# Double Calorimetry in Liquid Scintillator Detectors

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# What

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

# Why

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

# How

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

*(possibly implemented through independent detection systems)*

**Disclaimer**: limited time ▸ illustration rather than full explanation

# Motivation

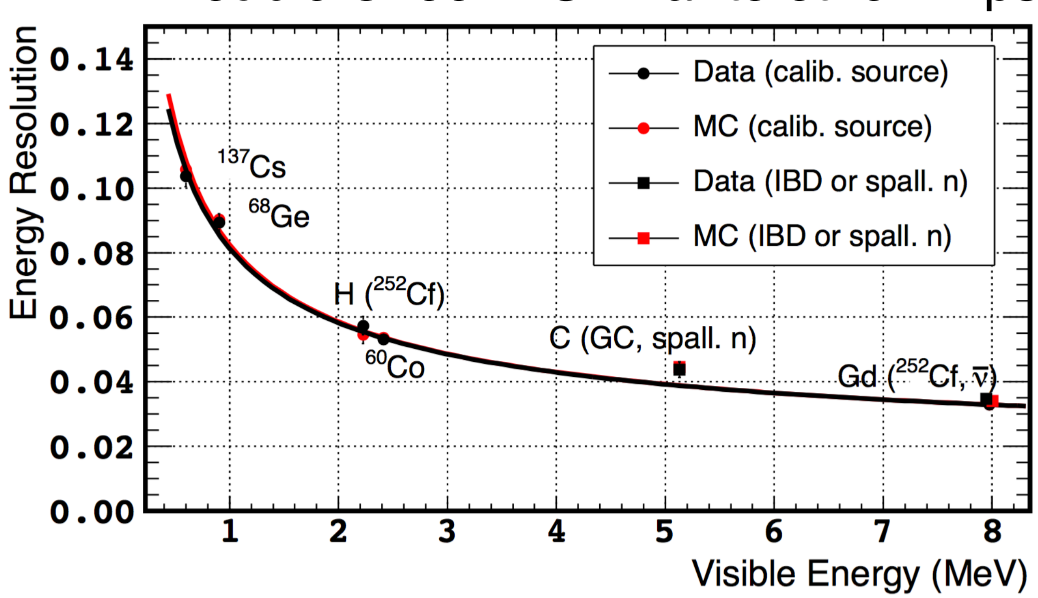
Calorimetry of (anti)neutrino interactions

Example: $\theta_{13}$ experiments

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

Resolution dominated by photostatistics

Double Chooz - Similar to other Exps




$\sigma_{NST}$: residual issues in detector modeling after calibration (linearity, stability, uniformity)

Next generation detector: **improve resolution** (more than x2)

$\sigma_{NST}$ no longer negligible

$\sigma_{ST} \sim 7\%$ $\sigma_{NST} \sim 2\%$

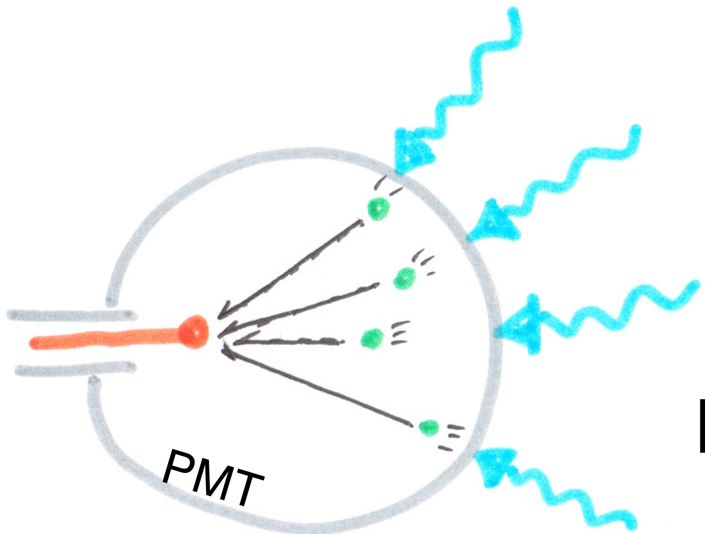
Understating systematics is pivotal

# Two Calorimetry Observables in LS Detectors

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

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

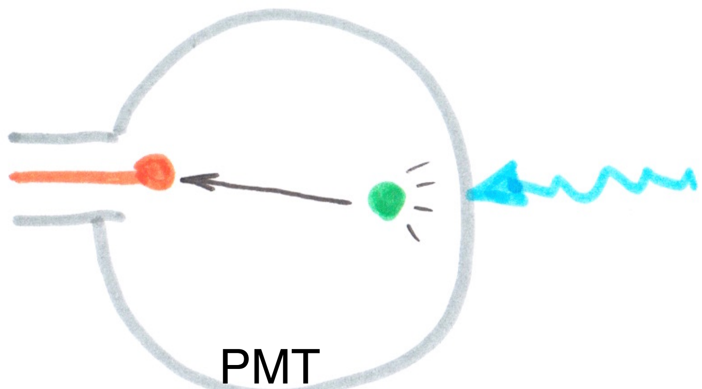
**CHARGE INTEGRATION**




$\lambda > 0.5$

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

**PHOTON COUNTING**




$\lambda \lesssim 0.5$

PE = hit

PMT gain linearity
gain = gain(PE)?

Different
Systematics

Single photoelectron
threshold

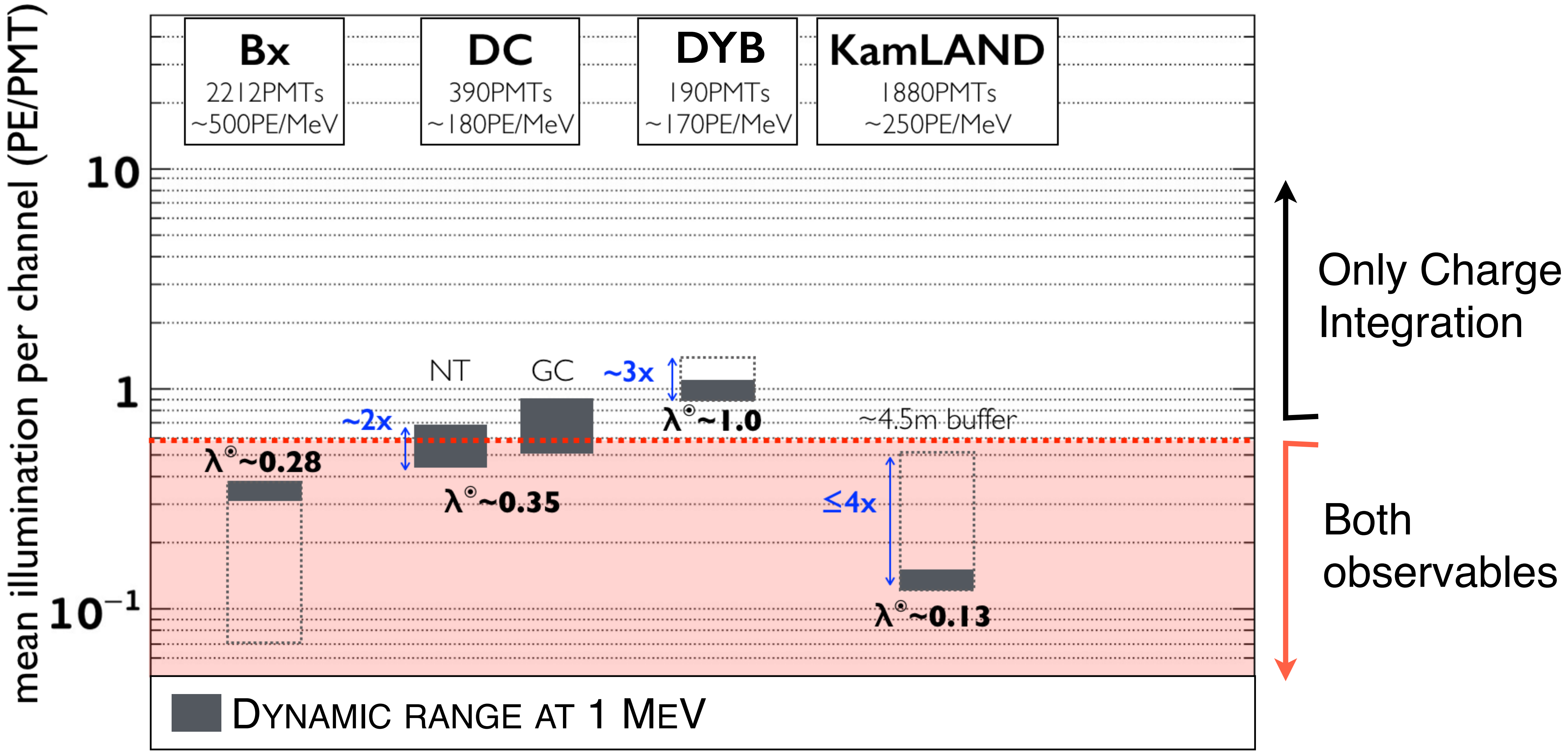
**REDUNDANCY**

# Calorimetry in Current LS Experiments

Experiments typically implement **one single observable**

**PARTLY BECAUSE**

Deposited energy (signal signature) + detector geometry ▶ dynamic range




Why shall we go beyond this paradigm?

# Calorimetry in Future LS Experiments

| | DETECTOR TARGET MASS | ENERGY RESOLUTION |
|---|---|---|
| KamLAND | 1000 t | 6%/√E |
| D. Chooz | 30 t | 8%/√E |
| RENO | 16 t | 8%/√E |
| Daya Bay | 20 t | 8%/√E |
| Borexino | 300 t | 5%/√E |
| JUNO | **20000 t** | **3%/√E** |

**MUST BE LARGER**

Sizable difference in collected light detector center vs detector edge

**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**
  - reactor antineutrino detection yields $\lambda \in [0.07, \sim 50]$ in JUNO

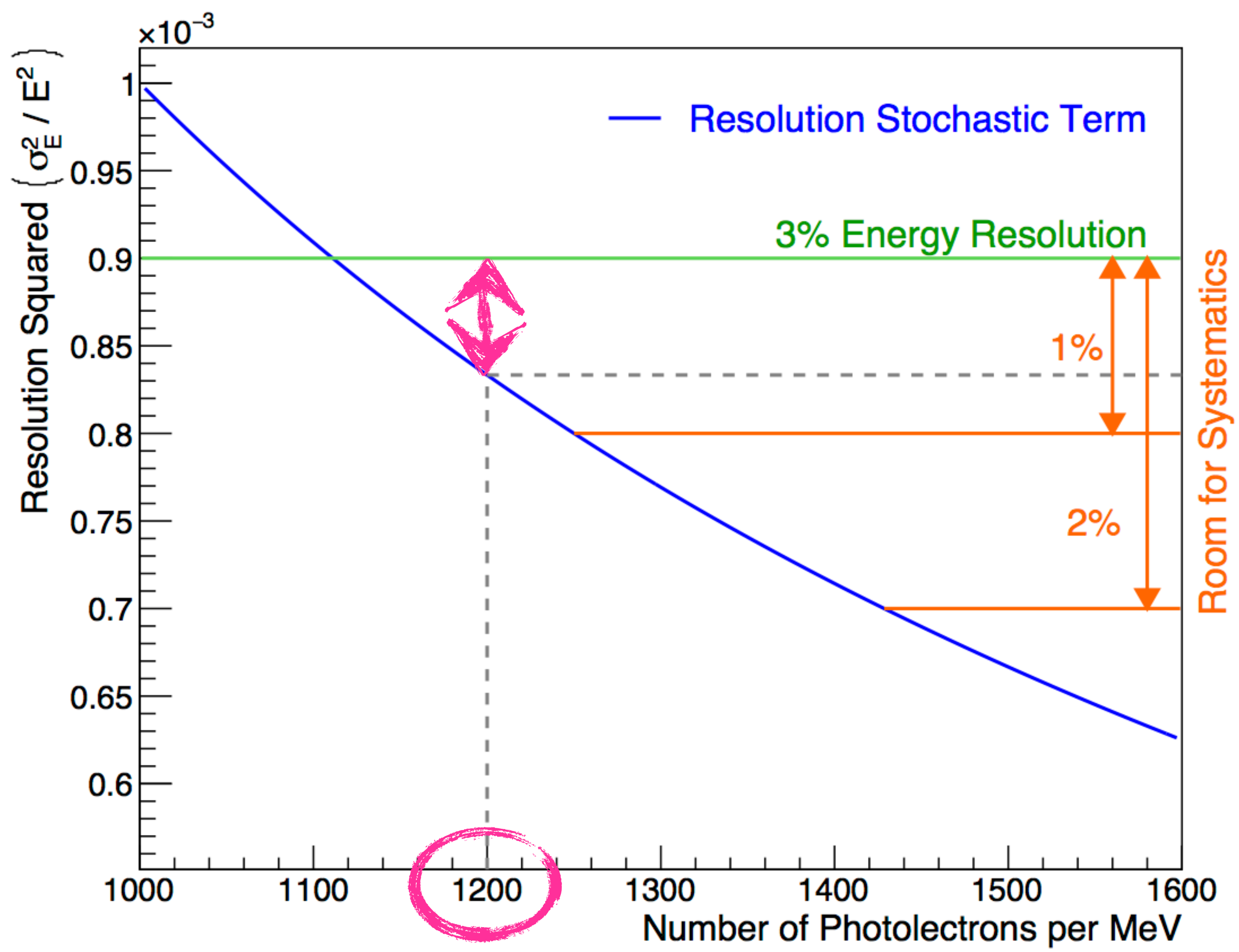

Deal with the detection of 1200 wild photoelectrons…

# JUNO Calorimetry

Light is not enough

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}}$$

**1 MeV Energy Deposition**




typical LS exp
$\sigma_{NST} \sim 2\%$

$\sigma_{NST}$ needs to be controlled at better than 1% level

Redundancy in systematics evaluation is pivotal

Double Calorimetry: born within JUNO

to better control / assess the resolution non-stochastic term

# Double Calorimetry in Action: Energy Reconstruction

$$E = f \times PE$$

$f$ : calibration

PE: raw detector response

ACCOUNTED FOR USING

**Uniformity** ← Position dependent

**Stability** ← Time dependent

**Linearity** ← Energy dependent

# Double Calorimetry in Action: Energy Reconstruction

$$E = f \times PE$$

$f$: calibration

PE: raw detector response

ACCOUNTED FOR USING

**Uniformity** ← Position dependent

**Stability** ← Time dependent

**Linearity** ← Energy dependent

Limited dynamic range
Nowadays σ(E)/E
(eg $\theta_{13}$ experiments)

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

EVALUATED INDEPENDENTLY

Wide dynamic range
Demanding σ(E)/E

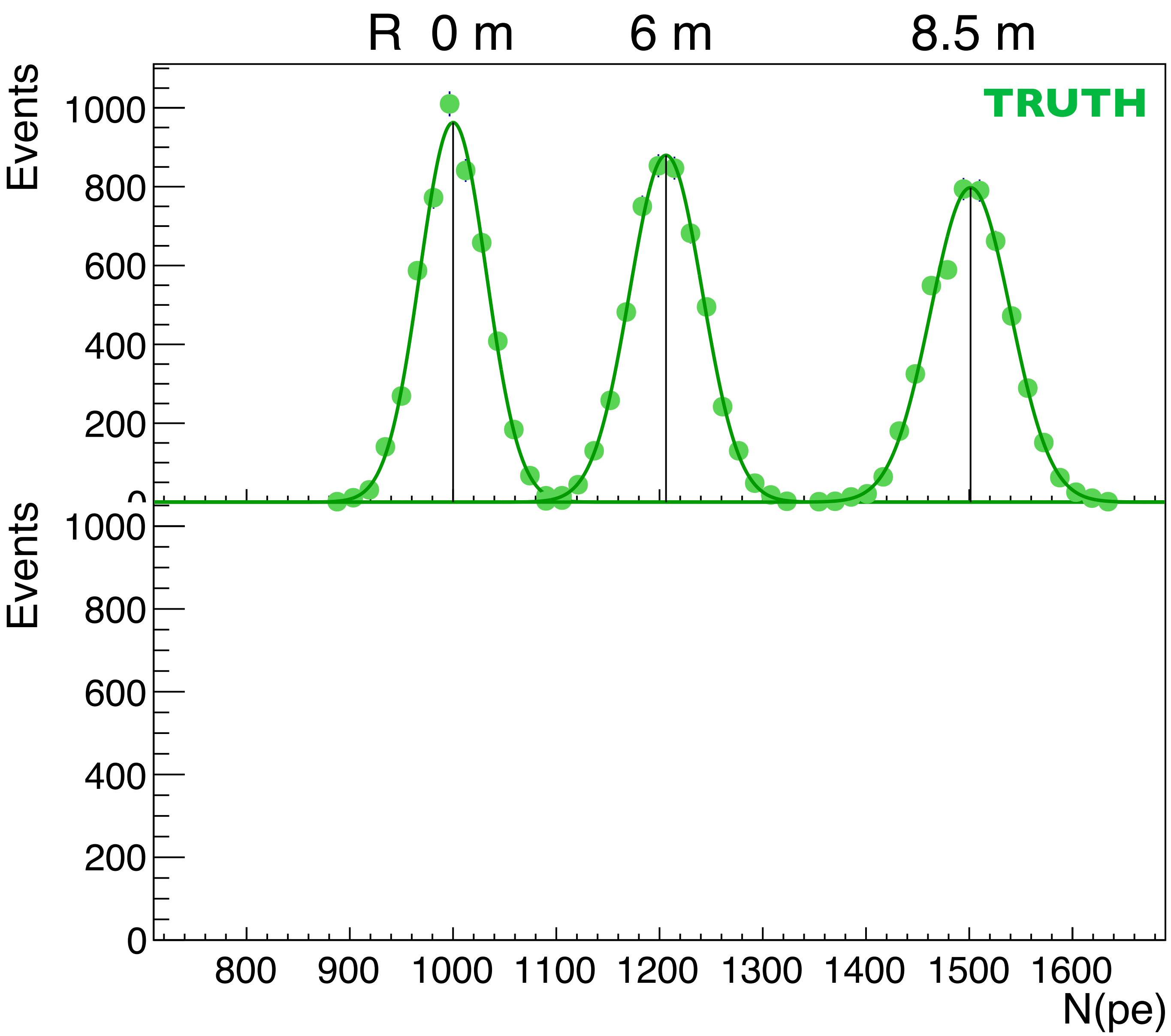
$$E\,[\mathrm{MeV}] = f^{\mathrm{ABS,\,U,\,S,\,L}}(r, t, PE) \times PE$$

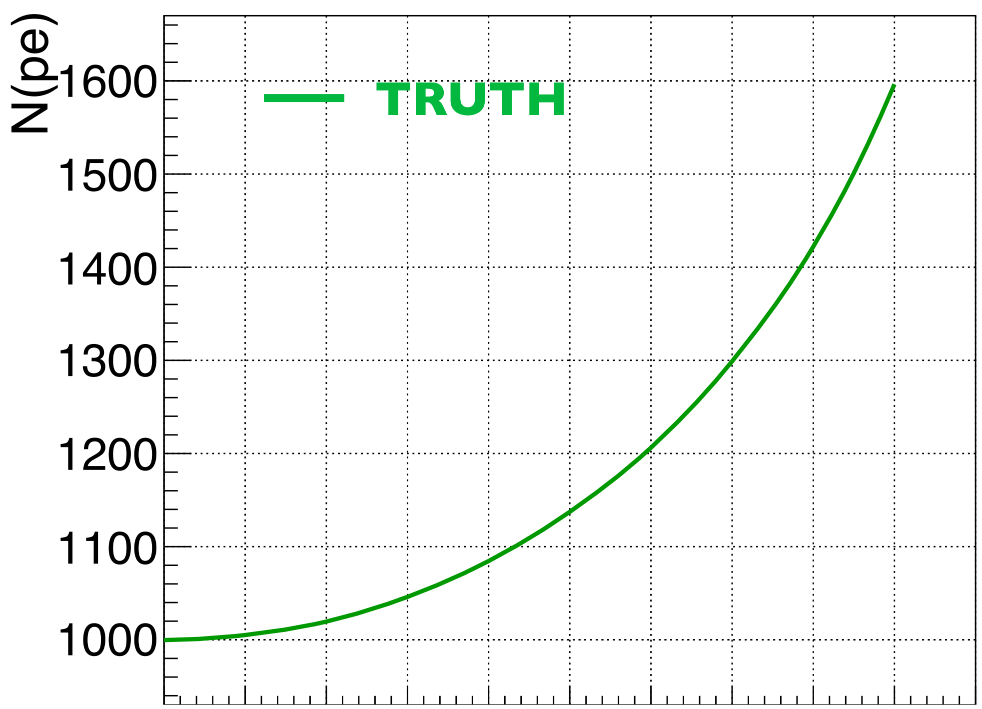
**Correlation** among $f$ terms might become relevant (degeneracy)

EXAMPLE ▶ ▶ ▶

# Correlation Among Calibration Terms (Illustration)

Deploy 1MeV calibration source at different positions (simulation)

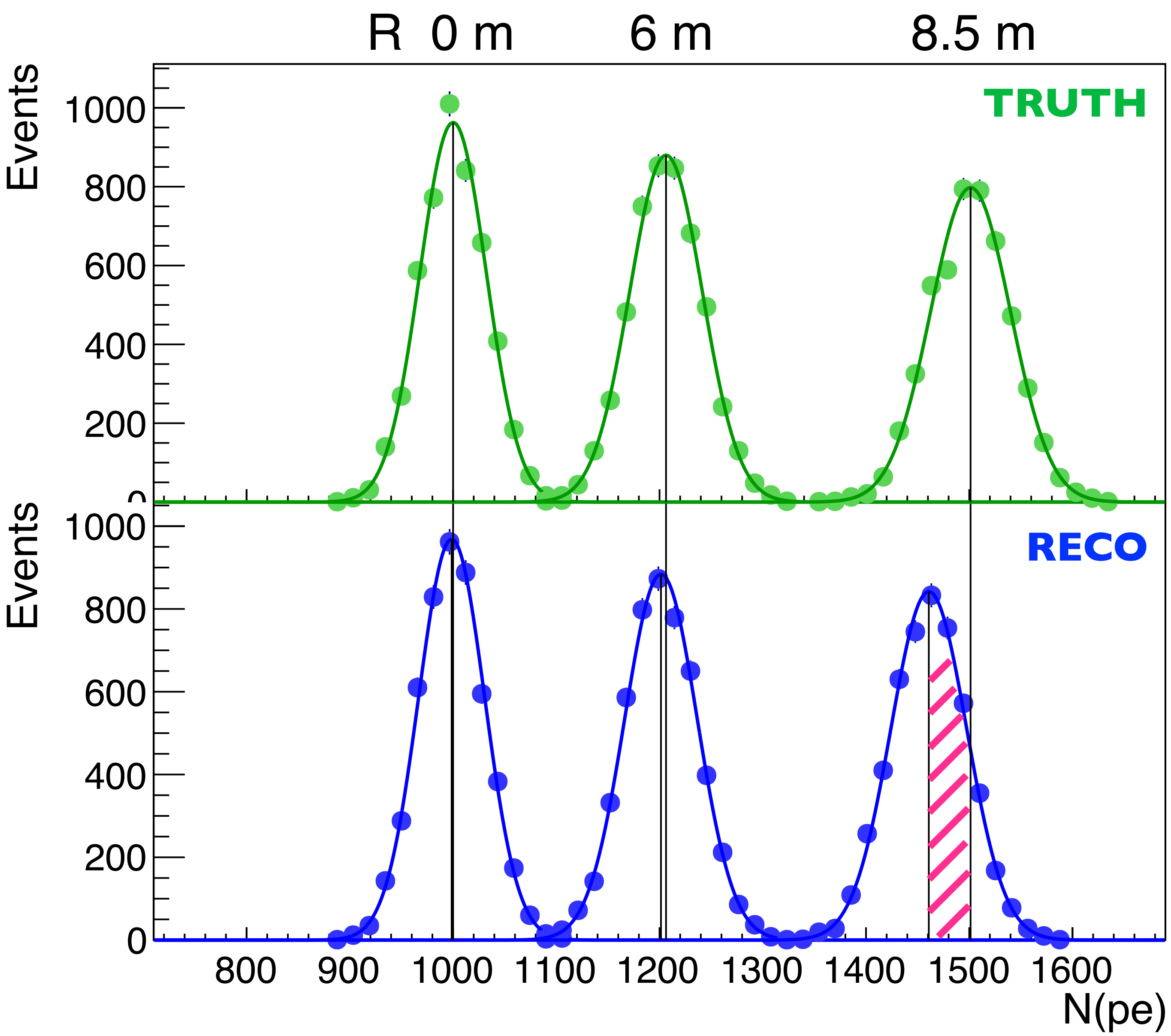


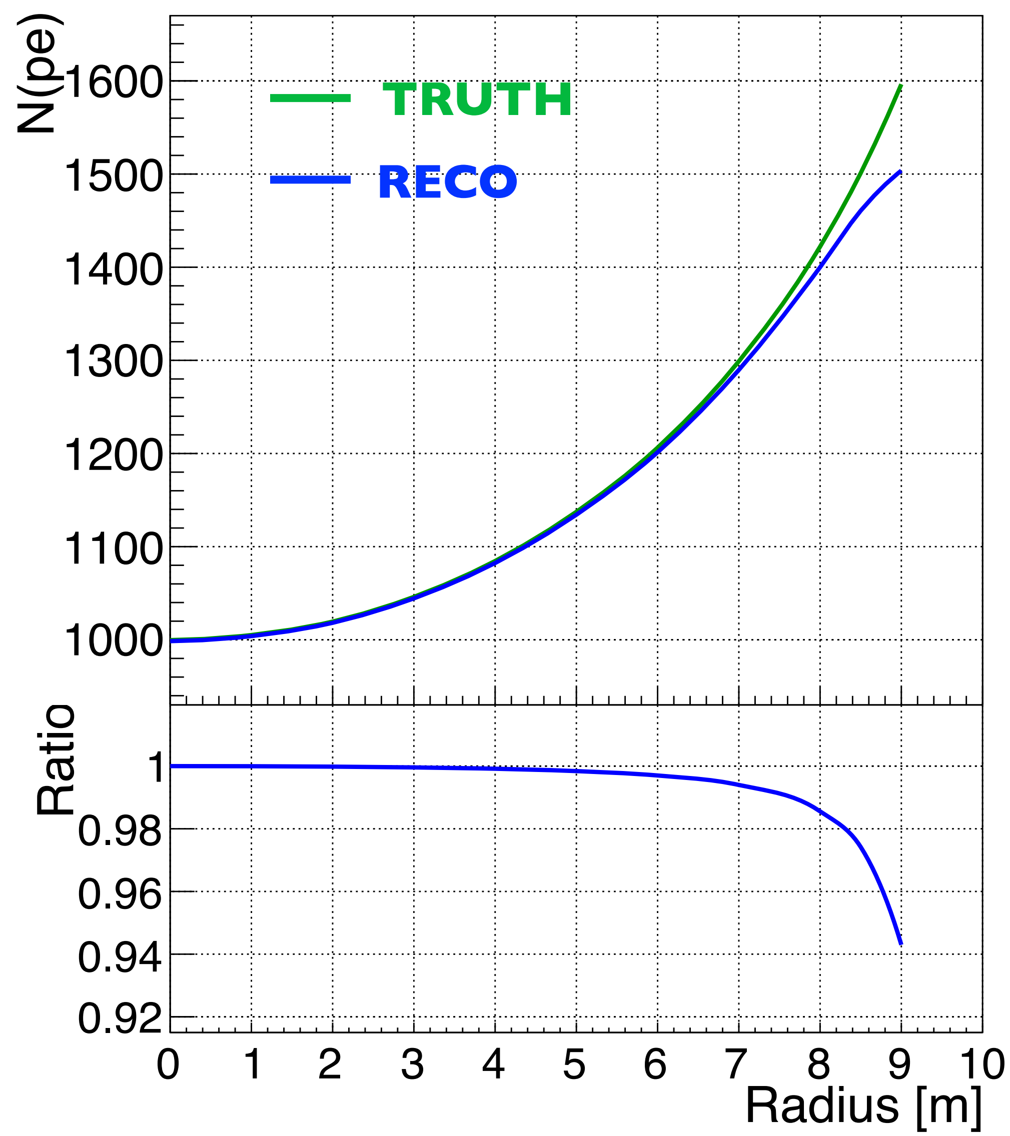




**TRUTH** : “Genuine” detector non-uniformity (geometry + LS attenuation)

# Correlation Among Calibration Terms (Illustration)

Deploy 1MeV calibration source at different positions (simulation)




**RECO**: Introducing a 1% bias for each detected pe

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

# Correlation Outcome

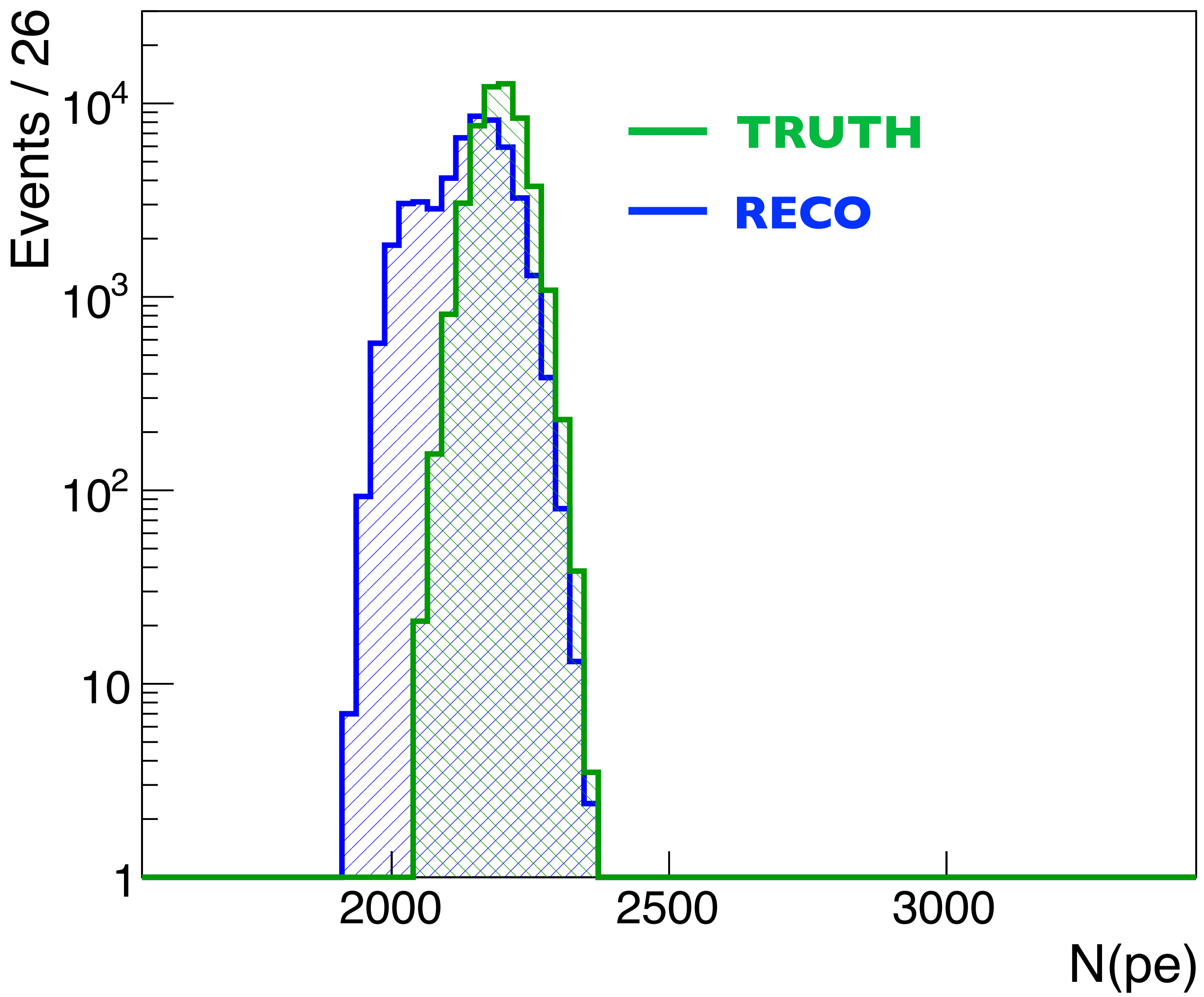
**Use response map derived at 1MeV**

Reconstruct 2.2 MeV gamma line from n captures on H

(uniformly distributed in the detector)

Actual resolution worse than intrinsic resolution

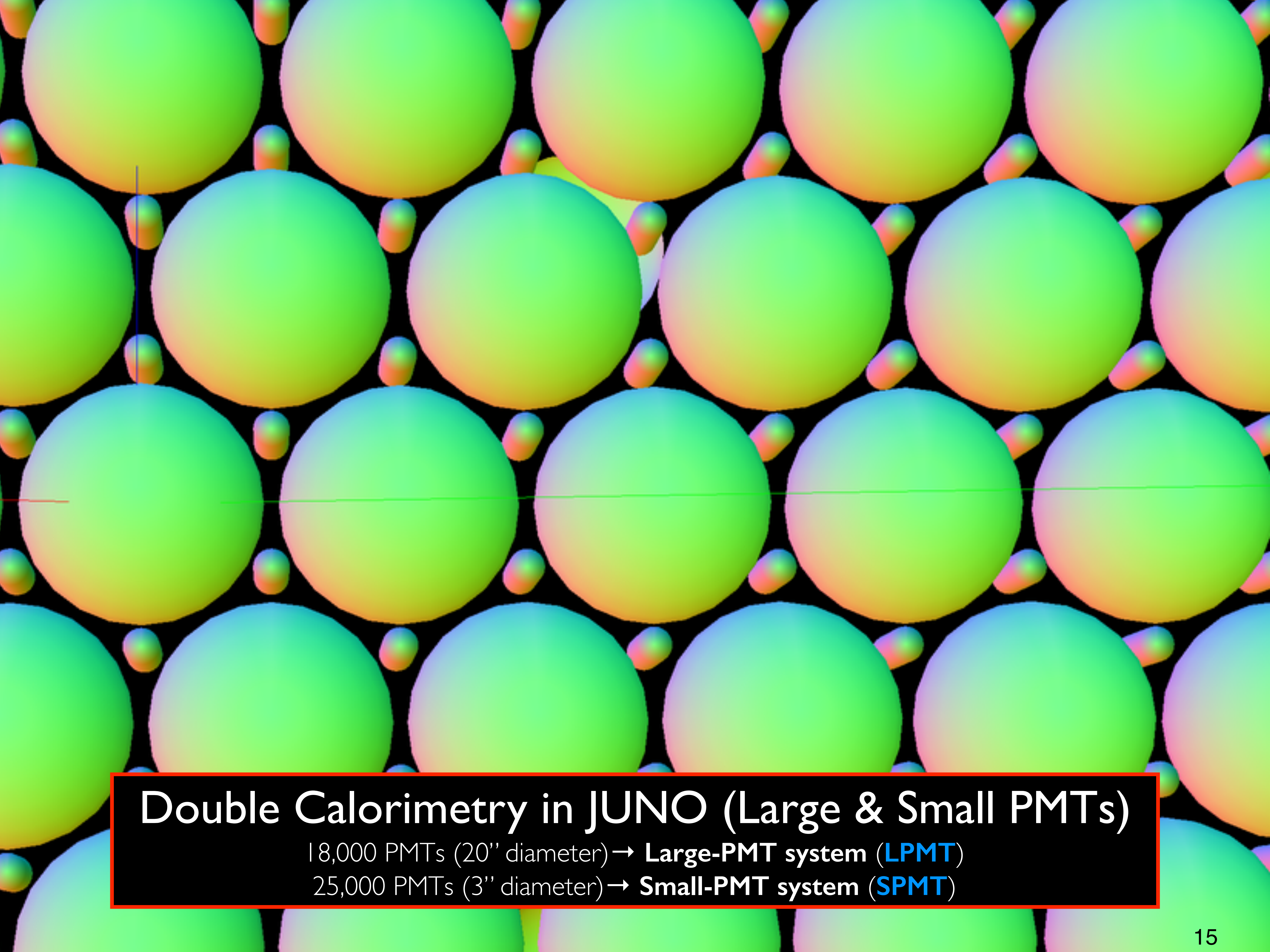
**$\sigma^2_{\text{NON-STOCH}}$ is dominant**




**Experimental Challenge**

Understand the source of additional resolution (& distortion)

How to break down systematic uncertainty budget?



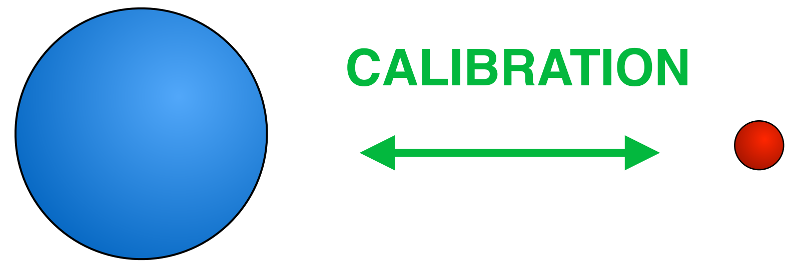
# Double Calorimetry in JUNO (Large & Small PMTs)

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

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

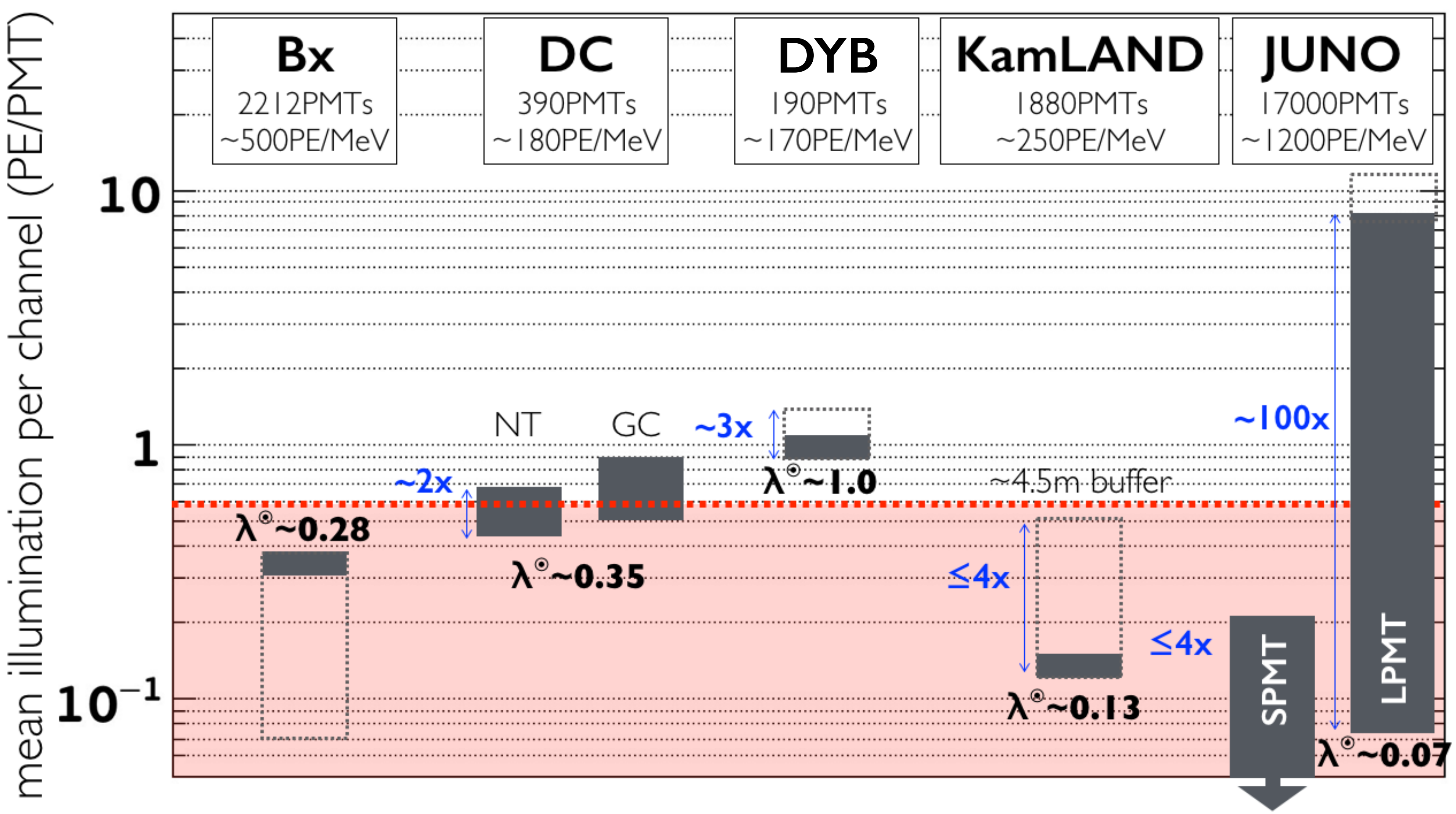
# Double Calorimetry in JUNO

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



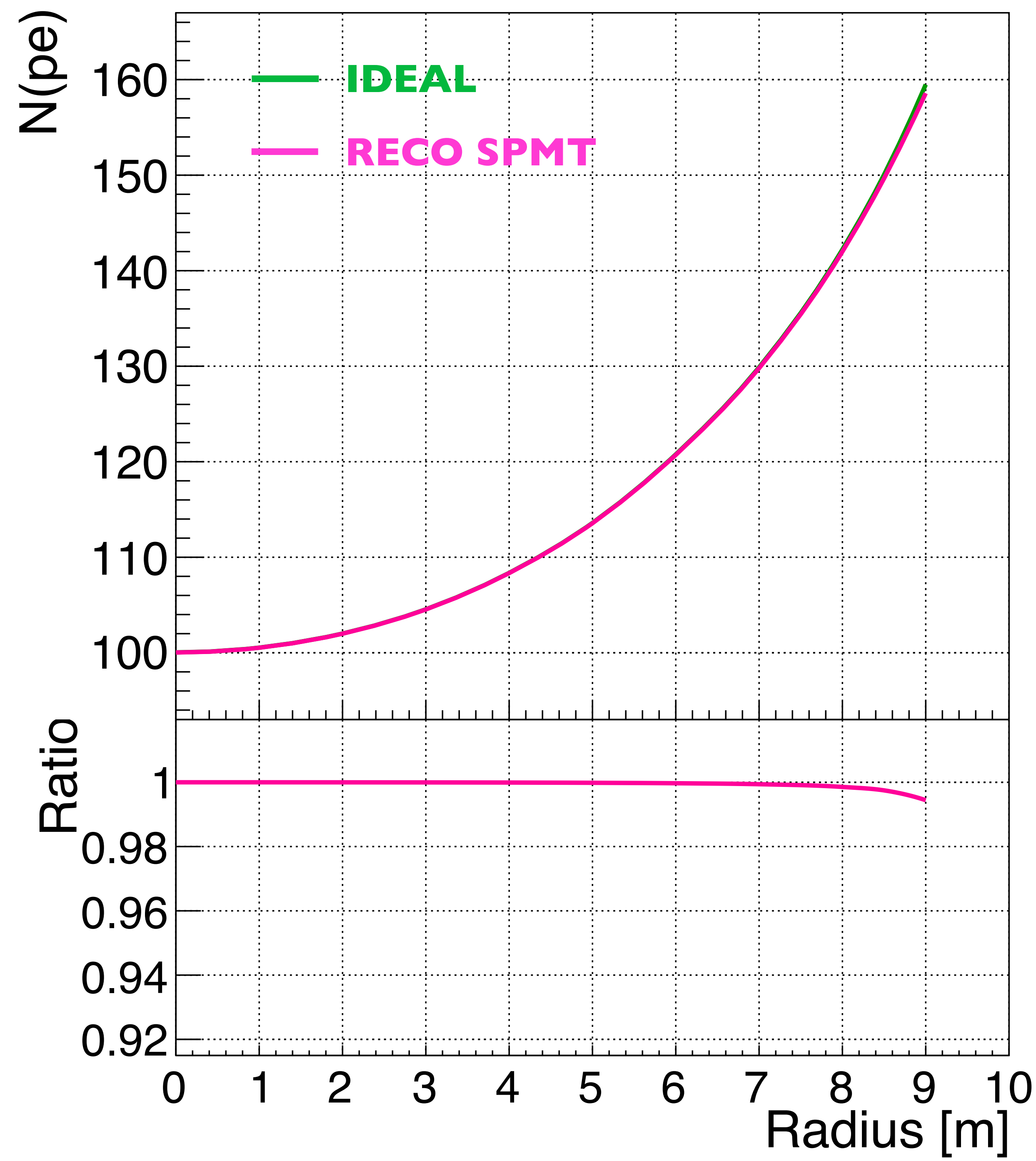

Small PMTs (SPMT)
3% photocoverage
50 PE/MeV
PE = hits

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



# Breakdown of the Non-Stochastic Resolution Term

Look at calibration data
**using SPMT**

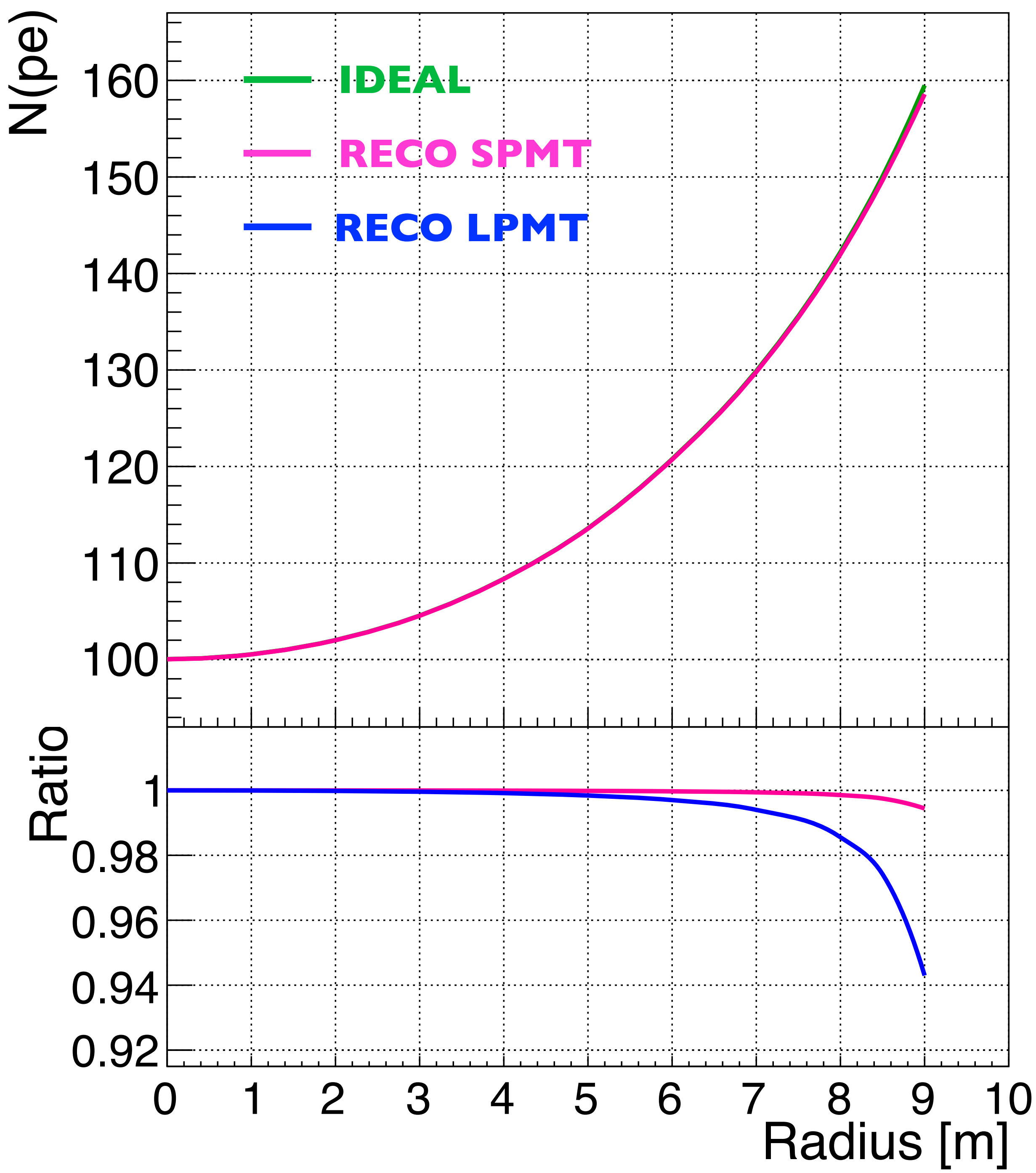


# Breakdown of the Non-Stochastic Resolution Term

Look at calibration data
**using SPMT**

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

SPMT provide a good reference
to understand LPMT response



# Breakdown of the Non-Stochastic Resolution Term

Look at calibration data
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Photon Counting Regime:
Negligible charge non-linearity
**Compared to LPMT**

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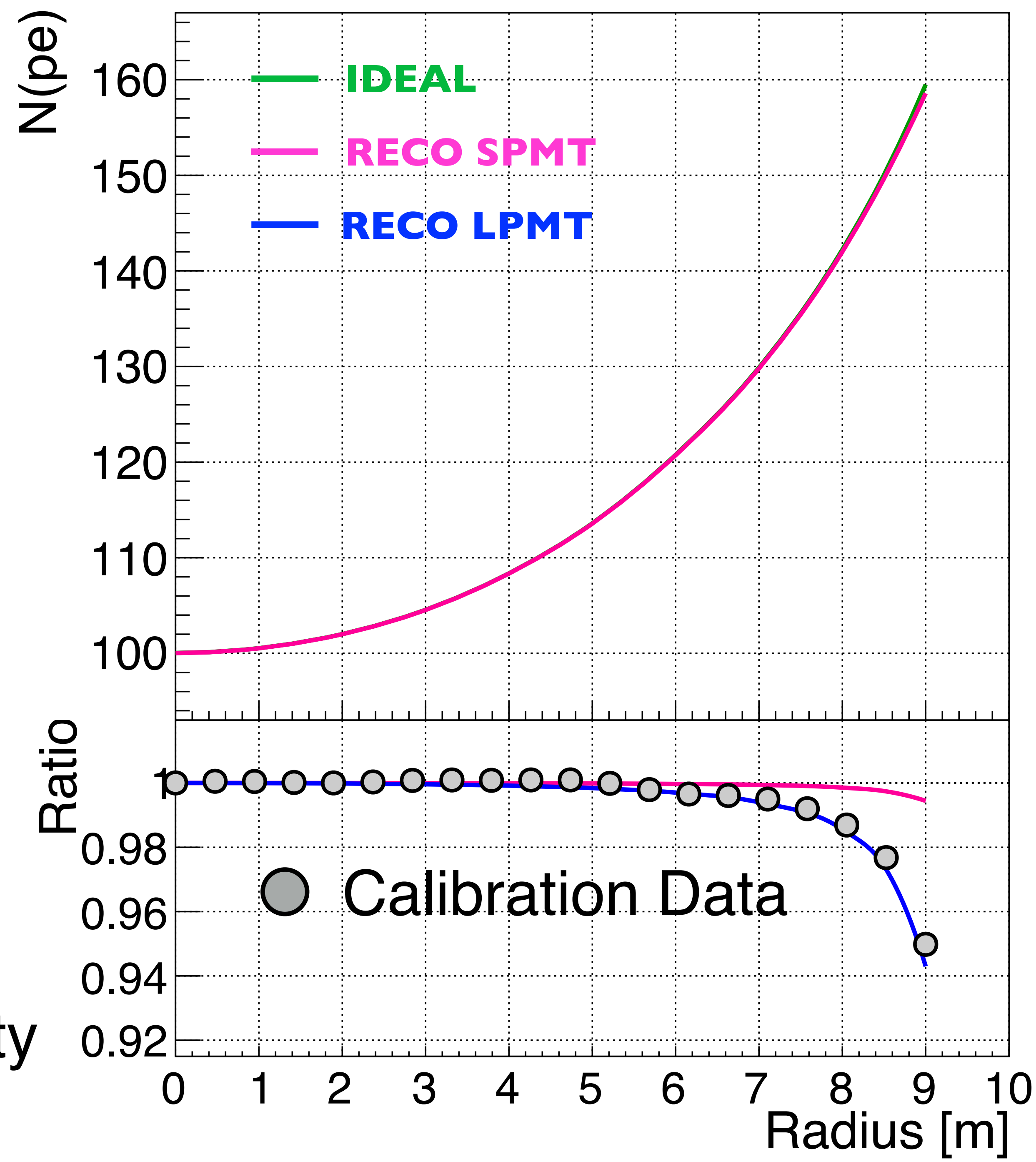
Ratio LPMT/SPMT " ● "

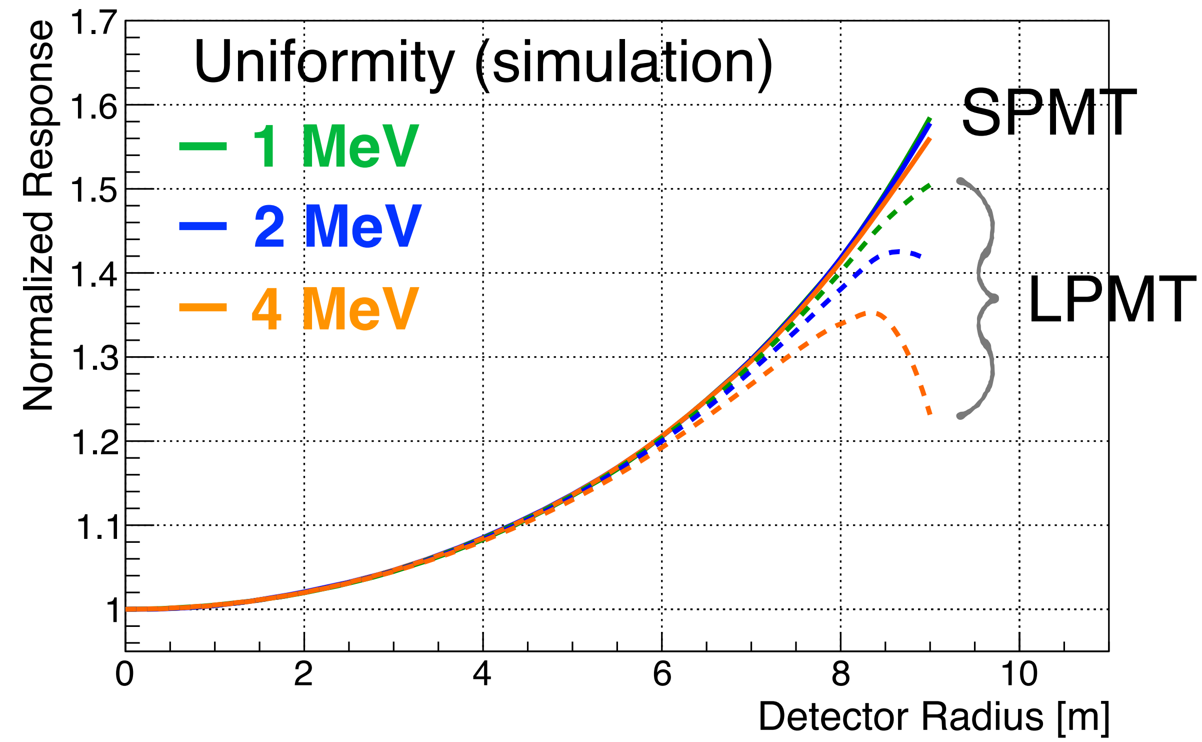
Extra resolution due to unaccounted charge non-linearity




**SPMT: resolve otherwise unresolvable response degeneracy**

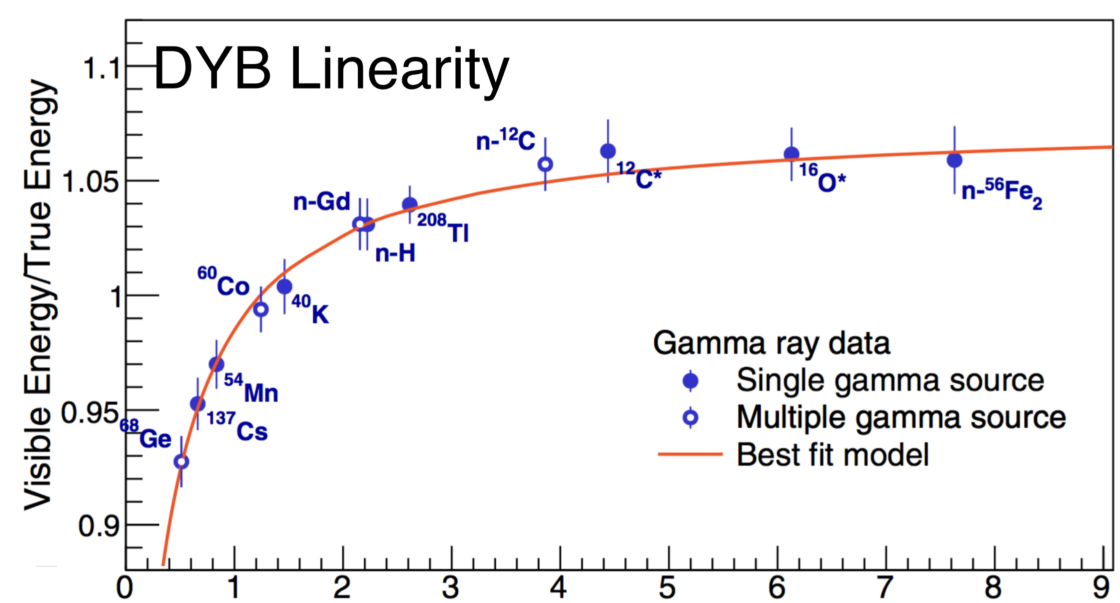
# Summary & Conclusions

Three **examples** of
Double Calorimetry in action




Detector **uniformity map**
valid at different energies

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




**Break correlation** among
calibration terms

**Redundancy: key ingredient to achieve high-precision calorimetry**