COSINUS

a direct dark matter search using cryogenic NaI detectors

Karoline Schäffner

Project review

via remote connection

December, 14 2020

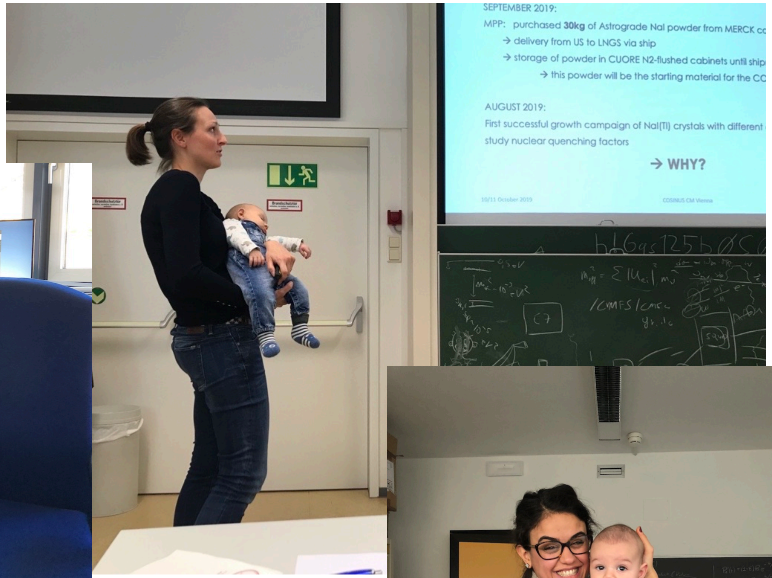
Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MAX-PLANCK-GESELLSCHAFT

FIRST PROJECT REVIEW for COSINUS

COSINUS started as Max Planck Research Group @ MPP in 04/2019

→ 05/2019 stop for maternity leave

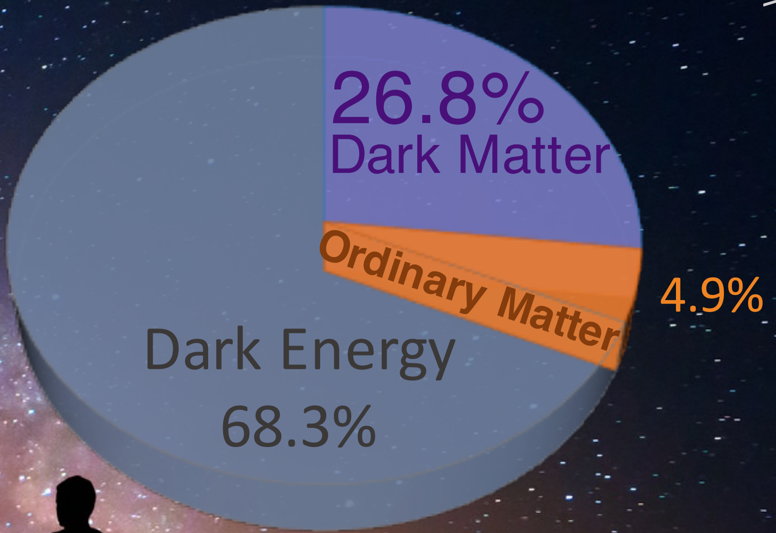


Now again full time → Thanks MPP for helping with Kita

… and COSINUS has very exciting times ahead !

Dark Matter

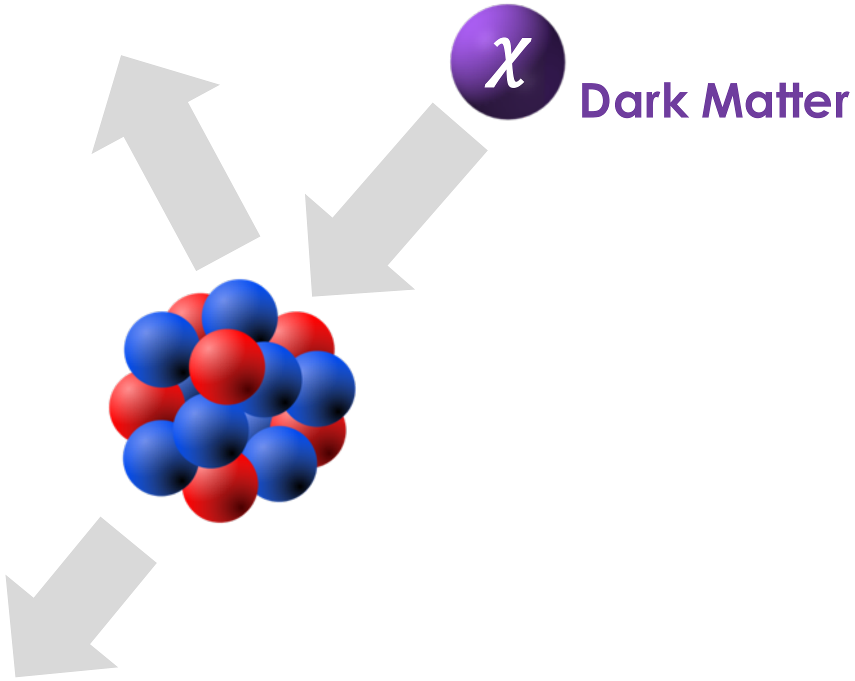
+ add extra and new ingredient



→Physics beyond the Standard Model

→→ **explains huge interest in community**

DIRECT DARK MATTER DETECTION



Assumption

Particle-like dark matter which interacts with Standard Model particles

Most common

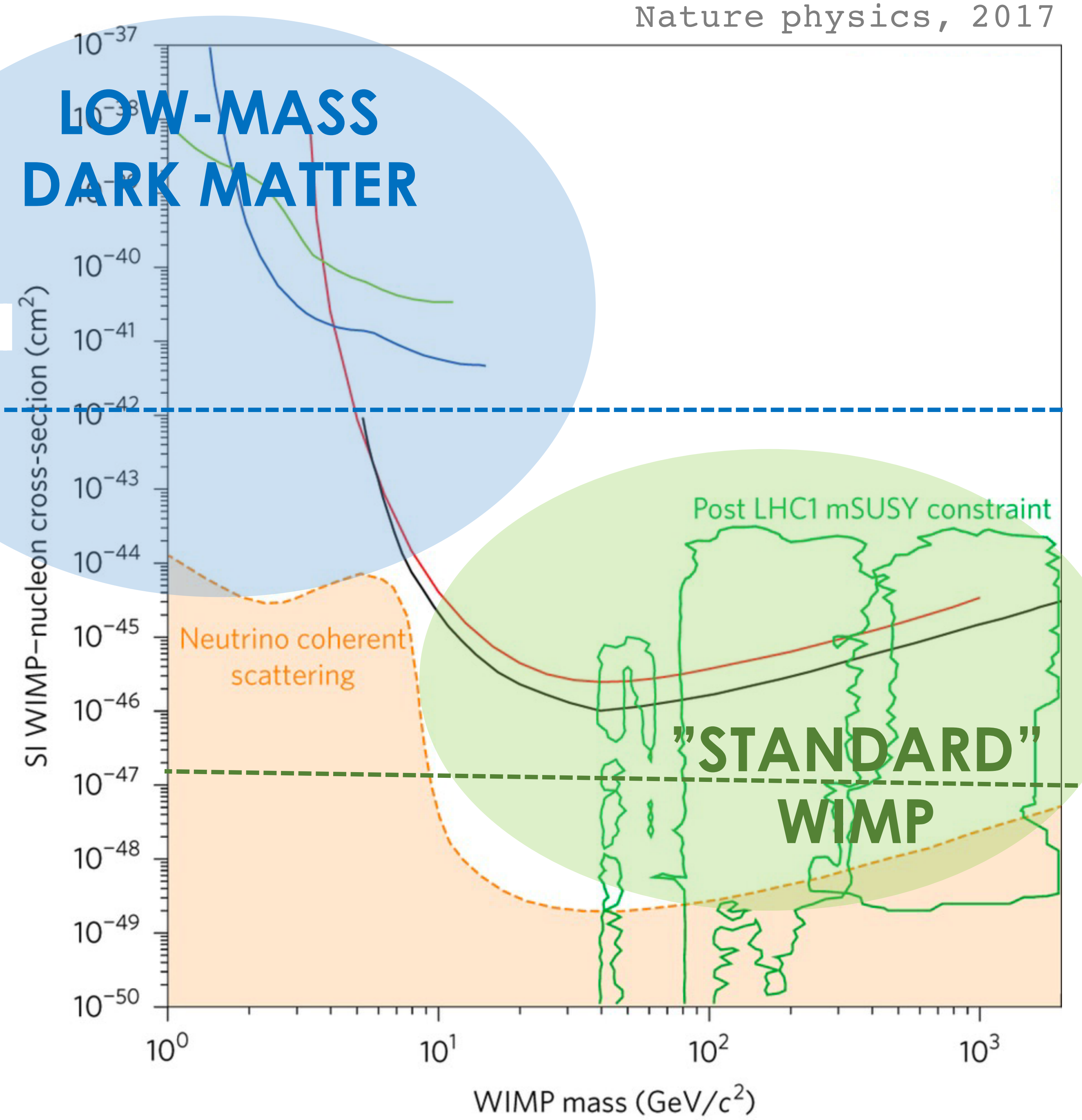
Dark matter particle scatters off the nucleus and induces a nuclear recoil

Also:

Electron recoils ? !

“EXOTICS”

far sub-GeV



~ 1 event/ kg-day

low energy threshold

→ performance

diverse technologies

large target

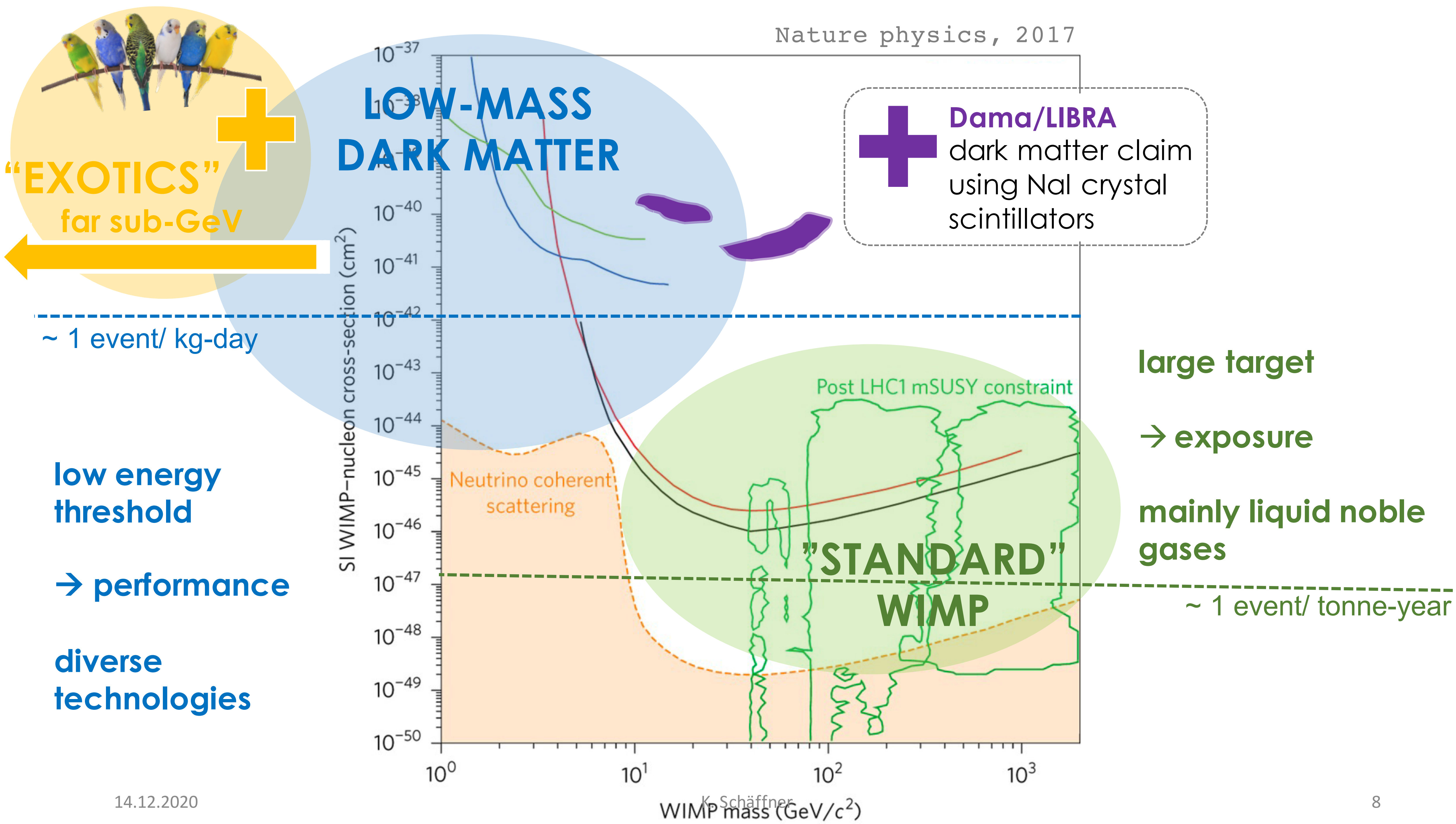
→ exposure

mainly liquid noble gases

~ 1 event/ tonne-year

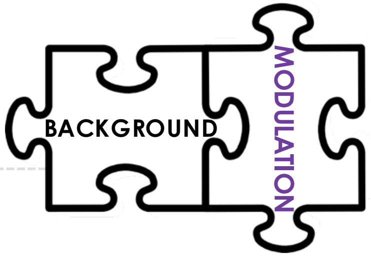
"STANDARD" WIMP

There is one exception ...

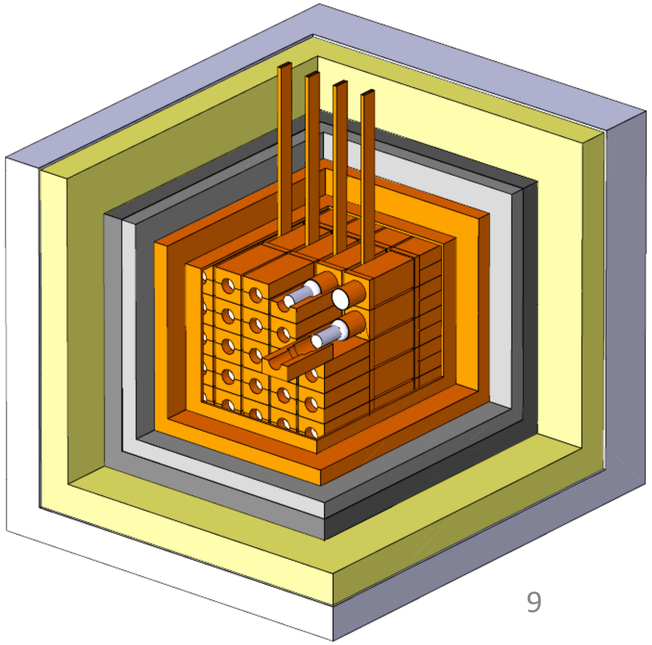


Nature physics, 2017
LOW-MASS
DARK MATTER
"EXOTICS"
far sub-GeV
~ 1 event/ kg-day
Dama/LIBRA
dark matter claim
using NaI crystal
scintillators
large target
→ exposure
mainly liquid noble
gases
~ 1 event/ tonne-year
"STANDARD"
WIMP
low energy
threshold
→ performance
diverse
technologies
Post LHC1 mSUSY constraint
Neutrino coherent
scattering
SI WIMP–nucleon cross-section (cm²)
WIMP mass (GeV/c²)

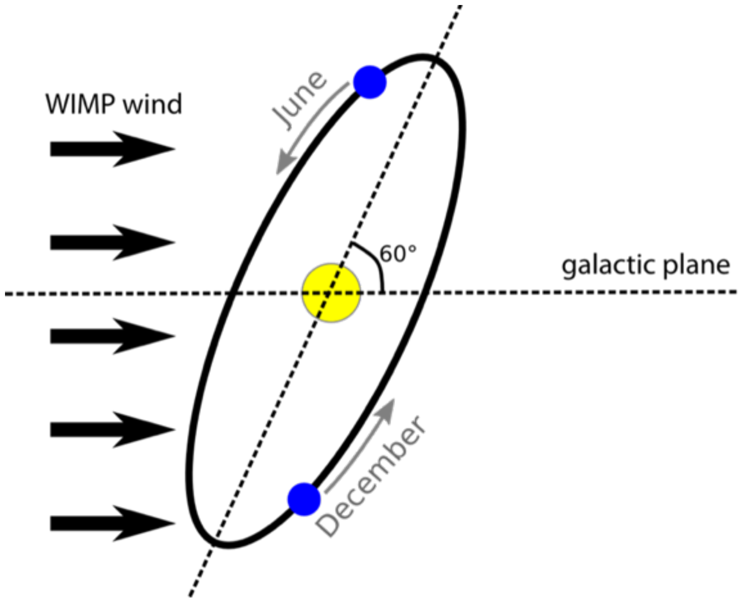
DAMA/LIBRA experiment

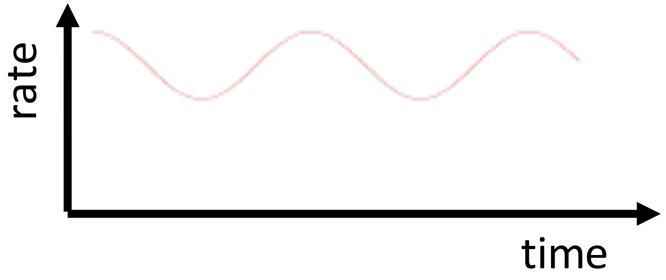


MATERIAL	250 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	**1keVee**
DATA TAKING	since 1996



MODULATION

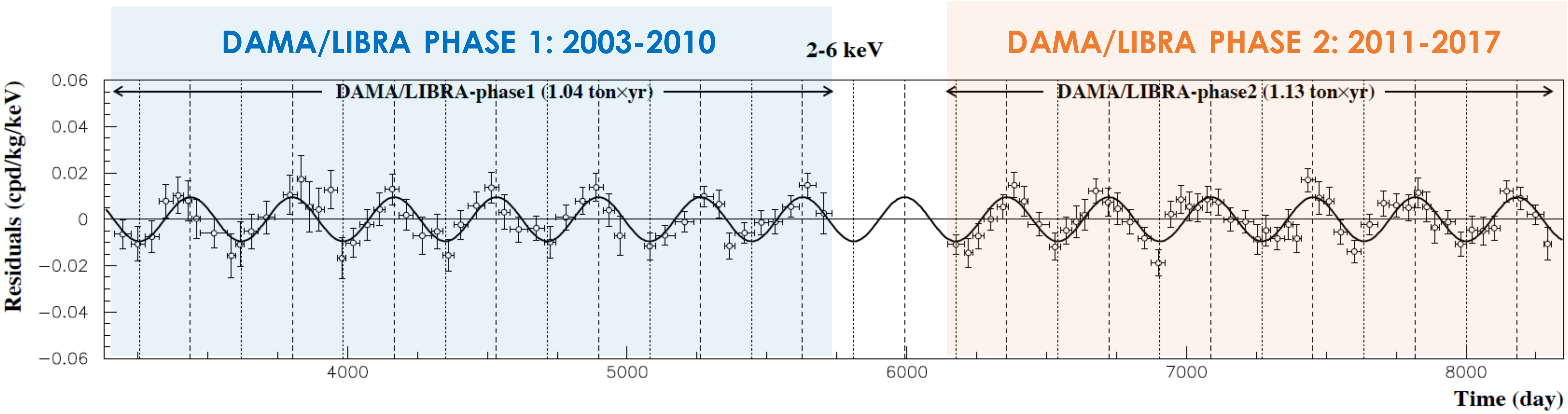




motion of the Earth causes
modulation of relative velocity → **annual variation in the rate**

DAMA/LIBRA: **TIME DISTRIBUTION**

NPAE 2018, vol. 19, issue 4

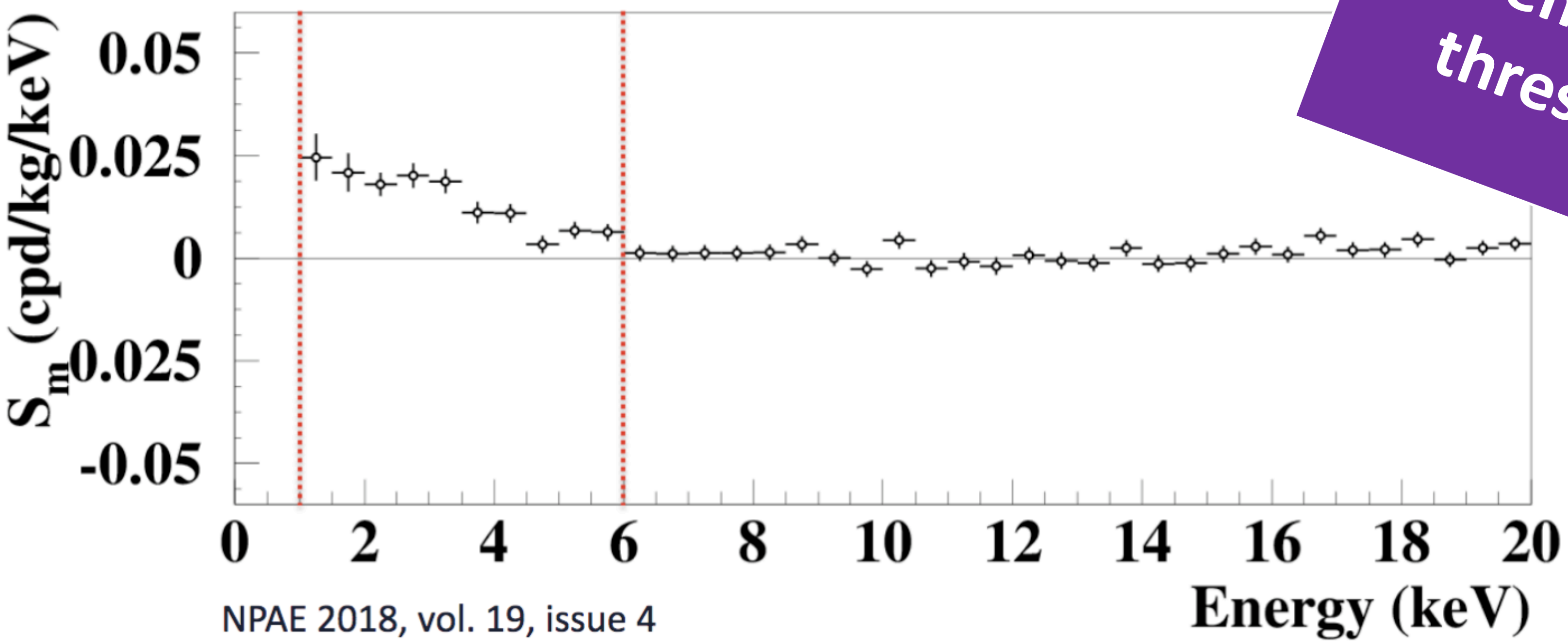


Total exposure: 2.17 tonne years (phase 1 + 2)
Statistical significance: >11.9 σ

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

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

DAMA/LIBRA: **ENERGY DISTRIBUTION**



NPAE 2018, vol. 19, issue 4

2018: lower energy threshold

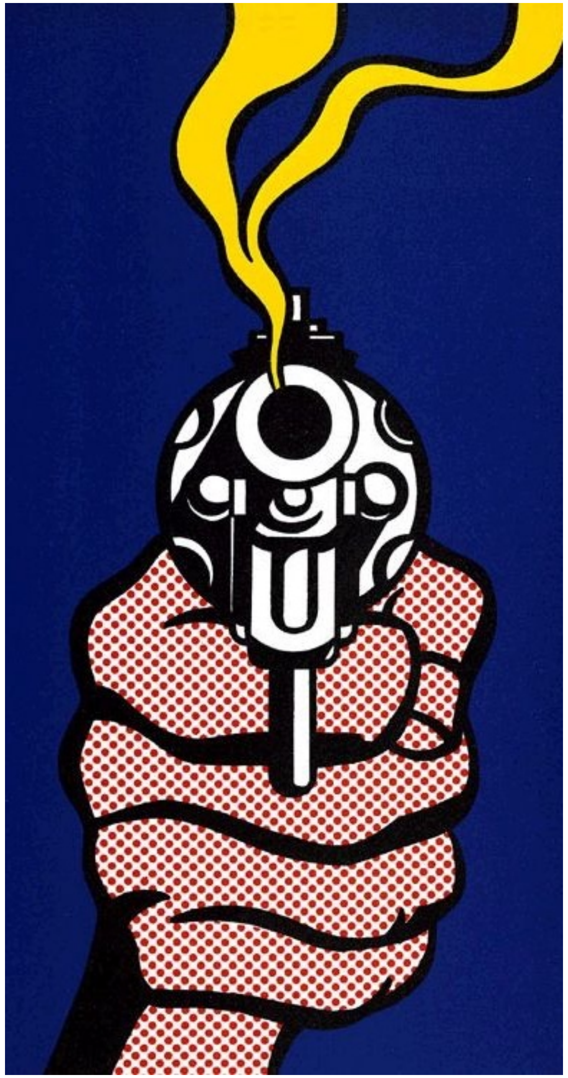
THE SMOKING GUN EVIDENCE?

Statistics: 12.9 σ ✓

Period: 0.999 ± 0.001 years * ✓

Phase: 25th May +/- 5 days ✓
(cosine peaking June 2nd)

Convincing non-DM explanation ✗

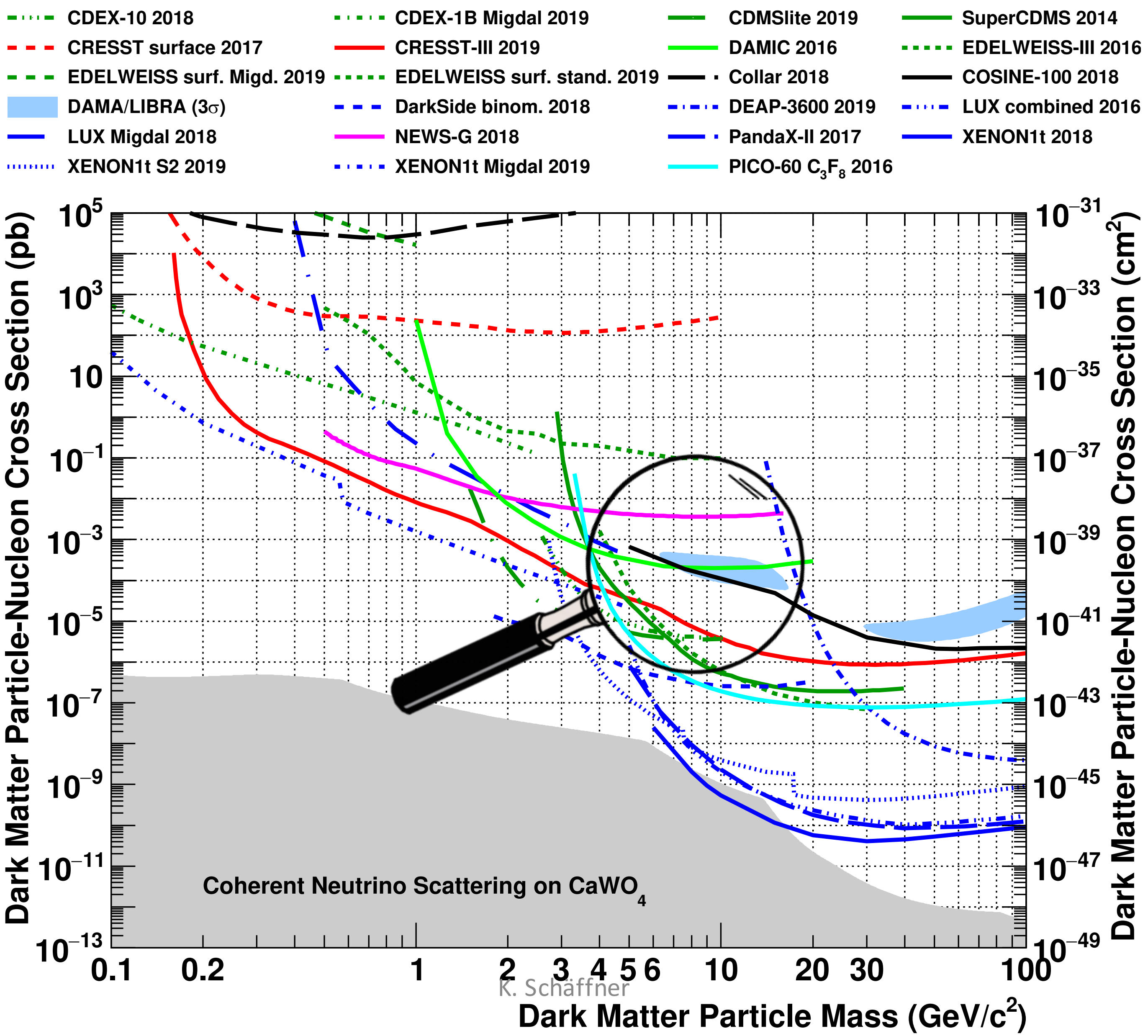


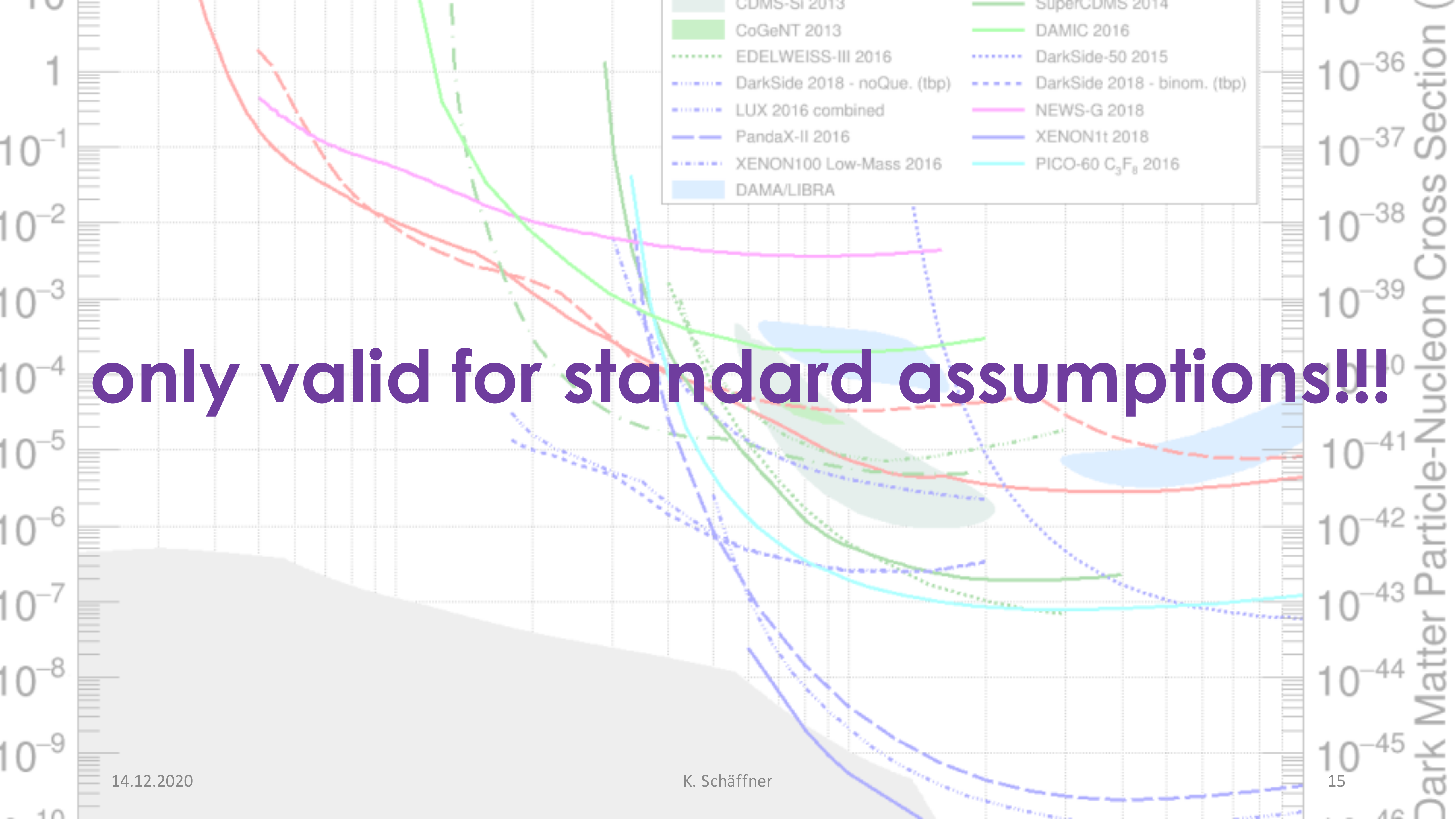
*in (2-6) keVee interval

COMPARISON OF EXPERIMENTS

Null results shown as:
90% C.L upper limits on the spin-independent elastic DM-nucleon cross section

DAMA/LIBRA:
3σ allowed parameter space





only valid for standard assumptions!!!

WHAT ARE THE **UNKNOWNS**?

galactic escape velocity

velocity distribution

DM-nucleus cross-section

$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v \, f(\vec{v}) \, v \, \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

minimal velocity to produce a recoil of energy E_r

~ A^2
~ form factor

Astro physics

dark matter halo
velocity distribution

Particle physics

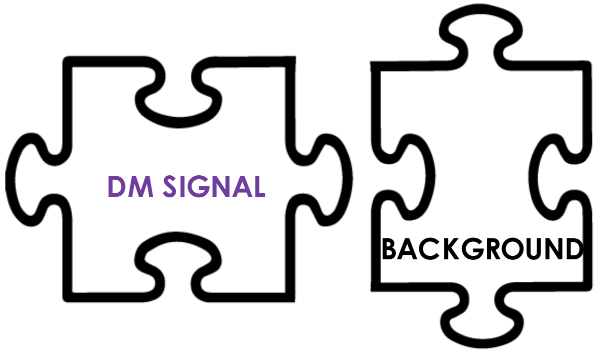
interaction mechanism

We have a dependence on the target material

→ cross-check DAMA/LIBRA signal with **same-target experiment**

COSINUS

Why do we need COSINUS?



- First NaI detector with particle discrimination
- lower energy threshold for nuclear recoils using cryogenic detectors → model independent test of DAMA

Eur. Phys. J. C (2016) 76:441

COSINUS a Spin Off of CRESST technology

"NaIce" detectors:

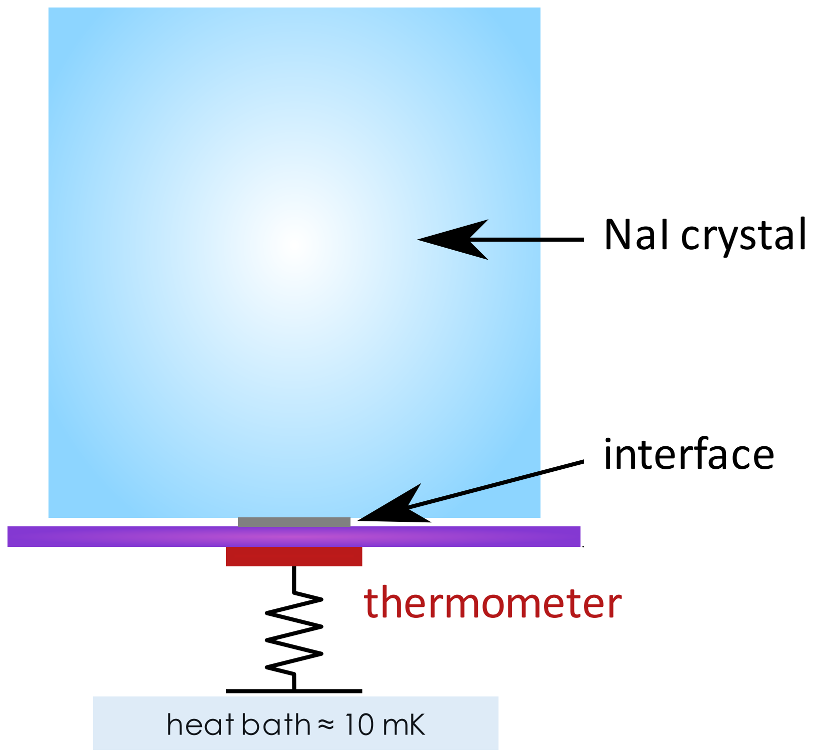
Dama\LIBRA same-target experiment
→ use NaI crystals

"Cool" detection technique:

Cryogenic scintillating calorimeters

→ make use of CRESST - technology

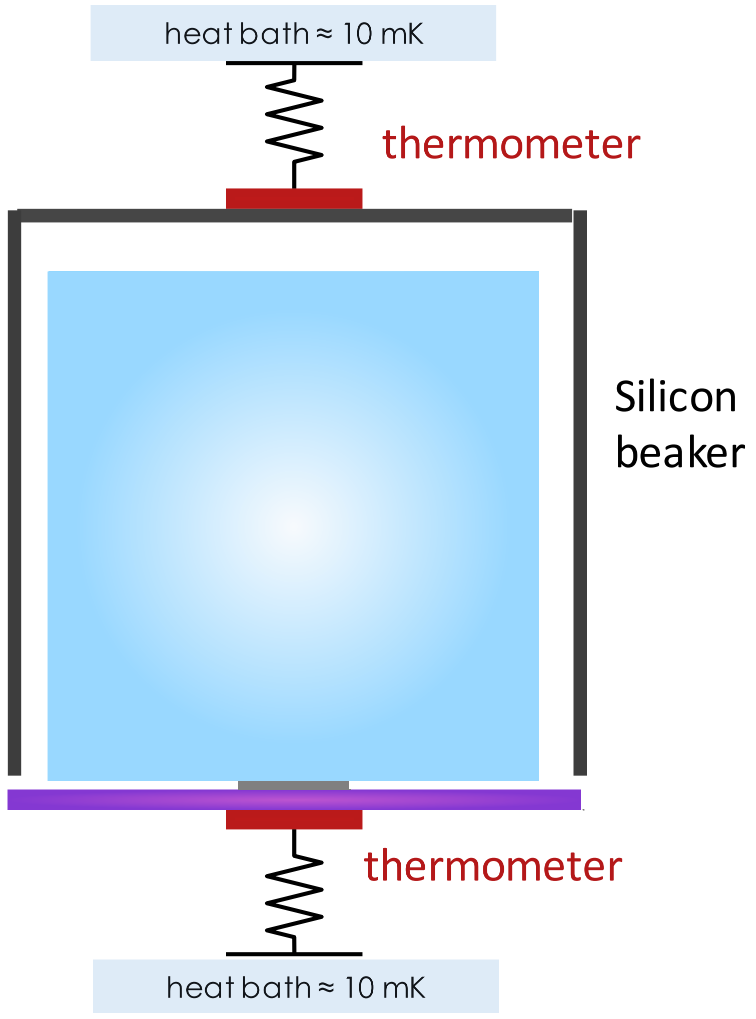
LOW-TEMPERATURE COSINUS DETECTOR



Phonon signal (~ 90 %)

- (almost) independent of particle type
- precise measurement of the deposited energy

LOW-TEMPERATURE COSINUS DETECTOR



Phonon signal (~ 90 %)

- (almost) independent of particle type
- precise measurement of the deposited energy

Scintillation light (few %)

- amount of emitted light depends on particle type
  → LIGHT QUENCHING

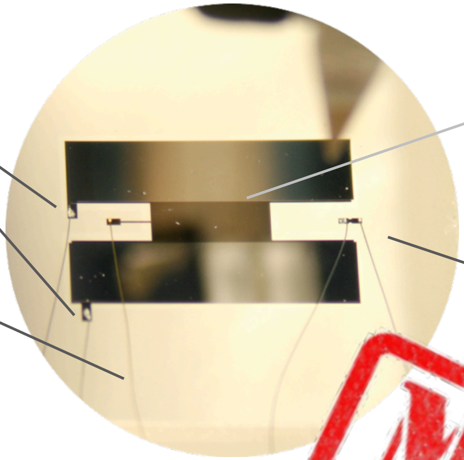
→ **add cryogenic light detector** for scintillation light detection

- discrimination of interacting particle via the **ratio of light to phonon signal** → LIGHT YIELD

TRANSITION EDGE SENSOR (TES)

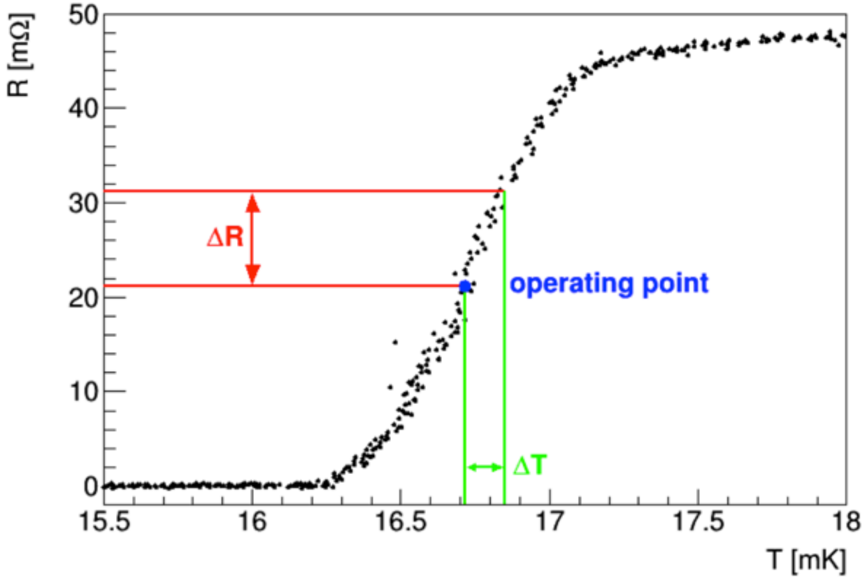
electrical contacts
aluminium

thermal link
GOLD

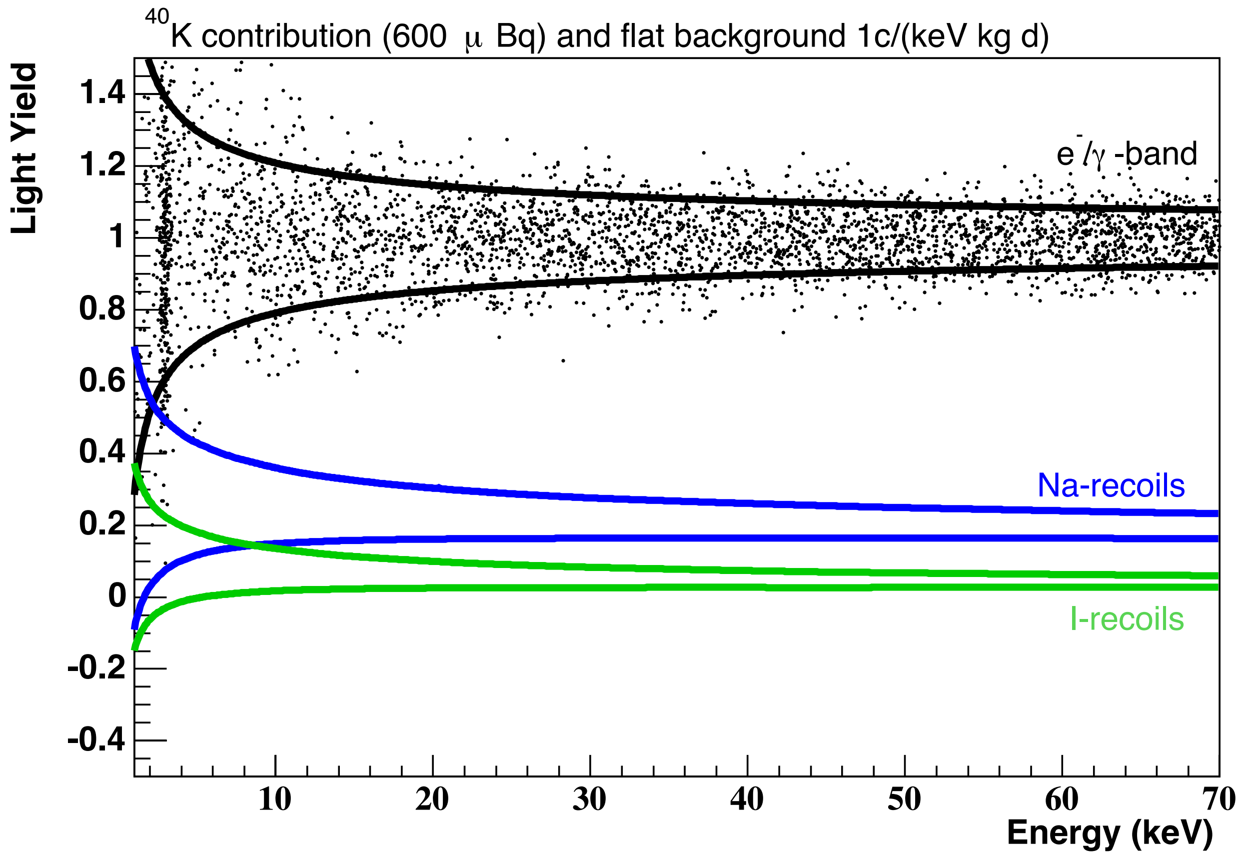


superconducting
tungsten film
(200 nm)

resistive TES heater



SIMULATED DATA FOR 100 kg days (gross-exposure)



Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

$$\text{LIGHT YIELD} = \frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$$

recoils off Na

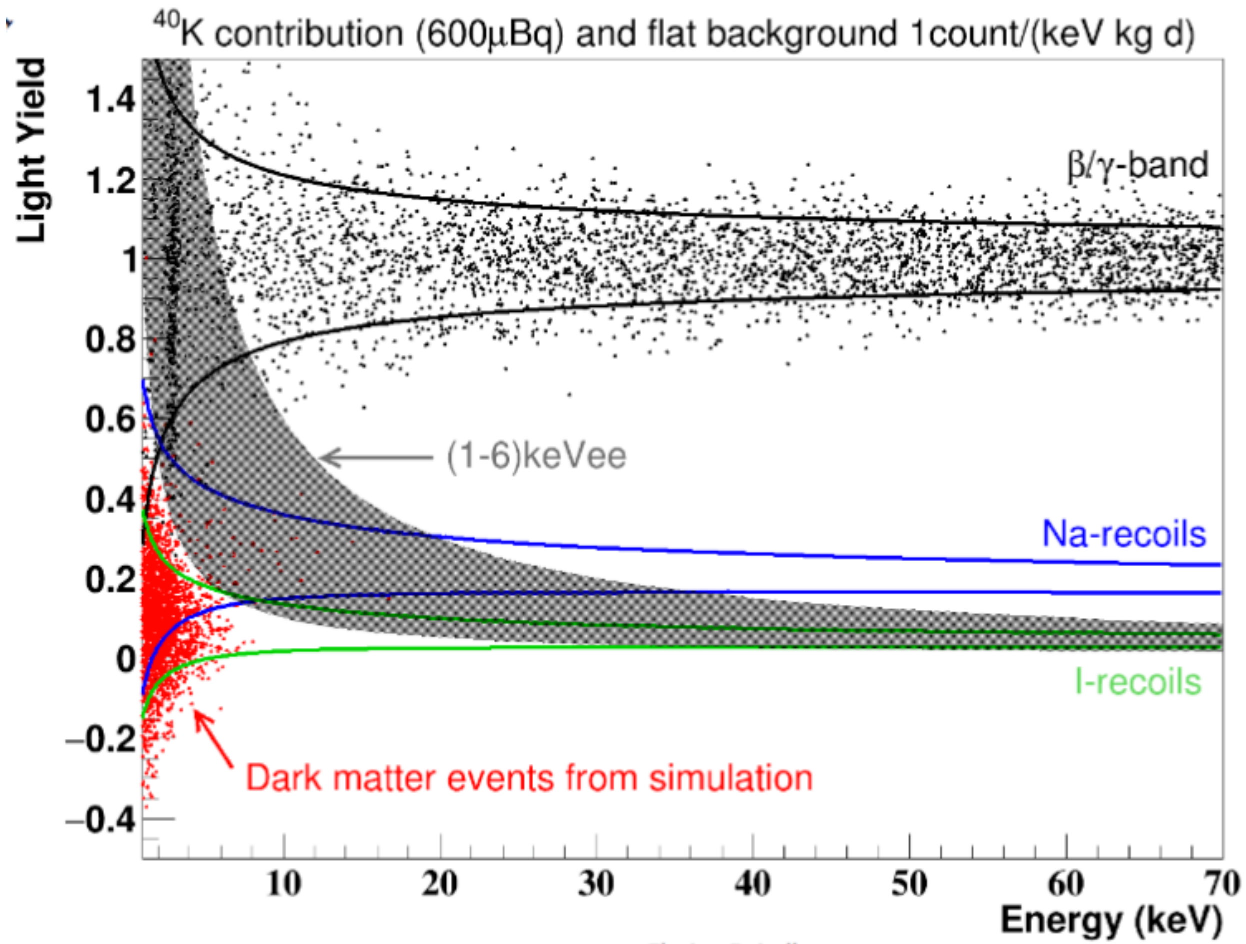
→ light quenching factor ~ 0.3

recoils off I

→ light quenching factor ~ 0.1

values for quenching factors from:
Tretyak, Astropart. Phys. 33, 40 (2010)

SIMULATED DATA FOR 100 kg days (gross-exposure)



Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

the modulation signal in DAMA/LIBRA is observed in the interval (1-6) keV_{ee}

PHYSICS REACH

On the way to Corno Grande (2912 m)
30.09.2018

PHYSICS POTENTIAL SUMMARY

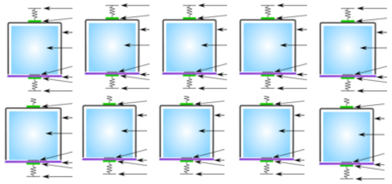
COSINUS has the unique potential to clarify a nuclear recoil origin of the DAMA/LIBRA signal

CONFIRM

+ not **too exotic** dark matter

Good chance for exposure $\mathcal{O}$ (100 kg days)

10 detector modules
about 50 g each



1 year of data taking
50% overall efficiency

Low-background cryogenic facility
underground lab, shields, dilution refrigerator

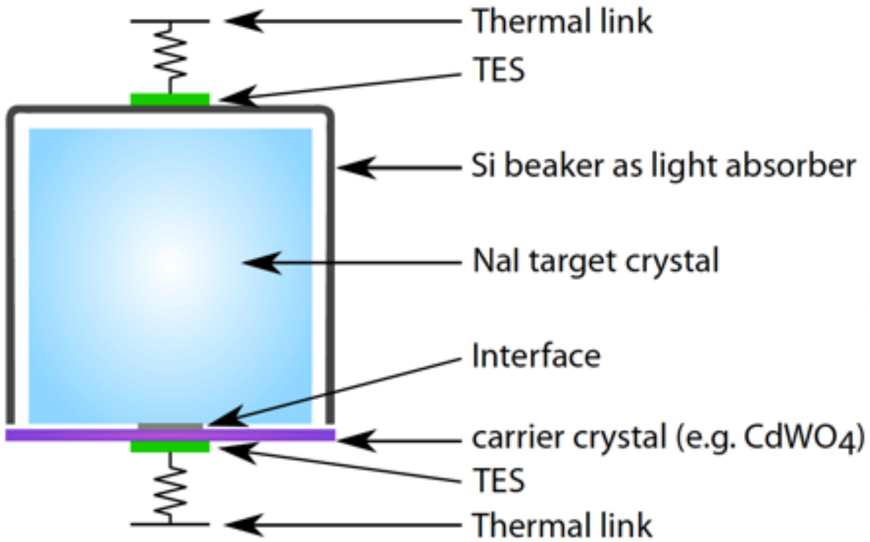
RULE-OUT

$\mathcal{O}$ (100 kg days): strong statement

$\mathcal{O}$ (1000 kg days): fully model-independent

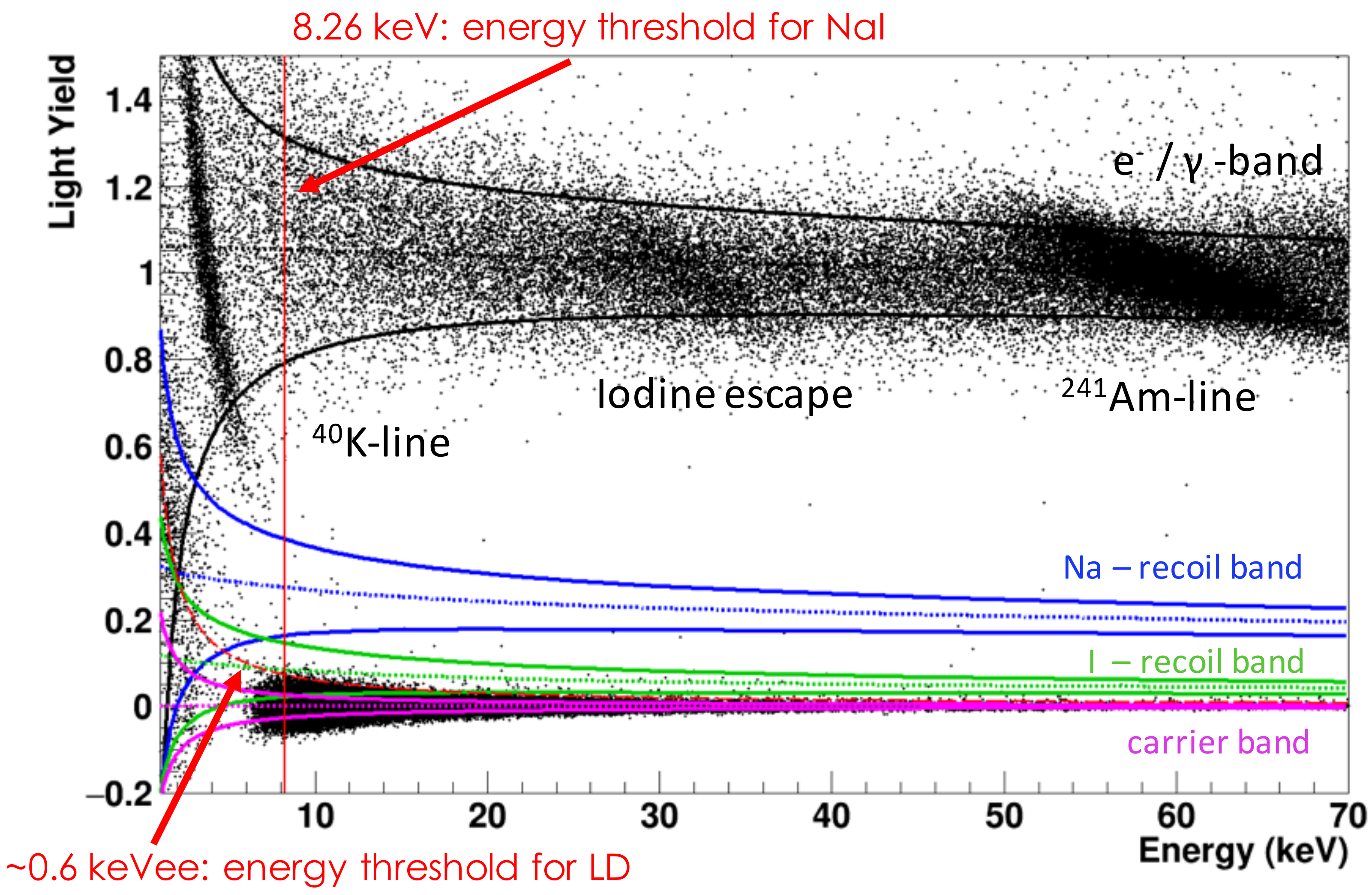
JCAP 1805 (2018) no.05, 074

Proof of Principle of final detector design



- interface: epoxy resin
- beaker-shaped Si light absorber
- NaI crystal: 66 g

2nd PROTOTYPE DETECTOR



- NaI energy threshold is $(8.26 \pm 0.02\ (\text{stat.}))$keV
- width of the ^{241}Am peak is $(4.508 \pm 0.064\ (\text{stat.}))$ keV
- carrier events identified by pulse shape
- 13% of emitted scintillation light detected in Si beaker

Schäffner, K. et al. J Low Temp Phys (2018). https://doi.org/10.1007/s10909-018-1967-3

TO DO LIST FOR DARK MATTER MODULE

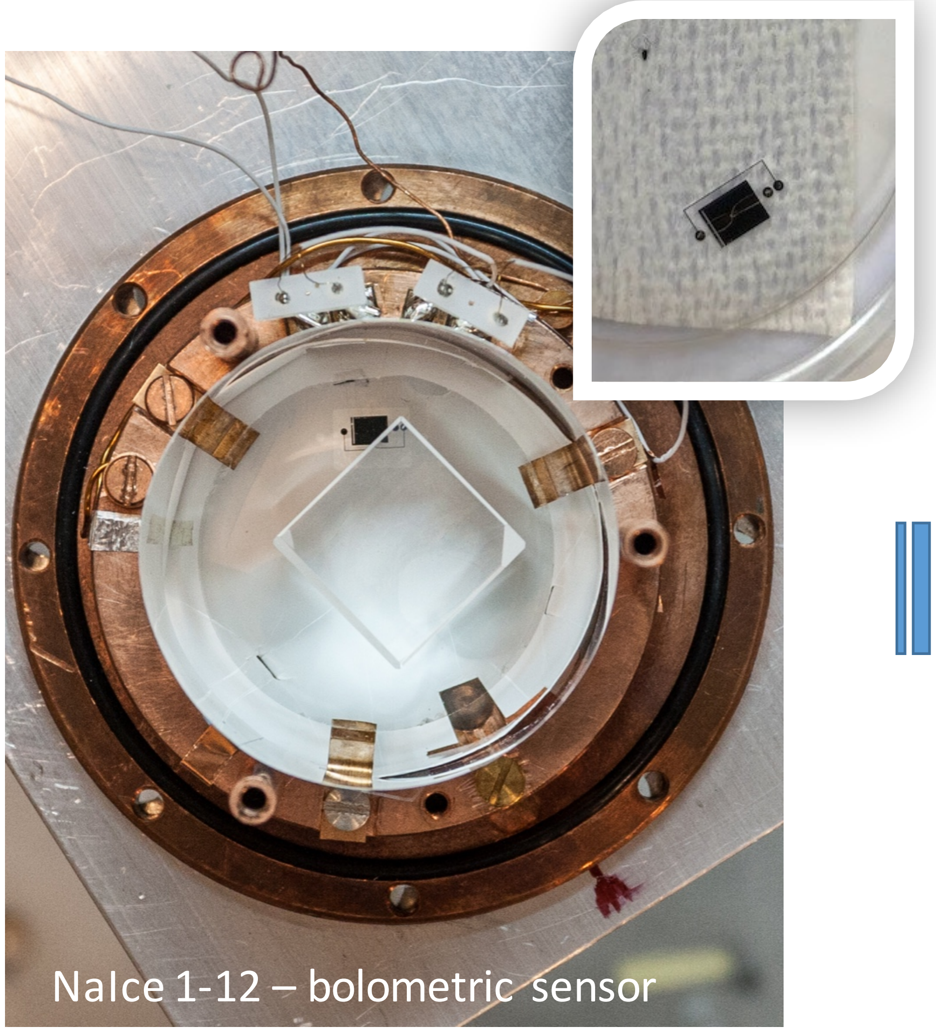
Prototype measurement results:
G. Angloher et al. JINST 12 P11007 (2017)
F. Reindl et al., J. Phys. Conf. Ser. 1342 012099 (2020)
Schäffner, K. et al. J Low Temp Phys (2018)

- [x] operate NaI as cryogenic detector
- [x] beaker-shaped light detector
- [x] radiopure NaI crystals
- [x] Extended pulse shape model for NaI detector

- [ ] phonon threshold of 1keV: 10keV→8.5 keV→6.5keV →… goal:1keV

→ TES optimization using information from the EPSM

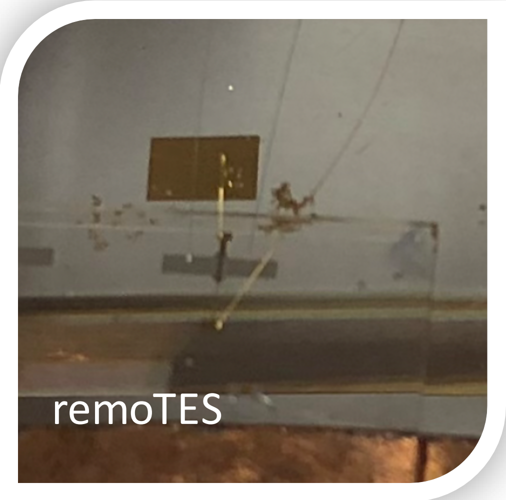
OPTIMISATION OF THE THERMAL SENSOR @ MPP



NaIce 1-12 – bolometric sensor

Calorimetric sensors

NaIce 14



remoTES

COSINUS at MPP

Detector physics:

- TES production
- detector optimization
- detector testing

Many, many thanks to CRESST
for sharing knowledge
and infrastructure !!

COSINUS at MPP

Detector physics:

- TES production
- detector optimization
- detector testing

Data Analysis + software:

- pulse reconstruction with EPM
- development of raw data analysis software

The HOW TO build an experiment ?

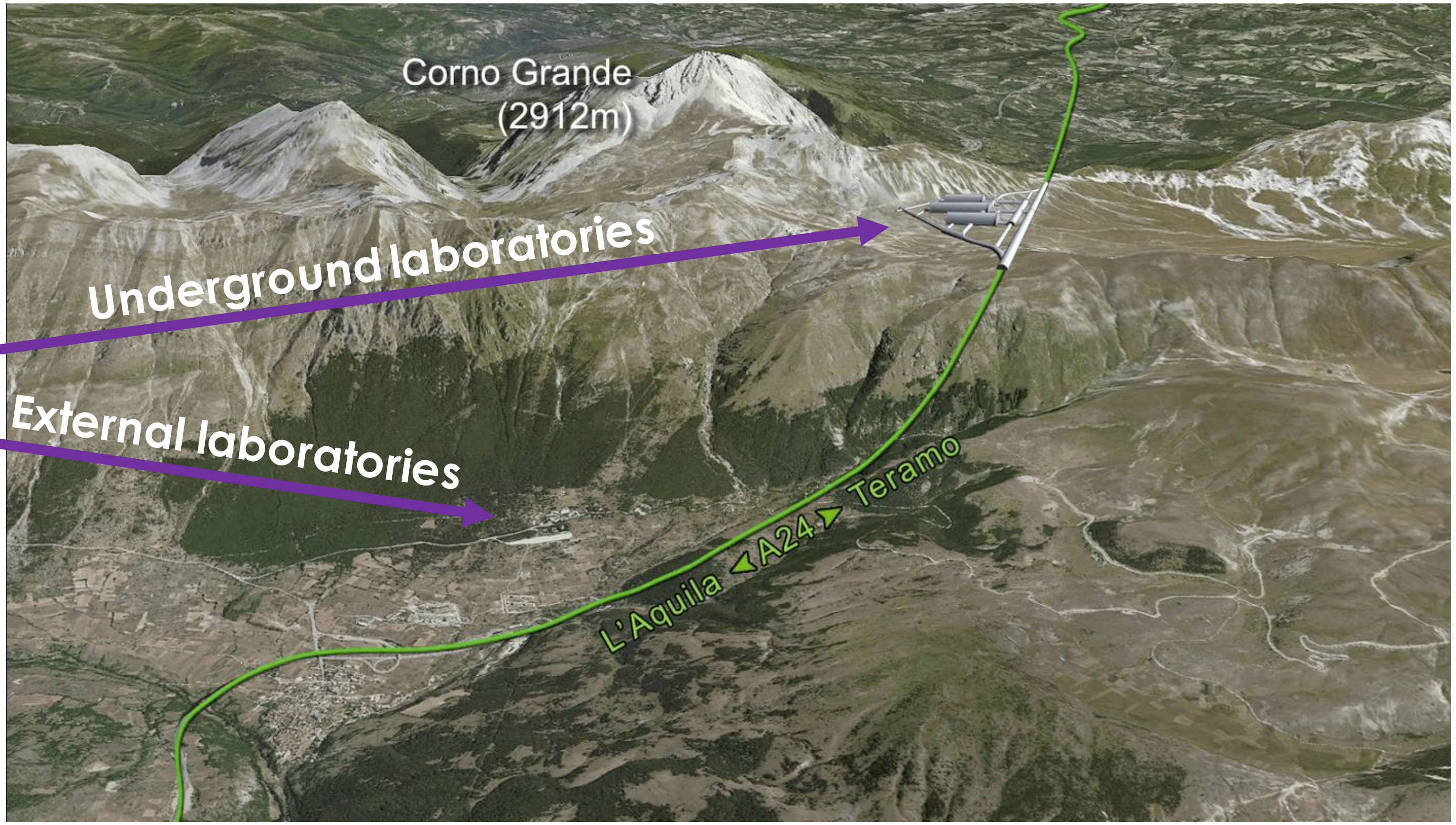
1.
Underground site

2.
Facility

4.
Electronics

3.
Cryostat

LABORATORI NAZIONALI DEL GRAN SASSO



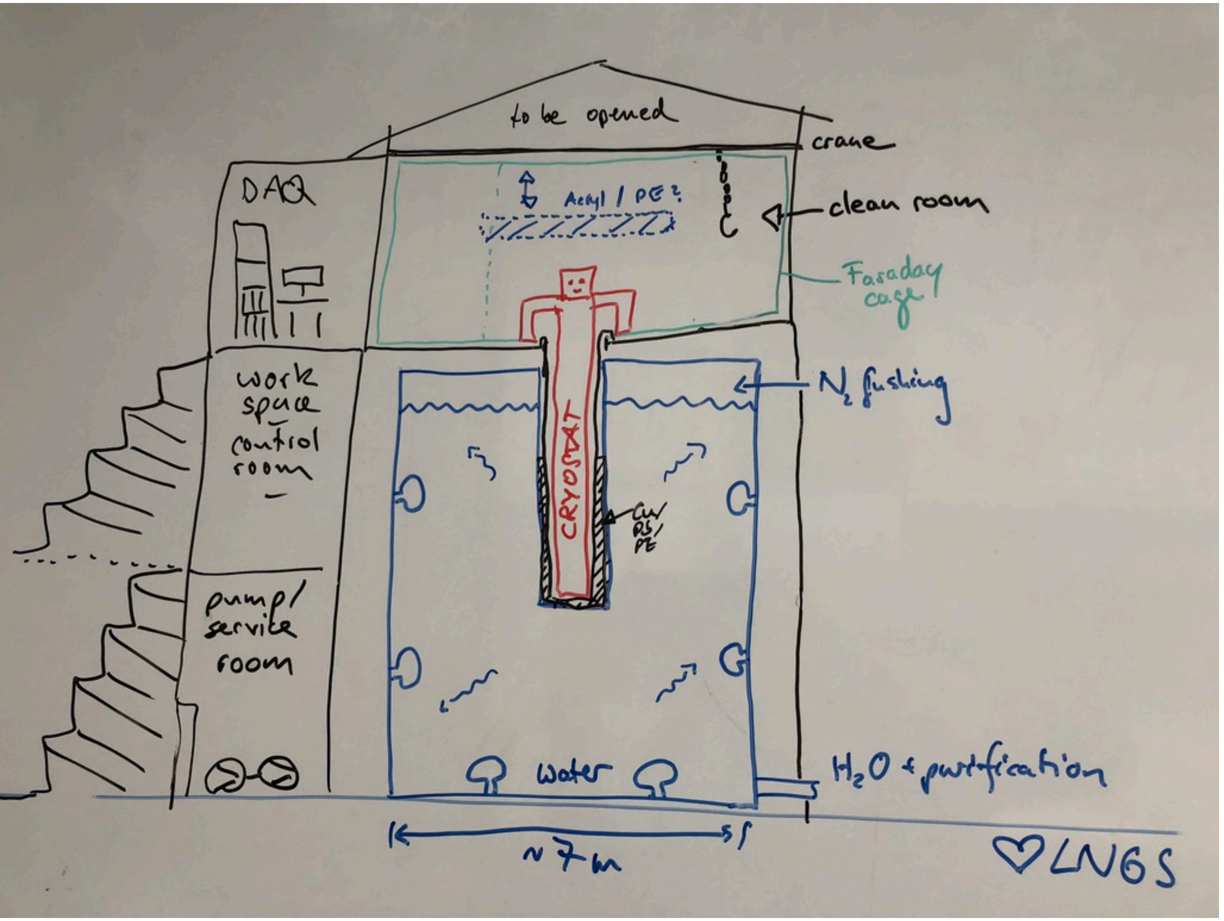
taken from MPI Munich

COSINUS: experimental site and facility

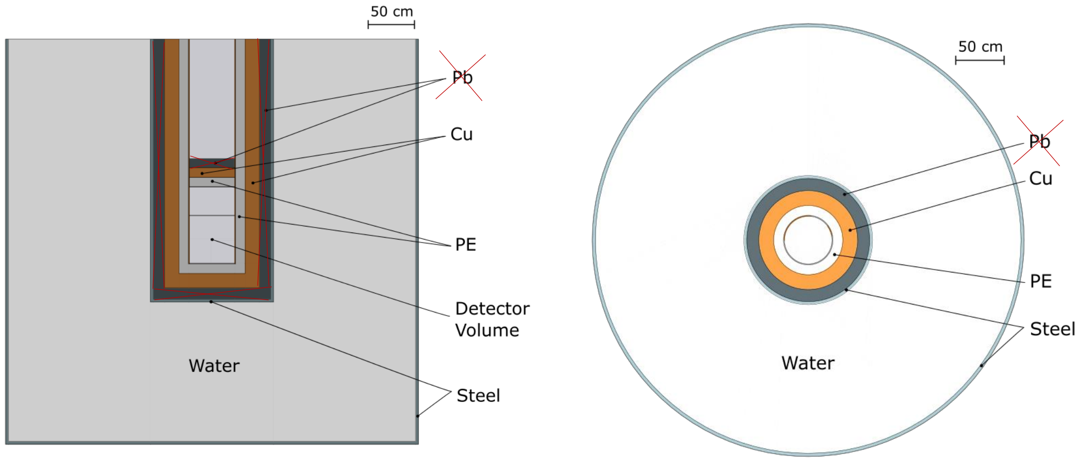
Hall B of the LNGS

located between the XENON-1T and LUNA-MV experiments

LOOKING BACK IN 10/2018



First Design Ideas...



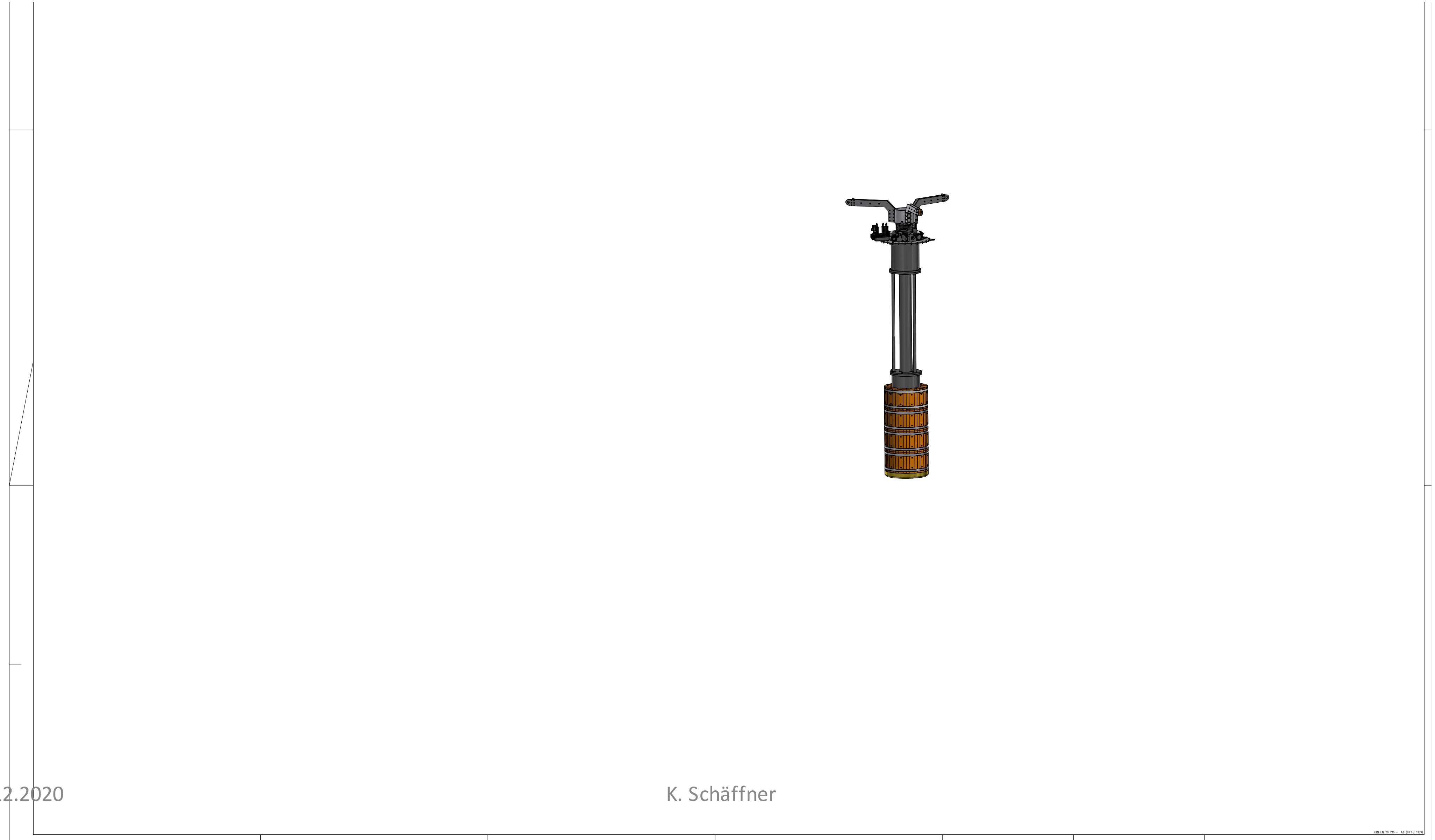
A. Fuss

Geant4 MC simulation:

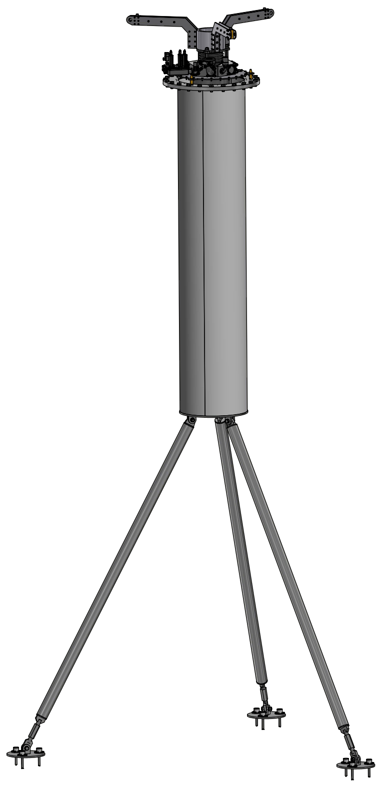
- Shielding concept — ~80%
- Optical simulation for Cerenkov veto — Just started

COSINUS: experimental facility 12/2020

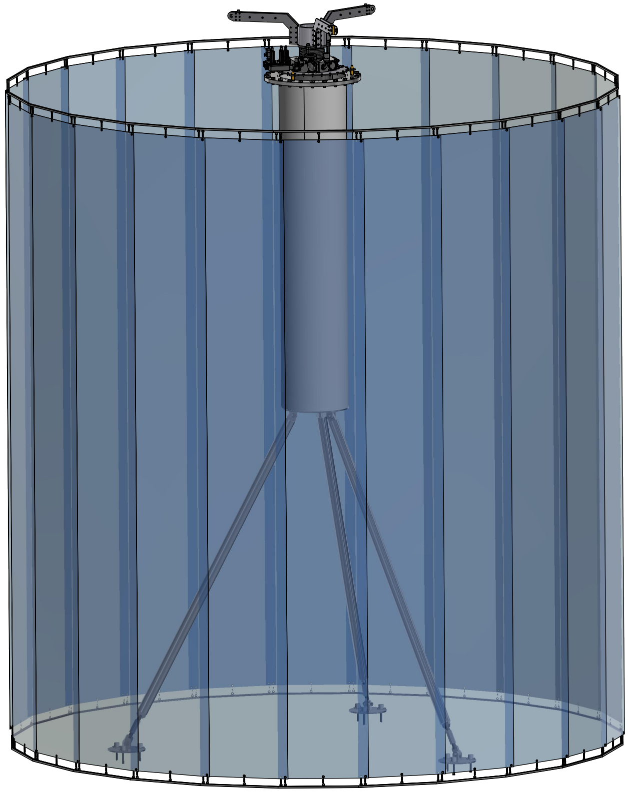
COSINUS: experimental facility 12/2020



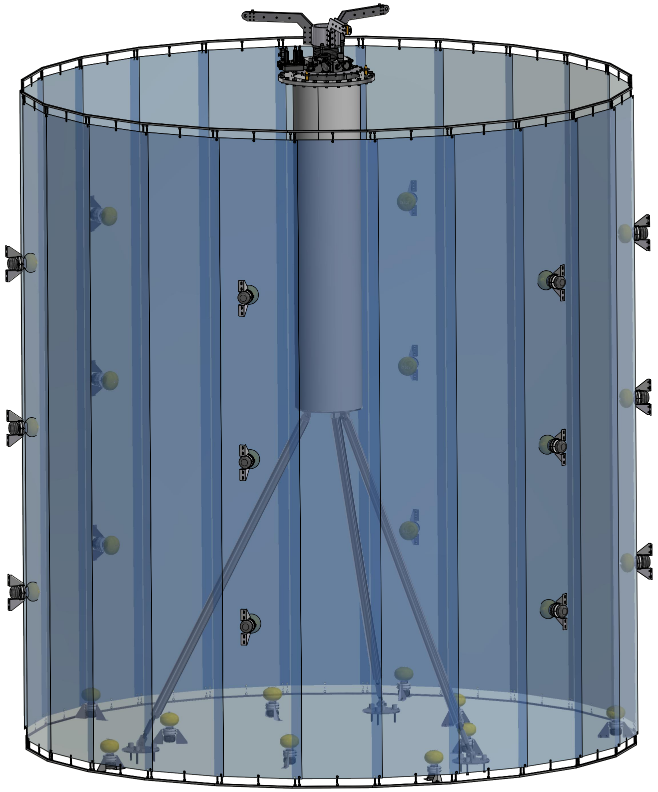
COSINUS: experimental facility 12/2020



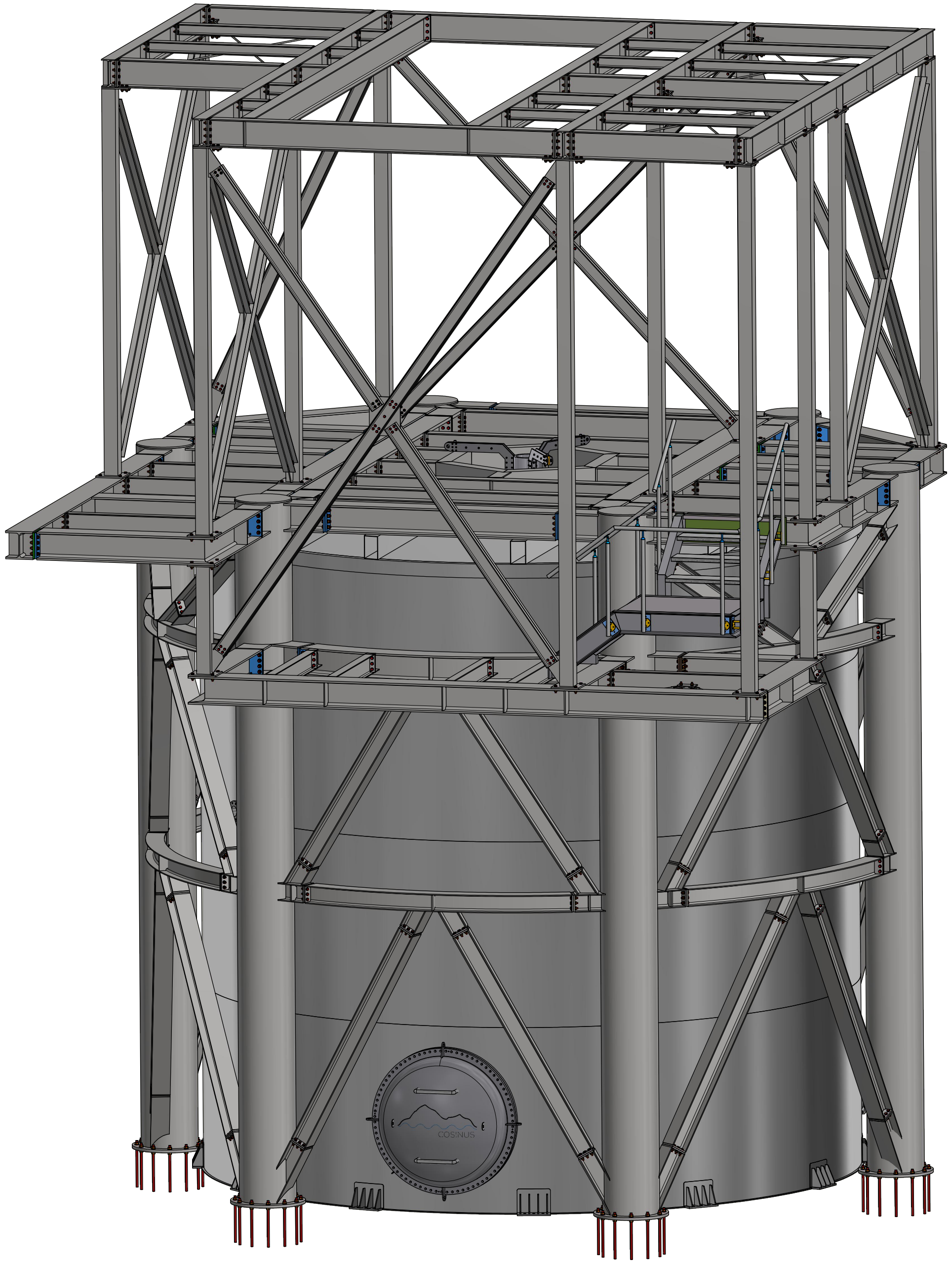
COSINUS: experimental facility

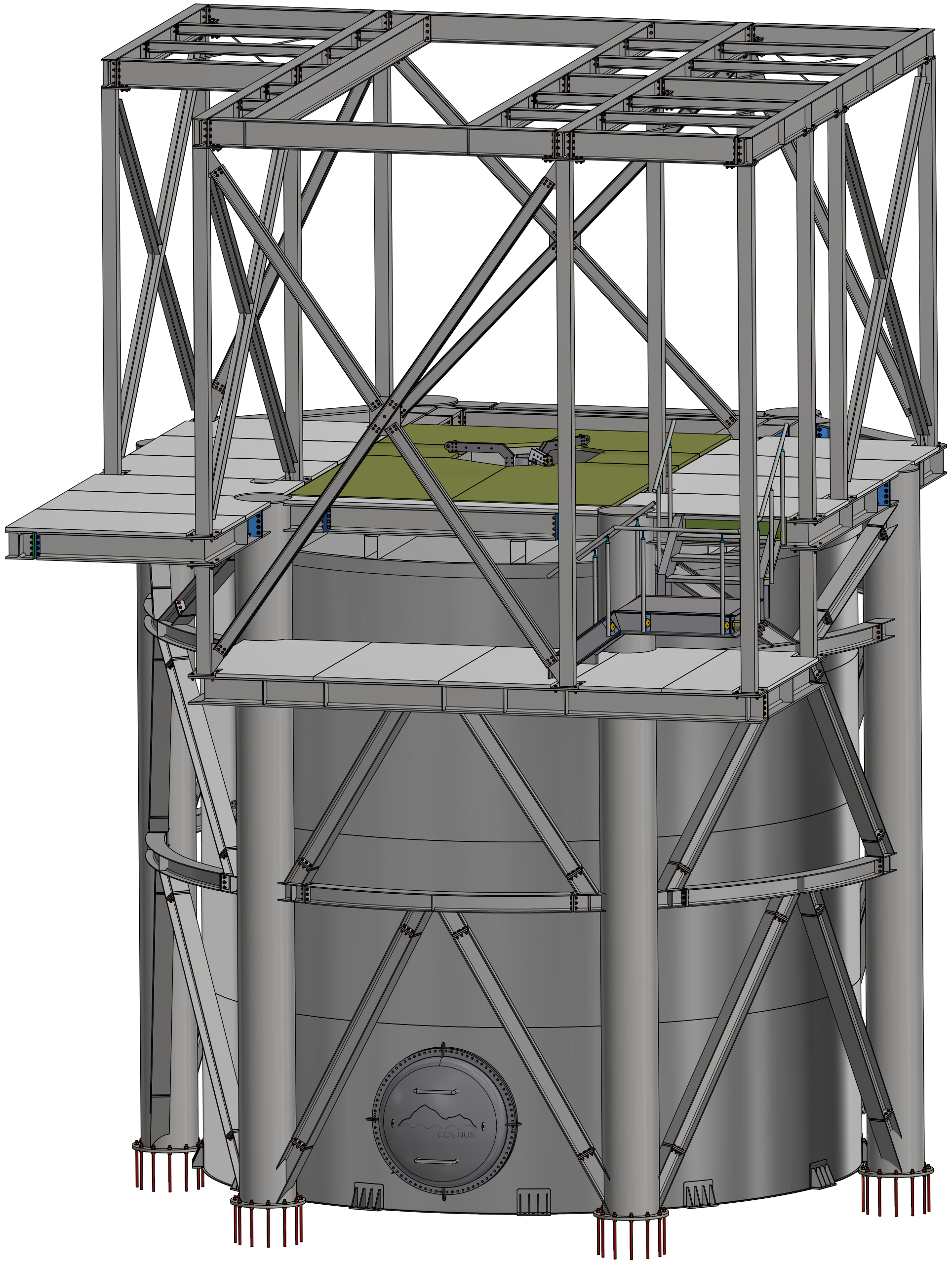


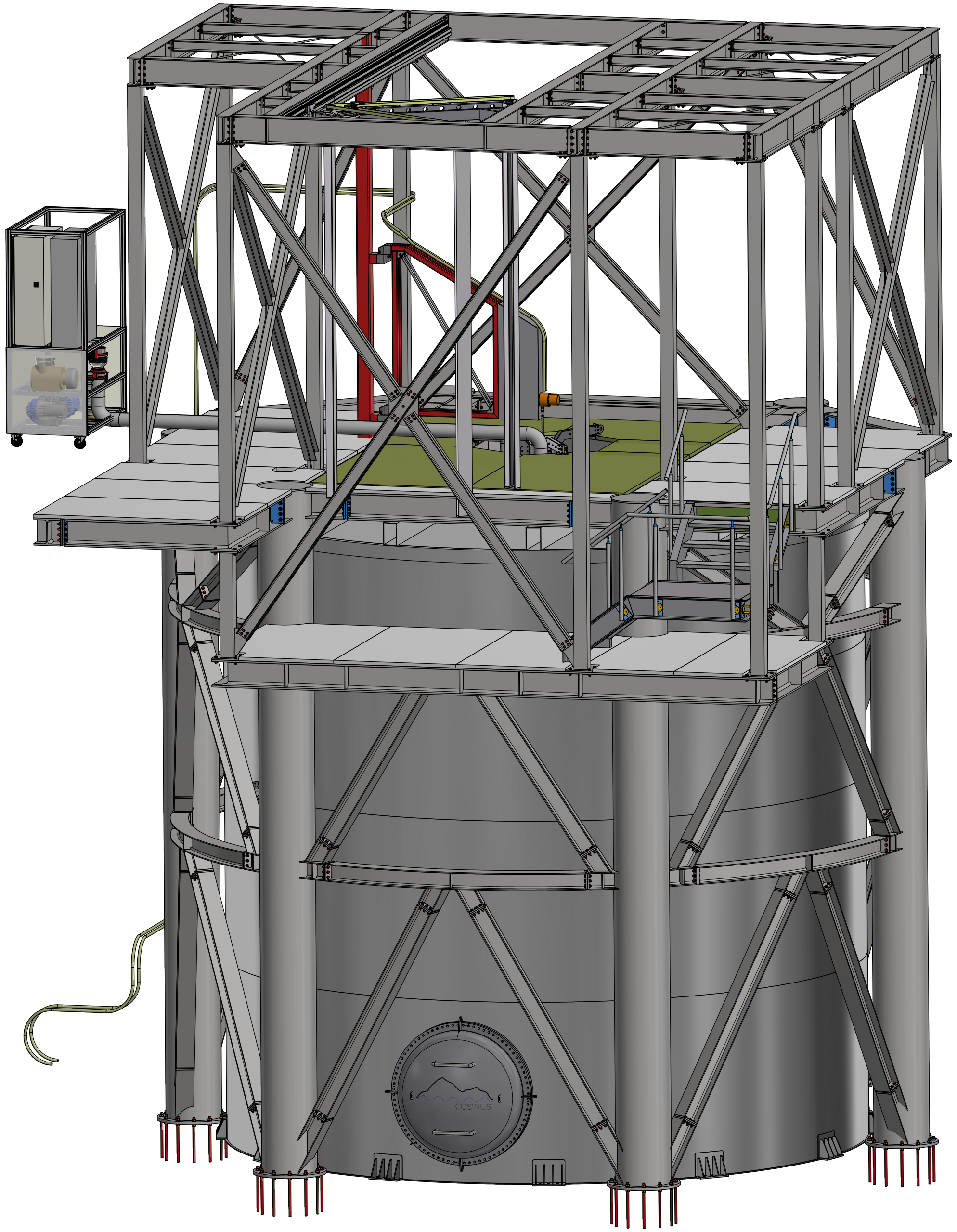
COSINUS: experimental facility

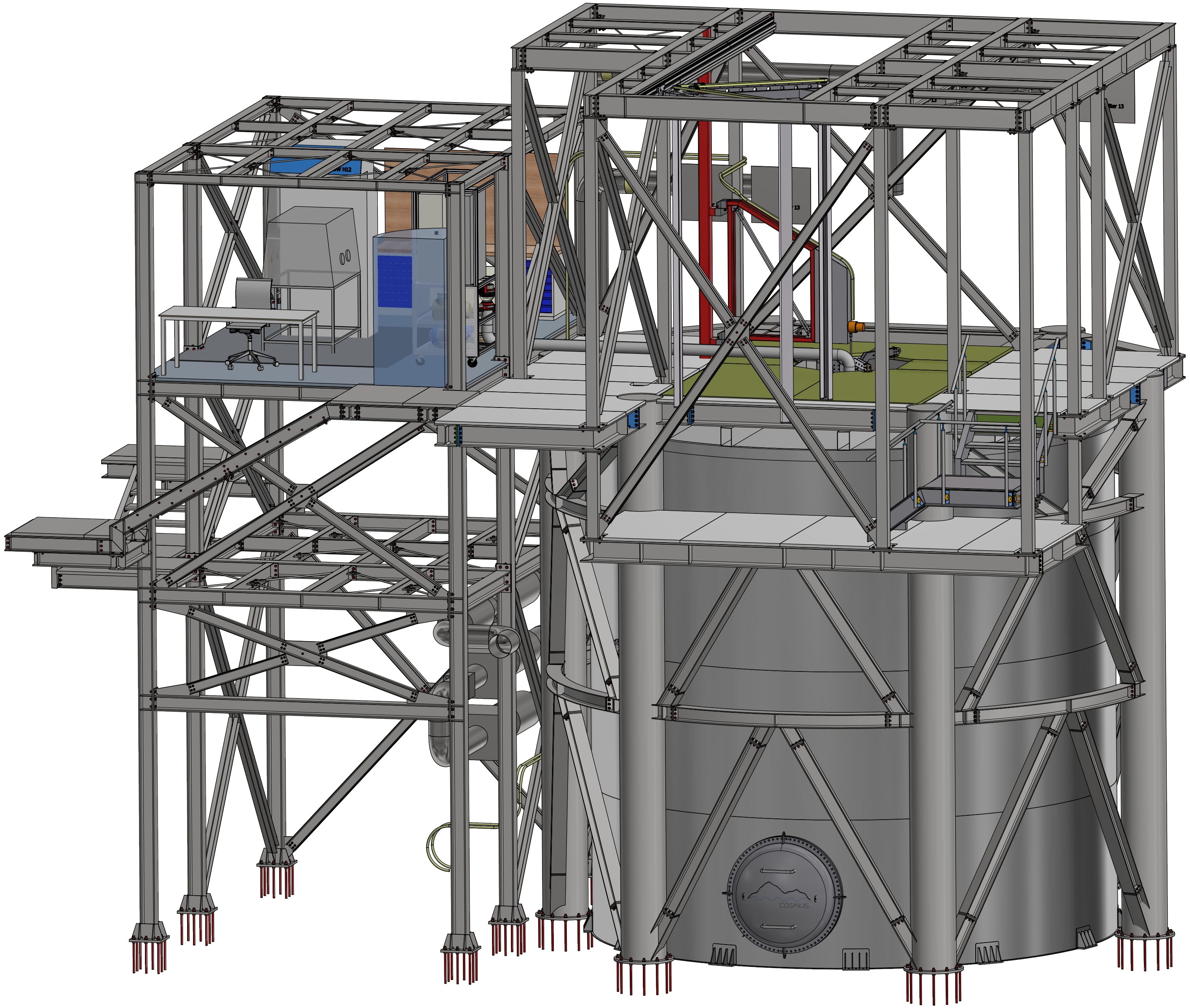


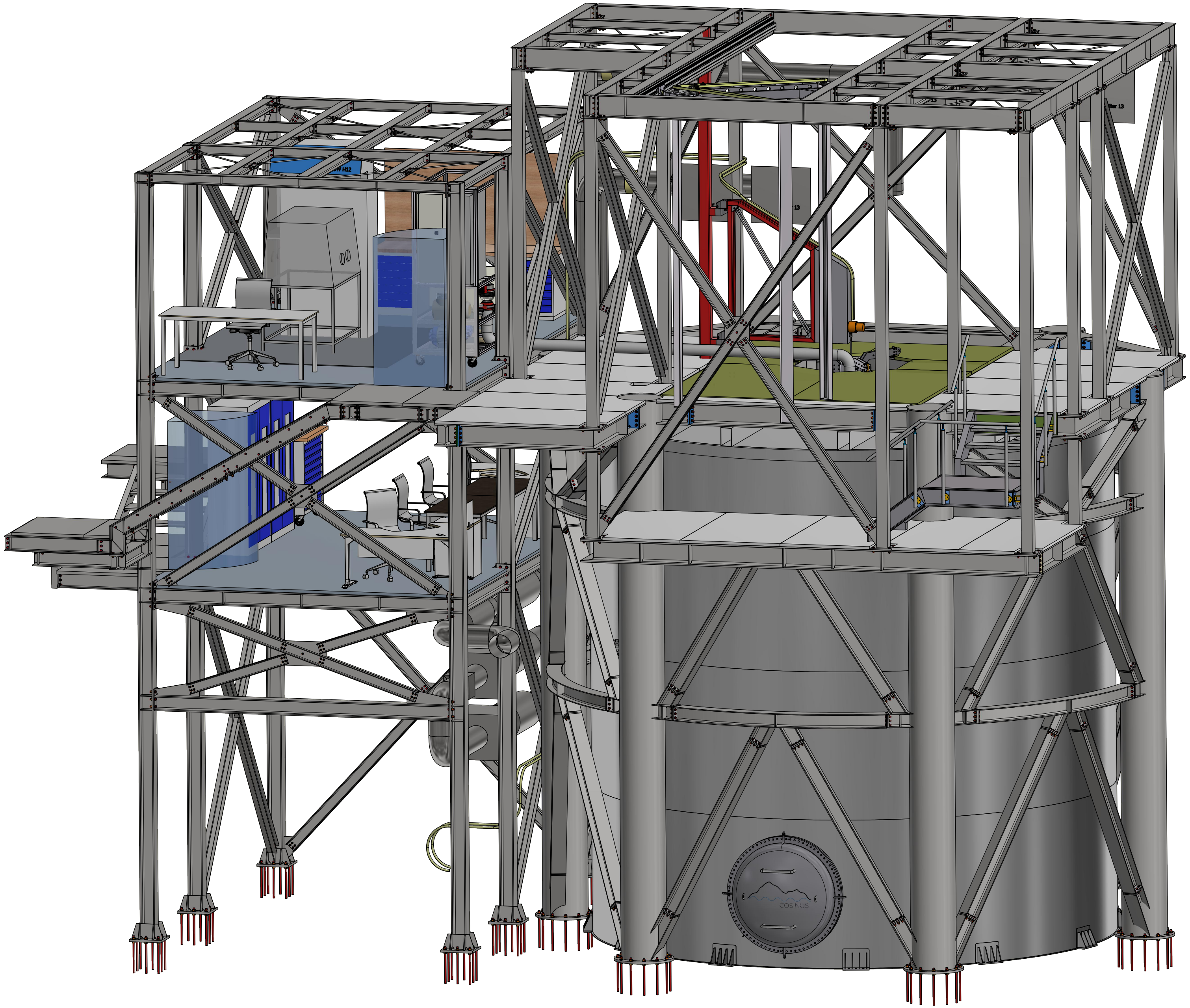
COSINUS: experimental facility

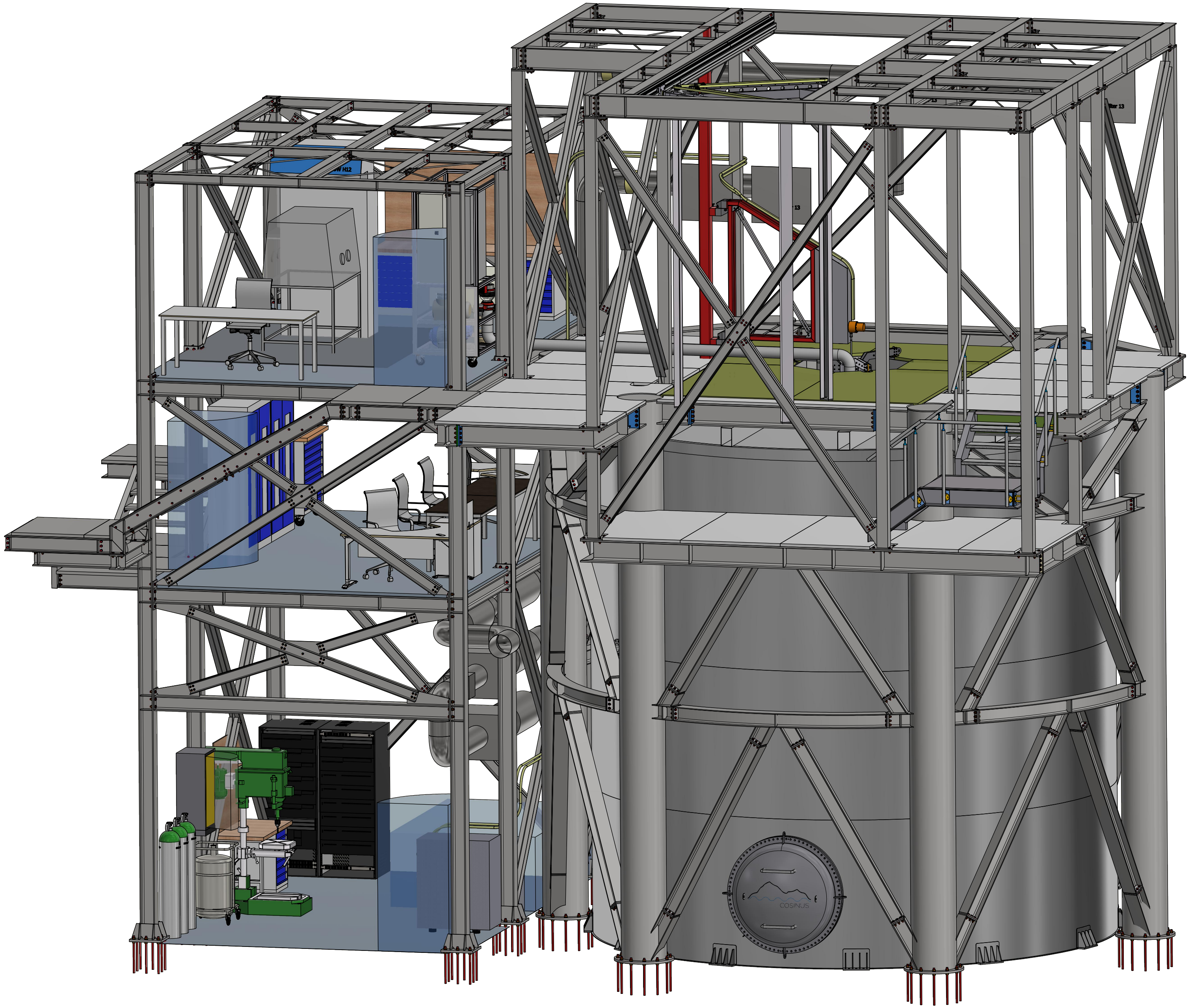


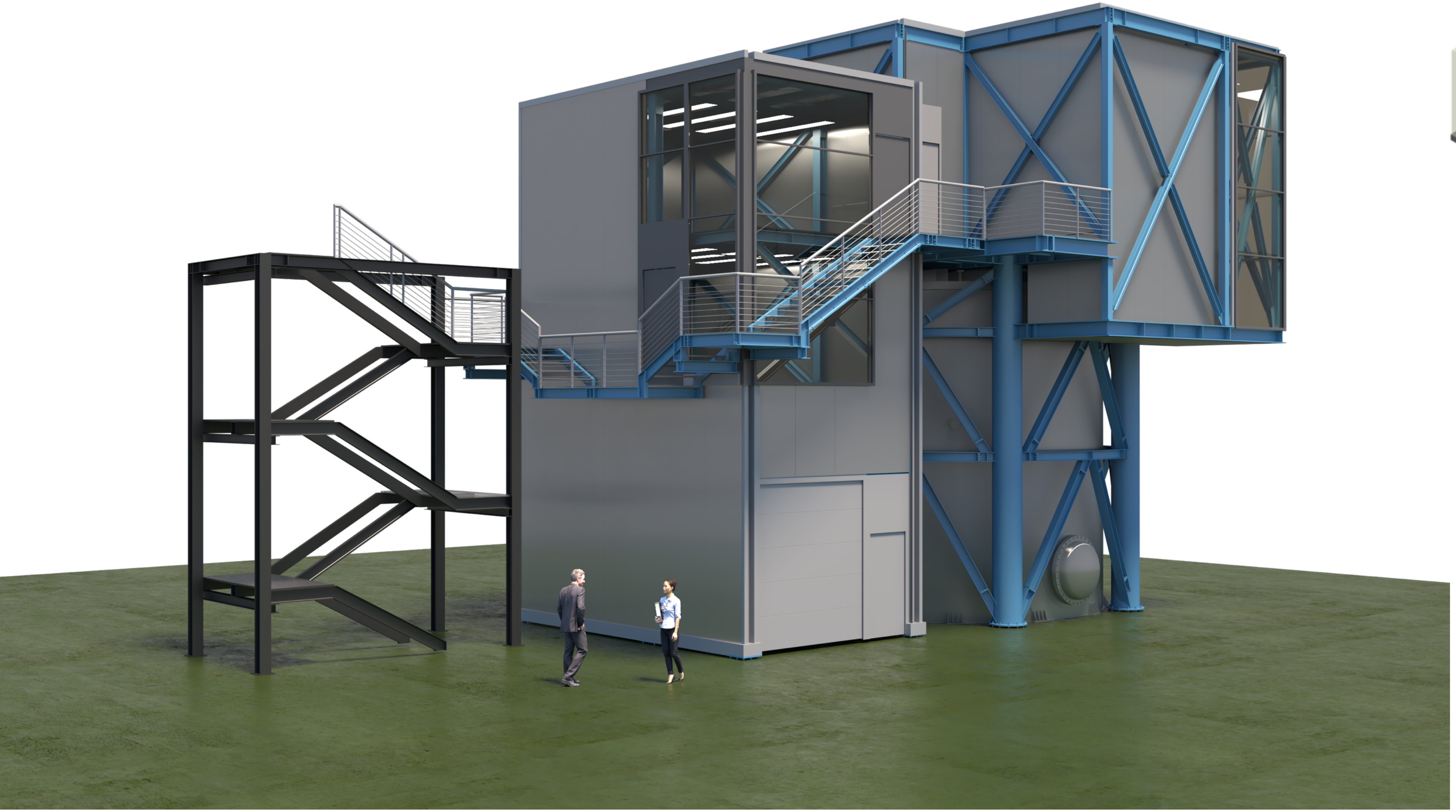

COSINUS

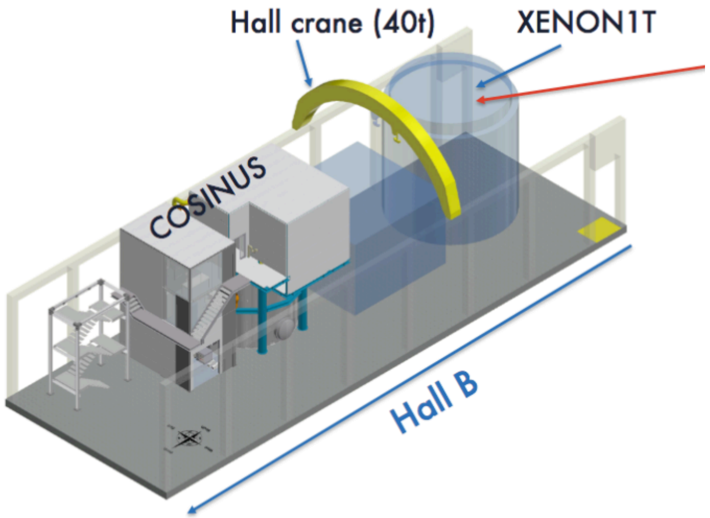











Hall crane (40t)
XENON1T
COSINUS
Hall B

COSINUS at MPP

Detector physics:

- TES production
- detector optimization
- detector testing

Data Analysis + software:

- pulse reconstruction with EPM
- development of raw data analysis software

Experimental setup:

- project management and complete setup planning
- dilution refrigerator and implementation at LNGS
- lifting system and rotary valve structure for the cryostat
- inner copper shielding + implementation
- detector parts

COSINUS members at MPP

PhDs:

- Moritz Kellermann (start 01/21)
- Raghunath Mukund (planned 02/21)

Postdocs:

- Vanessa Zema
- Martin Stahlberg

Senior scientists / staff:

- Karoline Schäffner (MPRG group leader)
- Godehard Angloher
- Peter Mühlbauer

Construction/Electronics:

- Robert Stadler
- Christopher Jablonski
- Jens Schlammer

Members from CRESST:

- Federica Petricca
- Michele Mancuso
- Franz Pröbst

WHO WE ARE ?

Max-Planck-Institut für Physik (Werner-Heisenberg-Institut)

HEPHY INSTITUTE OF HIGH ENERGY PHYSICS

TU WIEN

INFN LNGS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Gran Sasso

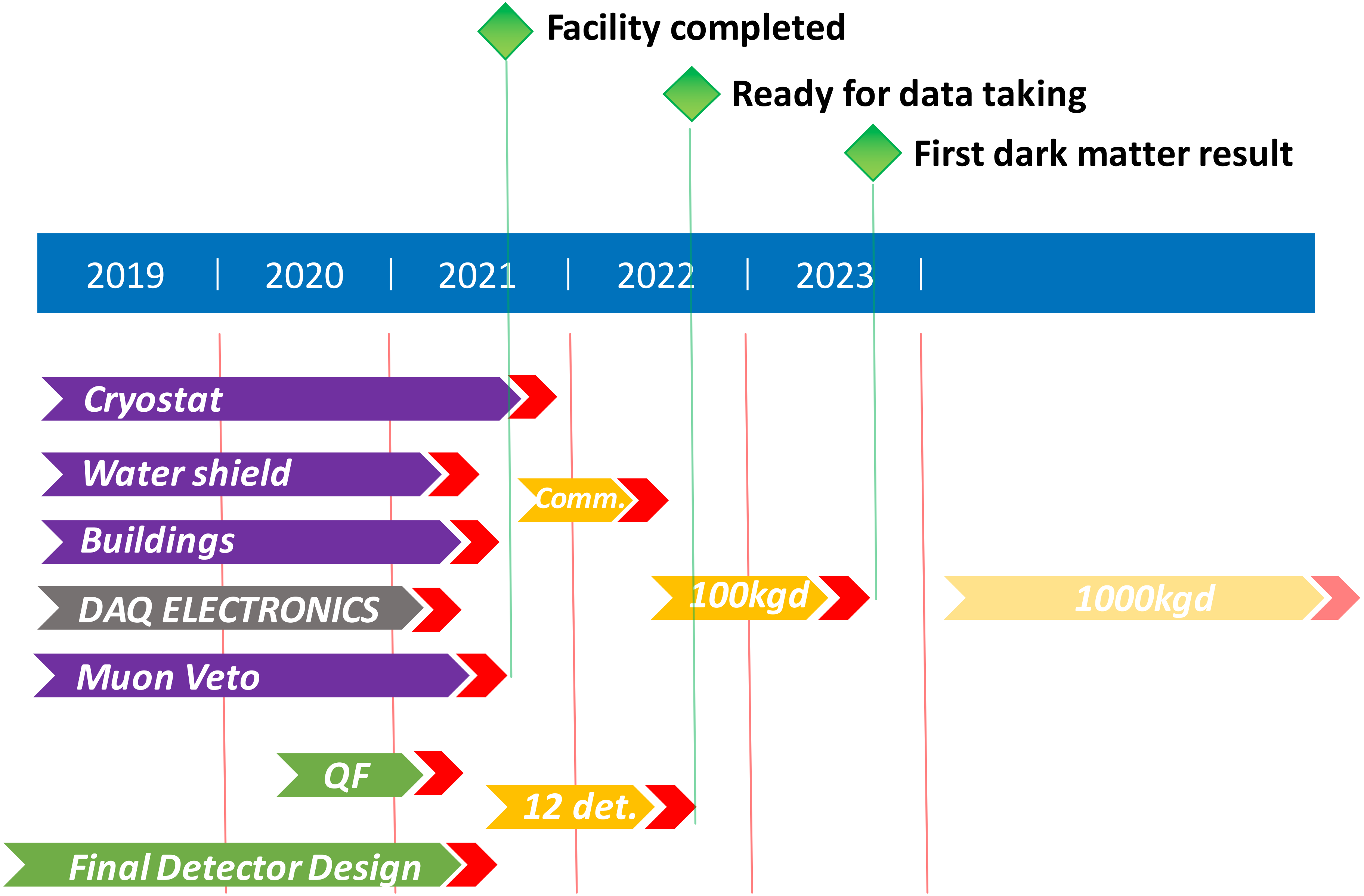
GSSI

NEW

HELSINKI INSTITUTE OF PHYSICS

SICCAS Since 1928

TIME LINE



Facility completed
Ready for data taking
First dark matter result
2019
2020
2021
2022
2023
Cryostat
Water shield
Buildings
DAQ ELECTRONICS
Muon Veto
QF
Final Detector Design
Comm.
100kgd
1000kgd
12 det.

Thank you for your support

and stay tuned, exciting time are ahead!

EXTRA MATERIAL

Extended pulse shape model

$$\Delta T_e(t) = \sum_{i=1}^{3} A_i \, [e^{\lambda_i t} - e^{-t/\tau_n'}] + \sum_{i=1}^{3} B_i \, [e^{\lambda_i t} - e^{-t/\tau_\ell}]$$

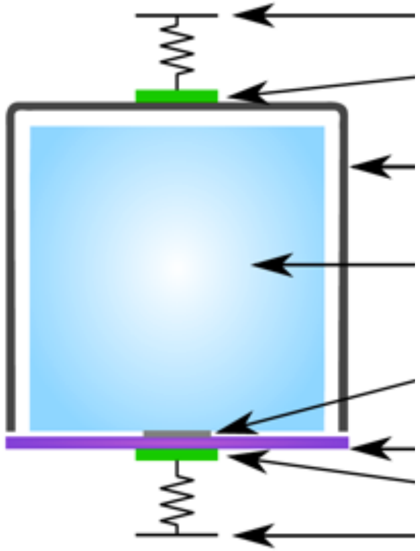
Based on F. Pröbst et al., J. Low Temp. Phys. 100, 69 (1995)
developed by V. Zema, paper in preparation

5 time constants
6 amplitude parameters
+ pulse onset

Considers carrier as additional detector component, in particular power input from-and-to the carrier

Interpretation:

A-part = „phonon part“, B-part = „light part“



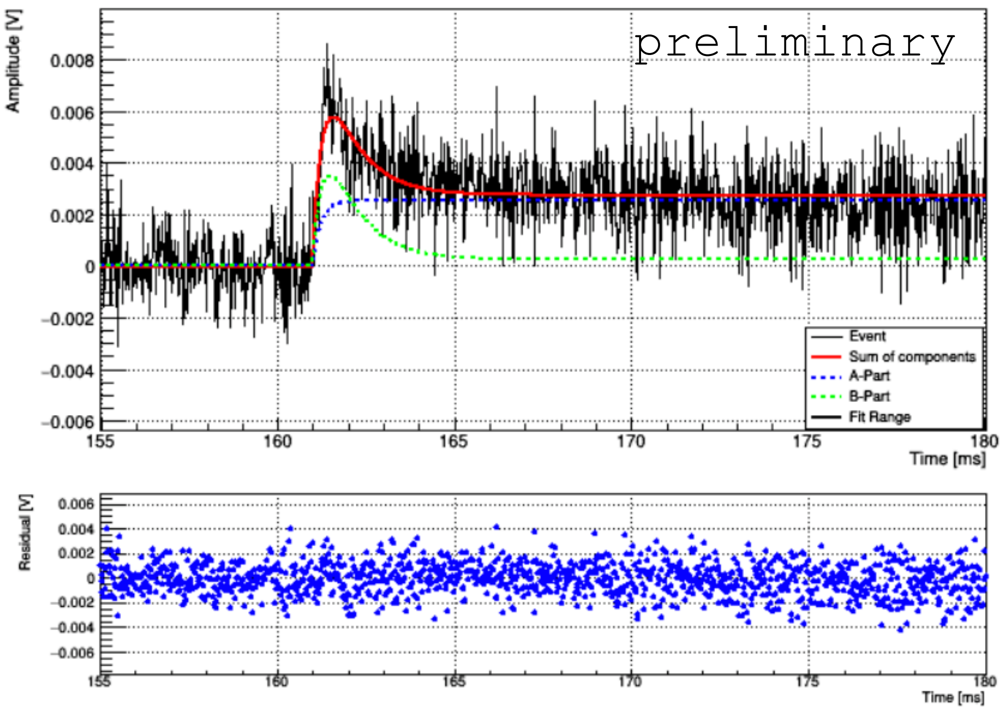
Validation against data

$$\Delta T_e(t) = \sum_{i=1}^{3} A_i\,[e^{\lambda_i t} - e^{-t/\tau'_n}] + \sum_{i=1}^{3} B_i\,[e^{\lambda_i t} - e^{-t/\tau_\ell}]$$

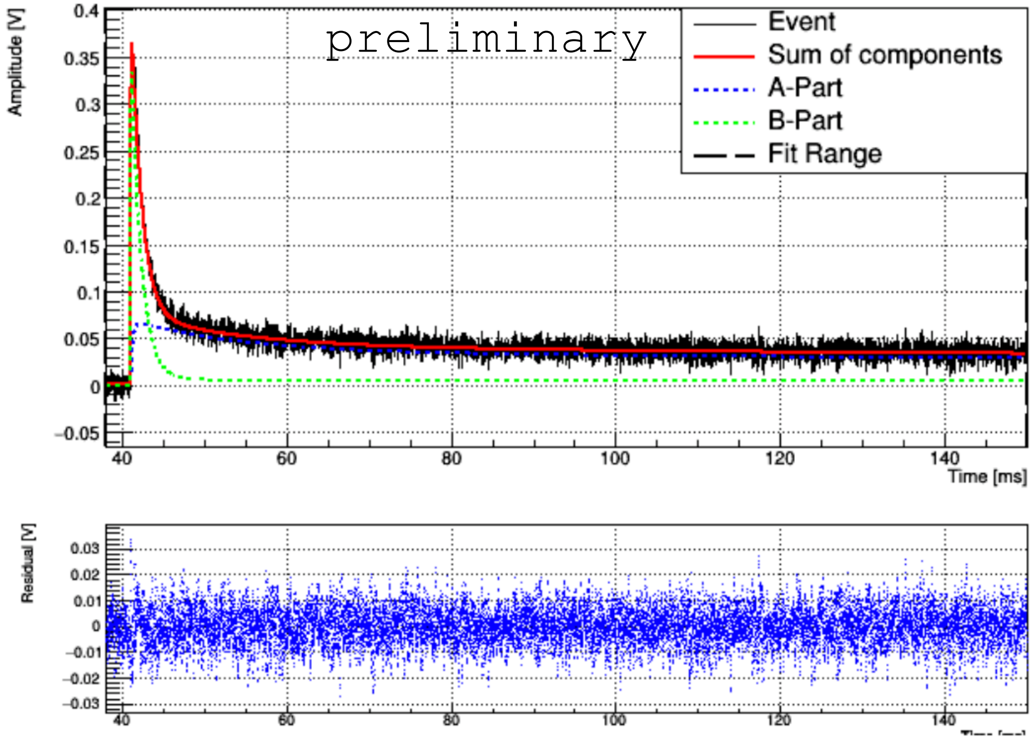
Blue = A – part
”phonon NaI part”

Green = B – part
”light part”

NaIce6

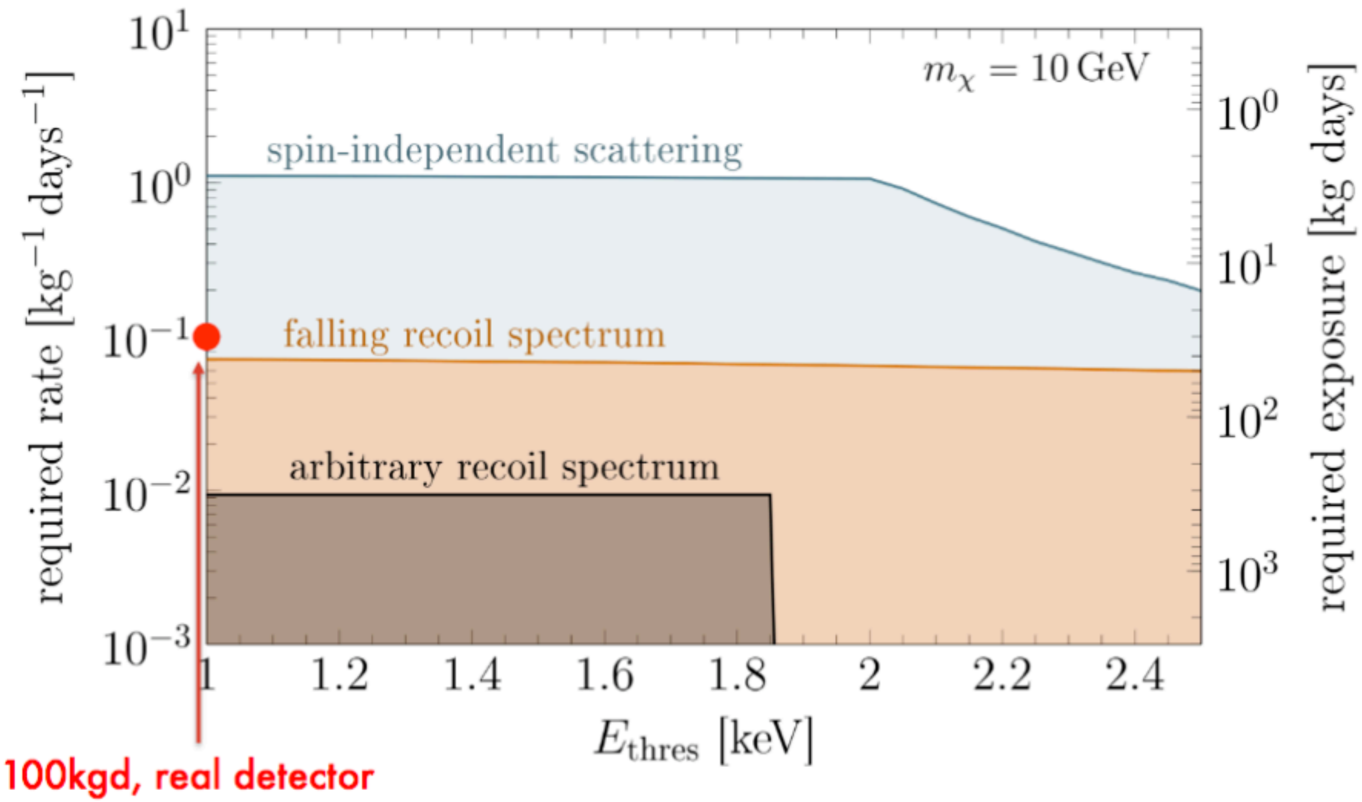


NaIce12



RESULT

F. Kahlhöfer, KS et al., JCAP 1805 (2018) no.05, 074



Threshold:
1.8 keV sufficient

optimize rather exposure (mass) than threshold

Warning: Not updated for new DAMA result with 1keVee threshold

Outlook: Cut and count only → Make use of spectral information for potentially stronger bounds

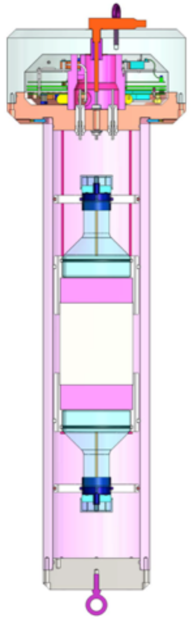
NaI EXPERIMENTS *incomplete list!*

DM-Ice17

South pole
17 kg NaI

energy: 4 keV_{ee}

3.5 y physics run
no hint

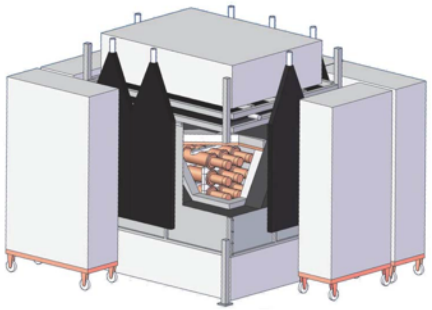


ANAIS-112

LSC - Spain
112.5 kg NaI

energy: < 1 keV_{ee}

spring 2017



COSINE-100

Y2L Korea
KIMS NaI + DM-Ice
106 kg

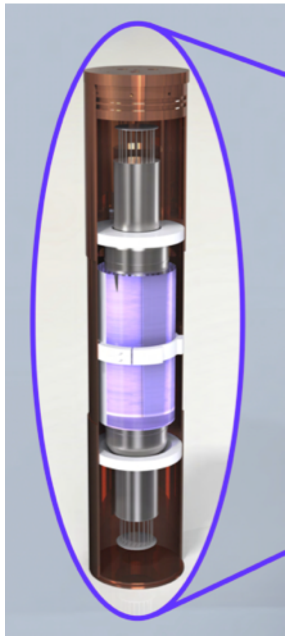
energy: ~ 2 keV_{ee}

since Sept. 2016

SABRE

Gran Sasso/Australia
40-50 kg NaI

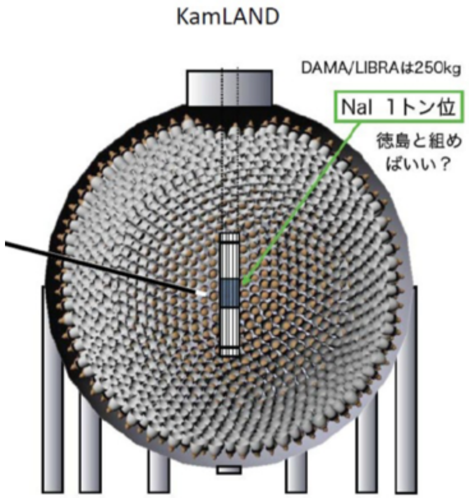
construction phase
PoP 2020



KamLand-PICO-Ion

KamLand/Japan
1t NaI

planning/
prototyping phase

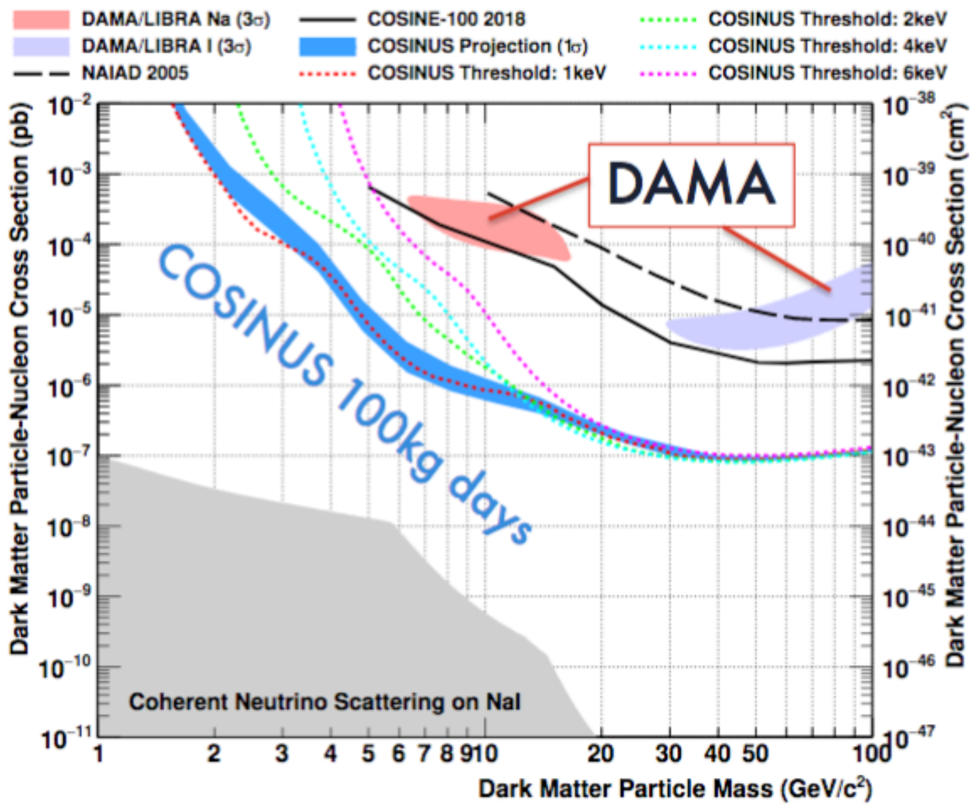


NaI crystal radiopurity
Preliminary ICP-MS Results S. Nisi (LNGS)

Sample	Powder	Crystal Grower	K	Rb	Pt	Tl	Th	U
			ppb	ppb	ppb	ppm	ppb	ppb
MLL_V1	SICCAS	SICCAS	28000	8	<0.6	2.5	<0.015	<0.015
MLL_V2	SICCAS	SICCAS	1100	<3	6	180	<0.015	<0.015
NaI 4_1_1	Astrograde	SICCAS	350	<3	250	1800	0.1	0.2
DAMA/LIBRA crystal*			~13	<0.35			$0.7 – 10 \times 10^{-3}$	$0.5 – 7.5 \times 10^{-3}$

* Bernabei et al., NIM A592 (2008) 297-315

COSINUS in STANDARD SCENARIO



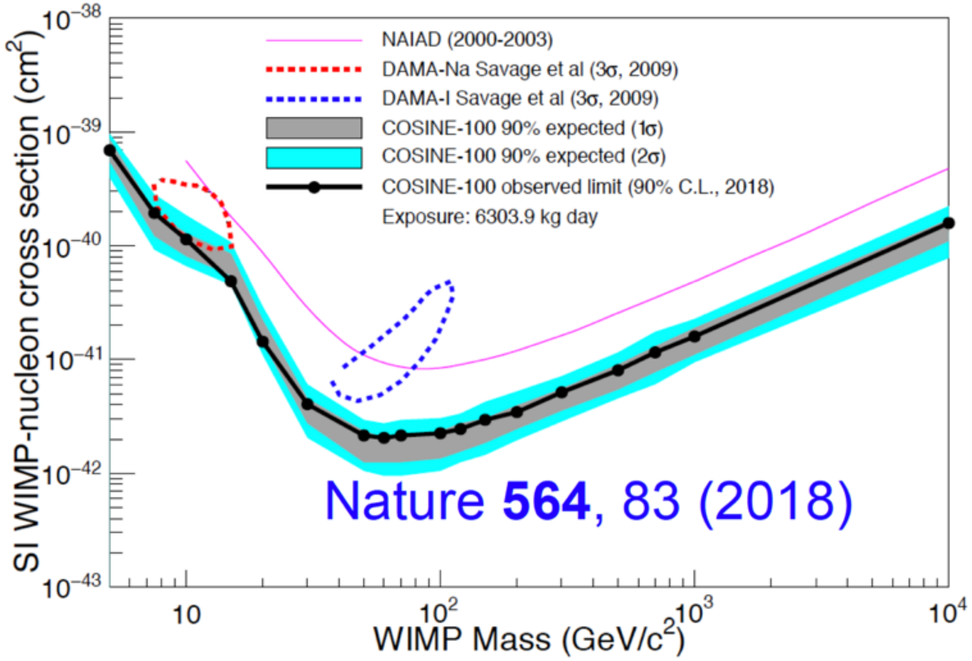
Standard dark matter halo
Fixed quenching factors:
QF_{Na}=0.3, QF_{I}=0.09

Blue band: COSINUS projection (incl. stat. fluctuation) for 100kg days and 1keV nuclear recoil threshold

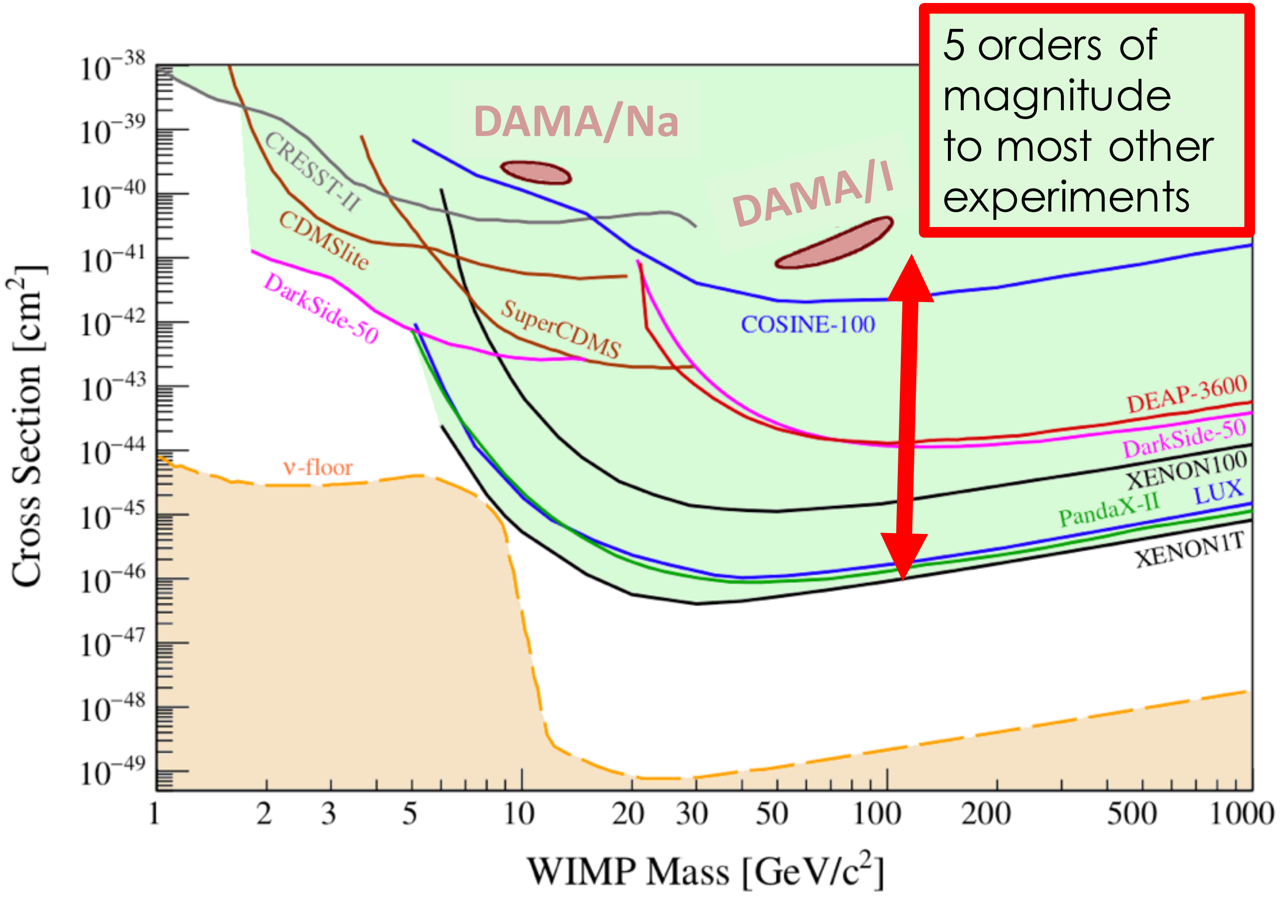
Dotted lines: Exemplary COSINUS projections for 100kg days and thresholds as in legend

DAMA/LIBRA and STANDARD SCENARIO

COSINE-100



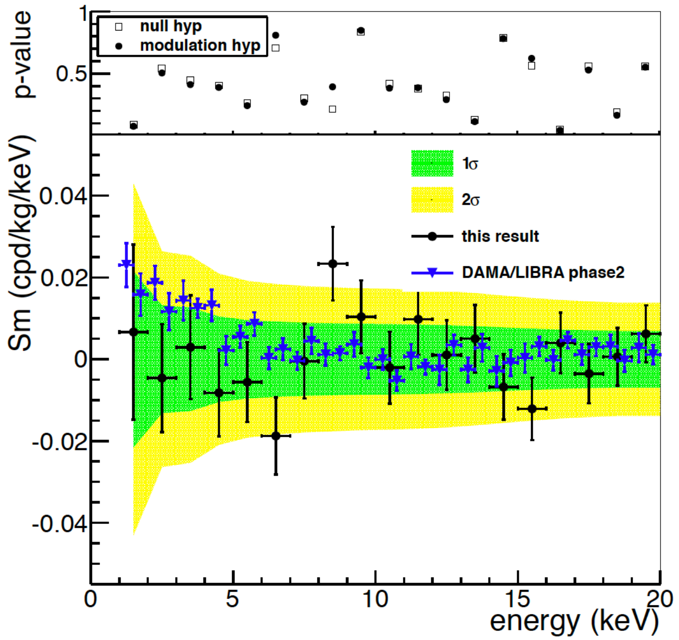
COSINE-100 excludes DAMA/LIBRA signal as standard SI WIMP interaction with standard halo model and using **NaI(Tl) crystals**



Most of experiments in exclude standard SI WIMP interaction with standard halo model

RECENT NaI-based MODULATIONRESULTS

ANAIS-112



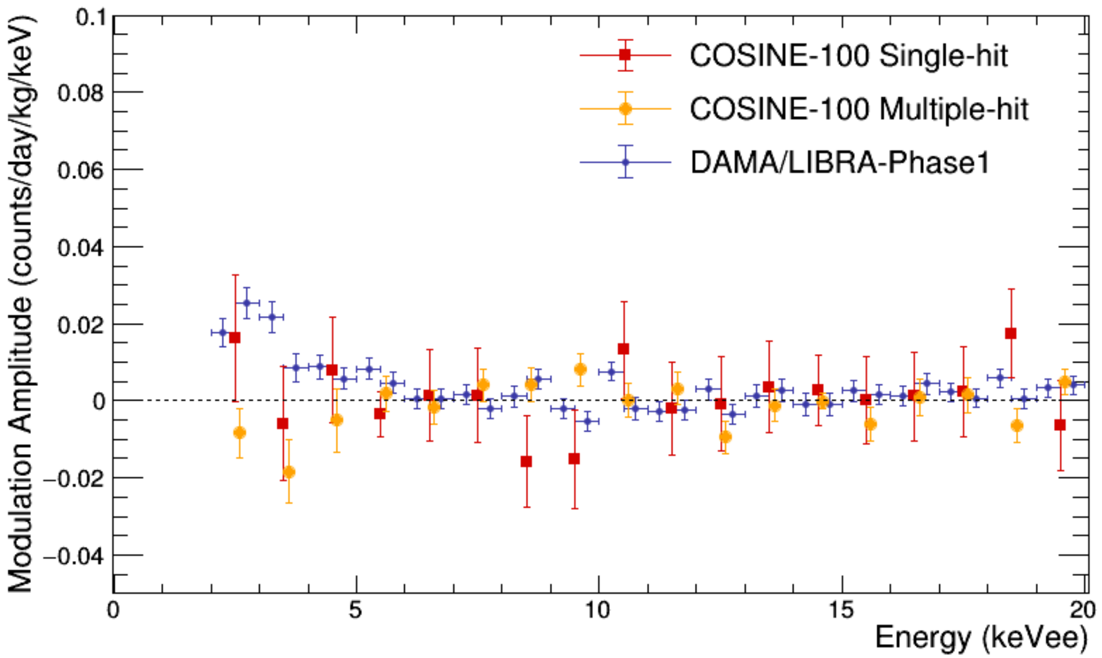
time: 1.5 years of data

exposure: 157.55 kg year

best fits are consistent with the absence of modulation

arXiv:1903.03973

COSINE-100



time: 09/2016 to 07/2018

→ results from SET2 data

consistent for both with and without absence of modulation

Taken H.S. Lee at *"Revealing the history of the universe with underground particle and nuclear research"* **on March 8, 2019**