Solar axion search by annual modulation with XMASS-I detector

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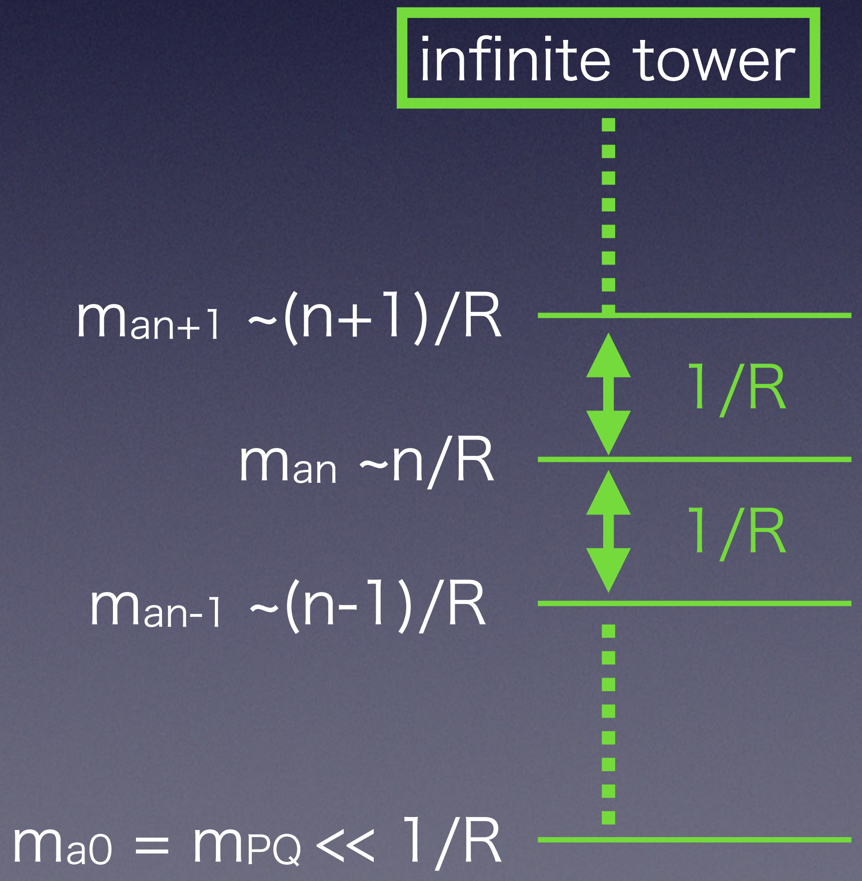
Contents

- Introduction of solar Kaluza-Klein (KK) axion
- XMASS-I detector
- Data Analysis
- Results

Introduction of KK axion

- Axions arise from Peccei-Quinn solution to strong CP problem in QCD.
- On the other hand, large extra dimensions are also proposed to solve the gauge hierarchy problem.
  - Extra dimensions are thought to be “compactified ” in a certain radius R.
  - Motions of a particle in the extra dimensions can be seen as mass state of Kaluza-Klein (KK) excitations, which are separated in 1/R

- In theories with n extra dimensions, axions may be able to propagate and acquire KK excitations.
  - axions acquires an infinite tower of KK modes where the lowest KK state is the normal PQ axions.
- Assumed model
  - n= 2 extra dimensions
  - δ =2 extra dimensions that axions can propagate in
  - → mass spacing of the KK axion 1/R ~ 1 eV


infinite tower

m_{an+1} ~(n+1)/R

1/R

m_{an} ~n/R

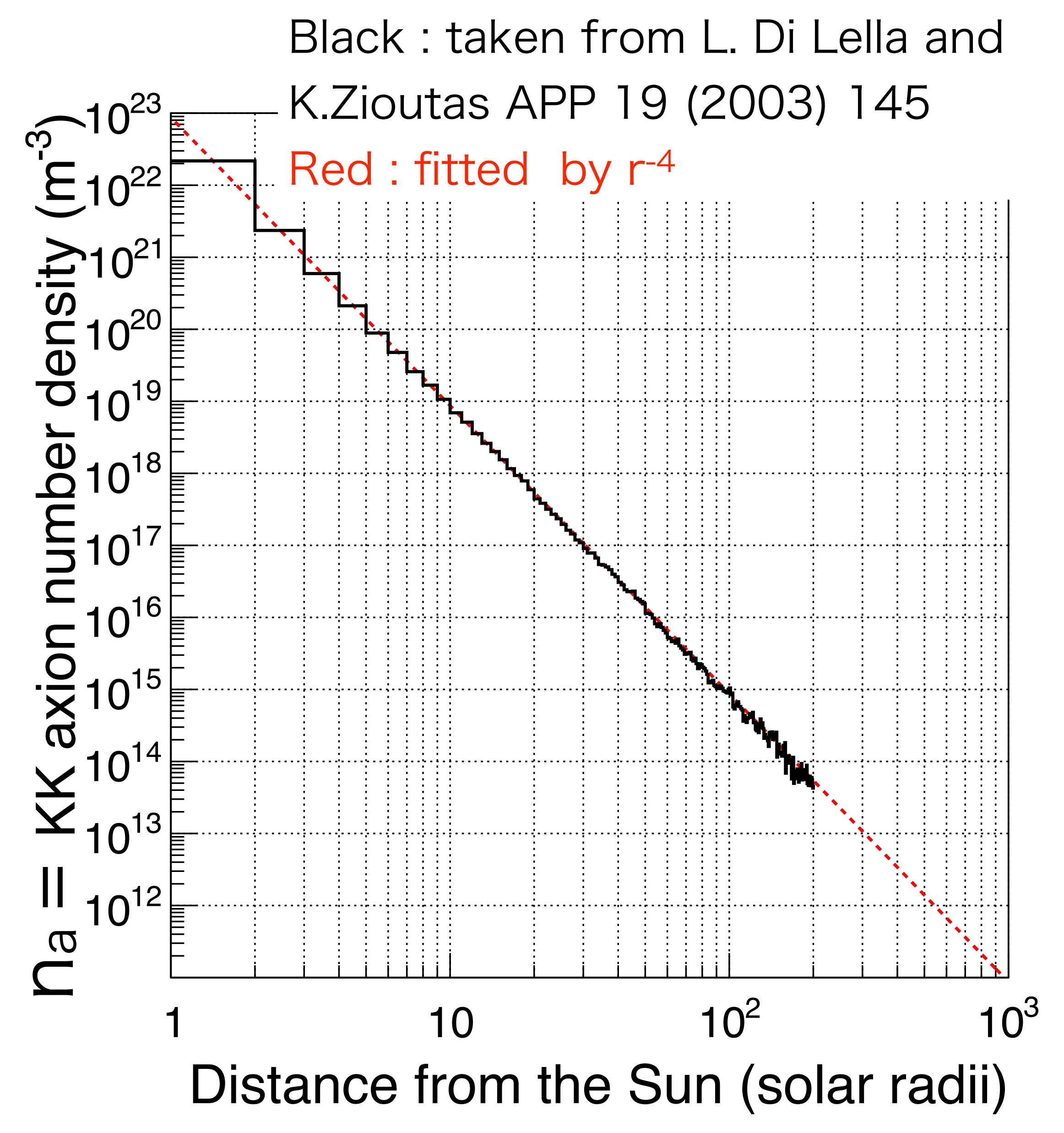
1/R

m_{an-1} ~(n-1)/R

$m_{a0} = m_{PQ} << 1/R$

Introduction of solar KK axion

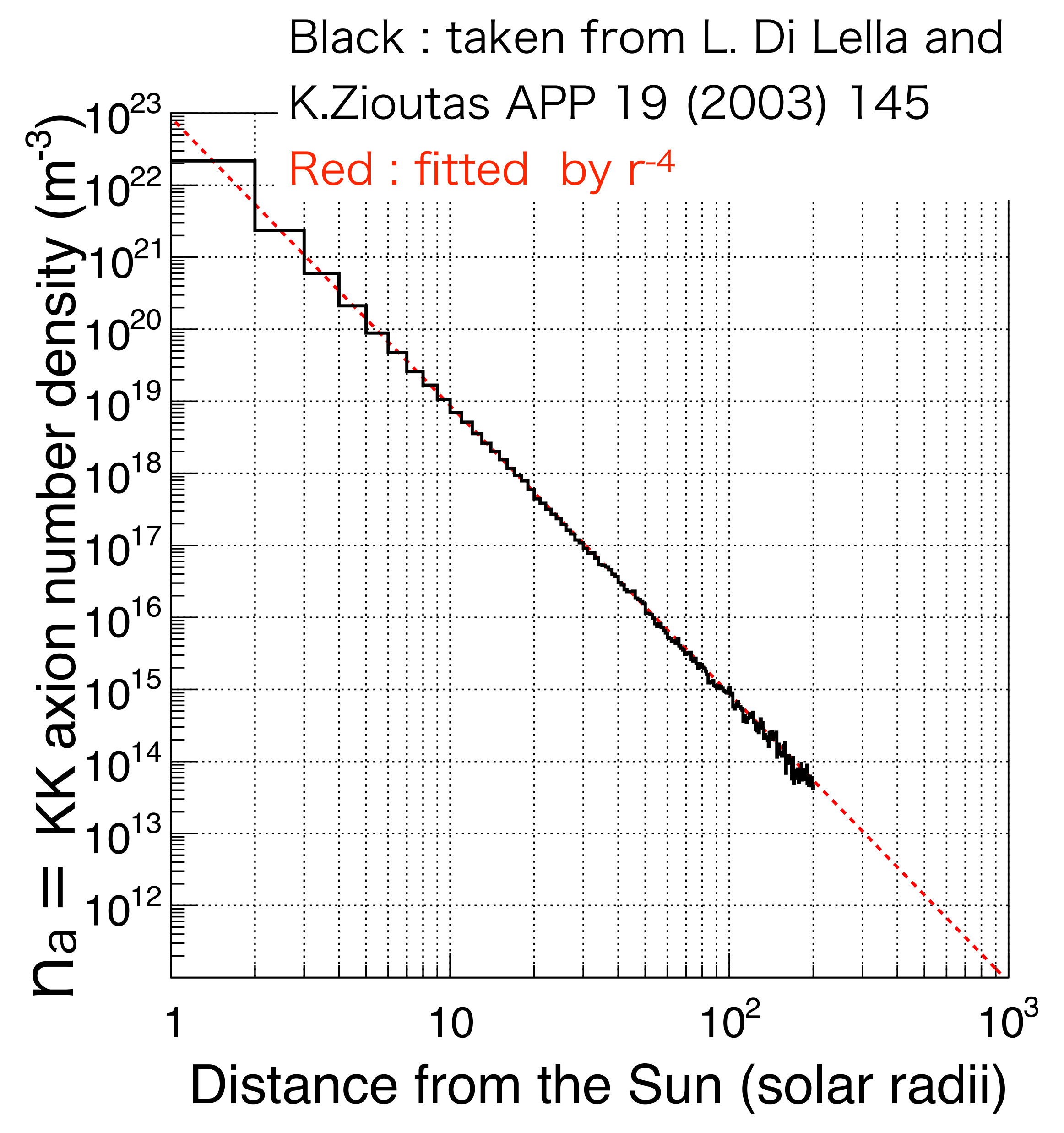
- KK axion would be produced in the Sun via the Primakoff effect ($\gamma Z \rightarrow aZ$) and a photon coalescence mechanism ($\gamma\gamma \rightarrow a$)
- A small fraction is trapped by the gravity of the Sun.
- Such solar/stellar KK axion can explain the solar corona problem and so on by massive axion decay
- In APP 19 (2003) 145, they assume KK axion photon coupling **$g_{a\gamma\gamma}$ = 9.2x10^{-14} GeV^{-1}** by requiring that axion decay is responsible for the X-ray surface brightness of the quiet Sun



Solar KK axion reference : APP 19 (2003) 145, ApJ 607 (2004) 575 and APP 23 (2005) 287 etc.

Introduction of solar KK axion

- we can predict the present density of trapped solar axion with the following assumptions
  - KK axion photon coupling $g_{a\gamma\gamma}$ = 9.2×10^{-14} GeV^{-1}
  - number of extra dimension δ = 2
  - Compactification radius R = 10^3 keV^{-1}
  - Mass splitting of KK axion : 1 eV



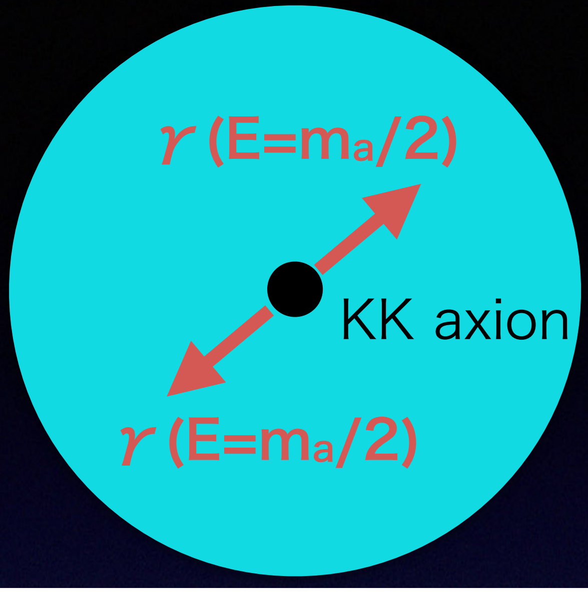
Black : taken from L. Di Lella and K.Zioutas APP 19 (2003) 145

Red : fitted by r^{-4}

$n_a = 4.36\times10^{13}\ m^{-3}$ at perihelion $211.4\ R_\odot$

$n_a = 3.81\times10^{13}\ m^{-3}$ at aphelion $218.6\ R_\odot$

Expected energy spectra



inside the terrestrial det.

- The expected KK axion decay rate R :

$$R = (2.5 \times 10^{11} m^{-3} day^{-1})(\frac{g_{a\gamma\gamma}}{GeV^{-1}})^2(\frac{n_a}{m^{-3}})$$

(B.Morgun et al, APP 23 (2005) 287)

- distance between the Sun and the Earth:

$$r(t) = a(1 - ecos\frac{2\pi(t-t_0)}{T})$$

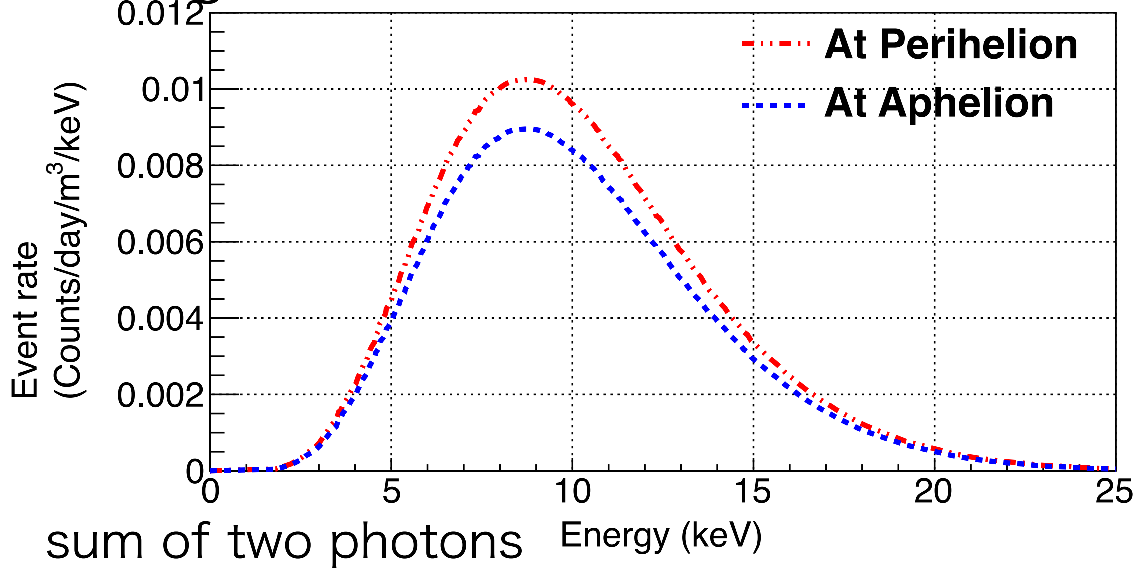
- KK axion density n$_a$ is a function of r^{-4} :

$$n_a(t) = \overline{n}_a(1 - ecos\frac{2\pi(t-t_0)}{T})^{-4}$$

$$\approx \overline{n}_a[1 + 4e(cos\frac{2\pi(t-t_0)}{T}) + \frac{5}{2}ecos^2\frac{2\pi(t-t_0)}{T}]$$

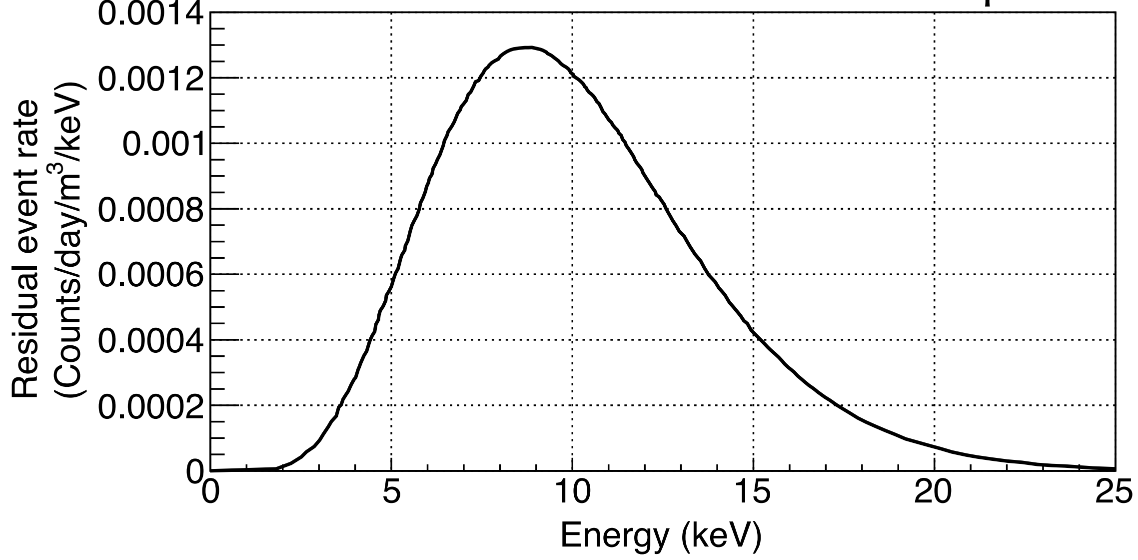
- **Modulated signal is expected**

$g_{a\gamma\gamma}$ = 9.2x10^{-14} GeV^{-1} is assumed



sum of two photons

difference between Perihelion and Aphelion



XMASS-I detector

- Located in the Kamioka mine in Japan (~2700 m.w.e.)
- Single phase liquid xenon detector with 832 kg LXe, 0.288m^3 sensitive volume.
- 642 low background 2inch PMTs : 62% photo-cathodes coverage
- **<u>High light Yield (~15 p.e. / keV) and Low energy threshold</u>**
  - **Energy threshold is enough low to search for solar KK axion.**
- **<u>High sensitivity for e/γ events as well as nuclear recoil</u>**
  - Able to detect Axion Like Particles (ALP), hidden photon, WIMP-Xe inelastic scattering and so on, as well as “Standard” WIMPs
- **<u>Stable data taking over years gives the modulation analysis method</u>**

Φ10m x 10m ultra pure water shield
70 20-inch PMTs for muon veto

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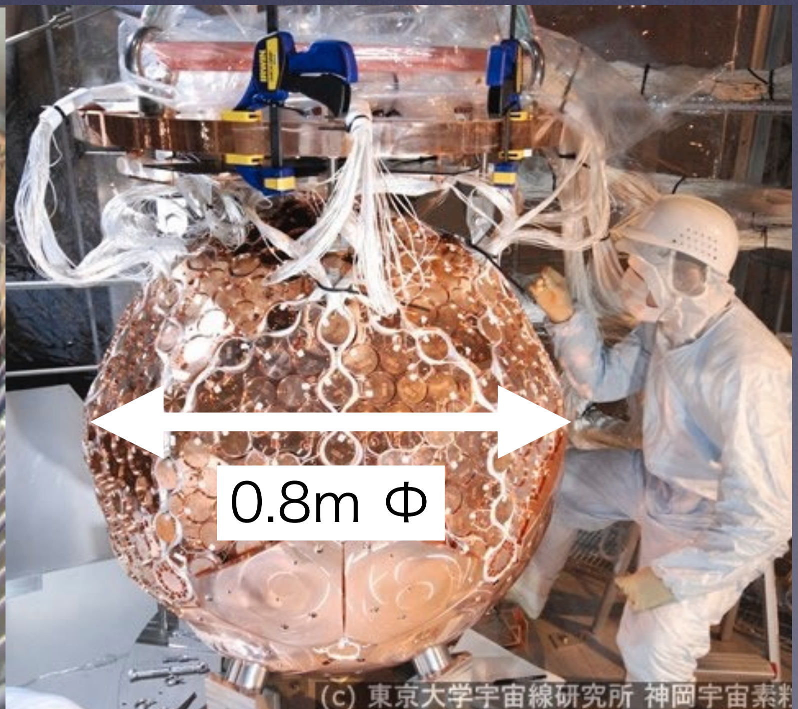

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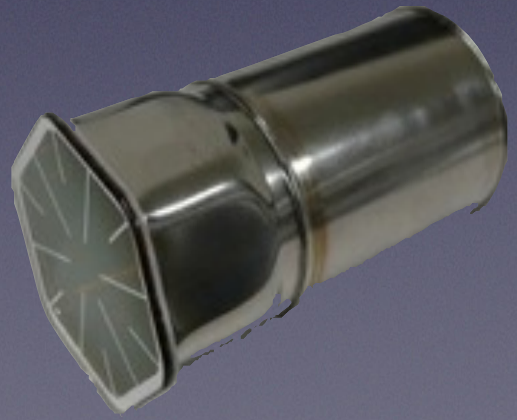
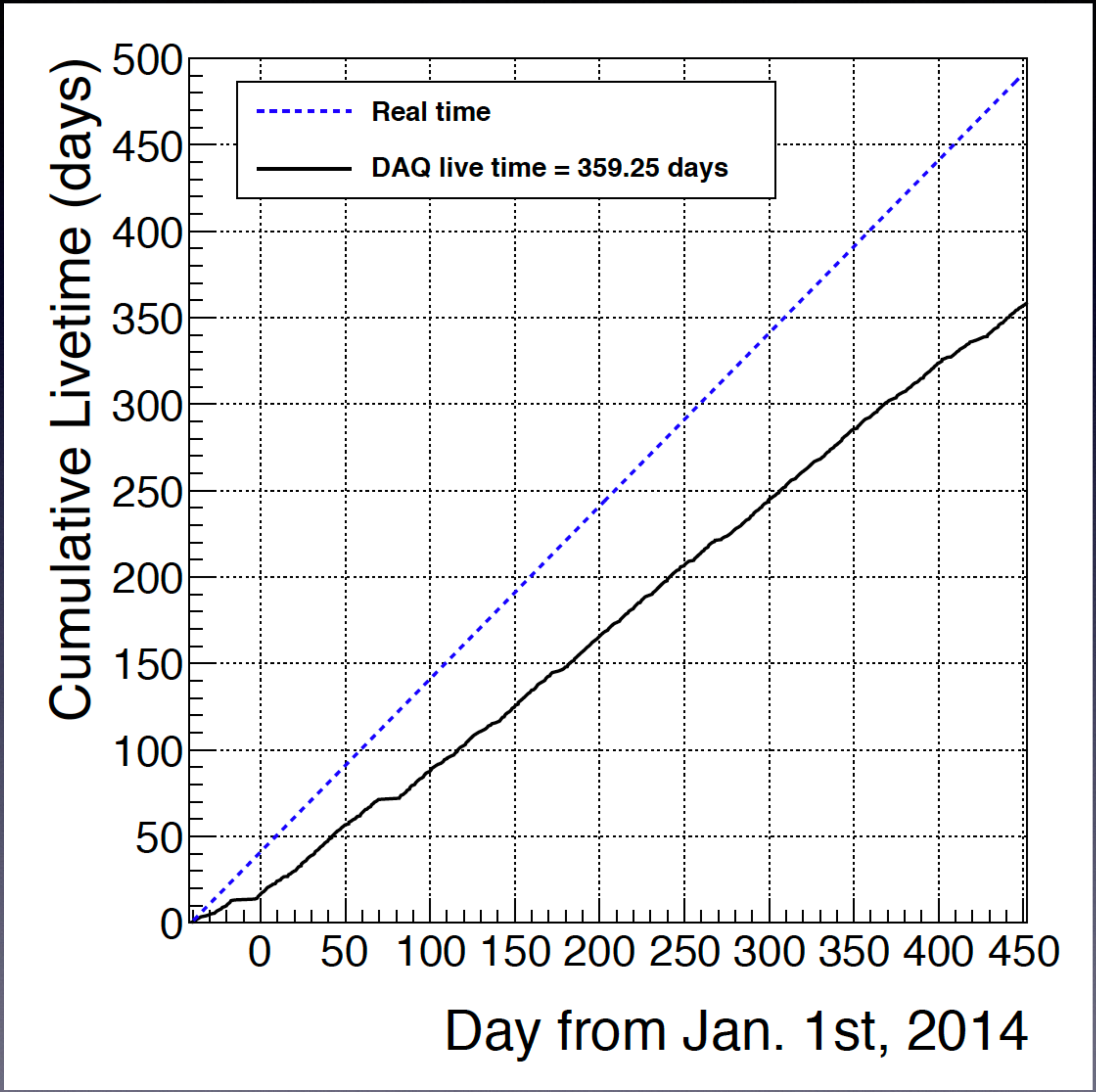
PMT R10789

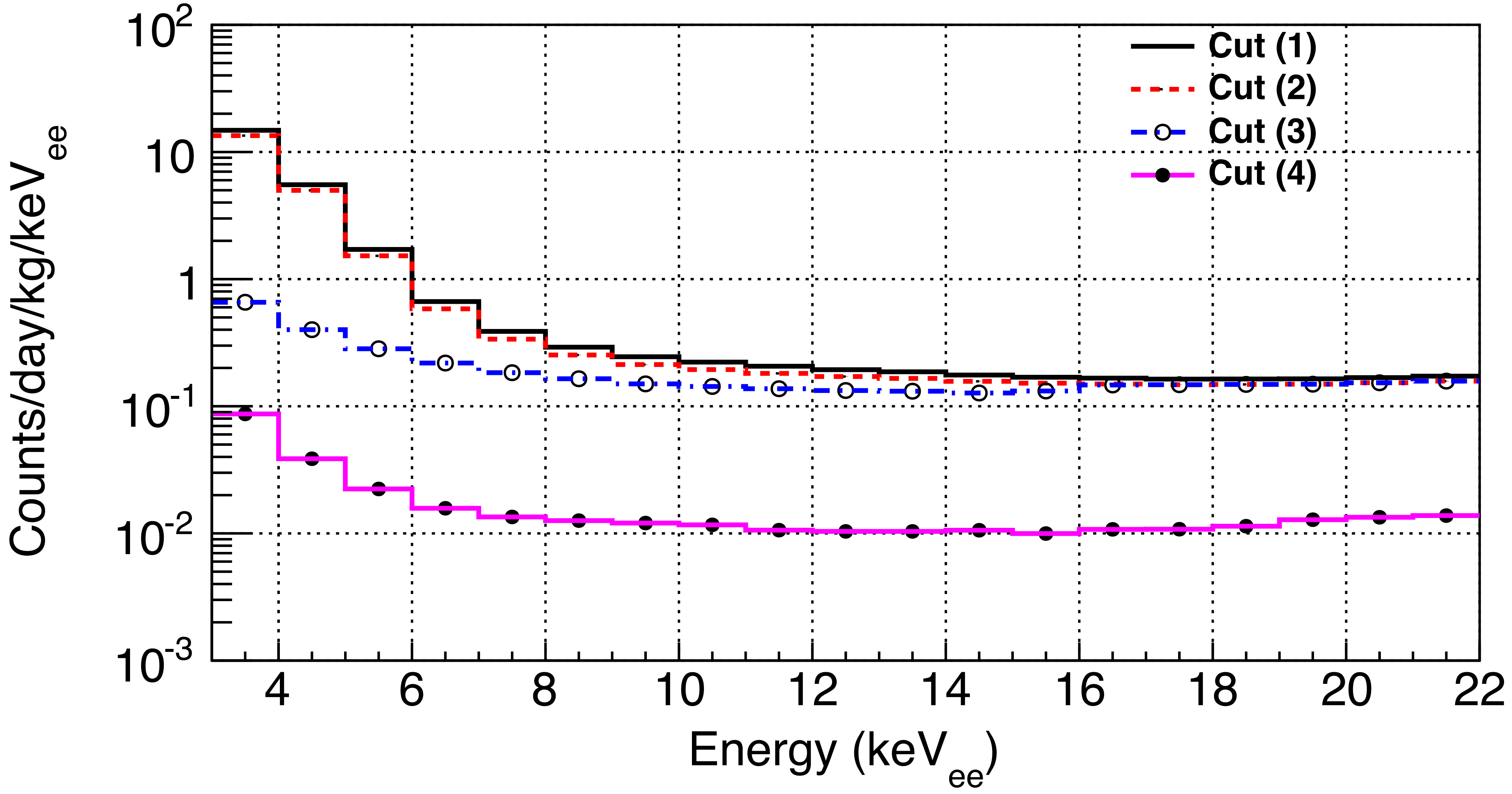


Data set



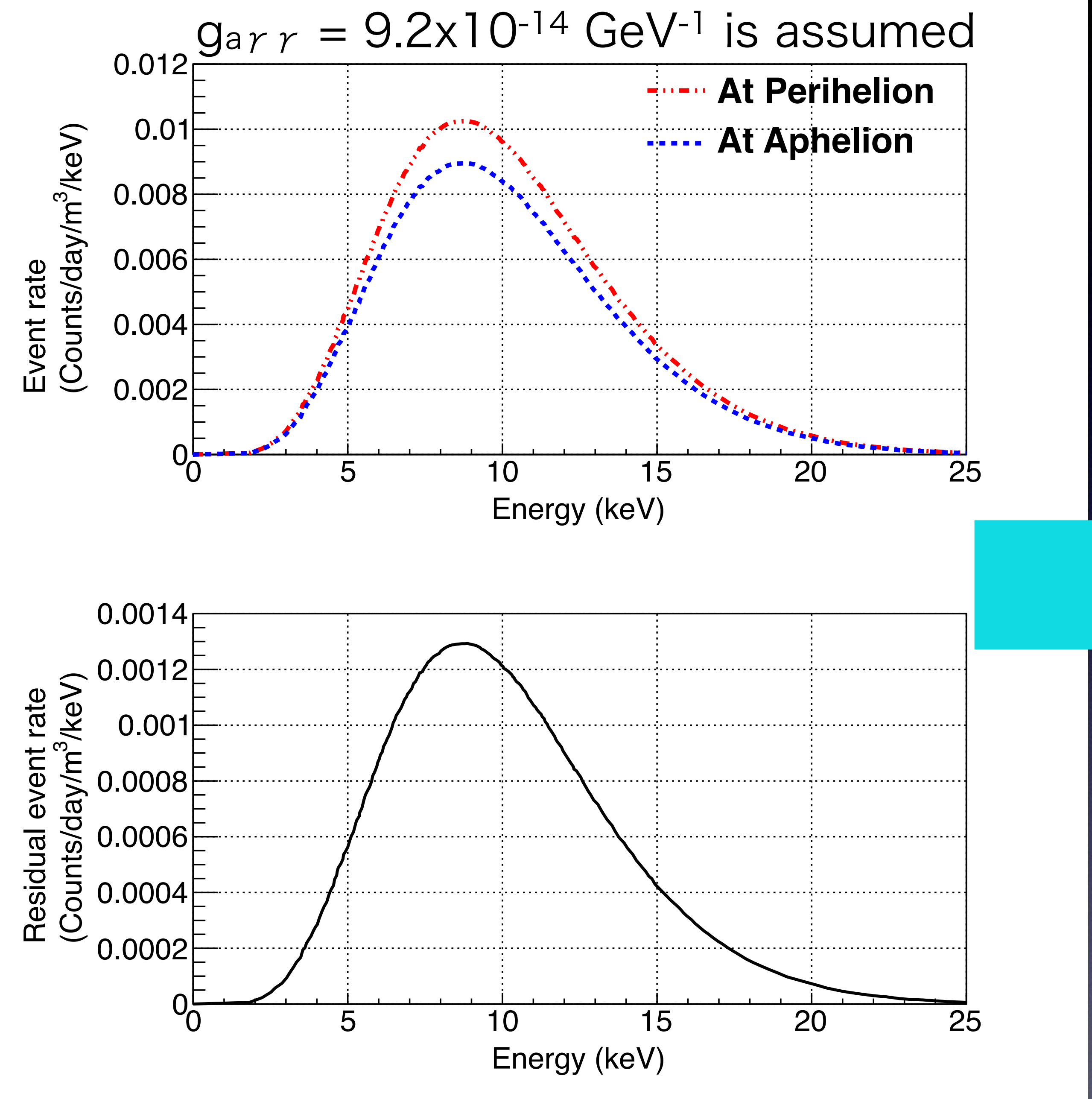
- November 2013 - March, 2015
- 504 calendar days with a total live time of 359 days
  - This data set was used for direct DM search by annual modulation. PLB 759 (2016)64
- Data taking is still ongoing.

Event Selection



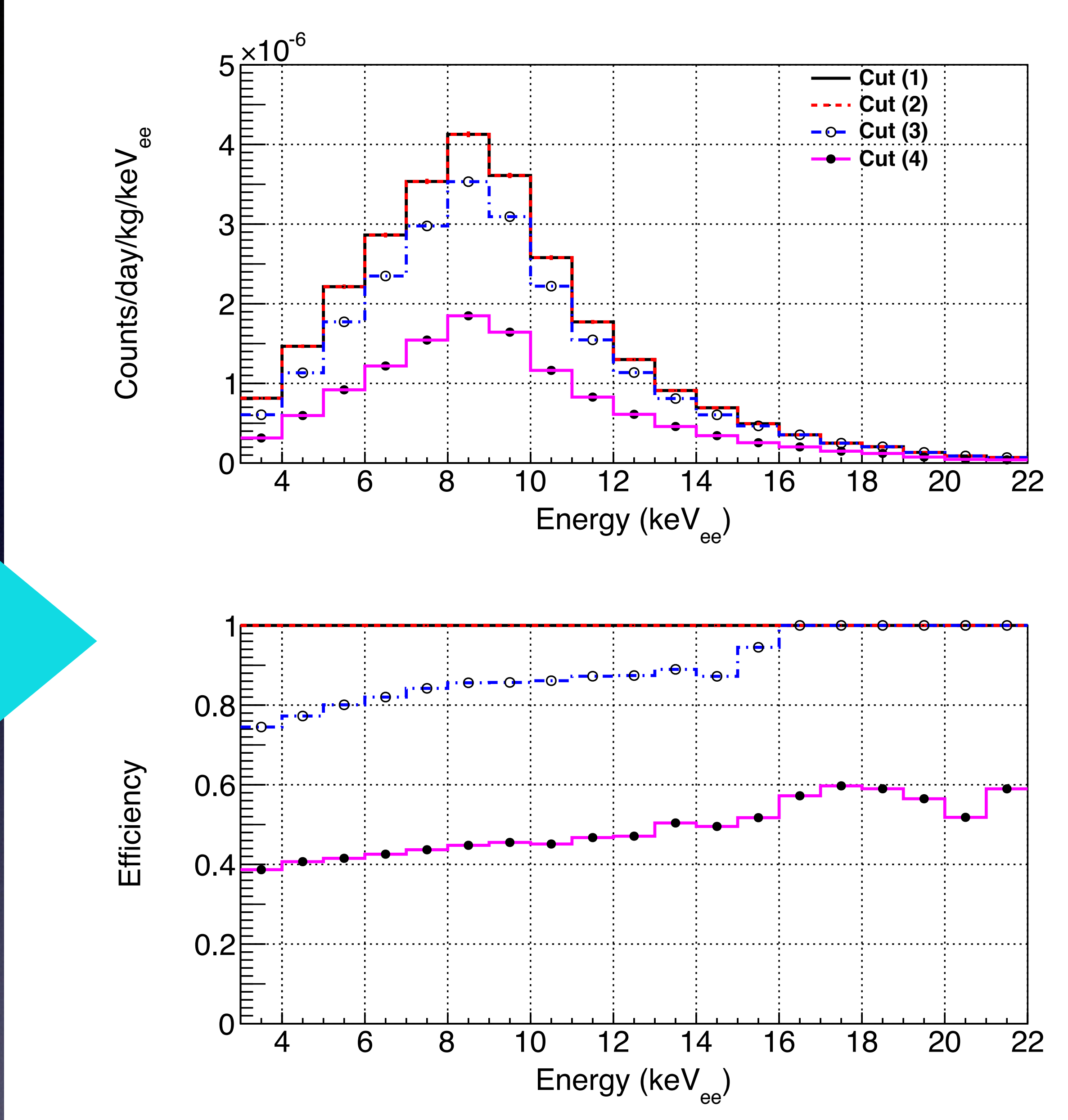
- Cut1 : triggered only by Inner detector, ≧ 4 PMT hits
- Cut2 : Noise events due to afterpulse reduction
    - 10ms veto from previous ID events
    - RMS of hits timing < 100ns
- Cut3 : Cherenkov events reduction
    - # of hits in the first 20ns is < 40% of total hits. which have < 200 observed p.e.
- Cut4 : BG events occurring in front of a PMT window reduction
    - Events which have large MaxPE/TotalPE ratio are removed.

Signal Simulation



Input the decay spectra (sum of 2 photons)
not including detector response

n_a = 4.36x10^{13} m^{-3} at perihelion 211.4 R$_\odot$
n_a = 3.81x10^{13} m^{-3} at aphelion 218.6 R$_\odot$

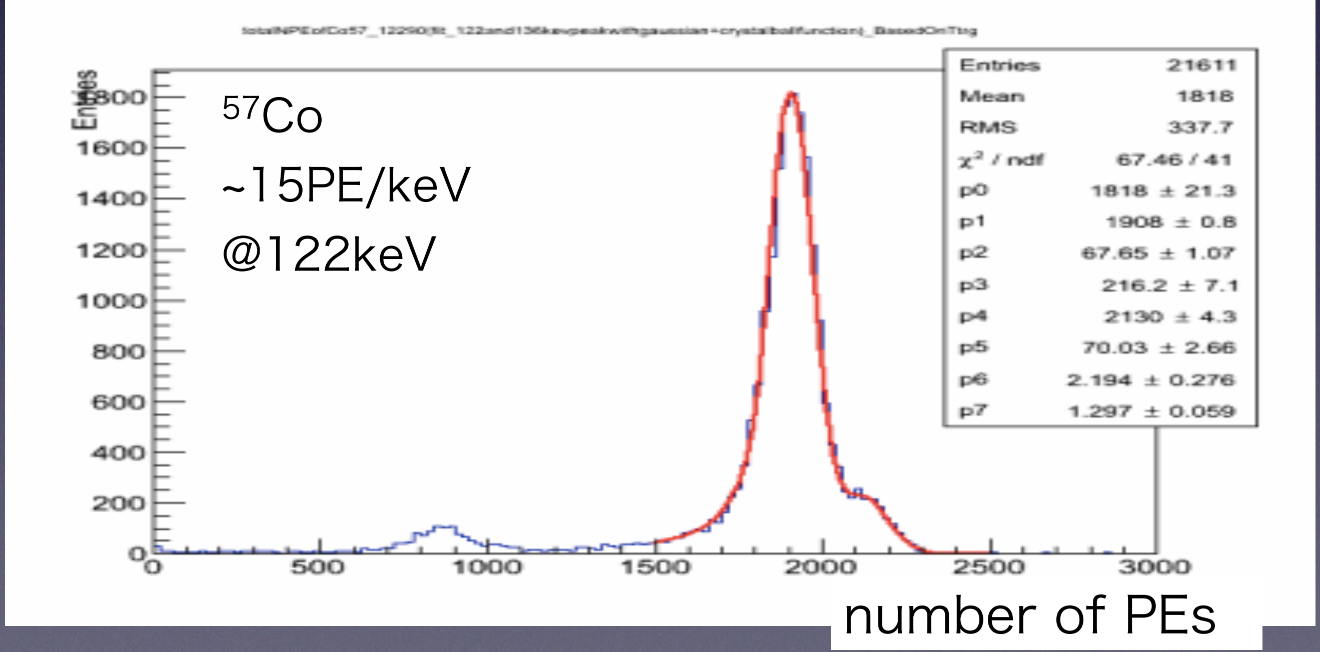


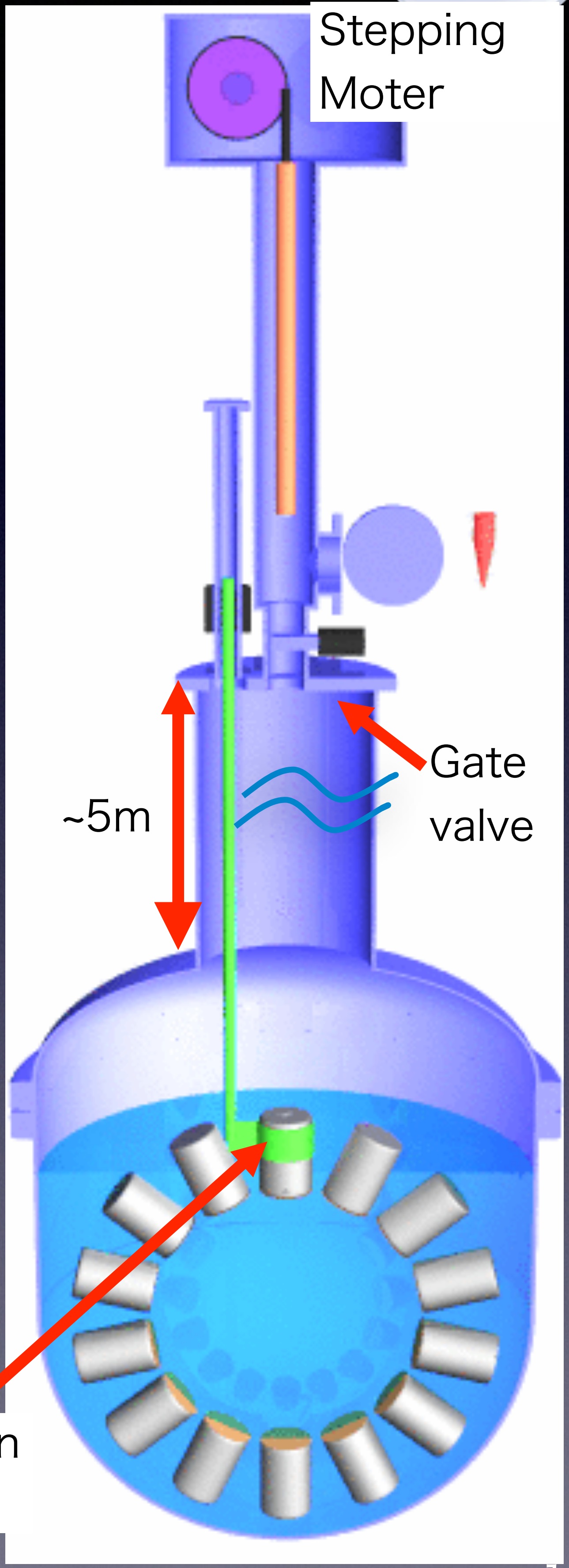
Signal simulation in XMASS-I using Geant4
including detector response
after each cut

Assumption :
Distance = 215.0R$_\odot$, semi major axis
n_a = 4.07 x 10^{13} m^{-3}
$g_{a\gamma\gamma}$ = 9.2x10^{-14} GeV^{-1}

Stability Check by Detector calibration

- Inner Calibration sources : ^{55}Fe, ^{109}Cd, ^{241}Am, ^{57}Co and ^{137}Cs
- The scintillation light yield response was traced by ^{57}Co 122 keV calibration data taken every (bi-)week, from Z=-40cm to +40cm
- Intrinsic light yield of the liquid xenon scintillator, absorption and scattering length for the scintillation light extracted from the data/MC comparison





Stability Check by Detector calibration

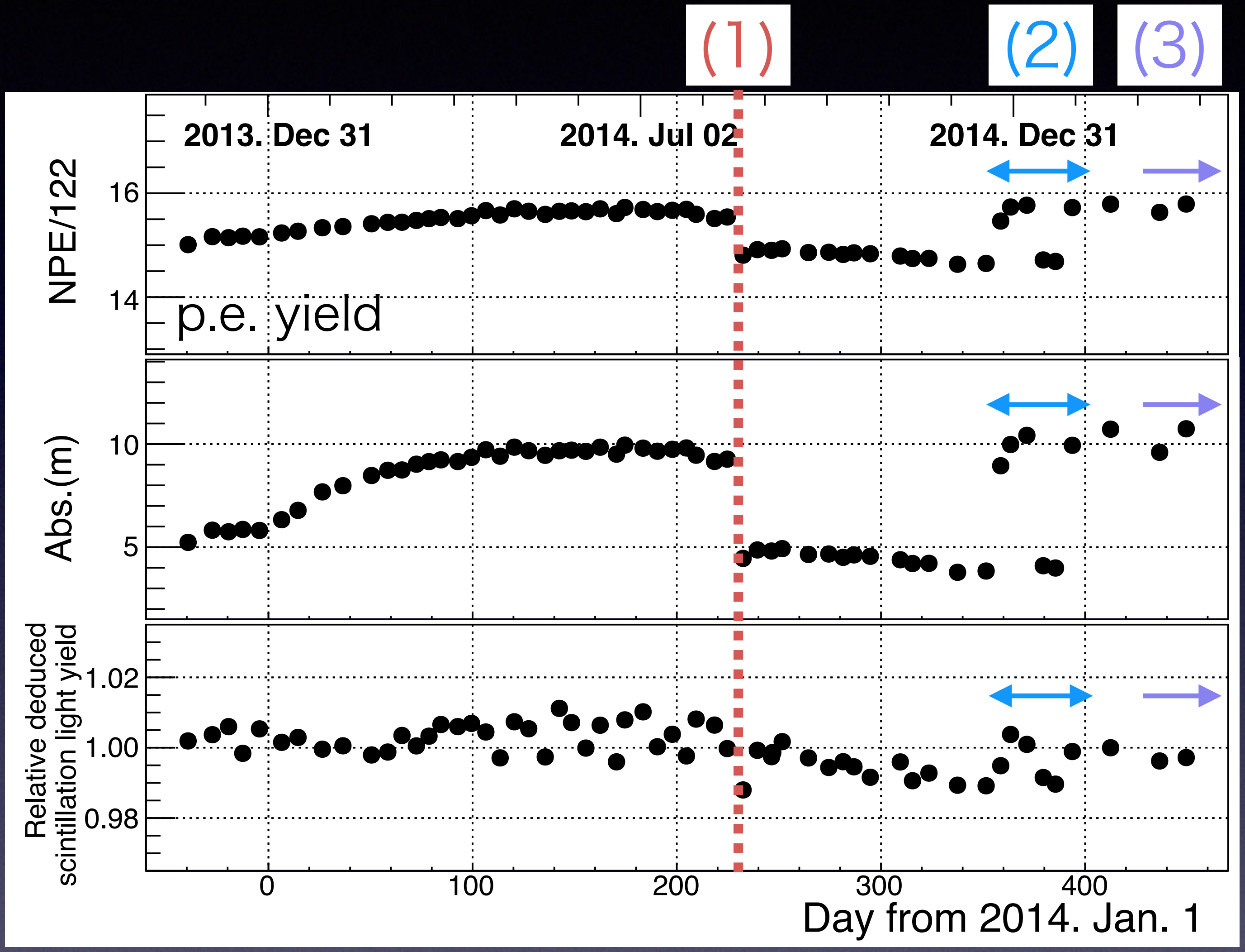
- We take ^{57}Co calibration data every week and we observed p.e. yield changes :

1)sudden drop at the power failure

2)It recovered after purification work in gas phase

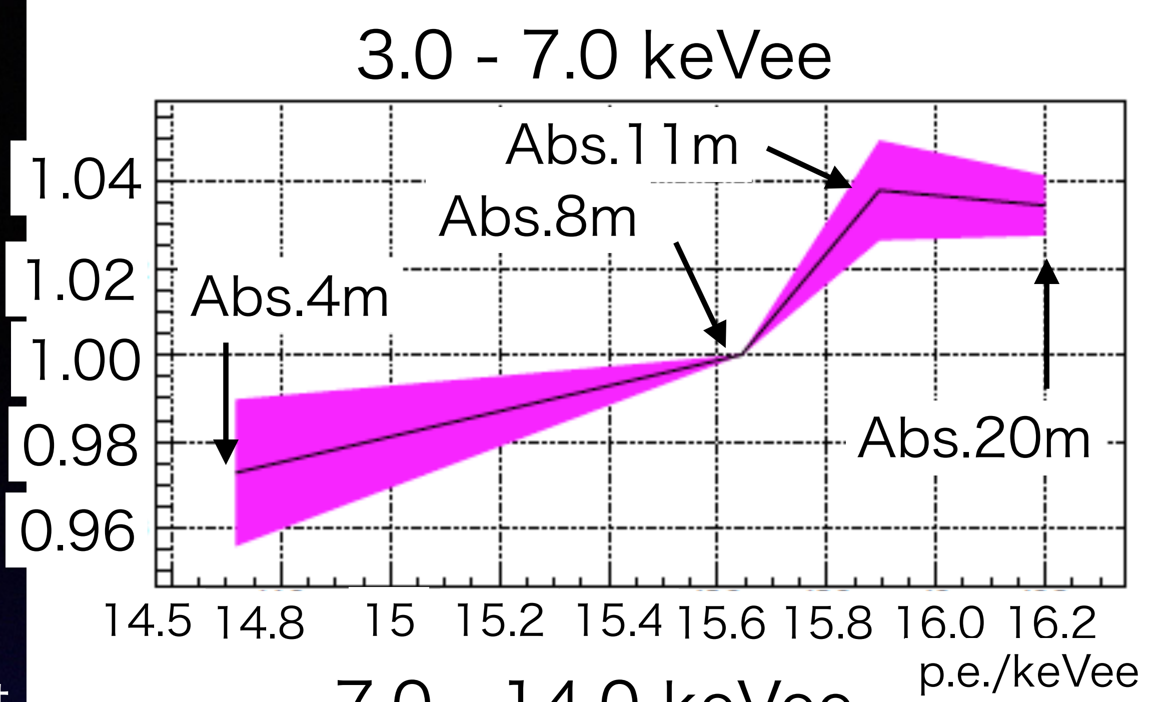
3)we continuously circulate the gas purification

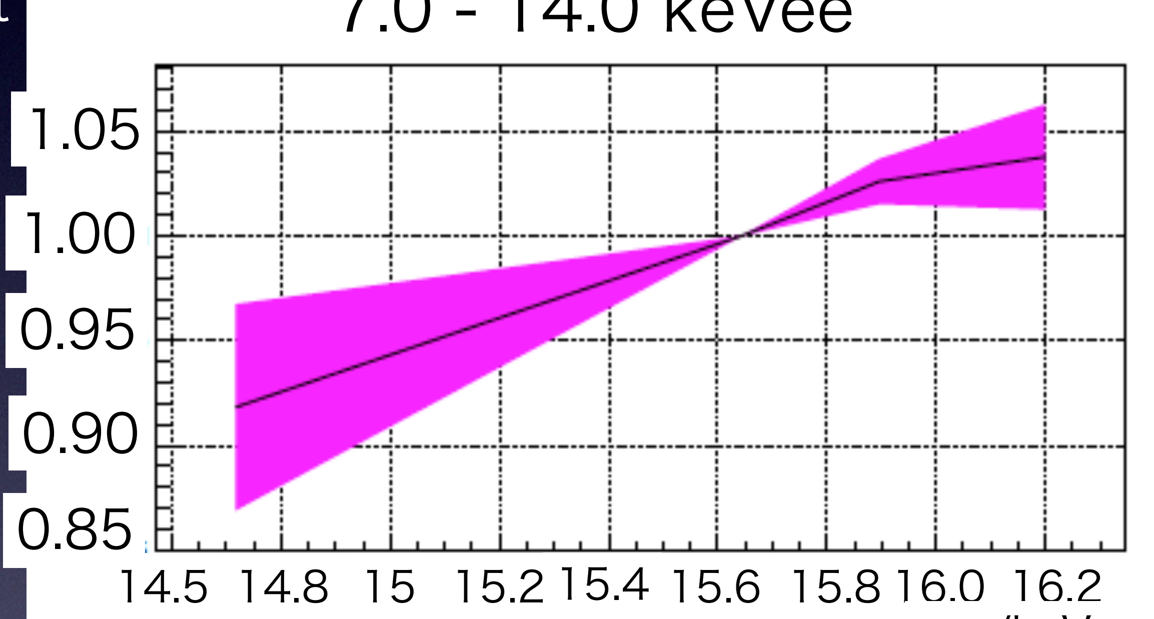
- We can trace observed p.e. yield change as a changes the absorption length.
- Absorption length change : 4m ~ 11m. Uncertainties due to this instability is taken into account.
- Relative intrinsic light yield : stayed within ±1%

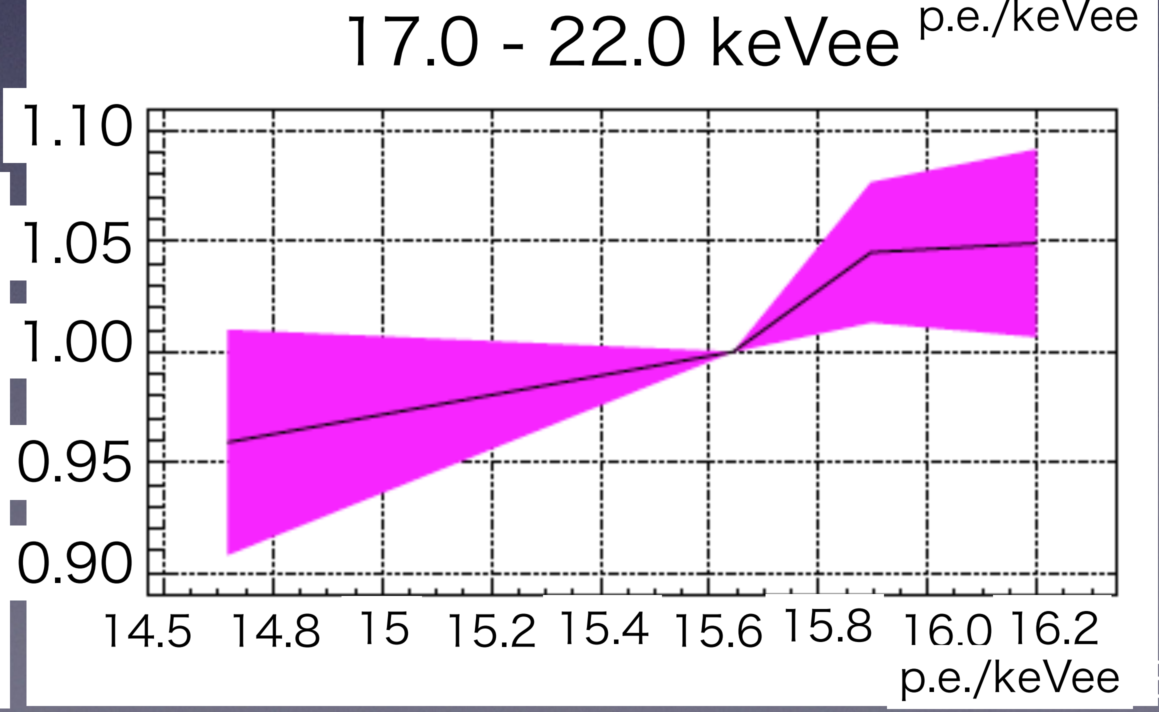


Relative cut efficiency

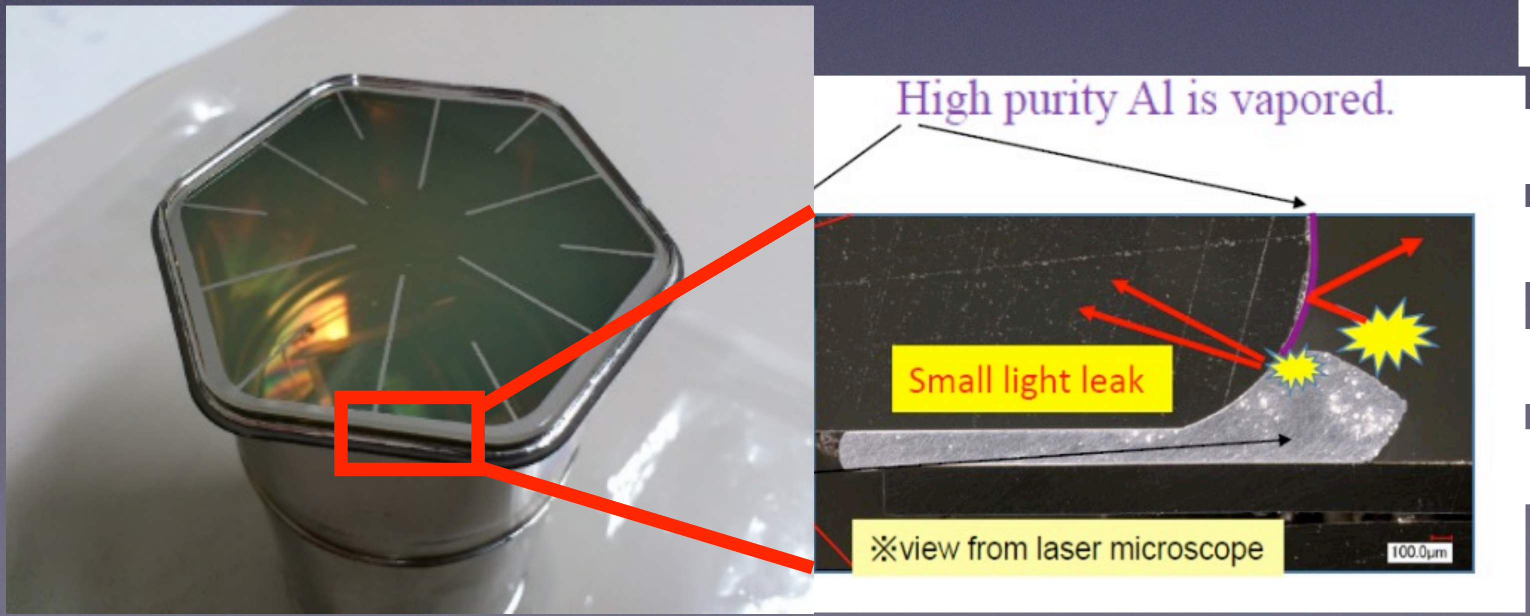
- The change of absorption length affects cut efficiency
- The relative change of cut efficiency is evaluated using BGMC, and data is corrected by this obtained relative efficiency
- MC : Dominant BG, summed up corresponds to its amount
  - U-Chain(^{238}U-^{230}Th, ^{210}Pb) in the Al seal used for PMT window and body
  - ^{210}Pb in the copper plates on the surface of the ID
- Error band : Al seal shape modeling dependence,±5%
- Other error, such as non-linearity of scintillation eff are also taken into account.


3.0 - 7.0 keVee


7.0 - 14.0 keVee


17.0 - 22.0 keVee

PMT R10789



Modulation analysis method

- The data set was divided into 33 time-bin (roughly 15 days each)
- The data in each time-bins were further divided into energy-bin (bin width = 1 keV_{ee})
  - 3-22 keVee, except for 14-17 keVee to avoid systematic effect associated with the end of the range over which the Cherenkov cut is applied
- A least Chi-squares fit all energy/time bins simultaneously to obtain an annual modulation amplitude

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

$K_{i,j}$: relative eff. systematic error

α , β : pull term

$$R^{ex}_{i,j} = \int_{t_j-\frac{1}{2}\Delta t_j}^{t_j+\frac{1}{2}\Delta t_j} [C_i + \xi \times (A_i - \beta L_i)\underbrace{(cos\frac{2\pi(t-t_0)}{T} + \frac{5}{2}ecos^2\frac{2\pi(t-t_0)}{T}]}_{\text{Modulation term}}$$

C_i : constant term

A_i : expected amplitude

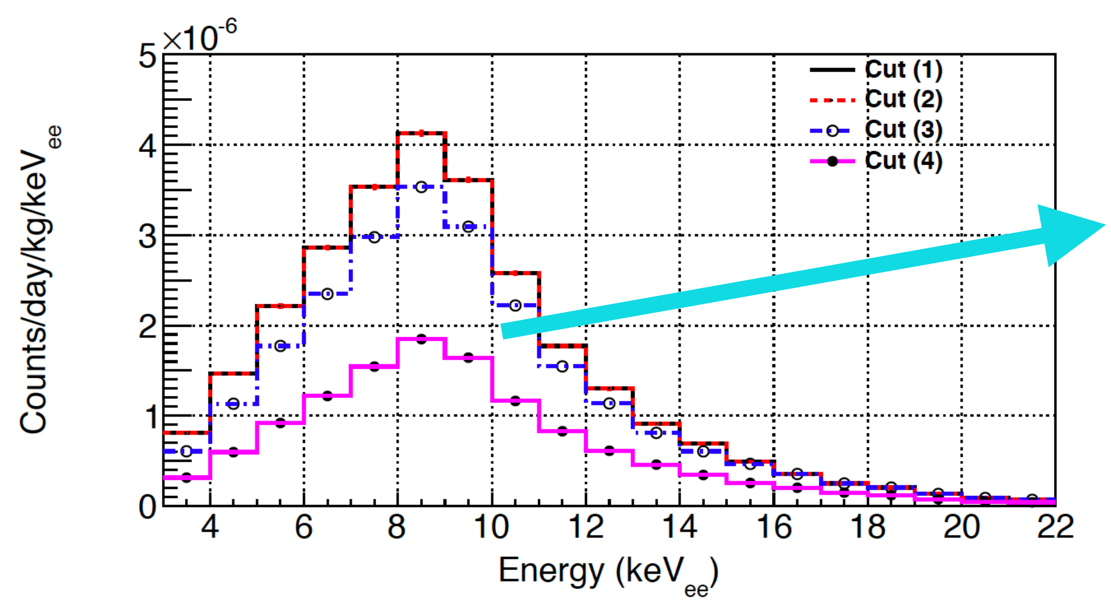
L_i : non-linearity of the scintillation eff.

ξ : the ratio of the expected amplitude between the data and the considered model

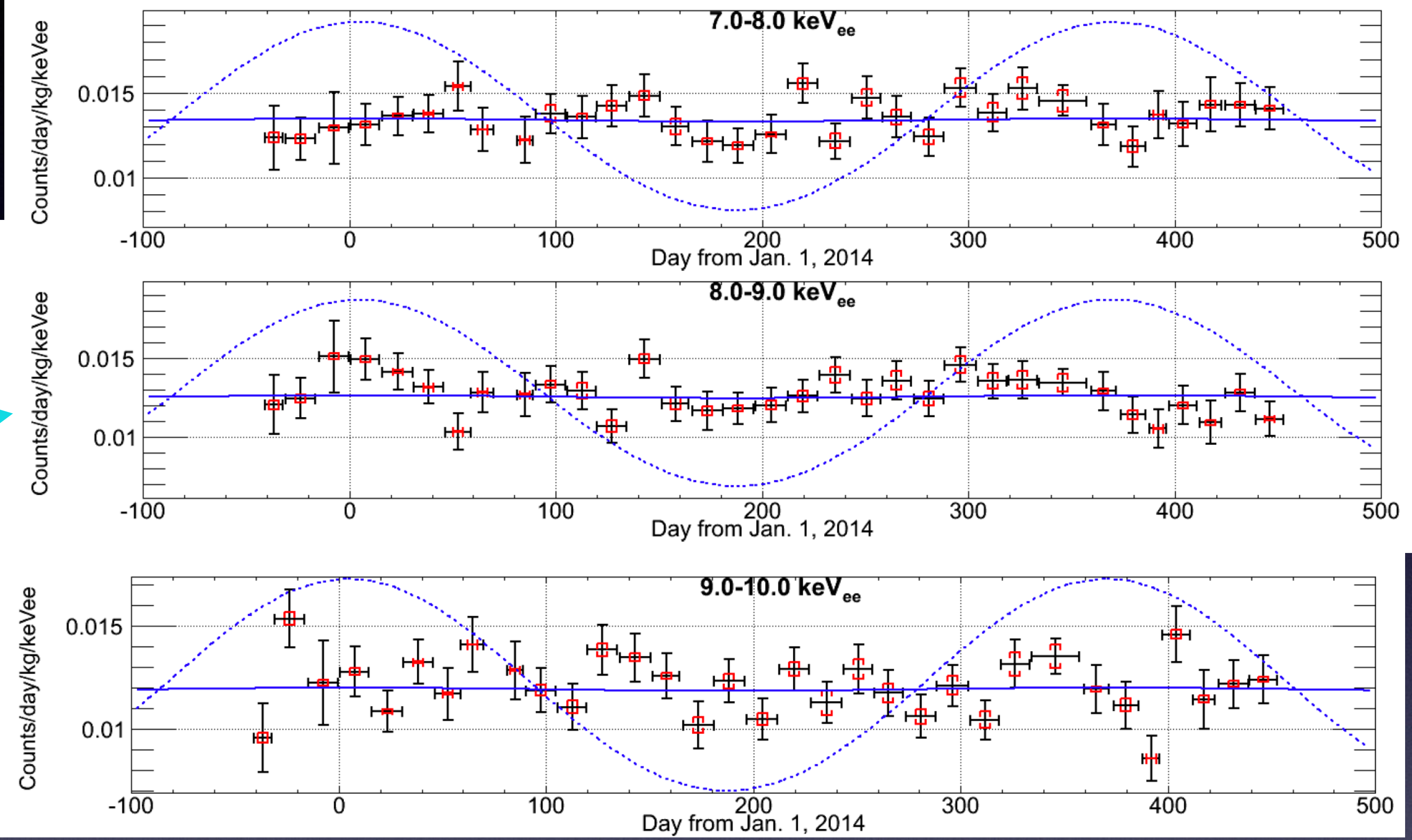
$$\xi = \frac{g^2_{a\gamma\gamma}}{(9.2 \times 10^{-14} GeV^{-1})^2} \frac{\overline{n}_a}{(4.07 \times 10^{13} m^{-3})}$$

Free parameter : C_i and ξ

Time variation of event rate



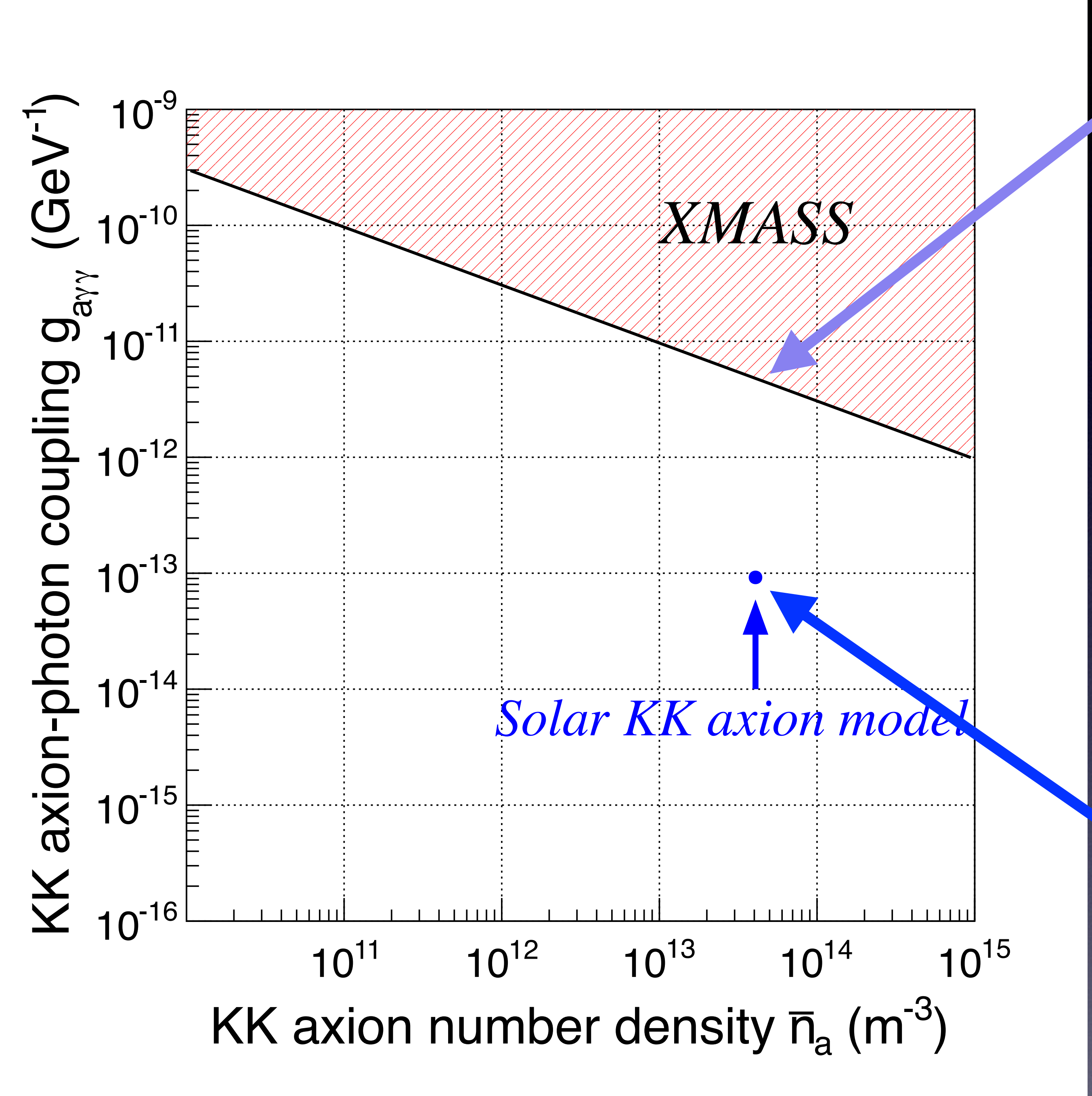
Time variation



- No significant excess in amplitude is found
- Best fit $\xi = 8.2\times10^{2}$ with $\chi^{2}/\mathrm{ndf} = 522.4/492$
- 90% CL upper limit $\xi = 2.7\times10^{3}$
- **$g_{a\gamma\gamma} < 4.8\times10^{-12}$ GeV^{-1} for $\bar{n}_a = 4.07\times10^{13}$m^{-3}**

data
syst.err
(solid):best fit result
(dot) : 90% CL upper limit, x20 enhanced

Result



- $g_{a\gamma\gamma} < 4.8\times10^{-12}$ GeV^{-1} for $\bar{n}_a = 4.07\times10^{13}$ m^{-3}
- Rate < 234 m^{-3} day^{-1} (90% CL)
- First experimental constraint for KK axions
- Submitted to “Progress of Theoretical and Experimental Physics (PTEP)”

Blue point as a benchmark
from L. Di Lella and K.Zioutas APP 19 (2003) 145
To explain X-ray surface brightness of the quiet Sun

$$R = (2.5\times10^{11}m^{-3}day^{-1})\left(\frac{g_{a\gamma\gamma}}{GeV^{-1}}\right)^2\left(\frac{n_a}{m^{-3}}\right)$$

Summary

- Solar KK axion would be produced in the Sun and a small fraction is trapped by the gravity of the Sun. Decays into two photons.
- XMASS searched the decay of solar KK axions by annual modulation (832x359 kg・days)
- No significant excess in amplitude is found. and we set 90% CL upper limit :
- **$g_{a\gamma\gamma} < 4.8\times10^{-12}\ \mathrm{GeV}^{-1}$ for $\bar{n}_a = 4.07\times10^{13}\ \mathrm{m}^{-3}$**
- **This is the First experimental constraint for KK axions.**
- Submitted to Progress of Theoretical and Experimental Physics (PTEP)

Backup

KK axion lifetime

standard electromagnetic coupling

axion model factor ~1

Axion couples to two photons: $g_{\alpha\gamma\gamma} = \frac{\alpha_{EM}}{\pi} \frac{C_a}{f_{PQ}}$

symmetry breaking
energy scale

This implies decay to two photons with mean lifetime: $\tau = \frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3}$

However, astrophysical constraints imply τ too long to observe:

$$10^9 GeV \leq f_{PQ} \leq 10^{12} GeV; 10^{30} \leq t \leq 10^{45} days$$

But propagation in extra dimensions
allows shorter, observable, lifetime

$$m_a = m_{an} \sim \frac{n}{R}$$

Solar KK axion mass spectrum

Basis for an experimental search:

B. Morgan, N. Spooner et al, D. Hoffmann et al., K. Zioutas...

B. Morgan et al. Astrop. Phys 23 (2005) 287,

- **Leads to differential decay spectrum:**

$$\frac{dR}{dm_a} = \frac{g_{a\gamma\gamma}^2}{64\pi} n_0 m_a^3 f(m_a)$$

$$R = (2.5\times10^{11} m^{-3} day^{-1}) \left(\frac{g_{a\gamma\gamma}}{GeV^{-1}}\right)^2 \left(\frac{n_0}{m^{-3}}\right) \Longrightarrow$$

Typical rate ~ 1 m^{-3} day^{-1} (~keV events)

Result for trapped axions in orbits around Sun $g_{a\gamma\gamma} = 9.2\times10^{-14} GeV^{-1}$ $n_0 = 10^{14} m^{-3}$
(local number density depends on $g_{a\gamma\gamma}$)

Mass spectrum for solar axions trapped in orbits around the sun

L. Di Lella and K. Zioutas, Astrop. Phys., 19 (2003) 145