Distributed Imaging for Scintillation Detectors

(of antineutrinos and all sorts of other things)

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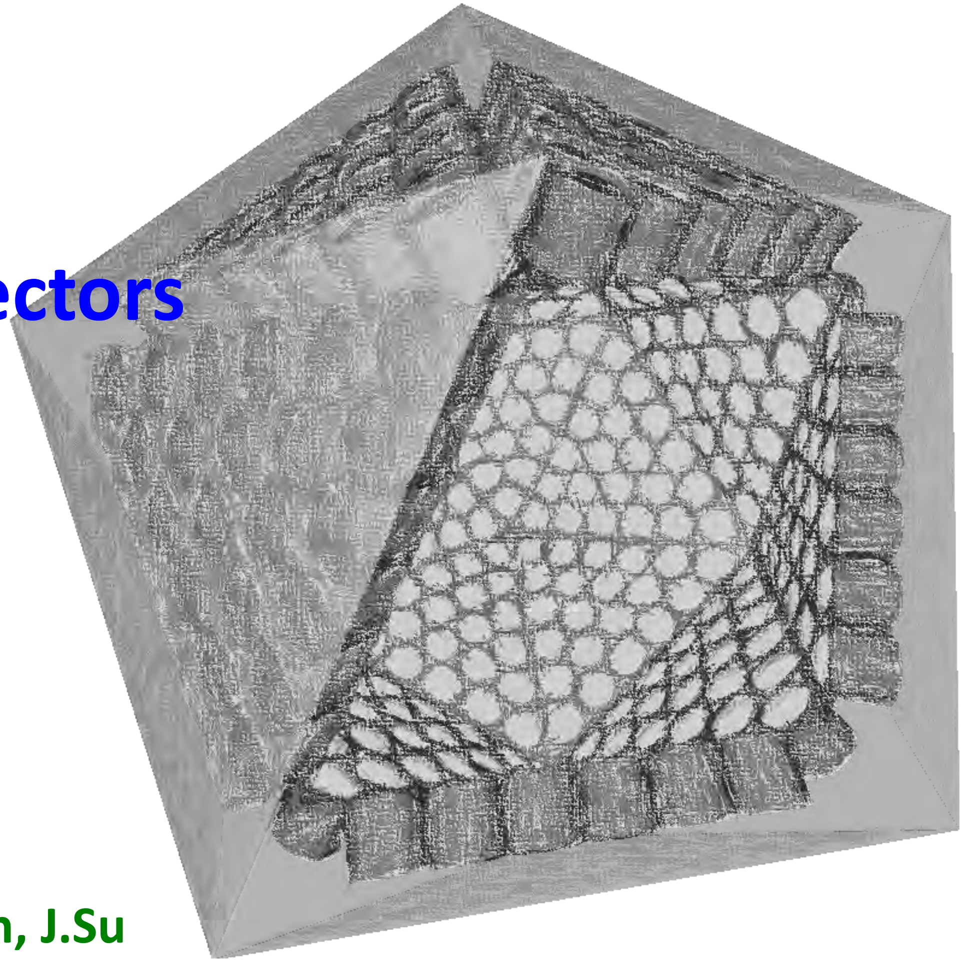
Most of the work done by J.Dalmasson, A.Jamil, S.Kravitz, M.Malek, K.Wells, J.Bentley, S.Steven, J.Su



It is a frustration of mine that we are still using ~the same organic scintillators developed in the 1920's, readout by vacuum tubes also developed in the 1920's.

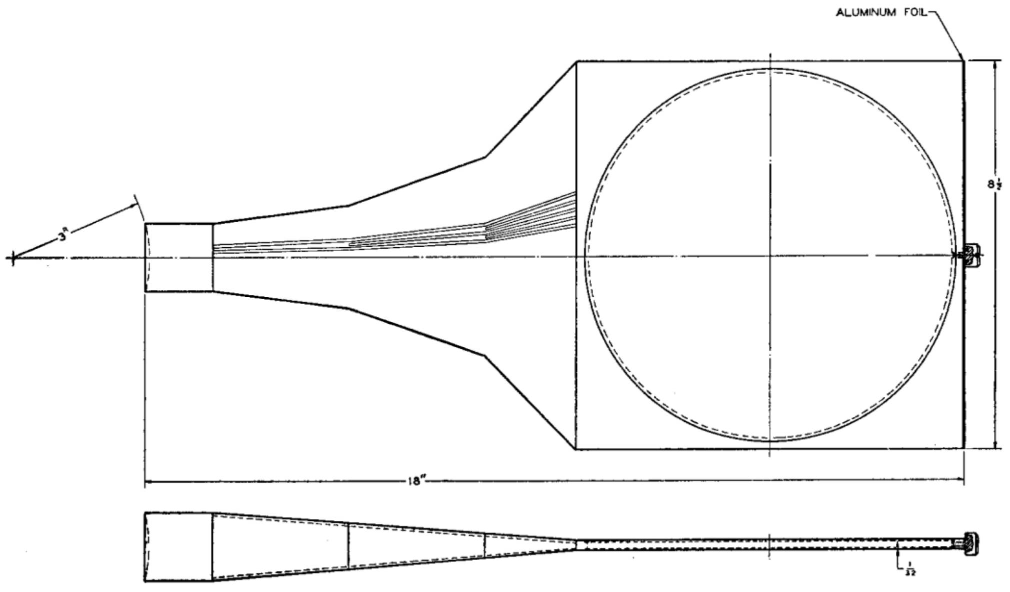
Somehow our field has not been reached by modern advances in material science.

So, it is fitting that I start with a couple of old papers, generically pointed out to me by John Learned, probably while on some boring KamLAND shift…

R. L. Garwin The Design of Liquid Scintillation Cells,
Rev Sci Inst 23, 755 (1952)

R. L. Garwin The Collection of Light from Scintillation Counters,
Rev Sci Inst 31, 1010 (1960)

These papers, basically, mark the beginning of "adiabatic lightguides" and can be summarized by saying that evil M. Liouville is the origin of lots of trouble.



Applied to large scintillation detectors, this principle puts serious constraints on the possibility of imaging tracks. This is because the are very few photons produced by a scintillator* and these photons are produced with an emittance

$$\eta = V \times 4\pi$$

where V is the entire volume of the detector and 4π is the full solid angle.

Quibbles and notes:

1) Strictly speaking this is not true, for a pointlike source $\eta = 4\pi$, because $V = 0$, but, unfortunately, we do not know where the event is in the detector, so, in practice the emittance contains the entire volume

2) The emittance also contains Δt and ΔE, or equivalent. For photons one has really only access to Δt. Indeed this can be traded for other variables. An infinitely reflective sphere can extract all photons out of a tiny hole by waiting a very long time. In practice infinitely reflective things do not exist and I am not sure it is wise to give up timing, so I will ignore this possibility.

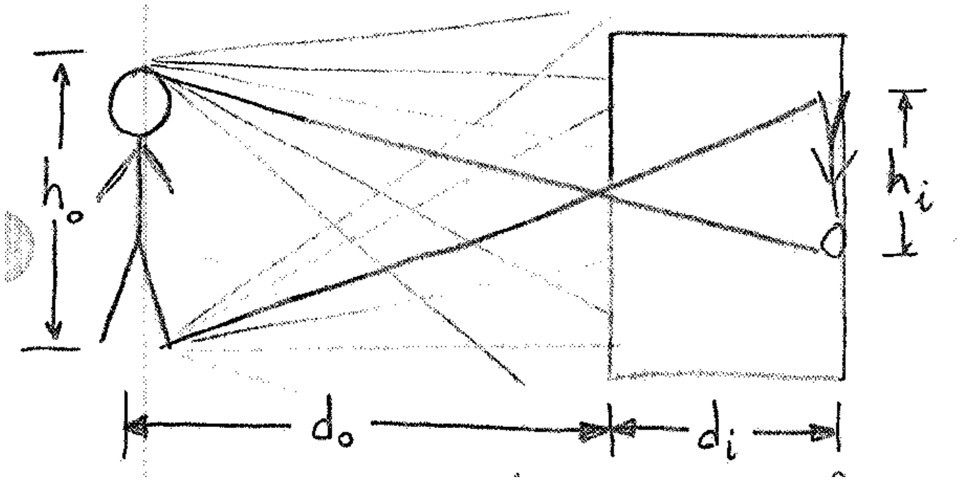
* This is not to say scintillator are "stupid". Typical energetic efficiencies are in the neighborhood of 10%, with is only one order of magnitude different from 100% and explains why it is so hard to make better scintillators!

Hence imaging in a scintillator with a (a few) camera(s) with finite size lenses is a non-starter (irrespective of the sensitivity/gain/whatever of the camera).

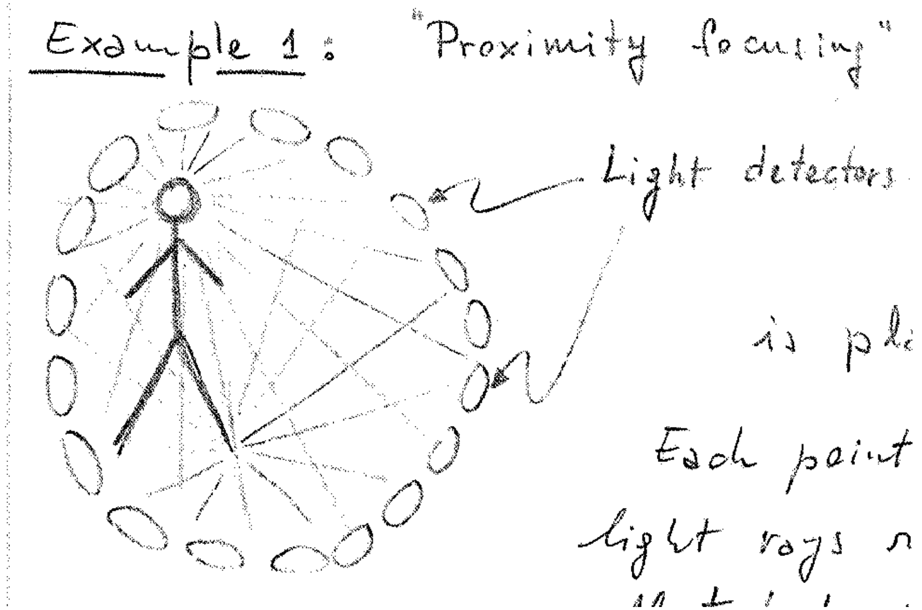
Not enough photons.

Yet, lots of things could be done with imaging, witness the many segmented detectors shown here…

Two extreme cases of "imaging"



Pinhole camera:
Pro: image infinitely sharp
Con: infinitely inefficient



Large liquid scintillation detector:
Pro: collect every single photon
Con: no imaging

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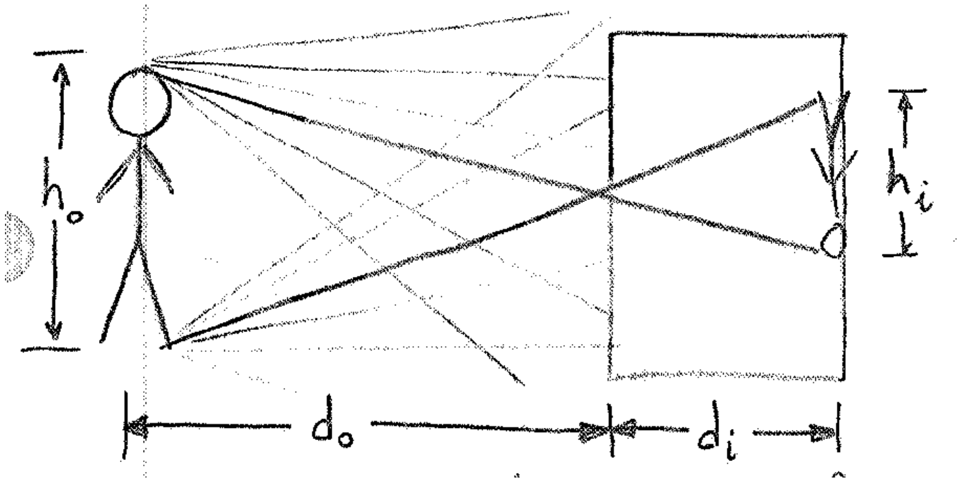

Pinhole camera:
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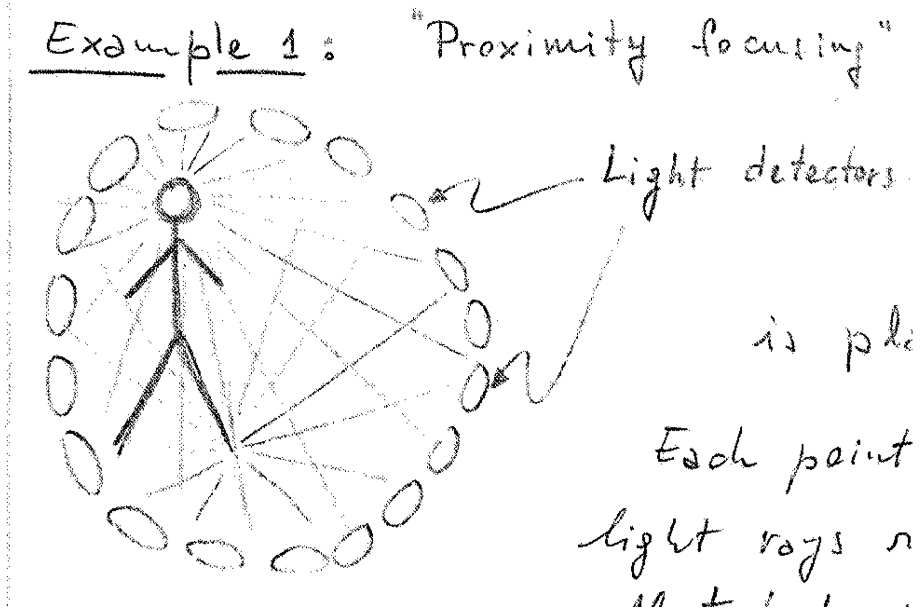


Large liquid scintillation detector:
- **Pro: collect every single photon**
- **Con: no imaging**

However, note that the rays hitting a particular PMT here do contain angular information. …if we only knew how to record it!

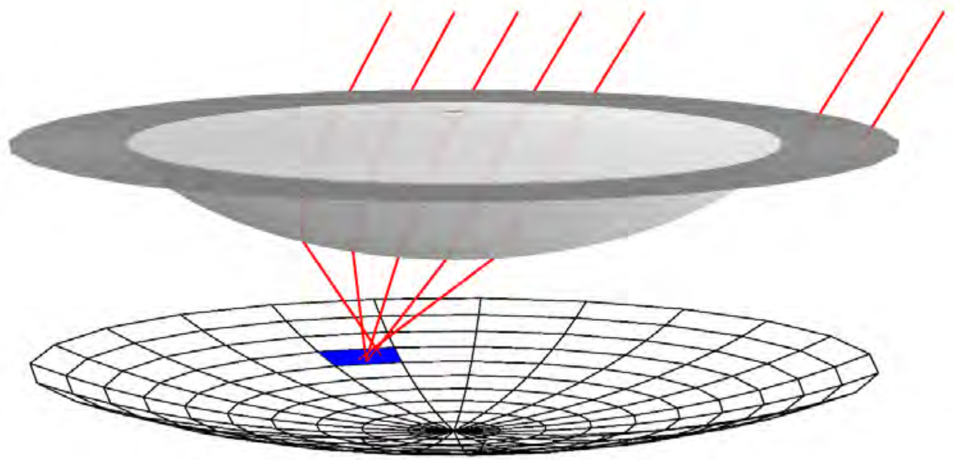
It turns out that measuring angles of incoming photons (or wavefronts) is done in some exotic ("plenoptic") cameras [e.g. Lytro (US), Raytrix (Germany)].

This allows 3D imaging out of a single lens or "offline refocusing".

R. Ng et al. "Light Field Photography with a Hand-Held Plenoptic Camera." Stanford University Computer Science Tech Report CSTR 2005-02, April 2005.

Idea:

- **Interpose a lenslet array in front of the CCD, with the CCD in the focus**
- **Each lenslet transforms the angle of the incident wavefront into a position on a subarray of the CCD**
- **Obtain an array of images also containing information on the depth**
- **Need a very large pixel count, as in some way this encodes the depth**
- **Needs plenty of software processing**

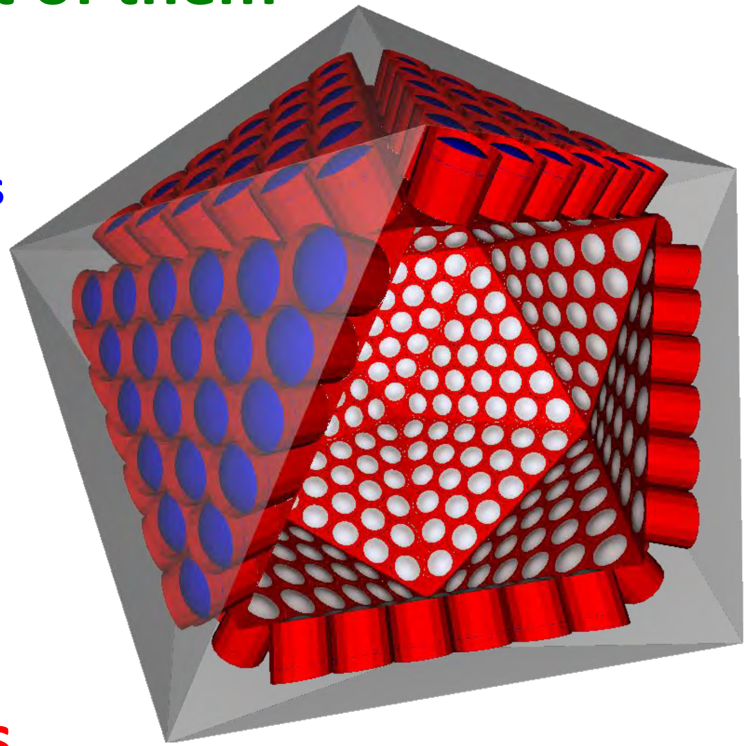


Use a similar principle:

- further pixelate large photodetectors

(think of the KamLAND PMTs pixelated)

- use lenses in front of them



Topological reconstruction then proceeds as tracking in a TPC: Each photon has
- a position of impact -- the “optical module”,
  with uncertainty related to its diameter
- a direction of origin -- related to the quality of the lens
  and the size of the pixels

Warning: don’t get confused, in this “mode” depth of focus means nothing. All lenses are focused to infinity!

Note that no lens “owns” an image, not enough photons.

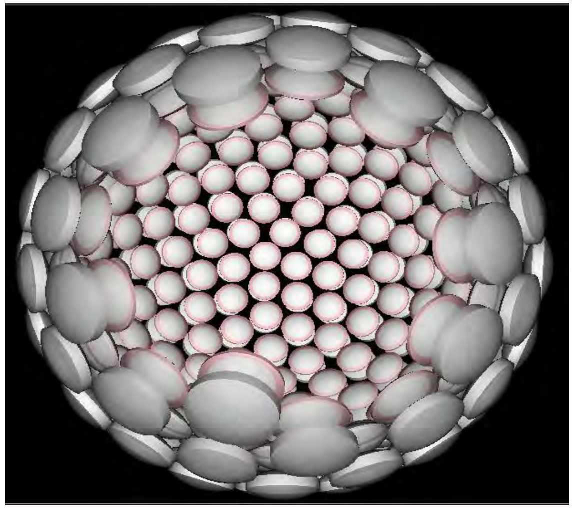
This is an important difference with respect to plenoptic cameras. Here only putting together many lenses results in imaging.

Detectors parameters are quite realistic, in terms of q.e. (33%) and scintillator yield (8000 photons/MeV)

But to get started a number of approximations/simplifications are used:

- Lens is stopped down for performance and the light outside of the active lens is suppressed (one could collect it for energy)
- Absorbing baffles between lens modules (simpler reconstruction)
- The detector is a icosahedron (simpler geometry)

➔ Inscribed sphere is 14.8m for this case, basically like KamLAND



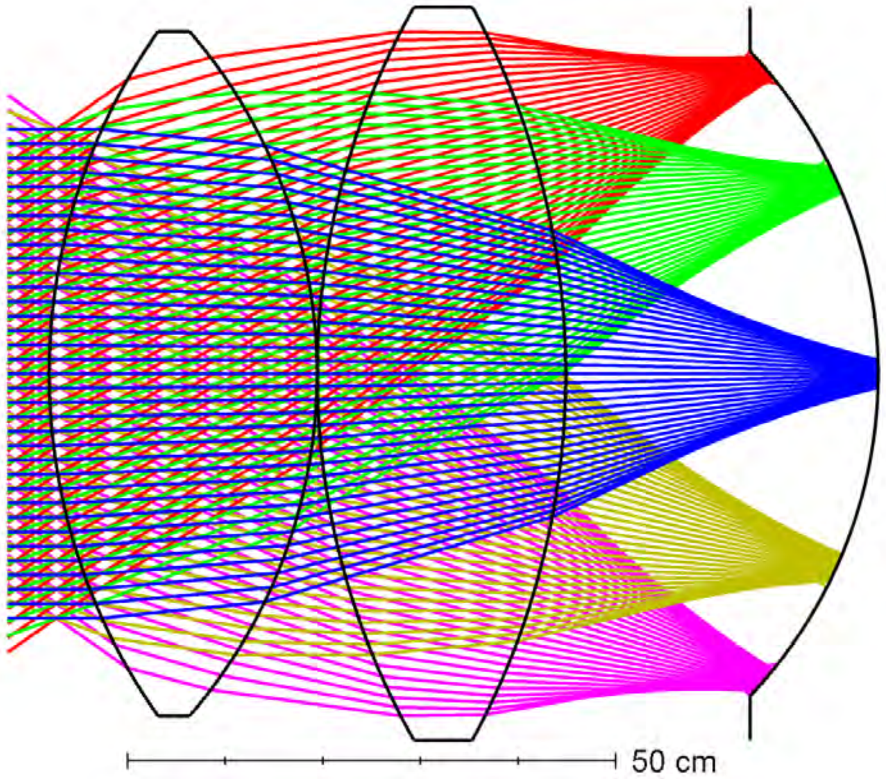
By now we also have a spherical detector model.

Note the 2 lenses, photodetectors not shown
Performance is similar, but this is still work in progress

Lens design is non-trivial (in fact, this held us up for a long time)

- Want a realistic system, in particular has to work in scintillator with n_{scint}= 1.5
- Require a very large NA (this is a very non-paraxial system, so forget most of what they taught you in school!)
- Focal surface is a spherical segment (simplifies the lens system)
- At least chromatic aberrations are not an issue
- Turns out that a single asphere is not necessarily the best solution, because one can to limit large changes of refractive at single surfaces
- From a first look air lenses appear less good, but I do not think we have investigated this enough

Parameter	Value
Number of elements	2 (spherical)
NA_{MAX} (=n_{scint}sin[atan(R_{pupil}/f_{eff})])	0.64
Field of view	±40°
$R_{lens}/R_{focal\_surface}$	1
Angular resolution	4°
n_{lens} (glass: S-NPH2, Ohara)	1.98



How to optimize a detector

Set the total number of pixels ➔ **our choice is 10^5**

This sets the ~cost of the detector

(for 2000 KamLAND-style PMTs would mean ~8x8 pixels in the place of one 20-inch PMT)

Change the size of the lenses, hence changing the number of pixels/lens and find the best performance, given some desired property.

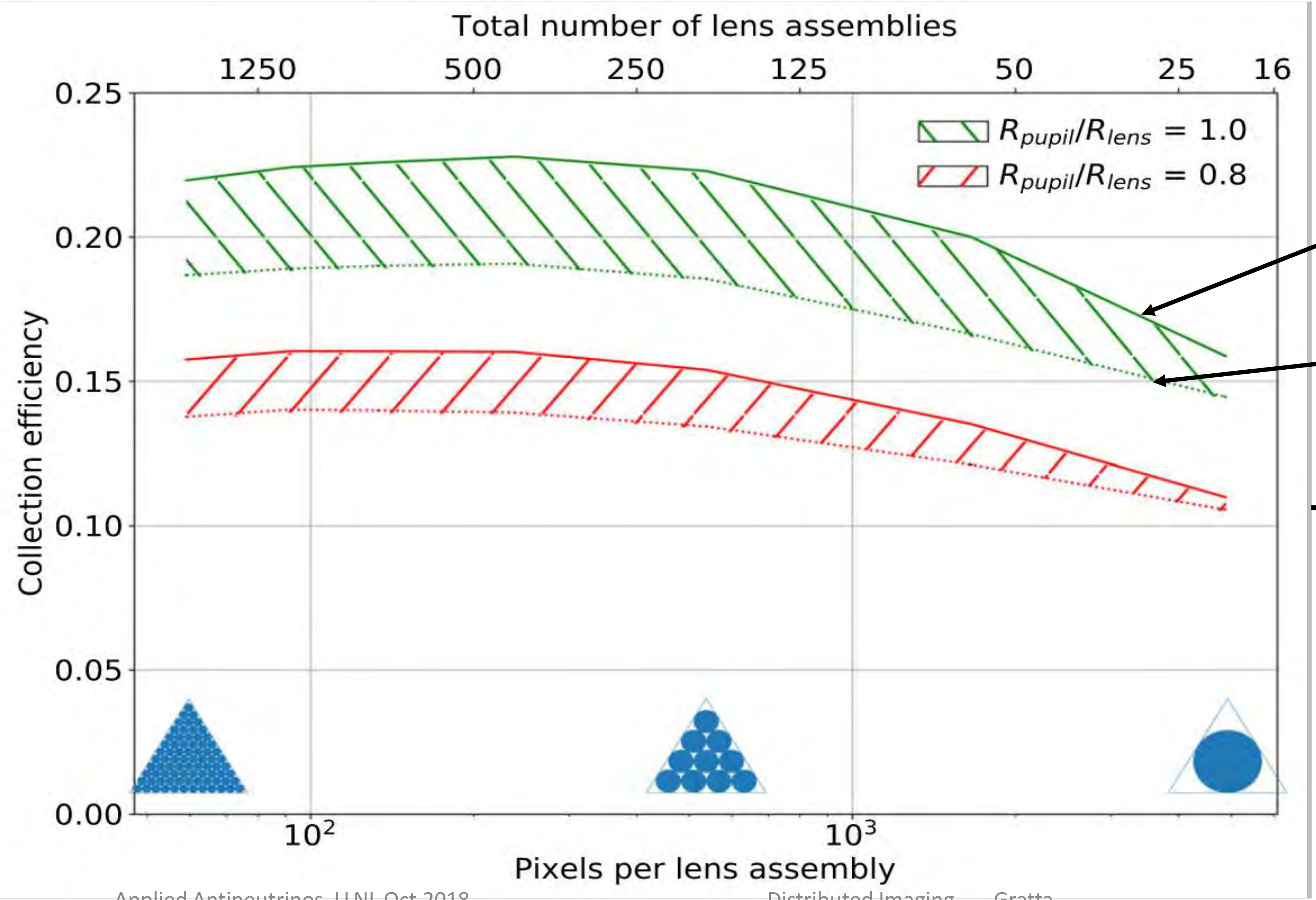
Larger lenses ➔ more pixels/lens ➔ better angular resolution for the direction of the photons ➔ worse position resolution for the origin of the photon track

Smaller lenses ➔ fewer pixels/lens ➔ worse angular resolution ➔ better position resolution

Note that lenses scale by similar transformations, so no need to re-design the lens in the optimization process.

I am not a mathematician, so I do not have a "proof", but I believe there is a theorem that says that this is the optimal way to optimize imaging.

Results (2MeV deposited in the scintillator)



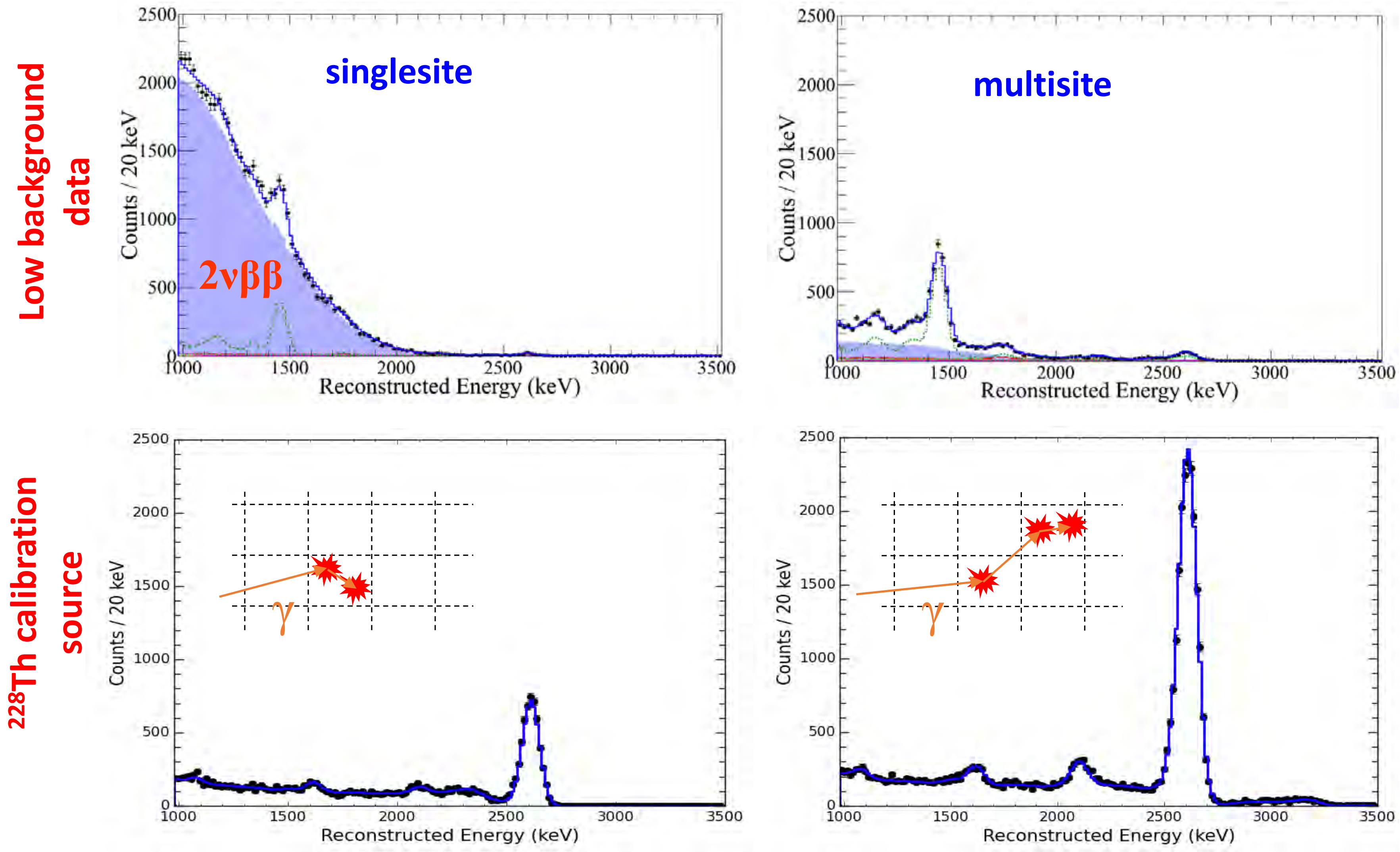
r_{event} < 1m

3m < r_{event} < 4m

This should come as no surprise: infinite round lenses fully cover the surface

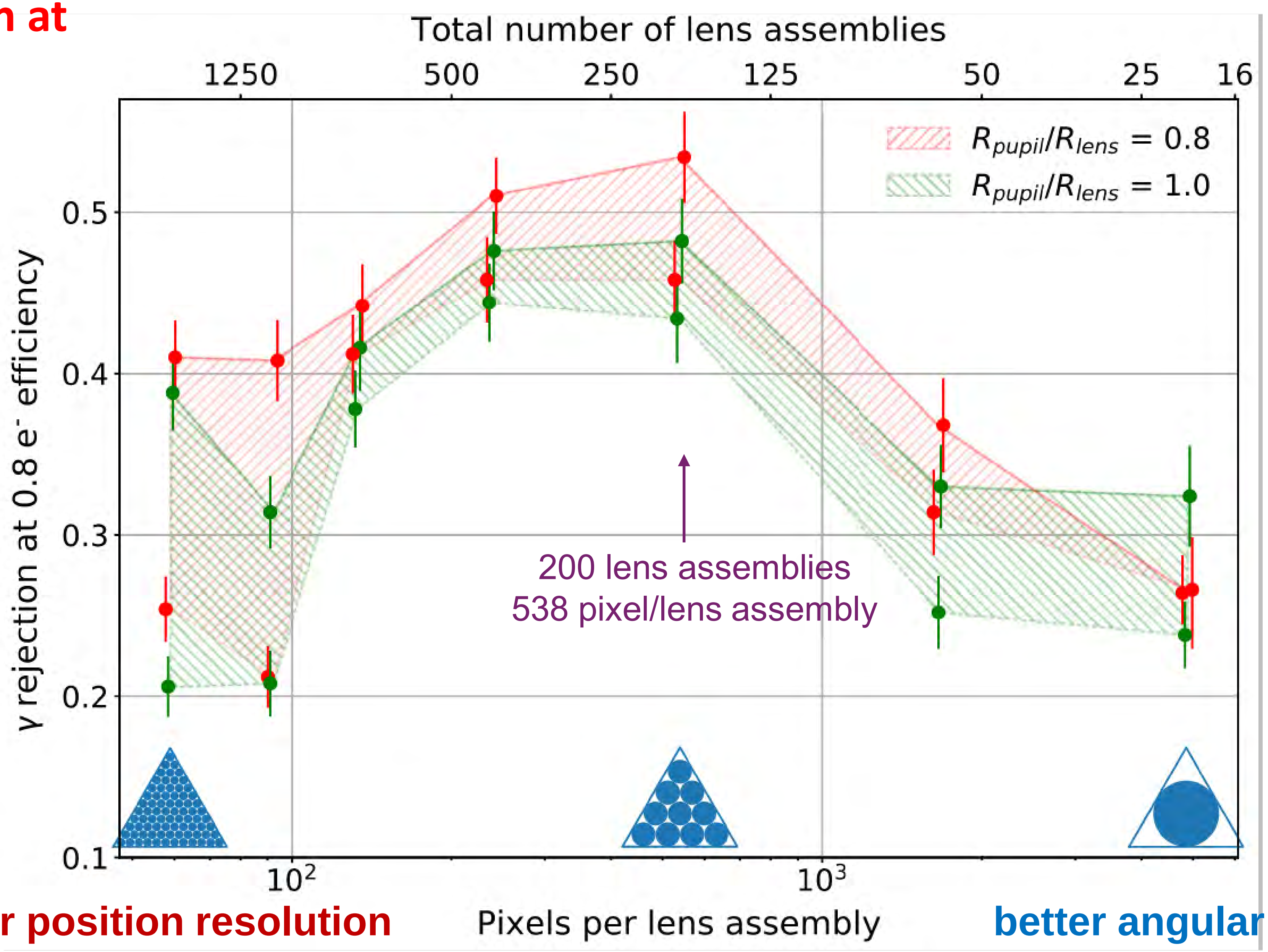
We choose as desired property the ability of discerning γs from single e^- at a fixed energy of 2MeV

This is something that timing alone cannot do, and yet is it very important to reject some backgrounds



EXO-200 data

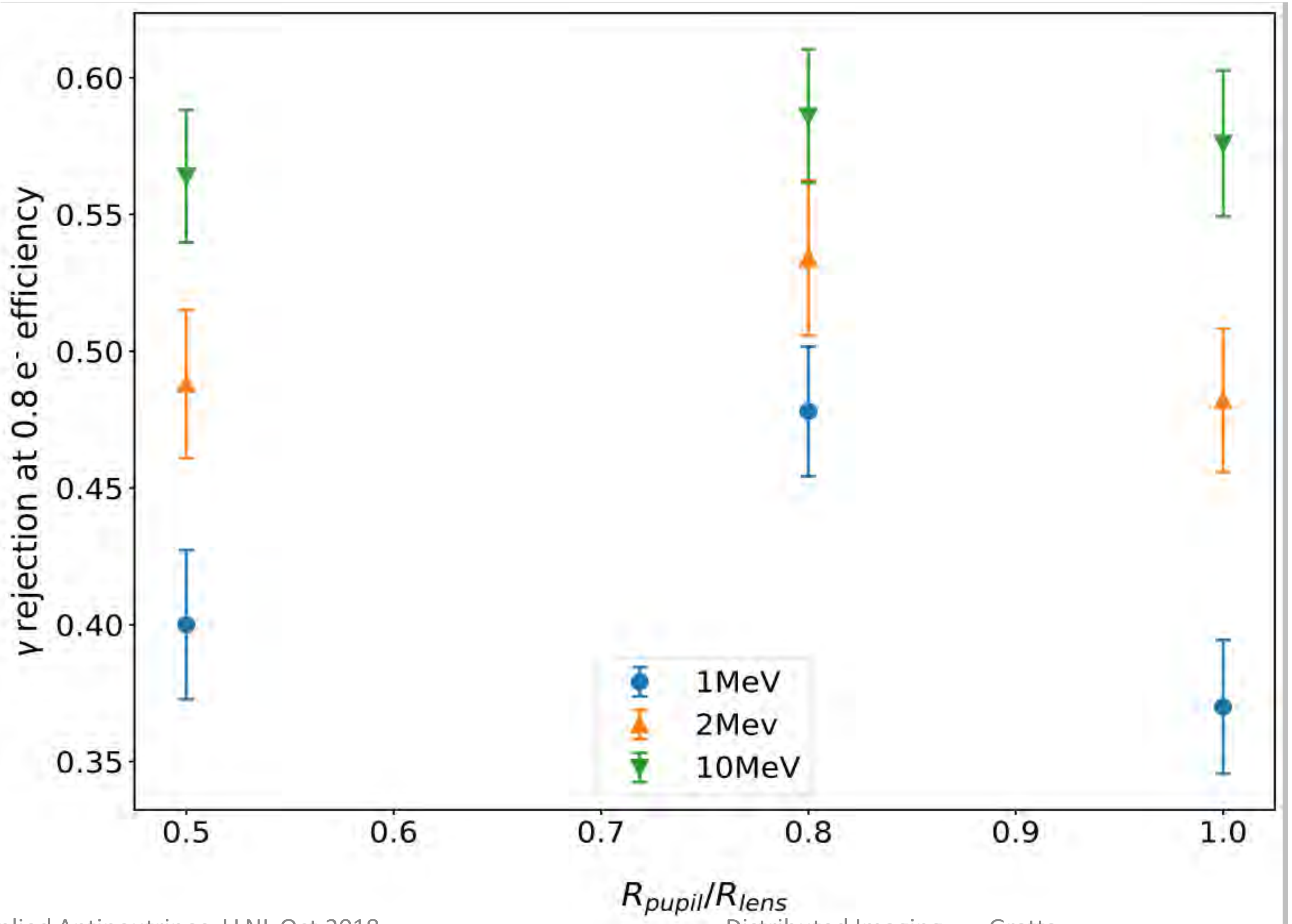
γ rejection fraction at 80% e^- efficiency



better position resolution ←

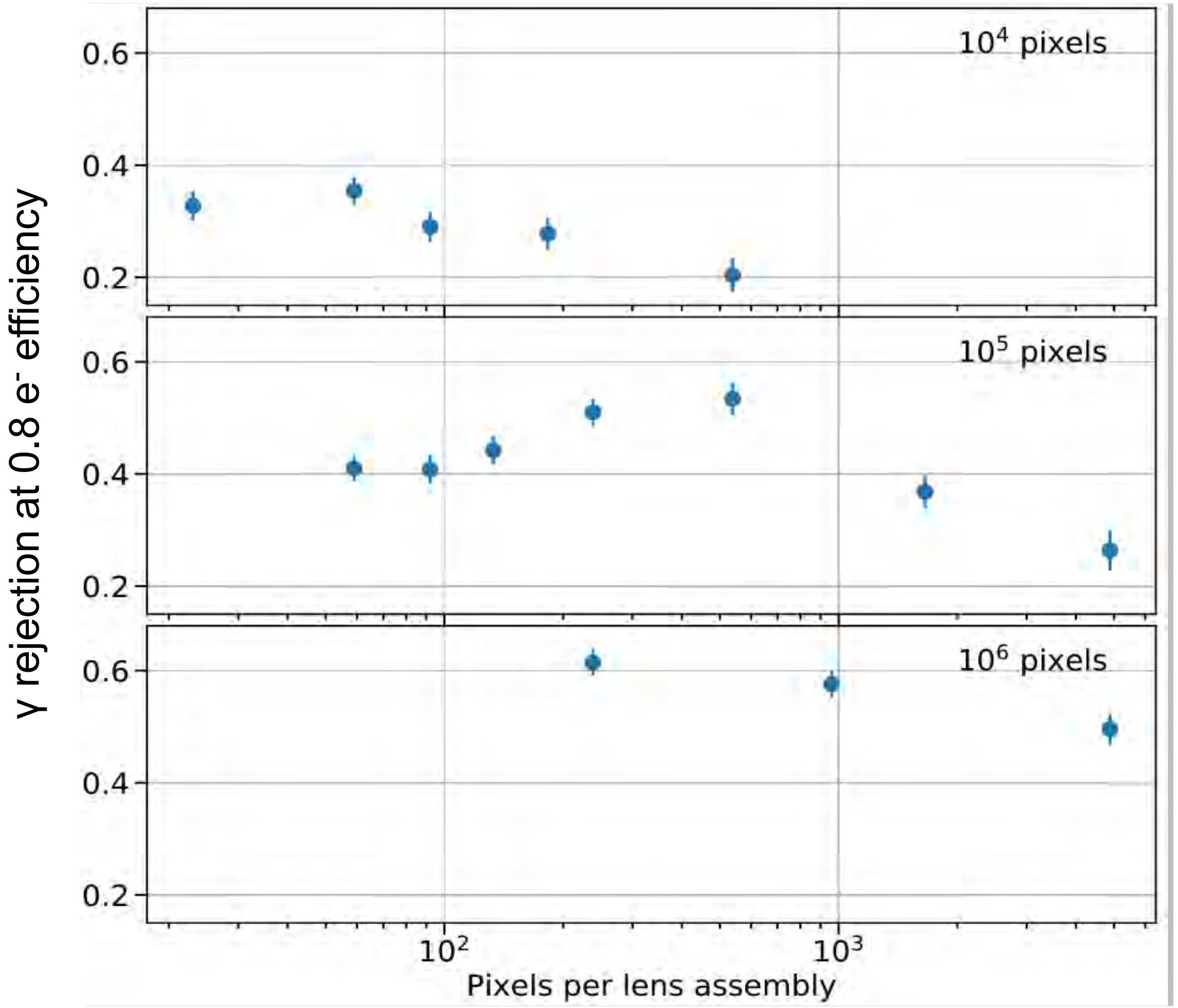
better angular resolution →

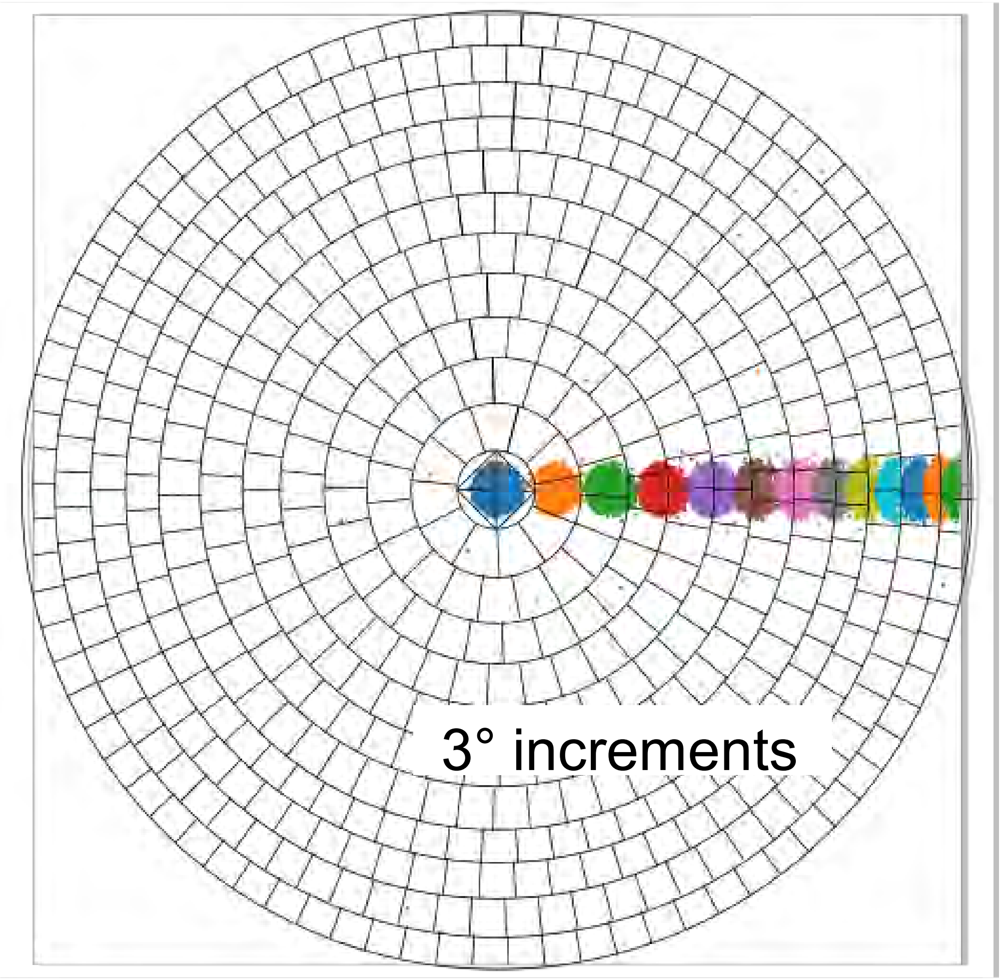
Higher energy achieves better performance and is less sensitive to the system segmentation



200 lens assemblies, 538 pixels/lens, r_{event}<1m

Tradeoff between lens quality and number of pixels (these two have to be matched to each other)





Conclusions

We have found the optimal way to do imaging in scintillation detectors.

Note that, unlike reconstruction by time of arrival (that is constant, no matter the detector size) in this new technique $\delta d/D$=const (D is the detector size), so that in small detectors, for the same number of pixels the resolution improves.

There may be applications to applied domains, where smaller detectors and better resolution are required.

Adding timing information will improve reconstruction, for large detector size

For large detectors the timing information should be added and will no doubt improve things some.

Need to investigate machine learning techniques, that should be a good match for this.

Need help!   Others should check us and improve things further.

Details in J.Dalmasson et al., Phys. Rev. D 97 (2018) 052006.

And, most important, we need to develop better photodetectors!!
How come CRTs have all but disappeared from our desks while PMTs still reign in our labs?