Multi Calorimetry in Liquid Scintillator Neutrino Detector

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SYSU-PKU Collider Physics forum For Young Scientists

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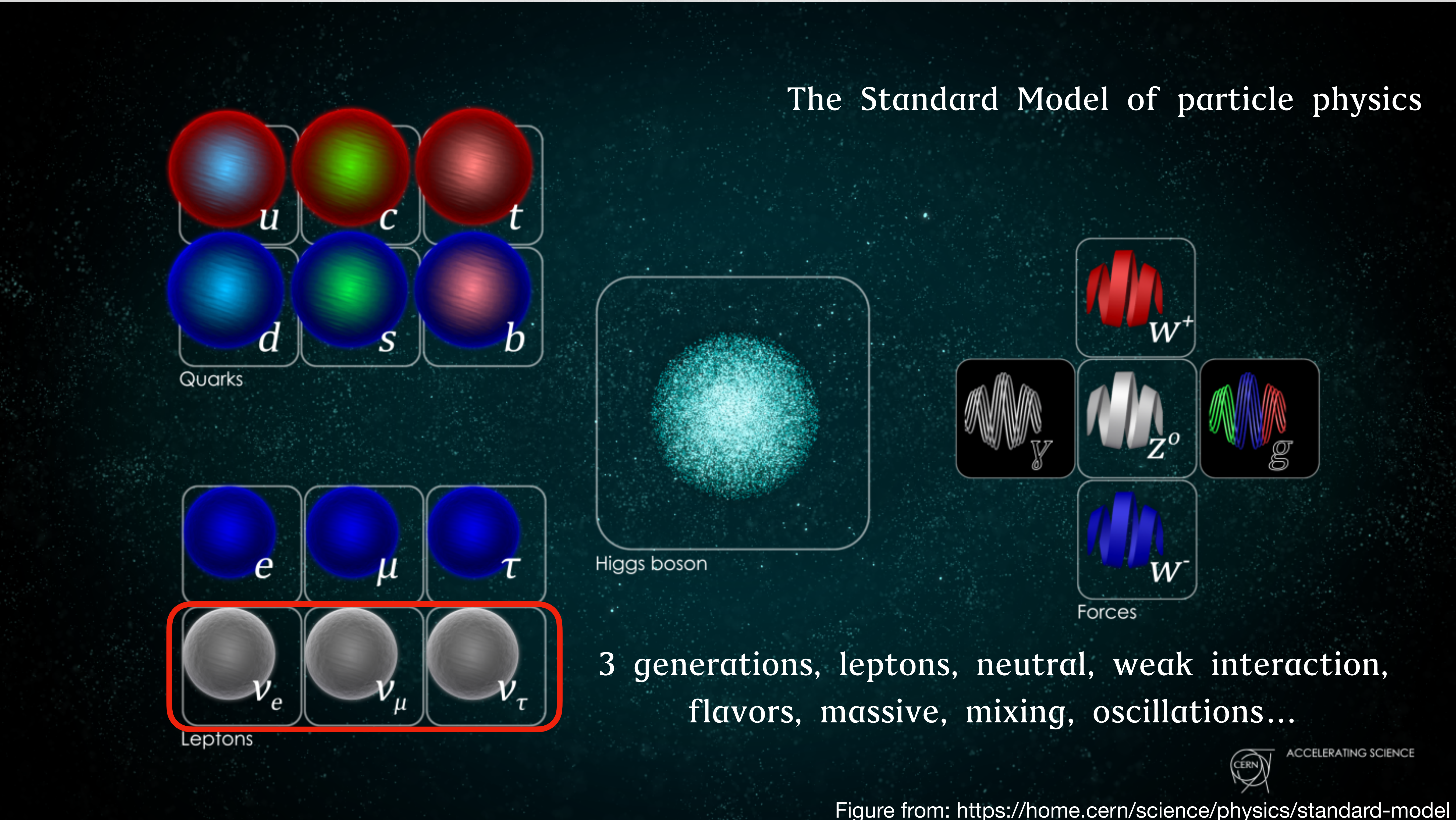
Some background information about neutrinos and oscillations…

for audience not in neutrino field…

Neutrinos



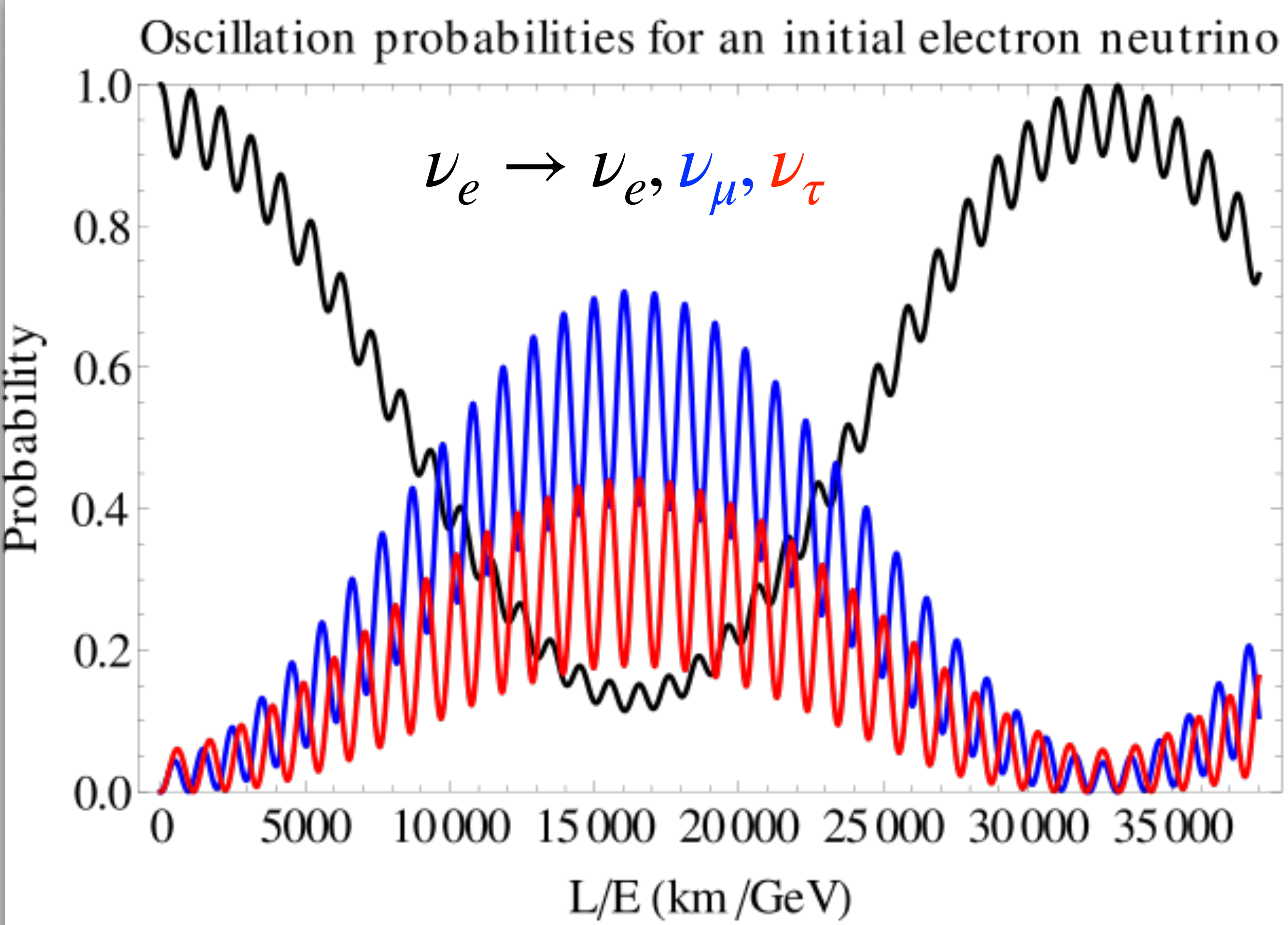
The Standard Model of particle physics

3 generations, leptons, neutral, weak interaction, flavors, massive, mixing, oscillations…

Figure from: https://home.cern/science/physics/standard-model

Neutrino oscillation

Neutrino flavor transformation



http://demonstrations.wolfram.com/NeutrinoOscillations/

Neutrino mass and mixing

Flavor Eigenstates		Lepton mixing matrix ("PMNS")	Mass Eigenstates

$$\begin{bmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{bmatrix} = \begin{bmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{bmatrix} \begin{bmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix}$$

Amplitude
$(\theta_{12}, \theta_{23}, \theta_{13}, \delta_{CP})$

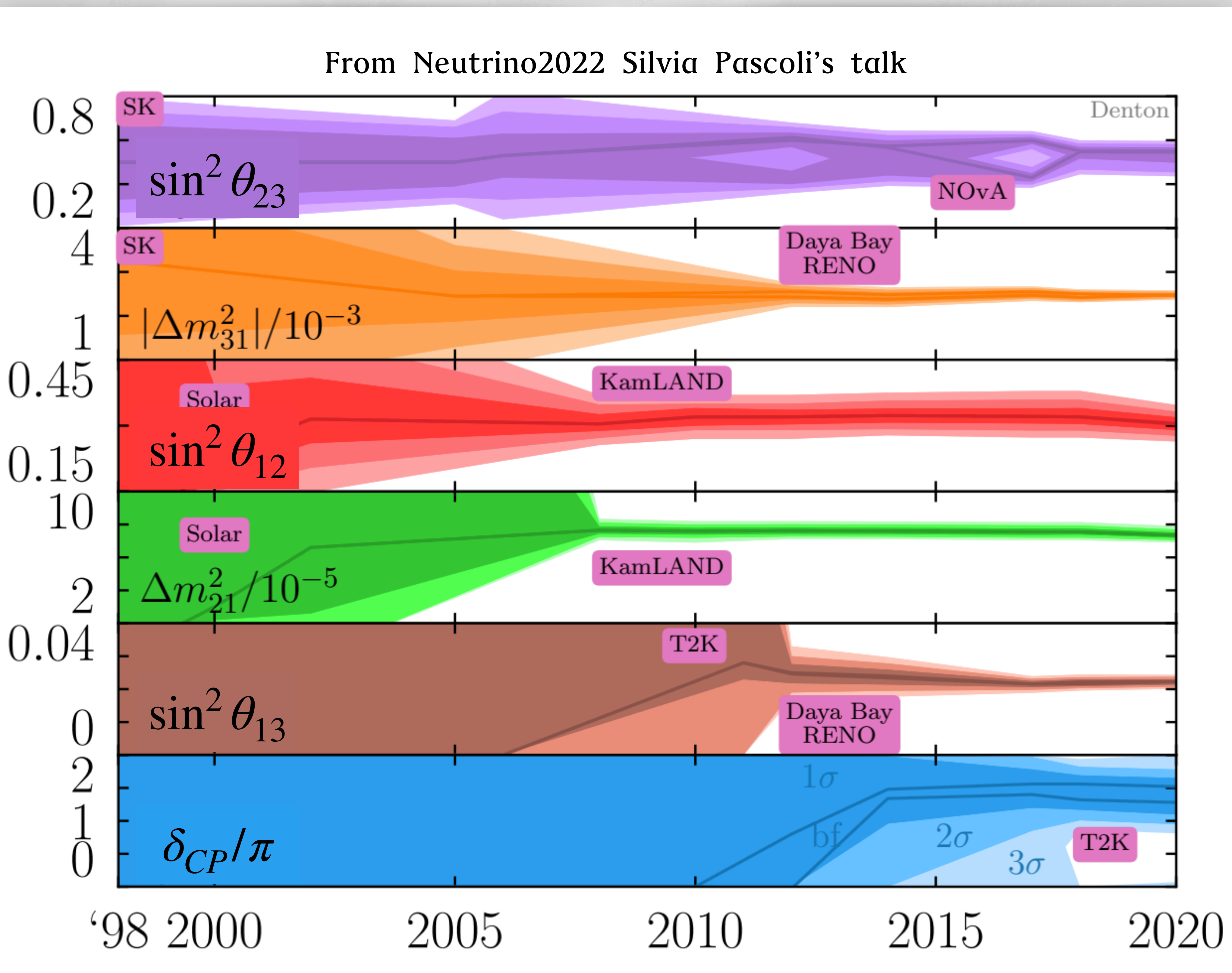
Frequency
$(\Delta m^2_{21}, \Delta m^2_{32}, \Delta m^2_{31})$

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sum_{i=1}^{3} \sum_{j=1}^{3} U^*_{\alpha i} U_{\beta i} U_{\alpha j} U^*_{\beta j} exp(-i \frac{\Delta m^2_{ij} L}{2E}).$$

(vacuum)

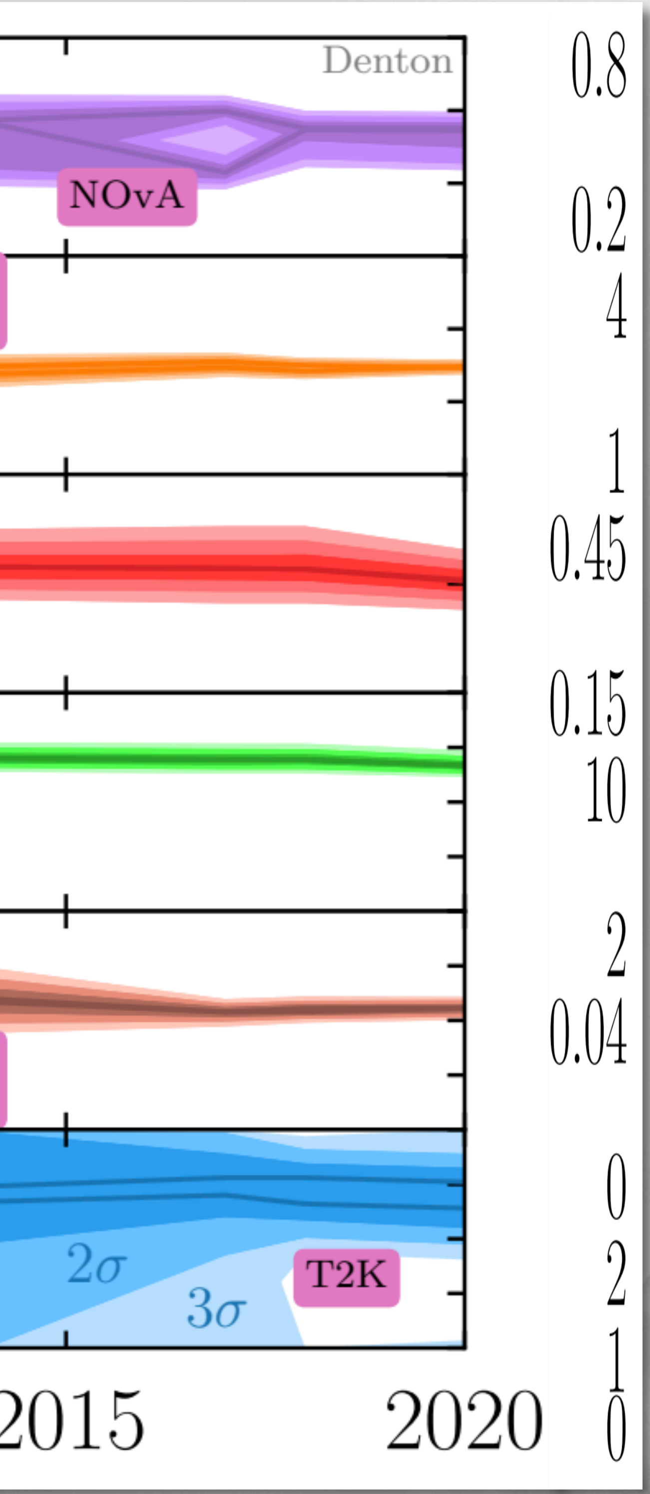
$(\Delta m^2_{21} + \Delta m^2_{32} + \Delta m^2_{13} = 0)$

Global picture of oscillation parameters



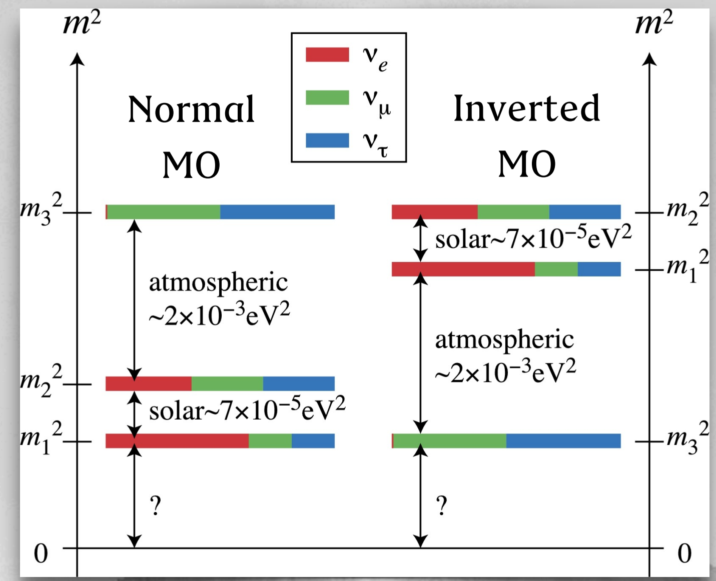
Most at few % level

Unknowns



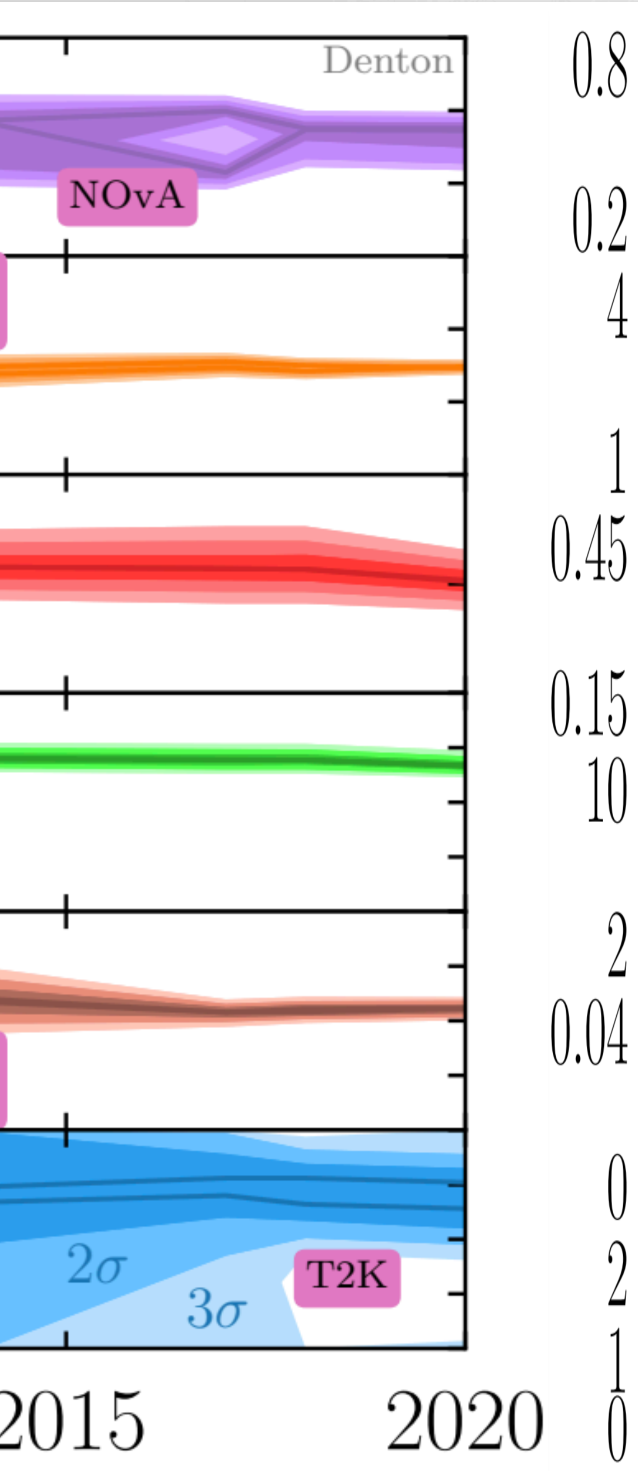
$\sin^2\theta_{23}$ — Octant: $\theta_{23} > \frac{\pi}{4}$, or $< \frac{\pi}{4}$?

$|\Delta m^2_{31}|$ — Mass Ordering(MO): $\Delta m^2_{31} > 0$, or < 0 ?



δ_{CP} — CP conservation or violation?

Unknowns and Efforts



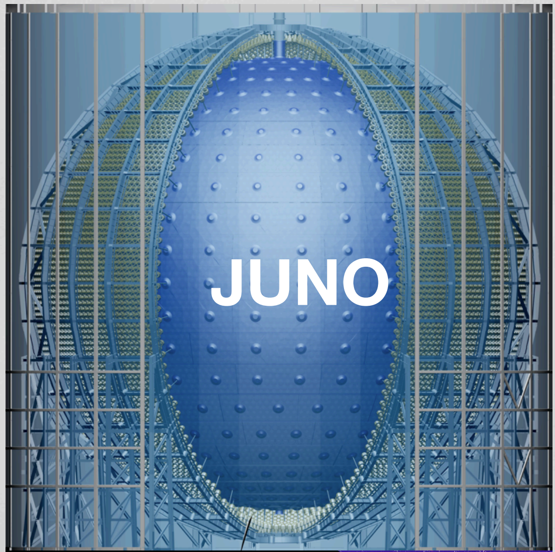
$\sin^2\theta_{23}$ — Octant: $\theta_{23} > \frac{\pi}{4}$, $or < \frac{\pi}{4}$?

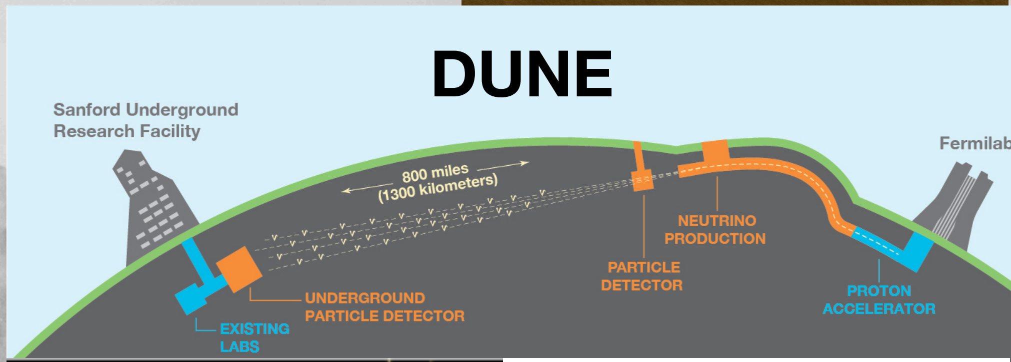
$|\Delta m^2_{31}|$ — Mass Ordering(MO): $\Delta m^2_{31} > 0$, $or < 0$?

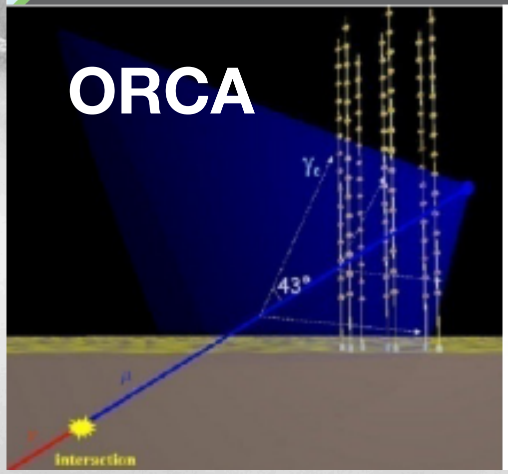
Future: high precision era

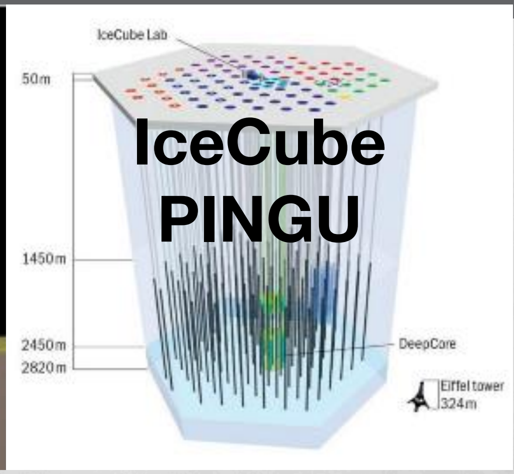
(Huge Detector & Precise systematics control)

δ_{CP} — CP conservation or violation?





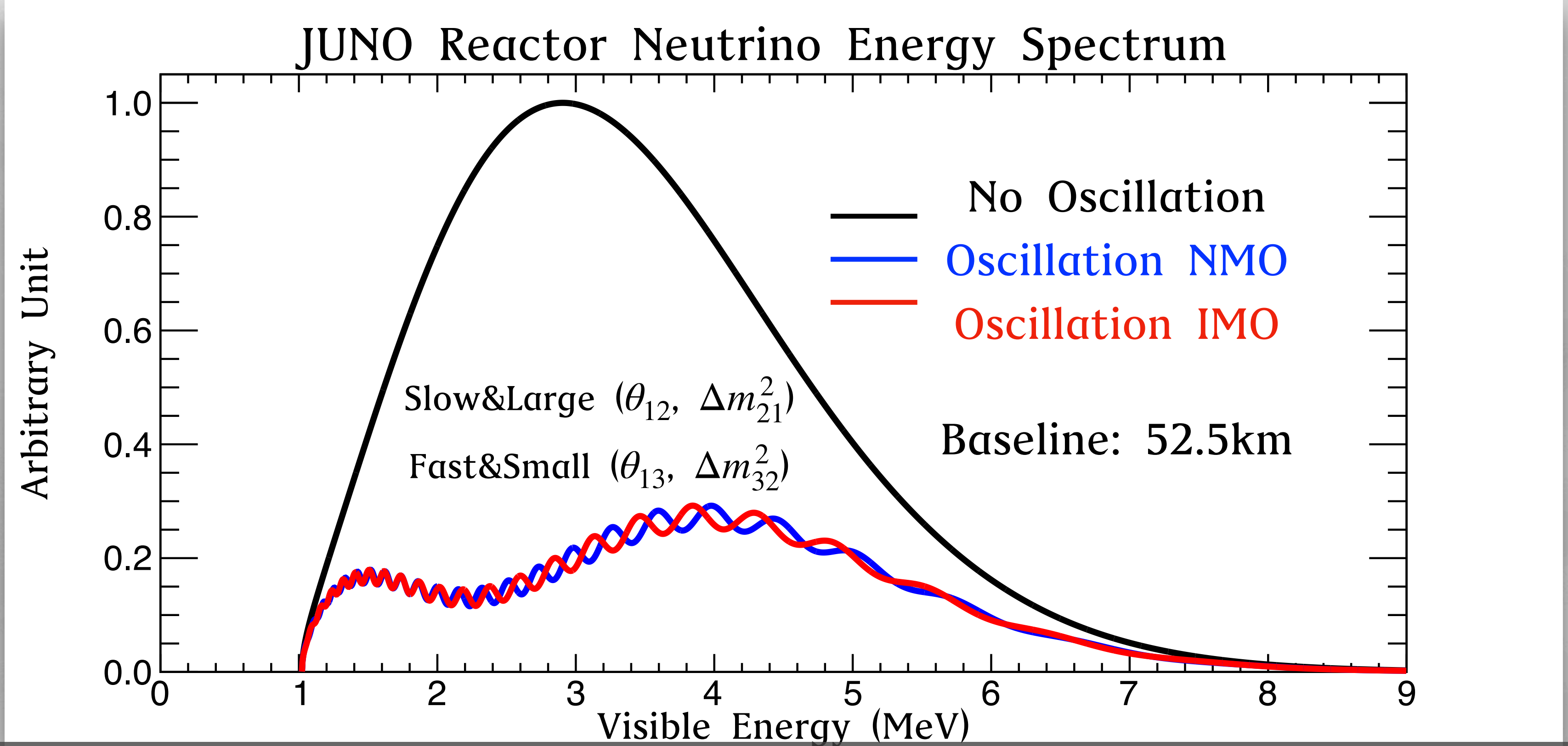




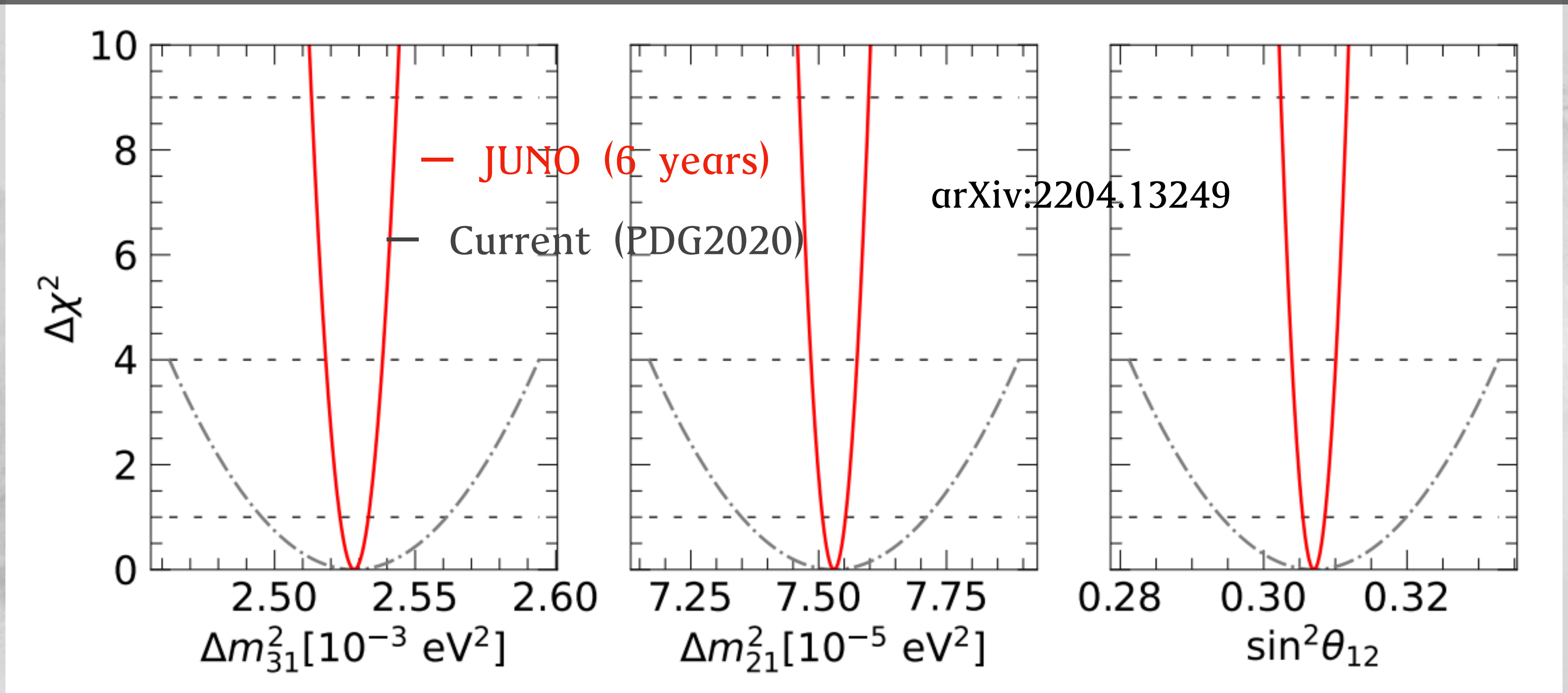
JUNO in brief

Primary Physics Topics:

Neutrino Mass Ordering: ~3σ (6 years)

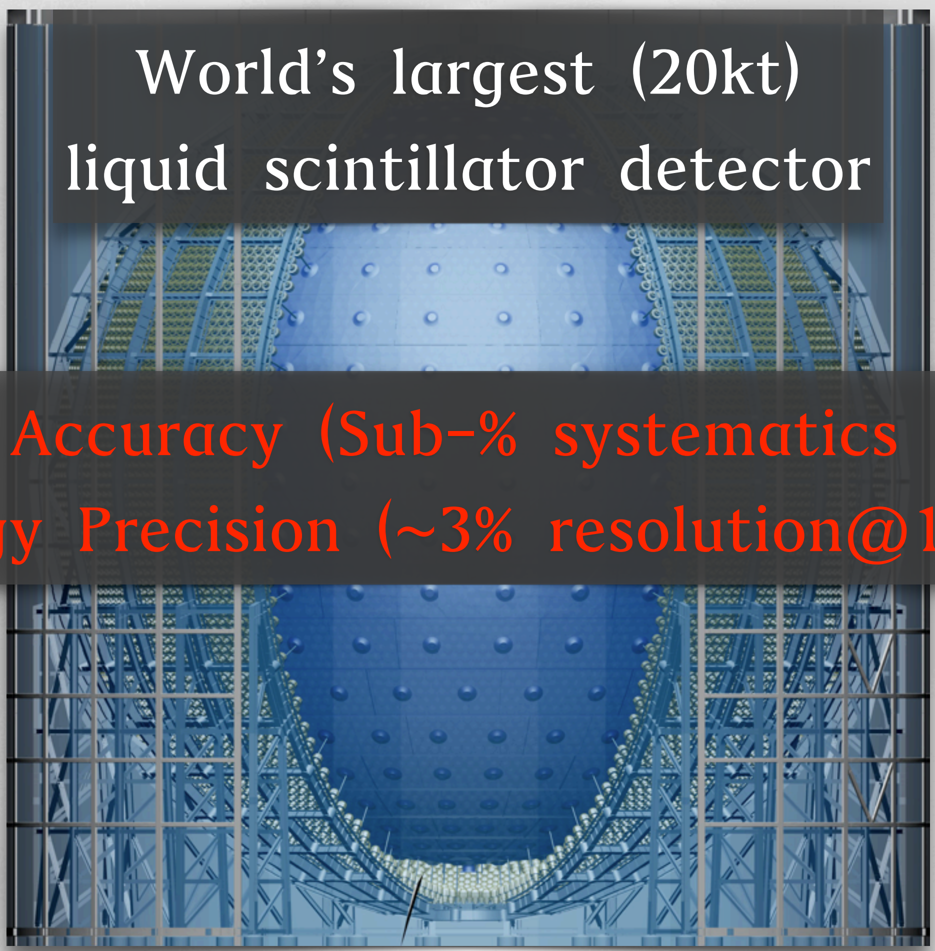


Sub-% Precision Oscillation Parameters (Δm^2_{31}, Δm^2_{21} and $\sin^2\theta_{12}$)



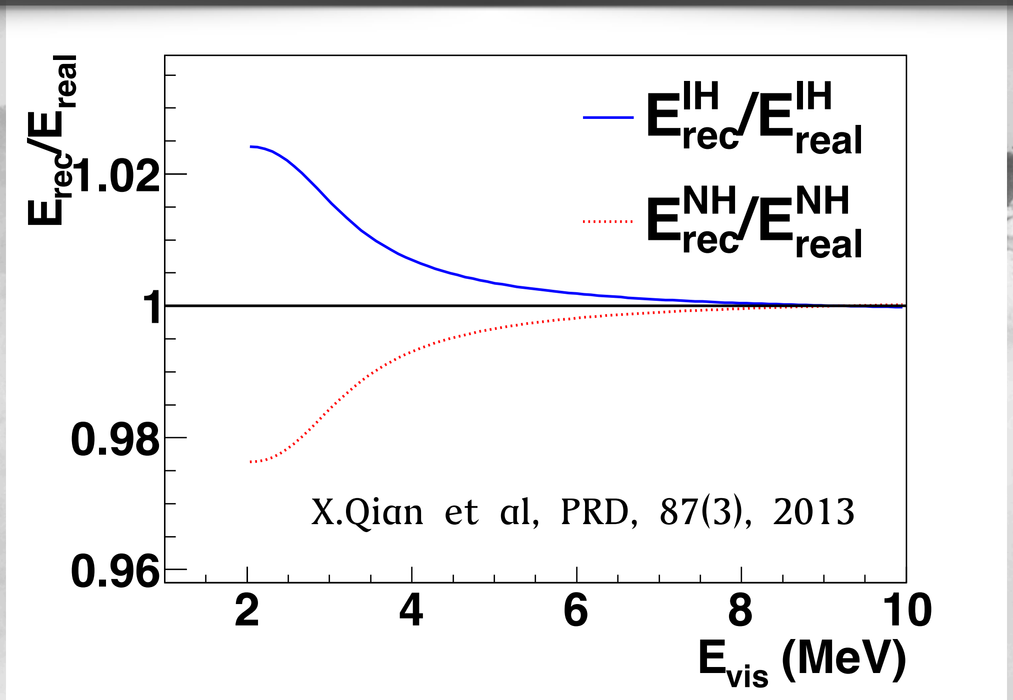
JUNO in brief

World's largest (20kt)
liquid scintillator detector



Energy Accuracy (Sub-% systematics control)
Energy Precision (~3% resolution@1MeV)

Example: Energy systematics (unnoticed non-linearity) → Misinterpretation of MO



Liquid Scintillator Neutrino Detector

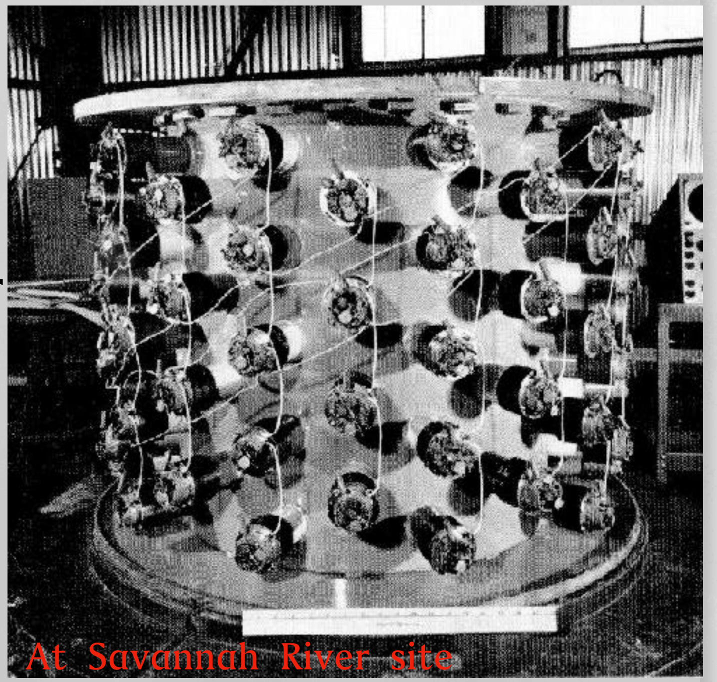
—one of the most successful and widely used neutrino detection technology

Liquid Scintillator Neutrino Detector

A few examples along history...

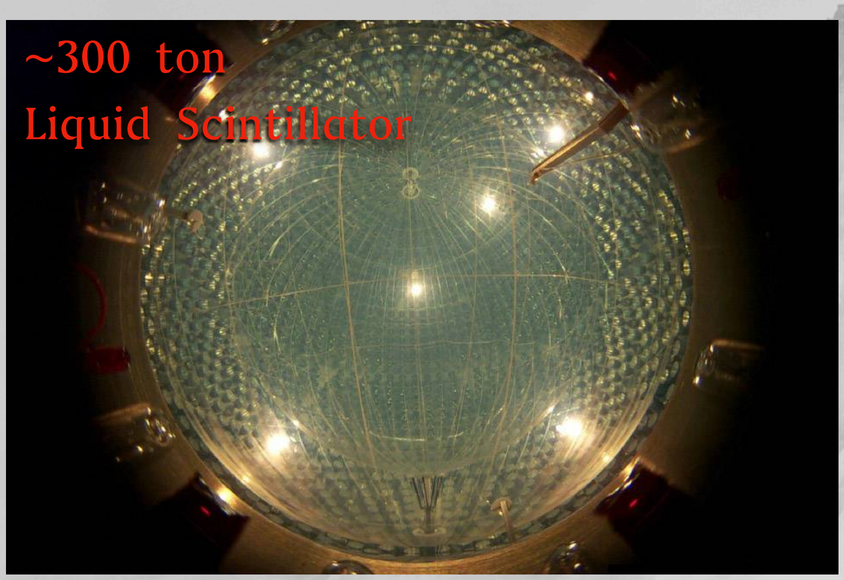
Reines and Cowan
liquid scintillator counter

"Discovery of neutrino"
(1950s)

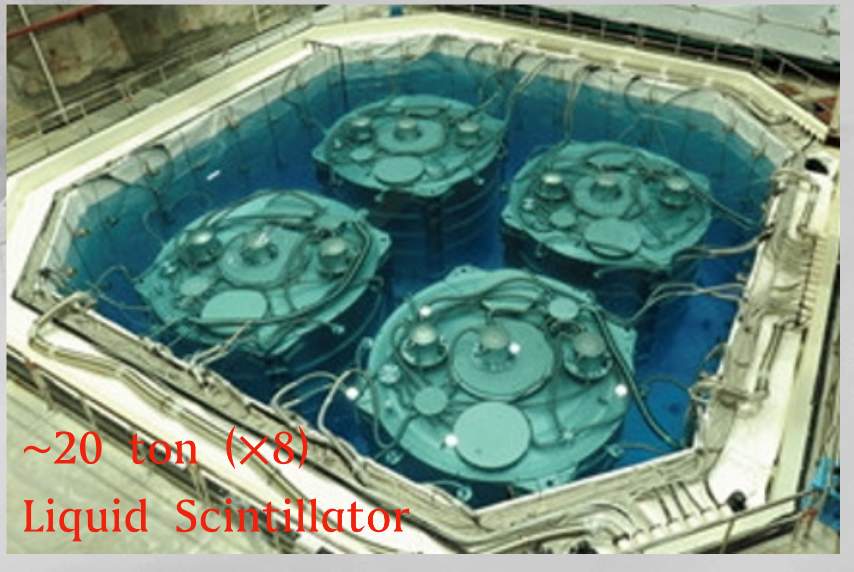


KamLAND Detector
(2002~now)
(Kamioka Liquid Scintillator Antineutrino Detector)
"Reactor neutrino oscillation"

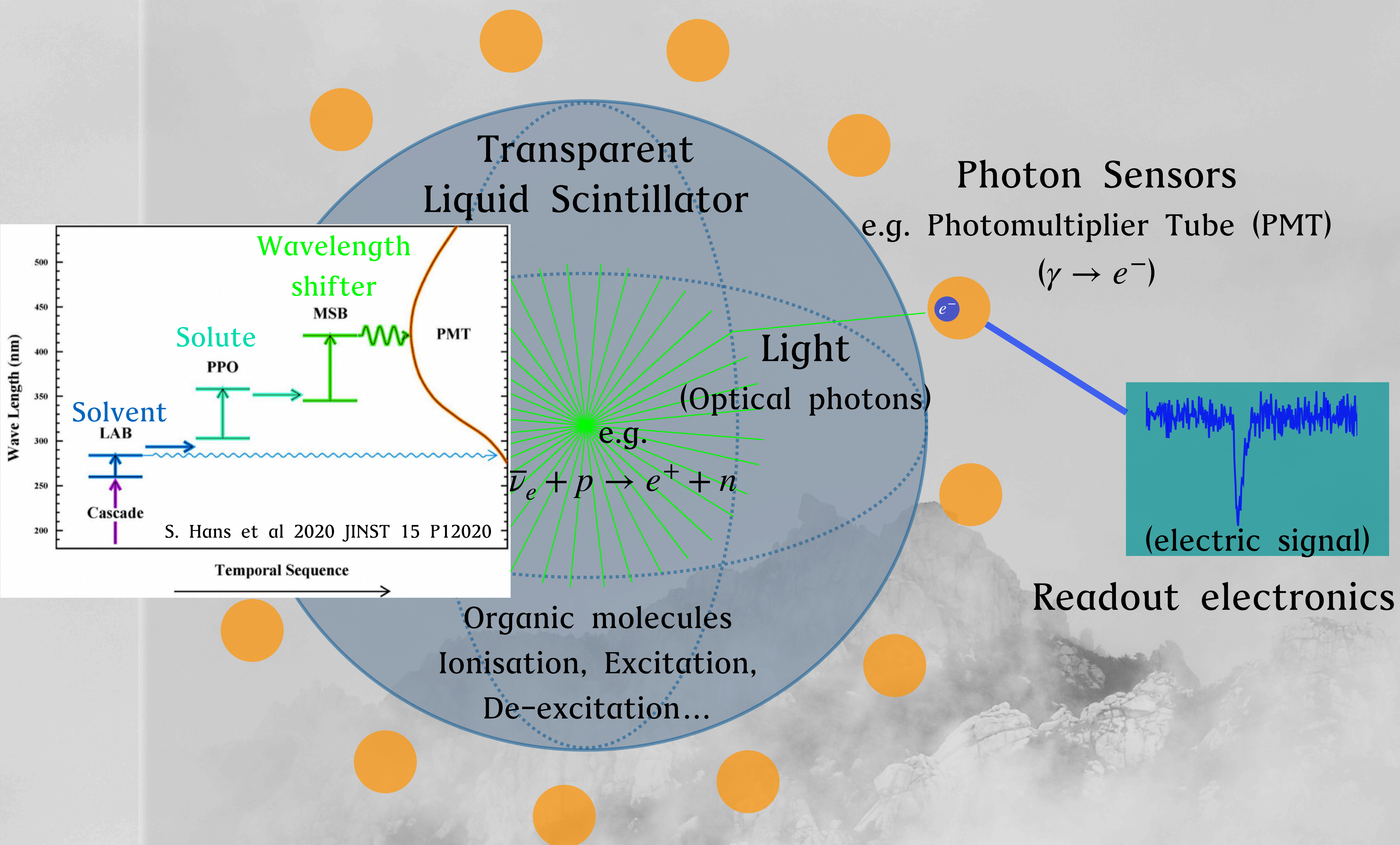
Borexino Detector (2007~now)
"Solar neutrino detection"



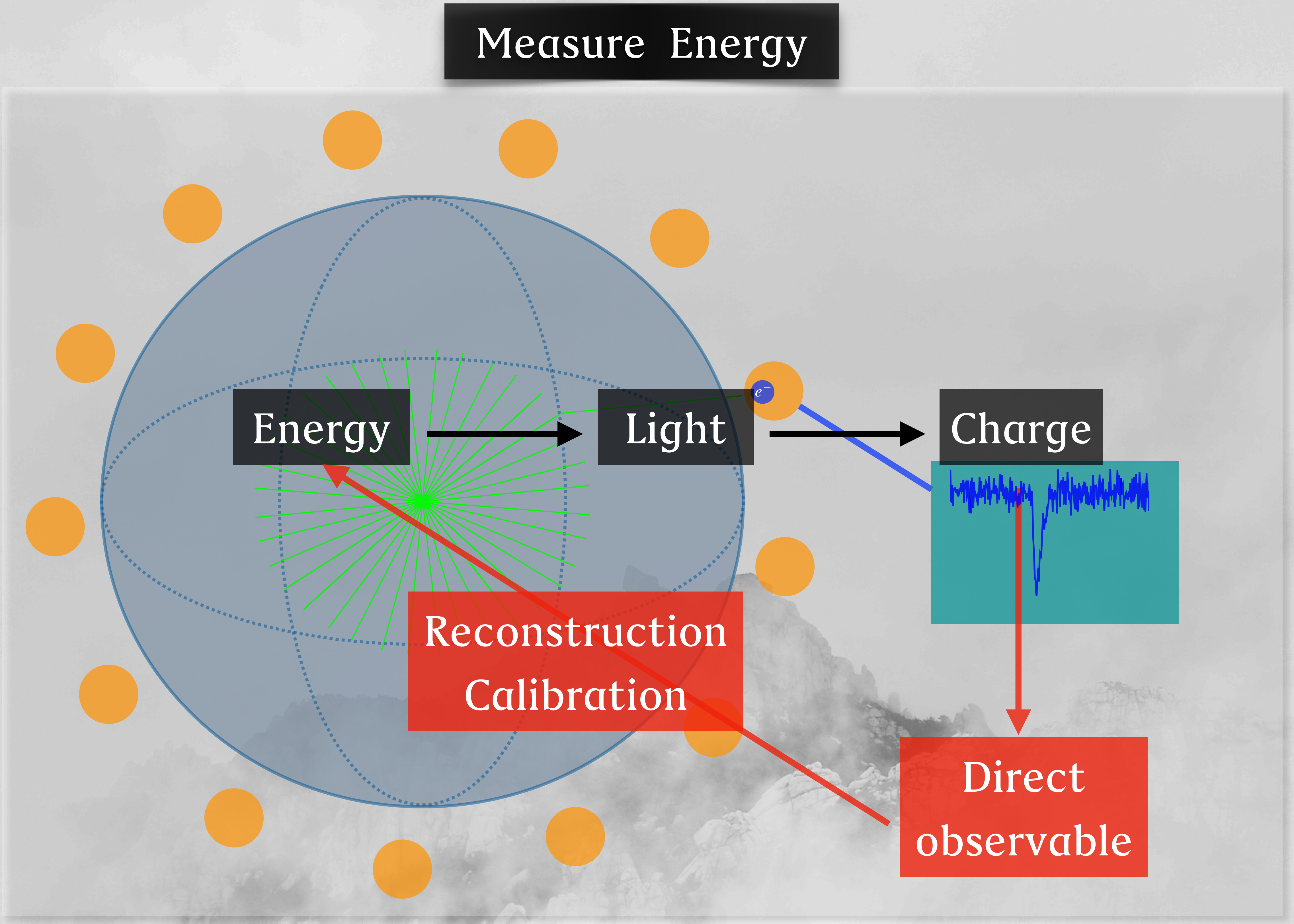
Daya Bay Detector (2011~2020)
"Neutrino oscillation θ_{13}"



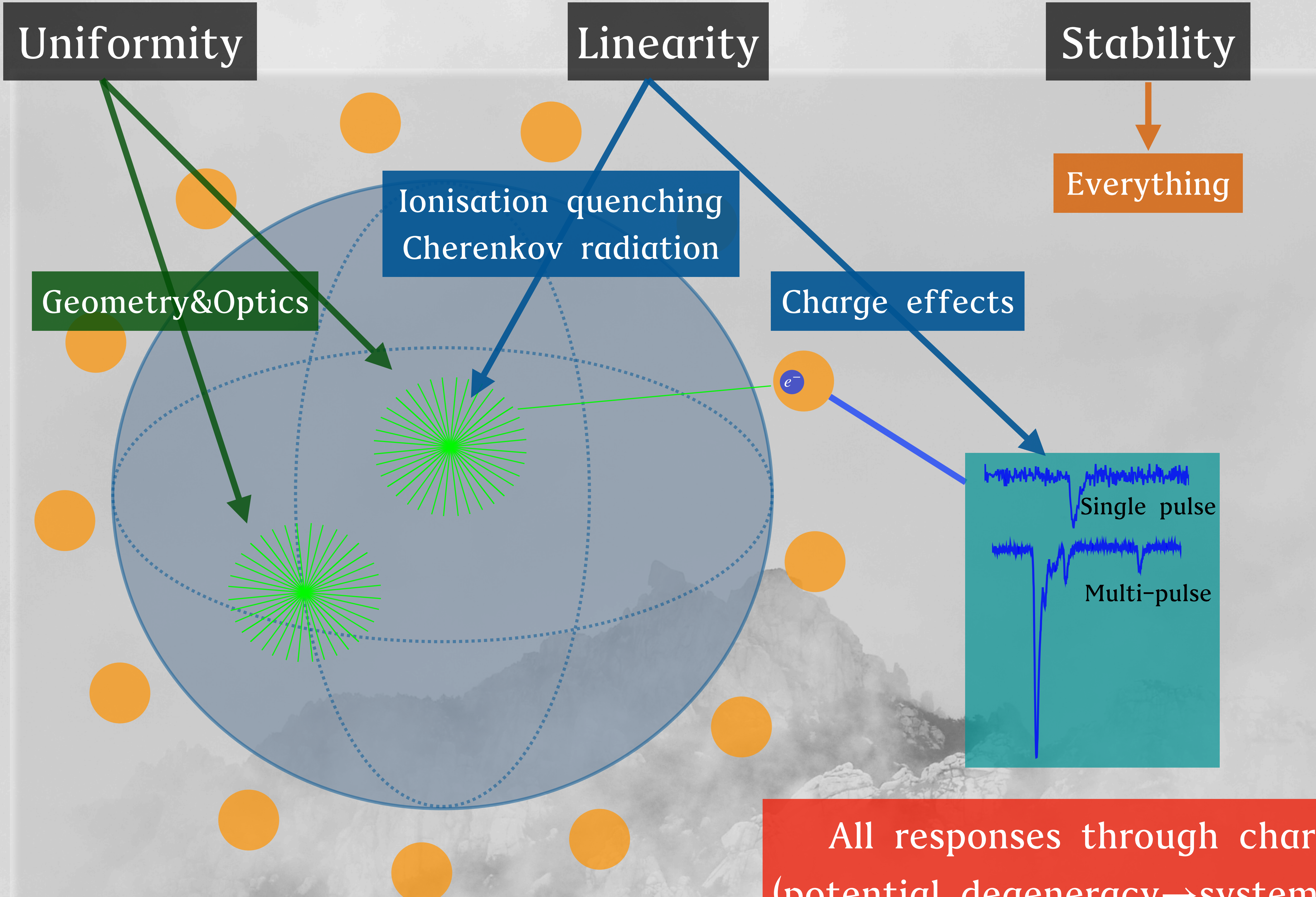
Main Components



Calorimetric Aspect



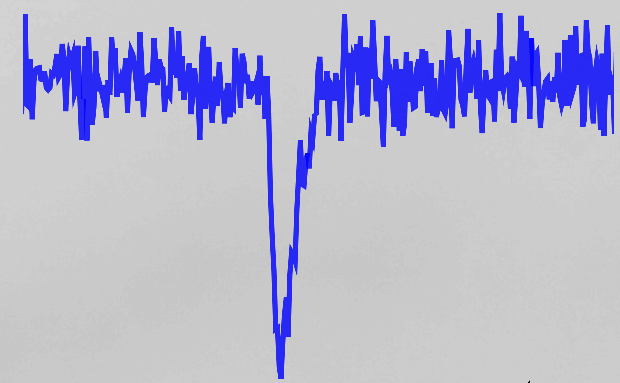
Calorimetric Responses



All responses through charge
(potential degeneracy→systematics)

Calorimetry in terms of charge

Small (enough) pixel
Photon sensor

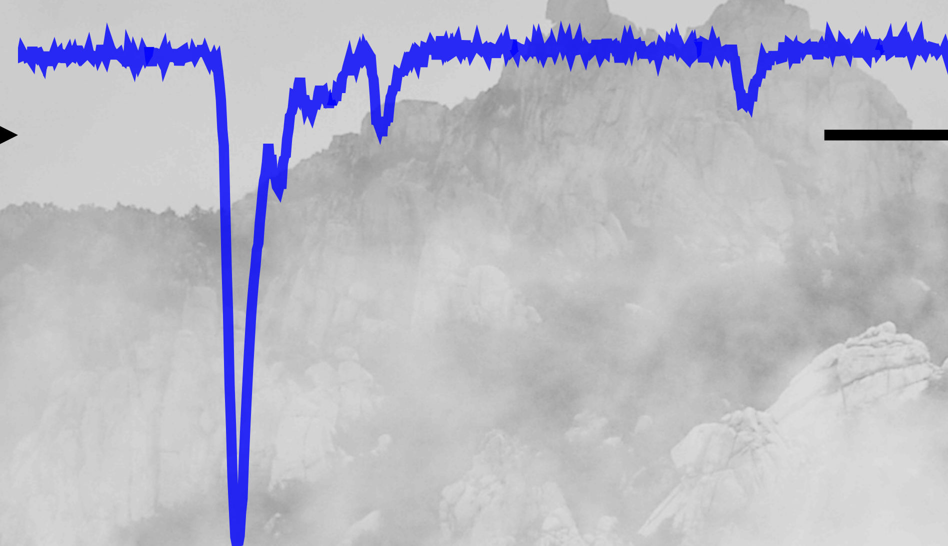


Single charge pulse (always)

"Counting" 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

	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%

*Physics (energy) dependent

Calorimetry examples

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Large pixel
(coverage&channels)
Cost effective

L.J. Wen et al. NIM.A 947 (2019) 162766

Single
"Integration"
Calorimetry*

Systematics
~
Detector size

*Physics (energy) dependent

Calorimetry examples

	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
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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

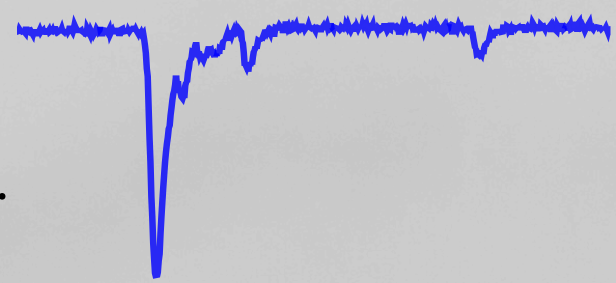
Calorimetric challenge

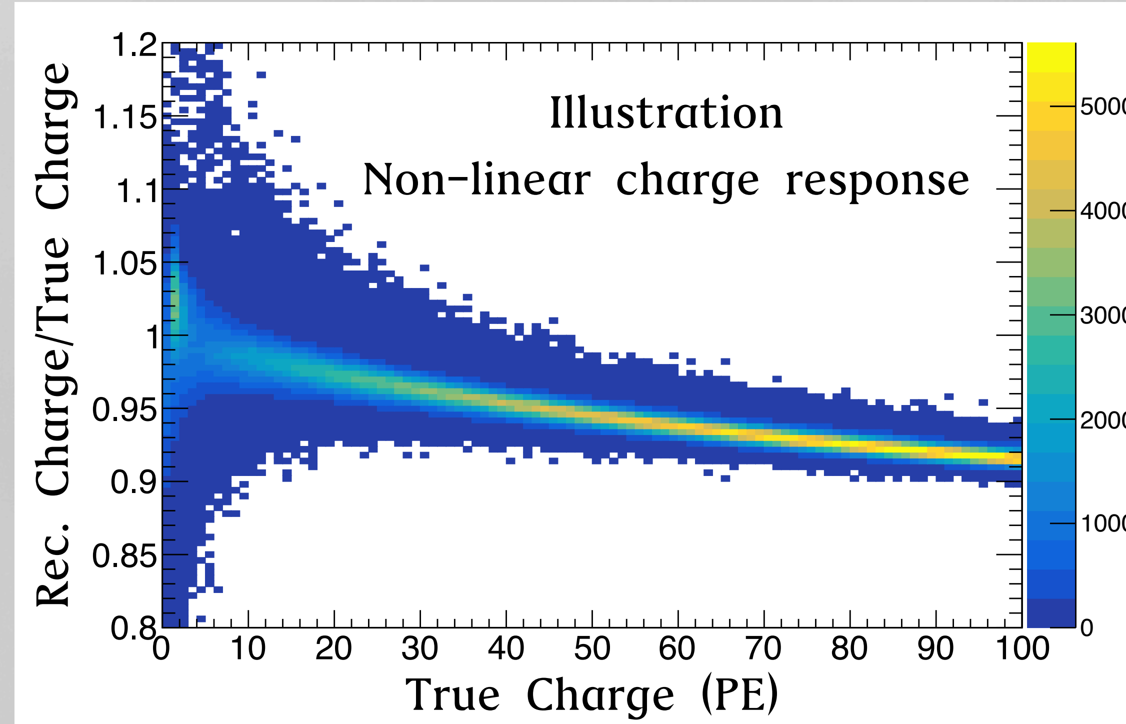
in "integration" Calorimetry

- Direct charge response control.

  PMT charge pulse waveform reconstruction.

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



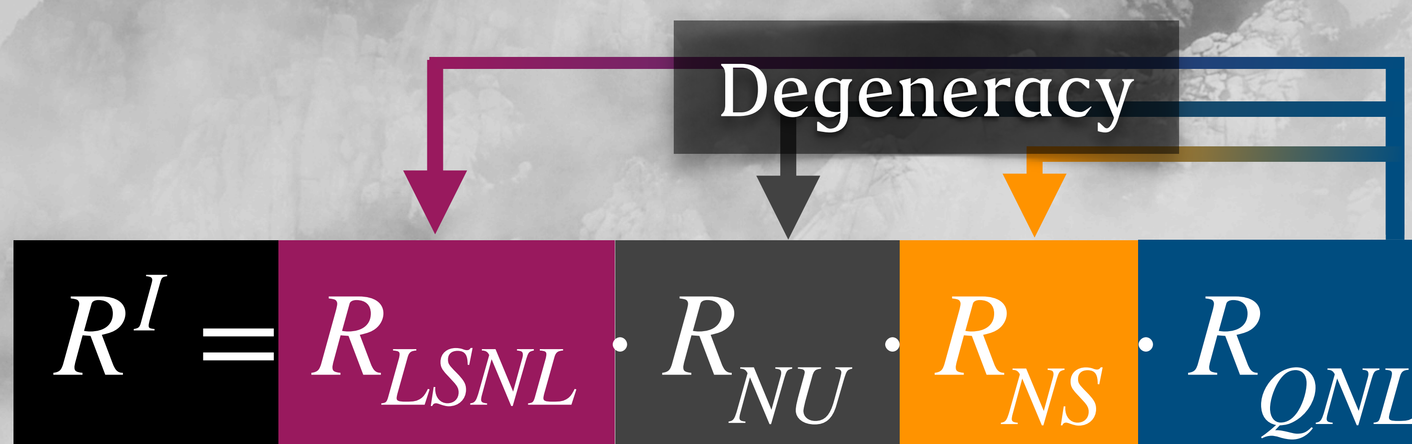


  Challenging systematics control,

  even for diagnosis…

- Response degeneracy

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



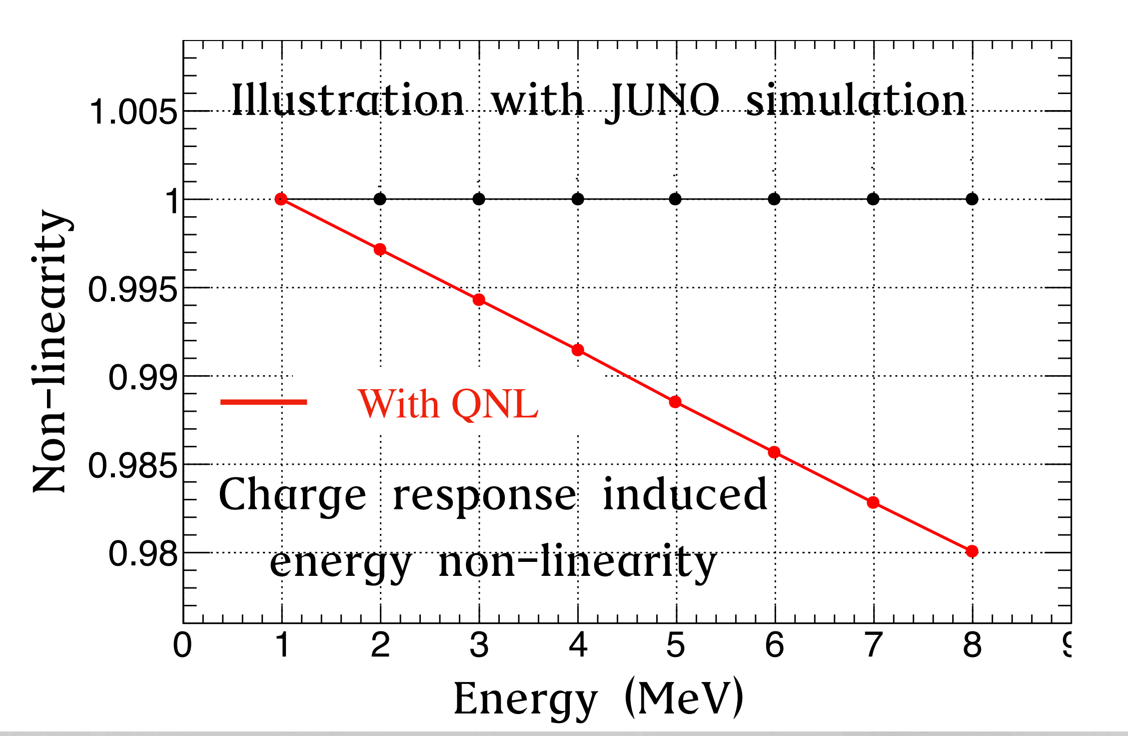
$$R^I = R_{LSNL} \cdot R_{NU} \cdot R_{NS} \cdot R_{QNL}$$

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

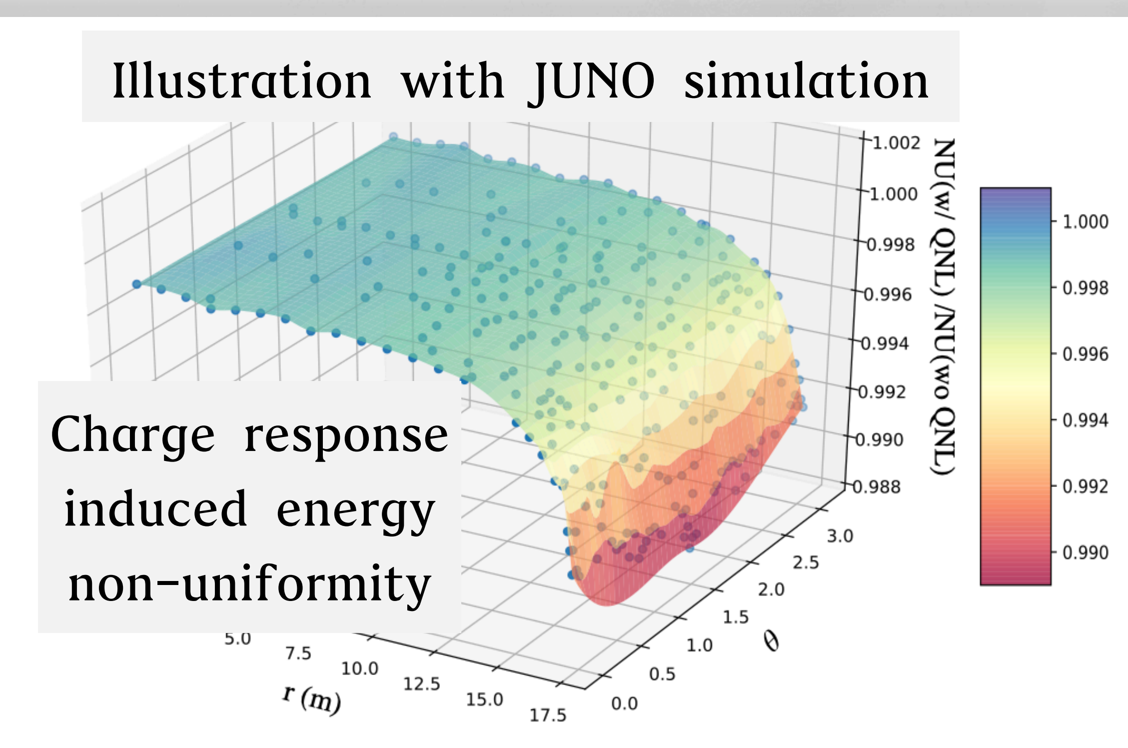
Calorimetric challenge

Response degeneracy examples:

- Energy non-linearity induced by charge response



- Energy non-uniformity mimicked by charge response

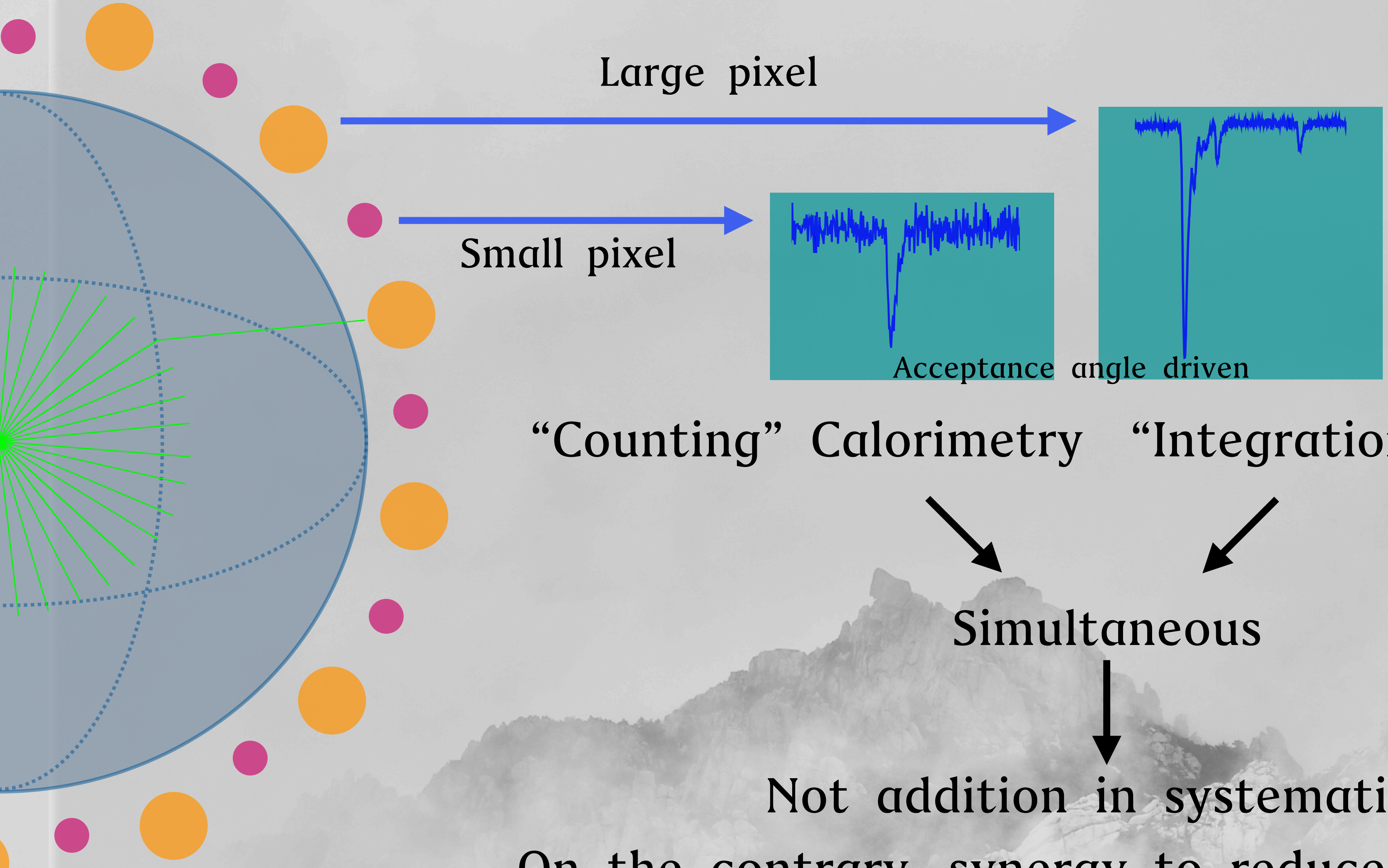


Challenge for diagnosis&calibration in single calorimetry!

Multi Calorimetry

—for high precision calorimetry systematics control

Multi Calorimetry Concept



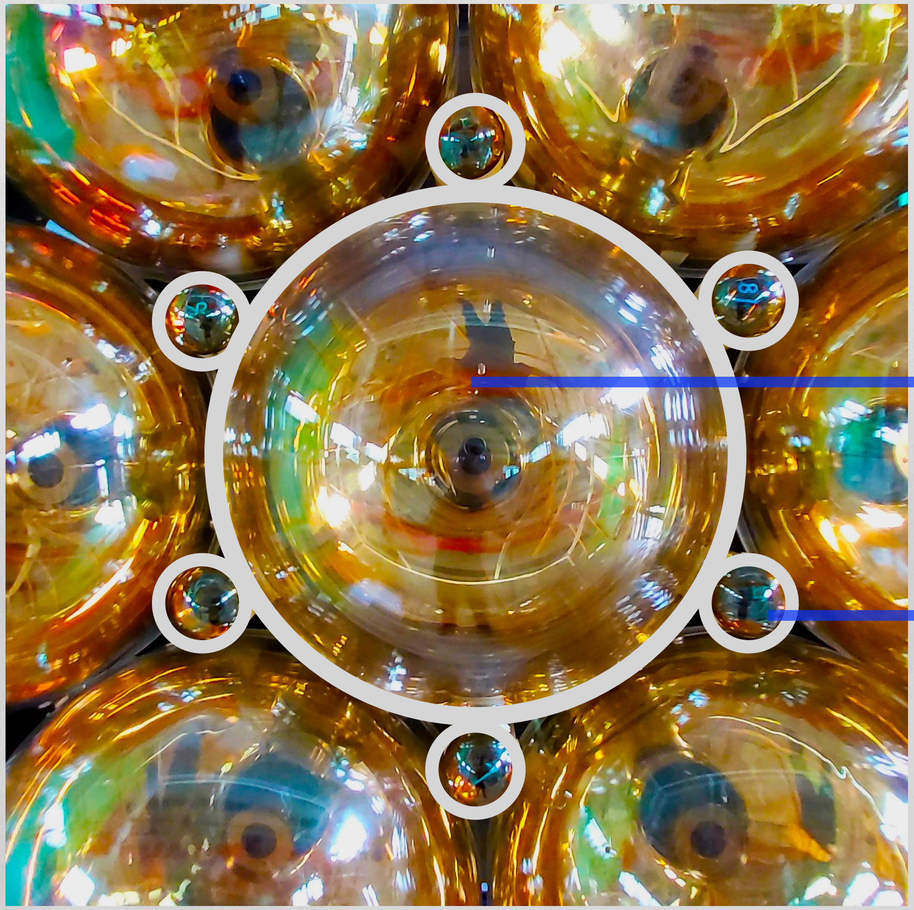
“Counting” Calorimetry “Integration” Calorimetry

Simultaneous

Not addition in systematics.

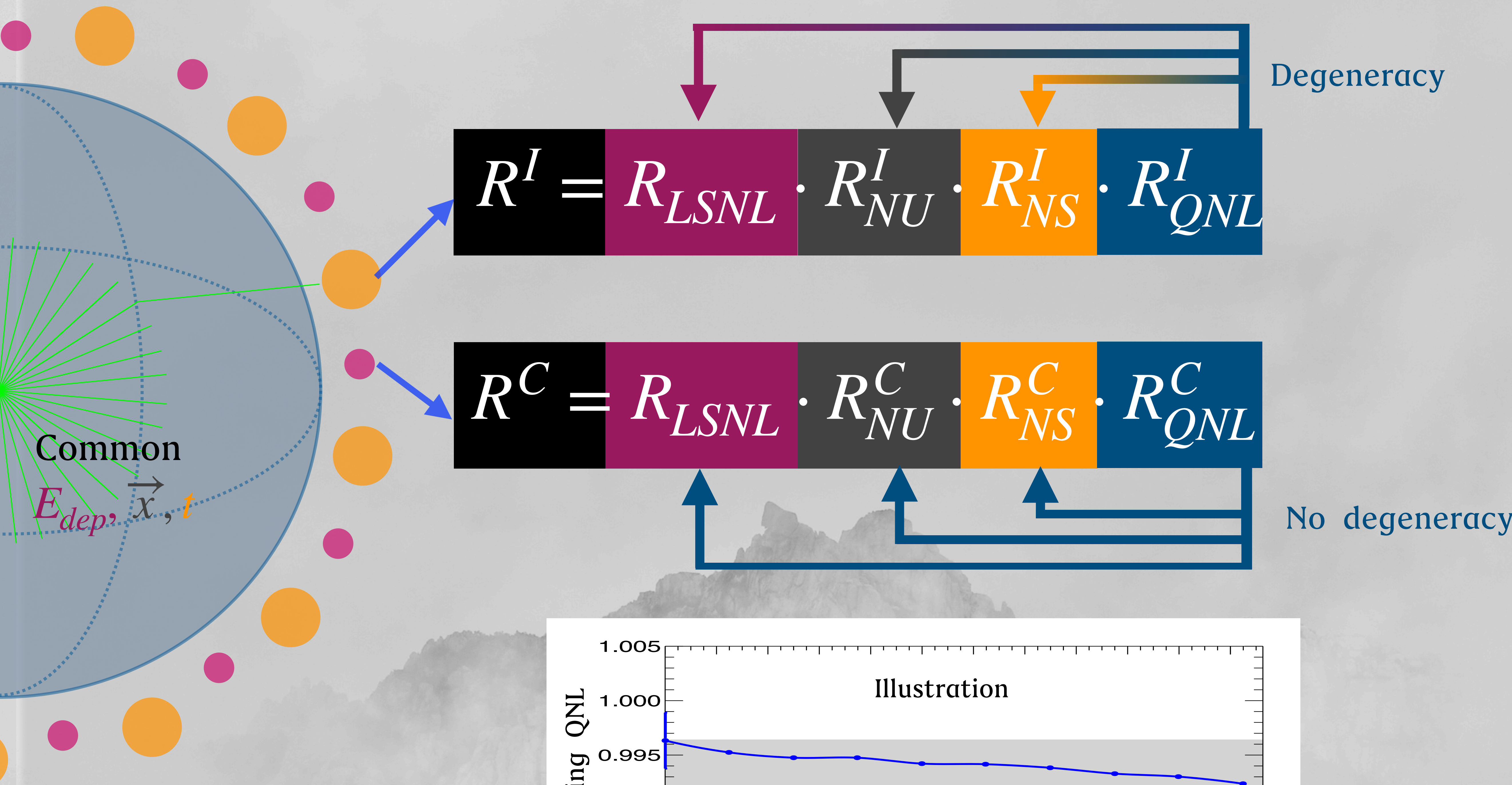
On the contrary, synergy to reduce systematics.

Dual Calorimetry@JUNO



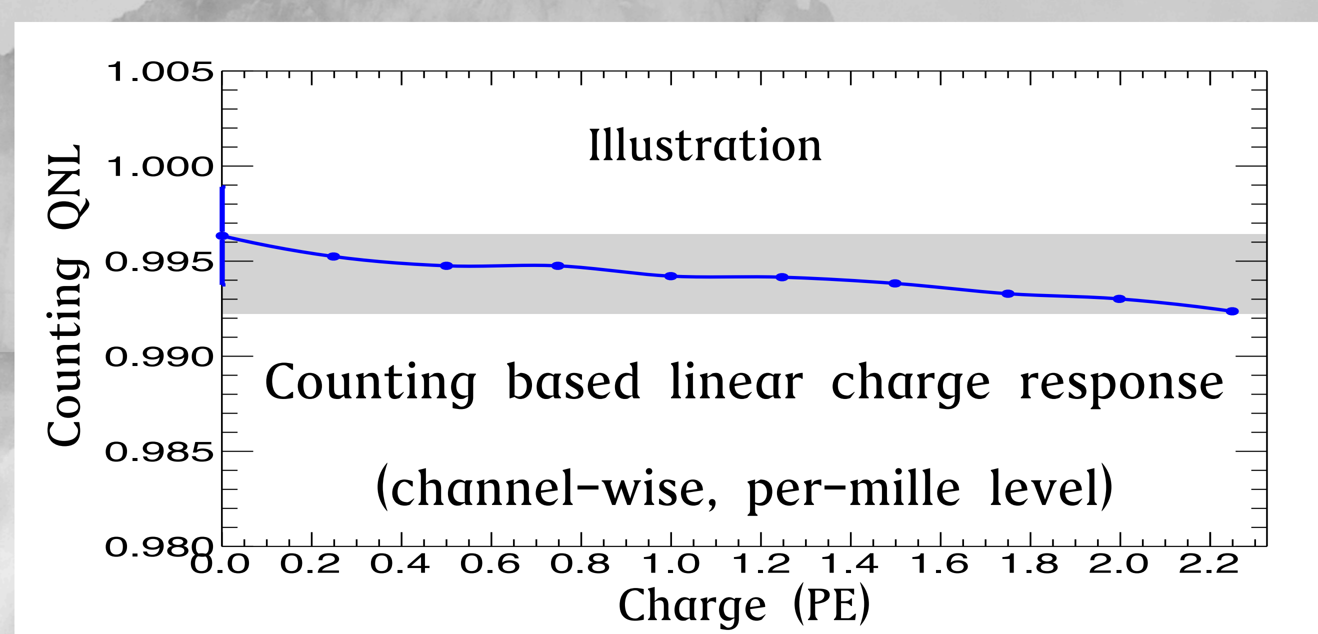
	Target Mass (ton)	Nb. of PMTs	PMT Dimension (inch)	Light Yield (PE/MeV)	Single PMT mean illumination @1MeV@center	Single PMT charge range (For 1~10 MeV)	Energy systematics
JUNO	20,000	~18,000 (main)	20-inch (main)	~1300	~0.1	1~100PE	<1% (required)
		~25,600 (secondary)	3-inch (secondary)	~50	~0.002	1PE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

Multi Calorimetry Principle

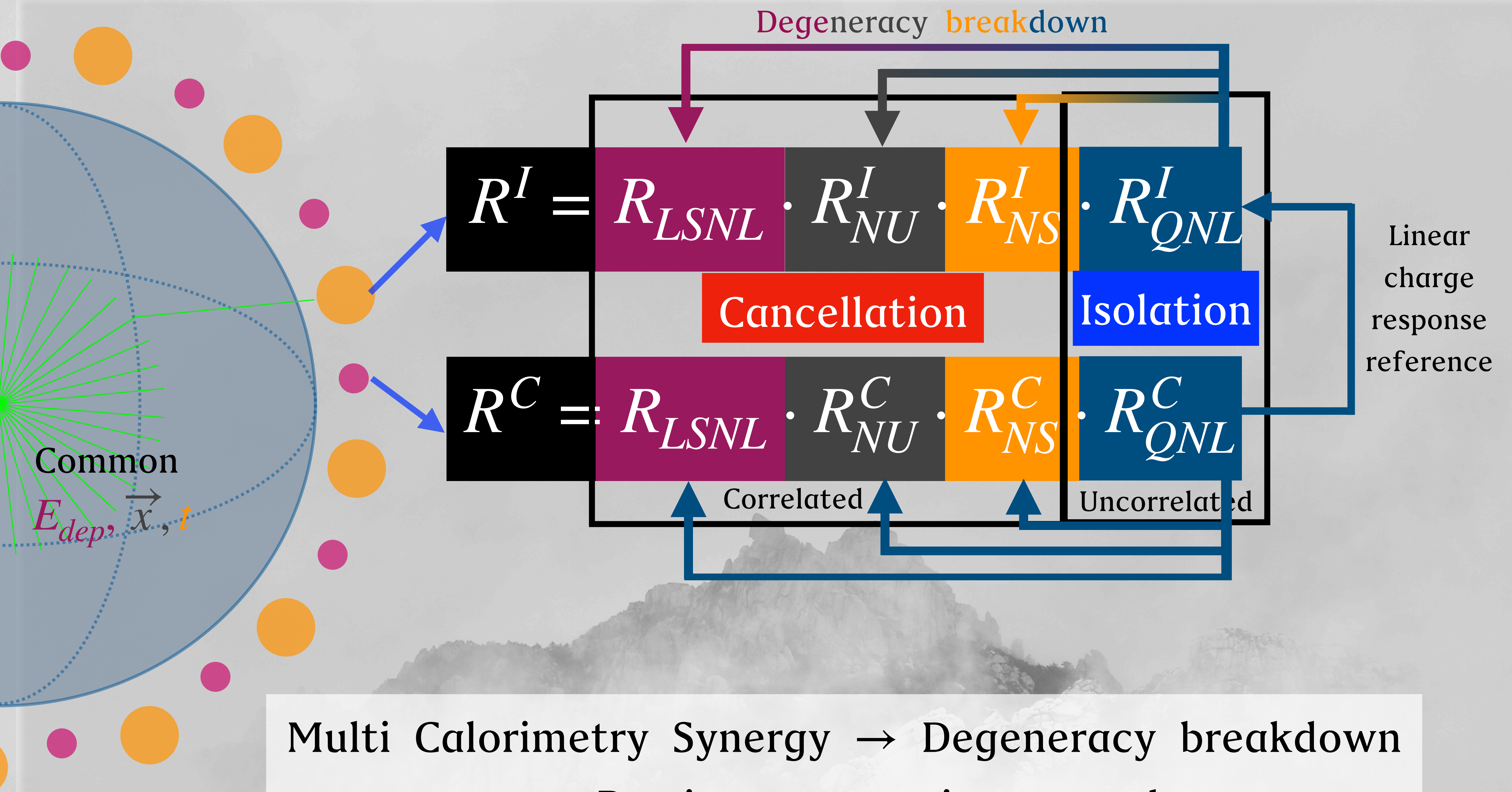


$$R^I = R_{LSNL} \cdot R^I_{NU} \cdot R^I_{NS} \cdot R^I_{QNL}$$

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



Multi Calorimetry Principle



Multi Calorimetry Synergy → Degeneracy breakdown

→ Precise systematics control

Skip detailed methodologies to reach Multi Calorimetry

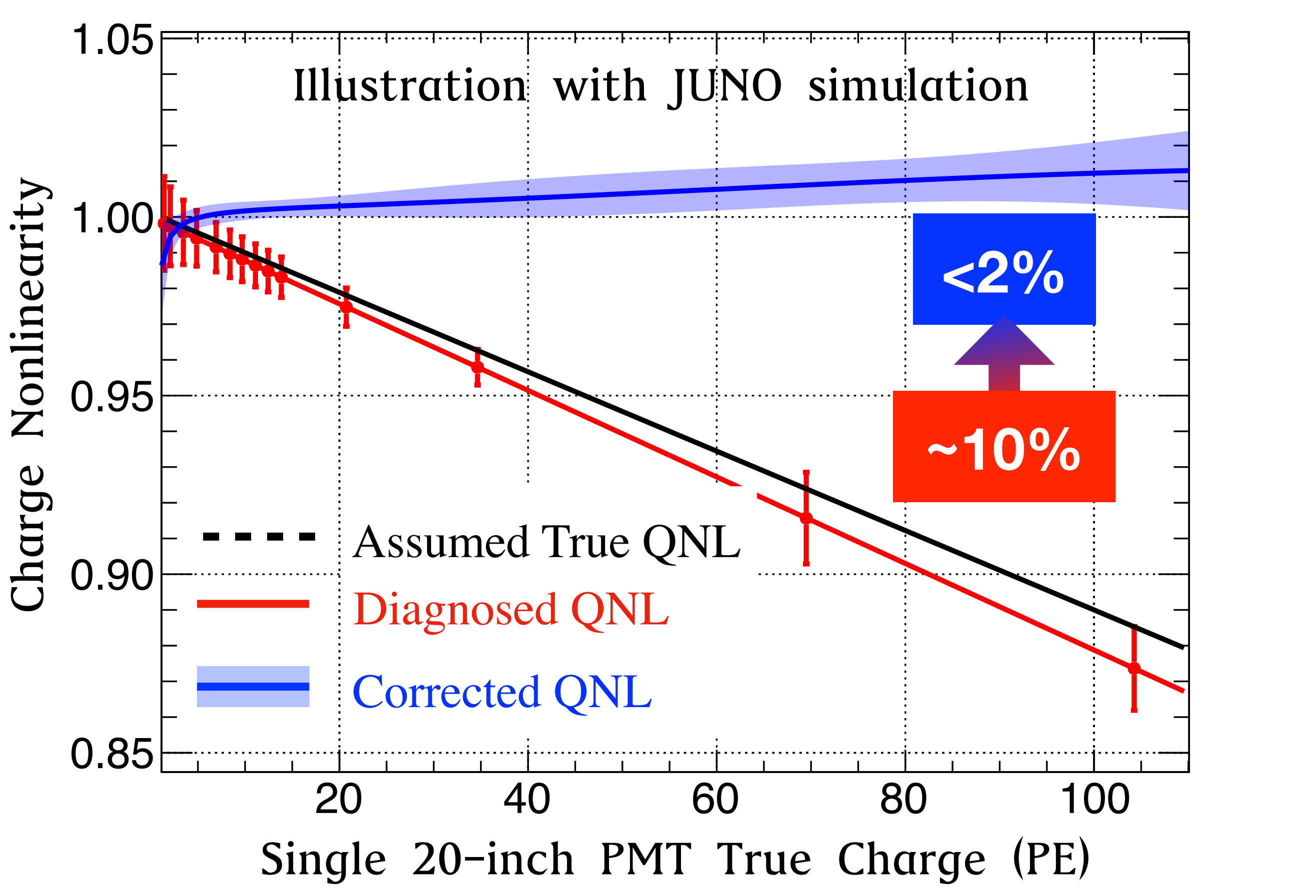
Focus on: potential precise systematics control in energy linearity and uniformity, with JUNO as an example

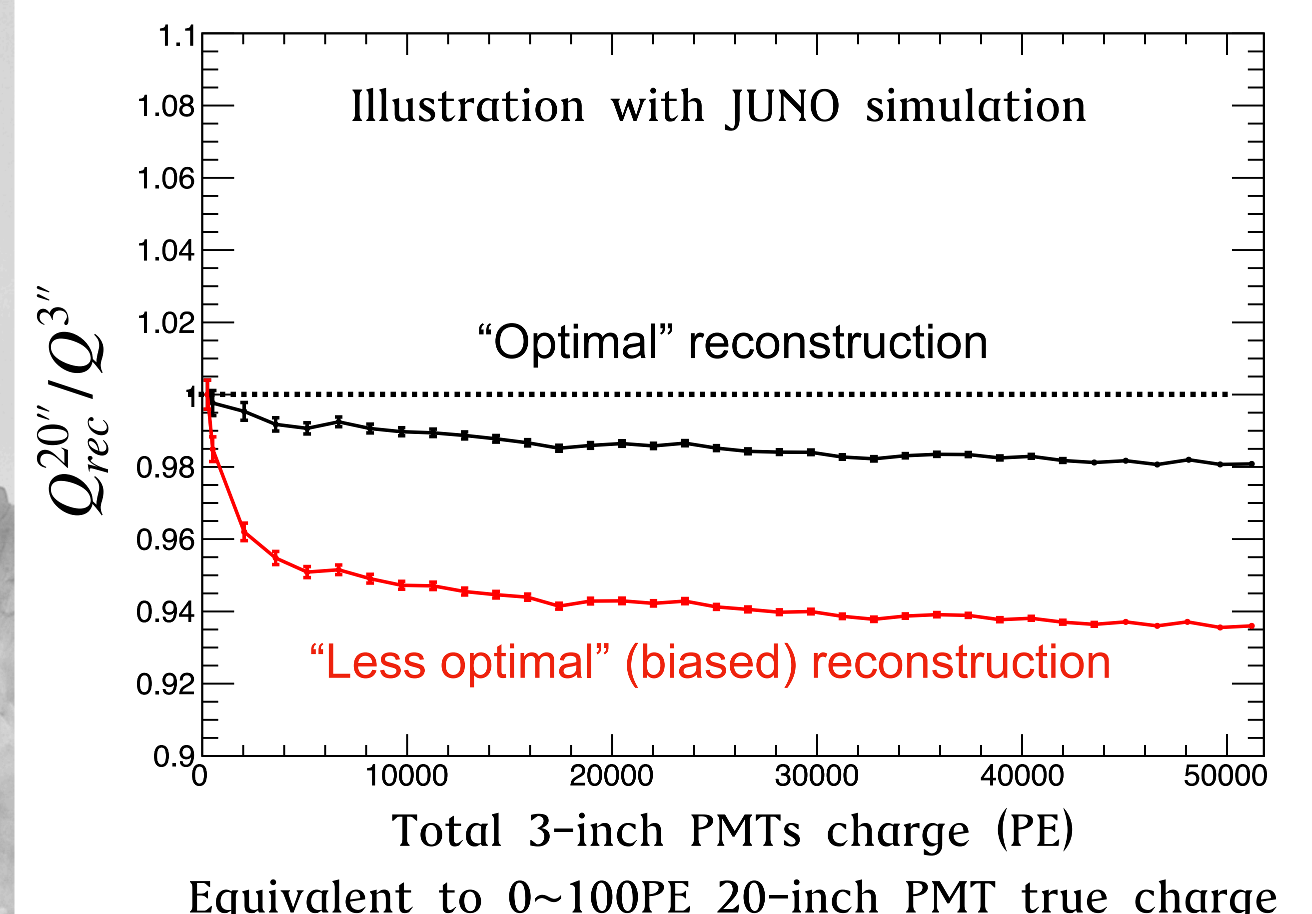
Multi Calorimetry Potentials

Direct charge response non-linearity (QNL) control

Through calibration ⊕ Through reconstruction

(e.g. waveform deconvolution)

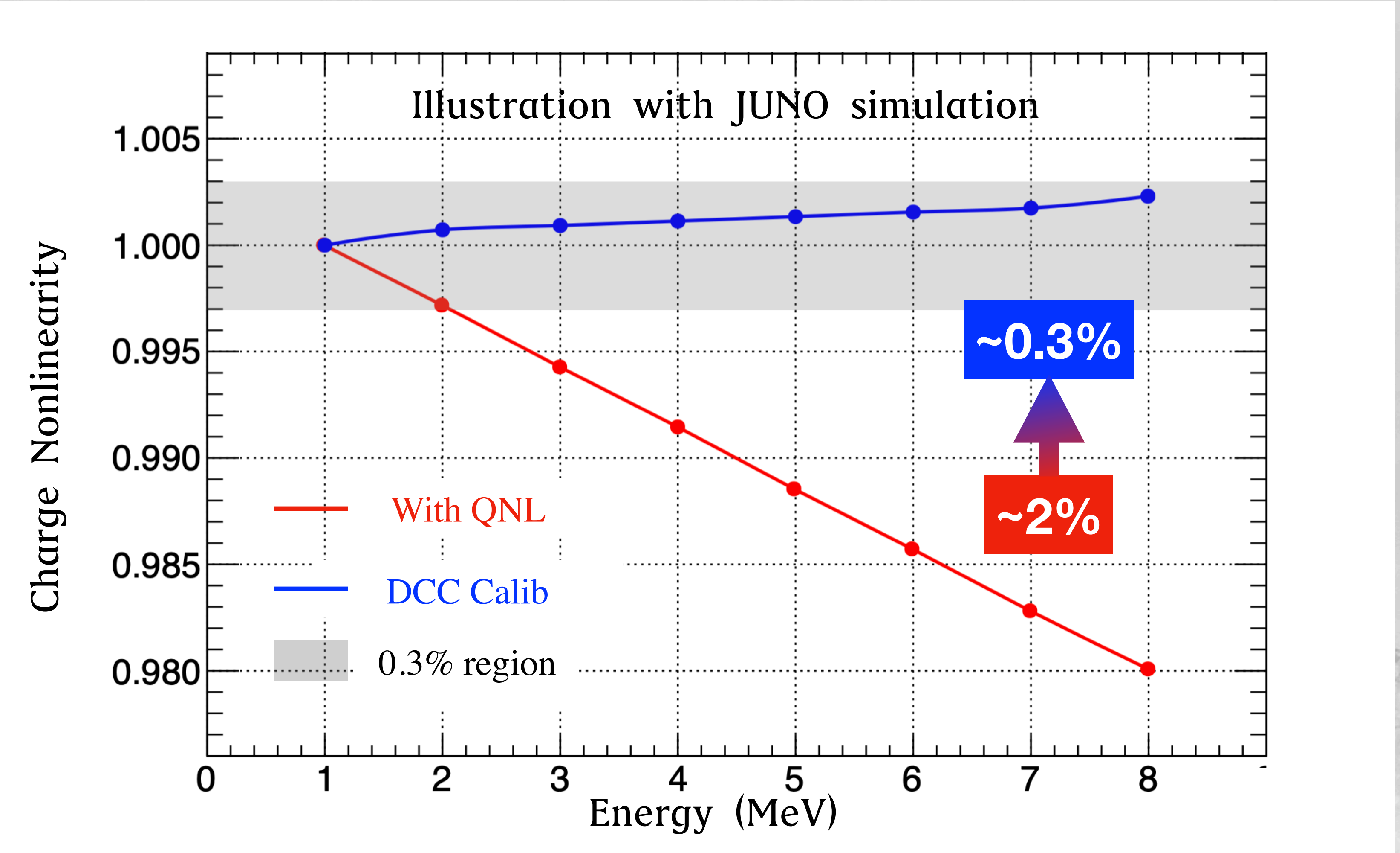




Multi Calorimetry Potentials

Degeneracy breakdown

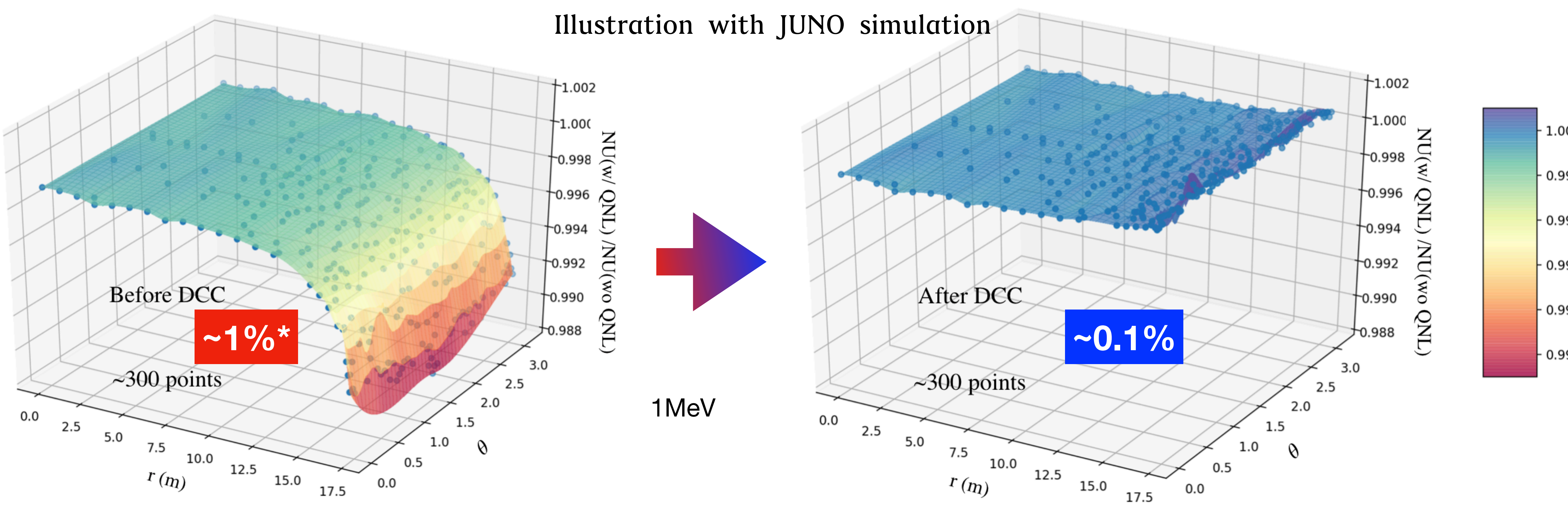
Charge response induced energy non-linearity control



Multi Calorimetry Potentials

Degeneracy breakdown

Charge response mimicked energy non-uniformity control



Conclusion

Neutrino oscillation in high precision measurement era.

Huge Detector $\otimes$ Precise Systematics Control $\otimes$ Cost ...

↑

Multi Calorimetry offers an option.

For JUNO (already), and also beyond...