IFD2015

INFN Workshop on Future Detectors

16-18 December 2015 - Torino - Italy

What’s new for dark matter (WIMPs) detection?

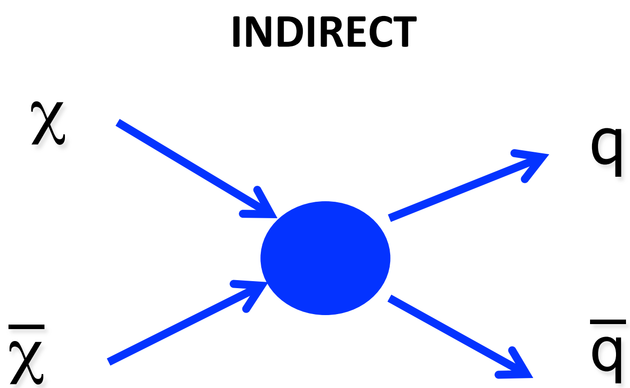
Aldo Ianni,

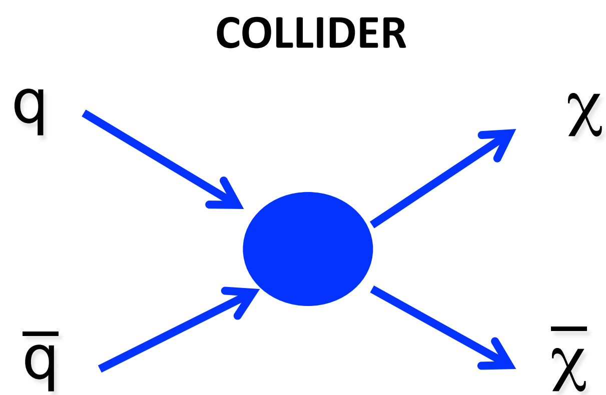
Canfranc Laboratory & INFN-LNGS

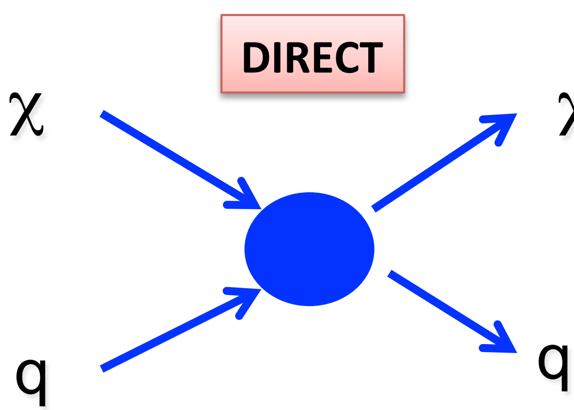
Outline

- Introduction
  - Direct Detection of Dark Matter
  - WIMPs search for low and high masses
- A “not exhaustive” review of present and future detectors for WIMPs search
- Conclusions and perspectives
- Many backup slides for discussions …

The quest for Dark Matter







χ = DM particle
q = Standar Model particle

DM particle candidates

- **WIMPs**
  - Weakly Interacting Massive Particles:
    for the last ~ 20 years the main scenario for DM
  - Mass ~ 1 – 100 GeV/c^2
  - Local number density ~ 10^5 – 10^7 cm^{-3}
- **Axion-like particles**
  - the interest in these particles as DM candidates is growing

$$\Omega_a \approx \left(\frac{10^{-5}\ \mathrm{eV}}{m_a} \right)^{\frac{7}{6}}$$

  - QCD axions as DM with mass ~ 1 – 100 μeV
  - Local number density ~ 10^{12} – 10^{15} cm^{-3}

The quest for axions as DM

(see Caterina Braggio this meeting)

- The only experiment in operation at present is **Axion DM eXperiment (ADMX)** a cryogenic microwave cavity in 8T magnetic field sensitive to ~100 MHz
  - **Cavity haloscope**: axion-photon conversion enhanced in resonant cavity
  - improving performances for GHz range sensitivity
- **CAST-CAPP** and **RADES** (UZ and IFIC Valencia)
  - Microwaves cavitities in CAST magnet with GHz sensitivity
  - Prototypes installed and tested in 2016
- **Dielectric resonant cavities** with sensitivity at 10-100 μeV (mainly MPI, Munchen)
  - Reflecting surfaces convert axion-like particles into photons
  - More broadband effect than from resonant cavities
- Quest for Axions (**QUAX**) at INFN and Univ. of Padova
  - Probe axion-electron coupling by detecting spin flip induced in a magnetic field on a target "magnetic sample"

"Standard" cross-section

Spin Independent interaction: $$\sigma^{SI}(E_r) = \sigma_p^{SI}\left[Z + (A-Z)\frac{f_n}{f_p}\right]^2\left(\frac{\mu}{\mu_p}\right)^2 F_{SI}^2(E_r)$$

So for the "standard" $f_p = f_n$, $\boldsymbol{\sigma^{SI} \sim A^2}$

Spin Dependent interaction: $$\sigma^{SD}(E_r) = \sigma_p^{SD}\frac{4}{3}\frac{J+1}{J}\left(\langle S_p\rangle + \langle S_n\rangle\frac{f_n}{f_p}\right)^2\left(\frac{\mu}{\mu_p}\right)^2 F_{SD}^2(E_r)$$

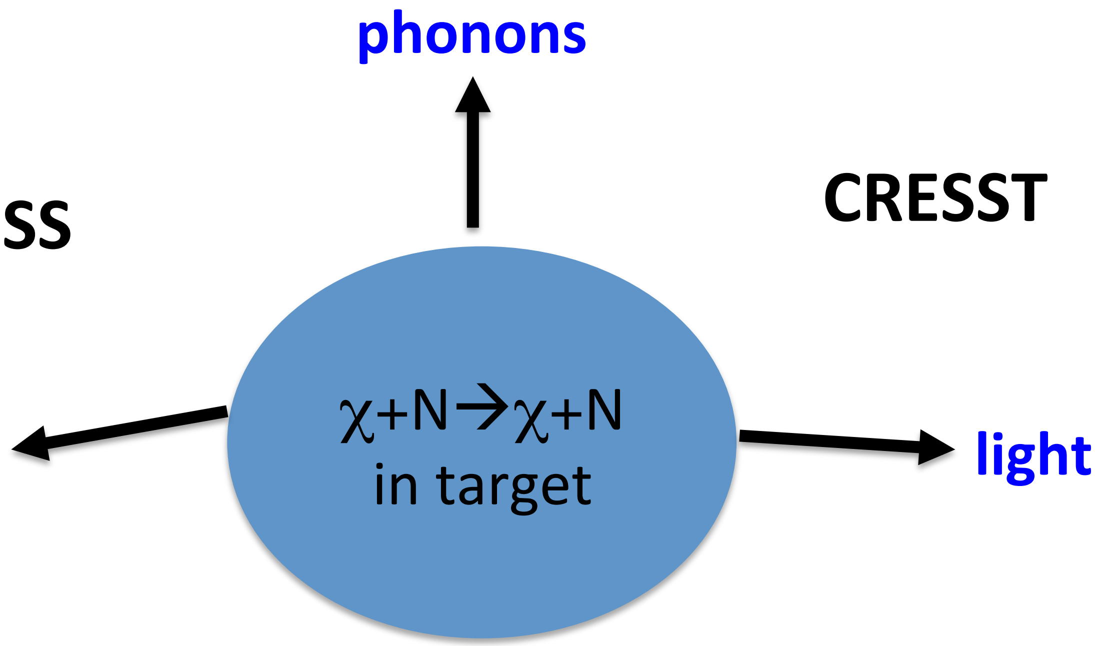
$\boldsymbol{\sigma^{SI}/\sigma^{SD} \sim A^2}$

Deviations from the "standard" scenario are being considered:

- Isospin Violating Interactions, $f_n/f_p \sim -0.7$
  - reduces the coupling with Xe target
- $f_n/f_p \sim -0.8$ reduces the coupling with Ge target
- Electromagnetic coupling
- ...

Important to use different target detectors

WIMPs Detection Methods



CDMS
EDELWEISS

CRESST

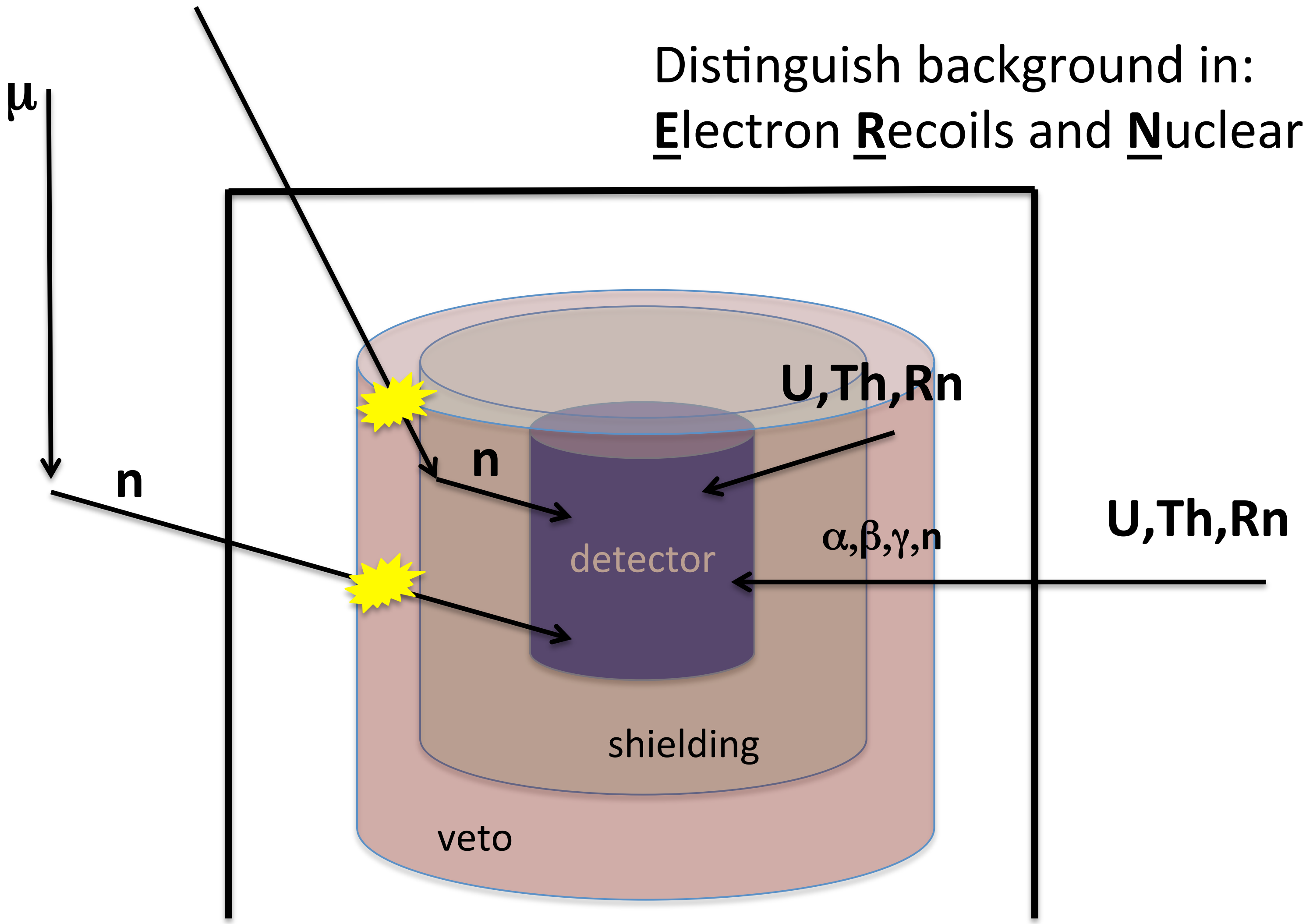
NEWS-SNOlab
DAMIC
CDEX

DAMA
DEAP
XMASS
KIMS

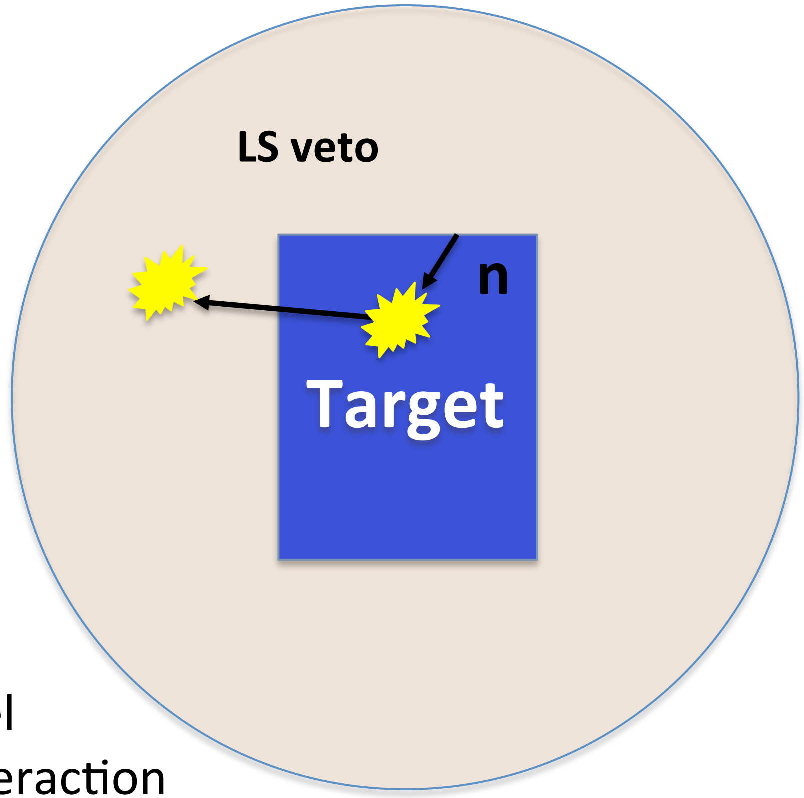
Xenon, LUX,PandaX,
ArDM, DarkSide

Background for WIMPs search

Distinguish background in:
Electron **R**ecoils and **N**uclear **R**ecoils

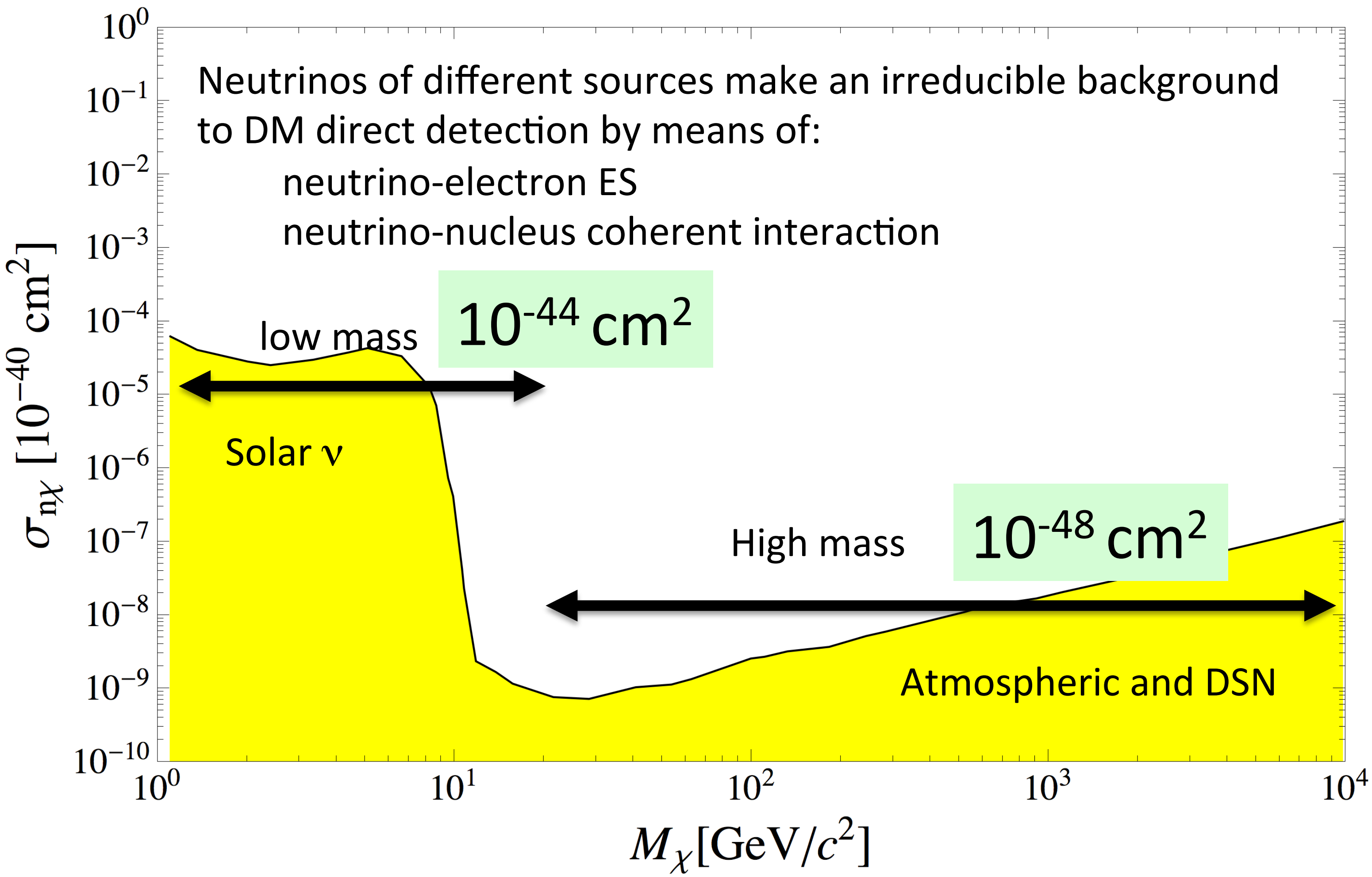


An active Neutron Veto for WIMPs search: general idea

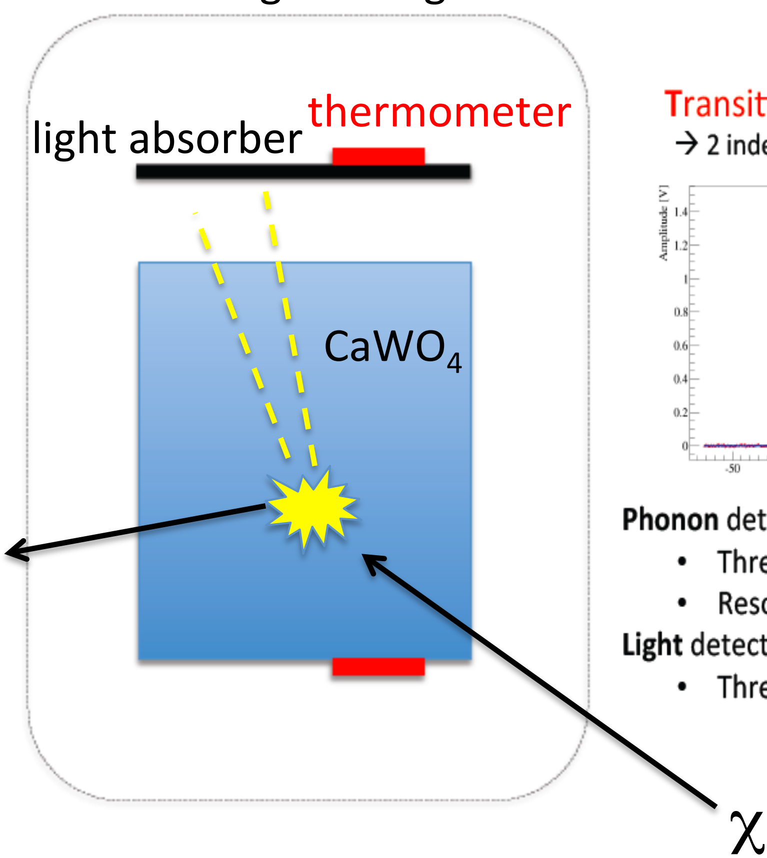


A radiogenic neutron
from the cryostat steel
or PMTs makes an interaction
in target (WIMP-like) and later
is captured in the LS veto.
This type of event is rejected.

“Neutrino floor” for DM

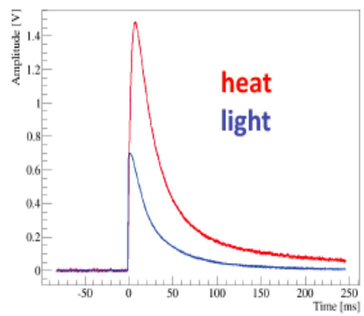


Background rejection: an example with CRESST



Transition-Edge-Sensors

→ 2 independent calorimeters



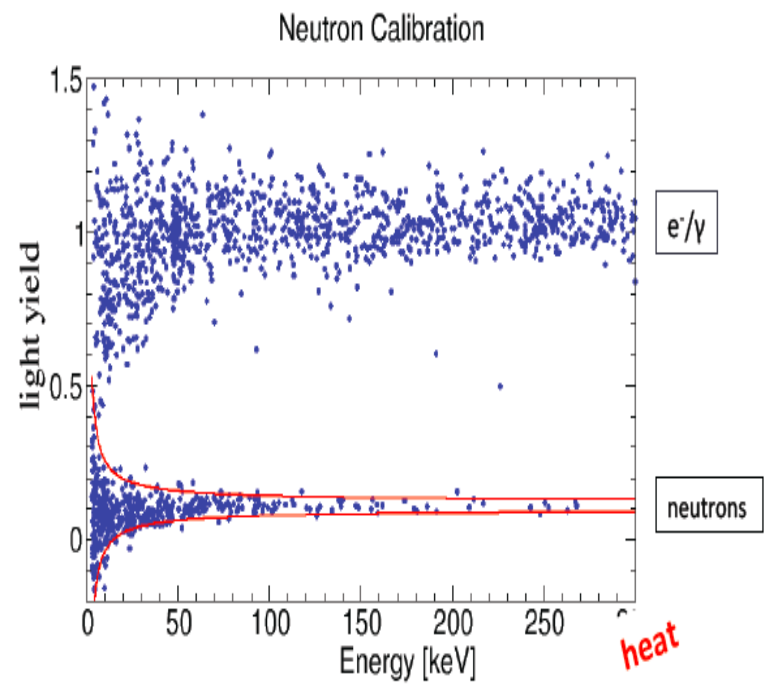
Phonon detector ($CaWO_4$)

- Threshold: $E_{th} \geq 300$ eV
- Resolution: $\sigma \approx 60\text{-}200$ eV

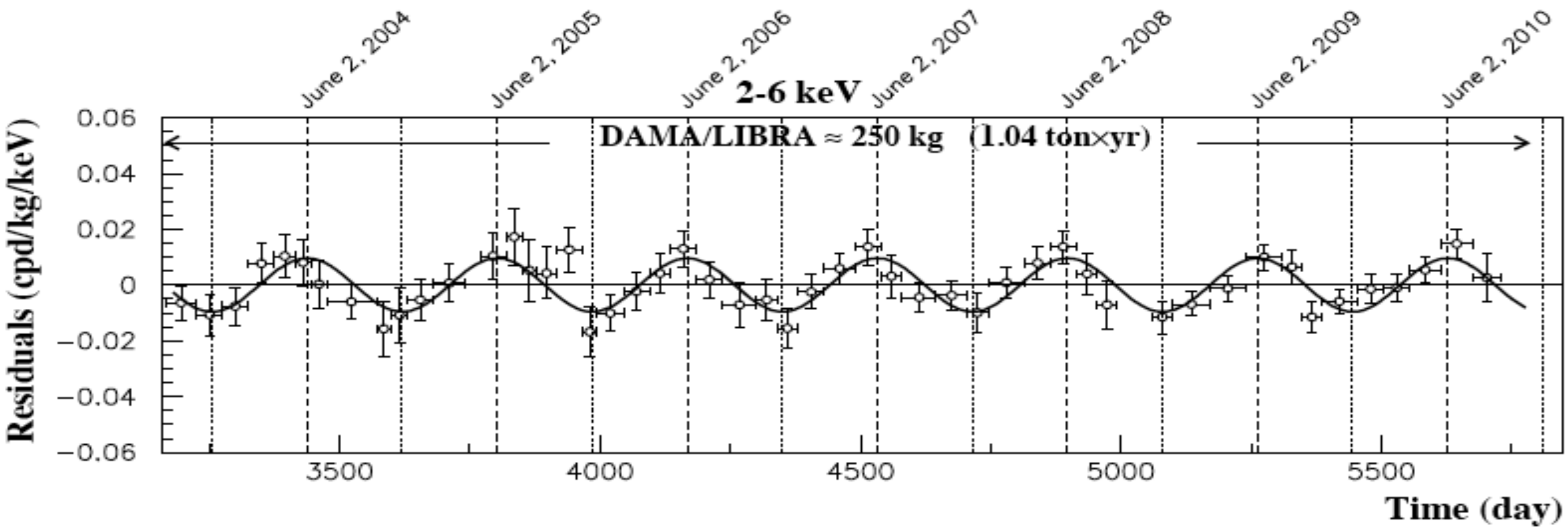
Light detector (SOS)

- Threshold $E_{th} \approx 5$eV

$\frac{\text{light}}{\text{heat}}$



DAMA/LIBRA: results



- Modulation observed over 14 cycles
- Cumulative exposure = 1.33 ton-year
- Significance of modulation signal is 9.3σ
- Modulation amplitude in [2,6]keV = 0.0112±0.0012 cpd/kg/keV
- Phase = 144±7 days
- Period = 0.998 ± 0.002 year

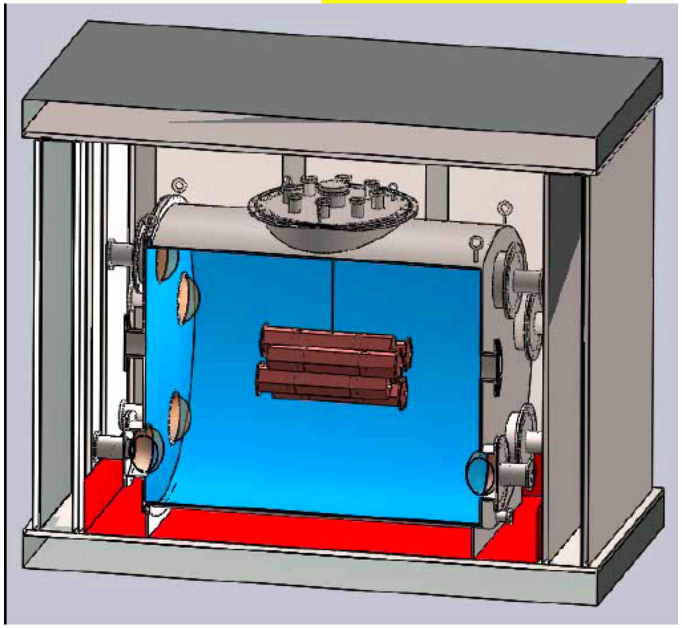
DAMA/LIBRA: present and future

- High purity NaI(Tl) crystals + light guides + PMTs in passive shielding
- Upgrade end of 2010 to replace all PMTs with new ones with high QE to lower the detection threshold
- Fall 2012 upgraded electronics with new preamplifiers and trigger modules
- Detector running with new configuration
  - LY improved to ~ 10 pe/keV
- Further improvement to increase light yield:
  - Reduce radioactivity of PMTs
  - Remove 10cm long light guides and couple crystals to PMTs

NaI(Tl) detectors for DM search

- **DAMA/LIBRA** in operation
  - Total rate in ROI ~ 1 cpd/kg/keV (1 DRU)
- **ANAIS** at Canfranc
  - 112 kg of NaI(Tl) in 2016
  - Crystal arrays in passive shielding + muon veto
- **SABRE** at LNGS and Stawell (Australia)
  - ~60 kg NaI(Tl) + Liquid Scintillator active veto
  - 2016 crystal characterization
- **KIMS-NaI**
  - 200 kg x 3 years in Yangyang (Korea)
  - Liquid Scintillator active veto
  - 2016 crystal characterization
- **PICO-LON** in Kamioka
  - 200 kg NaI(Tl) target mass
  - 2016 crystal characterization/run
- **ALL efforts have**
  - **> 10 p.e./keV yield**
  - **Issues with intrinsic radiopurity from ^{40}K, ^{210}Pb, …**
  - **Cosmogenic background will delay physics run by 1-2 years since t_0**

SABRE design

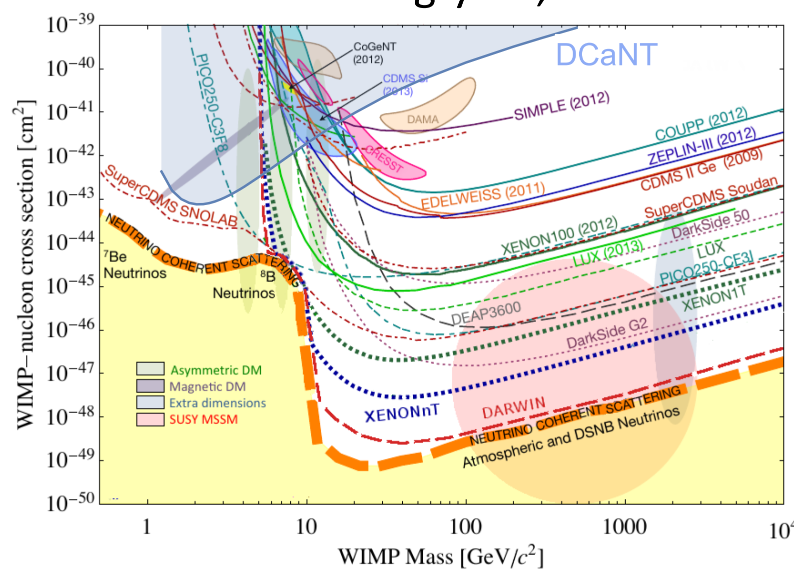


Important goal: ungerground crystal production

Diurnal Modulation of DM

- **Diurnal modulation ~ x 0.02 vs annual modulation**
- Carbon NanoTubes (CNT) lattice for DM search (DCaNT)
  - aligned CNT as target (~ g/cm^3)
  - scattered C ions escapes (channeling) parallel to central axis; anisotropy give key for diurnal modulation detection
  - C ions detected in low pressure gas TPC
  - C ion energy and direction measured
  - Goal: test channeling idea
- Nuclear Emulsions for DM search
  - NE as target and tracking device
  - Rotating structure holding the target-detector and shileding
- Anisotropic Detectors for Dark Matter Observation (ADAMO)
  - Light output depends on direction of incoming particle wrt crystal axes
  - $ZnWO_4$ taken into consideration for low background and large A
- TPC which exploit incoming particle direction wrt electric field direction

30 kg-year, 1 keV Th

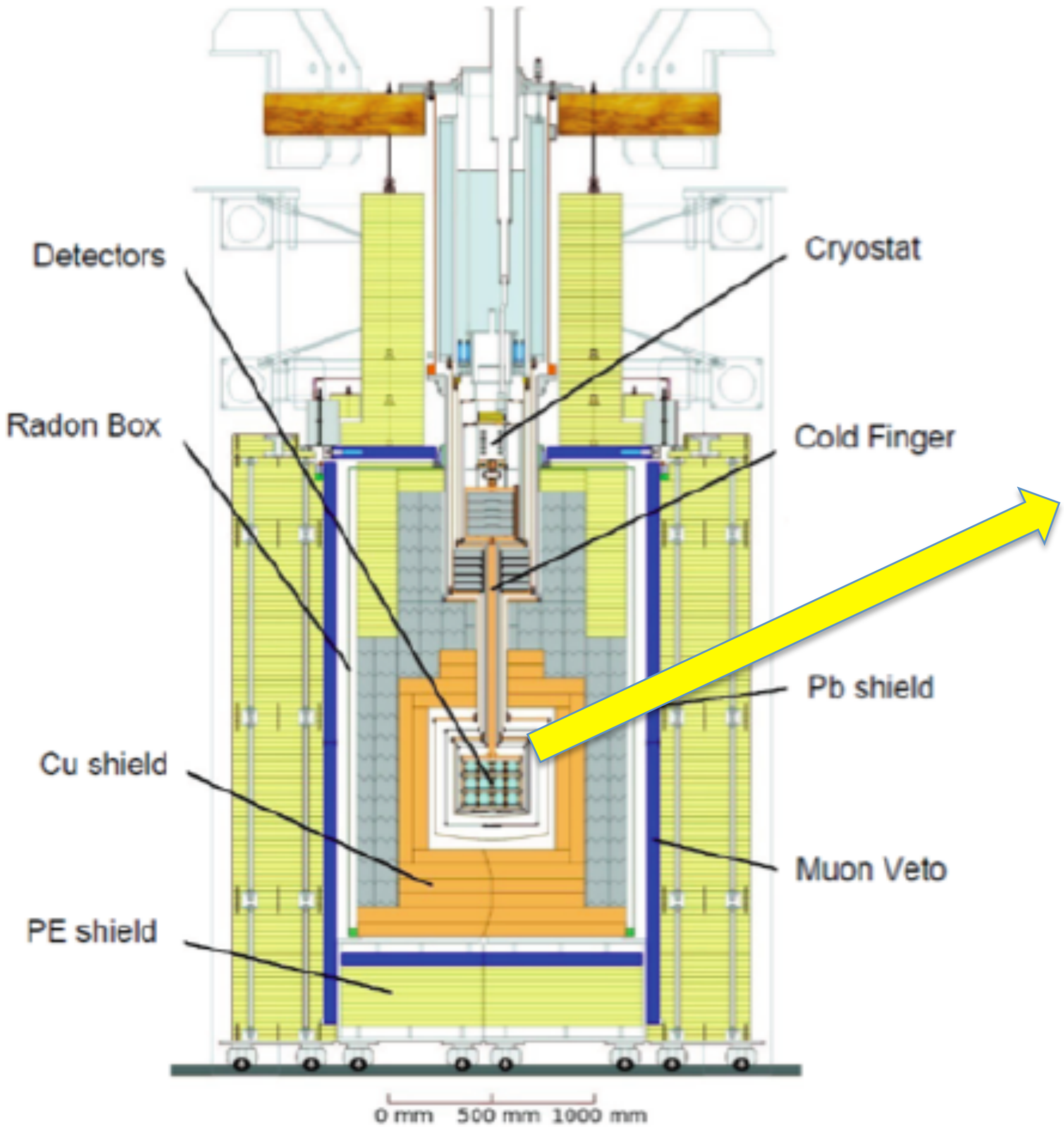


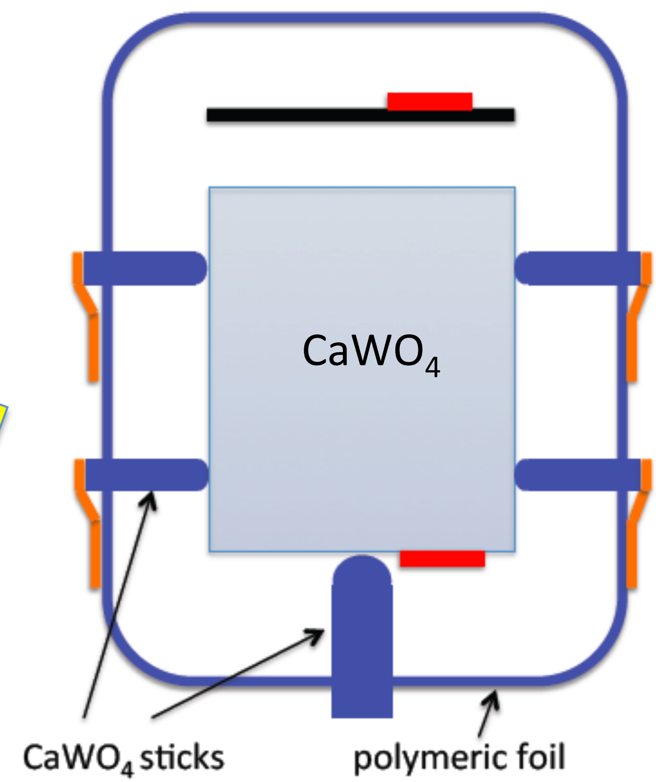
Low Mass WIMPs

$m_p \rho_{DM}/\rho_b \sim 5 GeV/c^2$

- **SuperCDMS/EDELWEISS (SNOlab/Modane)**
  - phonon + charge on Ge and Si (> ~150eV)
- **CRESST (LNGS)**
  - phonon + light on $CaWO_4$ (>300eV)
- **CDEX (CJPG)**
  - Charge on Ge + NaI(Tl) anti-compton (>~100 eV)
- **DAMIC (SNOlab)**
  - Charge on CCD at -150C in Cu+Pb shielding (>~40eV)
- **NEWS-SNOlab**
  - charge on Ne or He (>~100eV)
- Sensitivity to low masses ~10 GeV/c^2 with LXe

CRESST-II

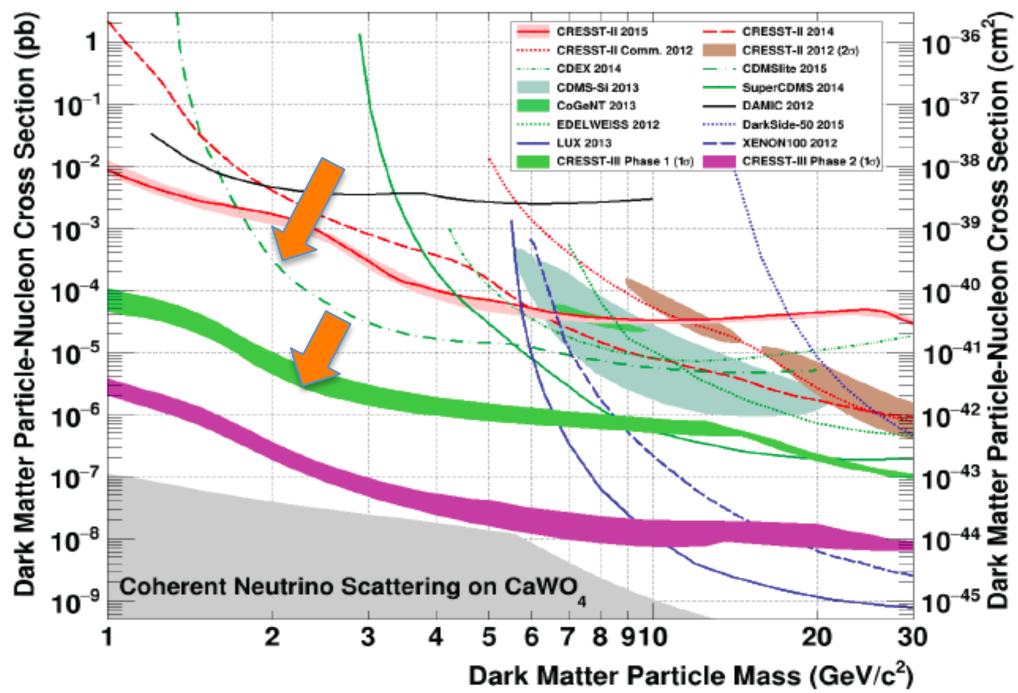

Detectors
Radon Box
Cu shield
PE shield
Cryostat
Cold Finger
Pb shield
Muon Veto
0 mm 500 mm 1000 mm


$CaWO_4$
$CaWO_4$ sticks
polymeric foil

CRESST @ LNGS: next steps

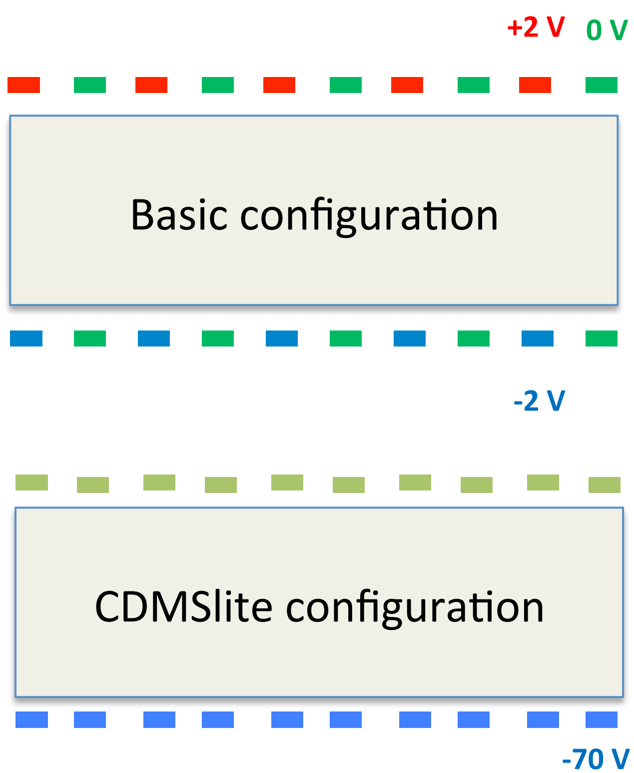
- Background from clamps ($^{210}Po \rightarrow {}^{206}Pb(103keV)+\alpha(5.3MeV)$)
  - To improve rejection of this background **avoid non-scintillating materials** in crystal housing. Use $CaWO_4$ sticks
- **Make crystal at TUM** to improve radiopurity
  - Already working very well
- Improve light detector due to smaller volume of crystal housing and new light absorber design

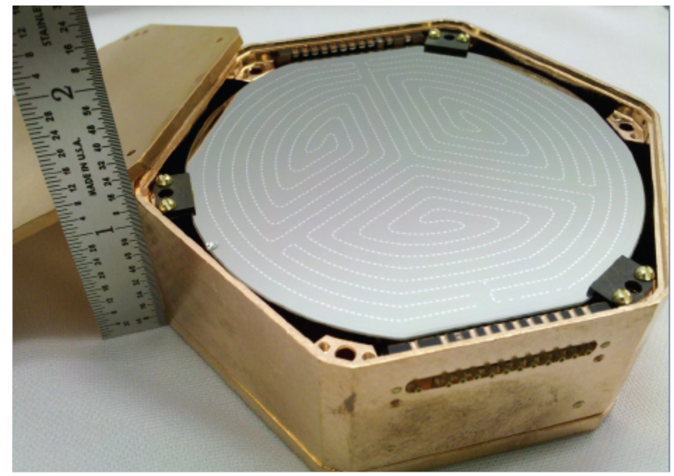
Projections for CRESST-III



CDMS/SuperCDMS

- Ge single crystals (620g each)
- Read-out: Superconducting Phase Transition Sensor (T_c=50-100 mK)
- Basic configuration: low voltage (4V)
- One detector: high voltage 70V





Detector configuration at **Soudan Lab**:

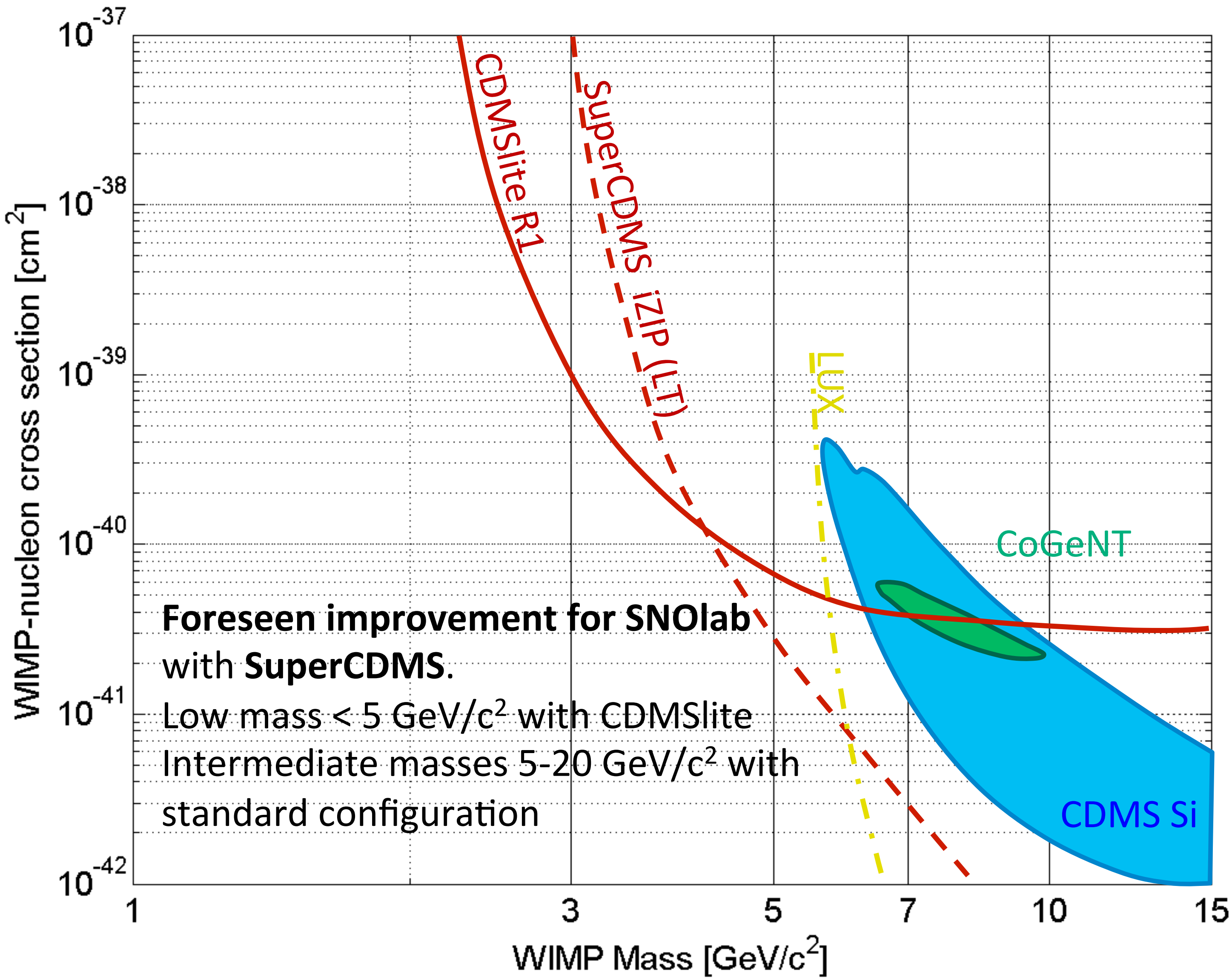
stack **3 detectors in a "tower"**

5 towers for 9.3 kg

shielding with Pb+PE+muon-veto

at 2 keVe 100% trigger efficiency

CDMSlite ~ 170 eVee threshold


10^-37
10^-38
10^-39
10^-40
10^-41
10^-42
WIMP-nucleon cross section [cm^2]
1
3
5
7
10
15
WIMP Mass [GeV/c^2]
CDMSlite R1
SuperCDMS iZIP (LT)
LUX
CoGeNT
CDMS Si
Foreseen improvement for SNOlab
with **SuperCDMS**.
Low mass < 5 GeV/c² with CDMSlite
Intermediate masses 5-20 GeV/c² with
standard configuration

China Dark Matter EXperiment (CDEX) @ CJPL

- China **Jin-Ping Laboratory** (CJPL)
  - 2400 m depth with 6 μ/m^2/month
  - 6x6x40(L) m^3 Hall in operation
  - new excavation underway
    - Four 14x14x130(L) m^3 Halls ready in 2016
- **CDEX**
  - 1kg p-type point-contact Ge detector with NaI(Tl) anti-compton, Cu+Pb shielding and muon veto
  - Next future development
    - 10/100 kg Ge detector in LN or LAr

CDEX sensitivity

Search for **low mass WIMPs**

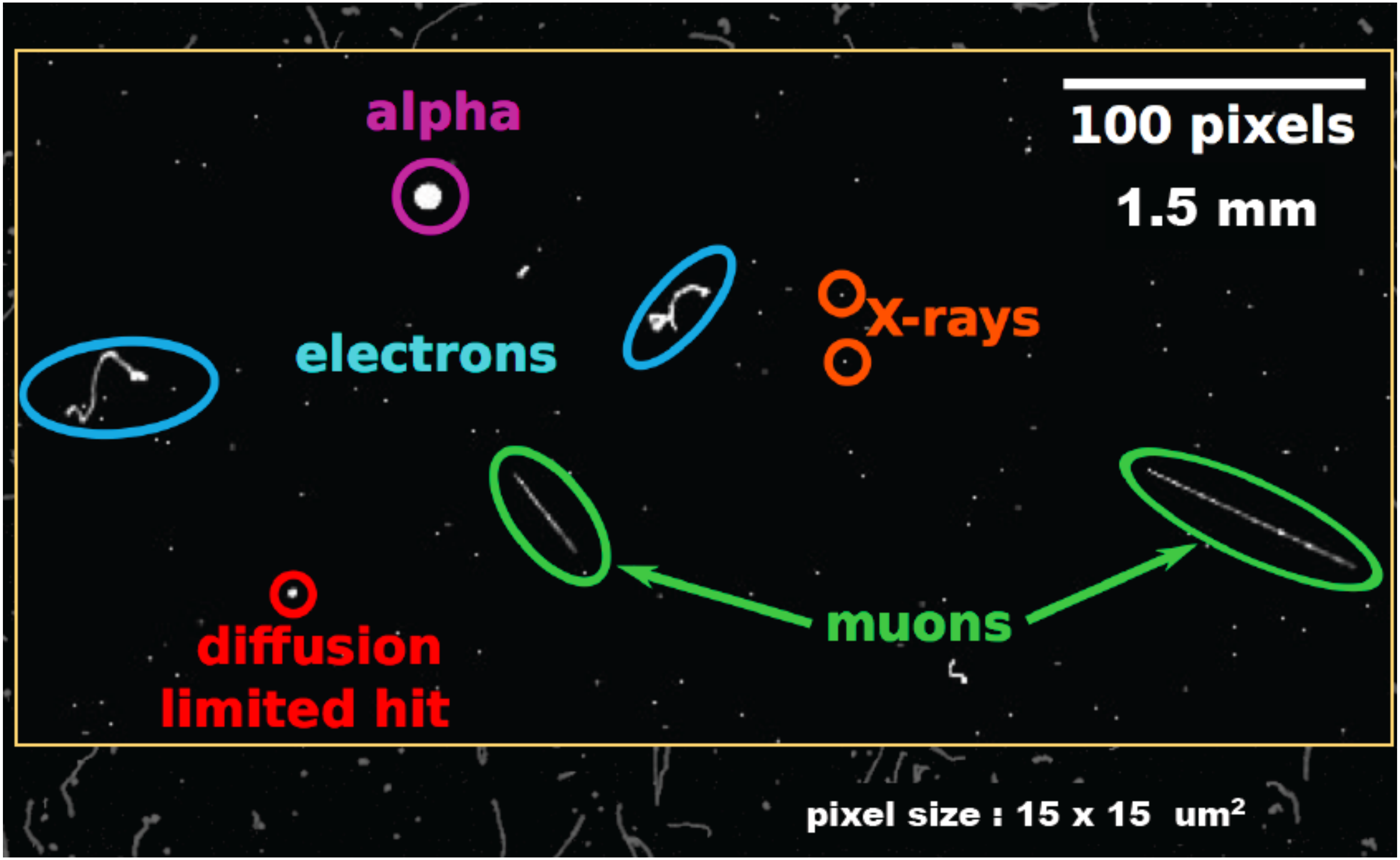
- Use background subtraction based on
  - muon veto + very low muon flux at CJPL
  - anti-compton veto
  - PSD to reject surface background from pulse timing amplitude features

- Sensitivity
  - CDEX-1 (current result) with threshold at 500 eV and **4 cpd/kg/keV**: $\sim 10^{-41}$ cm^2 @ 8 GeV/c^2
  - CDEX-1 with threshold at 100 eV and **1 cpd/kg/keV**: $\sim 3 \times 10^{-42}$ cm^2 @ 2-10 GeV/c^2
  - CDEX-10 with threshold at 100 eV and **0.1 cpd/kg/keV**: $\sim 3 \times 10^{-43}$ cm^2 @ 2-10 GeV/c^2
  - CDEX-1000 with threshold at 100 eV and **0.01 cpd/kg/keV**: $\sim 10^{-44}$ cm^2 @ 8 GeV/c^2
    - **Implies underground Ge growth**

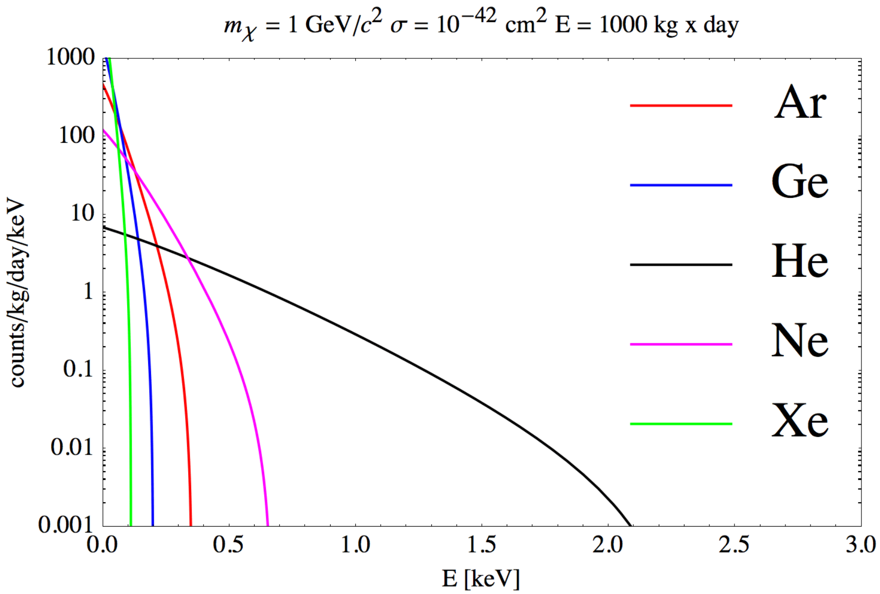
DArk **M**atter **I**n **C**CD (DAMIC)

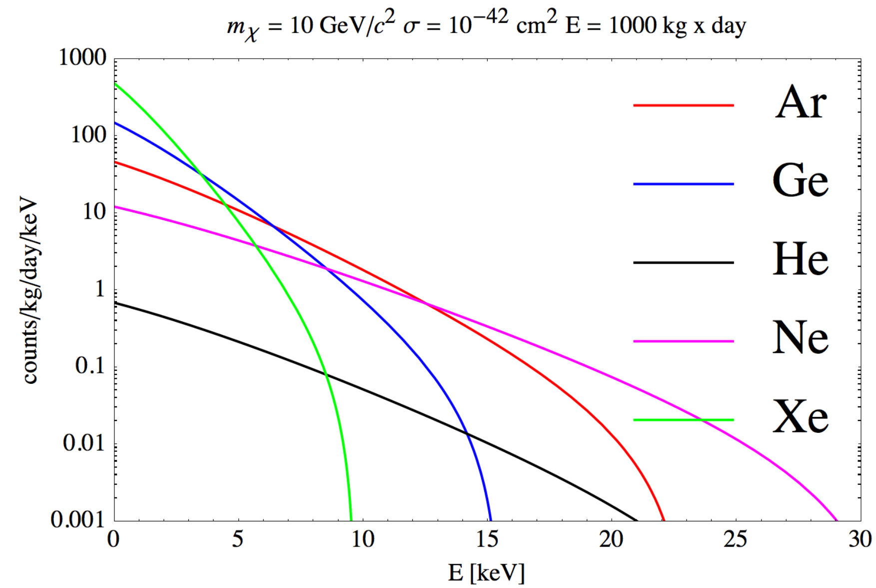
- DAMIC 2011 test run at FNAL with 0.5 g CCD and 107 g x day (CCD made at LBNL)
- CCD at -150C in Cu+Pb shielding
- **40 eV detection threshold**
- Event simulation based on model for diffusion of charge from muon tracks
- $\alpha - \beta$ discrimination based on topology of track
- **Measured NR quenching down to ~1 keV$_r$** (0.05 keV$_e$)
- DAMIC100 (2016) with 100 g detector, 18 CCD at SNOlab
- Mass sensitivity down to ~1 GeV/c^2
- Cross-section sensitivity ~10^{-41} cm^2 at a 3-10 GeV/c^2
- Long term for 1kg detector (10^{-43} cm^2)

Particle Identification in CCD



Very Low Mass WIMPs

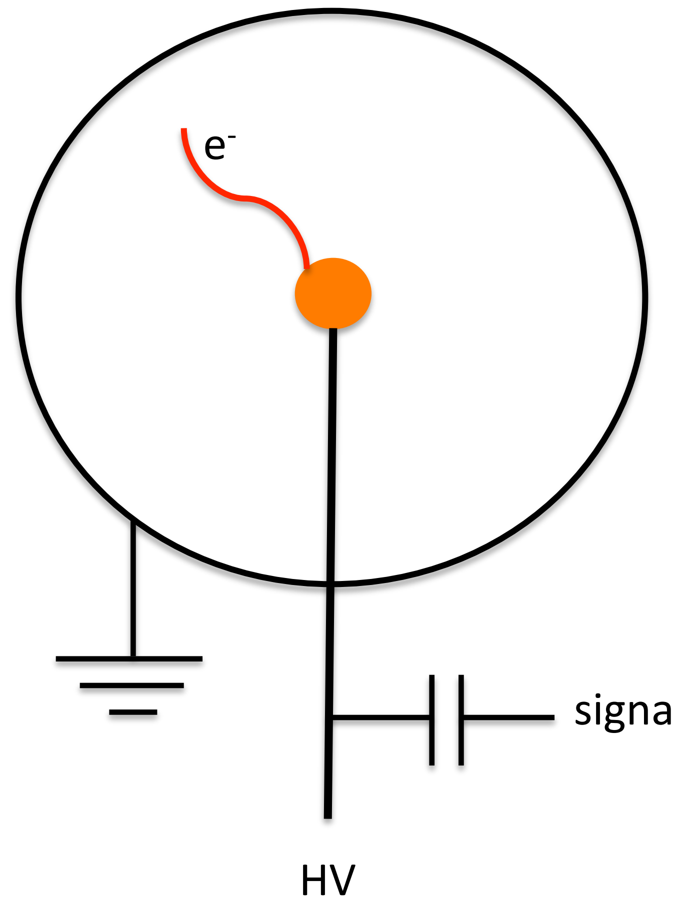




- Spherical TPC for very low mass WIMPs
  - Goal: search for WIMPs in the range **0.1 – 5 GeV/c²**
- Detector: spherical TPC with light target nuclei (He, Ne)
- Original idea: I. Giomataris (JINST 3,2008) and SEDINE detector at LSM

The NEWS-SNO project

- Based on the idea of a Spherical Gas Detector
- Large spherical cavity in ultrapure Cu on ground potential
- Small number of materials: high radiopurity
- Sphere inside Water Tank
- Small spherical sensor at high voltage (> 1kV)
  - 10 bar operating pressure
  - << 1keV thereshold (tested with ^{37}Ar at 260 eV)
  - Ionization with drift of charge toward the center and amplification of signal close to detector
  - Diffusion time and risetime distribution allows PSD between ER and NR



High Mass WIMPs

- **LUX/Xenon1t/PandaX (Homestake/LNGS/CJPL)**
  - light + charge on LXe
- **DarkSide/ArDM (LNGS/LSC)**
  - Light + charge on LAr
- **DEAP-3600 (SNOlab)**
  - light on LAr
- **XMASS (Kamioka)**
  - light on LXe

Liquid Noble Gases Detectors

- **Single phase** (XMASS, DEAP)
  - 4π geometry for high light collection
  - Prompt, S1, signal + PSD
- **Two-phase** (Xe1t, LUX, PANDA-X,ArDM, DarkSide …)
  - Cylindrical geometry with a TPC
  - Prompt, S1, and delayed, S2, signals + PSD
- Locate cryostat inside a Water Cherenkov muon veto with passive or active neutron shielding/veto

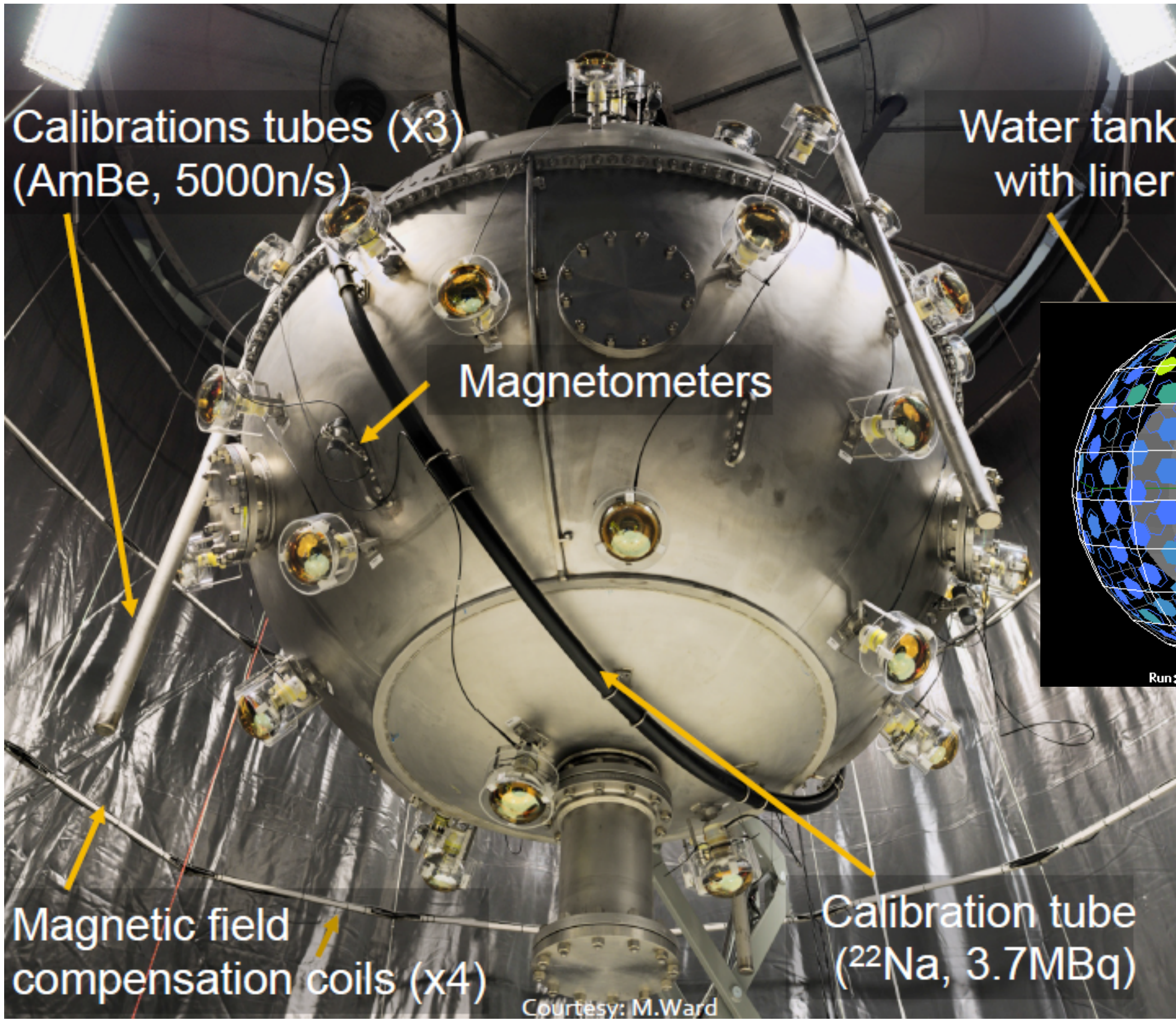
LXe program on DM

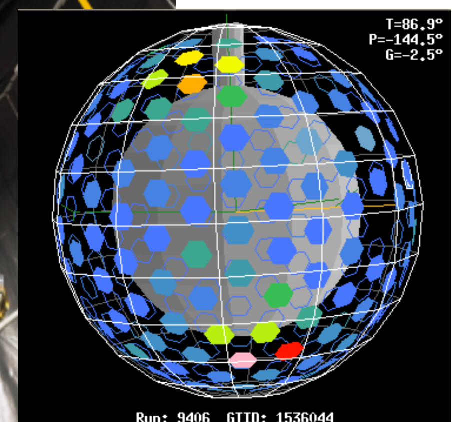
- **LUX @ Homestake**
  - 250 kg dual-phase LXe TPC with two 61-array PMTs in Water Tank
  - 85.3 days and 118.3 kg exposure
  - 2-30 phe window with **8.8 phe/keVee** @ null field
  - Best limit on WIMP SI search: **7.6×10^{-46} cm^2 at 33 GeV/c^2**
  - LUX will turn into **LUX-ZEPLIN** (> 2018) with 7 tons LXe and **Gd-loaded LS**
- **XENON1t @ Gran Sasso (based on success of XENON100)**
  - Under construction/commissioning at LNGS
  - Expected LY ~ 7.7 phe/keV
  - 3.5ton LXe (1ton FM) in Water Tank in total for projected sensitivity at ~ 10^{-47} cm^2
  - Future development to a few tons ….
- **PandaX at CJPL**
  - 2.4ton LXe (1ton FM) in 2016
- **XMASS @ Kamioka**
  - 835 kg (100 kg fiducial) single-phase in Water Tank
  - First commissioning with unexpected background

LAr program on DM

- **DarkSide @ LNGS**
  - 50 kg dual-phase LAr TPC in Water Tank with active Liquid Scintillator veto
  - 71 days and 37 kg exposure with **150 kg of UAr** in cryostat
  - 20-460 phe window with **~8 phe/keVee** @ null field
  - Best limit on WIMP SI search with LAr: **$2x10^{-44}$ cm^2 at ~60 GeV/c^2**
  - Future development conceptual idea: 20ton and ~10^{-48} cm^2
- **ArDM @ LSC**
  - Run in 2015 in single phase with 870 kg active mass and 2ton of LAr
  - Status: two-phase run in 2016
- **DEAP-3600 @ SNOLab**
  - 1 ton fiducial with 3600 LAr
  - Status: final commissioning
  - Predicted sensitivity: **10^{-46} cm^2 at ~100 GeV/c^2**
  - Future development conceptual idea: 50ton and ~10^{-48} cm^2

DEAP-3600 Detector in Shield Tank





The problem of ^{39}Ar

- Ar is naturally present in the atmosphere at 1% level
- Atmospheric Ar contains ^{39}Ar which is formed by cosmic muon interactions
  - ^{40}Ar(n,2n)^{39}Ar
- ^{39}Ar is a β decay emitter with Q_{β}=565 keV and $T_{1/2}$=269 years
- ^{39}Ar is at the level of 1 Bq/kg
  - ~ 9×10^{4} decays/kg/day
  - WIMPs(100GeV, 10^{-45} cm^{2}) ~ 10^{-4} events/kg/day

Underground Argon

- ^{40}Ar produced from ^{40}K
- The Earth is reach in ^{40}K in underground
- ^{40}Ar moves into the atmosphere and makes ^{39}Ar with muons interactions
- Underground Ar is expected to be much less contaminated in ^{39}Ar, due to the lower muon flux

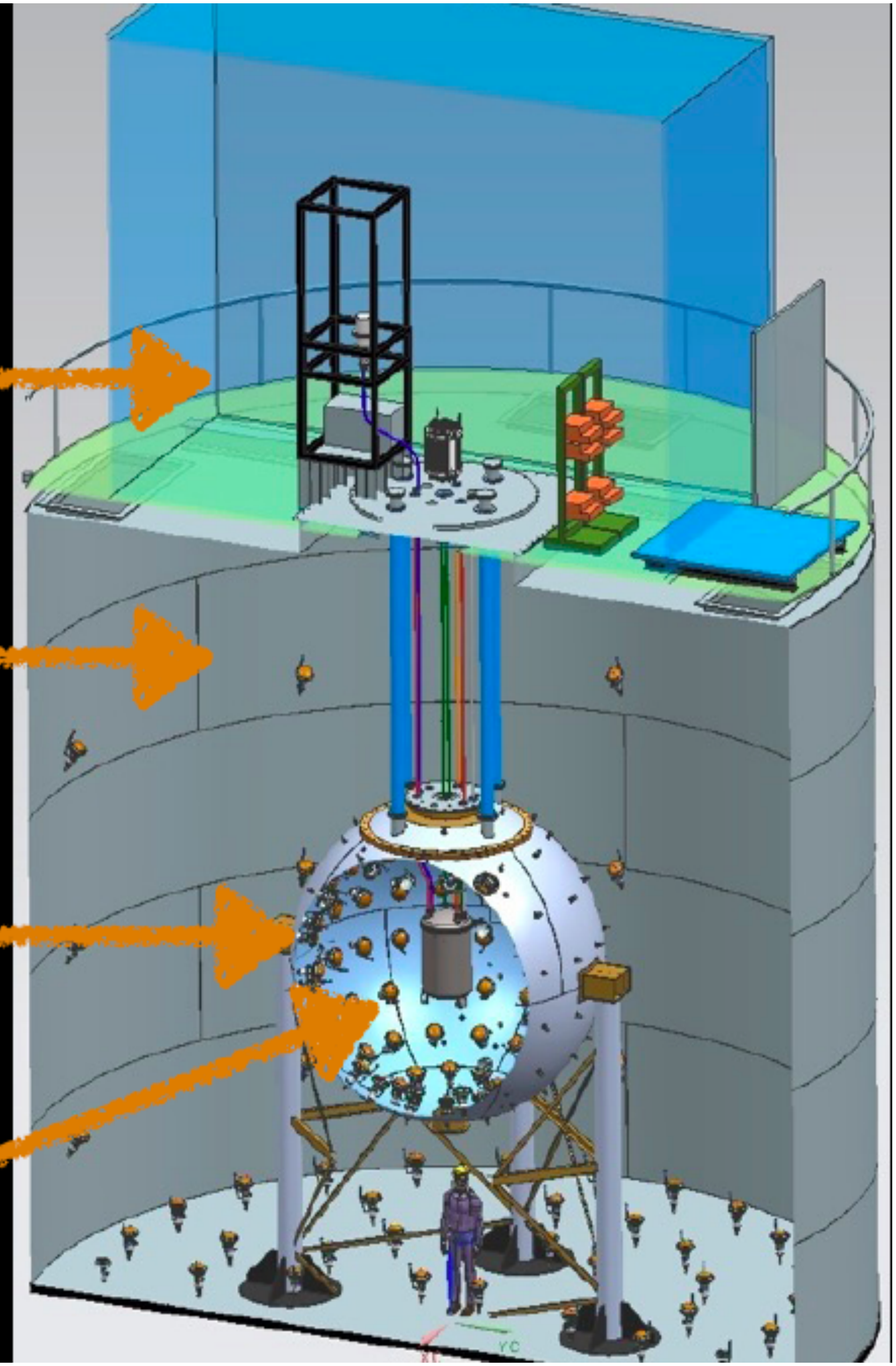
DarkSide 50

Radon-free Assembly
Clean Room

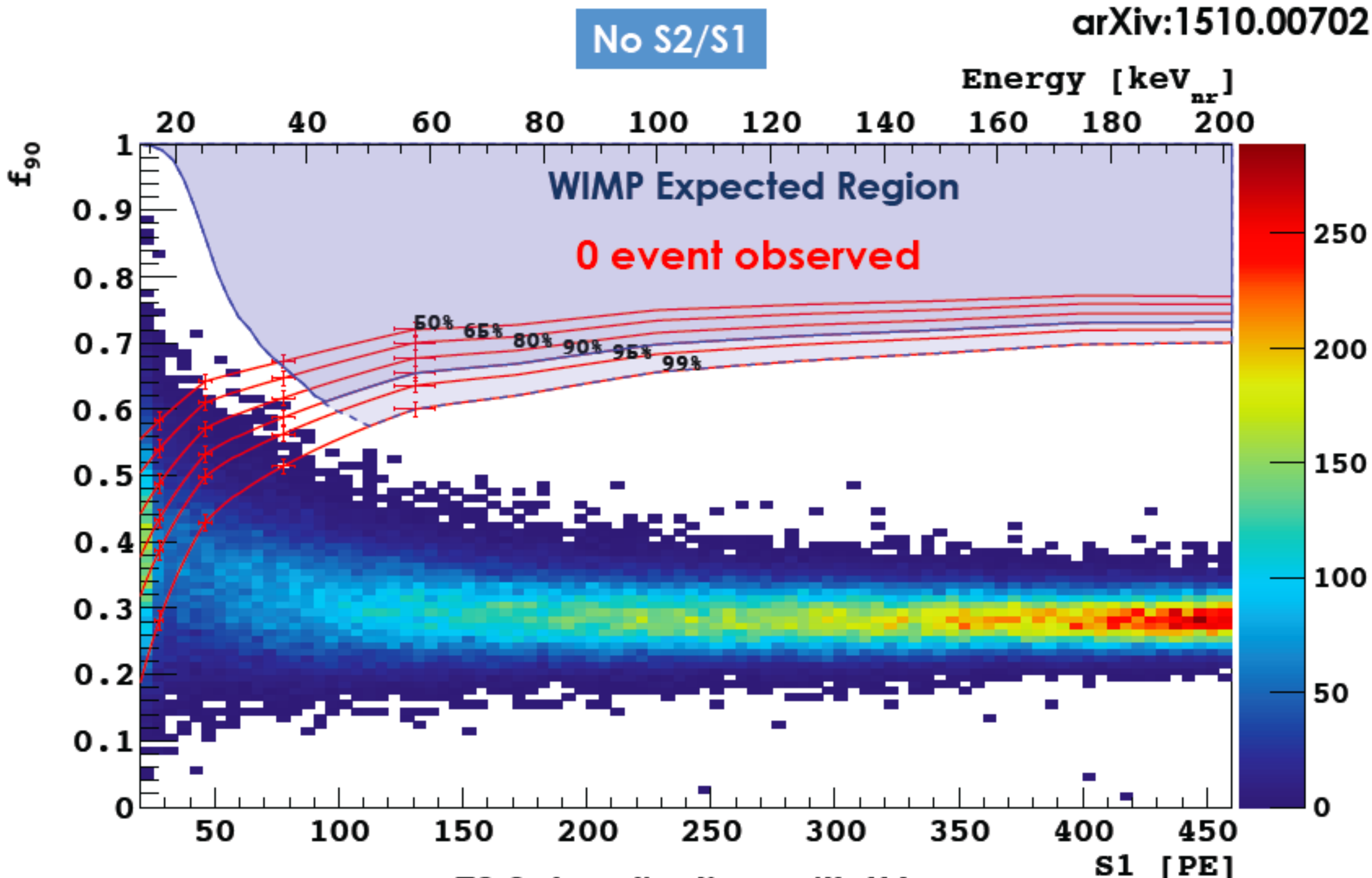
1,000-tonne Water-based
Cherenkov **Cosmic Ray Veto**

30-tonne Liquid Scintillator
Neutron and γ's Veto

Inner detector **TPC**

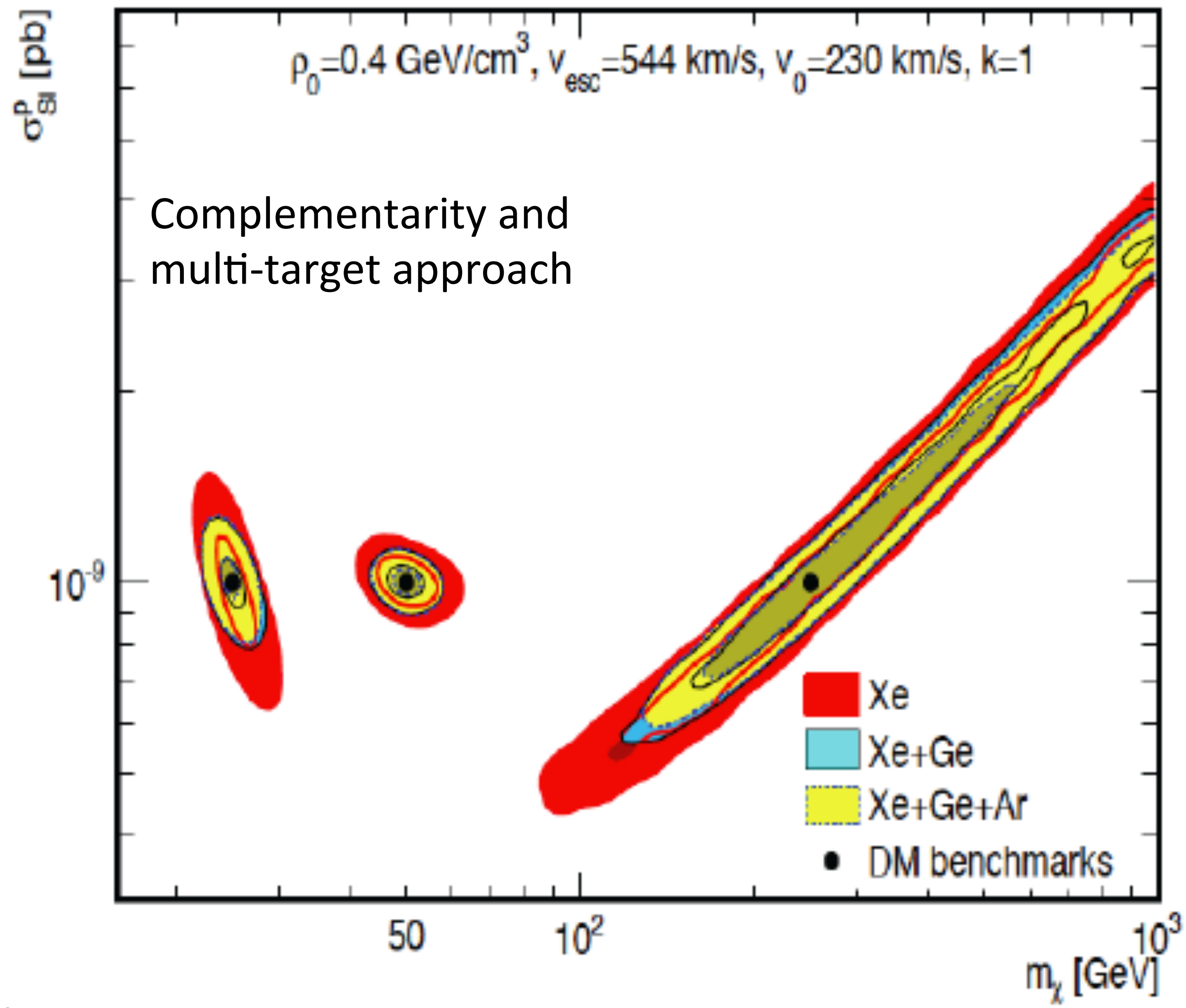


PSD in LAr TPC



70.9 days livetime with UAr

In case of discovery …



Pato et al., arXiv:1012.3458

Conclusions [1]

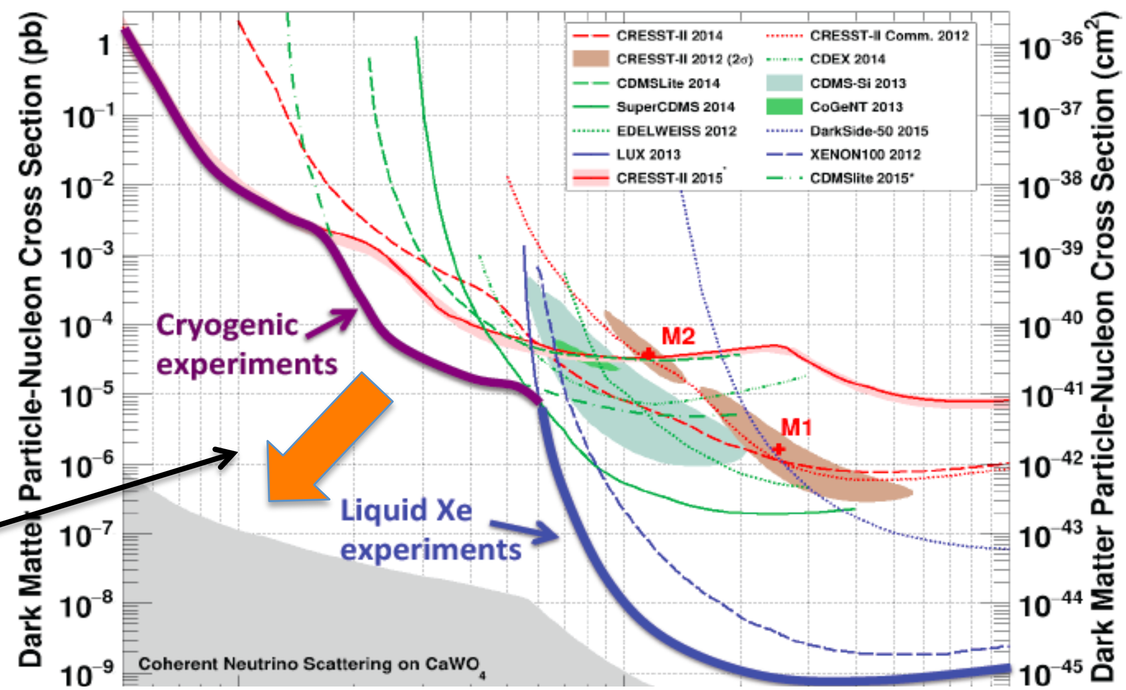
- We are searching in the "dark"
  - we do not know the interaction process
  - we do not know the interacting particle features
  - we use "guidelines" from our poor understanding of DM
- Recipe:
  - probe as much as possible the space of parameters
  - search for WIMPs and axions
  - Probe more target materials
- Ultimate goal:
  - establish particle nature of DM
  - determine properties of interaction to understand characteristics of DM particles

Conclusions [2]

- A huge effort underway on Direct Dark Matter search for Axions and WIMPs (mainly)
  - in 10 years sensitivity improved by a factor ~10^6
- Probe low mass
  - CRESST, SuperSDMS, CDEX, NEWS-SNOlab …
- Probe high mass
  - LXe, Lar
- Probe model intependent signatures (annual and diurnal)
- Reduce background with
  - Water Tank + LS veto (B-loaded or Gd-loaded)
- Null experiments not in agreement with positive and model independent observation (DAMA/LIBRA)
  - Efforts to test DAMA/LIBRA result underway

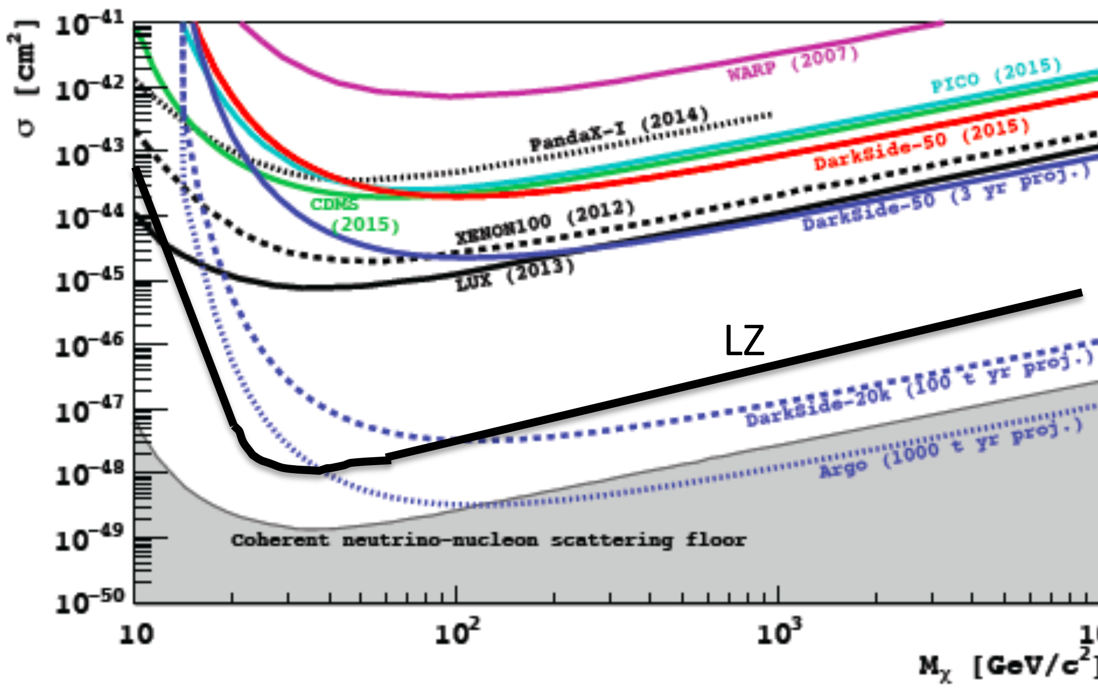
Perspectives in ~ 10 years time scale

Low WIMP masses



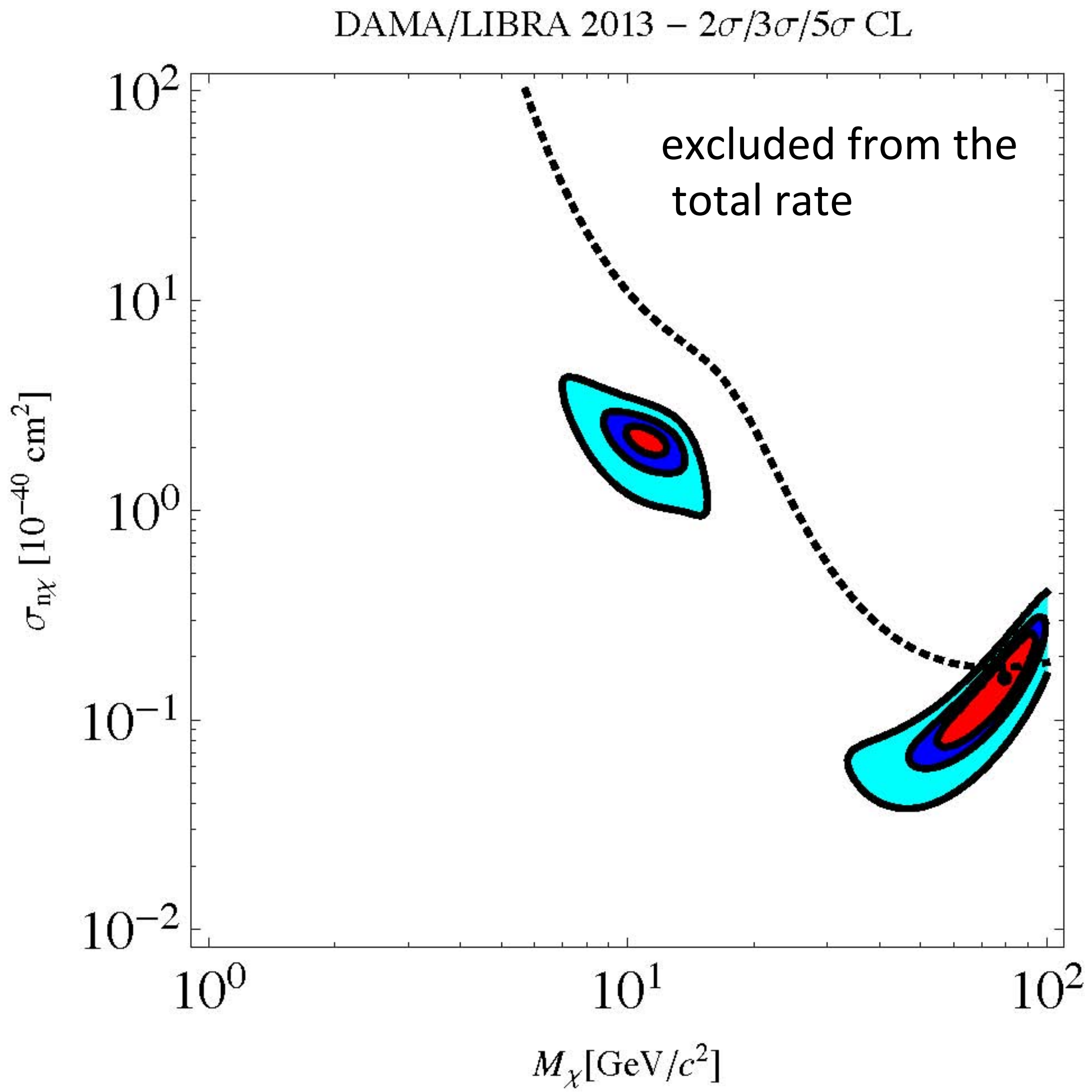
Improving detector performances (CRESST,SuperCDMS)

Large WIMP masses

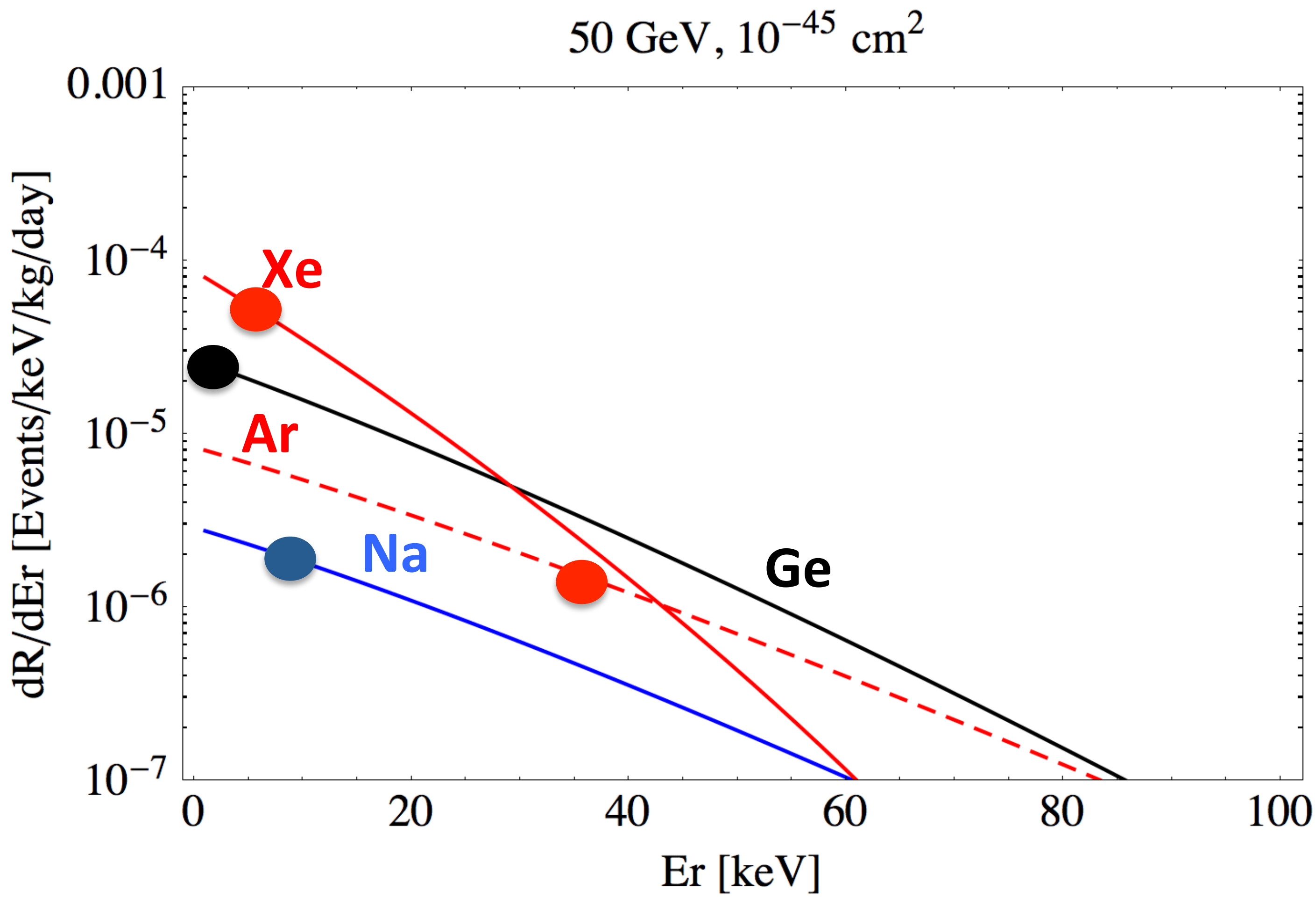


Thank you

DAMA/LIBRA fit for "standard" SI WIMPs

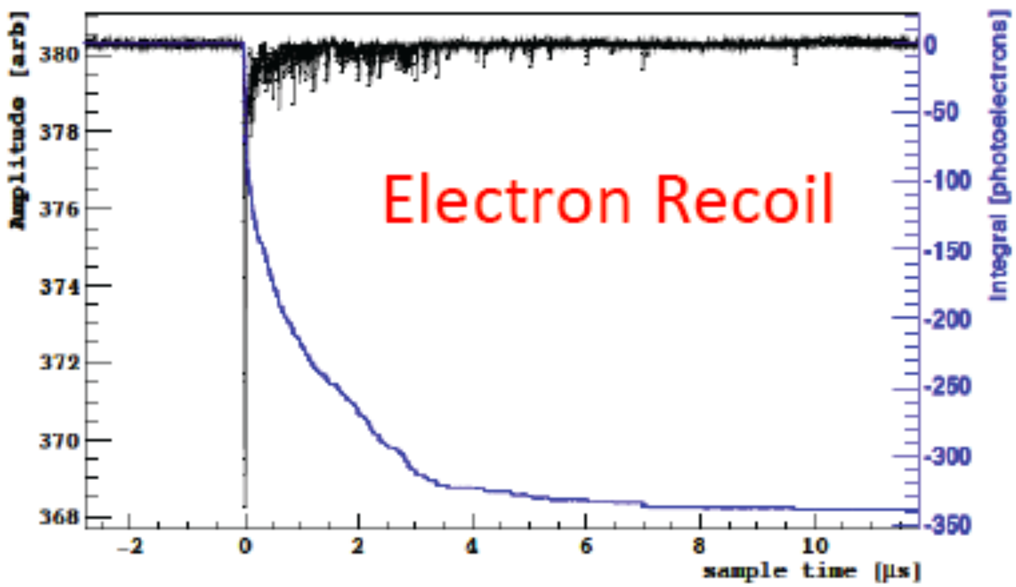


WIMPs Recoil Spectrum [1]



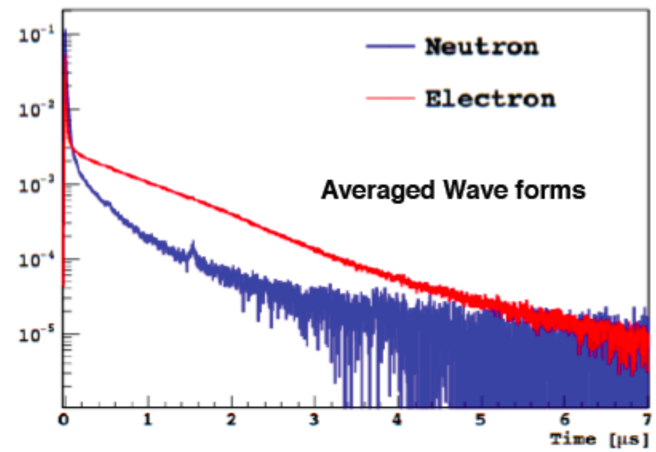
0.3 events/kg/year in Xe for 10^{-45} cm^2 and 50 GeV/c^2

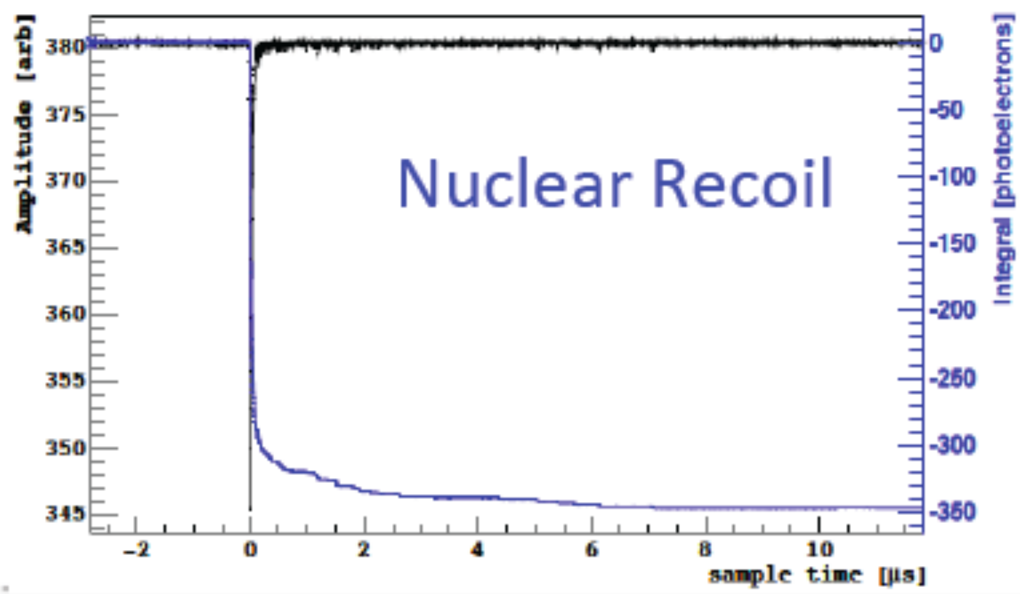
Pulse Shape Discrimination in LAr

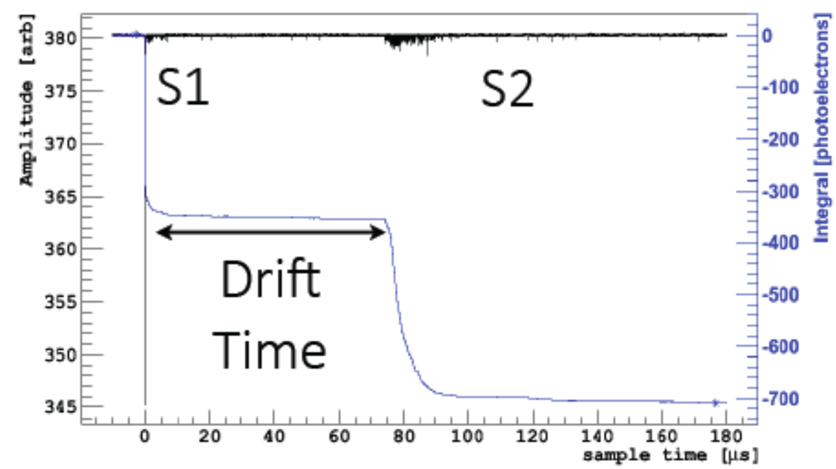


$\tau_{singlet} \sim 7$ ns

$\tau_{triplet} \sim 1500$ ns

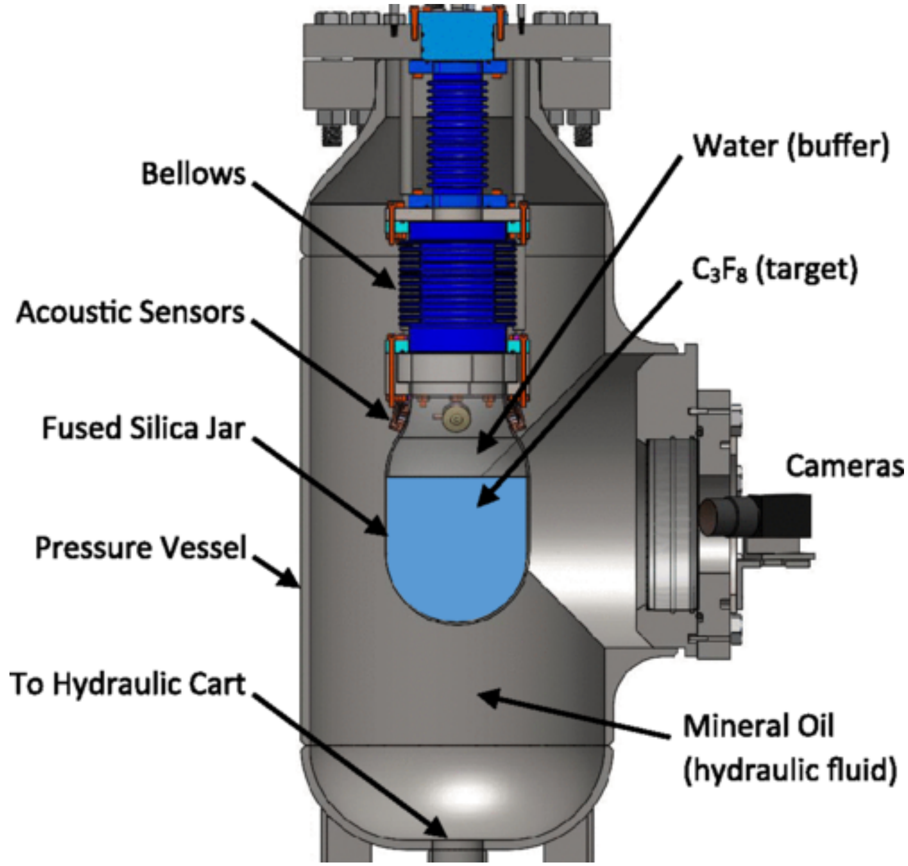






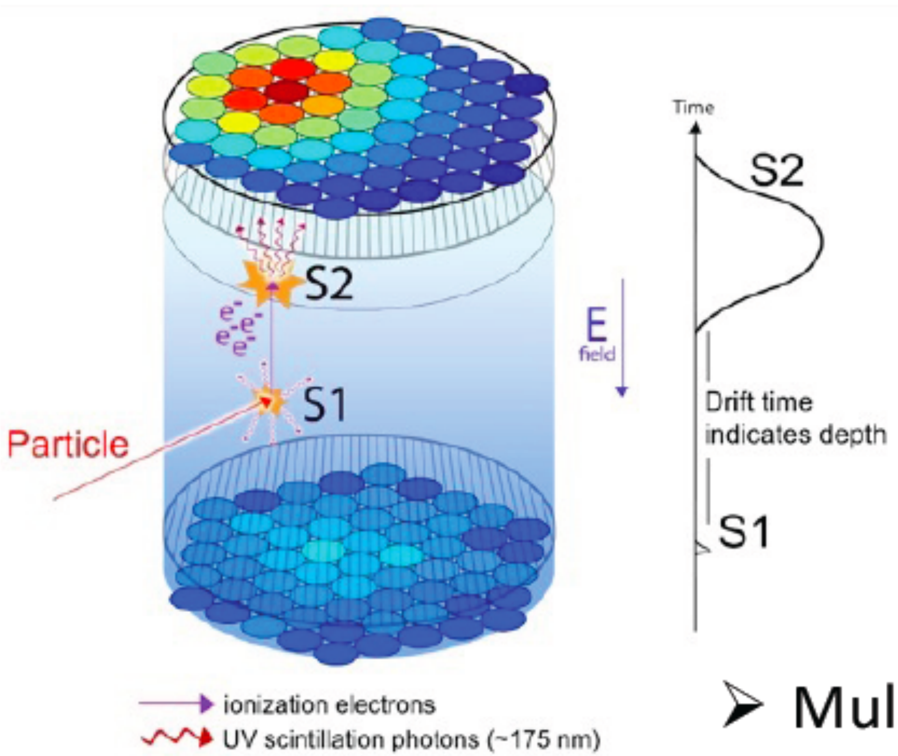
Bubble Chamber

- PICO at SNOlab
  - Fused silica vessel with acoustic sensors + CCD
  - Alpha vs NR discrimination by acoustic sensors
  - Operating a BC with 37kg of CF_3I and a BC with 3kg of C_3F_8
  - A 500kg detector in development
  - SD cross-section limit at 10^{-39} cm^2



- MOSCAB
  - Results from 0.5L prototype (done)
    - NR studied
    - MC simulation tuned
  - Developed 40 kg detector at Milano (done)
  - Install detector at LNGS: future

Two-phase LXe TPC



- Primary scintillation light ("S1") at the particle - Liquid Xe interaction vertex
- Electrons extracted from the interaction drifted by electric field to the surface and into the Gas Xe. Proportional scintillation light ("S2")

➢ Multiple scatter event identification (via S2)

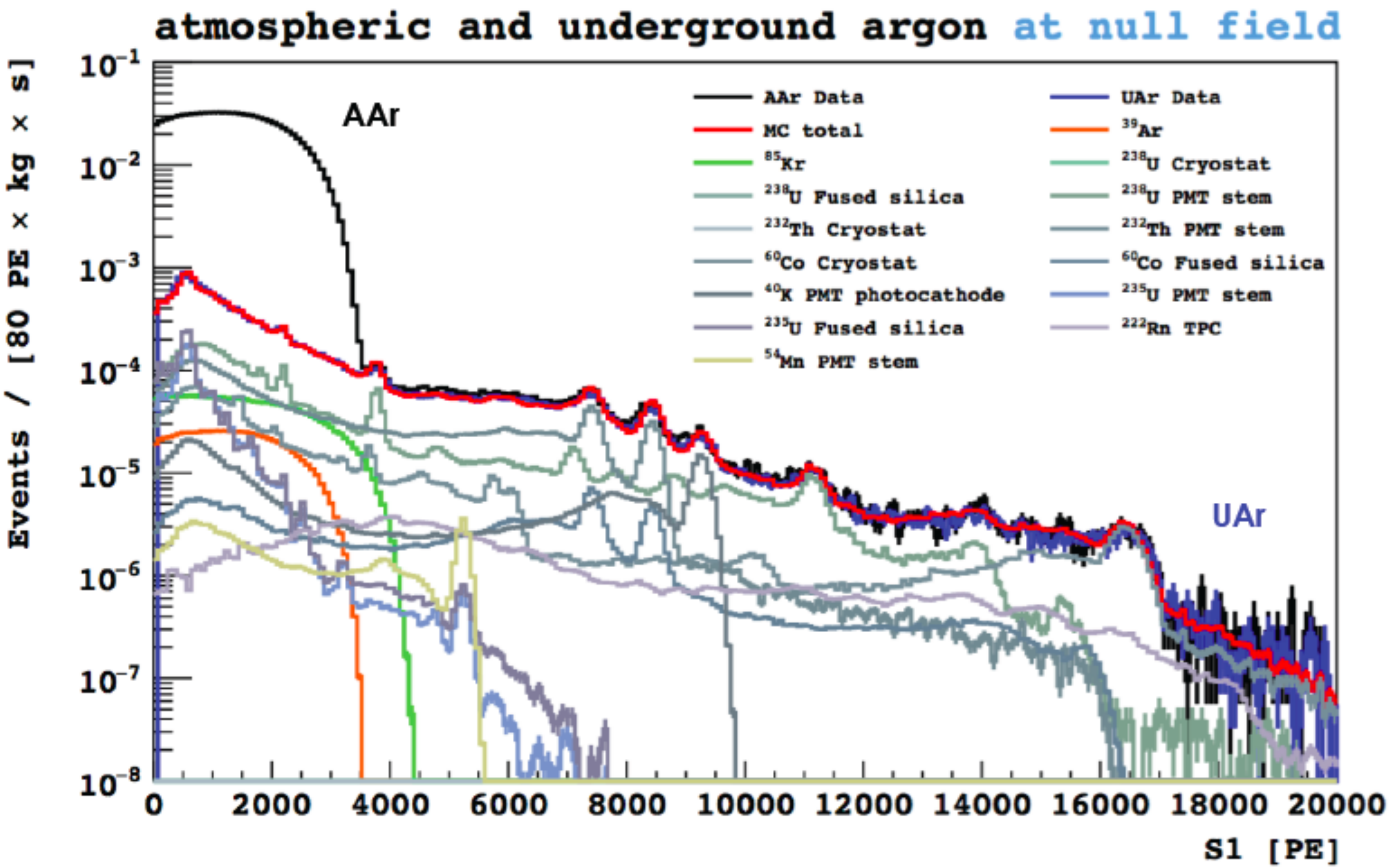
➢ 3-D localisation of each vertex (via S1 and S2)

➢ ER/NR discrimination (via S2/S1)

➢ Sensitivity to single electrons (S2)

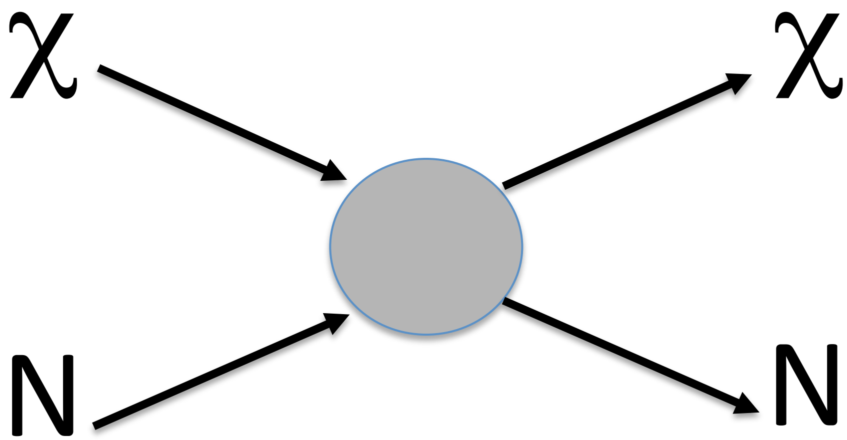
P. Beltrame

The Depleted Argon in DarkSide50



Direct Search for WIMPs: nuclear recoil tagging

Goodman and Witten, PRD31, 1985



$$E_{recoil} = \frac{m_N M_\chi^2}{(m_N + M_\chi)^2} v^2 (1 - \cos\theta^*)$$

$v \sim 300$ km/s $\beta \sim 10^{-3}$

$E_{recoil} \sim 1 - 100$ keV

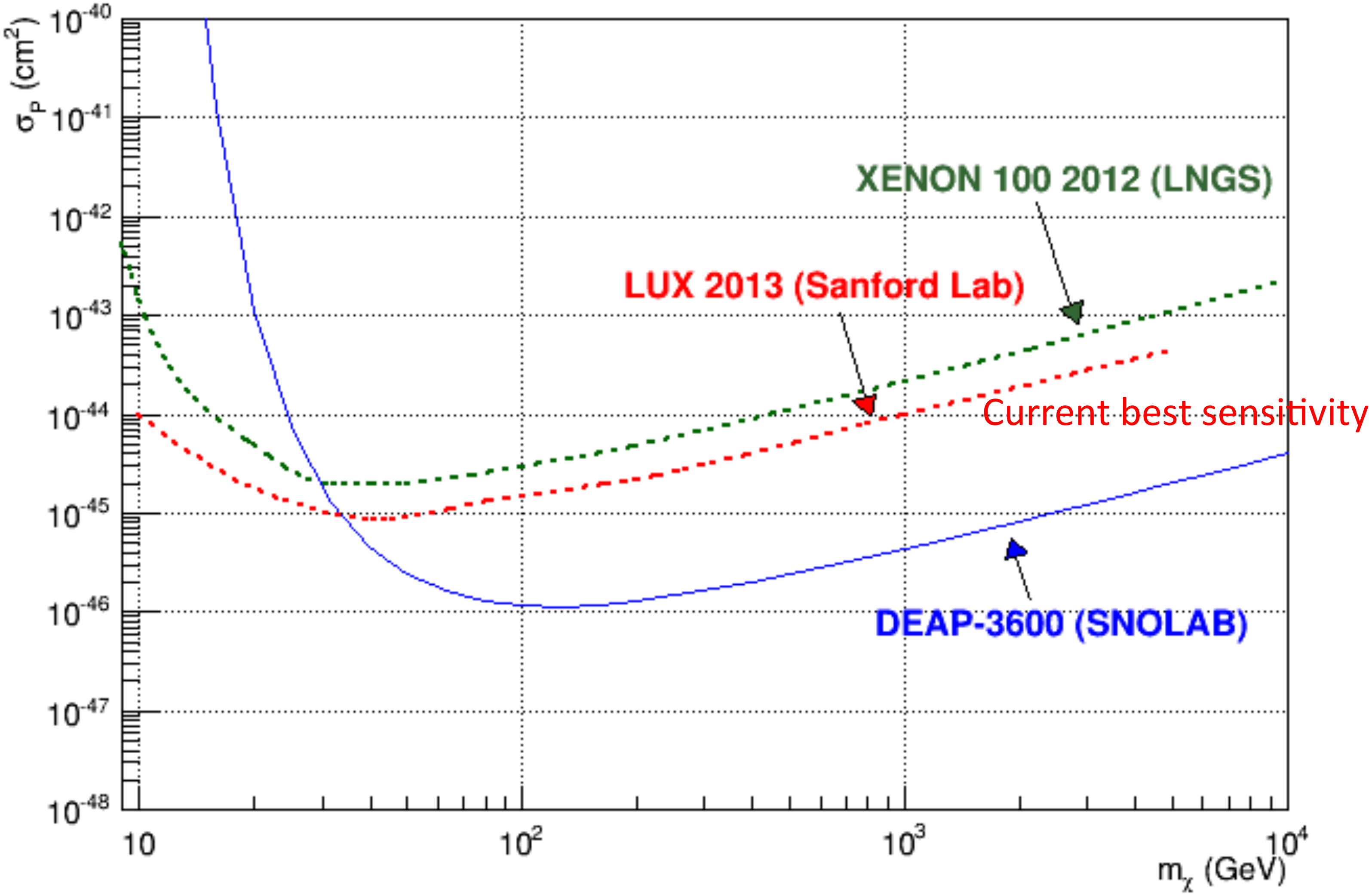
$$\frac{\lambda}{2\pi} = \frac{h}{p} = \frac{\hbar c}{mc^2 \beta} \approx \frac{197 \cdot 10^{-13}\,\text{MeVcm}}{100\text{GeV}\ 10^{-3}} \approx 2 \cdot 10^{-13}\,cm$$

$$\frac{dR}{dE} = N_t \frac{\rho_\chi}{m_\chi} \frac{m_N}{\mu_n^2} A^2 \sigma_{\chi n} F^2(E) \int_{v \geq v_{\min}(E)} d^3v \frac{f(v)}{v}$$

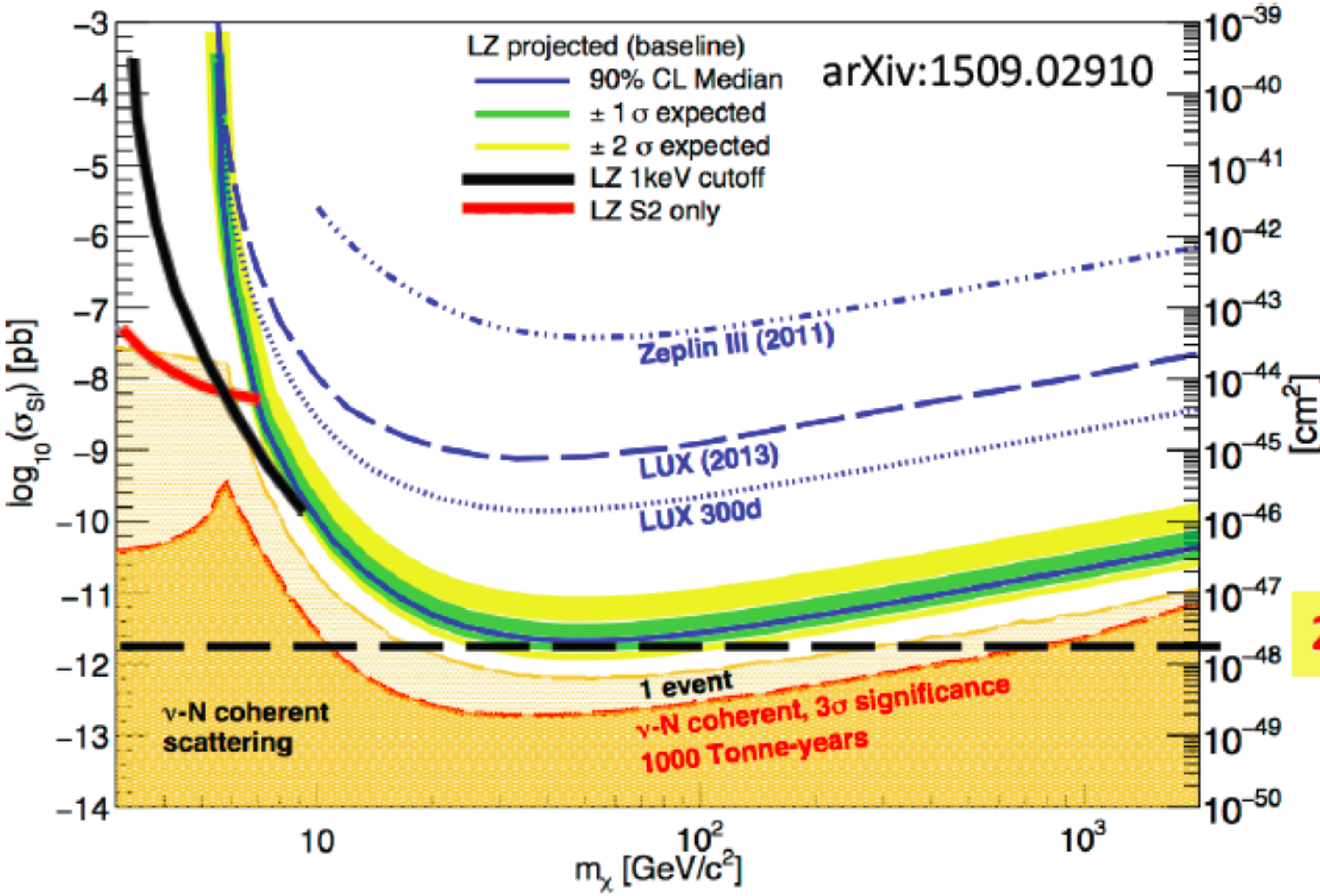
$$f(v) = \begin{cases} \frac{1}{N} e^{-\left(\frac{|v_\chi + v_{sun} + v_{Earth}|}{v_0}\right)^2}, & |v_\chi + v_{sun} + v_{Earth}| < v_{esc} \\ 0, & \text{elsewhere} \end{cases}$$

- 170 km/s < v_0 < 270 km/s
- 450 km/s < v_{esc} < 650 km/s
- ρ_χ ~ 0.3 Gev/cm^3
- F(E) = nuclear form factor
- f(v) = velocity distribution of WIMPs in the galaxy

DEAP-3600 Projected Physics Sensitivity

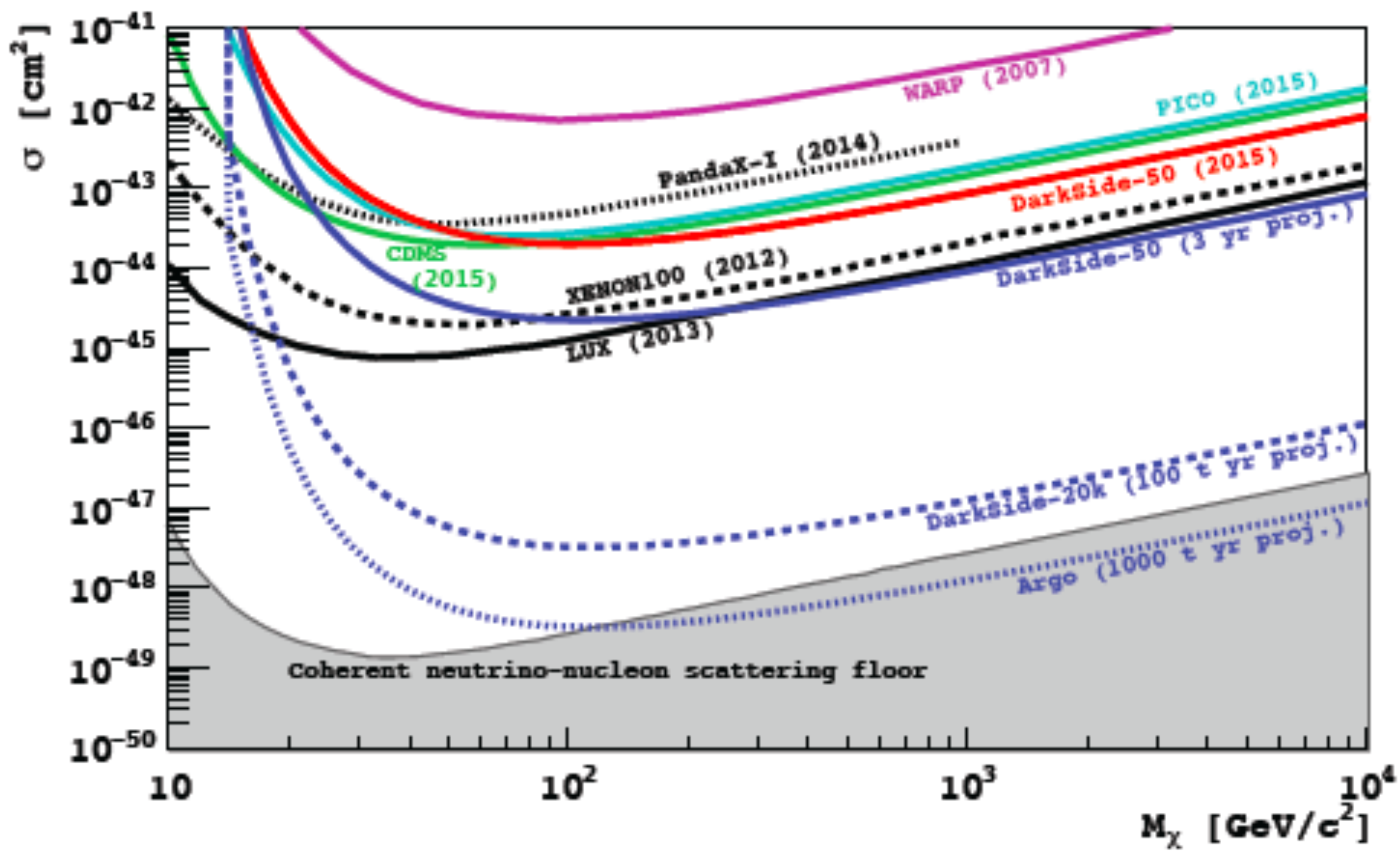


Ultimate goal with LXe



2×10^{-48} cm^2

Ultimate goal with LAr for DM



Summary of DM properties

- **DM evidence** based only on gravitational interaction
- Make up ~**85% of matter** in the Universe
- **DM could be made by unknown** particle(s)
  - WIMPs, axions, …
  - This paradigm shows some subtle points for simplest generic WIMPs
    - Discrepancy between N-body simulations and astrophysical observations at galaxy scale
- These particles are neutral and **gravitationally interacting**
  - Self interactions ??
  - Dissipative processes ??
- $\boldsymbol{\Omega_{DM} \sim 5\Omega_b\ (m_p\rho_{DM}/\rho_b \sim 5GeV/c^2)}$
  - Baryon density is asymmetric. What about DM density?
- **Cold** (p/m <<1 at CMB formation)
- **Stable** or very long lived (> 10^{10} years)

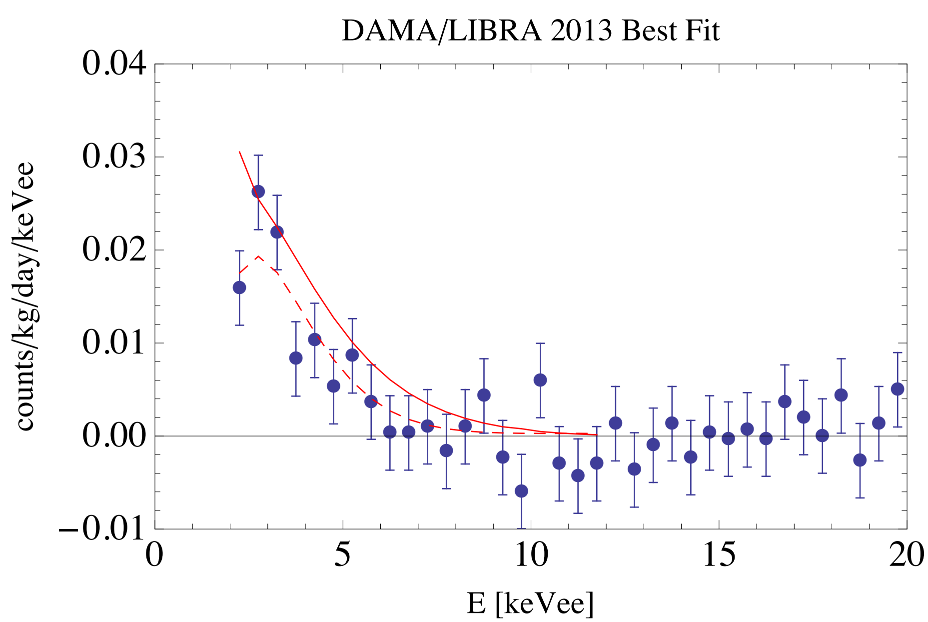
In brief: evidence of Dark Matter

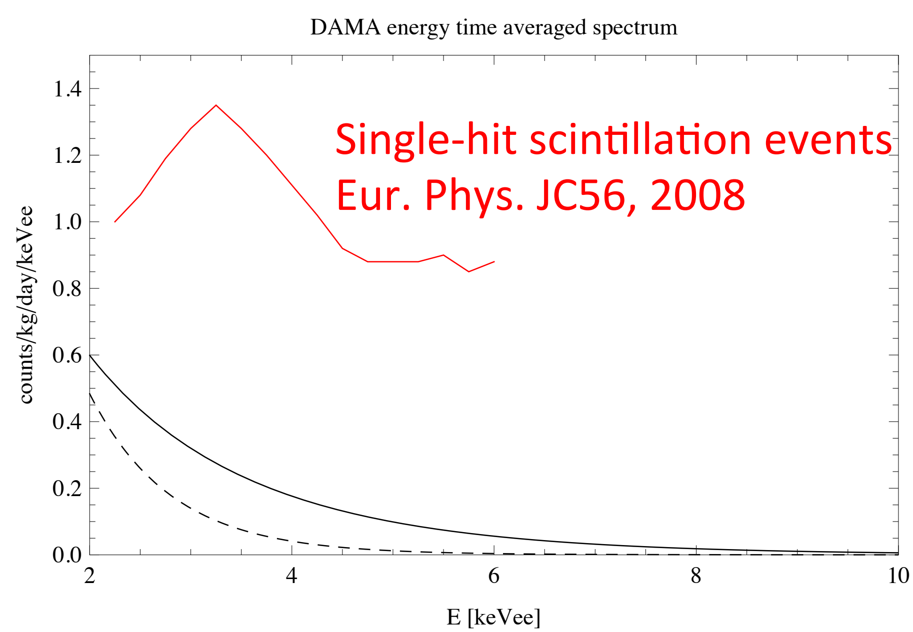
- Spiral galaxies **rotation curves**: $\Omega_{halo} \sim 10\Omega_{stars}$ **(Ω_{matter}>0.1)**
- **Clusters of galaxies**: Ω_{matter}**~0.2-0.3**
- **CMB anisotropy and BB nucleosynthesis**:

  Ω_{matter}**~0.27**, $\Omega_{baryons}$~0.04
  - **~85% of mass in the Universe dark and non-baryonic**
  - **$<\rho_{DM}> \sim 0.23\rho_{crit} \sim 10^{-6}$ GeV/cm^3**
  - around our Sun: $\rho_{DM\text{-}Sun}$ **~ 0.3-0.4 GeV/cm^3**
- **Large Scale Structures**:
  - Formation of structures by gravitational clustering support evidence of "cold" DM

DAMA/LIBRA: WIMPs fit

Target	LY [pe/keV]	Threshold ER [keVe]	Threshold NR [keVr]	σ/E
NaI(Tl)	5.5-7.5	2	6.7(Na) 22(I)	~7% at 60keV





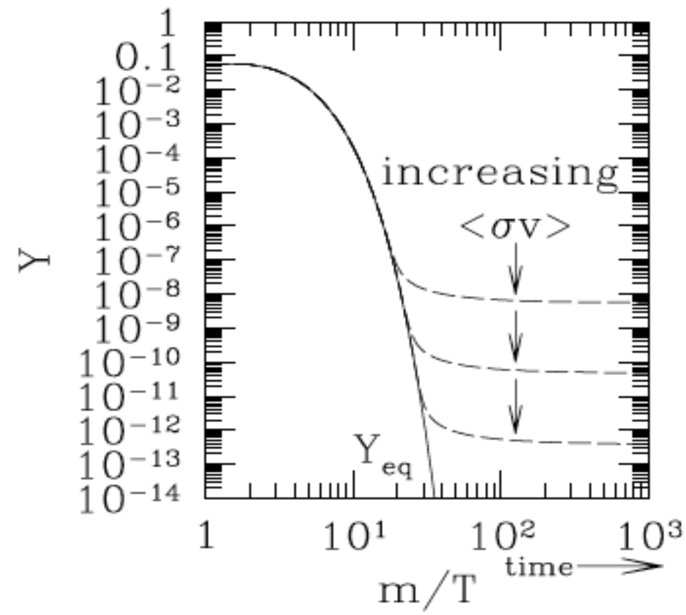
——— M_χ = 12 GeV/c^2 $\sigma_{\chi p}$ = 1.5×10^{-41} cm^2 χ^2/Ndof = 1.02

- - - - - M_χ = 8.6 GeV/c^2 $\sigma_{\chi p}$ = 1.9×10^{-41} cm^2 χ^2/Ndof = 1.69

WIMPs

- A general class of weakly interacting massive (1GeV – 10 TeV) particles not from the Standard Model

- Assuming thermal equilibrium in the early Universe and non-relativistic decoupling, the energy density for these relic particles is predicted to be:
  - **$\Omega_\chi \sim 0.2$ for $\sigma \sim 10^{-36}$cm^2**



Technologies

- **Cryogenic solid state**
  - Ionization spectrometer + bolometer operated at < 100mK
  - CDMS(Si and Ge); CRESST(Ca); EDELWEISS(Ge)
- **Two-phase TPC with LXe** (XENON100, LUX) **or LAr** (DarkSide, ArDM)
  - Scintillation + ionization
- **Superheated liquid**
  - Nuclear recoil induce bubble nucleation
  - Mainly with F for SD
- **Scintillator crystal detectors**
  - DAMA/LIBRA (NaI), CoGeNT (Ge), KIMS(CsI), XMASS(LXe), DEAP(LAr)
- **Spherical gas TPC**
  - Use H, He, Ne

WIMPs signal and background

- **Signal**
  - Low energy nuclear recoils (1 – 100 keV)
  - Low rate (~ few counts/year/ton at 10^{-47} cm^2)
  - No specific features in recoils spectrum

- **Background**
  - Electron Recoils (**ER**) from e, γ radioactivity
    - ✓ can be rejected by a number of discrimination cuts
  - Nuclear Recoils (**NR**) from **radiogenic and cosmogenic neutrons**
  - **Solar/Atmospheric neutrinos**:
    - ✓ Elastic Scattering interactions will limit the sensitivity depending on the ER rejection power of the experiment
    - ✓ Neutrino-nucleus coherent interactions set the limiting sensitivity

DM as Axion-like Particle

- $m_a \sim 6\times10^{-6}$ eV $(10^{12}\,\mathrm{GeV}/f_a)$
- Axions are effectively collisionless
- A non-relativistic population of axions can be present to match DM energy density
- For $m_a = 10^{-4}$ eV the number density of axions $\sim 3 \times 10^{14}\ \mathrm{m}^{-3}$
- Mass range for **Axion Cold DM**: $\sim10^{-5}$ eV
  - $\Omega_a \sim (10^{-5}\ \mathrm{eV}/m_a)^{7/6}$
  - $v/c \sim 10^{-3}$

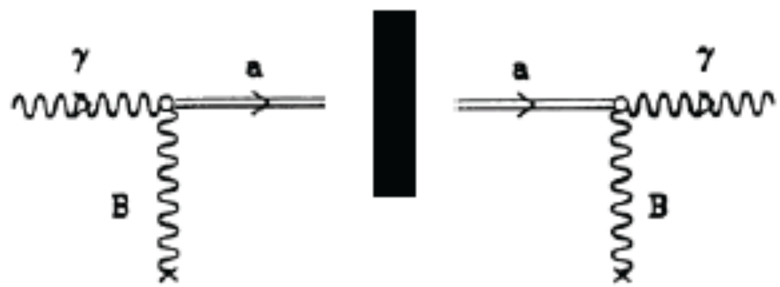
"Standard" Direct Axions Searches

Searching for axions and ALPs

- **Haloscope**: Axion DM eXperiment (ADMX)
  - resonant conversion of axion to photons in a microwaves cavity permeated by a strong magnetic field (B = 8 Tesla)
  - Enhancement when photon's frequency corresponds to cavity's resonant frequency's, Q ~ 10^6 [Sikivie, PRL 51, 1415, 1983]

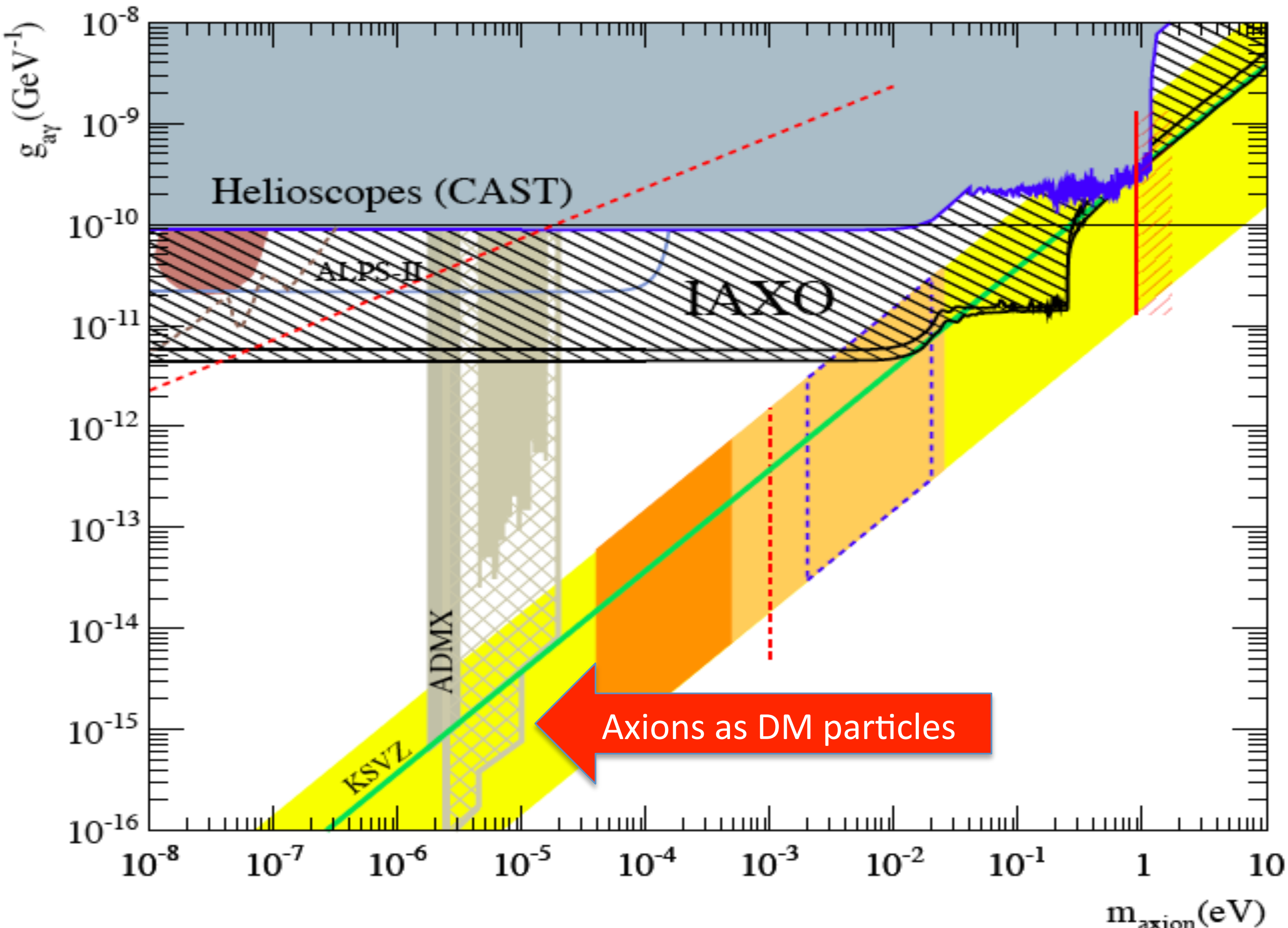
$$h\nu = m_a c^2 \left(1 + \frac{1}{2}\beta^2\right)$$

- **Helioscope**: CAST (2003 – 2015) -> IAXO
- **Photon regenerations**:
  OSQAR, ALPs-II

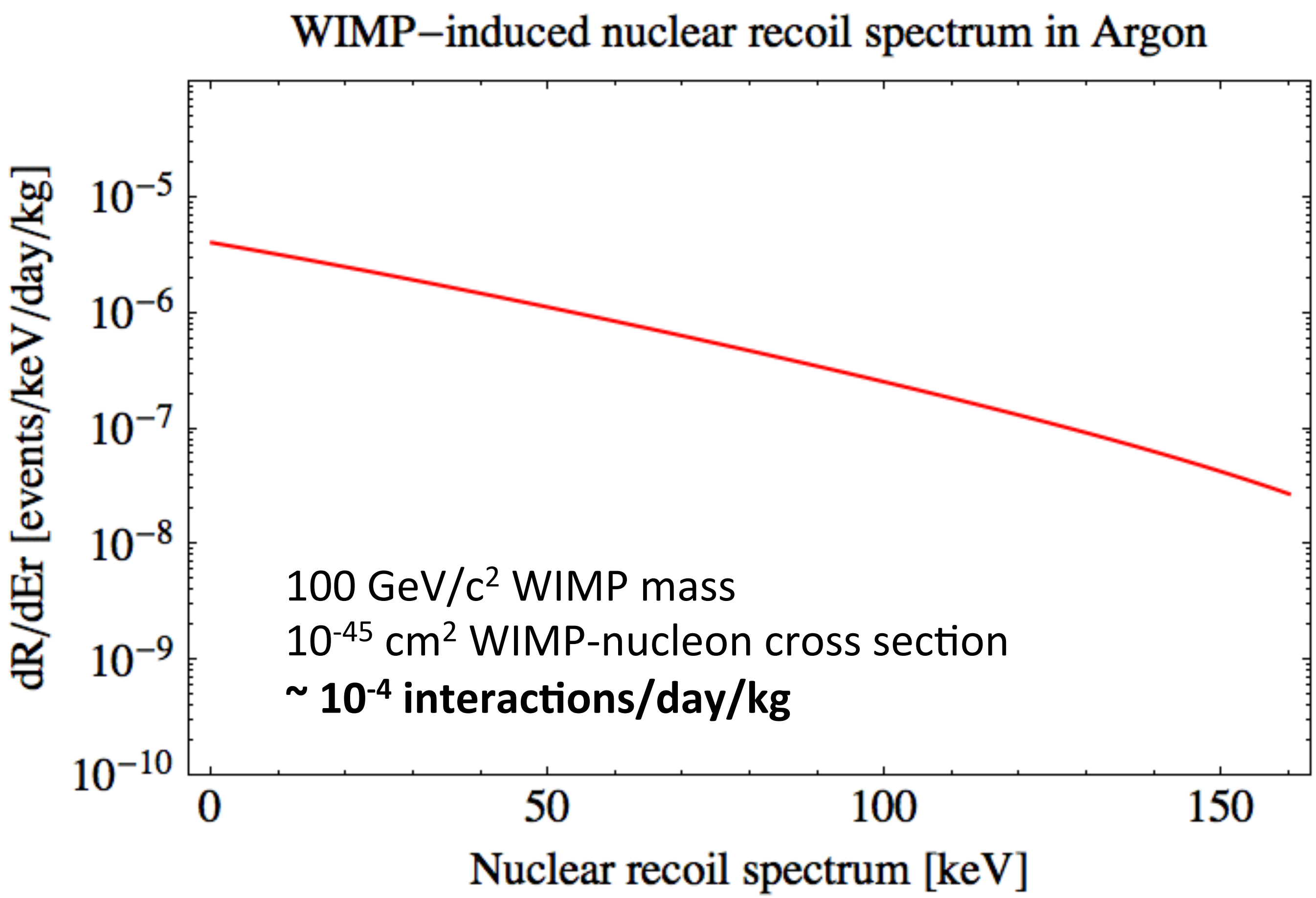


$$P(\gamma \rightarrow a \rightarrow \gamma) \propto \left(g_{a\gamma} BL\right)^4 \left|F(q)\right|^4$$

Axions searches: sensitivities



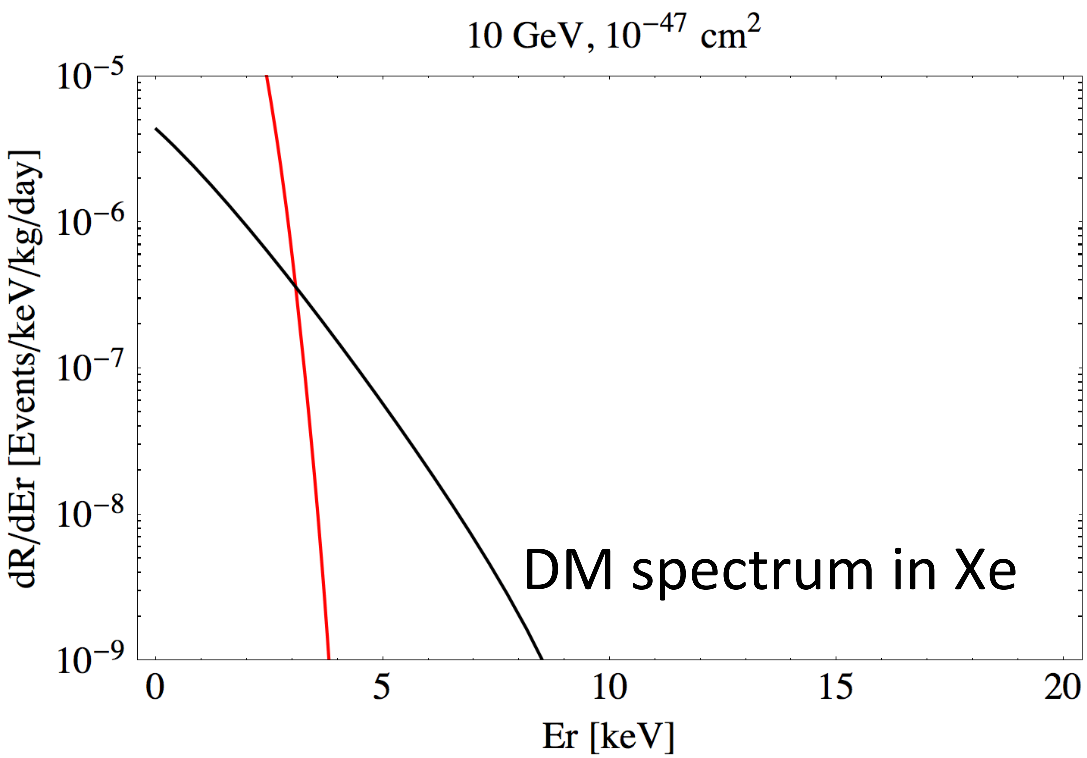
Expected WIMPs Signal in LAr



Exposure of 1 ton-year gives about 40 events with these assumptions
Exposure of 50 kg x 3 years gives about 5 events

Solar Neutrinos Background in the NR channel

- ν-nucleus coherent scattering
  - Maximum recoil energy for ^8B neutrinos = 4.3 keV
  - Flux of $^8B \sim 6\times10^6$ $cm^{-2}s^{-1}$



Liquified noble gases as WIMPs target

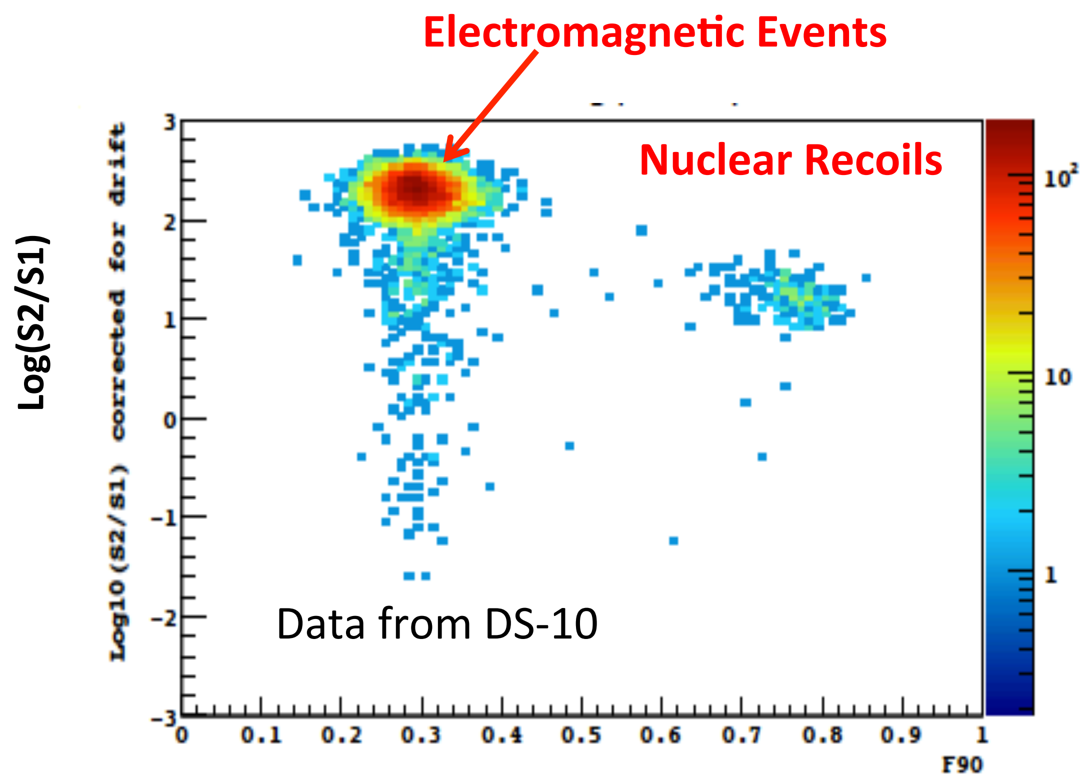
	Ar	Xe	Ne
Atomic number	18	54	10
Mean atomic mass	40	131.3	20.2
Melting point @ 1atm [K]	83.8	161.4	24.6
Density for liquid [g/cm^3]	1.40	2.94	1.21
Volume fraction in atmosphere [ppm]	9340	0.09	18.2
Scintillation λ [nm]	128	178	78
Scint. fast component [ns]	7	3	
Scint. Slow component [ns]	1600	27	

Two-phase TPC at Work: figure-of-merit for background discrimination

Background reduction performed by exploiting

a) Pulse shape of S1 through a parameter which measures the fraction of fast to slow component in scintillation.
F90 = Int_S1(<90ns) / Int_S1(all)

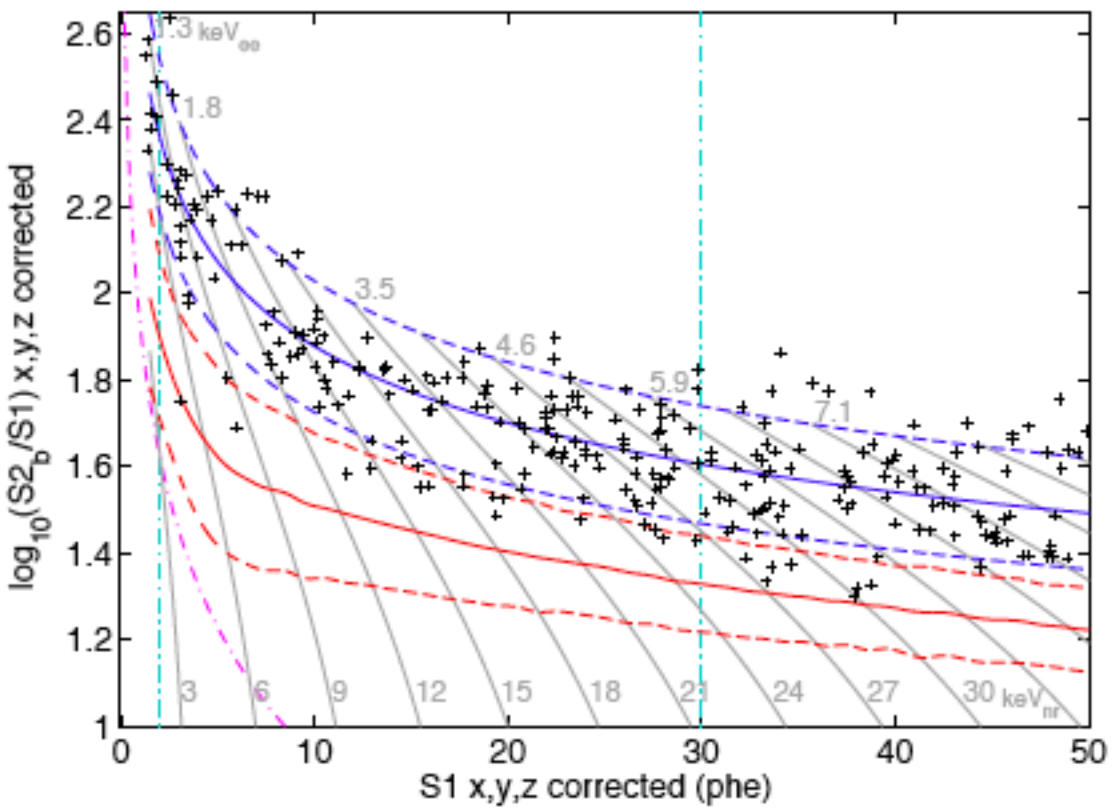
b) S2/S1: larger for e-like



LUX 2013 results

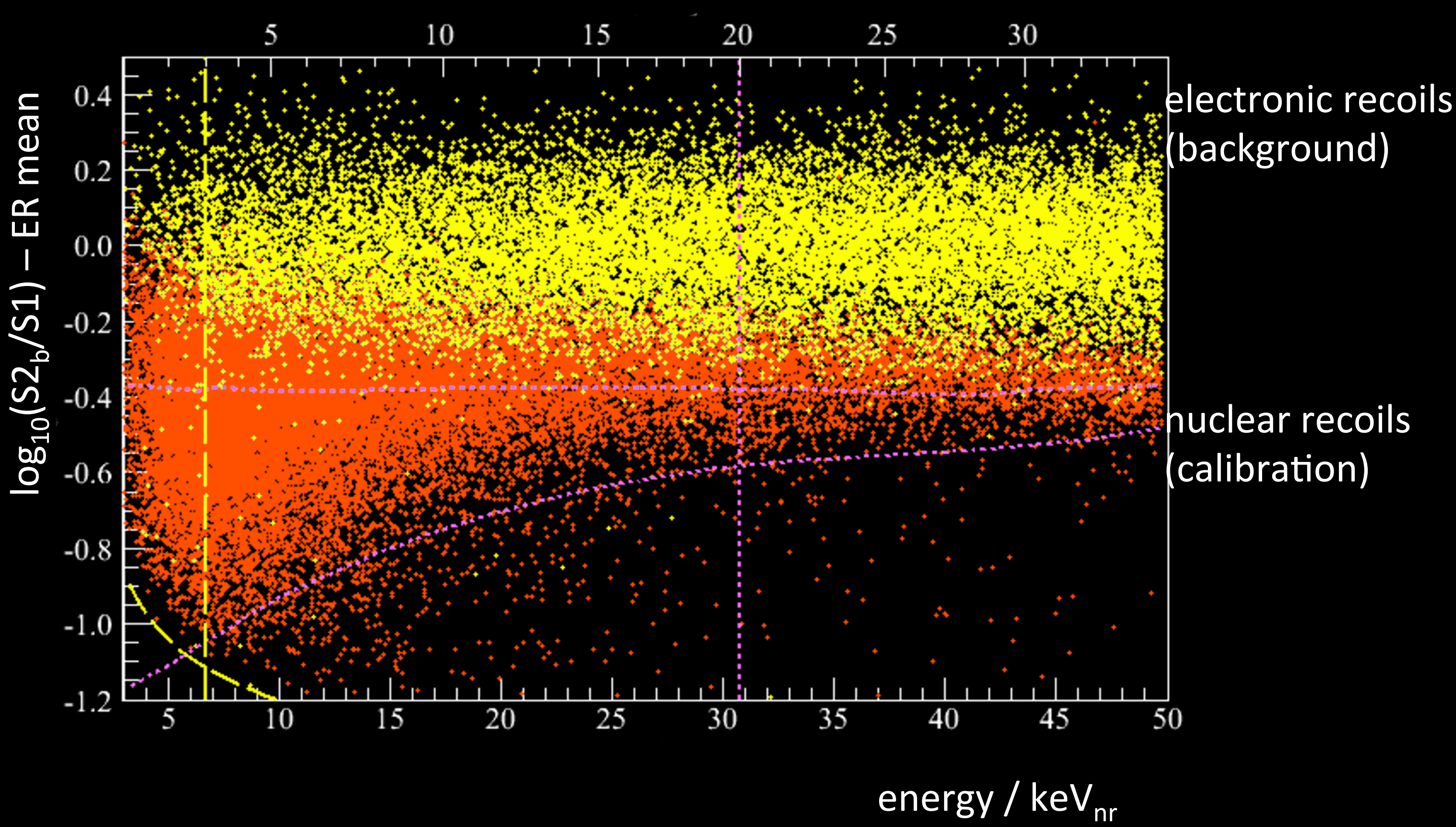
- 118 kg and 85.3 days

No events observed with 50% NR acceptance and 0.64±0.16 events of ER background



Discrimination using S2/S1 in XENON100

^{60}Co, ^{232}Th and $^{241}AmBe$ calibration



99.5% ER rejection @ 50% NR acceptance

KIMS-CsI

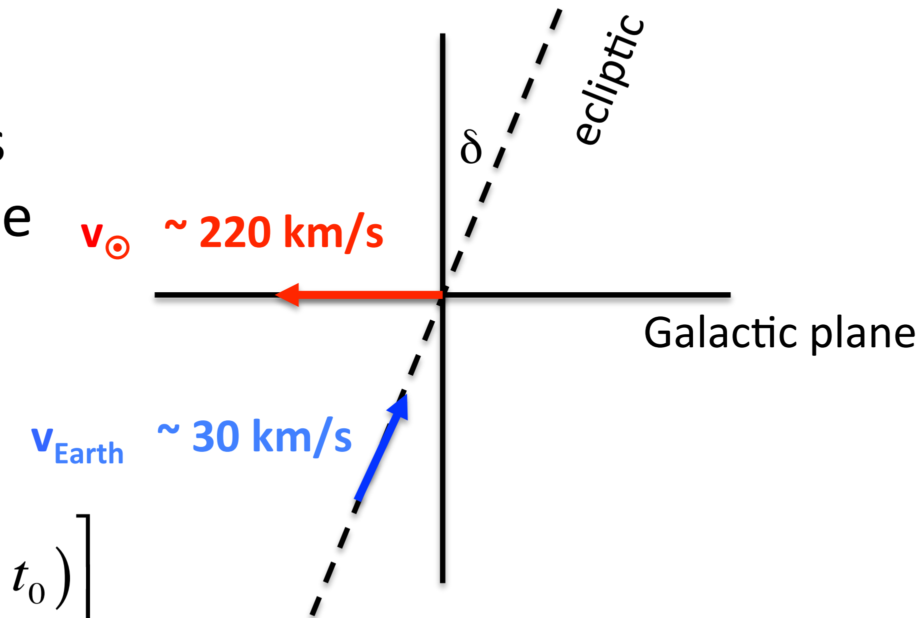
- Korea Underground Lab.

- 12 crystals of CsI – 104.4 kg
  - Thereshold 1.5 keV
  - Background ~ 2 cpd/keV/kg
  - 2.5 years of data
  - PSD cut applied

- Result: mean amplitude in 3-6 keV is 0.008 ± 0.068 cpd/keV/kg

Annual Modulation of WIMP interaction rate

The WIMPs interaction rate is oscillating during one year due to the relative motion of the Sun with respect to the halo reference frame



$$v_\chi(t) = v_{sun} + v_{earth} \sin\delta \cos\left[\frac{2\pi}{T}(t - t_0)\right]$$

$$v_\chi(t) \sim 220 + 15\cos\left[\frac{2\pi}{365}(t - 153)\right] \text{ km/s}$$

$$R(E_r, t) = R_0(E_r) + R_1(E_r)\cos\left[\frac{2\pi}{365}(t - 153)\right]$$

Expected modulation (at **% level**) of

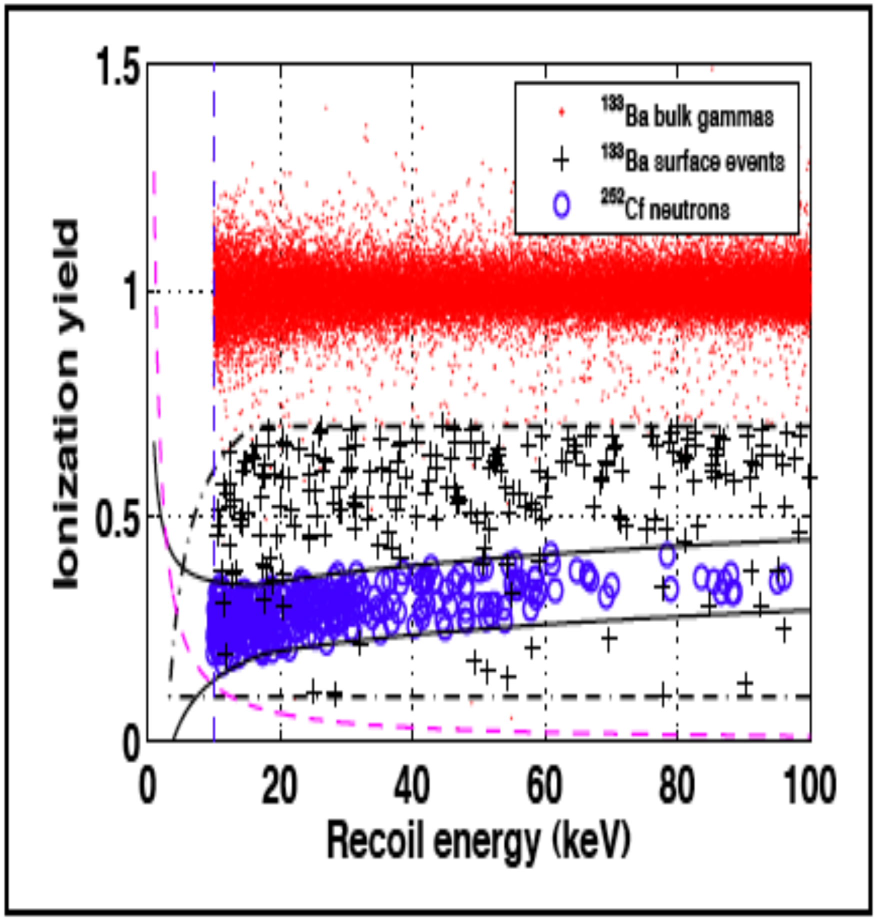
1. rate
2. spectral shape

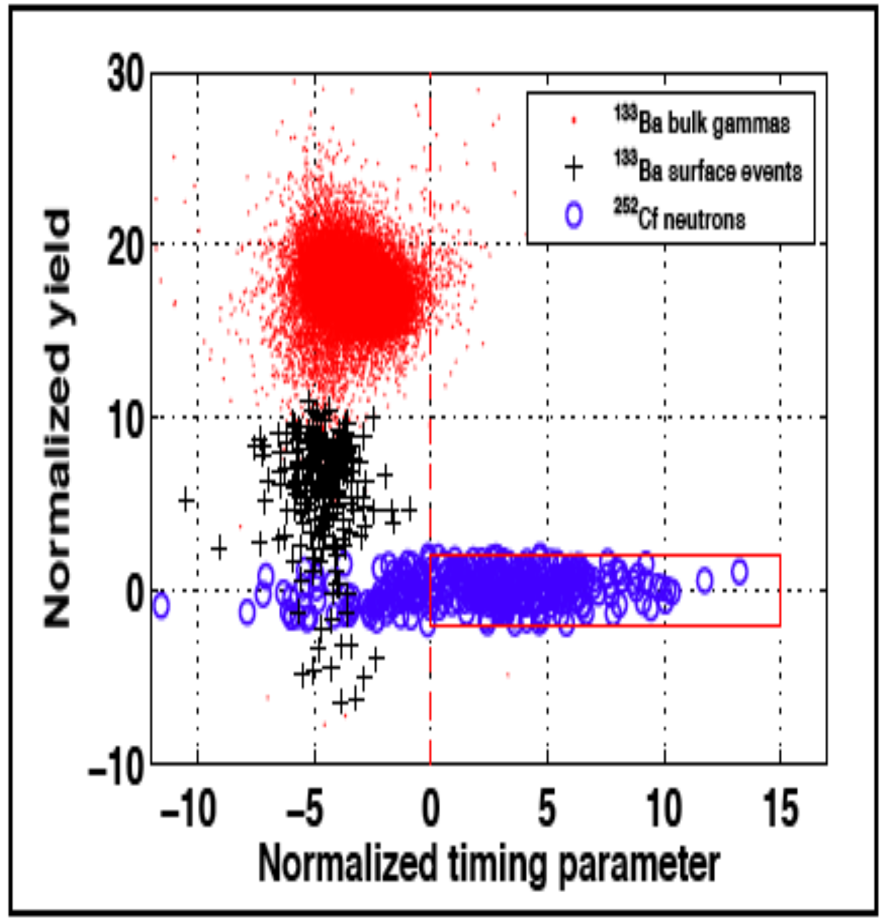
This is a **model independent signature**

CDMS II

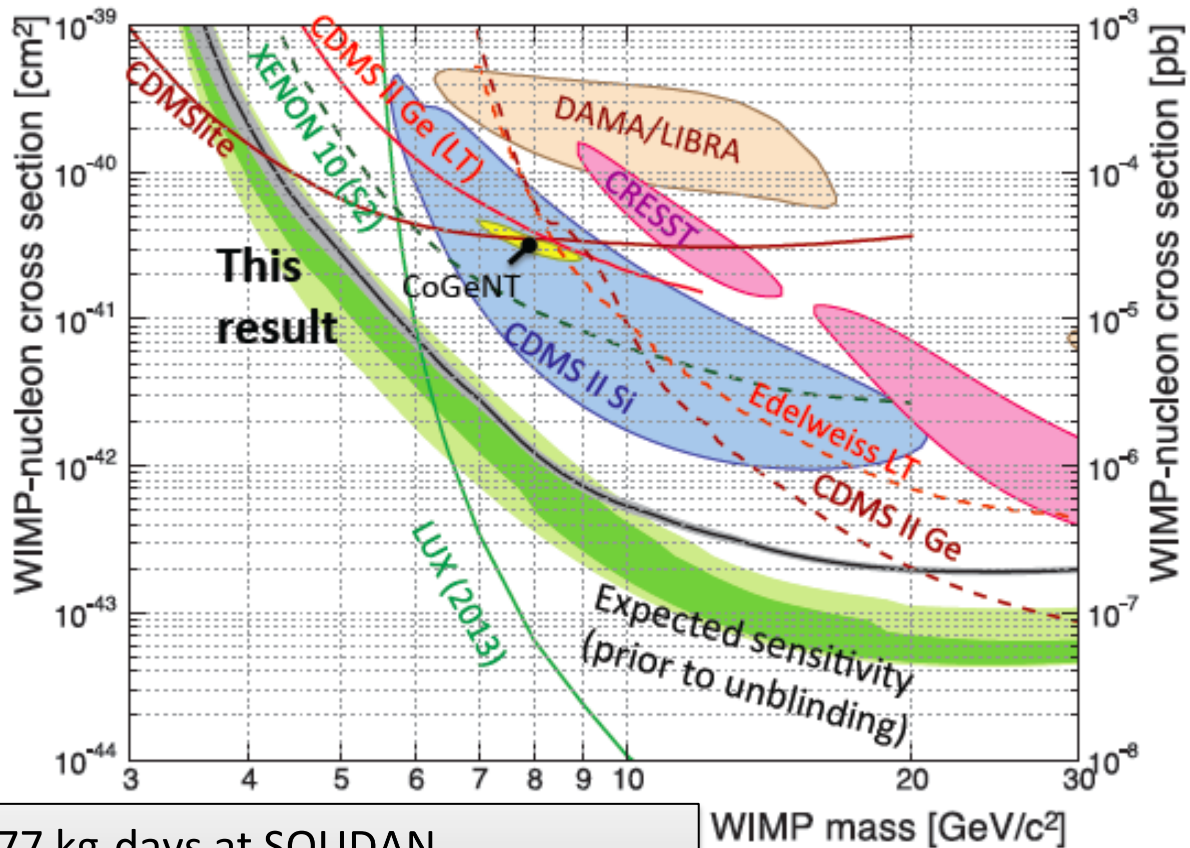
- 30 detectors (19 Ge, 11 Si) in Soudan Underground Lab (4.6 kg Ge + 1.2 kg Si)
- Data taking finished, moving to SuperCDMS (260 kg Ge array @ SNOlab)
- Measures ionization and phonons (TES read-out)
- Discrimination
  - NR yield ~ 0.3
  - ER yield ~ 1
  - Surface events rejected by timing properties of phonon and charge pulses

CDMS II Discrimination





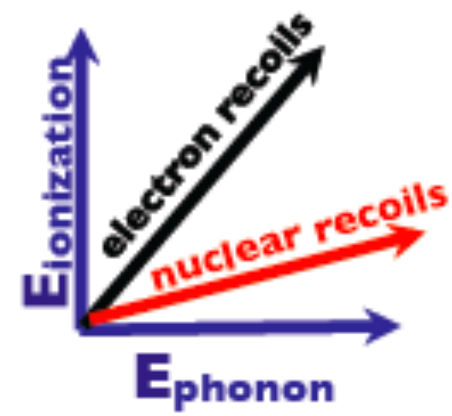
SuperCDMS: SI constraint at low mass



11 candidates seen

Expected backg. = $6.6^{+1.1}_{-0.8}$

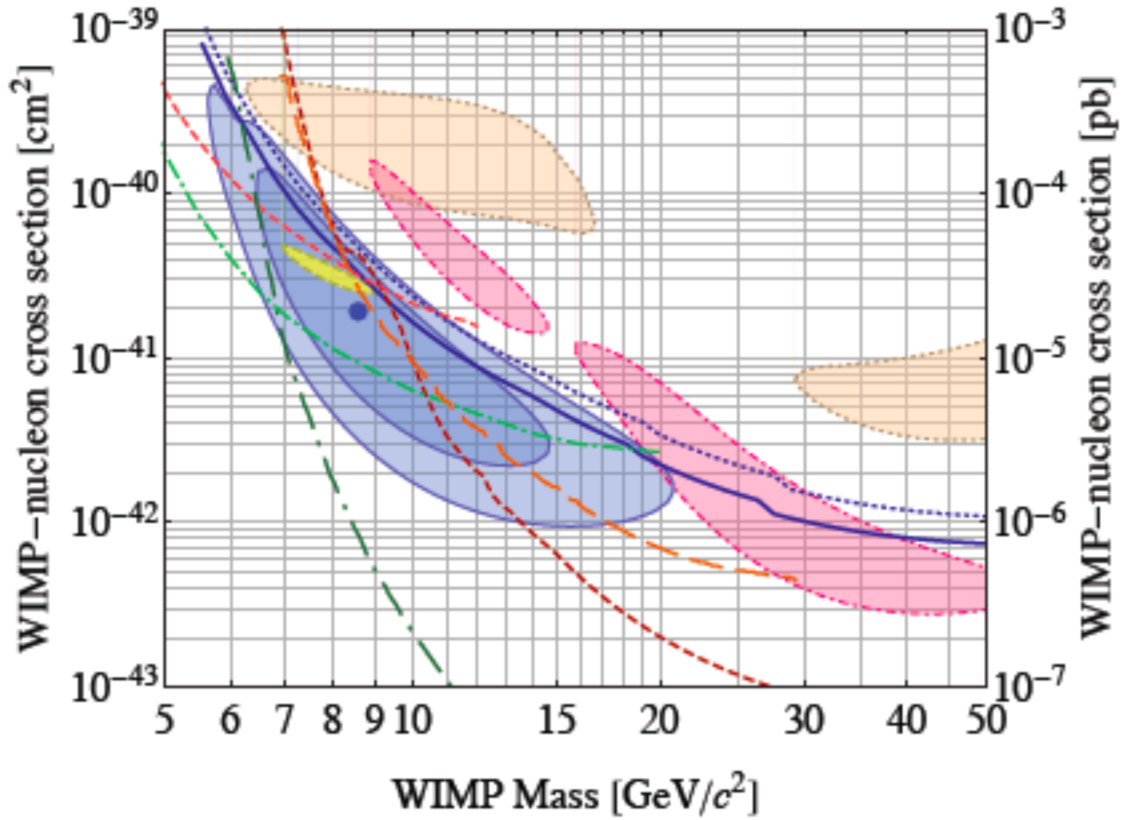
Feldman-Cousin gives a 90% CL upper limit at 11.2



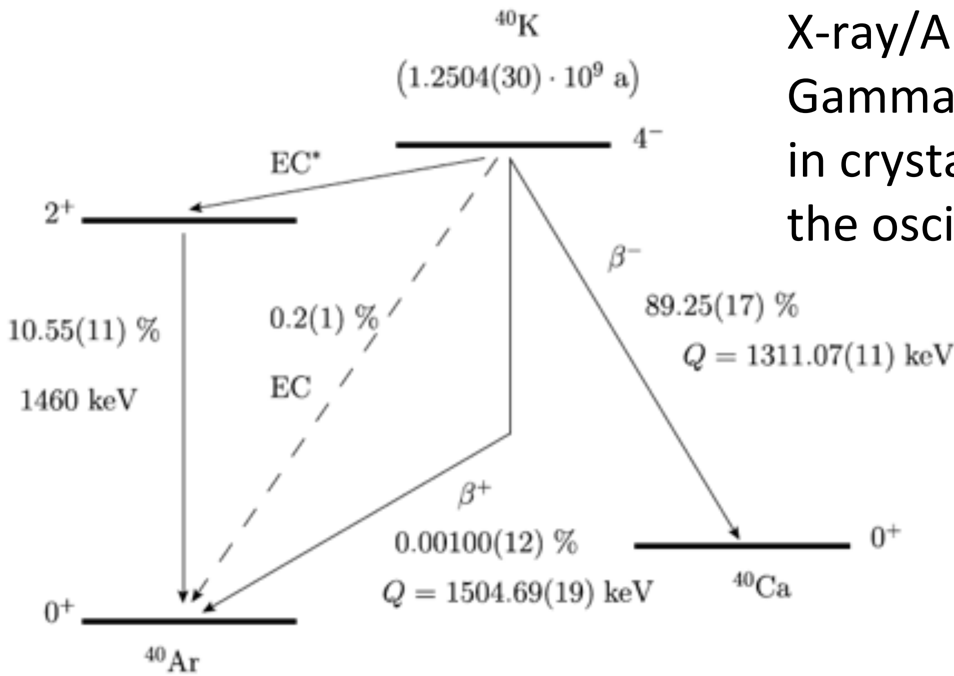
577 kg-days at SOUDAN underground site
Threshold at 1.6 keVr

CDMS II – Si results

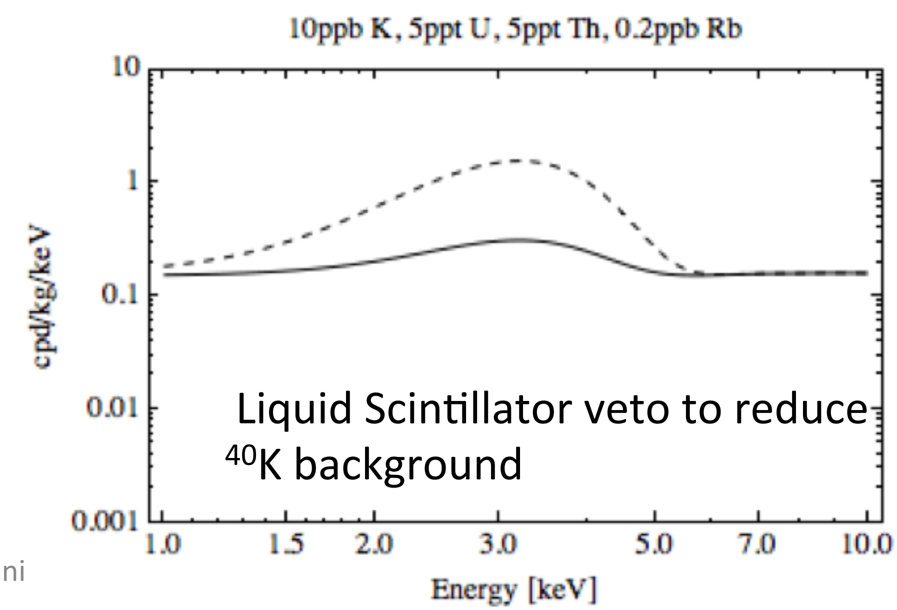
- 140.2 kg-day
- 3 events observed
- Surf. backg. ~ 0.4
- n backg < 0.13
- 0.08 NR from ^{210}Pb
- p-value for null hypothesis is 0.19%
- **Best-fit**:
  - $M_{\chi} = 8.6$ GeV/c^2
  - $\Sigma_{\chi p} = 1.9\times10^{-41}$ cm^2



Considerations on NaI(Tl) detectors for DM

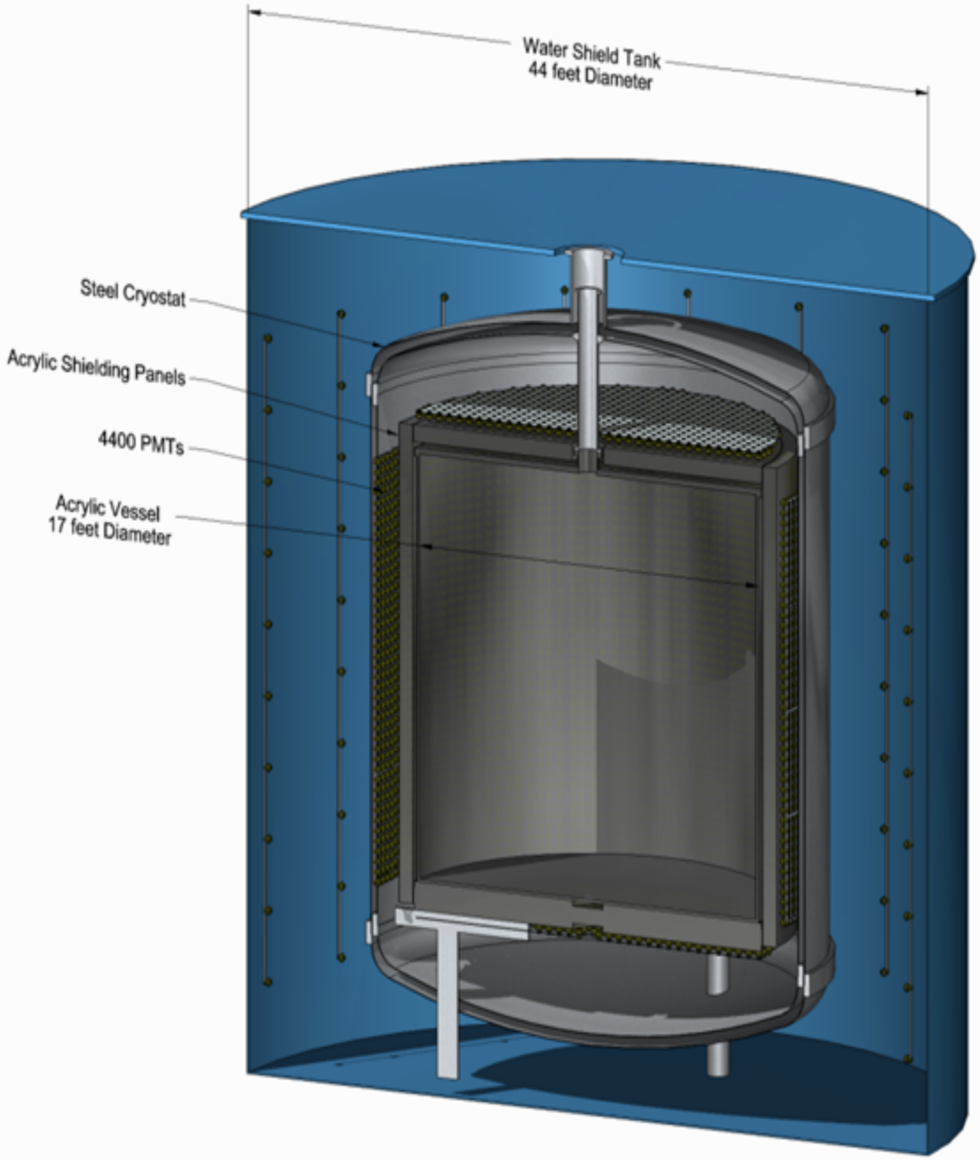


X-ray/Auger at 3keV with 1460keV Gamma-ray from ^{40}K contamination in crystal gives a peak right where the oscillation amplitude has a maximum



Liquid Scintillator veto to reduce ^{40}K background

50-Tonne liquid argon detector (conceptual only)



"Conventional" ultra-clean acrylic vessel, constructed UG

Sanded over ~months to remove deposited daughters, meets requirement (can tolerate higher surface backgrounds in larger detector!)

150-tonnes DAr in AV 50-tonne fiducial

Requires UG storage of argon target

Will investigate PMTs versus SiPMs

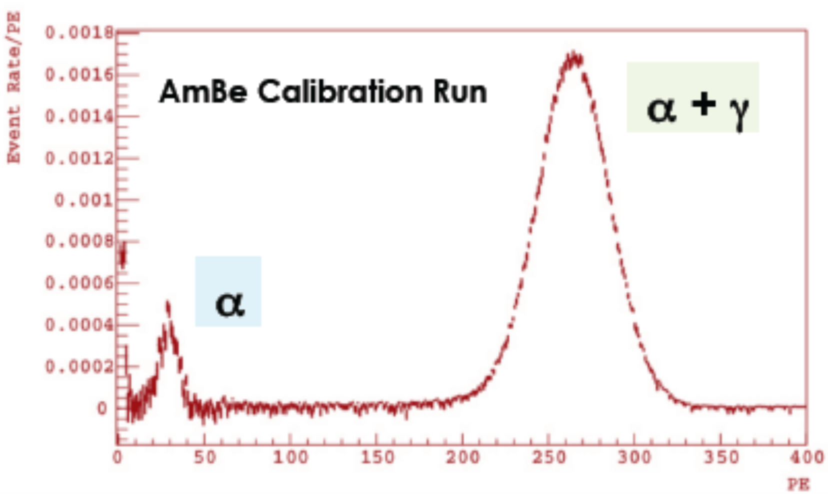
Underground Argon

- In exhaust stream gas (CO_2) of commercial mining facilities Ar at 400-600ppm level
  - In DS extraction site: CO_2 plant output, CO_2(96%)+N_2(2.4%)+He(0.4%)+Ar(0.06%)
- Make on-site preconcentration to ~40,000ppm, then cryogenic distillation at FNAL
  - After distillation: CO_2(~0)+N_2(<0.05%)+He(~0)+Ar(>99.95%)
- Purified depleted argon produced at 1 kg/day
- ^{39}Ar depleted at <0.6% level wrt atmospheric level
  - ~500 decays/kg/day
  - For WIMPs ~ 10^{-4} interactions/kg/day
- Use LAr scintillation properties to perform background reduction
  - Prompt signal PSD shows: 90% n-recoil acceptance with <10^{-5} e-recoil leakage

The Neutron Veto in DarkSide50

$n + {}^{10}B$ →

- ${}^{7}Li$ (1015 keV) + α (1775 keV) (6.4%)
- ${}^{7}Li^*$ (839 keV) + α (1471 keV) (93.7%)
  - ↓ ${}^{7}Li + \gamma$ (478 keV)



Neutron Veto Efficiency

Efficiency from capture signal alone at > 99%
(from calibrations and simulations)

- ~0.6% of lost neutrons because of escaping proton capture gamma
- ~0.05% of neutrons leave no signal in LSV at all

Larger total efficiency due to thermalization signal

Cut at 1 PE threshold: ~0.9% acceptance loss

Solar Neutrinos as Background in ER channel