YITP Workshop MiN16
July 31-August 2, 2016

BGOegg experiments at LEPS2

χSR and axial U(1) anomaly

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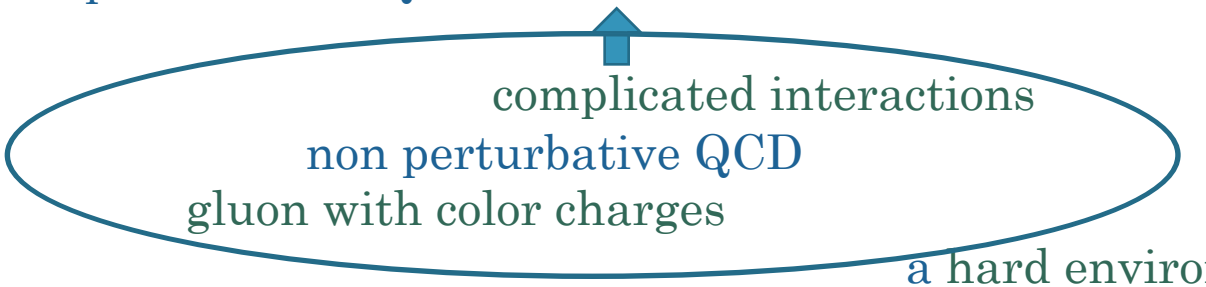
BGOegg-LEPS2 Collaboration

- Motivation
  - mass generation of hadrons
  - axial U(1) anomaly
  - η′ in nuclear matter
- Construction of BGOegg
- Capabilities of BGOegg
- Summary

Mass generation of hadrons
(in light quark sectors)

- QCD in the standard model
  - Non perturbative QCD sectors are still not well understood.



a hard environment

  - Questions to be solved in QCD:
    confinement and mass generation of hadrons
  - Effective theories and lattice QCD have been working well for the subject of hadron mass generation.

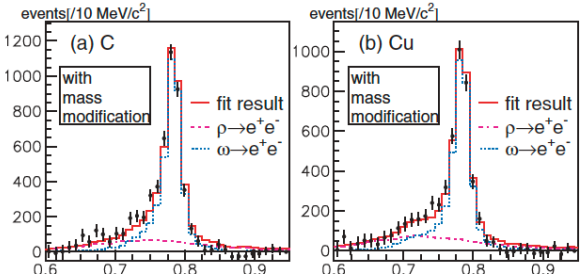
- Scenario of hadron mass generation ⇐ SBχS
  - $\bar{q}q$ condensation in the vacuum mainly determines hadron masses.
    $M = m - 2g\langle\bar{q}q\rangle$ for constituent quark masses
  - ⟨q̄q⟩ is expected to change in the nuclear medium. ⇐ **experiments**

What about experimental evidence for this scenario?

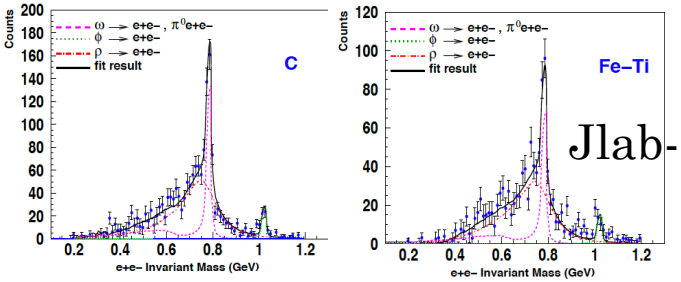
Experimental results
(fixed-target experiments)

- Dilepton decay of vector mesons in the nuclear medium

ρ/ω



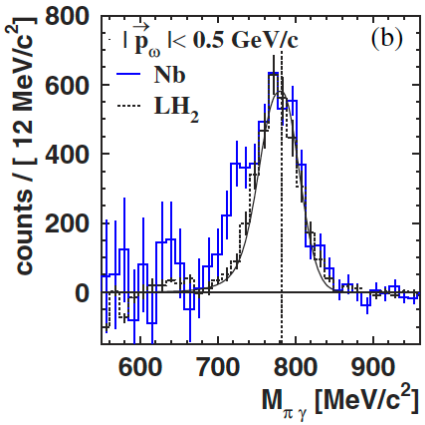
KEK-E325



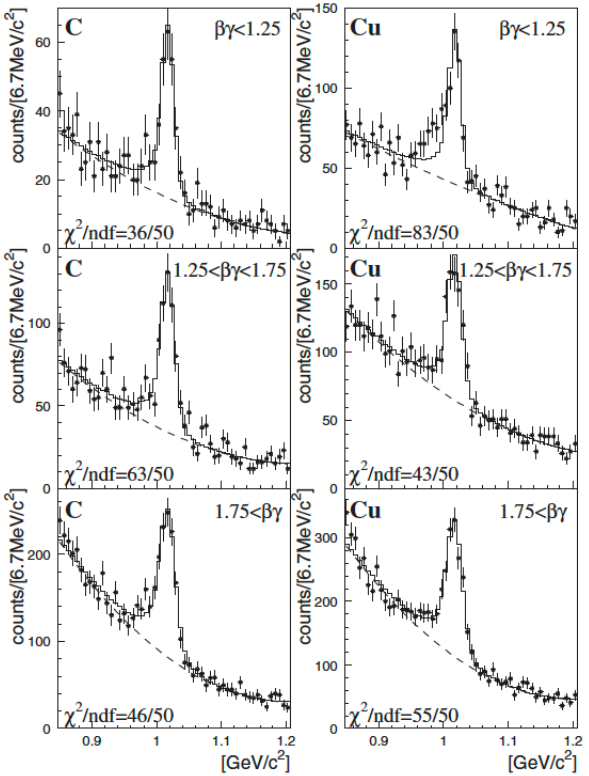
Jlab-CLAS

$\omega \to \pi^0\gamma$

CBELSA/TAPS



$\phi \to e^+e^-$



We need more experiments with more statistics!

$U(1)_A$ anomaly

$$\psi = \begin{pmatrix} q_1 \\ q_2 \\ q_3 \end{pmatrix} = \begin{pmatrix} u \\ d \\ s \end{pmatrix}, \qquad m = \begin{pmatrix} m_1 & 0 & 0 \\ 0 & m_2 & 0 \\ 0 & 0 & m_3 \end{pmatrix} \quad m_i < \Lambda_{QCD}$$

- Classical QCD Lagrangian

$$\mathcal{L}_{QCD} = \bar{\psi}(i\gamma^\mu D_\mu - m)\psi - \frac{1}{4}F^a_{\mu\nu}F^{\mu\nu a}$$

- $U(3)_L \otimes U(3)_R$ chiral symmetry

$$U(3)_L \otimes U(3)_R \simeq U(1)_V \otimes U(1)_A \otimes SU(3)_V \otimes SU(3)_A$$

- Noether currents (classical fields)

$$\begin{aligned} \partial_\mu(\bar{\psi}\gamma^\mu\psi) &= 0 \\ \partial_\mu(\bar{\psi}\gamma^\mu\gamma_5\psi) &= 2im_i\bar{q}_i\gamma_5 q_i \simeq 0 \\ \partial_\mu(\bar{\psi}\gamma^\mu\lambda^a\psi) &= i(m_i - m_j)\bar{q}_i\lambda^a q_j \simeq 0 \\ \partial_\mu(\bar{\psi}\gamma^\mu\gamma_5\lambda^a\psi) &= i(m_i + m_j)\bar{q}_i\lambda^a q_j \simeq 0 \end{aligned}$$

topological charge operator

- Axial U(1) current (quantum fields) (No change for other currents)

$$\partial_\mu(\bar{\psi}\gamma^\mu\gamma_5\psi) = 2im_i\bar{q}_i\gamma_5 q_i + 2N_F\frac{1}{8\pi}\frac{g^2}{4\pi}F^a_{\mu\nu}\tilde{F}^{a\mu\nu} \neq 0$$

- An effective theory based on the NJL model $[U(3)_L \otimes U(3)_R]$

$$\mathcal{L} = \bar{\psi}(i\partial\!\!\!/ - m)\psi + \frac{g_S}{2}[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2] \quad \hookrightarrow U(1)_V \otimes SU(3)_L \otimes SU(3)_R$$

$$+ g_D[\det \bar{q}_i(1-\gamma_5)q_j + h.c.] \quad \text{KMT interaction} \quad \cancel{U(1)_A}$$

Pioneering works with this Lagrangian: T. Kunihiro, PLB219(1989)363, NPB351(1991)593, …

$\eta'(\eta_0)$ meson in nuclear matter

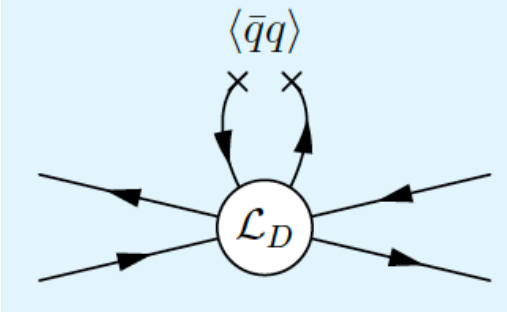
- SB $SU(3)_L \otimes SU(3)_R$ chiral symmetry due to $\langle \bar{\psi}\psi \rangle \neq 0$

$$SU(3)_L \otimes SU(3)_R \simeq SU(3)_V \otimes SU(3)_A$$

not fully broken — SB in the χ limit

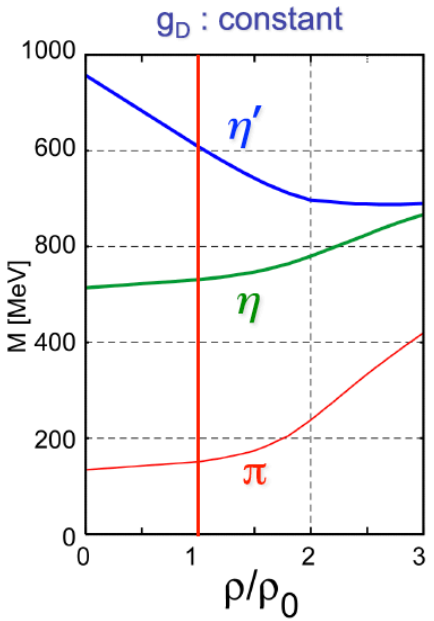
8 PS NG bosons $(3\pi, 4K, \eta)$

- Partial restoration of χS expected in the nuclear medium ➡ $|\langle \bar{\psi}\psi \rangle| \downarrow$
- Strong reduction of η' mass predicted by NJL model + KMT interaction



$\Delta m_{\eta'} \approx 150\ MeV\ @\ \rho_0$

KMT terms contribute to η' mass



H. Nagahiro et al.
PRC74 (2006) 045203

➡ A bound state of η' and a nucleus exists?
(search for an η' mesic nucleus)

➡ $U(1)_A$ symmetry restoration when χSR.

A simple question

Does χS restoration affect $U_A(1)$ restoration?

- $U_A(1)$ anomaly is originated from quantum effects of gluon fields.
- KMT terms are introduced in effective theories to break $U_A(1)$ symmetry.

topological charge $\overset{?}{\Leftrightarrow}$ **6 quark interaction**

➢ Jido Daisuki PRC85(2012)032201
[T.D. Cohen, PRD54(1996)1867, SH. Lee, T. Hatsuda, PRD54(1996)1871]

$\mathcal{L}_{QCD}$: $SU(3)_L \otimes SU(3)_R$ chiral symmetry (no $U(1)_A$ symmetry)
invariant under octet axial transformations Q_5^a

$$\eta_0 \sim \bar{q} i\gamma_5 q \quad \Rightarrow \quad [iQ_5^a, \eta_0] = \bar{q}\frac{\lambda^a}{\sqrt{6}}q \sim S^a$$ mixed with S_8

$$S^b \quad \Rightarrow \quad [iQ_5^a, S^b] = d^{abc}\bar{q} i\gamma_5 \frac{\lambda^c}{\sqrt{6}}q \sim d^{abc}P^c$$

- η_0 and η_8 are mixed to each other.
- Rχ S ⟹ η_0 and η_8 degenerate

$$\left[\frac{\lambda^a}{2}, \frac{\lambda^b}{2}\right] = if^{abc}\frac{\lambda^c}{2}, \qquad \left\{\frac{\lambda^a}{2}, \frac{\lambda^b}{2}\right\} = d^{abc}\frac{\lambda^c}{2}$$

➢ Su Houng Lee IJMP E22(2013)1330008 and talk yesterday

- $m_{\eta'}^2$ ⟹ 0 at high T ⟸ pseudo scalar gluonic correlators

As far as the arguments over symmetry effective theories with KMT terms seem to work.

Have to be verified experimentally

General requirements for a meson

in the measurement of character change in the nuclear medium

$$m - i\Gamma/2$$

- *Appropriate mesons to be investigated:*

✓ **$\Gamma \geq 10$ MeV to get meson decay inside a nucleus effectively**

✓ **a decay channel including no strong interacting particles**

➡ **The meson should have an EM decay channel as well as strong decay channels**

	π^0	η	σ	ρ^0	ω	η'	ϕ
m (MeV)	135	548	500	775	783	958	1019
Γ	7.8eV	1.3keV	~500MeV	149MeV	8.5MeV	198keV	4.3MeV
EM decay	$\gamma\gamma$	$\gamma\gamma$	$\gamma\gamma$	l^+l^-	l^+l^-	$\gamma\gamma$	l^+l^-
BR	99%	39%	$\sim 10^{-5}$	$\sim 5 \times 10^{-5}$	$\sim 7 \times 10^{-5}$	2.2%	$\sim 3 \times 10^{-4}$

$\Gamma_{EM} \approx O(keV)$

○ ○ ○ △ ○

meet the requirements

Metag says, “Hopeless!”

Measurements of the spectral function of η′ in the nuclear medium

$\eta' \to \gamma\gamma$

- Determination of the η′-nucleus optical potential by CBELSA/TAPS
  - η′–A optical potential

$$U = V + iW$$
$$V = -(40 \pm 8 \pm 15)\ \text{MeV}$$
$$W = -(13 \pm 3 \pm 3)\ \text{MeV}$$

  - in-medium width of η′ @ ρ_0

$$\Gamma_0 \approx 26\ \text{MeV}$$

Metag's talk
PLB727 (2013) 417
PLB710 (2012) 600

$T_A^C = \frac{12 \cdot \sigma_{\gamma A \to \eta' X}}{A \cdot \sigma_{\gamma C \to \eta' X}}$ transparency ratio

- Propagator of η′(958) with momentum p

$$i\Delta(p;\rho) = \frac{i}{p^2 - m^2 - \Sigma(p;\rho)}$$

self energy

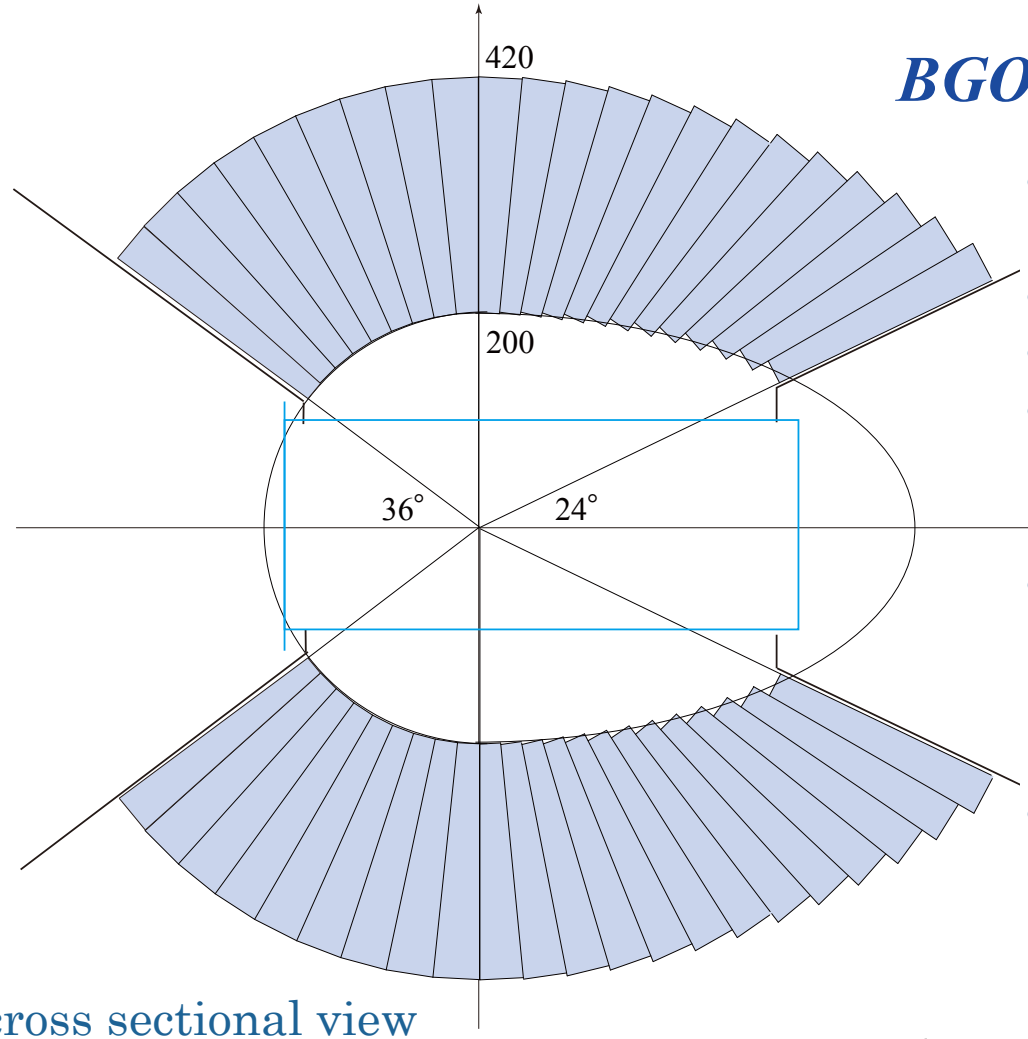
η′ meson in A

m	**958 MeV?**
Γ_0	**~26 MeV**
$\Gamma_{\gamma\gamma}/\Gamma_0$	**~10^{-4}**

- Spectral function of η′

$$S(p;\rho) = -\frac{1}{\pi}\frac{\text{Im}\Sigma(p;\rho)}{[p^2 - m^2 - \text{Re}\Sigma(p;\rho)]^2 + [\text{Im}\Sigma(p;\rho)]^2}$$

Construction of BGOegg



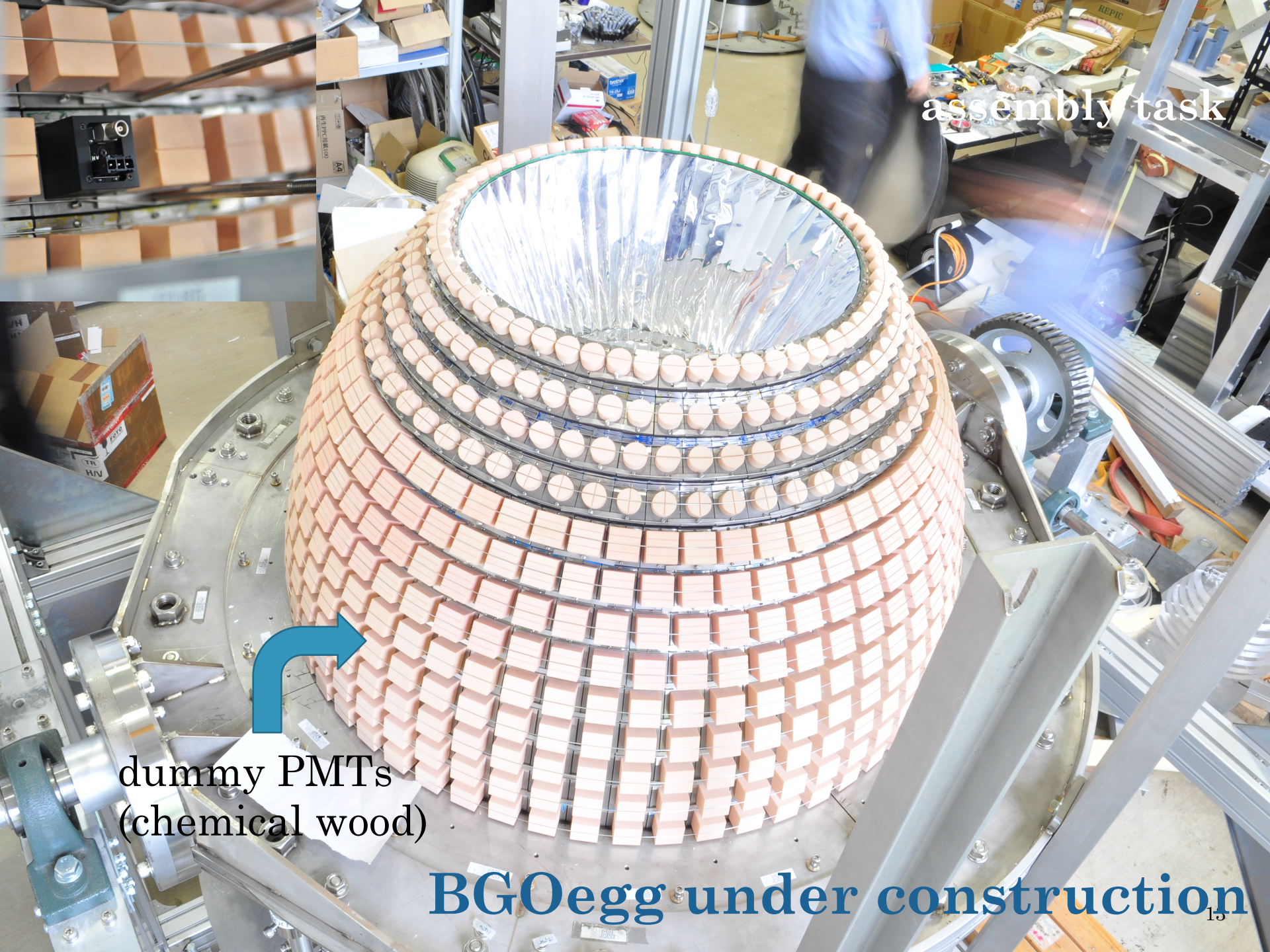
cross sectional view

BGOegg

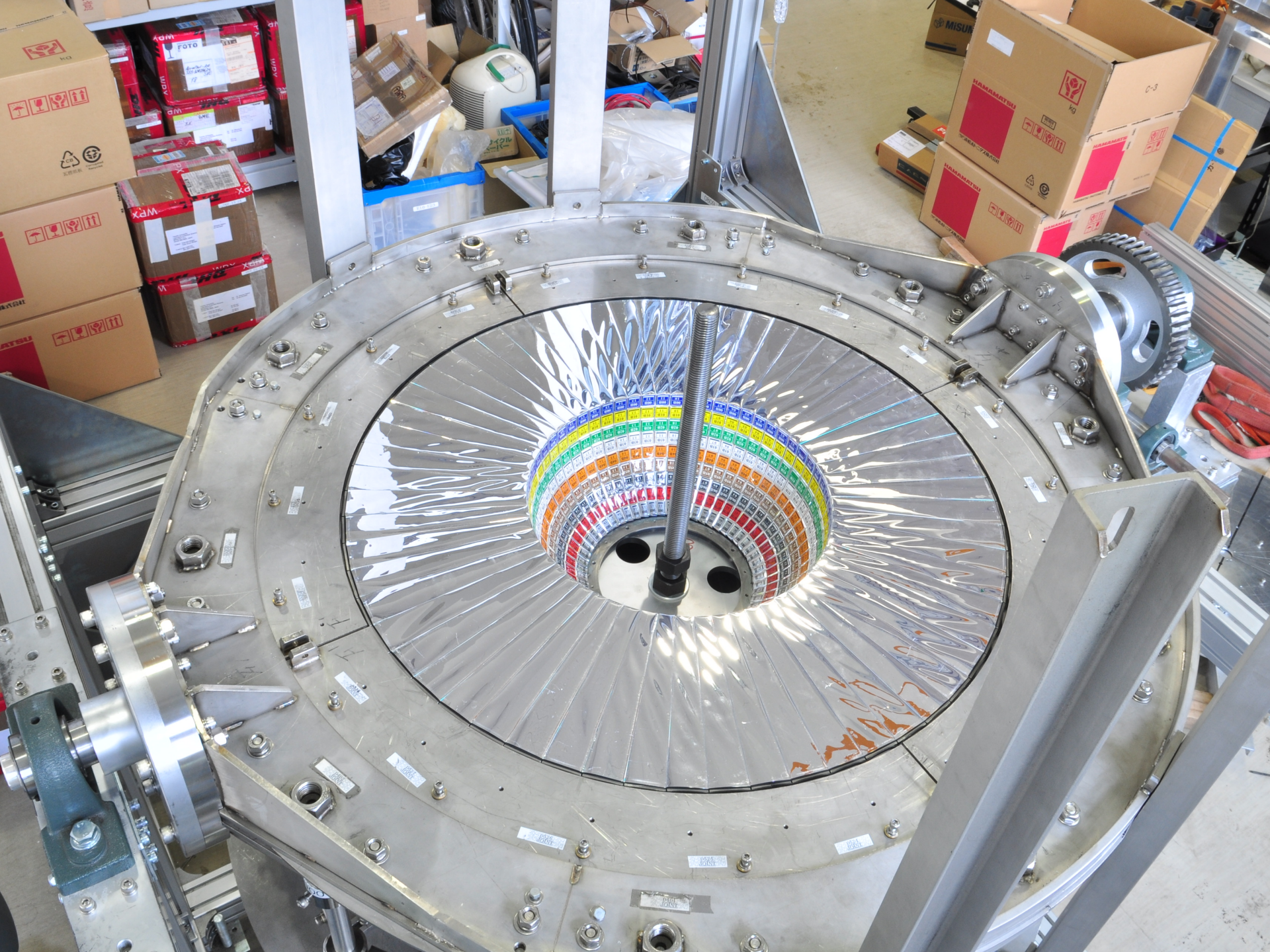
- egg-shape assembly of 1320 BGO crystals
- polar angle $24° \leq \theta \leq 144°$
- good segmentation of ~6°
- sufficient thickness of 220 mm ($20X_0$)

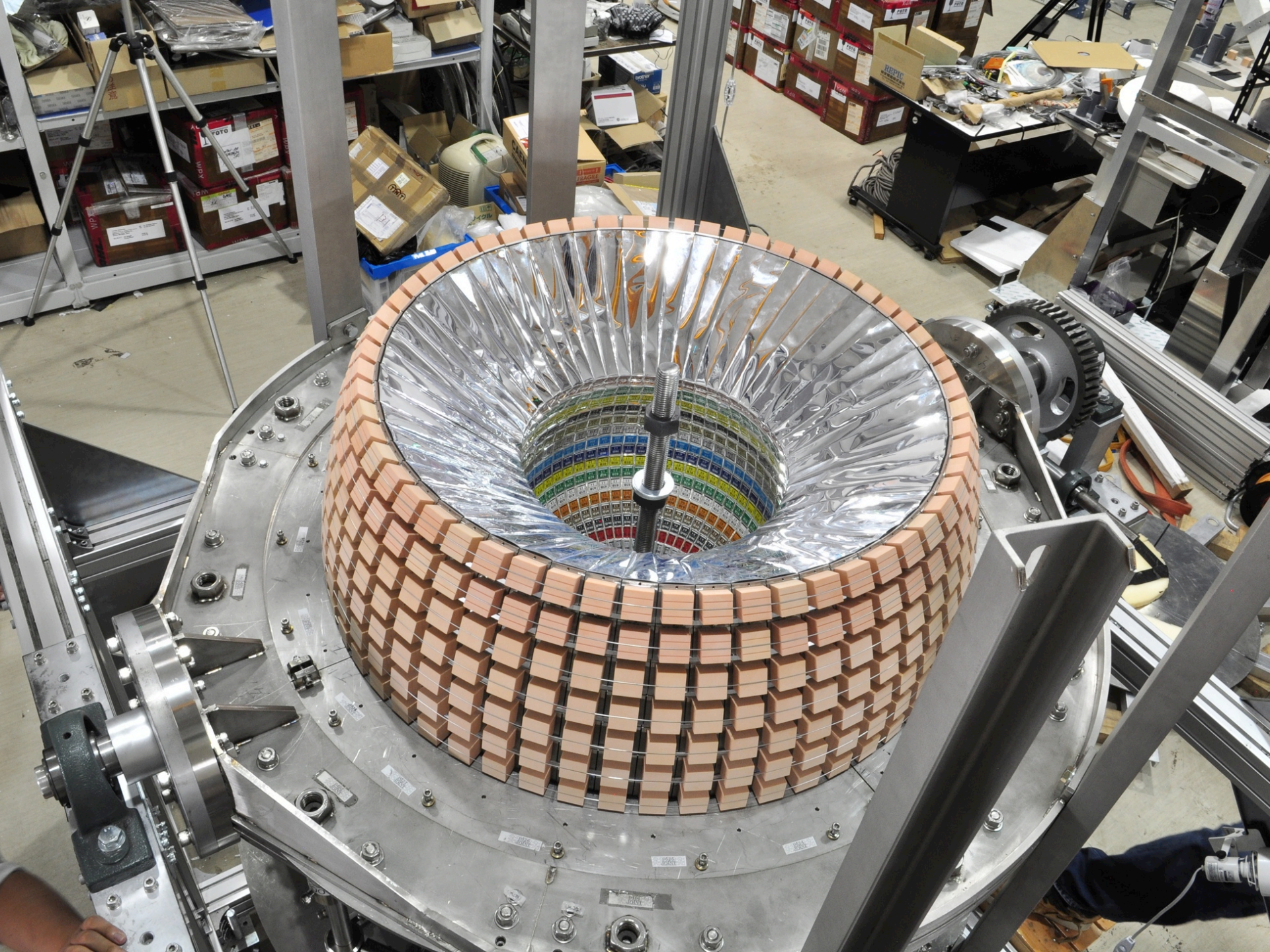
- self-supporting structure to hold the whole crystals of about 2t in weight w/o insensitive area
- world highest energy-resolution of 1.3% for 1 GeV photons

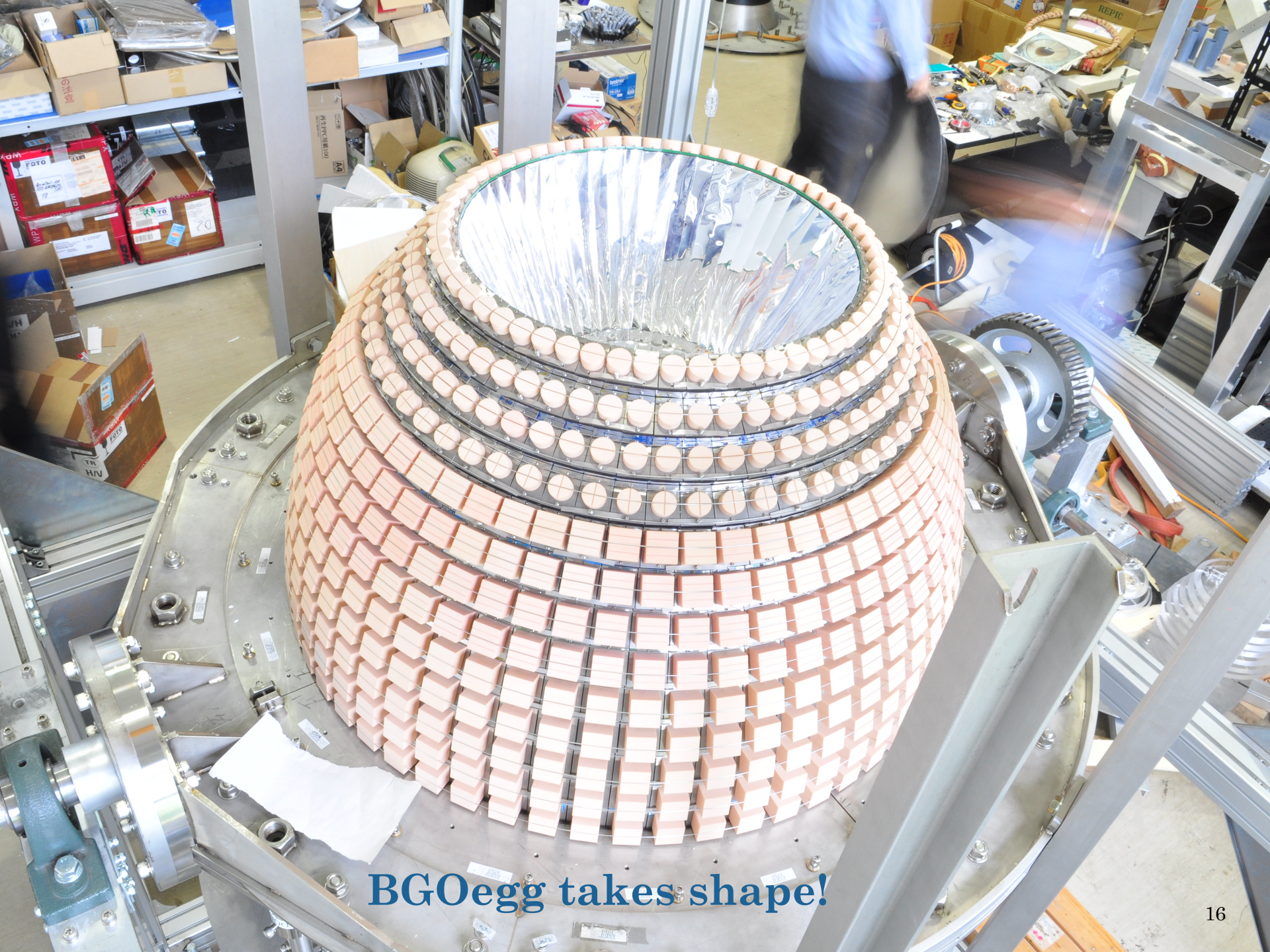
not the maximum instantaneous value



BGOegg under construction

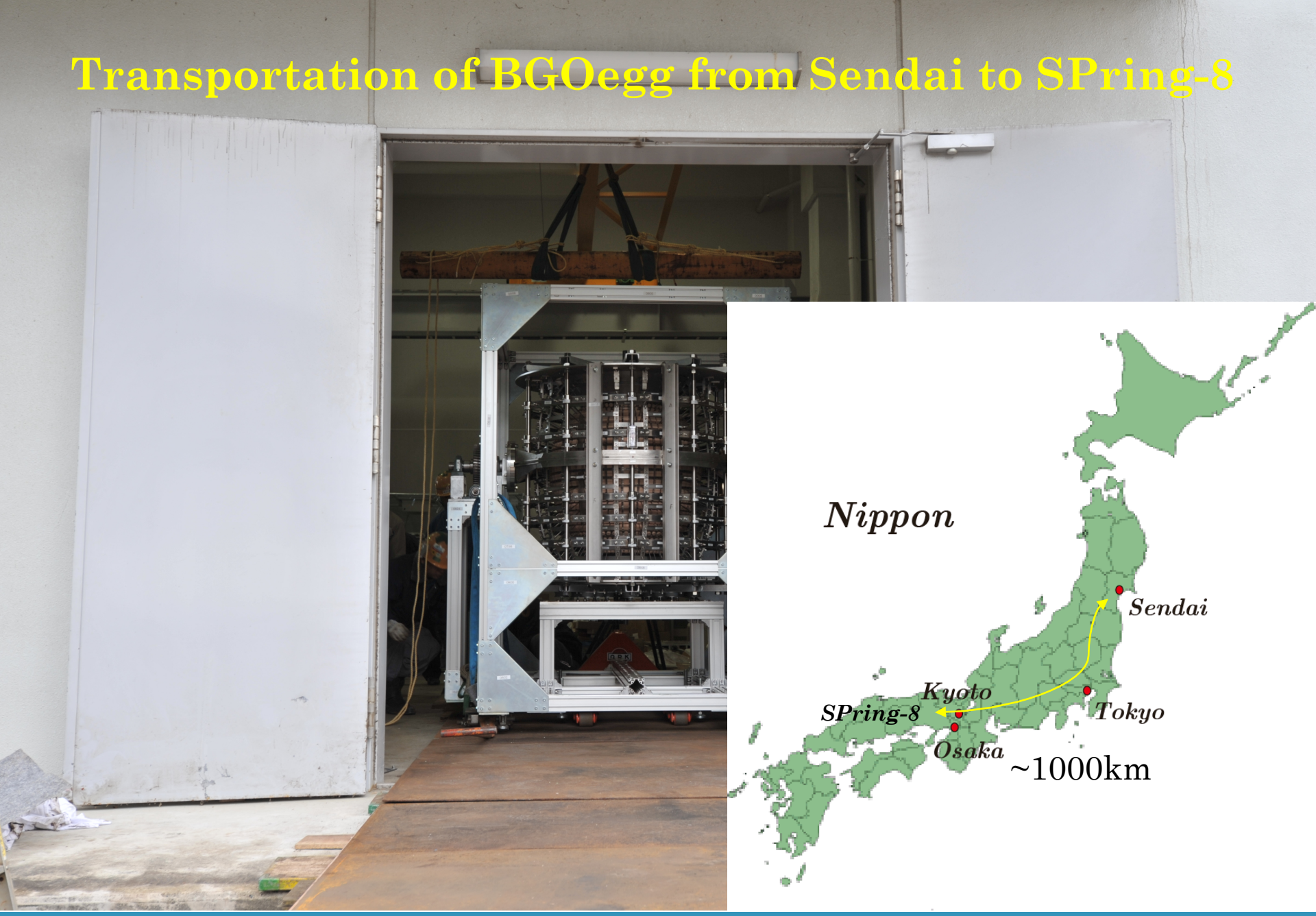




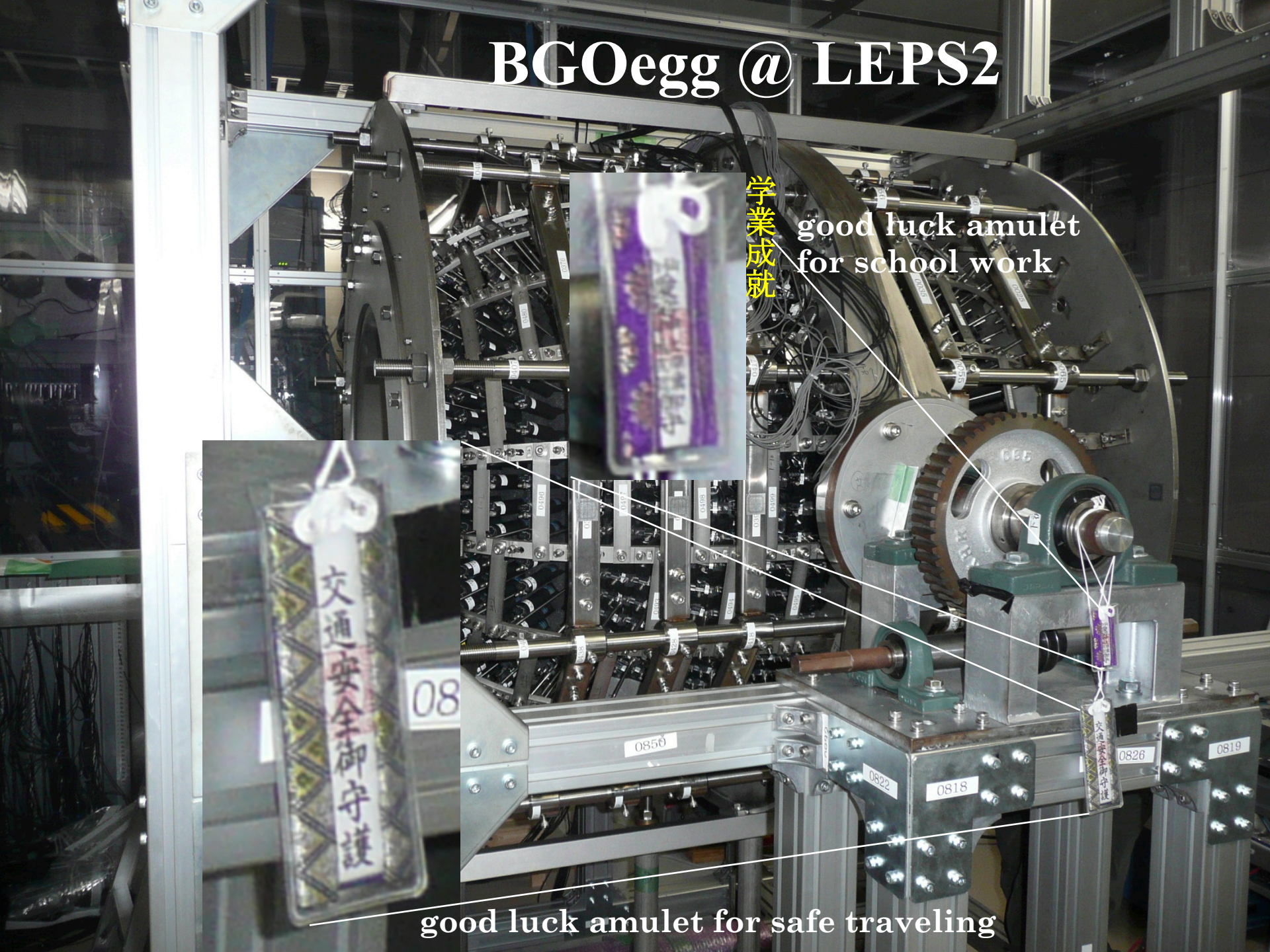


BGOegg takes shape!

Transportation of BGOegg from Sendai to SPring-8



BGOegg @ LEPS2



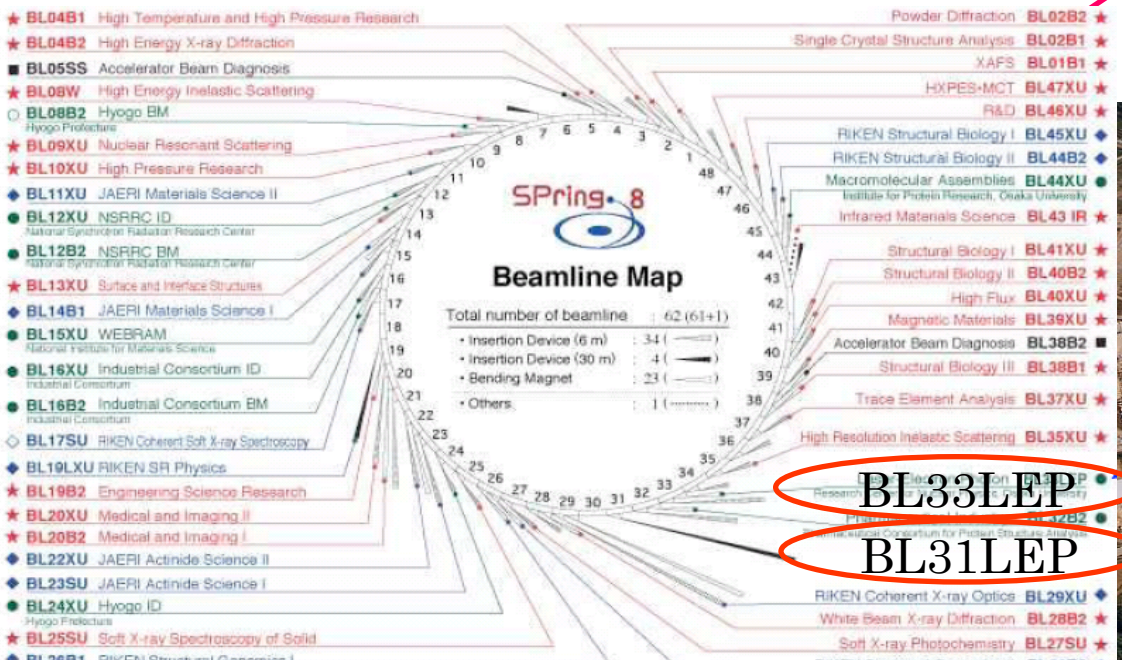
BGOegg milestones

The Great East-Japan Earthquake took place Mar.11, 2011

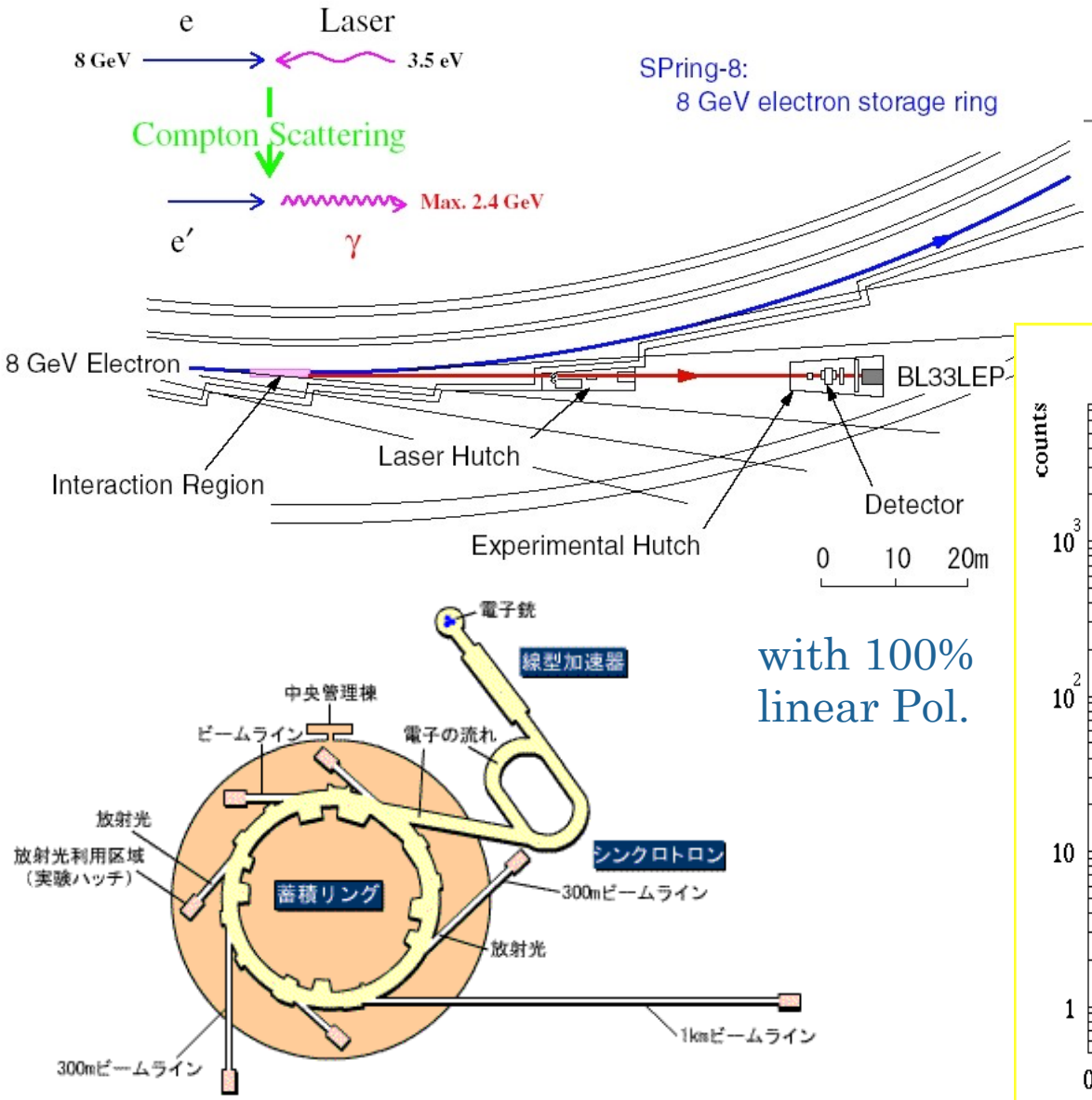
- Construction of the frame started. Sep. 26, 2011
- 1st BGO crystal was placed. Oct. 15, 2011
  A trial and error approach was made to solve the problems on supporting structures and light shielding...
- All 1320 BGO crystals were installed. Oct. 09, 2012
- BGOegg moved out of ELPH, Sendai Dec. 13, 2012
  and arrived at SPring-8. Dec. 15, 2012
- Installation of 300 PMT was completed. Jan. 09, 2013
- Beam tests were made. until Feb. 07, 2013
- Reassembling all the PMT started. May 08, 2013
  and finished. Nov. 13, 2013
- Cabling were completed. Dec. 13, 2013
- BGOegg-LEPS2 experiments started Apr. 10, 2014

SPring-8

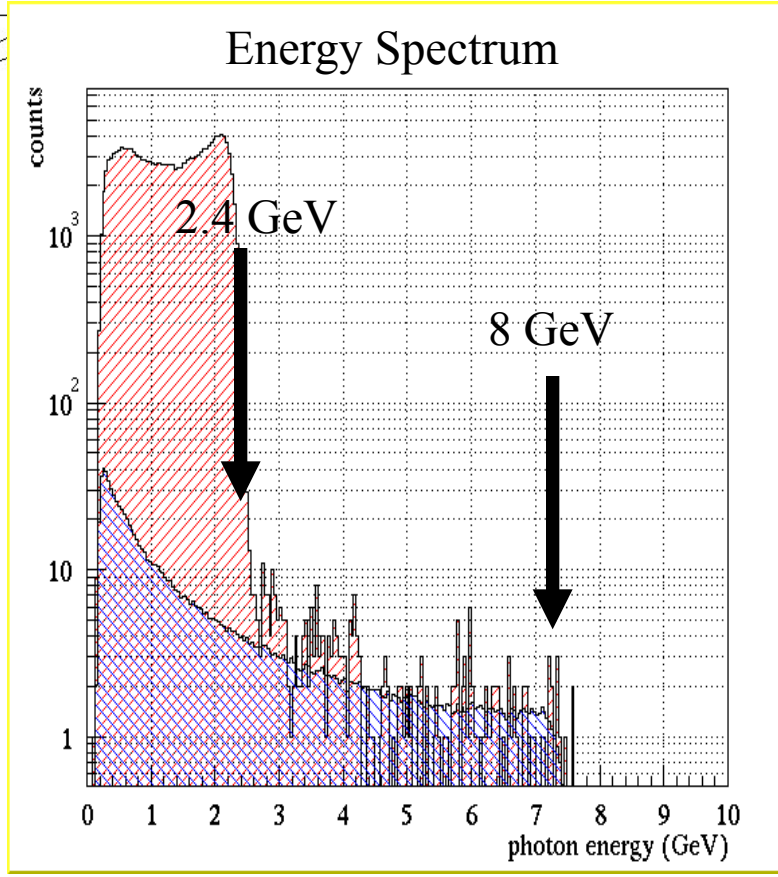
- 3rd-generation synchrotron radiation facility
- circumference: 1436 m
- 100 mA (ε_x=6x10^{-9} m·rad)
- top-up operation (every few minuetes)
- 62 beamlines



LEPS beam (BL33LEP)



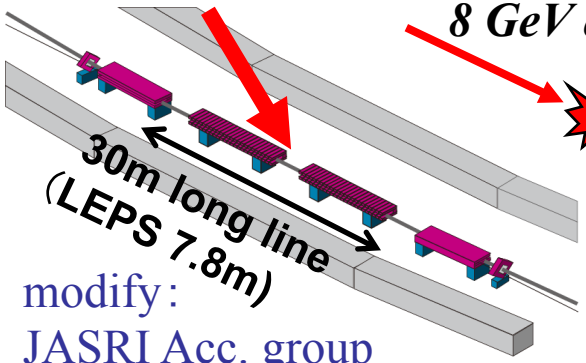
with 100% linear Pol.



LEPS2 facility

Coordination project between 2 Joint Usage/Research Centers

Backward Compton Scattering

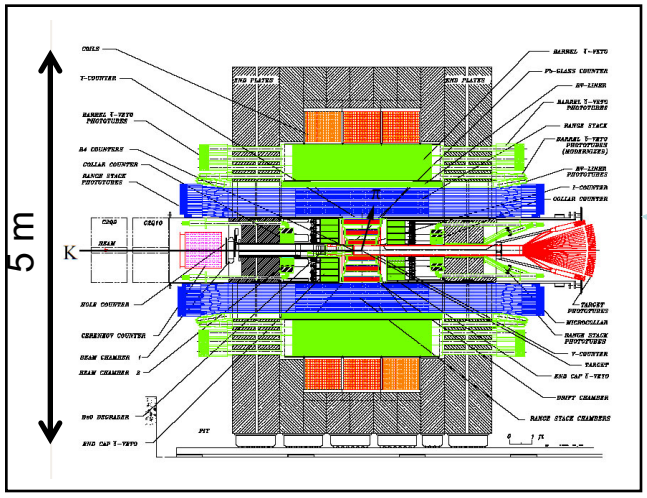


High intensity:
multi laser LRNB round beam
~10 7 photons/s (LEPS ~10 6)
High energy: Re-injection of X-ray from undulator
(Tohoku U., JASRI)
Eγ < 7.5GeV *(LEPS < 3GeV)*

modify:
JASRI Acc. group

a) SPring-8 SR ring

b) Laser hutch

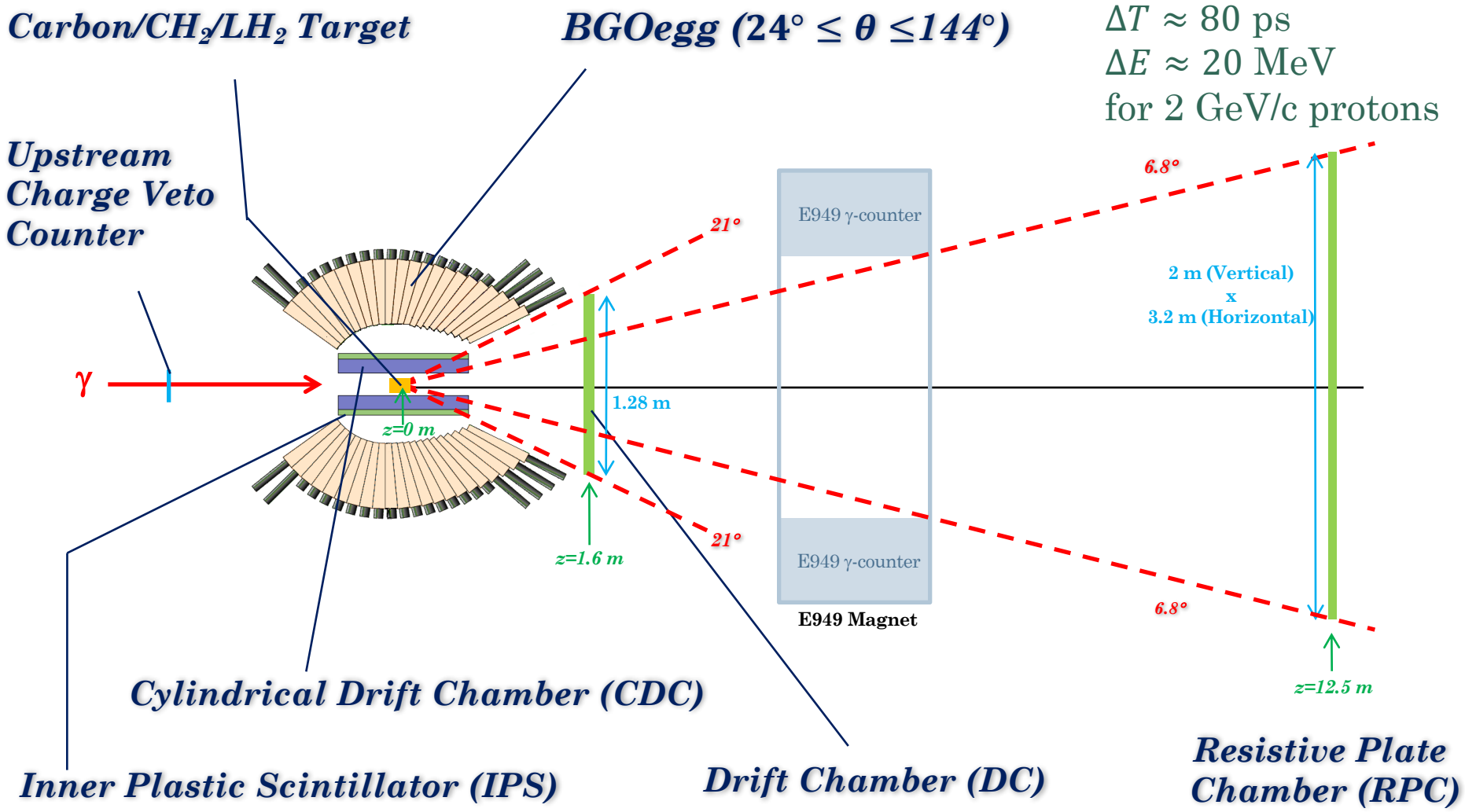


BNL-E949 detector

BGOegg (Tohoku U.)
Large decay spectrometer
Forward spectrometer
New DAQ system

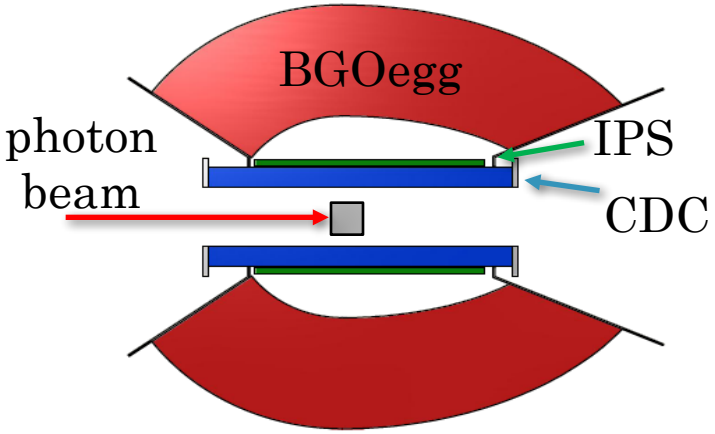
c) Experimental hutch

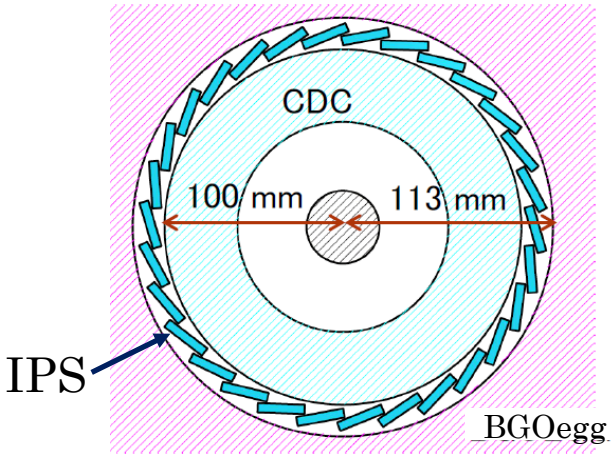
Layout of BGOegg experiments



Charged particle detection

with Inner Plastic Scintillator (IPS) and Cylindrical Drift Chamber (CDC)

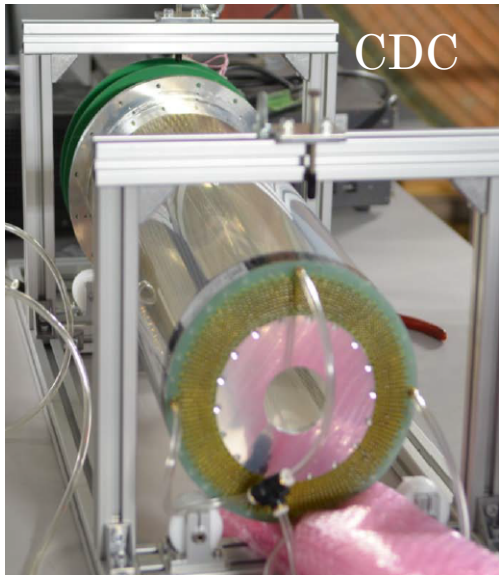




specifications

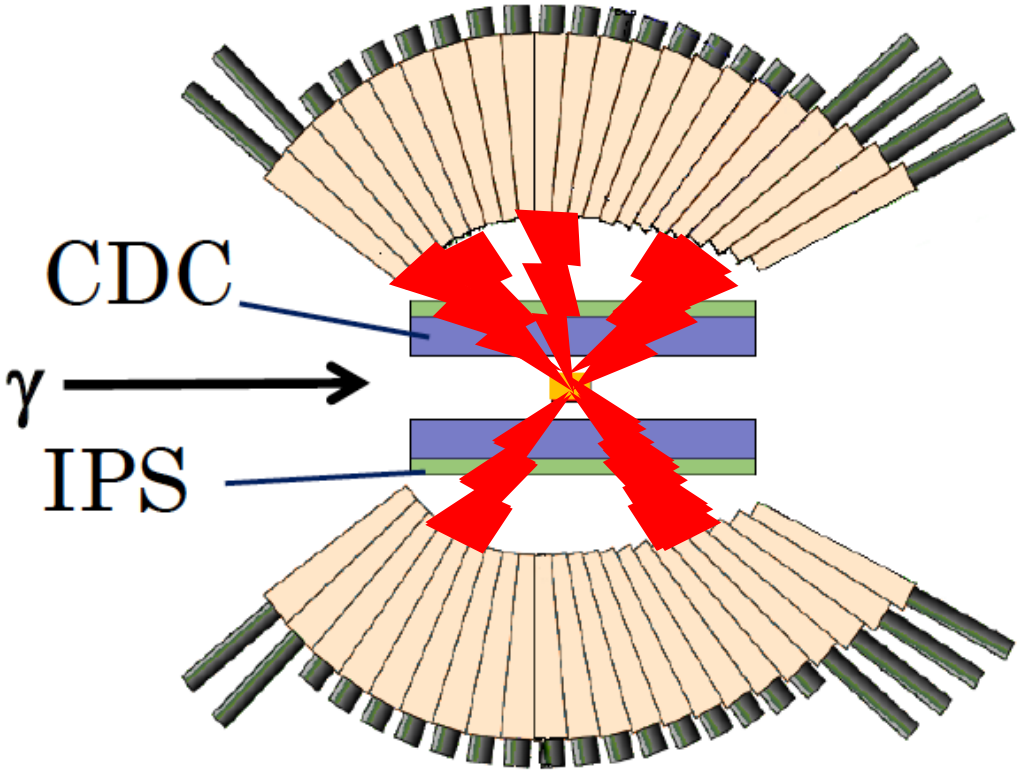
IPS: 30 plastic scintillator
453 mm x 26 mm x 5 mm
Multi Pixel Photon Counter(MPPC)
are placed only on one edge

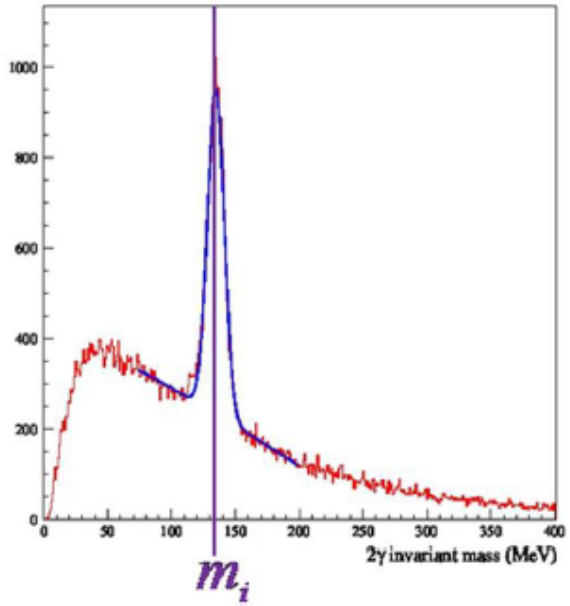
CDC: 72 stereo wires, 4 layers
inner diameter = 116 mm
outer diameter = 196 mm
chamber length = 550 mm
thickness = 40 mm



Energy calibration of BGOegg

- Huge amounts of $\pi^0 \rightarrow \gamma\gamma$ events were used.
- Calibration was made so as to get π^0 mass out of $\gamma\gamma$.
- Iterations are necessary to reach the final calibration result.





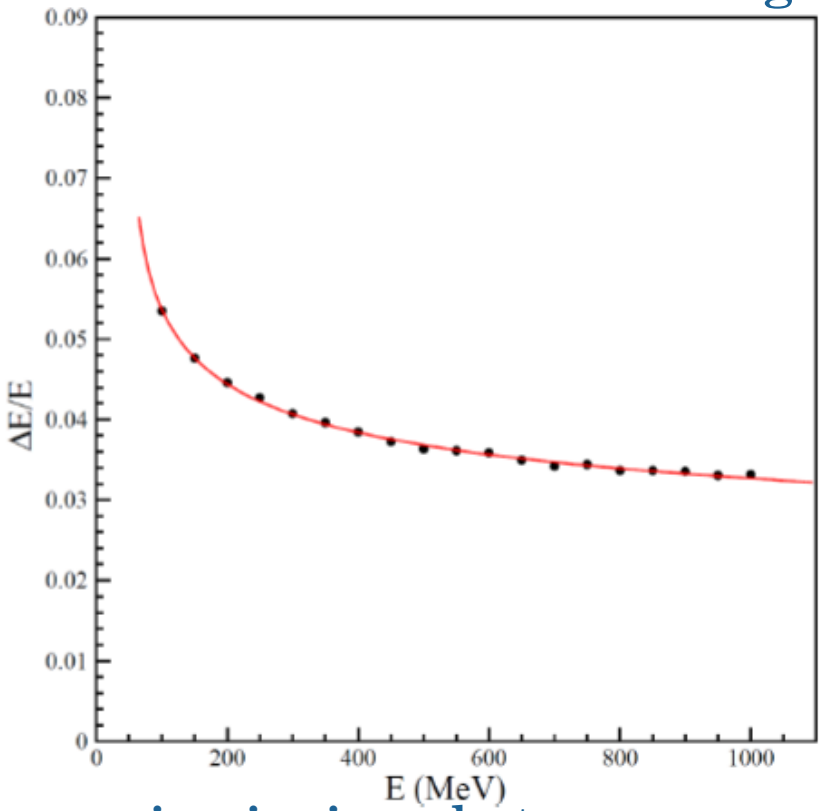
$m_i \rightarrow m_\pi = 134.98\,\mathrm{MeV}$

BGOegg calibration updated

- Overall calibration with $\pi^0 \rightarrow \gamma\gamma$ events yields

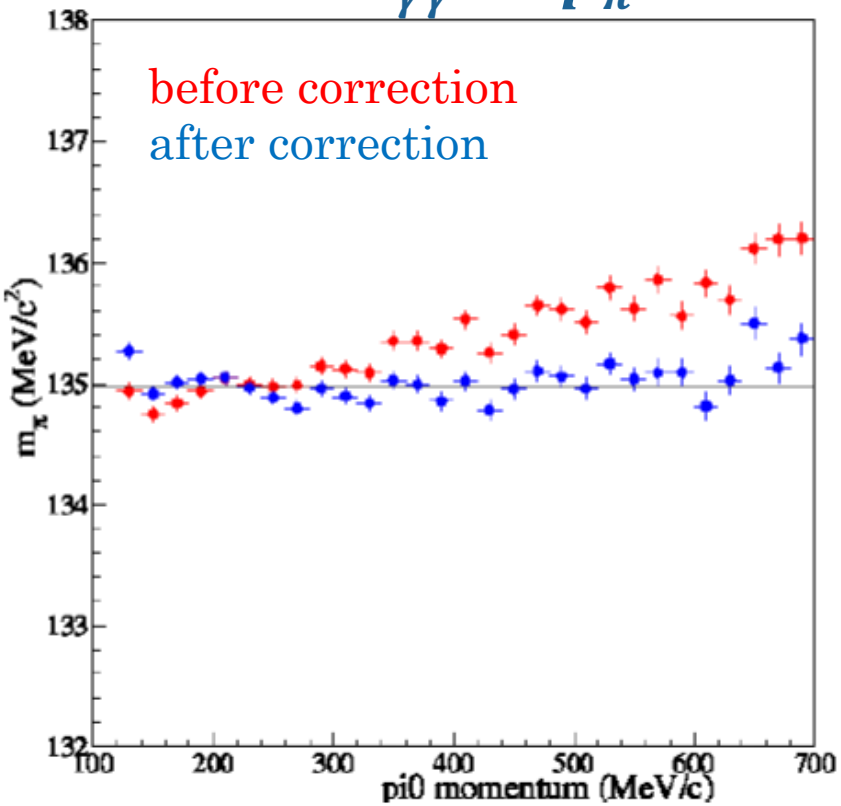
η : 556MeV (PDG 548MeV) and η' : 978MeV (PDG 958MeV)

fraction of shower leakage



impinging photon energy

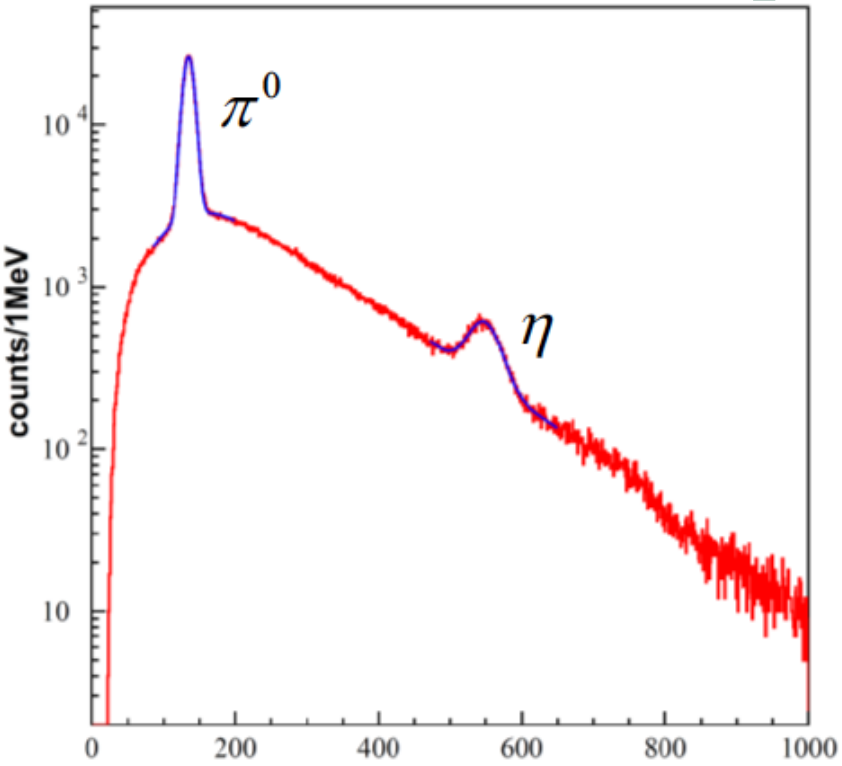
$m_{\gamma\gamma}$ vs p_π

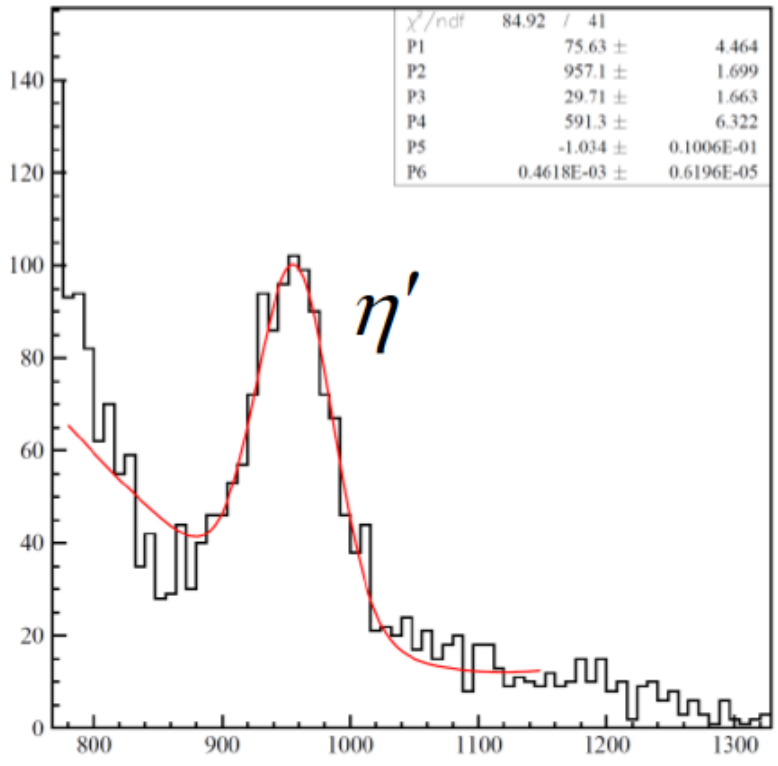


π^0 momentum

γγ invariant mass distribution

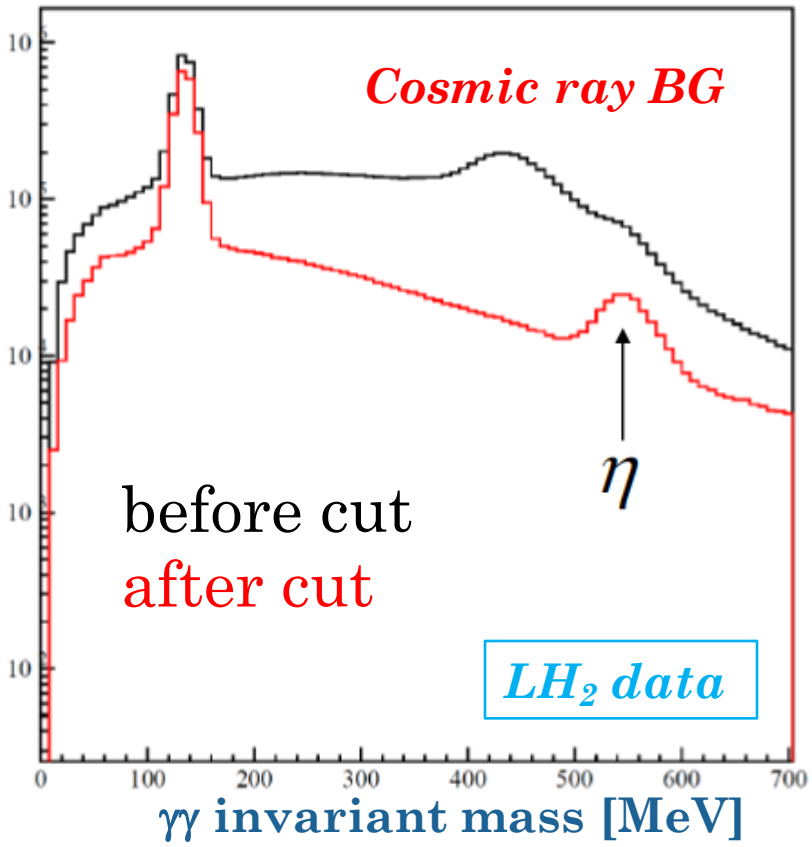
LH_2 target

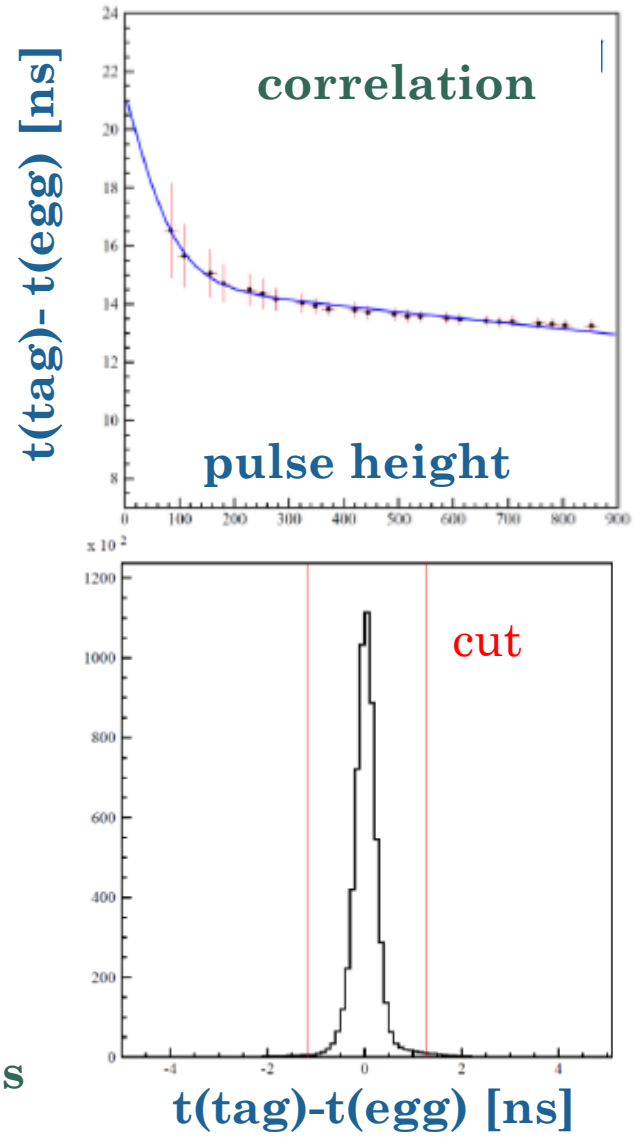




	$m(\pi^0)$=134.9(1) MeV	$m(\eta)$=547.5(3) MeV	$m(\eta')$=957.1(2) MeV
	$\sigma(\pi^0)$= 7.7(1) MeV	$\sigma(\eta)$= 21.1(3) MeV	$\sigma(\eta')$= 29.7(2) MeV
PDG:	134.98	547.86	957.78 MeV

BGOegg timing calibration





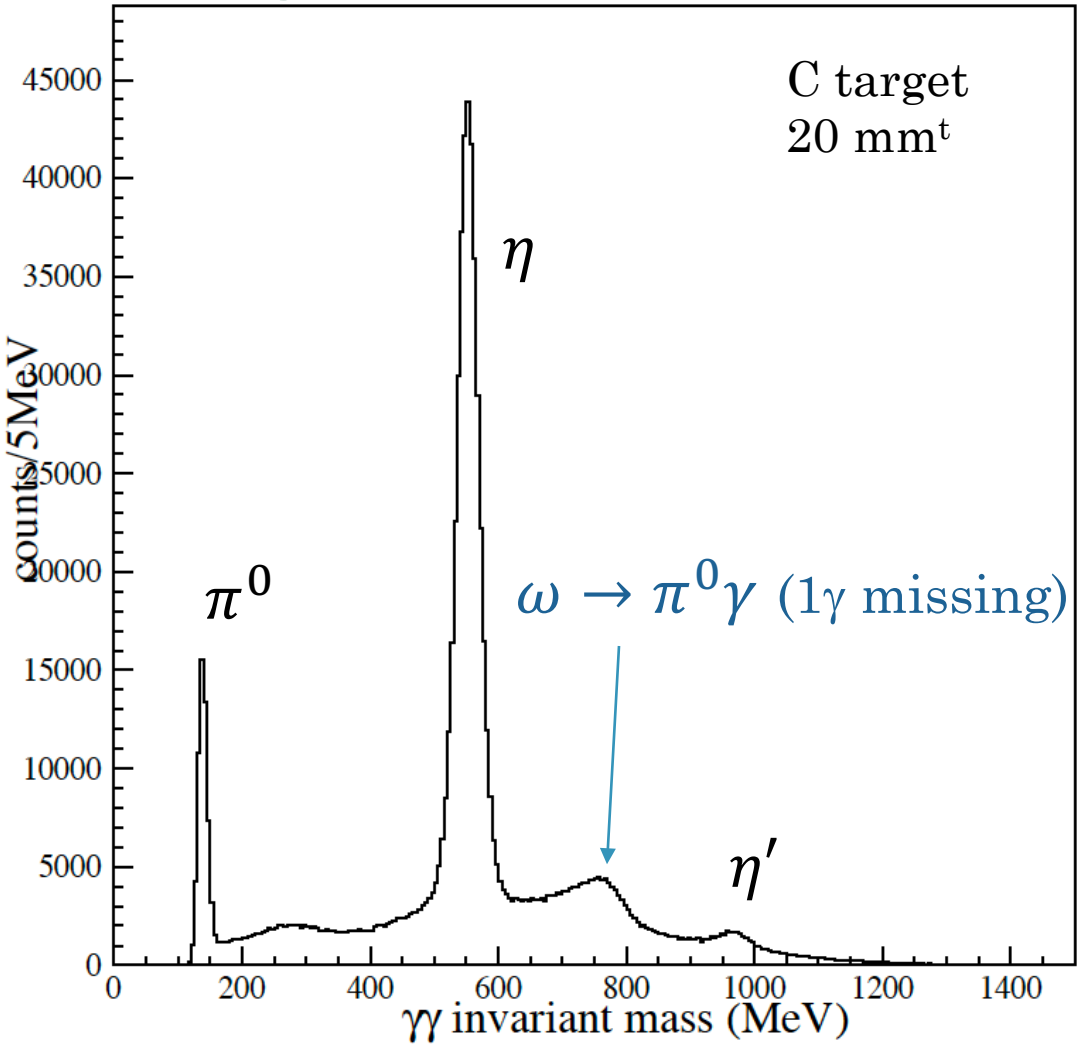
- slewing correction
- RF(2ns) separation
- time resolution of BGOegg: σ=210ps

Summary of data collection

Period	Target	Integrated # of γ's (tagged E_γ region) = tagger counts × dead time corr. × DAQ eff. corr.
2014A (Apr.~July)	**Carbon/CH_2** [20 mm]	**C: 1.31×10^{12}, CH_2: 1.58×10^{12} with RPC** (In total, C: 4.29×10^{12}, CH_2: 2.56×10^{12}) ***Test sample for η'-mesic nuclei search***
2014B (Nov.~Feb.)	**LH_2** [40 mm]	**Hori: 2.24×10^{12} , Vert: 2.01×10^{12}** ***N^* physics, etc (with spin observable)***
2015A (Apr.~July)	**Carbon** [20 mm]	**9.77×10^{12}** ***η'-mesic nuclei search***
2015B (Sep.~Dec.)	**LH_2** [40 mm]	**About 1.6 × 2014B** (Vert. & hori. half by half) ***More data for γp reactions***
2016A (Apr.~July)	**Carbon** [20 mm]	***η' in nucleii***

Spectrum of $\gamma\gamma$ invariant mass

good mass resolutions

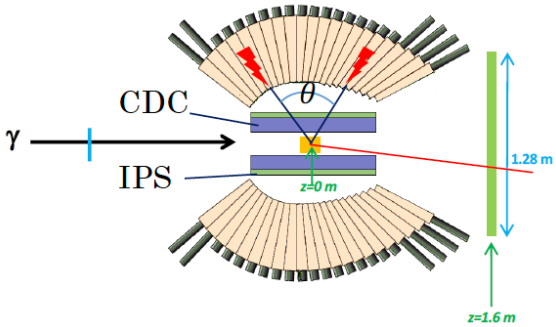


data set: 2015A

trigger and cut conditions:

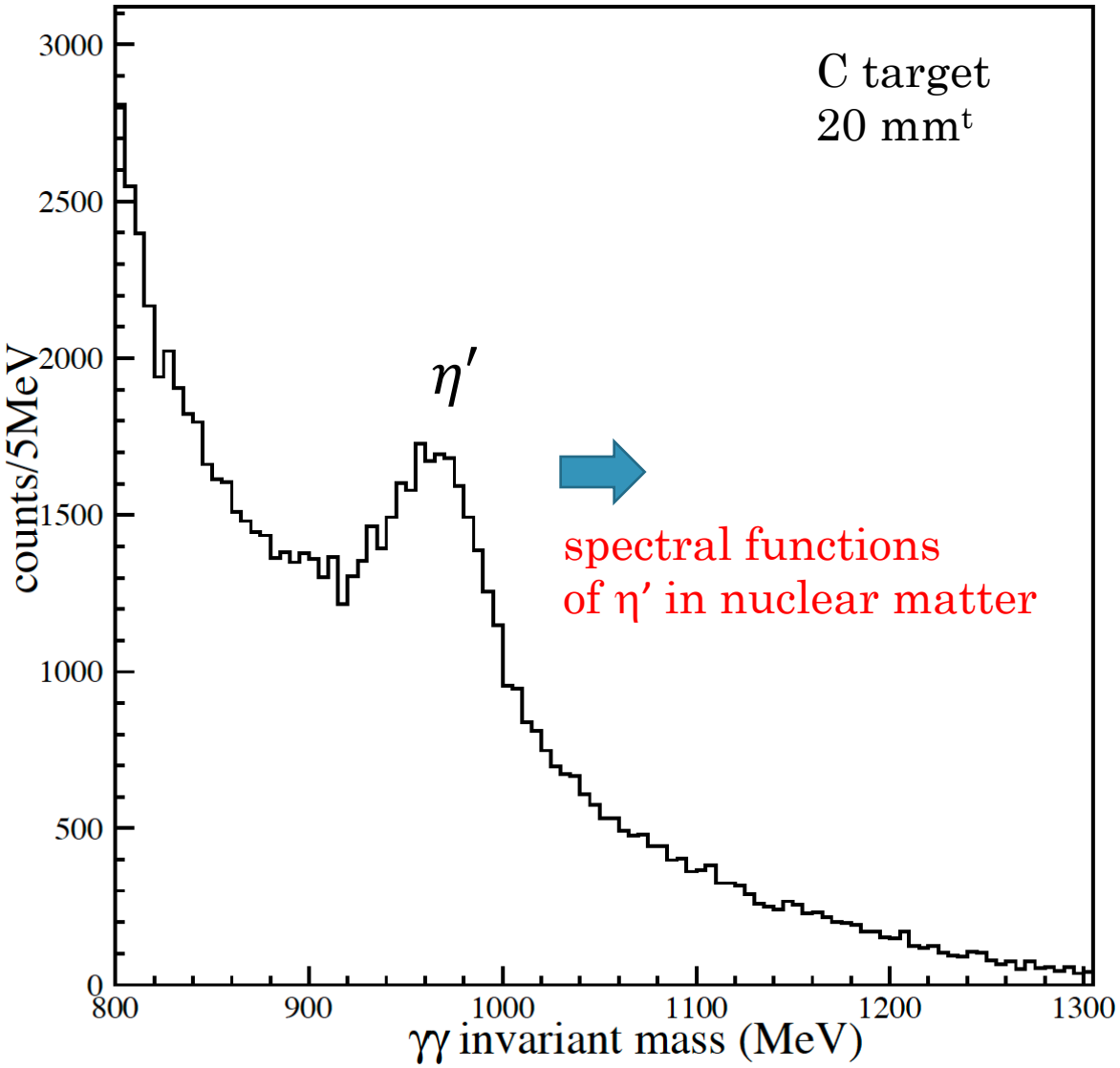
2 neutral clusters

+ 1 charged track



- $\theta > 40°$
- $M_{\gamma\gamma} \approx m_N \pm 200$ MeV

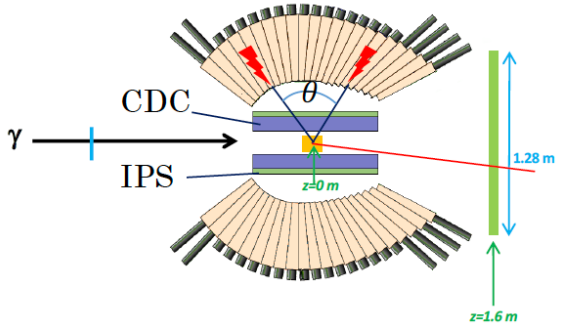
Spectrum of $\eta' \rightarrow \gamma\gamma$ in close-up



data set: 2015A

trigger and cut conditions:

- 2 neutral clusters + 1 charged track



- $\theta > 40°$
- $M_{\gamma\gamma} \approx m_N \pm 200$ MeV

Summary

- BGOegg experiments have been conducted at SPring-8/LEPS2.
- Goals of BGOegg experiments:

  to measure the spectral function of η' via $\eta' \to \gamma\gamma$

  in the nuclear medium

  to search for a η' mesic nucleus
- Data are accumulated for 2 years. (about 1 year for C)
- Precise energy calibration was made for BGOegg.

  obtained $\gamma\gamma$ mass resolutions:

  $\sigma(\pi^0) \approx 7MeV$, $\sigma(\eta) \approx 16MeV$, $\sigma(\eta') \approx 21MeV$ (with C)

  intrinsic energy resolution of BGOegg: $\sigma(\gamma)/E_\gamma \approx 1.3\%@1GeV$
- Ready for analyzing data for physics.

What is born from this egg?