

JUNO

(double calorimetry)



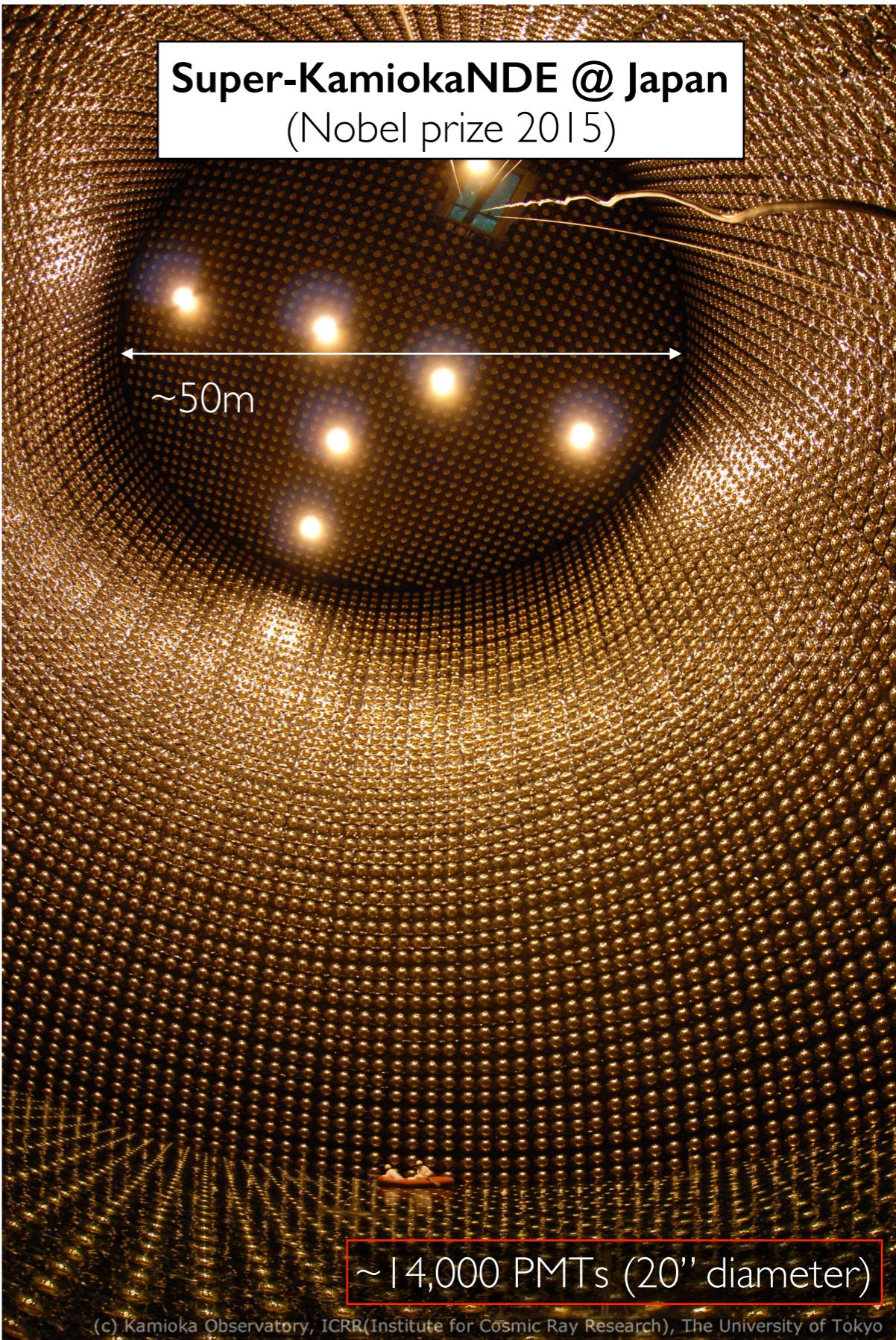
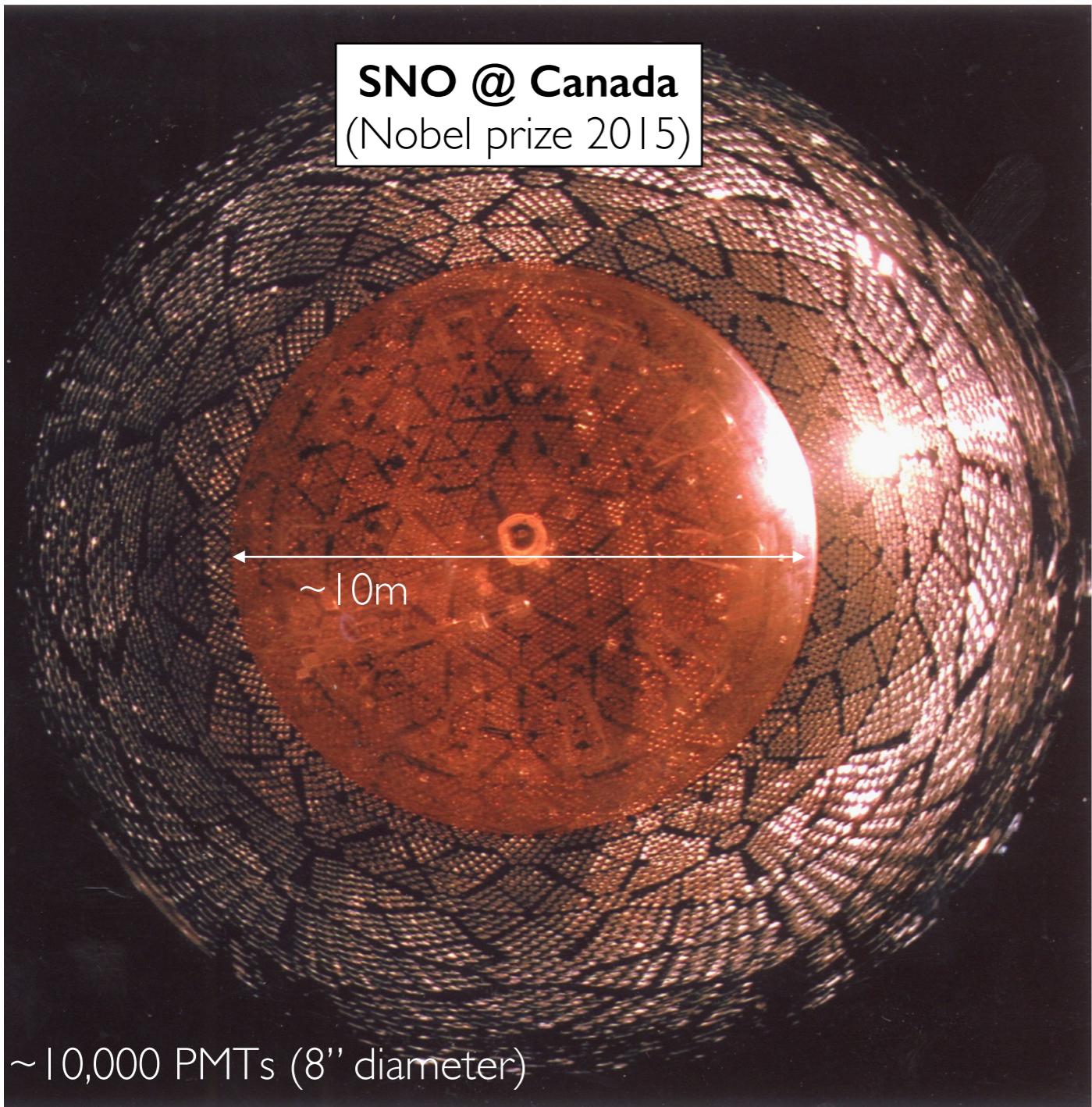
FCPPL meeting

IPHC, Strasbourg, France — March 2016

Anatael Cabrera

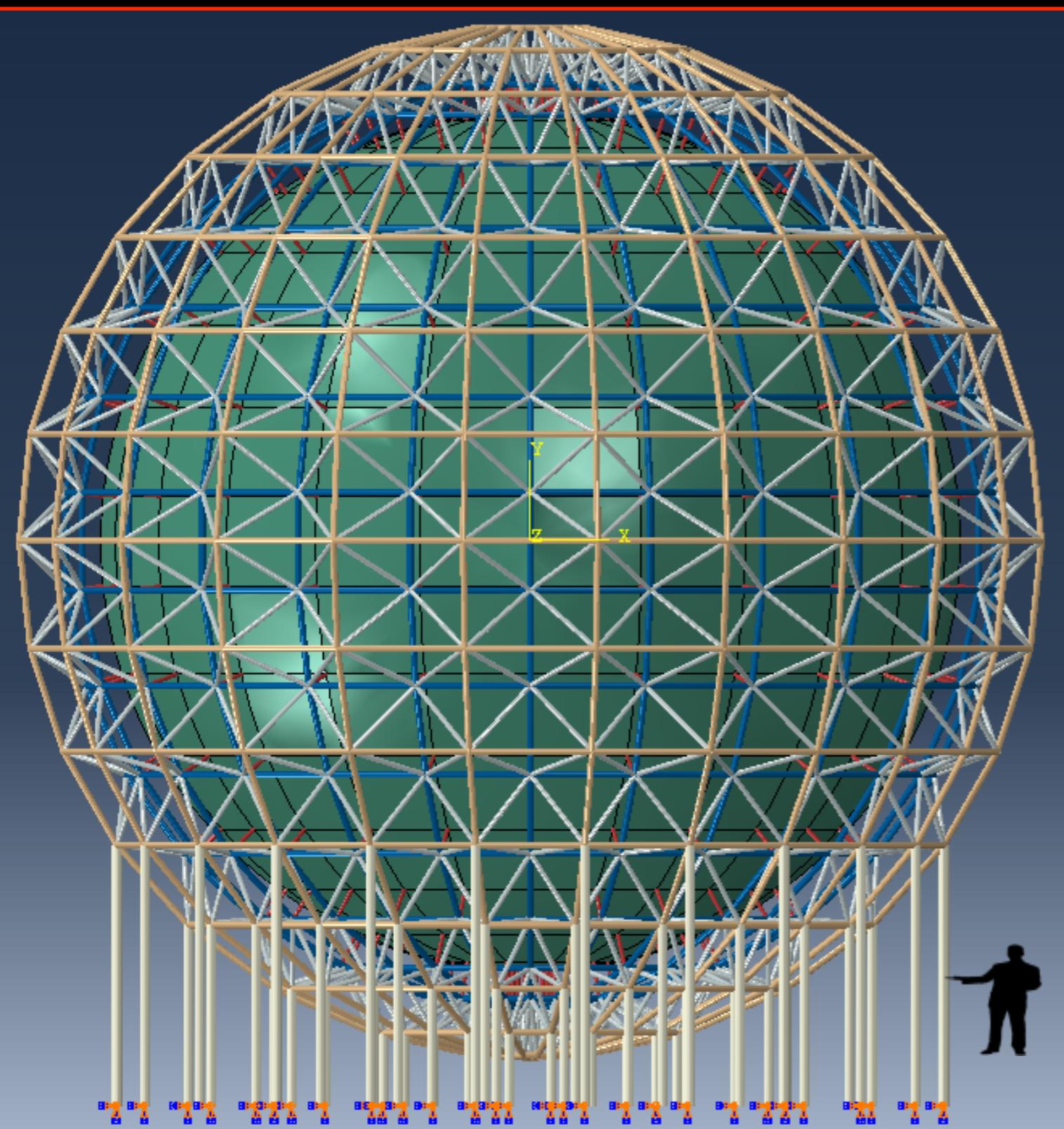
CNRS / IN2P3 @ APC (Paris)

the JUNO detector (predecessors)...



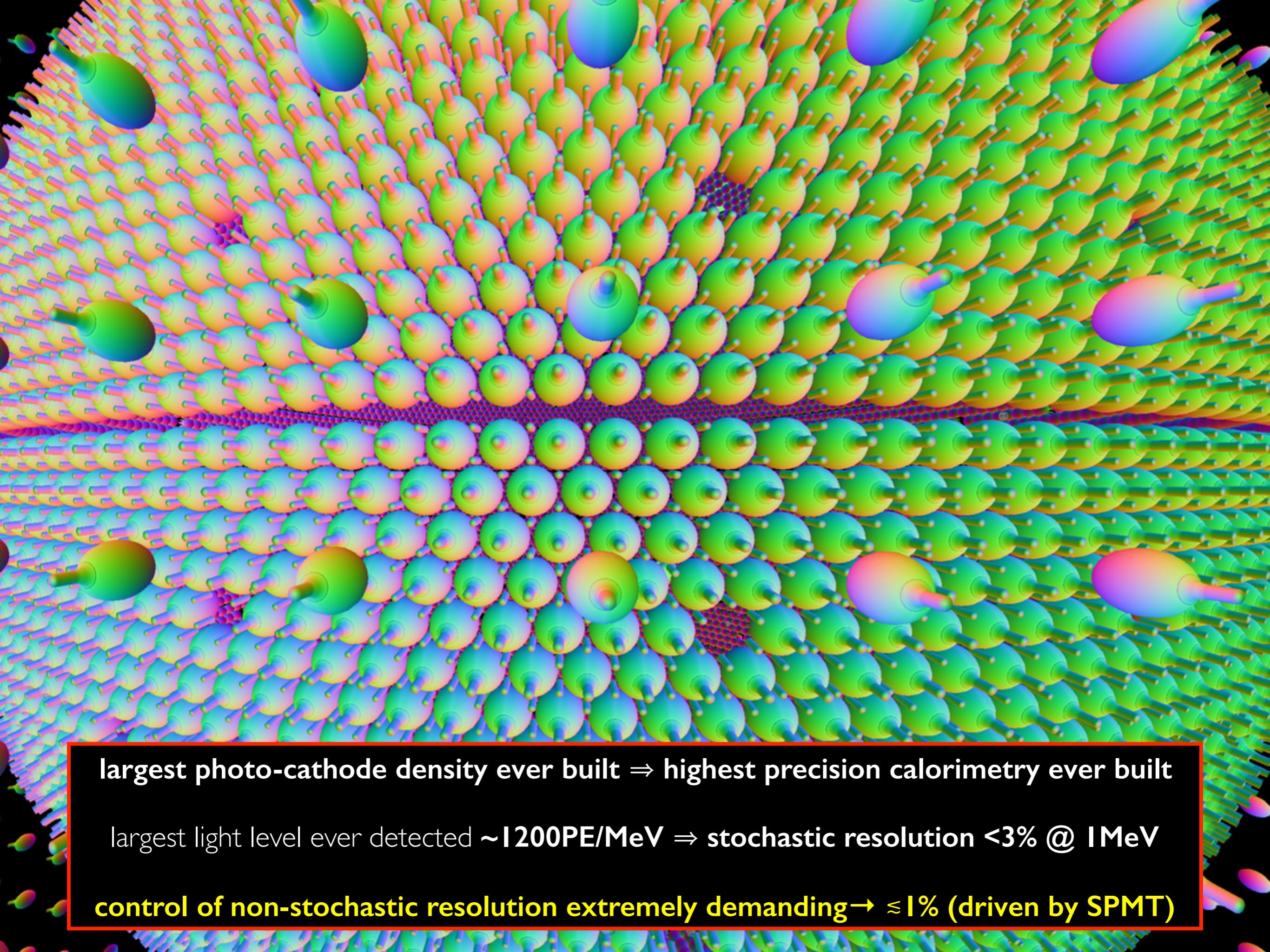
JUNO can be regarded as a hybrid of both...
(filled with liquid-scintillator → **~100x more light**)

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: $\sim 1.2\text{kPE/MeV}$
 - systematics control (transparency)
- **must be large** (reactors @ $\sim 50\text{km}$)
 - over-designed for all other physics
- $\sim 20\text{kt}$ spherical liquid scintillator detector
 - $\sim 1.5\text{m}$ of buffer (isolation + optics)
 - **$\sim 18\text{k } 20'' \text{ PMTs}$** ($\sim 80\%$ photo-coverage)
 - **$\sim 36\text{k } 3'' \text{ PMTs (calorimetry control)}$**
 - excellent μ -tracking → ${}^9\text{Li}+{}^8\text{He}$ 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 \Rightarrow highest precision calorimetry ever built

largest light level ever detected $\sim 1200 \text{ PE/MeV} \Rightarrow$ stochastic resolution $< 3\% @ 1 \text{ MeV}$

control of non-stochastic resolution extremely demanding $\rightarrow \lesssim 1\%$ (driven by SPMT)

double calorimetry . . .

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

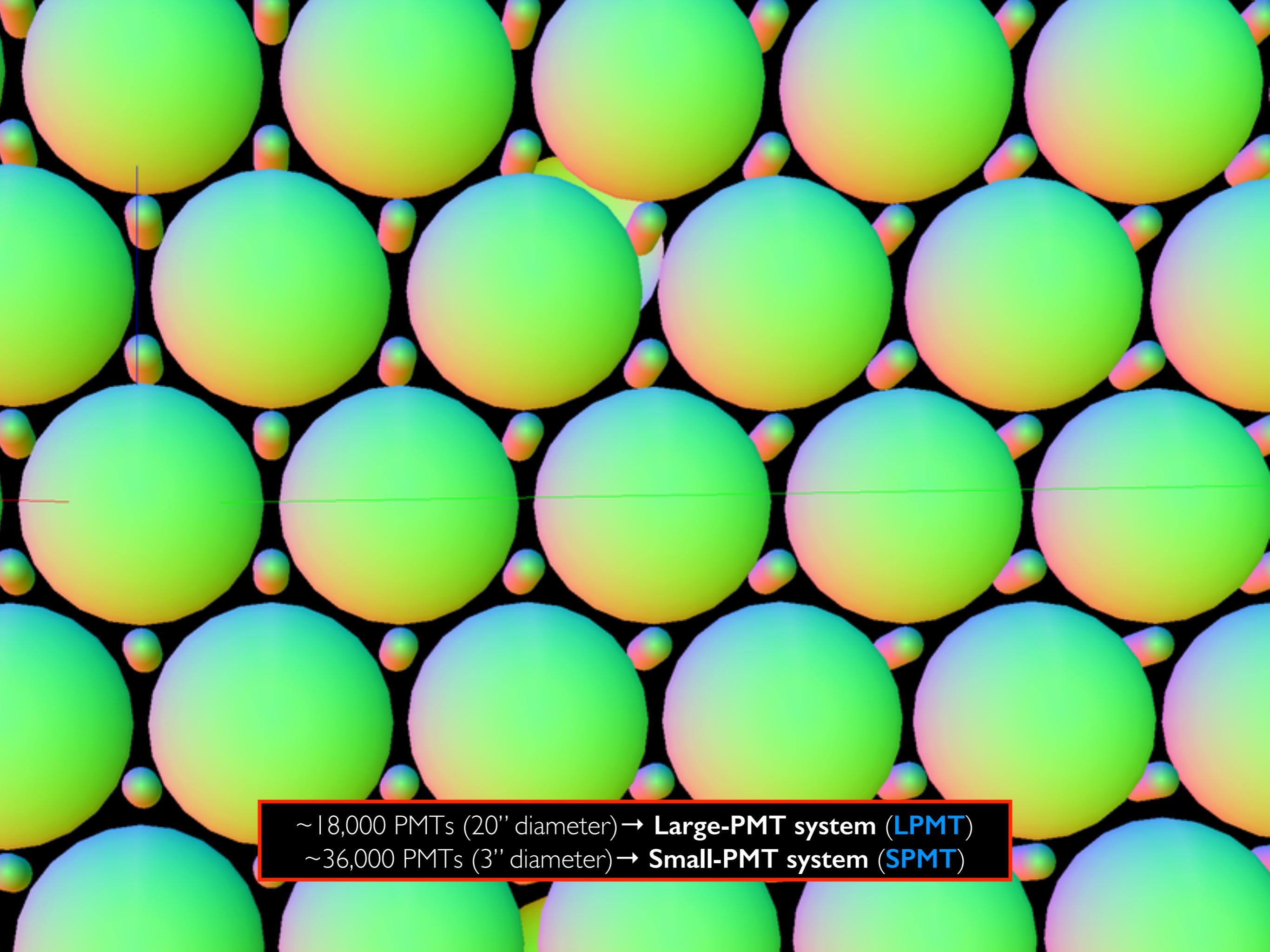
- Padova-INFN (Padova)

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)**

SPMT is anything but small

~36,000 PMTs is huge!

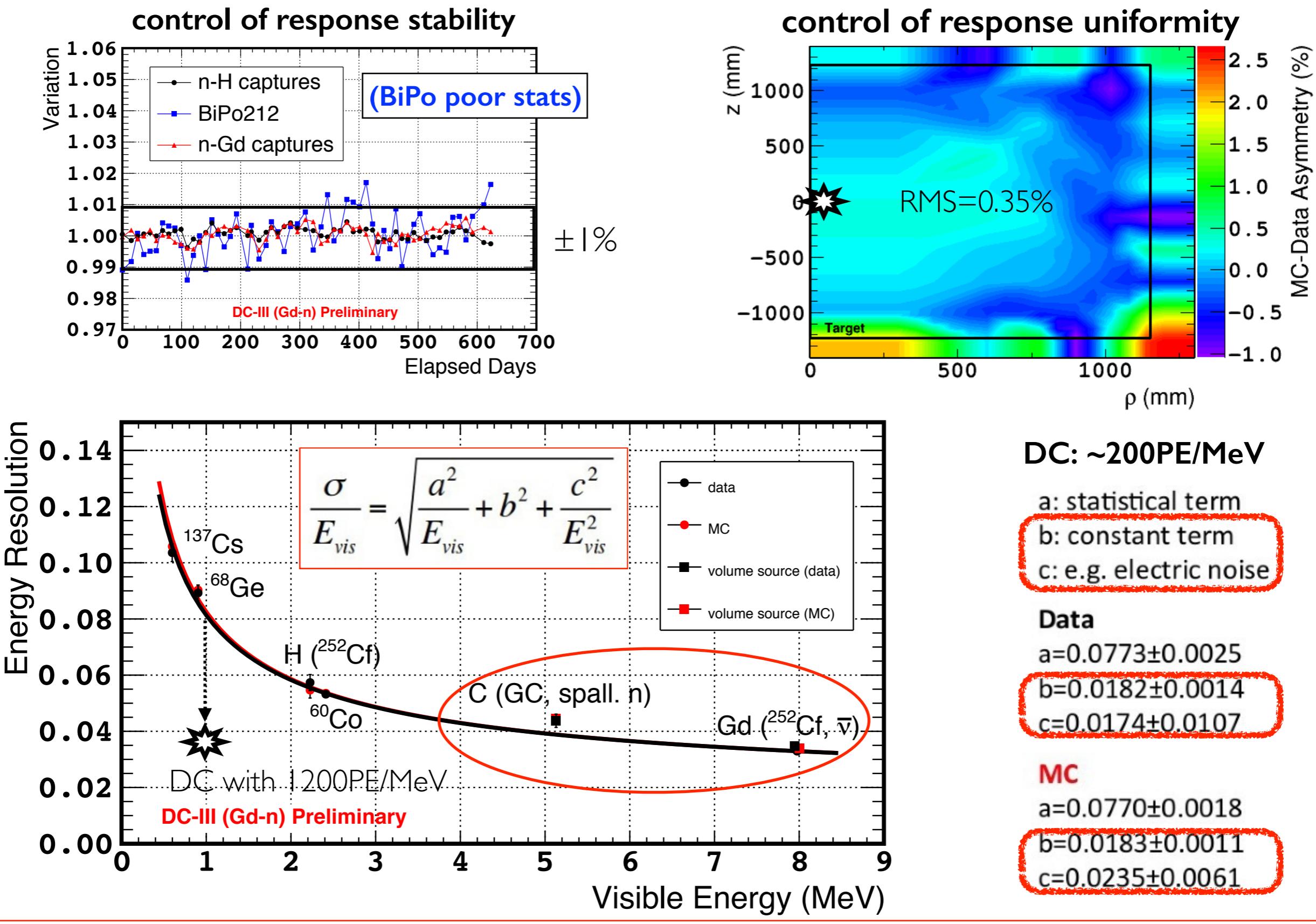
(only the PMTs are smaller → circumstantial @ JUNO)

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

motivation...

— why the SPMT? —

DC as prototype for JUNO...



no perfect world...

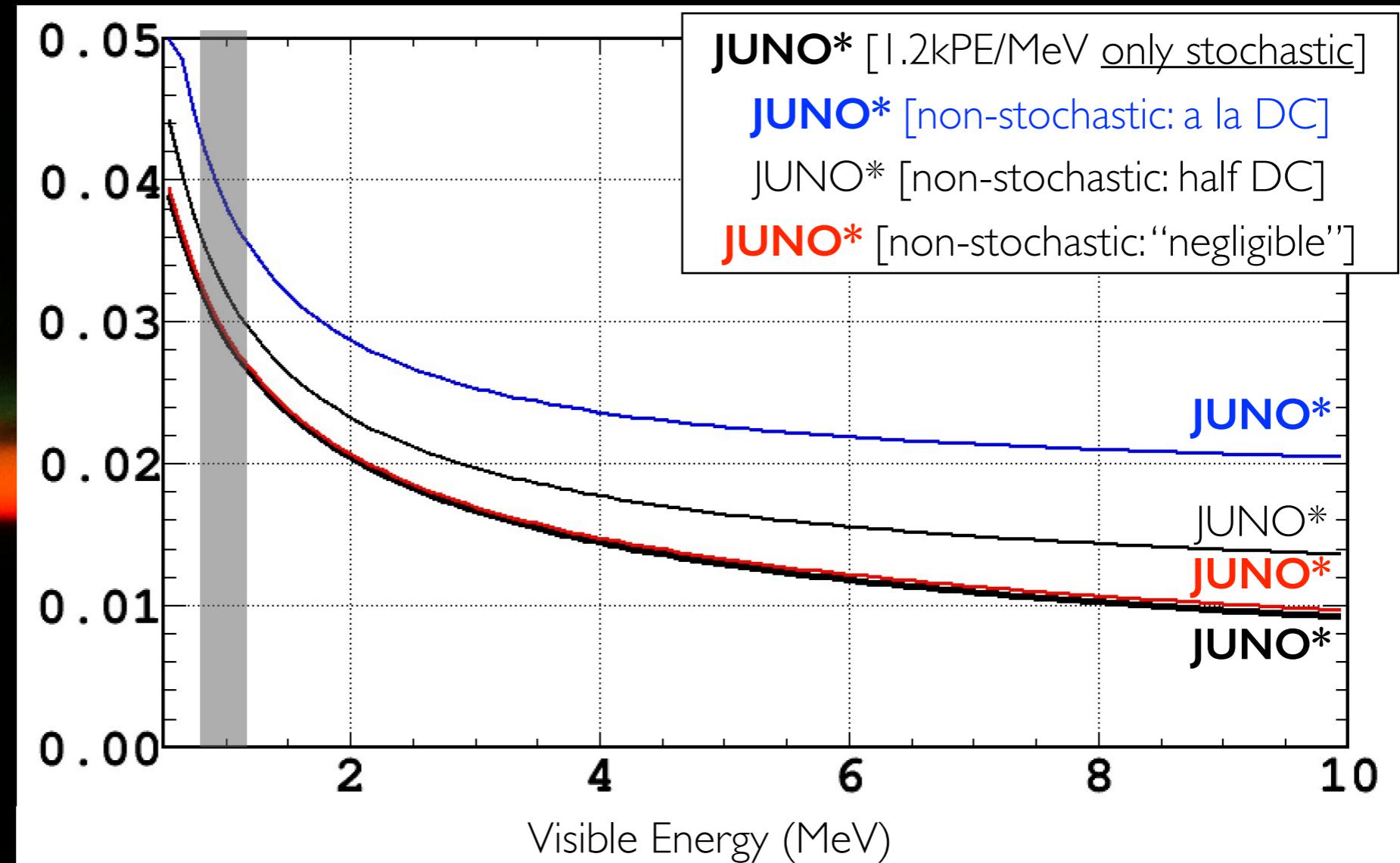
$$\sigma(E)^2 = \sigma(E)_{\text{stoch}}^2 + \sigma(E)_{\text{non-stoch}}^2 \Rightarrow \text{empiric formulation:}$$

(1200PE/MeV) (??%)

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

~1.2k PEs
 $\sigma(E)_{\text{stoch}} < 3\%$

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



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

- if perfect calibration: $\sigma(E)_{\text{non-stoch}}^2 \rightarrow 0$ (i.e. **perfect correction of dispersive effects**)

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

control of systematics...
A horizontal band of blurred light from a projector, showing a gradient from red at the bottom to green at the top, centered on the slide.

(i.e. non-stochastic effects)

the double calorimetry...

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

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

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

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

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

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

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

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“double-calorimetry”

articulate 2 energy estimators (different behaviours)

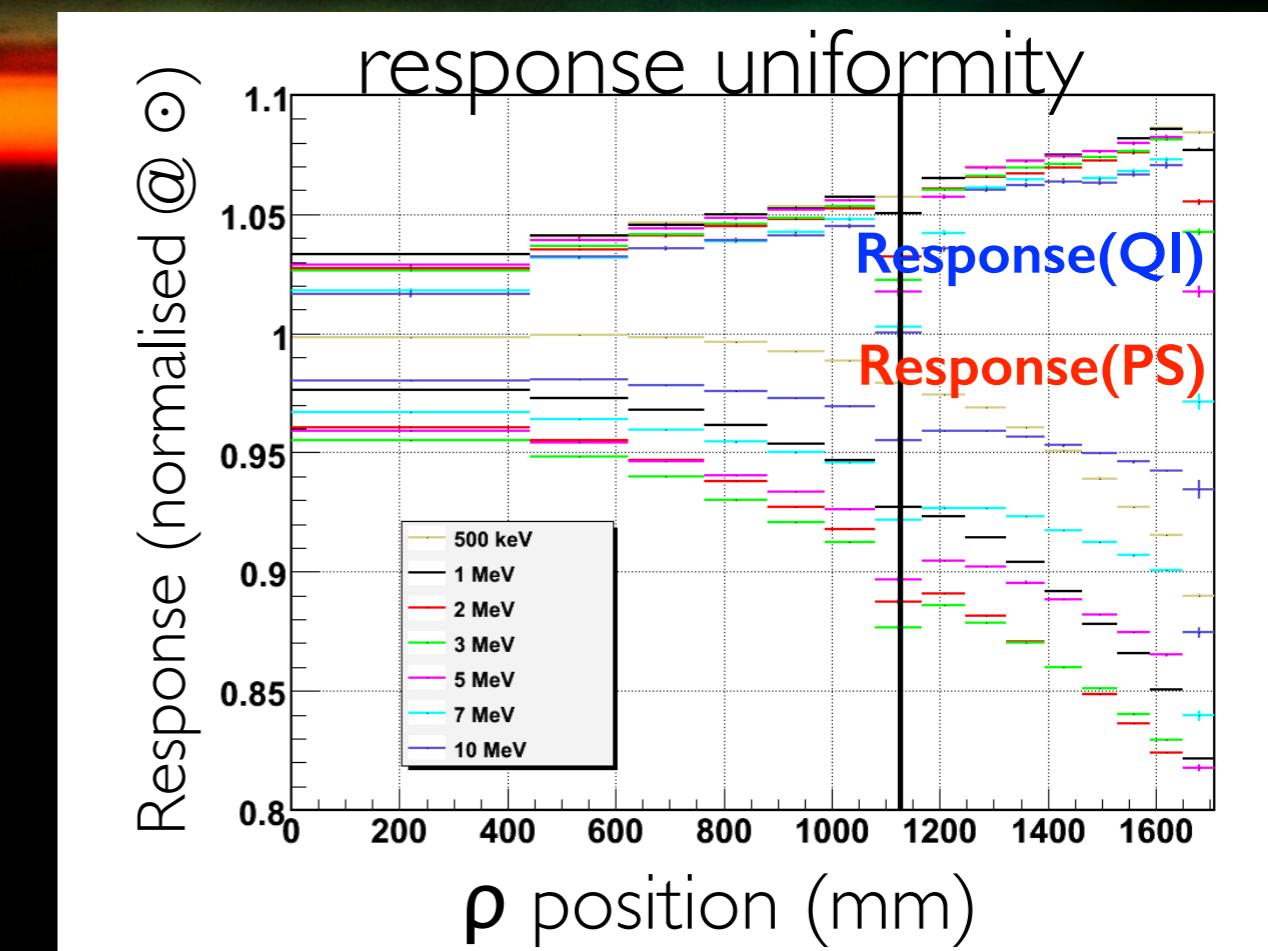
Energy(photon-counting) i.e. digital (**PS**)

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

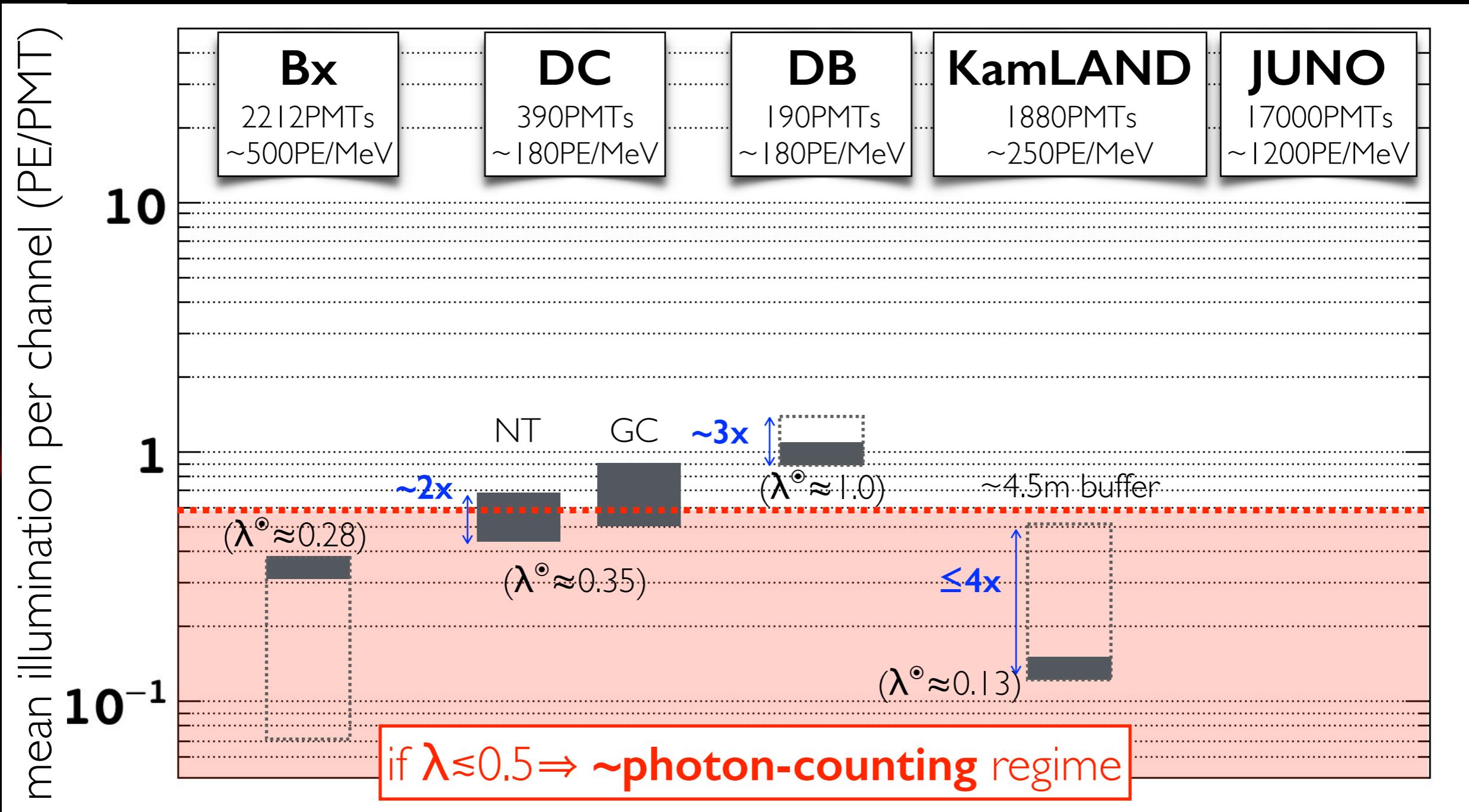
$$\Rightarrow E(\text{response},x,y,z)^{\text{DC}} = E(\text{PS}) \oplus E(\text{QI})$$

[via NN, correction, etc]

control/reduction $\sigma(E)^2_{\text{non-stoch}}$ & redundancy
[if $\pm \Delta m^2 \rightarrow$ convince JUNO can]



@IMeV

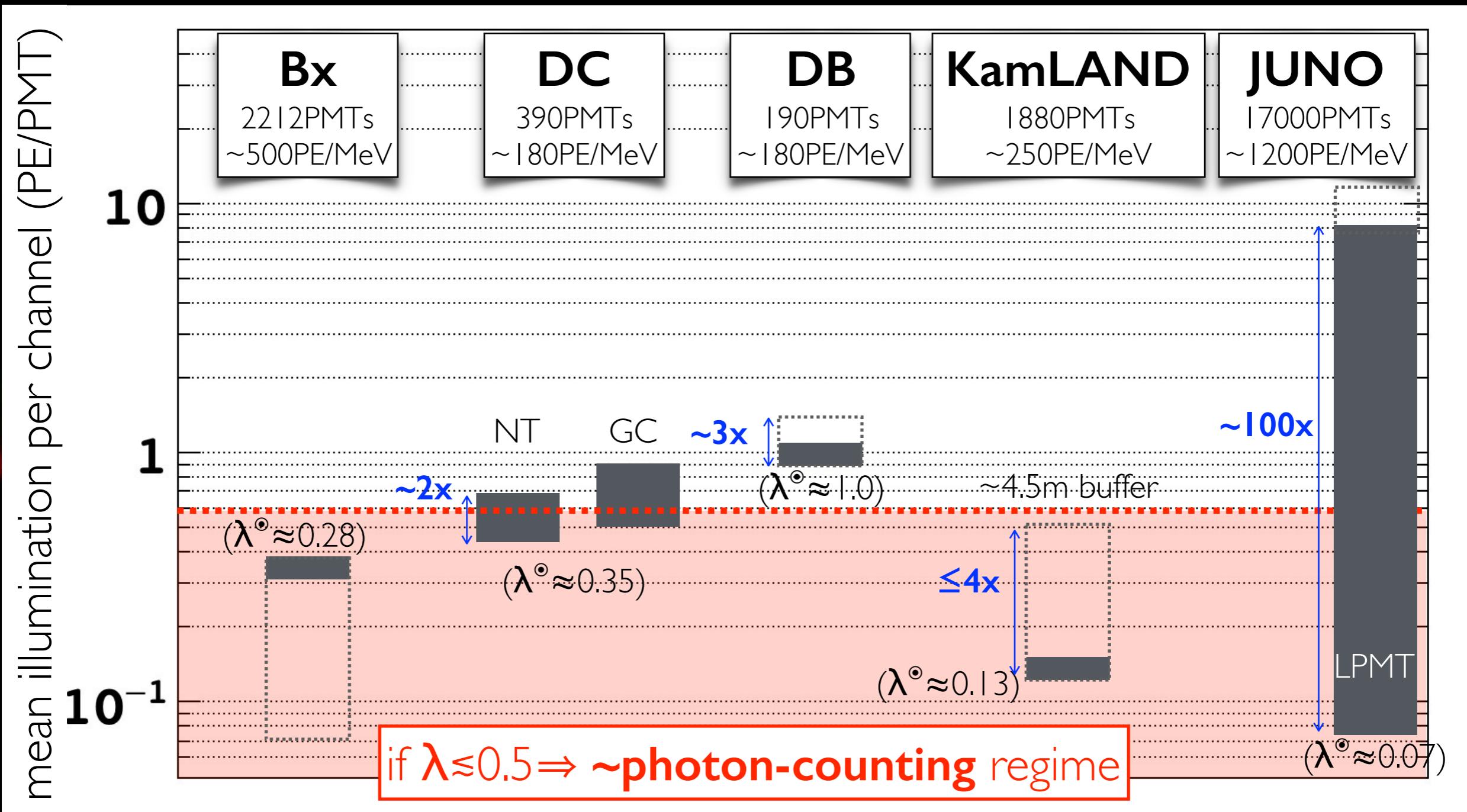
 $\lambda^\odot = \text{mean illumination per channel @ center}$


HIGHEST precision calorimetry ($\leq 3\% @ 1\text{MeV}$)

⊕

LARGEST dynamic range in calorimetry (channel-wise) [$\Rightarrow \text{uniformity} \oplus \text{linearity} \oplus \text{stability}$]

@IMeV

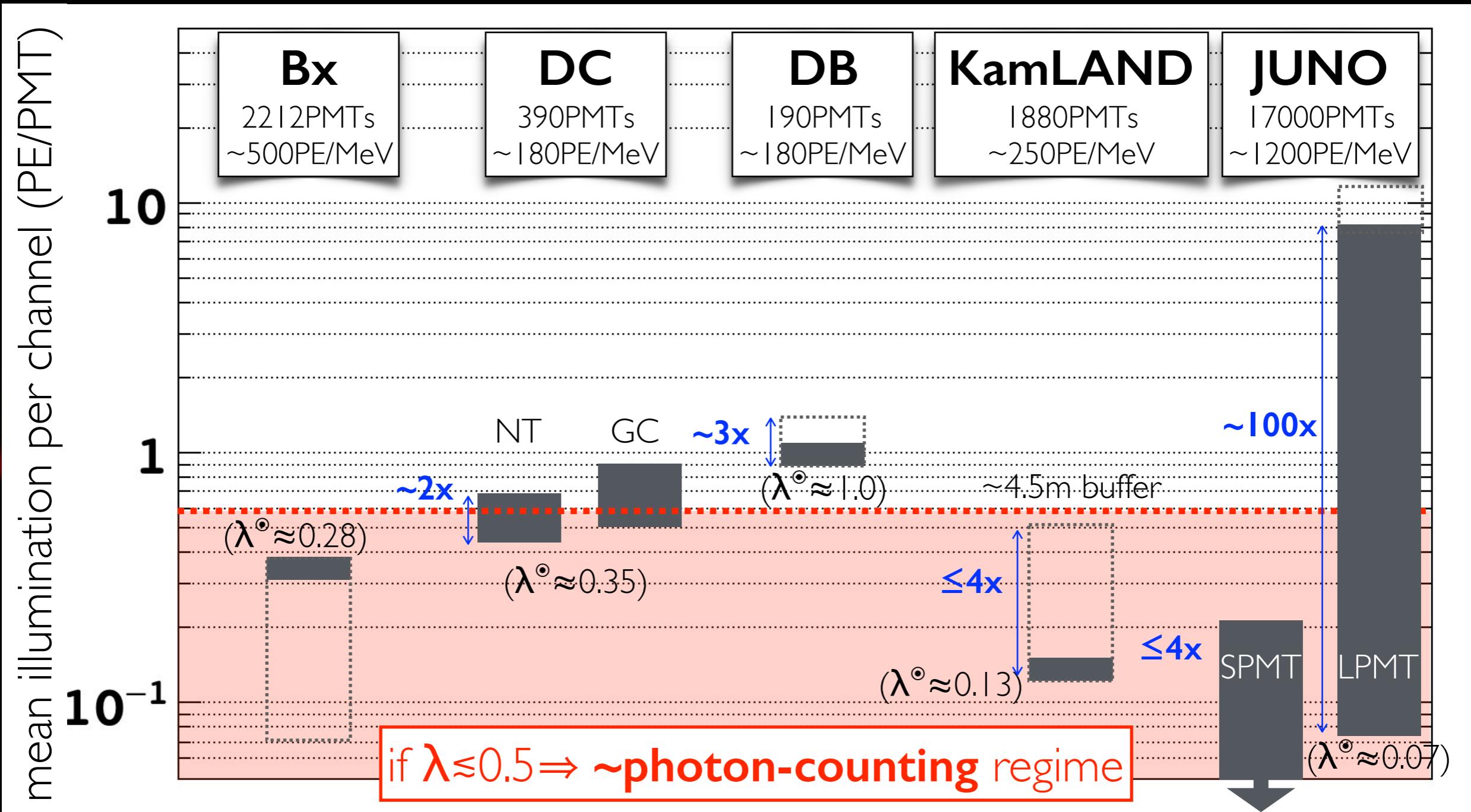
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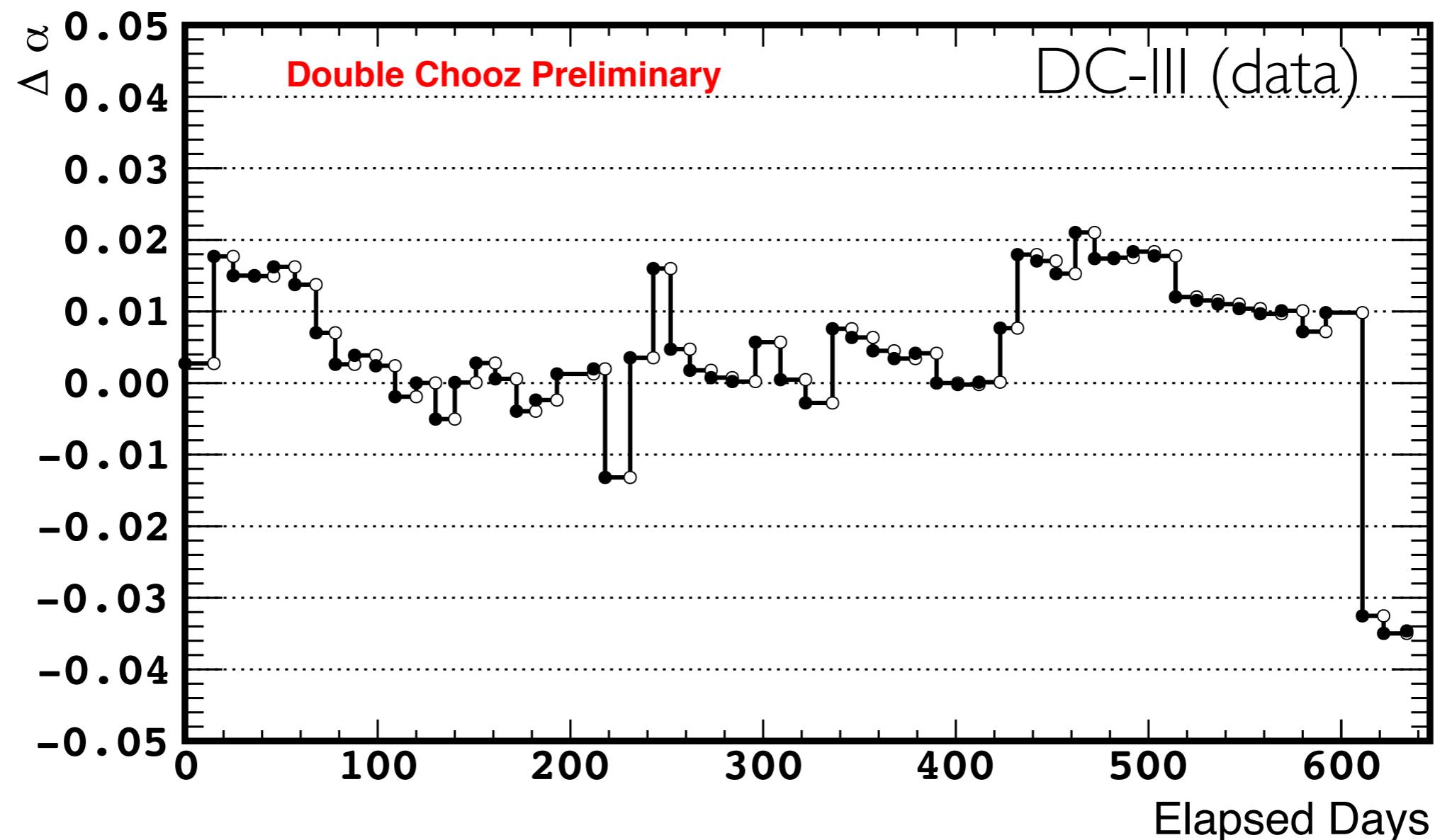
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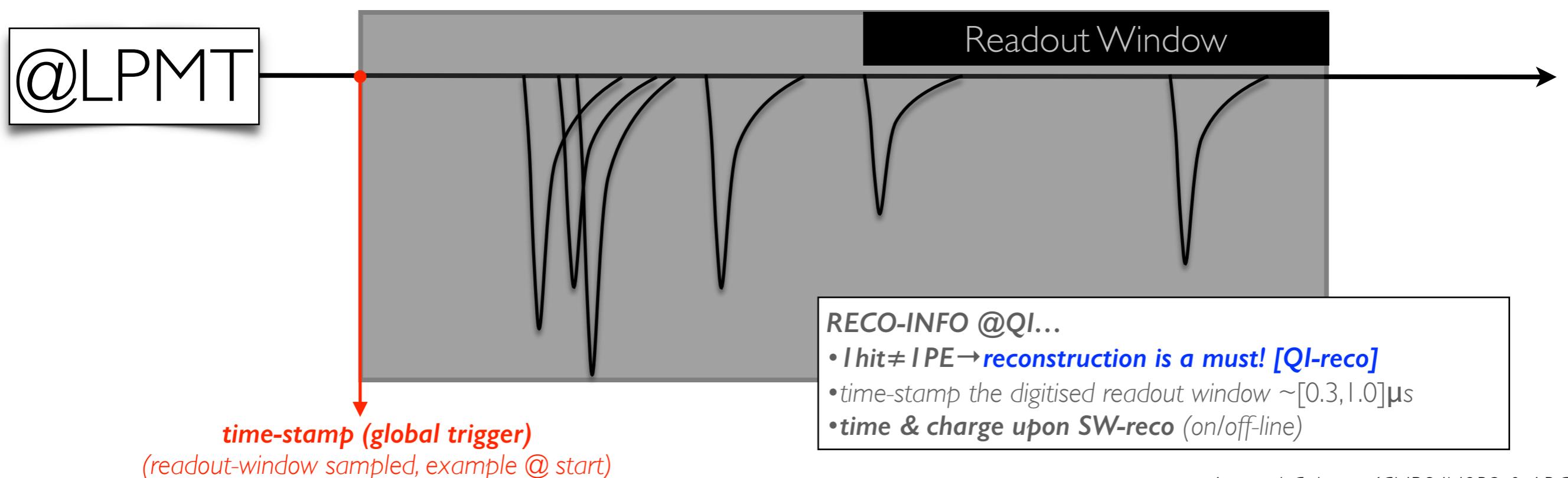
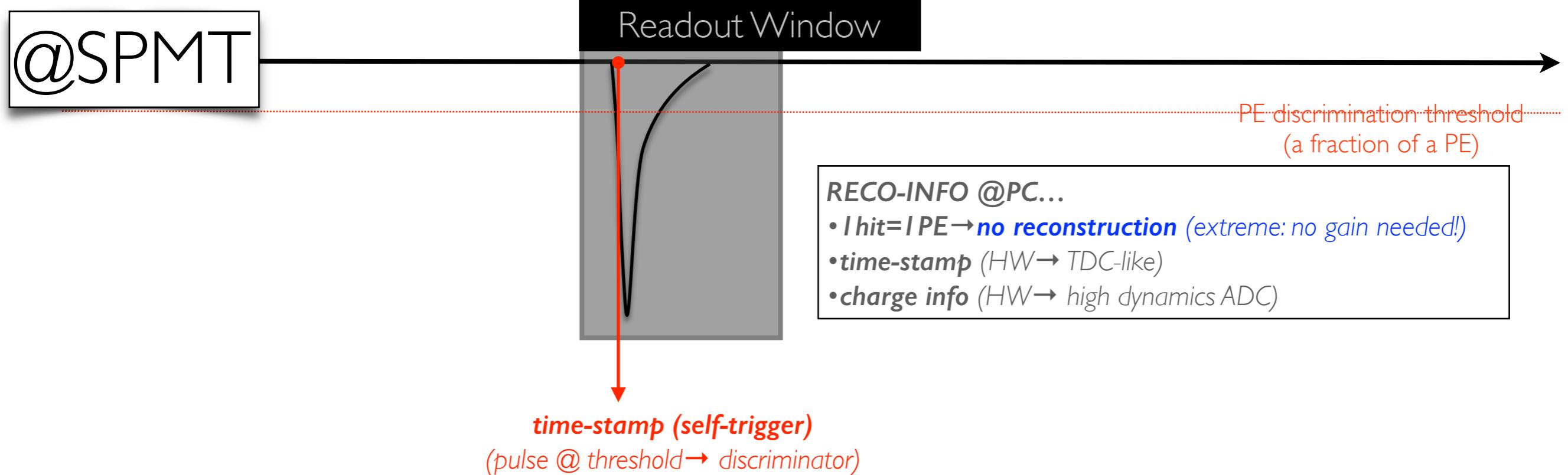
response stability



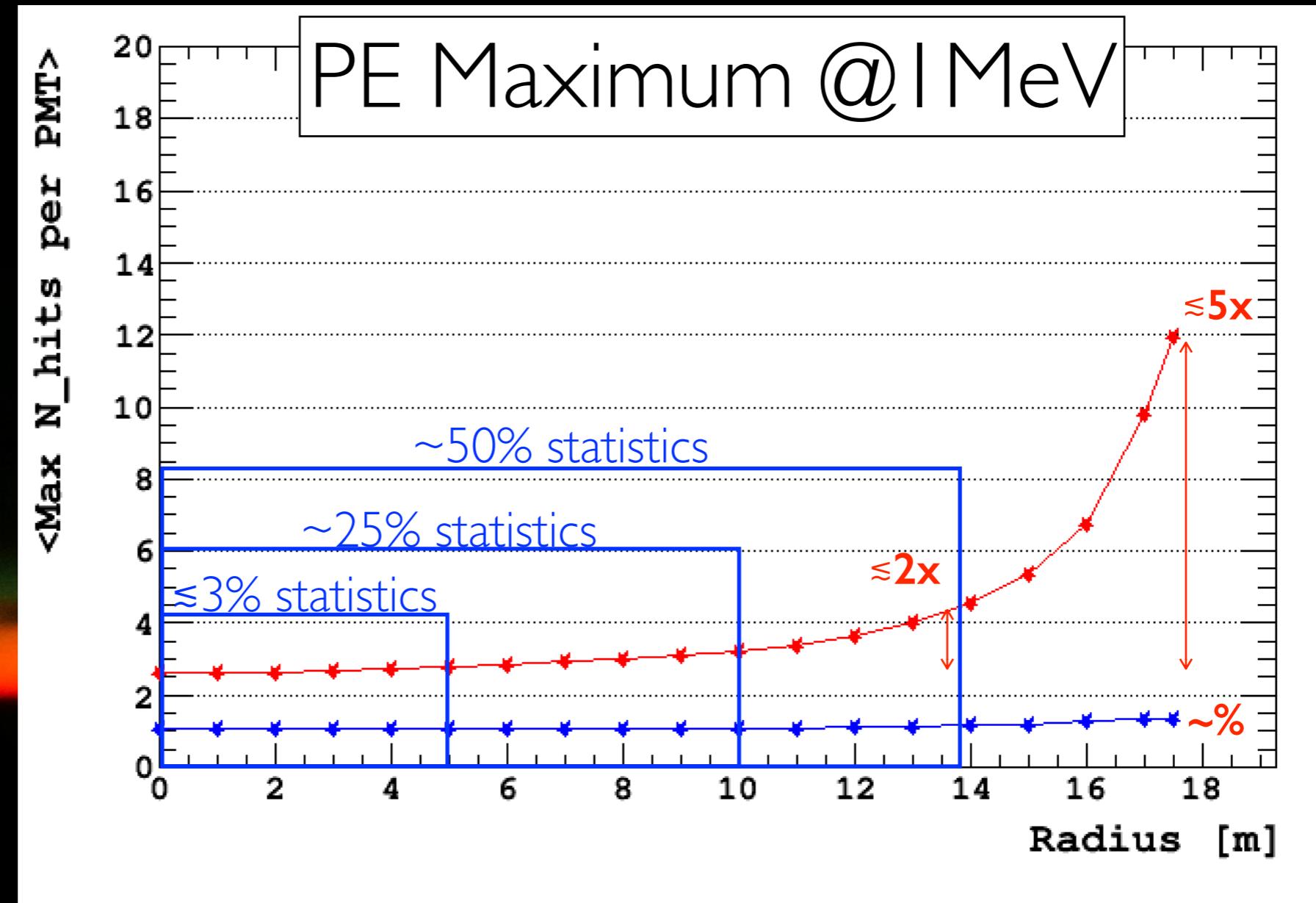
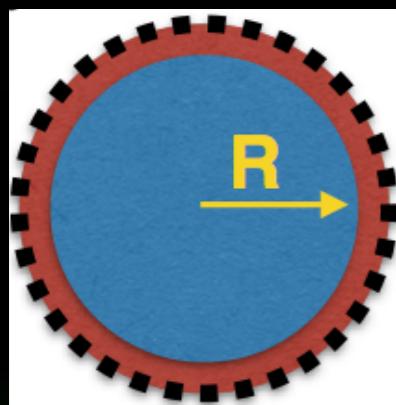
“digital” response stability @ 2.2MeV (zero tracking⊕other effect)
 (invisible to charge integration estimator alone)

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

Photon-Counting vs Charge-Integration...



the SPMT & LPMT calorimetry regimes...



LPMT has dramatic variation across volume (\rightarrow systematics and/or biases)

(wildest variation in region with large fraction of statistics)

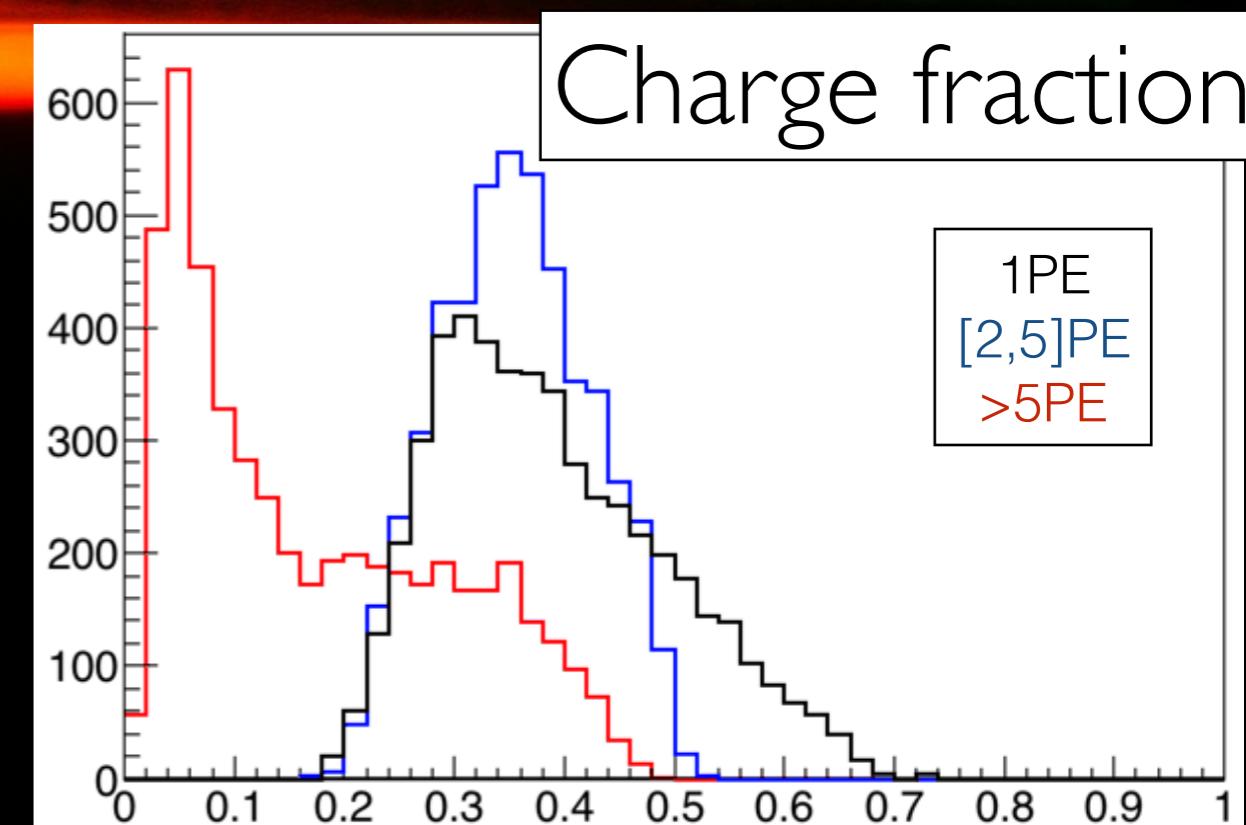
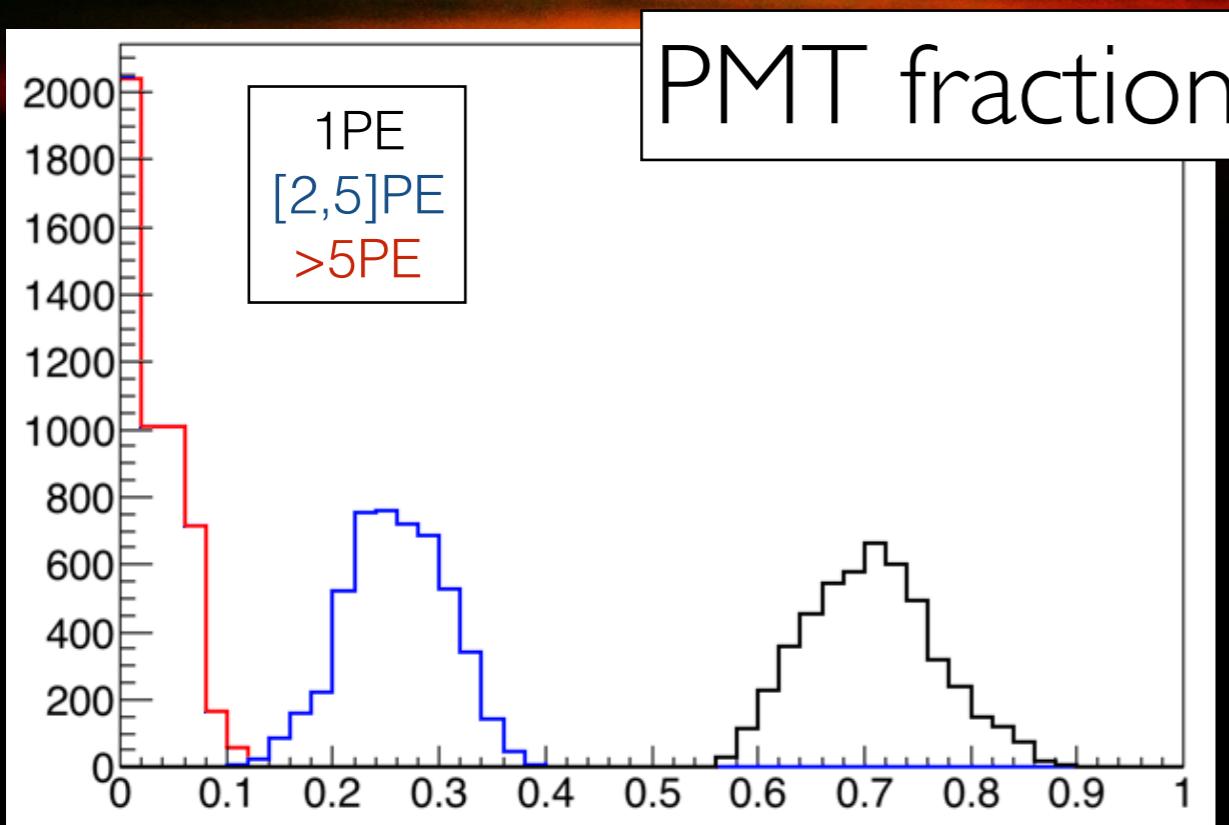
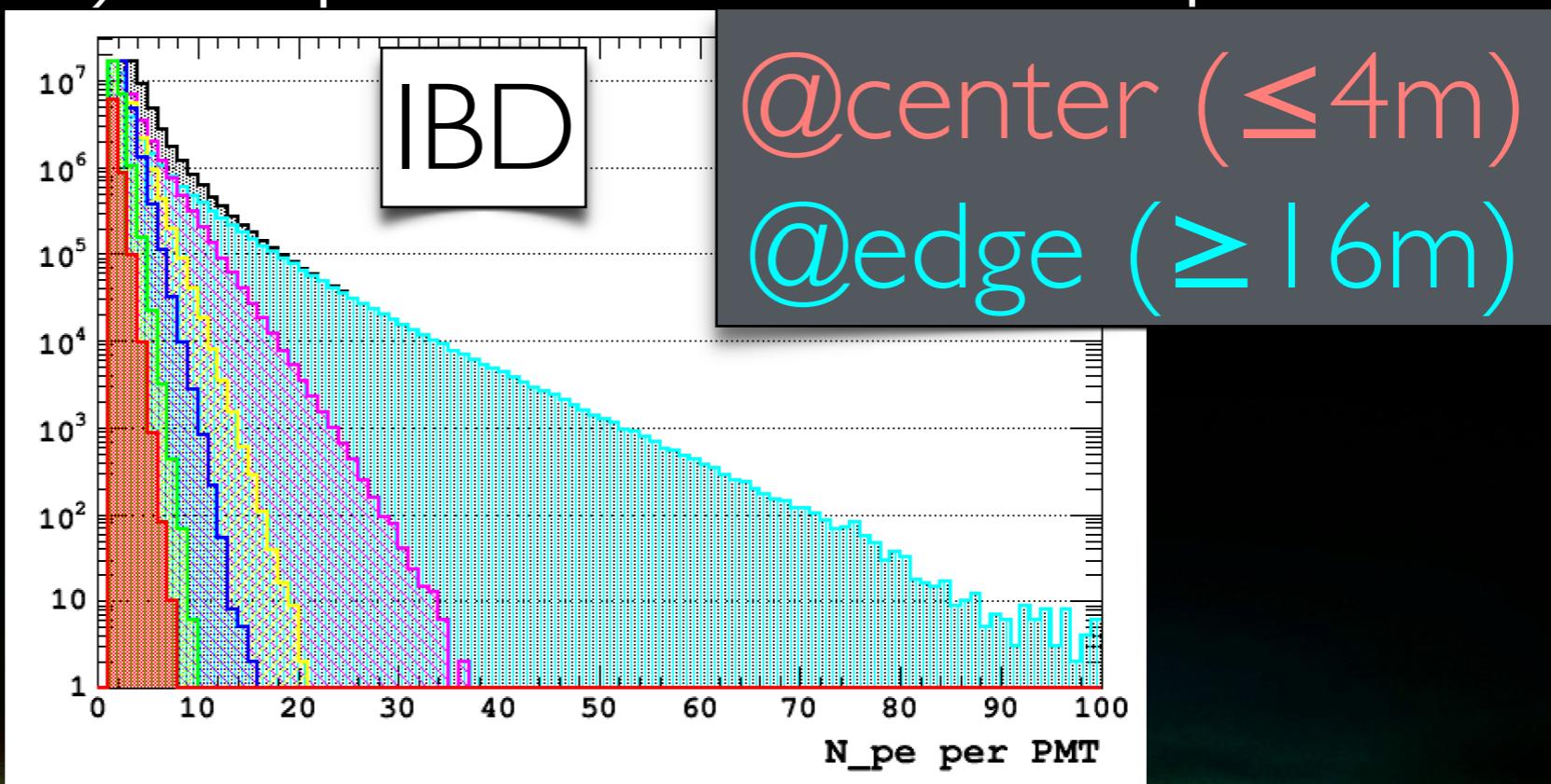
(opposite) **SPMT has FLAT response across volume (by construction)**

(SPMT ideal input for Trigger)

(illustration) response/channel vs position...

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

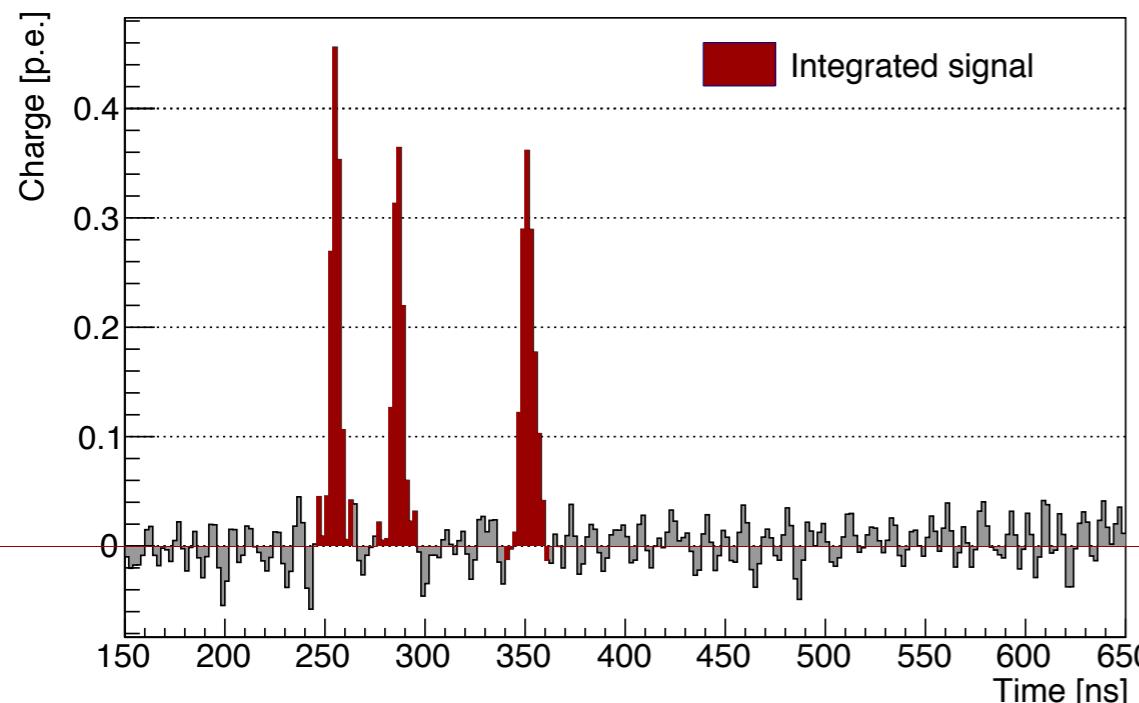
LPMT only



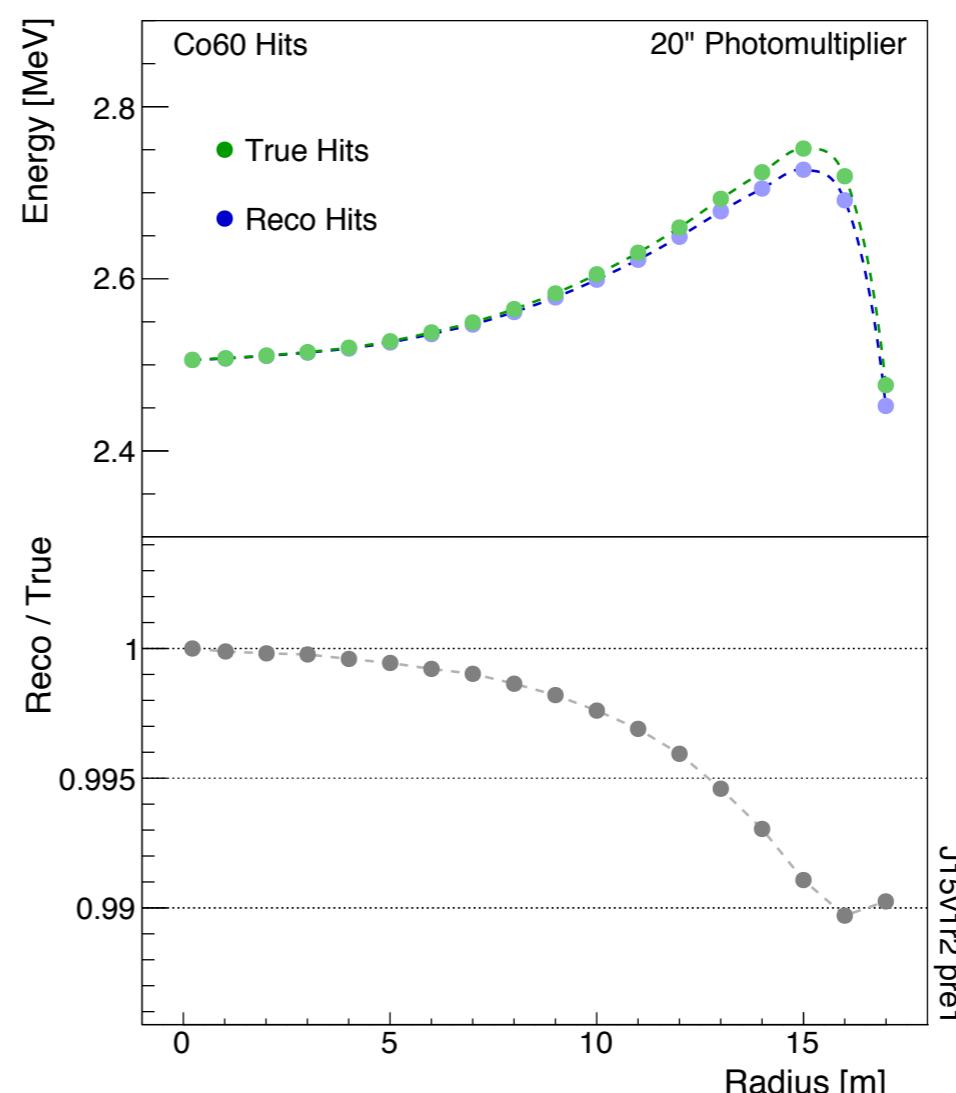
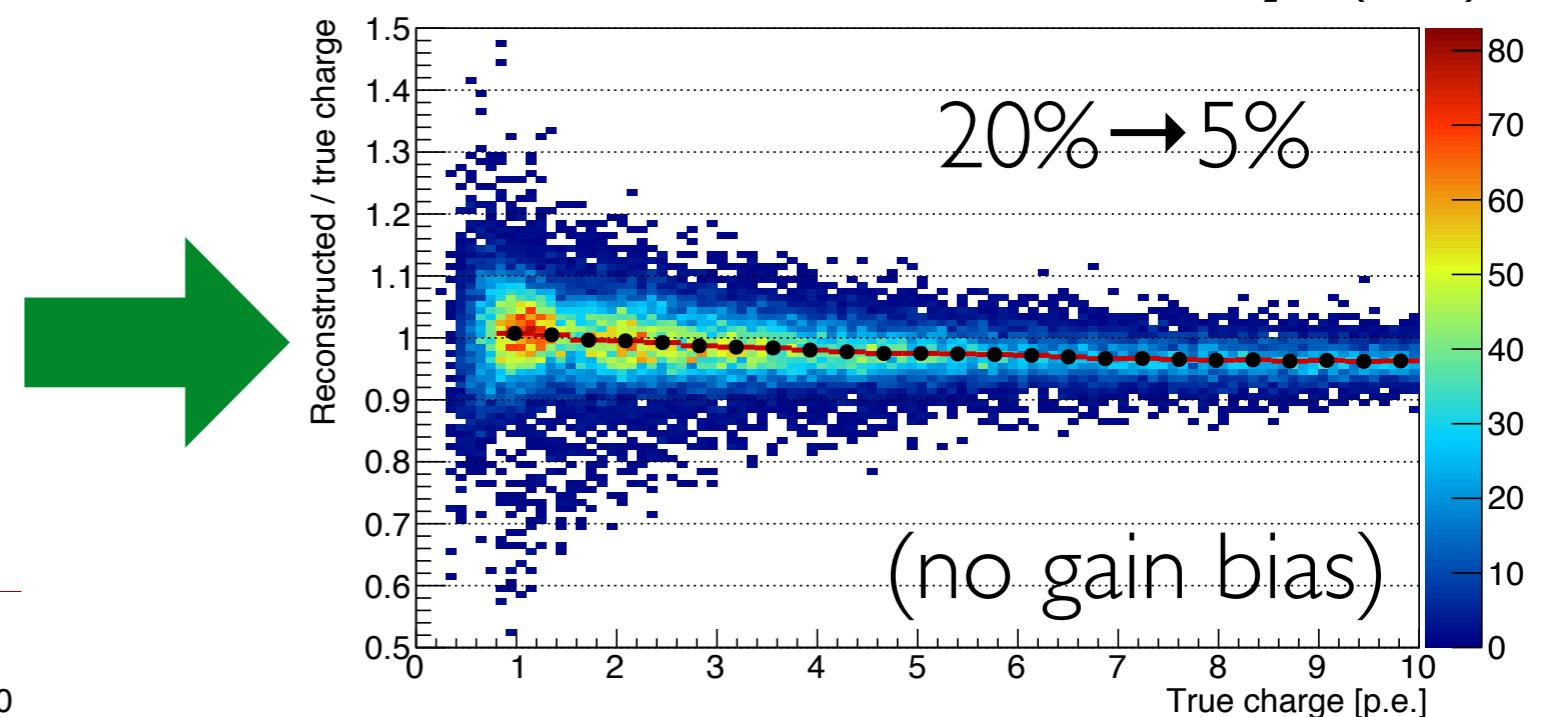
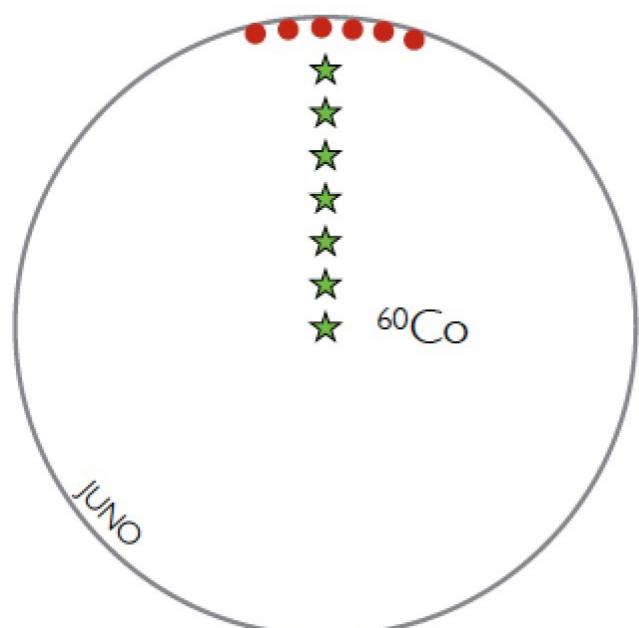
small bias in few LPMTs \Rightarrow large impact to over calorimetry!

energy reconstruction bias estimation (I)...

realistic pulse reco (QI)



**calibration
mimicking**

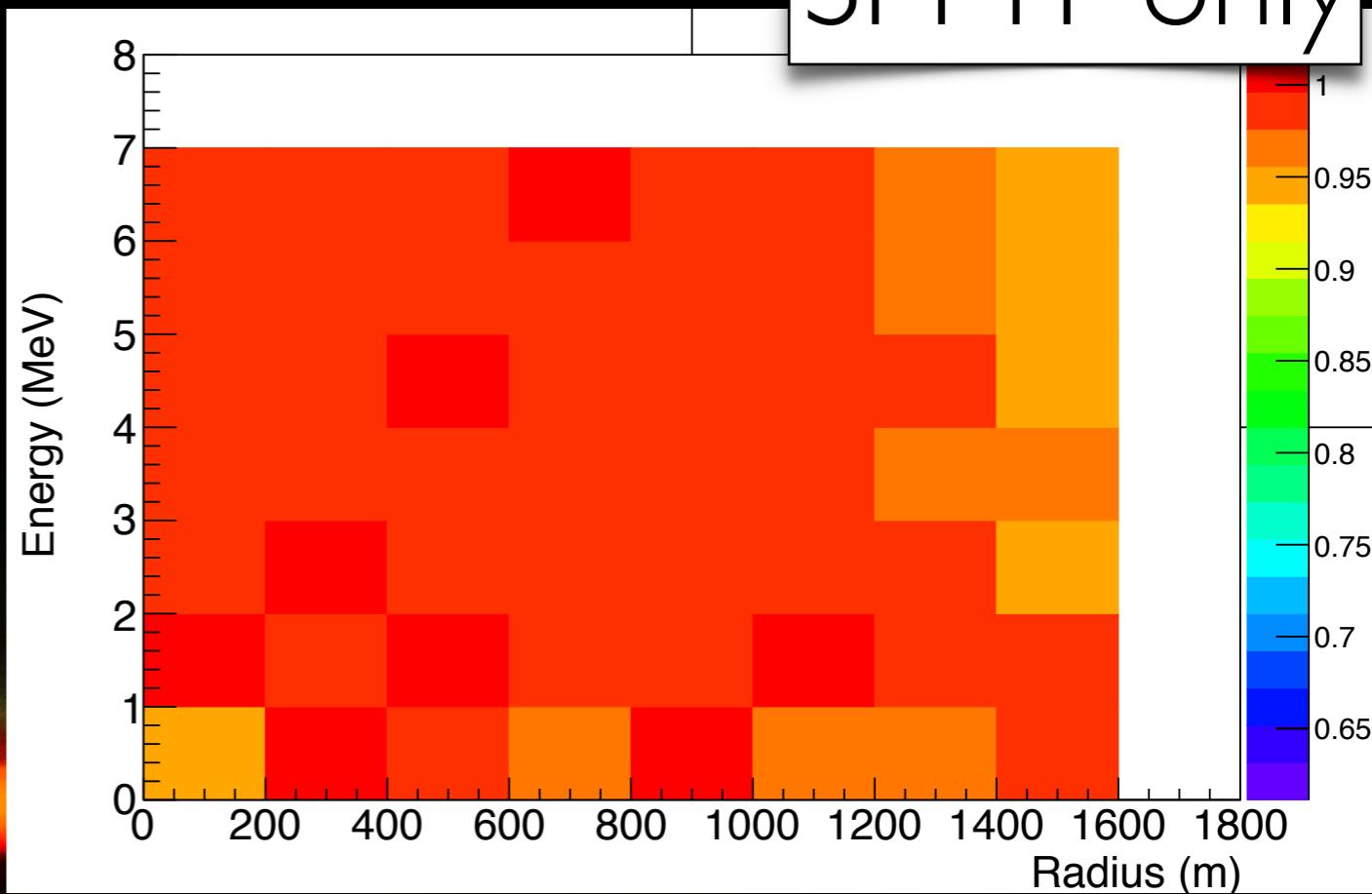


non-linearity
(channel-wise)

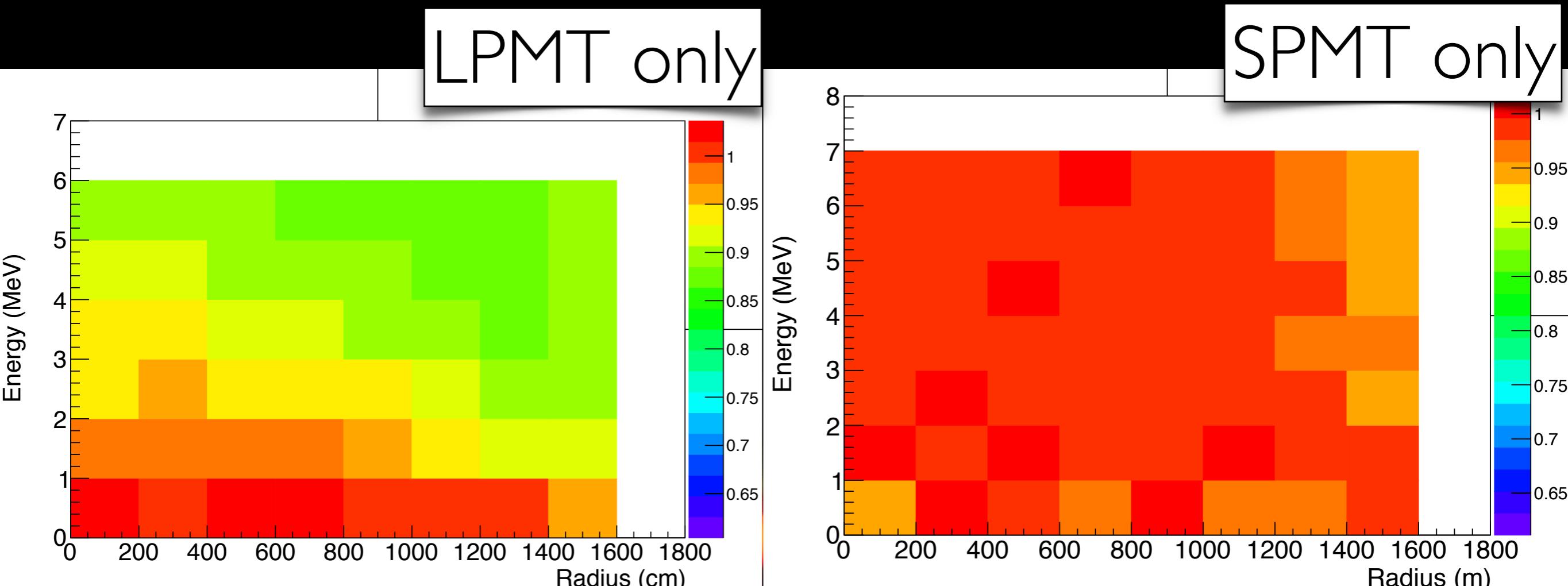
non-uniformity
(position-wise)
[QI regime variations]

worsens resolution
(full detector)

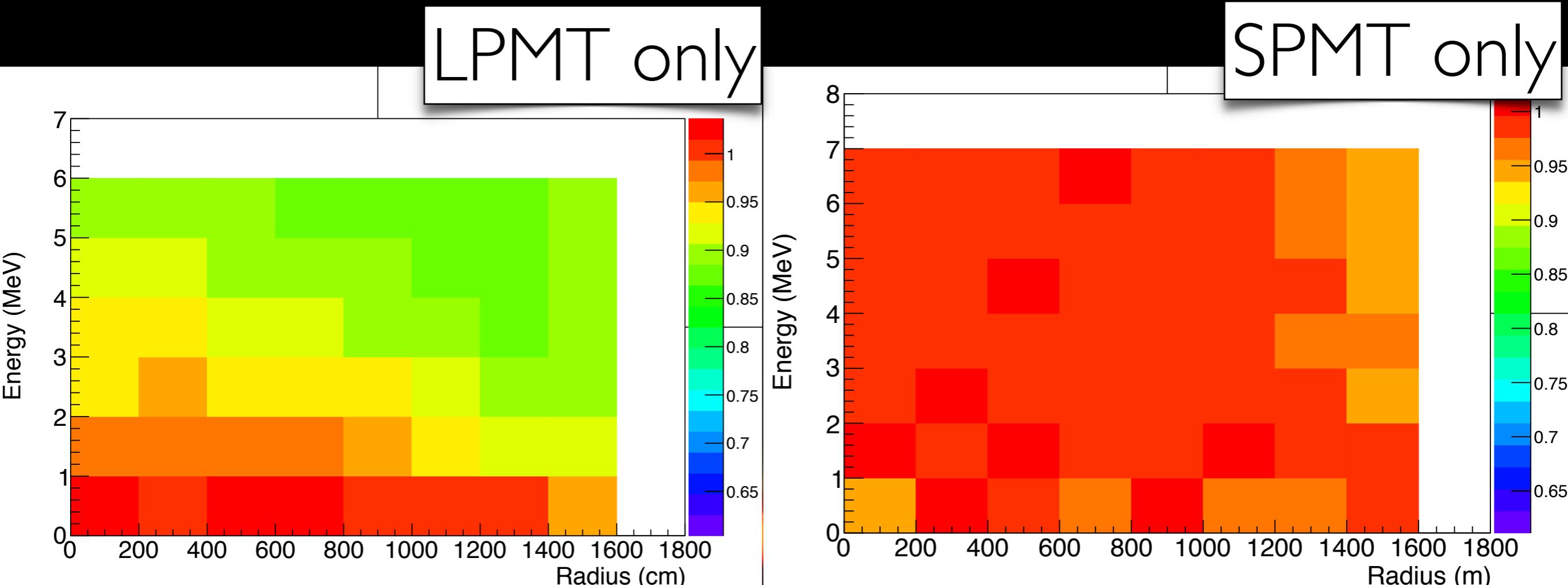
linearity⊕uniformity crosstalk handling...

SPMT only

linearity⊕uniformity crosstalk handling...

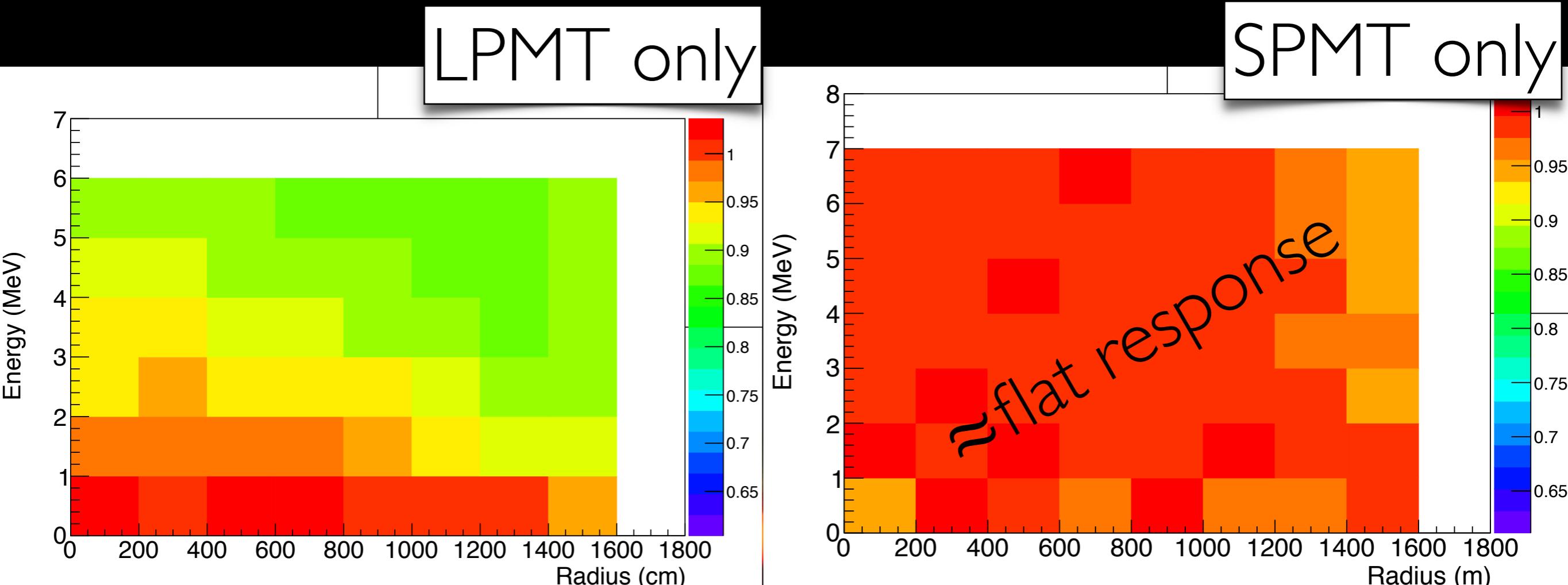


linearity⊕uniformity crosstalk handling...



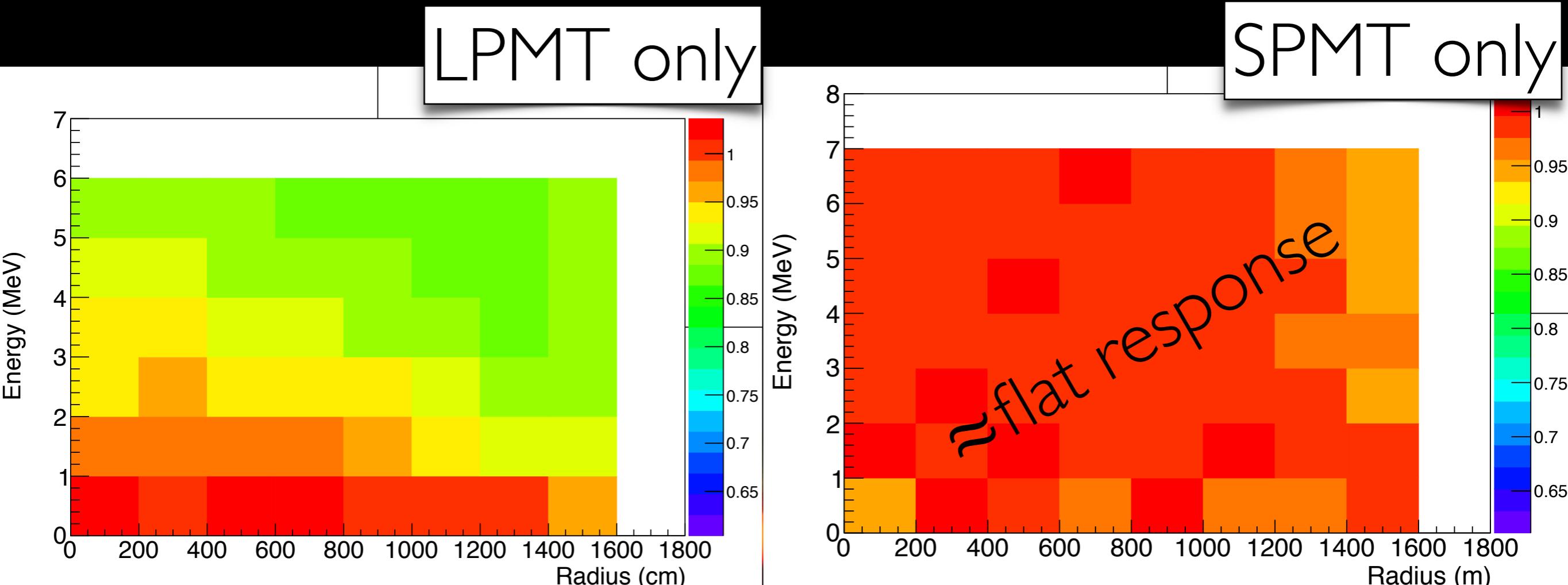
if linearity⊕uniformity \Rightarrow **LPMT 3D-maps a must!**

linearity⊕uniformity crosstalk handling...



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

linearity \oplus uniformity crosstalk handling...



if linearity \oplus uniformity \Rightarrow **LPMT 3D-maps a must!**

SPMT: uniformity map & linearity \Rightarrow (independent) 3D-map validation
 (simpler, complementary & robust \rightarrow unique, if SPMT)

response summary...

LPMT: uniformity • linearity • stability $\neq 0$
(i.e. not orthogonal bias/systematics)

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SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

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VS



SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

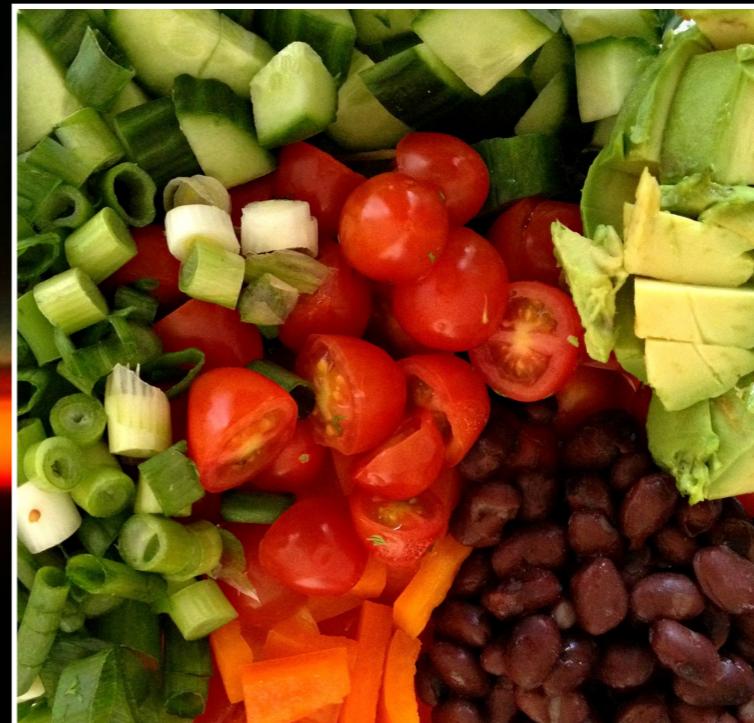
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vs



SPMT: uniformity • linearity • stability ≈ 0

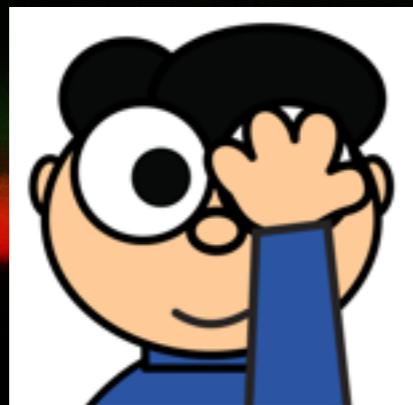
(i.e. effective orthogonal bias/systematics)

(far more knowledge when combining)

JUNO
(before)

JUNO
(now)

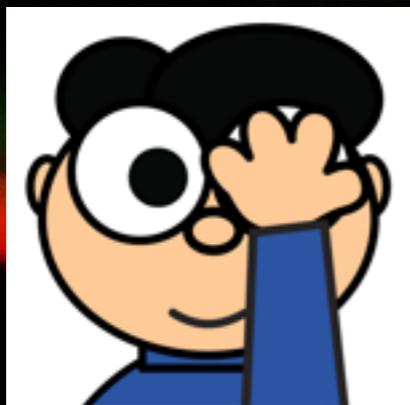
JUNO
(before)



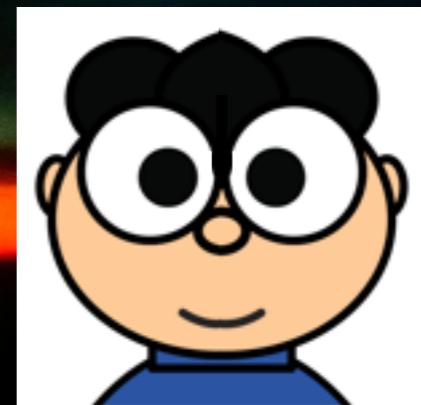
JUNO
(now)

single-calorimetric

JUNO
(before)

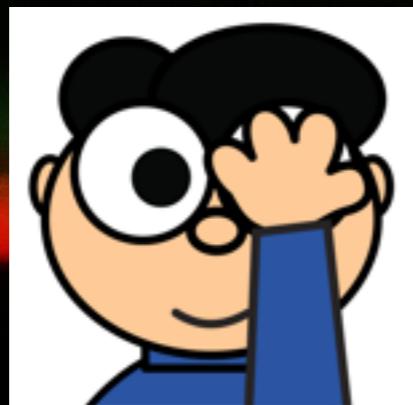


JUNO
(now)

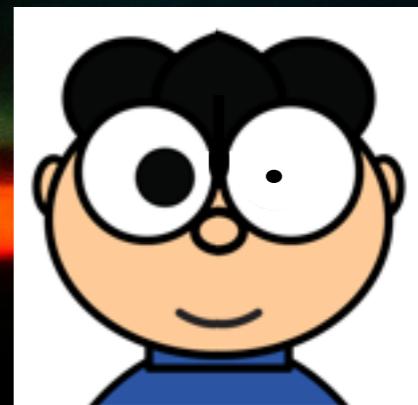


single-calorimetric

JUNO
(before)



JUNO
(now)



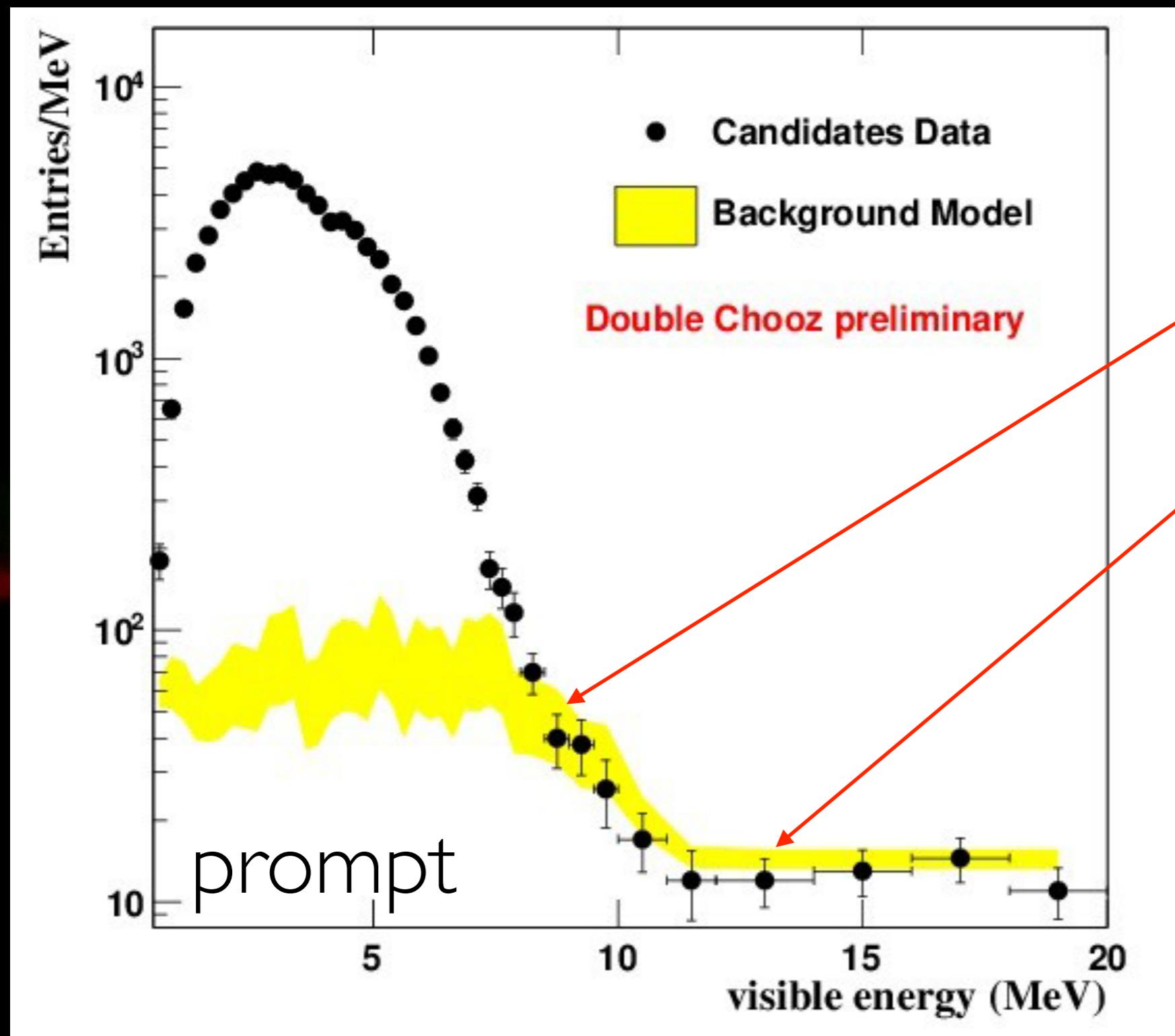
single-calorimetric

double calorimetric

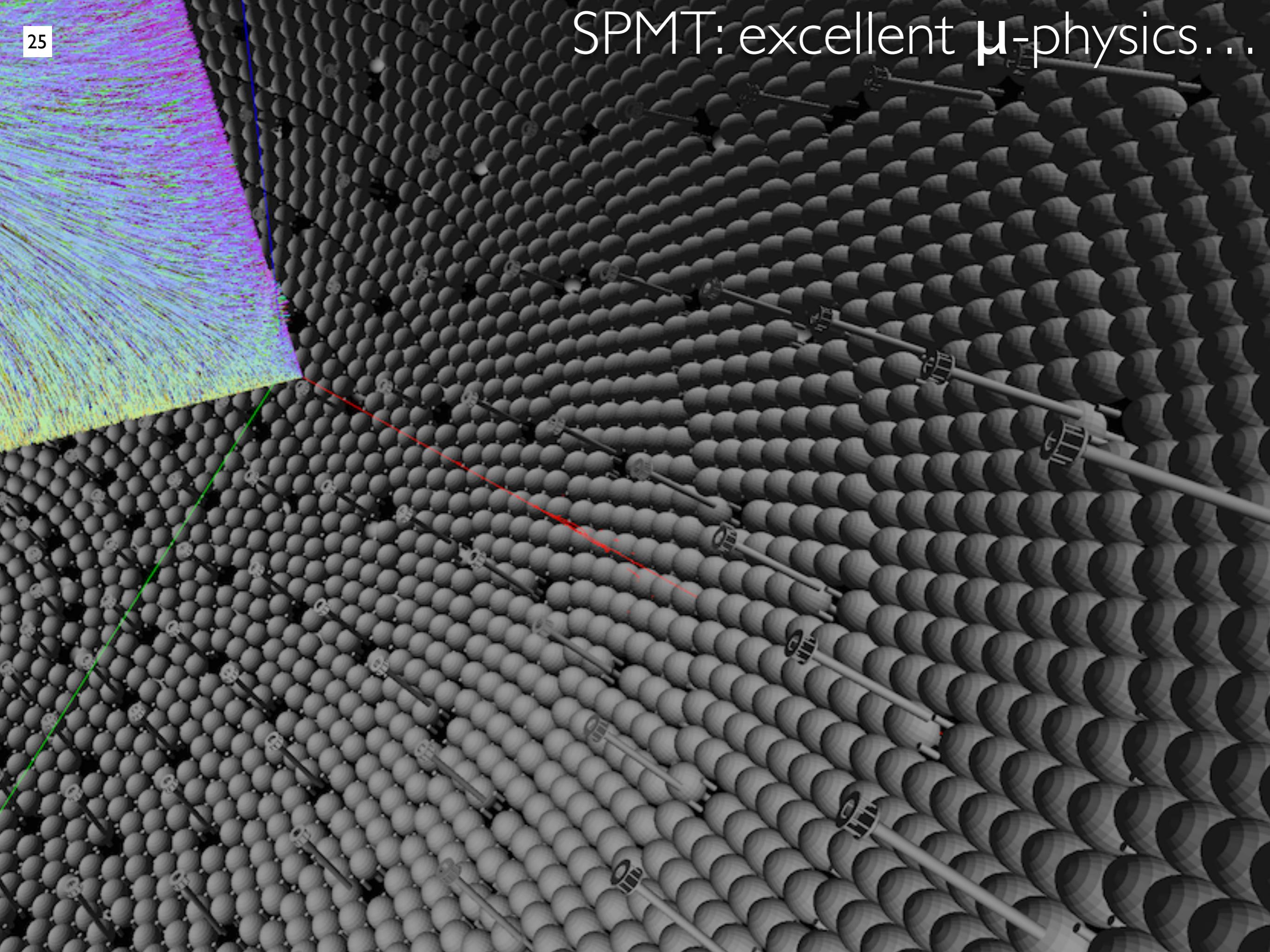
SPMT system: much more...



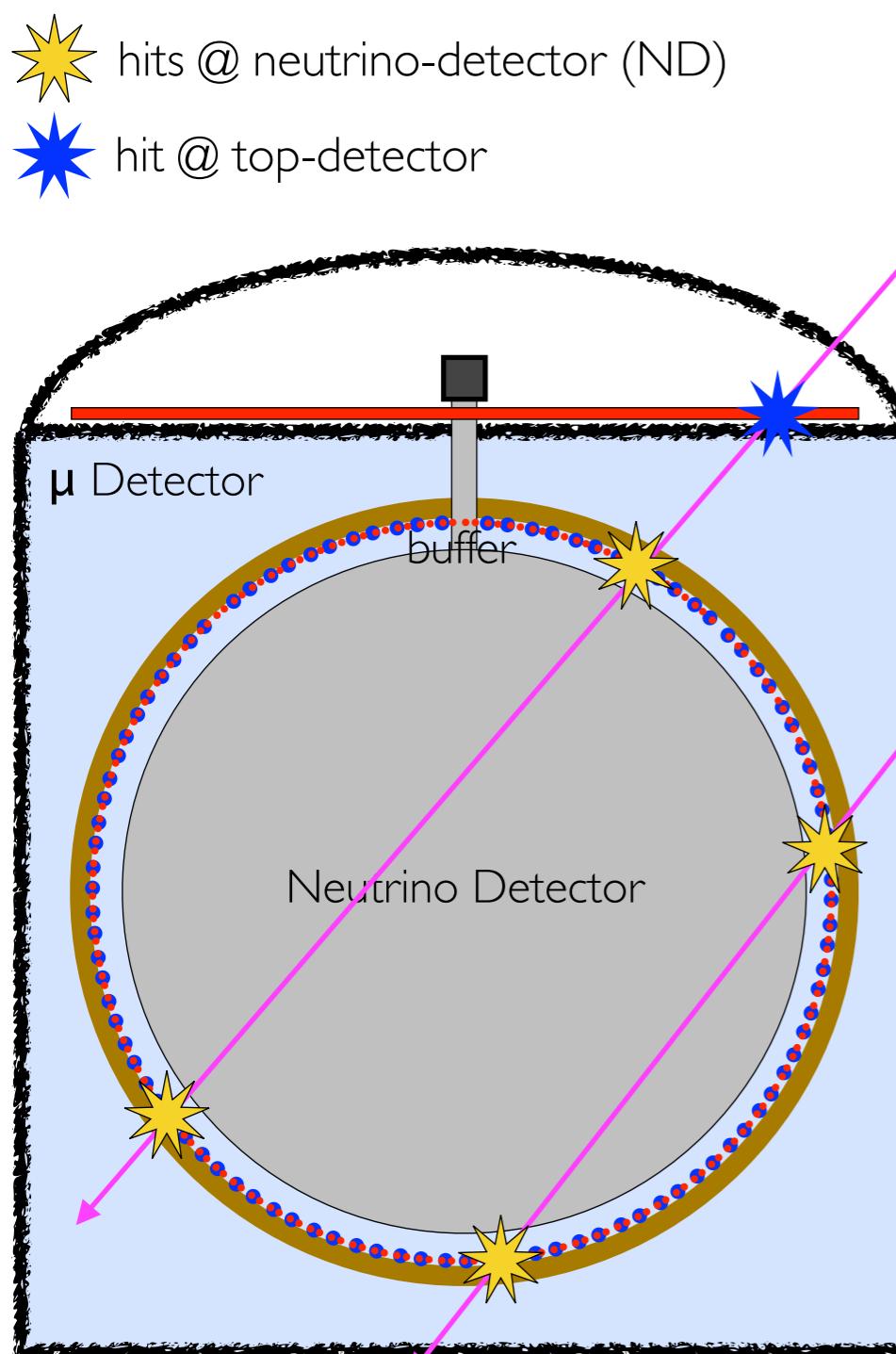
the most dangerous background...



- ${}^9\text{Li}$ (+ a little ${}^8\text{He}$)
(dominant \rightarrow rejection via μ -tracking)
- fast-n (+ little stopped- μ s)
(still visible & knowledge @ <10%)

SPMT: excellent μ -physics...

high precision μ -tracking...

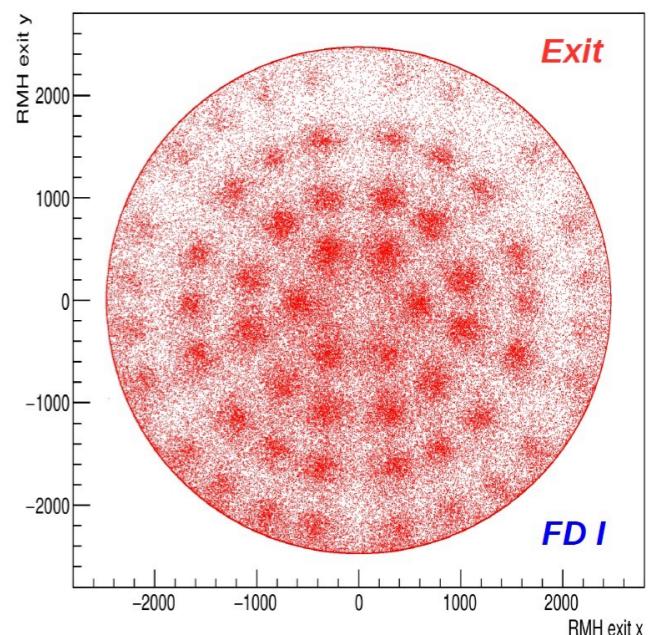
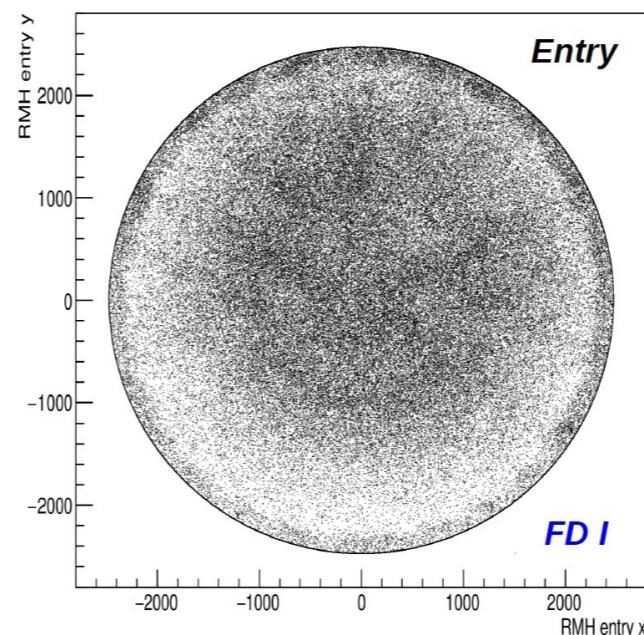


hits @ neutrino-detector (ND)

hit @ top-detector

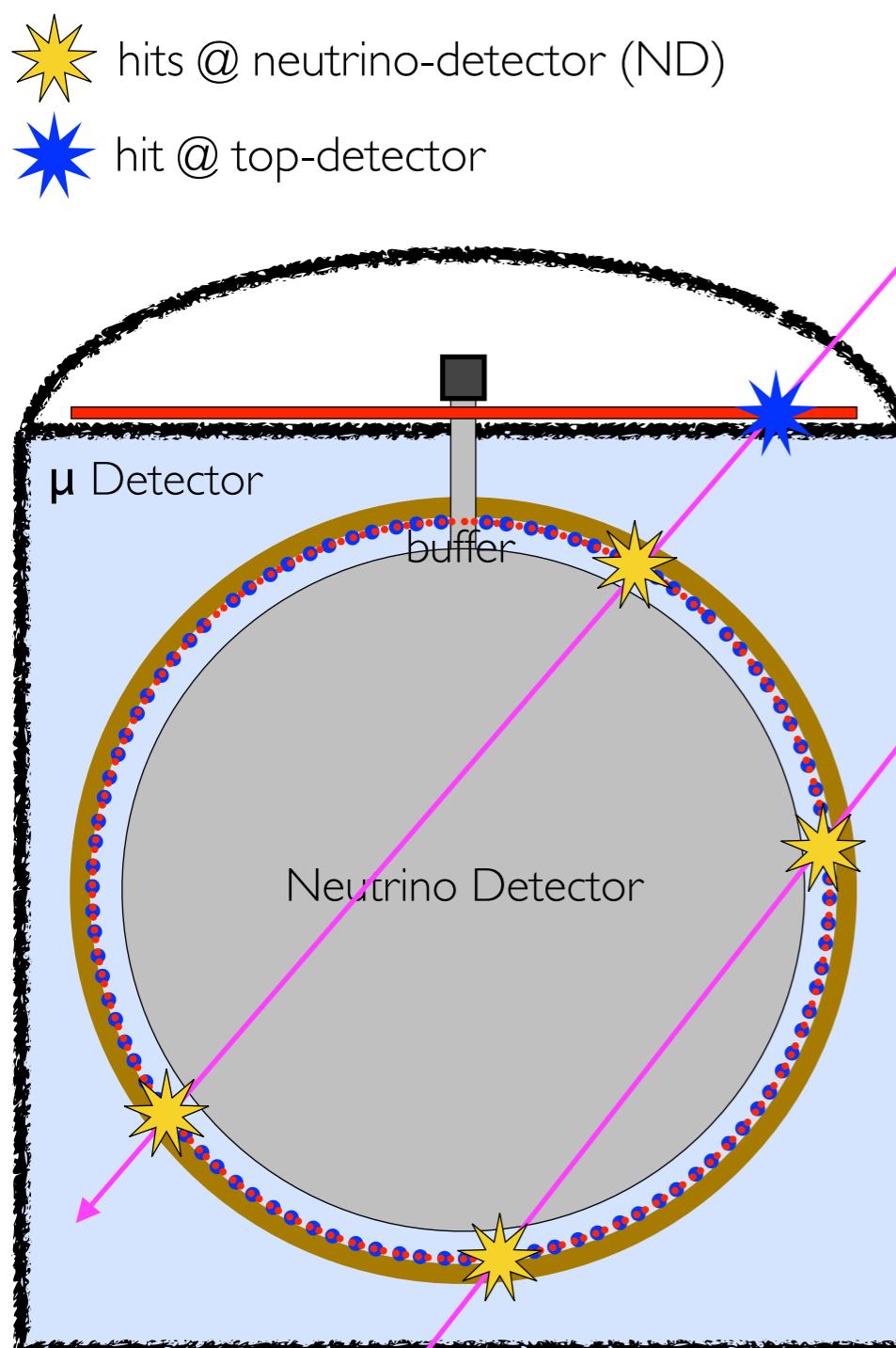
μ 's topology in LSD is **entry** and **exit** points

challenge: how many μ 's? (if a few at once \rightarrow same cosmic ray)



μ 's tracking must be $4\pi \Rightarrow$ all μ 's!!!

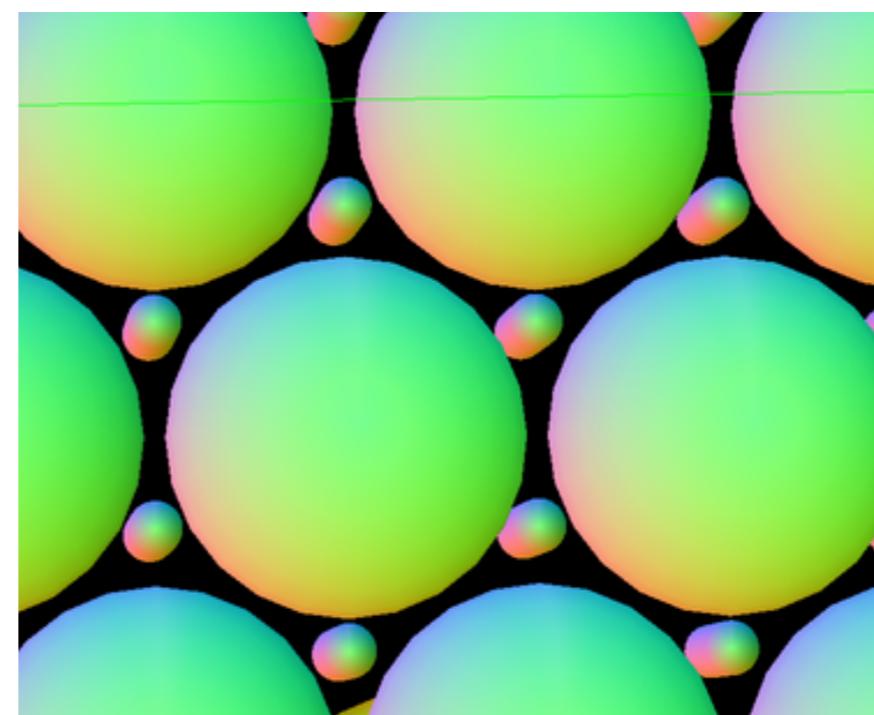
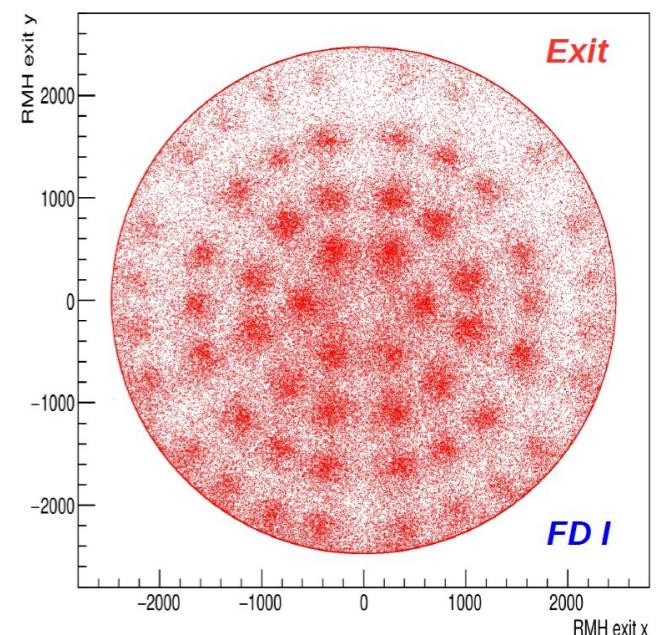
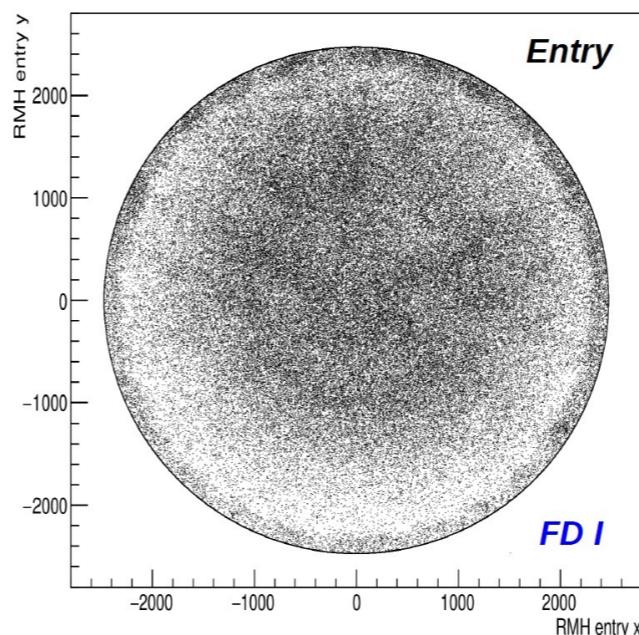
high precision μ -tracking...



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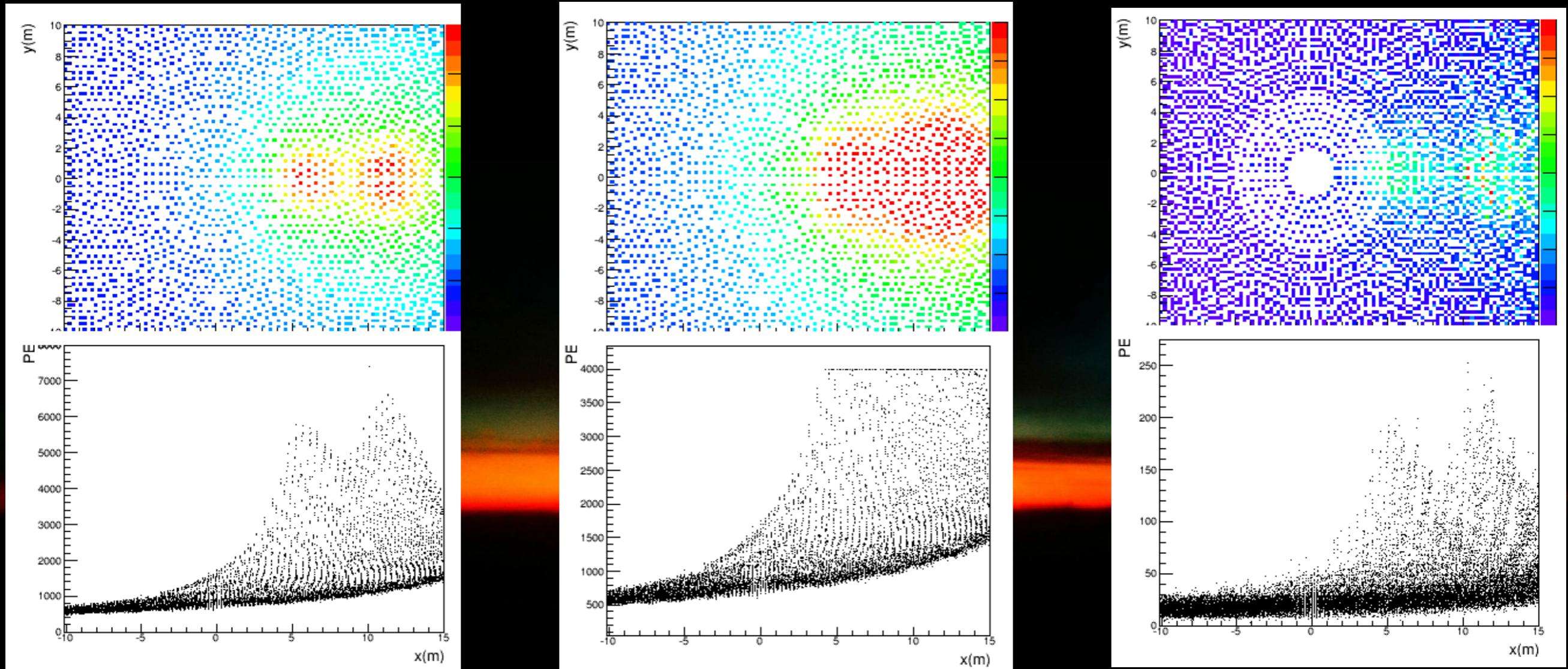
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challenge: how many μ 's? (if a few at once \rightarrow same cosmic ray)



μ -reco depends...

- **PMT density** (\rightarrow LPMT)
- **PMT timing** (typical few ns)
 - more light (further info)
- **high resolution triangulation** (SPMT)

multi- μ identification...

LPMT (no saturation)

LPMT (saturation at 4000PE)

SPMT

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

$\mu: \leq 300\text{PE}$ per SPMT
(no saturation whatsoever)

evidently so...

when dealing with μ 's...

when dazzling...
(i.e. saturation)

...less is more! (\rightarrow SPMT)

SPMT as an “aider” to the LPMT...

A. high precision calorimetry response systematics IBD physics

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

B. improve inner-detector μ -reconstruction resolution

(highest priority: aide $^{12}\text{B}/^9\text{Li}/^8\text{He}$ 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)

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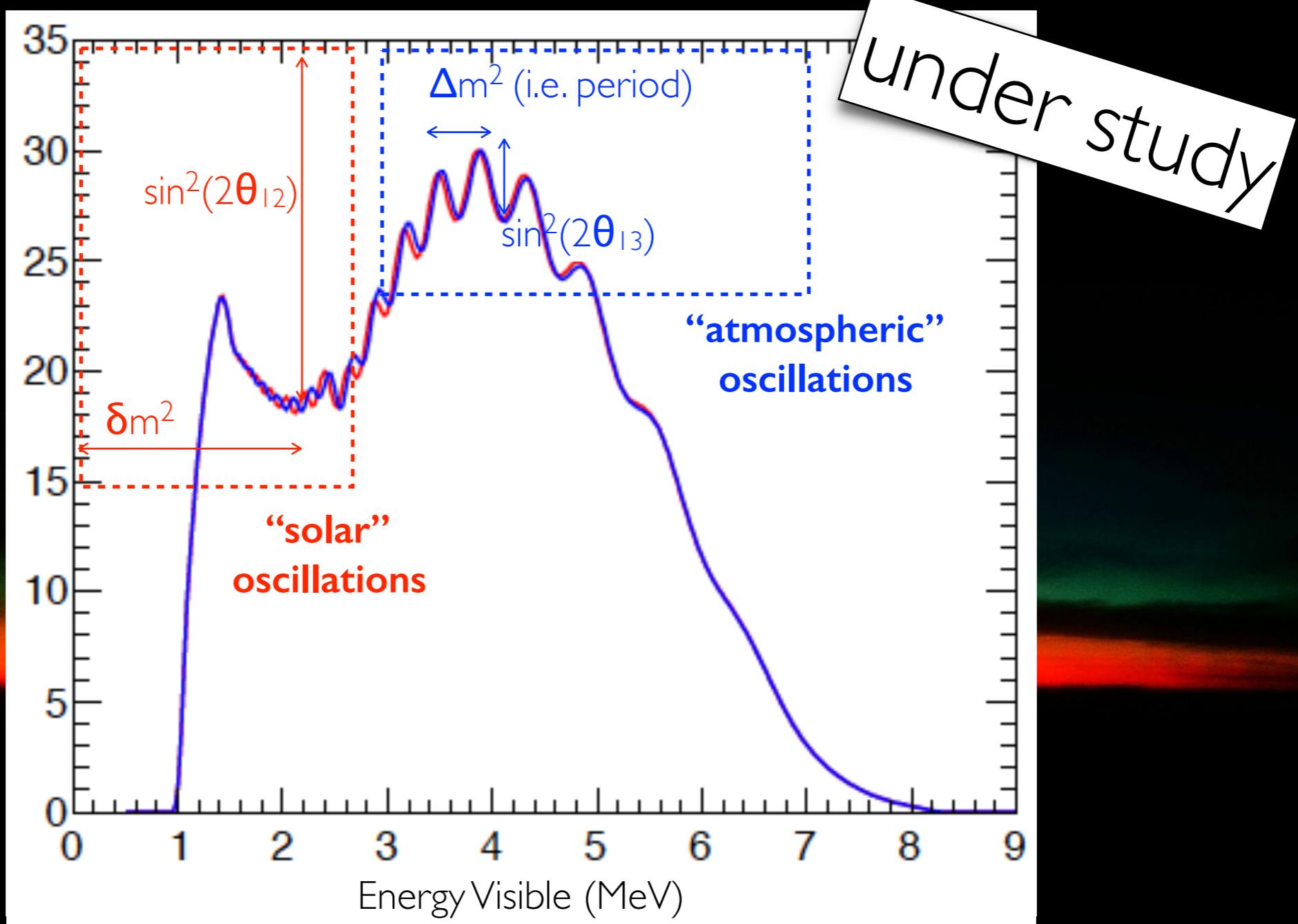
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how about neutrino physics?

high precision ($\theta_{12}, \Delta m^2$) also with SPMT?



JUNO several Δm^2 (<1% precision)...
(only 2 fully independent)

$(\Delta m^2)^{\text{SPMT}}$ independent (**digital** calorimetry)
 $(\Delta m^2)^{\text{LPMT}}$ independent (**integration** calorimetry)
 $(\Delta m^2)^{\text{LPMT} \oplus \text{SPMT}}$ independent (**double** calorimetry)

use $(\Delta m^2)^{\text{SPMT}}$ to validate linearity (or bias) of $(\Delta m^2)^{\text{LPMT}}$ & $(\Delta m^2)^{\text{LPMT} \oplus \text{SPMT}}$

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

let's build it...

China: IHEP+SYSU

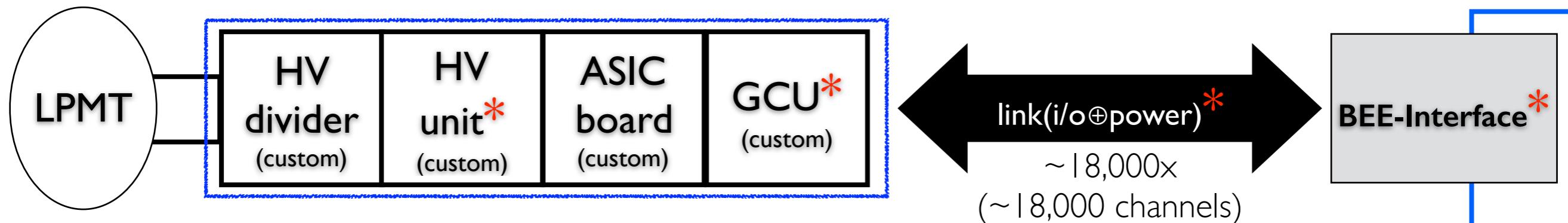
France: APC+CPPM+LLR+Omega+SUBATECH

IHEP major support...

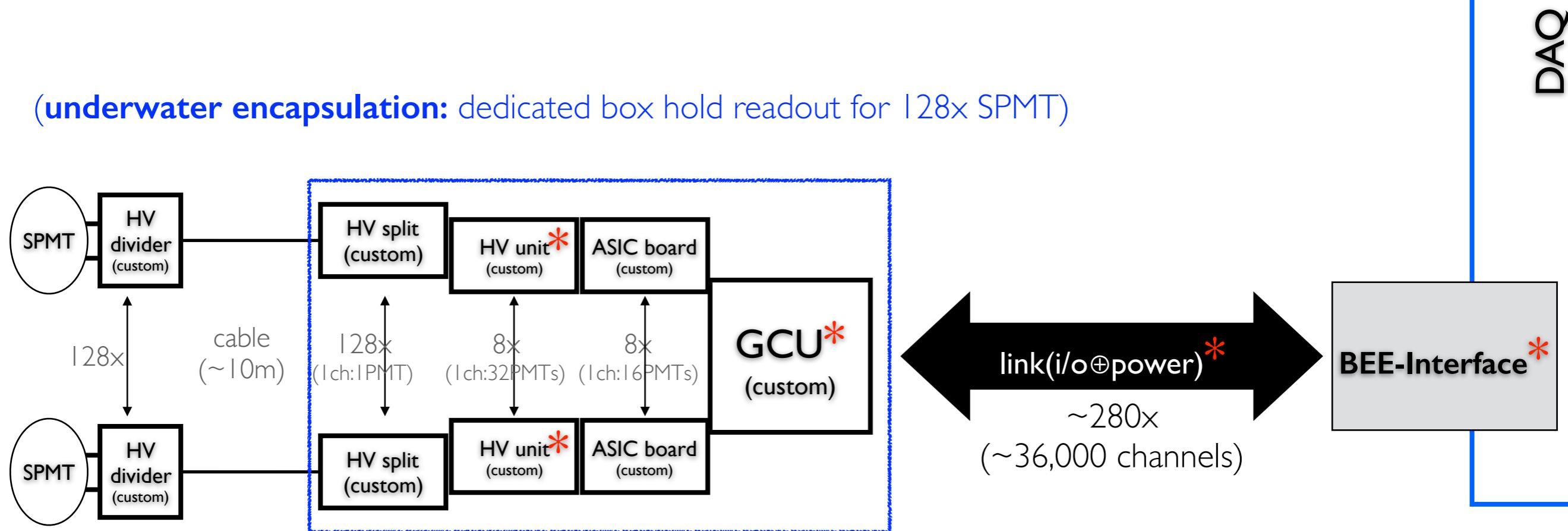
- installation & integration
- PMT suport & potting
- and a long etc...

(impossible without)

JUNO-SPMT readout system (one channel)...



(underwater encapsulation: all attached (i.e. potted) to each LPMT base)

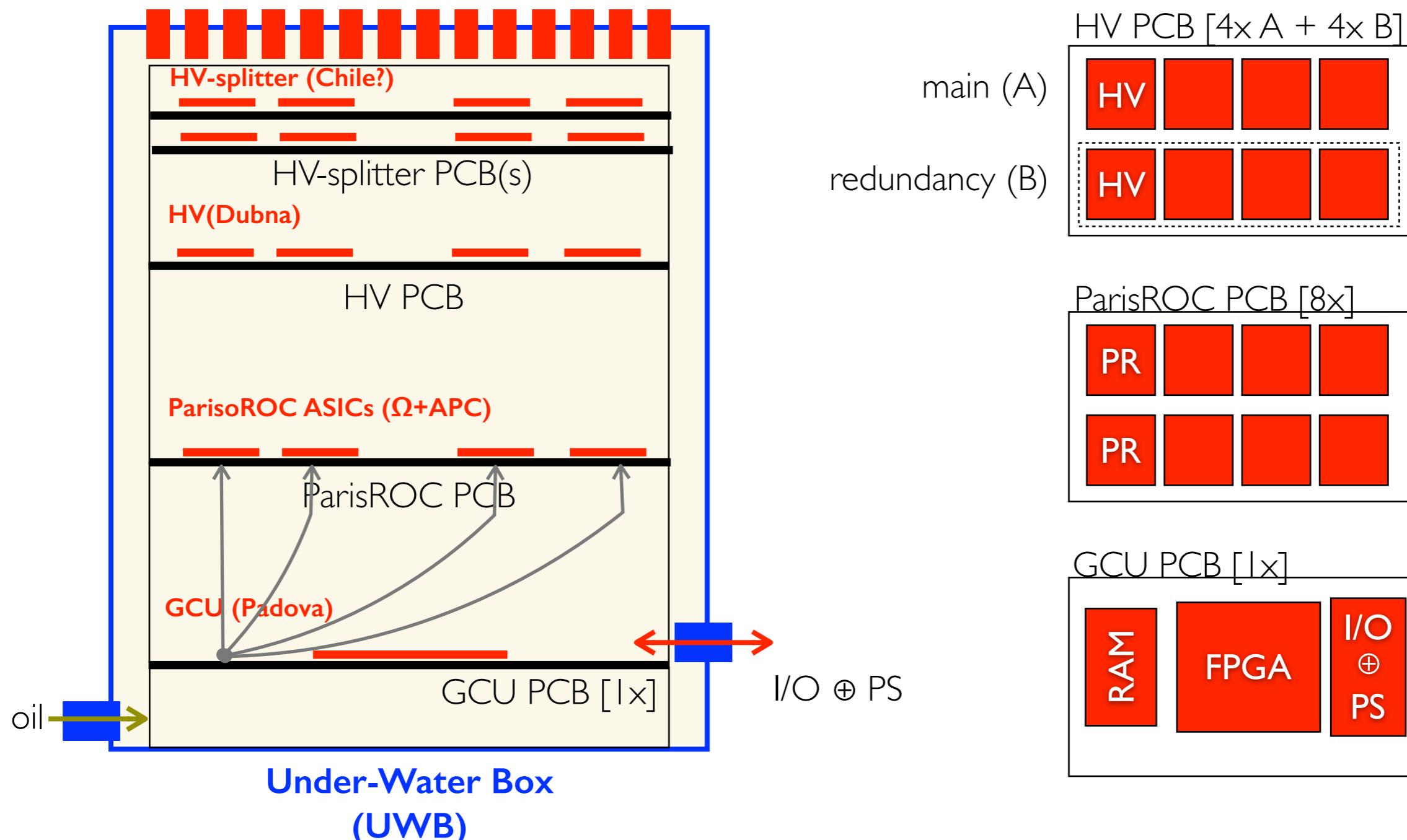


(*): items **common** to both LPMT & SPMT system (cost-effective & trivial integration)

logical perspective UWB (128x SPMT)...

(strategy: under-water-box → largest PMT#)

connection strategy → delicate interface [dedicated slides]

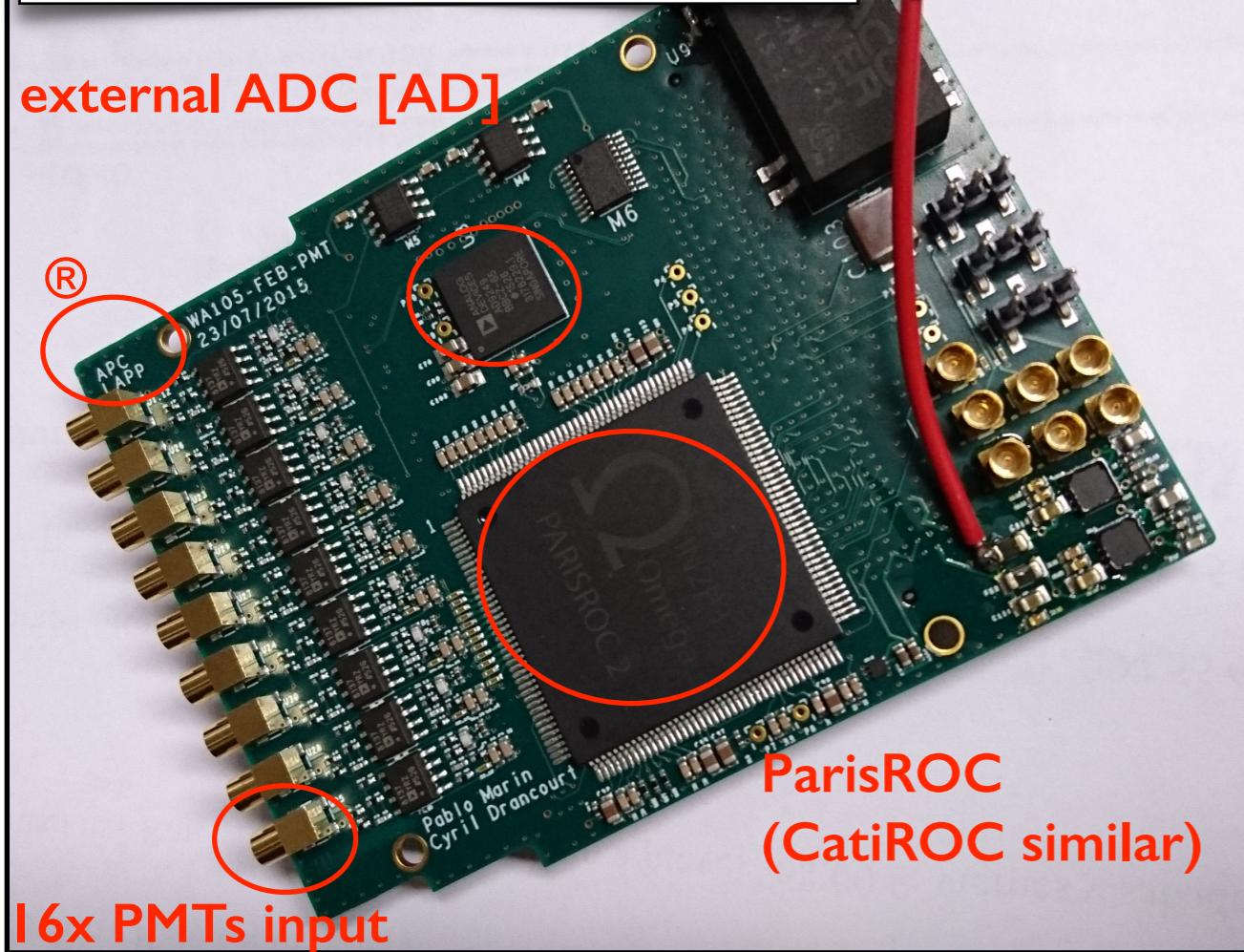


[physical location of elements might change]

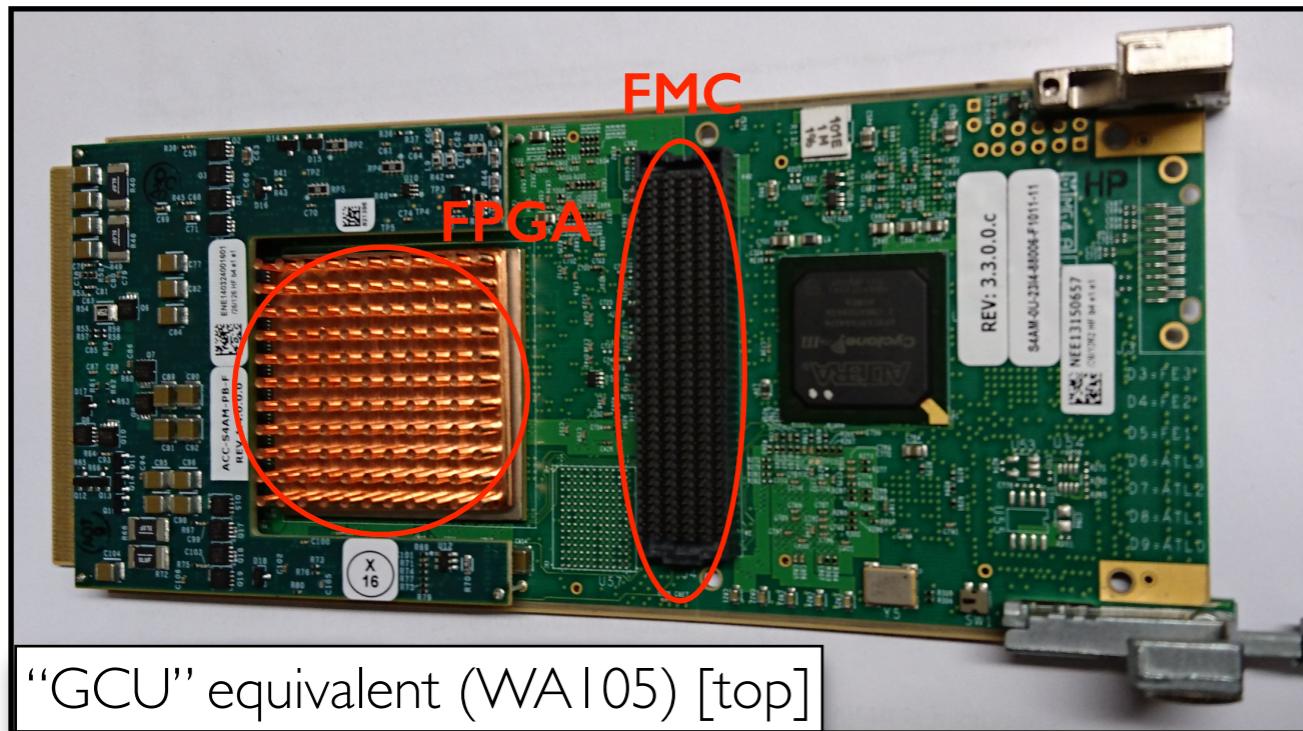
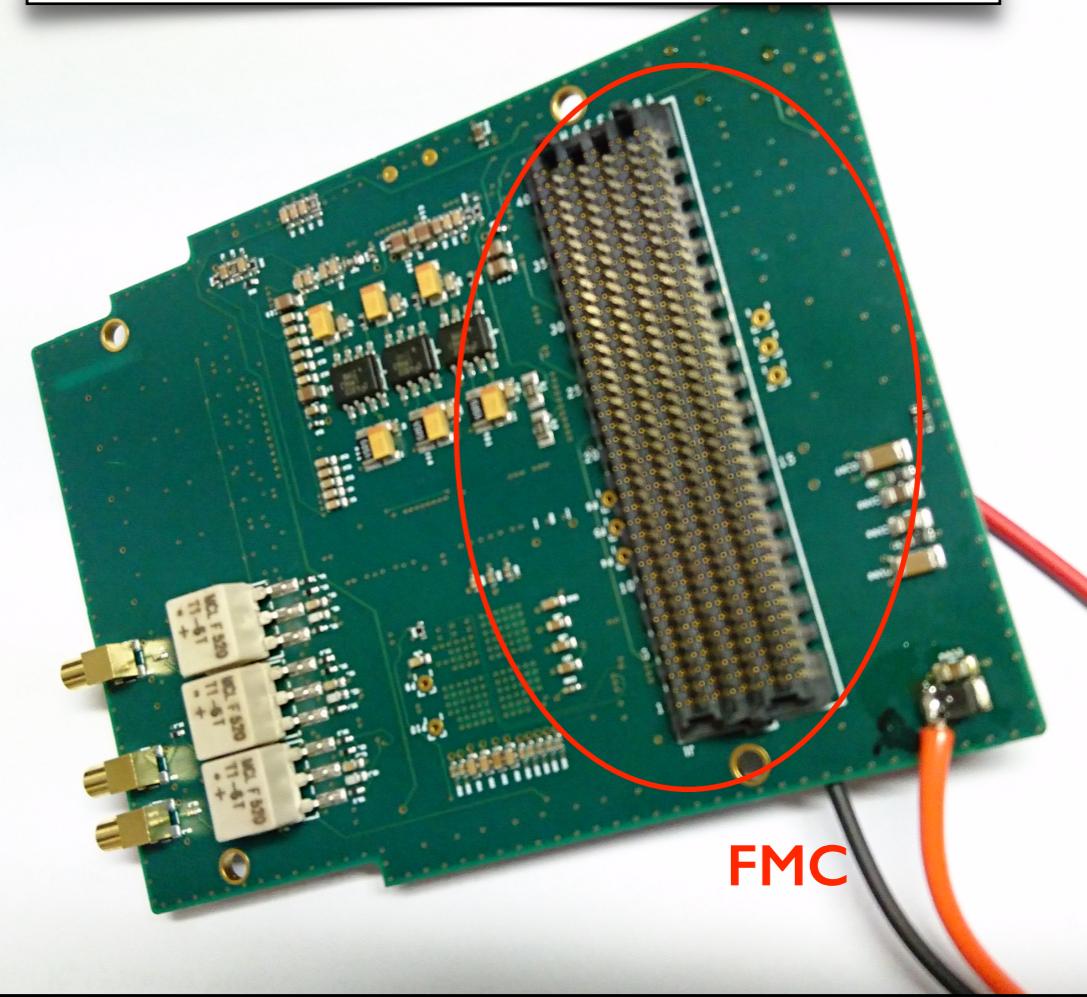
how does it look? (inspiration)...

Mezzanine ParisROC (WA105) [top]

external ADC [AD]



Mezzanine ParisROC (WA105) [bottom]



all these pieces @ APC (→ aide JUNO development)

prototypes to be produced 2016

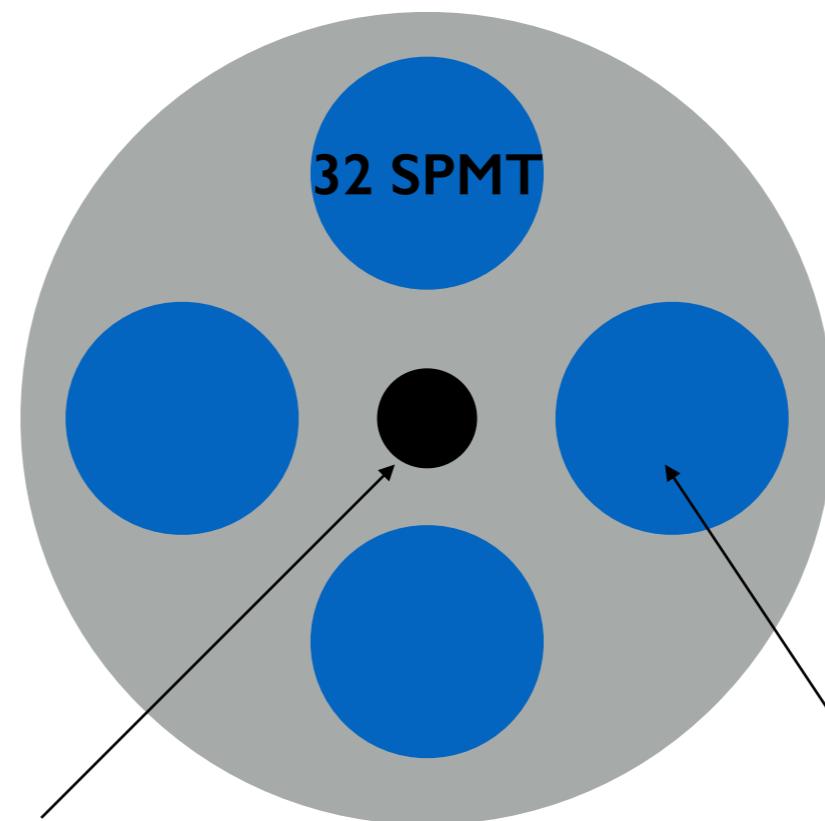
→ JUNO prototype readiness end-2016

major effort within 2016-2017 (JUNO schedule)

CPPM+APC under-water box (**UWB**) design...



Under-Water Box
(cylinder: excellent shape for high pressure)



$128 = 4 \times 32 \text{ SPMTs}$

CAT5+ cable (power + signals)
(interface: same as LPMT @ IHEP)

SPMT interface 1 per SPMT
(no connector & water-proof)

[next slide: [photo sample](#)]

design: PUC-Chile + CPPM-France engineers
manufacture: industry (cost $\leq 1\text{k}\epsilon$)

readout industrialisation...



APC⊕OMEGA⊕Padova
CAEN⊕WeeROC
(meeting @ APC yesterday)

- **double calorimetry...**

- **major improvement of LS-detectors**
- one of the most striking (instrumentation) novelties @ FRoST-16 conference

- **detector improvements...**

- **improve calorimetry systematics control** (non-stochastic terms)
- major improvement in μ -tracking → cosmogenic isotope rejection
- (**physics @ JUNO**) **neutrino oscillation, supernova, proton-decay**, etc
- (**instrumentation**) trigger, dynamic range, etc

- **novel readout scheme concept...**

- applications for many detectors → **industrialisation in EU** (CAEN⊕WeeROC)
 - world-leading IN2P3 micro-electronics ‘know-how’ & investments
 - joining strong forces with Chinese ‘know-how’ → benefit JUNO leading physics

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 Bust, 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, Ziyang Deng, Yan 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 Giannotti, 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 $p \rightarrow K^+ + \bar{\nu}$ 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.

Comments: Version submitted to Journal of Physics G, with minor typo corrections. 222 Pages, 147 figures
 Subjects: **Instrumentation and Detectors (physics.ins-det)**; High Energy Physics – Experiment (hep-ex)
 Journal reference: J. Phys. G 43 (2016) 030401
 DOI: [10.1088/0954-3899/43/3/030401](https://doi.org/10.1088/0954-3899/43/3/030401)
 Cite as: [arXiv:1507.05613 \[physics.ins-det\]](https://arxiv.org/abs/1507.05613)
 (or [arXiv:1507.05613v2 \[physics.ins-det\]](https://arxiv.org/abs/1507.05613v2) for this version)

more info...

JUNO's Physics Summary... (published)

JUNO Conceptual Design Report

T. Adam, F. An, G. An, Q. An, N. Anfimov, V. Antonelli, G. Baccolo, M. Baldoncini, E. Baussan, M. Bellato, L. Bezrukov, D. Bick, S. Blyth, S. Boarin, A. Brigatti, T. Brugière, R. Brugnera, M. Buizza Avanzini, J. Bust, A. Cabrera, H. Cai, X. Cai, A. Cammi, D. Cao, G. Cao, J. Cao, J. Chang, Y. Chang, M. Chen, P. Chen, Q. Chen, S. Chen, S. Chen, S. Chen, X. Chen, Y. Chen, Y. Cheng, D. Chiesa, A. Chukanov, M. Clemenza, B. Clerbaux, D. D'Angelo, H. de Kerret, Z. Deng, Z. Deng, X. Ding, Y. Ding, Z. Djurcic, S. Dmitrievsky, M. Dolgareva, D. Dornic, E. Doroshkevich, M. Dracos, O. Drapier, S. Dusini, M.A. Díaz, T. Enqvist, D. Fan, C. Fang, J. Fang, X. Fang, L. Favart, D. Fedoseev, G. Fiorentini, R. Ford, A. Formozov, R. Gaigher, H. Gan, A. Garfagnini, G. Gaudiot, C. Genster, M. Giannotti, et al. (325 additional authors not shown)

(Submitted on 28 Aug 2015 (v1), last revised 28 Sep 2015 (this version, v2))

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 $3-4\sigma$, and determine neutrino oscillation parameters $\sin^2 \theta_{12}$, $|\Delta m_{21}^2|$, and $|\Delta m_{ee}^2|$ 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. ~17,000 508-mm diameter PMTs with high quantum efficiency provide ~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.

Comments: 328 pages, 211 figures
 Subjects: **Instrumentation and Detectors (physics.ins-det)**; High Energy Physics – Experiment (hep-ex)
 Cite as: [arXiv:1508.07166 \[physics.ins-det\]](https://arxiv.org/abs/1508.07166)
 (or [arXiv:1508.07166v2 \[physics.ins-det\]](https://arxiv.org/abs/1508.07166v2) for this version)

JUNO's CDR... (published)

JUNO...

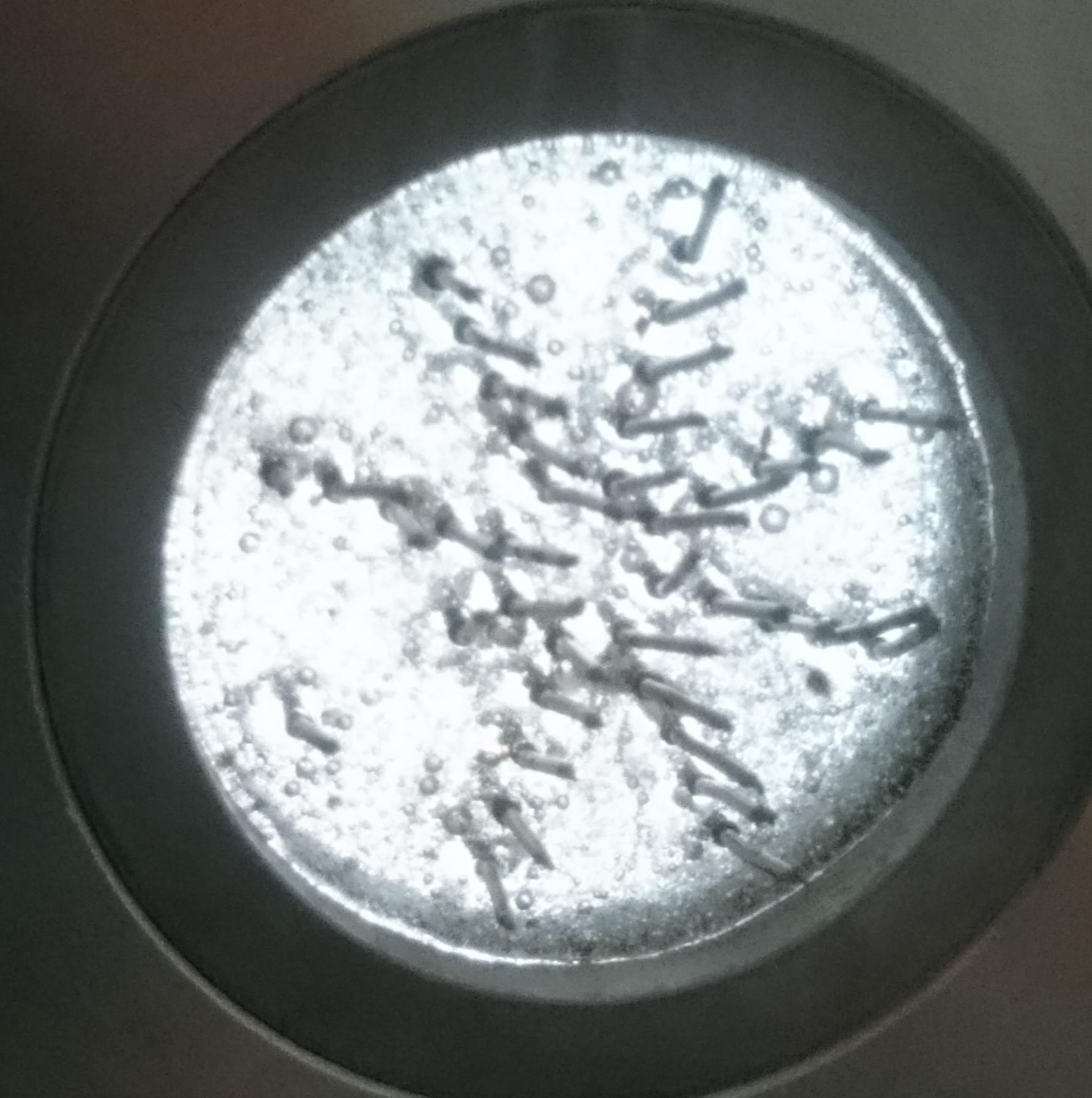


Small-PMT \oplus Large-PMT

“equilibrium between extremes”

the end....

(inexpensive) water-proof interface...



this is **exactly** how a **PMT works** (dynode pins @ base)...

Natalie Cabrera (CNRS-IN2P3 & APC)

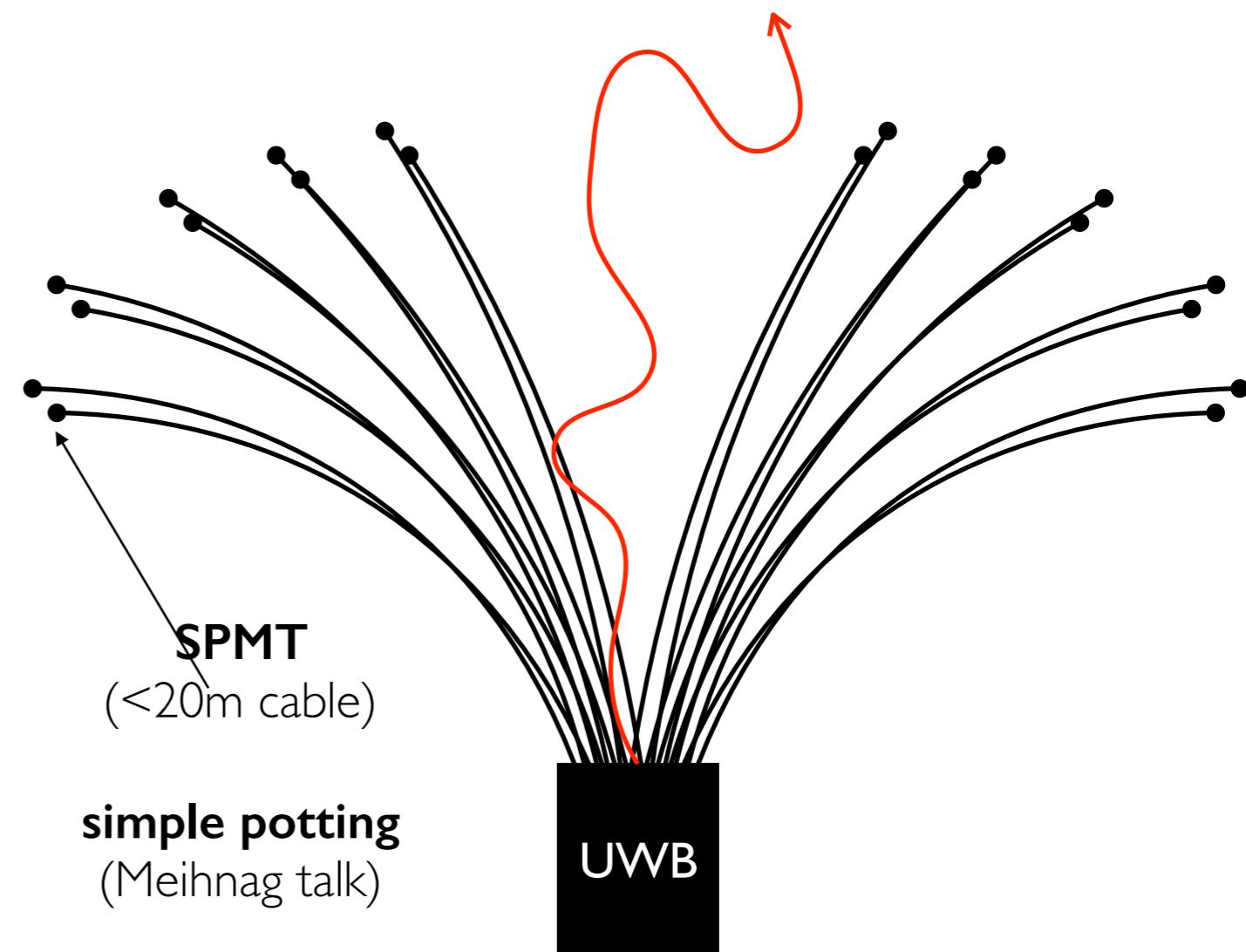
the medusa unit (**MU**)...

I UWB (IGCU) = I28SPMTs = IMedusa-Unit

(128 per MU → cost vs integration balance)

CAT5+

(100m cable to surface)



(each fully integrated/tested on surface)

how to install a medusa-unit?