JUNO

(double calorimetry)

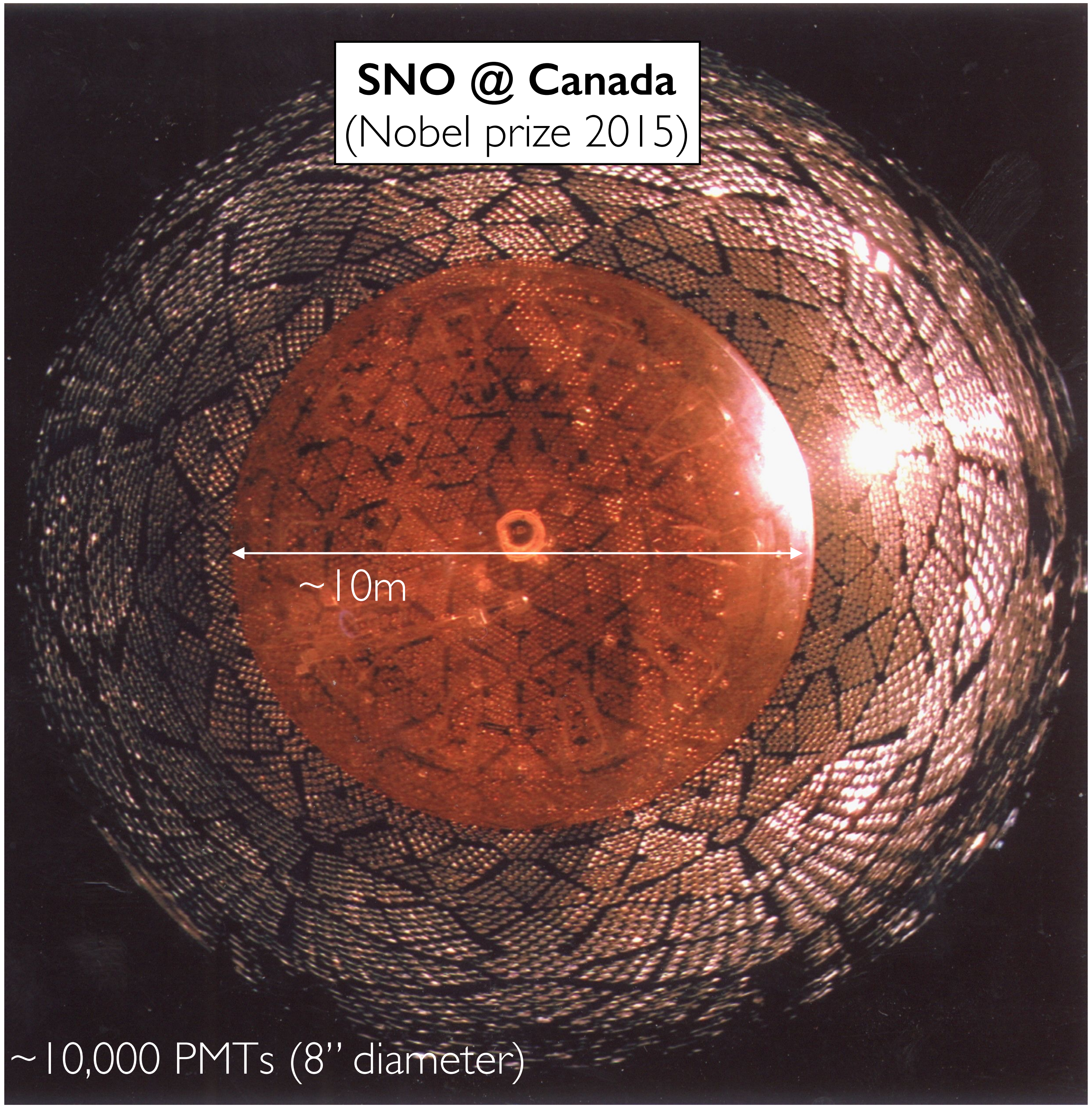
seminar

APC, Paris, France — March 2016

Anatael Cabrera

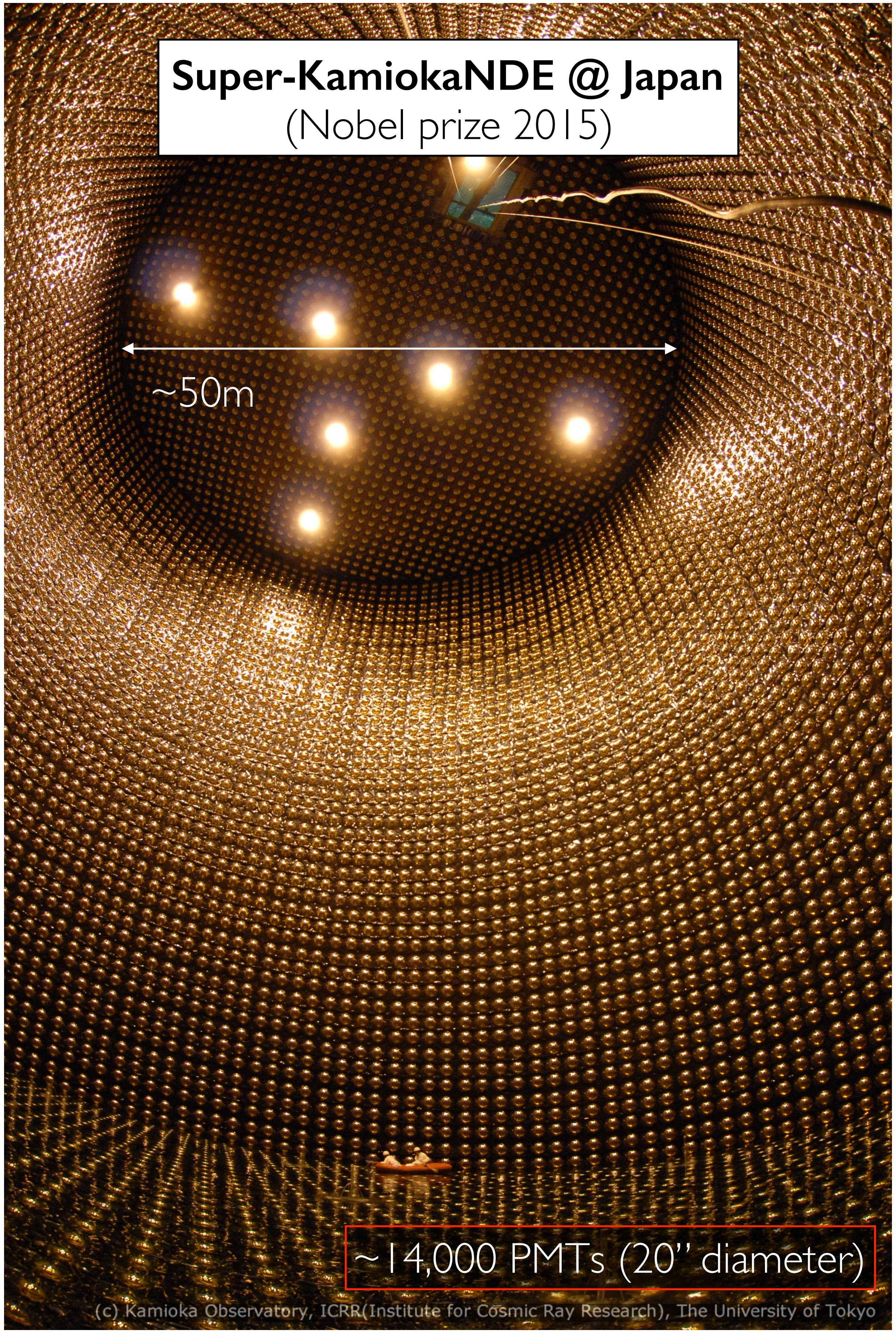
CNRS / IN2P3 @ APC (Paris)

the JUNO detector (predecessors)…



SNO @ Canada
(Nobel prize 2015)

~10,000 PMTs (8'' diameter)



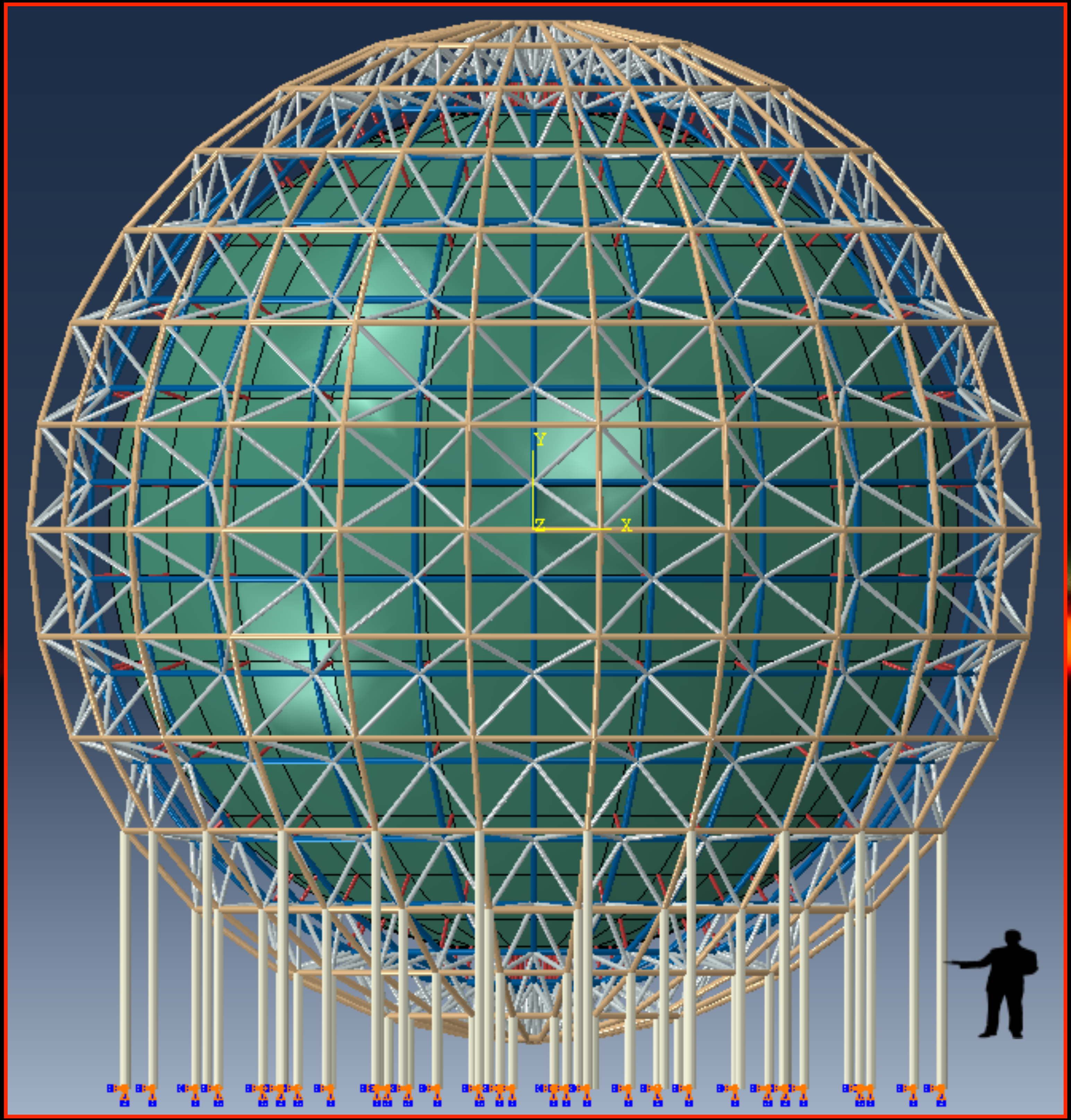
Super-KamiokaNDE @ Japan
(Nobel prize 2015)

~14,000 PMTs (20'' diameter)

(c) Kamioka Observatory, ICRR(Institute for Cosmic Ray Research), The University of Tokyo

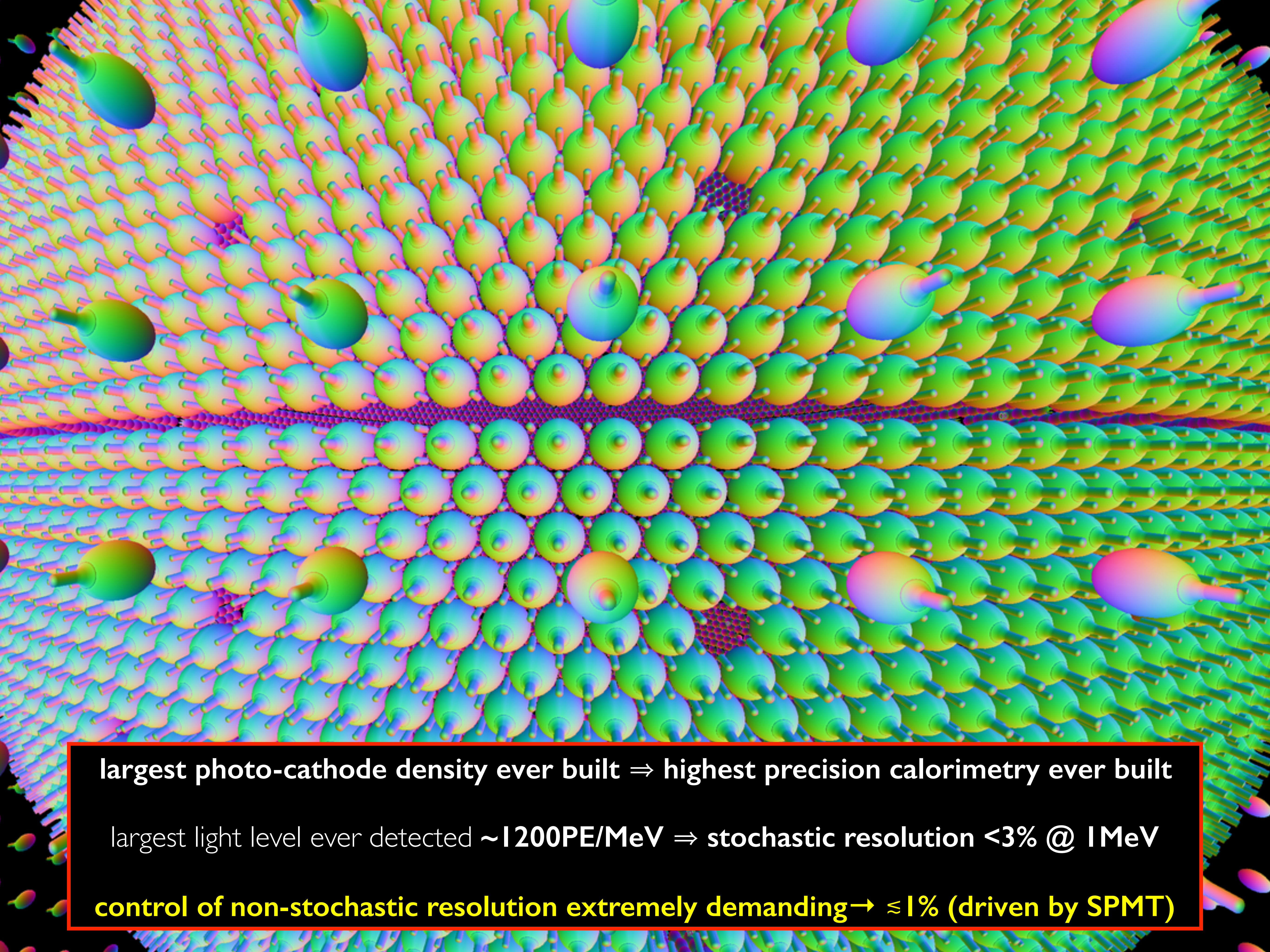
JUNO can be regarded as a hybrid of both…
(filled with liquid-scintillator➝ **~100x more light**)

JUNO neutrino detector system…



~1/2x SuperKamiokaNDE
~20x KamLAND/SNO
~600x DC or ~300 DYB

- JUNO detector major requirement (MH)
    - **high precision calorimetry**
        - highest light yield: **~1.2kPE/MeV**
        - systematics control (transparency)
    - **must be large** (reactors @ ~50km)
        - → over-designed for all other physics
- ~20kt spherical liquid scintillator detector
    - ~1.5m of buffer (isolation + optics)
    - **~18k 20" PMTs** (~80% photo-coverage)
    - **~36k 3" PMTs (calorimetry control)**
    - excellent μ-tracking→**^{9}Li+^{8}He rejection**
- cylindrical water pool system (surrounding)
    - shield (radioactivity + fast-n moderator)
    - muon active veto (Water-Cherenkov)
- top-tracker detector systems (→OPERA)
    - stopping-muons & fast-neutrons
    - critical complementarity to ν-detector
- →Borexino, DB, DC, KamLAND, SuperK, etc



largest photo-cathode density ever built ⇒ highest precision calorimetry ever built

largest light level ever detected **~1200PE/MeV ⇒ stochastic resolution <3% @ 1MeV**

control of non-stochastic resolution extremely demanding→ ≲1% (driven by SPMT)

double calorimetry…

control of systematics…

(i.e. non-stochastic effects)

Anatael Cabrera (CNRS-IN2P3 & APC)

our (very international) team…

>15 laboratories so far…

Brasil
- FABC (Sao Paulo)
- PUC (Rio de Janeiro)

Belgium
- UBL (Brussels)

Chile
- PUC (Santiago)

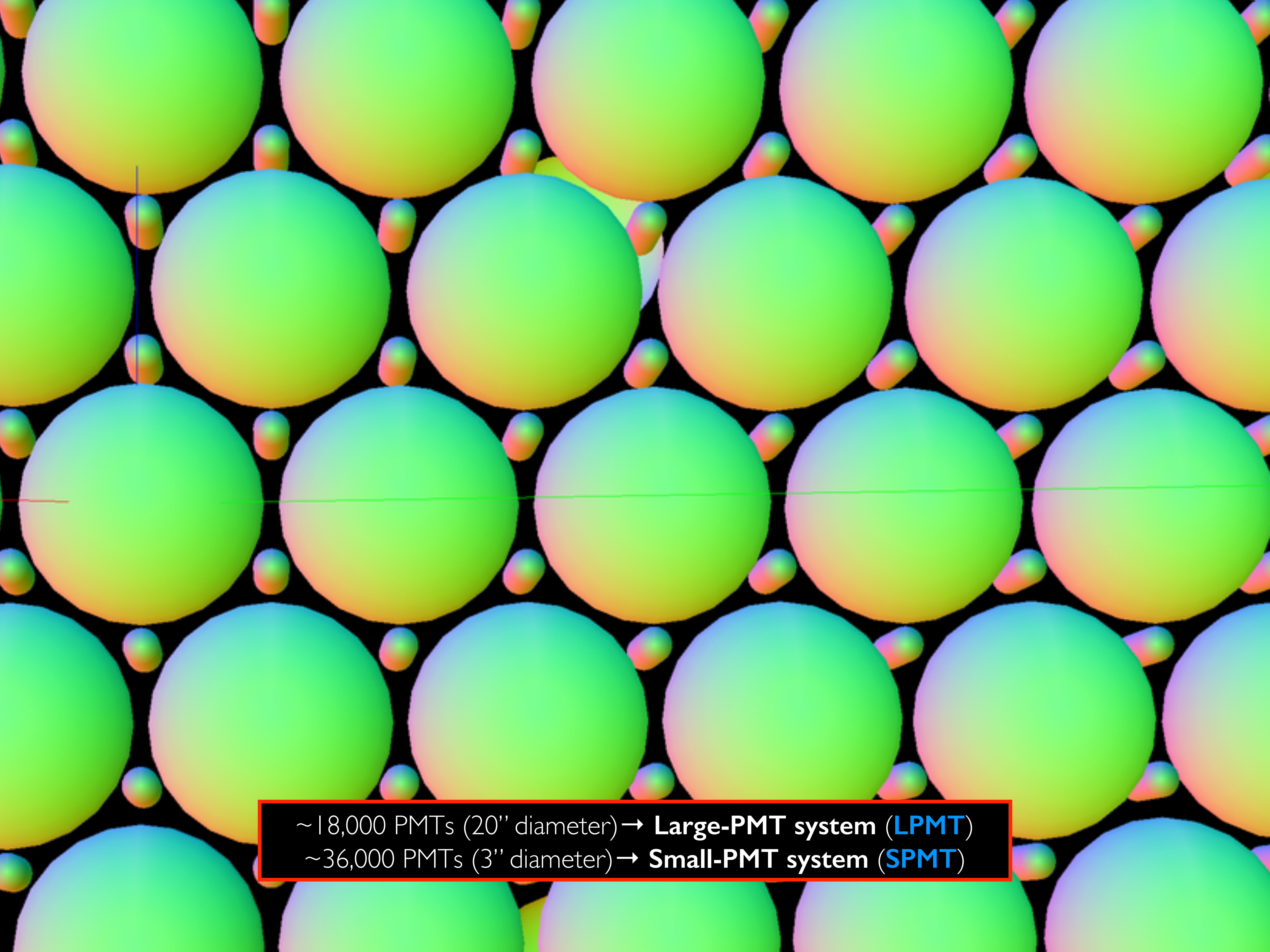
China
- IHEP (Beijing)
- SYSU (Guangzhou)

France
- APC (Paris) **(coordination)**
- CPPM (Marseille)
- LLR (Paris)
- OMEGA (Paris)
- SUBATECH (Nantes)

Italy
- Padova-INFN (Padova)

Taiwan
- National Taiwan University NTU (Taipei)
- National Chiao Tung University NCTU (Hsinchu)
- National United University NUU (Miaoli)

A **few more institutions joining**…



~18,000 PMTs (20” diameter)→ **Large-PMT system** (LPMT)
~36,000 PMTs (3” diameter)→ **Small-PMT system** (SPMT)

don’t forget…

SPMT is ***<u>anything but small</u>***

~36,000 PMTs is huge!

(only the PMTs are smaller→ circumstantial @ JUNO)

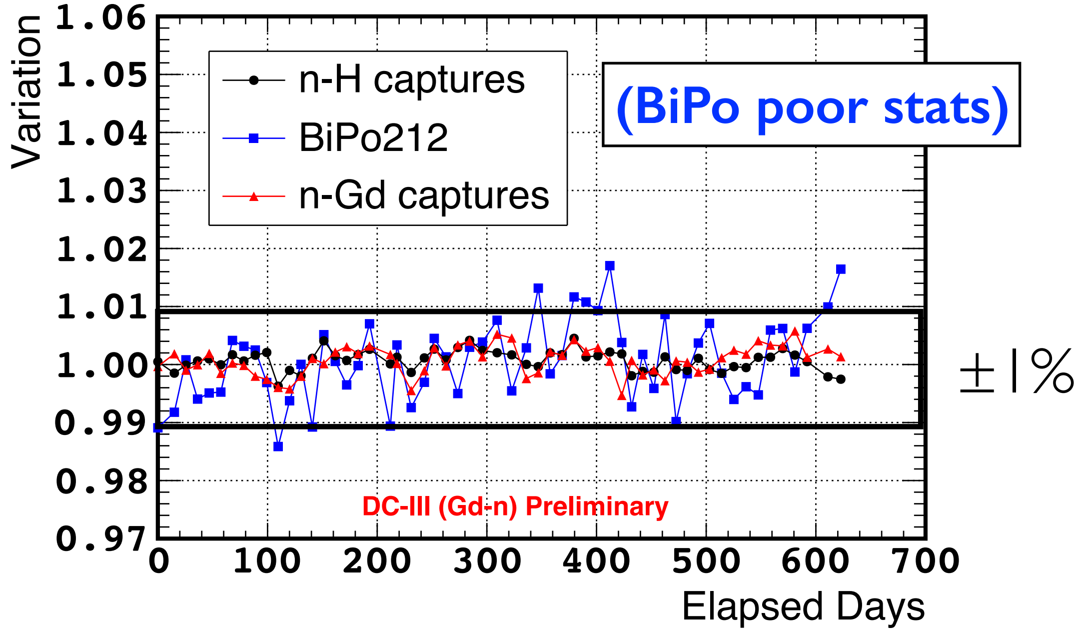
(this is ~1/3 of Hyper-KamiokaNDE readout)

motivation…

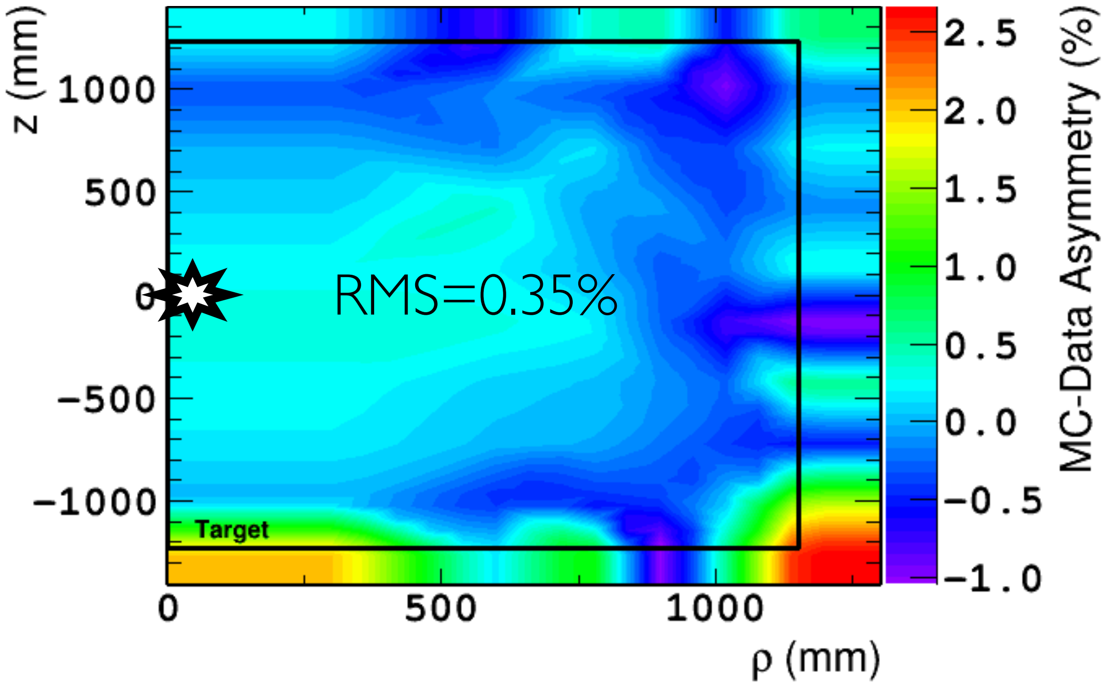
— why the SPMT? —

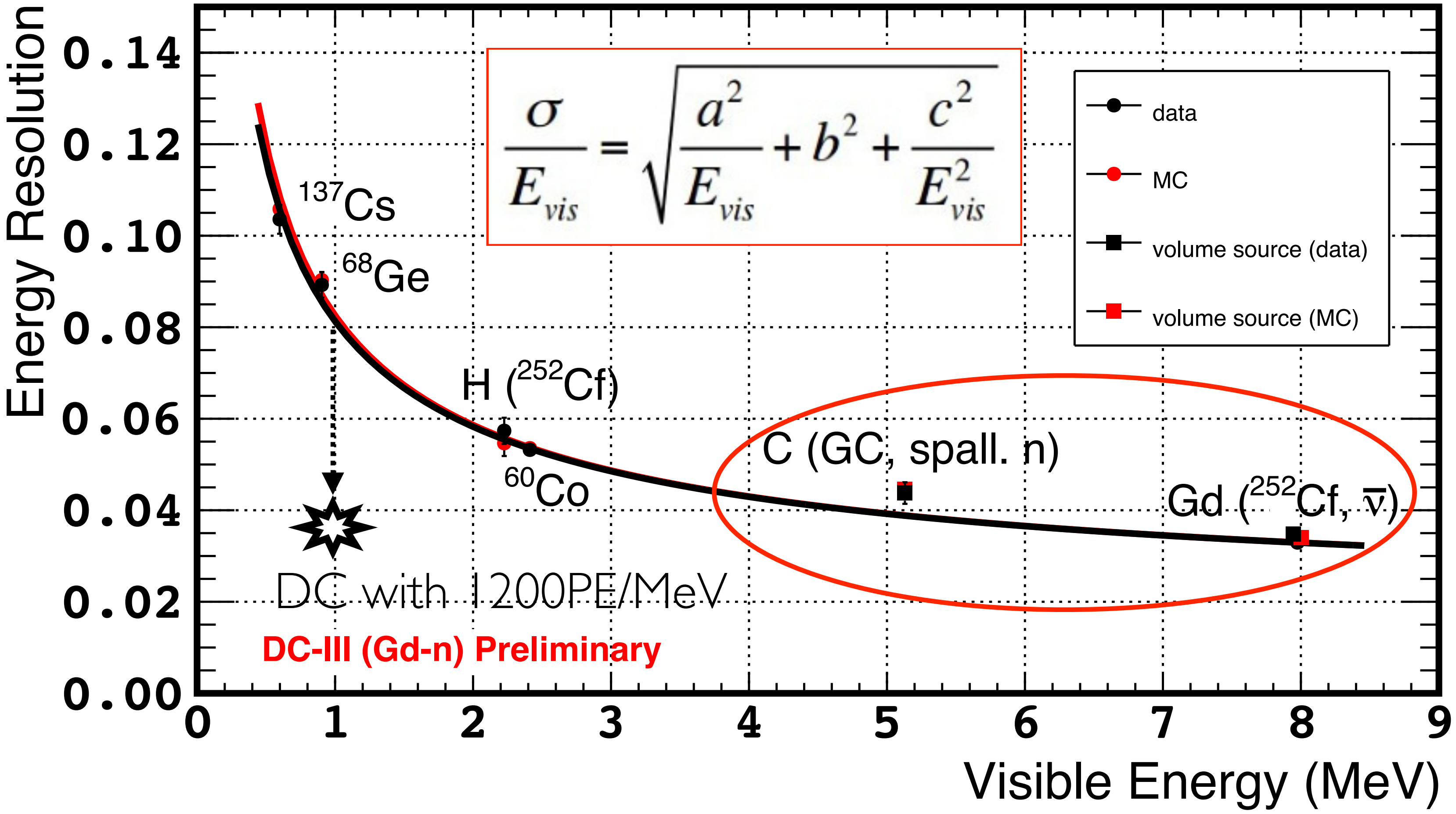
DC as prototype for JUNO…

control of response stability



control of response uniformity





$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

DC: ~200PE/MeV

a: statistical term
b: constant term
c: e.g. electric noise

Data
a=0.0773±0.0025
b=0.0182±0.0014
c=0.0174±0.0107

MC
a=0.0770±0.0018
b=0.0183±0.0011
c=0.0235±0.0061

non-stochastic terms (i.e. b & c): very sensitive to high energy level arm (understood?)

no perfect world…

$\sigma(E)^2 = \sigma(E)^2_{stoch} + \sigma(E)^2_{non\text{-}stoch}$ ⟹ empiric formulation:

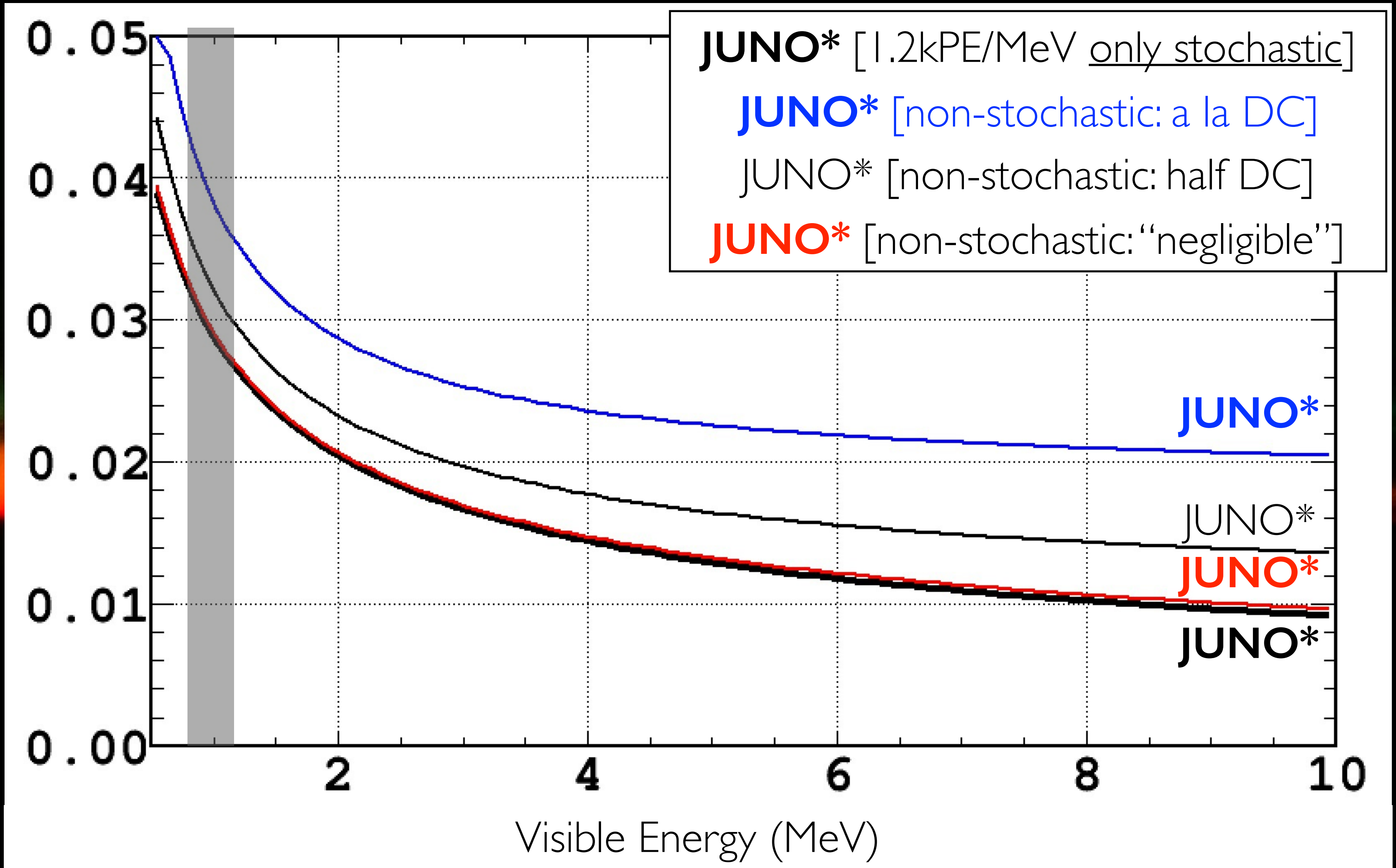
(1200PE/MeV) (??%)

$$\frac{\sigma}{E_{vis}} = \sqrt{\frac{a^2}{E_{vis}} + b^2 + \frac{c^2}{E_{vis}^2}}$$

~1.2k PEs

$\sigma(E)_{stoch} < 3\%$

the impact of $\sigma(E)_{non\text{-}stoch}$ dominates!!



- **if perfect light measurement: $\sigma(E)^2_{non\text{-}stoch} \rightarrow 0$** (i.e. LS⊕PMT⊕electronics **no dispersive effects**)
- **if perfect calibration: $\sigma(E)^2_{non\text{-}stoch} \rightarrow 0$** (i.e. **perfect correction of dispersive effects**)

(unfortunately) **none is true!!**

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the double calorimetry…

$\sigma(E)^2 = \sigma(E)^2_{\text{stoch}} + \sigma(E)^2_{\text{non-stoch}}$

(**1200PE @ 1MeV**) **if $\sigma(E)^2 \leq 3.0\%$** ⇒ **$\sigma(E)^2_{\text{stoch}}=2.89\%$** & + **$\sigma(E)^2_{\text{non-stoch}}=0.82\%$** (remaining)

@DC: $\sigma(E)^2_{\text{non-stoch}} \gtrsim 2\%$

now consider **(1200±50)PEs** @ 1MeV (same condition as before)⇒

- **+50PEs** implies **$\sigma(E)^2_{\text{stoch}}=2.83\%$** & + **$\sigma(E)^2_{\text{non-stoch}}=1.00\%$** (remaining)
- **-50PEs** implies **$\sigma(E)^2_{\text{stoch}}=2.95\%$** & + **$\sigma(E)^2_{\text{non-stoch}}=0.55\%$** (remaining)

↕ **~2x**

≥1300PE/MeV
(→$\sigma_{\text{non-stoch}} \geq 1.0\%$)

small difference in light level (>1150PE/MeV)⇒ major impact to $\sigma(E)^2_{\text{non-stoch}}$: most challenging!!

"double-calorimetry"

articulate 2 energy estimators (different behaviours)

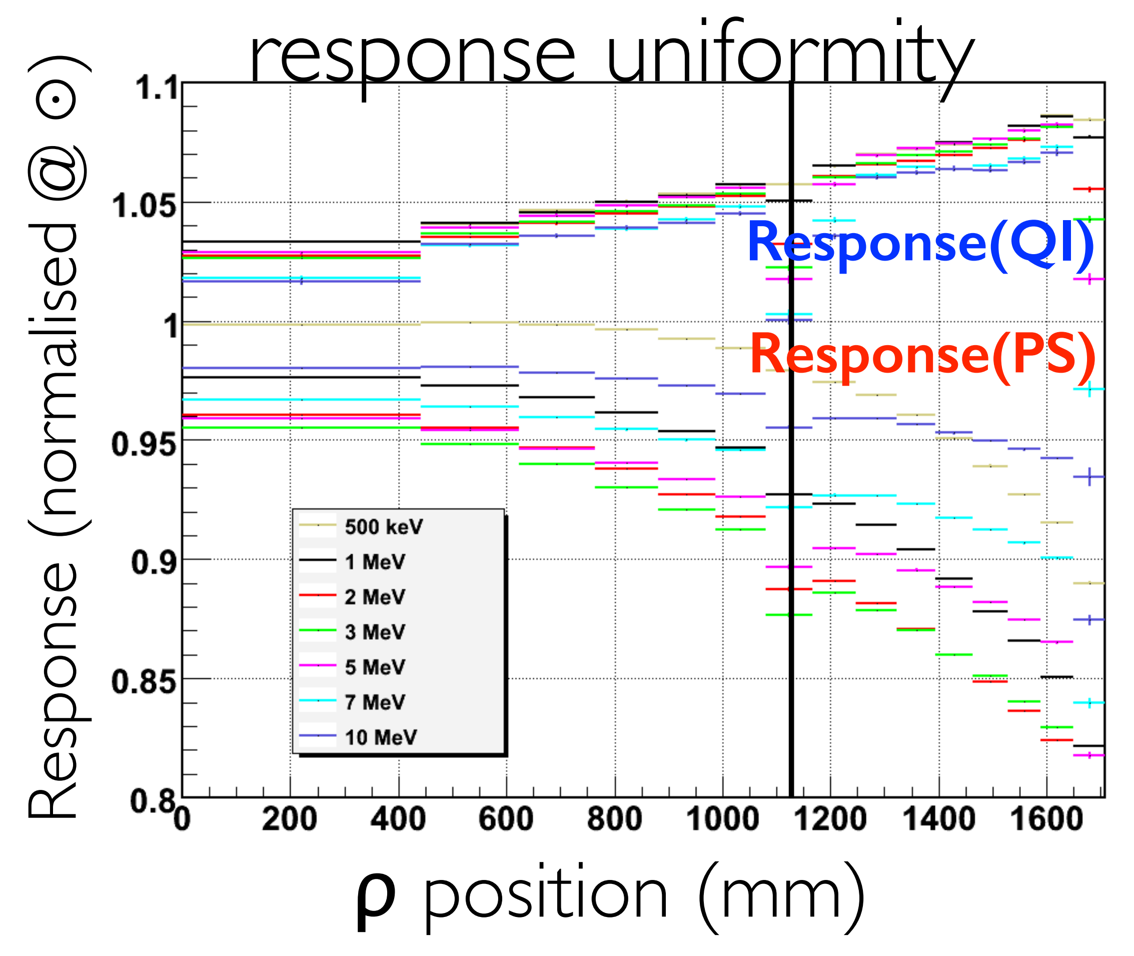
Energy(photon-counting) i.e. digital (**PS**)

Energy(charge integration) i.e. digital (**QI**)

⇒ **$E(\text{response},x,y,z)^{DC} = E(PS) \oplus E(QI)$**

[via NN, correction, etc]

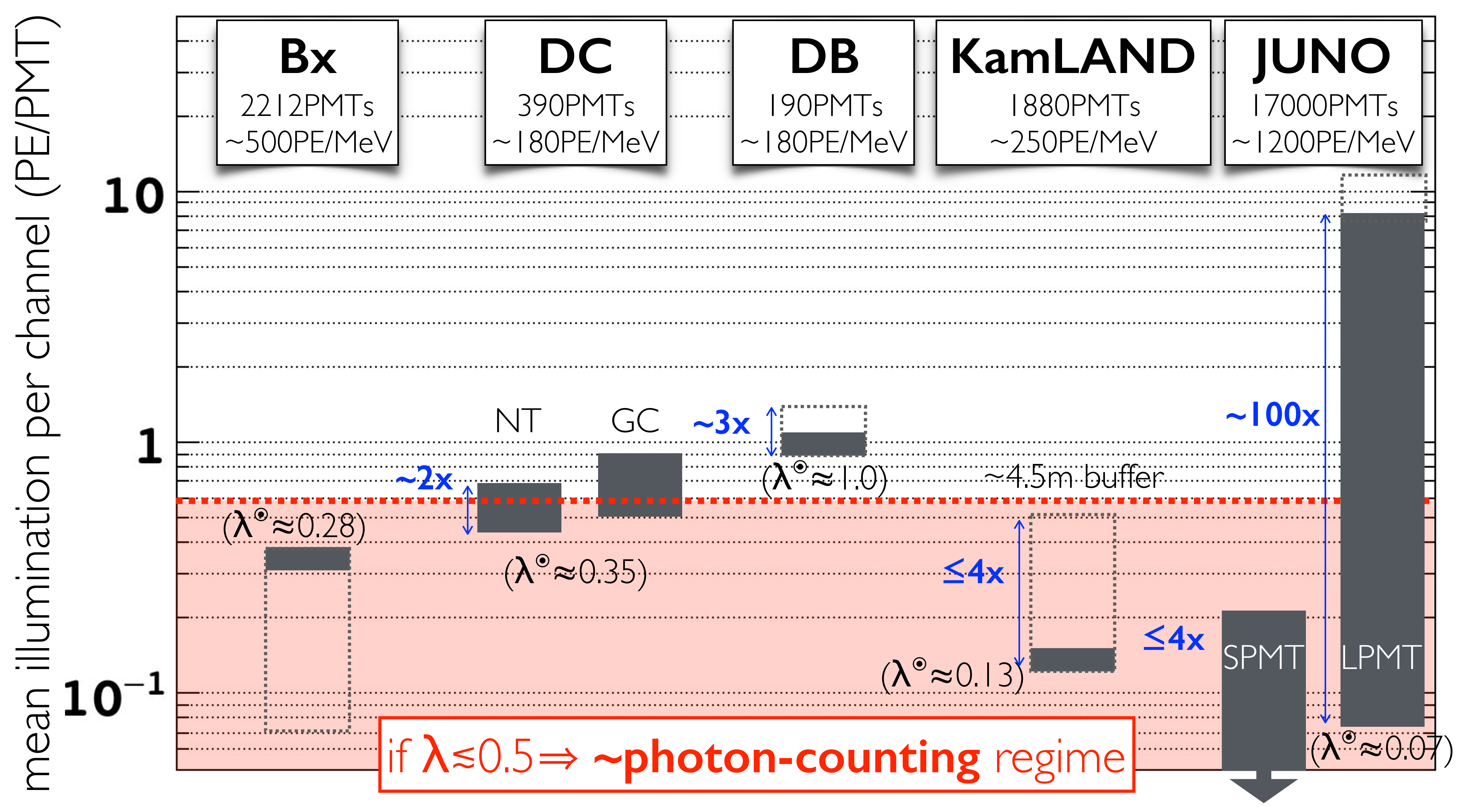
control/reduction $\sigma(E)^2_{\text{non-stoch}}$ & redundancy
[if ±Δm^2→ convince JUNO can]



the JUNO challenge…

@1MeV

$\lambda^{\odot}$ = mean illumination per channel @ center



HIGHEST precision calorimetry (≲3% @ 1MeV)

⊕

LARGEST dynamic range in calorimetry (channel-wise) [⇒ **uniformity⊕linearity⊕stability**]

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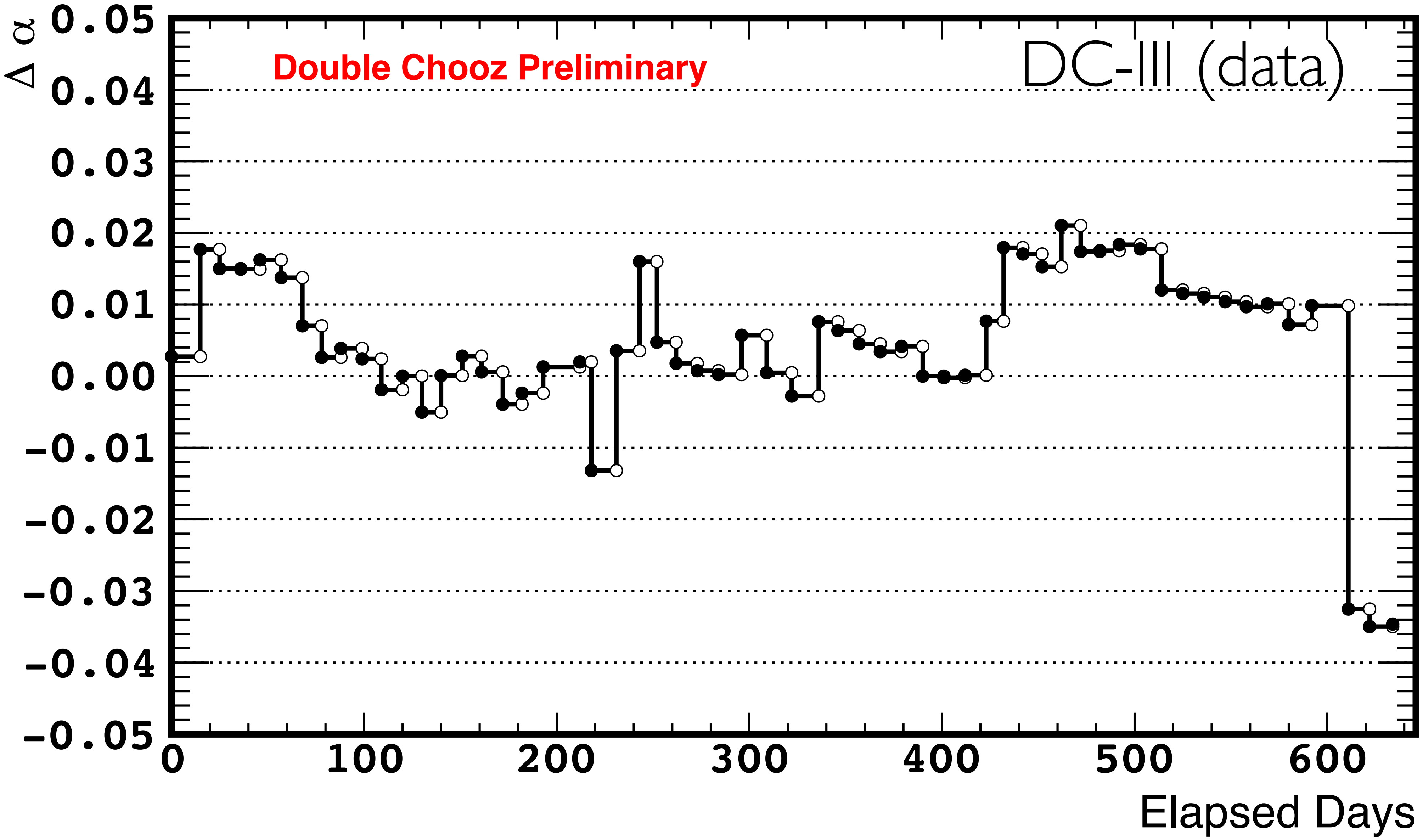
PS vs QI in action…

response stability



"digital" response stability @ 2.2MeV (zero tracking⊕other effect)

(invisible to charge integration estimator alone)

Energy(PC) & Energy(QI) are highly complementary!!

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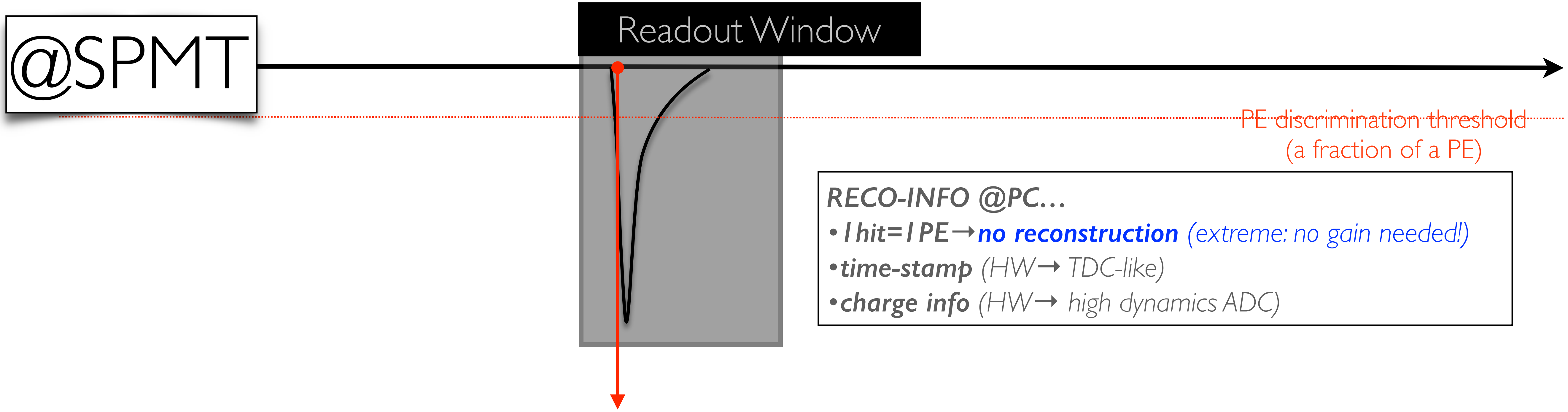
Photon-Counting vs Charge-Integration…

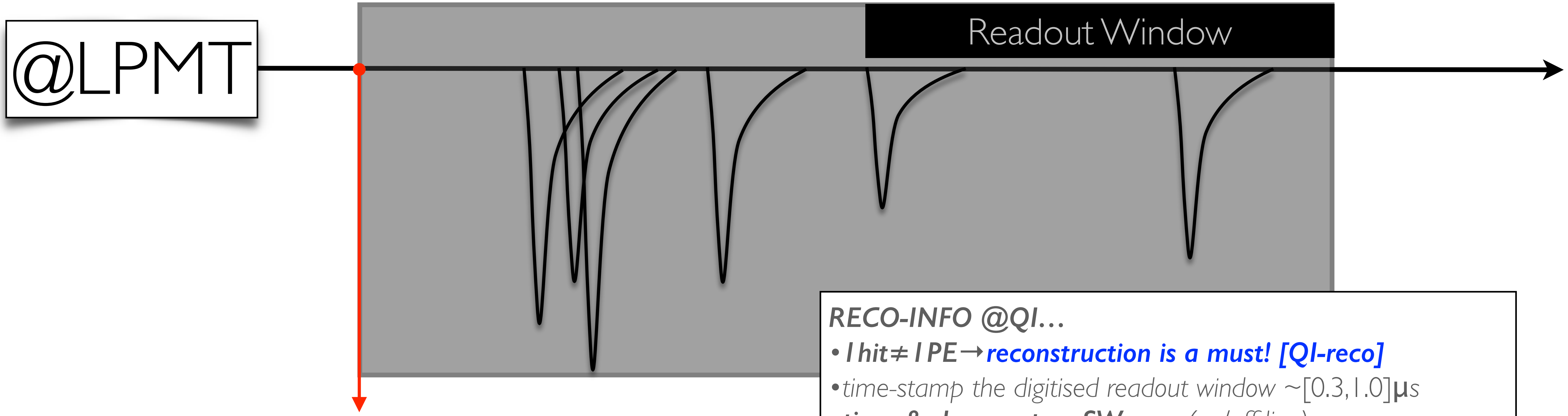


RECO-INFO @PC…

- ***1 hit=1 PE→no reconstruction** (extreme: no gain needed!)*
- ***time-stamp** (HW→ TDC-like)*
- ***charge info** (HW→ high dynamics ADC)*

time-stamp (self-trigger)

(pulse @ threshold→ discriminator)



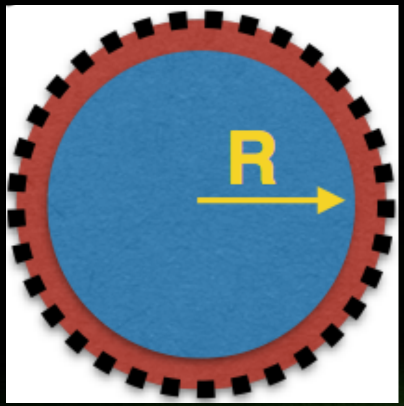
RECO-INFO @QI…

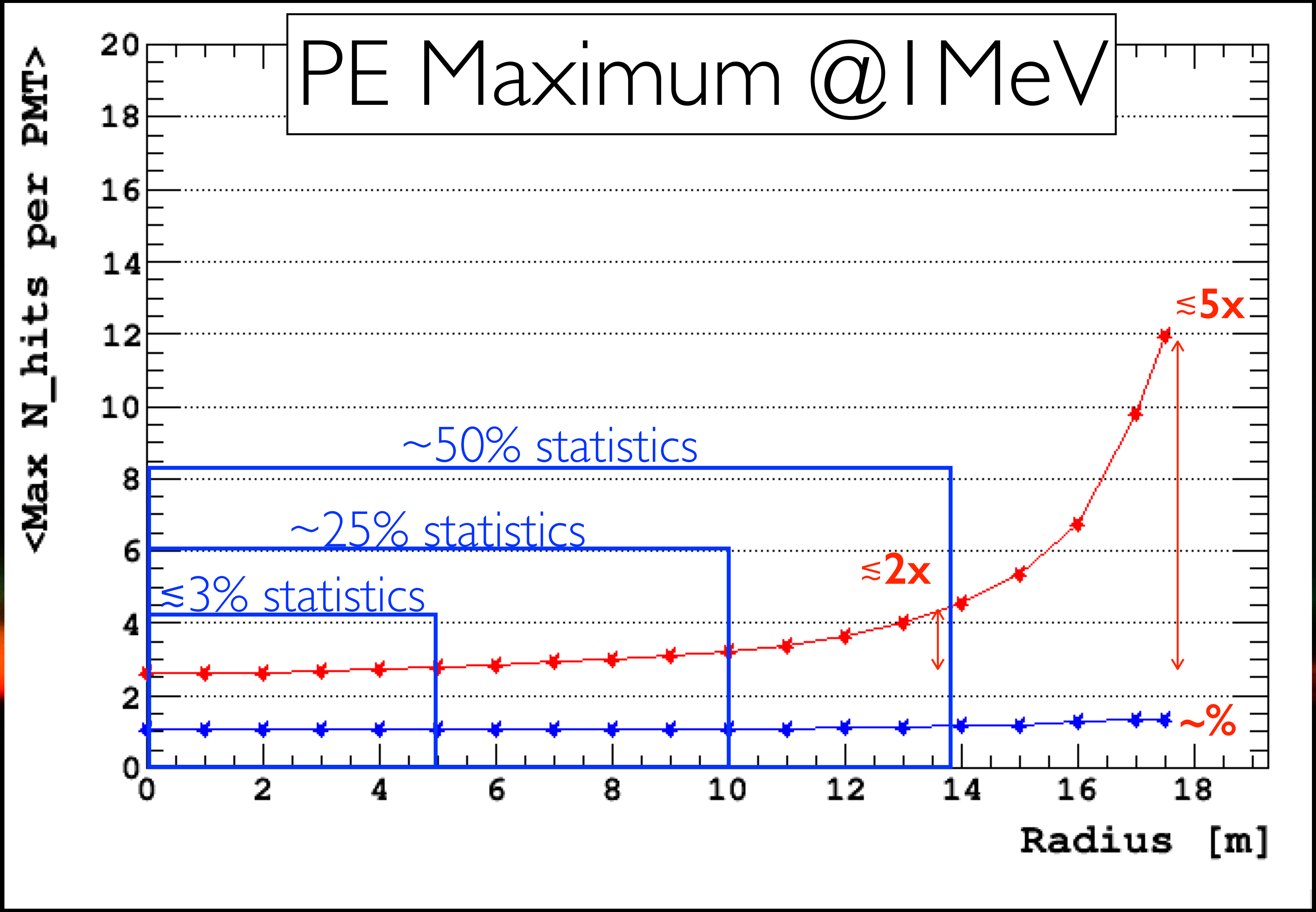
- ***1 hit≠1 PE→reconstruction is a must! [QI-reco]***
- *time-stamp the digitised readout window ~[0.3,1.0]µs*
- ***time & charge upon SW-reco** (on/off-line)*

time-stamp (global trigger)

(readout-window sampled, example @ start)

the SPMT & LPMT calorimetry regimes…





LPMT has dramatic variation across volume (→ systematics and/or biasses)

(wildest variation in region with large fraction of statistics)

(opposite) **SPMT has FLAT response across volume (by construction)**

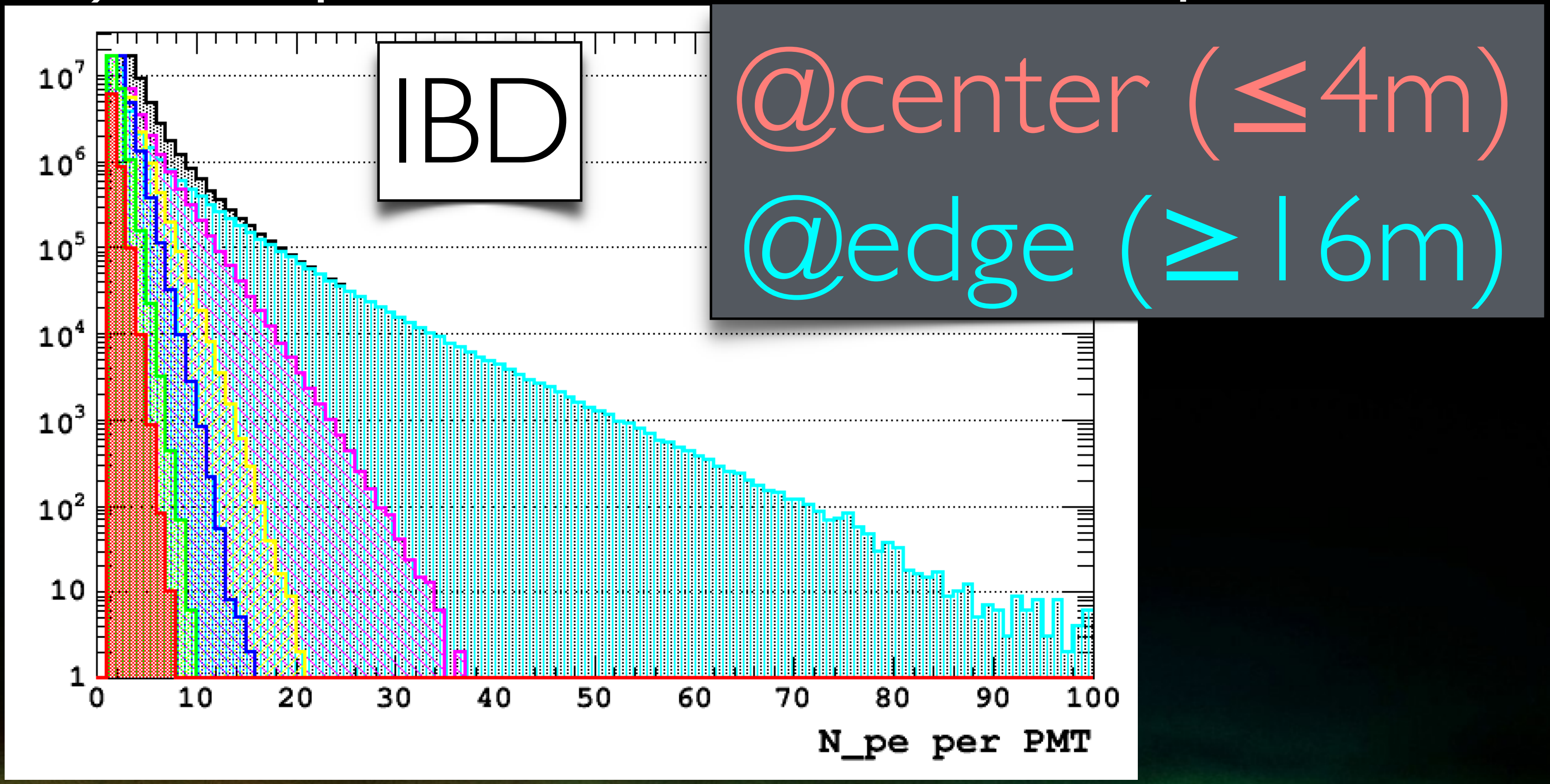
(**SPMT ideal input for Trigger**)

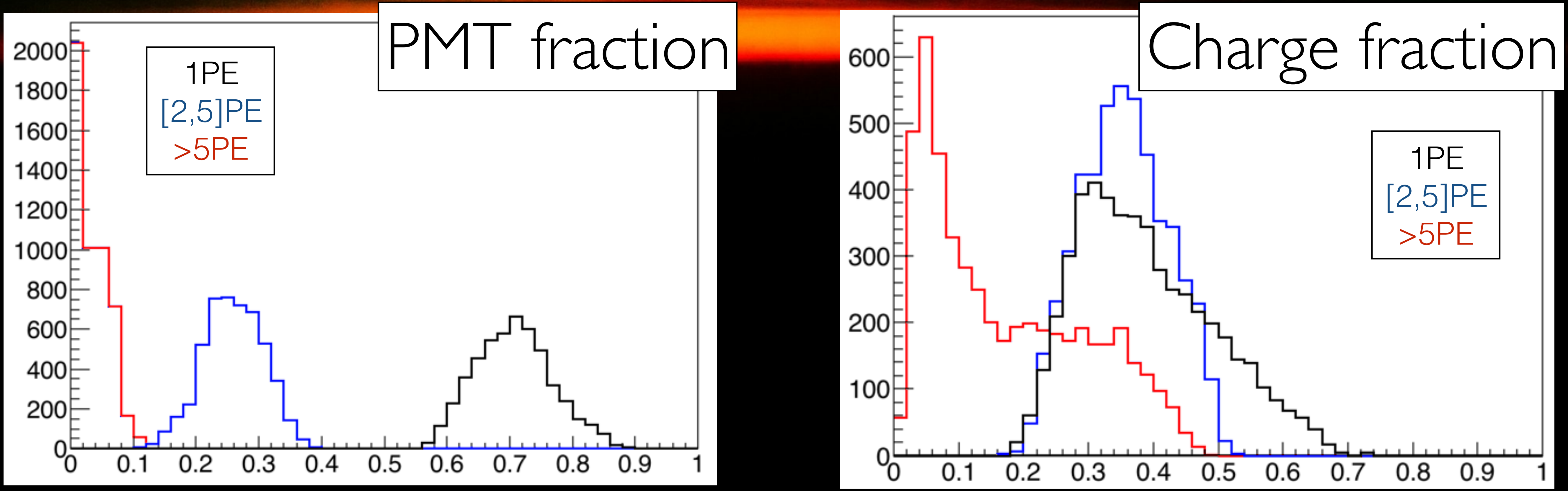
Anatael Cabrera (CNRS-IN2P3 & APC)

(illustration) response/channel vs position…

Large PMTs can detect up to 100pe for an IBD event in the last shell (20% of events)

LPMT only





small bias in few LPMTs⇒ large impact to over calorimetry!

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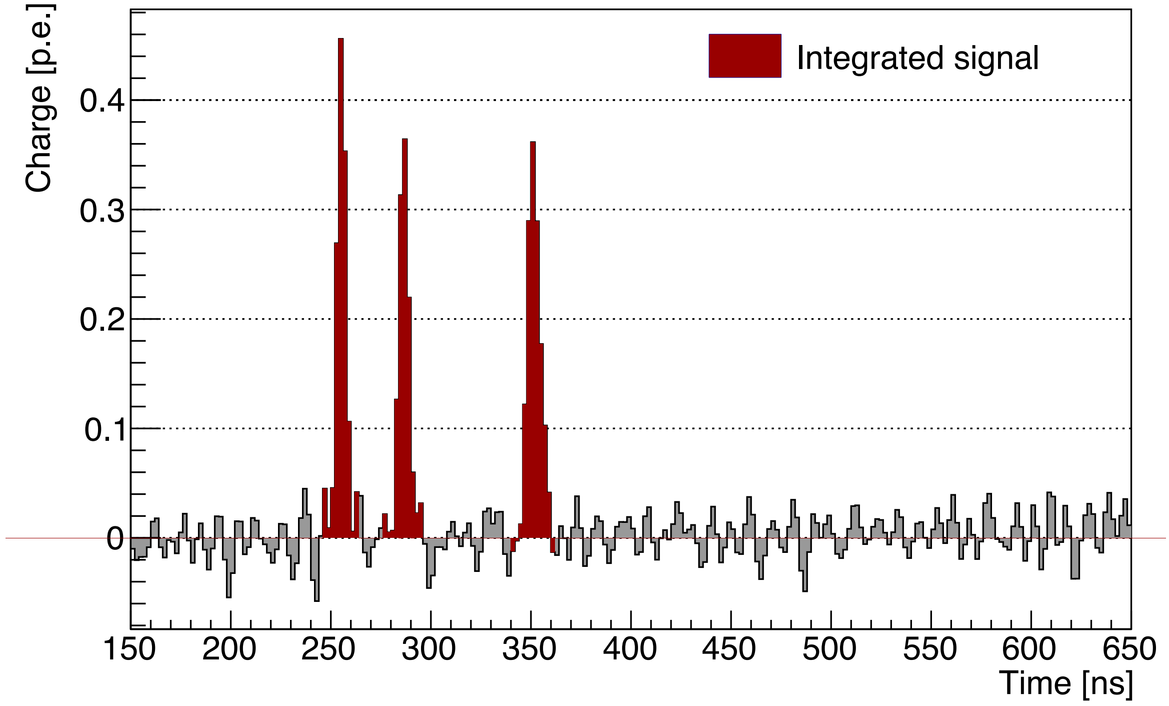
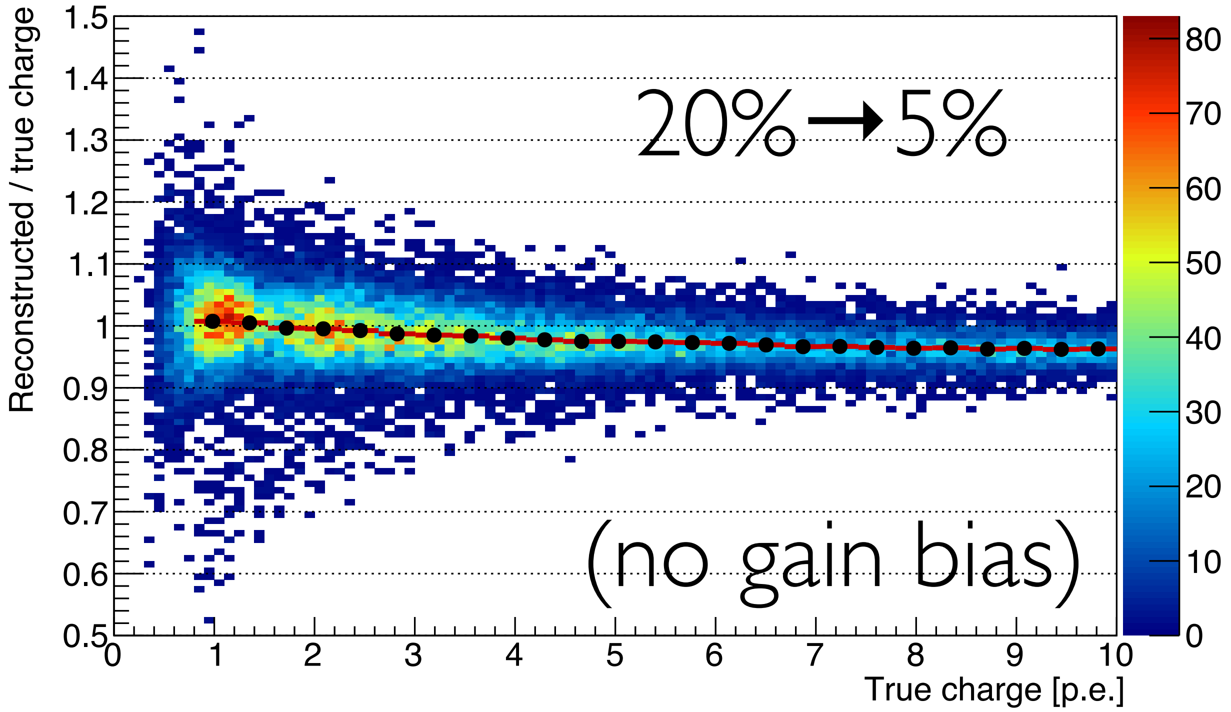
energy reconstruction bias estimation (I)...

realistic pulse reco (QI)



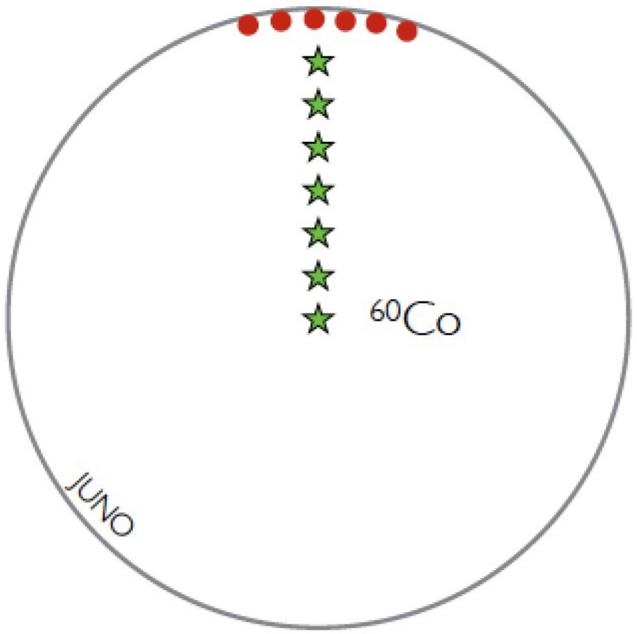
non-linearity (QI)

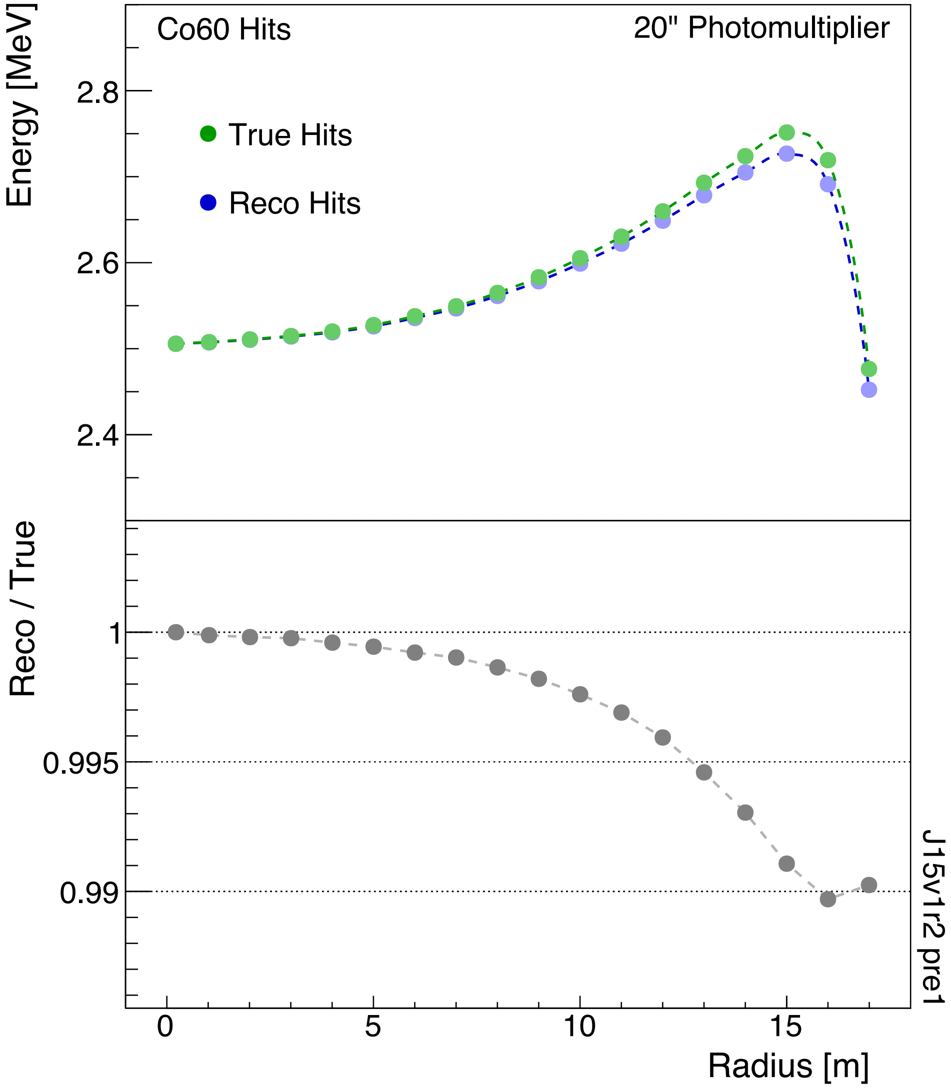


20%→5%

(no gain bias)

calibration mimicking





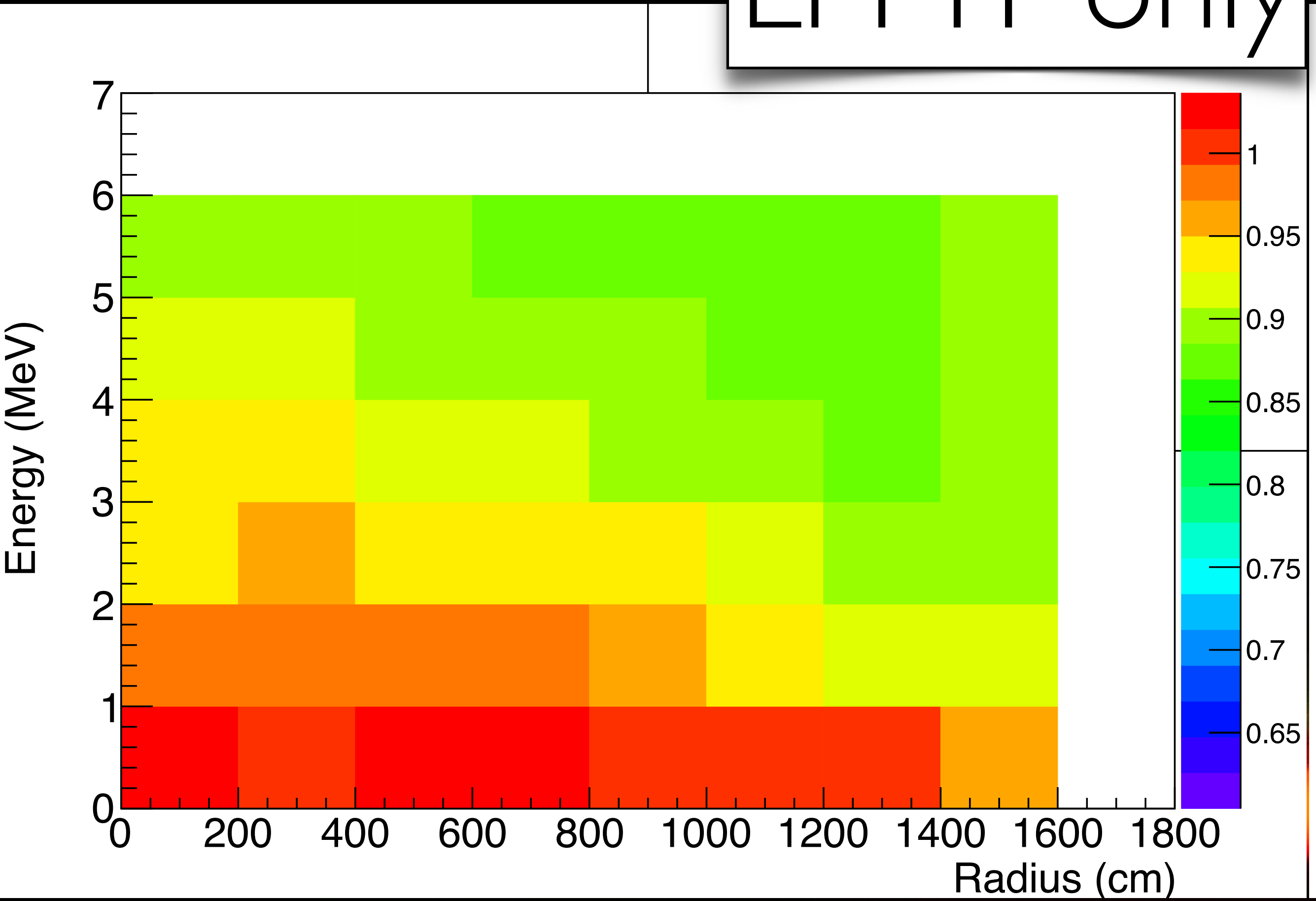
non-linearity
(channel-wise)

non-uniformity
(position-wise)
[QI regime variations]

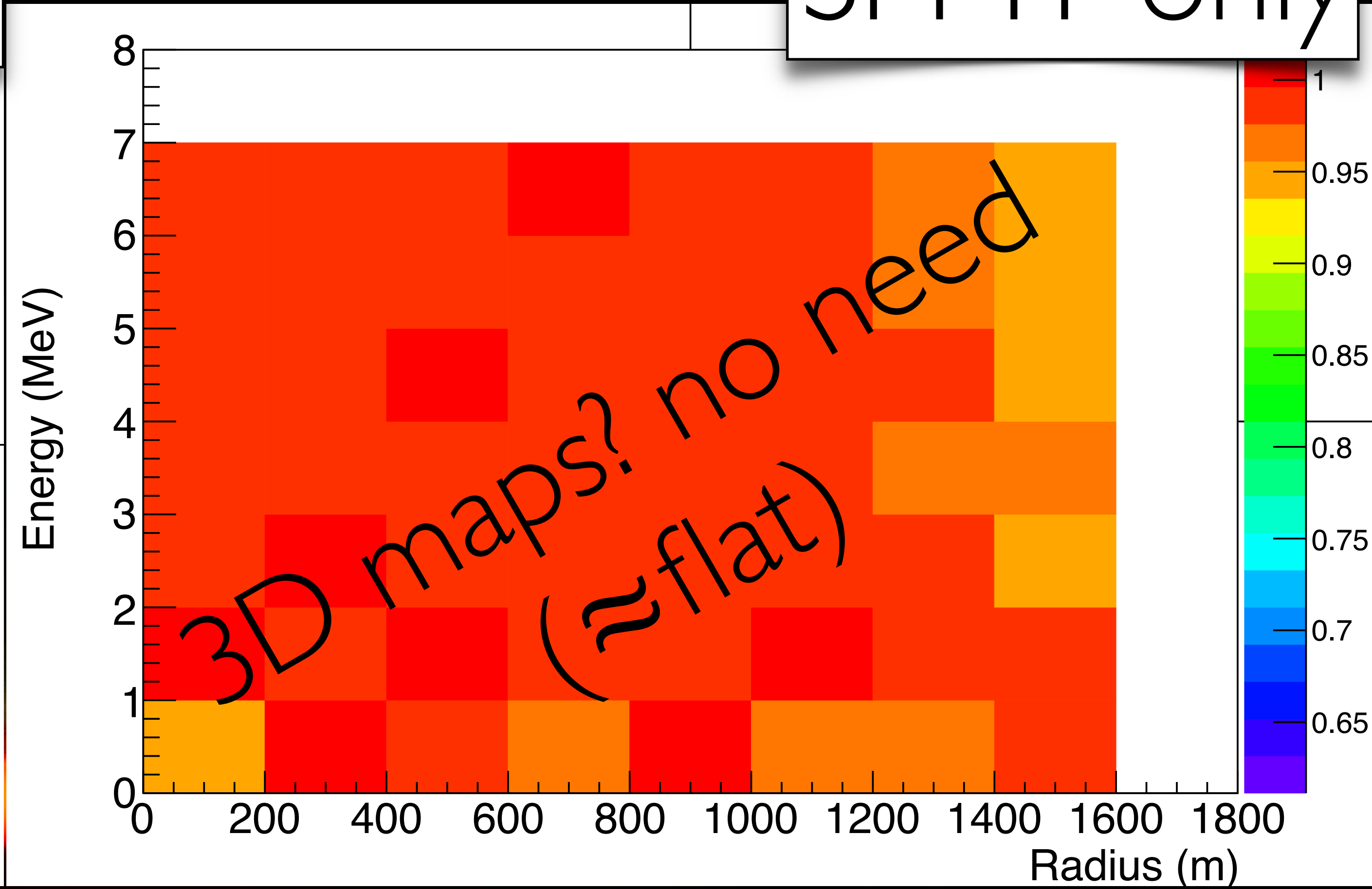
worsens resolution
(full detector)

Cabrera (CNRS-IN2P3 & APC)

linearity⊕uniformity crosstalk handling…



LPMT only



SPMT only

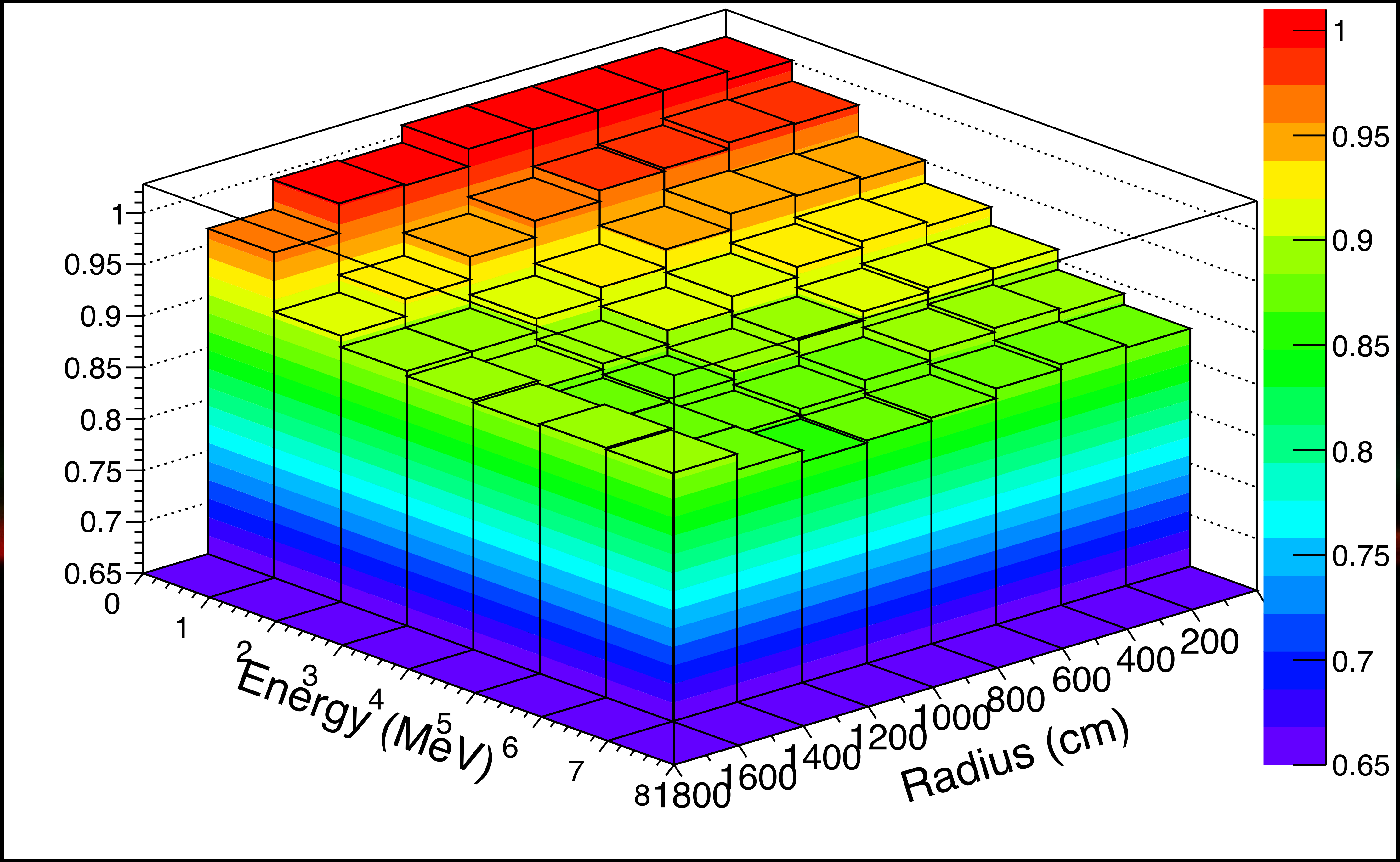
3D maps? no need (≈flat)

if linearity⊕uniformity⇒ **LPMT 3D-maps a must!**

SPMT: uniformity map & linearity⇒ (independent) 3D-map validation

(simpler, complementary & robust→ unique, if SPMT)

(illustration) LPMT 3D calibration maps…



LPMT 3D map (easy to say), but **which source?**

Anatael Cabrera (CNRS-IN2P3 & APC)

response summary…

LPMT: uniformity • linearity • stability ≠ 0

(i.e. not orthogonal bias/systematics)

vs

SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

(**far more knowledge when combining**)

JUNO upgrade…

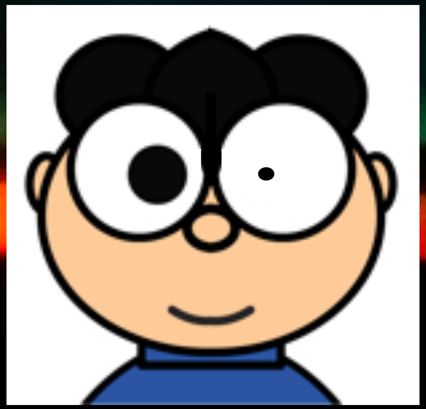
JUNO

(before)

single-calorimetric

JUNO

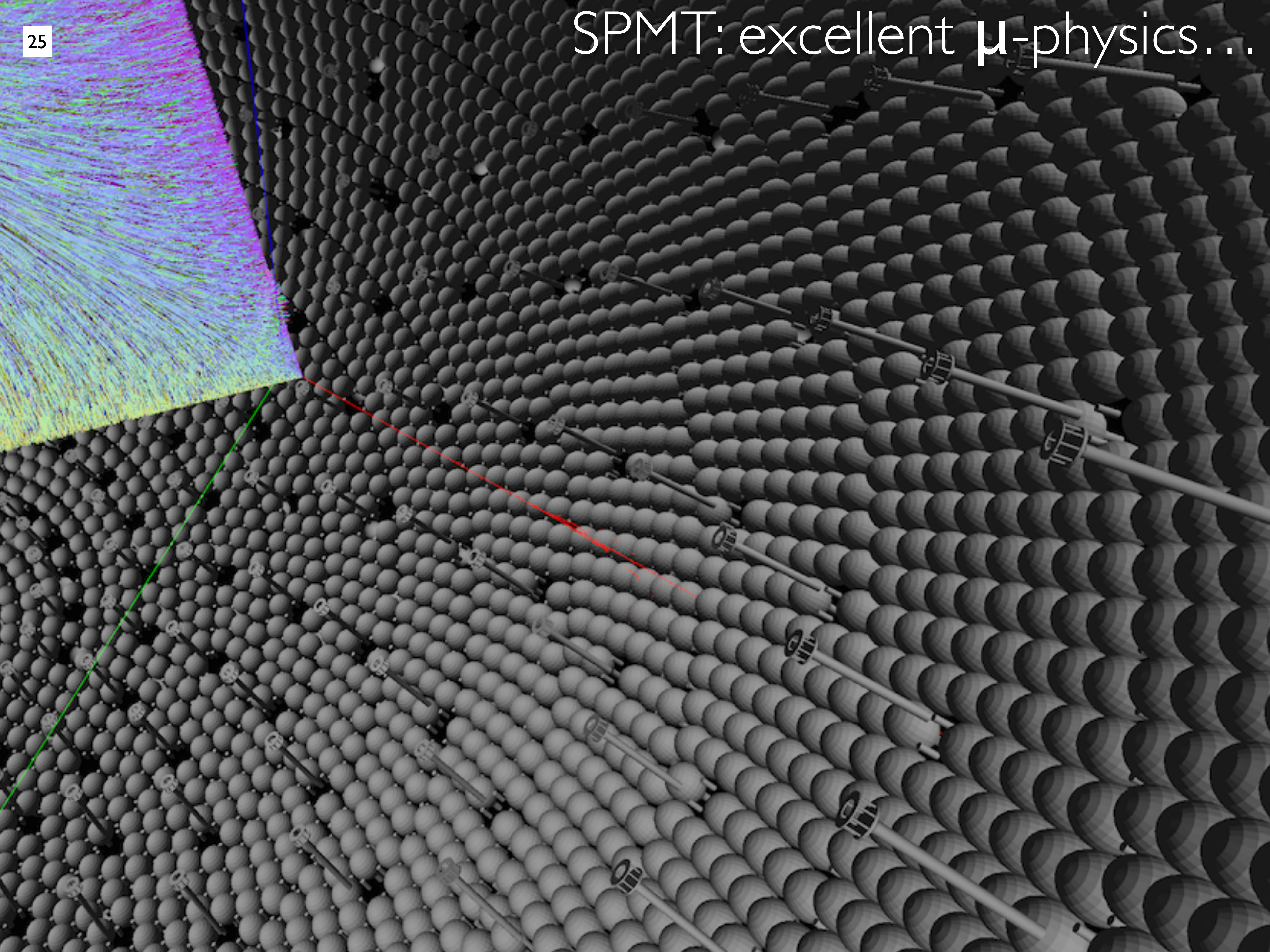
(now)



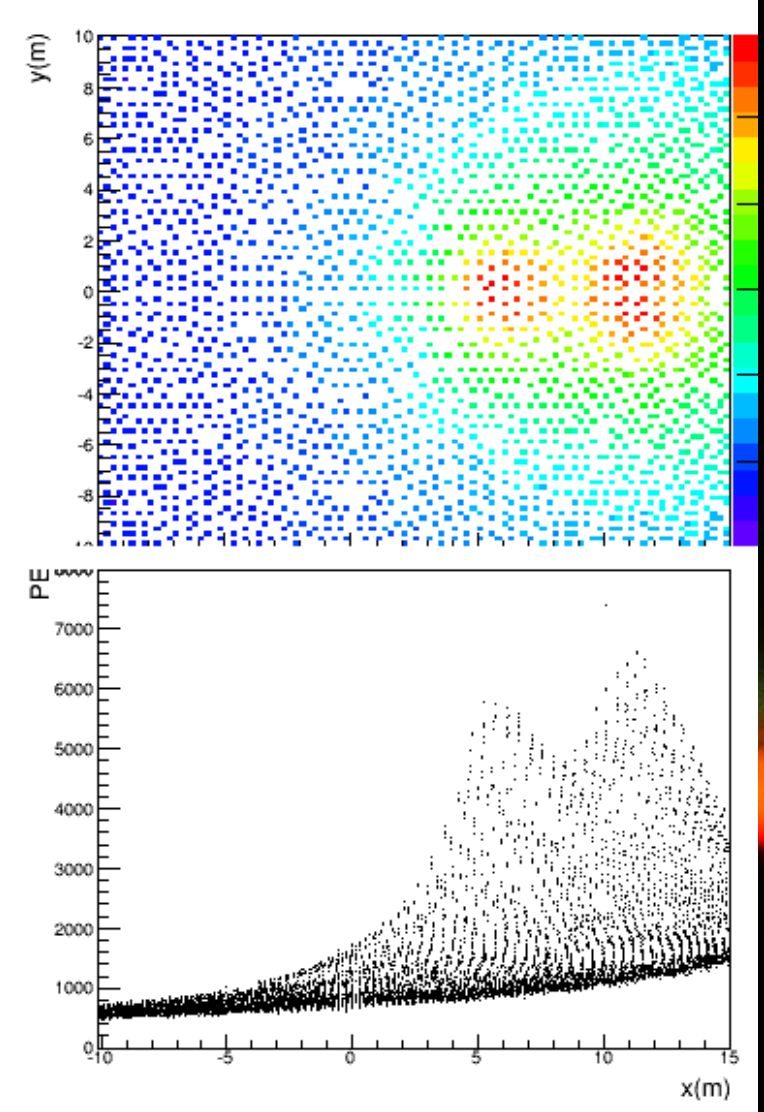
double calorimetric

SPMT system: much more…

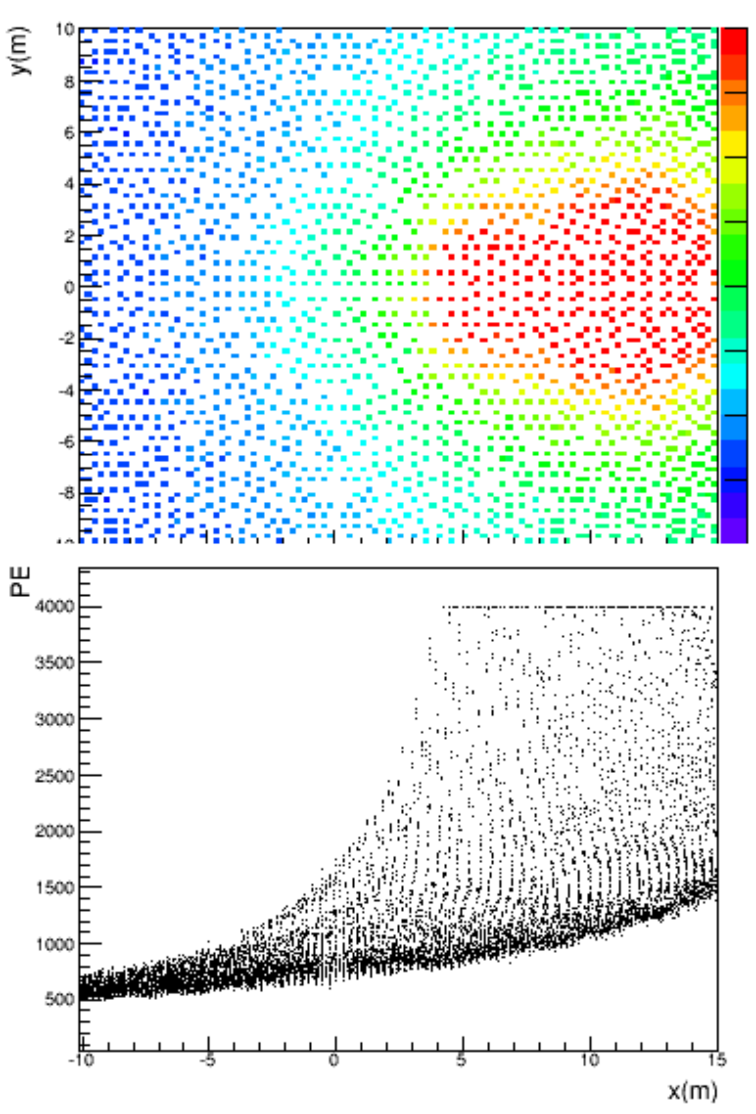
SPMT: excellent **μ**-physics…



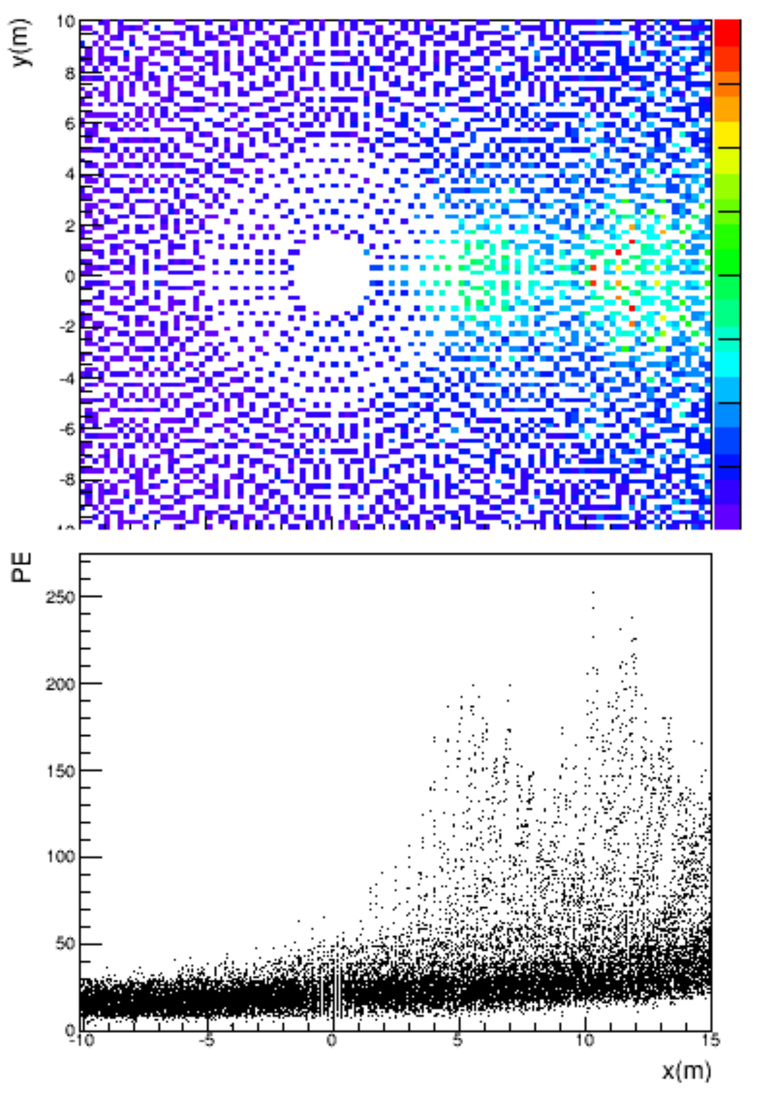
improving multi-μ identification…?



LPMT (no saturation)



LPMT (saturation at 4000PE)



SPMT

saturation model very complex (not uniform, no flat, etc)

μ: ≲300PE per SPMT
(no saturation whatsoever)

evidently so…

when dealing with **μ**'s…

when dazzling…
(i.e. saturation)

…less is more! (→SPMT)

Anatael Cabrera (CNRS-IN2P3 & APC)

SPMT as an **"aider"** to the LPMT…

A. **high precision calorimetry response systematics IBD physics**

(highest priority: **aide $\lesssim$3% @ 1MeV resolution**)

B. **improve inner-detector μ-reconstruction resolution**

(highest priority: **aide ^{12}B/^{9}Li/^{8}He tagging/vetoing**)

C. **high rate SN pile-up (if very near)**

(medium priority: **minimise bias in absolute rate & energy spectrum**)

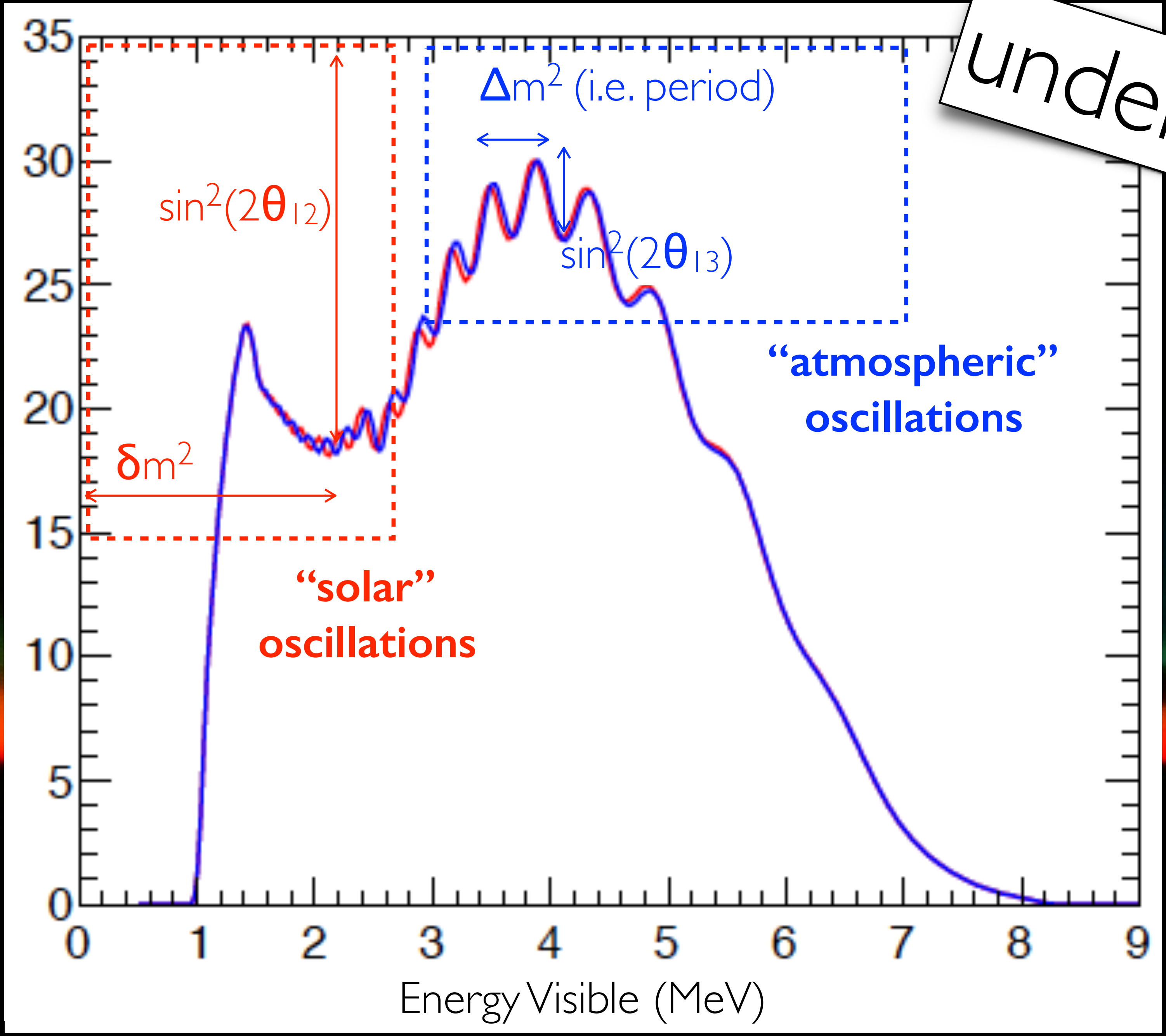
D. **vital complementarity: time resolution, dynamic range & trigger**

(articulate **additional complementary to LPMT system**: better/simpler)

how about neutrino physics?

high precision (θ_{12},δm^2) also with SPMT?

under study



JUNO several δm^2 (<1% precision)…
(only 2 fully independent)

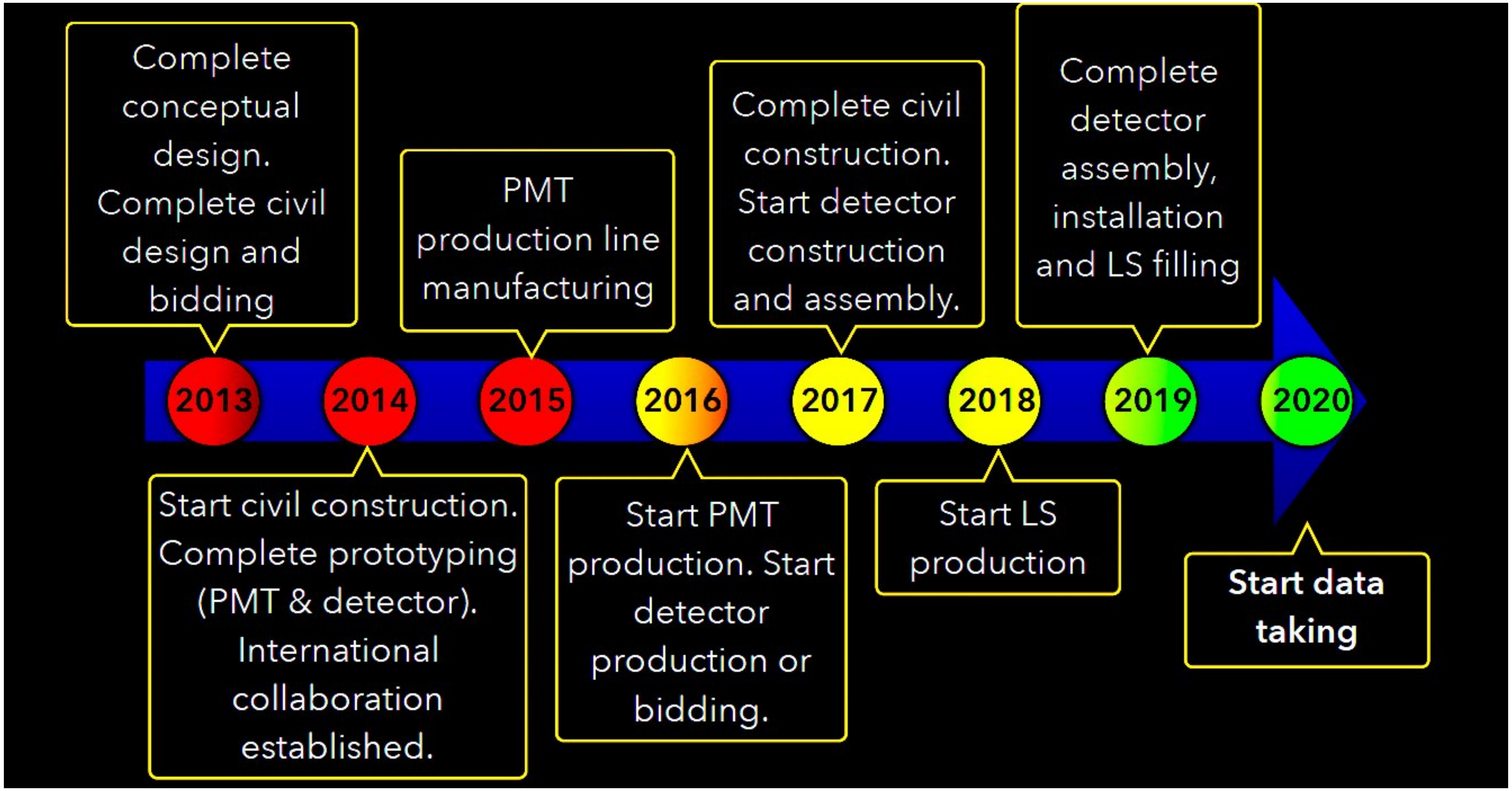
(δm^2)$^{\mathrm{SPMT}}$ independent (**digital** calorimetry)
(δm^2)$^{\mathrm{LPMT}}$ independent (**integration** calorimetry)
(δm^2)$^{\mathrm{LPMT \oplus SPMT}}$ independent (**double** calorimetry)

use **(δm^2)$^{\mathrm{SPMT}}$** to validate linearity (or bias) of **(δm^2)$^{\mathrm{LPMT}}$** & **(δm^2)$^{\mathrm{LPMT \oplus SPMT}}$**

(use solar disappearance to cross-calibrate calorimetry for Mass Ordering precision & accuracy)

Anatael Cabrera (CNRS-IN2P3 & APC)

conclusions…



2013: Complete conceptual design. Complete civil design and bidding

2014: Start civil construction. Complete prototyping (PMT & detector). International collaboration established.

2015: PMT production line manufacturing

2016: Start PMT production. Start detector production or bidding.

2017: Complete civil construction. Start detector construction and assembly.

2018: Start LS production

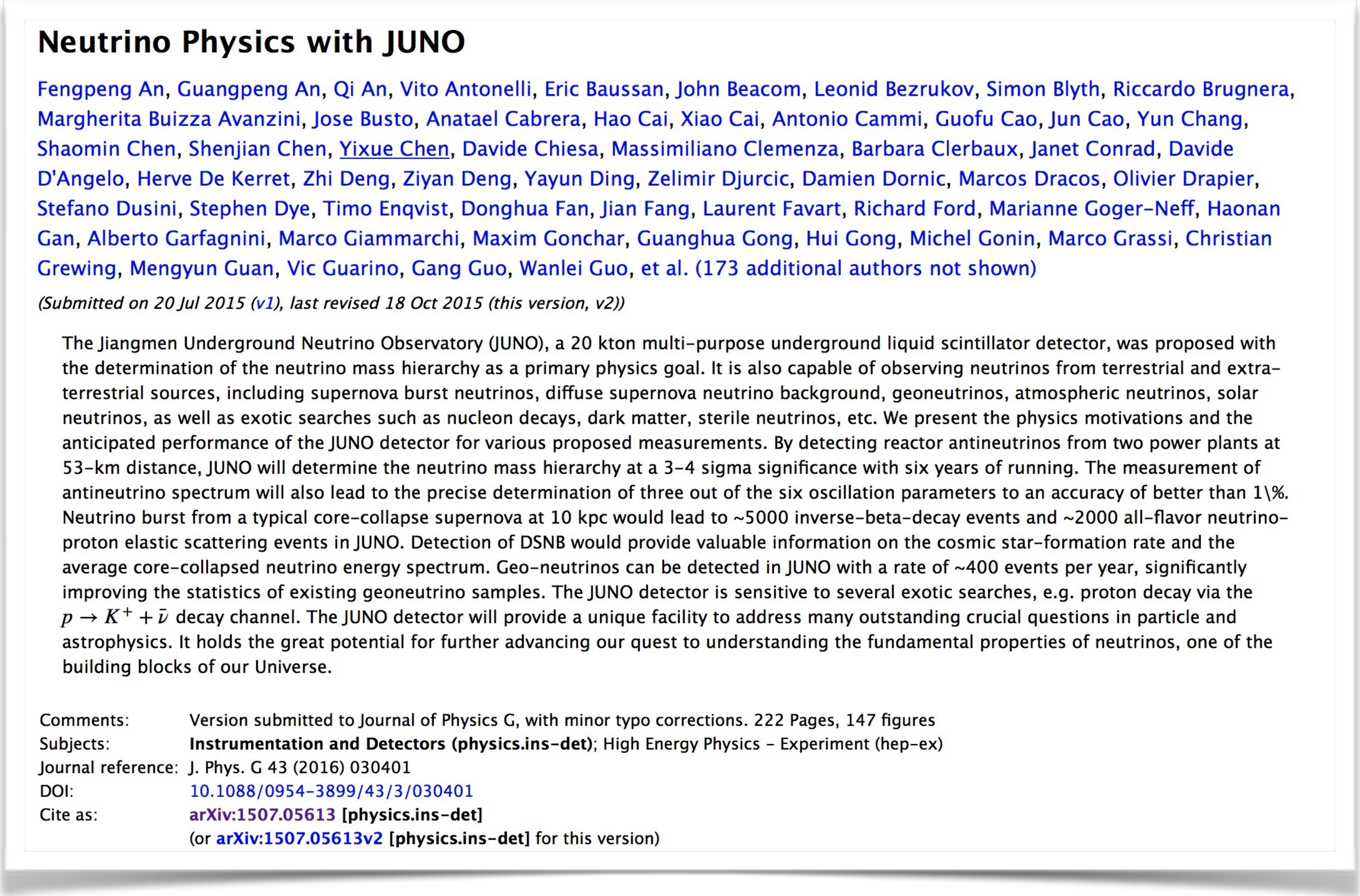
2019: Complete detector assembly, installation and LS filling

2020: **Start data taking**

- JUNO unprecedented large & high precision calorimetry liquid scintillator detector
- high precision neutrino oscillation with reactor-ν…
  - (atmospheric) mass-ordering with no matter effect enhancement (complementary)
  - (solar sector) ≤1% high precision solar terms → needed for CP-violation (complementarity)
  - (non-reactor ν's) vast leading physics capabilities→ fantastic leading edge detector [novelties]
- JUNO international collaboration (since July 2014) & funded→ data taking by ~2020

Anatael Cabrera (CNRS-IN2P3 & APC)

more info…



Neutrino Physics with JUNO

Fengpeng An, Guangpeng An, Qi An, Vito Antonelli, Eric Baussan, John Beacom, Leonid Bezrukov, Simon Blyth, Riccardo Brugnera, Margherita Buizza Avanzini, Jose Busto, Anatael Cabrera, Hao Cai, Xiao Cai, Antonio Cammi, Guofu Cao, Jun Cao, Yun Chang, Shaomin Chen, Shenjian Chen, Yixue Chen, Davide Chiesa, Massimiliano Clemenza, Barbara Clerbaux, Janet Conrad, Davide D'Angelo, Herve De Kerret, Zhi Deng, Ziyan Deng, Yayun Ding, Zelimir Djurcic, Damien Dornic, Marcos Dracos, Olivier Drapier, Stefano Dusini, Stephen Dye, Timo Enqvist, Donghua Fan, Jian Fang, Laurent Favart, Richard Ford, Marianne Goger-Neff, Haonan Gan, Alberto Garfagnini, Marco Giammarchi, Maxim Gonchar, Guanghua Gong, Hui Gong, Michel Gonin, Marco Grassi, Christian Grewing, Mengyun Guan, Vic Guarino, Gang Guo, Wanlei Guo, et al. (173 additional authors not shown)

(Submitted on 20 Jul 2015 (v1), last revised 18 Oct 2015 (this version, v2))

The Jiangmen Underground Neutrino Observatory (JUNO), a 20 kton multi-purpose underground liquid scintillator detector, was proposed with the determination of the neutrino mass hierarchy as a primary physics goal. It is also capable of observing neutrinos from terrestrial and extra-terrestrial sources, including supernova burst neutrinos, diffuse supernova neutrino background, geoneutrinos, atmospheric neutrinos, solar neutrinos, as well as exotic searches such as nucleon decays, dark matter, sterile neutrinos, etc. We present the physics motivations and the anticipated performance of the JUNO detector for various proposed measurements. By detecting reactor antineutrinos from two power plants at 53-km distance, JUNO will determine the neutrino mass hierarchy at a 3-4 sigma significance with six years of running. The measurement of antineutrino spectrum will also lead to the precise determination of three out of the six oscillation parameters to an accuracy of better than 1\%. Neutrino burst from a typical core-collapse supernova at 10 kpc would lead to ~5000 inverse-beta-decay events and ~2000 all-flavor neutrino-proton elastic scattering events in JUNO. Detection of DSNB would provide valuable information on the cosmic star-formation rate and the average core-collapsed neutrino energy spectrum. Geo-neutrinos can be detected in JUNO with a rate of ~400 events per year, significantly improving the statistics of existing geoneutrino samples. The JUNO detector is sensitive to several exotic searches, e.g. proton decay via the $p \to K^+ + \bar{\nu}$ decay channel. The JUNO detector will provide a unique facility to address many outstanding crucial questions in particle and astrophysics. It holds the great potential for further advancing our quest to understanding the fundamental properties of neutrinos, one of the building blocks of our Universe.

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DOI:	10.1088/0954-3899/43/3/030401
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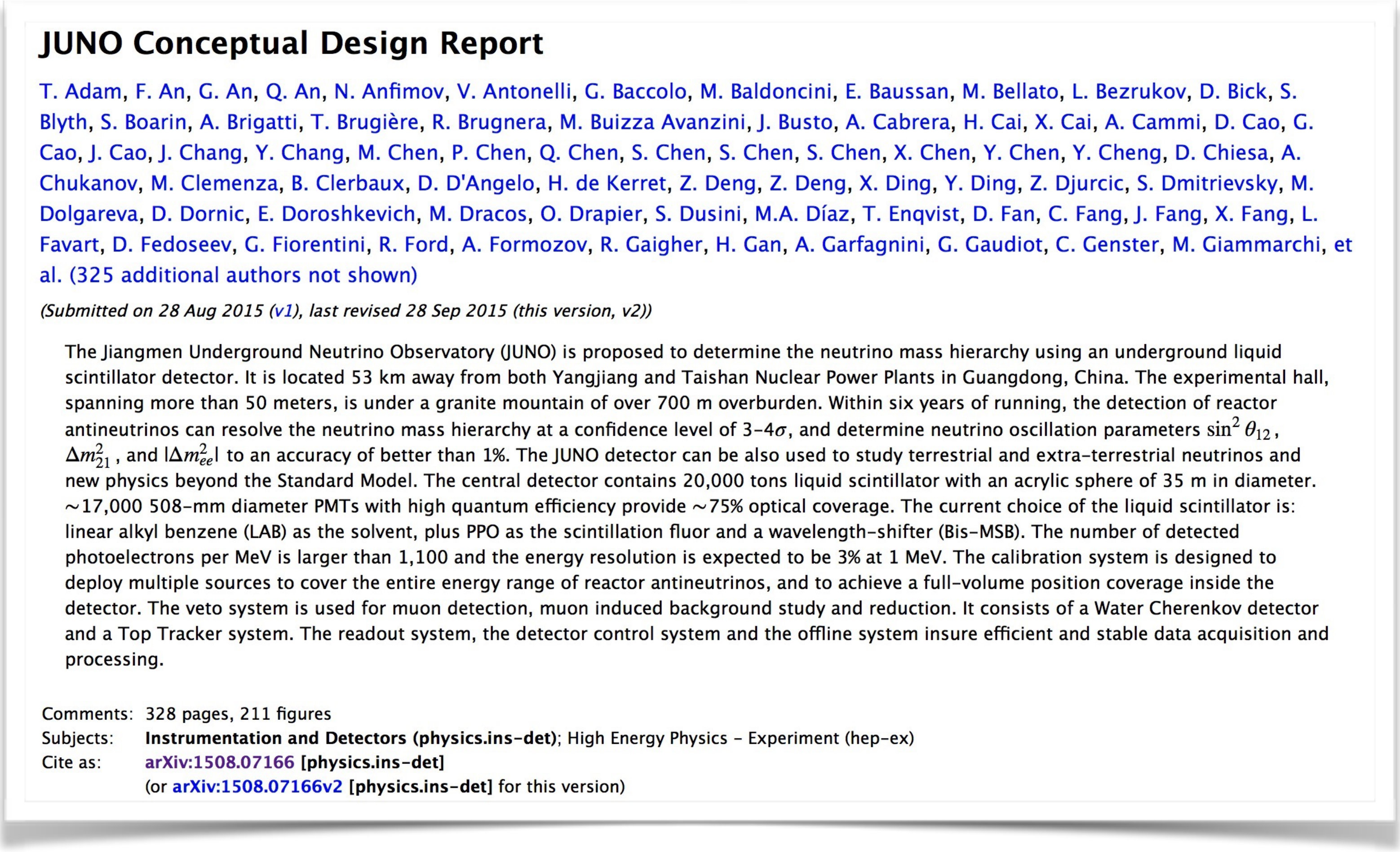
JUNO's Physics Summary…
(published)



JUNO Conceptual Design Report

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The Jiangmen Underground Neutrino Observatory (JUNO) is proposed to determine the neutrino mass hierarchy using an underground liquid scintillator detector. It is located 53 km away from both Yangjiang and Taishan Nuclear Power Plants in Guangdong, China. The experimental hall, spanning more than 50 meters, is under a granite mountain of over 700 m overburden. Within six years of running, the detection of reactor antineutrinos can resolve the neutrino mass hierarchy at a confidence level of 3-4σ, and determine neutrino oscillation parameters $\sin^2\theta_{12}$, Δm^2_{21}, and $|\Delta m^2_{ee}|$ to an accuracy of better than 1%. The JUNO detector can be also used to study terrestrial and extra-terrestrial neutrinos and new physics beyond the Standard Model. The central detector contains 20,000 tons liquid scintillator with an acrylic sphere of 35 m in diameter. $\sim$17,000 508-mm diameter PMTs with high quantum efficiency provide $\sim$75% optical coverage. The current choice of the liquid scintillator is: linear alkyl benzene (LAB) as the solvent, plus PPO as the scintillation fluor and a wavelength-shifter (Bis-MSB). The number of detected photoelectrons per MeV is larger than 1,100 and the energy resolution is expected to be 3% at 1 MeV. The calibration system is designed to deploy multiple sources to cover the entire energy range of reactor antineutrinos, and to achieve a full-volume position coverage inside the detector. The veto system is used for muon detection, muon induced background study and reduction. It consists of a Water Cherenkov detector and a Top Tracker system. The readout system, the detector control system and the offline system insure efficient and stable data acquisition and processing.

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