NaIce Dark Matter Experiments

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COSINUS

GRAN SASSO SCIENCE INSTITUTE
SCHOOL OF ADVANCED STUDIES
Scuola Universitaria Superiore

INFN
Istituto Nazionale di Fisica Nucleare

WHAT WE **KNOW** about

NON-BARYONIC

- height of acoustic peaks in the CMB
- power spectrum of density fluctuations
- primordial Nucleosynthesis

COLD (non-relativistic)

- structure formation of the Universe

STABLE

- still observable today

→ INTERACTION via GRAVITY and probably on the weak scale

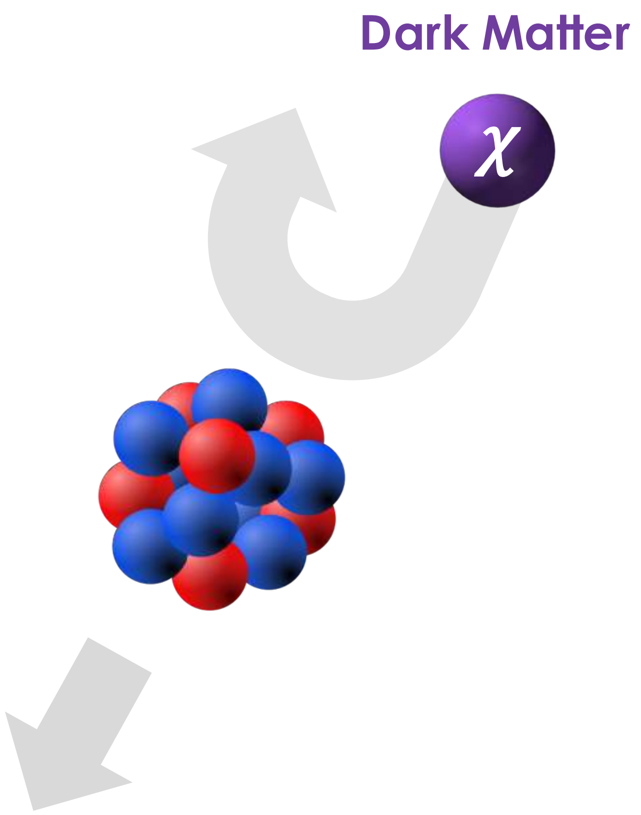
DIRECT DARK MATTER INTERACTION

Assumption

Particle-like dark matter which interacts with Standard Model particles

Most common

Dark matter particles scatters off the nucleus and induce nuclear recoils



DARK MATTER **RATE**

Total rate

DM velocity

$$R = \frac{M_{target}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} \cdot v \cdot \sigma(v)$$

number of target nuclei

local DM flux

DM-nucleon cross-section

DARK MATTER **RATE**

Total rate:

$$R = \frac{M_{target}}{m_N} \cdot \frac{\rho_\chi}{m_\chi} \cdot v \cdot \sigma(v)$$

Differential rate:

galactic escape velocity

velocity distribution

DM-nucleon cross-section

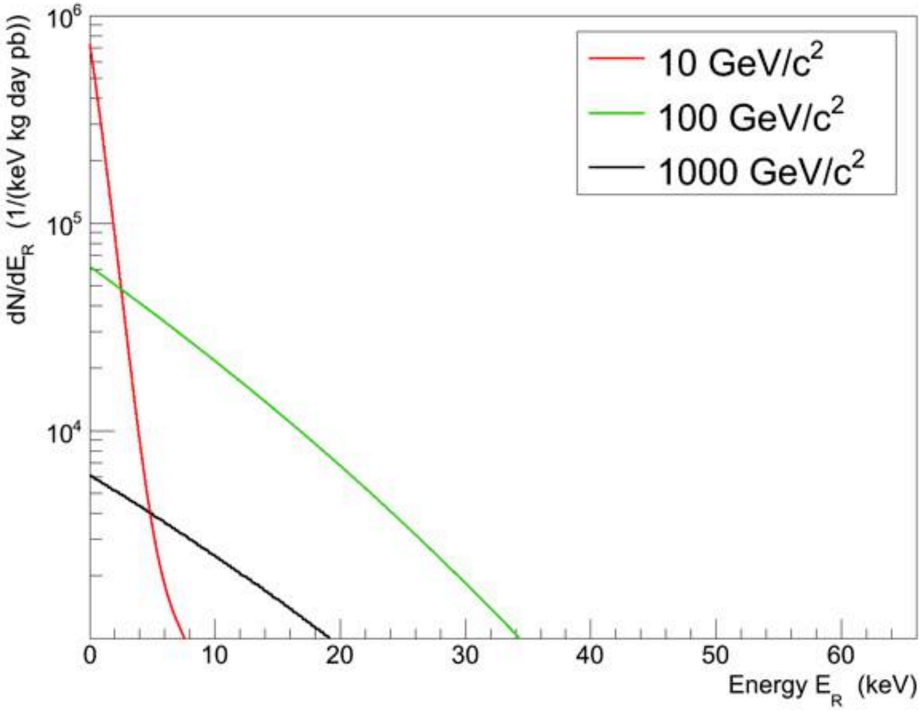
$$\frac{dR}{dE_r} = \frac{\rho_\chi}{m_N m_\chi} \cdot \int_{v_{min}}^{v_{esc}} d^3 v\, f(\vec{v})\, v \frac{d\sigma(\vec{v}, E_r)}{dE_r}$$

minimal velocity to produce a recoil above threshold

~ A^2
~ form factor

SPECIFIC **SIGNATURE**

rate and shape of recoil spectrum depend on target material

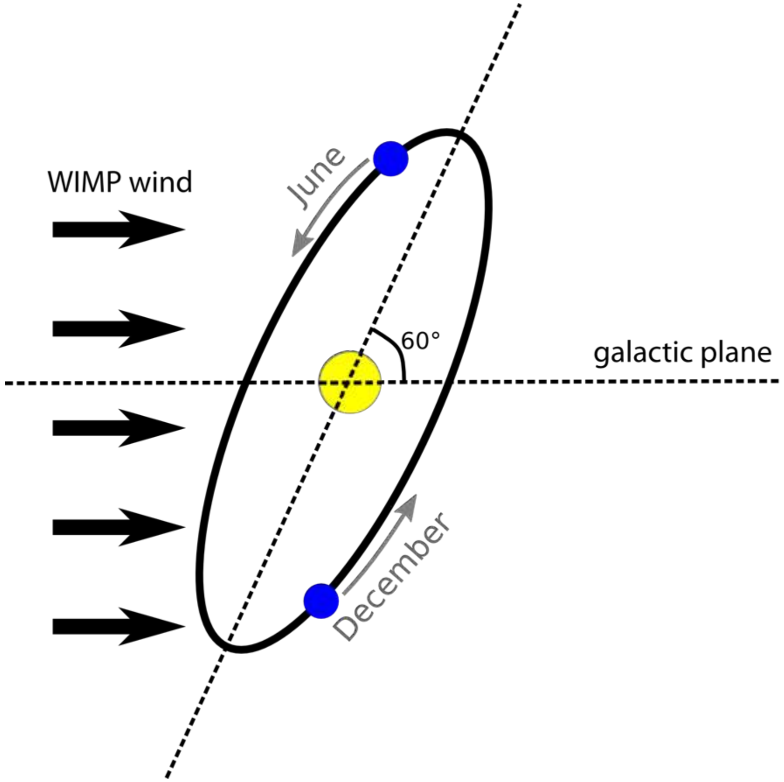


- very small energy deposits
- extremely rare interaction rate

→ FLAT, FEATURELESS SPECTRUM

MODULATION

rate and shape of recoil spectrum depend on target material



AND

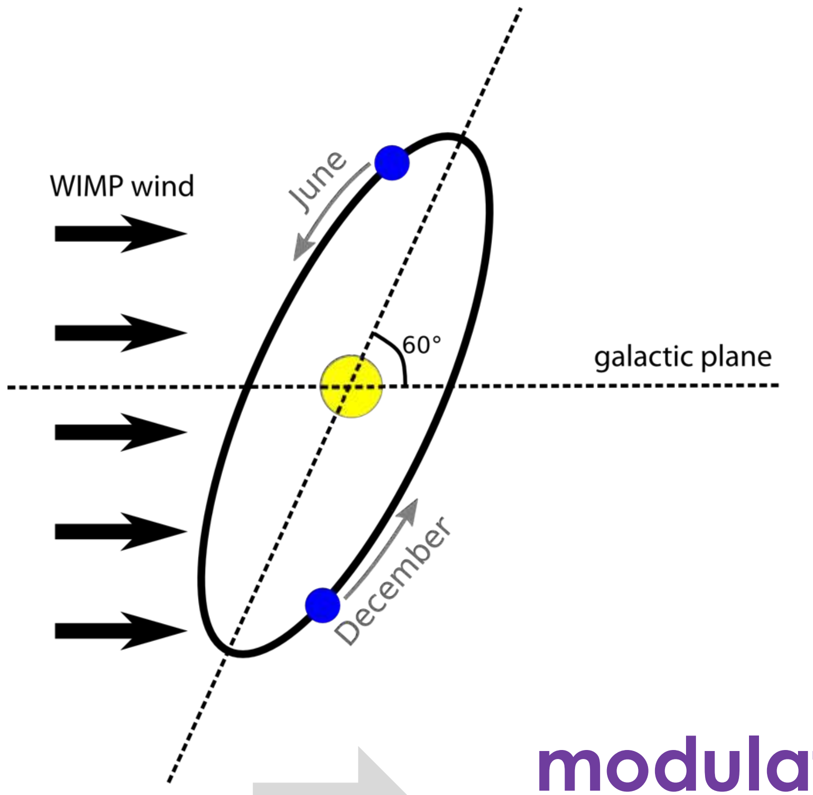
motion of the Earth causes relative modulation of velocity

→ **annual variation in the rate**

Period: 1 year
Phase: cosine peaking June 2nd

MODULATION

rate and shape of recoil spectrum depend on target material

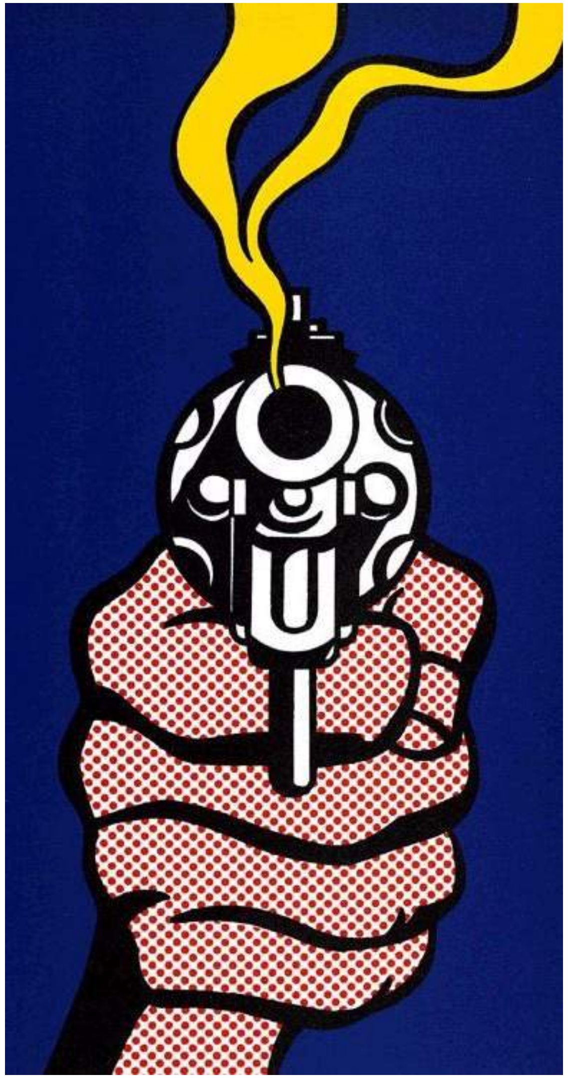


AND

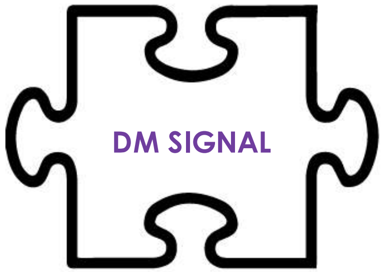
motion of the Earth causes relative modulation of velocity

→ annual variation in the rate

modulation signal detection
a smoking gun evidence ?!?



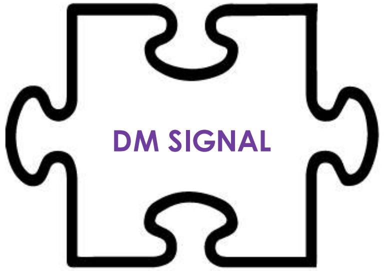
EXPERIMENTAL CHALLENGE



DARK MATTER SIGNAL

- energy deposits few keV - tens of keV
- few events per ton per year
- modulation detection

EXPERIMENTAL CHALLENGE



DARK MATTER SIGNAL

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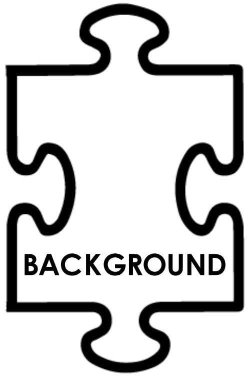
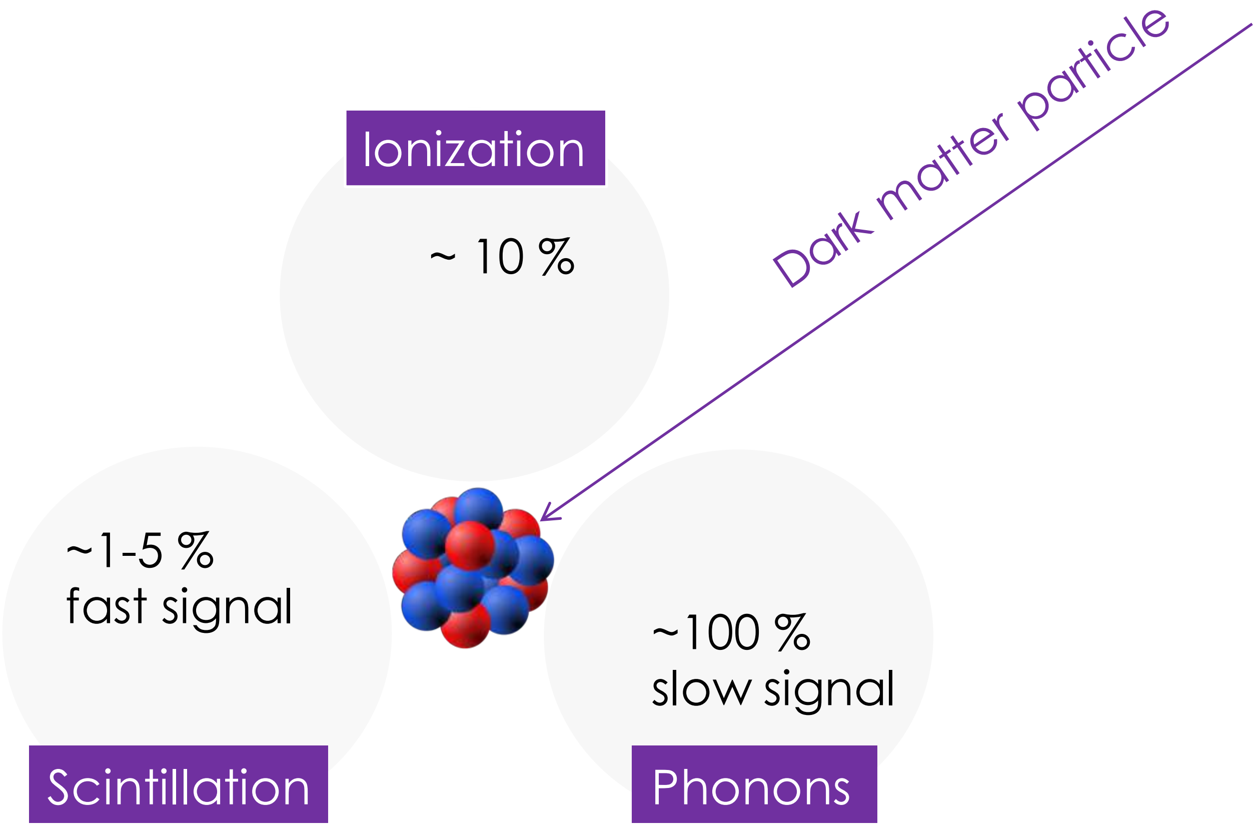


BACKGROUND

- depends on experimental setup
- is typically millions of times higher than signal
- is constant in time (or at least not modulating as DM)

WORLDWIDE EFFORT

DIRECT DETECTION **CHANNELS**

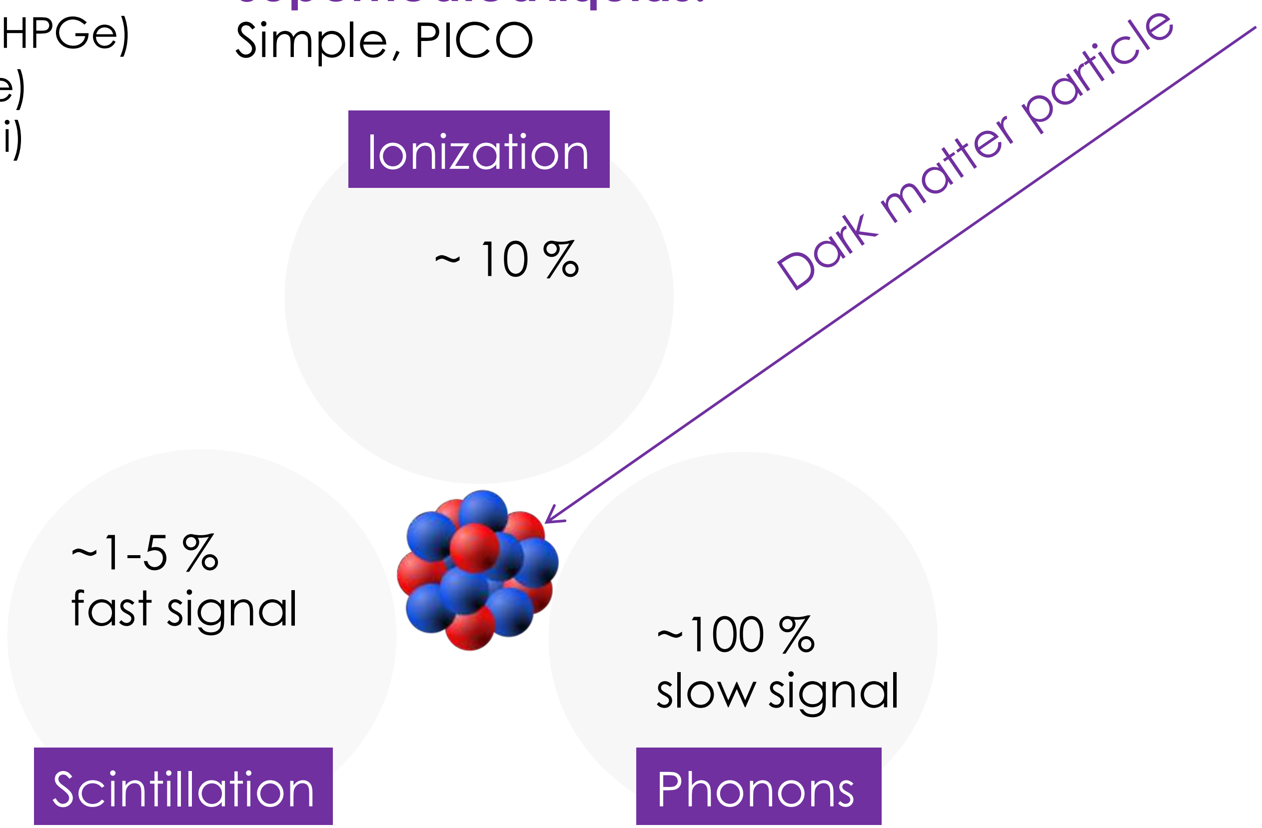


SINGLE CHANNEL DETECTION

not complete list!

Semiconductors:
- CoGent (HPGe)
- CDEX (Ge)
- DAMIC (Si)

Superheated liquids:
Simple, PICO



Inorganic scintillators:
DAMA/LIBRA, COSINE, KIMS, DM-Ice

Single-phase liquid nobles:
DEAP, MiniCLEAN, XMASS

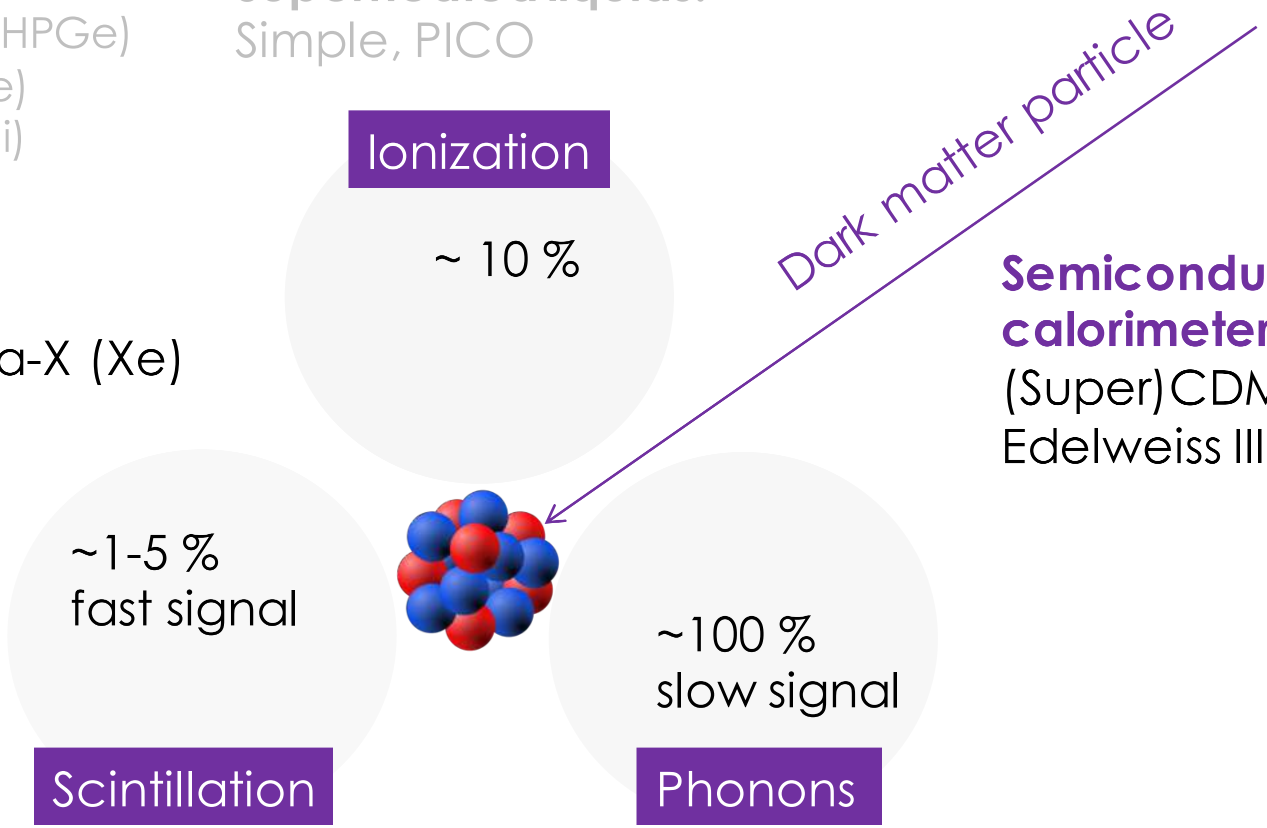
DUAL CHANNEL DETECTION

not complete list!

Semiconductors:
- CoGent (HPGe)
- CDEX (Ge)
- DAMIC (Si)

Superheated liquids:
Simple, PICO

2-phase noble liquids:
XENON 1t, LUX/LZ, Panda-X (Xe)
Darkside-50 (Ar)



Semiconducting calorimeters:
(Super)CDMS (Ge, Si)
Edelweiss III (Ge)

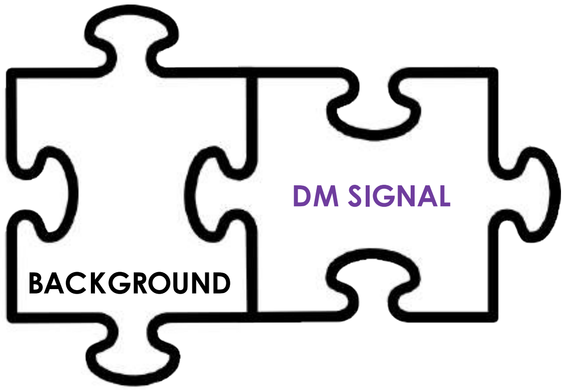
Inorganic scintillators:
DAMA/LIBRA, KIMS

Single-phase liquid nobles:
DEAP, MiniCLEAN, XMASS

Scintillating calorimeters
CRESST-III ($CaWO_4$)

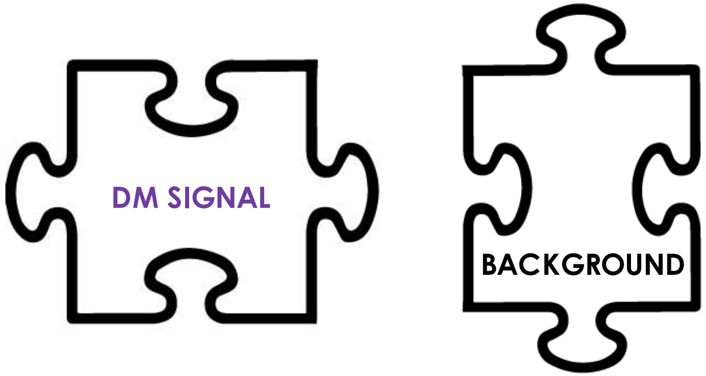
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



VS.

DUAL CHANNEL



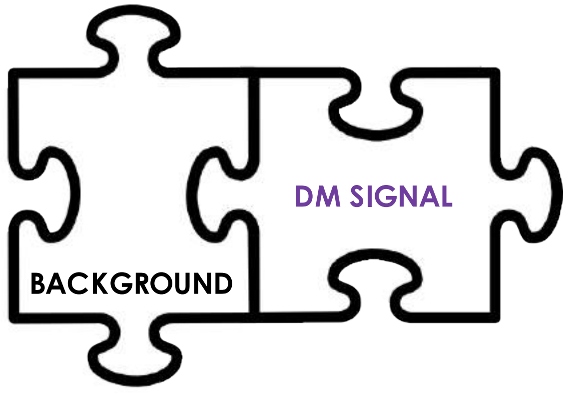
DISCRIMINATION

nuclear recoil events

to β/γ-events

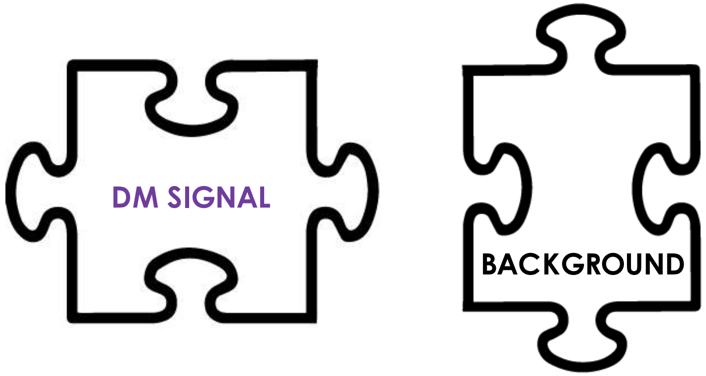
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



VS.

DUAL CHANNEL

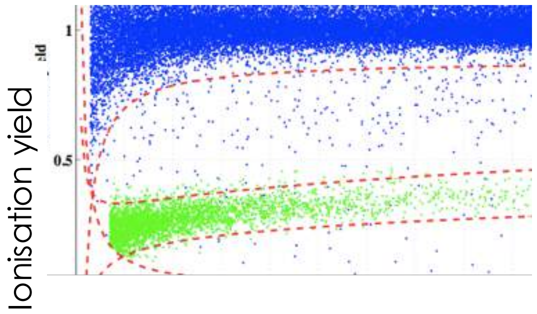


DISCRIMINATION

nuclear recoil events

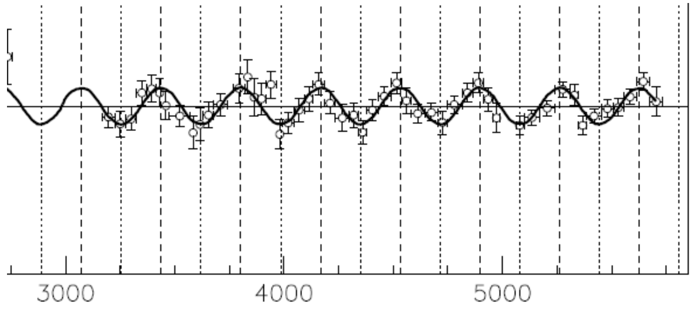
to β/γ-events

COUNTING EXPERIMENT



XENON

MODULATION EXPERIMENT



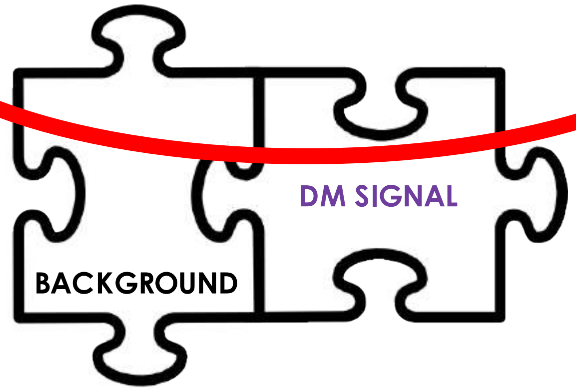
comparison of

result requires

model assumption

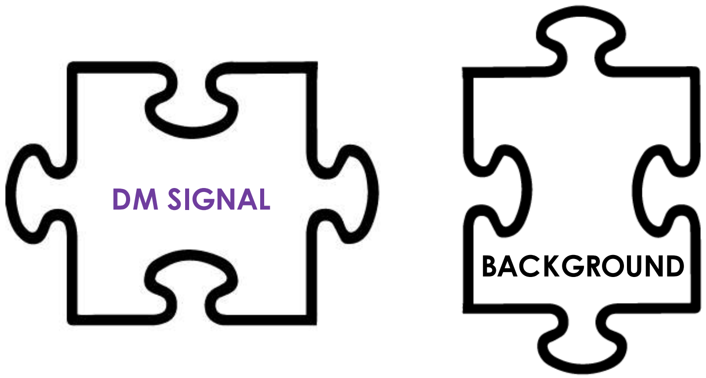
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



VS.

DUAL CHANNEL



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nuclear recoil events

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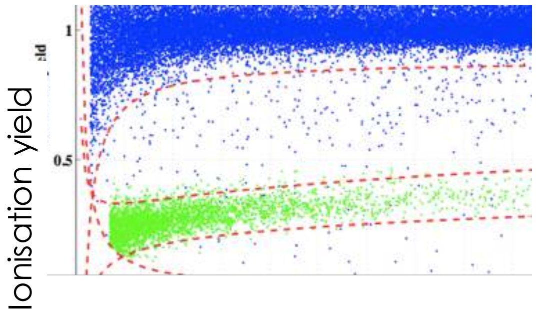
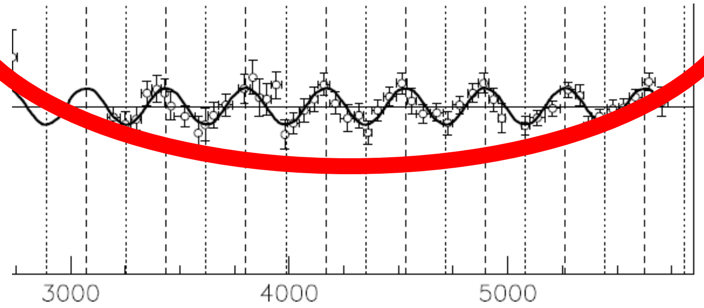


XENON

MODULATION EXPERIMENT

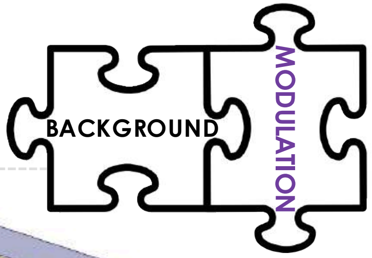


comparison of

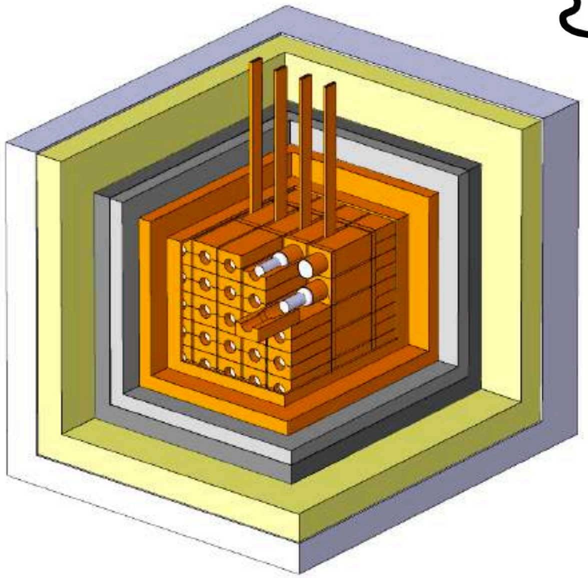
result requires

model assumption

DAMA/LIBRA experiment

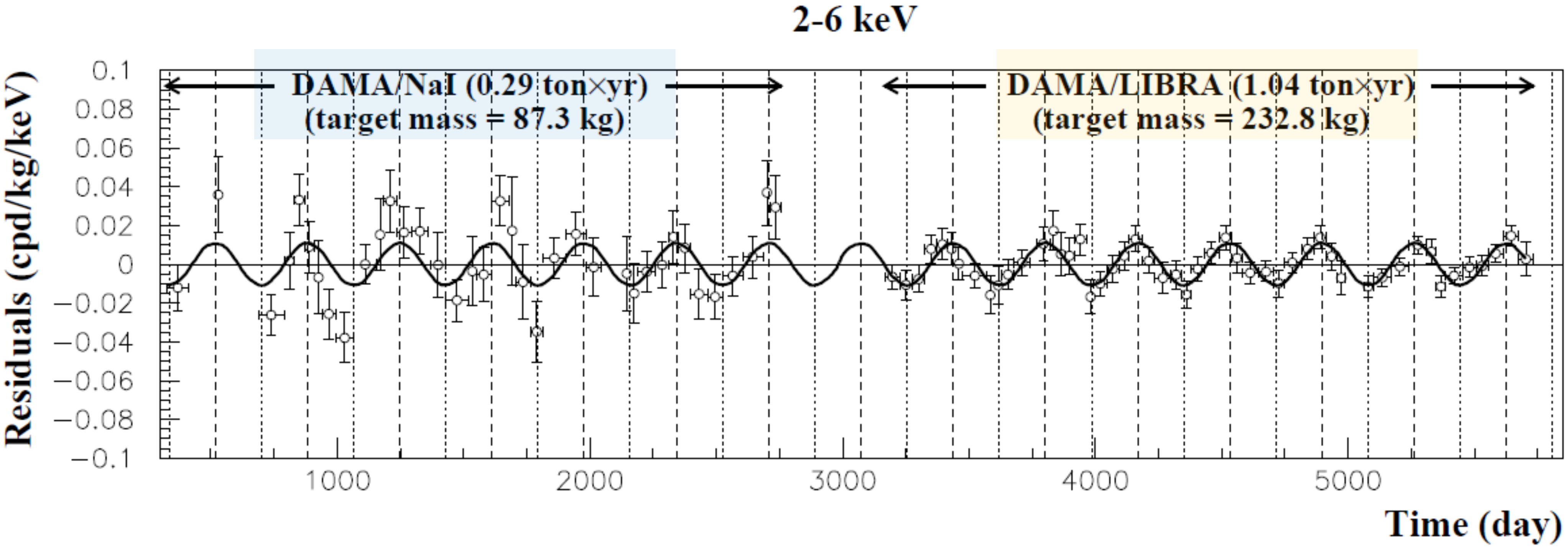


MATERIAL	250 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	LNGS/Italy
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	2keVee
DATA TAKING	since 1996
EVIDENCE	yes



DAMA/LIBRA: **TIME DISTRIBUTION**

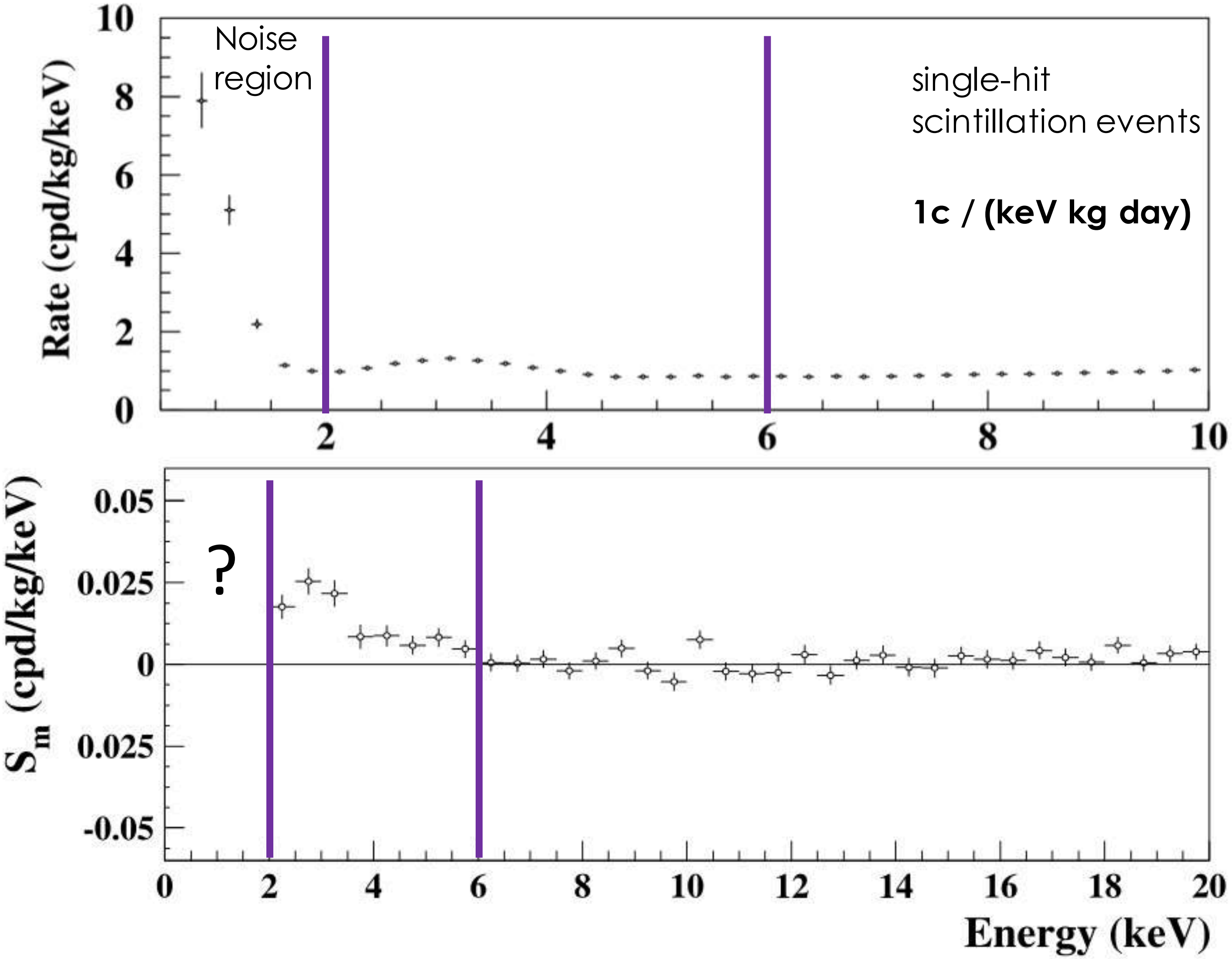
Eur.Phys.J. C 56 333 (2008), arXiv:0804.2741



Total exposure: 1.33 ton years
Statistical significance: >9.3 σ
Annual cycles > 13

DAMA/LIBRA: **ENERGY SPECTRUM**

R. Bernabei et al., EPJ C 56 (2008) 333–355.
Plot from: Bernabei et al. EPJ (2013) 73:2648



DAMA/LIBRA BACKGROUND

^{40}K < 20 ppb

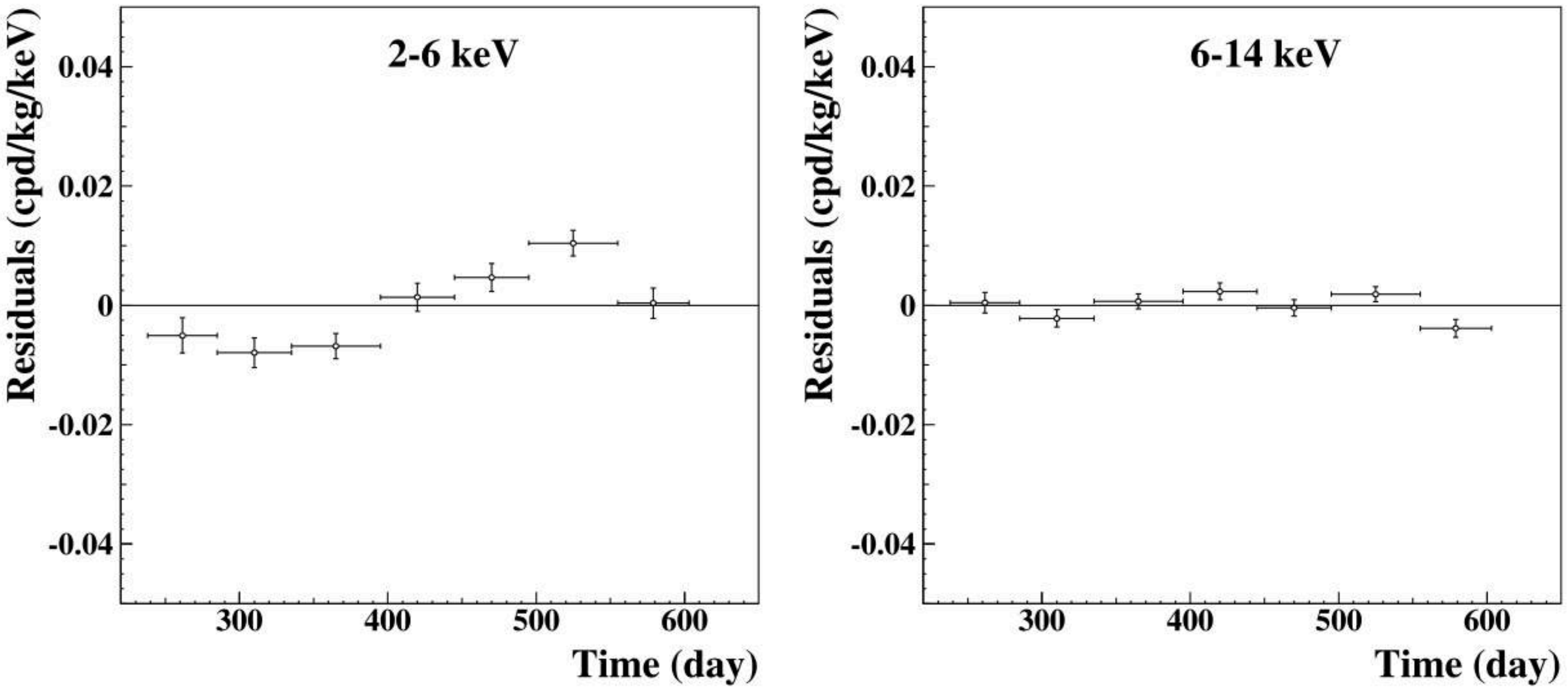
^{238}U < 0.7-10 ppt

^{232}Th < 0.5-7.5 ppt

^{210}Po < 0.5 mBq/kg

DAMA/LIBRA: **ENERGY CROSS-CHECK**

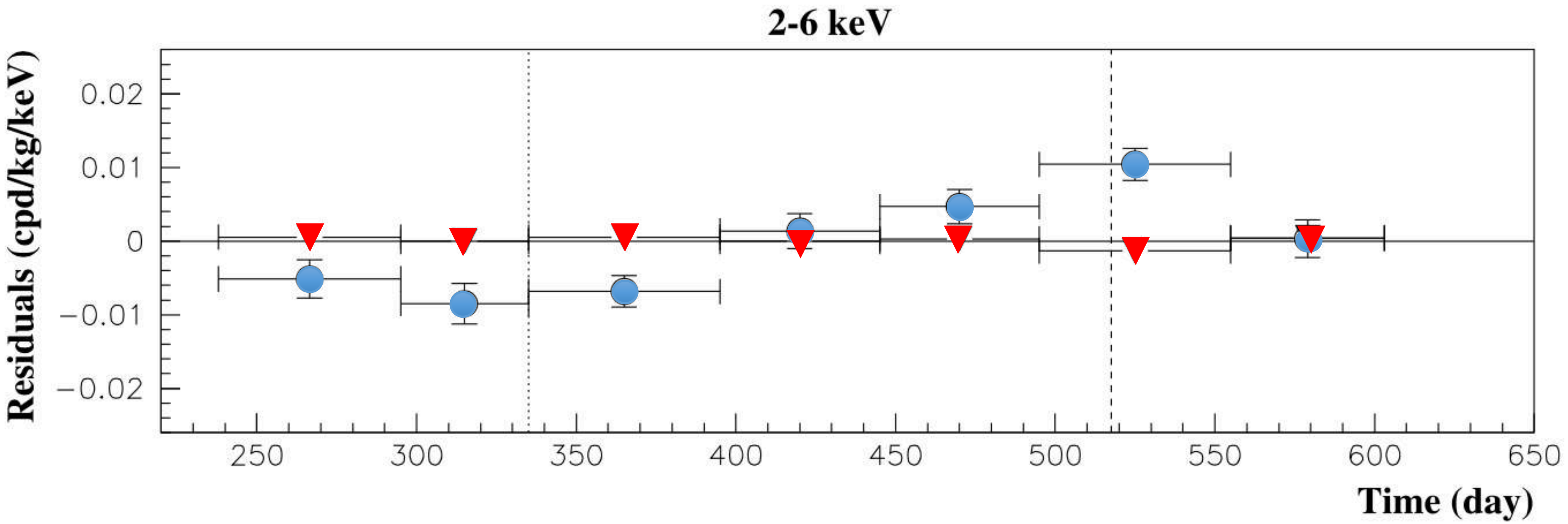
Plot from: Bernabei et al. EPJ (2013) 73:2648



DAMA/LIBRA: **SINGLE vs. MULTI HIT EVENT**

Plot from: Bernabei et al. EPJ (2013) 73:2648

● Single hit = incl. DM ▼ Multiple hit = Background



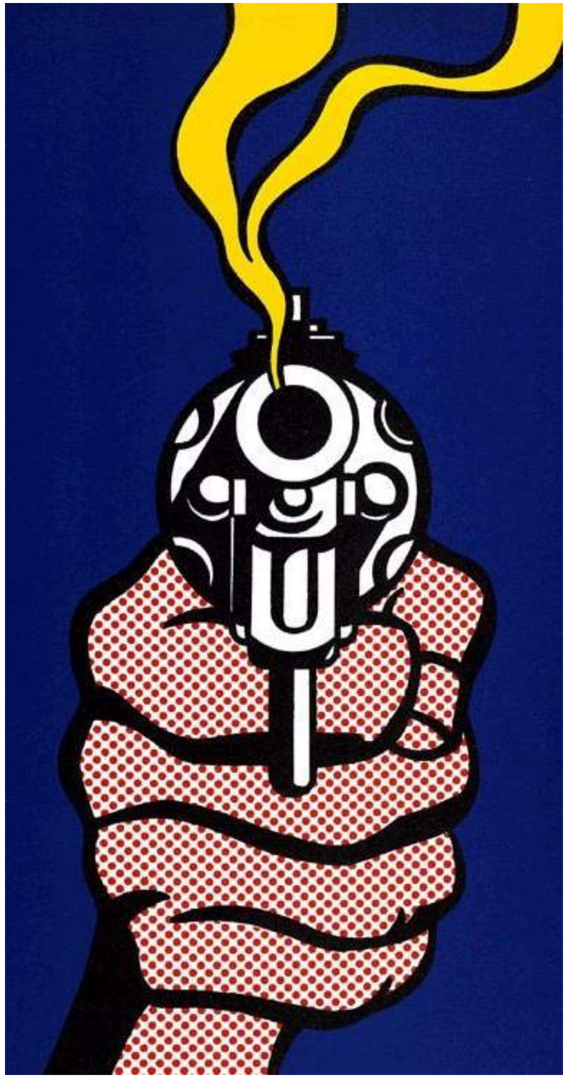
THE SMOKING GUN EVIDENCE?

Statistics: > 9σ ✓

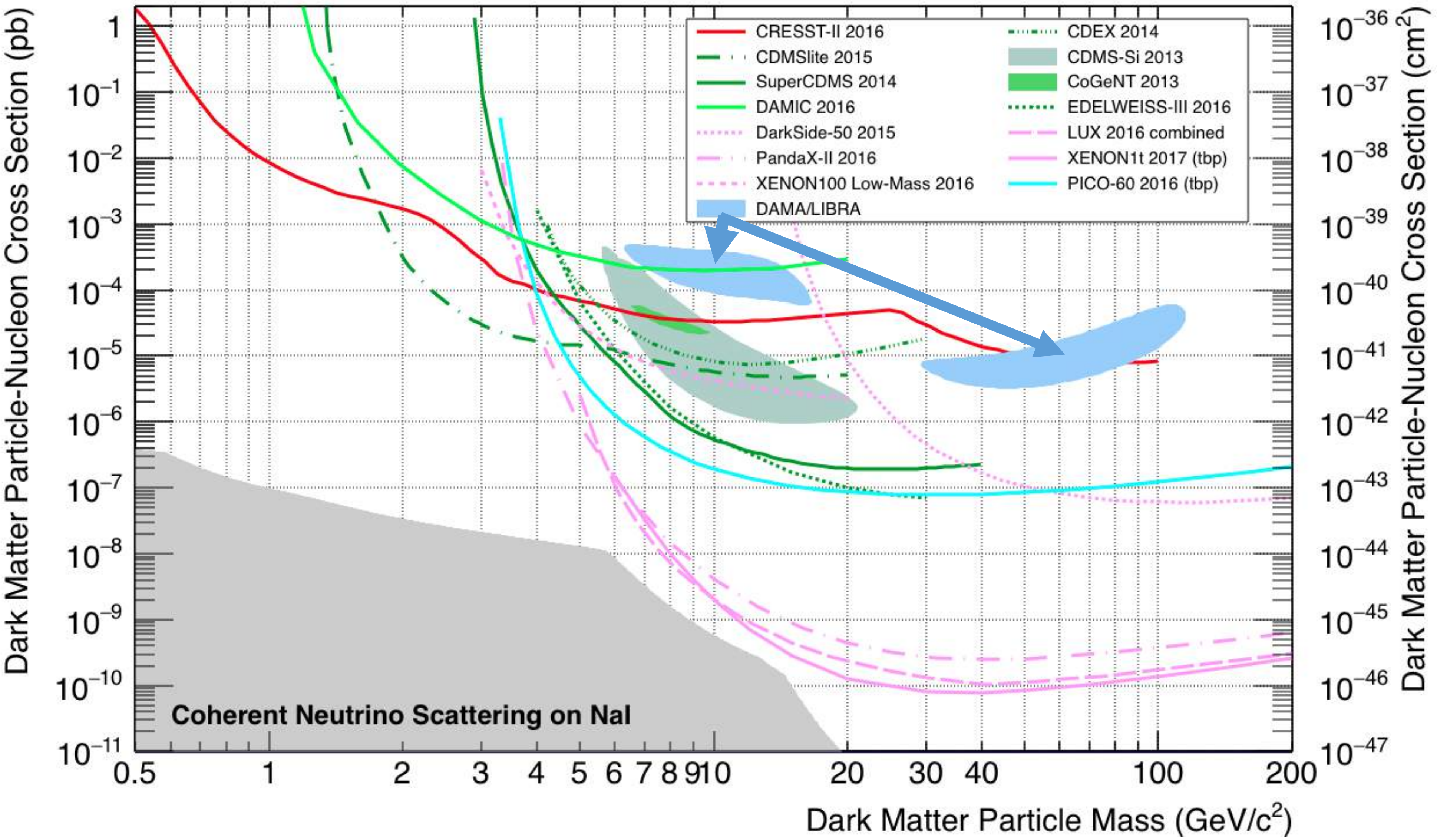
Period: 0.998 ± 0.002 years ✓

Phase: 24th May +/- 7 days ✓
(cosine peaking June 2nd)

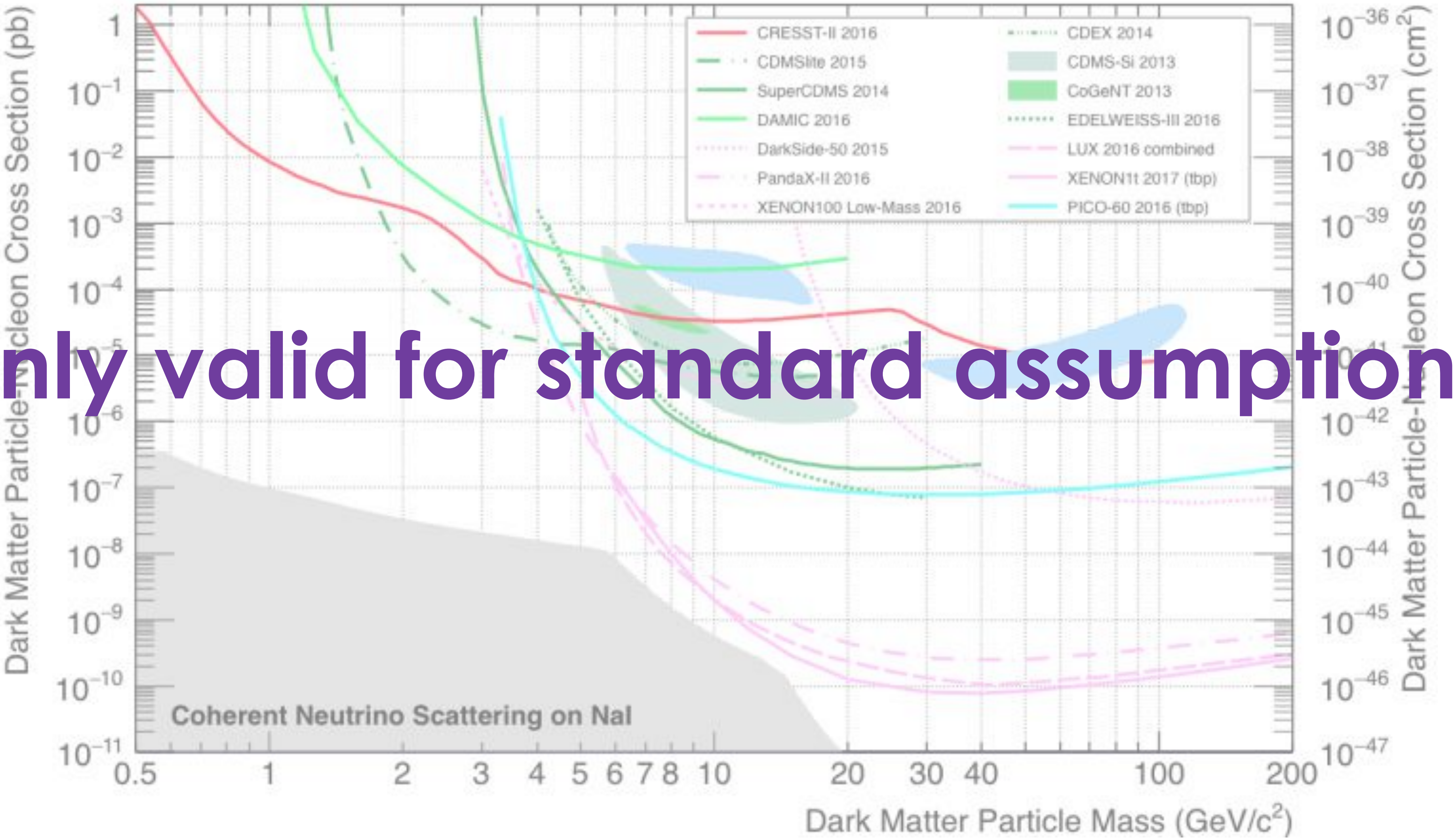
Convincing non-DM explanation ✗



DARK MATTER LANDSCAPE



Only valid for standard assumptions!!!



WHAT ARE THE **UNKNOWNS**?

galactic escape velocity

velocity distribution

DM-nucleon 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 above threshold

Astro physics

dark matter halo

velocity distribution

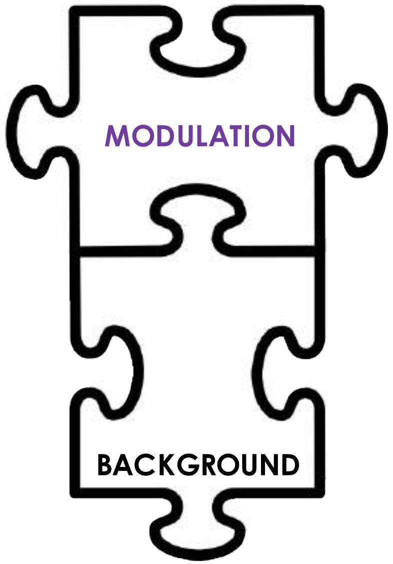
Particle physics

interaction mechanism

We have a dependence on the target material

→ cross-check DAMA/LIBRA signal with a NaI-based detector

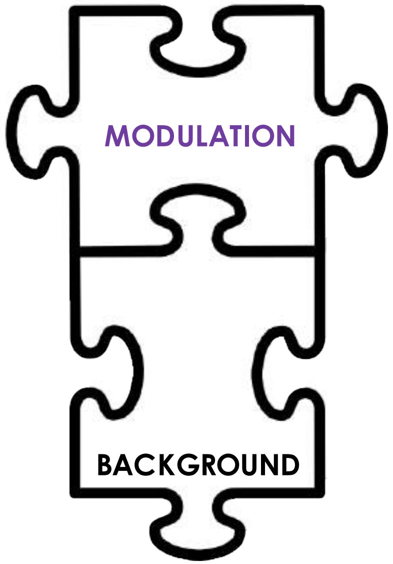
NaI EXPERIMENTS



DAMA/LIBRA
DM-Ice
KIMS-NaI
COSINE
ANAIS-112
SABRE
PICO-LON

- large mass
- low background
- **no** β/γ-discrimination

NaI EXPERIMENTS



DAMA/LIBRA
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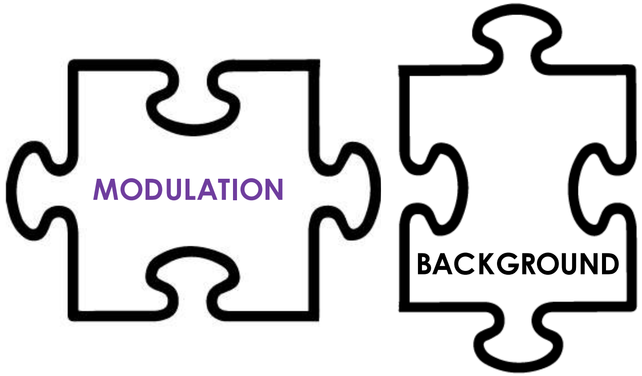
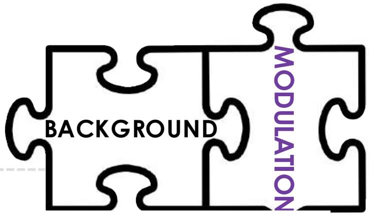


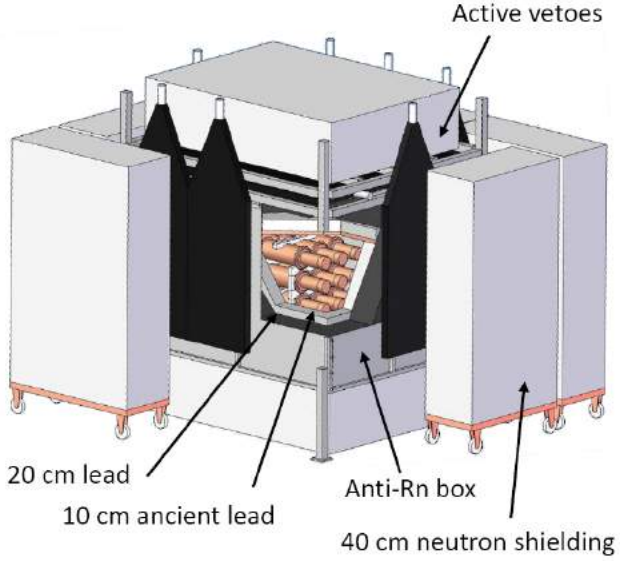
COSINUS

- β/γ-discrimination
- lower threshold, in particular for nuclear recoils

ANAIS-112 experiment

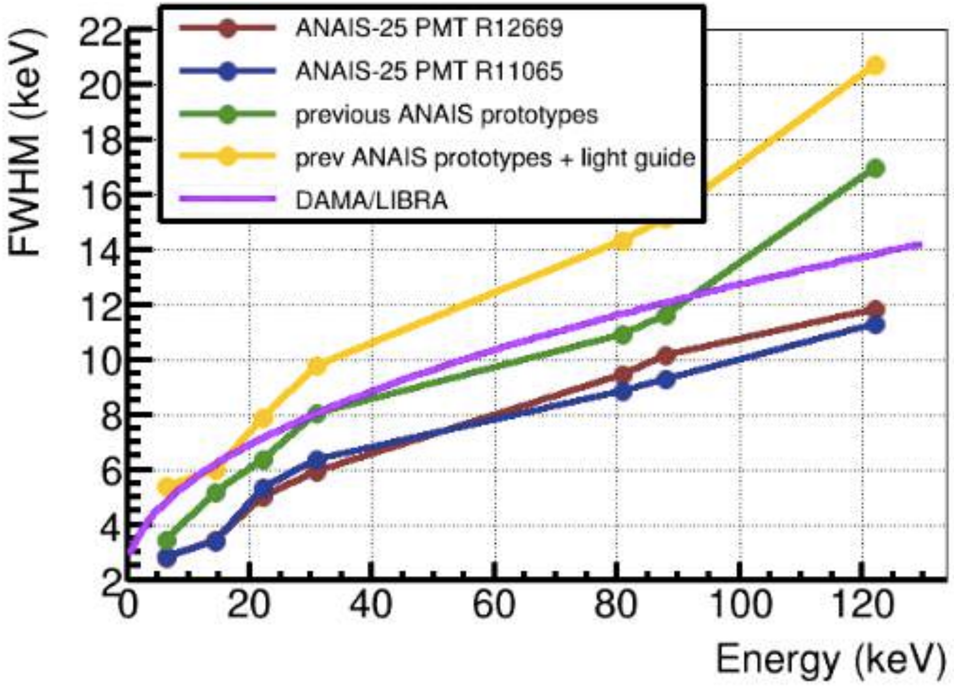


MATERIAL	112 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	Canfranc/Spain
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	~ 0.9 keVee
DATA TAKING	since 2017
EVIDENCE	no



ANAIS-112: **LIGHT COLLECTION**

M.A. Oliván et al, Astropart. Phys. 93 (2017) 86



M. Martinez, IBS-MultiDark-IPPP Workshop, 11/2016

high light collection
in all modules ~ 15 p.e./keV

→ good energy resolution

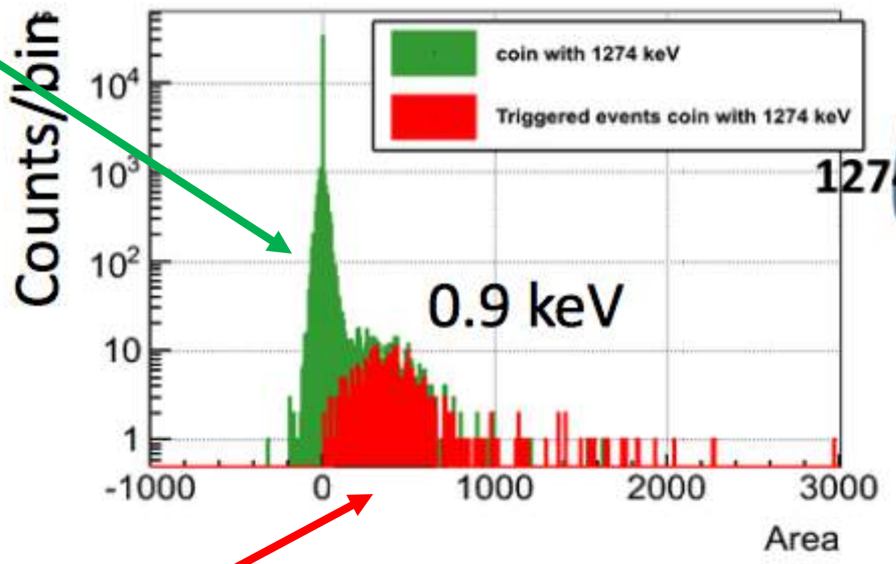
→ **low threshold: <1keVee**

ANAIS-112: **ENERGY THRESHOLD**

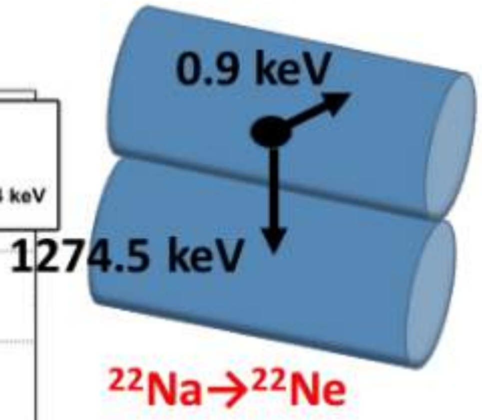
C. Cuesta et al., EPJ C 74 (2014) 3150

1274keV

Coincidence events

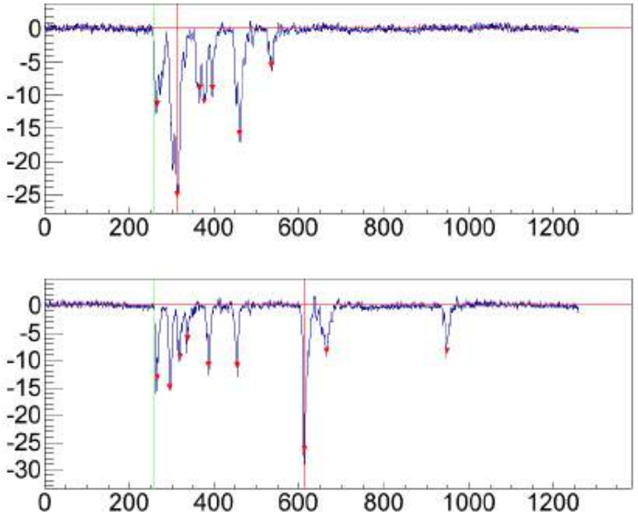


0.9keV triggered,
coincidence events



Triggering below 1 keVee:

bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas

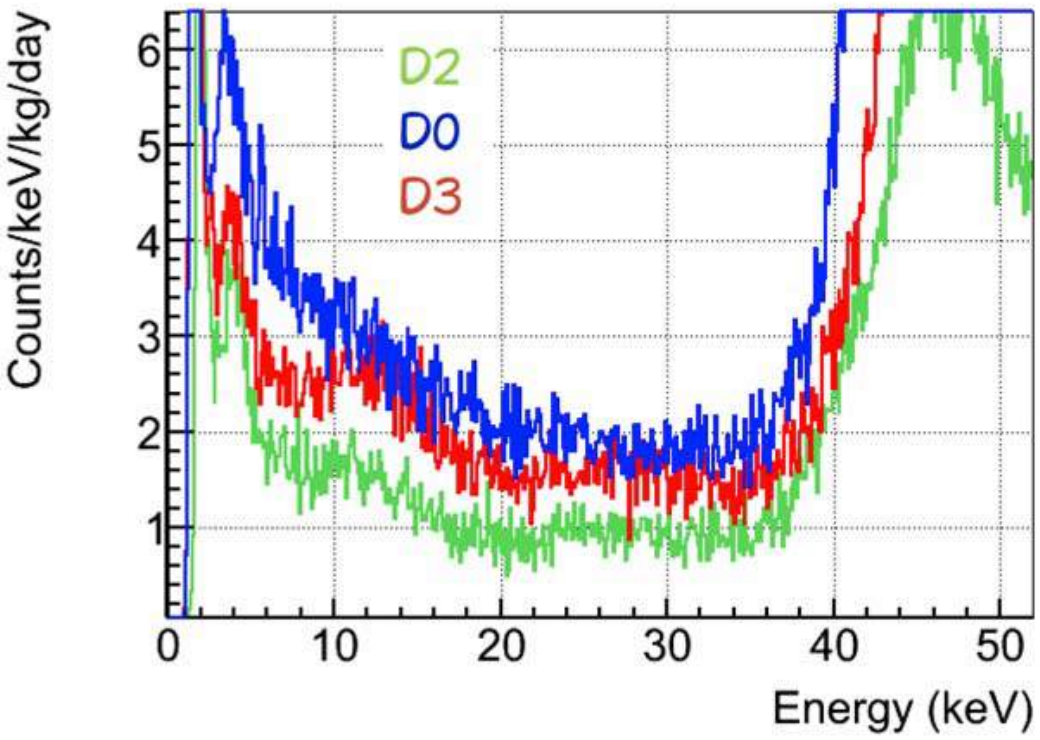


S. Cebrián, TAUP2017, Sudbury, 25th July 2017

ANAIS-112: **BACKGROUND**

J. Amaré et al, Eur. Phys. J. C 76 (2016) 429; JCAP 02 (2015) 046

^{40}K and ^{22}Na peaks and ^{210}Pb (bulk+surface) are the most significant contributions in the very low energy region



S. Cebrián, TAUP2017, Sudbury, 25th July 2017

Summary of crystal activity (from ~30.1 days in ANAIS-112)

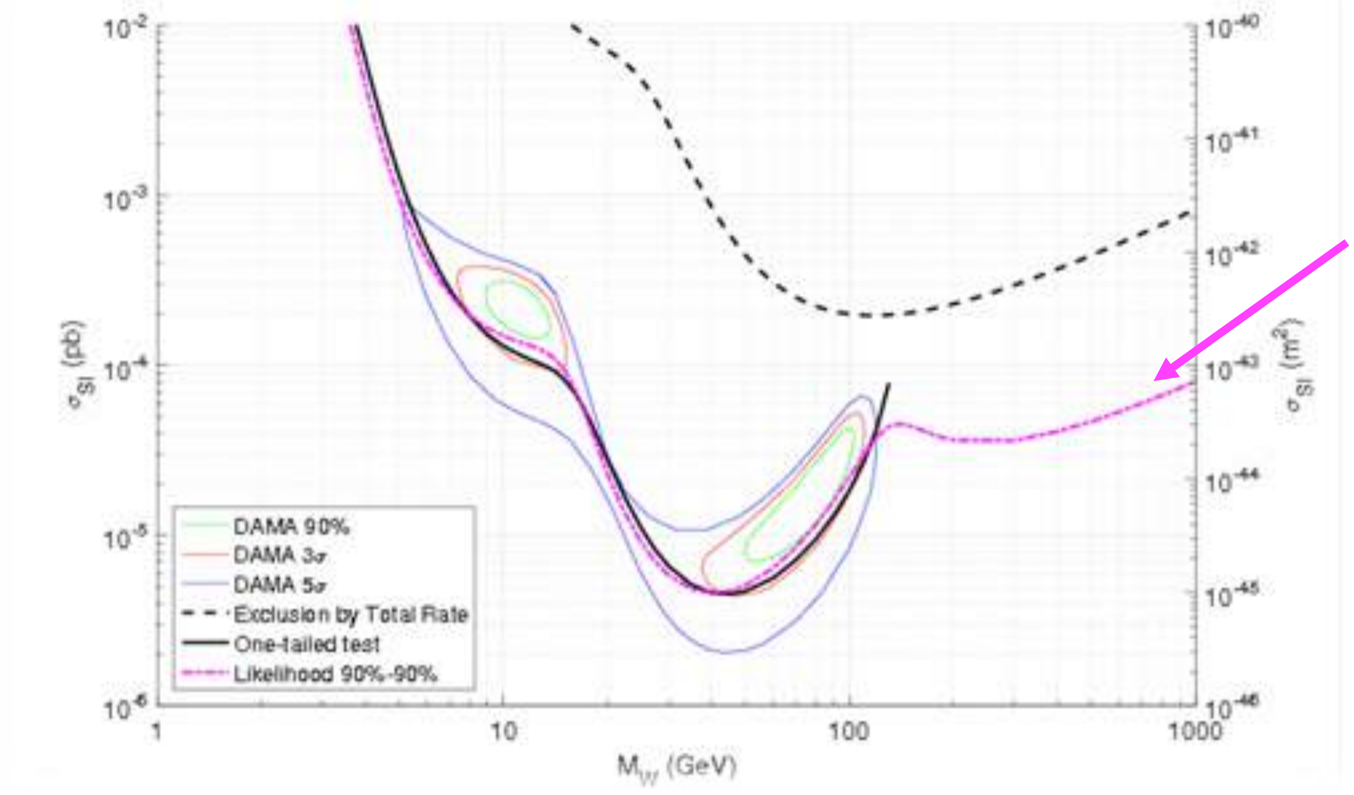
Detector	^{40}K (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.1	3.15
D1	1.4	3.15
D2	0.9	0.70
D3	0.7	1.8
D4	1.0	1.8
D5	1.0	0.75
D6	1.1	0.76
D7	1.0	0.75
D8	0.6	0.72
average	**1.0**	**1.5**

DAMA/LIBRA: ~20 ppb K = 0.6 mBq/kg ^{40}K

ANAIS-112: **PROJECTED SENSITIVITY**

I. Coarasa et al, arXiv:1704.06861v1

5 years data taking



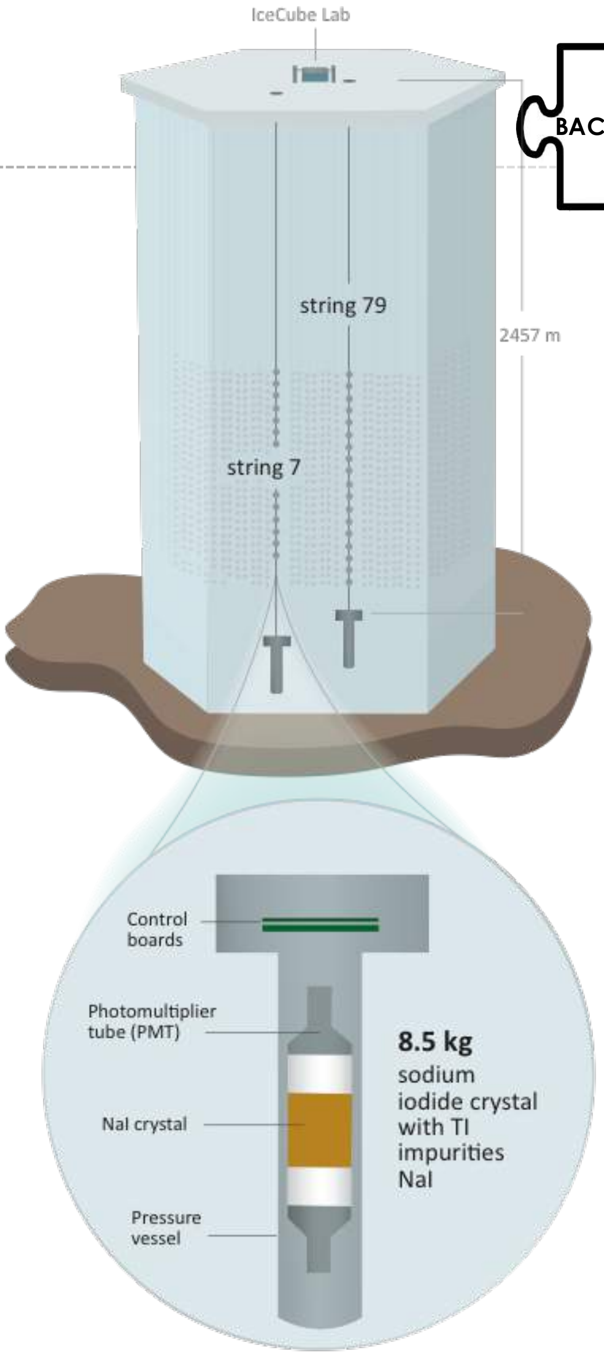
90% probability of detecting an annual modulation signal at 90% C.L.

ANAIS-112 can detect the annual modulation in the 3σ region compatible with the DAMA/LIBRA result

DM-Ice experiment

BACKGROUND MODULATION

MATERIAL	17 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	south pole
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	4 keVee
DATA TAKING	since 2011
EVIDENCE	no

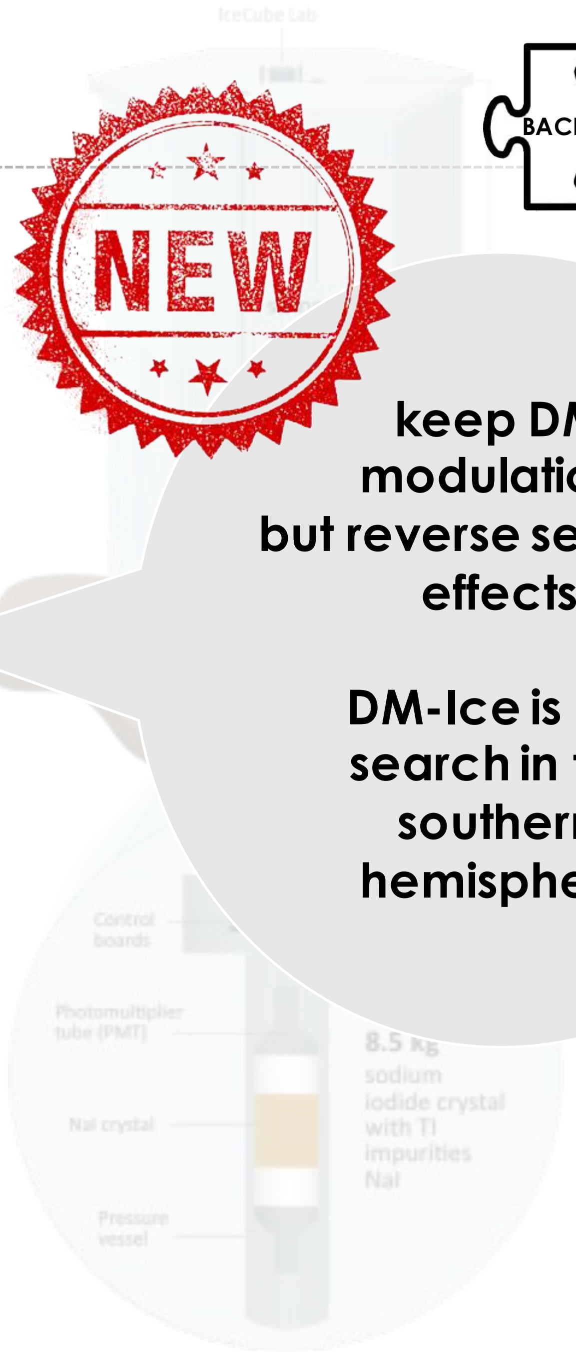


DM-Ice experiment

BACKGROUND MODULATION

NEW

MATERIAL	17 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	south pole
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	4 keVee
DATA TAKING	since 2011
EVIDENCE	no



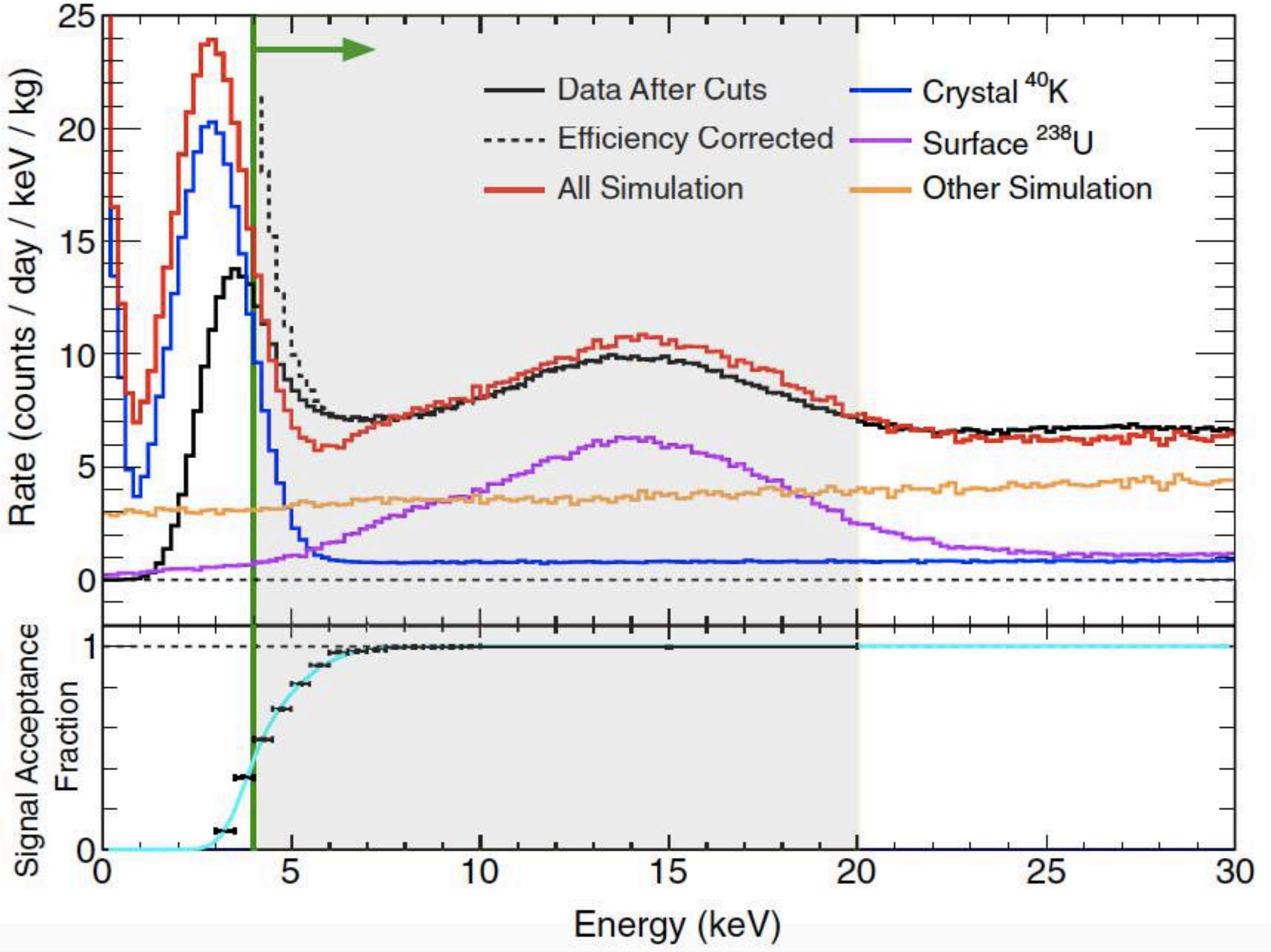
keep DM modulation,
but reverse seasonal effects

DM-Ice is first search in the southern hemisphere

DM-Ice: **BACKGROUND**

E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006

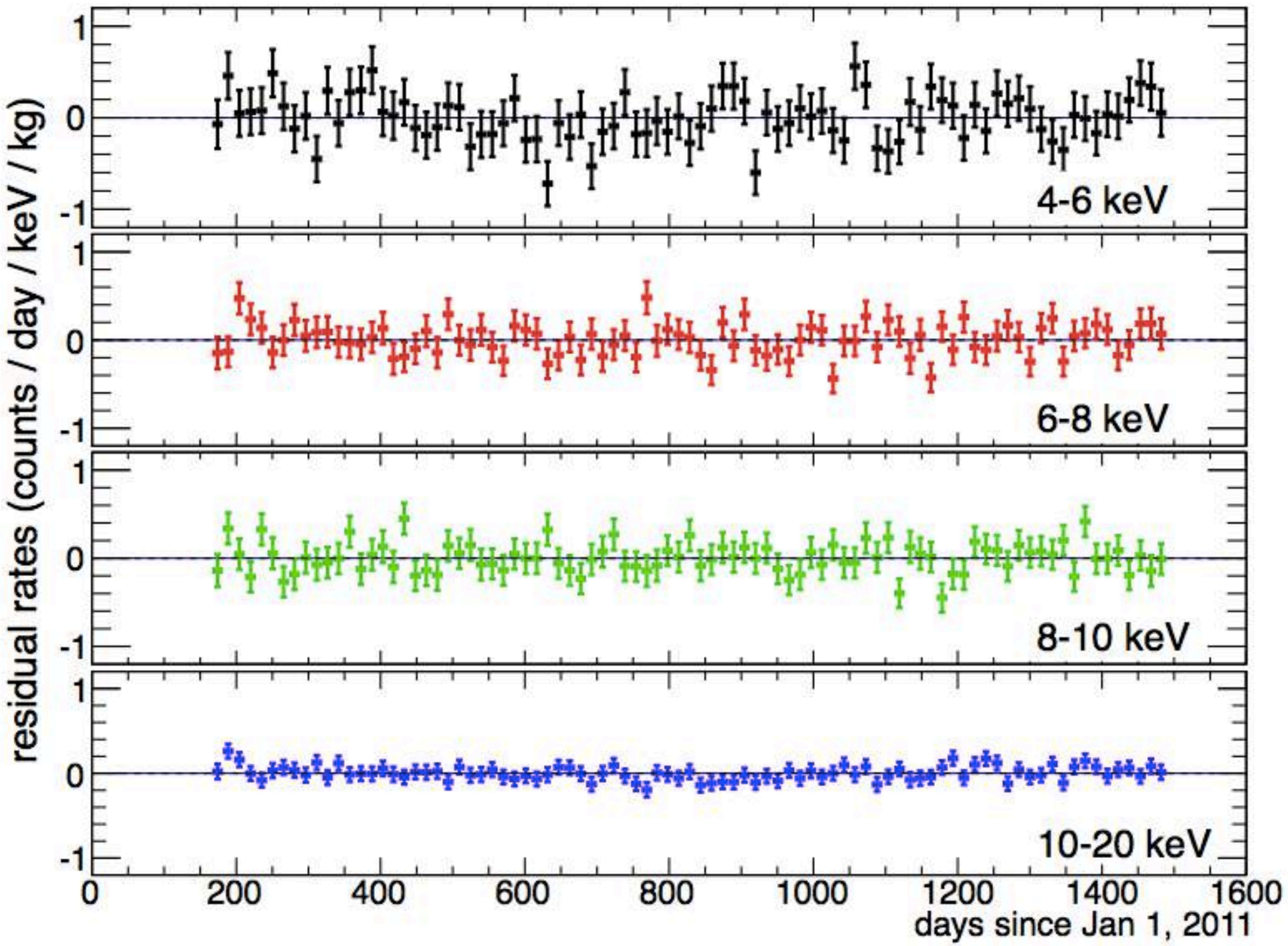
PHYSICAL REVIEW D **95,** 032006 (2017)



- 3.6 years of data taking
- total exposure of 60.8 kg yr
- energy range of 4–20 keVee

DM-Ice **results**

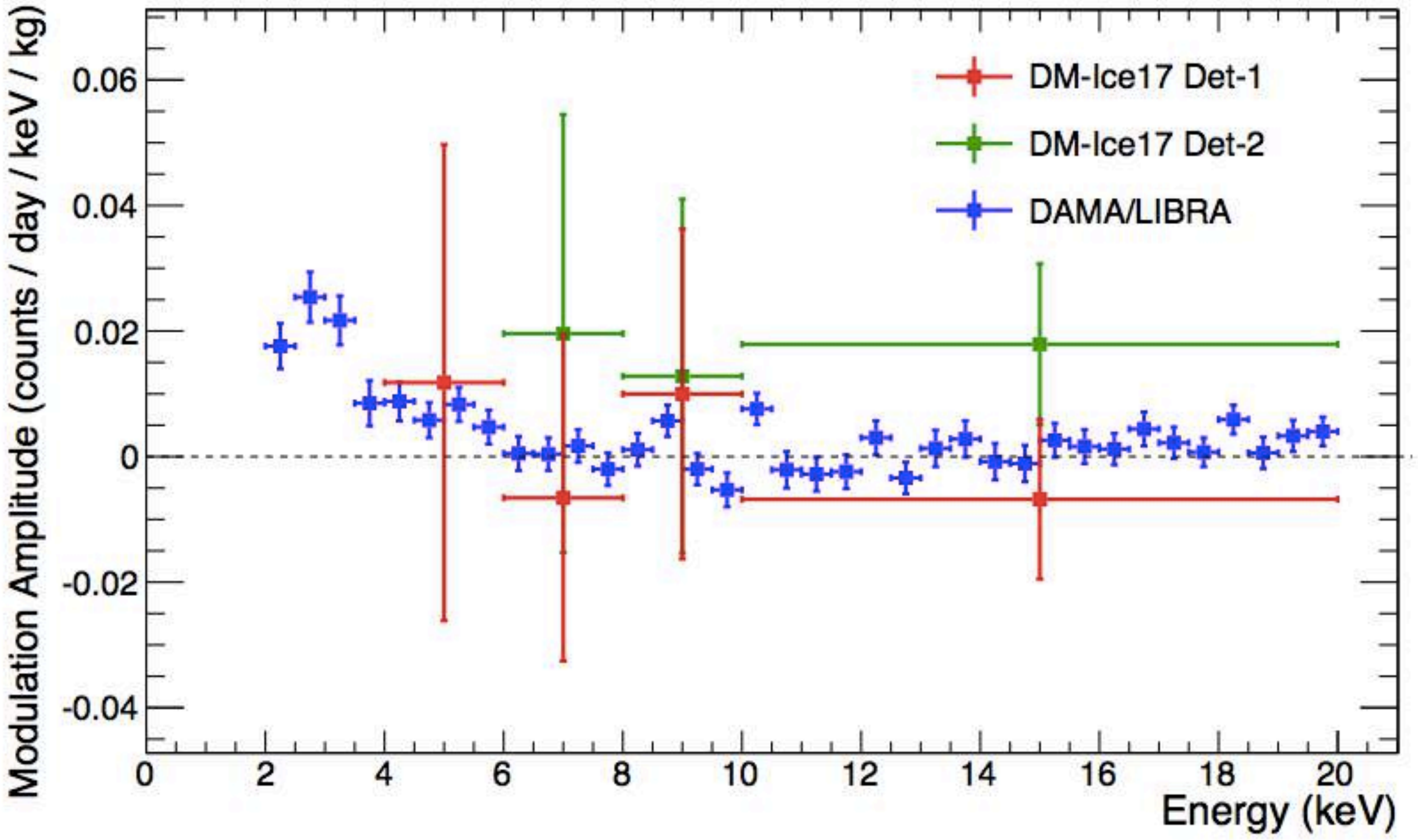
E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006



- horizontal error bars represent the half-month bin width
- vertical error bars represent ±1σ error due to statistical and uptime uncertainties

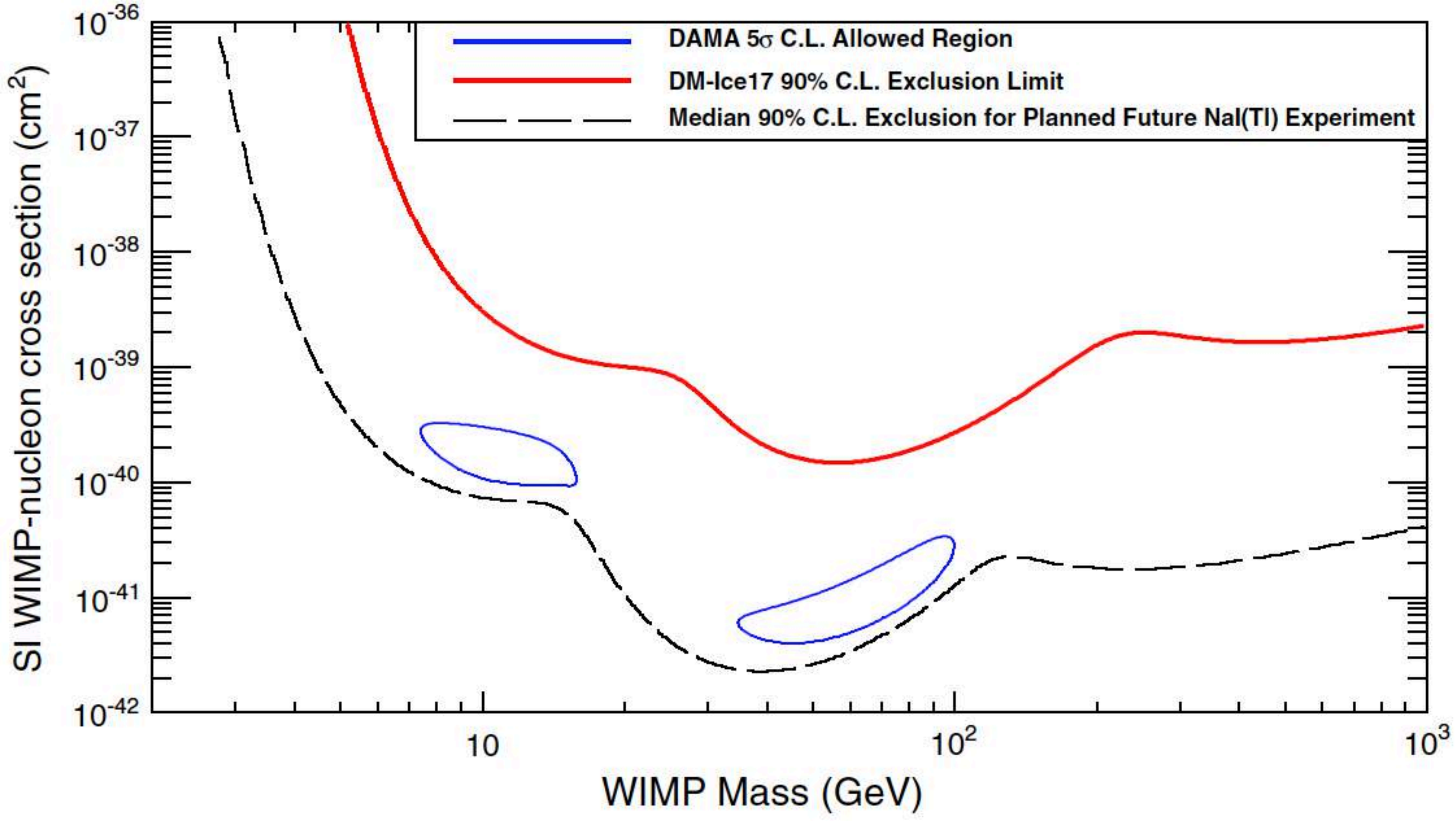
DM-Ice **results**

E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006



DM-Ice: **SENSITIVITY**

E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006



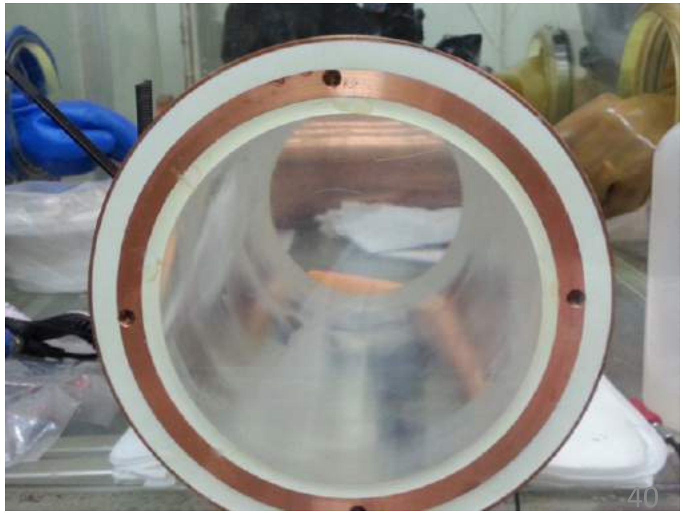
dashed black line:

future NaI(Tl)-based search

- 2 counts/ (day keV kg)
- 500 kg year
- 2 keVee analysis threshold

COSINE-100: Coll. of DM-Ice+KIMS NaI

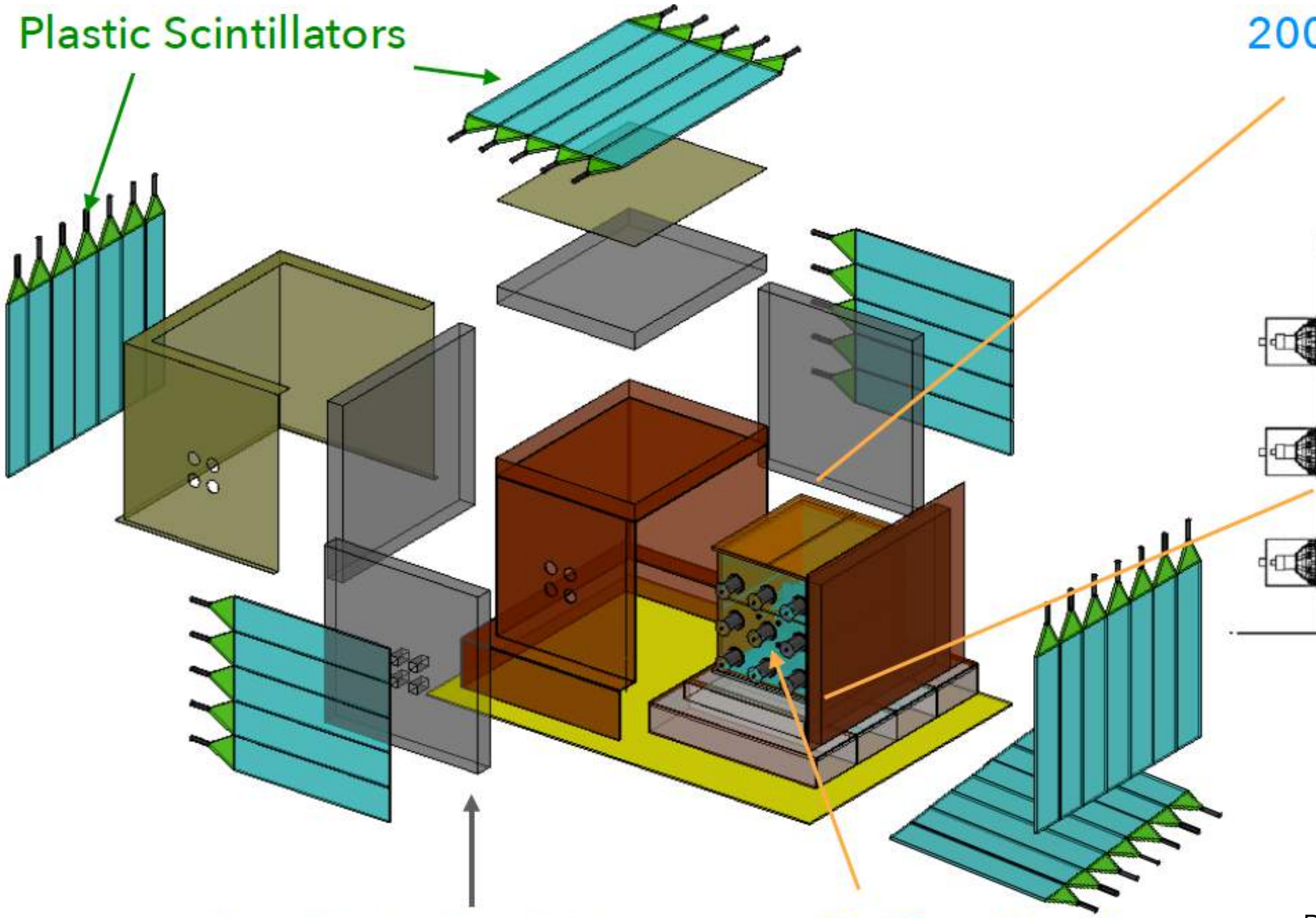
MATERIAL	106 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	Yang Yang Lab.
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	~2 keVee
DATA TAKING	since Sept. 2016
EVIDENCE	no

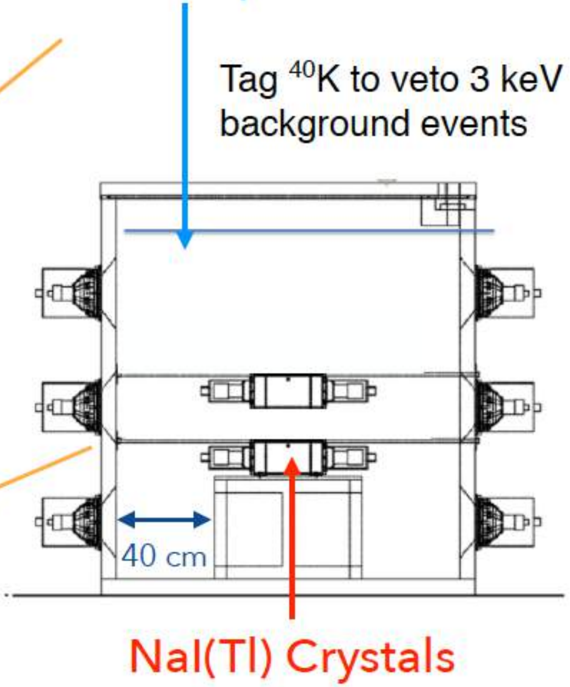


COSINE-100: **NEW features**

Tagging of muon-induced events

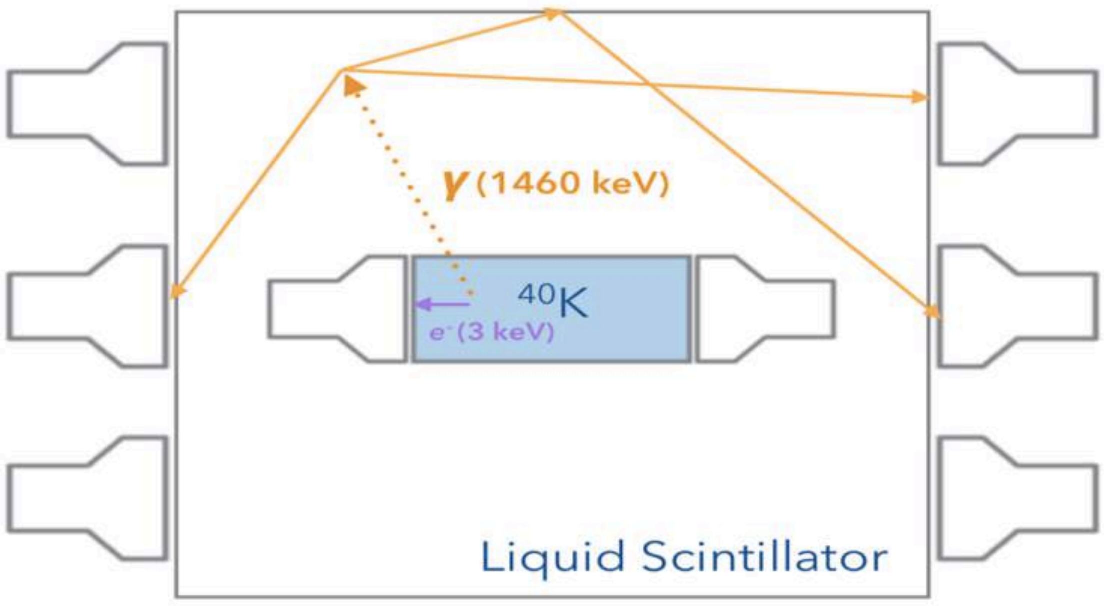
Tagging of ^{40}K of outer crystals

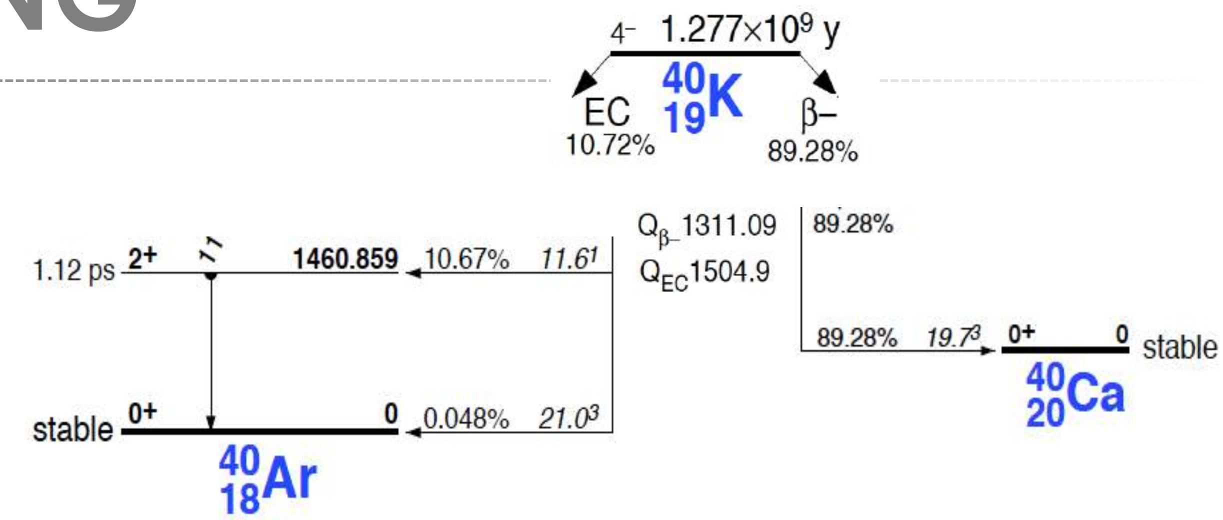




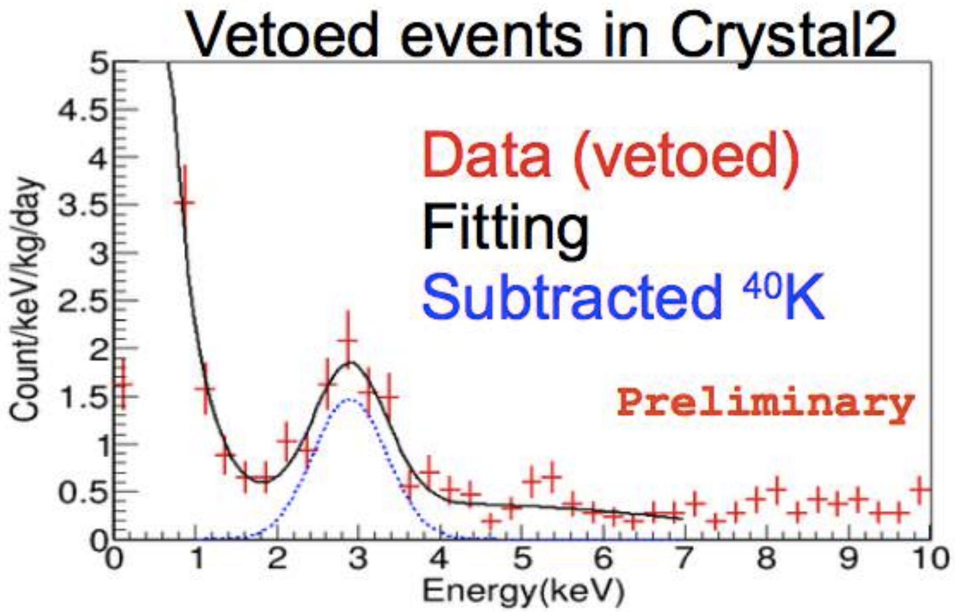
R. Maruyama, *COSINE-100*, TAUP 17 conference,

COSINE-100: ^{40}K TAGGING



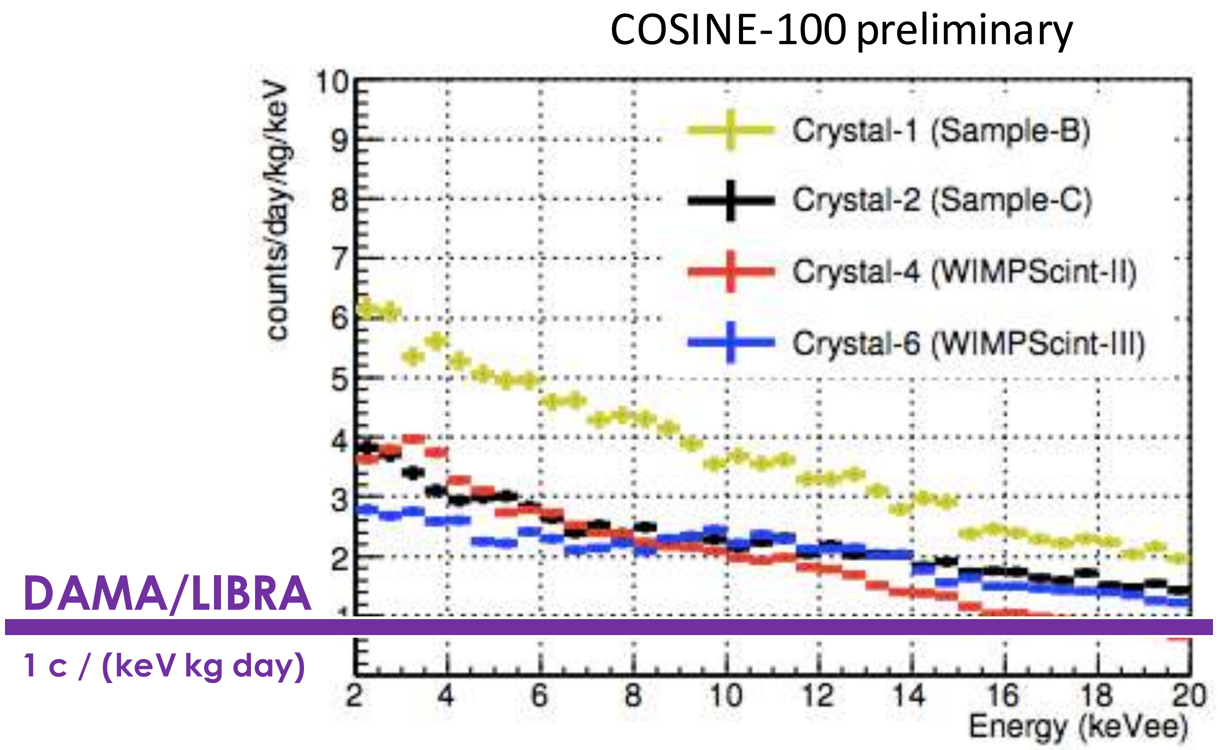


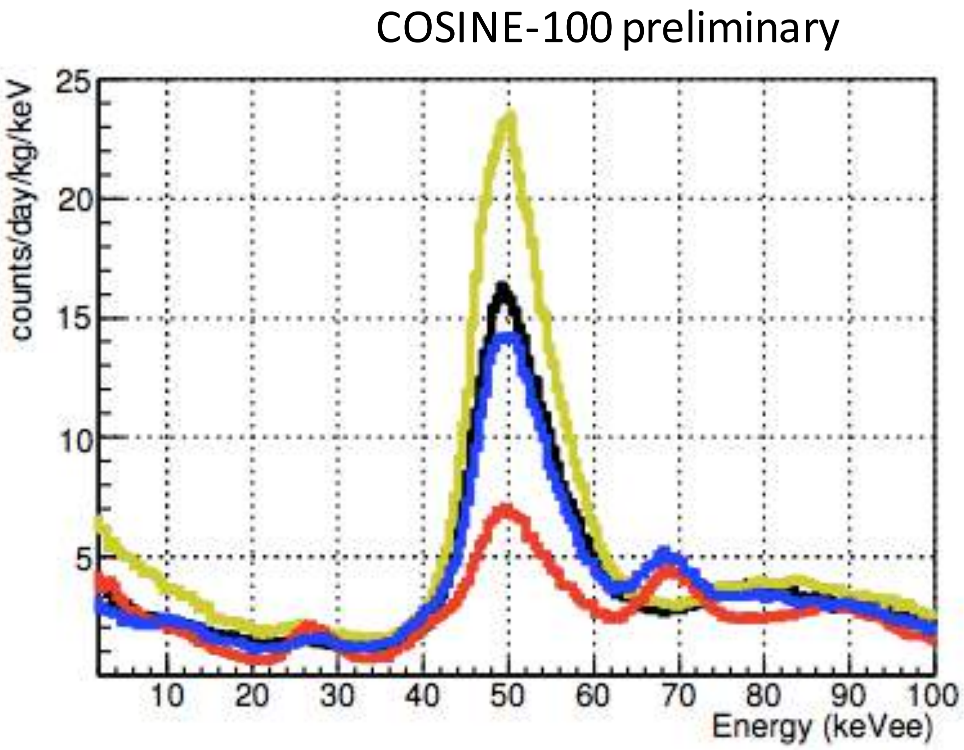
Effective tool to reduce ^{40}K background in ROI



COSINE-100: **BACKGROUND**

R. Maruyama, *COSINE-100*, TAUP 17 conference,



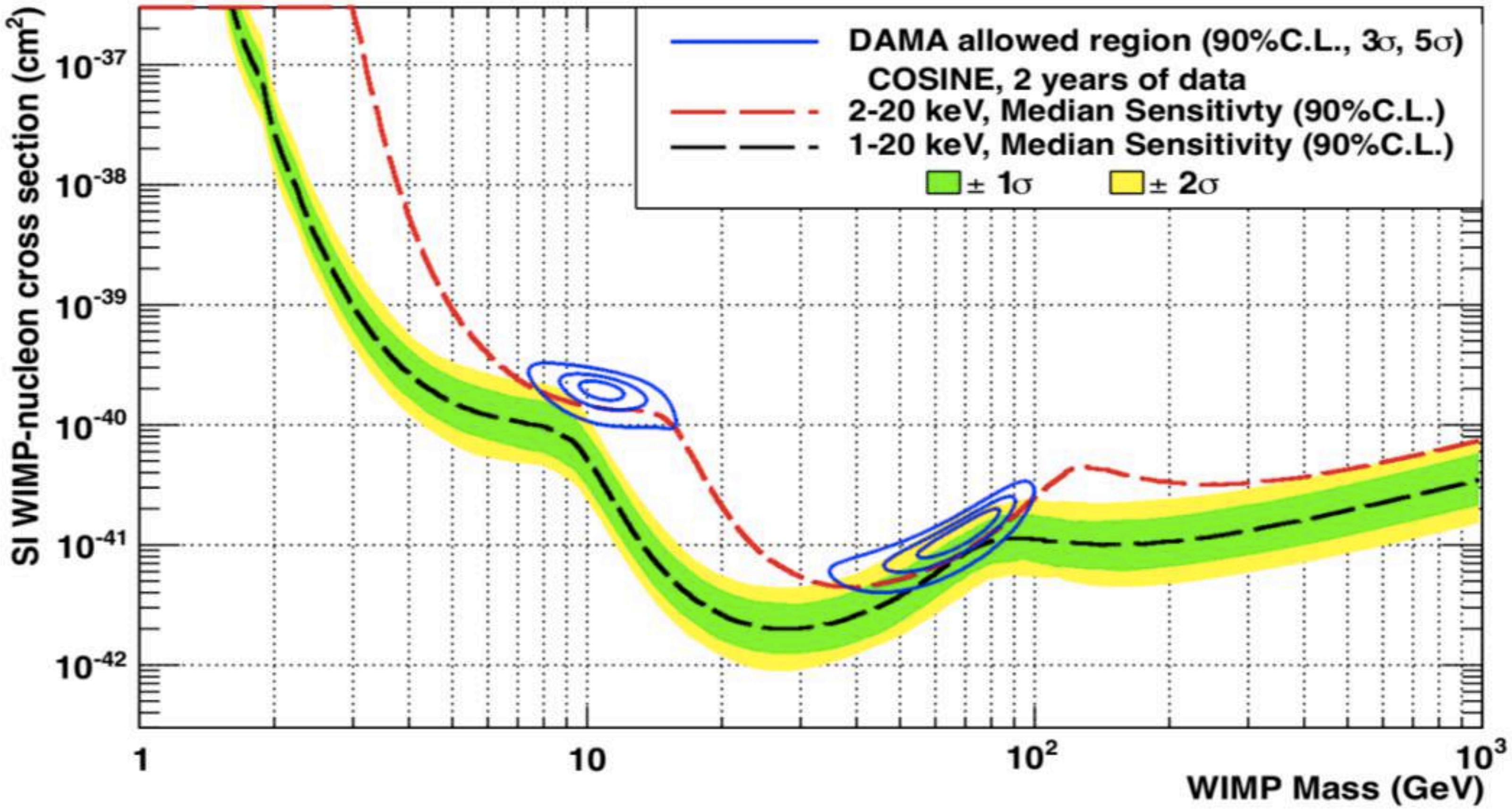


2 to 4 counts/ (keV kg day) in the ROI

^{210}Pb: internal and external is an issue

work on radiopurity of NaI to match DAMA/LIBRA level

PROJECTED SENSITIVITY

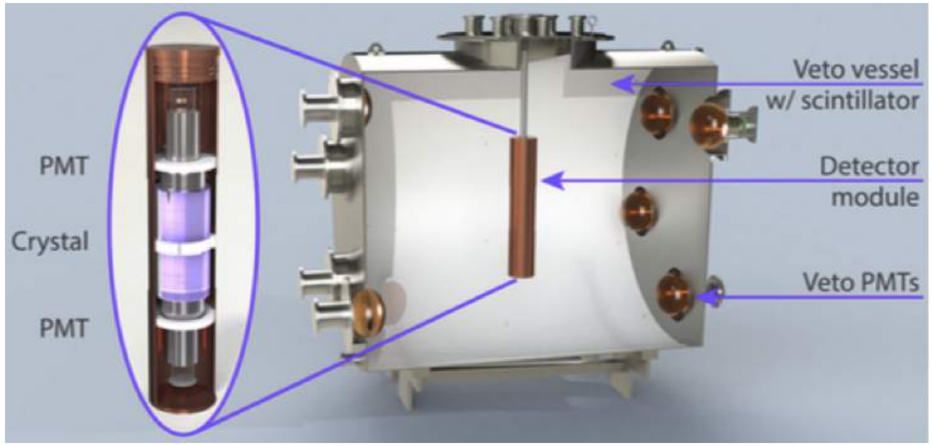


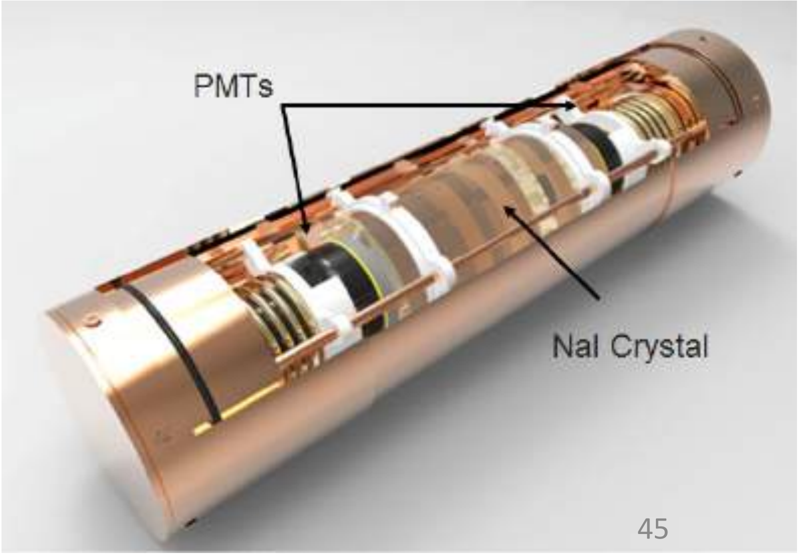
- 2 - 4 dru flat background is assumed
- 2 years of data with 1 keV analysis threshold provide sensitivity comparable to DAMA's 90% C.L allowed region

Reminder: Two years would be end of 2018

SABRE experiment

MATERIAL	> 50 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	LNGS Italy + SUPL Australia
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	<2 keVee
DATA TAKING	PoP in 2017
EVIDENCE	no





SABRE: **ULTRA-PURE NAI PRODUCTION**

^{nat}K contamination 9 ppb
(DAMA crystal 13 ppb)

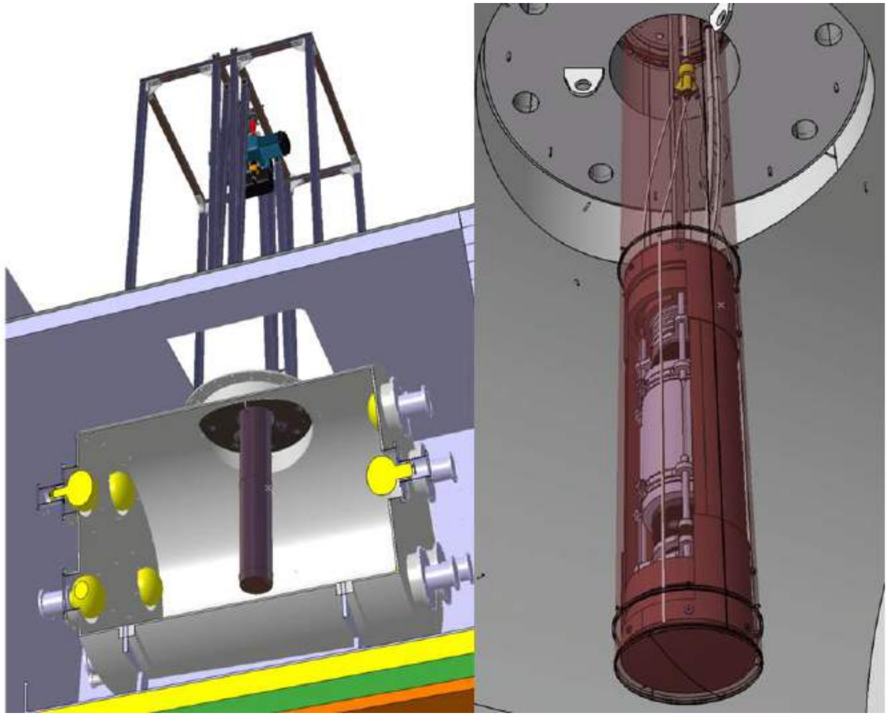
Ultra-pure NaI(Tl) crystals:

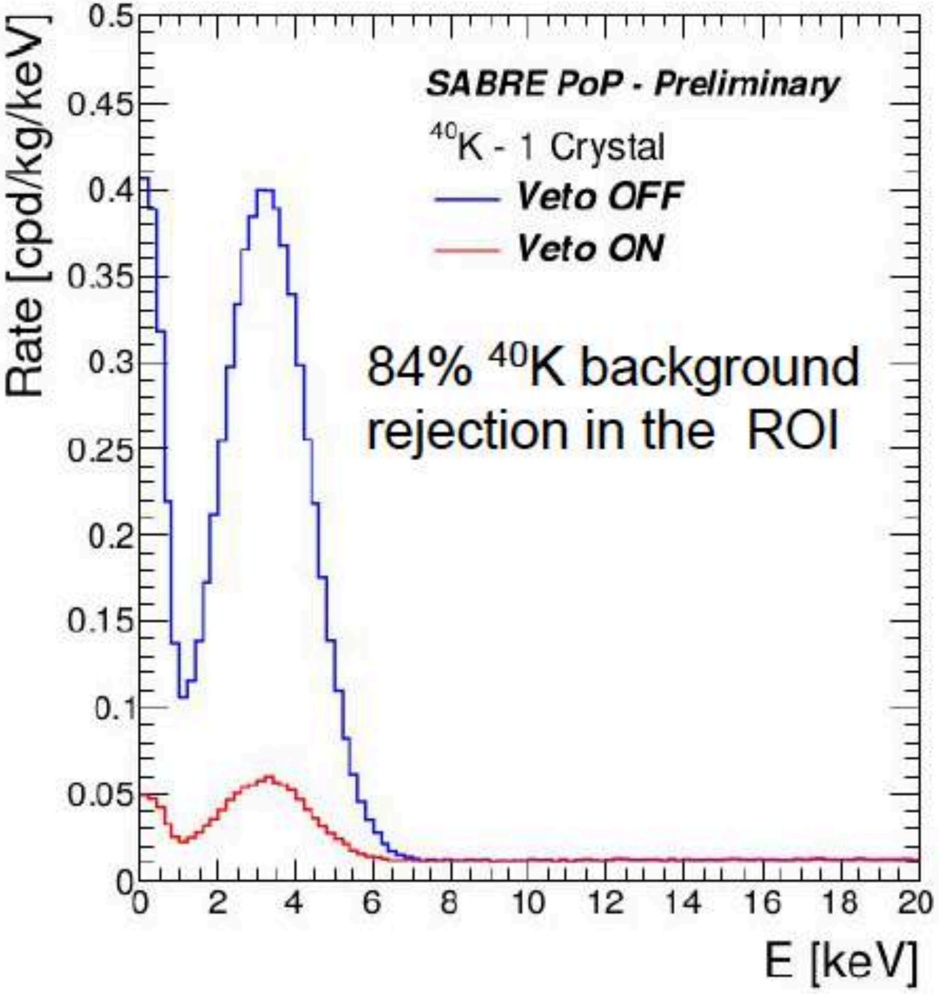
- collaboration between Princeton and Sigma-Aldrich
- low contamination Astrograde powder

→ **FIRST 2 kg CRYSTAL has ^{40}K below DAMA/LIBRA level**

SABRE: **Proof-of-Principle**

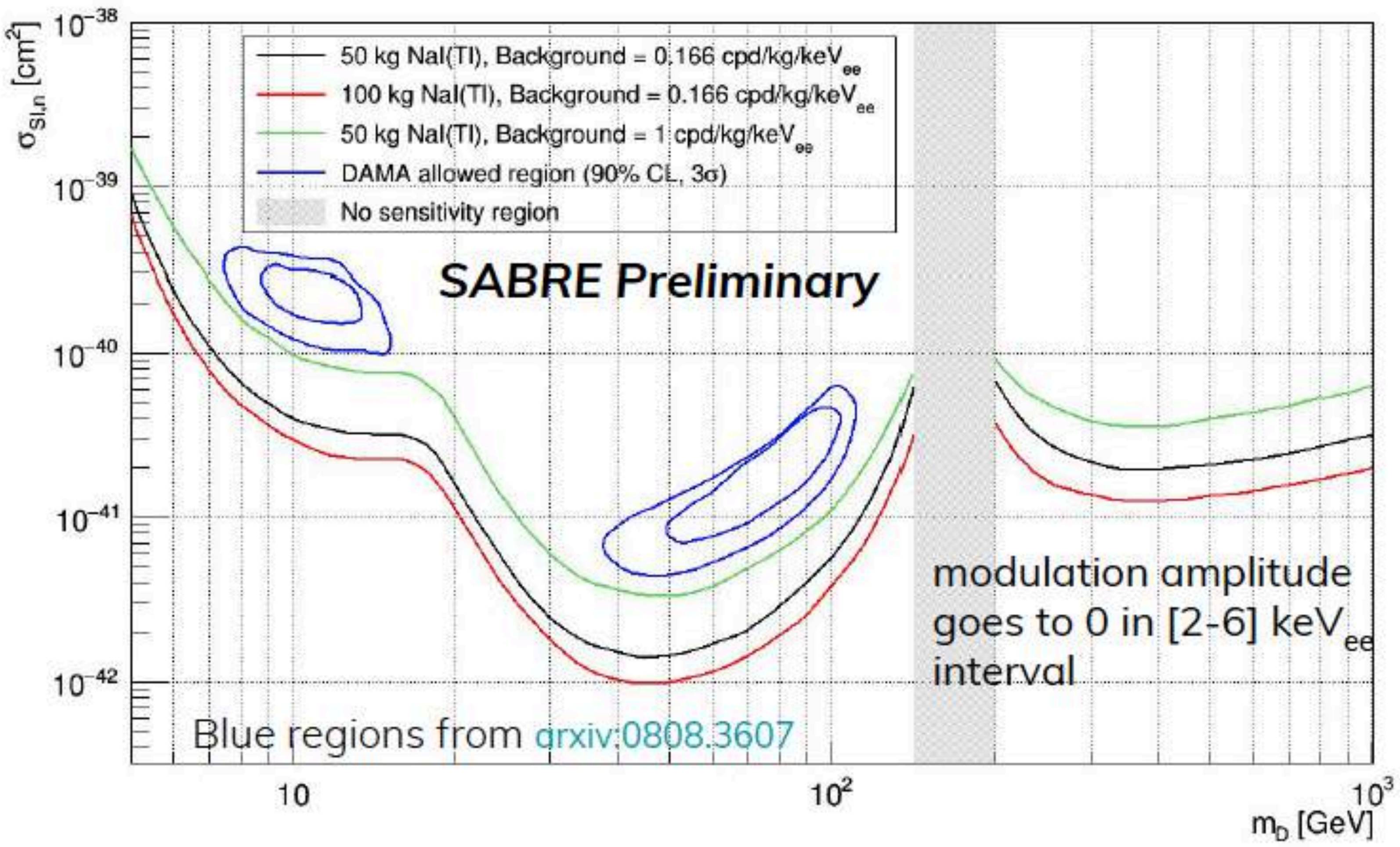
First Phase : PoP @ LNGS
5 kg crystal inside liquid scintillator
(~ 2 tons PC + PPO 3 g/l)





Giulia D'Imperio*, TAUP 17, Sudbury, Canada

SABRE: **PROJECTED SENSITIVITY**

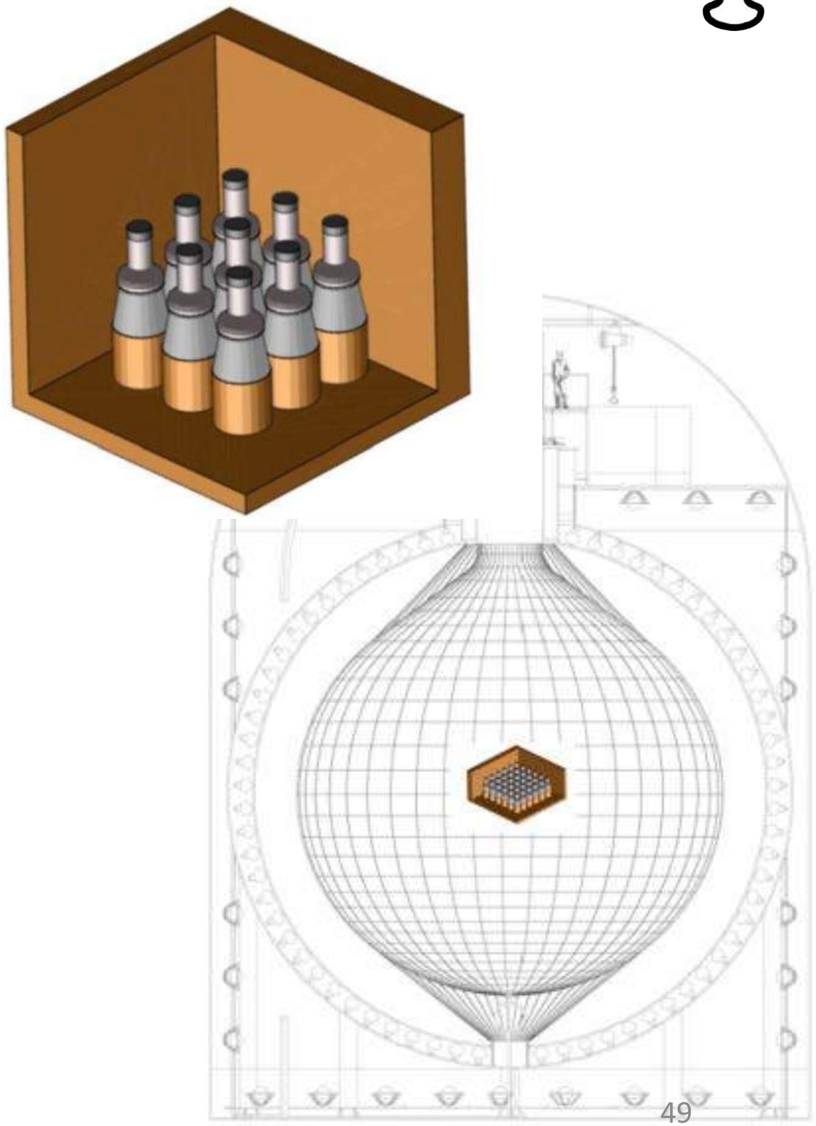


Giulia D'Imperio*, TAUP 17, Sudbury, Canada

- 2-6 keVee
- 50 kg of NaI(Tl)
- 3 years exposure
- bkg from simulation:
  ~0.2 c /(keV kg d)

PICO-LON project

MATERIAL	NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	Kamioka,Japan
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	2 keVee
CRYSTAL GROWTH	R&D phase
EVIDENCE	no

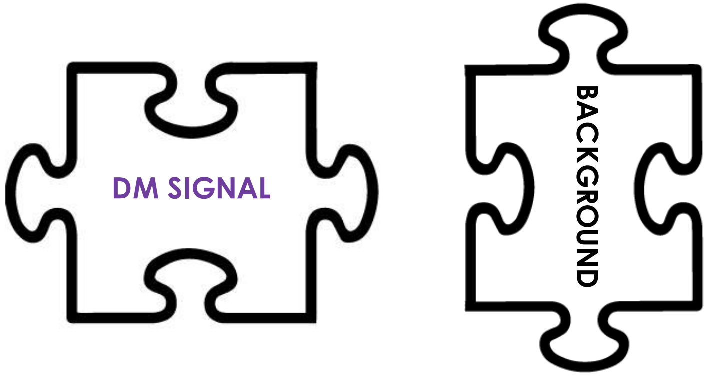


COSINUS project

MATERIAL	NaI (undoped)
SIGNAL(s)	Light and heat (TES)
LOCATION	LNGS Italy
β/γ-DISCRIMINATION	YES!
THRESHOLD GOAL	1 keV
FUNDING	R&D project

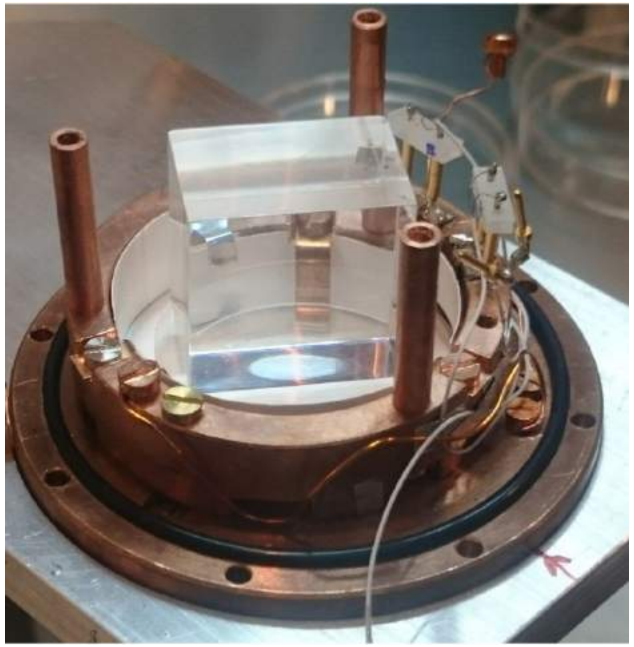
NEW

NEW



www.cosinus.it

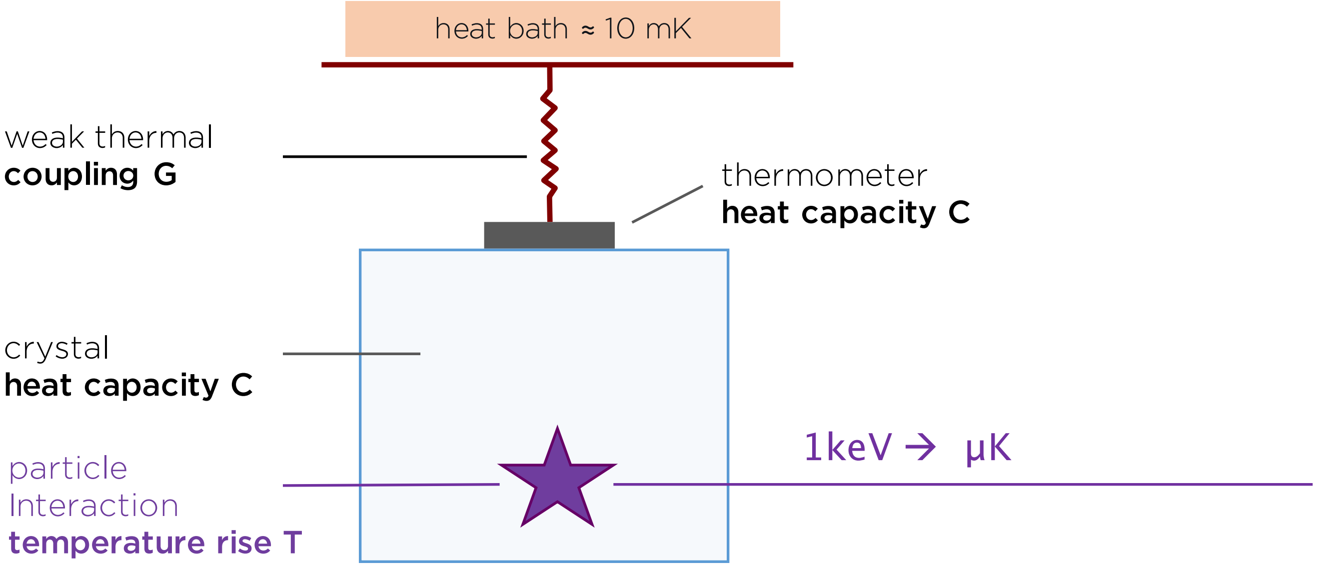
Eur. Phys. J. C (2016) 76:441



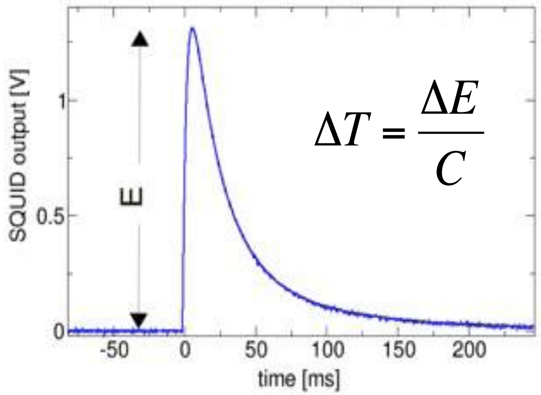
LOCATION

taken from MPI Munich

COSINUS: **CRYOGENIC CALORIMETER**



Temperature pulse



$$\Delta T = \frac{\Delta E}{C}$$

Irreducible thermal fluctuations

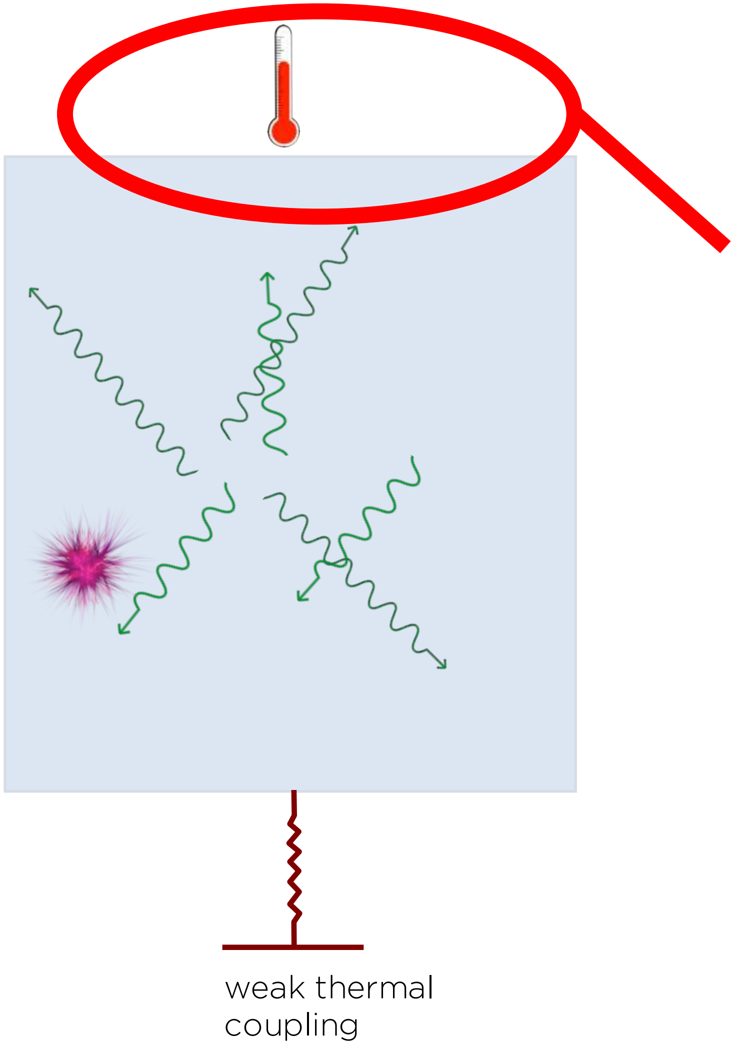
$$\langle \Delta E^2 \rangle = k_b T^2 C$$

Ultimate energy resolution is determined by how well you can measure **T** against thermodynamic fluctuations

low temperatures → better energy sensitivity

low heat capacity → careful selection of materials

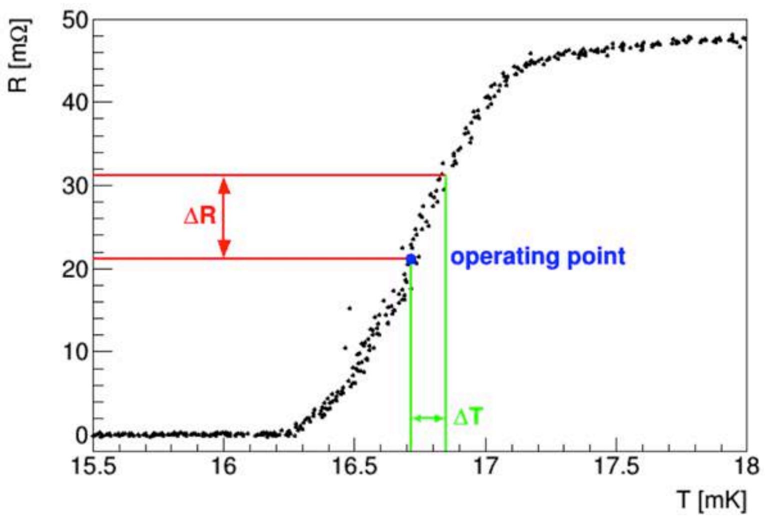
HOW TO MEASURE TEMPERATURE ?



What to use as thermometer?

TRANSITION EDGE SENSOR (TES)

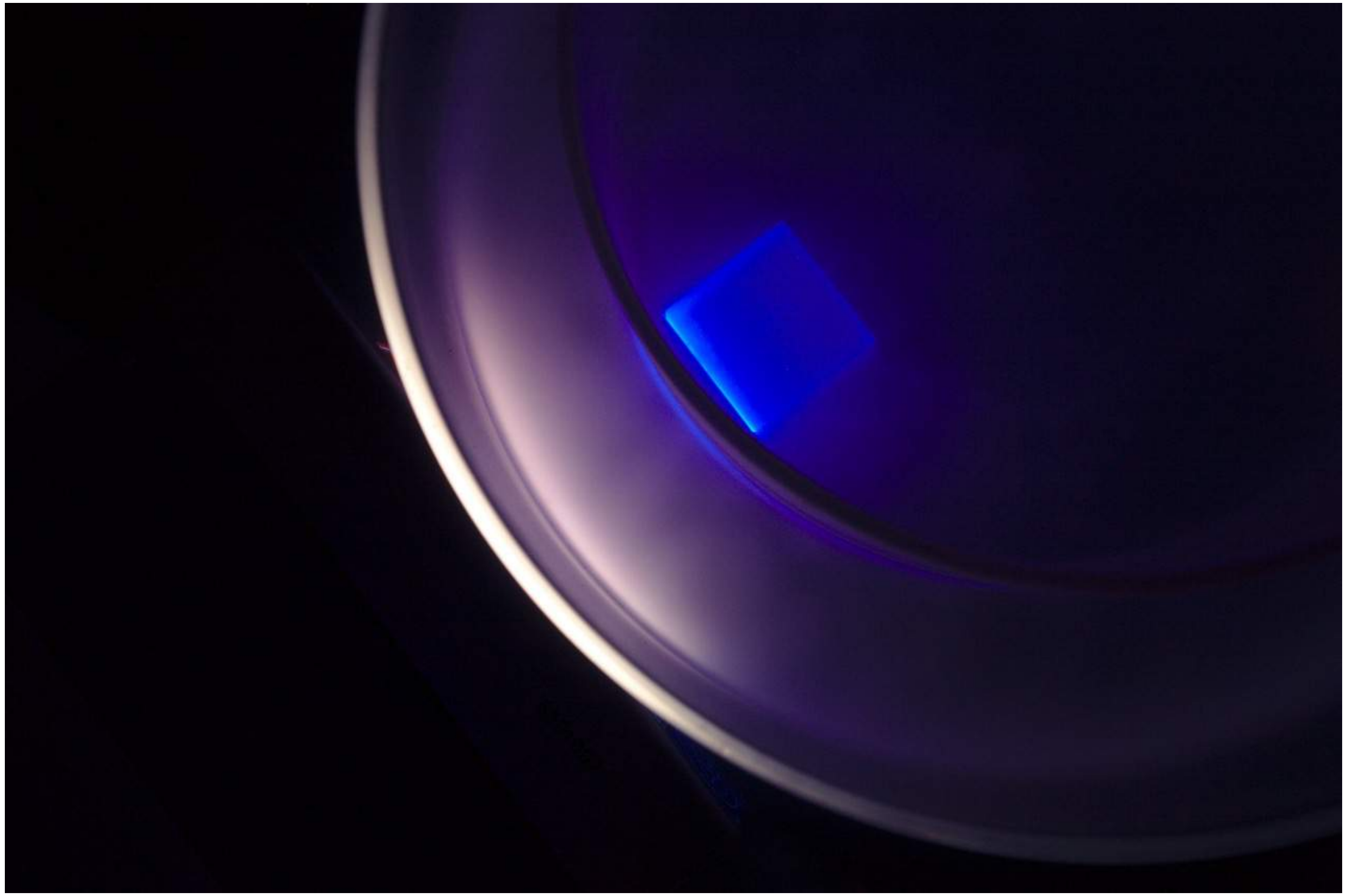
TRANSITION EDGE SENSOR (TES)



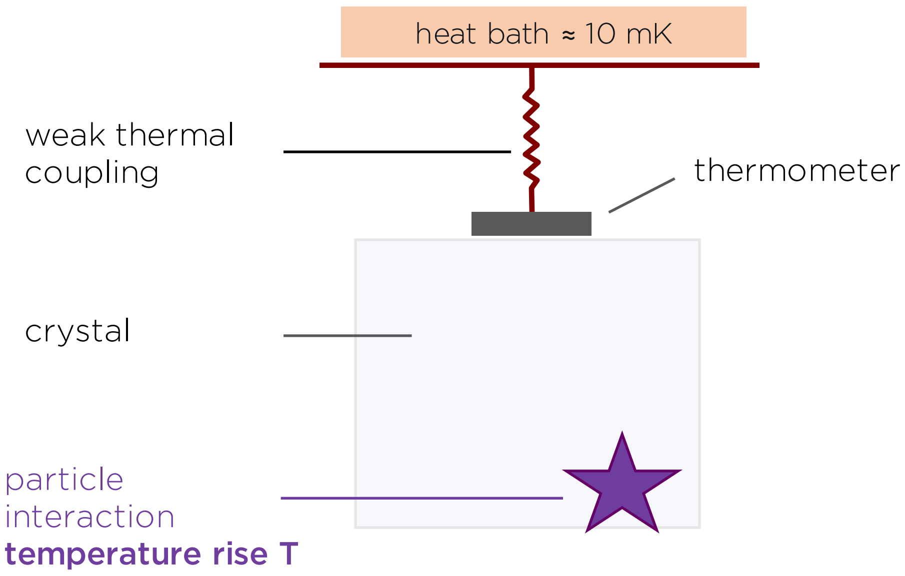
W-film evaporated onto the carrier crystal

- temperature stabilized between normal and superconducting phase
- particle interaction creates phonons
  → rise of film temperature
- resistance change of the film measured with SQUID-based readout

NaI at low-temperatures



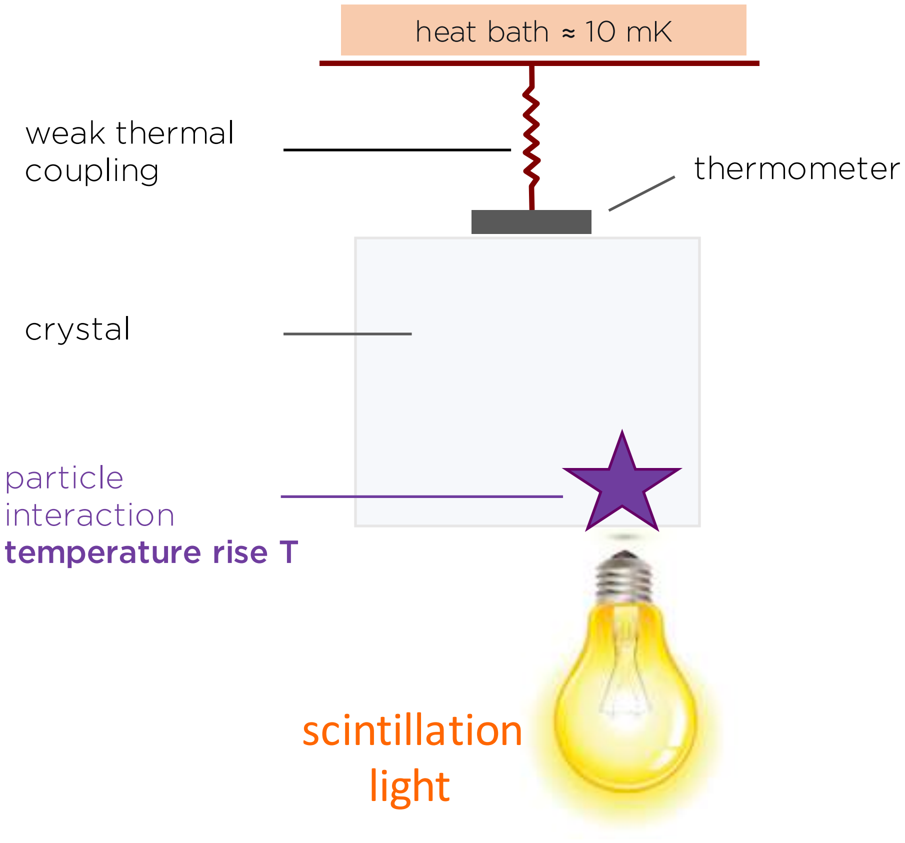
NaI-based **SCINTILLATING CALORIMETER**



Phonon signal (~ 90 %)

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

NaI-based **SCINTILLATING CALORIMETER**



Phonon signal (~ 90 %)

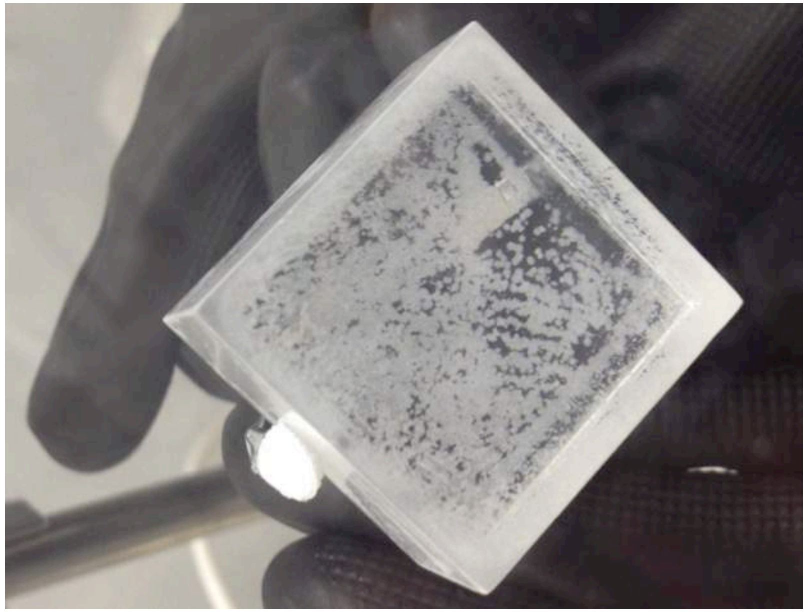
- (almost) independent of particle type
- precise measurement of the deposited energy

Scintillation light (few %)

- amount of emitted light depends on particle type
  → LIGHT QUENCHING
- discrimination of interacting particle via the **ratio light to phonon signal**
  → LIGHT YIELD

… but NaI is not that NaIce!

- hygroscopic nature



handle in controlled atmosphere:

- glove box
- special container for cooldown in dilution refrigerator

… but NaI is not that NaIce!

- low Debye temperature

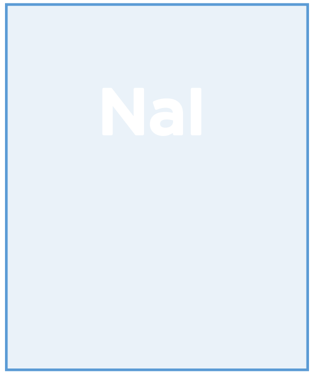
Properties	NaI(pure)	CsI(pure)	$CdWO_4$	$CaWO_4$
Density [g/cm^3]	3.67	4.51	7.9	6.12
Melting point [°C]	661	894	1598	1650
Structure	CsCl	CsCl	Wolframite	Scheelite
λ_{max} at 300 K [nm]	~300	~315	~475	420-425
Hygroscopic	yes	slightly	no	no
Θ_D [K]	169	125	-	335
Photons per keV at 3.4 K	19.5 $\pm$1.0	58.9$\pm$5.6	-	-
Mean energy of emitted photon [eV]	3.3	3.9	-	3.14

PREPARE FOR:

small signal amplitudes

- develop highly sensitive W-TES
- surface of NaI optically polished

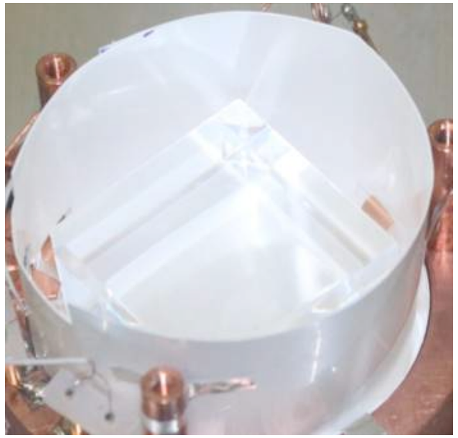
COSINUS **DETECTOR CONSTRUCTION**



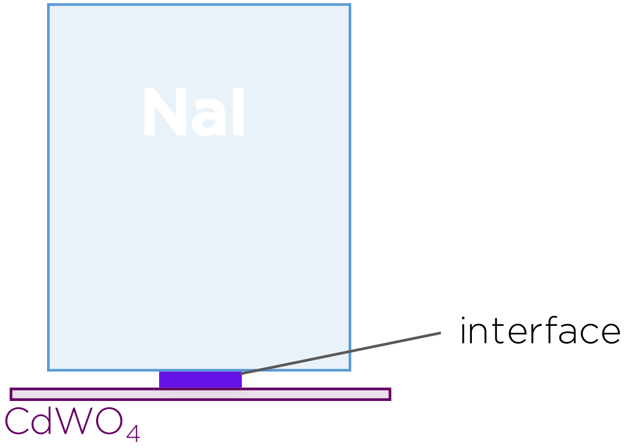
NaI Target Crystal

- scintillator
- multi-element target
- mass: ~ 50 – 300 g

$_{11}Na\ _{53}I$

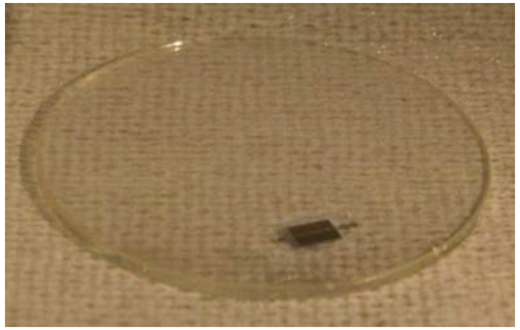


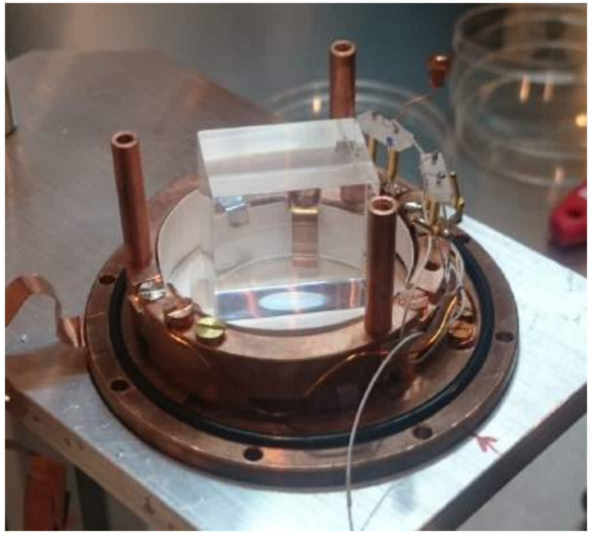
COSINUS DETECTOR DESIGN



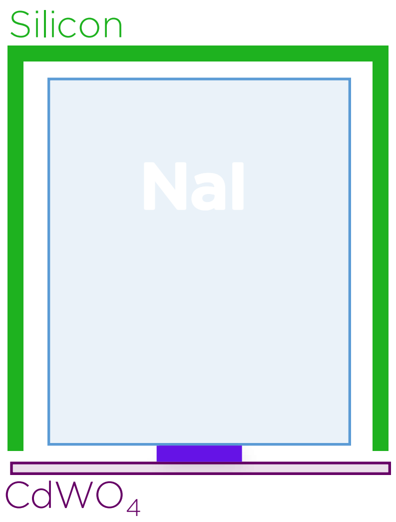
$CdWO_4$ carrier crystal

- carries the W-TES
- glue/oil as interface
- mass: ~ 5-15 g



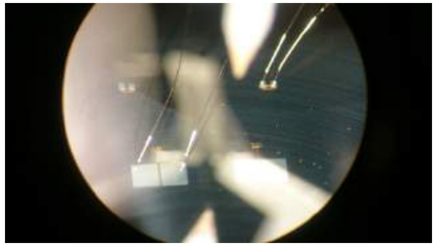


COSINUS DETECTOR DESIGN

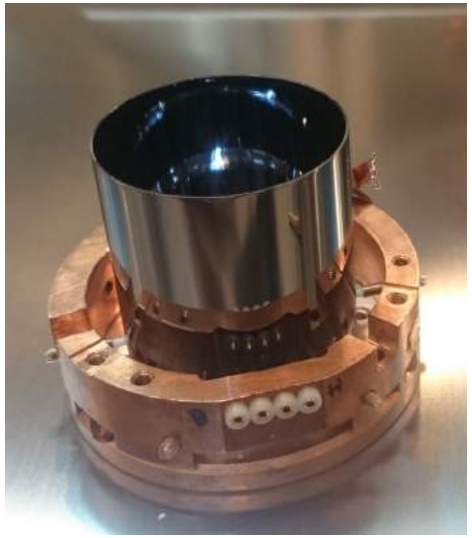


Light absorber

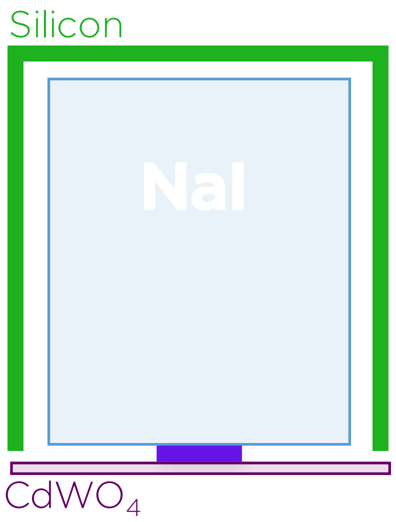
- beaker shape
- 40 mm diameter & height



High Purity silicon



COSINUS DETECTOR DESIGN

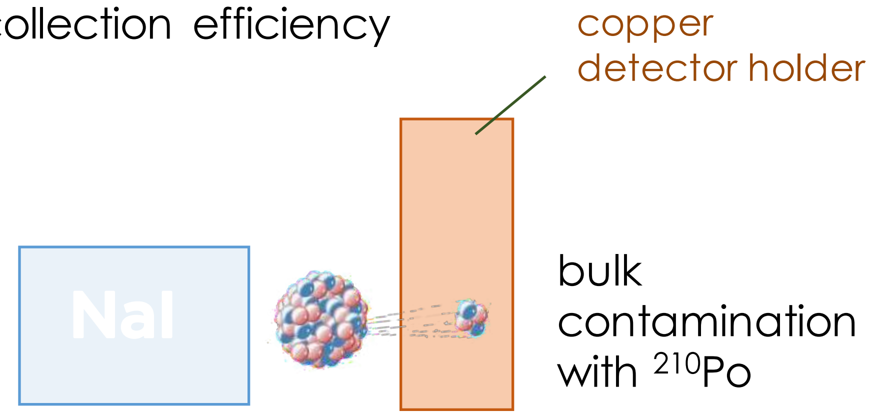


Light absorber

- ~ 40 mm diameter & height
- fully active veto

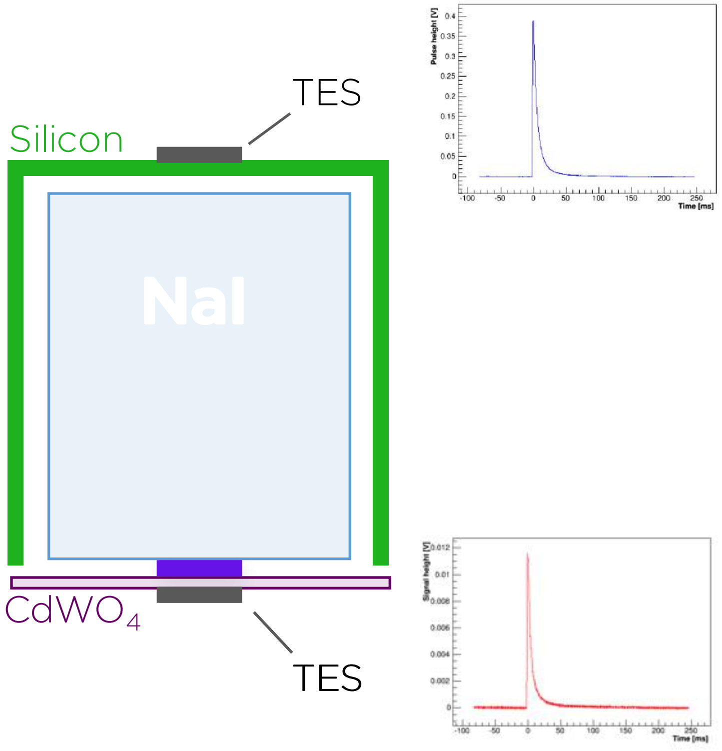
  → reject surface backgrounds

  → high light collection efficiency



$^{210}\text{Po} \rightarrow {}^{206}\text{Pb}$ (103 keV) + a (5.3 MeV)

COSINUS DETECTOR DESIGN



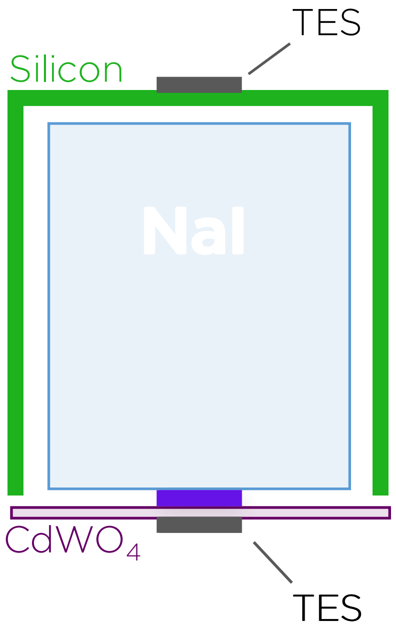
2 independent channels

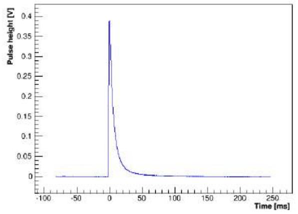
- W-TESs as thermometers
- simultaneous readout of

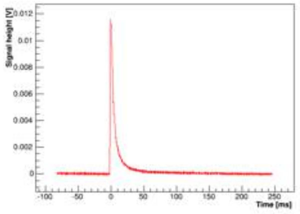
→ phonon signal in NaI

→ scintillation light

COSINUS DETECTOR DESIGN

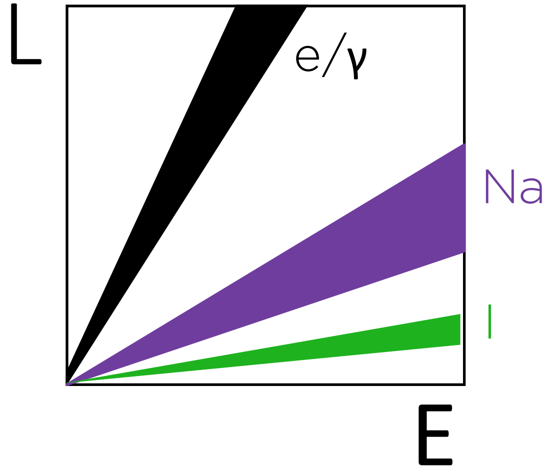




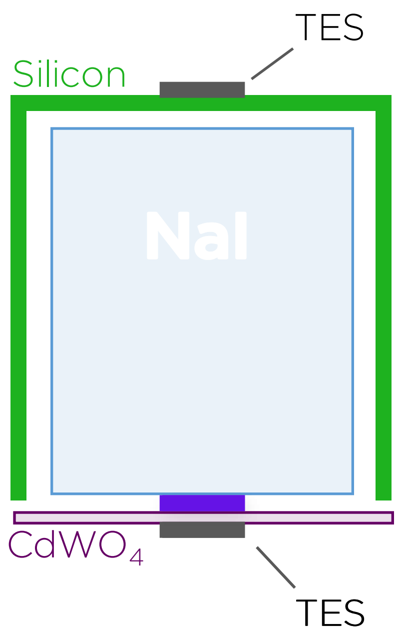


Particle discrimination

- simultaneous detection of:
  - energy in the crystal E
  - scintillation light L
- discrimination of interacting particle via the ratio L/E



COSINUS DETECTOR DESIGN



Performance goal

- NaI detector:

  nuclear recoil energy threshold ~ 1 keV

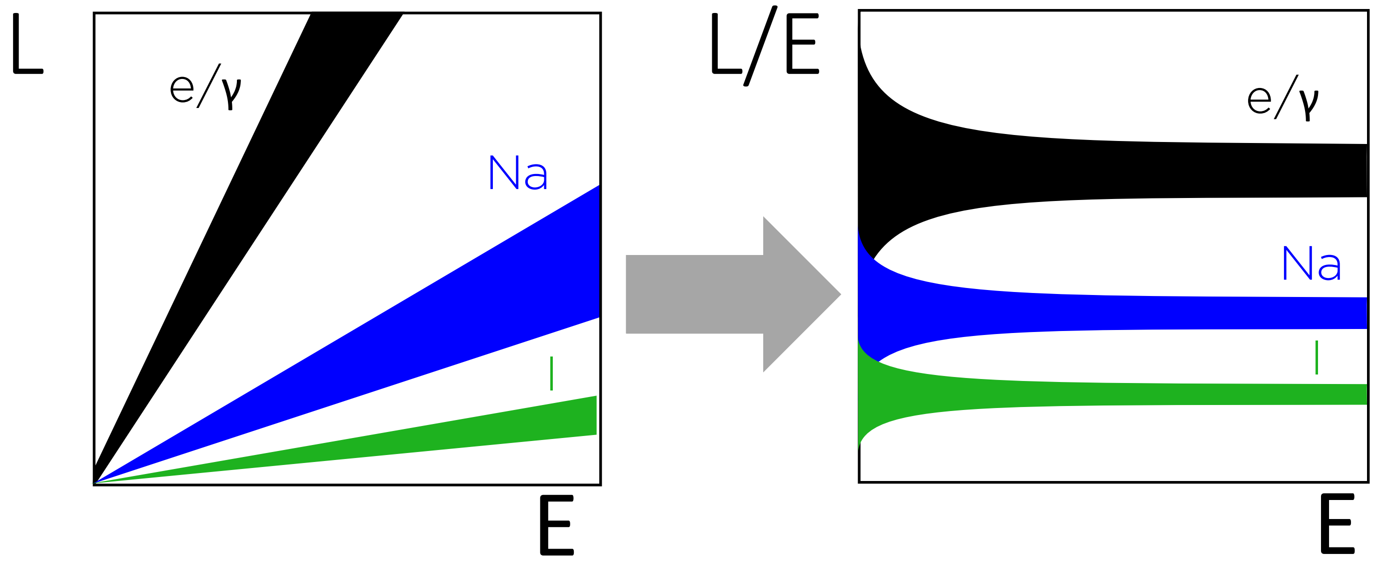
- light detector:

  4% of deposited energy detected in light

bring performance in-line with existing bolometers e.g. produced within **CRESST-II**

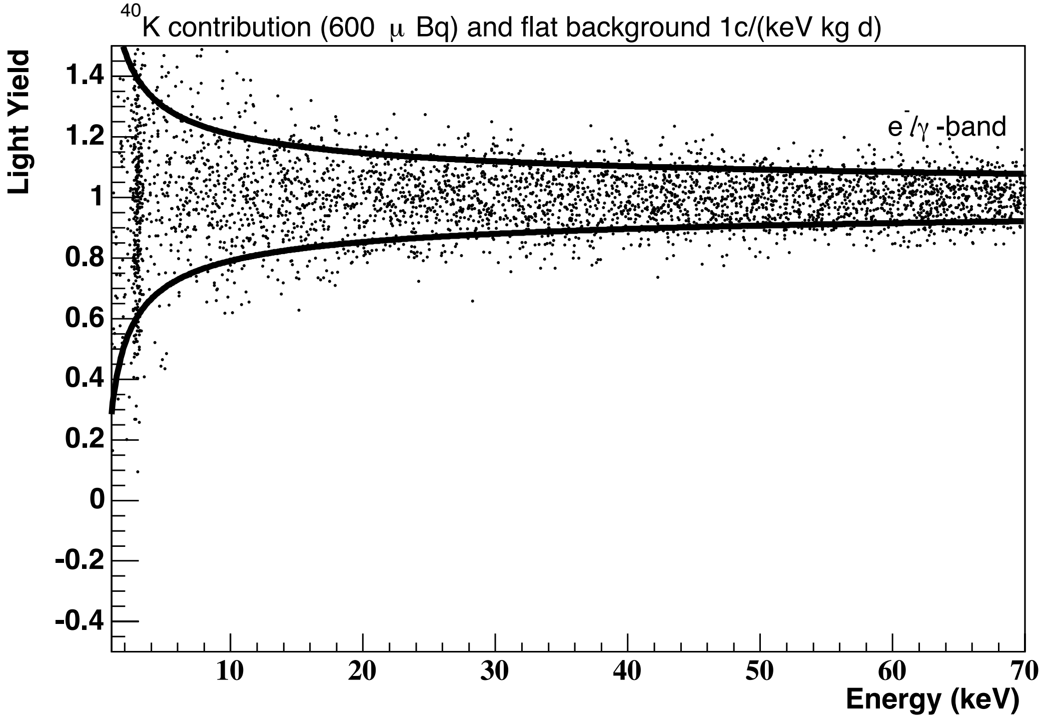
LIGHT YIELD

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



SIMULATED DATA FOR 100 kg days

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

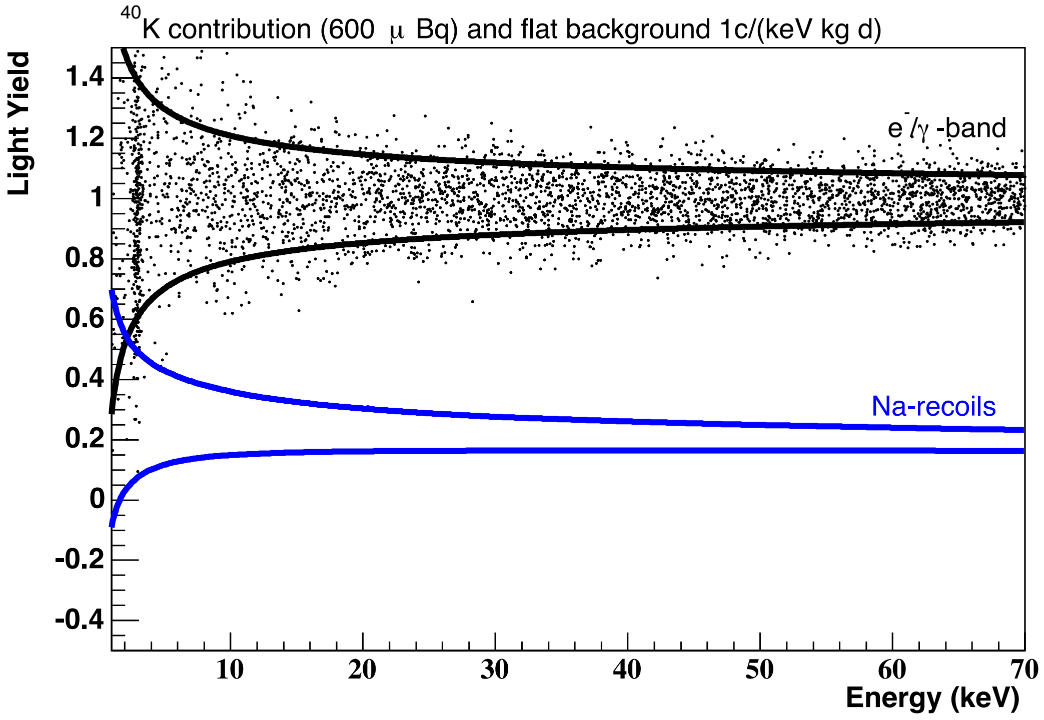


Eur. Phys. J. C (2016) 76:441
DOI 10.1140/epjc/s10052-016-4278-3

- NaI energy resolution σ=200 eV
- NaI energy threshold 1 keV
- 4% of deposited energy detected in form of light
- light detector baseline noise σ=10 eV
- **black events**:
  flat background: 1 /(keV kg day)
  + ^{40}K background: 600uBq/kg = DAMA
- **exposure before cuts: 100 kg-days**
- **solid lines: 80% bands**

SIMULATED DATA FOR 100 kg days

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



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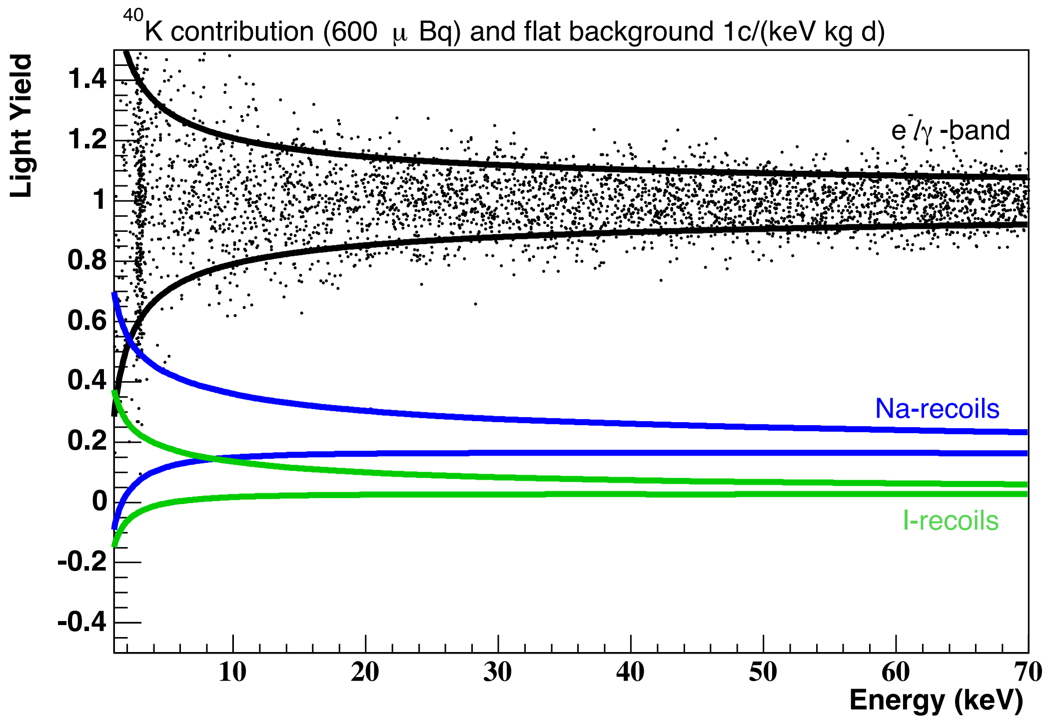
- black events:
  flat background: 1 /(keV kg d)
  + ^{40}K background: 600uBq/kg
- exposure before cuts: 100 kg-days
- **recoils off Na**
  QF from Tretyak, Astropart. Phys. 33, 40 (2010)

SIMULATED DATA FOR 100 kg days

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



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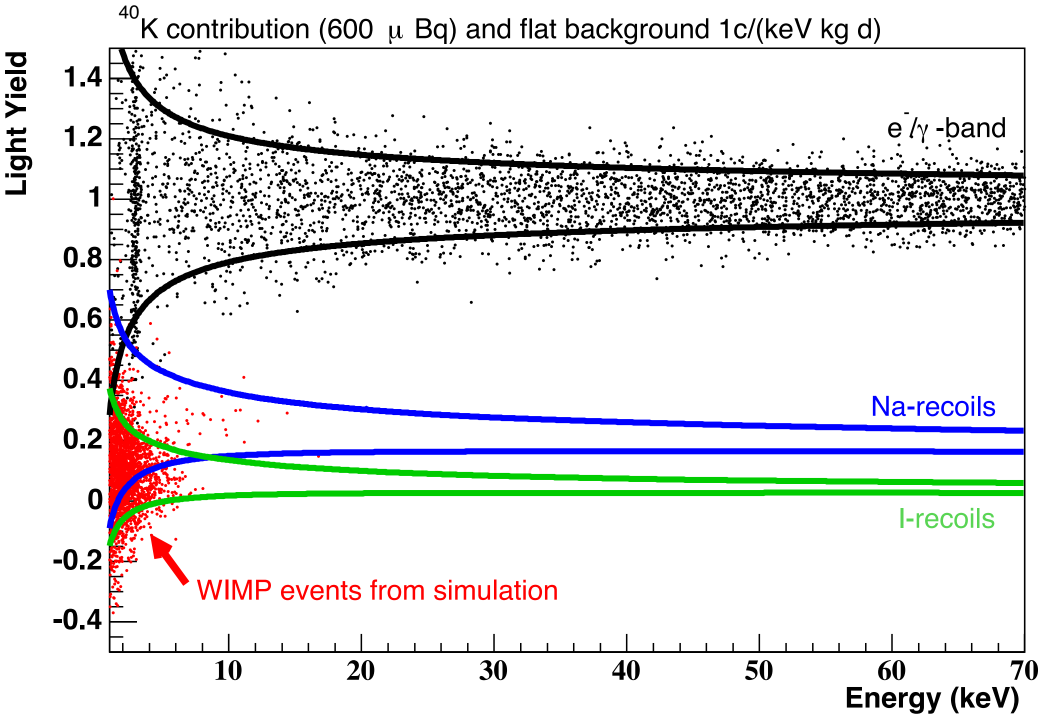
SIMULATED DATA FOR 100 kg days

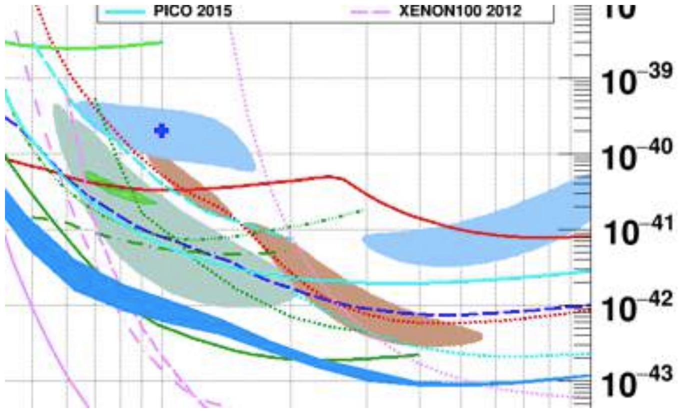
$$\text{LIGHT YIELD} = \frac{\text{LIGHT SIGNAL}}{\text{HEAT SIGNAL}}$$



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

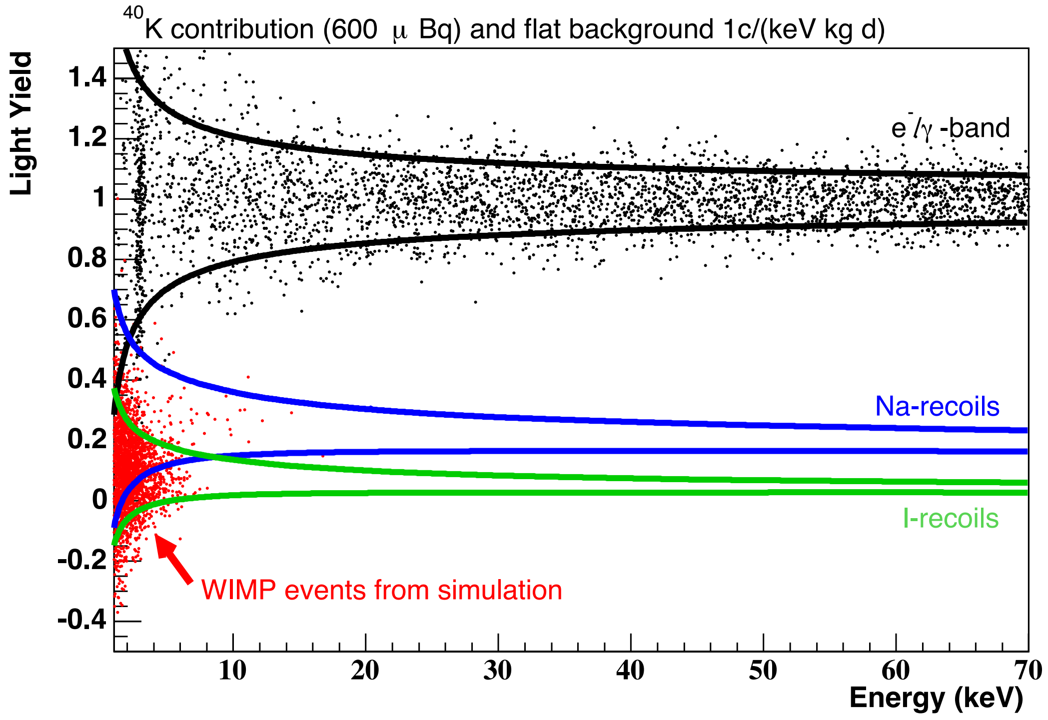
- black events:
  flat background: 1 /(keV kg d)
  \+ ^{40}K background: 600uBq/kg

- **red events:**
  10 GeV/c² WIMP with 2E-04 pb as from Savage et al.



SIMULATED DATA FOR 100 kg days

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



Eur. Phys. J. C (2016) 76:441
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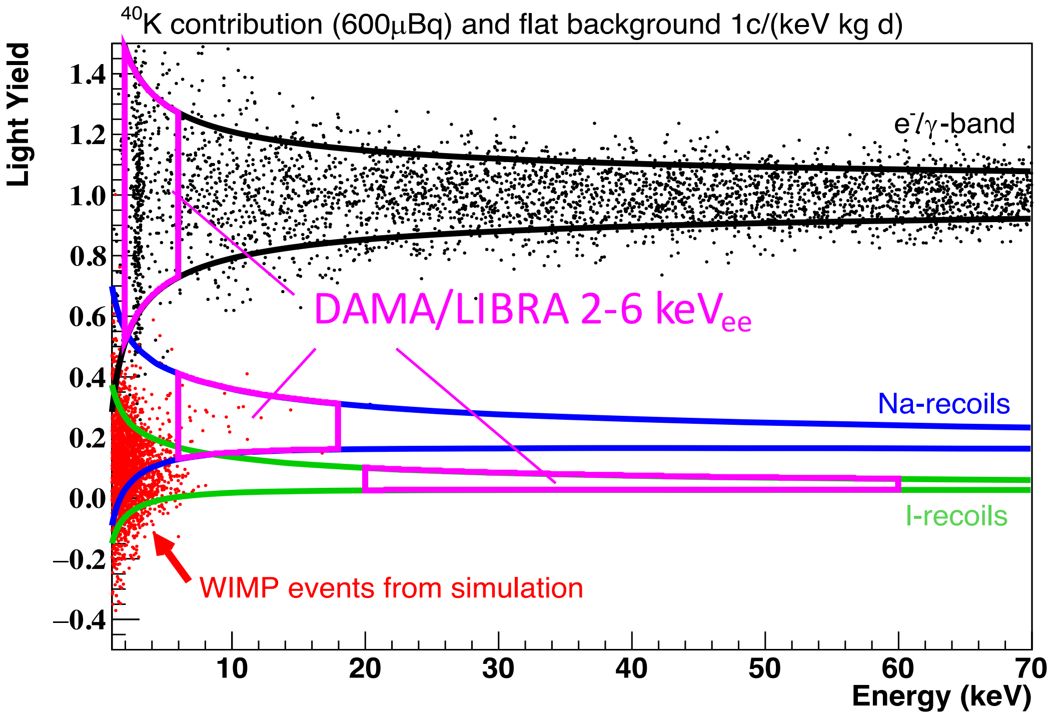
- **red events:**
  10 GeV/c² WIMP with 2E-04 pb
  Savage et al.

Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

SIMULATED DATA FOR 100 kg days

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



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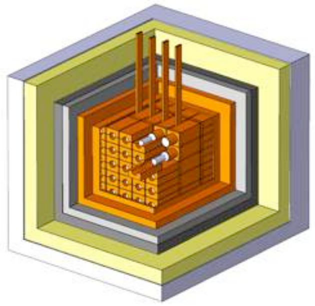
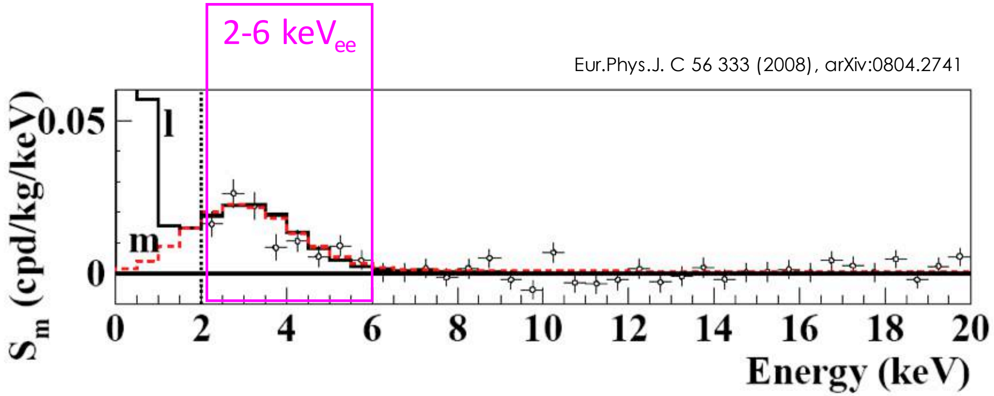
- **pink colored boxes** correspond to DAMA/LIBRA signal regions in the standard elastic scattering scenario

Energy	# Events	Fraction
1-2 keV	1078	45 %
2-6 keV	1262	53 %
> 6 keV	46	2 %
TOTAL	**2386**	**100 %**

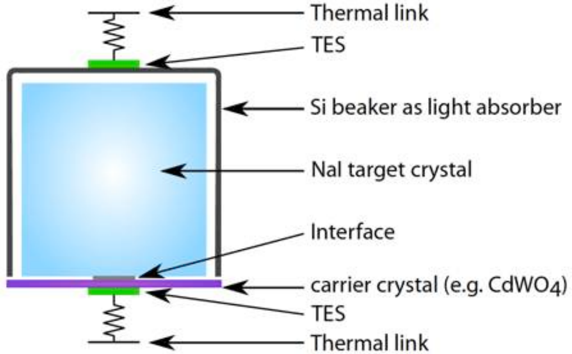
COMPARISON

DAMA/LIBRA

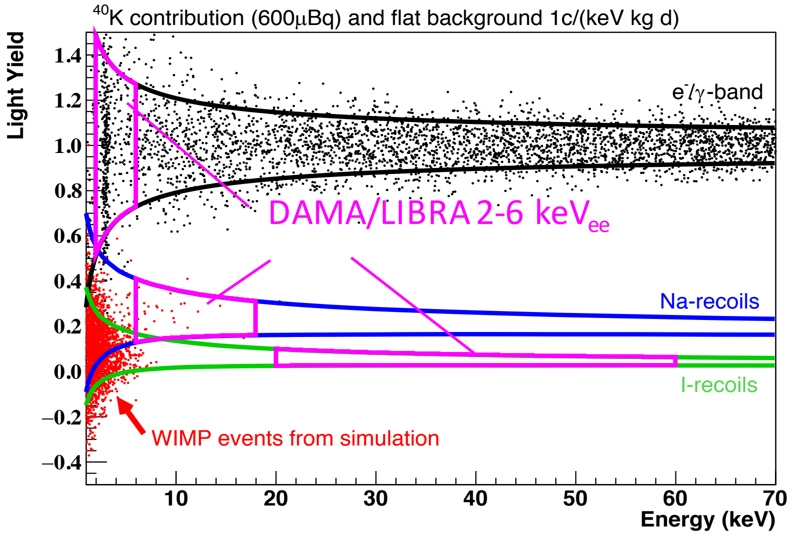




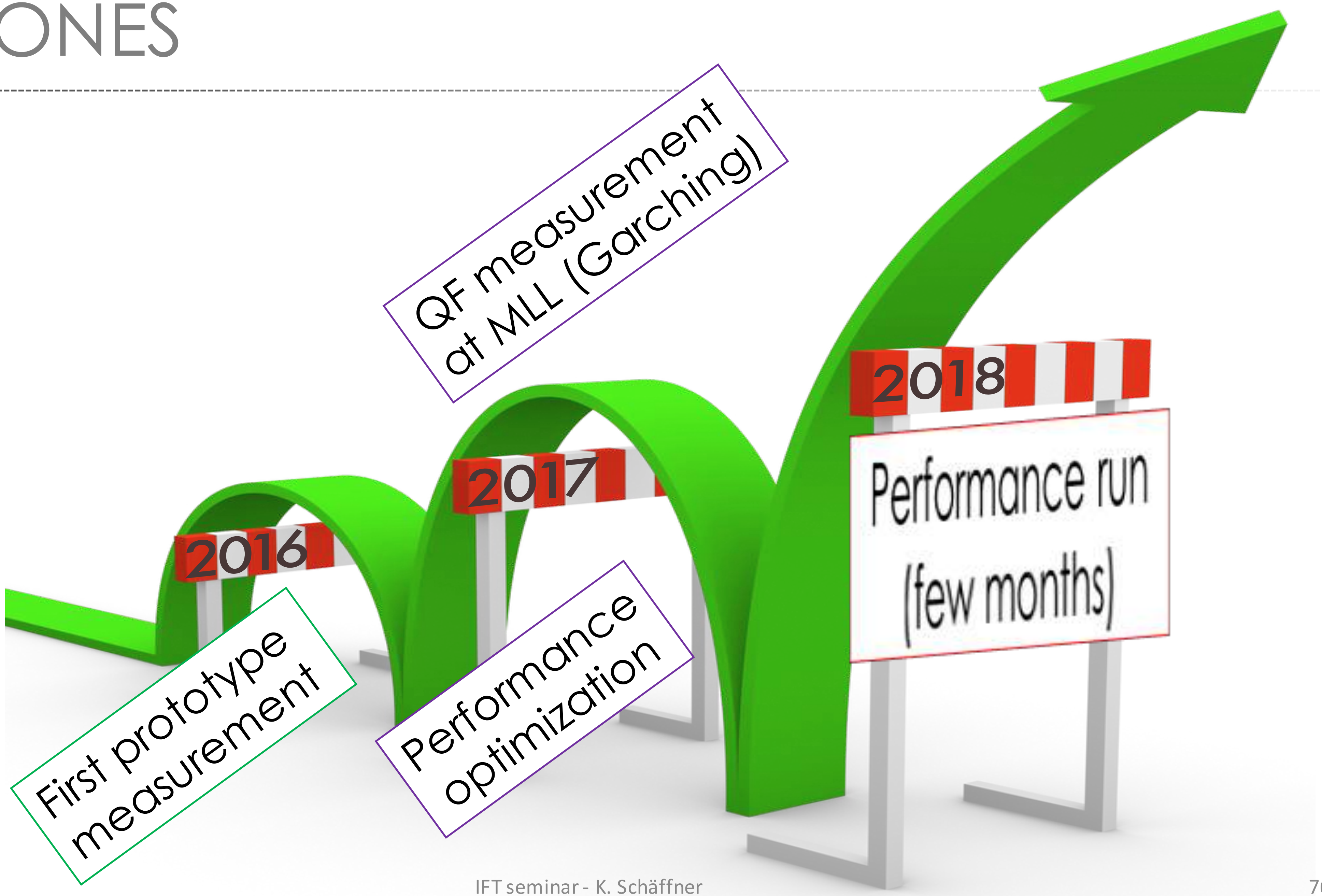
COSINUS



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



MILESTONES

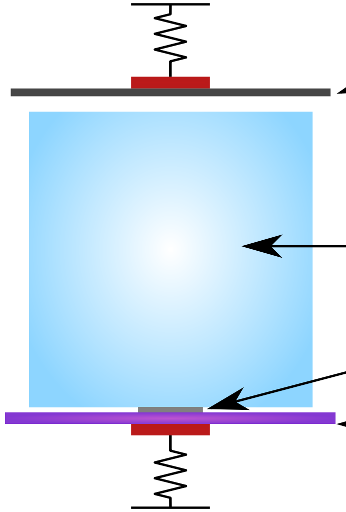

QF measurement
at MLL (Garching)
2016
2017
2018
Performance run
(few months)
First prototype
measurement
Performance
optimization

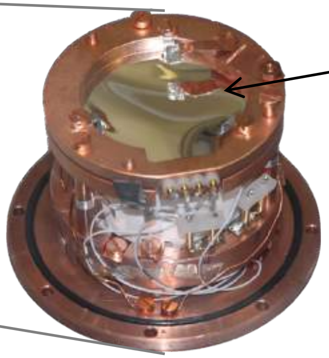
1st PROTOTYPE

5 cm of Pb to shield radioactivity from the dilution unit of the cryostat

decoupling system
to reduce microphonic noise

copper housing



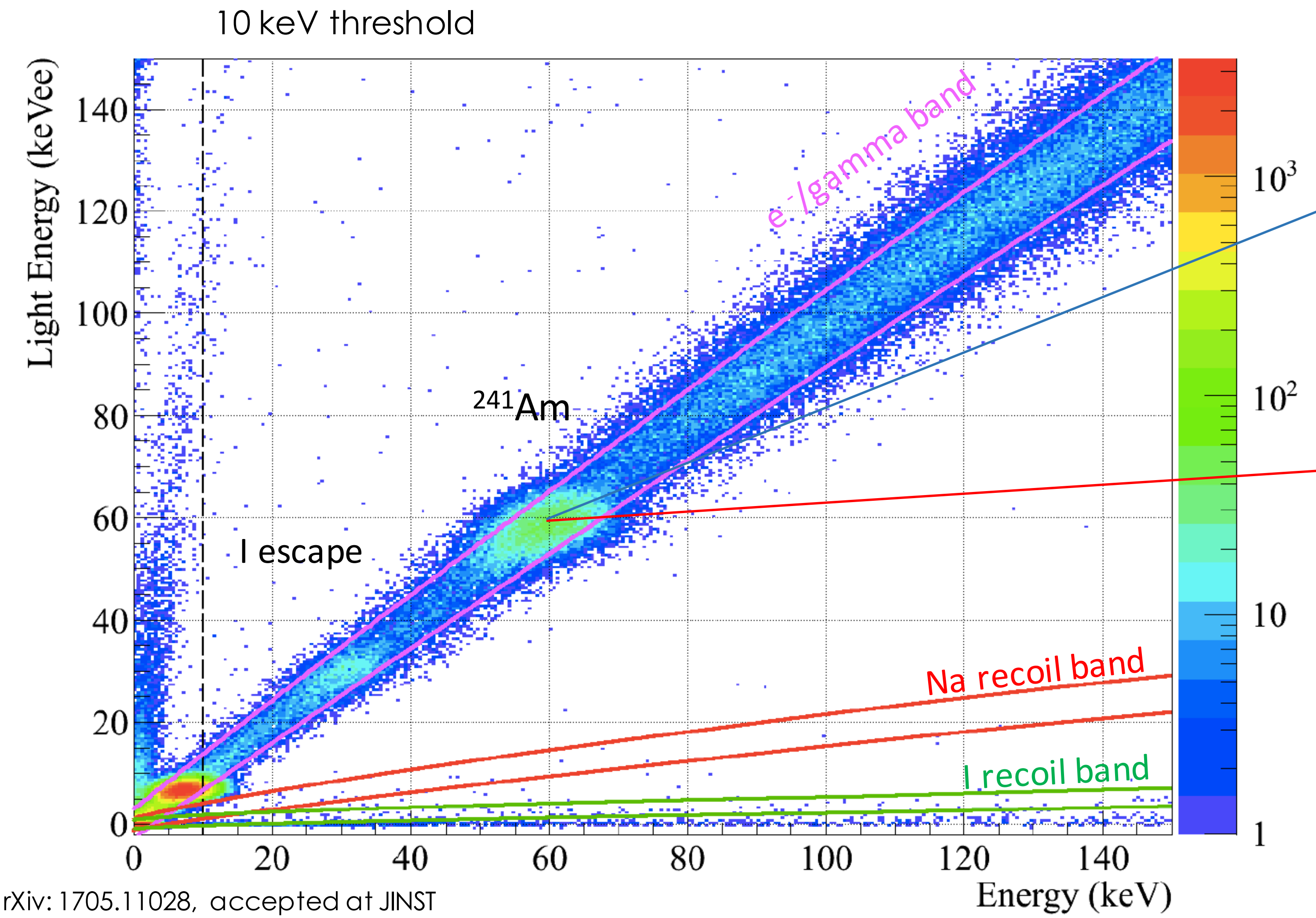


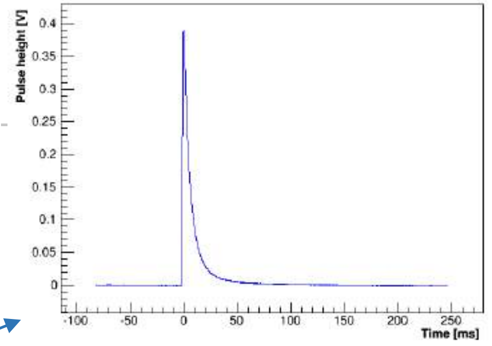
light detector

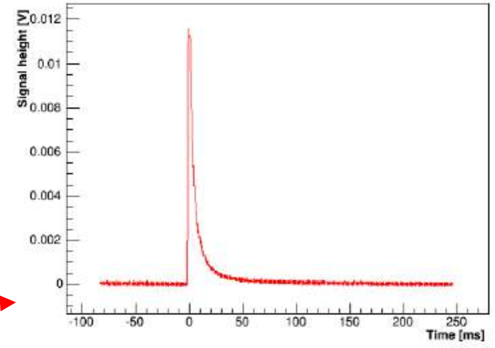
NaI detector

arXiv: 1705.11028
accepted at JINST

1st PROTOTYPE RESULTS



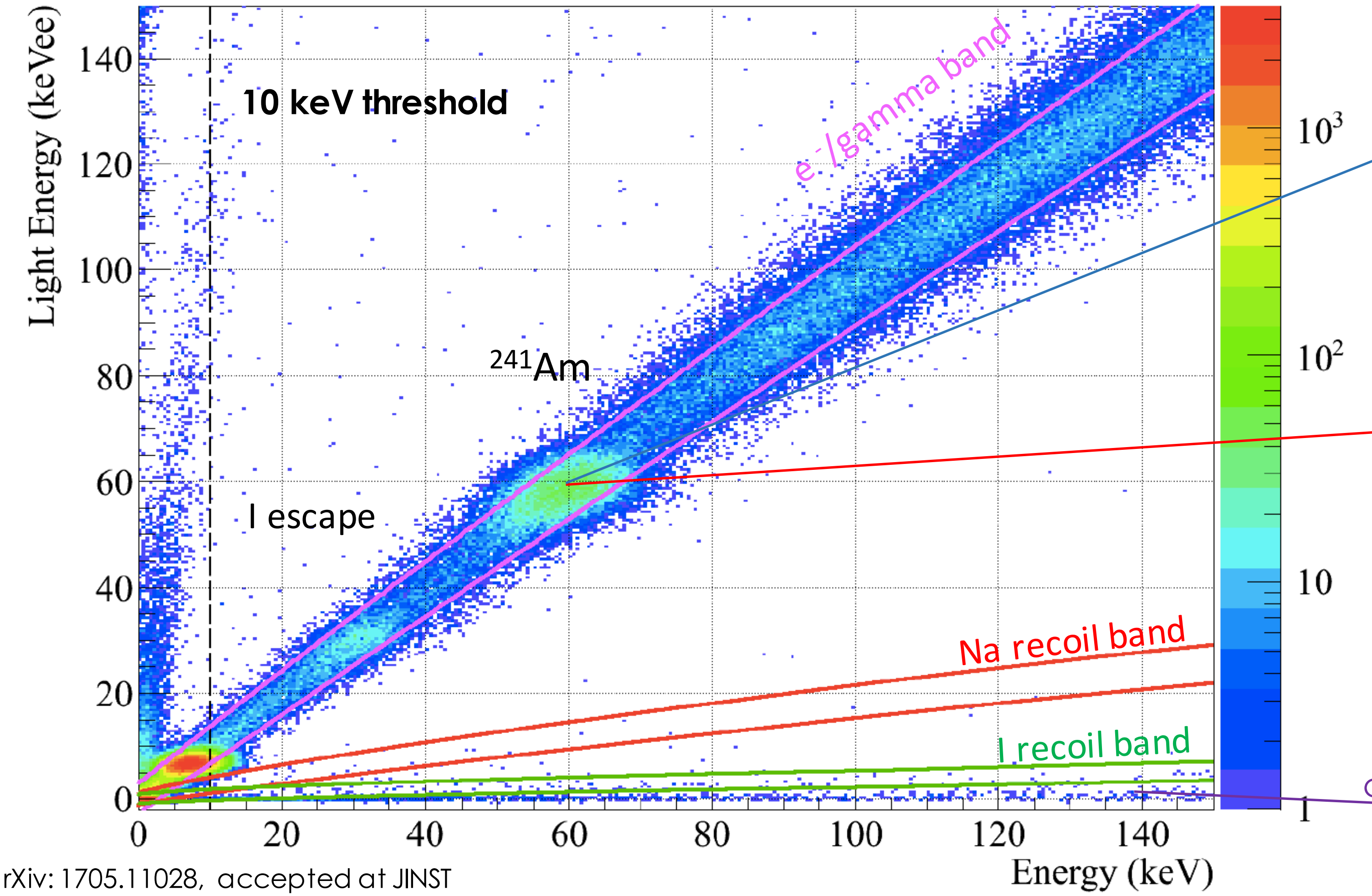


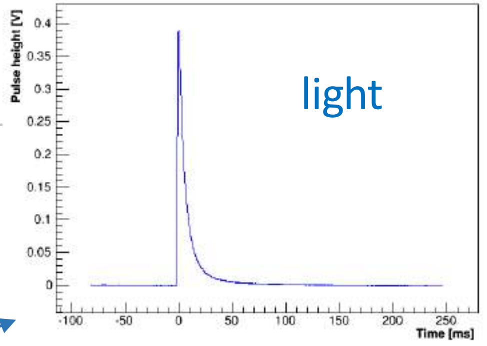


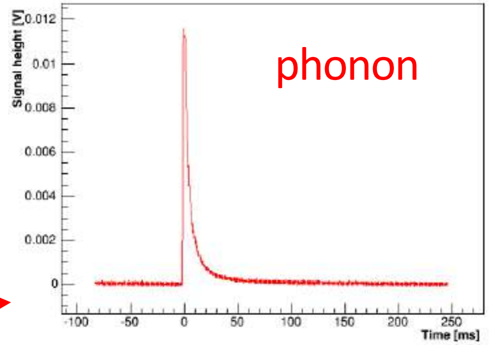
plot: arXiv: 1705.11028, accepted at JINST
QF from Tretyak, Astropart. Phys. 33, 40 (2010)

1st PROTOTYPE RESULTS

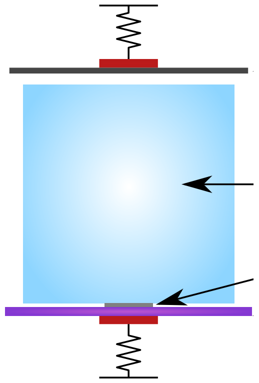
Linear relation between light output and deposited energy!





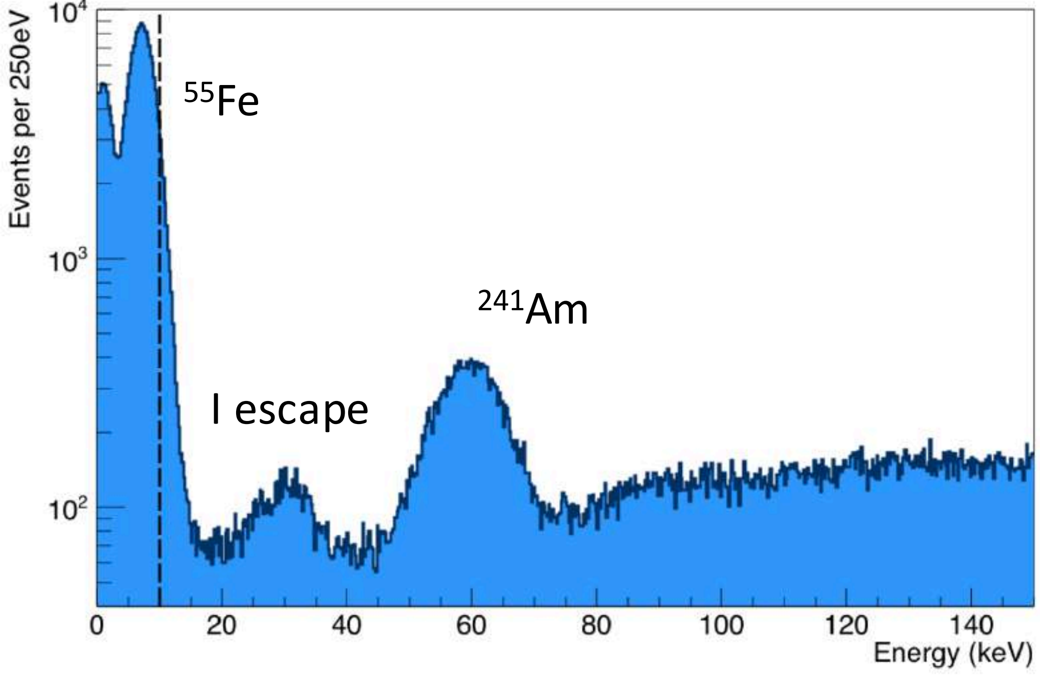


carrier events



plot: arXiv: 1705.11028, accepted at JINST
QF from Tretyak, Astropart. Phys. 33, 40 (2010)

1st PROTOTYPE RESULTS



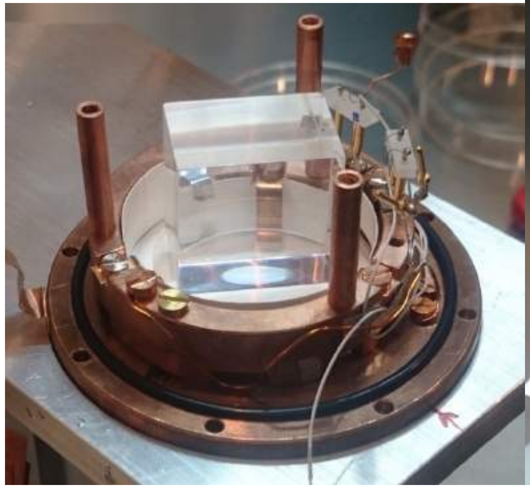
plot: arXiv: 1705.11028

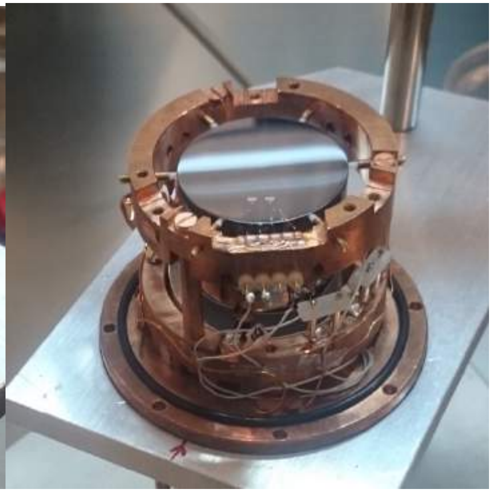
- **energy threshold**: 10 keV
- **for β/γ-events:**
  3.7% of the energy deposited in the NaI crystal is measured by the light detector (design goal 4%)
  =
  11.2 detected photons per keV of energy deposition

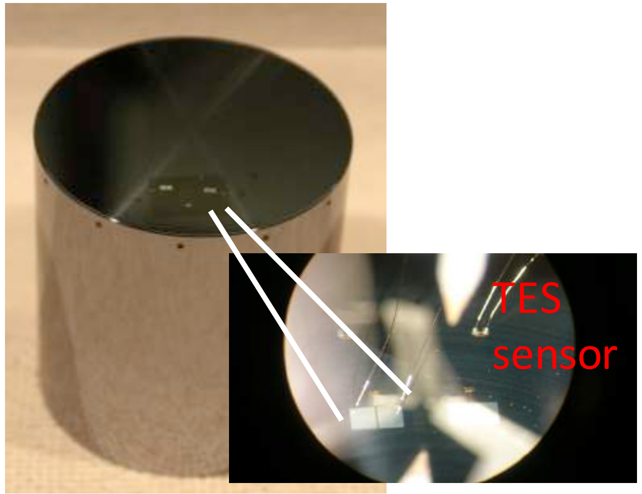
- first successful measurement of a NaI crystal as cryogenic detector
- publication accepted at JINST arXiv: : 1705.11028

- improve detector performance
- no beaker-shaped light detector

2nd PROTOTYPE DETECTOR





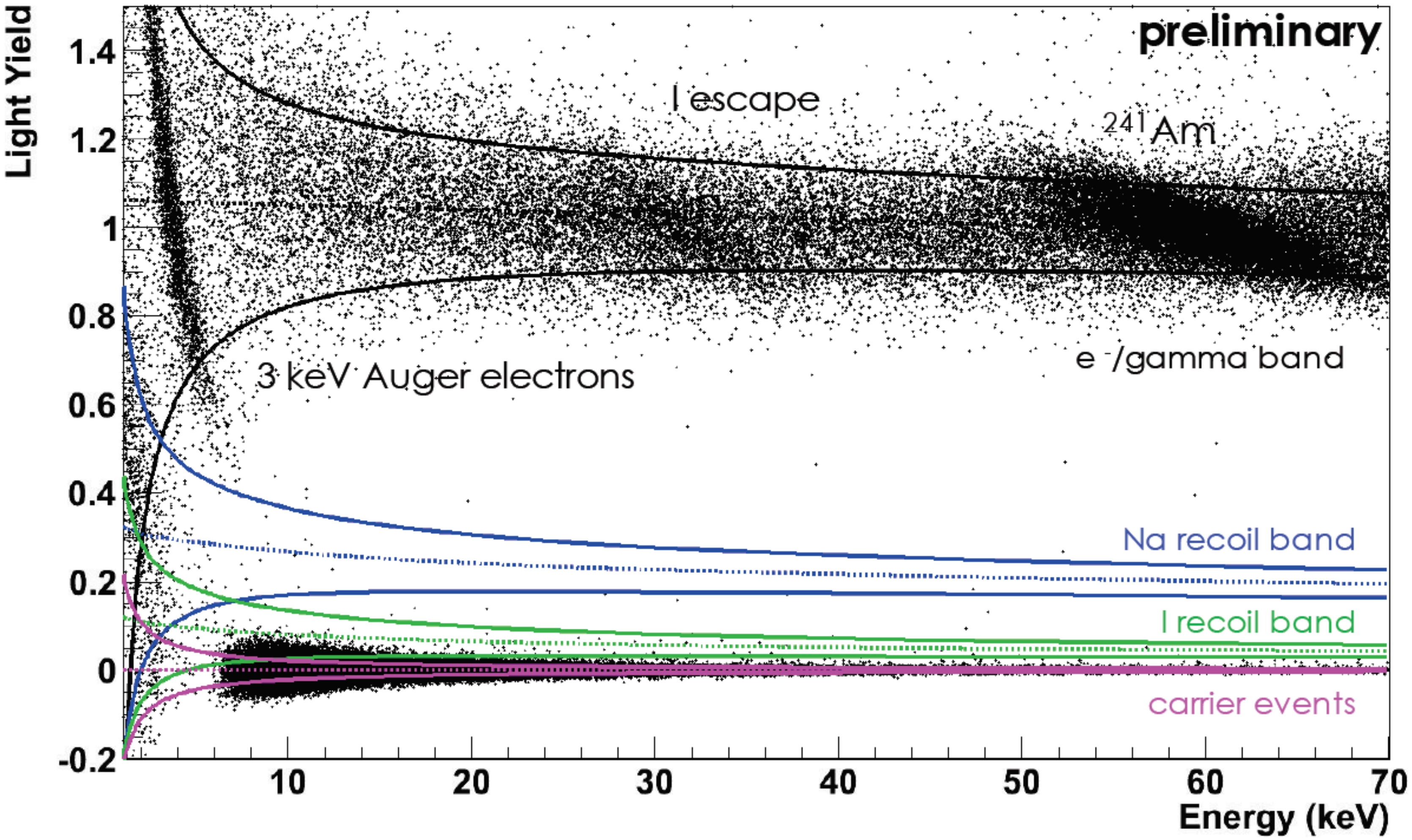


- interface: epoxy resin
- beaker-shaped Si light absorber
- NaI crystal: 66 g

ACHIEVED PERFORMANCE:

- phonon detector resolution (at zero energy): 1.0 keV
- absolute light yield for a β/γ-event: **13 %** (~39 photons/keV)
- intrinsic energy resolution of light detector @ smallest injected testpulse energy: **15 eV**

2nd PROTOTYPE DETECTOR

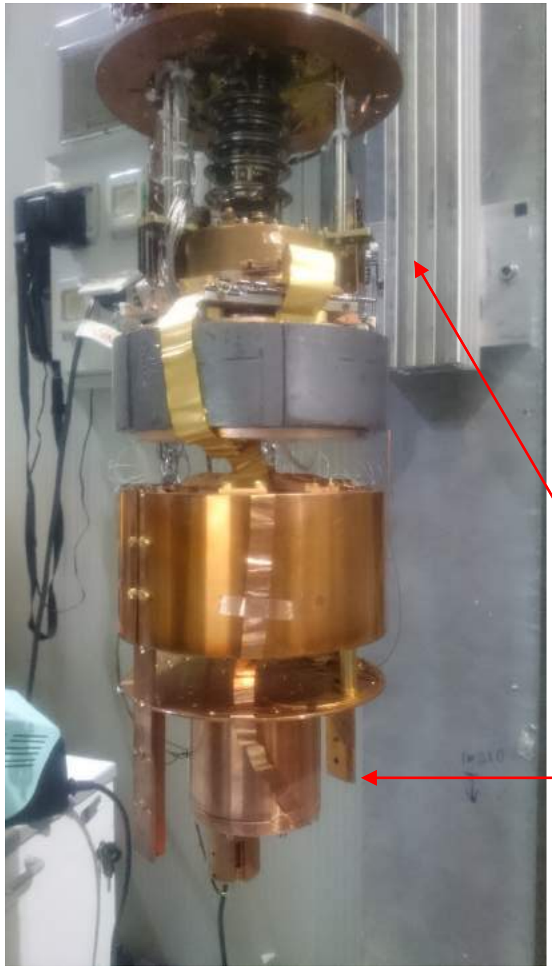


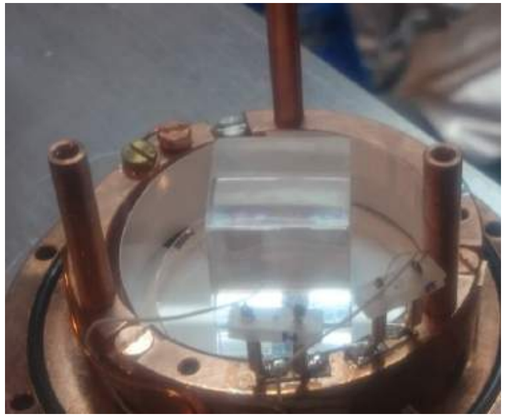
- NaI energy threshold is (8.26 ± 0.02 (stat.))keV
- width of the ^{241}Am peak is (4.508 ± 0.064 (stat.)) keV
- carrier events identified by pulse shape

2nd PROTOTYPE DETECTOR

- successful test of final detector concept
- beaker-shaped light detector exceeds performance goal
- NaI is an excellent scintillator at low temperatures
- improve detector performance of NaI calorimeter to reach 1keV energy threshold
- 205 ppm of ^{40}K in the HILGER crystal

3rd PROTOTYPE DETECTOR





Hall C dilution unit

COSINUS detector module

- first measurement in a low background cryostat (hall C at LNGS)
- installed SQUIDs and dedicated heater / bias lines in the cryostat
- COSINUS DAQ commissioned
- NaI is of 30 g

GOAL:

- test setup in new faciltiy
- **neutron calibration** campaign to proof particle discrimination

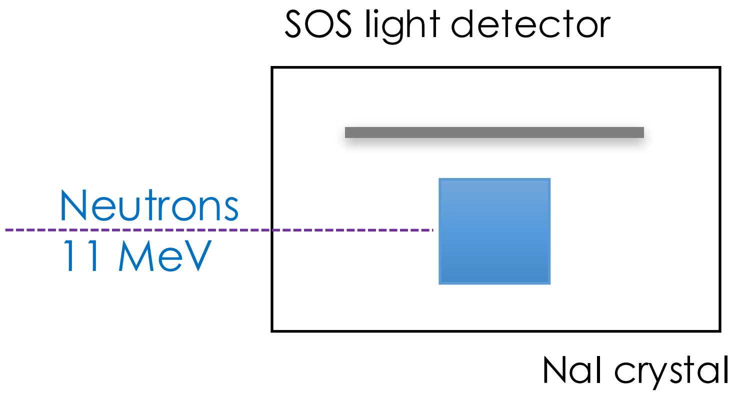
3rd PROTOTYPE DETECTOR

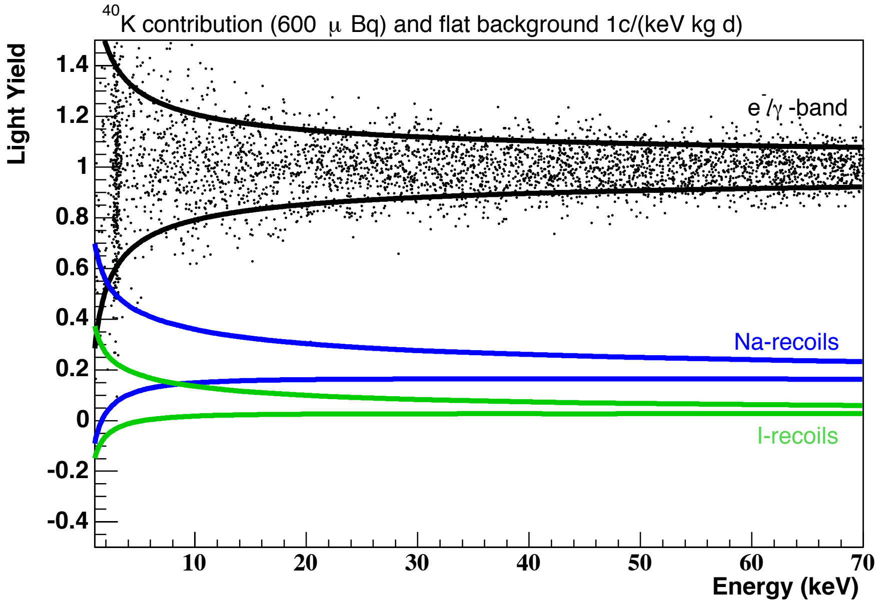
- successful commissioing of experimental setup in hall C

- successful test of new COSINUS DAQ

DATA ANALYSIS STILL ONGOING …Stay tuned!

QUENCHING FACTOR MEASUREMENT



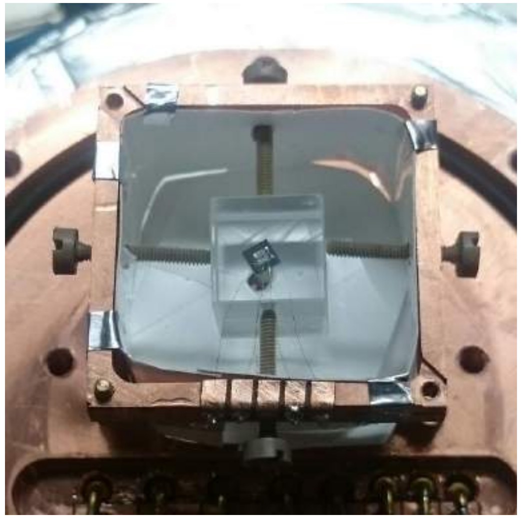


- Tandem accelerator of Maier-Leibnitz Laboratorium (MLL) of LMU in Garching, Germany
- 11 MeV neutrons
- dilution refrigerator available
- small NaI detector module

GOAL:

precise determination of light quenching factor for Na and I at mK-temperatures

QUENCHING FACTOR MEASUREMENT **STATUS**



MARCH/APRIL 2016:

commissioning of the cryostat and the setup

MAY 2016:

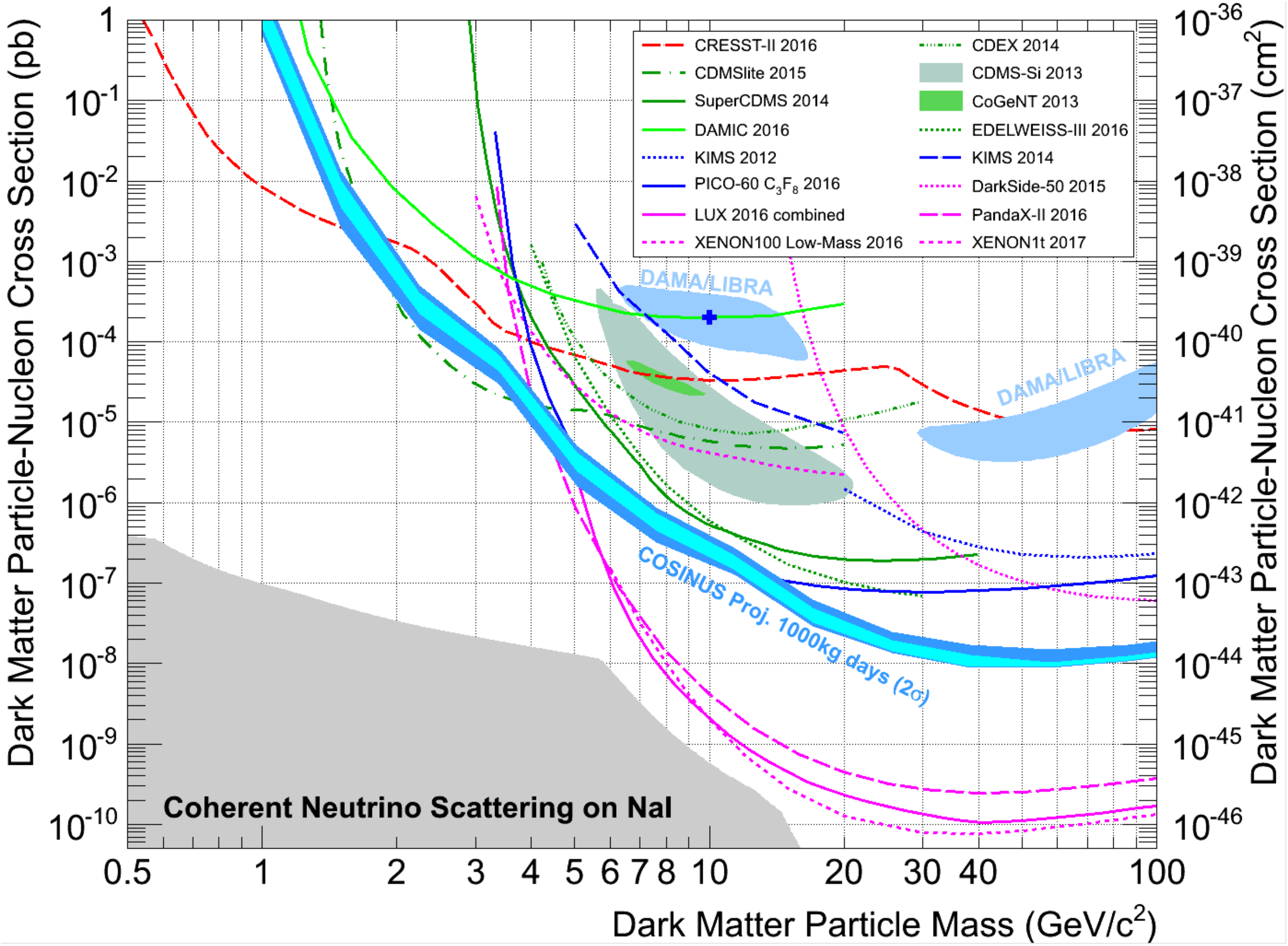
small detector module mounted in cryostat

JUNE-AUGUST 2016:

- couple of cryostat cooldowns
- base temperature **not** reached but hints for problems identified:
  → ^{3}He/^{4}He mixture added first week of August
  → improved thermal heat sinking of all wiring

beam-time **postponed to mid of November 2017**

OUTLOOK: PROJECTION FOR 1000 kg days



- e/gamma background-only simulation
- projected limit for spin-independent elastic scattering off nuclei
- anticipated sensitivity is about two orders of magnitude better than the interpretation of the DAMA/LIBRA claim under <u>standard assumptions</u>

CONCLUSION **COSINUS**

- COSINUS aims to develop the **first NaI detector with particle discrimination**
- first NaI prototype module successfully operated at LNGS in 2016 → publication at JINST

in 2017:

- further investigations and R&D to improve threshold and energy resolution of the NaI detector (new TES-design and interface solution)
- precise **measurement of quenching factors** at the neutron beam at TUM

COSINUS is on a good way to achieve CRESST-II like performance. If we succeed:

- Only few 100 kg-days needed to answer whether DAMA sees a nuclear recoil signal, or not
- upgrading to ~ 10 kg, the COSINUS is also sensitive for modulation detection

CONCLUSION **NaI EXPERIMENTS**

- **Radiopure NaI is the key-issue for all DAMA-like experiments**
- **no** experiment arrived yet in producing massive NaI(Tl) crystals at purity level of DAMA/LIBRA → we have to work harder!
- DAMA/LIBRA: 1keVee threshold (publish this year ?)
- COSINE-100: data taking since Sept 2016 (first results 2018 ?)
- ANAIS-112: started physics run (data taking planned for 2 years)
- SABRE: start PoP within 2017 (promising ultrapure NaI(Tl))
- COSINUS: performance test run planned for 2018

HAPPY BIRTHDAY MODULATION SIGNAL

TAUP conference 1997

DAMA presents first evidence for modulation signal

HAPPY BIRTHDAY MODULATION SIGNAL

TAUP conference 1997

DAMA presents first evidence for modulation signal

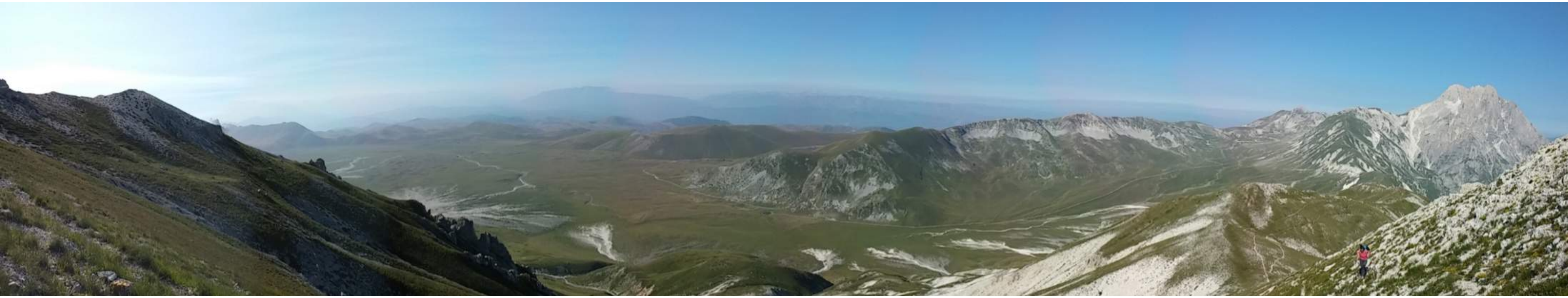
E. Barberio (SABRE, Australia): “The more one looks into their experiment, the more one realizes that it is very well done.”

HAPPY BIRTHDAY MODULATION SIGNAL

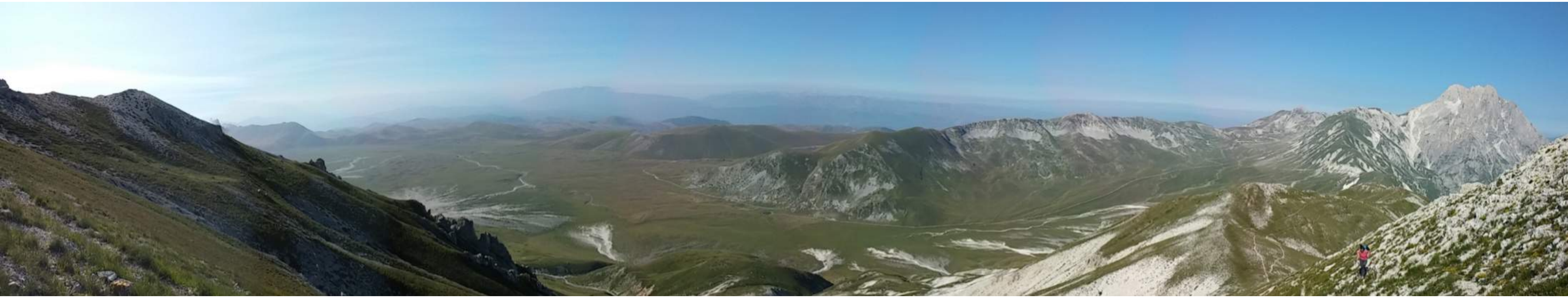
TAUP conference 1997

DAMA presents first evidence for modulation signal

My colleague F. Reindl says:
"This will not take another two decades!"

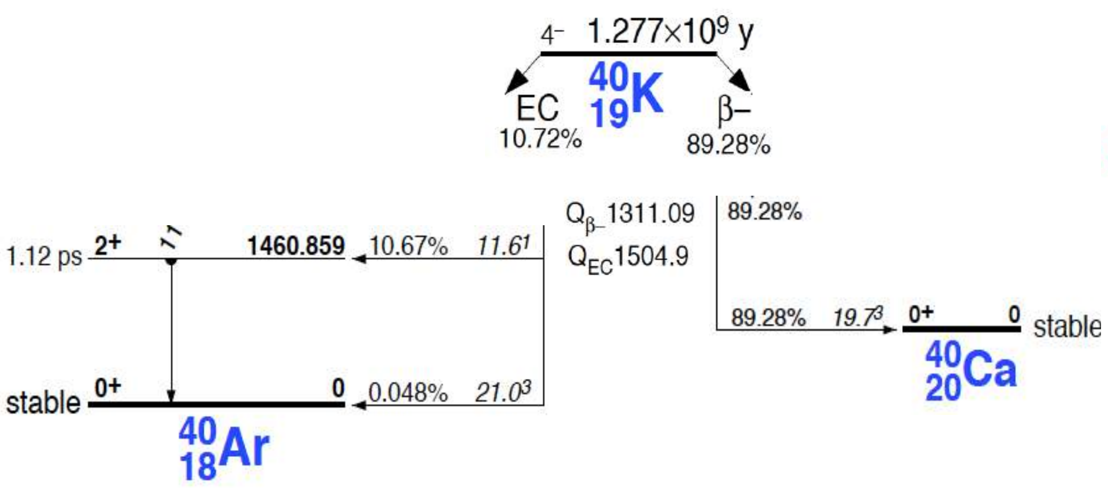


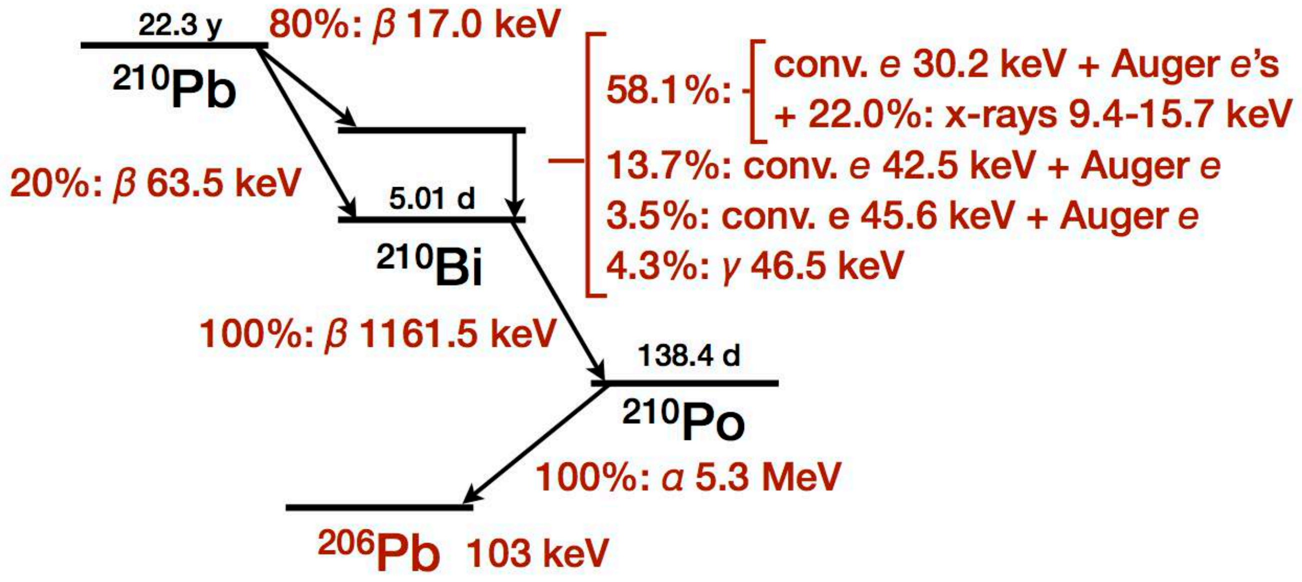
Thank you for your attention!

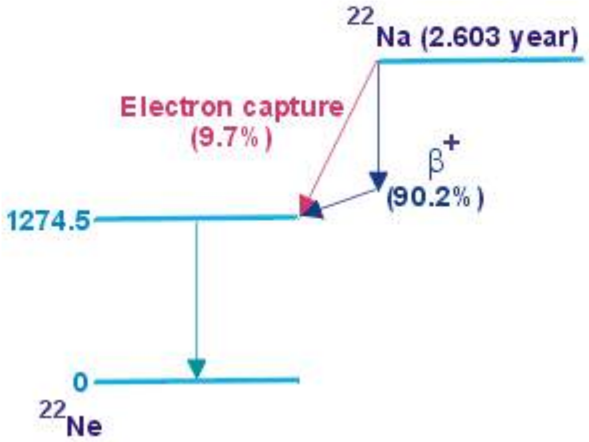


EXTRA MATERIAL

General enemies







COSINE-100

	Mass (kg)	Powder Type	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	^{210}Po (mBq/kg)	Light Yield (npe/keV)
Crystal 1	8.26	Powder B	34.74±4.74	<0.02	1.31±0.35	3.20±0.04	14.67±0.62
Crystal 2	9.15	Powder C	60.64±4.64	<0.12	<0.63	2.06±0.03	14.56±0.54
Crystal 3	9.16	WIMPScint-II	34.34±3.10	<0.04	0.44±0.19	0.76±0.02	15.75±0.76
Crystal 4	18.01	WIMPScint-II	33.32±3.50		<0.3	0.74±0.02	14.69±0.46
Crystal 5	18.28	Powder C	82.33±5.49		2.35±0.31	2.06±0.03	6.26 ±0.34
Crystal 6	12.5	WIMPScint-III	16.79±2.46	<0.018	0.56±0.19	1.52±0.02	14.52±0.51
Crystal 7	12.5	WIMPScint-III	18.69±2.79		<0.6	1.54±0.02	14.41±0.50
Crystal 8	18.28	Powder C	54.25±3.82		<0.9	2.05±0.02	3.27 ±0.20
DAMA			<20	0.7 - 10	0.5 - 7.5	<0.5	5.5 - 7.5

DARK MATTER IN THE MILKY WAY

Standard assumptions

- Maxwellian velocity distribution
- asymptotic velocity of 220 km/s
- galactic escape velocity of 544 km/s
- local dark matter density

  0.3 GeV/cm^3

→ 3000 (100 GeV/m_x) WIMPs per m^3

→ FLUX OF WIMPS ON EARTH:

~10^5 (100 GeV/m_x) cm^{-2} sec^{-1}

Motivation for low-mass Dark Matter

WIMP "Miracle"

- Thermally produced in early Universe
- Weak scale yields correct relic density
- $10 GeV/c^2 \sim 1 TeV/c^2$

Asymmetric dark matter

- $\Omega_{DM}/\Omega_B \sim 5$: Why?
- Link asymmetries for baryons and DM in early Universe
- $0.1 GeV/c^2 \sim 10 GeV/c^2$

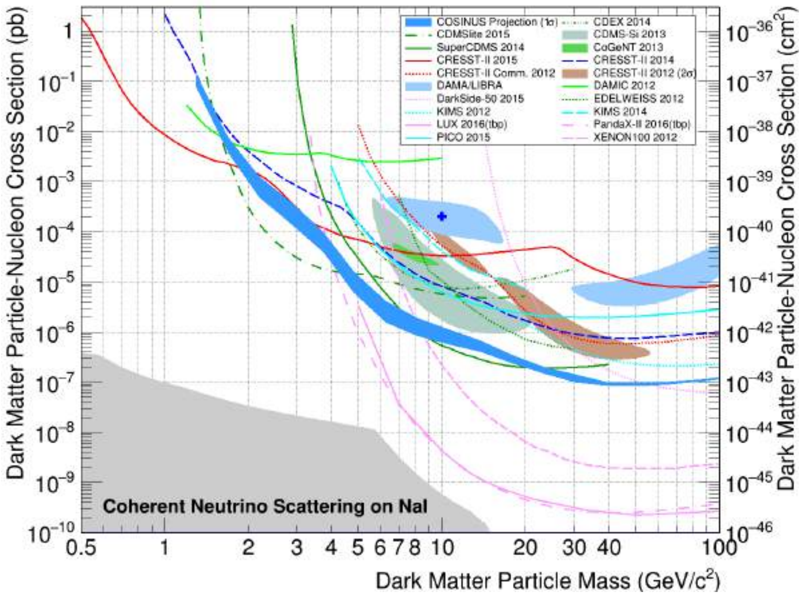
5

NEUTRINOS as background

Electronic recoils from pp solar neutrinos: ~ 10^{-48} cm^2

Nuclear recoils from ^{8}B solar neutrinos: below 10^{-44} cm^2 for low-mass WIMPs

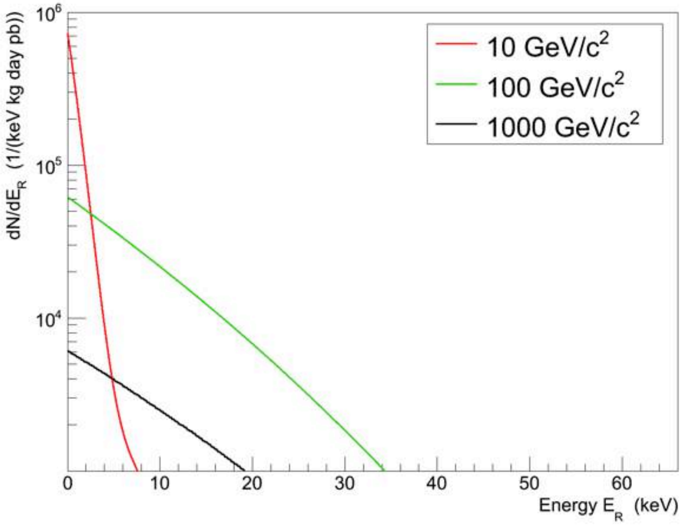
Nuclear recoils from atmospheric + DSNB: below 10^{-48} cm^2



BESIDES,
measurement of CNNS
is also an interesting
physics case itself

DIFFERENTIAL SCATTERING RATE

$$\frac{dR}{dE_r} = \frac{\sigma_0}{m_\chi} \frac{F^2(E_r)}{\mu^2} \frac{\rho_\odot T(E_r)}{v_\odot \sqrt{\pi}}$$



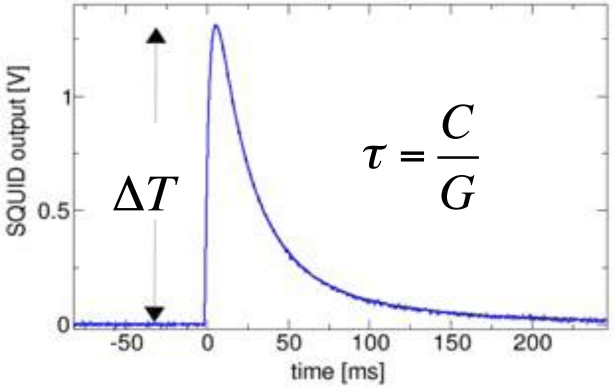
σ_0	interaction cross action at zero momentum transfer
m_x	mass of dark matter particle
$F^2(E_r)$	nuclear form factor
$\mu = \frac{m_x m_N}{m_x + m_N}$	reduced mass
$T(E_r) = \frac{\sqrt{\pi}}{2} v_\odot \int_{v_{min}}^{v_{esc}} \frac{f_1(v)}{v} dv$	Integral over local dark matter velocity distribution
$v_{min} = \sqrt{\frac{E_r m_N}{2\mu^2}}$	minimal velocity to produce a recoil of E_r

Prepare detector for:

- very small energy deposits (few keV - tens of keV)
- extremely rare detection rate (few events per ton per year)
- signal embedded in a background that is millions of times higher

DIRECT DARK MATTER INTERACTION

Temperature pulse $\Delta T = \frac{E}{C}$



N is the total excitations which have a mean energy $\mathbf{k_B T}$

$$N \propto CT / k_B T \quad \text{and} \quad \delta N = \sqrt{N}$$

$$\delta E = \delta N k_B T = \sqrt{k_B T^2 C}$$

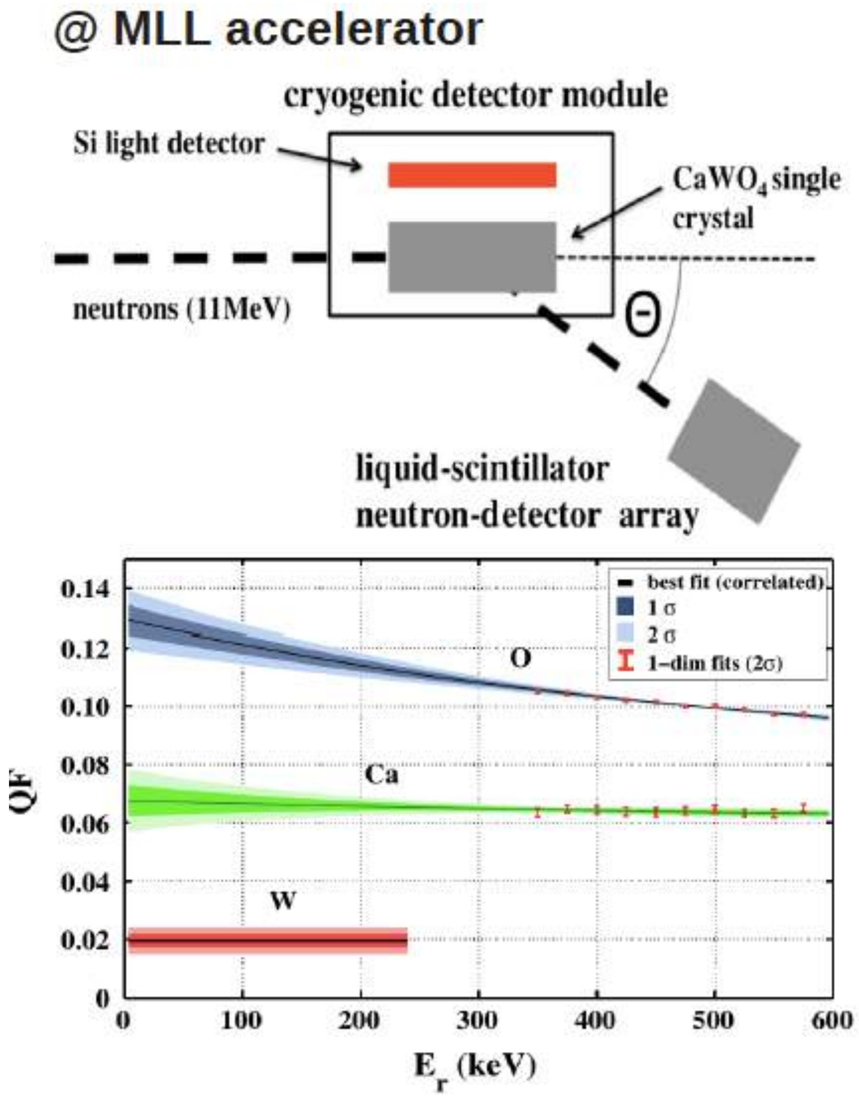
Noise comes from irreducible random thermodynamic fluctuations in energy due to transport across the thermal link

Ultimate energy resolution is determined by how well you can measure **T** against thermodynamic fluctuations

low temperatures → better energy sensitivity

low heat capacity → careful selection of materials

Quenching Factor Measurement of CRESST



Precise determination of QFs for O, Ca & W @mK temperatures

Values (in ROI)

- O: (11.2 ± 0.5)%
- Ca: (5.94 ± 0.49)%
- W: (1.72 ± 0.21)%

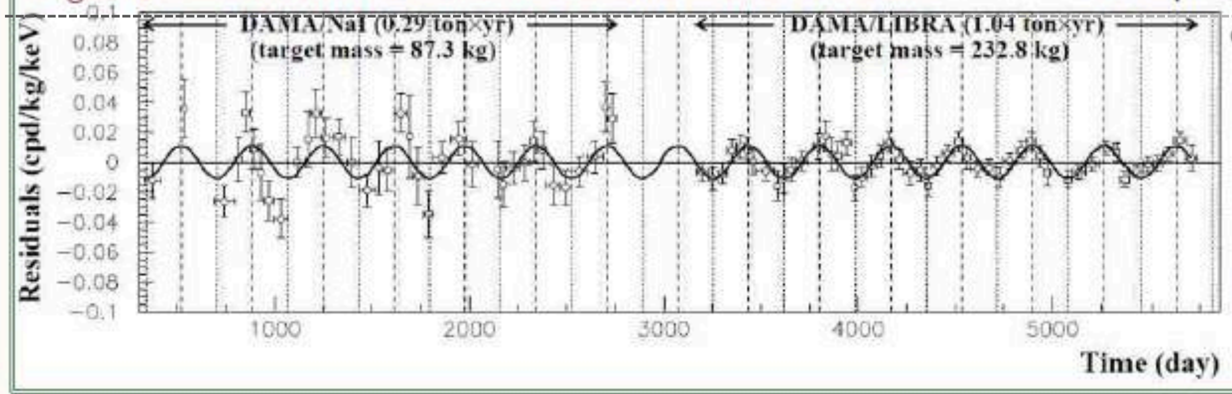
Eur. Phys. J. C (2014) 74:2957

Model Independent Annual Modulation Result

DAMA/NaI + DAMA/LIBRA-phase1 Total exposure: 487526 kg×day = **1.33 ton×yr**

Single-hit residuals rate of scintillation events vs time in 2-6 keV

EPJC 56(2008)333, EPJC 67(2010)39, EPJC 73(2013)2648



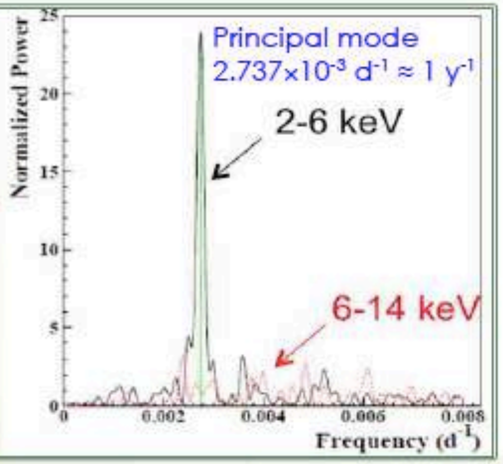
continuous line: t_0 = 152.5 d, T = 1.0 y

A=(0.0110±0.0012) cpd/kg/keV
χ^2/dof = 70.4/86 9.2 σ C.L.

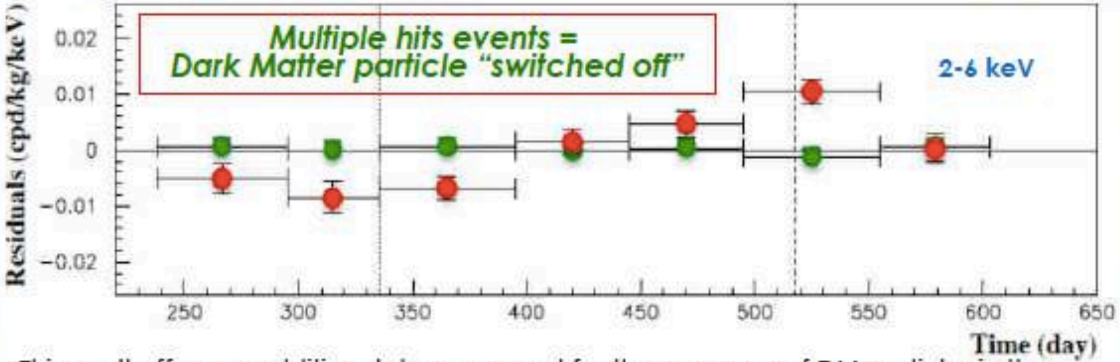
Absence of modulation? No
χ^2/dof=154/87 P(A=0) = 1.3×10^{-5}

Fit with all the parameters free:
A = (0.0112 ± 0.0012) cpd/kg/keV
t_0 = (144±7) d - T = (0.998±0.002) y

Power spectrum



Comparison between **single hit residual rate (red points)** and **multiple hit residual rate (green points)**; Clear modulation in the single hit events; No modulation in the residual rate of the multiple hit events
A=-(0.0005±0.0004) cpd/kg/keV



This result offers an additional strong support for the presence of DM particles in the galactic halo further excluding any side effect either from hardware or from software procedures or from background

No systematics or side reaction able to account for the measured modulation amplitude and to satisfy all the peculiarities of the signature

The data favor the presence of a modulated behaviour with all the proper features for DM particles in the galactic halo at about 9.2σ C.L.

Taken from: P. Belli UCLA Dark Matter 2016, Los Angeles, USA

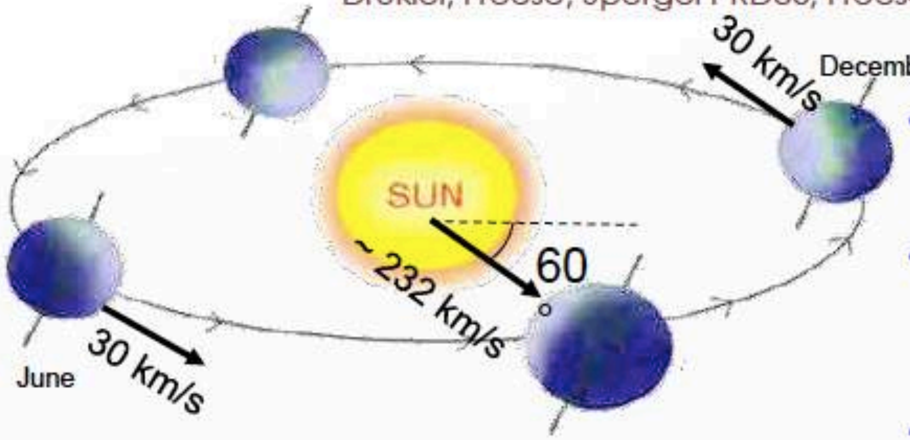
The annual modulation: a model independent signature for the investigation of DM particles component in the galactic halo

With the present technology, the annual modulation is the main model independent signature for the DM signal. Although the modulation effect is expected to be relatively small a suitable large-mass, low-radioactive set-up with an efficient control of the running conditions can point out its presence.

Drukier, Freese, Spergel PRD86; Freese et al. PRD88

Requirements:

1) Modulated rate according cosine
2) In low energy range
3) With a proper period (1 year)
4) With proper phase (about 2 June)
5) Just for single hit events in a multi-detector set-up
6) With modulation amplitude in the region of maximal sensitivity must be <7% for usually adopted halo distributions, but it can be larger in case of some possible scenarios



- v_{sun} ~ 232 km/s (Sun vel in the halo)
- v_{orb} = 30 km/s (Earth vel around the Sun)
- $\gamma = \pi/3$, $\omega = 2\pi/T$, T = 1 year
- t_0 = 2nd June (when $v_\oplus$ is maximum)

$$v_\oplus(t) = v_{sun} + v_{orb} \cos\gamma \cos[\omega(t-t_0)]$$

$$S_k[\eta(t)] = \int_{\Delta E_k} \frac{dR}{dE_R} dE_R \cong S_{0,k} + S_{m,k} \cos[\omega(t-t_0)]$$

the DM annual modulation signature has a different origin and peculiarities (e.g. the phase) than those effects correlated with the seasons

To mimic this signature, spurious effects and side reactions must not only - obviously - be able to account for the whole observed modulation amplitude, but also to satisfy contemporaneously all the requirements

Taken from: P. Belli UCLA Dark Matter 2016, Los Angeles, USA