Distributed Imaging for Liquid Scintillator Detectors

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Liquid Scintillators

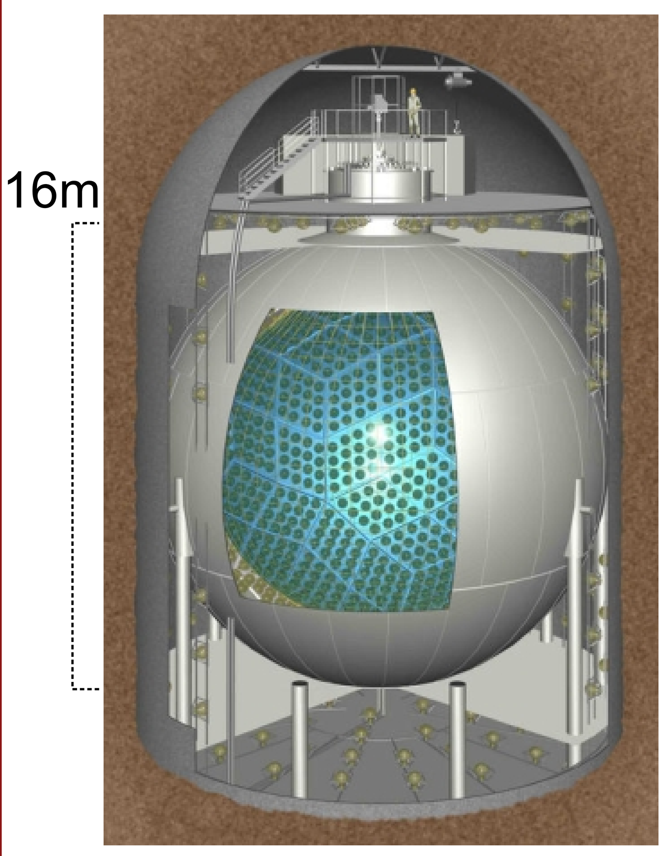
Organic liquid scintillators have been an extremely successful technology in particle detector, enabling fundamental steps forward in our current understanding of neutrino physics. Although these detectors can count on a **high light yield** and **low energy threshold**, the topology of the event is usually poorly reconstructed. This information is important as it can help to **discriminate** more efficiently **background events** (e.g. distinguish between electron and gamma interaction). Imaging the scintillation light emitted is challenging if not impossible with conventional cameras due to the limited amount of photons produced, the high-emittance of the source.

Distributed Imaging

Our technique, which we named *distributed imaging*, aims to solve this imaging problem by measuring the incoming direction of each photon, and triangulating back these reconstructed directions in a sort of 3D image.

HOW DO WE DO IT?

We considered a traditional liquid scintillator detector and substituted the PMTs with **lens assemblies** (LAs) consisting of converging lenses followed by a focal array pixelated with photo-detectors.



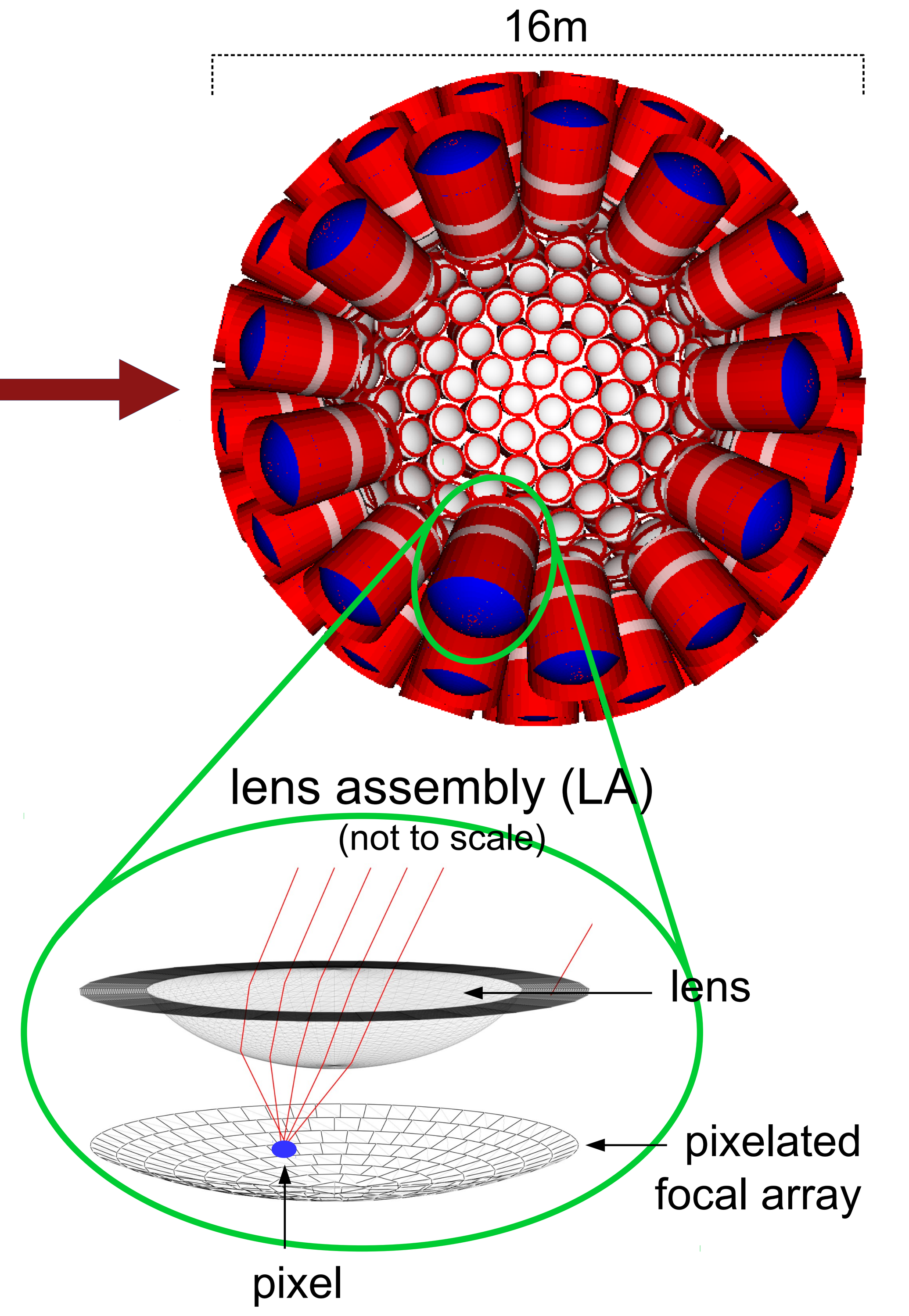
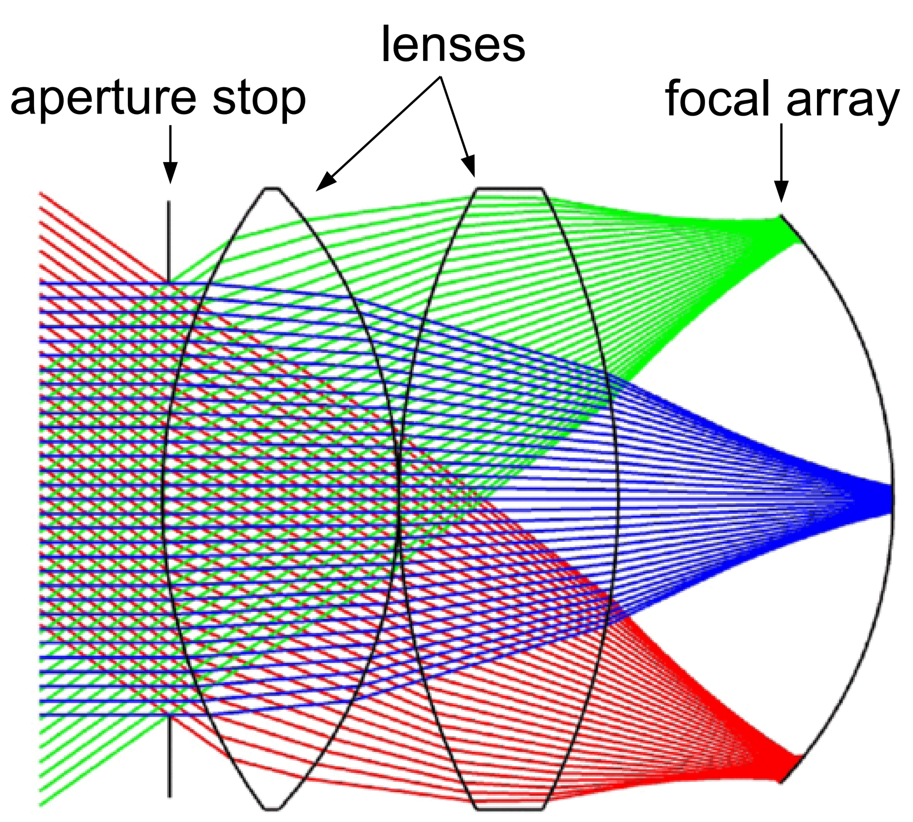


Fig. 1: *top left.* A traditional liquid scintillation detector (KamLAND). *Top right.* Conceptual design of our detector with lens assemblies (LAs) substituting the PMTs, each assembly is wrapped in a baffle (red cylinder) blocking stray light. *Bottom right.* Zoomed in view of one LA. Also shown, ray traces focused by the lens or blocked by the aperture stop.



The lens maps **incident angles** into **positions** on the focal array, so that each pixel traces back a particular direction in the detector. By **triangulating back the directions** from all the LAs, the topology of the event can be reconstructed. It is not easy to design a system with accurate resolution and wide field of view in liquid

Fig 2: Ray diagram of one LA. This shows how different bundles of parallel rays focus to different points on the focal array. On the left, the aperture stop is shown.

Our Analysis

As exploratory study, we simulated such detector and generated inside it electron and gamma events. Since the deposit of energy with the gammas is more spatially spread than with the electrons, we estimated which percentage of **gamma events we can reject when we correctly identify 80% of the electron events** for different detector configurations.

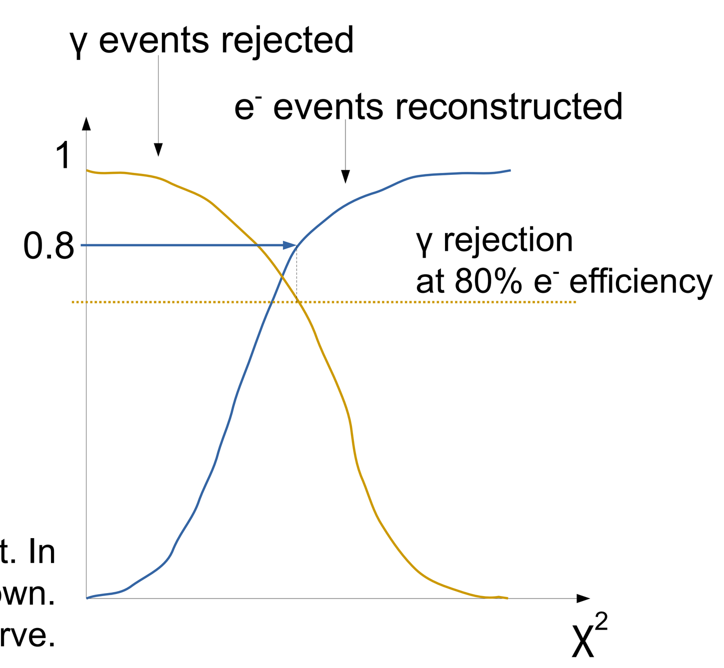


Fig 3: Conceptual sketch of the discrimination plot. In blue, the electron reconstruction efficiency curve is shown. In orange, the gamma rejection curve.

Detector Simulation

The propagation of the scintillation photons to the detector is simulated with Chroma, a GPU based Python package.

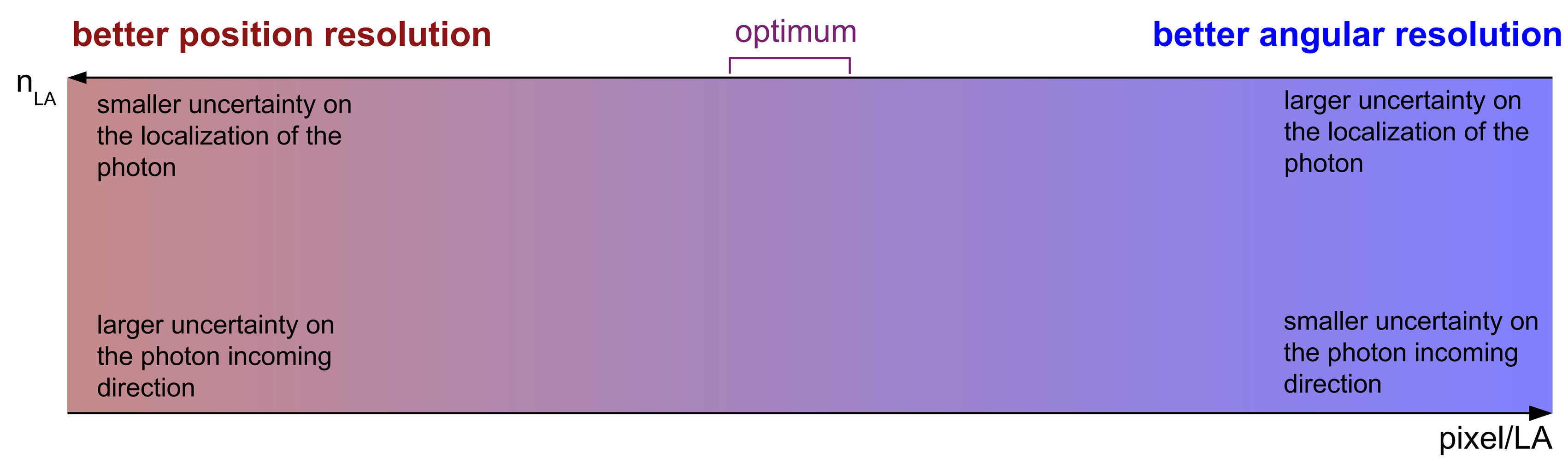
DETECTOR CONFIGURATION

In the table below the main optical parameters of the LA are reported:

number of elements	2 (spherical)
field of view	33°
refractive index	1.98
$R_{lens}/R_{focal\ array}$	1
angular resolution (at the focal array center)	2.5°

Table 1: We require wide field of view to maximize the collection of light. Since the liquid scintillator has n=1.5, we need high index material for the lenses. To reduce the number of optical elements, we adopted a curved focal array.

We varied the total number of LAs keeping fixed the overall number of pixels to 100k: increasing the number of LAs, results in fewer pixels behind each LA. We expect the presence of an optimal number of LA to maximize our gamma rejection.



Results

We present here the results of detector configurations with different numbers of LA. The light collection efficiency is pretty insensitive to the total number of LAs, slightly decreasing for detectors with fewer LAs. The collection efficiency is around 22% (19%) for centered (off-centered) events. This breaks down in 73% (63%) of geometrical acceptance 30% of the pixels QE. The presence of the aperture stop rescales the amount of light by the geometrical factor.

GAMMA REJECTION EFFICIENCY

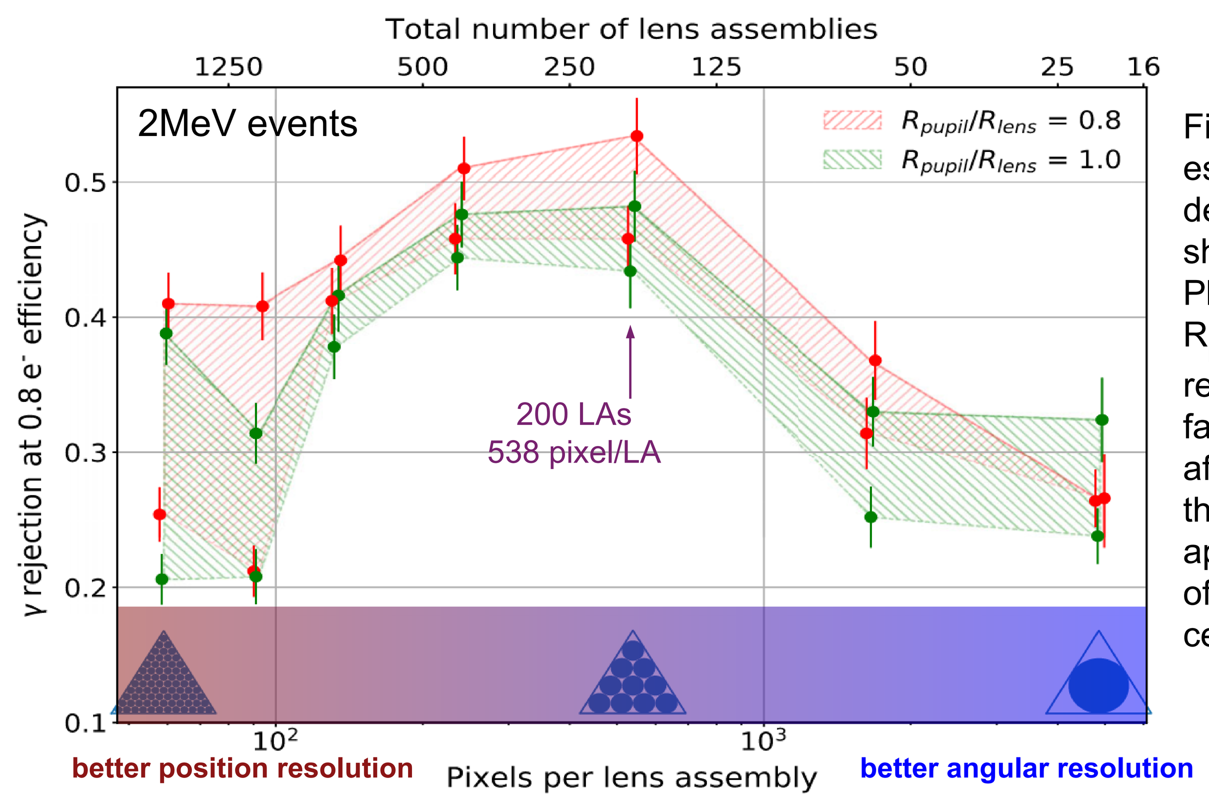
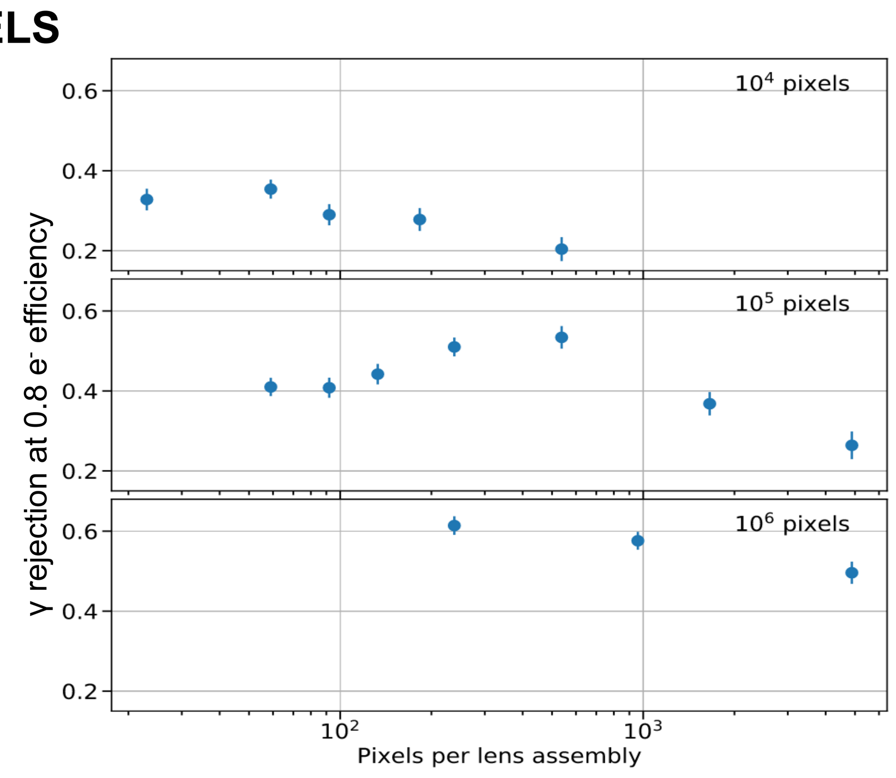


Fig 5: γ rejection efficiency as estimated in Fig 3 for different detector configuration. The result shows best performance for 200LAs. Placing an aperture stop with radius $R_{pupil}=0.8R_{lens}$ further improves the rejection efficiency. This is due to the fact that in a lens, the area mostly affected by aberrations is the one at the edge, which is masked by the aperture stop. The top (bottom) part of each band is for centered (off-centered) events.

VARYING THE TOTAL NUMBER OF PIXELS

Fig 6: Rejection efficiency plot for 2MeV events in the center of the detector with $R_{pupil}/R_{lens}=0.8$. *Top.* Total number of pixels scaled down to 10k. The overall performance significantly worsens with fewer larger pixels. *Middle.* Rejection efficiency for a 100k detector as shown in fig. 5 (red solid line). *Bottom.* Performance with 1M pixels. Although the pixels are smaller, with a finer angular resolution, the gamma rejection does not improve considerably. From this we can infer that we are aberration dominated and in this case, the image of the point-spread function is bigger than the size of the pixel.



Current and Next Steps

- In order to improve our background discrimination we need a better lens design, with at least 3x better angular resolution (last row in table 1)
- We are currently working on alternative reconstruction methods based on machine learning: in the last few years, convolutional neural networks have been proven to be a robust method for image classification and reconstruction in experimental particle physics. A tailored architecture could improve the overall e-/γ discrimination
- Unlike techniques based on timing, here, the dimension of the detector can be scaled down without losing information on the event topology. As proof of concept, we want to scale down the detector (~1.5m diam.) and build a neutron telescope. In fact, the direction of a fast neutron (E<20MeV) could be in principle reconstructed by localizing the first two scattering and by measuring its initial energy.

References

R.L. Garwin, (1952), *Rev. Sci. Inst.*, 23:755
J. Dalmasson et al., (2018), *Phys. Rev. D*, 97:052006
https://chroma.bitbucket.io/

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