Testing DAMA's Long-standing Claim for Dark Matter Detection

Reina Maruyama
Yale University

ICEHAP Seminar, Chiba Japan
17 May 2021

Yale

Wright Laboratory

EPJC 73:2648 (2013)

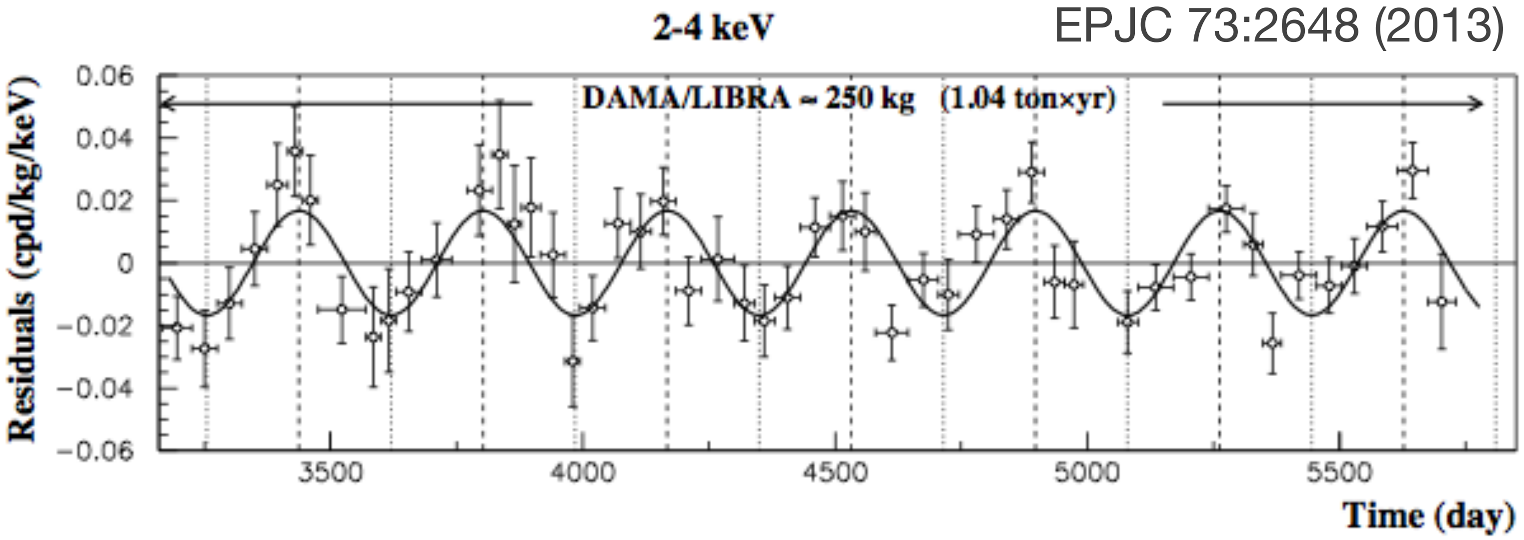
DAMA Phase 1

DAMA Phase 1

- 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

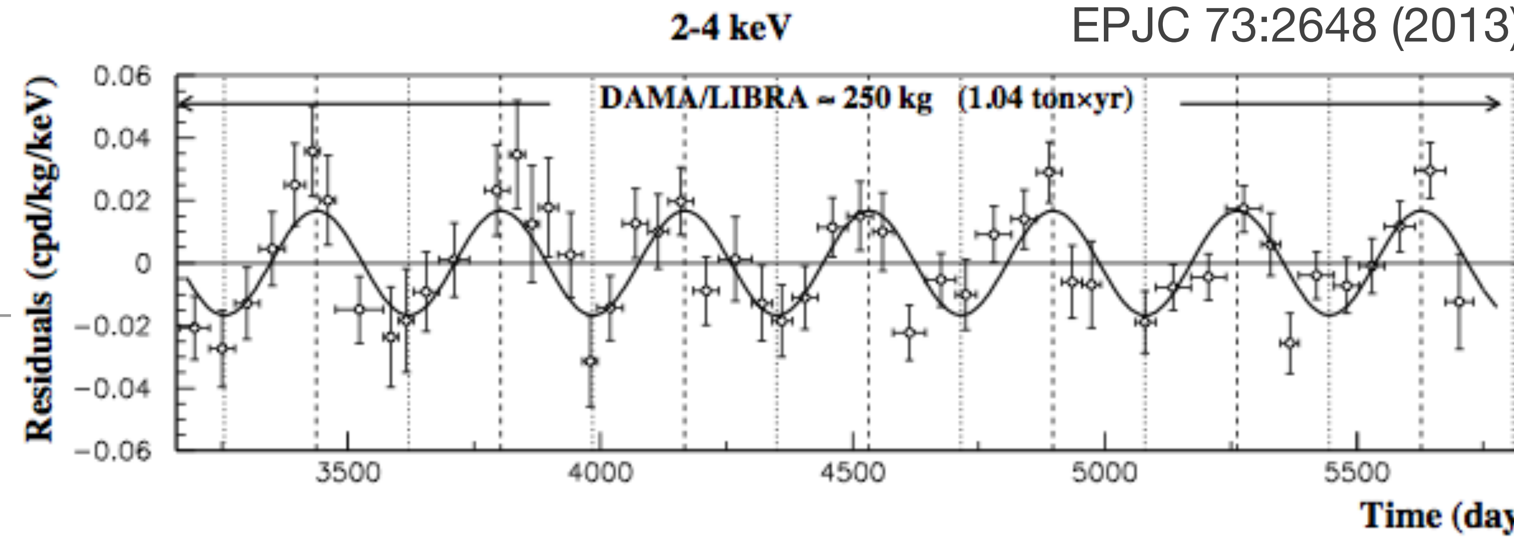
DAMA Phase 1

EPJC 73:2648 (2013)

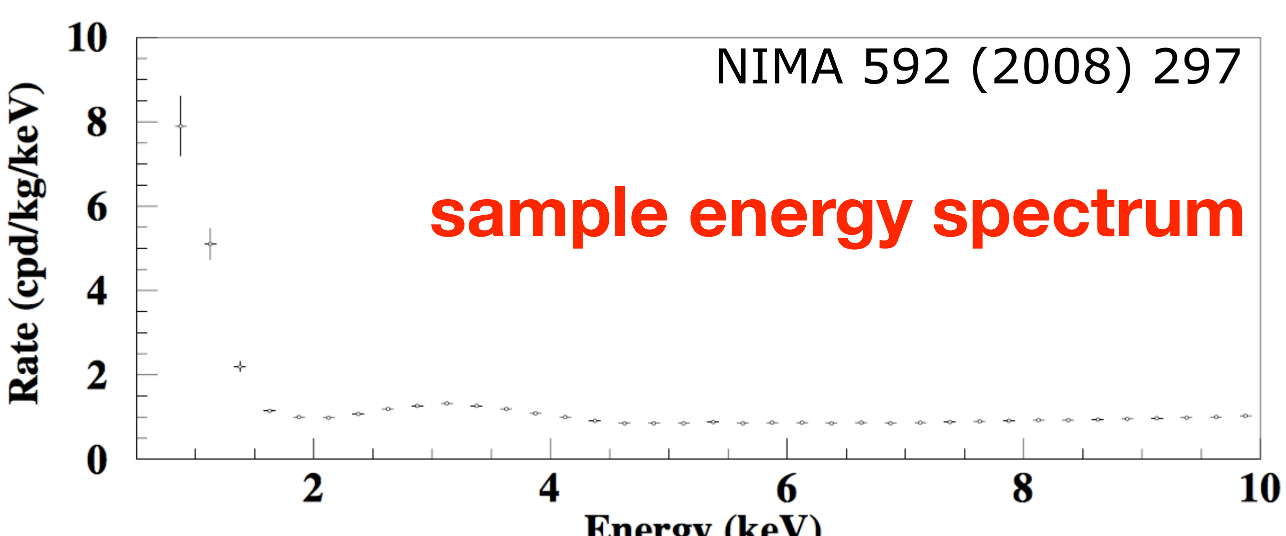


- Phase & Period consistent with dark matter
- Two generations:
  - DAMA/NaI: 100 kg (1996 - 2003)
  - DAMA/LIBRA-phase1: 250 kg (2003 - 2010)
    - Background: ~ 1 count/keV/kg/day
- 1.33 ton-yr over 14 annual cycles

DAMA Phase 1

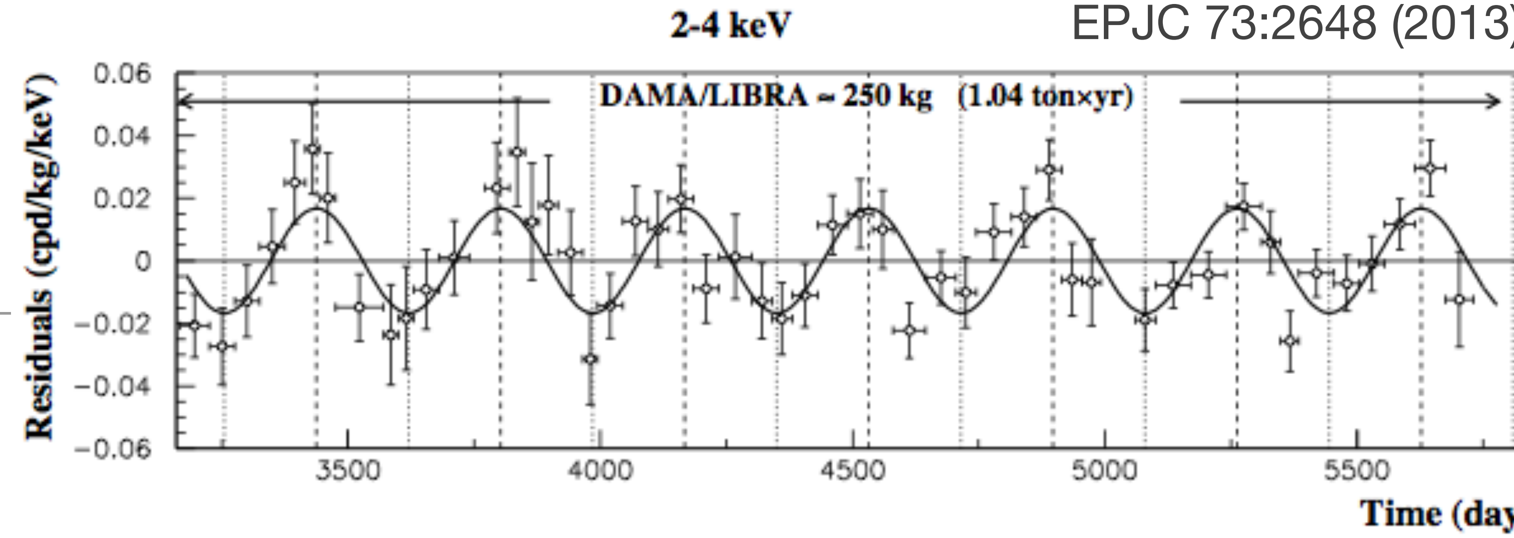


- Phase & Period consistent with dark matter
- Two generations:
  - DAMA/NaI: 100 kg (1996 - 2003)
  - DAMA/LIBRA-phase1: 250 kg (2003 - 2010)
    - Background: ~ 1 count/keV/kg/day
- 1.33 ton-yr over 14 annual cycles

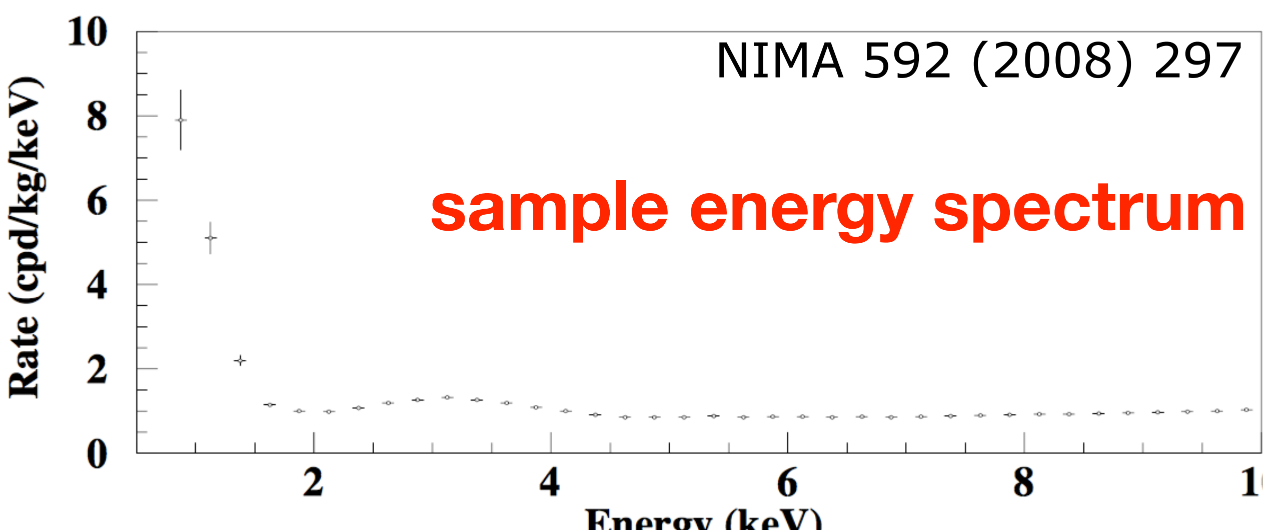


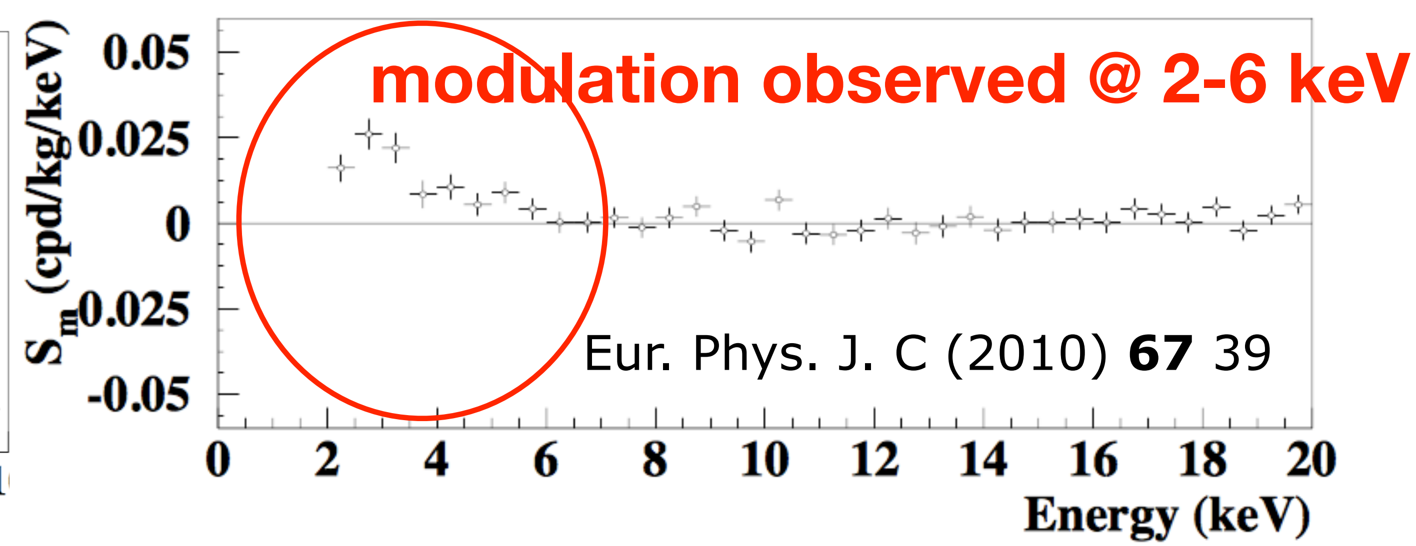
DAMA Phase 1

EPJC 73:2648 (2013)



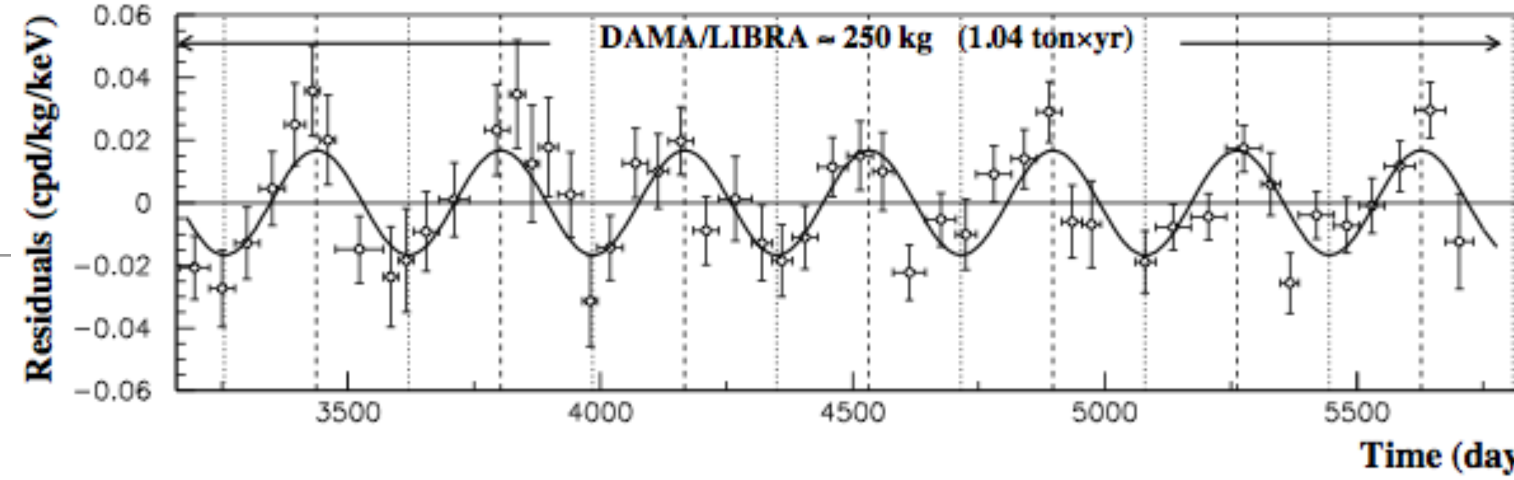
- Phase & Period consistent with dark matter
- Two generations:
  - DAMA/NaI: 100 kg (1996 - 2003)
  - DAMA/LIBRA-phase1: 250 kg (2003 - 2010)
    - Background: ~ 1 count/keV/kg/day
- 1.33 ton-yr over 14 annual cycles



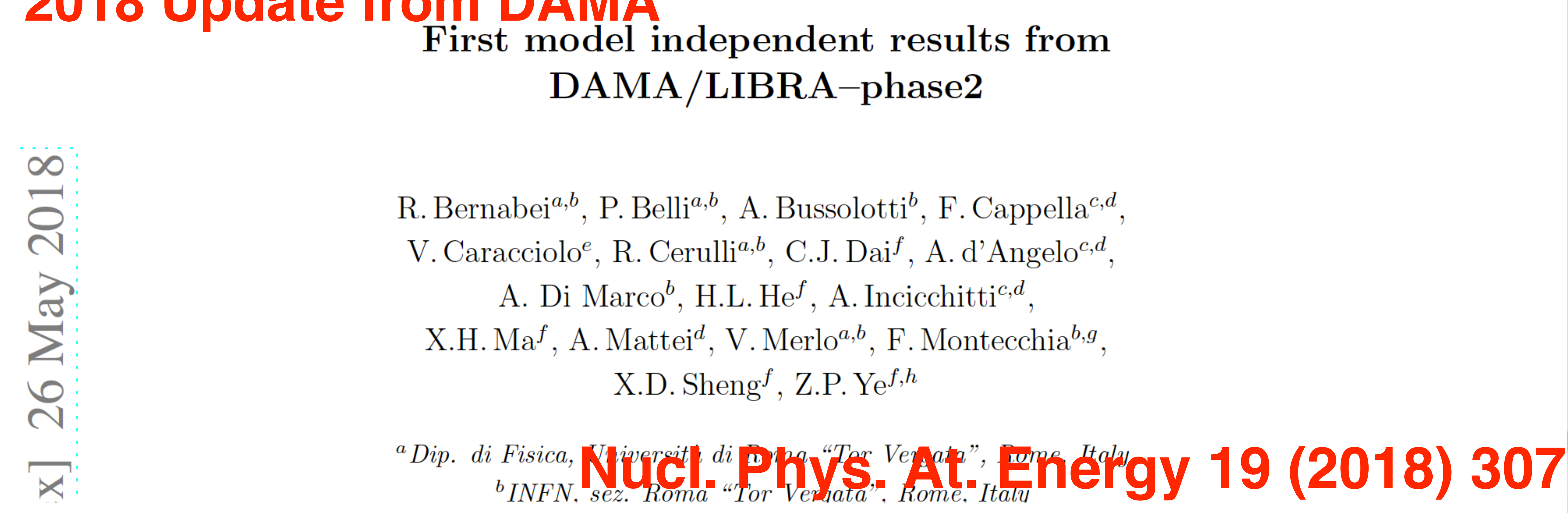


DAMA Phase 1

EPJC 73:2648 (2013)



2018 Update from DAMA


First model independent results from DAMA/LIBRA–phase2

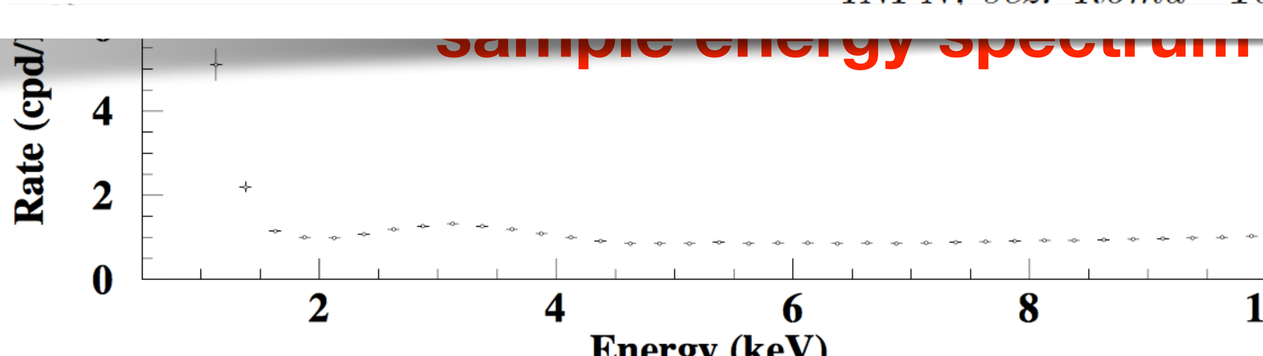
R. Bernabei[a,b], P. Belli[a,b], A. Bussolotti[b], F. Cappella[c,d], V. Caracciolo[e], R. Cerulli[a,b], C.J. Dai[f], A. d'Angelo[c,d], A. Di Marco[b], H.L. He[f], A. Incicchitti[c,d], X.H. Ma[f], A. Mattei[d], V. Merlo[a,b], F. Montecchia[b,g], X.D. Sheng[f], Z.P. Ye[f,h]

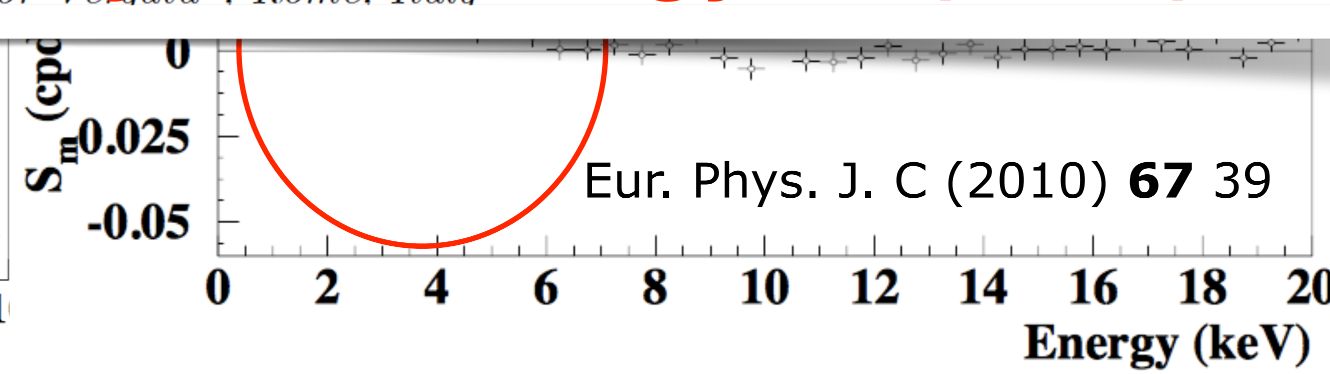
[a] Dip. di Fisica, Università di Roma "Tor Vergata", Rome, Italy

[b] INFN, sez. Roma "Tor Vergata", Rome, Italy

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

sample energy spectrum



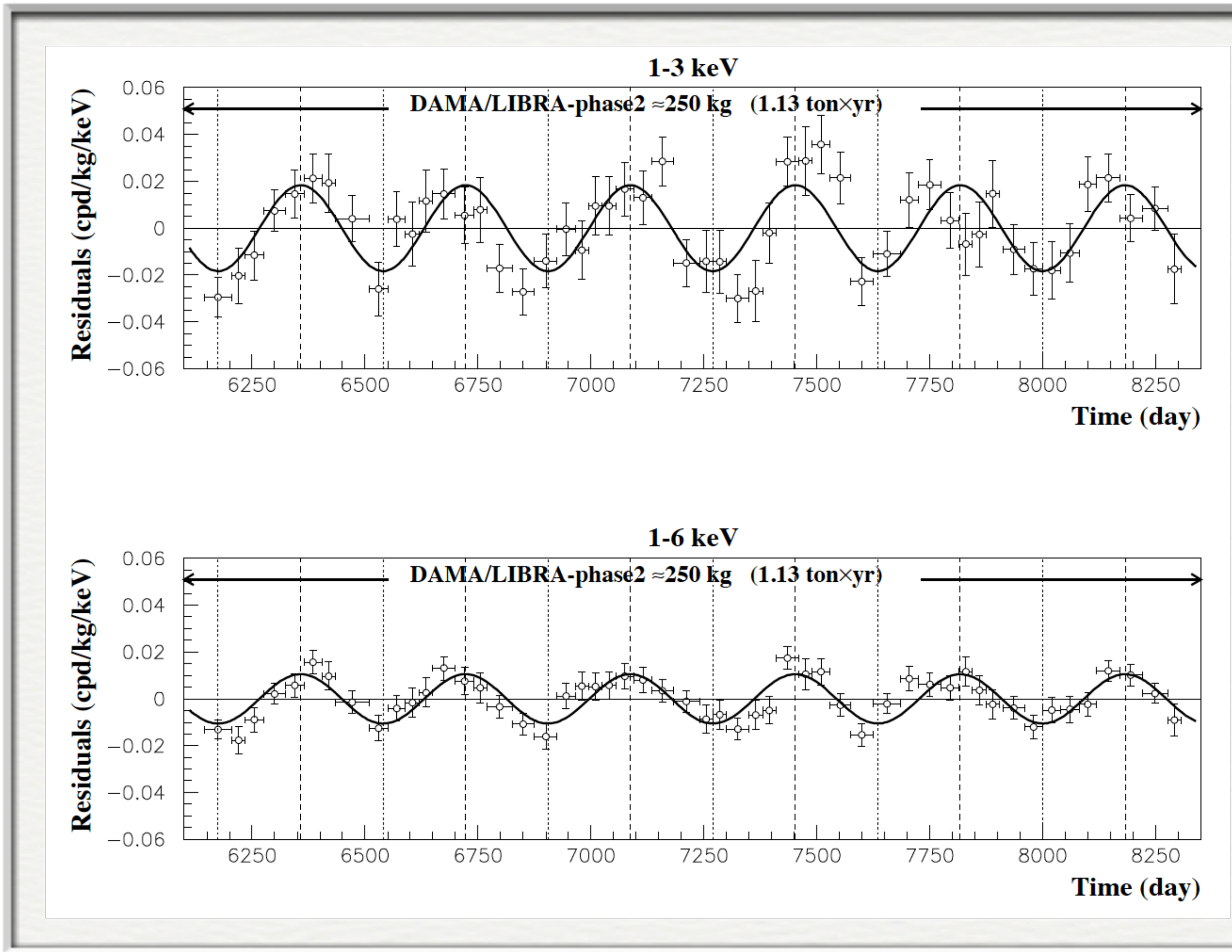


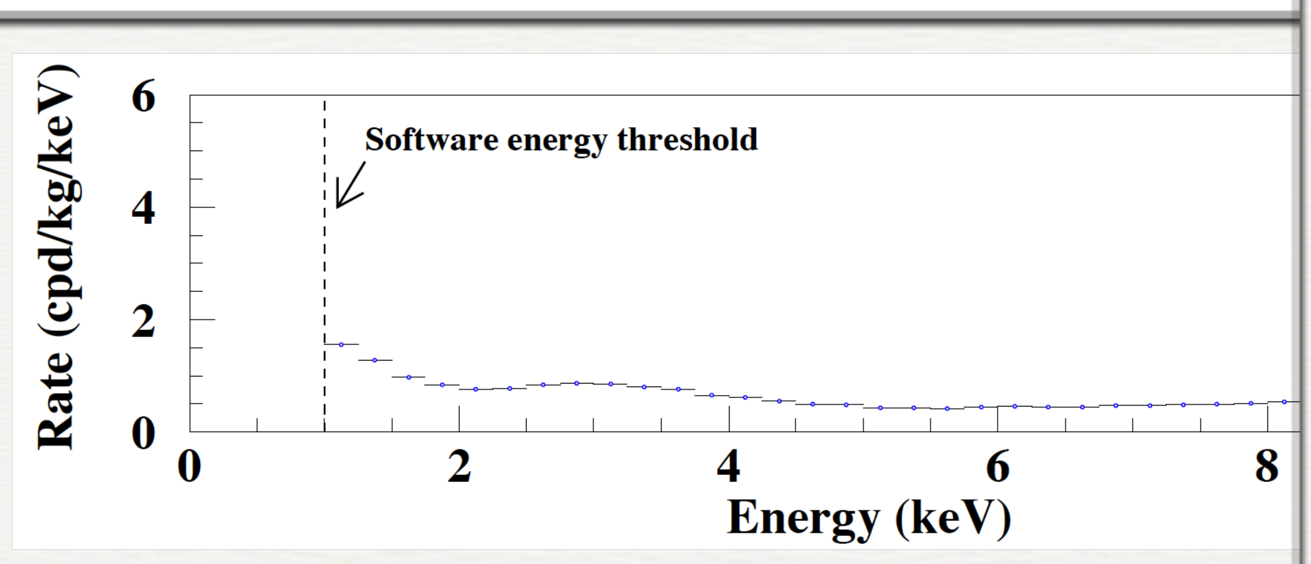
Eur. Phys. J. C (2010) **67** 39

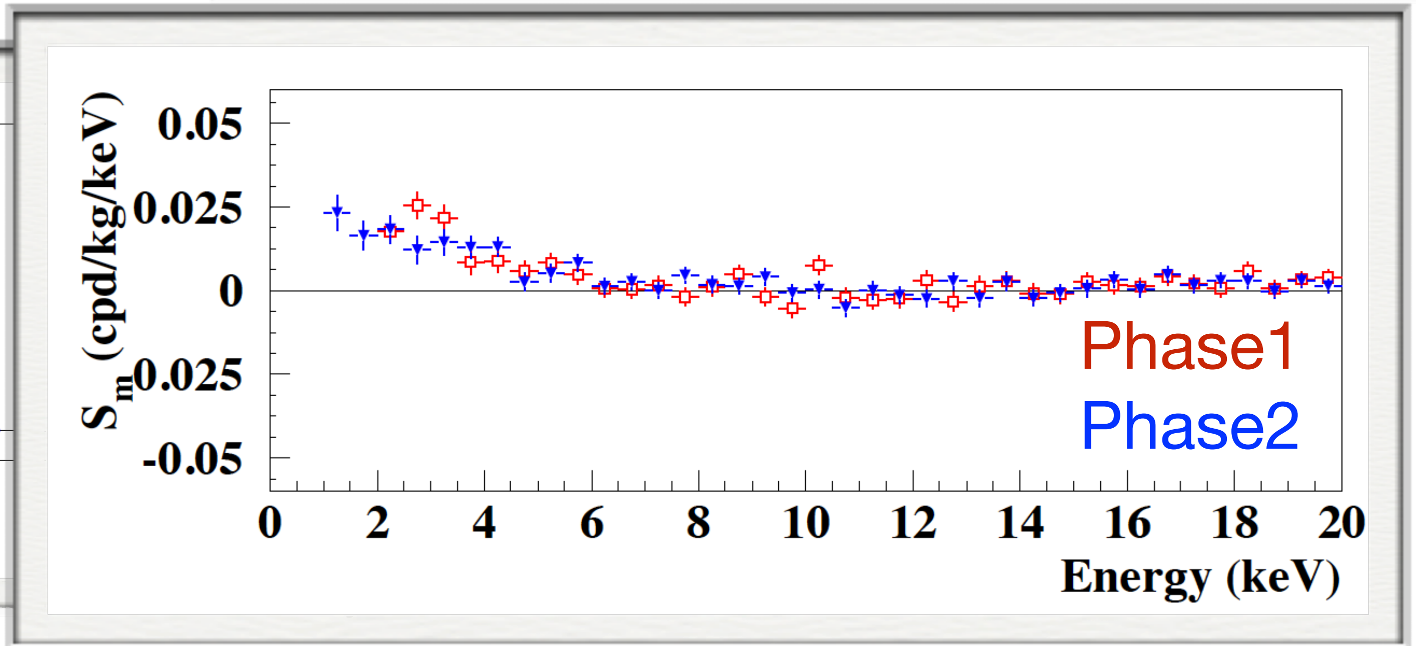
DAMA Persists

Nucl. Phys. At. Energy 19 (2018) 307
arXiv:1805.10486

- Modulation persists in DAMA Phase 2
    - 6+ additional years / 1.13 ton-year
    - Threshold lowered to 1 keV
- **(1 – 6) keV: 9.5σ from 1.13 ton- year**
- **(2 – 6) keV: 12.9σ from 2.46 ton-year**
- Modulation amplitude: (0.0103 +/- 0.0008) cpd/kg/keV
- Phase: (145 +/- 5) days
- period: (0.999 +/- 0.001) year
- Data from Nov. 2011 - Sept. 2017



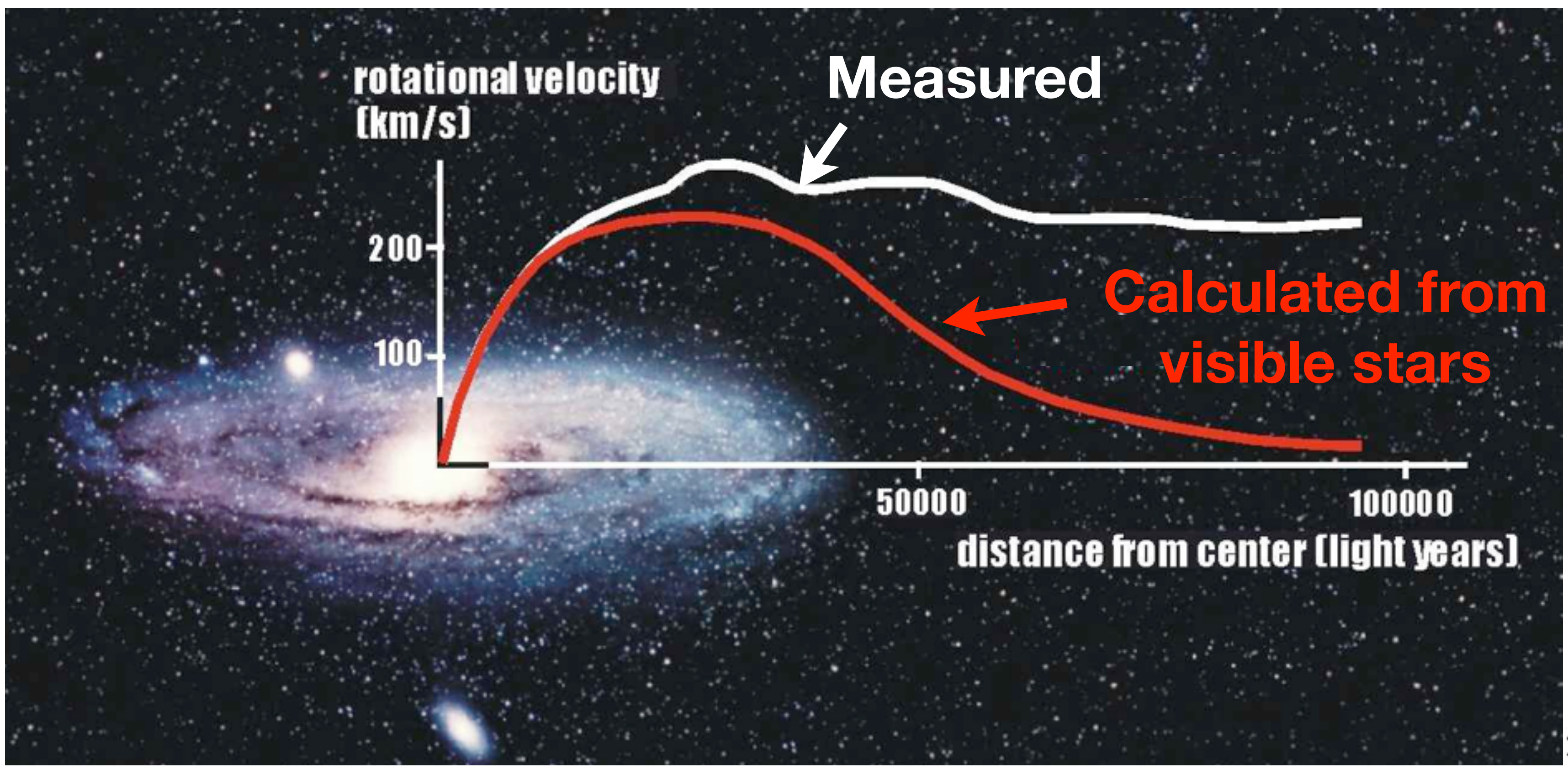


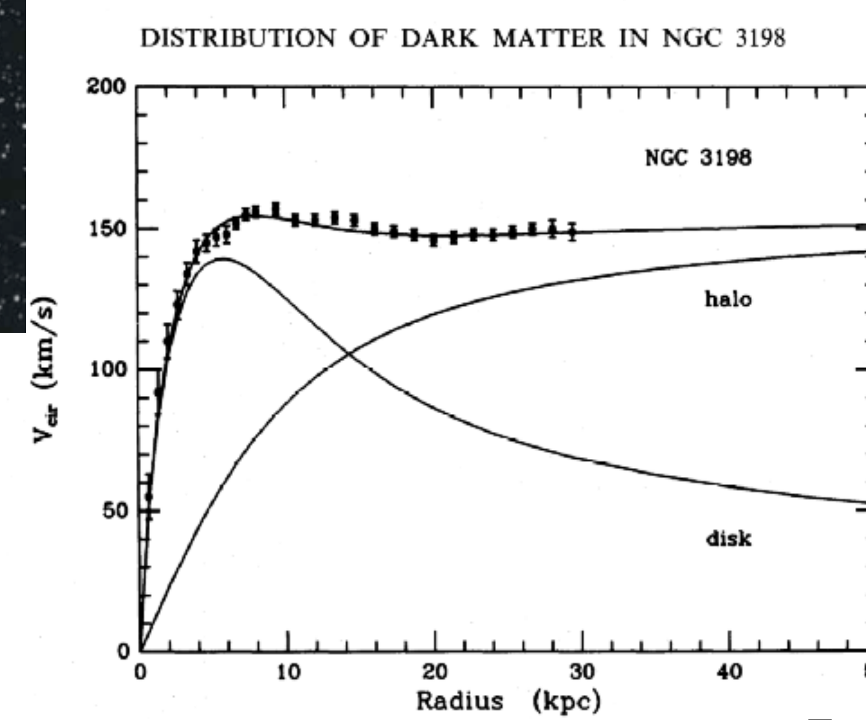


Discovery of Dark Matter

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

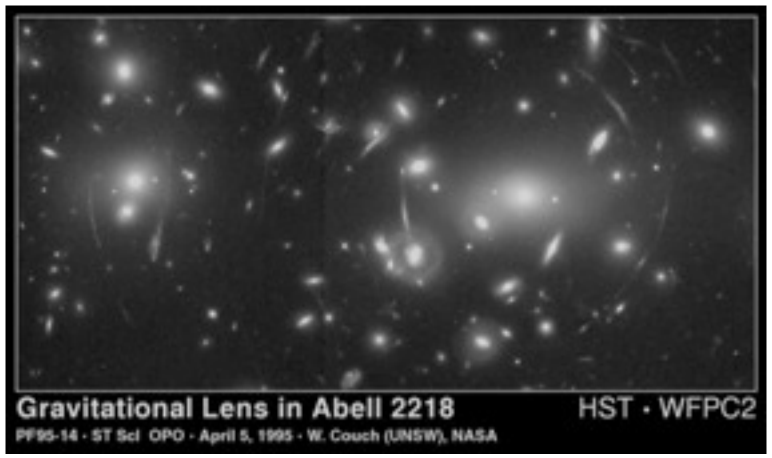
Rotation Curve of Galaxies

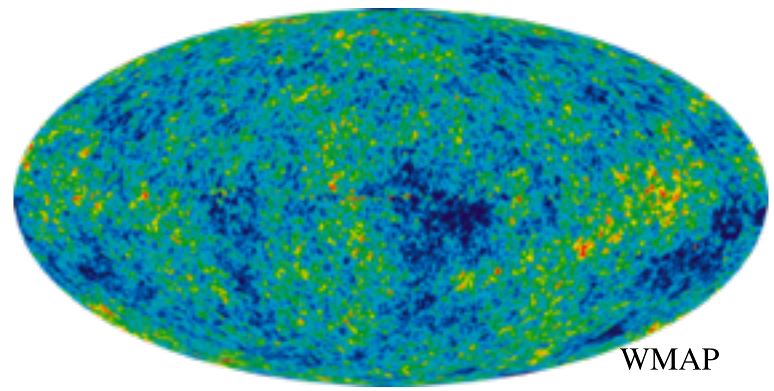




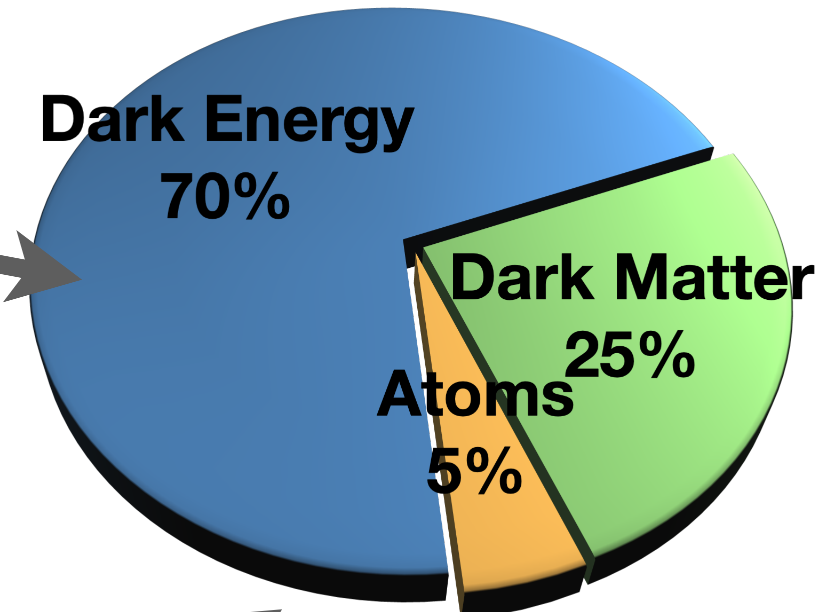
“What you see in a spiral galaxy ...
is not what you get.”

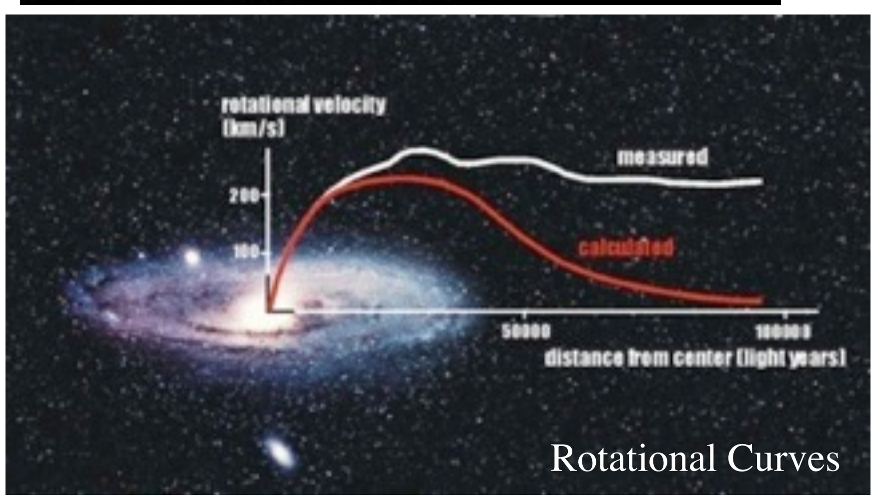
Evidence for Dark Matter

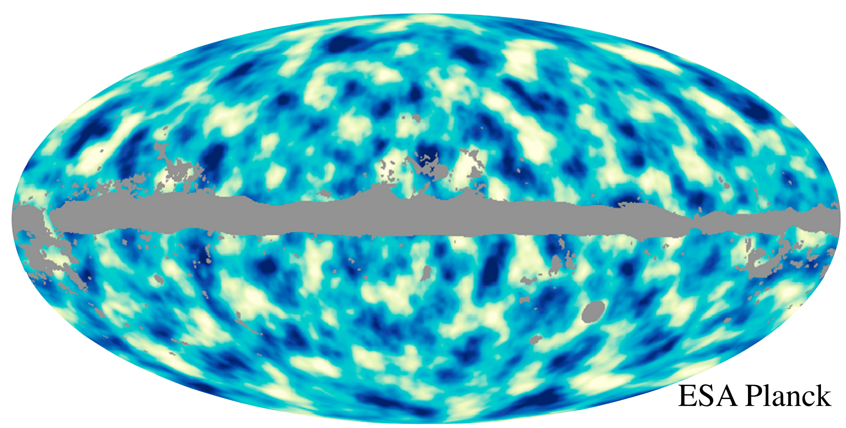




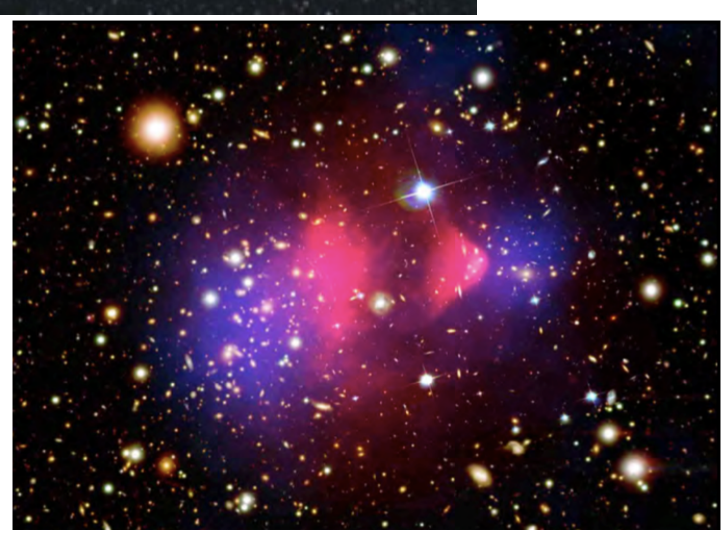
WMAP







ESA Planck



All consistent with ~25% dark matter

First publication on an underground experimental search for cold dark matter

Volume 195, number 4 PHYSICS LETTERS B 17 September 1987

LIMITS ON COLD DARK MATTER CANDIDATES FROM AN ULTRALOW BACKGROUND GERMANIUM SPECTROMETER

S.P. AHLEN [a], F.T. AVIGNONE III [b], R.L. BRODZINSKI [c], A.K. DRUKIER [d,e], G. GELMINI [f,g,1] and D.N. SPERGEL [d,h]

[a] *Department of Physics, Boston University, Boston, MA 02215, USA*
[b] *Department of Physics, University of South Carolina, Columbia, SC 29208, USA*
[c] *Pacific Northwest Laboratory, Richland, WA 99352, USA*
[d] *Harvard-Smithsonian Center for Astrophysics, Cambridge, MA 02138, USA*
[e] *Applied Research Corp., 8201 Corporate Dr , Landover MD 20785, USA*
[f] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[g] *The Enrico Fermi Institute, University of Chicago, Chicago, IL 60637, USA*
[h] *Institute for Advanced Study, Princeton, NJ 08540, USA*

Received 5 May 1987

An ultralow background spectrometer is used as a detector of cold dark matter candidates from the halo of our galaxy Using a realistic model for the galactic halo, large regions of the mass–cross section space are excluded for important halo component particles. In particular, a halo dominated by heavy standard Dirac neutrinos (taken as an example of particles with spin-independent Z^0 exchange interactions) with masses between 20 GeV and 1 TeV is excluded. The local density of heavy standard Dirac neutrinos is <0.4 GeV/cm^3 for masses between 17.5 GeV and 2 5 TeV, at the 68% confidence level.

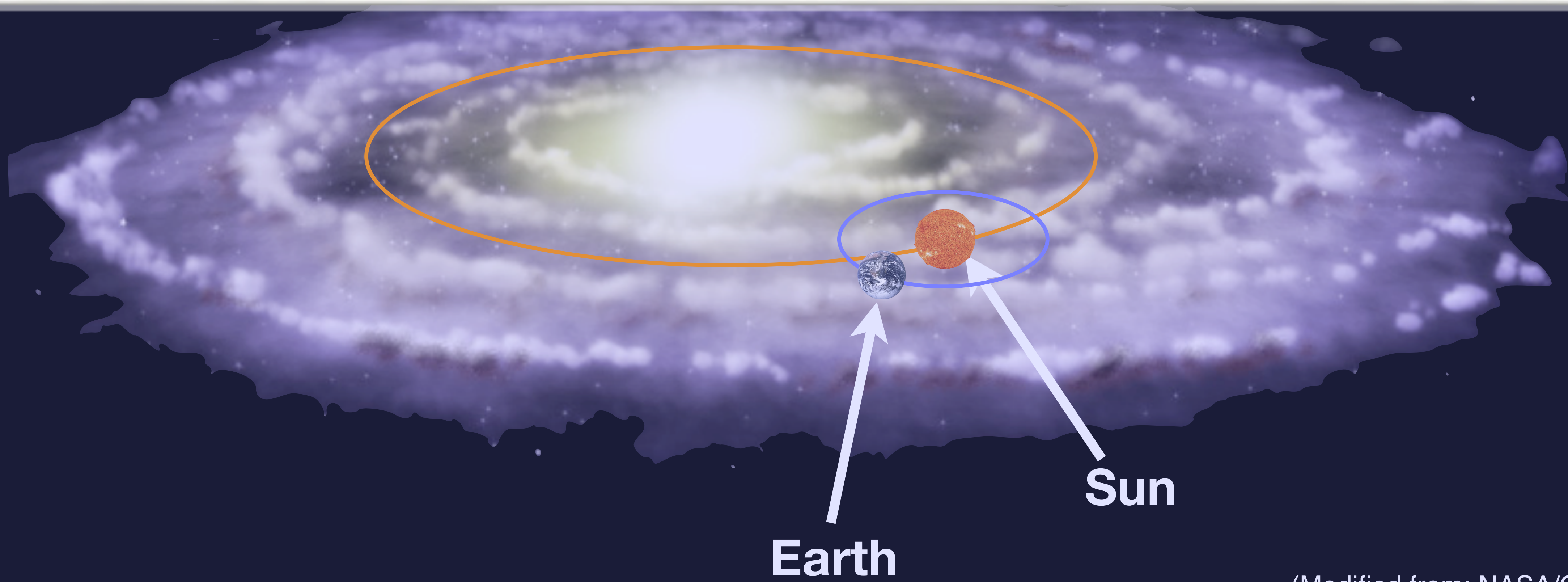
Ahlen et al. Phys. Lett. B **195**, 603 (1987)

Direct Detection Dark Matter Search Strategies

PHYSICAL REVIEW D VOLUME 31, NUMBER 12 15 JUNE 1985

Detectability of certain dark-matter candidates

Mark W. Goodman and Edward Witten
Joseph Henry Laboratories, Princeton University, Princeton, New Jersey 08544
(Received 7 January 1985)



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

Direct Detection Dark Matter Search Strategies

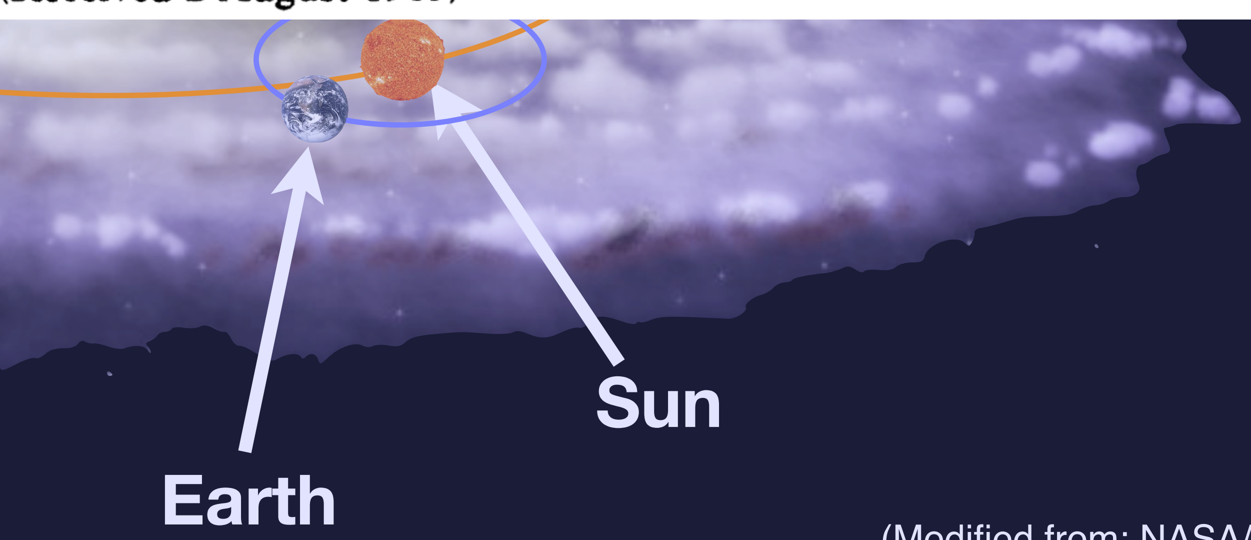
PHYSICAL REVIEW D VOLUME 33, NUMBER 12 15 JUNE 1986

Detecting cold dark-matter candidates

Andrzej K. Drukier
*Max-Planck-Institut für Physik und Astrophysik, 8046 Garching, West Germany
and Department of Astronomy, Harvard-Smithsonian Center for Astrophysics,
60 Garden Street, Cambridge, Massachusetts 02138*

Katherine Freese and David N. Spergel
*Department of Astronomy, Harvard-Smithsonian Center for Astrophysics, 60 Garden Street,
Cambridge, Massachusetts 02138*
(Received 2 August 1985)

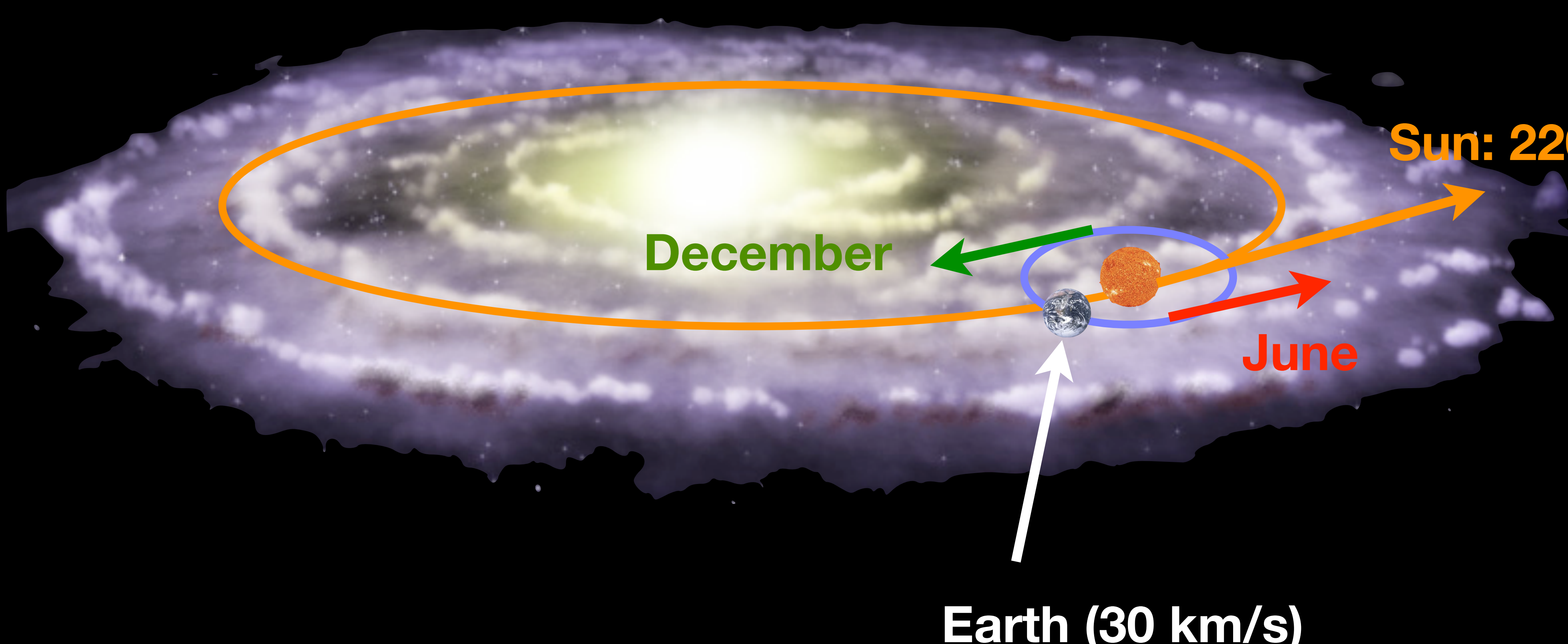




Drukier, Freese & Spergel PRD**33** 3495 (1986)

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

Annual Modulation



Rates Peak in June.

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

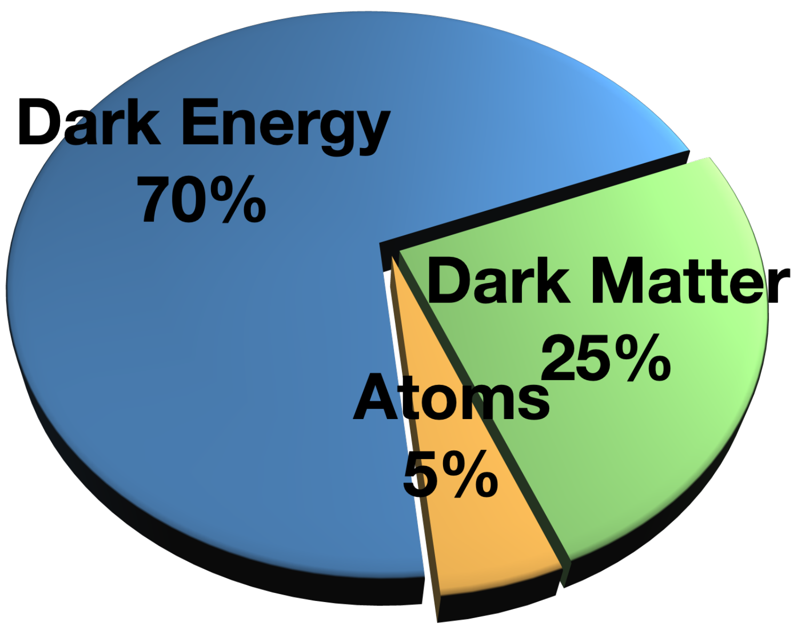
Characteristics of dark matter

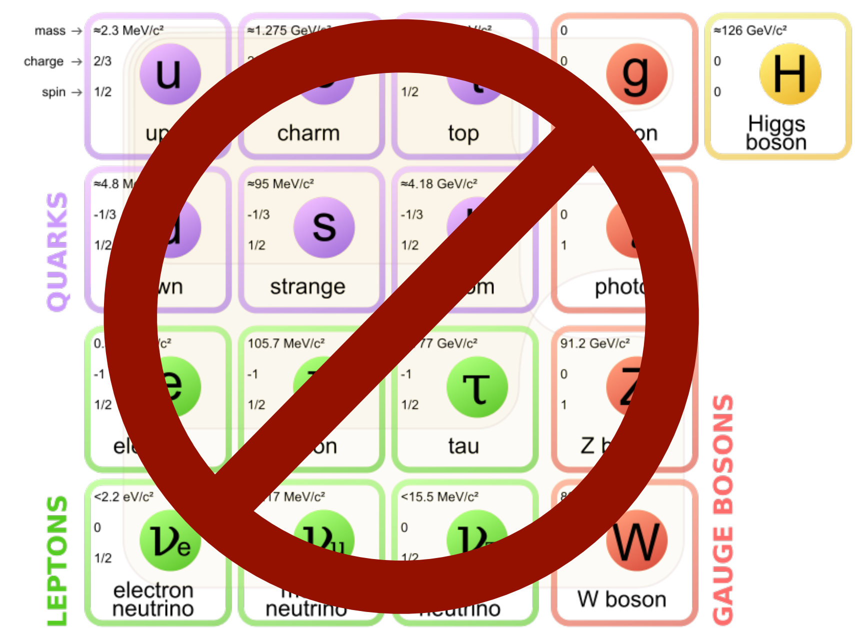
Naturally give right cosmic density

- *thermal production in hot primordial plasma.*

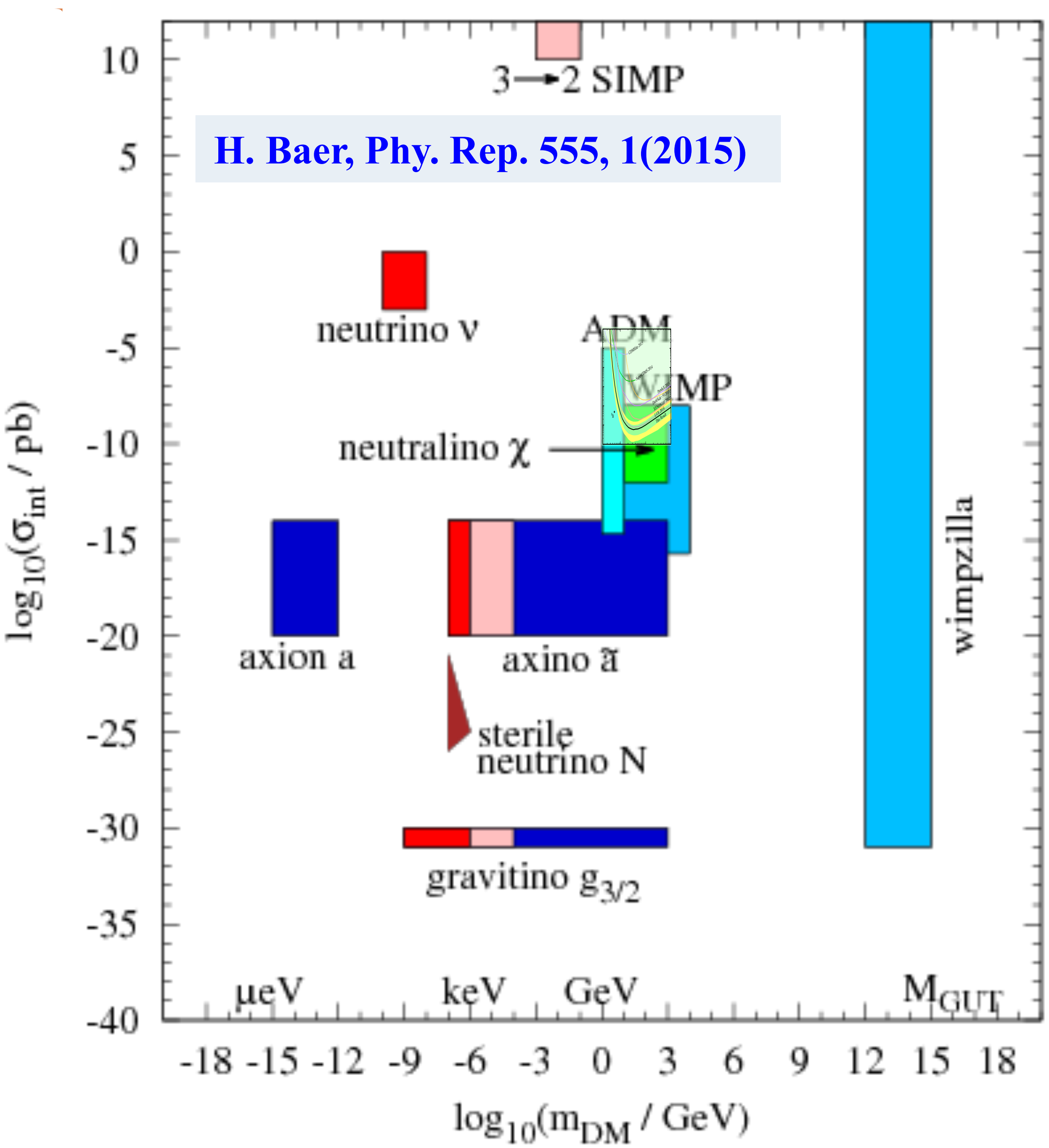
Matches requirements from DM evidence

- *Non-baryonic*
- *non-relativistic and exerts gravity*
- *Interact little with ordinary matter*
- *Stable and long-lived*
- *local density: ρ = 0.39 ± 0.03 GeV/cm3*





Dark Matter Candidates



Leading Candidates:

WIMPs: Weakly Interacting Massive Particles

- mass of 1 GeV – 10 TeV
- weak scale cross sections results in observed abundance
- DAMA, CDMS, LUX/LZ, XENON, PICO, DarkSide, PandaX, …
- Recent developments for low-mass …

Axions

- mass ~10^{-3} – 10^{-6} eV
- Arises in the Peccei-Quinn solution to the strong-CP problem
- ADMX, HAYSTAC, Radio-DM, ABRA, CASPEr, …

Where Can We Find Dark Matter?

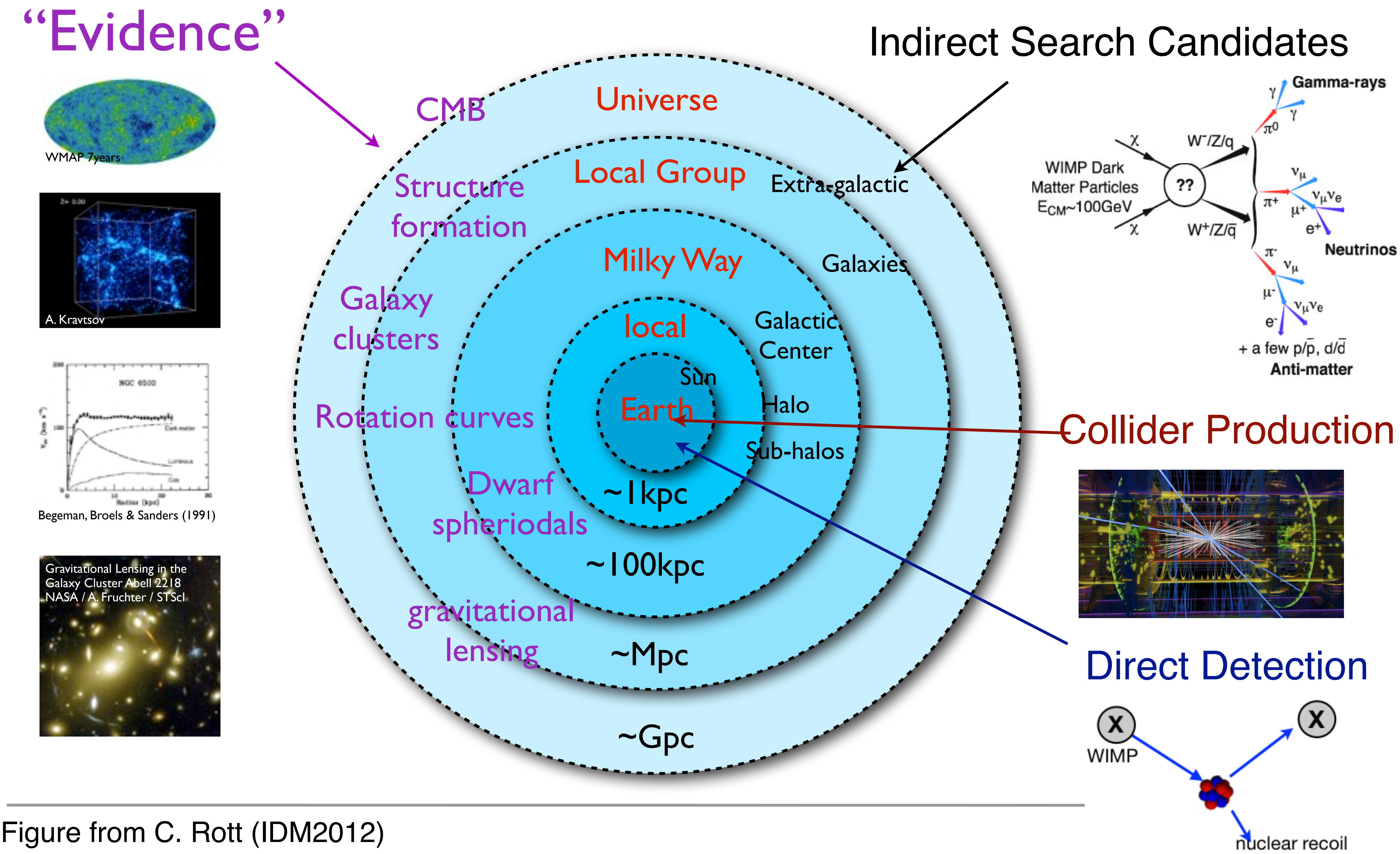
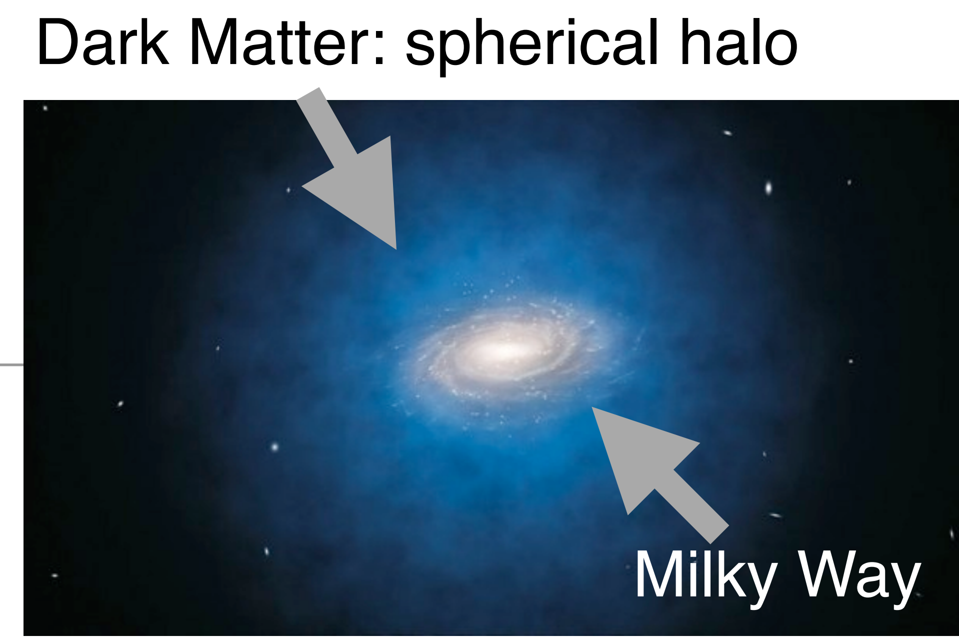


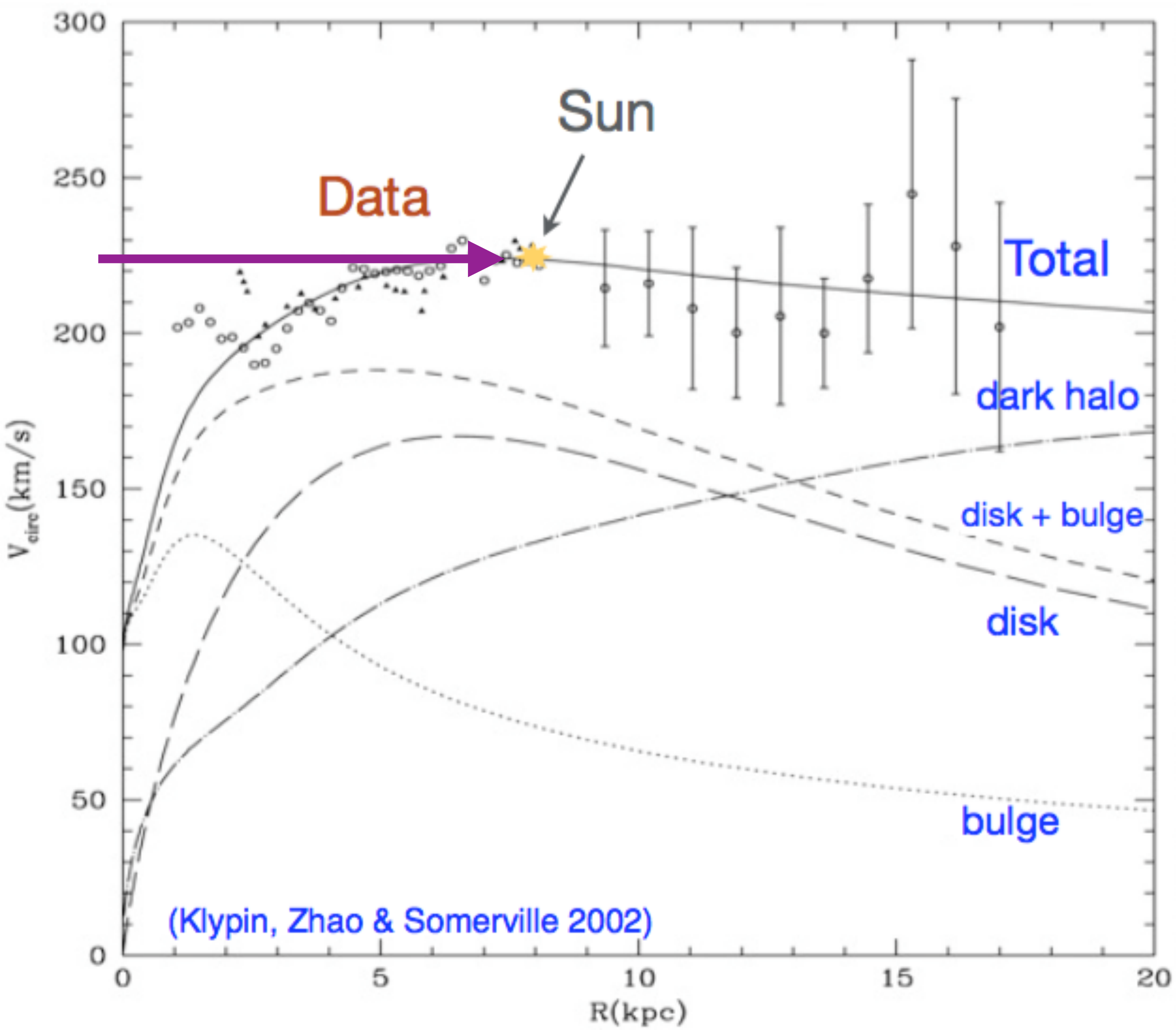
Figure from C. Rott (IDM2012)

Dark Matter Distribution



Remember…

$\rho_{DM} = 0.39 \pm 0.03$ GeV/cm^3



Assume: $m_{DM} = 100$ GeV/c^2

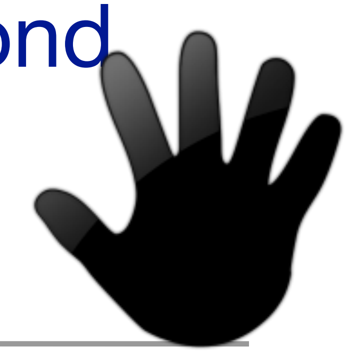
$n_{DM} = \rho_{DM}/m_{DM}$

$= 0.004/\text{cm}^3$

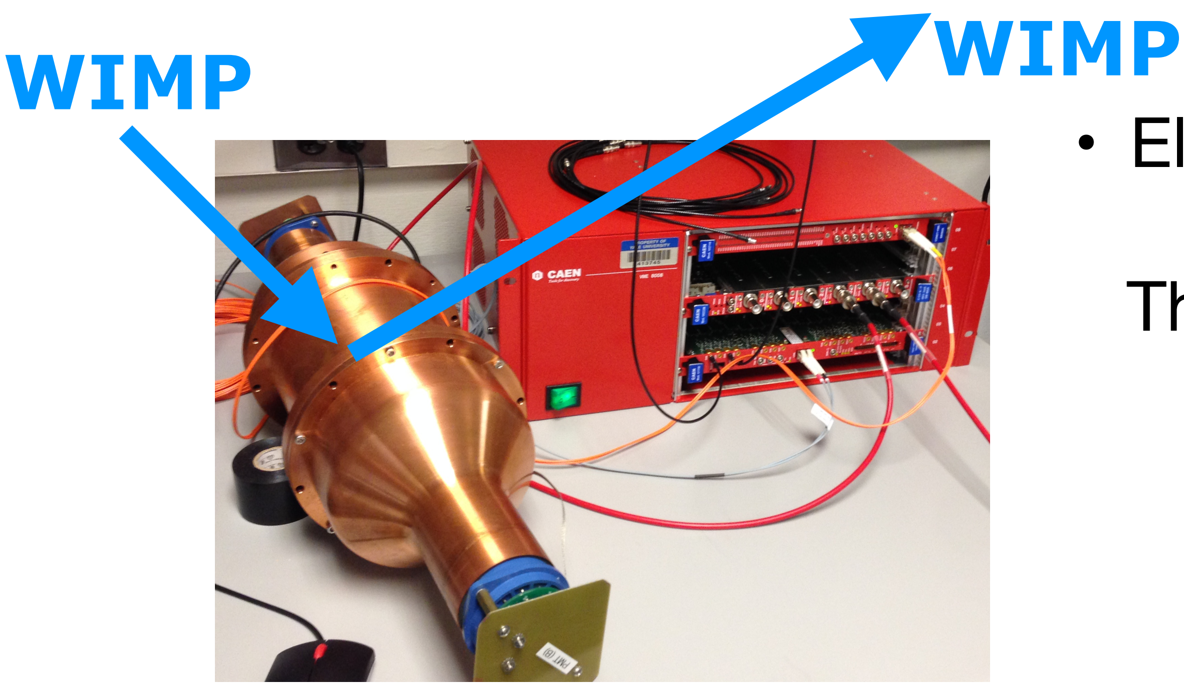
$= 4/\text{liter}$

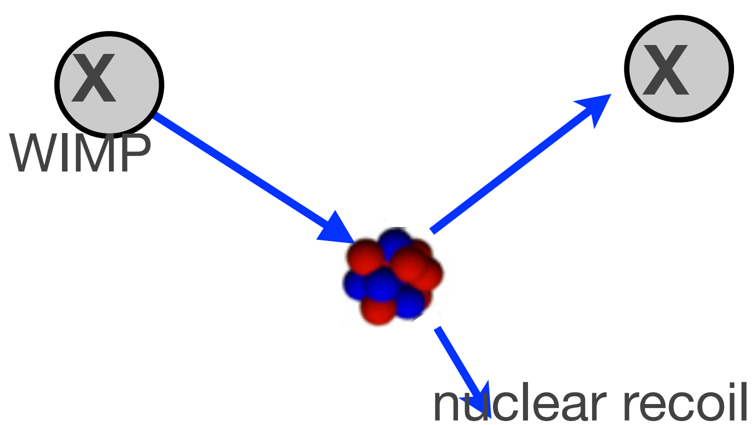
Sun's velocity: ~220 km/s

~10 million wimps pass thru a hand per second



Direct Detection of WIMPs





- Elastic collision between WIMPs and target nuclei

The recoil energy of the nucleus:

$$E_R = \frac{|\vec{q}|^2}{2m_N} = \frac{\mu^2 v^2}{m_N}(1-\cos\theta)$$

q = momentum transfer

μ = reduced mass

(m_N = nucleus mass, m_X = WIMP mass)

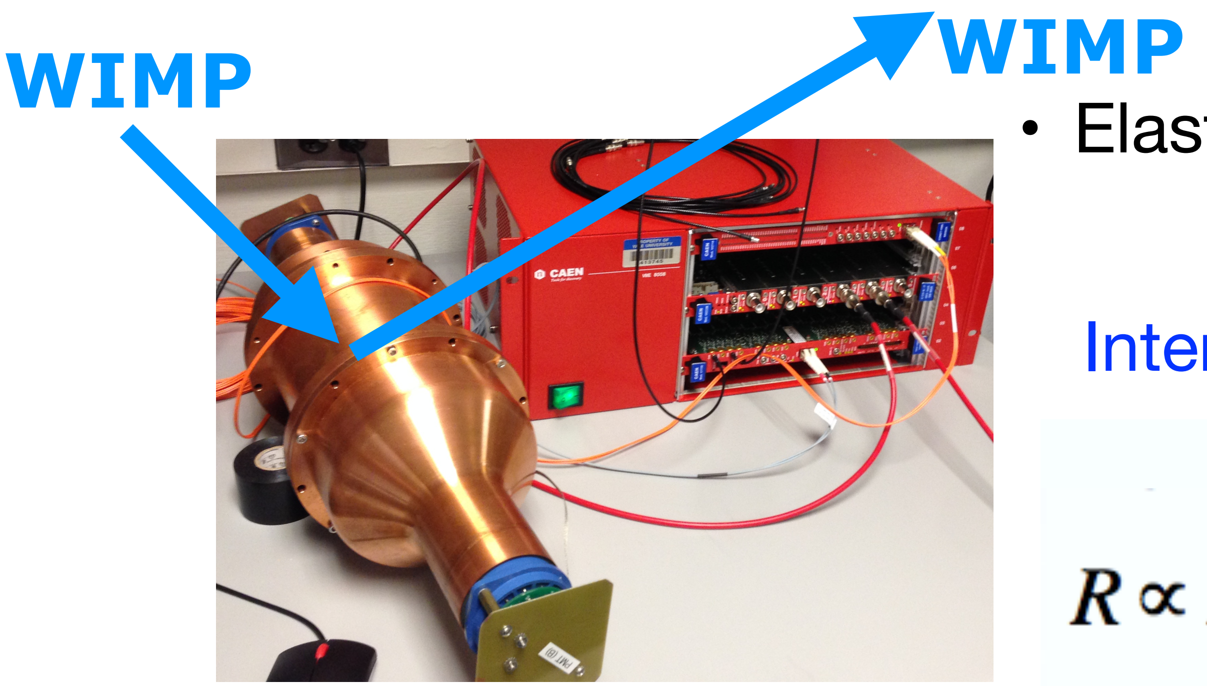
$\mu = m_N m_N/(m_{N+} m_N)$

v = mean WIMP-velocity w.r.t target

θ = scattering angle in center of mass system

~30 keV recoil

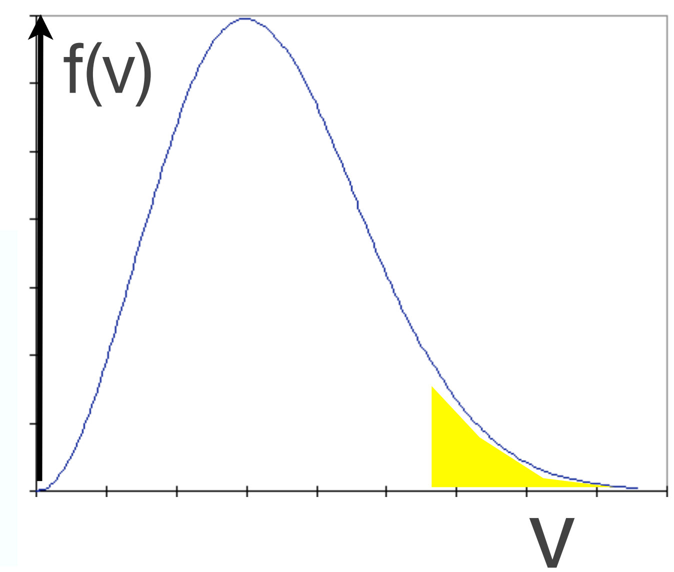
Direct Detection of WIMPs



- Elastic collision between WIMPs and target nuclei

Interaction Rate:

$$R \propto N \frac{\sigma_{\chi N}}{m_\chi} \rho_\chi \int_{v_{min}}^{v_{esc}} \frac{f(v)dv}{v}$$



Nuclear/Particle Physics

$\sigma_{SI} \sim \sigma_0 A^2 |F(q)|^2$
$\sim 10^{-45}$ cm^2
v_{min} : detector threshold

Astrophysics

WIMP distribution in the galaxy

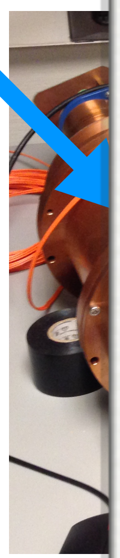
$\rho_0 = 0.39$ GeV/cm^3
$v_{rms} \approx 230$ km/s
$v_{max} \approx 550$ km/s

~ 30 keV

< 1 event/kg/year

Direct

WIMP



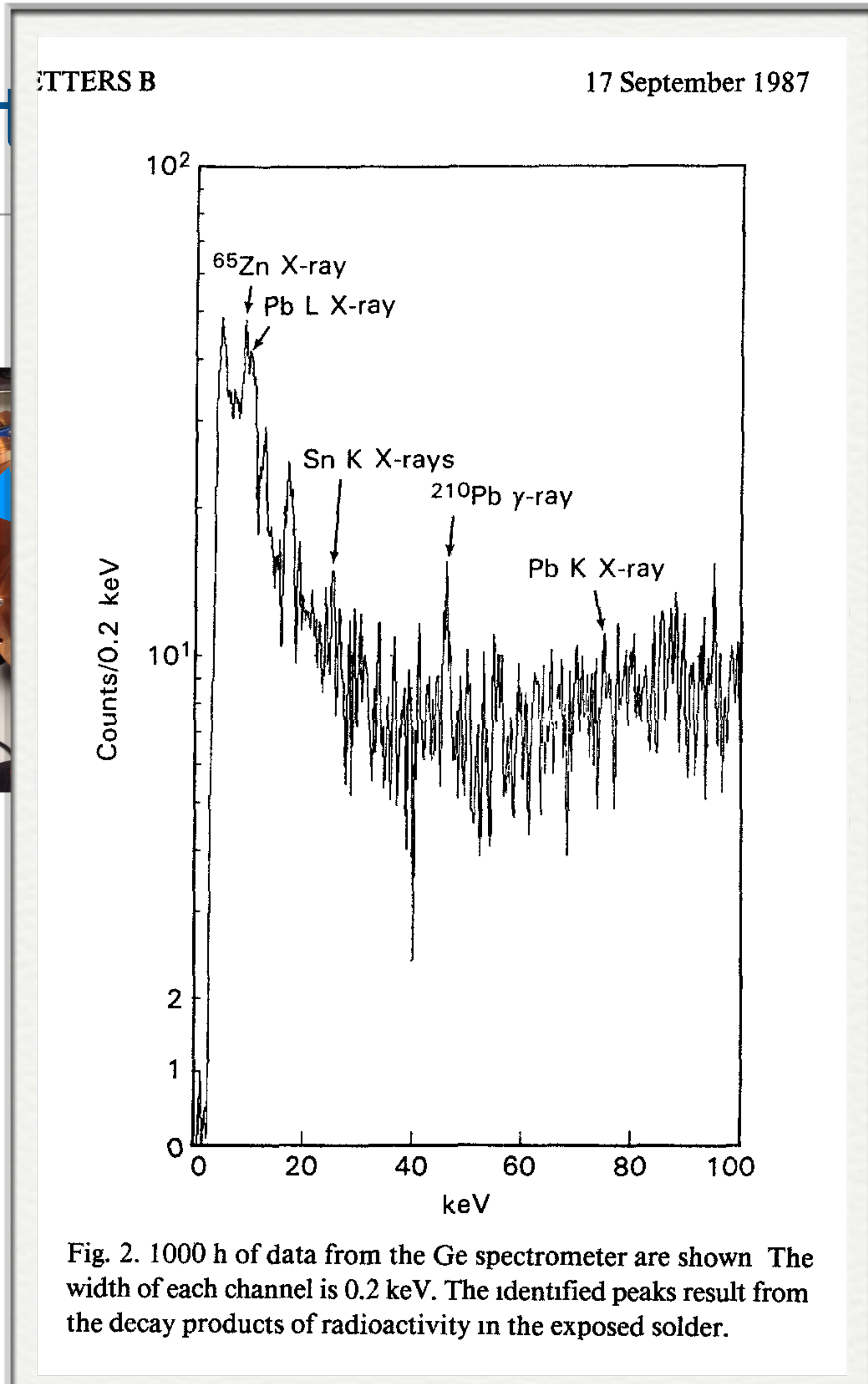

ETTERS B 17 September 1987

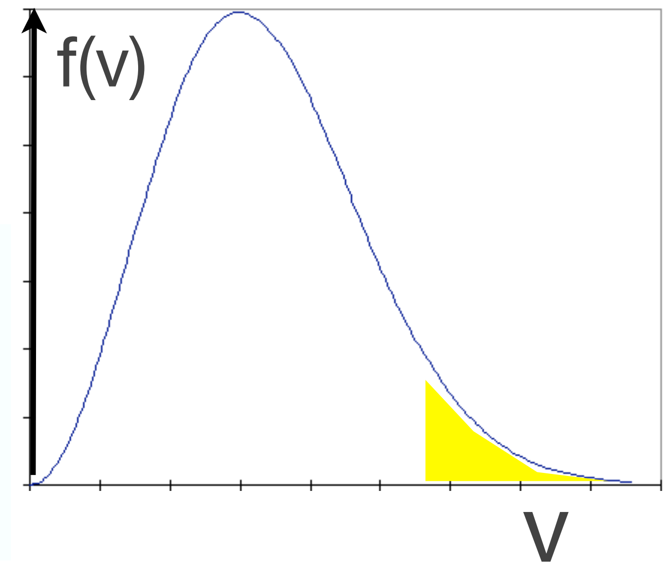
Fig. 2. 1000 h of data from the Ge spectrometer are shown The width of each channel is 0.2 keV. The identified peaks result from the decay products of radioactivity in the exposed solder.

sion between WIMPs and target nuclei

Rate:

$$\rho_\chi \int_{v_{min}}^{v_{esc}} \frac{f(v)dv}{v}$$

Astrophysics



WIMP distribution in the galaxy

ρ_0 = 0.39 GeV/cm^3

v_{rms} ≈ 230 km/s

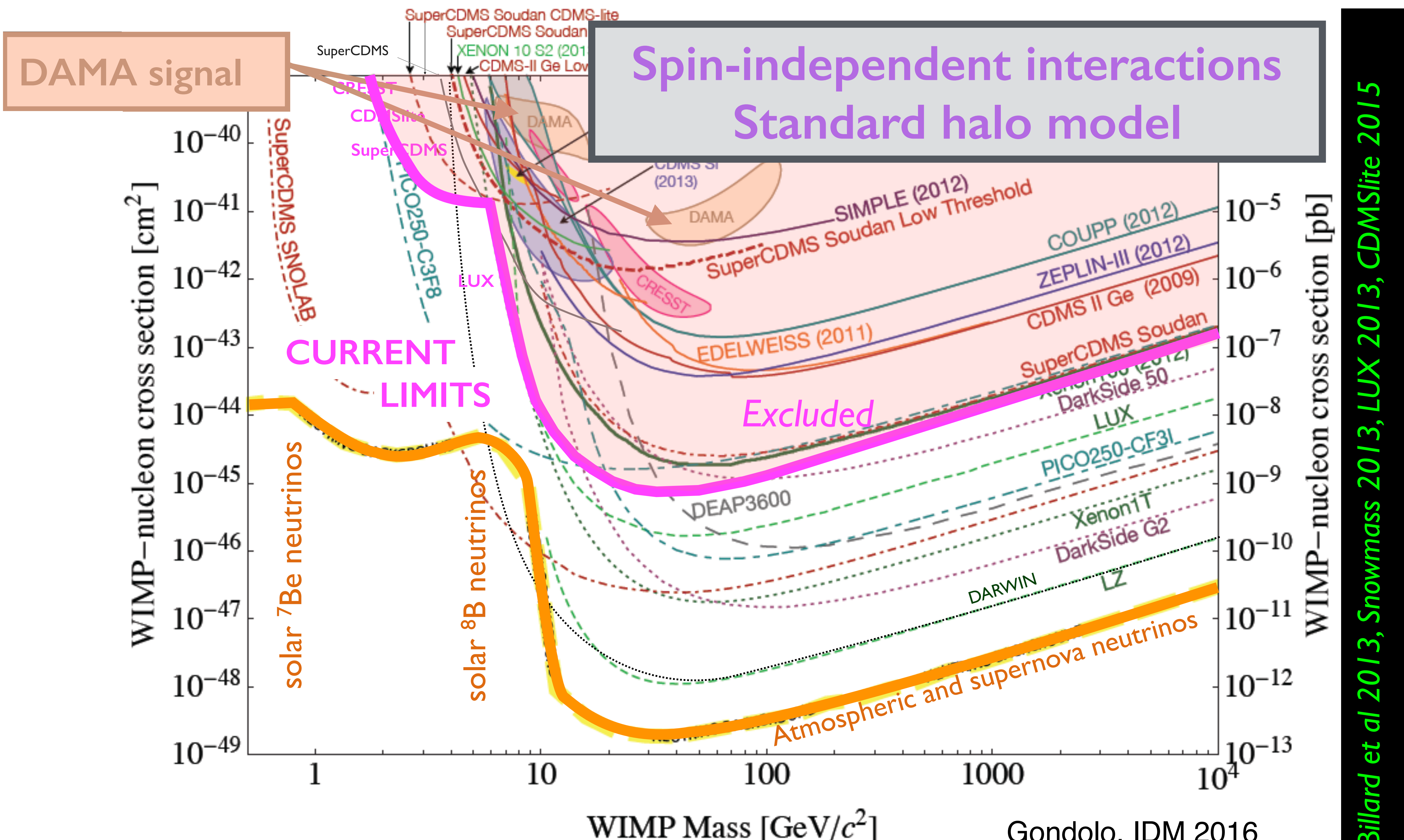
v_{max} ≈ 550 km/s

~ 30 keV

< 1 event/kg/year

Phys. Lett. B **195**, 603 (1987)

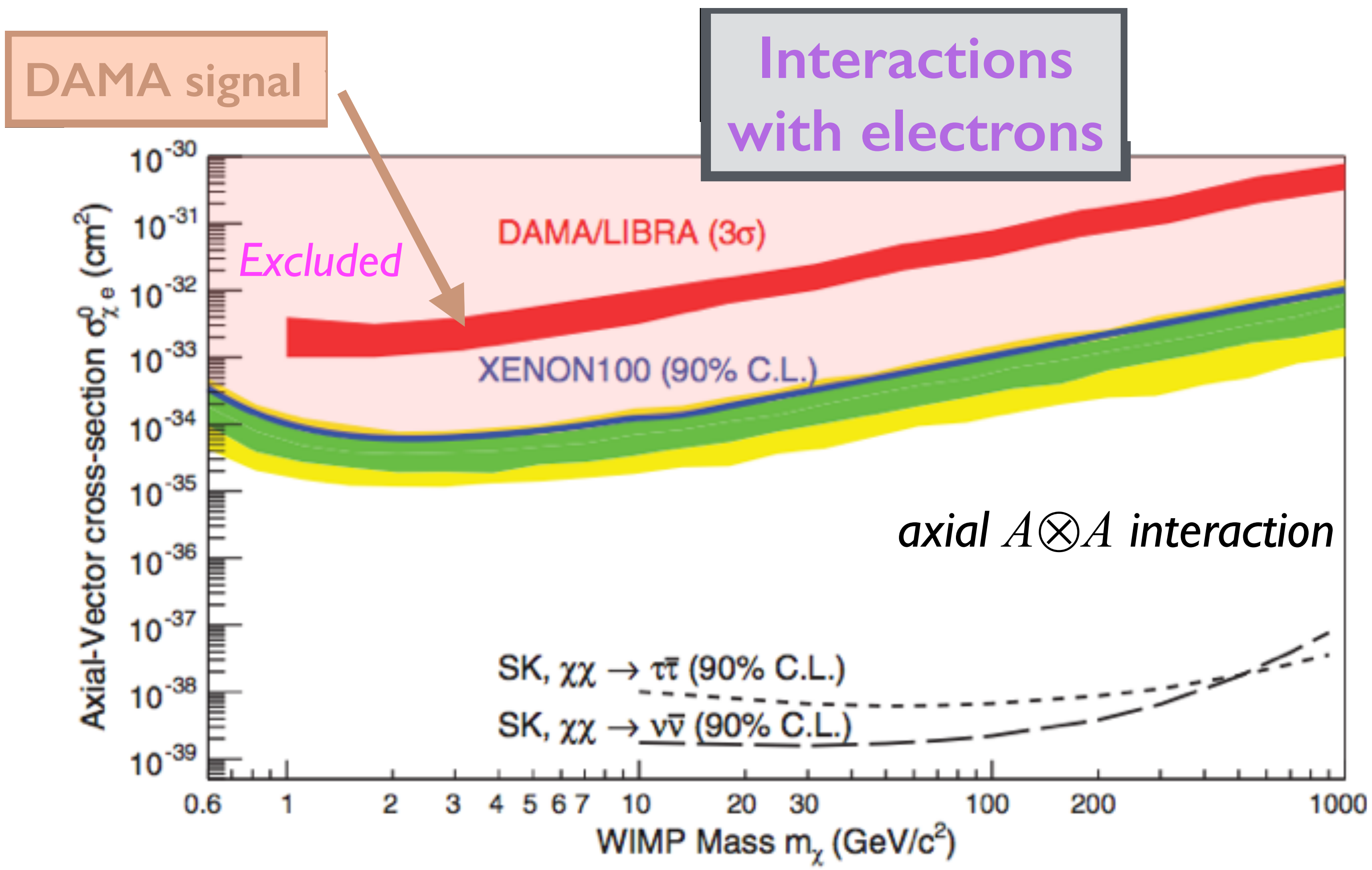
Direct WIMP Searches ca. 2016

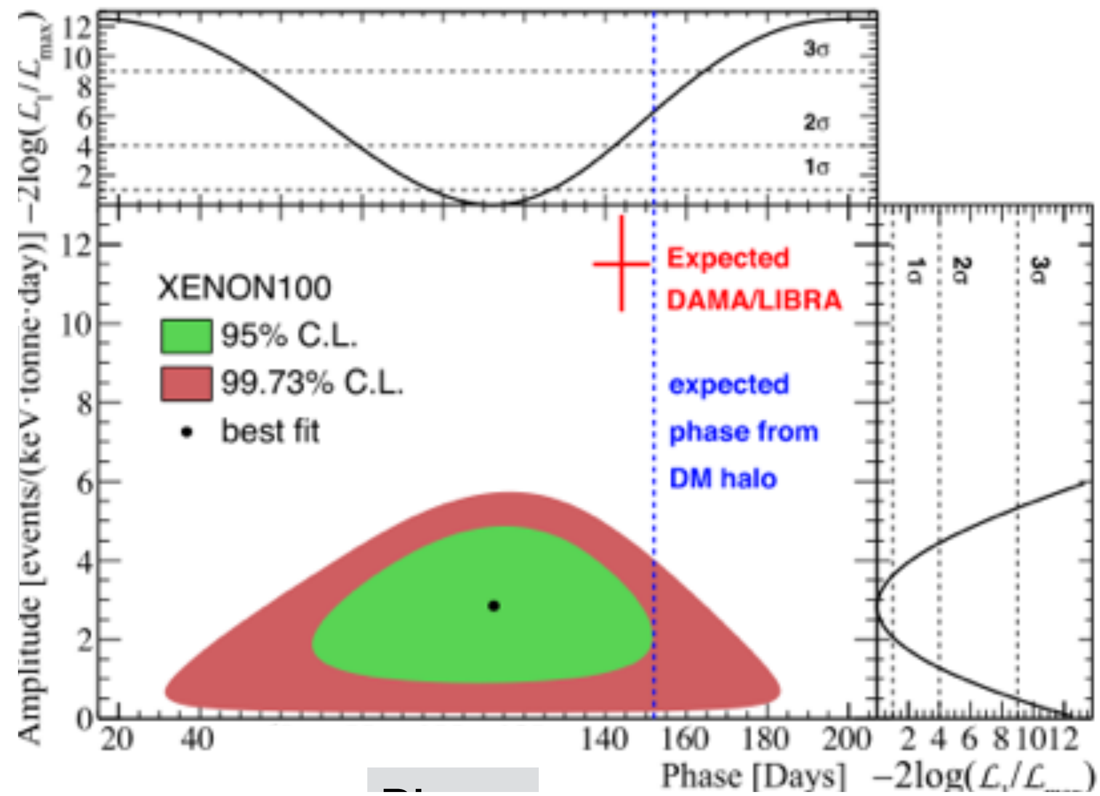


Gondolo, IDM 2016

DAMA Incompatible with Other Experiments

- No signal observed in Xenon
    - e.g. axial-vector, annual modulation



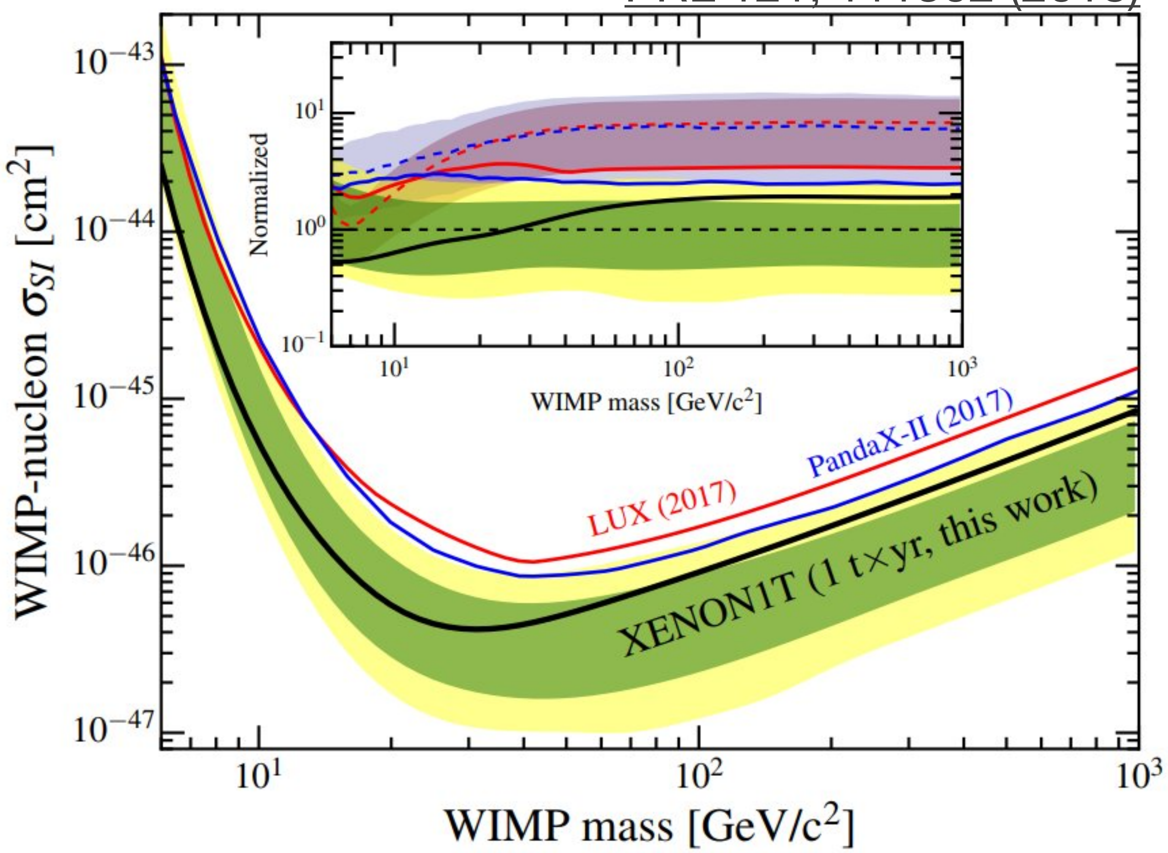


No dark matter-induced modulation observed by XENON

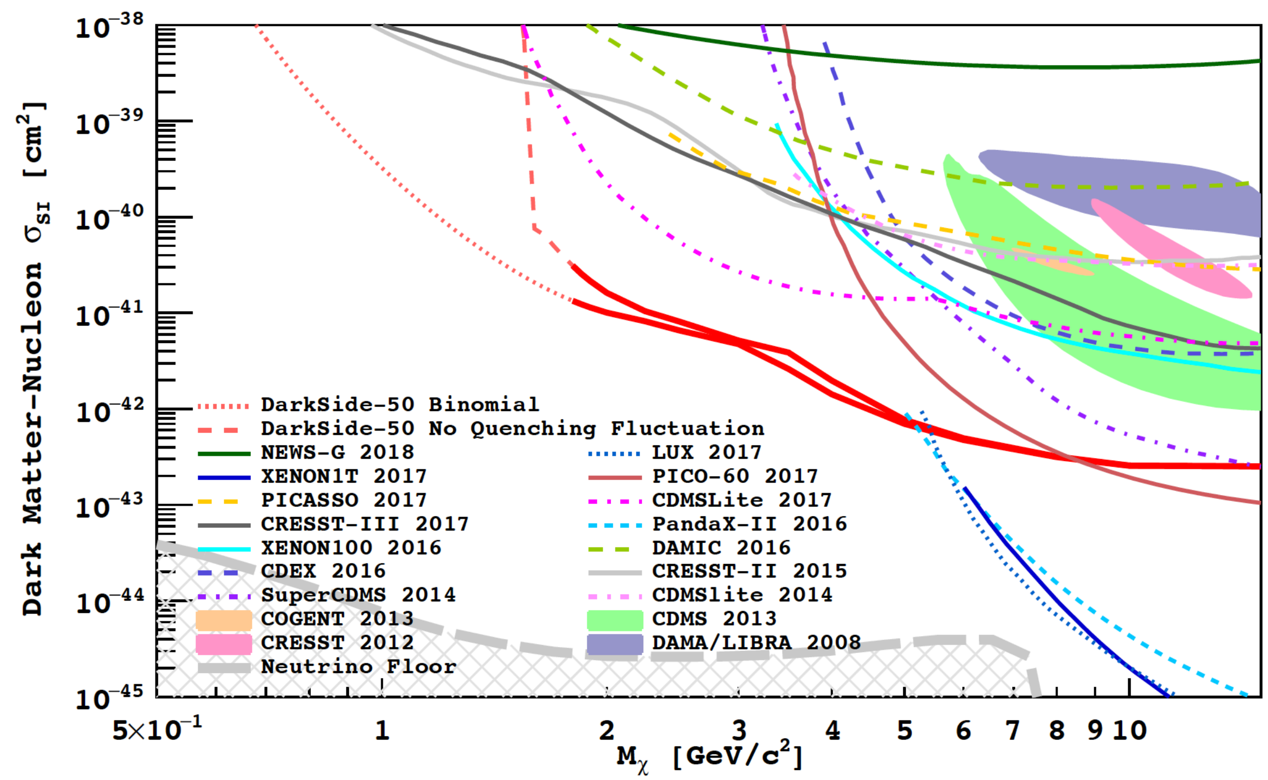
Aprile et al (XENON) 2015

Current status of Direct Dark Matter Searches

PRL 121, 111302 (2018)



arXiv:1802.06994



- No sign of WIMPs down to >10^{-46} cm^2 @ 30 GeV from XENON1t, LUX, Panda X
- No sign of spin-dependent WIMPs for >10^{-40} cm^2 from COUPP/PICO/IceCube
- Experiments driving innovations toward low mass dark matter searches
- DAMA's signal remains unresolved

nature International weekly journal of science

Home | News & Comment | Research | Careers & Jobs | Current Issue | Archive | Audio & Video | For A

News & Comment > News > 2015 > October > Article

NATURE | NEWS

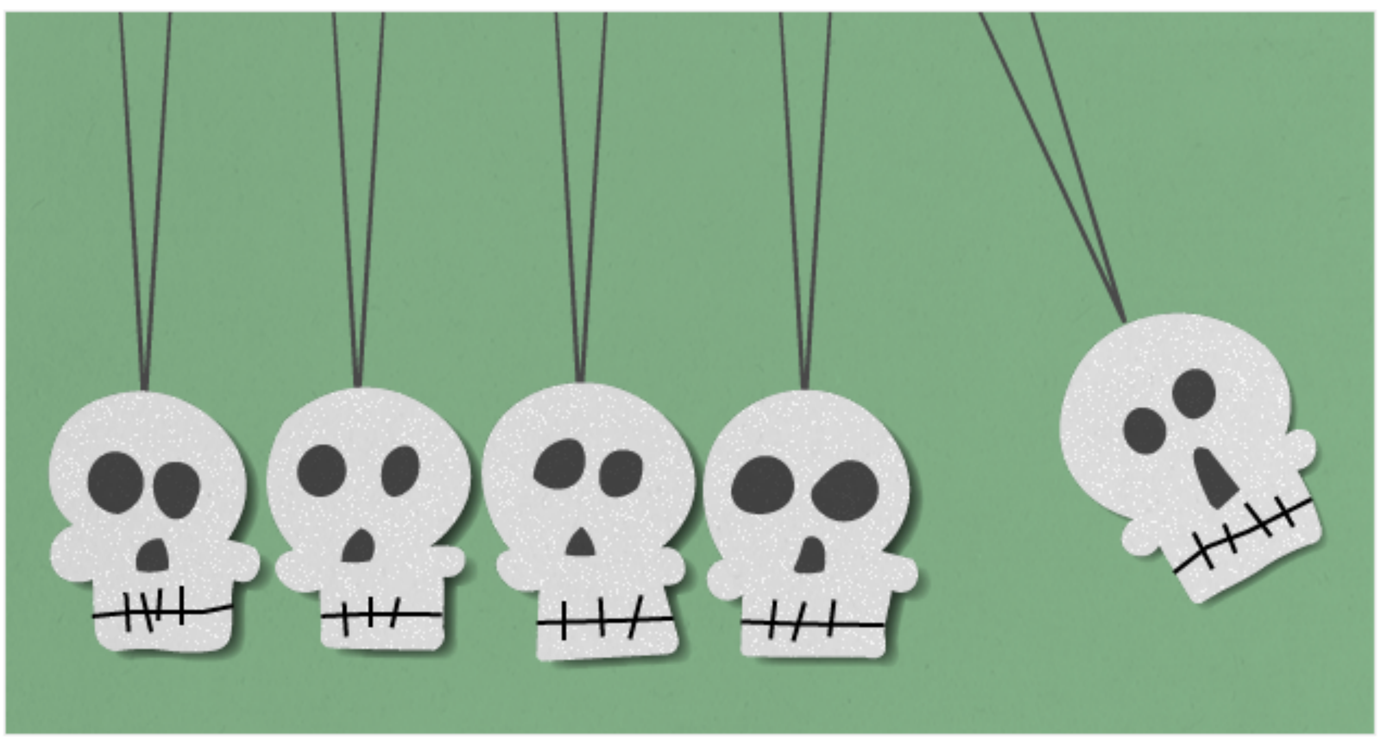
Zombie physics: 6 baffling results that just won't die

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

Davide Castelvecchi

30 October 2015

Rights & Permissions



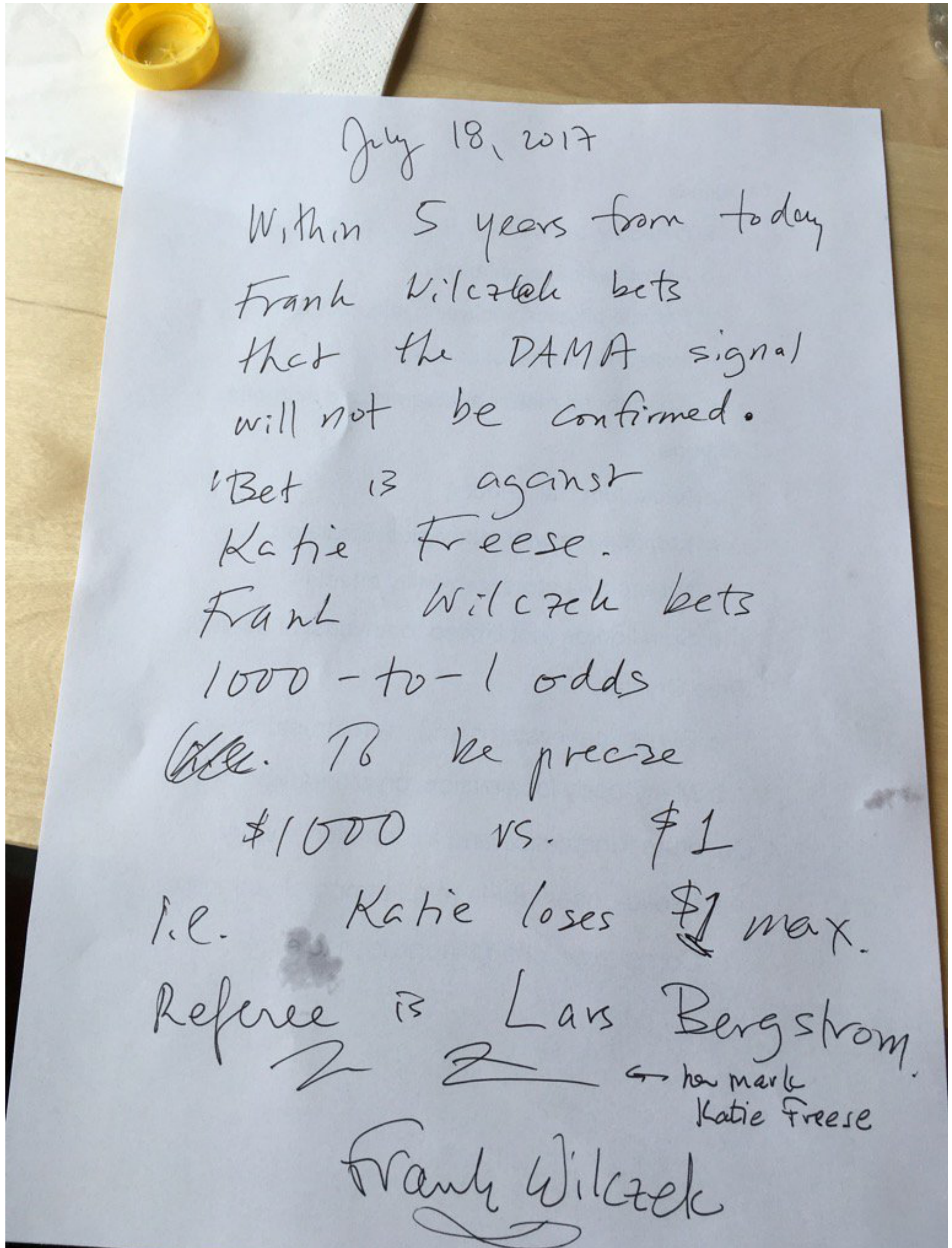
Seasonally spooky dark matter

… 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**…

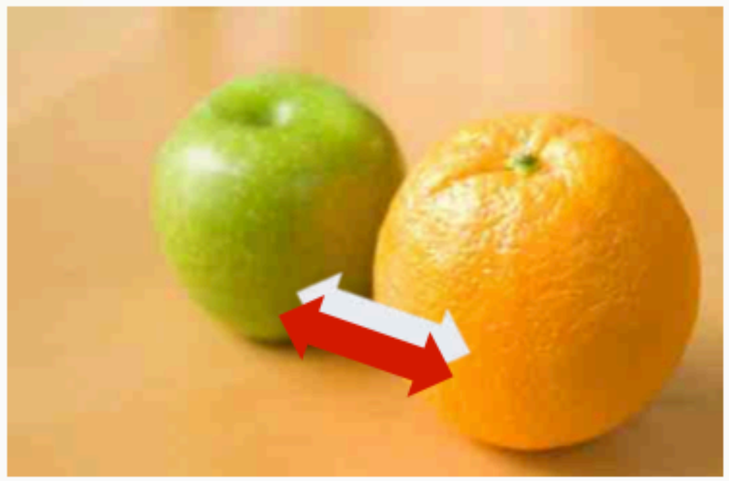
http://www.nature.com/news/zombie-physics-6-baffling-results-that-just-won-t-die-1.18685



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

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

DAMA Says…

Summary of the results obtained in the additional investigations of possible systematics or side reactions – DAMA/LIBRA-phase1

(NIMA592(2008)297, EPJC56(2008)333, J. Phys. Conf. ser. 203(2010)012040, arXiv:0912.0660, S.I.F.Atti Conf.103(211), Can. J. Phys. 89 (2011) 11, Phys.Proc.37(2012)1095, EPJC72(2012)2064, arxiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**$<2.5\times10^{-6}$ cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**$<10^{-4}$ cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**$<10^{-4}$ cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**$<1\text{-}2\times10^{-4}$ cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**$<10^{-4}$ cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**$<10^{-4}$ cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**$<3\times10^{-5}$ cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

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

l investigations
/LIBRA-phase1

010)012040, arXiv:0912.0660,
012)1095, EPJC72(2012)2064,
arXiv:1210.6199 & 1211.6346, IJMPA28(2013)1330022, EPJC74(2014)3196)

Source	Main comment	Cautious upper limit (90%C.L.)
RADON	Sealed Cu box in HP Nitrogen atmosphere, 3-level of sealing, etc.	**<2.5×10^{-6} cpd/kg/keV**
TEMPERATURE	Installation is air conditioned+ detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	**<10^{-4} cpd/kg/keV**
NOISE	Effective full noise rejection near threshold	**<10^{-4} cpd/kg/keV**
ENERGY SCALE	Routine + intrinsic calibrations	**<1-2 ×10^{-4} cpd/kg/keV**
EFFICIENCIES	Regularly measured by dedicated calibrations	**<10^{-4} cpd/kg/keV**
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

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

l investigations
/LIBRA-phase1
010)012040, arXiv:0912.0660,

arXiv:1102.0815

A testable conventional hypothesis for the DAMA-LIBRA annual modulation

David Nygren
Physics Division, Lawrence Berkeley National Laboratory
1 Cyclotron Road, Berkeley, CA 94720

	detectors in Cu housings directly in contact with multi-ton shield→ huge heat capacity + T continuously recorded	$<10^{-4}$ cpd/kg/keV
NOISE	Effective full noise rejection near threshold	$<10^{-4}$ cpd/kg/keV
ENERGY SCALE	Routine + intrinsic calibrations	$<1\text{-}2 \times 10^{-4}$ cpd/kg/keV
EFFICIENCIES	Regularly measured by dedicated calibrations	$<10^{-4}$ cpd/kg/keV
BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	$<10^{-4}$ cpd/kg/keV
SIDE REACTIONS	Muon flux variation measured at LNGS	$<3\times10^{-5}$ cpd/kg/keV

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

l investigations
/LIBRA-phase1
010)012040, arXiv:0912.0660,

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
1 Cyclotron Road, Berkeley, CA 94720

PRL 113, 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos

Jonathan H. Davis*
Institute for Particle Physics Phenomenology, Durham University, Durham DH1 3LE, United Kingdom
(Received 10 July 2014; revised manuscript received 5 August 2014; published 21 August 2014)

BACKGROUND	No modulation above 6 keV; no modulation in the (2-6) keV *multiple-hits* events; this limit includes all possible sources of background	**<10^{-4} cpd/kg/keV**
SIDE REACTIONS	Muon flux variation measured at LNGS	**<3×10^{-5} cpd/kg/keV**

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

l investigations
/LIBRA-phase1
010)012040, arXiv:0912.0660,

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
1 Cyclotron Road, Berkeley, CA 94720

PRL 113, 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos

arXiv: 1803.10110

Is DAMA Bathing in a Sea of Radioactive Argon?

D. N. McKinsey[1,2,*]
[1] *University of California Berkeley, Department of Physics, Berkeley, CA 94720, USA*
[2] *Lawrence Berkeley National Laboratory, 1 Cyclotron Rd., Berkeley, CA 94720, USA*
(Dated: March 28, 2018)

BACKGR

SIDE REA

+ they cannot satisfy all the requirements of annual modulation signature

Thus, they cannot mimic the observed annual modulation effect

l investigations
/LIBRA-phase1
010)012040, arXiv:0912.0660,

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
1 Cyclotron Road, Berkeley, CA 94720

PRL 113, 081302 (2014) PHYSICAL REVIEW LETTERS week ending 22 AUGUST 2014

Fitting the Annual Modulation in DAMA with Neutrons from Muons and Neutrinos

arXiv: 1803.10110

Is DAMA Bathing in a Sea of Radioactive Argon?

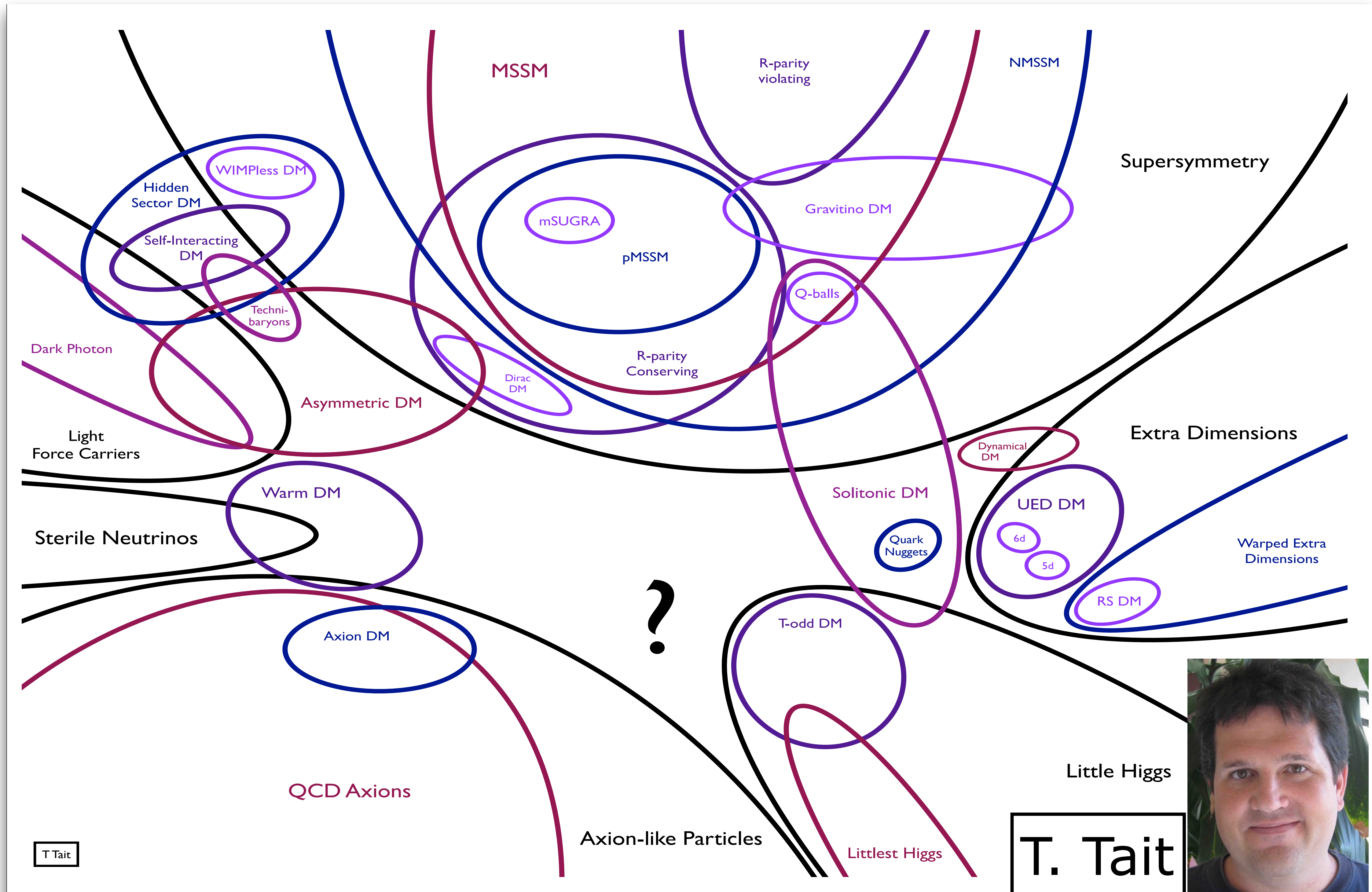
arXiv: 1901.02139

Helium Migration through Photomultiplier Tubes – The Probable Cause of the DAMA Seasonal Variation Effect

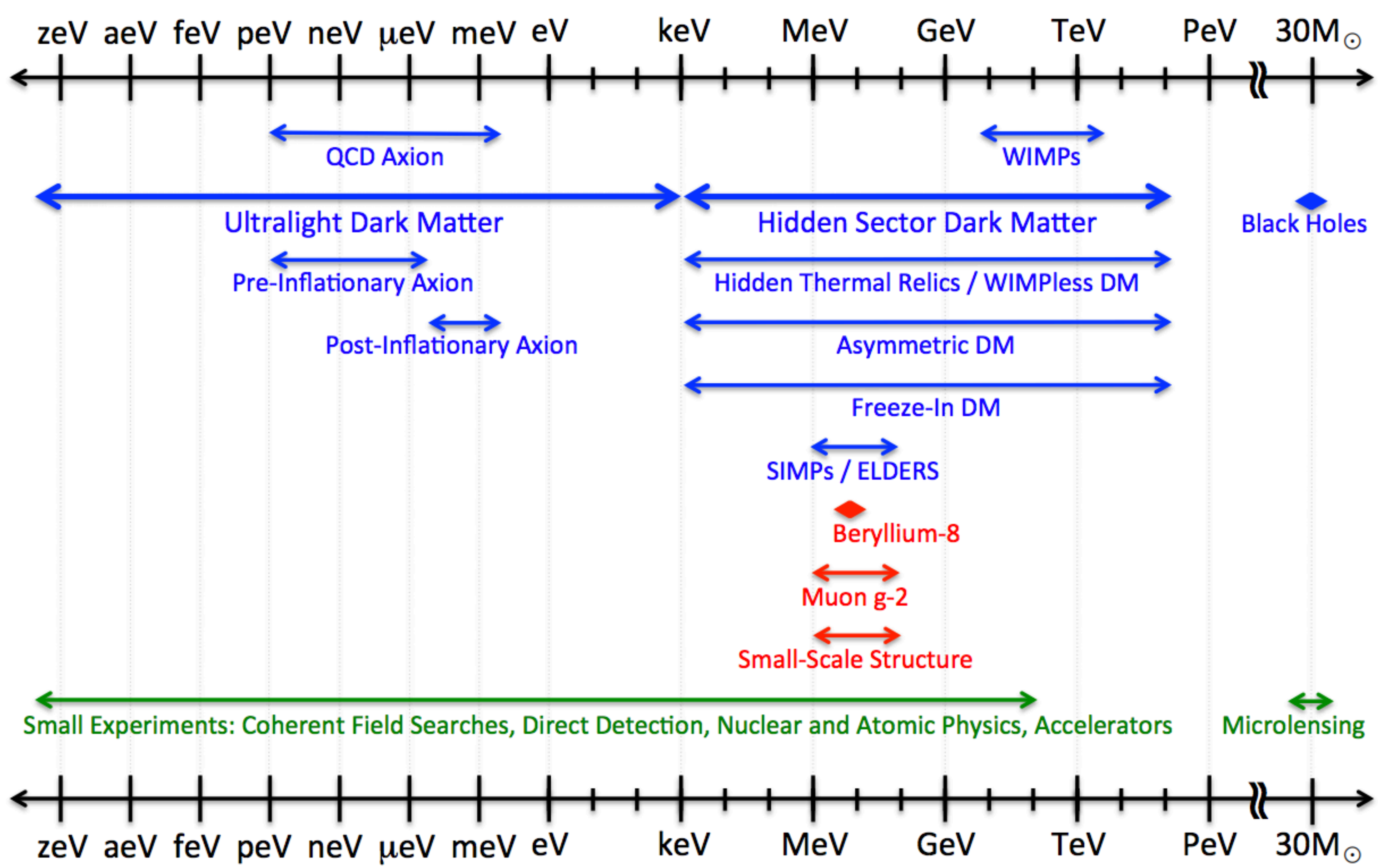
Daniel Ferenc[1,3,*] Dan Ferenc Šegedin[2,3], Ivan Ferenc Šegedin[3], Marija Šegedin Ferenc[3]

BACKGR
SIDE REA

What is Dark Matter?



Dark matter candidates



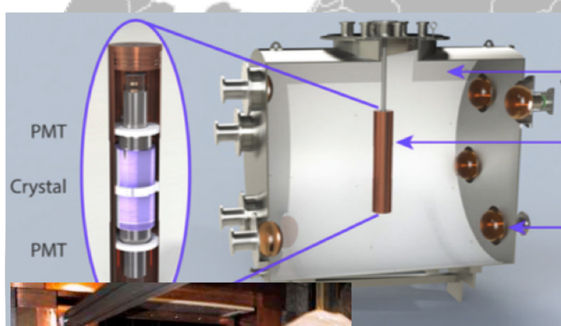
US Cosmic vision

NaI(Tl) Experiments

DAMA

SABRE **COSINUS**

★ Gran Sasso + Australia

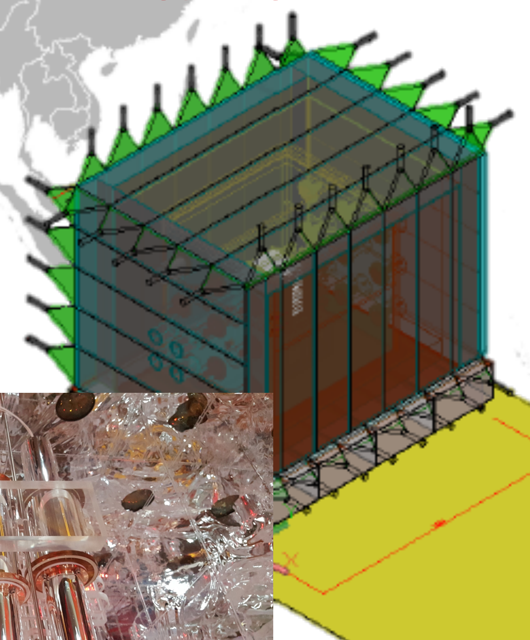


Eur.Phys.J. C **78** 107 (2018)
Eur.Phys.J. C **77** 437 (2017)
Phys.Rev. D **90** 052006 (2014) (CsI)
Nature **564** 83-86 (2018)
arXiv:1903.10098 (2019) -> PRL

KIMS (+ DM-Ice)

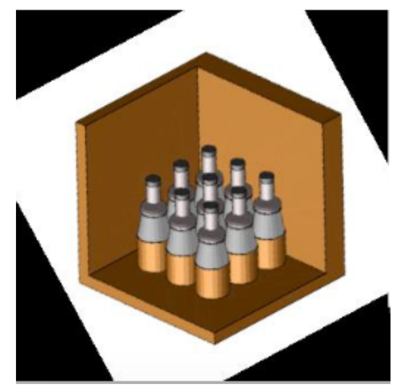
COSINE-100

★ Yangyang



PICOLON

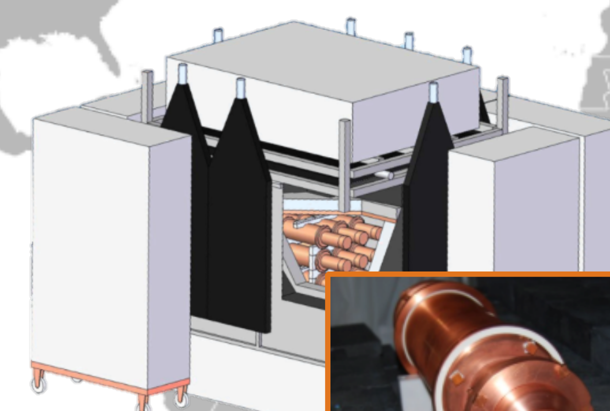
★ Kamioka

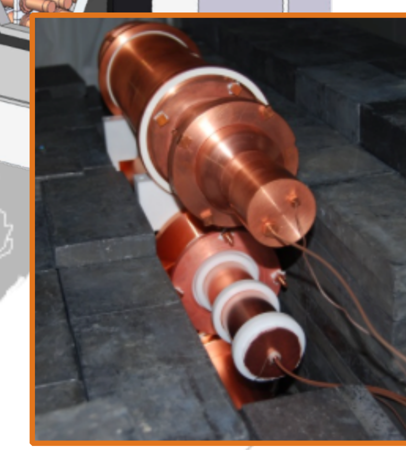


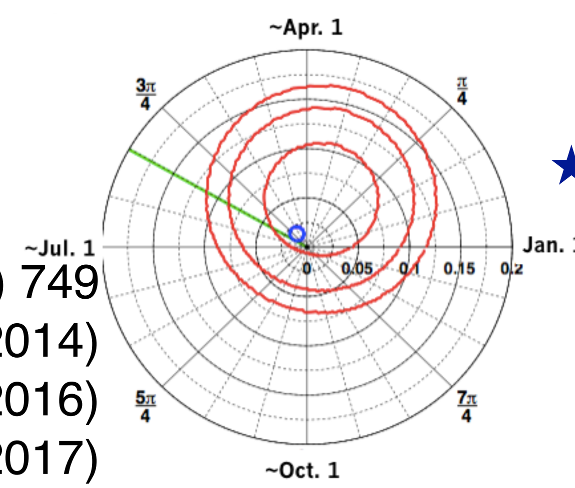
ANAIS

★ Boulby

★ Canfra



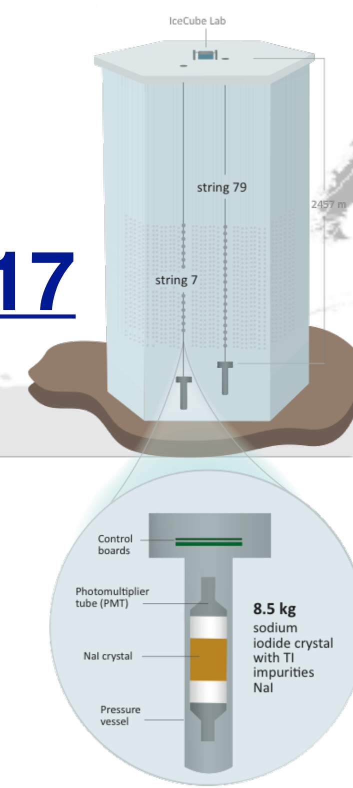


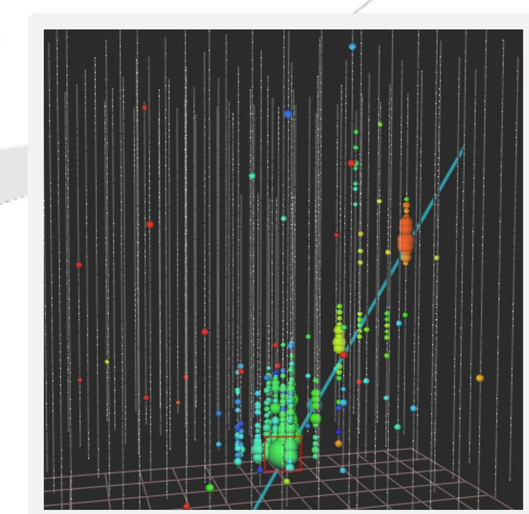


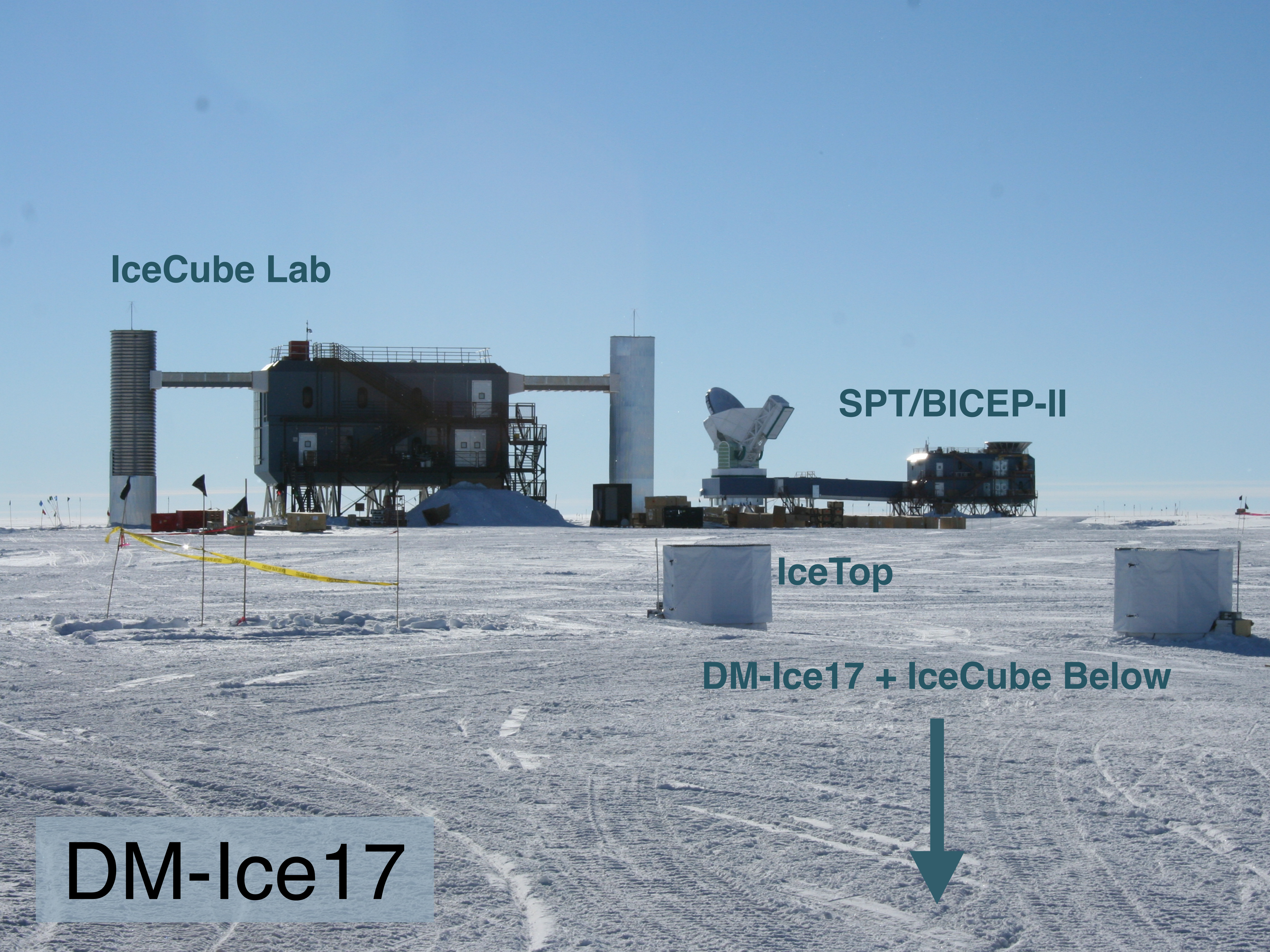
Astropart. Phys. **35** (2012) 749
Phys. Rev. D **90** 092005 (2014)
Phys. Rev. D **93** 042001 (2016)
Phys. Rev. D **95** 032006 (2017)

DM-Ice17

★ South Pole

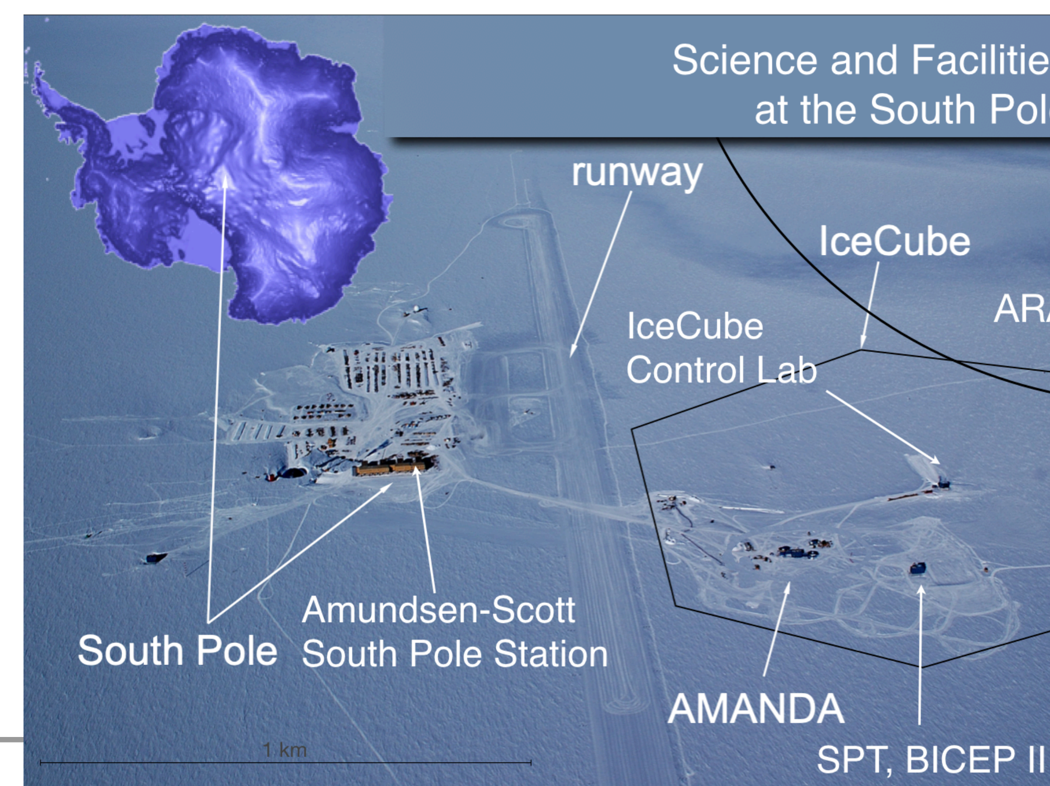





IceCube Lab
SPT/BICEP-II
IceTop
DM-Ice17 + IceCube Below
DM-Ice17

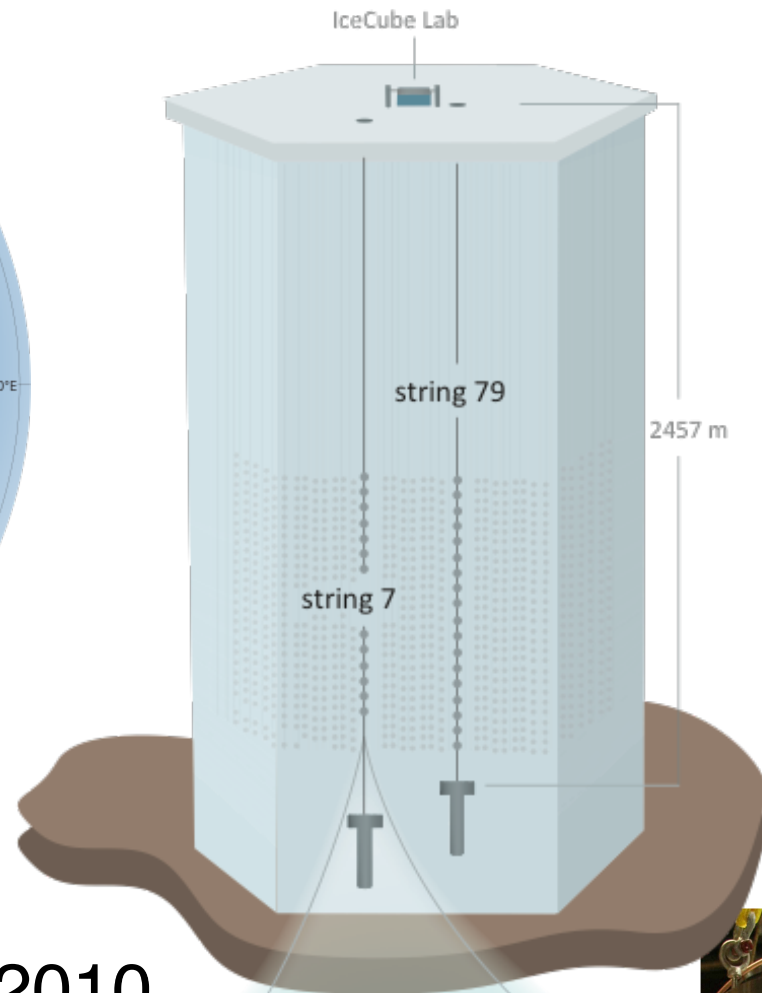
South Pole

- Opposite seasons between Northern and Southern Hemispheres
- Overburden: 2450 m ice (2200 m.w.e.)
  - Clean Ice
  - H_2O “tank”
- Stable “underground” environment
- South Pole Station + IceCube
  = Science Infrastructure + muon tag

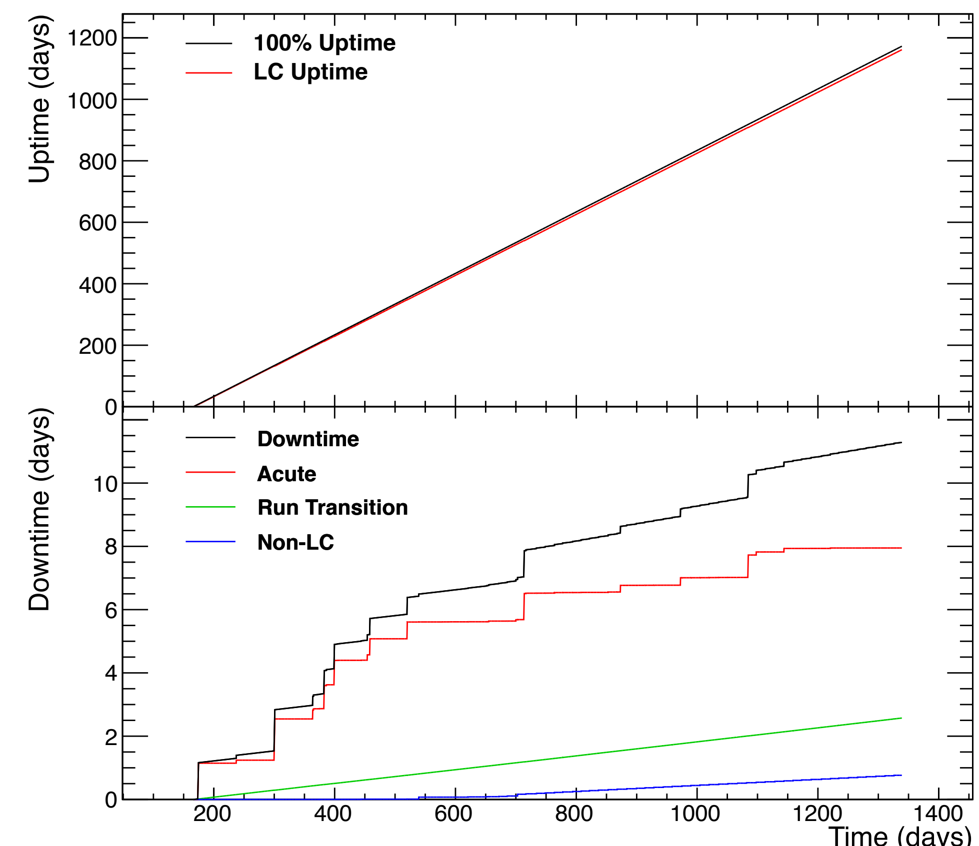


Cherwinka *et al.* Astropart. Phys. **35** (2012) 749

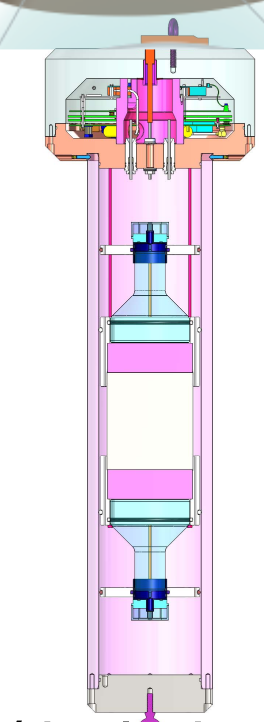
DM-Ice17

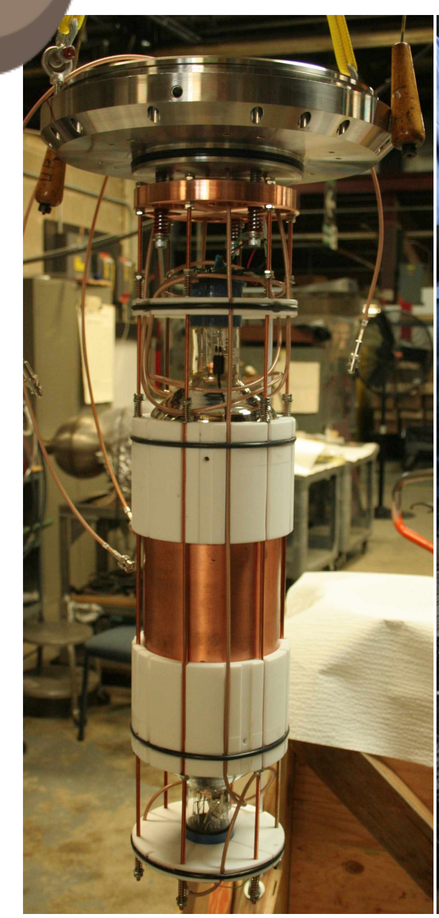


Phys. Rev. D 90, 092005 (2014)



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



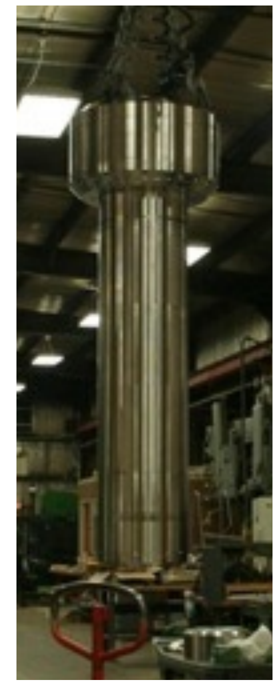


DM-Ice17 establishes…

- Feasibility
- Environmental Stability
- Radiopurity of the antarctic ice / hole ice

DM-Ice-17 Construction & Deployment

Design begin Feb. 2010



IceCube Detector Completion
December 2010

DM-Ice17

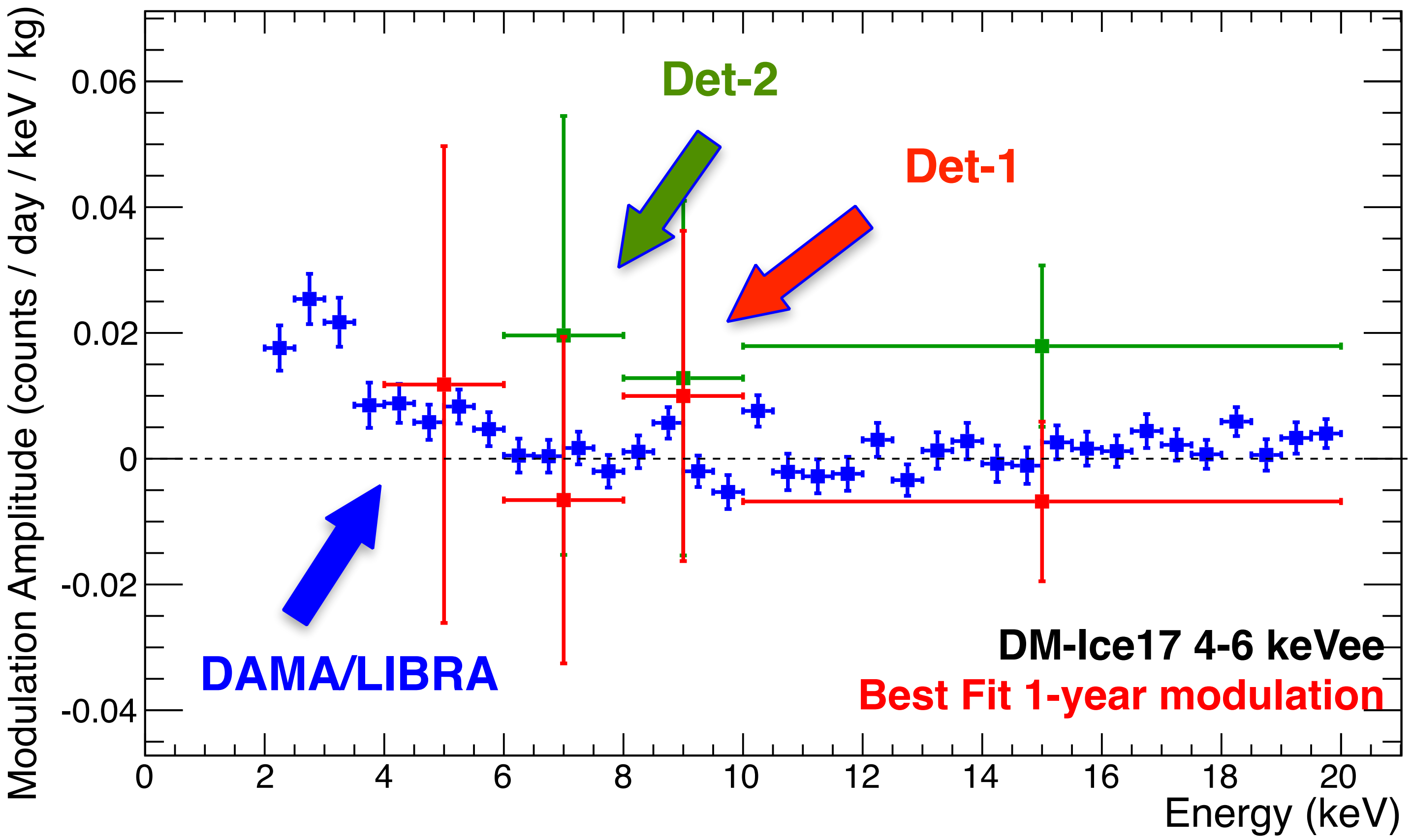
PRD **90** 092005 (2014)
PRD **93** 042001 (2016)
PRD **95** 032006 (2017)

http://dm-ice.yale.edu

DM-Ice17

PRD **90** 092005 (2014)
PRD **93** 042001 (2016)
PRD **95** 032006 (2017)

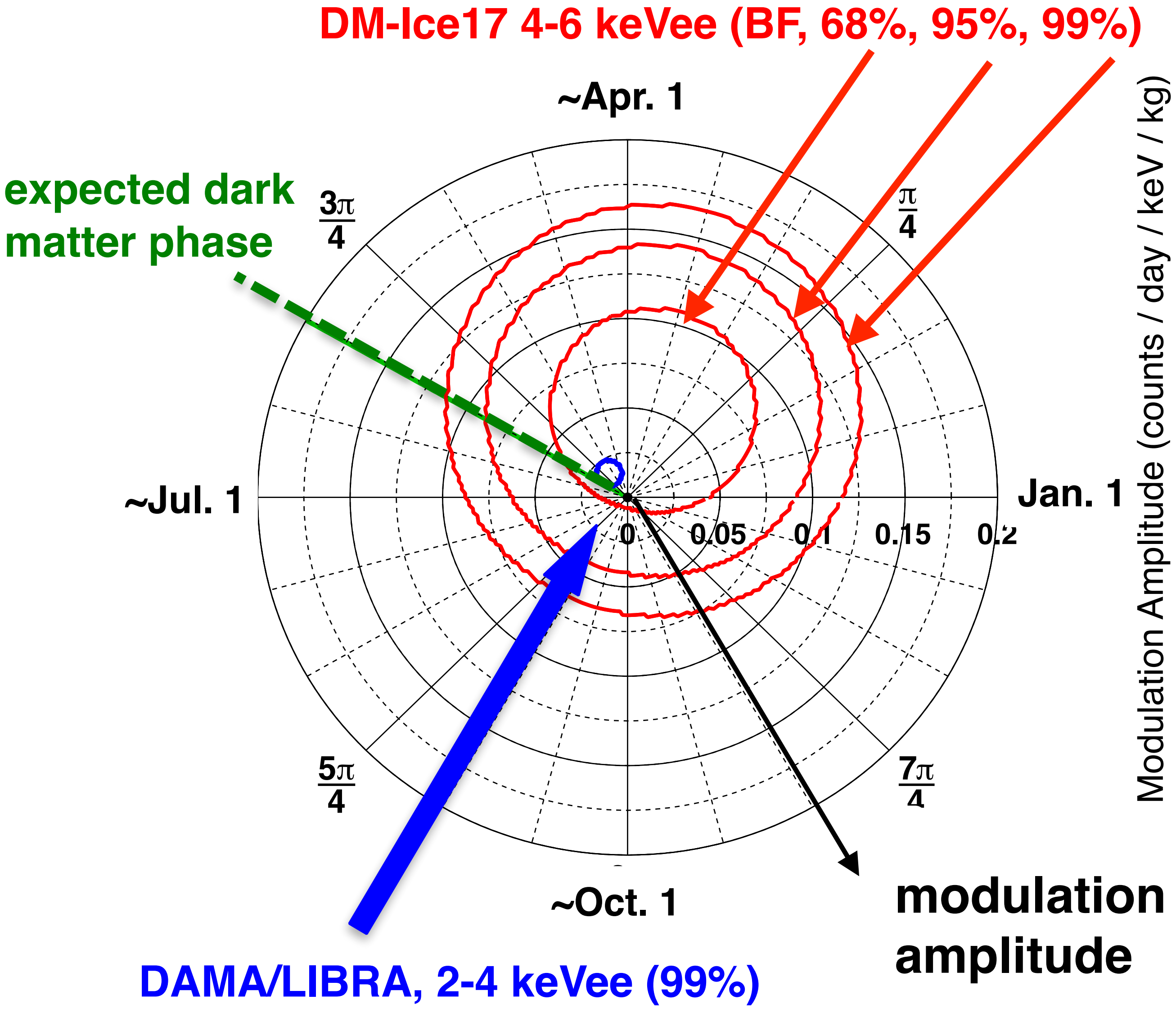
http://dm-ice.yale.edu

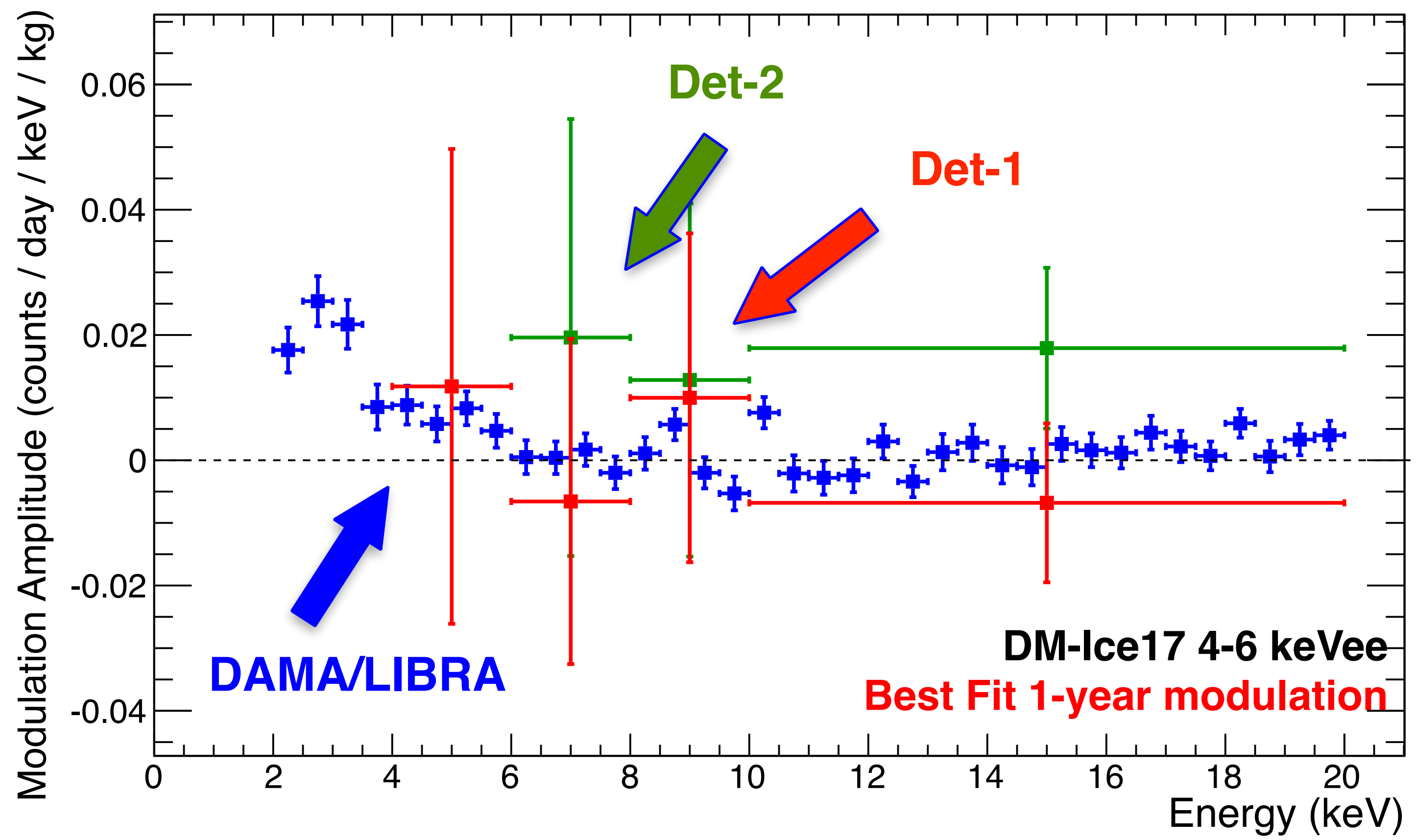


DM-Ice17

PRD **90** 092005 (2014)
PRD **93** 042001 (2016)
PRD **95** 032006 (2017)

http://dm-ice.yale.edu

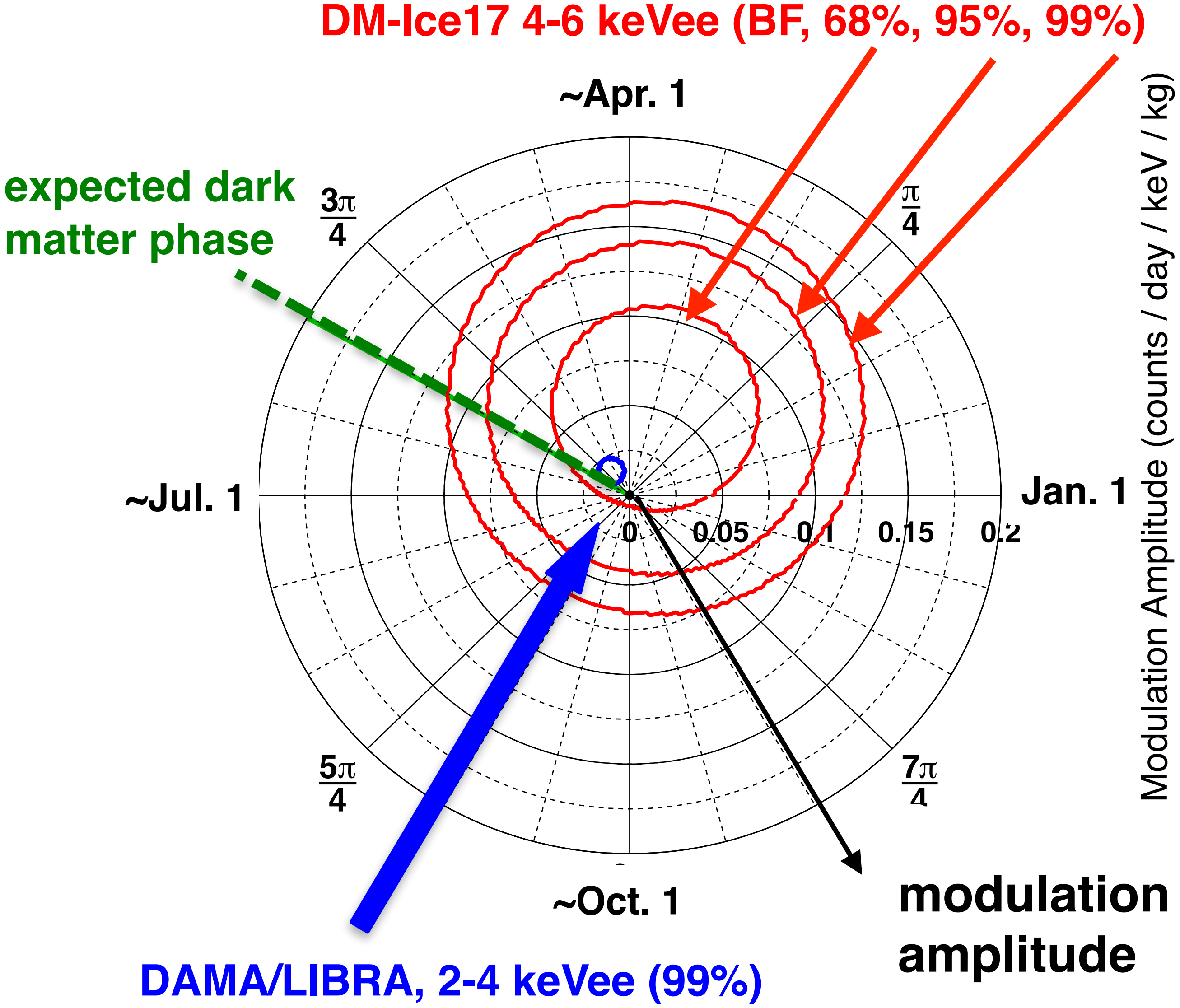


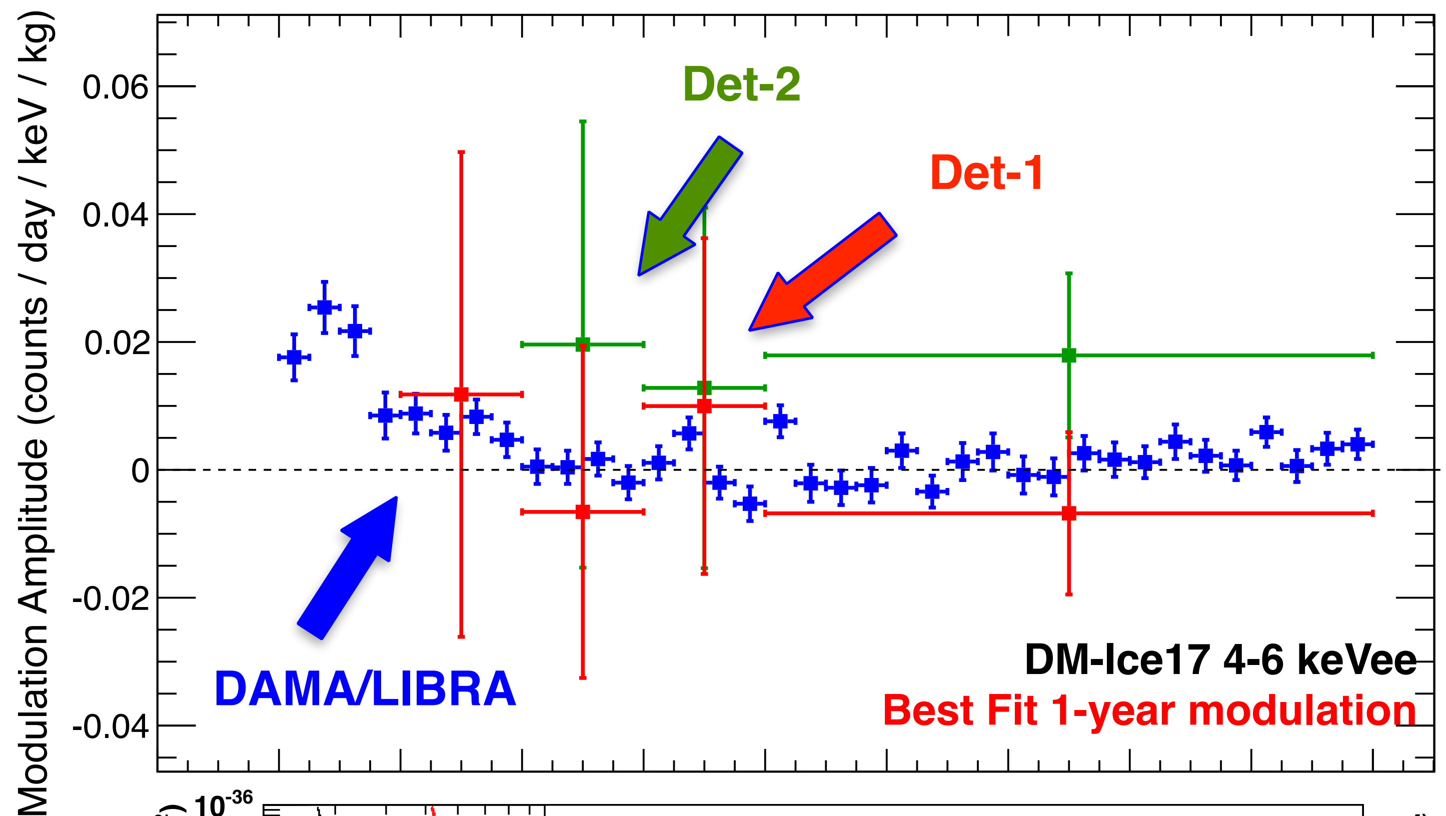


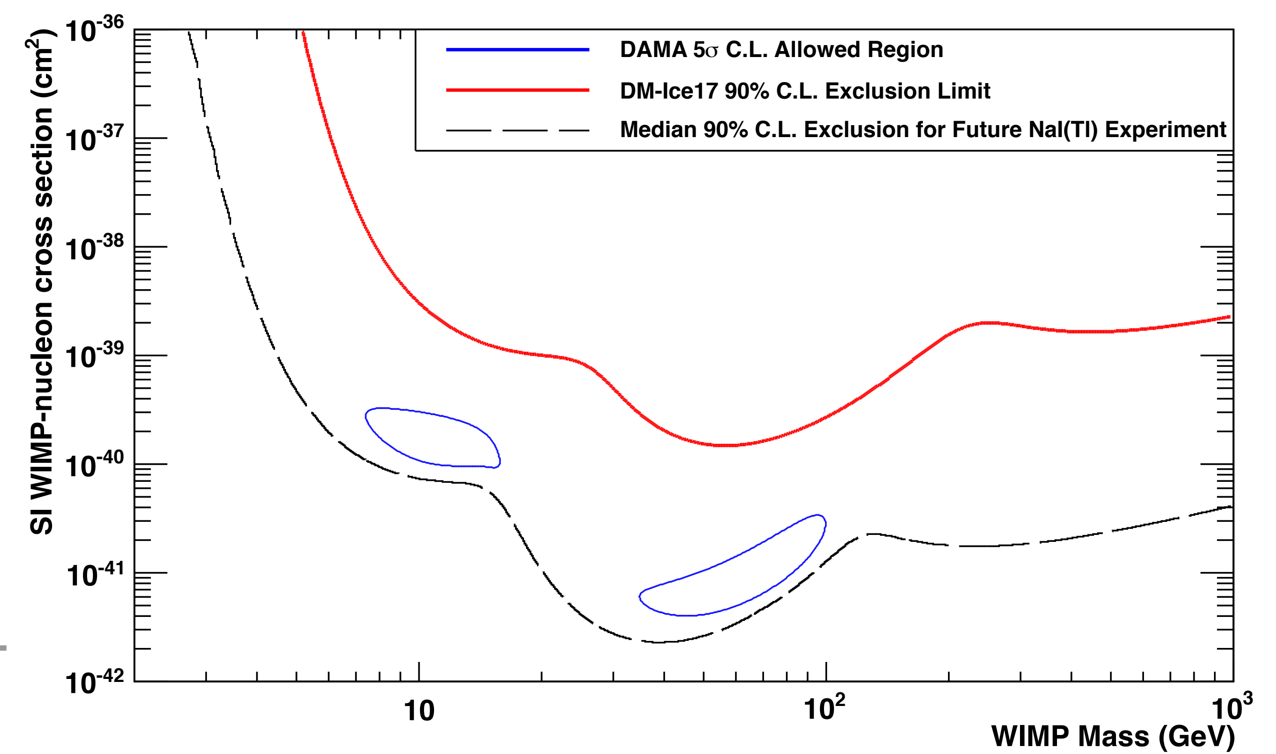
DM-Ice17

PRD **90** 092005 (2014)
PRD **93** 042001 (2016)
PRD **95** 032006 (2017)

http://dm-ice.yale.edu



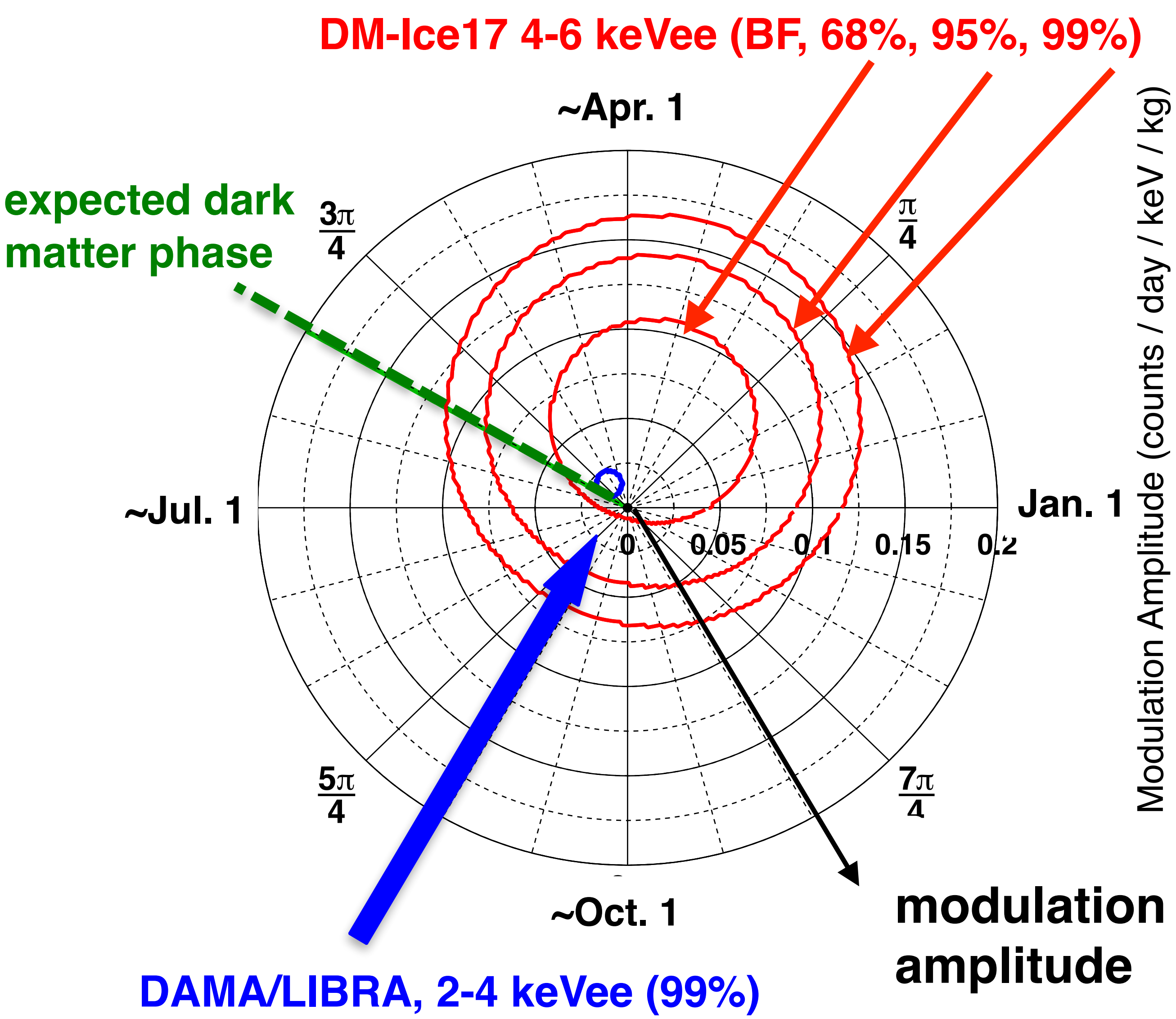


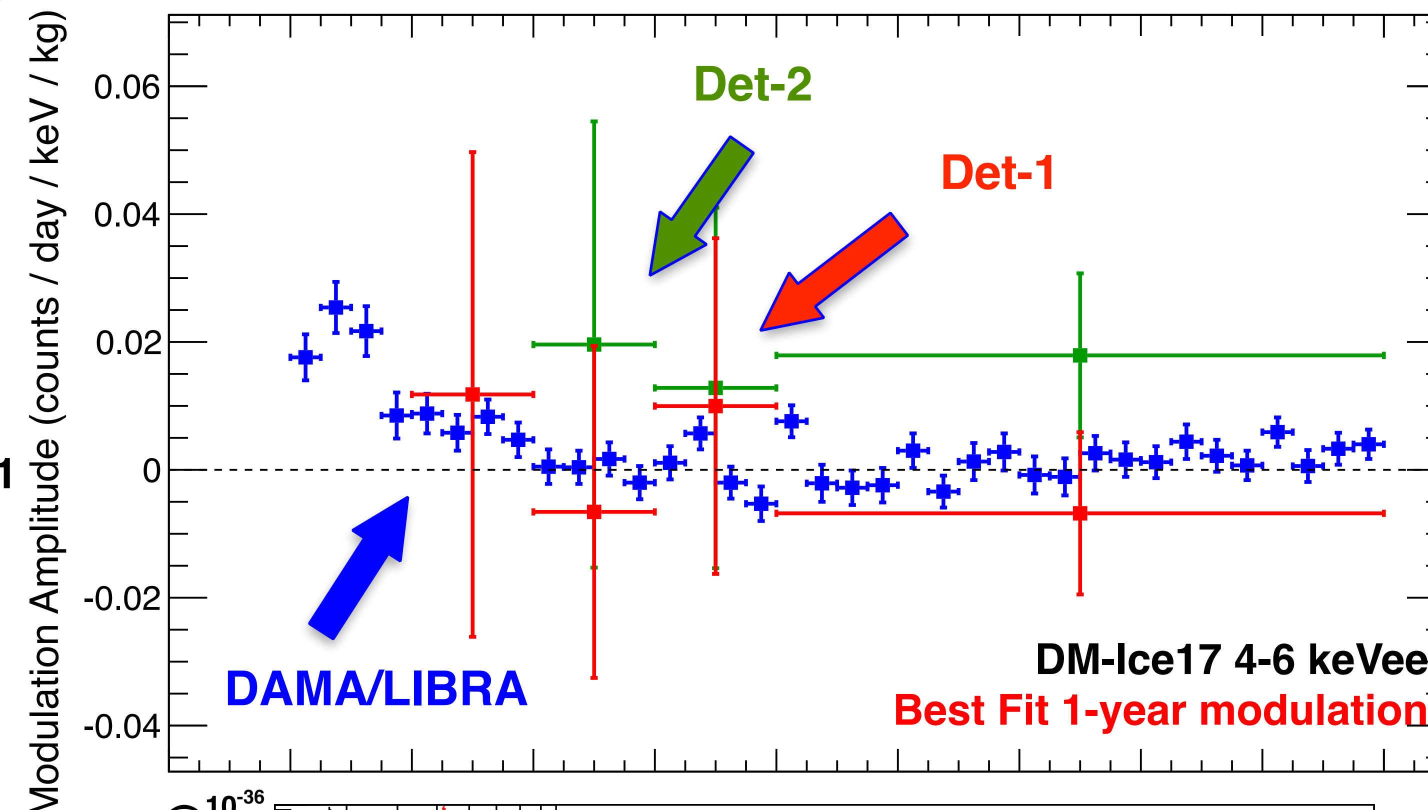


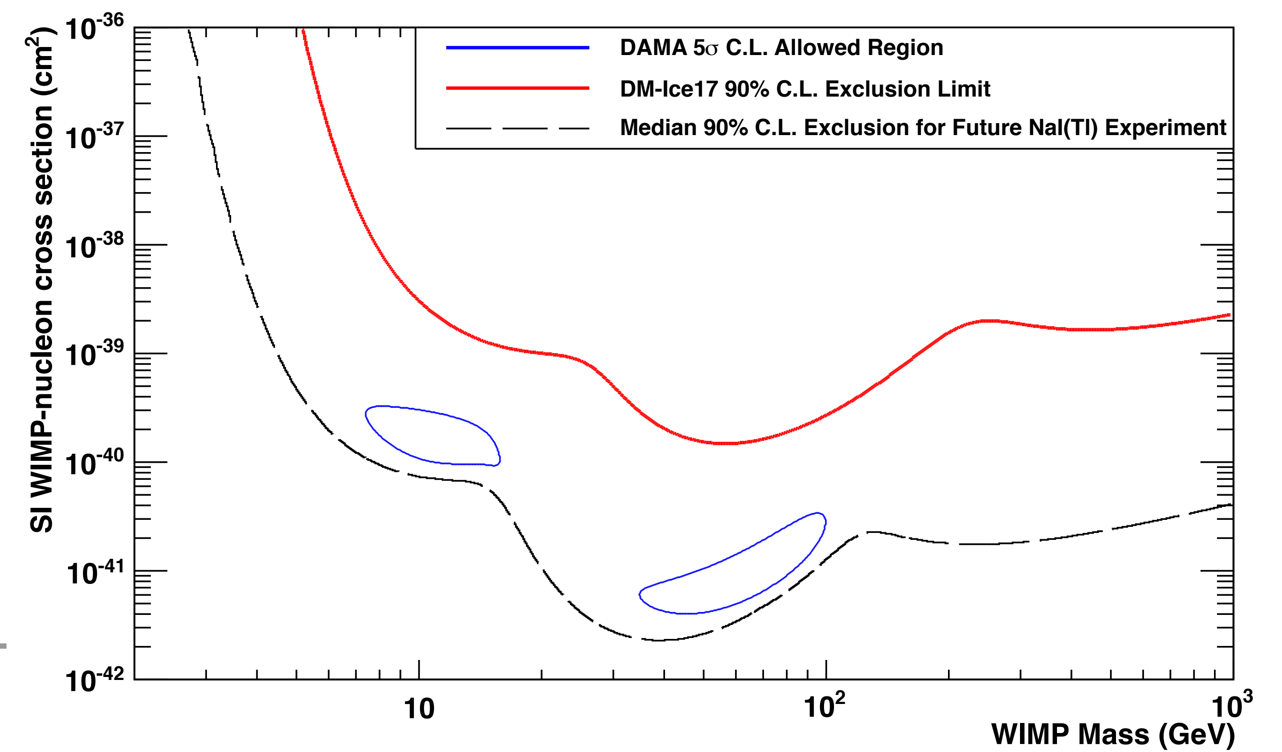
DM-Ice17

PRD **90** 092005 (2014)
PRD **93** 042001 (2016)
PRD **95** 032006 (2017)

http://dm-ice.yale.edu







- Proof of principle
- Southern Hemisphere operations
- Awaiting for IceCube upgrade

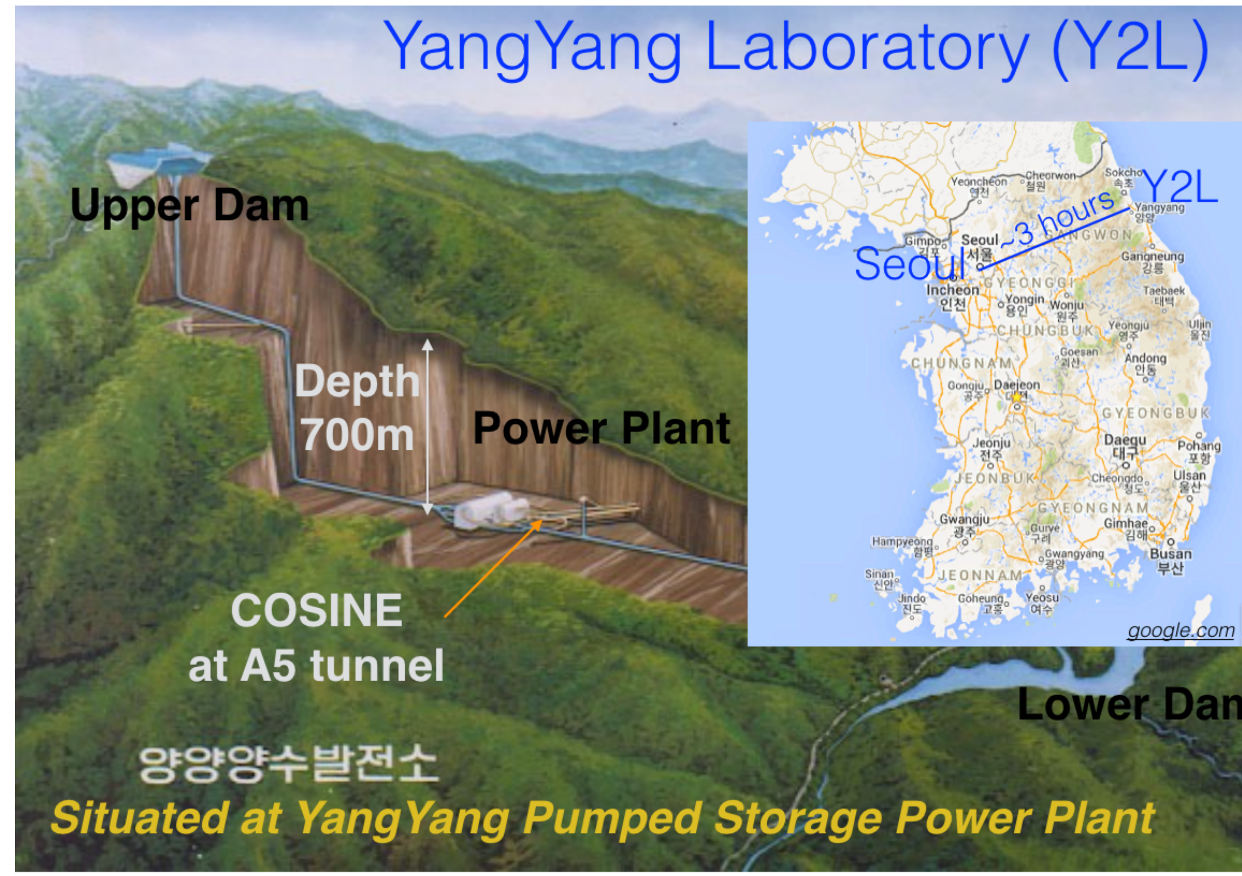
NaI(Tl) Experiments

COSINE-100

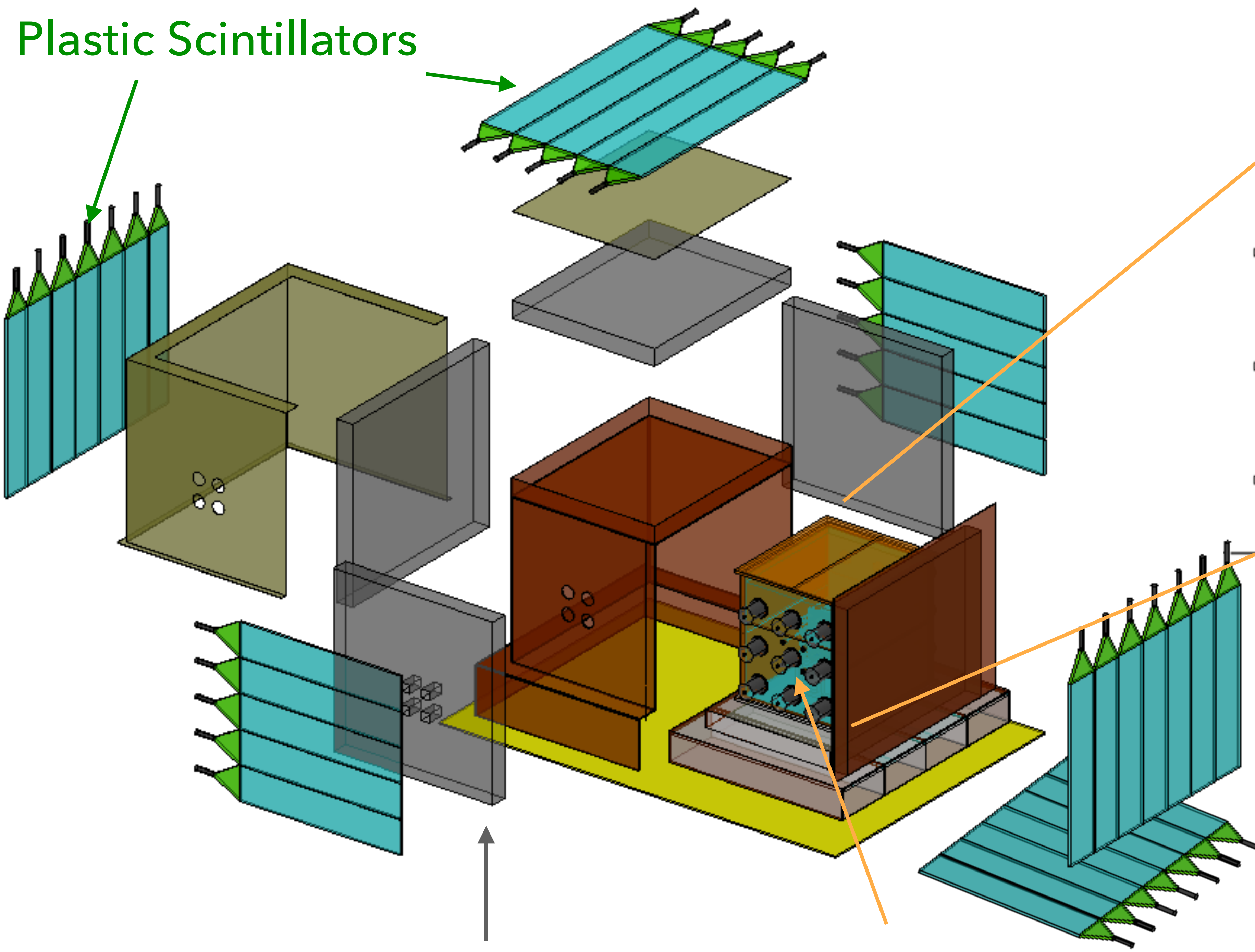
http://cosine.yale.edu

KIMS Korea Invisible Mass Search Experiment + DM-ICE

- 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
- **Physics run started September 2016**

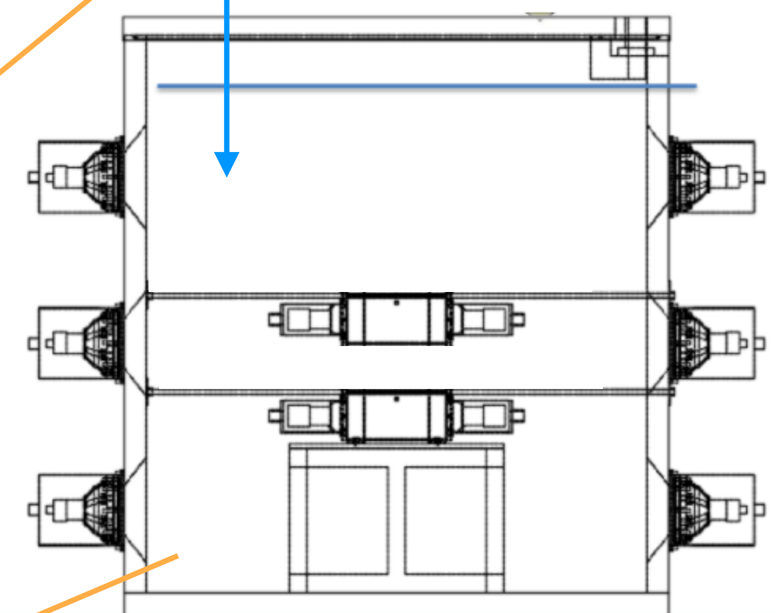


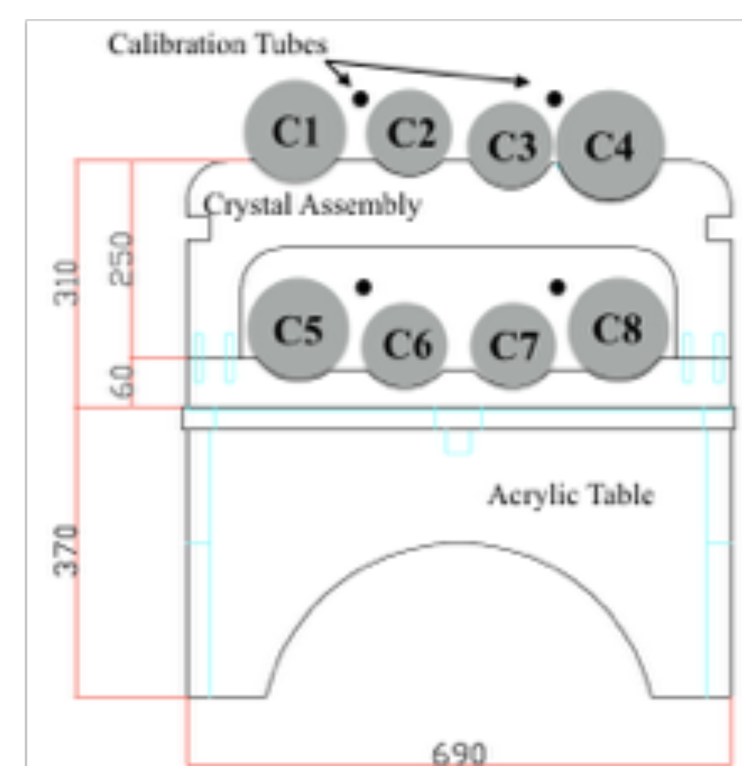
COSINE-100 Experimental Setup



2000 L Liquid Scintillator

Tag ^{40}K to veto 3 keV background events

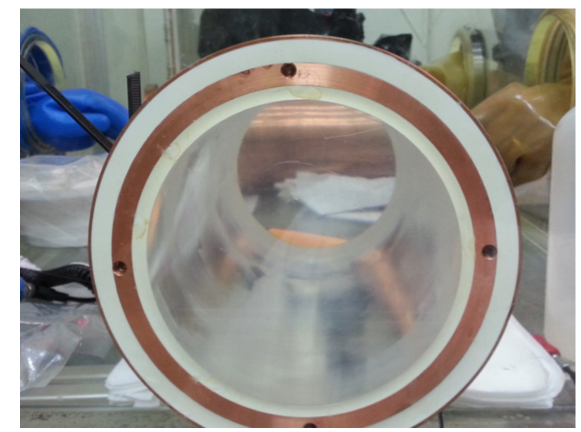


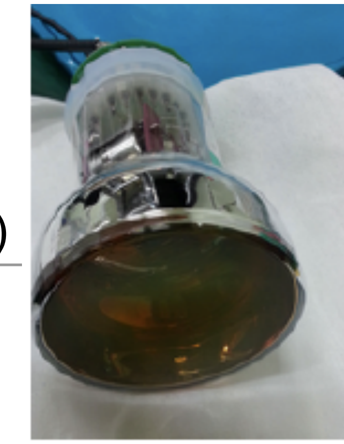


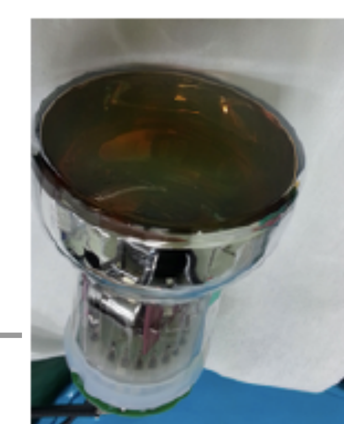
COSINE-100 NaI(Tl) Crystals

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

- 8 crystals, total 106 kg
- Culmination of R&D program 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



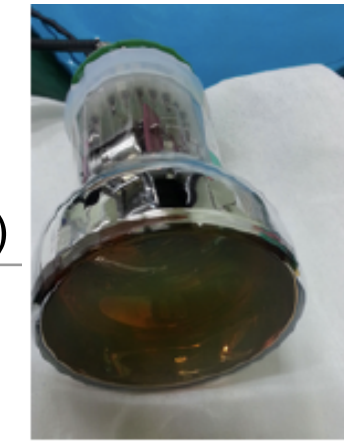




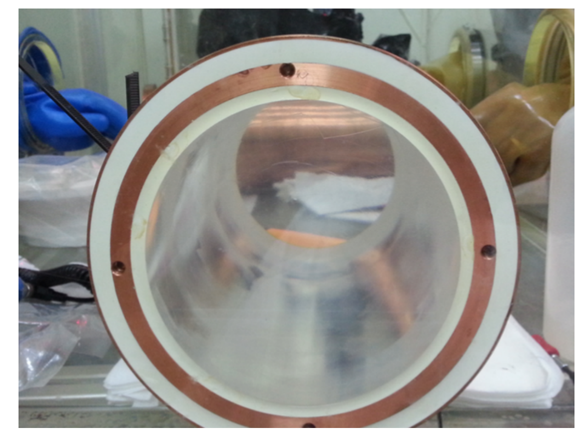
Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 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
Crystal 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

COSINE-100 NaI(Tl) Crystals

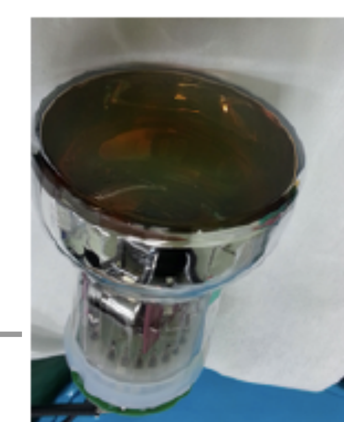
Eur.Phys.J. C **78** 107 (2018)



- 8 crystals, total 106 kg
- Culmination of R&D program 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



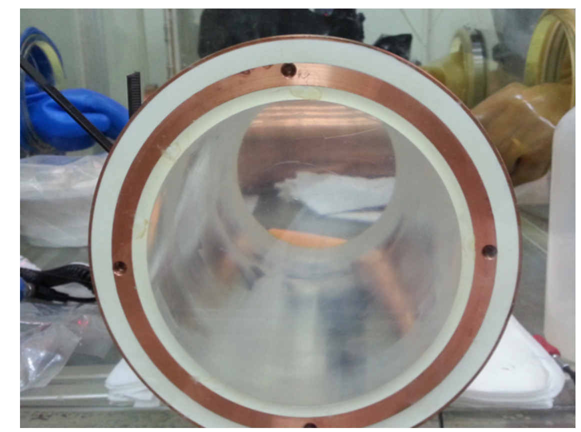
Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 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
Crystal 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

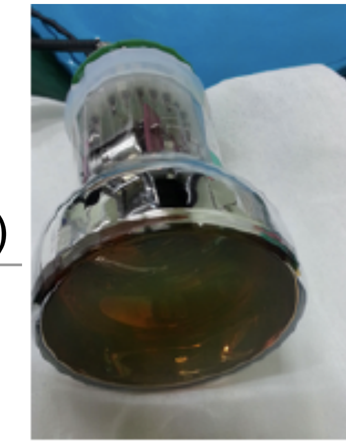


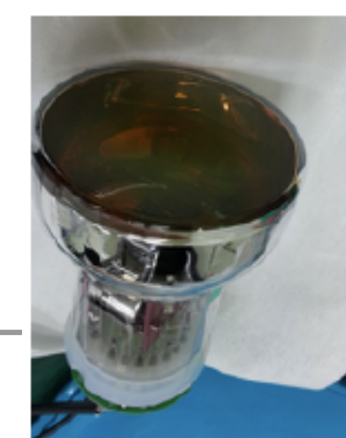
COSINE-100 NaI(Tl) Crystals

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

- 8 crystals, total 106 kg
- Culmination of R&D program 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



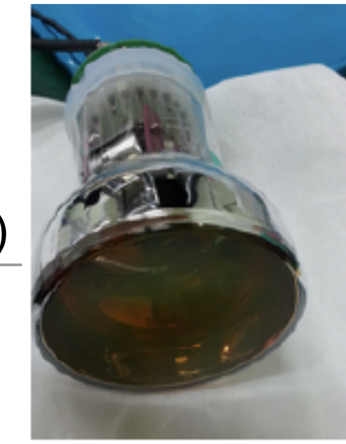




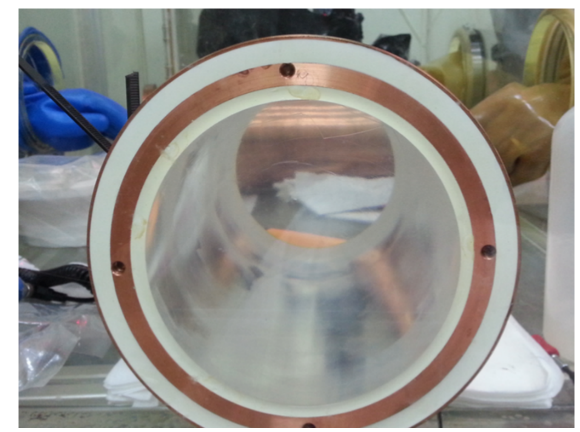
Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 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
Crystal 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

COSINE-100 NaI(Tl) Crystals

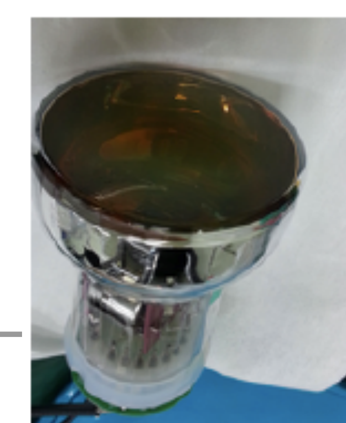
Eur.Phys.J. C **78** 107 (2018)



- 8 crystals, total 106 kg
- Culmination of R&D program 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

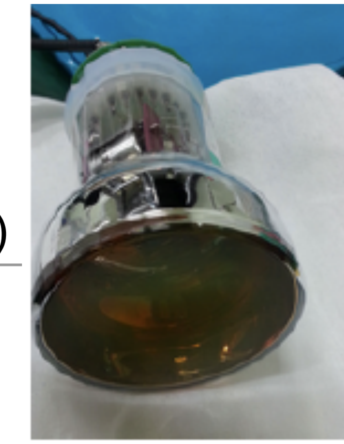


Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 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
Crystal 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

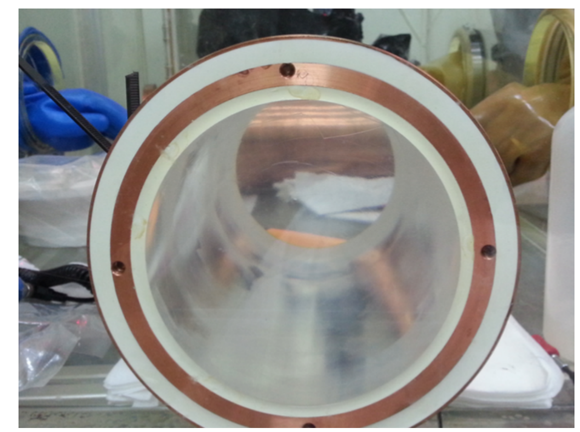


COSINE-100 NaI(Tl) Crystals

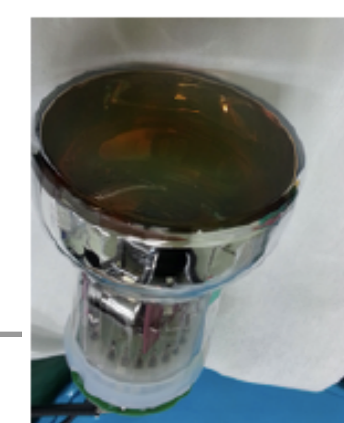
Eur.Phys.J. C **78** 107 (2018)



- 8 crystals, total 106 kg
- Culmination of R&D program 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

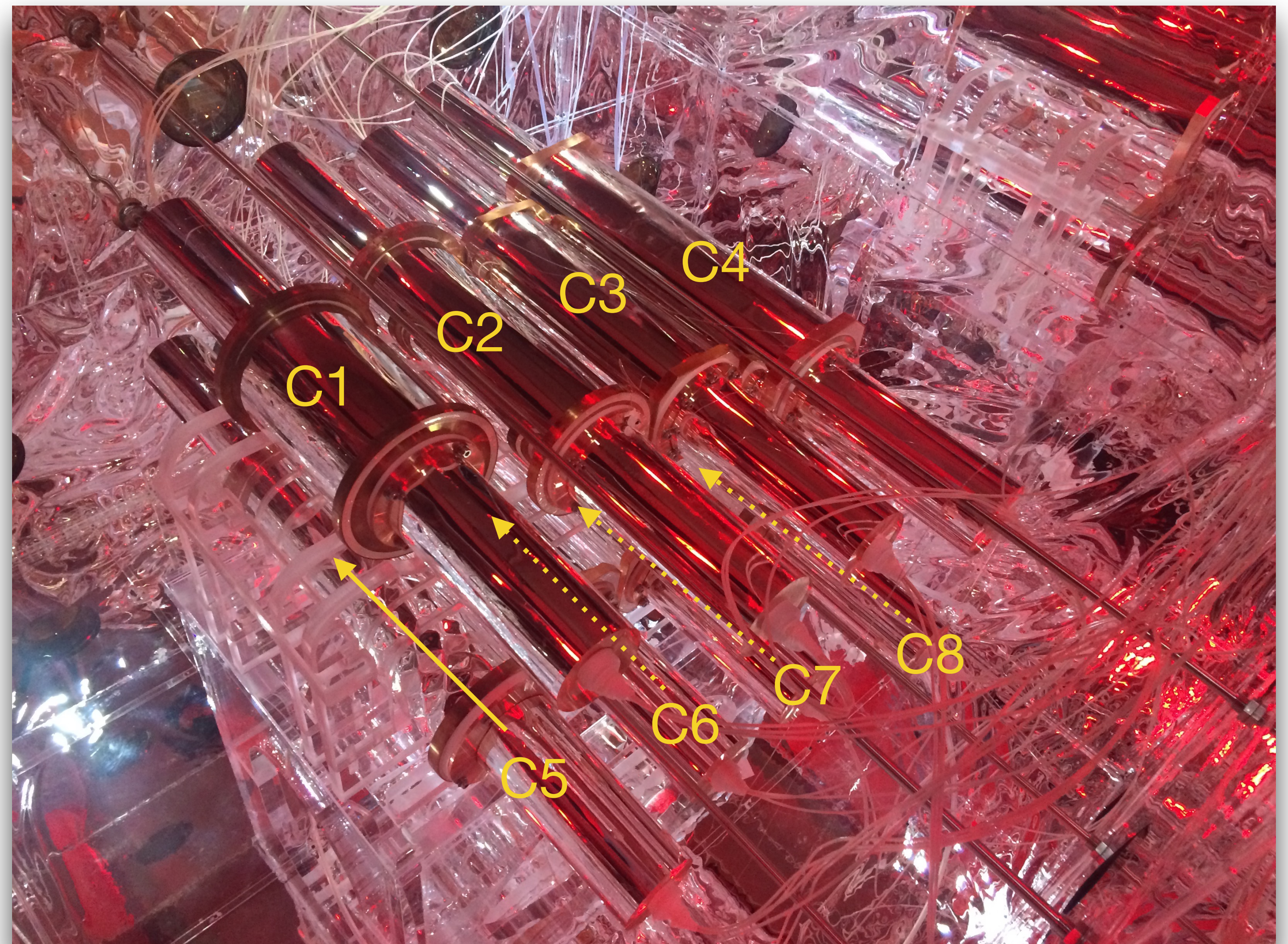


Crystal	Mass (kg)	Powder	Alpha rate (mBq/kg)	^{40}K (ppb)	^{238}U (ppt)	^{232}Th (ppt)	Light yield (p.e./keV)
Crystal 1	8.3	AS-B	3.20 ± 0.08	43.4 ± 13.7	< 0.02	1.31 ± 0.35	14.88 ± 1.49
Crystal 2	9.2	AS-C	2.06 ± 0.06	82.7 ± 12.7	< 0.12	< 0.63	14.61 ± 1.45
Crystal 3	9.2	AS-WS II	0.76 ± 0.02	41.1 ± 6.8	< 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
Crystal 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

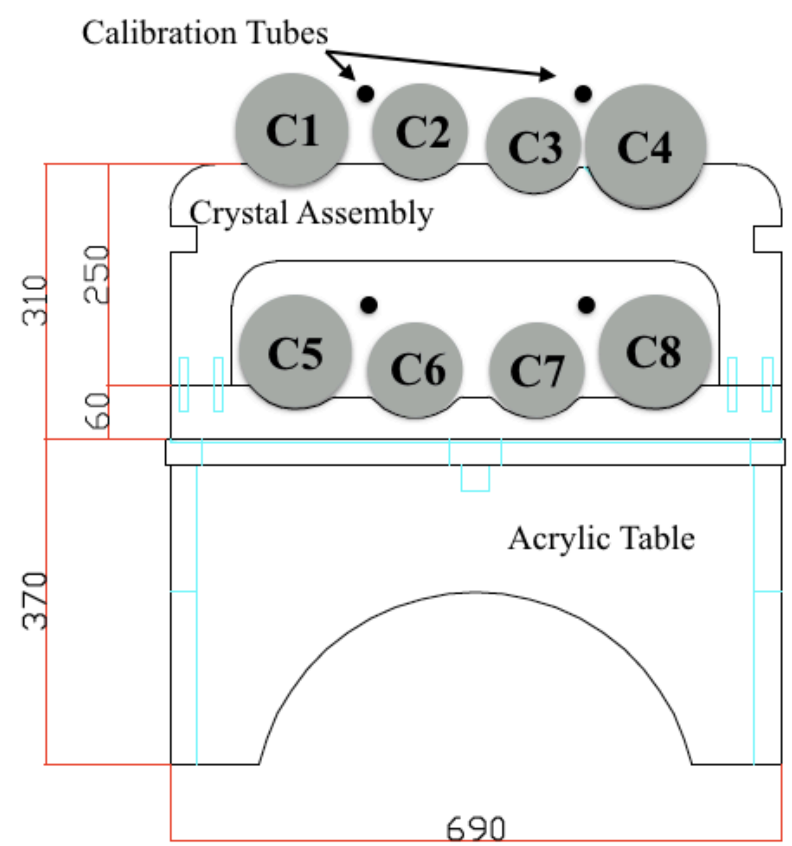


NaI(Tl) Detectors

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



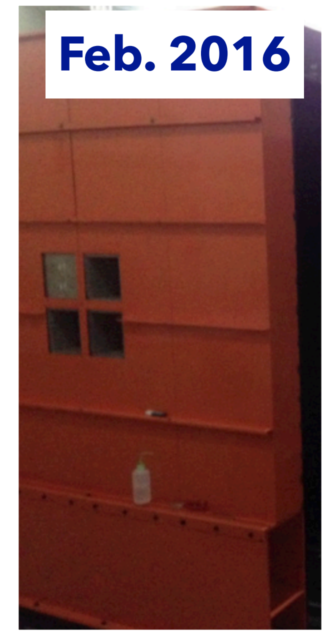
COSINE-100 Construction

COSINE-100 Construction

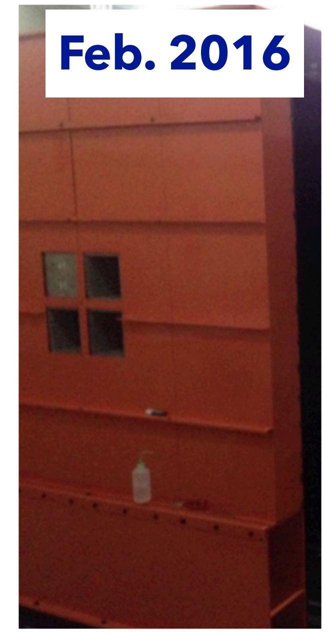
COSINE-100 Construction

COSINE-100 Construction

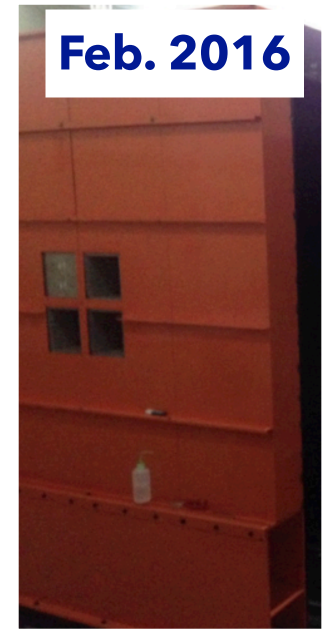
COSINE-100 Construction

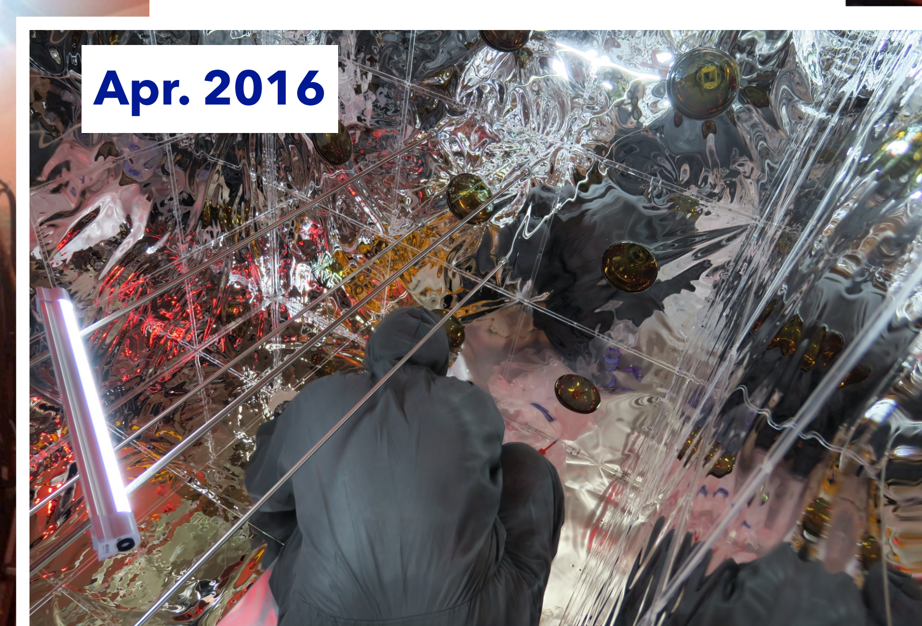


COSINE-100 Construction



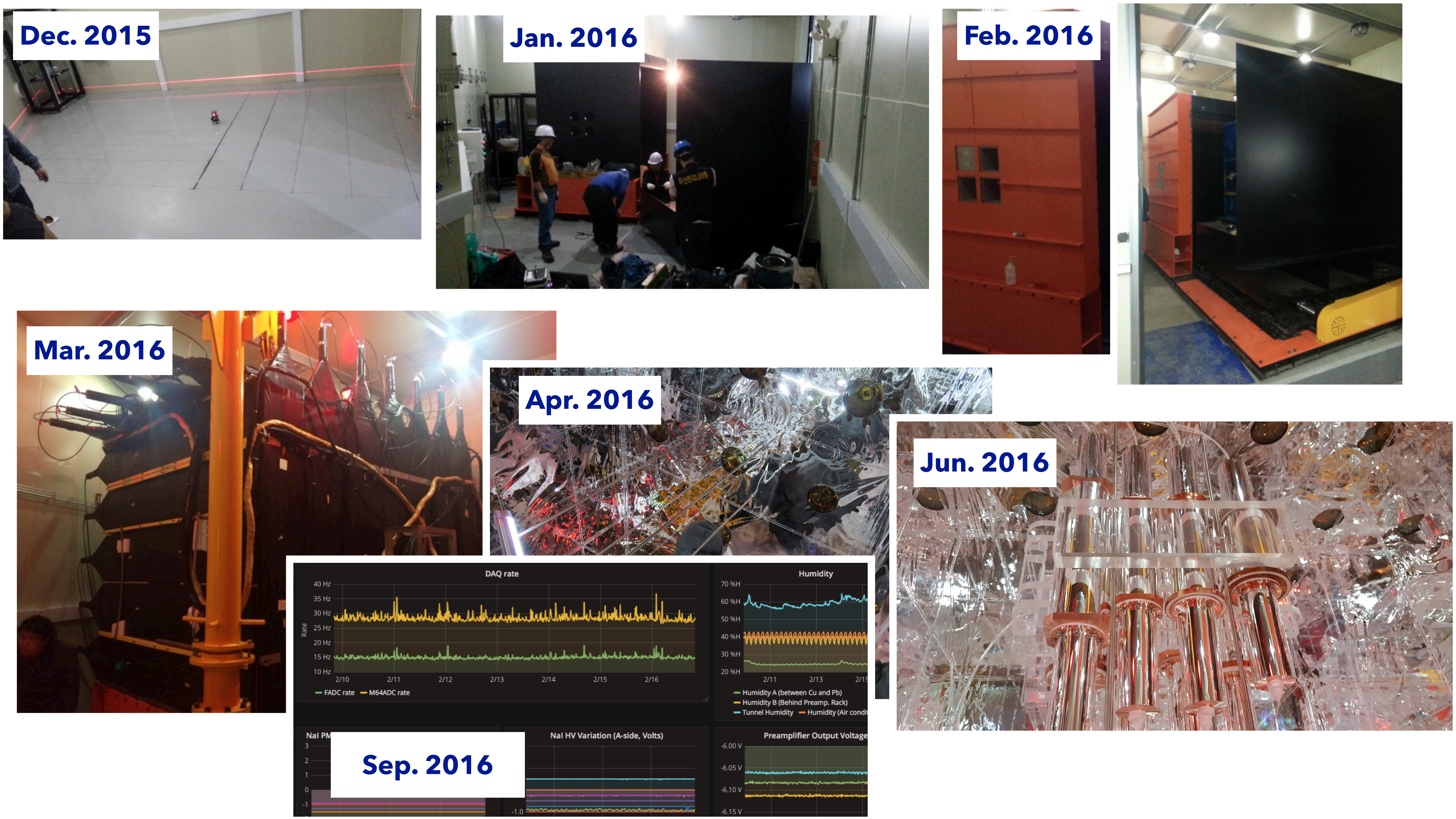
COSINE-100 Construction





COSINE-100 Construction

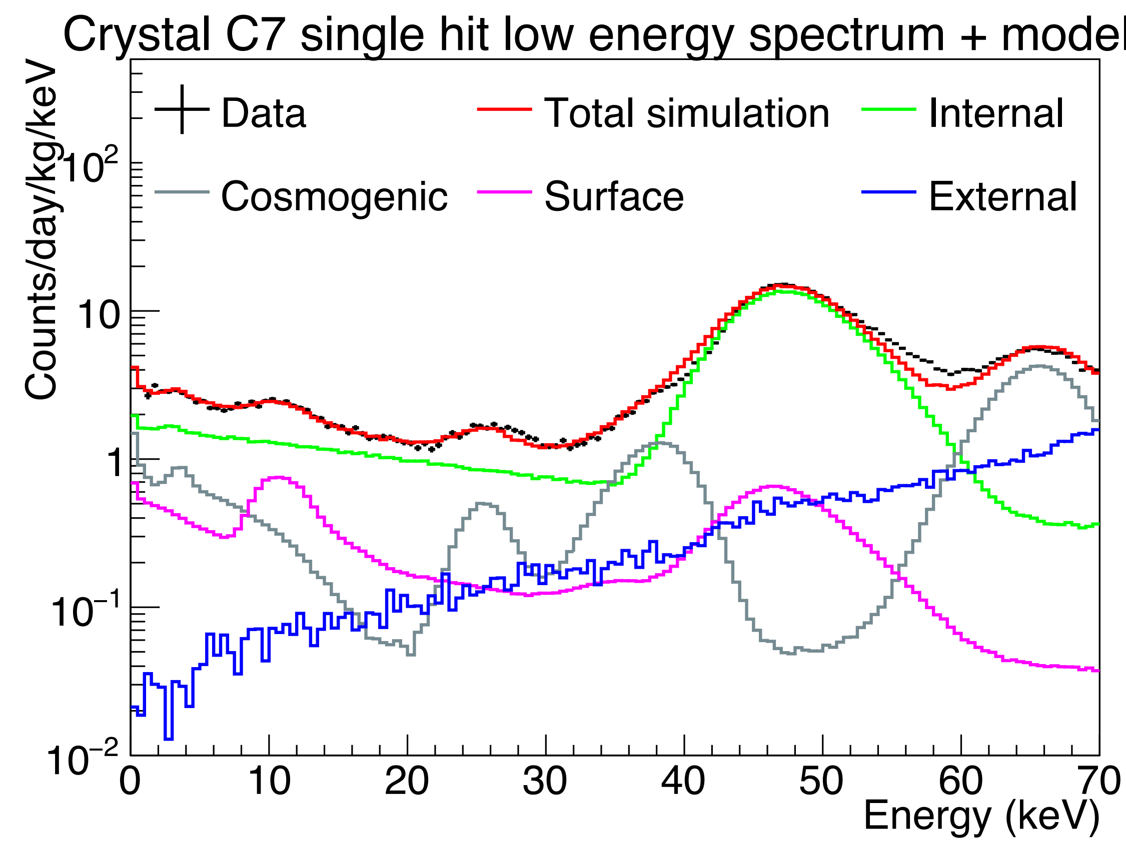
COSINE-100 Construction

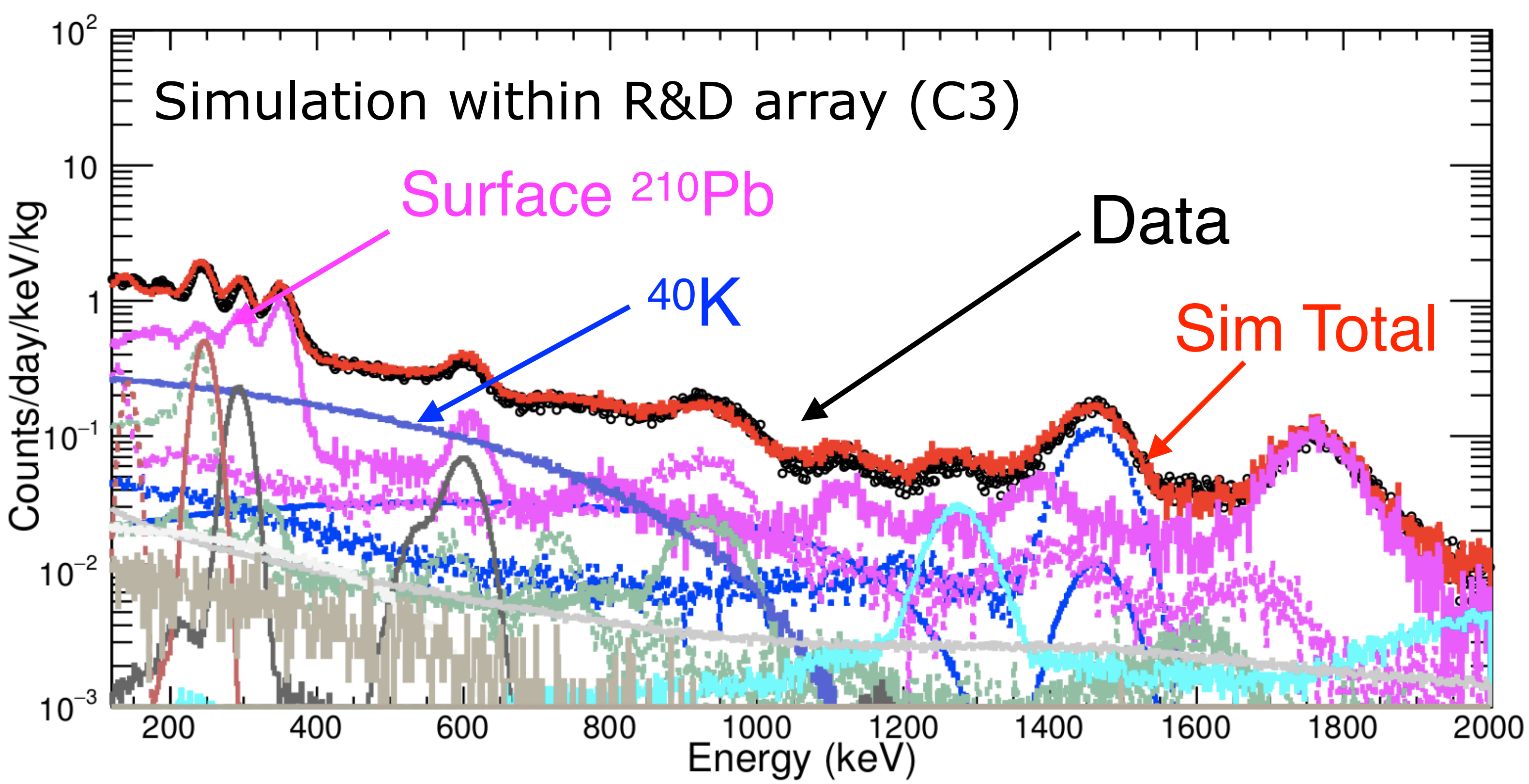


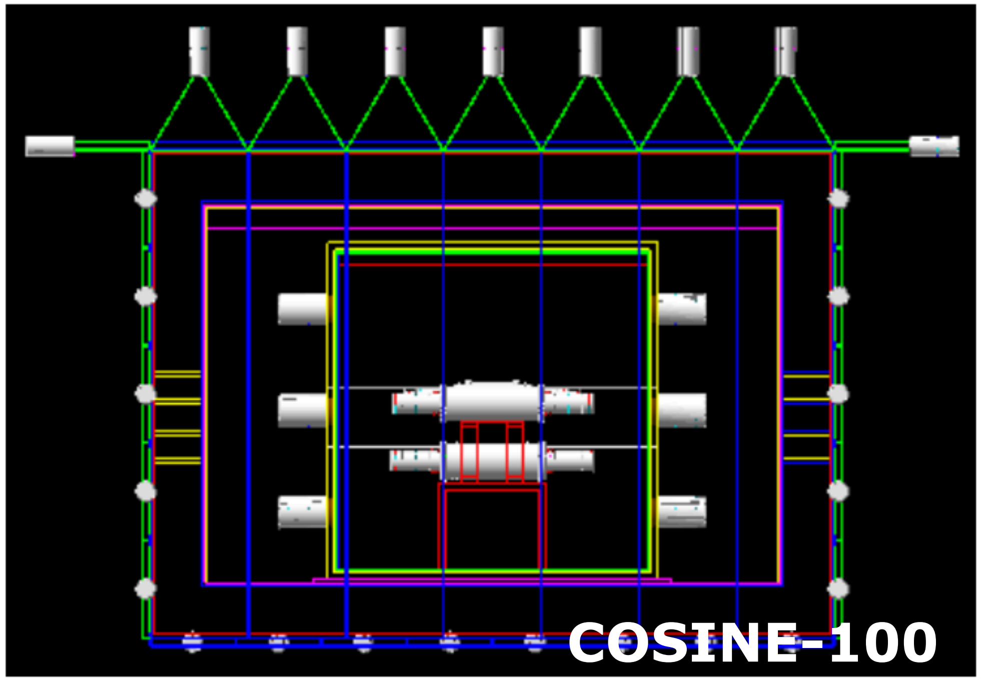
Background in Data vs. Simulations

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

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

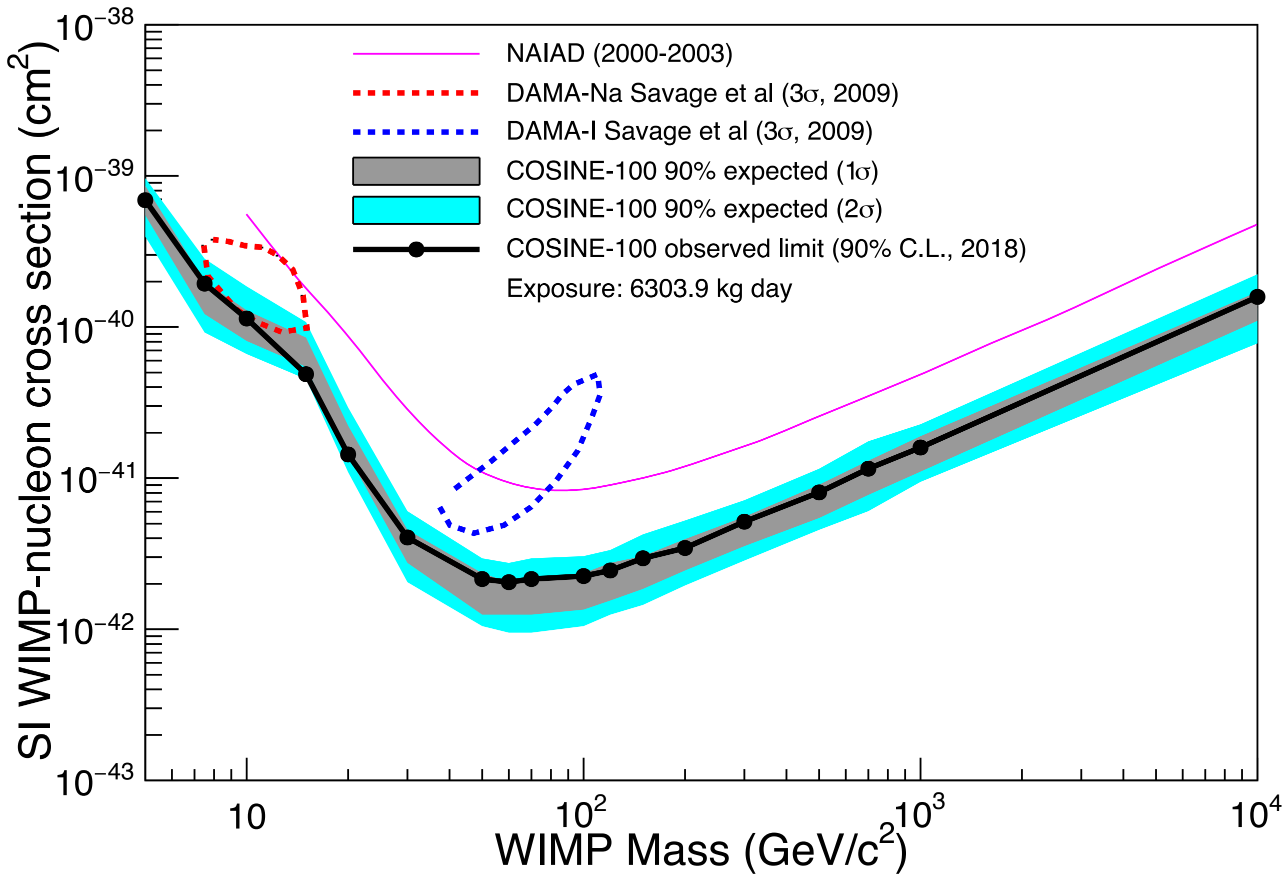


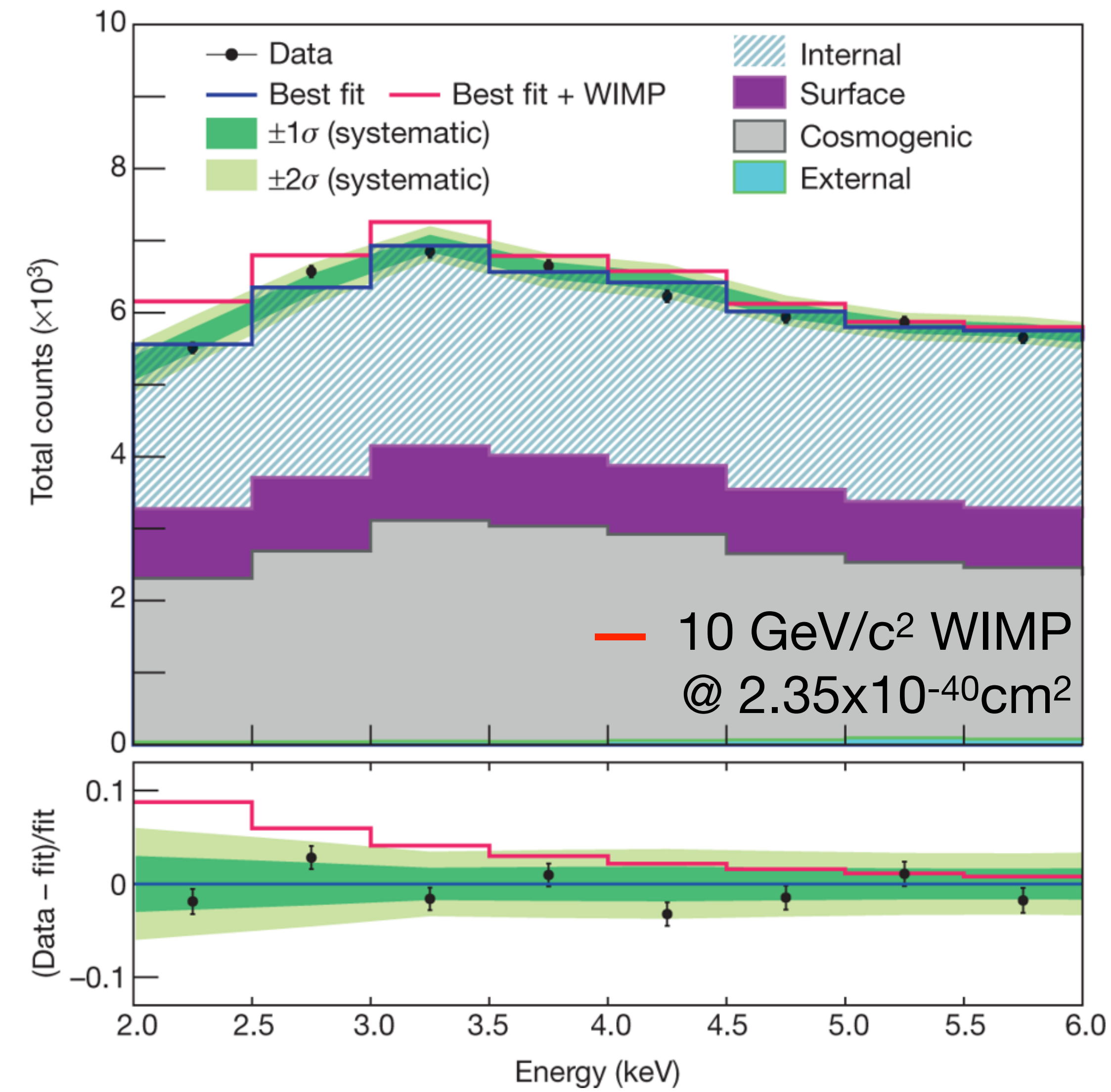




Spin-Independent WIMP Search

Nature **564** 83-86 (2018)





- Exclude interpretation of DAMA/LIBRA-phase1's signal as spin-independent WIMP with NaI(Tl) with 59.5 days of exposure
- Confirms null results from other direct detect experiments with different target medium

ScienceNews

NEWS PARTICLE PHYSICS

A controversial sighting of dark matter is looking even shakier

The COSINE-100 experiment finds no evidence of the evasive subatomic particles

BY EMILY CONOVER 1:00PM, DECEMBER 5, 2018

NEWS PARTICLE PHYSICS

ScienceNews

A controversial sighting of dark matter is looking even shakier

Science

Underground experiment casts doubt on controversial dark matter claim

By Adrian Cho | Dec. 5, 2018 , 1:40 PM

ScienceNews

NEWS PARTICLE PHYSICS

A controversial sighting of dark matter is looking even shakier

Science

Underground experiment casts doubt on controversial dark matter claim

PHYSICS TODAY

Long-standing dark-matter detection claim takes a hit

Using similar detector technology to that of the DAMA experiment, a new dark-matter search finds no evidence of WIMPs.

Andrew Grant

ScienceNews

NEWS PARTICLE PHYSICS

A controversial sighting of dark matter is looking even shakier

Science

Underground experiment casts doubt on controversial dark matter claim

PHYSICS TODAY

Long-standing dark-matter detection claim takes a hit

The Economist

Still in the dark

ıatter search finds no

A persistent claim to have detected dark matter looks wrong

Exploring the composition of the universe

ScienceNews

NEWS PARTICLE PHYSICS

A controversial sighting of dark matter is looking even shakier

Science

Underground experiment casts doubt on controversial dark matter claim

PHYSICS TODAY

Long-standing dark-matter detection claim takes a hit

The Economist

Still in the dark

A persistent claim to have detected dark matter looks wrong

ıatter search finds no

Spektrum.de

ASTROPHYSIK

Rückschlag für umstrittenes Dunkle-Materie-Signal

ScienceNews

NEWS PARTICLE PHYSICS

A controversial sighting of dark matter is looking even shakier

Science

Underground experiment casts doubt on controversial dark matter claim

PHYSICS TODAY

Long-standing dark-matter detection claim takes a hit

The Economist

Still in the dark

A persistent claim to have detected dark matter looks wrong

ıatter search finds no

Spektrum.de

ASTROPHYSIK

Rückschlag für umstrittenes Dunkle-Materie-Signal

nature

素粒子物理学： 暗黒物質のシグナルはまだ見つからず

Nature **564**, 7734

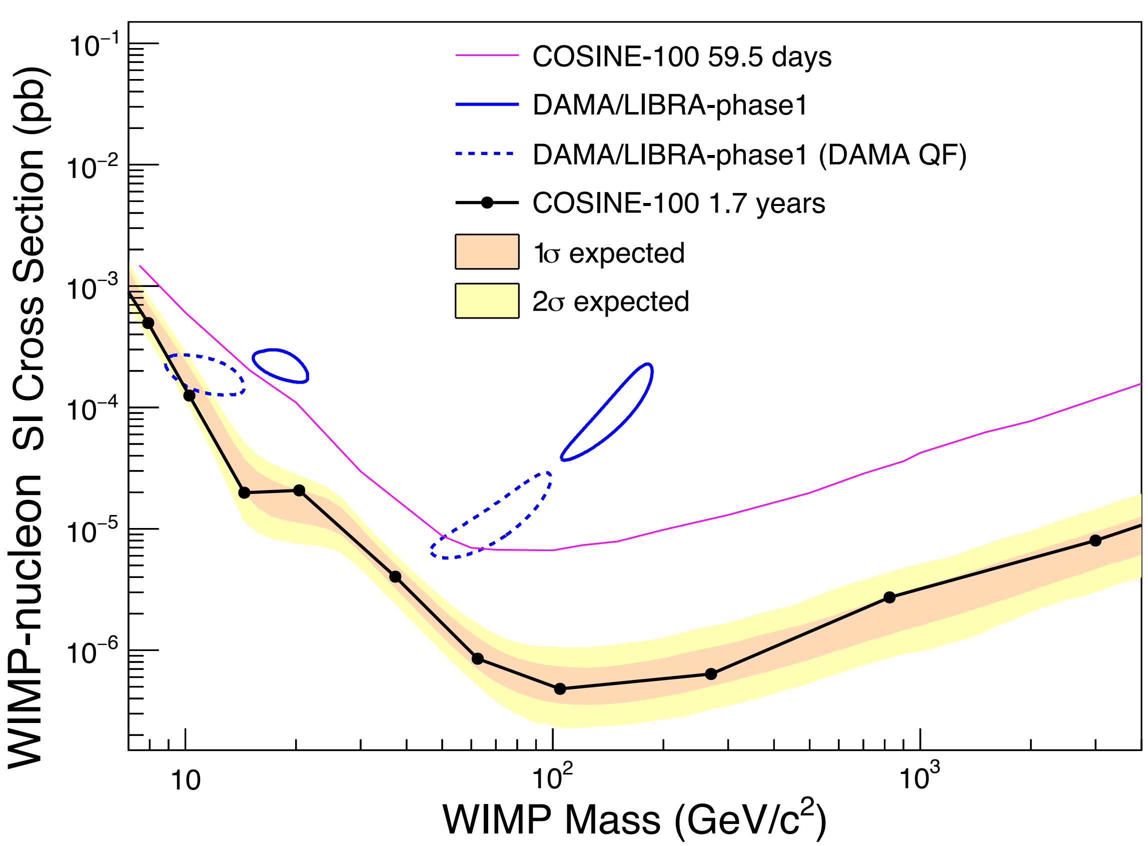
2018年12月6日

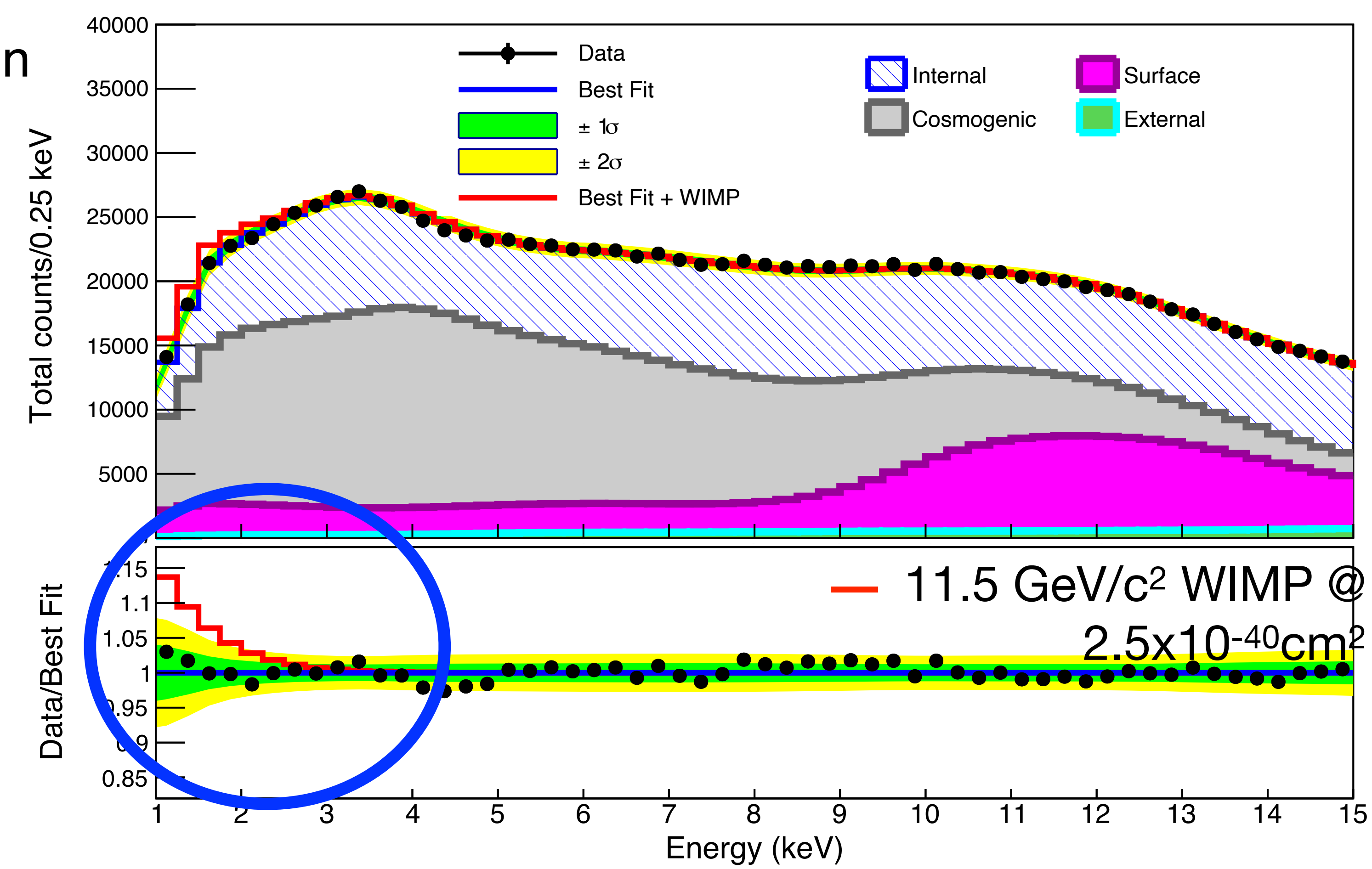
Update on Spin-Independent WIMP Search

arXiv:2104.03537

- 10x increased sensitivity with improved:
  - exposure: 59.5 live days → 1.7 years
  - threshold: 2 keV → 1 keV

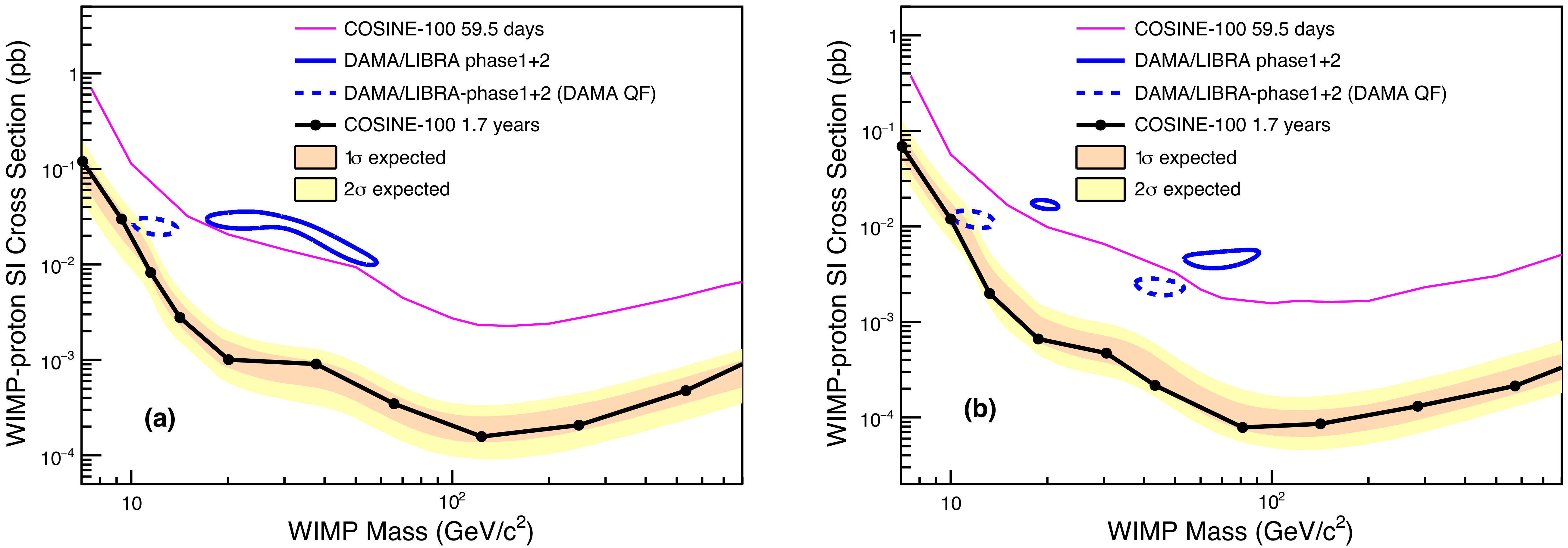
WIMP-nucleon spin-independent cross section



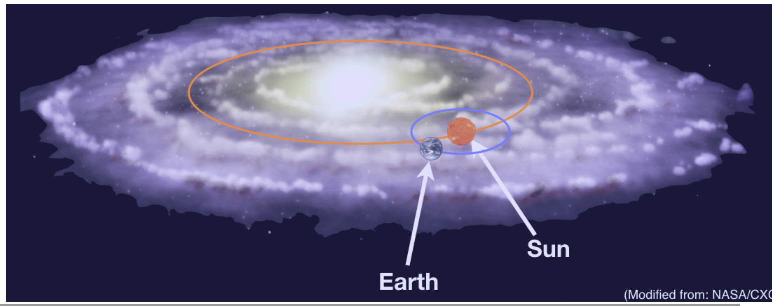


Update on Spin-Independent WIMP Search

arXiv:2104.03537

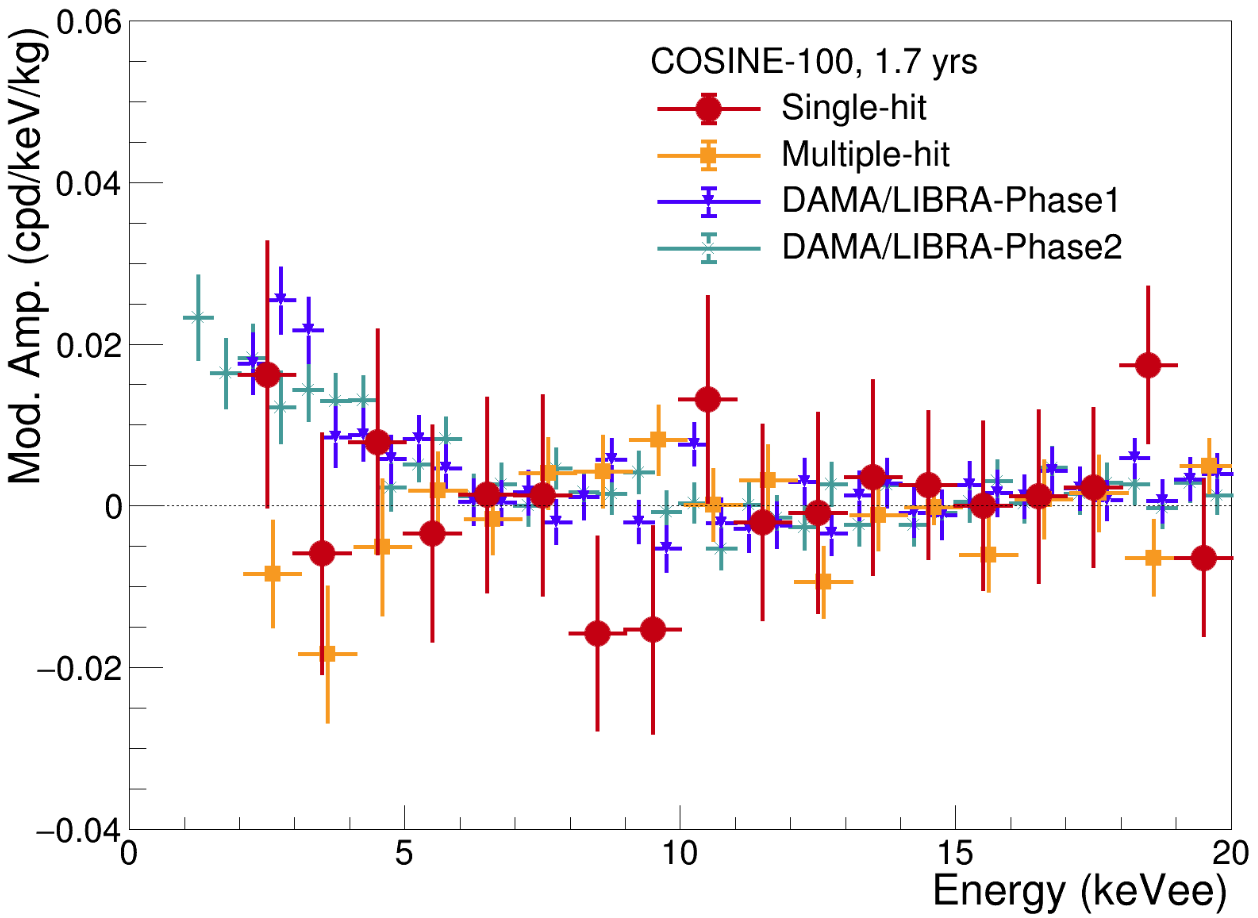


Ultimate Test: Annual Modulation



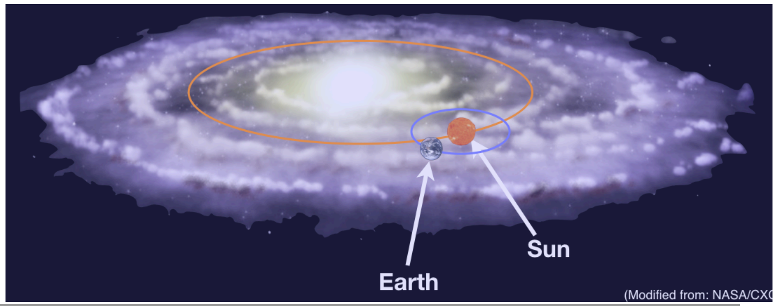
PRL **123** 031302 (2019)

COSINE-100 (1.7 years)



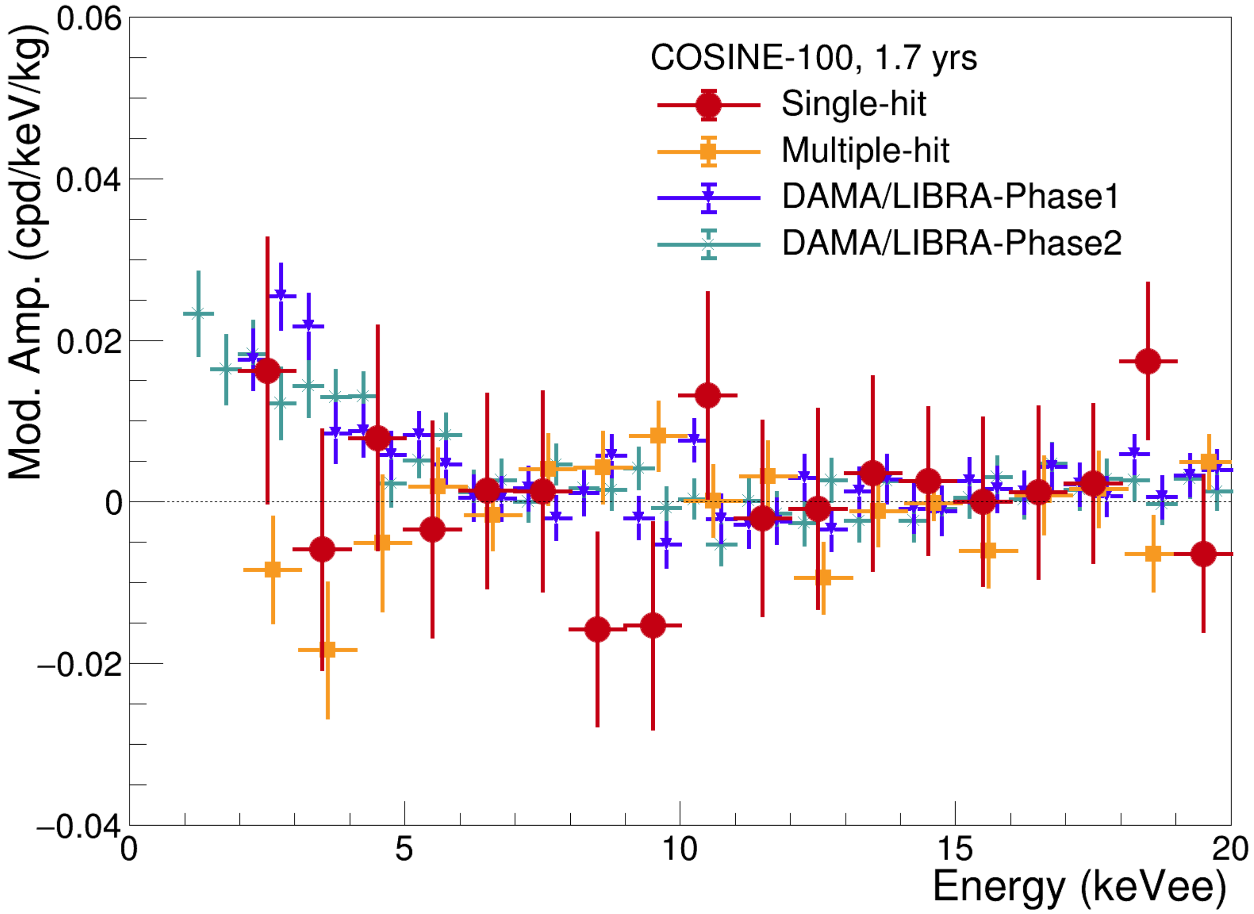
Stay tuned for updated search

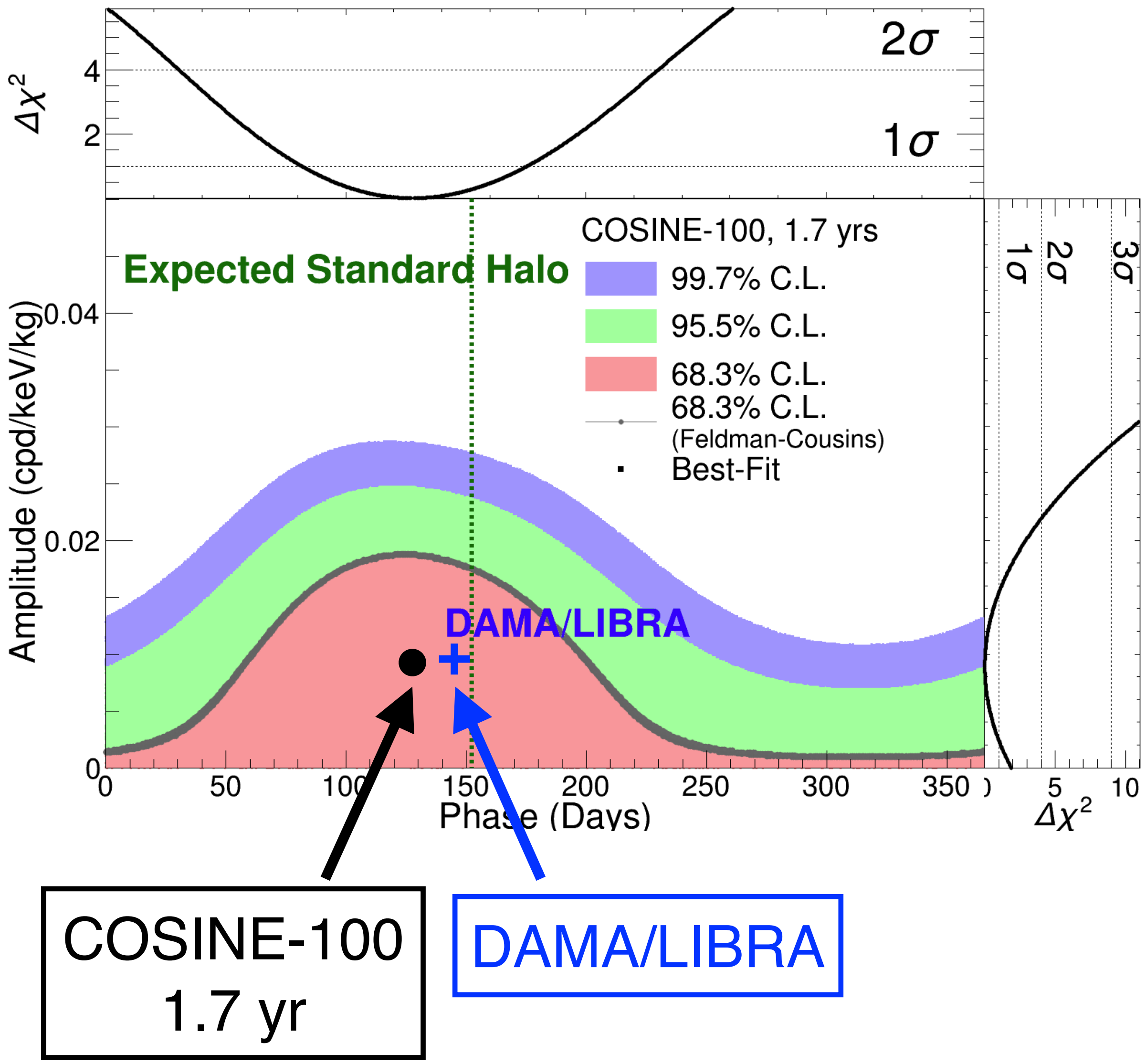
Ultimate Test: Annual Modulation



PRL **123** 031302 (2019)

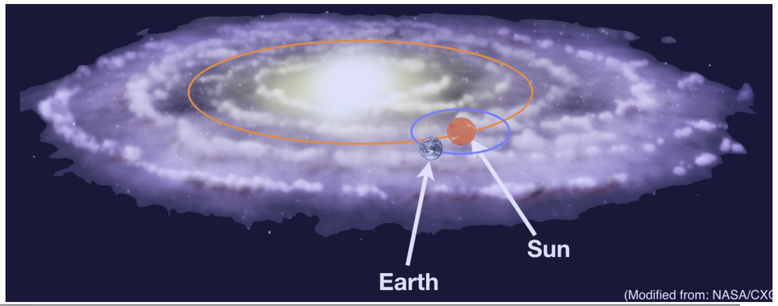
COSINE-100 (1.7 years)



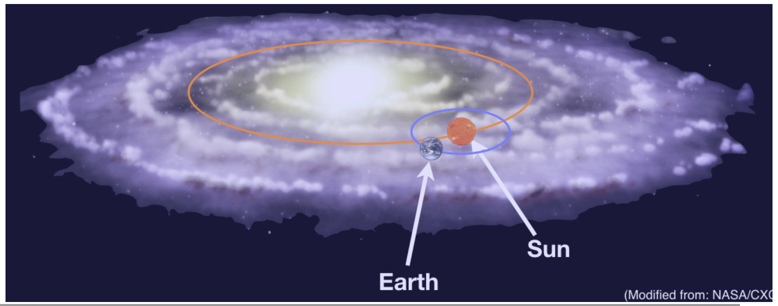


Stay tuned for updated search

Ultimate Test: Annual Modulation

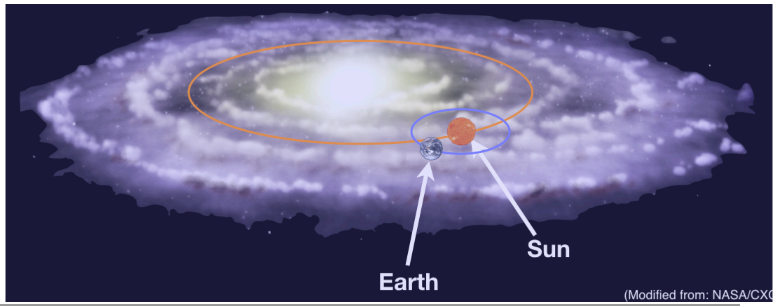


Ultimate Test: Annual Modulation

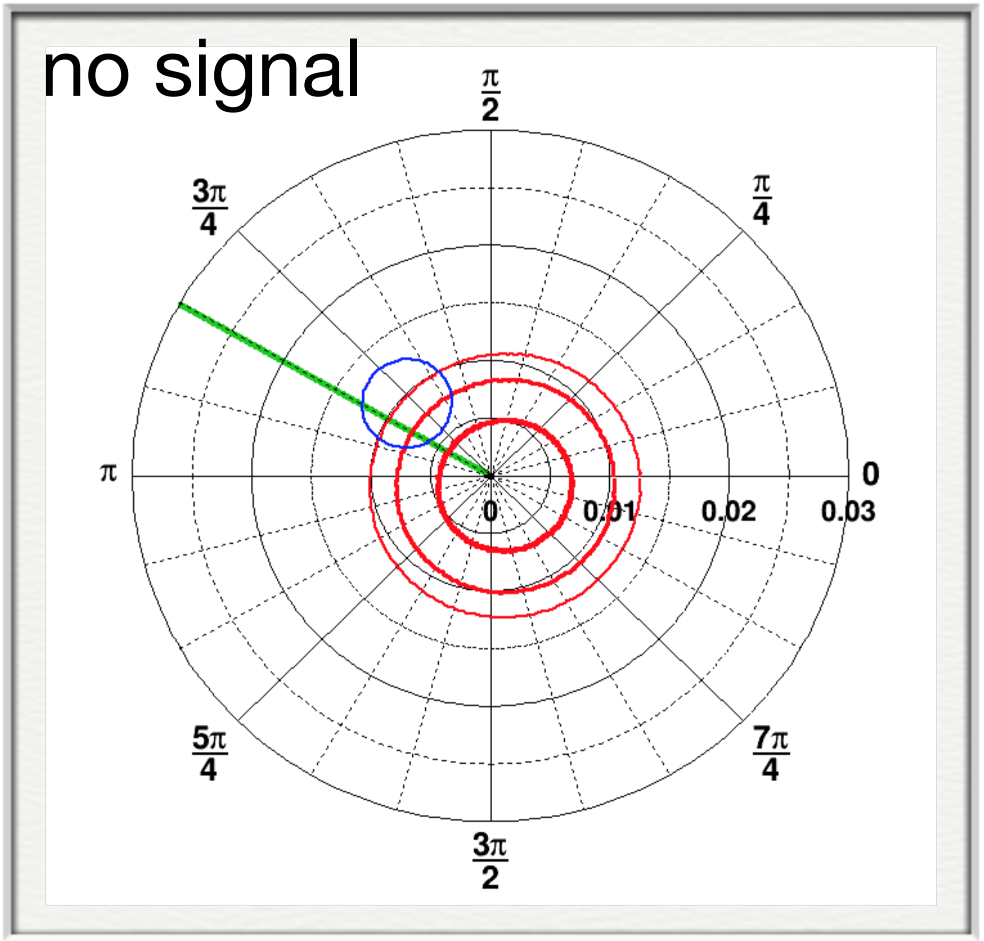


COSINE-100 Projection (5 years)

Ultimate Test: Annual Modulation



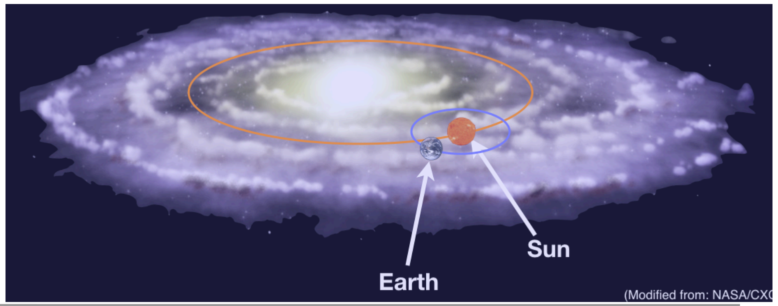
COSINE-100 Projection (5 years)



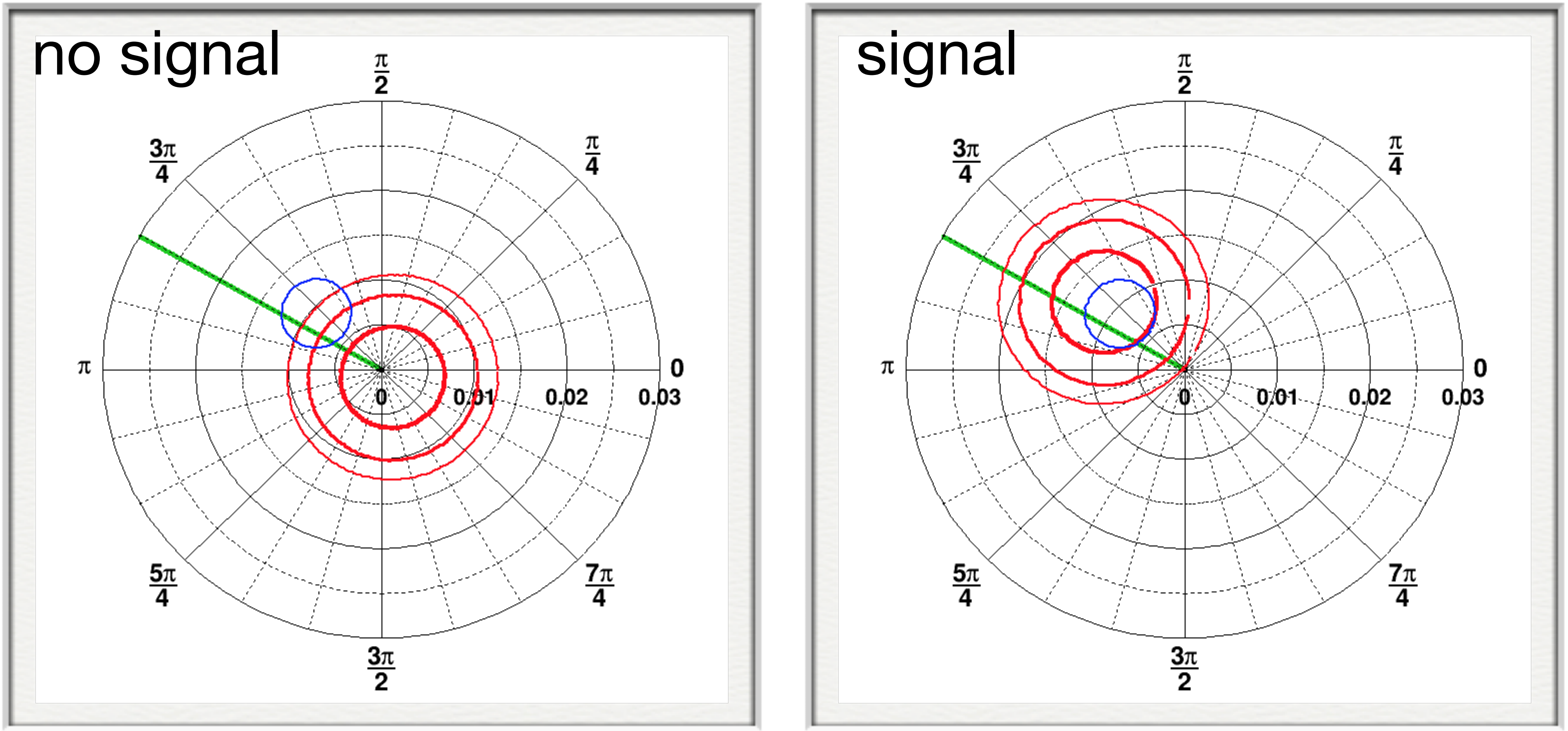
◉ DAMA (99%)

◉ COSINE-100, 5 yrs (68, 90, 99%)

Ultimate Test: Annual Modulation



COSINE-100 Projection (5 years)

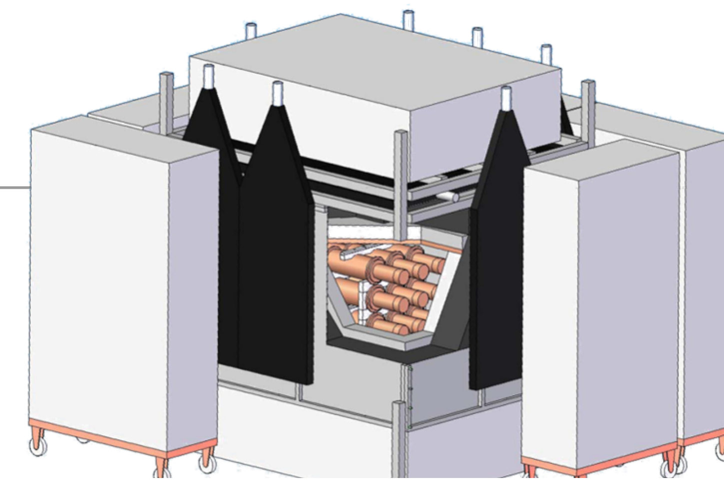


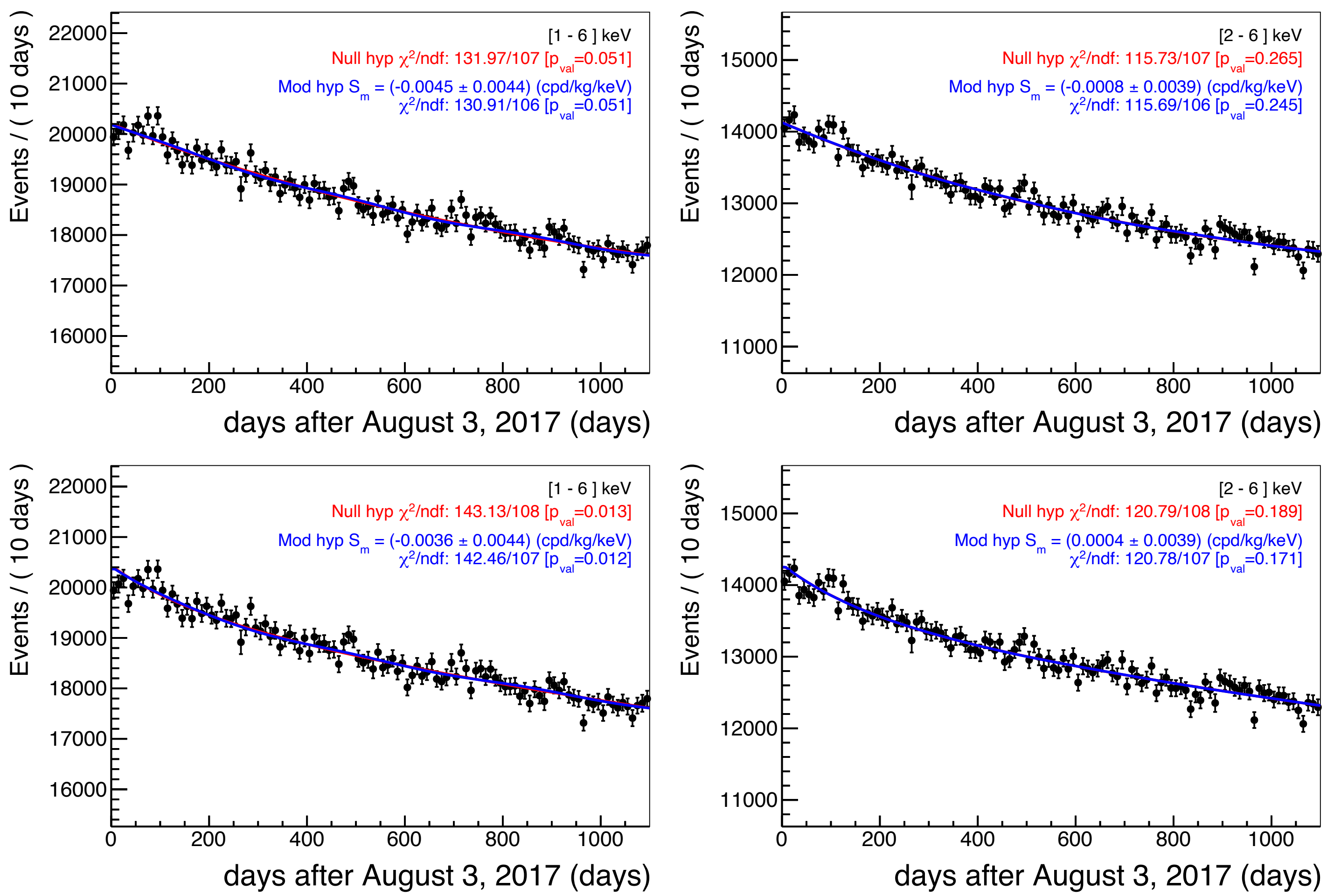
◉ DAMA (99%)

◉ COSINE-100, 5 yrs (68, 90, 99%)

Phys. Rev. Lett. **123** 031301 (2019)
Update w/ 3 years: arXiv:2103.01175

Sister Experiment: ANAIS-112





$$\phi_{bkg}(t_i) = 1 + f e^{-t_i/\tau}$$

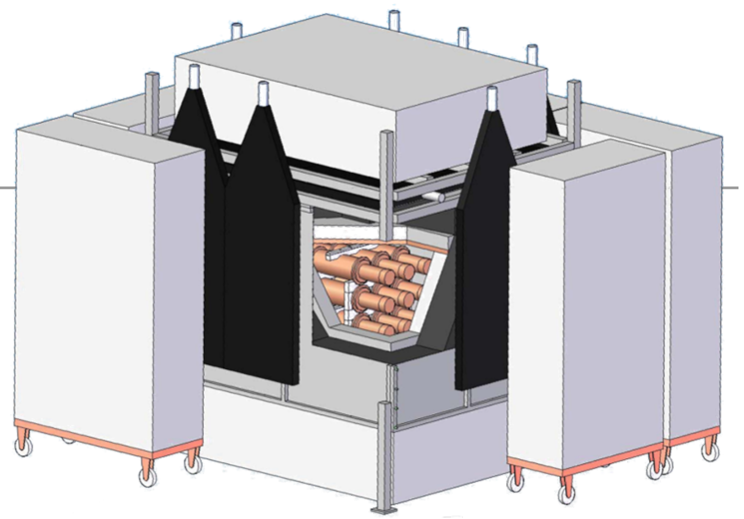
$$\phi_{bkg}(t_i) = 1 + f \phi_{bkg}^{MC}(t_i)$$

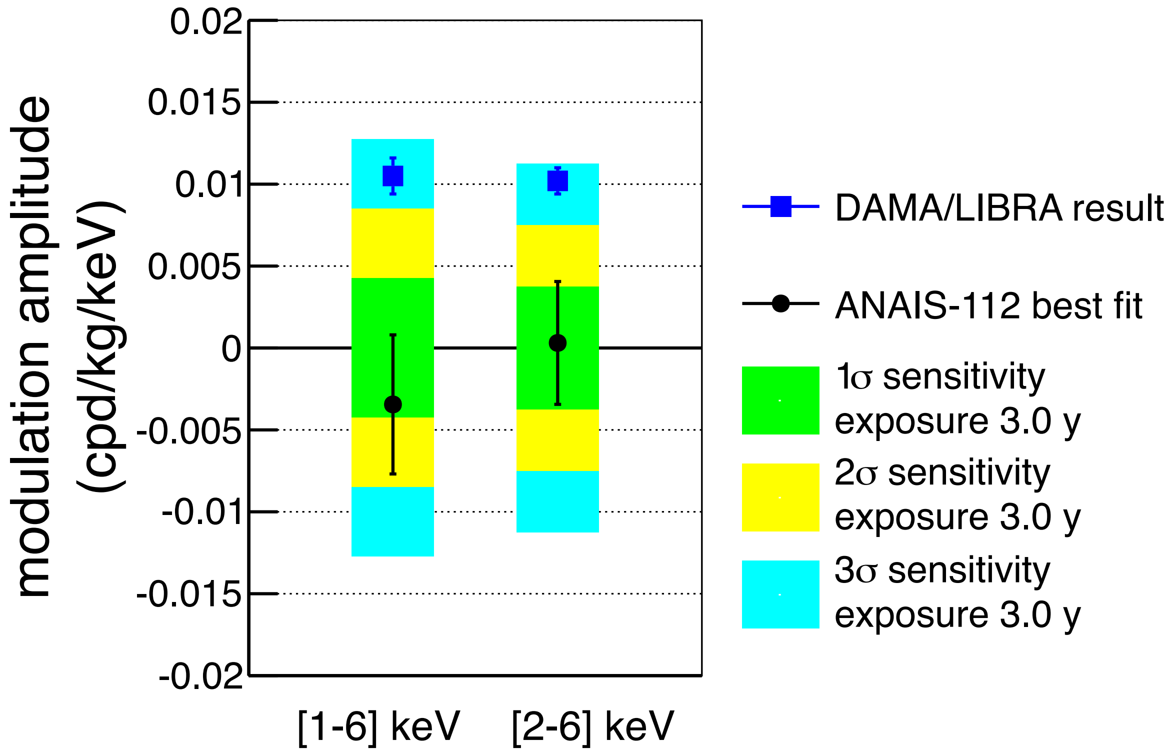
No Modulation Observed

Energy region	Model	χ^2/NDF null hyp	nuisance params	S_m cpd/kg/keV	p-value mod	p-value null
[1-6] keV	eq. 4	132 / 107	3	-0.0045±0.0044	0.051	0.051
	eq. 5	143.1 / 108	2	-0.0036±0.0044	0.012	0.013
	eq. 6	1076 / 972	18	-0.0034±0.0042	0.011	0.011
[2-6] keV	eq. 4	115.7 / 107	3	-0.0008±0.0039	0.25	0.27
	eq. 5	120.8 / 108	2	0.0004±0.0039	0.17	0.19
	eq. 6	1018 / 972	18	0.0003±0.0037	0.14	0.15

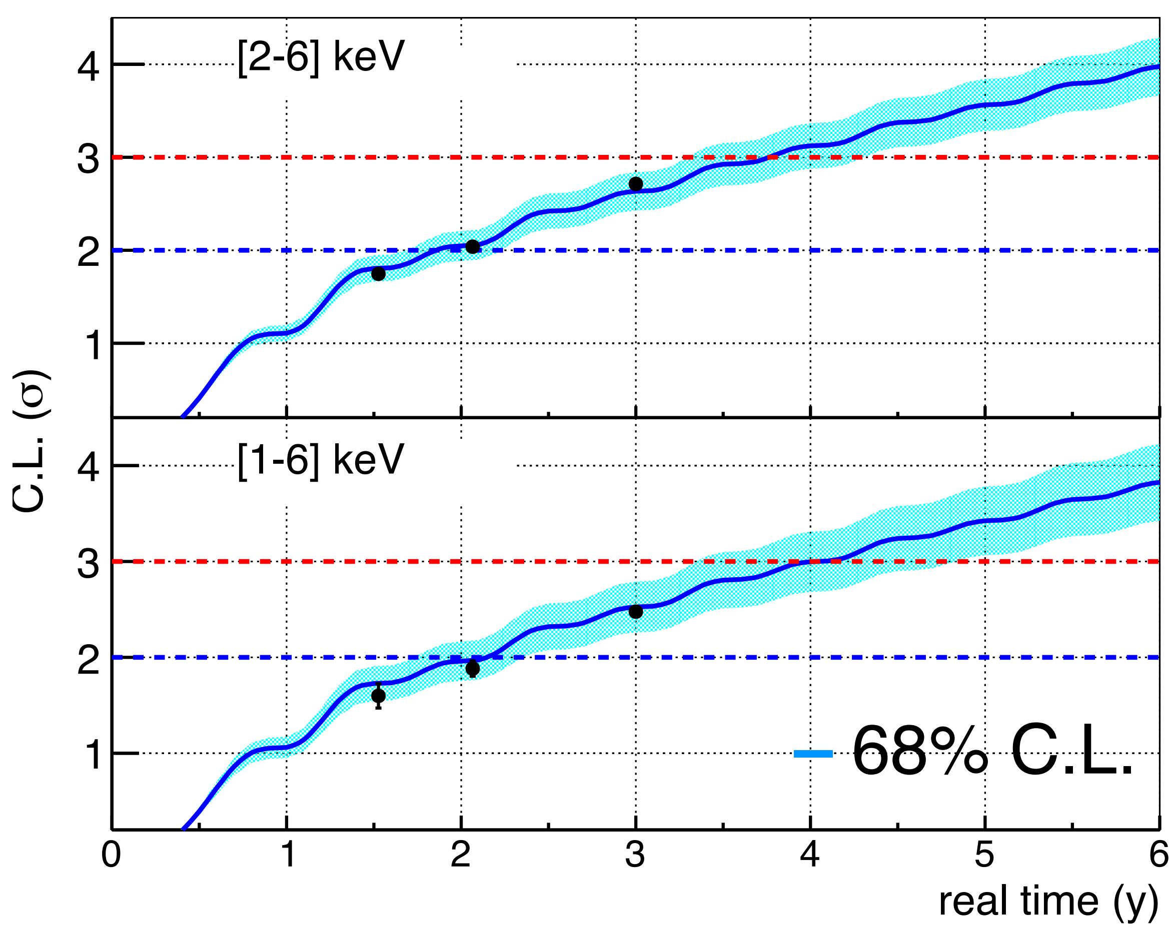
Phys. Rev. Lett. **123** 031301 (2019)
Update w/ 3 years: arXiv:2103.01175

ANAIS-112 Projections





Sensitivity to DAMA/LIBRA-size signal



3σ in 1-2 years

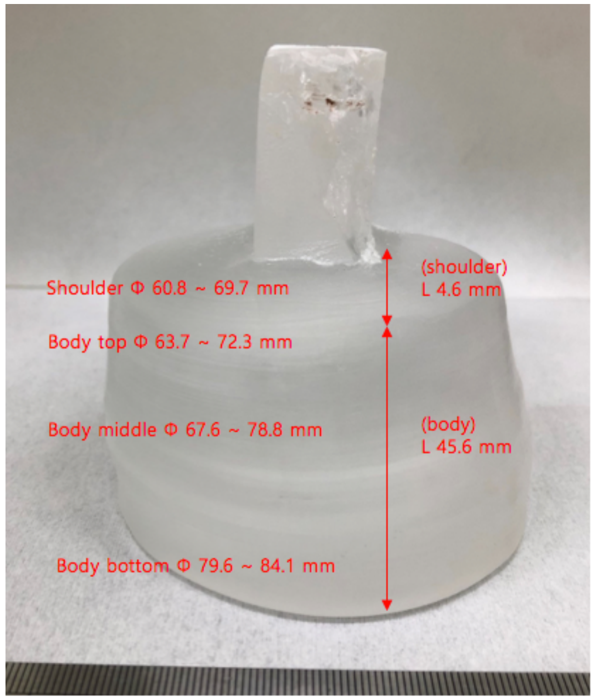
COSINE-200

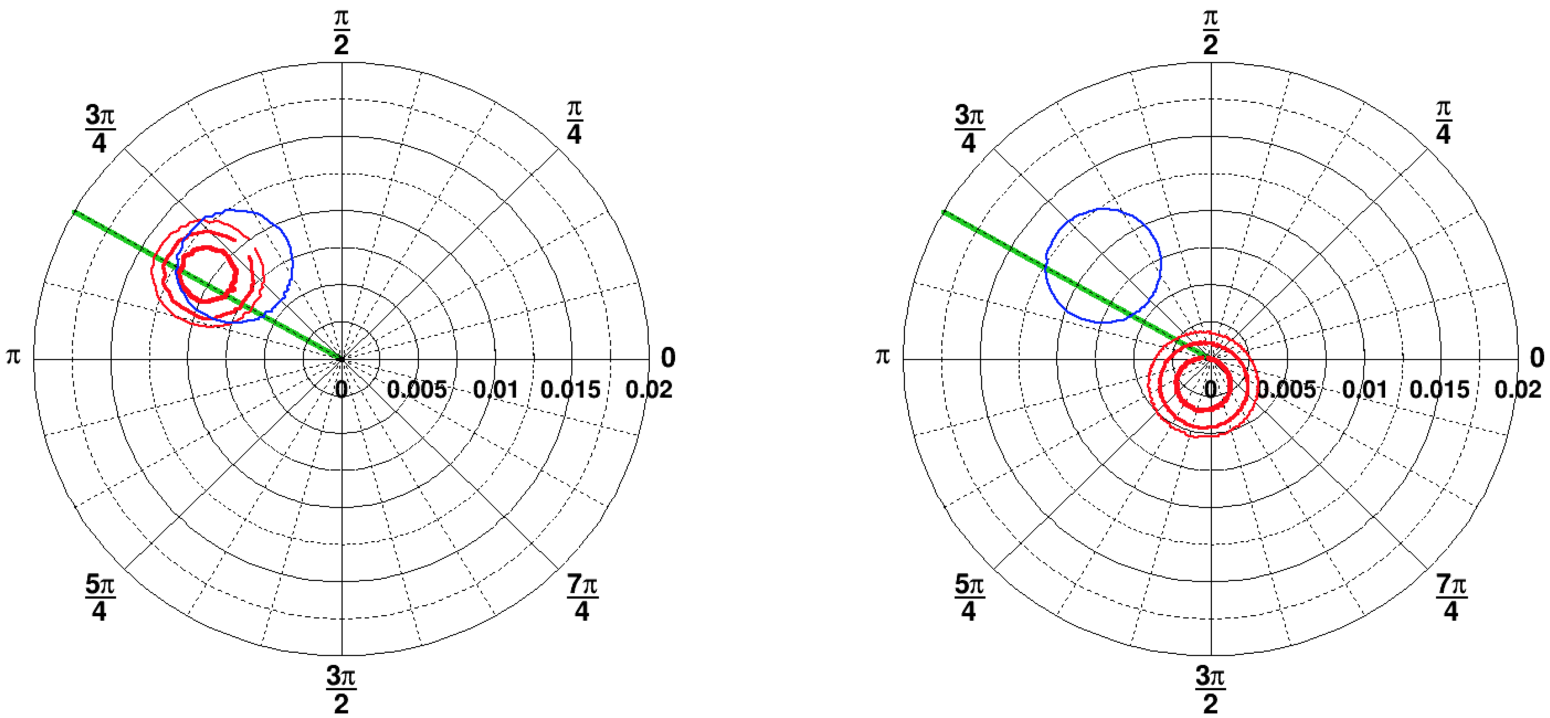
NaI(Tl) growing development at IBS

5 years, COSINE-200

200 kg, 1 count/day/kg/day

~ 100 kg NaI crystal (ingot) grower





no signal

signal

◉ DAMA (99%)

◉ COSINE-200 (68, 90, 99%)

Summary

Where are we now?

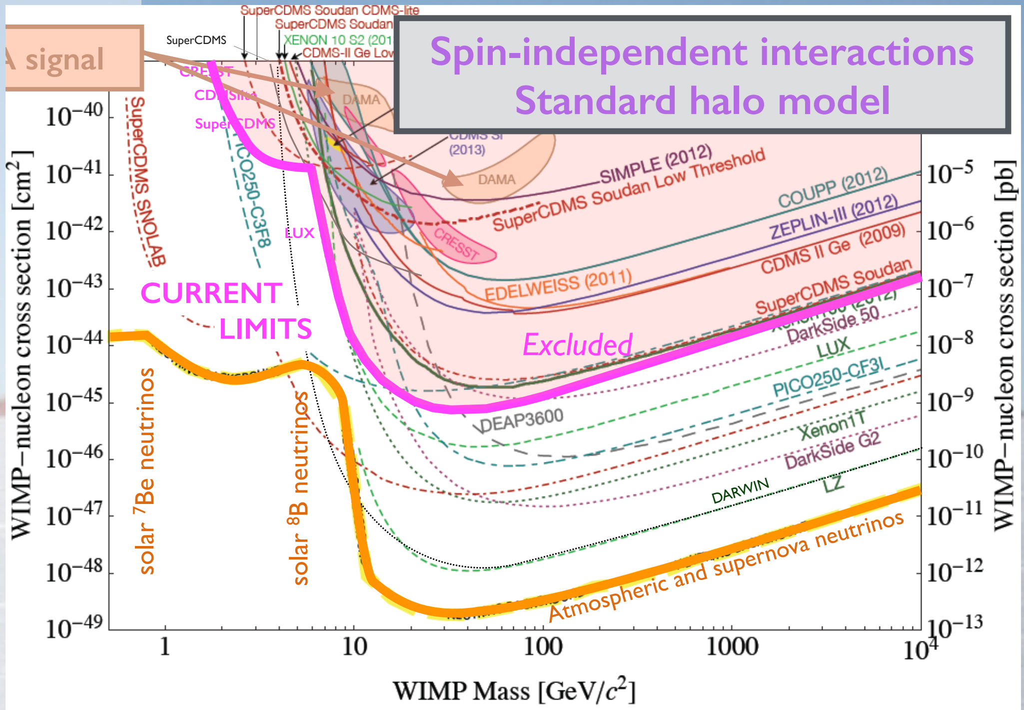
- 30 years of Direct Detection WIMP Search
- DAMA vs. null-results
- Hints from indirect detection
- Upcoming “Gen2” experiments may yield signal
- Where to after “neutrino floor”?

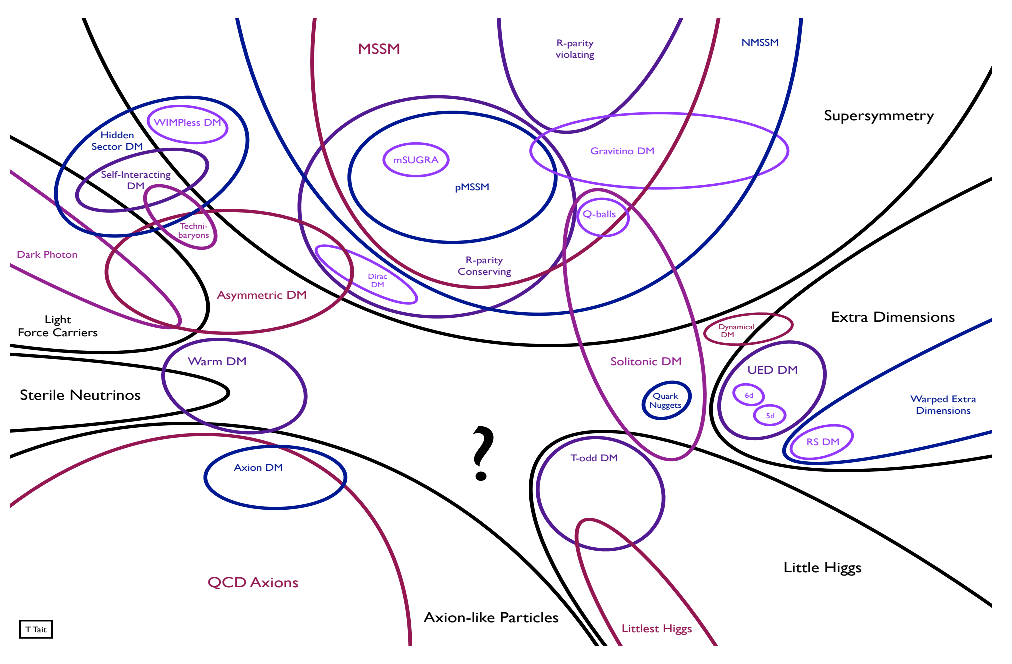
Where to?

- New WIMP and axion experiments are coming online.
- WIMPs? Low mass? Warm? Other forms of DM?

When do we say “YES!” ?

- Consistent w/ astrophysics observations +
  - reproducible
  - targets, cross section, annual modulation, …





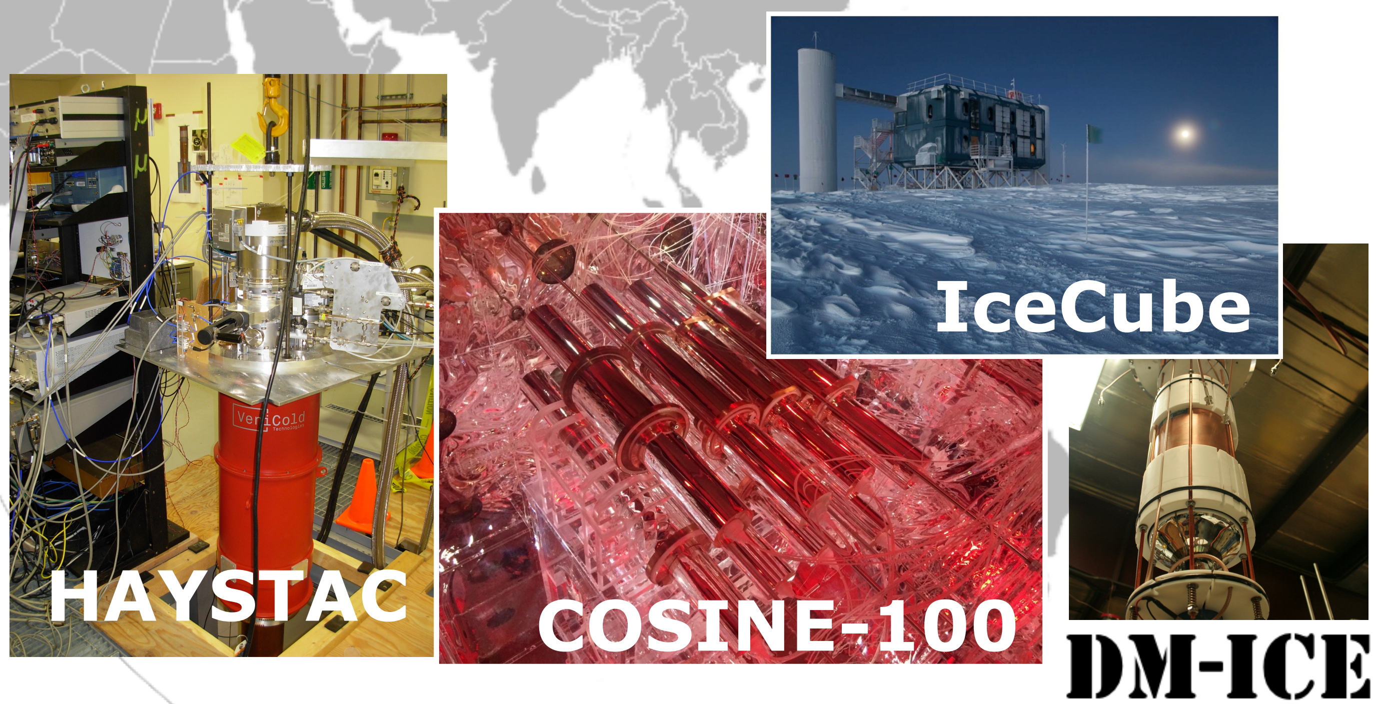
Research in Maruyama Group

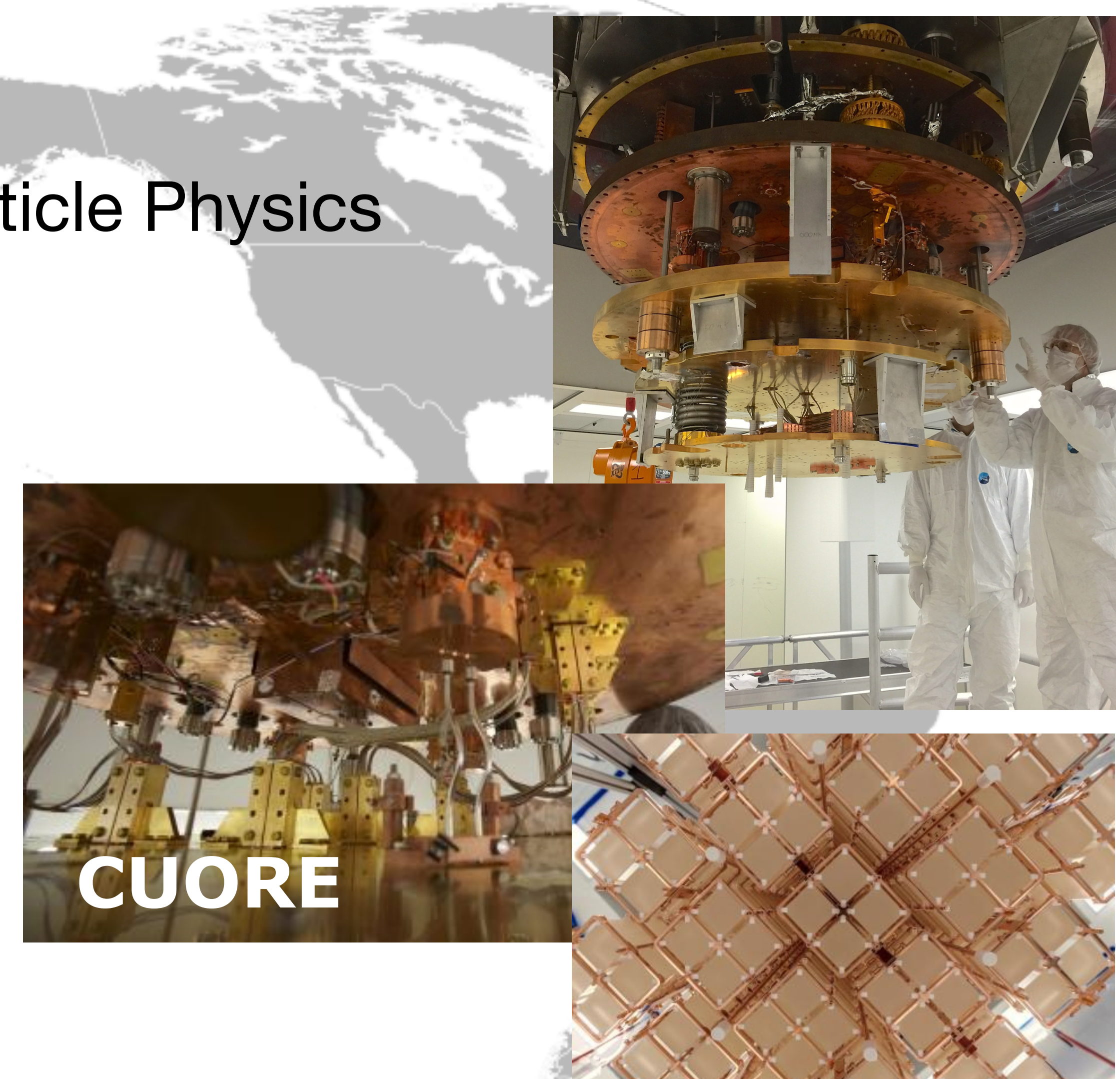
Wright Laboratory

http://maruyama-lab.yale.edu

Research

- Physics Beyond the Standard Model of Particle Physics
- Neutrinos and Dark Matter





- direct detection dark matter experiment at Yale, South Pole and South Korea.
- Is DAMA really seeing dark matter?

- Neutrinoless double beta decay
- Are neutrinos their own anti-particles? Are they Majorana particles?

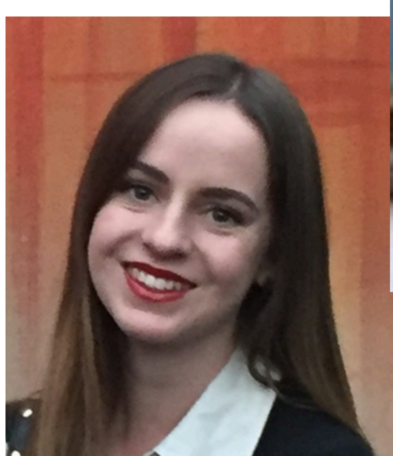
Yale
STEWARDSHIP SCIENCE GRADUATE FELLOWSHIP
WISCONSIN ICECUBE PARTICLE ASTROPHYSICS CENTER
U.S. DEPARTMENT OF ENERGY | Office of Science
ALFRED P. SLOAN FOUNDATION 1934
NSF

Maruyama Group @ Yale

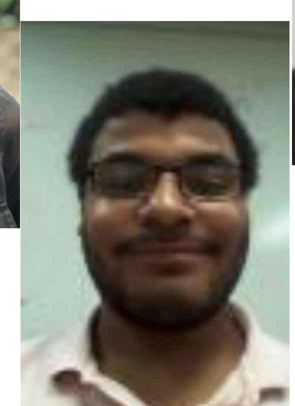











http://maruyama-lab.yale.edu