NaIce Dark Matter experiments

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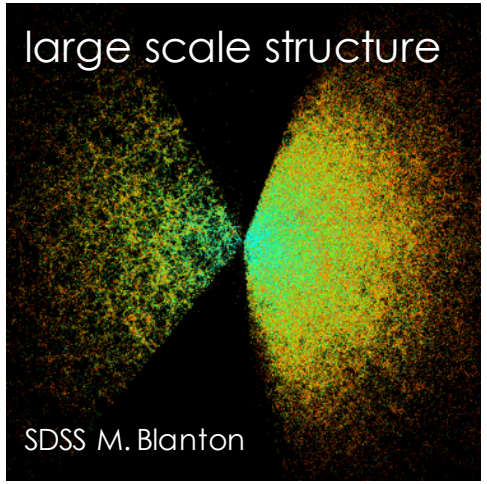
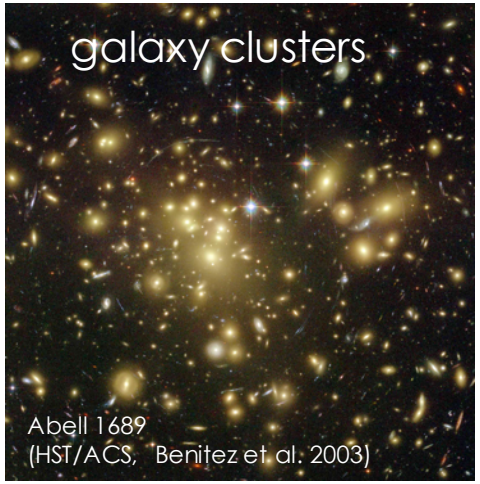
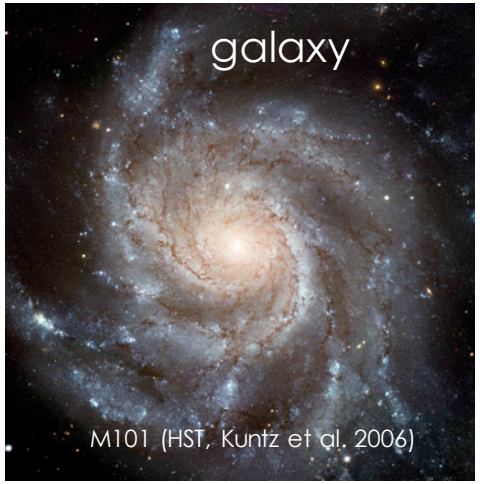
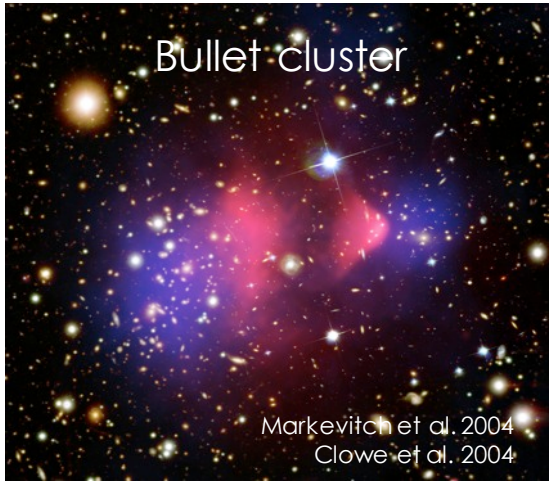
@Maurizio Verdecchia Photography

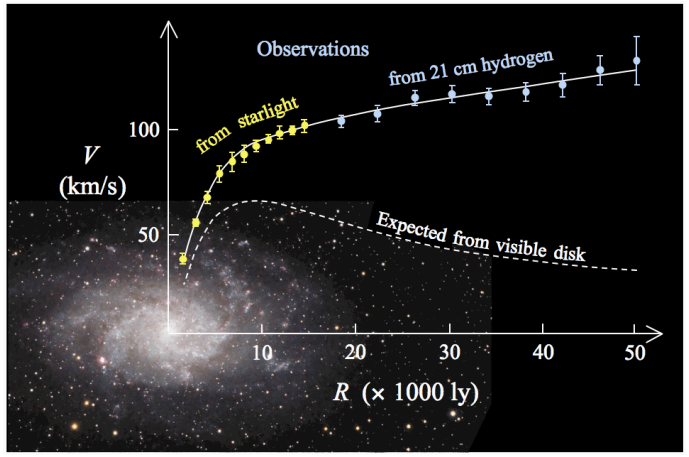
EVIDENCE FOR DARK MATTER





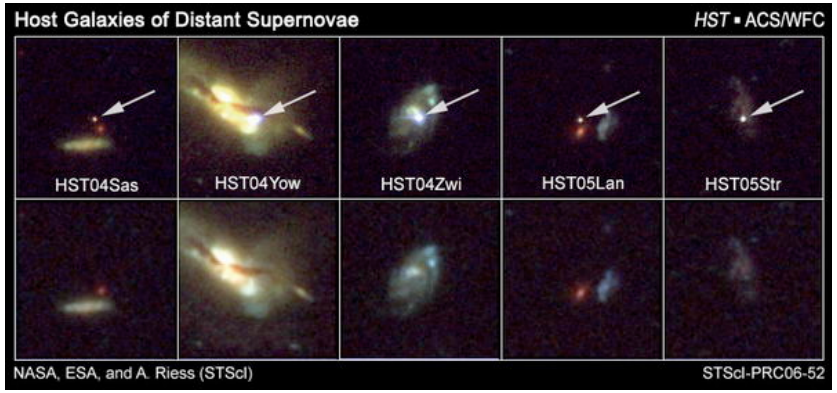






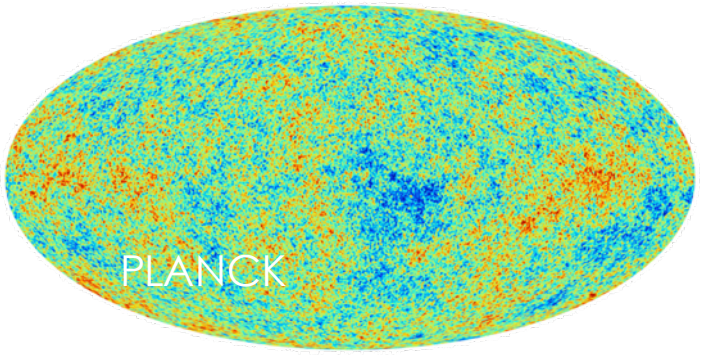
M33 Image.

Supernovae

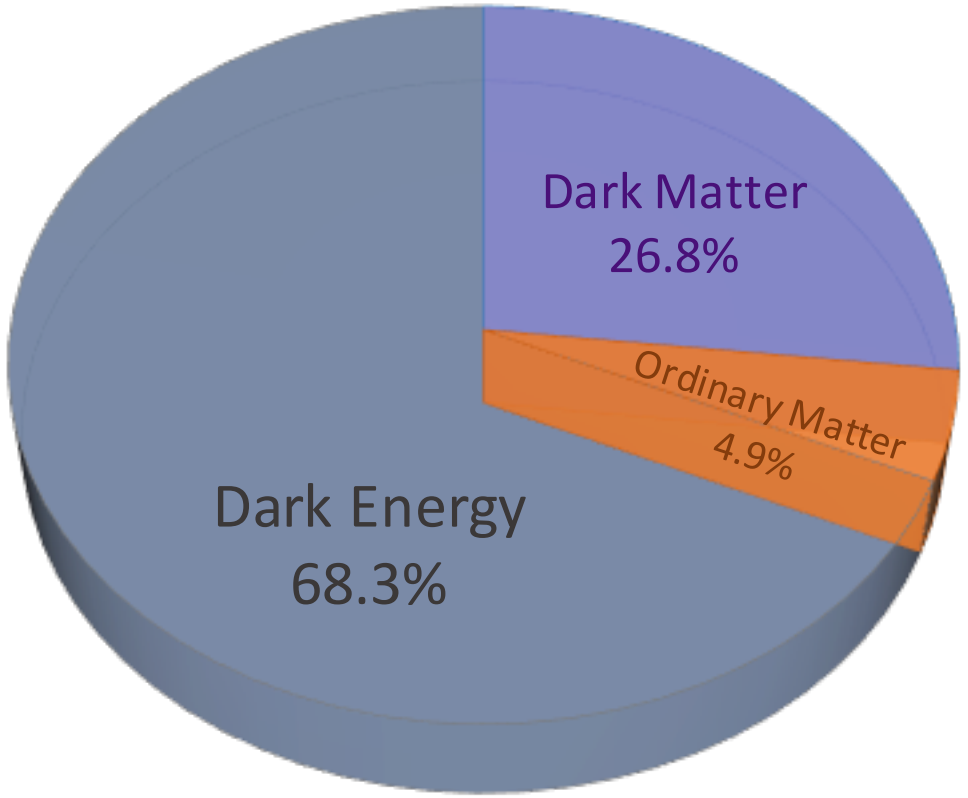


A. Riess

Cosmic Microwave Background



ENERGY CONTENT OF THE **UNIVERSE**



After PLANCK

UNCOVERING THE FACTS…

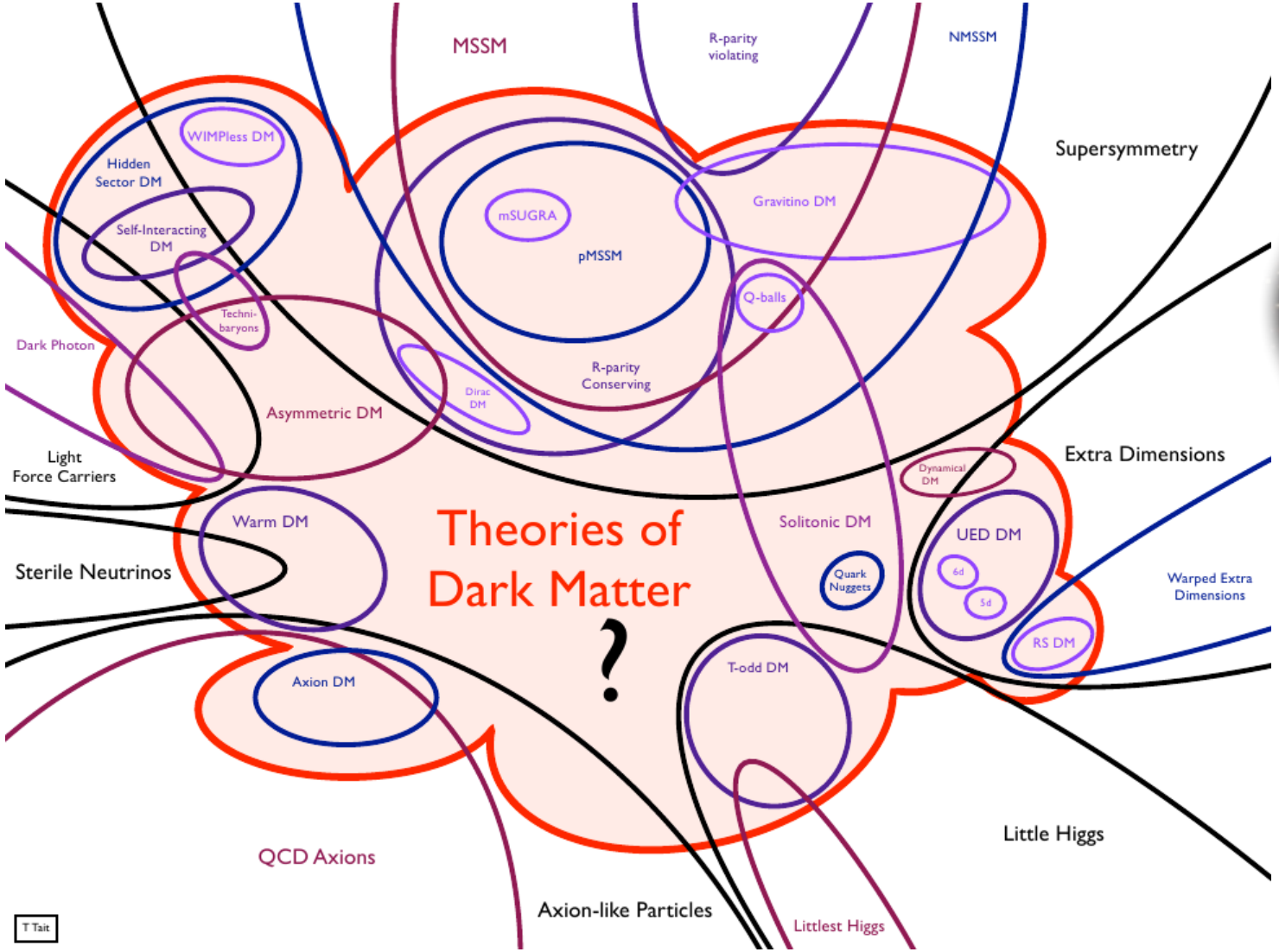
- ✓ non-baryonic
- ✓ cold (non-relativistic)
- ✓ stable
- ✓ interaction via gravity

and possibly on the weak scale

What we know is a drop, what we don‘t know is an ocean.

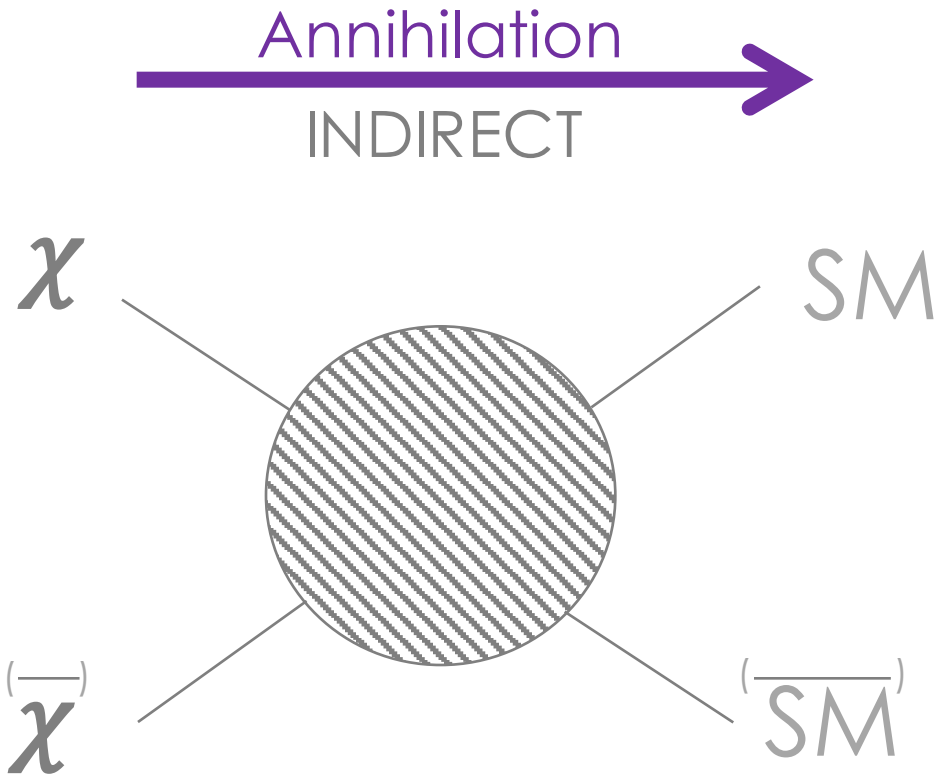
ISAAC NEWTON

DARK MATTER CANDIDATES

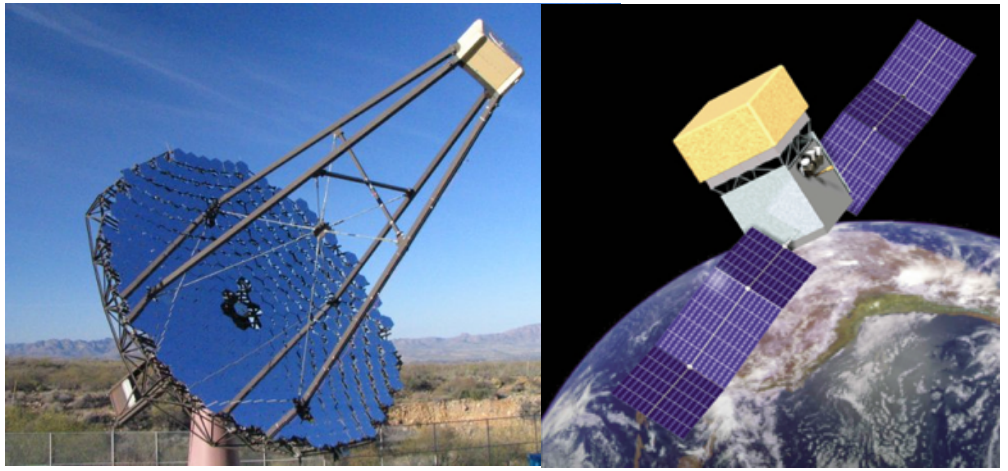


Taken from T. Tait at UCLA DM 2016

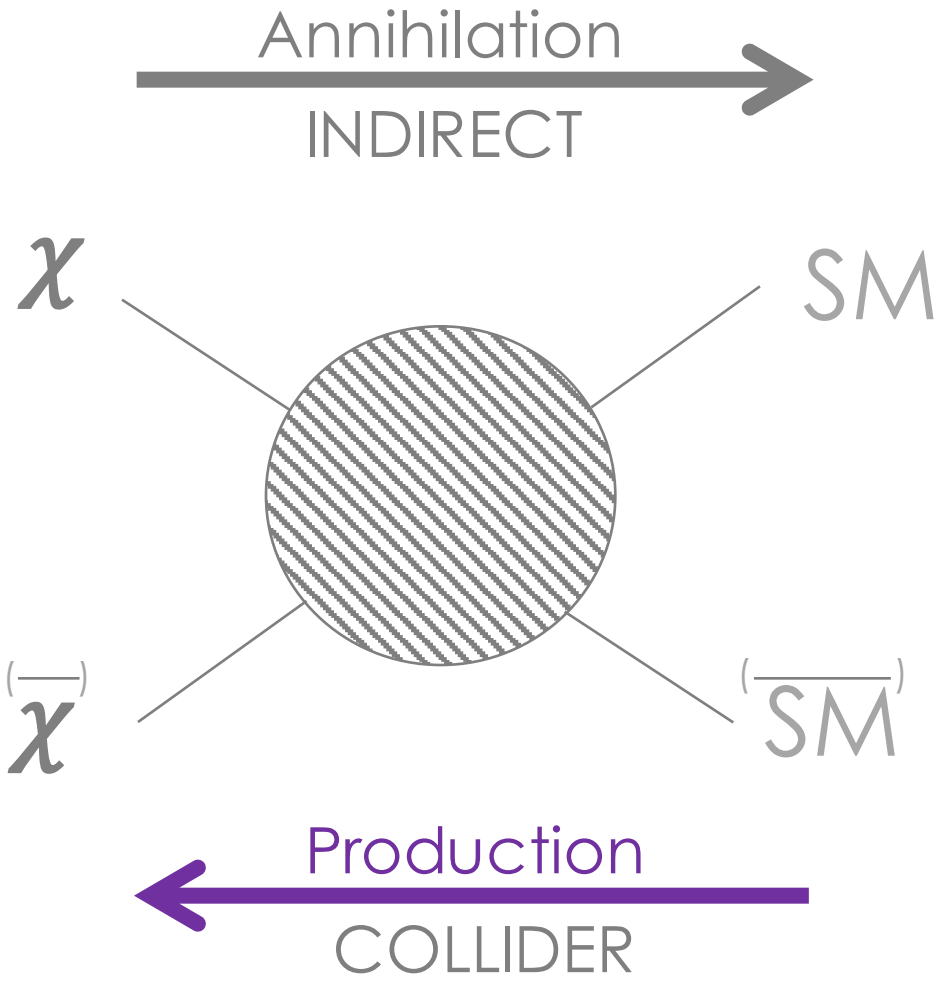
HUNT FOR DARK MATTER



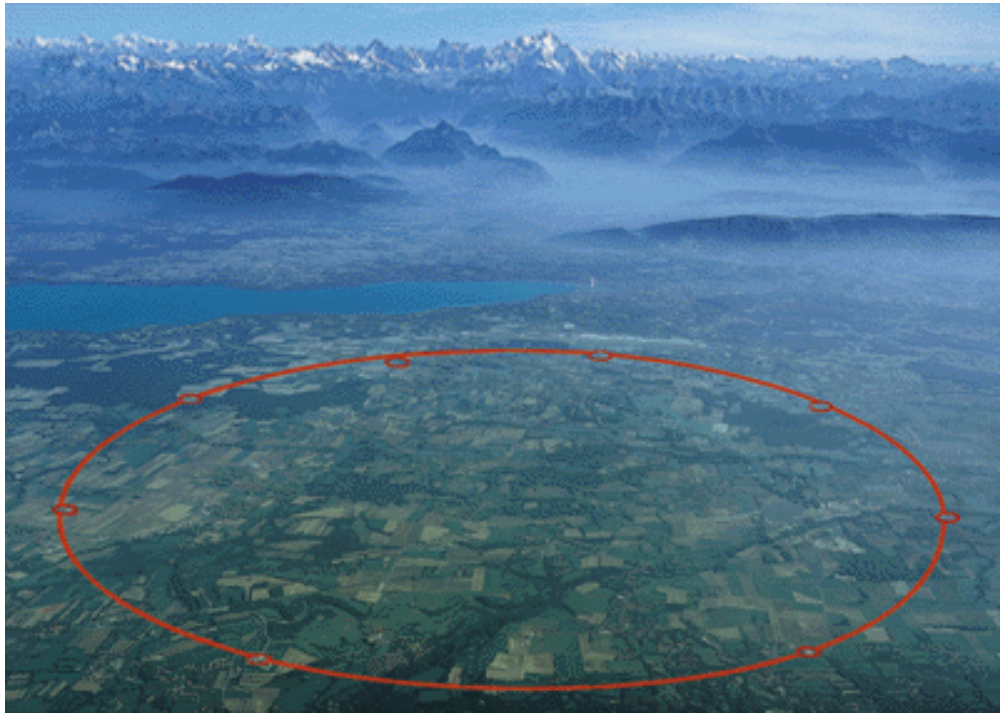
Dark matter particles can transform to ordinary particles, which are then detectable



HUNT FOR DARK MATTER



Searching for the conversion
protons → dark matter
e^+ / e^- → dark matter



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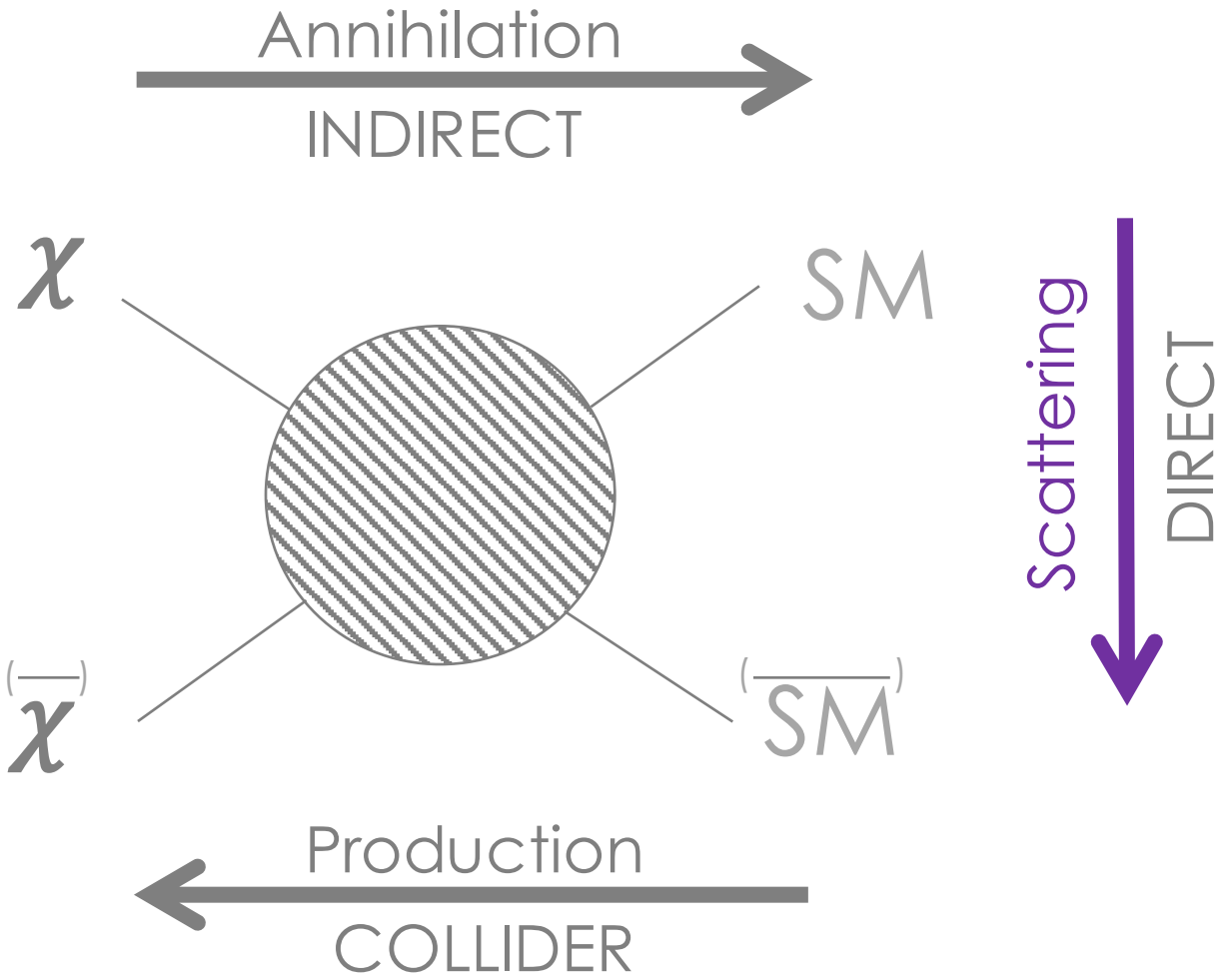
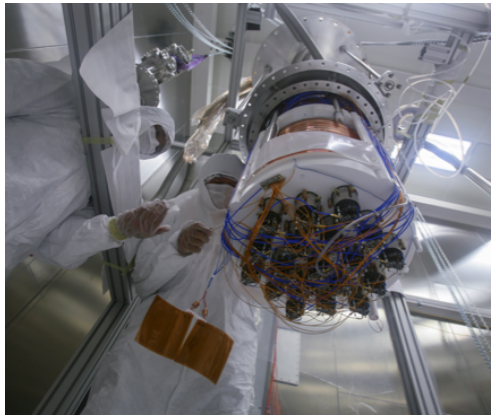


Dark matter particles scatter off nuclei or electrons in earth-bound detectors



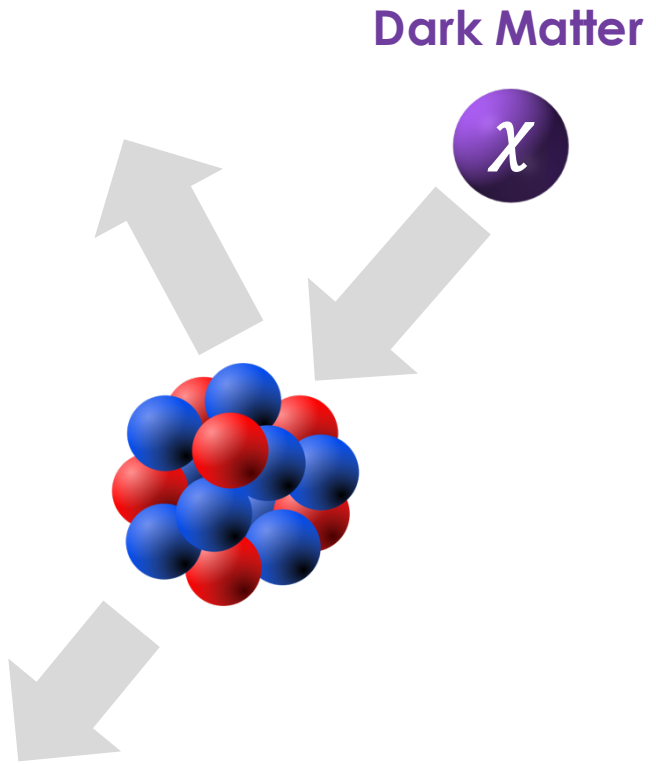
DIRECT DARK MATTER INTERACTION

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



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

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

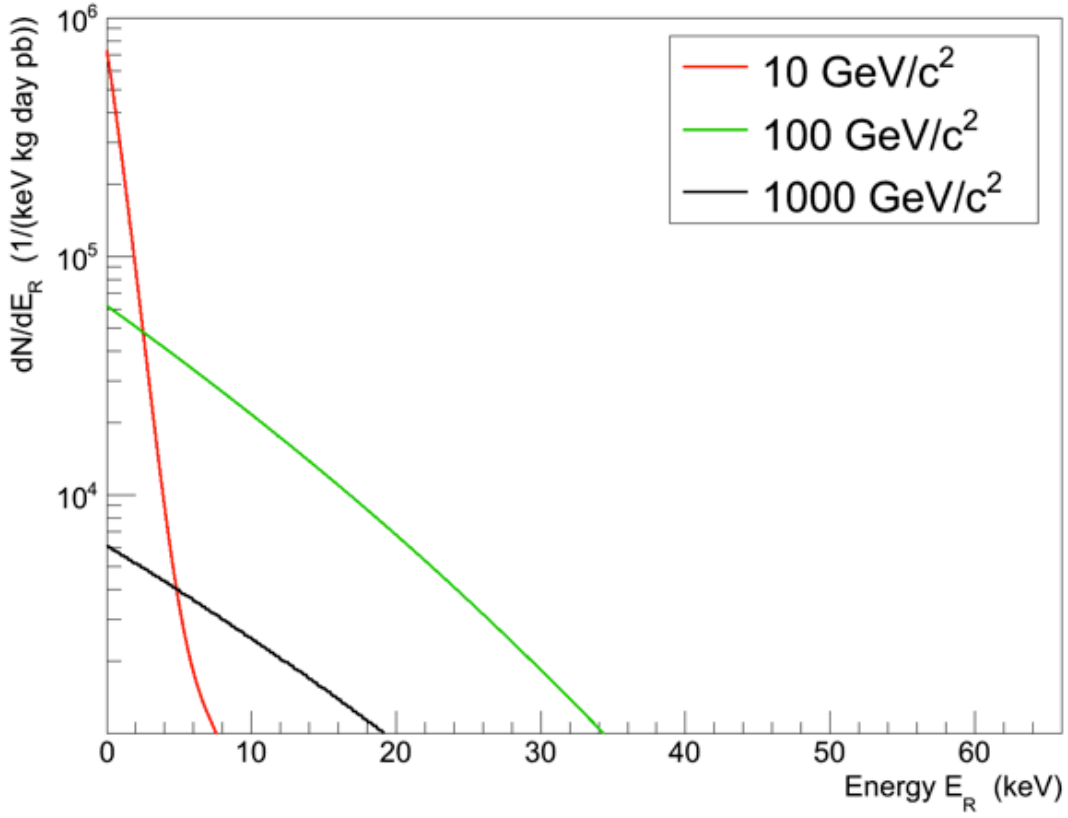
minimal velocity to produce a recoil above E_r

~ A^2

~ form factor

DARK MATTER **SIGNATURE**

rate and shape of recoil spectrum depend on target material



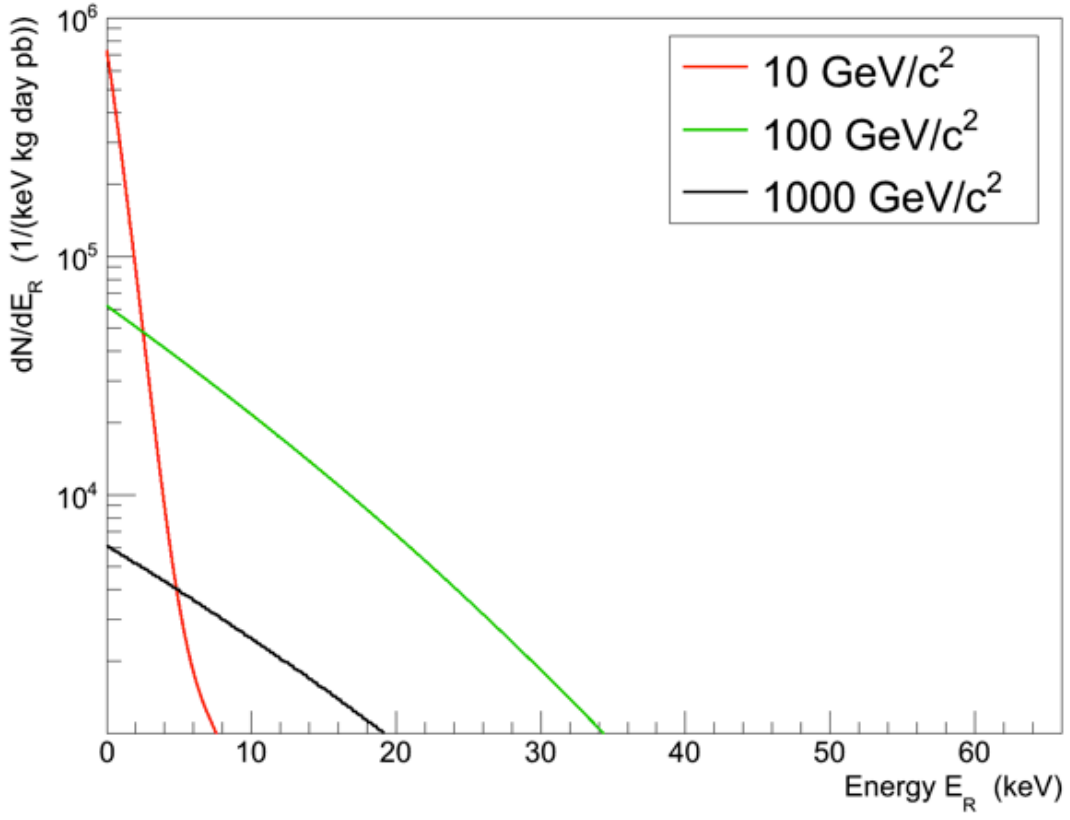
extremely rare interaction rate

current limit at $\mathcal{O}$ **(0.01) counts/(keV ton year) ***

* Xenon1t: arXiv:1805.12562v1

DARK MATTER **SIGNATURE**

rate and shape of recoil spectrum depend on target material



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small recoil energies of few ~ **keV range**

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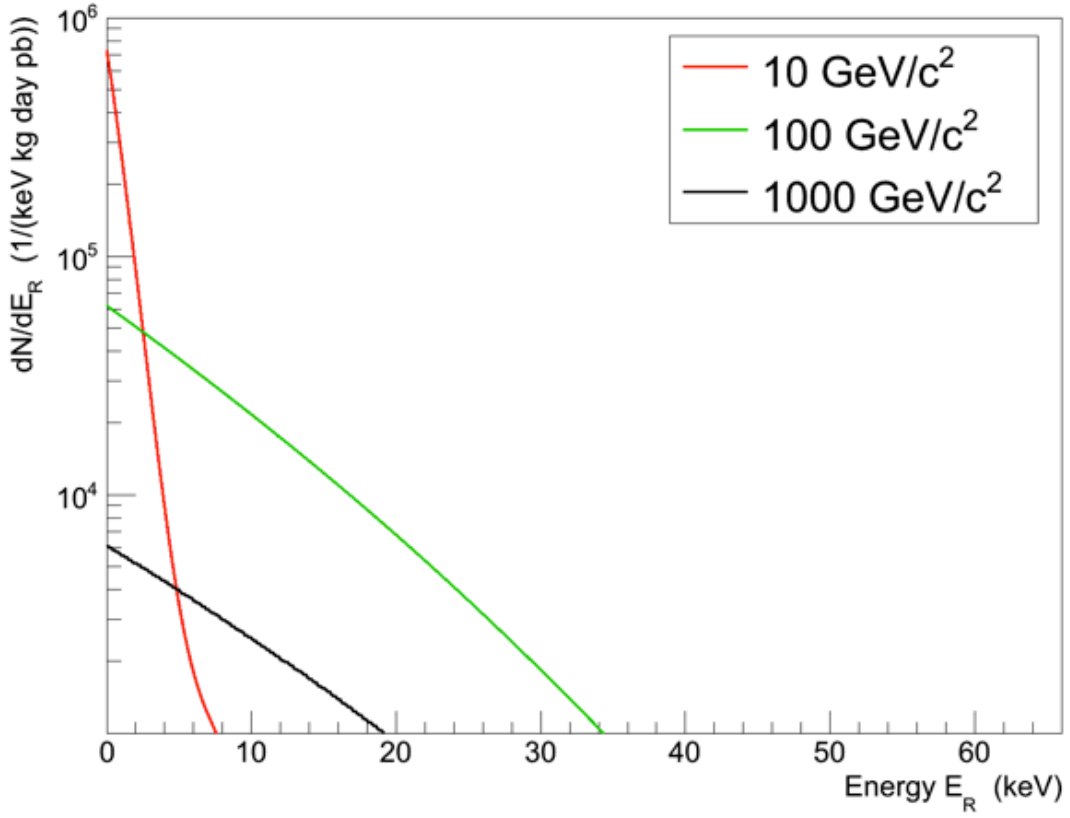


extremely rare interaction rate

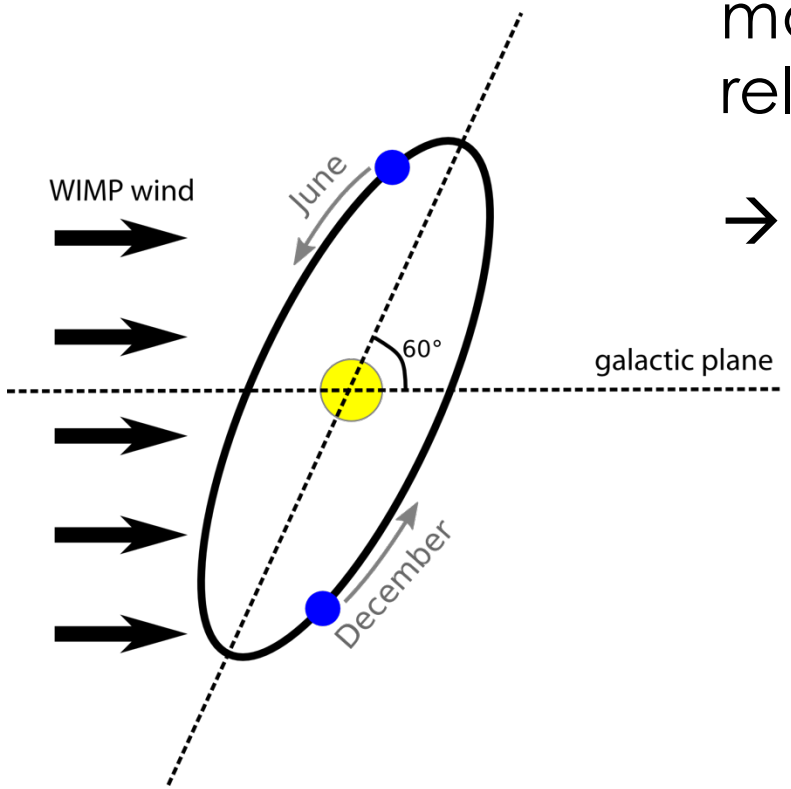
current limit at $\mathcal{O}$ **(0.01) counts/(keV ton year)** *

small recoil energies of few ~ **keV range**

flat and **featureless** spectrum !!

* Xenon1t: arXiv:1805.12562v1

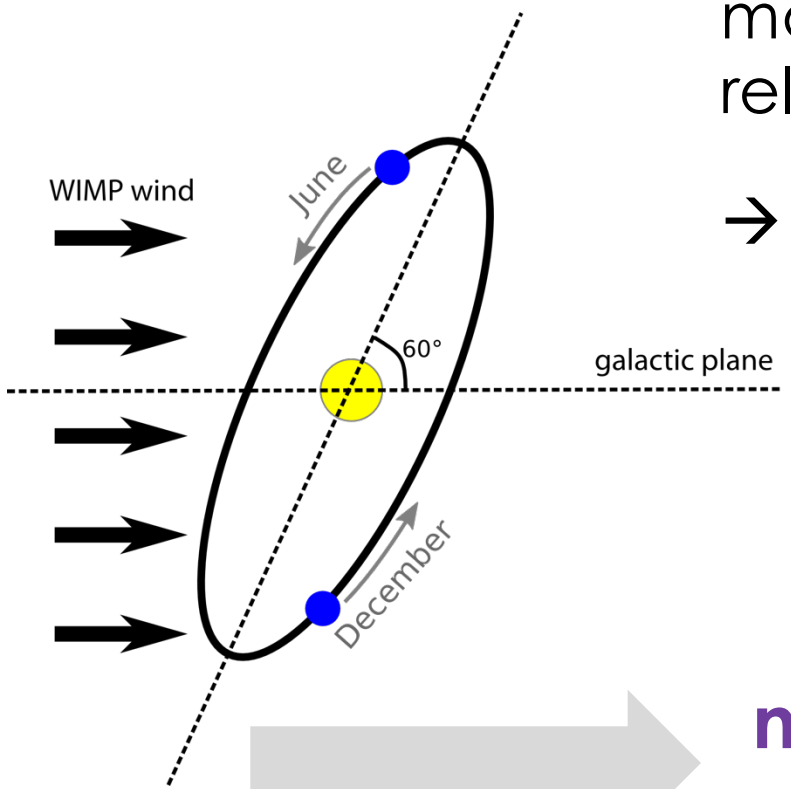
MODULATION



motion of the Earth causes
relative modulation of velocity

→ **annual variation in the rate**

MODULATION



motion of the Earth causes
relative modulation of velocity

→ annual variation in the rate

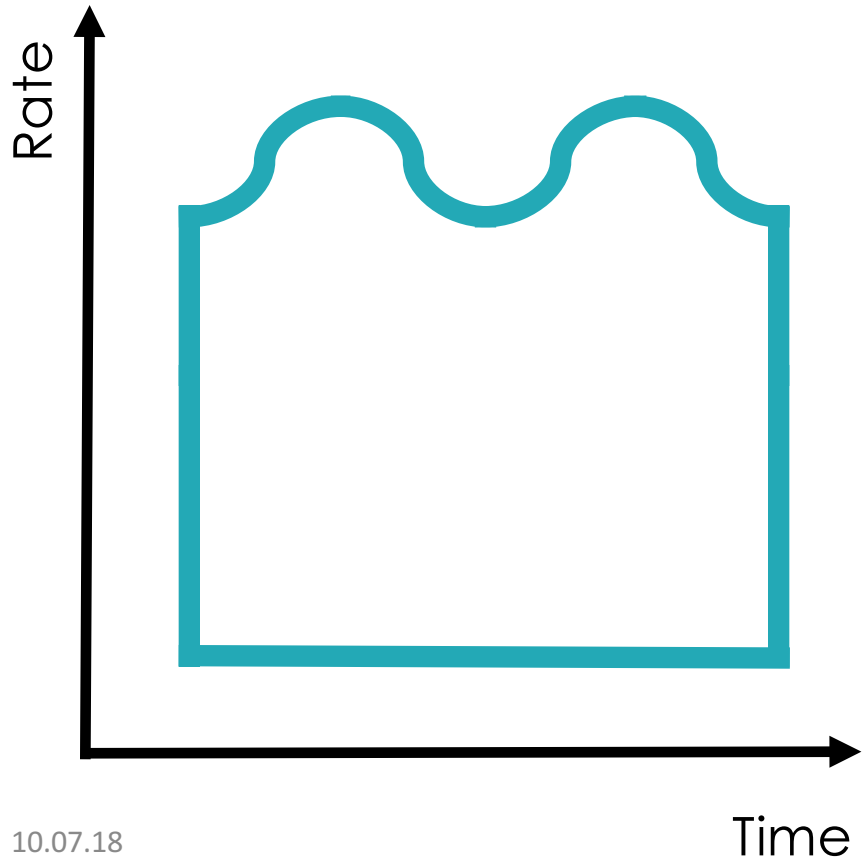
modulation signal a smoking gun evidence ?!?

EXPERIMENTAL SIGNATURE

CREDITS TO F. REINDL

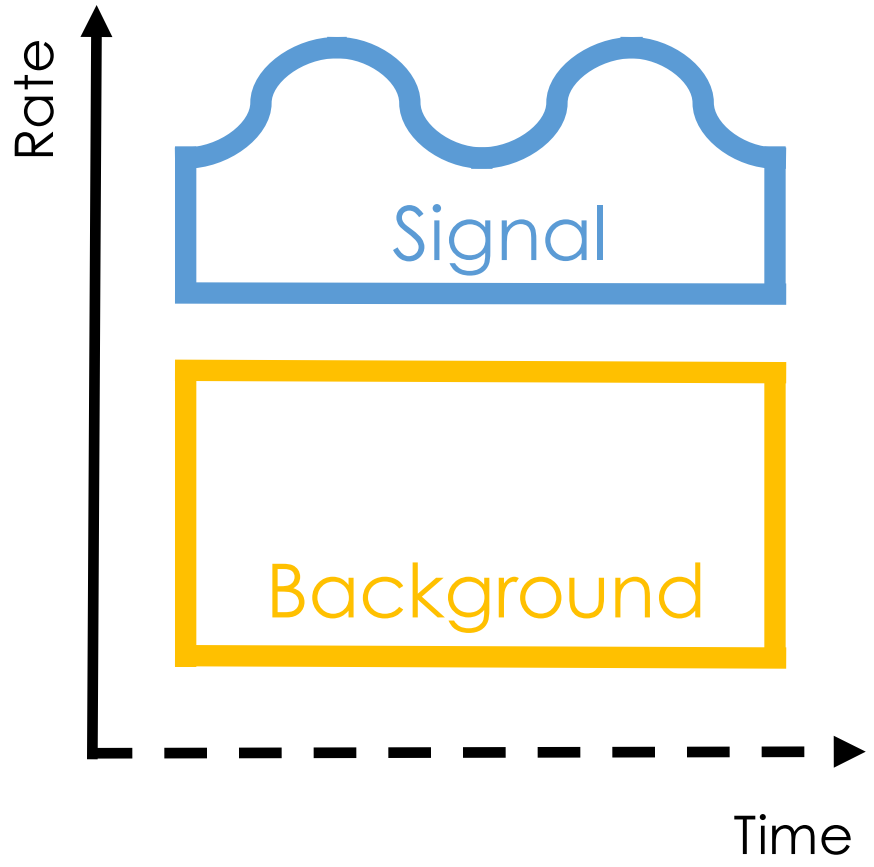
MODULATION

Rate vs. time

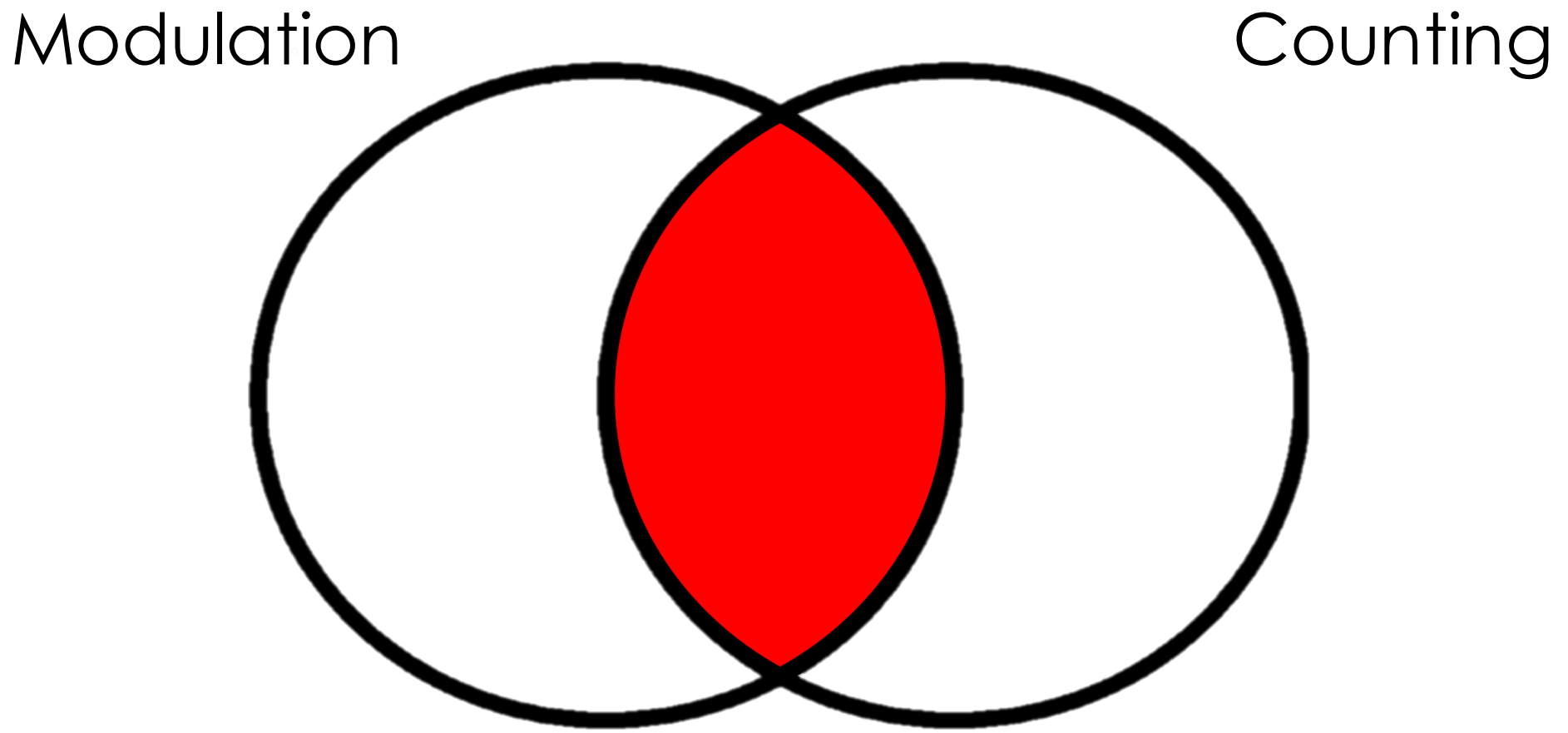


COUNTING

Signal above background



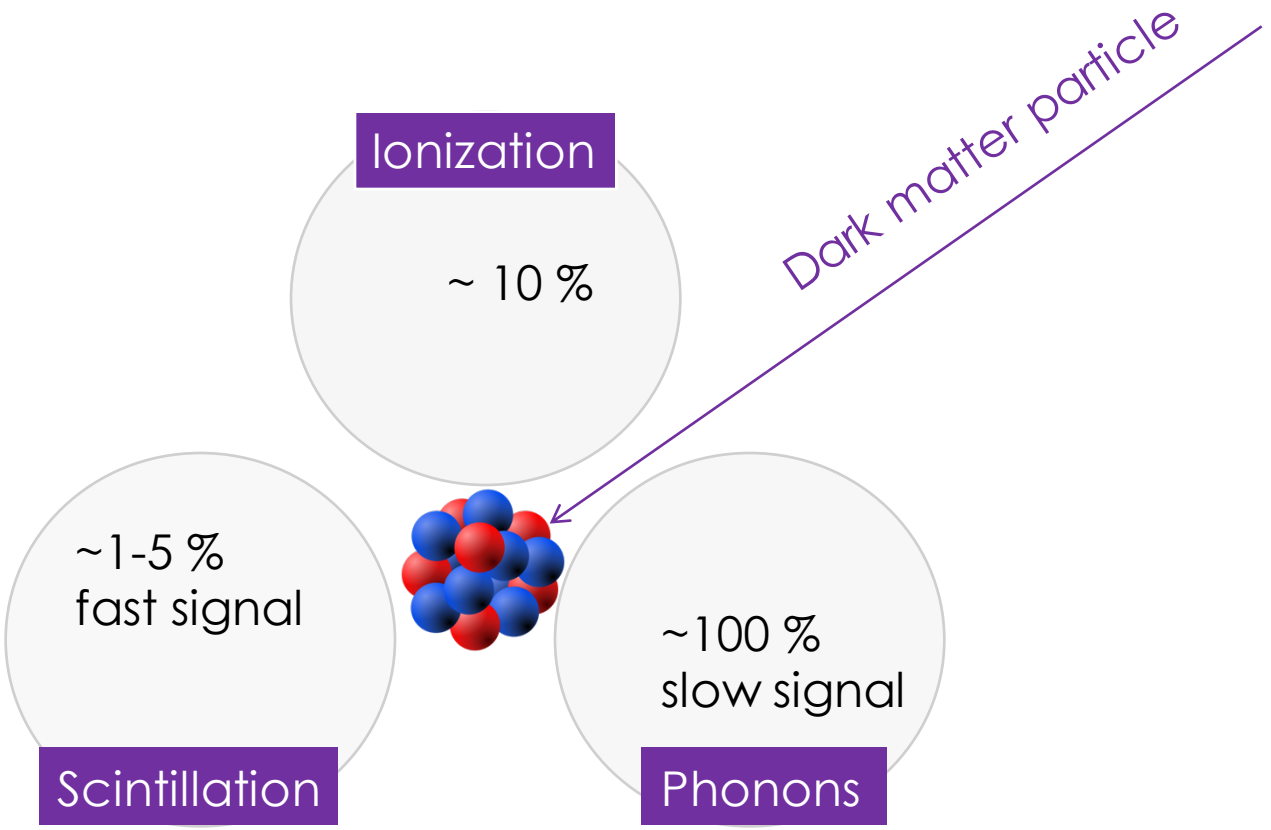
Not exclusive: An experiment may exploit both signatures (depending on the experimental technique and exposure)



CREDITS TO F. REINDL

WORLDWIDE EFFORT

DIRECT DETECTION **CHANNELS**



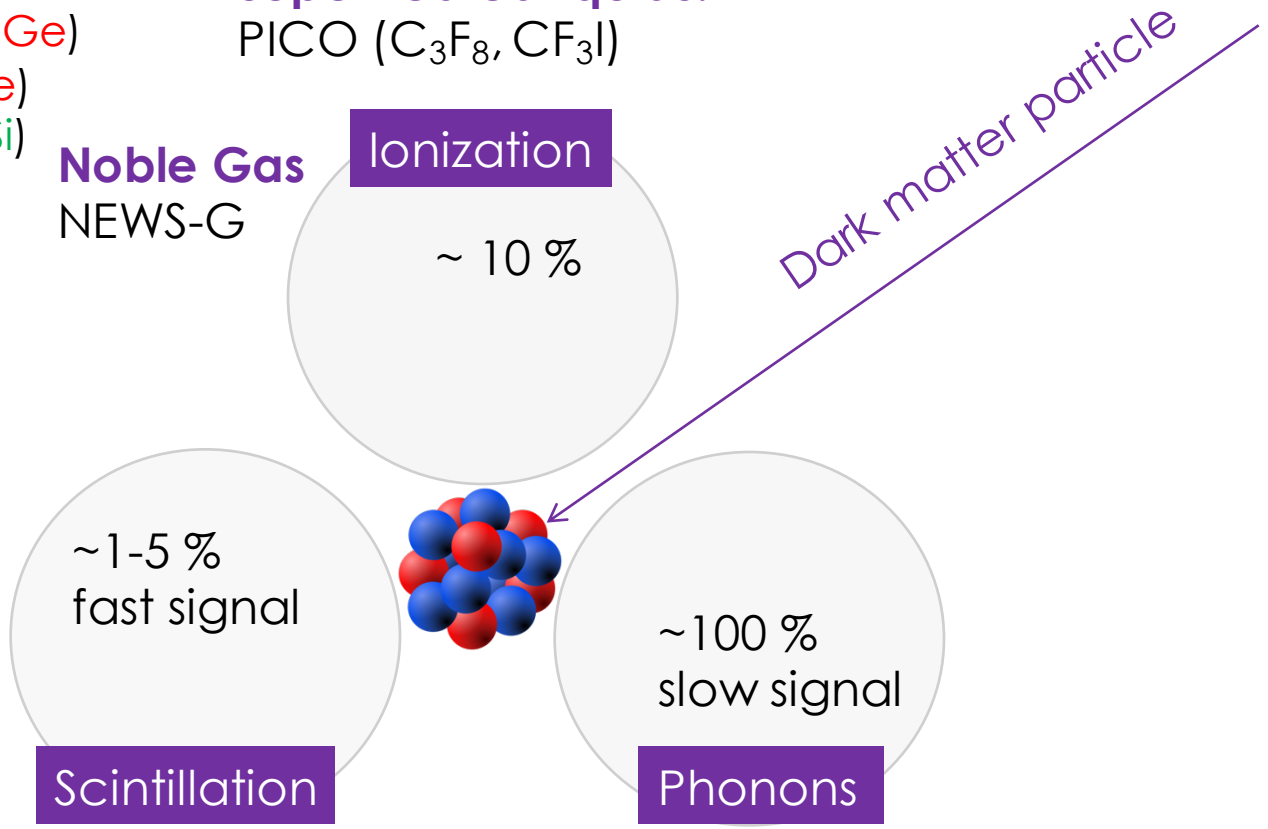
SINGLE CHANNEL DETECTION

not complete list!

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

Superheated liquids:
PICO (C_3F_8, CF_3I)

Noble Gas
NEWS-G



Inorganic scintillators:
DAMA/LIBRA (NaI),
COSINE (NaI), KIMS (CsI)

Single-phase liquid nobles:
DEAP (Ar), XMASS (Ar)

DUAL CHANNEL DETECTION

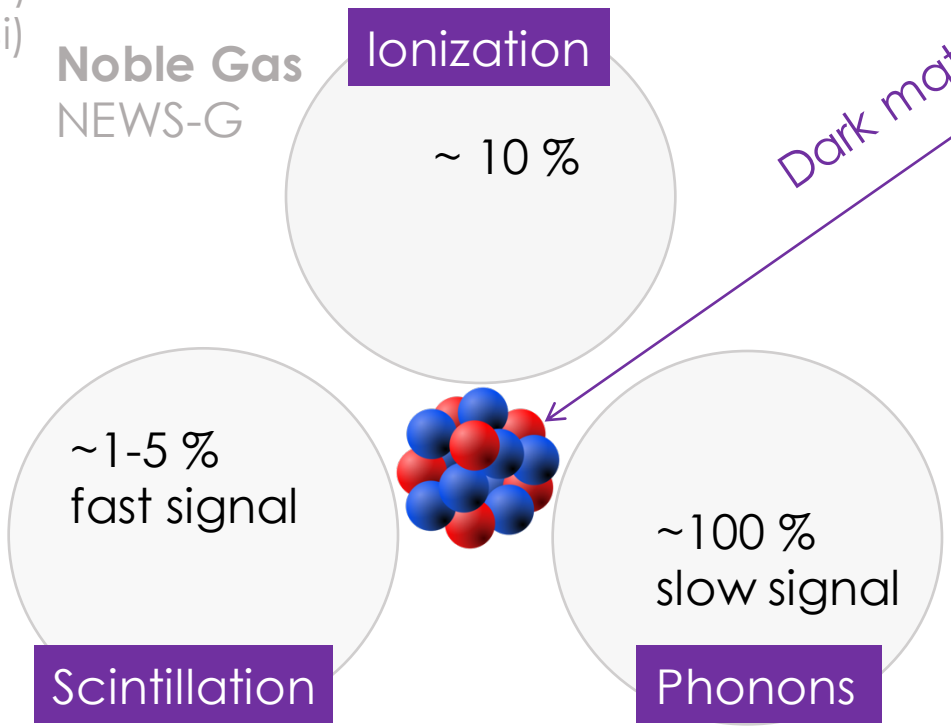
not complete list!

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

Superheated liquids:
PICO (C_3F_8, CF_3I)

Noble Gas
NEWS-G

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



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

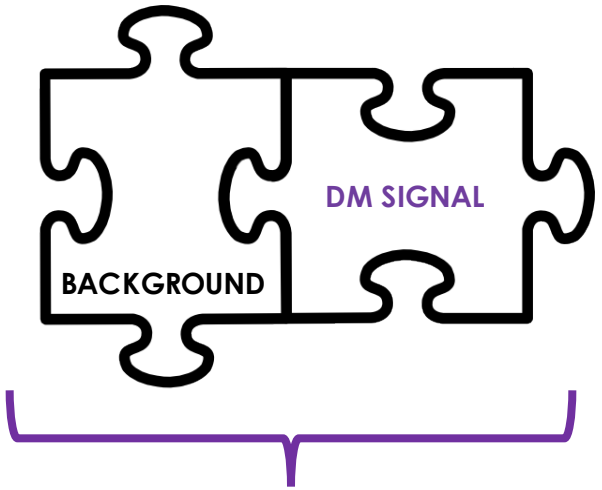
Inorganic scintillators:
DAMA/LIBRA (NaI),
COSINE (NaI), KIMS (CsI)

Single-phase liquid nobles:
DEAP (Ar), XMASS (Ar)

Scintillating calorimeters
- CRESST-III ($CaWO_4$)
- COSINUS (NaI)

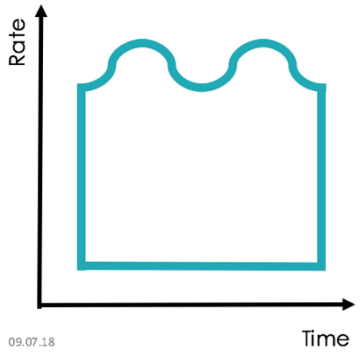
SAME SAME, BUT DIFFERENT

SINGLE CHANNEL



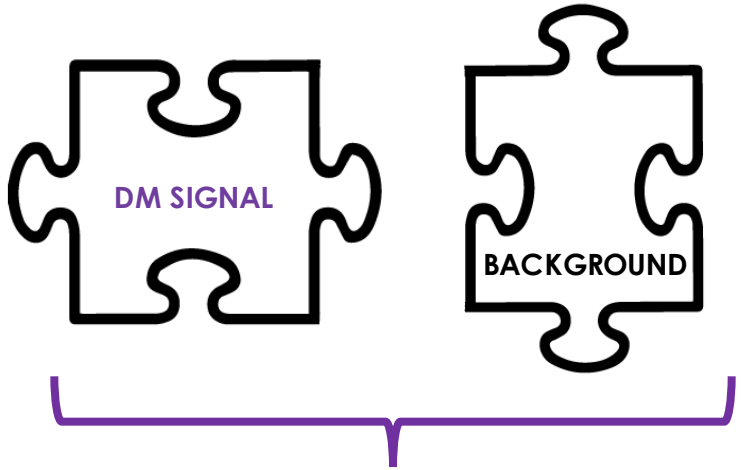
MODULATION

Rate vs. time



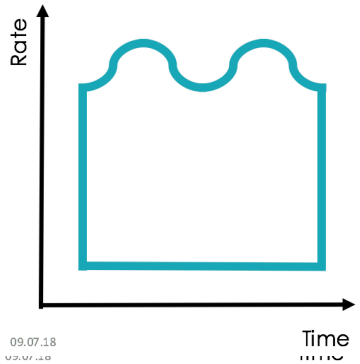
VS.

DUAL CHANNEL



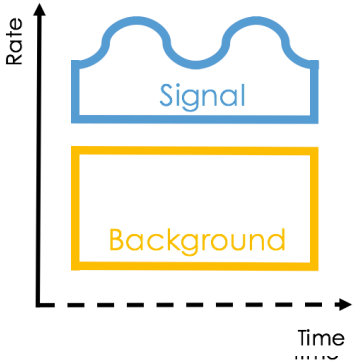
MODULATION

Rate vs. time



COUNTING

Signal above background

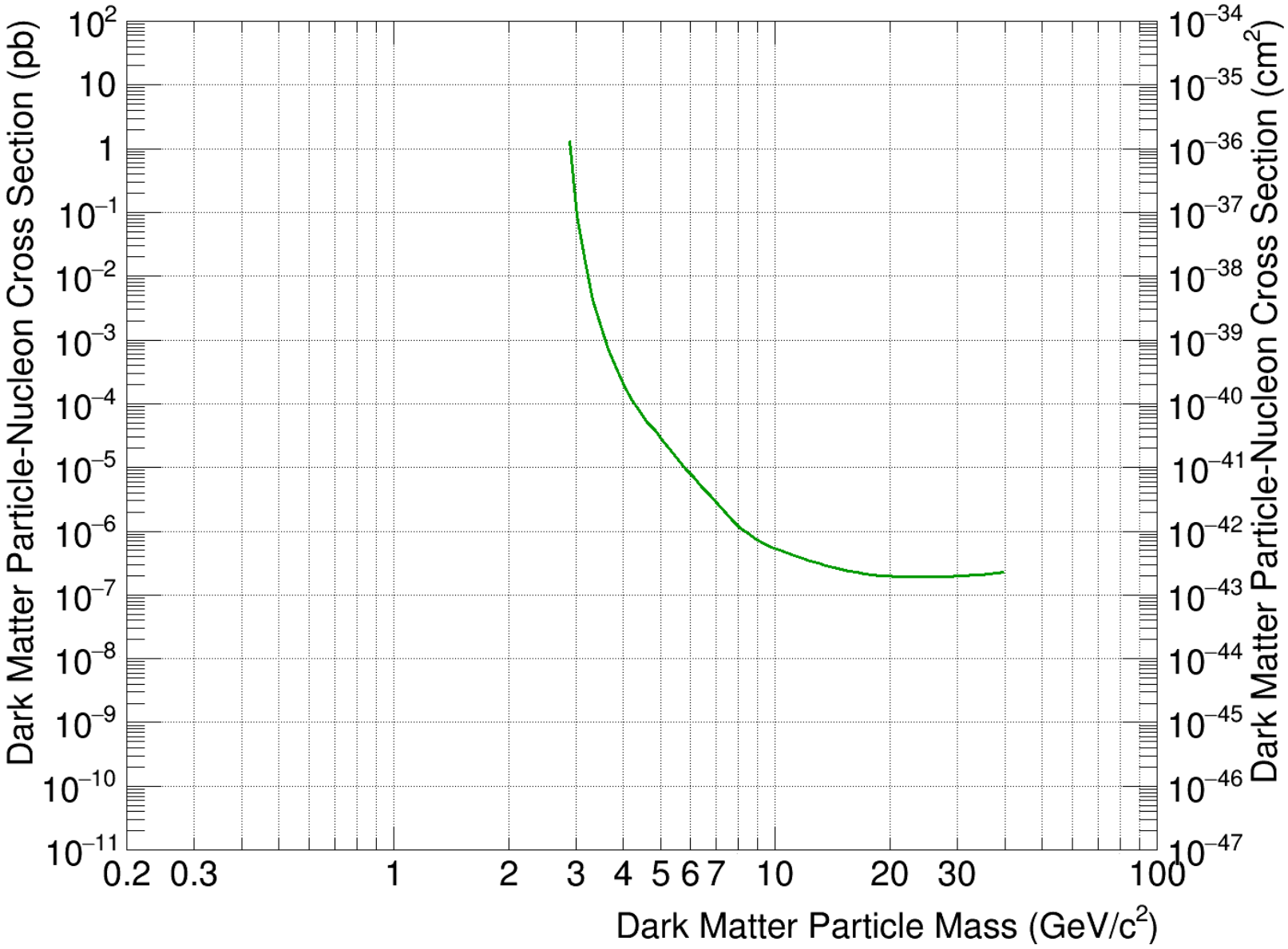


DISCRIMINATION

nuclear recoil events

to β/γ-events

HOW EXPERIMENTS COMPARE RESULTS ?



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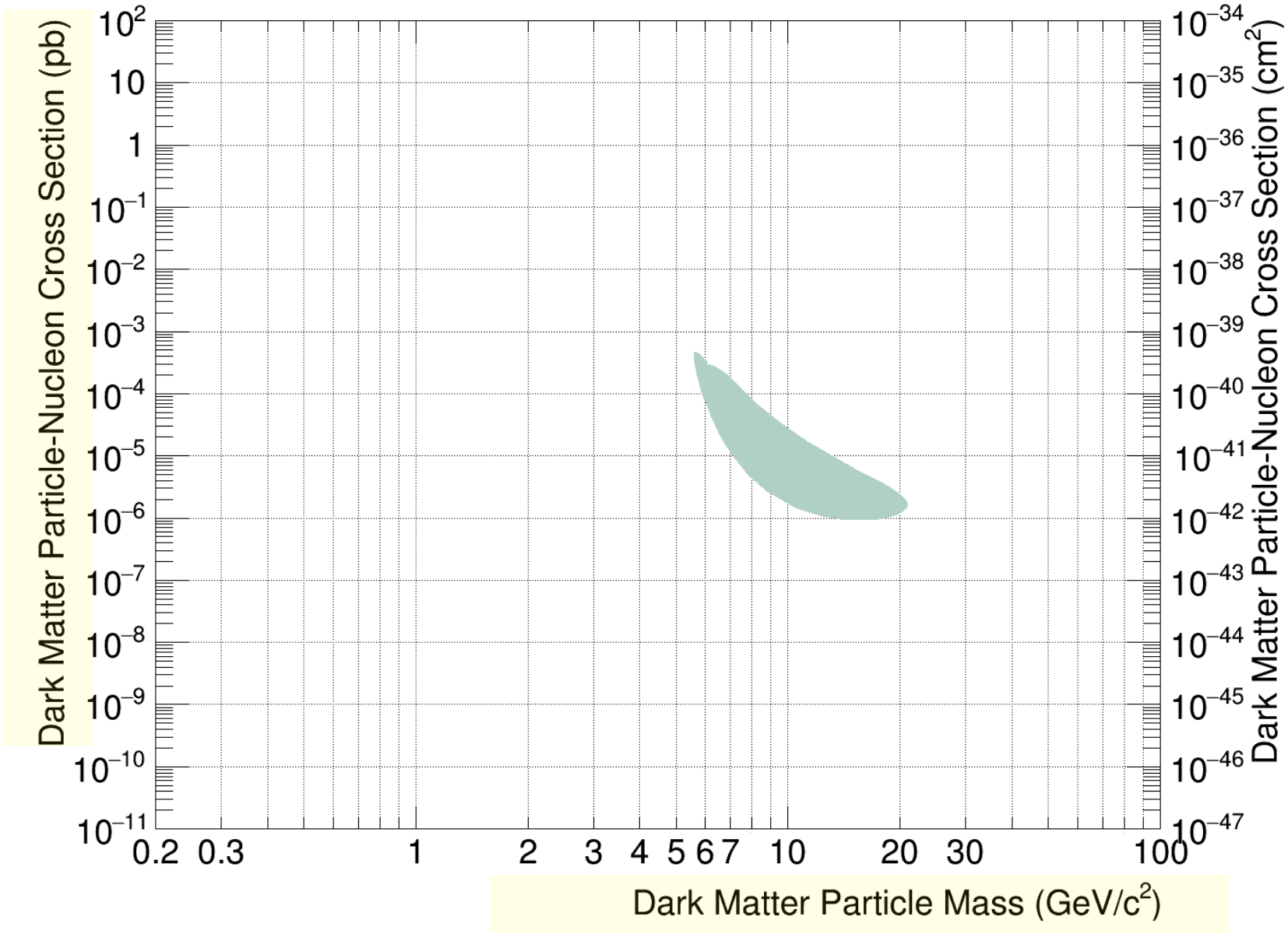
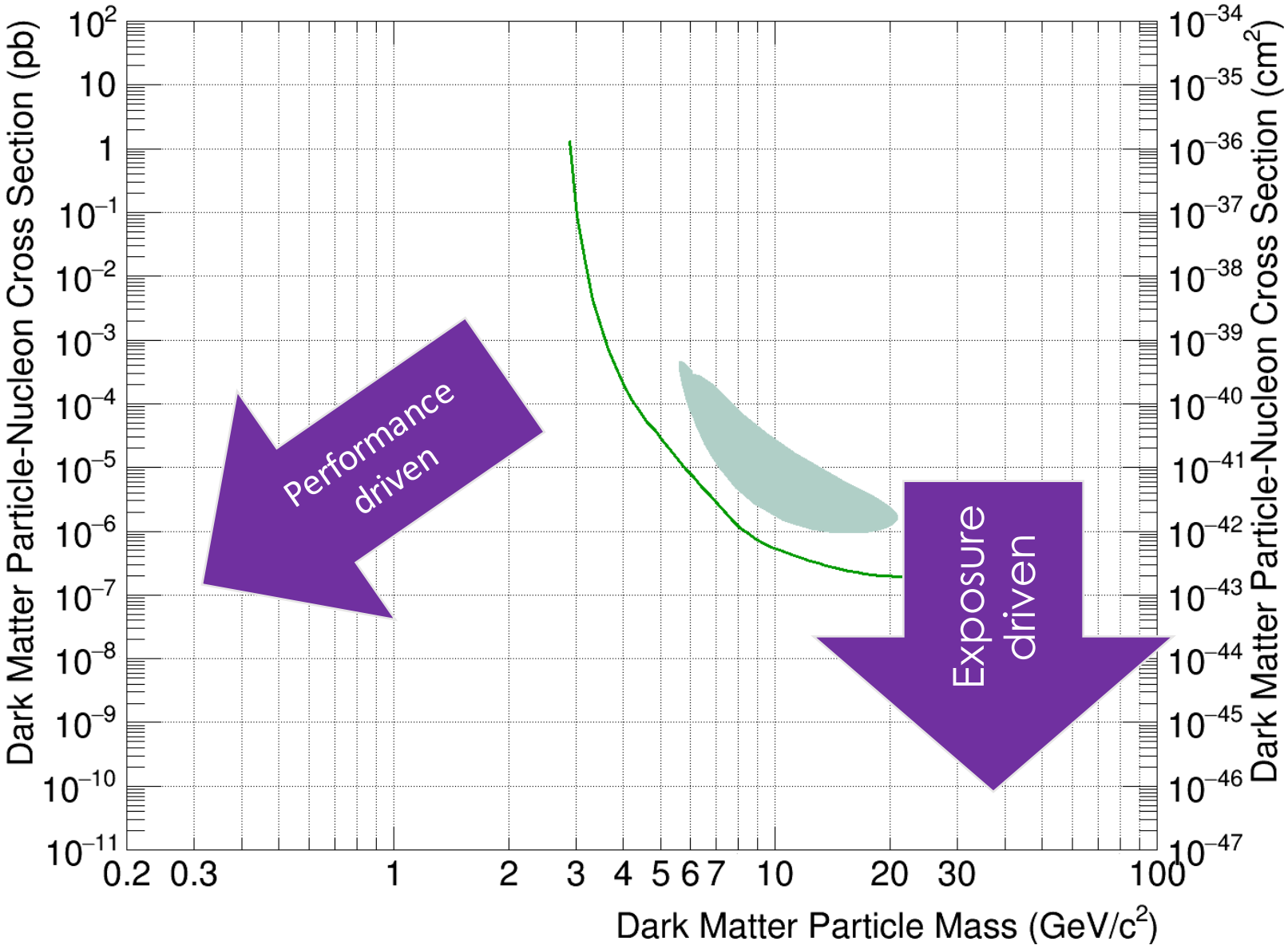
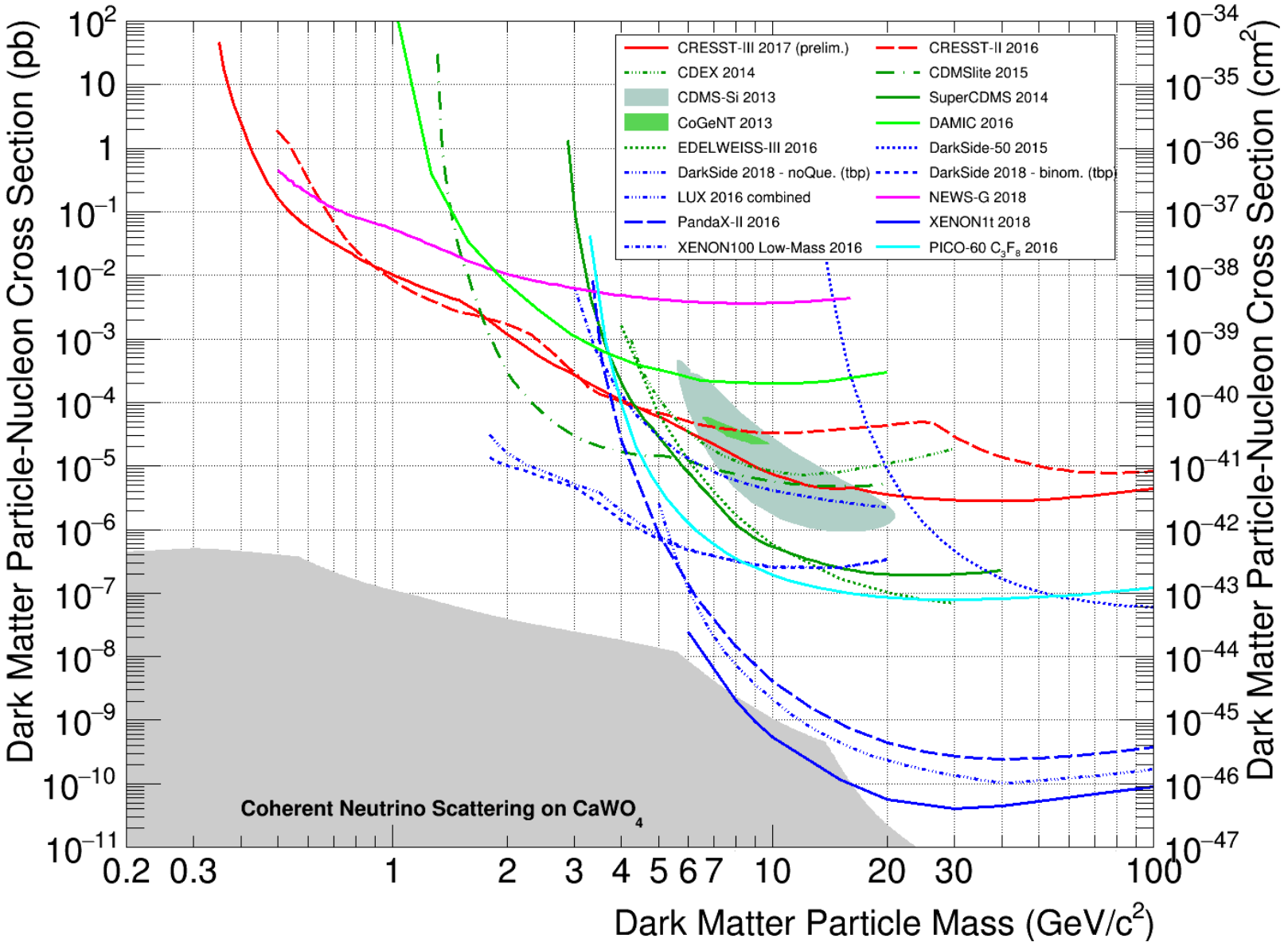


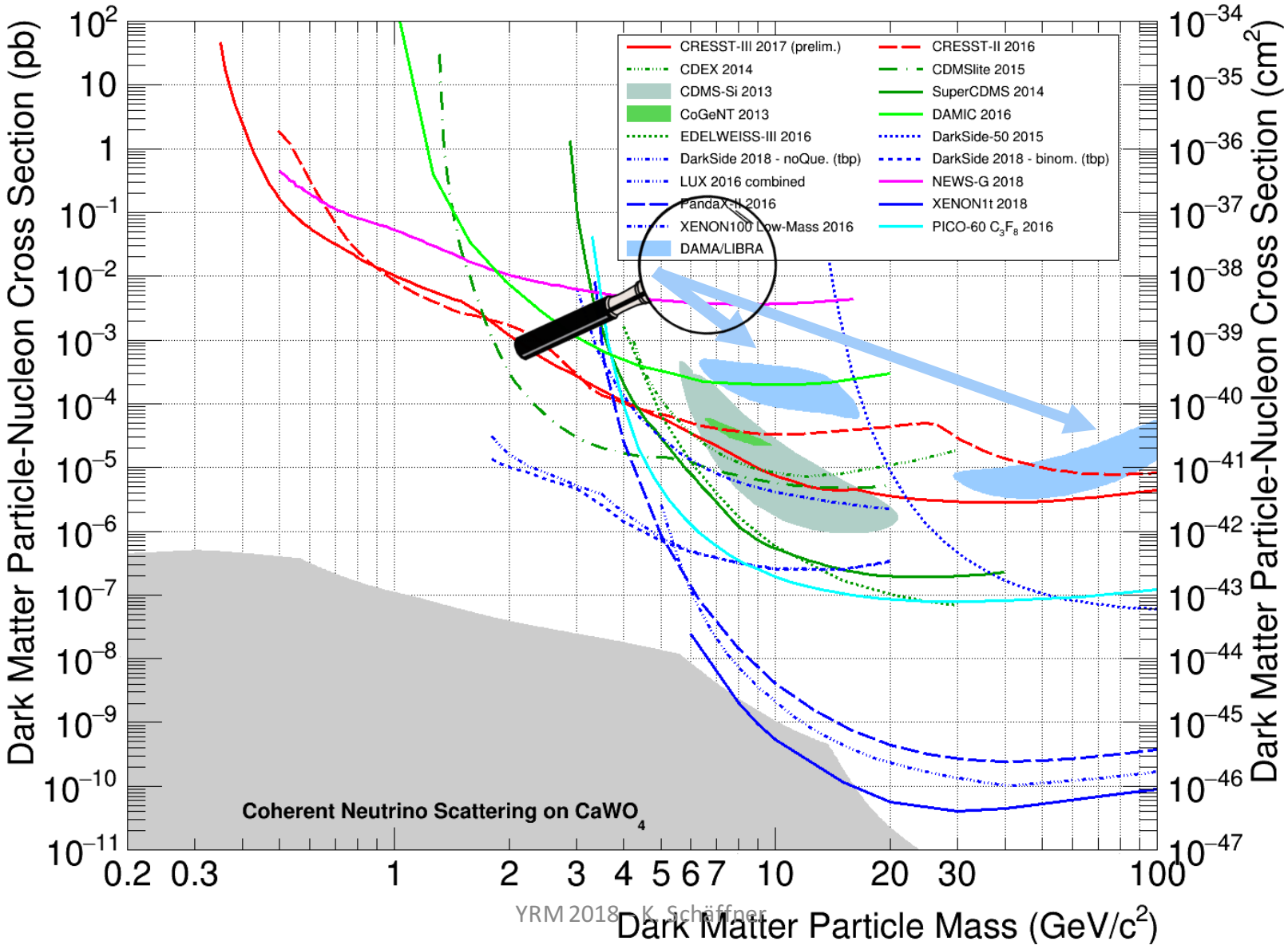
HOW TO IMPROVE ?



PRESENT STATUS OF (NULL)-RESULTS

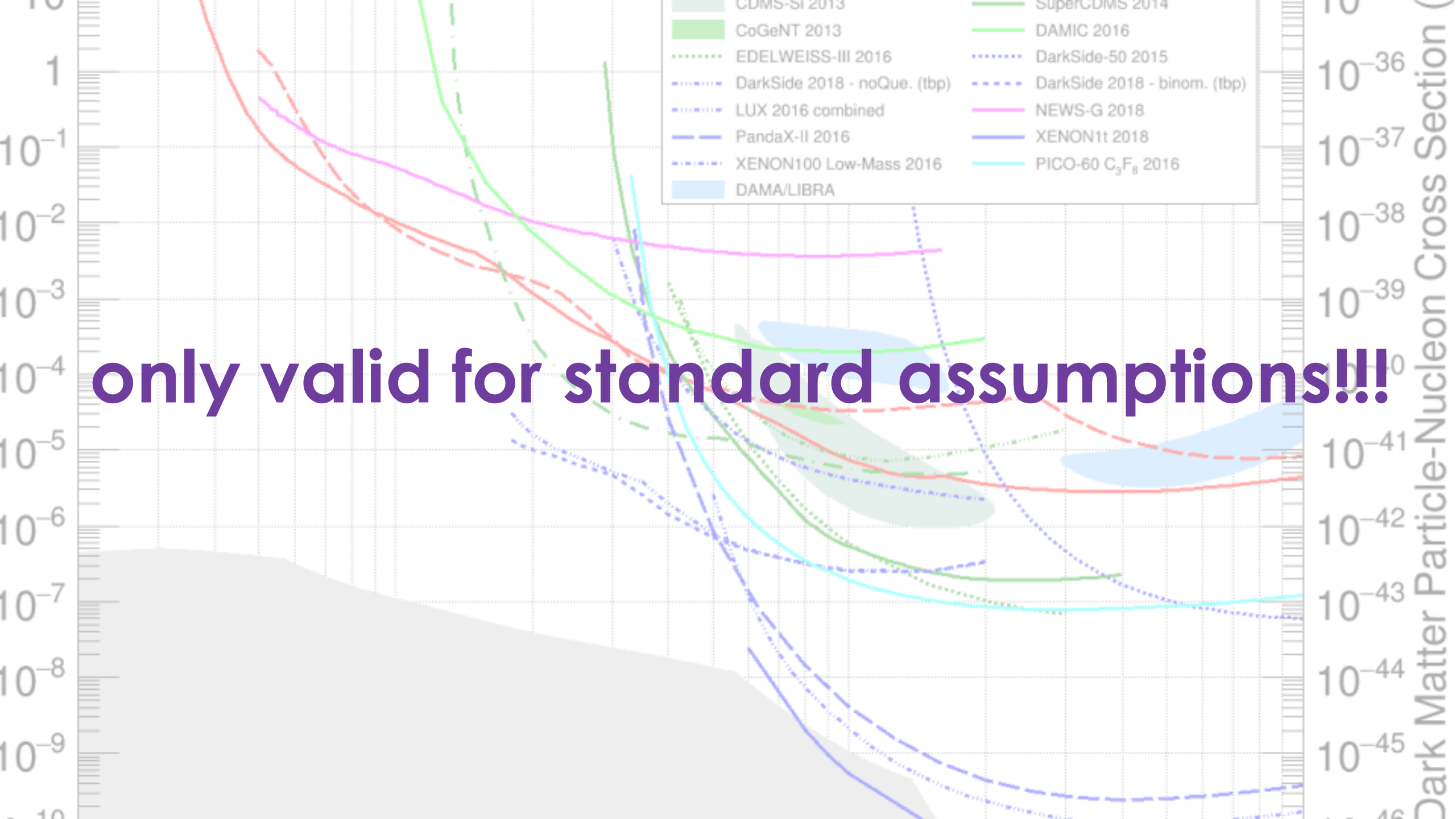


COMPLETE DARK MATTER LANDSCAPE



SUMMARY

- **no sign** of WIMPs down to cross sections $>10^{-46}$ cm^2 @ 30 GeV from LXe experiments like XENON1t, LUX, Panda X
- experiments recently also pushing their performance towards low-mass dark matter (e.g. CRESST III, NEWS-G, SuperCDMS)
- **DAMA's signal creates a contradicting situation !!**



only valid for standard assumptions!!!

WHAT ARE THE **UNKNOWNS**?

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

galactic escape velocity

velocity distribution

DM-nucleus cross-section

minimal velocity to produce a recoil of energy E_r

~ A^2

~ form factor

Astro physics

dark matter halo

velocity distribution

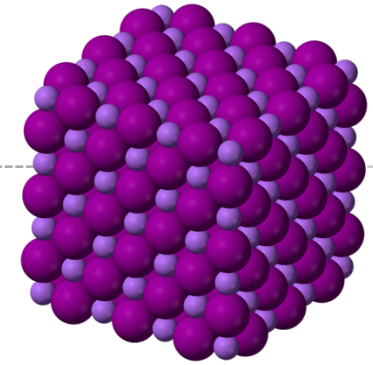
Particle physics

interaction mechanism

We have a dependence on the target material

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

NaI as TARGET MATERIAL

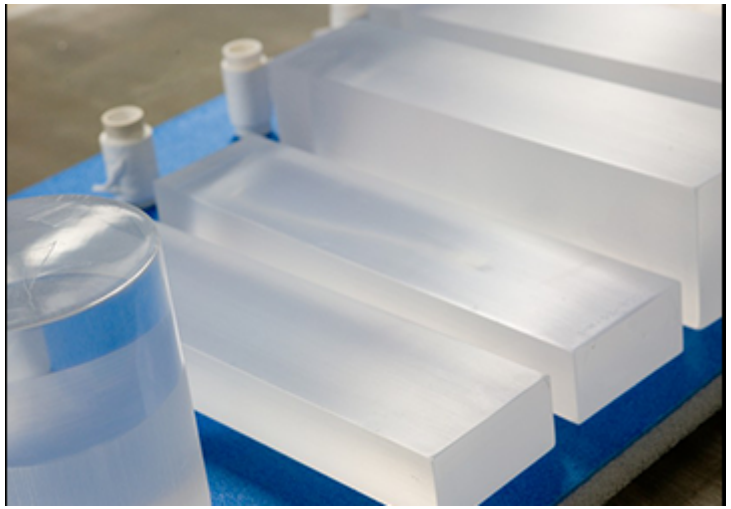


^{11}Na

53I

Sodium Iodide

- multi-target compound: **light Na** and **heavy I**
- very good scintillator at room temperature (> 15 P.E. / keV)
- NaI doped with thallium has suitable wavelength for Photomultipliers (PMTs)
- crystal is "easy" to grow and available as >10 kg blocks

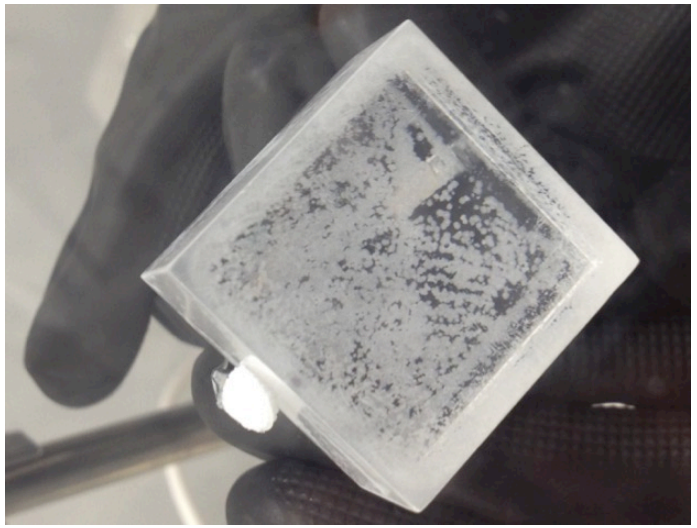


NaI

… but NaI is not that Nalce!

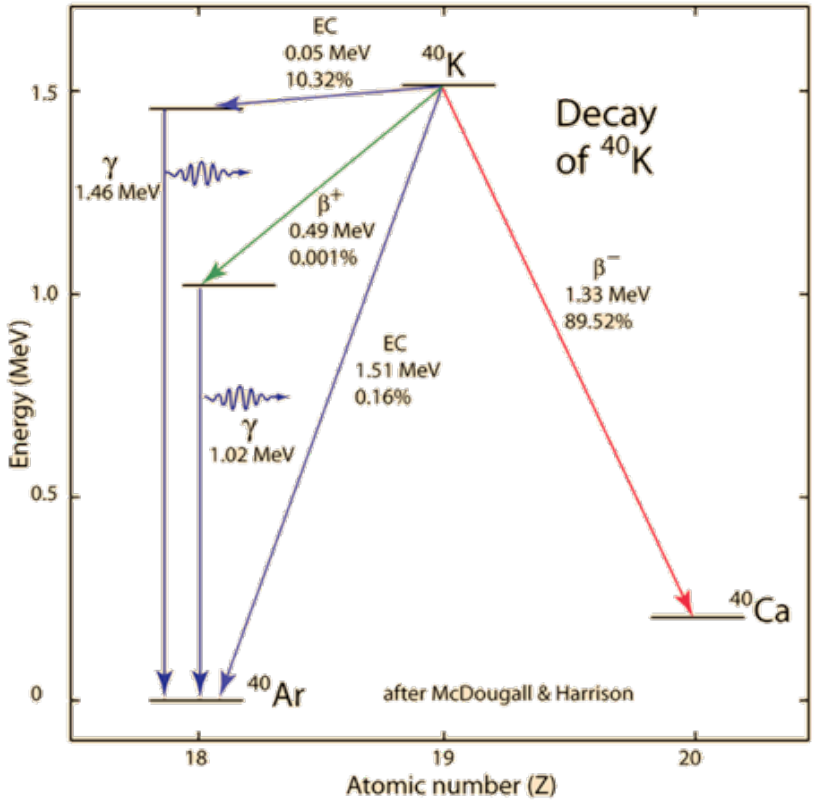
- hygroscopic nature

handle in controlled atmosphere

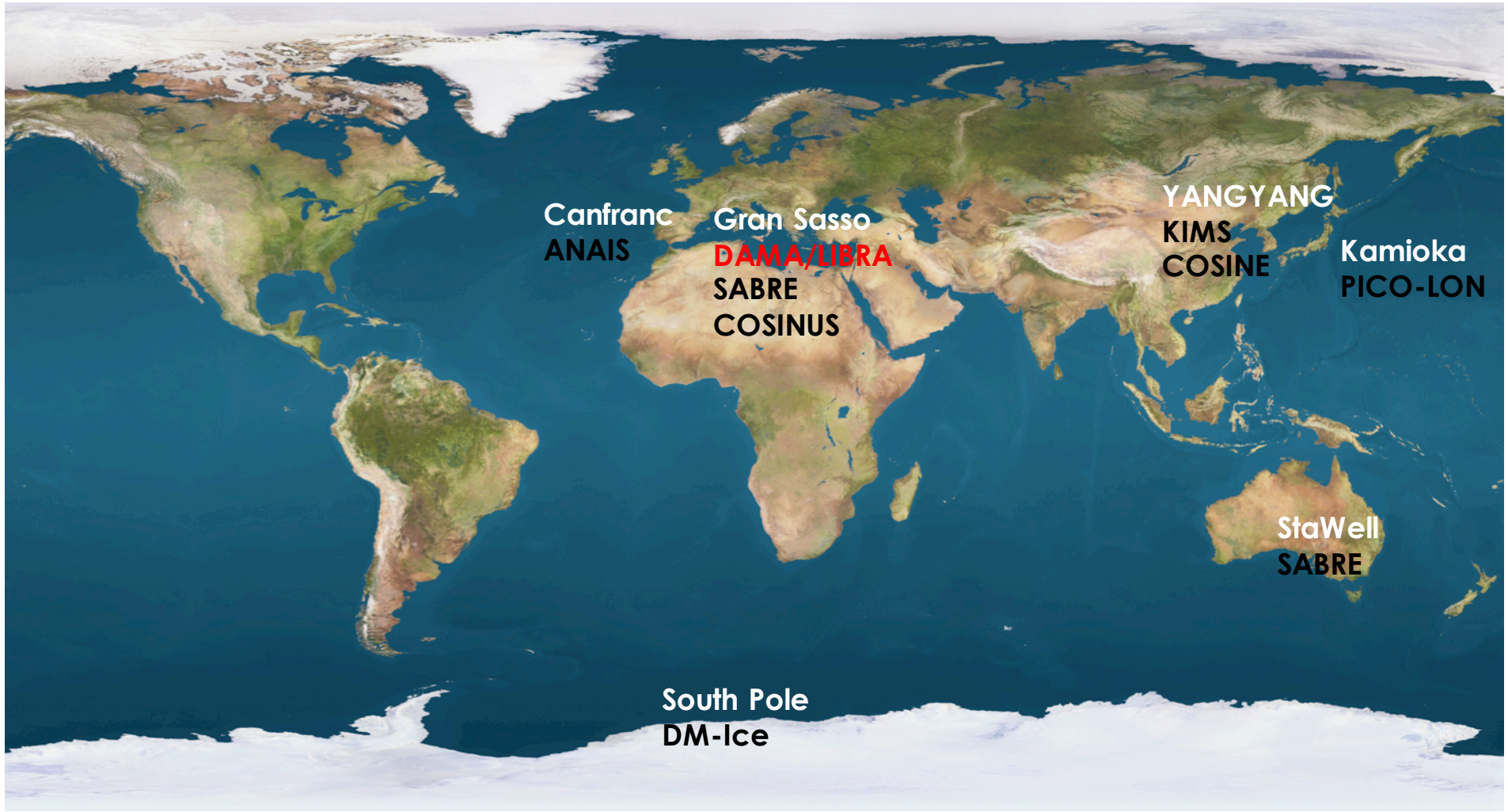


- typically high contamination with ^{40}K

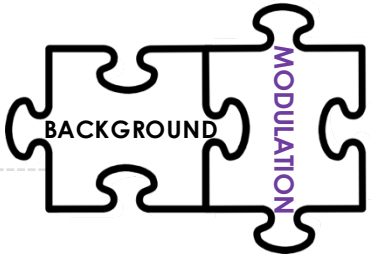
dangerous background is the **3 keV Auger electrons** emitted together with the 1.46 MeV gamma



GLOBAL NaI EFFORTS

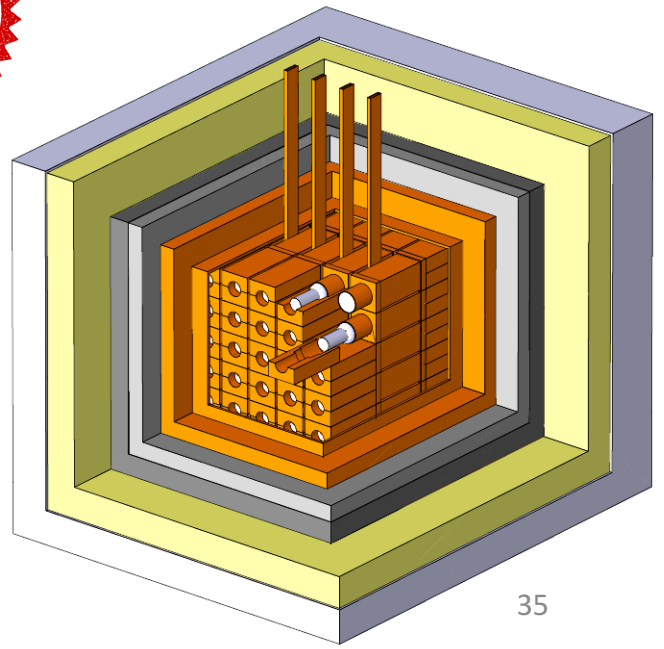


DAMA/LIBRA experiment



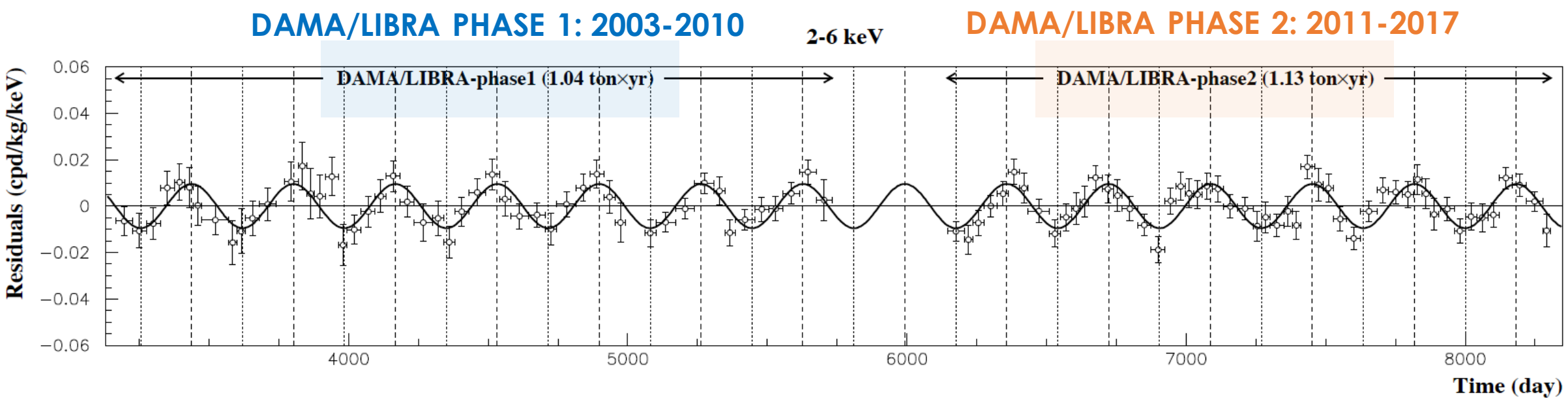
MATERIAL	250 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	**1keVee**
DATA TAKING	since 1996
EVIDENCE	yes

ChristianImages123.com



DAMA/LIBRA: **TIME DISTRIBUTION**

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



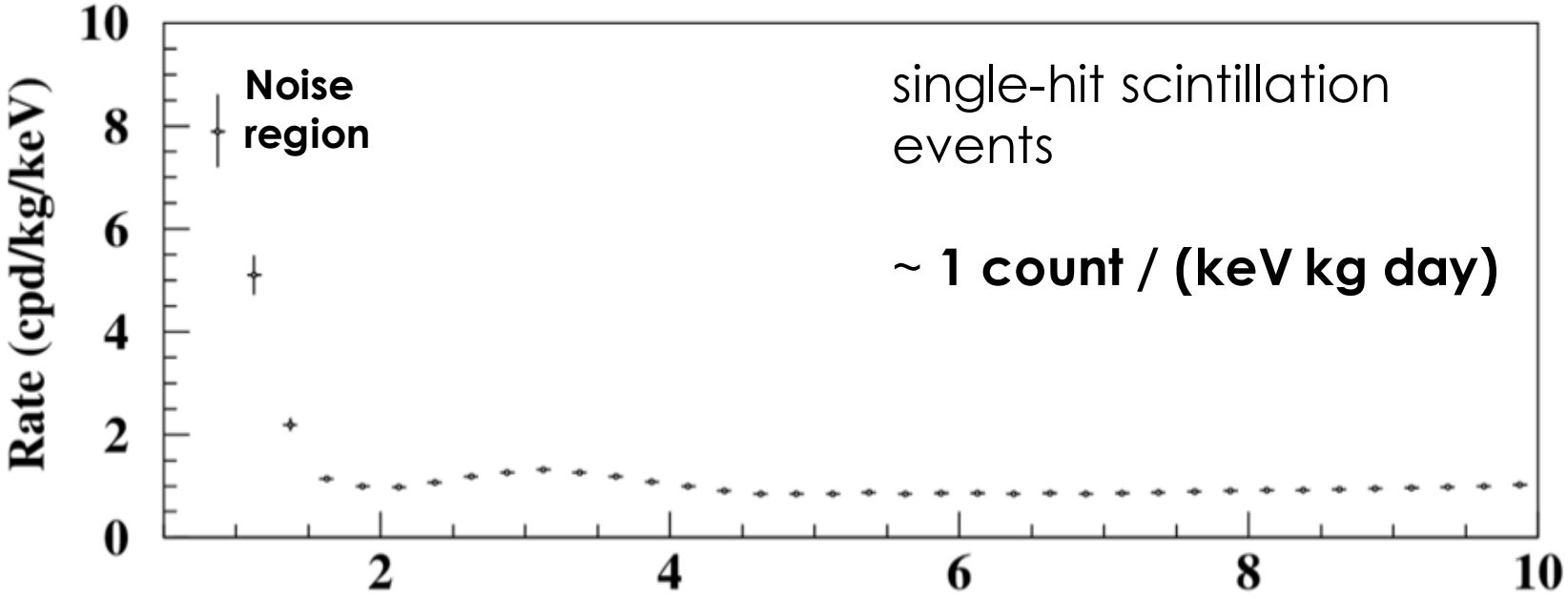
Total exposure: 2.17 tonne years (phase 1 + 2)
Statistical significance: >11.9 σ

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

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

DAMA/LIBRA: **ENERGY SPECTRUM**

DAMA/LIBRA PHASE 1



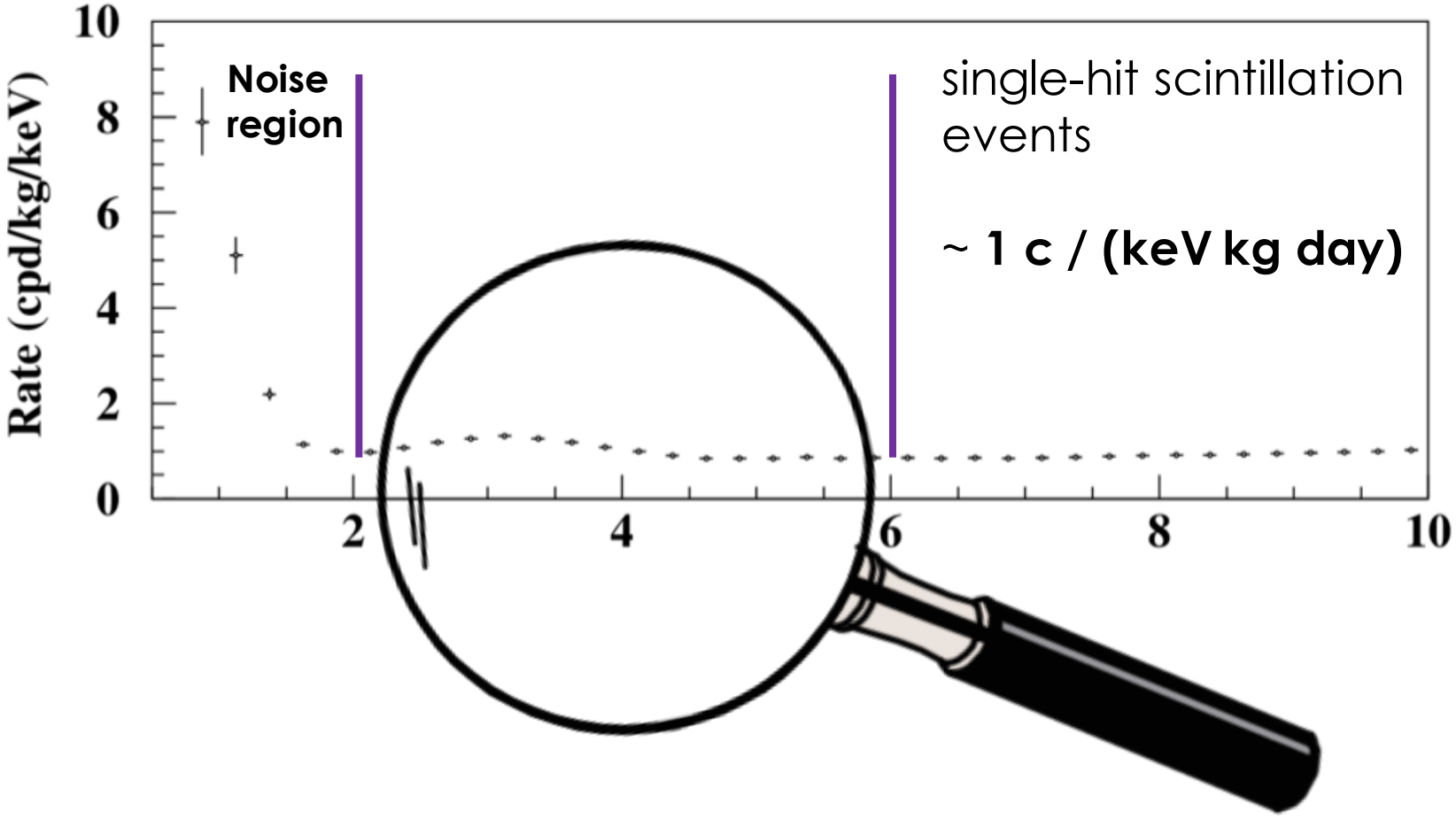
DAMA/LIBRA BACKGROUND

^{40}K	**< 20 ppb**
^{238}U	< 0.7-10 ppt
^{232}Th	< 0.5-7.5 ppt
^{210}Po	< 0.5 mBq/kg

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

DAMA/LIBRA: **ENERGY SPECTRUM**

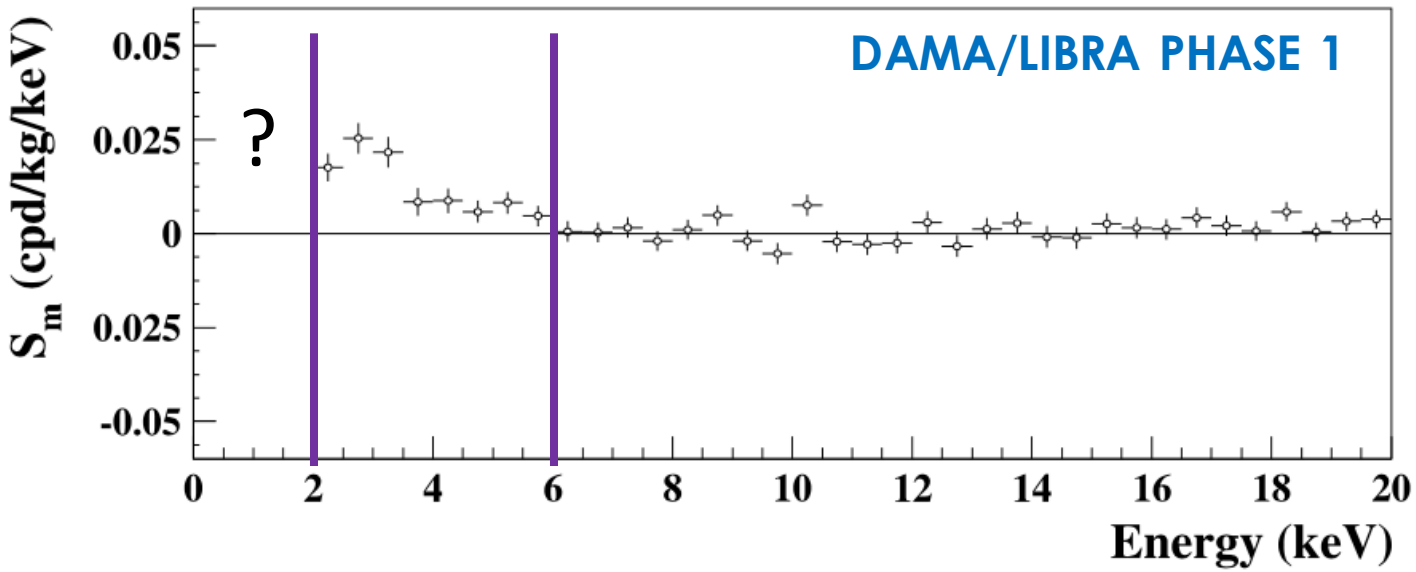
DAMA/LIBRA PHASE 1



Modulation signal in energy window: 2-6 keV_{ee}

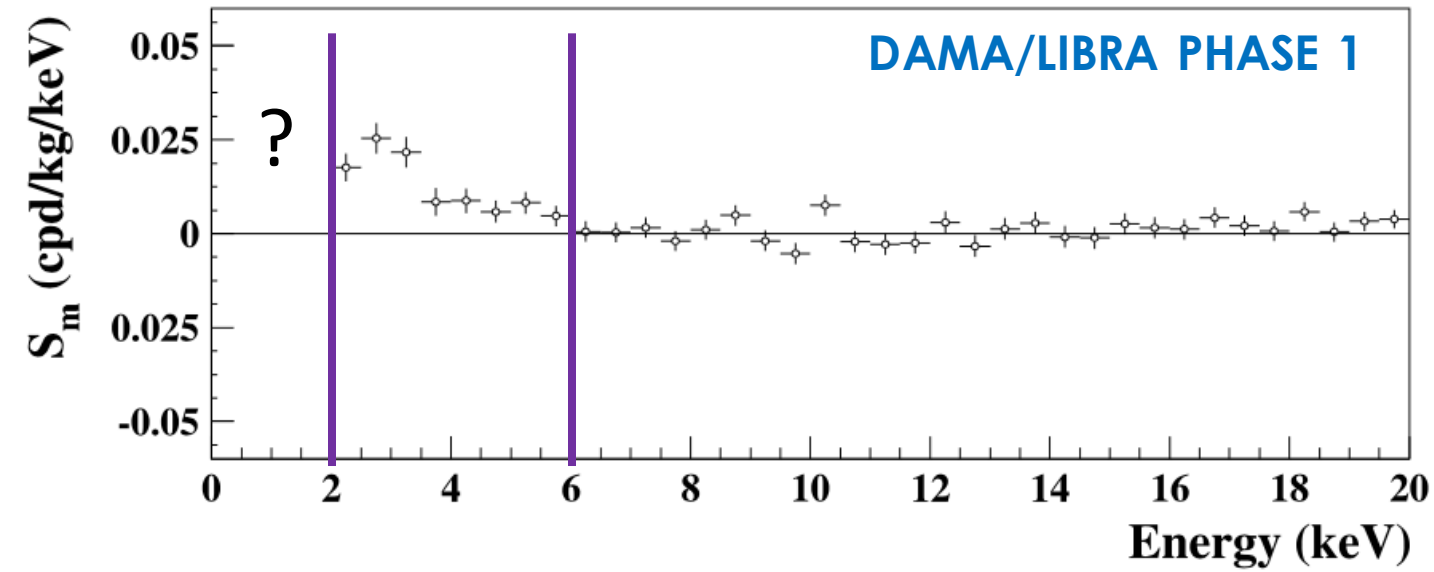
Plot from: Bernabei et al. EPJ (2013) 73:2648

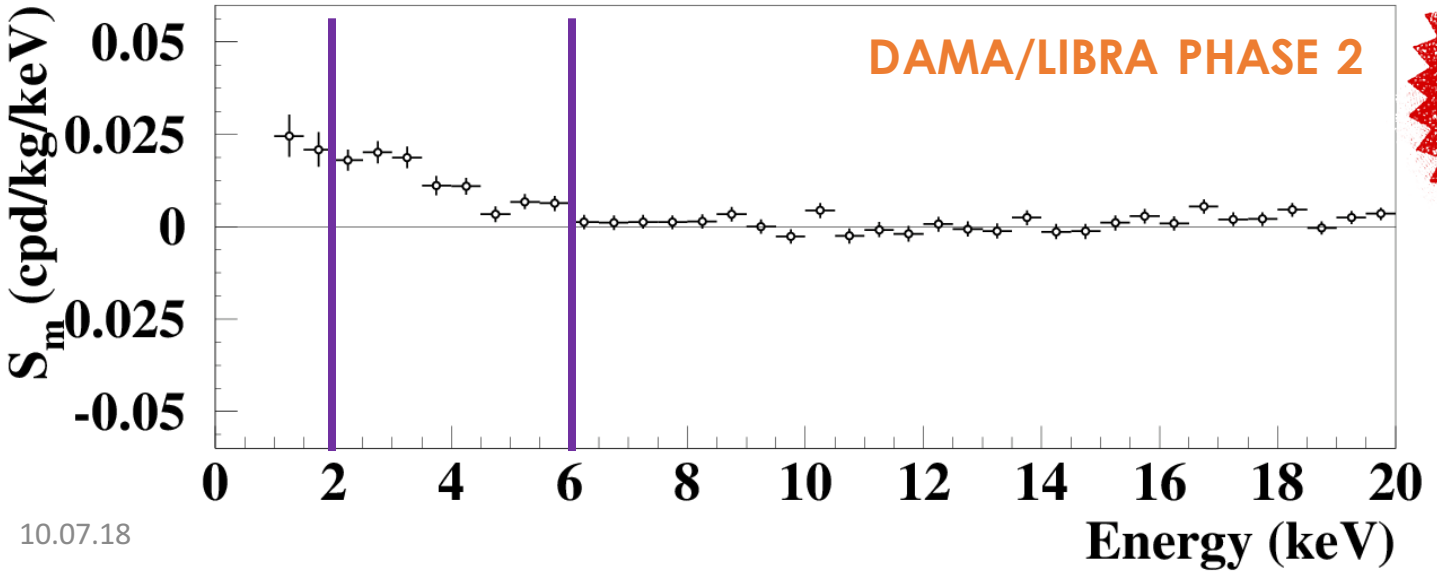
DAMA/LIBRA: **ENERGY DISTRIBUTION**



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

DAMA/LIBRA: **ENERGY DISTRIBUTION**

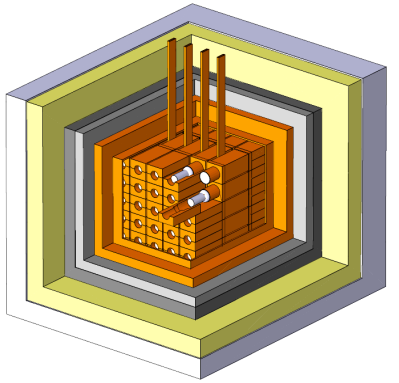




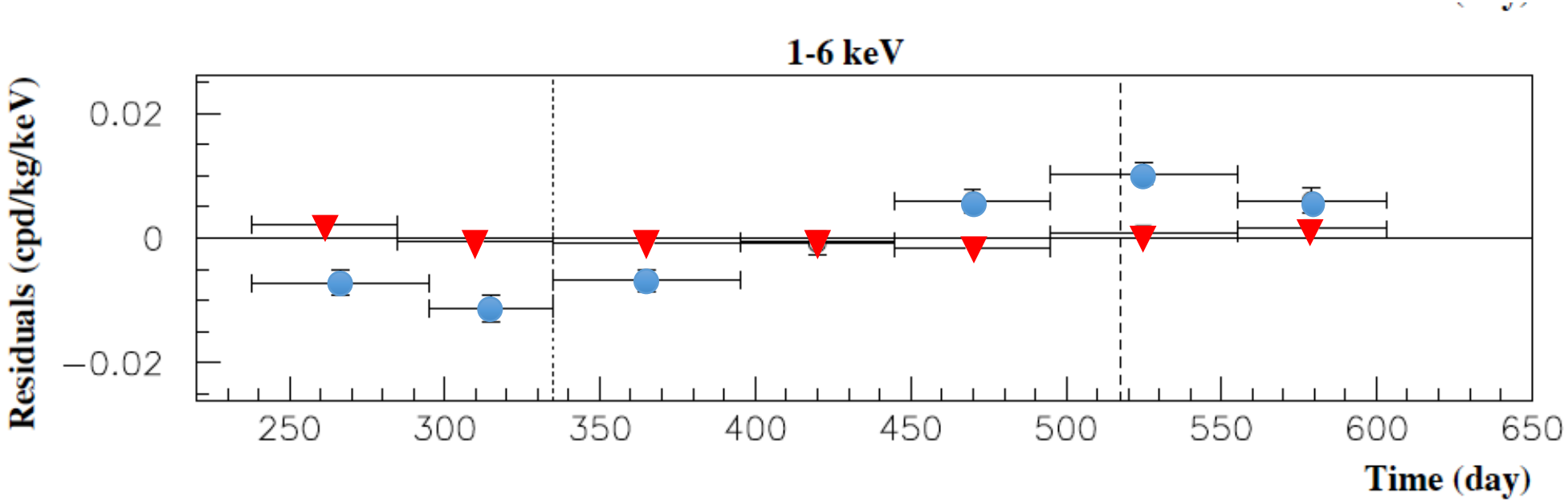
Plot from: Bernabei et al. EPJ (2013) 73:2648
Plot from: LNGS, SC Meeting, 04/2018

energy threshold lowered to 1keV$_{ee}$

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



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



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

THE SMOKING GUN EVIDENCE?

Statistics: > 11σ ✓

Period: 0.999 ± 0.001 years * ✓

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

Convincing non-DM explanation ✗

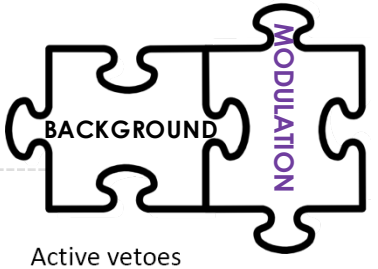
*in (2-6) keVee interval

MUST HAVE TO PROOF DAMA/LIBRA

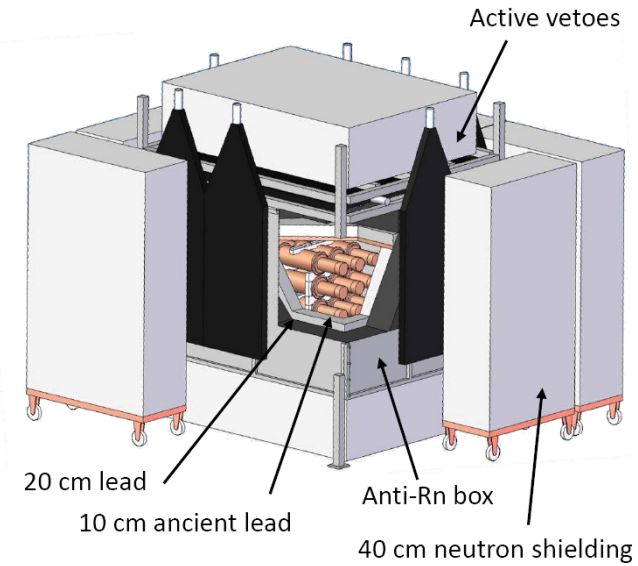
- energy threshold of < 2 keVee
- radiopure crystal: ~ 1 count / (keV kg day)
- large detector mass $\mathcal{O}$ (100 kg)

- active veto to reject background from ^{40}K
- muon veto to reject muon-induced background
- particle discrimination
  (nuclear recoils – electron/gammas)

ANAIS-112 experiment



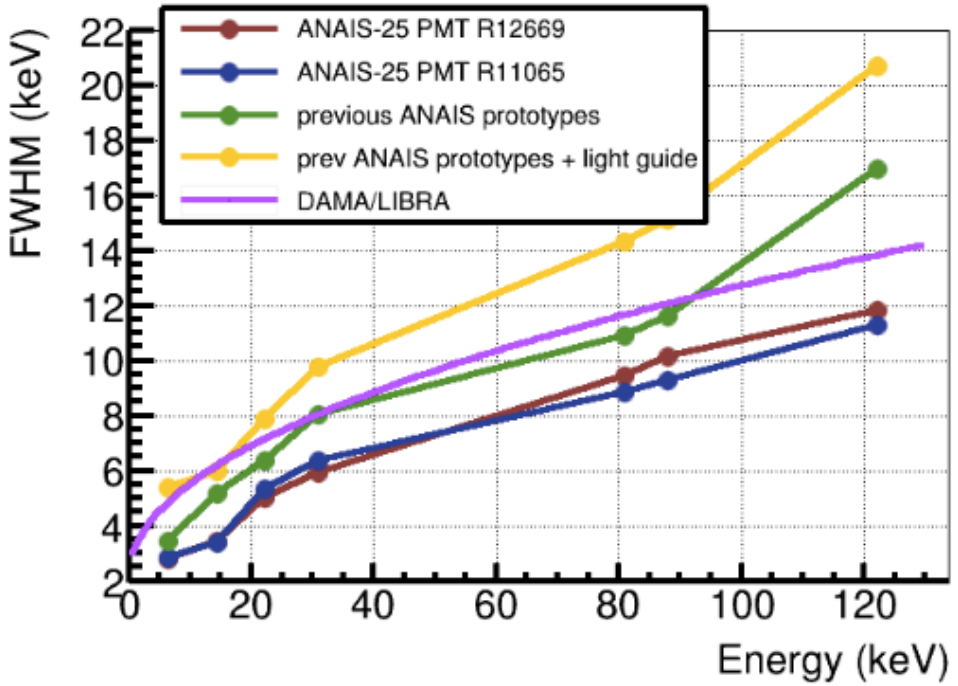
MATERIAL	112 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	Canfranc/Spain
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	~ 0.9 keVee
DATA TAKING	since 2017
BONUS	muon veto



ChristianImages123.com

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

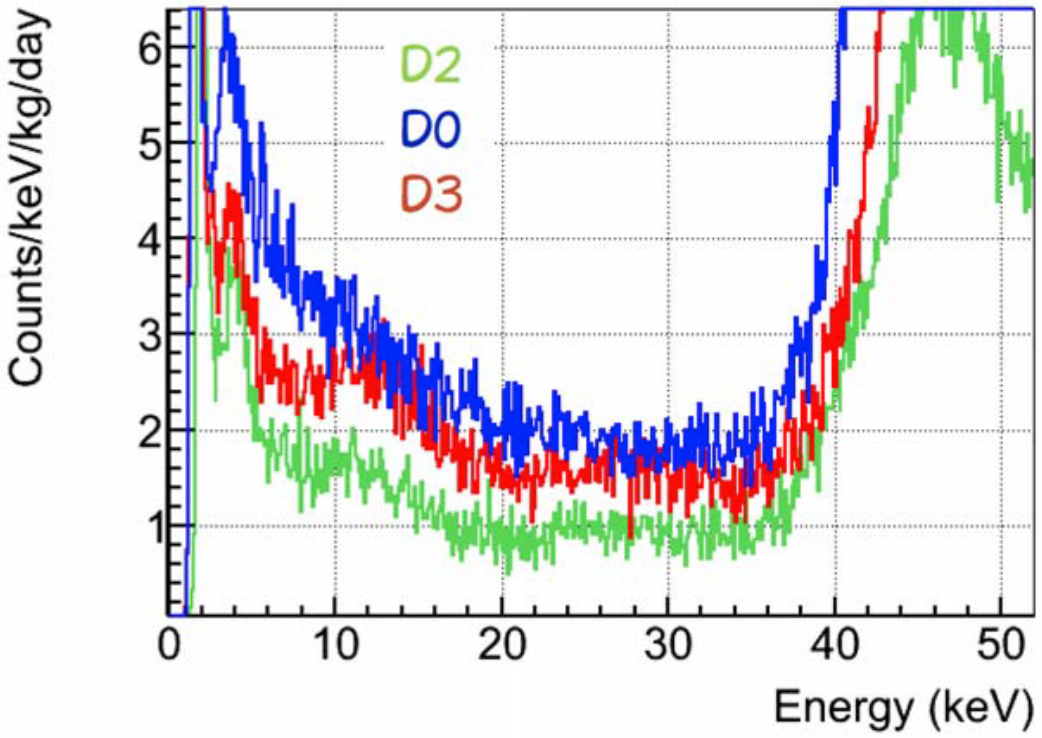
→ good energy resolution

→ **low threshold: < 1 keVee**

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)

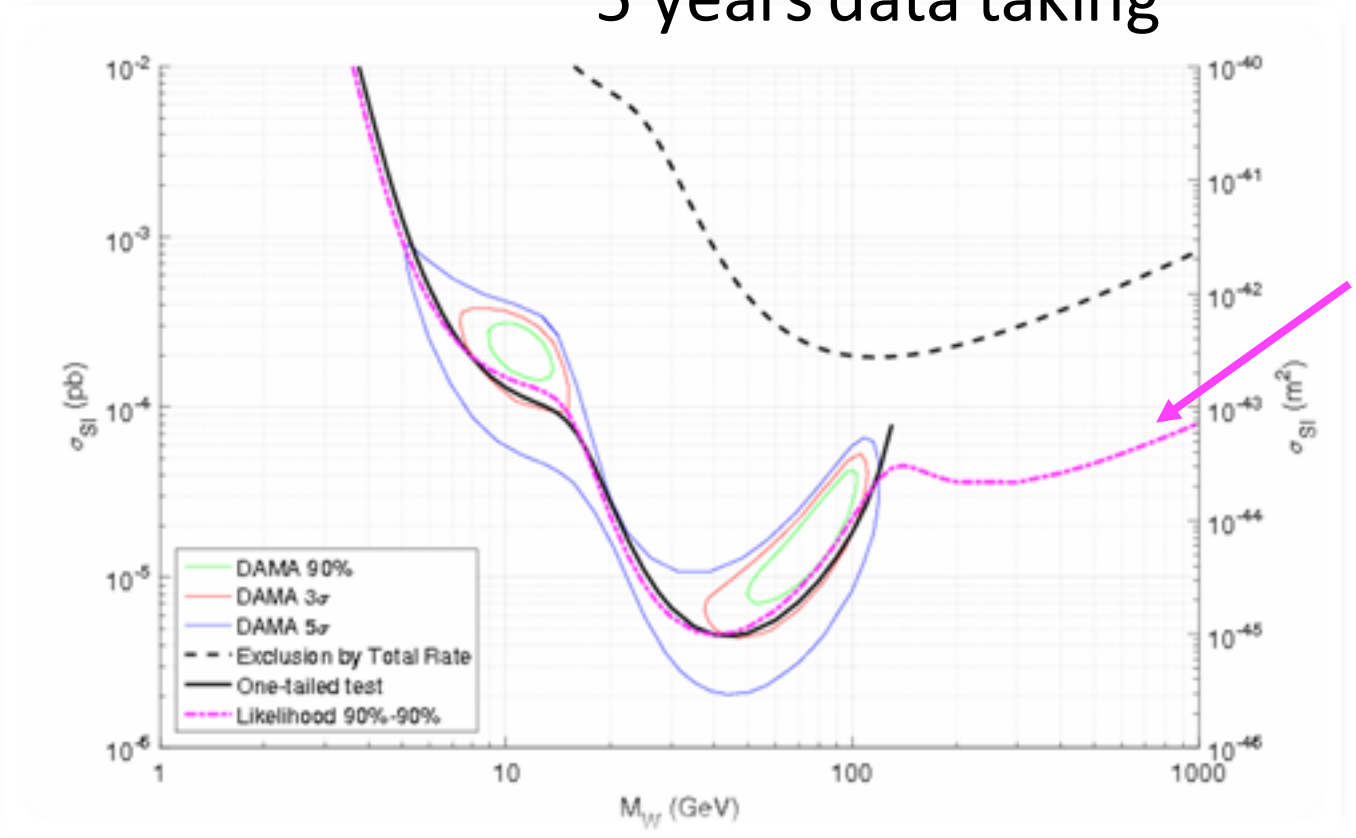
Detector	^{40}K (mBq/kg)	^{210}Pb (mBq/kg)
D0	1.1	3.15
D1	1.4	3.15
D2	0.9	0.70
D3	0.7	1.8
D4	1.0	1.8
D5	1.0	0.75
D6	1.1	0.76
D7	1.0	0.75
D8	0.6	0.72
average	**1.0**	**1.5**

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

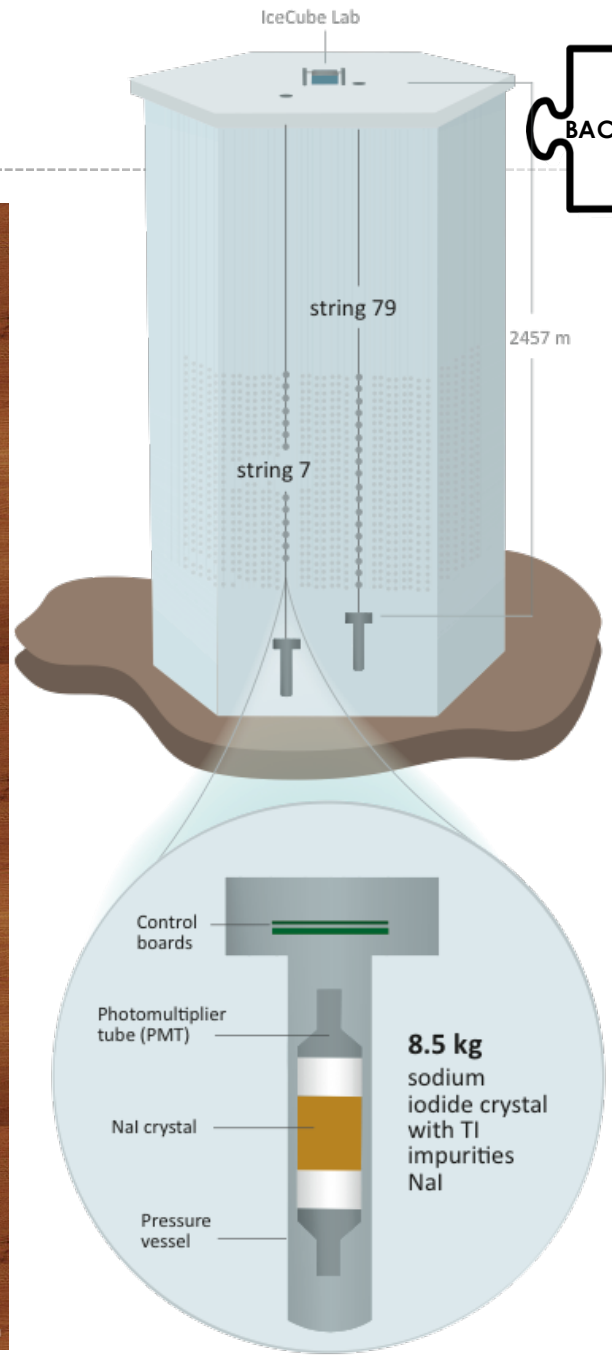


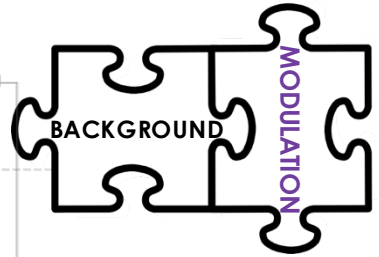
90% probability of detecting an annual modulation signal at 90% C.L.

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

DM-Ice experiment

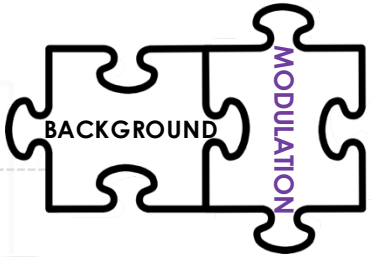
MATERIAL	17 kg NaI(Tl)
SIGNAL(s)	Light (PMTs)
LOCATION	south pole
β/γ-DISCRIMINATION	no
ENERGY THRESHOLD	4 keVee
DATA TAKING	since 2011
EVIDENCE	no





ChristianImages123.com

DM-Ice experiment



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

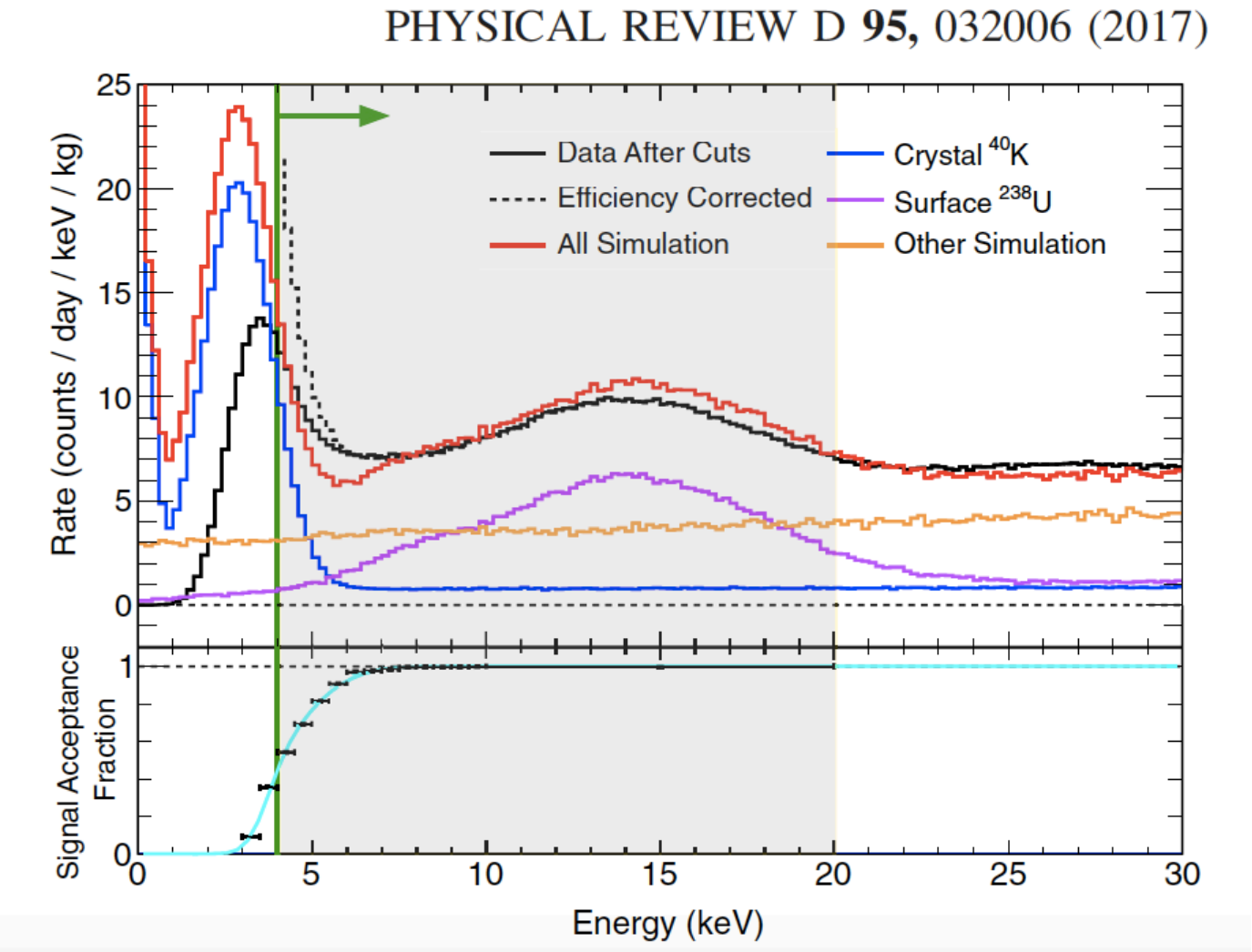
keep DM modulation, but reverse seasonal effects

DM-Ice is first search in the southern hemisphere

ChristianImages123.com

DM-Ice: **BACKGROUND**

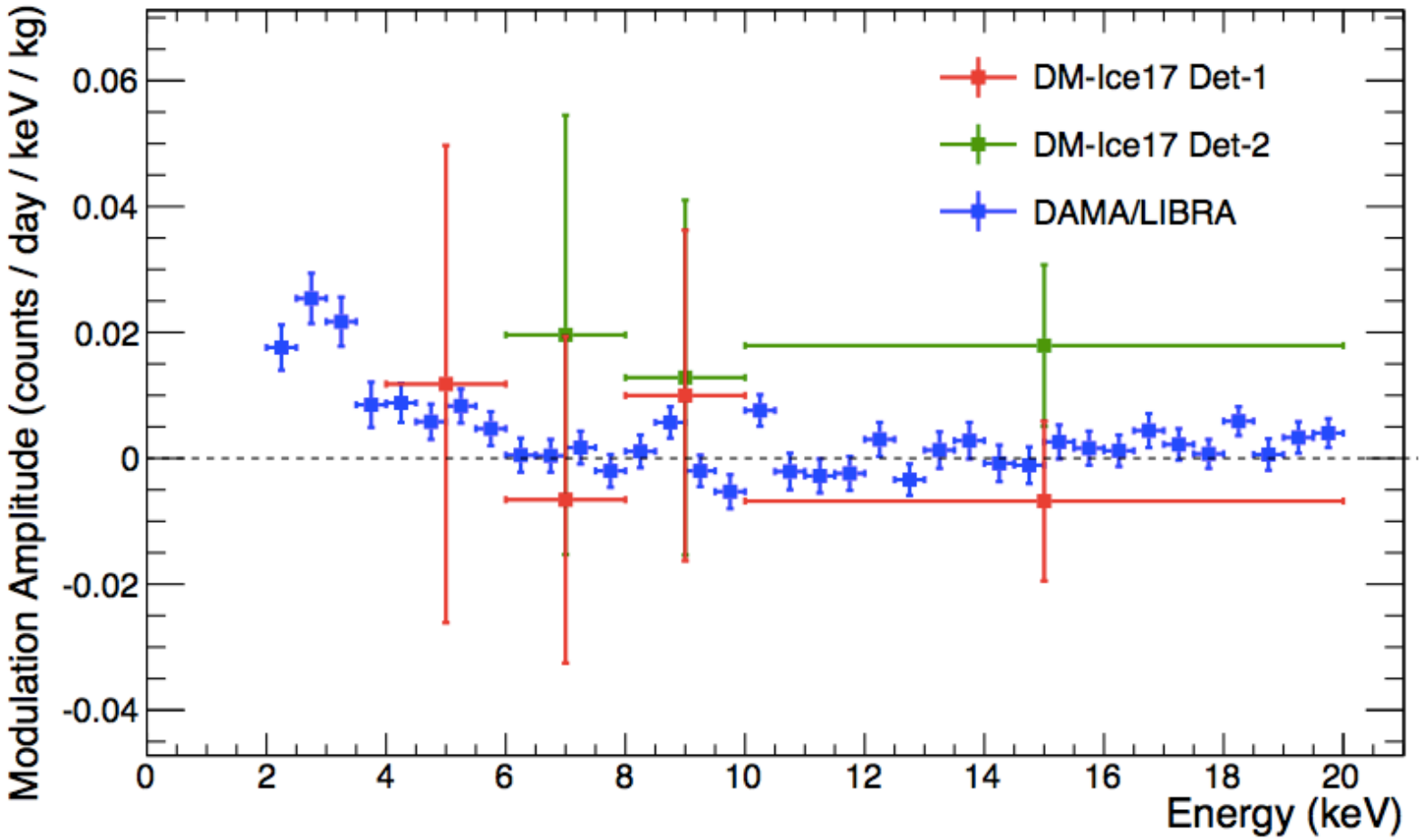
E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006 (2017)



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

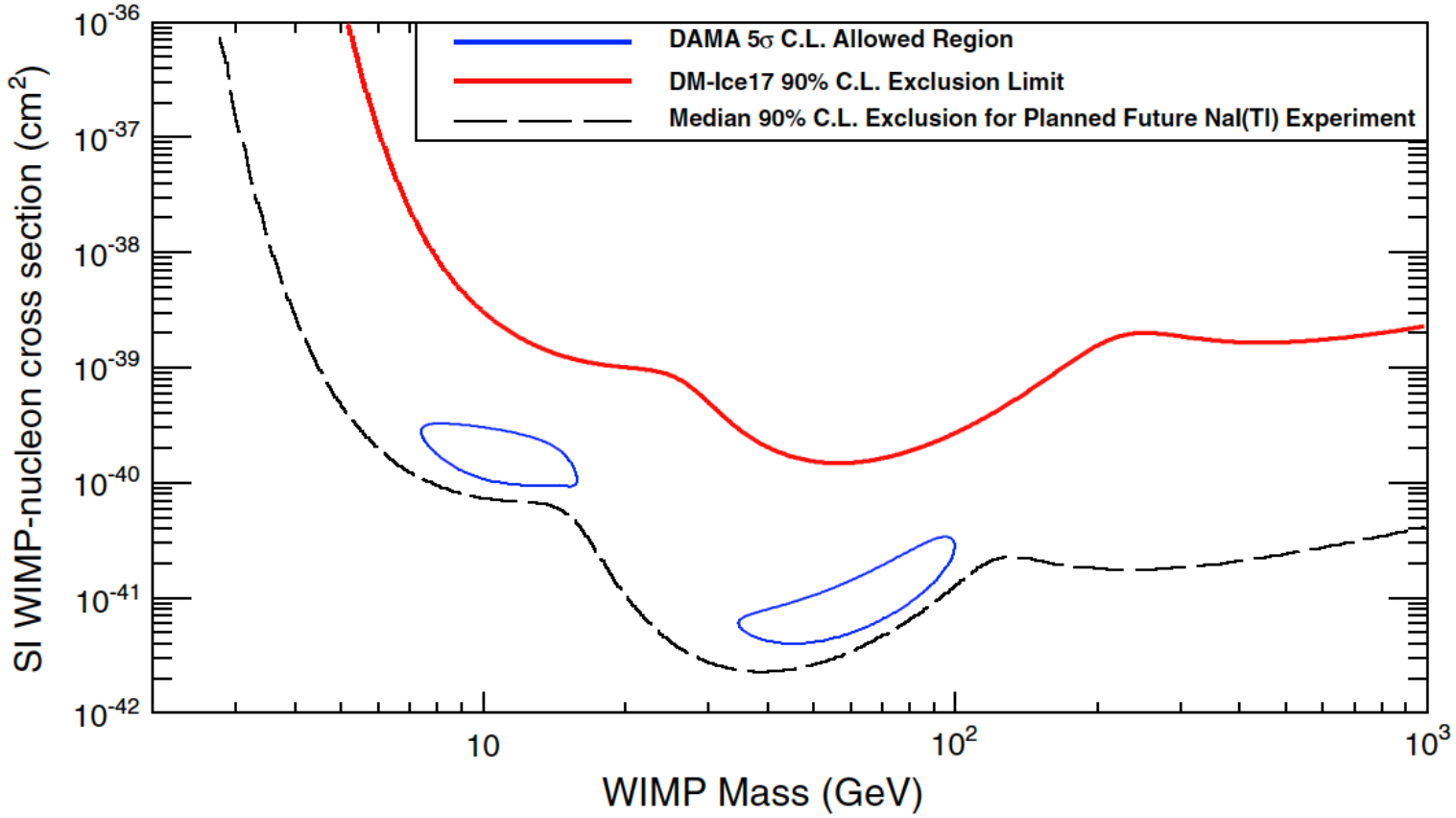
DM-Ice **results**

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



DM-Ice: **SENSITIVITY**

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

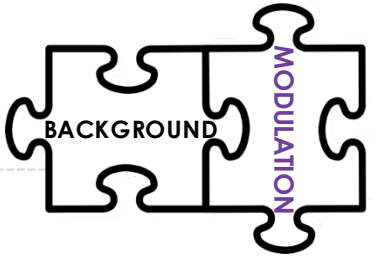


dashed black line:

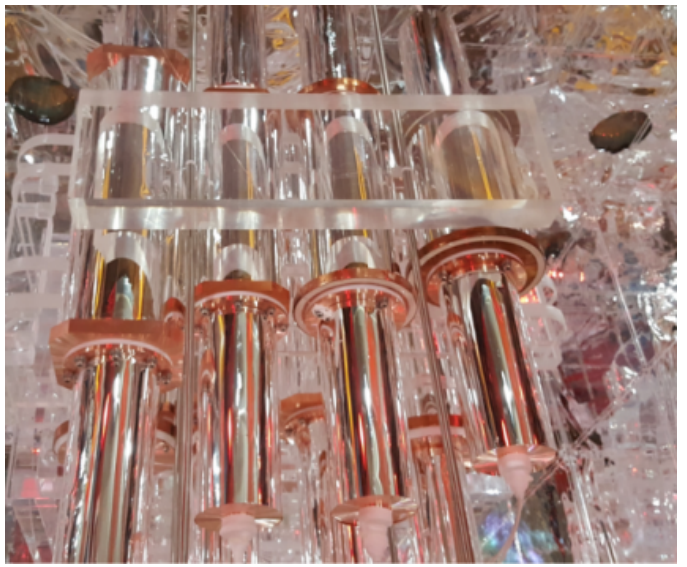
future NaI(Tl)-based search

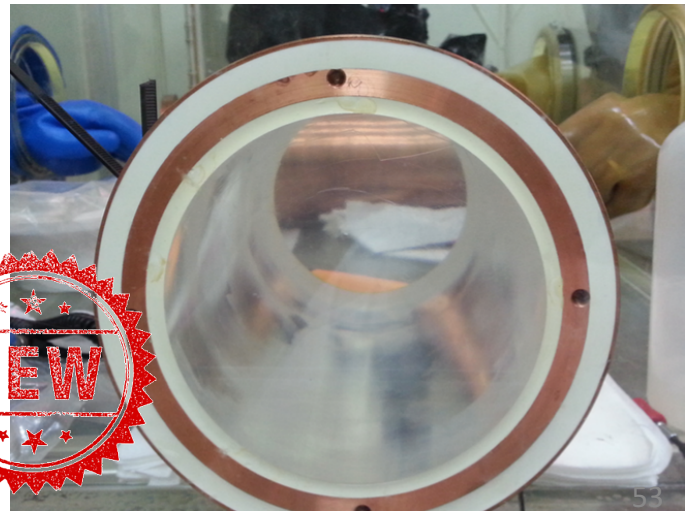
- 2 counts/ (day keV kg)
- 500 kg year
- 2 keVee analysis threshold

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
BONUS	liquid scintillator veto, muon veto

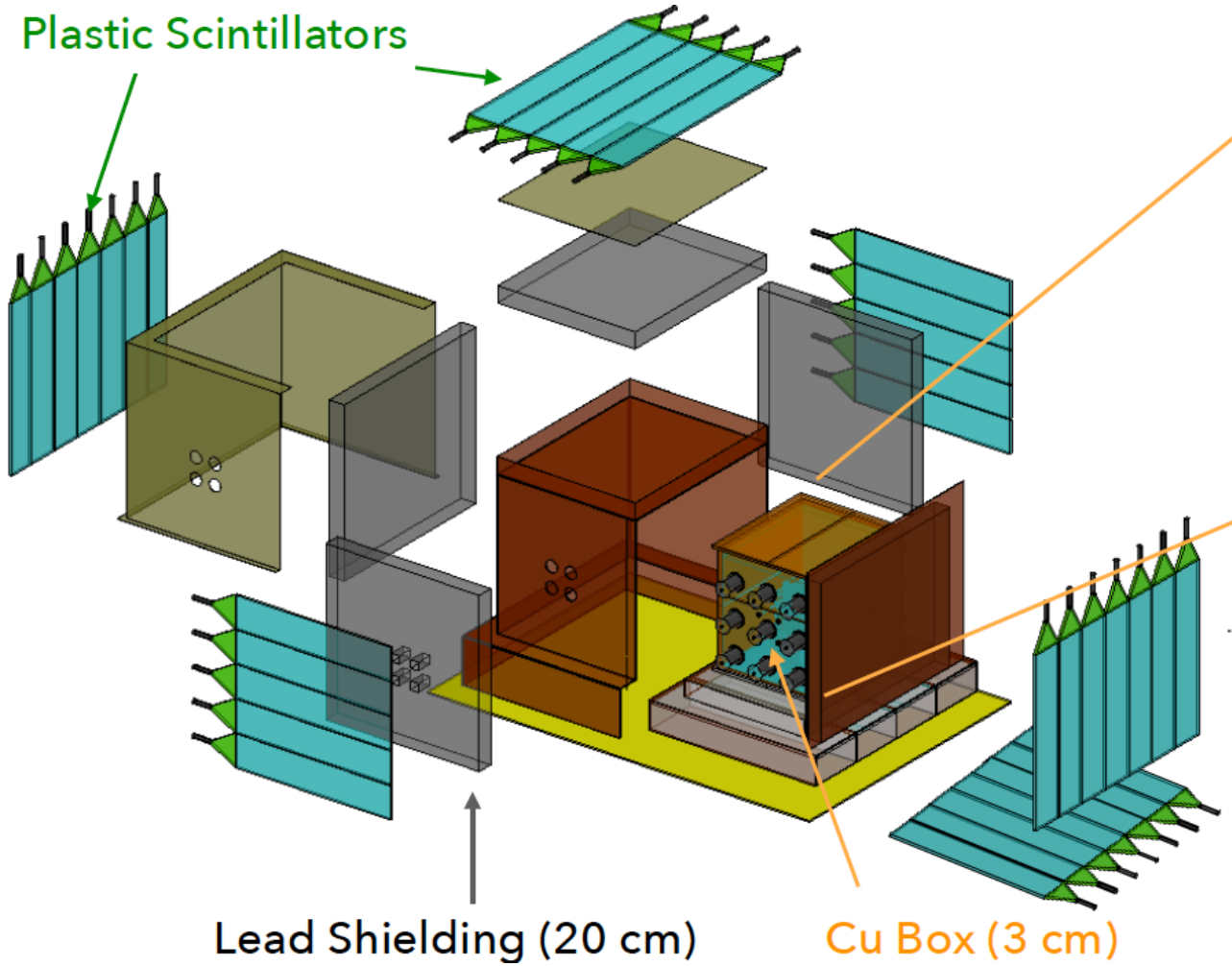




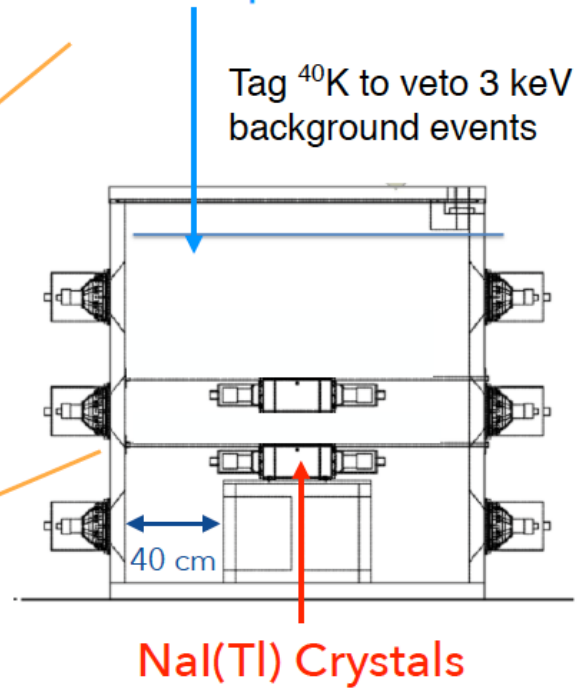
ChristianImages123.com

COSINE-100: **NEW features**

Tagging of muon-induced events



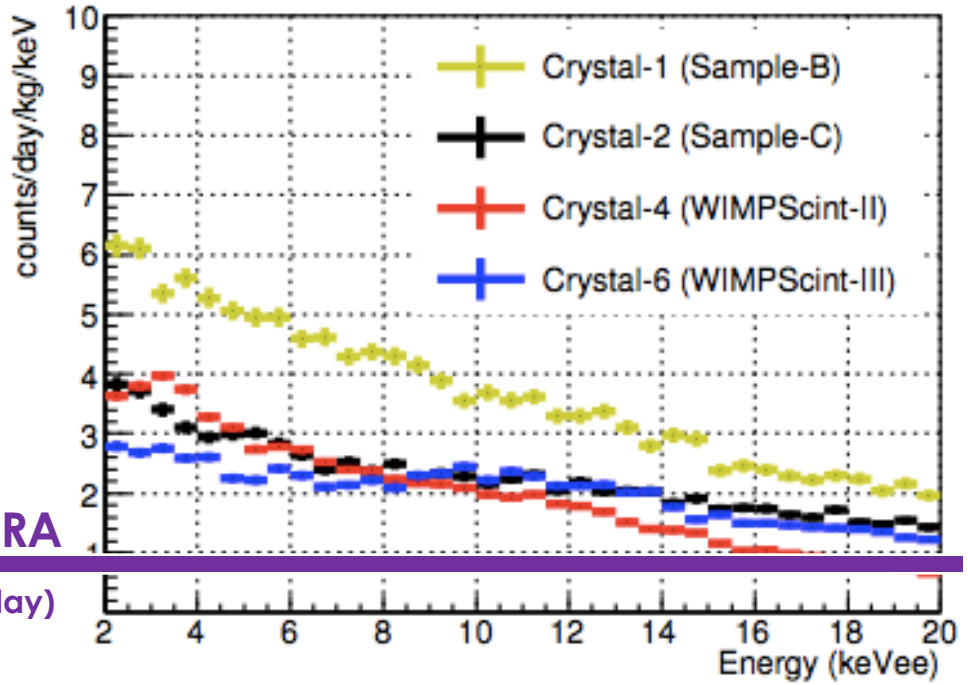
Tagging of ^{40}K of outer crystals



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

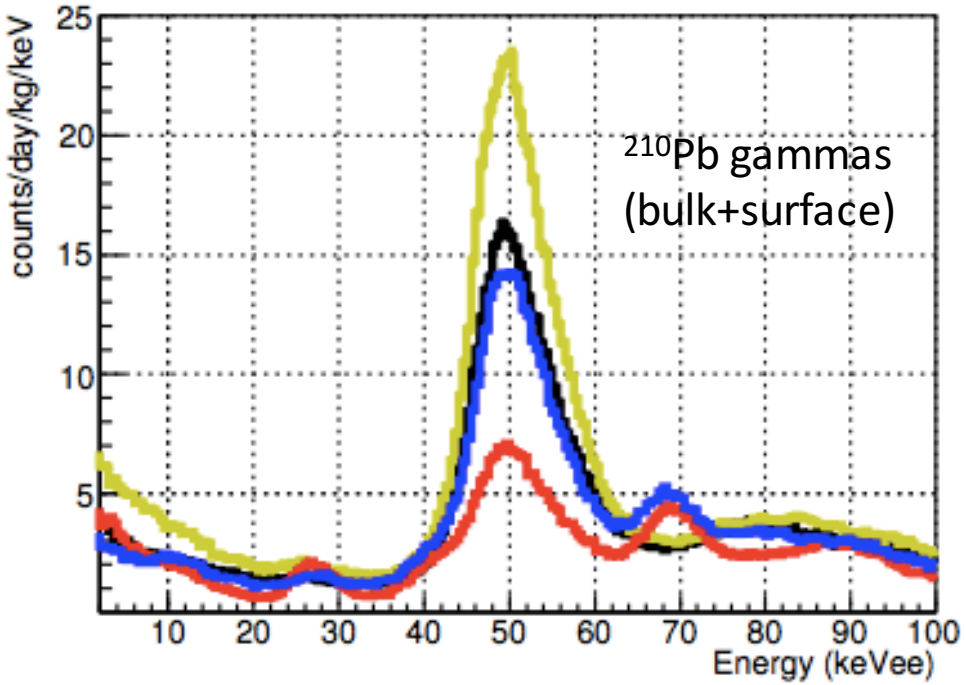
COSINE-100: **BACKGROUND**

EPJ C **78** 107 (2018)



DAMA/LIBRA

1 c / (keV kg day)



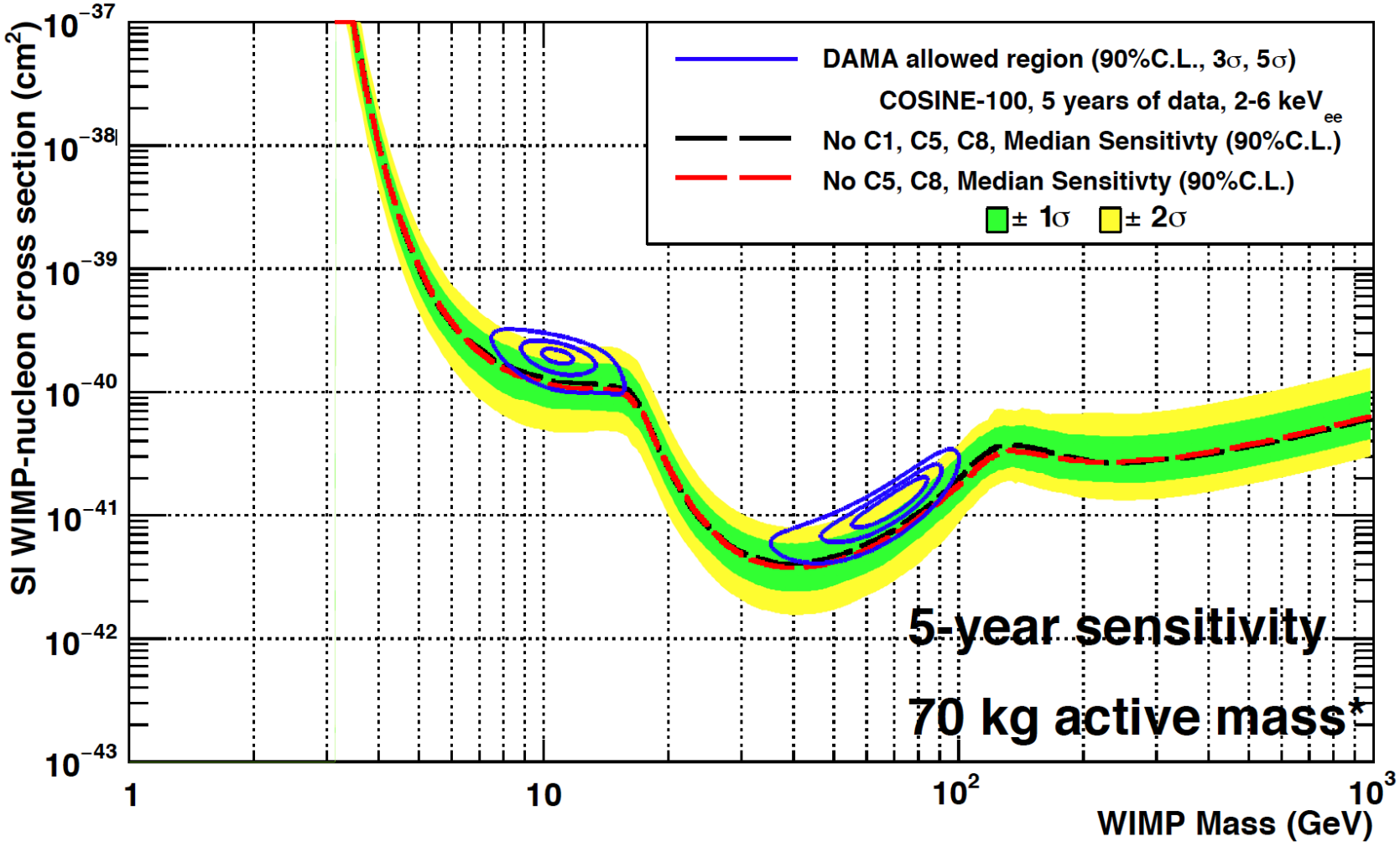
2 to 4 counts/ (keV kg day) in the ROI

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

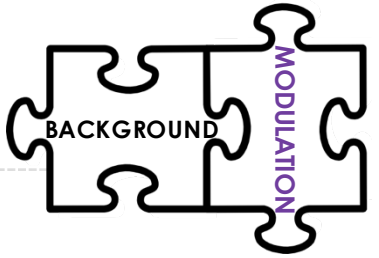
work on radiopurity of NaI to match DAMA/LIBRA level

PROJECTED SENSITIVITY

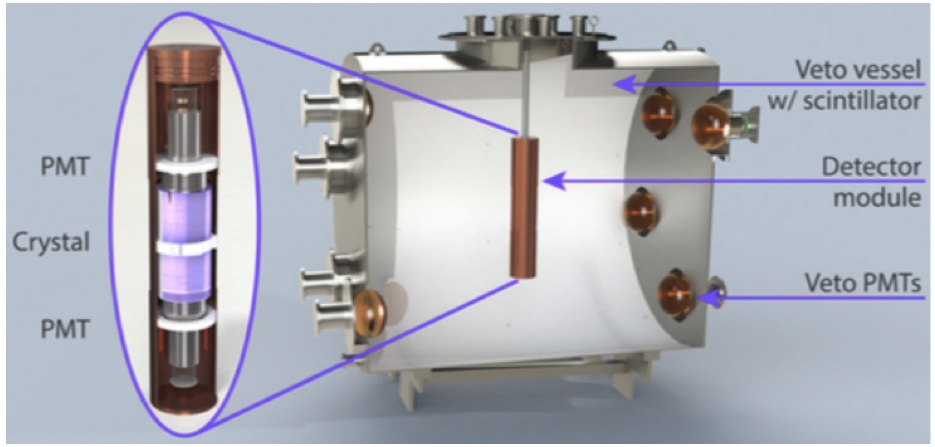
R. Maruyama, *COSINE-100*, CIPANP2018 conference

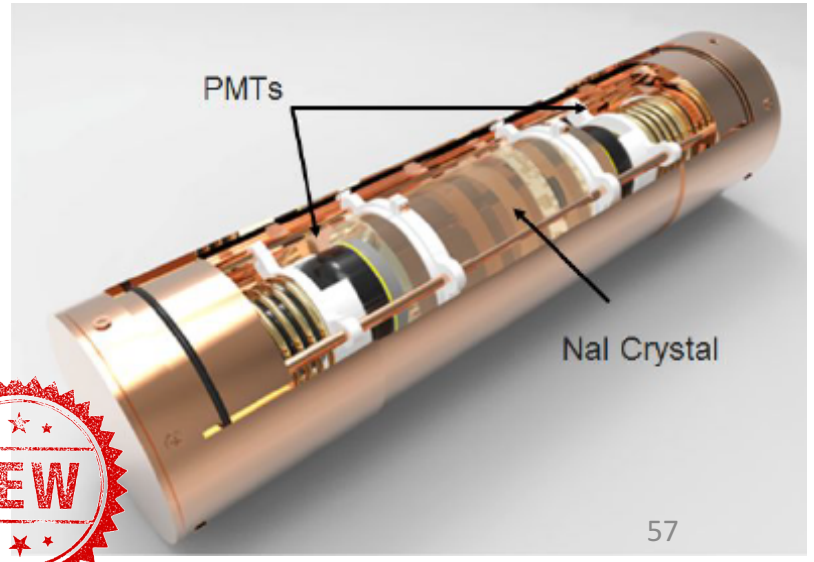


SABRE experiment



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 2018
BONUS	muon veto, liquid scintillator two exp. sites

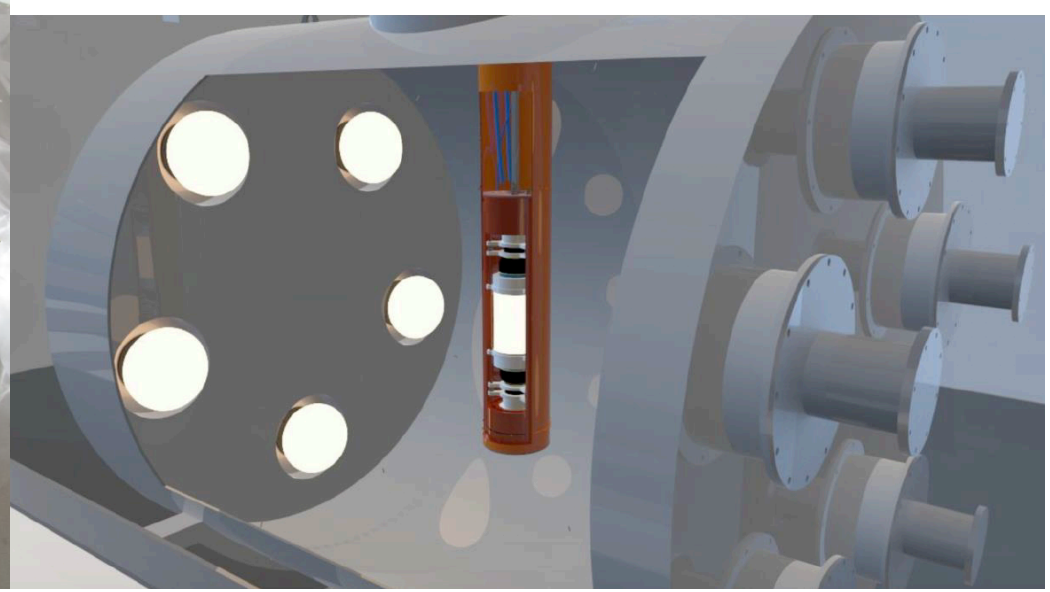


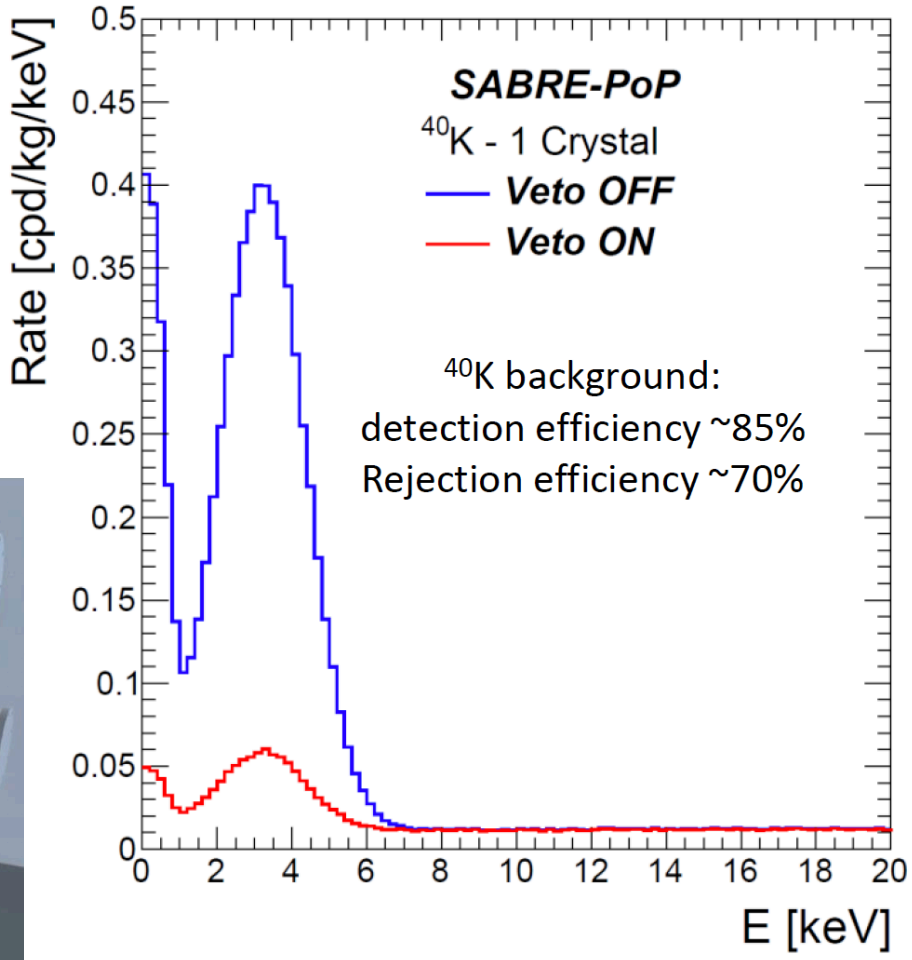


ChristianImages123.com

SABRE: **Proof-of-Principle ongoing**

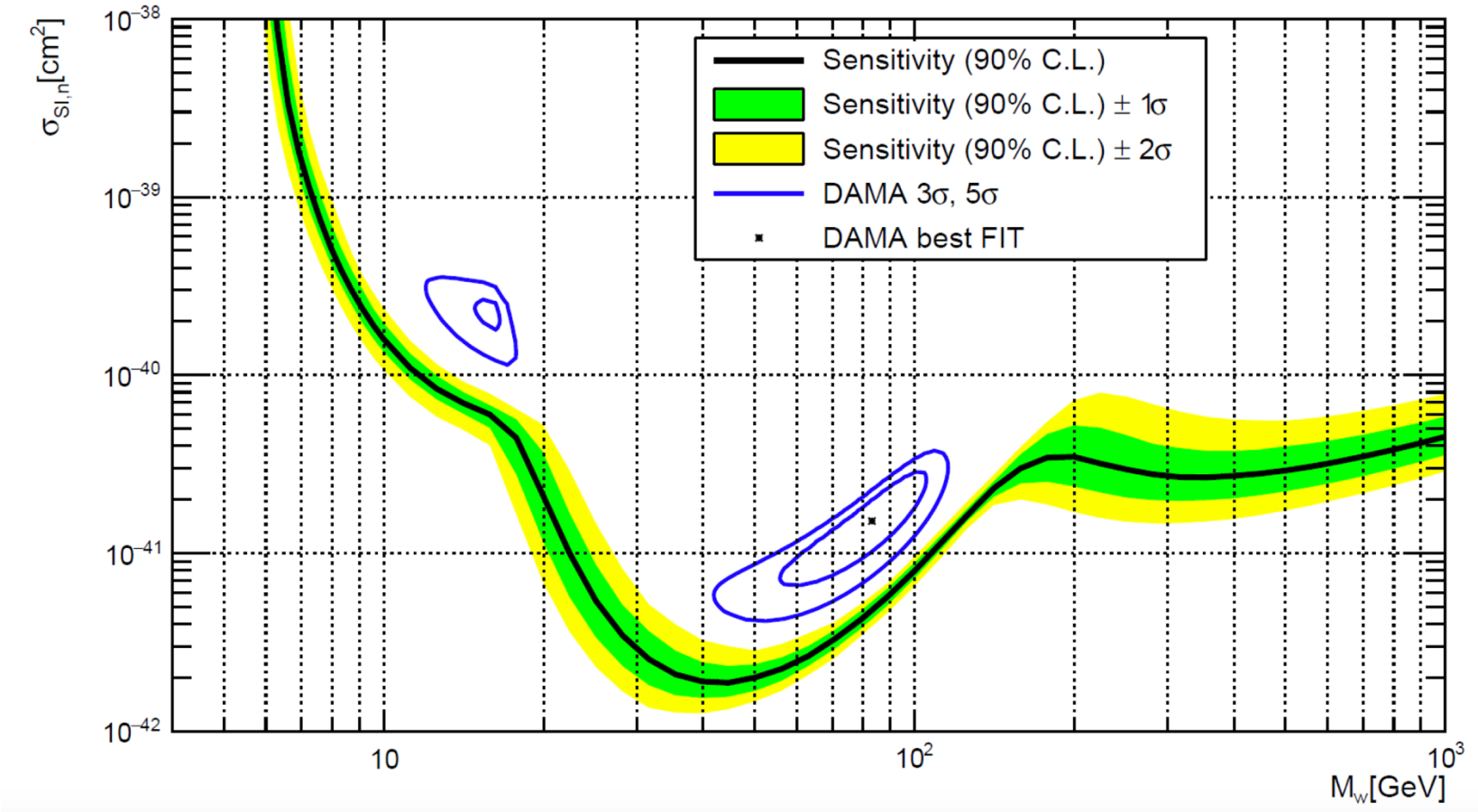
First Phase : PoP @ LNGS
5 kg crystal inside liquid scintillator
(~ 2 tons PC + PPO 3 g/l)





S. Copello, NDM 2018 conference, Korea

SABRE: **PROJECTED SENSITIVITY**

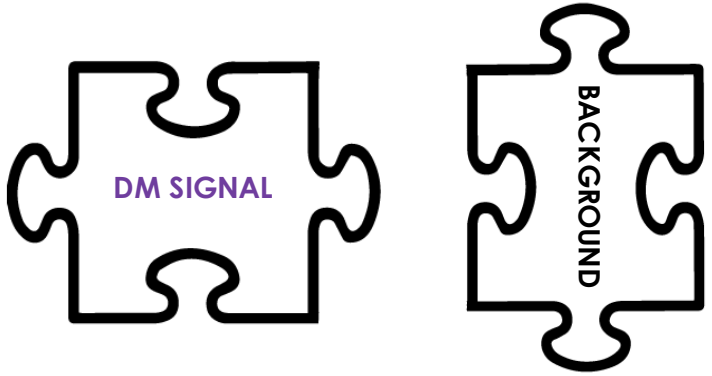


- 2-6 keVee
- 50 kg of NaI(Tl)
- 3 years exposure
- bkg from simulation:
  ~0.22 c /(keV kg d)

S. Copello, NDM 2018 conference, Korea

One more thing...

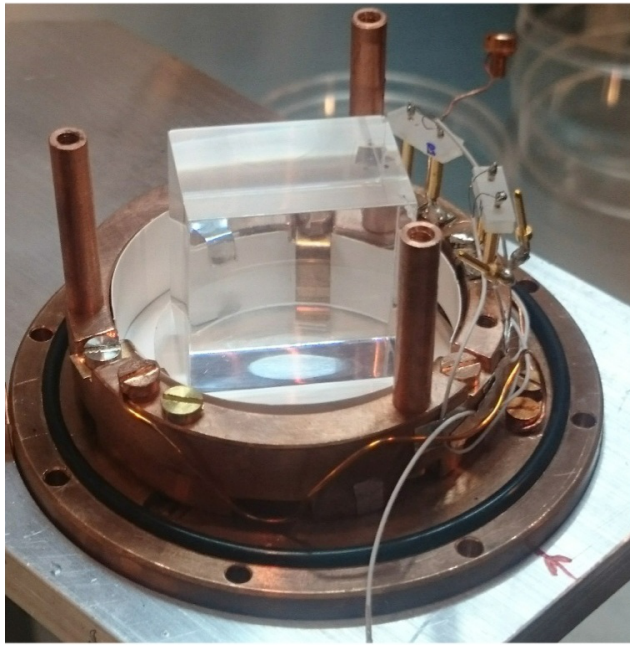
COSINUS project



MATERIAL	NaI (undoped)
SIGNAL(s)	Light and heat (TES)
LOCATION	LNGS Italy
β/γ-DISCRIMINATION	YES!
THRESHOLD GOAL	1 keV
BONUS	PID, lower energy threshold

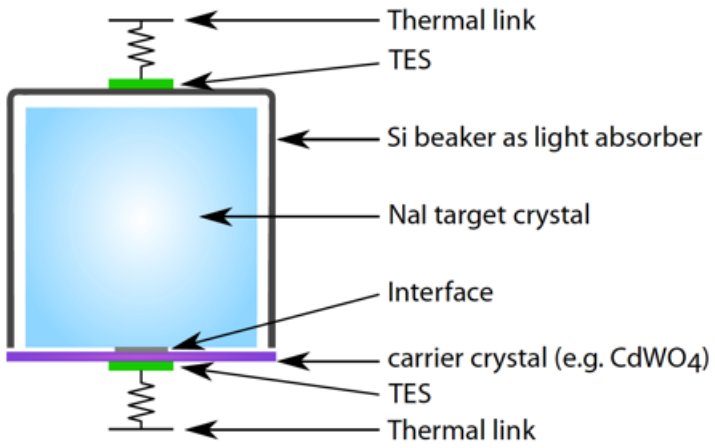
www.cosinus.it

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

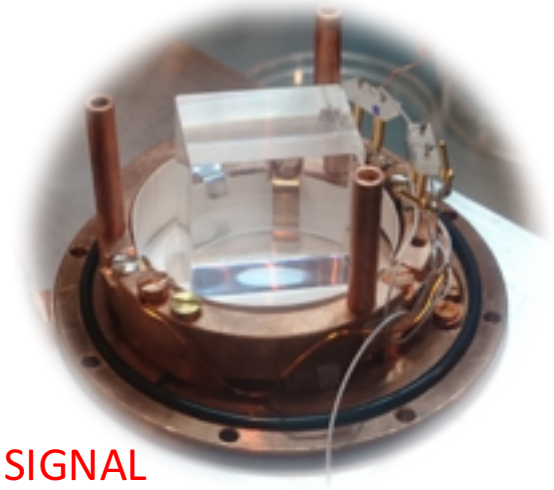


ChristianImages123.com

COSINUS: **DUAL CHANNEL READOUT**

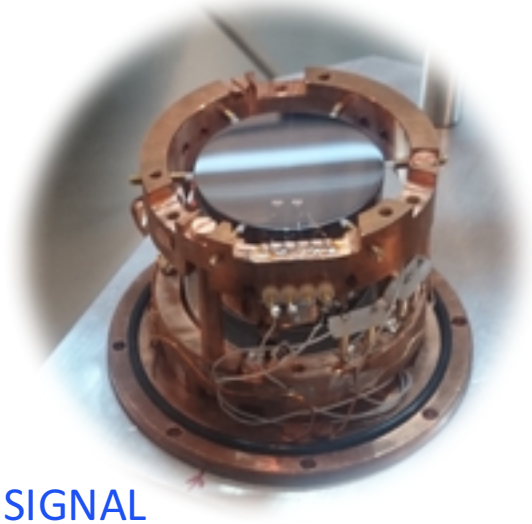


NaI crystal of 66 g



HEAT SIGNAL

Si light absorber on top



LIGHT SIGNAL

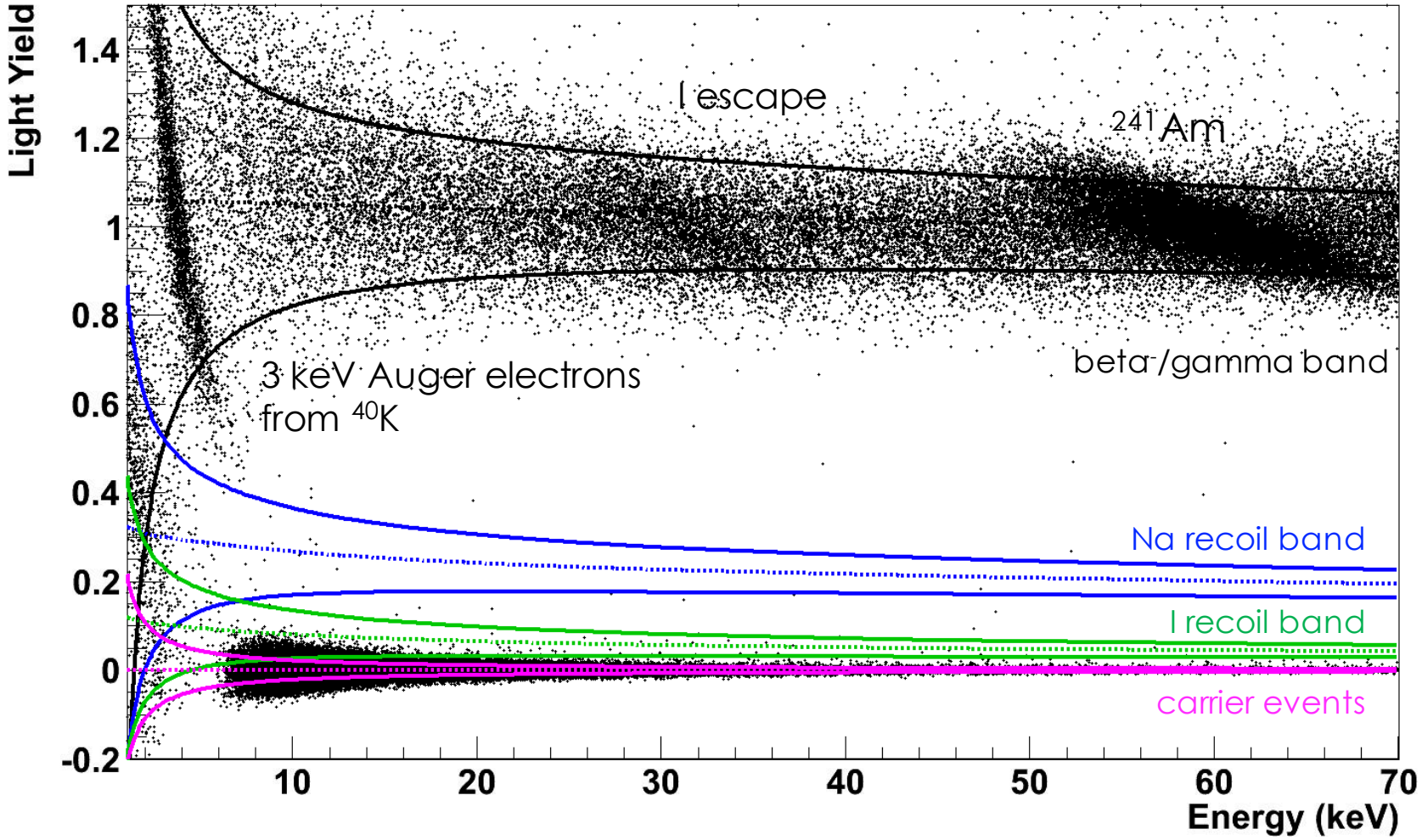
proof-of-principle of final detector design

- NaI energy threshold is (8.26 ± 0.02 (stat.))keV
- absolute light yield for a β/γ-event: 13 % (~39 photons/keV)

improve performance of NaI calorimeter to reach 1keV threshold

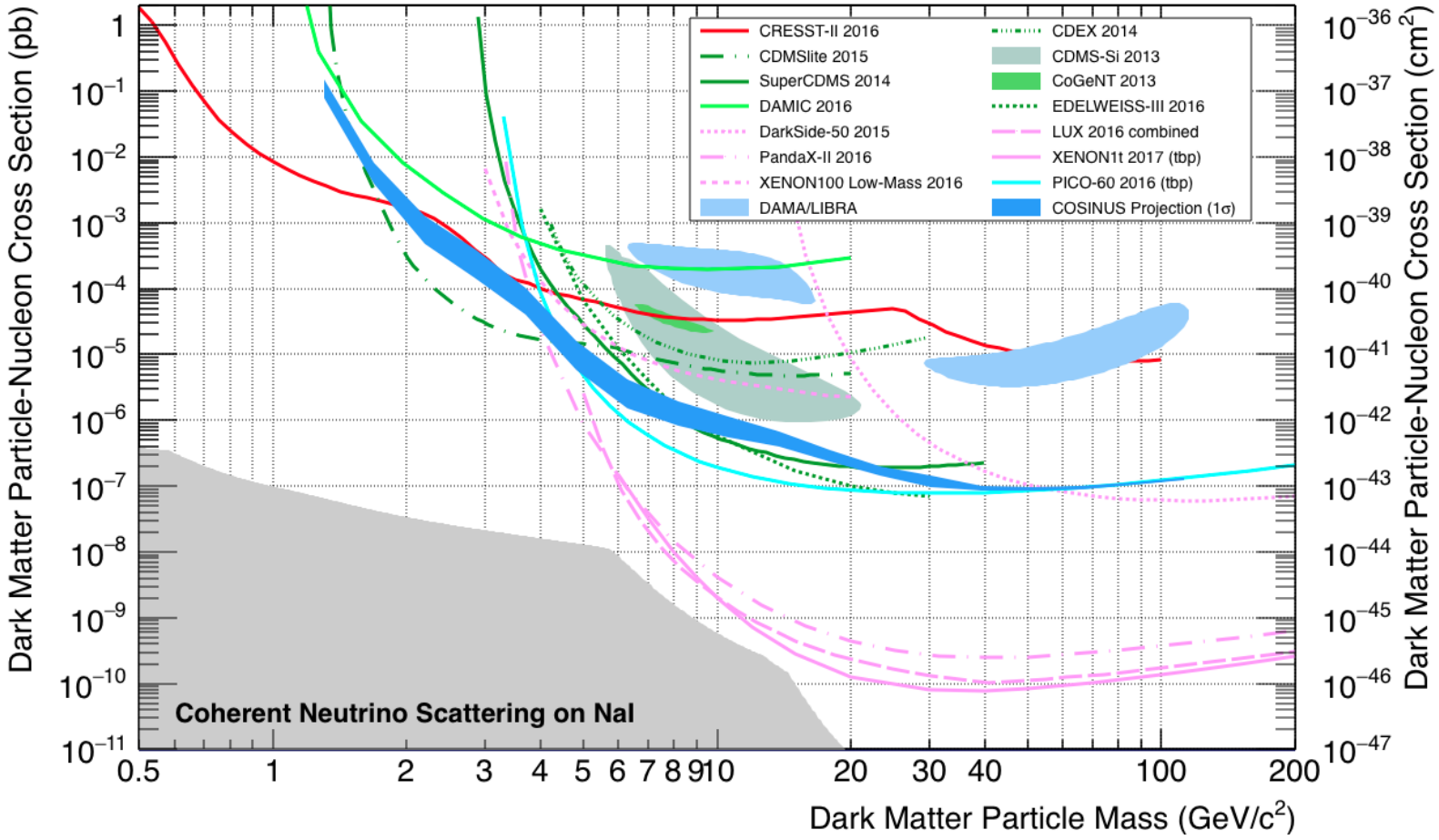
COSINUS: 2nd PROTOTYPE RESULTS

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



- width of the ^{241}Am peak is (4.508 ± 0.064 (stat.)) keV
- carrier events can be identified by pulse shape
- Quenching factors for Na and I as from Tretyak et al.

COSINUS: **PROJECTED SENSITIVITY**



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

- 100 kg -days exposure
- 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 standard assumptions

SUMMARY

- 1997: DAMA presents at TAUP first evidence for the modulation
- 2018: contradicting situation in the direct dark matter searches null-results are in conflict with DAMA observation
- HOWEVER: after more than 20 years the DAMA/LIBRA observation is **still not cross-checked** by a same-target experiment
- numerous NaI-based experiments in data taking or being set up
- **radiopure NaI crystals is the key-issue for all DAMA-like experiments**

  → **no** experiment in data taking at the moment is operating massive NaI(Tl) crystals at purity level of DAMA/LIBRA

- **stay tuned how this NaIce-story goes on!**

Thank you for your attention!
@Maurizio Verdecchia Photography

STANDARD SCENARIO

DARK MATTER IN THE MILKY WAY

Maxwellian velocity distribution

local dark matter density of 0.3 GeV/cm^3

→ assuming 100 GeV/m_x we have
~ 3000 DM particles per m^3

→ **FLUX of DM particles on earth:**
~10^5 (100 GeV/m_x) cm^{-2} sec^{-1}

DARK MATTER INTERACTION

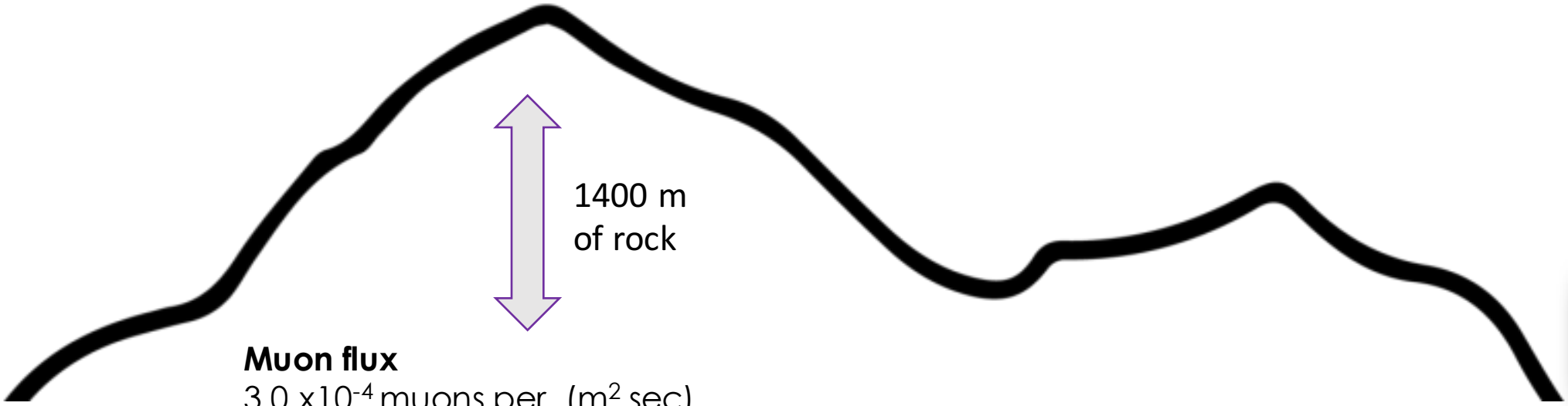
Dark matter particles scatter

- off nuclei
- elastically
- coherently: ~A^2
- (spin-independent)

BENEFIT OF UNDERGROUND SITES

The rate of the signal you search for you have to compare to the background rate

rare event search → **minimize background** → go to an underground site



Muon flux
3.0 x10^{-4} muons per (m^2 sec)
→ **10^6 reduction** to1 muon / (m^2 h)

Neutron flux
2.92 x 10^{-6} neutrons / (cm^2 sec) below 1keV
0.86 x 10^{-6} neutrons /(cm^2 sec) above 1keV

Radon in air: 20-80 Bq/m^3

MINIMIZING THE BACKGROUND

Layers of passive shielding:

- Water $\mathcal{O}$ (1)m
- Polyethylen $\mathcal{O}$ (10)cm
- Lead $\mathcal{O}$ (10)cm
- Copper $\mathcal{O}$ (10)cm

Active veto:

- Water $\mathcal{O}$ (1)m
- Plastic scintillator $\mathcal{O}$ (10)cm
- Liquid scintillator. $\mathcal{O}$ (1)m

Radon mitigation

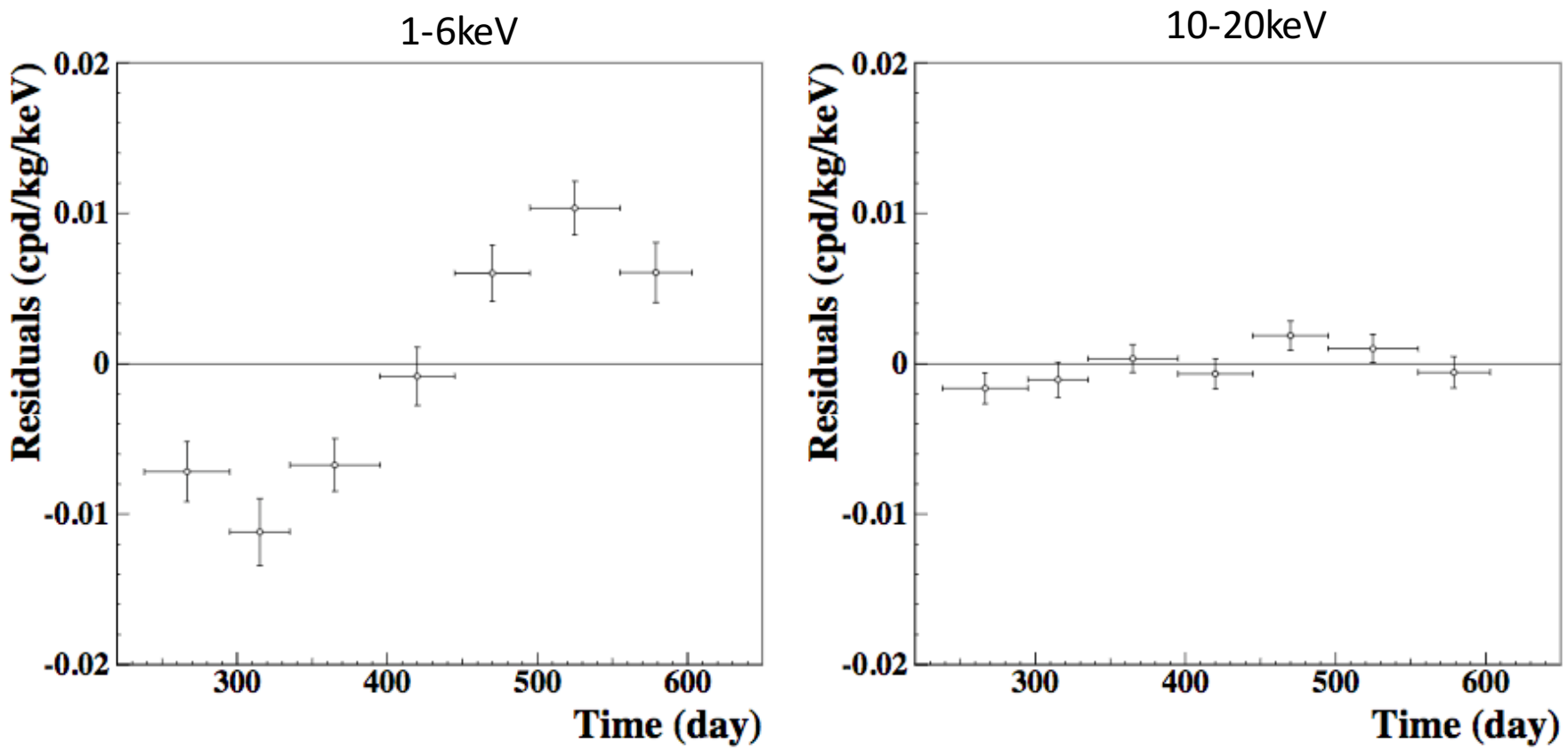
outside to inside

Material selection:

- Only low-radioactive materials
- Screening of materials
- careful material handling

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

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



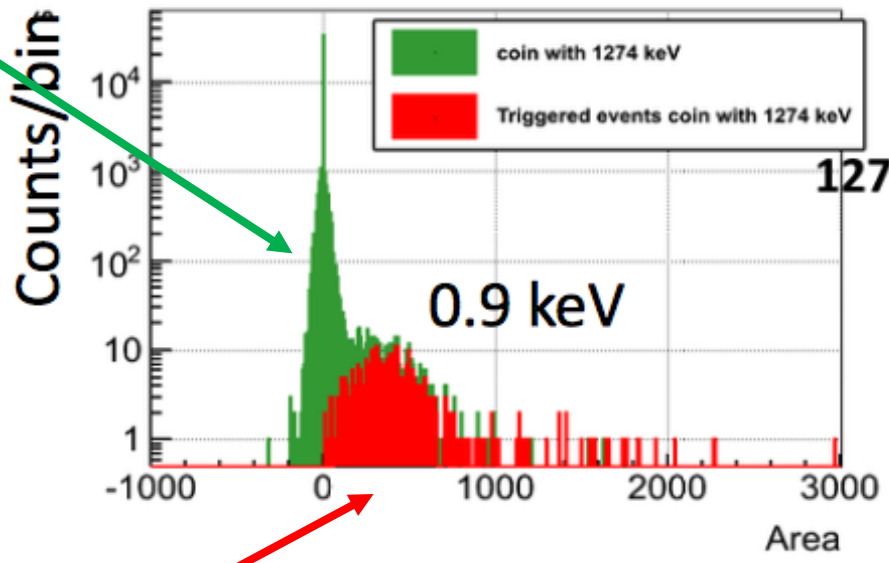
Modulation signal in energy window: 2-6 keV_{ee}

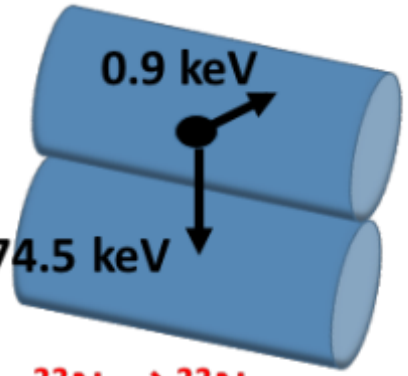
ANAIS-112: **ENERGY THRESHOLD**

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

1274keV

Coincidence events



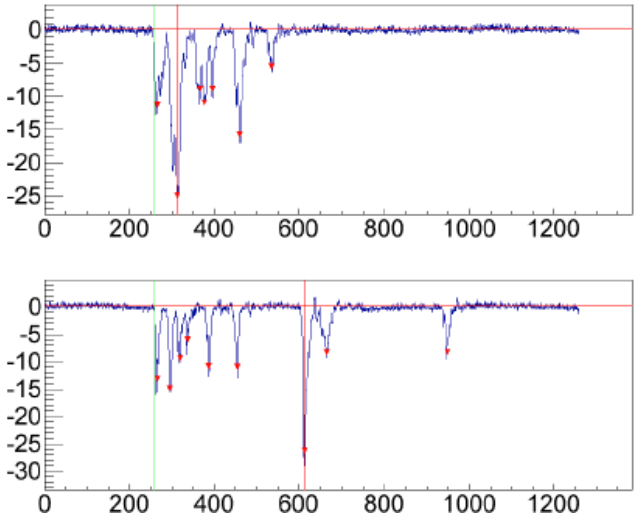


$^{22}Na \rightarrow ^{22}Ne$

0.9keV triggered, coincidence events

Triggering below 1 keV$_{ee}$:

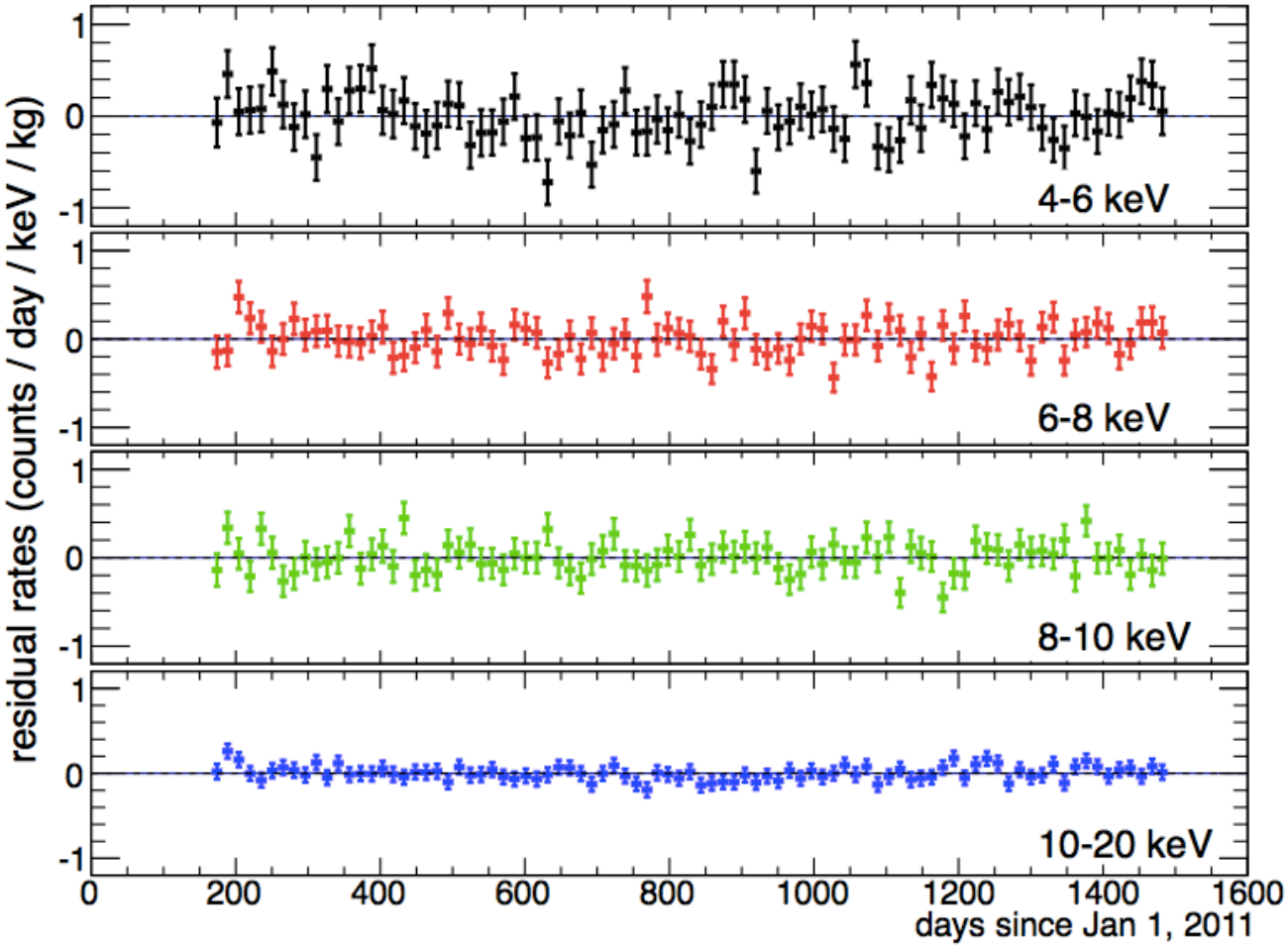
bulk ^{22}Na and ^{40}K events identified by coincidences with high energy gammas



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

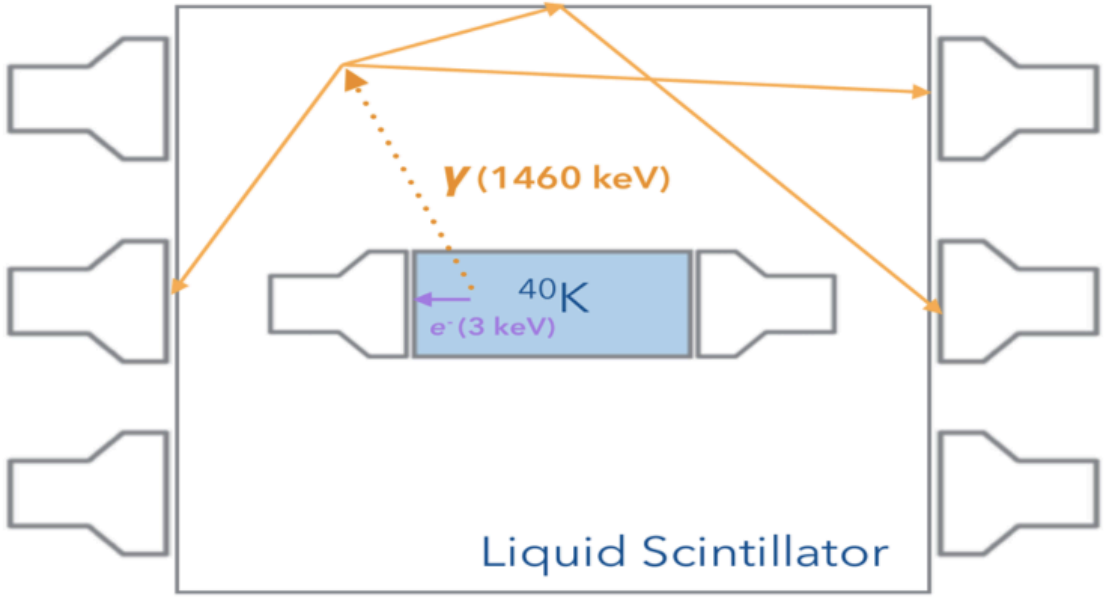
DM-Ice **results**

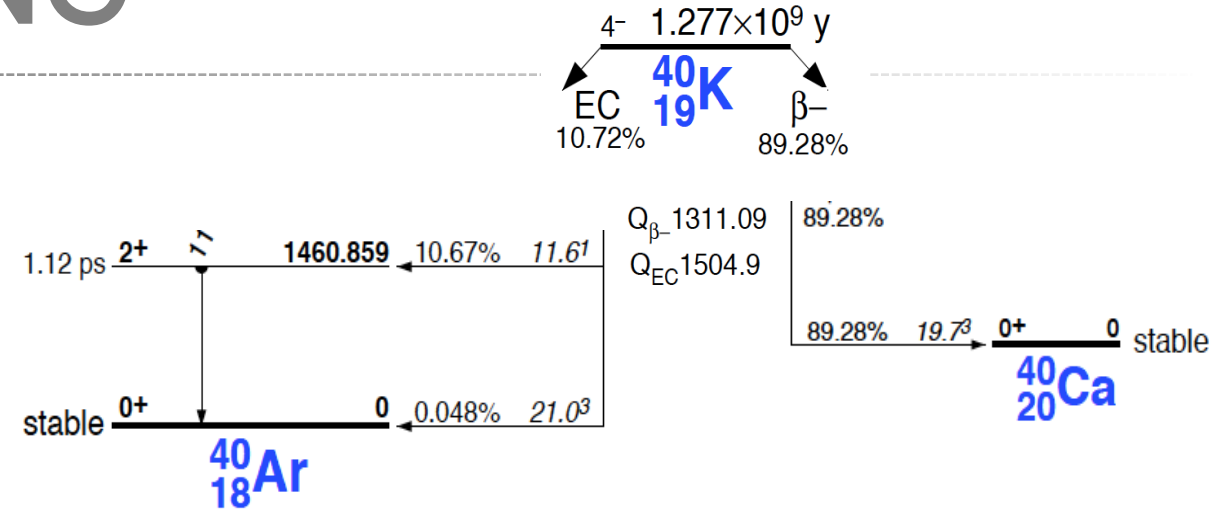
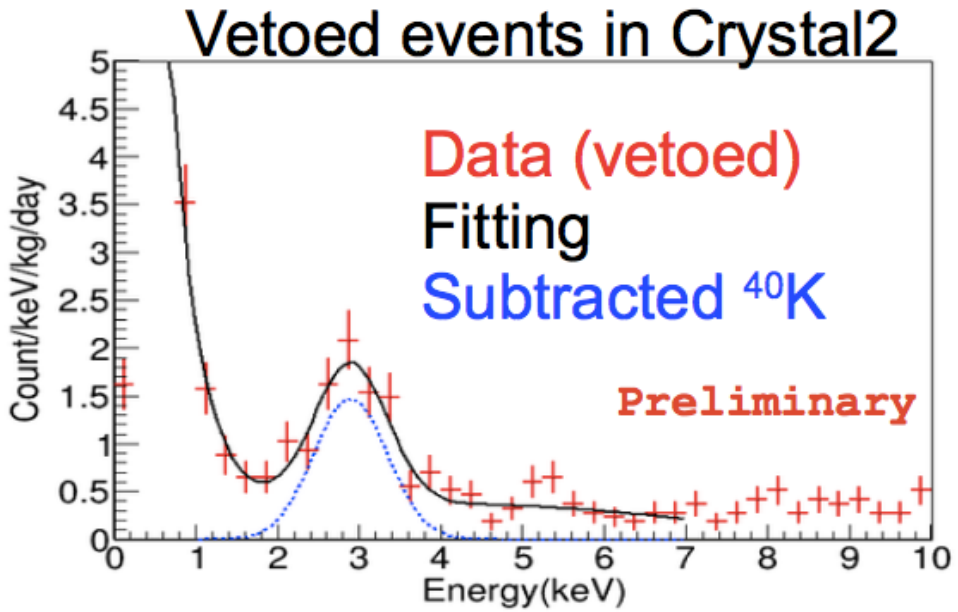
E. Barbosa de Souza *et al.* (DM-Ice Collaboration)
Phys. Rev. D 95, 032006



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

COSINE-100: ^{40}K TAGGING





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