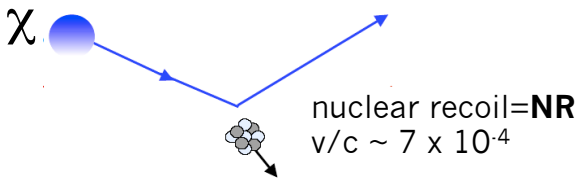
SABRE
(SODIUM IODIDE WITH ACTIVE BACKGROUND REJECTION)

Davide D'Angelo

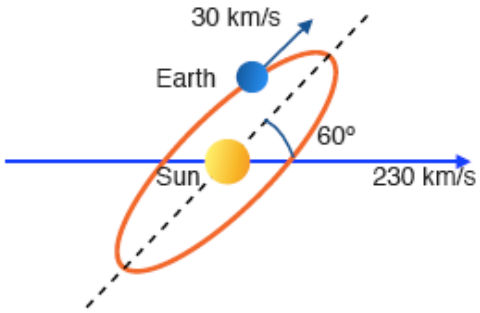
INFN

I.N.F.N. – Consiglio di Sezione
8th July 2015
Milano

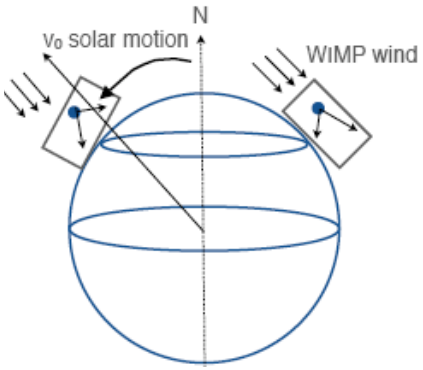
DIRECT DARK MATTER DETECTION: SIGNATURES



Count nuclear recoils



annual flux variation



diurnal directional modulation

Motion of the Earth and the detection of weakly interacting massive particles

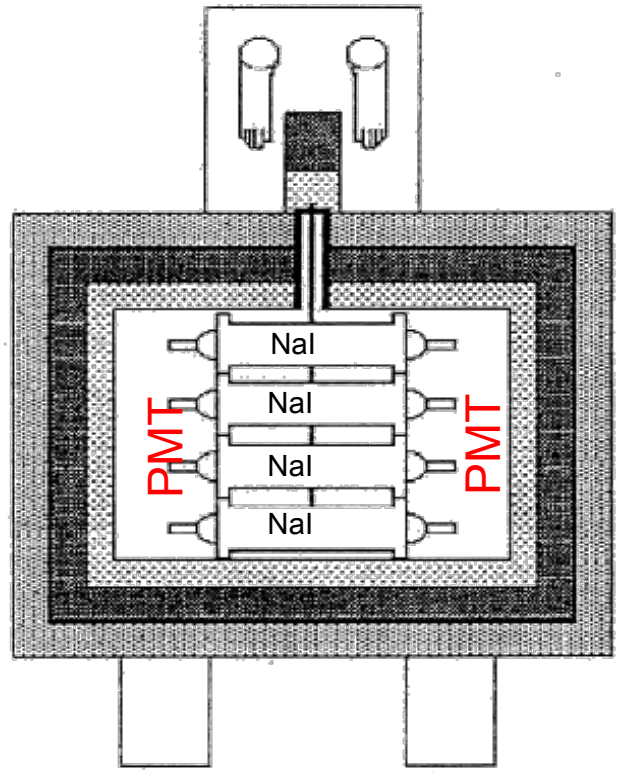
David N. Spergel*
Institute for Advanced Study, Princeton, New Jersey 08540
(Received 21 September 1987)

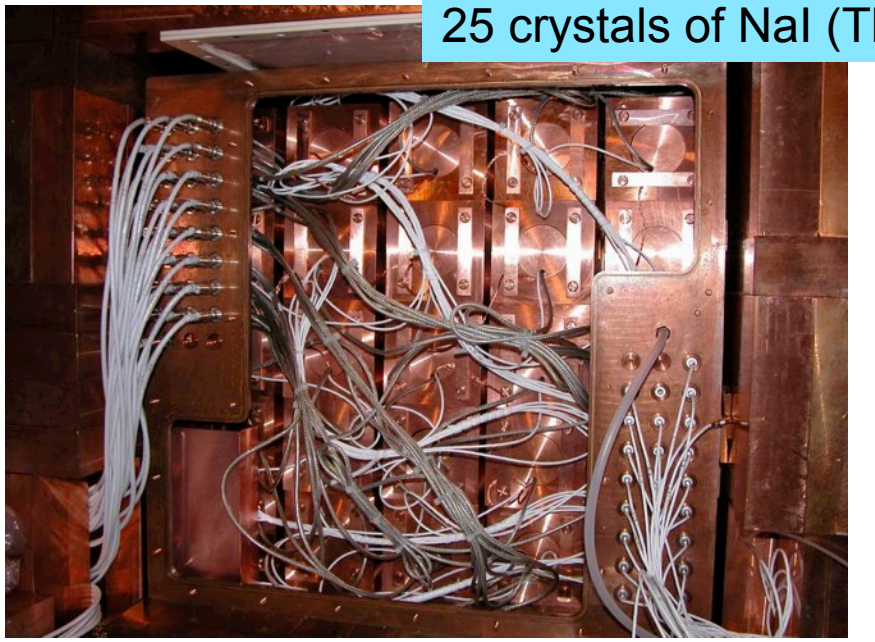
If the galactic halo is composed of weakly interacting massive particles (WIMP's), then cryogenic experiments may be capable of detecting the recoil of nuclei struck by the WIMP's. Earth's motion relative to the galactic halo produces a seasonal modulation in the expected event rate. The direction of nuclear recoil has a strong angular dependence that also can be used to confirm the detection of WIMP's. I calculate the angular dependence and the amplitude of the seasonal modulation for an isothermal halo model.

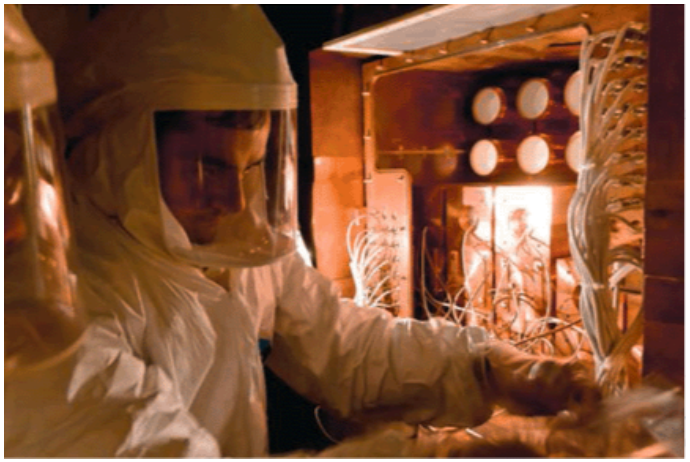
DAMA/LIBRA

Located at LNGS:

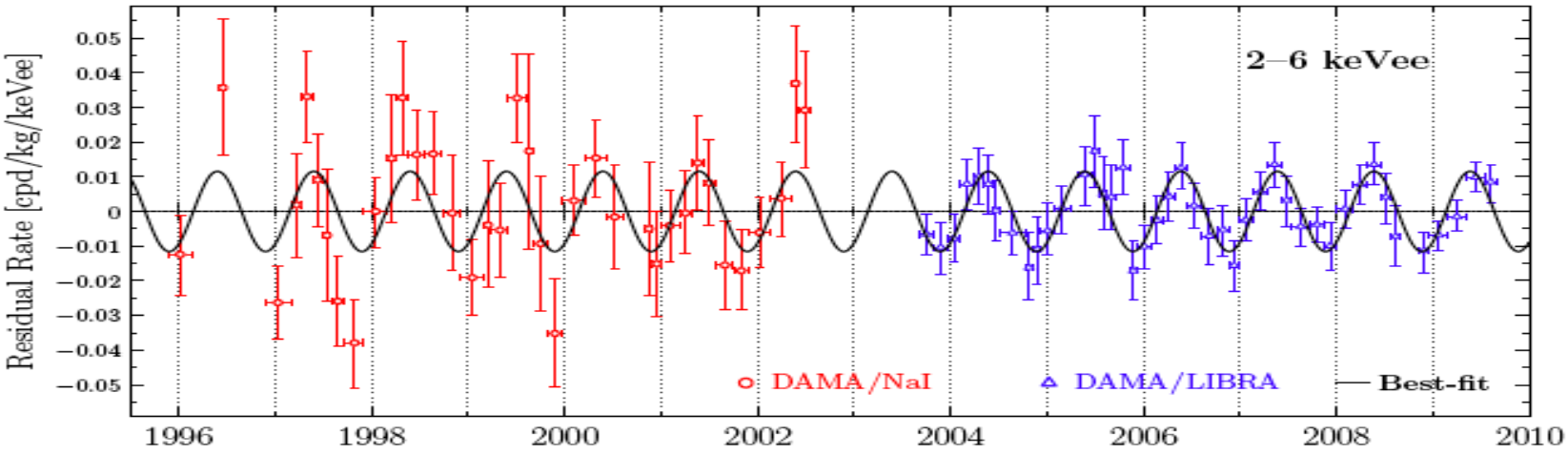
1. **DAMA (100kg) 1996-2002**
2. **DAMA/LIBRA (250kg) Phase I: 2003-2010**
3. **DAMA/LIBRA (250kg) Phase II: 2011-…**







THE DAMA/LIBRA MODULATION

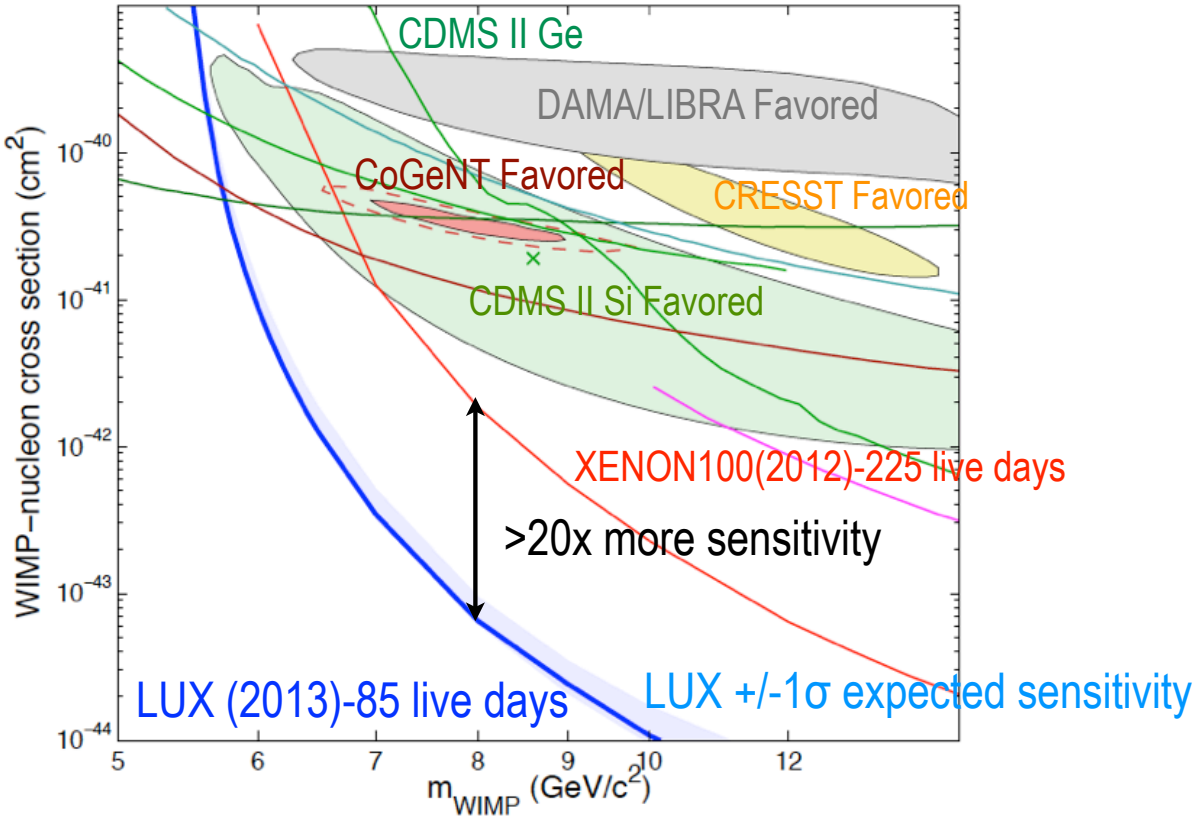


- 13 annual cycles (Dama/NaI + Dama/Libra)
- χ^2/ndf = 70.4/86
- 9.3σ significance
- (0.998±0.002) year period
- Phase is (144±7) days vs. Exp. DM phase 152.5 days
- Amplitude (0.0112±0.0012) cdp/kg/keV (~ 1.2% of signal)
- Can be explained as WIMP-nucleus SI interaction with

M_W~10GeV/c^2 and σ_W~10^{-40} cm^2

R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648.

THE LOW MASS SCENARIO



Most simple standard Spin Independent Wimp-nucleon scattering
Many alternatives exist: halo model, DM particle, interaction,…

A COMPLEX SCENARIO

- DAMA/LIBRA (DL) results (and other positive low mass results) are *"excluded"* by several other experiments.
- DL (and CoGeNT) observes DM annual modulation, while all others are counting experiments.
- No other experiments is using NaI as target material.
- **Theoretical** attempts to let DL coexist with other results:
  NO clear conclusion.
- Attempts to explain DL in terms of **background** have been made
  - ^{40}K
  - cosmogenic (and environmental) background

  NO clear conclusion
- DL has done an excellent job. Strong arguments to sustain the result.
  NO trivial mistake.

A COMPLEX SCENARIO

Low-mas compatibility

H. Hooper, J. Collar, J. Hall, D. McKinsey, C. Kelso, PR D 82 (2010) 123509.

C. Savage et al., JCAP 04 (2009) 010.

P.W. Graham et al., PR D 82 (2010) 063512.

D. Hooper, Phys. Dark Univ. 1 (2012) 1.

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A COMPLEX SCENARIO

Instrumental backgrounds (^{40}K)

J. Pradler, B. Singh and I. Yavin, PL B 720 (2013) 399-404

R. Bernabei et al. (DAMA coll.), (2012) arXiv:1210.6199 and arXiv:1211.6346;

J. Pradler and I. Yavin, (2012) arXiv:1210.7548.

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  NO trivial mistake.

A COMPLEX SCENARIO

Environmental backgrounds (Cosmic muons)

J. P. Ralston, (2010) arXiv:1006.5255

K. Blum, (2011) arXiv:1110.0857

E. Fernandez-Martinez and R. Mahbubani, JCAP 07 (2012) 029

S. Chang, J. Pradler and I. Yavin, PR D 85 063505 (2012)

J. Pradler, (2012) arXiv:1205.3675

R. Bernabei et al. (DAMA coll.), IJMP A 28 (2013) 1330022

- Attempts to explain DL in terms of **background** have been made
  - ^{40}K
  - cosmogenic (and environmental) background

  NO clear conclusion
- DL has done an excellent job. Strong arguments to sustain the result. NO trivial mistake.

A COMPLEX SCENARIO

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- DL (and CoGeNT) observes DM annual modulation, while all others are counting experiments.
- No other experiments is using NaI as target material
- **Theoretical** attempts to let DL coexist
  NO clear conclusion.
- Attempts to explain [illegible] **ground** have been made
  - ^{40}K
  - [illegible] environmental) background
  - [illegible] conclusion
- [illegible] has done an excellent job. Strong arguments to sustain the result.
  NO trivial mistake.

Another NaI measurement is needed!

SABRE KEY FEATURES

Detect Dark Matter annual modulation in NaI crystals

1. **New radio-pure NaI crystals**
    1. Higher purity NaI powder than ever achieved
    2. Further purification during crystallization
    3. Low background methods (used in Borexino and DarkSide) in handling and processing
2. **New low-background and high-QE photosensors**

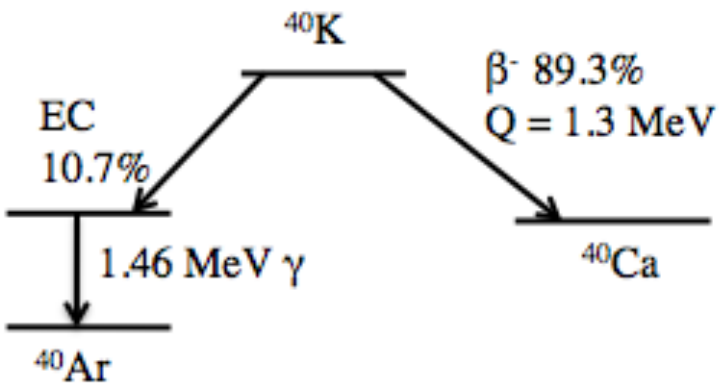
    3” PMTs. Hamamatsu R11065-20 (< 10mBq of gamma from U and Th) to be developed with:
    1. Sinthetic alumina feed-thorugh plates
    2. SBA photo-cathode
3. **Active Background rejection with liquid scintillator.**

THE ^{40}K ISSUE

DAMA/LIBRA signal peaked at 3 keV.

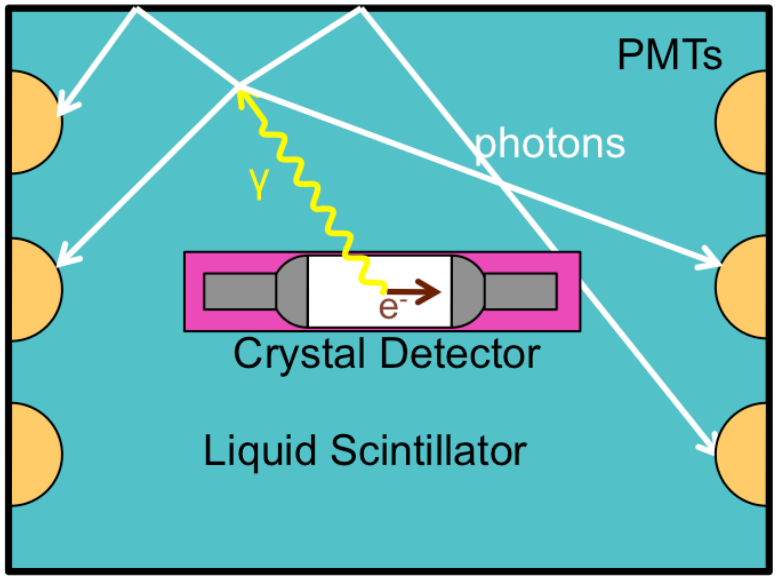
Background from ^{40}K decay? 13 ppb K in DAMA crystals.

Ultra-high purity NaI(Tl) detector + Active veto detector



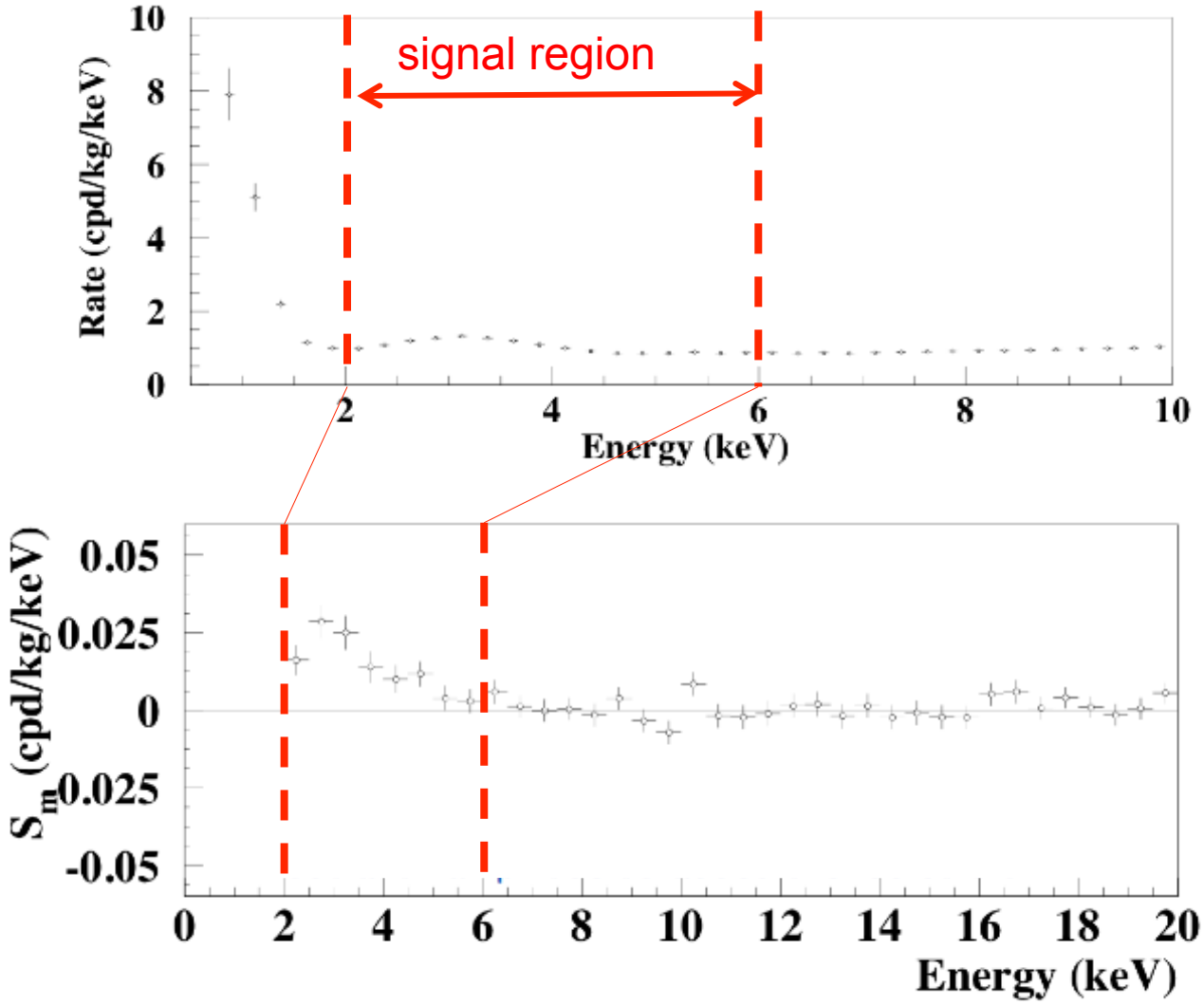
^{40}K→^{40}Ar, ~11% branch ratio

- 3 keV K shell X-ray, Auger e$^-$
- Background at ~3 keV if γ escapes



1.46MeV γ can be detected by a veto.
^{40}K background can be rejected.

THE DAMA/LIBRA SIGNAL



3 keV_e

R. Bernabei et al. (DAMA coll.), EPJ C (2013) 73:2648.

RADIO-PURE POWDER (USA WAY)

4-year work at Princeton University.

Purify precursors of NaI: Na_2CO_3

Element	MV laboratories	Sigma Aldrich "Astro-Grade"	DAMA powder
K	12ppb	3.5 ppb (18 ppb)	<100ppb (13 ppb in crystal)
Rb	14ppb	0.2 ppb	not reported
Th	<200ppt ~ 3.5ppt*	<1700ppt <1ppt*	20ppt
U	<100ppt <1ppt*	<500ppt <1ppt*	20ppt

* Preliminary by means of ICP-MS dilution method at PNNL

STD-purity crystal grown at RMD, high-purity in process

RADIO-PURE CRYSTAL (ITALIAN-CHINESE WAY)

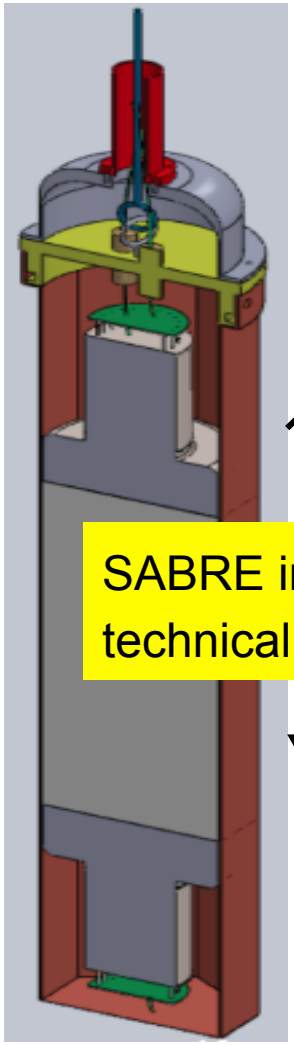
In 2015 INFN Started R&D with SICCAS company in Shanghai:

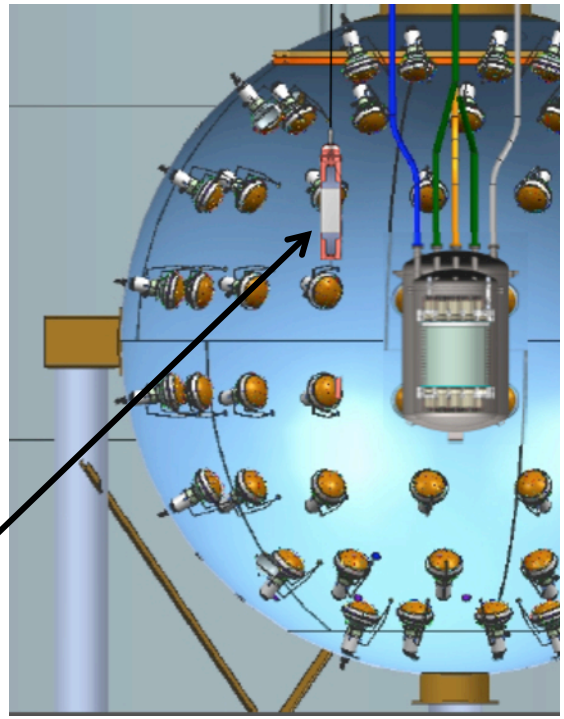
1. NaI powder with K~1ppm; U and Th <0.5ppb. (dev. May)
    1. Measured with HPGe in Bicocca (E. Previtali) and with ICPMS at LNGS (S. Nisi).
    2. Specs do not match -> sample from new production batch already shipped.
2. NaI test crystal growth Ø5cm, H12cm (exp. Aug)
3. NaI iterated crystal growth (exp. Oct)

Company tests indicate a x10 reduction in K is possible at every growth cycle

CRYSTALS TEST IN DARKSIDE

- Coincidence with neutron-veto detector
- 2-PMTs coincidence signal ORed with TPC trigger.
- NaI crystal inside water Cherenkov and active scintillator shielding
- 3” diameter x 4” length cyclindrical NaI crystal



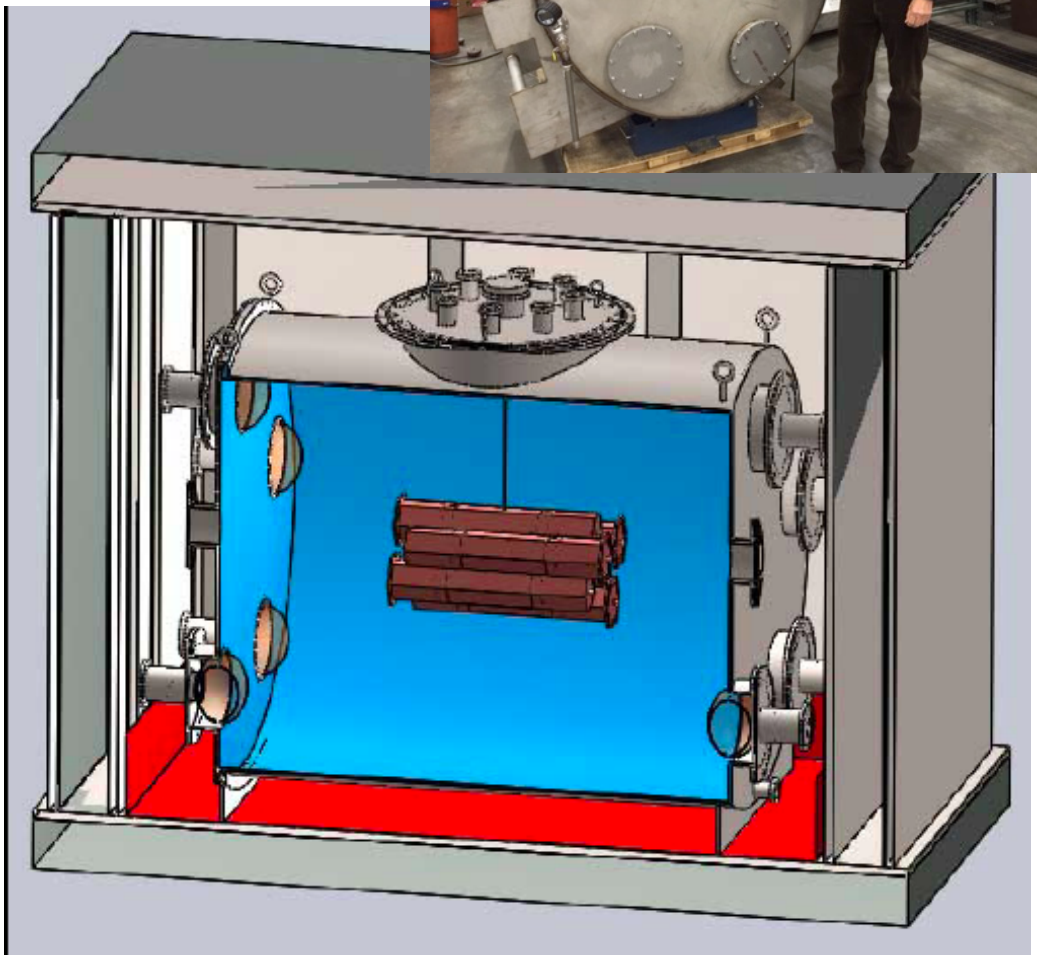


SABRE insertion system built, under technical review by DS technical board.

Low radioactivity copper housing: U, Th < μBq/kg

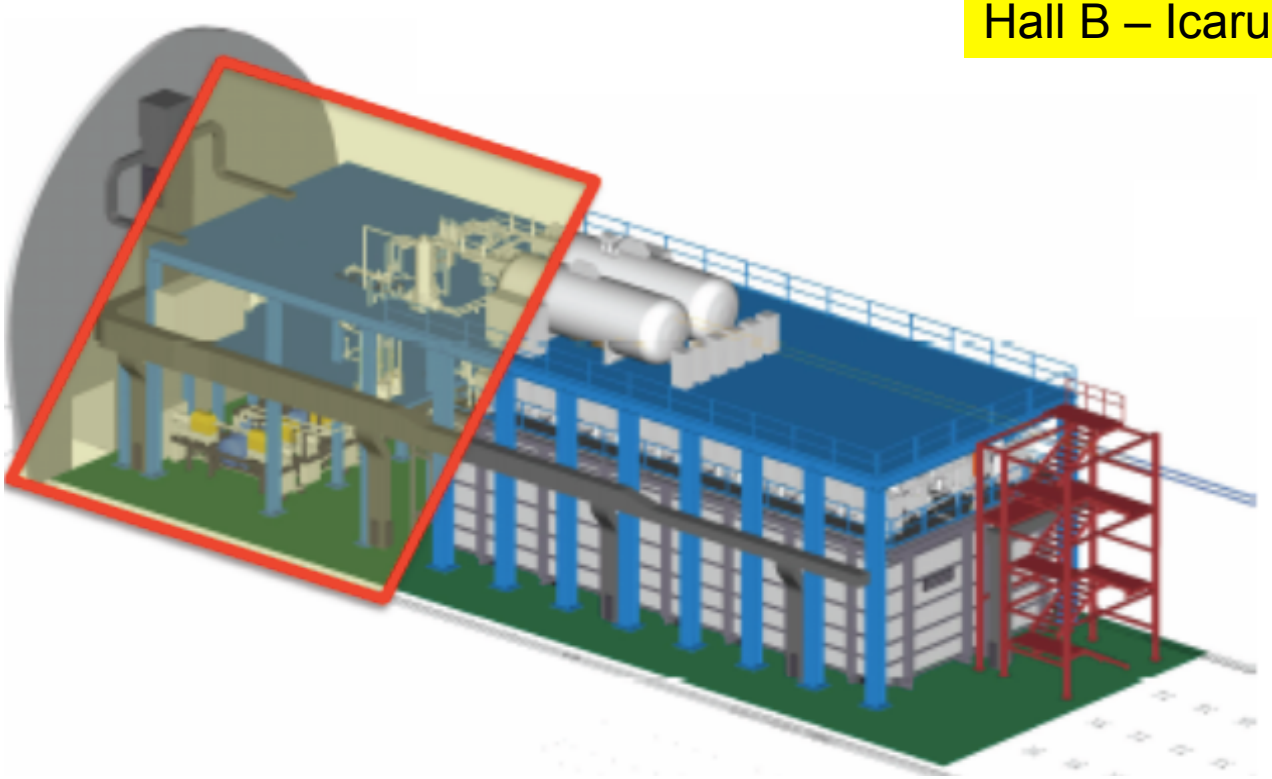
DETECTOR SCHEME

- Cylinder : 1.5 m x 1.5 m
- 2 tons LAB scintillator
- 10 8-inch PMTs
- Reflector in inner surface (>95%).
- Expected: 0.22 p.e./ keV
- Shielding: 25cm Pb
- Portable
- Minimum crystal array: ~50kg (10x5kg)



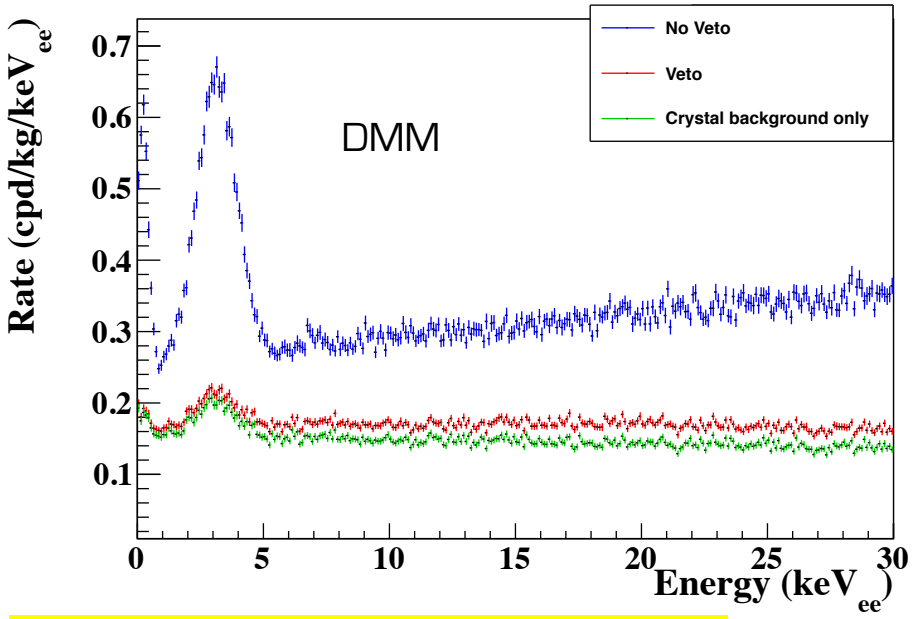
LOCATION AT LNGS

Hall B – Icarus structure



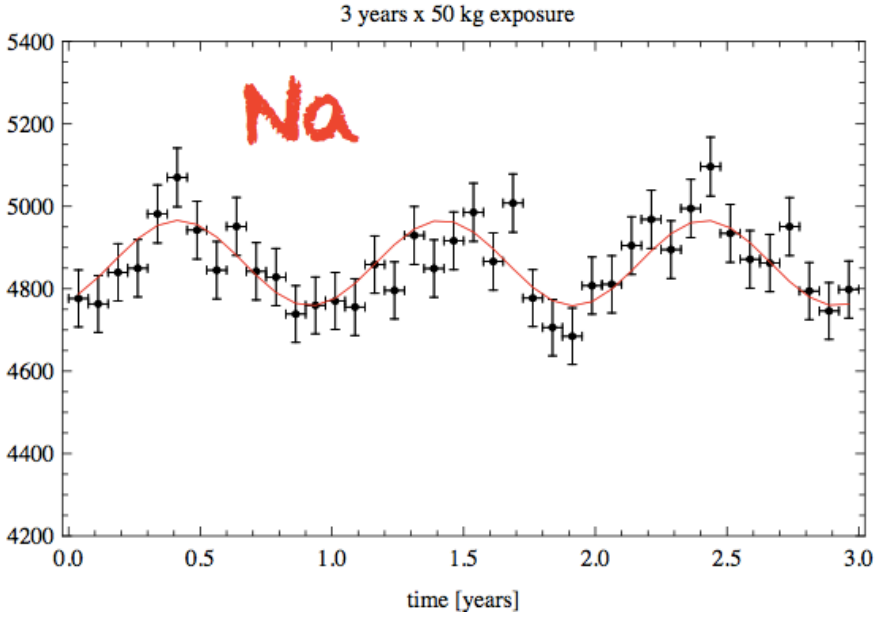
BACKGROUND SIMULATION

Based on radio-purity of NaI powder
(after crystal growth one could reach lower background rate)

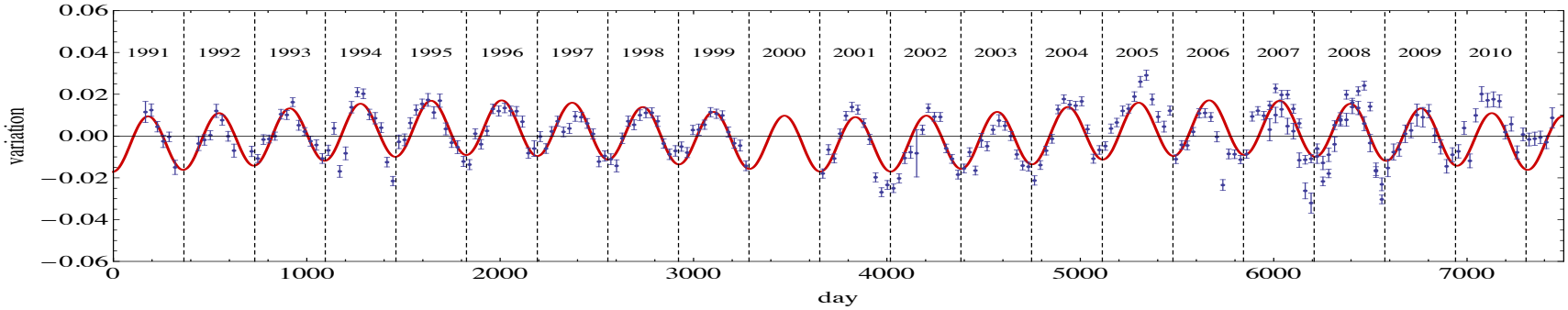


10x lower background cmp. D/L

4-5σ confirmation/refutation
with 50kg x 3y data



ALTERNATIVE EXPLANATIONS



Combined MACRO+LVD+Borexino muon flux modulation

Long standing question: can the DAMA/LIBRA results be explained in term of environmental and/or cosmogenic background?

The phase is off by ~30d

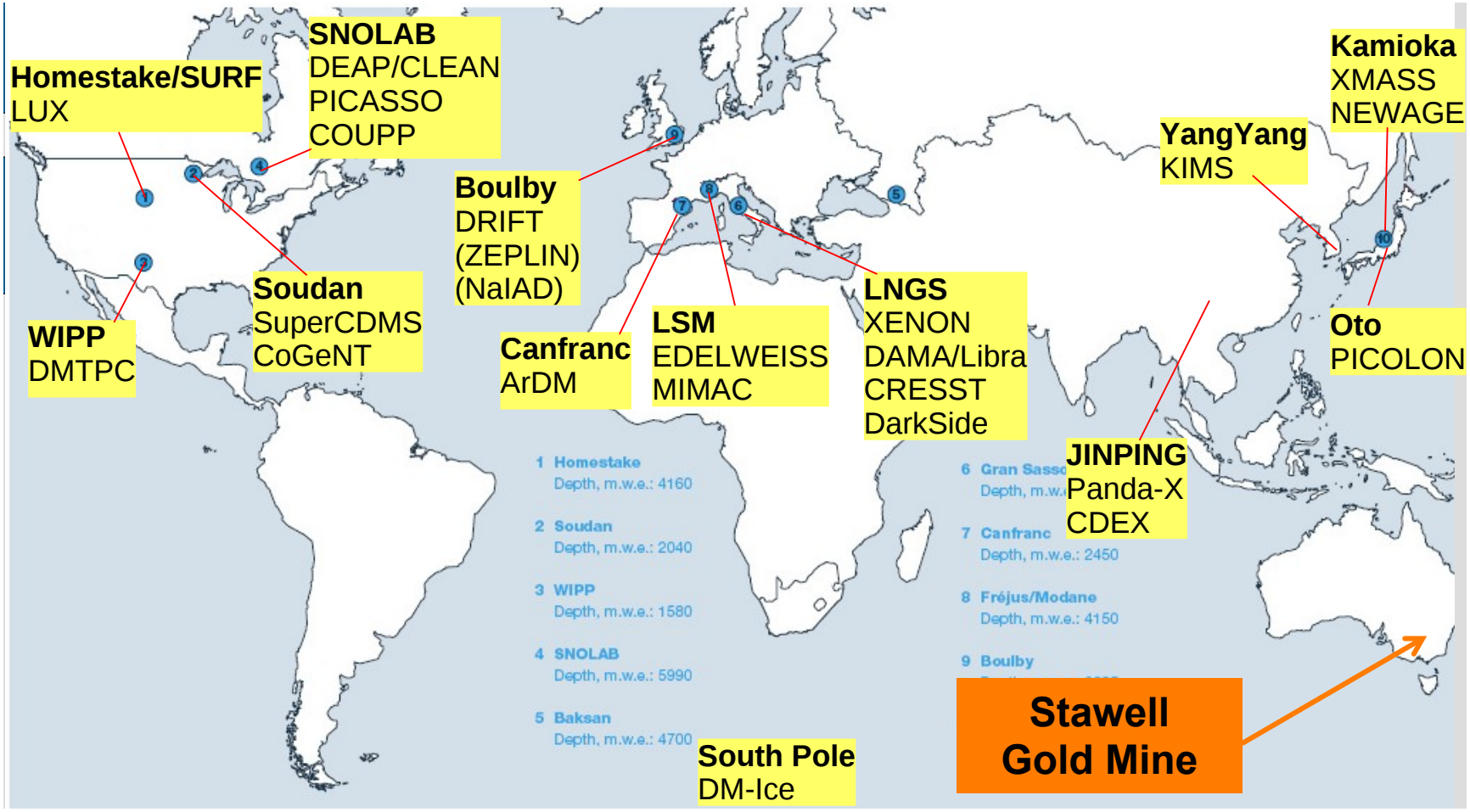
Hard to explain the only low energy nature of the signal

Hard to explain the only single-hit nature of the signal

Tens of papers written on the subject.

No clear conclusion

UNDERGROUND LABS

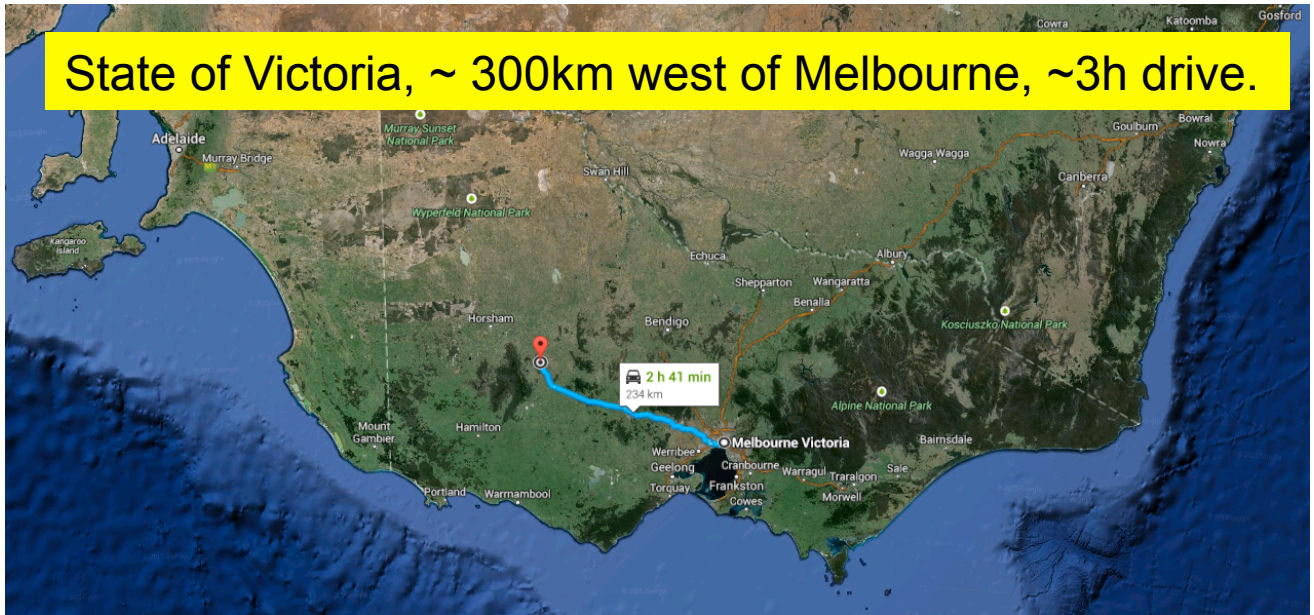


SABRE, A TWOFOLD EXPERIMENT

We want to perform the new measurement in *two* separate underground sites, using *twin* detectors.

Ideally the second location should be in *southern hemisphere*.

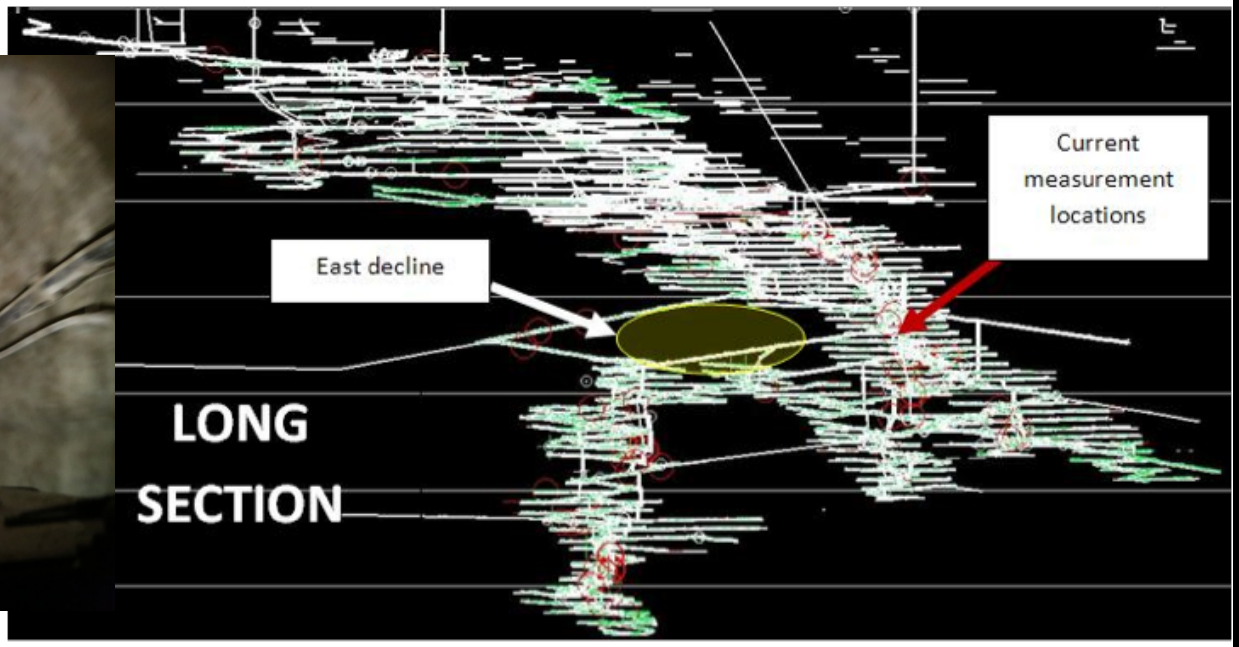
<u>LNGS + STAWELL MINE would do the trick.</u>



STAWELL MINE LAYOUT

Decline mine with dirt road
1.6 km maximum depth, with many caverns.
Served with electricity, optical fibre, compressed air,
and can be reached by car/truck.

Chosen lab site: cavern 1km underground,
(basalt density of the rock ~ 2.86 t/m^3)
~3.1km w. e. similar to LNGS.



BACKGROUND MEASUREMENTS SUMMARY

	LNGS	Stawell
Neutron Flux (n/s/cm^2)	4 x 10^{-6}	7 x 10^{-6}
Gamma-rayflux <3MeV (γ/s/cm^2)	0.73	~1
Rock Hall ^{238}U (ppm)	6.8-0.42-0.66	0.64
Rock Hall ^{232}Th (ppm)	2.2-0.06-0.06	1.63
Concrete ^{238}U (ppm)	1.05	<1.86 (wall) <2.18 (floor)
Concrete ^{232}Th (ppm)	0.66	3.84 (wall) 3.49 (floor)
Radon Bq/m^3 (12 day accumulation)	~50	408±40 (free air) 36±5 (comp. air)
Muon Flux (μ/h/m^2)	~1.2	**coming soon**

D. D'Angelo
(Milano University)

Prof. S. Ragazzi
(LNGS director)

LAB already funded for 3.5M AU$

Prof. E. Barberio
(Melbourne University)

Prof. A. Masiero
(INFN vice-president)

G. Piredda – C. Tomei
(Rome University)

THE SABRE COLLABORATION

Princeton University:

Frank Calaprice, Jingke Xu, Francis Froborg, Emily Shield

Jay. Benziger (Chemical Engineering).

PNNL:

E. Hoppe, J. Orrell, C. Overman

LNGS:

Aldo Ianni, Carla Macolino, Chiara Vignoli, G. di Carlo, M. Antonello

Milano University:

Davide Angelo

Rome:

Claudia Tomei, G. Piredda, I. Dafinei, P. Mosteiro

University Melbourne, Australia:

Elisabetta Barbario, Matteo Volpi, F. Nuti.

INFN – MILANO ACTIVITIES

- **Proponiamo l'apertura della sigla SABRE per il 2016**
  - 3 sezioni coinvolte: LNGS, Roma 1, Milano
  - Proposal sottomesso alla CSN2. I referee verranno assegnati asap.
  - Resp. nazionale Aldo Ianni (LNGS).
- **Milano FTE: 0.6**
  - Davide D'Angelo al 60% (+studenti)
  - collaboratori benvenuti
- **Attivita' di Milano**
  - Continuazione del R&D presso SICCAS (anche Roma 1)
    - Gia' finanziato con 35k nel 2015
  - Sviluppo PMT da 3" con Hamamatsu
    - Test prototipi di R11065 con fotocatodo SBA
  - Test di dissoluzione o-carborano in LAB (scint. liquido)

CAN WE HAVE A BETTER PMT?

Producer	Hamamatsu	Hamamatsu	Hamamatsu
Model	R12669	R11065-20	R11065-20MOD
Date	Mar-13	Sep-12	2015?
Used by	D/L phase II	DS-50	SABRE
Size	3" (70mm)	3" (64mm)	3" (64mm)
Body	Borosilicate glass	Metal	Metal
Window	Borosilicate glass	Synthetic silica	Synthetic silica
Radioactivity	~150mBq	~15mBq	~15mBq
Dynodes	10	12	12
HV	1500	1750	1750
Gain	10^6	5 10^6	5 10^6
Photocathode	SBA	LT-BA	SBA
QE at 420nm	35%	25-28%	35%
Dark Counts	~300cps	~3kcps	~300cps
Min T (C)	-30	-186	-30
Price (Euro)	3000	6500/4500	6500

HAMAMATSU R11065-20MOD

- No R&D cost required.
- Final cost not higher then R11065-20.
- Delivery first prototype: 135d

Offerta

HAMAMATSU
PHOTON IS OUR BUSINESS

Offerta n.: I105679
Data preventivo: 03/04/15
Revisione n.: 2

Ns. riferimento: Mauro Bombonati
Tel.: 00390293582303
Fax: 00390293581741
E-mail: bombonati@hamamatsu.it

Codice cliente: HPI000650
Vs. Rif.: DAVIDE D'ANGELO
RFQ n.:

Dr. DAVIDE D'ANGELO
INFN MILANO
VIA G. CELORIA, 16
20133 MILANO (MI)
ITALY

Pos.	Codice prodotto Descrizione	Quantità [pcs]	Prezzo unit. EUR	Importo netto EUR
1.1	R11065-20 MOD Metal Bulb PMT MOD: SBA photo cathode (operation at cryogenic temperature is not possible because of photocathode high resistivity) (NXK15-7137773)	1	5.070,00	5.070,00

Legame cambio:
I prezzi riportati in offerta sono riferiti ad un legame cambio di 135 JPY/EUR. Eventuali variazioni della valuta intervenute alla data di fatturazione verranno addebitate/accreditate.

Validità offerta: 4-mag-2015
Termini di spedizione: Porto Franco Vs sede con addebito in fattura €15,49
Termini di pagamento: R.D. 60 GG. D.F.
Garanzia: 12 Mesi
Tempi di consegna: 135 GG DRO

A NEUTRON DETECTOR?

The SABRE's liquid scintillator is primarily a gamma catcher.

However it could be exploited as a *neutron detector*:

- study (cosmogenic and environmental) neutron background.

Too small: requires neutron catcher.

LAB solvent is being purchased in Milano for JUNO (1 barrel).

- produced by SASOL in Augusta in Sicily.
- very good production method DETAL.
- extensive campaign of optical quality tests campaign in Perugia.
- possibility to have a small quantity for free.

B-LOADING THE LIQUID SCINTILLATOR

$$ {}^{1}_{0}n + {}^{10}_{5}\mathrm{B} \rightarrow \begin{cases} {}^{7}_{3}\mathrm{Li}(1.015\ \mathrm{MeV}) + {}^{4}_{2}\mathrm{He}(1.777\ \mathrm{MeV}) & 6\% \\ {}^{7}_{3}Li\ (0.840\ \mathrm{MeV}) + {}^{4}_{2}\mathrm{He}(1.47\ \mathrm{MeV}) + \gamma(0.478\ \mathrm{MeV}) & 94\% \end{cases} $$

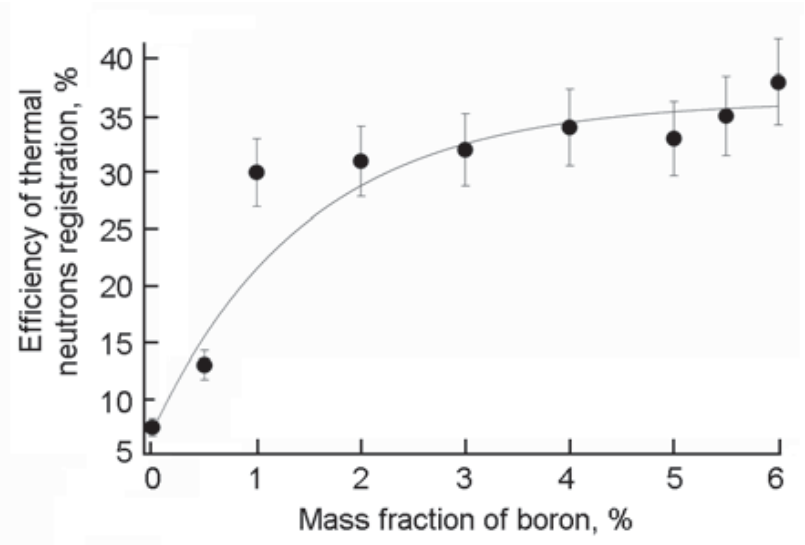
TMB - Trimethyl Borate

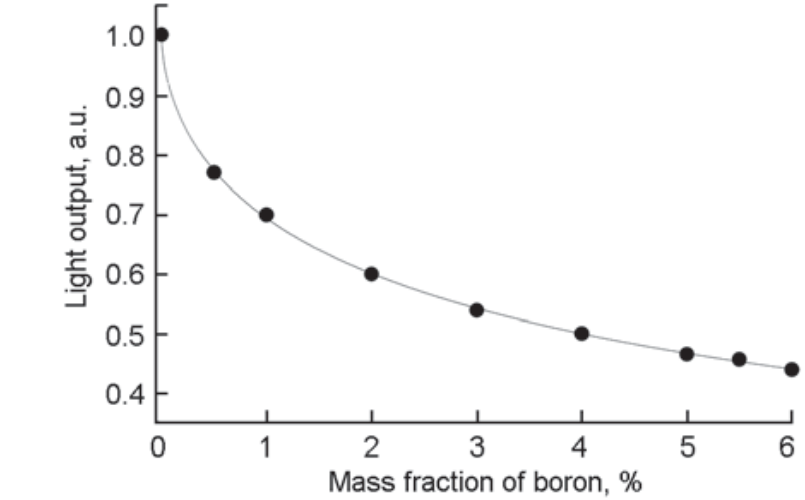
- 17.5% B content -> up to 50% loading
- organic liquid, extremely hazardous.

O-carborane

- 75% B content -> ~1% loading
- solid cristalline, dissolves easily, safe.

O-CARBORANE SMALL SCALE TESTS





LAB + 5g/l PPO + 25mg/l POPOP

small cell: 5cm⌀ x 2cm h

^{207}Bi neutron source

1% B loading could be a good compromise

Interesting R&D for commercial n detectors

I.B. Nemchenok et al. Funct. Mat. 20, No.3 (2013)
G. Bentoumi et al., NIM A 701 (2013) 221-224

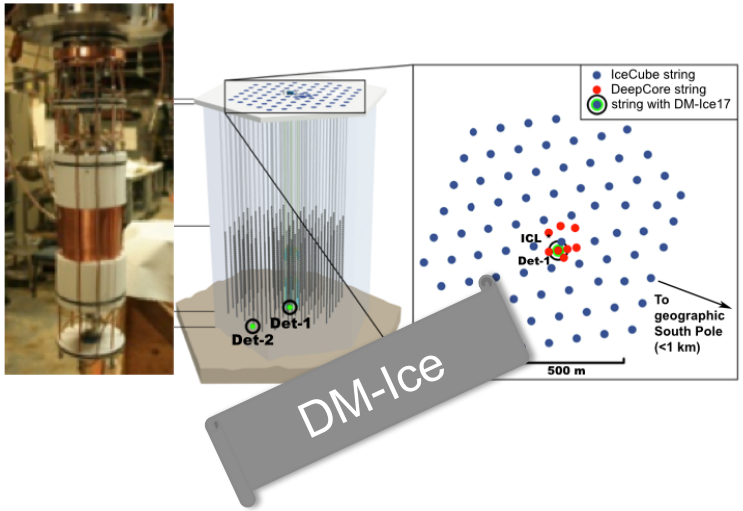
RICHIESTE MILANO

RICHIESTE FINANZIARIE Milano1

PRELIMINARY

	k€	
Missioni		
collaboration meeting a Princeton + interazione SICCAS	3	
Partecipazione al commissioning test facility LNGS	1	
Meeting WG e meeting ai LNGS	1	
	5	
Consumo		
Attività relativa alla caratterizzazione di polvere ultrapura di NaI		10
Apparati		
2 PMT Hamamatsu R11065	10	
Attività presso la SICCAS per prove di crescita cristalli ultrapuri	15	
Set up R&D per scintillatore con o-carborano	5	
TOTALE	**35**	**10**

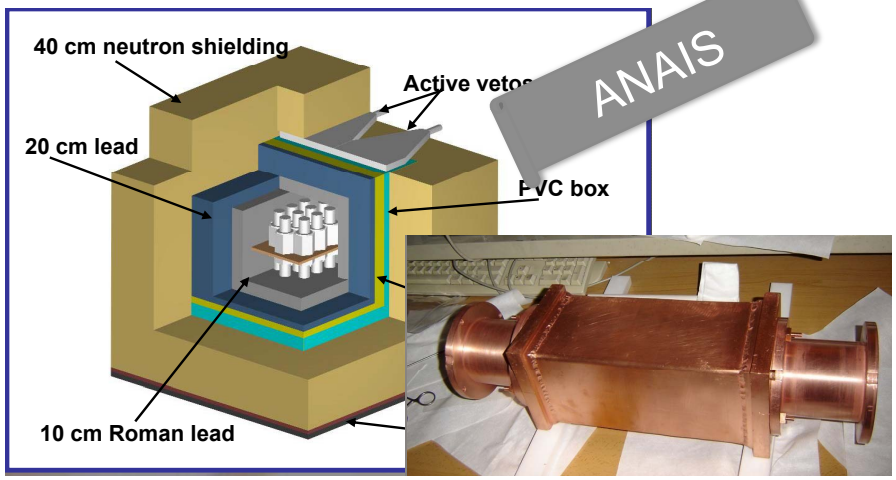
BACKUP



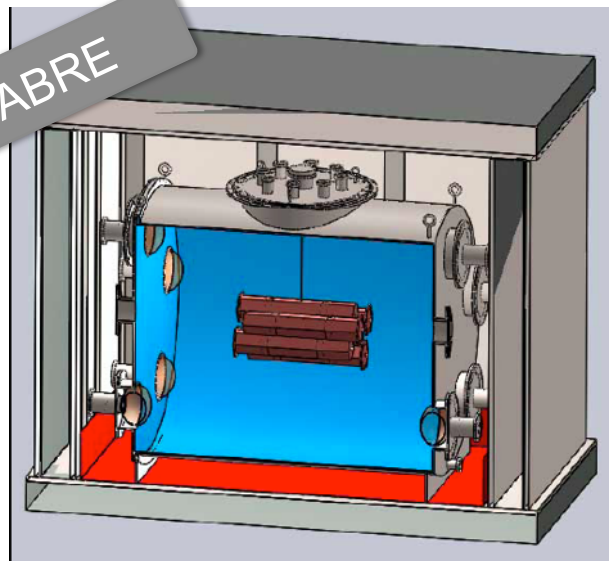
DM-Ice

KIMS

A WORLD WIDE EFFORT



ANAIS



SABRE