



COSINE-100

Unveiling the Dark Matter Mystery

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On behalf of COSINE Collaboration

March 31st, 2023

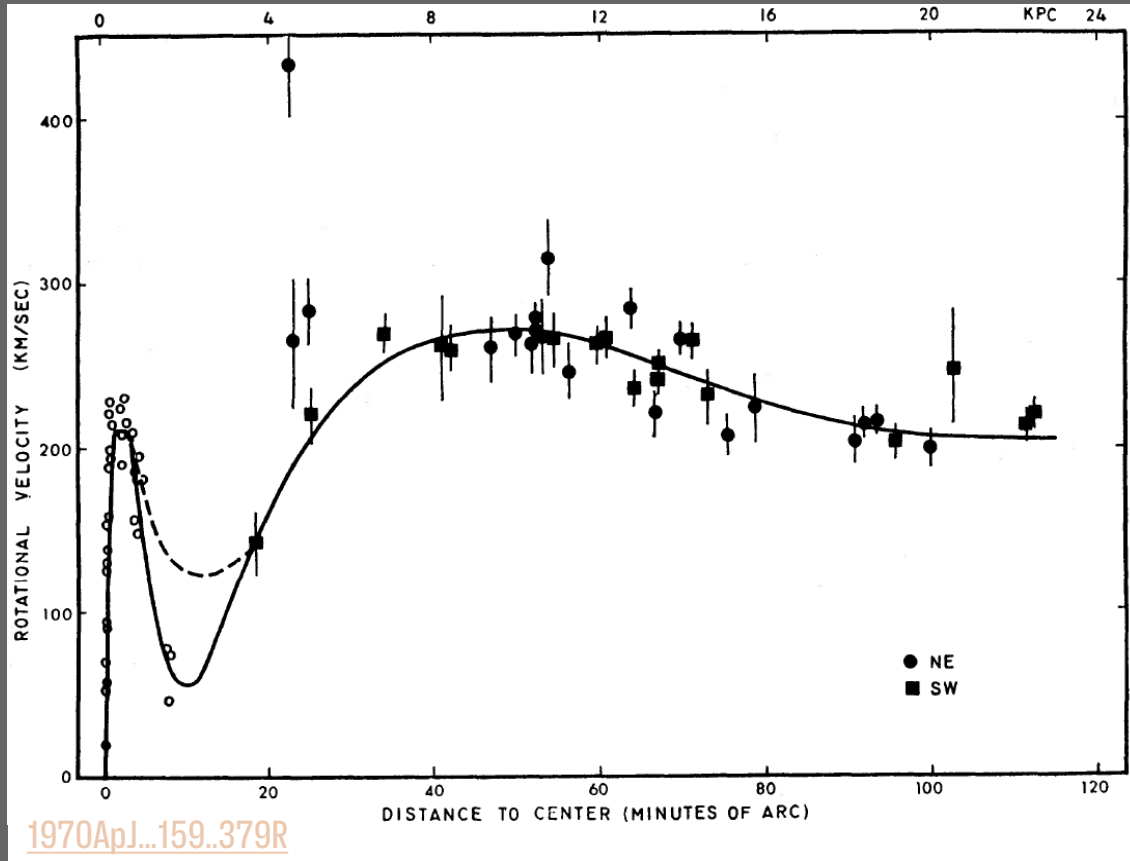
SNU-NAPP Workshop



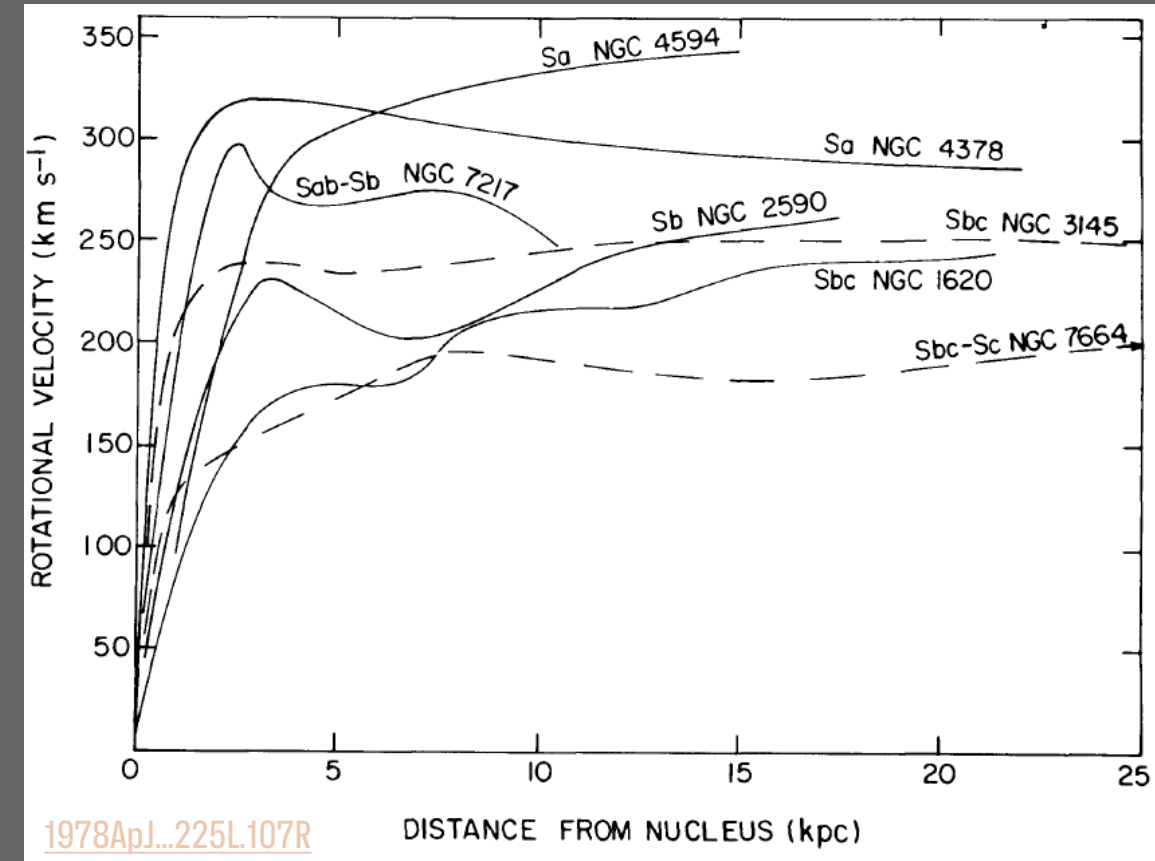
Rubin's Rotation Curve

Rubin, Vera C., Ford, W. Kent, Jr. (1970)

Rotation of the Andromeda Nebula from a Spectroscopic Survey of Emission Regions



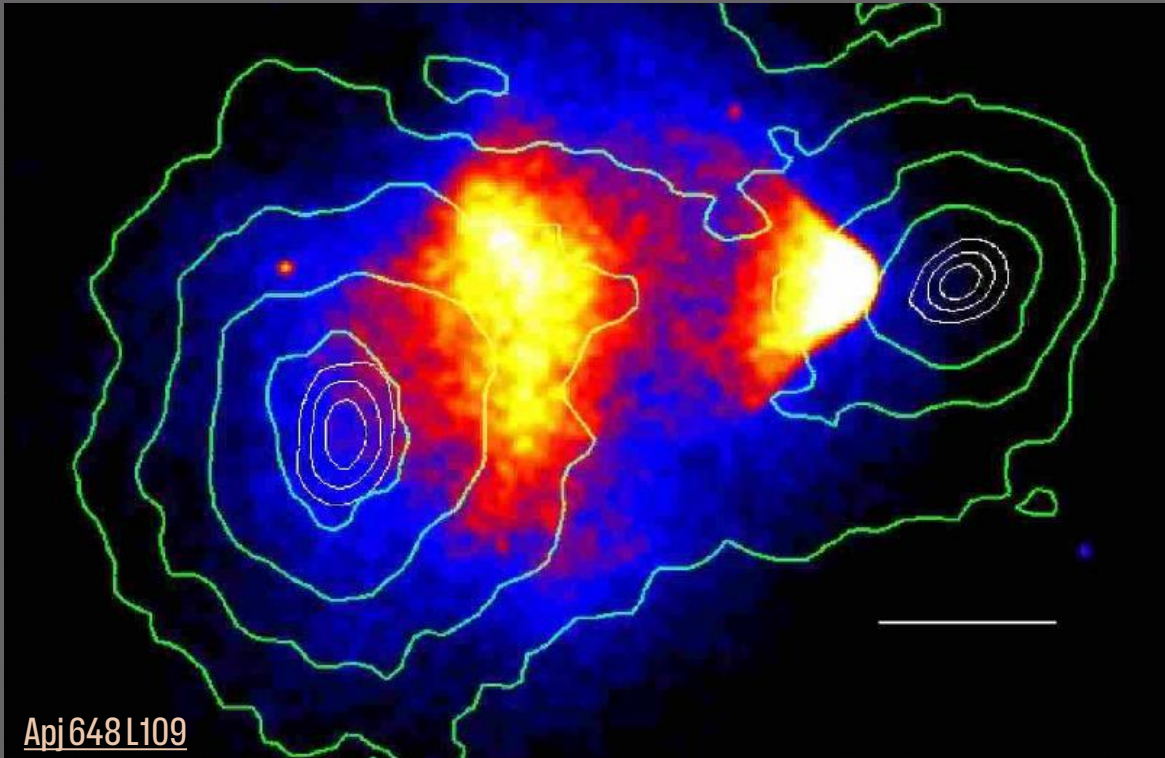
Rubin, Vera C., Ford, W. Kent, Jr., Thonnard, N. (1978)
 Extended Rotation Curves of High-luminosity Spiral Galaxies.
 IV. Systematic Dynamical Properties, Sa-Sc.



Bullet Cluster

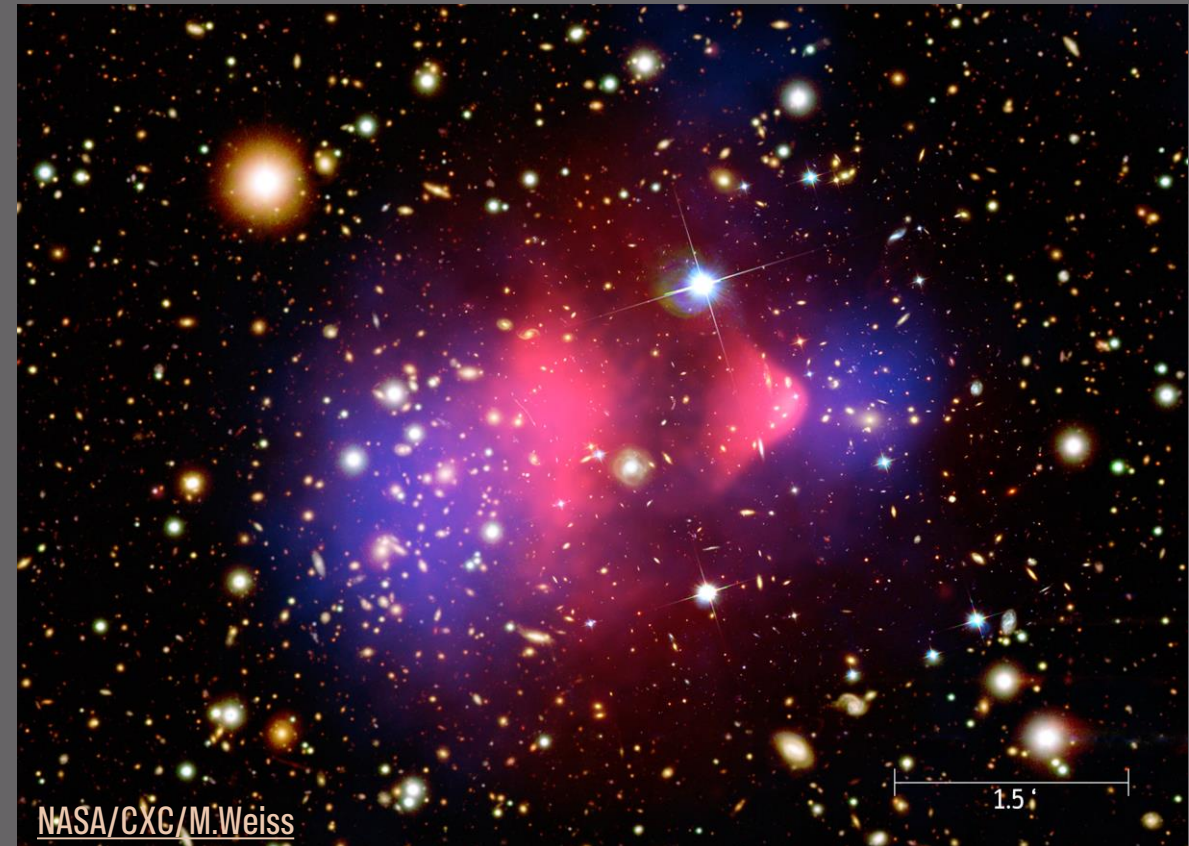
Douglas Clowe, et al. (2006)

A Direct Empirical Proof of the Existence of Dark Matter

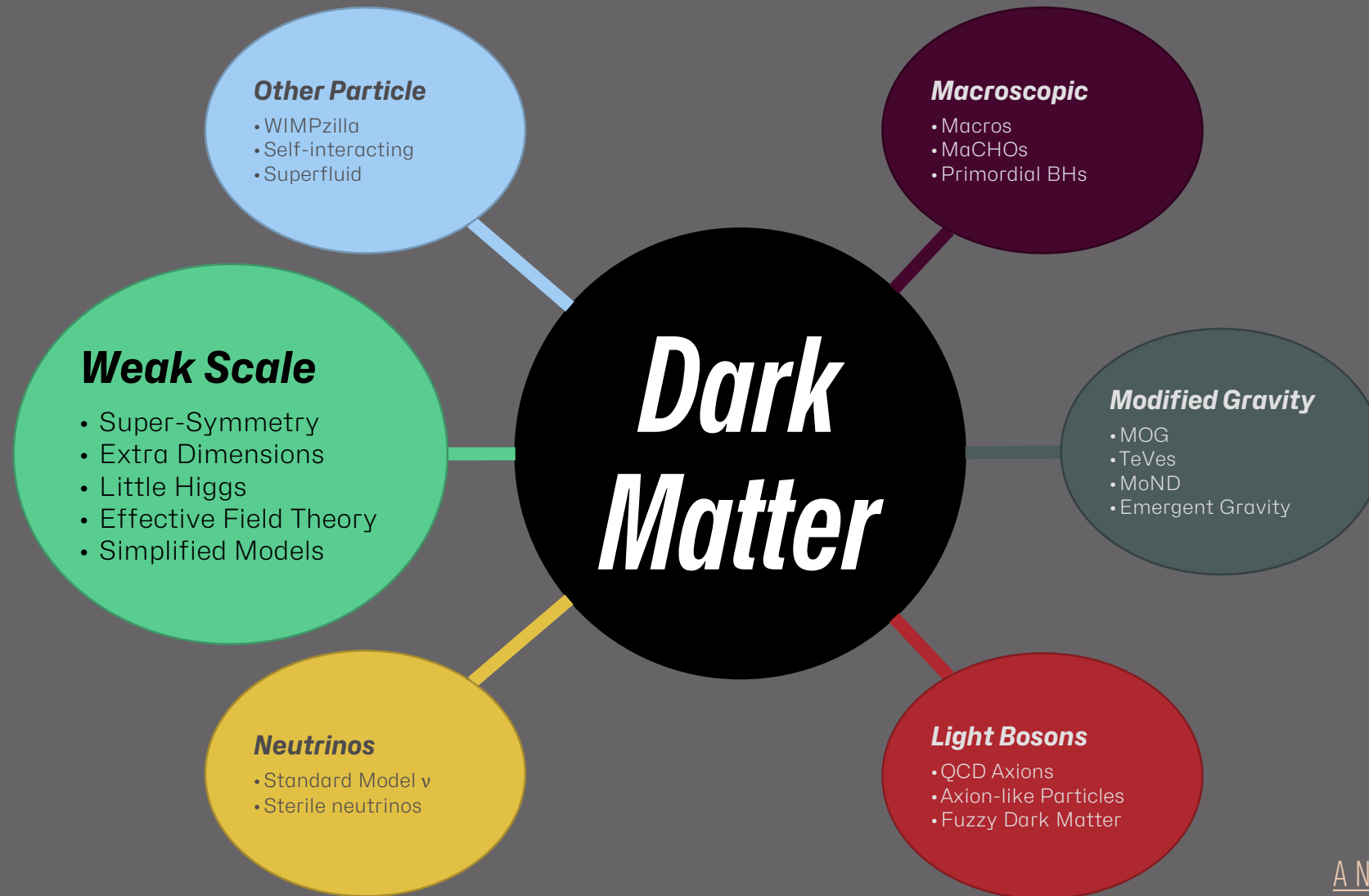


NASA/CXC/M. Weiss

Image of E1 0657-56 (Bullet Cluster). X-ray image (pink) superimposed over a visible light image (galaxies), with matter distribution calculated from gravitational lensing (blue)

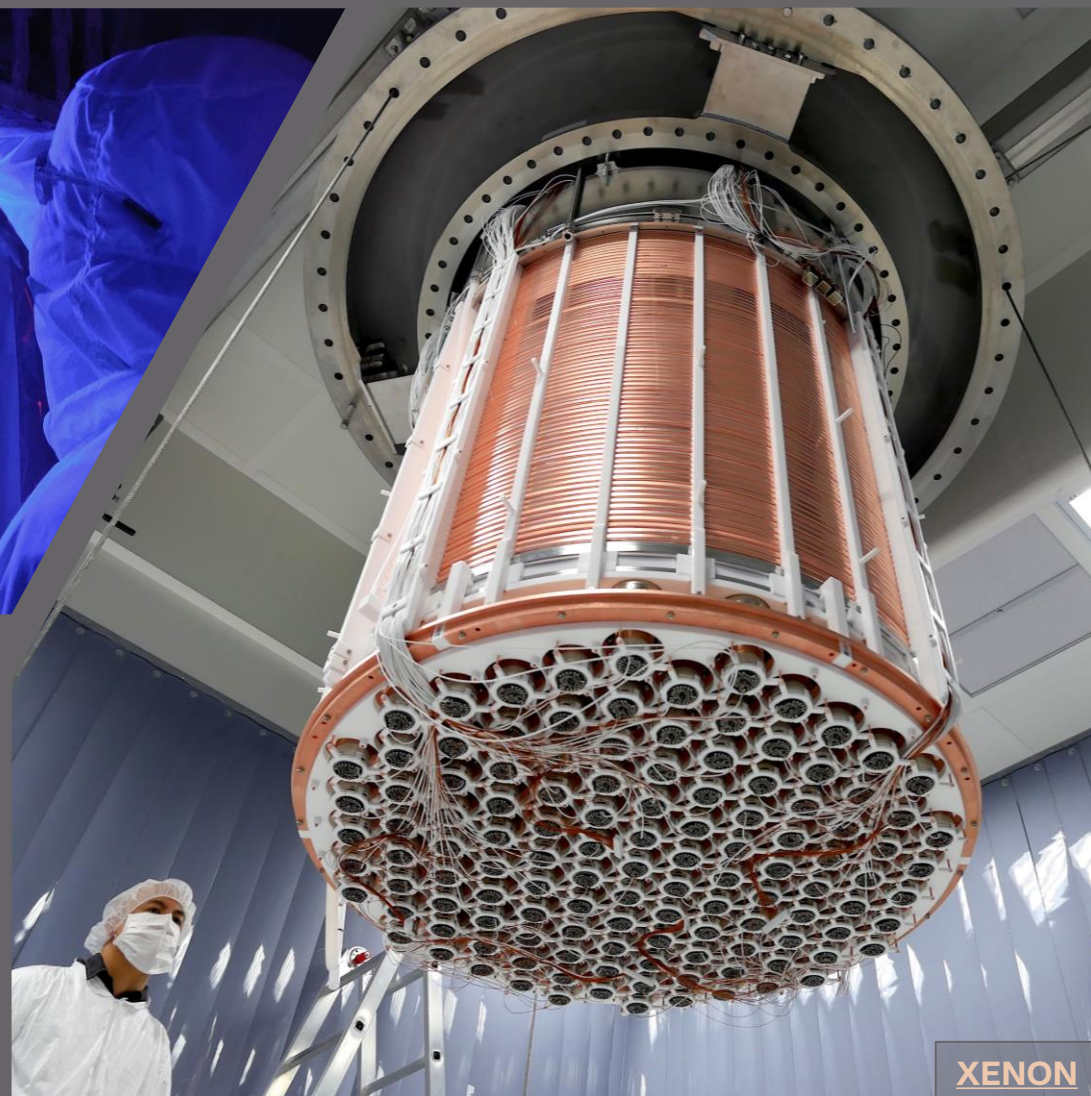


Dark Matter Candidate; WIMP



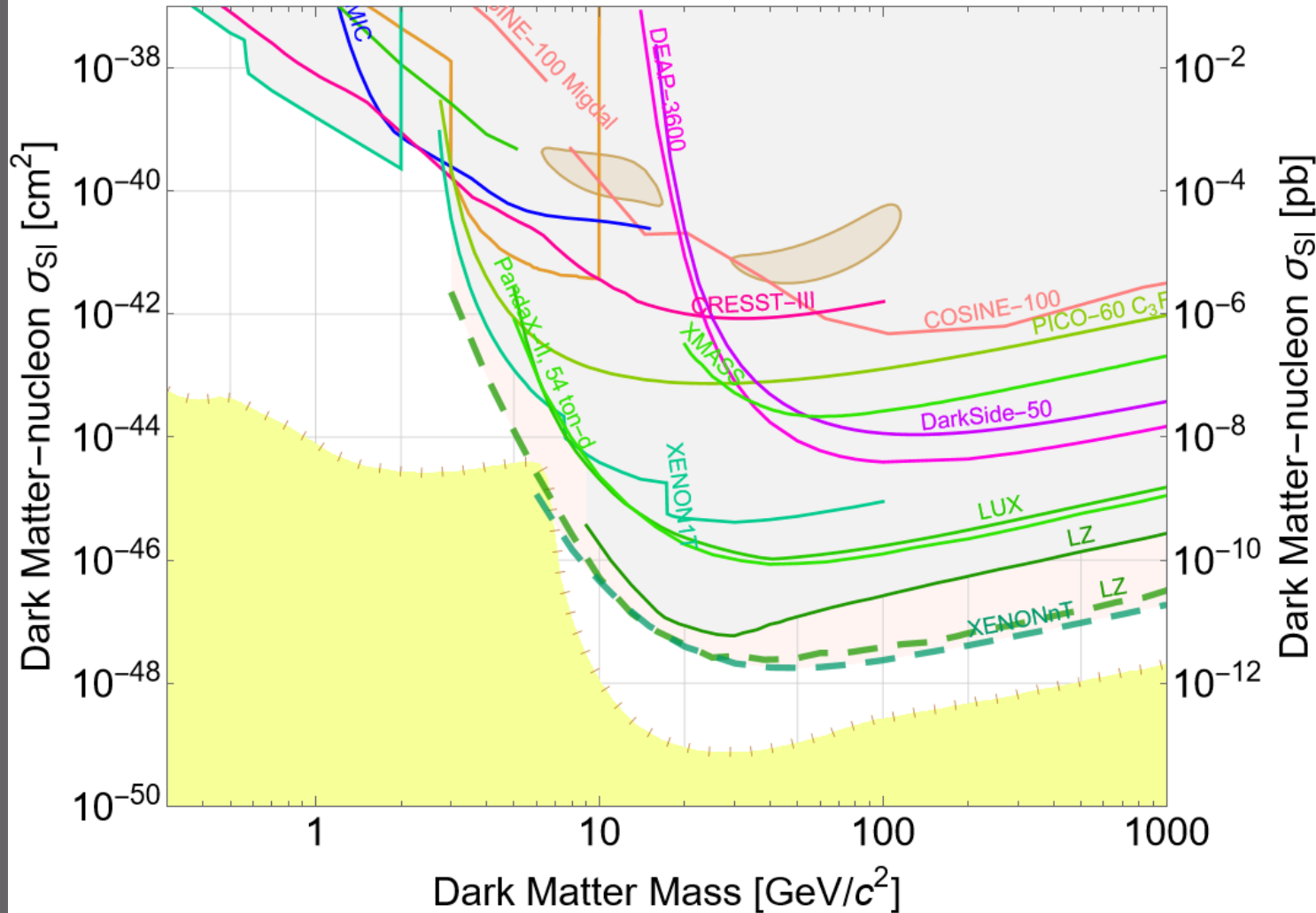
G. Bertone, T. M. P. Tait (2018)
A New Era in the Quest for Dark Matter

WIMP Search Experiments



WIMP Search Experiments

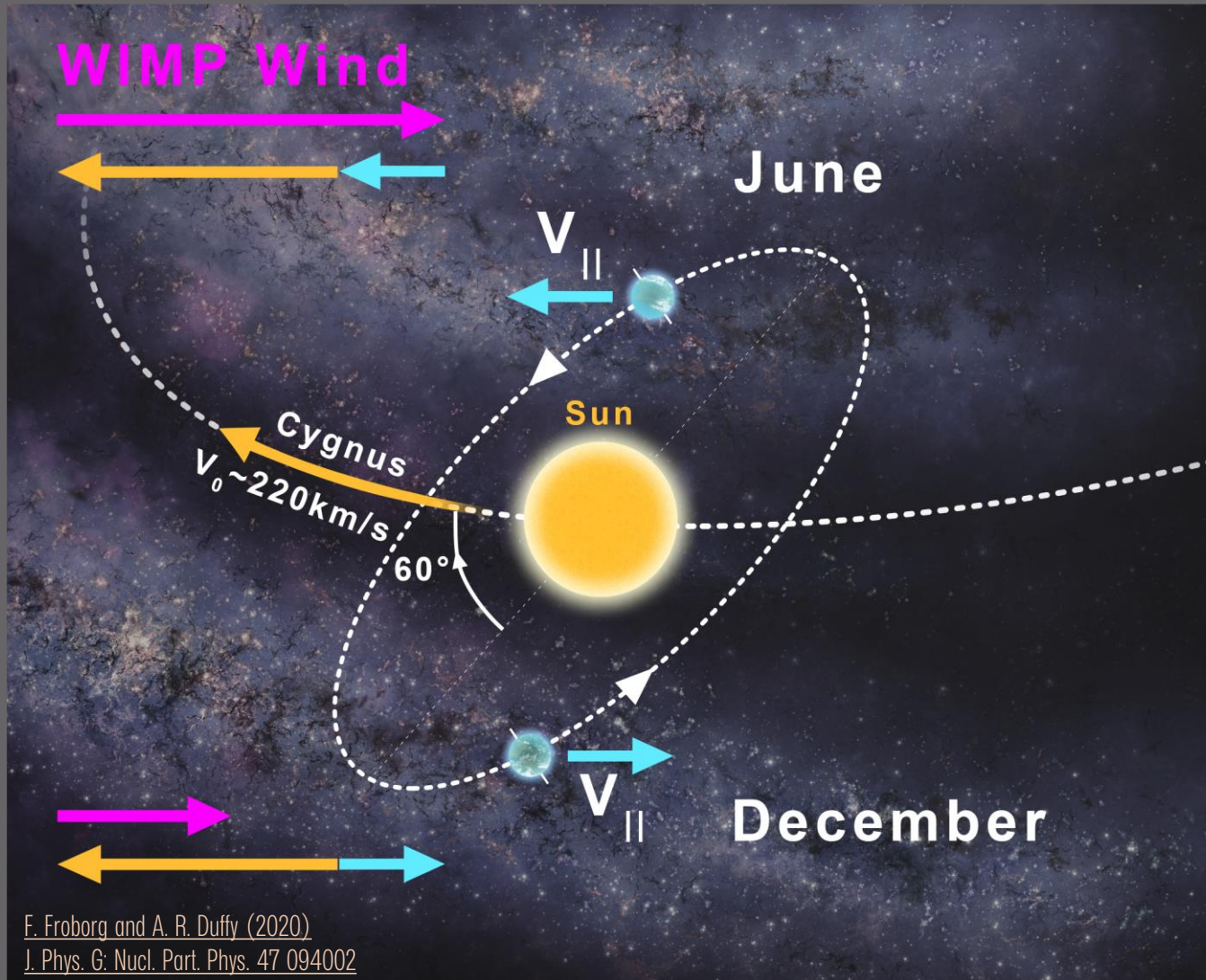
Dark Matter Limit Plotter (Sep 12, 2022)



- COSINE-100, 2021, 97.7 kg-year
- COSINE-100, 2021, 97.7 kg-yr, Migdal effect
- CDEX-1B, 2019, 737.1 kg-d; CDEX-10, 102.8 kg-d; Migdal effect
- DAMA/LIBRA, 2008, no ion channeling
- PICO-60, 2019, 1404 kg-d
- XMASS, 2018
- PandaX-II, 2017, 54 ton-d
- LUX, 2019, Migdal (Heavy scalar), 1.4×10^4 kg-d
- LUX, 2017, 34 ton-d
- LZ, 2022, 330 t-day
- XENON1T, 2019, 22 t-day
- XENON1T, Migdal, 2019, 22 t-day
- DAMIC, 2020
- DarkSide-50, 2018
- DEAP-3600 (231 days, 2019)
- CRESST-III, 2019, 3.64 kg-d
- - - LZ expected sensitivity
- - - XENONnT 20ty expected sensitivity
- Neutrino background for a Xe target

And much more...

Standard Halo Model and Annual Modulation

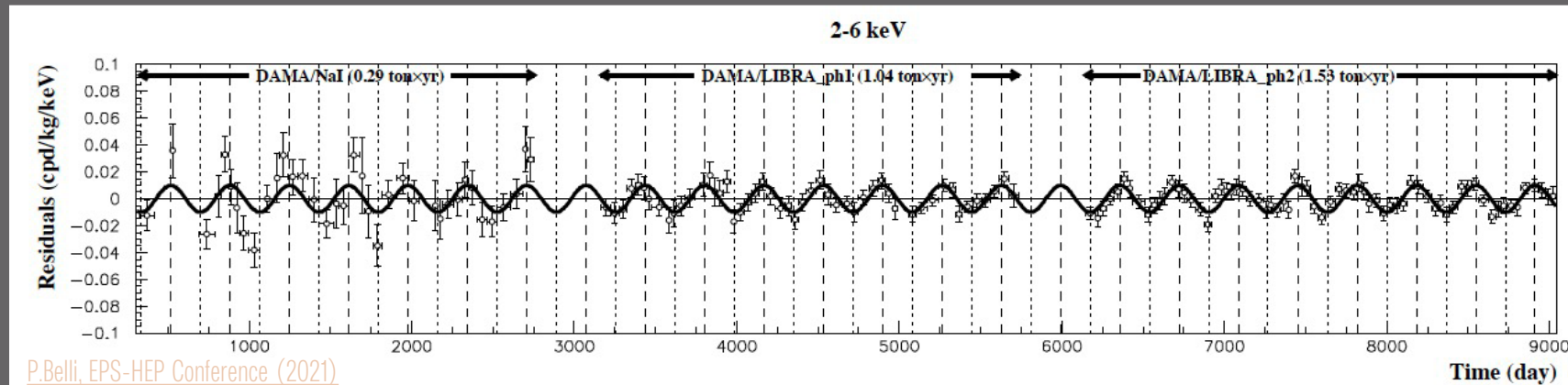


- Weakly interacting particles distribute spherically.
 - $\rho_{\text{DM}} \simeq 0.3 \text{ GeV/cm}^3$
($\sim \#3/\text{m}^3$ if $m_{\text{DM}} = 100 \text{ GeV}$)
- The WIMP wind varies annually.
 - $v_{\odot} = 217 \text{ km/s}$, $v_{\oplus} = 30 \text{ km/s}$.
 - Maximum on 152.5 day.
- There'll be a MODULATION in WIMP signal!

Annual Modulation in DAMA/LIBRA Experiment



- DAMA/LIBRA is an underground WIMP search experiment at the GSNL, Italy.
- Radiopure NaI(Tl) crystals are used.
 - Initially 100 kg, and now ~250 kg.
 - Full exposure: 2.86 t · yr (since 2002)
- **Annual modulation detected!**
 - 13.4σ at 2~6 keV. Phase and period are also consistent.
 - *But no other experiments could reproduce the result...*



Here Comes COSINE-100!

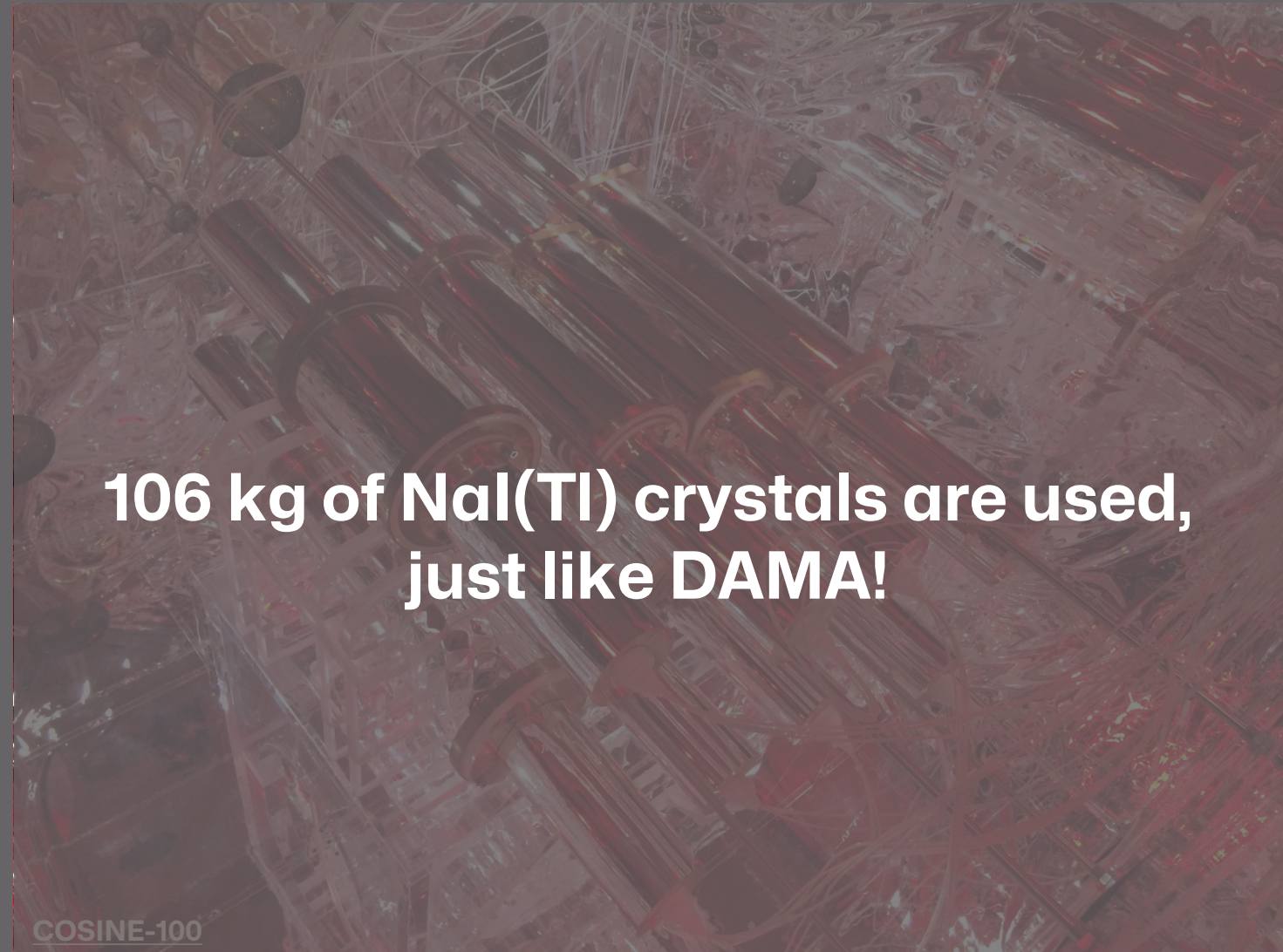


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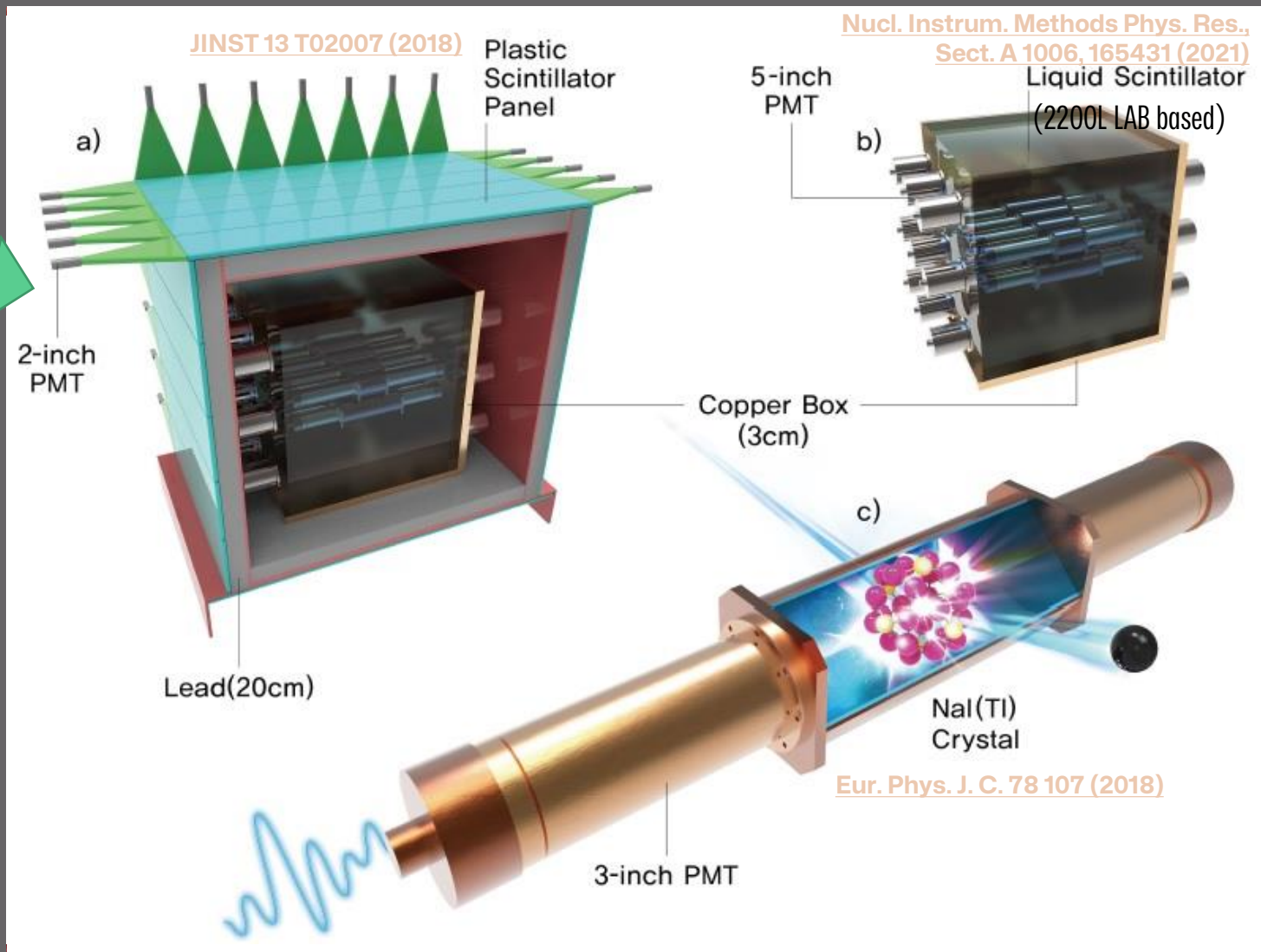


106 kg of NaI(Tl) crystals are used,
just like DAMA!

Here Comes COSINE-100!



Here Comes COSINE-100!



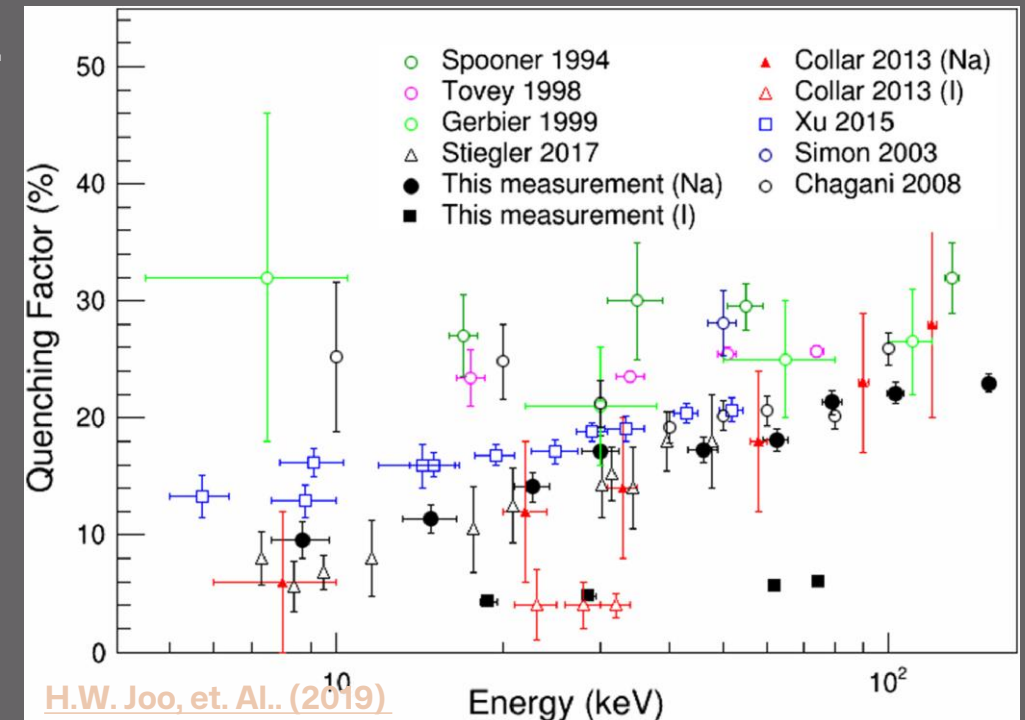
Crystals of COSINE-100

- 8 low background NaI(Tl) crystals developed with Alpha Spectra Inc..
- Light yield is high. Typically ~ 15 p.e./keV.
 - Note that DAMA's is $5\sim 10$ p.e./keV.
- Attached with R12669SEL PMT, with quantum efficiency $\sim 35\%$.
 - 12 mm quartz and 1.5 mm optical pad were inserted.



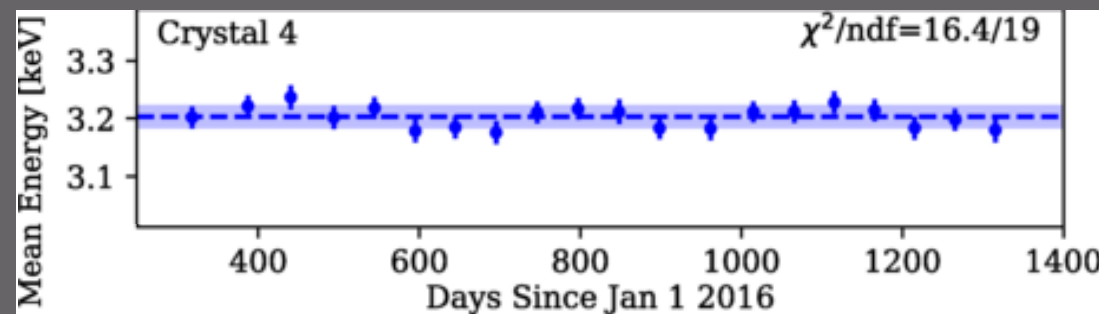
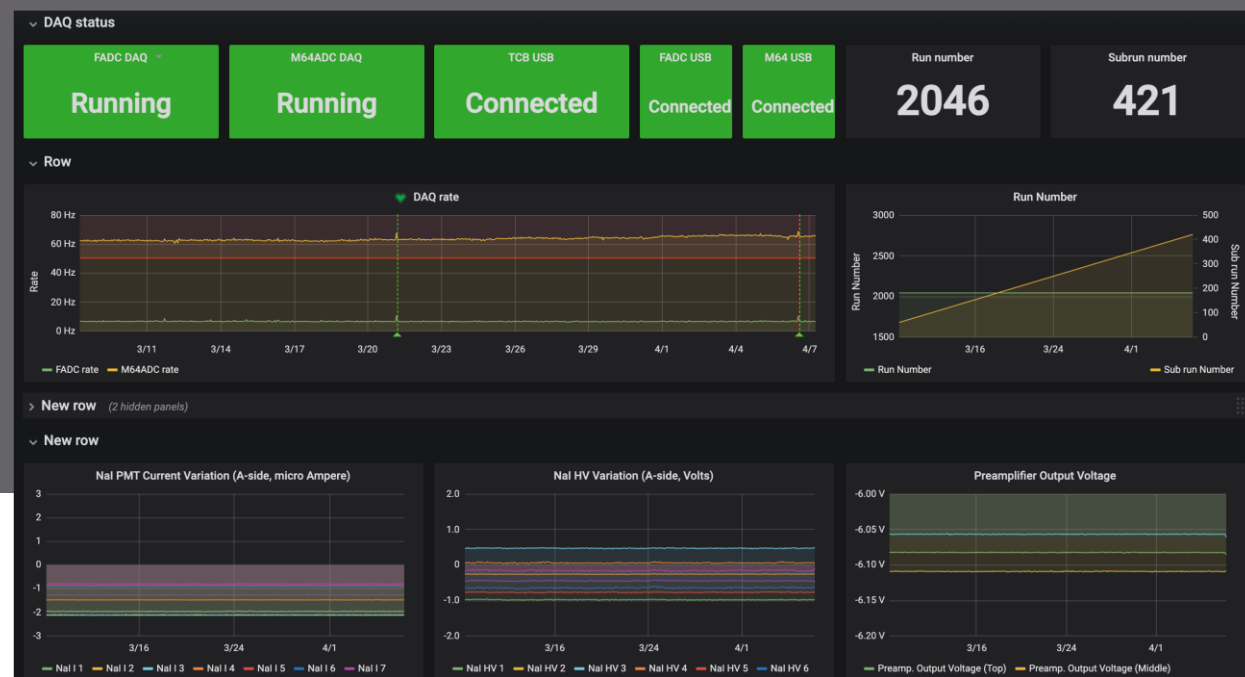
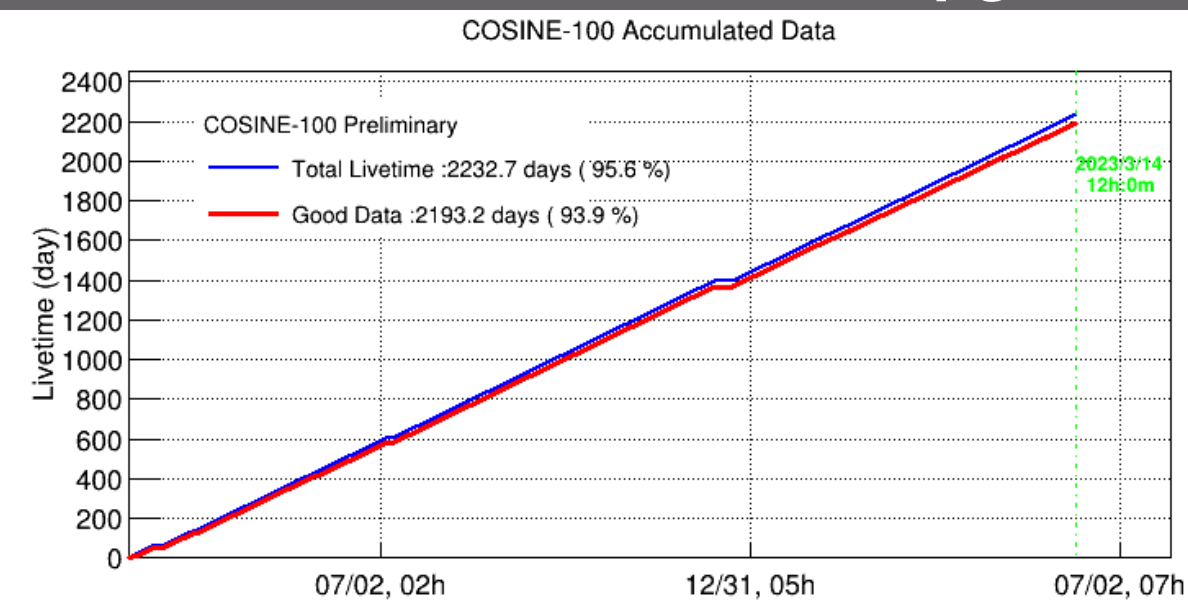
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- Attached with R12669SEL PMT, with quantum efficiency $\sim 35\%$.
 - 12 mm quartz and 1.5 mm optical pad were inserted.
- Quenching factor was measured in detail.
 - We saw energy dependency.
 - DAMA used constants. 0.30 for Na and 0.09 for I.



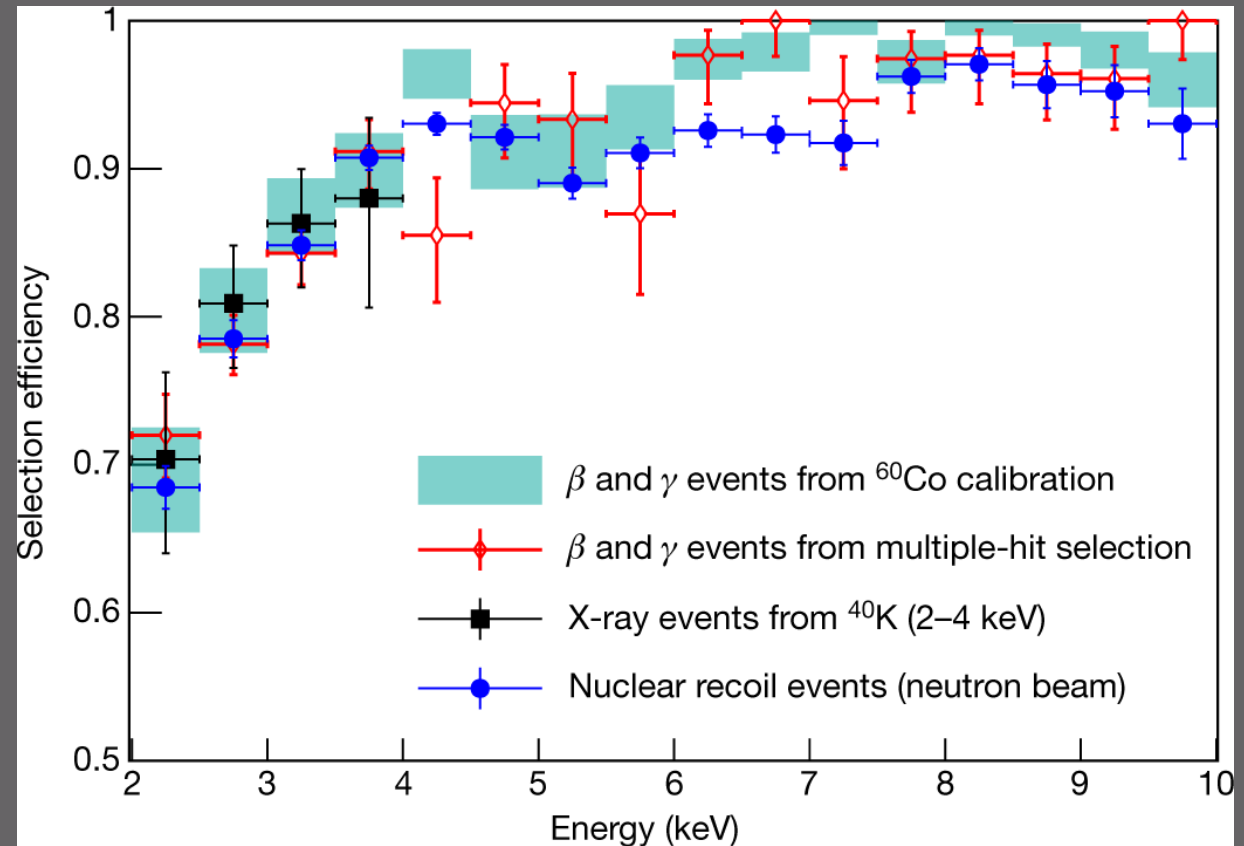
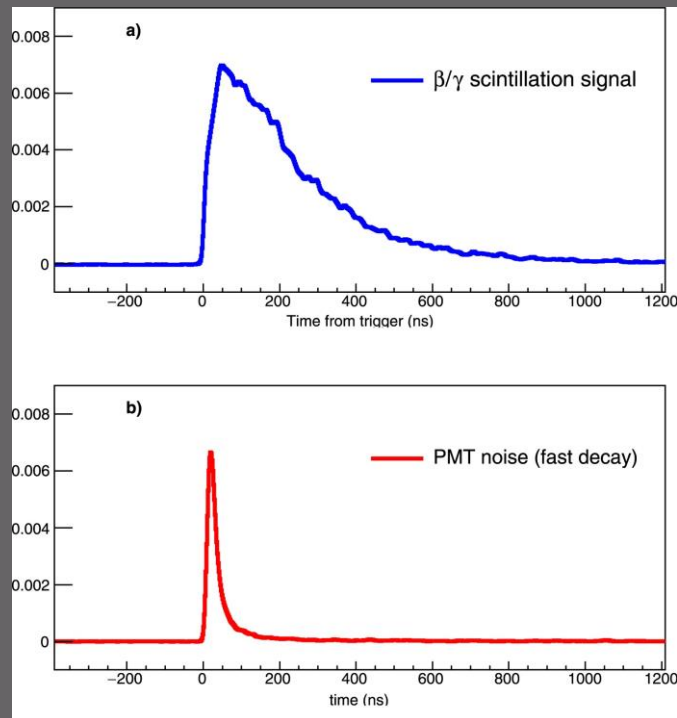
COSINE-100 Data Taking

- Data taken smoothly.
 - From Sep. 2016 to Mar. 2023.
 - ~94 %, 6.0 years of good data.
 - Monitored a lot of DAQ/Env variables.
 - Stable energy scale.
- Closed on last 14th Mar for upgrade!



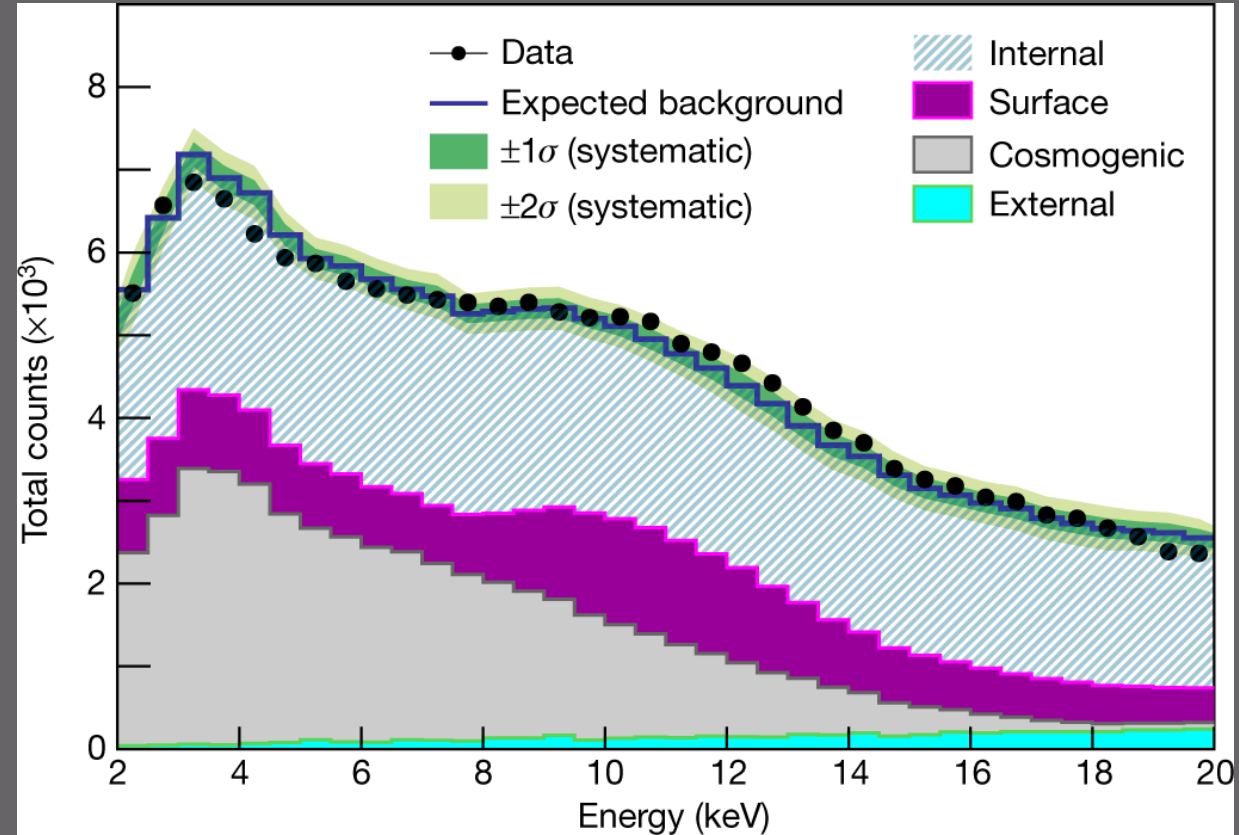
First 59.5 days; *Nature* volume 564, pp.83–86 (2018)

- Select events,
 - We used BDT, a multivariate analysis algorithm for noise rejection.



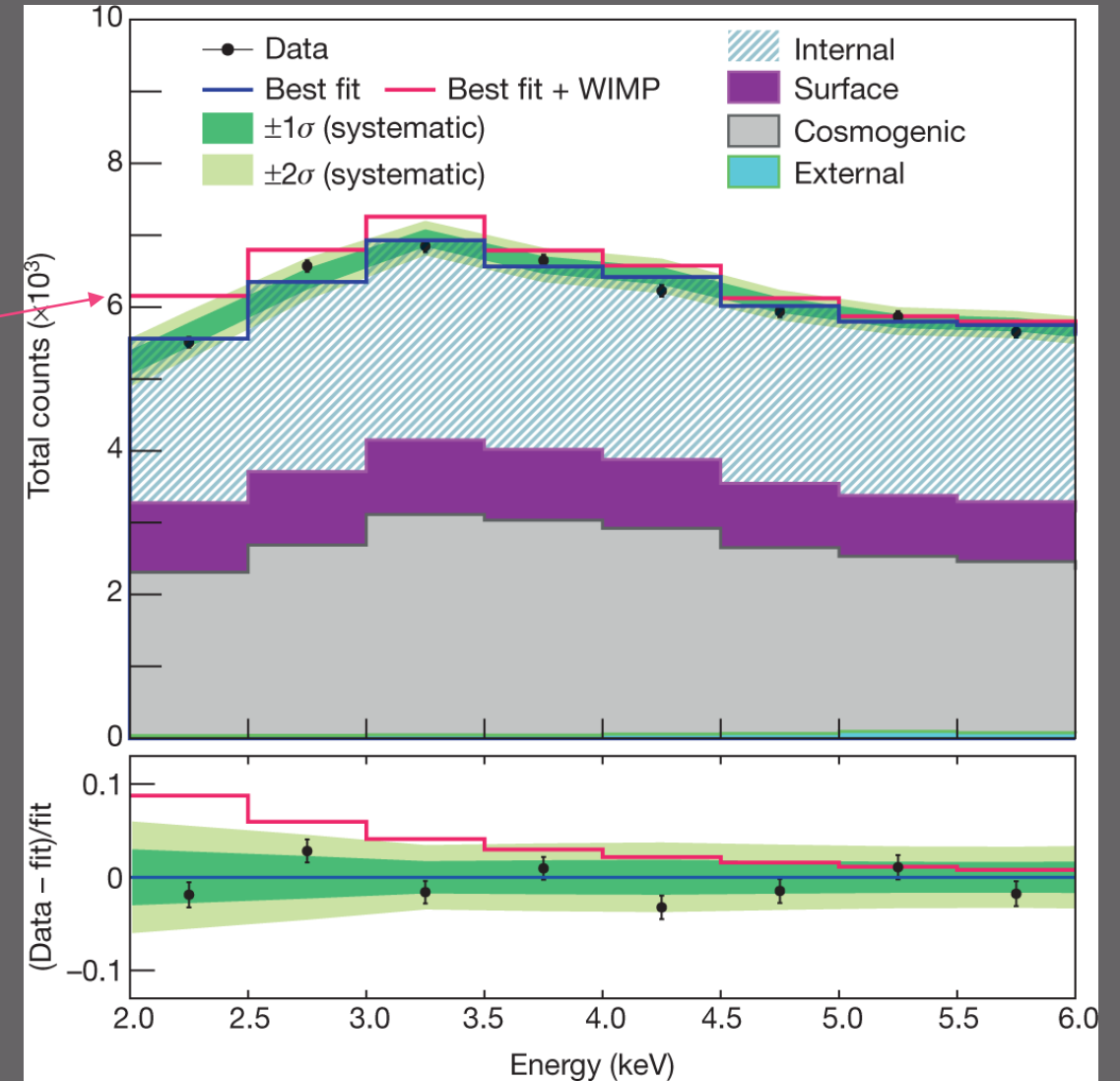
First 59.5 days; Nature volume 564, pp.83–86 (2018)

- Select events,
- Simulate the background spectrum,
 - U-238, Th-232, K-40, Pb-210, Cd-109, H-3, ...



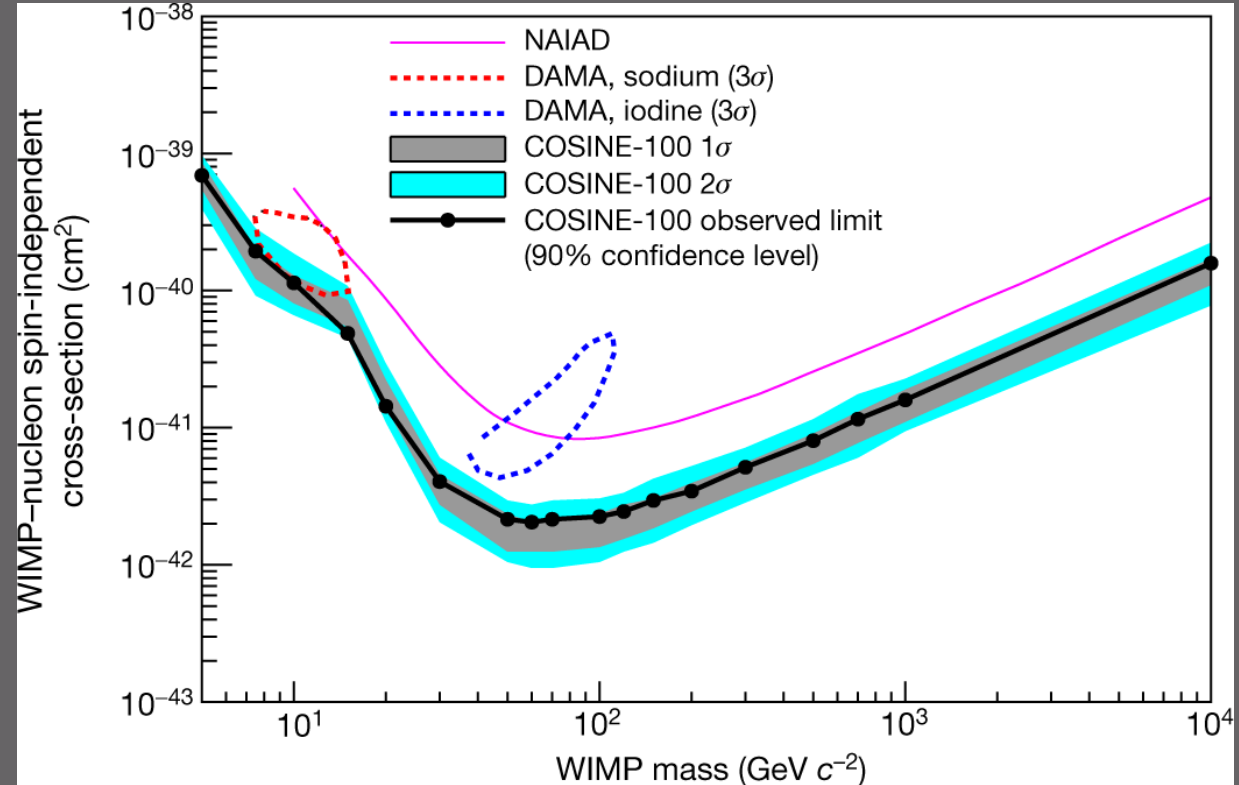
First 59.5 days; *Nature* volume 564, pp.83–86 (2018)

- Select events,
- Simulate the background spectrum,
- And compare with WIMP spectrum.
 - DAMA : $m = 10 \text{ GeV}/c^2$, $\sigma = 2.35 \times 10^{-40} \text{ cm}^2$.



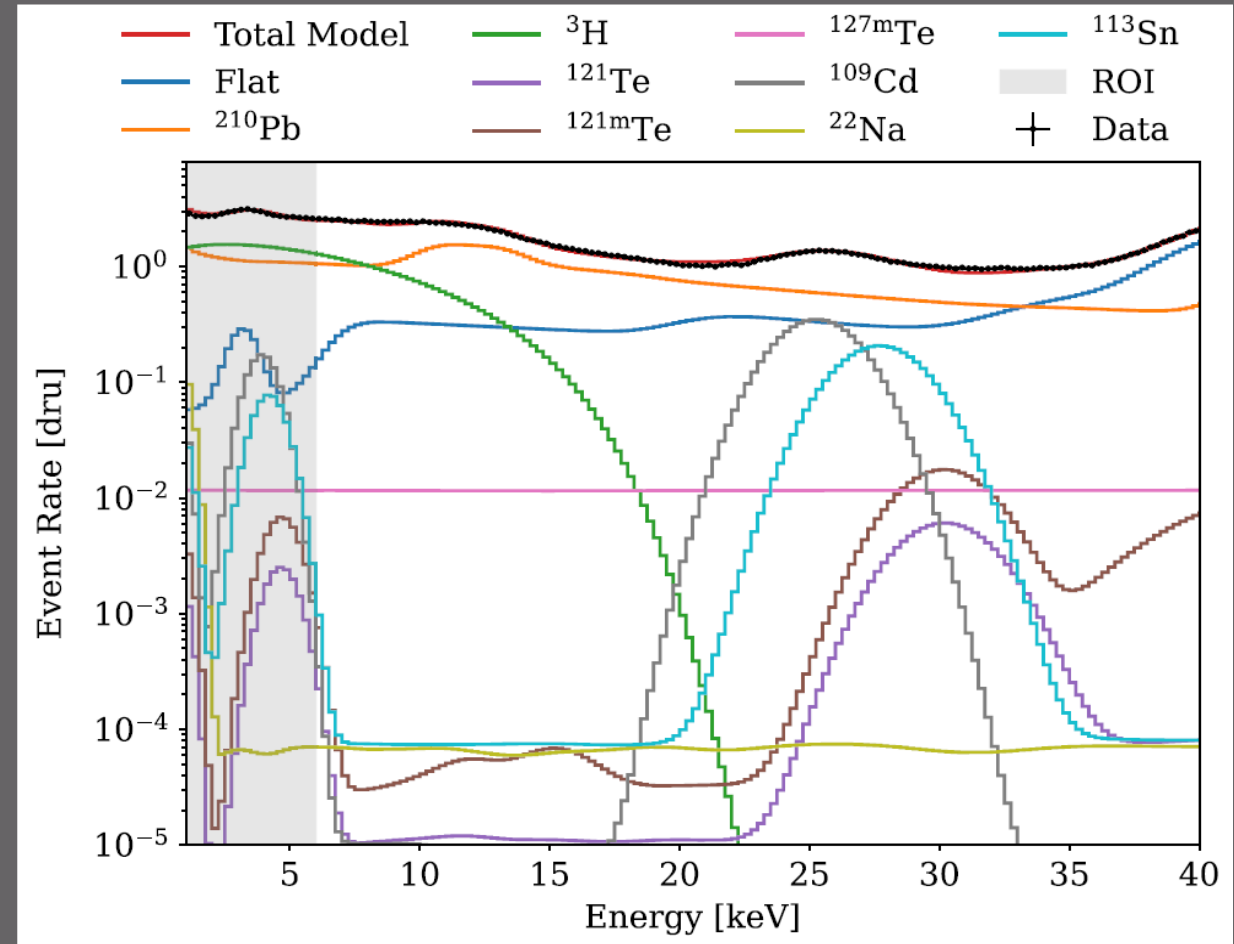
First 59.5 days; *Nature* volume 564, pp.83–86 (2018)

- Select events,
- Simulate the background spectrum,
- And compare with WIMP spectrum.
- We've rejected DAMA's signal.
 - But it is model-dependent.
- Let's see the modulation!



3 Years Modulation; *Phys. Rev. D 106, 052005 (2022)*

- Improved bkg modeling

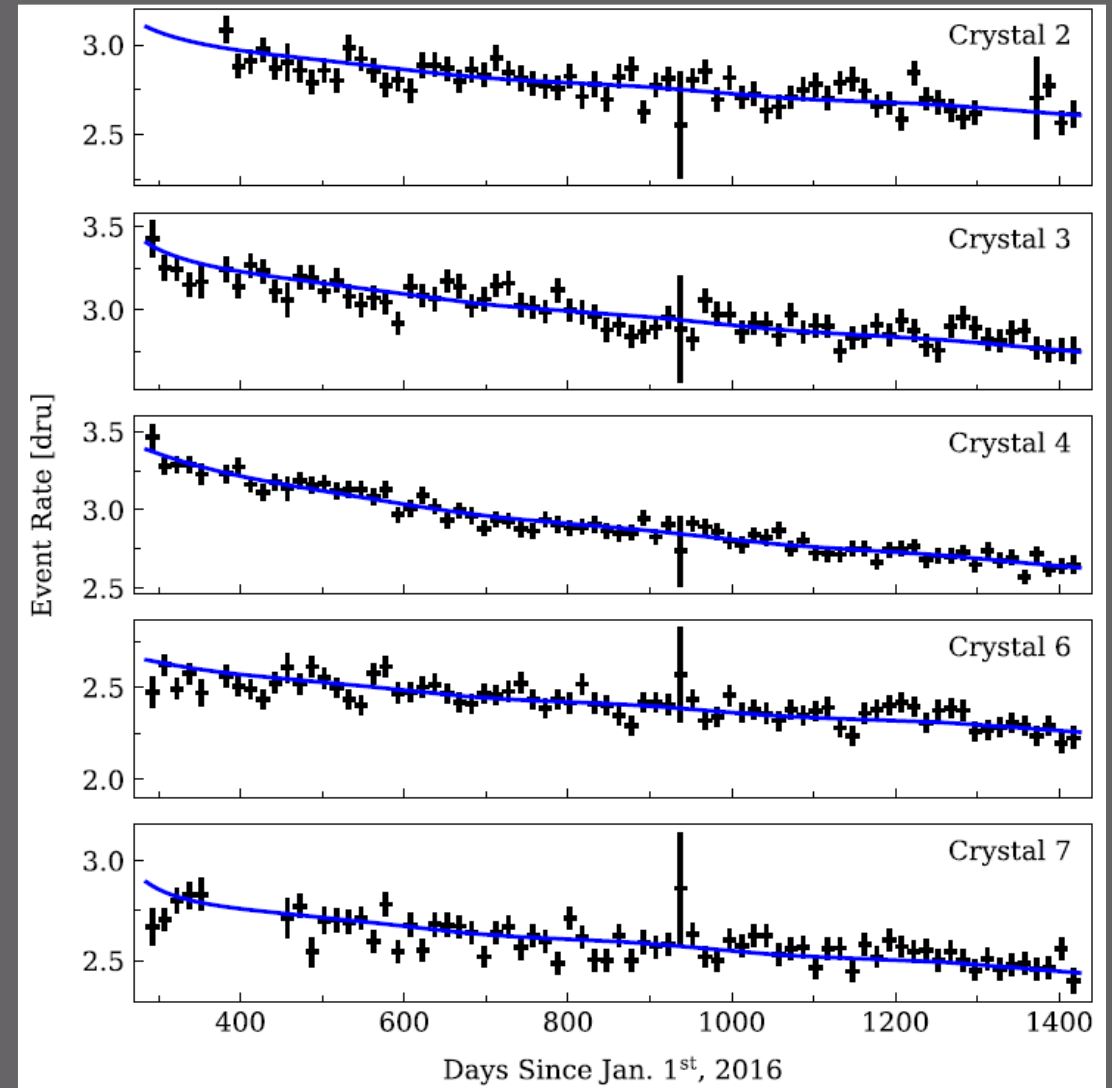


3 Years Modulation; *Phys. Rev. D 106, 052005 (2022)*

- Improved bkg modeling enabled us to fit without bias.

$$R^i(t|S_m, \alpha^i, \beta_k^i) = \alpha^i + \sum_{k=1}^{N_{bkgd}} \beta_k^i e^{-\lambda_k t} + S_m \cos(\omega(t - t_0)). \quad (1)$$

Component	Average activity (dru)
Total	$(2.74 \pm 0.23) \times 10^0$
^3H	$(1.41 \pm 0.18) \times 10^0$
^{210}Pb	$(1.12 \pm 0.15) \times 10^0$
Flat	$(1.35 \pm 0.08) \times 10^{-1}$
^{109}Cd	$(4.13 \pm 0.39) \times 10^{-2}$
^{113}Sn	$(1.55 \pm 0.16) \times 10^{-2}$
^{127}Te	$(6.59 \pm 0.52) \times 10^{-3}$
^{22}Na	$(5.88 \pm 1.34) \times 10^{-3}$
^{121m}Te	$(1.50 \pm 0.16) \times 10^{-3}$
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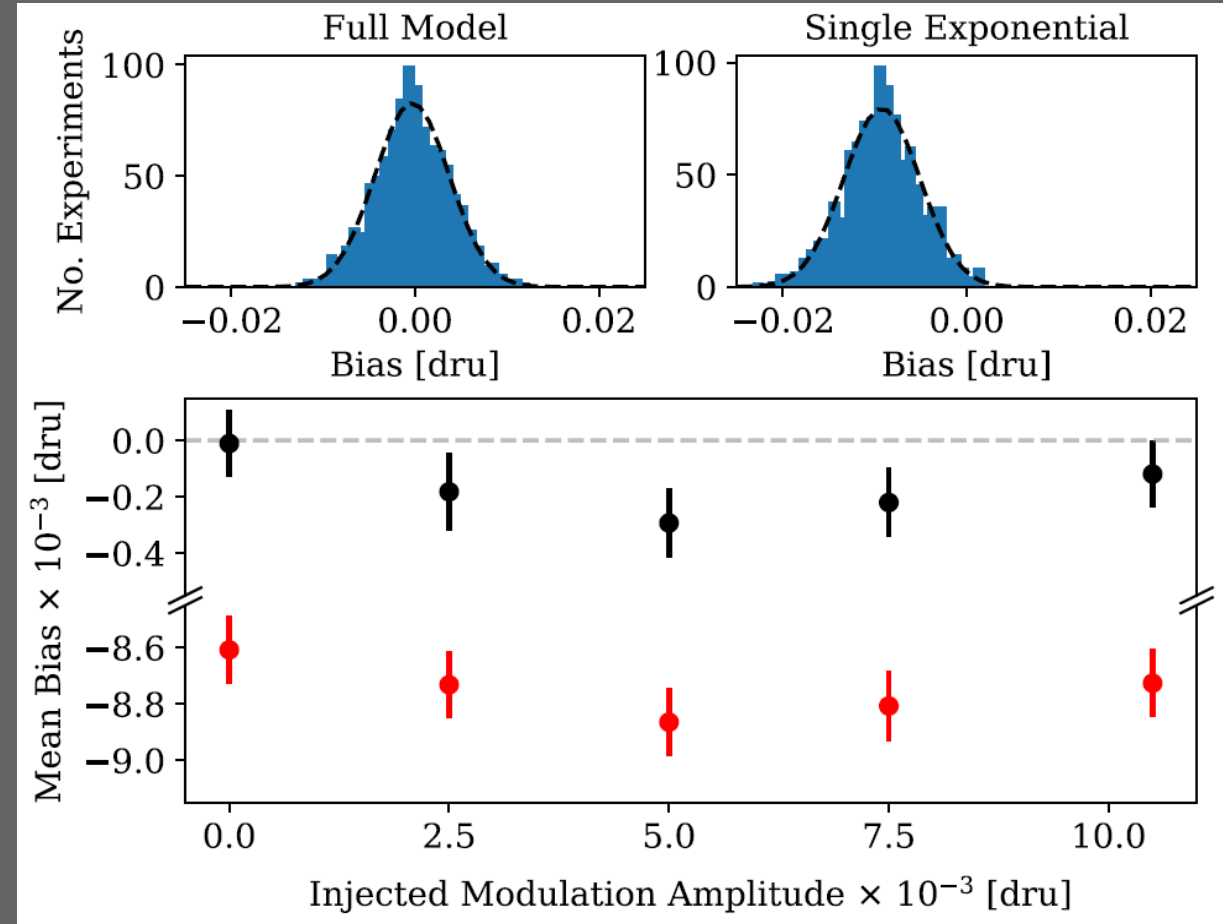


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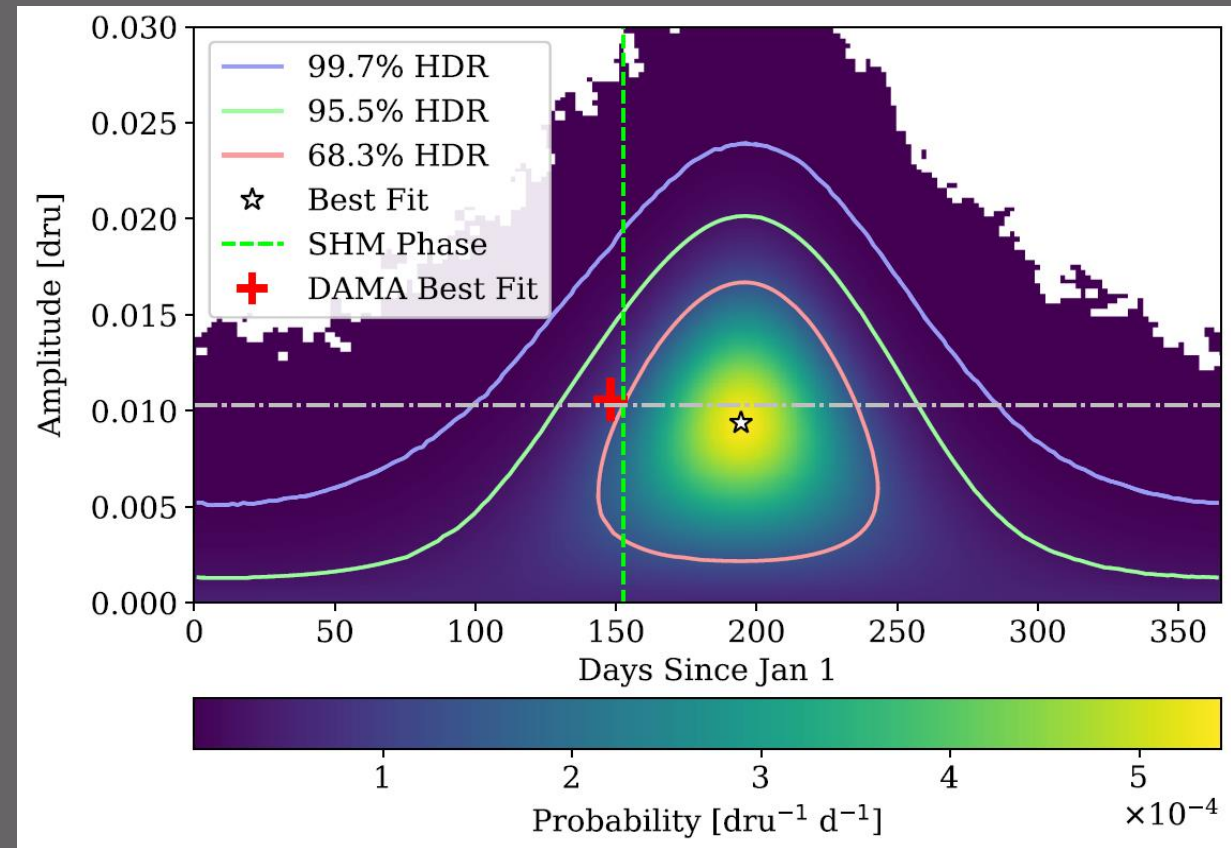
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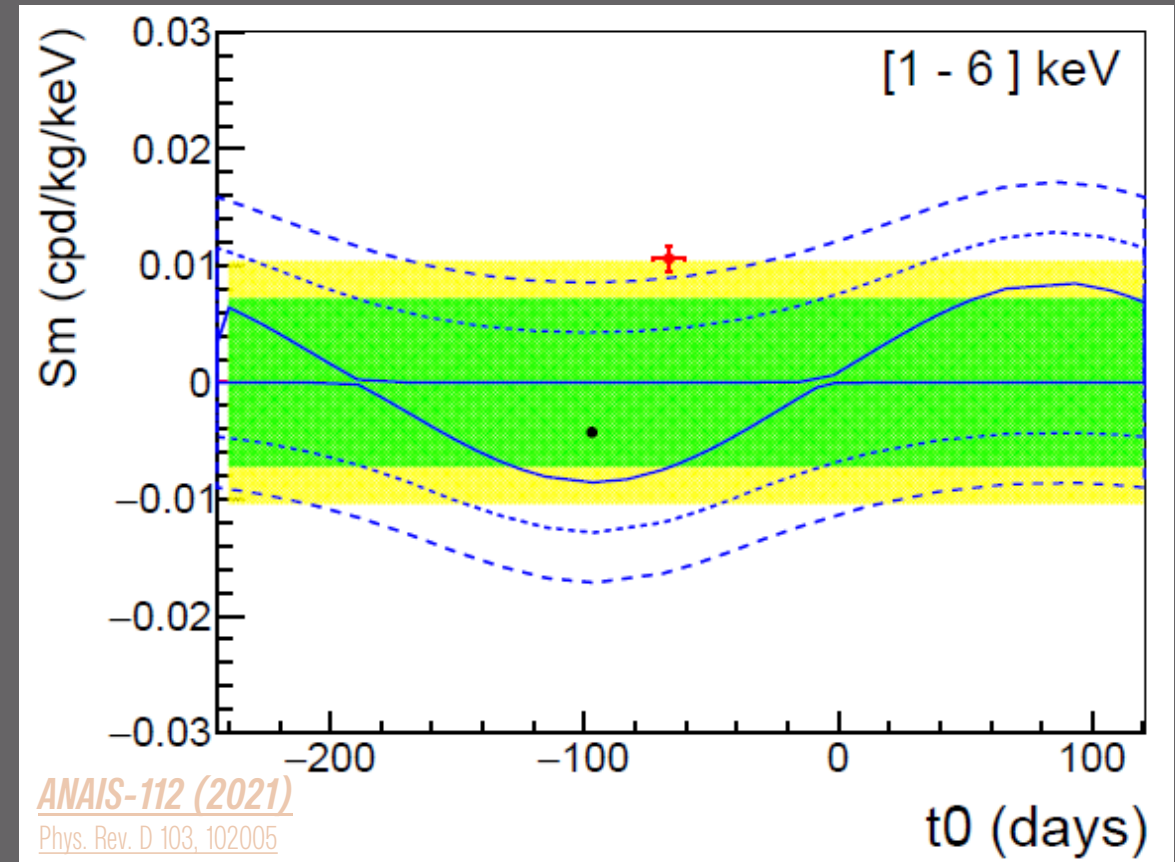
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- Our best fit did not match with that of DAMA/LIBRA.



3 Years Modulation; *Phys. Rev. D 106, 052005 (2022)*

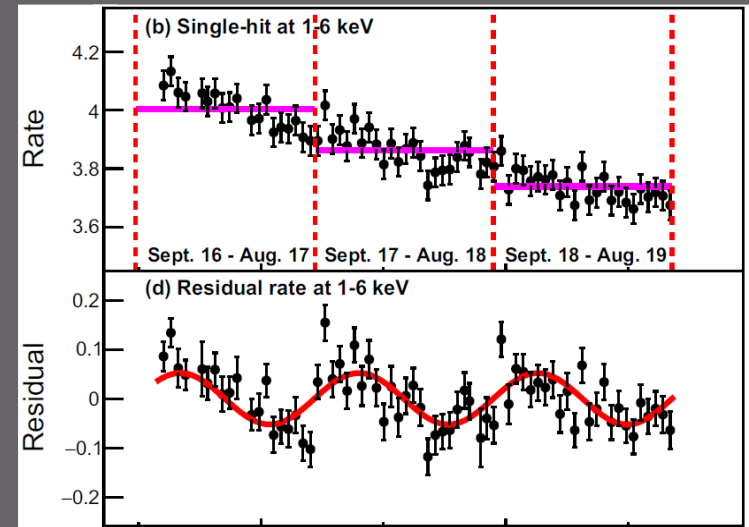
- Improved bkg modeling enabled us to fit without bias.
- Our best fit did not match with that of DAMA/LIBRA.
- Another NaI(Tl) experiment, called ANAIS-112, also showed similar result, but with opposite direction.
- **What Was the Modulation?**



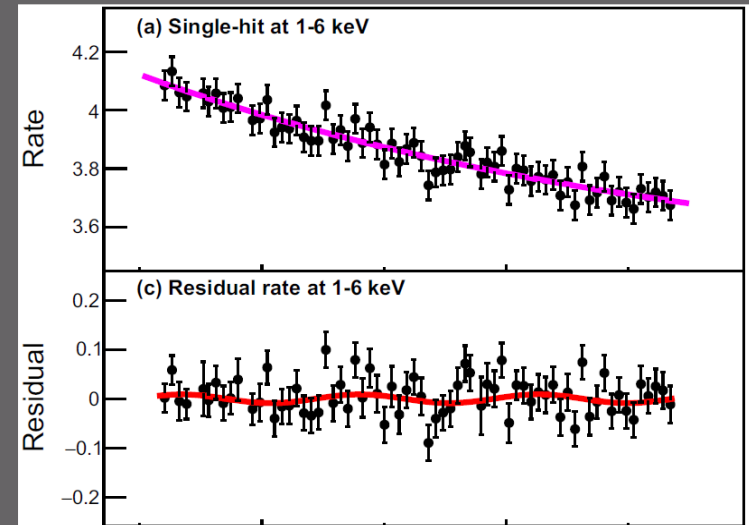
Was It a Statistical Illusion? *Sci Rep 13, 4676 (2023)*

- COSINE data + DAMA analysis method
→ Annual Modulation!

DAMA-like method

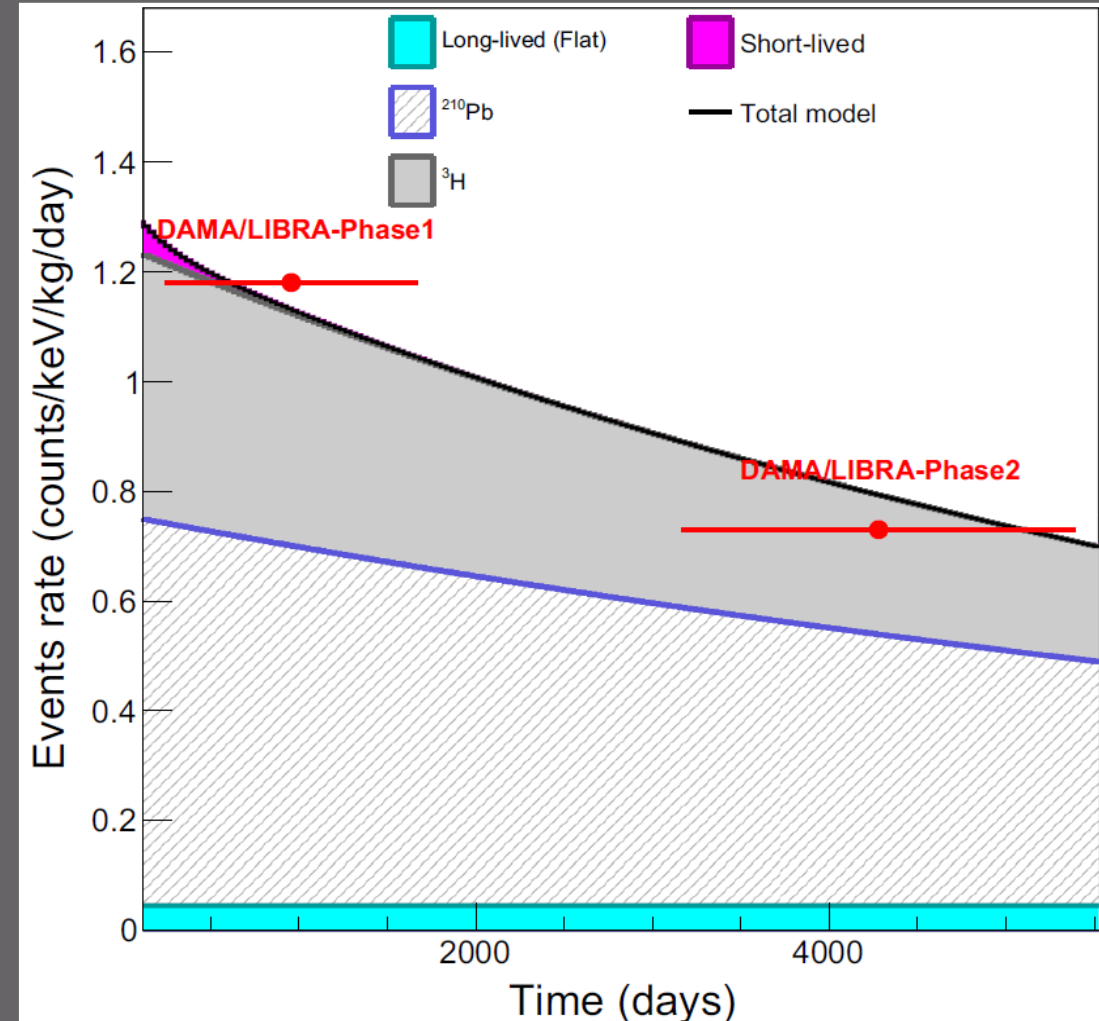


Single exponential



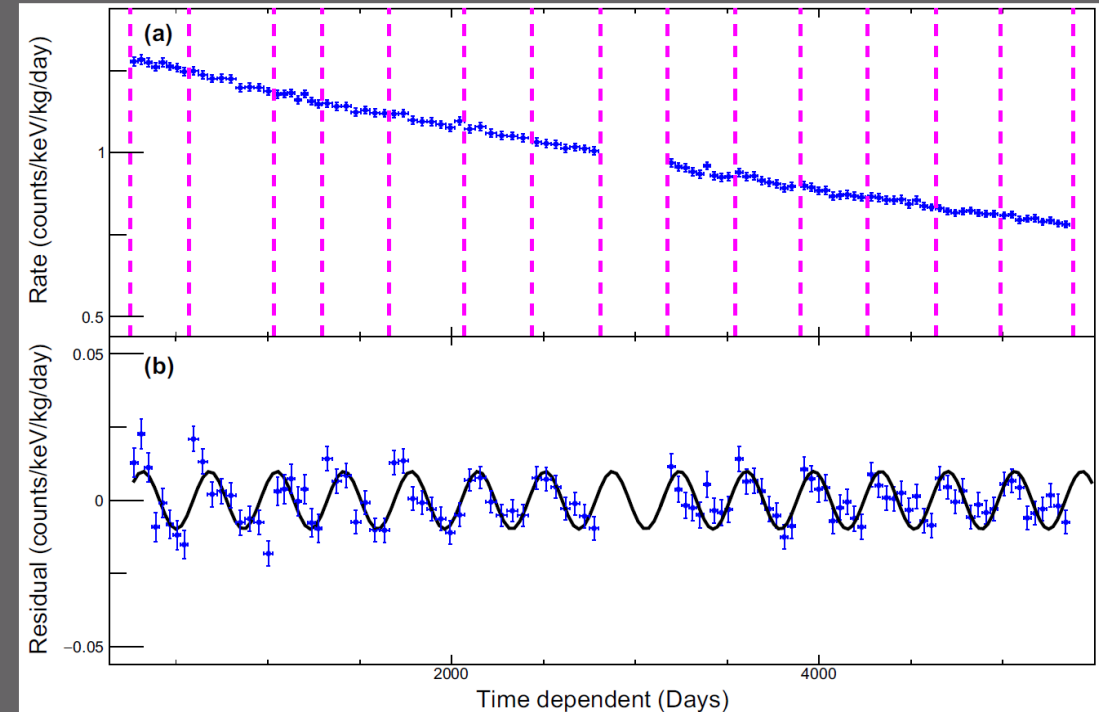
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- COSINE bkg model + DAMA event rate



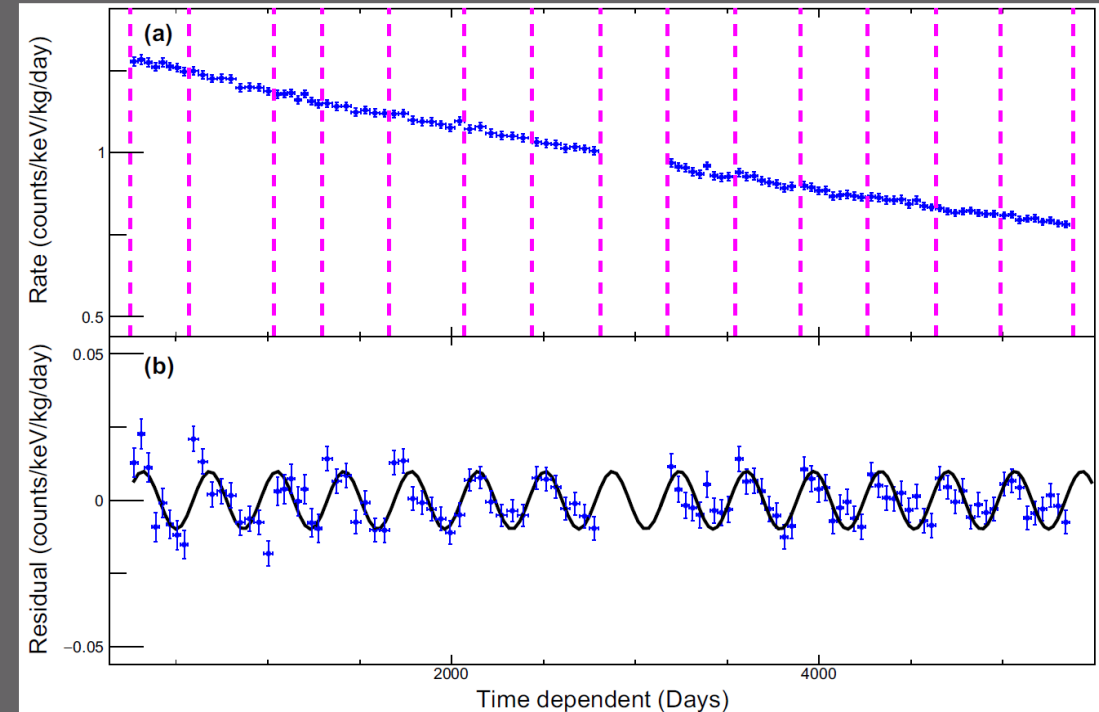
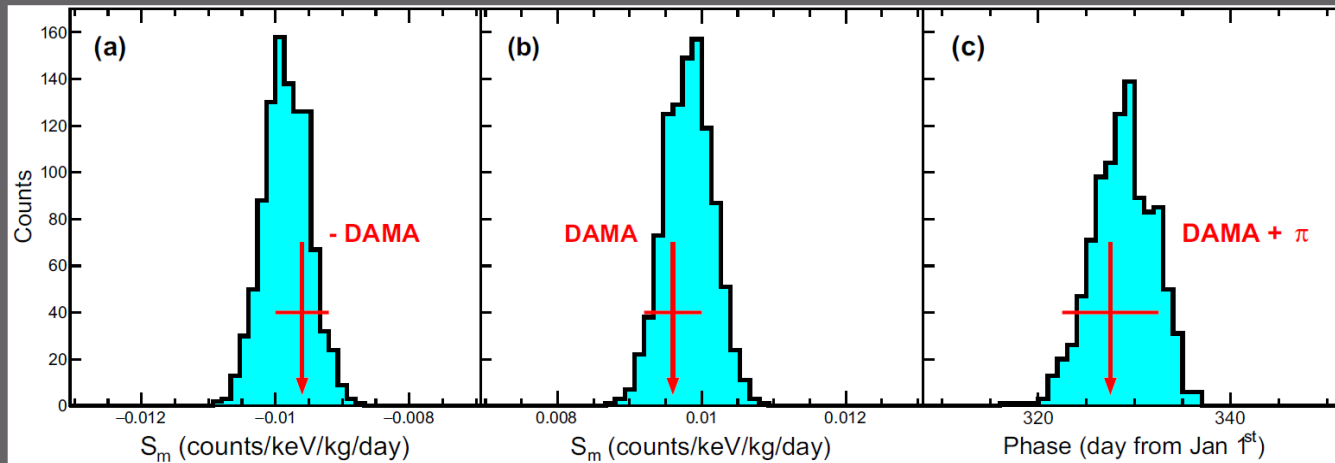
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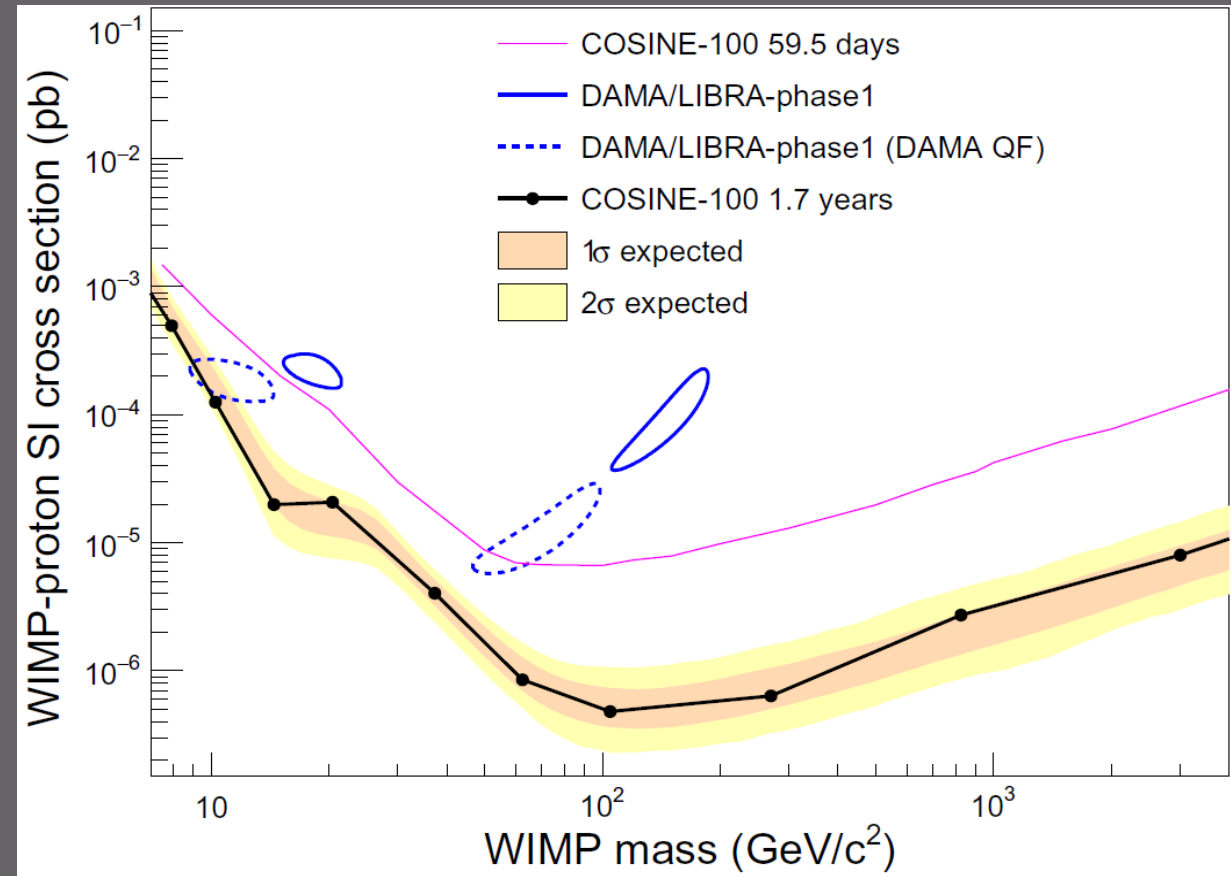
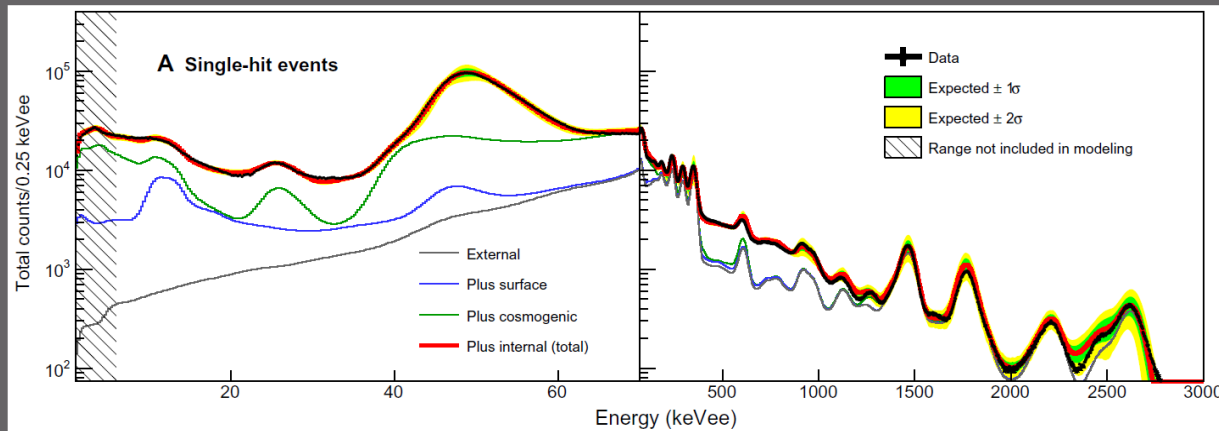
- COSINE data + DAMA analysis method
→ **Annual Modulation!**
- COSINE bkg model + DAMA event rate
→ **Annual Modulation!**
even same amplitude!



Further Exclusion of WIMP

- 1.7 years data gave stronger constraints on WIMP.

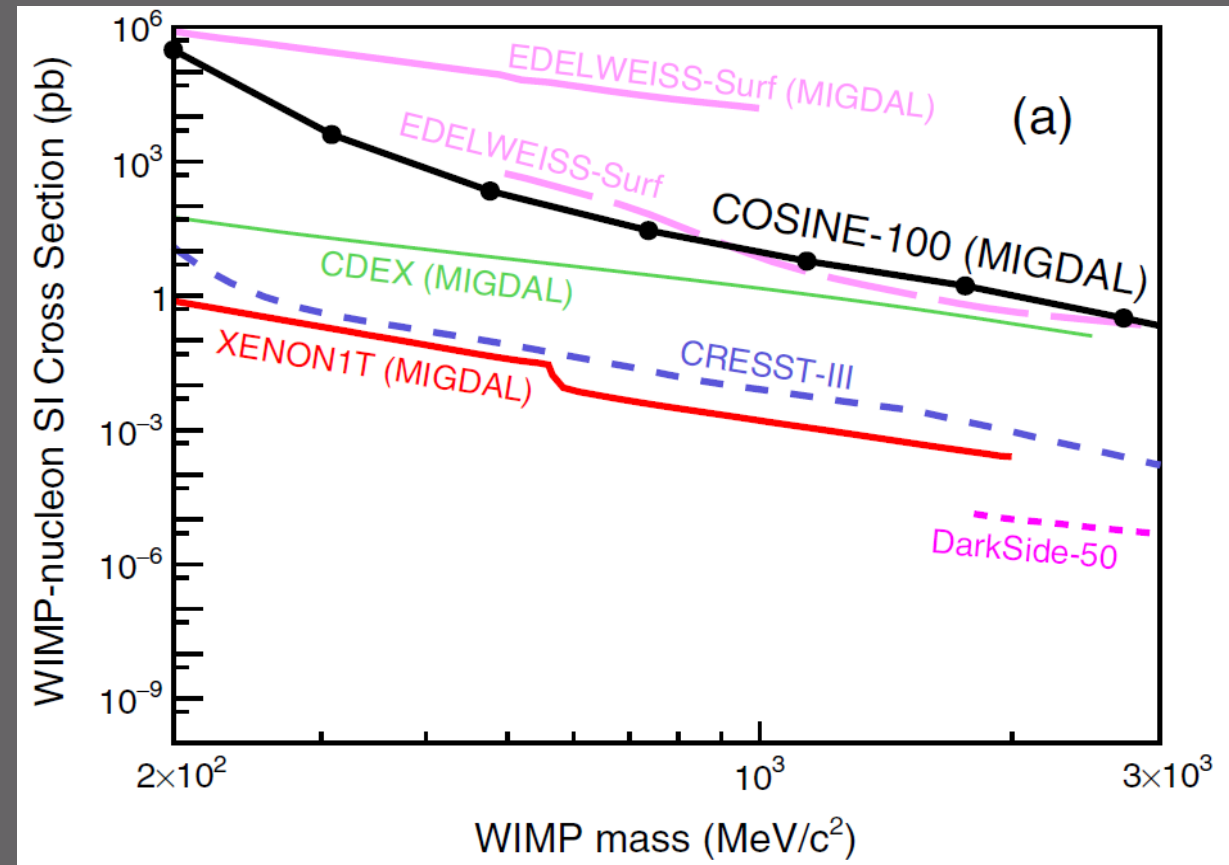
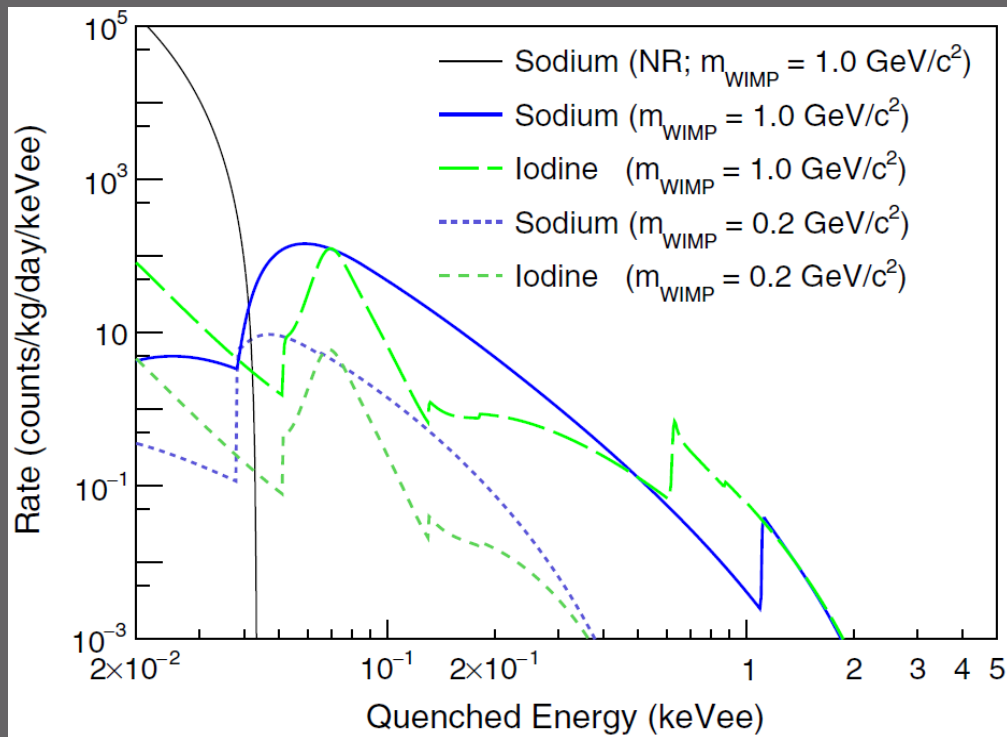
- Science Advances. 7, 46 (2021)
- Energy threshold lowered to 1 keV.
- Background modeling improved.



Further Exclusion of WIMP

- Lower WIMP mass could be probed considering the Migdal effect.

- [Phys. Rev. D 105, 042006](#)

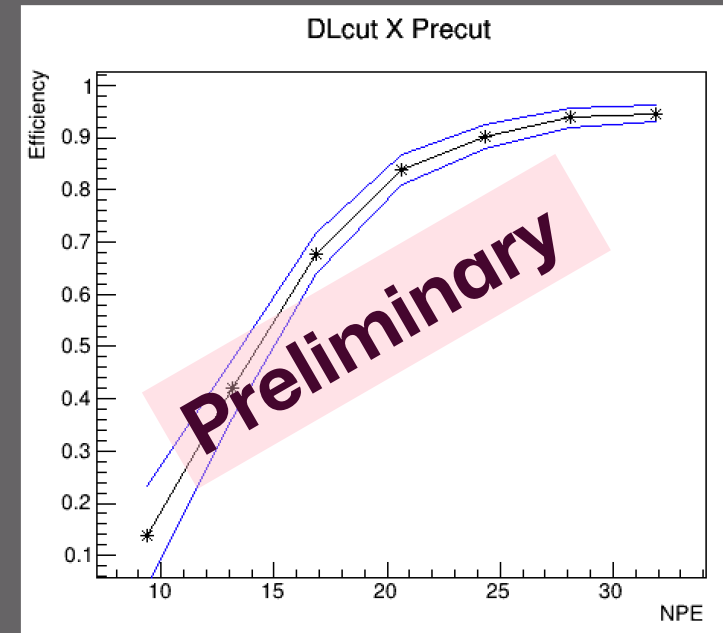
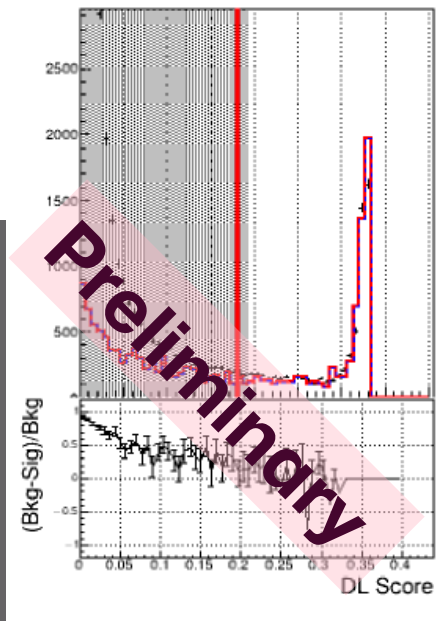


Evolving Analysis Techniques; Event Selection

- We are trying energy threshold less than 1 keV.
 - Many useful variables have been developed, using likelihood, FFT, intense works, ...
 - Aggregated those variables with MLP.
- 0.75 keV threshold is about to be achieved. 0.5 keV is under validation.
- Deep learning on the 'waveform' is also being studied.

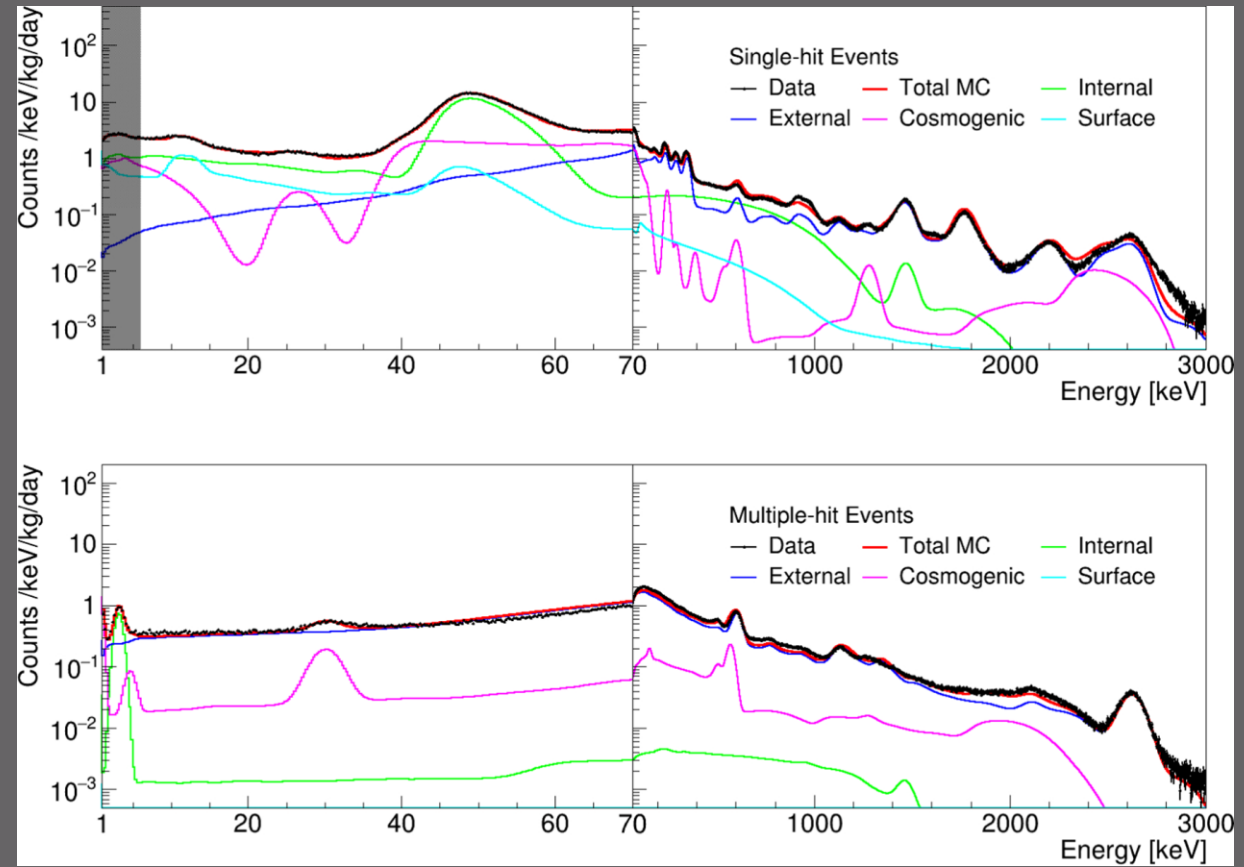
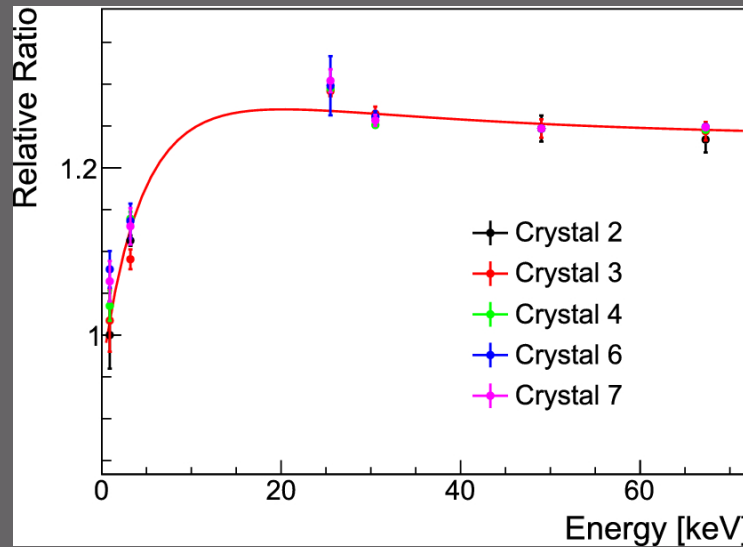
$E = 0.75 \sim 1$ keV

- Signal Sample
- Noise + Signal



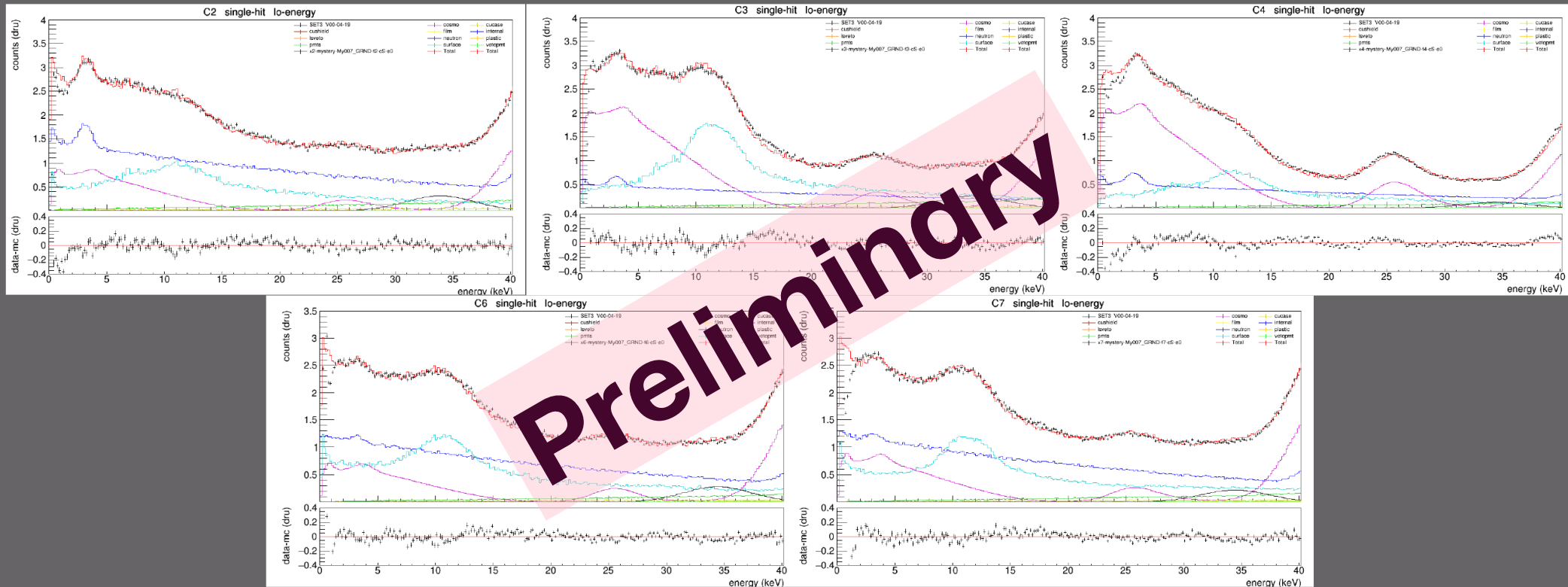
Evolving Analysis Techniques; Background Modeling

- 1.7 years data modeling was done.
 - [Eur. Phys. J. C. 81 837 \(2021\)](#)
 - More radioactive components
 - Better cosmogenic activity estimation
 - Non-proportional response considered.



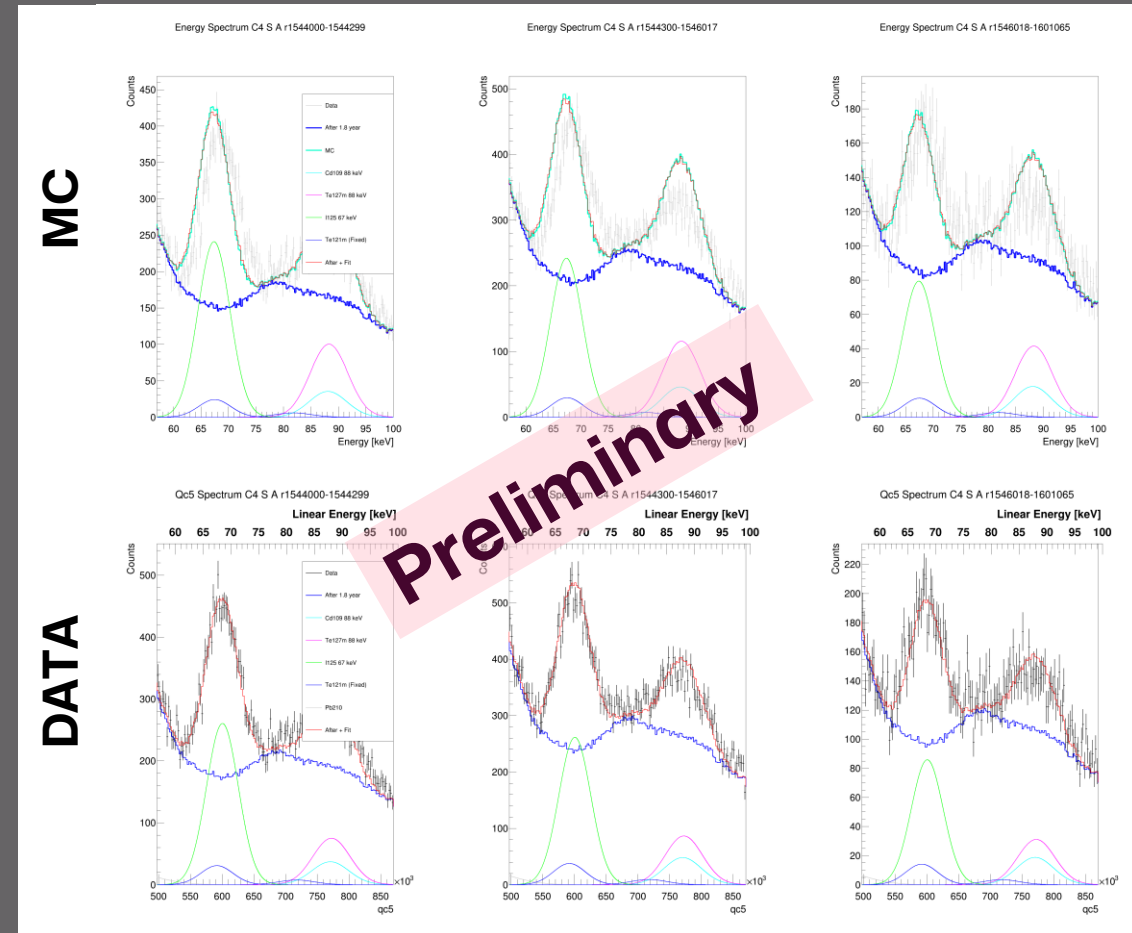
Evolving Analysis Techniques; Background Modeling

- 1.7 years data modeling was done.
- For 3 years data...
 - Fitting multiple channels simultaneously.



Evolving Analysis Techniques; Background Modeling

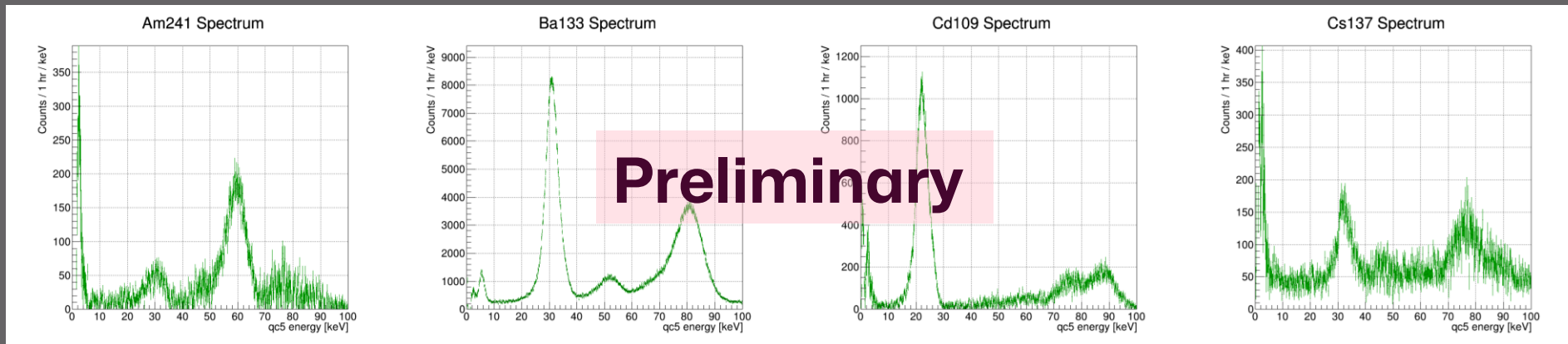
- 1.7 years data modeling was done.
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 - Measuring non-proportionality of NaI(Tl) crystals.



Evolving Analysis Techniques; Background Modeling

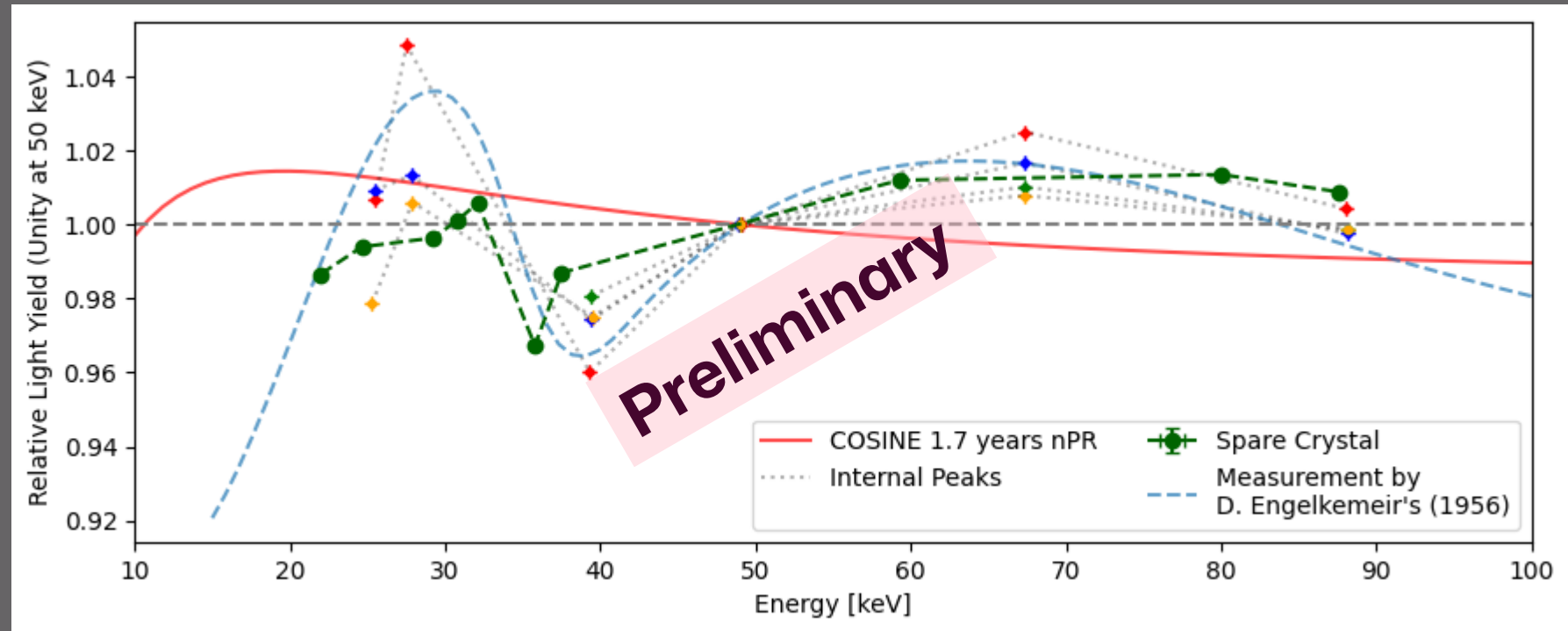
- 1.7 years data modeling was done.
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Measured gamma deposit on spare crystal
by Alpha Spectra inc.



Evolving Analysis Techniques; Background Modeling

- 1.7 years data modeling was done.
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Evolving Detector; COSINE-100 Upgrade

- The detector was disassembled recently.
 - COSINE-100 successfully completed a 7-year journey.



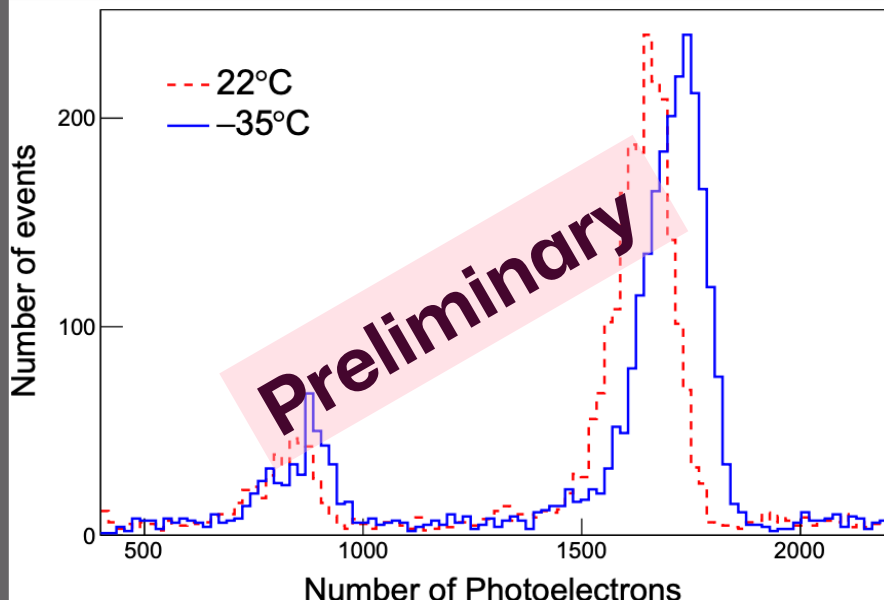
Evolving Detector; COSINE-100 Upgrade

- The detector was disassembled recently.
- Planning upgrades aiming for higher light yield.
 - Re-encapsulation without quartz.
 - Cask-shape machining.



Evolving Detector; COSINE-100 Upgrade

- The detector was disassembled recently.
- Planning upgrades aiming for higher light yield.
 - Re-encapsulation without quartz.
 - Cask-shape machining.
 - Operation at -35°C .
 - Expecting **30 % or more benefit** on the light yield.

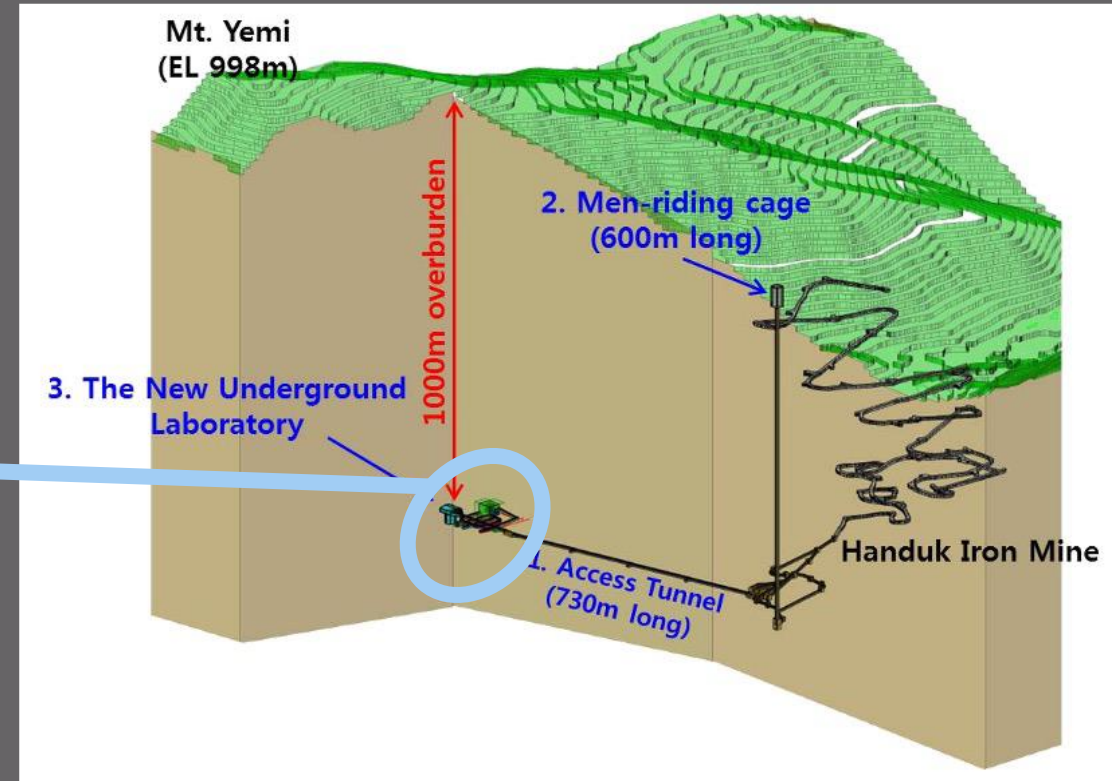
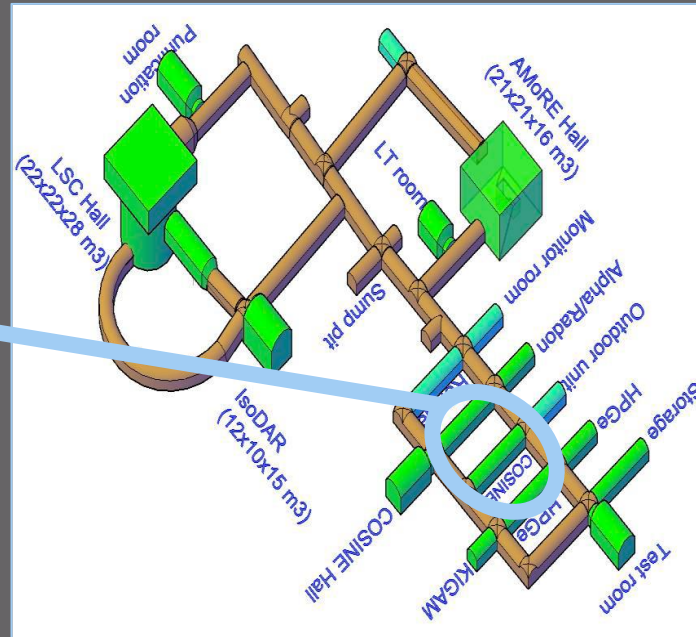


Temp. ($^{\circ}\text{C}$)	LY (PEs/keV)	σ/mean (%)
22	27.6 ± 0.3	3.8 ± 0.1
-35	28.9 ± 0.2	3.7 ± 0.1



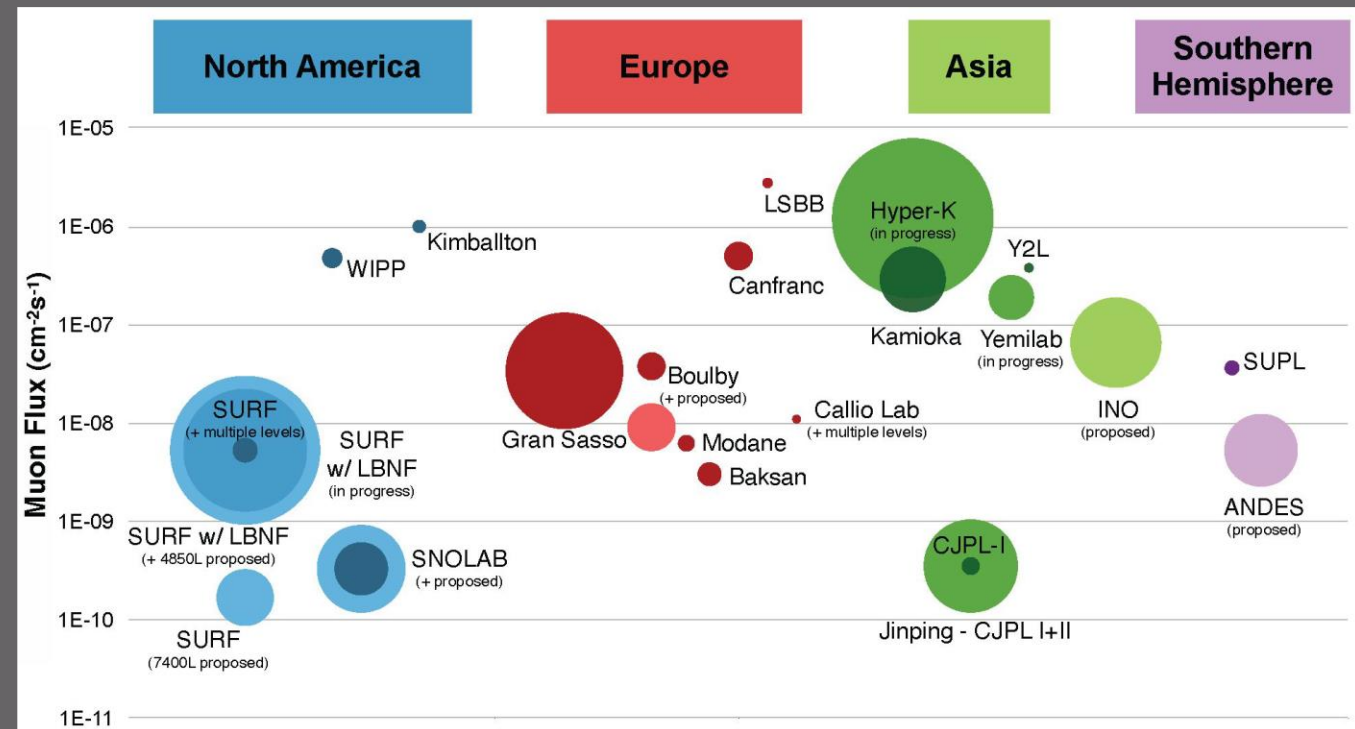
Evolving Detector; COSINE-100 Upgrade

- The detector was disassembled recently.
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- Moving to our new sweet home, Yemilab!



Evolving Detector; COSINE-100 Upgrade

- The detector was disassembled recently.
- Planning upgrades aiming for higher light yield.
- Moving to our new sweet home, Yemilab!
 - 6th large underground lab in the world.
 - We are moving in this summer!



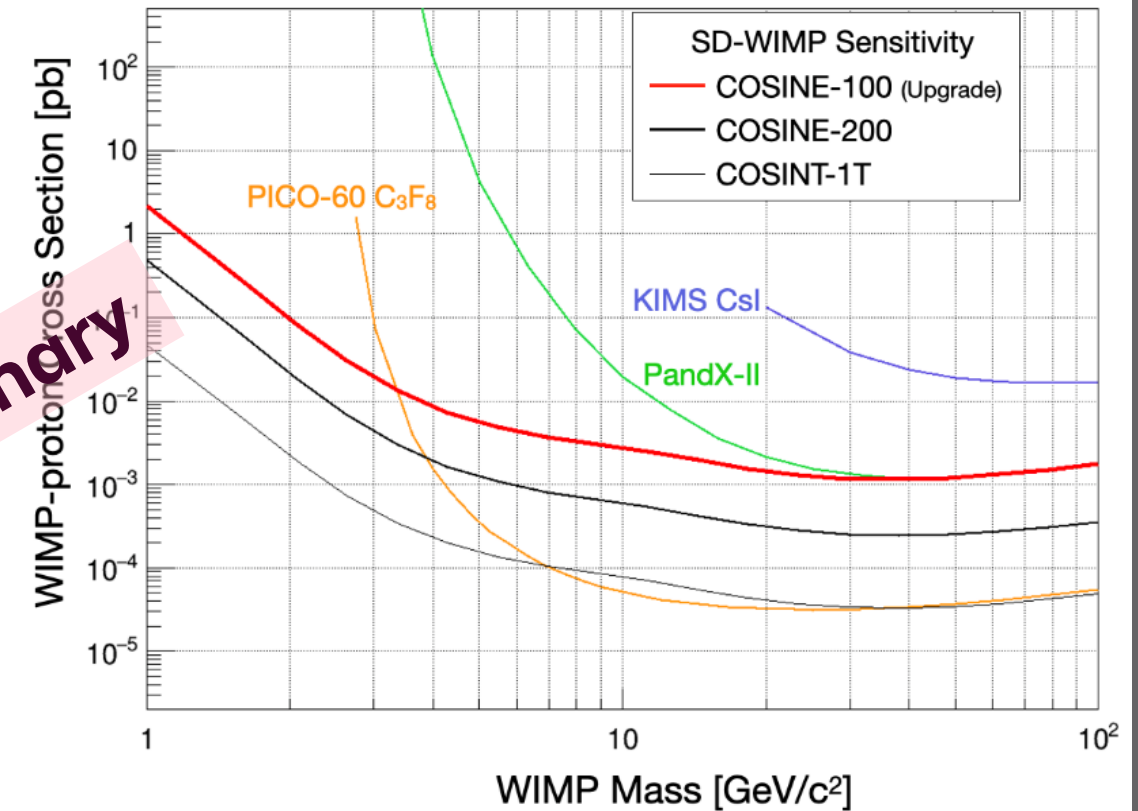
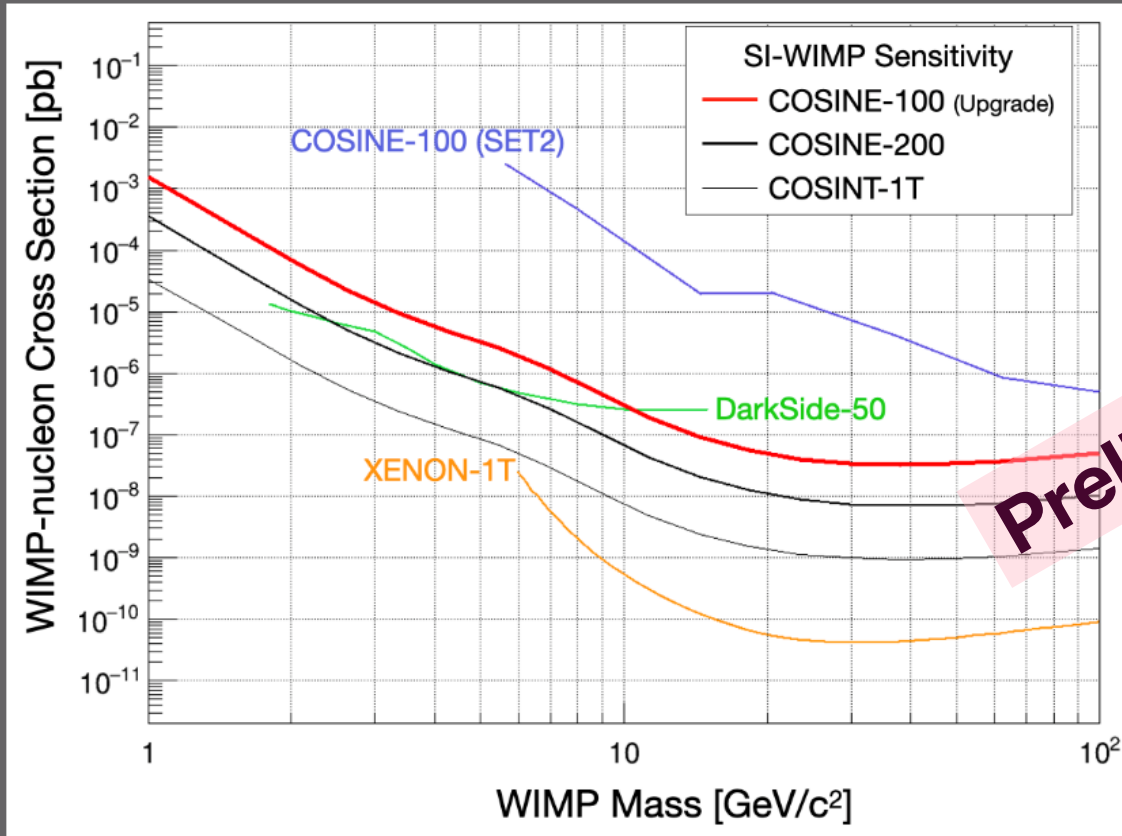
Evolving Detector; COSINE-100 Upgrade

Condition for COSINE 100(upgrade)

Light yields: 22 PEs/ keV

COSINE 100 level background

1 year with all 8 crystals utilized



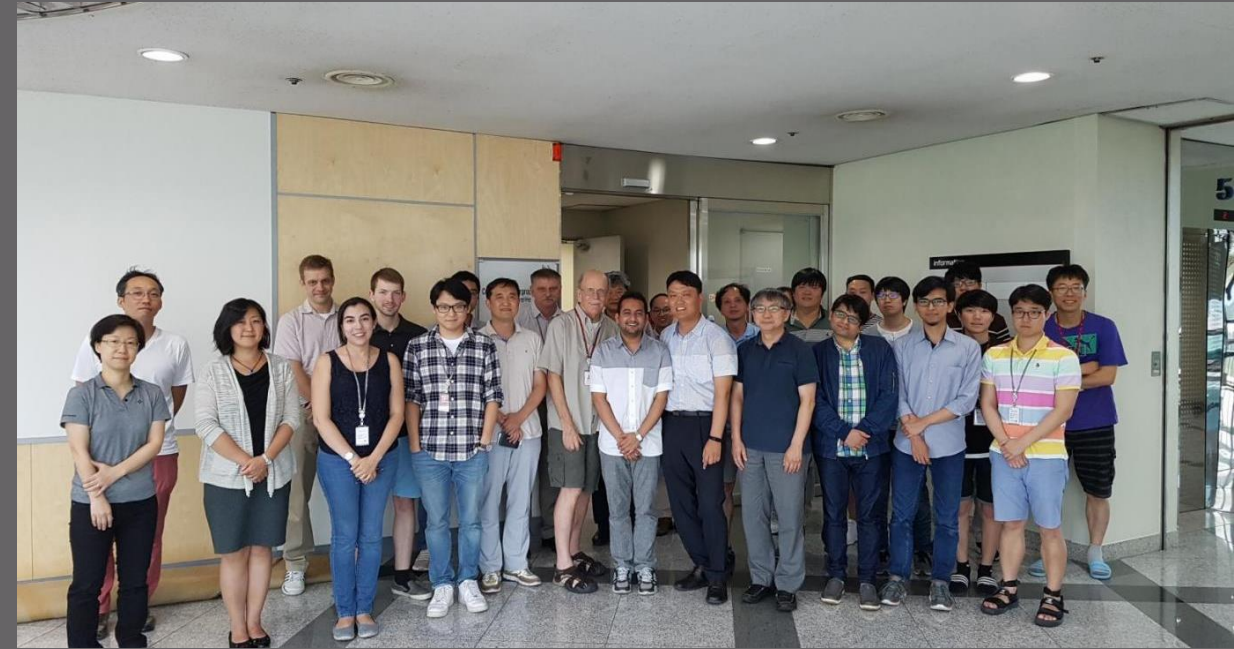
Preliminary

Stay Tune! This Summer Will Be Fun!

17 institutes, around 50 people



2nd collaboration meeting (2017)



LAST SLIDE