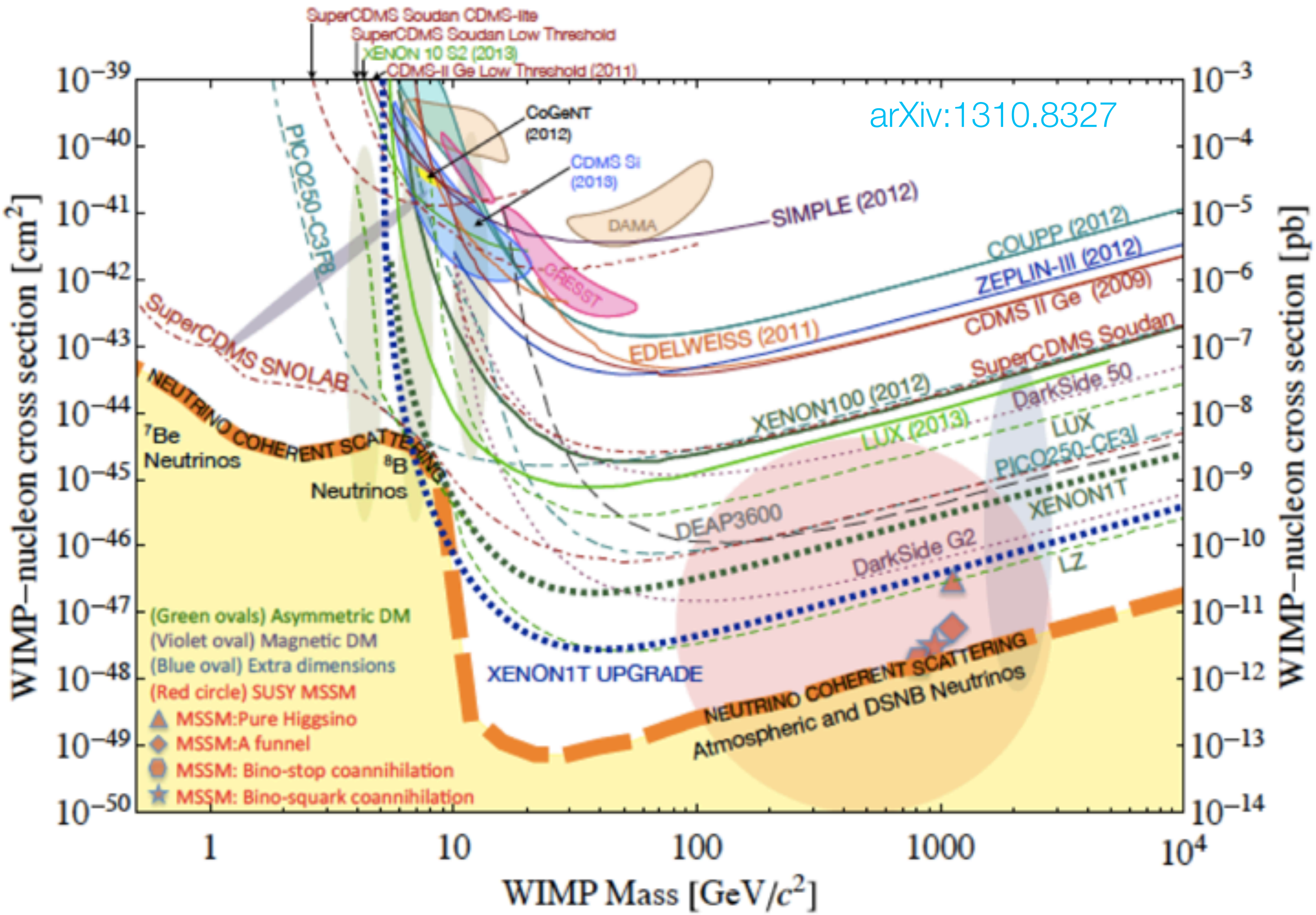
Future Scintillators for WIMPs

Neil Spooner, University of Sheffield

- WIMP world confusion, scintillators, ultimate sensitivity
- Noble liquid comments
- Scintillation signals - CRESST, DAMA...
- Future of Annual Modulation tests....
- DM-ICE

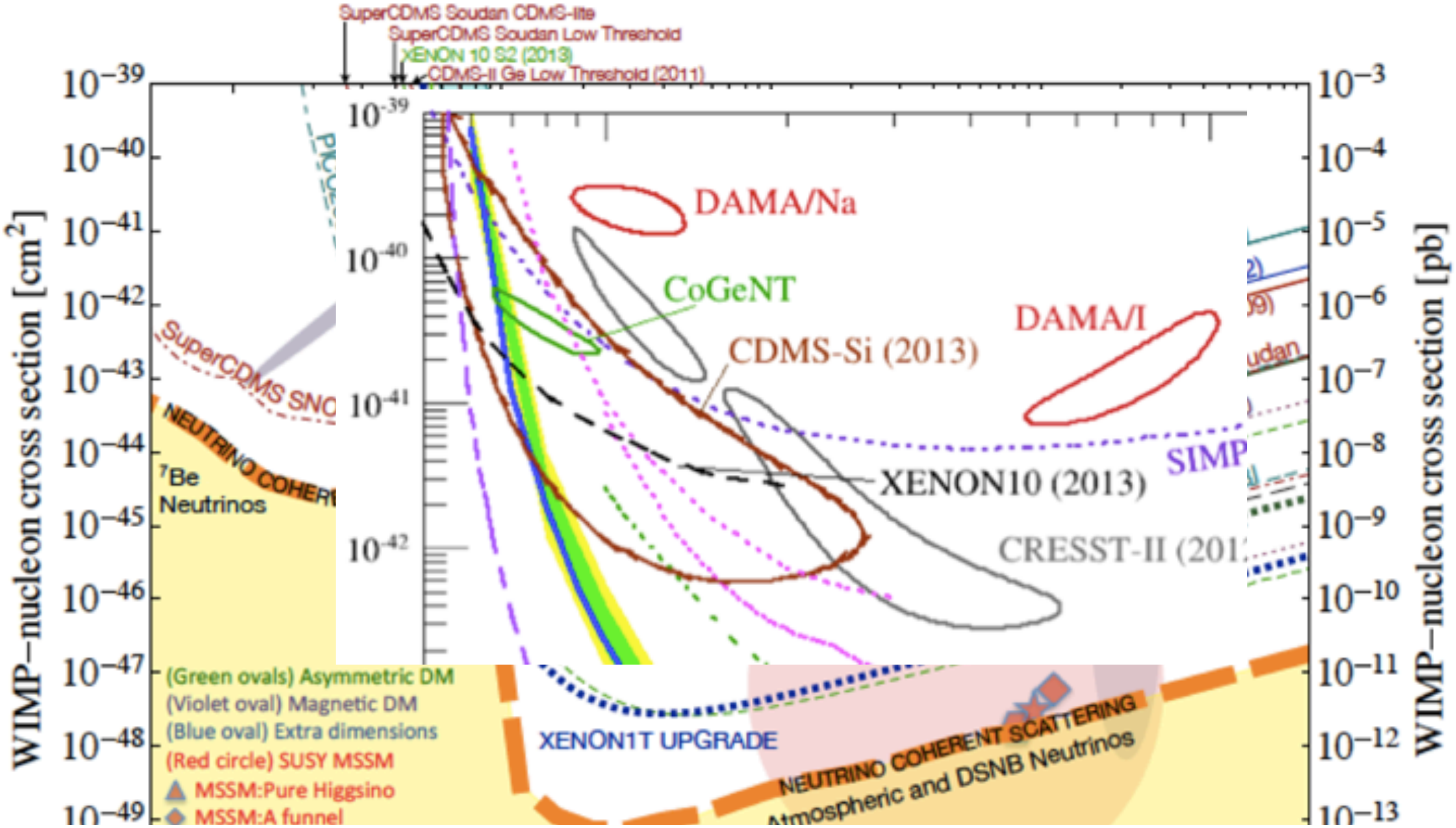
The WIMP World

Progress, confusion, hints, limits, tensions..... scintillators



The WIMP World

Does confusion at low WIMP mass reflect poor understanding of detector technology - calibrations, noise, backgrounds....?



Conclusion: either we have a WIMP signal or we need better detectors?

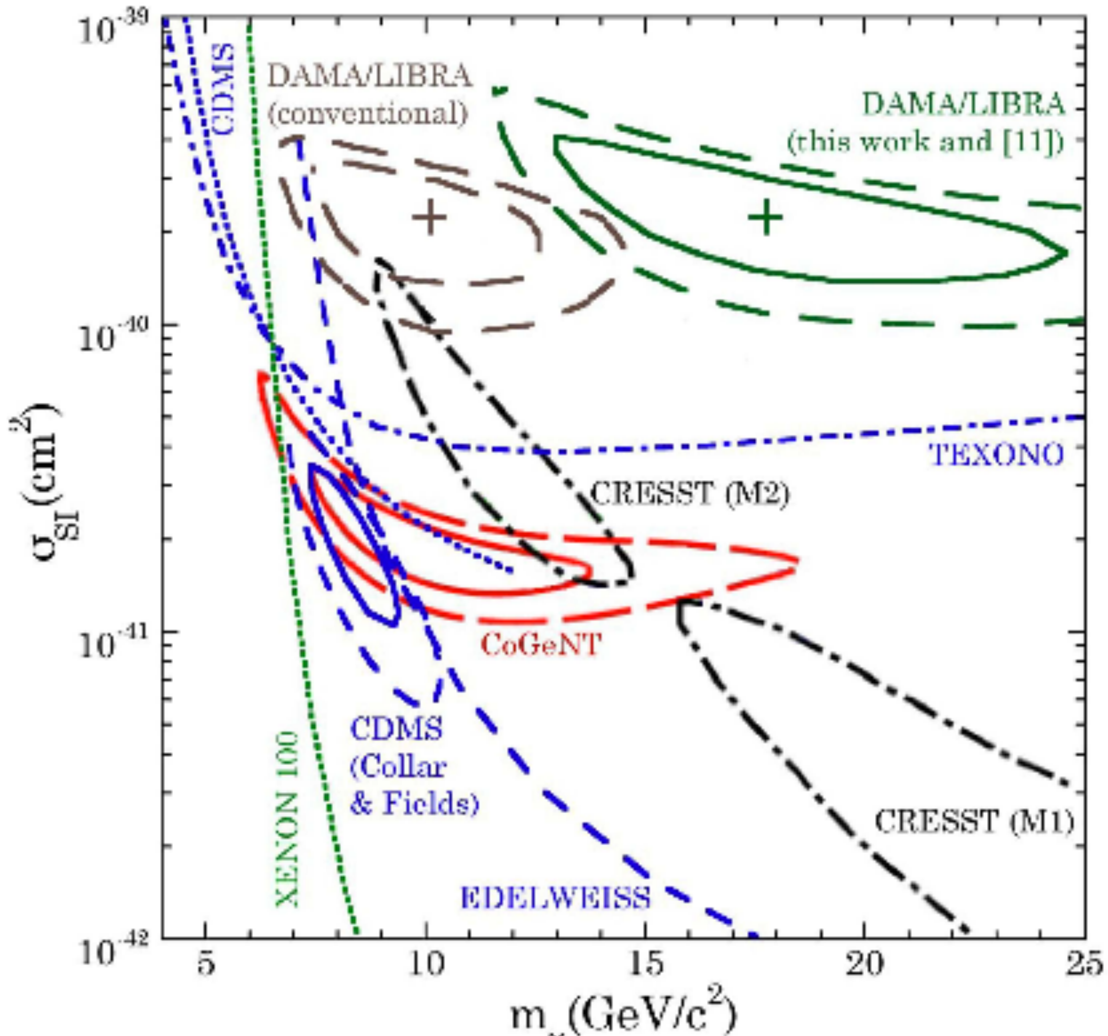
The WIMP World

$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \times \underset{\text{FIXED}}{\boxed{\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix}}} \times \underset{\text{FIXED}}{\boxed{(\text{astrophysics})}}$$

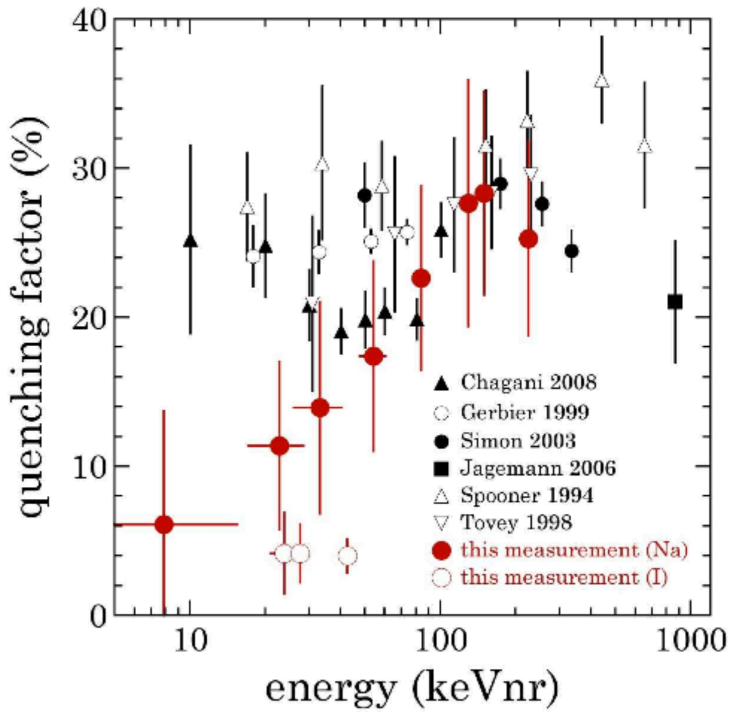
from Paolo Gondolo

NaI Scintillation Recoil Calibrations

Recent questions raised over NaI quench factors



J.J Collar 1303.2686v2

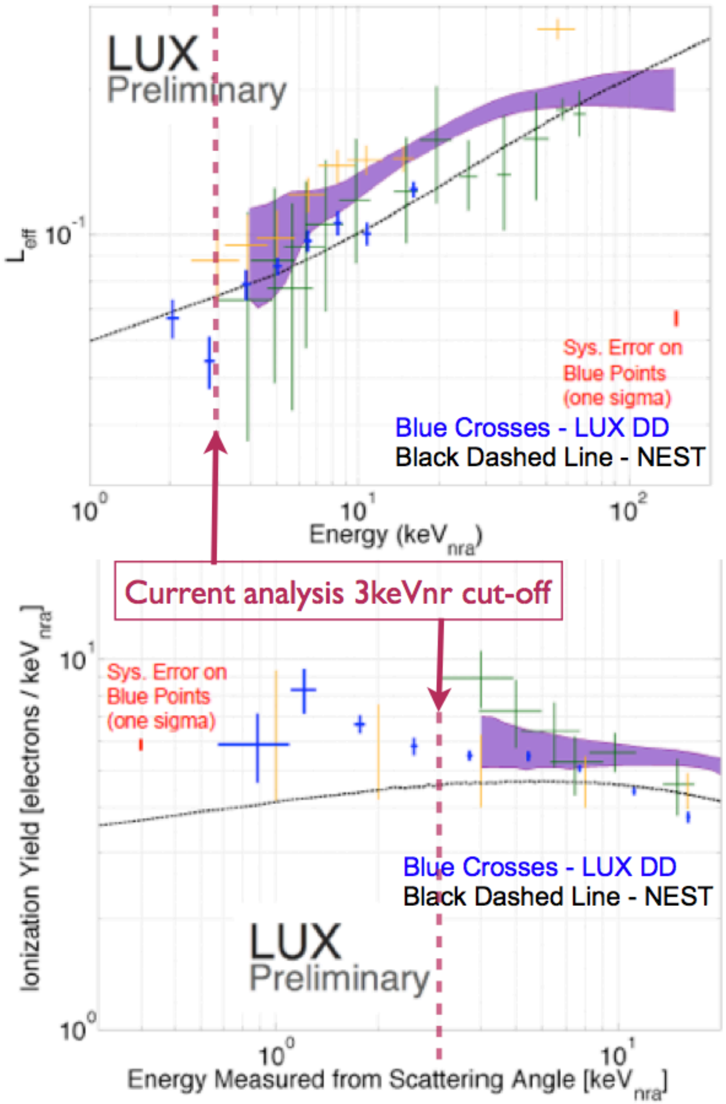


- increases tension with other experiments
- may have implications for other scintillators

LXe/LAr Scintillation Calibrations

Questions also raised over LXe and LAr QF and L_{eff}

(see previous talks at this workshop)



LXe/LAr Scintillation Calibrations

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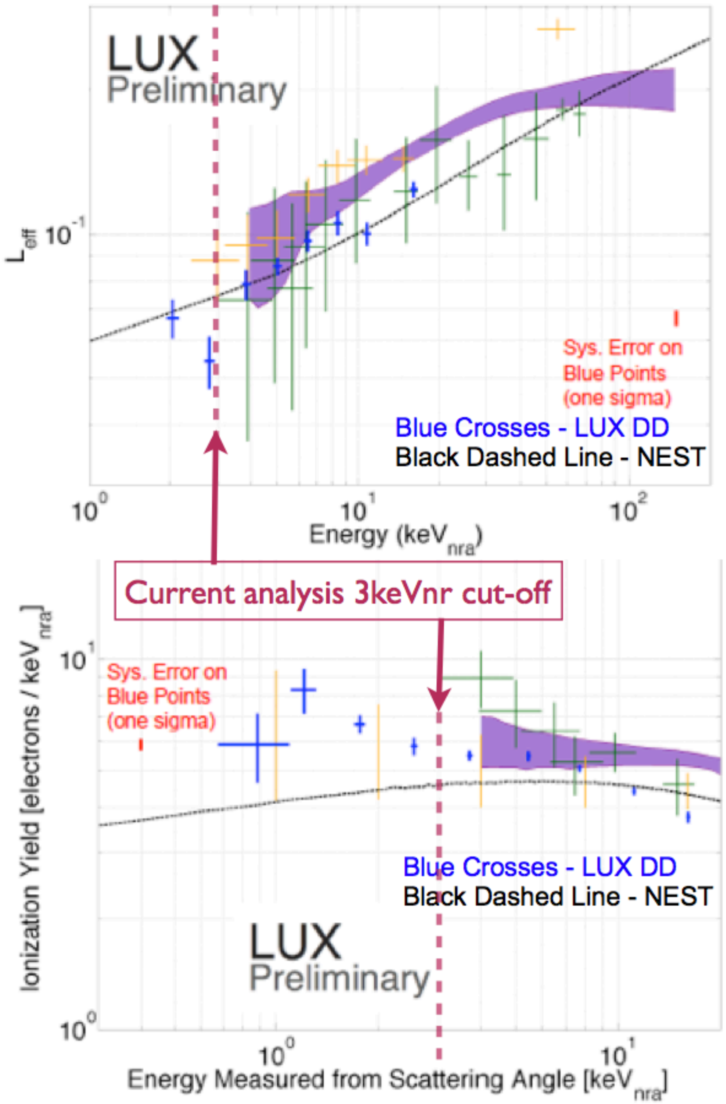
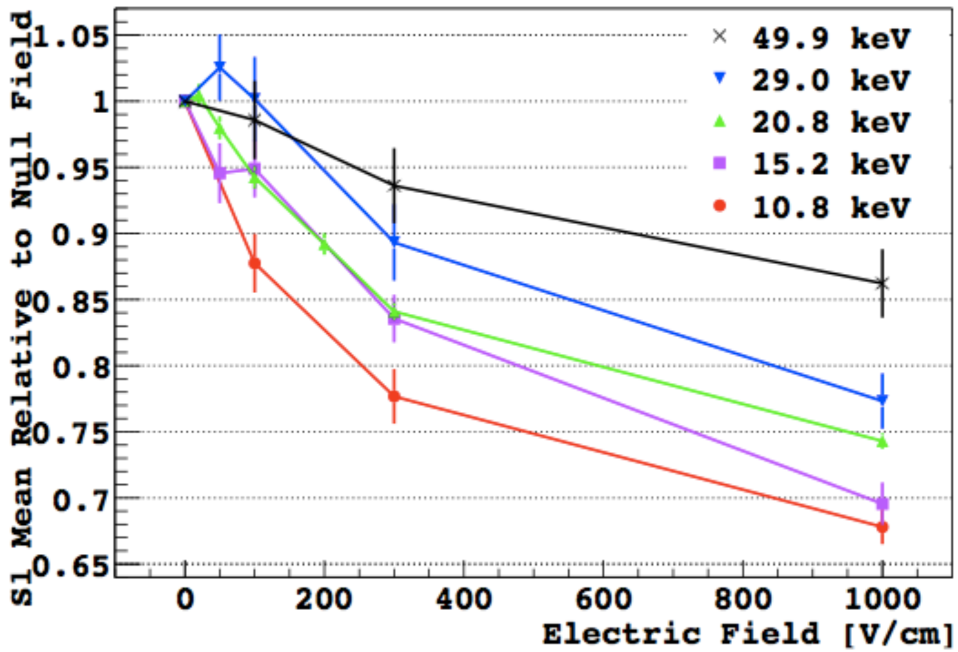


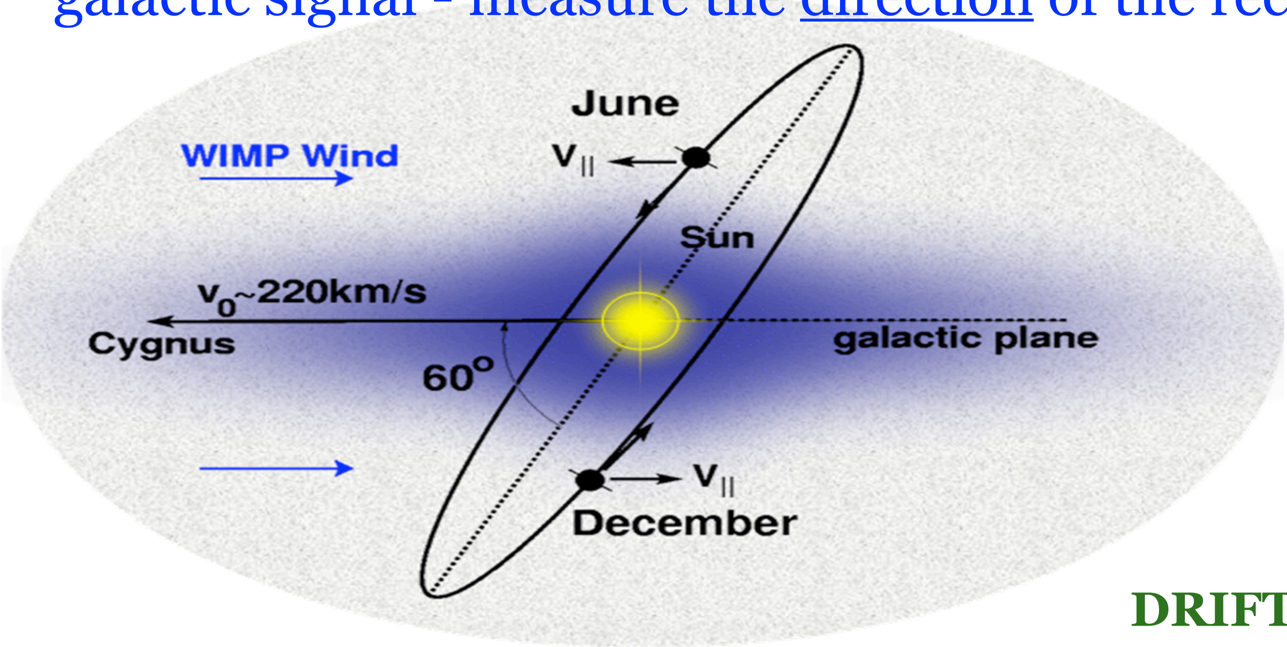
observation of a significant dependence (up to 32%) on drift field of liquid argon scintillation from nuclear recoils of energies between 10.8 keVand 49.9 keV.

arXiv:1306.5675v3

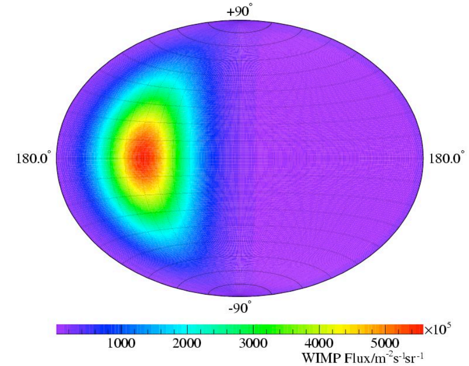


Aside - A better detector?

A directional detector might beat the neutrino limit and give a real galactic signal - measure the <u>direction</u> of the recoils from WIMPs

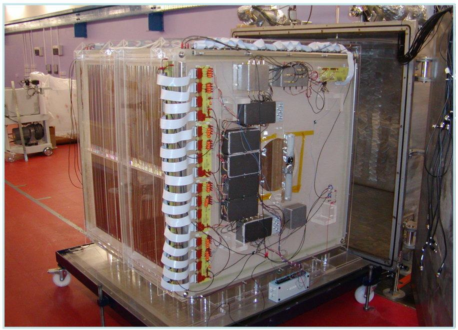


an unambiguous galactic signal?

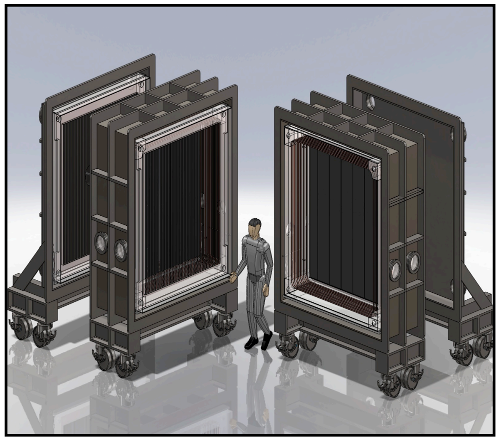


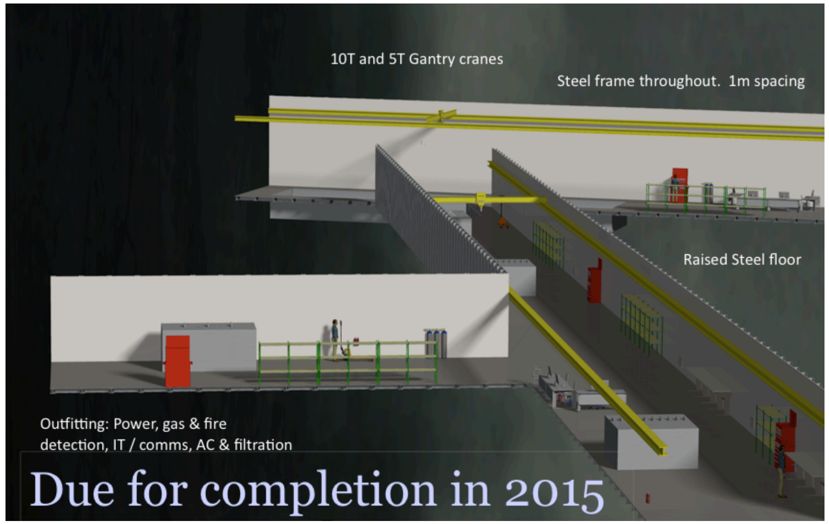
DRIFT III new lab @ Boulby

DRIFT II



DRIFT III

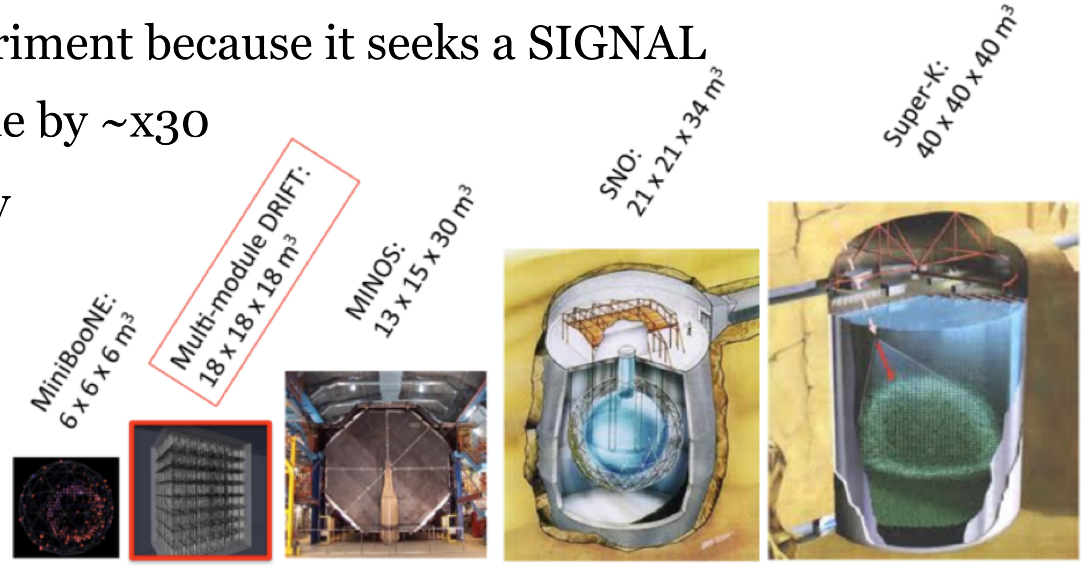


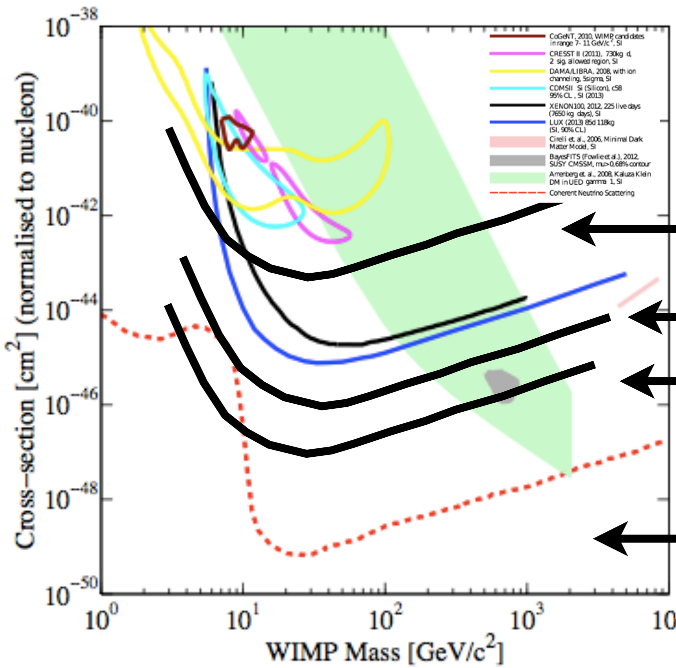


Directional Scale-up?

- DRIFT is the ultimate WIMP experiment because it seeks a SIGNAL
- DRIFT III is the next step - upgrade by ~x30
- Ultimate volumes for directionality are tough but not absurd nor necessarily unaffordable (?)

Existing particle physics detector volumes and equivalent mass of DRIFT gas....





- It's directional so in principle no known background, not even solar neutrinos?

24 m^3 DRIFT-III with low threshold upgrade

24 tons, SK volume is ~64 tons at 1kg/m^3

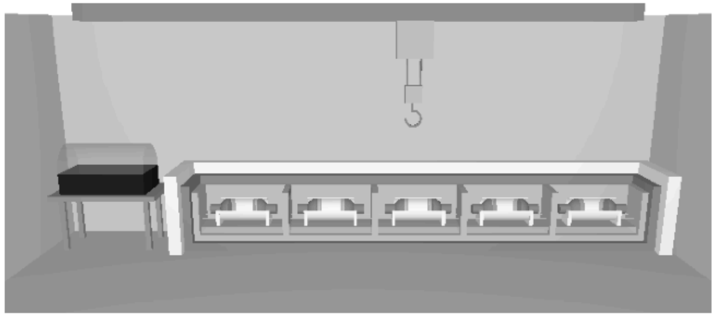
240 tons

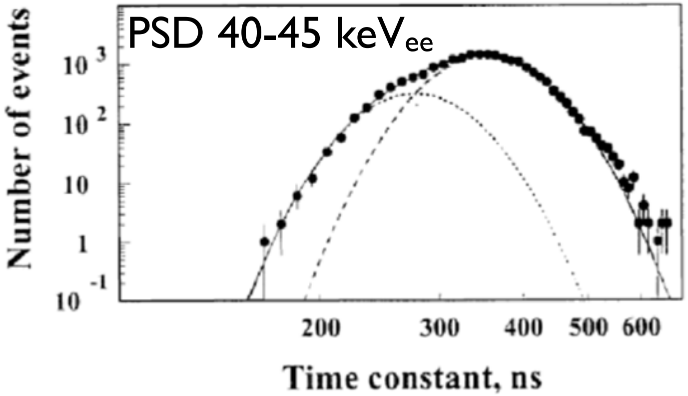
this is a thought experiment - just used scaling here so needs more work

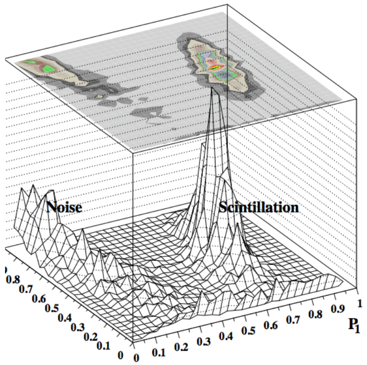
Scintillators rule (NaI) - 1995-2002

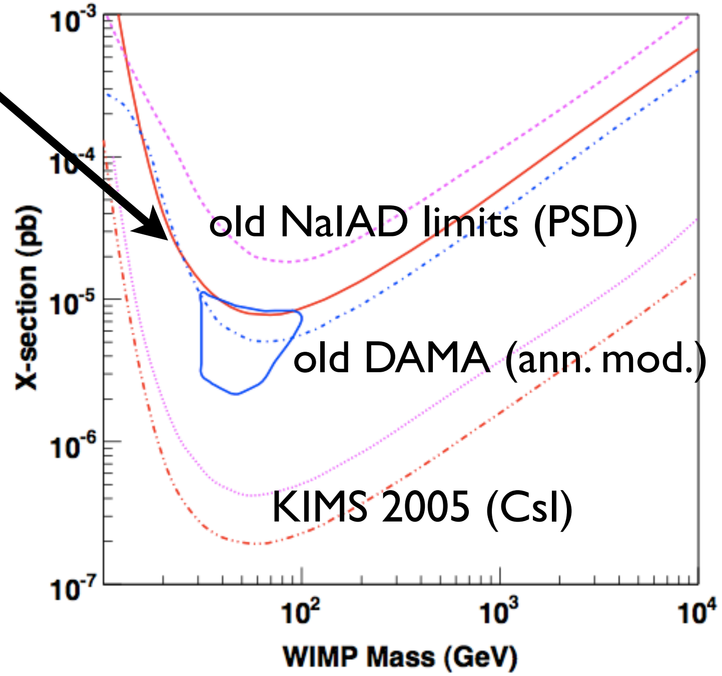
(1) NaIAD - used pulse shape disc.

The first real advances in direct WIMP searches where with scintillators - NaI with Pulse Shape Discrimination and annual modulation (starting around 1995)...









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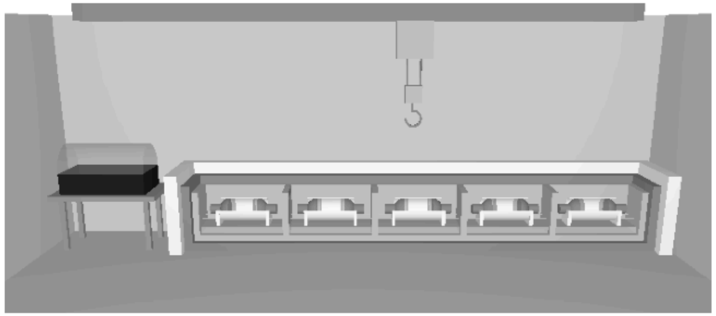
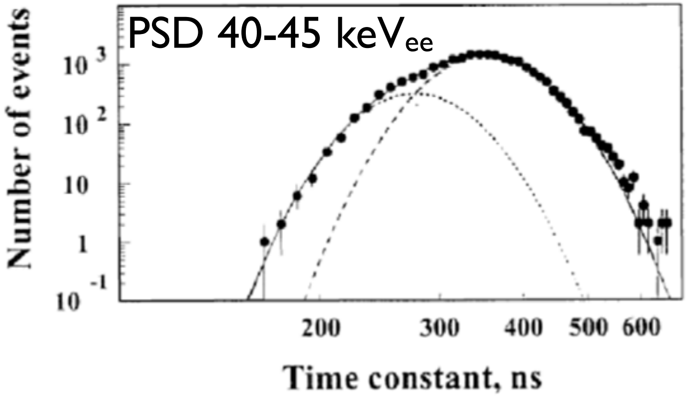
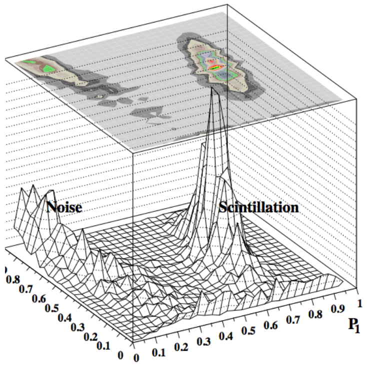
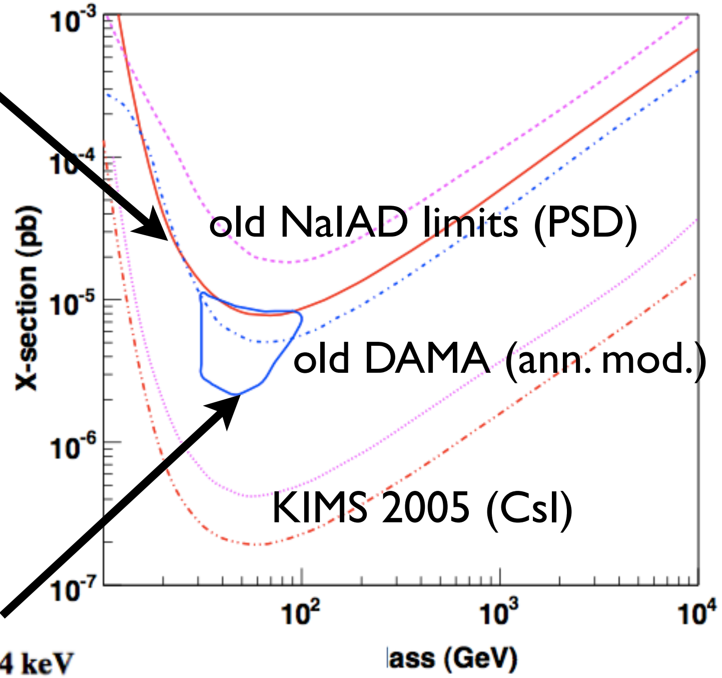
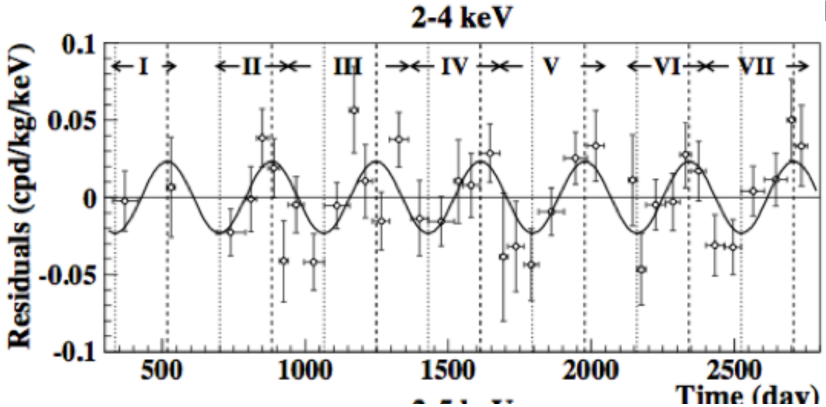






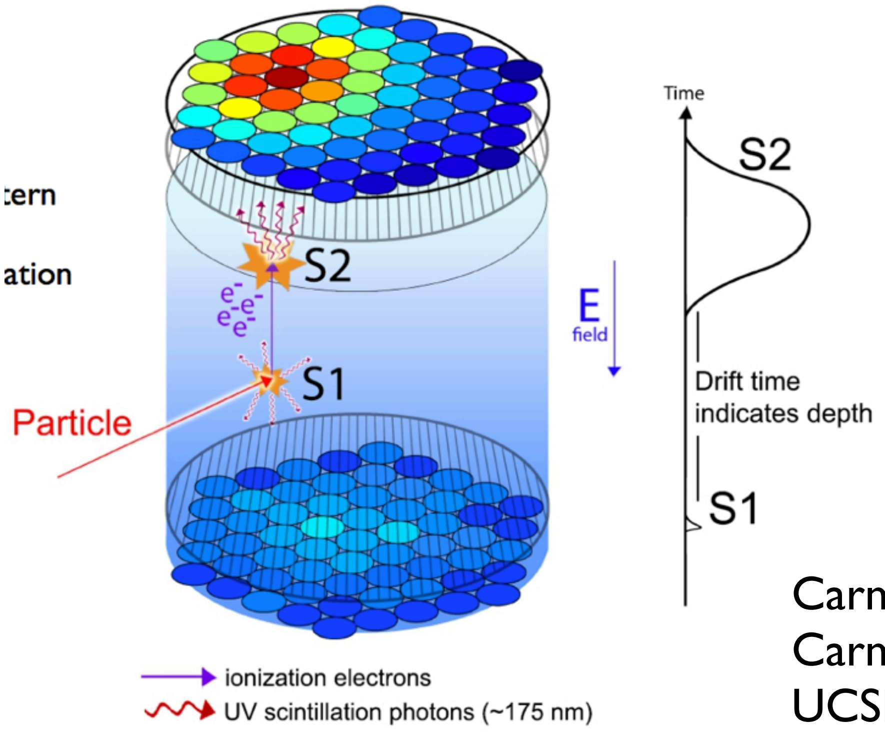


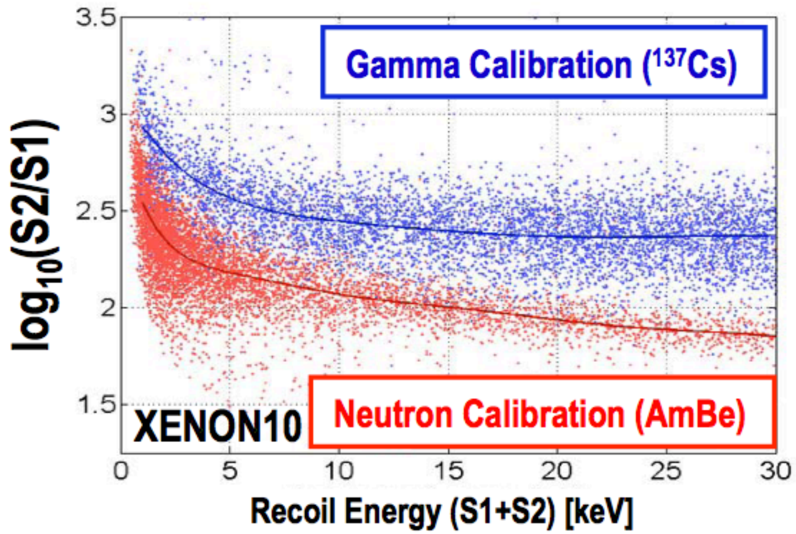
(2) DAMA - used annual modulation



Noble Liquid Scintillator (LXe) - 2004+

Combining charge collection and scintillation in noble gases gives discrimination - has led to several big LXe efforts...





Carmen Carmona - UCSB

- Excellent 3D imaging capability
  - Z position from S1 - S2 timing
  - X-Y positions from S2 light pattern
- S2 / S1 ratio => ER vs NR discrimination

Advance of Liquid Noble Gas - Liquid Xenon or Liquid Argon

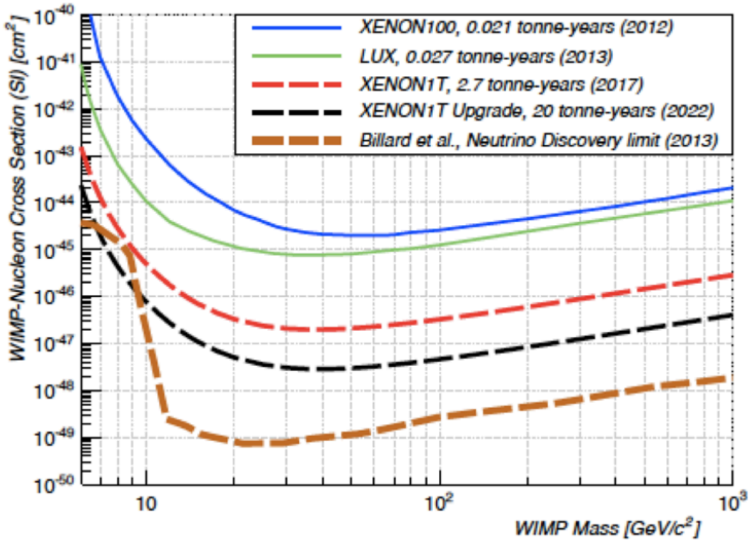
- LUX to LZ, XENON 100 to XENON 1T, XMASS, PandaX, DARWEN...
- DarkSide, DEAP, ArDM

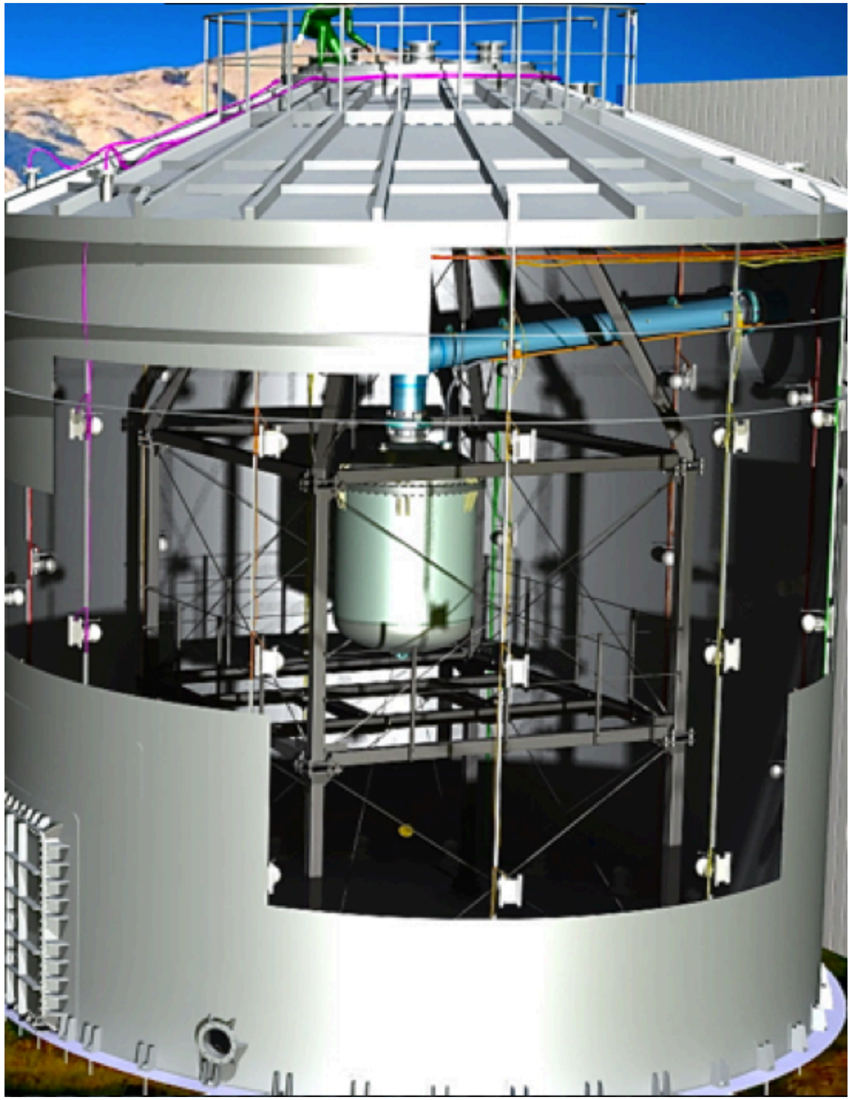
XENON 1T/XENONnT (2012-2022)

- 100 cm drift TPC - 3300 kg/7000 kg
- Fast track to data starting 2014 (1T)?

XENON1T: overview

- Two-phase TPC with 1 meter drift and ~1 m diameter electrodes filled with ~3.3 tonnes of Xe
- Experiment designed to enable a fast upgrade to a larger diameter TPC with ~7 tonnes of Xe
- Detector/associated systems use largely proven technologies developed for XENON100
- New challenges presented by the scale-up addressed with multiple R&D set-ups
- New 3 inch PMTs developed for XENON1T: average QE~36% at 178 nm and low activity
- Detector shielded by water instrumented as Cherenkov muon veto
- Status: under construction - commissioning of major plants at LNGS starts May 2014
- Science Goal: 10^{-47} cm^2 with 2 ton-years of data or by 2017
- Funding: 50% of capital cost covered by NSF
- Proposal submitted by US groups for an upgrade in 2018





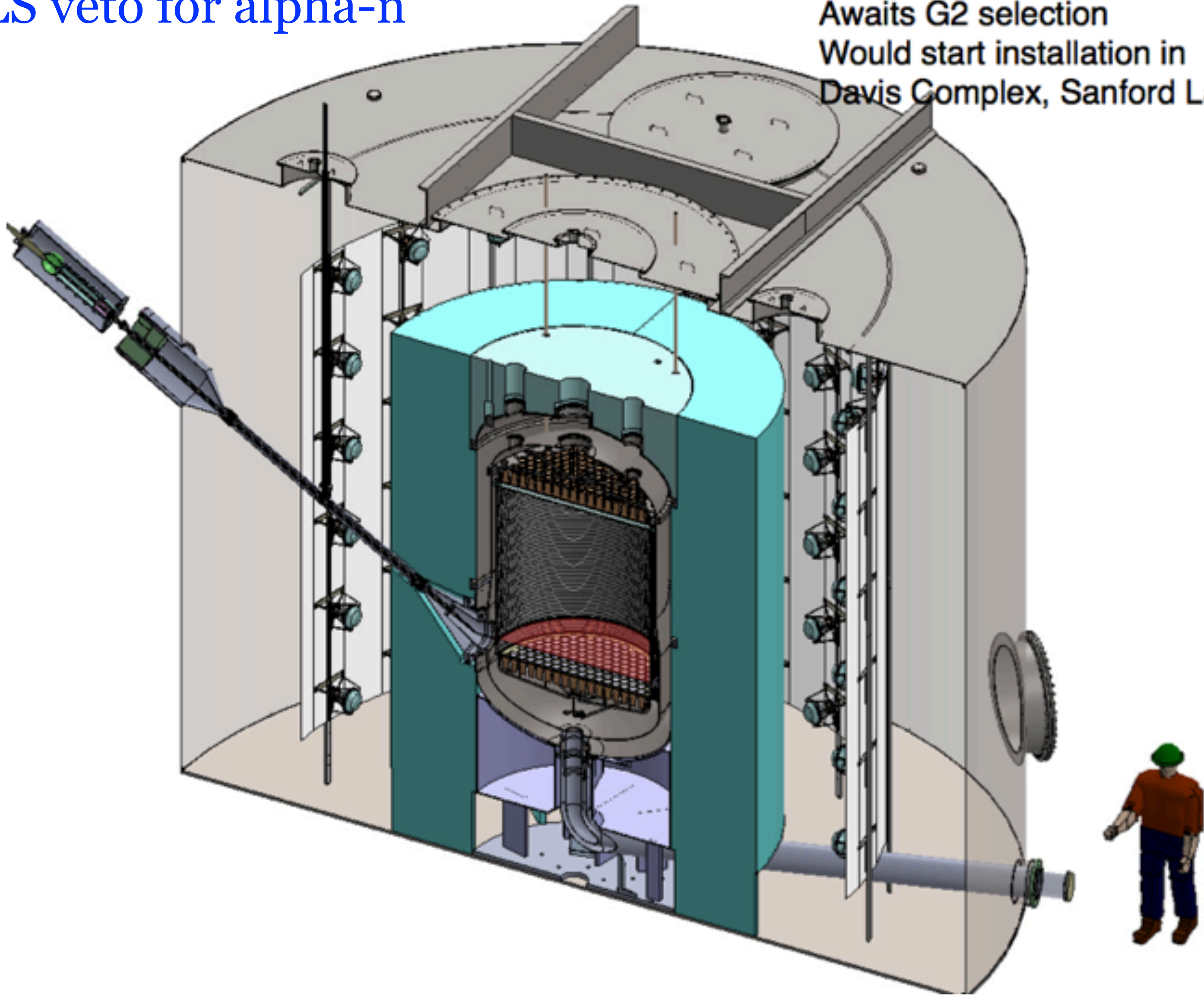
XENON 1T/XENONnT (2012-2022)

XENON 1T/XENONnT (2012-2022)

LUX-ZEPLIN (2016 +)

- 8 tonne Xe, 5.6t fiducial
- New Gd-LS veto for alpha-n

Awaits G2 selection
Would start installation in
Davis Complex, Sanford Lab in 2016

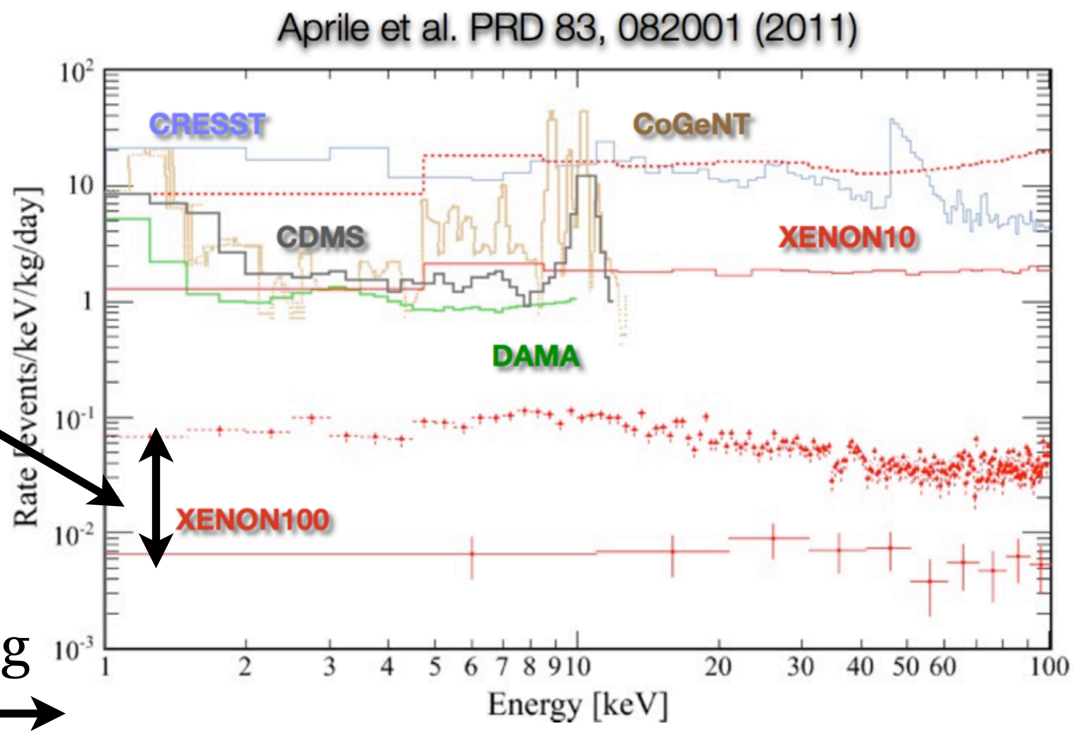


.UX / DOE

Scintillation Rules - Why and What

But good old NaI has surprisingly low INTRINSIC background

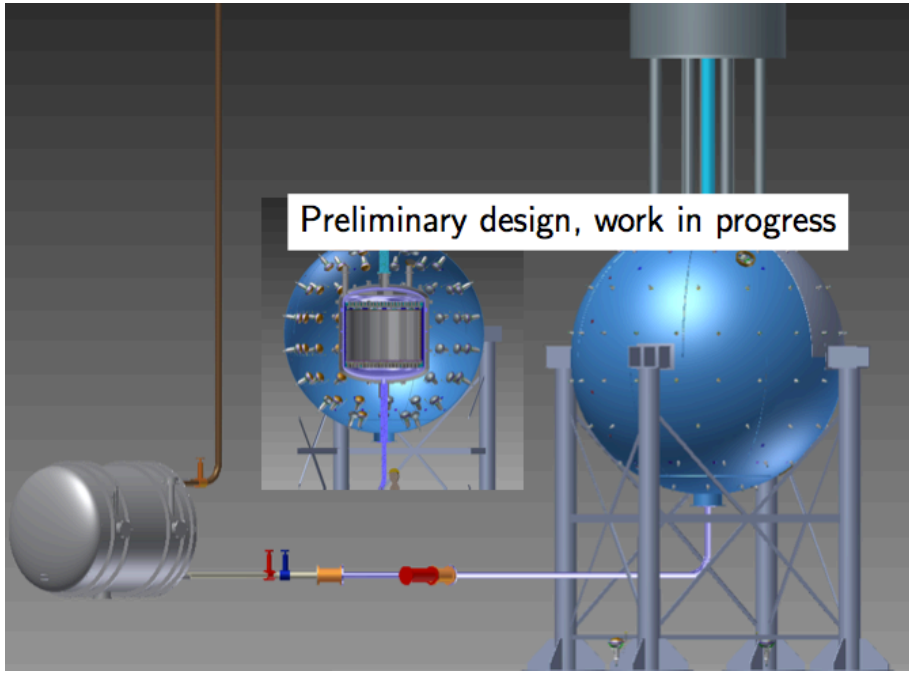
- Around a decade to get x 10 better intrinsic background!
- XMASS, LZ, etc will push passive shielding



- So actually the recoil discrimination by scint:heat ratio is not stellar, and will not be the dominant factor in background suppression
- LAr can also do discrimination by scint:heat ratio at a similar level - but actually in LAr pulse shape discrimination is probably much more powerful

LAr and return to Scintillation PSD

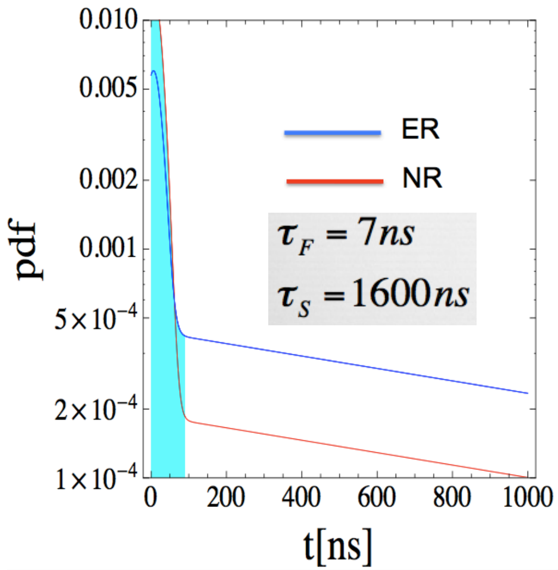
DarkSide (see Aldo's talk)

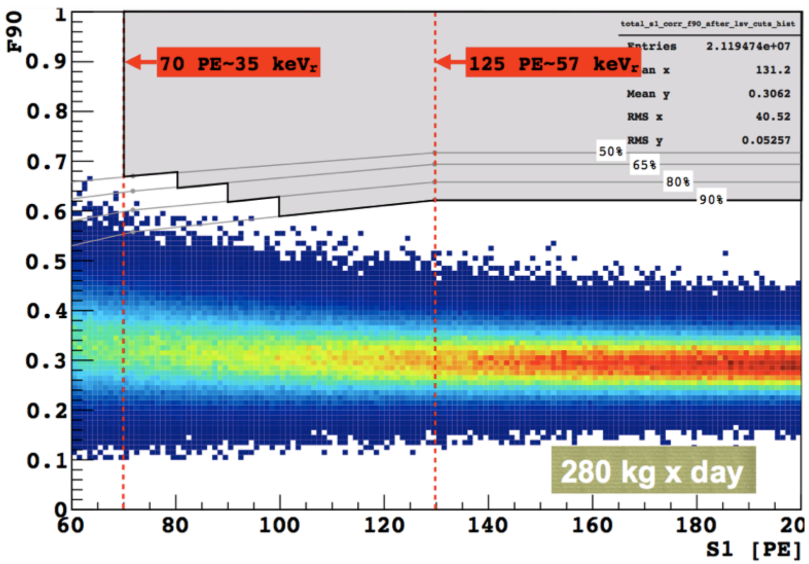


DarkSide-G2

- 3600 kg fiducial, two phase
- Can be built inside present DS-50 neutron veto
- Expected sensitivity 10^{-47} cm²

DS-50 result:
No background in PSD in upper 50% NR acceptance region in 3×10^7 events



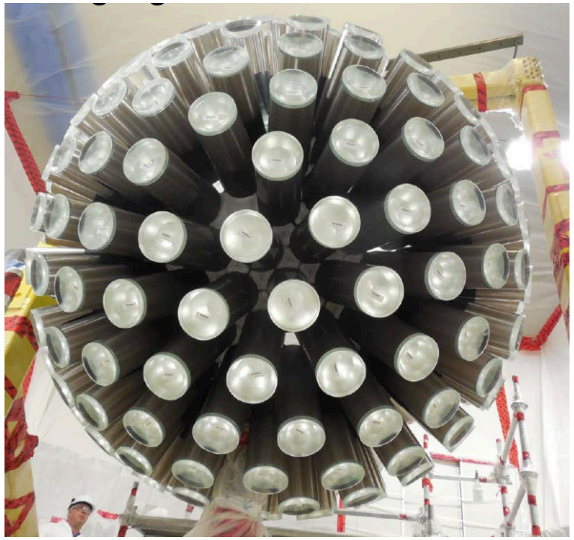


LAr - PSD only, single phase

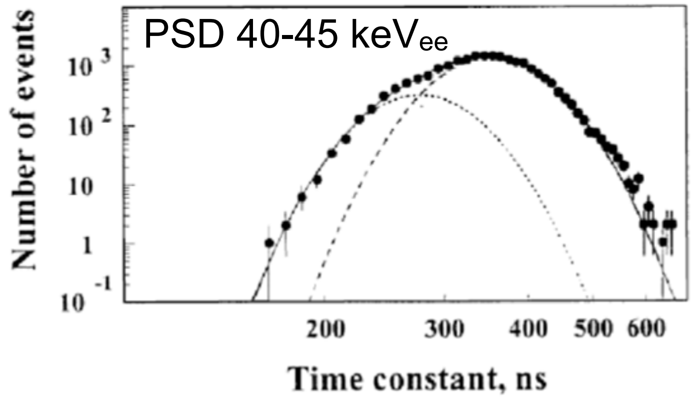
DEAP3600

at SNOLAB

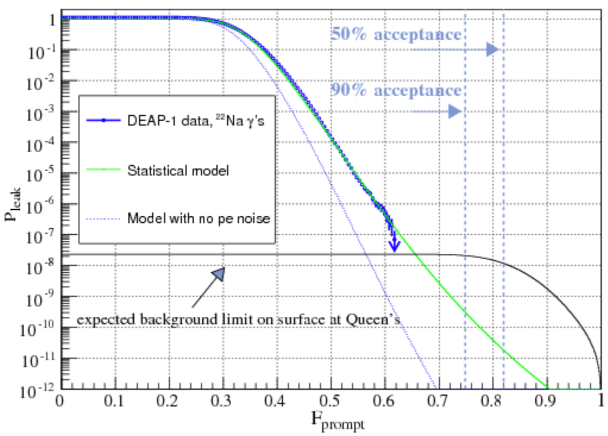
Pulse shape discrimination in LAr is a phenomenal improvement over NaI by > x 10^8



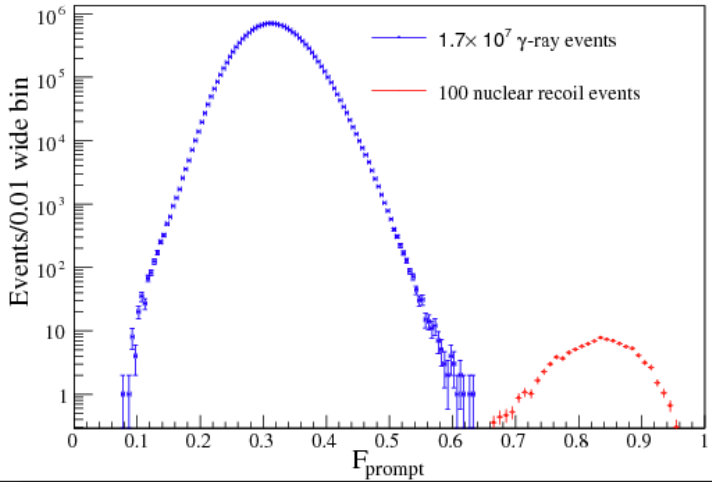
old NaIAD recoil discrimination (very poor!)



(PSD) achieved with DEAP-1 is 10^(-8) at 43 keV_{ee}



new DEAP LAr recoil discrimination (very good!)

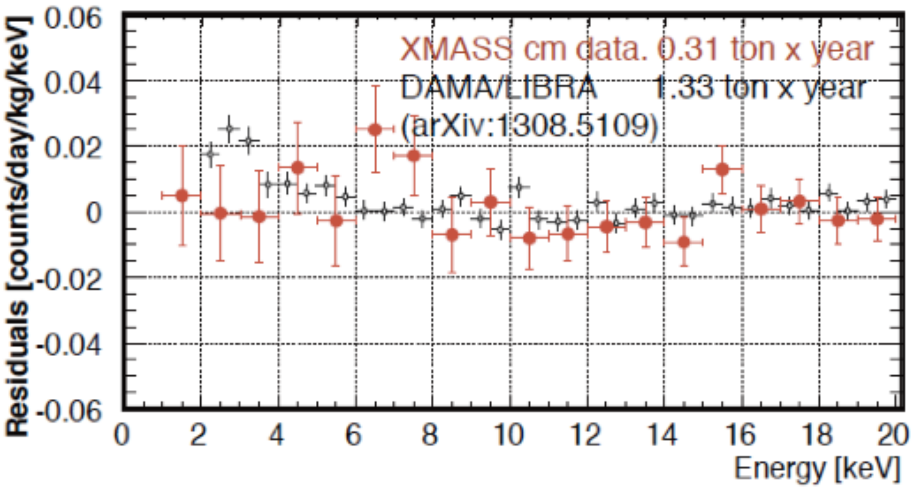


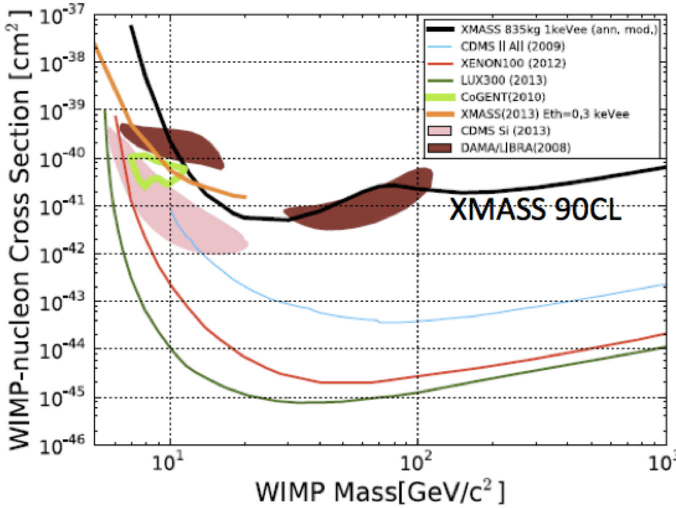
Passive shielding rules.... e.g. XMASS..

1m diameter detector, 835kg of LXe for sensitive region. (total 1t)

- 642 low background PMTs.
- Use outer xenon region as shield and make center region as low background fiducial

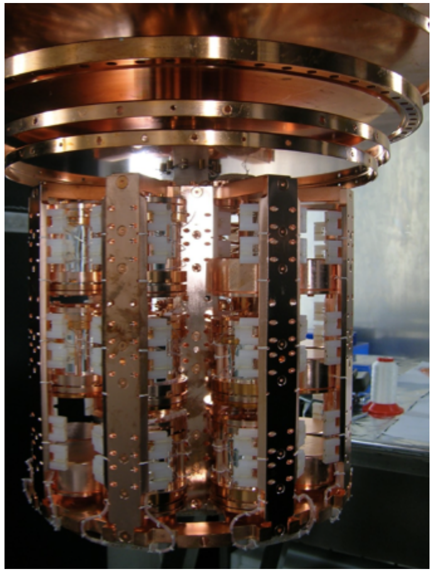
Also, engineering data of 0.31 ton year allowed start on annual modulation analysis (DAMA/LIBRA 1.33 ton year, 14 cycles)

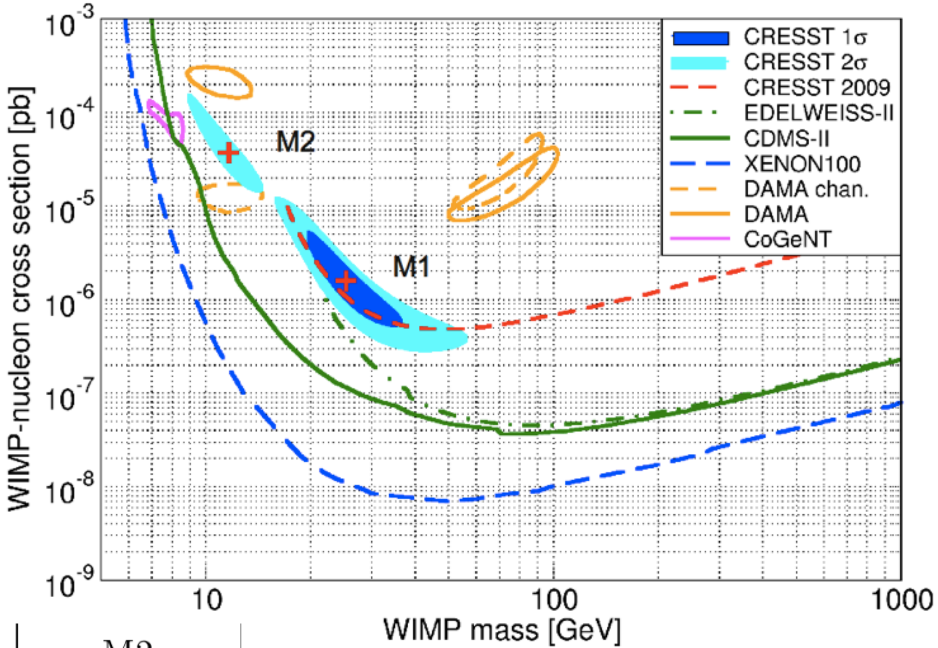




CRESST - scintillation with heat

Located in hall A of LNGS, Scintillating $CaWO_4$ target crystals, 33 crystals in modular structure (10 kg target mass), discrimination by observing phonons and scintillation





4.7 σ for M1
4.2 σ for M2

	M1	M2
e/γ-events	8.00 ± 0.05	8.00 ± 0.05
α-events	$11.5^{+2.6}_{-2.3}$	$11.2^{+2.5}_{-2.3}$
neutron events	$7.5^{+6.3}_{-5.5}$	$9.7^{+6.1}_{-5.1}$
Pb recoils	$15.0^{+5.2}_{-5.1}$	$18.7^{+4.9}_{-4.7}$
signal events	$29.4^{+8.6}_{-7.7}$	$24.2^{+8.1}_{-7.2}$
m_χ [GeV]	25.3	11.6
σ_{WN} [pb]	$1.6 \cdot 10^{-6}$	$3.7 \cdot 10^{-5}$

67 low energy nuclear recoils observed in acceptance region for a WIMP signal in 730 kg days of data.

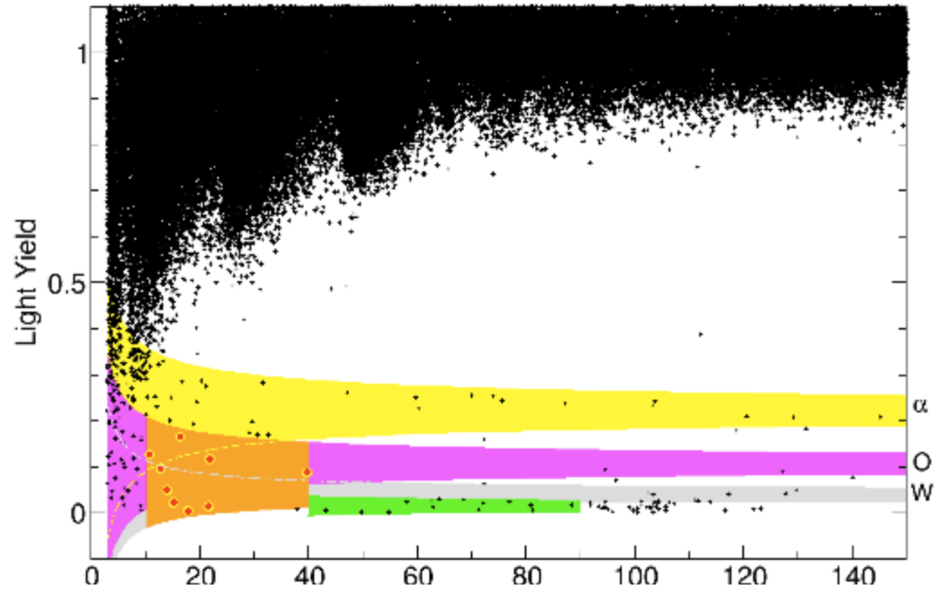
For ultimate clarification reduction is necessary to reduce possible uncertainties in modelling of these backgrounds.

CRESST - scintillation with heat

- Background issues in that data

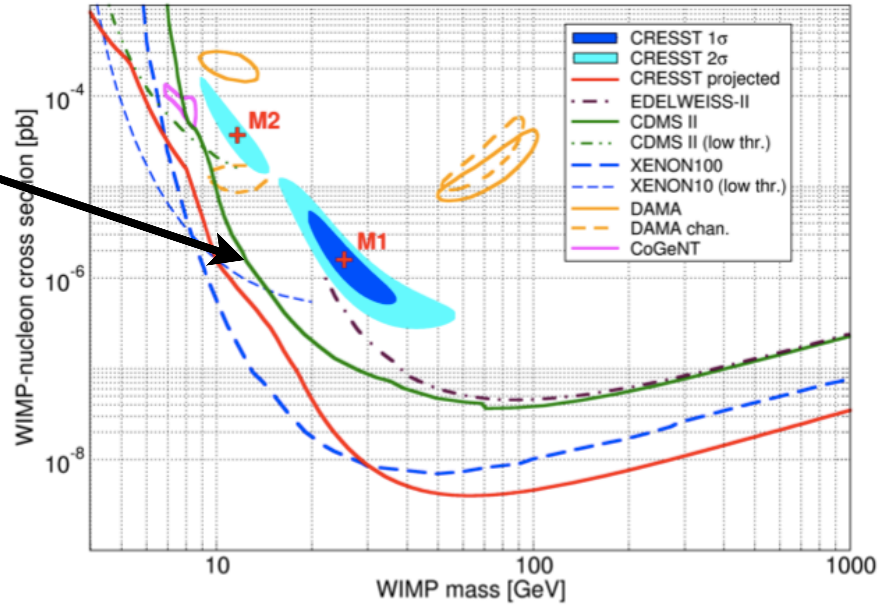
low energy α-events → α-contamination in clamps holding the crystals

^{206}Pb nuclei from ^{210}Po α-decays → ^{210}Po contamination on non scintillating Ag surface of clamps



- New runs underway using new designs of crystal holder- data

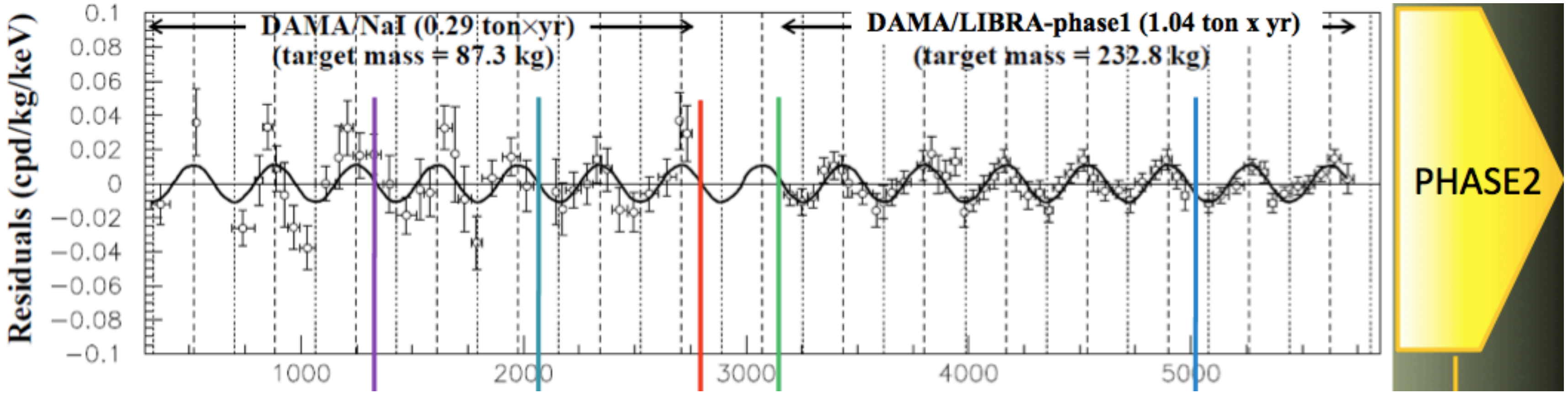
new projected sensitivity



New collected until January 2014

Main goal is lower neutron, α and ^{206}Pb recoil backgrounds by more than an order of magnitude to either confirm or reject the low mass WIMP hypothesis with high confidence.

DAMA/LIBRA - it continues...

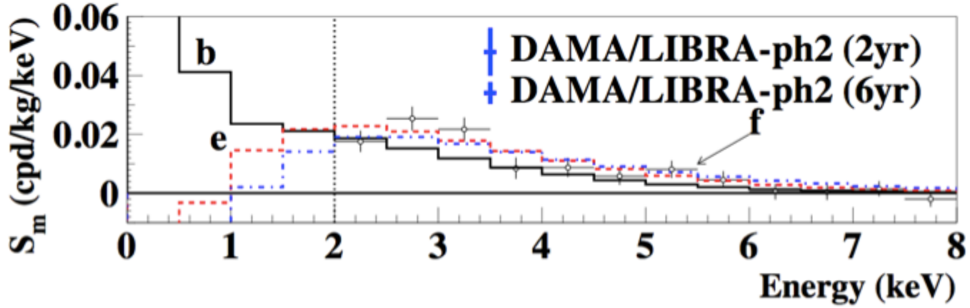


- DAMA/LIBRA essentially assume WIMPs have been detected, so they say what is needed is more statistics to investigate the signal
  - LIBRA (inc. phase II, 2010) upgrade has lower threshold (~ 1 keV), higher mass (250 kg) and lower background (~10^{-12} g/g ^{238}U..) - a good way to investigate the origin of the modulation - this is not the motive!
  - 2012 - installed new pre-amps and triggers
  - Current total exposure, inc. all previous runs, ~ 1.67 ton x years
  - No release of new modulation data until ~6 years of new data is collected, though recently some “engineering data” has been seen
  - Stability is < 1 %: temperature, humidity, radon, noise rates

DAMA/LIBRA

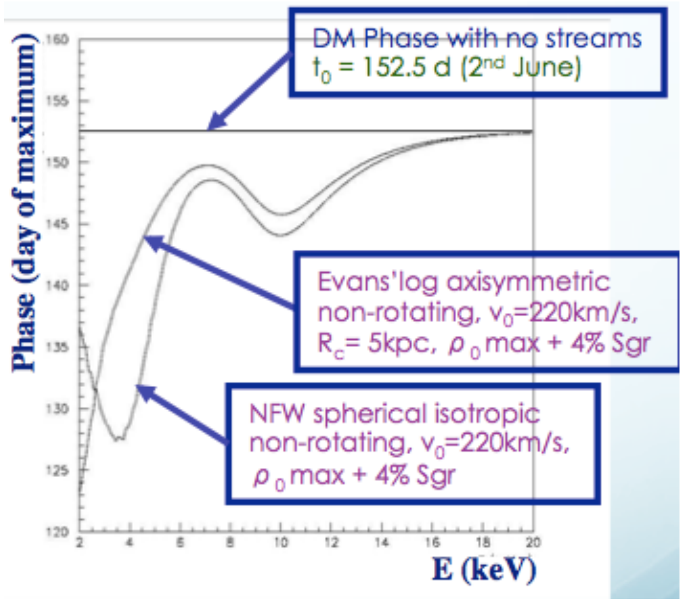
- Example Phase II WIMP characterisation studies

– Lower threshold and lower background allows discrimination between models via spectrum of modulation component e.g.:



WIMP: SI
b) 10 GeV-ch
e) 60 GeV
f) 100 GeV

– Improved statistics on phase measurement allows discrimination between halo models including existence of streams (caustics, Sun focussing etc) e.g.:



DAMA/LIBRA - a conclusion

Frank Calaprice

DAMA/LIBRA observes an annual modulation in count rate on NaI(Tl) target consistent with a WIMP dark matter signal.

- The modulation has very high (~9 σ) statistical significance.
- No explanation yet of the modulation due to normal-matter effects.
- Results favour light WIMPS, but are seemingly inconsistent with experiments using other targets. (LUX, XENON, CDMS...)
- Other hints of light WIMPS come from CoGeNT, CDMS-Si, and CRESST.
- Confirmation or refutation by another NaI(Tl) experiment is lacking.

This is starting to be addressed more seriously by several new experiments... DM-ICE, SABRE, KIMS, ANAIS....

SABRE

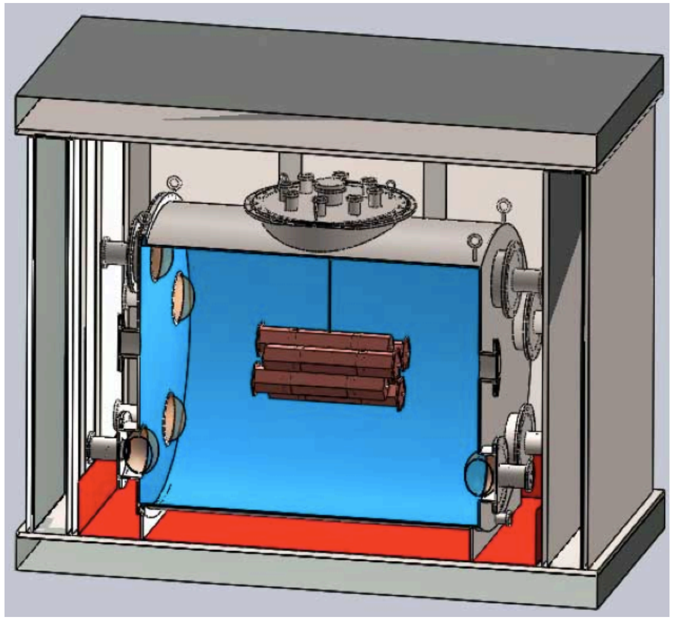
Propose new Ann. Mod search with NaI (Tl) with focus on production of lower background material and scintillator veto

$Na_2CO_3\,(aq) + 2HI\,(aq) \rightarrow 2\,NaI\,(aq) + H_2O + CO_2\,(g)$

Princeton University:
F. Calaprice, C. Galbiati, J. Benziger, F. Froborg, M. Wada, J. Xu, E. Shields, S. Westerdale, A. Nelson
University of Houston:
E. Hungerford, S. Davini, G. Korga
LNGS:
A. Razeto, Aldo Ianni
Milano University:
D. D'Angelo
PNNL:
E. Hoppe, J. Orrell, C. Overman

Current goal is to demonstrate high radio-purity, high light-yield 3-inch crystal modules.

- Under construction with NSF funding.
- Shielded in Darkside liquid scintillator veto.
- Hamamatsu 3" R11065-X PMTs.
- Electroformed copper encapsulation.
- Schedule: Expect to start taking data summer 2014.



Next goal, not yet funded, will be an array of 8-kg NaI(Tl) modules (50-60 kg) using new 4" PMTs.

- Start construction in 2015 and 2 years to complete.
- Taking data as modules are constructed is an option.

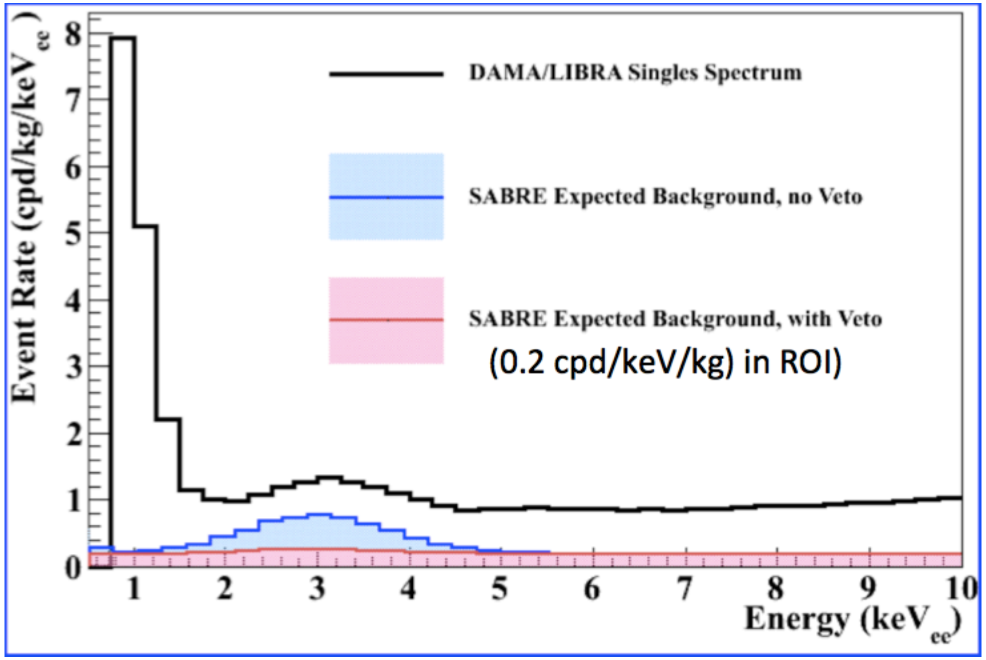
Possible full 70 kg experiment in DarkSide veto also proposed as an option

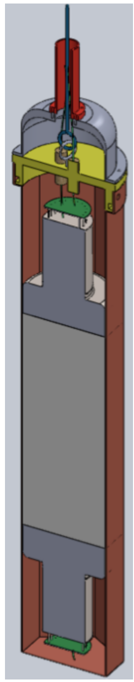
SABRE

With standard WIMP halo, a 10 GeV WIMP has most nuclear recoil energy spectrum below the 2 keV DL threshold.

- Observed modulation implies following non-modulating rates for 10 GeV WIMP:
- Whole nuclear recoil spectrum: 1.13 cpd/keV/kg
- ROI (2-4 keV): 0.13 cpd/keV/kg.
- The modulation and total WIMP in ROI imply a 14% modulation for 10 GeV WIMP.
- The modulation is diluted by background.

The SABRE 50-kg array with expected low background should detect big modulation.





ANAIS

Constructing a 250 kg NaI(Tl) array at the Canfranc Underground Laboratory (LSC)

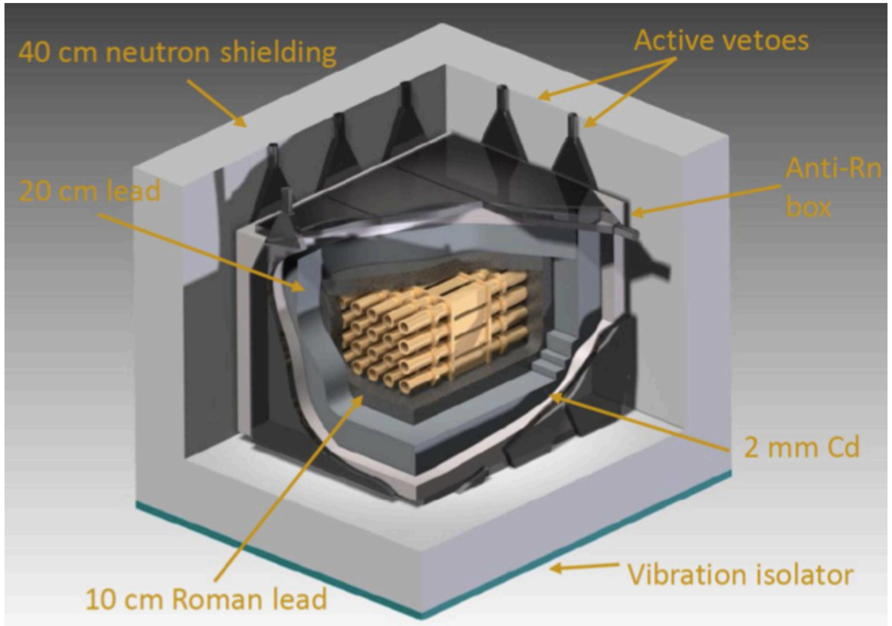
Propose active muon vetoes, anti-radon box etc

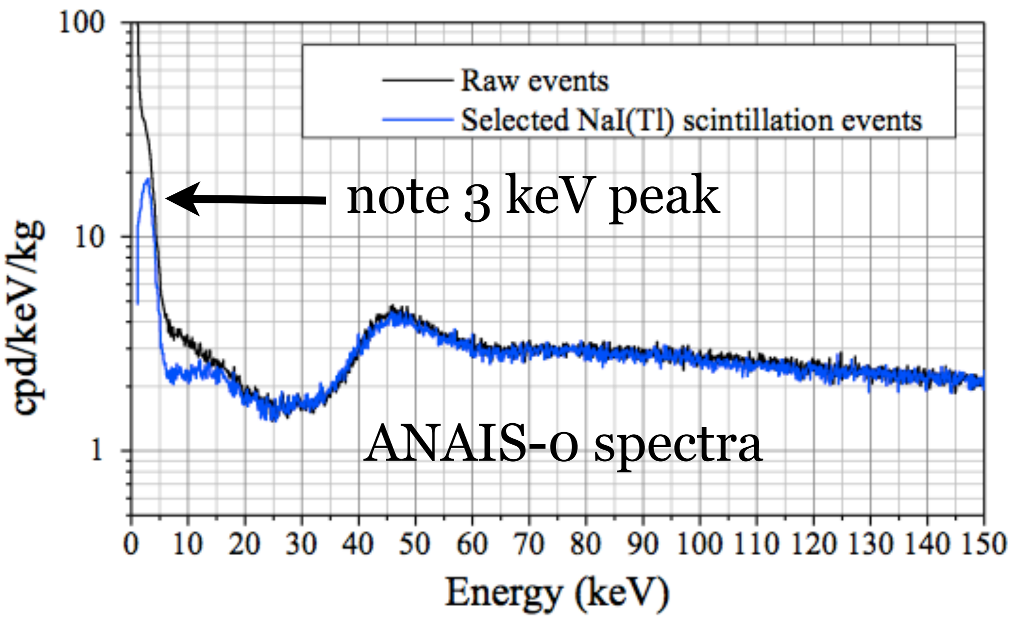
Extensive study of crystal purity, **Goal: <20 ppb of natK (0.6 mBq/kg)**

ANAIS-25: two NaI(Tl) crystals (12.5 kg each) from Alpha Spectra

- Main goal of ANAIS-25 to determine potassium content of the new crystals
- Powder "Alpha Spectra B":
- ^{40}K: 1.25±0.11 mBq/kg or natK: (41.7±3.7) ppb - 210Pb: 3.15mBq/kg

Implemented several improvements in crystal purification. U/Th reduction by factor ~3 expected, while maintaining K levels.





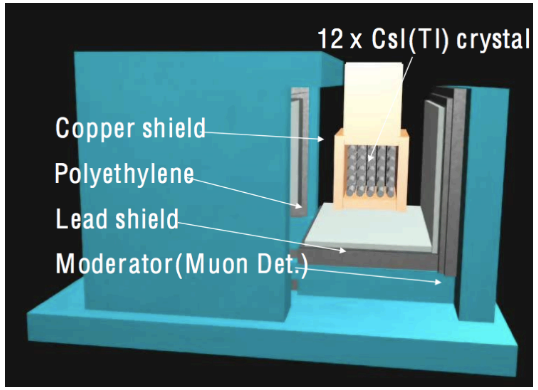
KIMS

WIMP search using CsI(Tl) at the Yangyang Underground Laboratory

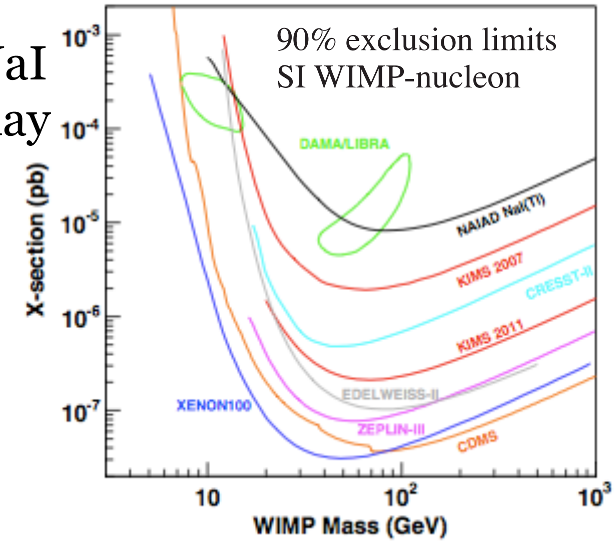
- A 12-module array of low background CsI(Tl) detectors, total mass 103.4 kg
- Each module is 8 x 8 x 30 cm³, with green-enhanced PMTs, 4-5 p.e./keV
- Total data exposed as published 24,324.3 kg.days

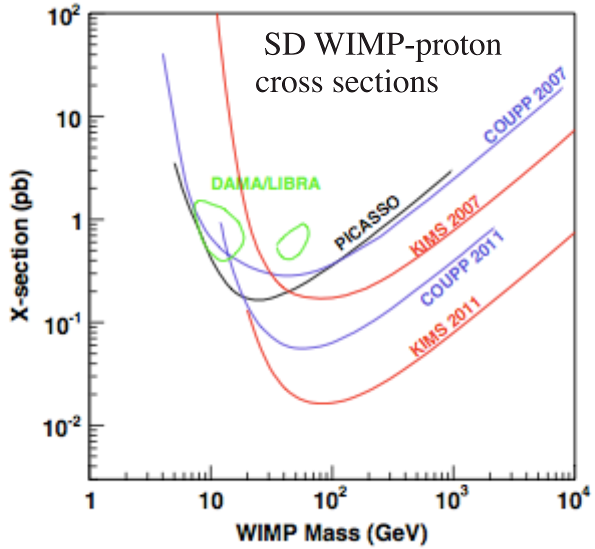
(1) WIMP search with PSD in CsI(Tl)

- Nuclear recoil (NR) event rate limit below DAMA/LIBRA annual modulation, disfavouring iDM model
- Electron equivalent 3-11 keV
- NR rate for 3.6-5.8 keV corresponds to 2-4 keV in NaI (Tl) is 0.0098 cts/kg/keV/day
- But QF issues also in CsI(Tl)!
- Now indicate ~30% correction?

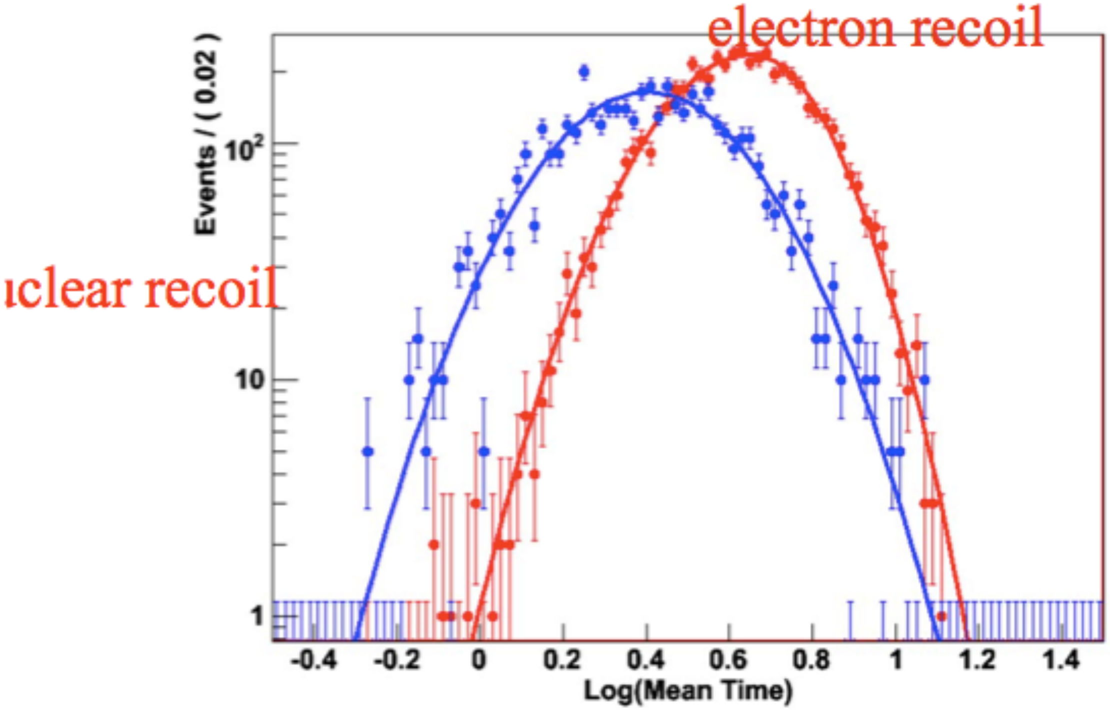


S.C. Kim et al., PRL 108 181301 (2012)





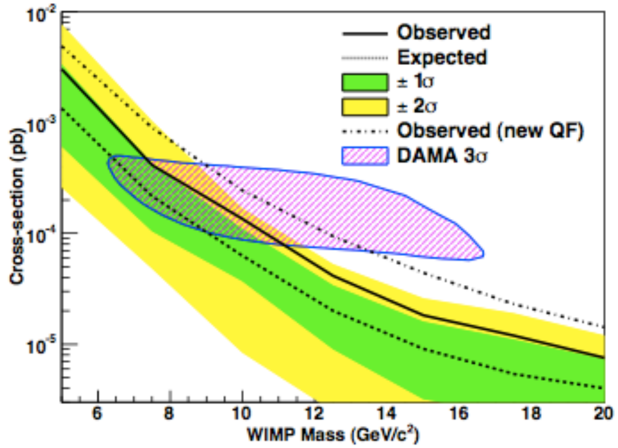
KIMS



electron recoil
ıclear recoil
Events / (0.02)
10^2
10
1
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
1.2
1.4
Log(Mean Time)

KIMS

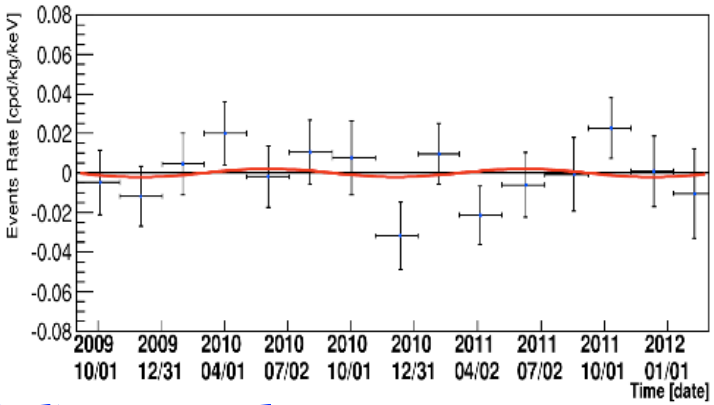
arXiv:1404.3443v1



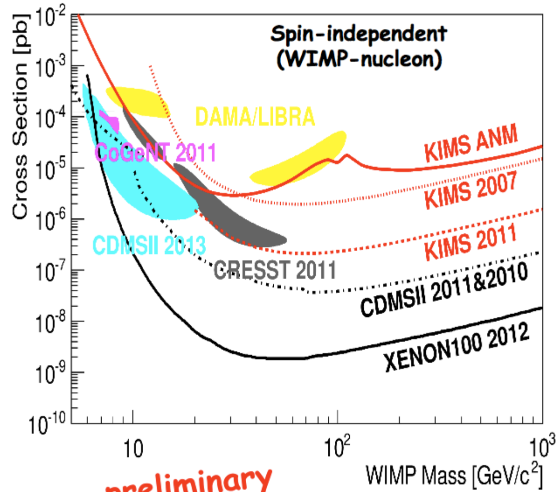
(2) Low WIMP mass such - no PSD

- Results of a search for low-mass WIMPs using 2 keV energy threshold applied to data from 2009-2010 runs.
- Previously used 3 keV to allow PSD

(3) Annual modulation attempt



< SI WIMP-nucleon Cross Section >



preliminary

(4) CsI(Tl) upgrade

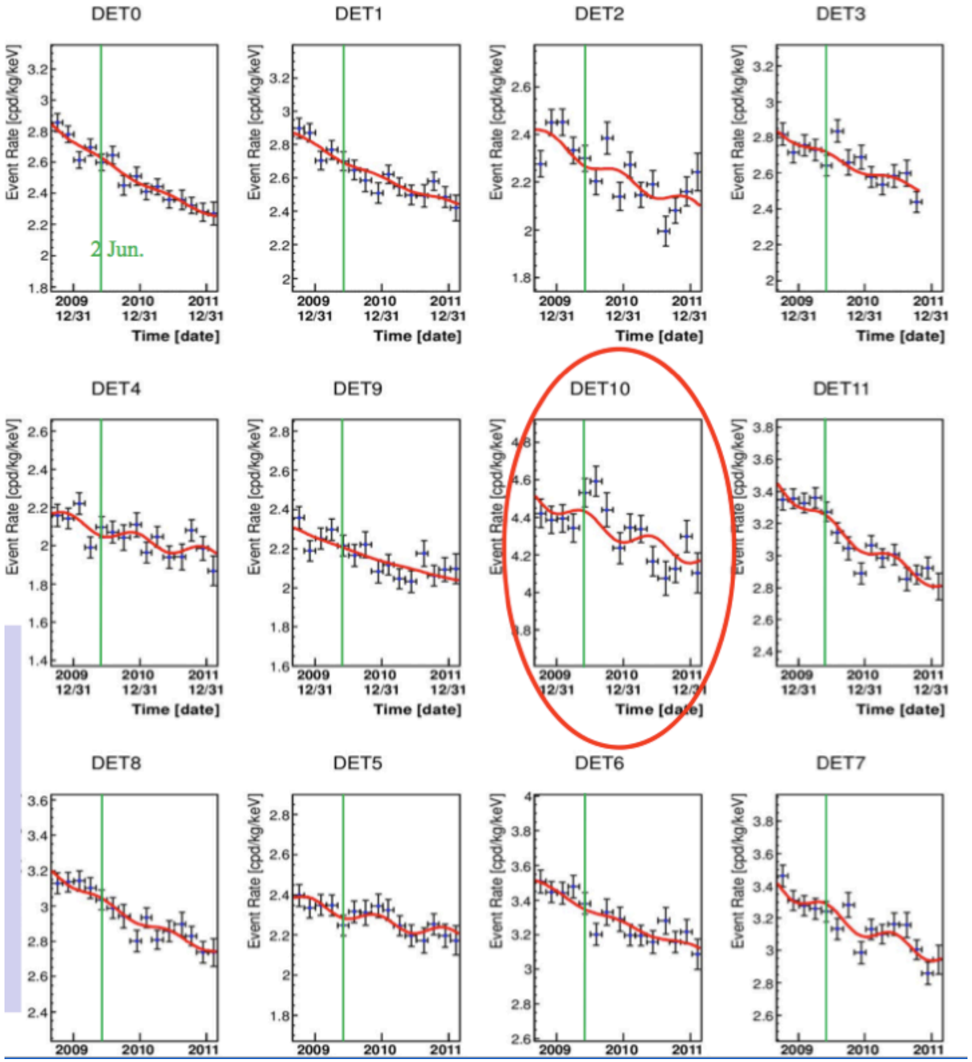
- Change PMTs to more sensitive and lower noise ones: lower threshold ~1.5 keV,

(5) NaI(Tl) development

- Programme on low background NaI(Tl) in collaboration (DM-ICE, ANAIS)
- First new NaI (Tl) crystals planned for 2014 in Y2L site

KIMS

Annual modulation amplitude is obtained including the exponential decay of ^{134}Cs for 2.5 years of data.



DM-ICE

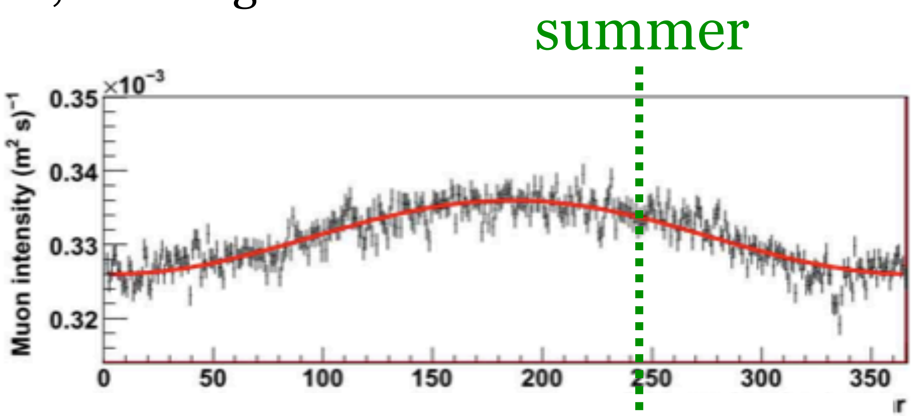
Recognises advantage of using an environment/location with different systematics - Southern Hemisphere

- Overburden 2500 m depth (2200 m.w.e.)
- ~85 muons/m²/day at bottom of IceCube, IceCube/DeepCore veto reduces rate by ~1-2 orders of magnitude, Ice is a good neutron moderator

- **LVD:**

Selvi, Proc. 31st ICRC. (2009)

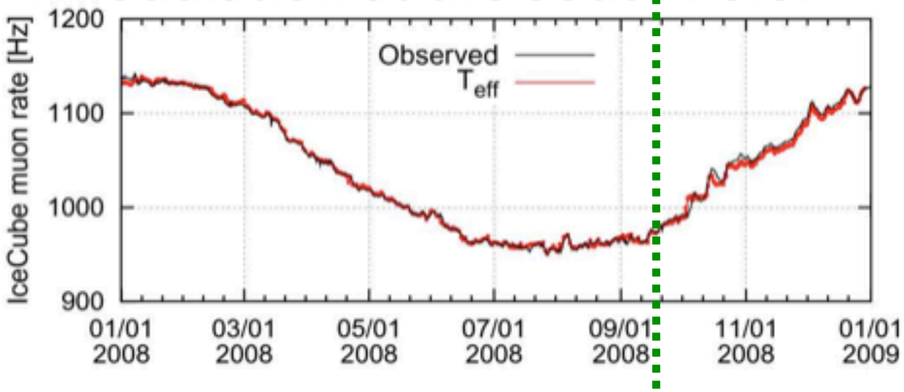
Gran Sasso



- **Opposite Muon modulation at the South Pole:**

Tilav, Proc. 31st ICRC. (2009)

South Pole



Muons and Seasonal Modulation

DM-ICE

An international collaboration with demonstrated track record in:
XENON, CUORE, NaIAD, SNO, IceCube, Daya Bay, KamLAND

30 scientists
11 institutions

Boulby Underground Science Facility
S. Paling

Columbia University
E. Aprile, A. Melgarejo

Fermilab
L. Hsu

NIST-Gaithersburg
P. Mumm

Purdue University
A. Brown, R. Lang

SNOLAB
B. Cleveland

University of Alberta
D. Grant

University of Sheffield
V. Kudryavtsev, M. Robinson, N. Spooner, S. Telfer,
L. Thompson, D. Walker

University of Illinois at Urbana Champaign
L. Yang

University of Wisconsin-Madison
J. Cherwinka, M. DuVernois, F. Halzen, A. Hubbard,
A. Karle, M. Kauer, W. Pettus, Z. Pierpoint, B. Reilly, T. Wise

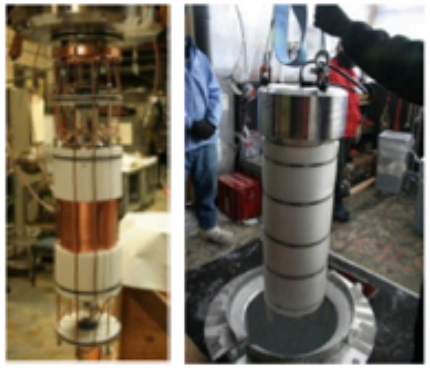
Yale University
J. Ashenfelter, K. Heeger, R. Maruyama*, B. Russell

**contact and spokesperson*

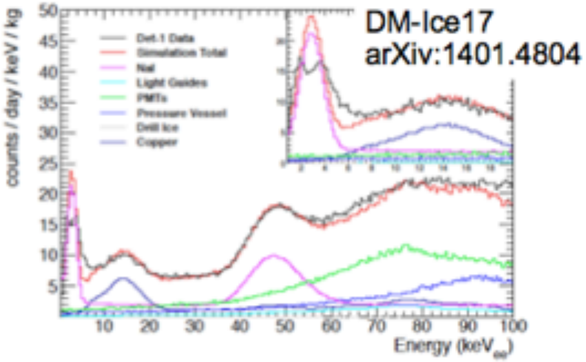
DM-ICE - a phased programme

Features
- low-background NaI(Tl) target
- movable detector array
- can run at the same time as DAMA, starting in 2016
- access to both Northern & Southern Hemispheres

DM-Ice17

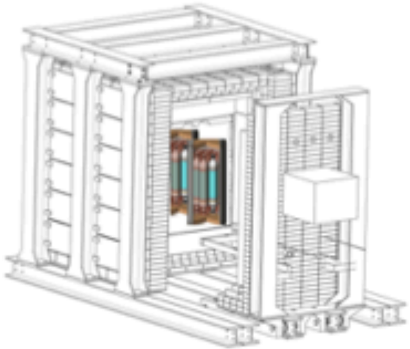


Test Detector at South Pole



17 kg of NaI(Tl) at 2450m depth
in operation since 2011

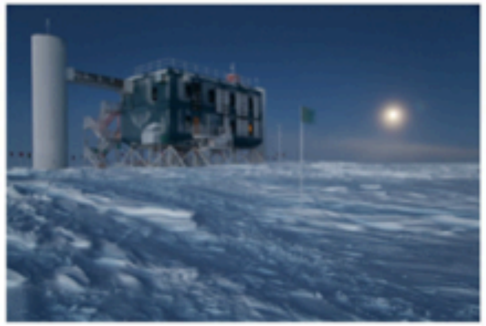
DM-Ice250 North



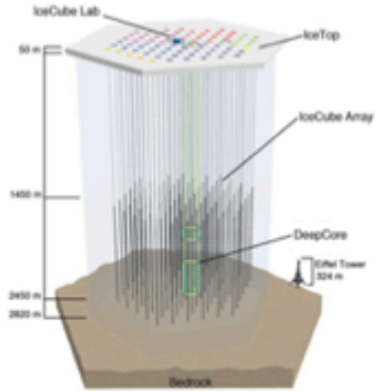
Modulation Search in Northern Hemisphere

portable 250kg NaI(Tl) array
existing shield, ready in 2015

DM-Ice250 South



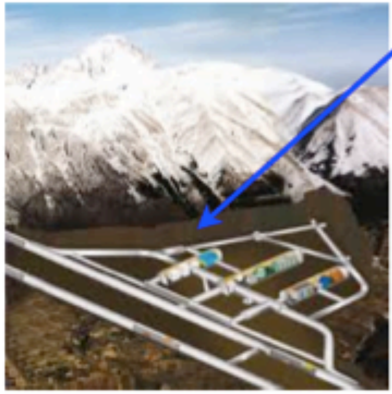
Modulation Search at South Pole

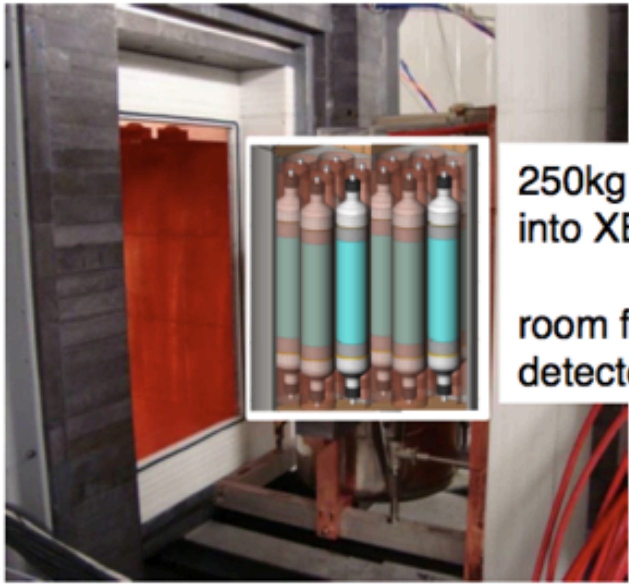


if modulation seen in North and
environmental effects ruled out

DM-ICE250 at LNGS - proposed phase I

Proposal to use XENON-100 shield for annual modulation search with NaI(Tl) starting 2015, prior to move to southern hemisphere





250kg of NaI(Tl) fit into XENON shield

room for other detectors (e.g. Ge?)

Detectors: Use 250kg of new, low-background NaI(Tl) detectors developed with Alpha Spectra, Inc in US. 36kg in hand and being tested. Remaining 220kg can be ready by end of 2015.

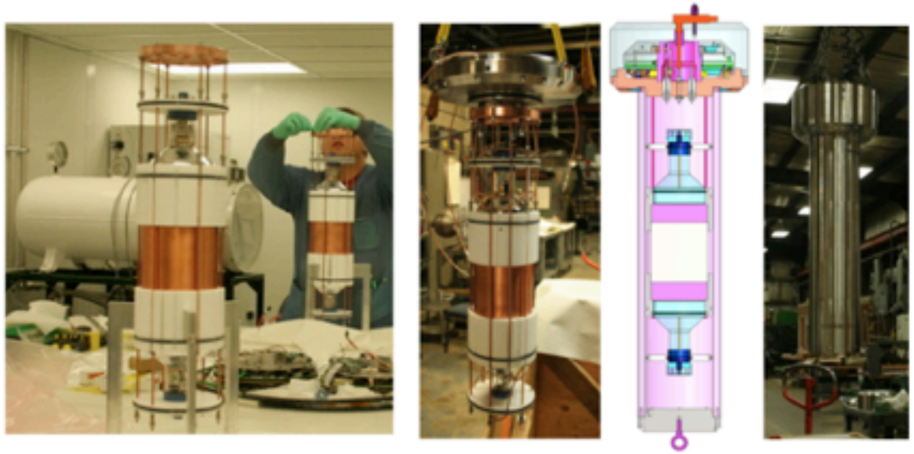
Shield: Make use of existing, well-understood XENON shield
- existing radio-assay of all shield materials
- Radon control (<1Bq/m^3)
- validated GEANT simulations

Infrastructure&Personnel: Modest upgrades required to hut for environmental control. Synergies with personnel of other experiments at LNGS.

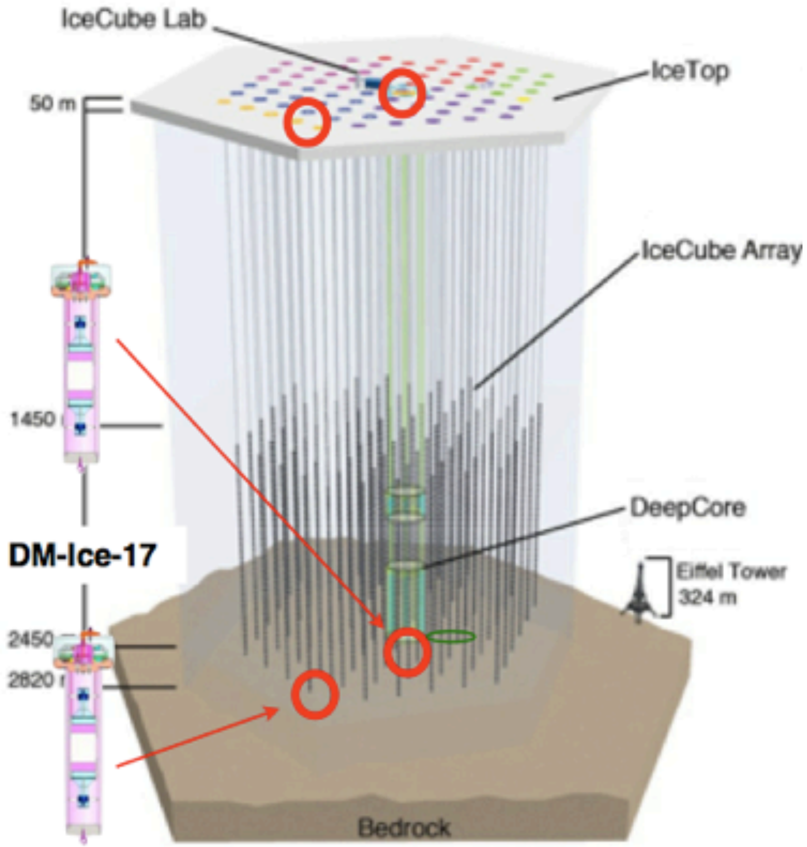
DM-ICE17 - South Pole proof of concept

17 kg test at South Pole - deployment, operation, data taking

Built in summer 2010

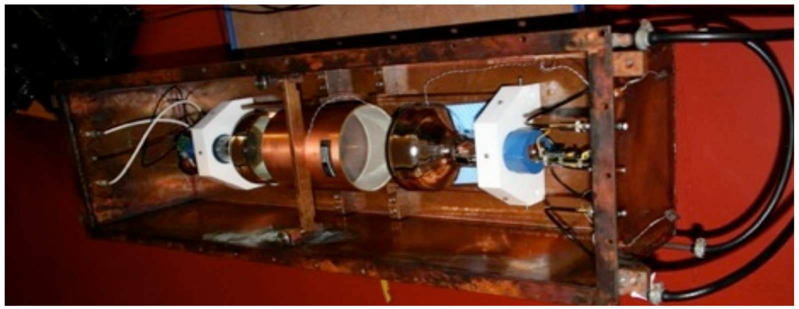


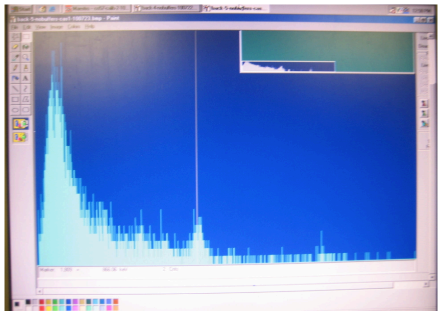
Deployed at the South Pole in December 2010



DM-ICE17 - re-use of NaIAD crystals

Tests of DM-ICE17 NaI at Boulby Lab at 1.1 km depth

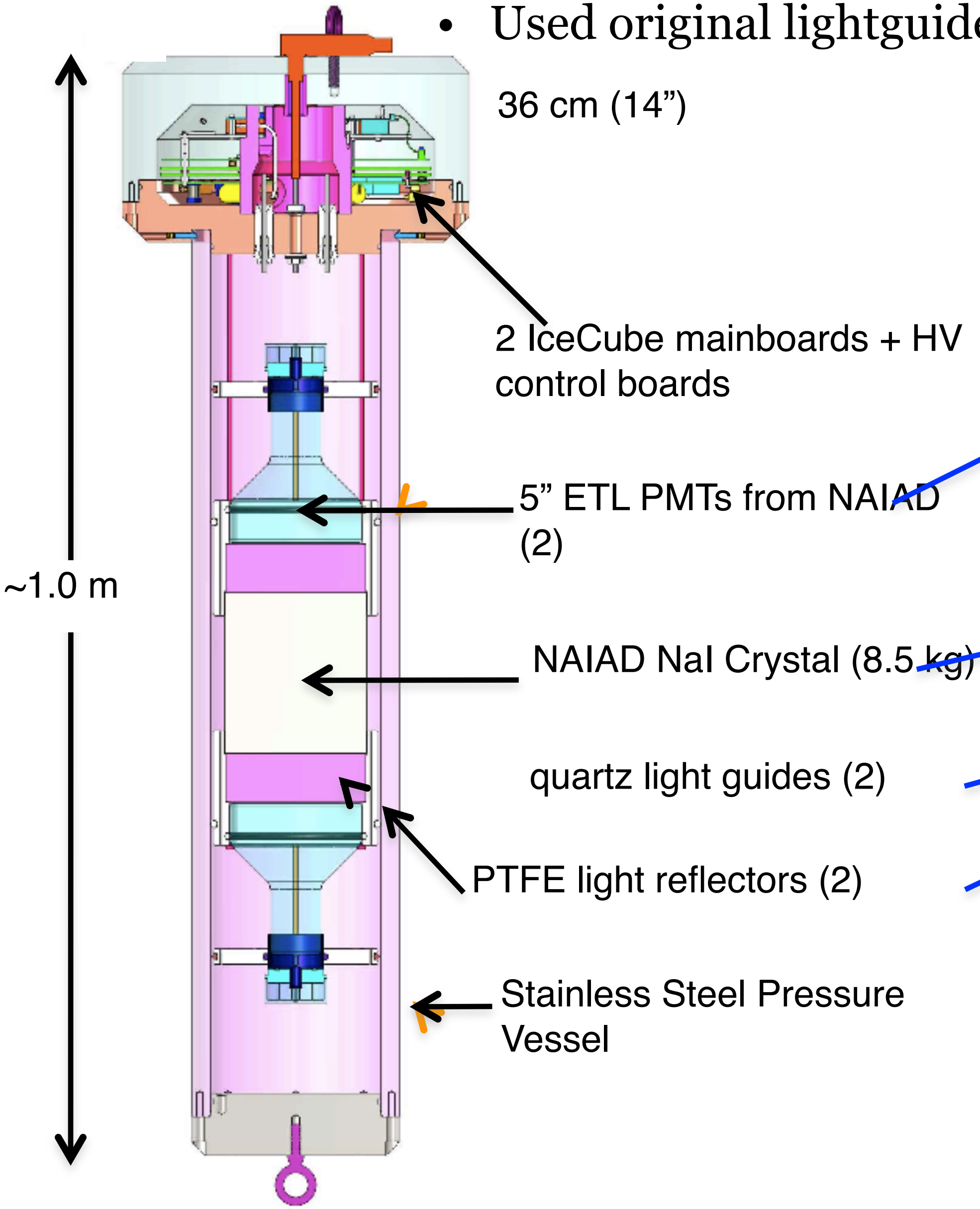


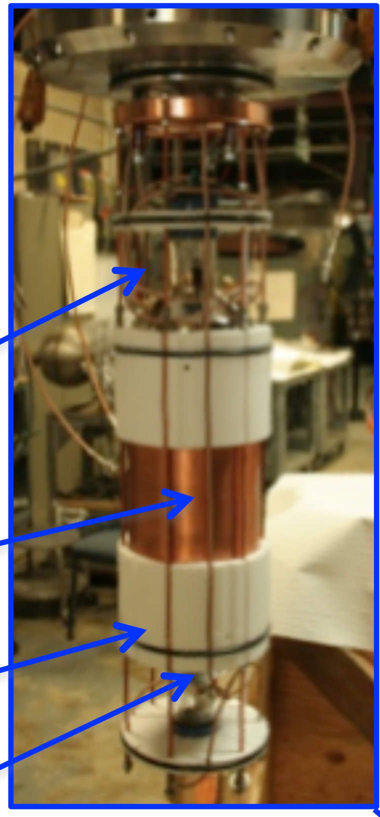


- Both crystals and PMTs tested and found to be in excellent condition
- Packed and shipped to Madison....

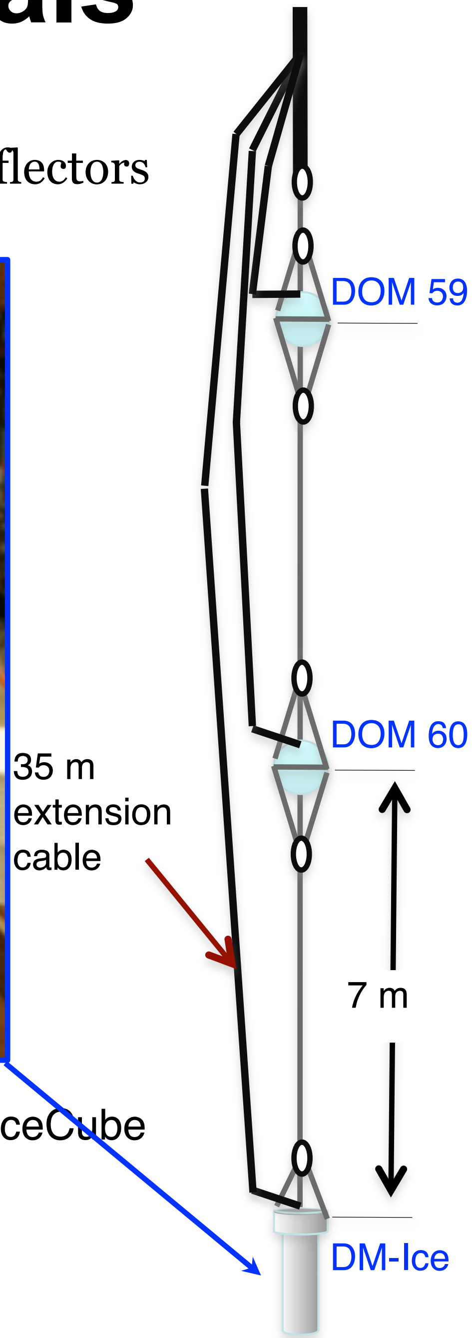
DM-ICE17 - detector internals

- Used original lightguides, PMTs, PTFE reflectors



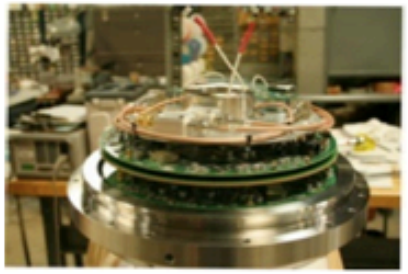


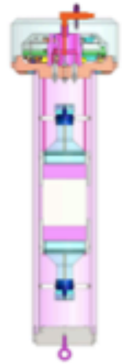
attached to end of IceCube strings



DM-ICE17 - first data

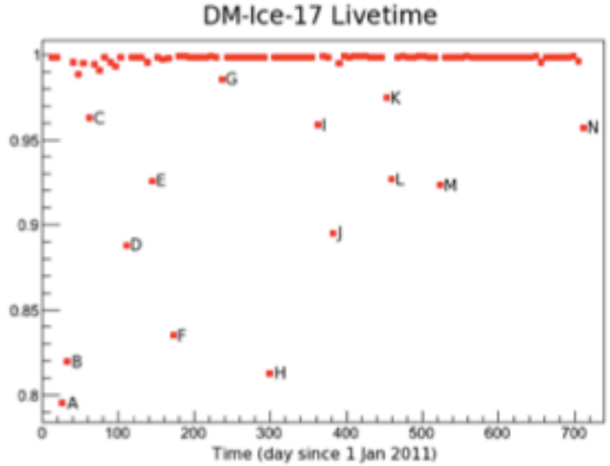
Test Detector Operation & Data





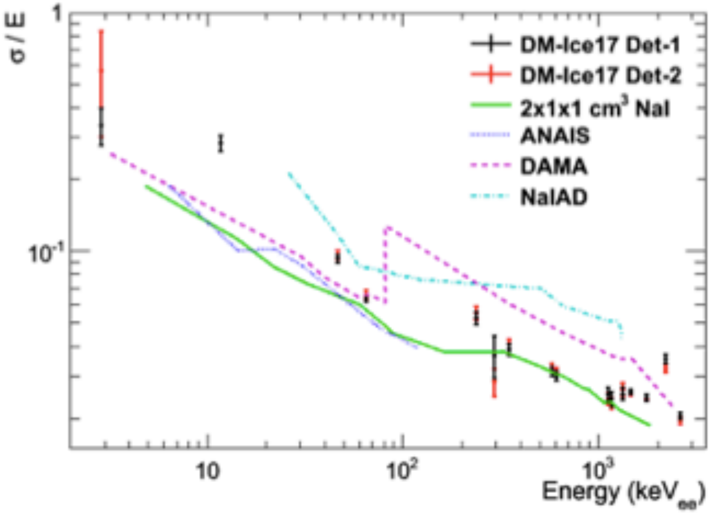
uses NaIAD crystals

Data run since June 2011, 99.8% uptime



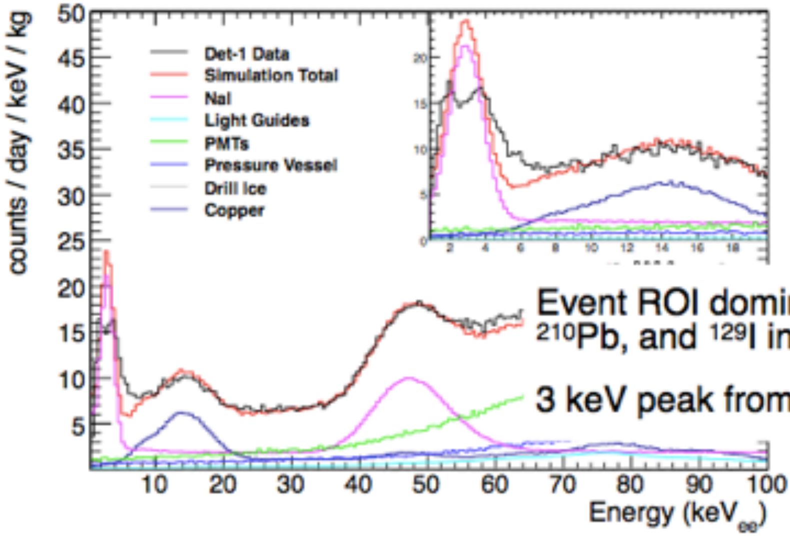
Light Collection and Energy Resolution

DM-Ice17: 4-6 pe/keV



DM-Ice Collaboration, arXiv:1401.4804v1

Energy Spectrum < 100 keV



Event ROI dominated by ^{40}K, ^{210}Pb, and ^{129}I in the crystal.

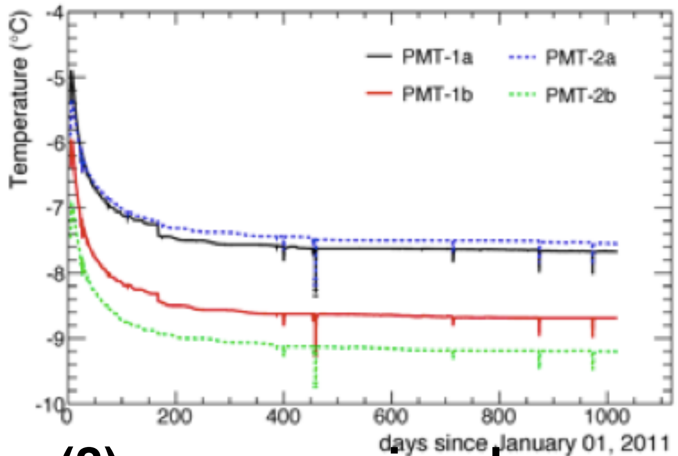
3 keV peak from ^{40}K observed

DM-ICE17 - operational stability

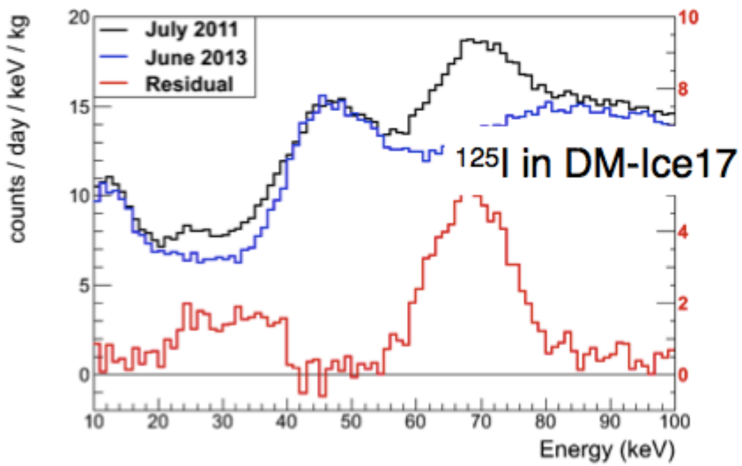
modulation analysis is hard

Detector has run continuously for ~2.5 years, demonstrating feasibility of SP deployment. Careful analysis does reveal the challenge of searching for a modulation signal that is not an experimental artefact particularly with use of "internal" calibration. It is quite easy to find fluctuations!

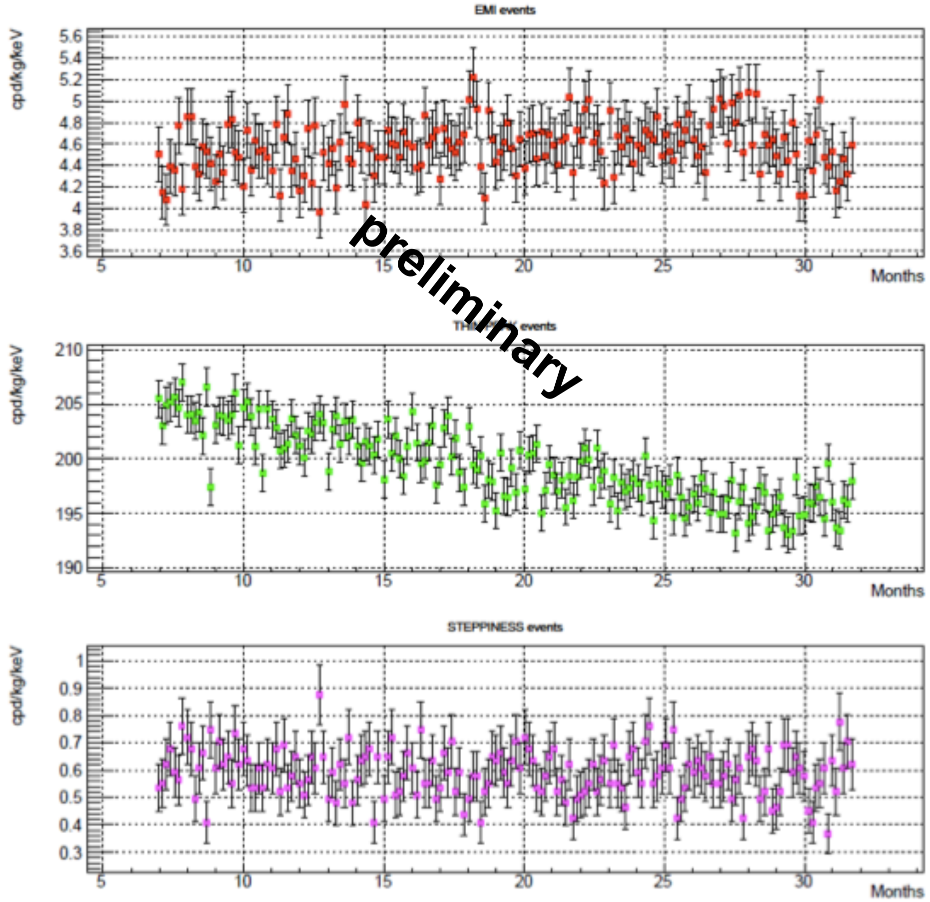
(1) temperature decay



(2) cosmogenics decay



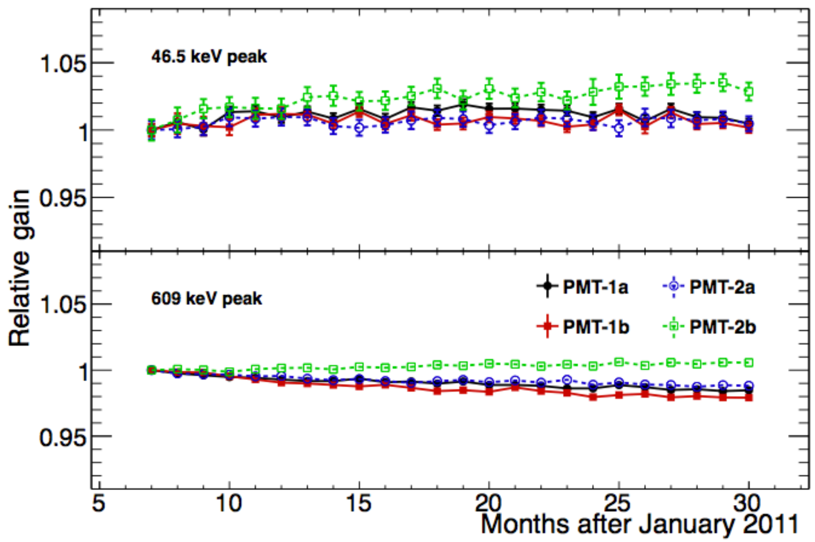
(3) example noise populations (4-6keV)



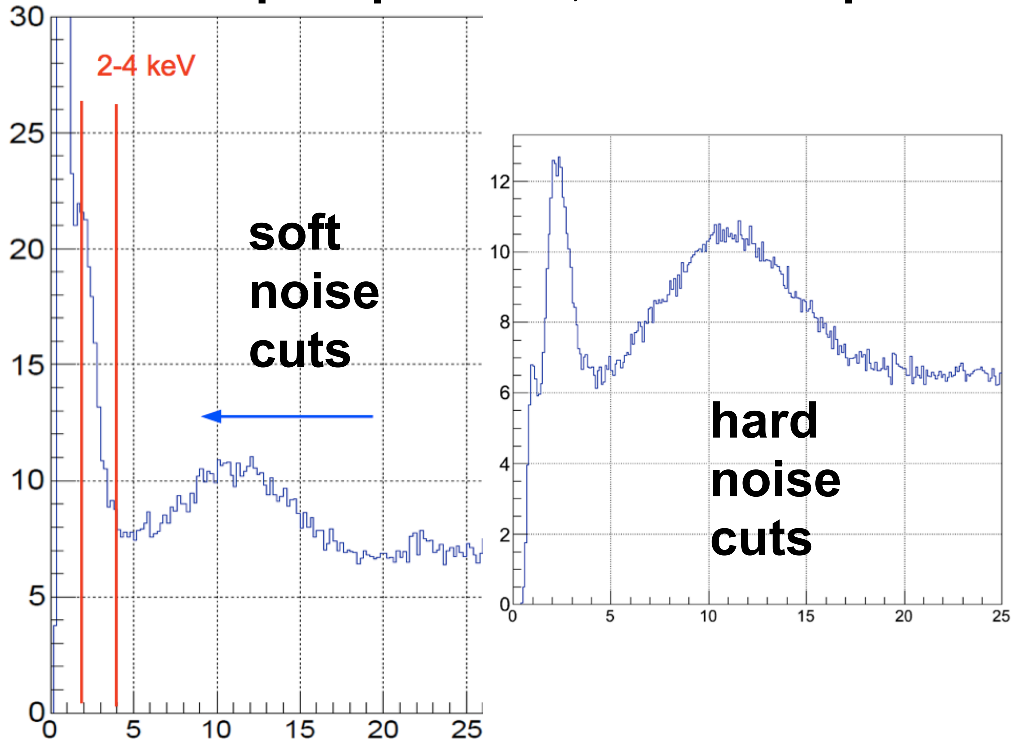
DM-ICE17 - operational stability

modulation analysis is hard

(4) <1 % gain shift



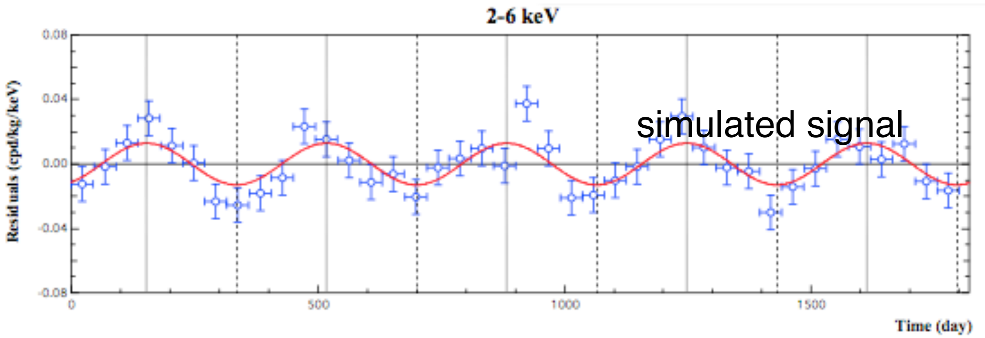
example spectrum, 3 KeV ^{40}K peak



- Even a <0.8% gain shift over 24 months is important to understand in detail because of the potential effect in noise cuts
- The combination of slight gain shifts, any changes in the rate of different noise classes, any residual cosmogenic decay can easily mimic both rises and falls in signal rates in the 2-6 keV region
- Probably at >3 years data will be needed to allow a full check

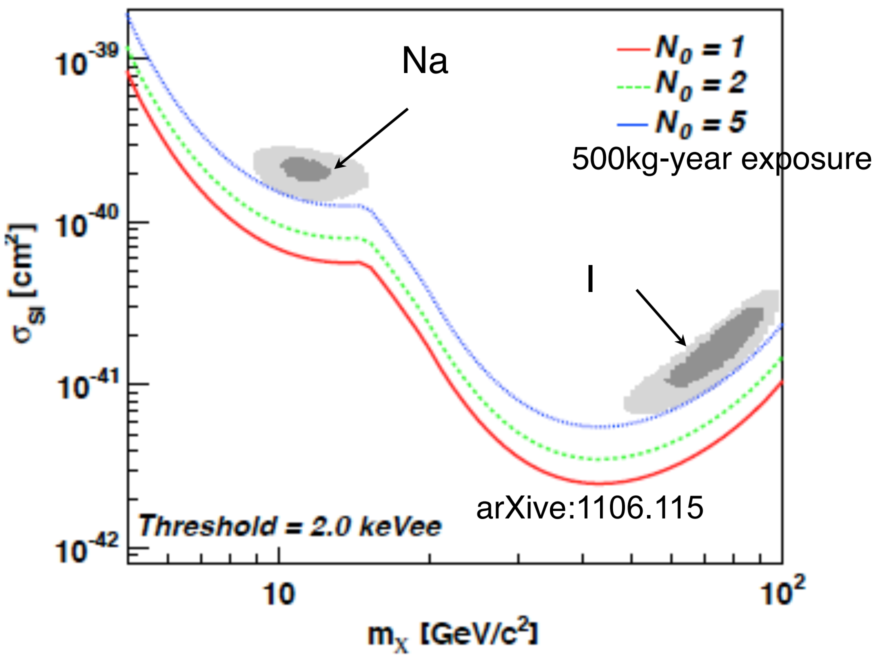
DM-ICE250 - sensitivities

Model-Independent: Assume DAMA-like signal, statistics



		2 NAIAD	NAIAD size	DAMA size
	Years	17.0 kg	44.5 kg	250 kg
NAIAD background	1	0.45	0.72	1.71
	3	0.77	1.25	2.96
	5	1.00	1.61	3.82
	7	1.18	1.91	4.52
50% NAIAD background	1	0.63	1.02	2.42
	3	1.09	1.77	4.18
	5	1.41	2.28	5.40
	7	1.67	2.70	6.39
Double DAMA background	1	0.85	1.37	3.26
	3	1.47	2.38	5.64
	5	1.90	3.07	7.29
	7	2.25	3.64	8.62
DAMA background	1	1.20	1.94	4.61
	3	2.08	3.37	7.98
	5	2.69	4.35	10.31
	7	3.18	5.14	12.19
1/10 DAMA background	1	3.80	6.15	14.57
	3	6.58	10.65	25.24
	5	8.50	13.75	32.59
	7	10.06	16.27	38.56

Spin-Independent



- 5-σ detection of DAMA-like signal with a 250-kg / 2-year running time (2 - 4 keV) and comparable backgrounds to DAMA

Conclusions

- Scintillation continues to play a key part in the quest
- But as ever the key issue, that probably causes the confusion is:

$$\begin{pmatrix}\text{event}\\ \text{rate}\end{pmatrix} = \begin{pmatrix}\text{detector}\\ \text{response}\end{pmatrix} \times \underbrace{\boxed{\begin{pmatrix}\text{particle}\\ \text{physics}\end{pmatrix}}}_{\text{FIXED}} \times \underbrace{\boxed{(\text{astrophysics})}}_{\text{FIXED}}$$

from Paolo Gondolo