HK detector design especially for low-energy events

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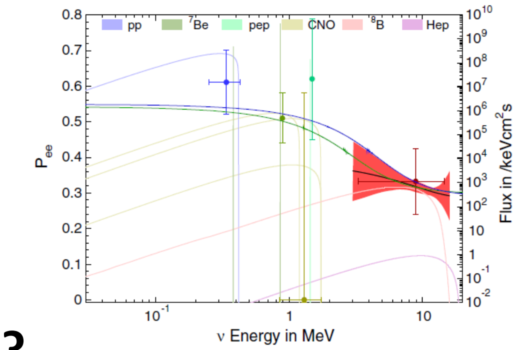
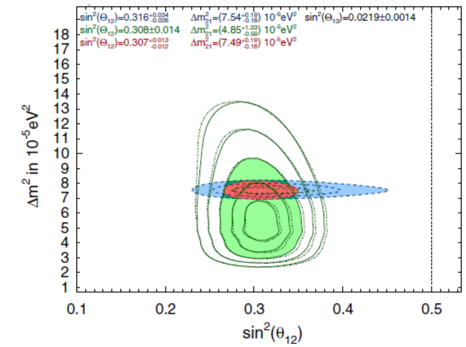
- Physics targets in low-energy region
- Typical low-energy events in SK
- Current design of HK detector
- Requirements from low-energy physics
  - high density sensors, source deployment, up/down asymmetry, radon BG, (external BG,) (spallation BG,) …
- Summary

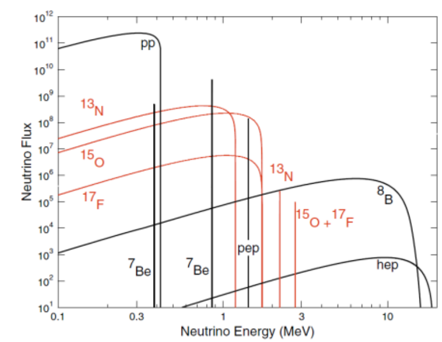
Mostly based on HK Design Report
KEK Preprint 2016-21, ICRR-Report-701-2016-1

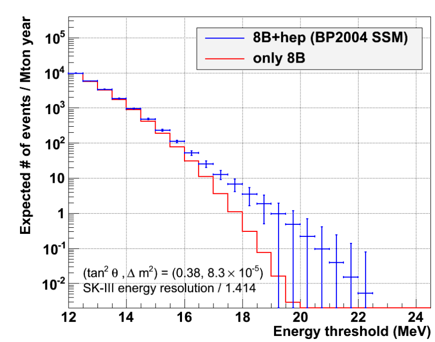
Physics targets in low-e region

- Solar neutrinos
  - Neutrino oscillation
    - Solar MSW
      - Flatter solar ^{8}B spectrum?
    - Terrestrial MSW
      - Tension among solar ν_e and reactor $\overline{\nu_e}$?
  - Solar astrophysics
    - Discovery hep neutrino signal
    - Discovery of solar flare neutrinos
    - Short time variation
- Supernova neutrinos
  - → next talk



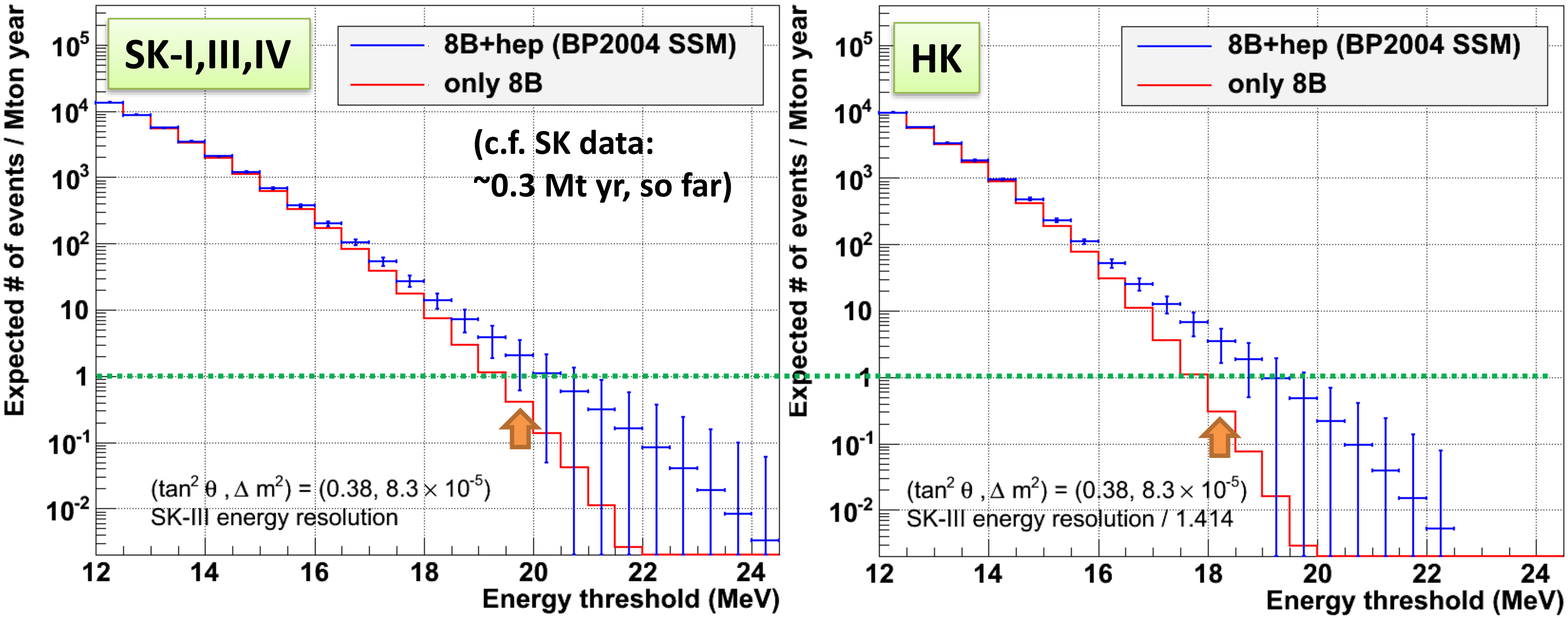






Solar hep neutrino

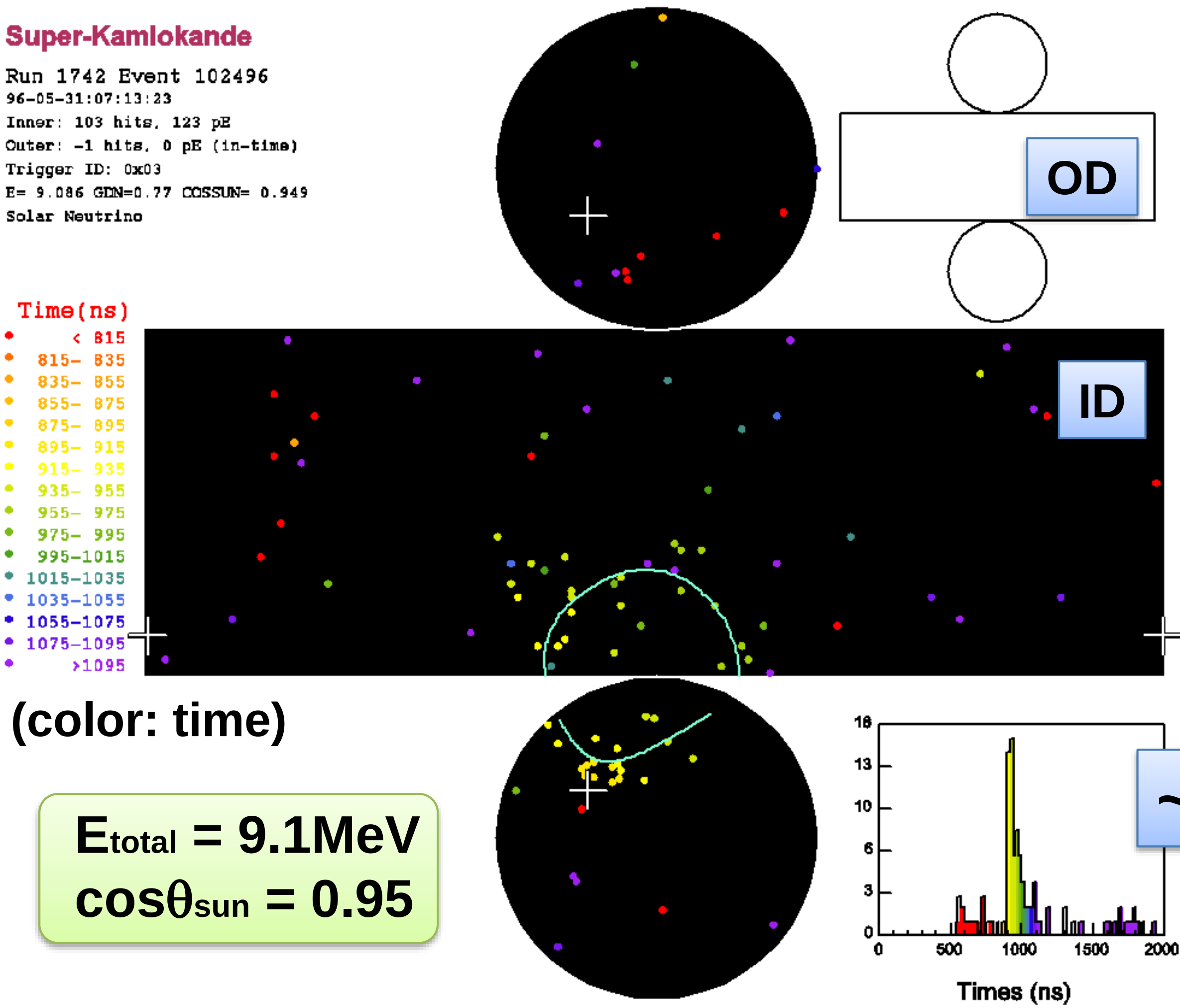
Integrated # of expected solar neutrino events



	E_{total} [MeV]	^{8}B [/Mt yr]	Hep [/Mt yr]	Hep / ^{8}B
SK-I,III,IV	19.5-25.0	0.41	1.62	3.9
HK	18.0-25.0	0.30	3.23	10.6

- First direct observation.
- Energy resolution (= High Density photo sensors) is essential.

Typical low-energy event



(color: time)

E_{total} = 9.1MeV
$\cos\theta_{sun}$ = 0.95

$\nu + e^- \rightarrow \nu + e^-$

(for solar neutrinos)

- Timing information
  ➡ vertex position
- Ring pattern
  ➡ direction
- Number of hit PMTs
  ➡ energy

~6 hit / MeV (SK-I,III,IV)

→ x ~2 (HK)

Resolutions (for 10MeV electrons) (software improvement)

Energy: 14%	Vertex: 87cm	Direction: 26°	SK-I
Energy: 14%	Vertex: 55cm	Direction: 23°	SK-III

Low-energy backgrounds in SK-I

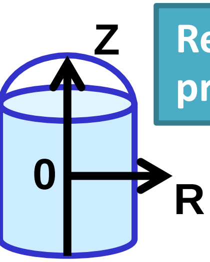
Misfit

External gamma

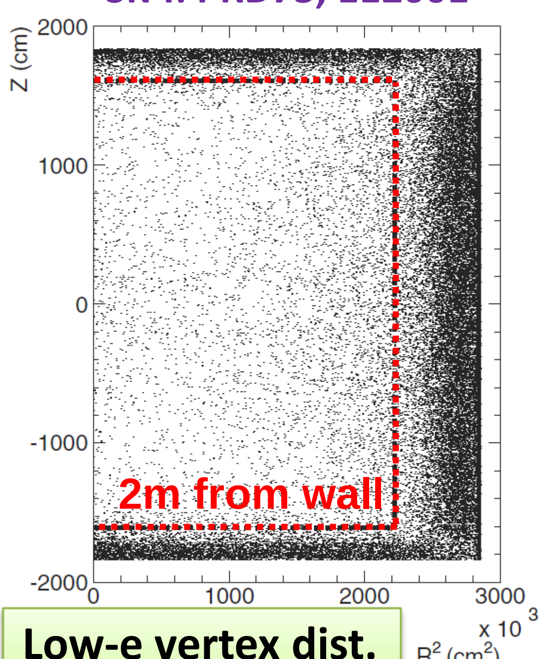
Radon, Misfit,
External gamma, etc.

Remaining spallation products (probably)

Spallation is dominant BG source in ~6.5-20MeV

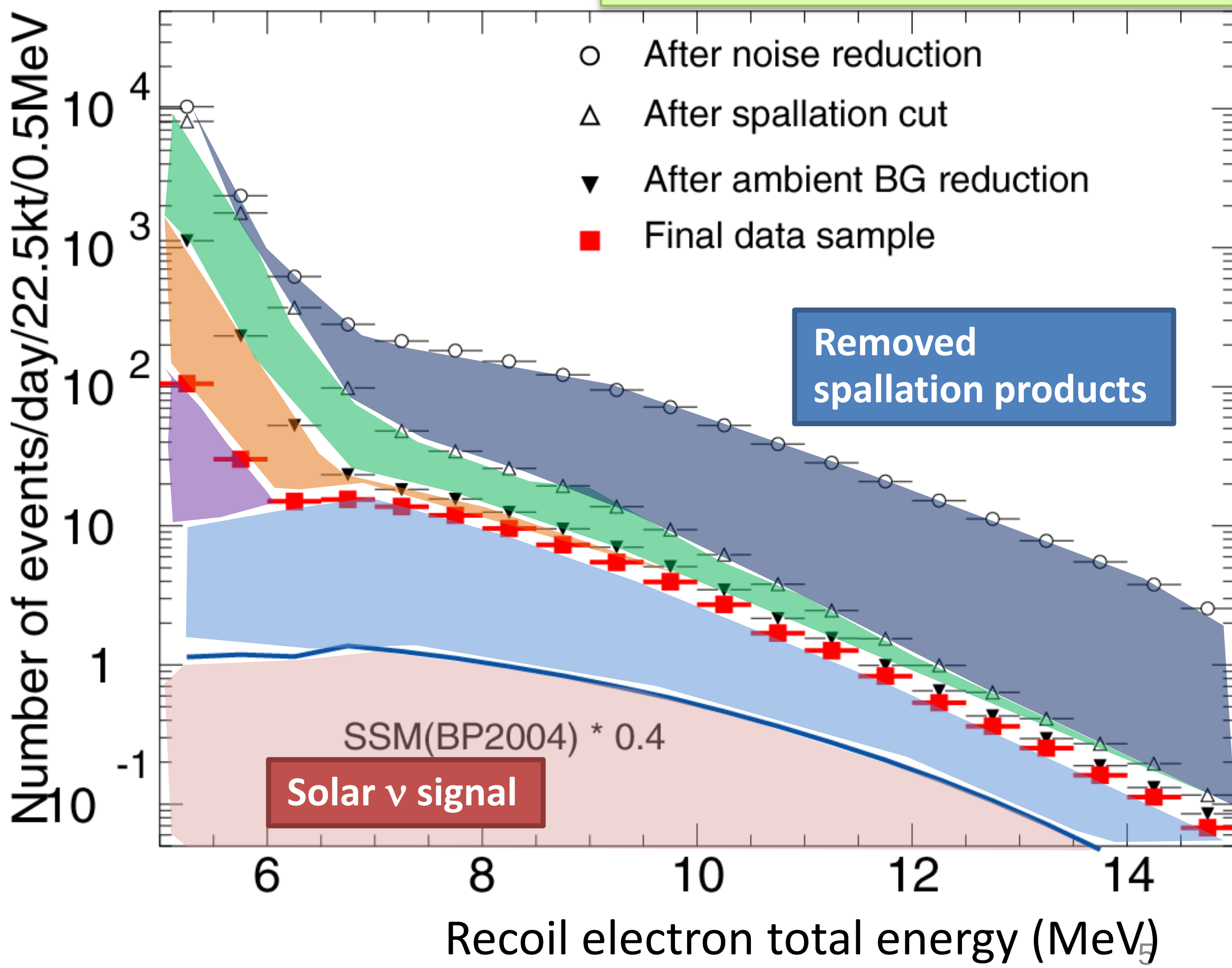


SK-I: PRD73, 112001

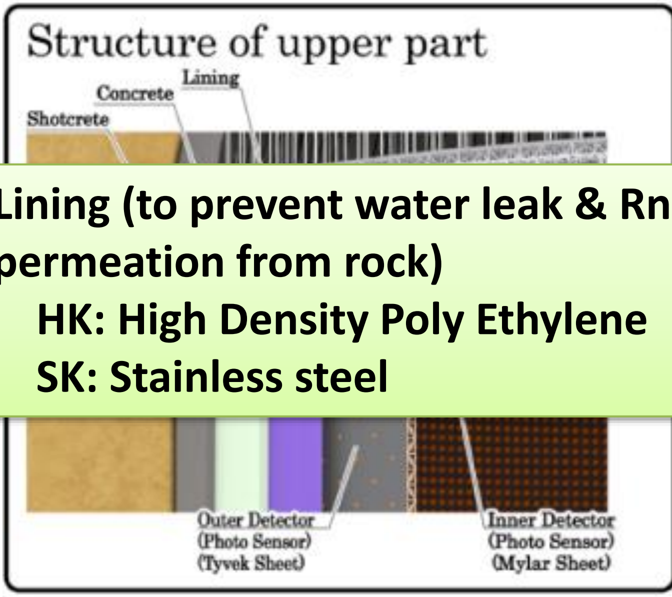


Low-e vertex dist.

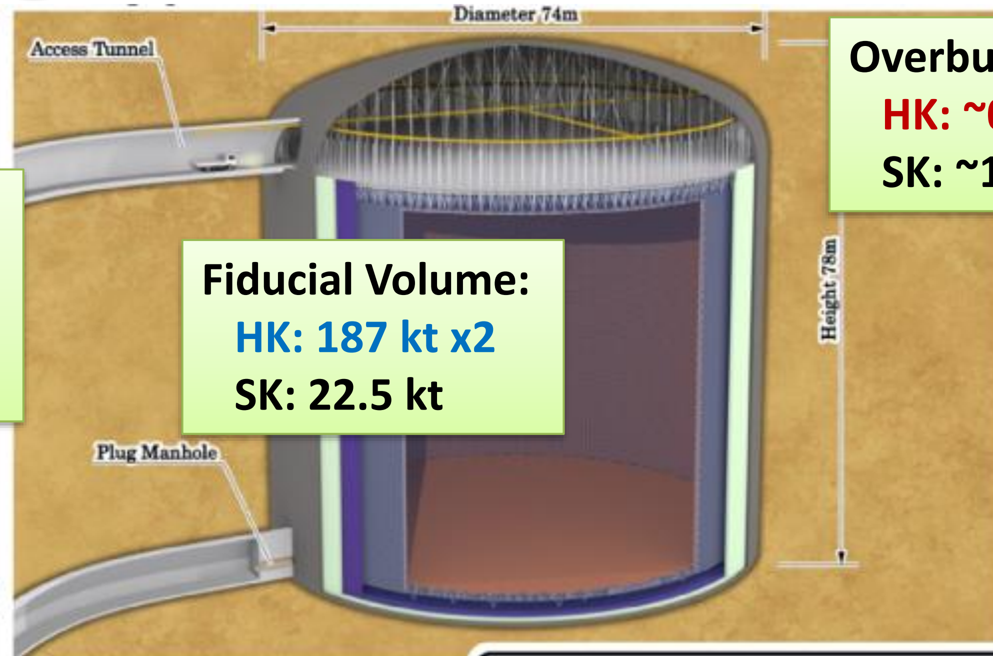
Solar ν data reduction in SK-I (in 2m fiducial volume, 22.5kt)



Current design of the HK detector

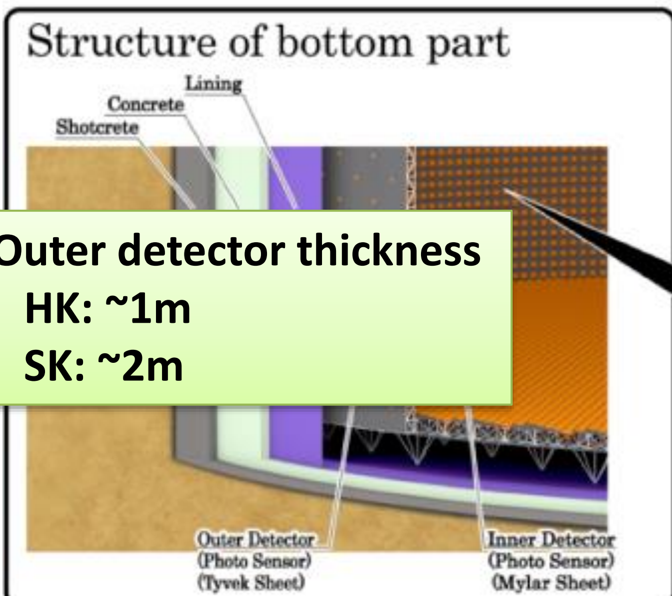


Lining (to prevent water leak & Rn permeation from rock)
- HK: High Density Poly Ethylene
- SK: Stainless steel



Fiducial Volume:
- HK: 187 kt x2
- SK: 22.5 kt

Overburden:
- HK: ~0.65km
- SK: ~1km



Outer detector thickness
- HK: ~1m
- SK: ~2m

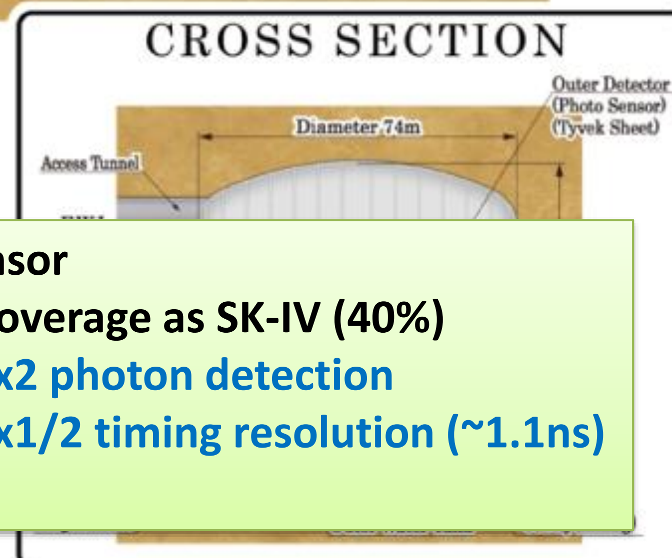


Photo-sensor
- Similar coverage as SK-IV (40%)
- SK-PMT x2 photon detection
- SK-PMT x1/2 timing resolution (~1.1ns)
- …

Requirements from low-e physics: 1

- Photon collection as much as possible
  - HK is about twice comparing to SK-I,III,IV ⇦
- Good timing calibration (relative diff. < ~0.5ns)
  - Better timing resolution of photo sensors would be good
- Dark noise should be low enough
  - Current design is ~8kHz, but trying to reduce
- Precise calibration (of energy scale)
  - SK tools are sufficiently good enough
  - In HK, a lot of spallation products, decay-electrons from stopping cosmic-ray muons, and so on could be also used.
- Position dependence should be understood
  - R&D of Ni-Cf source (~9MeV γ) deployment system ⇦
  - R&D of a new small neutron source for ^{16}N (~6 MeV γ)
    - In SK, a DT neutron generator is used (for $n+^{16}O \rightarrow p+^{16}N$)

Requirements from low-e physics: 2

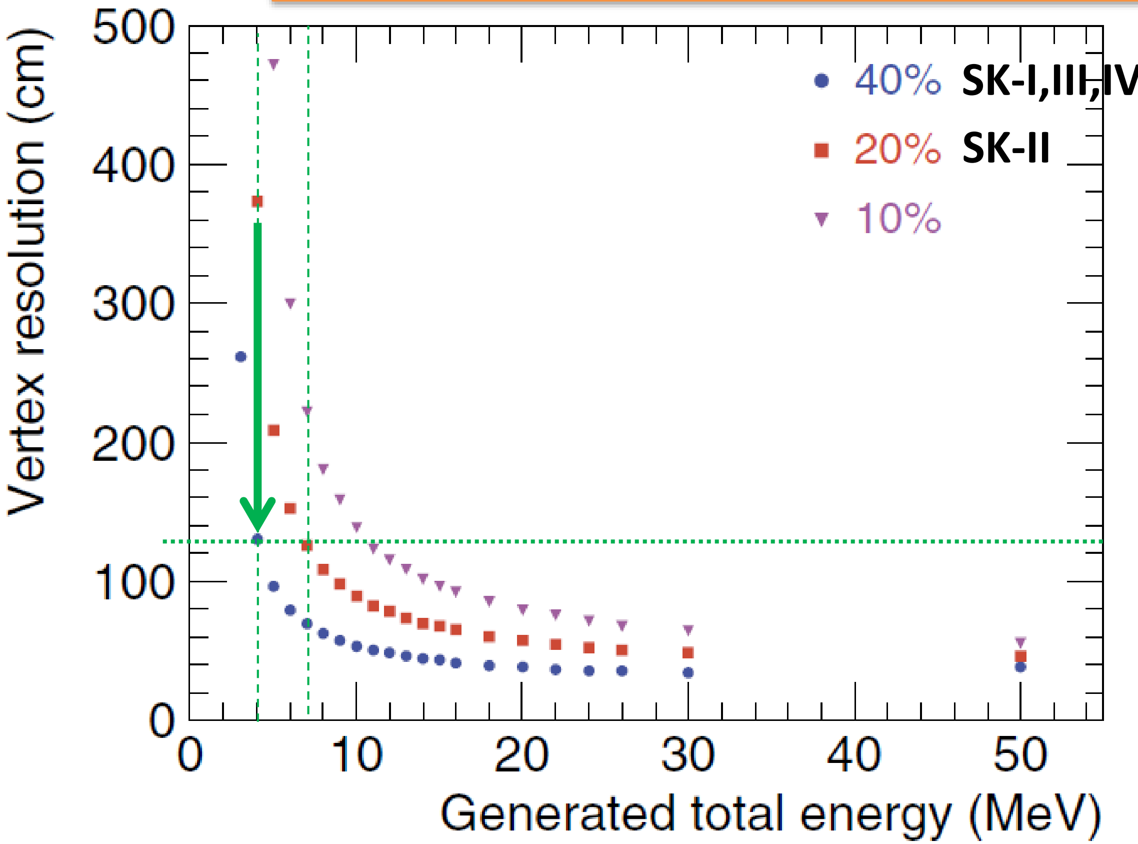
- Up/down asymmetry should be understood ⇦
  - Important for solar Day/Night analysis
- Radon should be low enough ⇦
  - ^{214}Bi: β_{max} = 3.27 MeV
  - A major factor to determine analysis energy threshold
- External events should be low enough ⇦
  - A major factor to determine fiducial volume
- Spallation products should be removed enough ⇦
- Gd option will realize many physics benefits
  - Supernova Relic Neutrinos (SRN), Reactor neutrinos, …
  - Inner acrylic vessel might be needed.

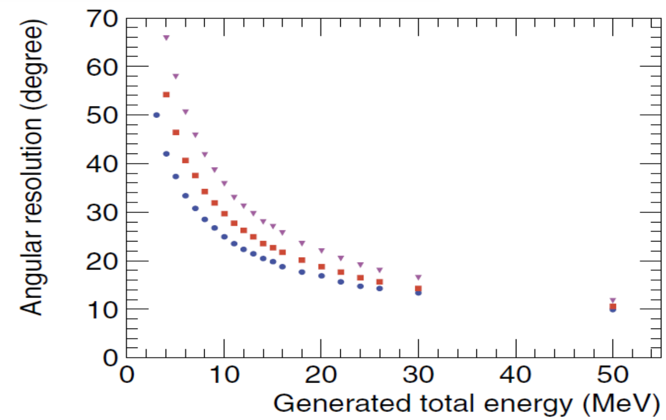
Problematic since KAMIOKANDE

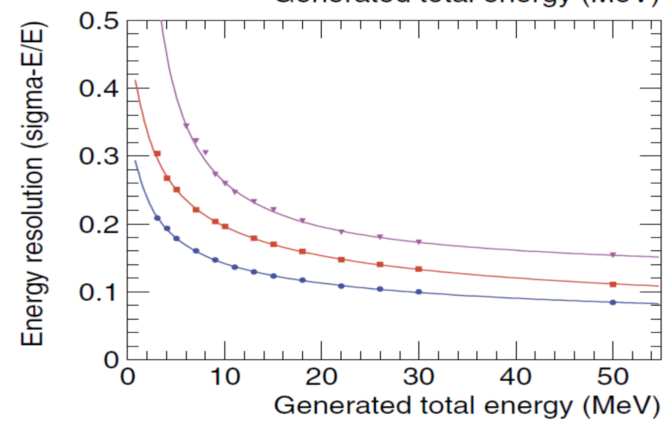
Effect of high density photo coverage:1

- Number of hit PMT/MeV: SK-II → x ~2 → SK-I,III,IV → x ~2 → HK
- Energy threshold (electron total): SK-II: 7.0 MeV, SK-IV: 4.0 MeV
- Better resolution especially around analysis threshold

A study with SK detector simulation (skdetsim)
(not HK detector geometry)

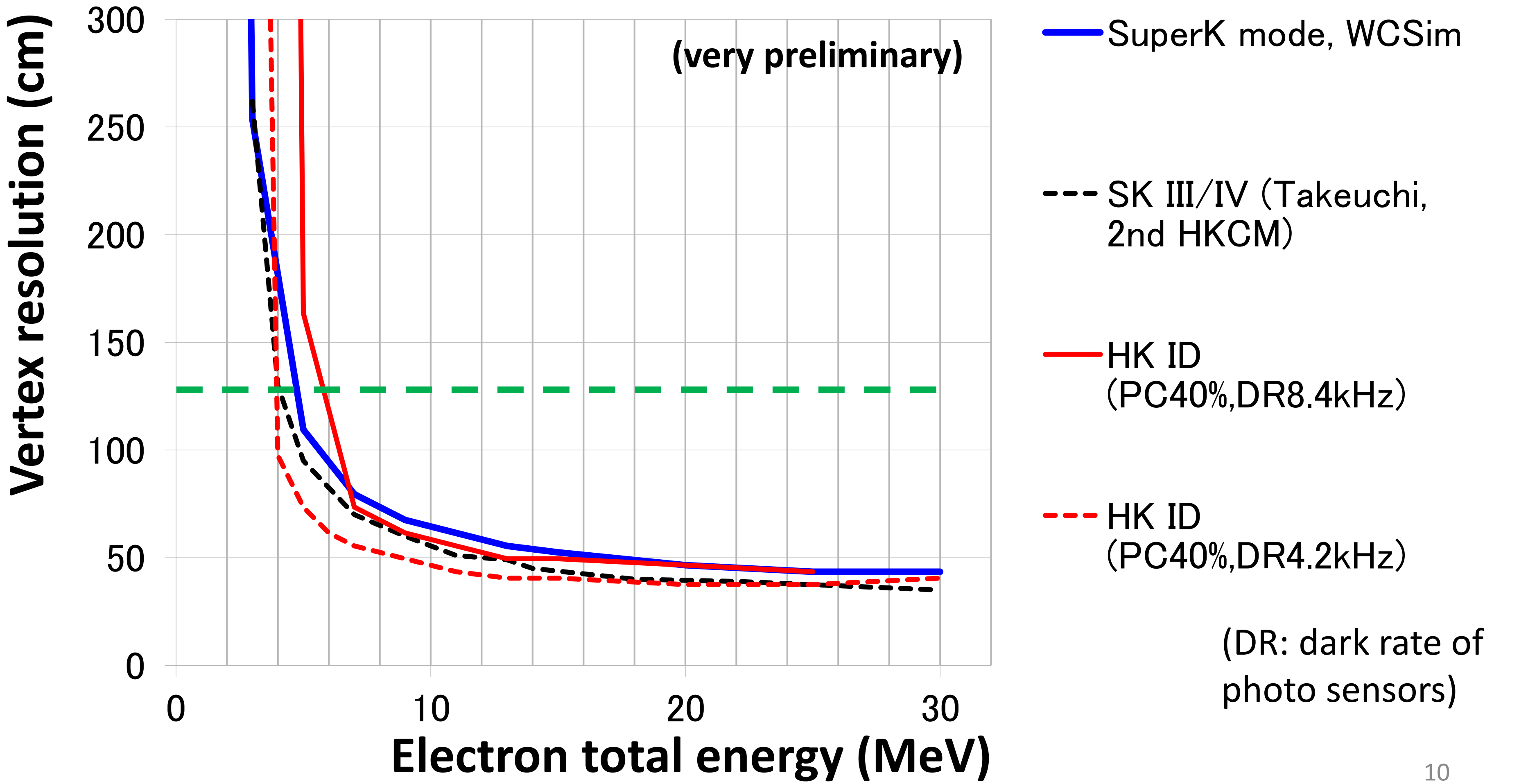






Vertex resolution study of HK detector

- A study of HK detector performance with WCSim is on going
  - Still very preliminary results
- Lowering threshold could be done in HK

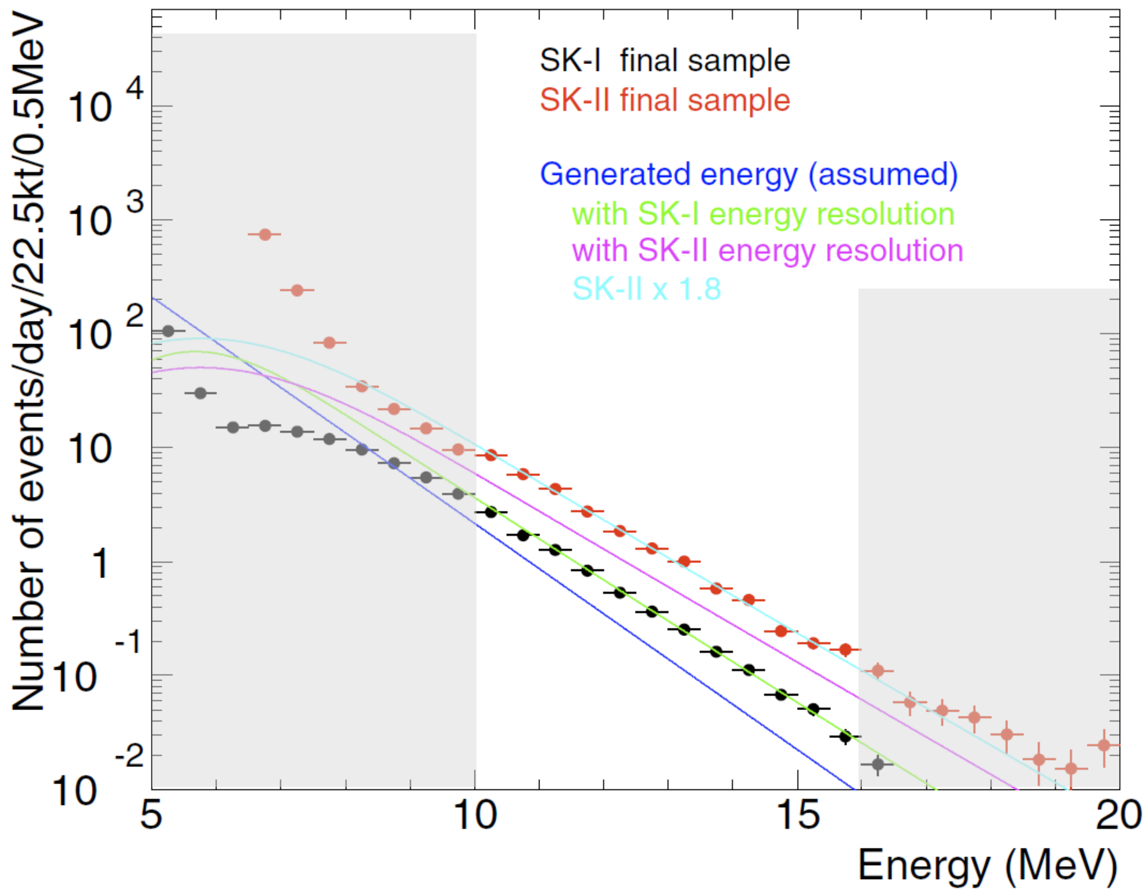


Effect of high density photo coverage:2

- Energy resolution: SK-I,III,IV = SK-II x ~1/sqrt(2)
- Other effect: SK-I = SK-II x 1/1.8 was observed
- Similar effect (better resolutions in analysis) would be exist in HK. → HK = SK-IV x ~1/1.8 ? (need study)

Comparison of energy distribution of final data sample of SK-I and SK-II

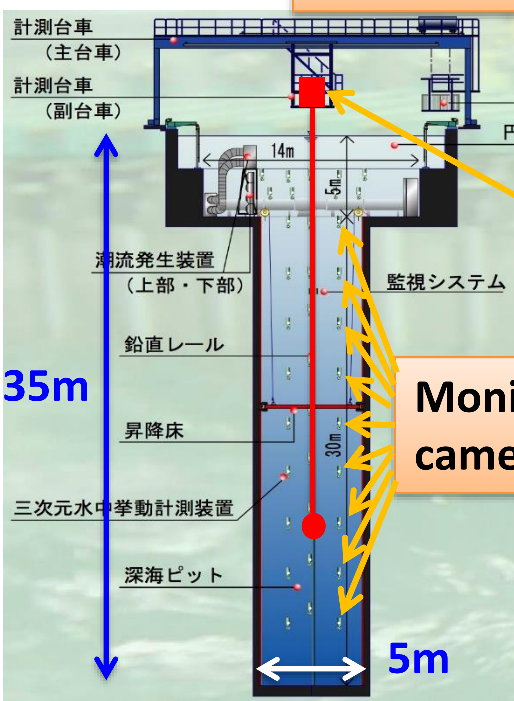
Assuming exponential type true energy distribution in around 10~16 MeV, factor 1.8 difference other than the energy resolution difference is observed.

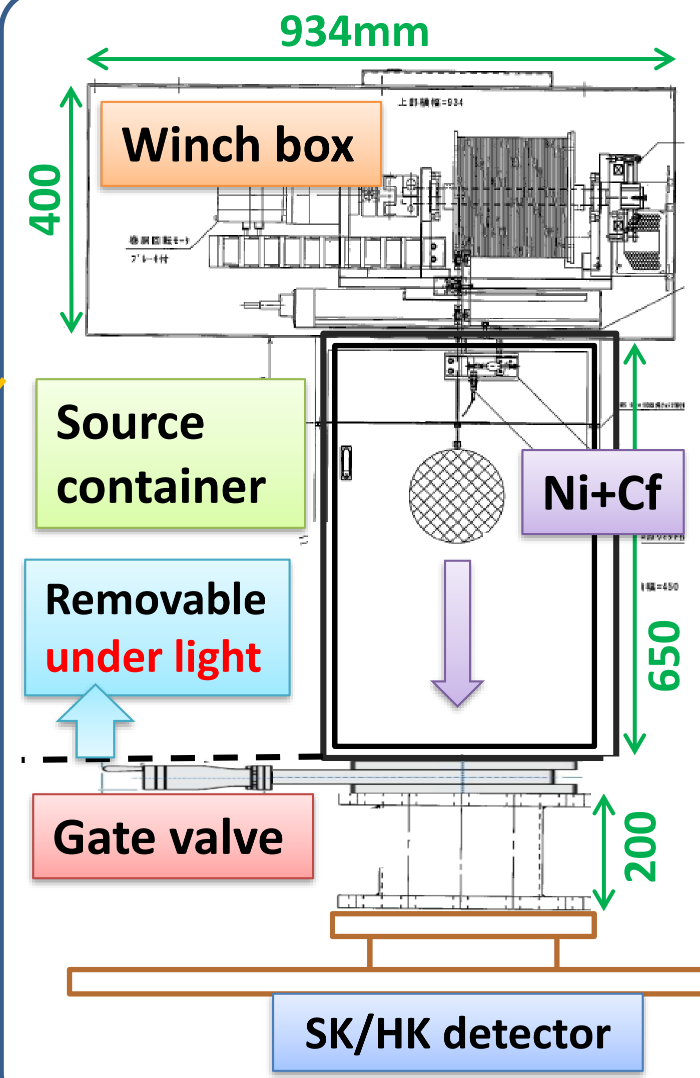


R&D of Ni-Cf deployment system

- Automated deployment by a sequencer
- Position precision: +/-5mm
- Will be used (=demonstrated) in SK
- Deep water test (~35m) was done at National Maritime Research Institute

NMRI: Deep water tank





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- Automated deployment by a sequencer
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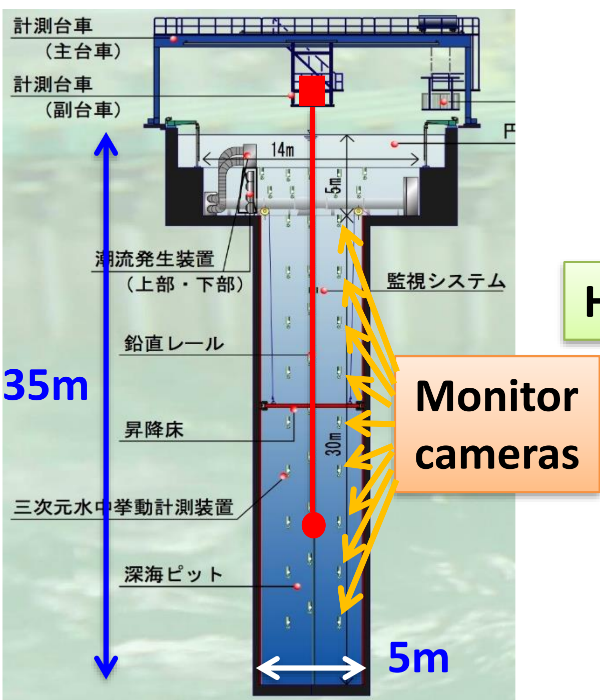
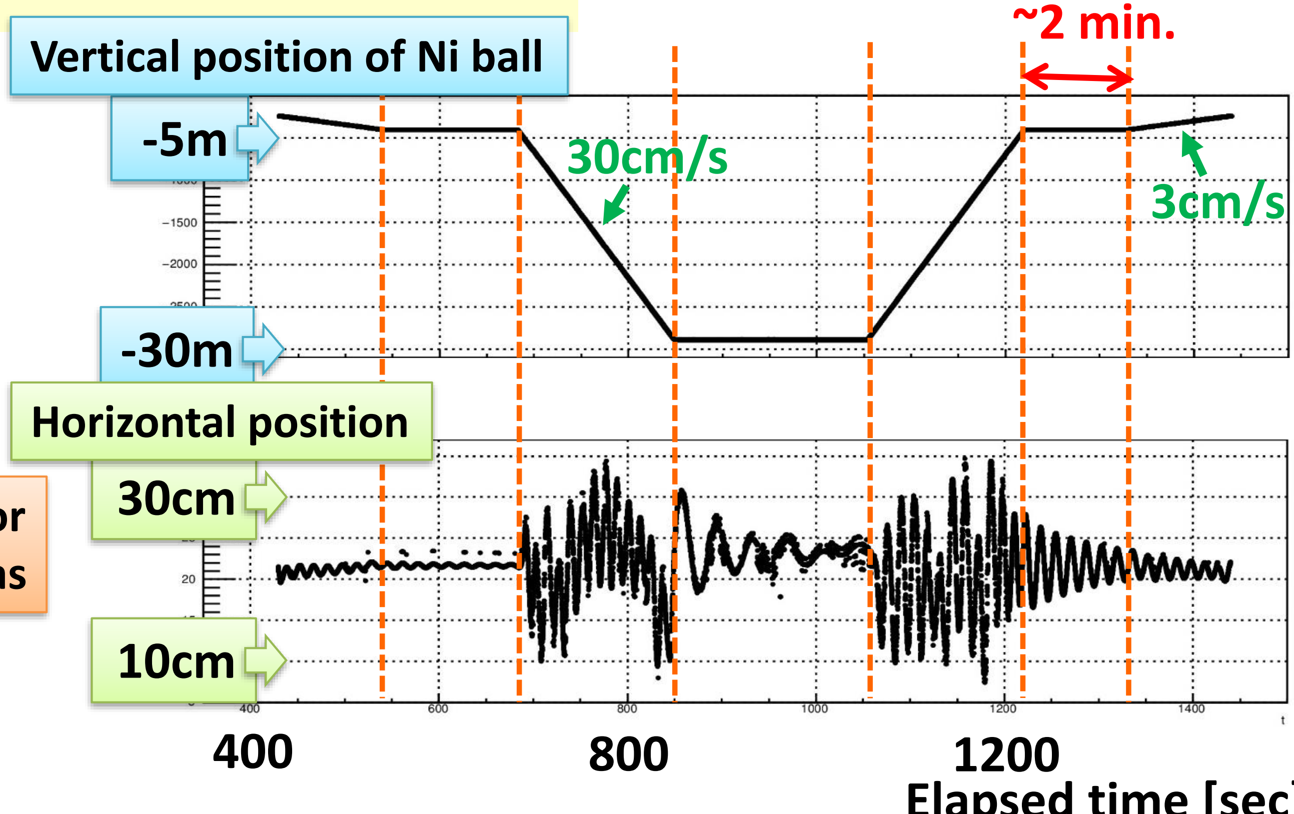
Need to wait for ~2 min. before going into pipe + flange part in SK/HK detector

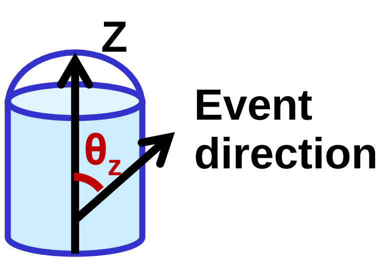


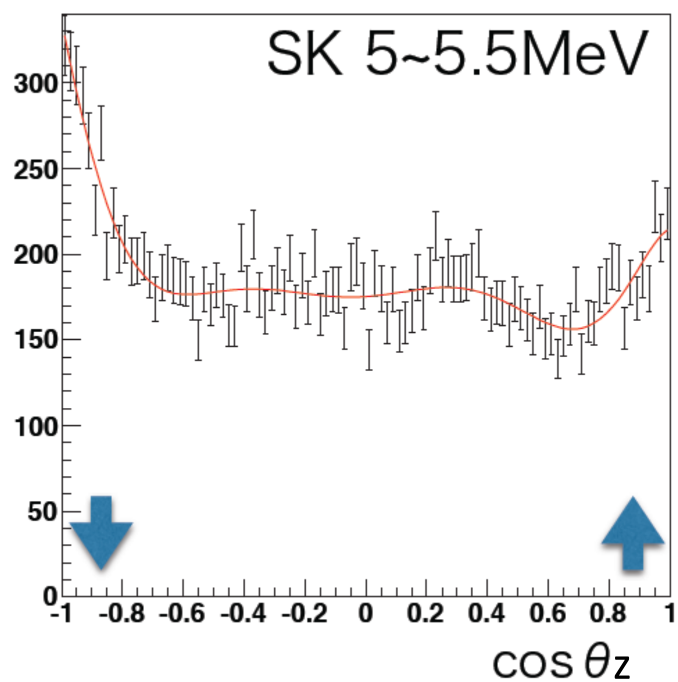


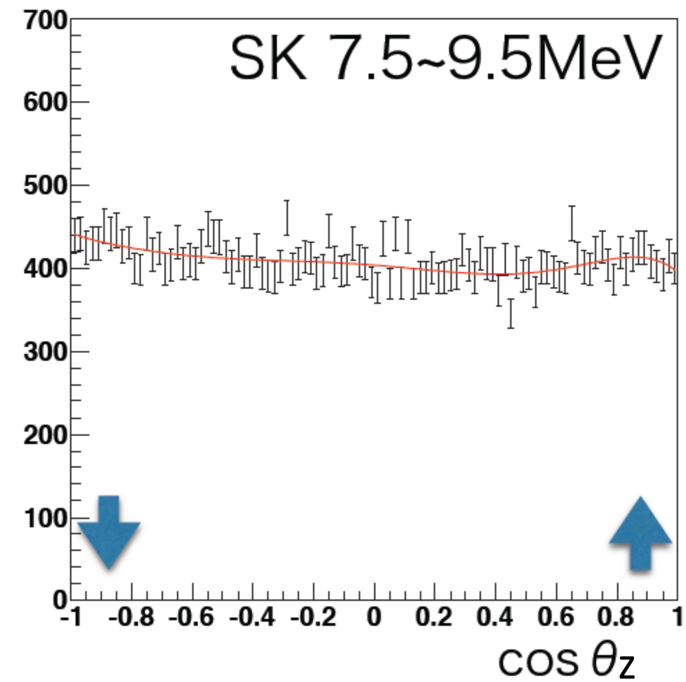
Up/down asymmetry

- **Dominant source of systematic uncertainty of solar day/night analysis in SK (~0.5%)**
  - **Low-E: non-uniform Rn in fiducial volume in SK water**
    - **In HK, Rn will be reduced by energy resolution (& higher threshold)**
  - **High-E: limited statistics for BG estimation**
    - **HK will have a lot of events**
- **Current goal in HK: 0.3%**

Final data sample to estimate BG shapes





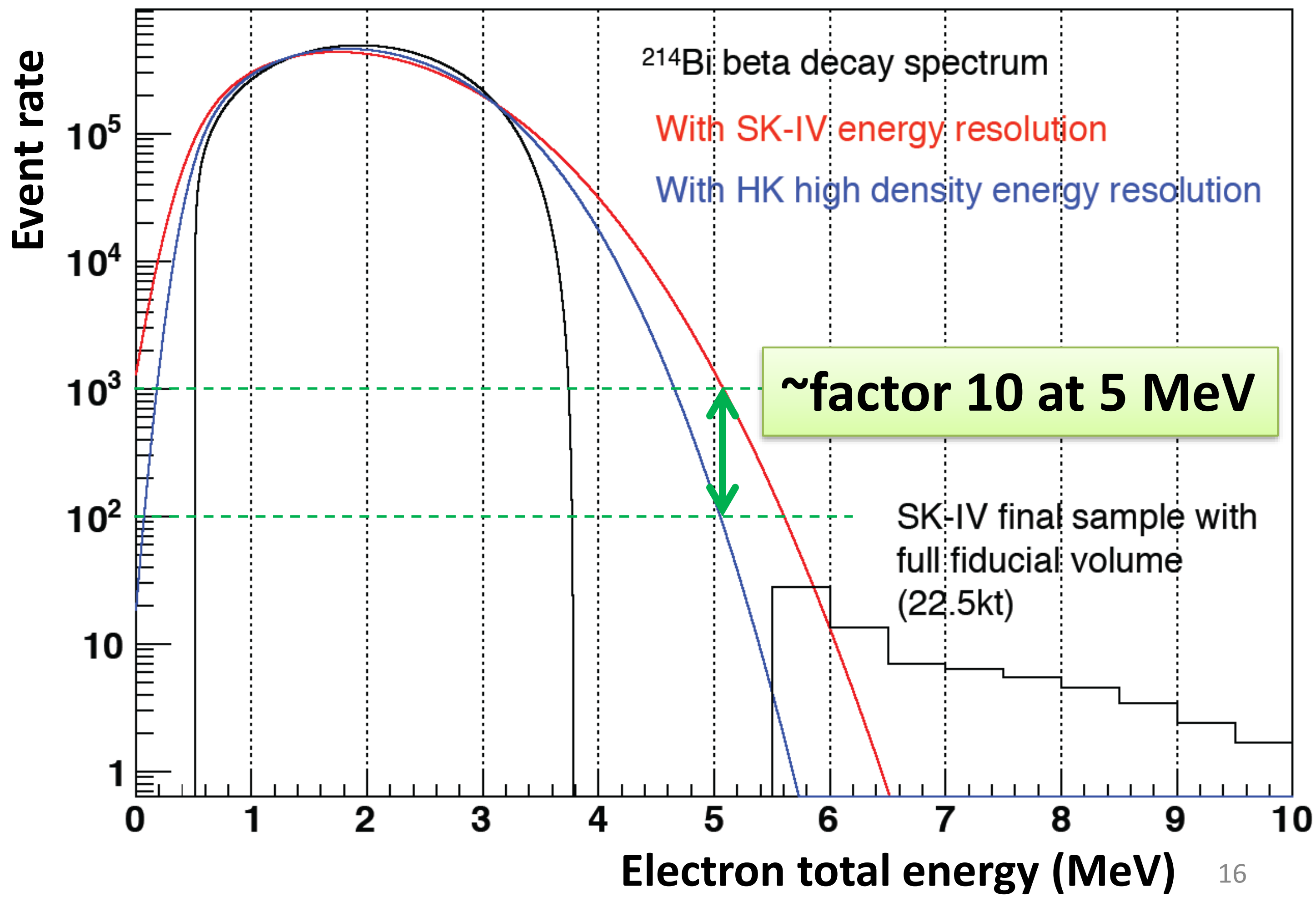


Radon in water in SK/HK detector

- A SK PMT emanates ^{222}Rn at a rate about 2 mBq/day → 10 mBq at equilibrium → 2.2mBq/m^3 in SK water.
  - Remove Rn by a vacuum degasifier system in SK
- Water purification techniques in SK will be applied in HK, then similar water quality as SK will be achievable in HK.
  - Water flow control in inner detector (ID) & outer detector (OD) will be also done in HK.
- In HK, a better energy resolution will further reduce radon events (at 5 MeV, a factor ~10)
  - → lower analysis threshold?
  - → better up/down asymmetry?

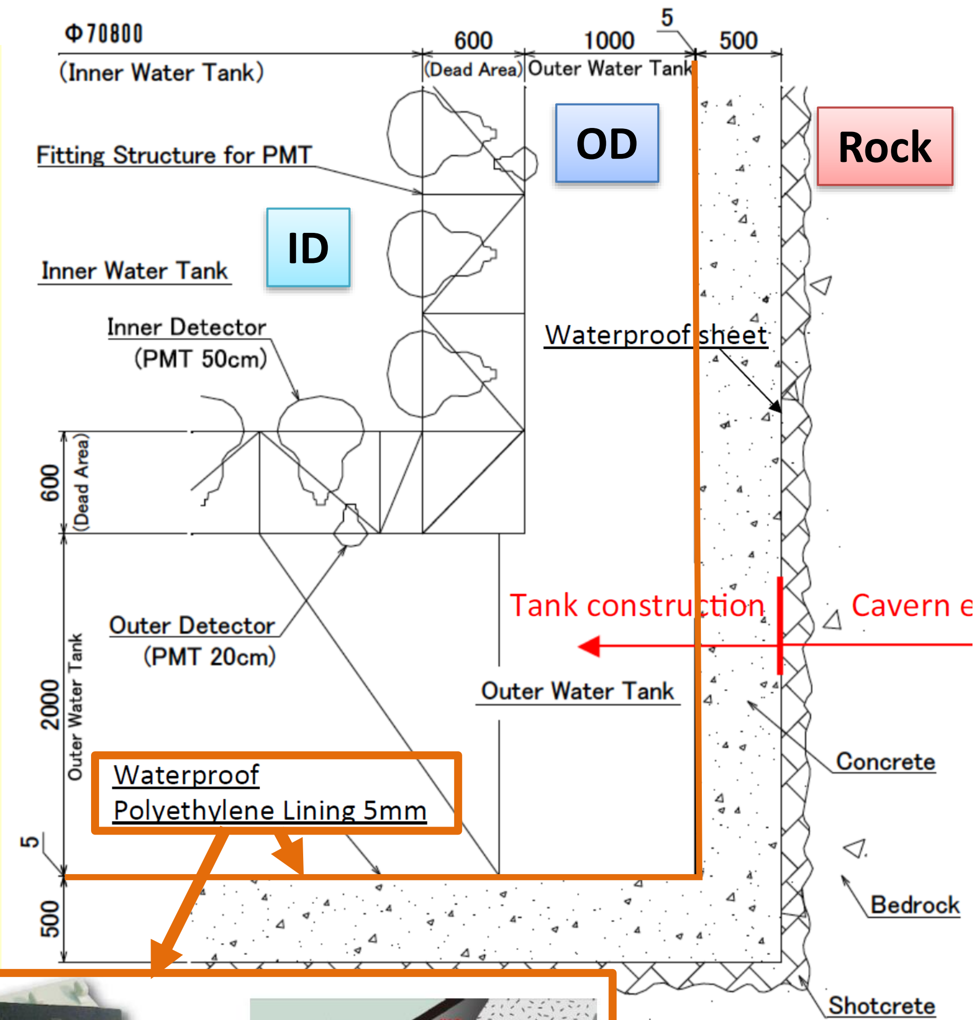
An estimation of Rn background

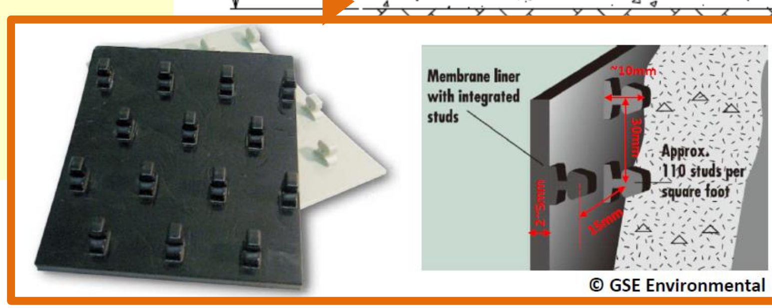
- **Radon events could be reduced in HK due to better energy resolution.**



Radon from surrounding rock

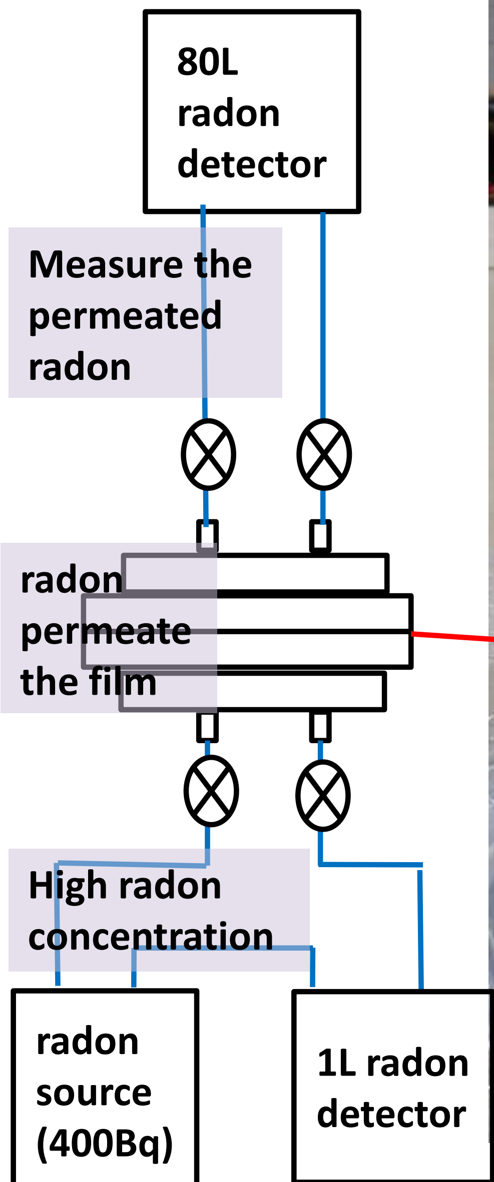
- **Lining**
  - **HK: HDPE**
  - **SK: stainless steel**
- **Expected/needed Rn concentrations**
  - **Outside (Rock) ~10 kBq/m^3**
    (very rough guess)
  - **Inside (ID) ~1 mBq/m^3**
    (requirement)
- **We would like to check Rn permeability of the HDPE sheet**

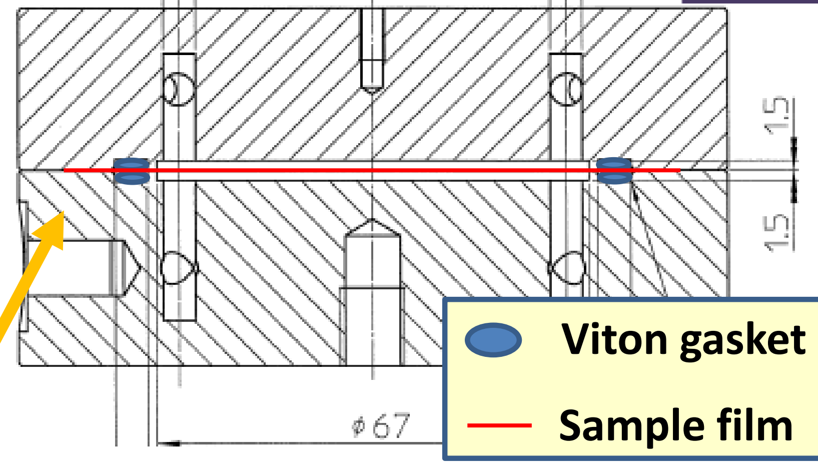


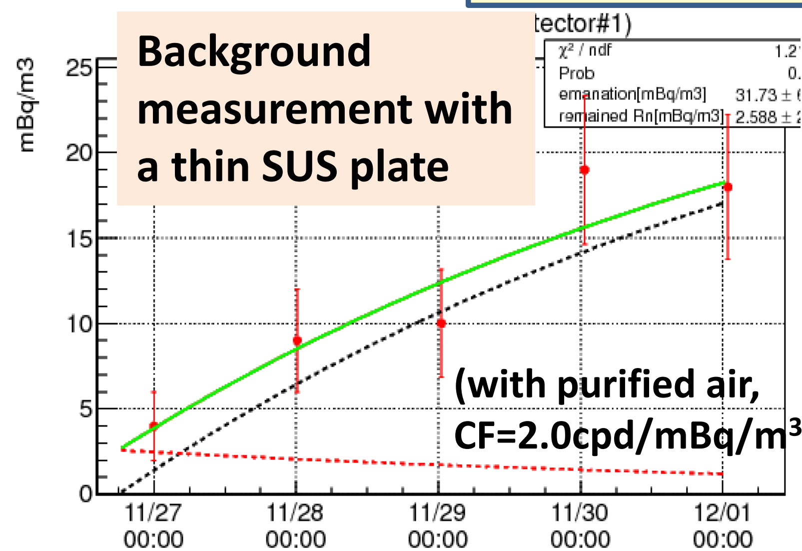


R&D of Rn permeability measurement system

http://www.lowbg.org/ugnd/ 科研費 KAKENHI



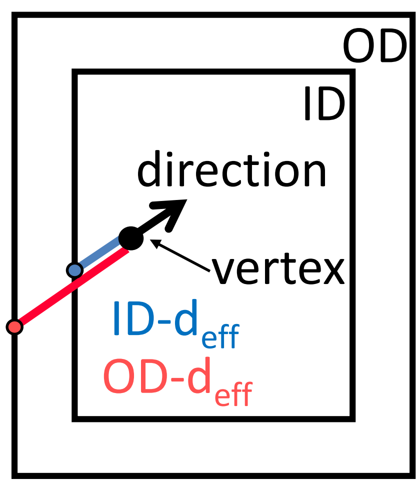




- Current background level = ~30mBq/m^3
- More improvement would be needed for the HDPE sheet measurement.

External events in SK

- **Barrel OD thickness of HK is 1m shorter comparing to SK**
  - **Need to think about external events from Rock.**
- **It looks current dominant external events are coming from ID wall in SK (at least, E_{total} < 7 MeV).**
  - **External event cut (=gamma-cut) using ID-d_{eff} works well.**
- **After SK-II, PMT covers are added, then low-energy external events are increased**
  - **Factor ~ 10 at 6 MeV, between SK-I and SK-III before quality cuts**
  - **Most of these are removed by a quality cut**



SK-I: PRD73, 112001

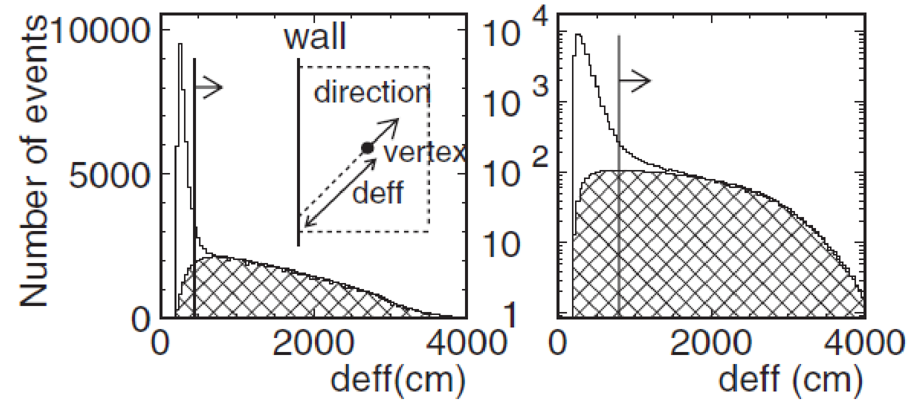
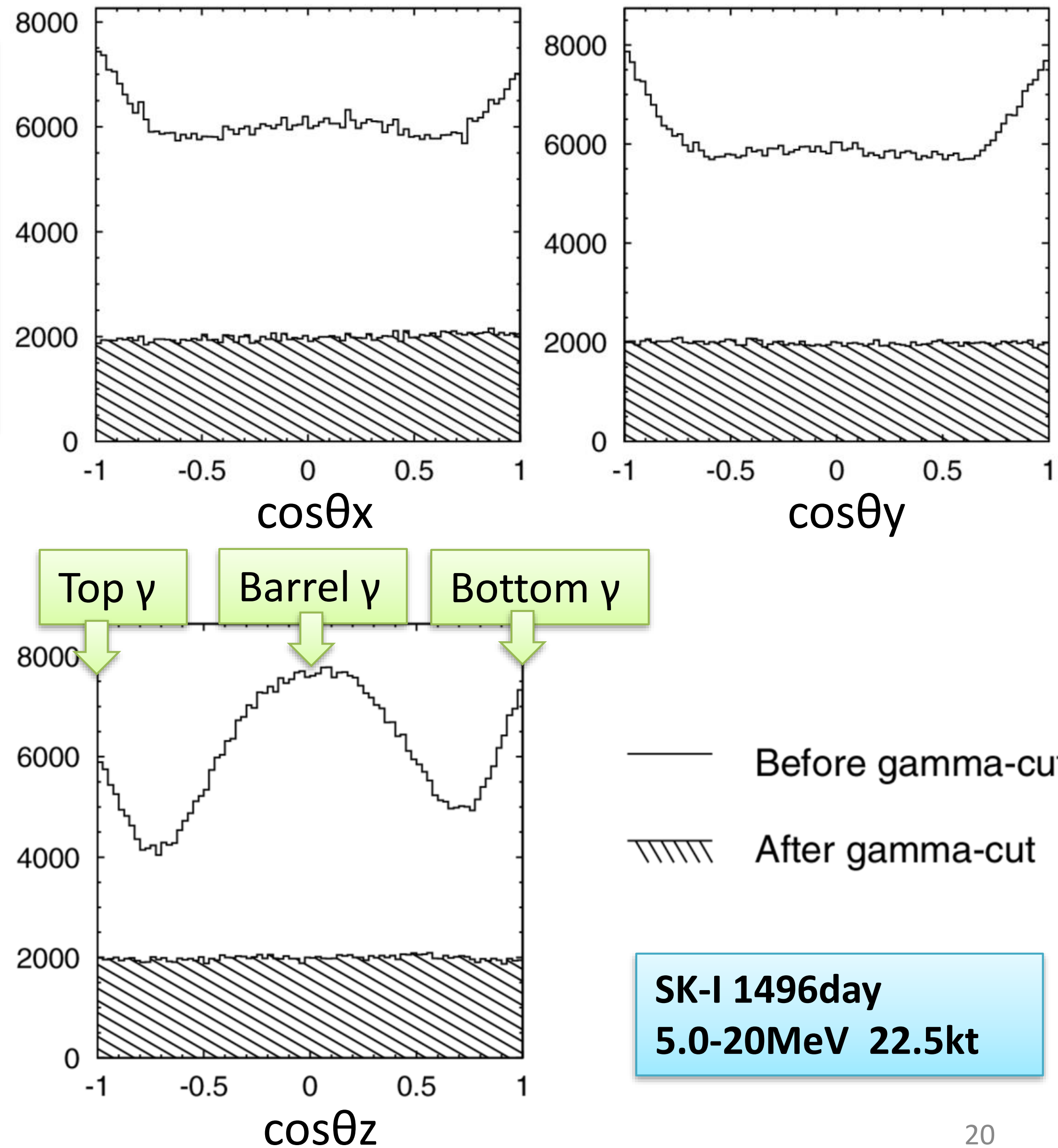
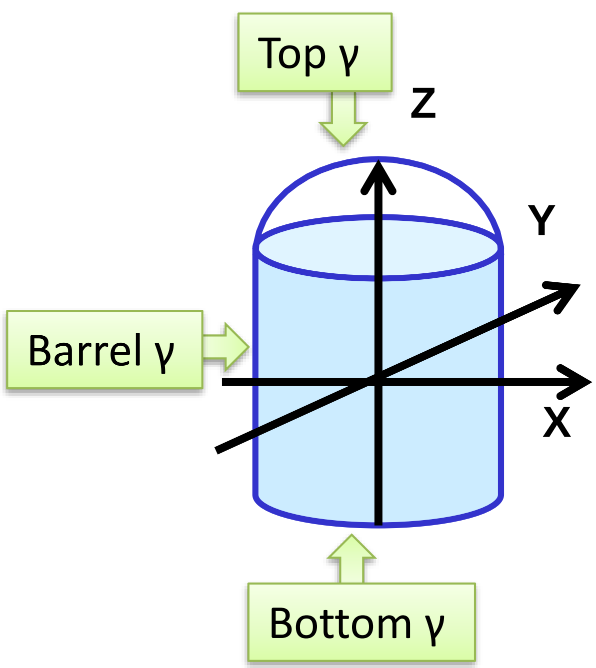


FIG. 35. Effective distance (d_{eff}) of $E \geq 6.5$ MeV (left) and 5.0 MeV $\leq E < 6.5$ MeV (right). Blank histogram shows data and hatched area shows solar neutrino MC.

External event cut in SK-I

If the external event cut using ID-d_{eff} (=ID gamma-cut) is applied, the remaining event direction becomes uniform.



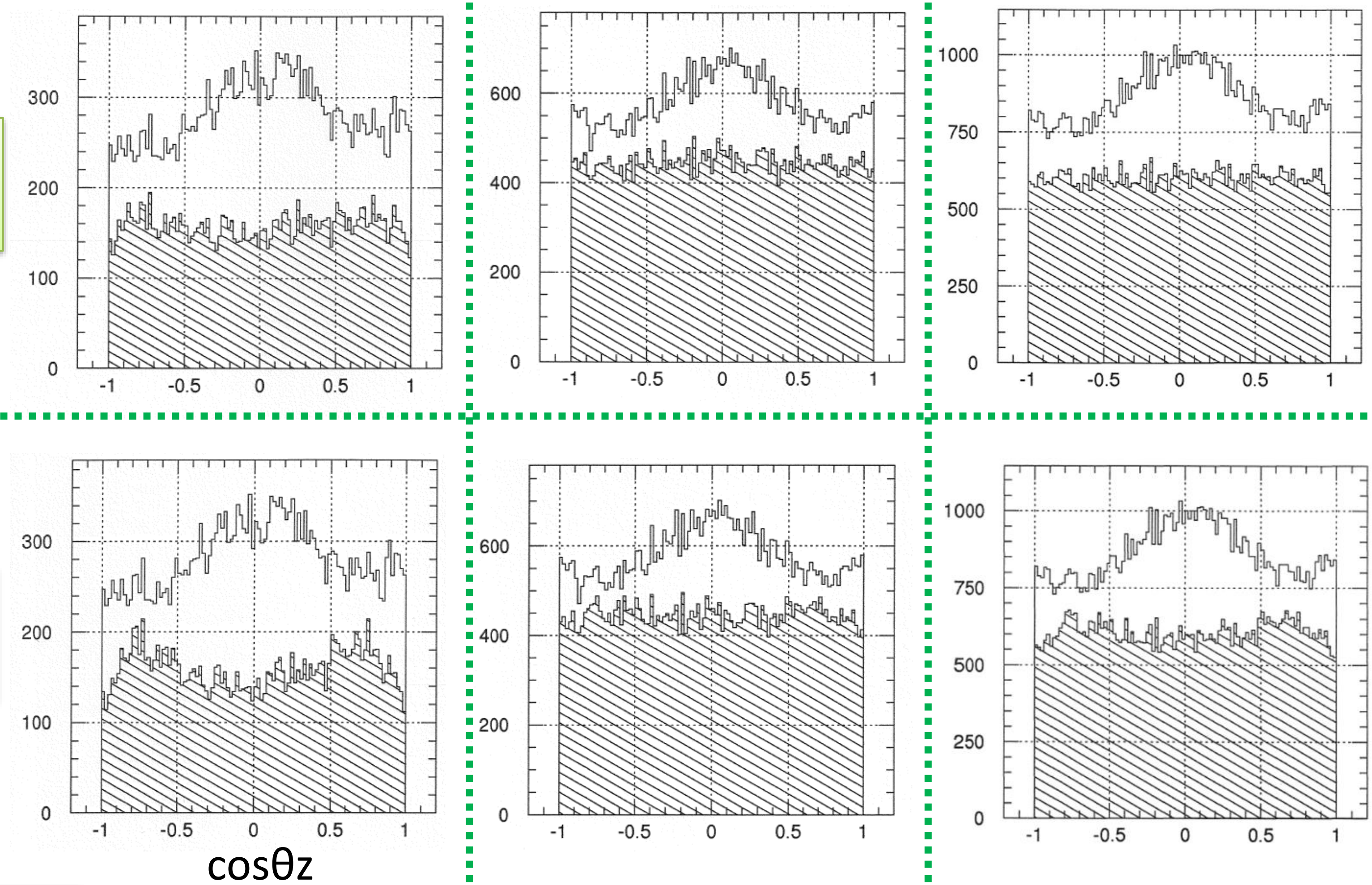


Comparison of ID & OD gamma-cut

	<7 MeV	>7 MeV	6.5-20 MeV

ID gamma-cut

OD gamma-cut



SK-I 300day
6.5-20MeV 22.5kt

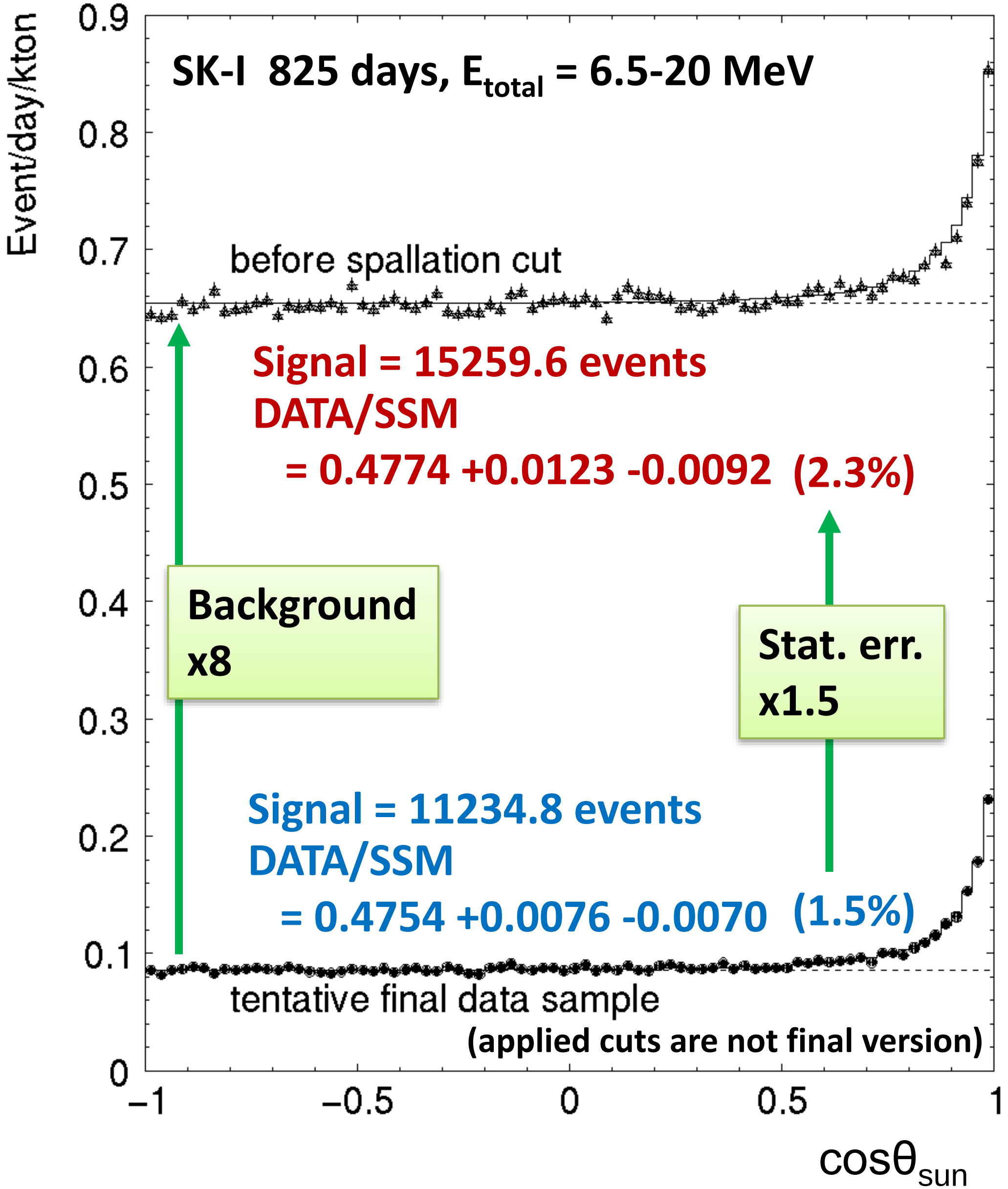
ID gamma-cut looks working well
→ Dominant source would be at ID wall

Estimation of spallation products

- Estimated cosmic-ray muon flux
  - HK in Tochibora: SK x (4.9+/-1.0) (muon density in HK)
- Then, estimate isotope production rate from muon energy
  - HK in Tochibora: SK x (4+/-1) (spallation event density in HK)
- Estimate spallation cut efficiency using SK data
  - Estimation by increasing muon event rate artificially.
    - Remaining spallation events will be x3 at muon density x5 (with keeping 80% signal efficiency)
  - Considering possible improvement of spallation cut in solar analysis considering a new PDF (longitudinal distance)
    - Remaining spallation events will be ~1/5 (based on a study with SK-II data)

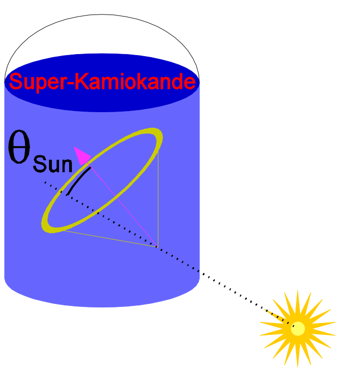
⇨ Increase of remaining spallation events $HK/SK_{current}$ = 2.7

A study of spallation products in SK-I



- Even though there are a lot of spallation products, solar neutrino extraction works well.
- **Angle information reduce the effect of background increase in the statistical uncertainty.**

c.f. HK LOI, arXiv:1109.3262



Summary

- **Current expectations and ongoing activities related to low-energy performance are reported.**
- **High density photo coverage would be most important for low-energy events.**
  - **Enables unique topics, like solar hep neutrino discovery**
- **For the lowest energy region, lower dark noise of photo sensors, low radio activity of materials are also important.**
- **Various studies / R&Ds in details are ongoing.**

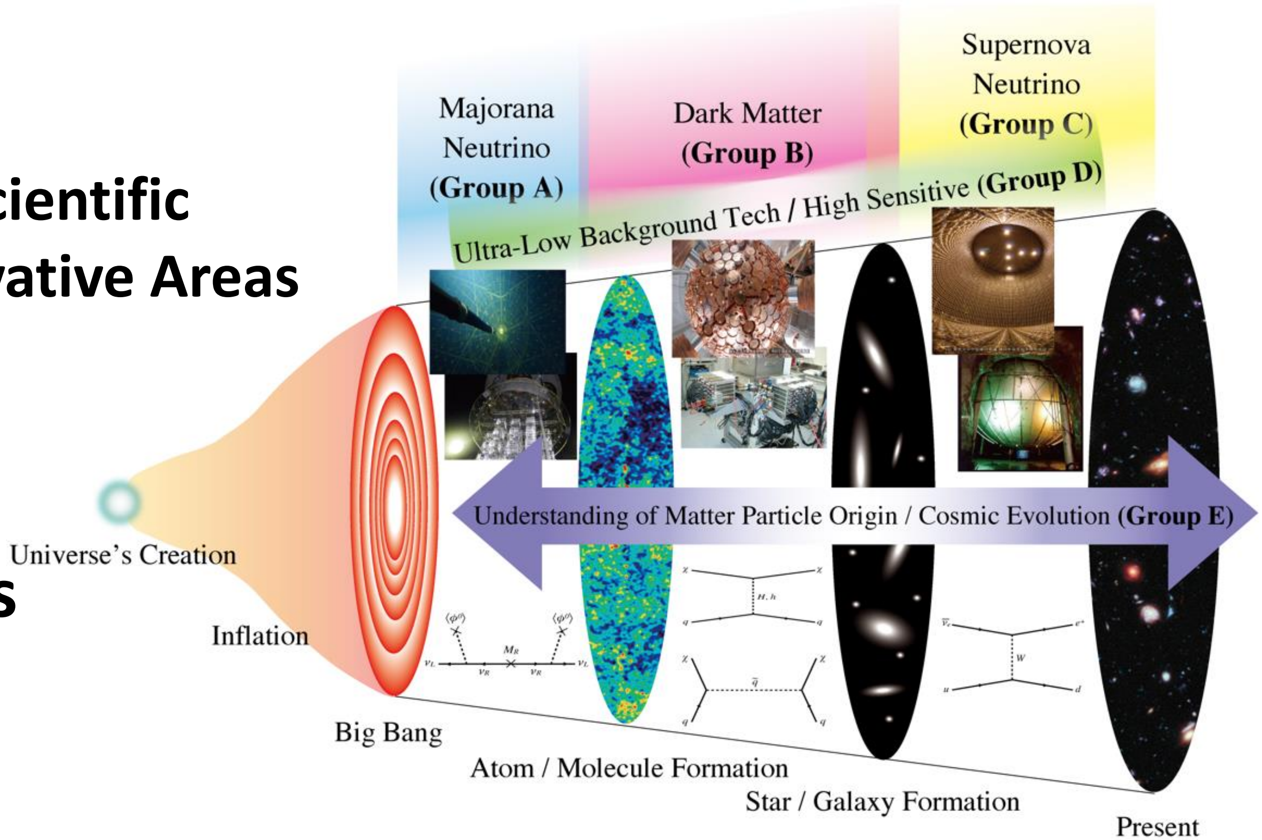
SUPPLEMENTS

“Revealing the history of the universe with underground particle and nuclear research”

http://www.lowbg.org/ugnd/

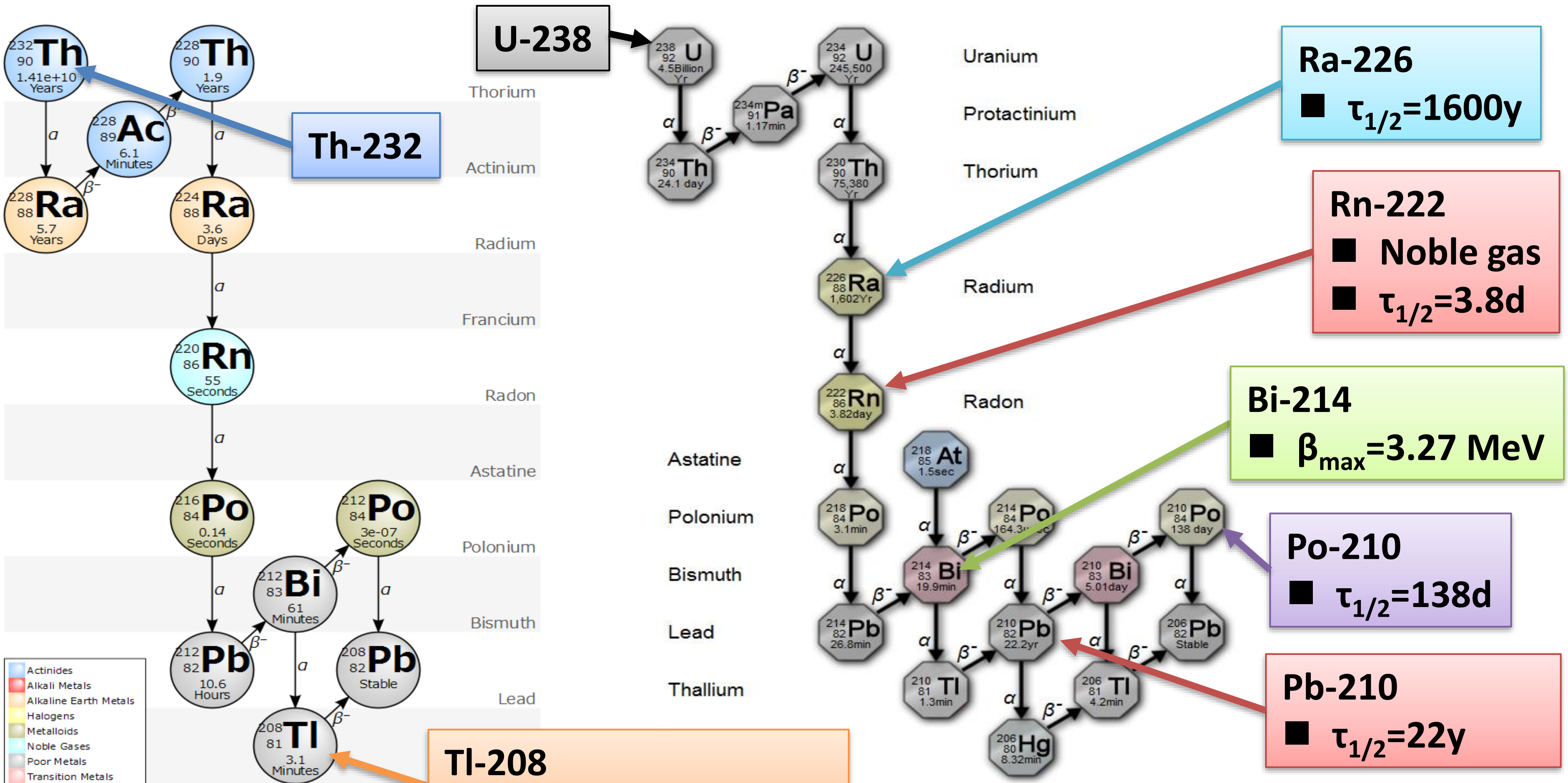
Cooperate among underground experiments, theorists, & low-BG researchers to achieve technical and scientific synergies.

- MEXT KAKENHI
  - Grant-in-Aid for Scientific Research on Innovative Areas
- JFY 2014 - 2018
- ~10 million US$
- 5 research groups
- ~70 researchers



U-series, Th-series

- In nature: 1～10 ppm(10^{-6})
  → In experiments: ppb(10^{-9}), ppt(10^{-12}), ppq(10^{-15}),,,



http://en.wikipedia.org/wiki/Decay_chain