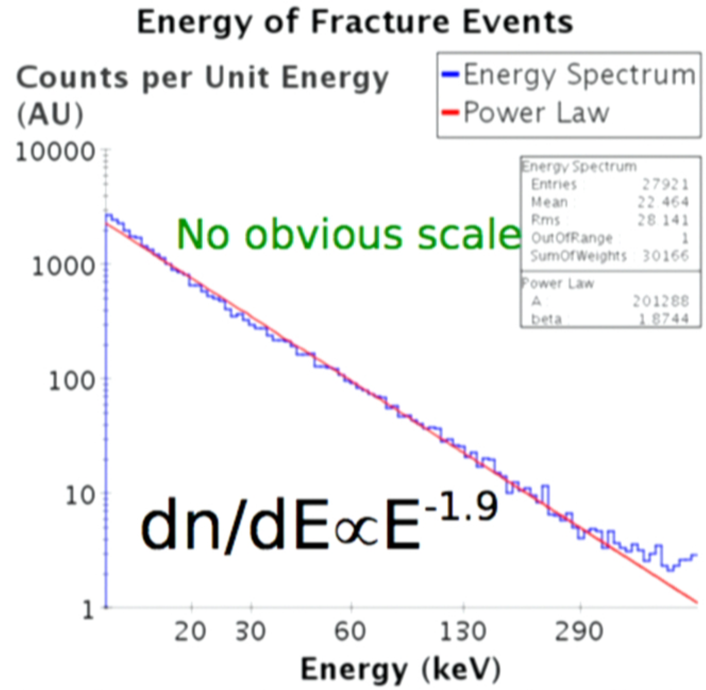
No more crack creation (hep-ex/0011064)

A Novel Measurement of Brittle Fracture

Phys. Lett. A356 (2006) 262, physics/0612081

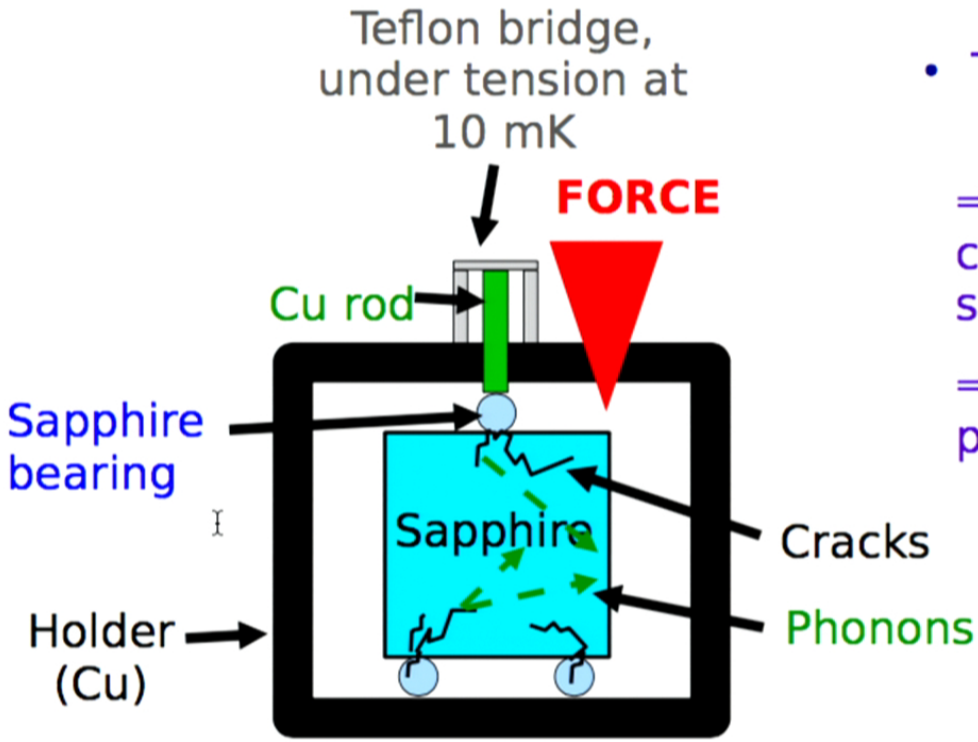
CRESST 1999 background = brittle fracture

- Direct measurement of crack energy: $\Delta T = E/C$
- Calibrated down to keV energies
- Many statistical similarities to earthquakes



Gutenberg-Richter distrib. OK down to few hundred bonds (34 orders of magnitude below San Francisco 1906 earthquake)

CRESST et les 12 Billes de Saphir



- Teflon shrinks by ≈ 1% @ 10 mK

⇒ Sapphire balls crack, crystal is scratched

⇒ High frequency phonons released

Solution:
Softer contacts between crystal and holder

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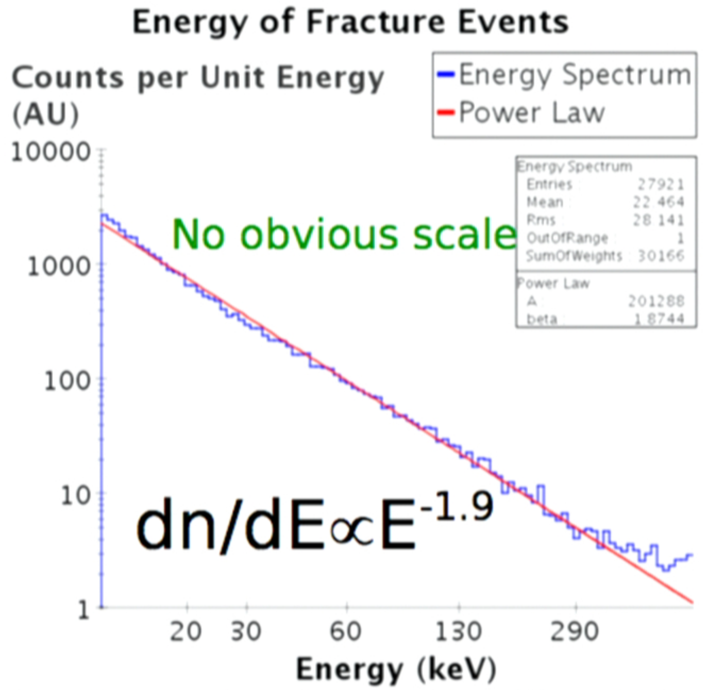
- Calibrated down to keV energies
- Many statistical similarities to earthquakes



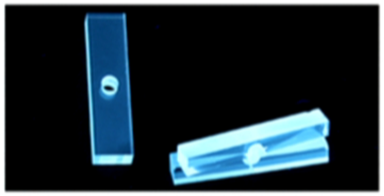
Gutenberg-Richter distrib. OK down to few hundred bonds (34 orders of magnitude below San Francisco 1906 earthquake)

Fractures in scintillators:
would there be light?

ventional background events. The small NR events now contain information in only the x_1 (phonon) channel with x_2 (scintillation) lost in noise. This category of x_1 only events could be subject to other forms of fake background such as the "crack-o-phonics" that have been seen to emanate from crystal mounts. The current numbers for the 300 g $CaWO_4$ set up (given that 0.68%

no-light band from the acceptance region. The shaded histogram in Fig.16 illustrates which of the accepted events are found in the band where no-light events are expected. Removing the no-light band from the acceptance region eliminates most of the accepted ^{206}Pb background events but also

Synopsis: Son et Lumière



Courtesy A. Tantot, P. Di Stefano (Université de Lyon, Queen's University)

Sound and Light from Fractures in Scintillators

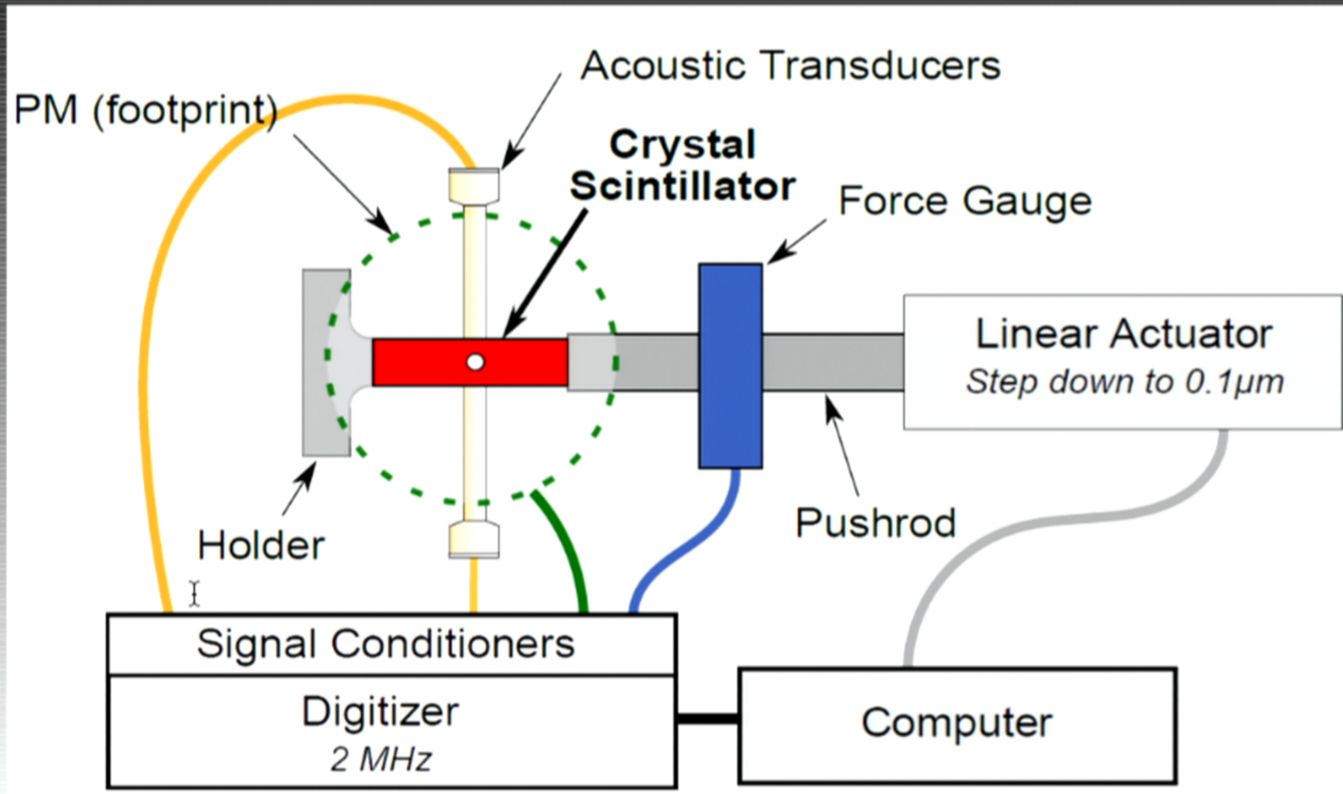
A. Tantot, S. Santucci, O. Ramos, S. Deschanel, M.-A. Verdier, E. Mony, Y. Wei, S. Ciliberto, L. Vanel, and P. C. F. Di Stefano

Phys. Rev. Lett. **111**, 154301 (2013)

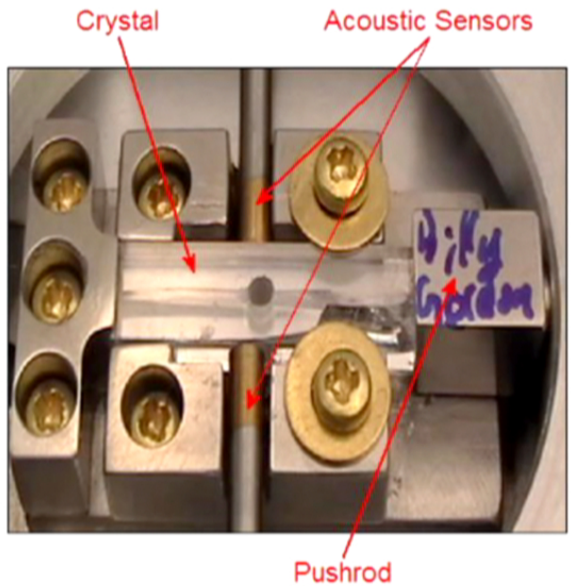
Published October 10, 2013

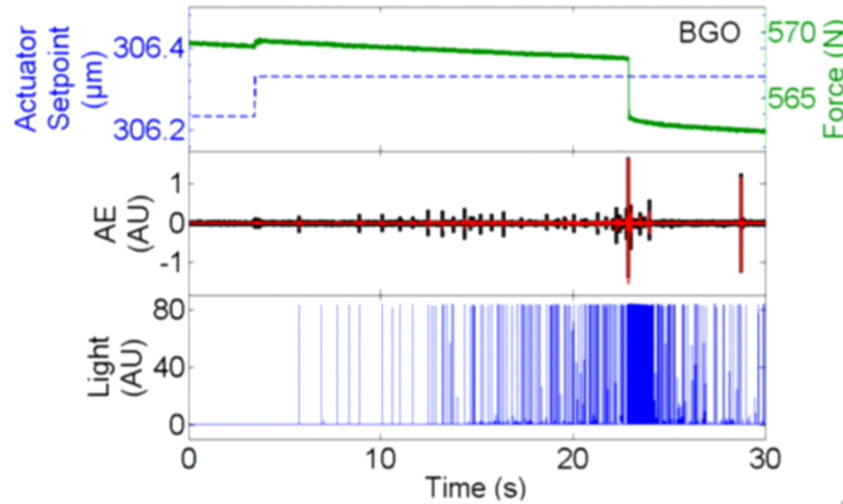
Physics spotlighting exceptional research

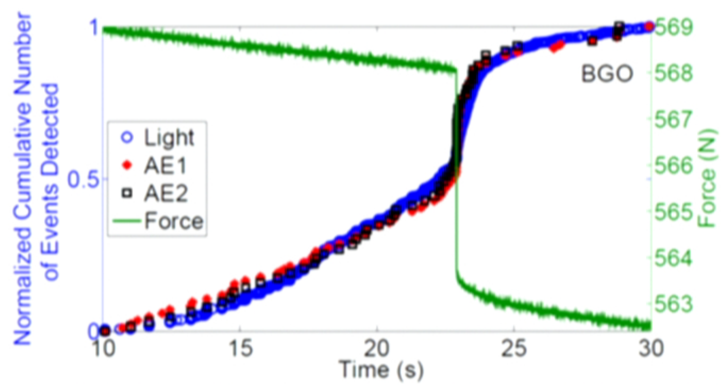
Setup to study correlation between acoustic and light emission in stressed scintillators



Fracture of a BGO sample







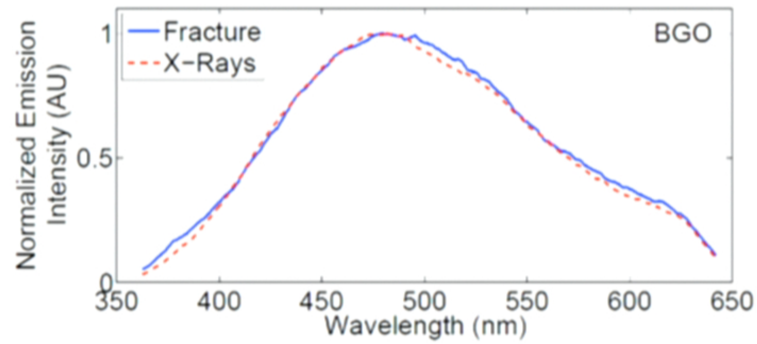
Correlation between:

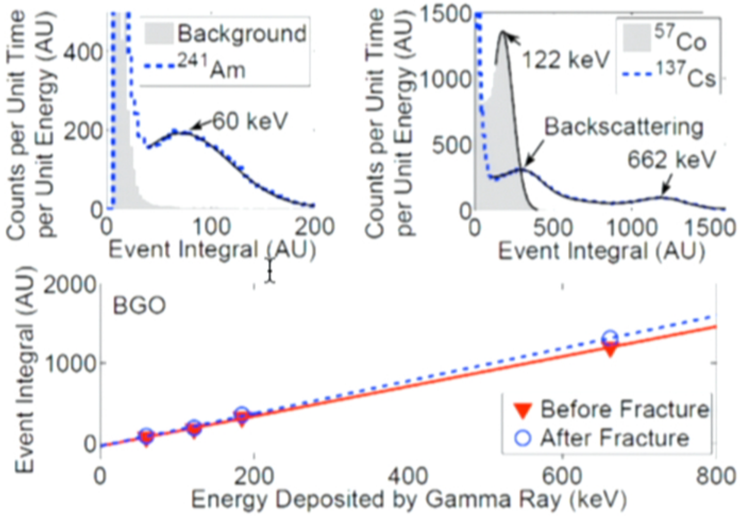
- Fracture (drop in force, AE signals)
- Emission of light

Calibration of light energy

Added insight from using scintillators for mechanoluminescence :

Last stage of the scintillation mechanism = last stage for the light emission during the fracture.





Light energy calibration with radioactive sources.

Actual Energy Emitted
= (Equivalent Gamma Energy Deposit)
x(Light Yield)
x(Average Photon Energy)

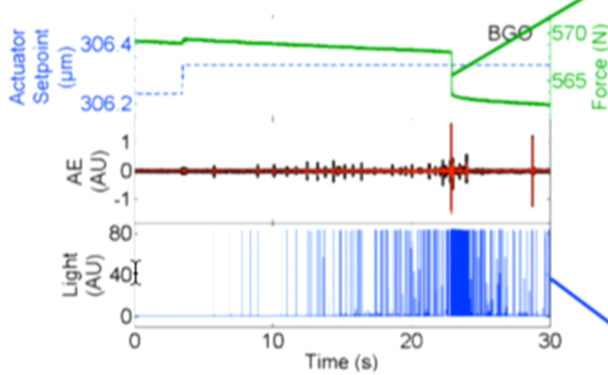
BGO :

Light Yield = 8 photons / keV

Average Photon Energy = 2.6 eV

Contributions to energy budget

Elastic energy =
Broken bonds
+ light
+ phonons (AE and others)



Drop of Elastic Energy :

$$\Delta E_{elastic} = \Delta\left(\frac{\left(F/_S\right)^2 . V}{2E}\right) = -30\ \mu J$$

Young's modulus

Surface creation energy :

$$-\frac{\Delta E_{elastic}}{Area} = 0.5\ J/m^2$$

Typical values :
0.28 J/m² for BaF2, 1.2 J/m² for MgO

$$E_{light} \geq 6.5\ GeV = 10^{-9}\ J$$

$$Ratio = \frac{E_{light}}{-\Delta E_{elastic}} \geq 3 \times 10^{-5}$$

Possible mechanisms

- Emission of other particles (“fractoemission”: electrons, X-rays...) during fracture. These particles are then reabsorbed in scintillator creating light

  ➔Mechanism would also be relevant for ionization detectors, cryogenic detectors ...

- Strong electrical fields at fracture surface: create arcs in air, UV light that could be reabsorbed in BGO (?)

  ➔Test at much lower pressure (cf Paschen's law)

- Fractures directly produce excitons that then transfer energy to Bi^{3+} (?)

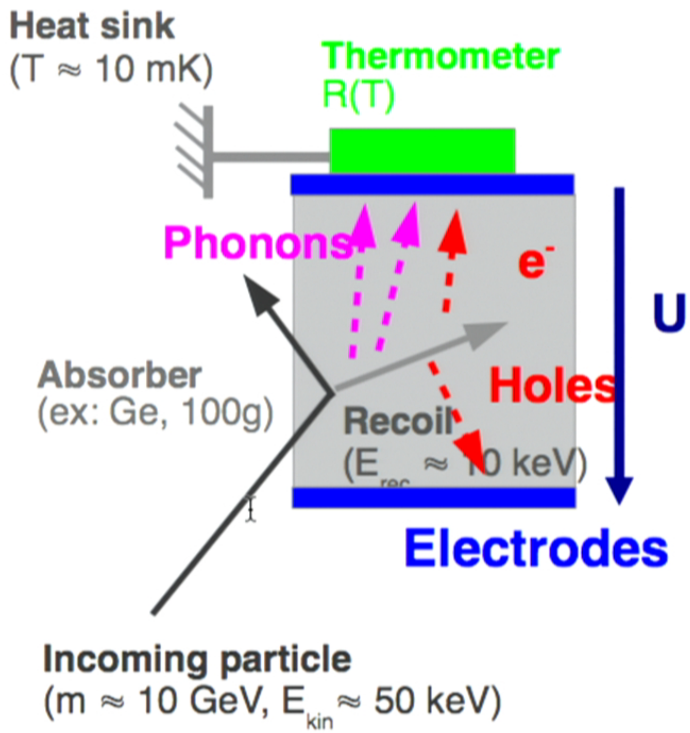
Mechanoluminescence in scintillators

PRL 111, 154301 (2013) arxiv.org/abs/1305.3644

- Rare-event detector physics:
  - Light and acoustic signal clearly correlated,
  - But no smoking gun for current excesses:
    - Mechanoluminescence not most likely background explanation of CRESST excess (cf Kuzniak Astropart Phys)
    - Hard to understand a mechanism to generate annual modulation in DAMA
  - Could affect other types of solid state detectors
- Condensed matter physics: a new method to study brittle fracture in certain materials
  - Better timing resolution than acoustic emission
  - Insight into energy budget

Reducing the Haystack: Ionization-Phonon Detectors

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

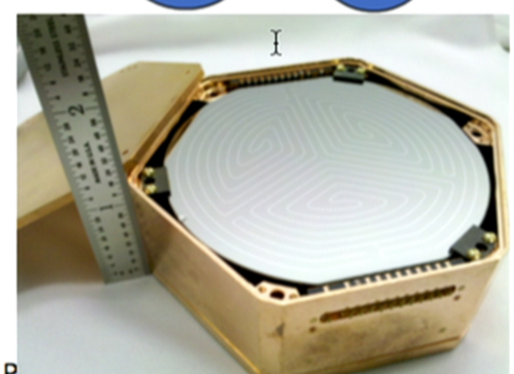


- Phonon signal: $\Delta T/T \approx$ 0.1% over ms
- Charge signal: ≈ 1000 pairs over μs
- β,γ particles ionize more than WIMPs, neutrons

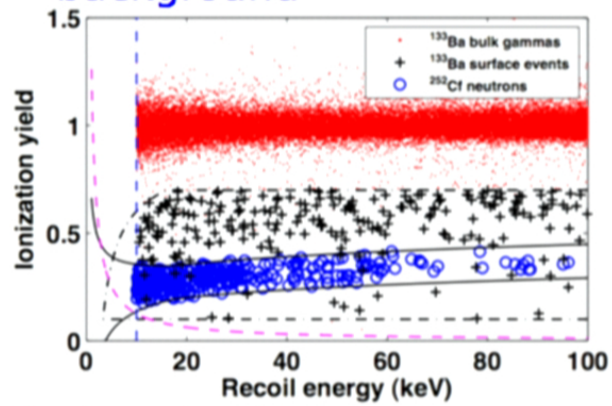
➔ Event by event background rejection

SuperCDMS Soudan Detectors

- 15 detectors deployed
- 600 g Ge each
- Operated at ~60 mK
- 2 x (2 charge + 4 phonon) readout

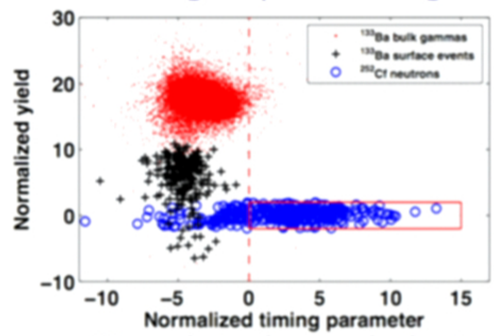


- Ionization yield → rejection of bulk background



(CDMS II)

- Surface background rejected by
  - Radial position
  - Timing of phonon signal



(CDMS II)

  - New: interleaved electrodes (iZIPs)

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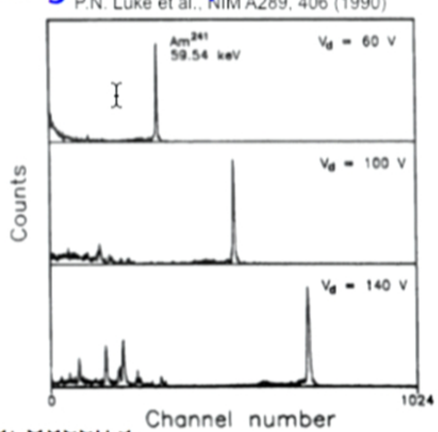
Luke-Neganov effect in CDMSLite:
Use phonons to read charge

- 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)

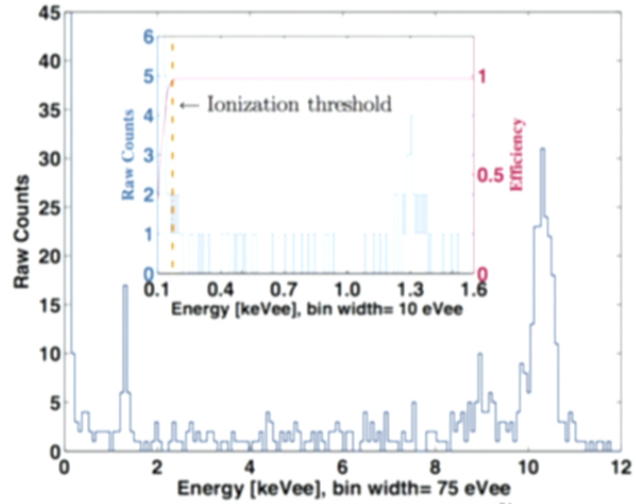


- Exposure 6.3 kg.d

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

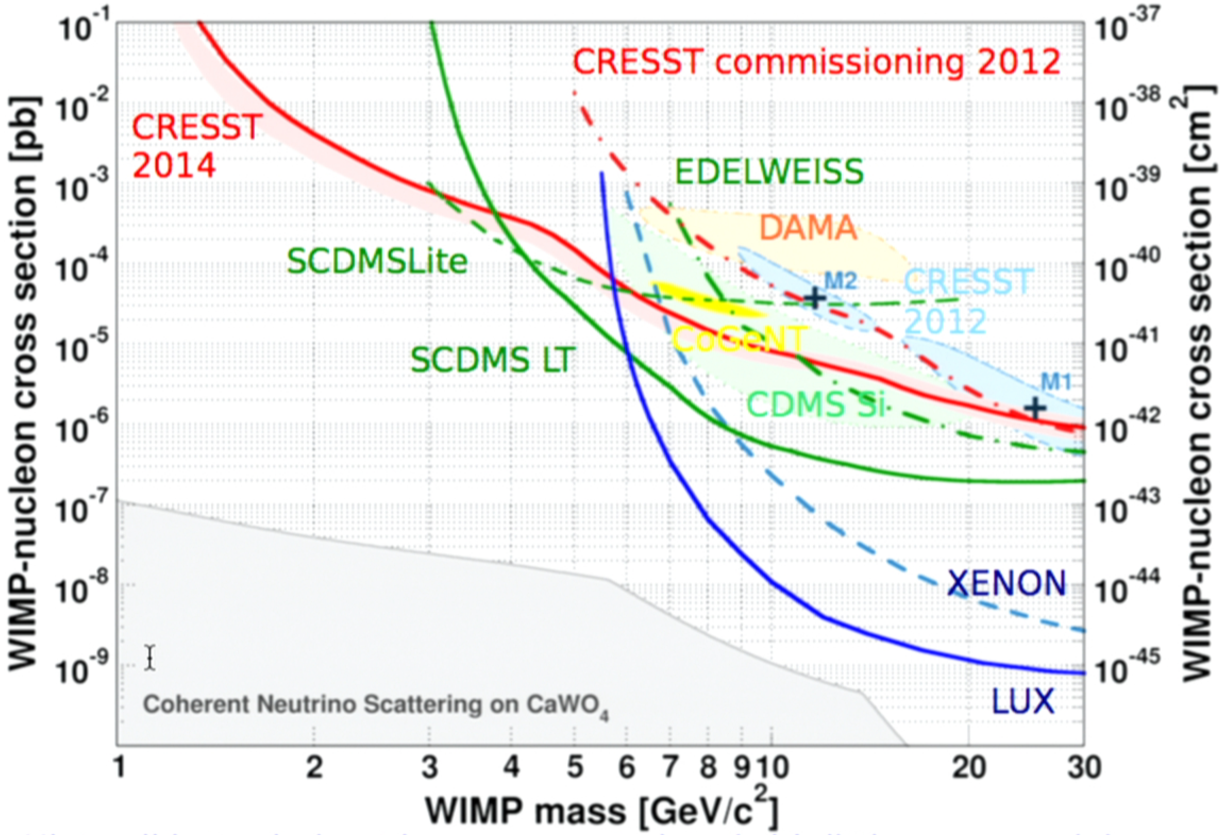
✘ Loss of background discrimination

✔ BG diluted with respect to signal



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

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

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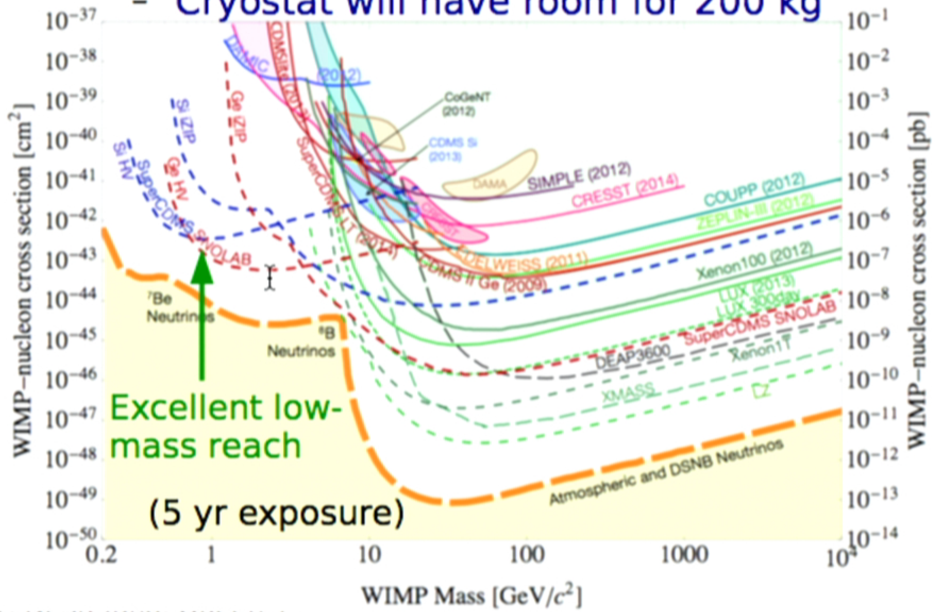
SuperCDMS @ SNOLAB

- Deeper, cleaner site to reduce BG
- Larger, cleaner experiment
  - 60.5 kg payload of improved detectors
    - Std: 50 kg Ge, 3.7 kg Si
    - Lite: 5.6 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
- Discussions with EURECA (CRESST+EDELWEISS) for collaboration
- Data-taking could start 2018
- (Soudan winding down; expect new results 2015:
  - High masses
  - Improved CDMSLite)

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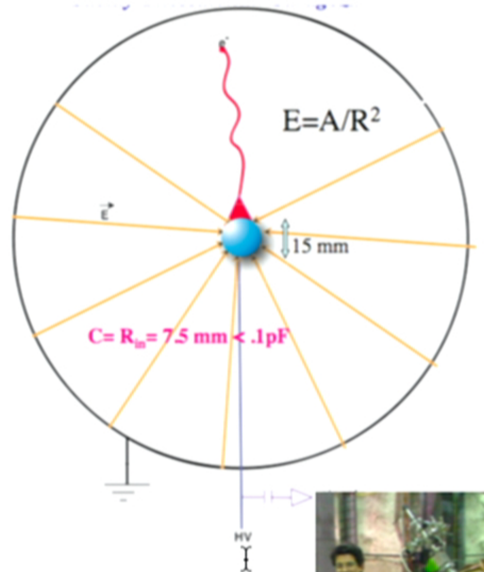
New kid on the low-mass block:

Spherical Time Projection Chambers (TPCs)

NEWS (New Experiment With Spheres)



- Gerbier (CERC Queen's) / Giomataris (Saclay)
- Gaseous TPC:
  - choice of gas, pressure
  - very low threshold
  - so far, poor BG discrimination
- Preliminary quenching measurements indicate sub-keV recoils visible in He (Di Stefano+LPSC Grenoble)

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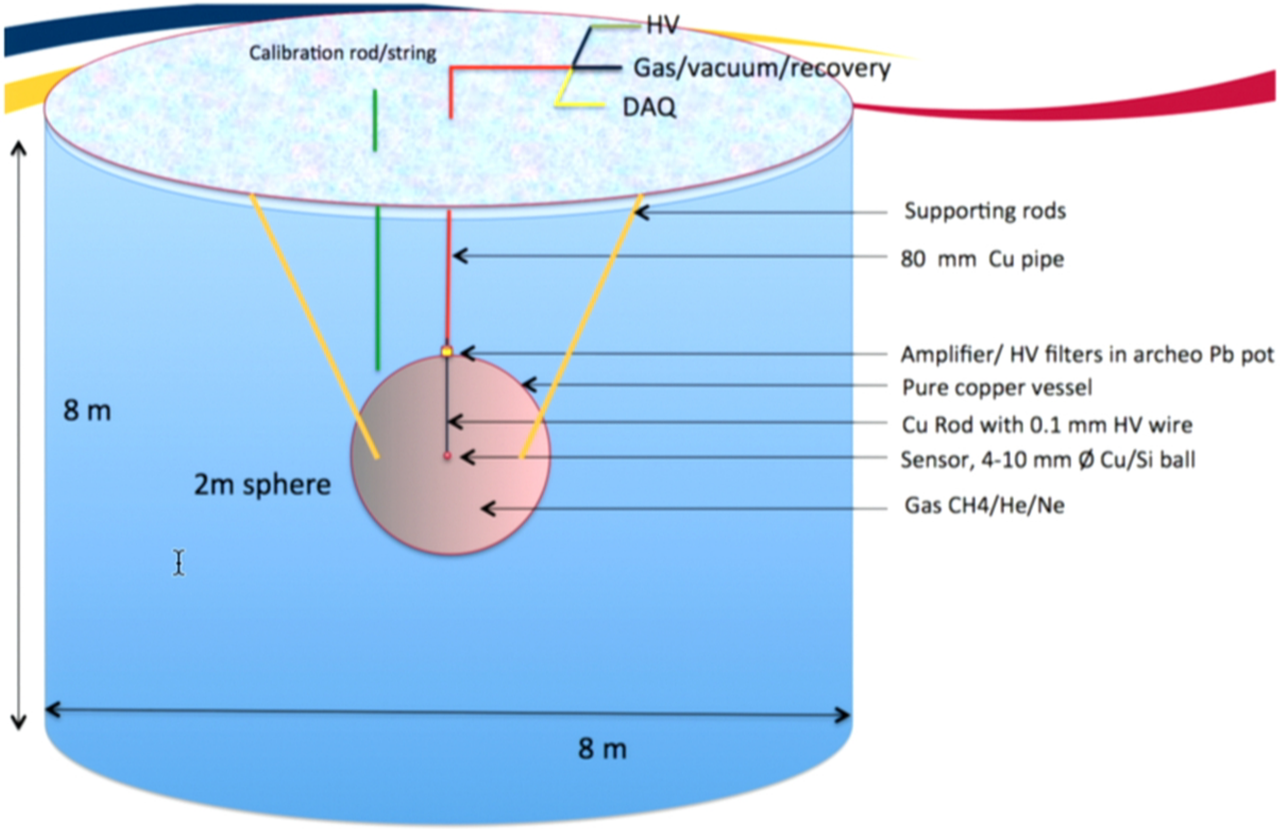
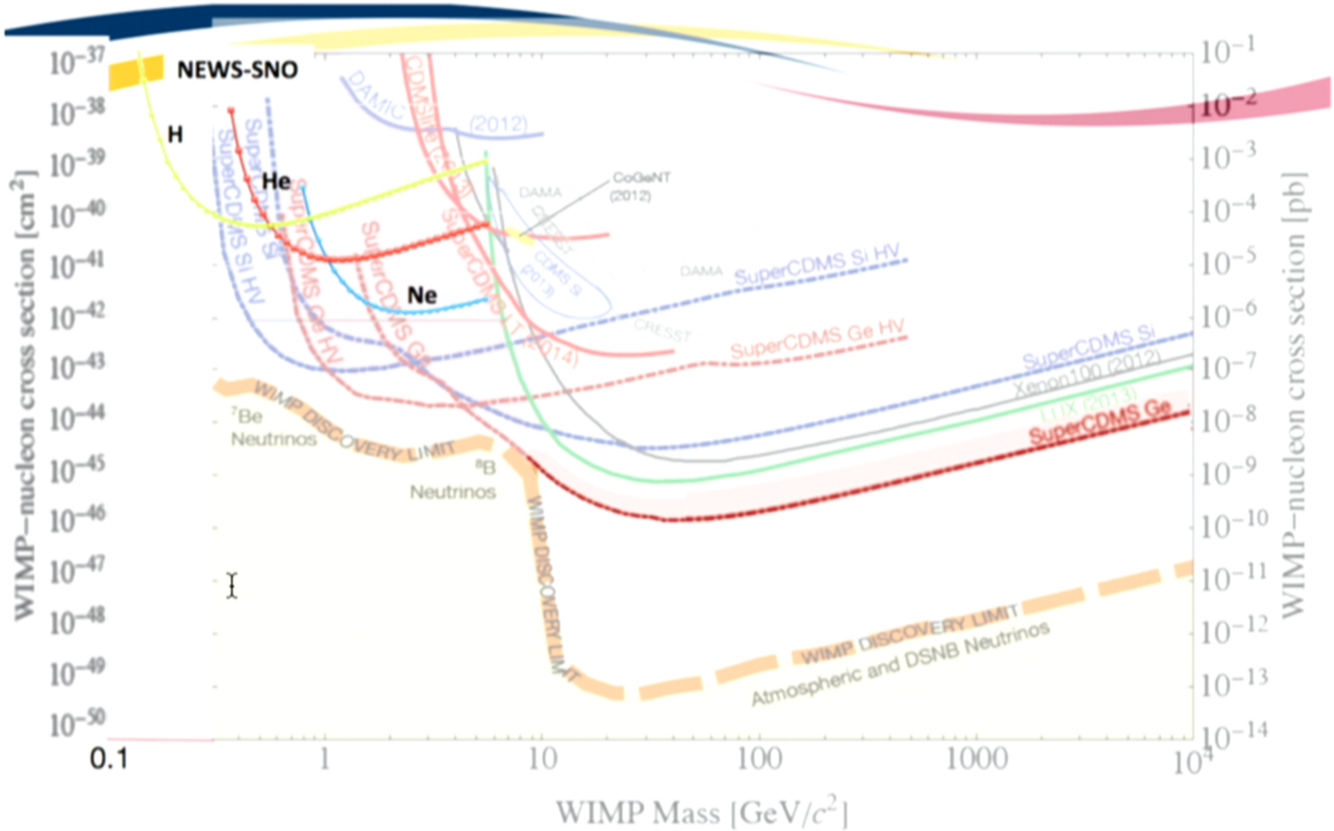
NEWS @ SNOLAB
(Gerbier)



NEWS Sensitivity @ SNOLAB

(Gerbier)

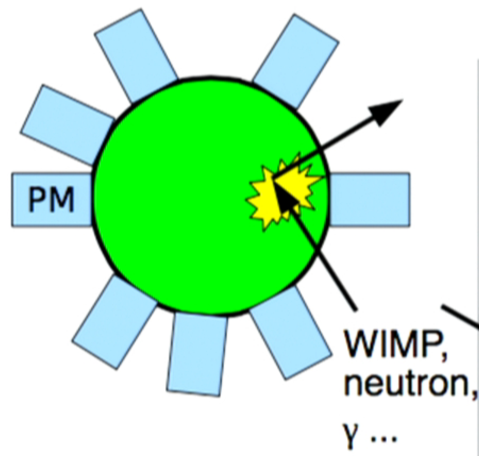


Ne: 10 bar, 2 T.d, 0.01 cnt/d/kg/keV

At High Masses: Noble Liquids
Discrimination & Mass

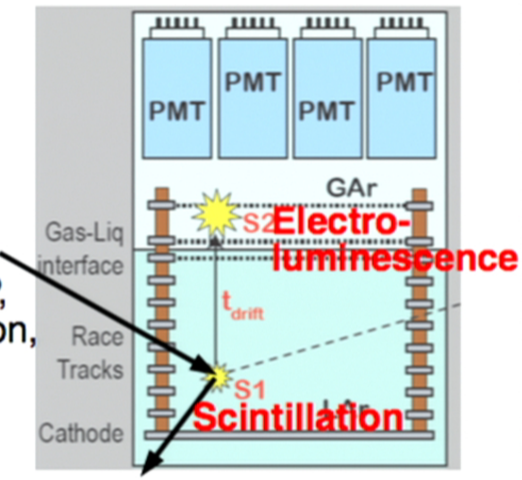
A	39.9	131.3
Boiling point (K)	87	165
Density (g/cm3)	1.4	2.9
Discrimination	S1/S2, S1 PSD	S1/S2
Radioactive isotopes	39Ar	
DM projects & experiments	WArP, ArDM, DEAP, CLEAN …	XENON, XMASS, LUX, PANDAX …

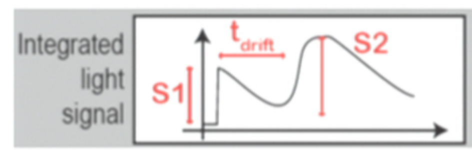
Single phase (XMASS, DEAP, CLEAN)



S1 only, + PSD

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





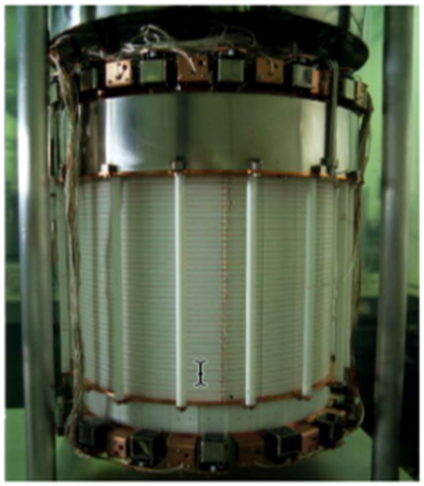
Figs. L Grandi, INFN Pavia (WArP)

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

XENON 100 @ Gran Sasso

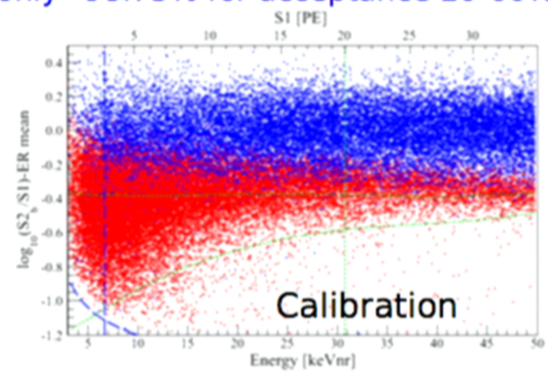
(Aprile, arXiv:1207.3458)

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

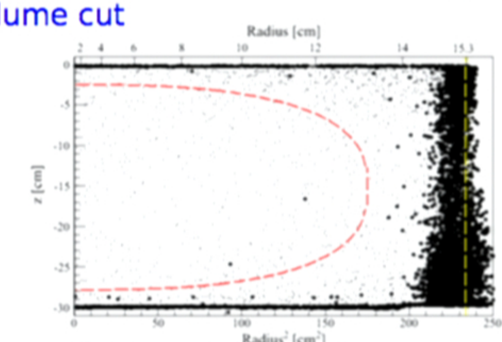


- Rapid progress and impressive **world-leading** (until 2013) results...

- ...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...

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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%

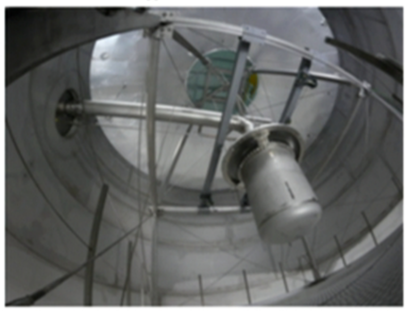
Detector shielded by water Cherenkov muon veto

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)



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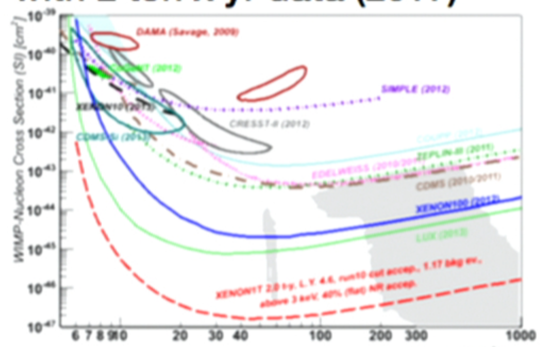
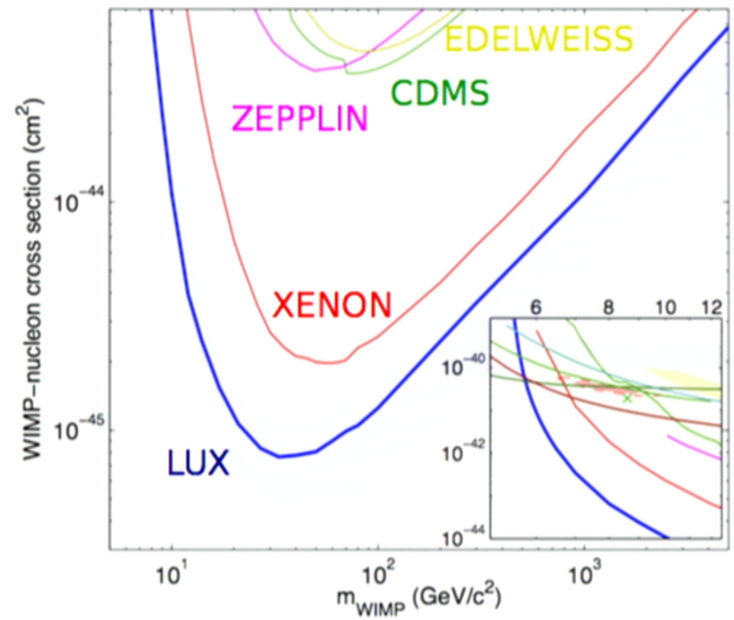
Courtesy E. Aprile



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



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

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*Sanford Underground Research Facility

P. Di Stefano, Queen's

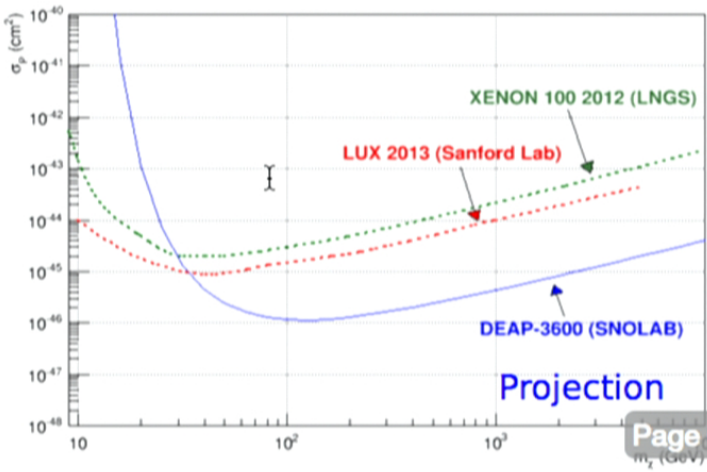
DEAP-3600 Dark Matter Search at SNOLAB

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

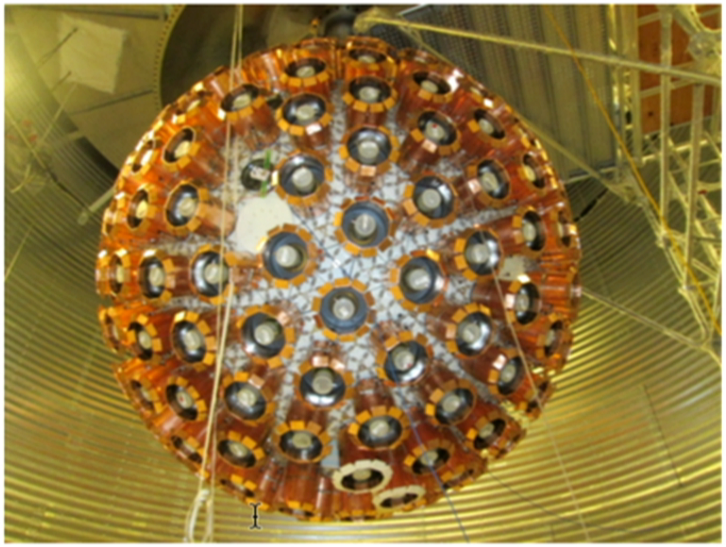
Turn-on PMT systems	Nov/Dec '14
Argon gas runs and in-situ background measurements, commissioning	Dec '14/ Jan '15
Physics Data start	Summer 2015

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

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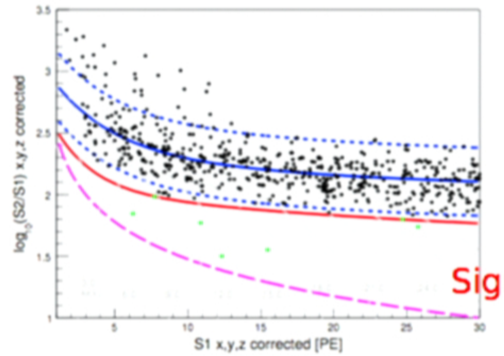
Recent results from PANDAX

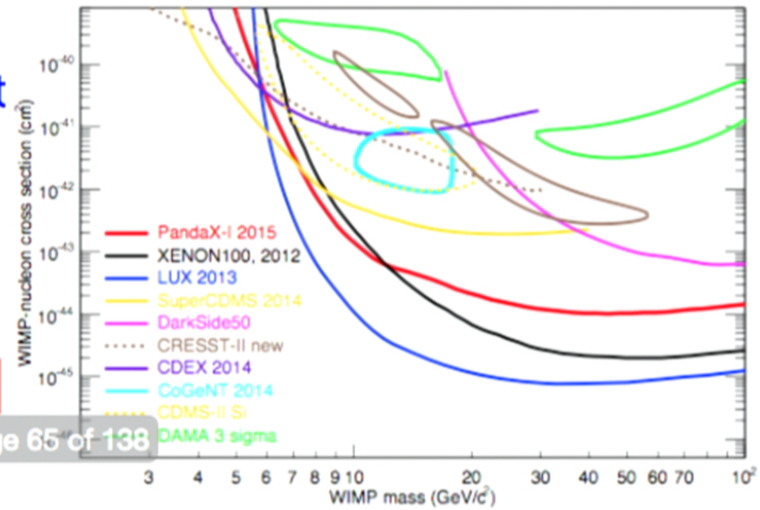
arXiv:1505.00771 May 4

- Jin-Ping, China
- 54 kg dual-phase Xe
- 4.3 T.d exposure
- Results consistent with BG; in signal region, “accidental” events (isolated S1 or S2 without obvious partners) dominate



Signal region

	ER	Accidental	Neutron	Total expected	Total observed
All	503.7	35.1	0.35	539.1	542
Below NR med	2.5	4.2	0.18	6.9	7



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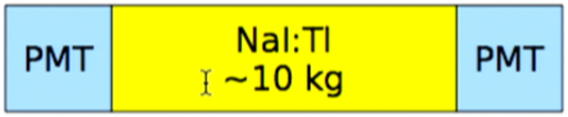
How to convincingly discover WIMPs?

- Large detector mass necessary to see WIMPs (esp. heavy WIMPs)
- Annual/diurnal modulation signatures not water-tight, especially if there is background, but useful (MIMAC, T-REX, NEWAGE, 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 show nothing will be easy
- Be open with data and in discussions

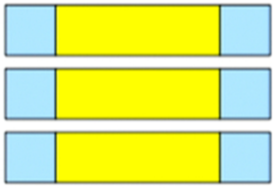
DAMA/LIBRA NIMA 592 (2008) 297

- 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

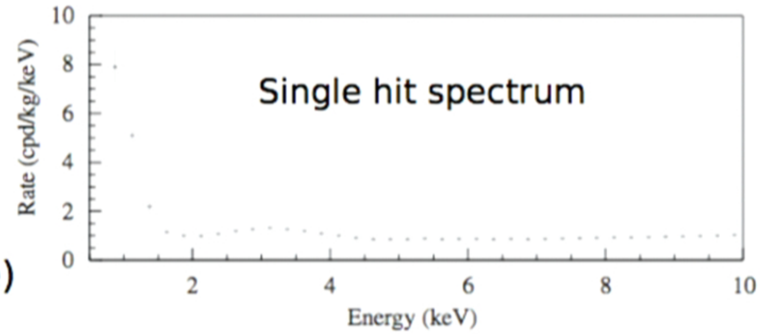
Module: trigger on coincidence between PMTs (see ~ 6 pe/keVee)



Self-shielding: reject coincidences between modules



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

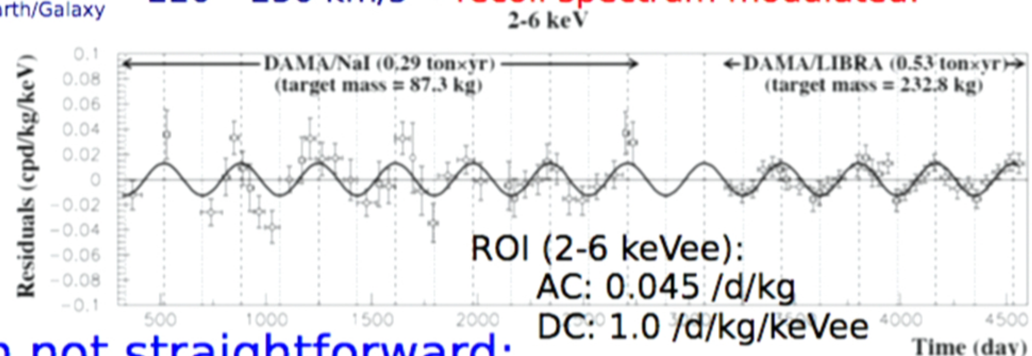


DAMA Results

- Significant annual modulation observed (>7σ)

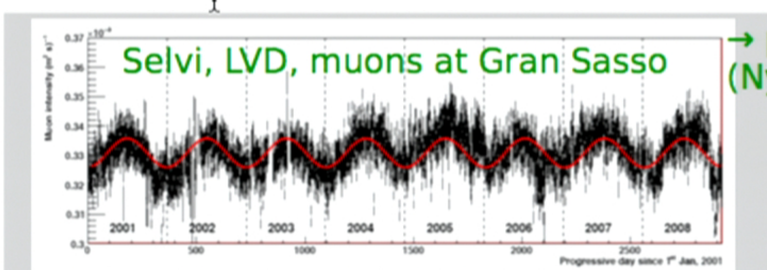
December - June

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



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

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



→ μ-induced fluorescence (Nygren 2011) ?

- Also, when include educated guess on BG, modulation fraction may be much higher than astro models predict (Pradler, Yavin 2013)

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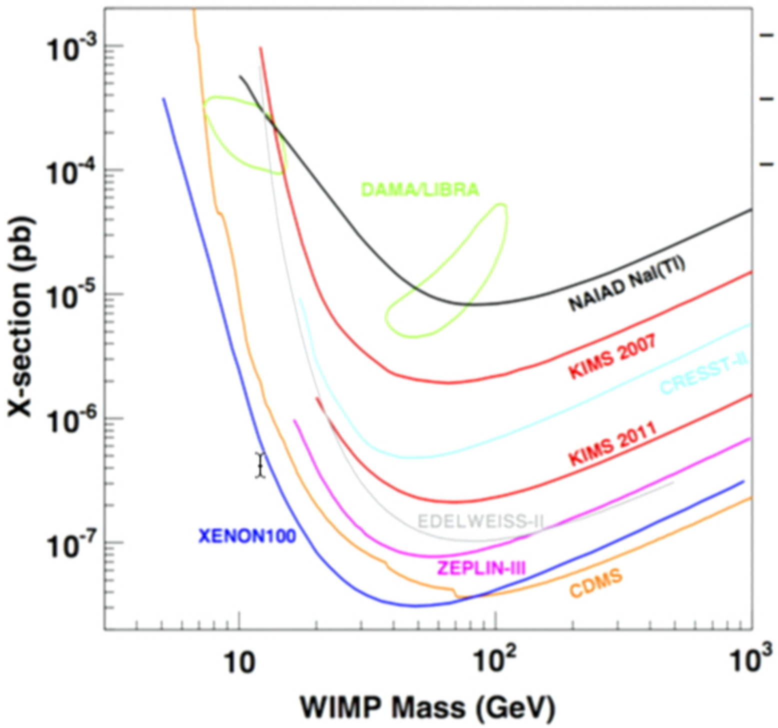
“Standard” interpretation of DAMA results in conflict with many other experiments



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

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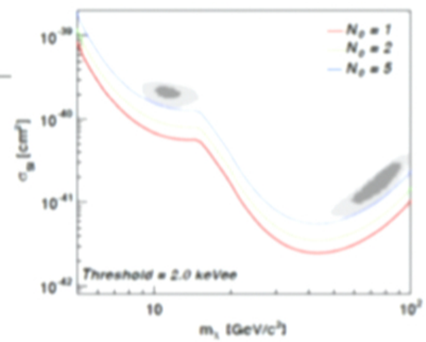
DM-Ice

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**



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

Key Features

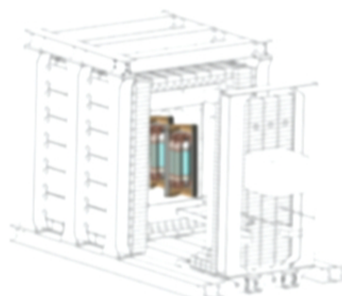
- NaI(Tl) target
- only experiment with access to both Northern & Southern Hemispheres

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 Page 70 of 138 tion

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 (Calaprice, Froborg, Xu)

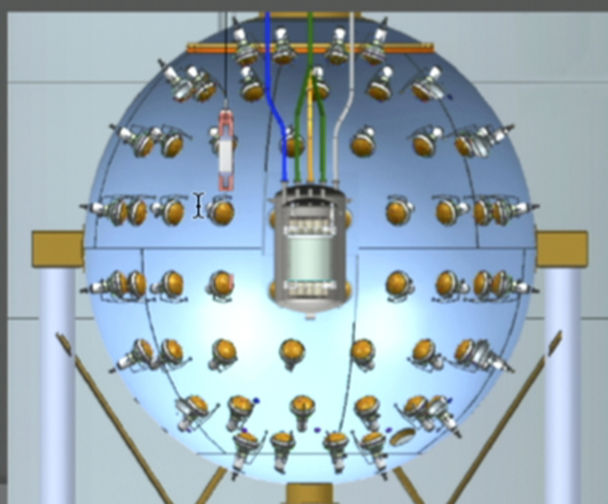
SABRE: Sodium Iodide with Active Background REjection

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

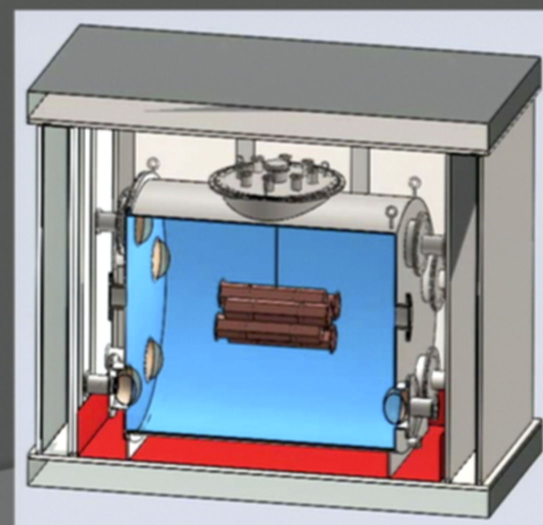
DarkSide veto (LNGS)

- 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



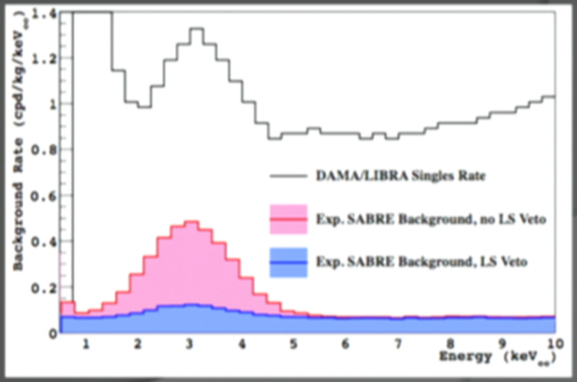
SABRE: Sodium Iodide with Active Background REjection

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:

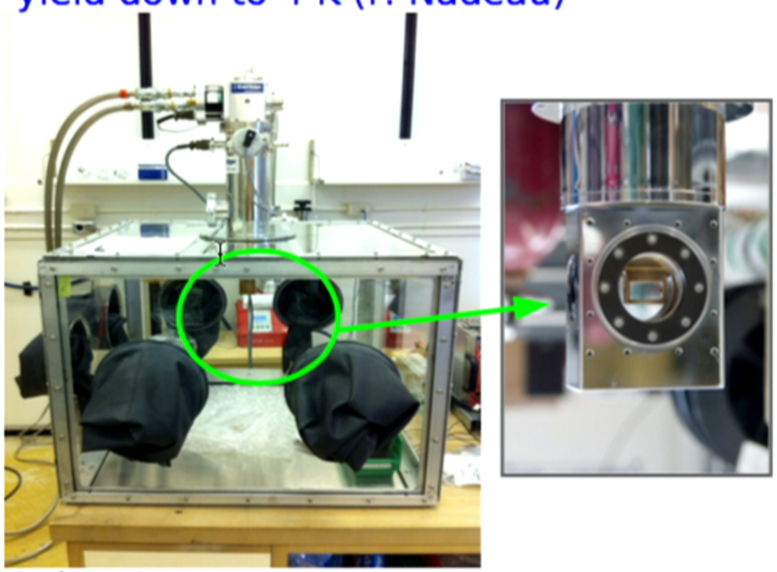
- Improve NaI powder purity by zone refining and improved production technique
- Improve NaI(Tl) crystal growth and processing
- Improve detector packaging with optimized optical coupling, lower humidity levels and lower contamination
- 50-kg array with background of 0.1 cpd/kg/keV, indicated by current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



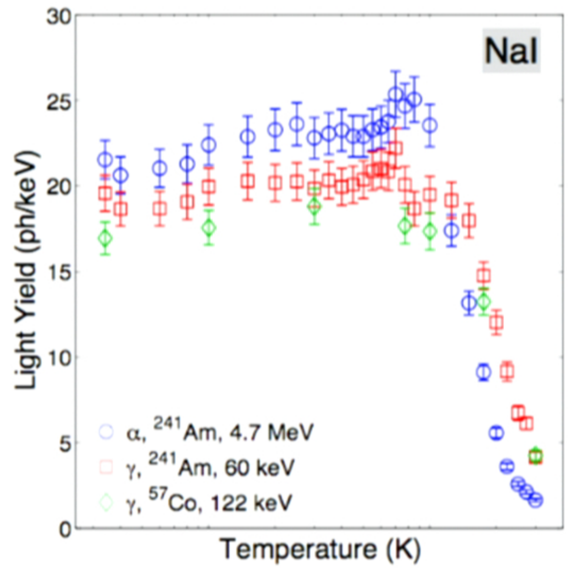
Expected SABRE background
Assuming same impurity levels as in powder

Alkali-Halide Cryogenic Detectors to Test DAMA?

- mK phonon + scintillation readout à la CRESST
- Potential payoff:
  - Less astro, particle dependence
  - Particle identification
- Queen's setup to measure light yield down to 4 K (P. Nadeau)



- Alpha and gamma light yields:



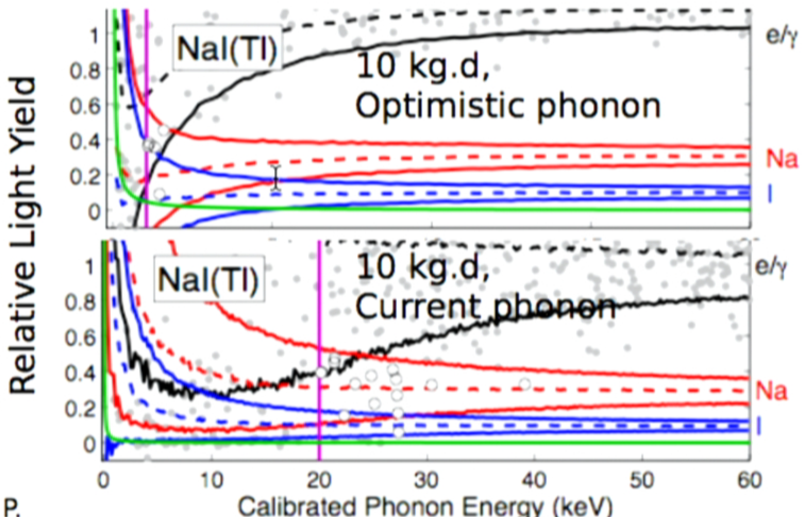
- 60 keV gamma LY @ 3.4 K
  - NaI: 20±1 ph/keV
  - NaI(Tl): 41±1 ph/keV
  - CsI: 59±5 ph/keV **All OK!**
  - *(cf CaWO4: 21 ph/keV)*

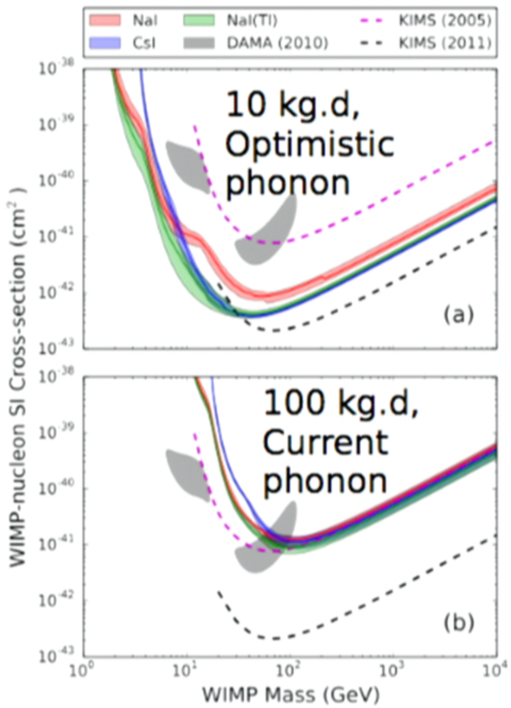
P. Di Stefano, Queen's

Standard Halo DC Sensitivity of Alkali-Halide Cryogenic Detectors with BG Rejection

Nadeau, Clark, Di Stefano… Yavin, Astroparticle Physics 67 (2015) 62

- Phonon channel a challenge (Schäffner et al, J Low Temp Phys (2012) 167:1075–1080 10 keV resolution in CsI)
  - Low Debye T
  - NaI hygroscopic
- Assume a phonon resolution, and demonstrated DAMA BG, then simulate rejection bands:





Small, ~5 kg detector or array sufficient if improved phonons

P.

Reasons to believe in optimistic phonon performances

arXiv:1503.01200v2 [astro-ph.IM] 12 Mar 2015

Optimized Designs for Very Low Temperature Massive Calorimeters

Matt Pyle,[1,*] Enectali Figueroa-Feliciano,[2] and Bernard Sadoulet[1]

[1]*Physics Department, University of California Berkeley*

[2]*Physics Department, Massachusetts Institute of Technology*

(Dated: March 13, 2015)

The baseline energy-resolution performance for the current generation of large-mass, low-temperature calorimeters (utilizing TES and NTD sensor technologies) is > 2 orders of magnitude worse than theoretical predictions. A detailed study of several calorimetric detectors suggests that a mismatch between the sensor and signal bandwidths is the primary reason for suppressed sensitivity. With this understanding, we propose a detector design in which a thin-film Au pad is directly deposited onto a massive absorber that is then thermally linked to a separately fabricated TES chip via an Au wirebond, providing large electron-phonon coupling (i.e. high signal bandwidth), ease of fabrication, and cosmogenic background suppression. Interestingly, this design strategy is fully compatible with the use of hygroscopic crystals (NaI) as absorbers. An 80-mm diameter Si light

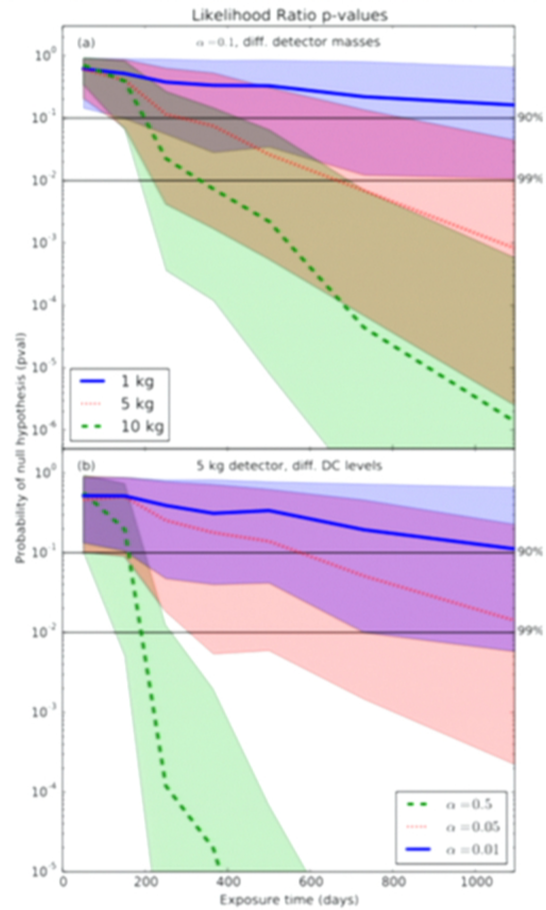
Potential:

- Ease of manufacturing (sensor fabrication decoupled from absorber)
- Excellent sensitivity

Sensitivity to a generic DAMA-size modulation

Nadeau et al, Astroparticle Physics 67 (2015) 62

- No astro, particle or BG assumptions
- Generic model for simulations:
  - AC component: fixed by DAMA (0.04 counts/d/kg)
  - DC component: unknown
    - Signal
    - Unrejected BG
  - → Study for different α=AC/DC
- Likelihood ratio test applied to simulations (DC, AC, phase free) → with what confidence a modulation can be distinguished from a statistical fluctuation of a constant background
- Similar result from Lomb-Scargle analysis



Small, ~5 kg detector or array sufficient

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
- SUSY still elusive, so interest has expanded to low masses *(though full GeV-TeV range still possible)*:
  - **No confirmed signal!**
  - *Would help if theoretical predictions could be more specific*
- Complementary mix of targets and technologies required to validate any discovery