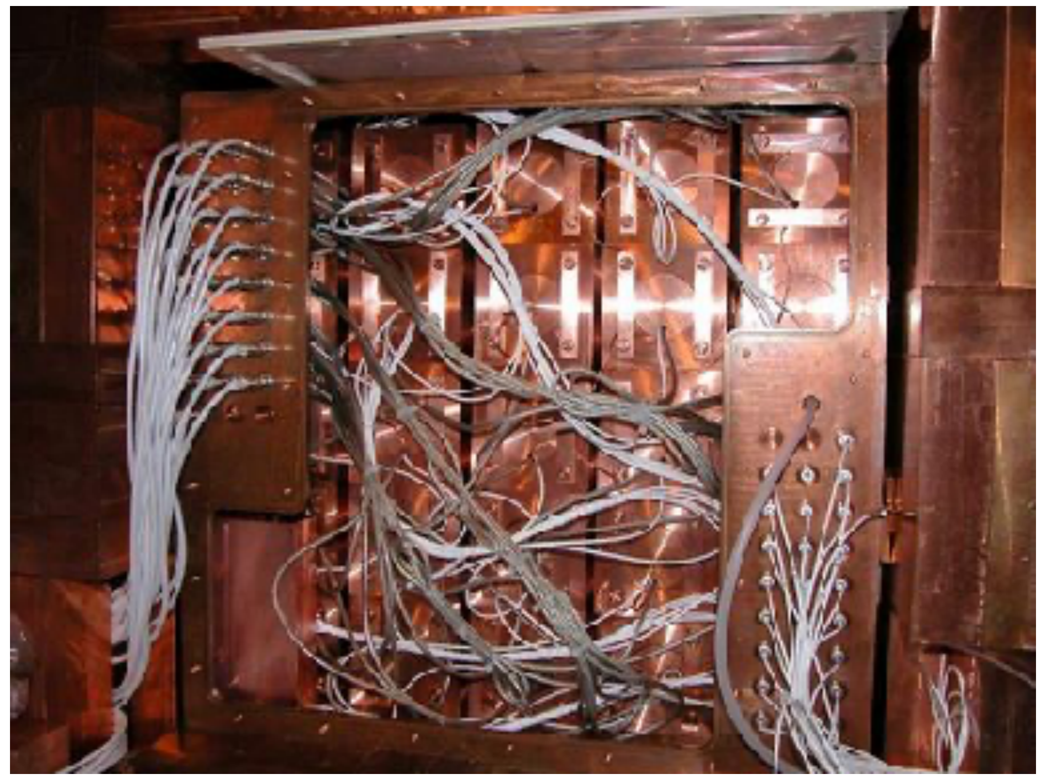
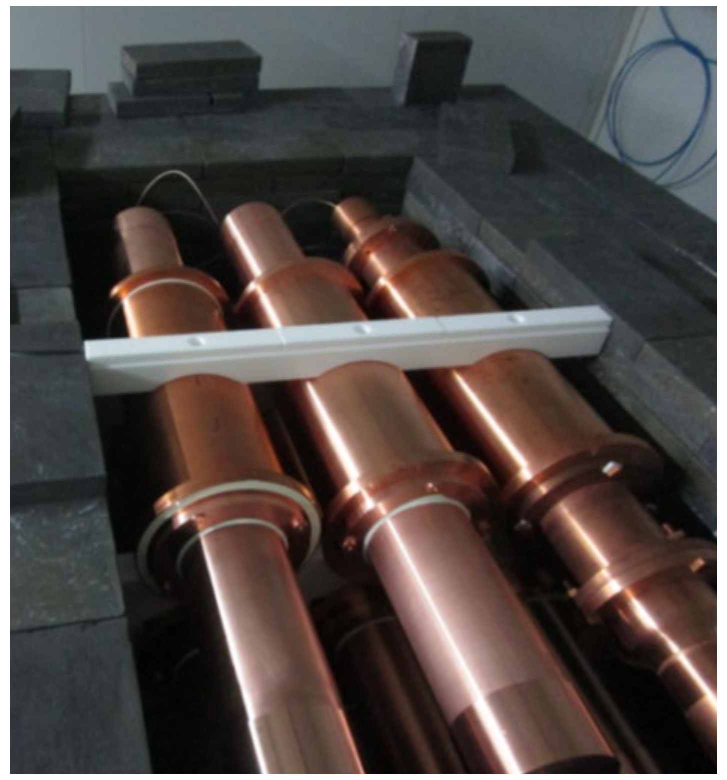
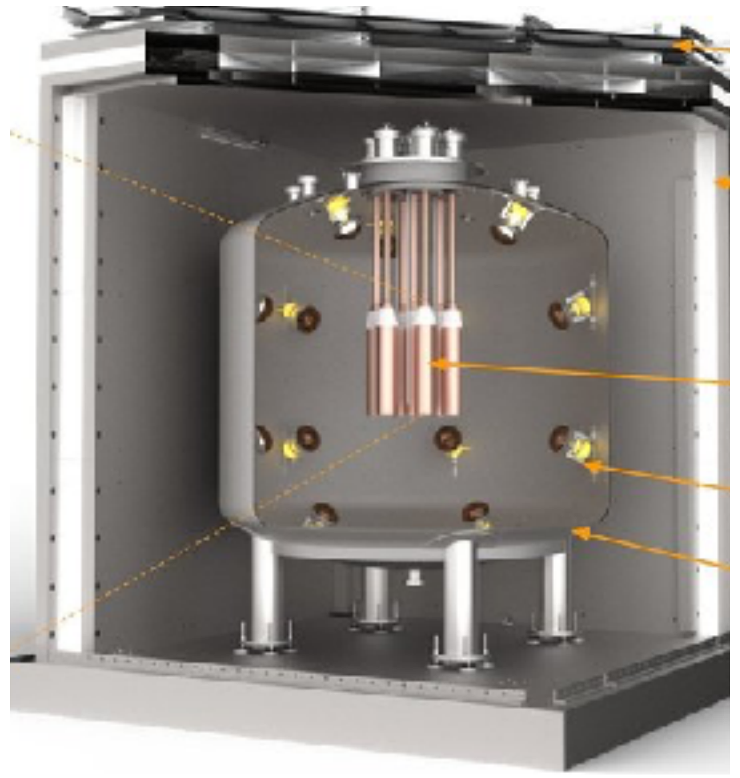
Resolving DAMA







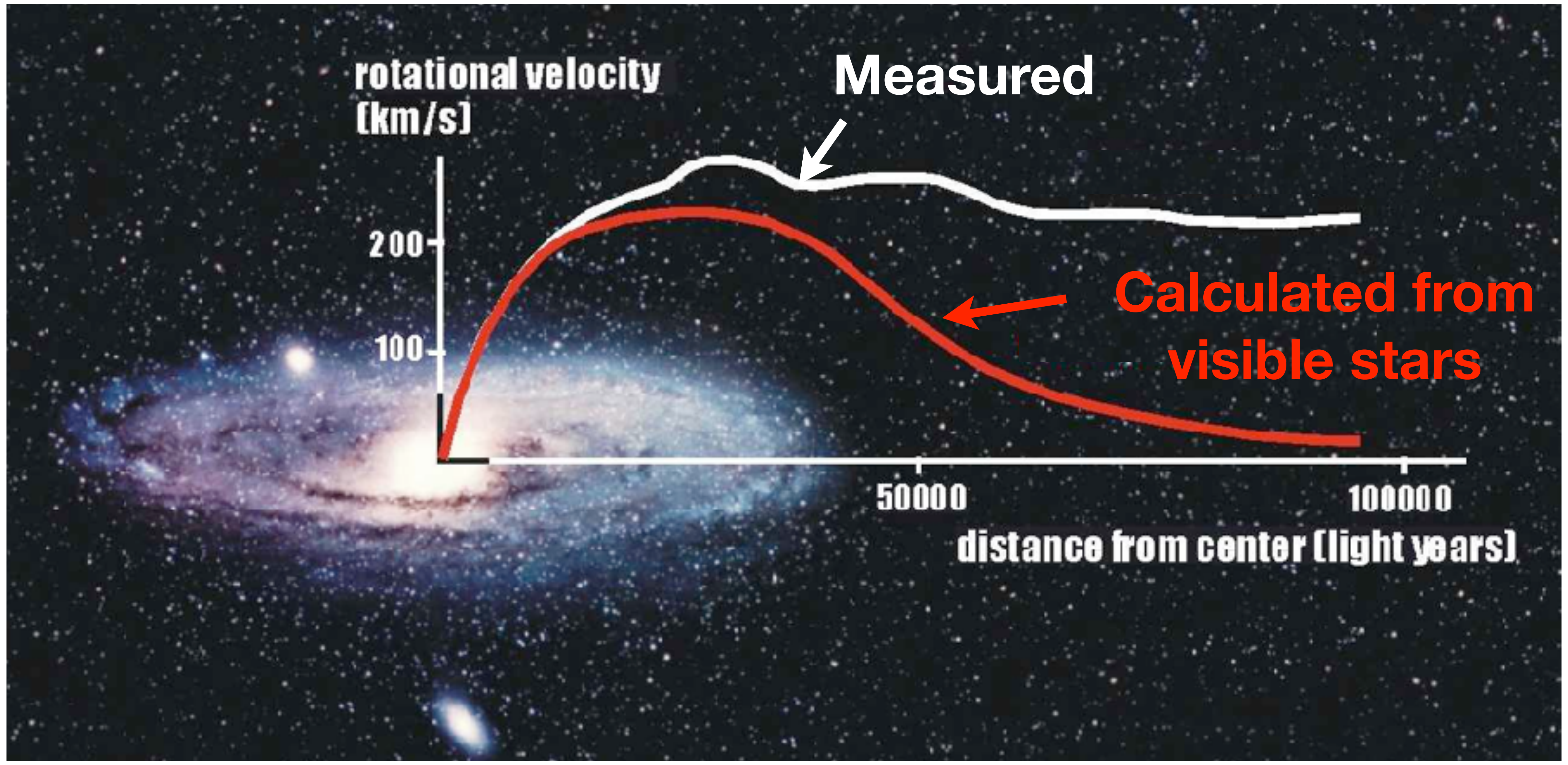

Reina Maruyama
Yale University

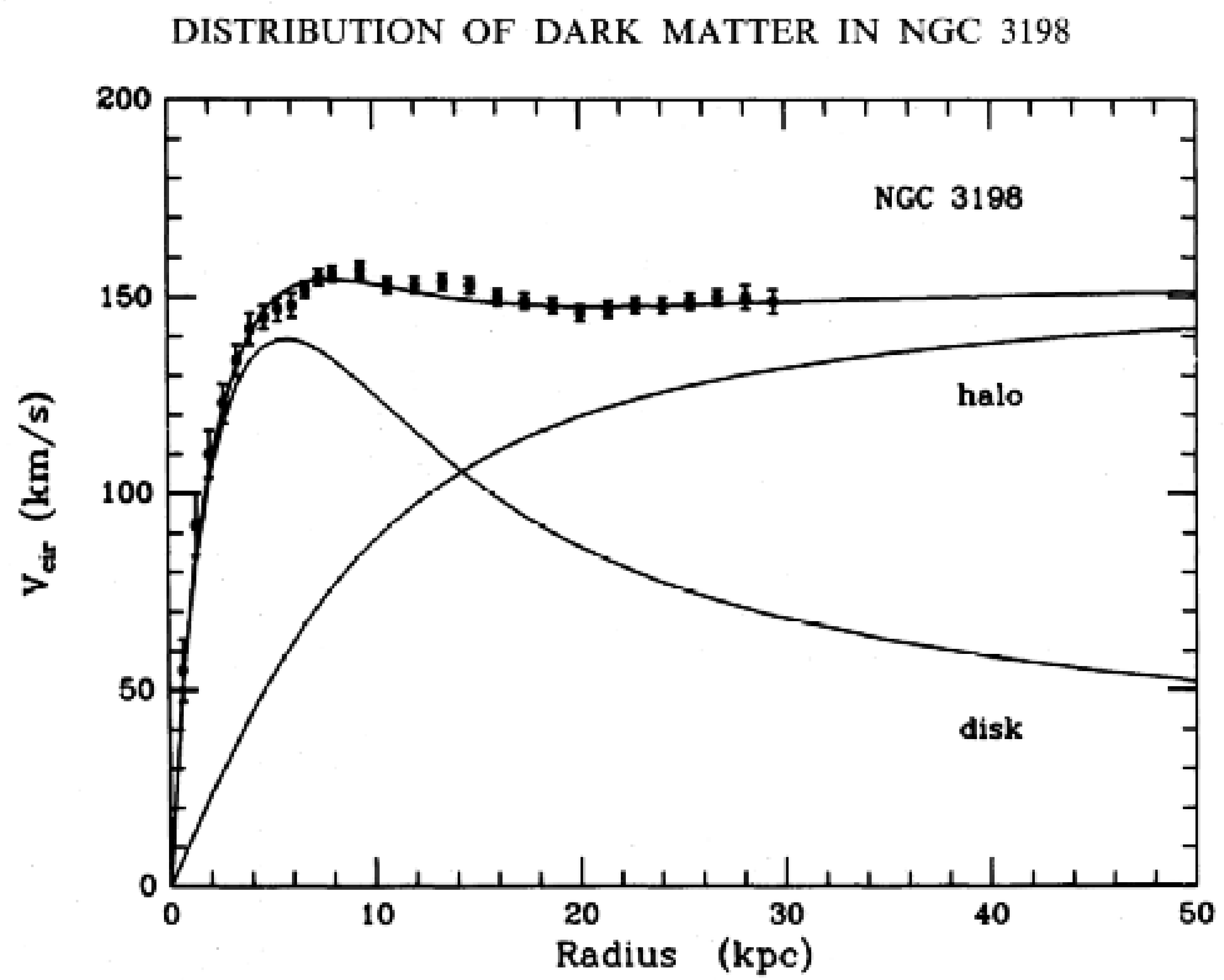
Joint IPMU(APEC)/ICRR/ILANCE Seminar
August 8, 2023

Discovery of Dark Matter

1970‘s: Vera Rubin and co. found that rotation curves are flat, indicating presence of dark matter

Rotation Curve of Galaxies

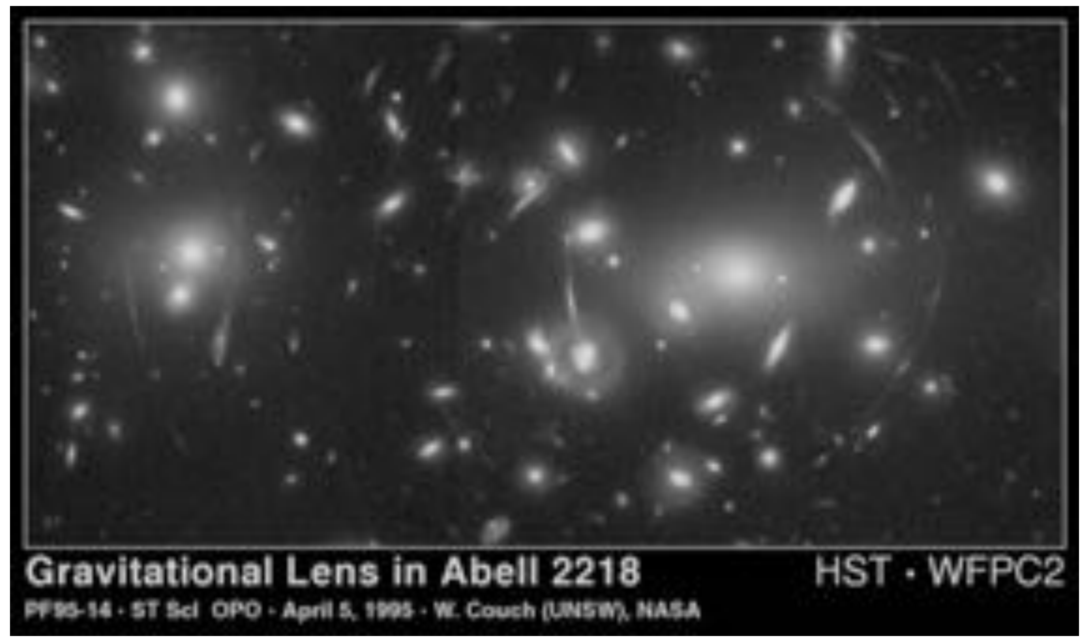


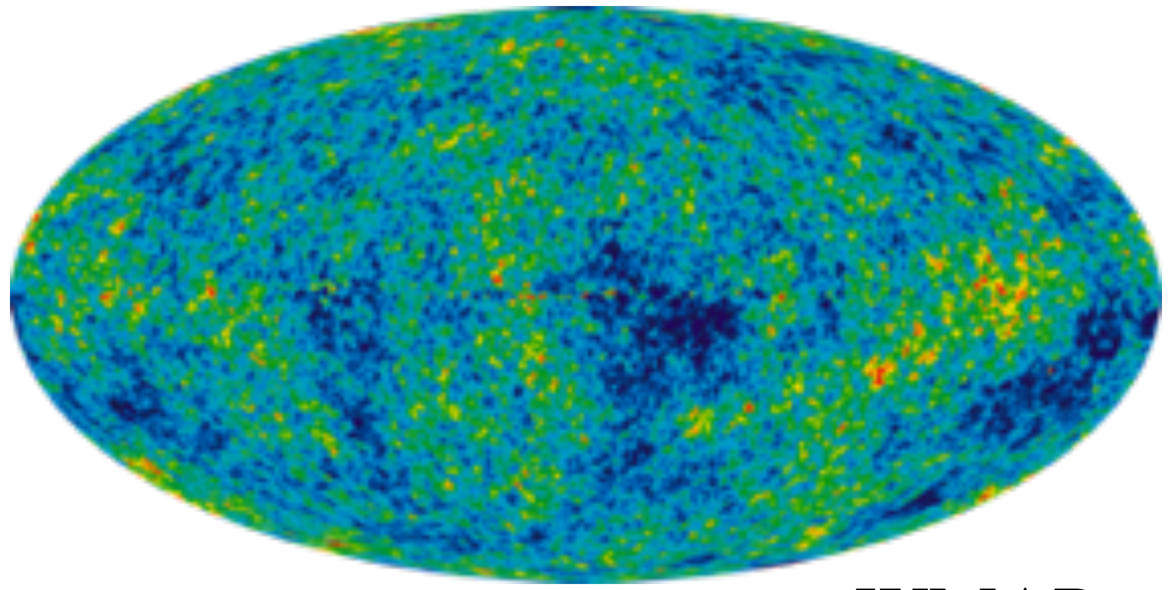


“What you see in a spiral galaxy ...
is not what you get.”

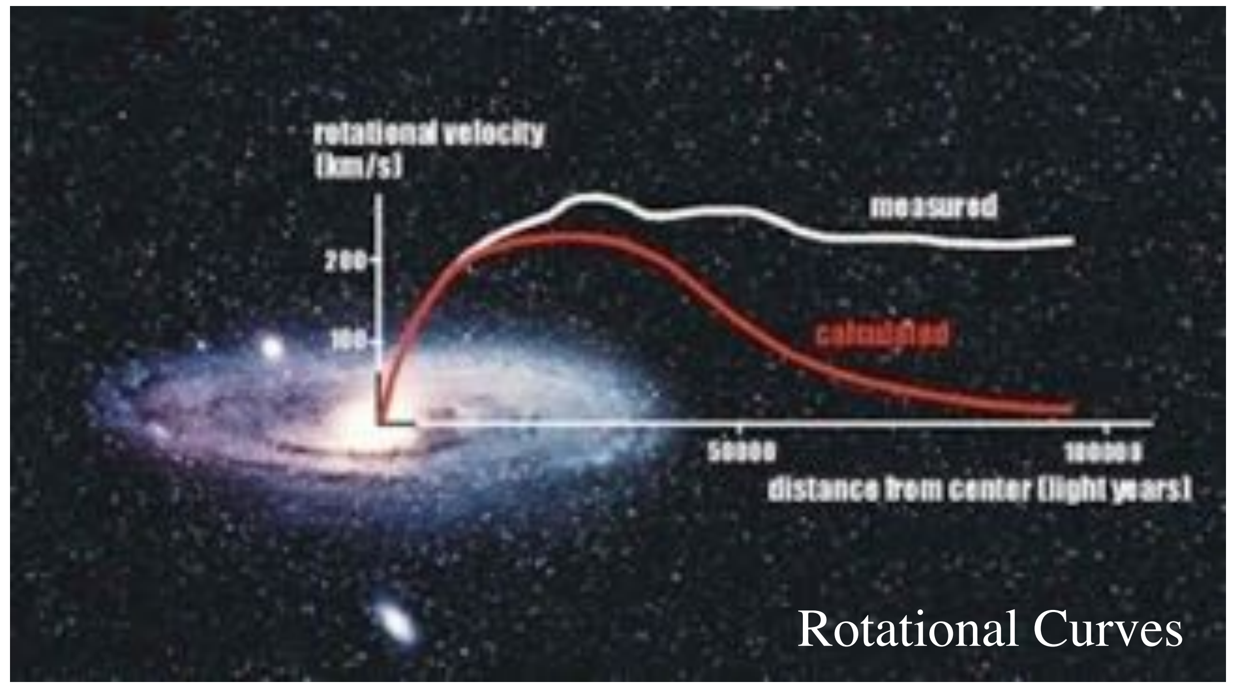
Our Universe Needs Dark Matter

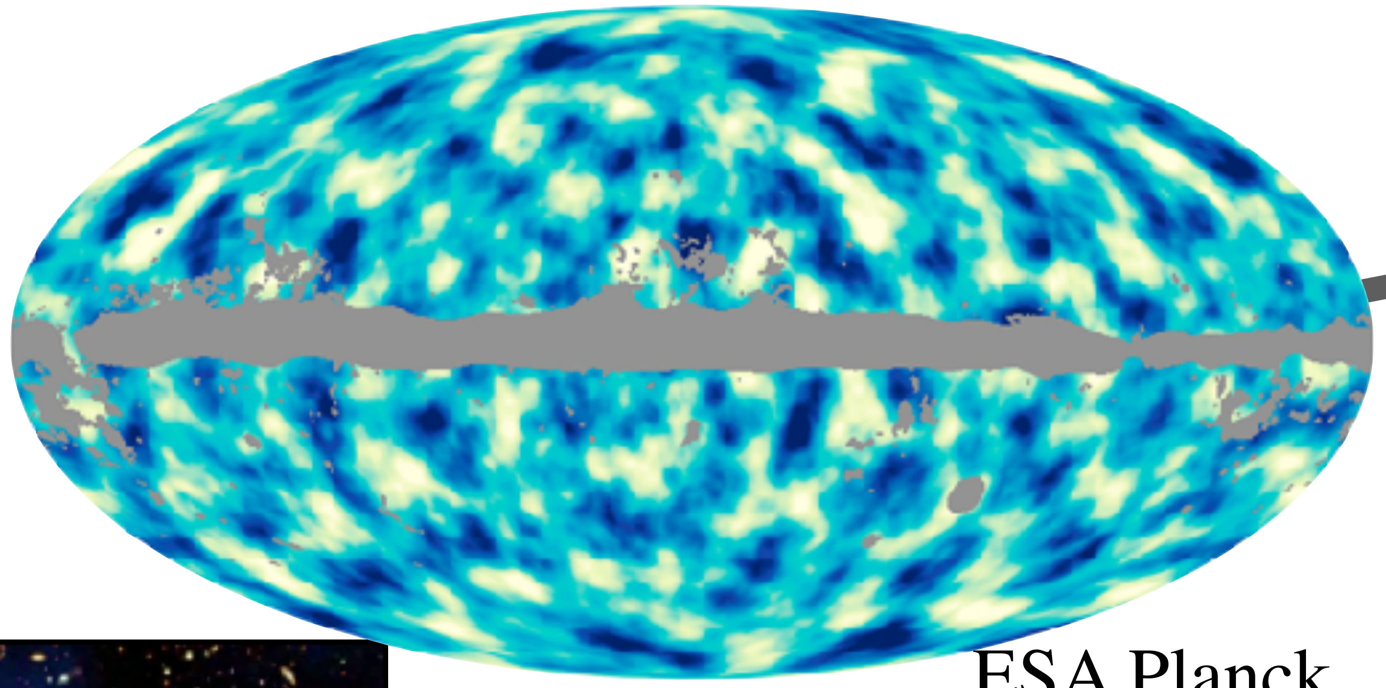
Astrophysical Observations



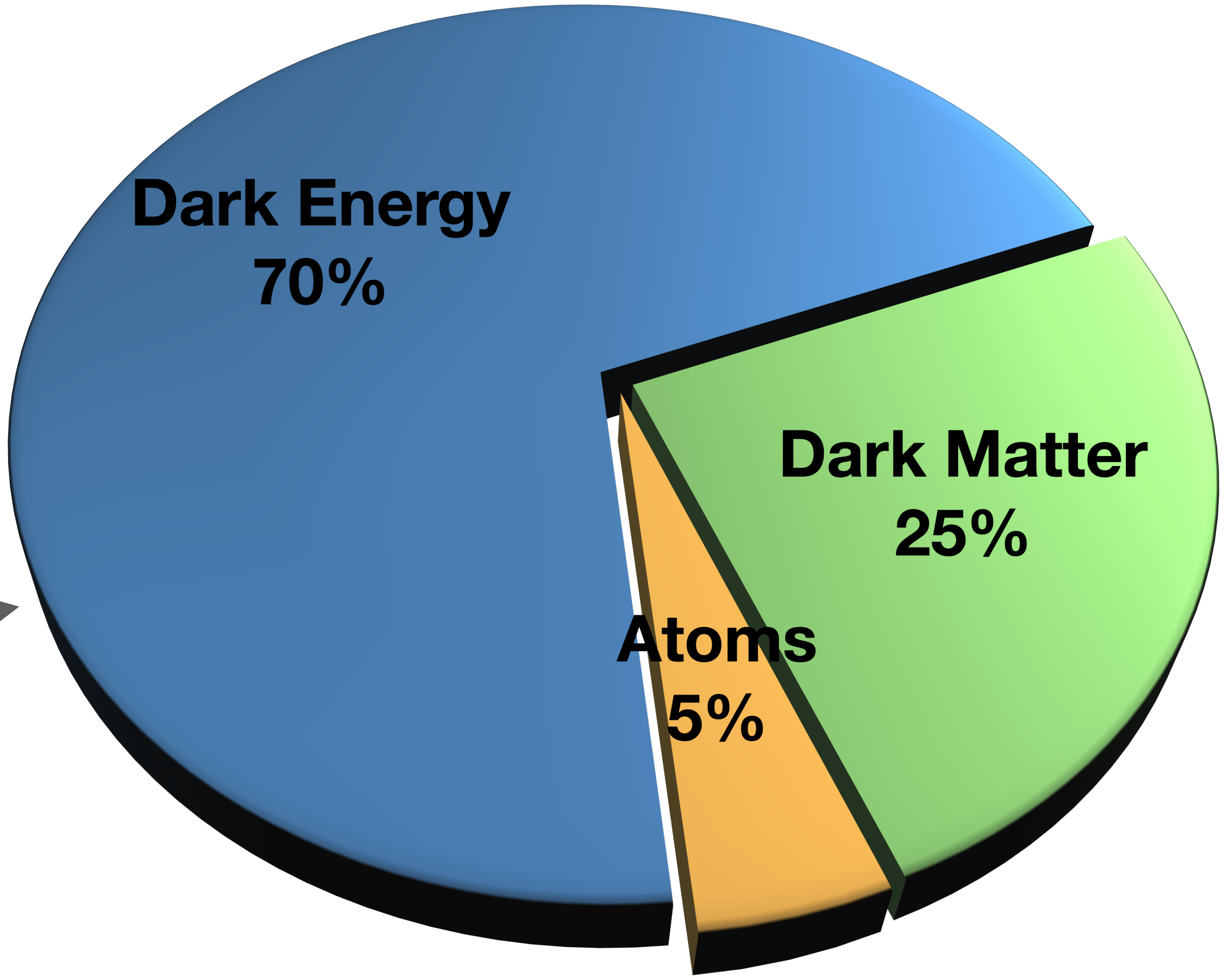


WMAP



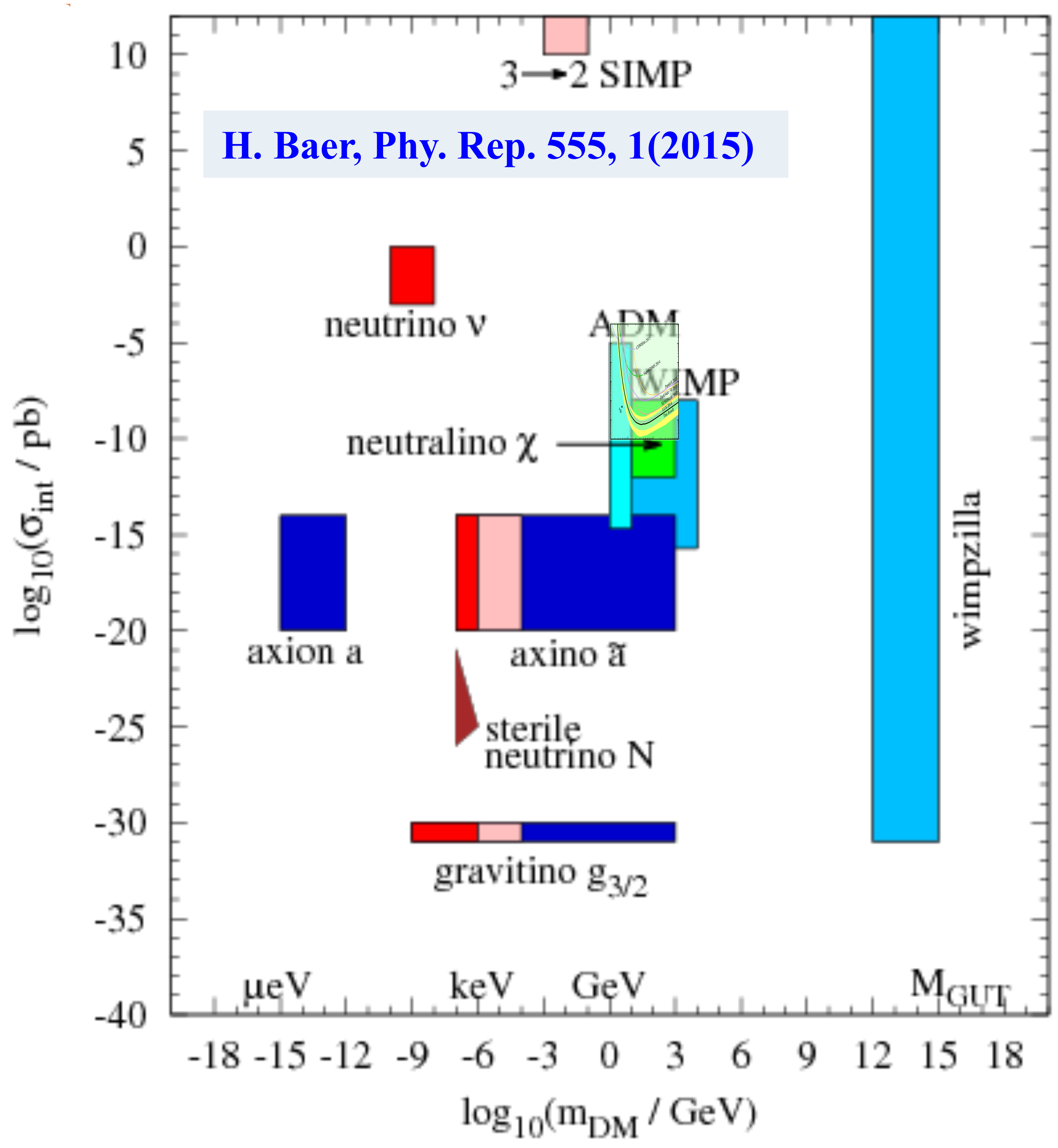


ESA Planck



All consistent with ~25% dark matter

Characteristics of dark matter



Dark matter must be…

- No charge
- Stable on cosmological times
- Have mass, moving slow
- Weak interactions with regular matter
- Interacted enough in the early Universe to come to thermal equilibrium
- local density: $\rho = 0.39 \pm 0.03$ GeV/cm^3

Leading Candidates:

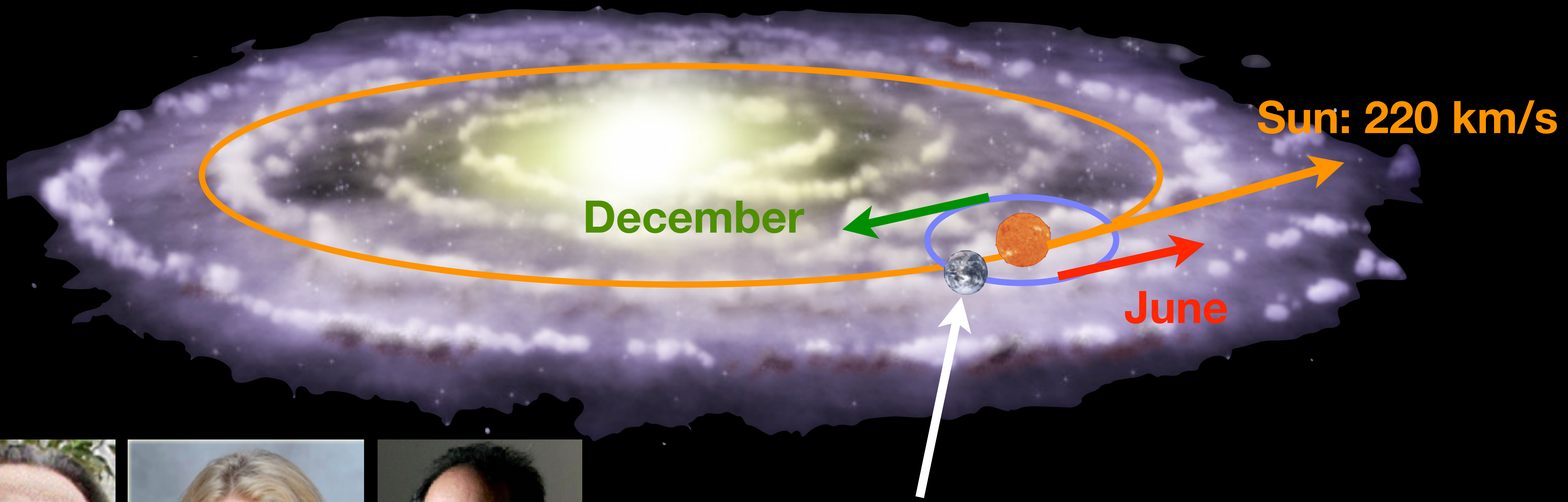
Axions

- mass ~$10^{-3} – 10^{-6}$ eV
- Peccei-Quinn solution to the strong-CP problem

WIMPs: Weakly Interacting Massive Particles

- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance

Direct Detection Dark Matter Searches

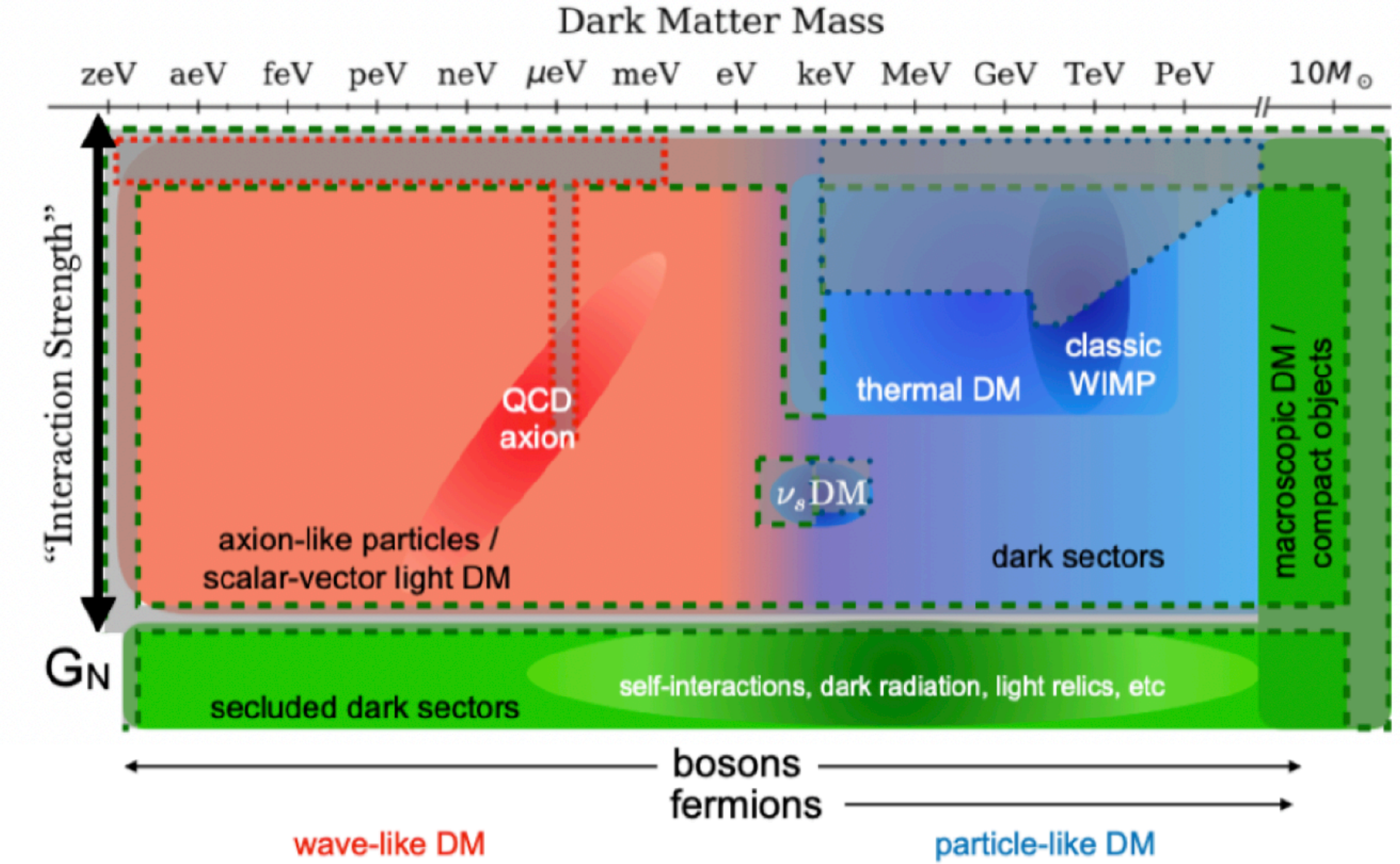


Rates Peak in June.

(Modified from: NASA/CXC/M.Weiss)

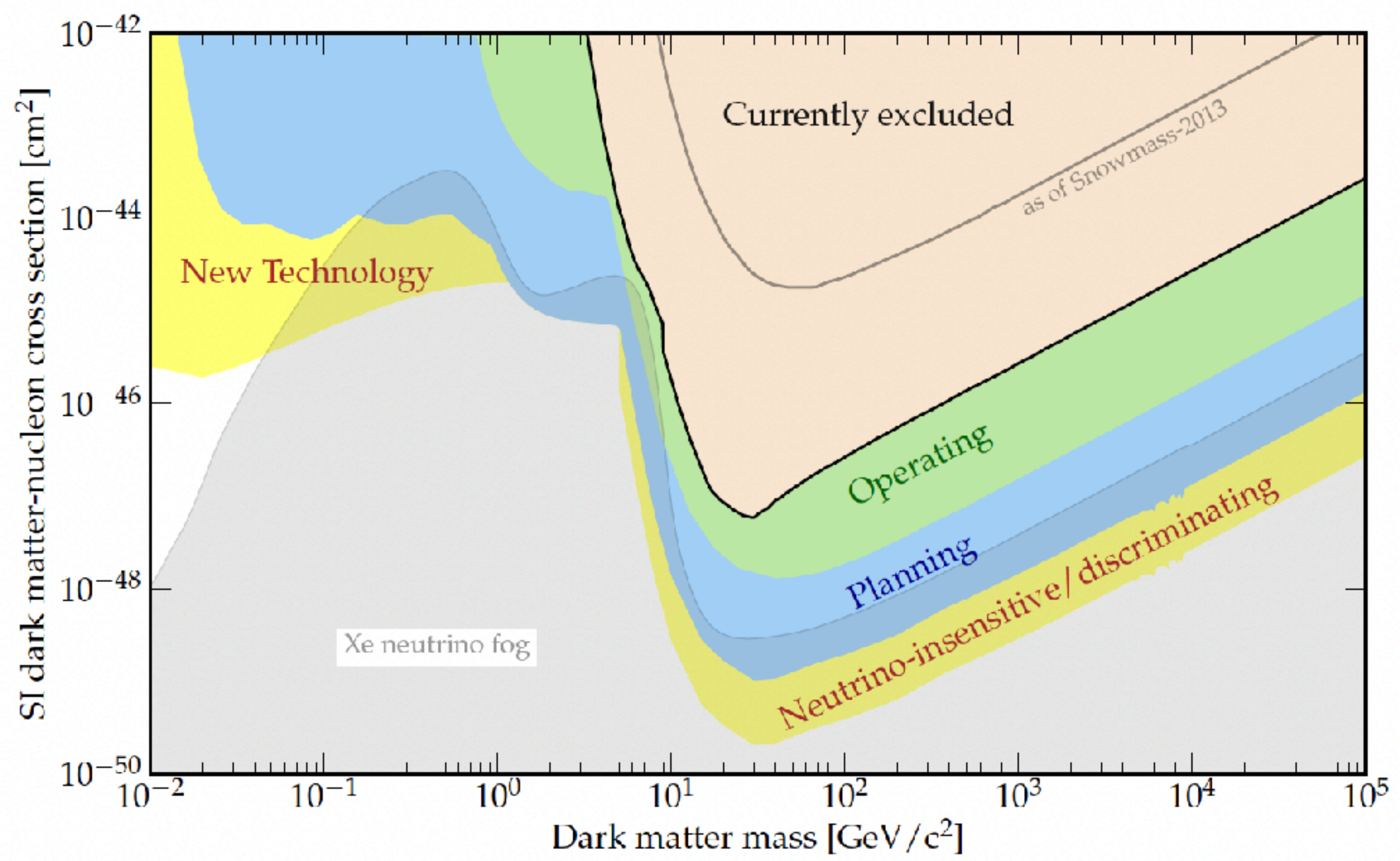
Drukier, Freese & Spergel PRD**33** 3495 (1986)

“Snowmass 2022”: U.S. Dark Matter Program



Snowmass 2022

WIMP Searches



XENONnT@LNGS

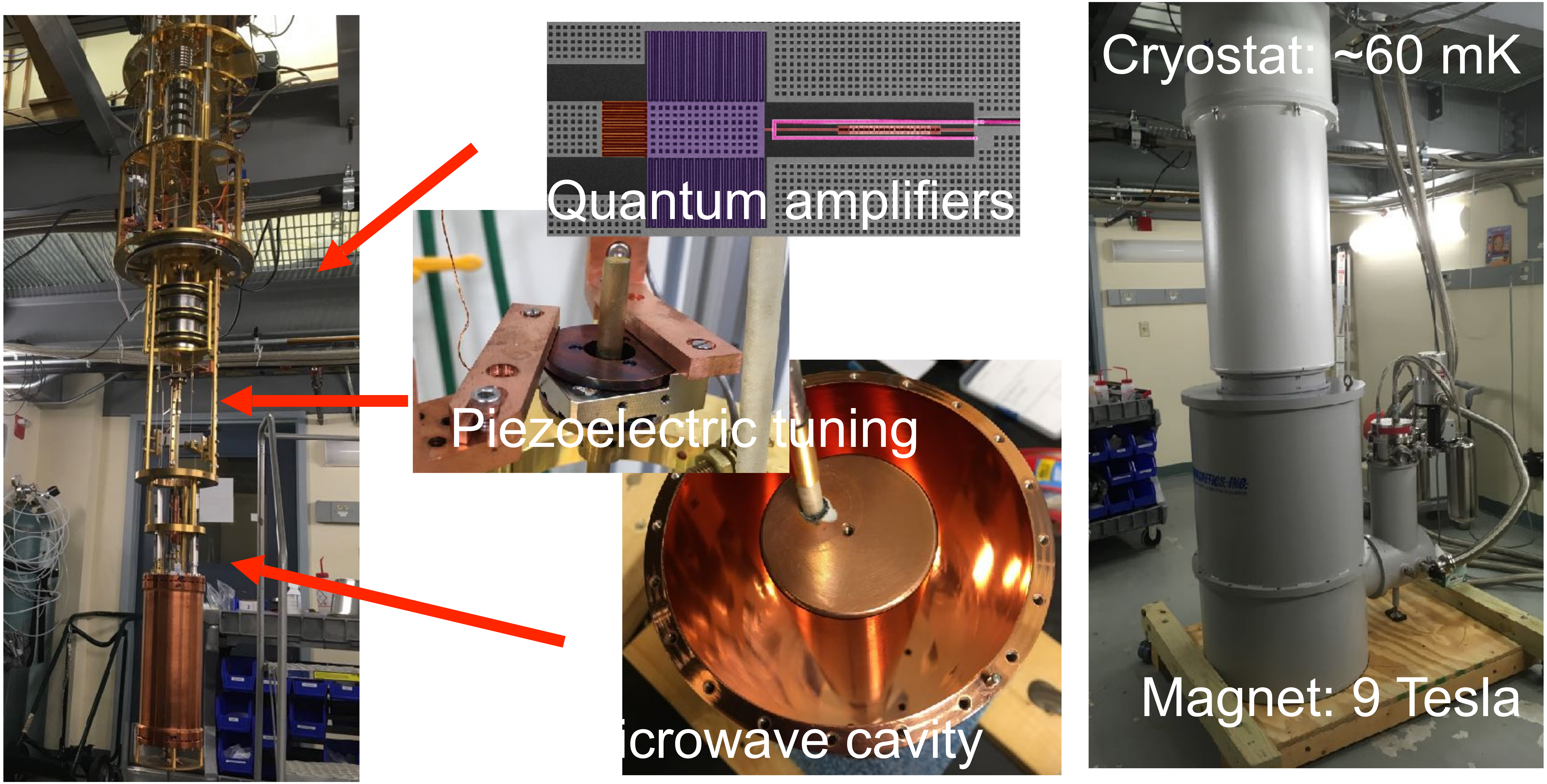
LZ@SURF

PandaX-4T@JinPing

- Worldwide effort, no sign yet of WIMPs

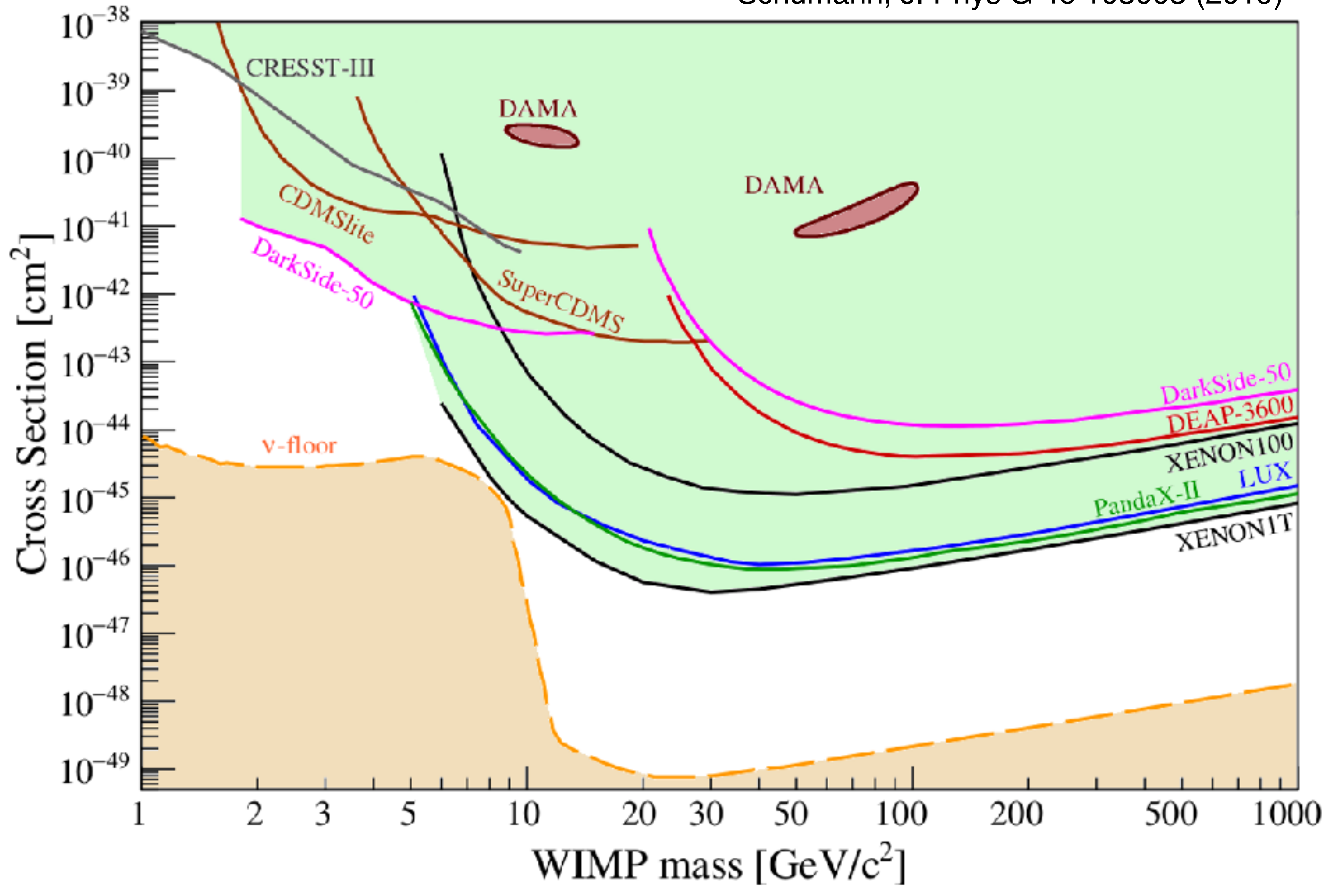
Haystac

Axion Searches, e.g. HAYSTAC Experiment



Current status of Direct Dark Matter Searches

Schumann, J. Phys G 46 103003 (2019)



No sign of spin dependent WIMPs

$>10^{-46}$ cm^2 @ 30 GeV

No sign of spin-dependent WIMPs

$>10^{-40}$ cm^2

Experiments driving innovations toward low mass dark matter searches

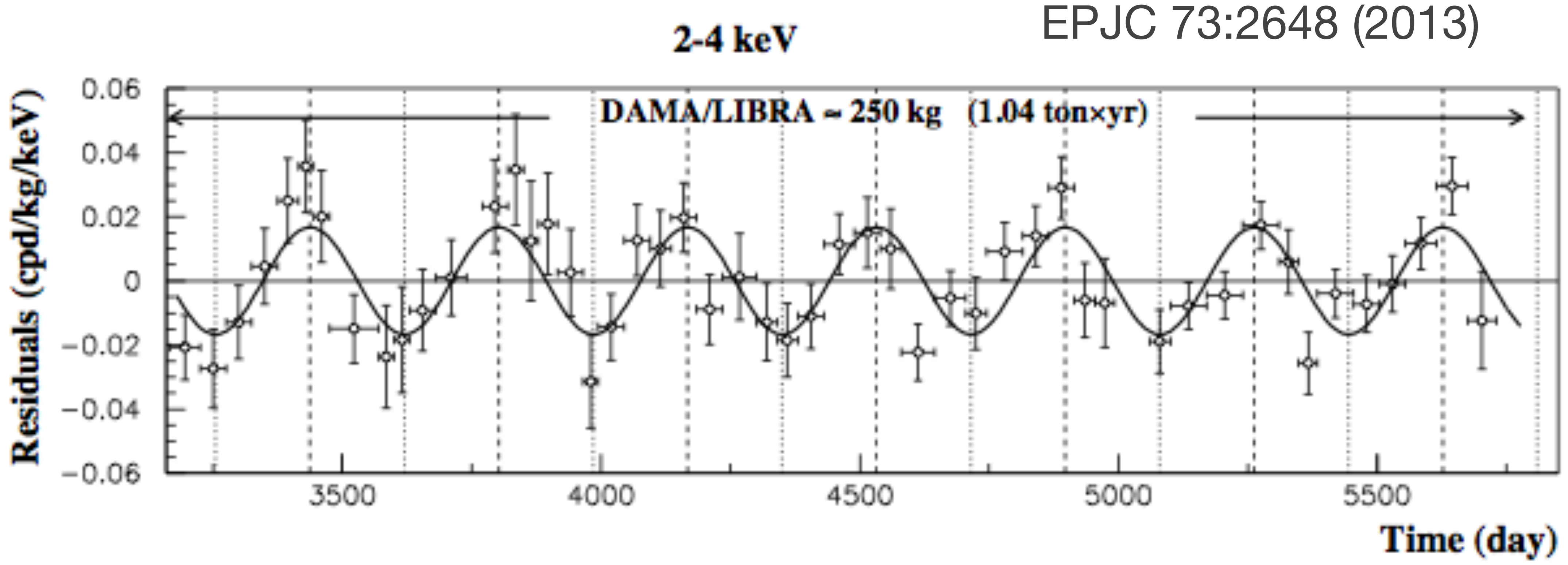
Difficult to reconcile DAMA vs. other experiments

DAMA/NaI & DAMA/LIBRA

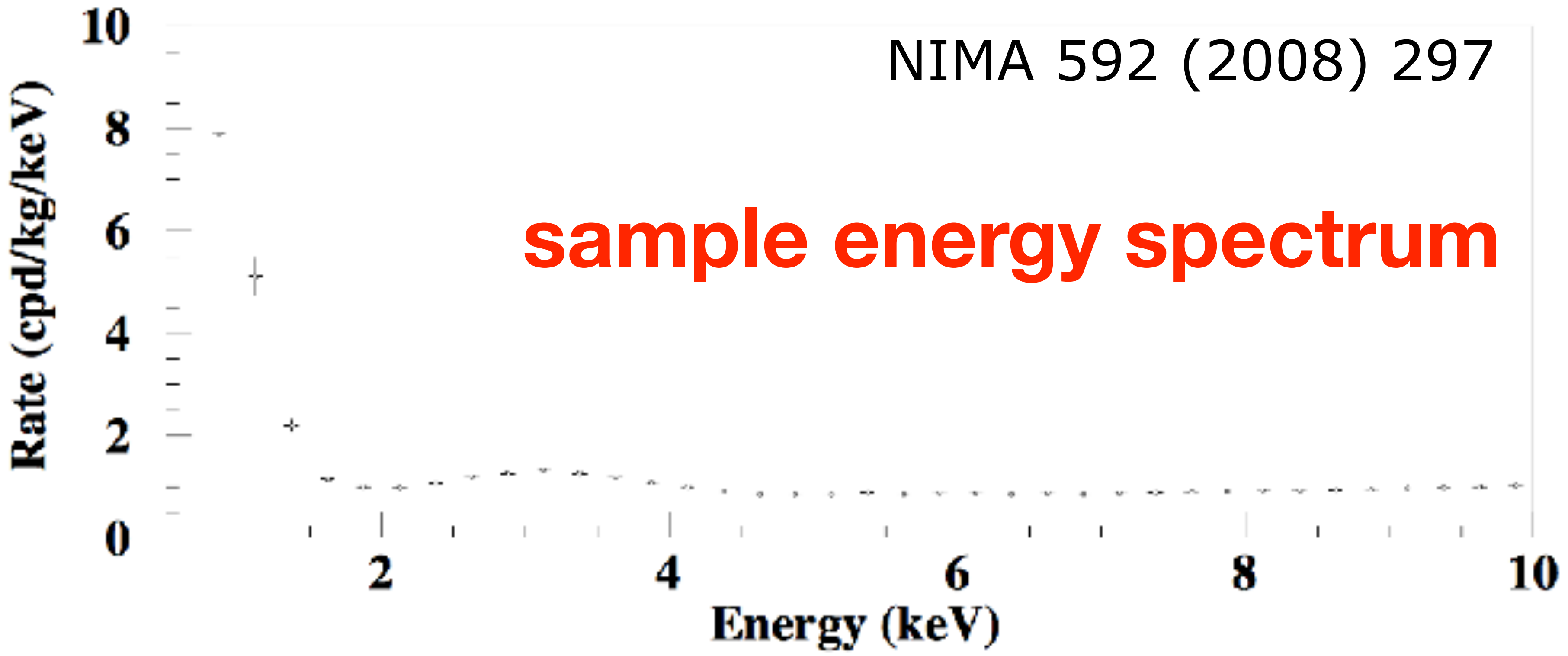
First claim for dark matter detection in 1997

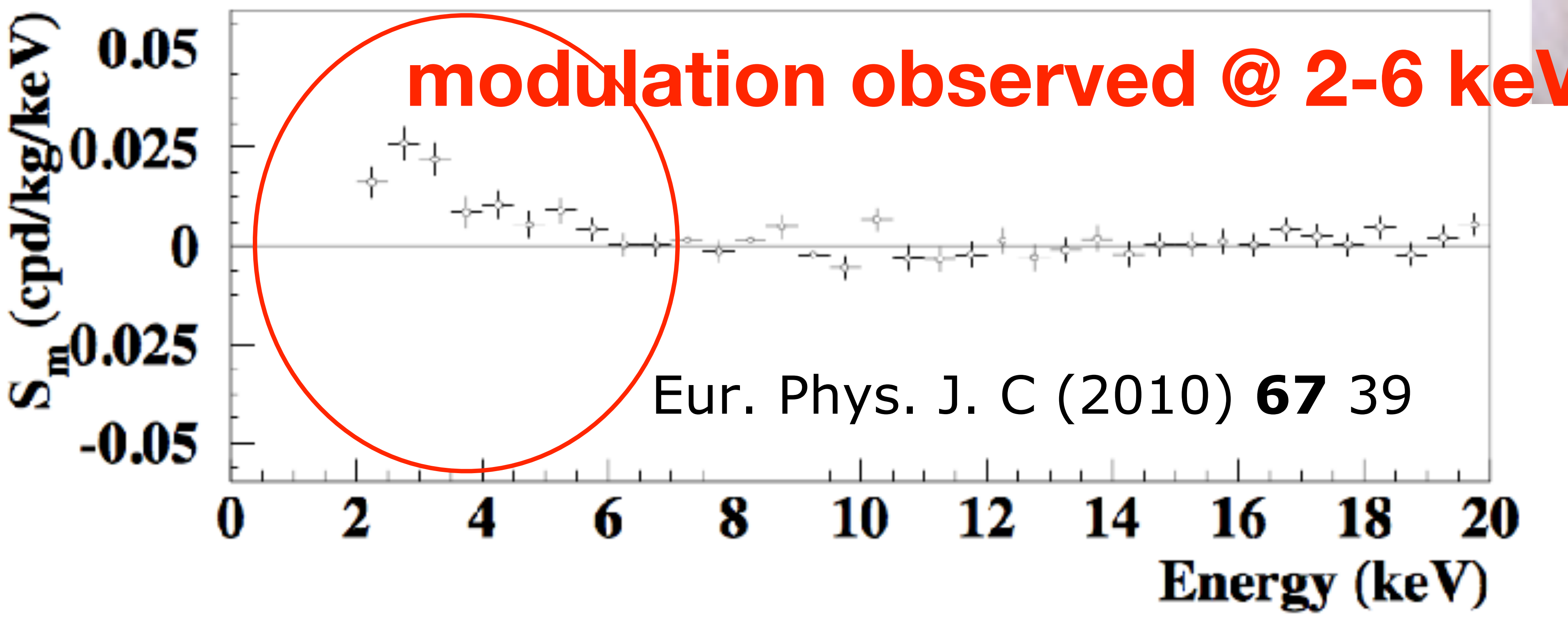
- Phase & Period consistent with dark matter
- Two generations:
  - DAMA/NaI: 100 kg (1996 - 2003)
  - DAMA/LIBRA-phase1: 250 kg (2003 - 2010)
    - Background: ~ 1 count/keV/kg/day
- 1.33 ton-yr over 14 annual cycles

EPJC 73:2648 (2013)



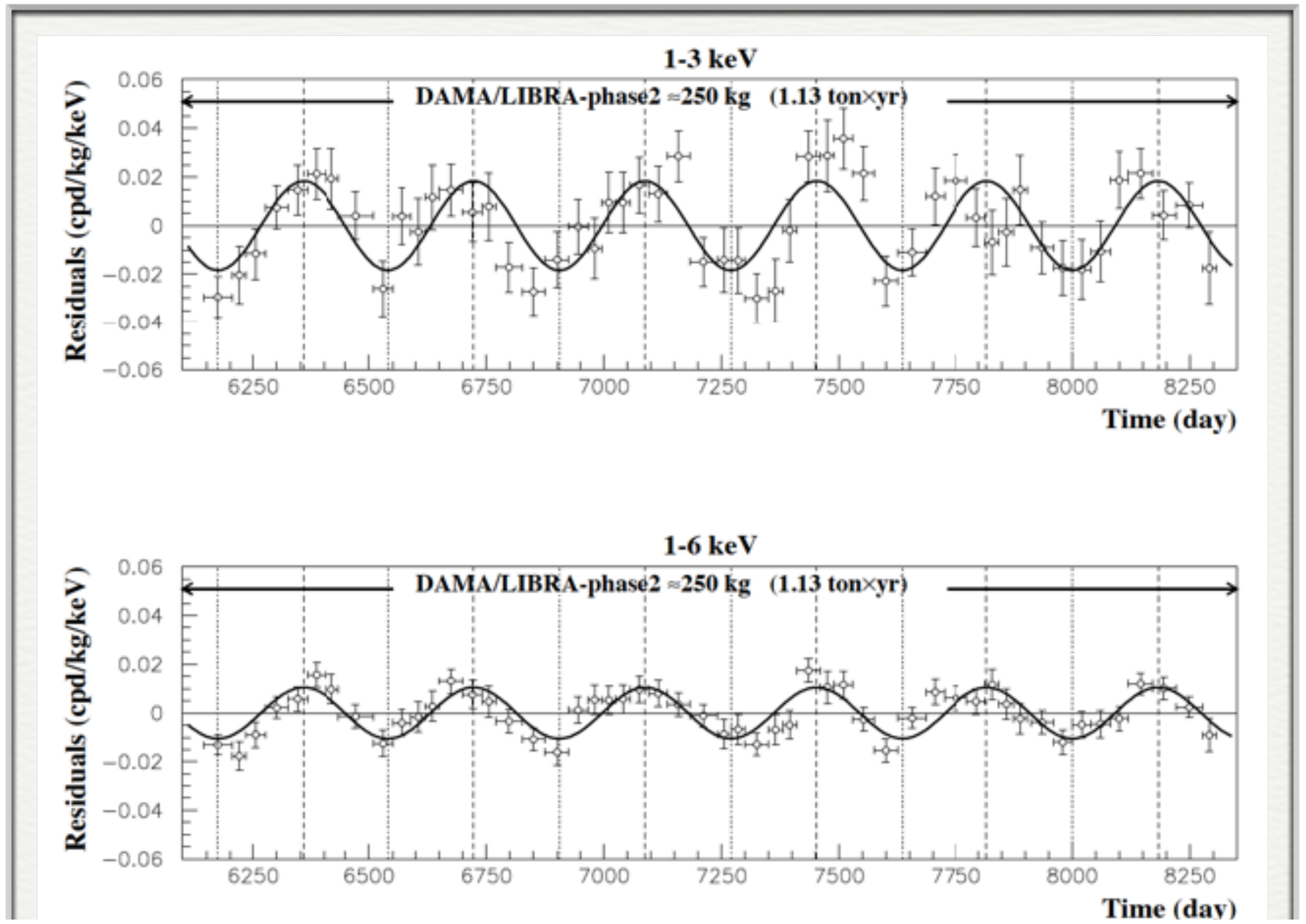
NIMA 592 (2008) 297





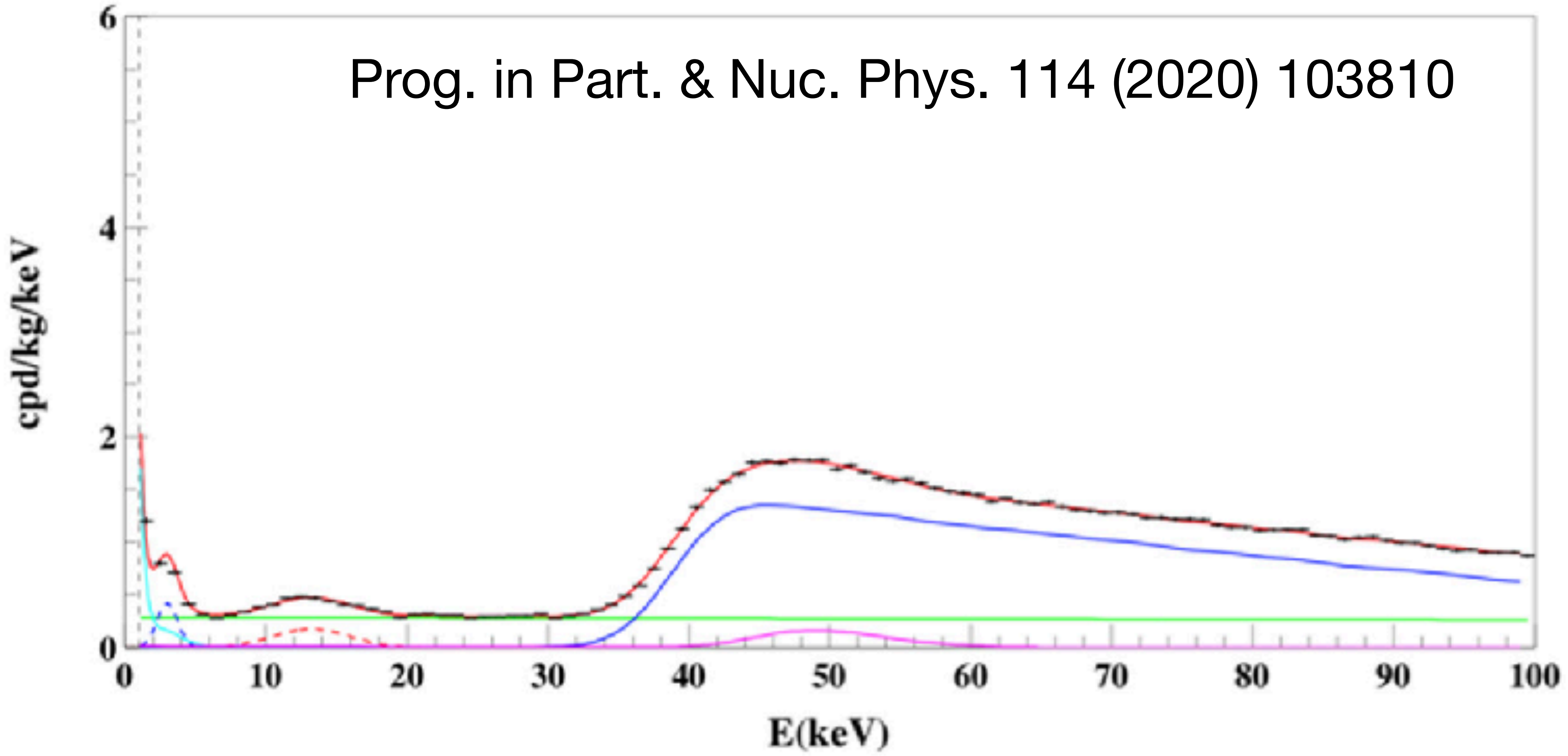
DAMA Sees Annual Modulation

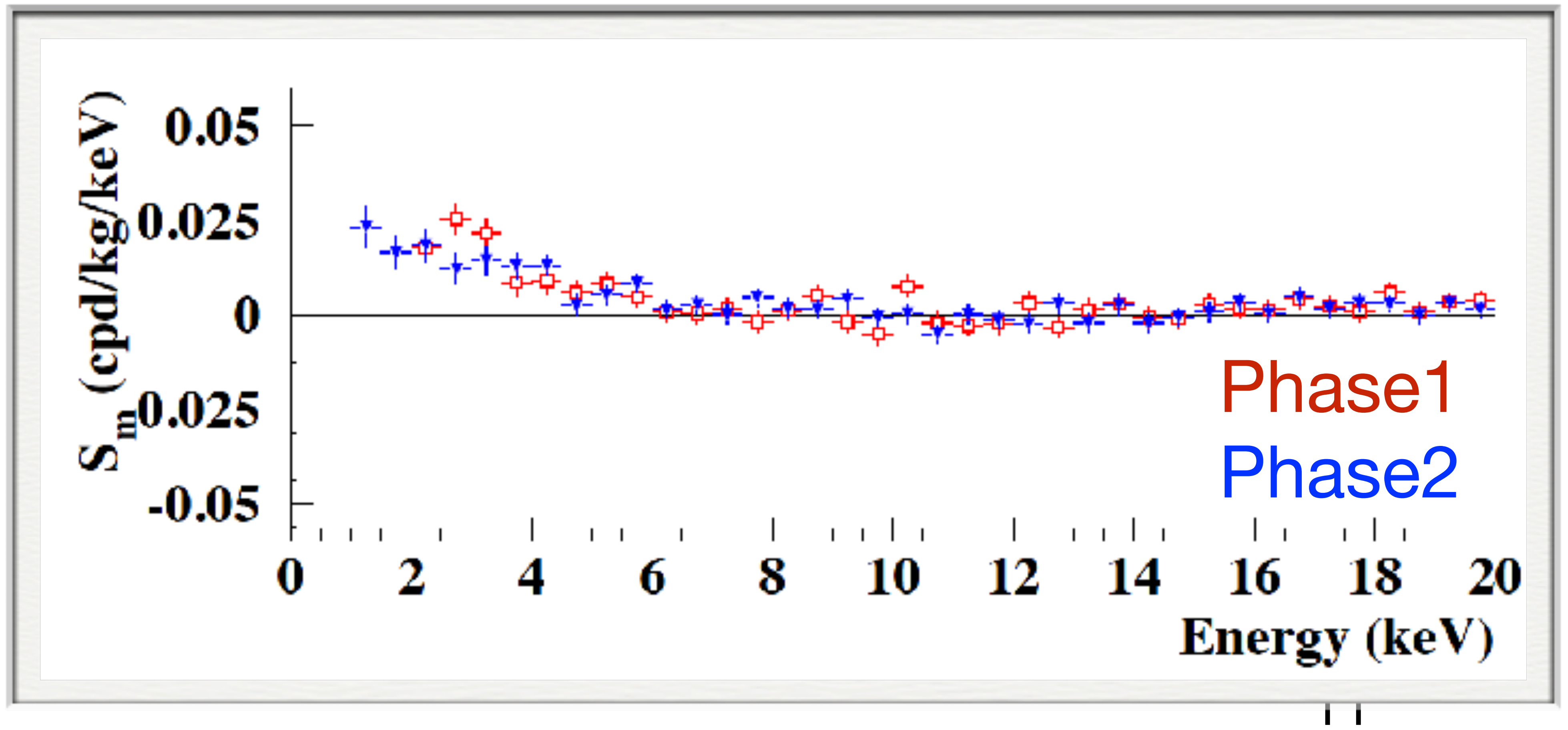
Nucl. Phys. At. Energy 19 (2018) 307



Modulation persists in DAMA Phase 2

- (1 – 6) keV: 9.5σ from 1.13 ton- year
- (2 – 6) keV: 12.9σ from 2.46 ton-year
- Mod. amplitude: (0.0103 +/- 0.0008) cpd/kg/keV
- Phase: (145 +/- 5) days
- period: (0.999 +/- 0.001) year





nature International weekly journal of science

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News & Comment > News > 2015 > October > Article

NATURE | NEWS

Zombie physics: 6 baffling results that just won't die

To celebrate Halloween, *Nature* brings you the undead results that physicists can neither prove — nor lay to rest.

Davide Castelvecchi

30 October 2015

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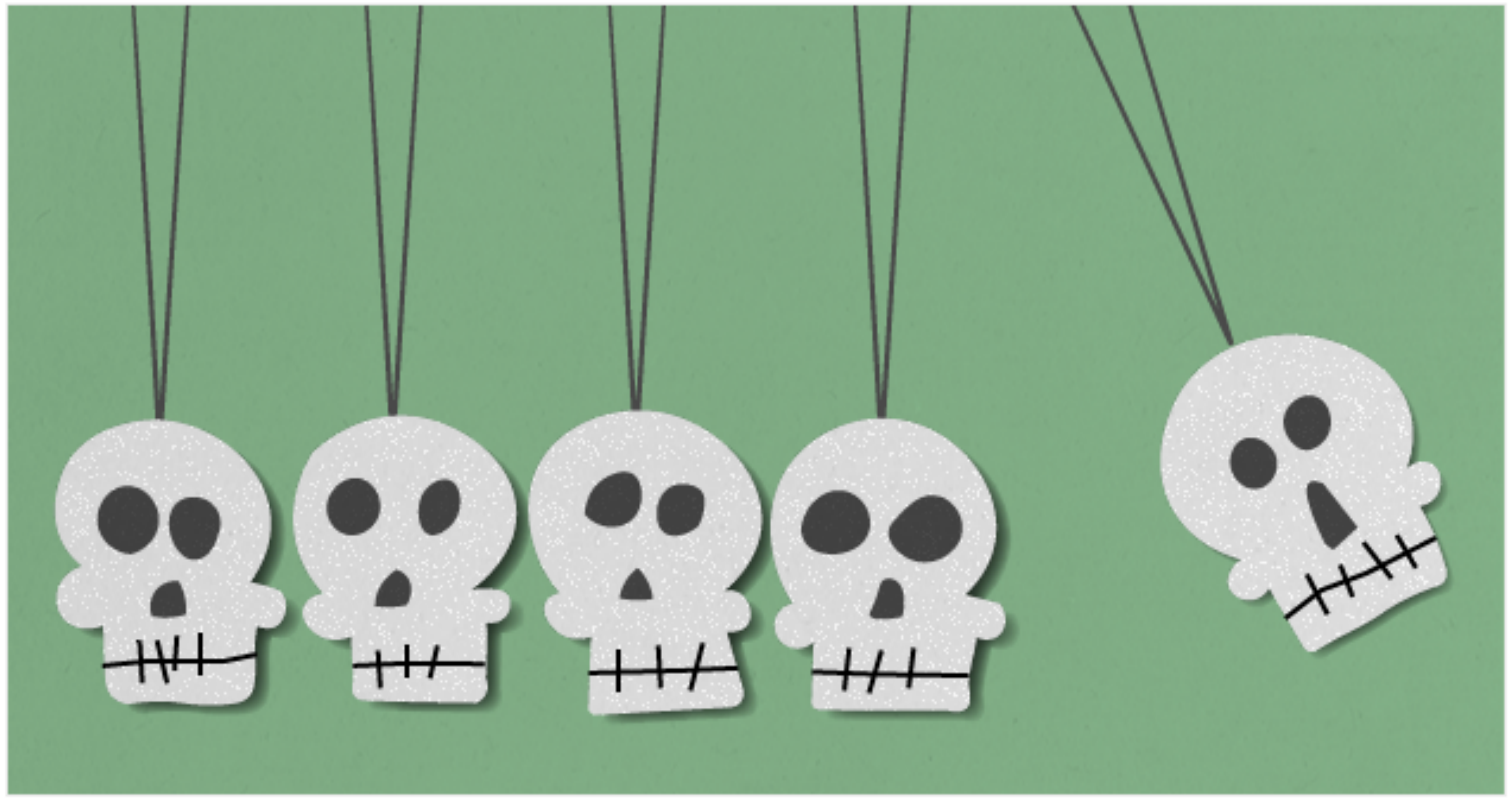


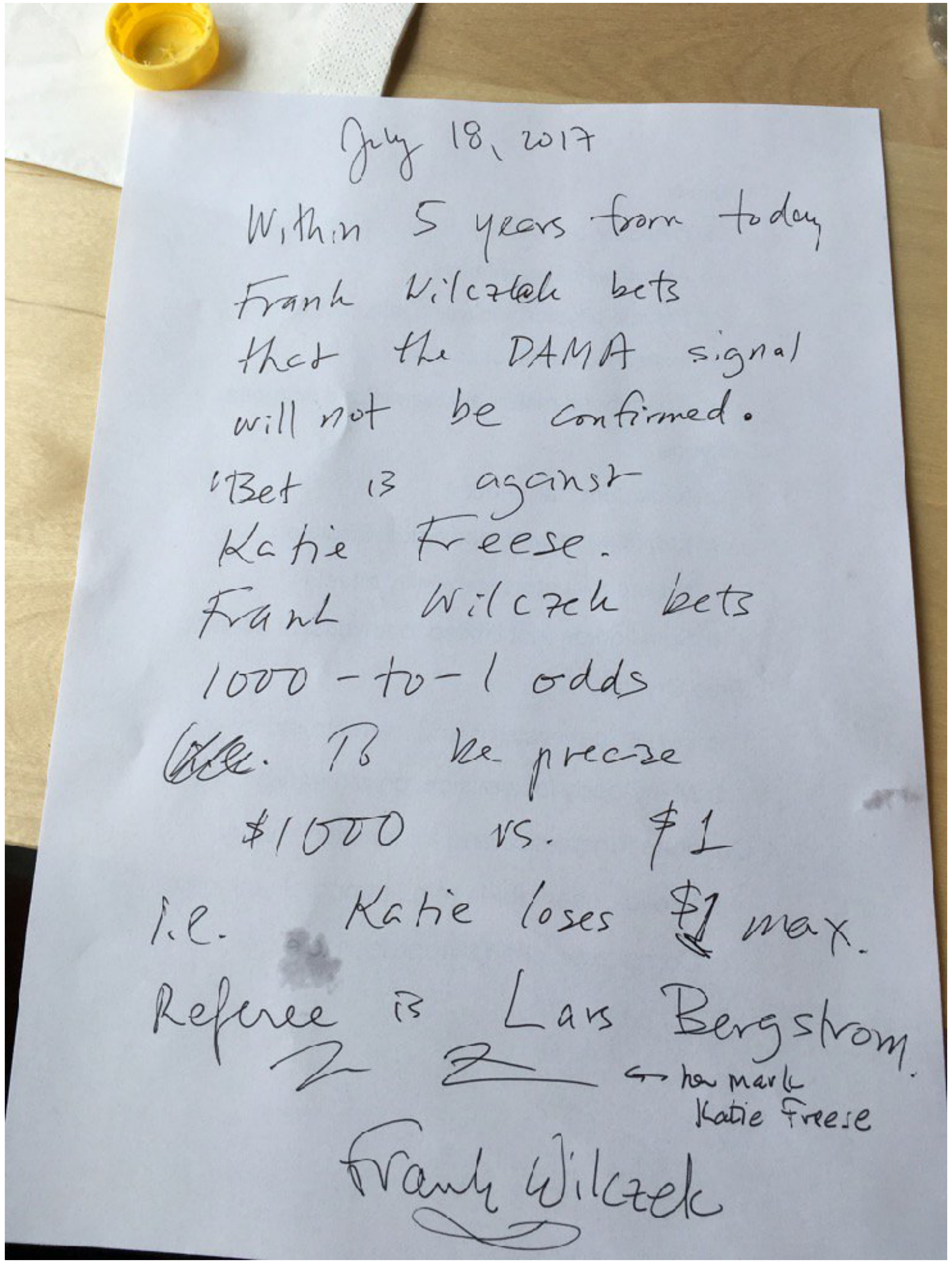
Seasonally spooky dark matter

… Since the late 1990s, however, physicists on the DAMA experiment … have been detecting what could be the interactions of dark matter with crystals of sodium iodide.

"Nobody has been able to come up with a conclusive argument as to what they're seeing," says **Reina Maruyama**, a physicist at Yale University in New Haven, Connecticut.

Two planned experiments in the southern hemisphere, where the seasons are reversed, could bring a resolution: one called **DM-Ice**…

http://www.nature.com/news/zombie-physics-6-baffling-results-that-just-won-t-die-1.18685



July 18, 2017

Within 5 years from today
Frank Wilczek bets
that the DAMA signal
will not be confirmed.
Bet is against
Katie Freese.
Frank Wilczek bets
1000-to-1 odds
To be precise
$1000 vs. $1
i.e. Katie loses $1 max.
Referee is Lars Bergstrom.

← her mark
Katie Freese

Frank Wilczek

https://twitter.com/ktfreese/status/888730718477713408

TAUP 2015, P. Belli

Summary ... ons
of possibl ... se1

...2.0660,
...)2064,
...)3196)

Source

RADON

TEMPERATURE

NOISE

ENERGY SCALE

EFFICIENCIES

BACKGROUND

SIDE REACTIONS

+ they can...
satisfy all the requi...
annual modulation...

arXiv:1006.5255

One Model Explains DAMA/LIBRA, CoGENT, CDMS, and XENON

John P. Ralston
Department of Physics & Astronomy, The University of Kansas, Lawrence, KS 66045

arXiv:1102.0815

A testable conventional hypothesis for the DAMA-LIBRA annual modulation

David Nygren
Physics Division, Lawrence Berkeley National Laboratory

PRL 113, 08130...

Fitting th...

arXiv:...

Contents lists available at ScienceDirect
Physics Letters B
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ELSEVIER

Dark Matter implications of DAMA/LIBRA-phase2 results

Sebastian Baum [a,b,*], Katherine Freese [a,b,c], Chris Kelso [d]

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[b] Nordita, KTH Royal Institute of Technology and Stockholm University, Roslagstullsbacken 23, 10691 Stockholm, Sweden
[c] Leinweber Center for Theoretical Physics, Department of Physics, University of Michigan, Ann Arbor, MI 48109, USA
[d] Department of Physics, University of North Florida, Jacksonville, FL 32224, USA

Baum, Freese, Kelso, Phys. Lett. B 2019

Daniel Ferenc[1,3,*] Dan Ferenc Šegedin[2,3], Ivan Ferenc Šegedin[3], Marija Šegedin Ferenc[3]

Progress in Particle and Nuclear Physics 114 (2020) 103810

Physics Letters B

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Dark Matter implications of DAMA/LIBRA-phase2 results

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ARTICLE INFO

ABSTRACT

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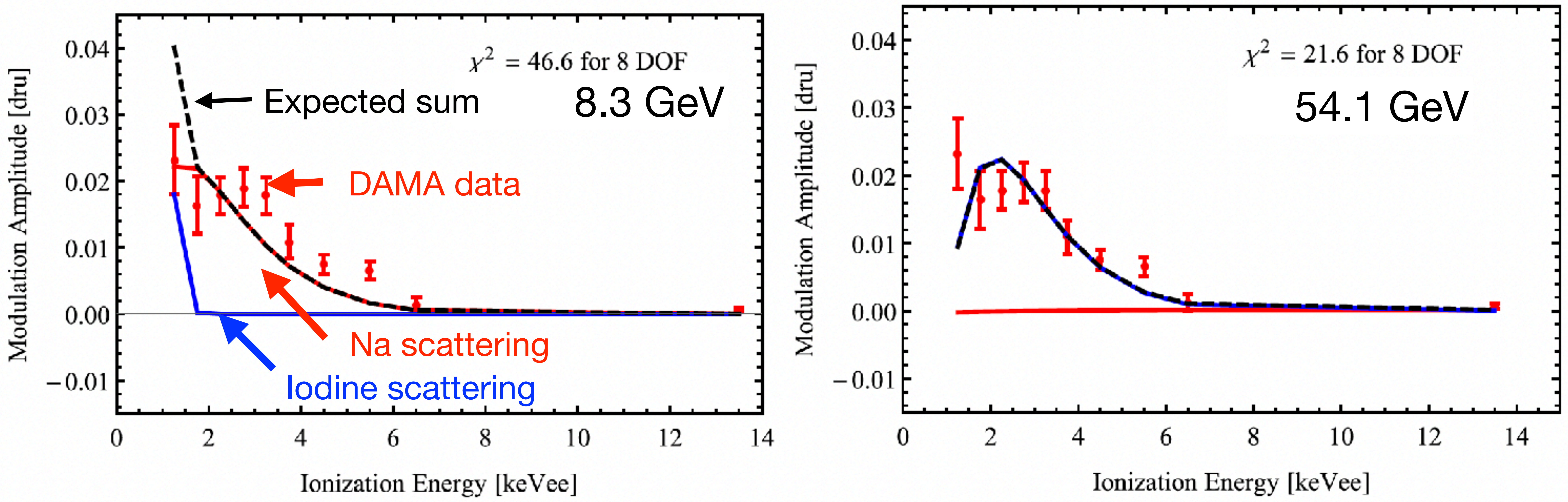
Editor: A. Ringwald

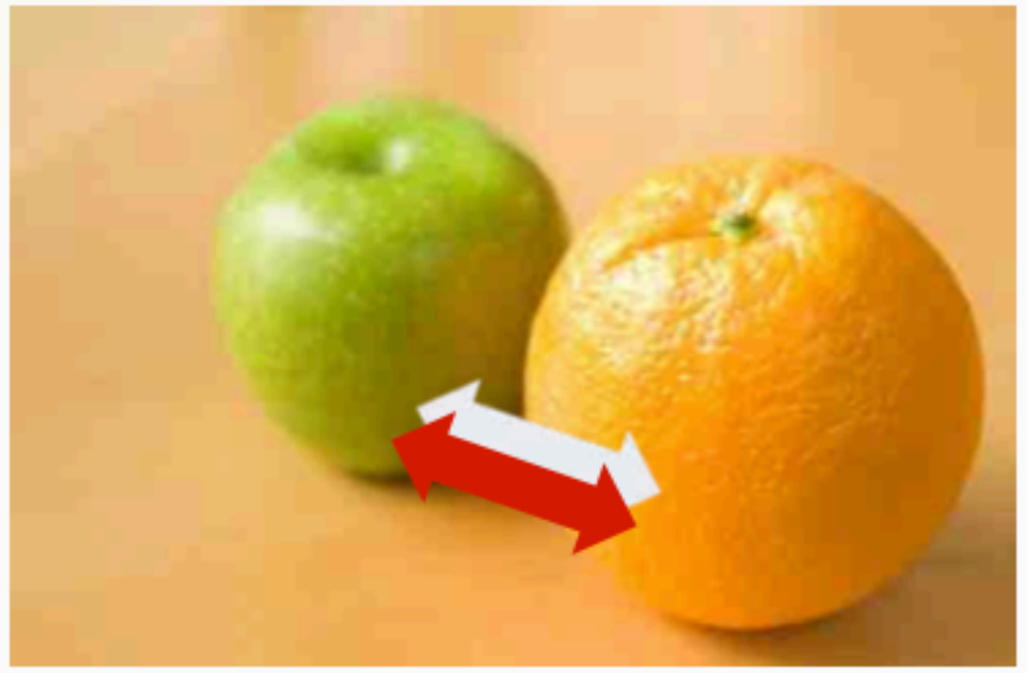
266

For canonical (isospin conserving) SI scattering



Interpretation of the DAMA Result

R. Bernabei



About interpretation

See e.g.: Riv.N.Cim.26 n.1(2003)1, IJMPD13(2004)2127, EPJC47(2006)263, IJMPA21(2006)1445, EPJC56(2008)333, PRD84(2011)055014, IJMPA28(2013)1330022

...models...

- Which particle?
- Which interaction coupling?
- Which Form Factors for each target-material?
- Which Spin Factor?
- Which nuclear model framework?
- Which scaling law?
- Which halo model, profile and related parameters?
- Streams?
- ...

...and experimental aspects...

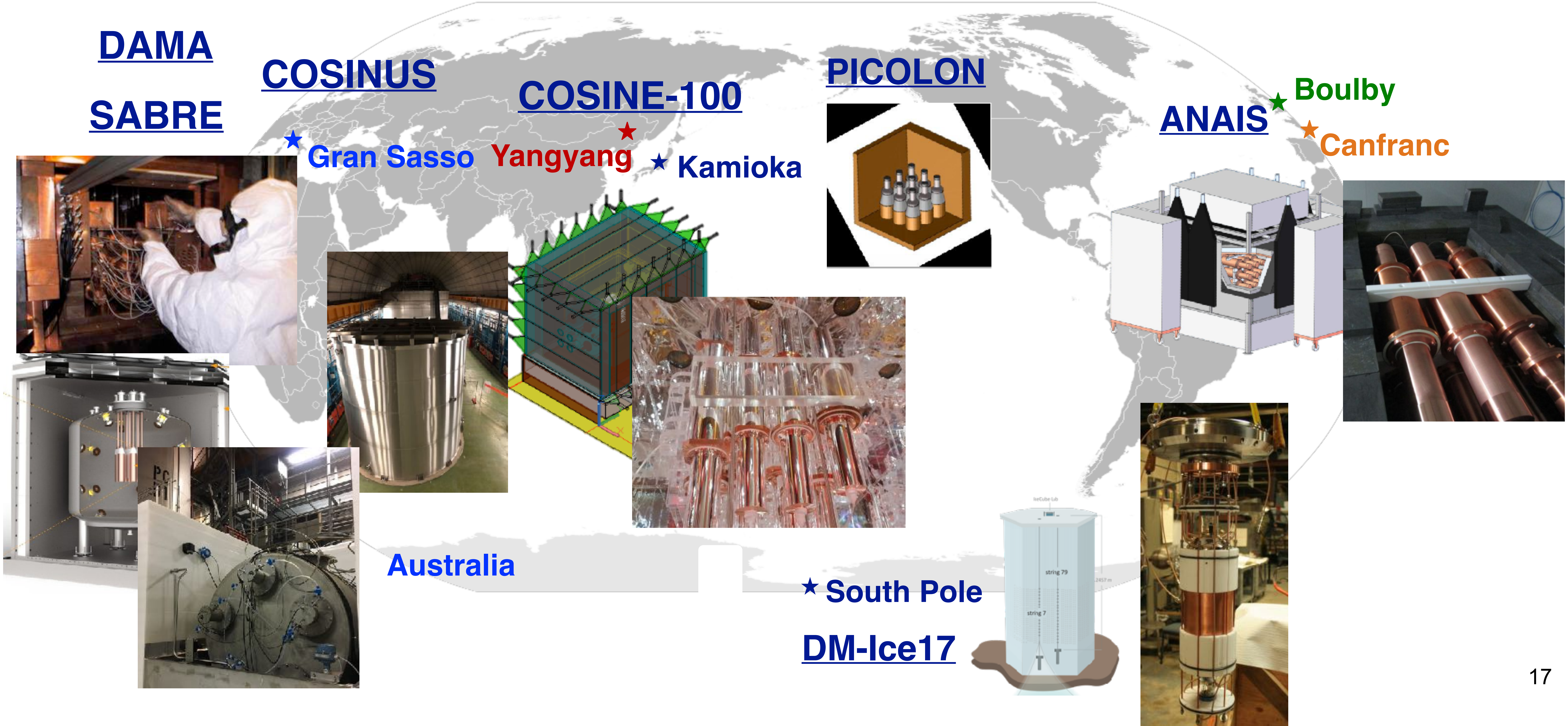
- Exposures
- Energy threshold
- Detector response (phe/keV)
- Energy scale and energy resolution
- Calibrations
- Stability of all the operating conditions.
- Selections of detectors and of data.
- Subtraction/rejection procedures and stability in time of all the selected windows and related quantities
- Efficiencies
- Definition of fiducial volume and non-uniformity
- Quenching factors, channeling, ...
- ...

Uncertainty in experimental parameters, as well as necessary assumptions on various related astrophysical, nuclear and particle-physics aspects, affect all the results at various extent, both in terms of exclusion plots and in terms of allowed regions/volumes. Thus comparisons with a fixed set of assumptions and parameters' values are intrinsically strongly uncertain.

No experiment can be directly compared in model independent way with DAMA

P. Belli, IDM2016

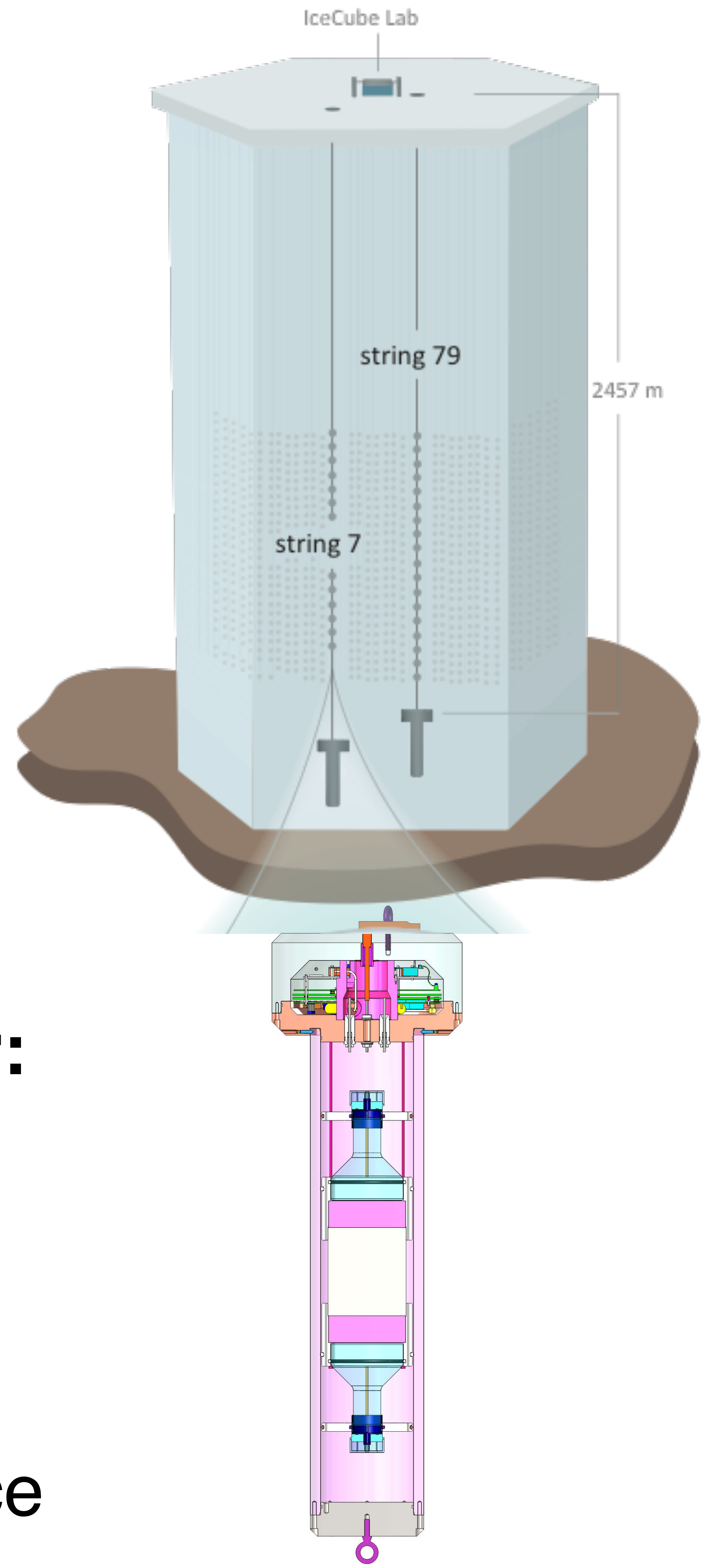
NaI Experiments: a Global Effort



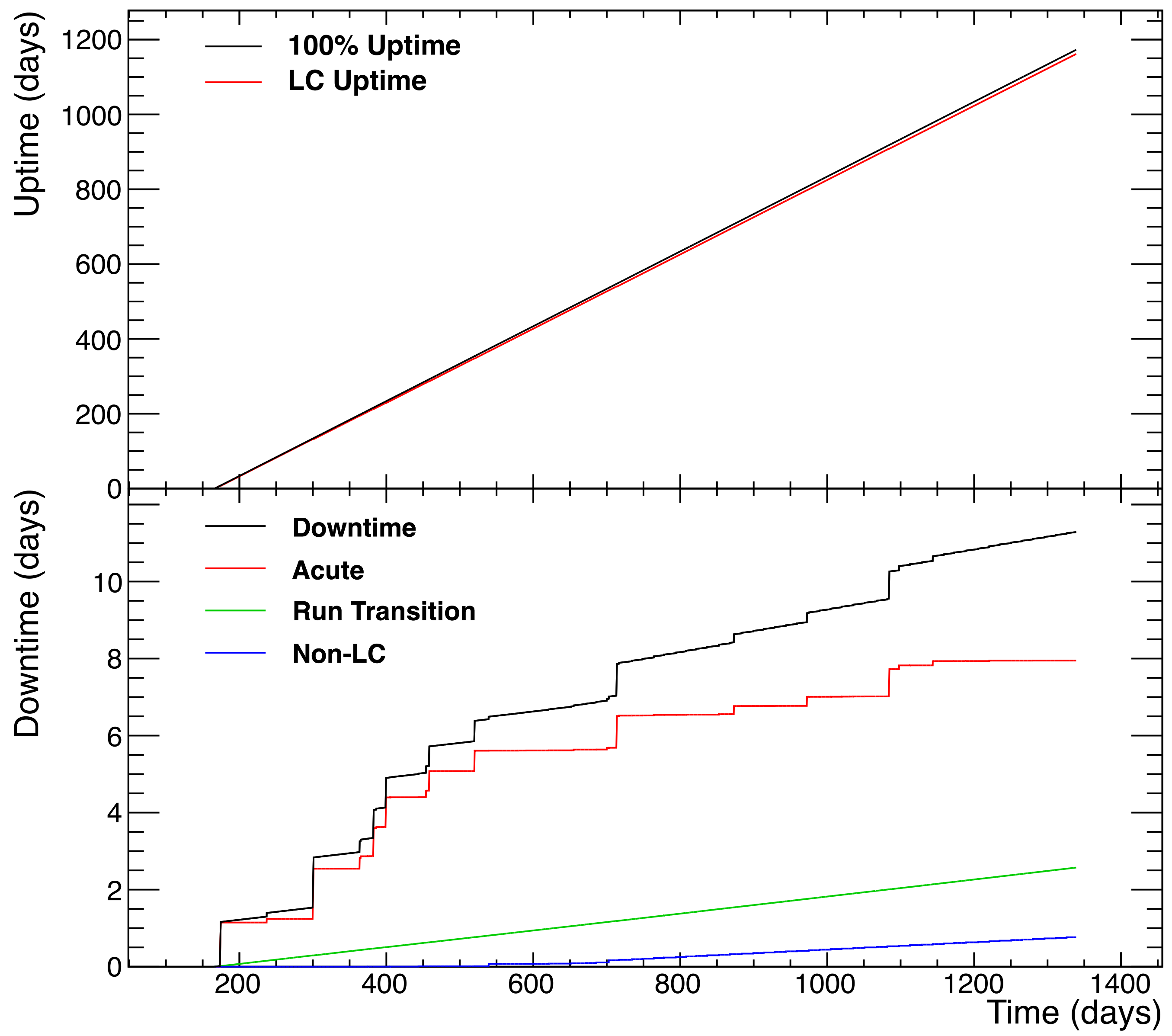

IceCube Lab
SPT/BICEP-II
IceTop
DM-Ice17 + IceCube Below
DM-Ice17

DM-Ice17

- 17 kg, NaI(Tl)
- Deployed December 2010
- 2200 m.w.e. overburden
- >99% uptime
- 3.5 years physics data



Phys. Rev. D 90, 092005 (2014)



Demonstrator for:

- Feasibility
- Environmental Stability
- Radiopurity of ice

DM-Ice-17 Construction & Deployment

Design begin Feb. 2010

Revive NAIAD xtals

July 2010

Detector assembly

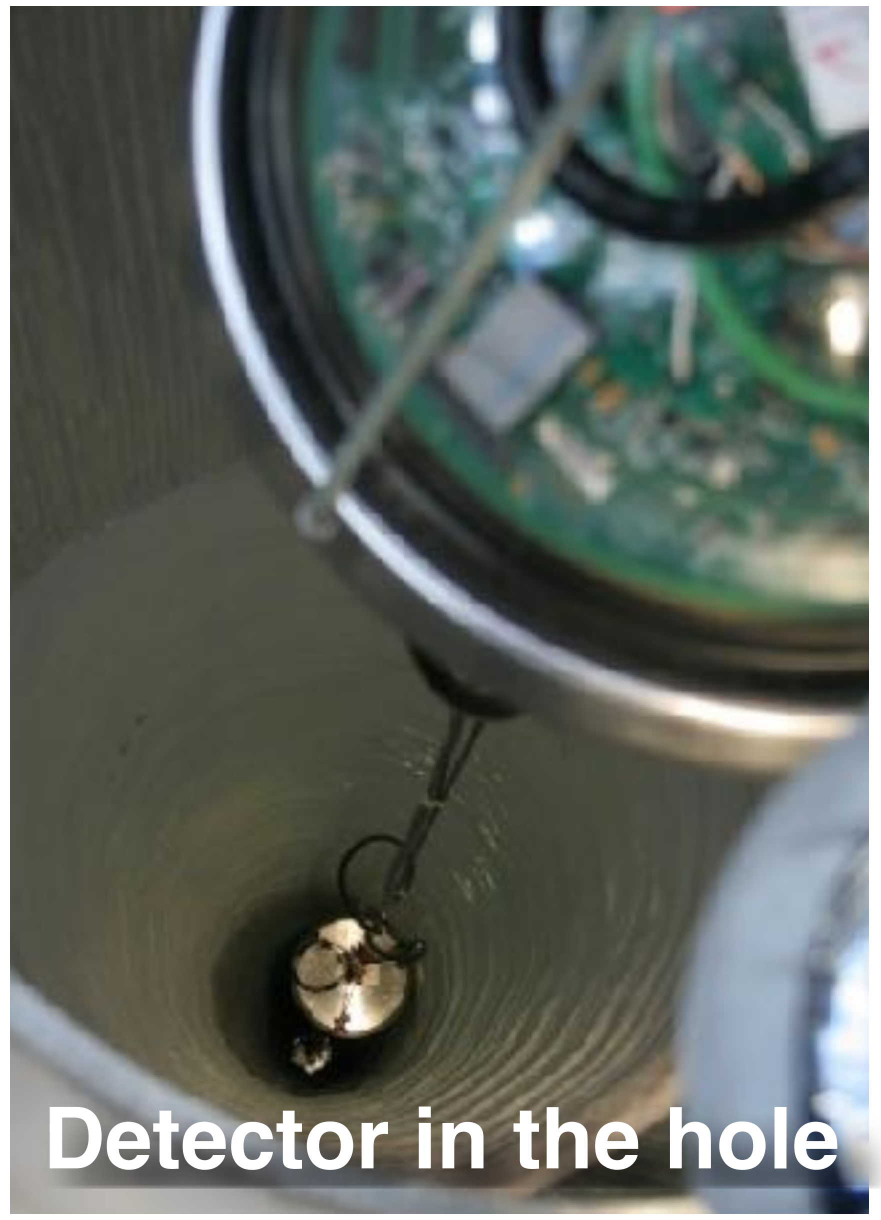
Sep - Oct. 2010

Shipment to Antarctica

Dec. 1, 2010

Deployment

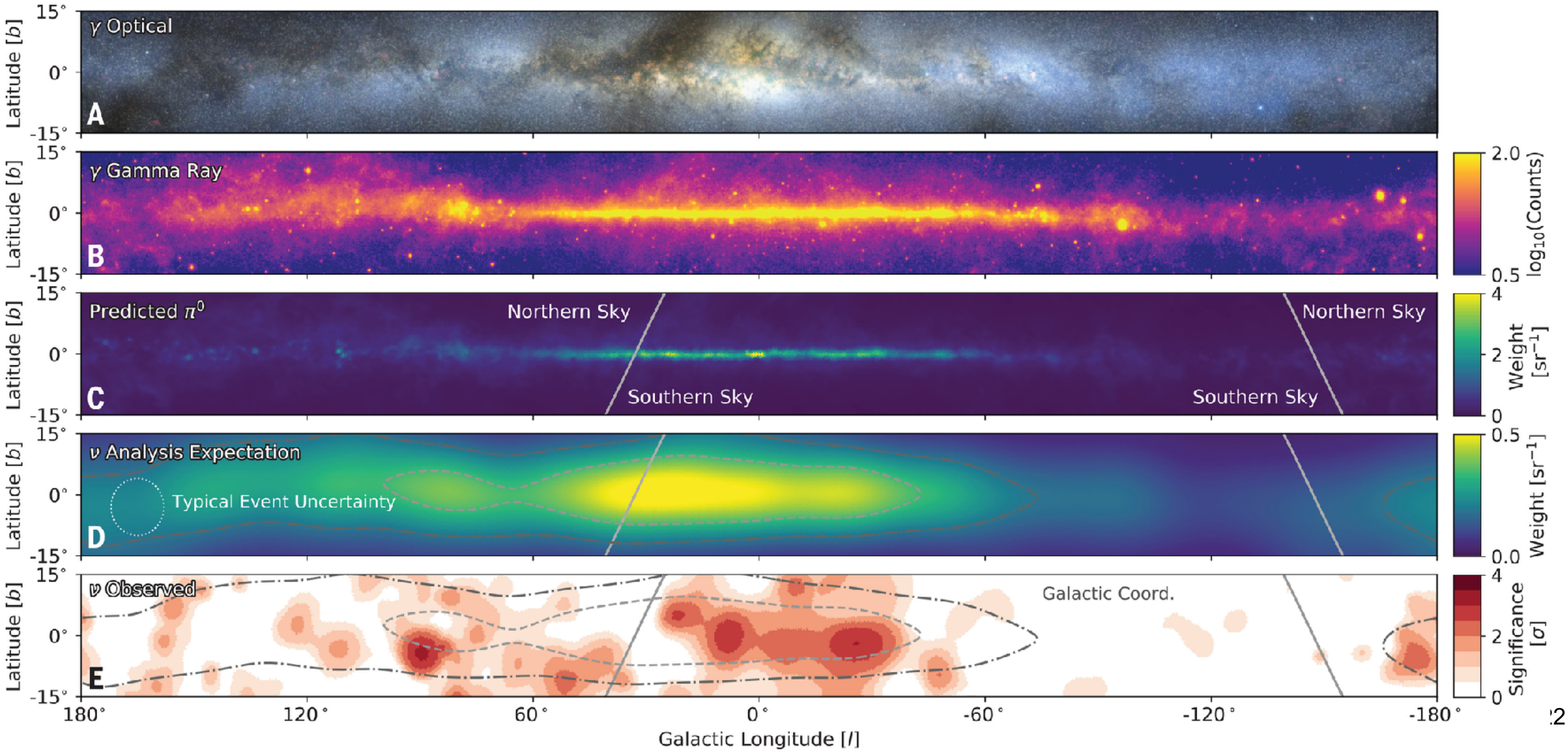
Dec. 11, 2010



Detector in the hole

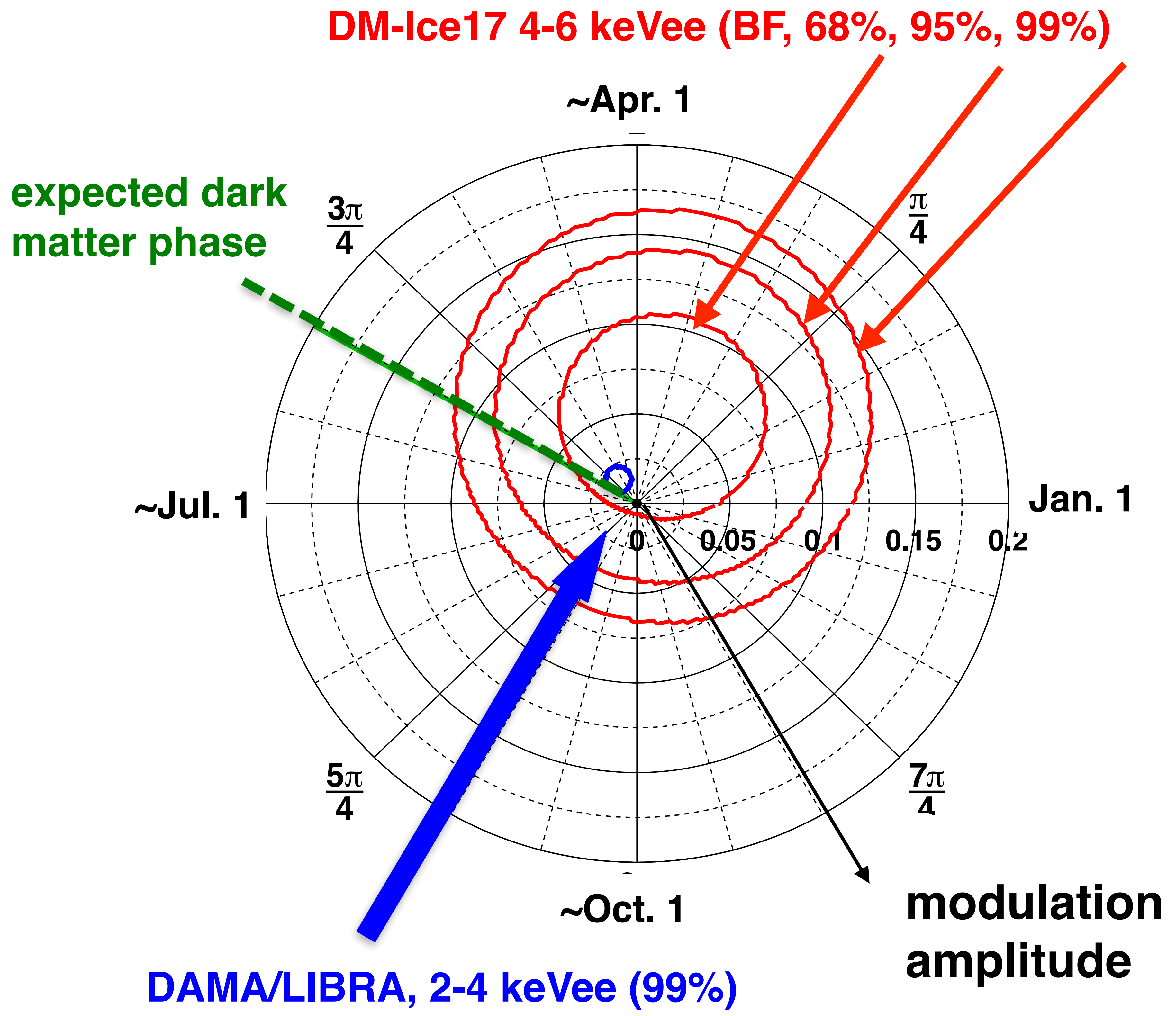
IceCube Detector Completion
December 2010

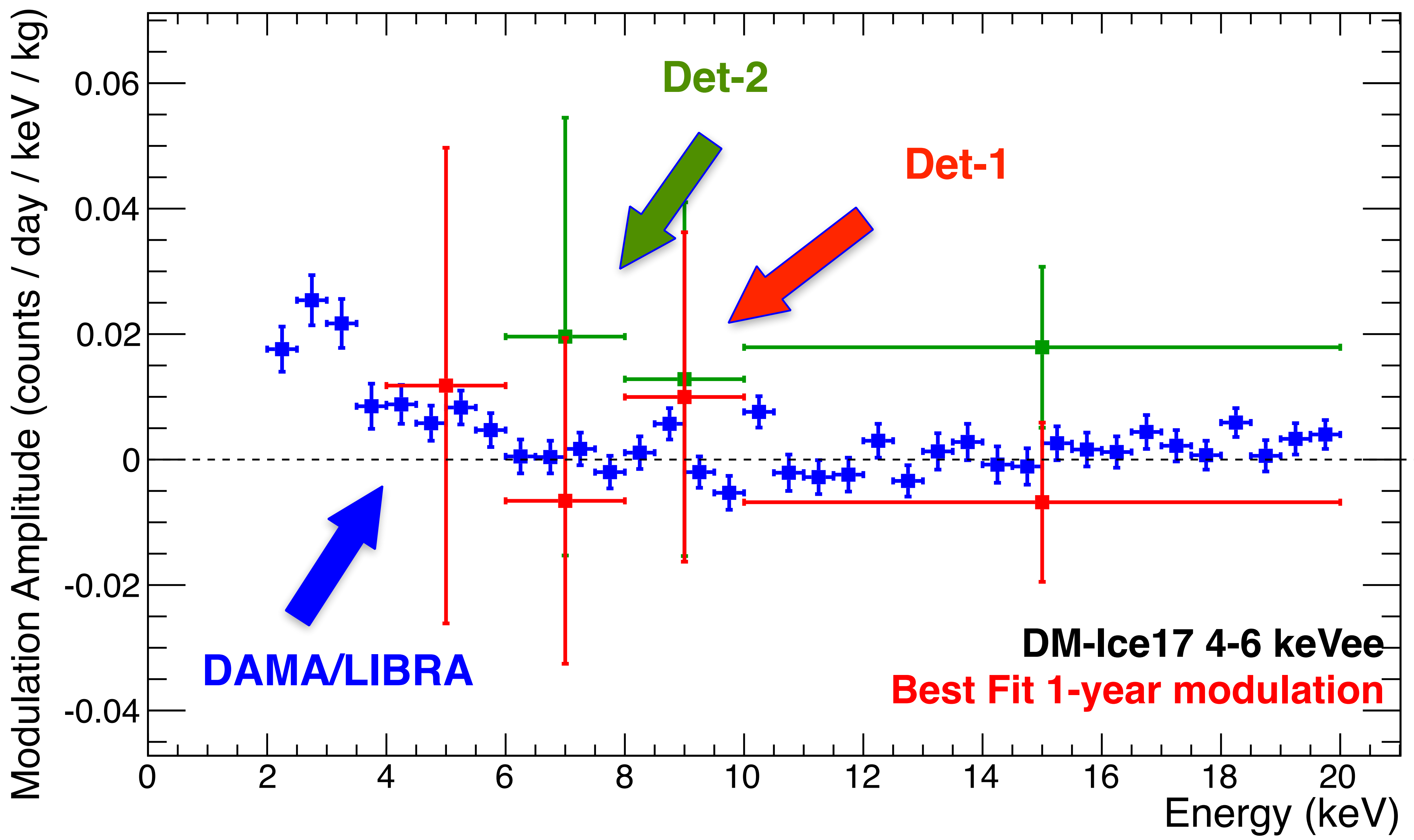
IceCube & neutrinos of Milky Way

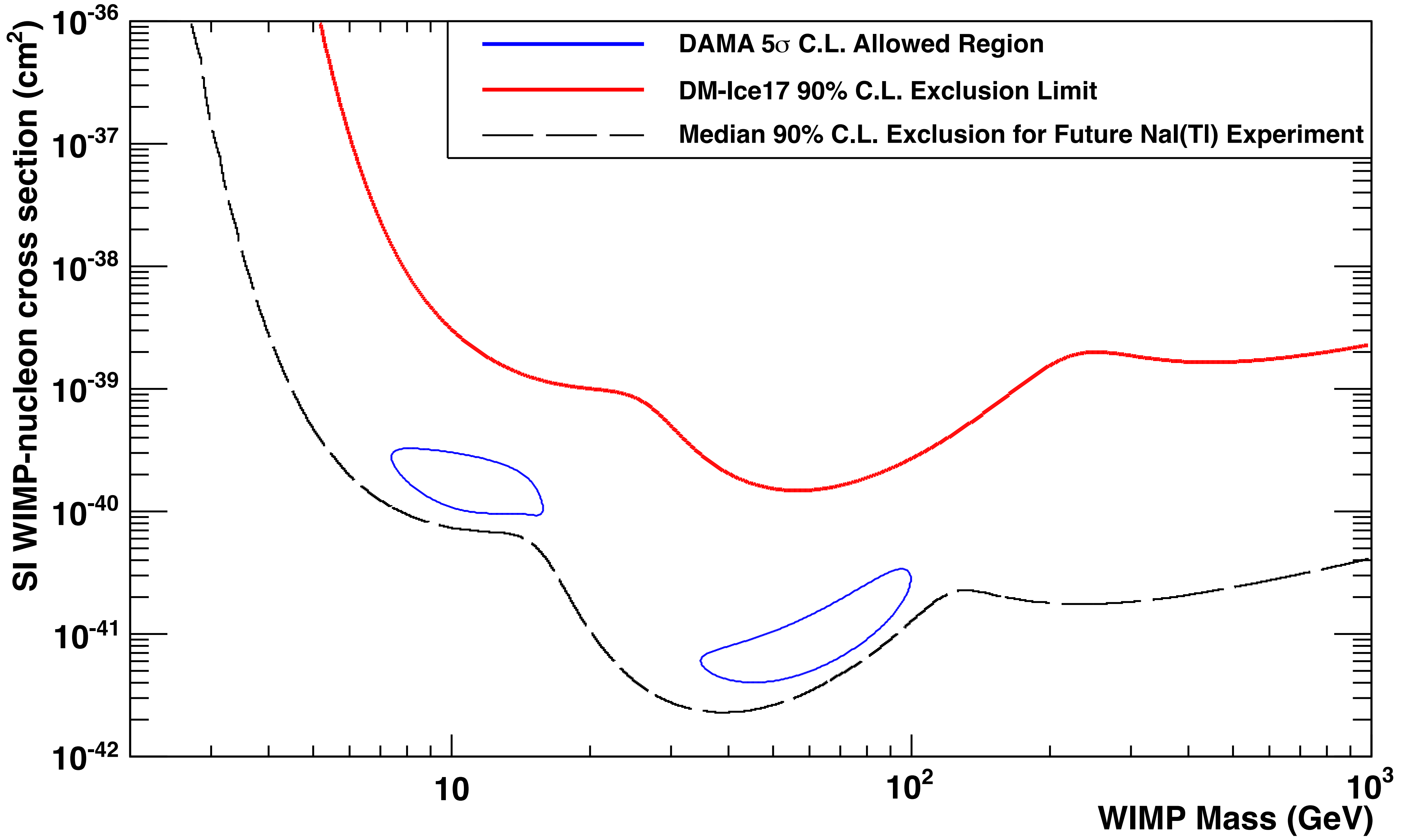


http://dm-ice.yale.edu
PRD **90** 092005 (2014
PRD **93** 042001 (2016
PRD **95** 032006 (2017

DM-Ice17 Results





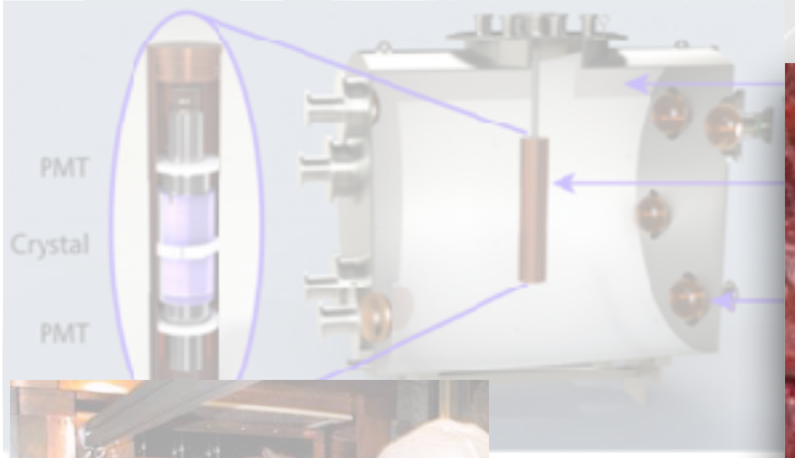


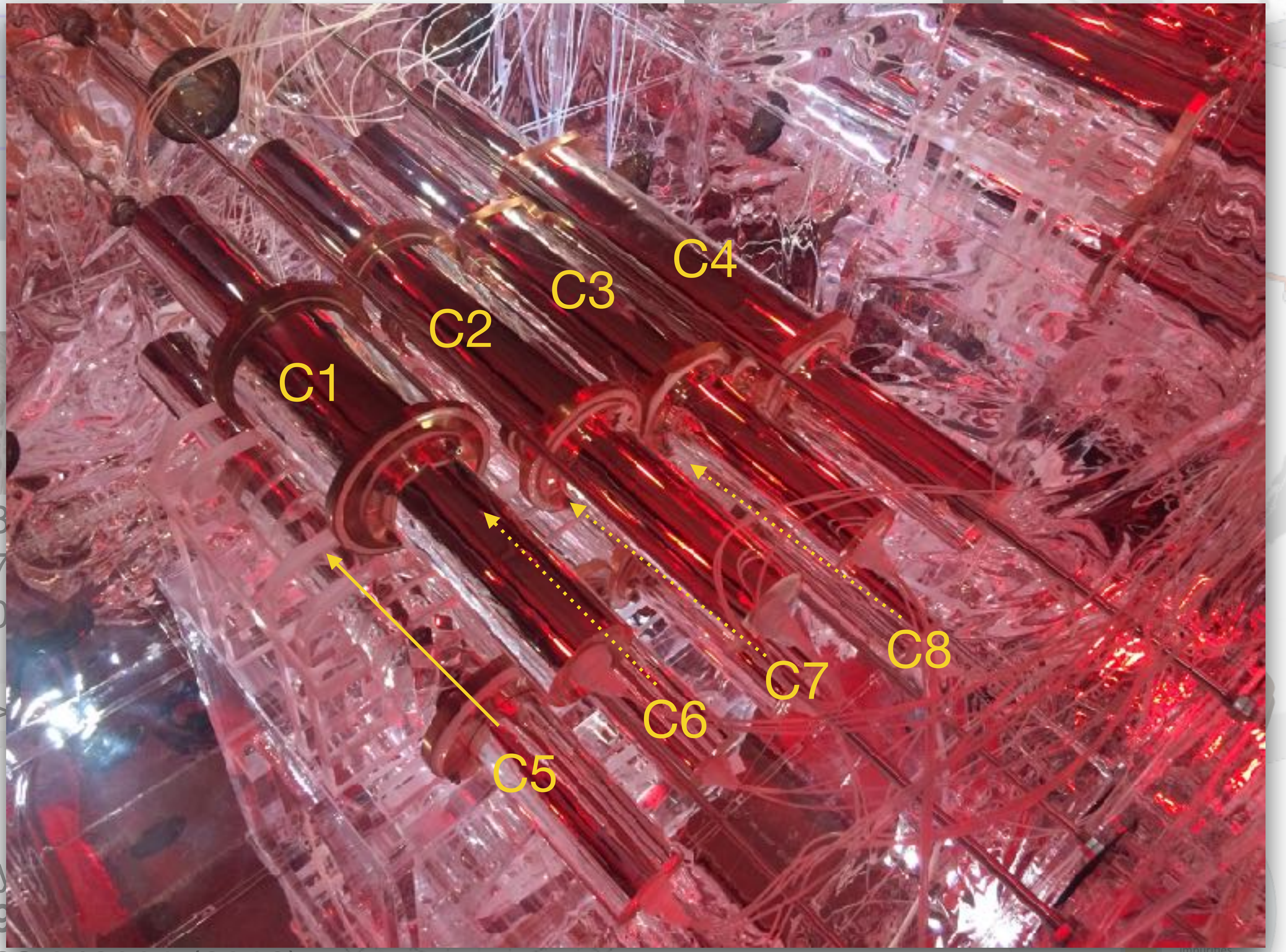
- Proof of principle
- Southern Hemisphere operations

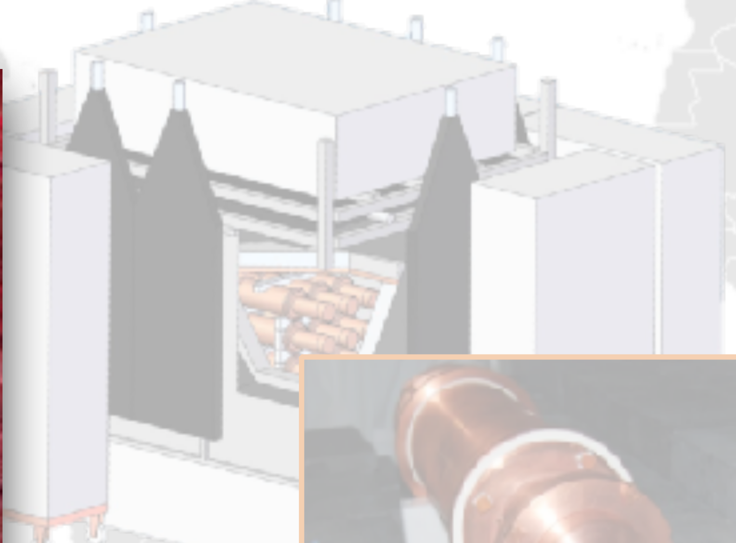
NaI(Tl) Ex

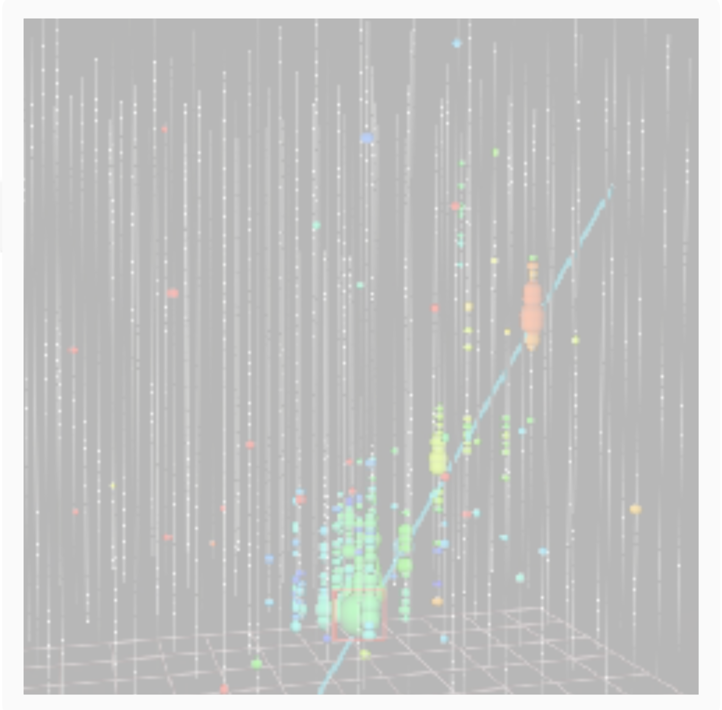
COSINE-100

DAMA
SABRE
COSINUS
★ Gran Sasso + Australia
COSINE-100
★ Yangyang
★ Kamioka
PICOLON
ANAIS
★ Boulby
★ Canfranc









Eur.Phys.J. C **78** 107 (2018
Eur.Phys.J. C **77** 437 (2017
Phys.Rev. D **90** 052006 (20
Nature **564** 83-86 (2018)
arXiv:1903.10098 (2019) ->

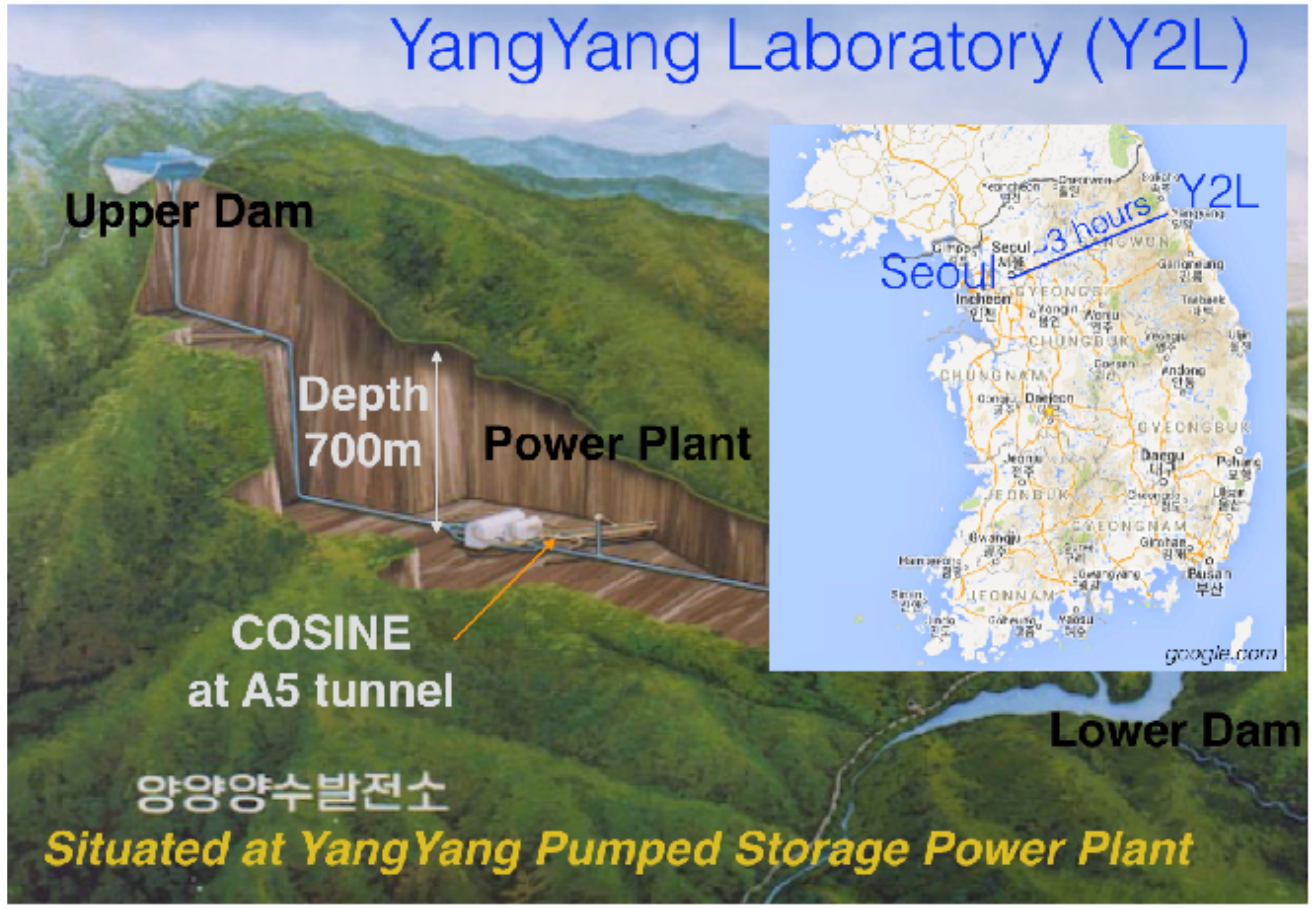
Astropart. Phy
Phys. Rev. D 9
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

http://cosine.yale.edu

COSINE-100

KIMS + DM-ICE

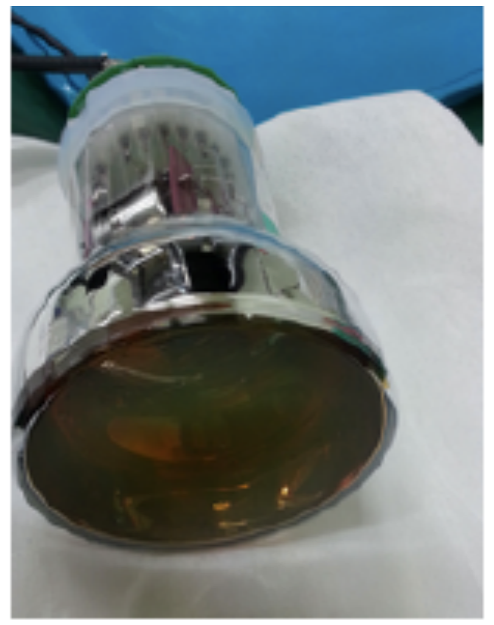
- 107 kg of NaI(Tl) detectors, former DM-Ice and KIMS collaborations
- Taking data since September 2016.
  - Joint effort between KIMS & DM-Ice
  - 8 NaI(Tl) crystals with 106 kg in total
  - Located at Yangyang Underground Laboratory (Y2L), South Korea
  - ~700 m rock overburden

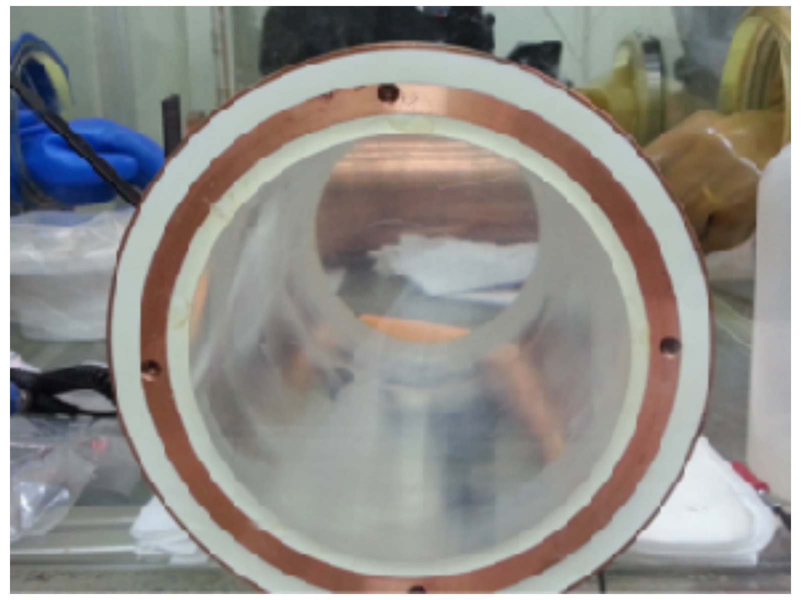


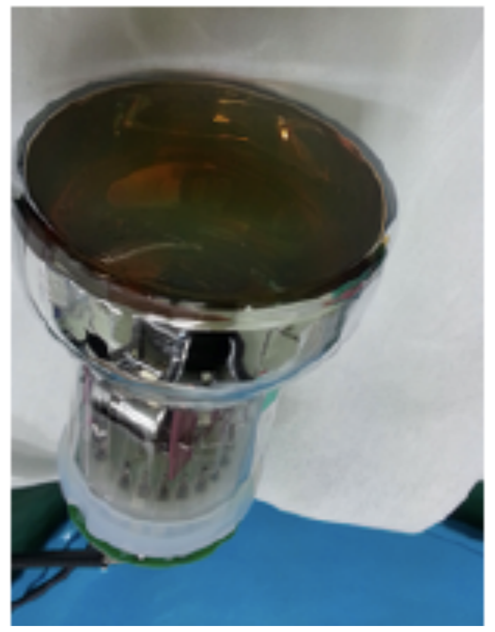
COSINE-100 NaI(Tl) Crystals

- 8 crystals, total 106 kg, result of R&D with Alpha Spectra
- U/Th/K below DAMA, ^{210}Po very close
- High Light yield
- Challenge: putting it all together
- Total Background: 2 - 4 x DAMA's avg.
- Crystal 5 & 8 used primarily for veto due to low light yield

Eur.Phys.J. C **78** 107 (2018)





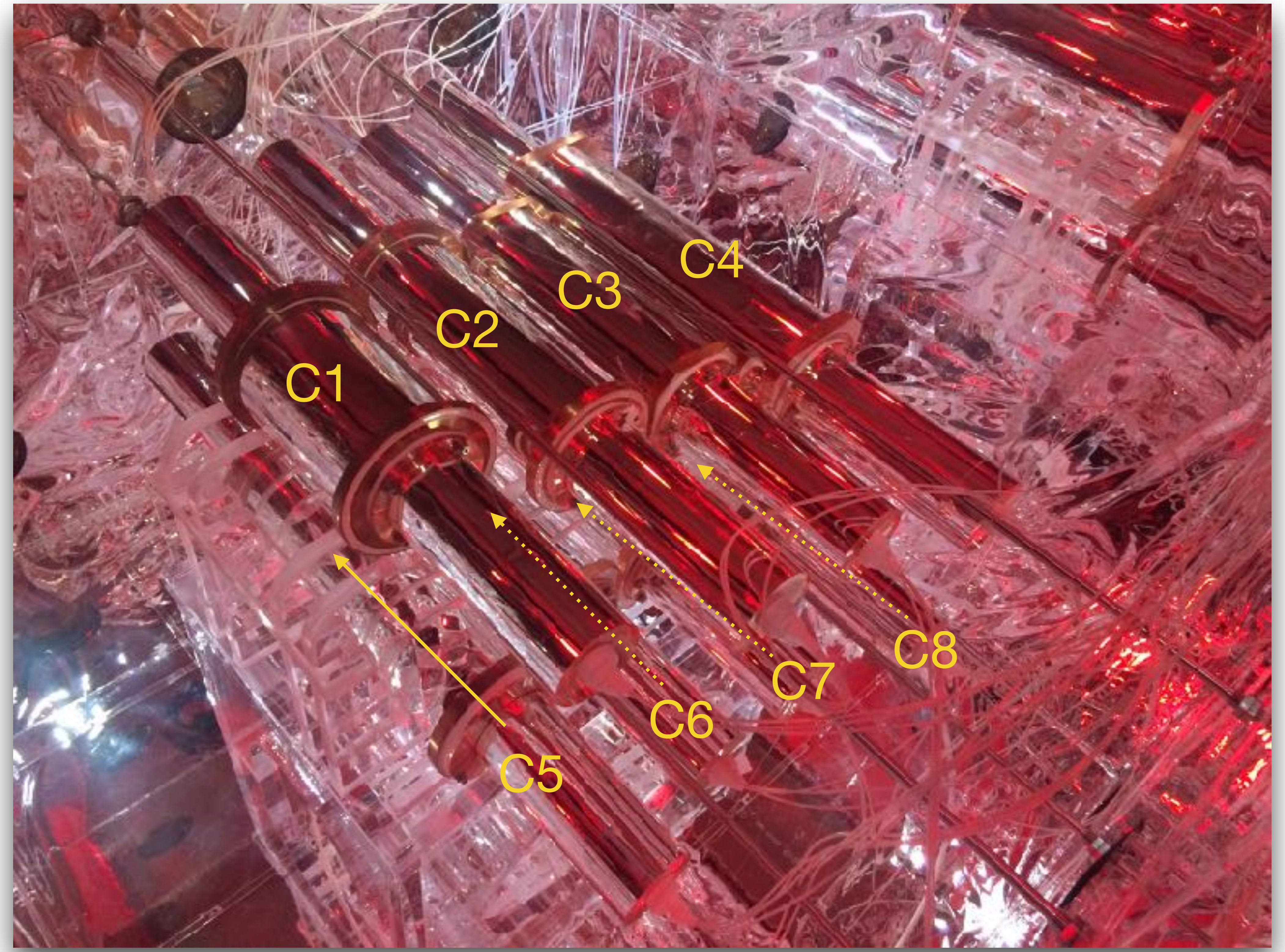


Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 0.04	0.44 ± 0.19	15.50 ± 1.64
Crystal 4	18.0	AS-WS II	0.74 ± 0.02	39.5 ± 8.3		< 0.3	14.86 ± 1.50
Crystal 5	18.0	AS-C	2.06 ± 0.05	86.8 ± 10.8		2.35 ± 0.31	7.33 ± 0.70
Crystal 6	12.5	AS-WS III	1.52 ± 0.04	12.2 ± 4.5	< 0.018	0.56 ± 0.19	14.56 ± 1.45
Crystal 7	12.5	AS-WS III	1.54 ± 0.04	18.8 ± 5.3		< 0.6	13.97 ± 1.41
tal 8	18.3	AS-C	2.05 ± 0.05	56.15 ± 8.1		< 1.4	3.50 ± 0.33
DAMA			< 0.5	< 20	0.7 - 10	0.5 – 7.5	5.5 – 7.5

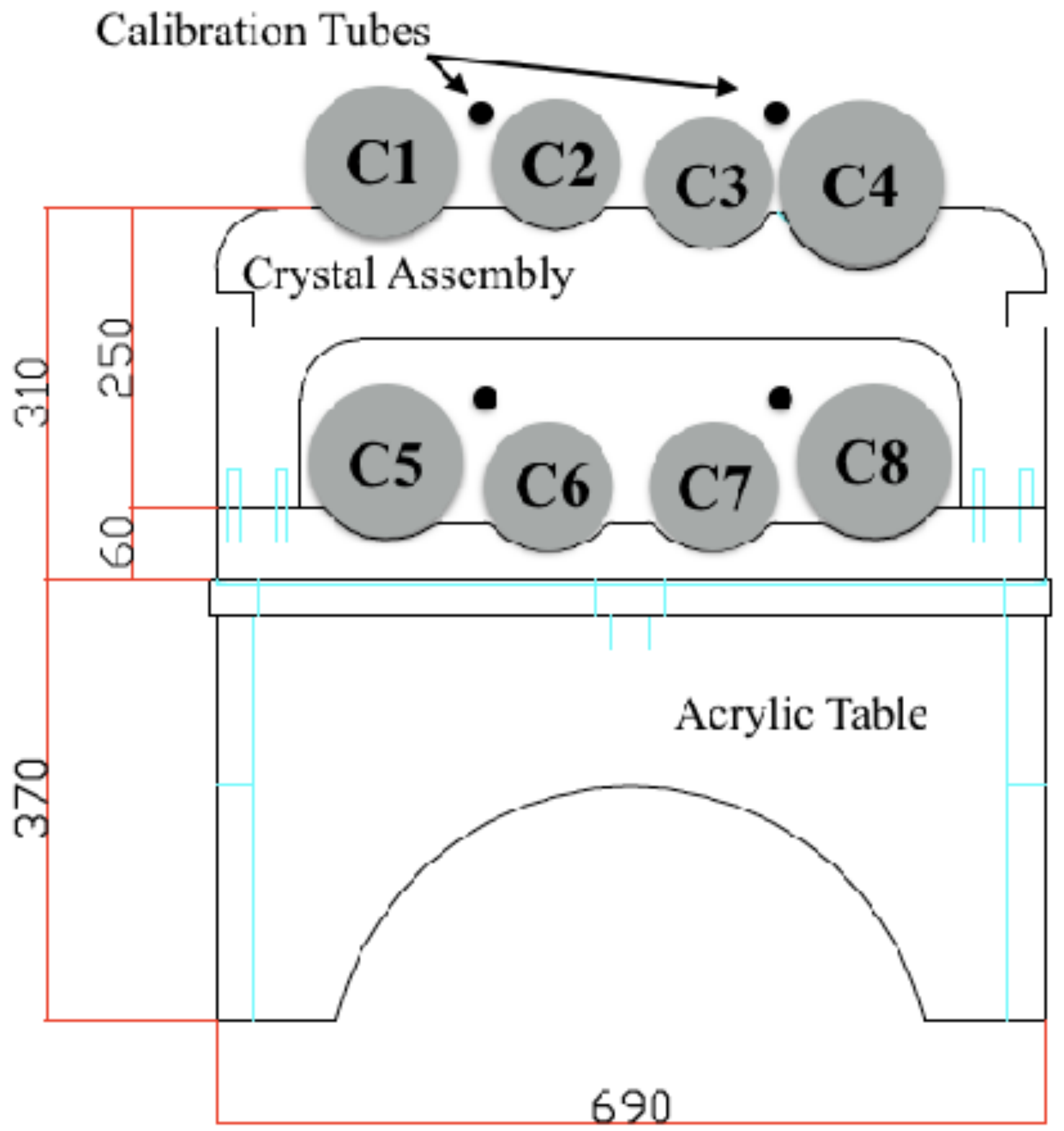
KIMS Korea Invisible Mass Search Experiment + DM-ICE

NaI(Tl) Detectors

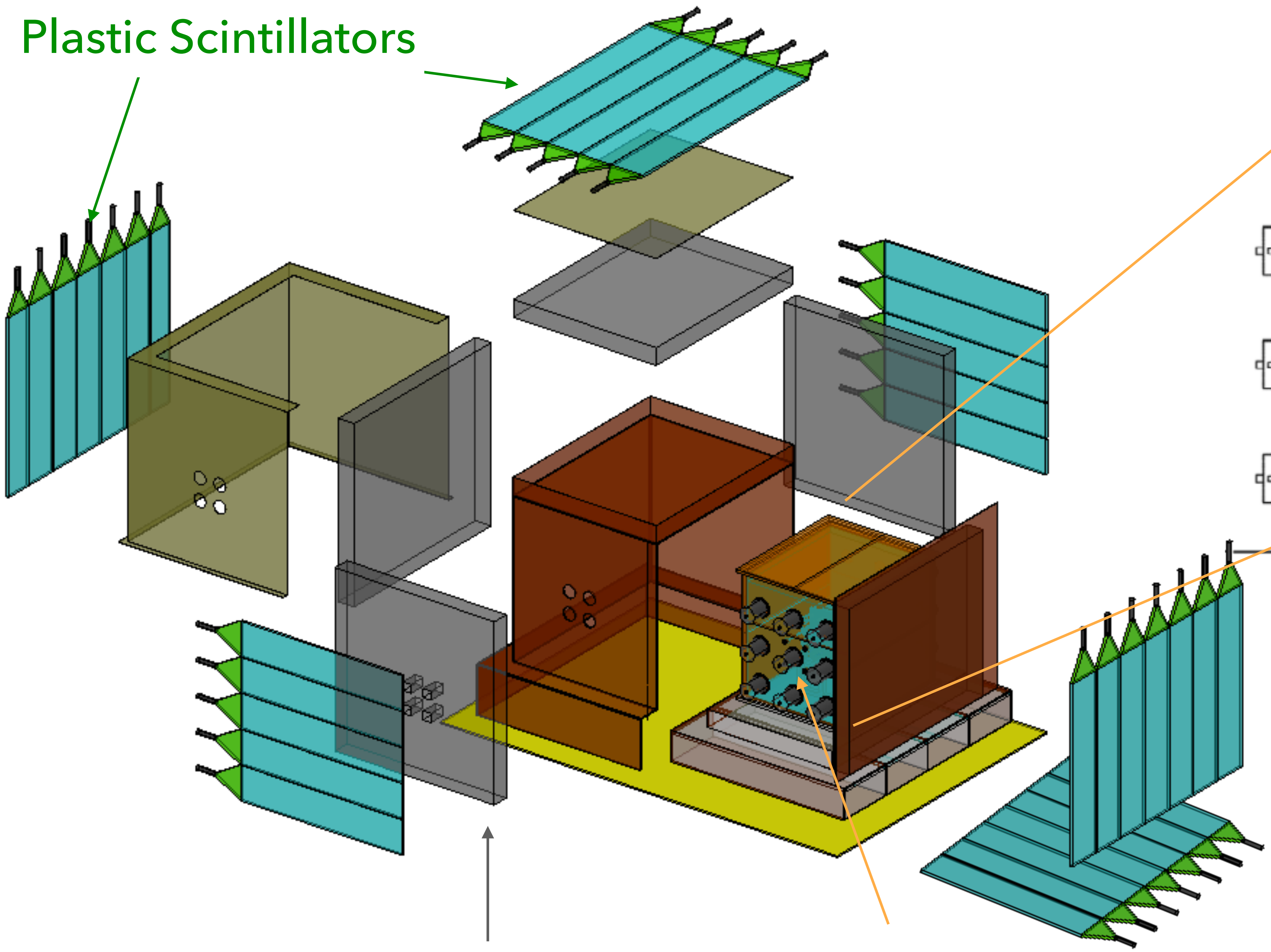
Eur.Phys.J. C **78** 107 (2018)
arXiv:1806.09788

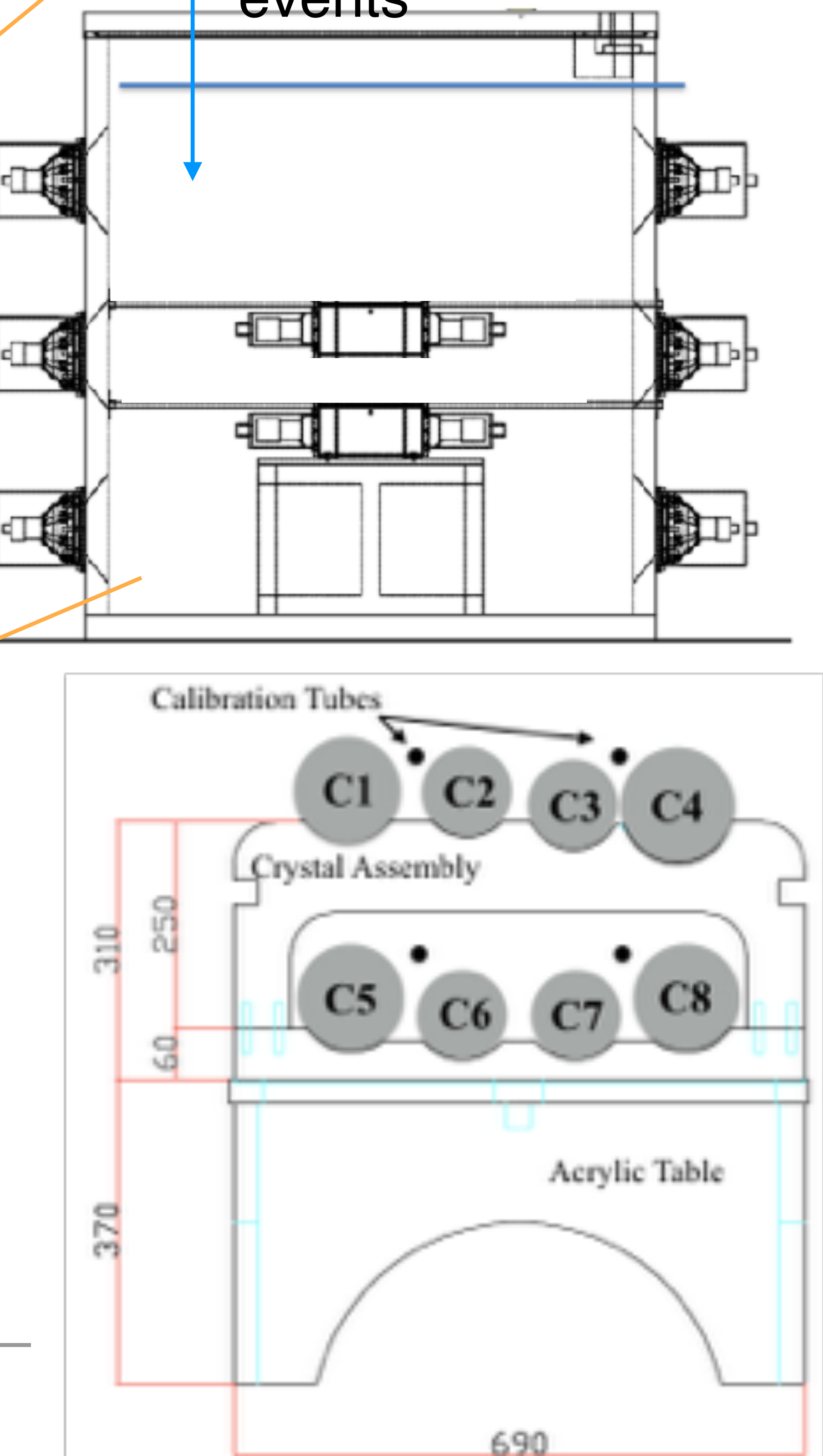


- Two PMTs coupled to each crystal
- Waveform for all crystals + liquid scintillator recorded when both PMTs cross ~0.2 p.e. threshold
- Calibration via sources through tubes

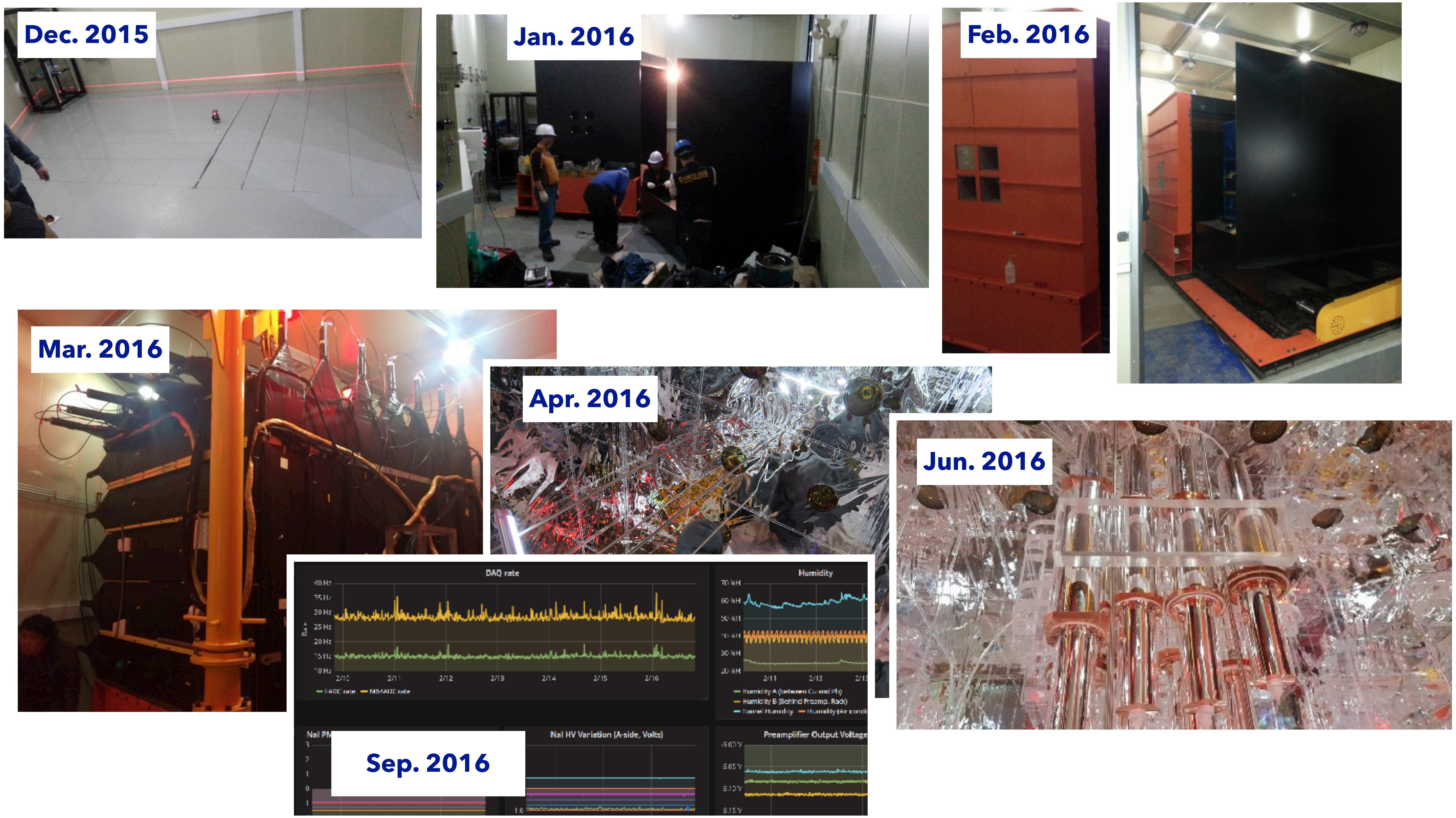


COSINE-100 Experimental Setup

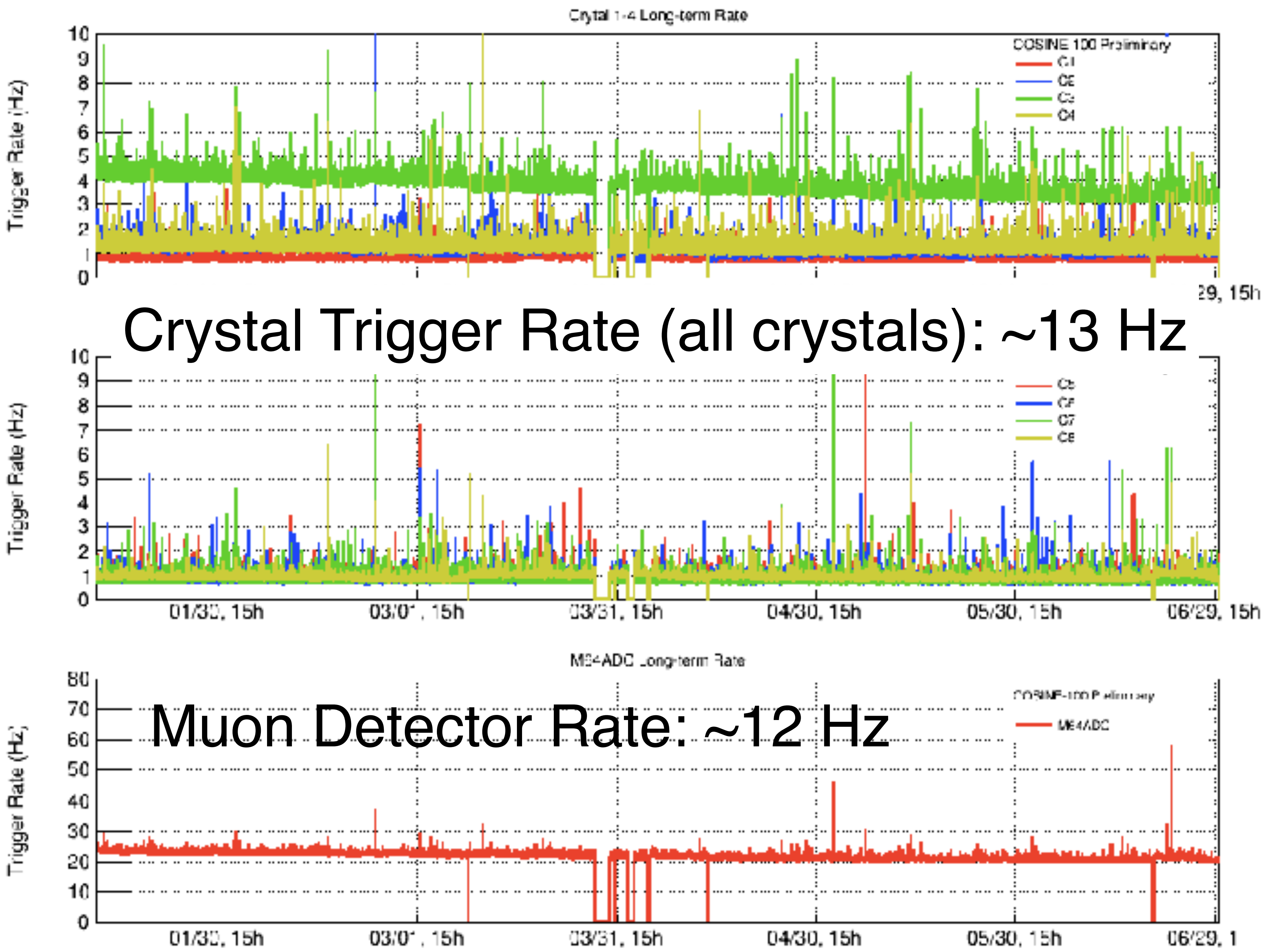




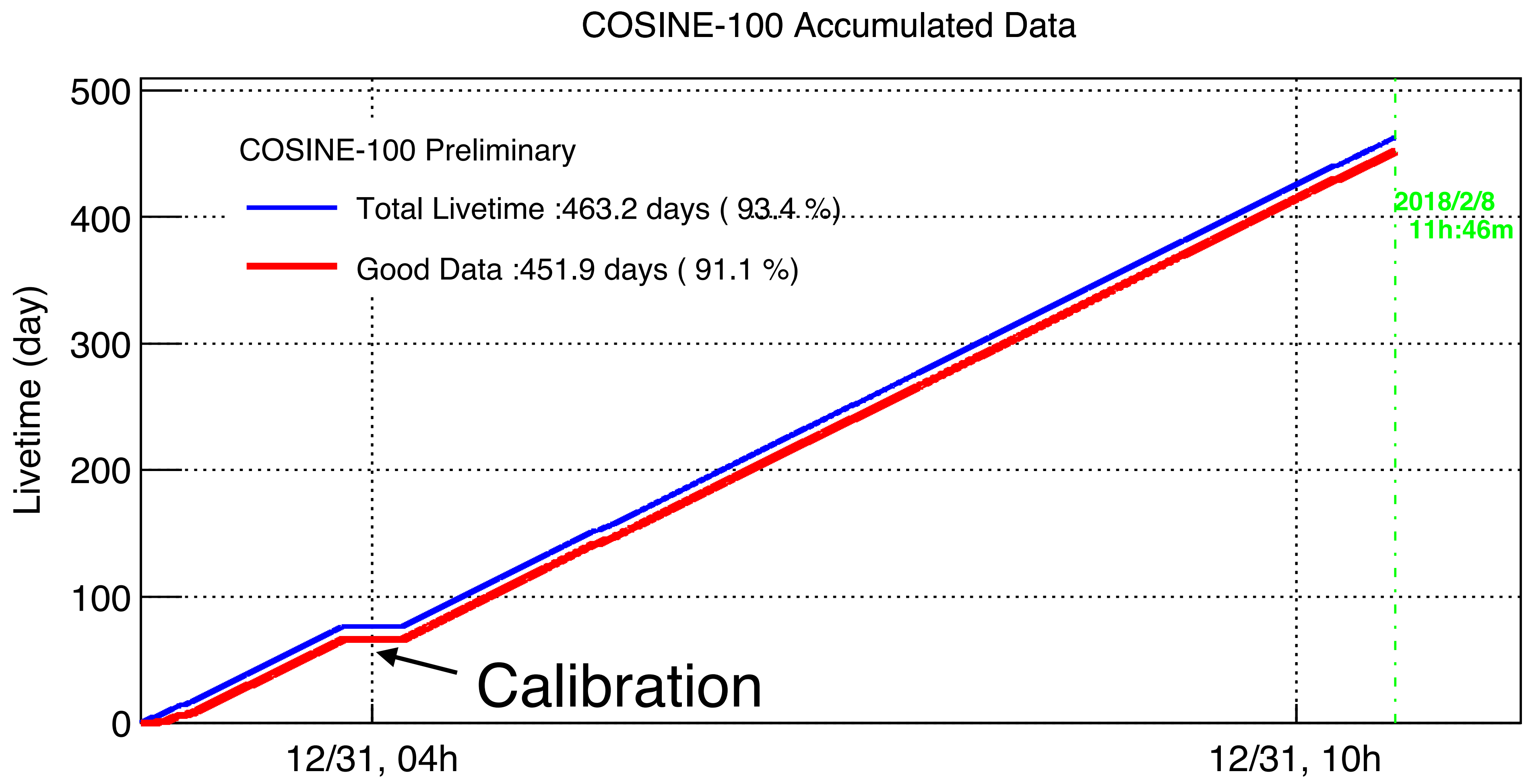
COSINE-100 Construction



COSINE-100 Operation

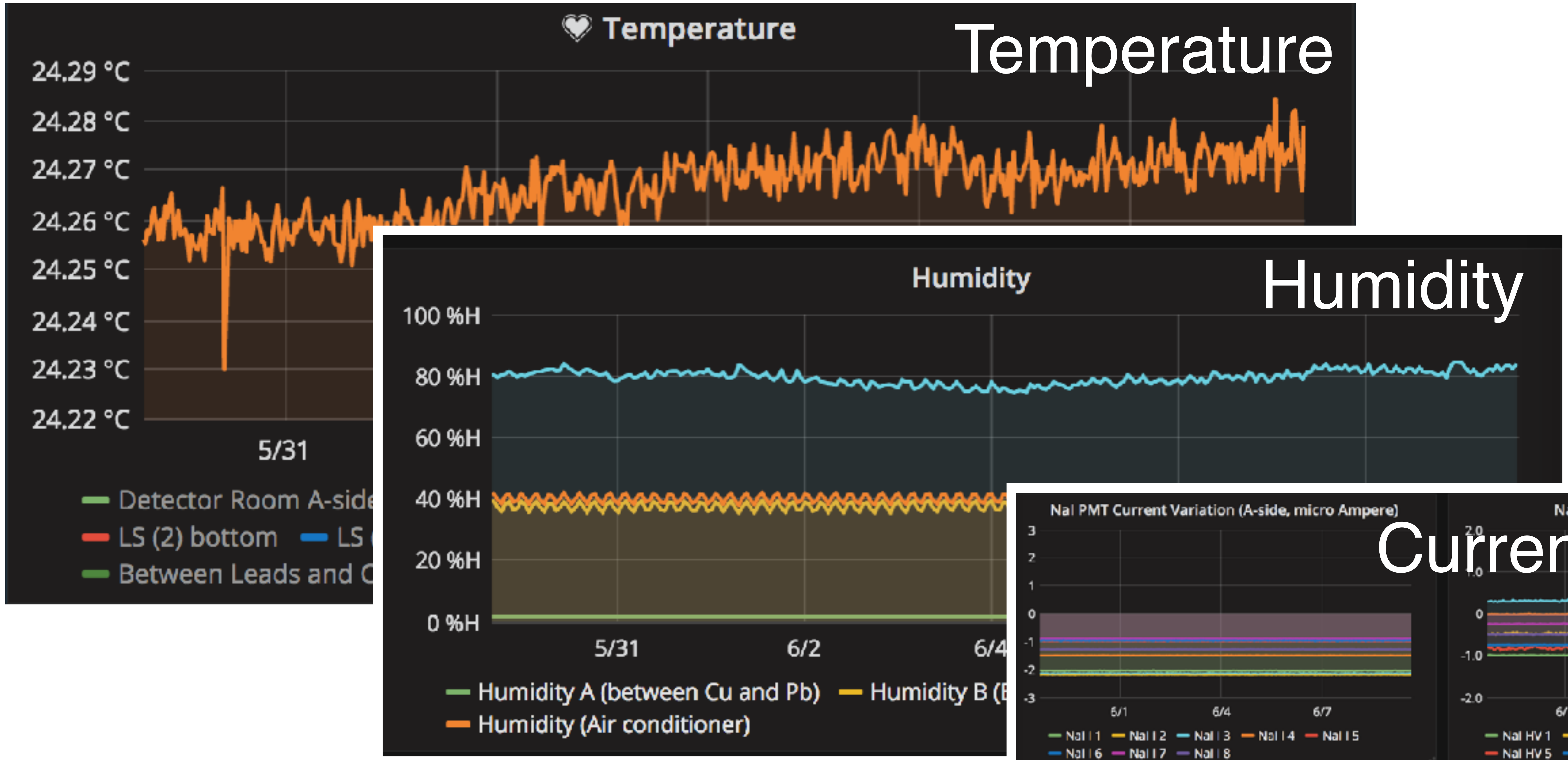


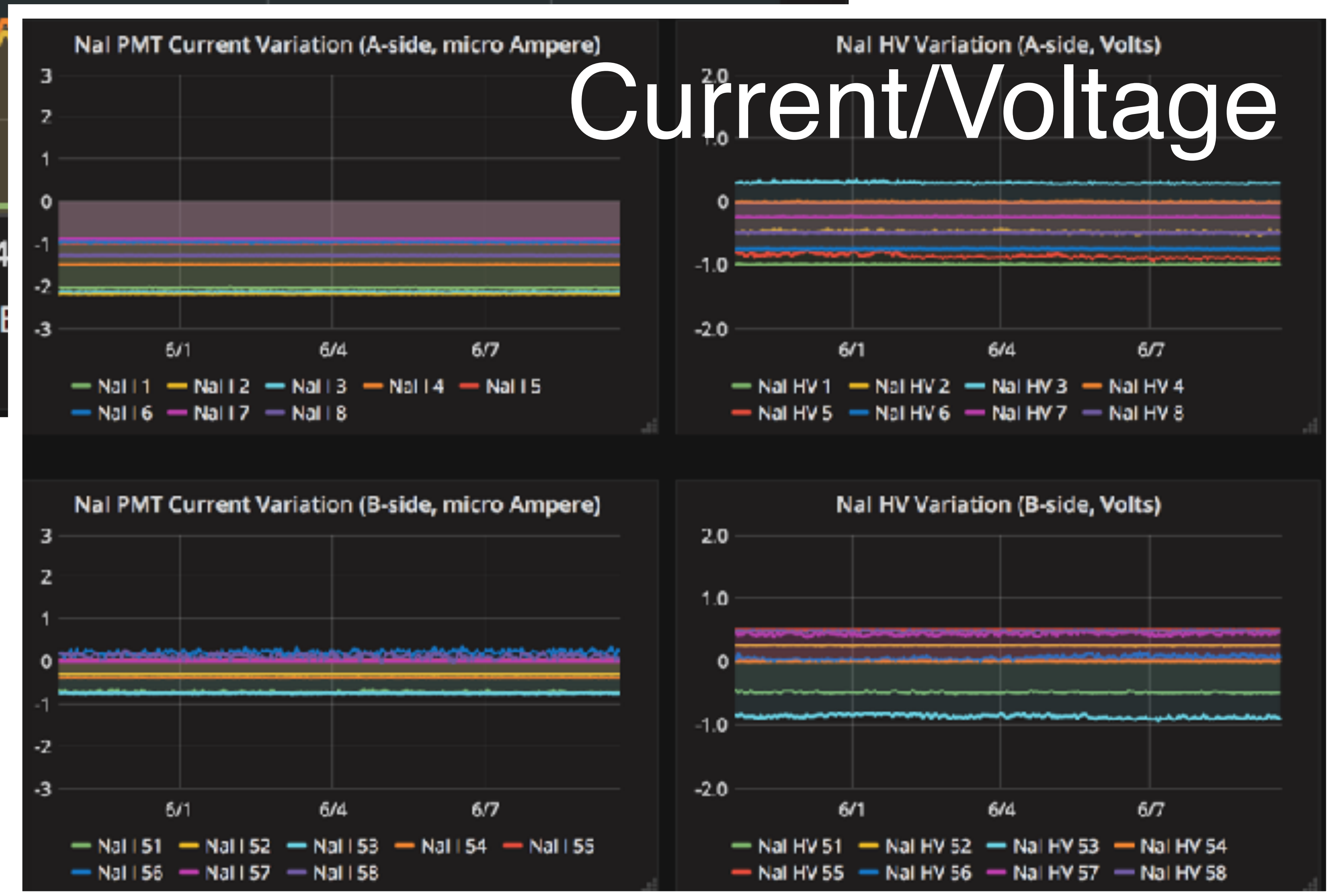
- Data taking since Sep. 2016
  - Stable operation
  - ~90% live time
  - Near 100% uptime when not calibrating
- Data taking ended in 2023, move to Yemilab



- **SET1** (59.5 days) - Background modeling, detector understanding, and WIMP analysis
- **SET2+SET3** (585 days) - Annual modulation analysis

Environmental Control & Monitoring

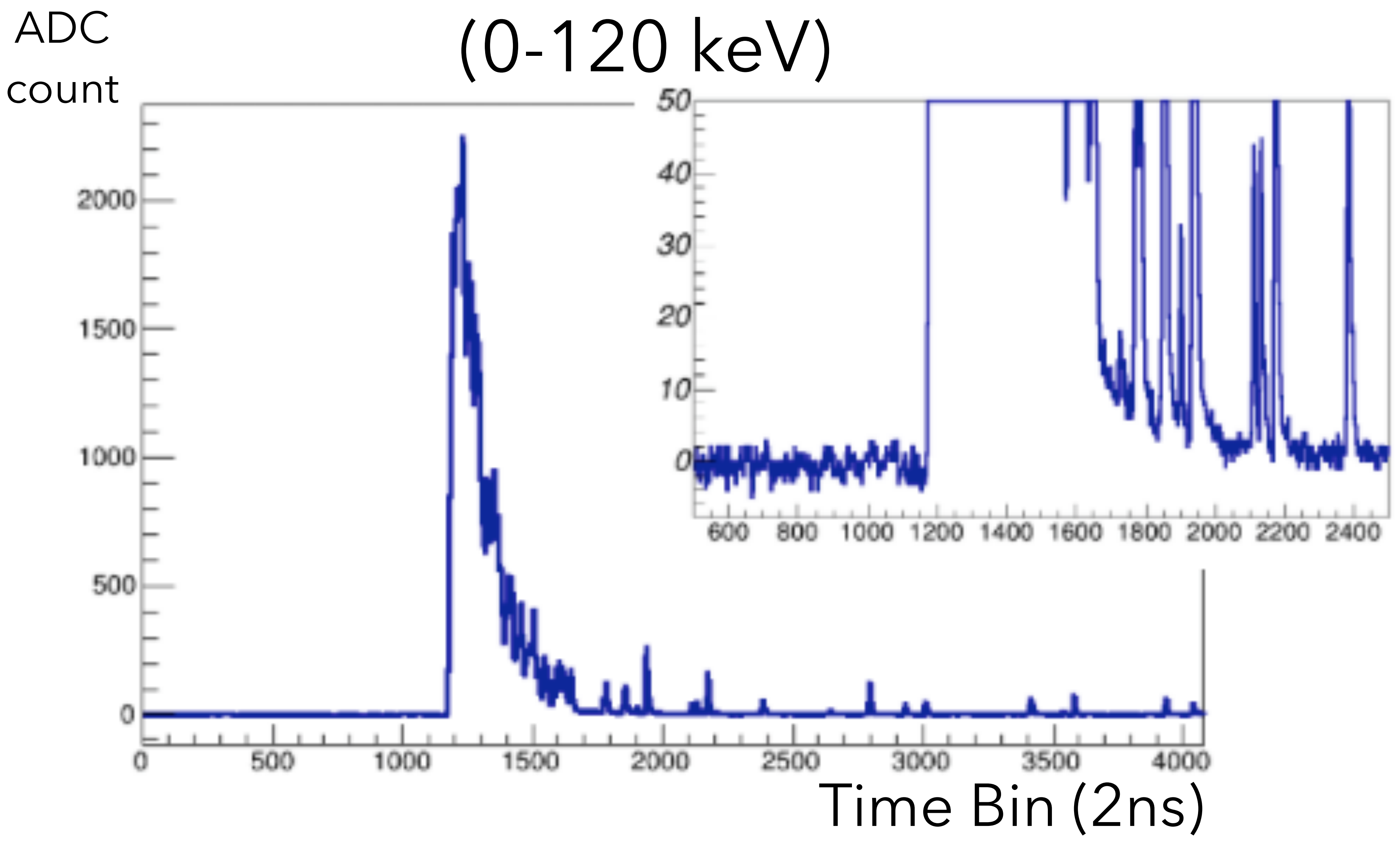




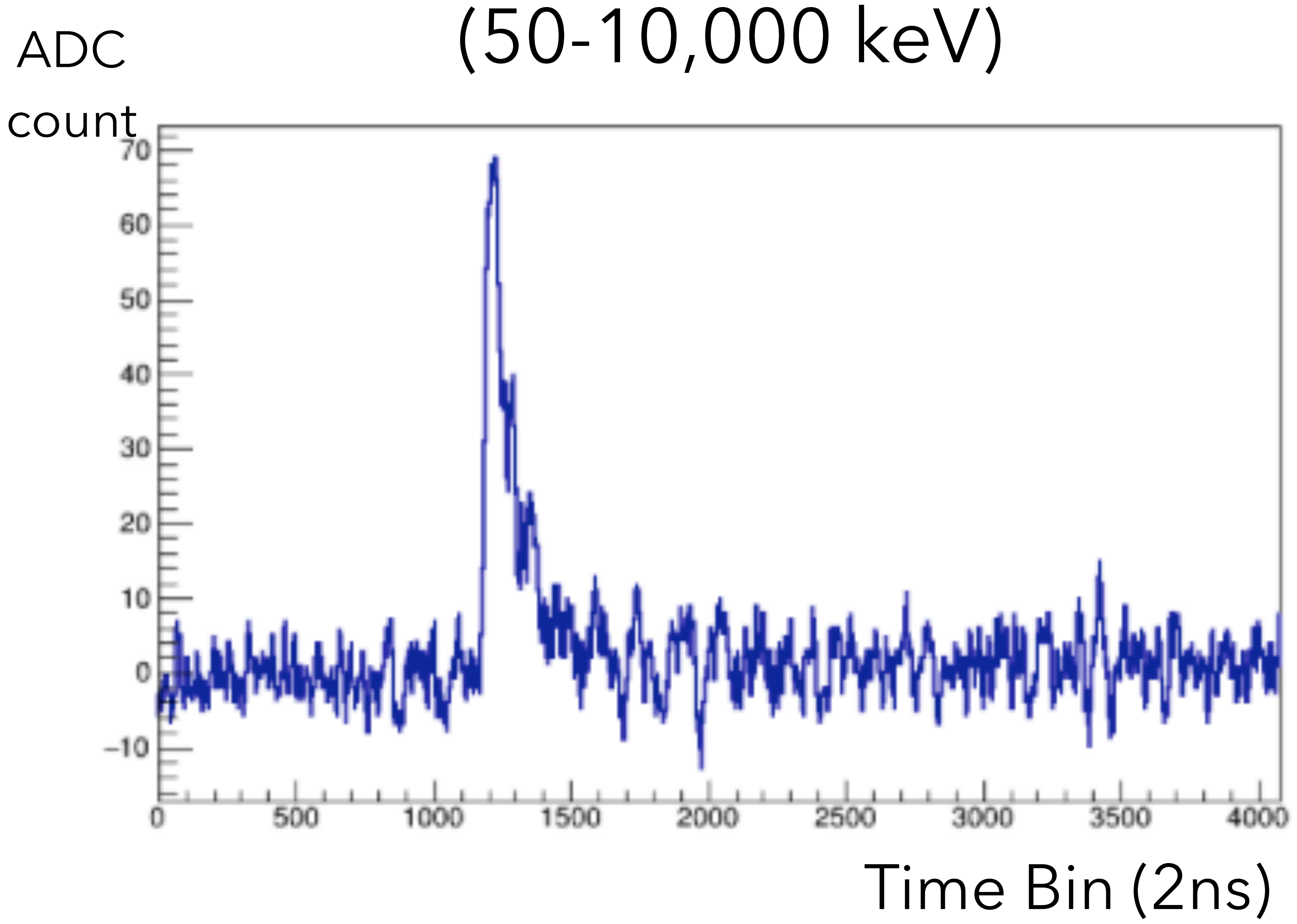
- < 0.1˚C temperature fluctuation of crystals in LS, 0.5˚C/2% humidity inside shielding
- Online monitoring of 150+ environmental variables including radon, daq rates, etc.

PMT Waveforms

Anode Waveform
(0-120 keV)

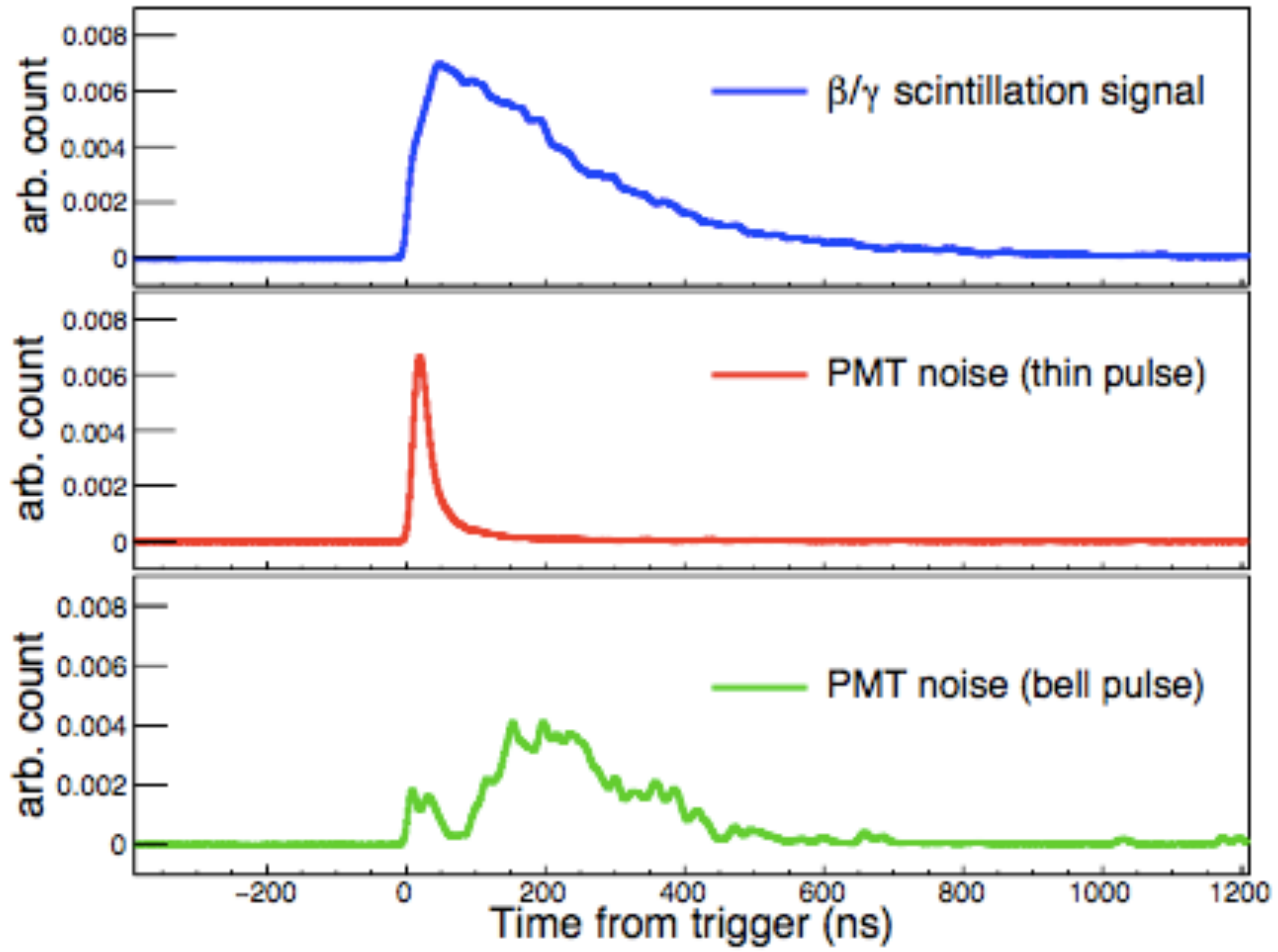


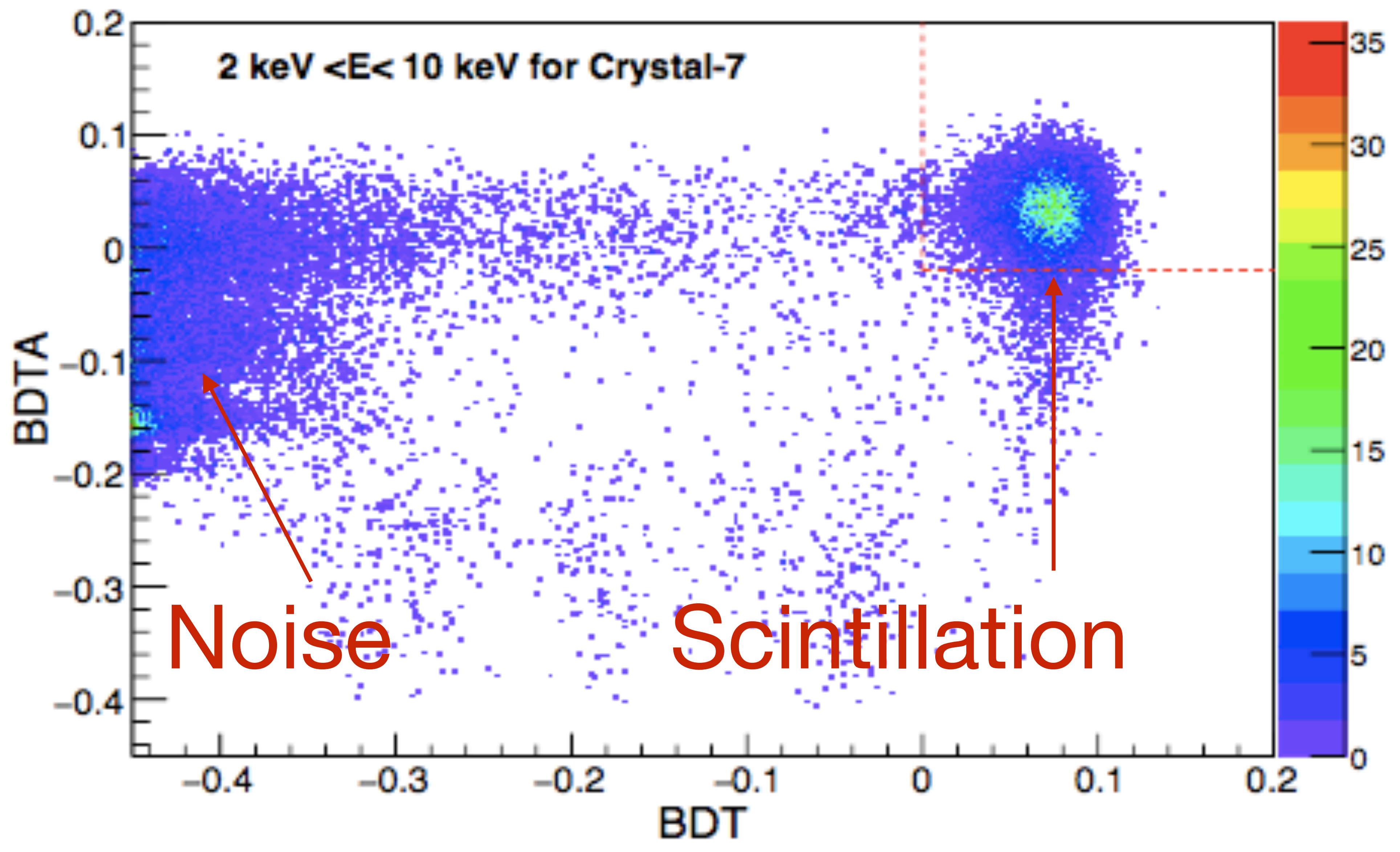
Dynode Waveform
(50-10,000 keV)

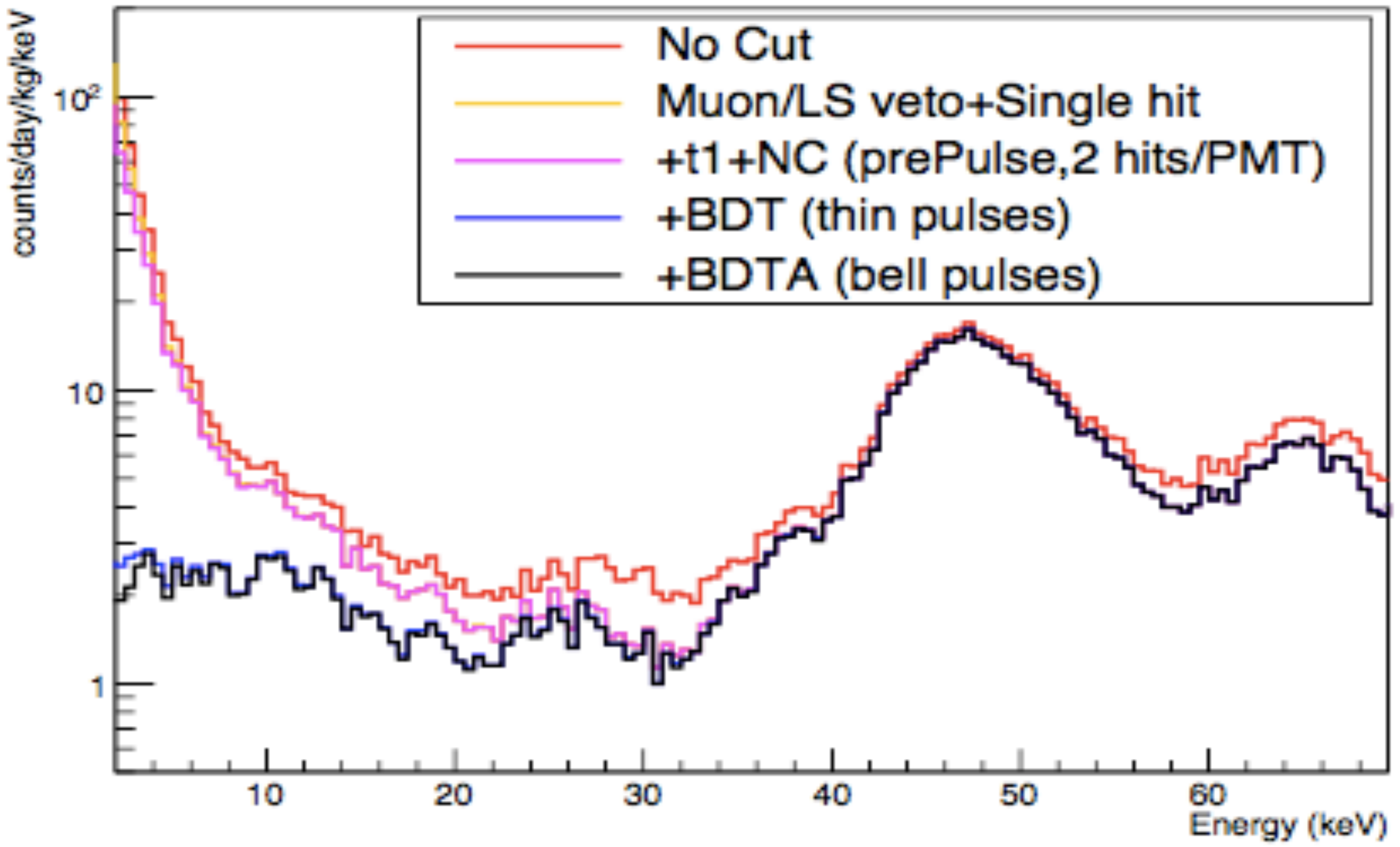


- The same events read in two channels: Anode and Dynode
  - **Anode** signal with waveform sensitivity at single-photon level: Primary channel for dark matter search
  - **Dynode** signal for high energy events: helps in understanding better the internal backgrounds in the crystals

PMT Noise Rejection





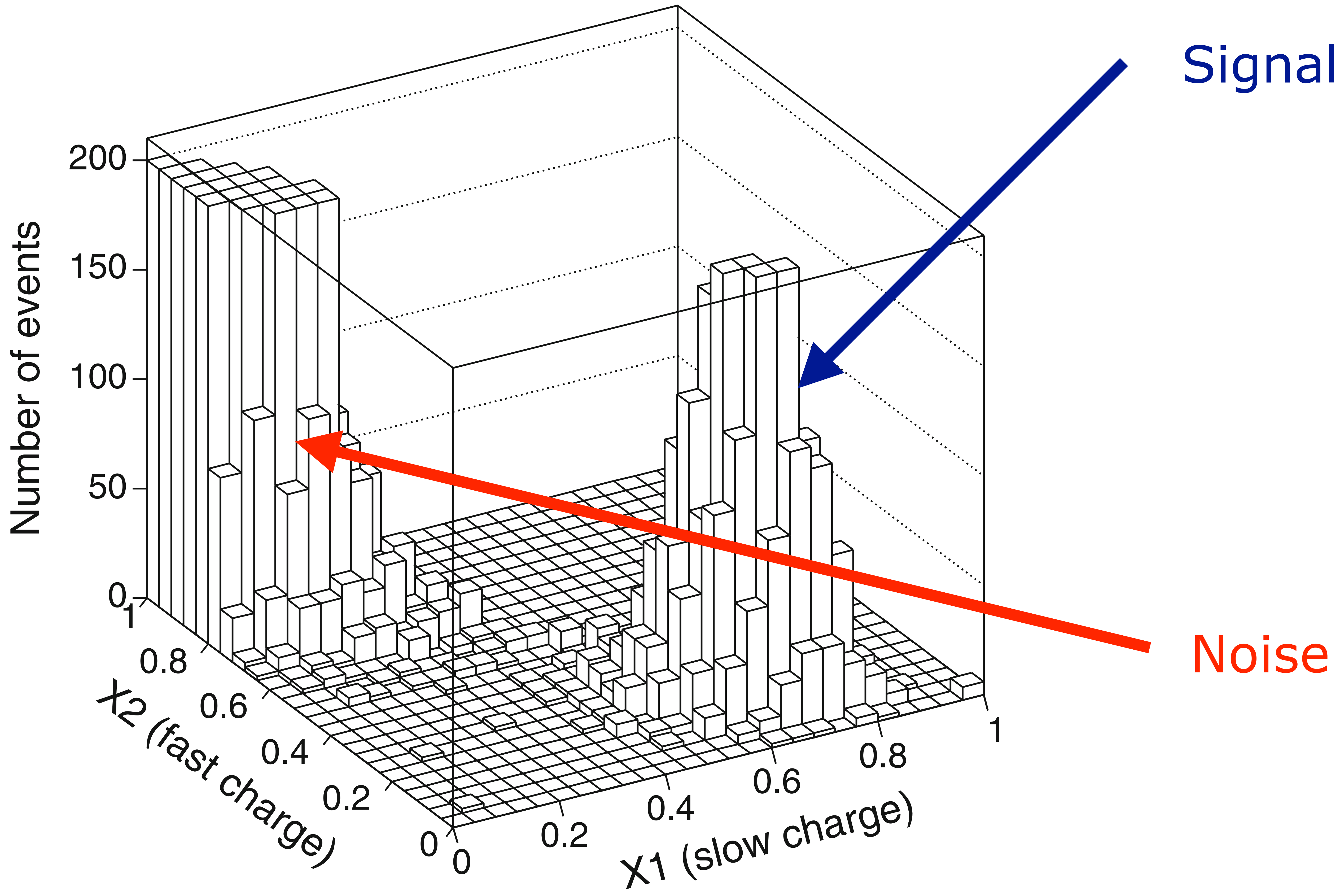


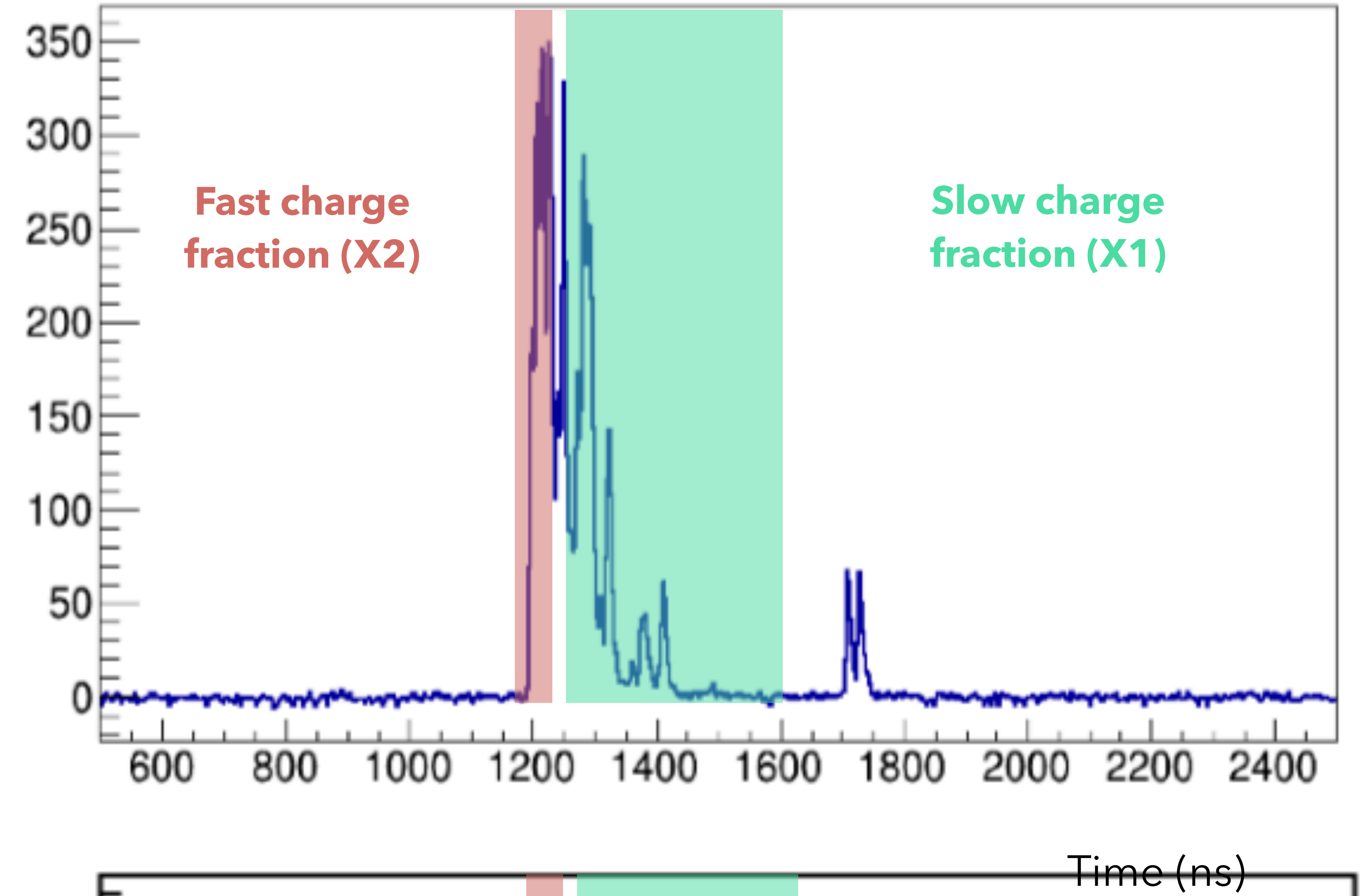
- Dominant noise from PMT noise
- Boosted Decision Tree (BDT) to clean up

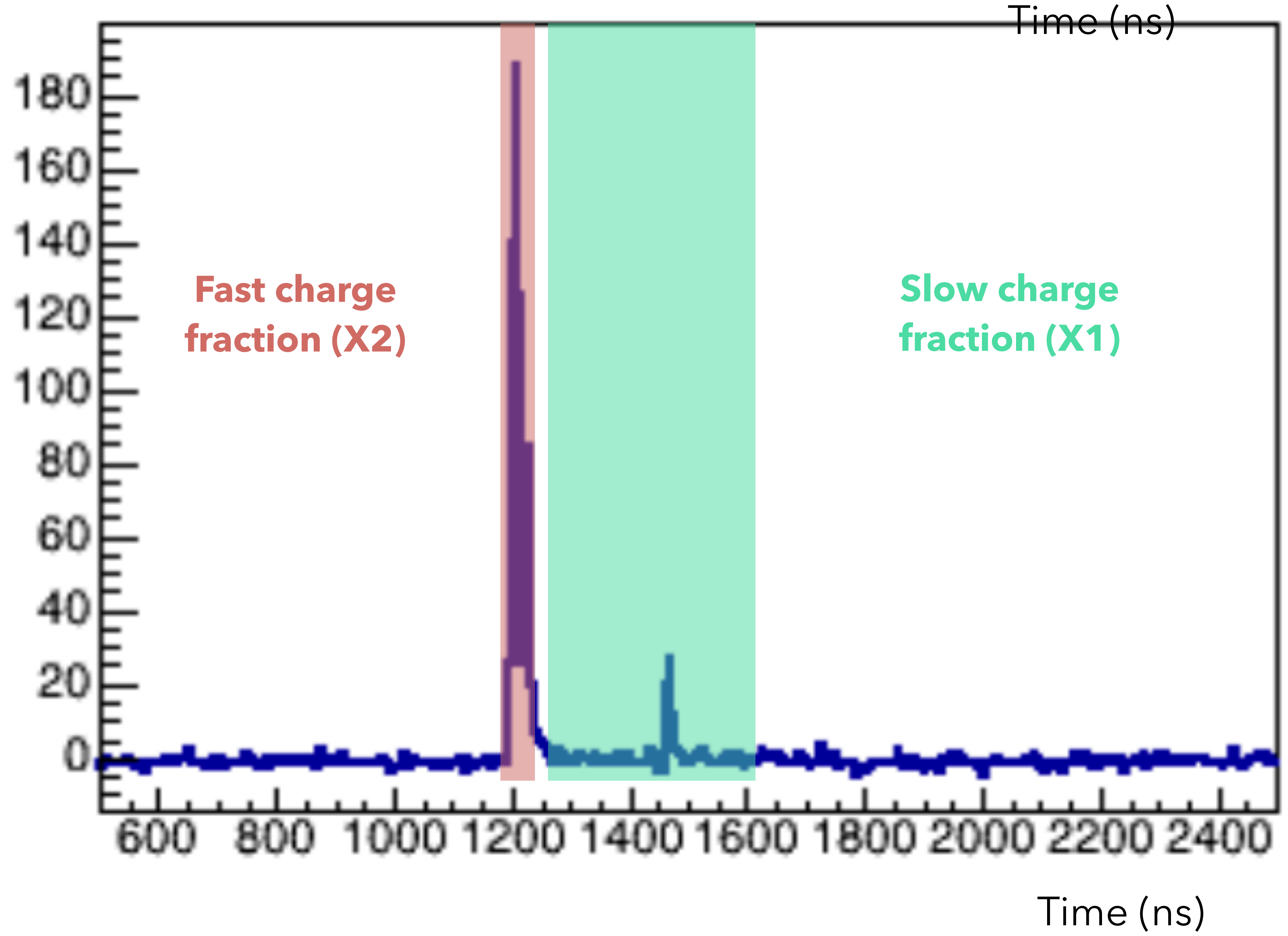
Eur.Phys.J. C **78** 107 (2018)

Event Selection

Separate noise via charge ratio of rising edge vs. falling edge

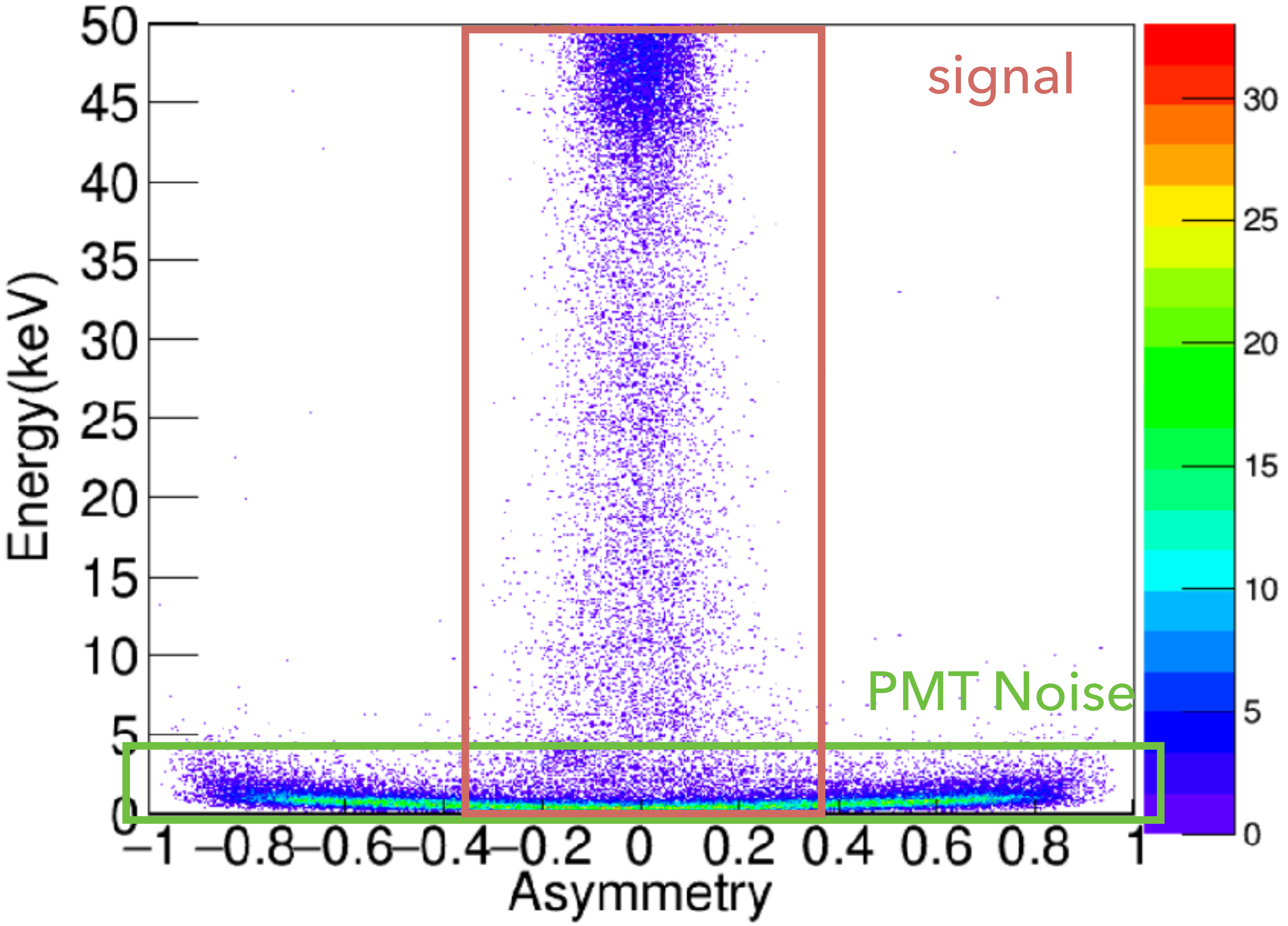


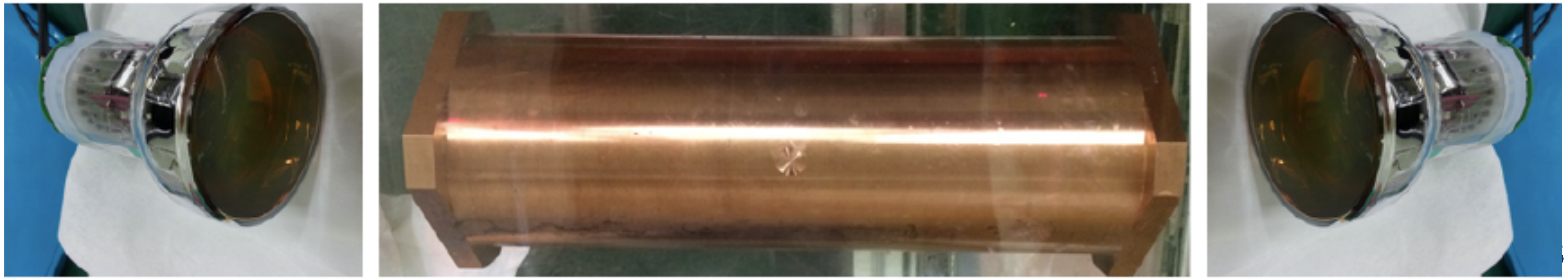




Event Selection: Asymmetry & Charge/Peak

- Additional noise reduction:
  - Charge asymmetry between 2 PMTs in each crystal
  - Charge/peak: Average charge per SPE
  - BDT

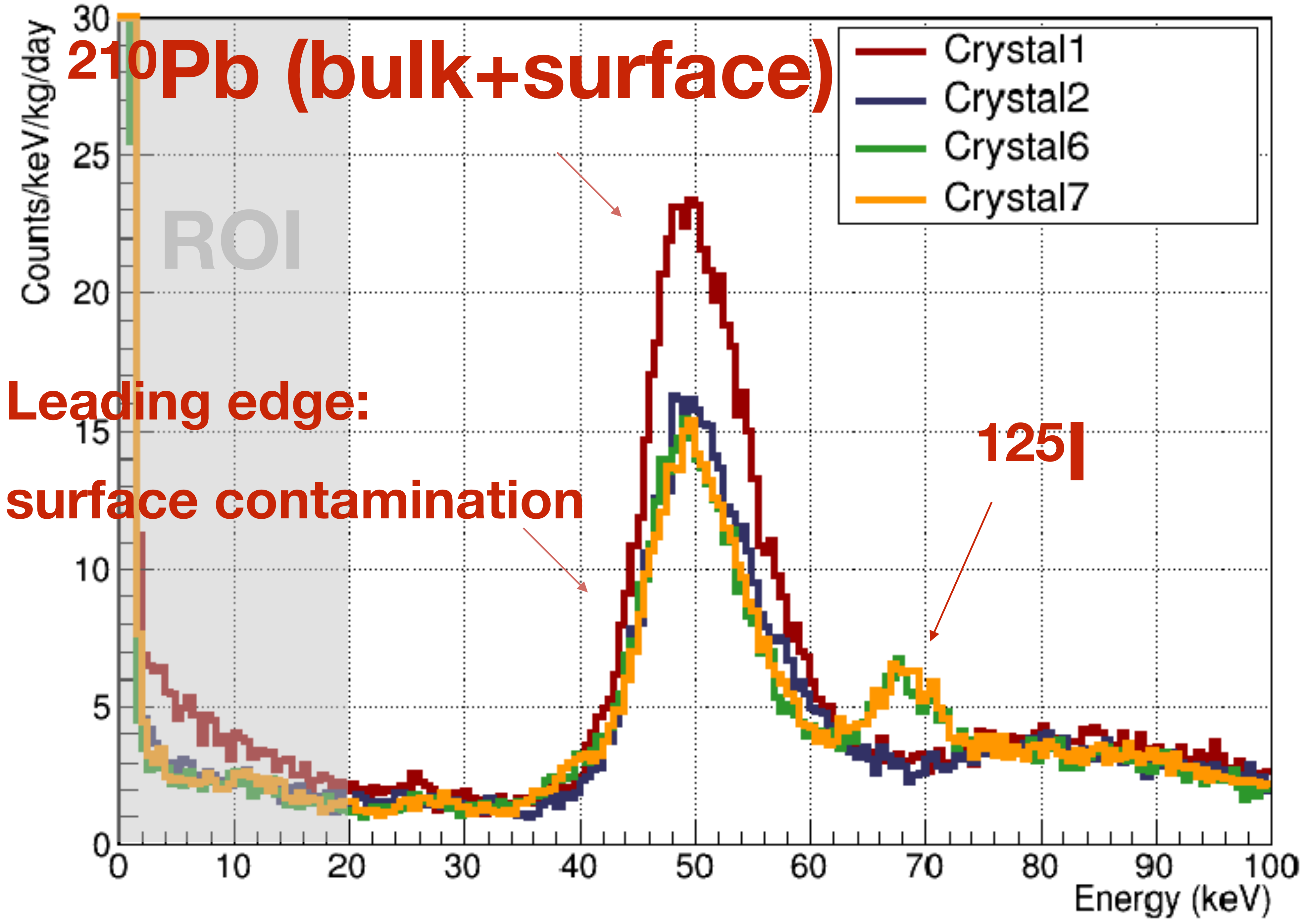


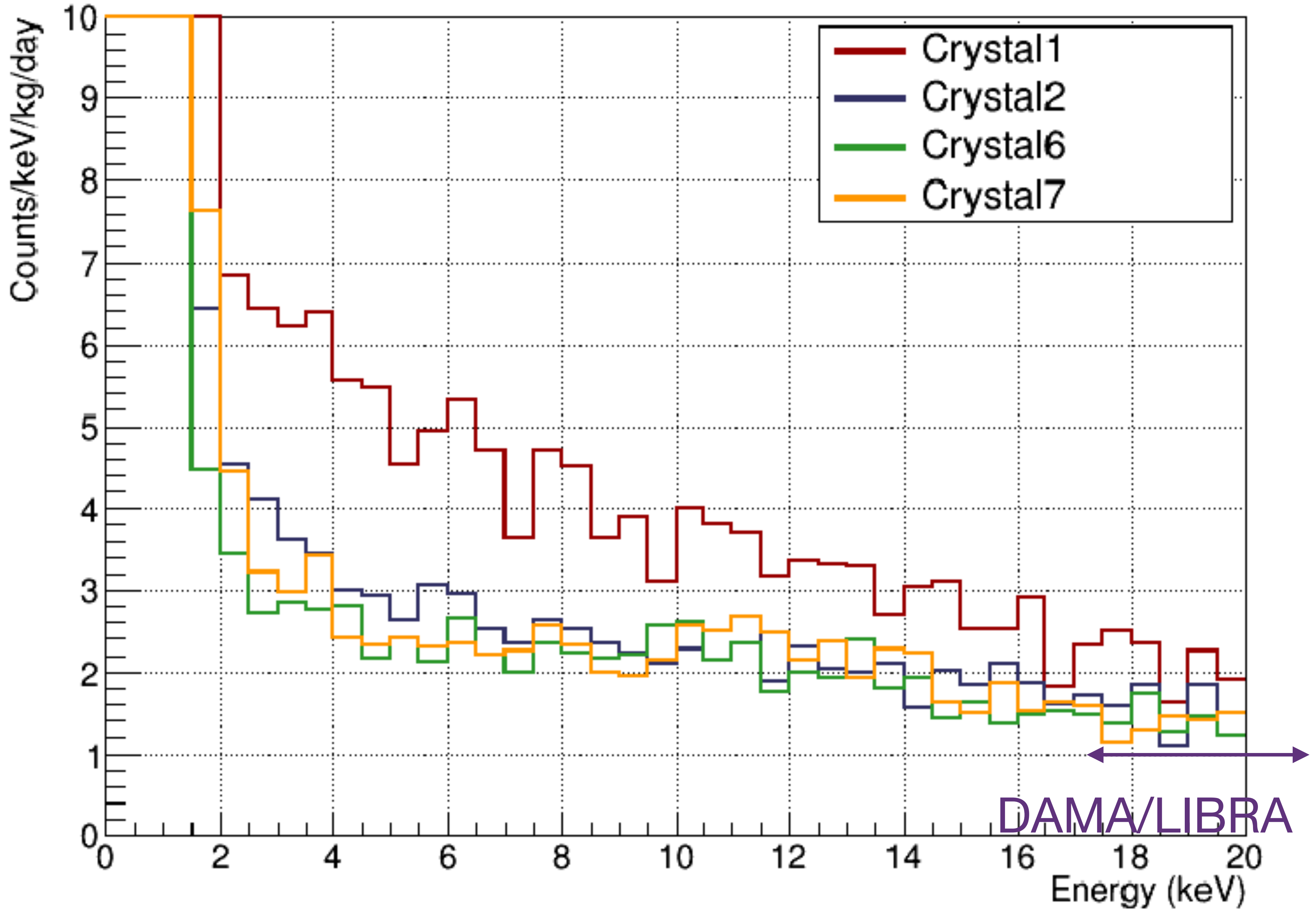


Low Energy Spectrum

Eur.Phys.J. C **78** 107 (2018)

- **2 - 4 counts/keV/kg/day in region of interest depending on the crystal**
- ^{210}Pb ($t_{1/2}$ = 22 yr), U/Th in internal components (crystal growing/raw material)
- ^{210}Pb on crystal & PTFE surface
- Cosmogenic components: ^{125}I (59 d), ^{109}Cd (461 d), ^{3}H (12 yr)

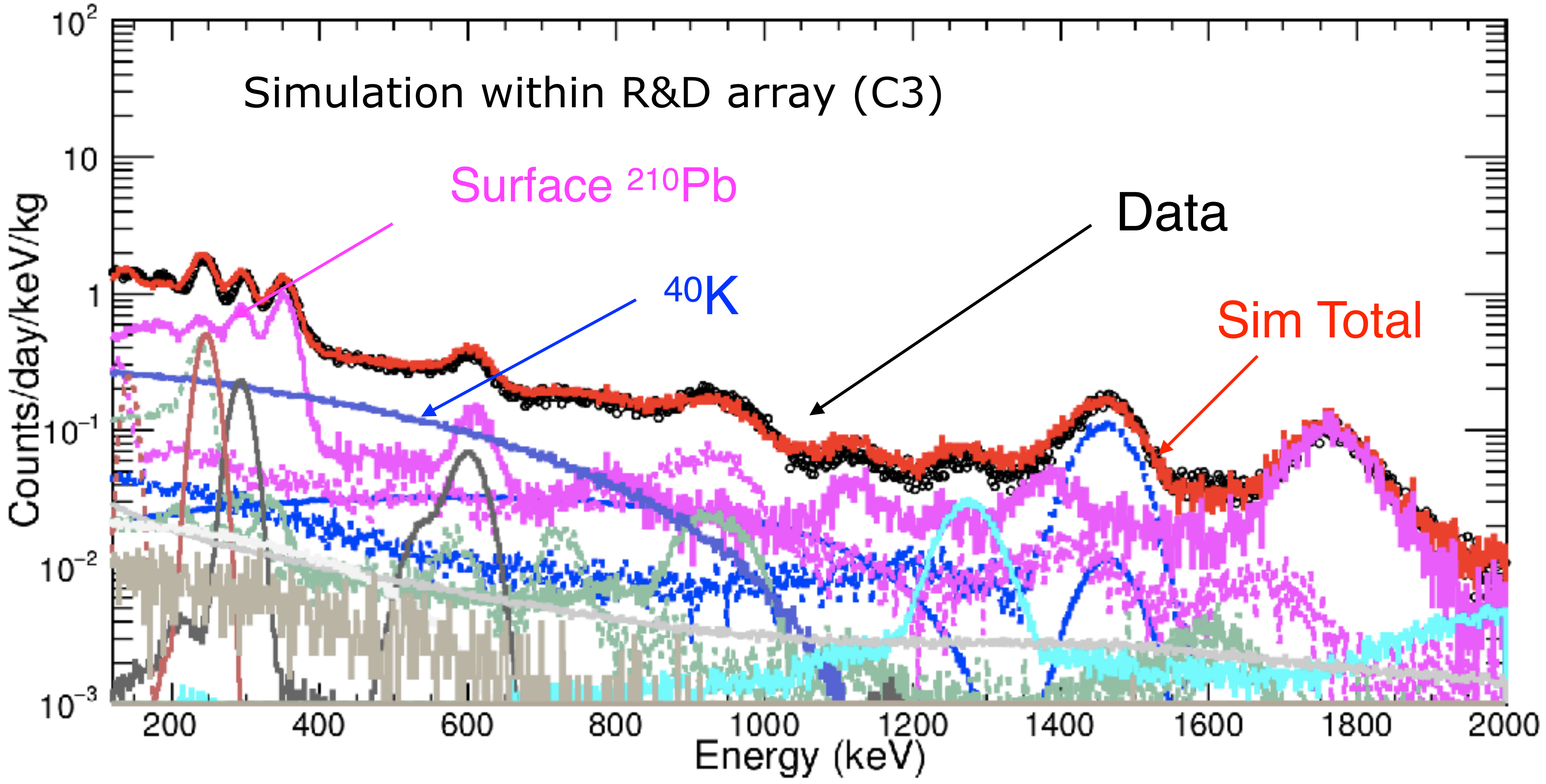


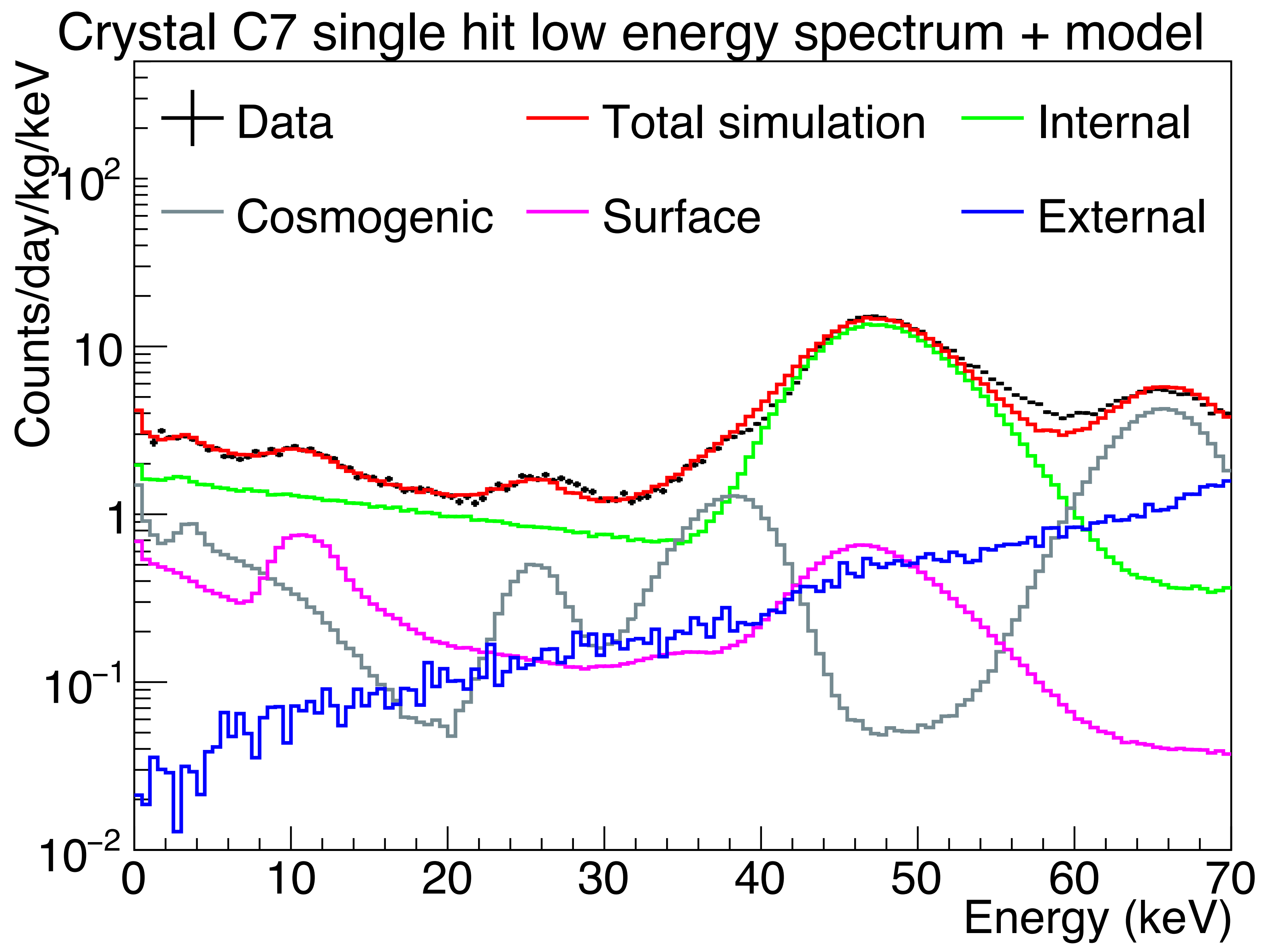


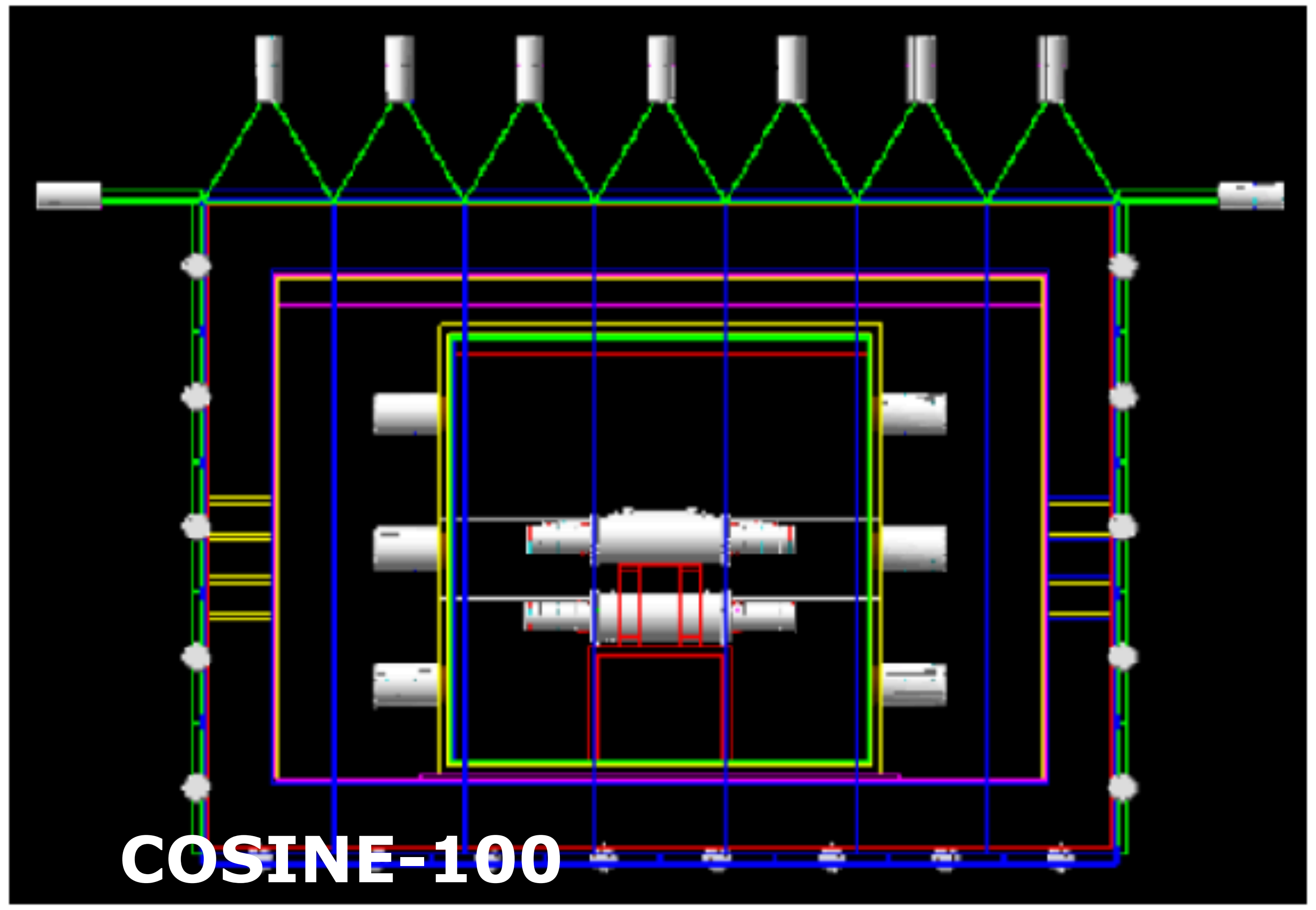
Eur.Phys.J. C **78** (2018) 490

Background in Data vs. Simulations

- Data compares well with Geant4 simulation
- Dominant backgrounds from ^{210}Pb & ^{40}K



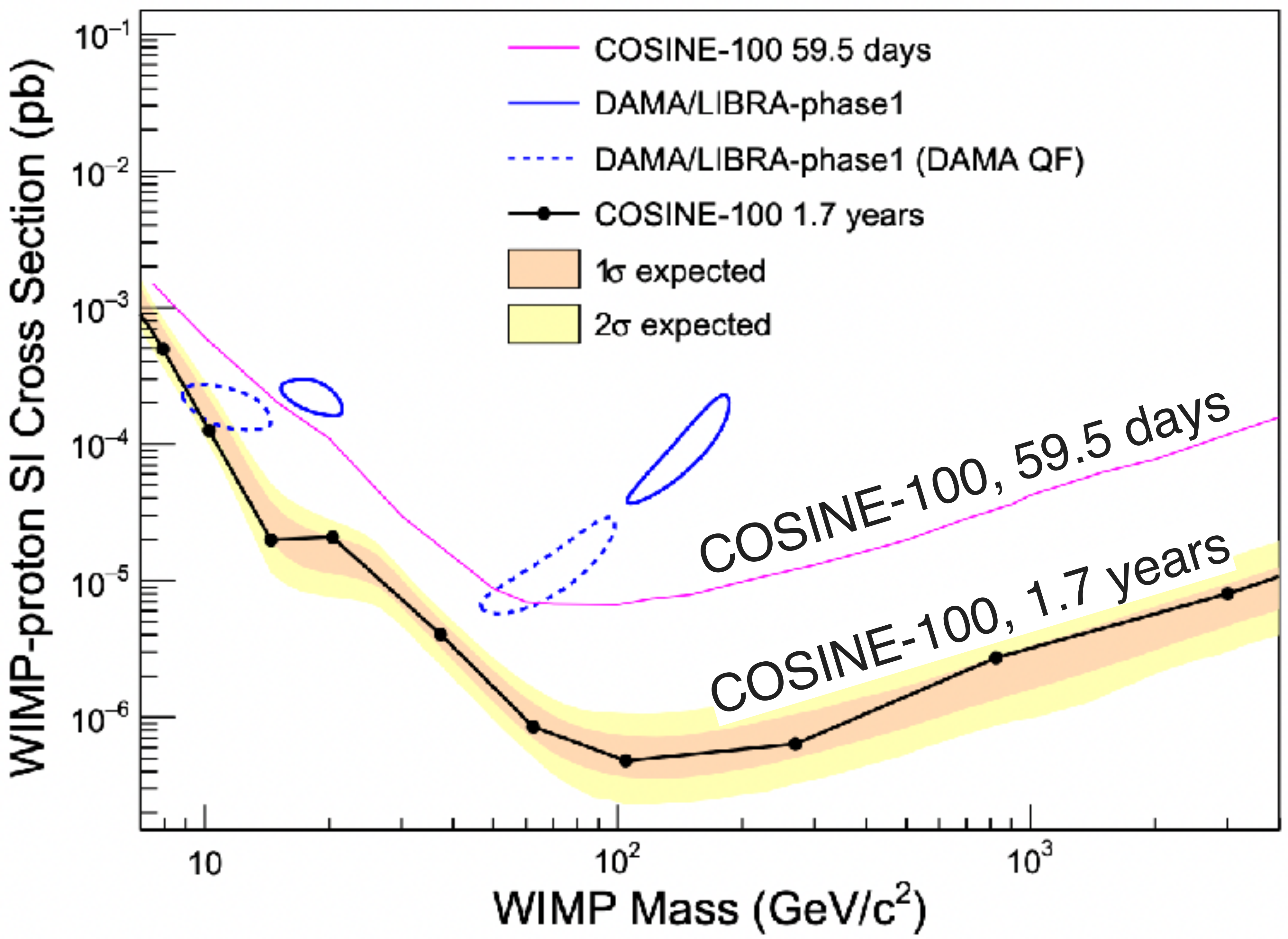


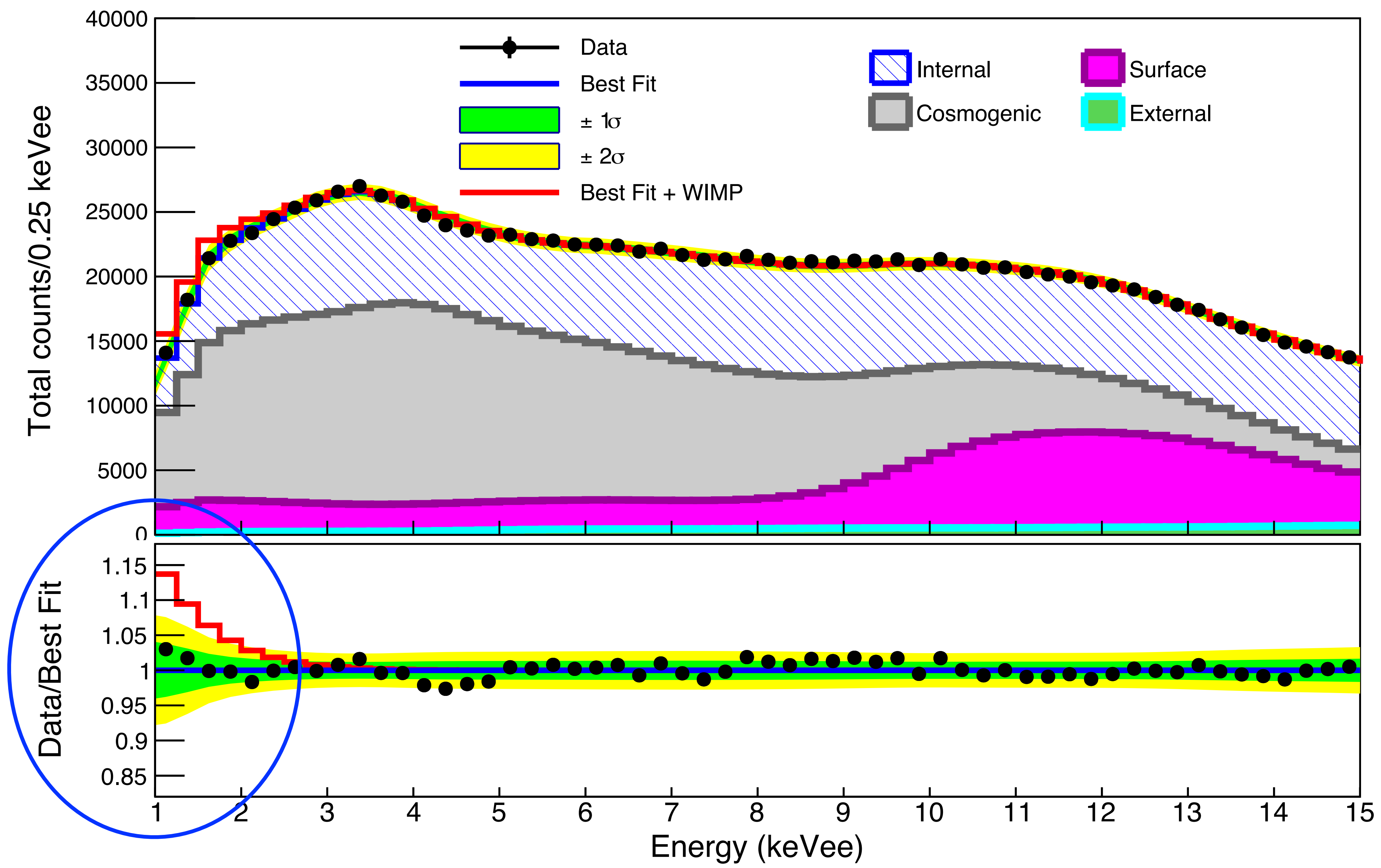


COSINE-100: no excess over known backgrounds

Same target medium, potential for variation among crystals

Nature 564, 83 (2018)
Sci Adv. 2021 Nov 12;7(46):eabk2699

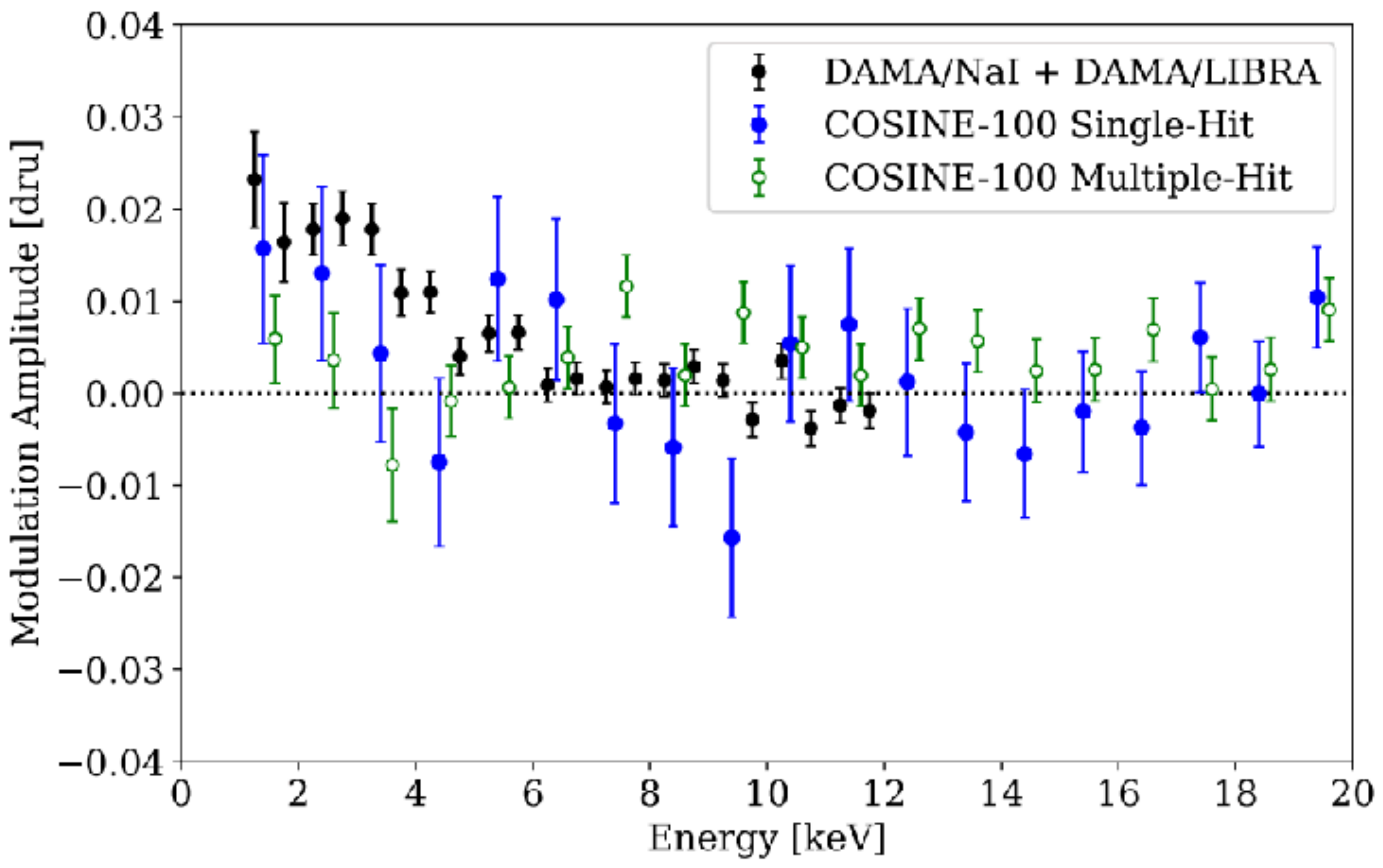


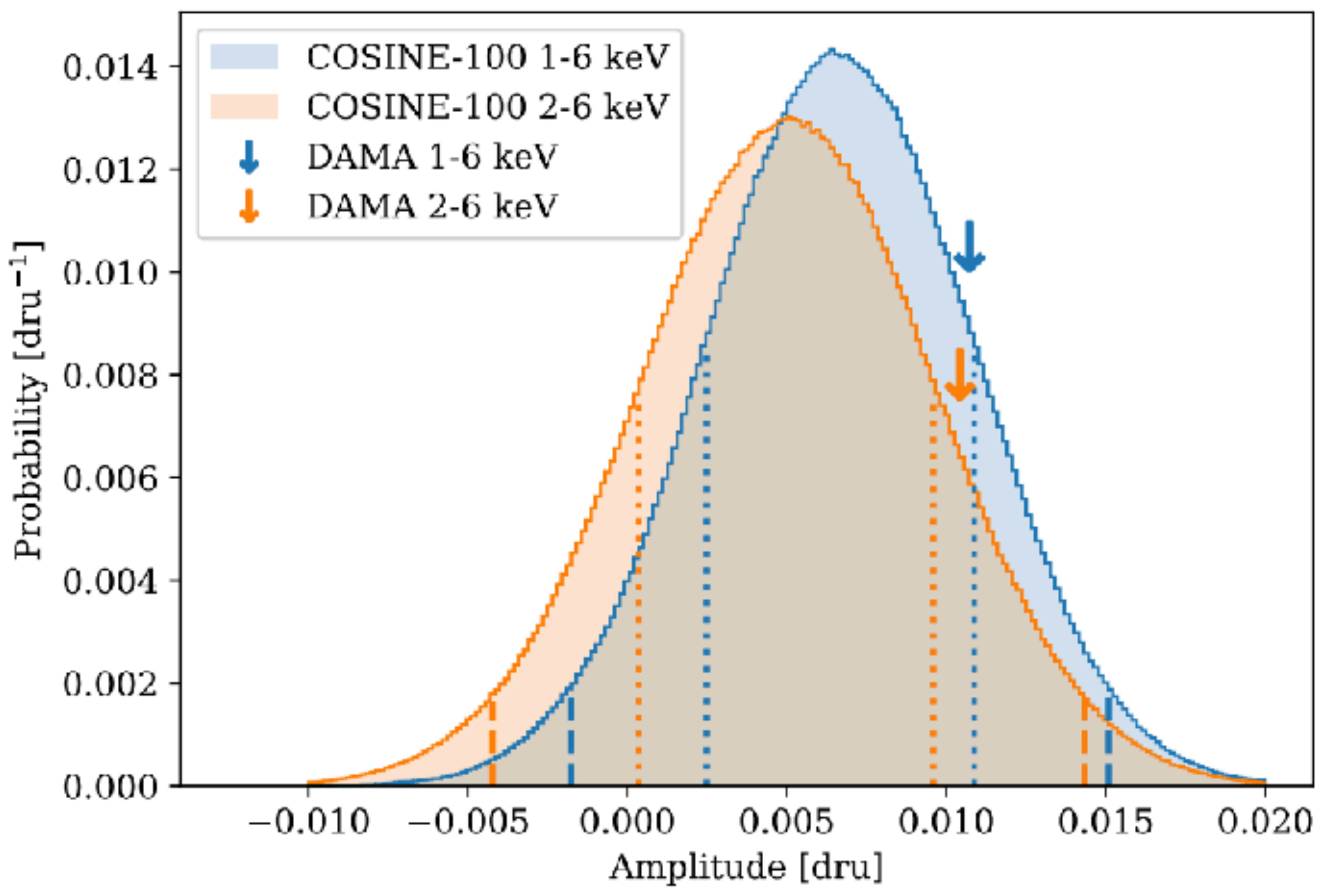


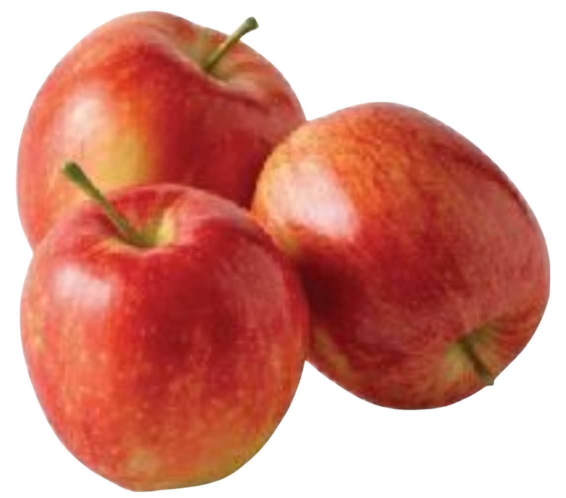
- Rules out WIMPs for DAMA with 60 days of data
- 1.7 yrs of data excludes WIMPs for pessimistic quenching factor

Phys. Rev. D. 106, 052005

2.8 yrs of COSINE-100 not yet conclusive







- 0.0067 ± 0.0042 cpd/kg/keV @ 1 – 6 keV
- Consistent with both DAMA and zero modulation
- Data ready for 3 more years exposure

Modulation introduced with DAMA-like analysis

COSINE analysis

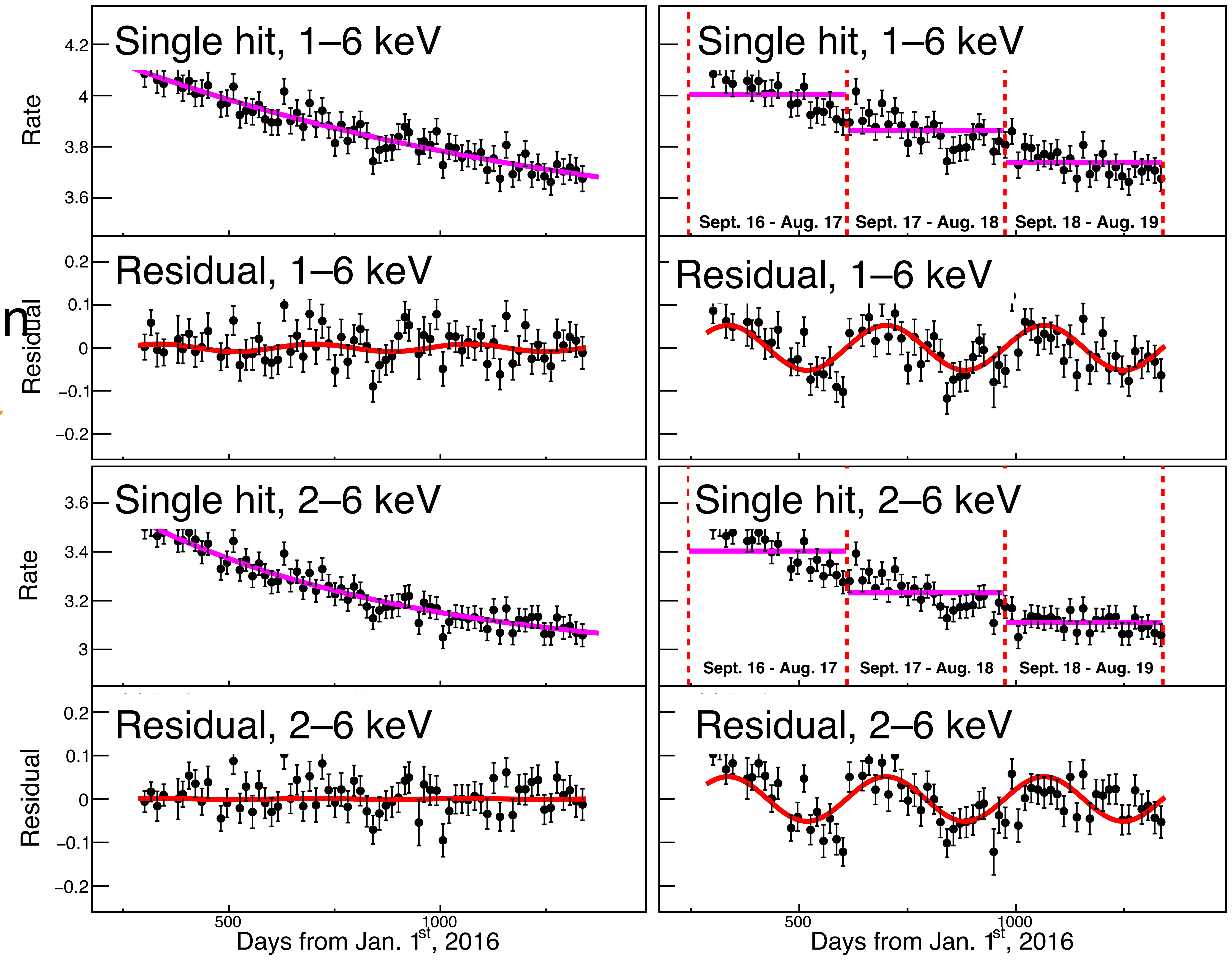
Fit for background,
7 exponentials

Fit residual for modulation

1–6 keV

2–6 keV

COSINE-100 data



DAMA-like analysis

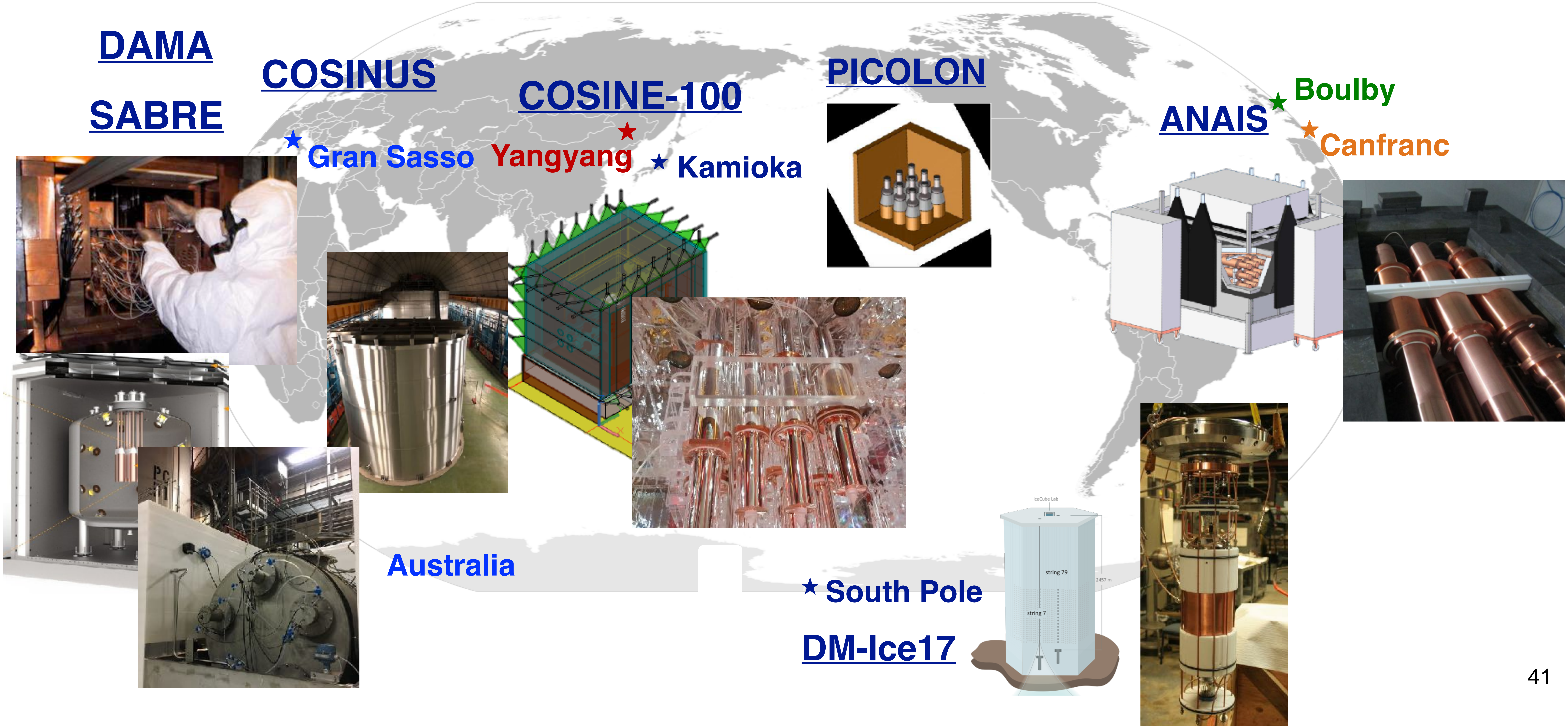
Subtract single average per dataset

Fit residual for modulation

~7σ modulation
opposite phase

Impossible to confirm without rate vs. time from DAMA

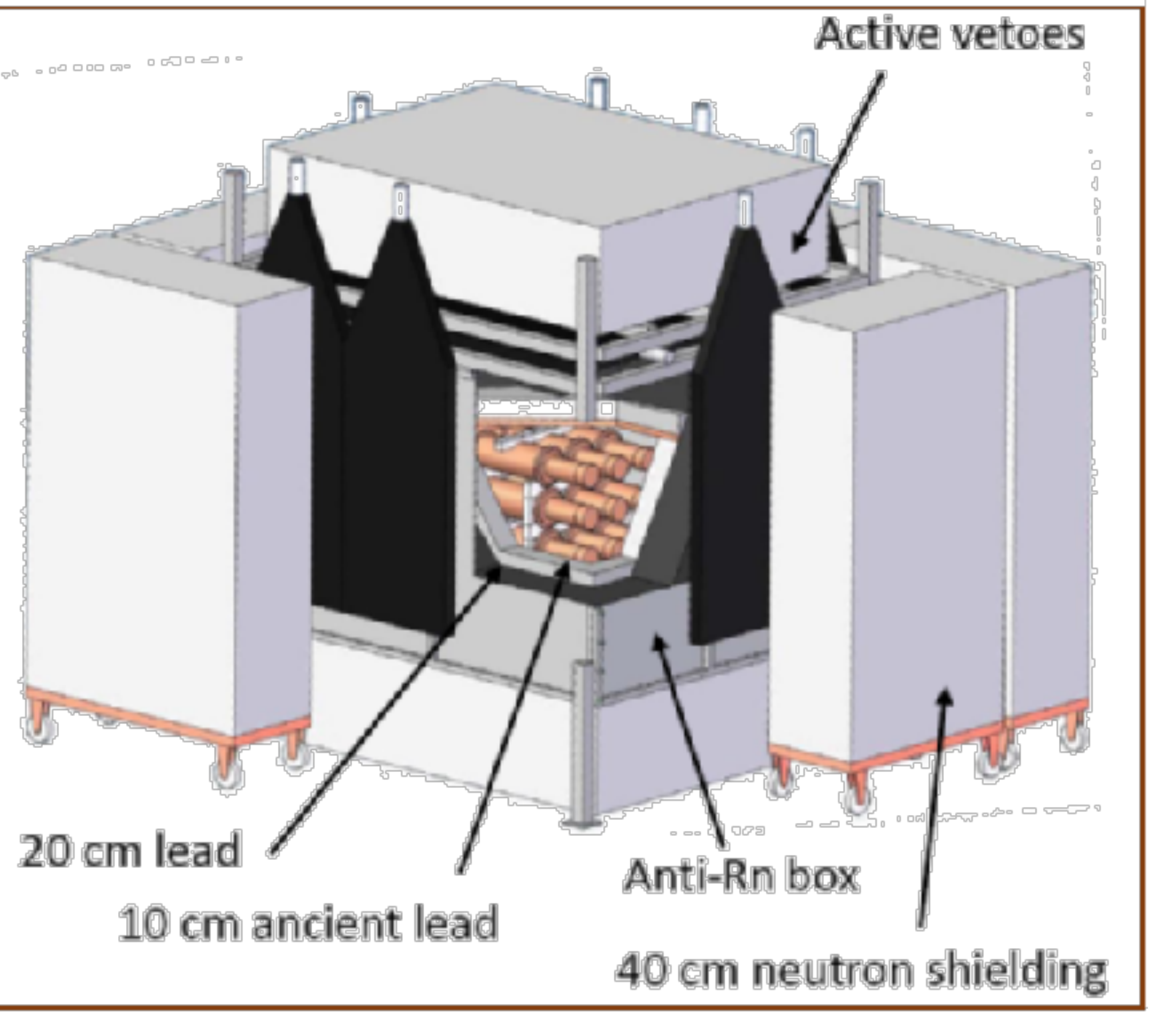
NaI Experiments: a Global Effort



ANAIS-112, Canfranc Underground Laboratory (LSC, Spain)

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

Two high QE PMTs per detector

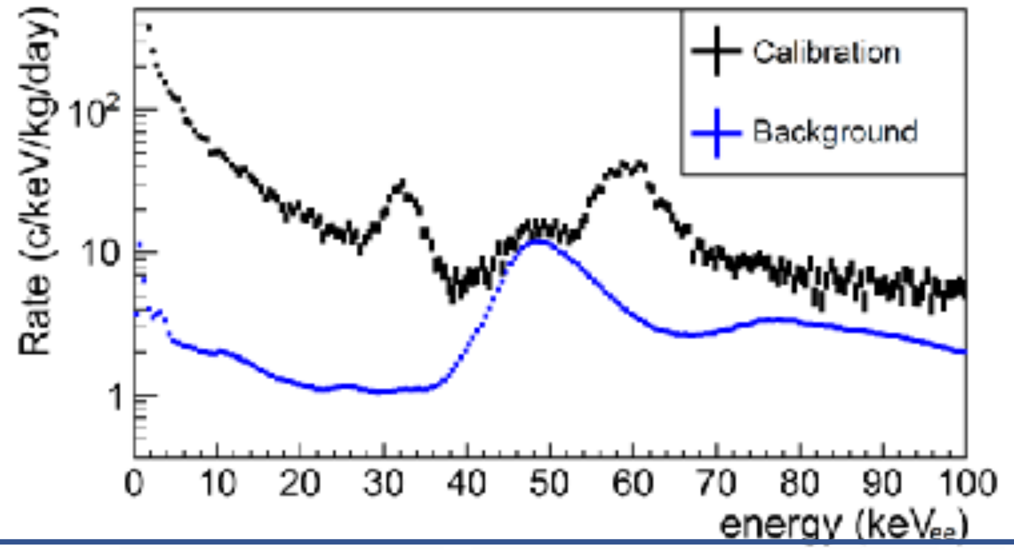


ANAIS-112 modulation results:

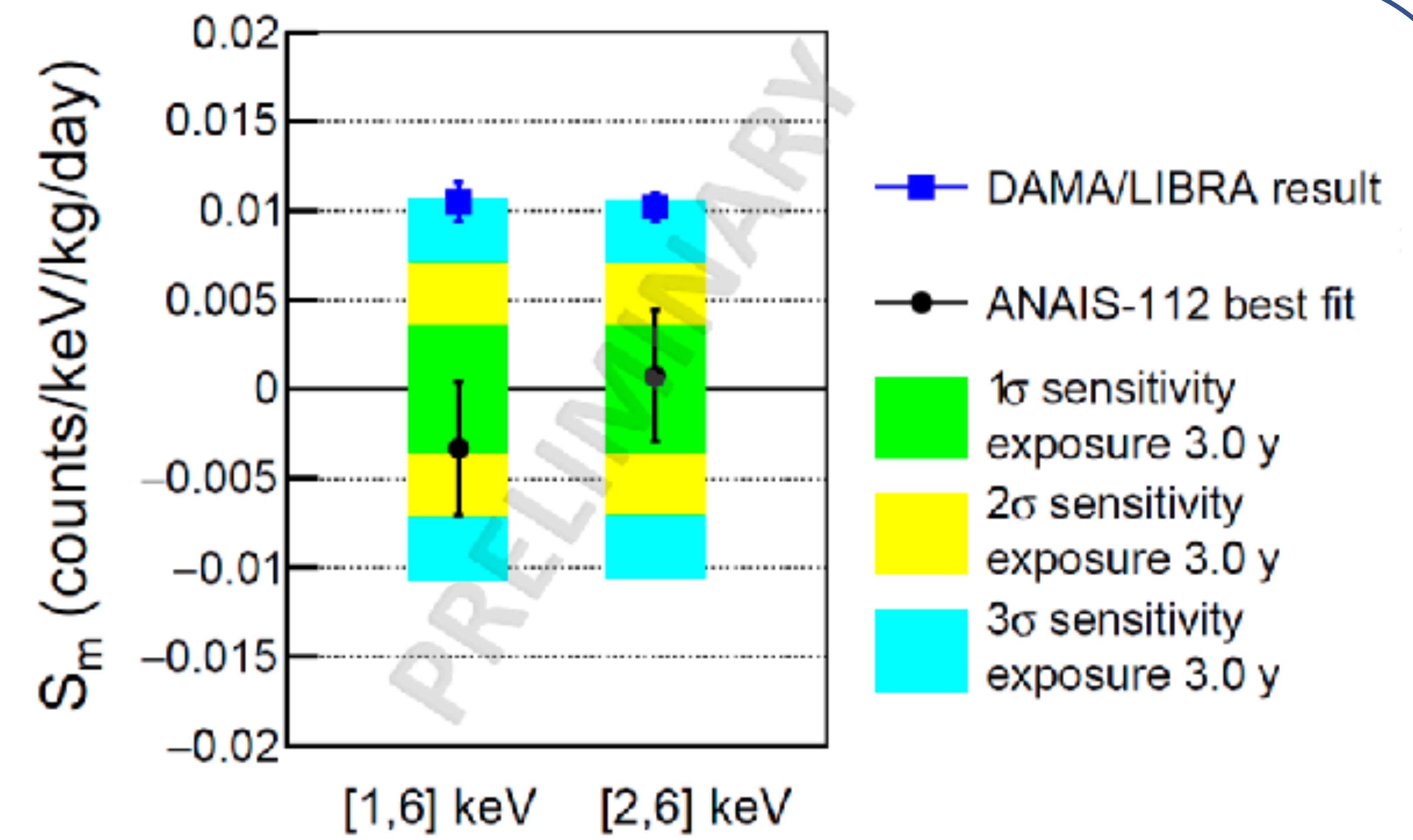
- 1.5y: Phys. Rev. Lett. 123, 031301 (2019)
- 2y: J. Phys. Conf. Ser. **1468,** 012014 (2020)
- 3y: arXiv: Phys. Rev. D 103, 102005 (2021)

“Improving ANAIS-112 sensitivity to DAMA/LIBRA signal with machine learning techniques”, I. Coarasa et al, JCAP11(2022)048

SIGNAL EVENTS: Neutron calibrations



NOISE EVENTS: “Blank” module (No NaI(Tl))

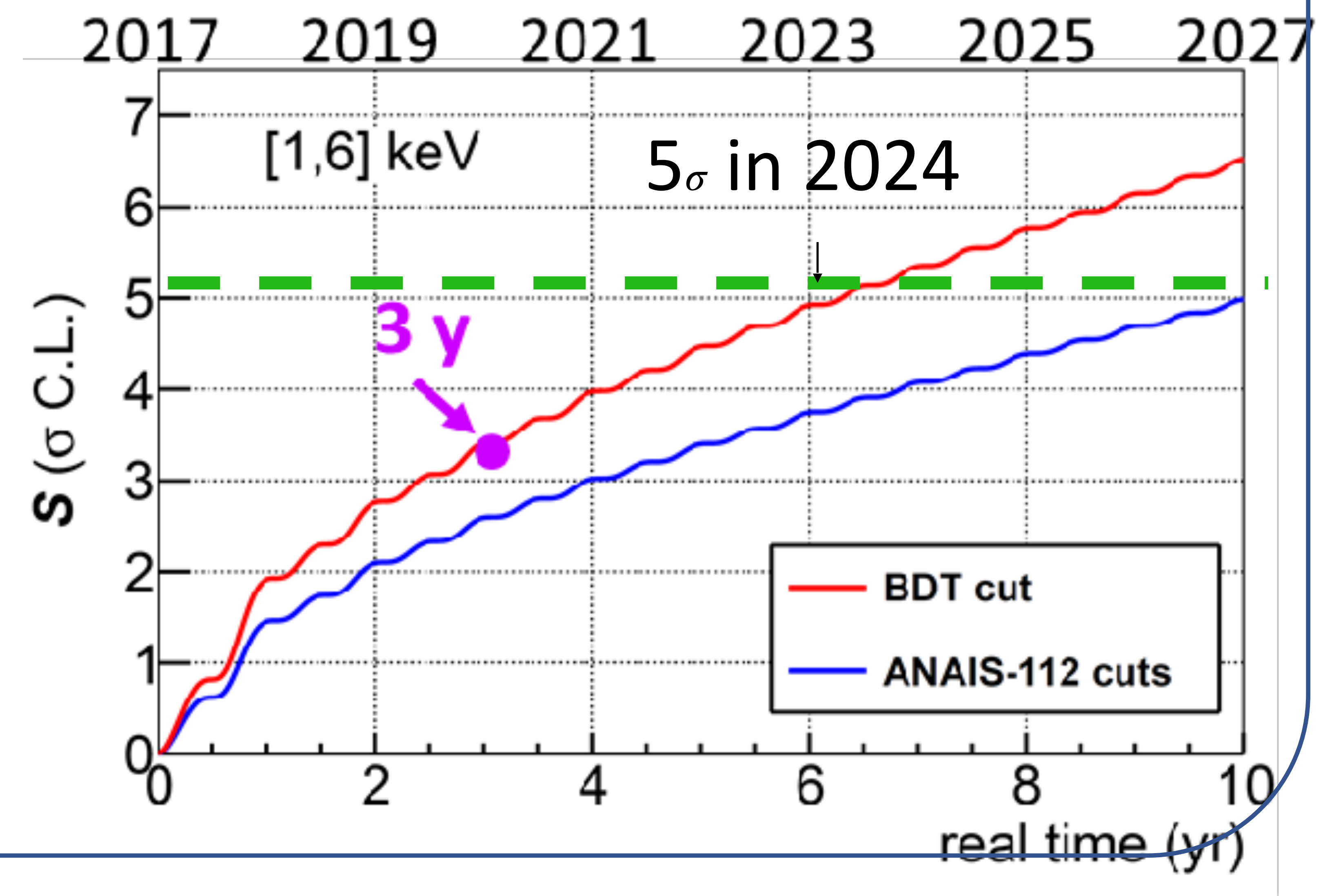


Best fit compatible with zero (1σ)

Incompatible with DAMA/LIBRA at 3.9σ (2.8σ) for [1-6] ([2-6]) keV

Sensitivity 3 yrs data: 2.9σ for [1-6] & [2-6] keV

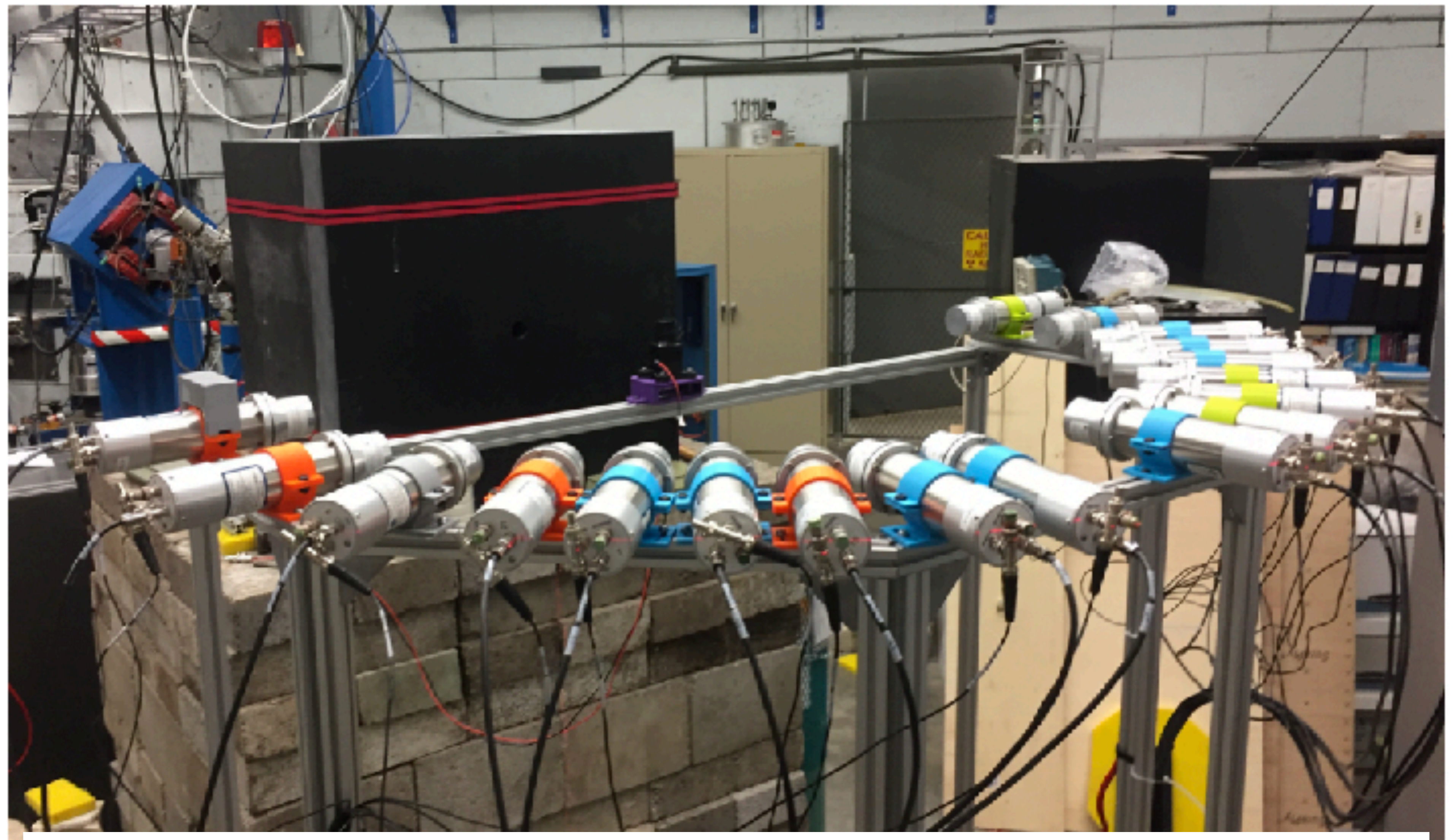
5σ in late 2025



Detector effects

- e.g. quenching factor & channeling
  - Potential variation among crystals

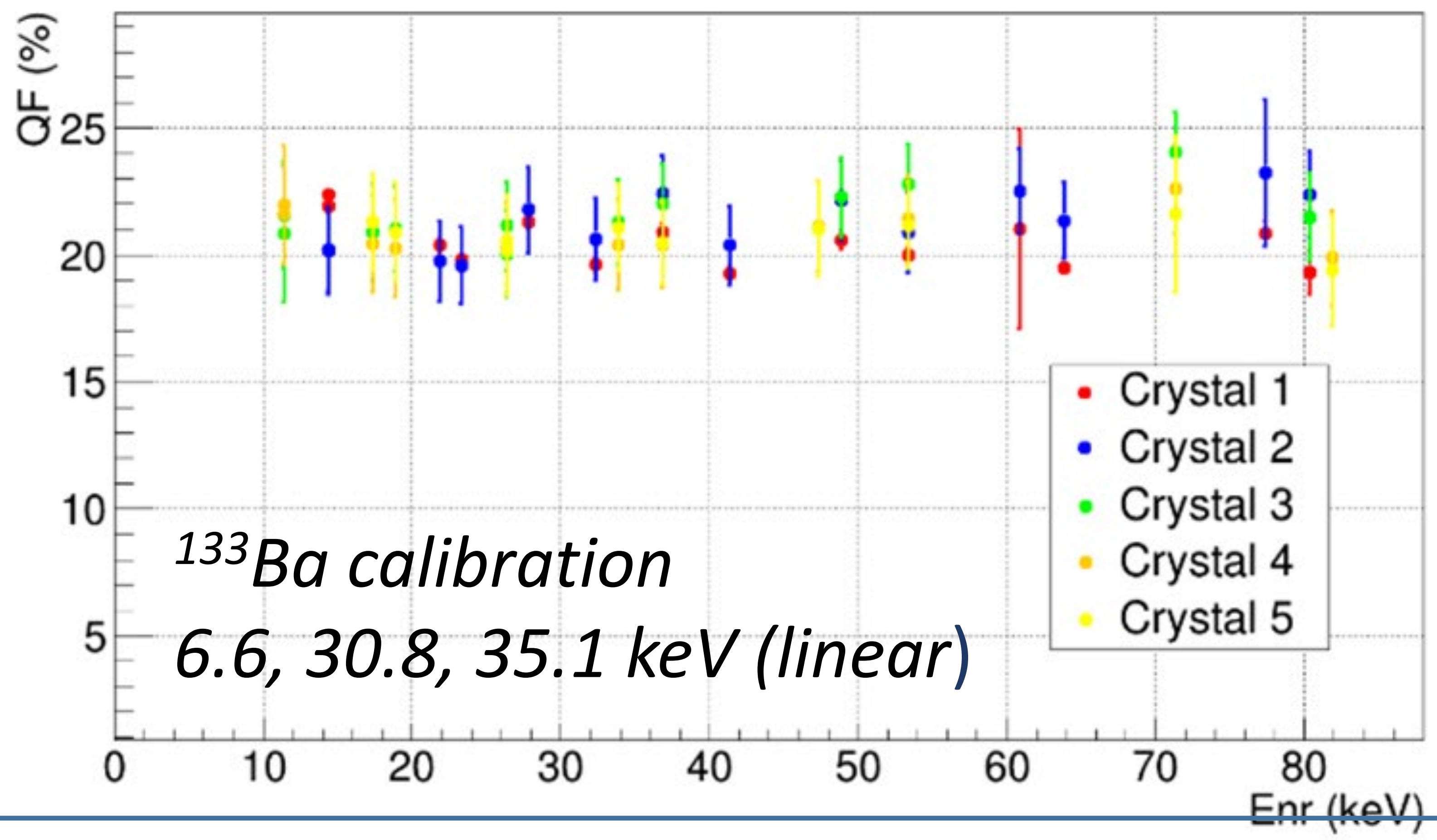
Measurement @ TUNL in collaboration w/ ANAIS

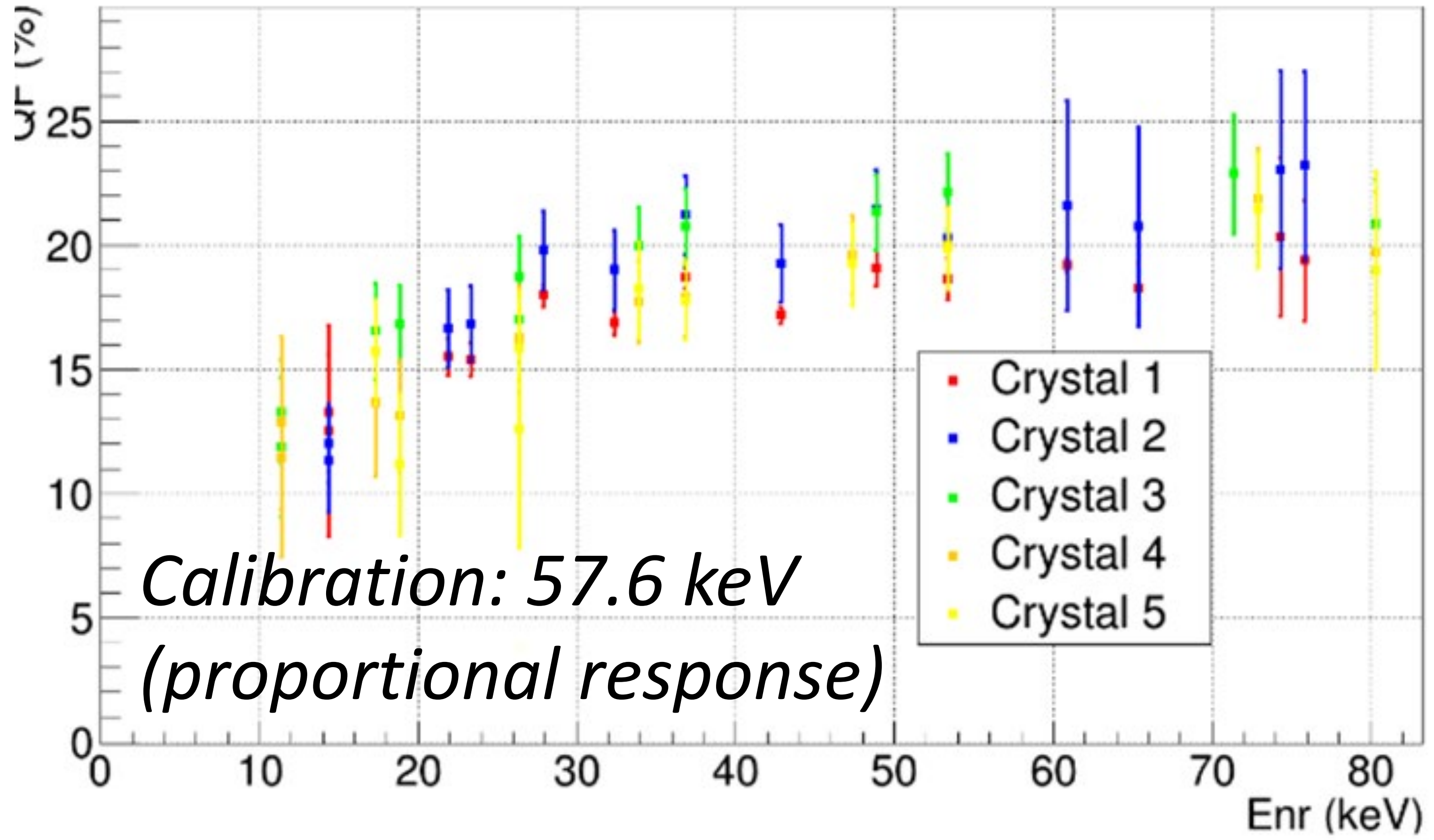


J. Physics (Conference series) 2156 (2022) 012065

Results for Na:

- No differences among different crystals
- QF_{Na}~20% @ 30 keVNR, but energy calibration method changes the energy dependence (non-linearity!)





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

Results for I:

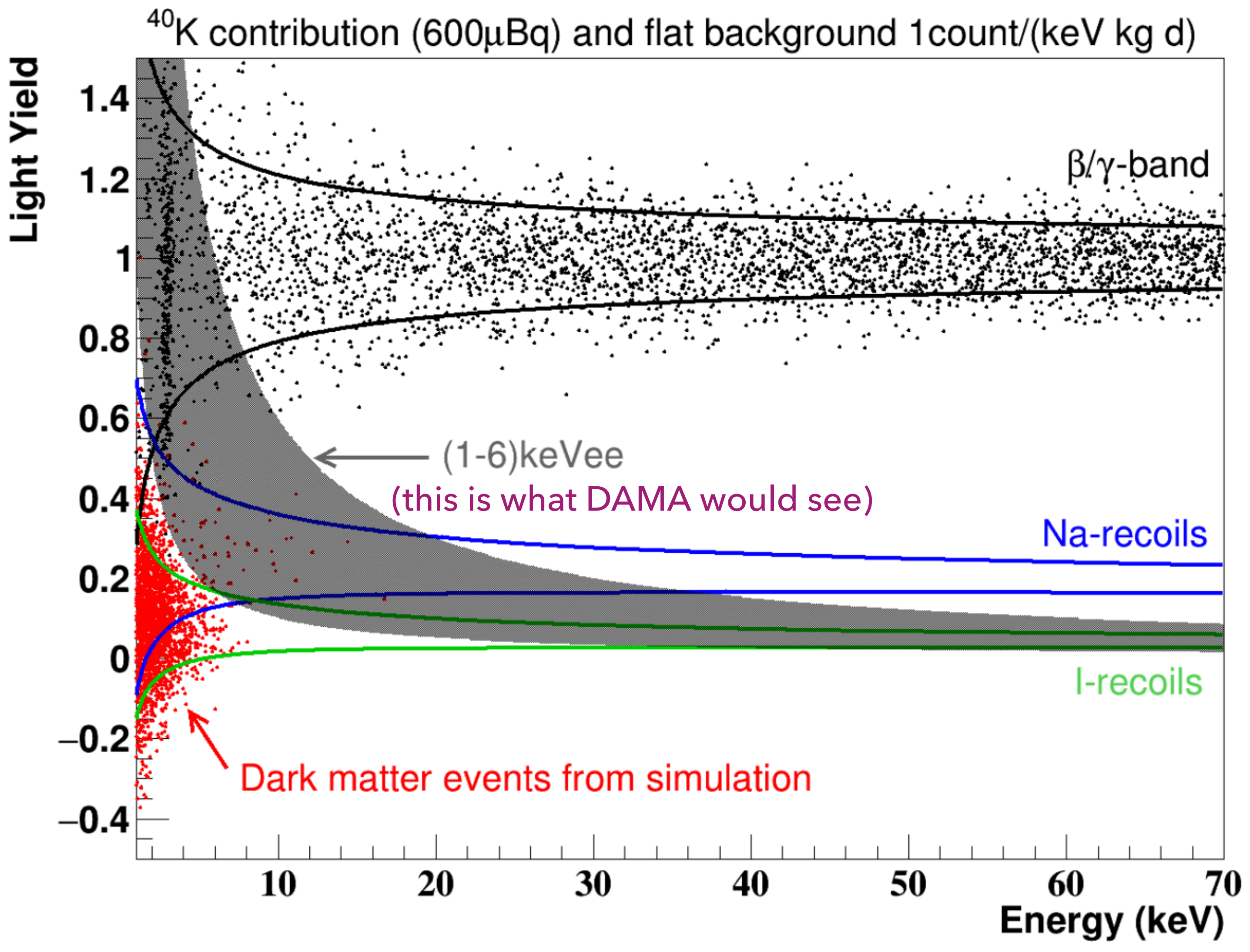
- Lower energy threshold needed for this measurement
- Only upper limits for two of the crystals

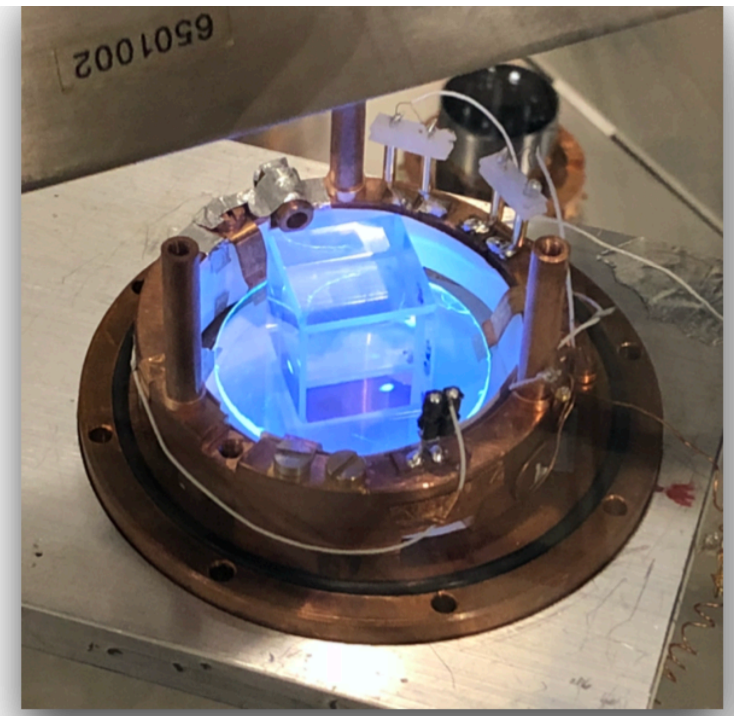
QF_I < 9.4 % @ 11.5 keV
QF_I < 8.2 % @ 13.6 keV

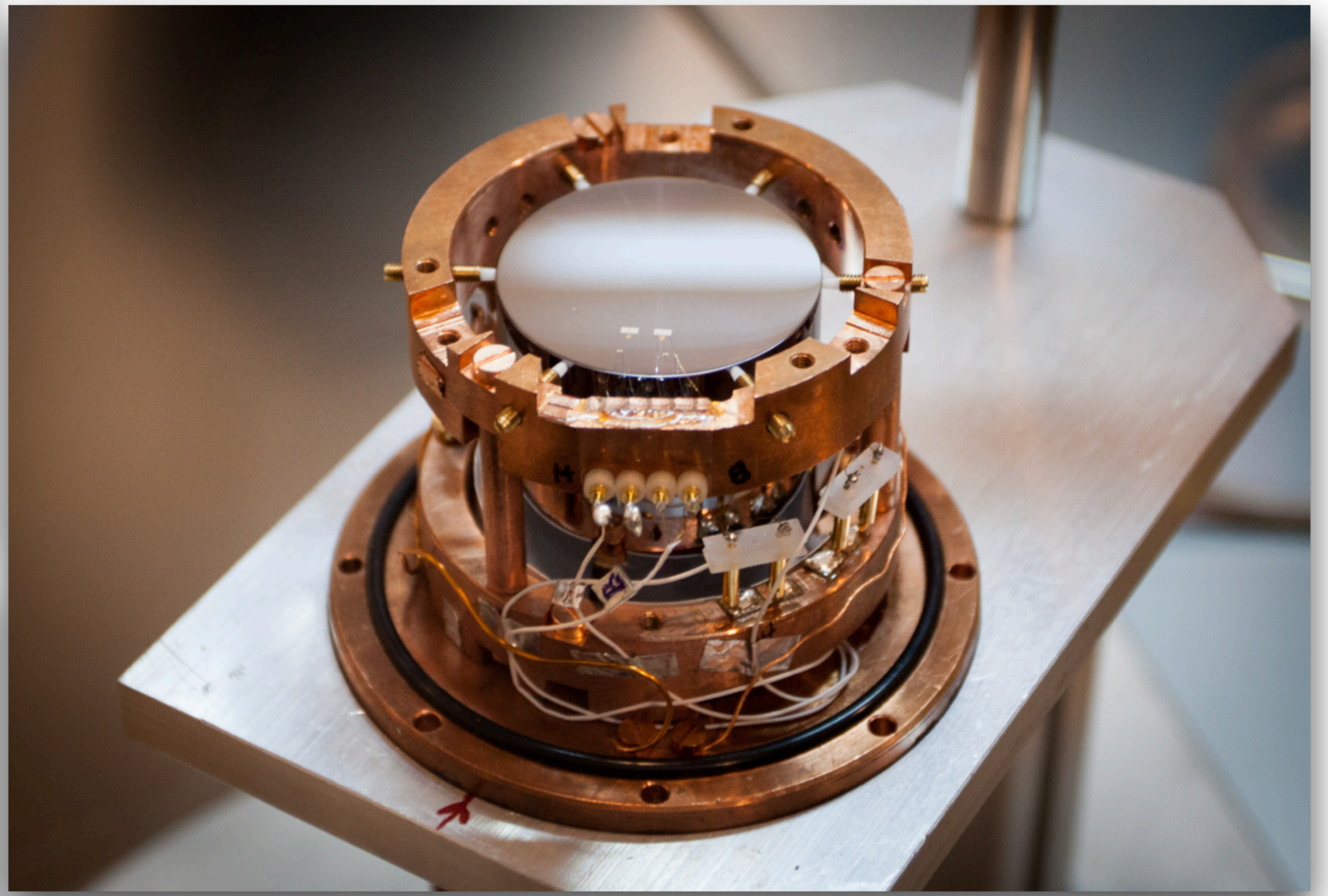
Curtesy of M. Martinez

COSINUS

- NaI crystals as cryogenic detectors
- NR vs ER via TES sensors + SQUIDs:
- - Heat (phonons) + scintillation





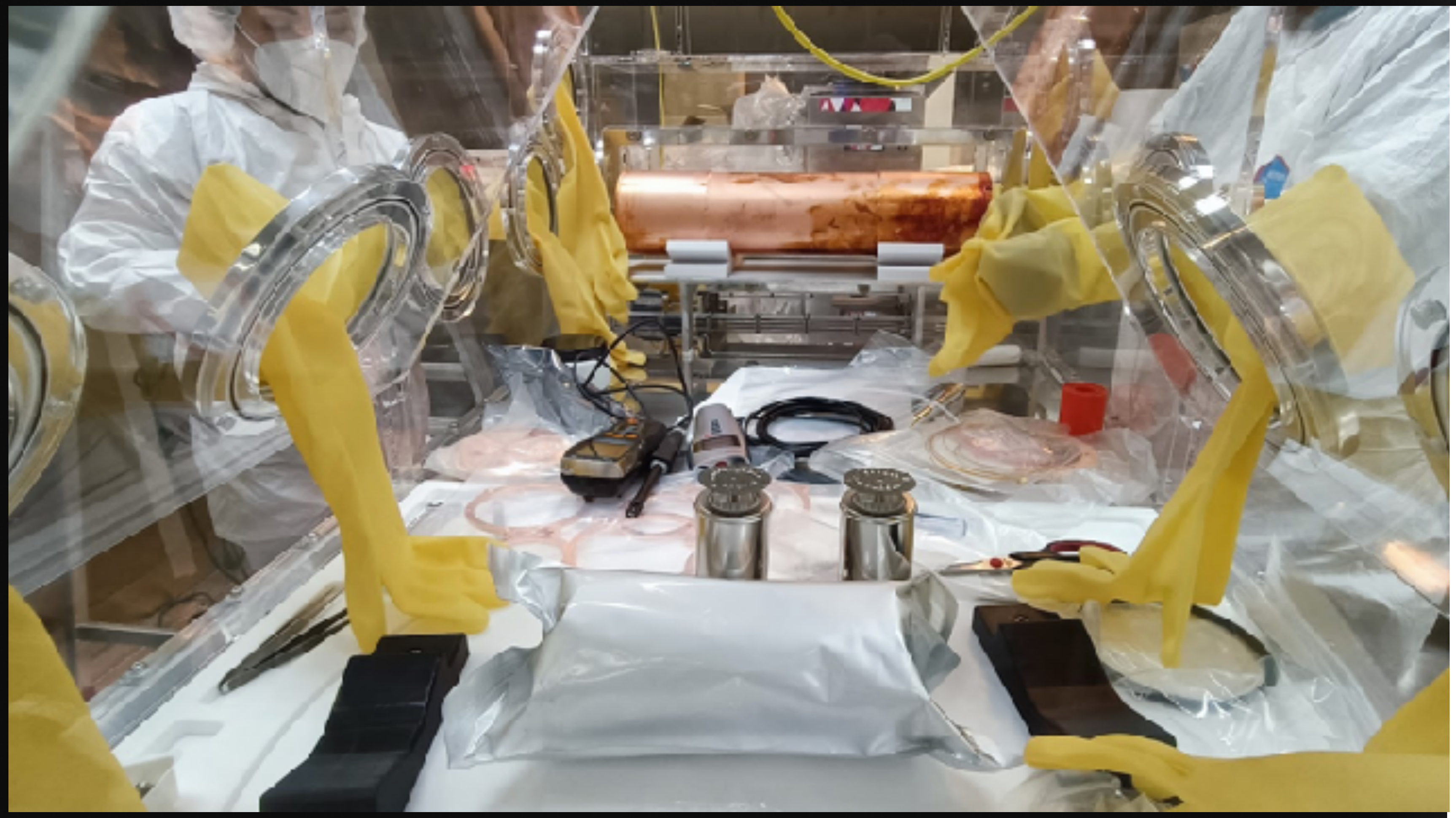


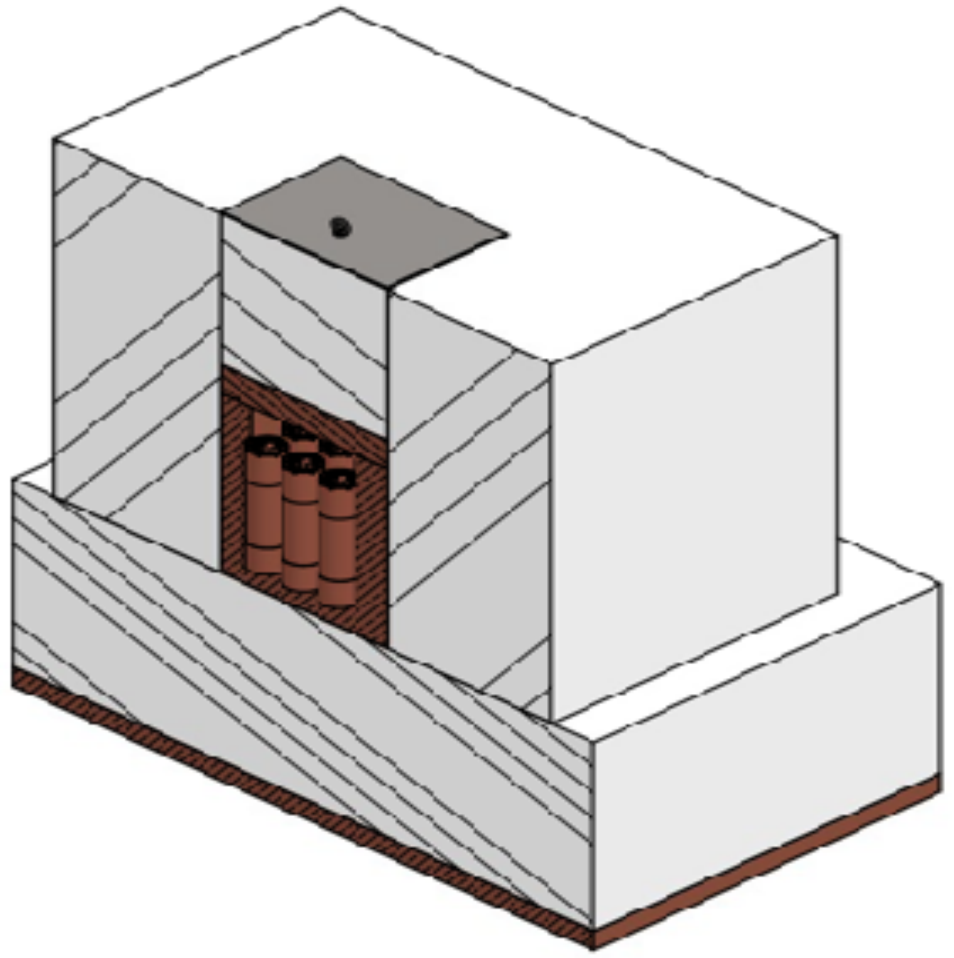
COSINUS

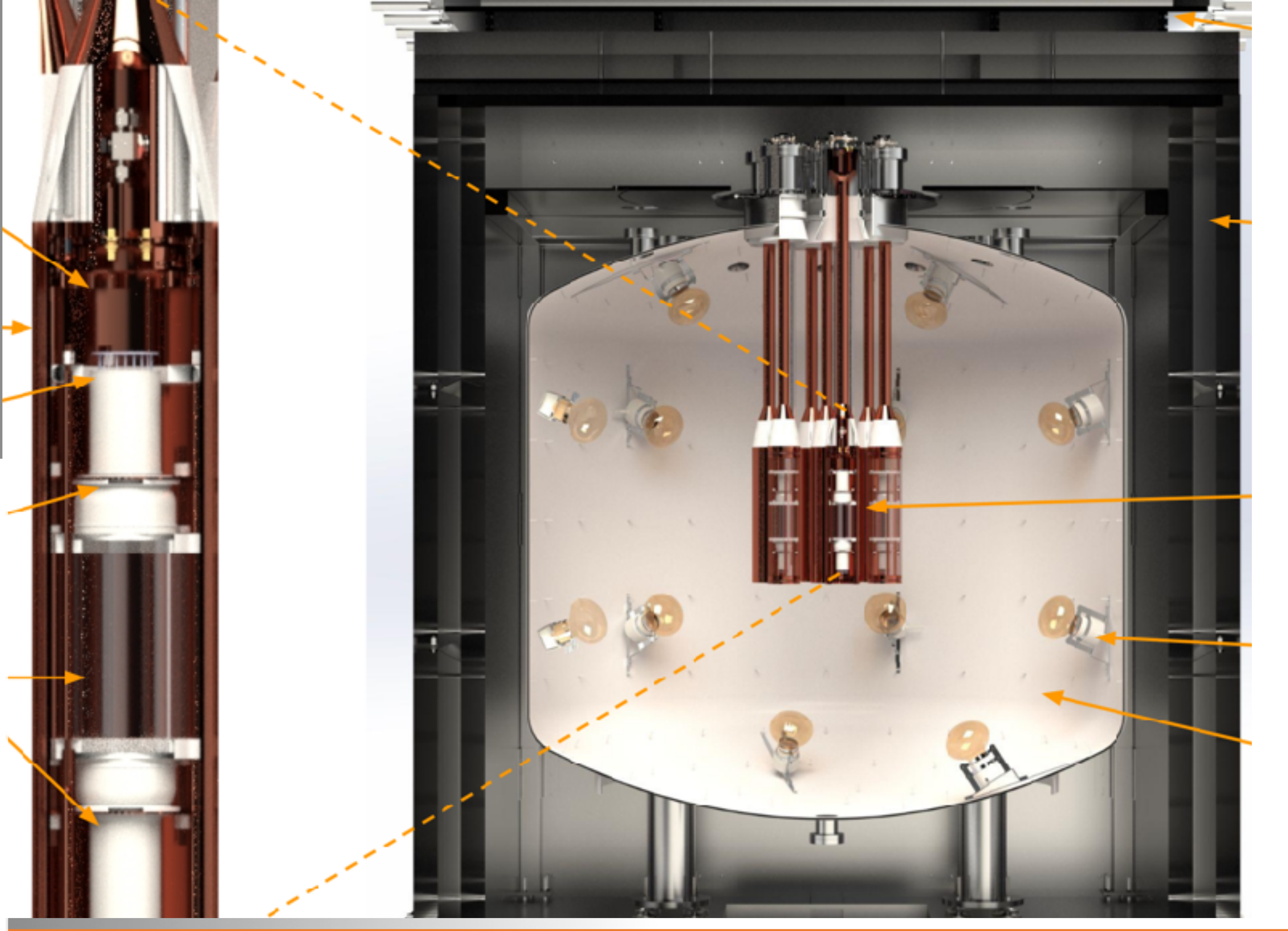
SABRE-North/South

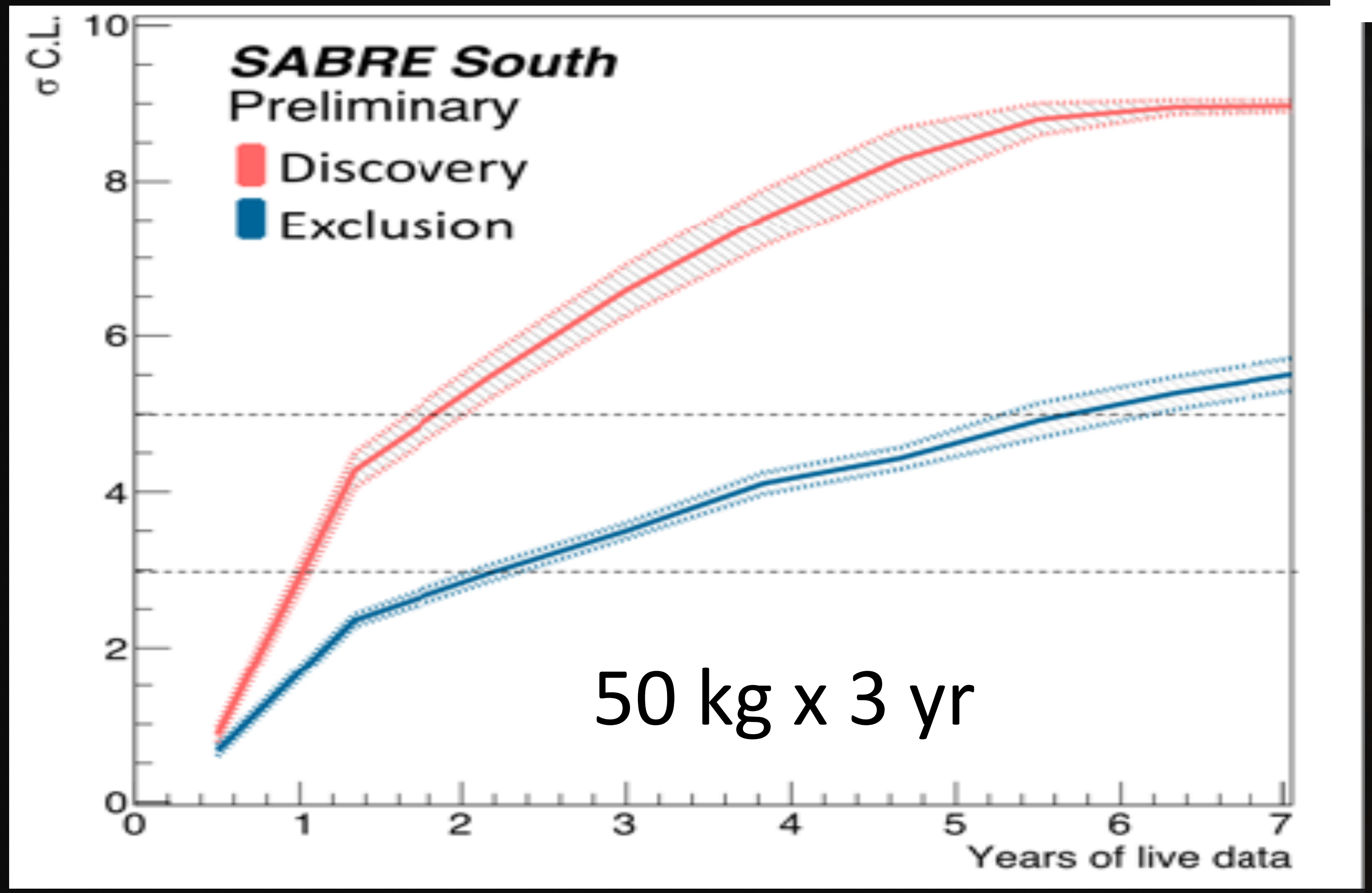
Goal: ~0.1 dru background

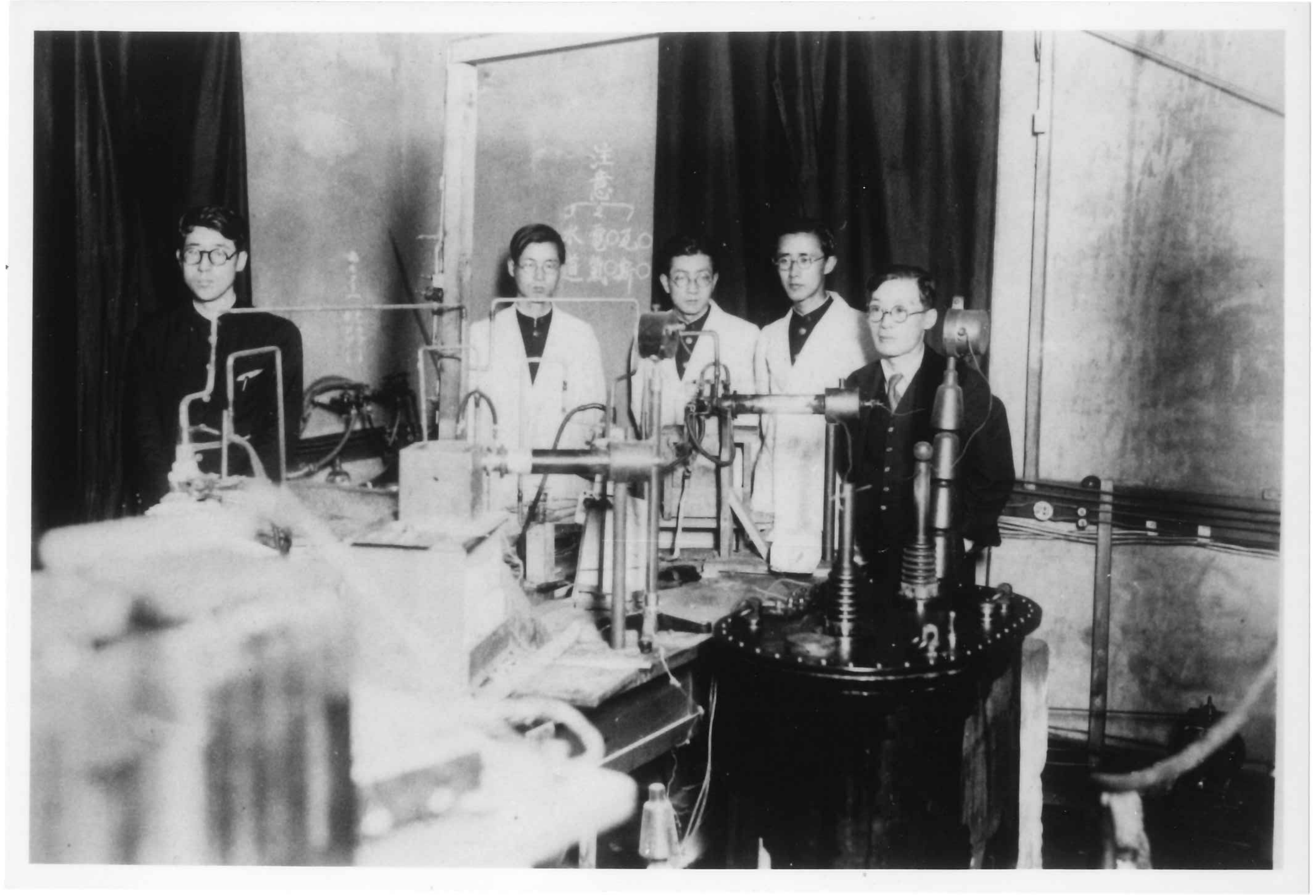
Unambiguous test by running in both hemispheres











吉田卯三郎

Yoshida Usaburo
Kyoto University, ~1930
(My great grandfather)

The Effect of an Electric Field on the Spectrum Lines of Hydrogen.

By

Toshio Takamine and Usaburo Yoshida.

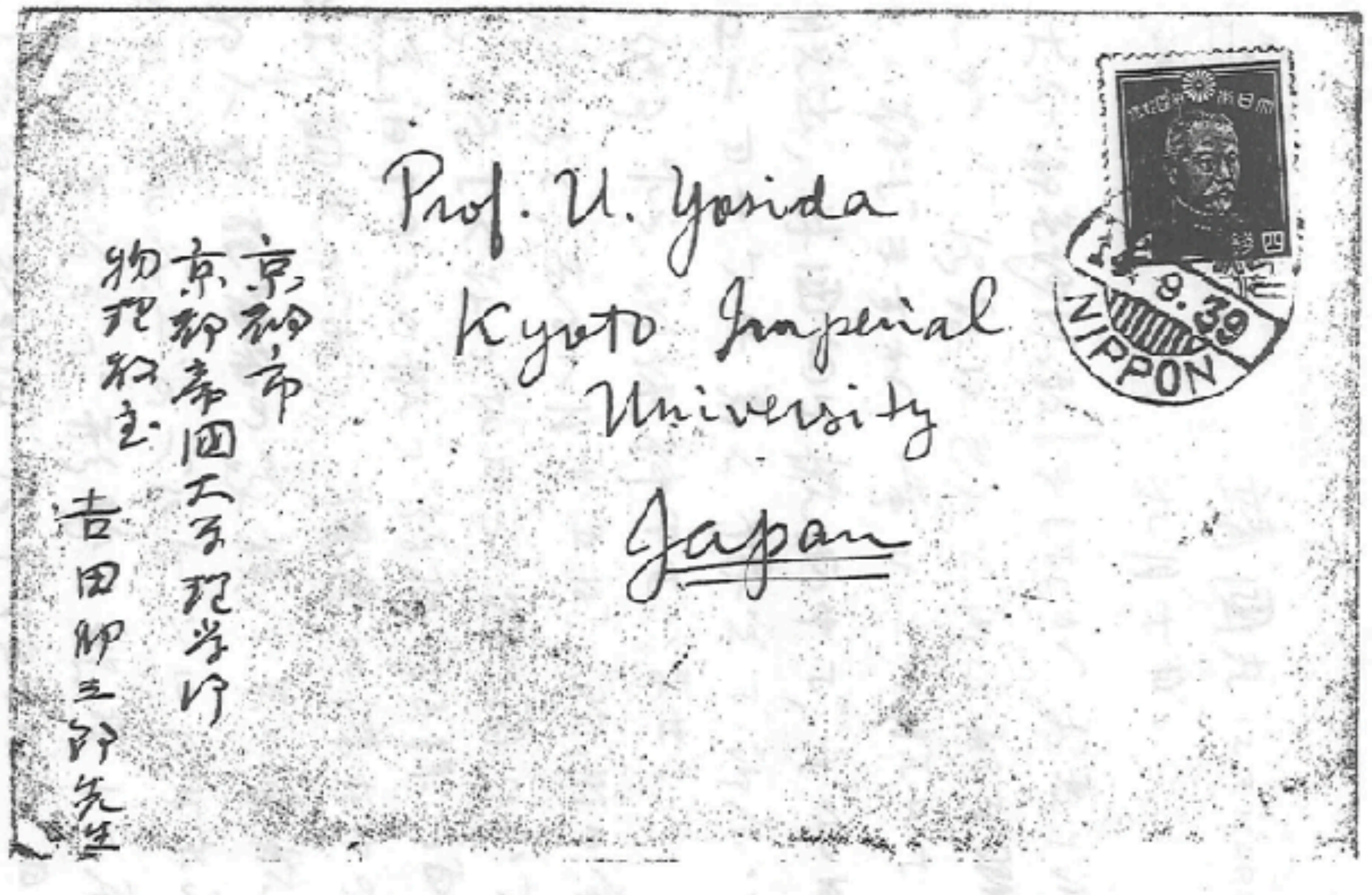
(Received January 26, 1917.)

§ 1. Introduction.

In 1913, the effect of an electric field on spectrum lines was investigated by Stark[1], and also by Lo Surdo[2] under different experimental conditions.

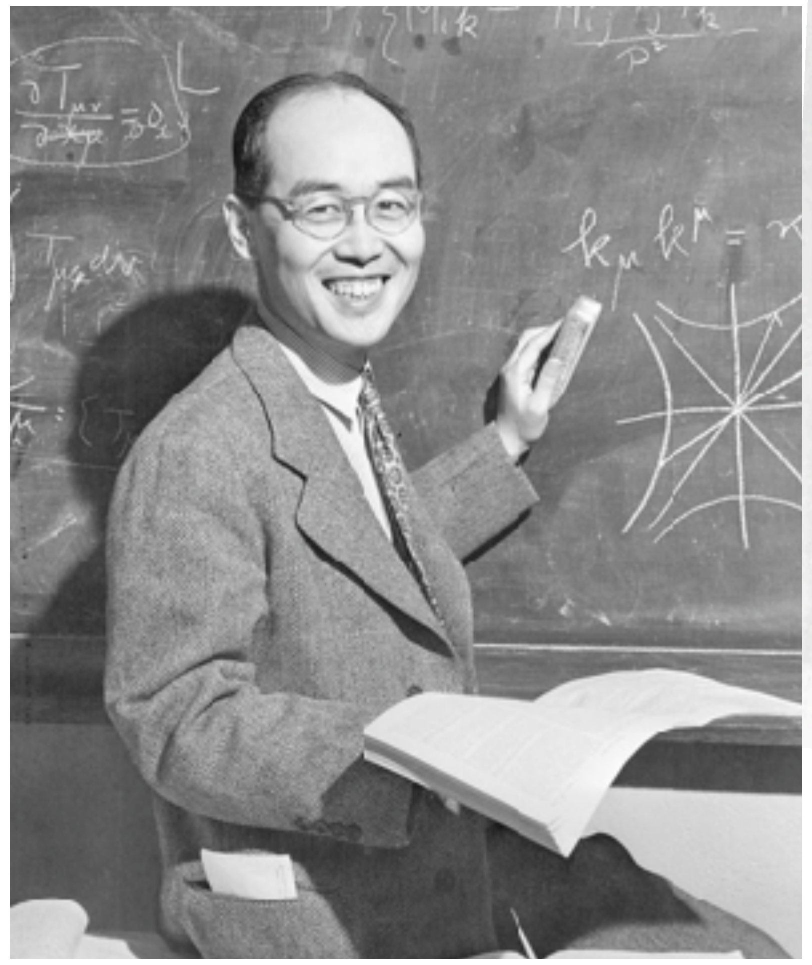
In a series of subsequent investigations undertaken by Stark and others, several elements beside hydrogen and helium were also examined. The results relating to these researches are collected in Stark's "Elektrische Spektralanalyse chemischer Atome."[3]

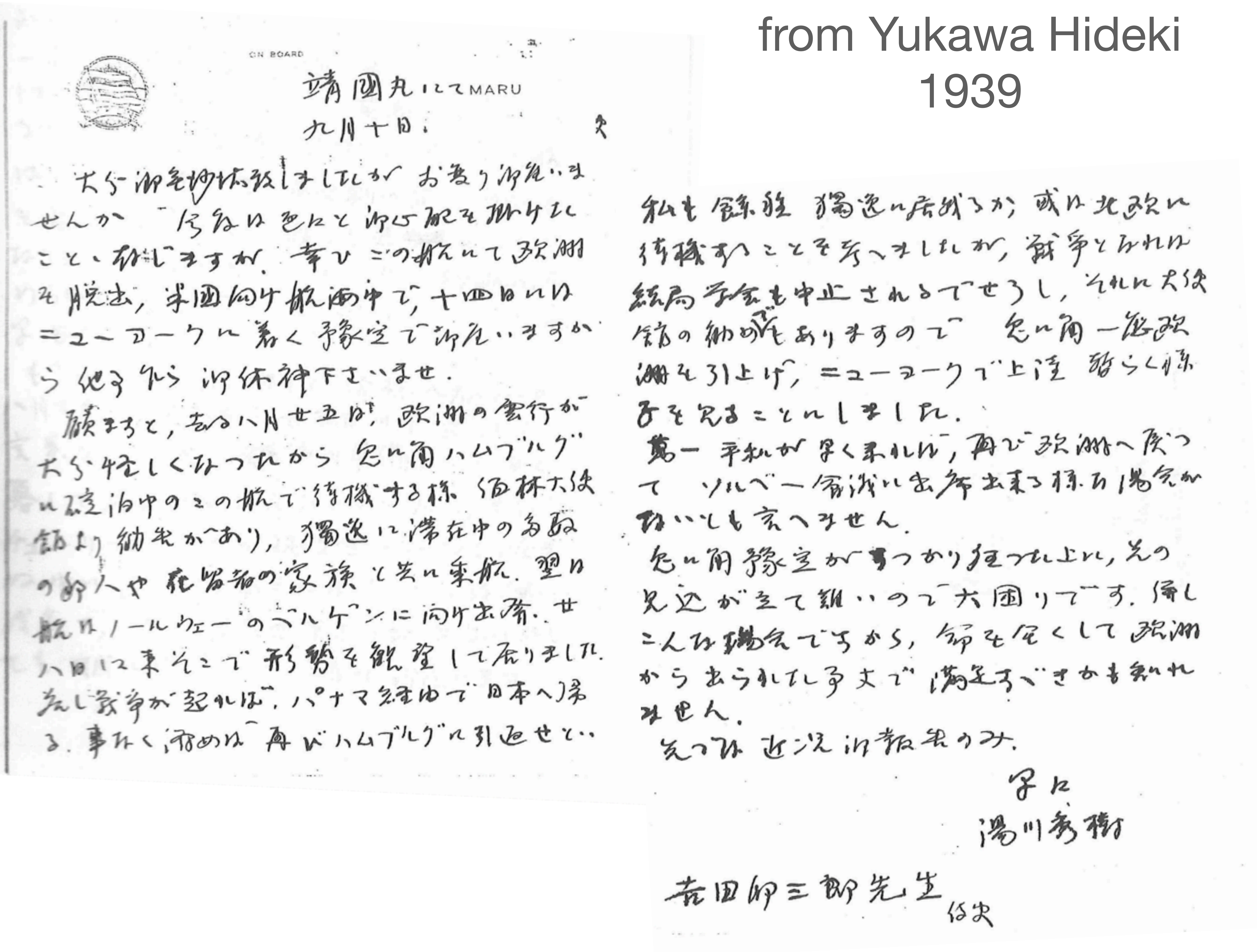
Letter to Yoshida from Yukawa Hideki 1939



京都市
京都帝国大学理学部
物理教室
吉田卯三郎先生

Prof. U. Yosida
Kyoto Imperial University
Japan





ON BOARD

靖国丸にて MARU

九月十日

大分御無沙汰致しましたが お変り御座いませんか 今後は色々と御心配を掛けたことゝ存じますが、幸ひこの船にて欧洲を脱出、米国向け航海中で、十四日にはニューヨークに着く予定で御座いますから 他事乍ら御休神下さいませ。

顧みると、去る八月廿五日、欧洲の雲行が大分怪しくなつたから 兎に角ハムブルグに碇泊中のこの船で待機する様 伯林大使館より納知があり、独逸に滞在中の多数の邦人や留学者の家族と共に乗船、翌日船はノールウェーのベルゲンに向け出帆、廿八日に来てそこで形勢を観望して居りました。若し戦争が起れば、パナマ経由で日本へ帰る。事なく済めば再びハムブルグに引返すといふ

私も結局独逸に居残るか、或は北欧に待機することを考へましたが、戦争となれば結局学会も中止されるでせうし、それに大使館の勧めもありますので 兎に角一応欧洲を引上げ、ニューヨークで上陸 暫らく様子を見ることにしました。

萬一平和が早く来れば、再び欧洲へ戻つて ソルベー会議に出席出来る様な場合がないとも言へません。

兎に角予定がすつかり狂つた上に、その見込が立て難いので大困りです。併しこんな場合ですから、命を全くして欧洲から出られた丈で満足すべきかも知れません。

先づは近況御報告のみ。

早々

湯川秀樹

吉田卯三郎先生 侍史

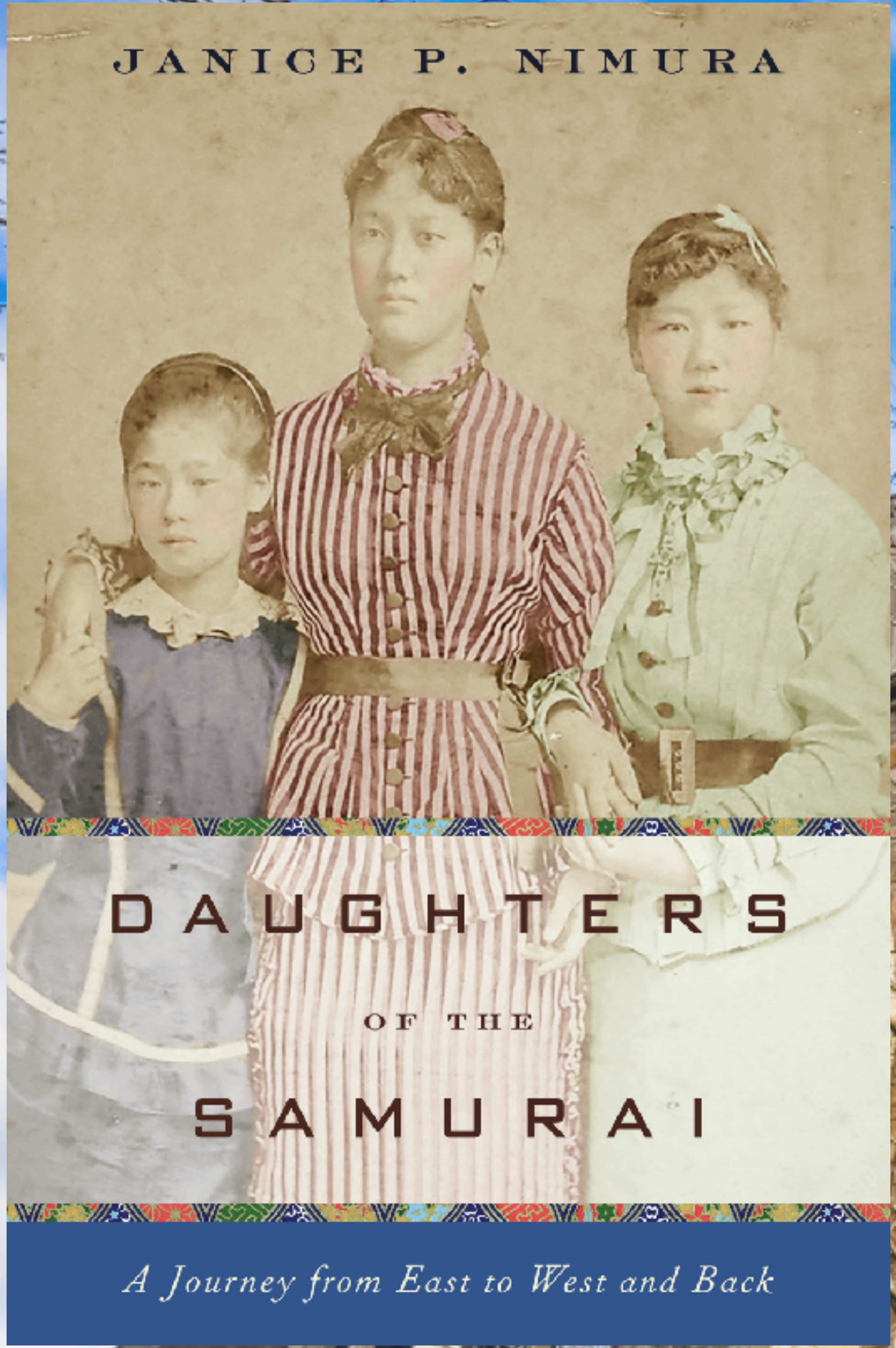
Historical Yale-東大 Physics Connection

Yamakawa Kenjirō
山川 健次郎

1854 – 1931

- First Japanese PhD from Yale in 1875 (Edward Bouchet - 1876)
- First Japanese professor of physics at Tokyo Imperial University (now University of Tokyo)
- President of Tokyo U, Kyushu, Kyoto
- Helped established physics in Japan

Historical Yale-Japan Connection



Daughters of the Samurai

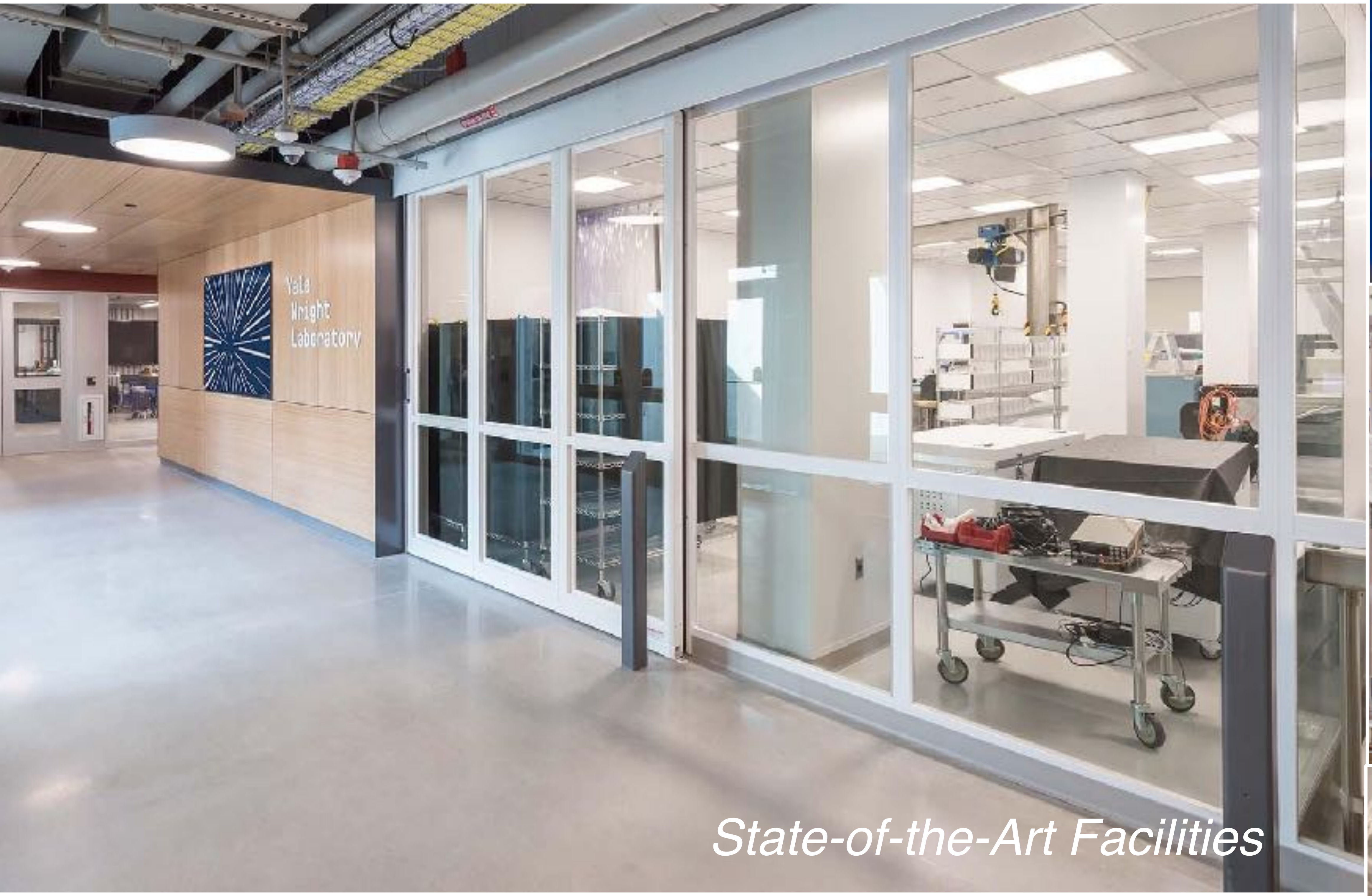
Janice P. Nimura

Chronicles the lives of Yamakawa Sutematsu (Yamakawa Kenjiro's sister), Nagai Shige, and Tsuda Ume who were sent to America as part of the Iwakura Mission in 1871

Yale Wright Laboratory

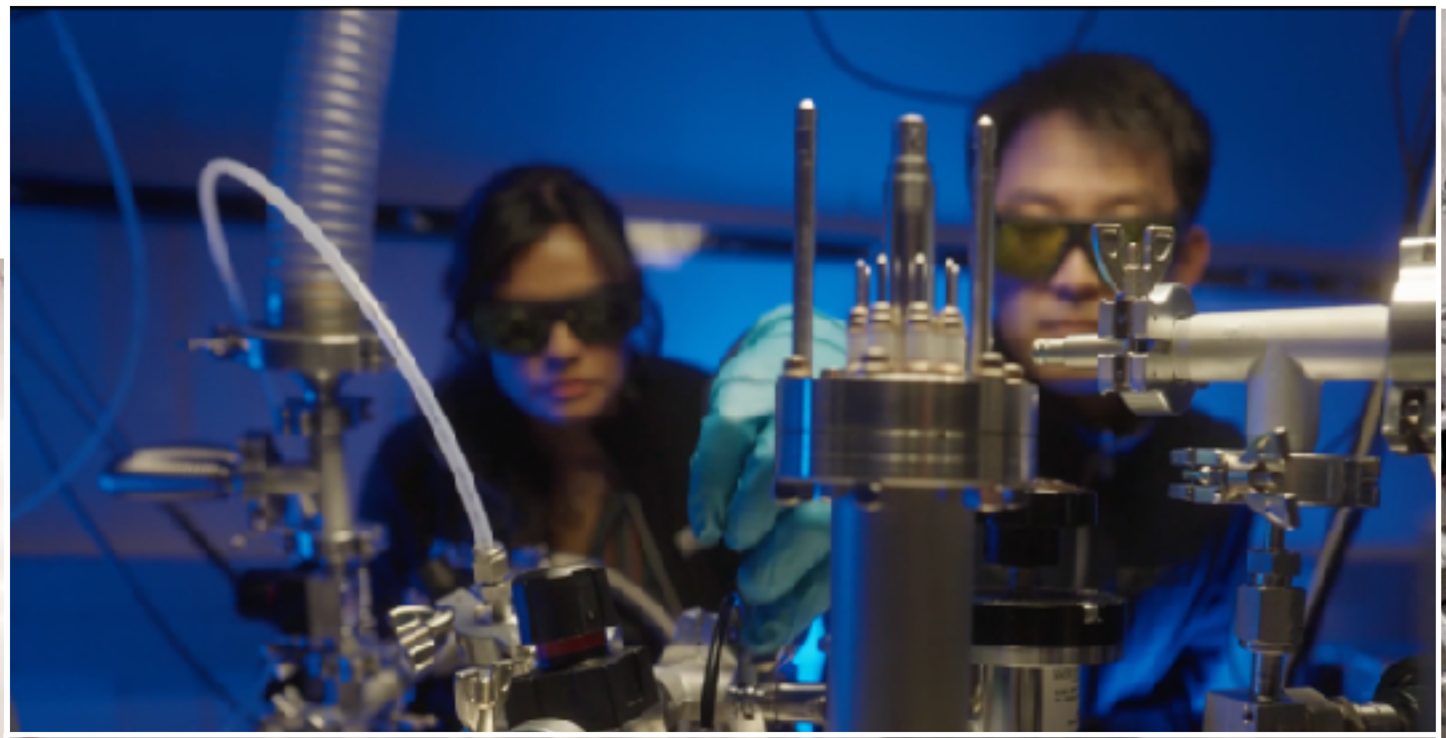
Developing Tools for Discoveries

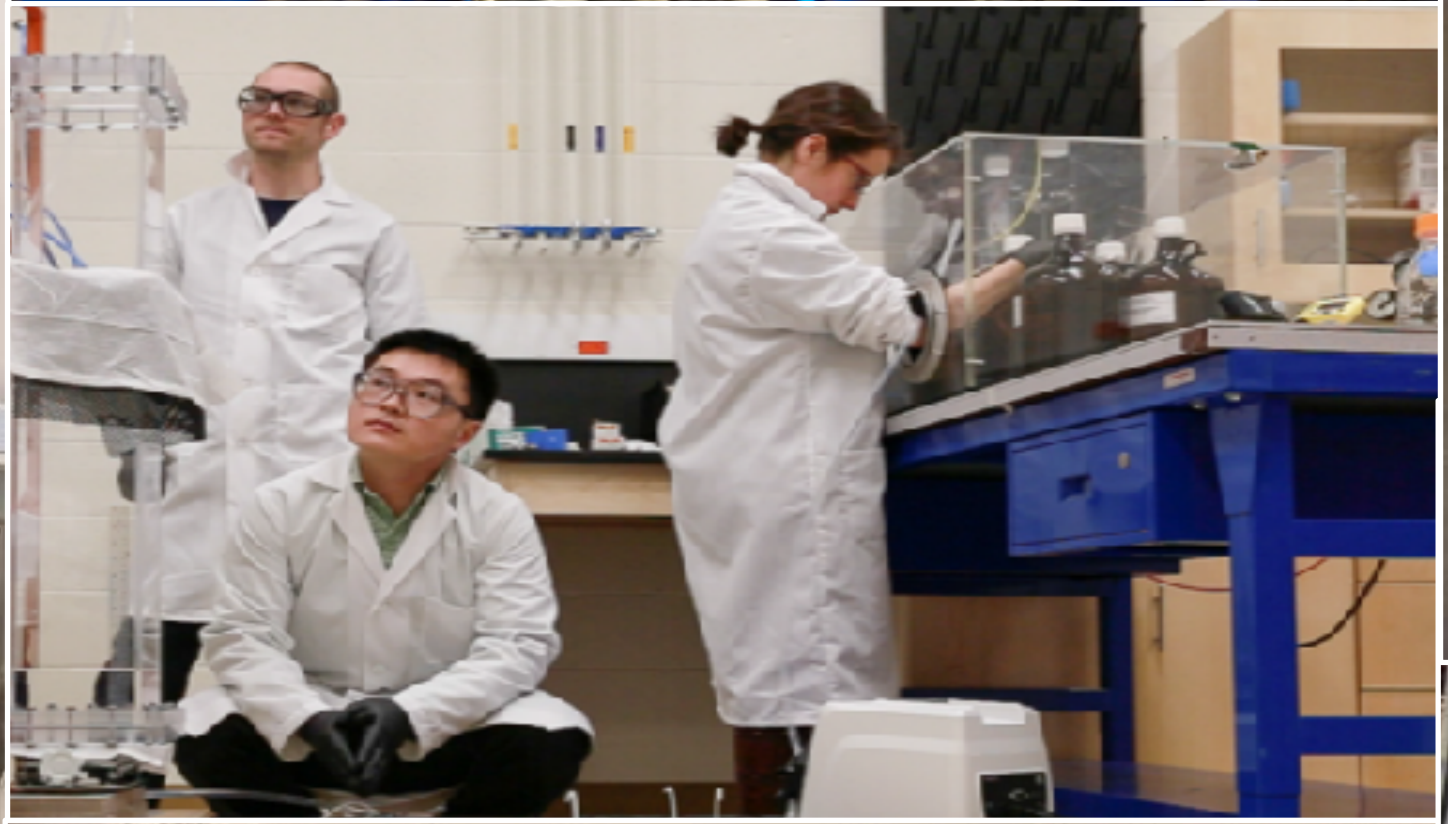
Exploring the Invisible Universe


State-of-the-Art Facilities

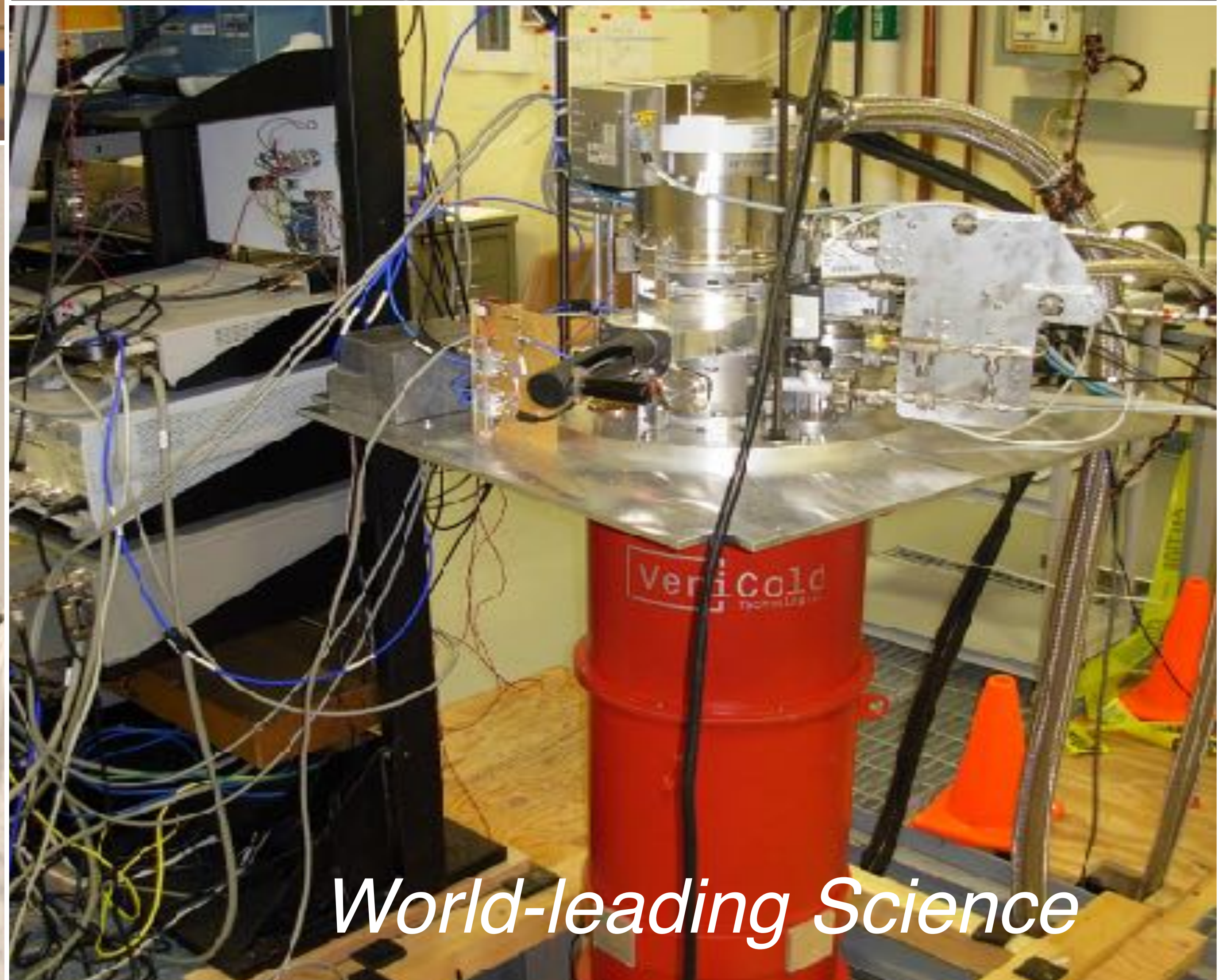
Advancing frontiers of nuclear, particle, and astrophysics including studies of **neutrinos**; searches for **dark matter**; understanding **matter**; exploration of **quantum science** and observations of **the early Universe**.

https://wlab.yale.edu






Training Future Scientists



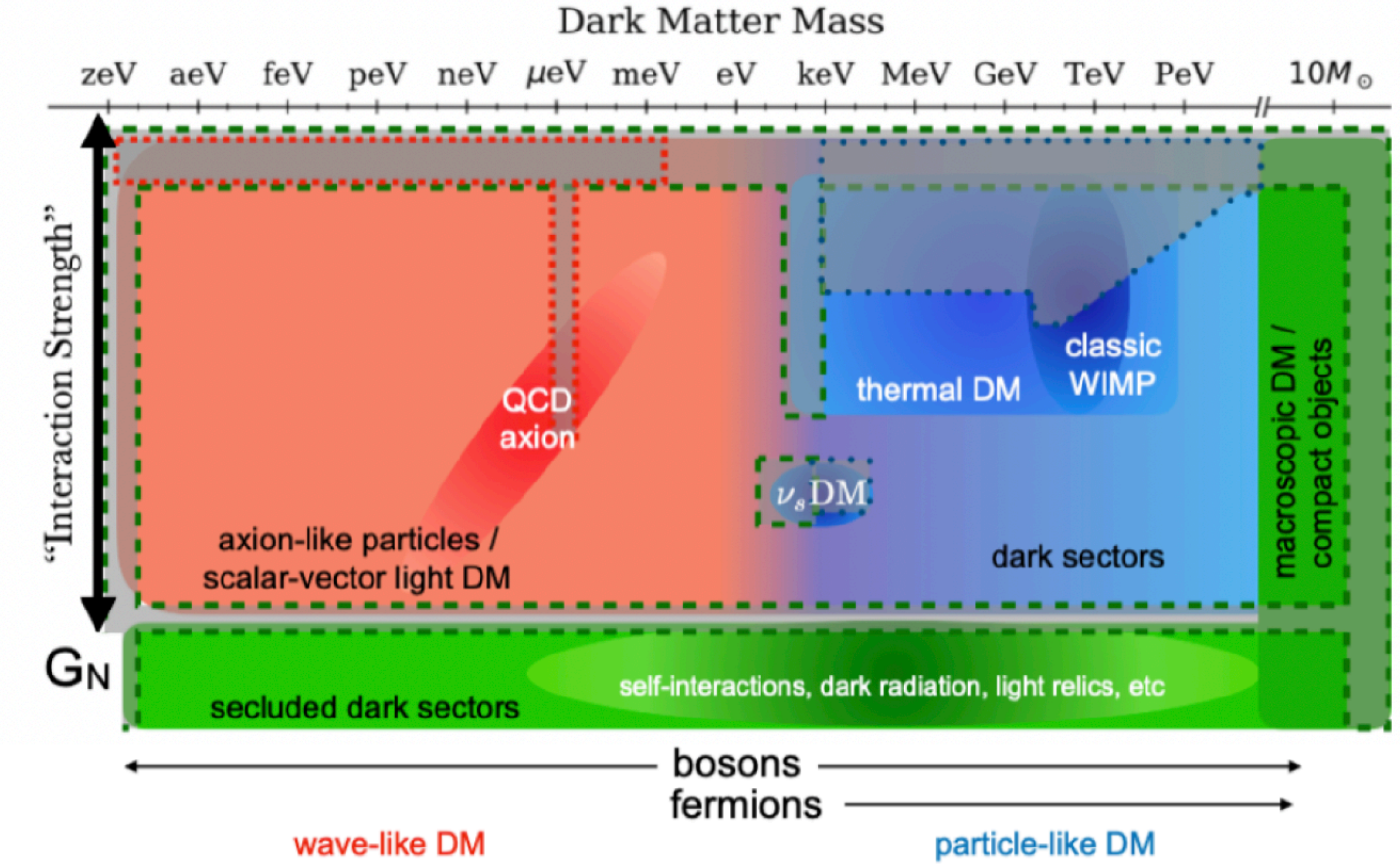
World-leading Science

Yale Wright Laboratory

Exploring the Invisible Universe

Research Worldwide

“Snowmass 2022”: U.S. Dark Matter Program



Snowmass 2022

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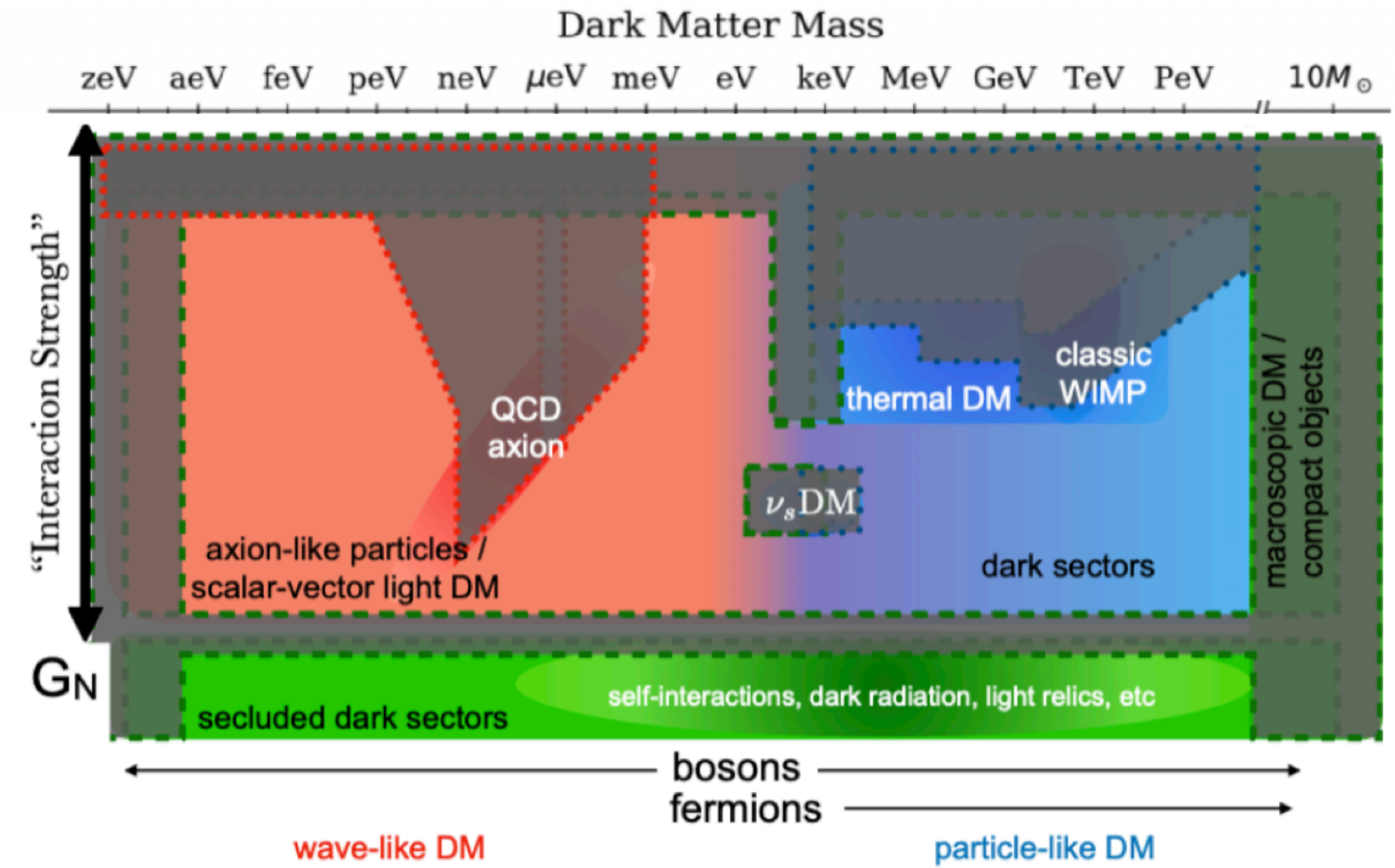
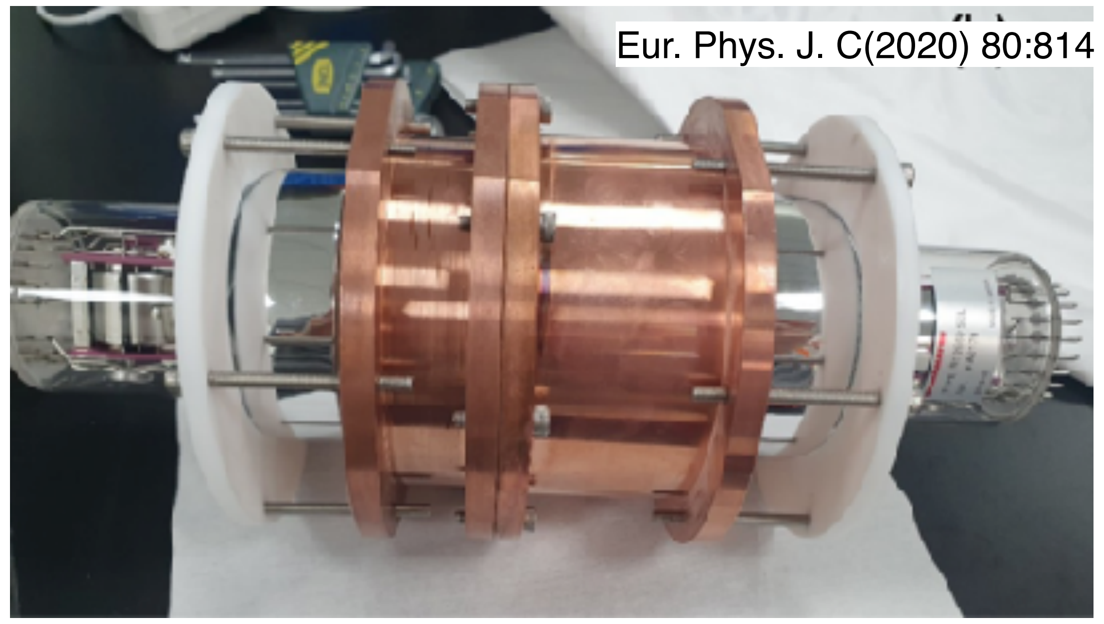


Snowmass 2022

Conclusions



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- DAMA sees annual modulation
- No signal from other direct detection experiments
- ANAIS-112 & COSINE-100 offer direct test, no clear observation of modulation
- However, no explanation for DAMA's signal
    - SABRE & COSINUS may offer new information
- NaI to continue with dark matter searches