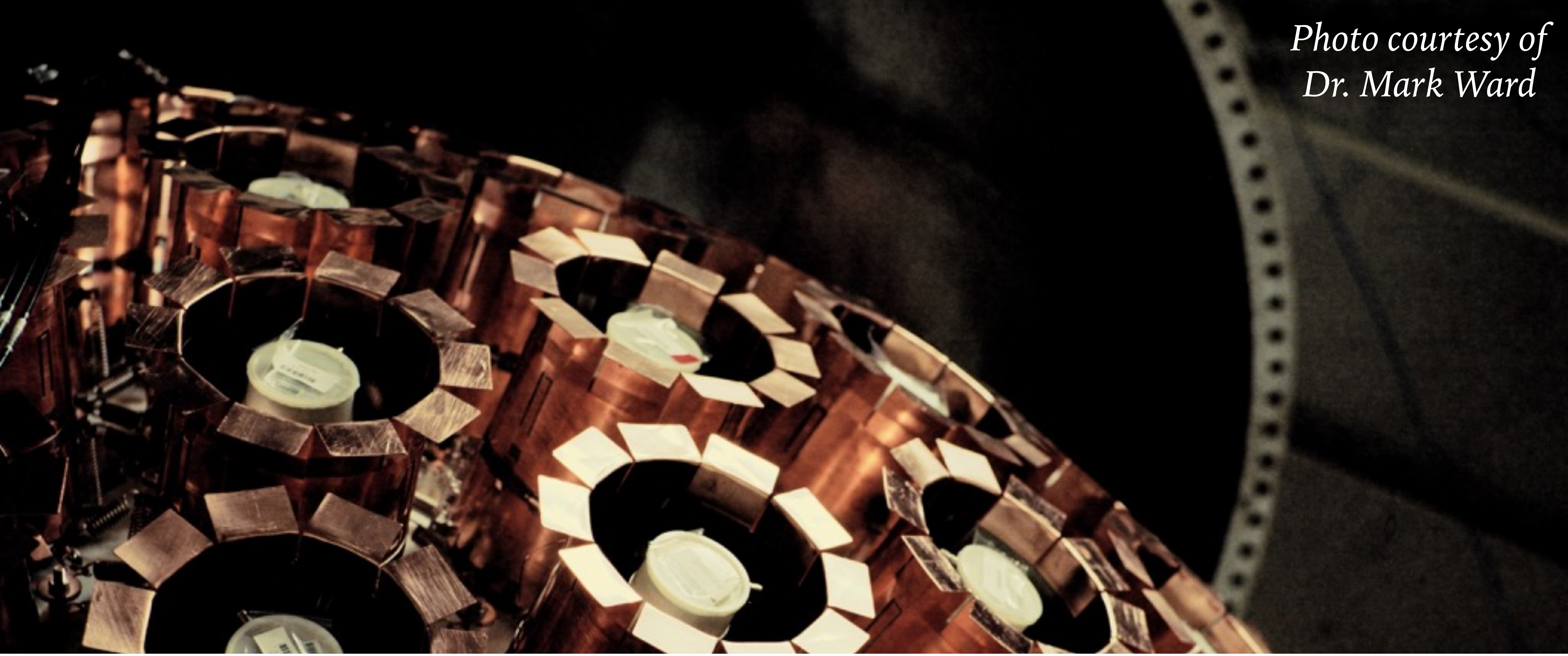


Photo courtesy of Dr. Mark Ward

POSITION RECONSTRUCTION IN DEAP-3600

(OR, WHERE DID WE PUT THE DARK MATTER?)

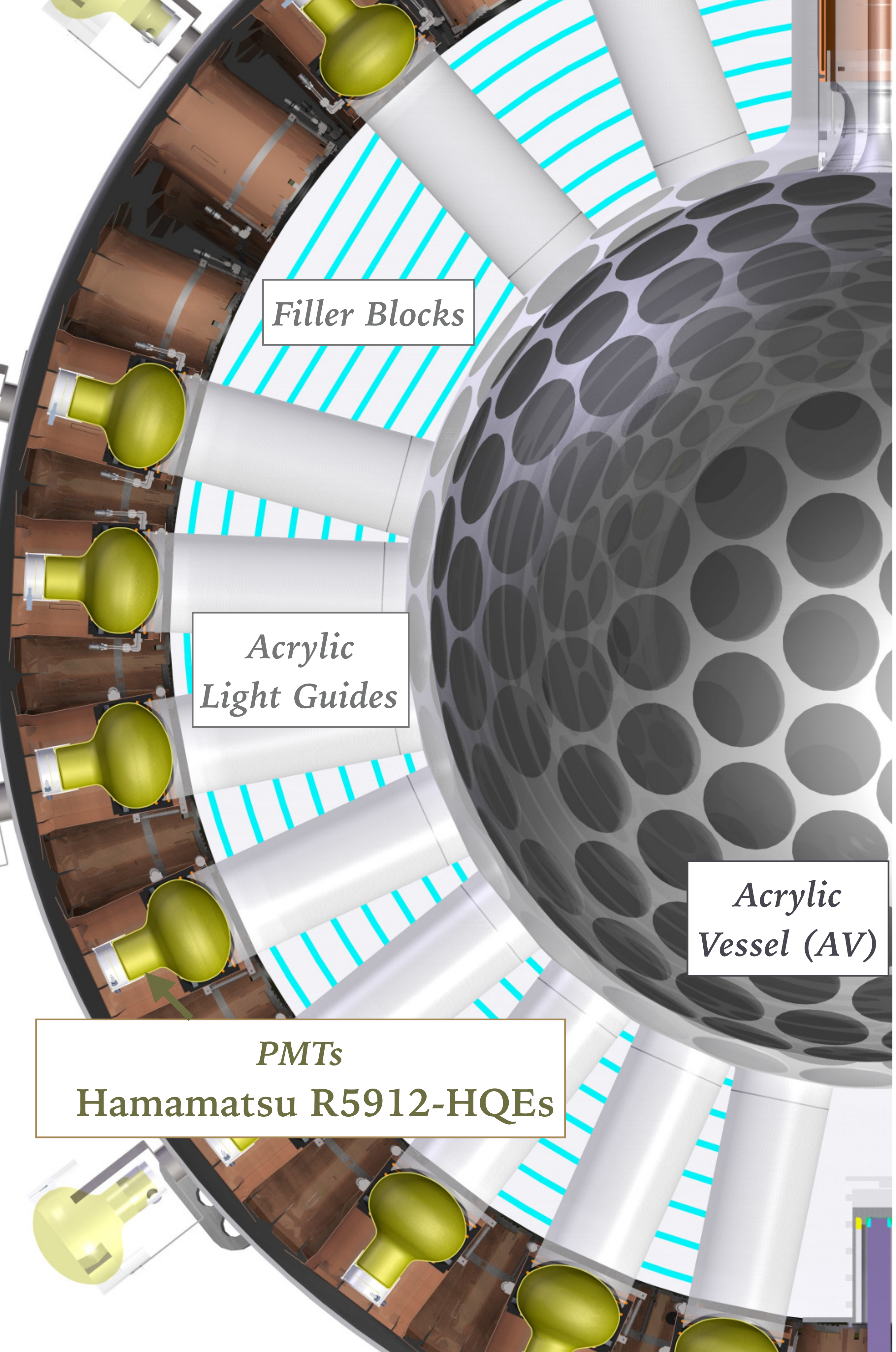
ROYAL HOLLOWAY UNIVERSITY OF LONDON

DEAP 3600

Navin Seeburn

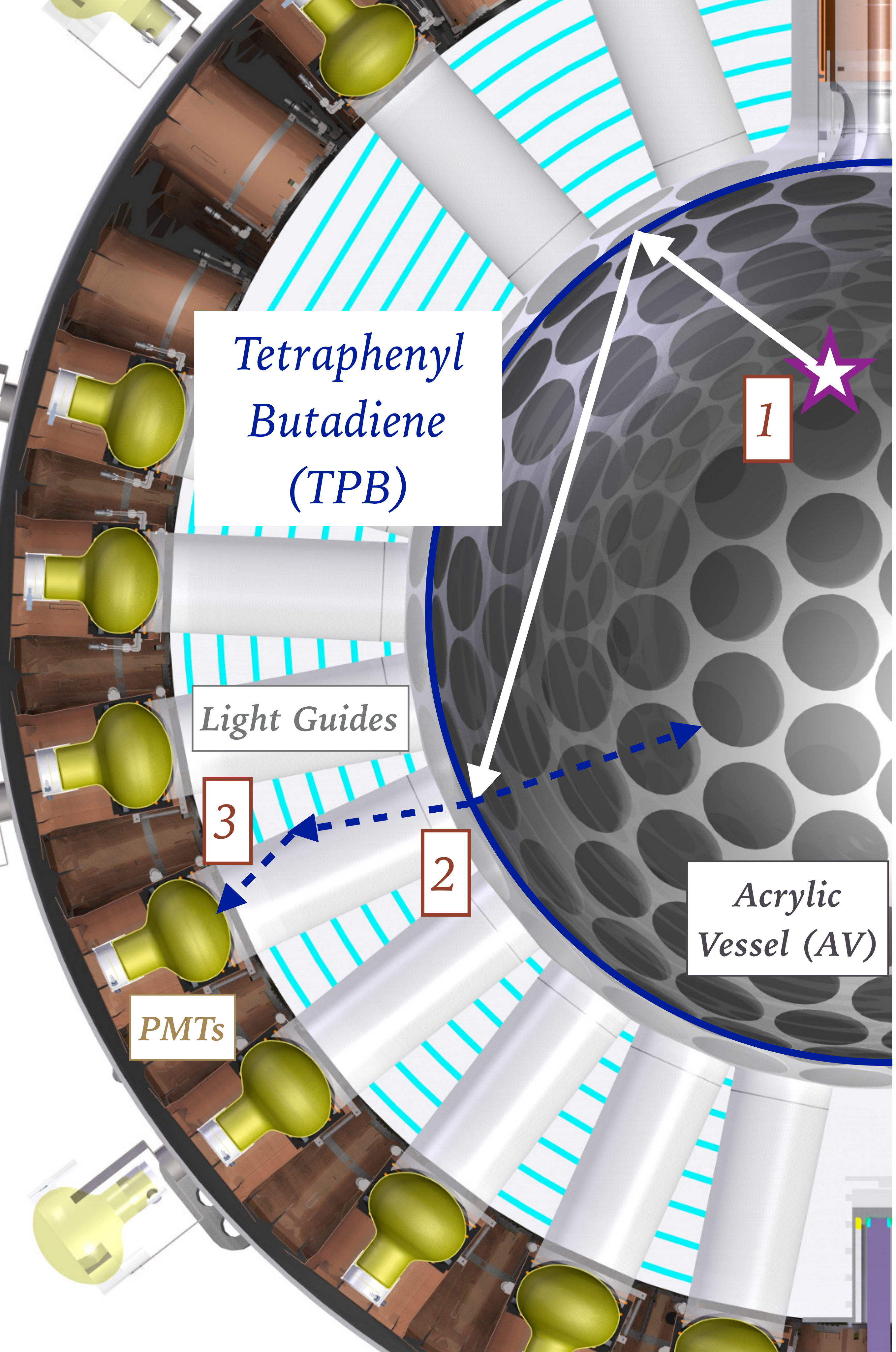
Royal Holloway, University of London

IOP Parallel Talks - IOP HEP/APP Sussex 2016



INTRODUCING RECONSTRUCTION

- Stands for "Dark Matter Experiment using Argon Pulse shape discrimination"
  - Single phase liquid argon
  - Scintillation only
  - WIMP direct detection
  - See N. Fatemighomi's talk for details
- An event in DEAP-3600 consists of a set of charges in 255 Photomultiplier Tubes (PMTs).
- We reconstruct event positions from these charges.
- Our reconstruction relies on:
  - Full Monte Carlo simulation with an optical model to produce…
  - A fast, parametrised model describing how light from an event propagates and produces photoelectrons (PE) in PMTs.



A DAY IN THE LIFE OF A PHOTON IN DEAP-3600

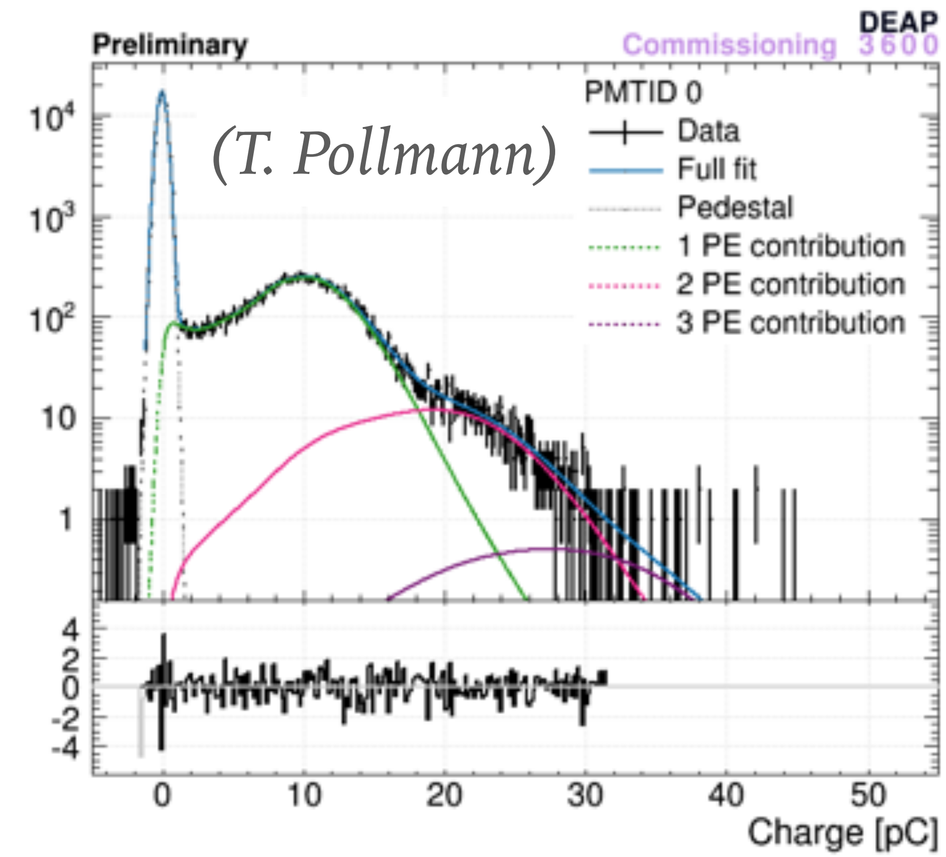
So what's an event?

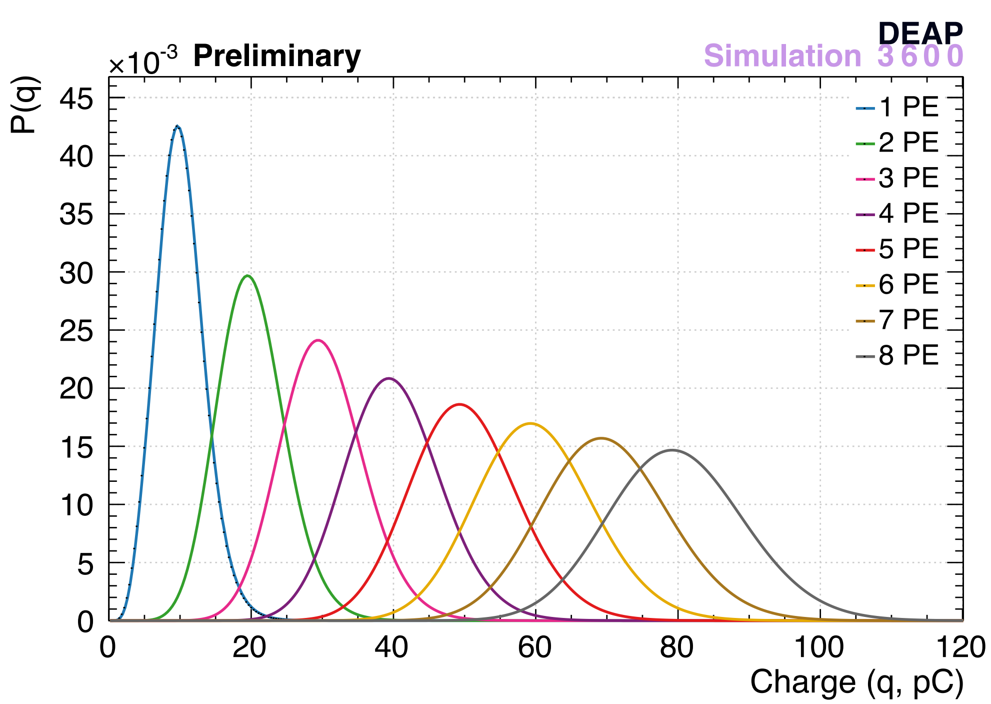
1. Scintillation in liquid argon emits UV light at 128nm
   - Argon is transparent to 128nm light
2. A 128nm photon is reflected around the AV until it is absorbed by Tetraphenyl Butadiene (TPB), and re-emitted isotropically at 440nm.
3. A 440nm photon reaches a PMT and produces a PE.
   - To get there, it's transmitted through the acrylic vessel and reflected down an acrylic light guide coated in a reflective material.
   - Every material between the TPB and the PMTs has similar a refractive index (n~1.5), minimising reflections at material boundaries.

- We measure charges Q(t) produced by these PE in each PMT.

RECONSTRUCTING CHARGE

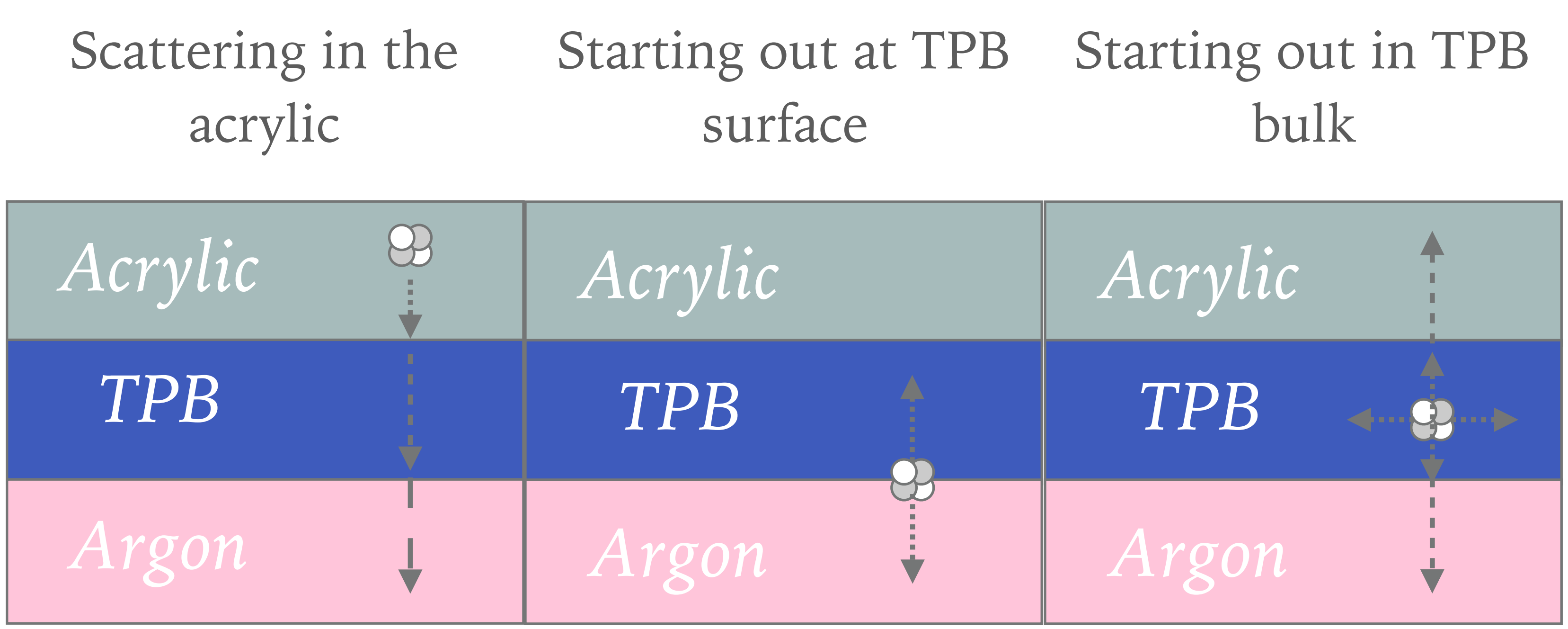
- PE produced at the PMT photocathode will transit through the PMTs, producing electronic pulses at the dynode, which have charges.
  - Single PE charge spectra measured in-situ inform our charge response model in simulation
- Electronic pulses are processed by Signal Conditioning Boards, and low and high gain output is sent to our DAQ's digitisers:
  - CAEN V1720s: high gain, 4ns timing resolution
  - CAEN V1740s: low gain, 15s timing resolution
- DAQ hardware response is included in our Monte Carlo simulation.
- Pulses shapes and pulse charges are reconstructed through pulse-finding algorithms.
- A Bayesian PE counting algorithm (arXiv:1408.1914) is used to estimate number number of PE we see from measured Q. We can reconstruct using PE or Q.





WHY RECONSTRUCT POSITION?

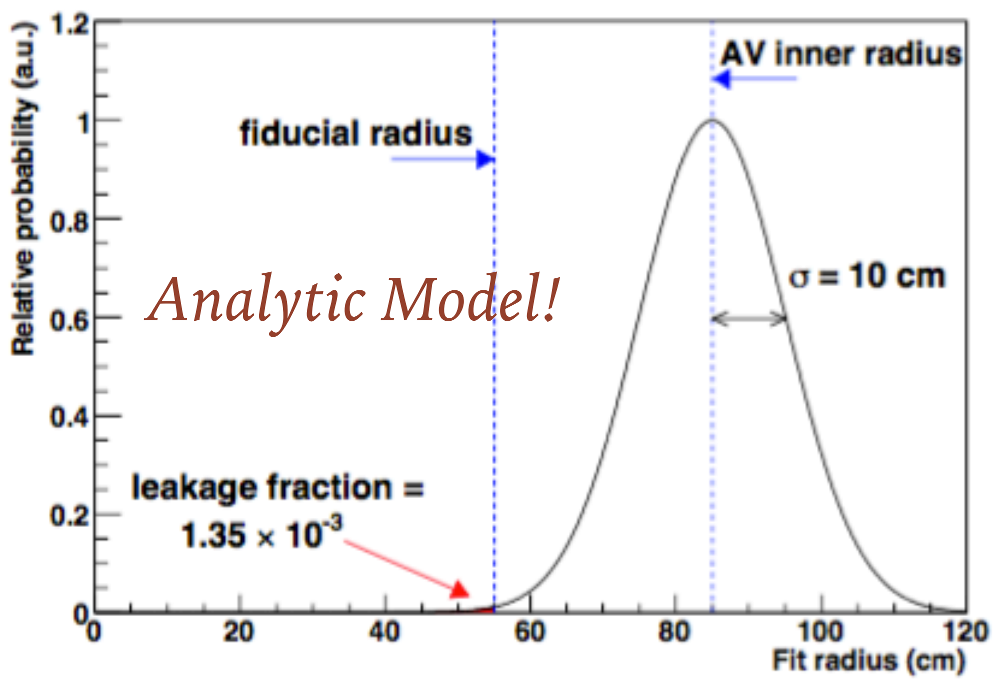
- *WIMPs won't be the only thing making light in our detector!*
- Alpha decays from Rn daughters in the TPB and AV surface can mimic a signal in our energy region of interest (120-240PE) - low energy alpha or recoiling daughter
- Scattering in the acrylic before reaching either the TPB or Ar can cause the alpha/daughter to scintillate with a lower incident energy, producing less light.
- High energy scintillation in TPB can produce low light events, as TPB has a lower light yield, 0.882 photons per keV (arXiv:1011.1012), compared to 40 per keV in liquid Ar (Nucl.Instrum.Meth. A269 (1988) 291-296)

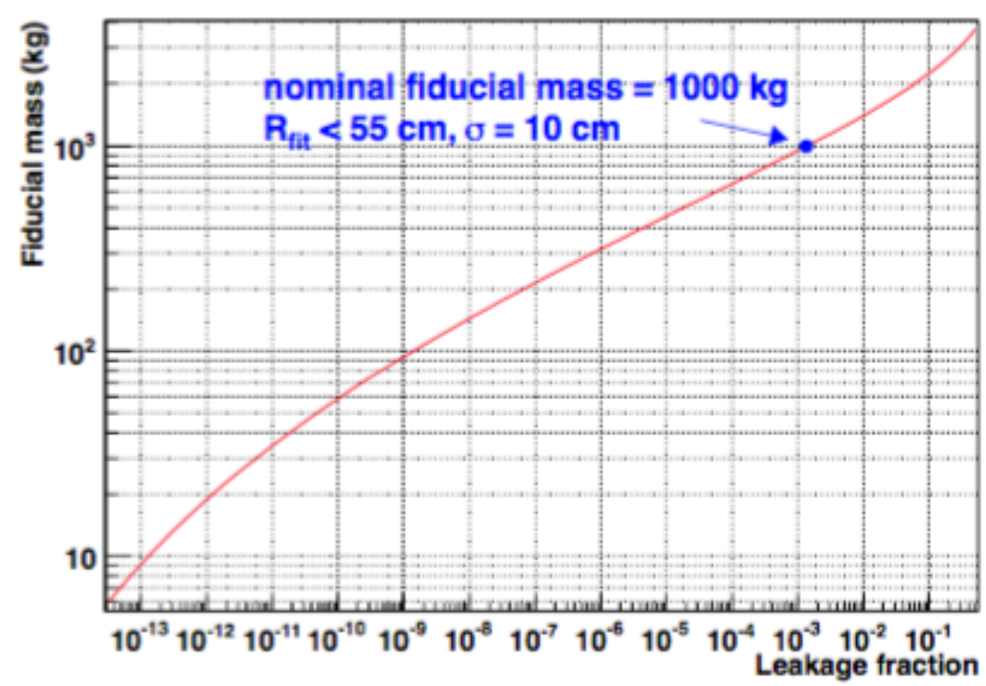


→ Scintillation in TPB/Argon

BACKGROUND REJECTION USING POSITION RECONSTRUCTION

- We make a fiducial volume cut at a fiducial radius R_{fid} to reject alphas from AV/TPB.
- Leakage - when events that originate from the surface reconstruct in $R<R_{fid}$
- Below is an analytic model assuming $\sigma_{surface}$=100mm.
- If we require <0.2 events in three years, we need 1.35e-3 leakage probability, R_{fid}=550mm





- The smaller the position reconstruction resolution, the closer surface α's reconstruct to the surface, and the larger our possible fiducial mass.
- This exemplifies the effect that position reconstruction has on our sensitivity!

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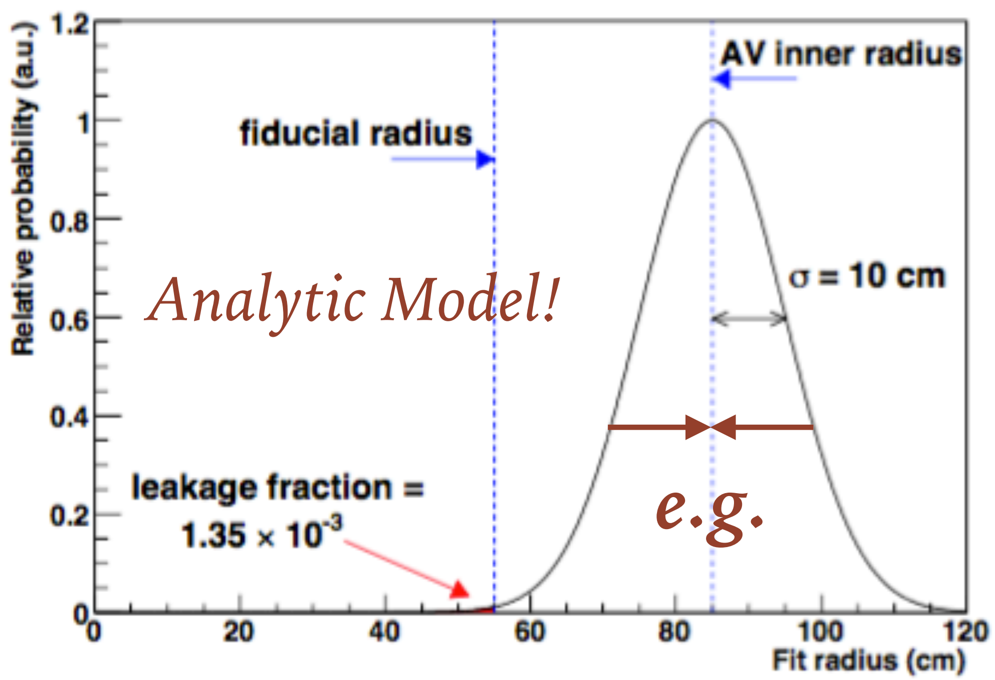

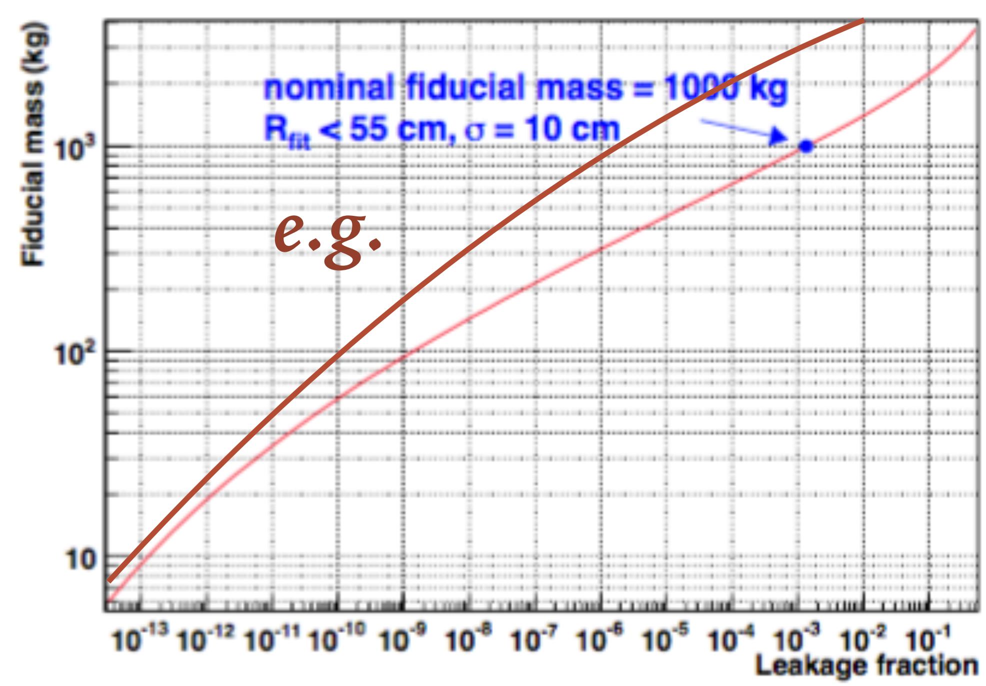

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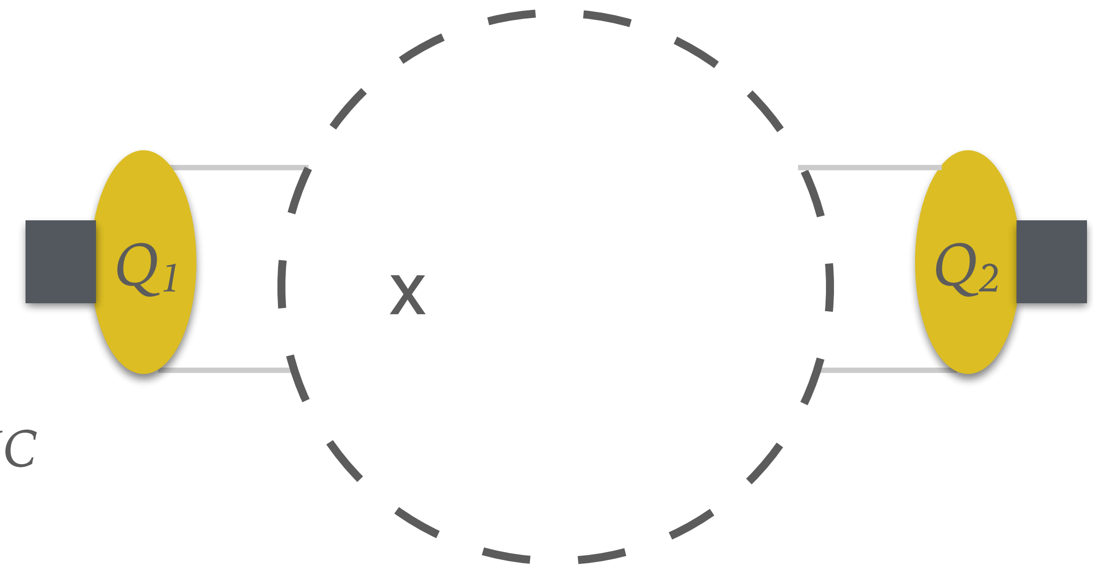
SO HOW DO WE RECONSTRUCT POSITIONS?

CENTRE OF CHARGE POSITION RECONSTRUCTION

- Simplest position estimate, for spherical volume surrounded by PMTs
- Calculates position based on charge weighted average of PMT positions
  - Centre of mass calculation, using charge instead of mass!

$$\vec{r}_{\mathrm{event}} = \frac{\sum_{i=1}^{N_{\mathrm{PMT}}} Q_i^2 \; \vec{r}_i}{\sum_{i=1}^{N_{\mathrm{PMT}}} Q_i^2}$$

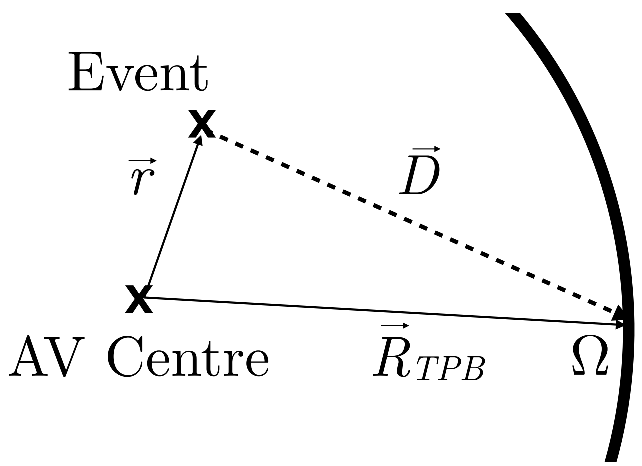
Power tuned to MC

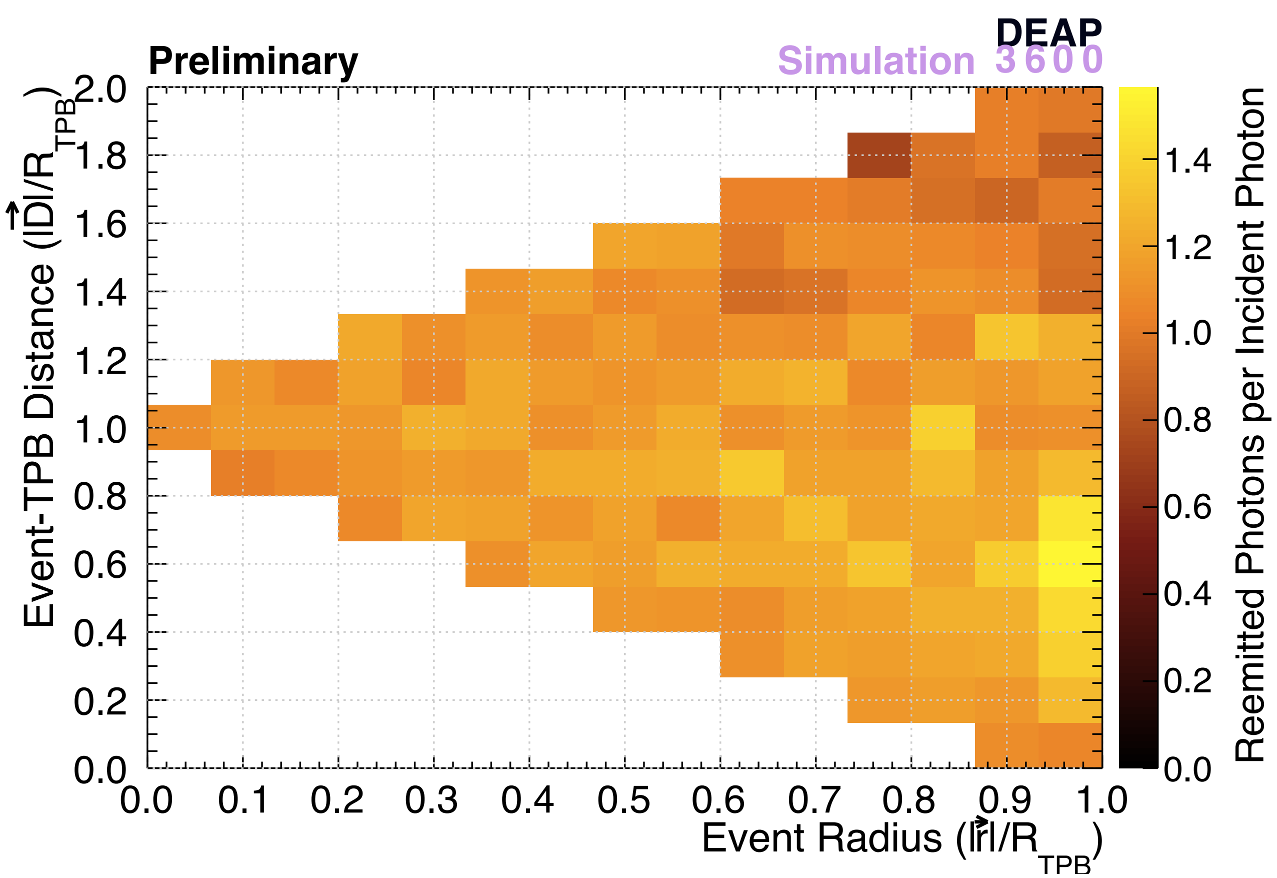


- Advantages:
  - Blind to event hypothesis
  - Can reconstruct positions outside Argon volume
  - Computationally cheap!
- Disadvantages:
  - Blind to detector geometry and optics!
  - Uses very little knowledge of detector physics

MONTE CARLO BASED POSITION RECONSTRUCTION: SHELLFIT

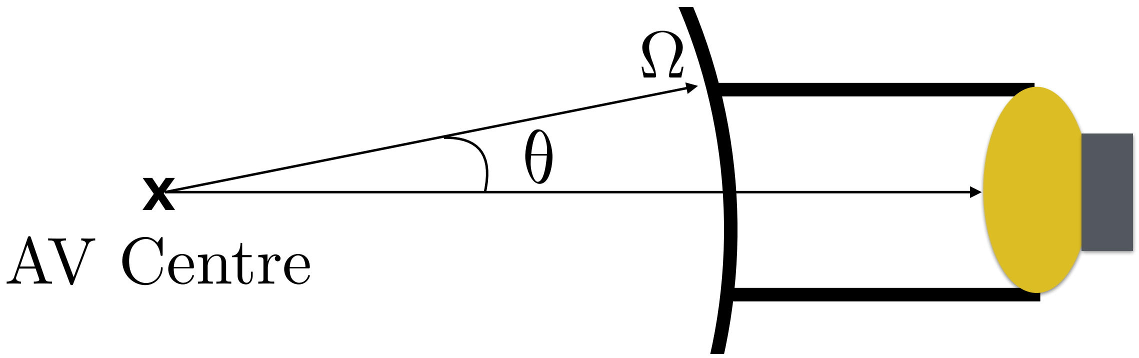
- ShellFit, written by S. Seibert, varies the event vertex and a charge model to match predicted charges to observed charges using a position-dependent charge model generated from a full Monte Carlo simulation.
- Before reconstructing data, isotropically distributed photons are generated at increasing radii, and two lookup tables are filled using photon tracking information.
- The first measures the probability that TPB reemits given an incident photon, generated at event radius $|\vec{r}|$ and distance $|\vec{D}|$ from the event to a point on the TPB Ω.

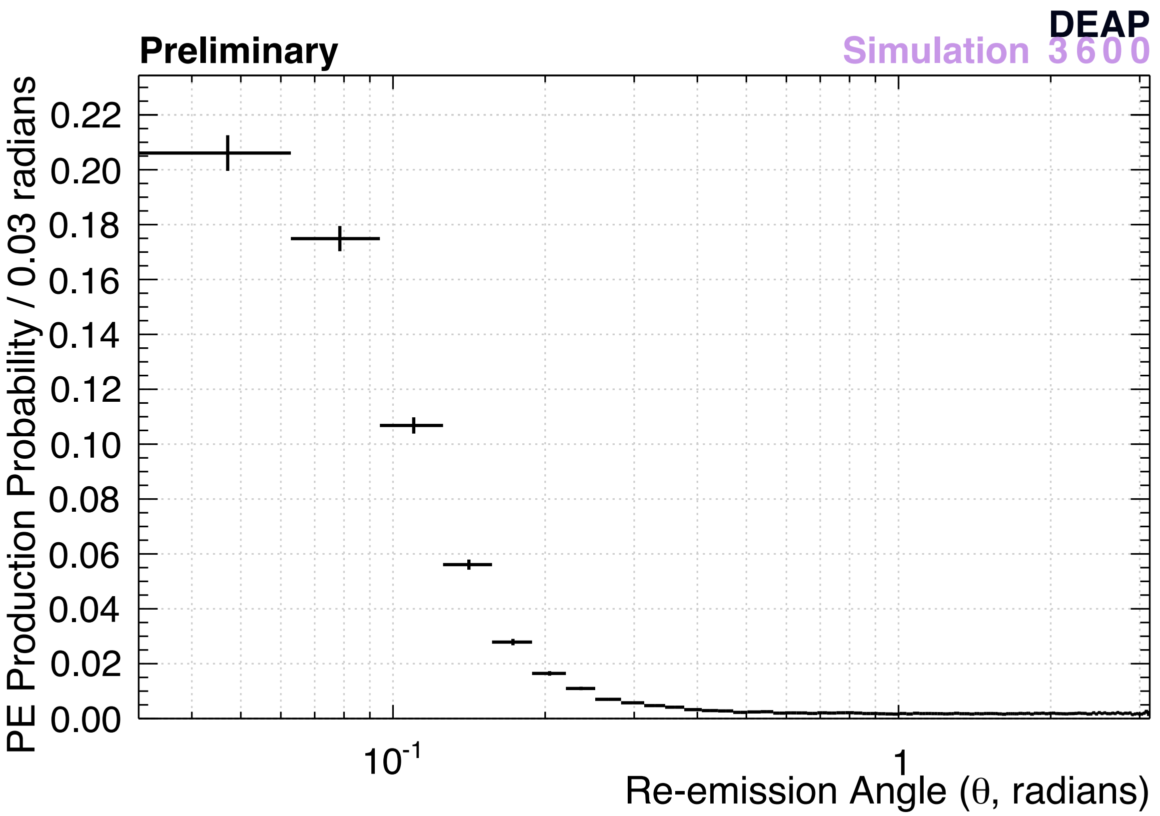




SHELLFIT - 2

- The second measures the probability that a photon remitted from a point on the TPB Ω produces a PE in a PMT at an angle θ away





1. The product of these two gives you the probability that:
   - A photon incident on a single point on the TPB causes re-emission
   - *AND* produces PE at a given PMT.
2. Integrating this quantity over all points on the TPB surface gives you the total probability that a PMT saw PE from a single photon emitted at the event vertex $\vec{r}$.
3. Multiplying that by the number of photons emitted by an event N_{UV} gives you the number of PE μ observed in a PMT due to all photons in the event at $\vec{r}$.

SHELLFIT LIKELIHOOD

- Given a set of observed PE in PMTs a model likelihood is calculated for a reconstructed position:

$$\mathcal{L}(\vec{x}, N_{UV}) = \prod_{i}^{N_{PMTs}} Pois(\underbrace{\mu_i}_{\text{Model PE}}(\vec{r}, N_{UV})|\underbrace{Q_{obs,i}}_{\text{Observed PE}})$$

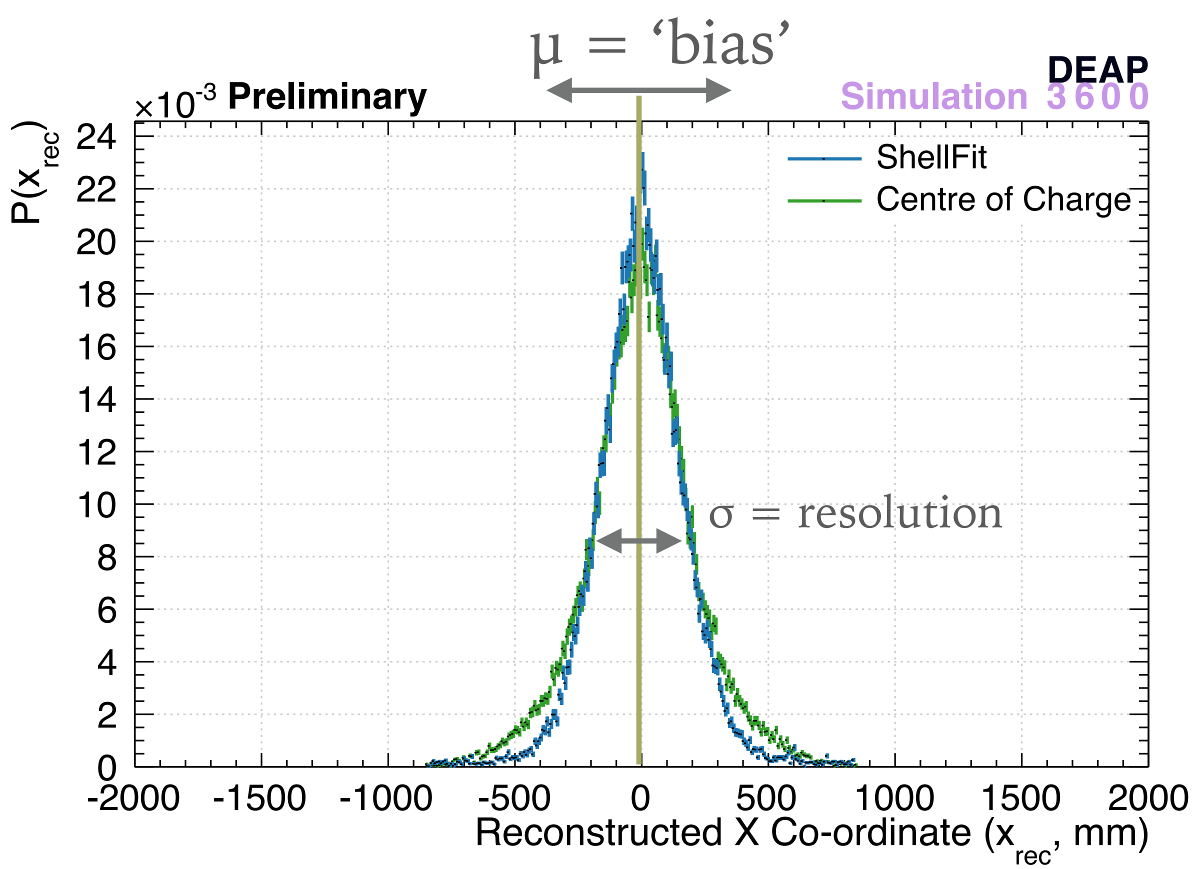
- The likelihood is maximised with respect to position $\vec{r}$ and number of photons N_{UV} emitted from the event vertex.
- Shellfit uses the optics from a full detector simulation to reconstruct events. It adapts its detector response model automatically with:
  - optical model parameter value updates
  - incremental detector geometry updates to reflect as-built values
  - varying detector phase during commissioning (i.e. vacuum, N2, gas Ar, partial fill, liquid Ar)

HOW DO WE KNOW IT WORKS?

MEASURING THE RECONSTRUCTION PERFORMANCE

- Work is underway to characterise our position reconstruction in different ways.
- One way to characterise our reconstruction: resolution and bias
- The difference between reconstructed and simulated position is approximately gaussian in x,y,z,r $\rightarrow P(r_{MC}-r_{rec}) \sim Gaus(\mu,\sigma)$
- Reconstruction based on an optical model improves our resolution compared to a simple charge weighted position.
- We don't however, *assume* a gaussian resolution response - we *measure* it using calibration sources

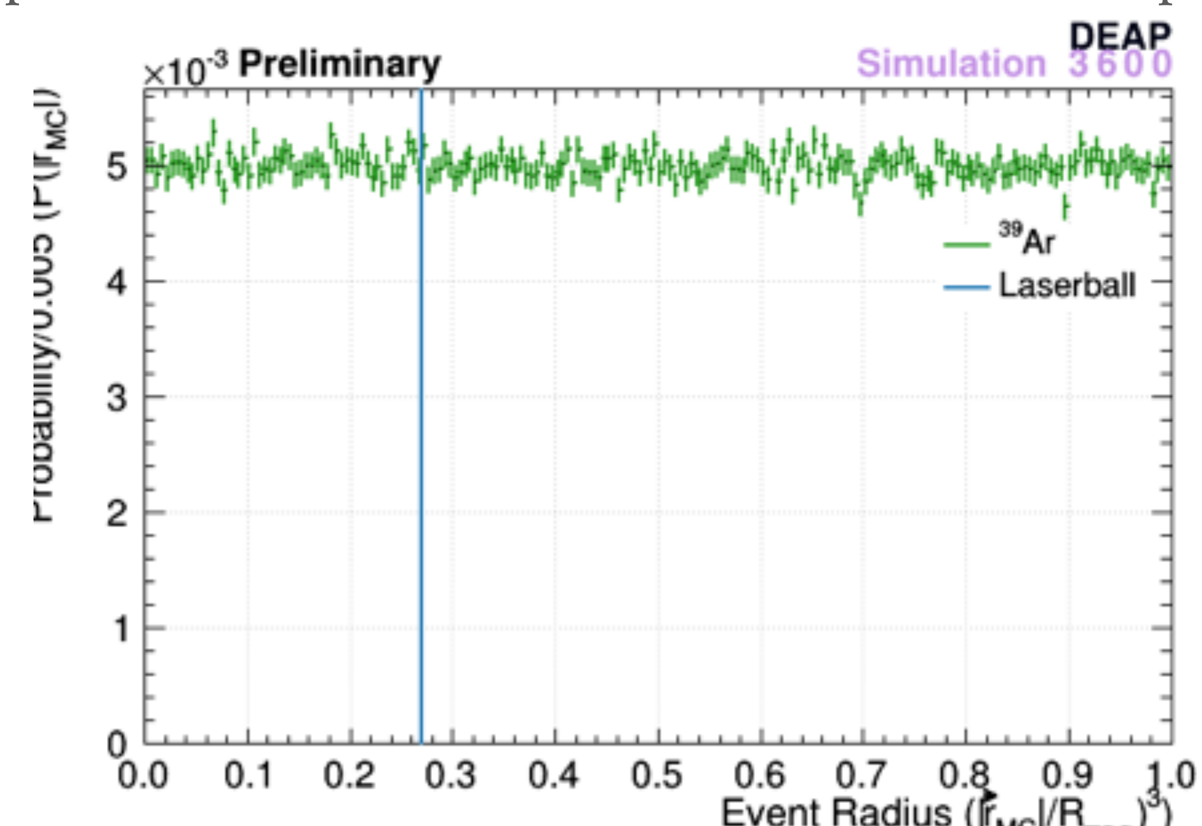
Shown below: 25keV electronic recoils from $^{39}Ar\ \beta^-$ decay, at R=0.



Our position reconstruction resolution is radially dependent, and improves at higher radii. Our radial resolution is better than our target resolution of 10cm at the surface of the detector and at the fiducial radius.

CALIBRATION SOURCES

- We can use our calibration sources (see N. Fatemighomi's talk) to benchmark our reconstruction and simulation using calibration data.
  - ^{39}Ar - Uniform throughout detector (shown below: ^{39}Ar β^- decay is uniform in R^3)
  - ^{22}Na, ^{232}Th - calibration tubes outside the outer steel shell
  - Laserball - point like source in vacuum at centre of detector and z=±550mm (shown below)
- For example: If we compare reconstruction of an Ar39 distribution uniform in R^3 we can calculate reconstruction biases if we see non-uniformity.
- Likewise, we can compare reconstructed Laserball data to its known position



OUTLOOK

- Our position reconstruction uses a detailed model informed by a full monte carlo simulation of our detector
- We are working on additions to our reconstructed model:
  - Adding time information from PMTs into our reconstruction
  - Producing a theta dependent model to adjust for the detector neck - a source of spherical asymmetry
- We are working on benchmarking the position reconstruction resolution using calibration source data:
  - A point source - the laserball at centre, $z = \pm 550$mm
  - Surface-like sources - ^{22}Na
  - Uniform sources - ^{39}Ar