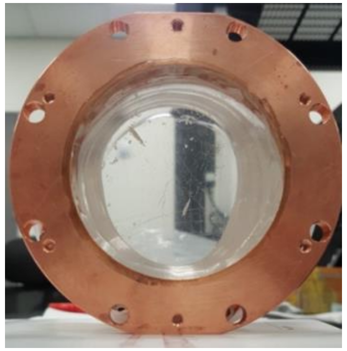



Status and Prospects of NaI Direct Detection Experiments

Martin Stahlberg

Light Dark Matter 2019, Venice

ÖAW AUSTRIAN ACADEMY OF SCIENCES
HEPHY INSTITUTE OF HIGH ENERGY PHYSICS
TU WIEN
COSINUS

Overview

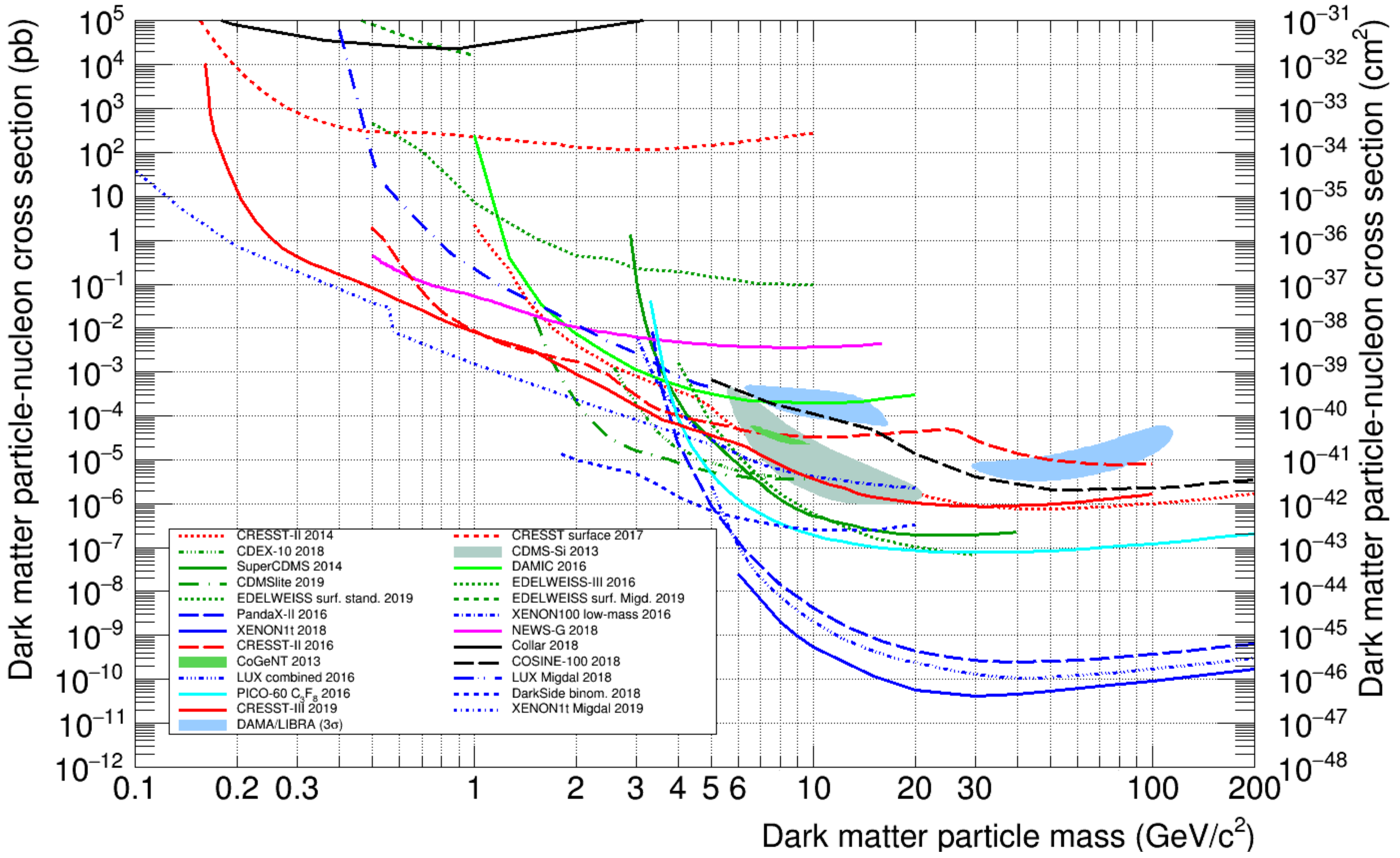
1) Why NaI ?

2) Different experiments and results

3) Upcoming projects

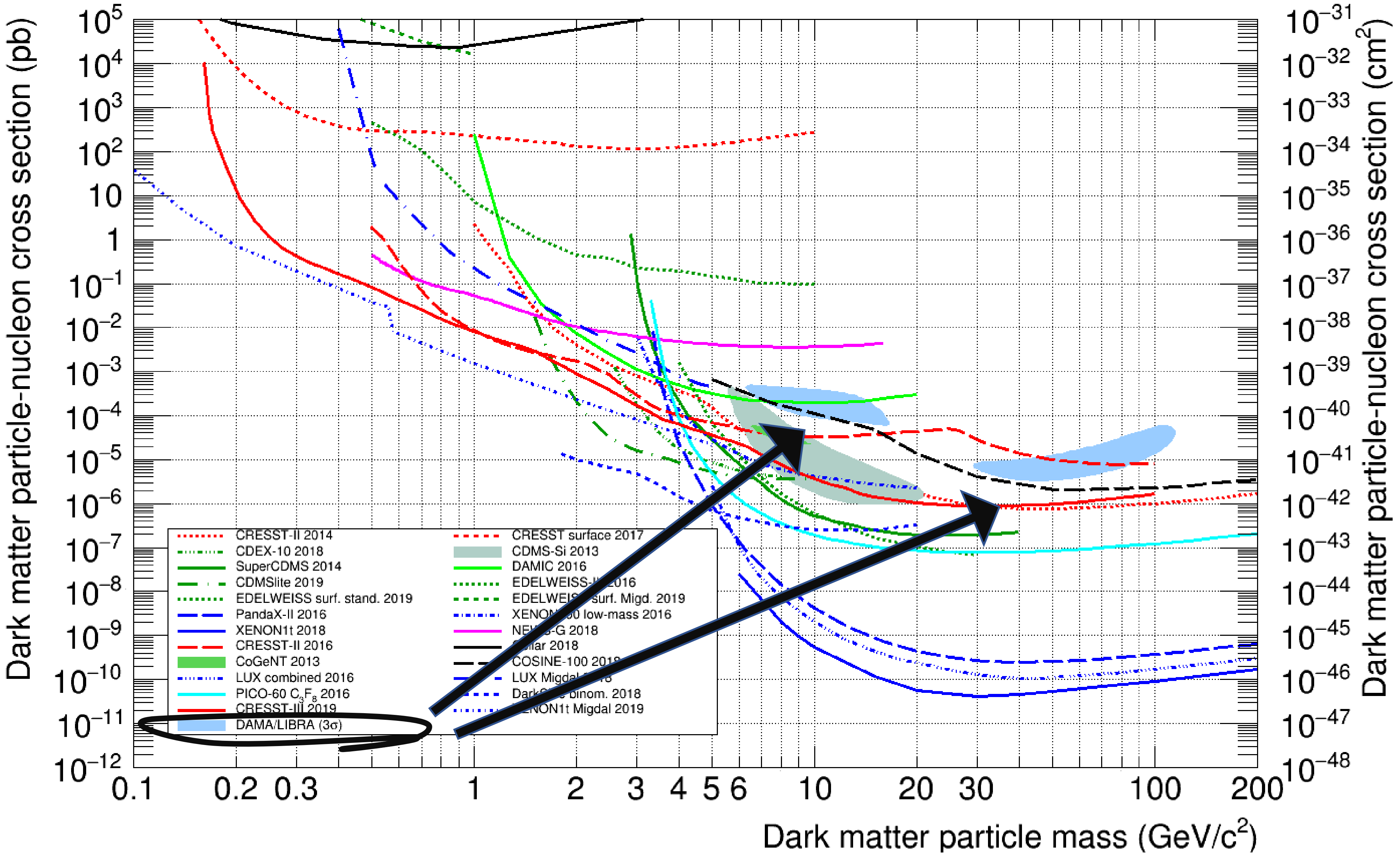
4) NaI as detector material

Why NaI?



Dark matter particle-nucleon cross section (pb)
Dark matter particle-nucleon cross section (cm^2)
Dark matter particle mass (GeV/c^2)
CRESST-II 2014
CDEX-10 2018
SuperCDMS 2014
CDMSlite 2019
EDELWEISS surf. stand. 2019
PandaX-II 2016
XENON1t 2018
CRESST-II 2016
CoGeNT 2013
LUX combined 2016
PICO-60 C_3F_8 2016
CRESST-III 2019
DAMA/LIBRA (3σ)
CRESST surface 2017
CDMS-Si 2013
DAMIC 2016
EDELWEISS-III 2016
EDELWEISS surf. Migd. 2019
XENON100 low-mass 2016
NEWS-G 2018
Collar 2018
COSINE-100 2018
LUX Migdal 2018
DarkSide binom. 2018
XENON1t Migdal 2019

Why NaI?



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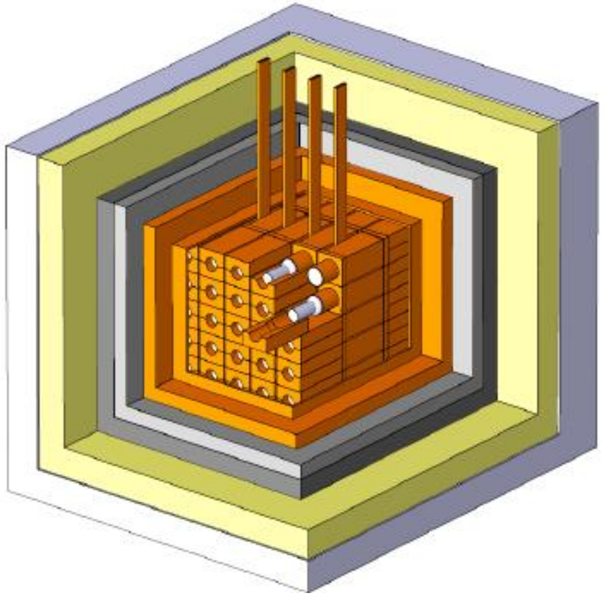
CRESST-III 2019
DAMA/LIBRA (3σ)
CRESST surface 2017
CDMS-Si 2013
DAMIC 2016
COSINE-100 2018
XENON1t Migdal 2019

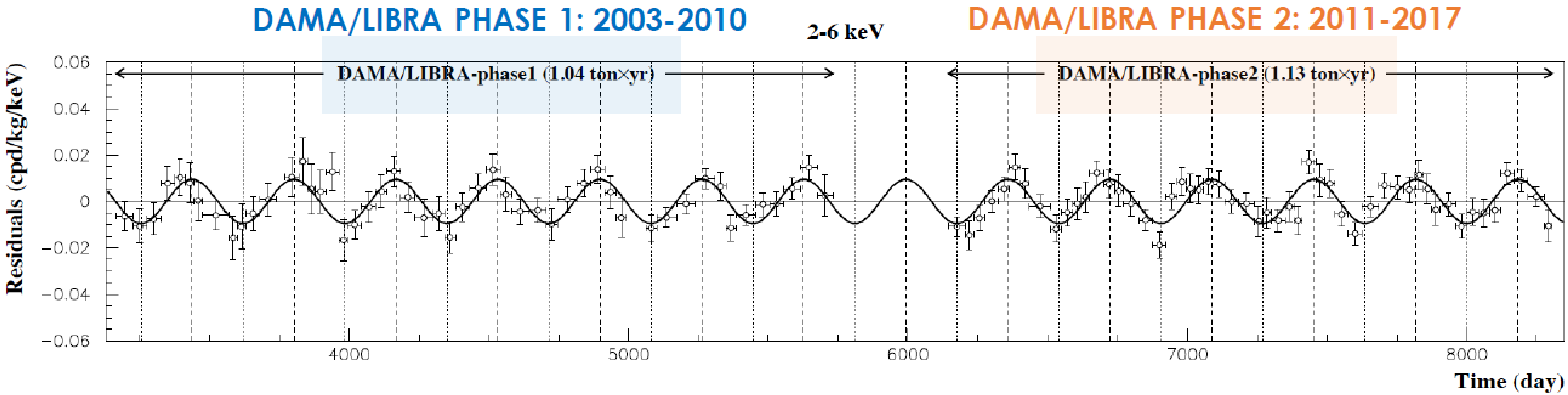
DAMA/LIBRA experiment

MATERIAL	250 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	1keVee
DATA TAKING	since 1996
EVIDENCE	yes



DAMA/LIBRA: **TIME DISTRIBUTION**

arXiv:1805.10486v1 [hep-ex] 26 May 2018



Total exposure: 2.17 tonne years (phase 1 + 2)
Statistical significance: >11.9 σ

combined with DAMA/NaI: 2.46 tonne years, 12.9σ !!!!

positive evidence for the presence of DM particles in the galactic halo

Smoking gun evidence?

Statistics: 12.9σ ✓

Period: 0.999 ± 0.001* ✓

Phase: 25th May +/- 5 days ✓

(cosine peaking June 2nd)

Convincing non-DM explanation ✗

The case for NaI

- DAMA results incompatible with null results from other experiments under standard assumptions – i.e. spin-independent DM-nucleon scattering & standard DM halo model
- BUT: different target materials in other experiments!
- Other scenarios?

NaI Experiments Worldwide

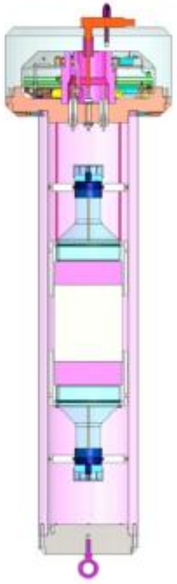
Current NaI Experiments

DM-Ice17

South pole
17 kg NaI

threshold: 4 keV_{ee}

3.5 y physics run
no hint

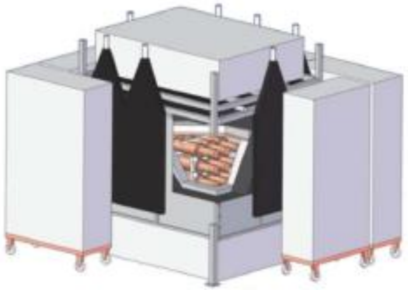


ANAIS-112

LSC - Spain
112.5 kg NaI

threshold: < 1 keV_{ee}

since spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

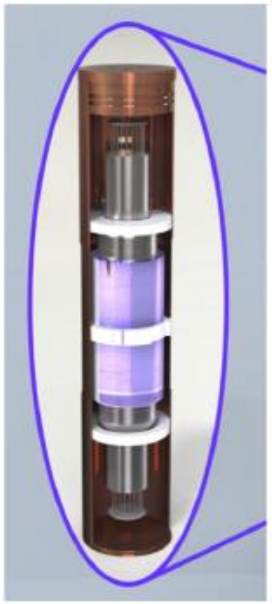
threshold: ~2 keV_{ee}

since Sept. 2016

SABRE

Gran Sasso/Australia
40-50 kg NaI

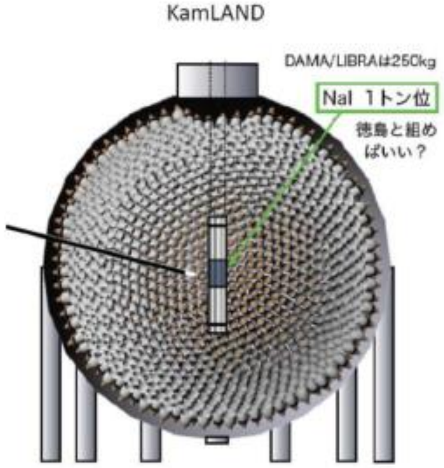
construction phase



KamLand-PICO

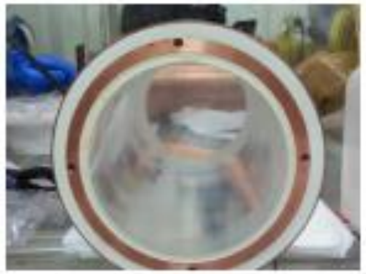
KamLand/Japan
1t NaI

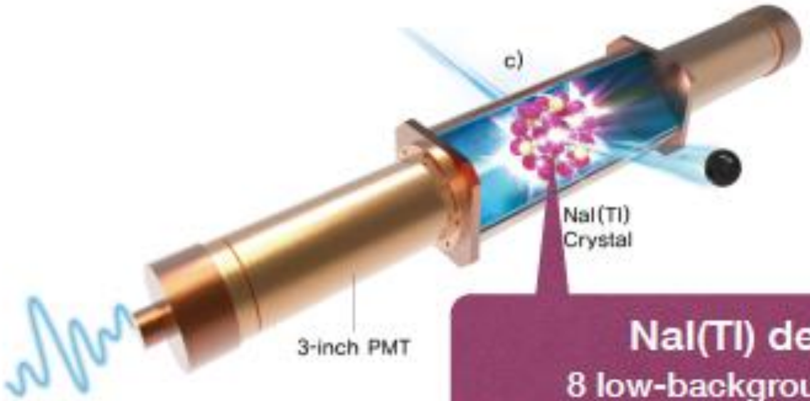
planning/
prototyping phase



COSINE-100 Detector

- 8 ultra low-background NaI(Tl) crystals with 106 kg in total
  - U/Th/K level is less than DAMA, but total alphas (~^{210}Pb) are higher than DAMA.
  - Total background is 2-3 times that of DAMA.
  - Higher light yield (15 p.e/keV) than DAMA
    - ✓ Can make the threshold lower easily



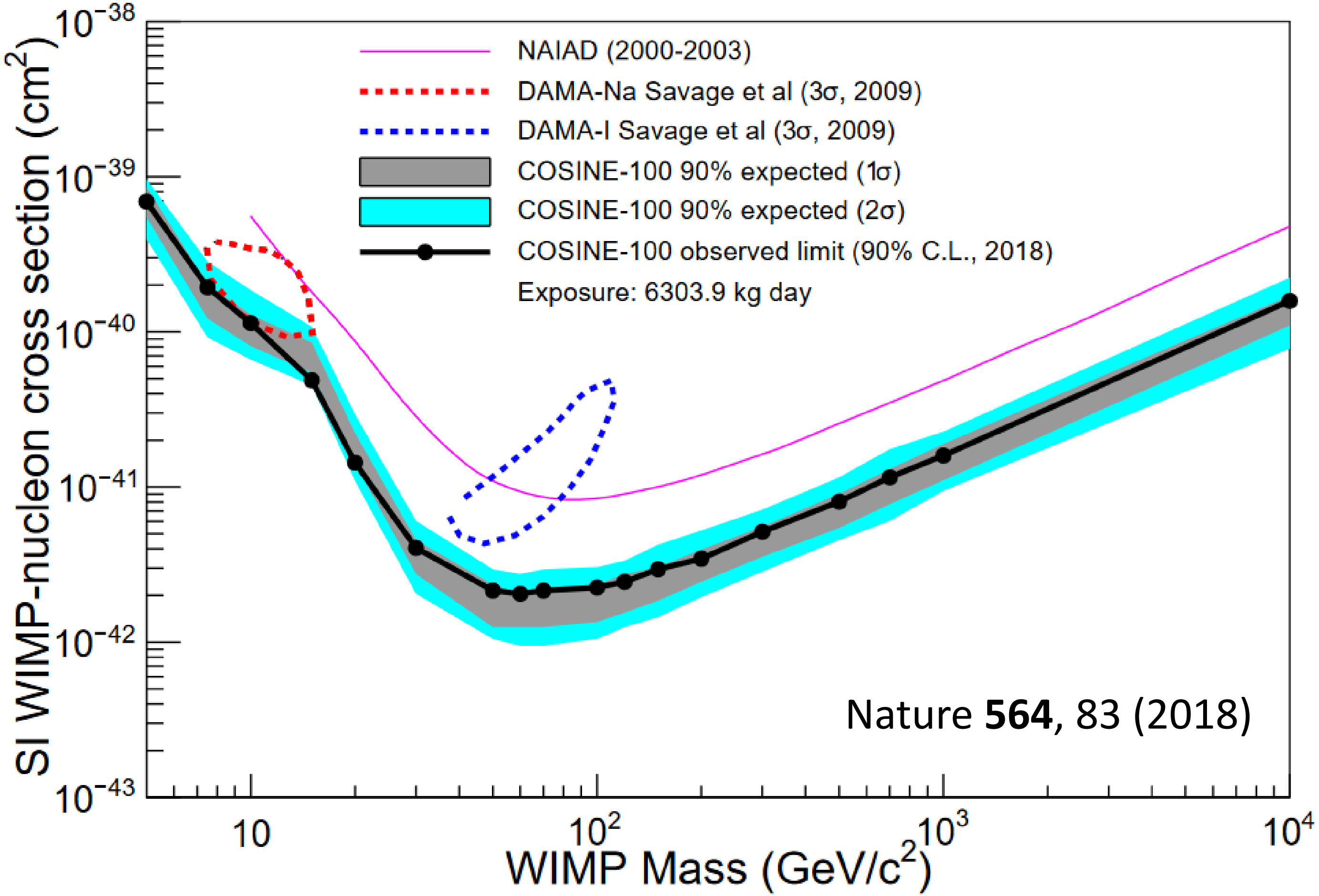


NaI(Tl) detector
8 low-background crystals
Each crystal is encapsulated in copper
Two 3-inch PMTs for each crystal
(R12669SEL)

Eur. Phys. J. C. 78 107 (2018)

- Rate above background model (no discrimination)

- Excludes DAMA signal under **standard assumptions**



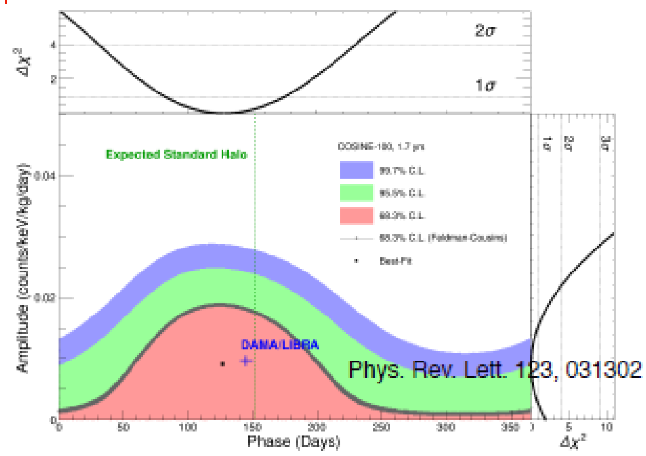
Nature **564**, 83 (2018)

COSINE-100: Modulation Results

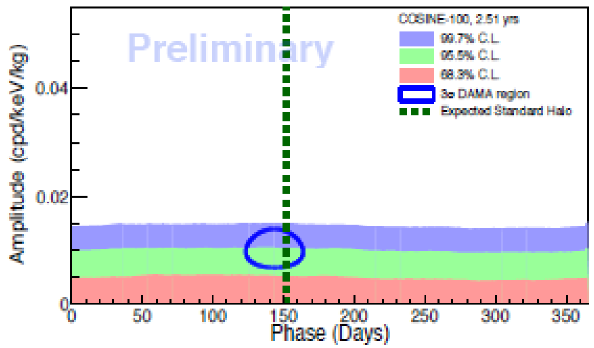
Annual modulation analysis

SET2 result

dama data : Nucl. Phys. At. Energy 19 (2018) 307



SET3 Predicted Sensitivity
Assuming no modulation case



- SET3 considers new event selection, ROI down to 1-6 keV range with 153.7 kg year exposure.
- SET3 analysis is under development with data still blinded.

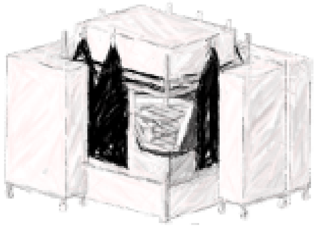
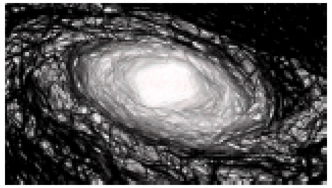
G. Adhikari, Sejong University 14 TAUP @ Toyama, Sep 11th

Plans for:

Cleaner crystals (DAMA level)
Lower threshold (DAMA level)
Higher mass:
1st 200kg, then 1tonne

(SET3 data since July 17, 2018, not yet unblinded)

ANAIS

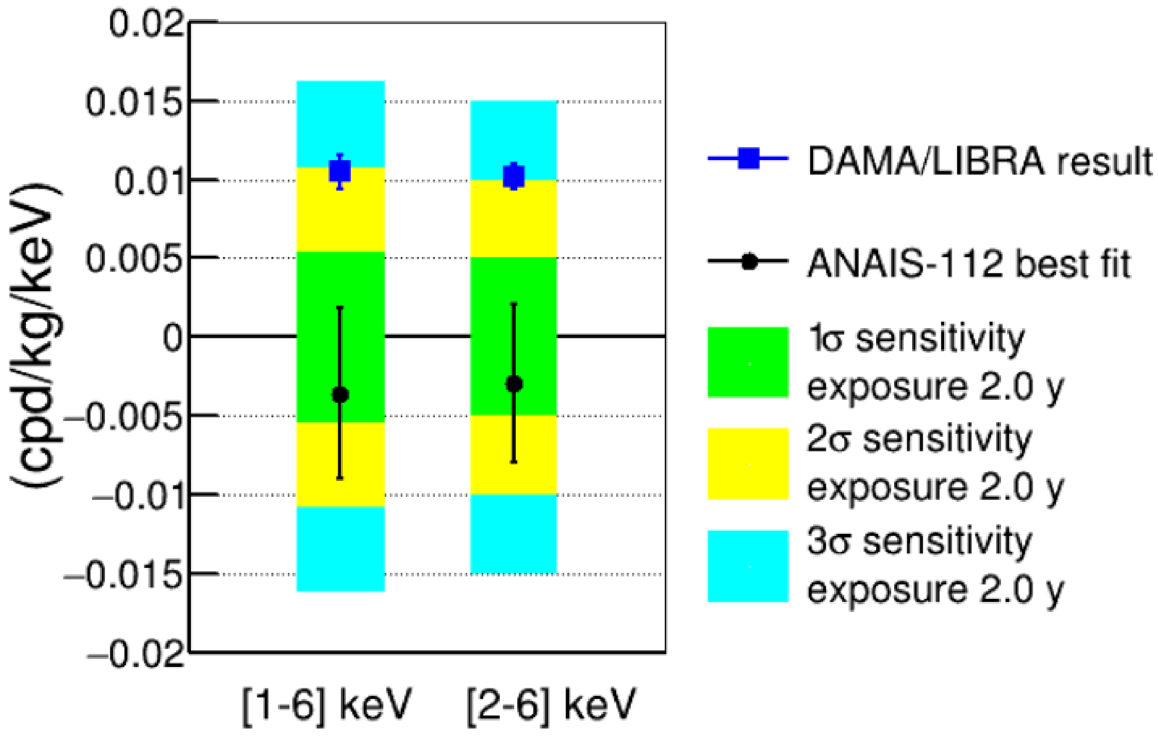




Summary and Outook

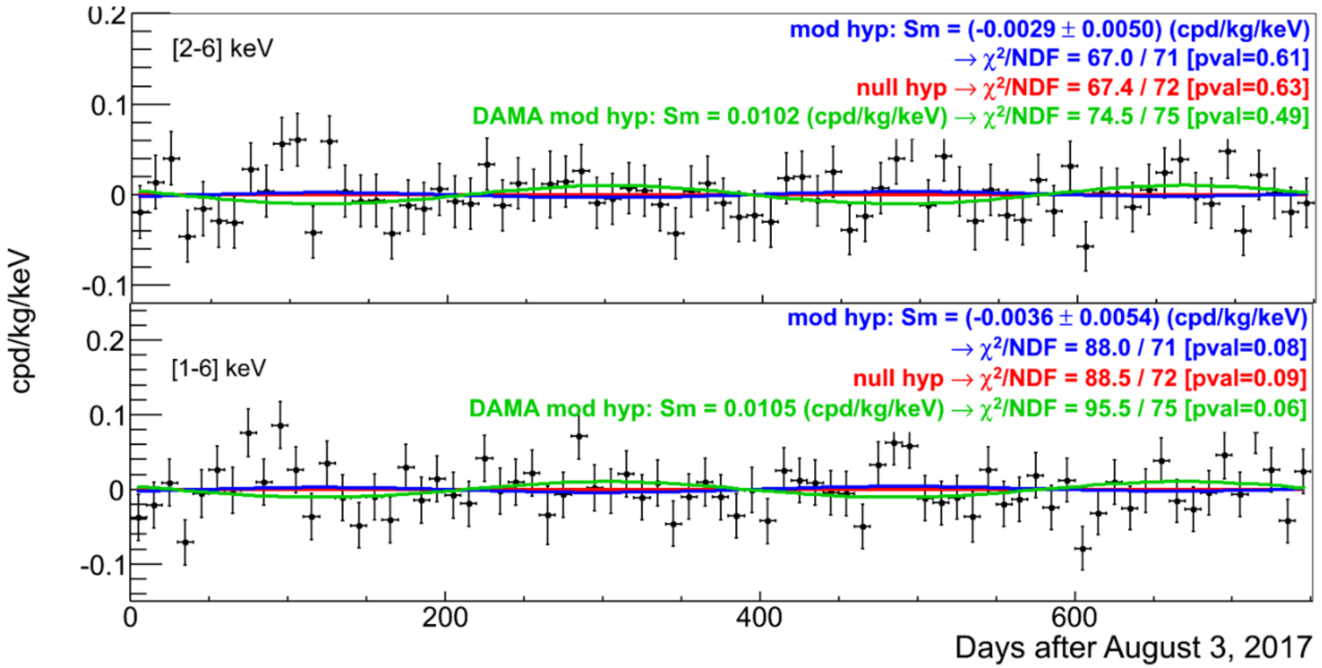
- **ANAI-112 is** taking data since August 2017: **112.5 kg of NaI** & running smoothly
  - Careful **low energy calibration** (from external gamma sources and bulk emissions)
  - Excellent **light collection** of **~15 phe/keV** and **triggering** below **1 keV$_{ee}$** in all modules
  - **1 keV$_{ee}$ analysis threshold** / limited by PMT events rejection procedure
  - Good **background understanding but in 1-2 keV energy region**
- **2 years of data** blind - analysed **for model independent annual modulation**
  - We confirm our sensitivity projections to DAMA/LIBRA result -> **3σ at reach in less than 3y more**
  - Null hypothesis is well supported by the χ^2 test
  - Best fits are incompatible at **2.6σ** with DAMA/LIBRA results, although **present sensitivity is 2σ**
- **Short term plan**:
  - **3 years more** of data taking in same conditions
  - Working in analysis improvements & background understanding at 1-2 keV
  - **Blank module** already installed to check systematics
  - REF for scintillation in ANAIS crystals measured at TUNL facility -> Analysis ongoing
  - ANAIS **data will be released** after use to allow independent analysis

(TAUP 2019)

ANAIS



(arXiv:1910.13365)



SABRE

SABRE Phase I - Proof of Principle

Setup ready at LNGS

Goals:

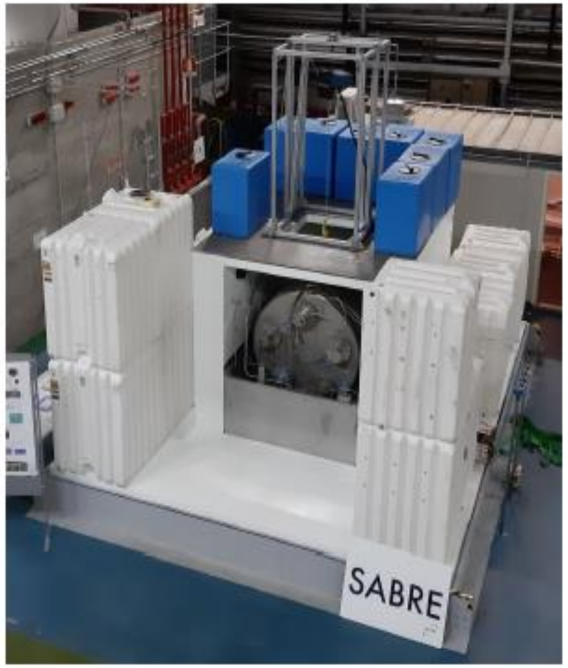
- Fully characterise SABRE NaI(Tl) intrinsic and cosmogenic backgrounds
- Test few (≈ 3) crystals
- Test active veto performance

Layout:

- 1 NaI(Tl) crystal module per time ("dry" insertion)
- Crystal mounted inside a Cu enclosure and directly coupled to 2 PMTs Hamamatsu ULB R11065-20 3" PMTs, High QE
- Active veto: 2 t PC+PPO (3g/l) scintillator (from Borexino exp) read by 10 Hamamatsu R5912-100 PMTs
- External passive shielding (lead, polyethylene and water) purged with gas nitrogen
- Material selection (using ICP-MS and HPGe)

Simone Copello - TAUP 2019, September 9th - Toyama, Japan 10

Proof of Principle status



All the needed infrastructures are completed:

- Fluid Handling
- Safety plant
- Slow control system
- Power (normal + UPS power)
- Network
- Control room (DAQ, High voltage...)

PoP is ready to be filled with liquid scintillator but we still waiting for the approval from the laboratory.

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Conclusions

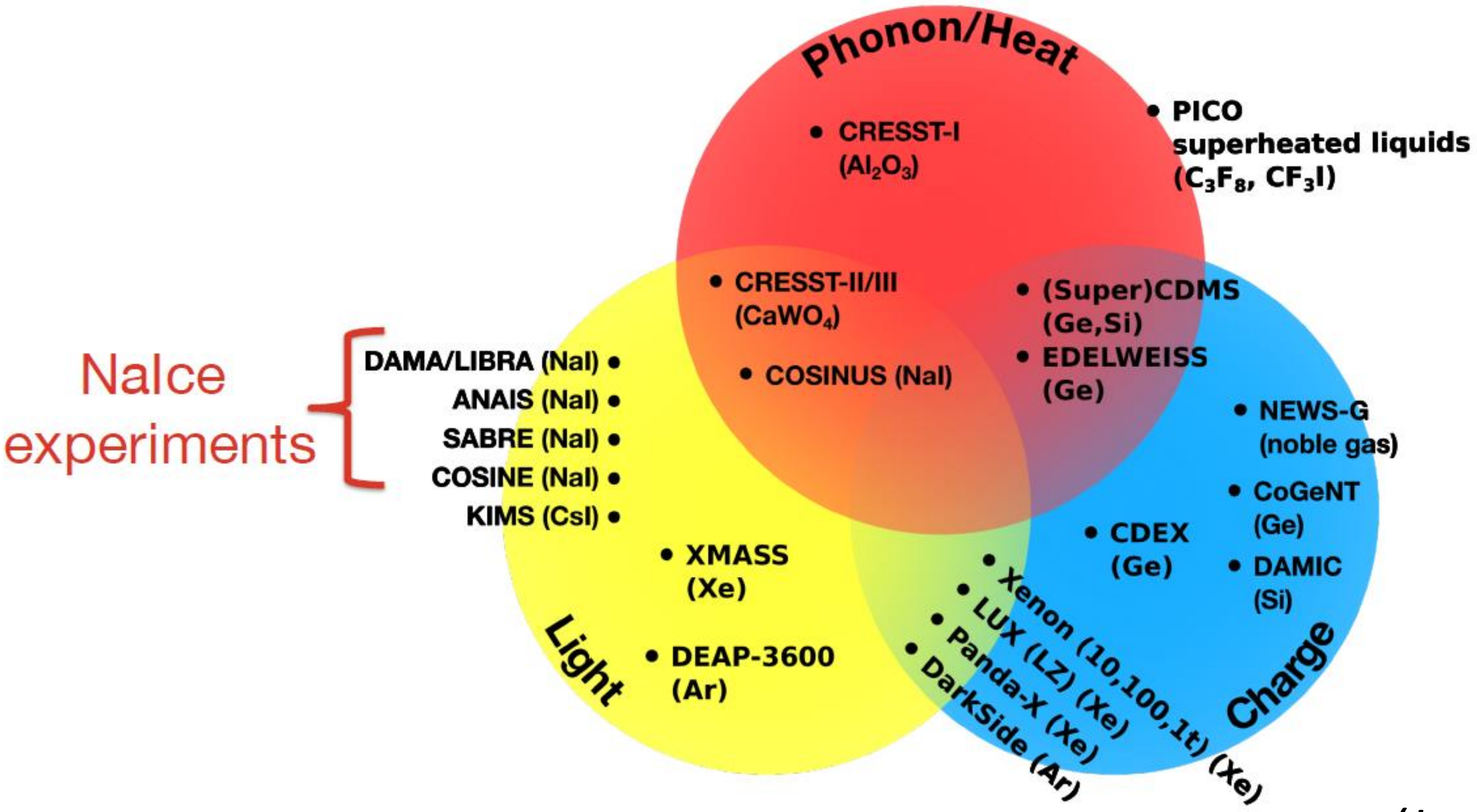
SABRE Proof of Principle

- Designed to test few crystals to validate the growth technique and the veto rejection capability
- **Ready to be filled with liquid scintillator** at Laboratori Nazionali del Gran Sasso

NaI-33 crystal (currently in measurement at LNGS) is a promising detector

- **^{40}K content ~ 4 ppb (ICP-MS)**, more than 3 times lower than DAMA
- **Good light yield 11 phe/keV** (preliminary)
- **Good energy resolution 12% @ 59.5 keV** (preliminary)
- **Current alpha rate is ~ 0.4 mBq/kg** (preliminary), possibly mainly due to ^{210}Po.

- Thanks for the attention -



Phonon/Heat
• CRESST-I (Al_2O_3)
• PICO superheated liquids (C_3F_8, CF_3I)
• CRESST-II/III ($CaWO_4$)
• COSINUS (NaI)
• (Super)CDMS (Ge,Si)
• EDELWEISS (Ge)
NaIce experiments
DAMA/LIBRA (NaI) •
ANAIS (NaI) •
SABRE (NaI) •
COSINE (NaI) •
KIMS (CsI) •
• NEWS-G (noble gas)
• CoGeNT (Ge)
• CDEX (Ge)
• DAMIC (Si)
• XMASS (Xe)
• DEAP-3600 (Ar)
• Xenon (10,100,1t) (Xe)
• LUX (LZ) (Xe)
• Panda-X (Xe)
• DarkSide (Ar)
Light
Charge

(Incomplete!)

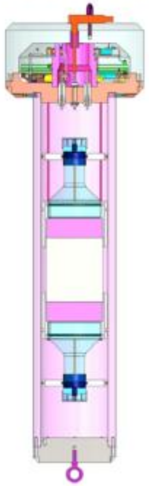
COSINUS

DM-Ice17

South pole
17 kg NaI

threshold: 4 keV_{ee}

3.5 y physics run
no hint

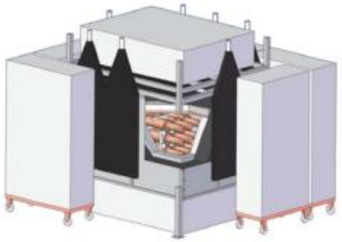


ANAIS-112

LSC - Spain
112.5 kg NaI

threshold: < 1 keV_{ee}

since spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

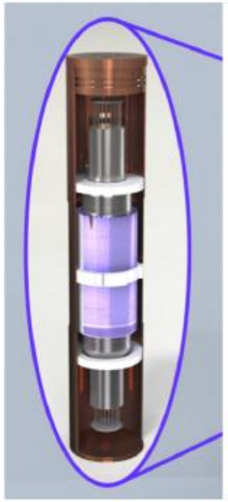
threshold: ~2 keV_{ee}

since Sept. 2016

SABRE

Gran Sasso/Australia
40-50 kg NaI

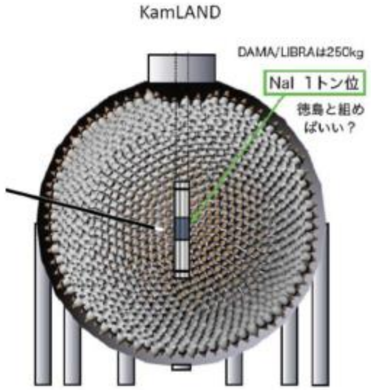
construction phase



KamLand-PICO

KamLand/Japan
1t NaI

planning/
prototyping phase



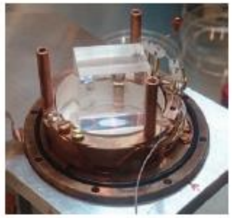
COSINUS

NEW

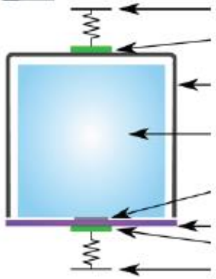
Gran Sasso
NaI as **cryogenic detector**

only NaI-based experiment with Particle Identification

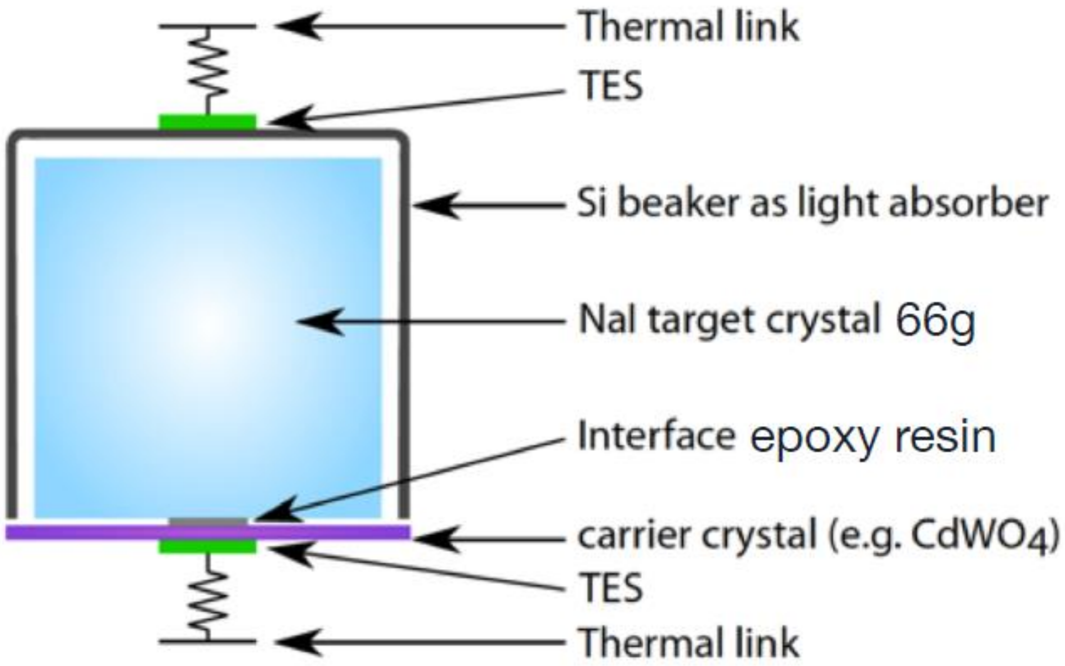
construction starts 2020

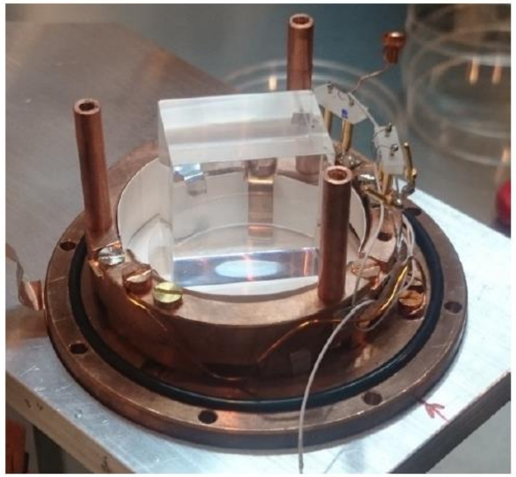


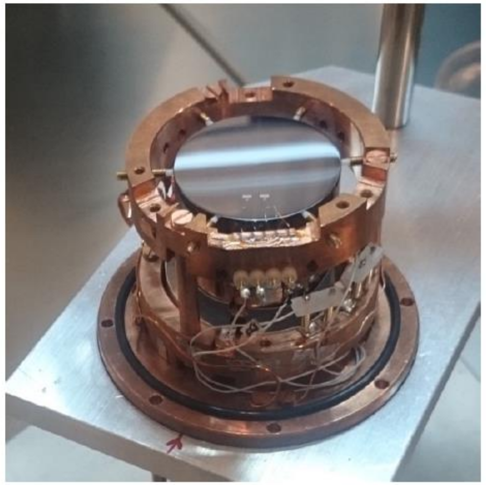
heat
&
light
readout



COSINUS







(Proof-of-principle: 2nd prototype, 2016/2017)

Two readout channels:

- Phonon signal (~90 % of deposited energy)
- Scintillation light (few percent)

$\longrightarrow$ **Particle discrimination**

Goal: NaI-based cryogenic detectors at level of existing ones (e.g. CRESST-II)

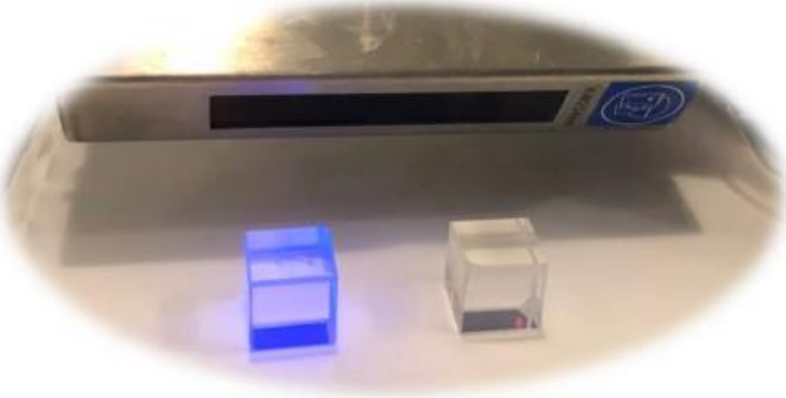
$\longrightarrow$ 1keV **nuclear recoil** threshold

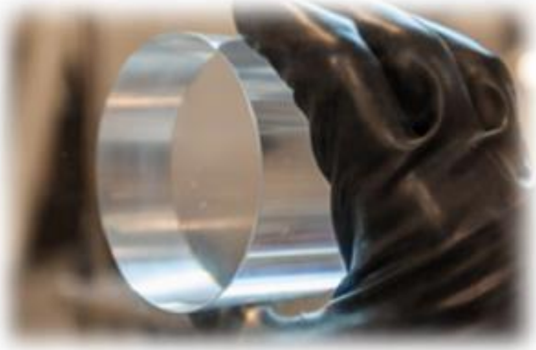
COSINUS – NaI Crystals

- Collaboration with I. Dafinei from INFN, Roma 1
- Yong Zhu from SICCAS joined the COSINUS collaboration
- Different batches of crystals tested:
  - ➢ NaI / NaI(Tl) grown from SICCAS powder (3 g – 30 g crystals)
  - ➢ Two 3-inch NaI crystals grown from Astrograde-powder at SICCAS
  - ➢ **Very promising radiopurity (ICP-MS analysis):**

    → 5-9 ppb of K at crystals' nose and 22-35 ppb at the tail

    → comparable or even higher purity than DAMA/LIBRA (~ 13 ppb)
  - ➢ NaI(Tl) with different amount of thallium dopant





COSINUS: Model-independent sensitivity

(Two-channel readout: Event discrimination!)

Mean rate
COSINUS

$$\overline{R} = \frac{1}{2}\,[R(t = \text{June } 1^{st}) + R(t = \text{Dec. } 1^{st})]$$

Modulation Amplitude
DAMA

$$S = \frac{1}{2}\,[R(t = \text{June } 1^{st}) - R(t = \text{Dec. } 1^{st})]$$

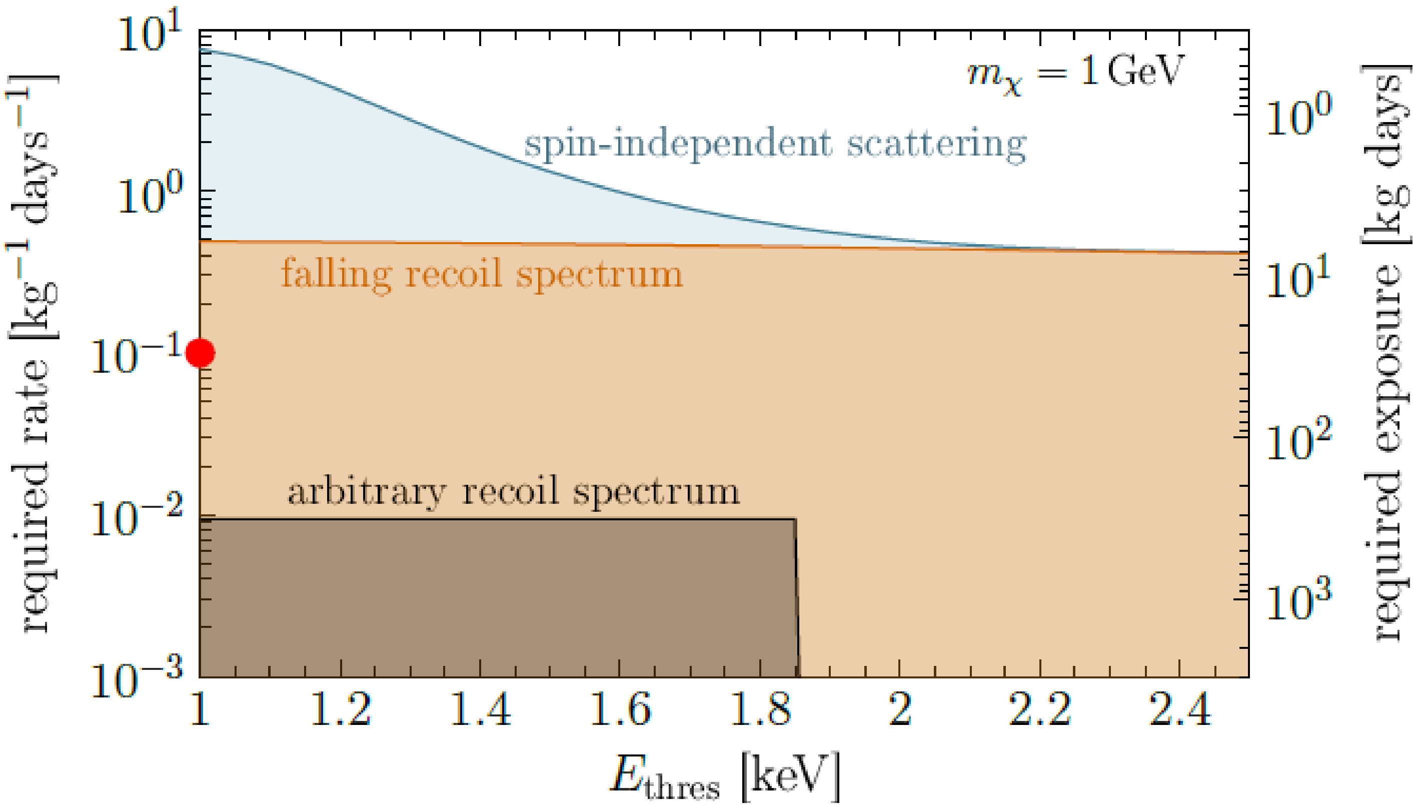
Central idea: The modulation amplitude (in a given experiment) cannot exceed the mean rate:

$$\overline{R} \geq S$$

(Felix Kahlhoefer et al, JCAP05(2018)074)

Model-independent sensitivity

(Felix Kahlhoefer et al, JCAP05(2018)074)



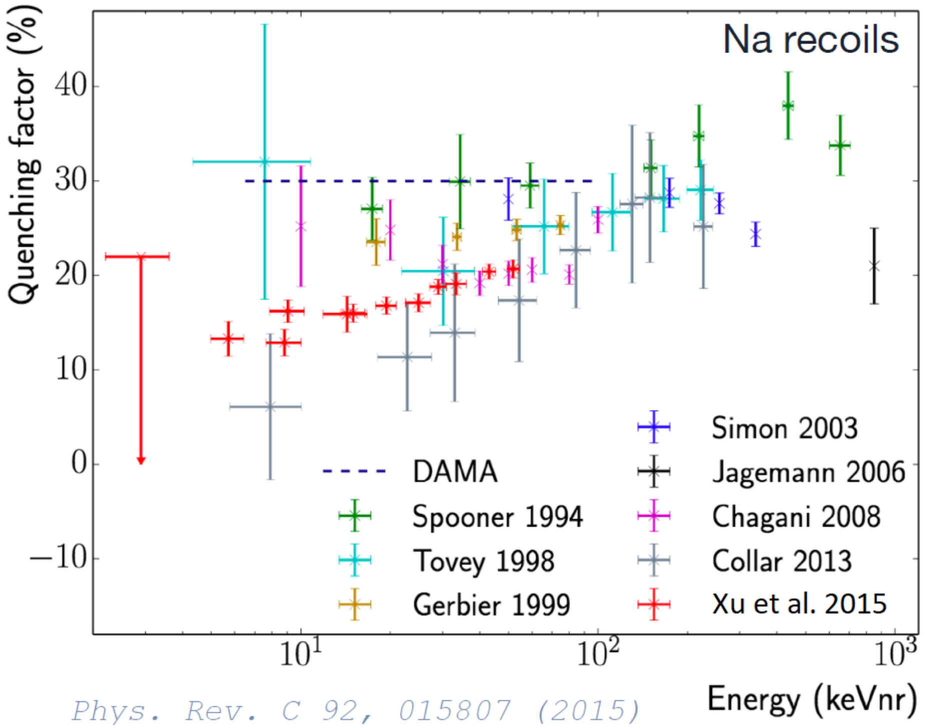
- COSINUS design goal:
  $E_{thres} = 1\mathrm{keV}$
  $R = 0.1\ \mathrm{kg}^{-1}\mathrm{d}^{-1}$

(Not updated for recent DAMA result with 1keVee threshold)

NaI as Detector Material

- Hygroscopic → handling in controlled atmosphere
- Good scintillator at room temperature when doped with Tl, widely used
- Contamination with ^{40}K (3 keV Auger e^-+ 1.46 MeV γ) → liquid scintillator veto in many experiments
- ``Quenching factor mystery``:

→ Effect on nuclear recoil energy scale!



Phys. Rev. C 92, 015807 (2015)

Summary

- The DAMA modulation…

  - is excluded by many experiments with **different target materials** (Xe, Ge, CaWO4, …) under **standard assumptions**

  - is excluded with **the same target material** (NaI) under **standard assumptions**

  - is incompatible with modulation results from XENON, LUX (Xe, particle discrimination) and XMASS (Xe, no discrimination; not covered in this talk)

  - has not been ruled out in a **model-independent** way by any experiment with **the same target material**

- Growing field of NaI experiments

  - First results from COSINE-100, ANAIS
  - SABRE in proof-of-principle phase
  - COSINUS construction beginning 2020

- The list of experiments covered in this talk is incomplete
- COSINUS point of view

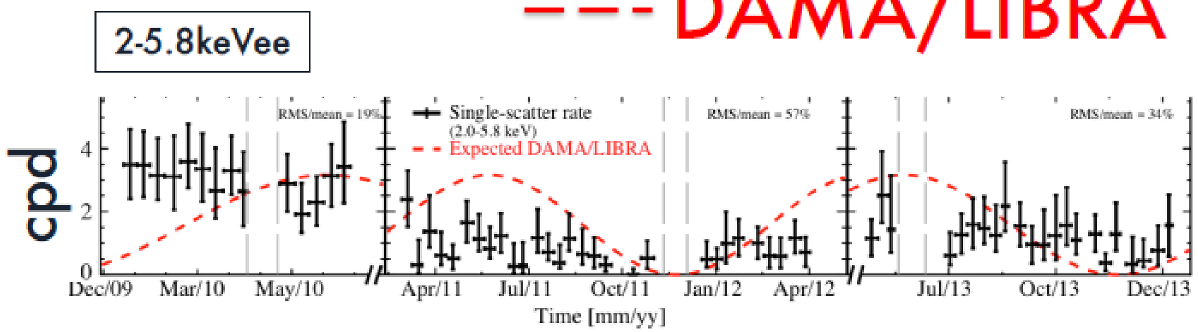
Thank you!

Most of the material in this talk was compiled by F. Reindl and K. Schäffner.

Leptophilic Dark Matter – Electron Recoils

XENON100

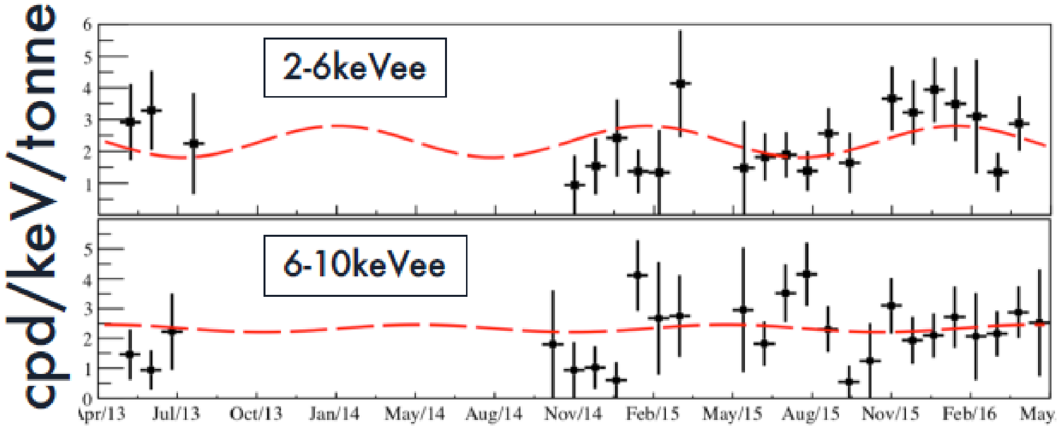
--- DAMA/LIBRA



PRL 118 (2017)

LUX

--- best fit

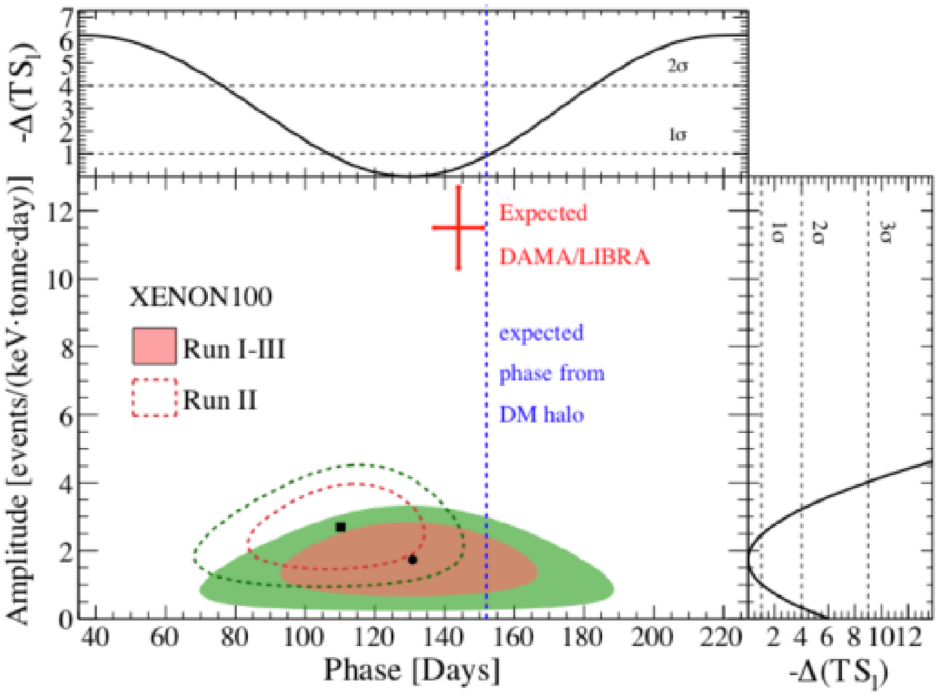


PRD 98 (2018)

Leptophilic Dark Matter – Electron Recoils

XENON100

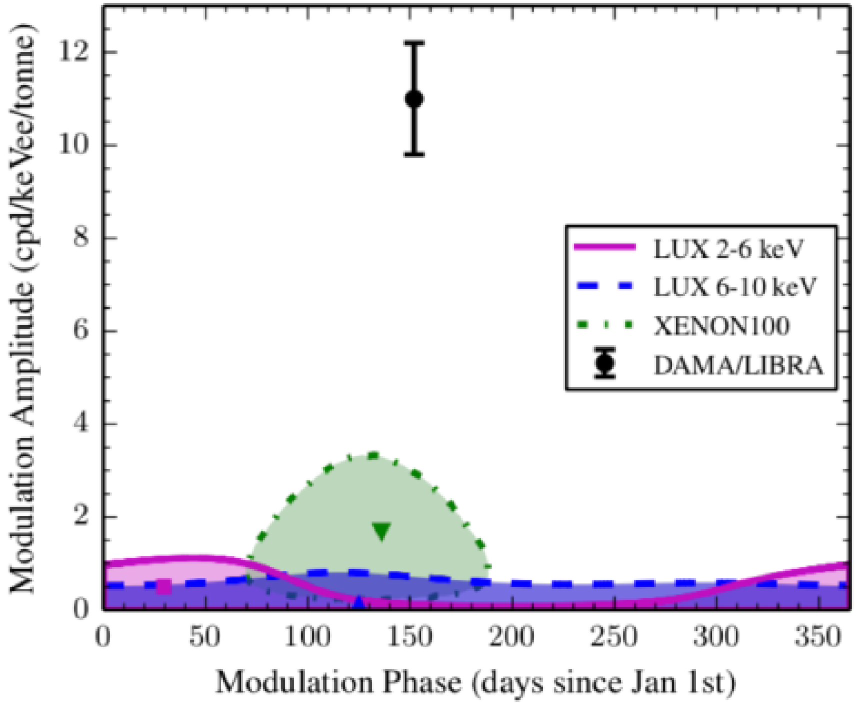
PRL 118 (2017)



>5σ tension with DAMA*

LUX

PRD 98 (2018)



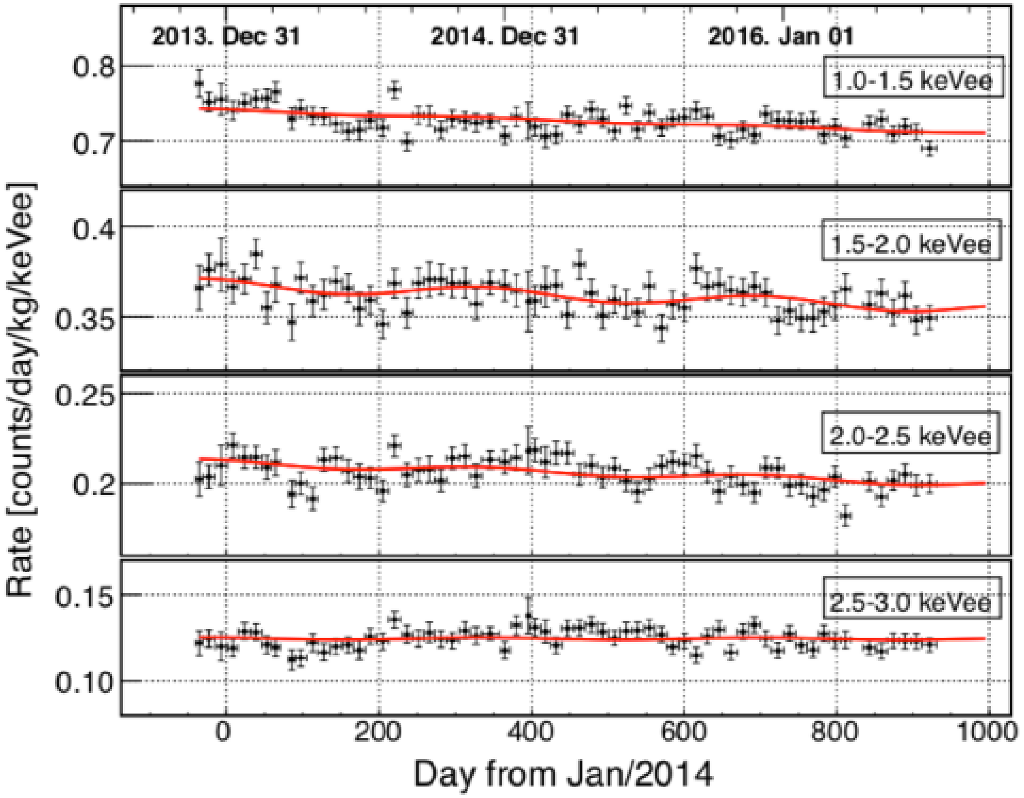
>9σ tension with DAMA*

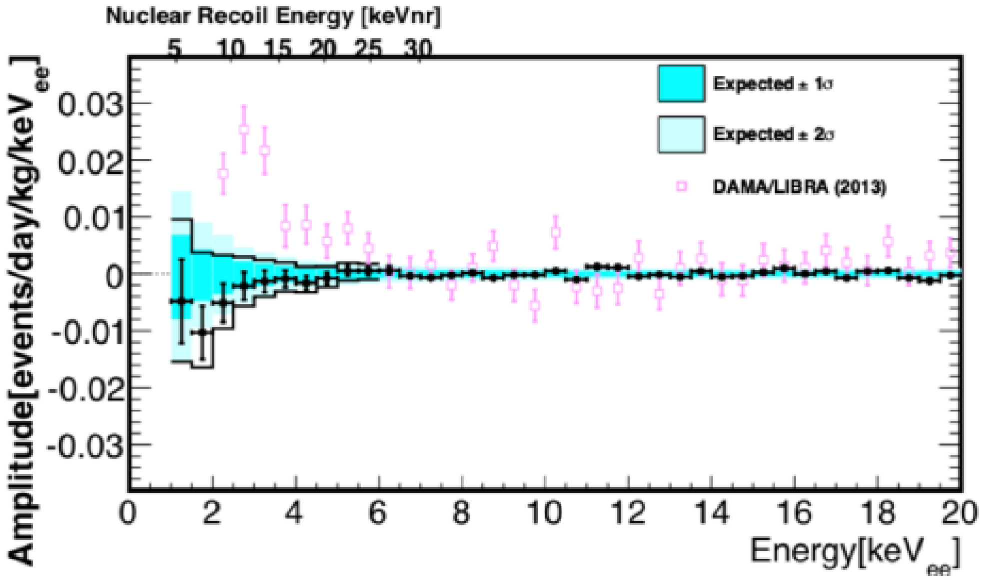
*DAMA/LIBRA phase 1 for leptophilic DM

Model Independent Modulation Analysis – XMASS (Single Phase lXe Detector)

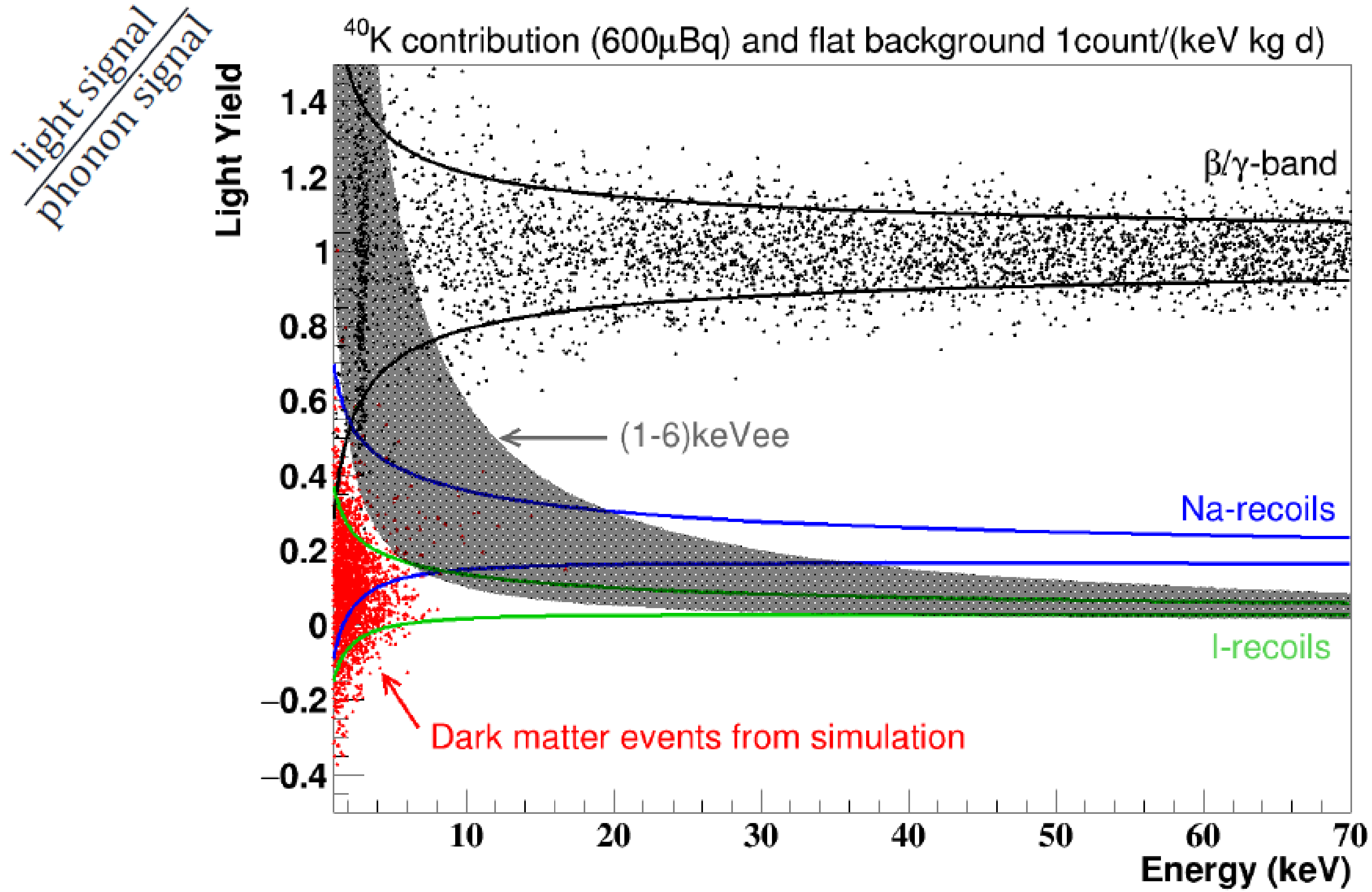
Threshold: 1keVee (4.8keVnr)

PRD 97 (2018)





COSINUS – Simulation (100 kg-days)



(1-6)keVee
=
modulation signal in DAMA