Multi Calorimetry in Liquid Scintillator Neutrino Detector

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Liquid Scintillator Neutrino Detector

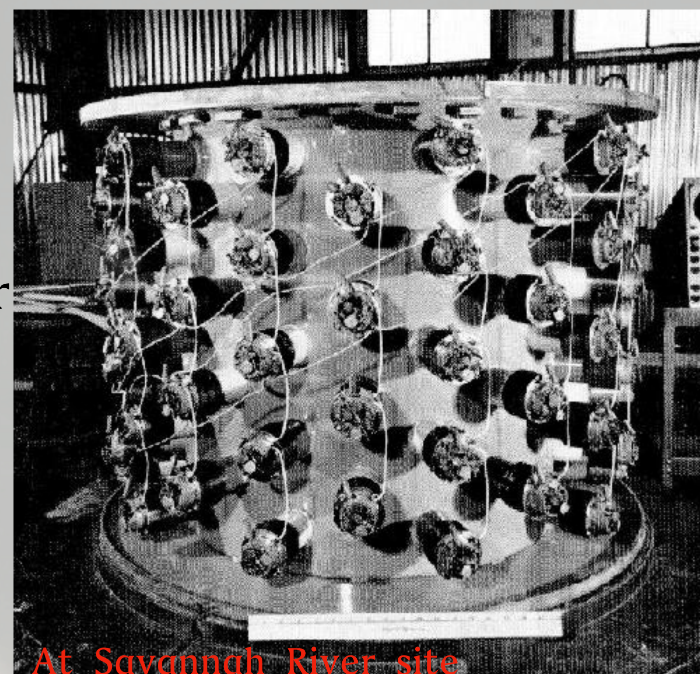
—one of the most successful and widely used neutrino detection technology

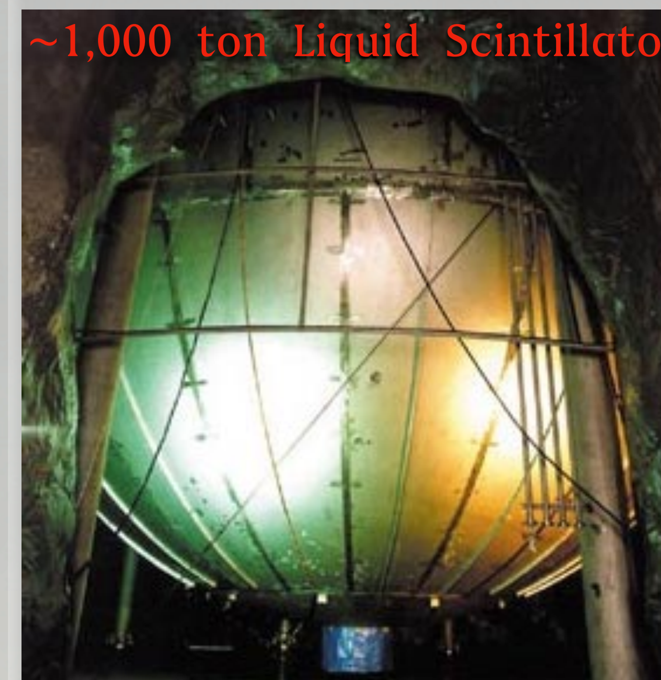
Liquid Scintillator Neutrino Detector

A few examples along history…

(Sorry for not listing all other LS detectors)

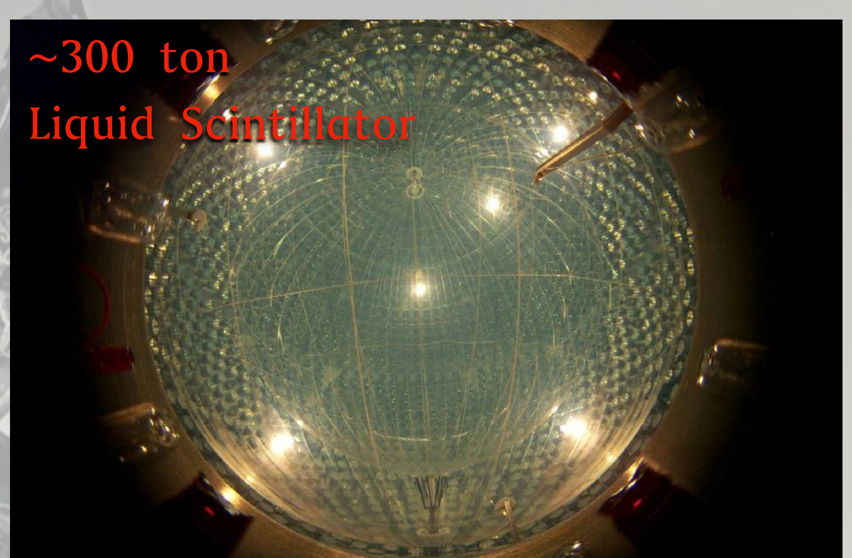
Reines and Cowan
liquid scintillator counter
"Discovery of neutrino"
(1950s)



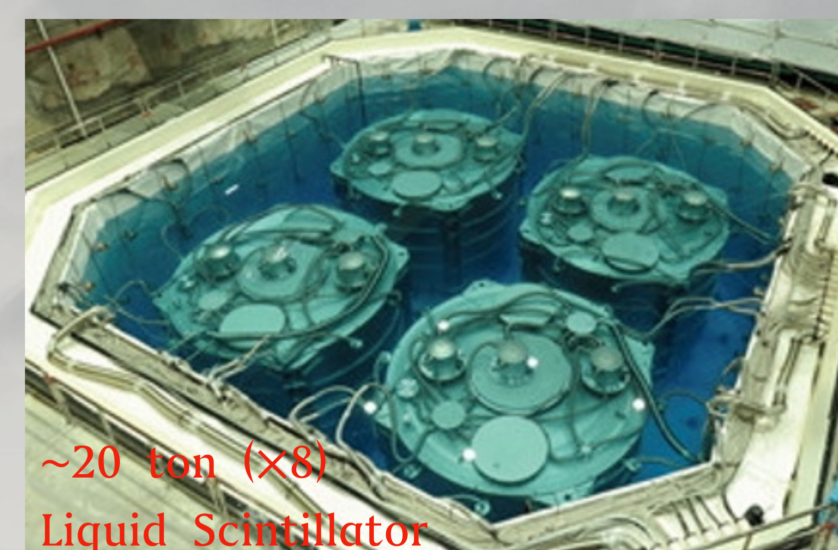


KamLAND Detector
(2002~now)
(Kamioka Liquid Scintillator
Antineutrino Detector)
"Reactor neutrino
oscillation"

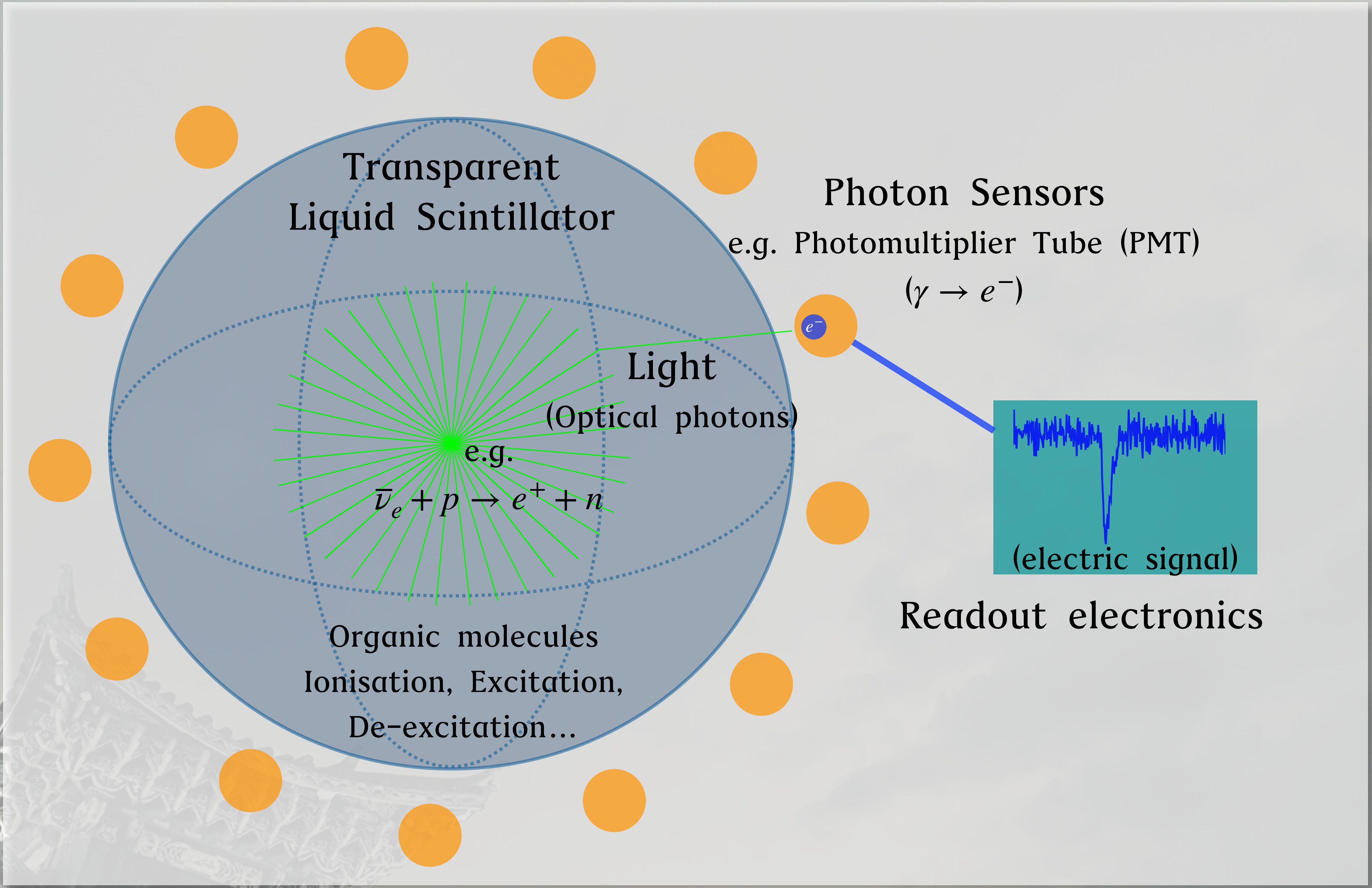
Borexino Detector (2007~now)
"Solar neutrino detection"



Daya Bay Detector (2011~2020)
"Neutrino oscillation θ_{13}"



Calorimetry Main Components



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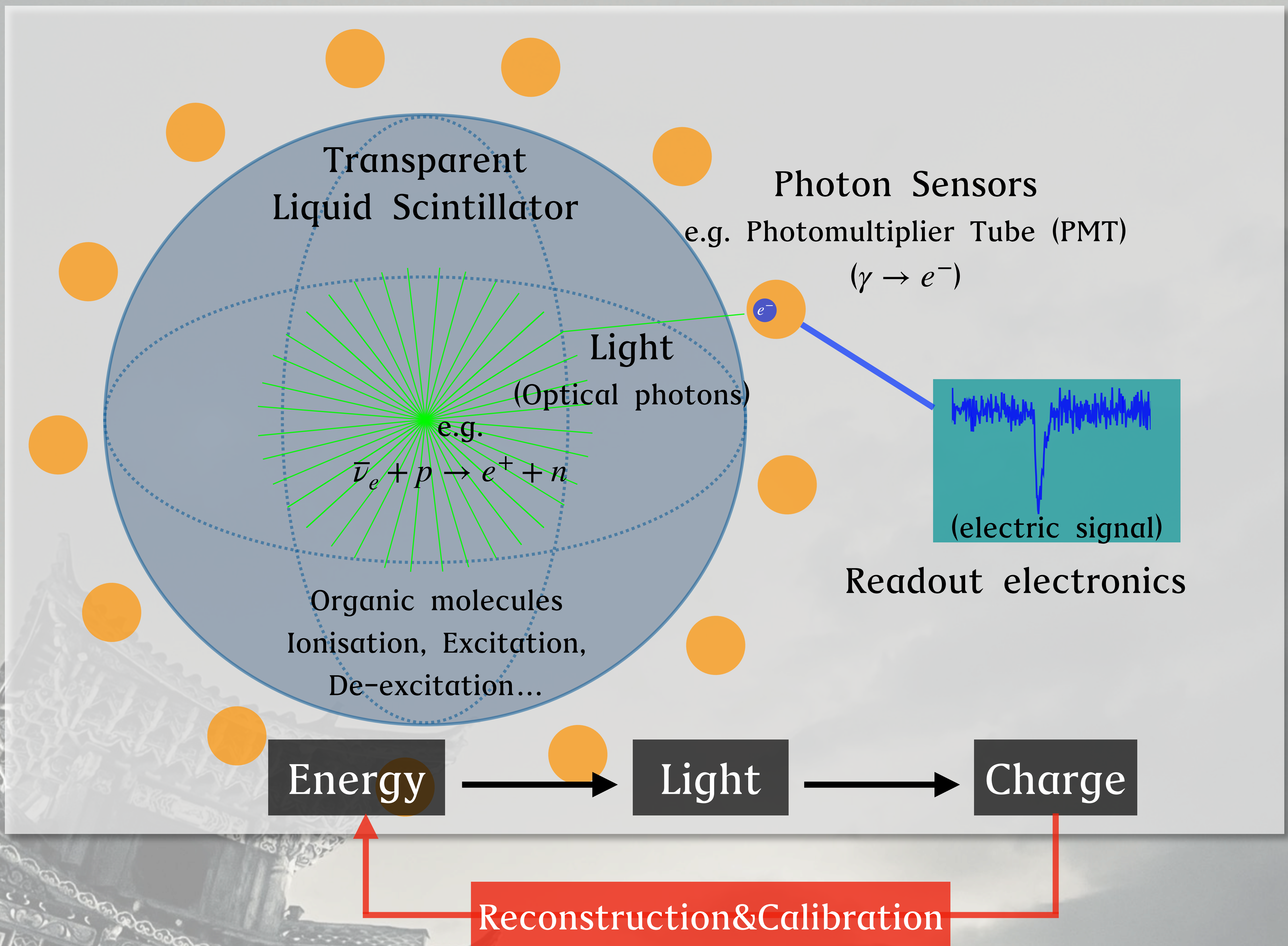
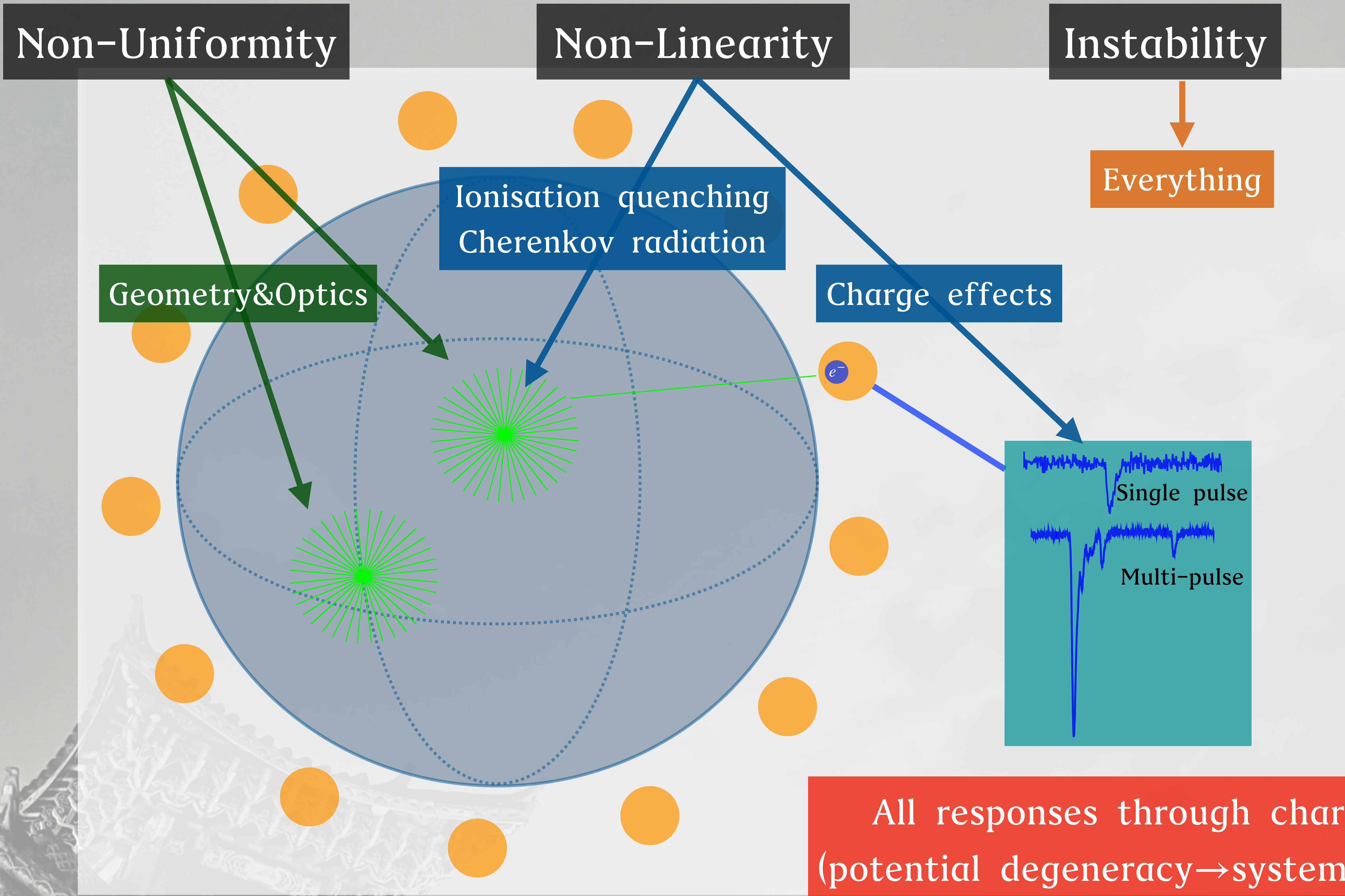


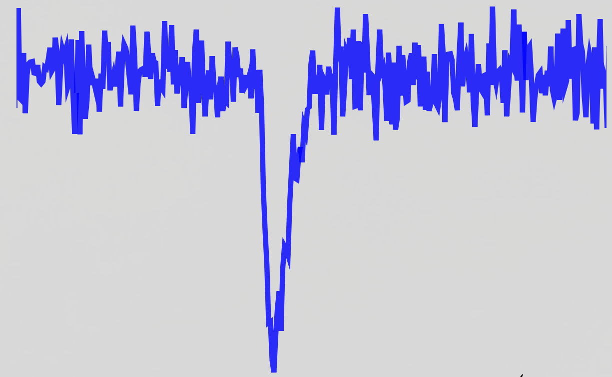
Calorimetric Responses



All responses through charge
(potential degeneracy→systematics)

Calorimetry in terms of charge measurement

Small (enough) pixel
Photon sensor

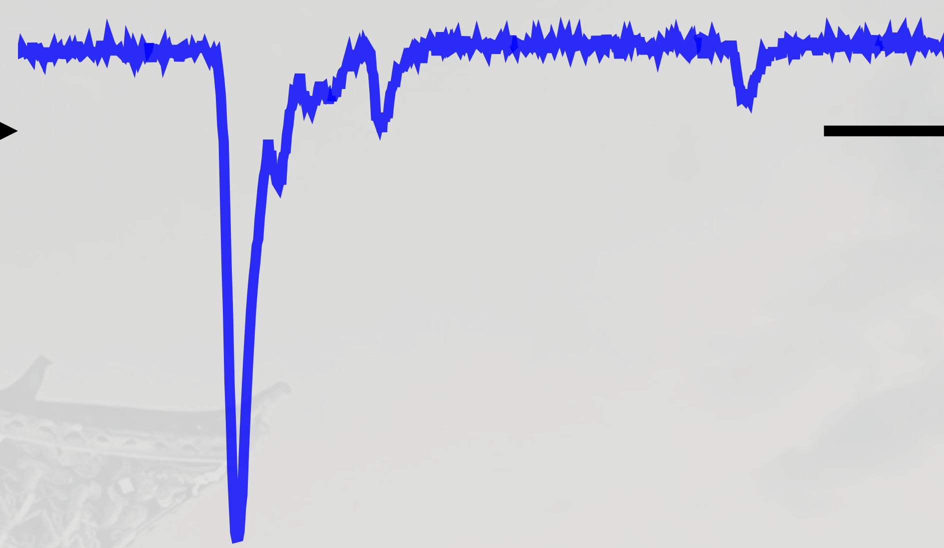


Single charge pulse (always)

“Digital” Calorimetry
“Photon” Counting

Simple Systematics:
Threshold (Noise-Signal)

Large pixel
Photon sensor



Multiple charge pulse

“Integration” Calorimetry
Charge Integration

Sophisticated Systematics:
Pulse waveform variation&distortion;
Noise baseline;
Integration strategy …

Calorimetry examples

(Sorry for not listing all other LS detectors)

	LS Target Mass (ton)	Nb. of PMTs	PMT Dimension (inch)	Light Yield (PE/MeV)	Single PMT mean illumination @1MeV@center	Single PMT charge range (For 1~10 MeV)	Energy resolution @1MeV	Energy systematics
KamLAND	1000	1880	20&17	~250	~0.1		~6%	~1.4%
Borexino	300	2212	8	~500	~0.3	Approximately 1~10PE	~5%	~1%
Daya Bay	20	190	8	~170	~0.9		~8%	<1%

Calorimetry examples

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Large pixel
(coverage&channels)
Cost effective (historically)

Single
"Integration"
Calorimetry*

Systematics
~
Detector size

*Physics (energy) dependent

Calorimetry examples

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Borexino	300	2212	8	~500	~0.3		~5%	~1%
Daya Bay	20	190	8	~170	~0.9		~8%	<1%
JUNO	20,000	18,000 (main)	20 (main)	~1300	~0.1	1~100PE	~3%	<1% (required)

Large Scale Detector ⊕ High Precision Energy Meas.
→ Calorimetric challenge

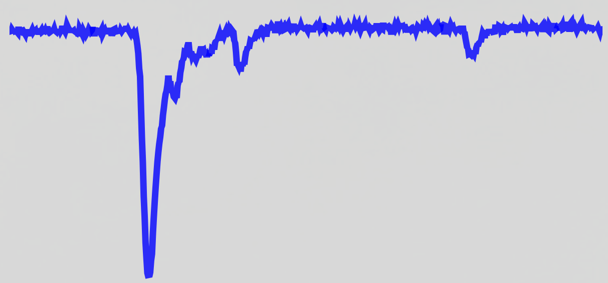
Calorimetric challenge

in "integration" Calorimetry

- Direct charge response control.

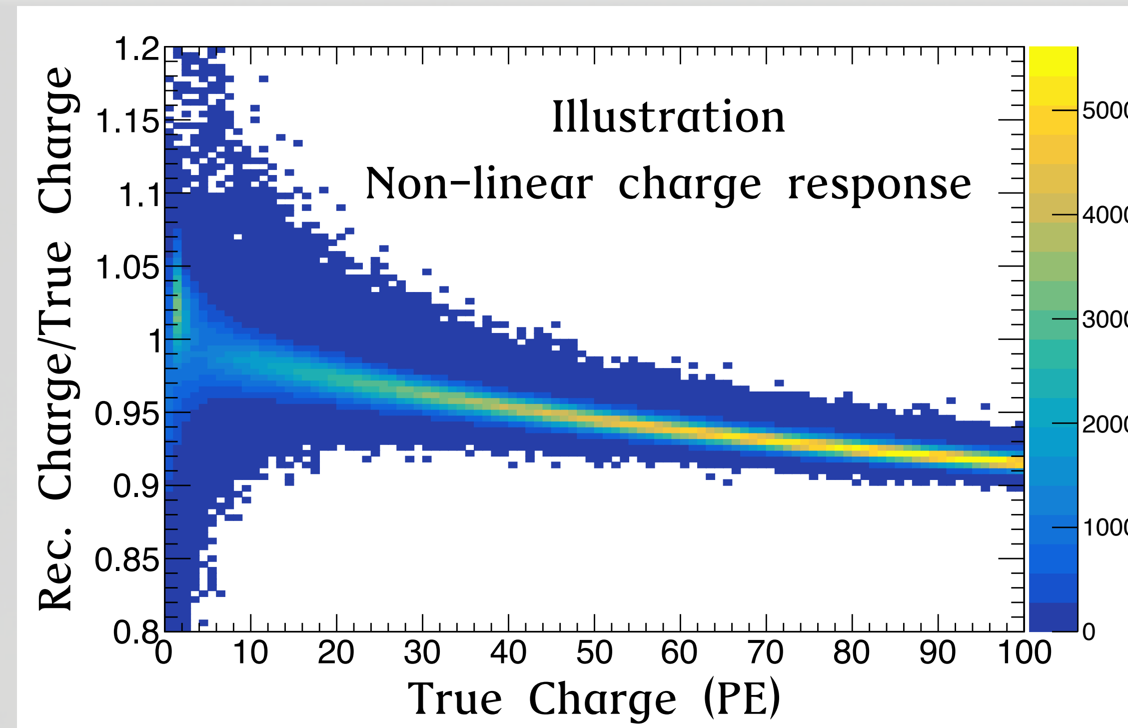
PMT charge pulse waveform reconstruction.

Simple: Integration.
Advanced: deconvolution,
fitting, machining learning…



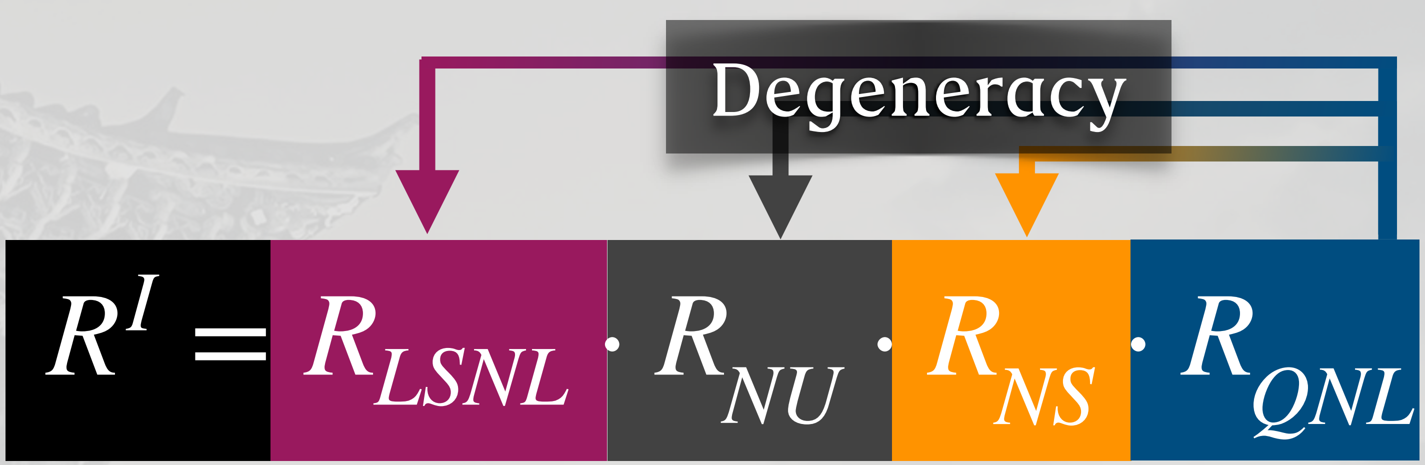
Challenging systematics control,

even for diagnosis…



- Response degeneracy

Charge response (QNL) coupled with: Liquid scintillator non-linear response (LSNL)
Non uniform response (NU)
Unstable response (NS)



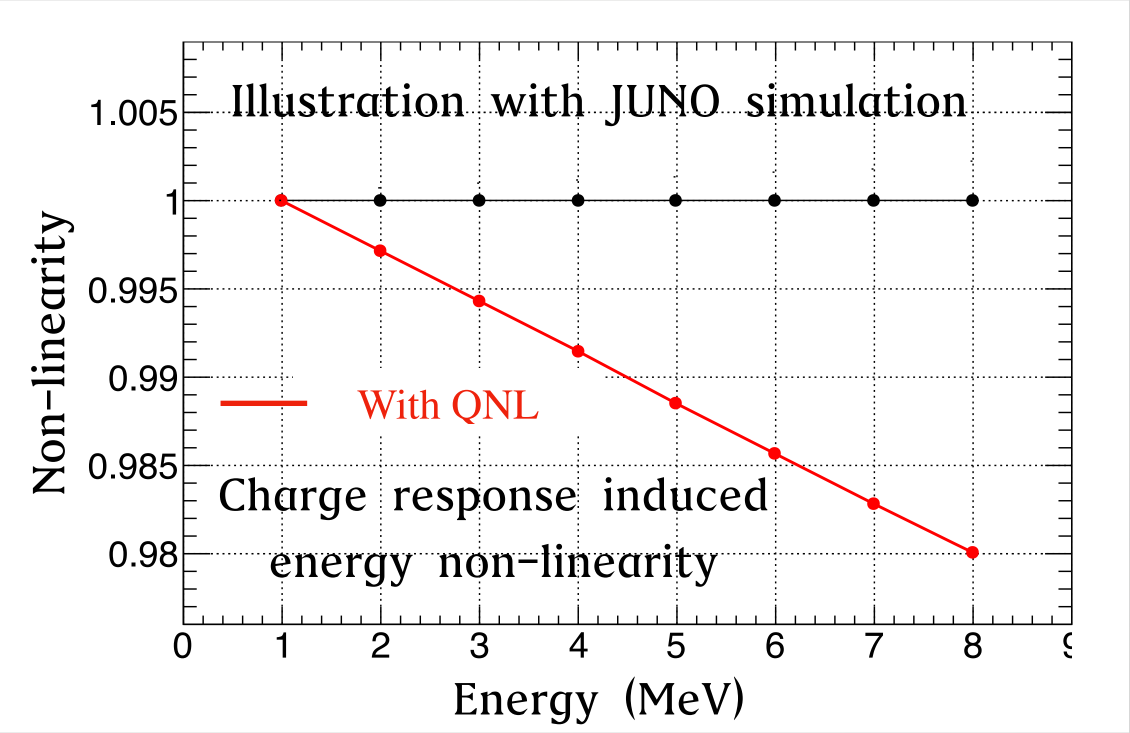
$$R^I = R_{LSNL} \cdot R_{NU} \cdot R_{NS} \cdot R_{QNL}$$

QNL: charge nonlinearity
LSNL: liquid scintillator non-linearity
NU: non-uniformity
NS: non-stability

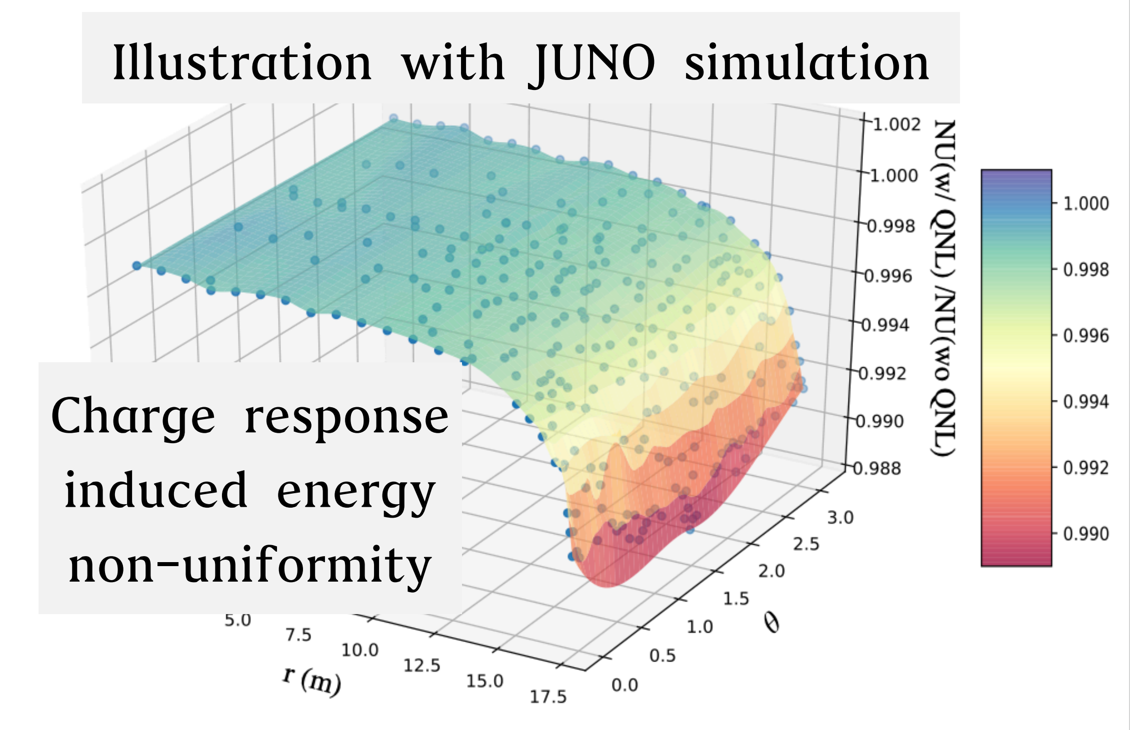
Calorimetric challenge

Response degeneracy examples:

- Energy non-linearity induced by charge response



- Energy non-uniformity mimicked by charge response

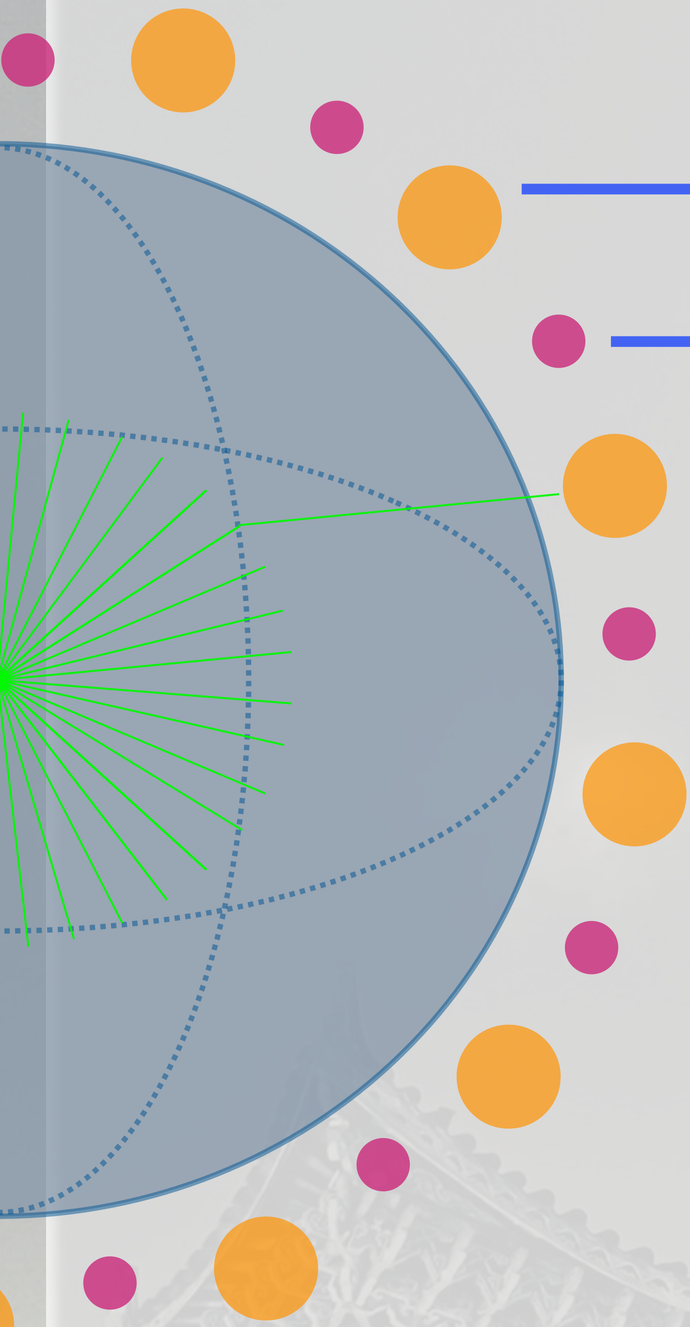


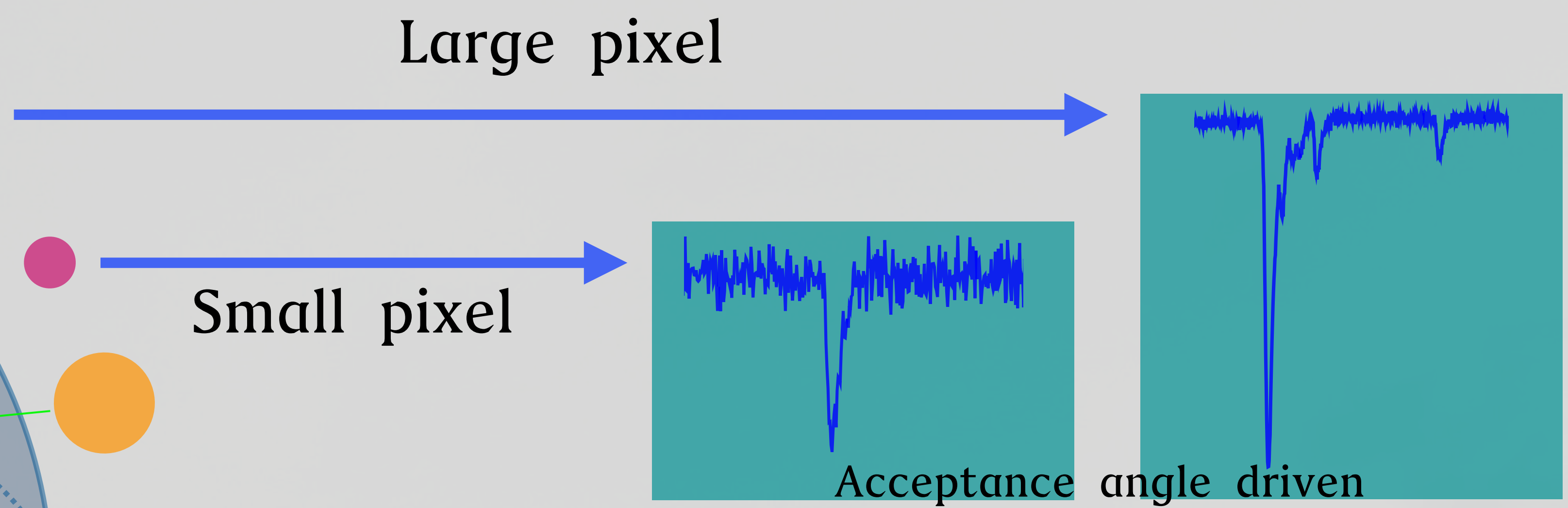
Challenge for diagnosis&calibration in single (integration) calorimetry!

Multi Calorimetry

—for high precision calorimetry systematics control

Multi Calorimetry Concept





"Digital" Calorimetry   "Integration" Calorimetry

Simultaneous

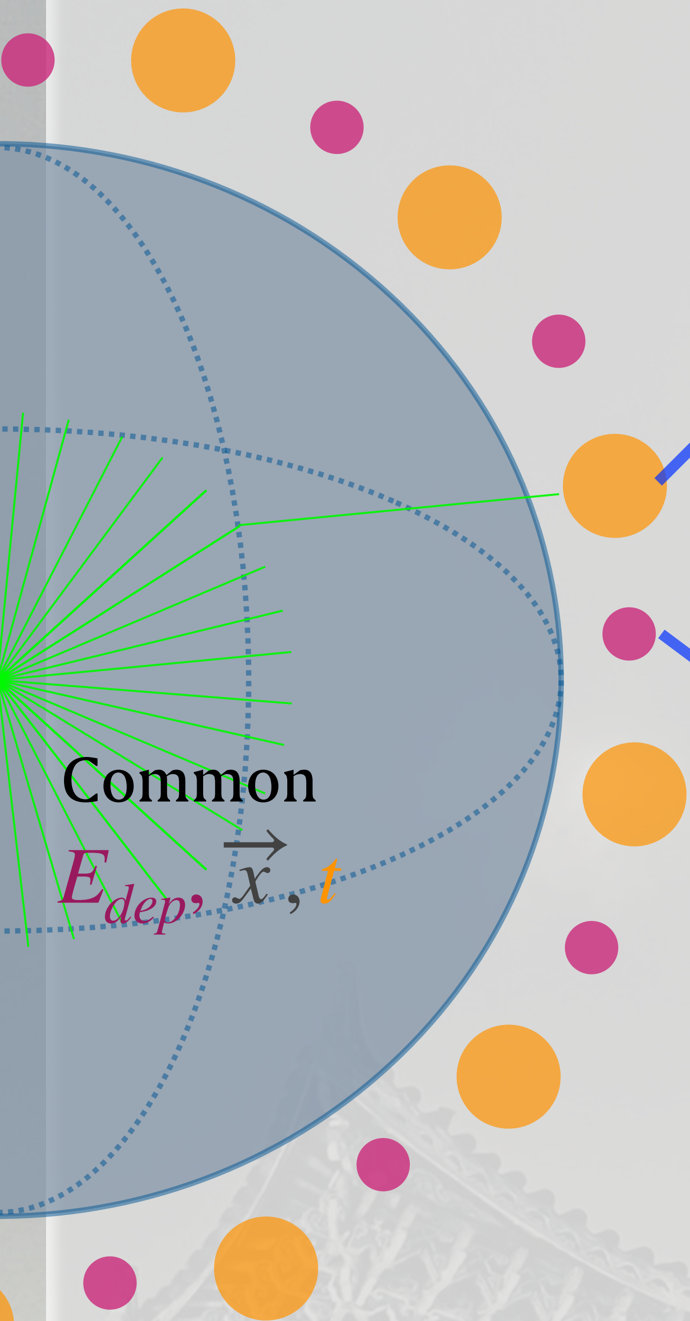
Not addition in systematics.

On the contrary, synergy to reduce systematics.

Dual Calorimetry@JUNO

	Target Mass (ton)	Nb. of PMTs	PMT Dimension (inch)	Light Yield (PE/MeV)	Single PMT mean illumination @1MeV@center	Single PMT charge range (For 1~10 MeV)	Energy systematics
JUNO	20,000	~18,000 (main)	20-inch (main)	~1300	~0.1	1~100PE	<1% (required)
		~25,600 (secondary)	3-inch (secondary)	~50	~0.002	1PE (Dominant)	

Multi Calorimetry Principle

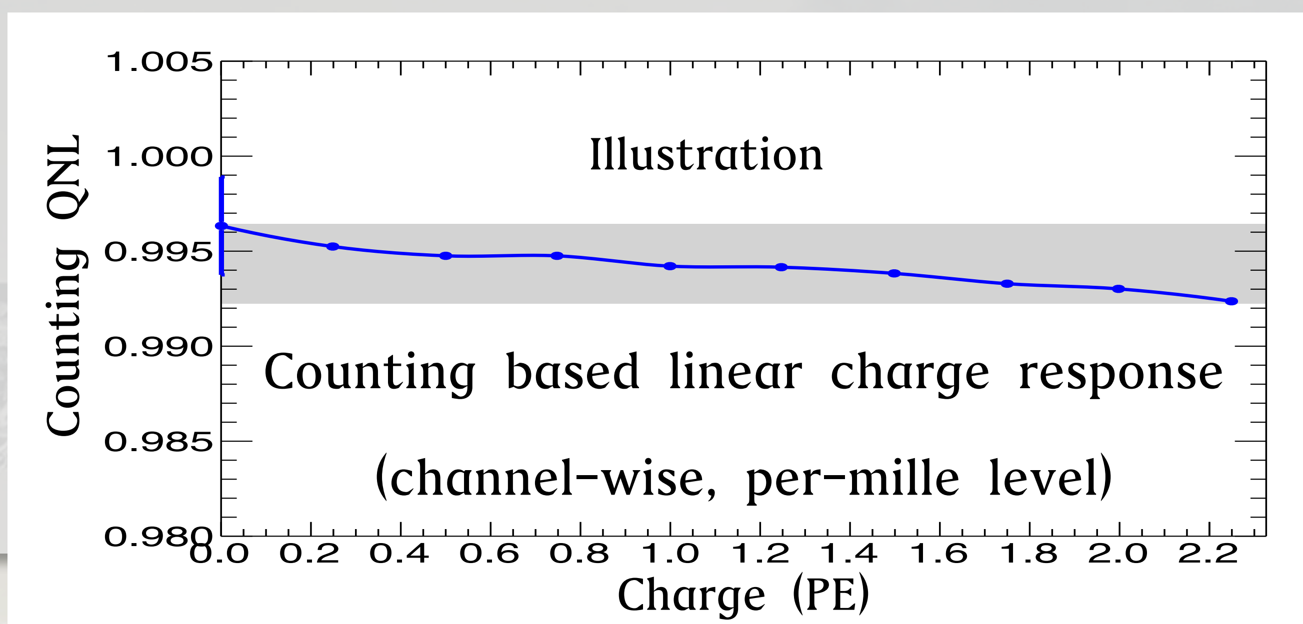


Degeneracy

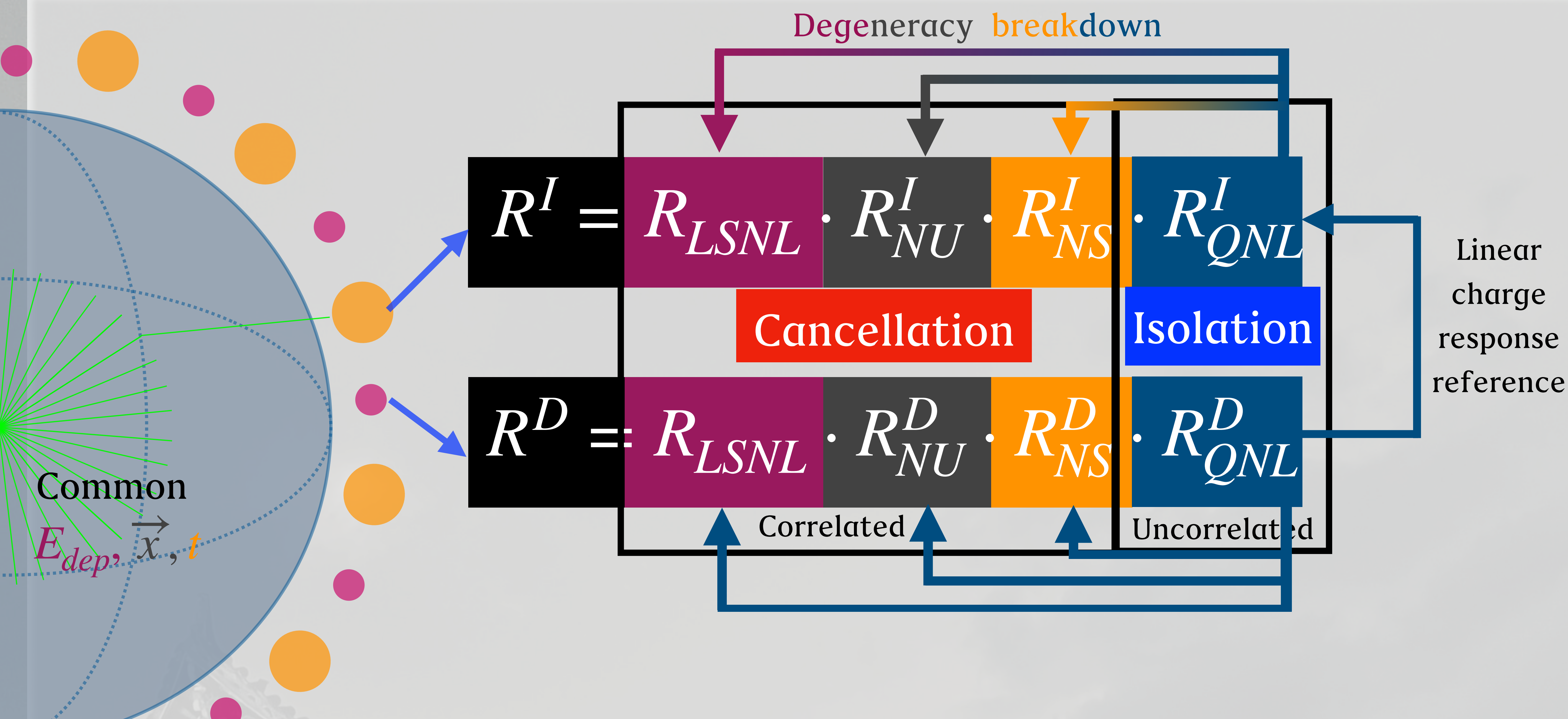
$$R^I = R_{LSNL} \cdot R^I_{NU} \cdot R^I_{NS} \cdot R^I_{QNL}$$

$$R^D = R_{LSNL} \cdot R^D_{NU} \cdot R^D_{NS} \cdot R^D_{QNL}$$

No degeneracy



Multi Calorimetry Principle



Multi Calorimetry Synergy → Degeneracy breakdown

→ Precise systematics control

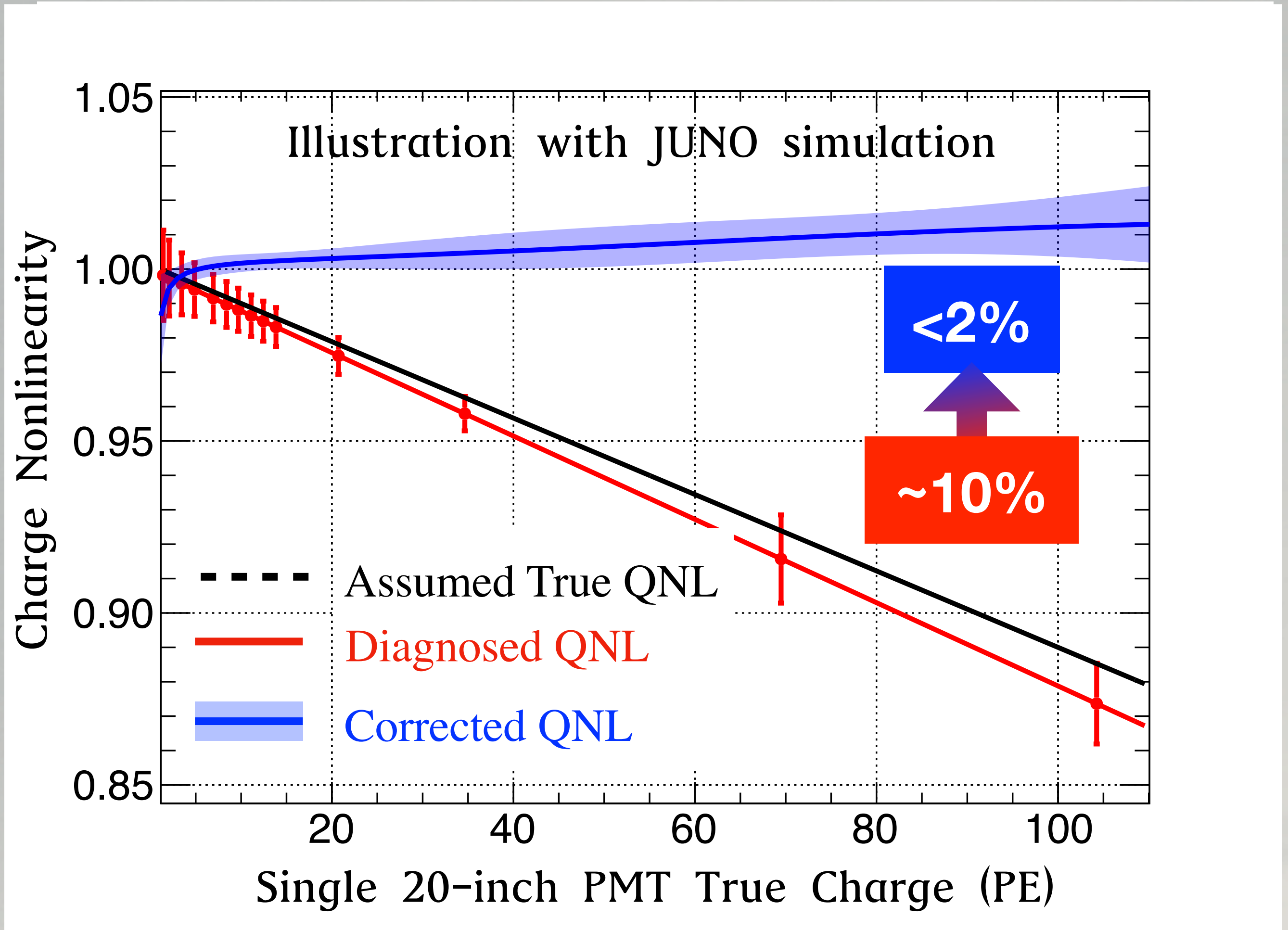
Skip detailed methodologies to reach Multi Calorimetry

Focus on: potential precise systematics control in energy linearity and uniformity, with JUNO as an example

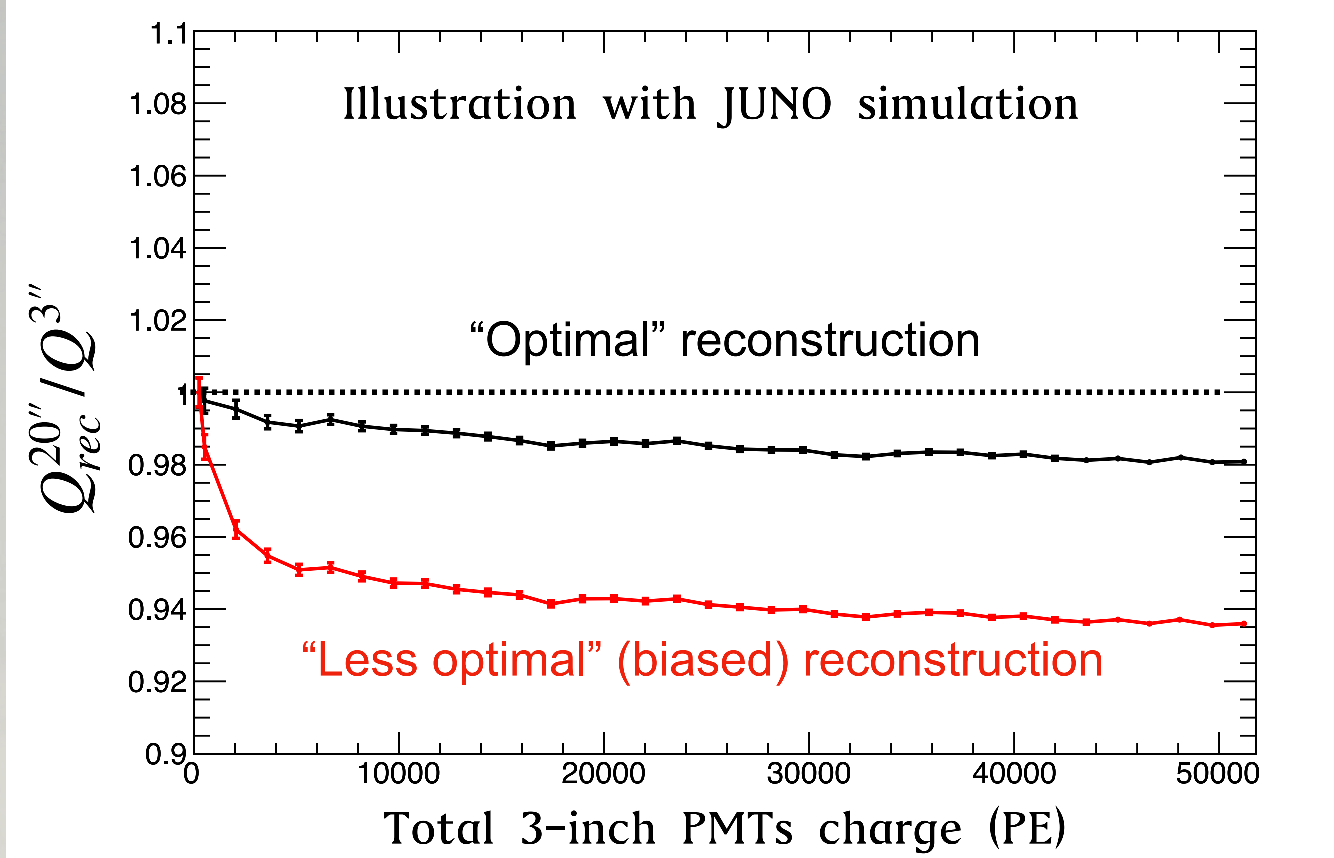
Multi Calorimetry Potentials

Direct charge response non-linearity (QNL) control

Through calibration ⊕ Through reconstruction



(e.g. waveform deconvolution)

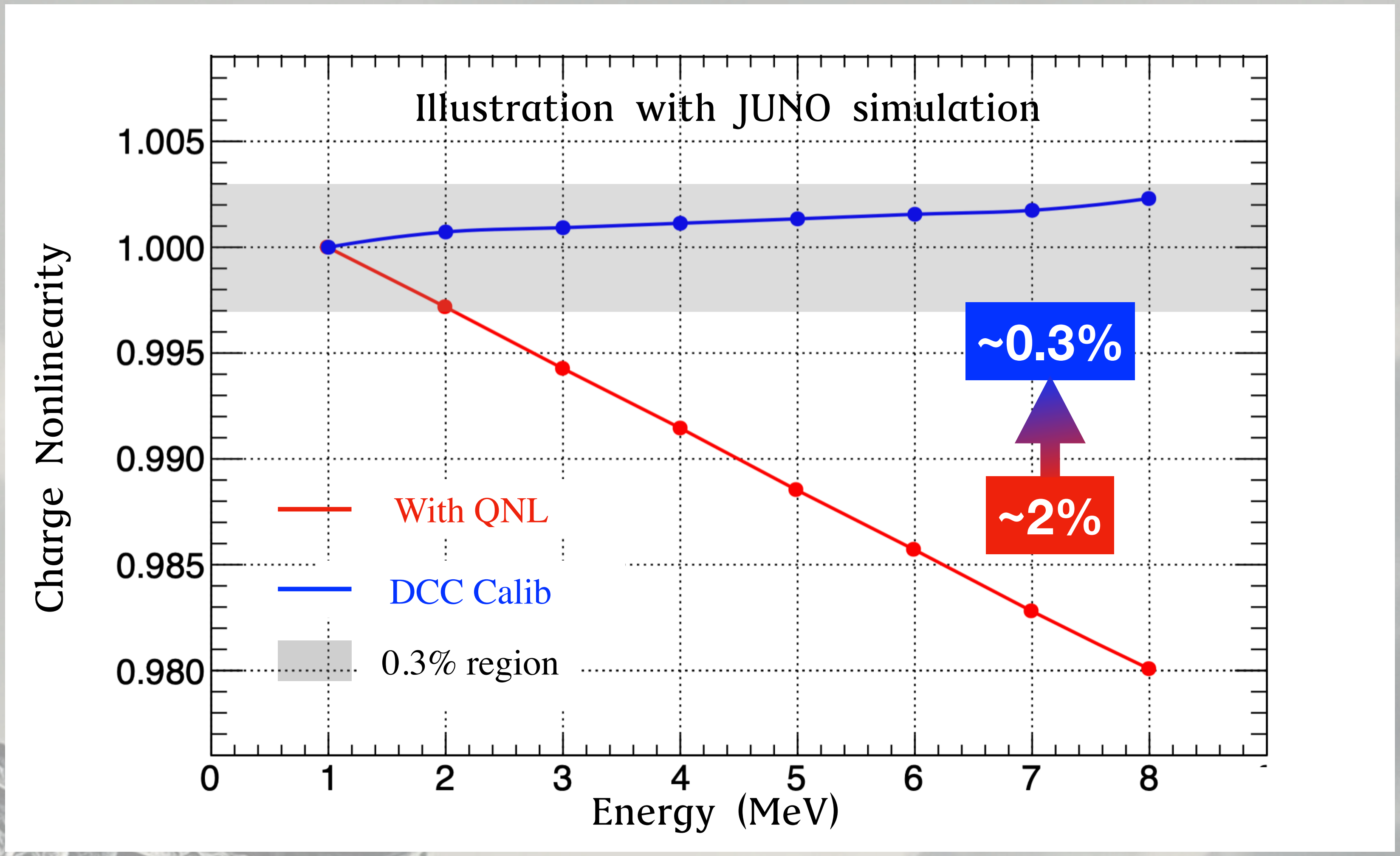


Equivalent to 0~100PE 20-inch PMT true charge

Multi Calorimetry Potentials

Degeneracy breakdown

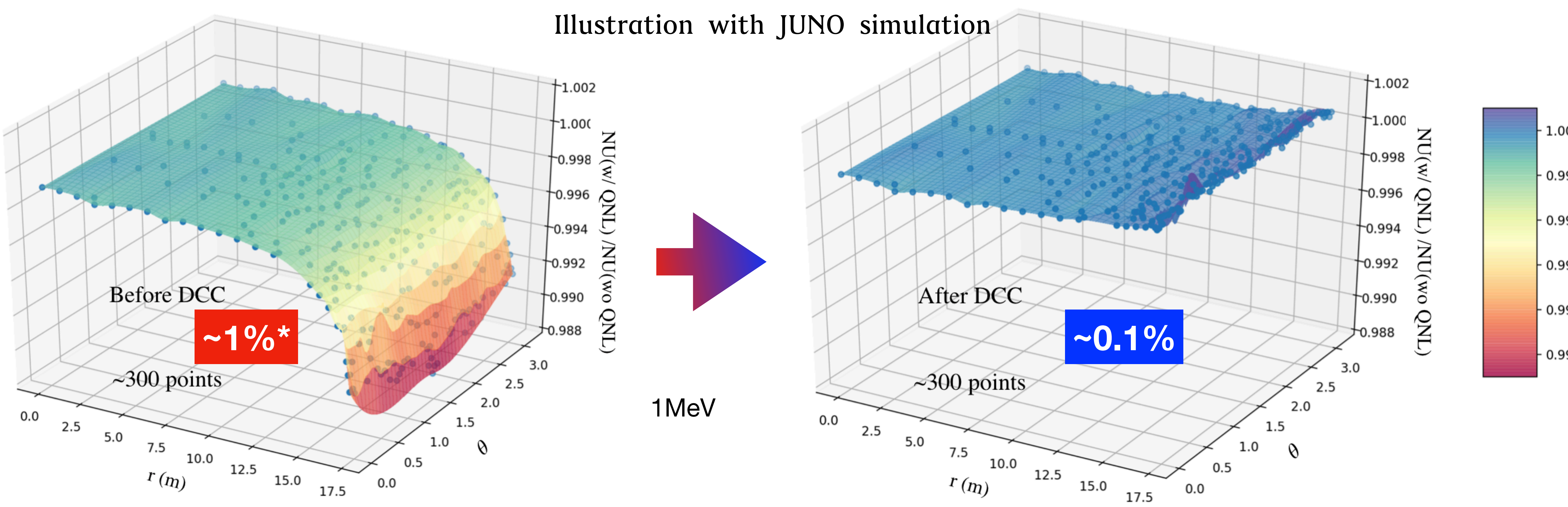
Charge response induced energy non-linearity control



Multi Calorimetry Potentials

Degeneracy breakdown

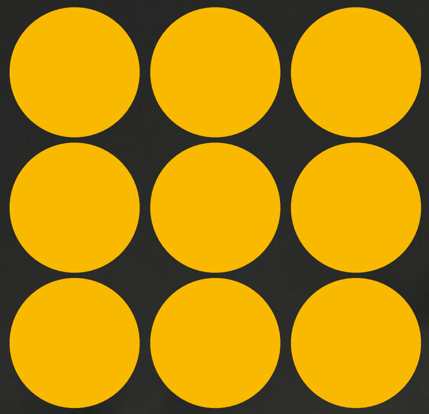
Charge response mimicked energy non-uniformity control



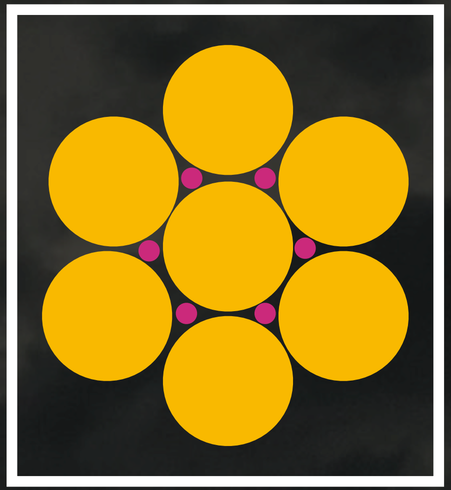
Conclusions

Liquid scintillator neutrino detector:

- Single Calorimetry (integration):
  - Great success in neutrino physics (relative low precision requirement)
  - Challenge in high precision requirement



- Multi Calorimetry (integration + digital):
  - Modification by adding auxiliary digital calorimetry
  - Improving calorimetry systematics control for high precision measurement
  - E.g. JUNO (huge detector)



A novel option!

- Full Digital Calorimetry
  - E.g. JUNO-TAO (SiPM, small detector)