Dark matter annual modulation with ANAIS-112: three years results

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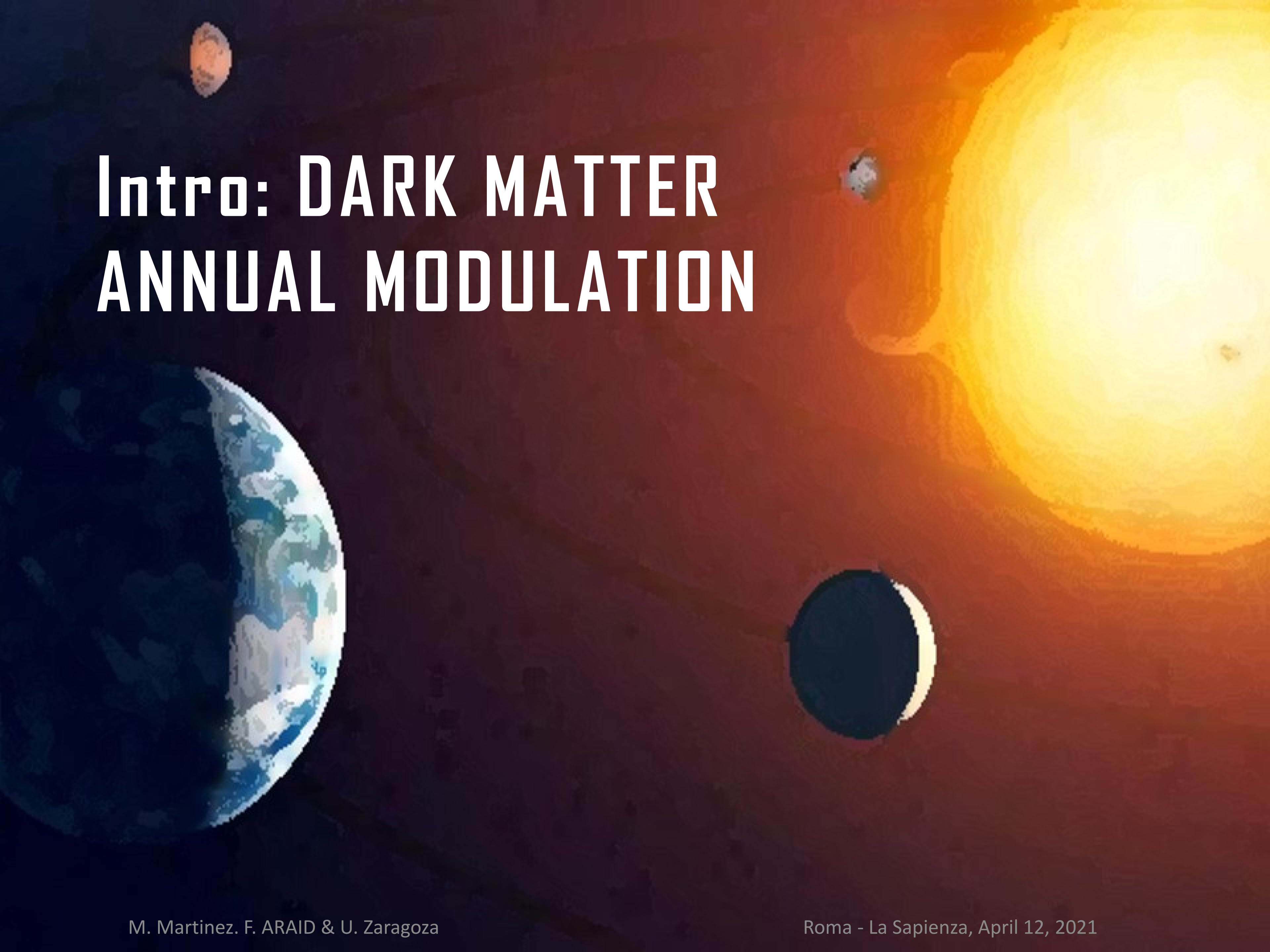
araid FUNDACIÓN AGENCIA ARAGONESA PARA LA INVESTIGACIÓN Y EL DESARROLLO
MultiDark Multimessenger Approach for Dark Matter Detection

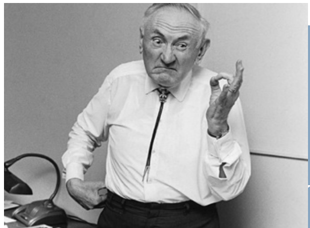
OUTLINE

- Intro: Dark matter annual modulation & DAMA/LIBRA signal
- Other NaI(Tl) experiments
- ANAIS-112
  - Experimental set-up
  - Detector performance
  - 3 years results on annual modulation
  - ANAIS-112 projected sensitivity
- Summary

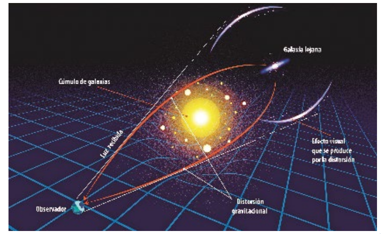
Intro: DARK MATTER ANNUAL MODULATION

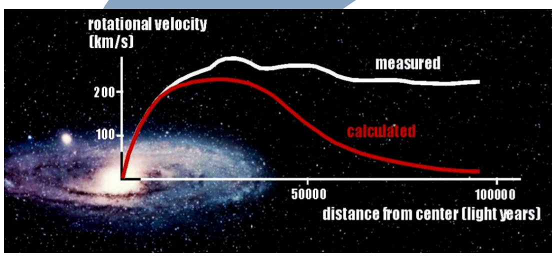


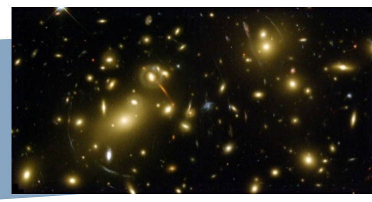
Evidence of Dark Matter

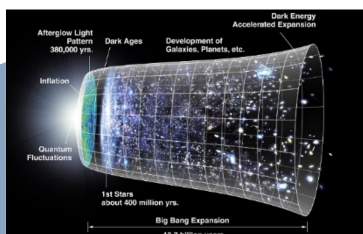


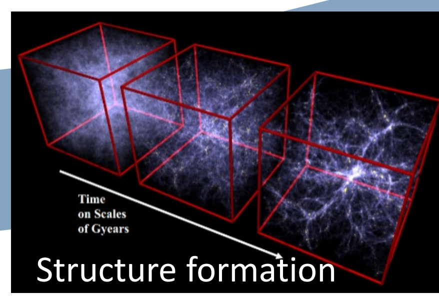
Zwicky (1933)



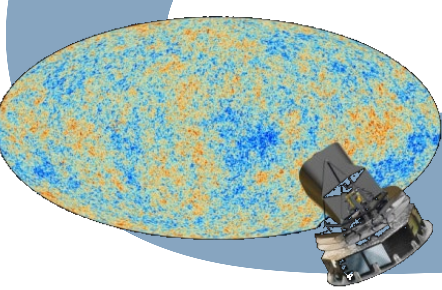


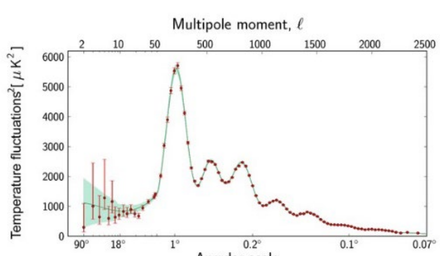


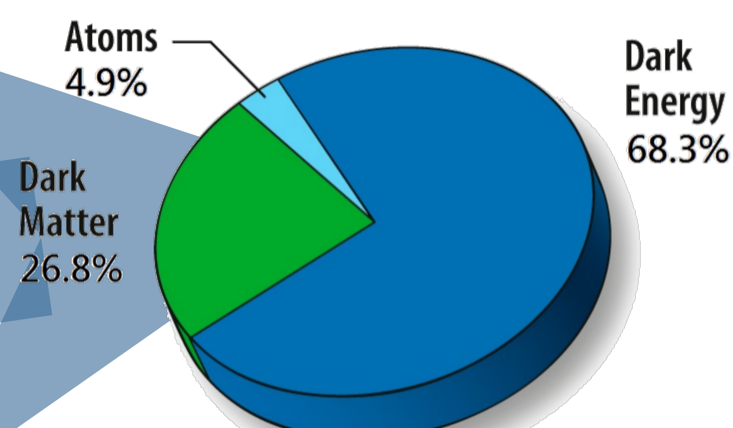




DM dominates all the structures of the Universe!

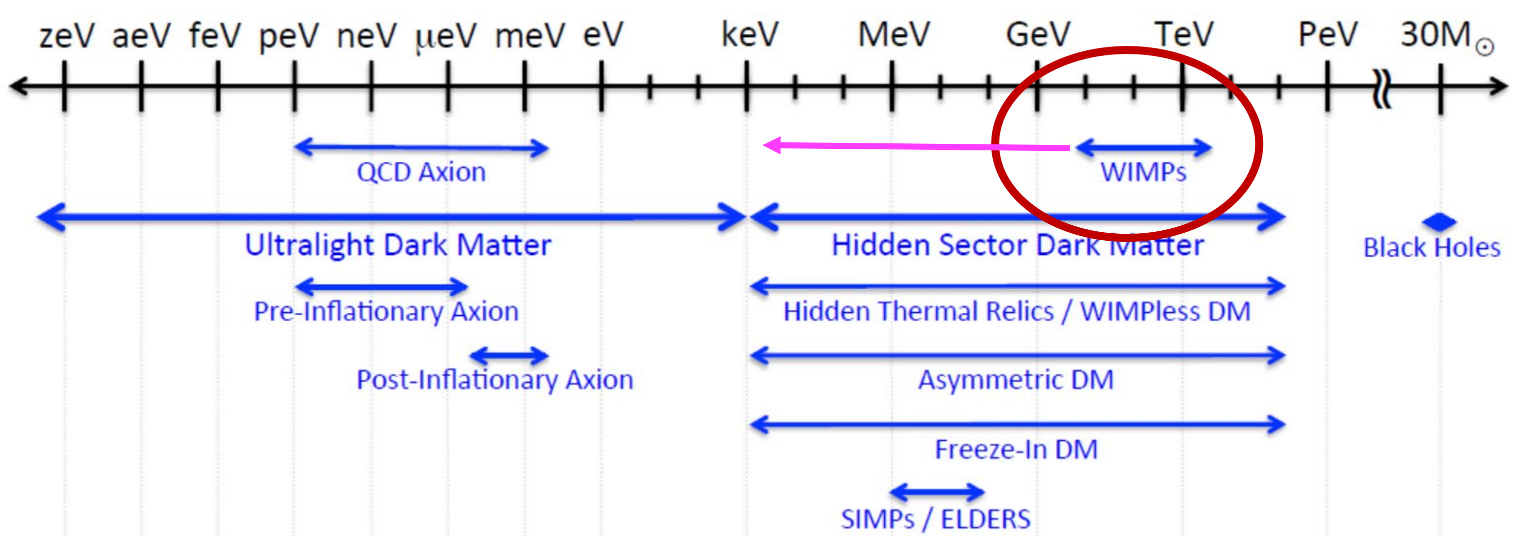






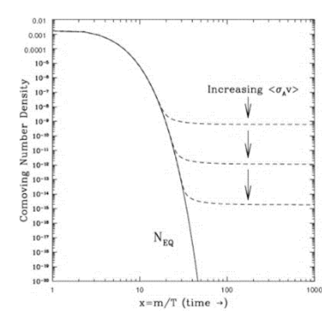
WIMPs

A plethora of candidates for DM…



Among them, Weakly Interacting Massive Particles (WIMPs) very well motivated

- Relic abundance from the freeze-out mechanism matches measured DM density for reasonable ranges of weak-scale annihilation cross section
- Arise spontaneously in SM extensions such as SUSY

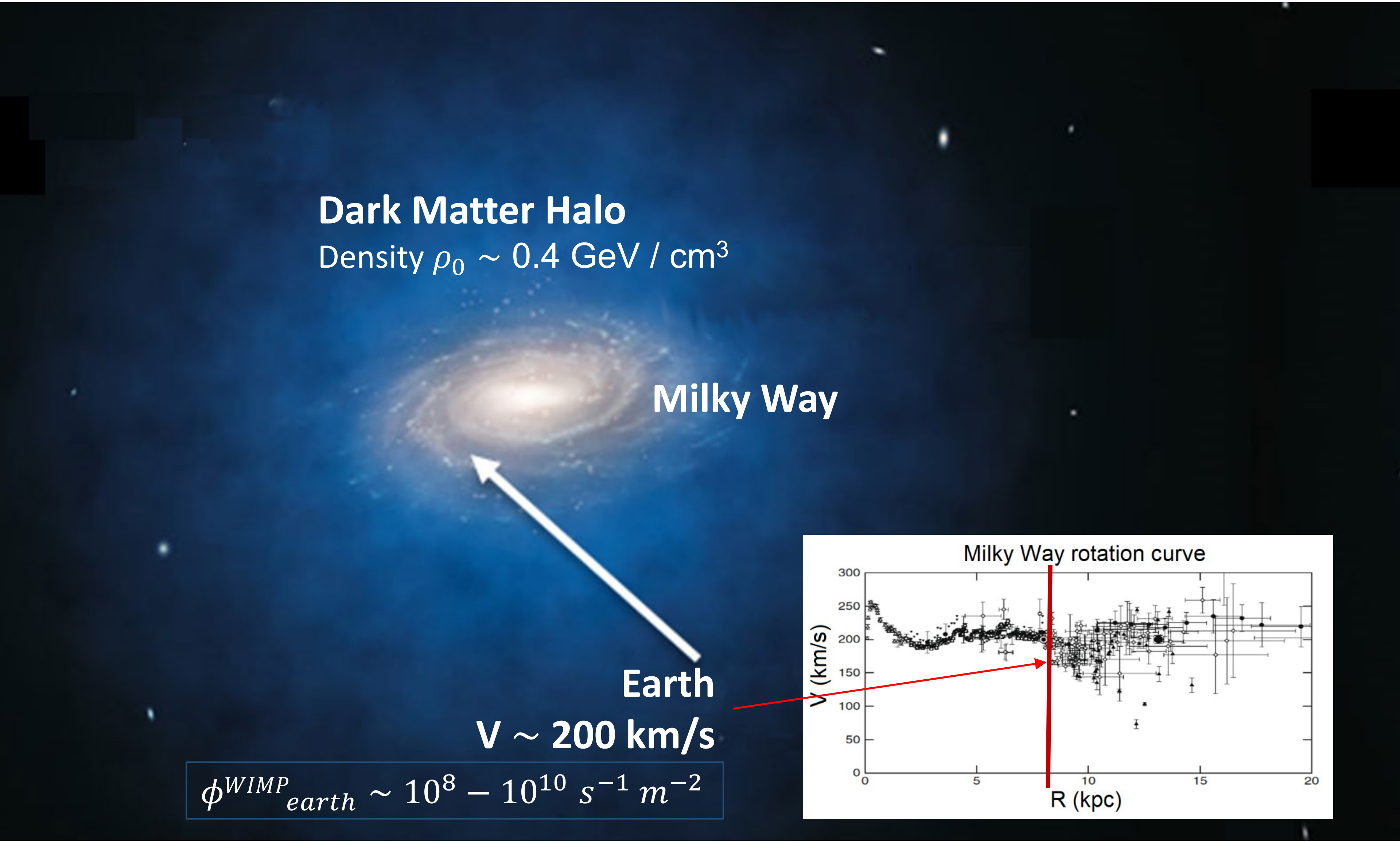


Jungman *et al* hep-ph/9506380

Abundance of a thermal relic

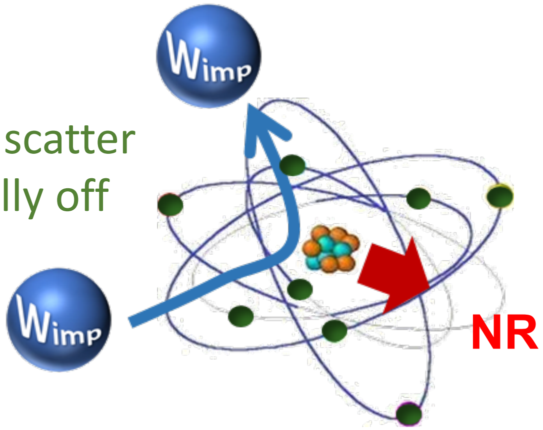
$$\sim \frac{0.1\,pb}{<\sigma_A\, v/c>}$$

WIMP direct detection



WIMP direct detection

WIMPs scatter elastically off nuclei



WIMP direct detection

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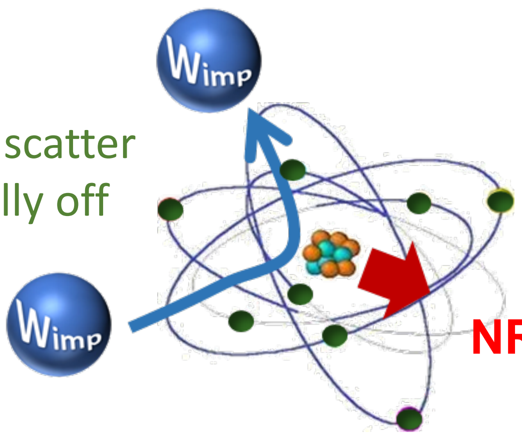


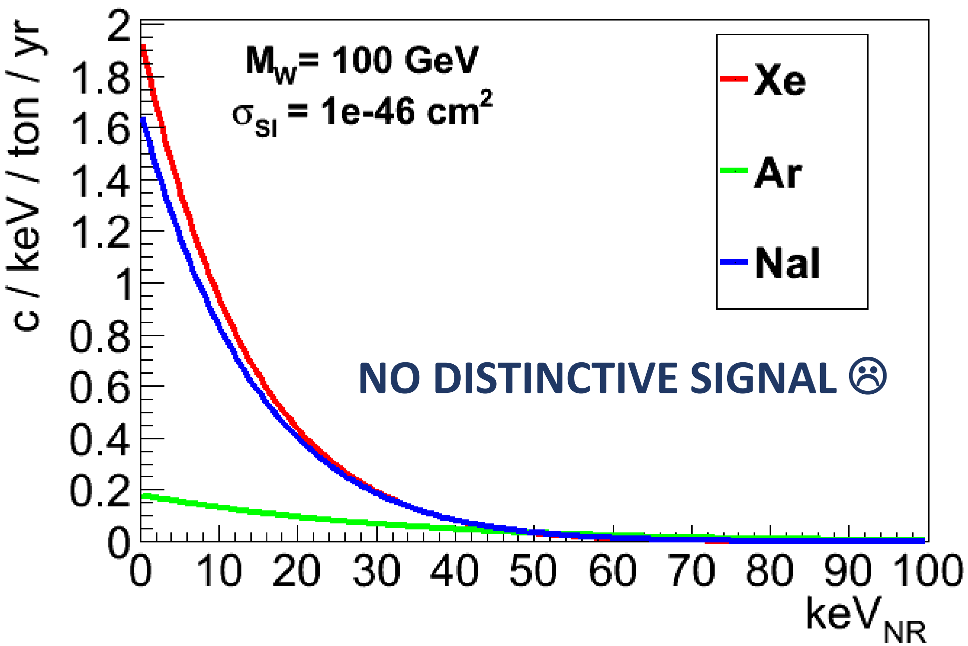
Expected rate @ Earth:

MODEL DEPENDENT!

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v)}{v} dv^3$$

Wimp model

Halo model



NO DISTINCTIVE SIGNAL ☹

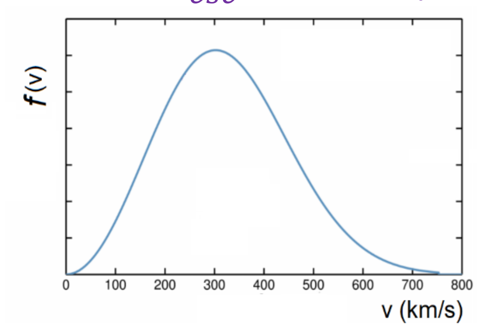
Naïve approximation: **SHM**

Isothermal sphere

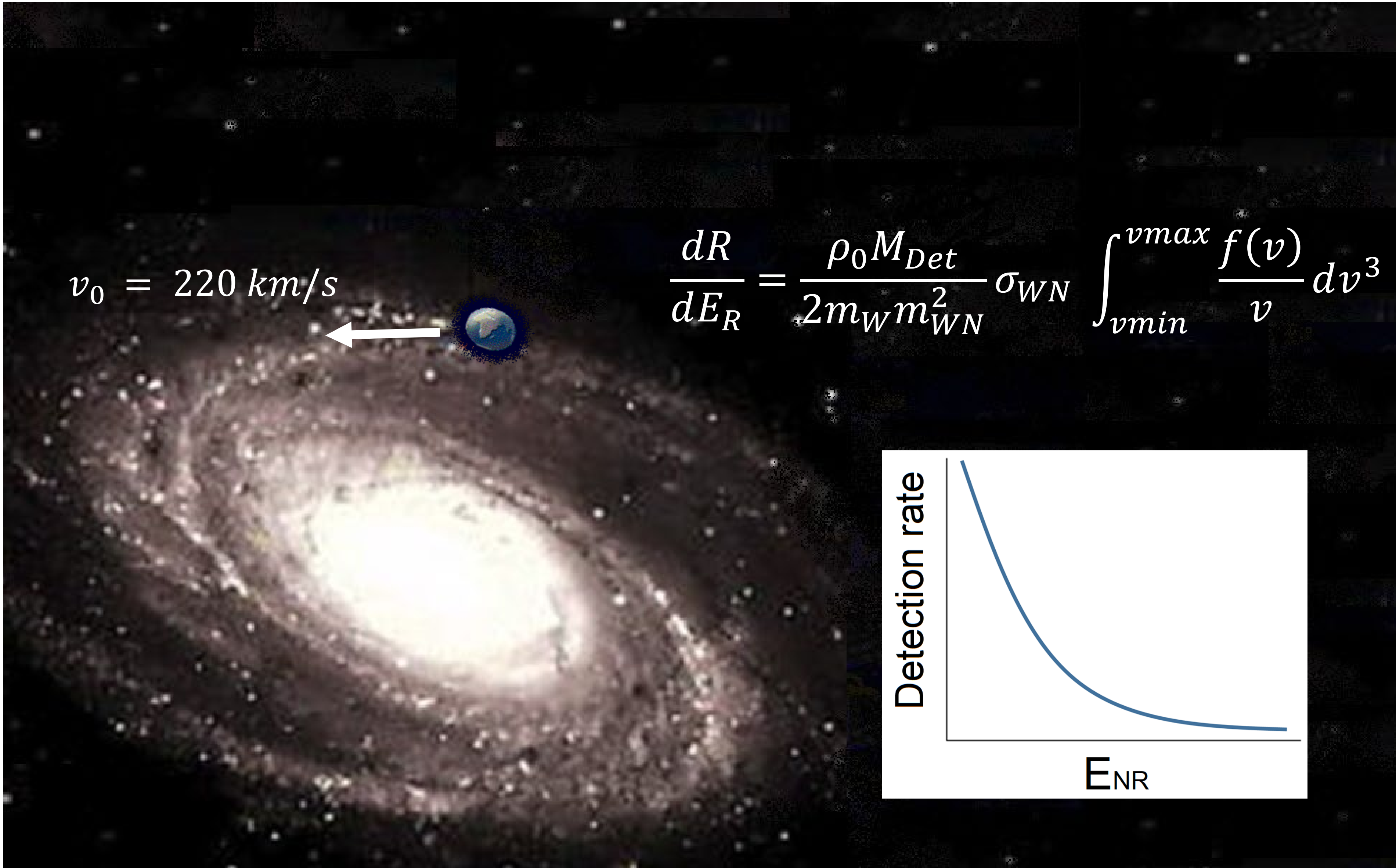
Maxwellian distribution

v_o = 220 km/s

Truncated at v_{esc} ~ 530 km/s



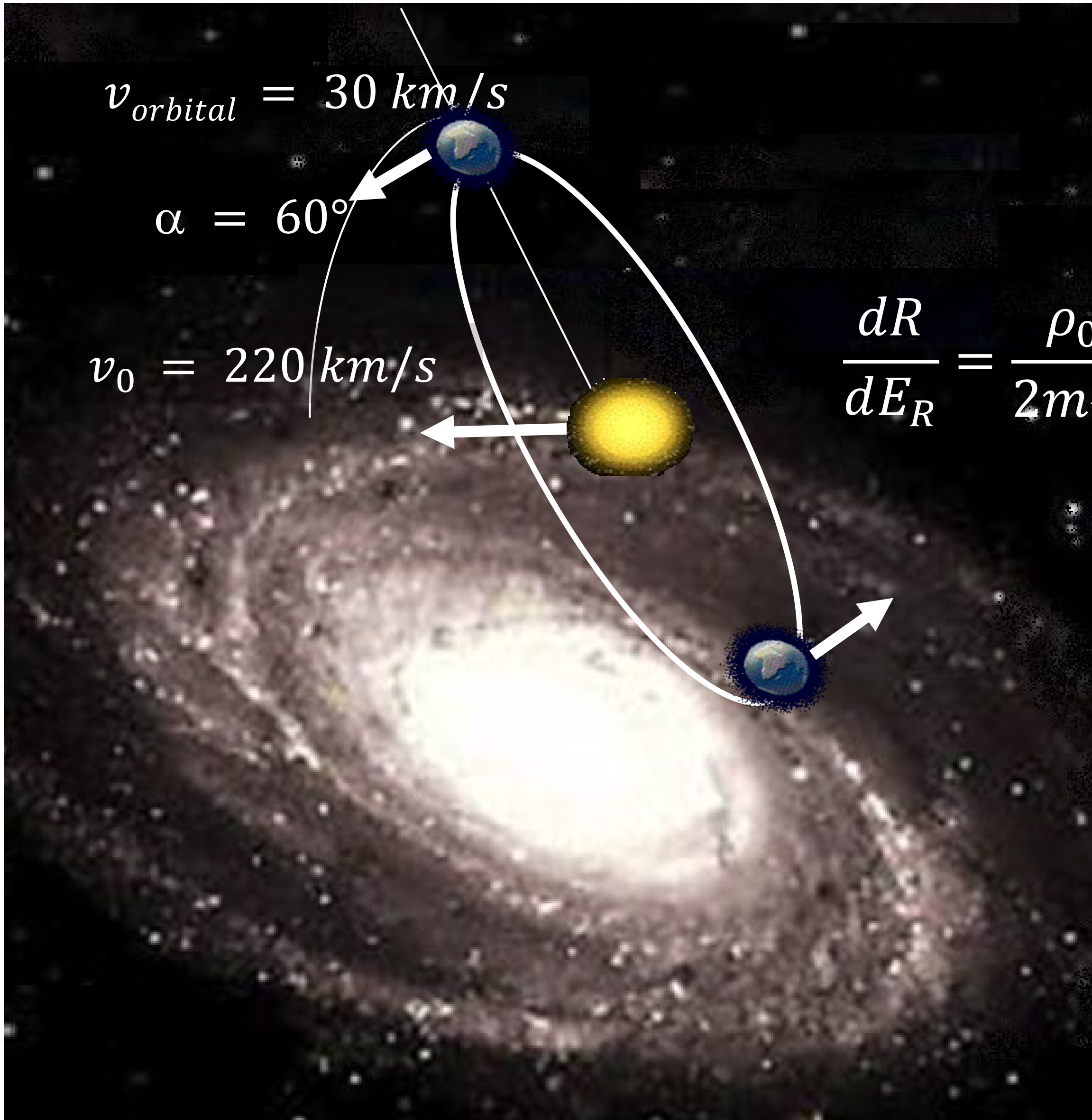
DM Annual modulation



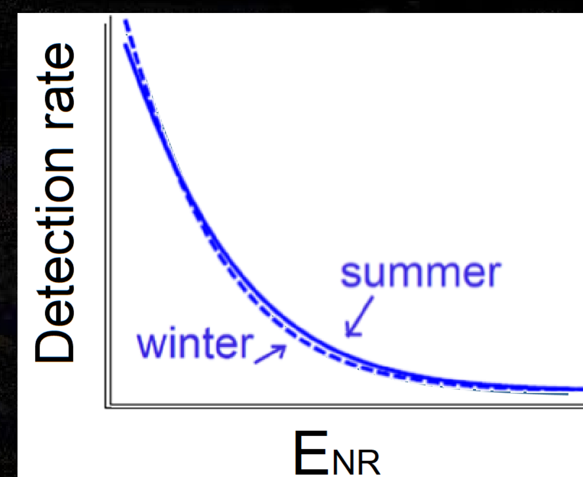
$$v_0 = 220\ km/s$$

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v)}{v} dv^3$$

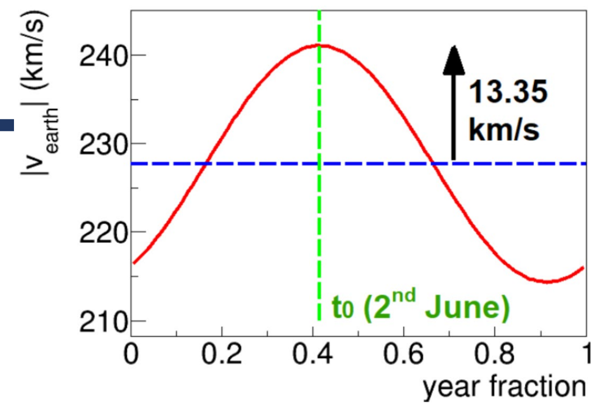
DM Annual modulation



$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v,t)}{v} dv^3$$



DM Annual modulation

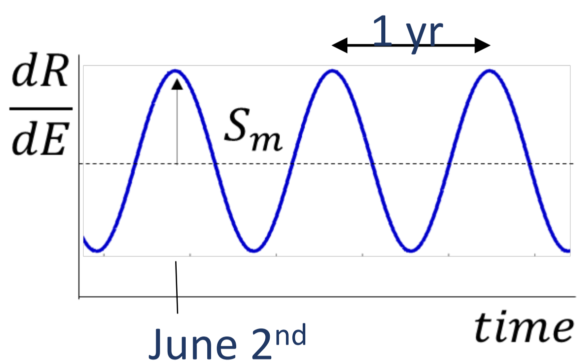


Due to the Earth revolution around the Sun, the relative speed Earth-halo is cosine-like with 1 year periodicity and small amplitude (~ 7%), and that implies **a modulation in the expected rate:**

$$\frac{dR}{dE}(E,t) \approx S_0(E) + S_m(E)\cos\omega(t-t_0)$$

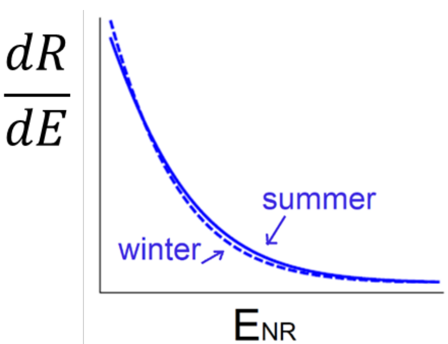
Where

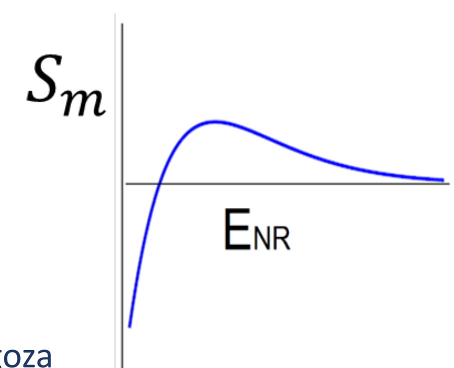
$$S_m(E) = \frac{1}{2}\left(\frac{dR}{dE}(E,t_0) - \frac{dR}{dE}(E,t_0+182)\right)$$



A distinctive signal hard to mimic by background

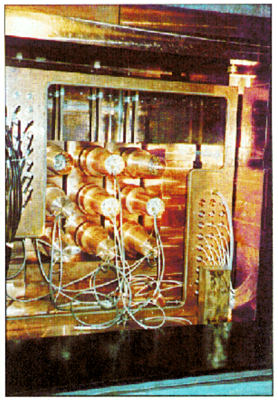
- ✓ **Cosine behaviour**
- ✓ **1 year period**
- ✓ **Maximum around June 2nd**
- ✓ **Weak effect** $\left(\frac{S_m}{S_0} \sim 0.01 - 0.1\right)$
- ✓ **Only noticeable at low energy**
- ✓ **Phase reversal at low E**





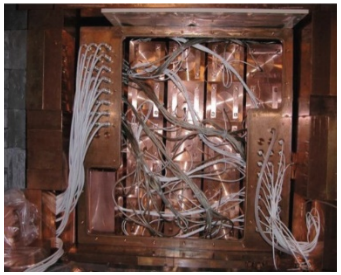
DAMA/NaI & DAMA/LIBRA (phase 1)

DAMA / NaI (1995-2002)

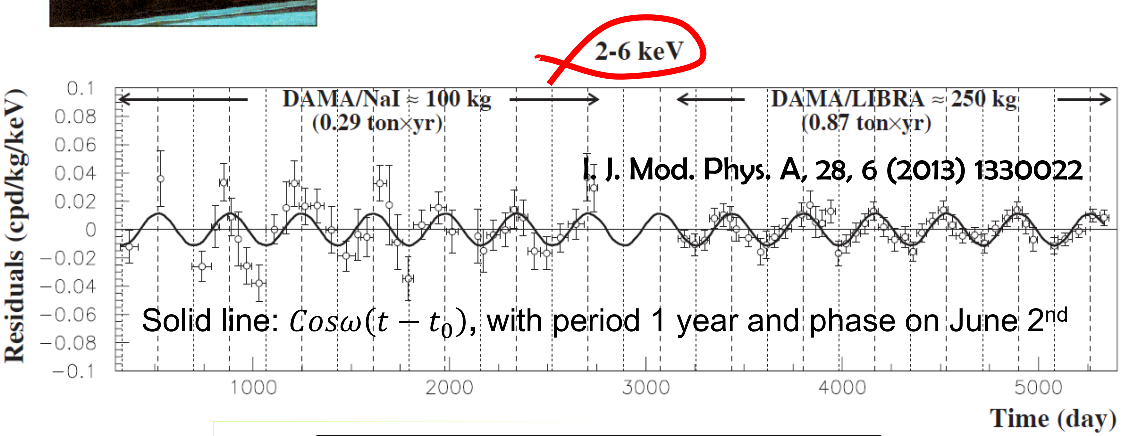


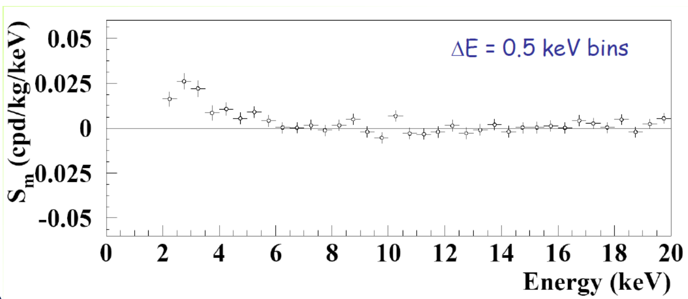
- 10 × 9.7 kg NaI(Tl) (3x3 matrix)
- 7 annual cycles
- Exposure : 0.29 ton × y

DAMA / LIBRA (2003-2010)

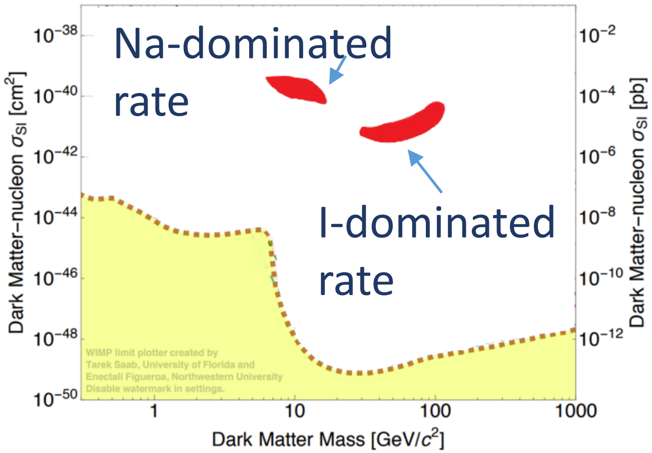


- 25 × 9.7 kg NaI(Tl) (5x5 matrix)
- 7 annual cycles
- Exposure : 1.17 ton × y





The signal satisfies all requirements for DM and **can be interpreted as a "canonical" WIMP:**

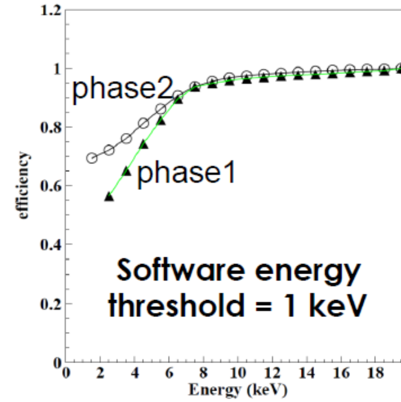


DAMA/LIBRA phase2

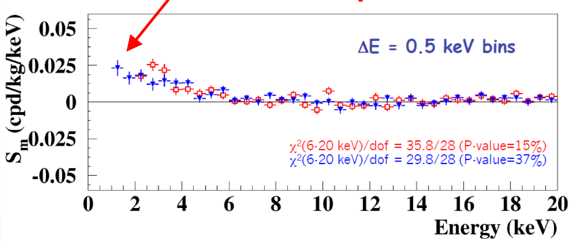
DAMA / LIBRA ph2 (2011-2018)

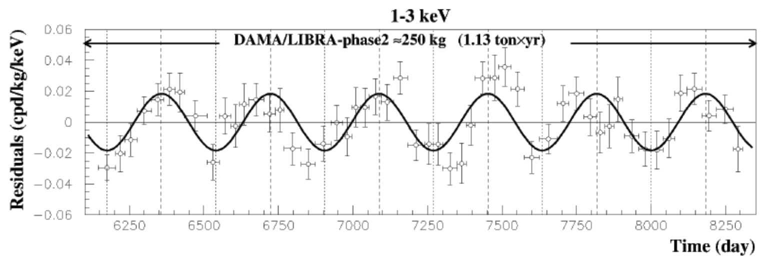
all PMTs replaced with new ones of higher Q.E.

➡ **Threshold lowered from 2 keV → 1 keV**

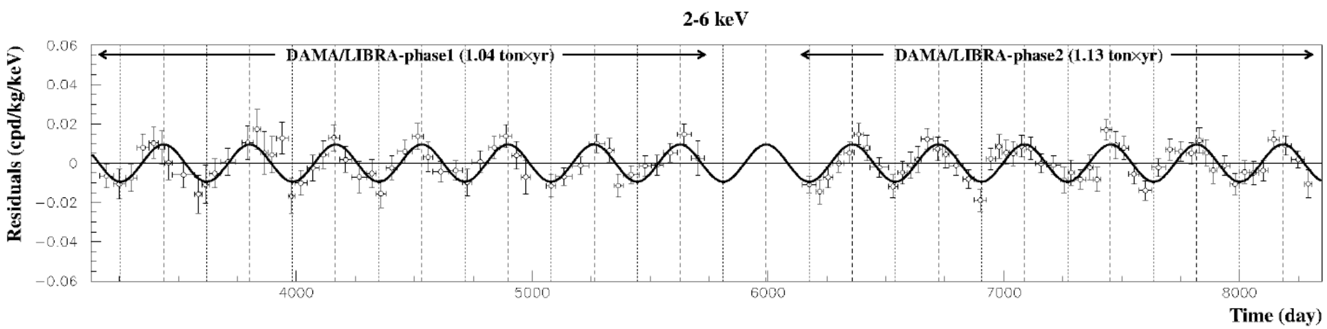


2 more points





- 6 annual cycles
- Exposure: 1.13 ton × y
- Modulation observed in
  [1-6] keV
  [2-6] keV

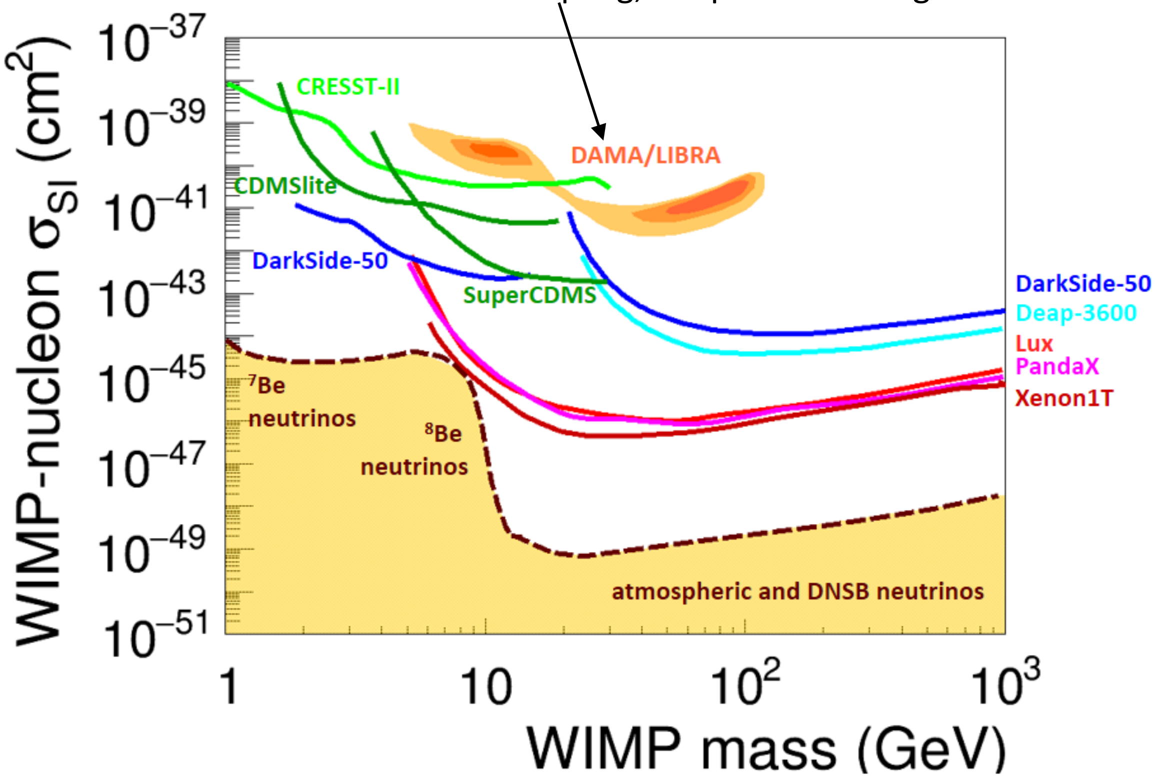


The data of DAMA/LIBRA phase1+phase2 favor the presence of a modulation with proper features at **11.9σ CL** (2.17 ton × yr)

1805.10486, Nucl. Phys. At. Energy 19, 307 (2018)

Comparison with other experiments

Caveat: this region comes from [2-6] keV data. No solution for [1-6] keV with Std halo & SI coupling, isospin conserving



DAMA clearly sees an annual modulation at 12.9σ but **the parameter's region singled out by DAMA/LIBRA is excluded by most sensitive experiments**

But this comparison is model dependent

Model dependency

Wimp model

TARGET DEPENDENT!

Expected rate @ Earth:

$$\frac{dR}{dE_R} = \frac{\rho_0 M_{Det}}{2 m_W m_{WN}^2} \sigma_{WN} \int_{vmin}^{vmax} \frac{f(v)}{v} dv^3$$

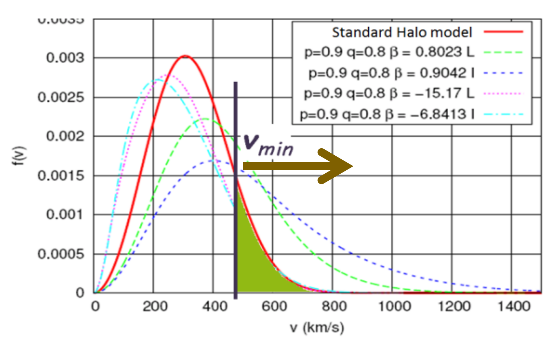
Halo model

In order to compare experiments using different targets usually **we assume:**

- WIMPs interacting through elastic scattering off nuclei
- Only SI or SD coupling
- For SI: - Isospin conserving (couplings are identical for protons and neutrons)
  - A scaling law for the cross section

$$\sigma_{SI} \propto \frac{m_{WN}^2}{m_{Wn}^2} A^2 \; F^2 \sigma_{SI}^{nucleon}$$

- A model for the WIMPs velocity distribution, usually the standard Halo Model (Maxwellian distribution)



$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu_{NW}^2}}$$

- A good knowledge of the NR quenching factor

Model dependency

Still many model-related uncertainties

- Quenching factors
- Form factors
- Halo model
  - Tidal streams
  - caustics
  - ....
- Channeling effects
- …

There are scenarios for compatibility

- Isospin violating
- Effective models
- Inelastic DM
  - Protophilic SD
- Mirror DM
- DM interacting with electrons
- …

TO AVOID ANY MODEL DEPENDENCE, AN INDEPENDENT CONFIRMATION WITH THE SAME TARGET , NaI(Tl), IS REQUIRED

Model dependency

Wimp model

TARGET DEPENDENT!

Expected rate @ Earth:

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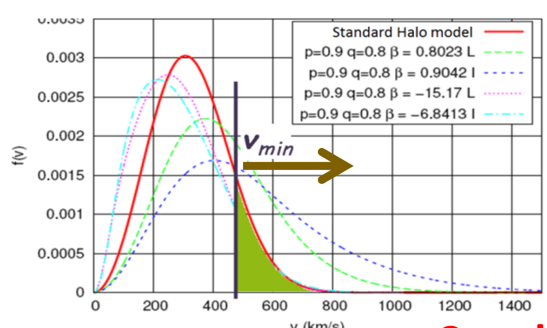


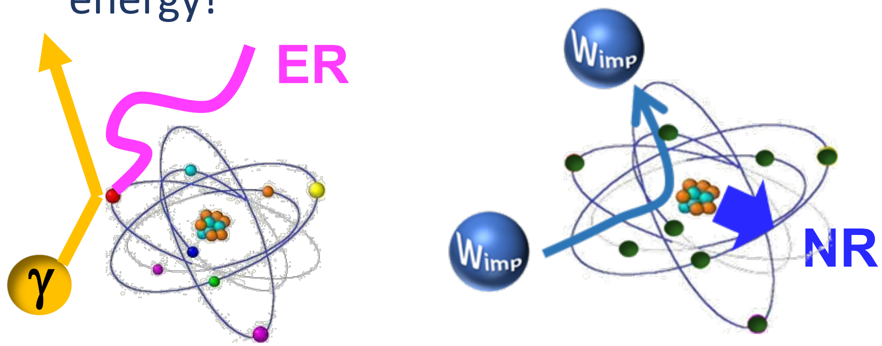
$$v_{min} = \sqrt{\frac{m_N E_{th}}{2\mu_{NW}^2}}$$

- A good knowledge of the NR quenching factor

Can different NaI(Tl) have different NR quenching factors?

NR quenching factor

In a scintillator, an **ER** produces much more light than a **NR** of the same energy!

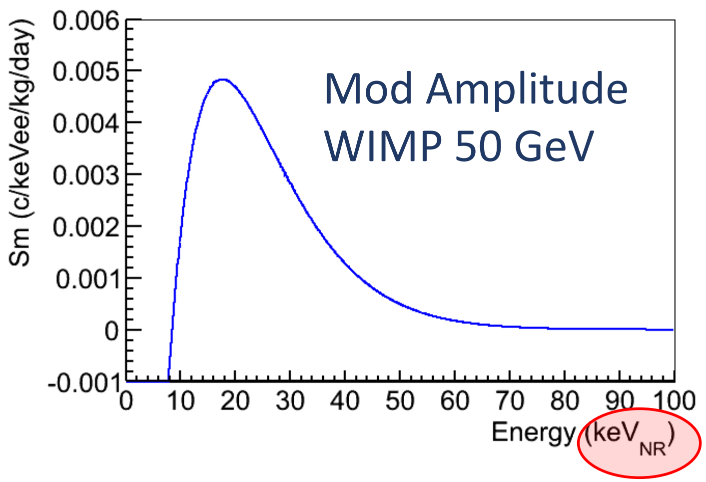


The spectra are calibrated with X/γ sources, so are given in keVee(*). In order to be interpreted as NR, QF **has to be measured** to correct the energy scale:

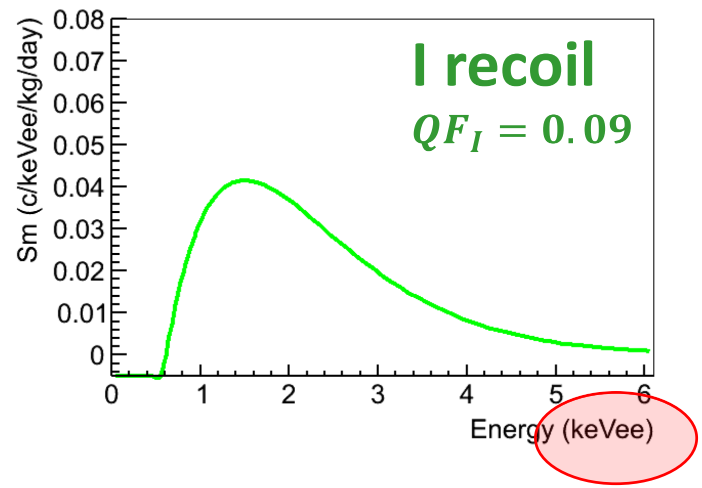
$$QF = \frac{signal_{NR}/keV}{signal_{ER}/keV}$$

(*) keVee: electron-equivalent keV

The “true” NR energy is:



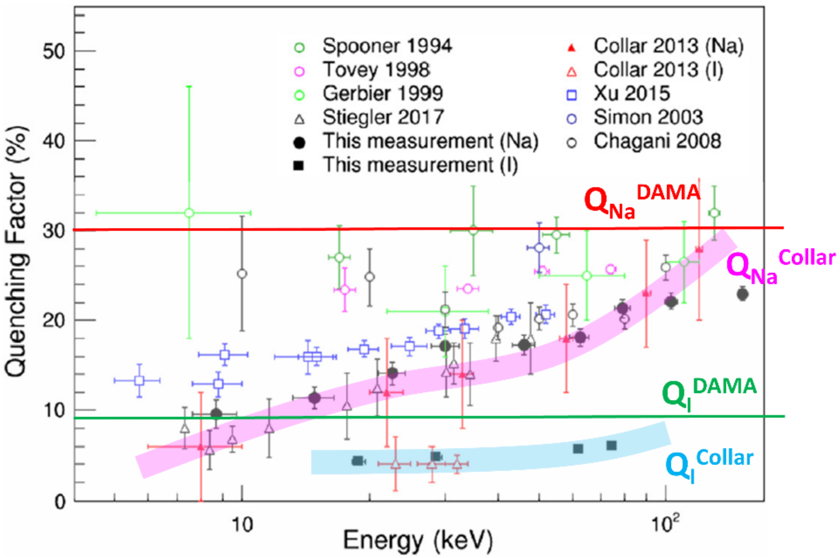
But I measure:



NR quenching factor measurements

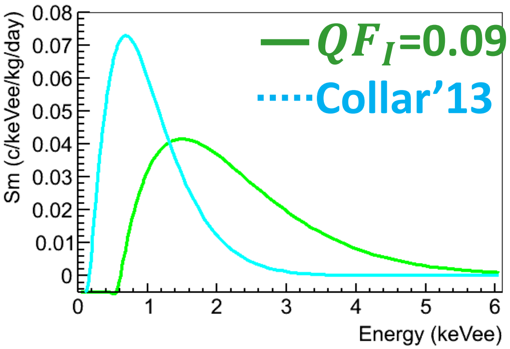
DAMA reported constant values (Phys Lett B 389 (1996) 757) ($QF_{Na} = 0.3$ $QF_I = 0.09$) but recent measurements give lower values. Na quenching decreases when decreasing the energy.

Joo, et al. Astrop. Phys. 108 (2019) 50

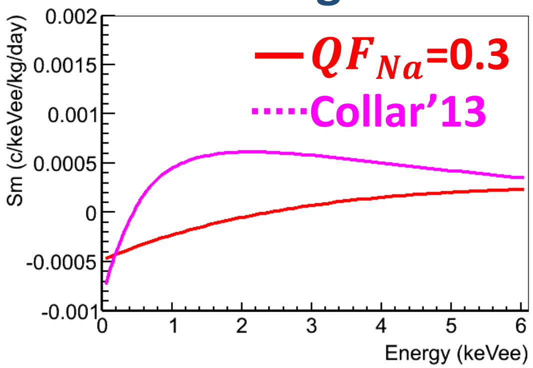


Mod Amplitude in keVee WIMP 50 GeV

Iodine signal



Na signal



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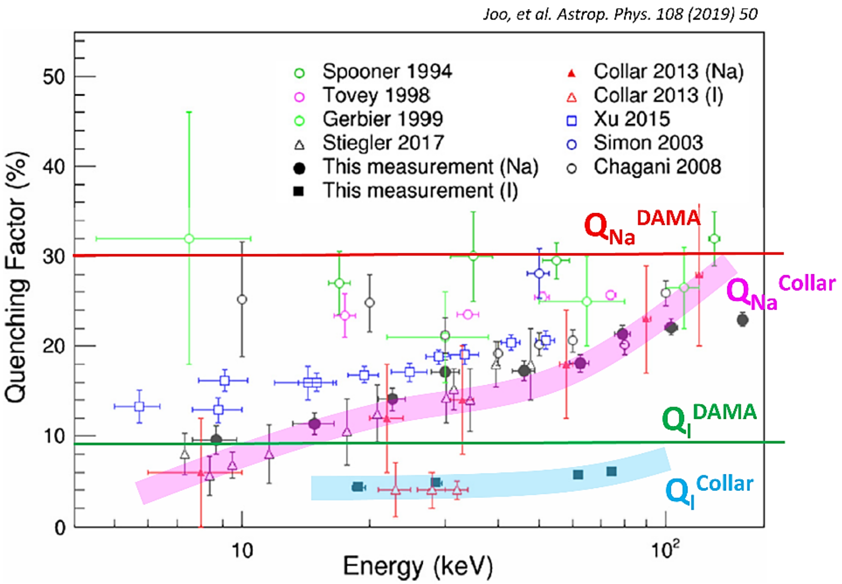
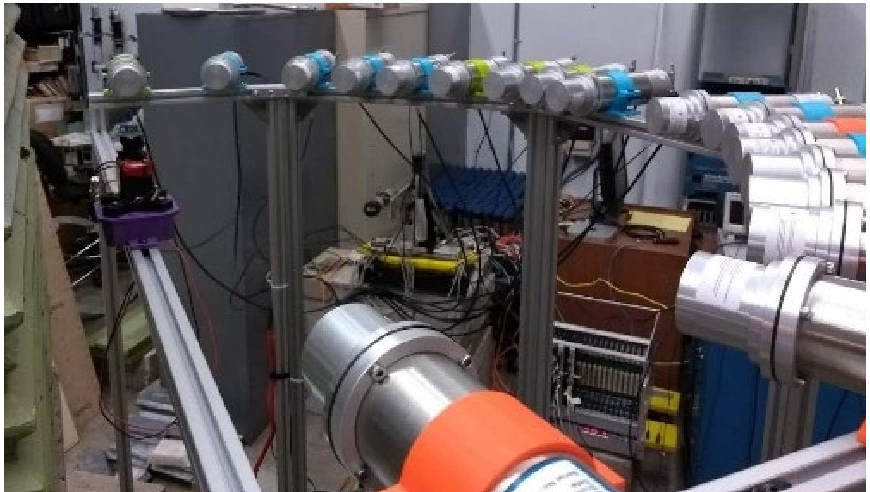


Does the QF depend on the crystal?

- Impurities
- Tl level
- Crystal quality
- …

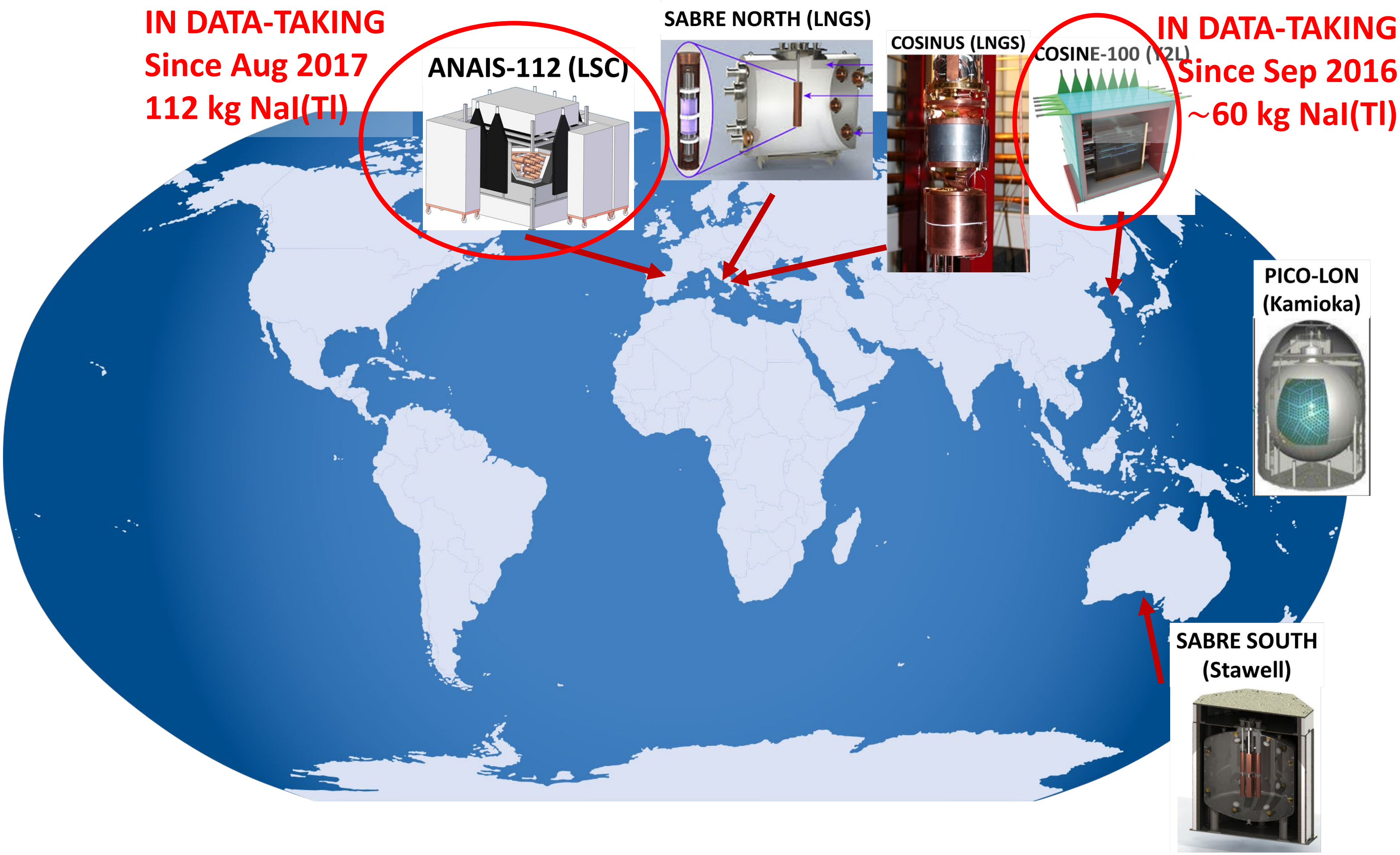
Or the spread in QF measurements is due to systematics?

To answer this question,
Anais + Yale
QF measurements @ TUNL (Duke Univ.)
different NaI(Tl) crystals (ANAIS & COSINE)
in the same setup
Results soon!



Other NaI(Tl) experiments

Other NaI experiments around the World



Current sensitivity-limiting factor

$$\text{Sensitivity} \propto \sqrt{\frac{MT\epsilon}{B}}$$

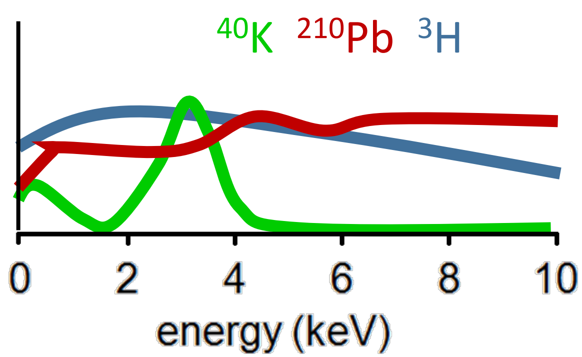
Large mass

Stable conditions over years

High efficiency at very low energy

Very low radioactive background

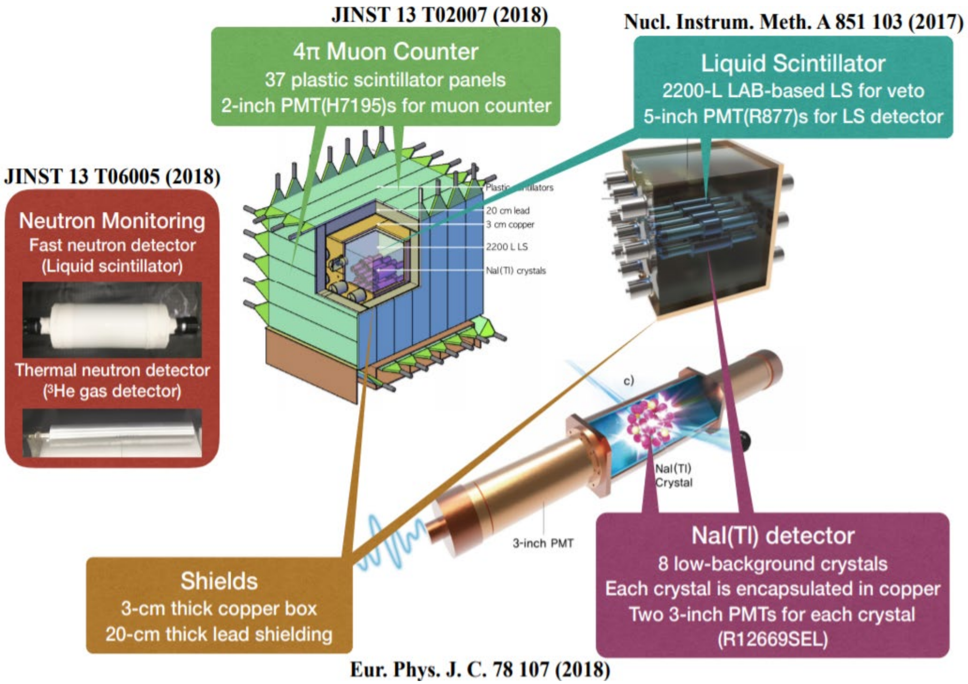
- **The main contribution to the background comes from the crystal itself**
- Long effort of ANAIS team looking for ultra pure NaI(Tl), R&D with Alpha Spectra → crystals now used by ANAIS-112 and COSINE-100
- **only very recently the quality of the DAMA crystals is at reach**



	K (ppb)	^{210}Pb (mBq/kg)
DAMA (Saint Gobain)	13	0.01-0.03
ANAIS/COSINE (Alpha Spectra)	18-44	0.7-3

COSINE-100

From Y. J. Ko @ TAUP2019



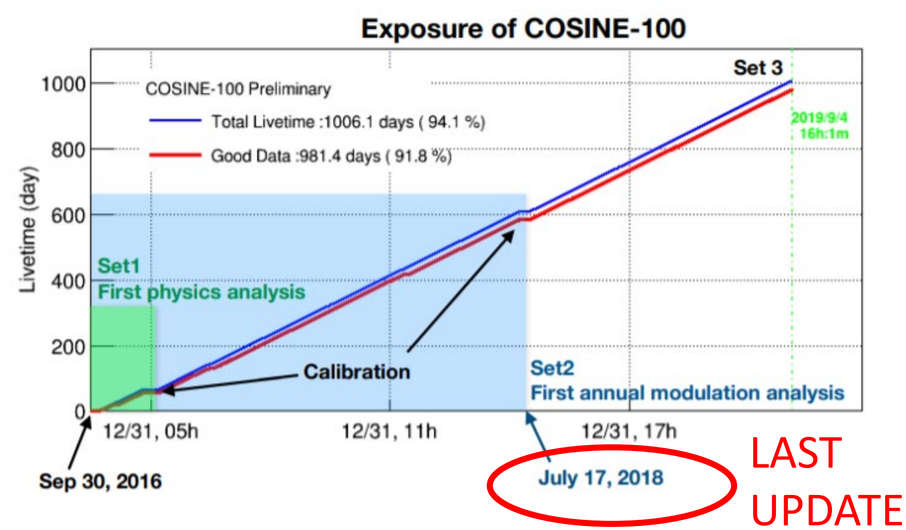
- Data-taking started in Sep 2016, Y2L (South Korea)
- 8 ultra low-background NaI(Tl) crystals with 106 kg in total (**but only ~60 kg usable for DM search**)
- Inside lead shielding and Liquid Scintillator tank to reject coincident events (^{40}K!)
- Muon veto & neutron monitoring

NEXT STEP: COSINE-200

Goal: Run 200 kg NaI(Tl) in the same set-up, with improved background (lower than DAMA/LIBRA)

Status: Power purification, crystal growing and handling facilities established, but a factor 2 or more improvement in bkg is needed.

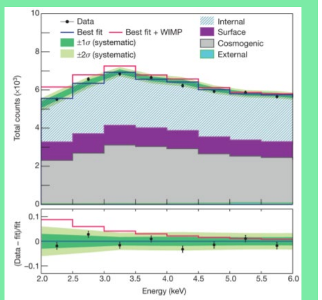
From G. Adhikari @ TAUP2019

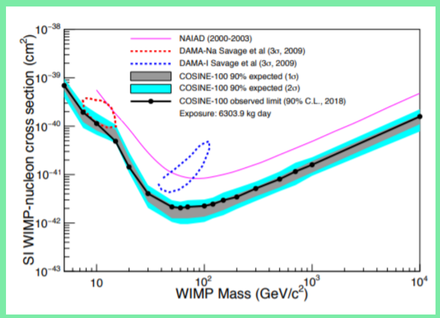


COSINE-100 results

- **MODEL DEPENDENT ANALYSIS: background model + WIMP signal fit to data**

SET1 (59.5 days) (2 keV threshold)

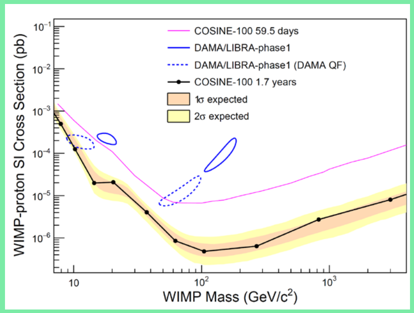




90% CL COSINE limits excluded DAMA region in SI scenarios

Nature 564 (2018) 83

SET2 (1.7 y, 97.7 kg·year exposure)



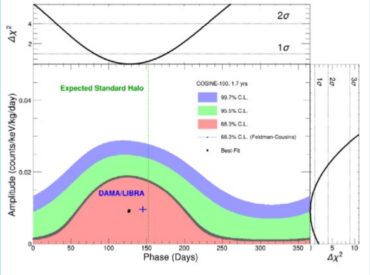
- 1 keV threshold
- **Using COSINE QF measurement**
- Strong constraint also in other alternative scenarios

Last week: arXiv:2104.03537

- **ANNUAL MODULATION ANALYSIS:**

SET2 (1.7 y & ~60 kg -> 97.7 kg·year exposure)

Configuration	χ^2	$d.o.f.$	p-value	Amplitude (counts/keV/kg/day)	Phase (Days)
COSINE-100	175.3	174	0.457	0.0092±0.0067	127.2±45.9
DAMA/LIBRA (Phase1+Phase2)	–	–	–	0.0096±0.0008	145±5

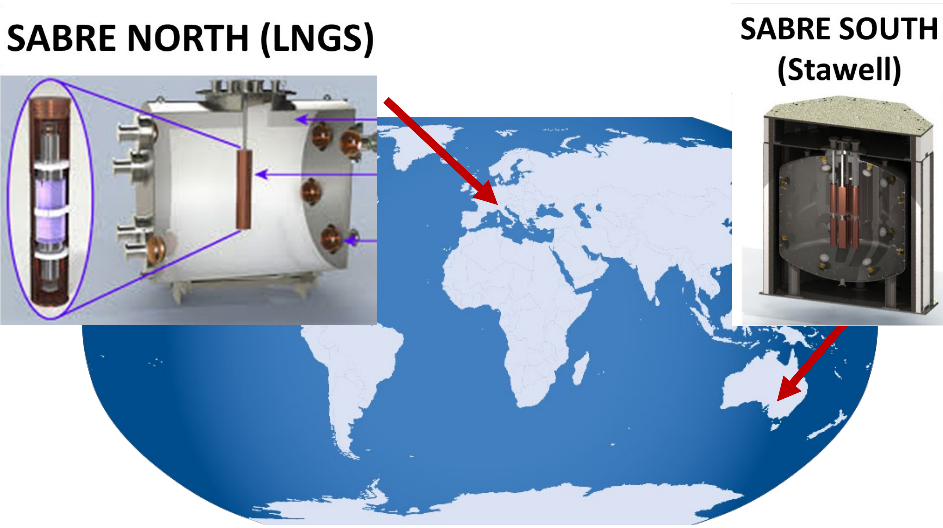


At 68.3% C.L., result is consistent with both a null hypothesis and DAMA/LIBRA's best fit value.

Phys.Rev.Lett. 123 (2019) 031301

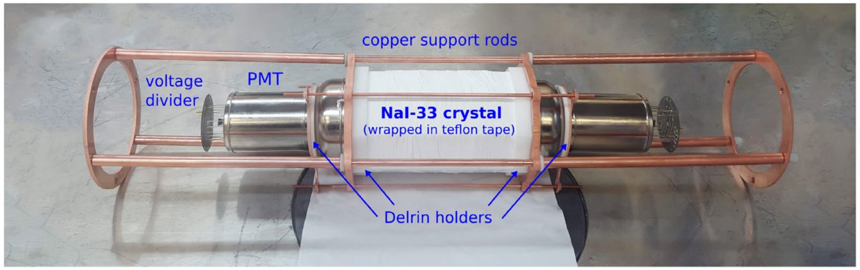
SABRE

Eur. Phys. J. C79 (2019) 363
arXiv: 2012.02610



- Ultra-clean NaI(Tl) (Princeton)
- Two sites (LNGS/ Stawell)

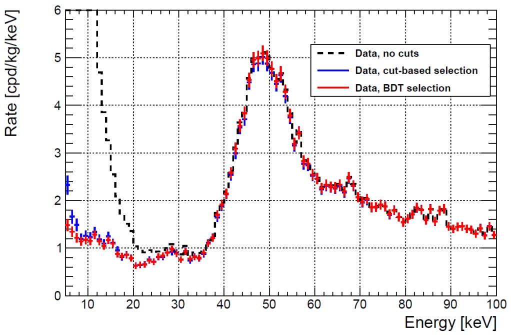
Proof of Principle: one NaI crystal in LS vessel



Since August 2020 taking data at LNGS inside LS vessel

NaI-33 crystal (3.4 kg) characterization

	K (ppb)	^{210}Pb (mBq/kg)
SABRE	4	0.53
DAMA	13	0.01-0.03
ANAIS	18-44	0.7-3

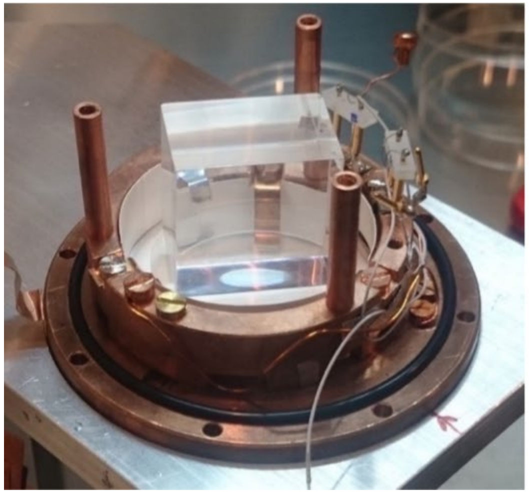


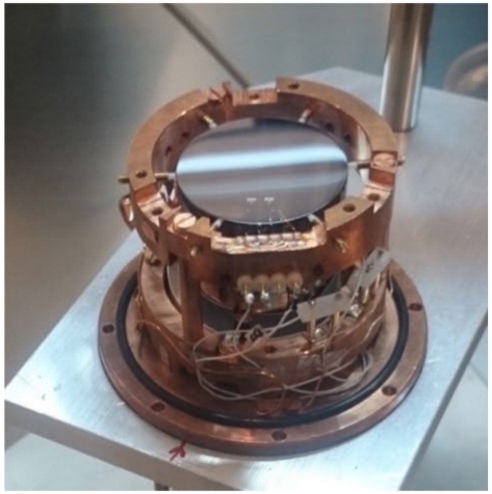
World record!

COSINUS

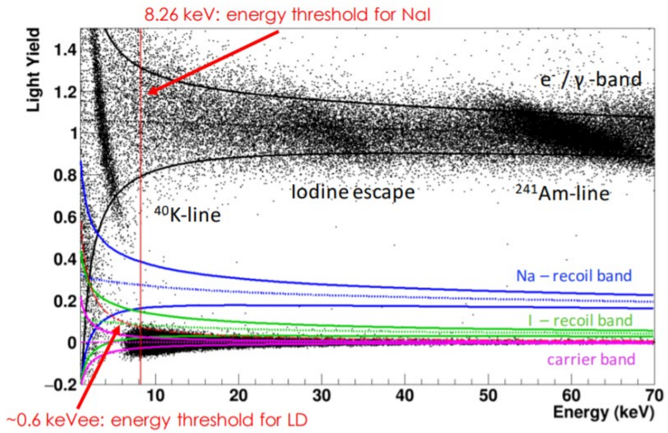
First NaI detector with particle discrimination
(Two channel approach: HEAT and LIGHT)

J. Low Temp. Phys. 193 (2018) 1174
JINST 12 (2017) P11007





With a moderate exposure of few O(100) kg-days , can confirm or rule-out a **nuclear recoil origin** of the DAMA/LIBRA dark matter claim



Present threshold:
8.26 keV_{NR}
(Goal: 1 keV_{NR})


ANAIS-112 experiment

ANAIS-112

Annual Modulation with NaI Scintillators

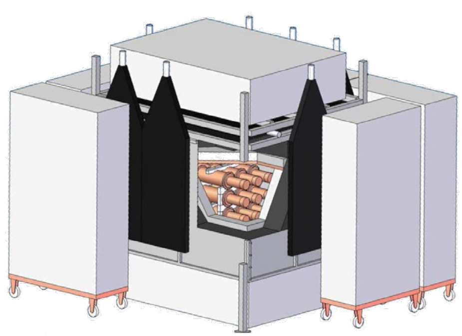
J. Amaré, I. Coarasa, S. Cebrián, D. Cintas, E. García, M. Martínez, M.A. Oliván,
Y. Ortigoza, A. Ortiz de Solórzano, J. Puimedón, A. Salinas, M.L. Sarsa

GOAL:

Confirmation of DAMA-LIBRA modulation signal with the same target and technique
(but different experimental approach and environmental conditions)

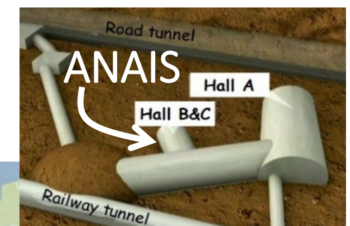
THE DETECTOR:

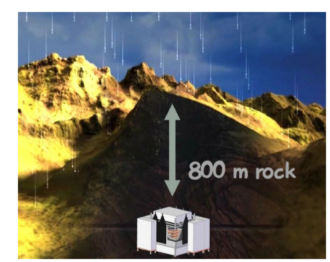
3x3 matrix of 12.5 kg NaI(Tl) cylindrical modules = **112.5 kg** of active mass



WHERE:

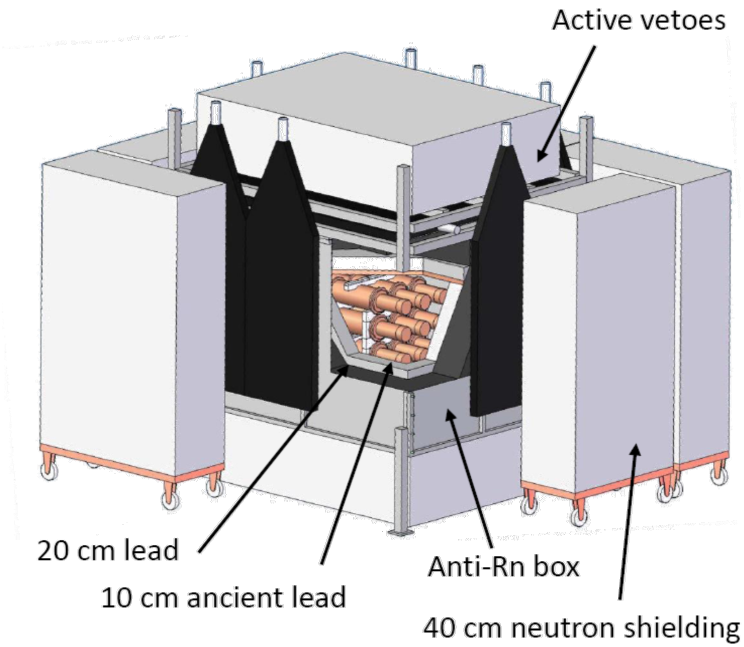
At Canfranc Underground Laboratory, @ **SPAIN** (under **2450 m.w.e.**)



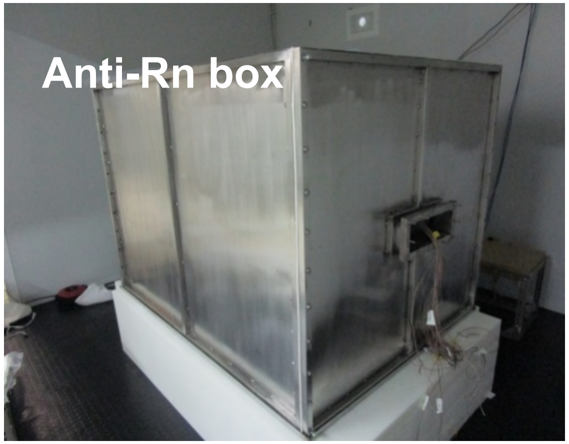


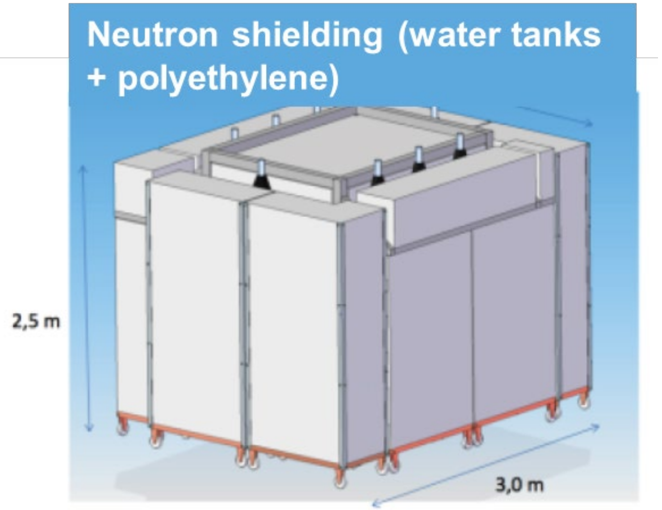
taking data since August 2017

ANAIS-112: experimental setup



- 9 NaI(Tl) cylindrical crystals (12.5 kg each) in 3x3 matrix
- Ultrapure NaI powder (Alpha Spectra Inc)
- Each coupled to two Hamamatsu R12669SEL2 PMT (QE ~40%)



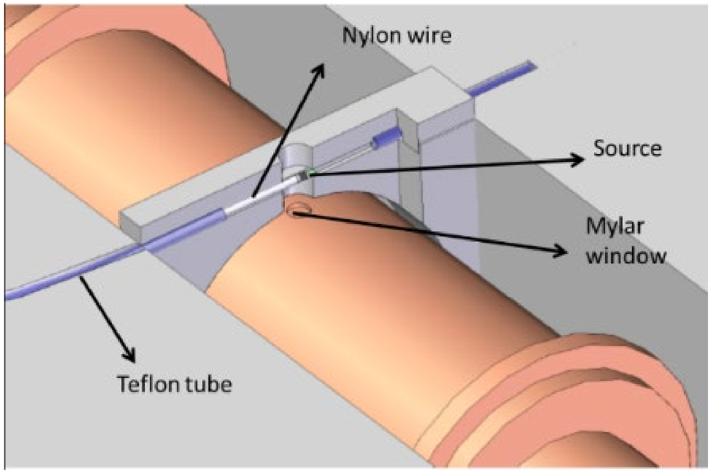


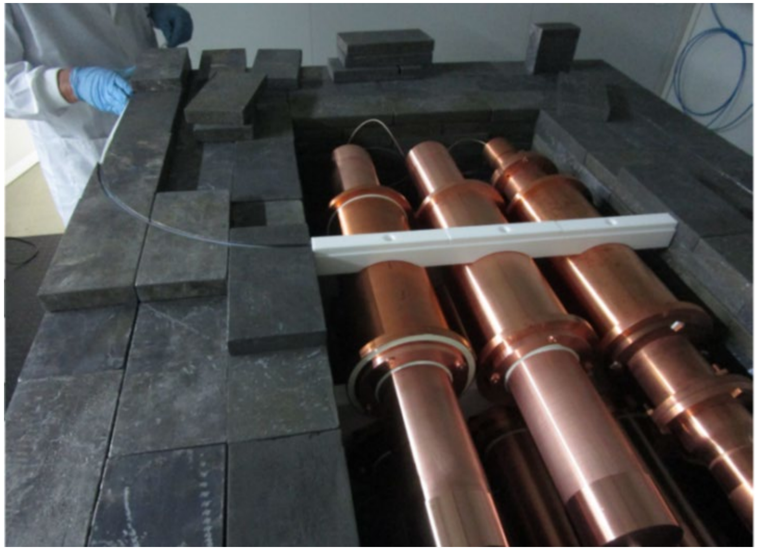
ANAIS-112: Low energy calibration

Detectors equipped with a **Mylar window**!

Radon-free system for low energy calibration:

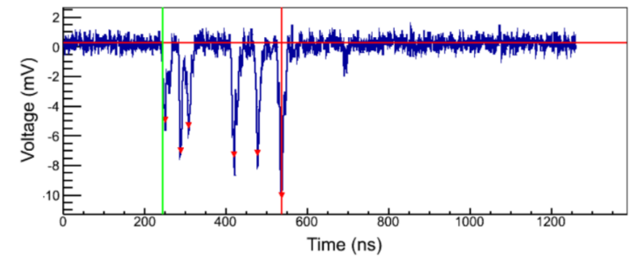
- ^{109}**Cd sources** on flexible wires (radon-free)
- Energies: 11.9, 22.6 and 88.0 keV
- Simultaneous calibration of the nine modules
- Performed every two weeks

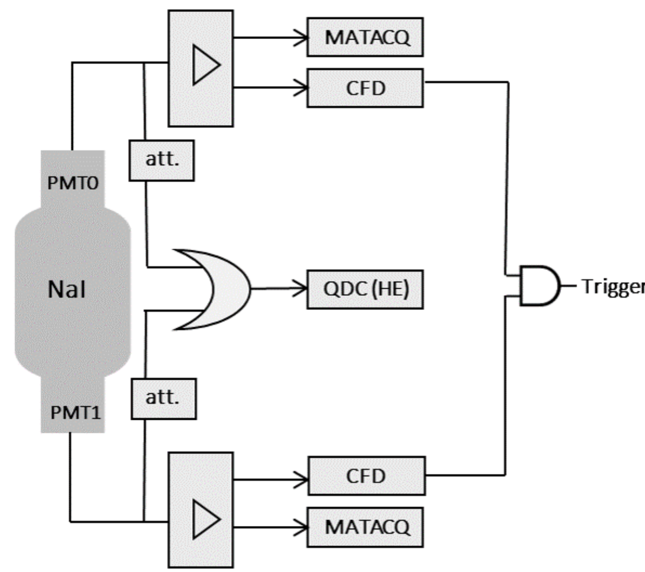


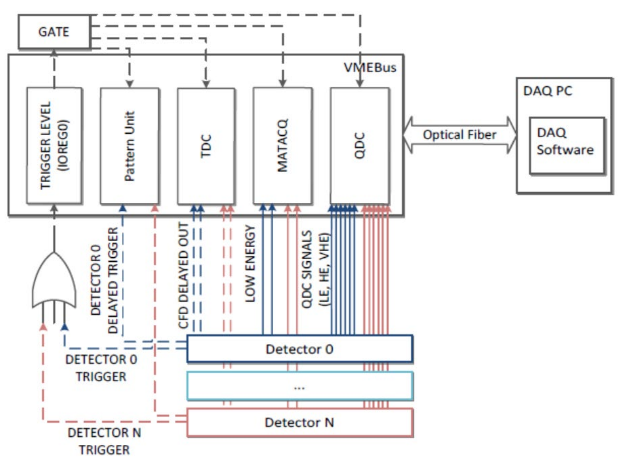


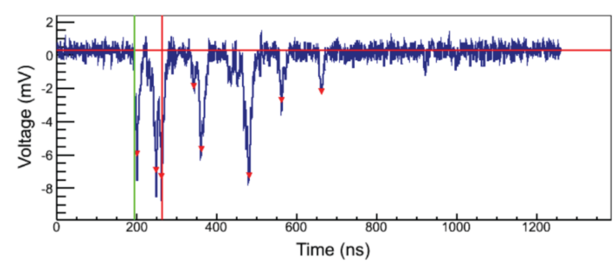
ANAIS-112: Data acquisition system

- Individual PMT signals **digitized** and fully processed **(14 bits, 2 GS/s)**
- Trigger at phe level for each PMT signal
- AND coincidence in 200 ns window
- Redundant energy conversion by QDC
- Trigger in OR mode among modules
- Electronics at air-conditioned-room to decouple from temperature fluctuations
- Muon detection system: tag every muon event to offline processing



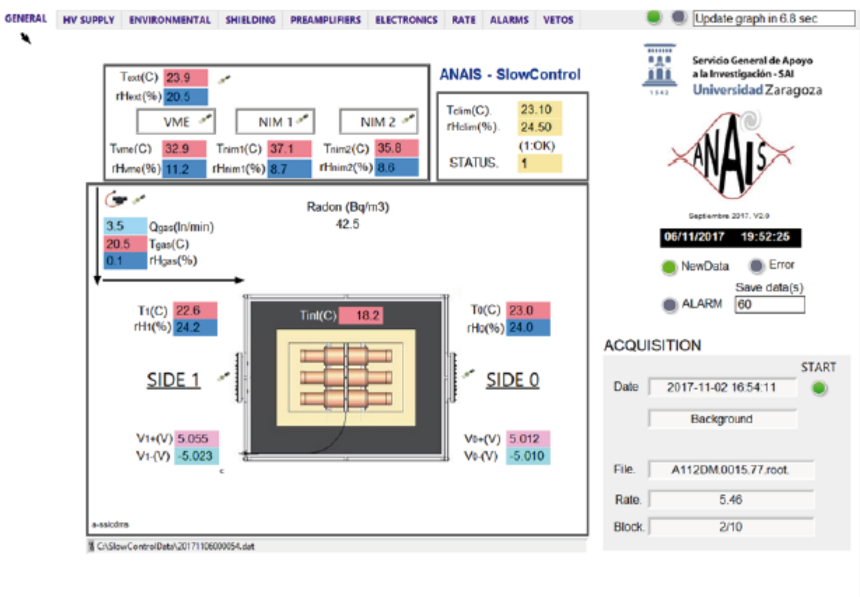


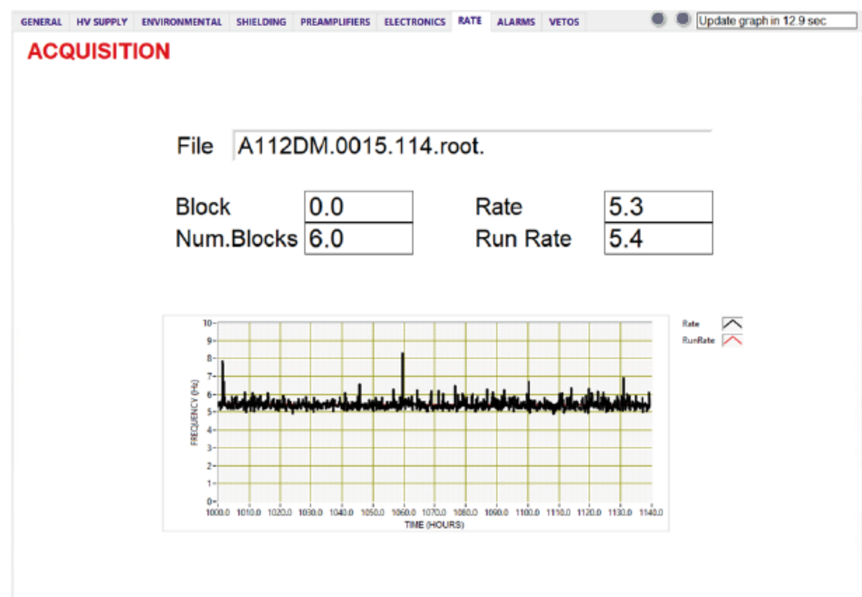




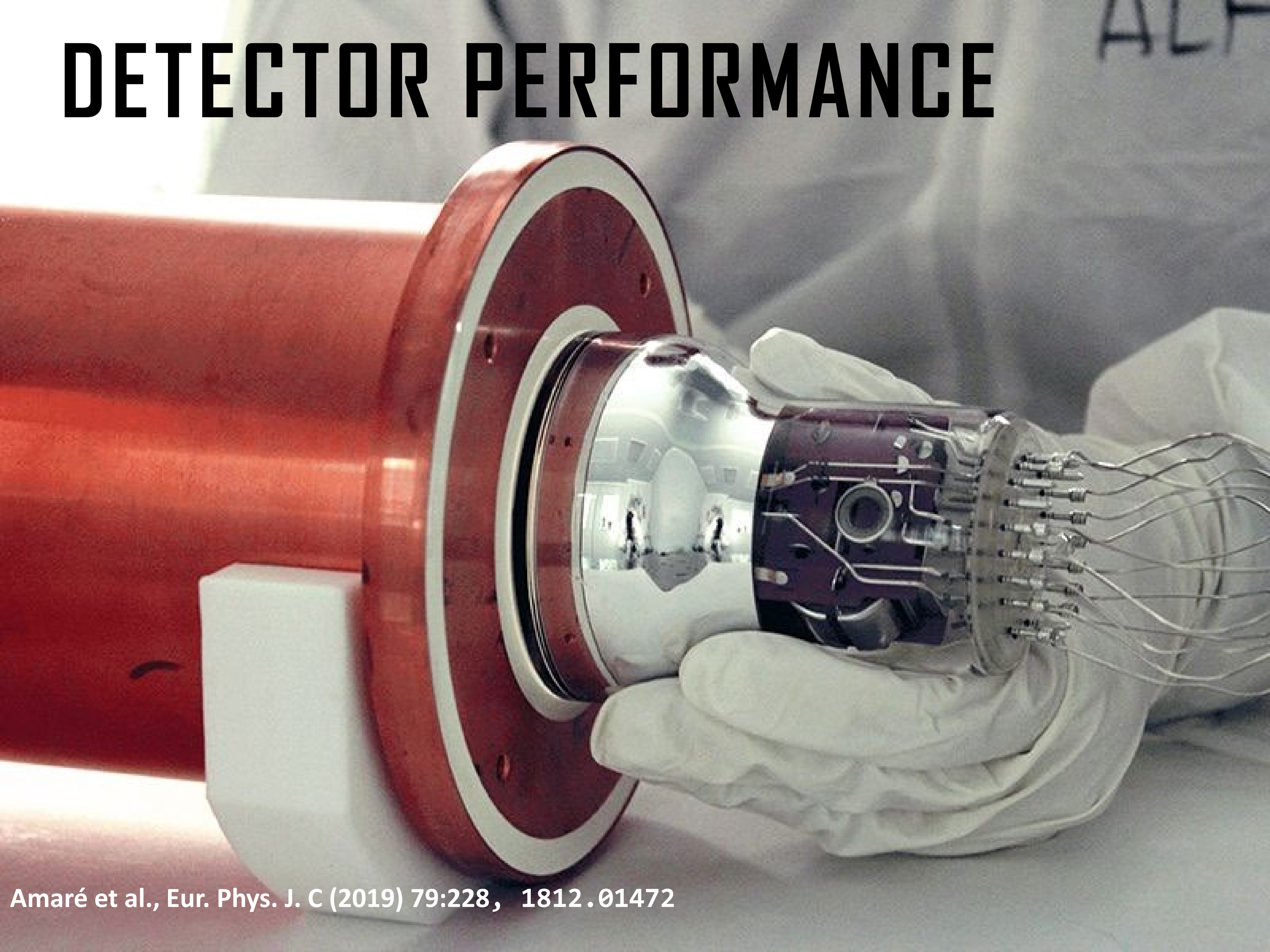
ANAIS-112: Slow control

- Monitoring **environmental parameters** since the start of DM run
  - Monitoring:
    Rn content, humidity, pressure, different temperatures, N_2 flux, PMT HV, muon rate, …
    Data saved every few minutes and alarm messages implemented
  - Stability checks:
    gain, trigger rate, …





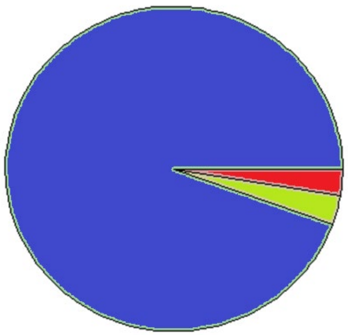
DETECTOR PERFORMANCE

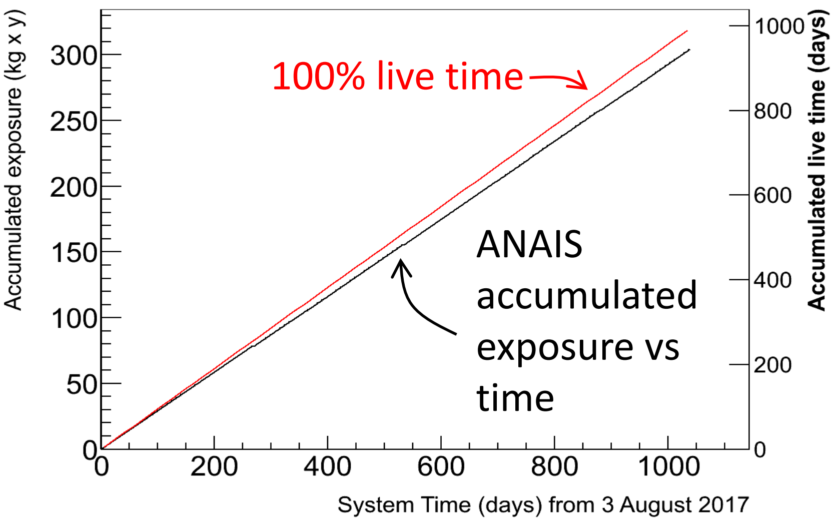


Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

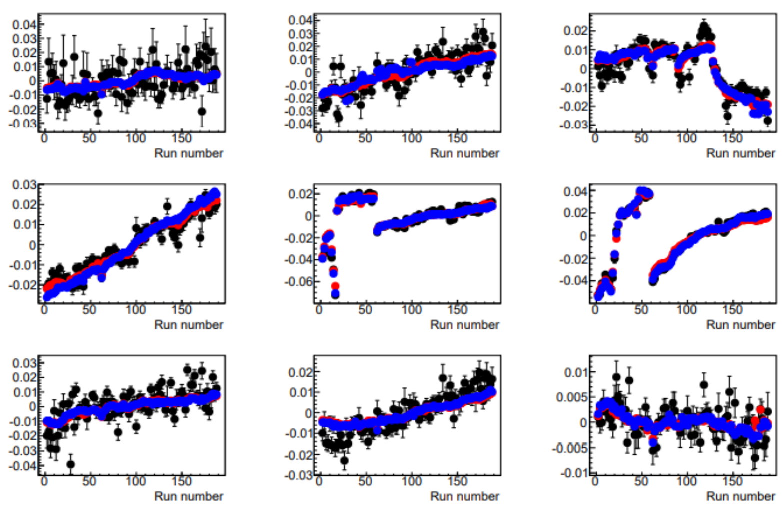
Detector Response: duty cycle & stability

- Excellent **duty cycle**





- Good **total rate and gain stability**



Evolution of ^{109}**Cd lines from calibrations** along the whole data-taking (~ 3 year) show good stability except for D4 & D5 (HV changed after first year)

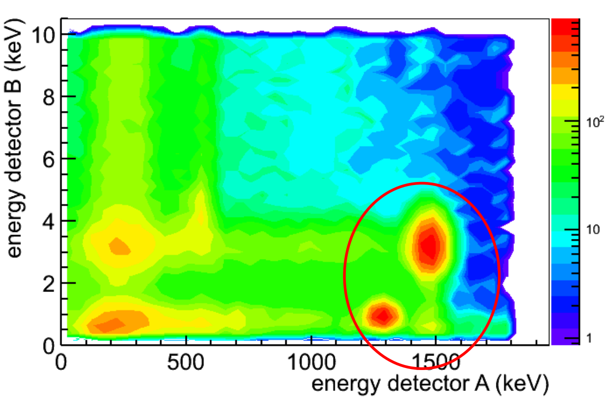
Thanks to the periodic calibration **we can correct** the small (few percent) gain variations

Detector response: light yield & threshold

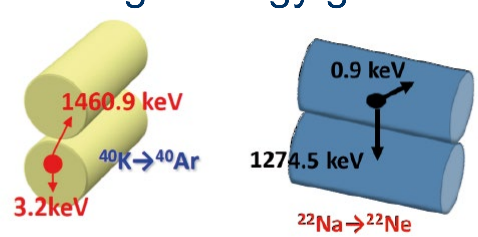
- **Excellent light collection** (2x DAMA ph1)

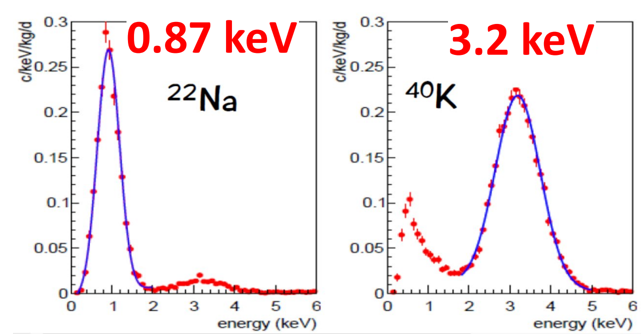
Module	Q.E. PMT0/PMT1 (%)	Total light collection (p.e./keV) 2017 results [33]	3 years results average	3 years results std. deviation	Energy resolution FWHM @ 3.2 keV (keV)
D0	38.2/37.2	14.6 ± 0.1	14.49	0.11	1.26 ± 0.03
D1	39.7/39.7	14.8 ± 0.1	14.64	0.15	1.30 ± 0.04
D2	39.2/42.6	14.6 ± 0.1	14.21	0.30	1.25 ± 0.03
D3	37.3/39.4	14.5 ± 0.1	14.33	0.12	1.14 ± 0.05
D4	40.1/41.8	14.5 ± 0.1	14.33	0.13	1.34 ± 0.06
D5	43.6/43.9	14.5 ± 0.1	14.82	0.23	1.22 ± 0.02
D6	40.4/38.9	12.7 ± 0.1	12.74	0.12	1.35 ± 0.04
D7	41.9/42.5	14.8 ± 0.1	14.55	0.18	1.38 ± 0.04
D8	41.6/43.4	16.0 ± 0.1	15.81	0.21	1.30 ± 0.05

- Effectively **triggering below 1 keV$_{ee}$** checked with internal contaminants ^{22}Na, ^{40}K



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

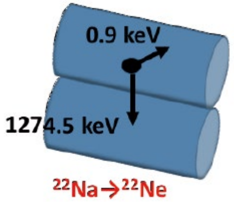


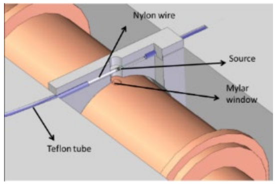


Blinded analysis

ANALYSIS STRATEGY

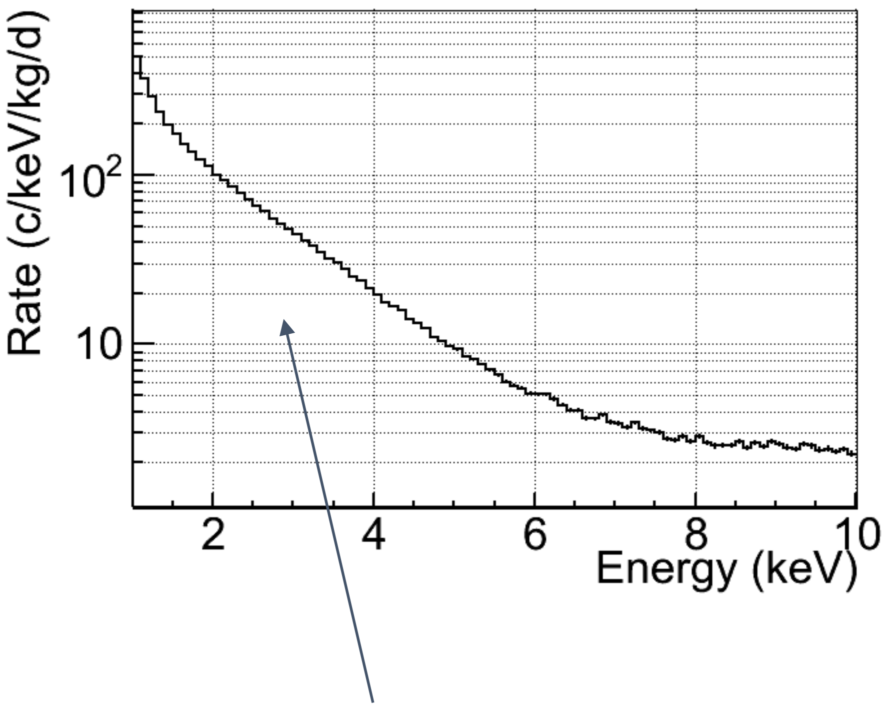
- Multiplicity-1 events in the RoI (1-6 keV) **blinded**
- We use **multiplicity-2 events** in the RoI and **calibration events** to tune the **filtering** algorithms and calculate the **cut efficiencies**





- We unblind 10% (~30 days randomly distributed along the first year) data for background assessment

10% unblinded data



Bkg in the ROI dominated by non-bulk scintillation events!

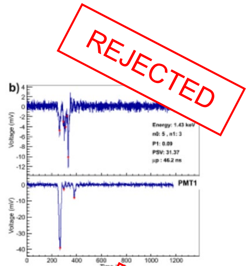
Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

Event selection & efficiency

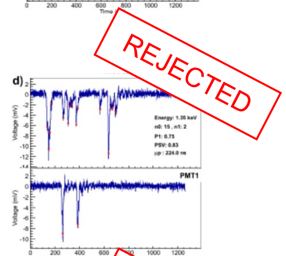
Procedure fixed before unblinding

CUTS

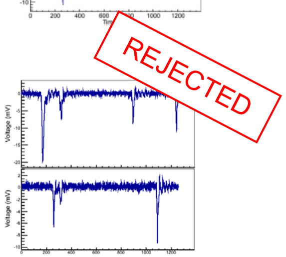
1. Pulse shape cut to remove pulses not compatible with NaI(Tl) scintillation constant



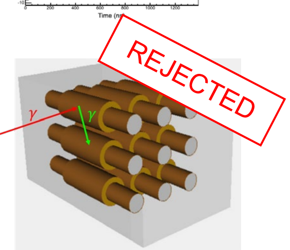
2. We remove asymmetric events (<2 keVee) with origin in the PMT



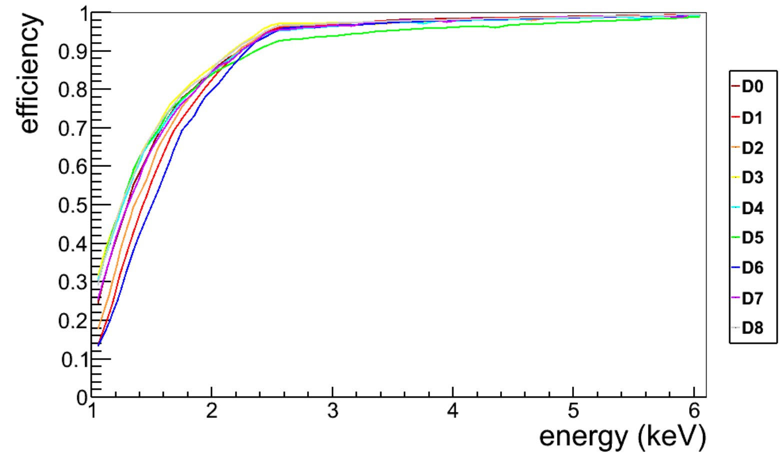
3. Remove 1 s after a muon passage



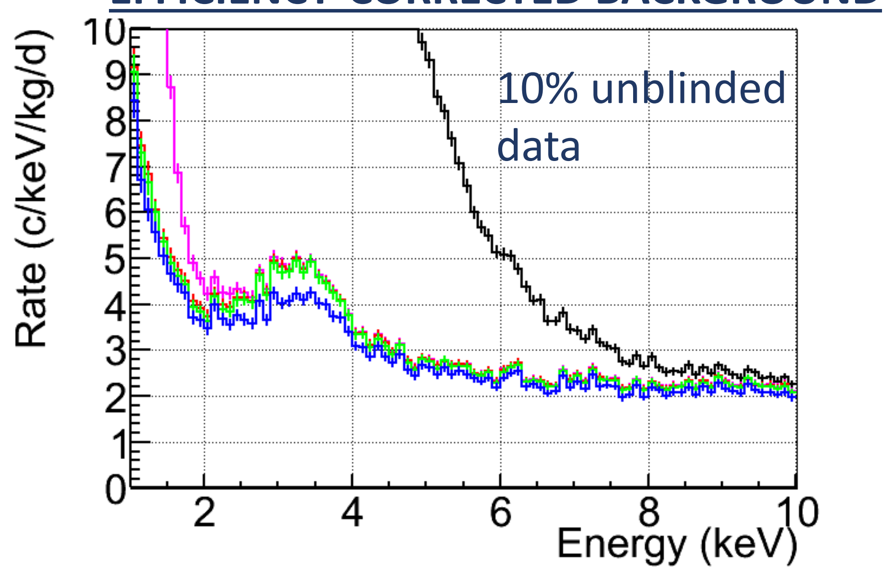
4. Multiplicity > 1 (Reject events that deposit energy simultaneously in more than one crystal)



TOTAL EFFICIENCY

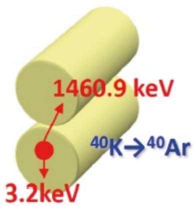


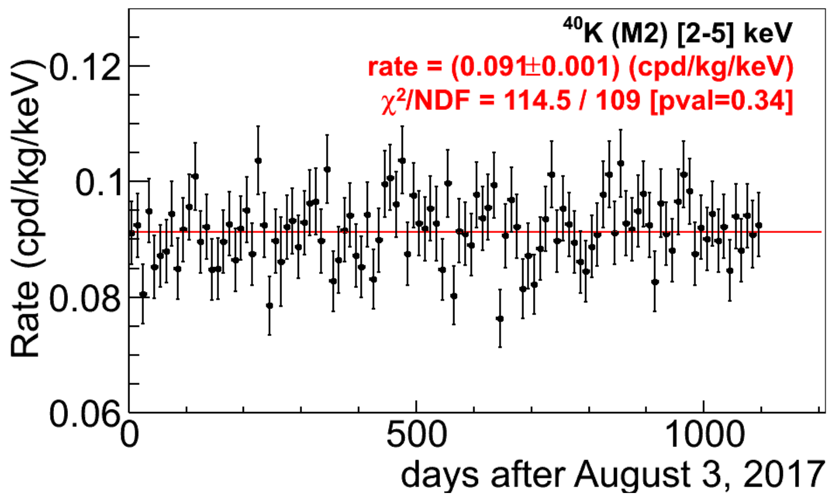
EFFICIENCY-CORRECTED BACKGROUND



Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.0147

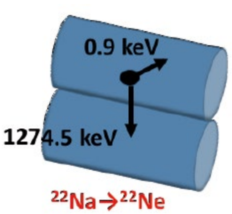
Stability check with control populations

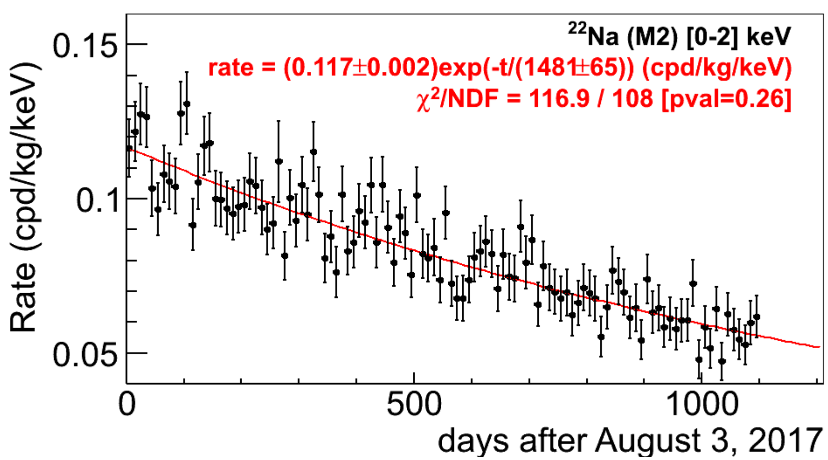




^{40}K ($T_{1/2} = 1.28 \times 10^9 y$)

[2-5] keV rate in coincidence with HE gamma compatible with constant

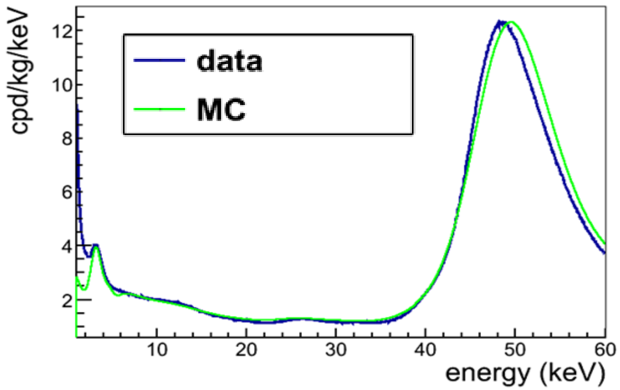




^{22}Na ($T_{1/2} = 2.6\ y$)

[0-2] keV rate in coincidence with HE gamma compatible with ^{22}Na decay (exponential decay with $\tau = 1481 \pm 65$ d)

Background model



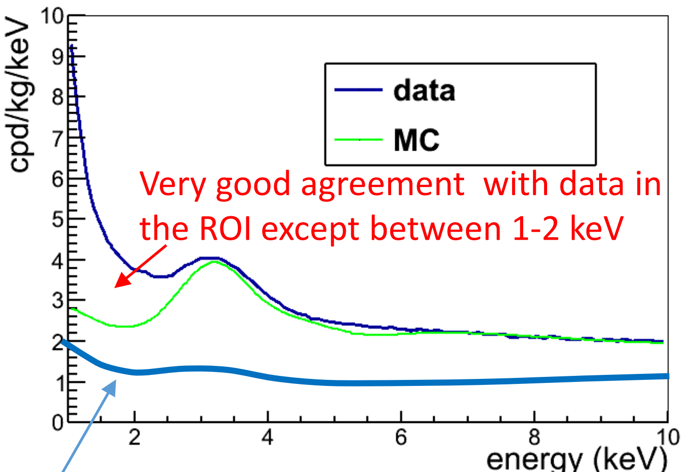
Amaré et al., Eur. Phys. J. C (2019) 79:228, 1812.01472

Geat4 MC simulation including:

- activity from external components measured wiht HPGe
- internal and cosmogenic activity directly assessed from data.

At very low energy (<20 keV), main contribution to background from internal contamination:

- **^{40}K** and **^{22}Na** ($T_{1/2}$ = 2.6 y) peaks
- **^{210}Pb** (bulk+surface) ($T_{1/2}$ = 22.3 y)
- **^{3}H** ($T_{1/2}$ = 12.3 y)

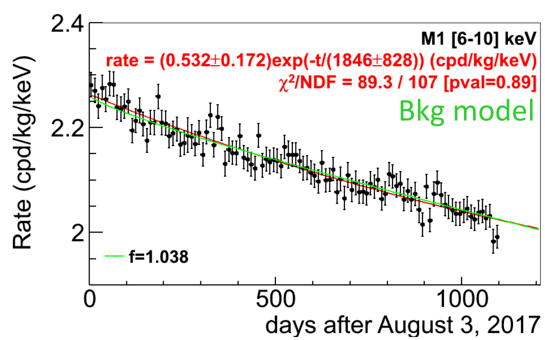


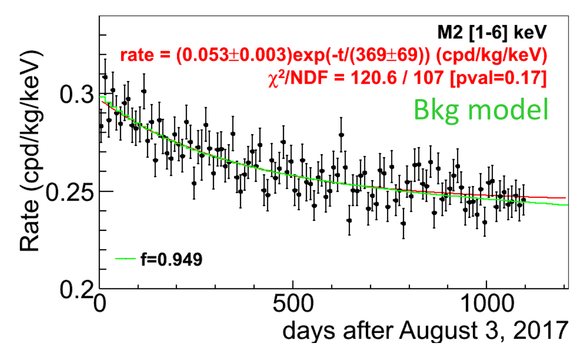
DAMA/LIBRA

Universe 4, 116 (2018), 1805.10486

Cosmogenic isotopes (^{3}H, ^{22}Na, …) and ^{210}Pb are decaying

→ Our MC model reproduce satisfactorily the time evolution for non-blinded populations





RESULTS ON ANNUAL MODULATION

Analysis strategy

arXiv: 2103.01175
Submitted to PRD

Focus on model independent analysis searching from modulation

- In order to better compare with DAMA/LIBRA results
  - **use the same energy regions ([1-6] keV, [2-6] keV)**
  - **fix period 1 year and phase to June 2nd**
- ChiSquare minimization: $\chi^2 = \sum(n_i - \mu_i)^2/\sigma_i^2$

where the expected number of events depends on the **bkg model** ($\phi_{bkg}(t_i)$):

$$\mu_i = \left[R_0 \boldsymbol{\phi_{bkg}(t_i)} + \boldsymbol{S_m} \cos\left(\omega(t_i - t_0)\right)\right] M \Delta E \Delta t$$

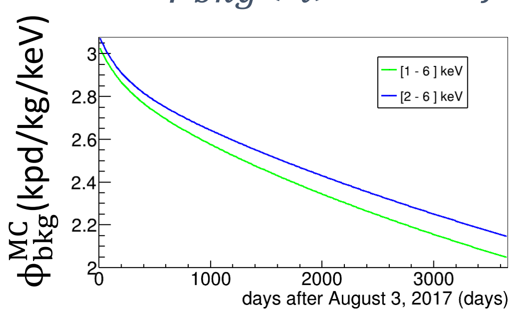
MODEL 1: assume exponential decay

$$\phi_{bkg}(t_i) = 1 + f exp\left(-\frac{t_i}{\tau}\right)$$

Free parameters: $R_o, f, \tau \ + S_m$

MODEL 2: Use MC simulation

$$\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$$

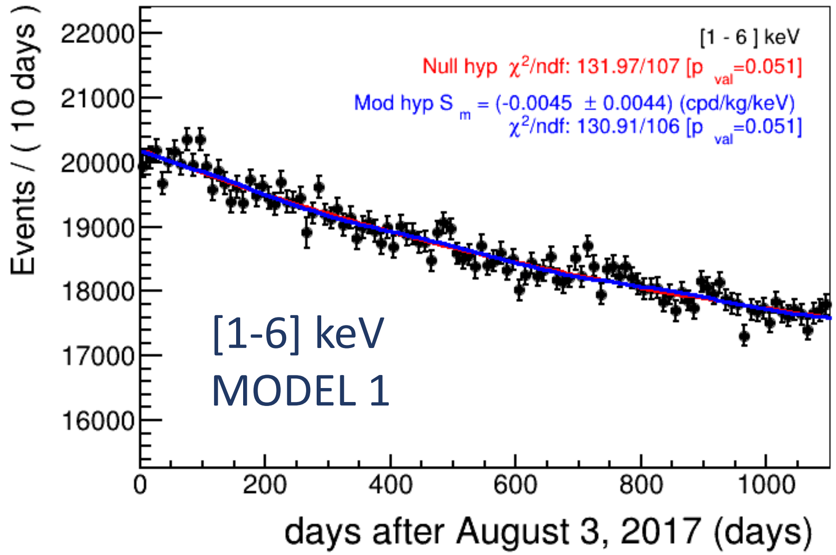


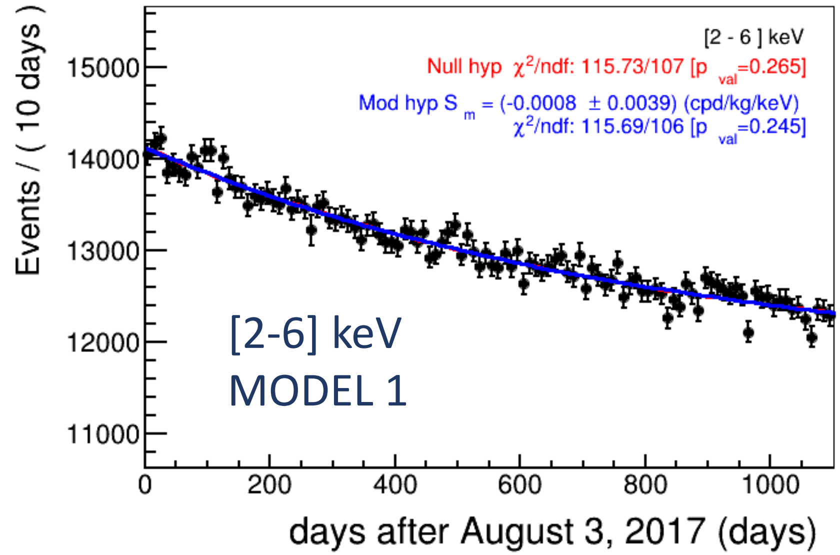
Free parameters: $R_o, f + S_m$

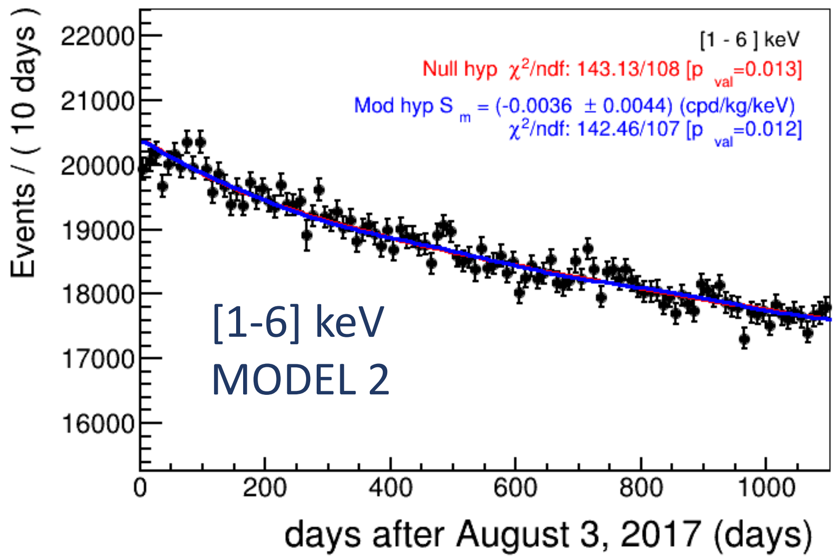
NOTE: the constant term in both equations represent any nonvarying rate, including the unmodulated term of an hypothetical WIMP component.

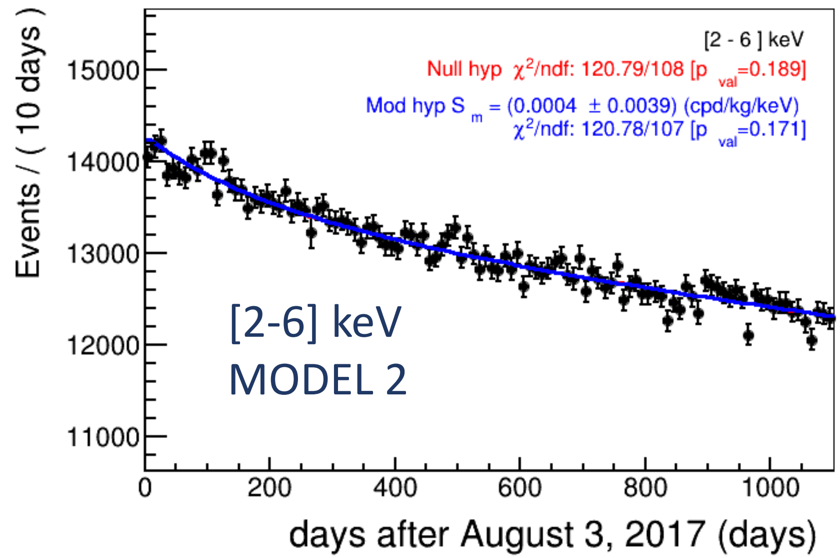
3 years results (313.95 kgxy)

arXiv: 2103.01175
Submitted to PRD







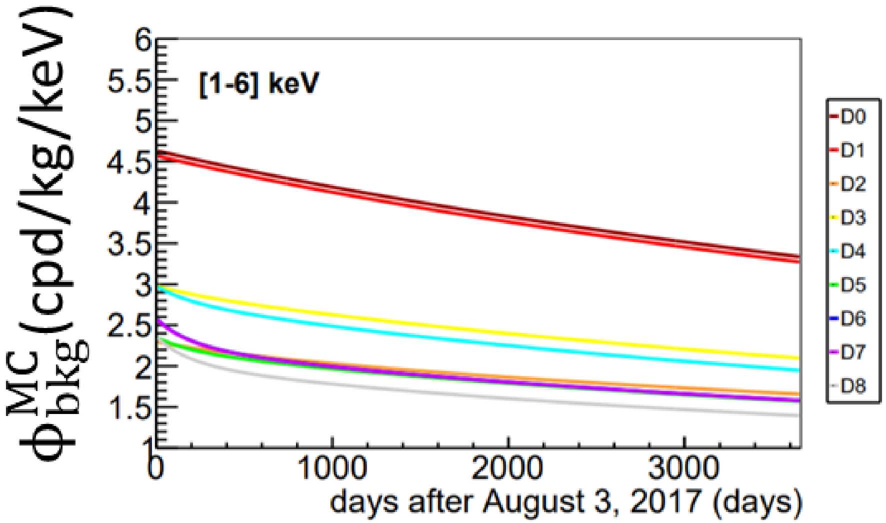


Improving data description

arXiv: 2103.01175
Submitted to PRD

MODEL 3: Simultaneous fit using data and bkg model separately for every detector

$$\mu_{i,d} = \left[R_{0,d}(1 + f_d \phi^{MC}_{bkg,d}(t_i) + \boldsymbol{S_m} \cos(\omega(t_i - t_0))\right] M_d \Delta E \Delta t$$



19 Free parameters: $R_{o,d}$, $f_d + S_m$

3 years results (313.95 kgxy)

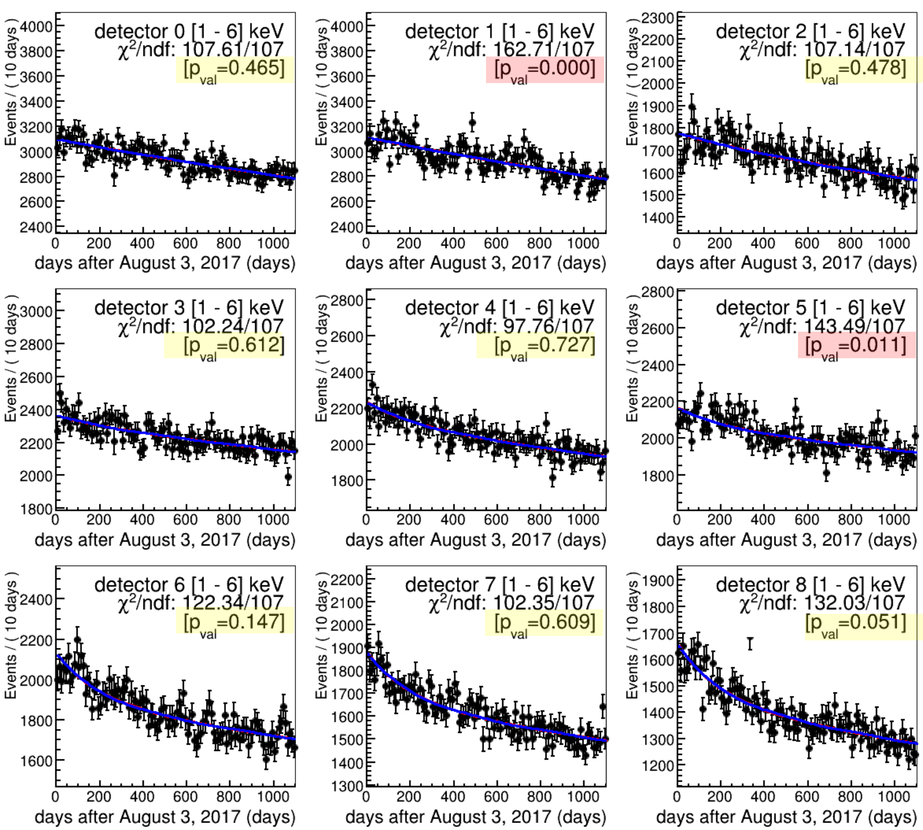
arXiv: 2103.01175
Submitted to PRD

MODEL 3: Simultaneous fit using data and bkg model separately for every detector

[1-6] keV

Null hyp χ^2/ndf: 1075.81/972 [p_{val}=0.011]   Mod hyp χ^2/ndf: 1075.15/971 [p_{val}=0.011]

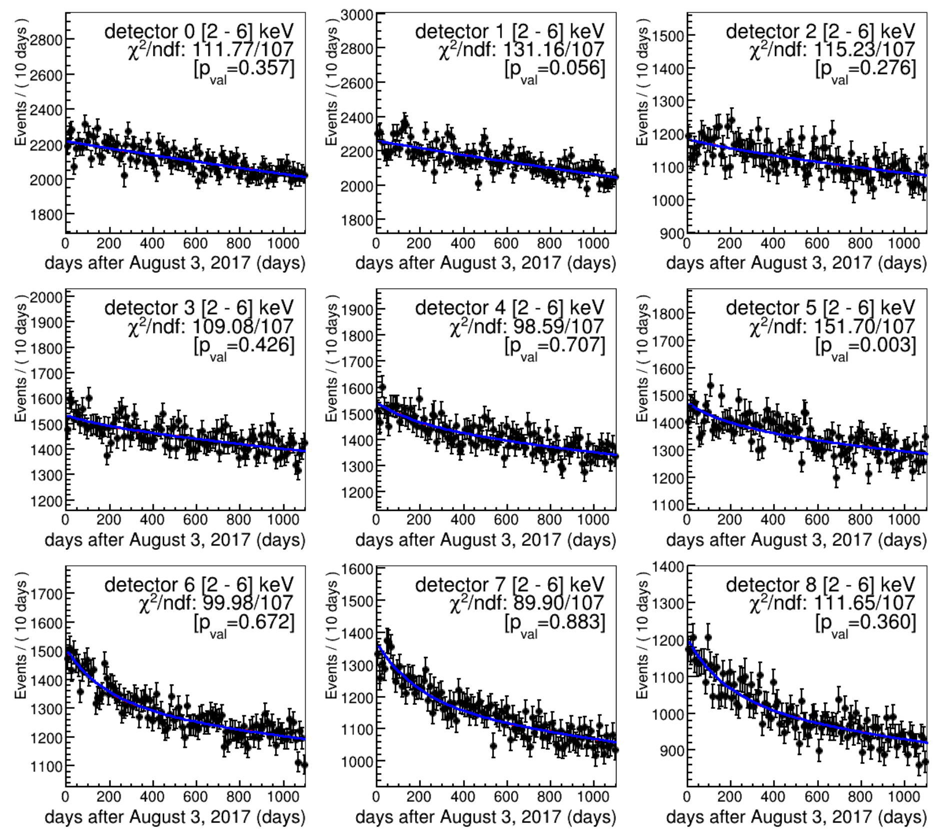
S_m = (-0.0034 ± 0.0042) (cpd/kg/keV)



[2-6] keV

Null hyp χ^2/ndf: 1018.19/972 [p_{val}=0.148]   Mod hyp χ^2/ndf: 1018.18/971 [p_{val}=0.143]

S_m = (0.0003 ± 0.0037) (cpd/kg/keV)



3 years results (313.95 kgxy)

arXiv: 2103.01175
Submitted to PRD

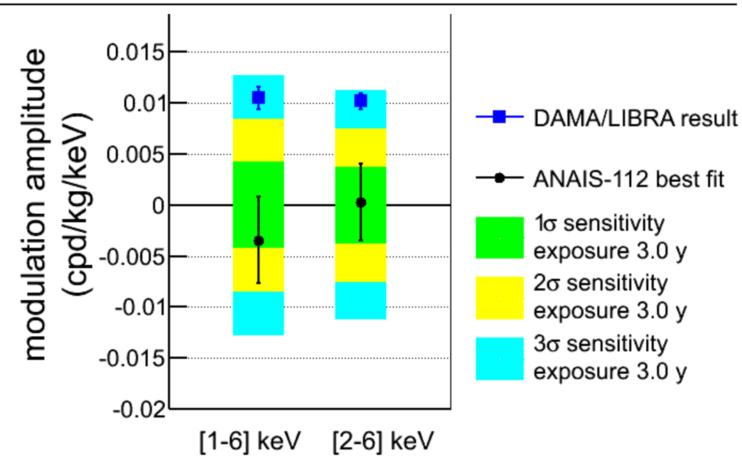
ANAIS-112 results:

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	1	132 / 107	3	-0.0045±0.0044	0.051	0.051
	2	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	3	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	1	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	2	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	3	1018 / 972	18	0.0003±0.0037	0.14	0.15

Prog. Part. Nucl. Phys. 114 (2020) 103810

		A (cpd/kg/keV)	$T = \frac{2\pi}{\omega}$ (yr)	t_0 (days)	C.L.
DAMA/LIBRA-phase2	1–6 keV	(0.0105 ± 0.0011)	1.0	152.5	9.5 σ
DAMA/NaI + DAMA/LIBRA-phase1 + DAMA/LIBRA-phase2	2–6 keV	(0.0102 ± 0.0008)	1.0	152.5	12.8 σ

- Compatible results for 3 different background descriptions / fit approaches
- **Data supports null hypothesis** (lower p-value for [1-6] keV mainly due to detectors 1 and 5)
- For the modulation hypothesis, we obtain in all **cases best fit modulation amplitudes compatible with zero at 1σ**
- As expected (Eur. Phys. J. C (2019) 79:233), Model 3 gives slightly slower $\sigma(S_m)$ and is taken to quote final result



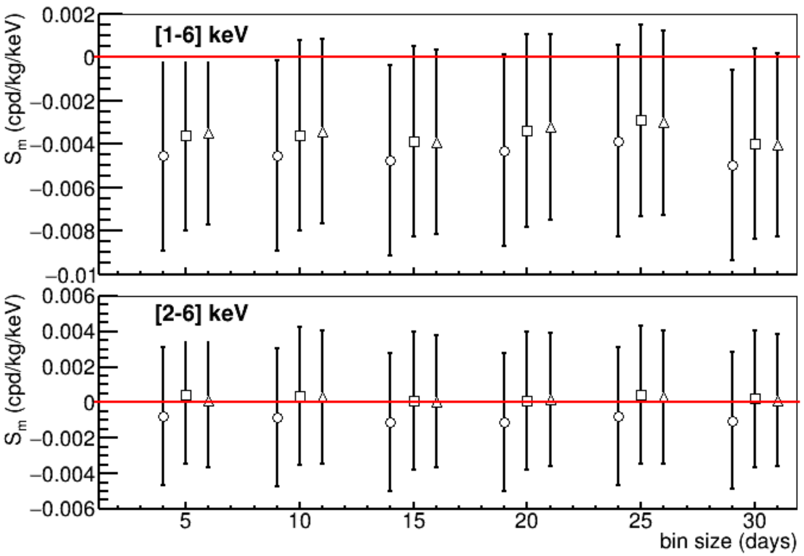
Current sensitivity: 2.5σ [1–6] keV
2.7σ [2–6] keV

Consistency checks

arXiv: 2103.01175
Submitted to PRD

- Time binning: negligible effect on results

MODEL 1
MODEL 2
MODEL 3

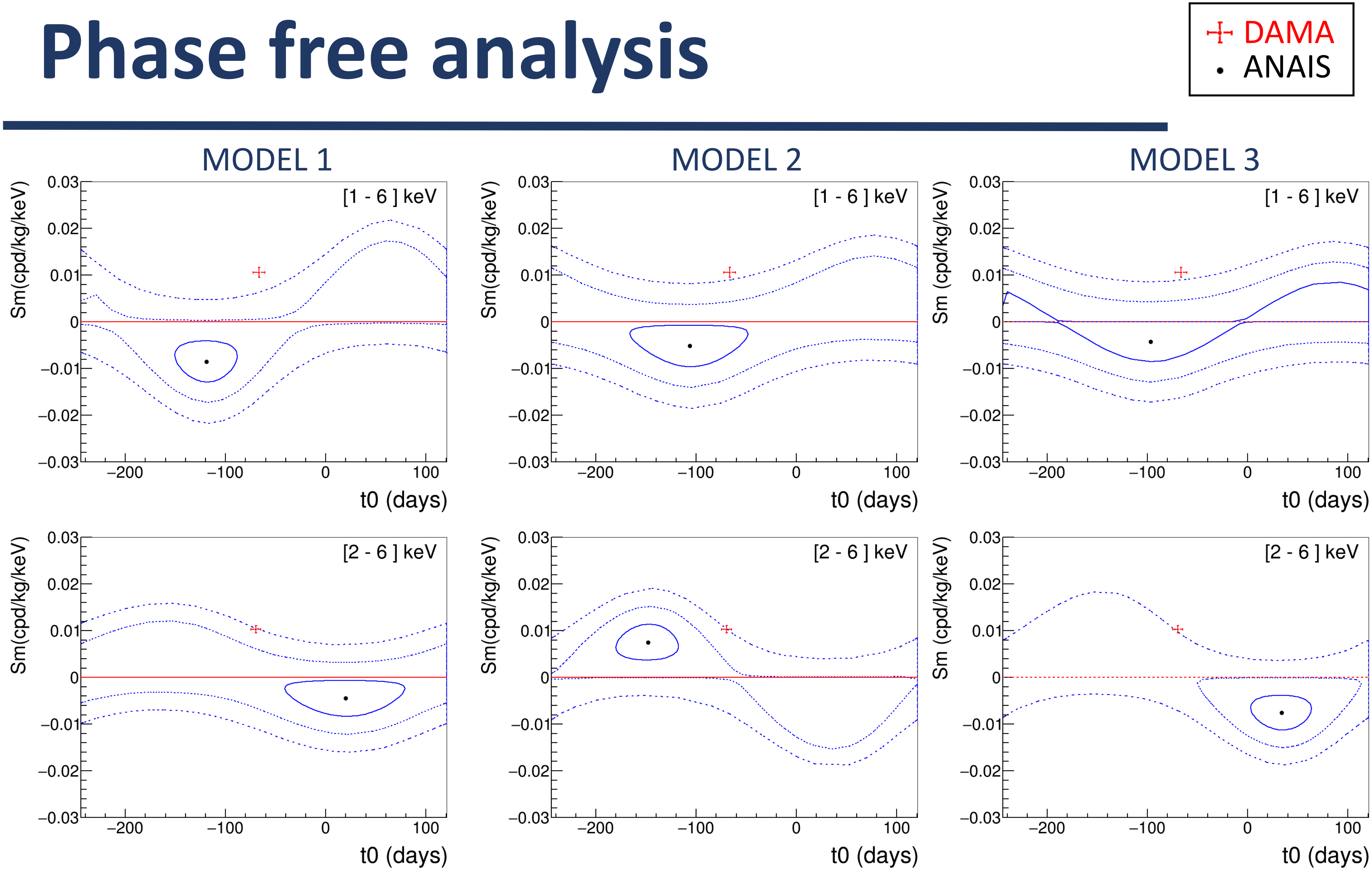


- Toy MC to check fit unbiasedness

Fit unbiased!

Energy region	Model	bias[null hypothess] cpd/kg/keV	bias[DAMA Sm] cpd/kg/keV
[1-6] keV	1	$(-3\pm6)\times10^{-5}$	$(-1\pm6)\times10^{-5}$
	2	$(-7\pm6)\times10^{-5}$	$(3\pm6)\times10^{-5}$
	3	$(-26\pm6)\times10^{-5}$	$(31\pm6)\times10^{-5}$
[2-6] keV	1	$(3\pm5)\times10^{-5}$	$(-10\pm5)\times10^{-5}$
	2	$(8\pm6)\times10^{-5}$	$(-10\pm6)\times10^{-5}$
	3	$(-28\pm5)\times10^{-5}$	$(29\pm5)\times10^{-5}$

Phase free analysis



- Best fit ANAIS 3σ away from DAMA result
- Compatible only at 2σ with absence of modulation

Phase free analysis

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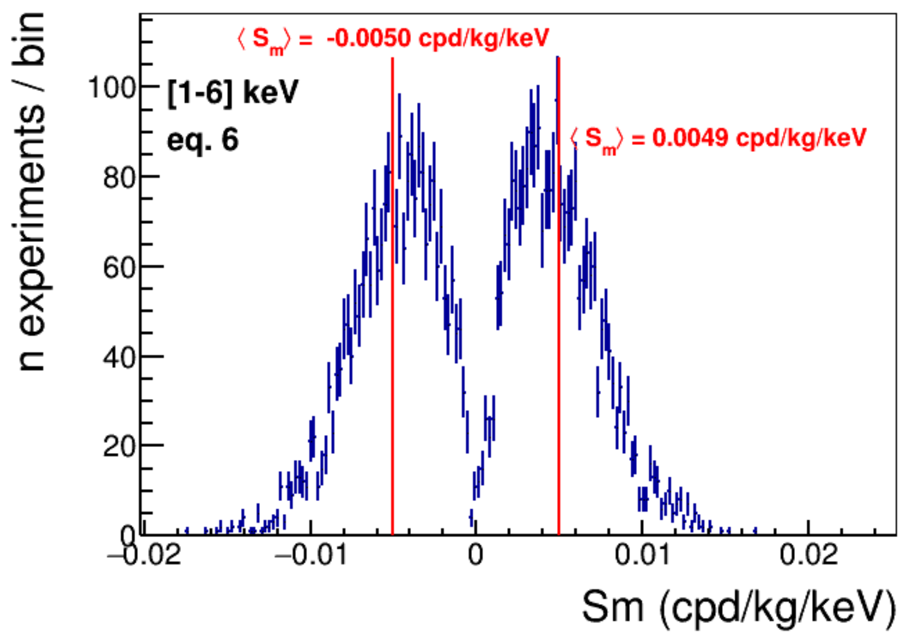
Submitted to PRD

But fit is non linear in the parameters

$$\mu_i = \left[\boldsymbol{R_0}\left(1 + \boldsymbol{f}\phi_{bkg}^{MC}(t_i)\right) + \boldsymbol{S_m}\cos\left(\omega(t_i - \boldsymbol{t_0})\right)\right] M\Delta E\Delta t$$

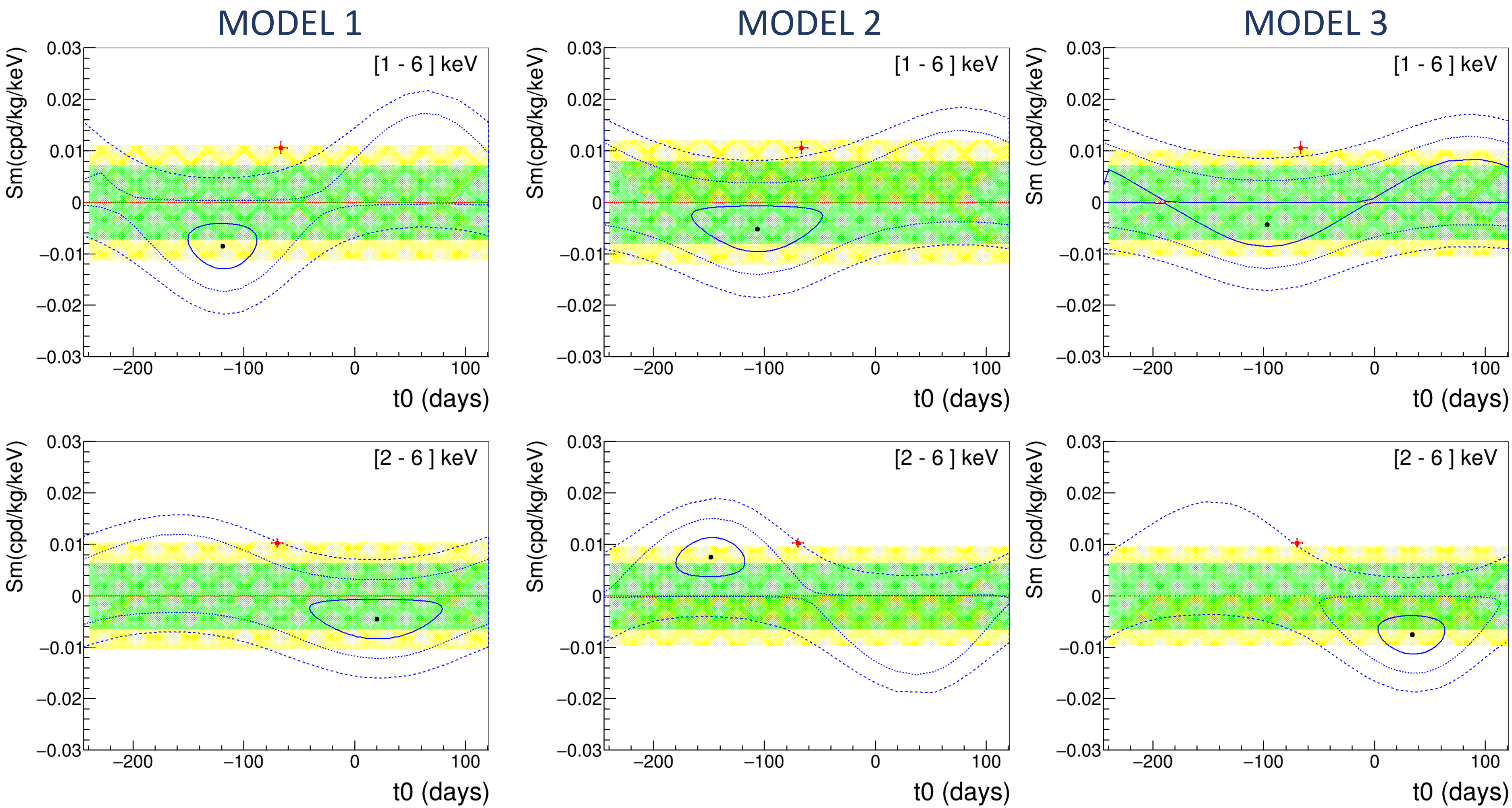
The fit with phase free is biased!! $\rightarrow$ $$E(S_m) = \sqrt{\frac{\pi}{2}}\sigma$$

Bias also checked with toy MC



Phase free analysis

DAMA
ANAIS



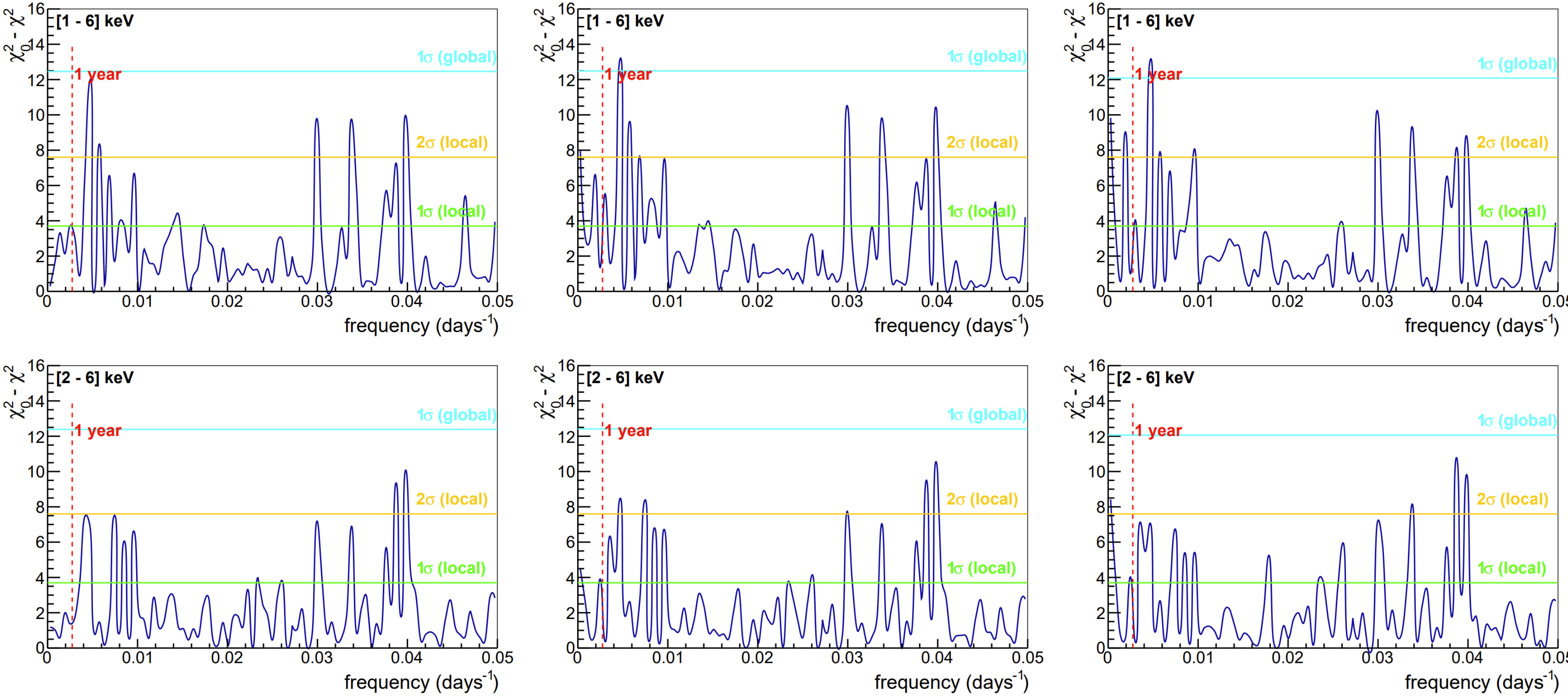
- Best fit ANAIS 3σ away from DAMA result
- **Considering bias, in most cases compatible at 1σ with absence of modulation**

Frequency analysis

arXiv: 2103.01175
Submitted to PRD

Least-squared periodogram:
for every frequency, fit to null and modulation hypothesis and compute $\chi_0^2 - \chi^2$

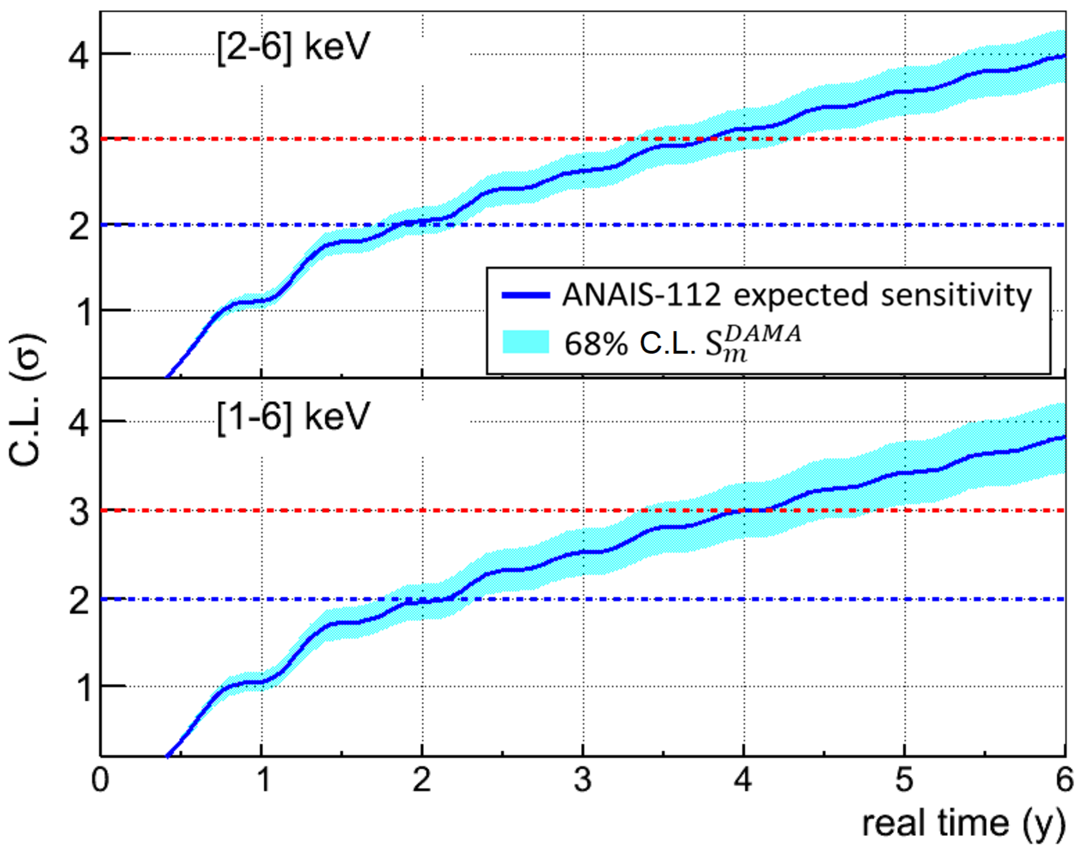
MODEL 1 MODEL 2 MODEL 3



→ **No statistically significant modulation at any frequency**

Expected sensitivity

See details in **Coarasa et al., Eur. Phys. J. C (2019) 79:233, 1812.02000**



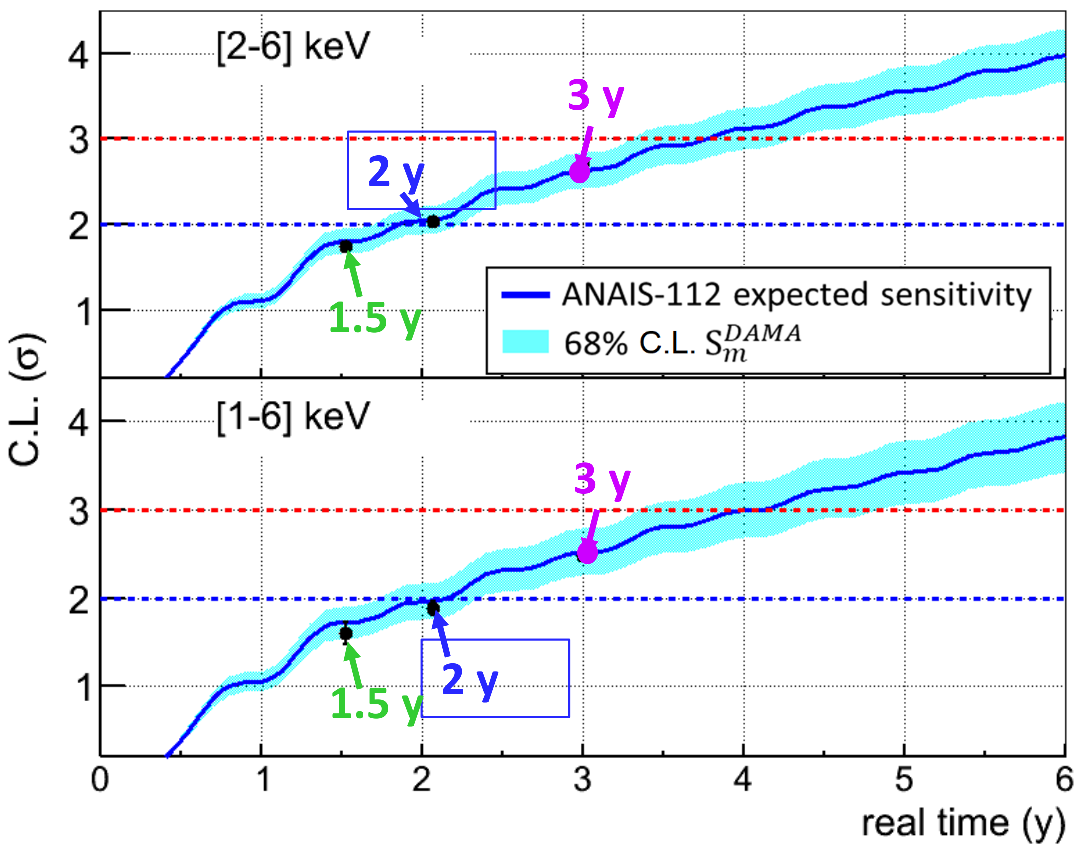
The experimental sensitivity is given by the standard deviation of the modulation amplitude $\sigma(S_m)$, that can be calculated analytically from :

- Updated background
- Efficiency estimate and its error
- Live time distribution

We quote our sensitivity to DAMA/LIBRA result as the ratio $S_m^{DAMA}/\sigma(S_m)$

Experimental sensitivity

See details in **Coarasa et al., Eur. Phys. J. C (2019) 79:233, 1812.02000**



3 data releases ANAIS-112:

- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468** (2020) 012014
- 3y: arXiv: 2103.01175 (2021)

data confirm our sensitivity projection

sensitivity @ 3 years: 2.5σ (2.7σ) in [1-6] ([2-6]) keV

3σ sensitivity at reach in about 1 year from now

Summary

- Annual modulation is a distinctive signature of Dark Matter.
- One positive signal (DAMA/LIBRA) for more than 20 years, in strong tension with other experiments, but comparison is model dependent.
- Currently, many efforts trying to provide an independent confirmation of DAMA/LIBRA signal with the same target. ANAIS-112 and COSINE-100 in data-taking.
- ANAIS-112: is taking data in stable condition @ LSC since 3rd August 2017 with excellent performances. Up to now it has accumulated more than 300 kg×y exposure.
- **ANAIS-112 results up to now are compatible with absence of modulation and incompatible with DAMA/LIBRA at 2.7σ (2.5σ) in [1-6] ([2-6]) keV after 3 years of data-taking. 3σ sensitivity at reach in about 1 year from now.**
- We are analyzing quenching factor on NaI crystals to discard systematic uncertainties in the comparison.
- Plan to make ANAIS data public after use to allow independent analysis .

Summary

Grazie!!

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