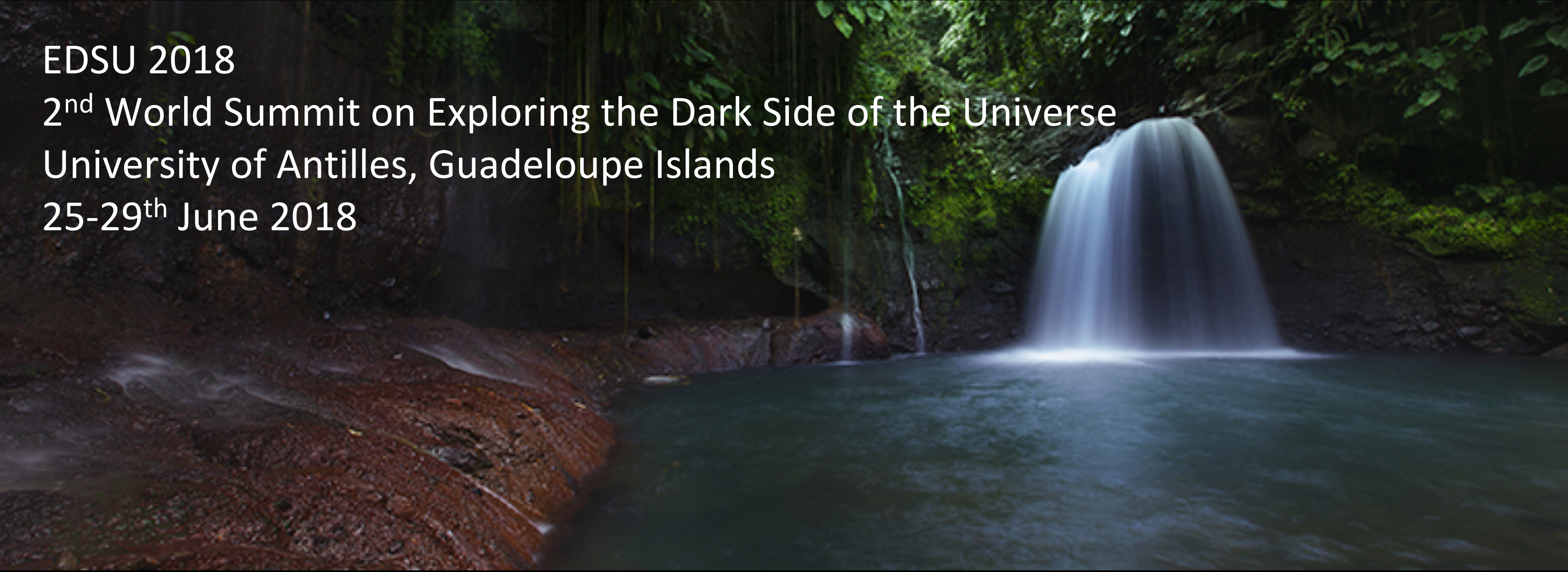


EDSU 2018
2nd World Summit on Exploring the Dark Side of the Universe
University of Antilles, Guadeloupe Islands
25-29th June 2018

Unraveling the mystery of Dark Matter's annual modulation

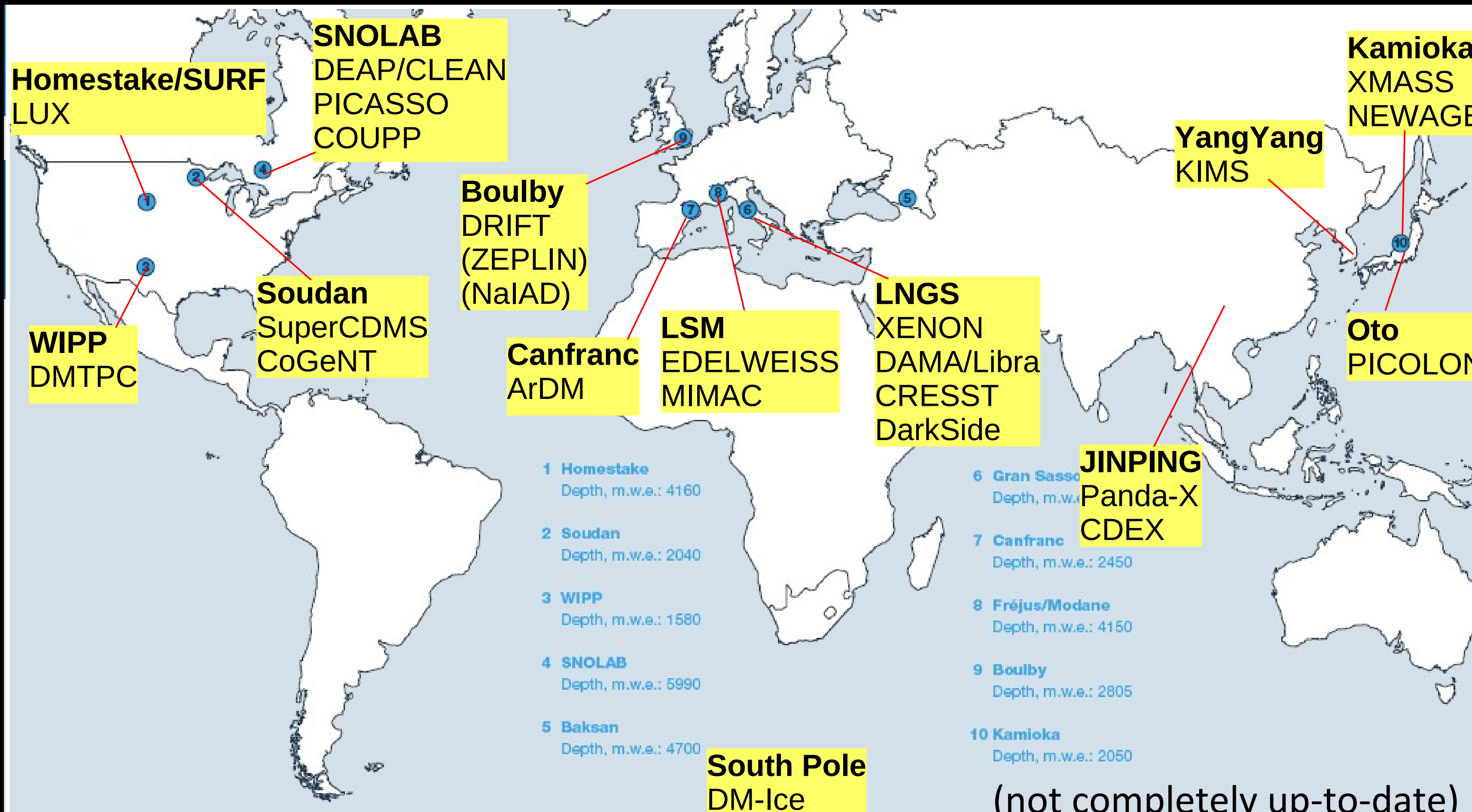
Davide D'Angelo
Università degli Studi di Milano and INFN

Overview

- What I will NOT discuss:
  - Why we believe there is Dark Matter
  - What we believe Dark Matter could be
  - The 3 ways to look for Dark Matter
    - Indirect, Direct, Collisions
  - The Standard Halo Model
  - What are the techniques for direct search
    - solid states, scintillators, bolometers, noble gases, …. and many many more.

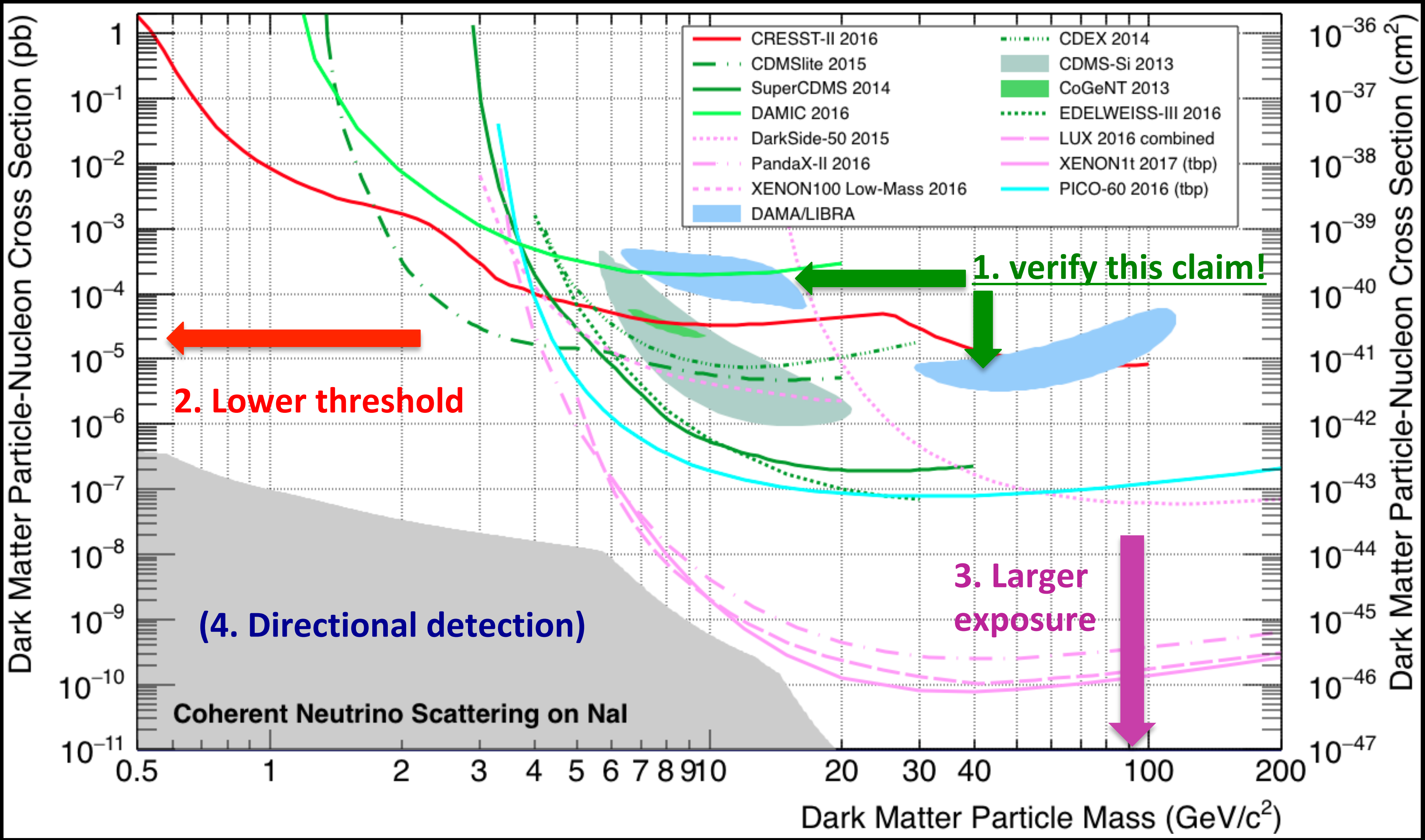
- What I will (try to) discuss:
  - Road map in direct search
  - Annual modulation signature
  - The DAMA claim
  - The new DAMA/LIBRA-Phase 2 results
  - Attempts to verify the claim
    - SABRE
    - DM-ICE
    - COSINE
    - ANAIS
  - Conclusions

Direct Dark Matter experiments



What are these guys trying to do?

3-steps direct search roadmap?



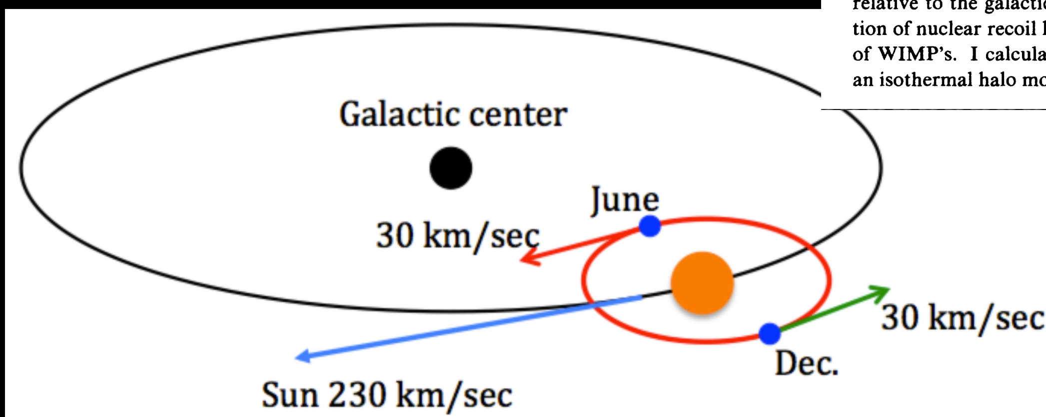
Plot by F. Rendl, Taup 2017

The Modulation DM signature

Motion of the Earth and the detection of weakly interacting massive particles

David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.



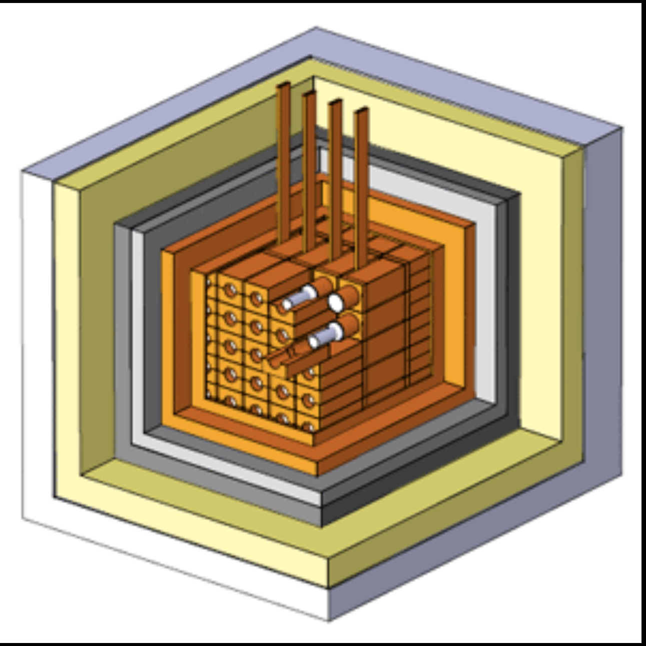
Spergel 1987

$$\frac{dR}{dE_R}(t) = S_0(E_R) + S_m(E_R)\cos\omega(t - t_0)$$

Annual modulation is a <u>model independent</u> signature of Dark Matter interaction

DAMA/LIBRA

- Underground location: LNGS
- Technique: NaI(Tl) scintillating crystals
- Detector's module:
  10kg crystal
  paired with two 3" PMTs
  - Light guides are used to keep PMTs distant from crystals and reduce background



- Geometry: 5x5 crystal matrix
- Total mass: ~250kg
- Energy threshold: 2keV → **1kev (new!)**

DAMA timeline

1. DAMA/NaI (100kg): 1996-2002
2. DAMA/LIBRA (250kg) Phase I : 2003-2010
   – Mass upgrade

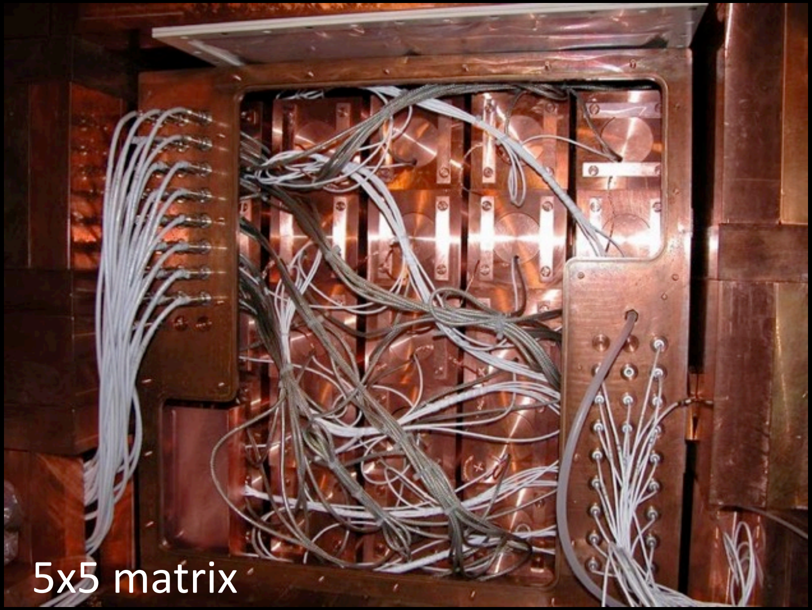
R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648.

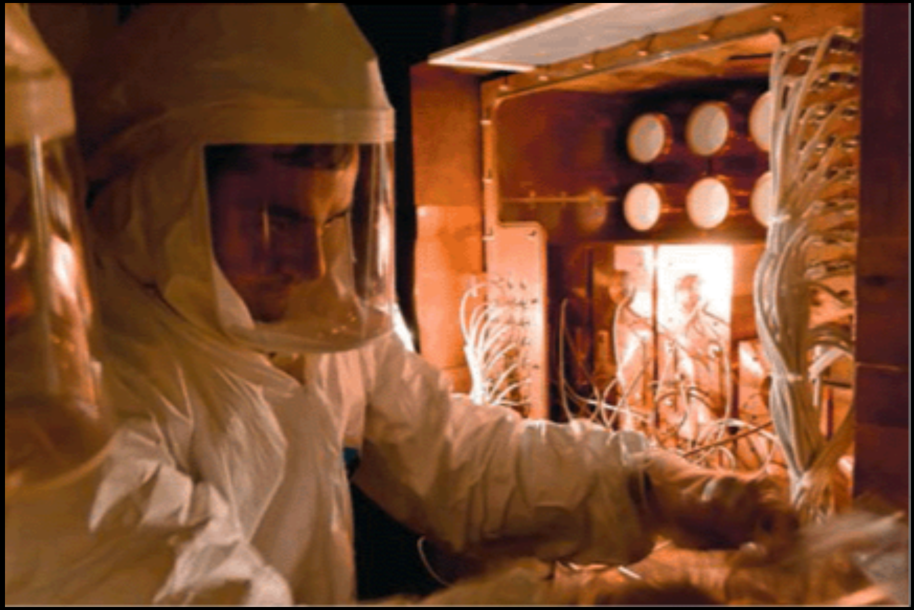
3. DAMA/LIBRA (250kg) Phase II: 2011-2017
   – New PMTs (low radioactivity, low noise)

Results released 1 month ago!

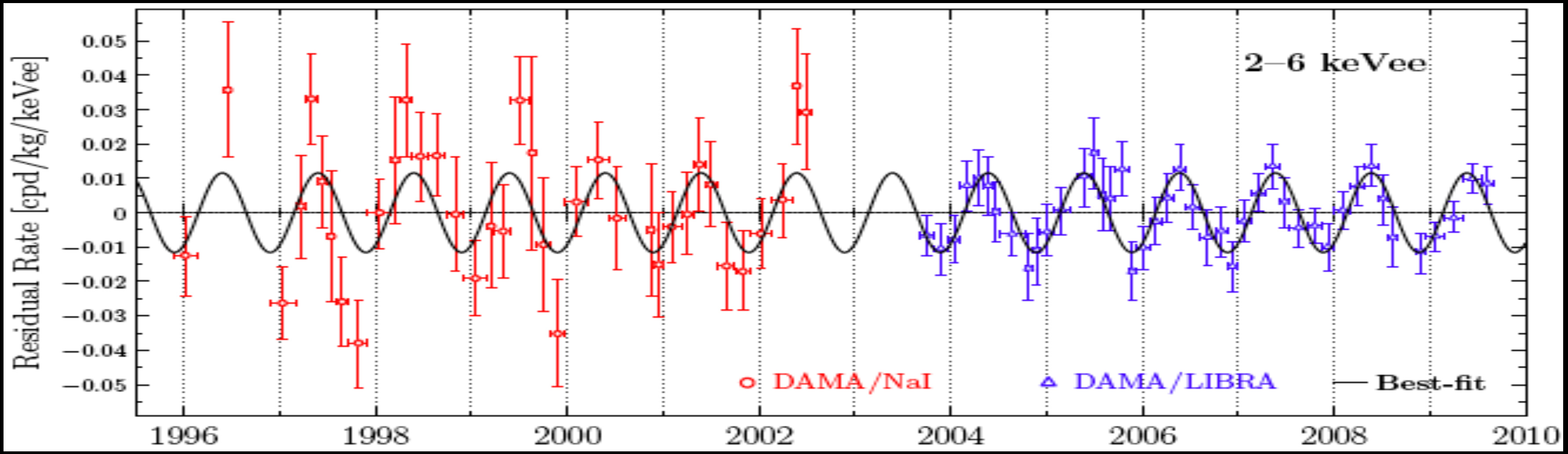
arXiv:1805.10486

4. DAMA/LIBRA (250kg) Phase III: ???
   – No light guides?



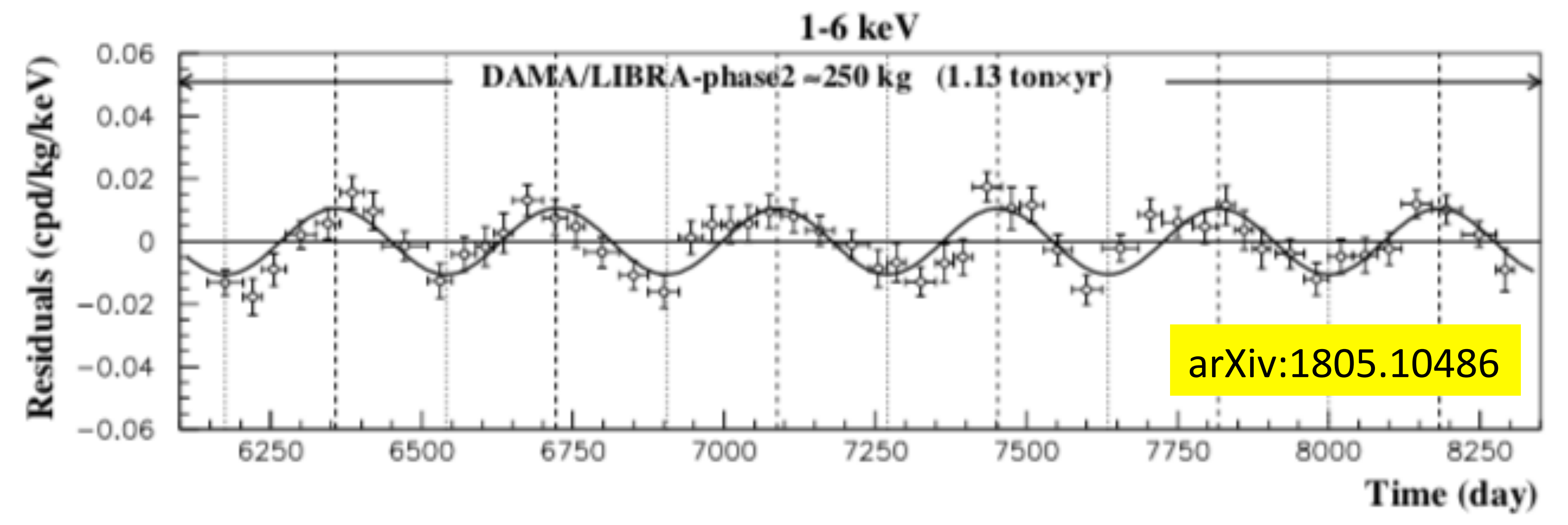


The DAMA modulation
DAMA/NaI + DAMA/LIBRA-Phase1



- 13 annual cycles (Dama/NaI + Dama/Libra)
- Exposure: 1.33 ton x yr
- χ^2/ndf = 70.4/86 (NaI+Ph1)
- 9.3σ significance
- (0.998±0.002) year period
- Phase is (144±7) days vs. Exp. DM phase 152.5 days
- Amplitude (0.0112±0.0012) cdp/kg/keV , i.e. ~ 1% of the experimental rate.

…and now including DAMA/LIBRA-Phase2



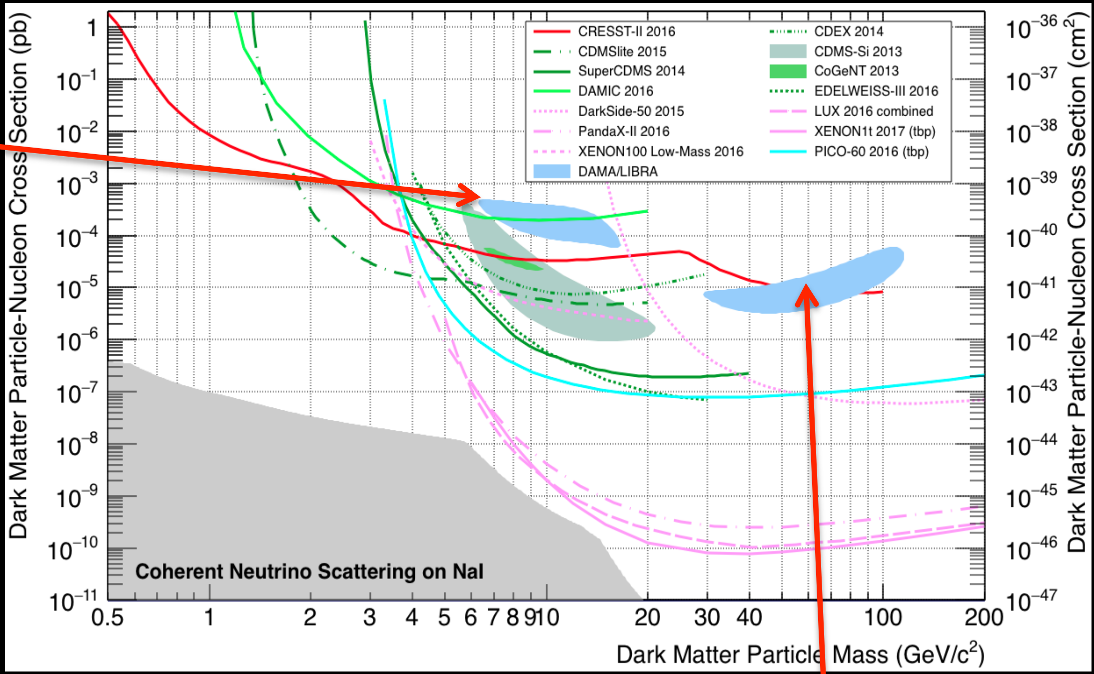
- 20 annual cycles (DAMA/NaI + DAMA/LIBRA-Phase1 + DAMA/LIBRA-Phase2)
- Exposure: 2.46 ton x yr
- χ^2/ndf = 150/52 (Ph2-only 1-6keV); 199/102 (Ph1+Ph2 2-6keV)
- 12.9σ significance
- (0.999±0.001) year period
- Phase is (145±5) days vs. Exp. DM phase 152.5 days
- Amplitude: (0.0103±0.0008) cdp/kg/keV, i.e. ~ 1% of the experimental rate.

Interpretation of DAMA/NaI + DAMA/LIBRA-Phase1 results

Interaction on Na nuclei

M_{wimp} ~ 10 GeV

$\sigma \sim 10^{-40}$ cm^2



In the simplest interpretation of SI WIMP-nucleus interaction there are two allowed regions with very similar χ^2

Interaction on I nuclei

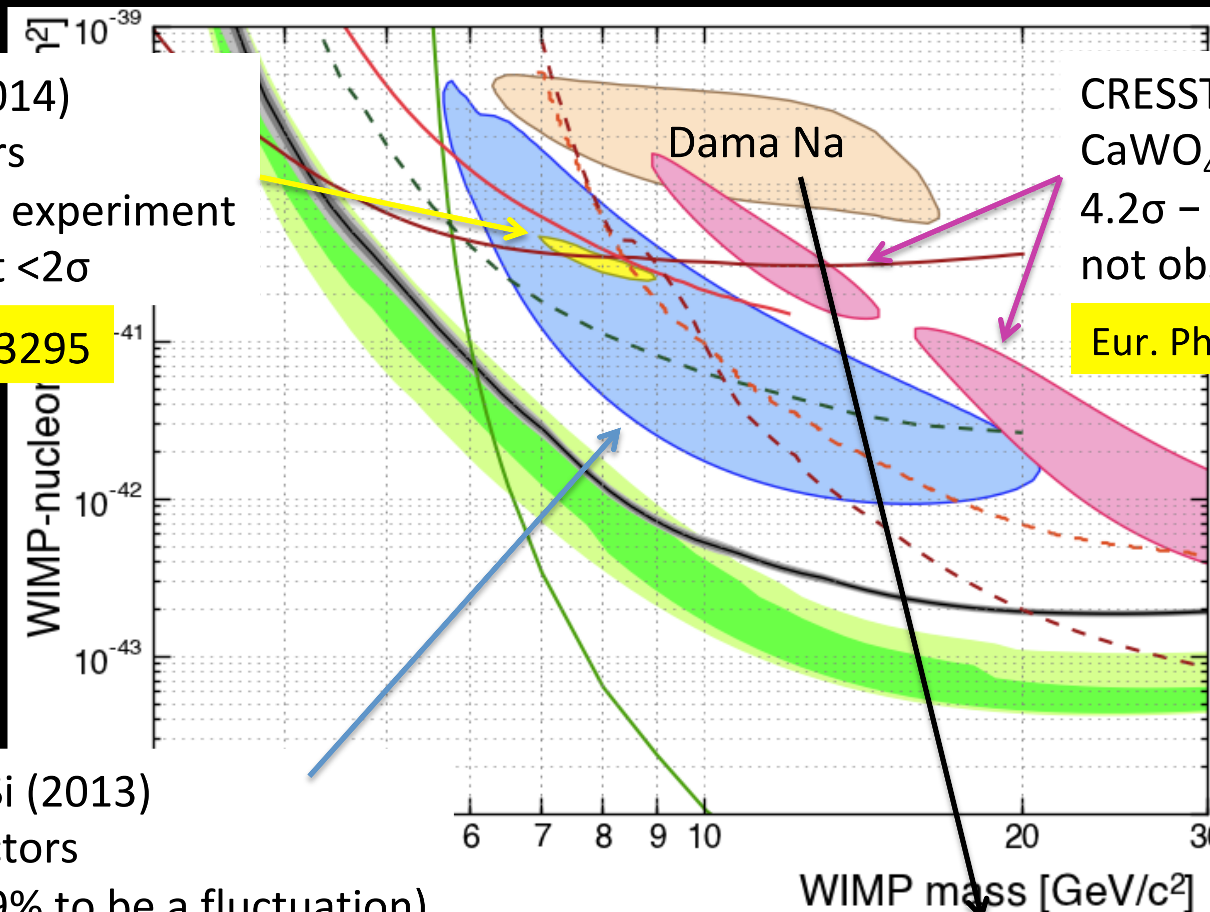
M_{wimp} ~ 80 GeV

$\sigma \sim 10^{-41}$ cm^2

However there are several assumptions here:

- ✓ Astrophysics: DM halo
- ✓ Dark matter candidate: WIMP
- ✓ Nature of interaction: elastic and Spin Independent
- ✓ Target of Interaction: nuclei

What about other positive results?



CoGeNT (2014)
Ge detectors
modulation experiment
latest result <2σ

arXiv:1401.3295

CRESST-II (2011)
$CaWO_4$ bolometers
4.2σ – 4.7σ
not observed in new setup

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

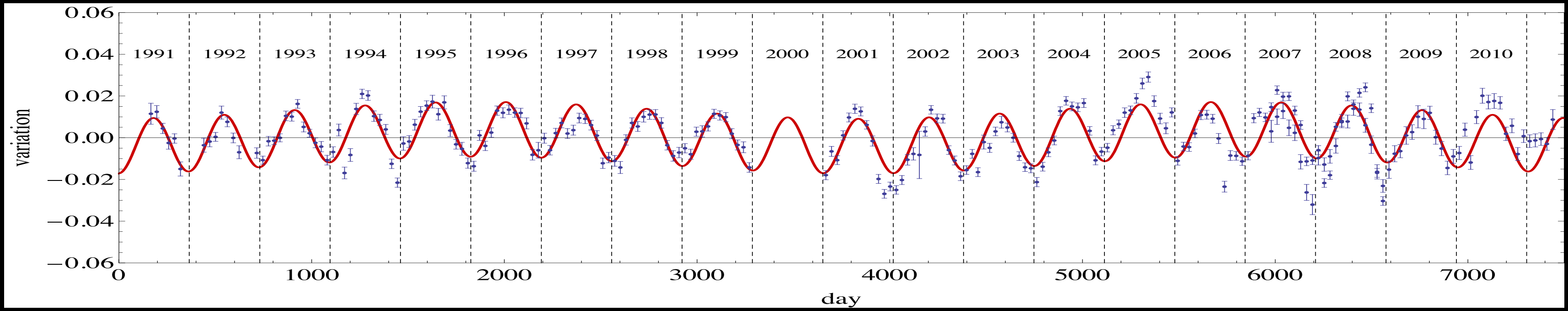
CDMS-Si (2013)
Si detectors
3σ (0.19% to be a fluctuation)
not observed in Ge

PRL 111 (2013) 251301

DAMA is the only truly significant

DAMA alternative explanations?

- The rate of cosmogenic muons is known to modulate due to seasonal expansion/contraction of the troposphere which changes the pion/kaon mean free path.
- Could muon-induced background such as nuetrons explain D/L modulation?
- Could there be other explanations of terrestrial origin? (e.g. radon emanation)
- Long standing questions: tens of papers written on the subject.
- **No convincing alternative explanation so far**

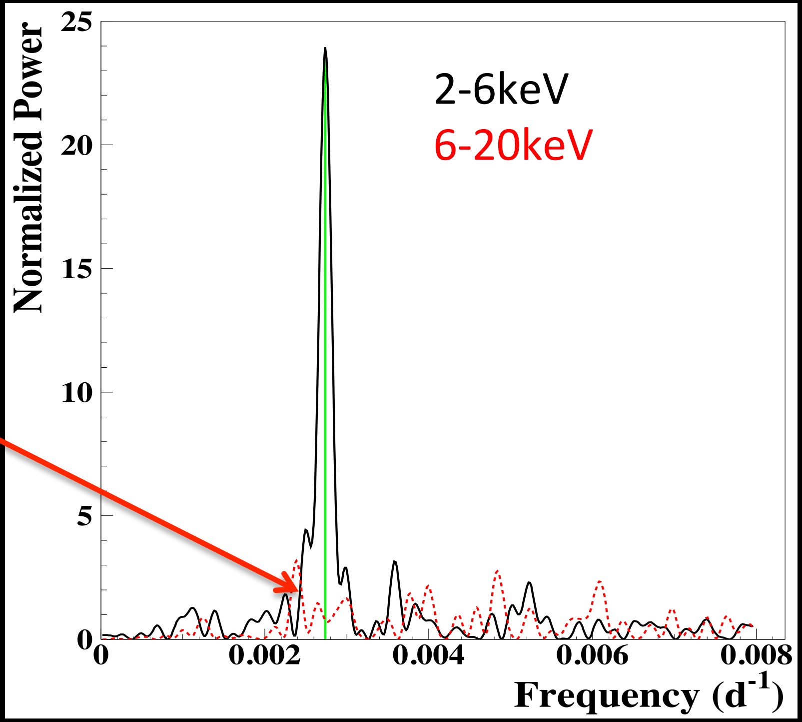


Combined MACRO+LVD+Borexino muon flux modulation

Why is DAMA/LIBRA robust?

1) All instrumental sources of modulations have been investigated and excluded:

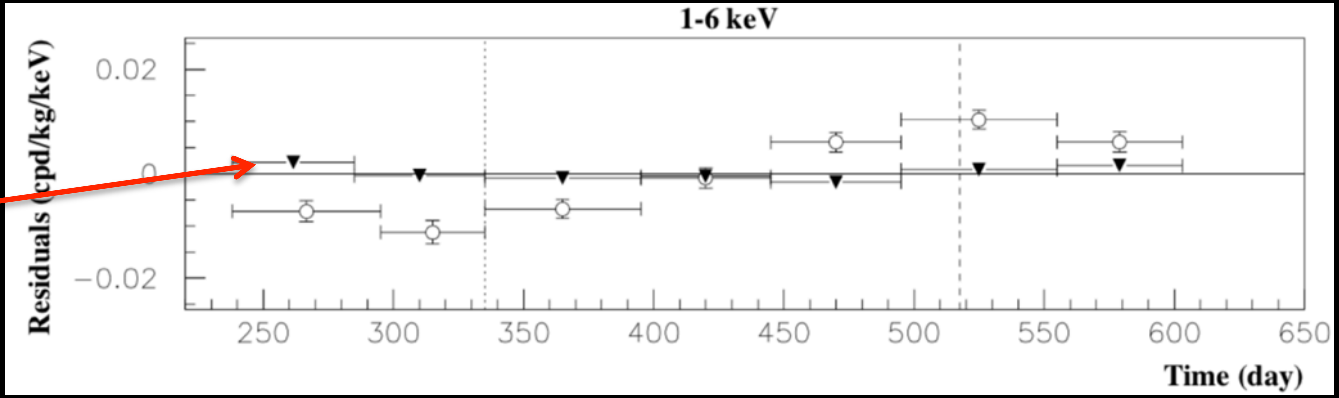
- ✓ radon
- ✓ temperature
- ✓ gas pressure
- ✓ noise
- ✓ energy scale
- ✓ efficiencies
- ✓ environmental neutrons



4) No modulation > 6keV

2) Phase: (145±5)d
cmp. muon: (182±6)d

3) No modulation in multi-hit events



A complex scenario

- DAMA results are "in tension" with several other experiments
  - but only assuming basic SI WIMP-nucleus interaction.
- Other experiments are counting experiments and use different target materials
  - <u>comparison is model dependent</u>
- DAMA has strong arguments to sustain the result
  - Several attempts to explain D/L in terms of background have been made -> **none convincing**.
- *A new measurement with the same target and technique is needed!*

A complex scenario

Low-mass compatibility and theoretical interpretations

H. Hooper, J. Collar, J. Hall, D. McKinsey, C. Kelso, PR D 82 (2010) 123509.

C. Savage et al., JCAP 04 (2009) 010.

P.W. Graham et al., PR D 82 (2010) 063512.

D. Hooper, Phys. Dark Univ. 1 (2012)

B.M. Roberts et al., PRL 116 (2016) 023201

R. Cerulli et al., EPJ C (2017) 77:83

  - comparison is model dependent
- DAMA has strong arguments to sustain the result
  - Several attempts to explain D/L in terms of background have been made -> **none convincing**.
- *A new measurement with the same target and technique is needed!*

Environmental backgrounds (Cosmic muons)

J. P. Ralston, (2010) arXiv:1006.5255

K. Blum, (2011) arXiv:1110.0857

E. Fernandez-Martinez and R. Mahbubani, JCAP 07 (2012) 029

S. Chang, J. Pradler and I. Yavin, PR D 85 063505 (2012)

J. Pradler, (2012) arXiv:1205.3675

R. Bernabei et al. (DAMA coll.), IJMP A 28 (2013) 1330022

D. Nygren arXiv:1102.0815 (2012) <- delayed phosphor. by UV irradiation

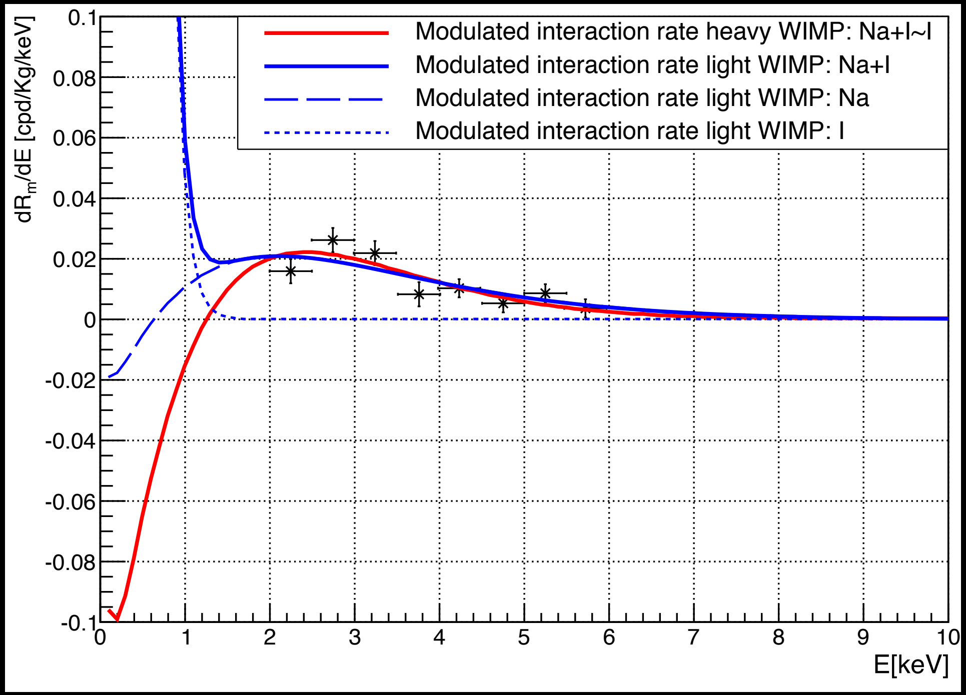
D.N. McKinsey, arXiv:1803.10110 (2018) <- Argon background (!?)

and many many more....

- DAMA has strong arguments to sustain the result
  - Several attempts to explain D/L in terms of background have been made -> **none convincing**.
- *A new measurement with the same target and technique is needed!*

Why is it important to go to low energy?

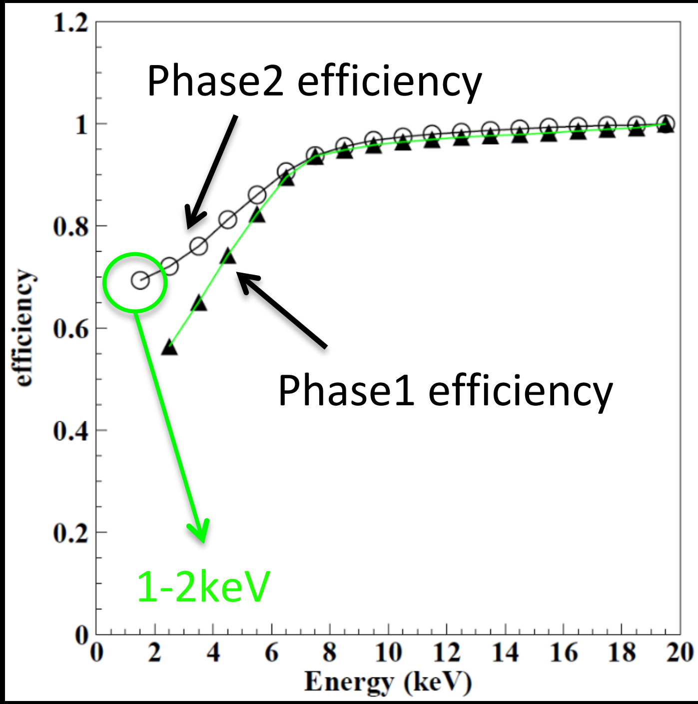
- Fit to the DAMA (NaI+Ph1) modulation amplitude returns light and heavy WIMP solutions.
- They differ below 2keV



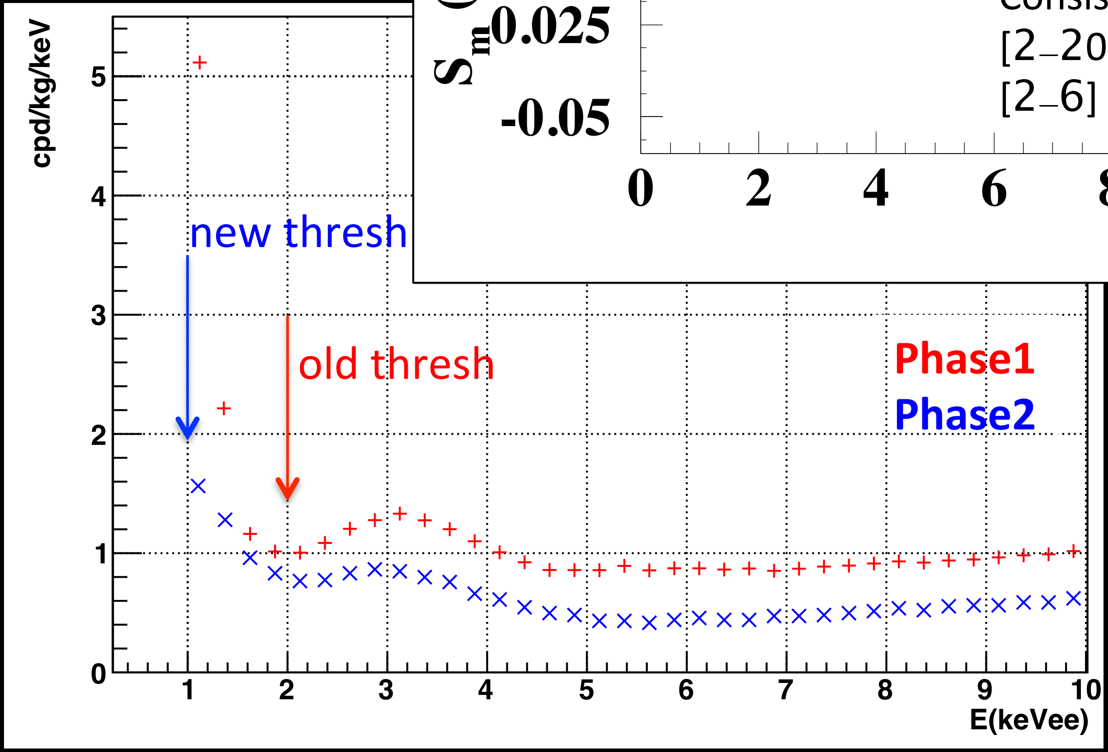
see also:
K. Freese, M. Lisanti, and C. Savage, Rev. Mod. Phys. 85 (2013) 1561

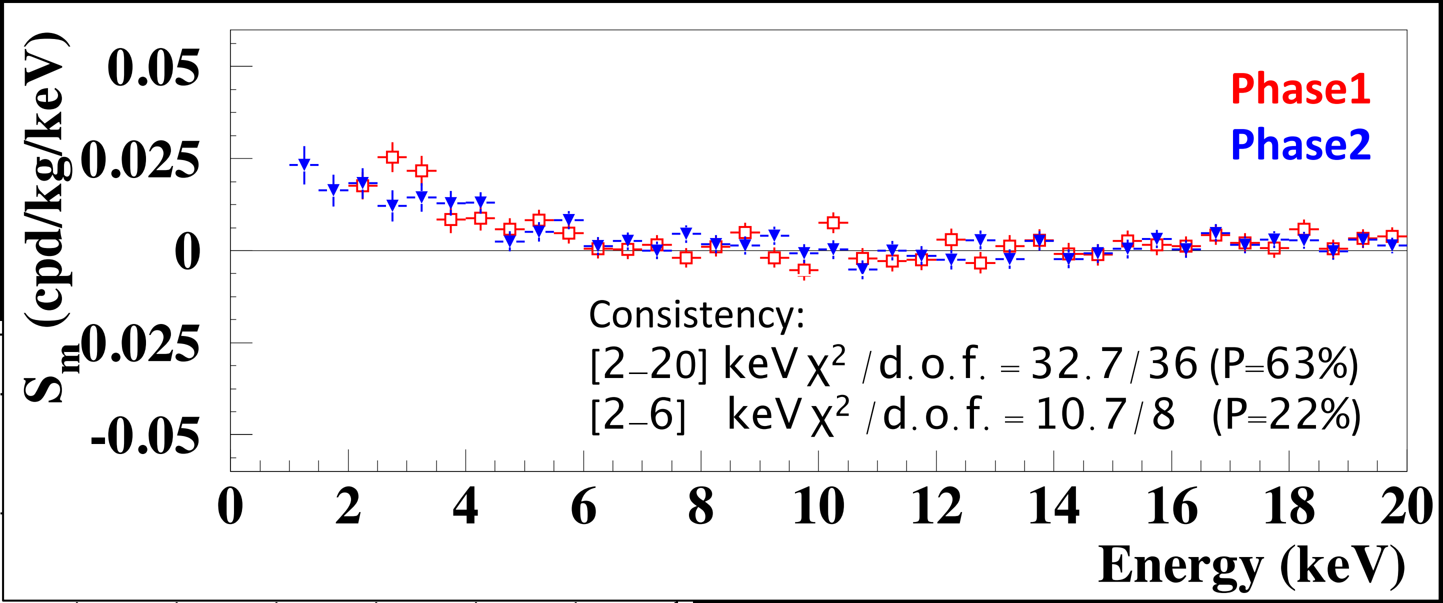
DAMA/LIBRA new PMTs for Phase-2

- EMI 9265-B53/FL and 9302-A/FL -> Hamamatsu R6233MOD
- Quantum efficiency: ~30% -> ~38% at peak
- Lower dark counts: ~100-500Hz
- Light collection: 5.5-7.5 ph/keV -> 6-10 ph/keV
- Analysis Threshold: 2keV -> 1keV



DAMA/LIBRA Phase-1 vs. Phase-2





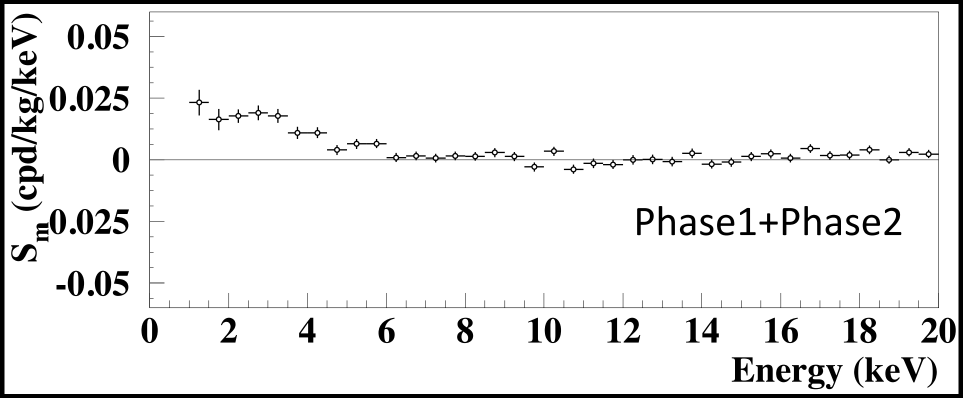
[plot grabbing from fig. 1 of EPJ C56 (2008) 333 and arXiv:1805.10486.]

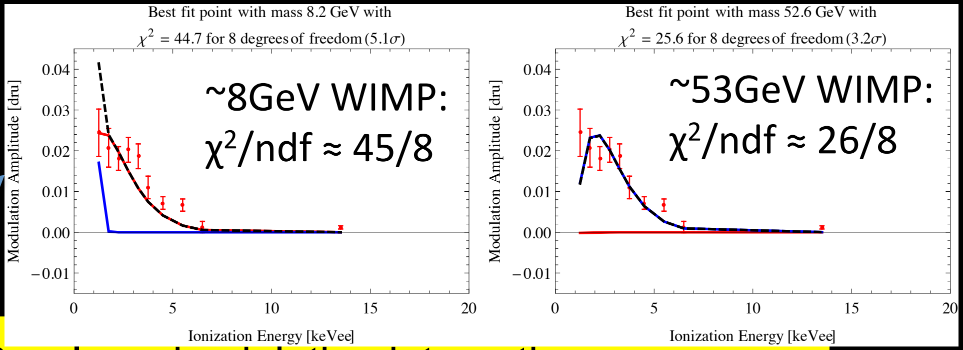
Background reduced almost 50% but PMT radioactivity is not so much lower

Interpretation including Phase2 ?

preliminary exercise seem to indicate:

- the SI WIMP nuclear scattering model is a worse fit to the data.
- "Heavy" WIMP region shifted from ~80GeV to ~45GeV.
- If penalty introduced for unmodulated rate
  - fit is very poor -> need for non standard halo parameters



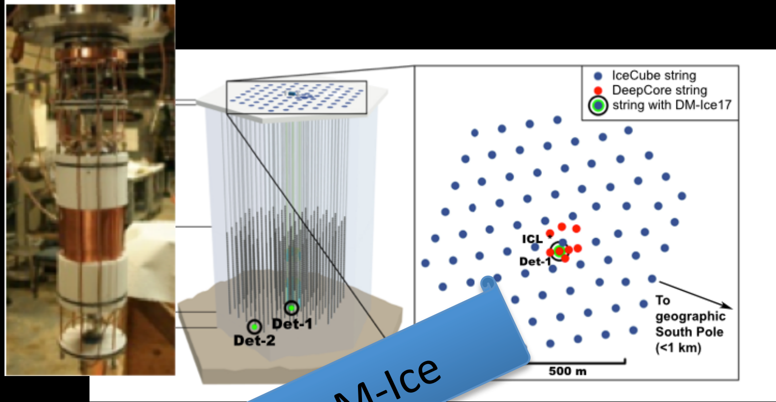


S. Baum, K. Freese, C. Kelso arXiv:1804.0123 <- Isospin-violating interactions
J. Herrero-Garcia et al. arXiv:1804.08437 <- Introducing two DM components
S. Kang et al. arXiv:1804.07528 <- Effective interaction models

DISCLAIMER: this interpretation is long "excluded" by several other experiments and DAMA collaboration does not support it -> announced a collaboration article on interpretation of the result.

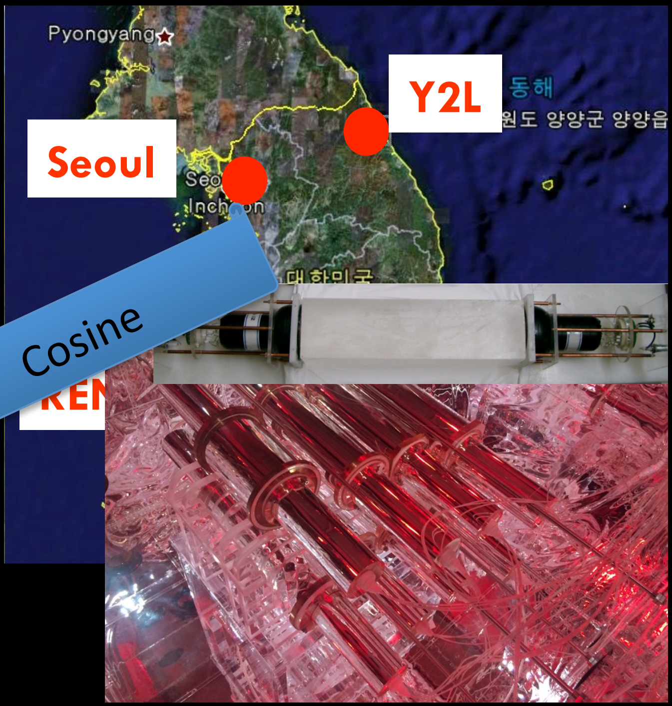
To unravel the mistery we need:

A new independent measurement with NaI(Tl) and superior sensitivity!



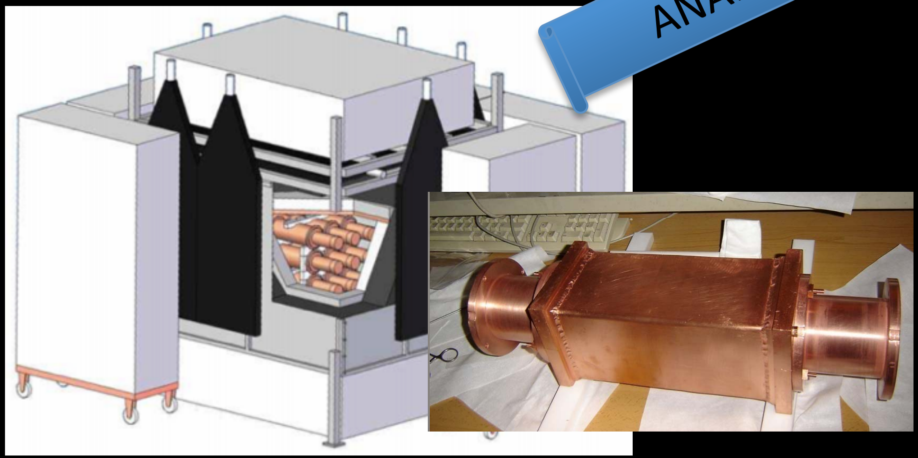
DM-Ice

Cosine

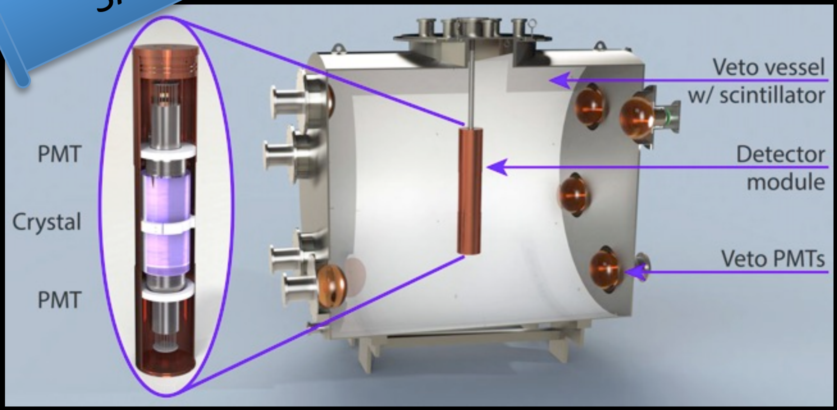


A world wide effort

ANAIS

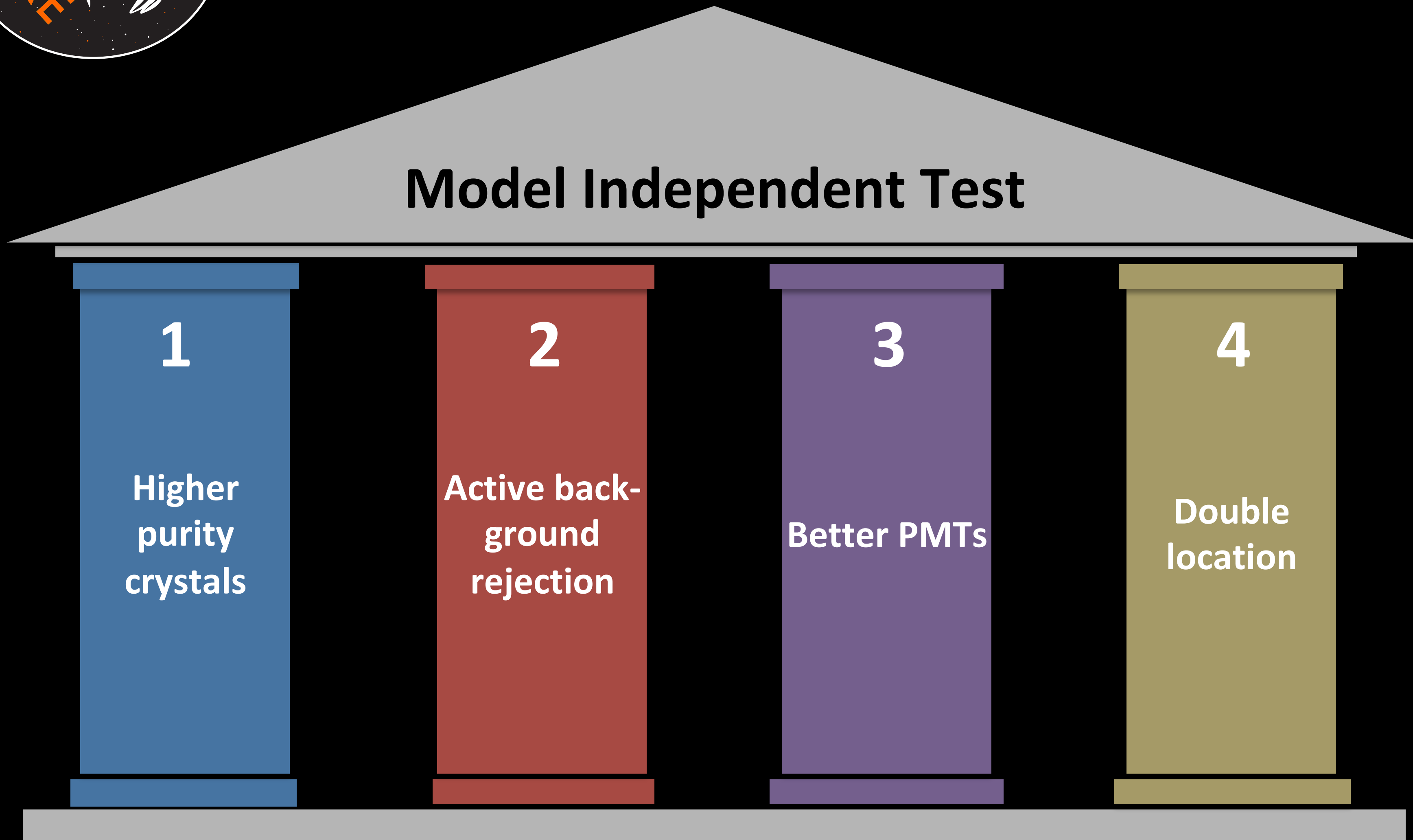


SABRE



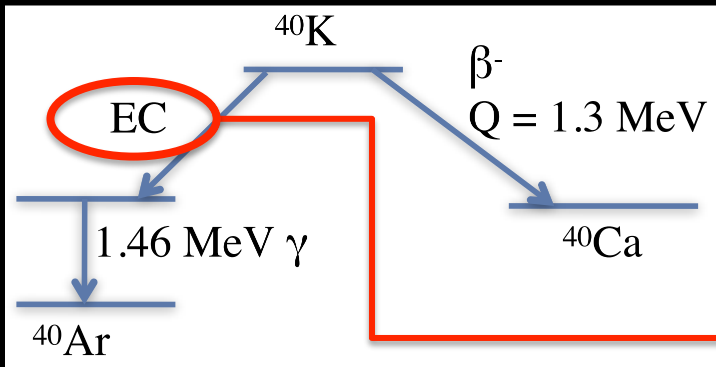
arXiv:1806.09340
arXiv:1806.09344

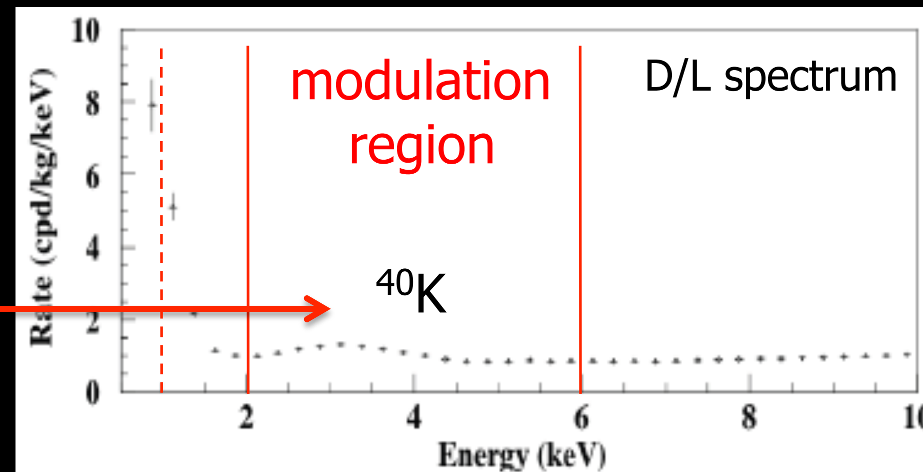
SABRE's four pillars



Not just a test but a higher sensitivity stand-alone experiment

Overcoming DAMA/LIBRA: background





^{40}K 3keV EC (10% BR) lies where the modulation amplitude is maximal

Pillar 1

Reduce K content in NaI

Pillar 1: High Purity NaI crystals

- Princeton University and industrial partners (now Sigma-Aldrich) have yielded Astro-Grade powder with higher purity then D/L crystals
  - 9ppb K and latest batch 4ppb K
- Test Crystal grown by RMD at the end of 2015

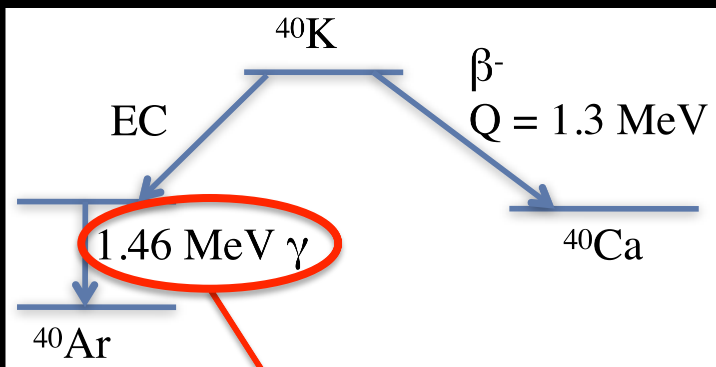
Element	DAMA powder [ppb]	DAMA crystals [ppb]	Astro-Grade [ppb]	SABRE crystal [ppb]
K	100	~ 13	9	9
Rb	n.a.	<0.35	<0.2	<0.1
U	~ 0.02	$0.5\text{-}7.5 \times 10^{-3}$	$<10^{-3}$	$<10^{-3}$
Th	~ 0.02	$0.7\text{-}10 \times 10^{-3}$	$<10^{-3}$	$<10^{-3}$

88 mm - 2 kg test crystal

Breakthrough!

- **First Full size 5.5 kg crystal <u>now</u> ready to be shipped to LNGS**

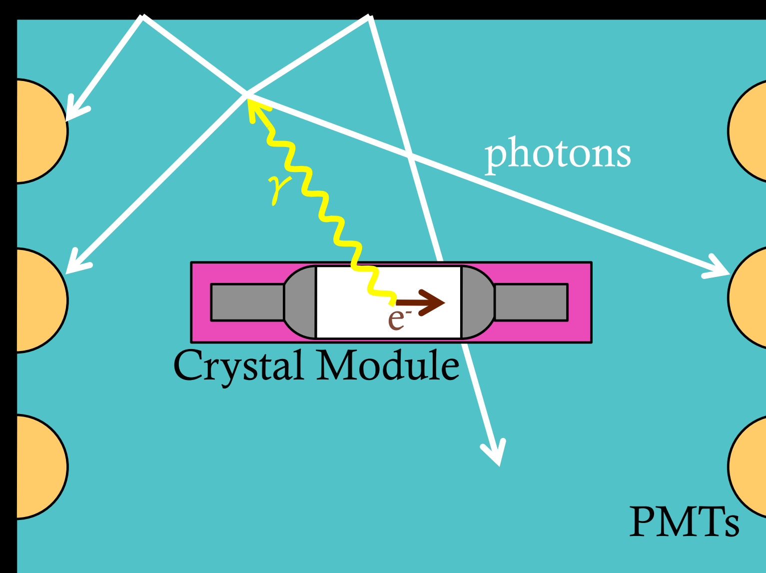
Pillar 2: Active Background Rejection



detect the gamma

Tag K

- Surround crystals with liquid scintillator
- 4π gamma detection
- high efficiency on ^{40}K suppression: >80%



Pillar 3: PhotoMultiplier Tubes (PMTs)

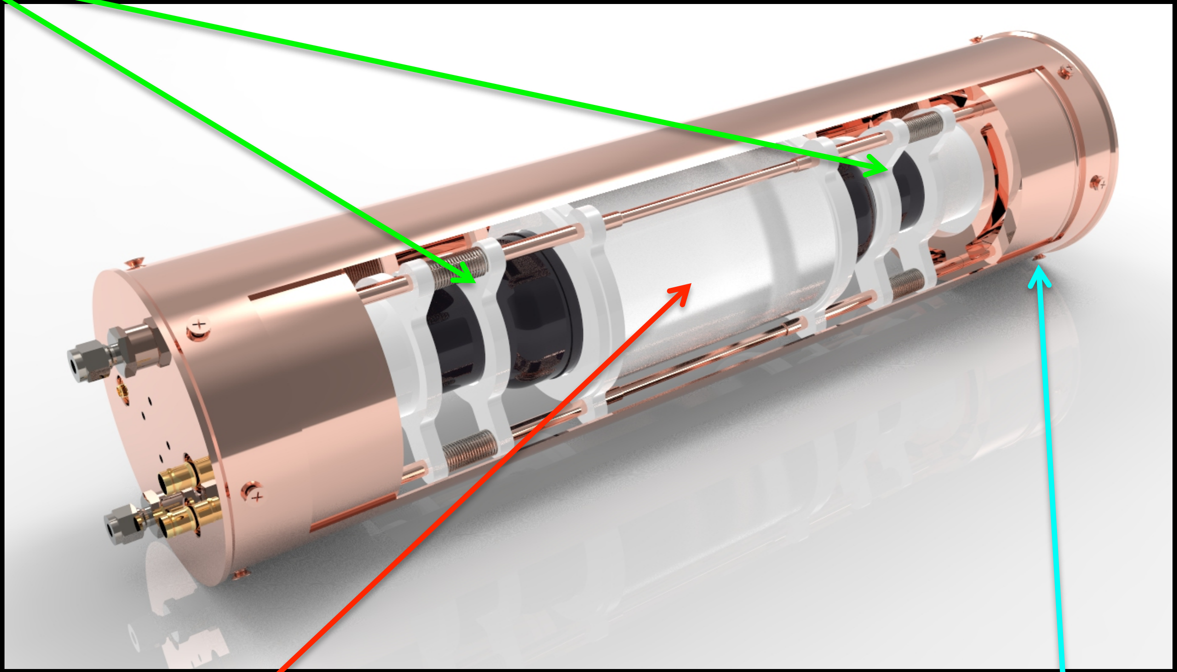
Baseline: R11065-20 3” PMTs

- 5.5mBq → Less background
  - no light guides → More light
- custom pre-amplifiers
  - reduced after-glow → Less noise

A >10pe/keV light collection is possible

High purity Cu enclosure

3” PMTs



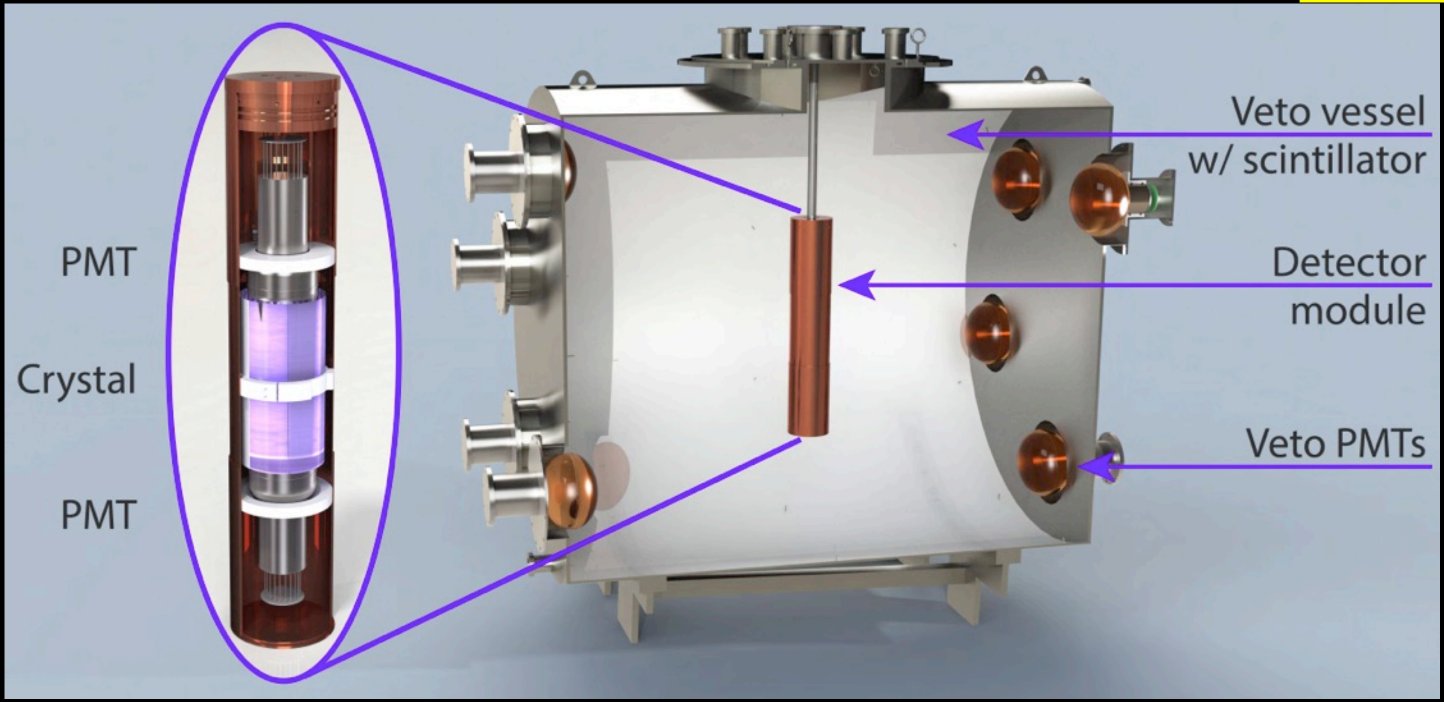
4” diameter x 8” length
cylindrical NaI(Tl) crystal (~5.5kg)

OFHC copper housing

SABRE Proof-of-Principle (PoP)

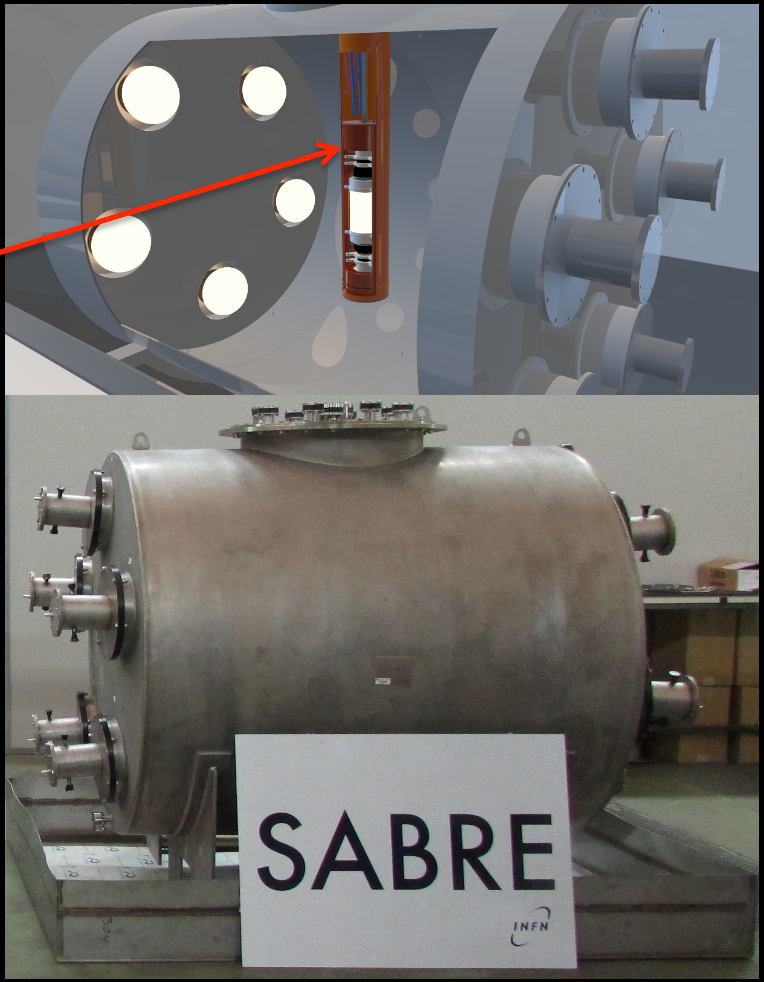
- Prototype phase @LNGS with single crystal
- Goal: fully characterize crystal background, detector design, and performance.

arXiv:1806.09340



SABRE-PoP vessel

- Crystal Insertion System (CIS)
- 1.3 m diameter x 1.5 m length stainless steel vessel
- ~2ton of liquid scintillator (PC+ppo from Borexino)
- 10 x 8” PMTs



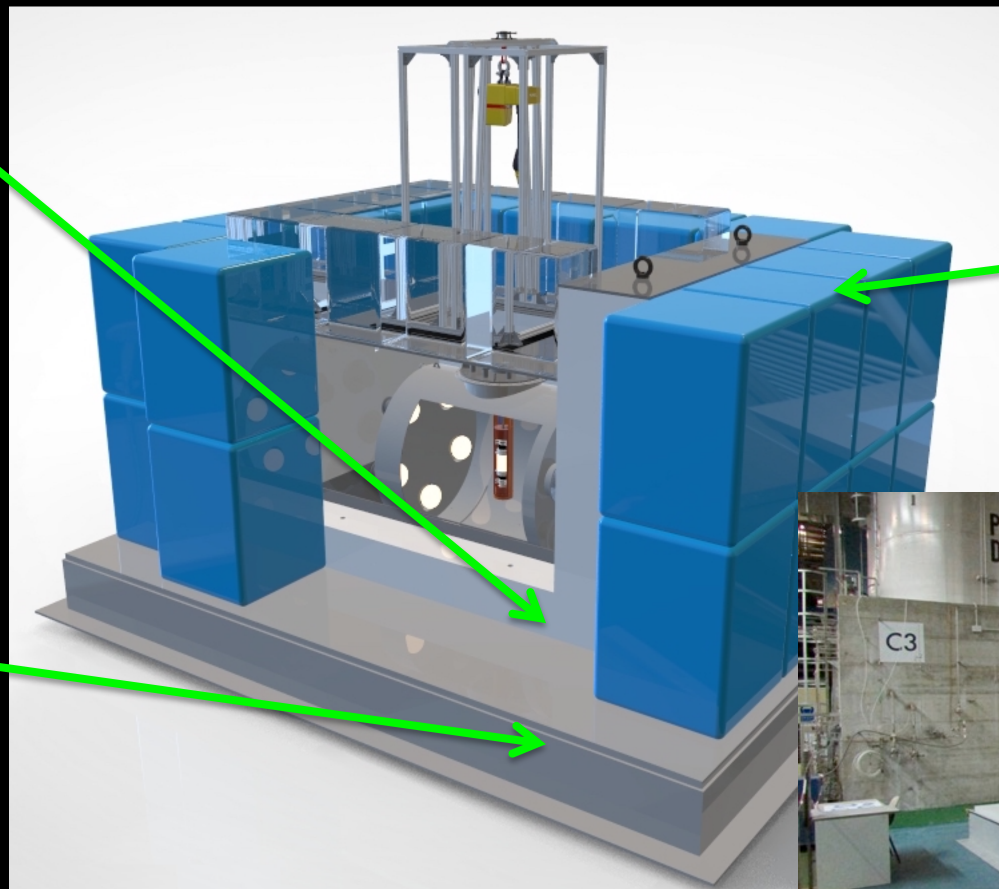
arXiv:1806.09340

SABRE-PoP shielding

Polyethylene

Water tanks

Lead basement



arXiv:1806.09340

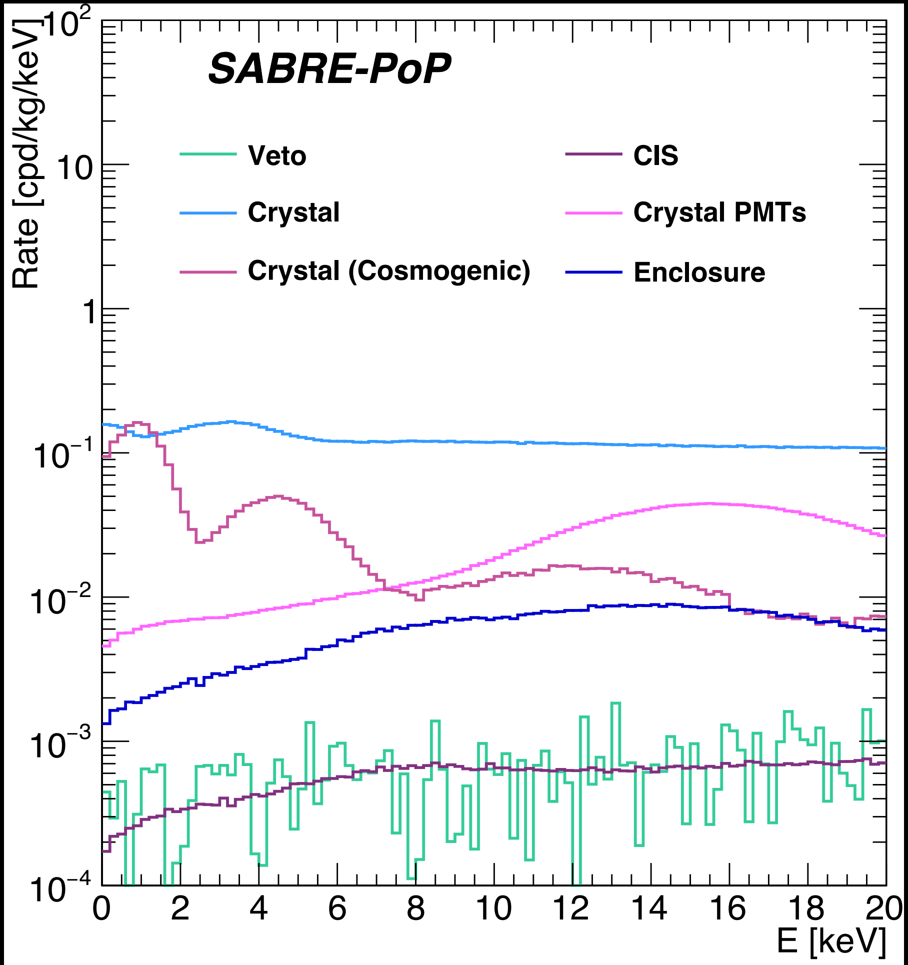
Construction completed June 2018

arXiv:1806.09344

Expected backgrounds (2-6 keV_{ee})

Monte Carlo simulations
(background contrib. in cpd/kg/keV_{ee}
past the application of the veto)

1. Crystals: ~0.15
   1. ^{40}K: 0.04
   2. ^{87}Rb: <0.06 (upper limit)
   3. ^{238}U, ^{232}Th: ~0.02
   4. ^{210}Pb: ~0.02
   5. ^{3}H: to be determined
2. Cosmogenics: ~0.04
3. PMTs: ~0.03
4. Enclosure, CIS, Veto, Rocks: negligible



Total: 0.22 cpd/kg/keV_{ee} – DAMA-Ph1: ~1 cpd/kg/keV_{ee}

arXiv:1806.09340

SABRE Sensitivity

1. Model-independent approach: 50k toy-MC data sets with/without signal yield 6σ/5σ power to verify/refute the claim at 90% C.L.
2. Classic sensitivity curve to SI WIMP-nucleon interaction

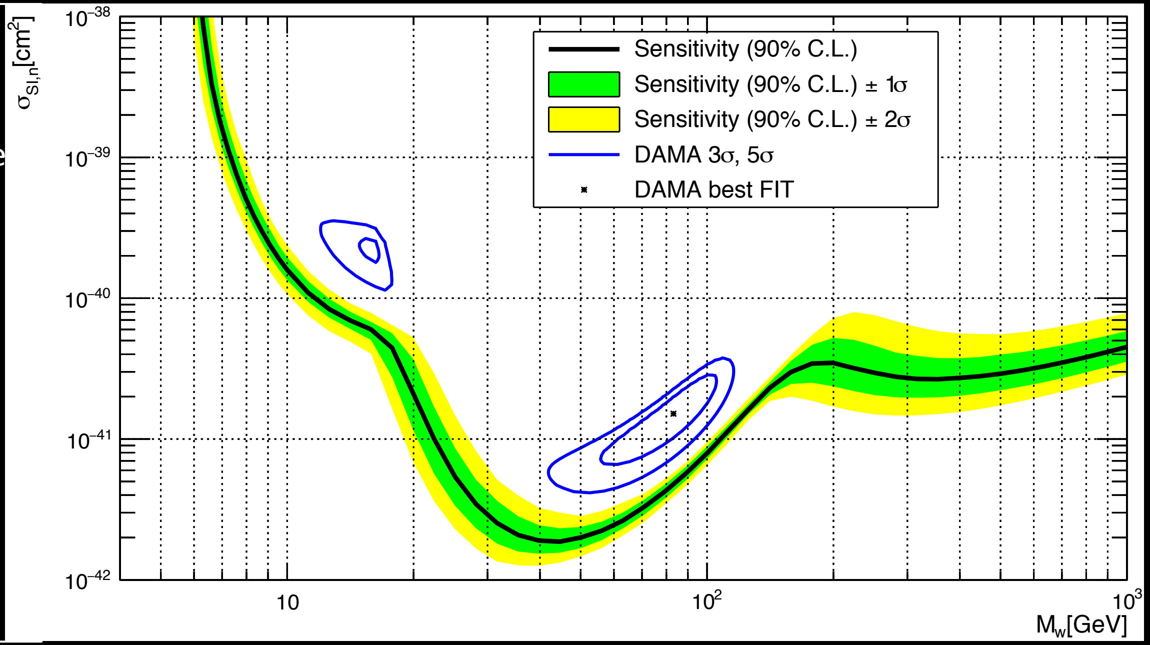
Exposure: 50 kg x 3 yr

Background: 0.22 cpd/kg/keV_{ee}

Quenching: Xu et al. PR C92 (2015) 015807.

Systematics: quenching, resolution, efficiency, background

DAMA islands: Phase1 only



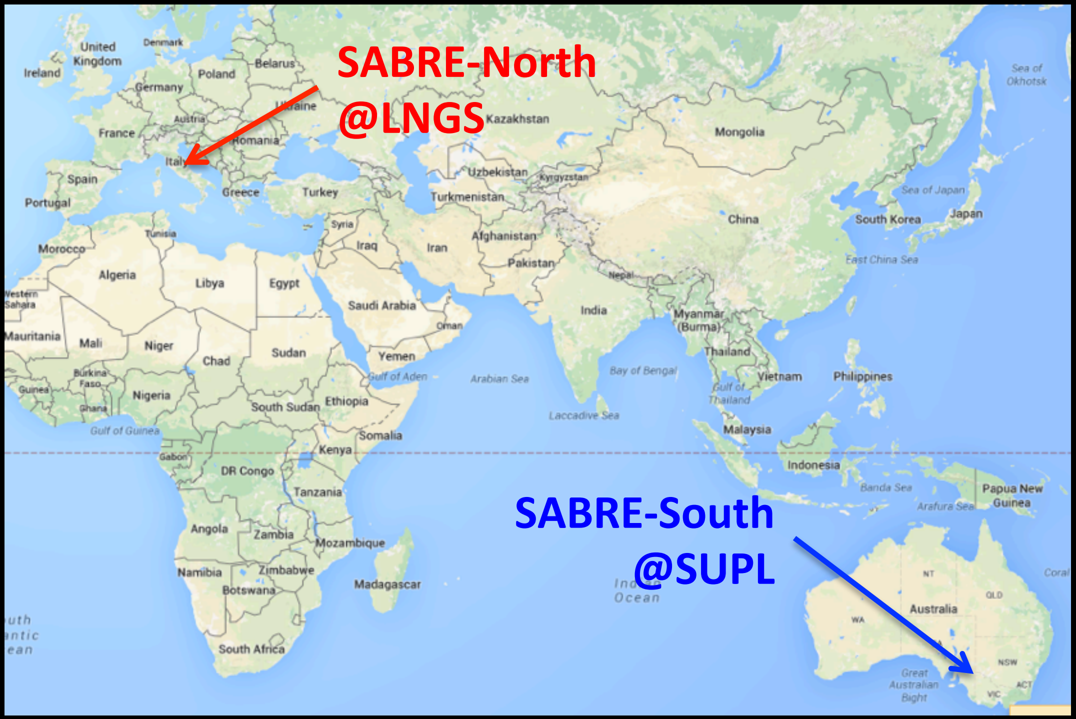
Pillar 4: Double location

Pillar 4

- SABRE Full scale experiment in two different laboratories

→ on opposite hemispheres

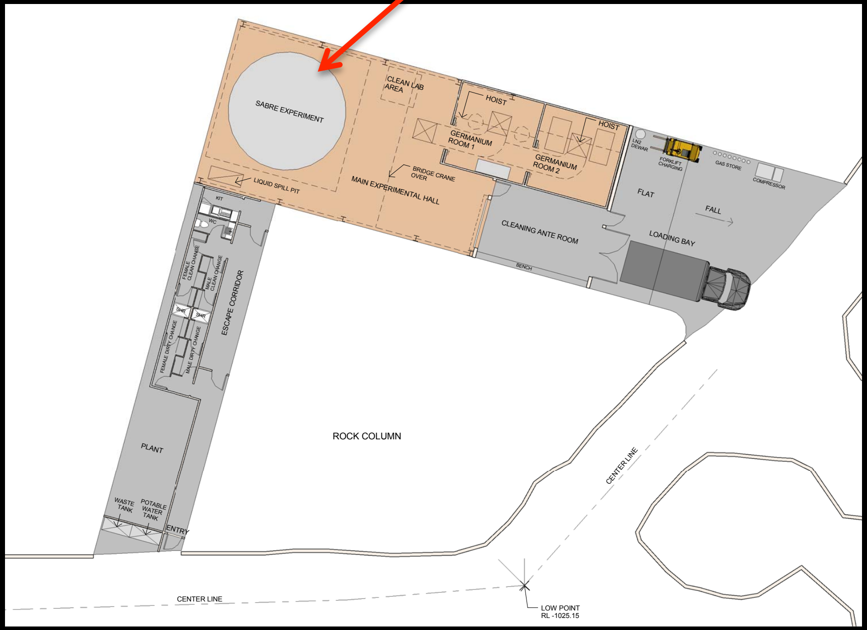
- Twin detectors for reduced systematics



Any season-related contribution to the modulation would reverse phase

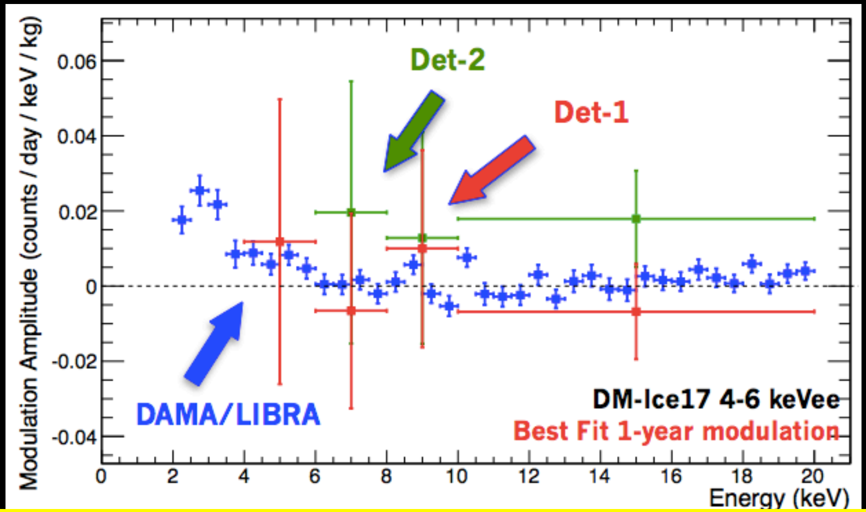
Stawell Underground Physics Laboratory (SUPL)

- Only underground lab in southern hemisphere
- Rock coverage: ~3100 m w.e.
- ~ 240 km west of Melbourne
- Decline gold mine (road entrance)
- Background conditions measured (rocks, cosmogenics): similar to LNGS.
- Radon-free air from surface
- Construction started!
- Expected completion: 2019

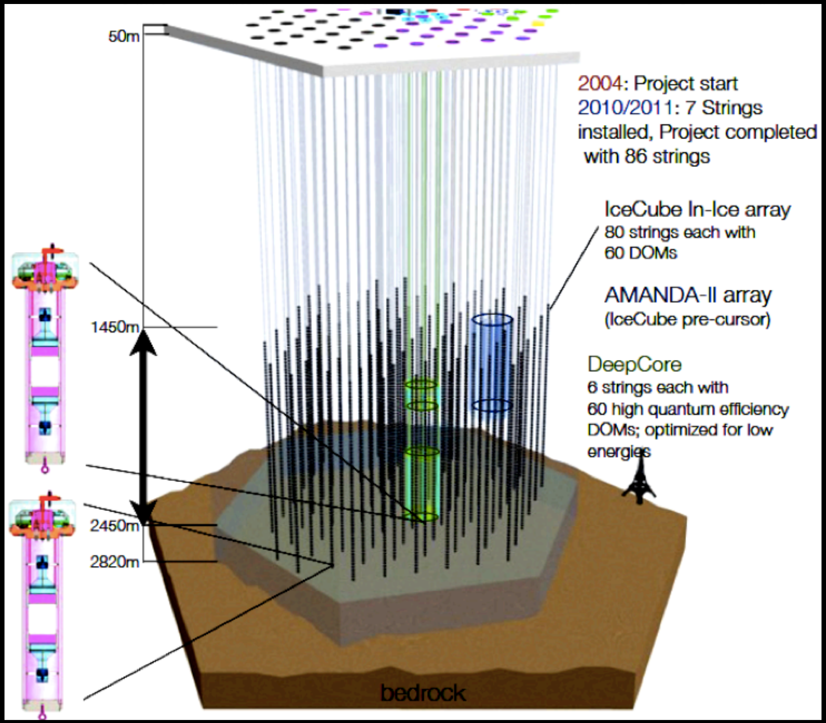


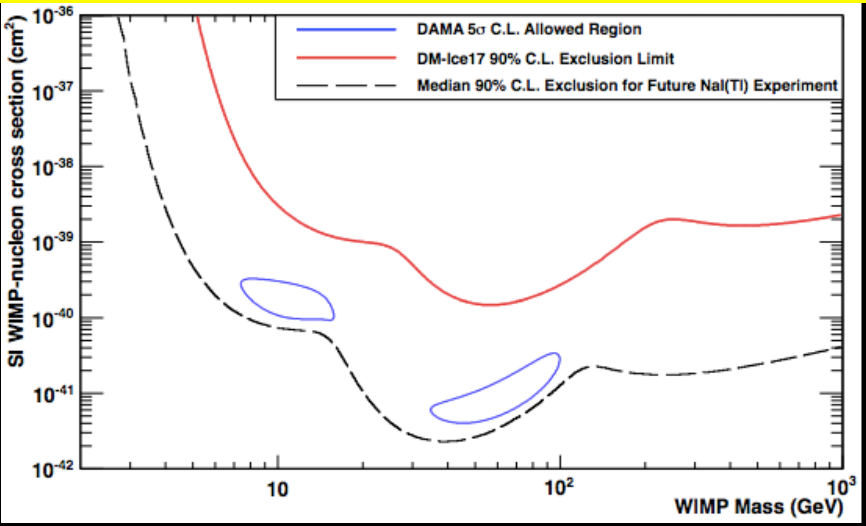
DM-ICE

- 2 x 8.5 kg crystals from NAIAD in IceCube
  - 2450 m depth
  - used as muon veto
  - very stable ice conditions
- Southern hemisphere!
- High backgrounds (~8 dru)
  - Not competitive yet
- Very interesting future possibility



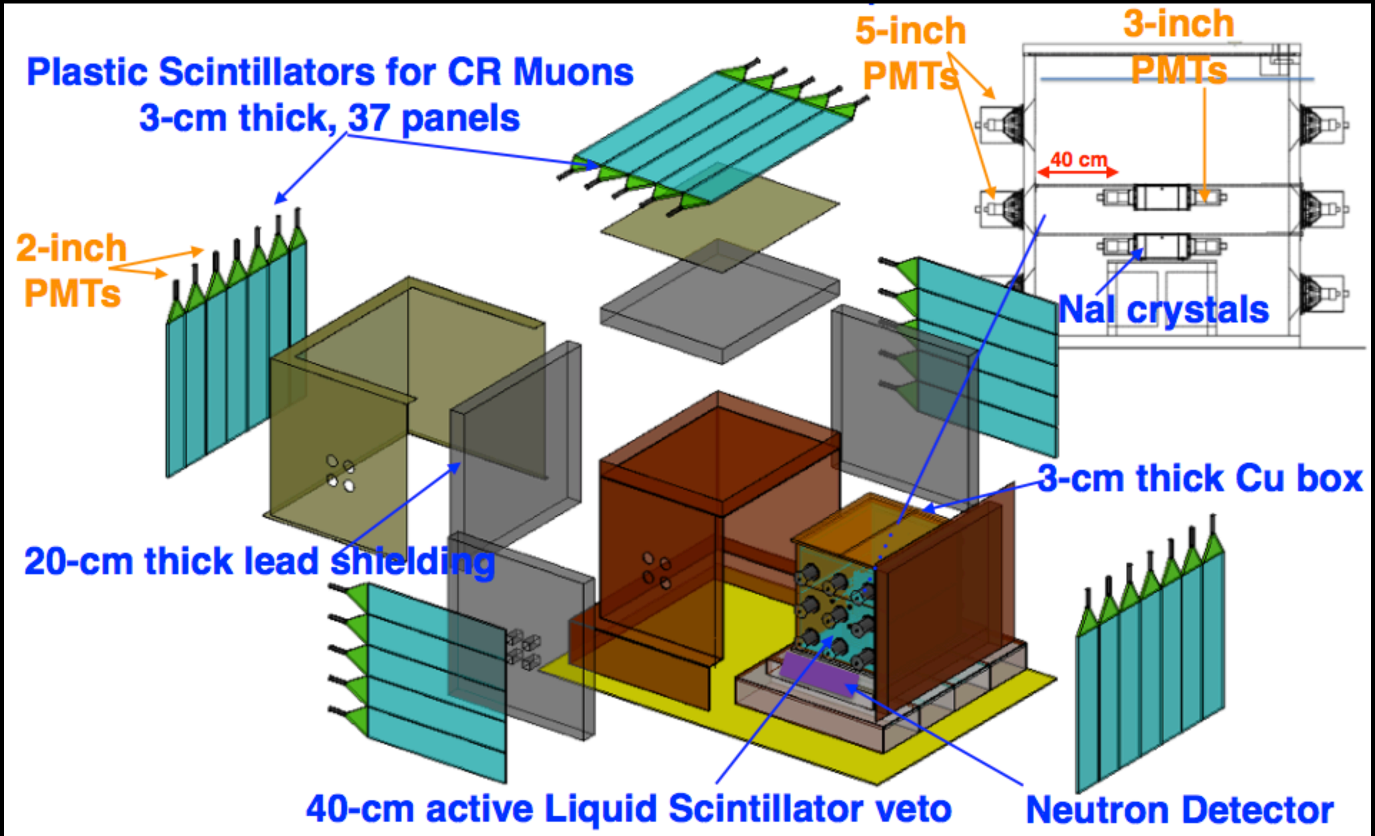
E. Barbosa de Souza et al. PR D95 (2017) 032006





Cosine-100

- Merging of DM-ICE and KIMS collaborations.
- Started data taking in Sep 2016.
- Also implementing liquid scintillator veto
  - but only ~40 cm.
  - Background suppression on ^{40}K: ~75%
- Location: Yang Yang (S. Korea)
  - Not deep -> need active muon tagging



Cosine-100 backgrounds

Crystal	Mass (kg)	Size (inches diameter×length)	Powder	α Rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light Yield (PEs/keV)
Crystal-1	8.3	5.0×7.0	AS-B	3.20 ± 0.08	43.4 ± 13.7	<0.02	1.3 ± 0.4	14.9 ± 1.5
Crystal-2	9.2	4.2×11.0	AS-C	2.06 ± 0.06	82.7 ± 12.7	<0.12	<0.6	14.6 ± 1.5
Crystal-3	9.2	4.2×11.0	AS-WSII	0.76 ± 0.02	41.1 ± 6.8	<0.04	0.4 ± 0.2	15.5 ± 1.6
Crystal-4	18.0	5.0×15.3	AS-WSII	0.74 ± 0.02	39.5 ± 8.3		<0.3	14.9 ± 1.5
Crystal-5	18.3	5.0×15.5	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.4 ± 0.3	7.3 ± 0.7
Crystal-6	12.5	4.8×11.8	AS-WSIII	1.52 ± 0.04	12.2 ± 4.5	<0.02	0.6 ± 0.2	14.6 ± 1.5
Crystal-7	12.5	4.8×11.8	AS-WSIII	1.54 ± 0.04	18.8 ± 5.3		<0.6	14.0 ± 1.4
Crystal-8	18.3	5.0×15.5	AS-C	2.05 ± 0.05	56.2 ± 8.1		<1.4	3.5 ± 0.3
DAMA				< 0.5	<13	0.7–10	0.5–7.5	5.5–7.5

"bad"

(almost) good

- 8 crystal of different sizes and production batches from Alpha Spectra
- Total mass: ~106kg
- Background levels: ^{40}K and ^{210}Pb (α rate) almost good, but not on the same crystals
- Surface contamination from exposure to Radon?

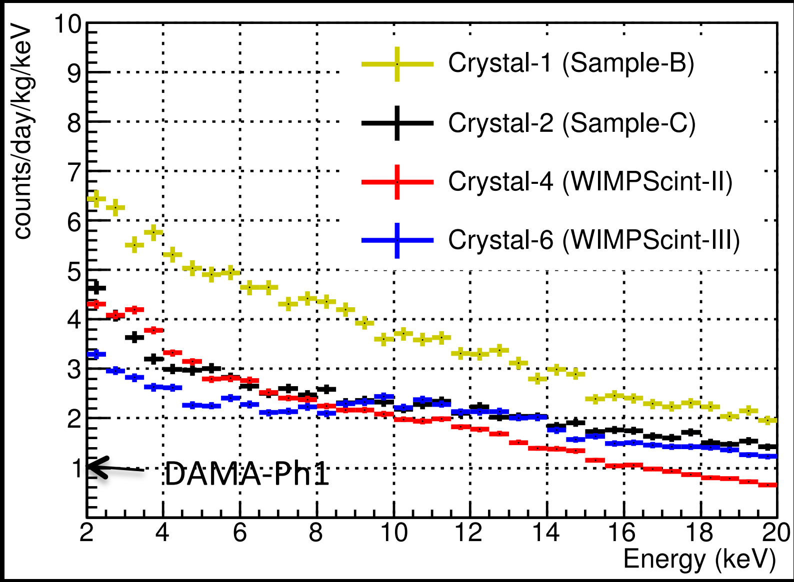
2 crystal optically degraded

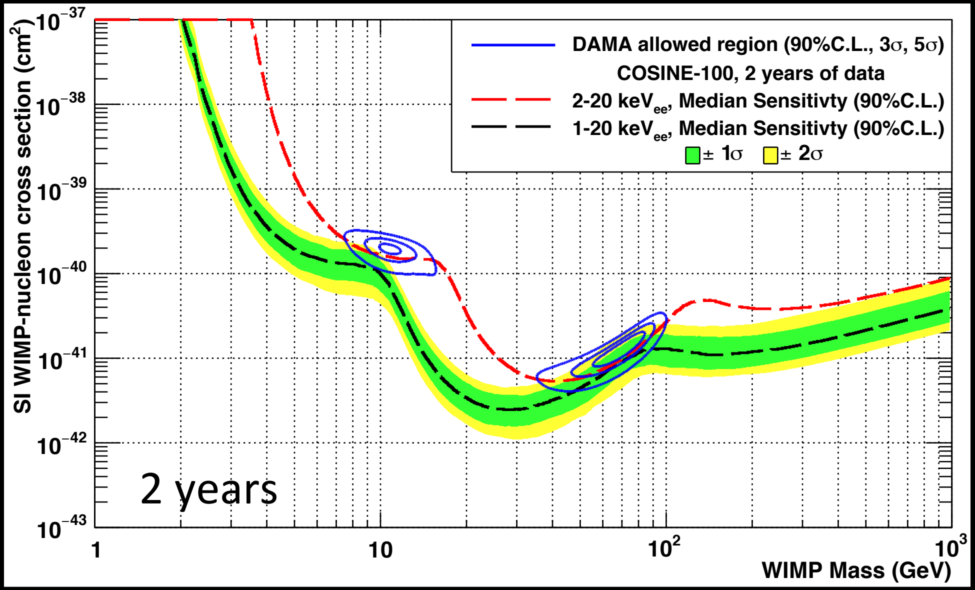
G. Adhikari et al., EPJ C (2018) 78:107 arXiv:1710.05299

Cosine-100 sensitivity

- Background level in the Region of Interest (2-6keV): 2-4 times DAMA-Ph1
- Very unlikely to reach Energy threshold <2keV: not included in spectra
- Possibly inconclusive test if negative?
- Ideas a new experiment with 250kg at new Laboratory (to be built)
- Two upcoming conferences in Korea, NDM and ICHEP
  - Will there be a release of the first results with ~1.5y data?

G. Adhikari et al.,
EPJ C (2018) 78:107
arXiv:1710.05299

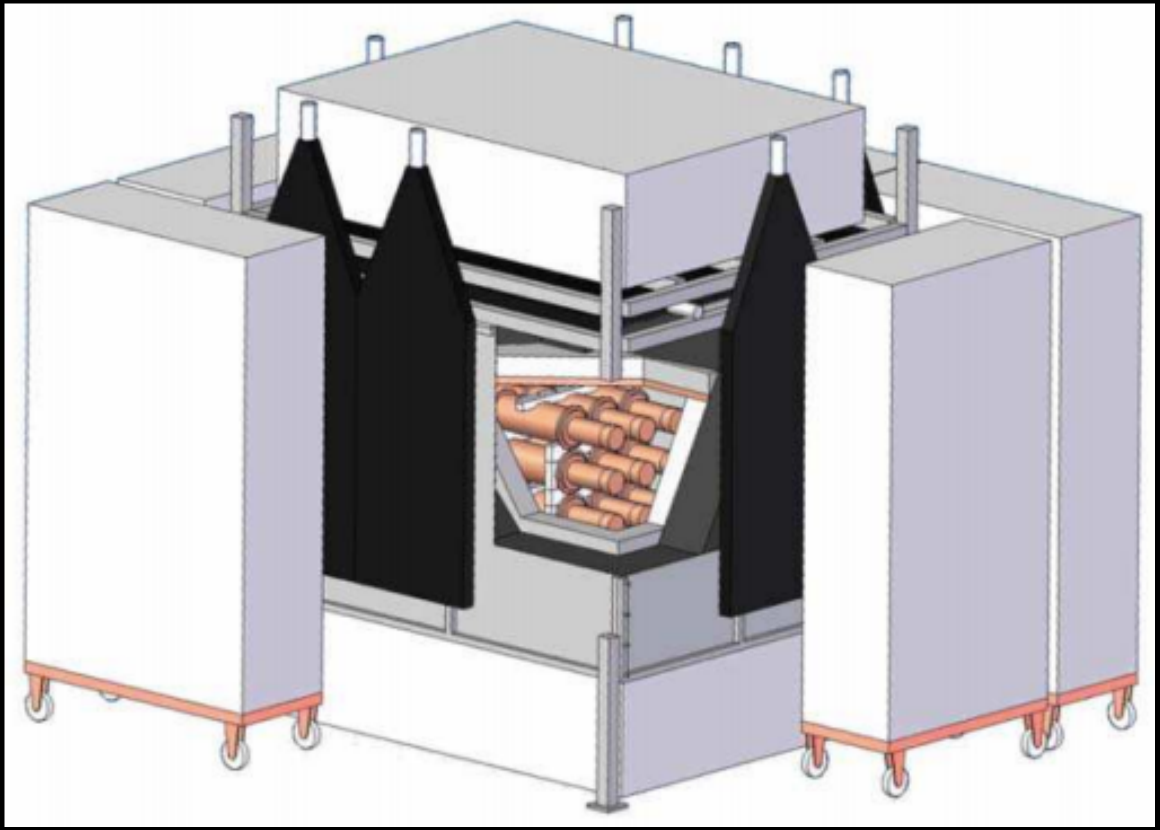




ANAIS-112

- Started physics run August 2017.
- Laboratorio Subterraneo de Canfranc (LSC) in Spain.
  - not deep -> need active muon veto.
- No liquid scintillator veto for gammas.

arXiv:1704.06861
arXiv:1710.03837



ANAIS-112 background

- 9 crystals, 12.5 kg each, produced by Alpha Spectra for 112 kg total mass
- Background levels very similar to COSINE:
  ~30ppb ^{40}K and 0.7-3.2mBq/kg in ^{210}Pb

Detector	Quality powder	Arrival date	Light collection (phe/keV)	^{40}K activity (mBq/kg)	^{210}Pb activity (mBq/kg)
D0	<90 ppb K	December 2012	15.3±1.1	1.1	3.15
D1	<90 ppb K	December 2012	14.8±0.5 *	1.4	3.15
D2	WIMPScint-II	March 2015	15.3±1.4	0.9	0.70
D3	WIMPScint-III	March 2016	14.6±0.8	1.0	1.8
D4	WIMPScint-III	November 2016	14.0±0.8	1.0	1.8
D5	WIMPScint-III	November 2016	14.0±0.8	1.0	0.75
D6	WIMPScint-III	March 2017	12.6±0.8	1.1	0.76
D7	WIMPScint-III	March 2017	17.0±2.0	1.0	0.75
D8	WIMPScint-III	March 2017	14.6±0.9	0.6 18ppb	0.72
average				1.0	1.5

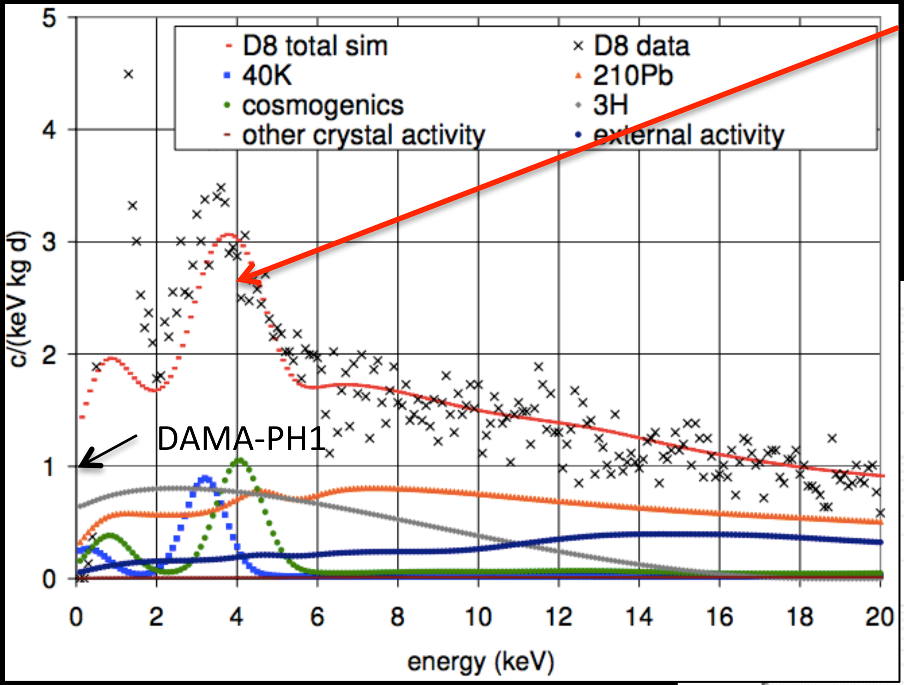
arXiv:1704.06861
arXiv:1710.03837

(1 mBq ^{40}K / kg = 32.3 ppb)

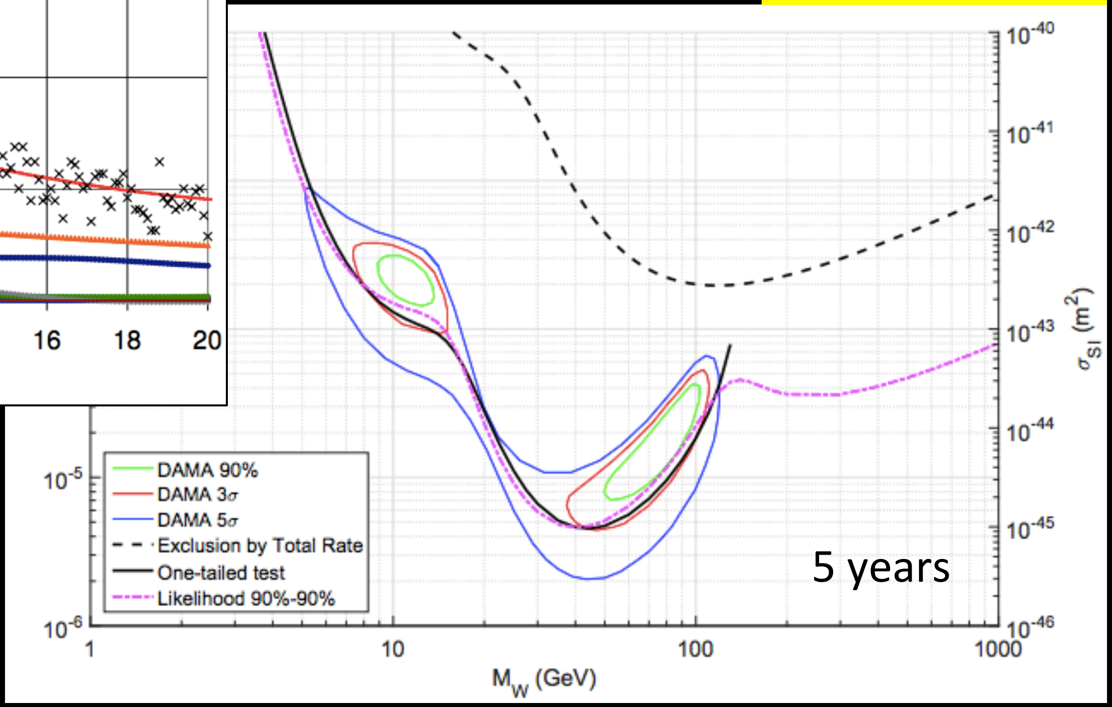
ANAIS-112 sensitivity

Best crystal D8 spectrum

- About 3x DAMA background in [2-6]keV
- Analysis threshold limited to >2keV ?



arXiv:1704.06861
arXiv:1710.03837



- Possibly inconclusive test if negative?
- Ideas to implement active veto

Conclusions

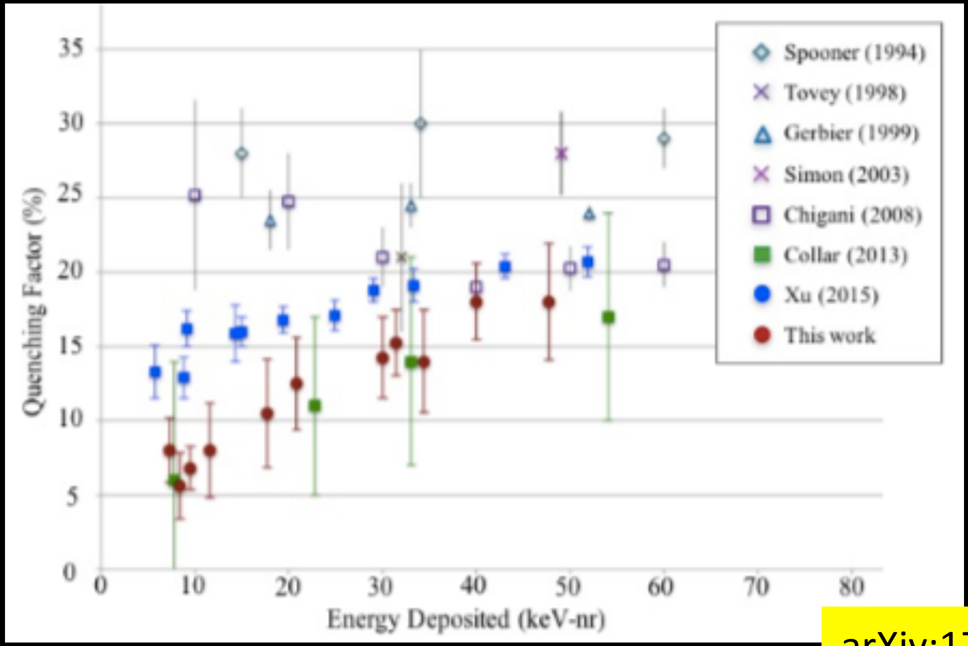
- DAMA/LIBRA-Phase2 confirms the observation of a modulation
  - in tension with other results only under certain assumptions
  - somewhat less easy to fit with a basic SI scenario
- <u>A model independent verification requires a new NaI(Tl) experiment</u>
- Several players around the world aim at this:
  - COSINE
  - ANAIS
  - SABRE
- Exciting times ahead!

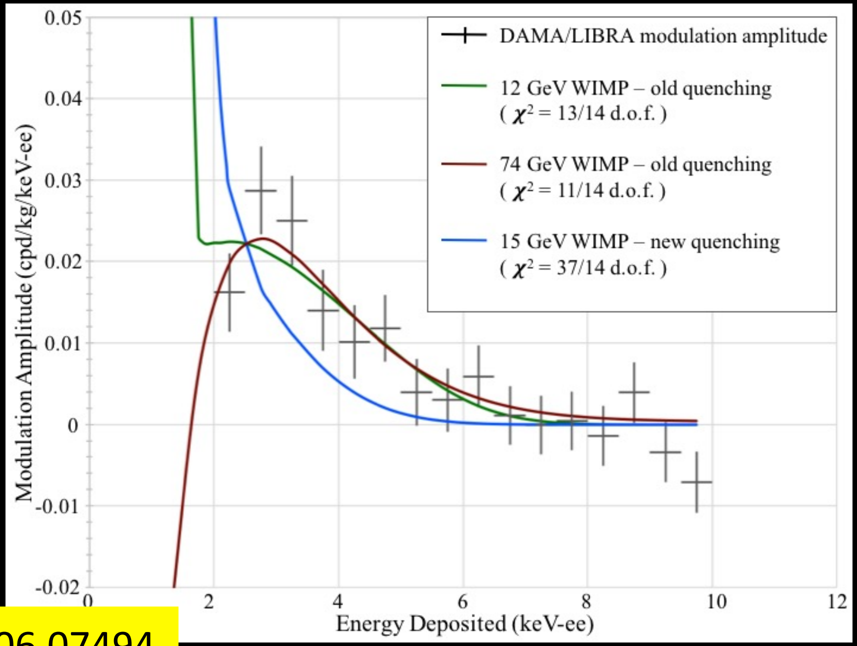
Thank you for your attention!

BACKUP SLIDES

The effect of Na Quenching

- Quenching of nuclear recoils on Na has been measured several times:
- DAMA uses a flat 30%, confirmed by several measurements in the '90s
- 2 more recent measurements point to a lower and energy dependent quenching
- Fit of the DAMA modulation is heavily dependent on the quenching





arXiv:1706.07494