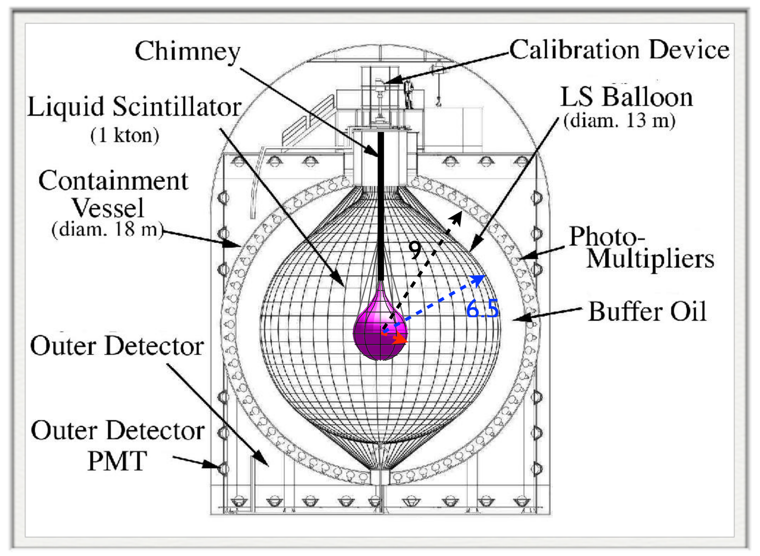
Background Identification and Dircetional Reconstruction in LS Detectors using Machine Learning

Zhenghao Fu, for the KamLAND-Zen collaboration
Massachusetts Institute of Technology

In rare event searches like those for neutrinoless double beta decay (0νββ), one of major backgrounds is caused by cosmic muon spallation. To remove these background events, a precise method with high efficiency is required to separate them from signal events. Machine learning offers a solution to this problem. For the spherical detector in KamLAND-Zen, convolutional neural networks (CNNs) based on a spherical system provides a way to classify the data. Besides the classification, a method aiming to reconstruct the direction of particles in a detector is also developed. This poster will cover the concept and usage of spherical CNNs for KamLAND-Zen's data, and the current performance of the direction-determination using simulations.

1. KamLAND-Zen:

- KamLAND-Zen is a Liquid Scintillator (LS) experiment, consisting of 1800 PMTs to measure light within the cavity.
- A mini-balloon loaded with ^{136}Xe Liquid Scintillator, deployed at the center of detector, is the source of ββ events. ^{10}C is the dominant background in 0νββ analysis.
- For each event, KamLAND detector produces a spherical hit map.



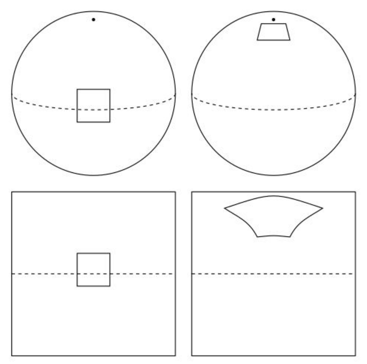
KamLAND Detector

	Period-1 (270.7 days)		Period-2 (263.8 days)	
Observed events	22		11	
Background	Estimated	Best-fit	Estimated	Best-fit
^{136}Xe $2\nu\beta\beta$	-	5.48	-	5.29
Residual radioactivity in Xe-LS				
^{214}Bi (^{238}U series)	0.23 ± 0.04	0.25	0.028 ± 0.005	0.03
^{208}Tl (^{232}Th series)	-	0.001	-	0.001
^{110m}Ag	-	8.5	-	0.0
External (Radioactivity in IB)				
^{214}Bi (^{238}U series)	-	2.56	-	2.45
^{208}Tl (^{232}Th series)	-	0.02	-	0.03
^{110m}Ag	-	0.003	-	0.002
Spallation products				
^{10}C	2.7 ± 0.7	3.3	2.6 ± 0.7	2.8
^{6}He	0.07 ± 0.18	0.08	0.07 ± 0.18	0.08
^{12}B	0.15 ± 0.04	0.16	0.14 ± 0.04	0.15
^{137}Xe	0.5 ± 0.2	0.5	0.5 ± 0.2	0.4

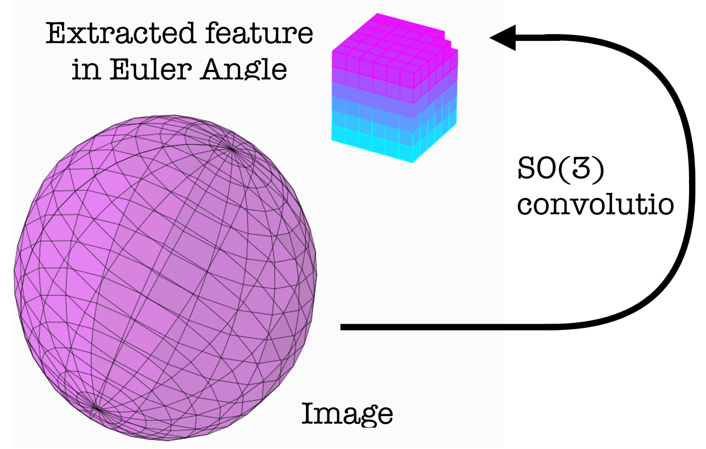
Summary of Backgrounds
PRL117, 082503 (2016)

2. Spherical CNNs:

- Normal CNNs distort the spherical image data from KamLAND-Zen. Our classification analysis adopts the Spherical CNNs by Cohen et al.(arxiv1801.10130). The algorithm is in SO(3) group, following rotational symmetry.
- In a normal CNN, the kernel scans the input image via partial regions with fixed size.
  In a Spherical CNN, the kernel covers the entire sphere, scanning in Euler Angle.



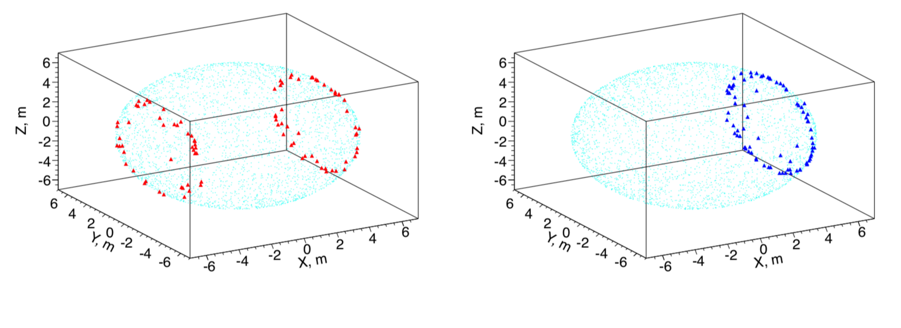
Distortion caused by projection of spherical images



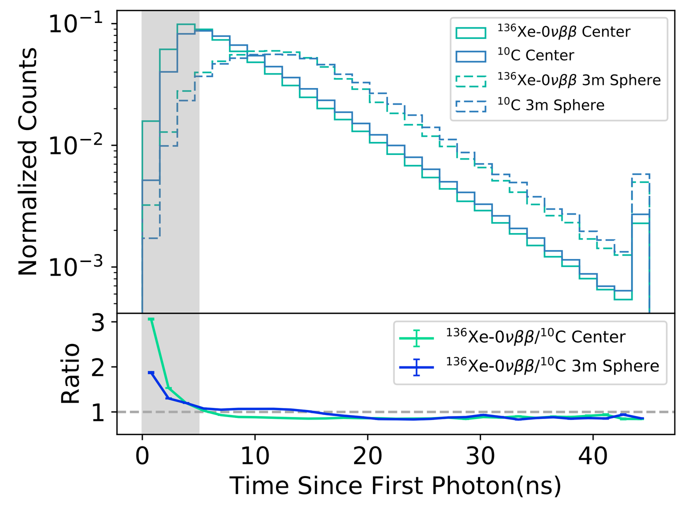
Algorithm of Spherical CNN

3. Muon Spallation Classification Study:

- Radioactive isotopes produced through cosmic muon spallation in the LS are background in 0νββ searches. The dominant spallation product is ^{10}C, with lifetime τ ~ 28 s.
- ^{10}C has only one Cherenkov ring and de-excitation gamma's, while 0νββ has two Cherenkov rings and not gamma's. The classification power seems to come from photon timing in the first 5 ns.



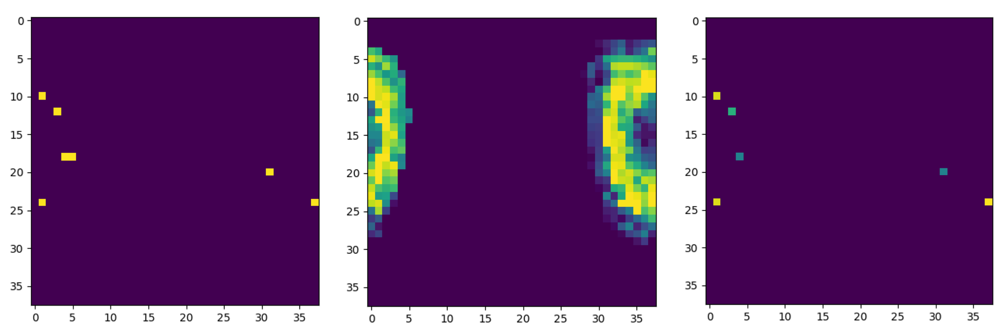
Cherenkov rings of signal & background
Nucl.Instrum.Meth. A849 (2017) 102-111



4. Directionality Reconstruction Study:

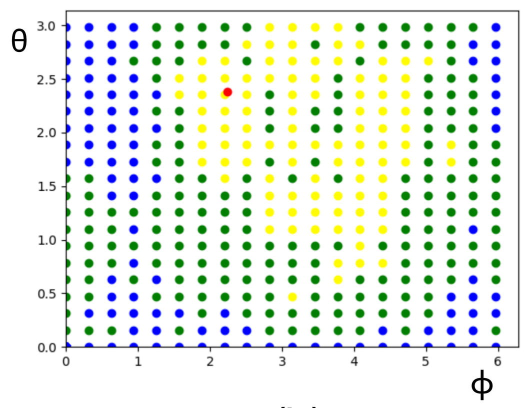
(Though the kernel covers entire spherical detector, feature maps in Spherical CNN retain information of directions. 2 methods are developed for direction determination.)

- Regional masks method:
  Various masks on sphere with corresponding directions are proposed, as in Fig.(a). Outputs are generated by using pre-trained classification networks. Difference between outputs of masked input and those of original input are calculated. Directions corresponding to the most similar masked output are selected.
  Top 25% masked output directions (yellow) and truth (red) directions are shown in Fig.(b).
- Pooling & fully-connected networks method:
  Normal CNNs are applied after spherical CNN, utilizing deep learning network to study relation between feature maps and directions. For spherical MNIST data, 95% direction predictions maintain within 30° from truth directions.
  For simulation, to avoid gradient vanishing/exploding, shallow masks (with weight coefficient 0.05%) with similar direction as events are added as in Fig.(c). The output prediction range is shown in Fig.(d), together with the truth direction.

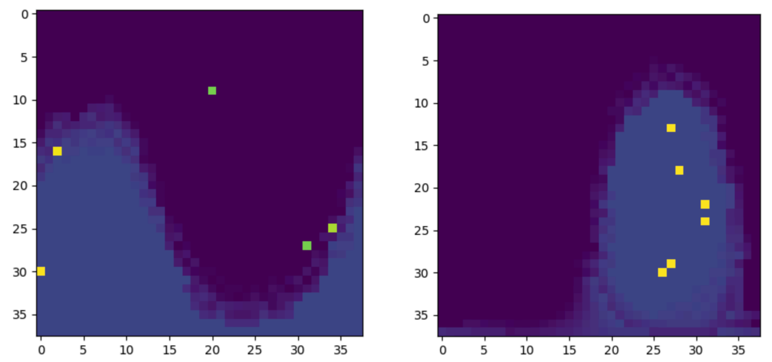


Original Input   Proposed Mask   Masked Input

(a)

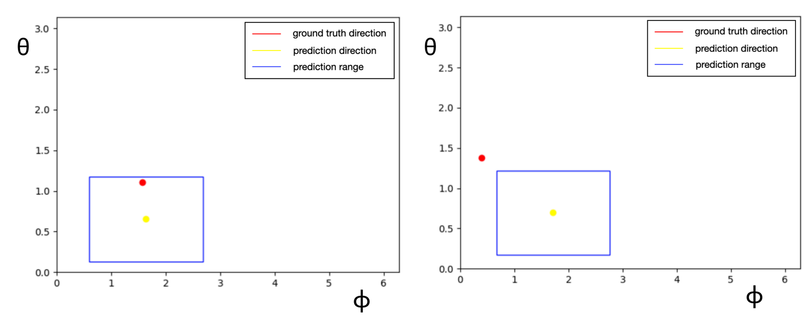


(b)



Shallow masks miss some hitting points.   Good shallow masks cover all points.

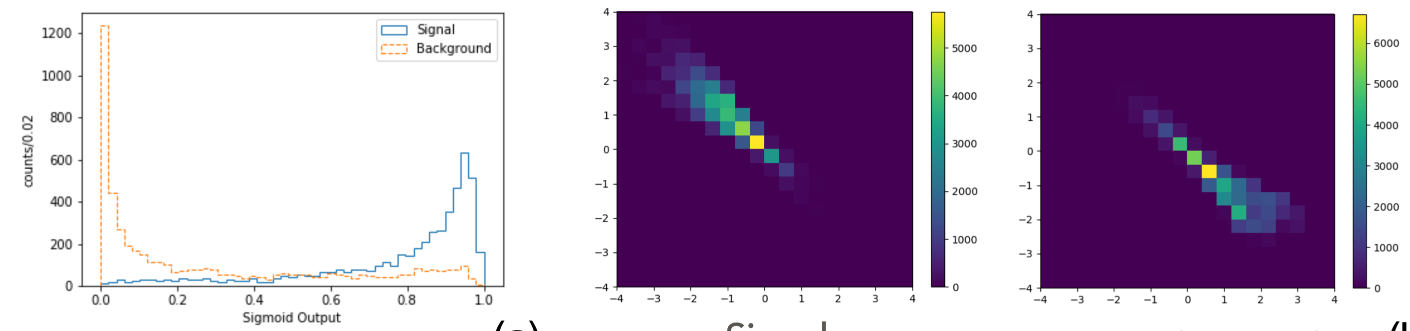
(c)



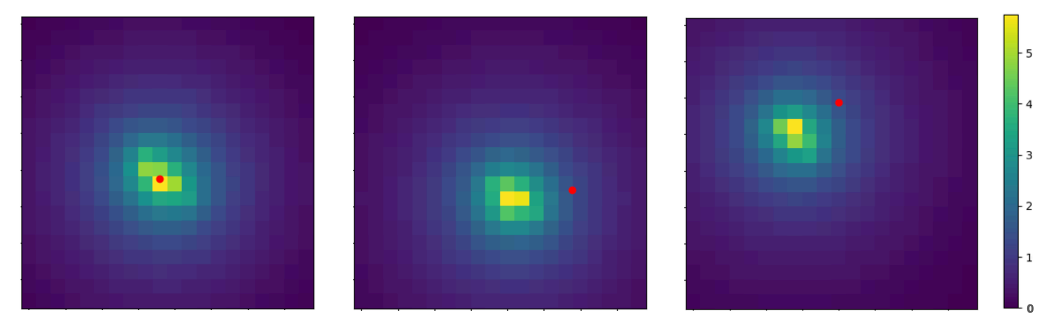
(d)

5. Result:

- Calssification result:
  Spherical CNN background rejection is 71% improved from 61% for normal CNN. Classification separation in Fig.(a) and posterior distributions via resampling in Fig.(b).
- Directionality result:
  For ββ decay simulation (no scintillation light), 50% direction predictions maintain within 60° from truth.
  Prediction distribution via resampling in Fig.(c).



(a)   (b)



(c)