Stereo Calorimetry in Liquid Scintillator Detectors

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What

Technique allowing **redundancy** for high precision calorimetry
with Liquid Scintillator detectors

Why

Upcoming high-resolution spectral measurements of **neutrino** interactions

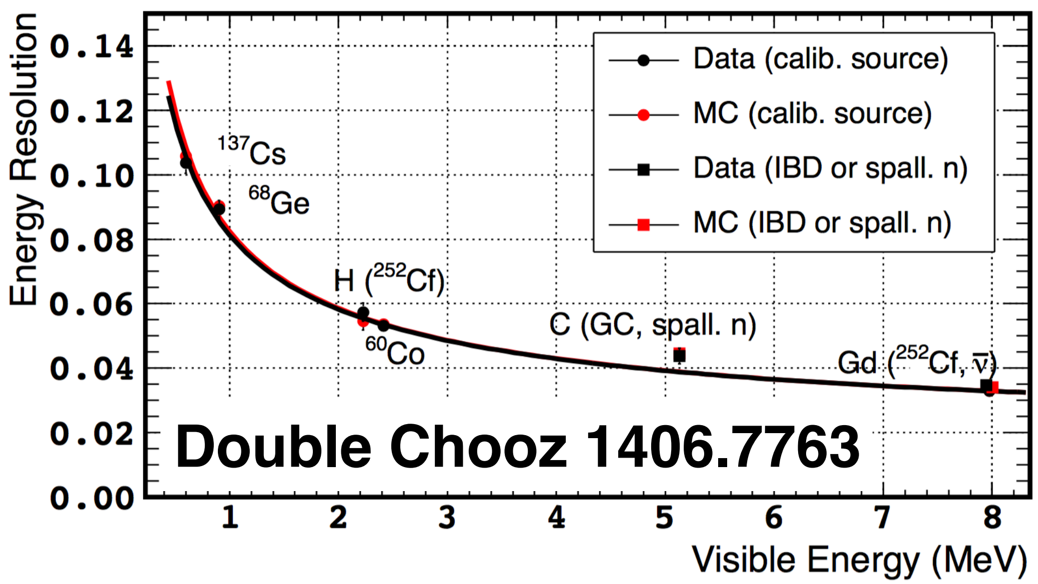
How

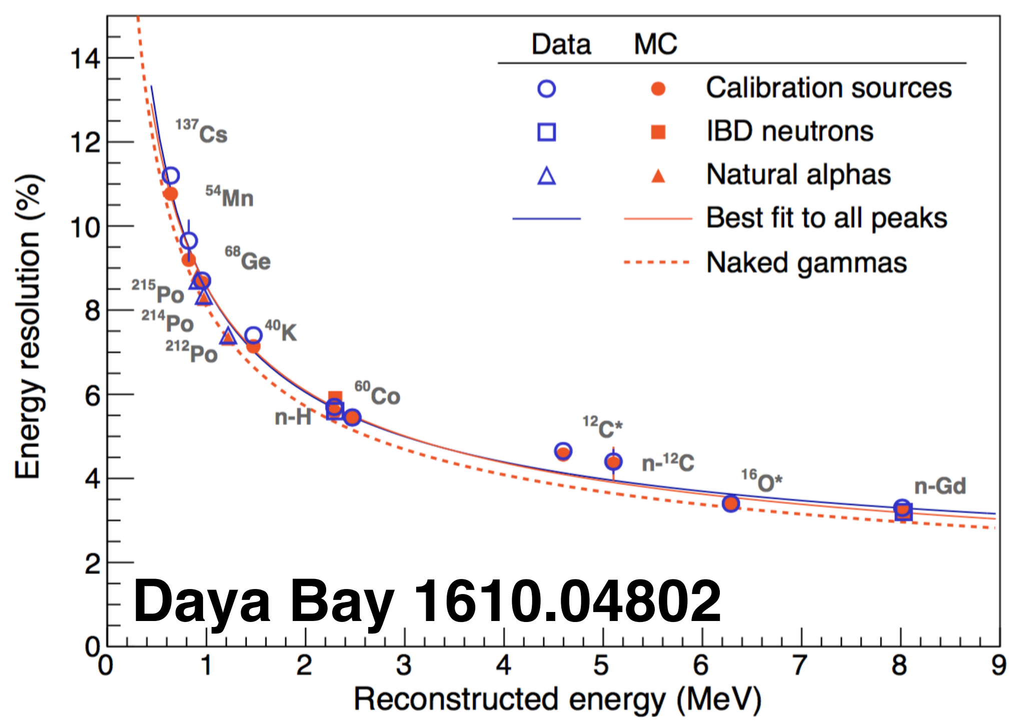
Exploit two independent **energy** estimators
experiencing different **systematic** uncertainties

(in JUNO, implemented through independent detection systems)

Motivation

$$\frac{\sigma(E)}{E} = \sqrt{\left[\frac{a}{\sqrt{E}}\right]^2 + [b(E)]^2}$$





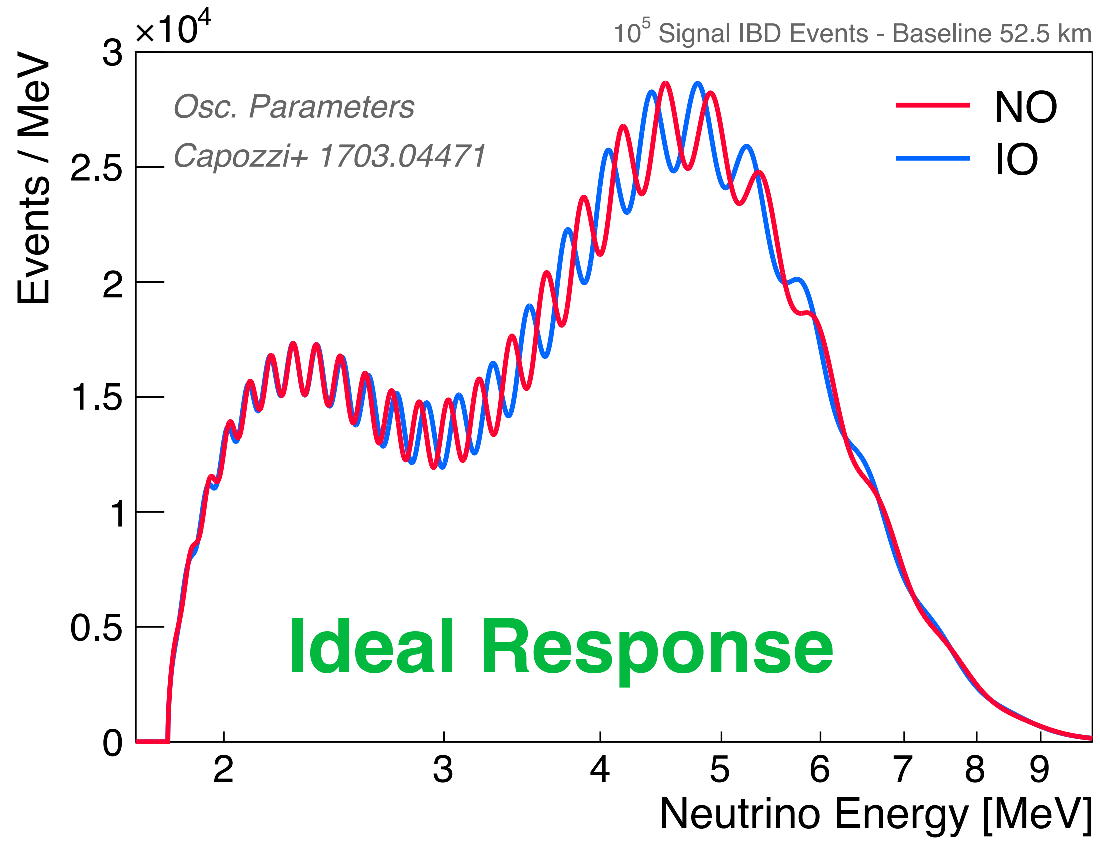
Non stochastic resolution term b:
Residual issues in detector modeling after calibration (linearity, stability, uniformity)

θ_{13} Experiments: **a** ~ 7% **b** ~ 1%
(monolithic liquid scintillator detectors)
Resolution dominated by photostatistics

Next generation liquid scintillator detectors:
Improve resolution (more than x2).
Precise neutrino spectral characterization.

b term no longer negligible.
Understating systematics is pivotal.
Possibly among hardest experimental tasks.

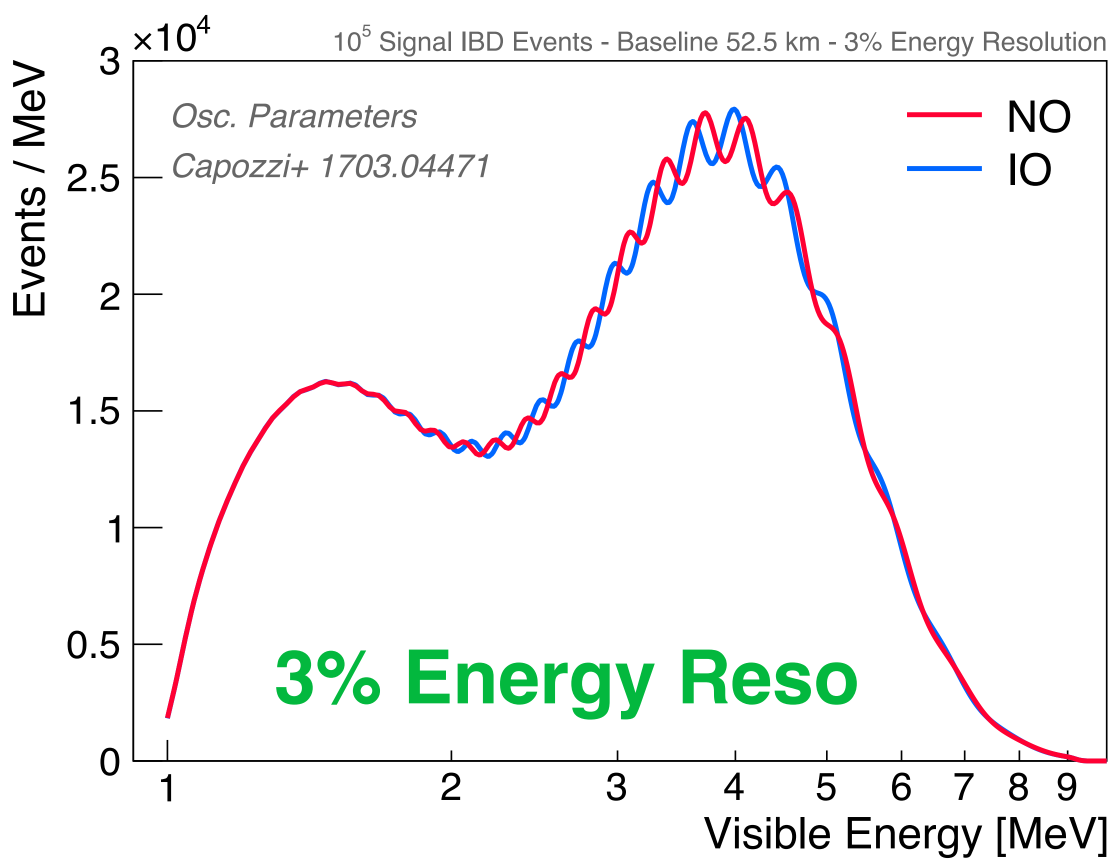
JUNO Requirements (Qualitative)

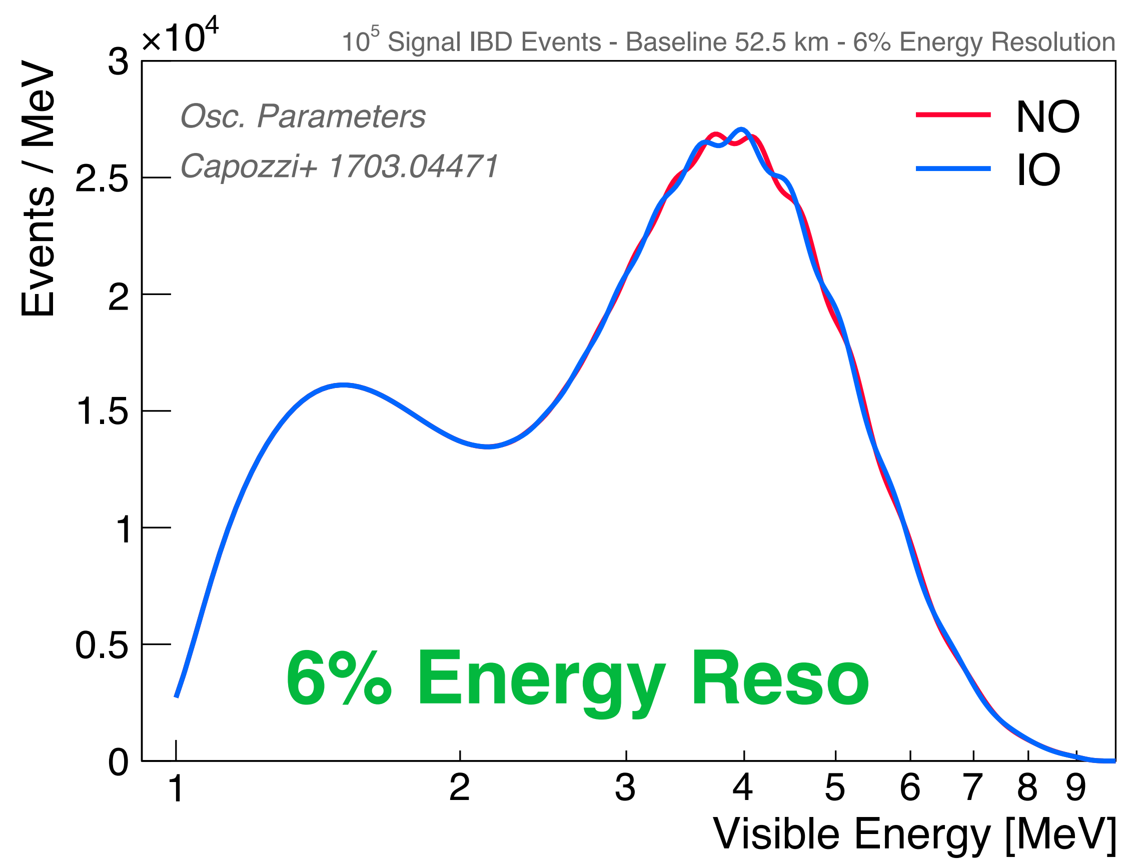


JUNO aims to determine neutrino mass ordering

Distinguish blue from red spectrum

It's all about energy response: Resolution & Linearity





JUNO Challenge (Quantitative)

	DETECTOR TARGET MASS	ENERGY RESOLUTION
KamLAND	1000 t	$6\%/\sqrt{E}$
D. Chooz	8+22 t	$8\%/\sqrt{E}$
RENO	16 t	$8\%/\sqrt{E}$
Daya Bay	20 t	$8\%/\sqrt{E}$
Borexino	300 t	$5\%/\sqrt{E}$
JUNO	20000 t	$3\%/\sqrt{E}$

MUST BE LARGER

Need to collect large statistics being 50km away from source

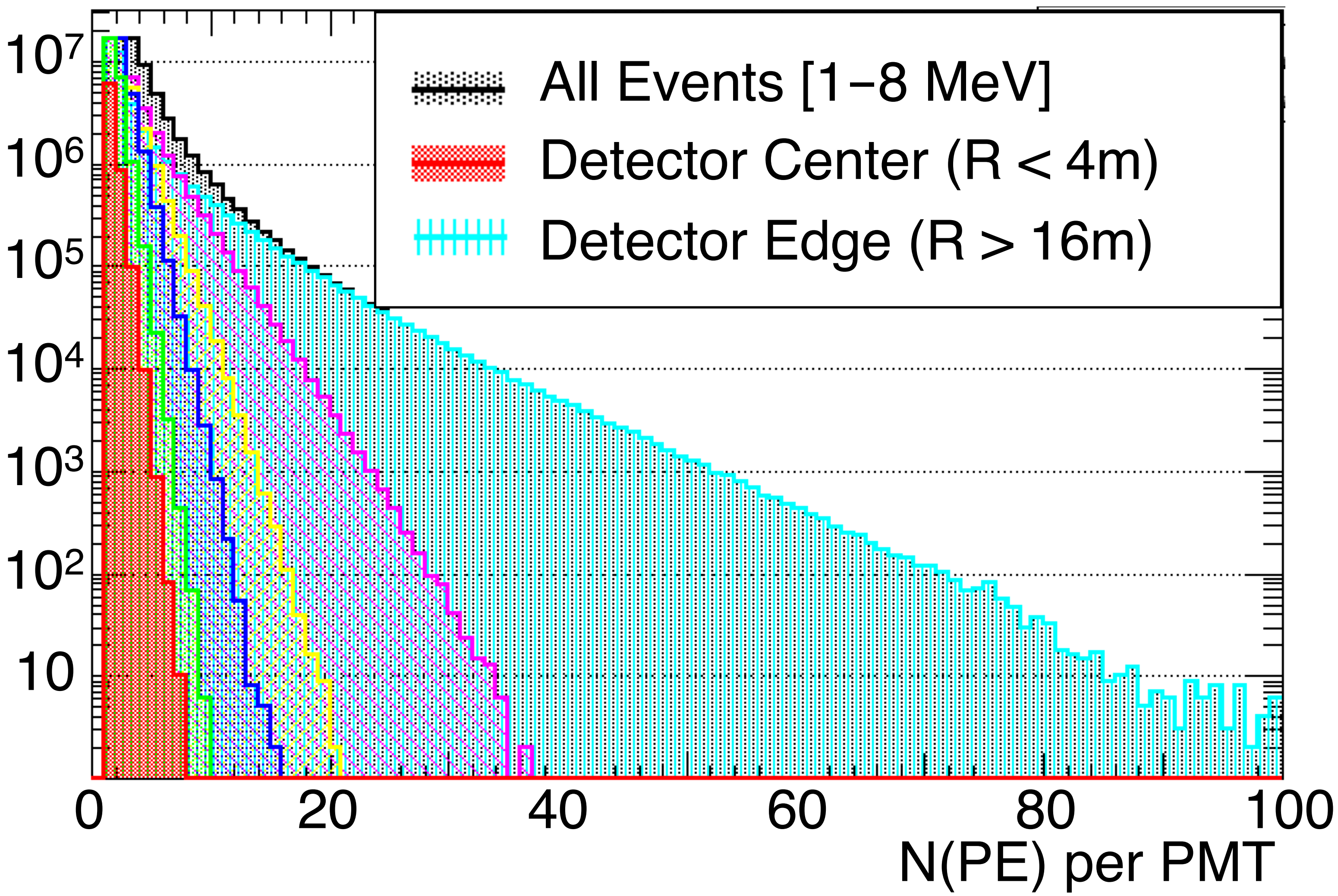
MUST BE MORE PRECISE

Unprecedented light level 1200 pe/MeV

Both features

- are highly expensive (civil engineering + photocathode density)
- result in extreme detector **dynamic range**

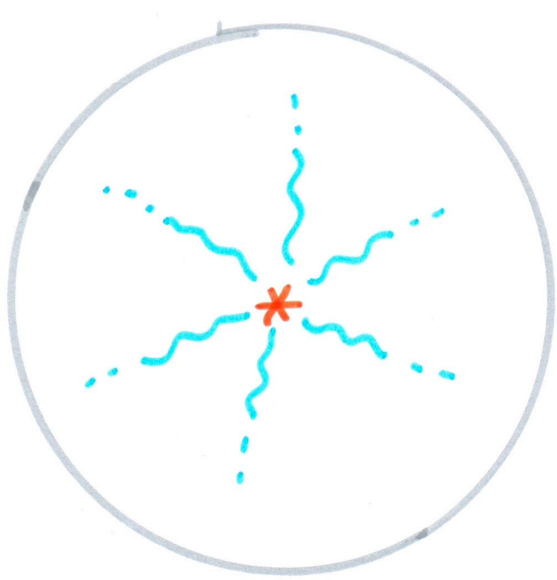
Light Level in JUNO

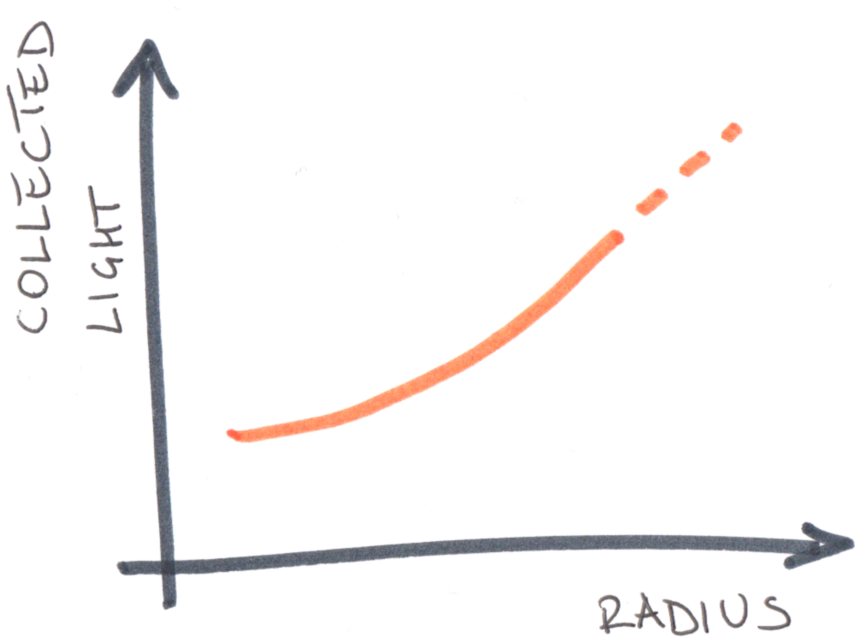


Collected light increases towards the edge of the detector:

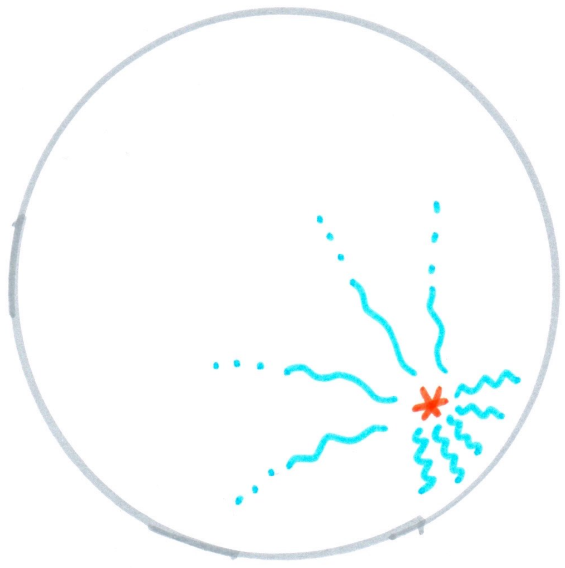
- Energy deposition at **center**: all the photons are attenuated equally
- Energy deposition at **edge**: some PMTs see many photons

Energy dep. at center





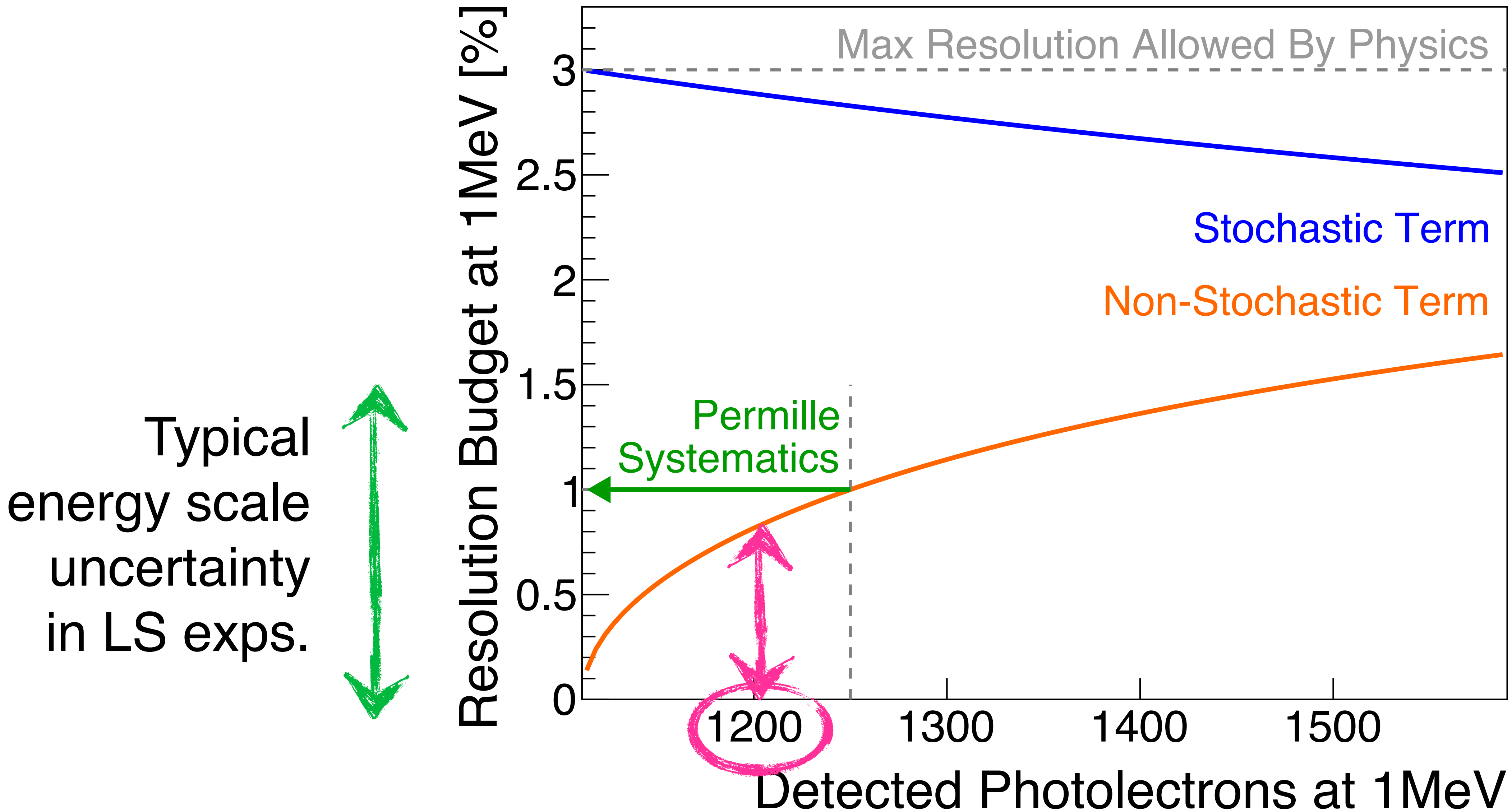
Energy dep. at edge



Deal with the detection of 1200 wild photoelectrons…

JUNO Calorimetry

Light is not enough $$\frac{\sigma(E)}{E} = \sqrt{\left[\frac{a}{\sqrt{E}}\right]^2 + [b(E)]^2}$$



Non stochastic term (b) needs to be controlled to permille level

Redundancy in evaluation of systematic uncertainties is pivotal

Double Calorimetry: born within JUNO

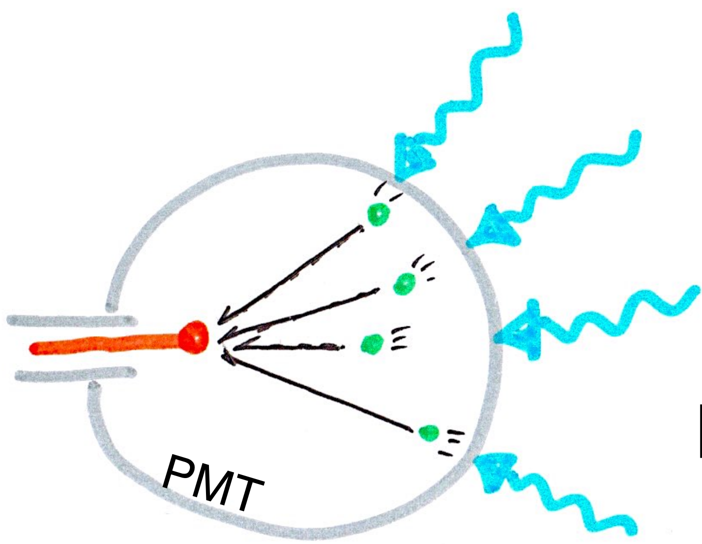
to better control / assess the resolution non-stochastic term

Two Calorimetry Observables in LS Detectors

ENERGY DEPOSITION → **LS Detector** MeV to PE → LIGHT DETECTION →

Mean PMT Illumination
$\lambda = \langle N(PE) \rangle / PMT$

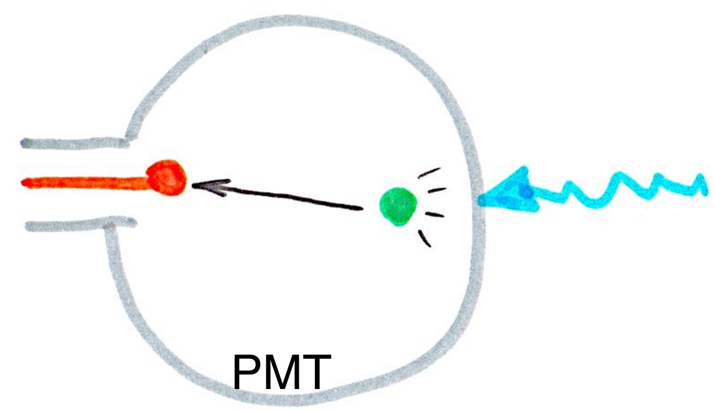
CHARGE INTEGRATION



$\lambda > 0.1$

$PE = \frac{charge}{gain}$

PHOTON COUNTING



$\lambda \lesssim 0.1$

$PE = hit$

PMT gain linearity
gain = f(PE)? ← Different Systematics → Single photoelectron threshold

REDUNDANCY

Stereo Calorimetry Prototyping

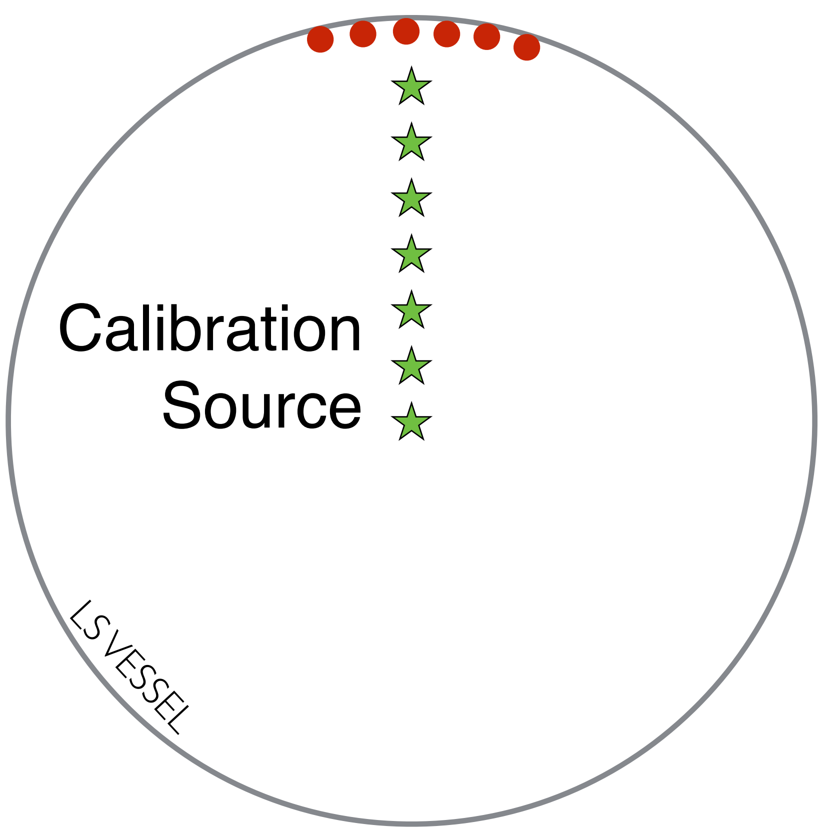
JUNO was the initial physics case to start thinking to multiple E estimators

However stereo calorimetry can be seen as a **general calorimetry technique**

In the following slides…

Test the rationale with a simple (JUNO-inspired) Toy MC

How



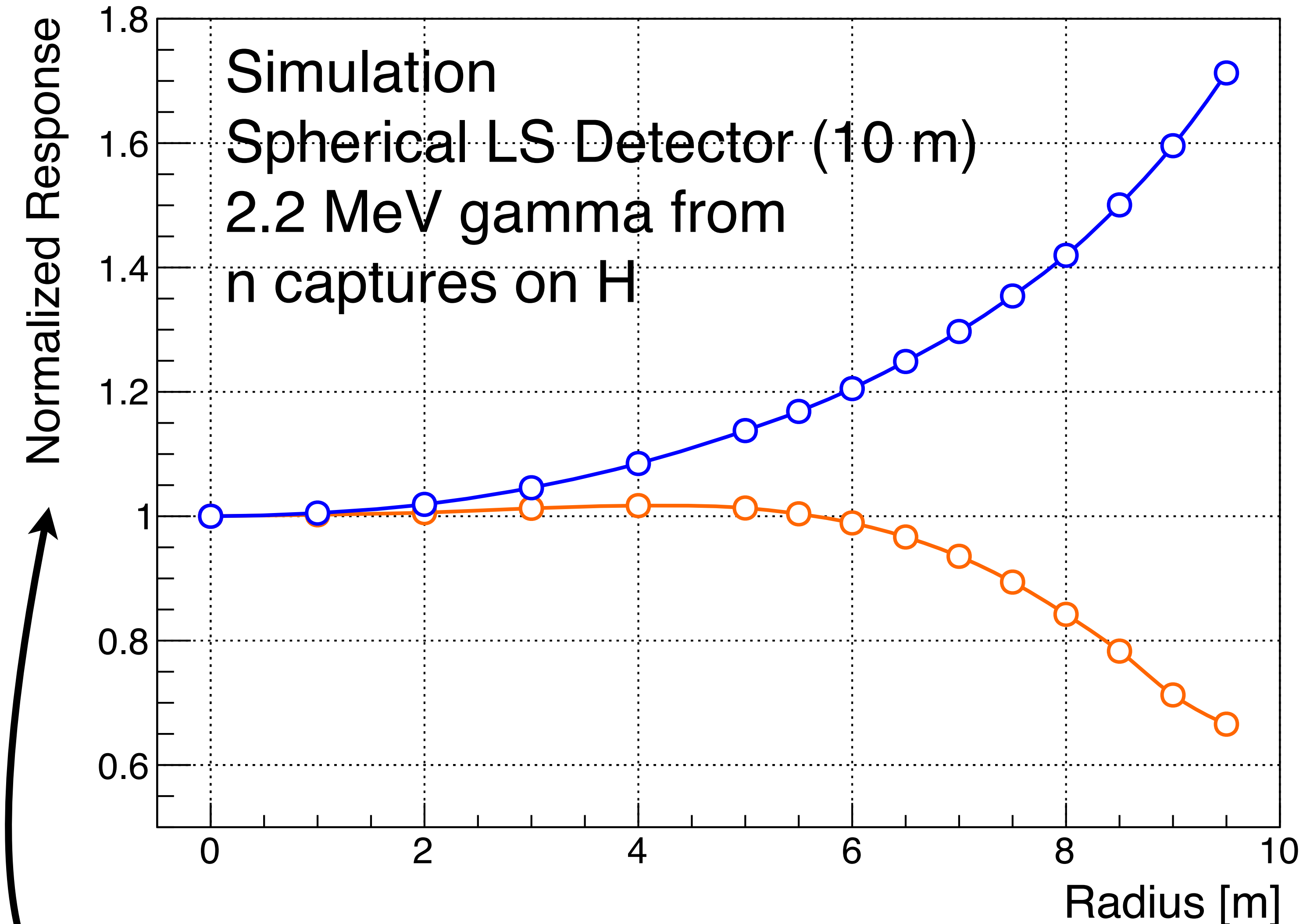
Spherical liquid scintillator detector (10m radius)

Light level: 1000 photoelectrons / MeV

Exponential LS attenuation length

Energy calibration sources
1 MeV (like ^{68}Ge)
and **2.2 MeV** (like γ from neutron capture on H)
deployed at several positions

Two Calorimetry Observables



Charge Integration

$E \sim \Sigma\, q_i$

Geometrical Coverage

LS Attenuation

Photon Counting

E ~ N(active PMTs)

Few PMTs are detecting scintillation light

Detected Light using either Total Charge or N(active PMTs)

Here both estimators are implemented using the **same** detection systems (the same set of PMTs)

To what extent the bias can be corrected using calibration sources?

Energy Reconstruction: from PE to MeV

$$E = f \times N(\text{PE})$$

f: calibration

N(PE): raw detector response

ACCOUNTED FOR USING

- **Uniformity** ← Position dependent
- **Stability** ← Time dependent
- **Linearity** ← Energy dependent

Energy Reconstruction: from PE to MeV

$$E = f \times N(\mathrm{PE})$$

f: calibration

N(PE): raw detector response

ACCOUNTED FOR USING

- **Uniformity** ← Position dependent
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Limited dynamic range
Nowadays σ(E)/E
(eg θ_{13} experiments)

$$E\,[\mathrm{MeV}] = f^{\mathrm{ABS}} \times f^{\mathrm{U}}(r) \times f^{\mathrm{S}}(t) \times f^{\mathrm{L}}[N(\mathrm{PE})] \times N(\mathrm{PE})$$

EVALUATED INDEPENDENTLY

Wide dynamic range
Demanding σ(E)/E

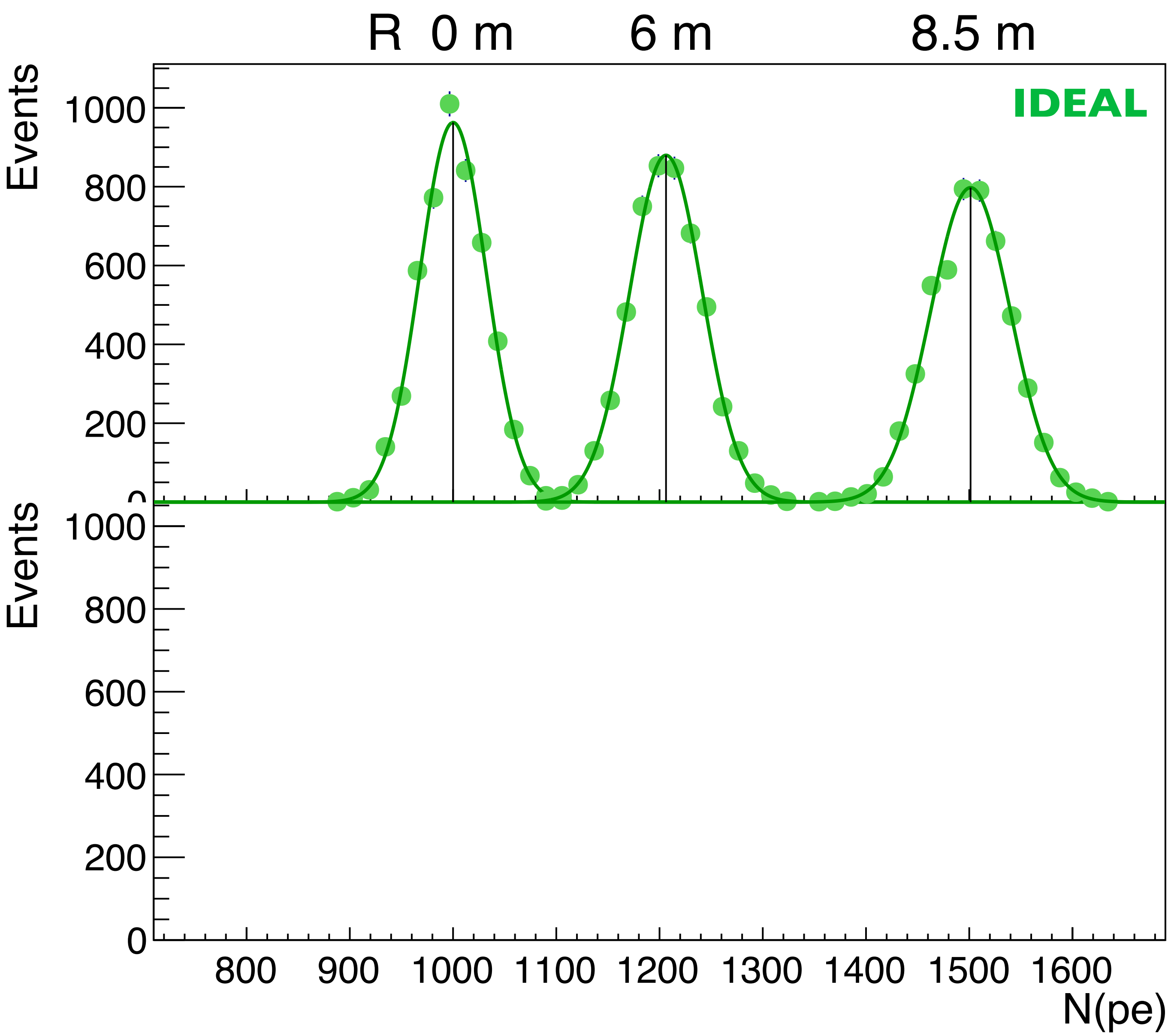
$$E\,[\mathrm{MeV}] = f^{\mathrm{ABS,\,U,\,S,\,L}}[r, t, N(\mathrm{PE})] \times N(\mathrm{PE})$$

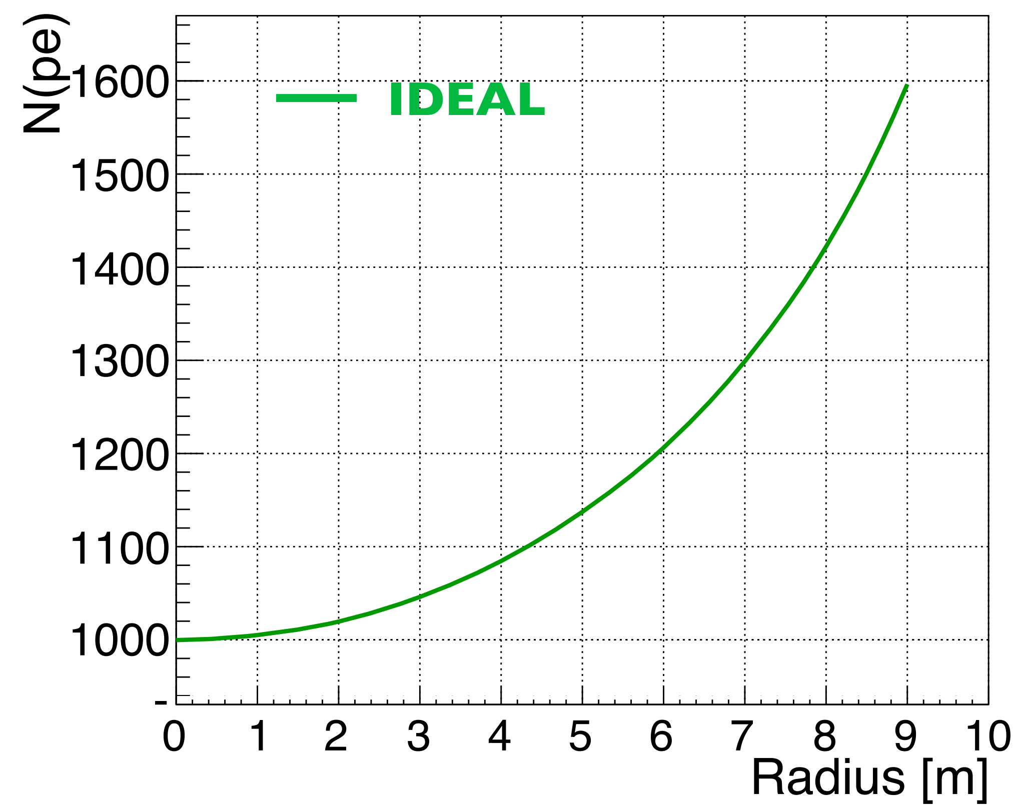
Correlation among f terms might become relevant (degeneracy)

EXAMPLE ▶ ▶ ▶

Correlation Among Calibration Terms (Illustration)

Deploy 1MeV calibration source at different positions (simulation)



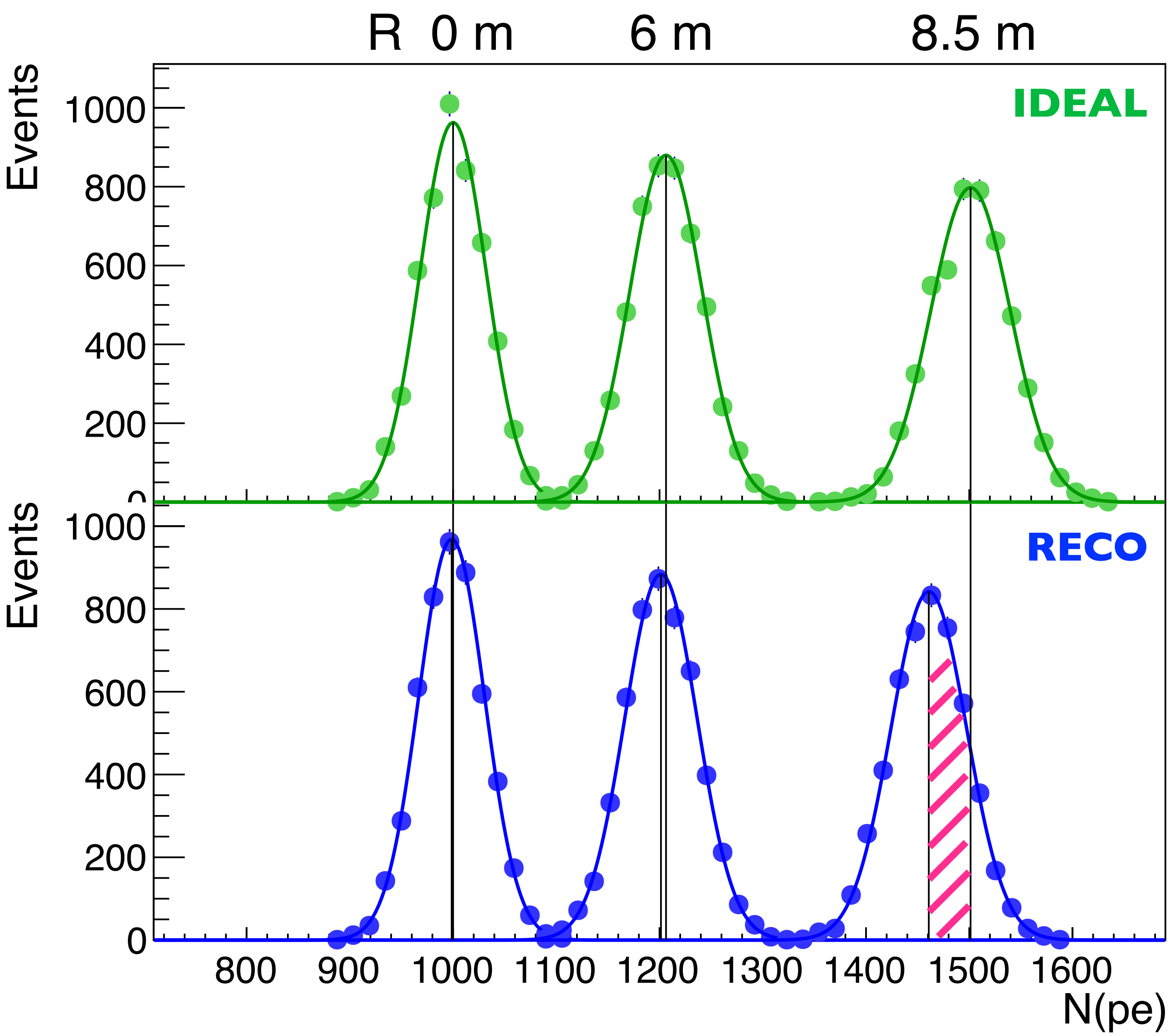


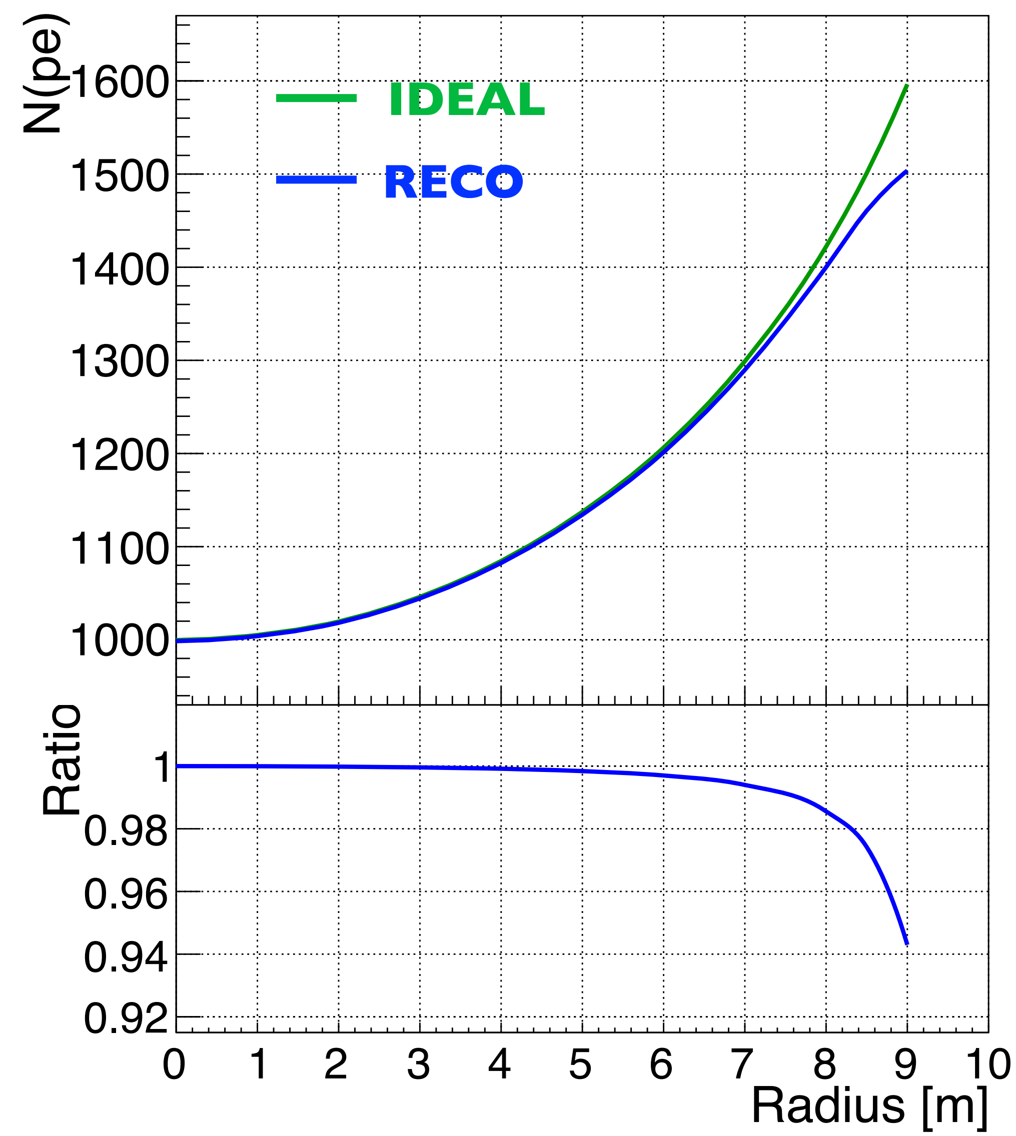
Detected Light vs Source Position

IDEAL : "Genuine" detector non-uniformity (geometry + LS attenuation)

Correlation Among Calibration Terms (Illustration)

Deploy 1MeV calibration source at different positions (simulation)





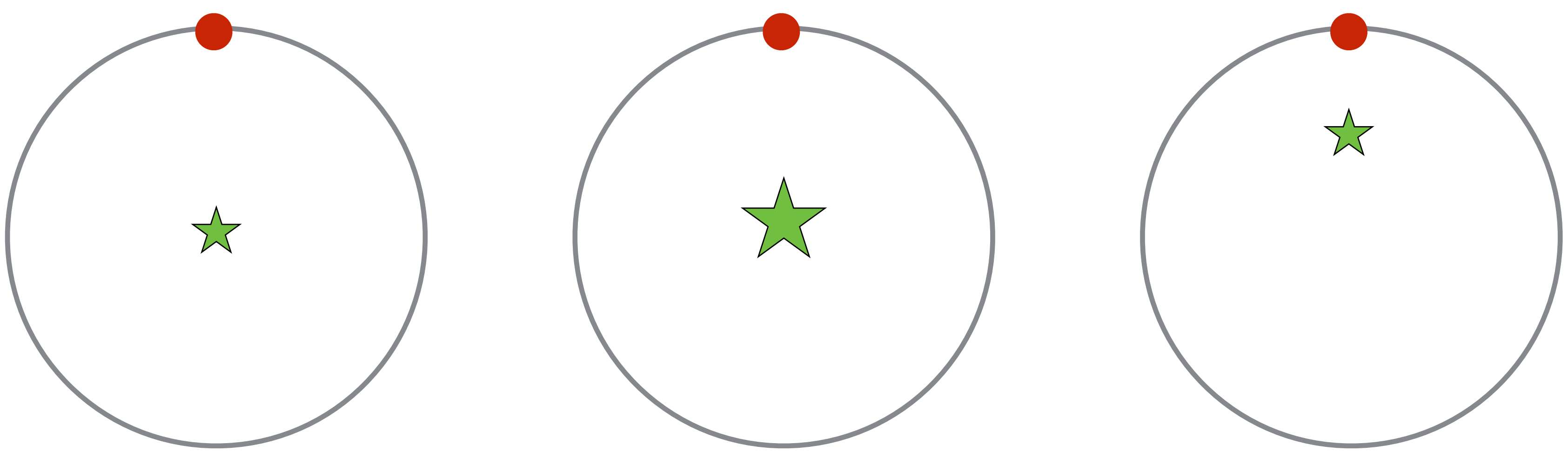
RECO: Introducing a 1% bias for each detected photoelectrons

Residual charge non-linearity shows up as additional non-uniformity

Degeneracy Among Calibration Terms

Residual charge non-linearity shows up as additional non-uniformity

		Position	
		Center	Edge
Energy	1 MeV	Reference	**More light (larger bias)**
	2.2 MeV	**More light (larger bias)**	



Any single-PMT charge-related systematics could potentially arise from

a uniformity issue
an energy issue
a combination of both

degeneracy

Correlation Outcome

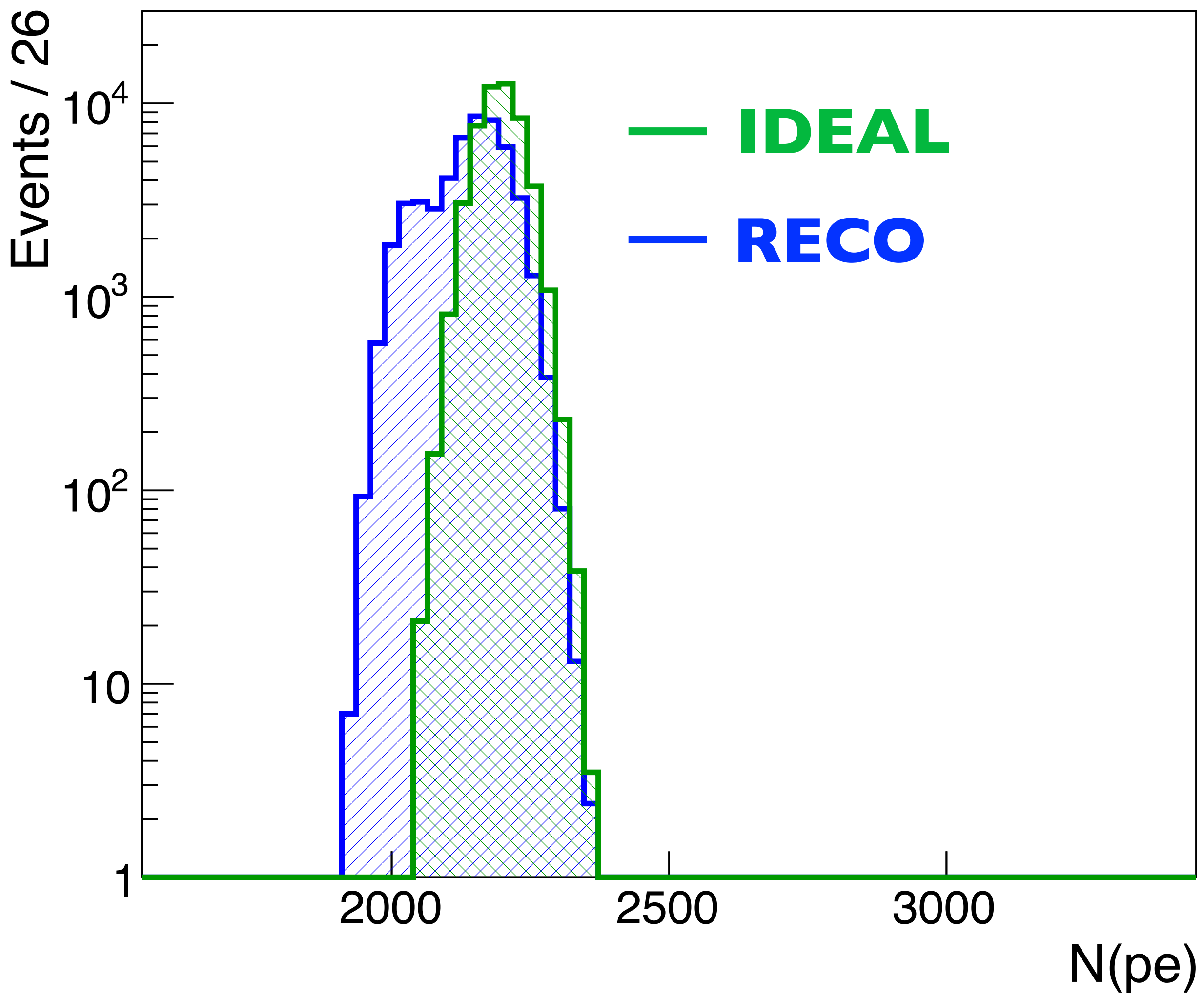
Use response map derived at 1MeV

Reconstruct 2.2 MeV gamma line from n captures on H

(uniformly distributed in the detector)

Actual resolution worse than intrinsic resolution

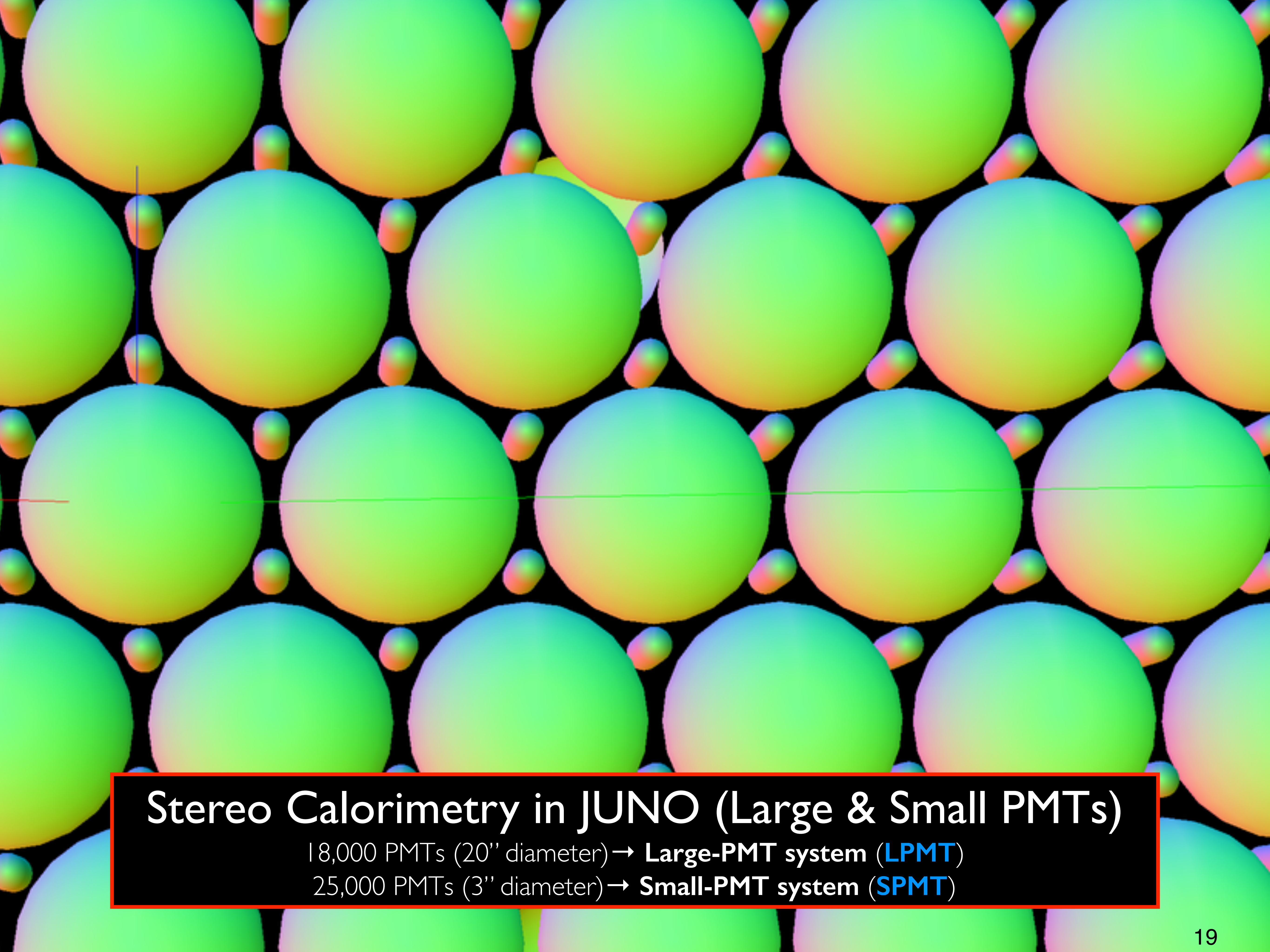
Non-Stochastic resolution term is dominant



Experimental Challenge

Understand the source of additional resolution (& distortion)

How to break down systematic uncertainty budget?



Stereo Calorimetry in JUNO (Large & Small PMTs)

18,000 PMTs (20" diameter) → **Large-PMT system** (**LPMT**)

25,000 PMTs (3" diameter) → **Small-PMT system** (**SPMT**)

A Stereo-Calorimetry Oriented Detector

The two energy estimators are implemented through **2 independent systems**

Large PMTs (LPMT)
75% photocoverage
1200 PE/MeV
N(PE) = charge / gain

Small PMTs (SPMT)
3% photocoverage
40 PE/MeV
N(PE) = N(HITS)

SPMT in **photon counting regime** across all dynamic range (energy & position)

Each SPMT sees either 0 or 1 photon

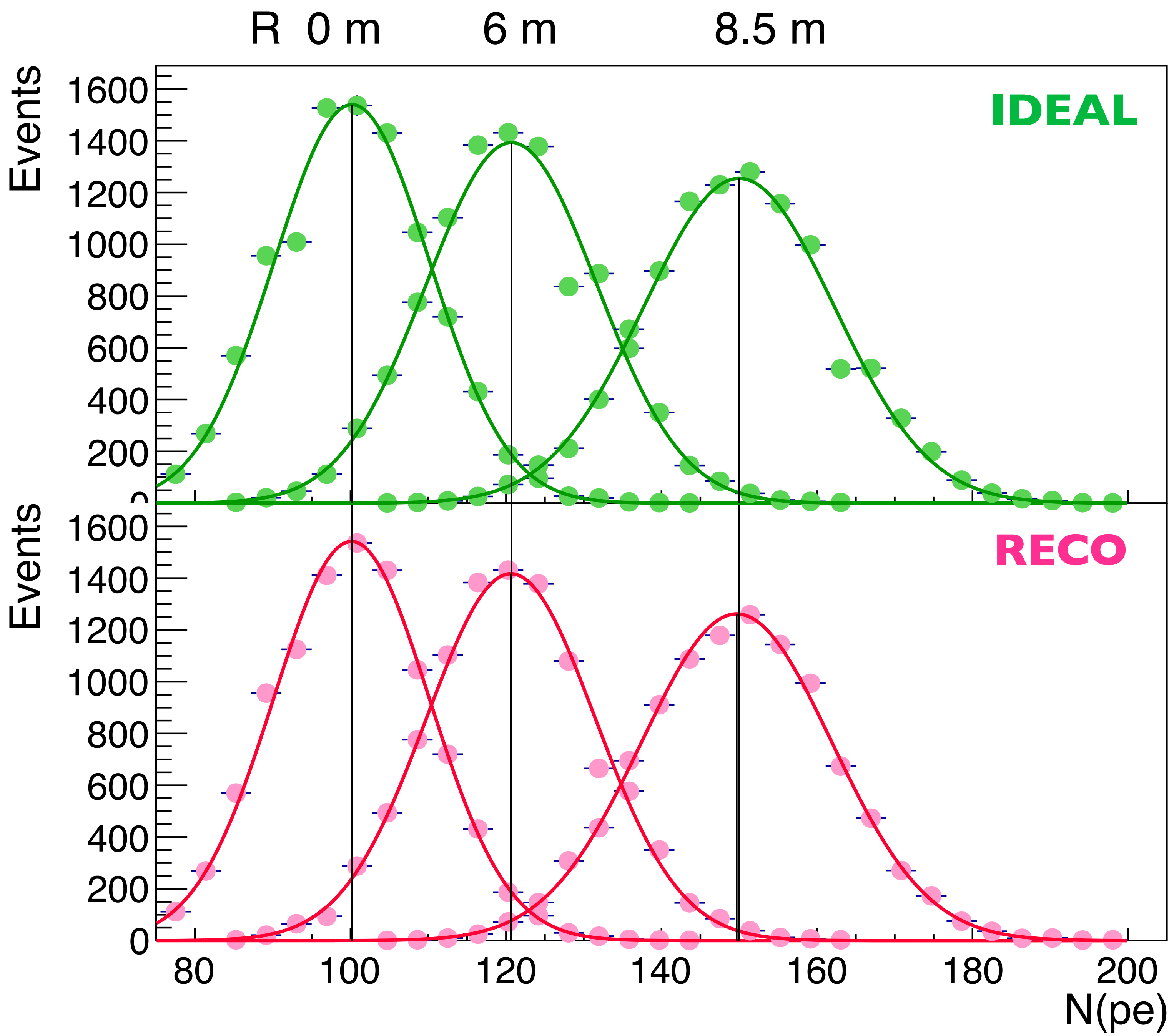
Effectively a **binary device**

Minimum possible dynamic range

Any charge-related issue is suppressed by construction

SPMTs Provide a Far Less Biased Energy Estimator

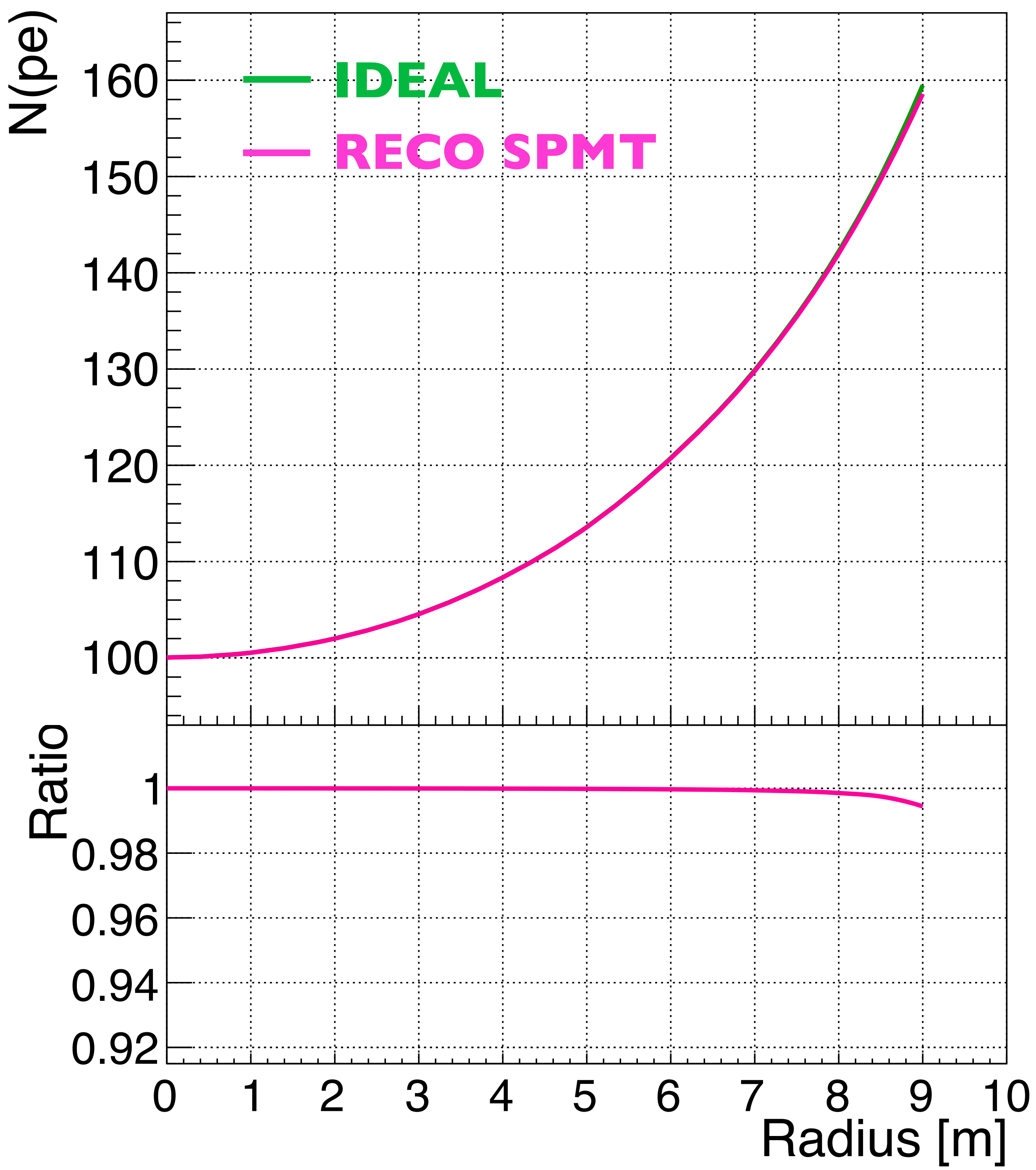
1 MeV calibration source as seen by the small PMTs



Negligible bias in energy reconstruction

SPMTs Provide an Unbiased Energy Estimator

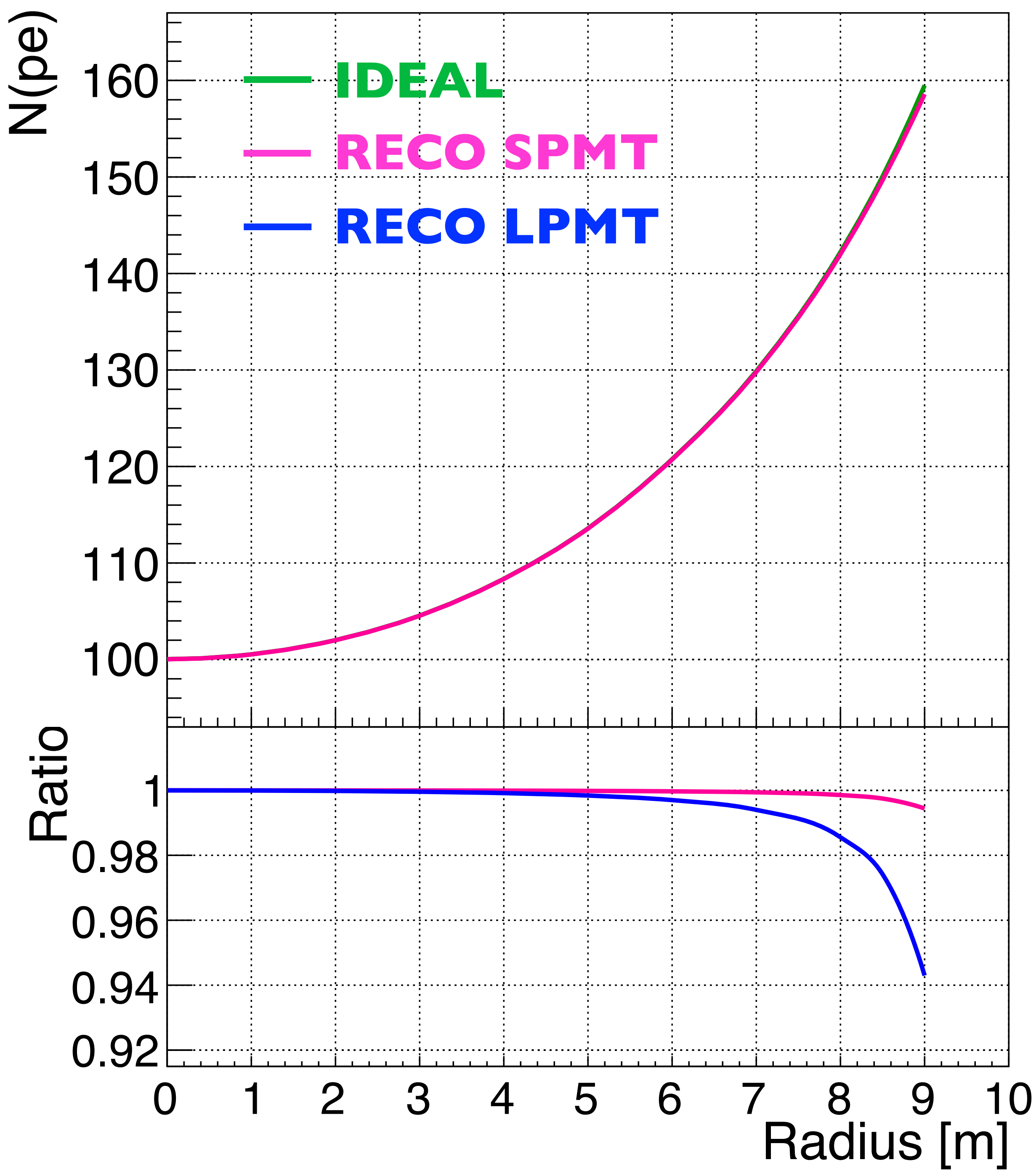
Look at calibration data
using SPMT



Breakdown of the Non-Stochastic Resolution Term

Look at calibration data
using SPMT

Photon Counting Regime:
Negligible charge non-linearity
Compared to LPMT



Breakdown of the Non-Stochastic Resolution Term

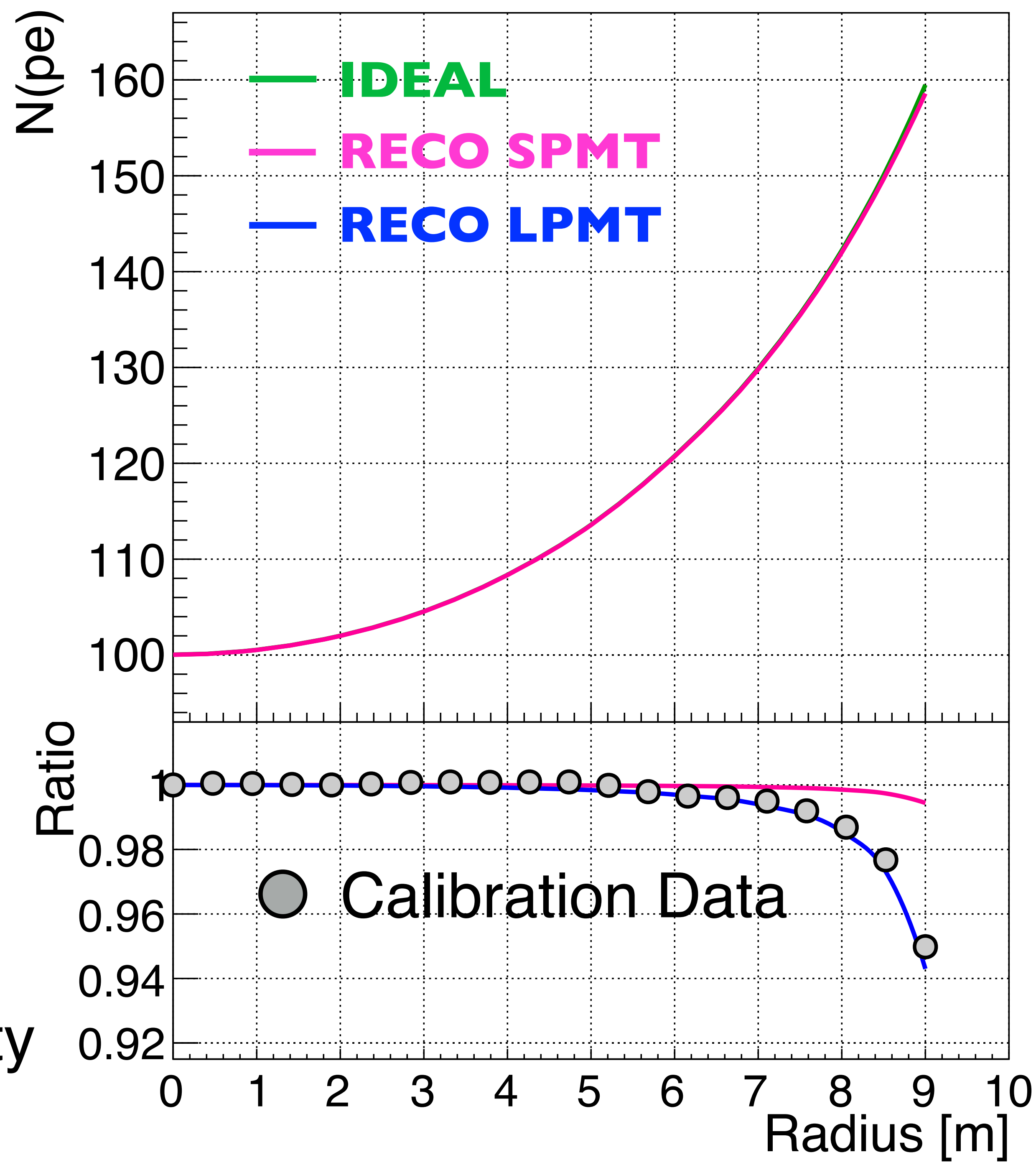
Look at calibration data
using SPMT

Photon Counting Regime:
Negligible charge non-linearity
Compared to LPMT

SPMT provide a good reference to understand LPMT response

Ratio LPMT/SPMT " ● "

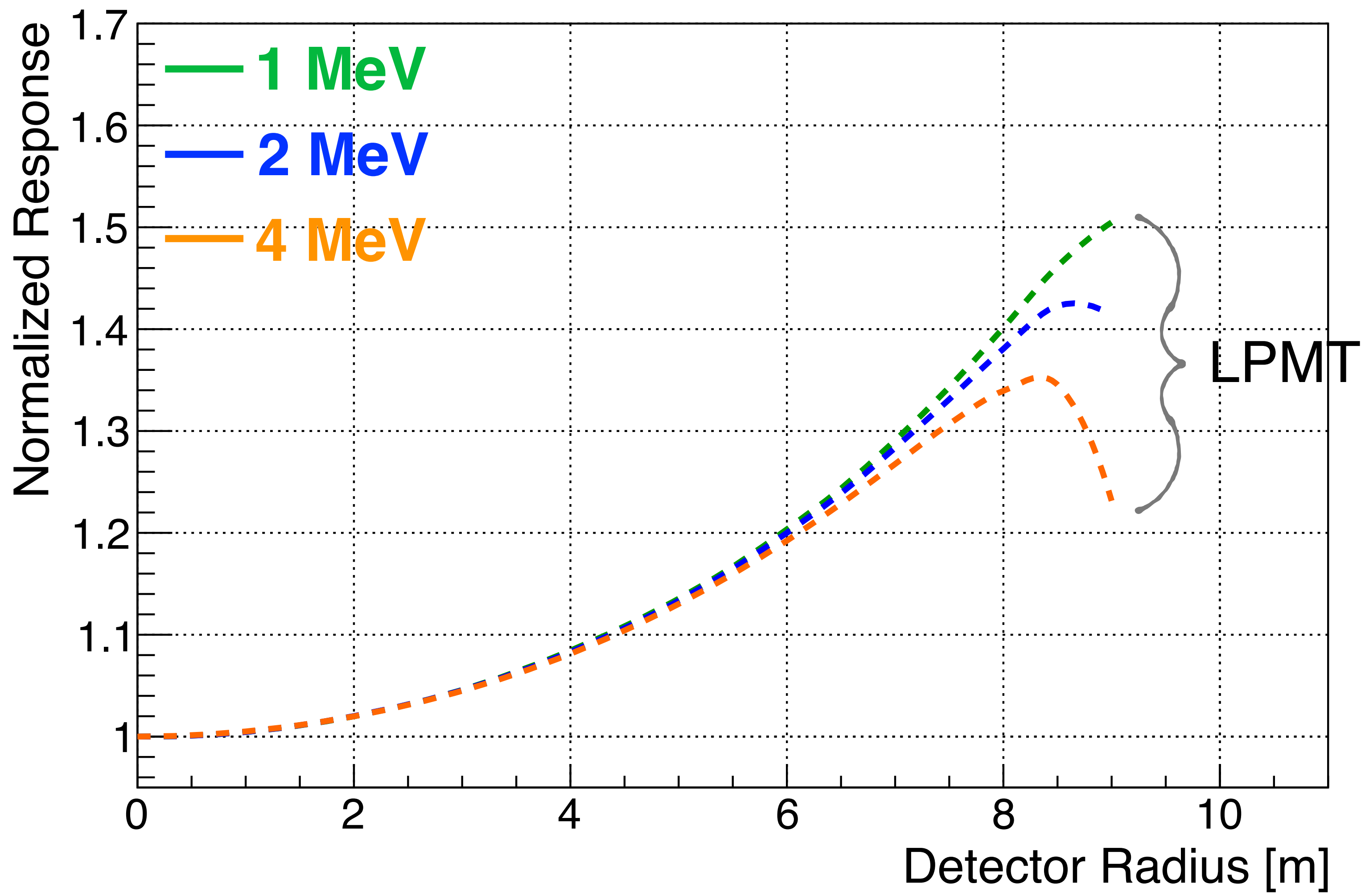
Extra resolution due to unaccounted charge non-linearity



SPMT: resolve otherwise unresolvable response degeneracy

Take-home message

Large dynamic range (at single photosensor) + High precision calorimetry (whole detector) = Correlation among systematics no longer negligible



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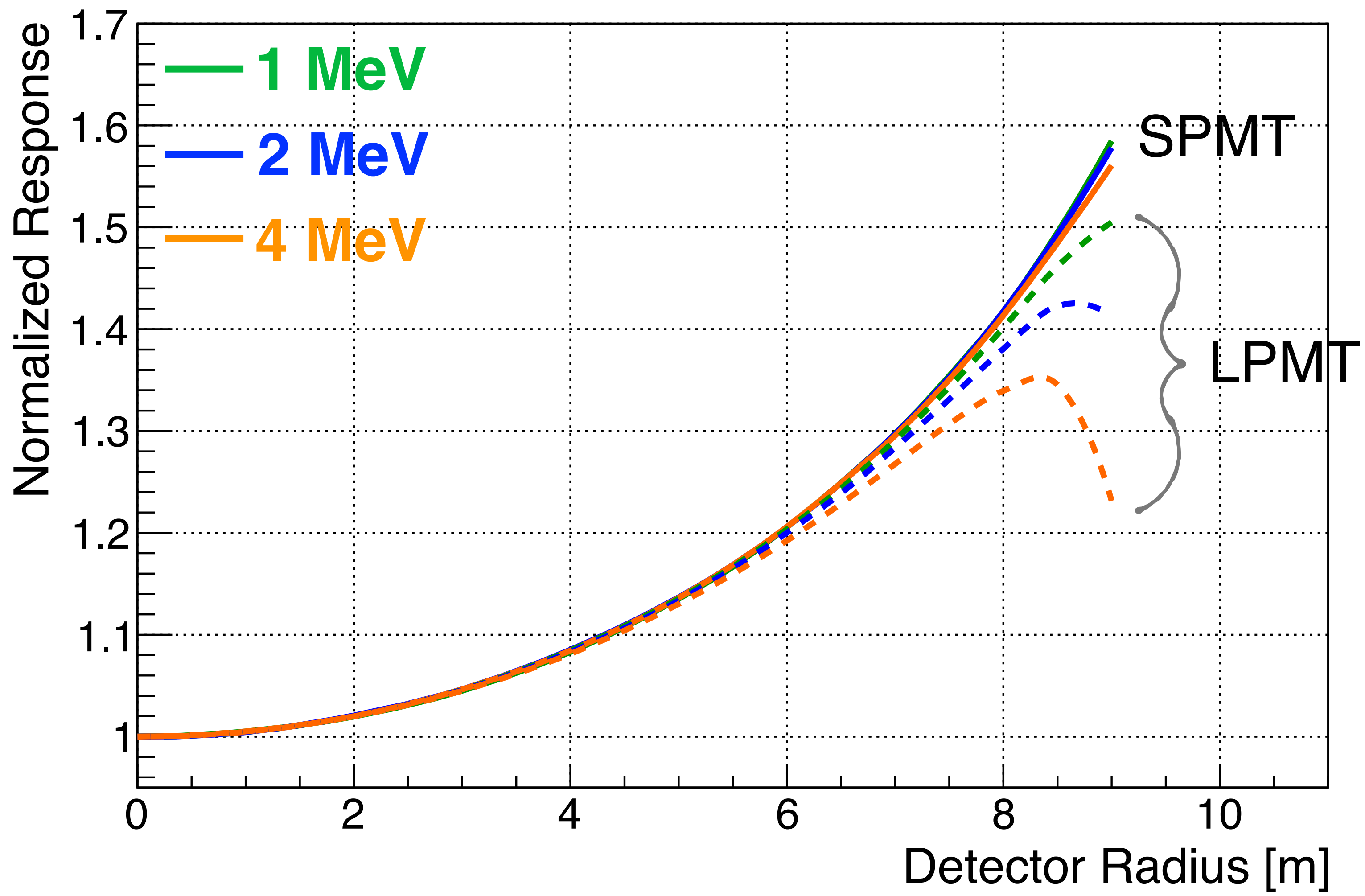

Best performance through specialized detection systems

LPMT: tackle **photostatistics** (maximize N(PE))

SPMT: tackle **systematics** (minimize dynamic range)

Redundancy is a key ingredient in high-precision calorimetry

Different energy estimators provide cross-check to **energy scale** understating

JUNO: energy estimators implemented via **dedicated hardware** (SPMT LPMT)

Independent systematic uncertainties by construction

3 examples of benefits arising from a system with limited dynamic range

Uniformity map valid at different energies

Reliable measurement of **light non-linearity** (LS quenching)

Break correlation among **calibration** terms