Recent Results *and* *Status of* COSINE-100 *and its* Upgrade

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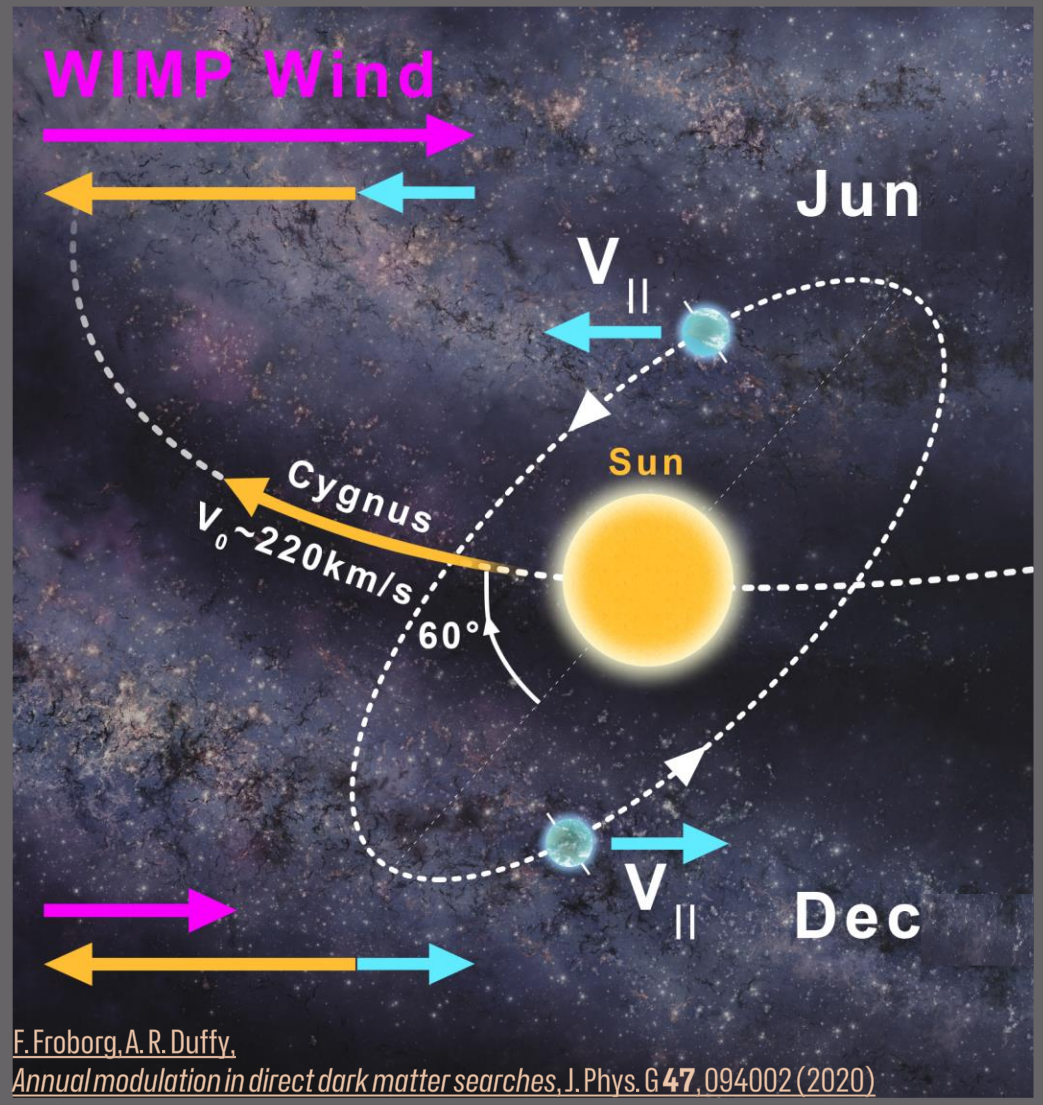
On behalf of COSINE Collaboration

November 8th, 2024

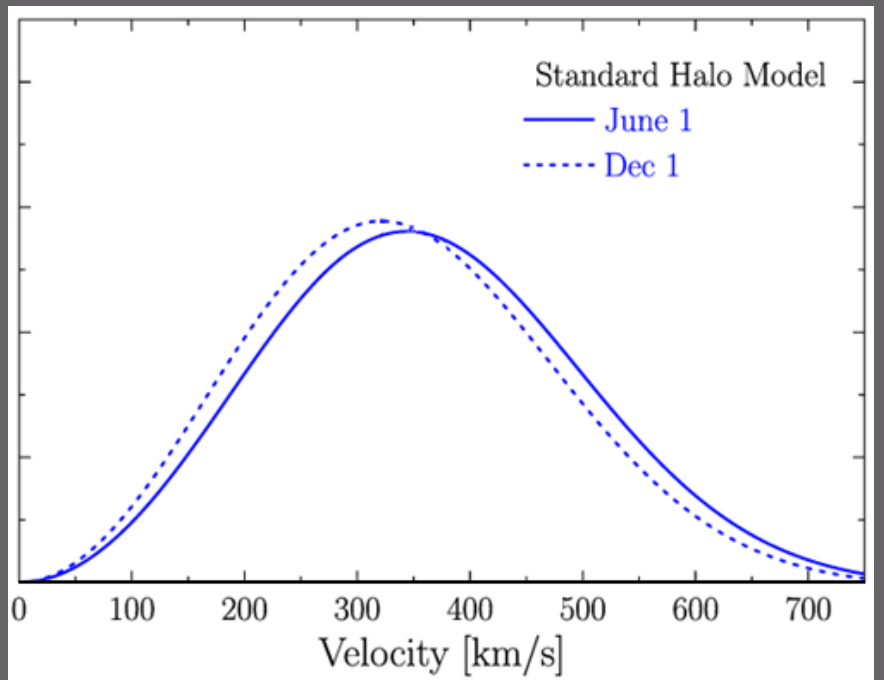
Dark World to Swampland 2024

CTPU Seminar Room, Institute for Basic Science, Daejeon, Korea

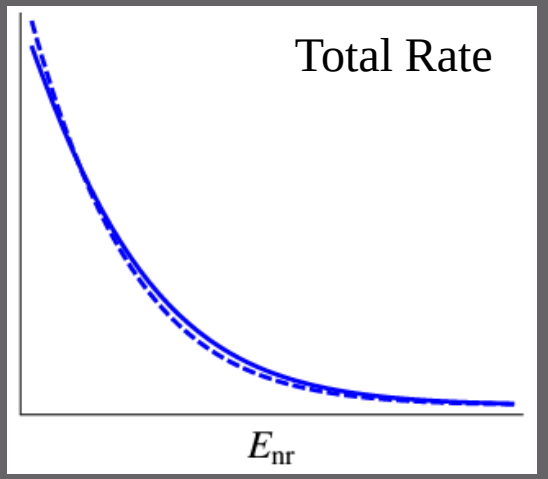
Standard Halo Model and Annual Modulation

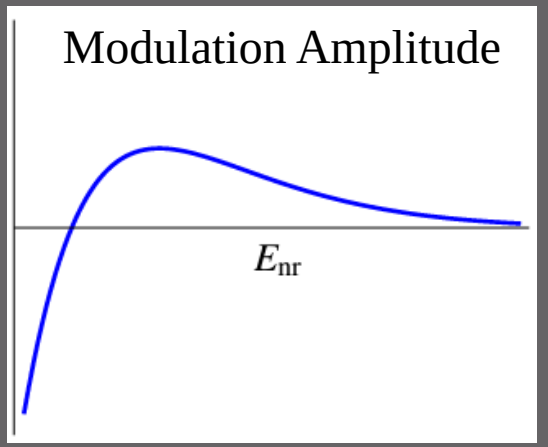


F. Froborg, A. R. Duffy,
Annual modulation in direct dark matter searches, J. Phys. G **47**, 094002 (2020)



K. Freese, M. Lisanti, C. Savage, *Colloquium: Annual modulation of dark matter*, Rev. Mod. Phys. **85**, 1561 (2013)





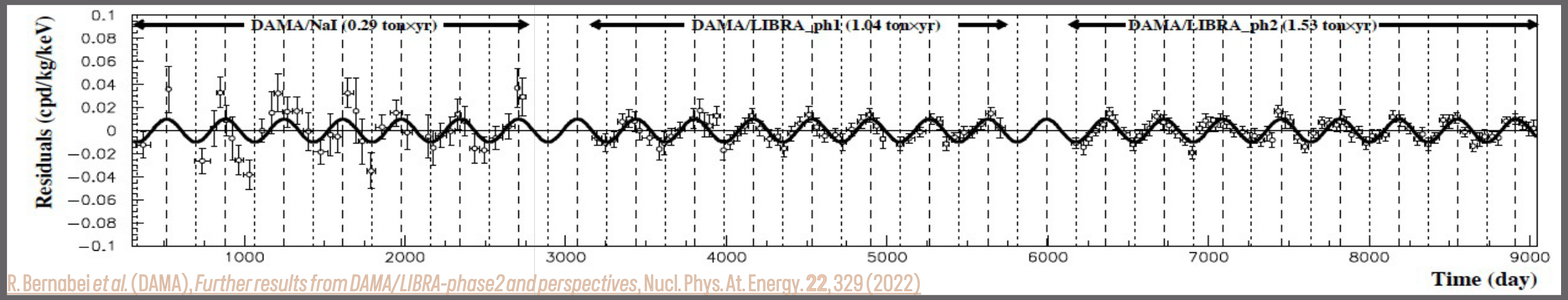
$$\frac{dR}{dE_{\rm nr}} = \frac{M_T}{m_N} \times \frac{\sigma_\chi F^2(q)}{2m_\chi \mu^2} \times \rho_0 \int_{v_{\rm min}}^{v_{\rm esc}} \frac{f(\vec{v},t)}{v} d^3v$$

Annual Modulation in DAMA Experiment


DAMA/NaI, DAMA/LIBRA

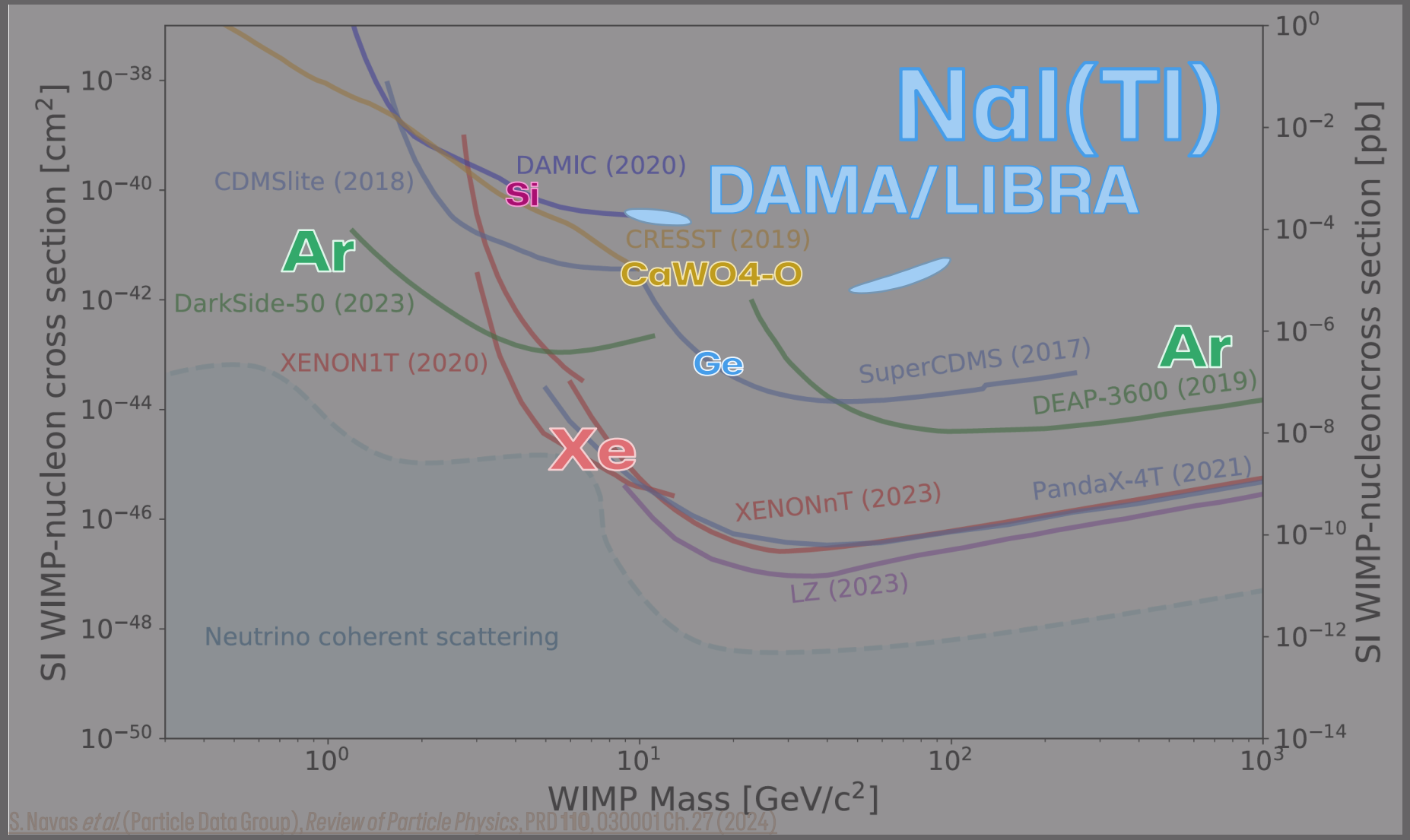
- DAMA detected the ***Annual Modulation***!
  - Using NaI(Tl) scintillator.

E (keV)	A (counts/day/kg/keV)	ϕ (day)	C.L.
$1-3$	0.0191 ± 0.0020	152.5 **(fixed)**	9.7σ
	0.0191 ± 0.0020	149.6 ± 5.9	9.6σ
$1-6$	0.01048 ± 0.00090	152.5 **(fixed)**	11.6σ
	0.01058 ± 0.00090	144.5 ± 5.1	11.8σ
$2-6$	0.00996 ± 0.00074	152.5 **(fixed)**	13.4σ
	0.01014 ± 0.00074	142.4 ± 4.2	13.7σ



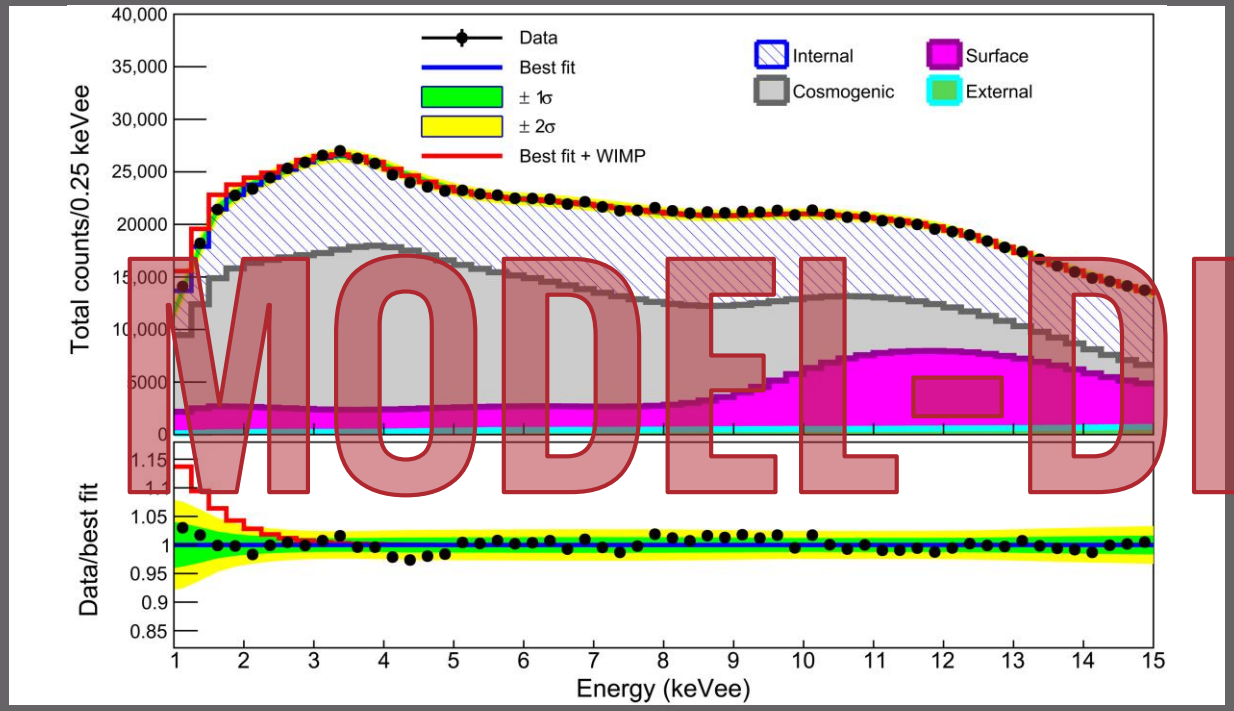
R. Bernabei *et al.* (DAMA), *Further results from DAMA/LIBRA-phase2 and perspectives*, Nucl. Phys. At. Energy. **22**, 329 (2022)

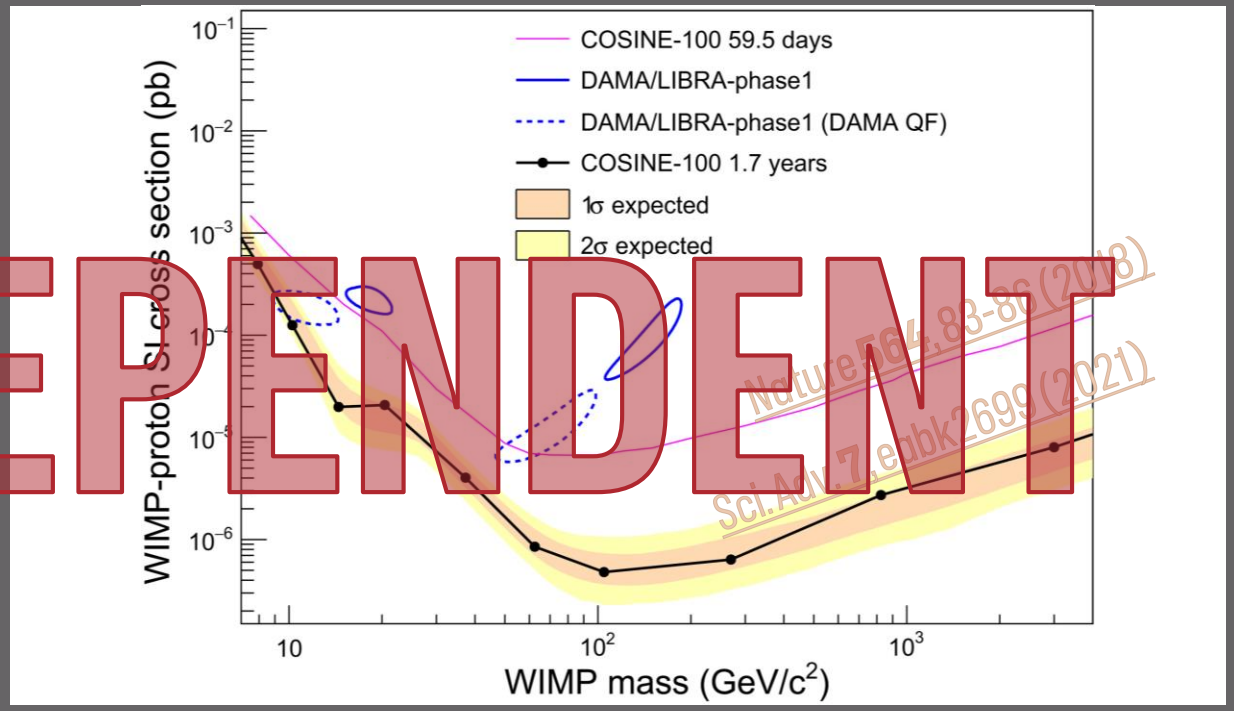
Check for DAMA's Signal; Target Material



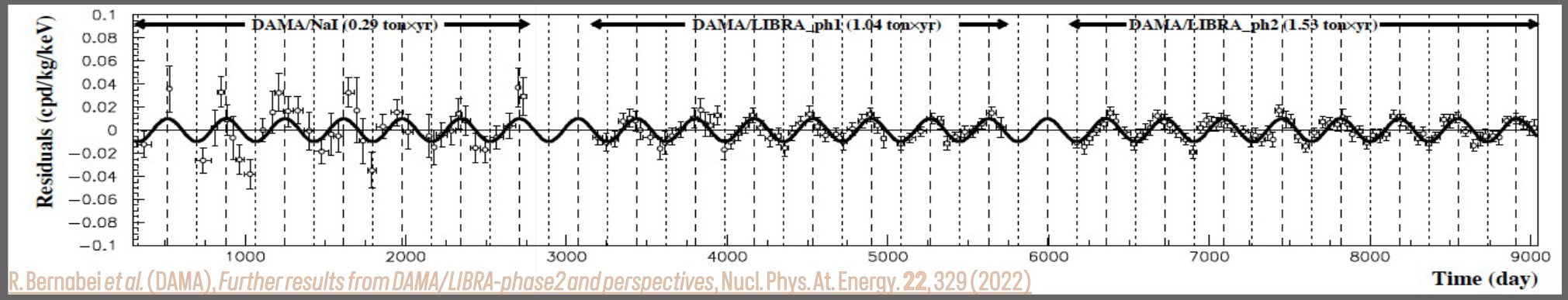
S. Navas *et al.* (Particle Data Group), *Review of Particle Physics*, PRD 110, 030001 Ch. 27 (2024)

Check for DAMA's Signal; Analysis Method





MODEL-DEPENDENT

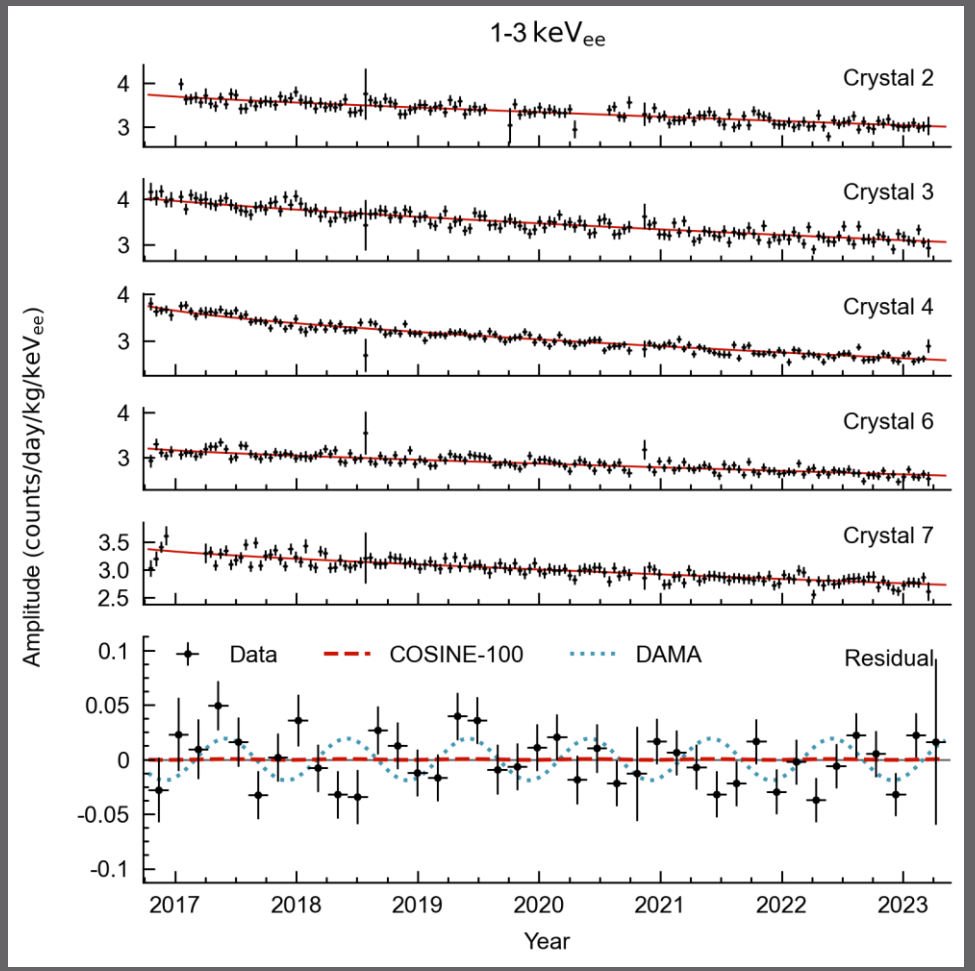


R. Bernabei *et al.* (DAMA), *Further results from DAMA/LIBRA-phase2 and perspectives*, Nucl. Phys. At. Energy. 22, 329 (2022)

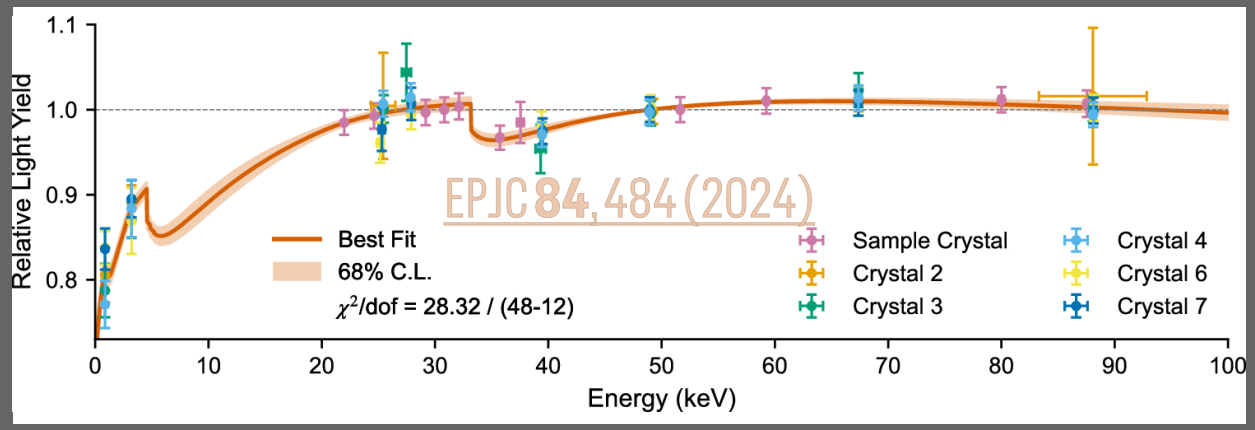
Model-Independent Test of DAMA

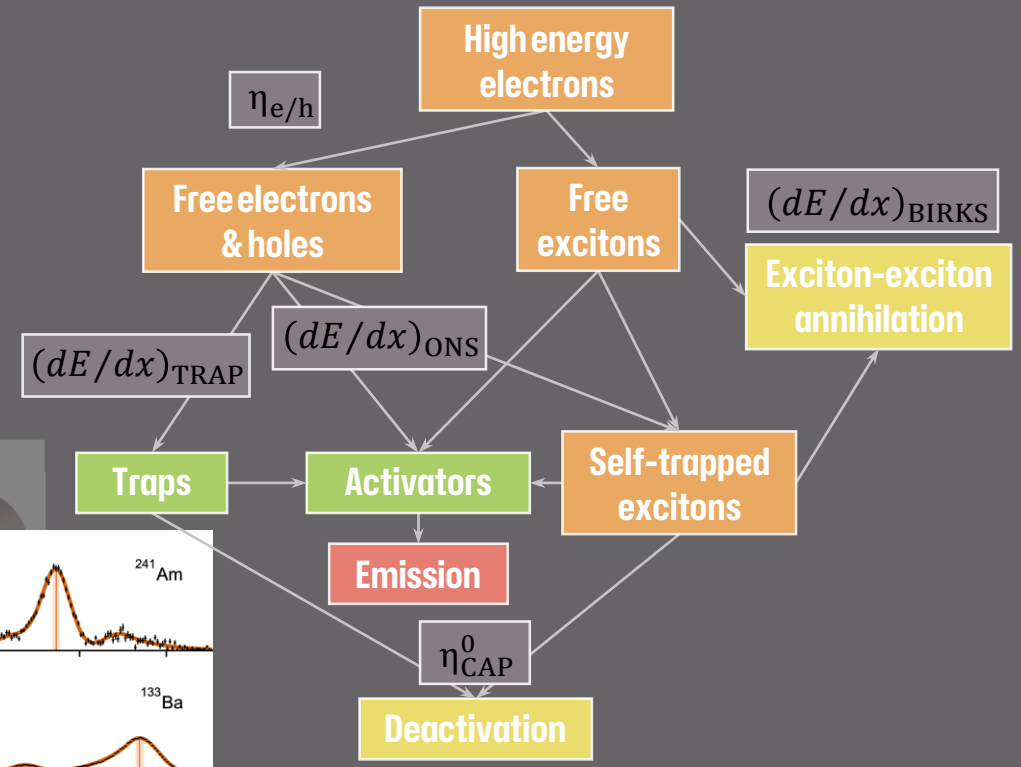
Same Material, NaI(Tl)

Same Domain, Time

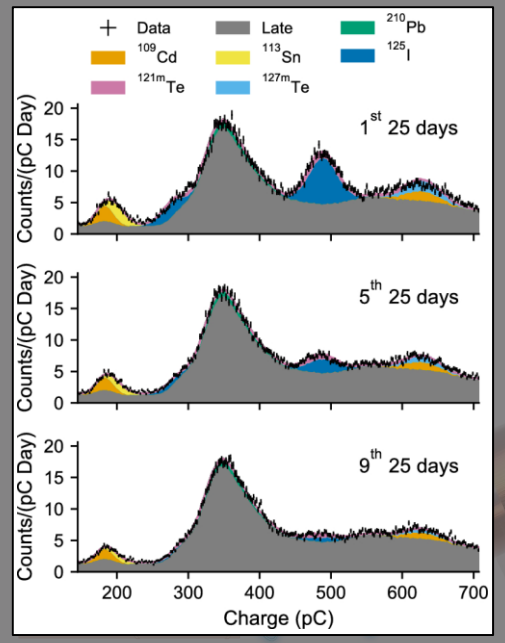


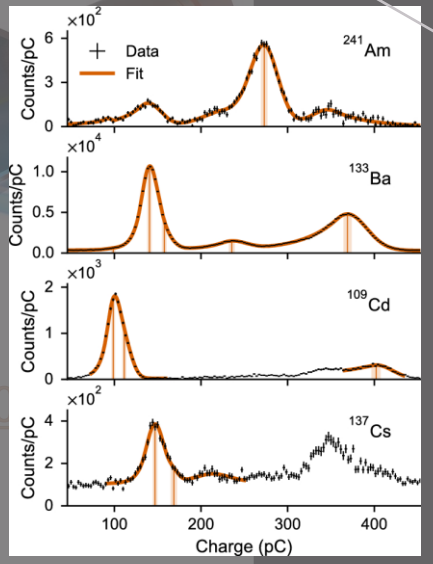
Install NaI(Tl) – COSINE-100 Detector





S. A. Payne *et al.*, *Nonproportionality of Scintillator Detectors: Theory and Experiment. II*, IEEE Trans. Nucl. Sci. **58**, 3392 (2011)





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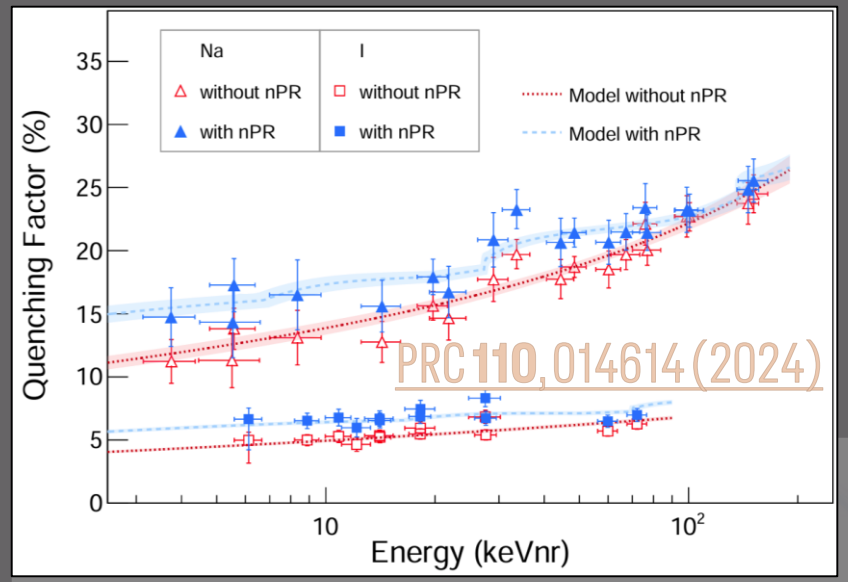
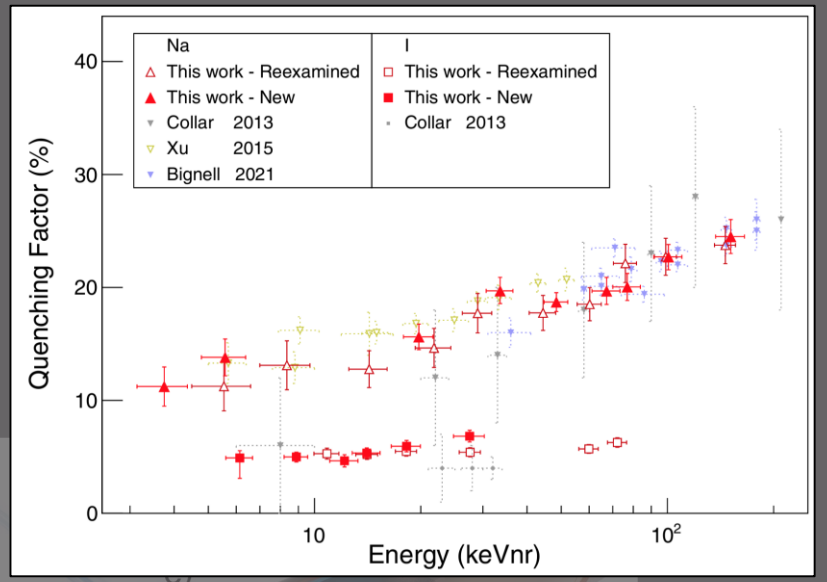
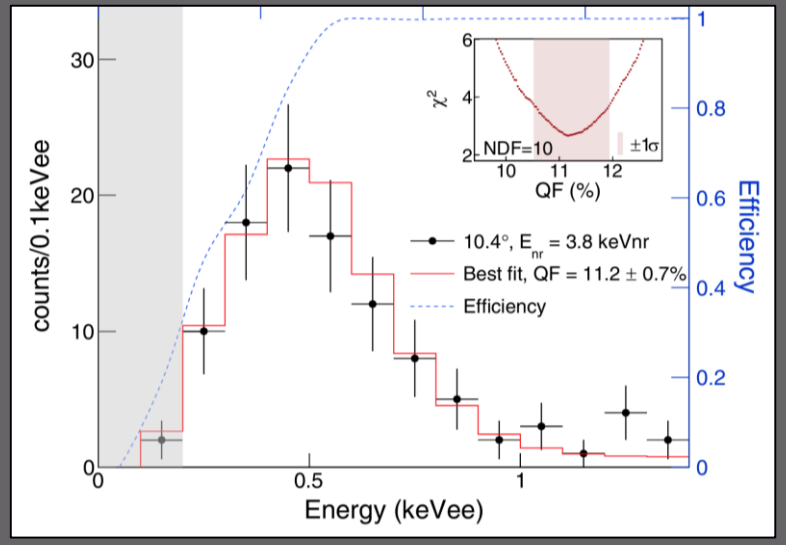
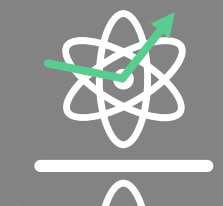
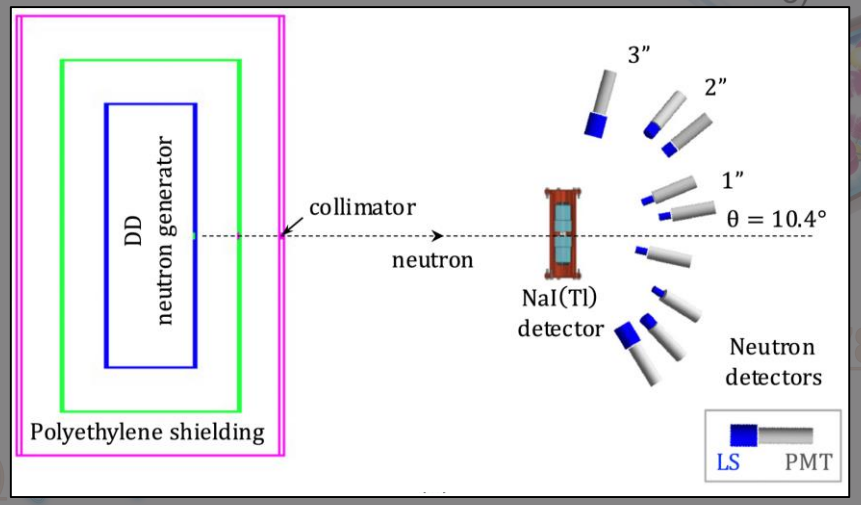
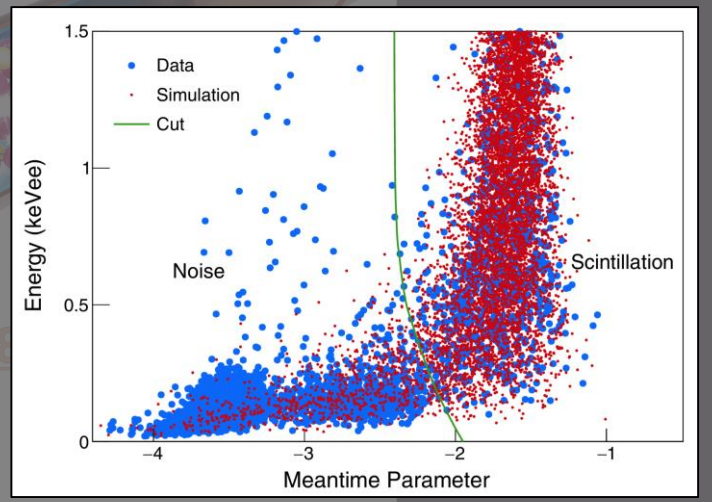


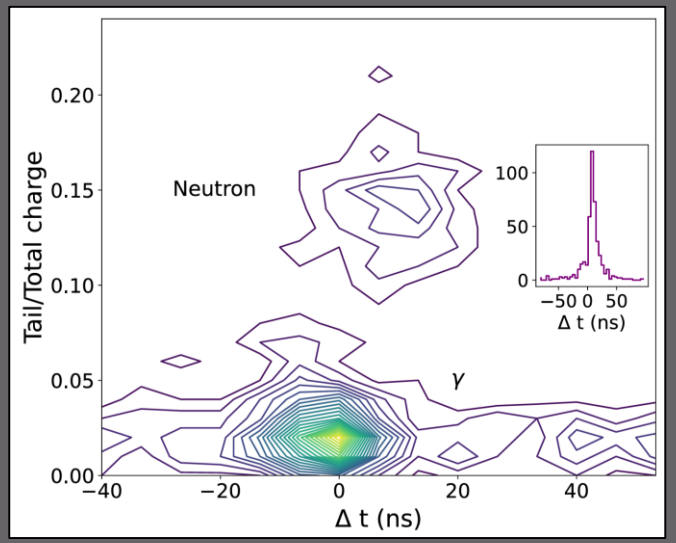






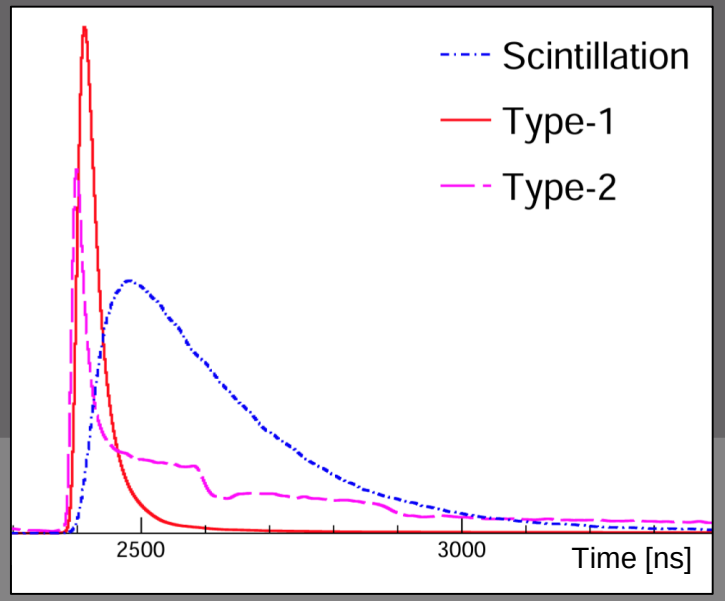






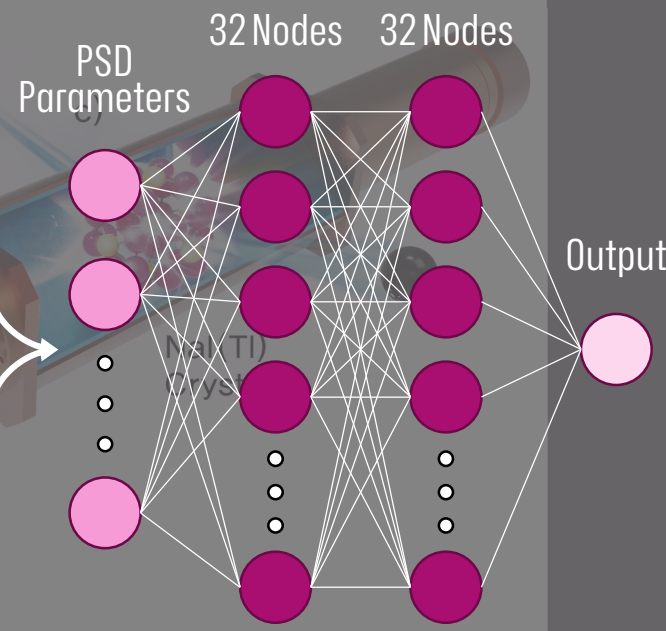
Nature 564, 83-86 (2018)

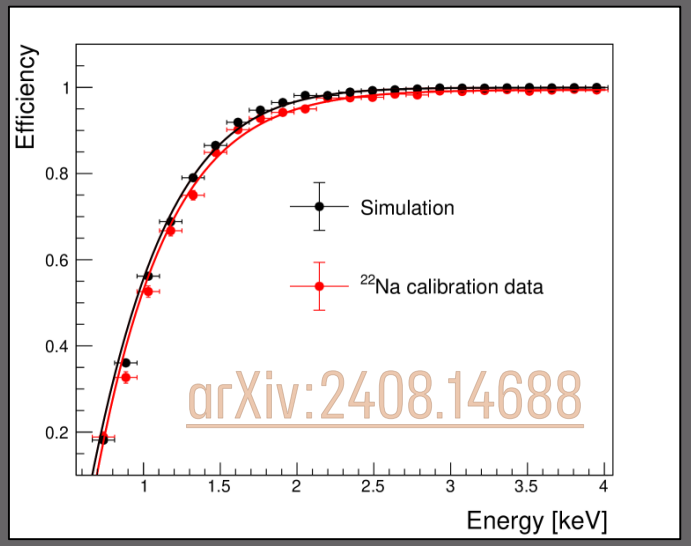
Install NaI(Tl) – COSINE-100 Detector

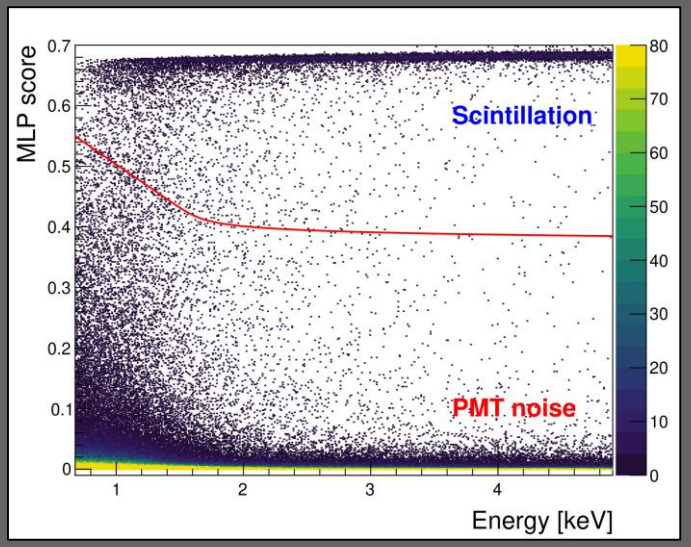


Signal Sample
^{22}Na Calibration Data

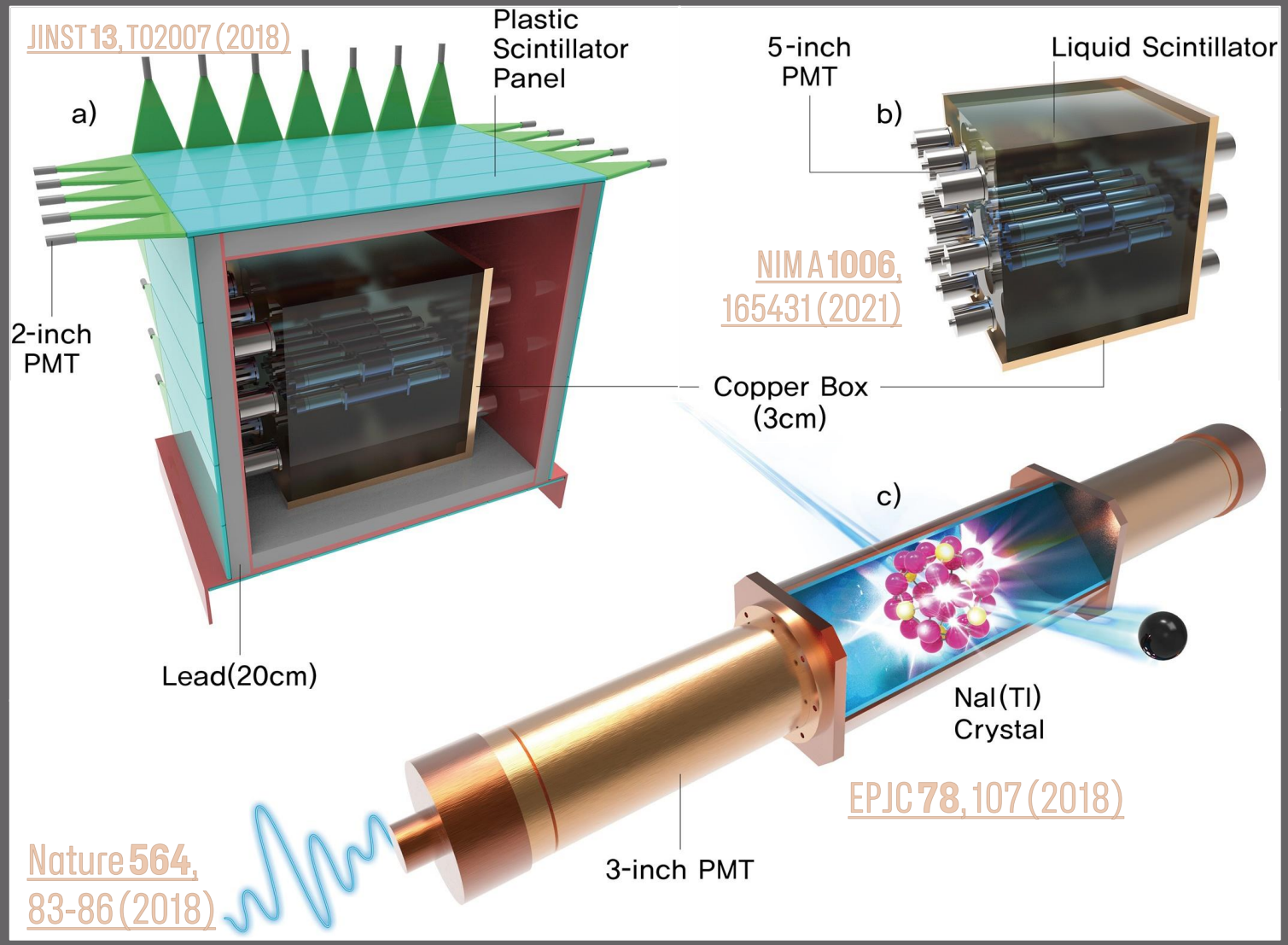
Noise Sample
15% of 3-year Data

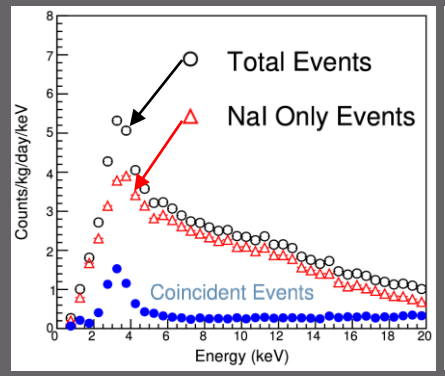


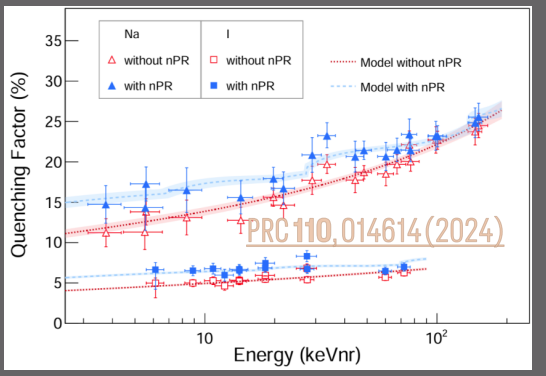


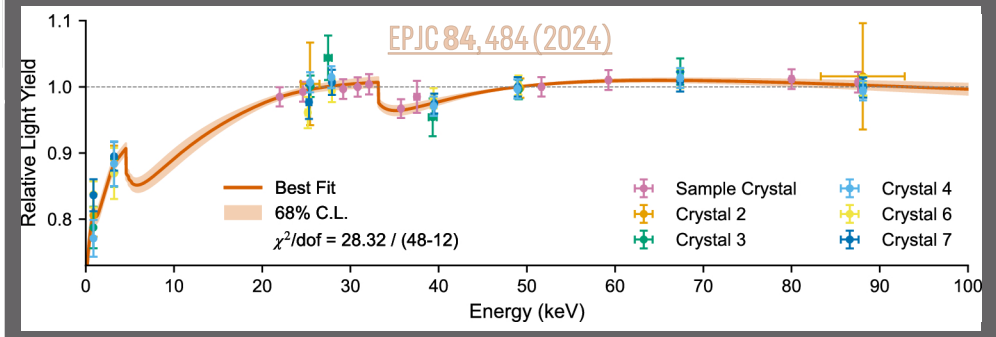


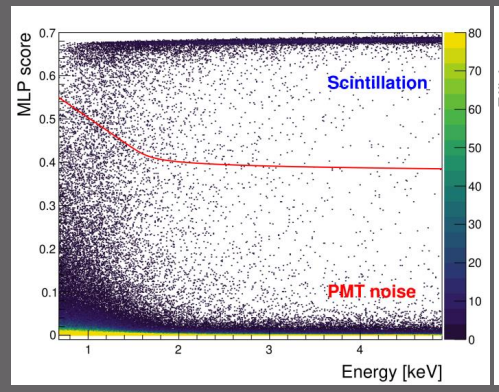
Install NaI(Tl) – COSINE-100 Detector

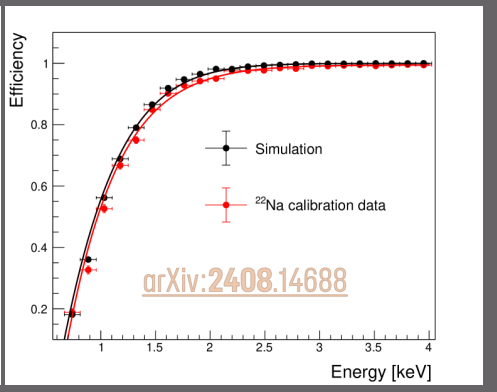




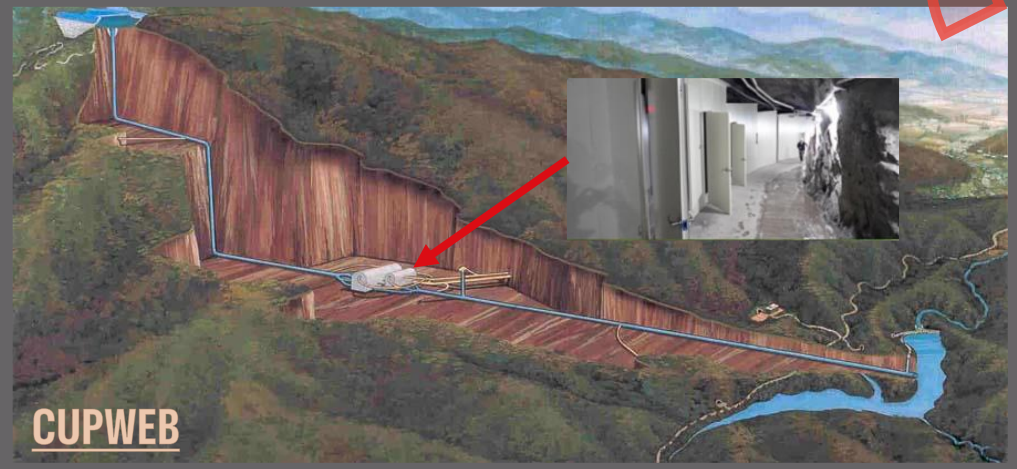




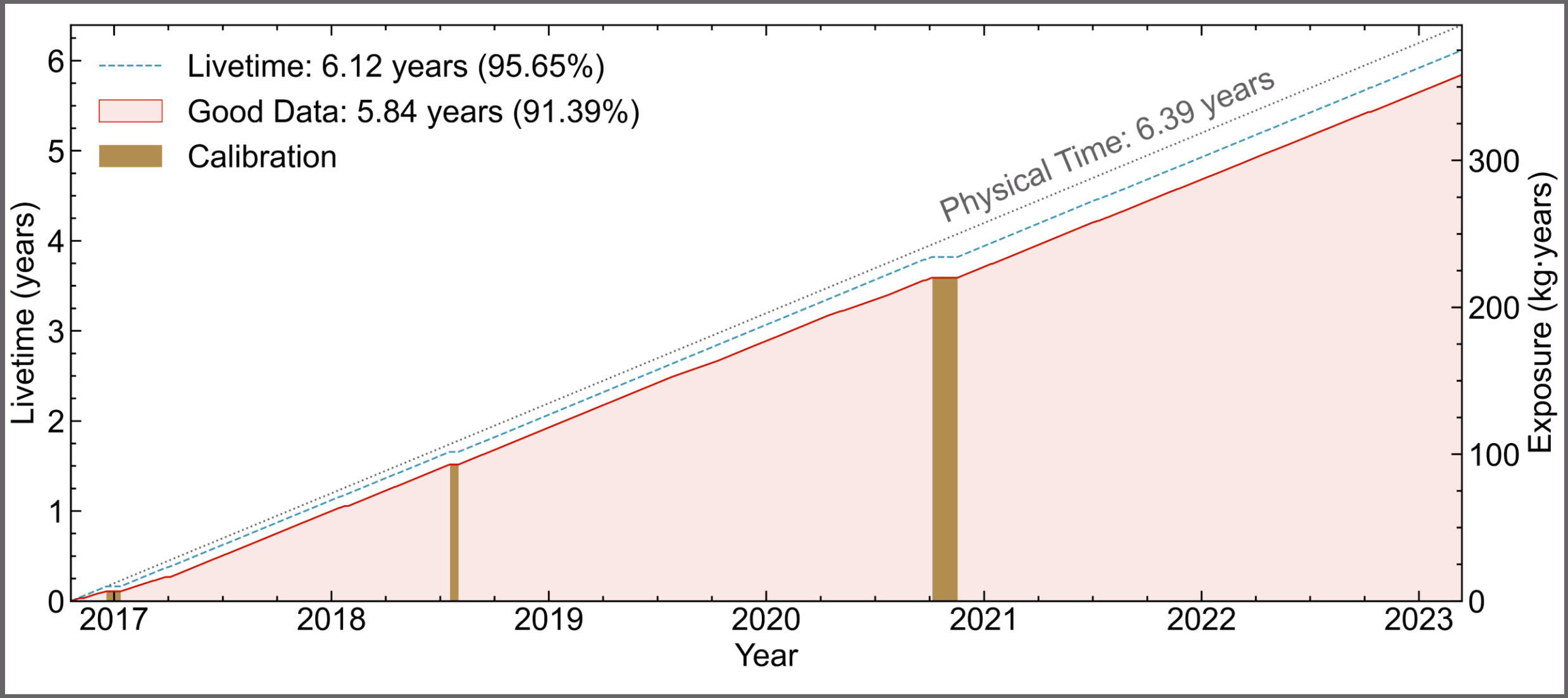




Install NaI(Tl) – Location

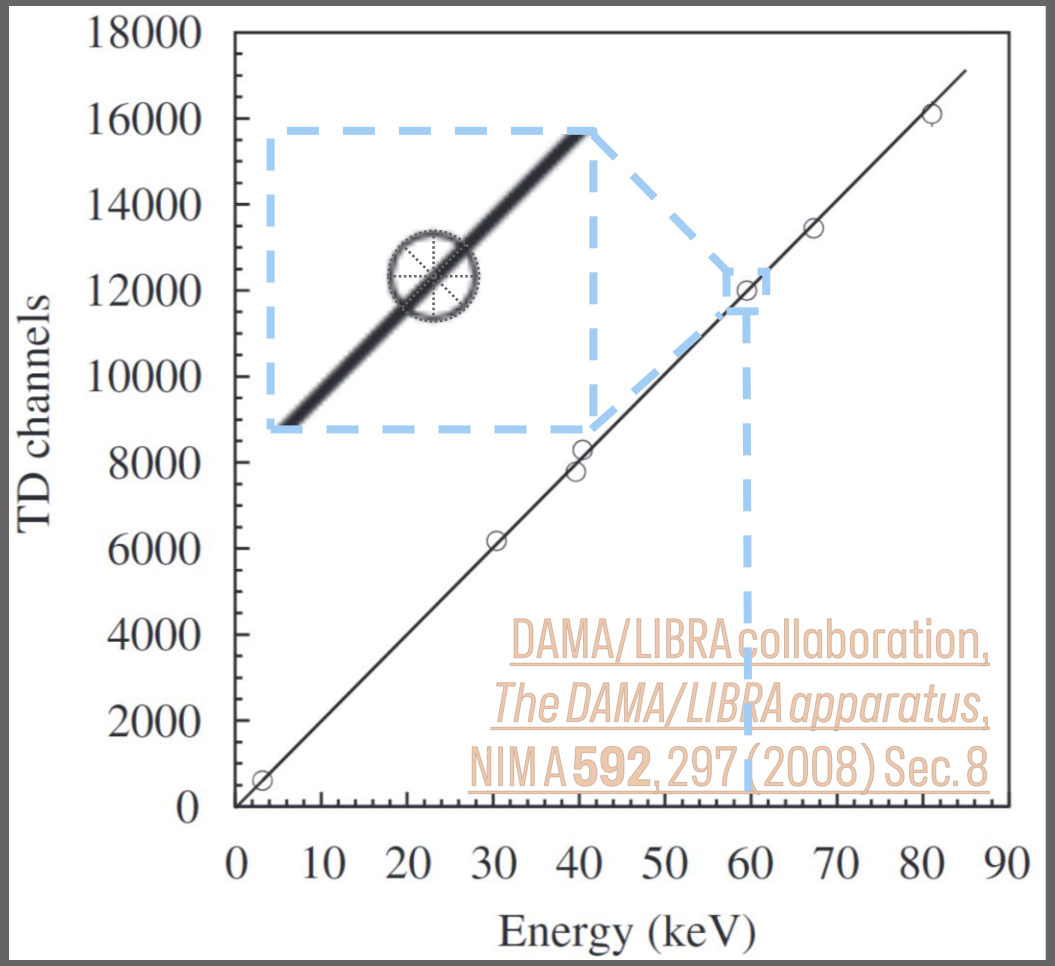


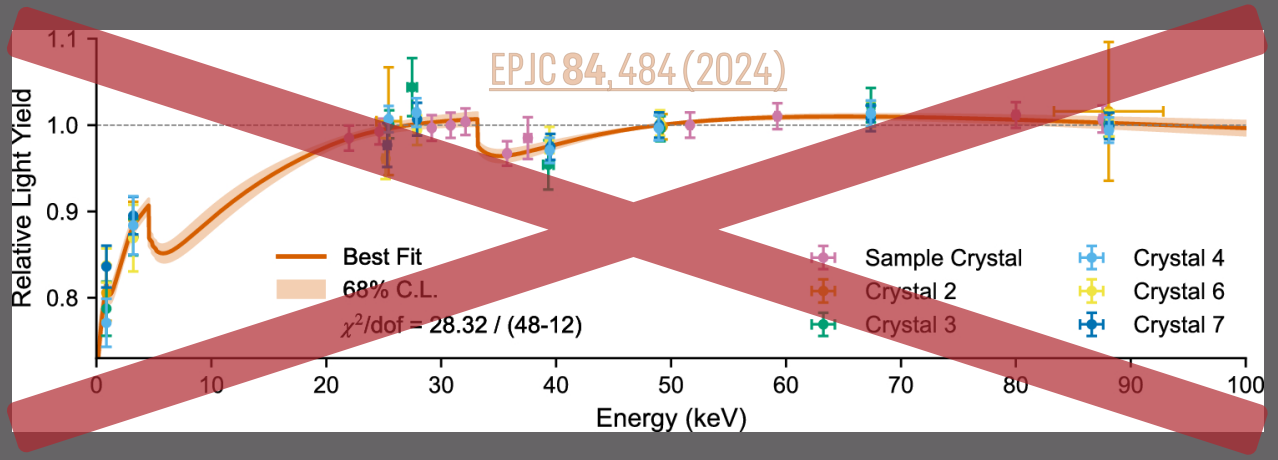
6 Years 4 Months 22 Days Later...



Calibration for Testing DAMA's Claim

Linear Calibration → keV_{ee}

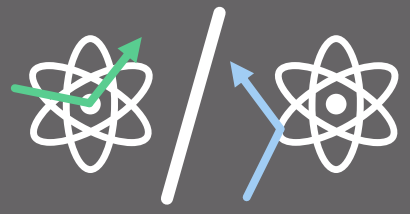


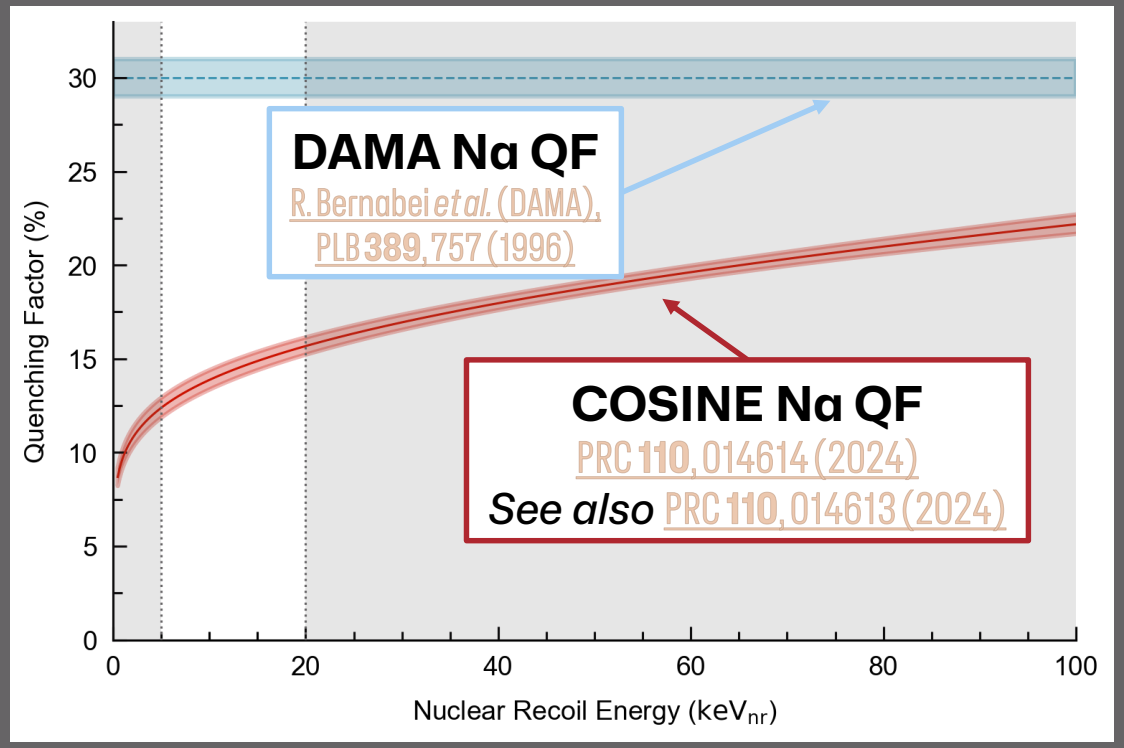


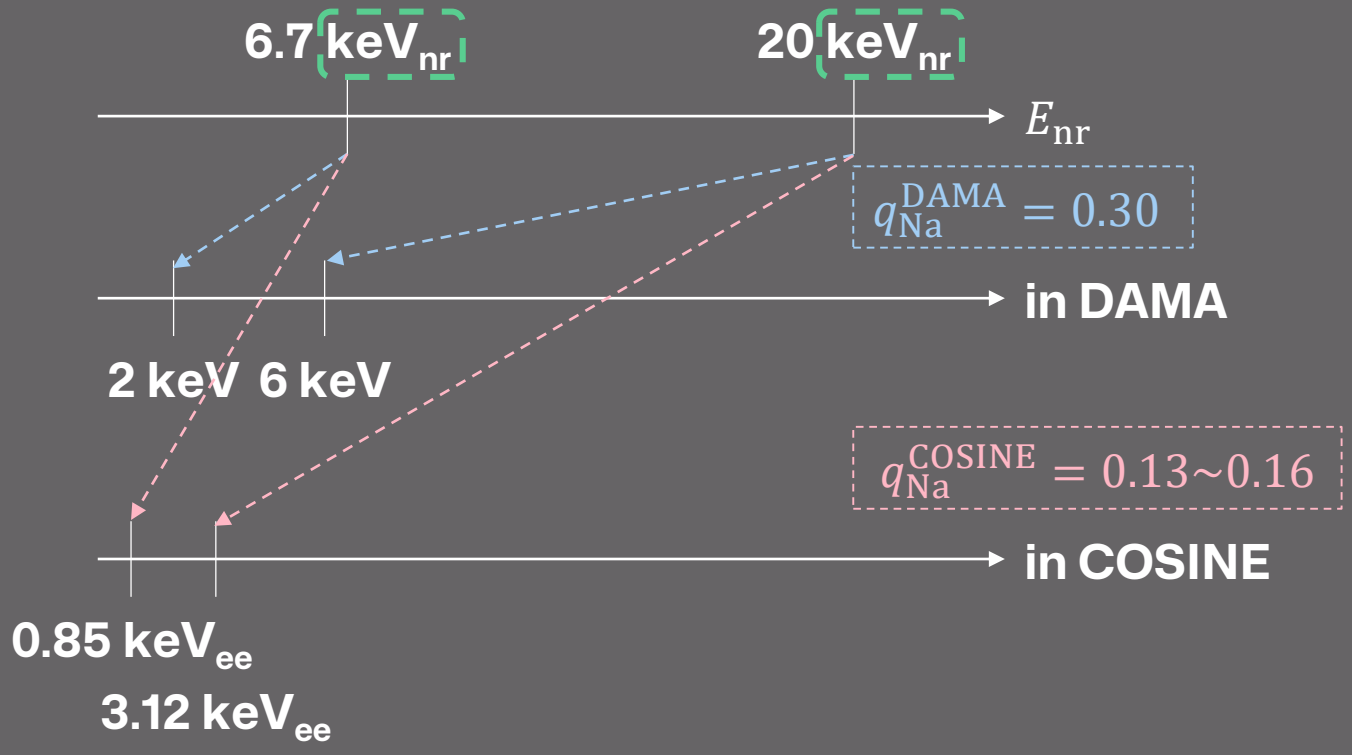
Calibration for Testing DAMA's Claim

Linear Calibration → keV_{ee}

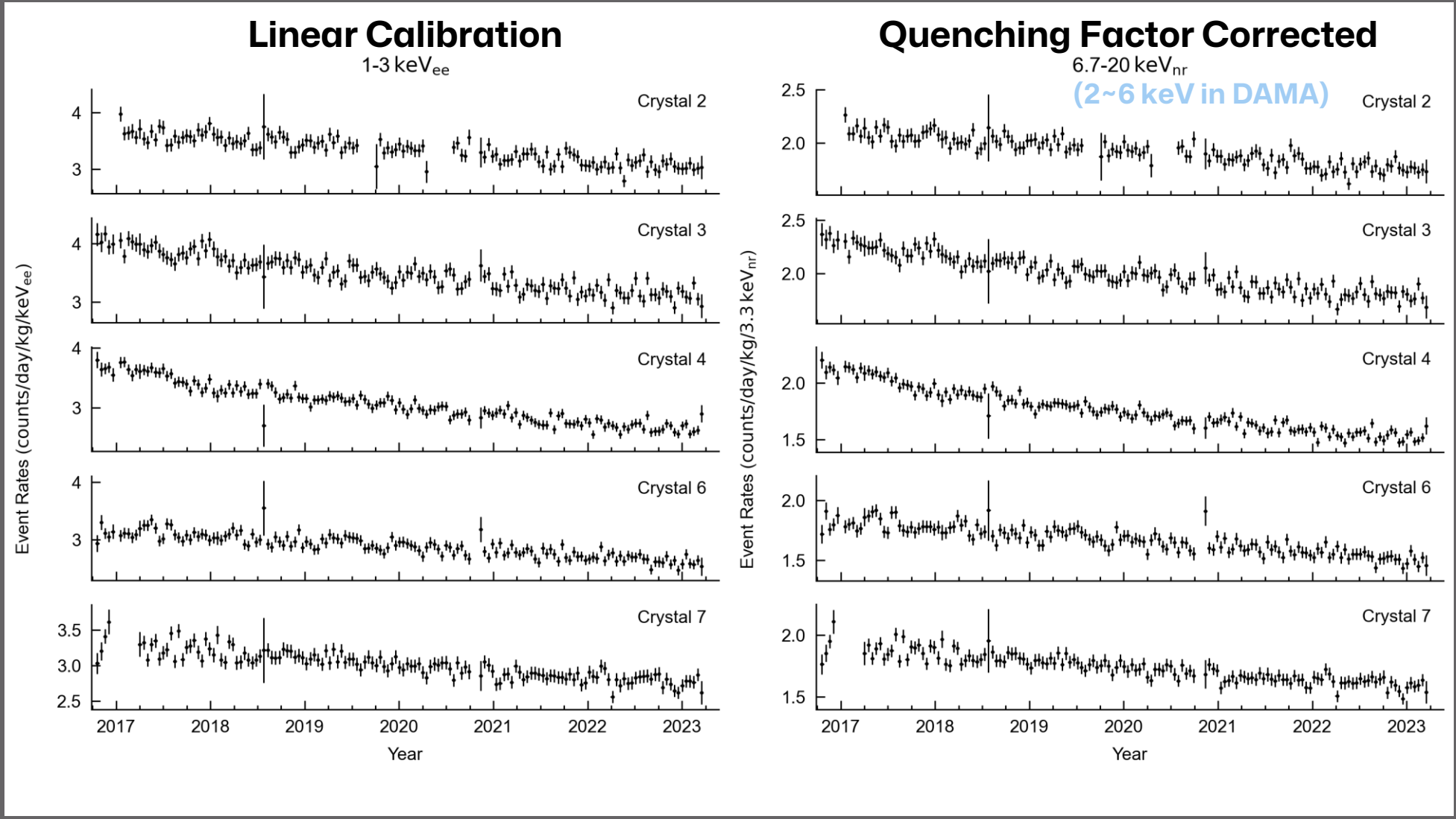
QF Corrected → keV_{nr}





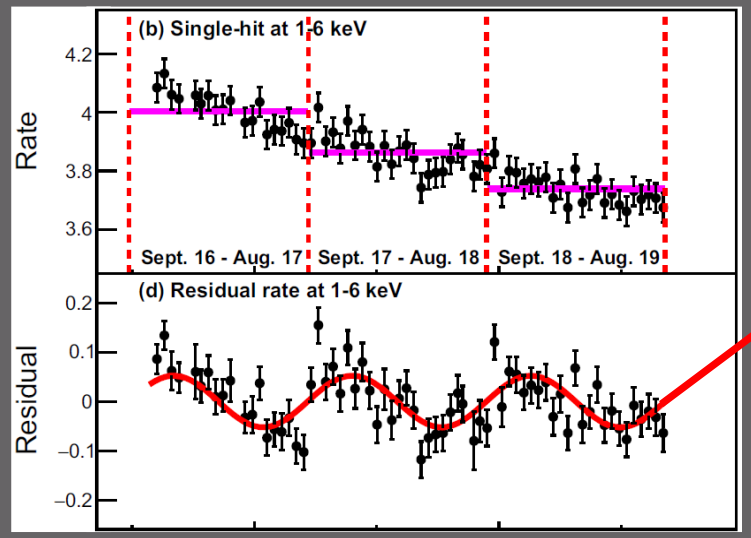


Event Rate


Linear Calibration
1-3 keV$_{ee}$
Quenching Factor Corrected
6.7-20 keV$_{nr}$
(2~6 keV in DAMA)
Crystal 2
Crystal 3
Crystal 4
Crystal 6
Crystal 7
Event Rates (counts/day/kg/keV$_{ee}$)
Event Rates (counts/day/kg/3.3 keV$_{nr}$)
Year
2017
2018
2019
2020
2021
2022
2023

Background Radioactive Isotopes

DAMA-like method



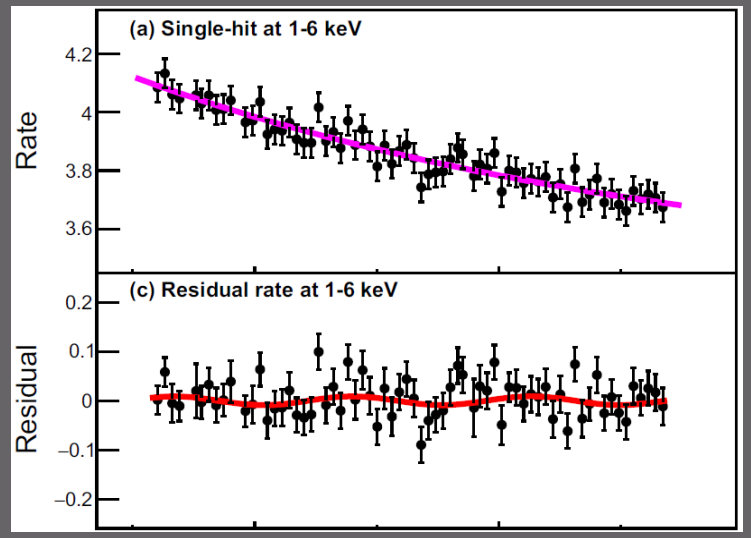
Sci. Rep. **13**, 4676 (2023)

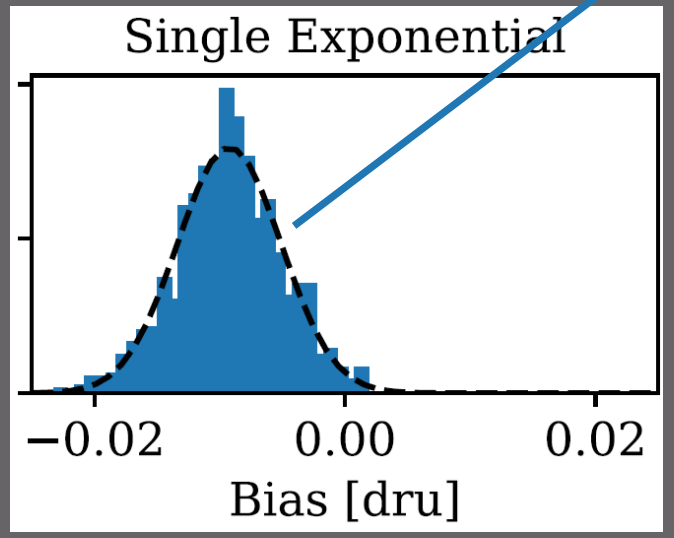
Bias=-0.040 Counts/day/kg/keV

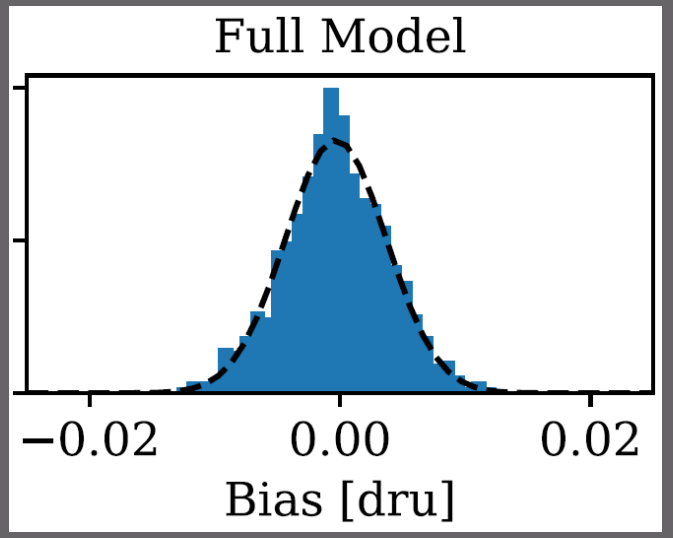
Bias=-0.009 Counts/day/kg/keV

PRD **106**, 052005 (2022)

Single exponential



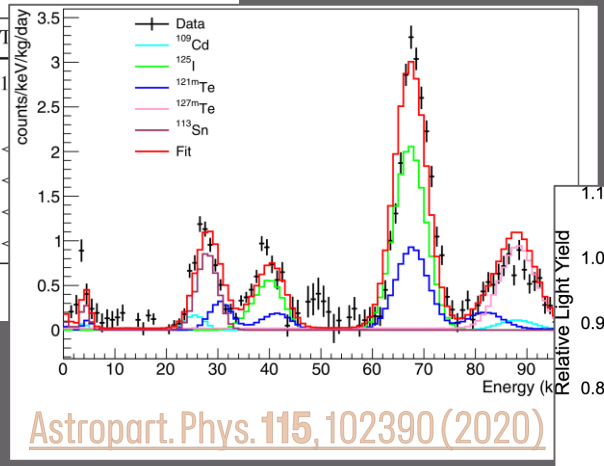




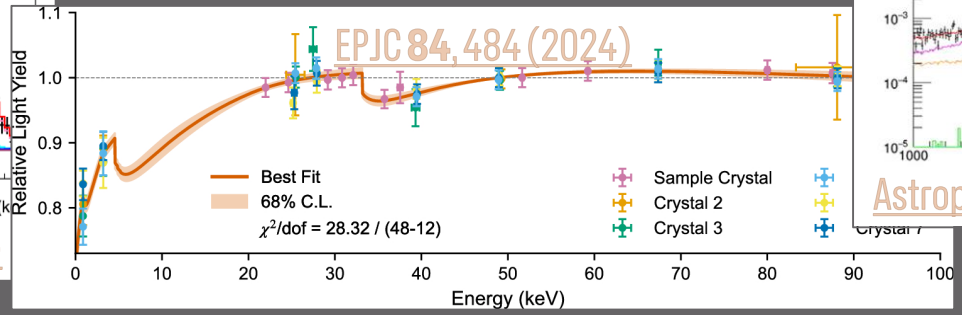
Background Radioactive Isotopes

External source	Radioactivity[a]
	U (^{214}Bi)
PMT [1]	25 ± 5
(R12669SEL[b])	
Quartz window	< 1.8
PTFE reflector	< 0.5
Cable ties	< 4.2
LS	< 2.7

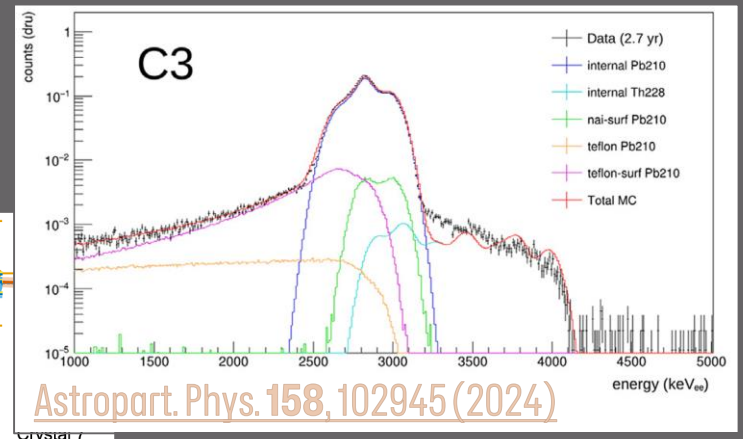
EPJC 78, 490 (2018)



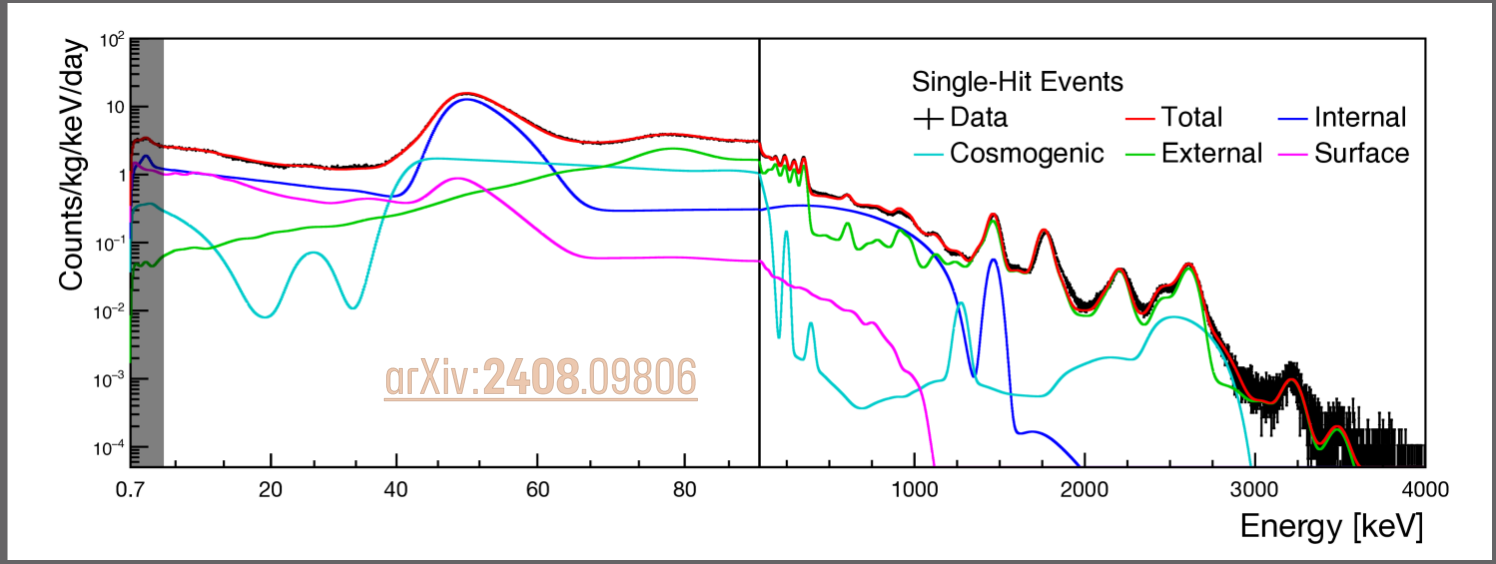
Astropart. Phys. 115, 102390 (2020)



EPJC 84, 484 (2024)



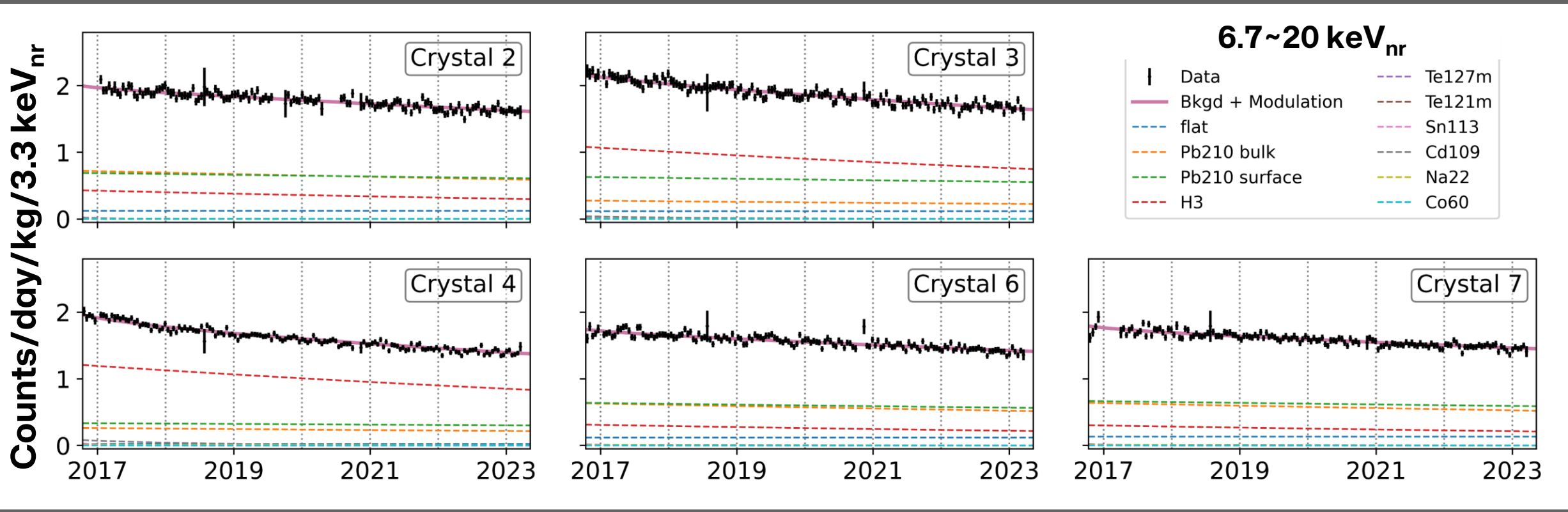
Astropart. Phys. 158, 102945 (2024)



arXiv:2408.09806

Event Rate and Model

$$R_i(t) = A\cos\left(\frac{2\pi(t-\phi)}{T}\right) + \sum_j C_{ij}e^{-\lambda_{ij}t}$$



Event Rate and Model

$$R_i(t) = A\cos\left(\frac{2\pi(t-\phi)}{T}\right) + \sum_j C_{ij}e^{-\lambda_{ij}t}$$

$$\hat{E}_{ik} = R_i(t_k)\Delta t m_i \Delta E \varepsilon_{ik}^{(\text{livetime})}\varepsilon_i^{(\text{selection})}, \qquad n_{ik} \overset{\text{iid}}{\sim} \text{Pois}(\hat{E}_{ik}).$$

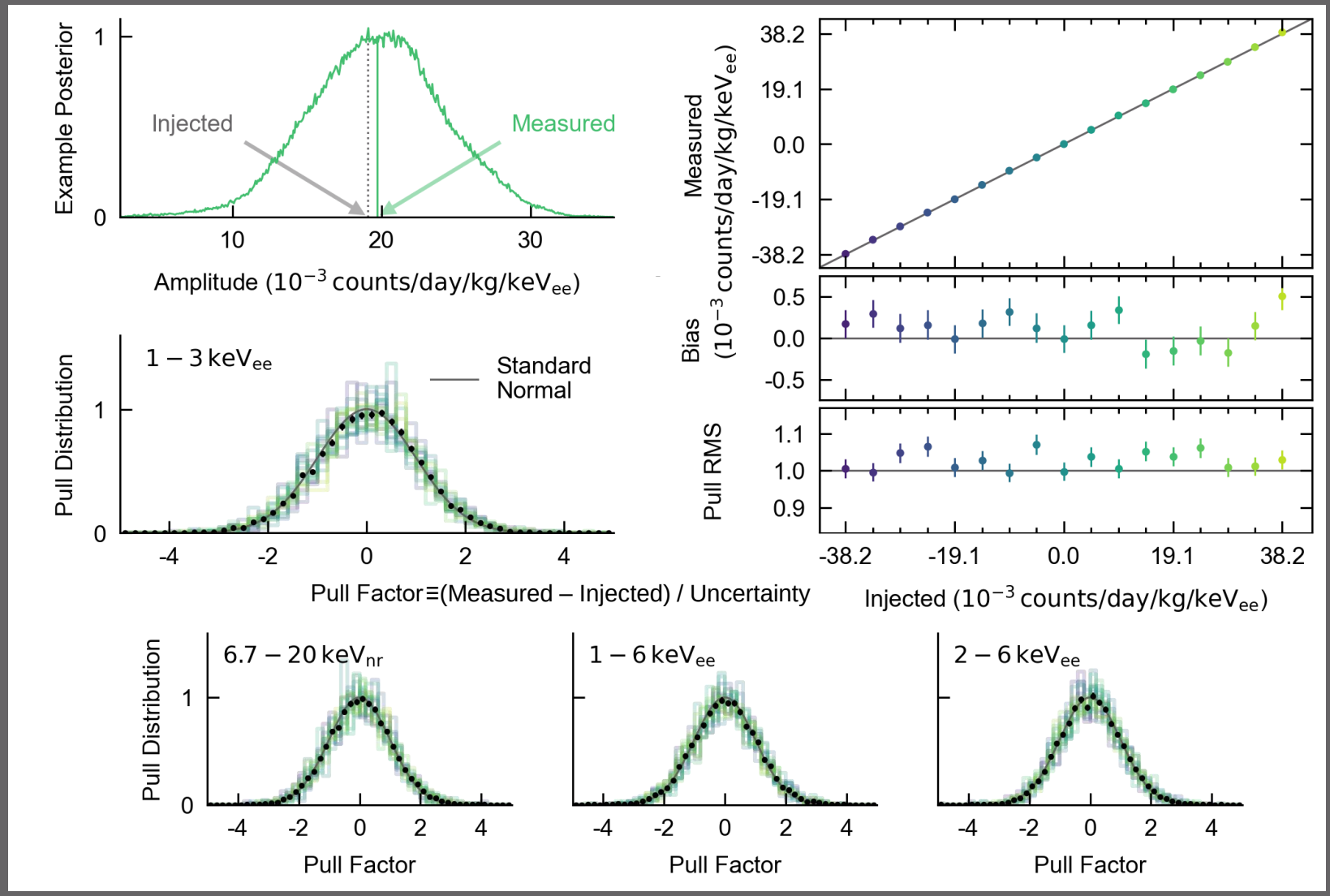
- $C_{ij} \overset{\text{iid}}{\sim} \mathcal{N}(\bar{C}_{ij}, \Delta C_{ij}^2)$ **for decaying components, while** $C_{i(\text{Flat})}$ **was unconstrained.**
  - $C_{i(\text{Flat})}$ **was unconstrained so that it can treat the stationary WIMP wind.**
  - **Bounded to be positive.**
- **The ^{210}Pb surface component's** $\lambda_{ij} \overset{\text{iid}}{\sim} \mathcal{N}(\bar{\lambda}_{ij}, \Delta\lambda_{ij}^2)$**. Others' were set constant.**
  - **Bounded to be positive.**
- **Utilized the Metropolis-Hasting MCMC algorithm.**

Constrained from the background understanding

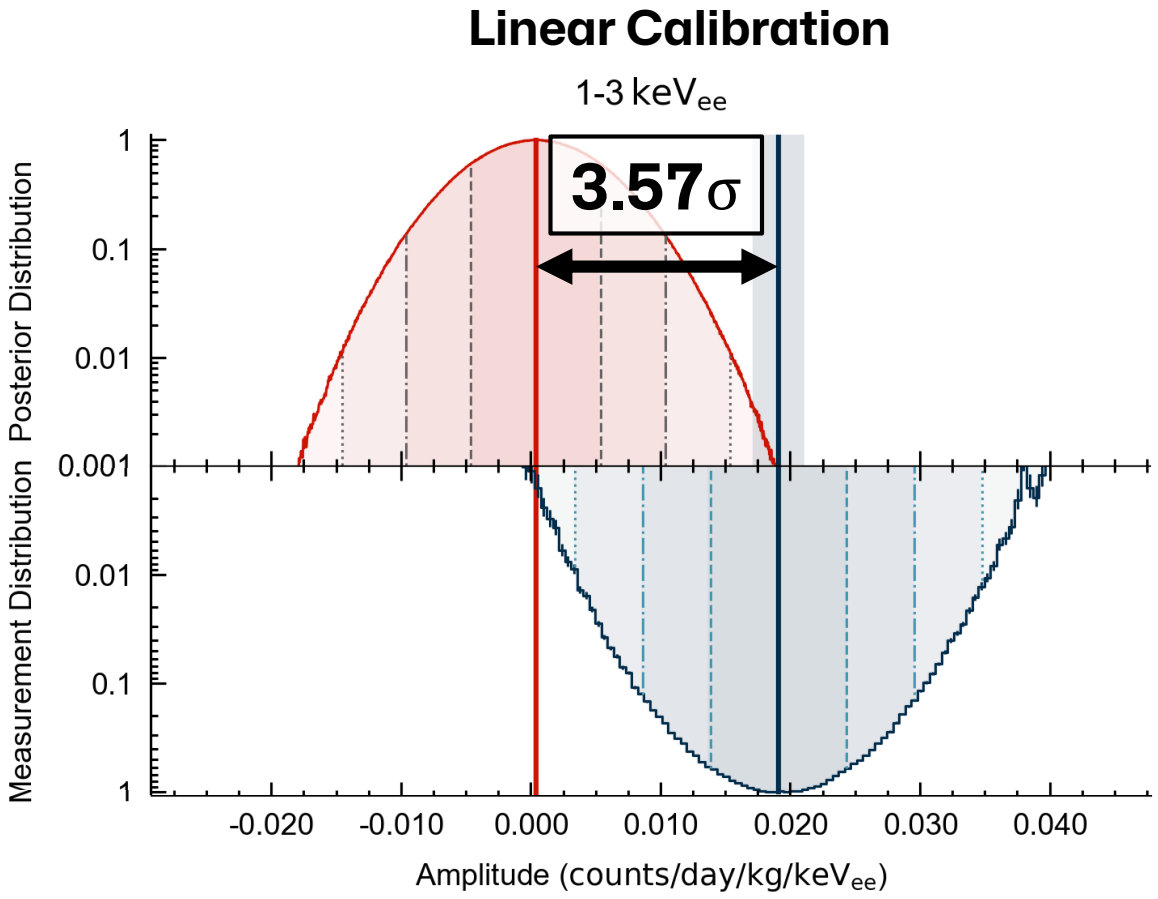
- **[Indices] crystal** i**, radioactive component** j**, time bin** k **(center** t_k**, width** Δt**).**
- $R_i(t)$**: event rate at time** t**. [dru]**
- A**: amplitude of the modulation signal. [dru]**
- ϕ**: phase of the modulation signal. [day]**
- C_{ij}**: initial event rate for the** j**-th radioactive component. [dru]**
- λ_{ij}**: decay constant for the** j**-th radioactive component. [day^{-1}]**

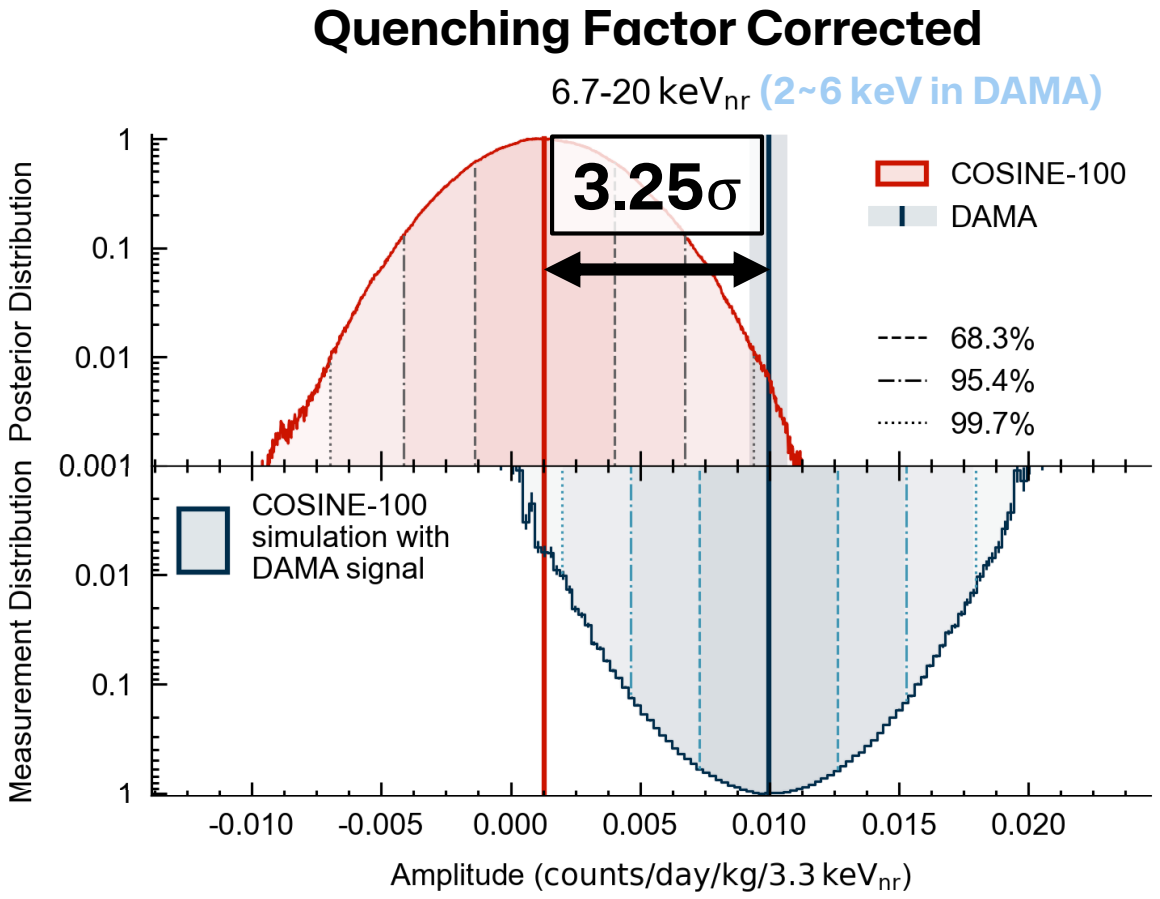
- $\hat{E}_{ik}$**: expected number of events in** k**-th time bin. [counts]**
- $\varepsilon_{ik}^{(\text{livetime})}$**: live time efficiency for that time bin.**
- $\varepsilon_i^{(\text{selection})}$**: event selection efficiency for the crystal.**
- n_{ik}**: measured number of events in the time bin. [counts]**
- T**: period of the modulation signal. (fixed as 365.25 days = 1 year)**
- m_i**: mass of crystal** i**. [kg]**
- ΔE**: width of the energy ROI. [keV]**

Pseudo Experiment Shows No Bias



No Modulation Detected





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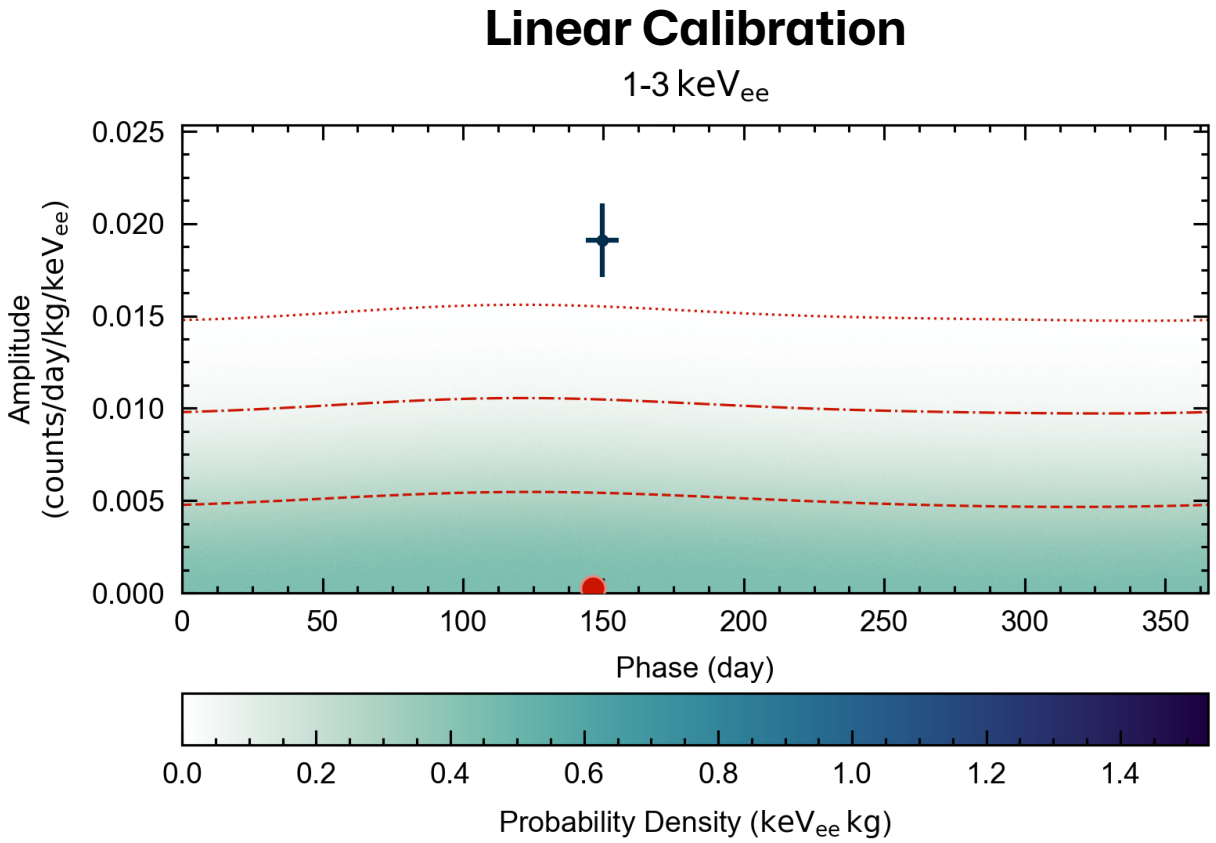

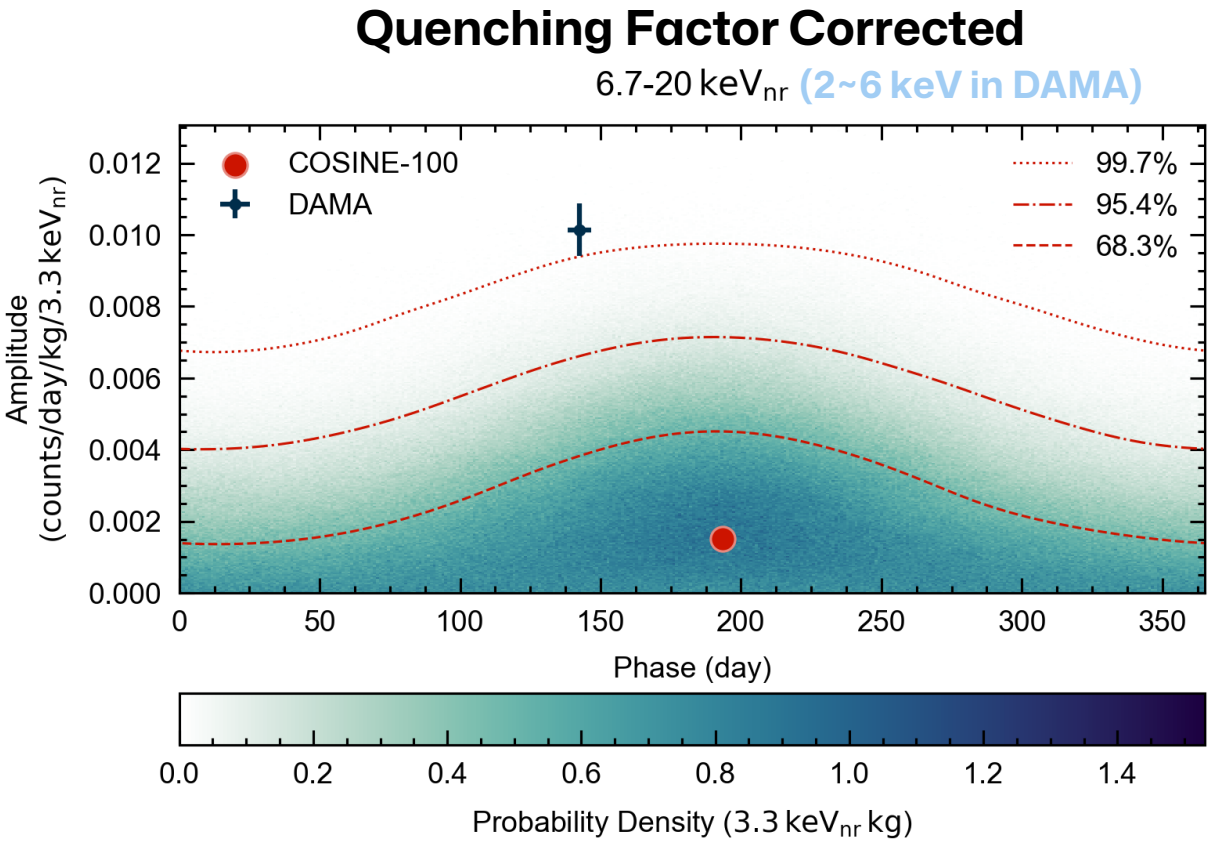

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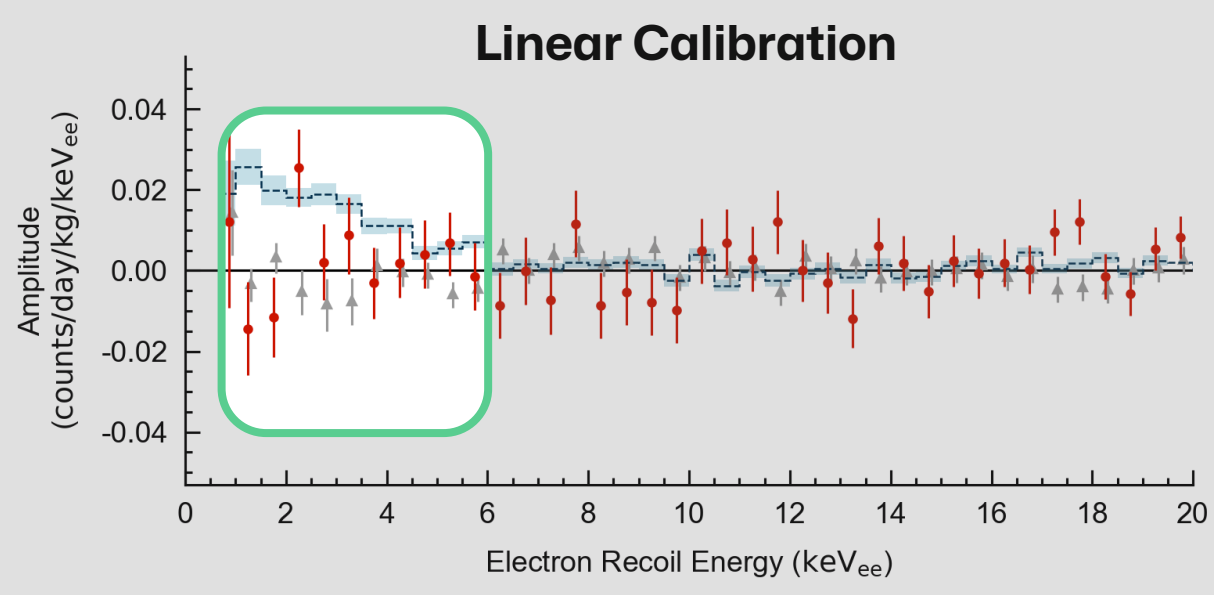
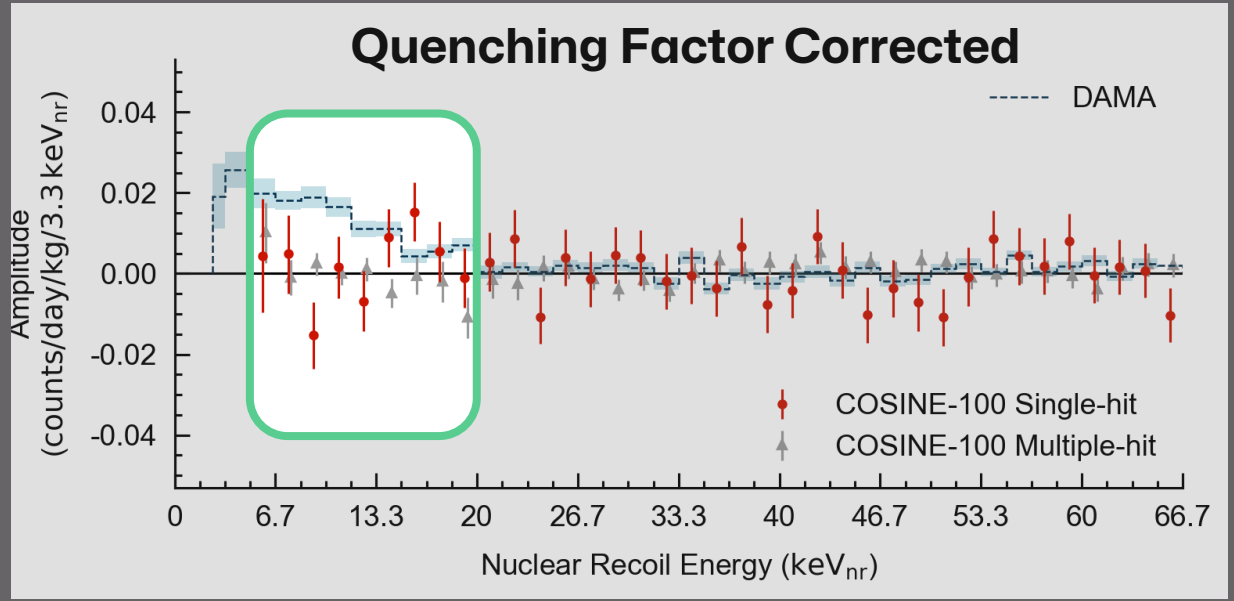
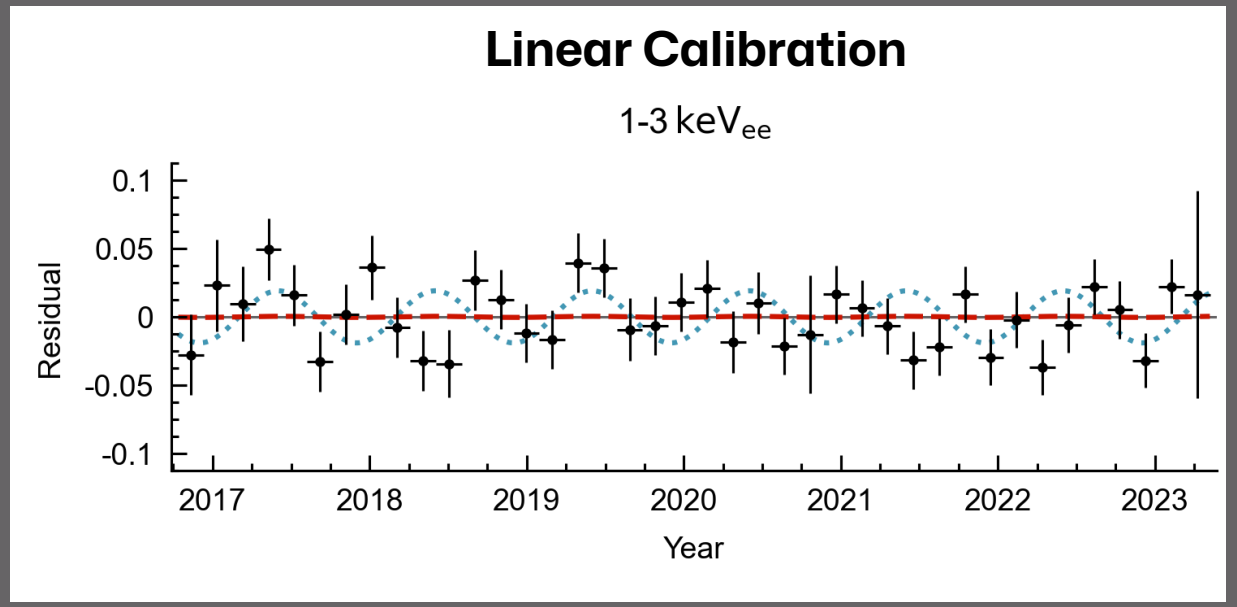


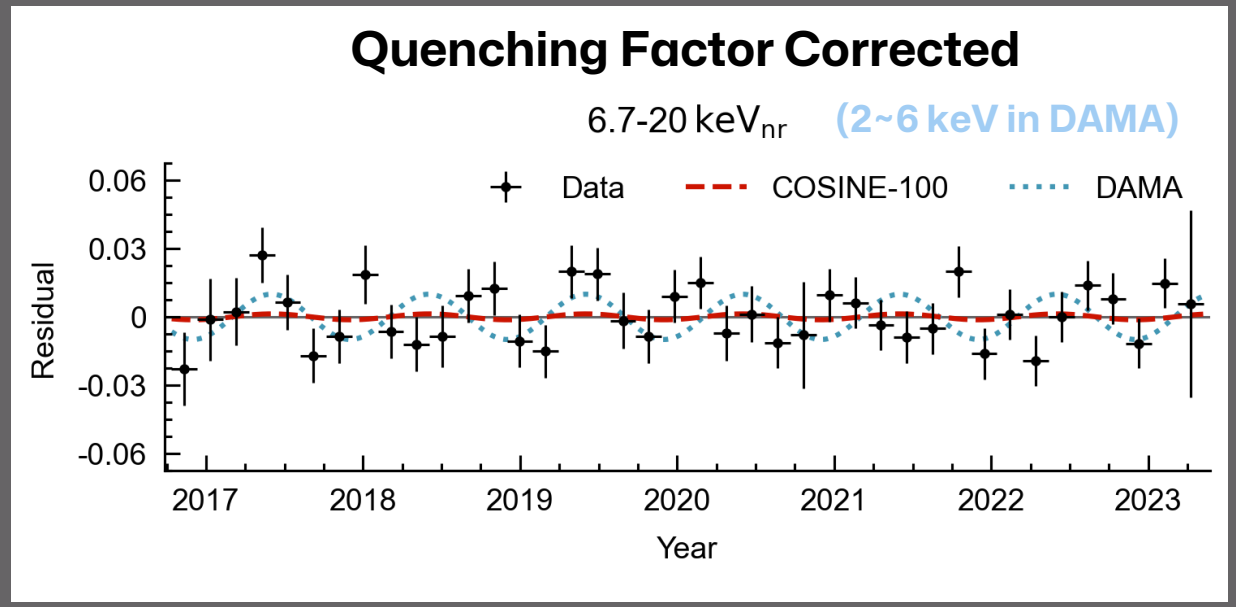


Data	Energy (keV$_{ee}$)	Model	χ^2	NDF	p (%)
Single	0.75-6	**Null**	**12.28**	11	**34.33**
		DAMA	**28.03**	11	**0.32**
	6-20	Null	28.10	28	45.91
Multiple	0.75-20	Null	37.13	39	55.53

Data	Energy (keV$_{nr}$)	Model	χ^2	NDF	p (%)
Single	5-66.7	**Null**	**11.26**	9	**25.86**
		DAMA	**30.67**	9	**0.03**
	20-66.7	Null	20.57	28	84.28
Multiple	5-66.7	Null	29.93	37	78.89

No Modulation Detected



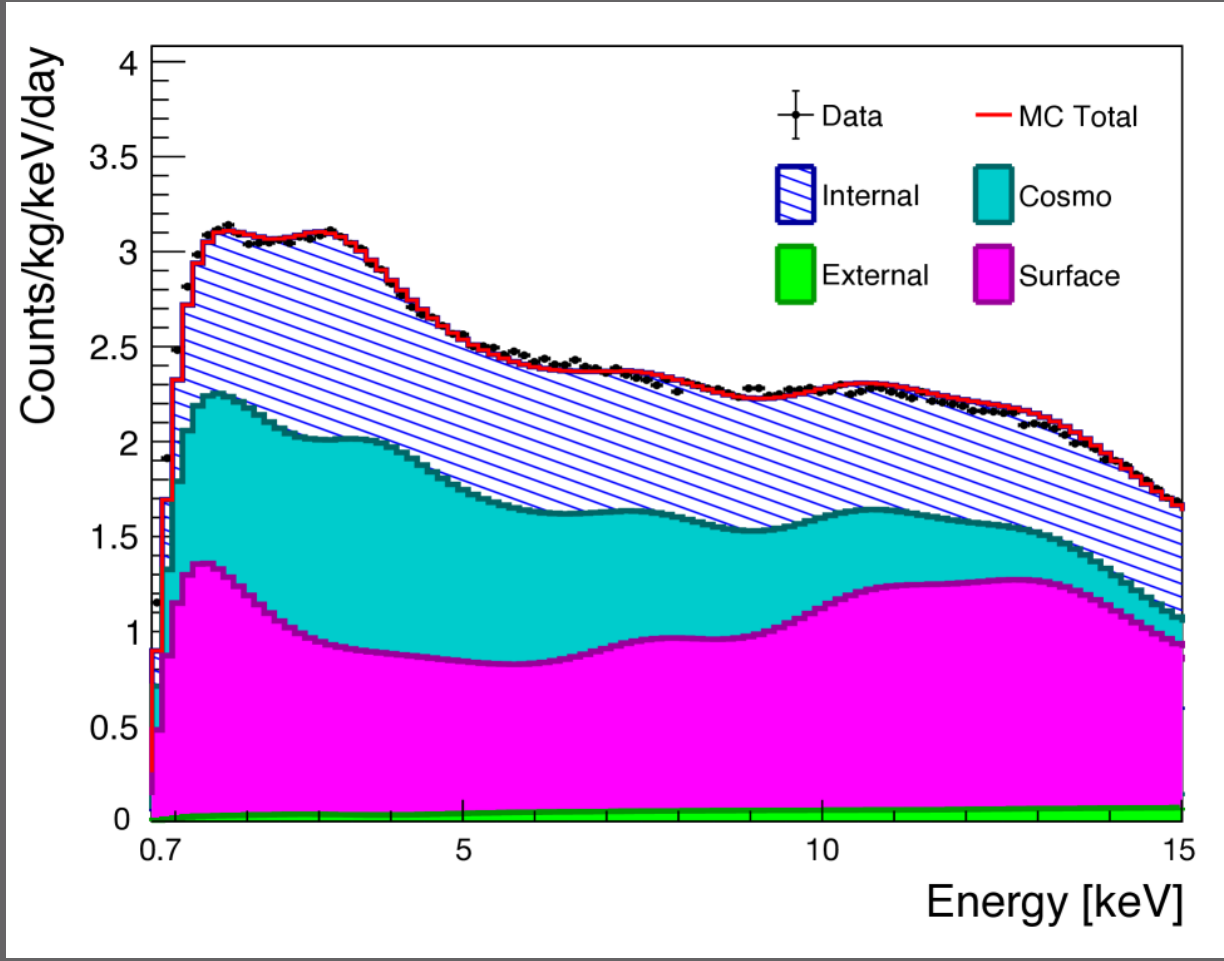


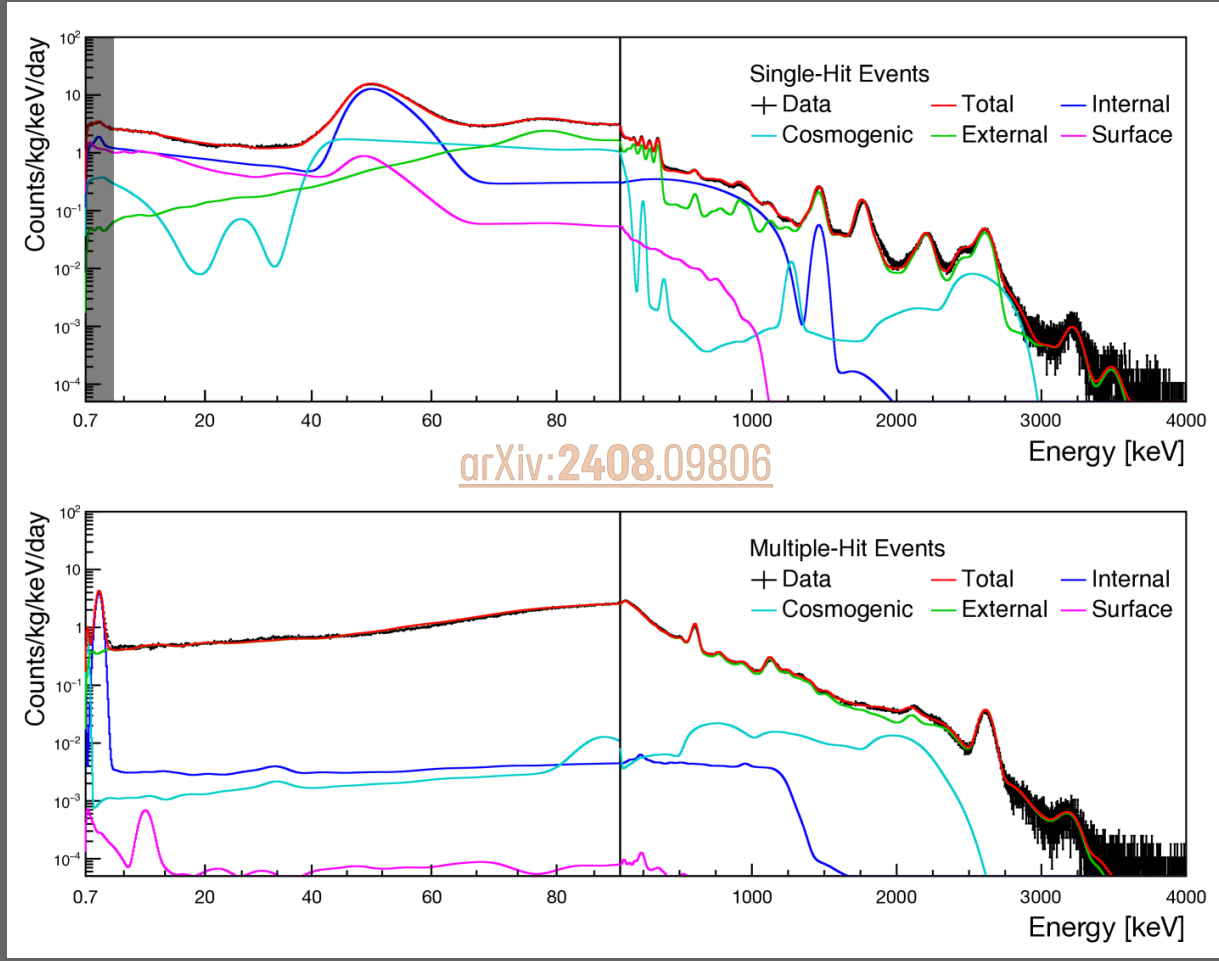
E (keV$_{ee}$)	A (counts/day/kg/keV$_{ee}$)	
	COSINE-100	DAMA/LIBRA
1-3	0.0004±0.0050	0.0191±0.0020
1-6	0.0017±0.0029	0.01048±0.00090
2-6	0.0053±0.0031	0.00996±0.00074

E (keV$_{nr}$)	A (counts/day/kg/3.3 keV$_{nr}$)	
	COSINE-100	DAMA/LIBRA
6.7-20	0.0013±0.0027	0.00996±0.00074

Preprint at arXiv:2409.13226

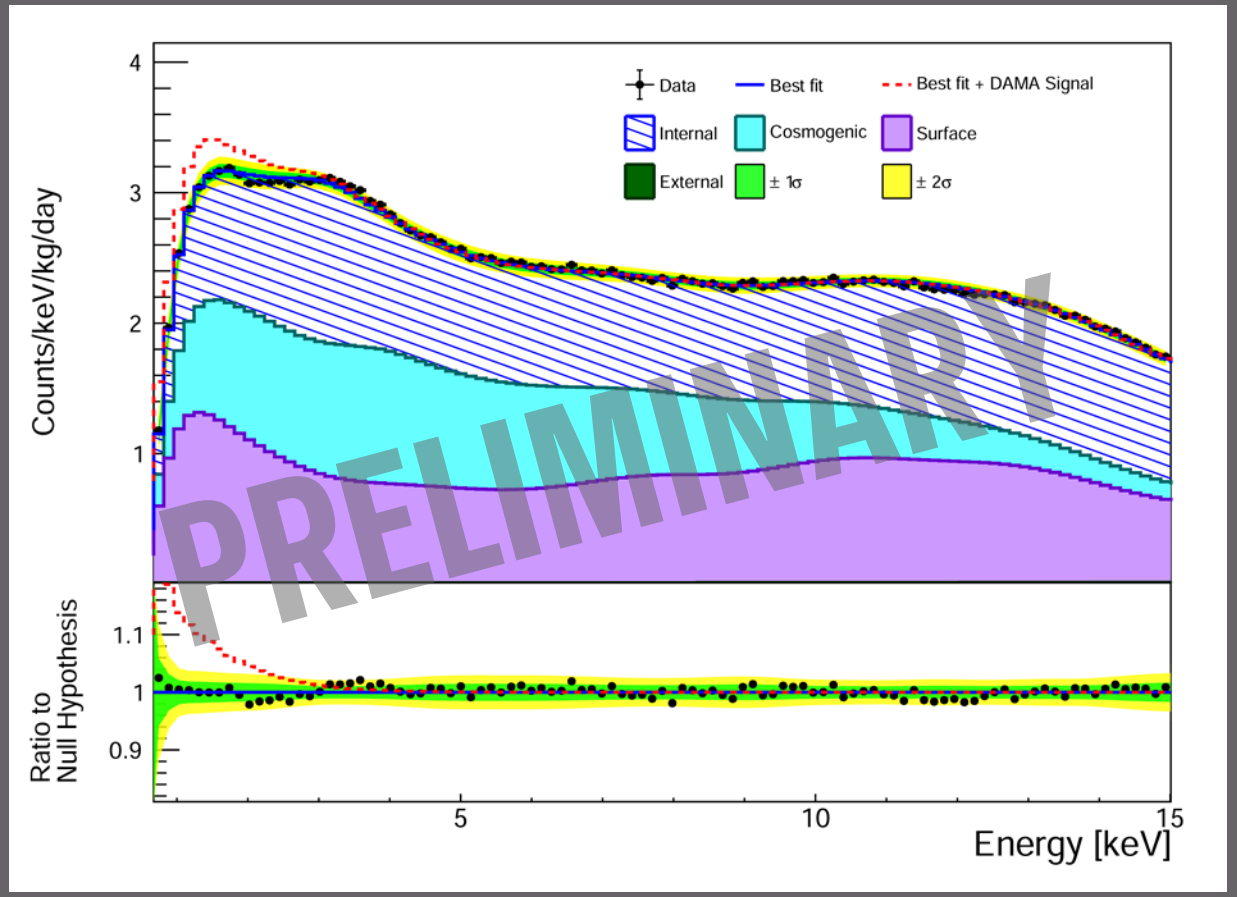
In 3 Years NaI(Tl) Spectrum...

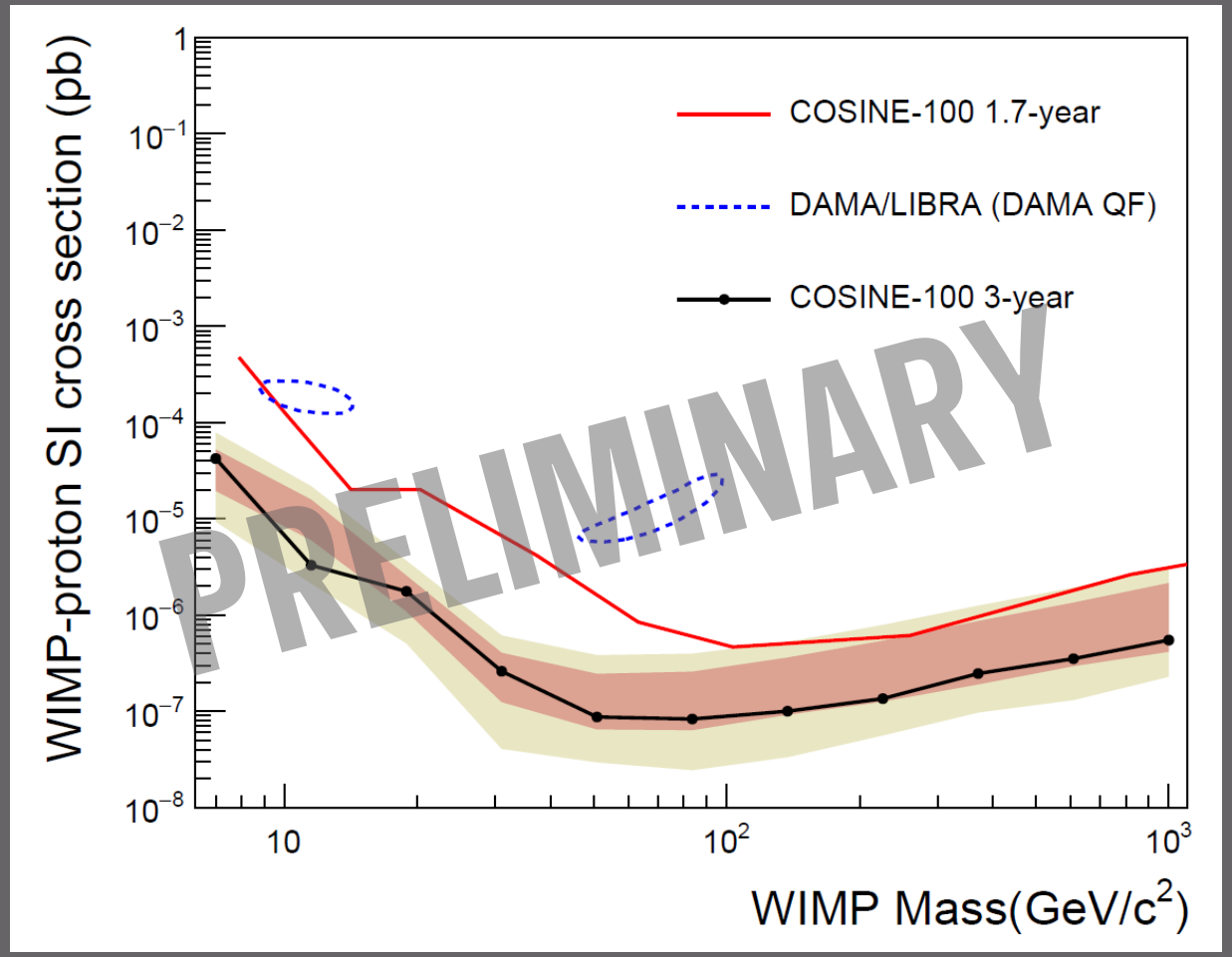




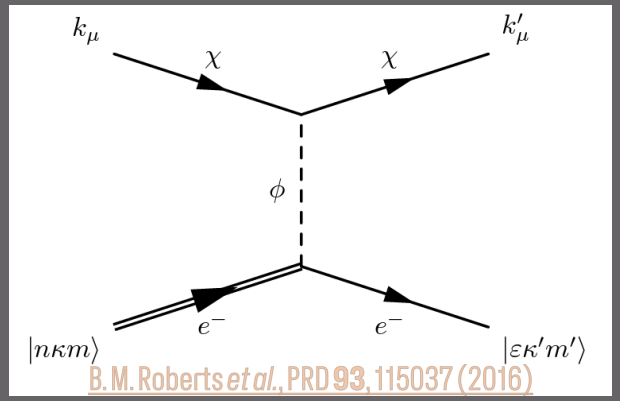
arXiv:2408.09806

In 3 Years NaI(Tl) Spectrum, No WIMP Signal





In 3 Years NaI(Tl) Spectrum, No WIMP-electron Signal



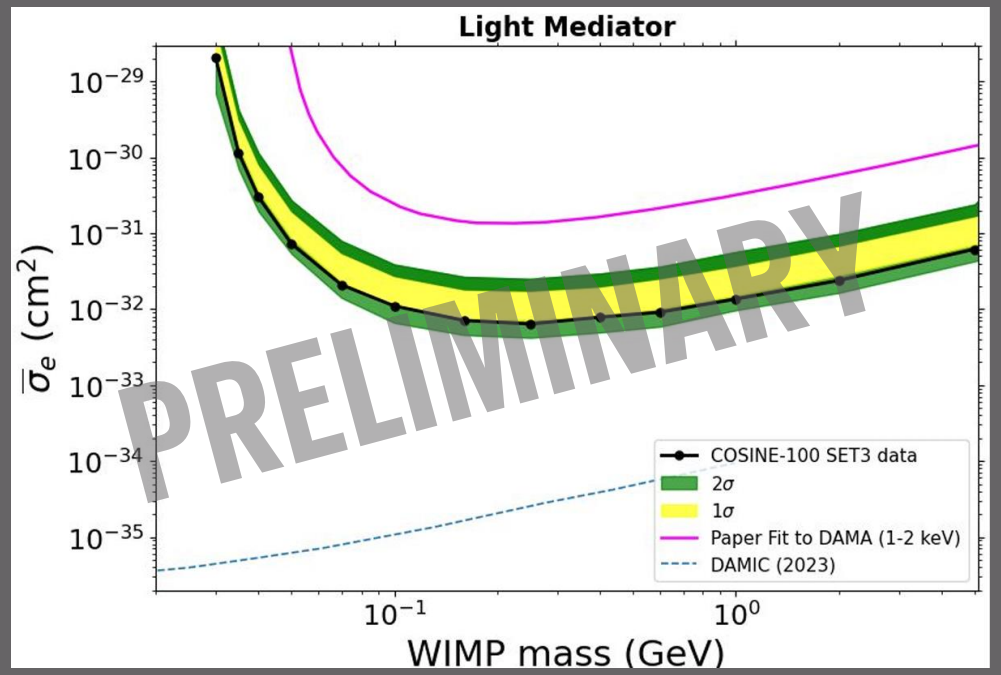
B. M. Roberts *et al.*, PRD 93, 115037 (2016)

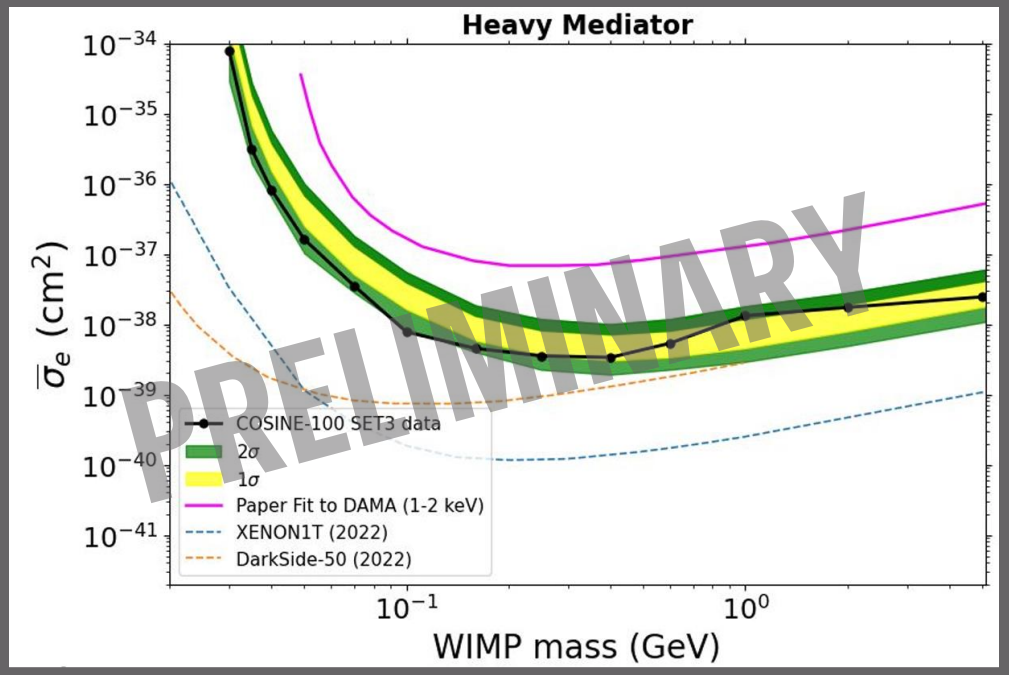
$$\frac{d\langle\sigma^{nl}_{ion}v\rangle}{d\ln E_{\rm er}} = \frac{\overline{\sigma}_e}{8\mu^2_{\chi e}}\int q\left|f^{nl}_{ion}(k',q)\right|^2\left|F_{\rm DM}(q)\right|^2\eta(v_{\rm min})\,dq$$

P. Agnes *et al.* (DarkSide), PRL 130, 101002 (2023)

$$\frac{dR_{ion}}{d\ln E_{\rm er}} = N_T\frac{\rho_{\rm DM}}{m_{\rm DM}}\sum_{nl}\frac{d\langle\sigma^{nl}_{ion}v\rangle}{d\ln E_{\rm er}}$$

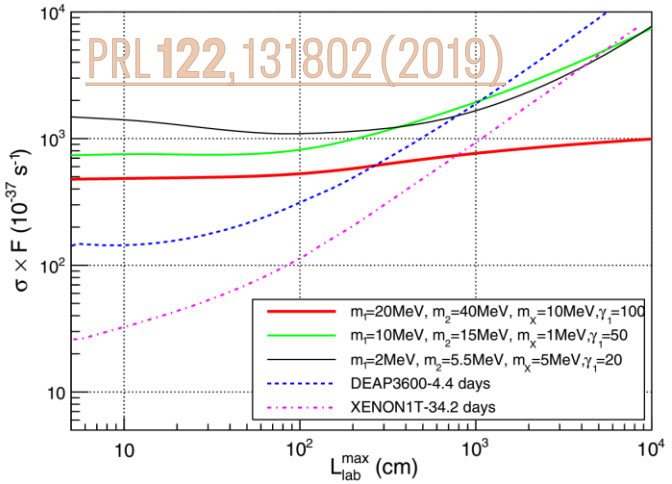
+ nPR, Resolution
Fit with the background model

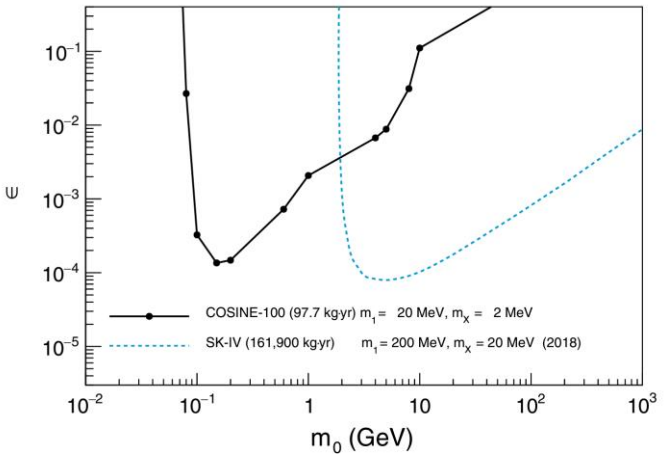


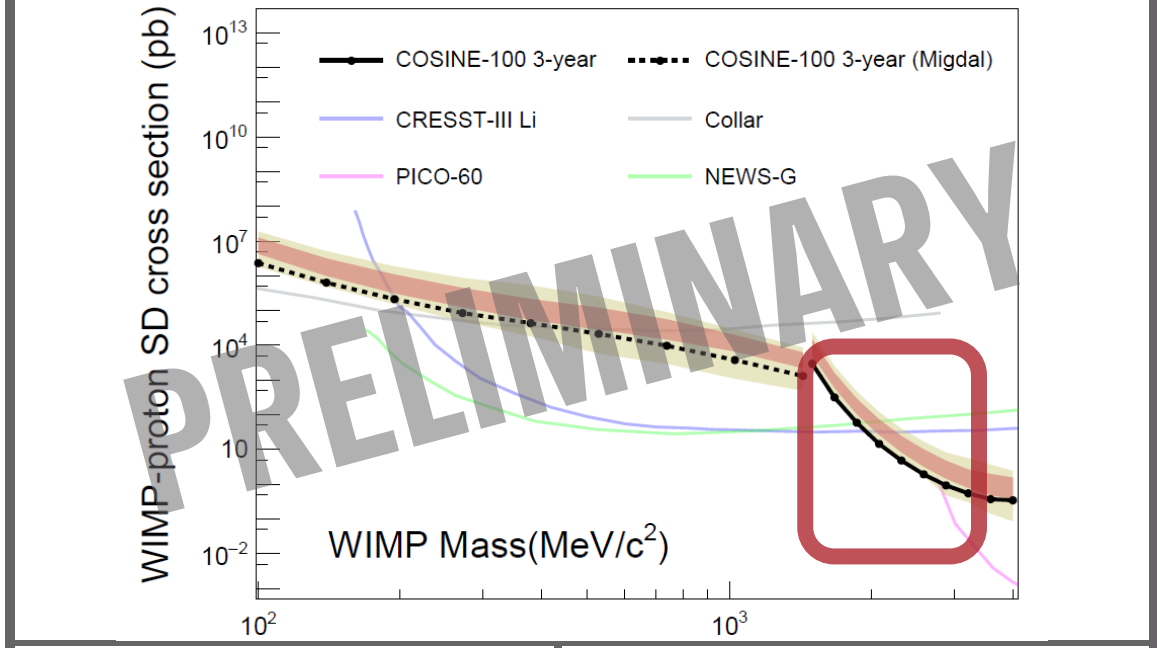


No Dark Matter in NaI(Tl)

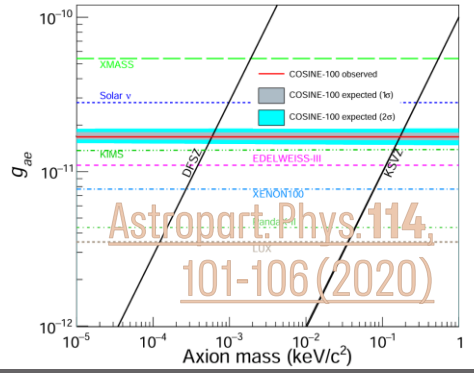
DM Boosted from GC



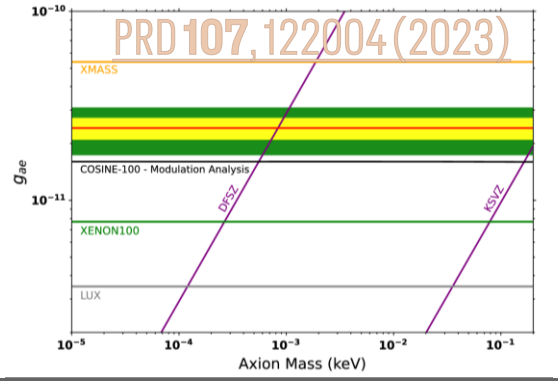




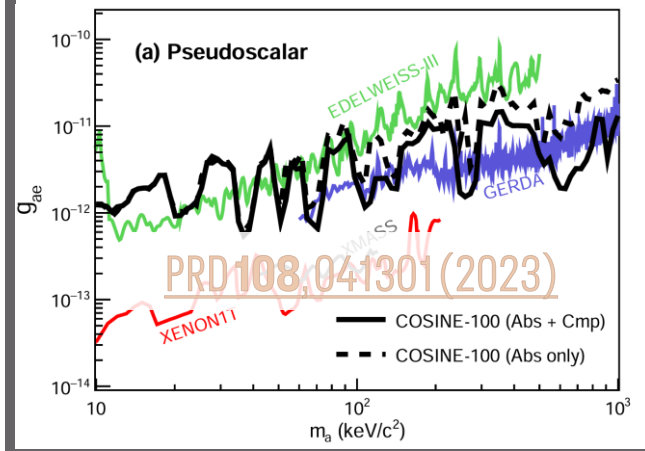
Solar Axion



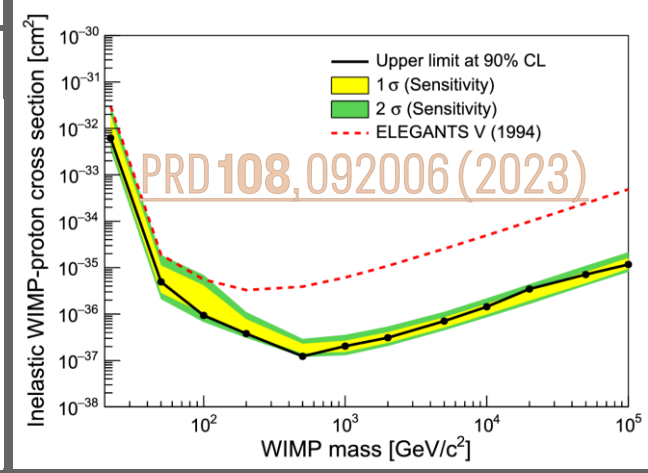
Solar Bosonic Particles



Bosonic Super WIMP



WIMP-Iodine Inelastic Scattering



COSINE-100Upgrade

Lower Threshold

New Deeper Site

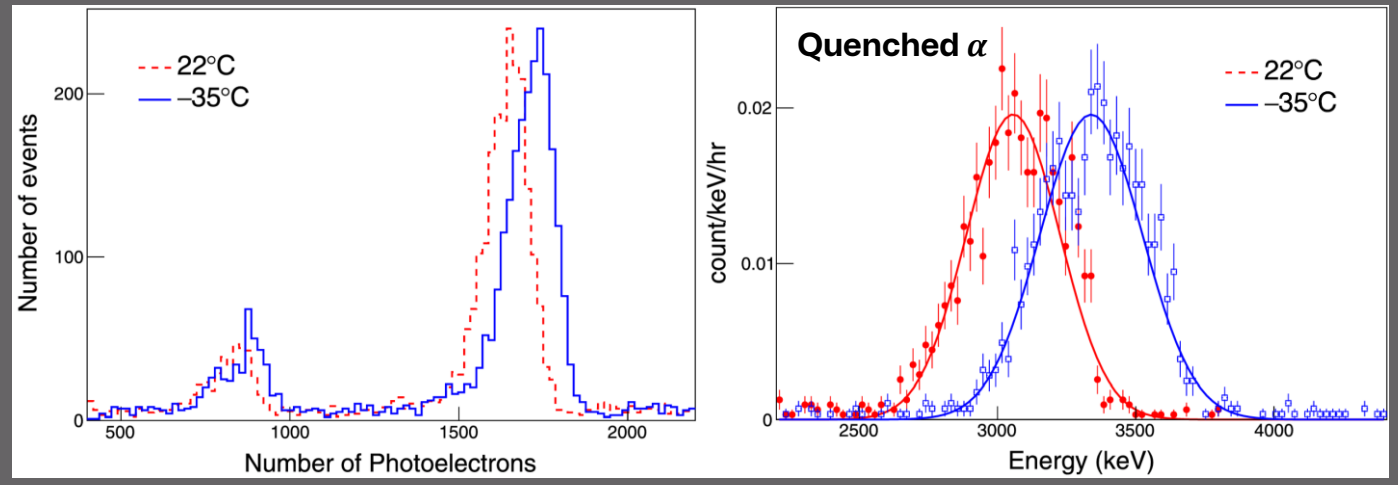
COSINE-100Upgrade

Lower Threshold

New Deeper Site

Operate at -30°C

Astropart. Phys. **141**, 102709 (2022)



Light yield +5%

Quenching factor +9%

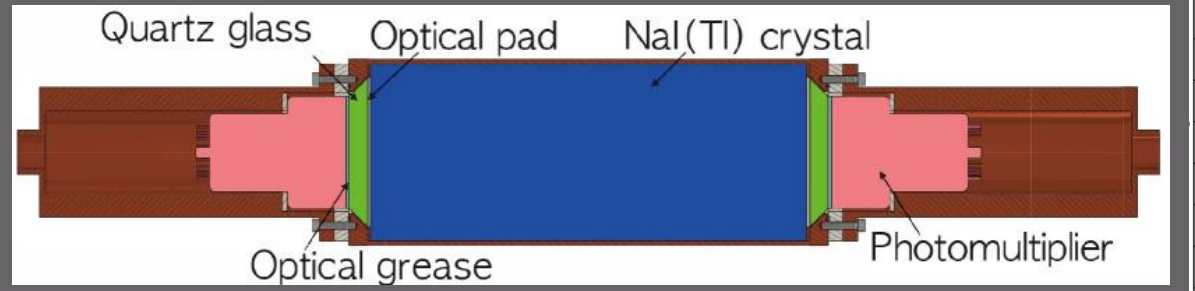
COSINE-100Upgrade

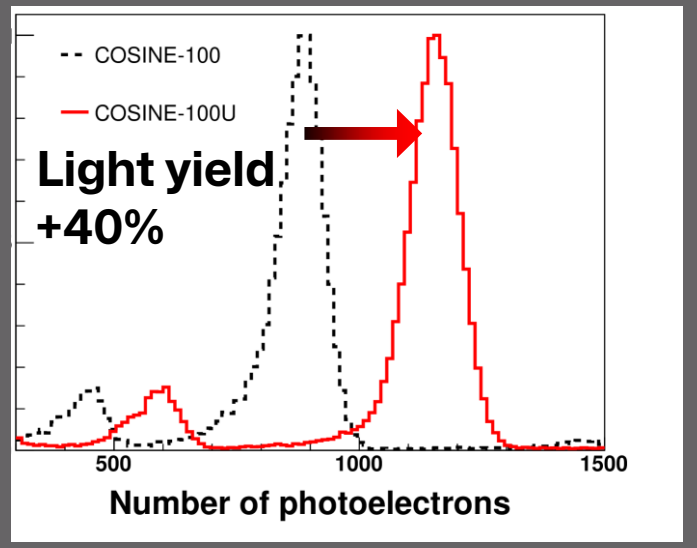
Lower Threshold

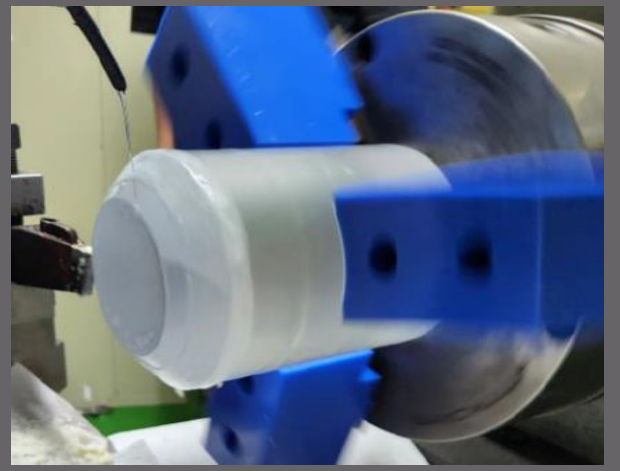
New Deeper Site

Minimize Encapsulation

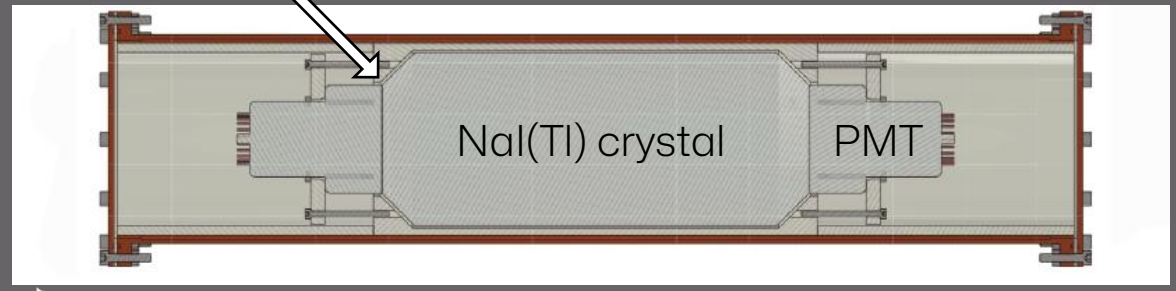
NIM A **981**, 164556 (2020), JINST **19**.P10020 (2024)

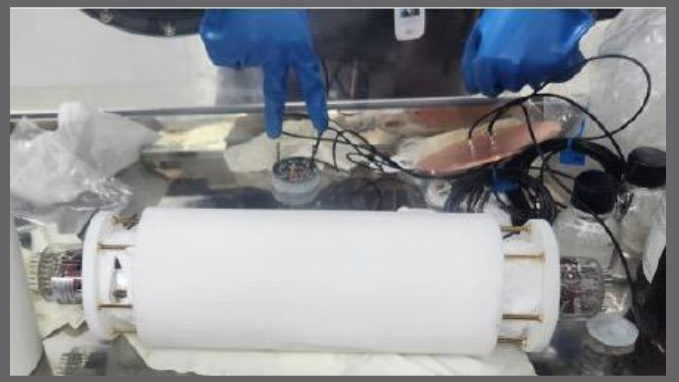






Optical pad ONLY



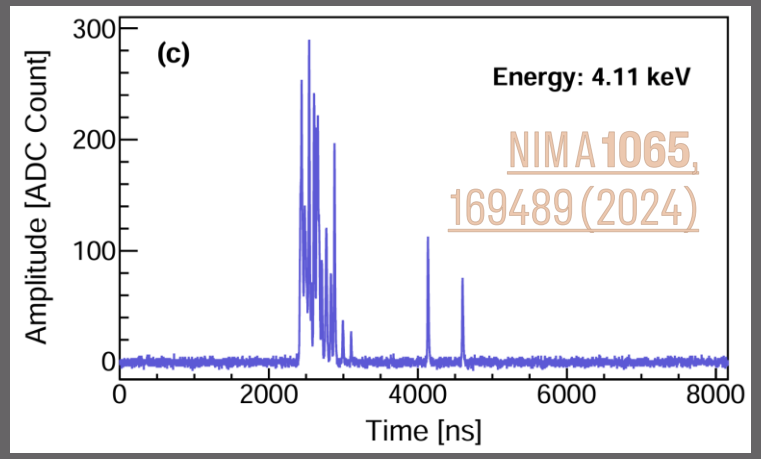


Lower Threshold

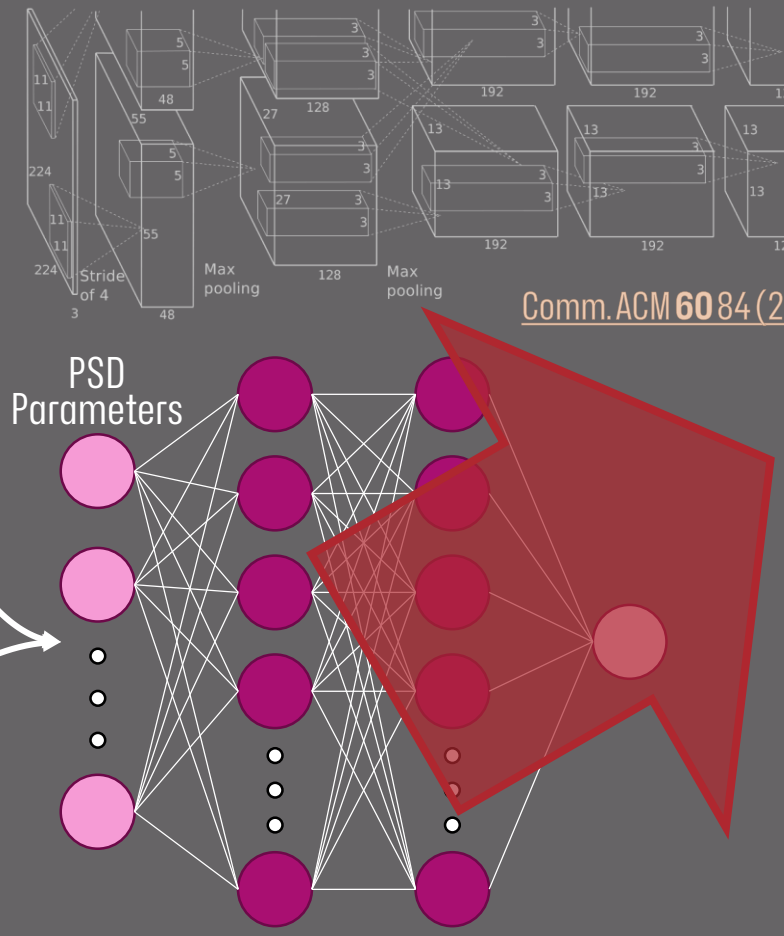
New Deeper Site

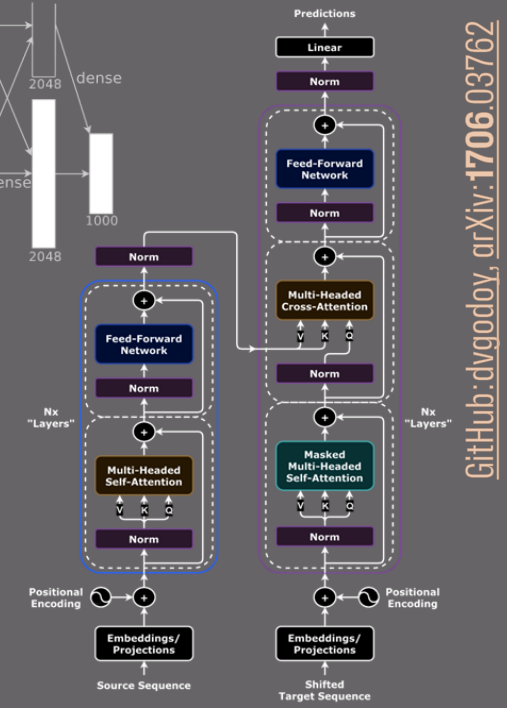
Signal Sample
^{22}Na Calibration Data

Waveform Simulation



Noise Sample
15% of 3-year Data





GitHub:dvgodoy, arXiv:1706.03762

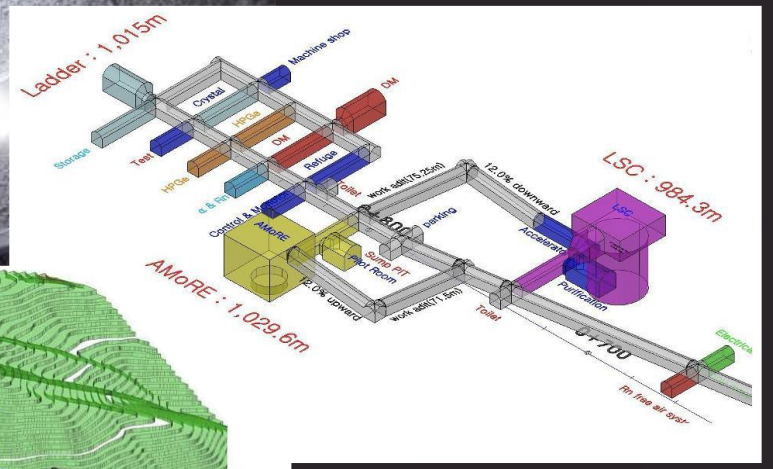
5 Photoelectrons Target Threshold

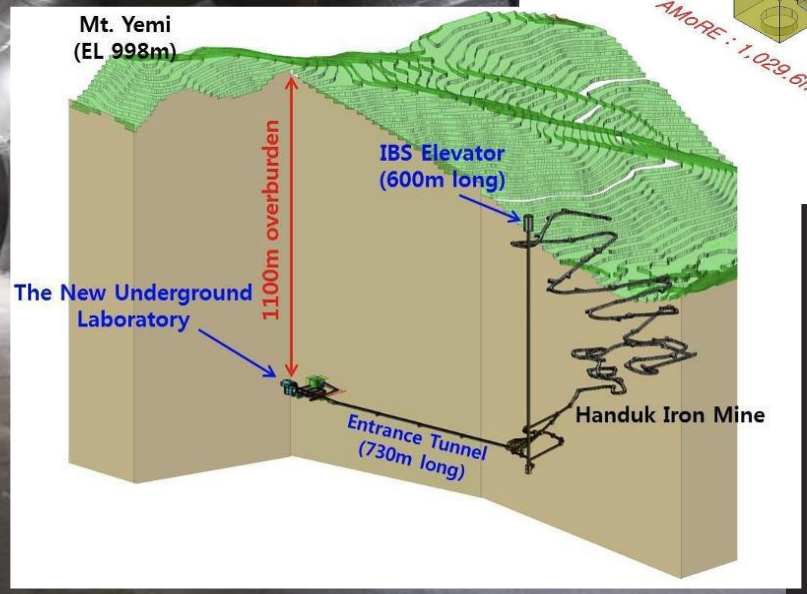
COSINE-100Upgrade

Lower Threshold

New Deeper Site; Yemilab

Front. Phys. **12**, 1323991 (2024)



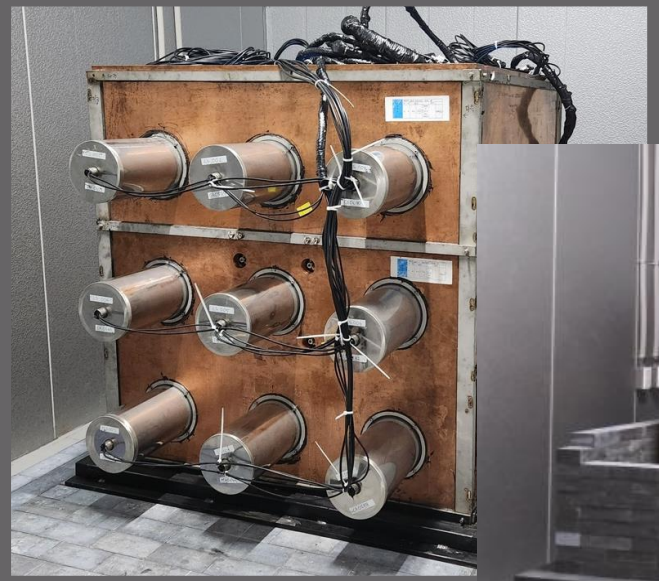


Nature News

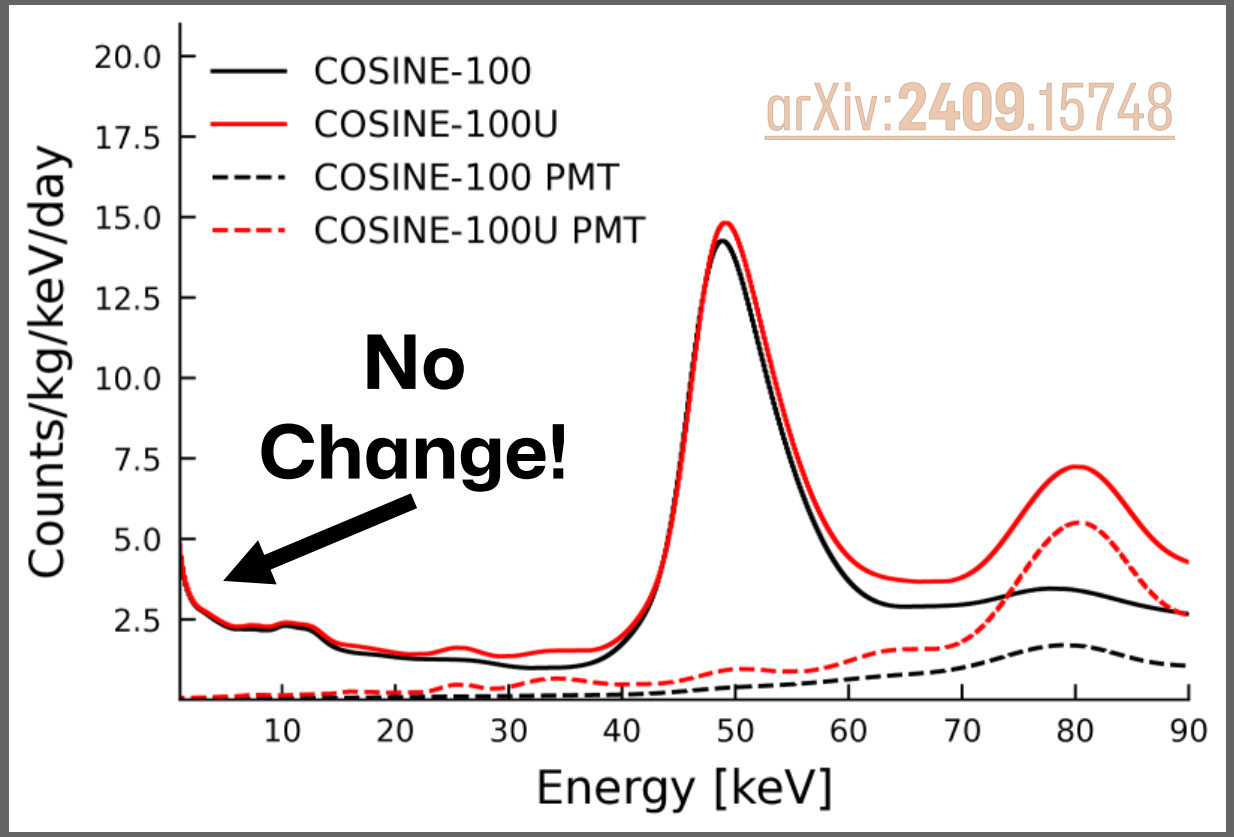
COSINE-100Upgrade

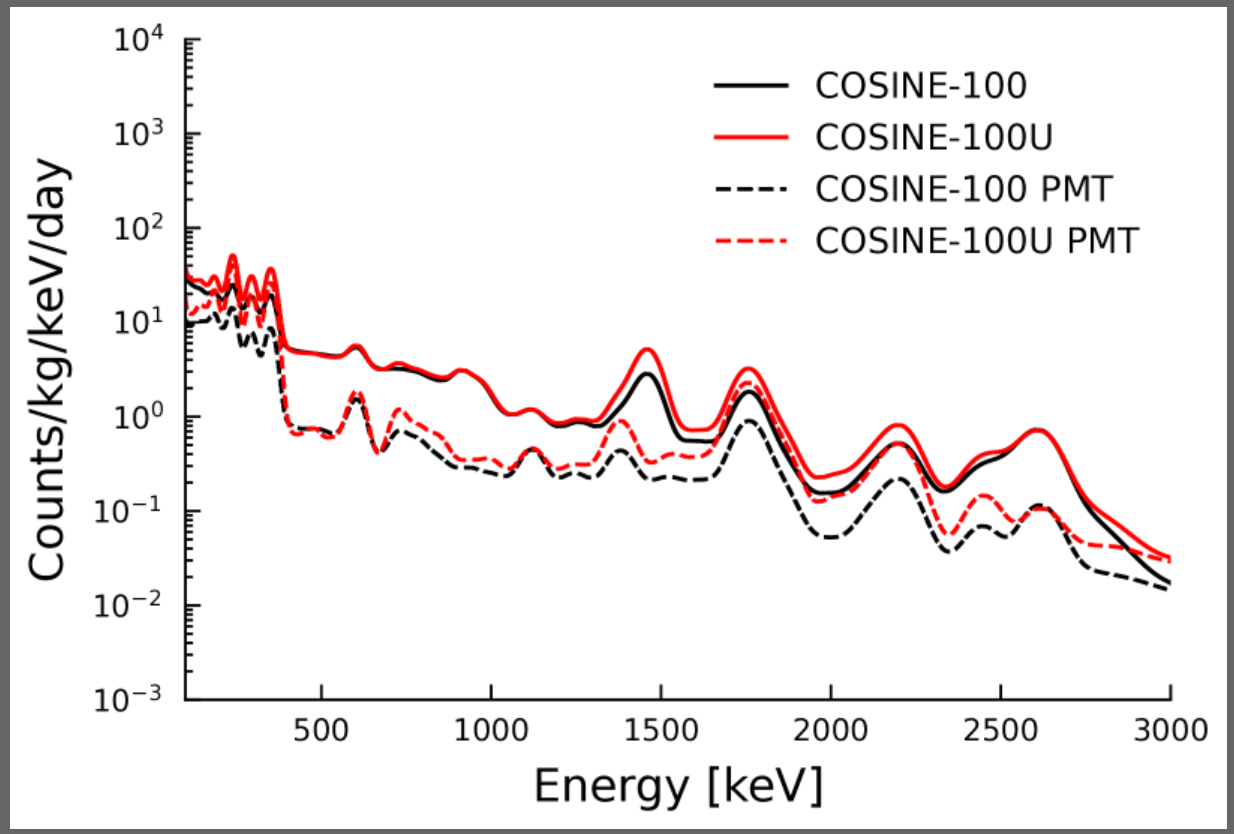
Lower Threshold

New Deeper Site; Yemilab

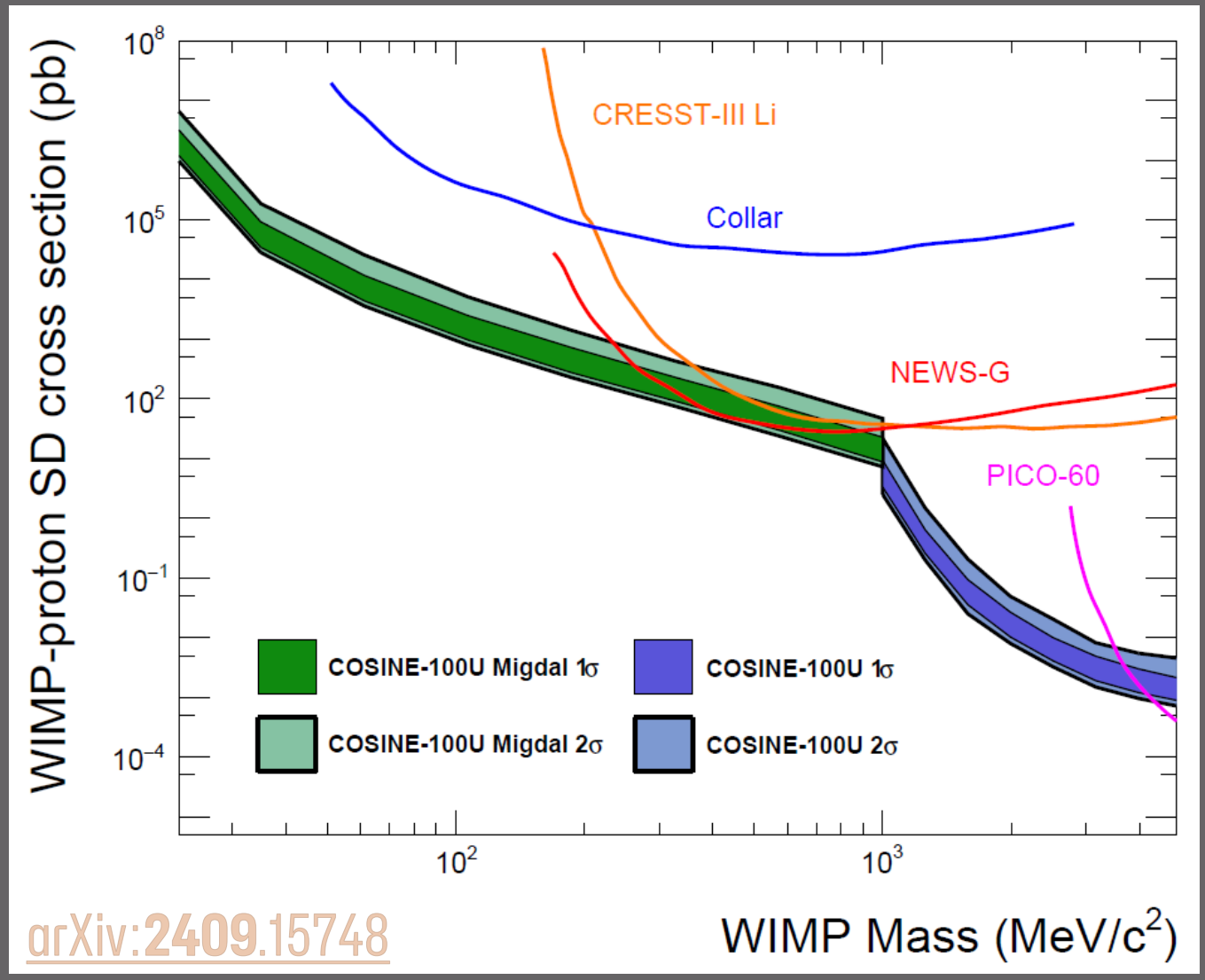


COSINE-100Upgrade Expected Background





COSINE-100U*pgrade* Prospects



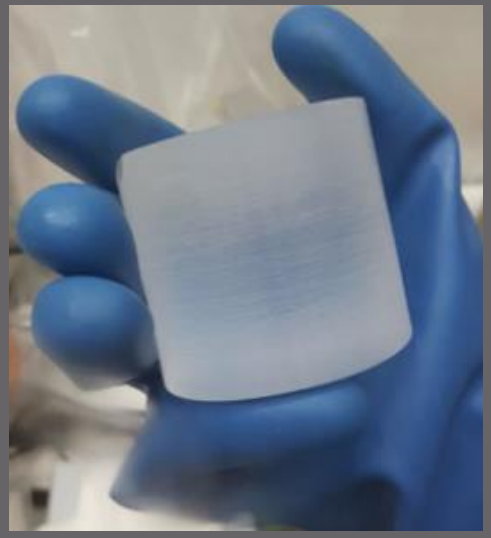
arXiv:2409.15748

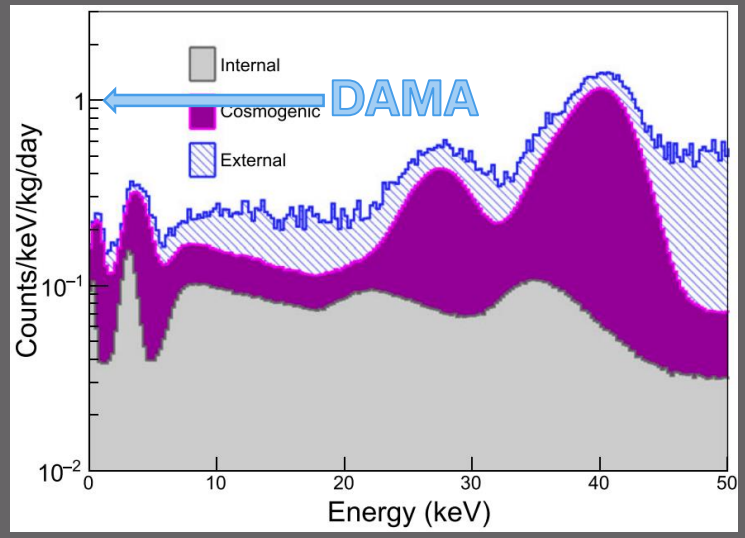
Ultra-pure NaI(Tl) Development for COSINE-200

- 400 kg of ultra-pure NaI powder is ready.
  - J. Rad. Nucl. Chem. **317**, 1329 (2018), JINST **15**, C07031 (2020)
  - EPJC **80**, 814 (2020), Front. Phys. **11**, 1142849 (2023)

(ppb)	K	Pb	U	Th
Initial	248	19.0	<0.01	<0.01
Purified	<16	0.4	<0.01	<0.01

- We grew 0.7 kg of crystal with 0.2 counts/day/kg/keV.
- Further R&D to grow large crystals within the safety regulation is ongoing.





DM-ICE + KIMS Korea Invisible Mass Search Experiment = COSINE