# Multi-Calorimetry in Light-based Neutrino Detector

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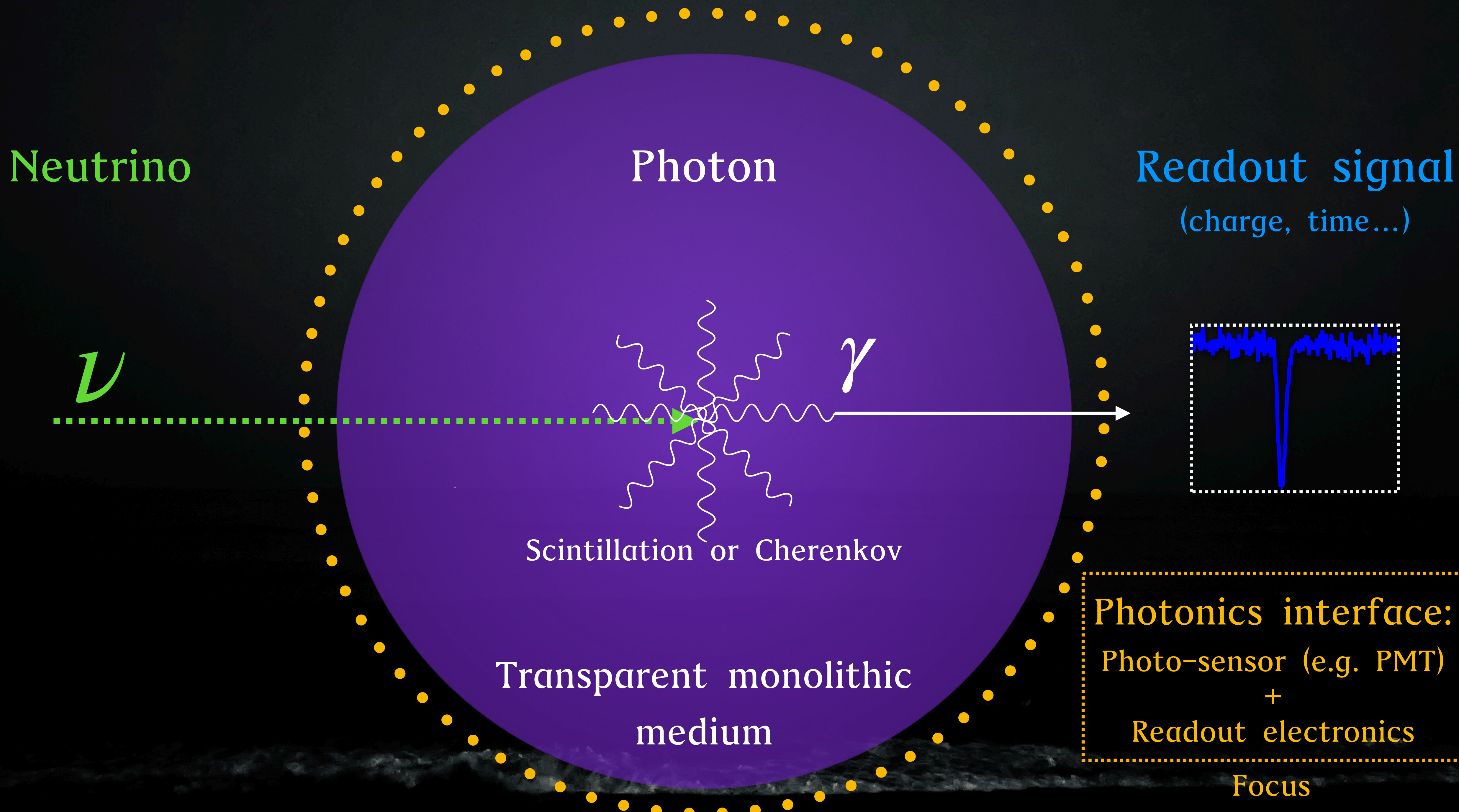
# In a light-based neutrino detector

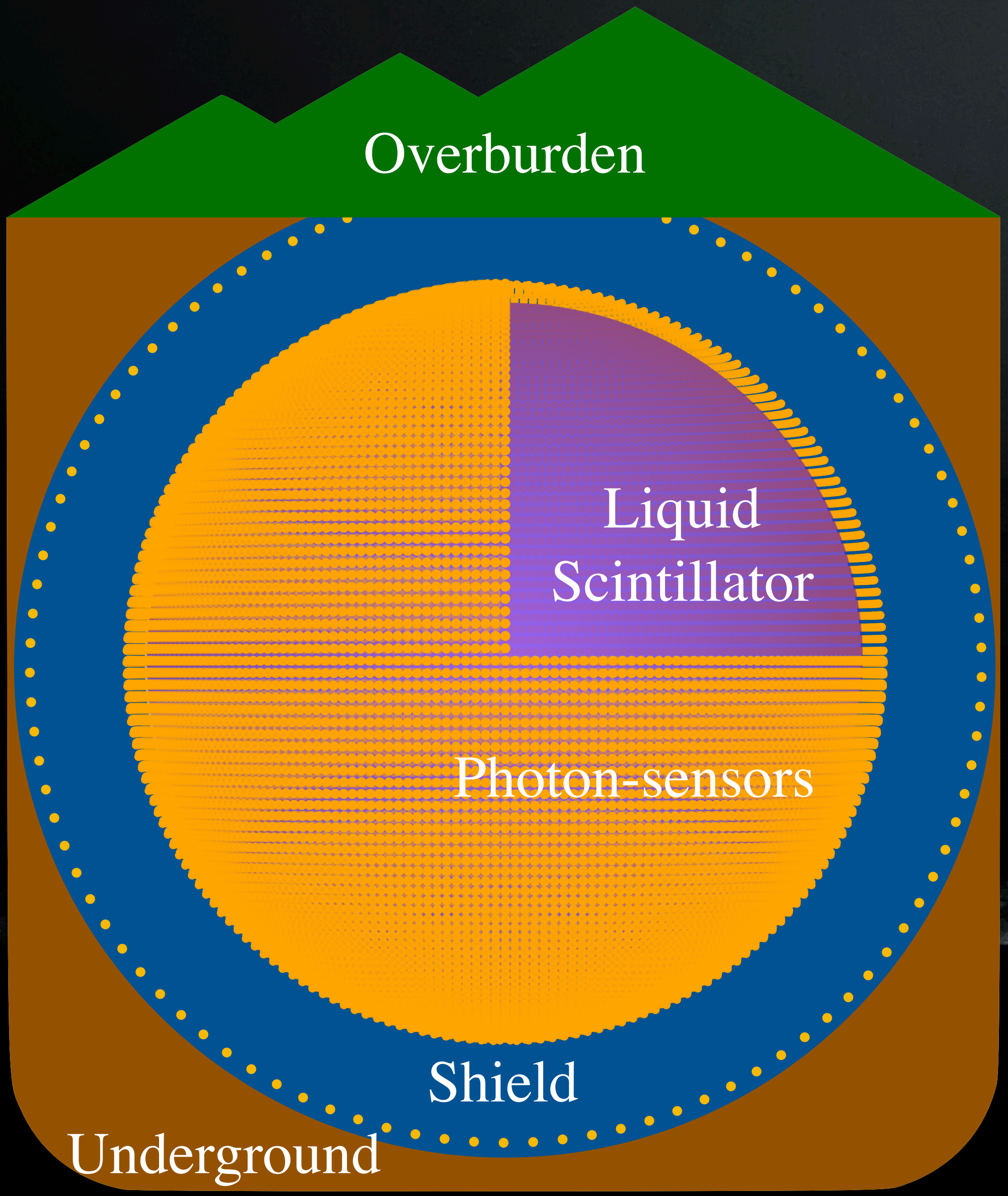



Advances in photonics interface contribute greatly to neutrino physics!

# Liquid scintillator detector (LSD)

One of the most widely used technology.

A typical monolithic LSD




Ideal calorimeter in MeV scale.

(Reactor neutrino, solar neutrino, geo-neutrino, $0\nu\beta\beta$ ...)

(LSD energy range: tens of keV to GeV)

LSD:

- More light w.r.t. only Cherenkov light: $O(10^2)$~$O(10^3)$ photon detected per MeV
- Higher energy resolution: up to % level @ 1MeV
- Lower energy threshold: down to ~tens of keV

Discussion based on calorimetry

(energy measurement)

in LSD in this talk.

(Other detectors, e.g. water Cherenkov, may benefit.)

# Calorimetry in LSD

## Calorimetry response:

Systematics from 3 types of effects

**Non-Linearity (NL)**

- Light non-linearity i.e. NL(l):
  Quenching and Cherenkov.
- Charge non-linearity i.e. NL(q):
  Photo-sensors, readout electronics, reconstruction and their interfaces. In-situ measurement is important.

**Non-Uniformity (NU)**

- Detector geometry and optical effects. Position-dependent.

**Non-Stability (NS)**

- Changes in time w.r.t. temperature, detector medium evolution, and readout configuration.

Overall: $R = R_o \cdot \alpha_{NU} \cdot \alpha_{NS} \cdot \alpha_{NL}$

$R$ : response $\alpha_i$ : normalized NU, NS and NL terms
$R_o$ : reference

$\alpha_{NL} \rightarrow \alpha_{NL(l)} \otimes \alpha_{NL(q)}$ Delicate & Challenging

Ideally: $\alpha_{NU} \otimes \alpha_{NS} \otimes \alpha_{NL} = 0$ ("orthogonality") → Independent precise control of each term.

Realistic complex scenarios with Response Entanglement can lead to:

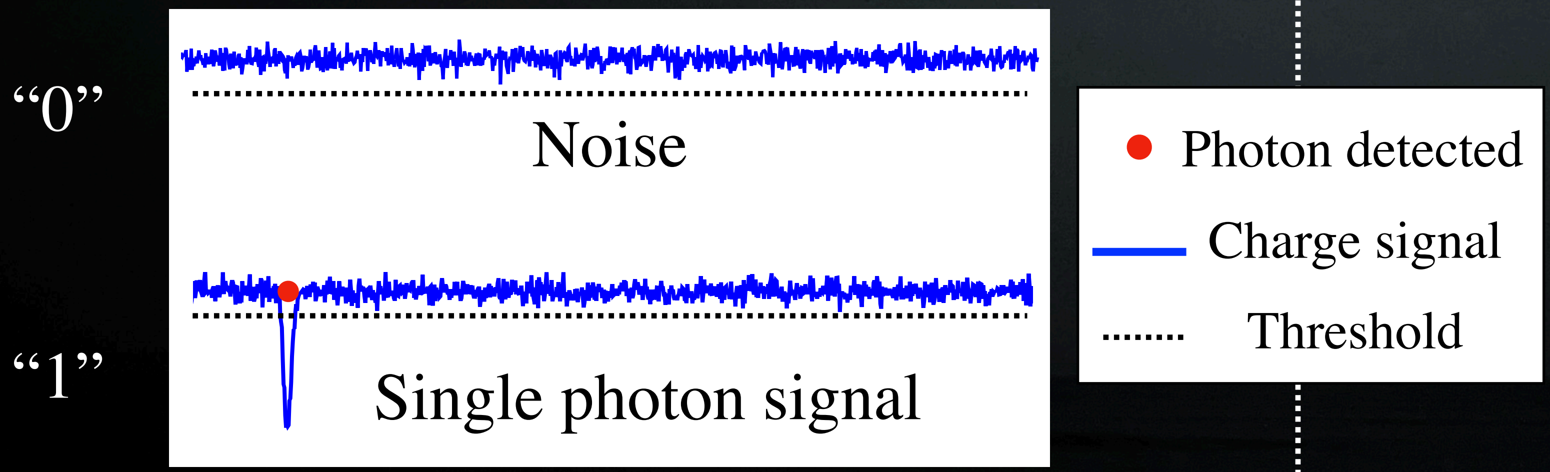
$\alpha_{NU} \otimes \alpha_{NS} \otimes \alpha_{NL} \neq 0$ → Challenge of systematics control !

# Calorimetry regimes

Energy measurement → Detection of photons → Direct observable: charge signal

## Photon-counting regime (PCR)

(Single-photon detection dominant)

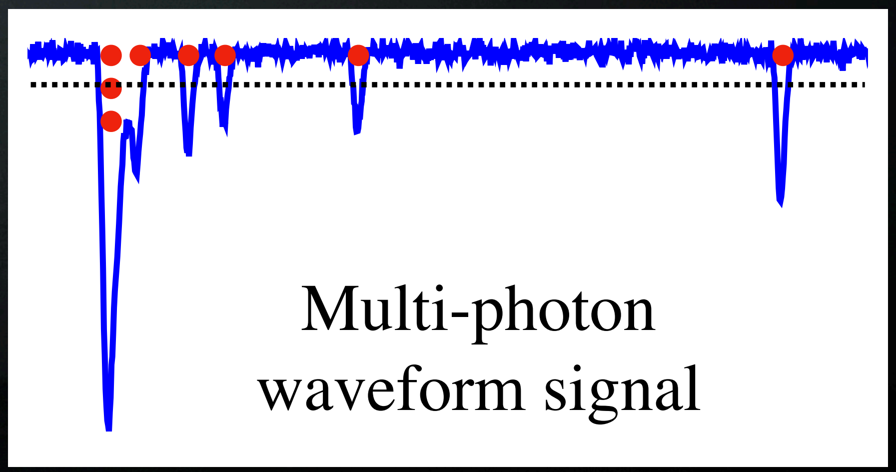



$\alpha_{NL(q)} \to 1$

- A discriminator for single-photon and noise.
- Photon directly counted. Digital "0" or "1".
- Immune to charge measurement and its systematics → robustness !
- Smaller photo-sensor → More channels

## Photon-integration regime (PIR)

(Multi-photon hit)




$\alpha_{NL(q)}$ !

- Sampling the signal pulse waveform and integrating over time.
- Photons indirectly inferred via e.g. waveform
- Charge measurement systematics and biases .
- Larger photo-sensor → Less channels

More channels traditionally lead to higher cost.

(Situation may change along the technology development.)

# Channel-wise light level

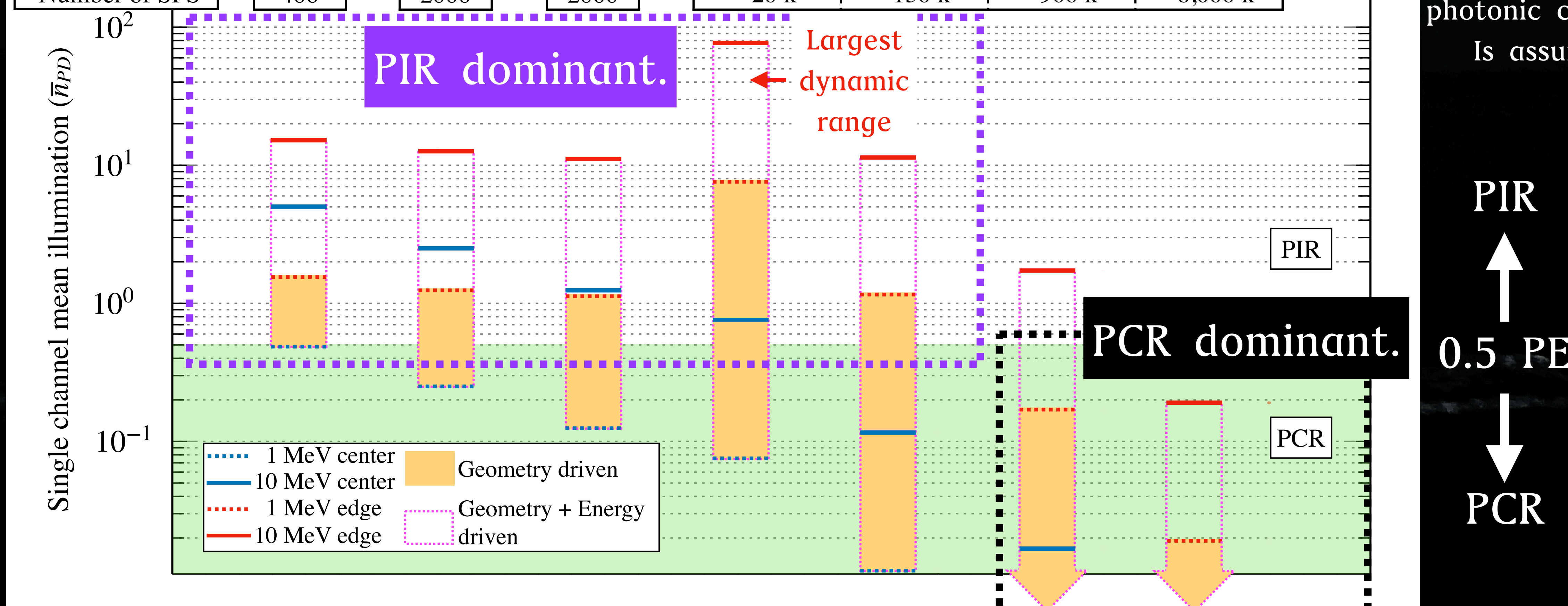
Average detected photons in single photo-sensor (SPS)

(Driven by energy of interest, detector geometry and SPS dimension.)

Hypothetical LSDs:

| LSD-S | LSD-M | LSD-L | LSD-XL |
|---|---|---|---|
| (reactor $\theta_{13}$-like) | (Borexino-like) | (KamLAND-like) | (JUNO-like) |

| | LSD-S | LSD-M | LSD-L | LSD-XL | | | |
|---|---|---|---|---|---|---|---|
| Detector size (m³) | ~10 | ~300 | ~1,000 | ~20,000 | | | |
| $N_{PD}$ per MeV | 200 | 500 | 250 | 1500 | | | |
| SPS dimension | 8-inch | 8-inch | 20-inch | 20-inch | 8-inch | 3-inch | 1-inch |
| Number of SPS | 400 | 2000 | 2000 | ~20 k | ~130 k | ~900 k | ~8,000 k |




Number of SPS, for LSD-XL, 80% photonic coverage Is assumed.

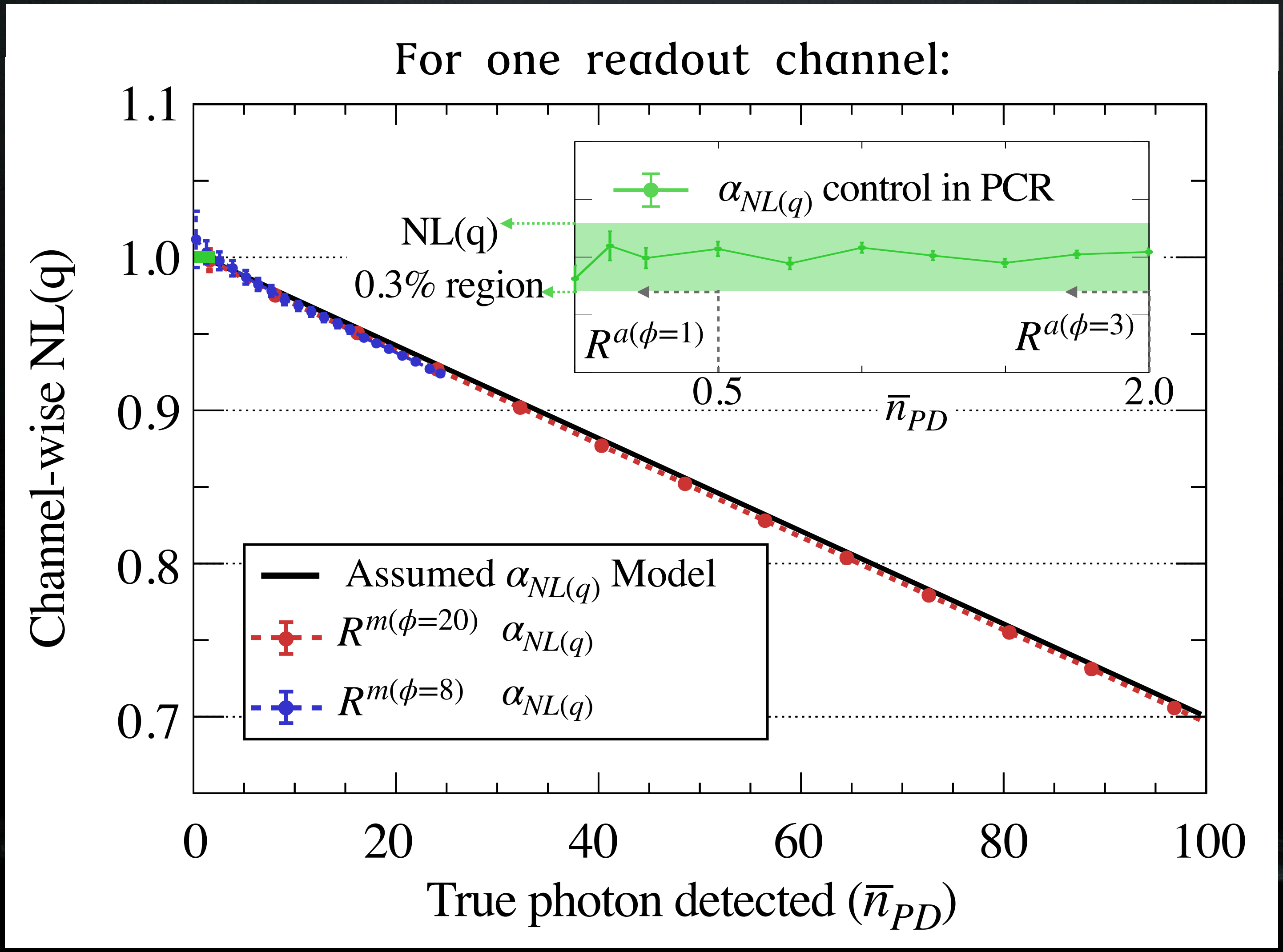
# Single Calorimetry LSD

Most LSD experiments so far !

$$R = R_o \cdot \alpha_{NU} \cdot \alpha_{NS} \cdot [\alpha_{Nl(l)} \otimes \alpha_{NL(q)}]$$ Delicate & Challenging

Take LSD-XL as an example (MC):

4 SPS configs:
- PIR: 20-inch
- PIR: 8-inch
- PCR: 3-inch
- PCR: 1-inch




By assuming the same NL(q) model,

In PCR: *$\alpha_{NL(q)} \to 1$, orthogonality! (see next)

In PIR: $\alpha_{NL(q)}$ matters. Response entanglement! (see next)

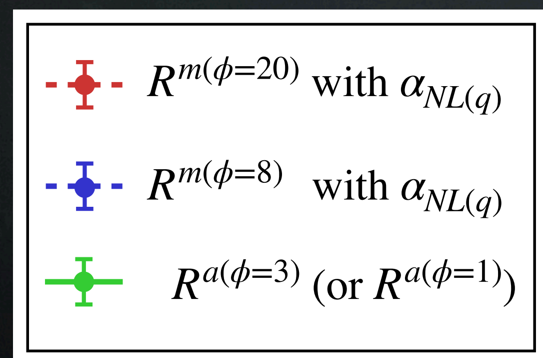
*upon corrections based on Poisson statistic feature.

# Entanglement in PIR; Orthogonality in PCR

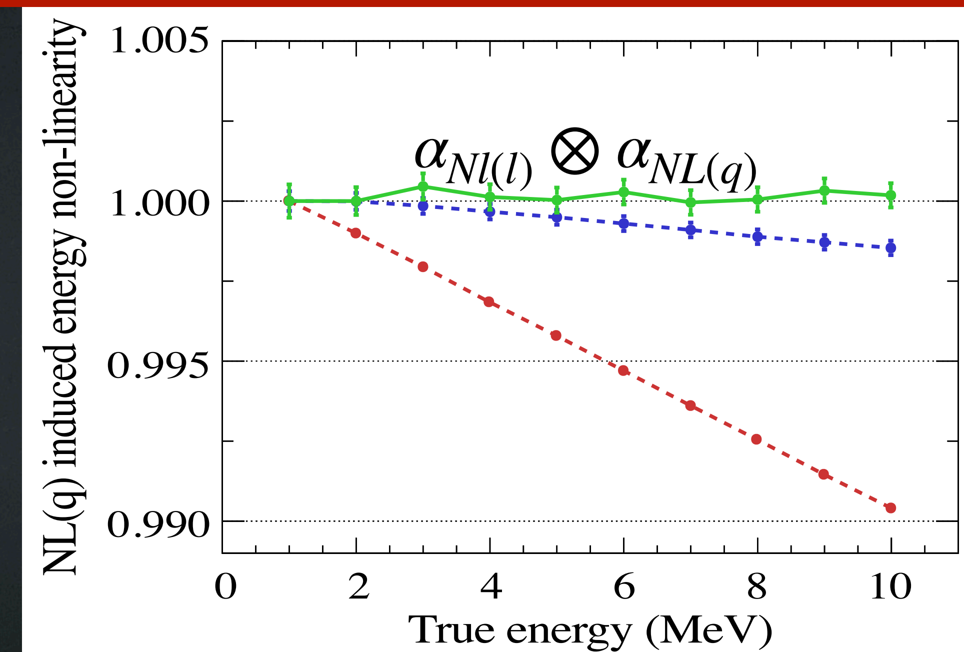
Channel-wise $\alpha_{NL(q)}$ impacts:

$$\alpha_{NU} \otimes \alpha_{NS} \otimes (\alpha_{NL(l)} \otimes \alpha_{NL(q)}) \neq 0$$

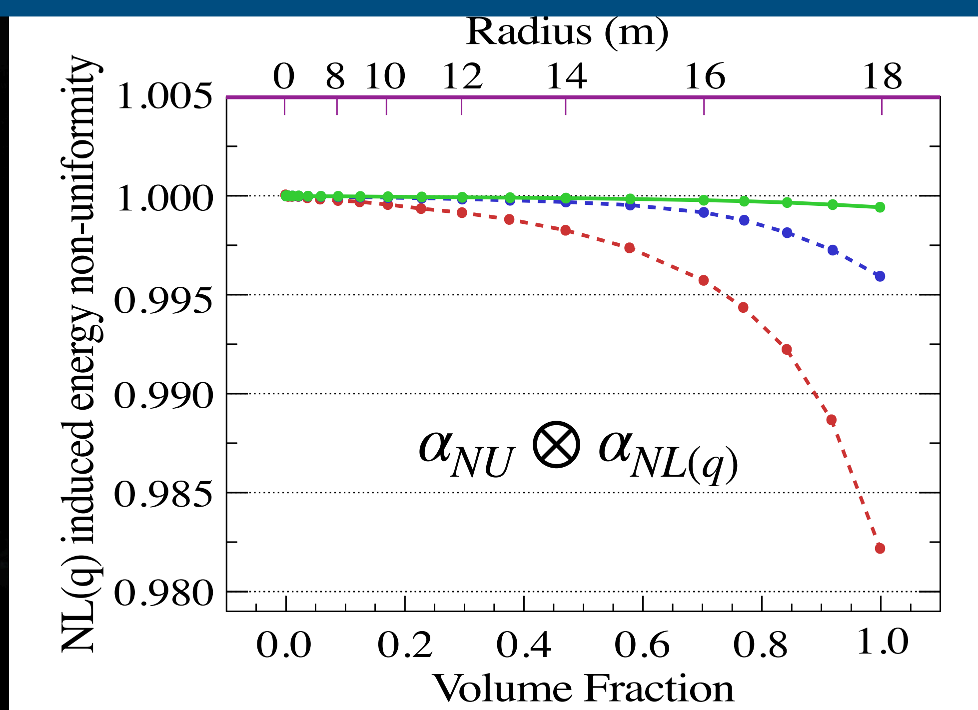
LSD-XL



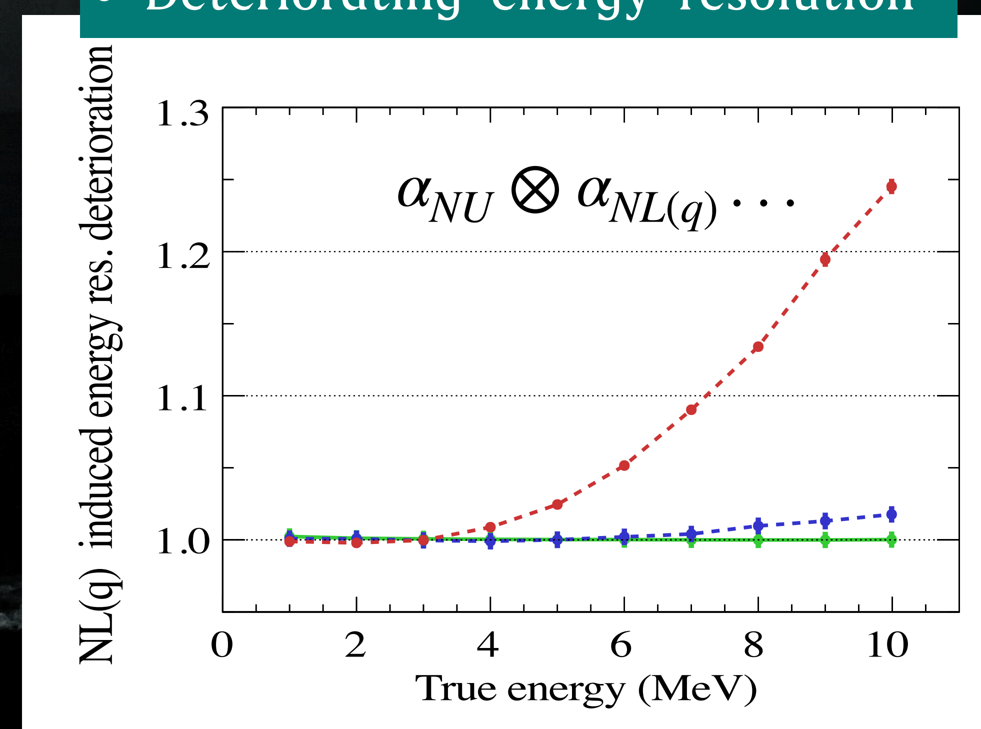

- Convolving into event-wise energy non-linearity




- Entangling with energy non-uniformity




- Deteriorating energy resolution




**Consequently deteriorating PIR calorimetry precision!**

(Beyond traditional calibration due to large $\alpha_{NU} \otimes \alpha_{NS} \otimes \alpha_{NL}$ phase space to be covered!)

While PCR is not reachable,

(e.g. sometimes not cost-effective for large detector)

PIR is the design.

↓

Stringent systematics (e.g. permille) control over large(st) photon dynamic range in PIR.

↓

How to improve the calorimetry design for more precise energy measurement?

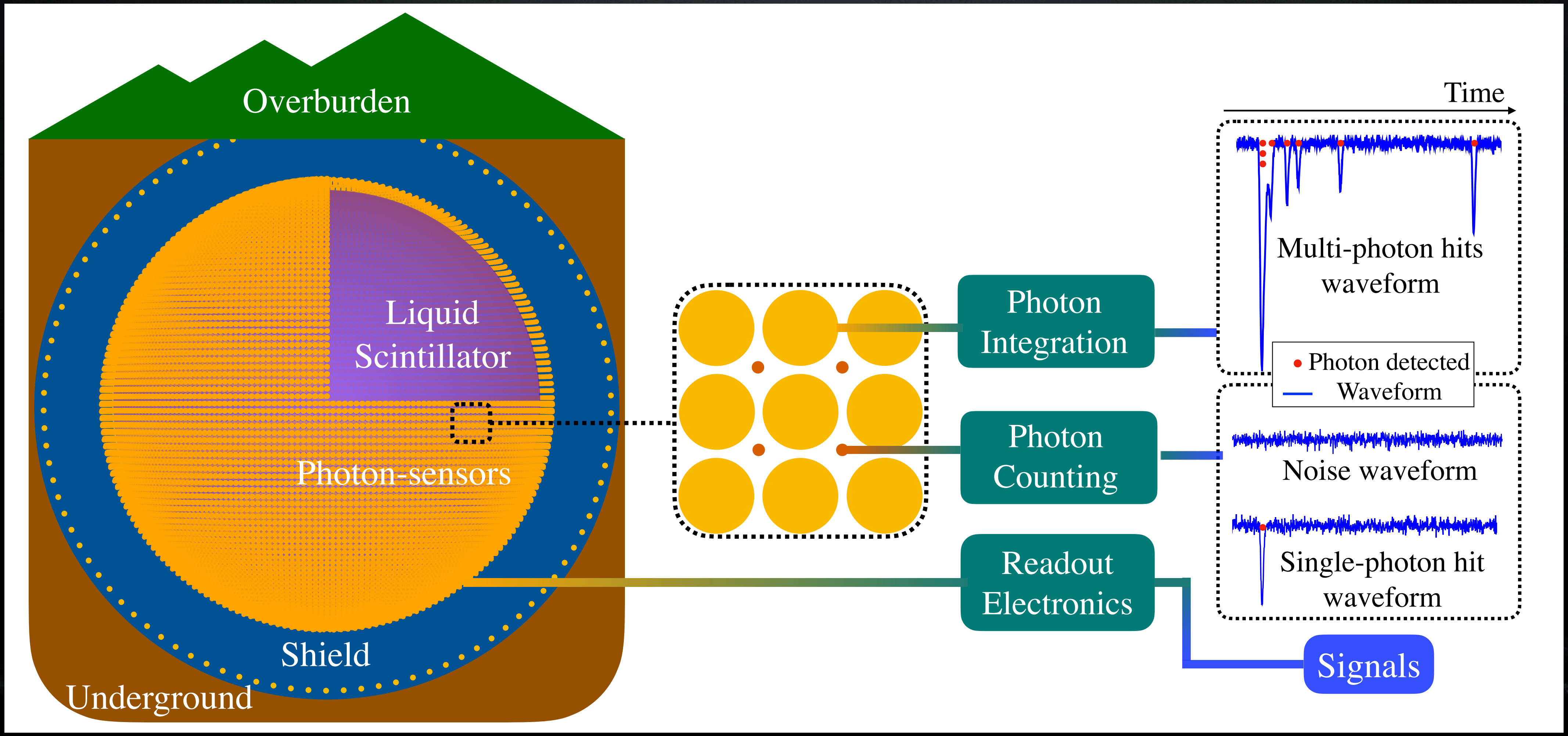
↓

Multi-Calorimetry!

# Multi-Calorimetry

For a common detection medium
*Holding PIR photonics interface as main calorimetry ($R^m$).
#Adding PCR photonics interface as auxiliary calorimetry ($R^a$).

One PIR and one PCR in a single LSD → Dual calorimetry




Exploiting synergy between PIR and PCR in single detector to achieve high precision calorimetry.

*For e.g. cost-effectiveness.
#No need high coverage.

# Synergy in Multi-Calorimetry LSD

- PIR and PCR connected by viewing same events

  → correlated NU, NS and NL(l) and uncorrelated & different NL(q)

- Robust NL(q) control in PCR ($\alpha_{NL(q)} \to 1$),

  auxiliary PCR: $R^a = R^a_o \cdot \alpha^a_{NU} \cdot \alpha^a_{NS} \cdot \alpha^a_{Nl(l)}$ ; $\alpha^a_{NU} \otimes \alpha^a_{NS} \otimes \alpha^a_{NL} = 0$, orthogonal reference

  while main PIR: $R^m = R^m_o \cdot \alpha^m_{NU} \cdot \alpha^m_{NS} \cdot [\alpha^m_{Nl(l)} \otimes \alpha^m_{NL(q)}]$

- PIR and PCR comparison:

$$\frac{R^m}{R^a} = \frac{R^m_o \cdot \alpha^m_{NU} \cdot \alpha^m_{NS} \cdot [\alpha^m_{Nl(l)} \otimes \alpha^m_{NL(q)}]}{R^a_o \cdot \alpha^a_{NU} \cdot \alpha^a_{NS} \cdot \alpha^a_{Nl(l)}}$$

$$\to \frac{R^m}{R^a} = \frac{R^m_o}{R^a_o} \cdot \alpha^m_{NL(q)}$$

Cancellation upon optimal strategy with calibration. (with sources like laser/ led, radioactive sources, and even physics signal.)

- Enable powerful in-situ channel-wise $\alpha^m_{NL(q)}$ control. (via reconstruction and calibration).
- Spot unknown readout systematics.

# MC demonstration

LSD-XL dual-calorimetry:

Config. I.

Main PIR: $R^{m(\phi=20)}$ (15k SPS)

Auxiliary PCR: $R^{a(\phi=3\ or\ 1)}$ (50k/100k SPS)

Config. II.

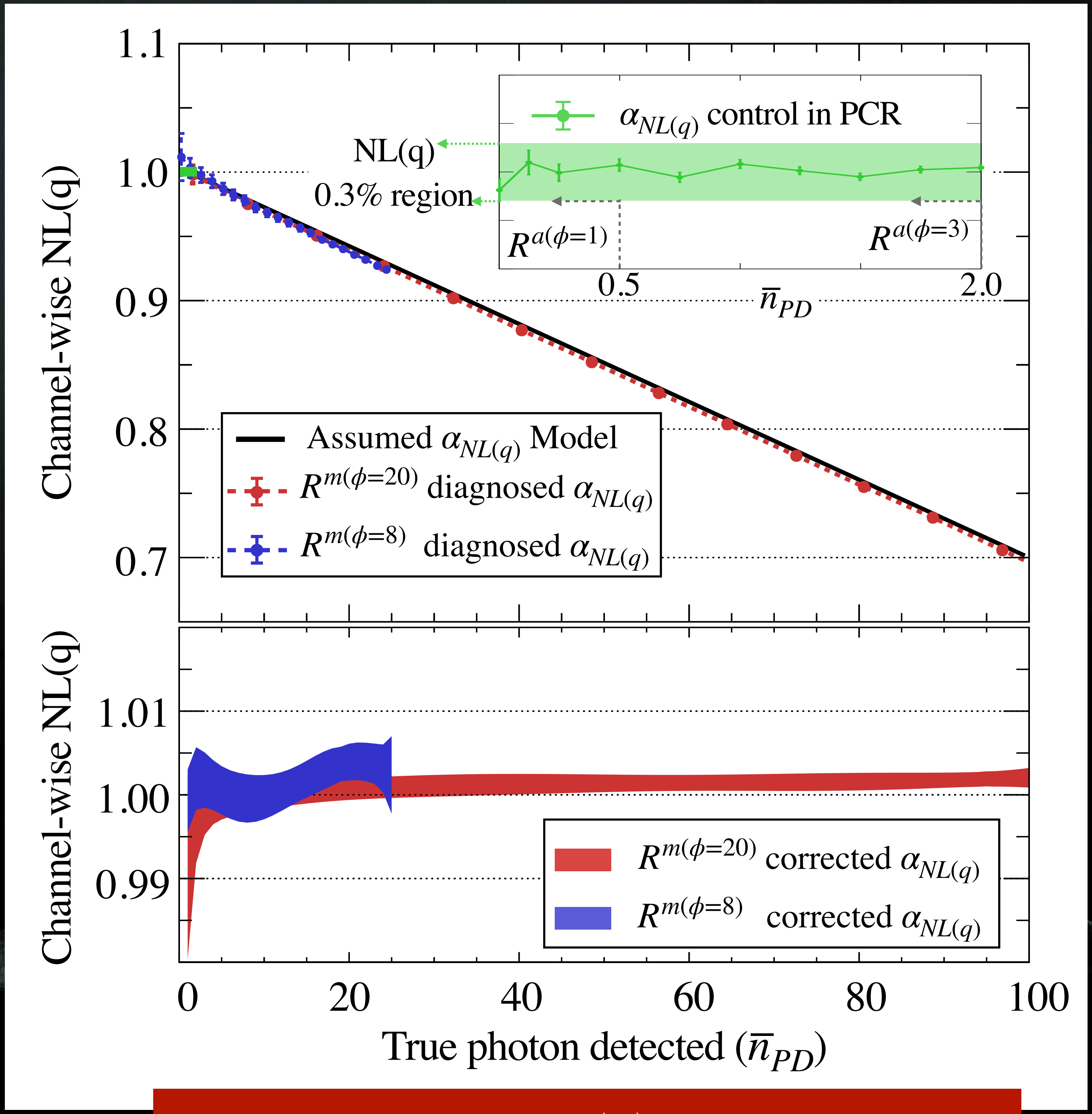
Main PIR: $R^{m(\phi=8)}$ (100k SPS)

Auxiliary PCR: $R^{a(\phi=3\ or\ 1)}$ (50k/100k SPS)

Detailed methodology

in tel-03295420

Direct NL(q) control with multi-calorimetry




**Per-mille level NL(q) control in PIR even with largest dynamic range!**

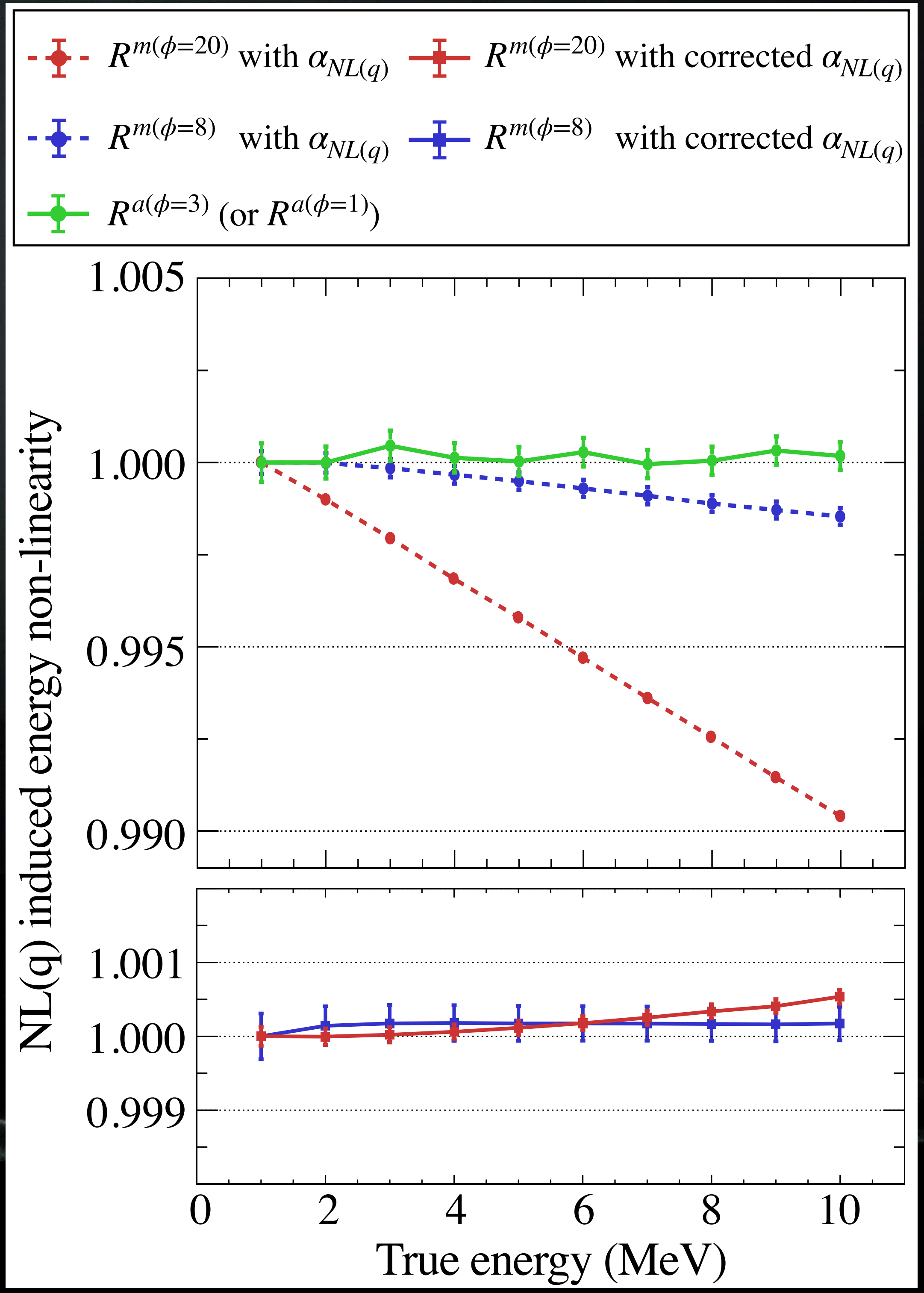
# MC demonstration: NL Disentangling

**Entanglement:**
channel-wise $\alpha_{NL(q)}$ convolving into event-wise energy non-linearity.

After $\alpha^{m}_{NL(q)}$ correction with multi-calorimetry

**Disentangling:**
control of $\alpha_{NL(q)}$ induced energy non-linearity to permille level !

$\alpha_{Nl(l)} \otimes \alpha_{NL(q)} = 0$

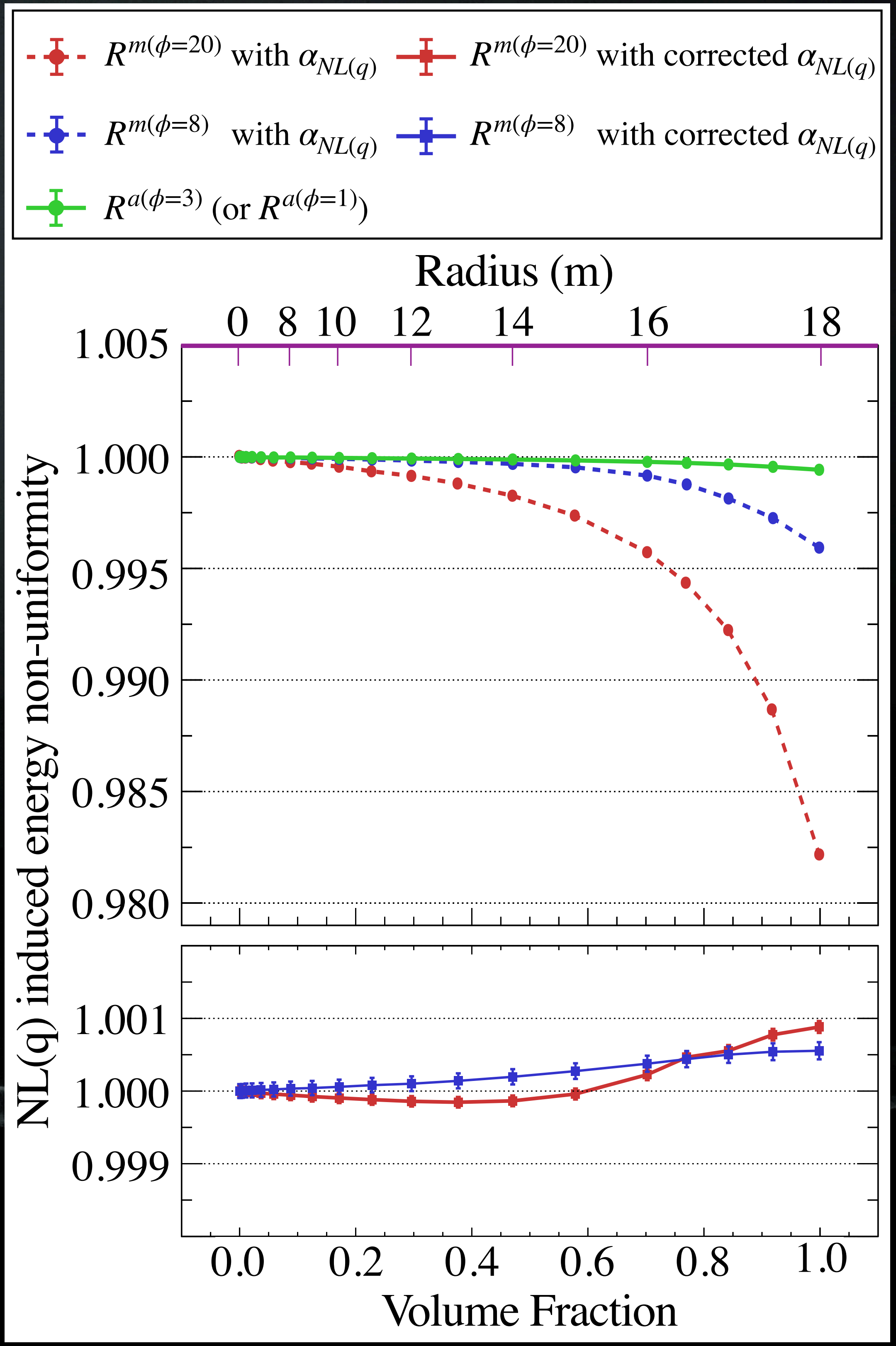


# MC demonstration: NU Disentangling

**Entanglement:**
channel-wise $\alpha_{NL(q)}$ engendering fake energy non-uniformity

After $\alpha^{m}_{NL(q)}$ correction with multi-calorimetry

**Disentangling:**
$\alpha_{NL(q)}$ induced fake energy non-uniformity to permille level !
$\alpha_{NU} \otimes \alpha_{NL} = 0$

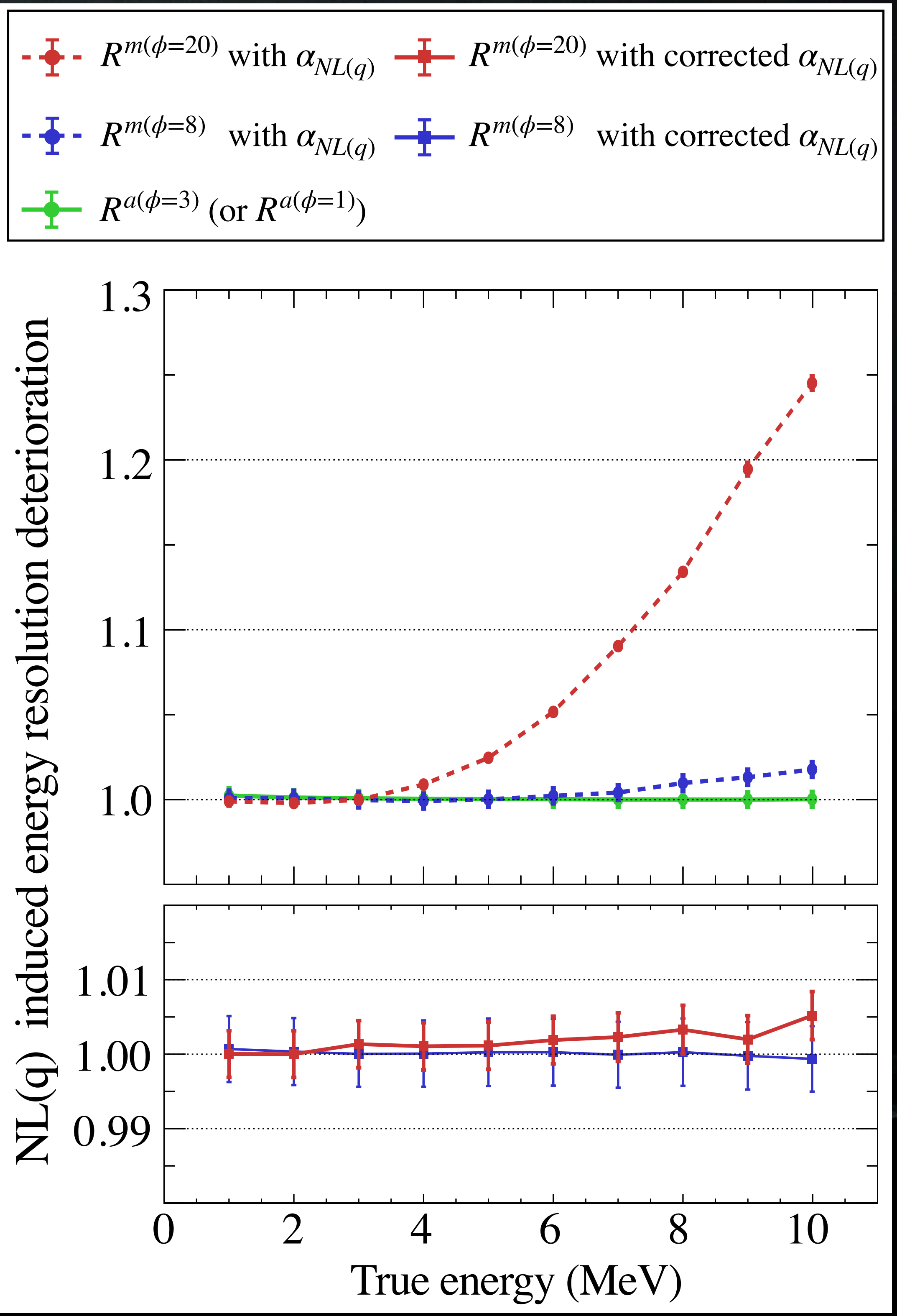


# MC demonstration: Resolution

Entanglement:
channel-wise $\alpha_{NL(q)}$ deteriorating energy resolution

After $\alpha^{m}_{NL(q)}$ correction with multi-calorimetry

Disentangling:
$\alpha_{NL(q)}$ induced energy resolution deterioration recovered!



# Summary

Towards future light-based neutrino detectors:

High precision
(stringent systematics control
permille level)

and/or

Large detector size
(large dynamic range)

+

cost-effectiveness

Multiple photonics interface calorimetry is a design to excel in above conditions.
(Considering the calorimetry systematics control at the detector design level.)

Minimal modification w.r.t single PIR calorimetry (most experiment so far).

Maximum calorimetry systematics control capability !

Thanks to response synergy and systematics complementarity/redundancy.