Annual modulation search by XMASS-I with 2.7 years of data

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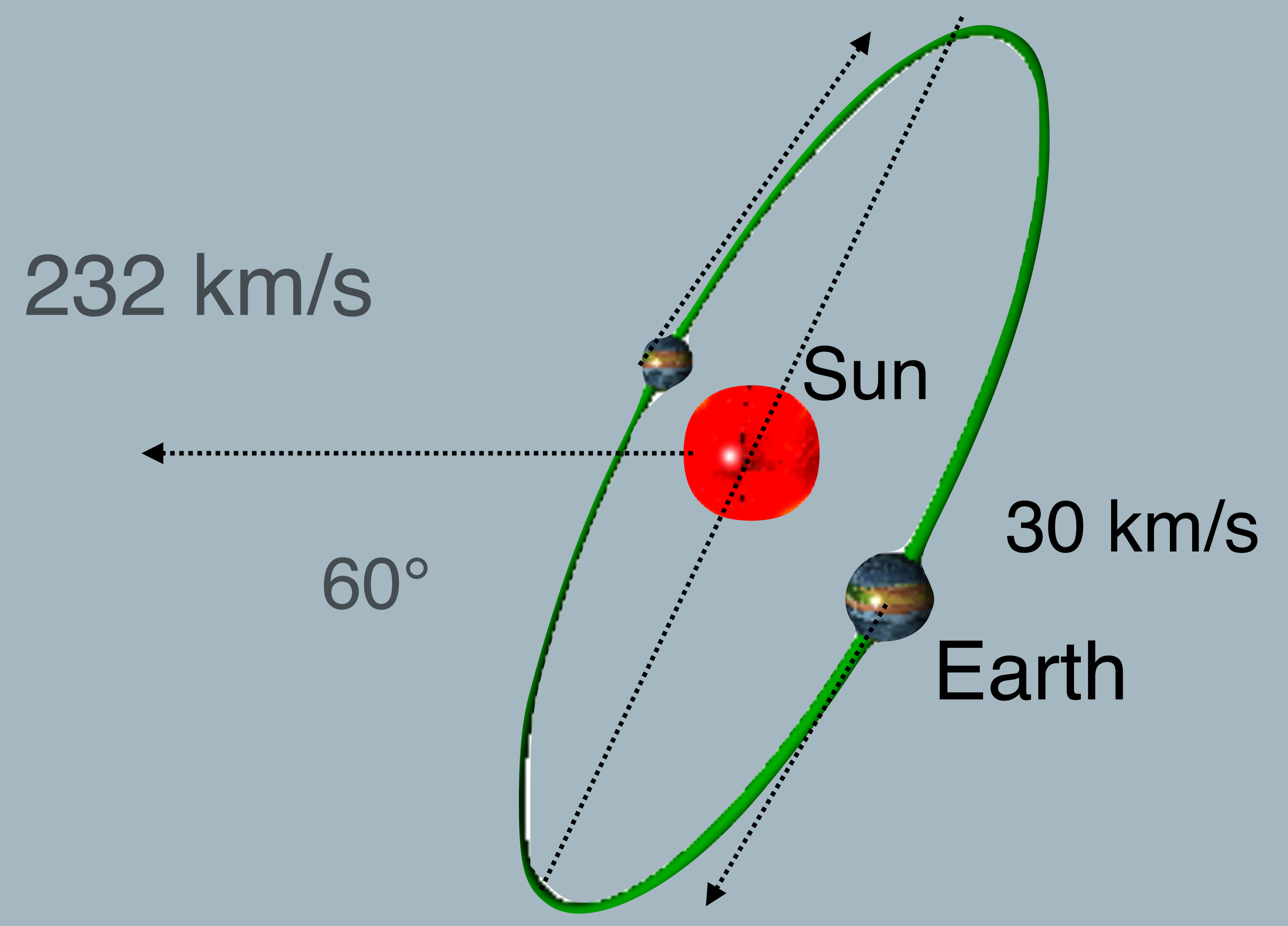
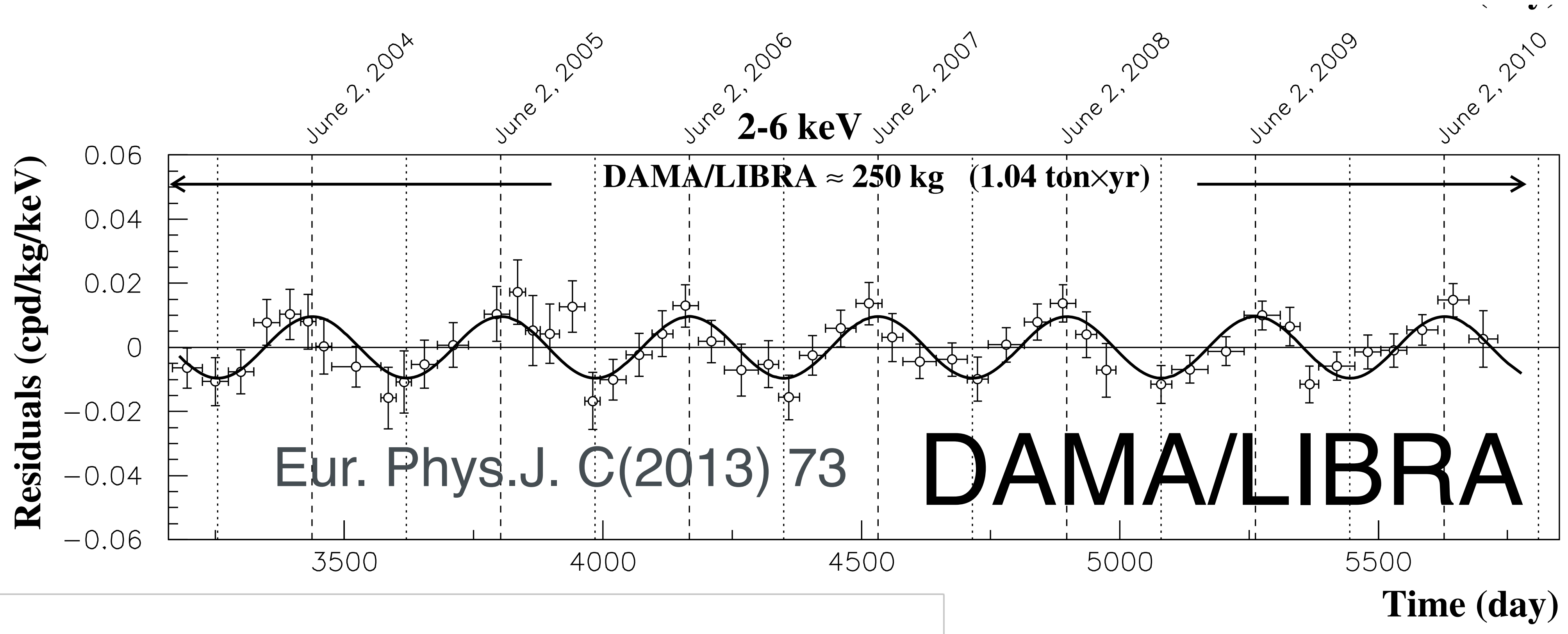


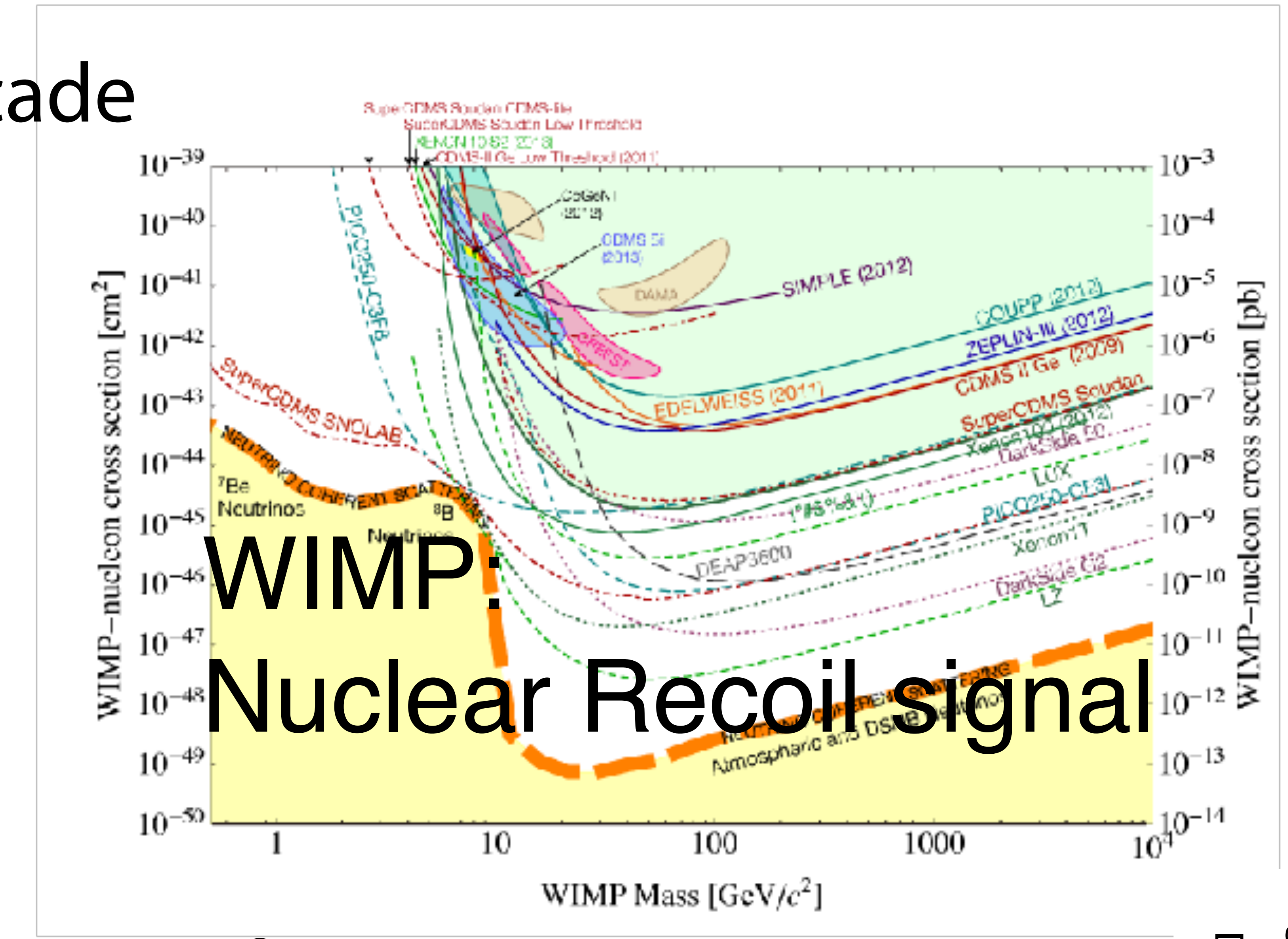
15th International Conference on Topics in Astroparticle and Underground Physics, TAUP2017

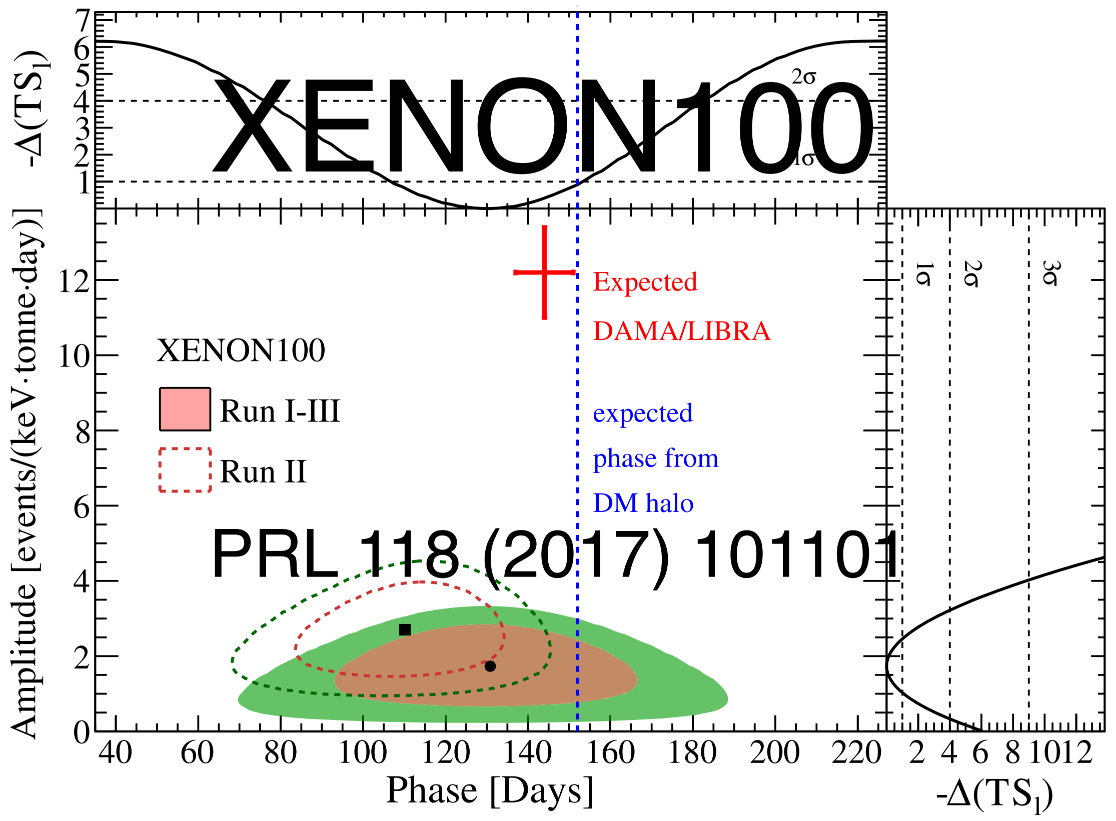
Modulation Searches

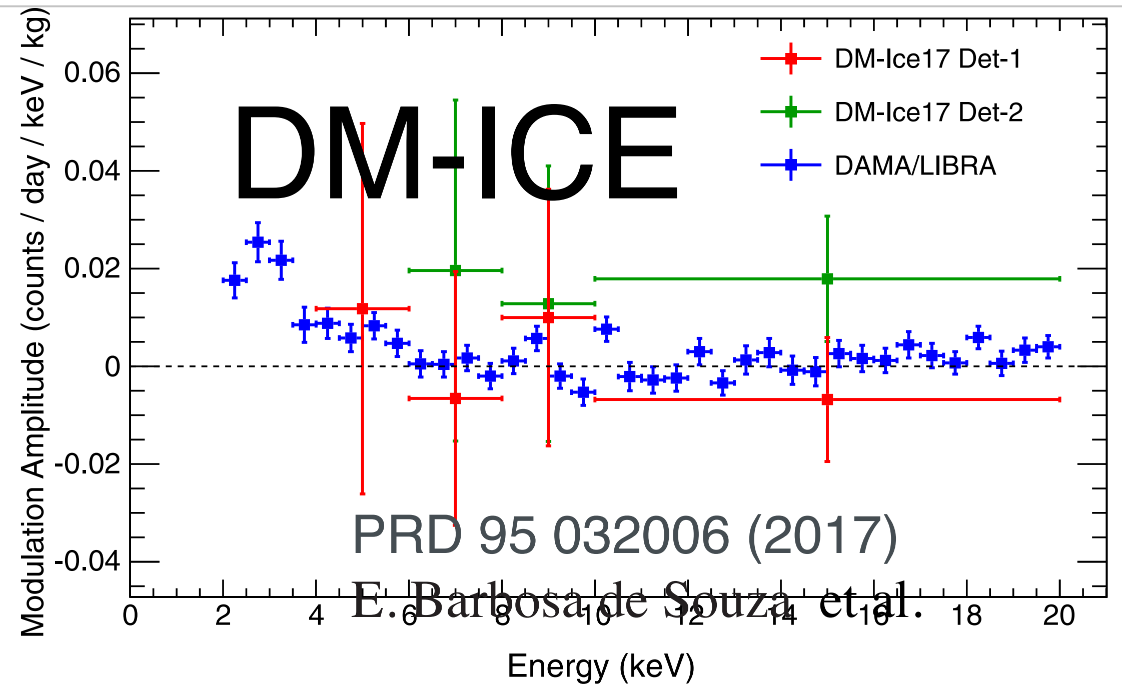
motivation

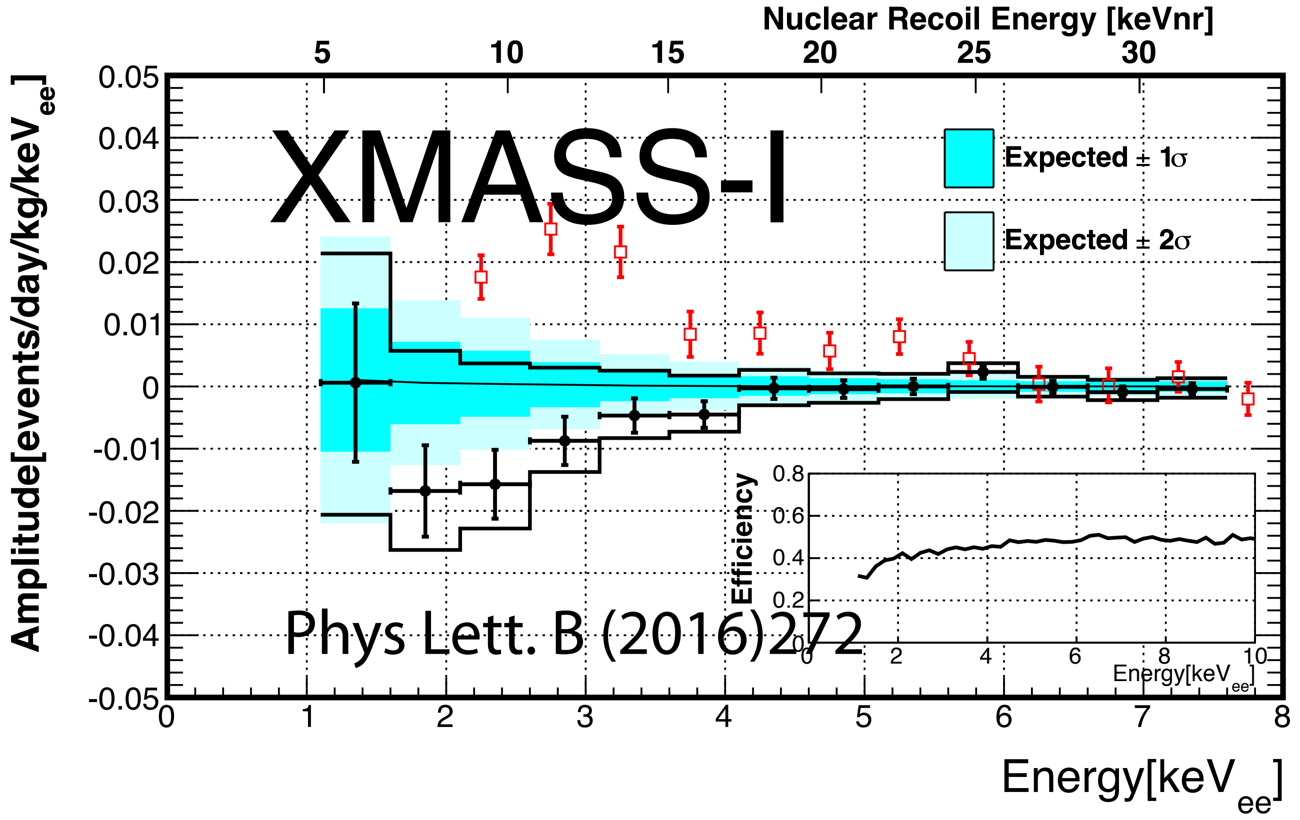
- DAMA/LIBRA NaI (Tl) result: modulation signal (9.3σ)
- No sign for SUSY particle at LHC so far.
- No sign in direct detection for more than decade with nuclear recoil signal.
- Important to look for variety candidates.
  - WIMP-electron scattering
    - R. Bernabei et al. PRD, 77 02308 (2008),
    - B.M. Roberts et al., PRL 116, 023201 (2016)
- Luminous dark matter
  - B. Feldstein et al., PRD 82, 075019 (2010)
- Mirror Dark Matter
  - R. Foot, Int. J. Mod. Pays. A 29, 126, (2014)
- Plasma Dark Matter
  - J. D. Clarke at el. axXiv1512.06471v
- The search can be also used for solar related physics, for instance, Kaluza Klein Axion search (7/26 by Ichimura)





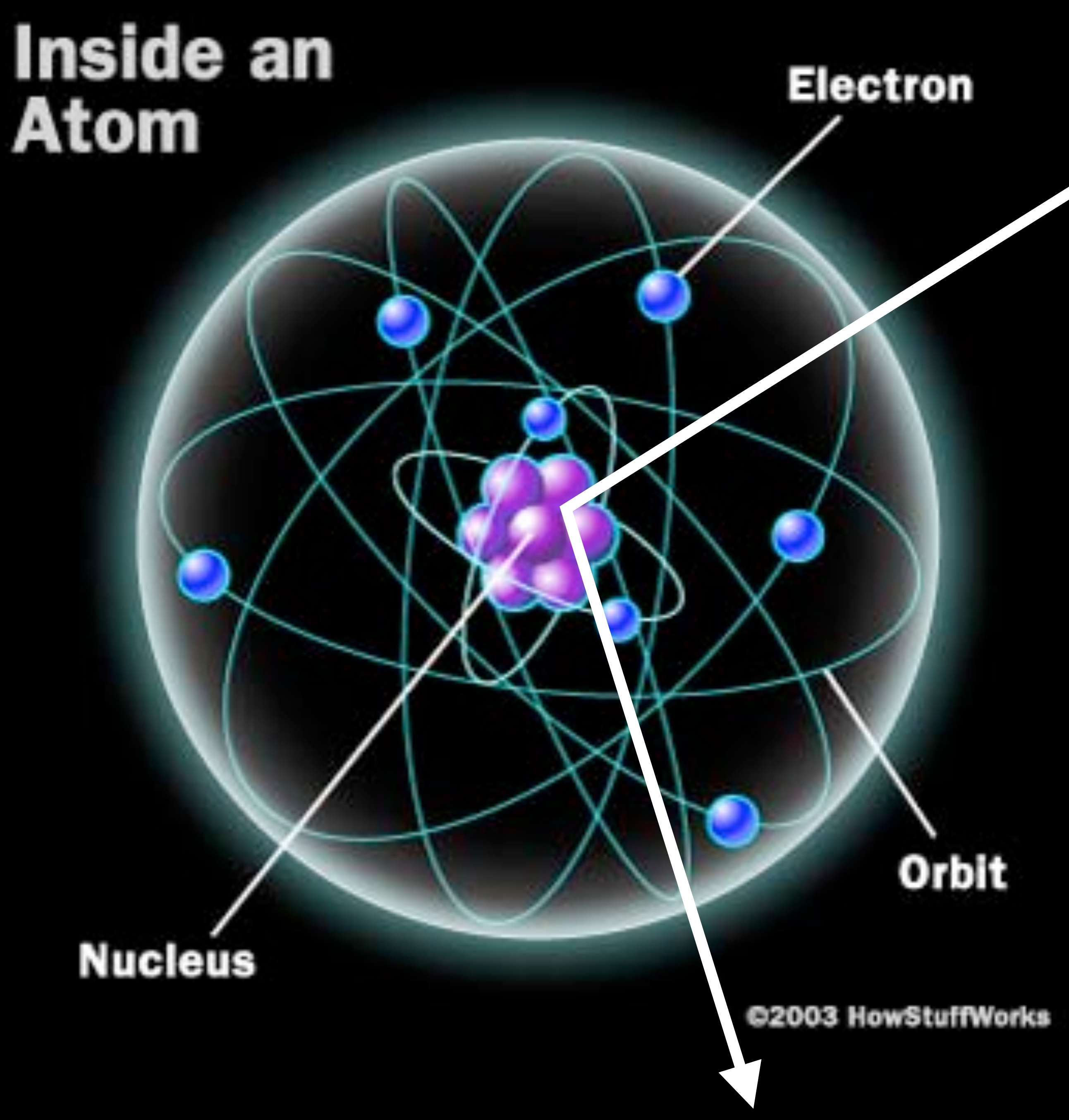






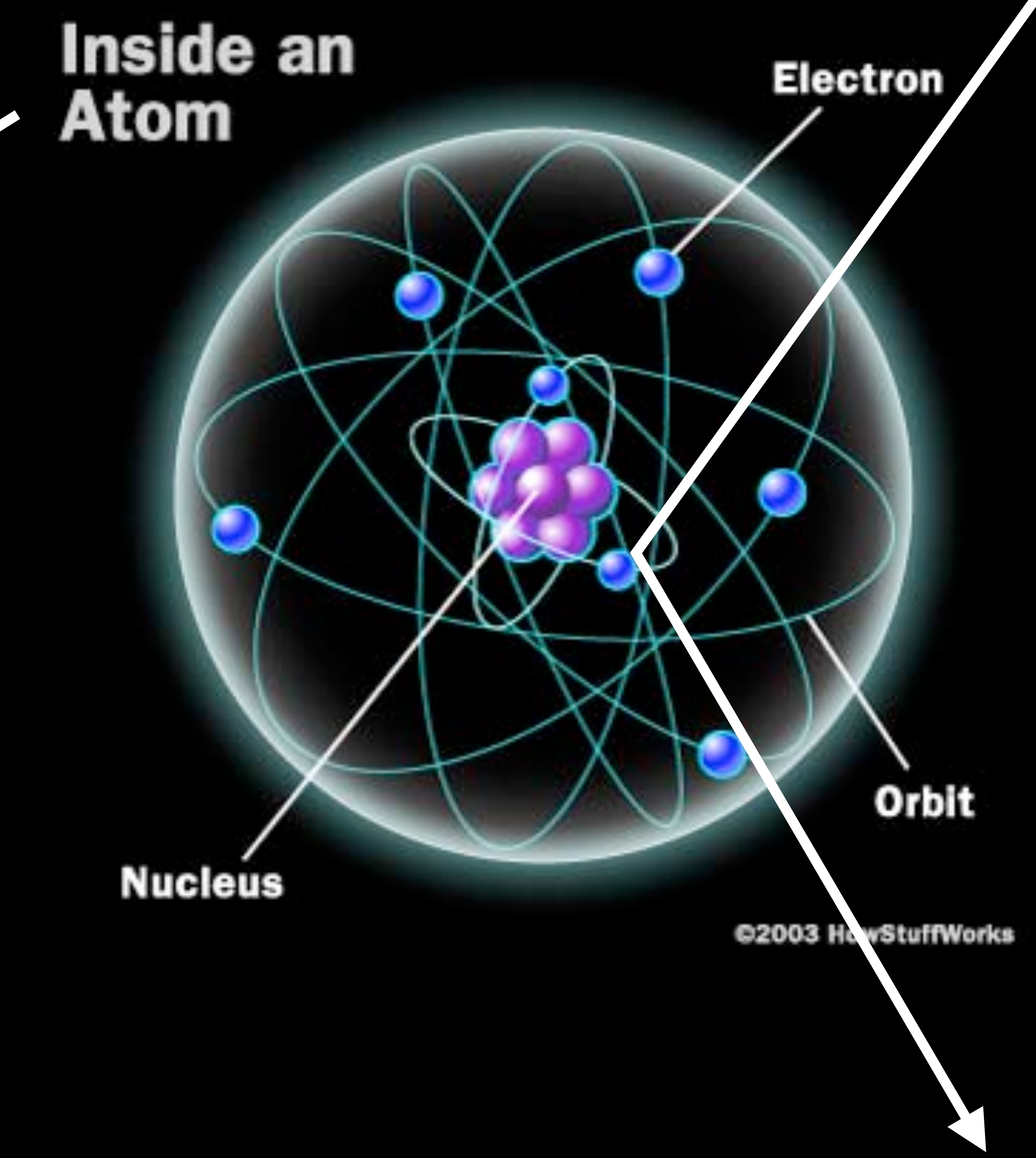
Interaction

nuclear recoil



fast neutron
WIMP
(SUSY, KK ...)

electronic recoil



-U/Th/^{40}K etc background

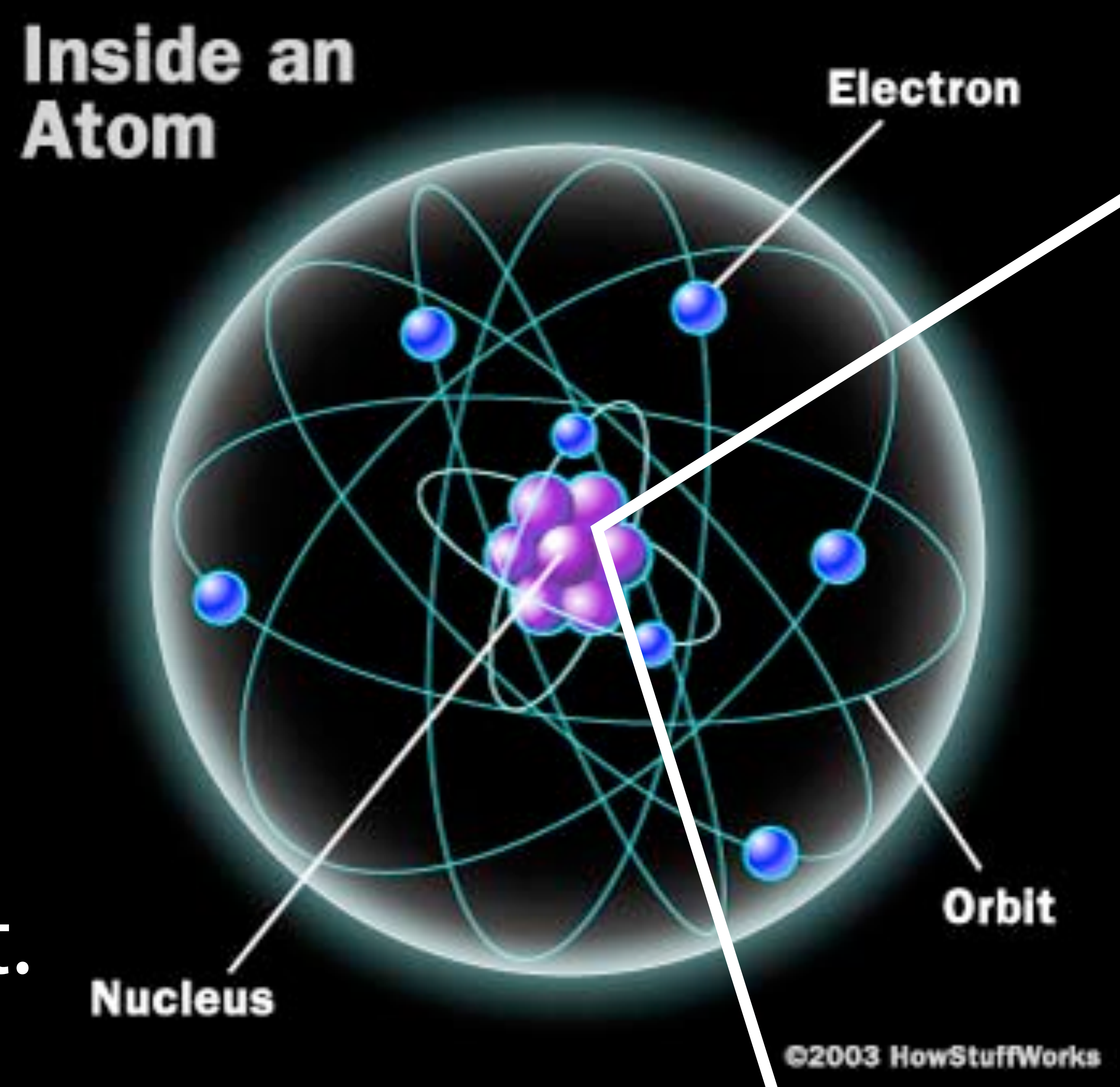
Interaction

- If the signal is not a nuclear recoil.
  - axial vector interaction
  - photon emission from excited DM (Luminous dark matter)
  - ….
- Axion like particle can not be candidate because σ ~1/v , dm flux ~ v.
- DAMA/LIBRA vs LXe
  - Energy deposit ~ 3 keV energy deposit. (from DAMA/LIBRA)

- Event rate is similar for Xe(z=54) and Iodine (z=53)

- modulation analysis is not depend on the halo model.

nuclear recoil

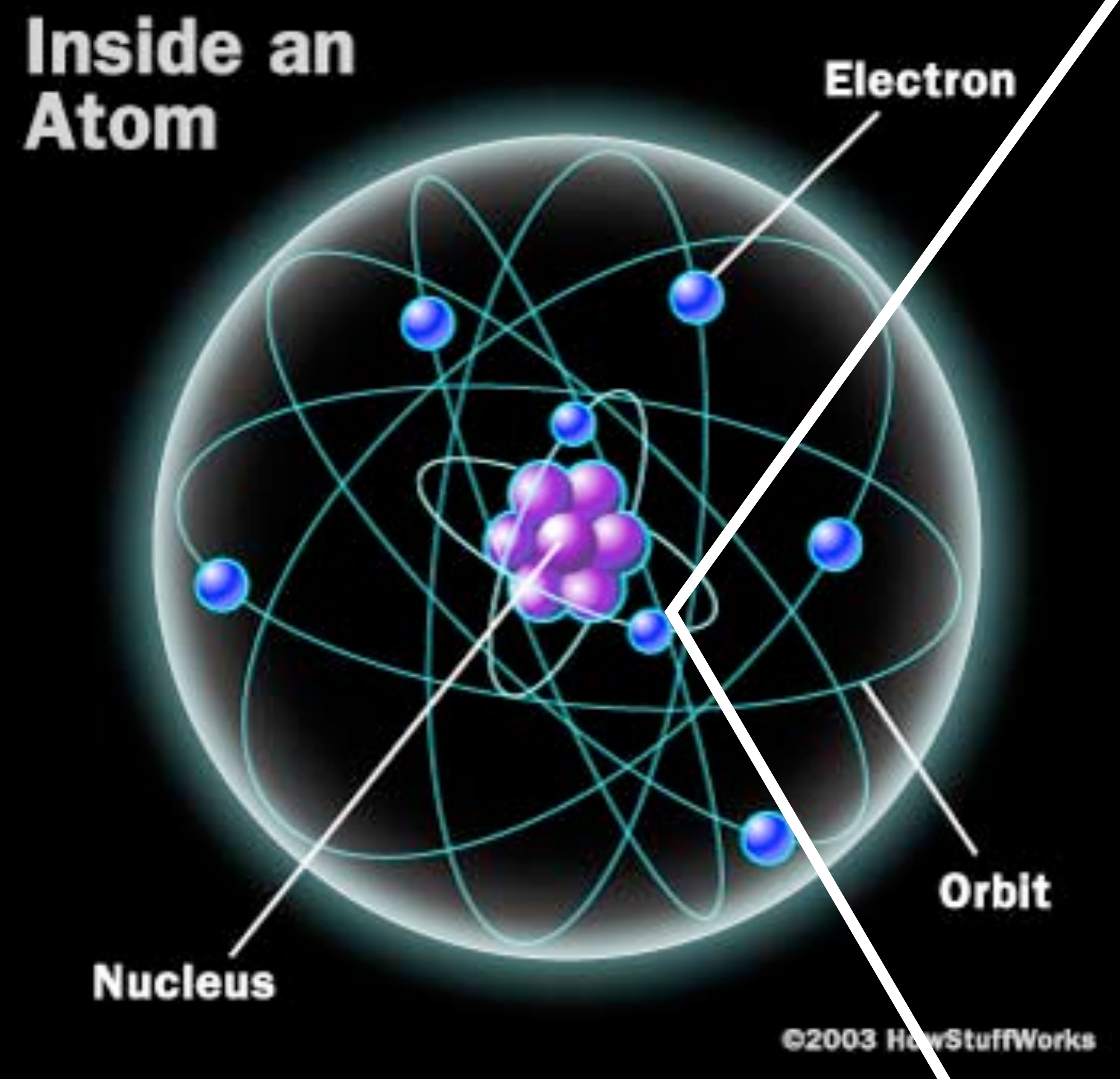


fast neutron

WIMP

(SUSY, KK …)

electronic recoil



-U/Th/^{40}K etc background

-WIMP-electron

-Super WIMP (bosonic)

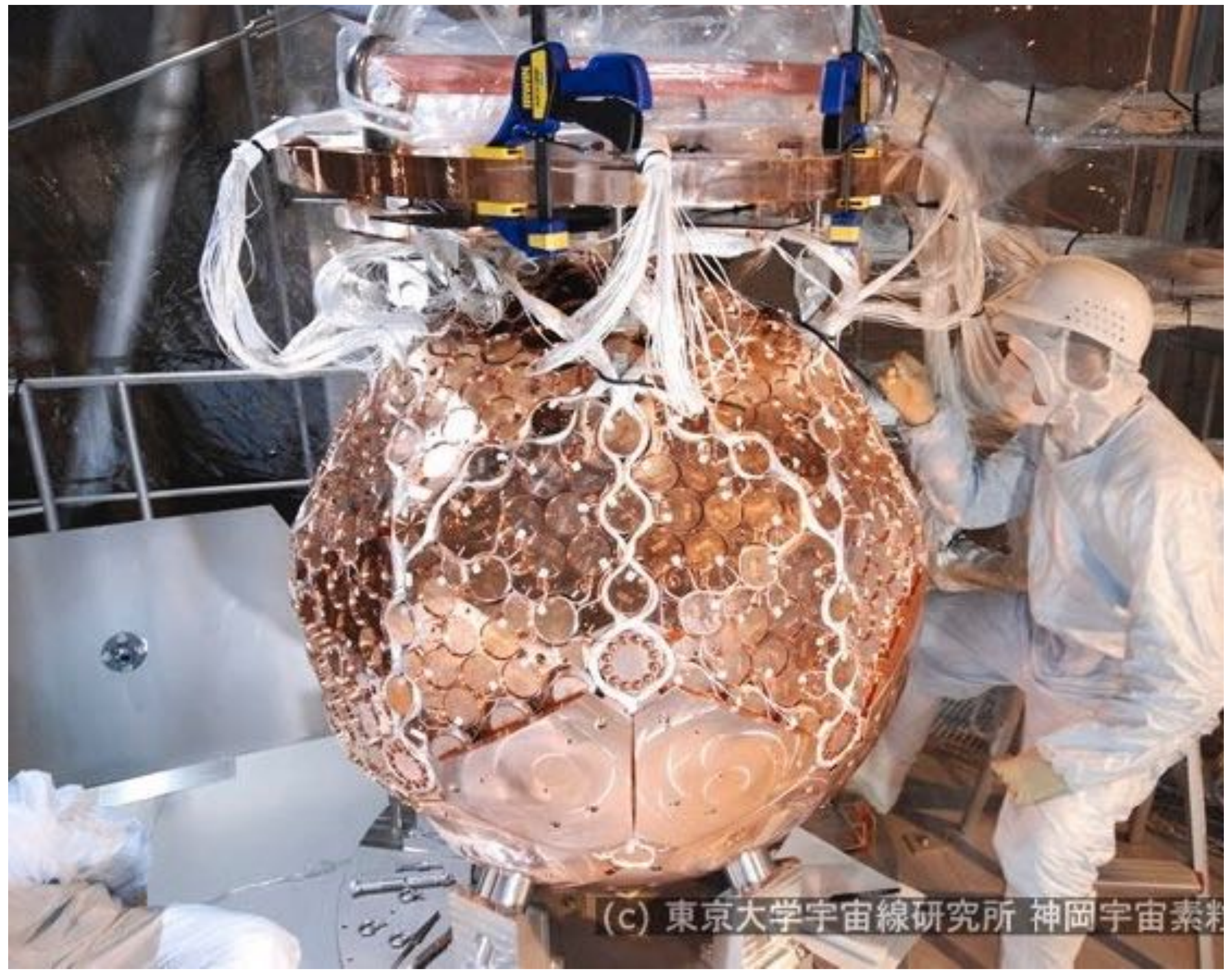
-Axion/Axion like particle

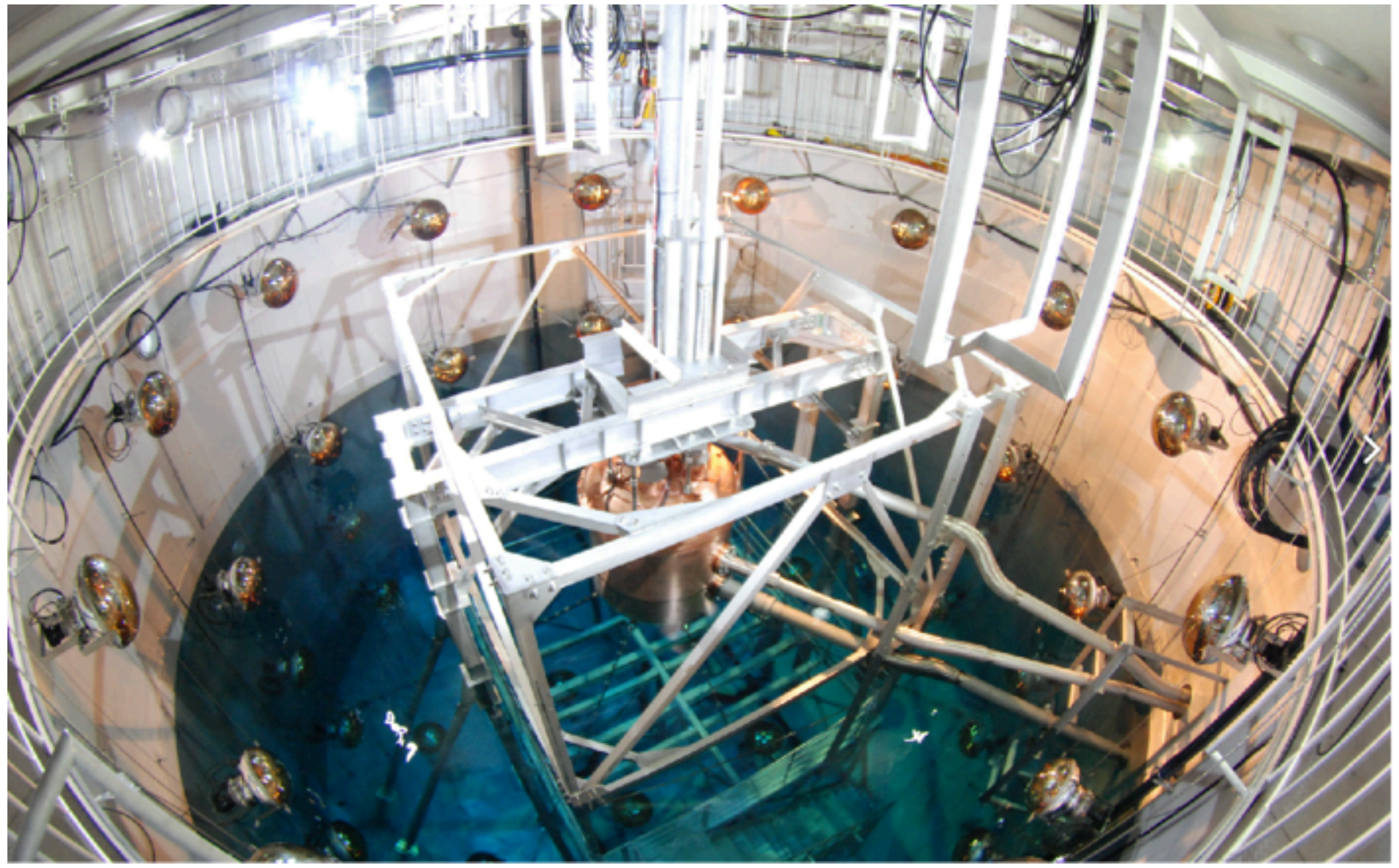
-Mirror DM

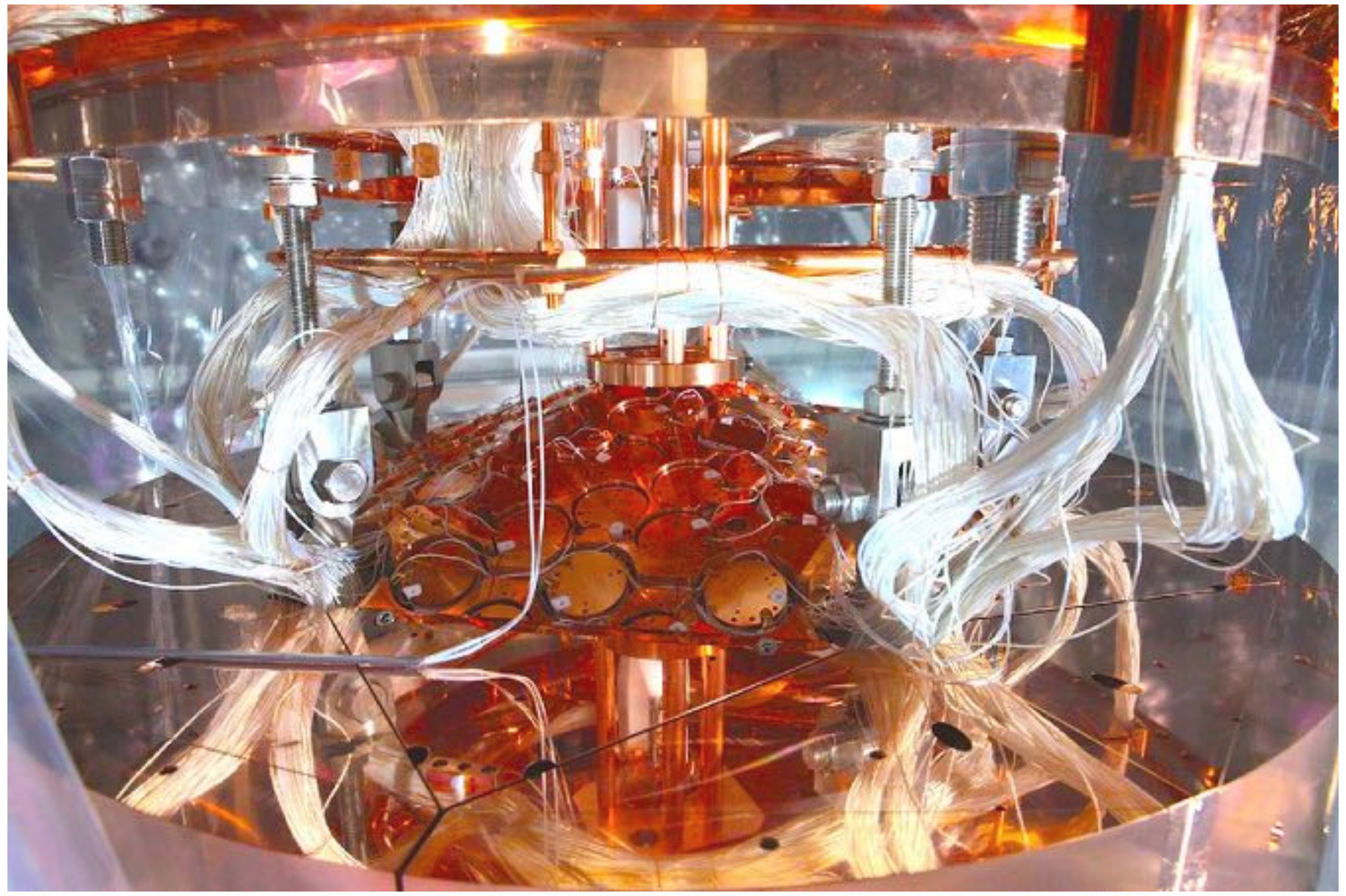
-Luminous DM …

XMASS experiment

- Kamioka Observatory in Japan (2700 m.w.e)
- Single phase LXe scintillation detector (832 kg)
- 642 low radioactive Hex PMT (R10789)
- ϕ10 m x 10 m Water Cherenkov active muon veto





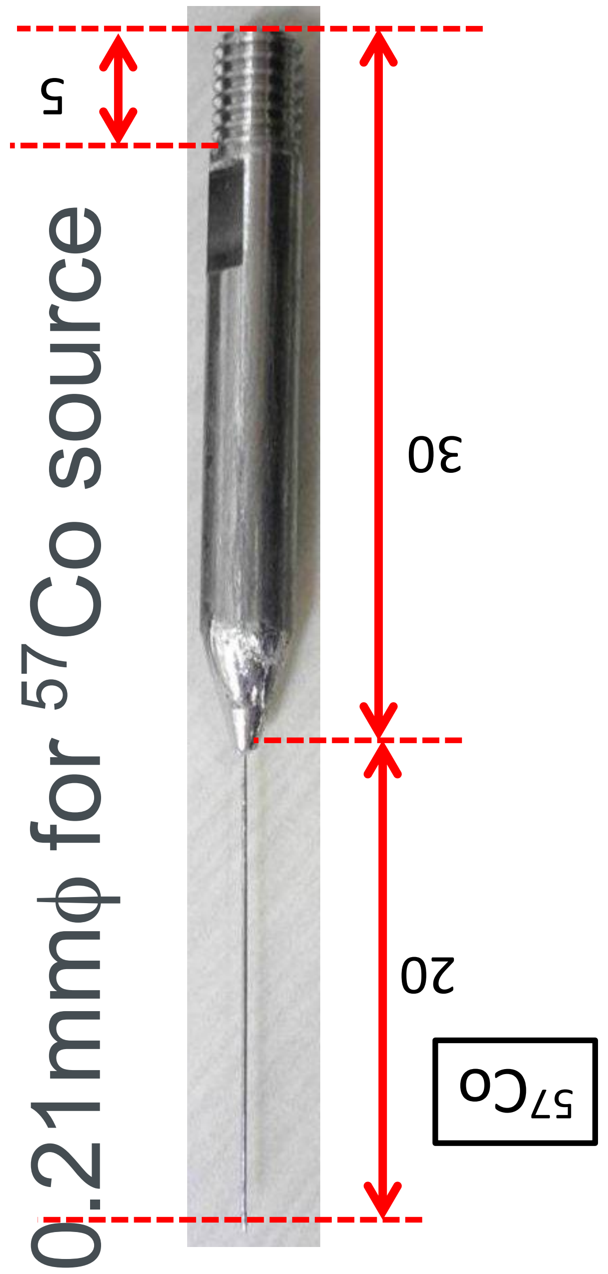


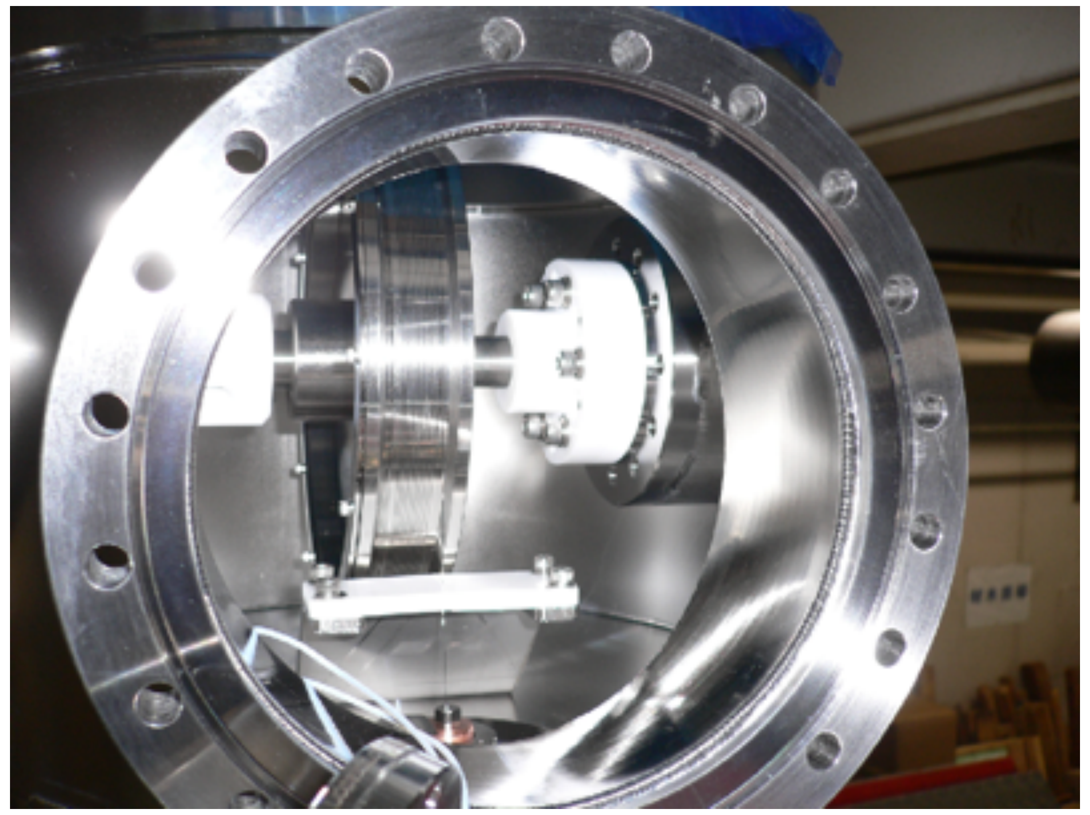
Detector calibration

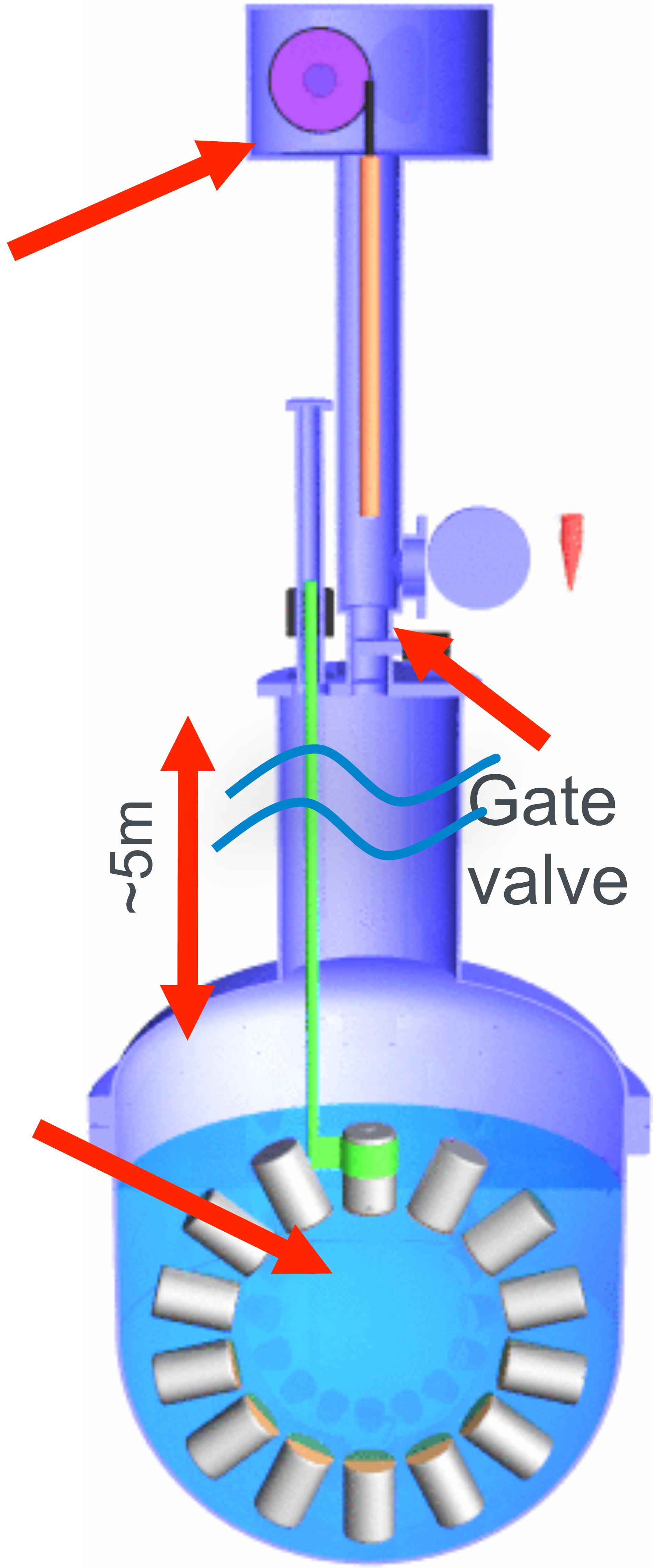
-Inner calibration is for energy calibration.

Isotopes	Energy [keV]	Shape
^{55}Fe	5.9	cylinder
^{109}Cd	1.65, 8(*1), 22, 58, 88	cylinder
^{241}Am	17.8, 59.5	thin cylinder
^{57}Co	59.3(*2), 122	thin cylinder
^{137}Cs	662	cylinder

sources made by Korean group



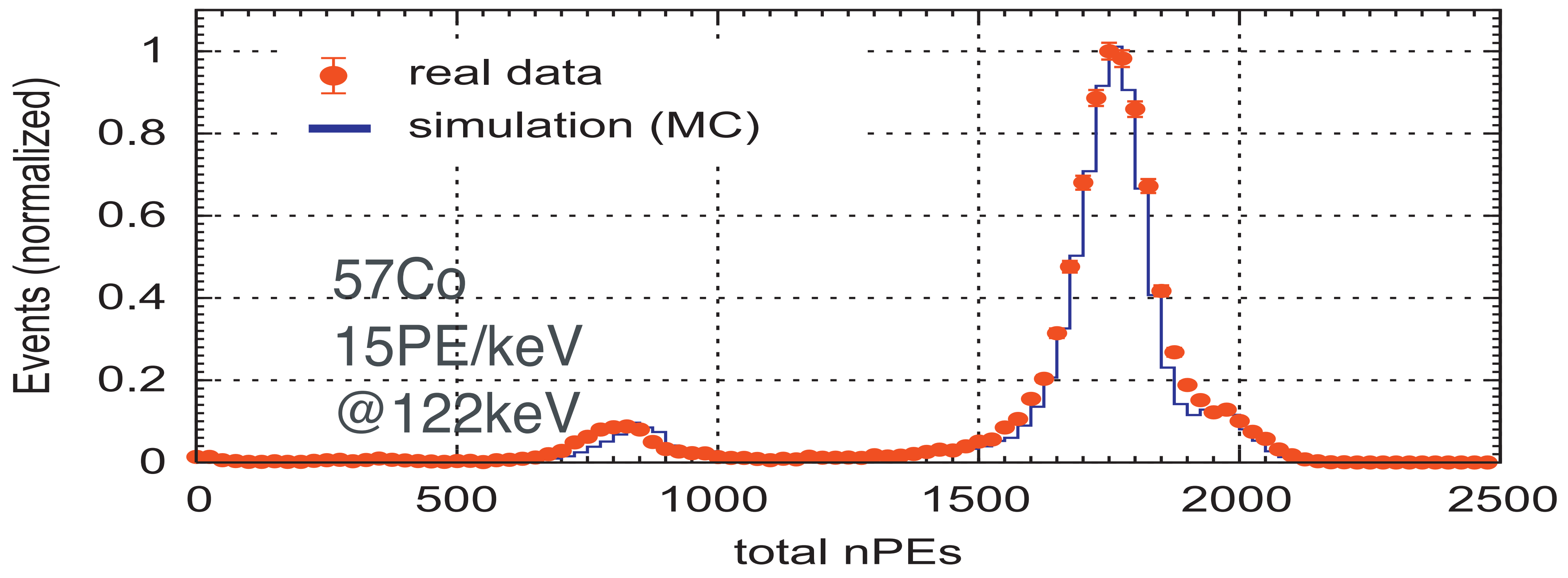


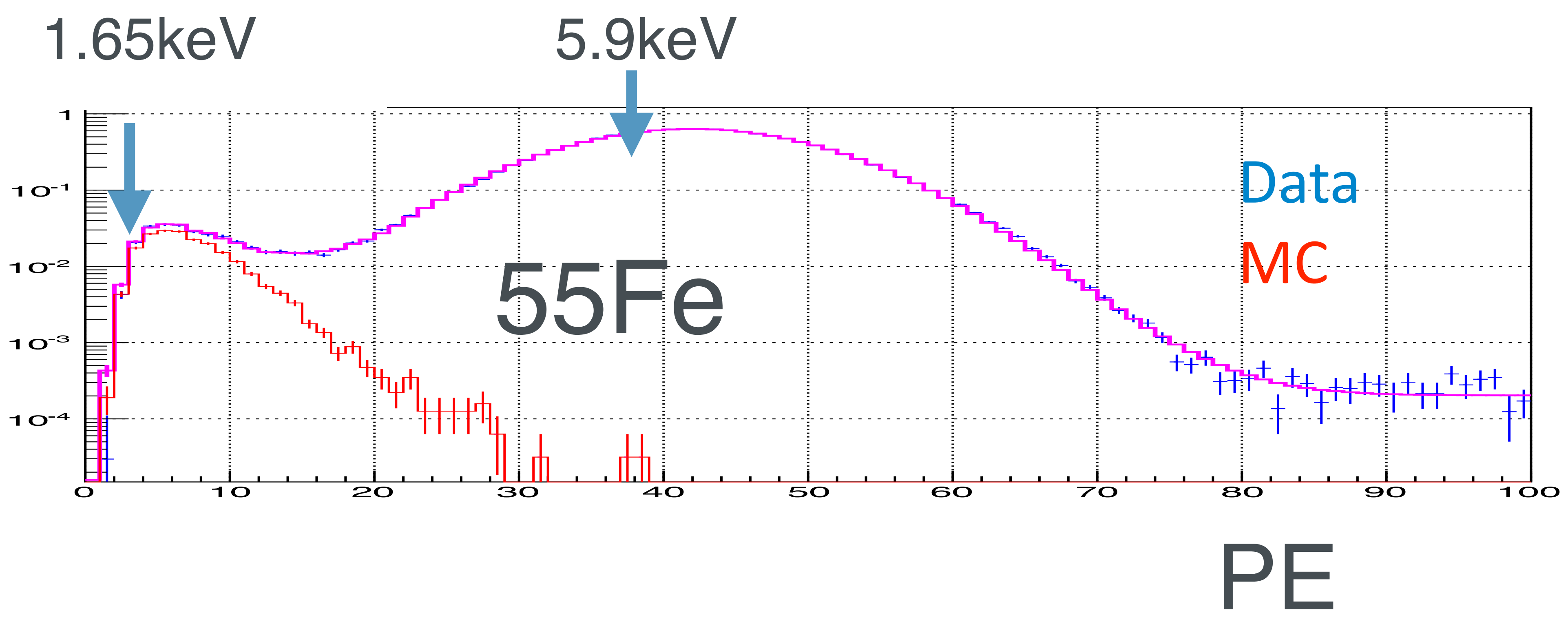


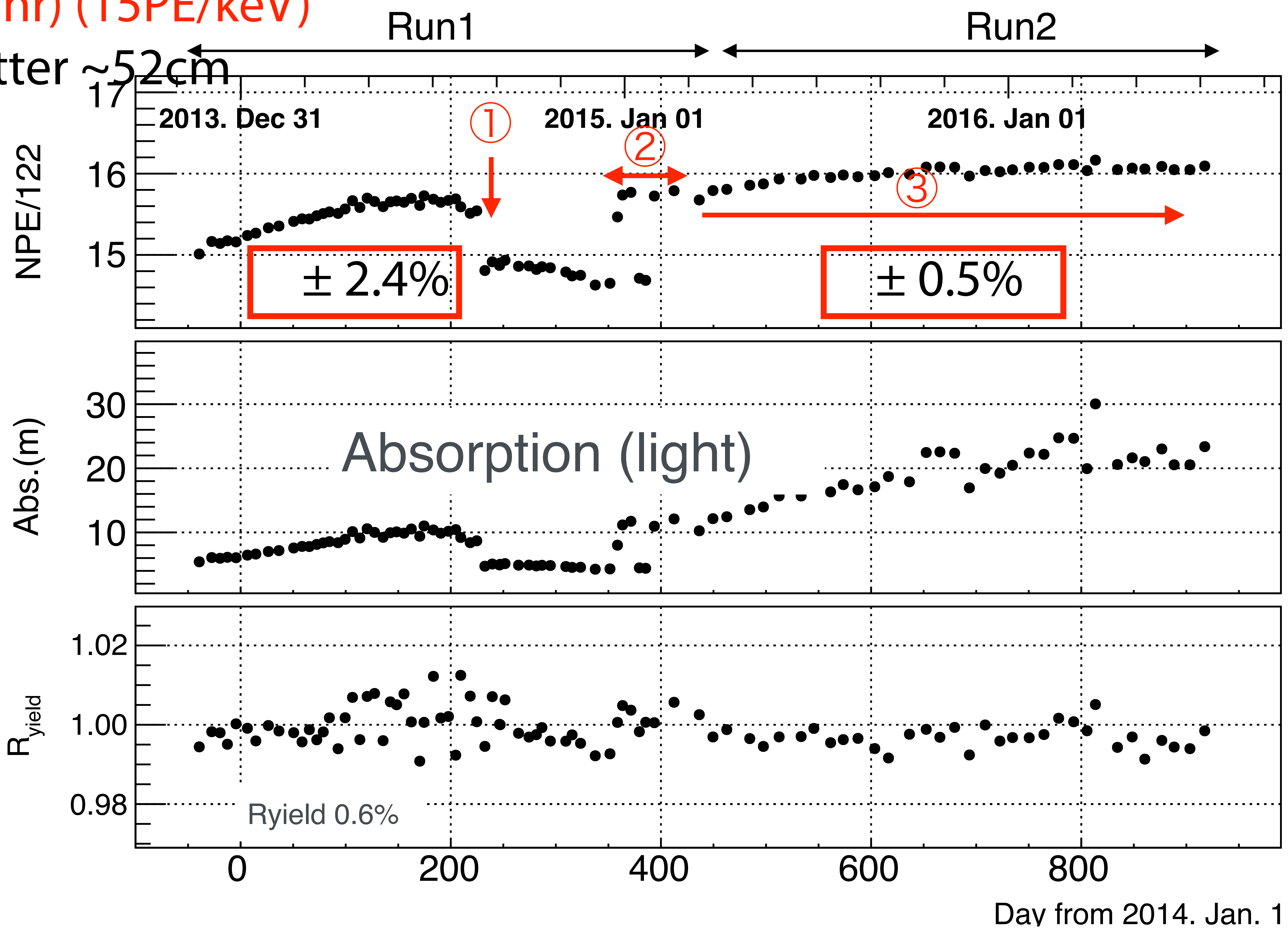
Energy calibration and stability

- Energy calibration 1.65 - 122 keVee
- High Photoelectron Yield ~15 PE/keV @122 keV
- Low energy threshold: 1.0 keVee (4.8 keVnr) (15PE/keV)
- Evaluated absorption length 4-30 m, scatter ~52cm
- Run1: Std ±2.4%, Run2 Std ±0.5%

① Power cut
② Purification work
③ continuous gas recirculation







Annual Modulation search

-Run 1 was reported in Phys Lett. B (2016)272.

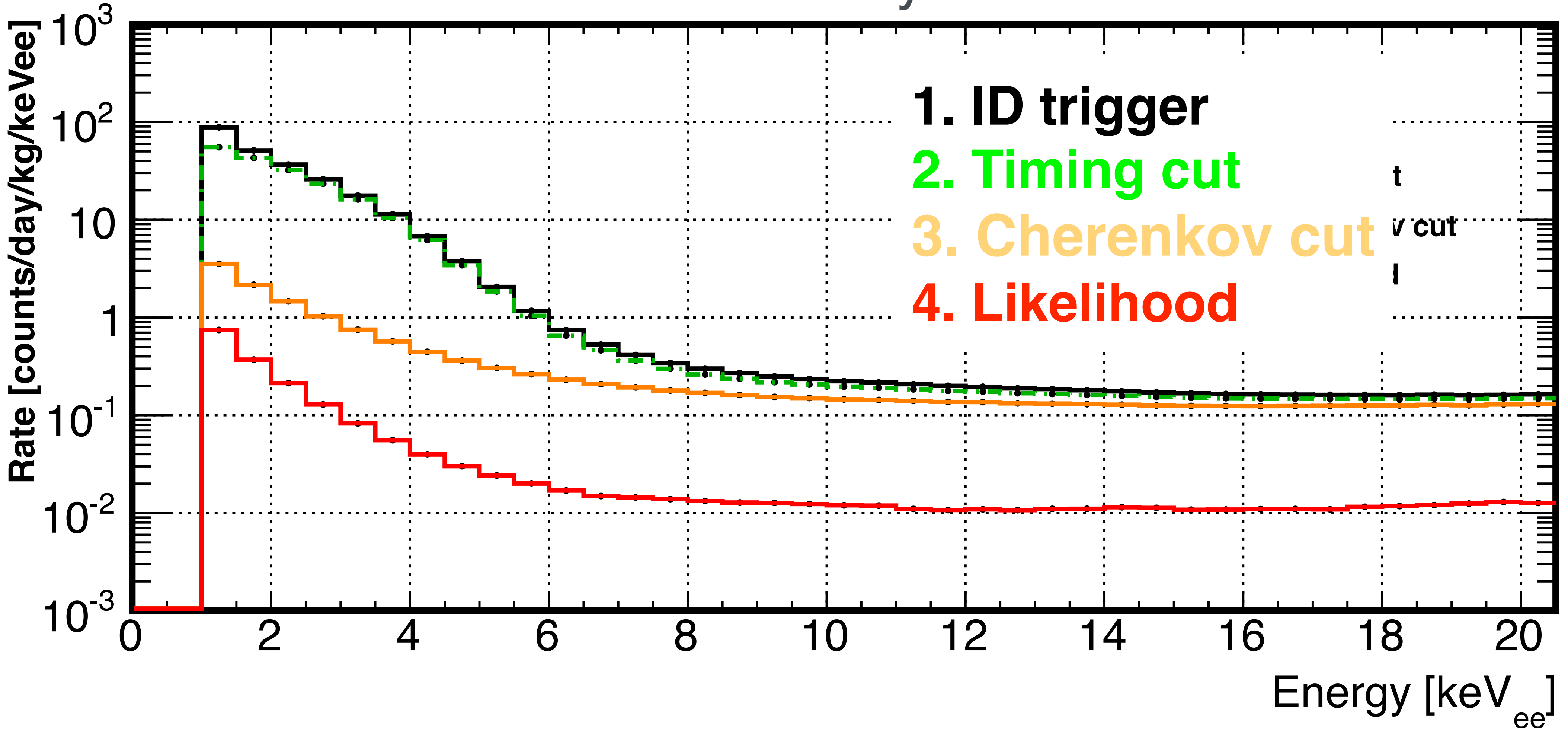
- Data set 2013/11/20 - 2016/07/20 (800.0 live days)

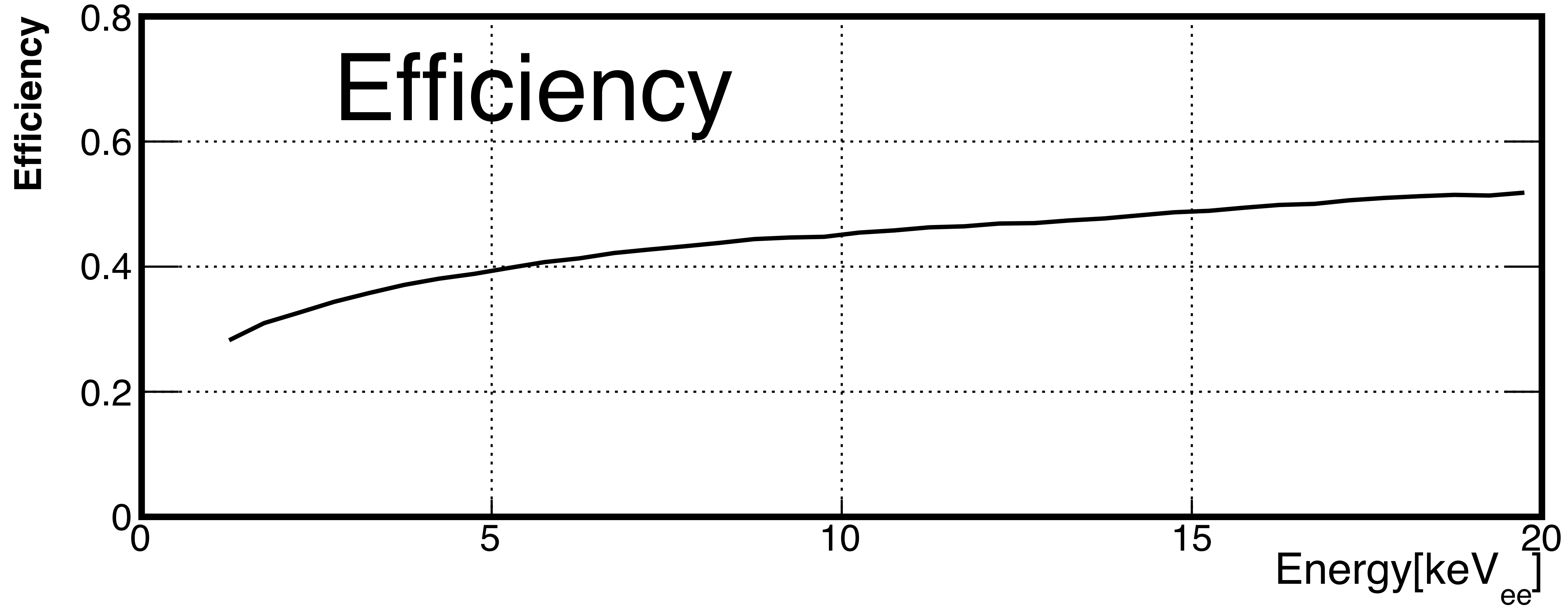
  XMASS (1.82 ton x year) ⇔ DAMA/LIBRA (1.33 ton x year)

-Quality cut + Likelihood analysis based on Sphericity, Aplanality, Maximum/Total PE

	Date	Live time [day]	Exposure [ton·year]
Run1	Nov/20/2013 - Mar/31/2015	387.8	0.884
Run2	Apr/1/2015 - Jul/20/2016	412.2	0.940
Total		800.0	1.82

#~20 days live time was recovered after PLB2016 in Run1





Fitting time variation data

- 2D fitting energy and time bins with the systematic errors from PE yield stability, Decay time, Leff
- Relative efficiency differences were taken into account for each period based on PE yield.
- The efficiency was normalized @ 8 m absorption length.(same as PLB2016)
- These errors are correlated with both energy and time bins and treated by pull term method.

WIMP case:

pull term

$$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \left(\frac{(R^{\rm data}_{i,j} - R^{\rm ex}_{i,j}(\alpha,\beta))^2}{\sigma({\rm stat})^2_{i,j} + \sigma({\rm sys})^2_{i,j}} \right) + \alpha^2 + \sum^{Nsys} \beta_i^2$$

Decay time($2.7^{+2.0}_{-1.5}$ ns) and Leff uncertainty

$$R^{\rm ex}_{i,j}(\alpha,\beta) = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \Bigg(\epsilon^b_i(\alpha) \cdot (B_i t + C^b_i) + \sigma_{\chi n} \cdot \epsilon^s_i \cdot \left(C^s_i(\beta) + A^s_i(\beta) \cos 2\pi \frac{(t-t_0)}{T} \right) \Bigg) dt$$

Model Independent case:

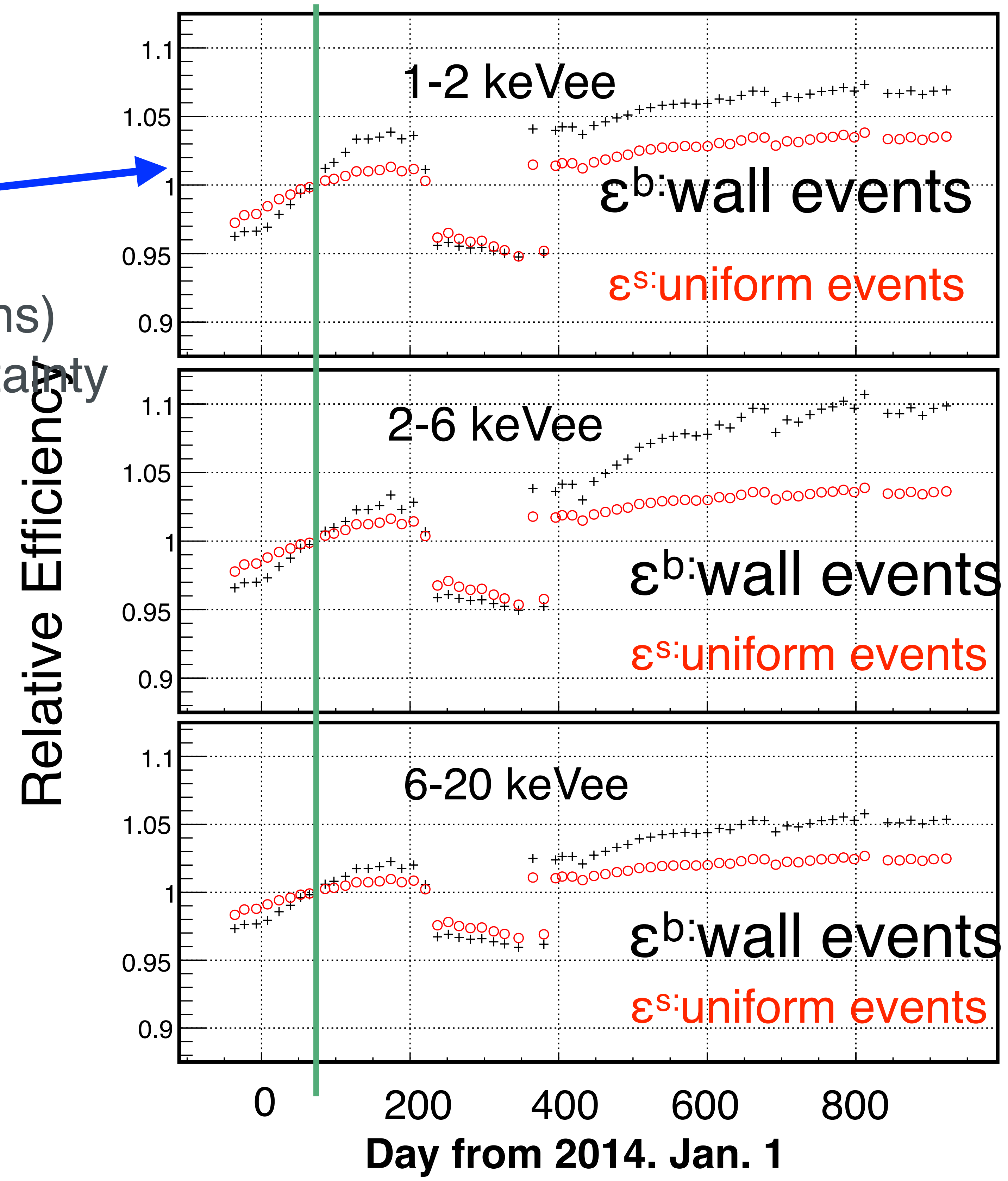
pull term

$$\chi^2 = \sum_i^{E_{bins}} \sum_j^{t_{bins}} \left(\frac{(R^{\rm data}_{i,j} - R^{\rm ex}_{i,j})^2}{\sigma({\rm stat})^2_{i,j} + \sigma({\rm sys})^2_{i,j}} \right) + \alpha^2$$

$$R^{\rm ex}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} \left(\epsilon^s_i A^s_i \cos 2\pi \frac{(t-t_0)}{T} + \epsilon^b_i(\alpha)(B_i t + C^b_i) \right) dt$$

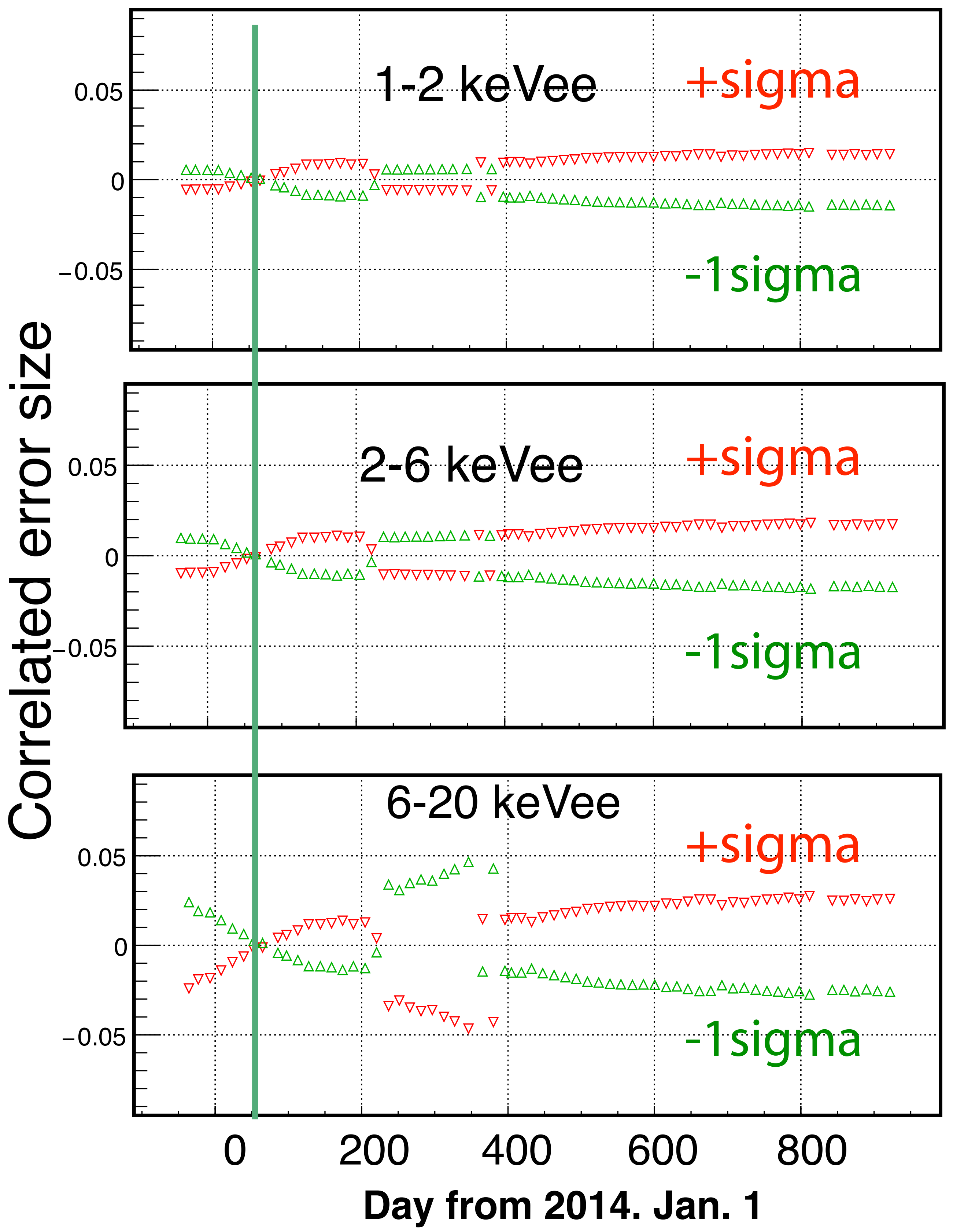
relative efficiency

normalized



alpha: Uncertainty for pull term

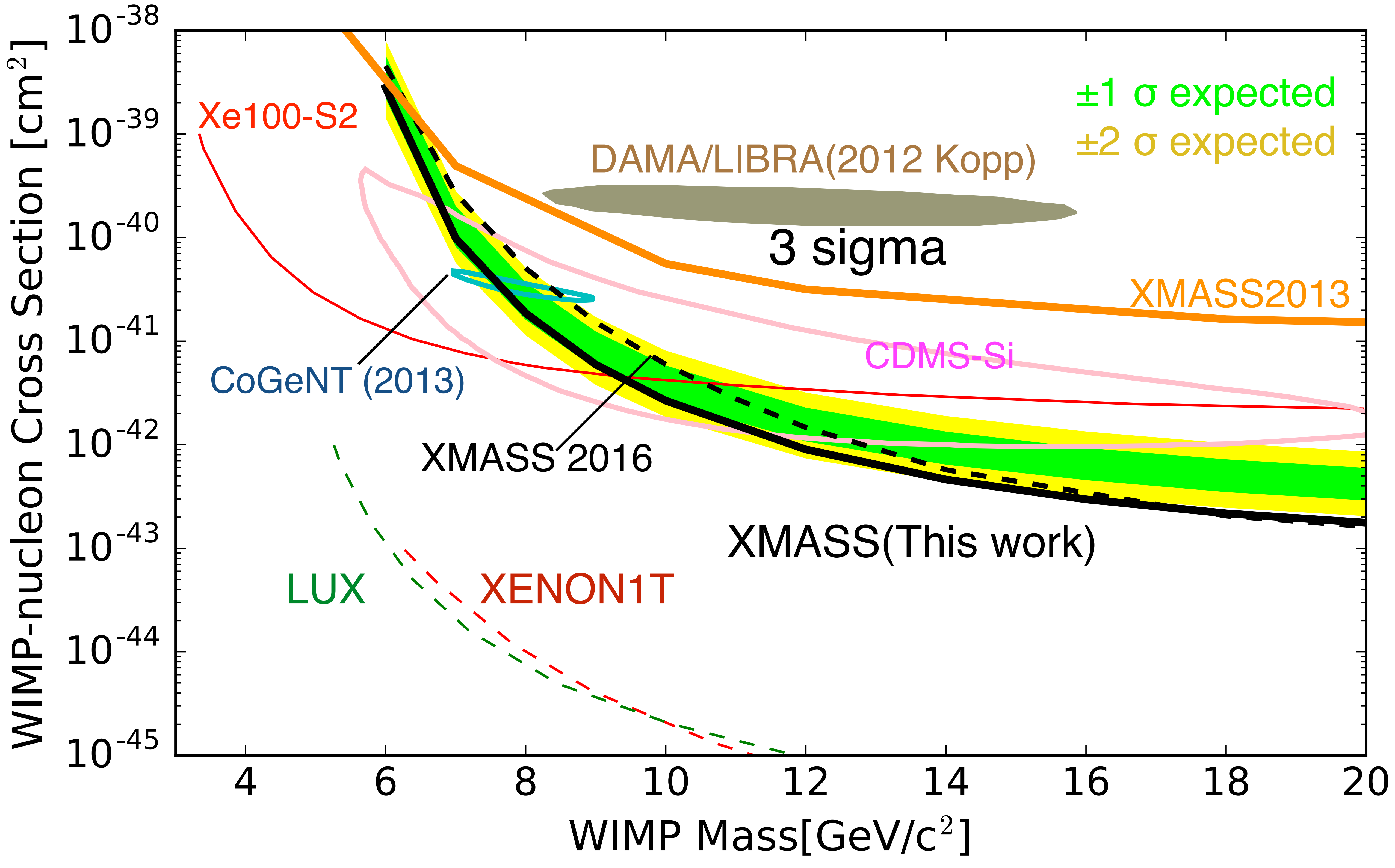
normalized



WIMP case

- Assuming WIMP(standard halo model)
  - Lewin and Smith (1996, APP)
  - T=1year, t0=152.5 day (fixed)
  - V_0 = 232 km/sec, V_{esc} = 544 km/s
  - ρ_{DM} = 0.3 GeV/cm^3
- 2D fitting (time and energy bin)
- DAMA/LIBRA region is excluded by annual modulation search.

  <1.9 x 10^{-41}cm^2 (90% CL) @ 8GeV

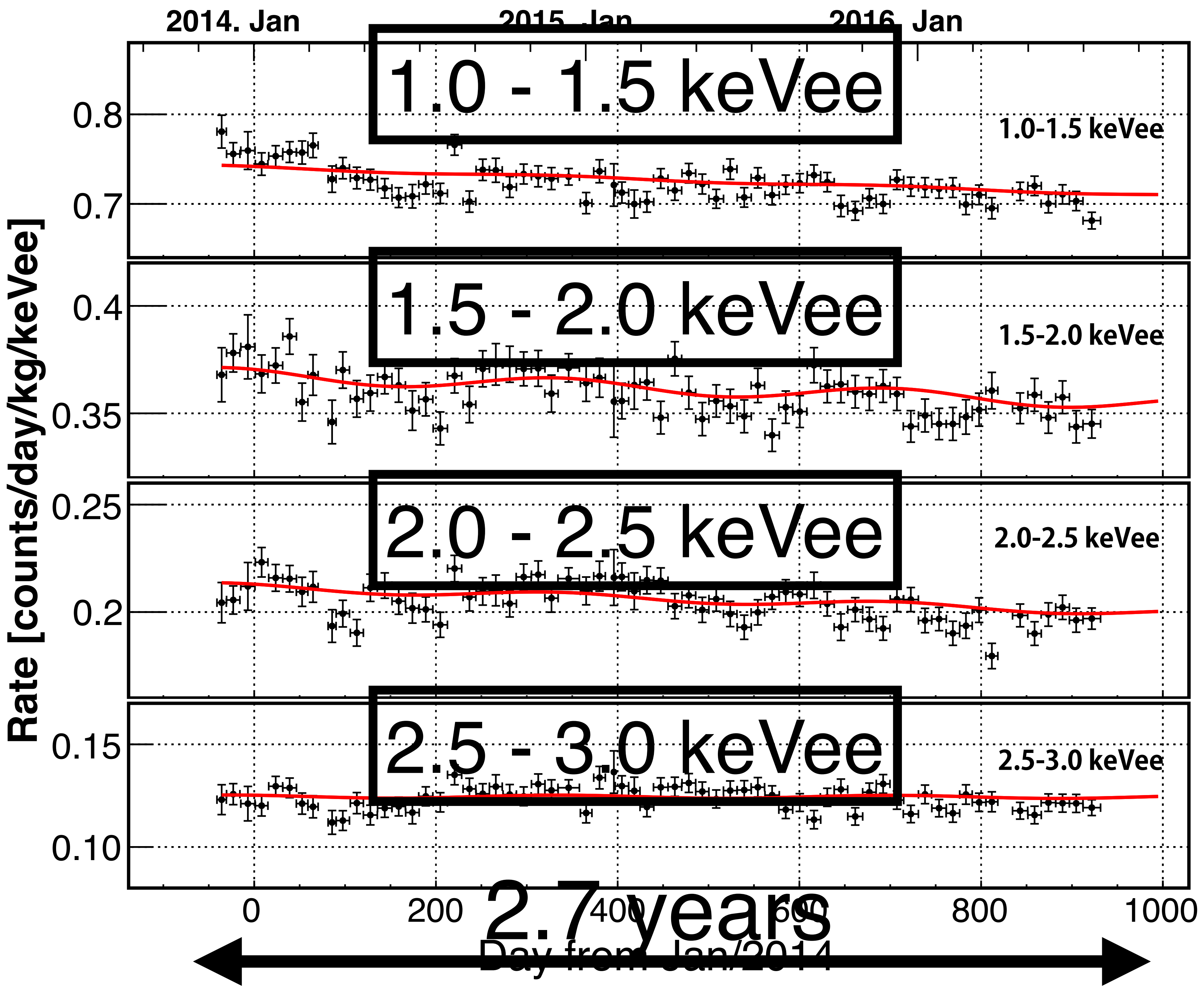


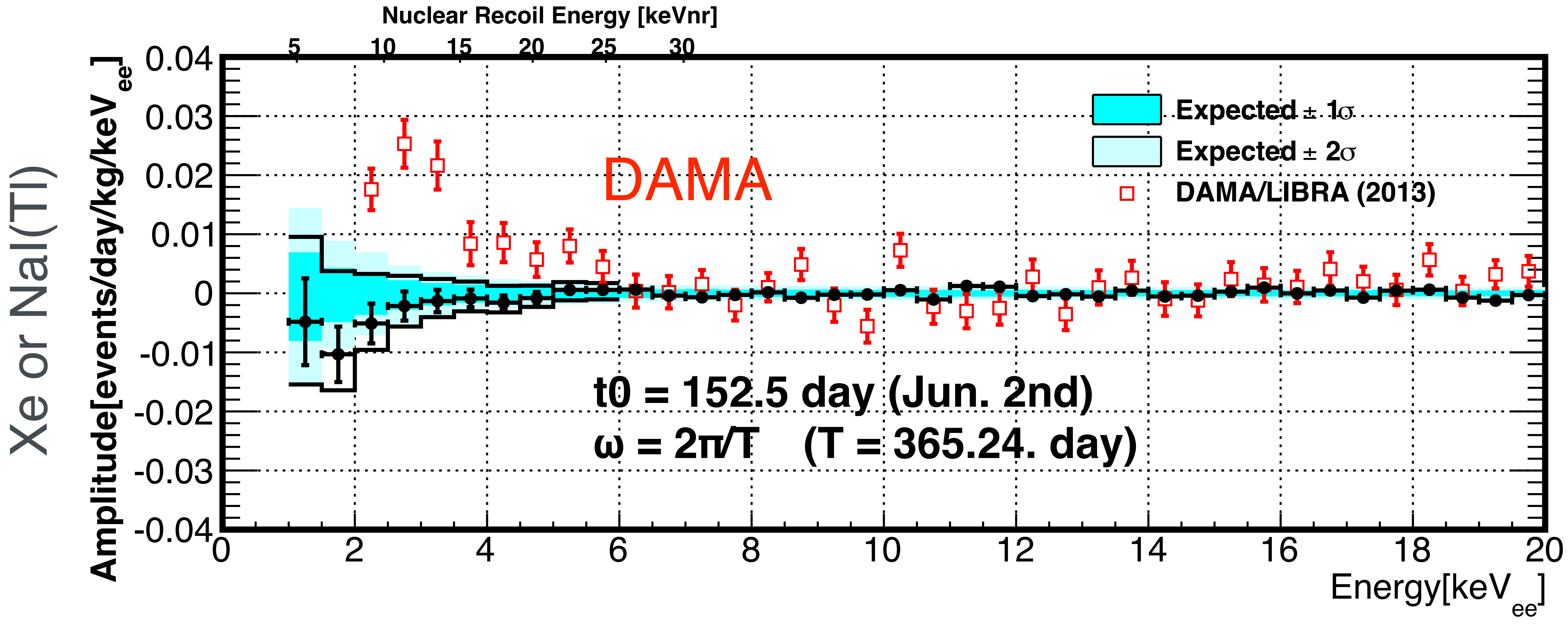
Model Independent Case

- Searching for without any model assumption.
- Fixed parameter : t0 = 152.5 day (Jun. 2nd) , T = 365.24. day
- Null hypotheses p-value: 0.11 (1.6σ), previous work (2.5σ).
- => Upper limit. Most stringent amplitude for modulation search.

(when models assumed, the relation btw NaI and Xe might be changed)

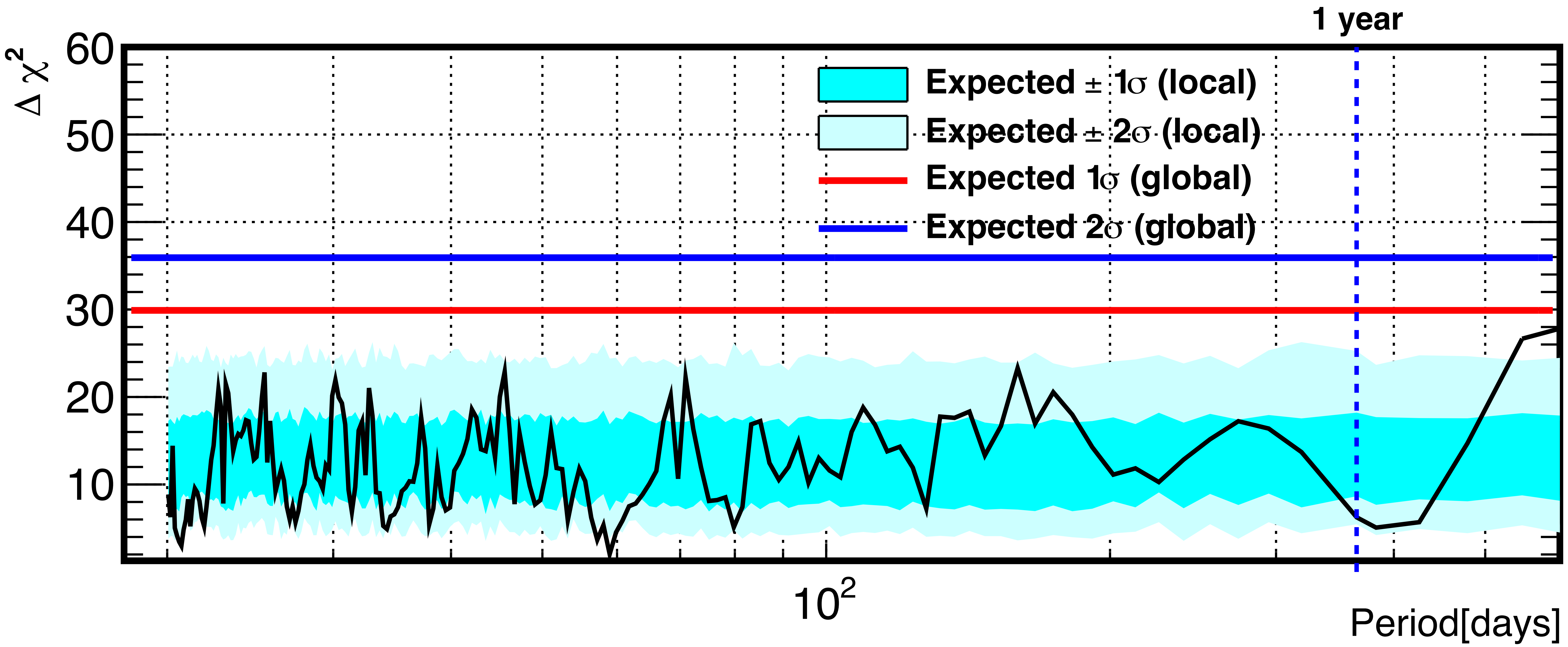
Experiment	Amplitude 10^{-3} (counts/day/kg/keVee)
DAMA/LIBRA(2013)	25@2.75 keVee
XENON100(2017)	1.67±0.73 (2.0-5.8 keVee), <3.1 90CL
XMASS-I (2017)	< 1.3-3.2 (2-6 keVee) 90CL





Power Spectrum

- To find any period in the data in the energy range of 1-6 keVee.
- Phase t_0 is a free parameter.
- $\Delta X^2 = X^2(\text{null}) - X^2(\text{periodic hypotheses})$
- Test statistic to evaluate significance.
- Global significance: the maximum ΔX^2 in the range to take into account `look elsewhere effect'.
- No significant period was found between 20 and 600 days.



NDF = 10

Conclusion and Summary

- It is important to look for any signal (not only nuclear recoil) for dark matter search.
- XMASS-I carried out annual modulation search with 2.7 years of data. (800 live days x 832 kg)
- We did not find any modulation signals
  - $<1.9 \times 10^{-41} cm^2$ (90% CL) @ 8GeV
  - $< 1.3\text{-}3.2 \times 10^{-3}$ counts/day/kg/days (2-6 keVee) 90CL
- We did not find any particular period between 20 - 600 days in the energy region of 1-6keVee.