

JUNO

(double-calorimetry)

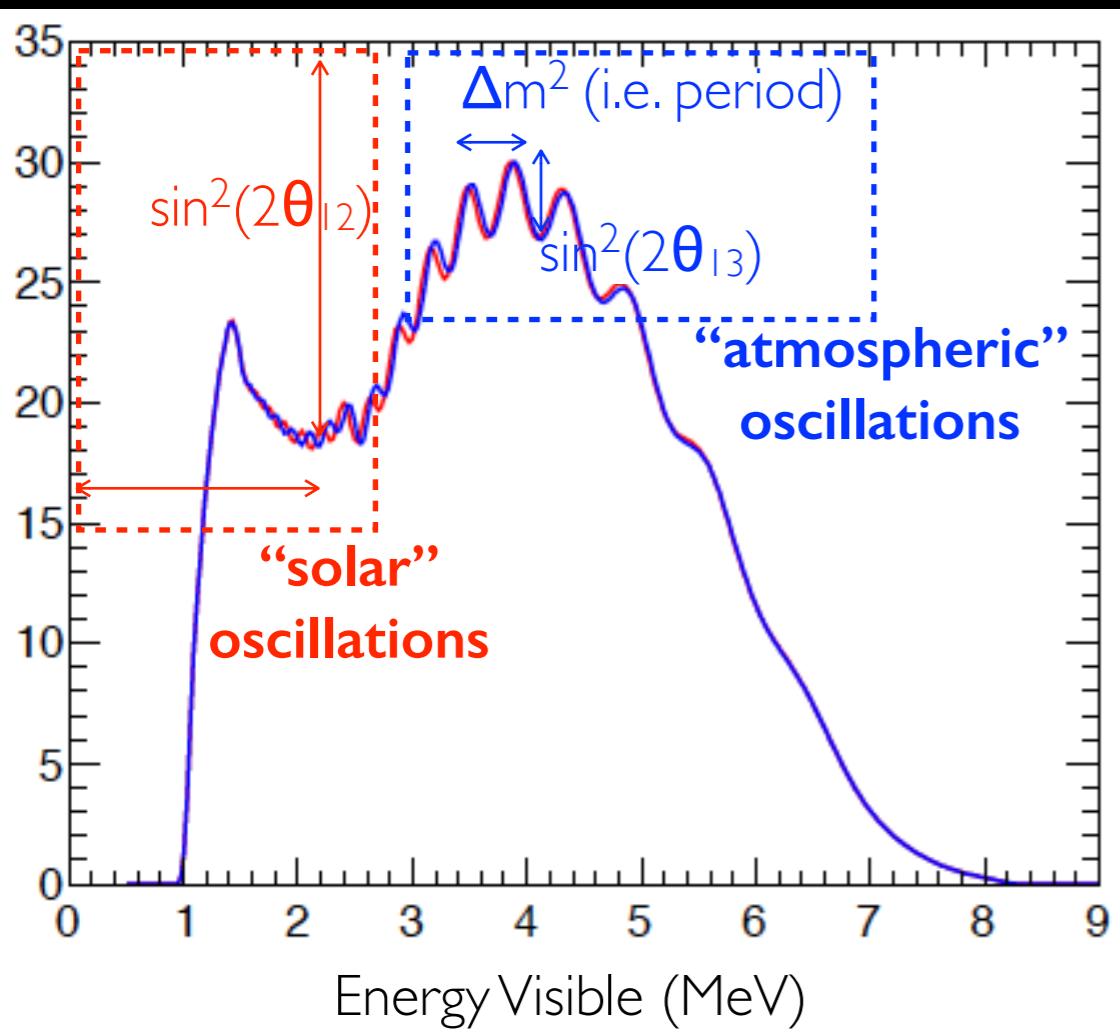
France GDR-Neutrino meeting @ Saclay

November 2015

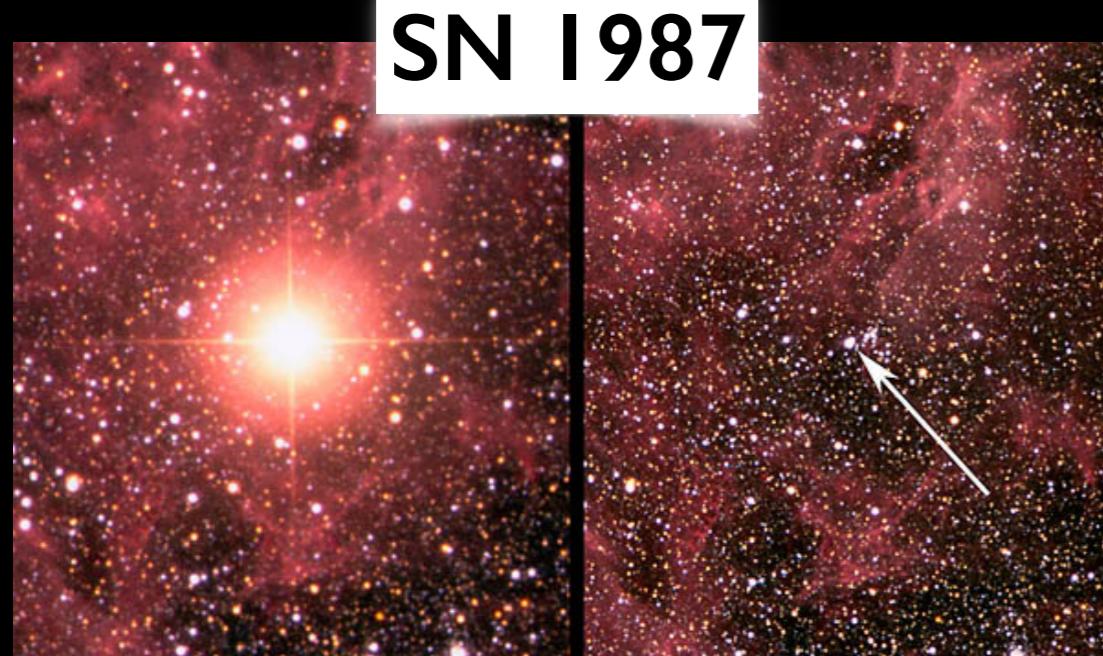
Anatael Cabrera

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APC Laboratory (Paris, FR)
LNCA Underground Laboratory (Chooz, FR)

² what to do with the largest LS detector in the world?



- (reactor- ν) unique solar \oplus atmospheric vacuum-oscillations fit
- (reactor- ν) mass hierarchy (atmospheric)...
 - subdominant (θ_{13} modulated) spectral distortion
 - driven by Δm^2 (atmospheric)
 - vacuum effect \rightarrow no via matter enhance effects
 - no θ_{23} -octant or δ_{CP} ambiguities
 - complementarity to NOvA, ORCA/PINGU, DUNE
- (reactor- ν) solar δm^2 & θ_{12} highest precision...
 - needed for CP-violation (Jarlskog Invariant) \rightarrow ambiguities!
 - complementarity to T2K \oplus NOvA & DUNE
 - test: Solar (MSW) vs KamLAND (complex baseline)
- (supernova- ν) unique capabilities (size & observation: IBD, ν_e , ν_x)
- (proton-decay) unique capabilities (size & unique channels)
 - proton fraction larger in scintillator than water (up to 2x)
- (geo- ν) observation (reactor- ν large BG) \rightarrow aid geo-physics
- other physics...
 - solar- ν , non-standard-interaction (different phase-space), etc

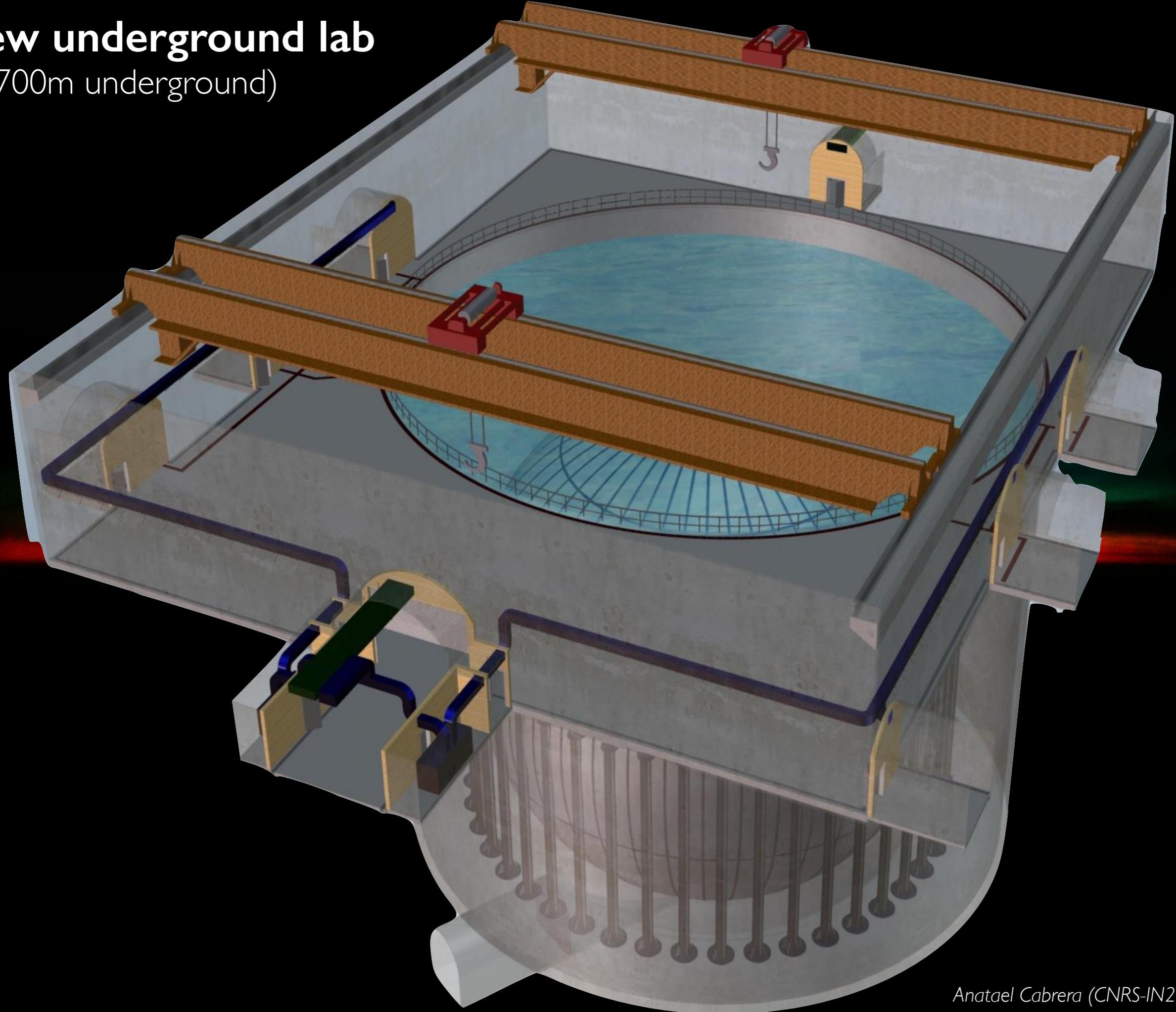




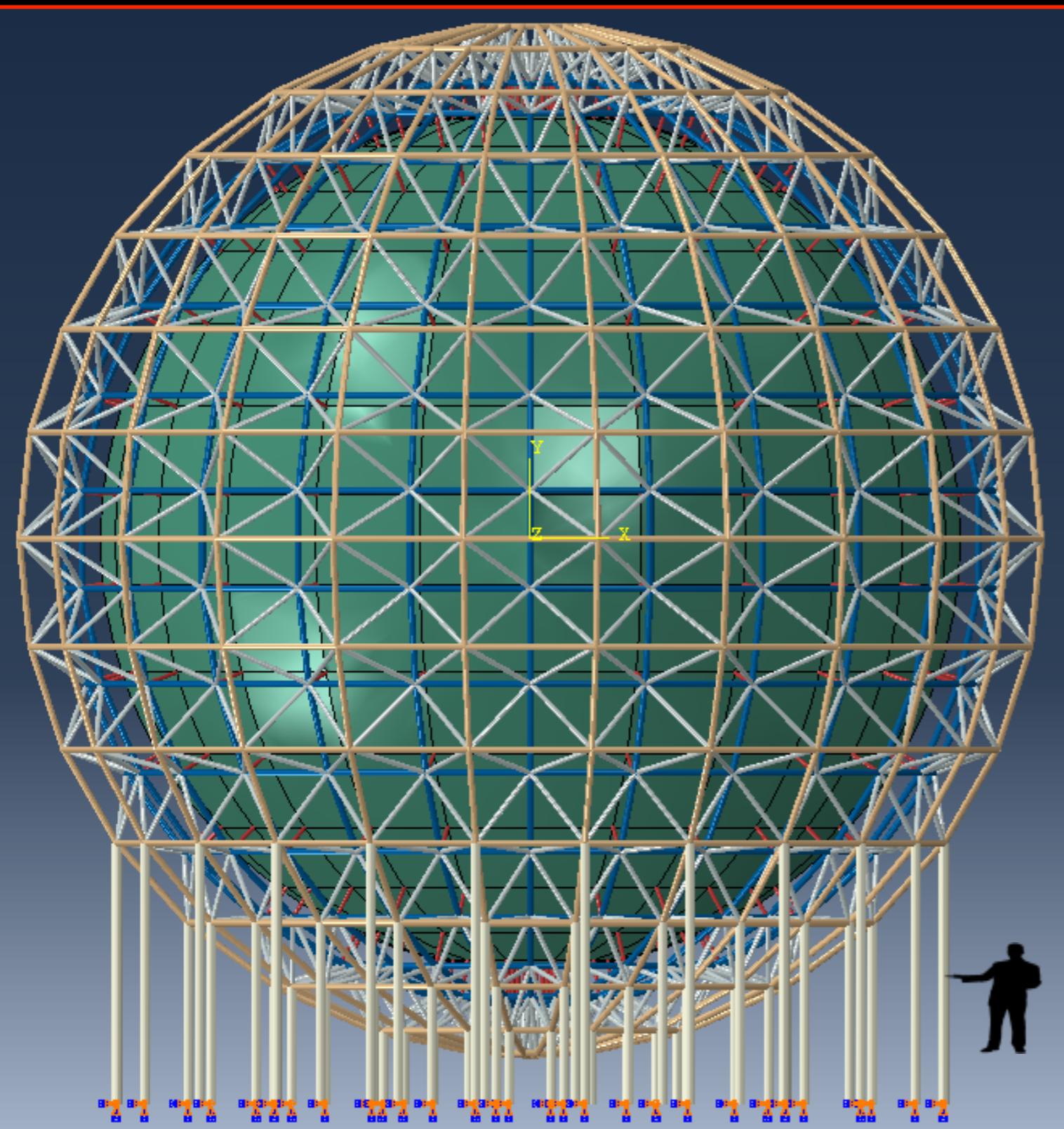
simplistic schedule: **data-taking by 2020**

new underground lab

(~700m underground)



JUNO neutrino detector system...

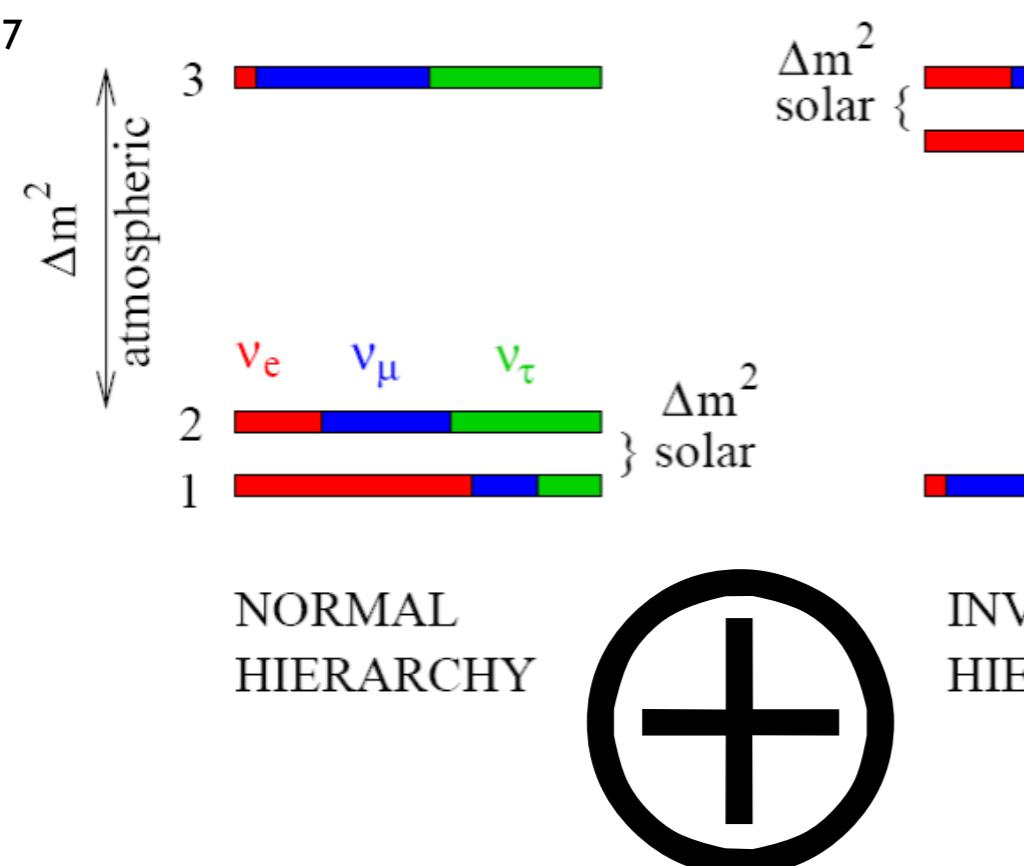


~1/2x SuperKamiokaNDE
 ~20x KamLAND/SNO
 ~600x DC

- 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)
 - $\sim 17\text{k} \times 20'' \text{ PMTs}$ ($\sim 80\%$ photo-coverage)
 - 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

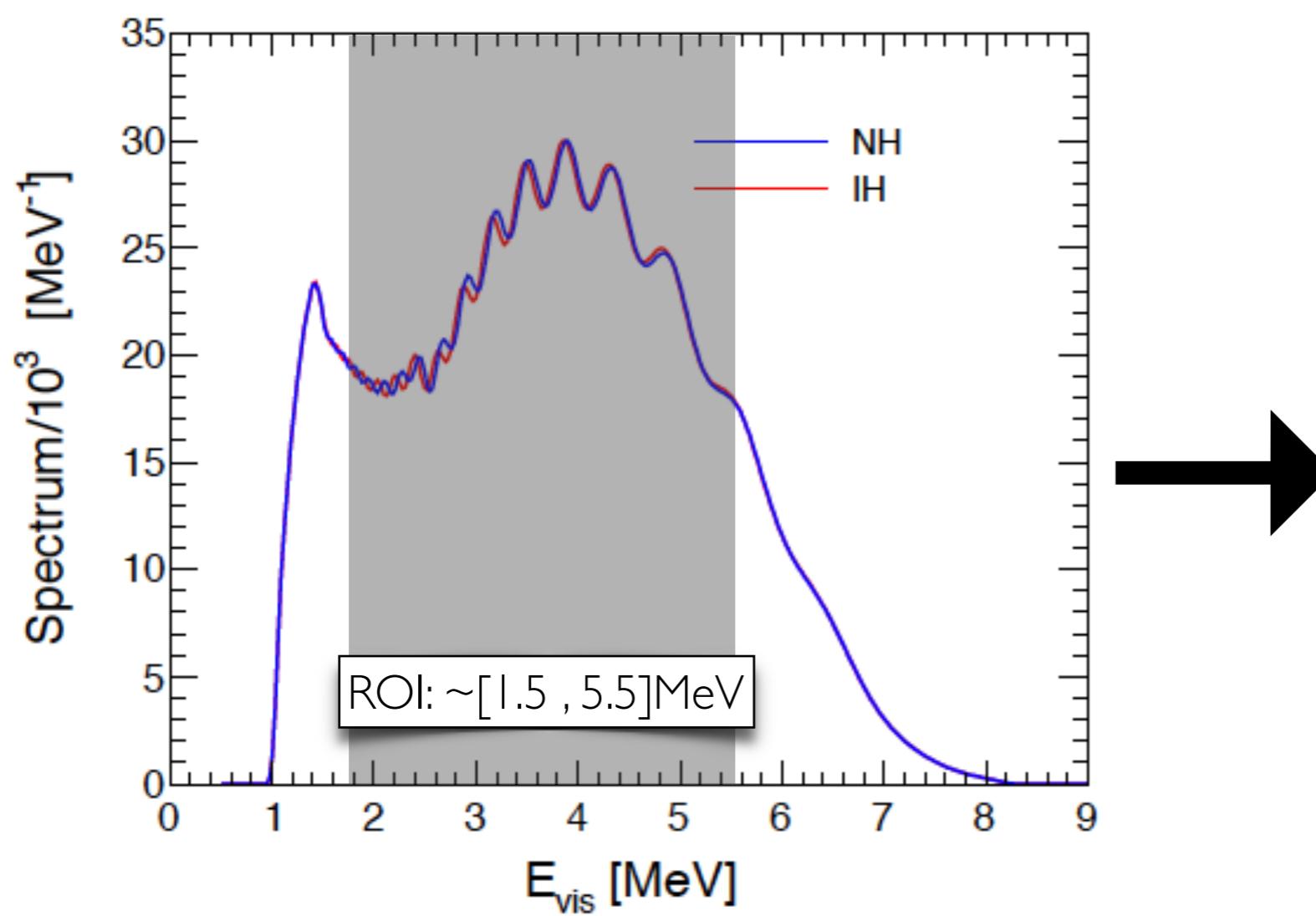
scientific motivation....

experimental constraint...



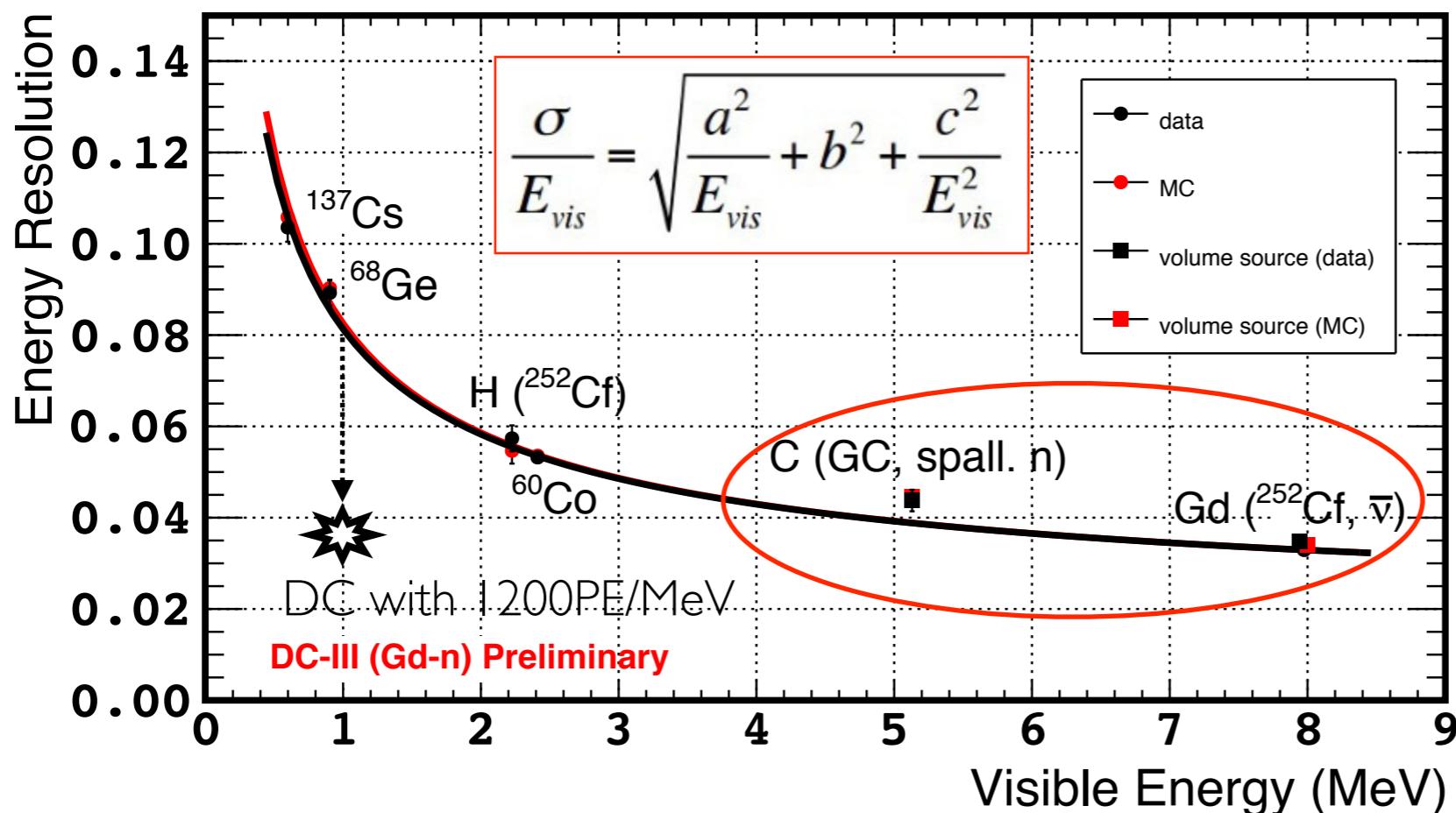
$$\Delta m_{31}^2(\text{IO}) \neq \Delta m_{31}^2(\text{NO})$$

$$\implies \delta \sim 3\% \text{ (i.e. } \delta m^2 / \Delta m^2)$$



$\sigma(E)/E \leq 3\% \text{ total}$
 (→ including non-stochastic terms)

DC as prototype...



DC: ~200PE/MeV

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

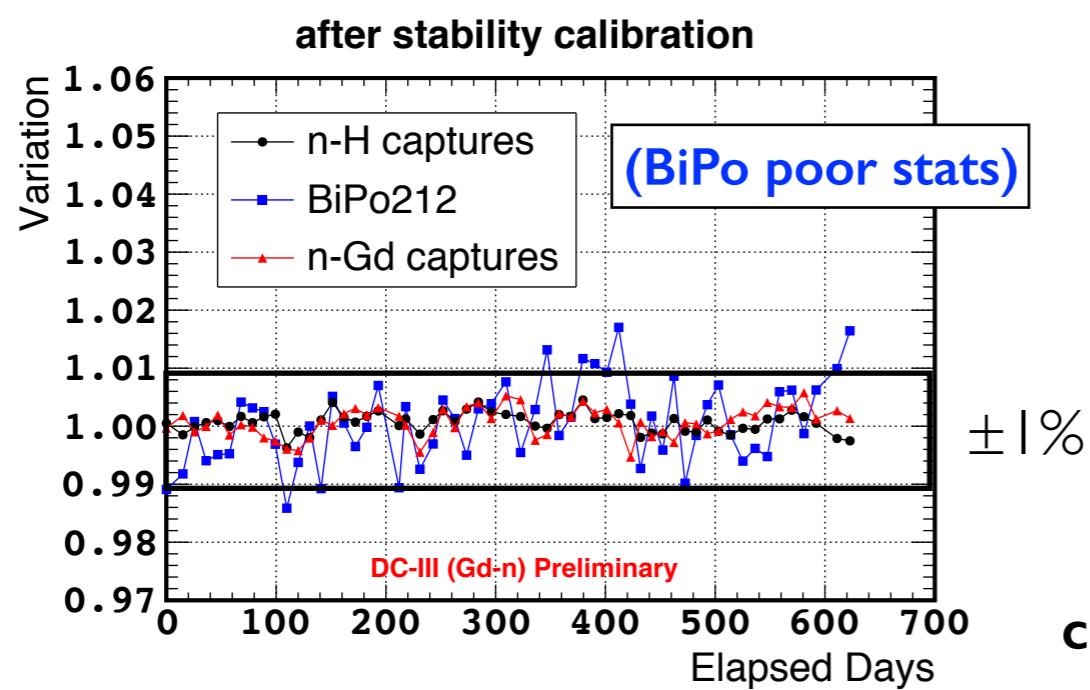
Data

$a=0.0773\pm 0.0025$
 $b=0.0182\pm 0.0014$
 $c=0.0174\pm 0.0107$

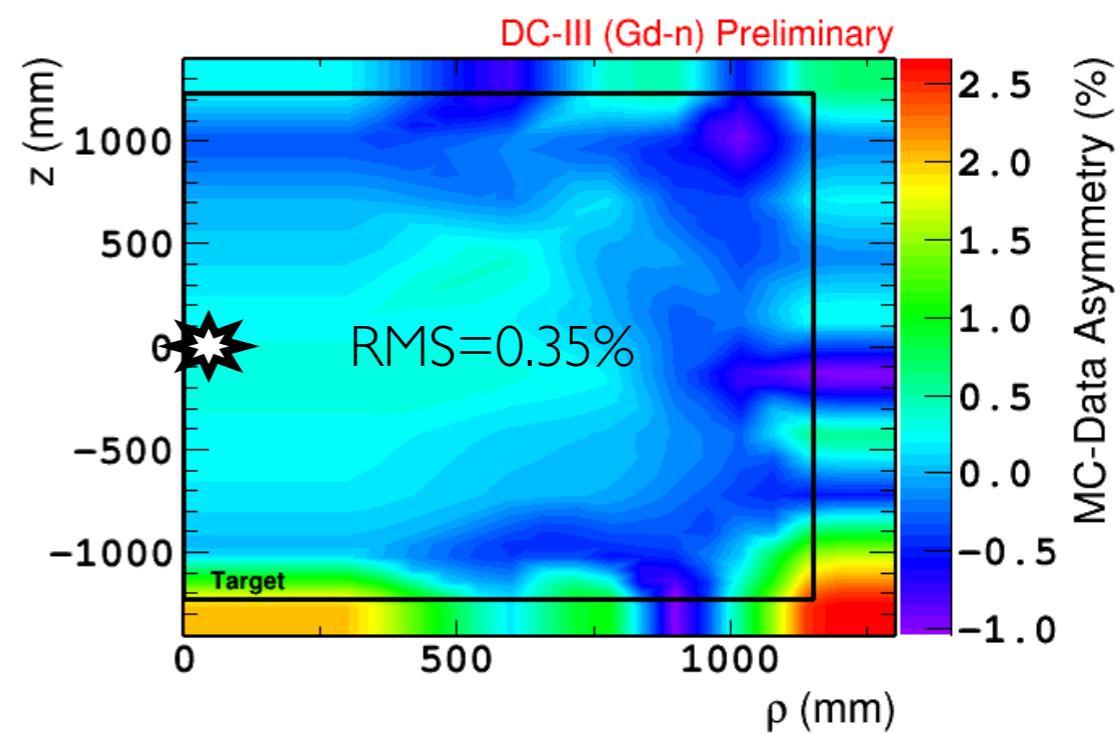
MC

$a=0.0770\pm 0.0018$
 $b=0.0183\pm 0.0011$
 $c=0.0235\pm 0.0061$

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



control of response uniformity



control

no perfect world...

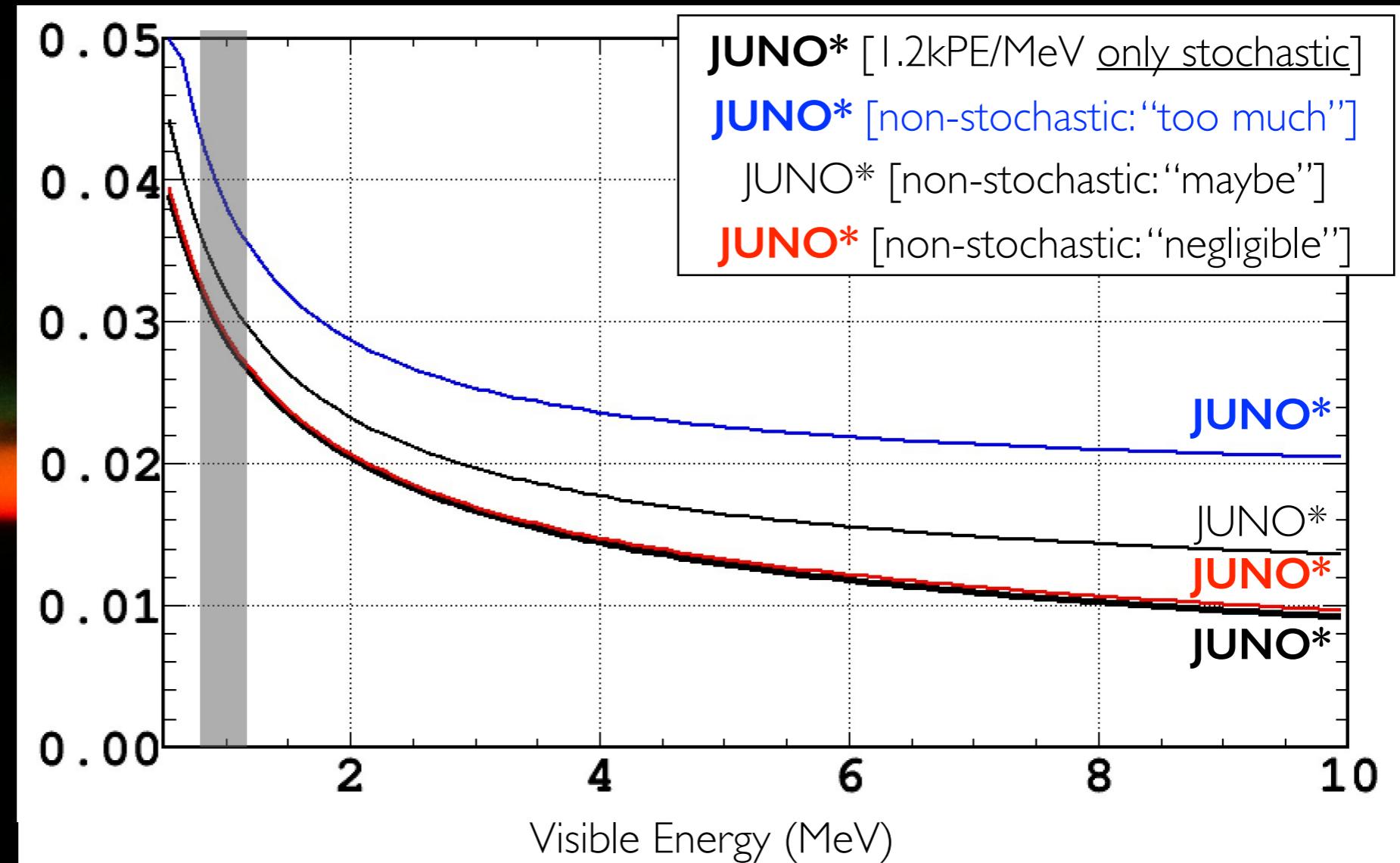
$$\sigma(E)^2 = \sigma(E)_{\text{stoch}}^2 + \sigma(E)_{\text{non-stoch}}^2$$

(1200PE/MeV) (??%)

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

$\sim 1.2k$ 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. PMT+electronics no dispersive effects)

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

(unfortunately) **none is true!**

the JUNO challenge (I)...

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

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

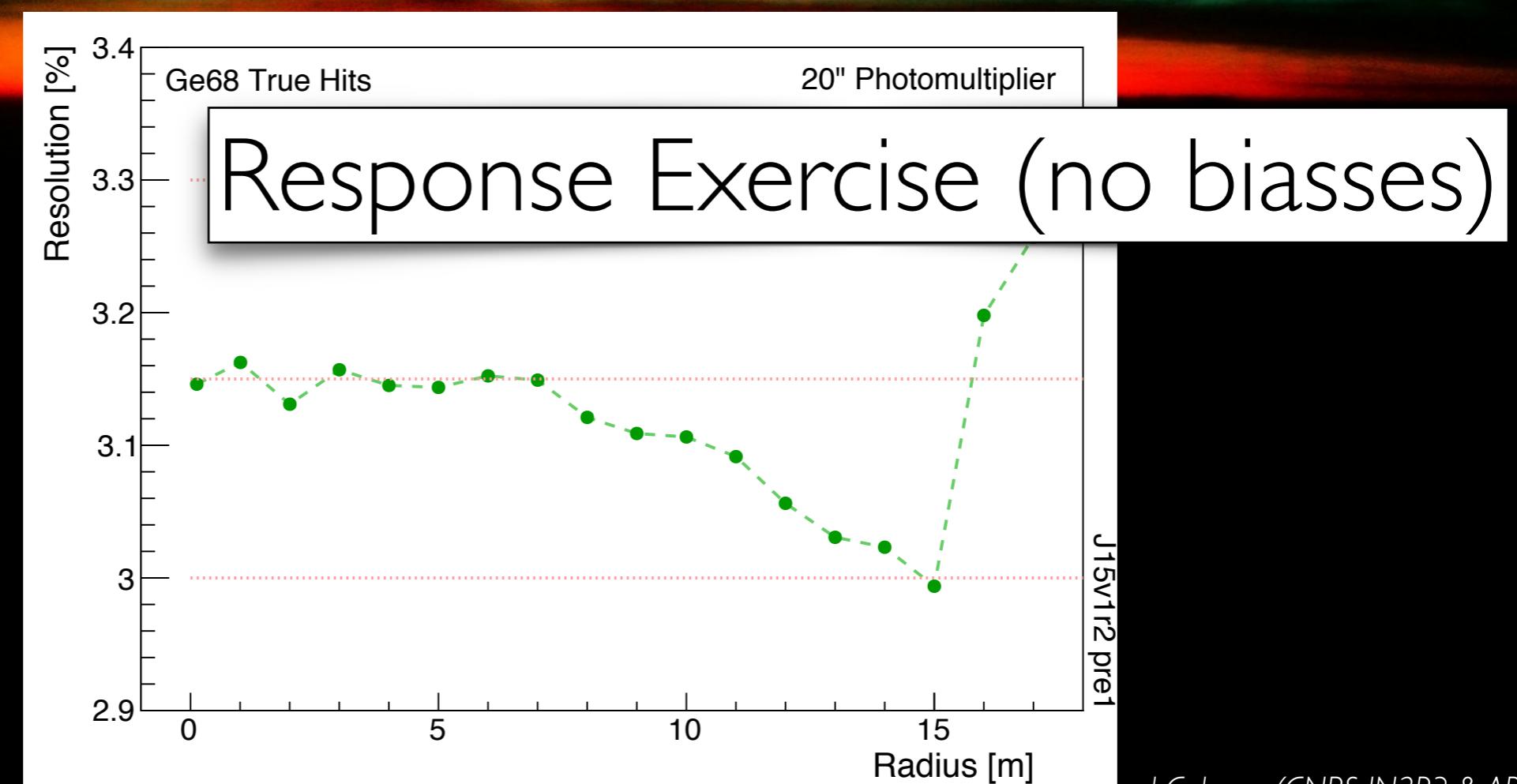
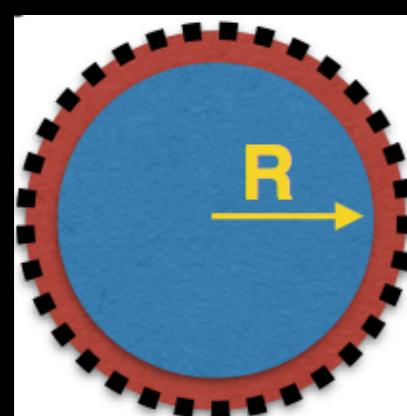
@DC: $\sigma(E)^2_{\text{non-stoch}} \sim 3\%$

now consider **(1200±50)PEs** @ 1 MeV (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
- $\geq 1300 \text{ PE/MeV}$
 $(\rightarrow \sigma_{\text{non-stoch}} \geq 1.0\%)$

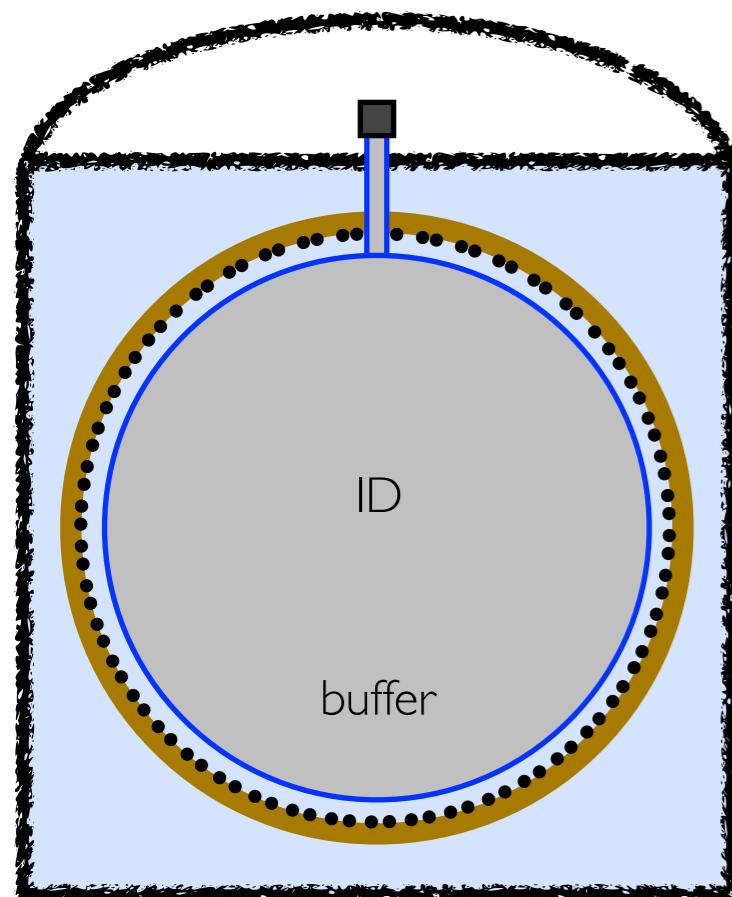
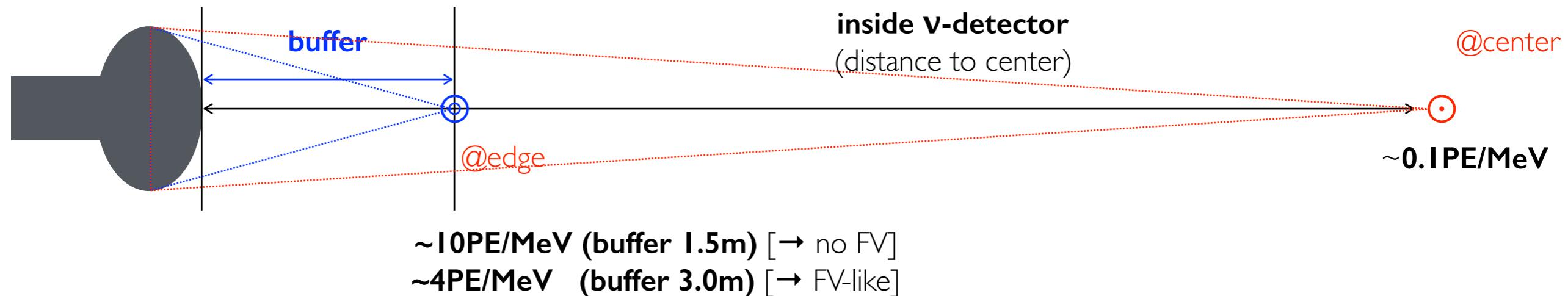
small difference in light level ($> 1150 \text{ PE/MeV}$) ⇒ major impact to $\sigma(E)^2_{\text{non-stoch}}$: most challenging!!

“double-calorimetry” aid reduction/control validation of $\sigma(E)^2_{\text{non-stoch}} \rightarrow$ redundancy

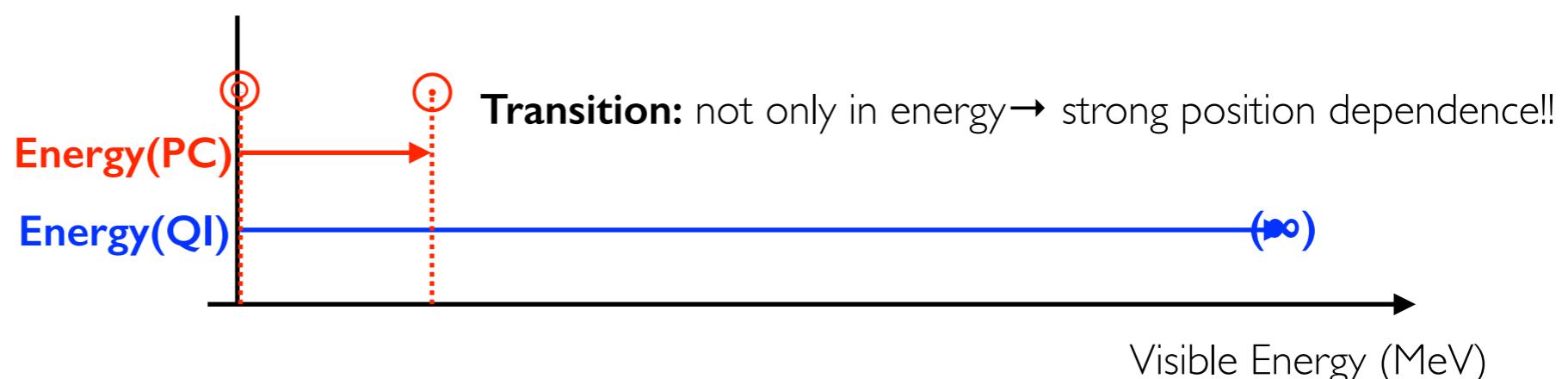


calorimetry regimes...

simple solid angle argument (1st order acceptance)...

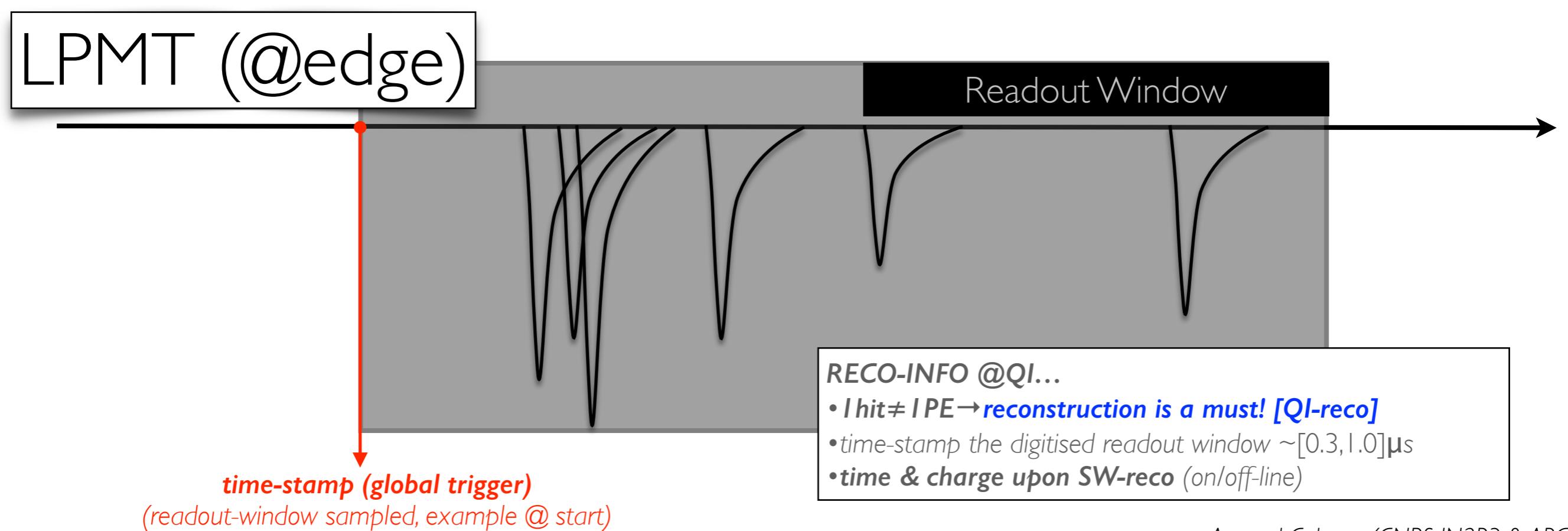
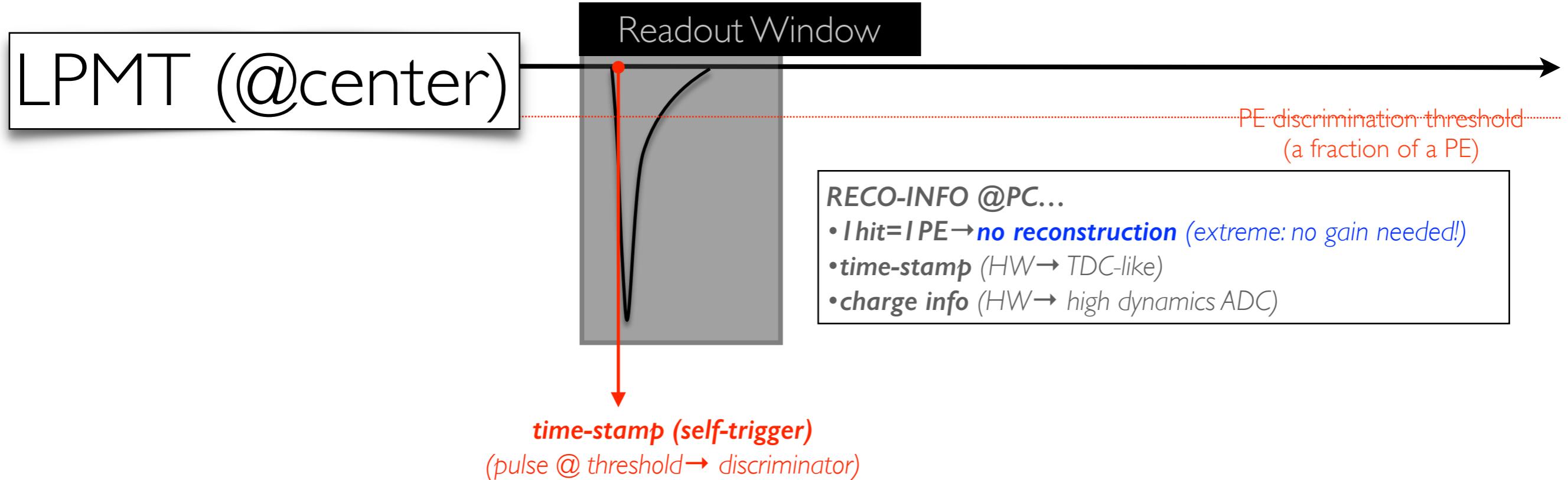


Energy Estimator via Photon-Counting (low light level)
Energy Estimator via Charge Integral (all light levels)

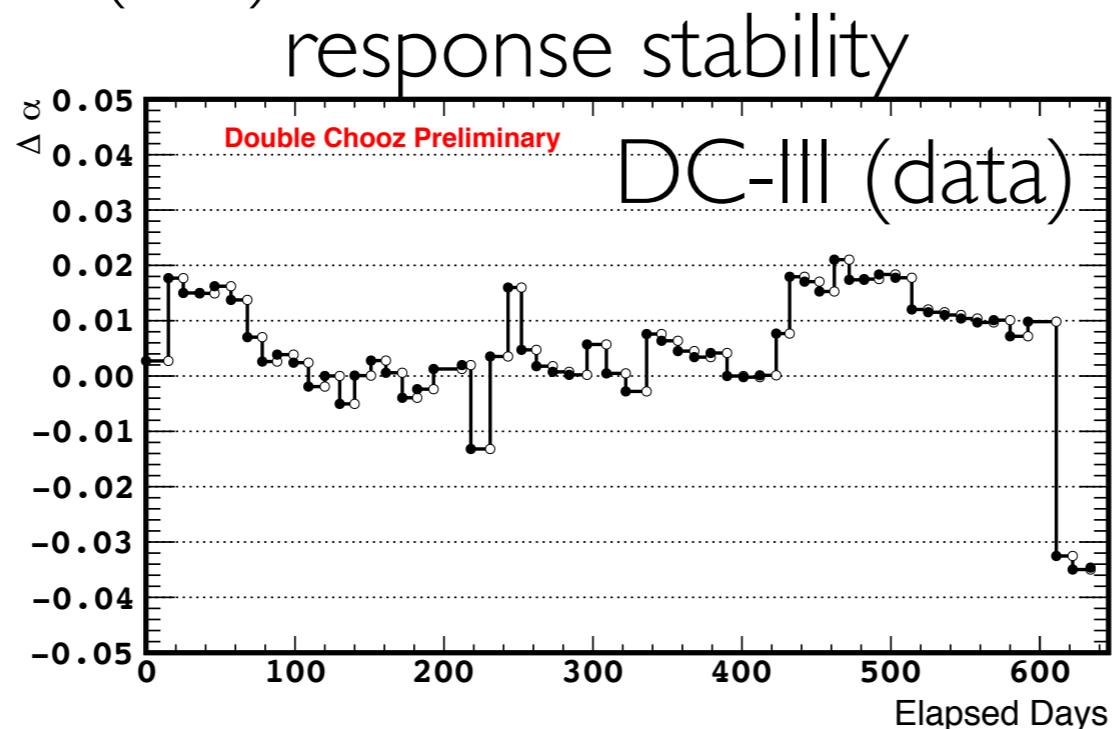
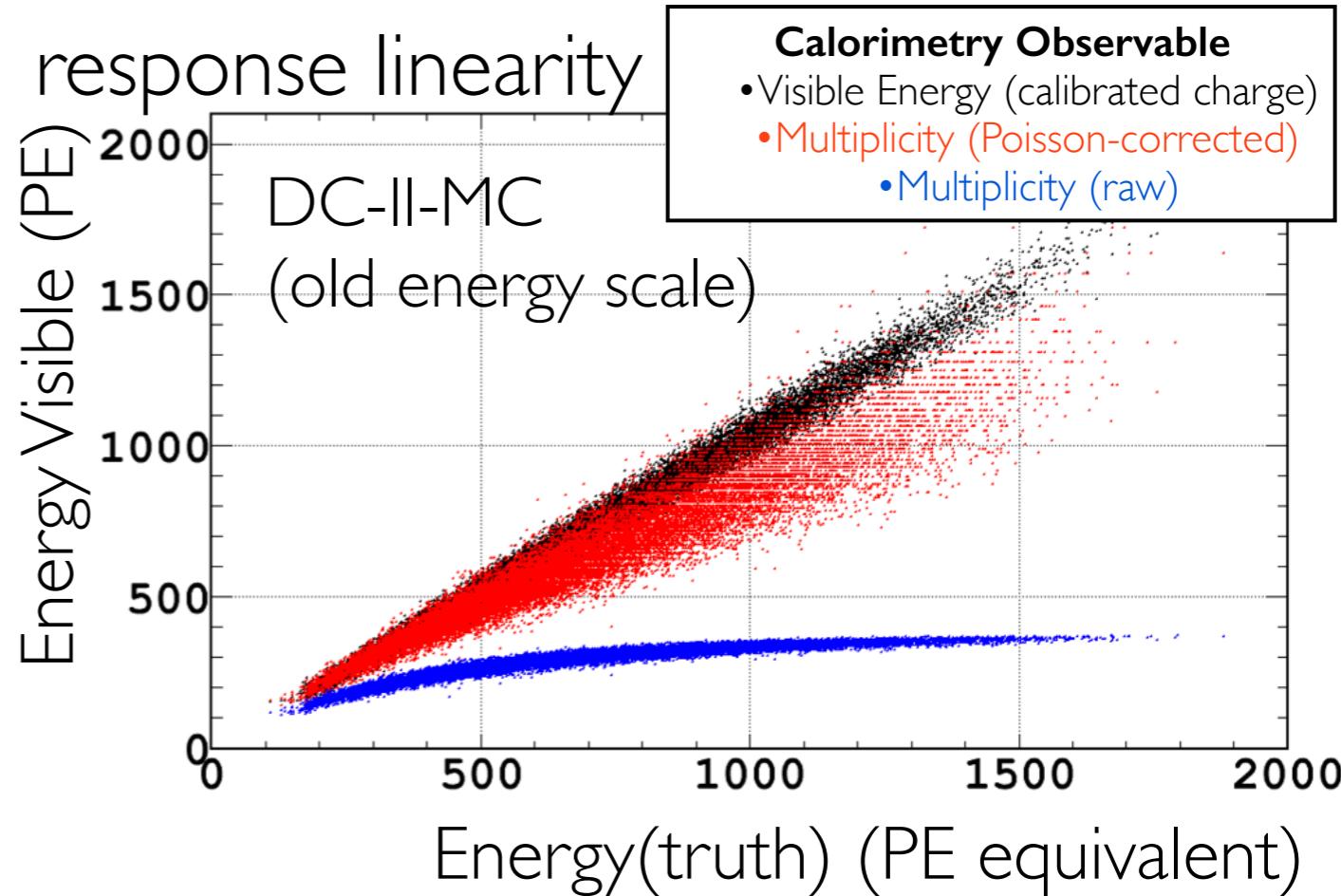
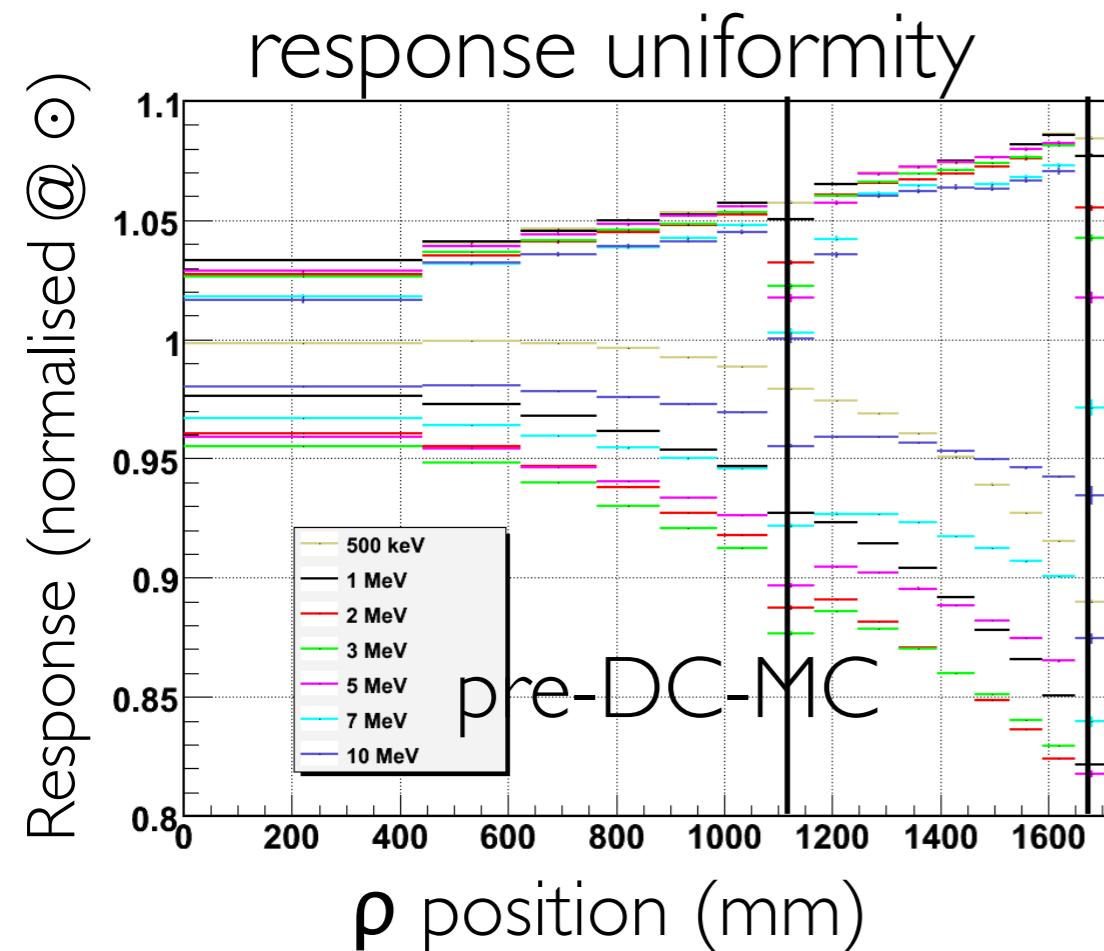


this detector (very small buffer; à la JUNO) \rightarrow **E(\odot) is VERY different from E(\odot)** [~100x]

Photon-Counting vs Charge-Integration...



Photon Counting vs Charge Integration in action...

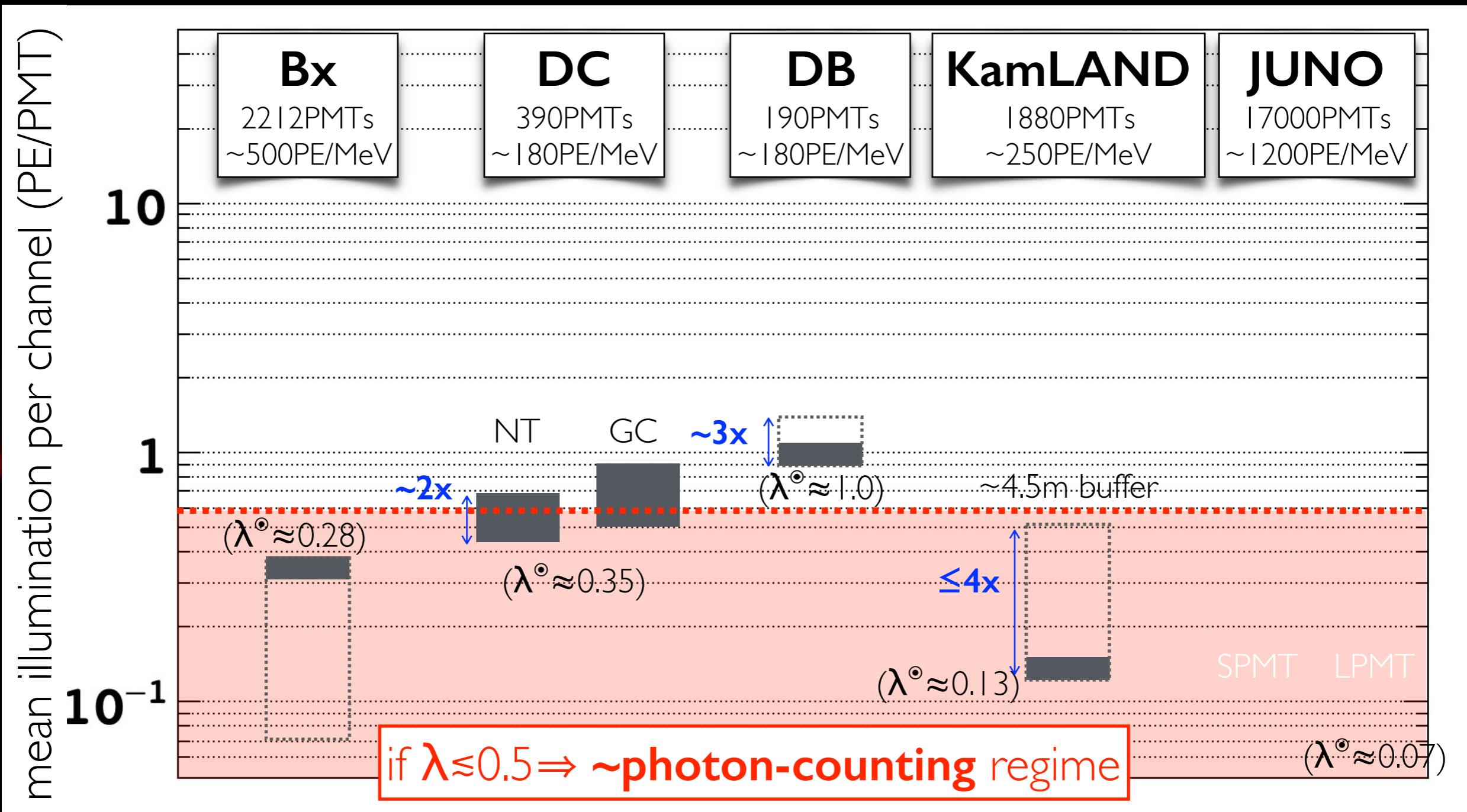


example: “digital” stability
(zero tracking + other)
applied in latest DC (effect
invisible to charge integration
estimator)

E(PC) & E(QI) are both useful → **highly complementary!!**

the JUNO challenge (2)...

@IMeV

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

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

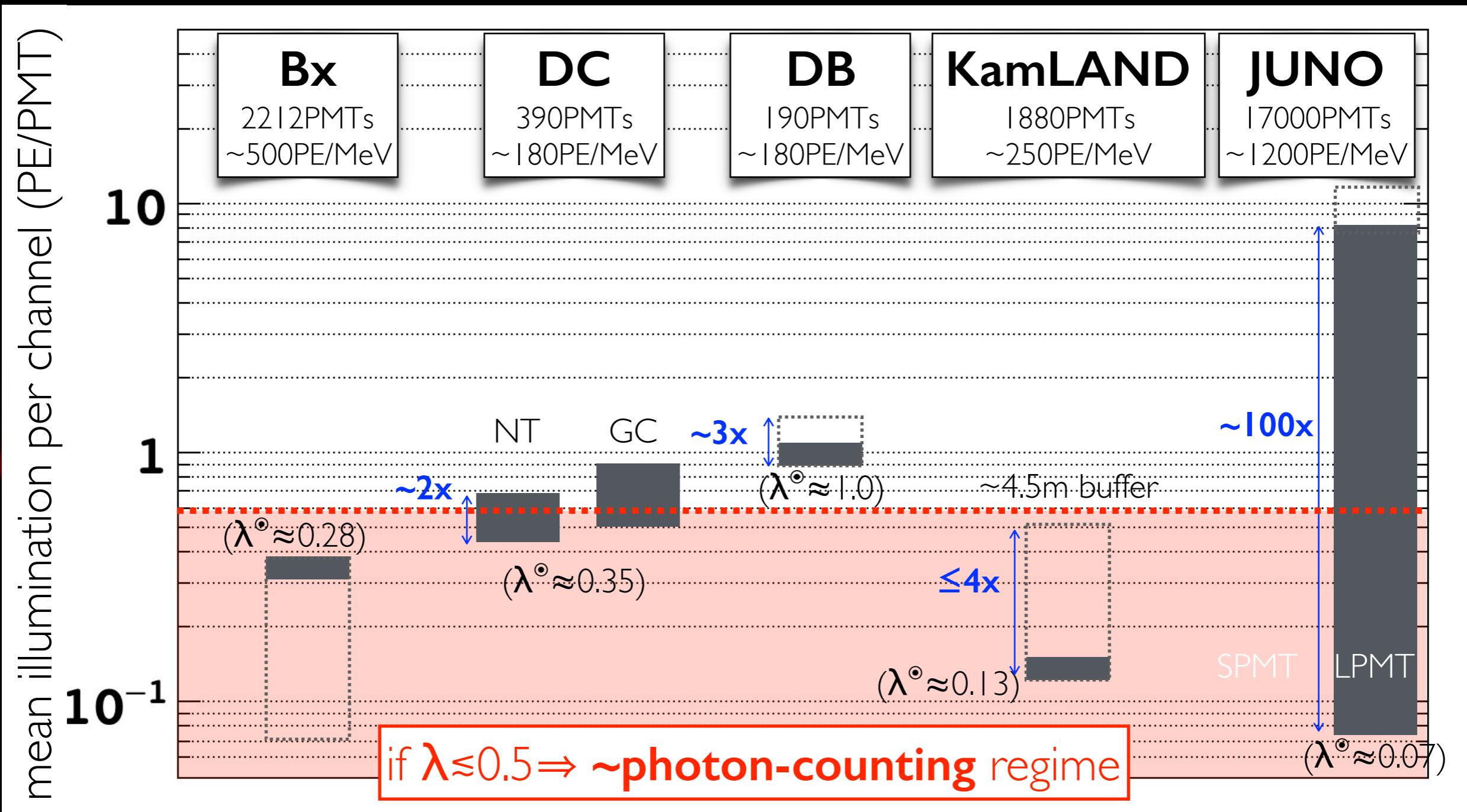
⊕

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

the JUNO challenge (2)...

@IMeV

λ^\odot = mean illumination per channel @ center



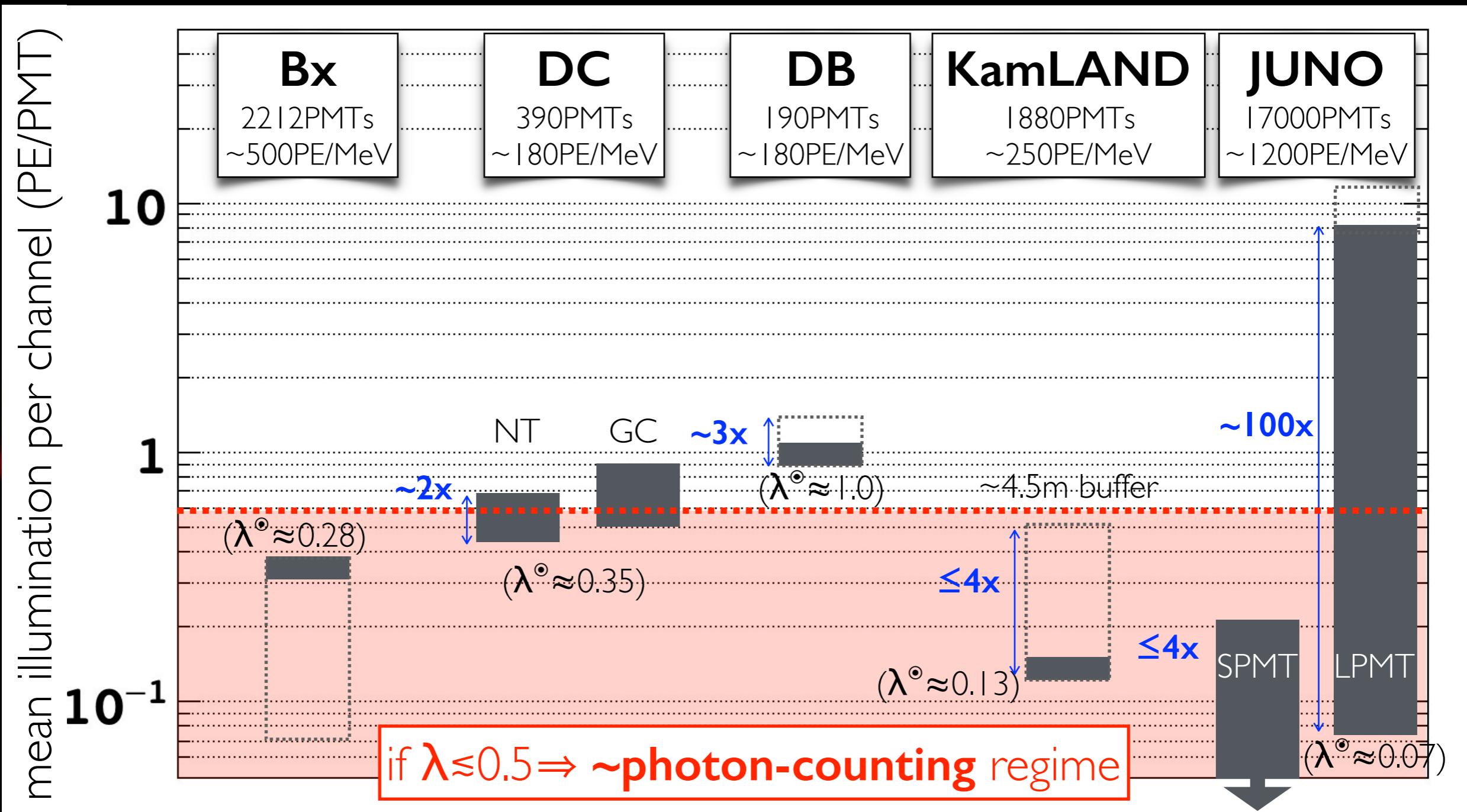
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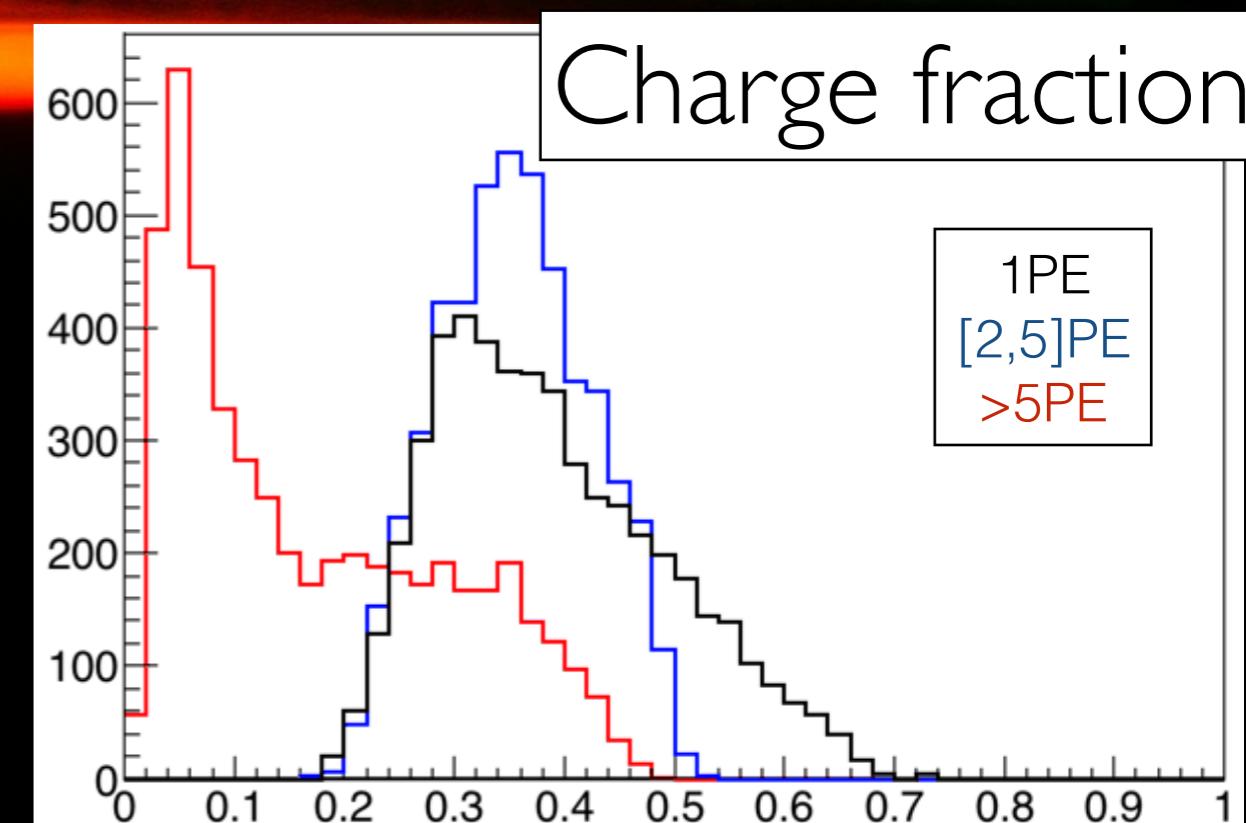
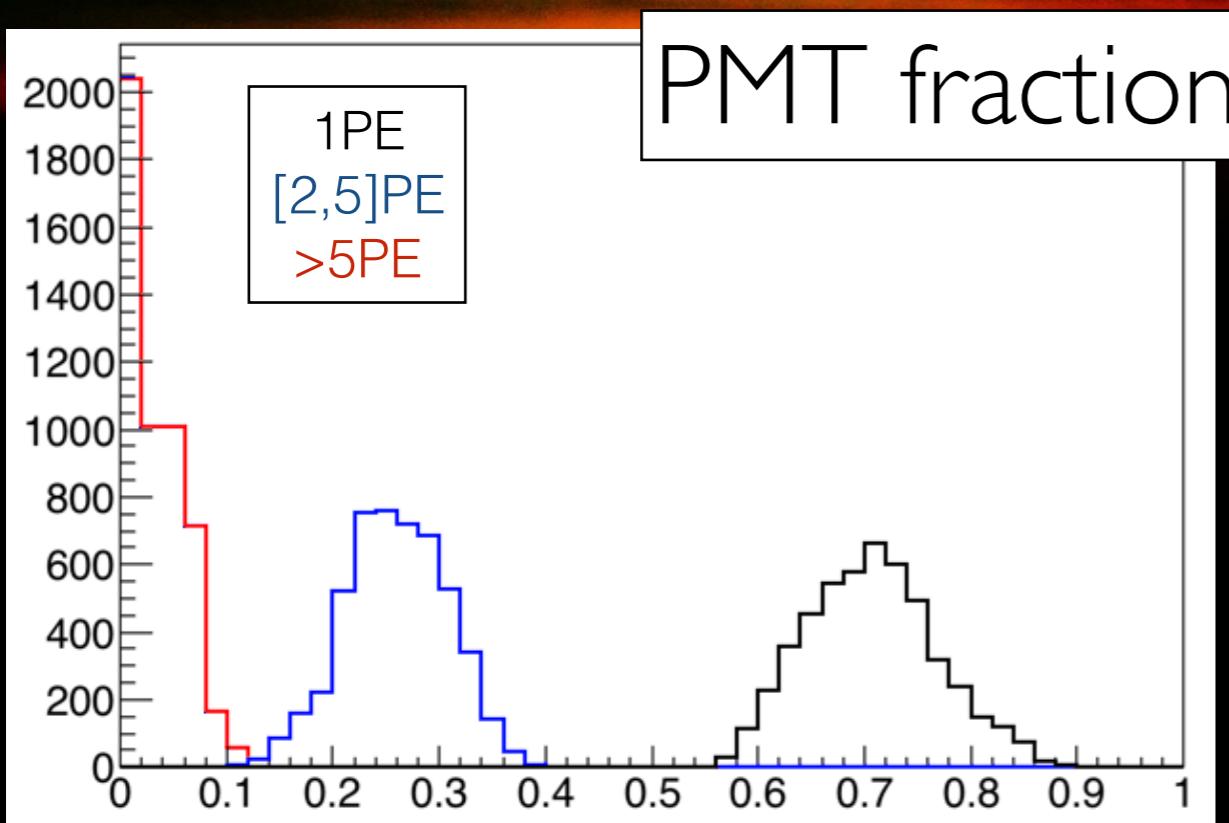
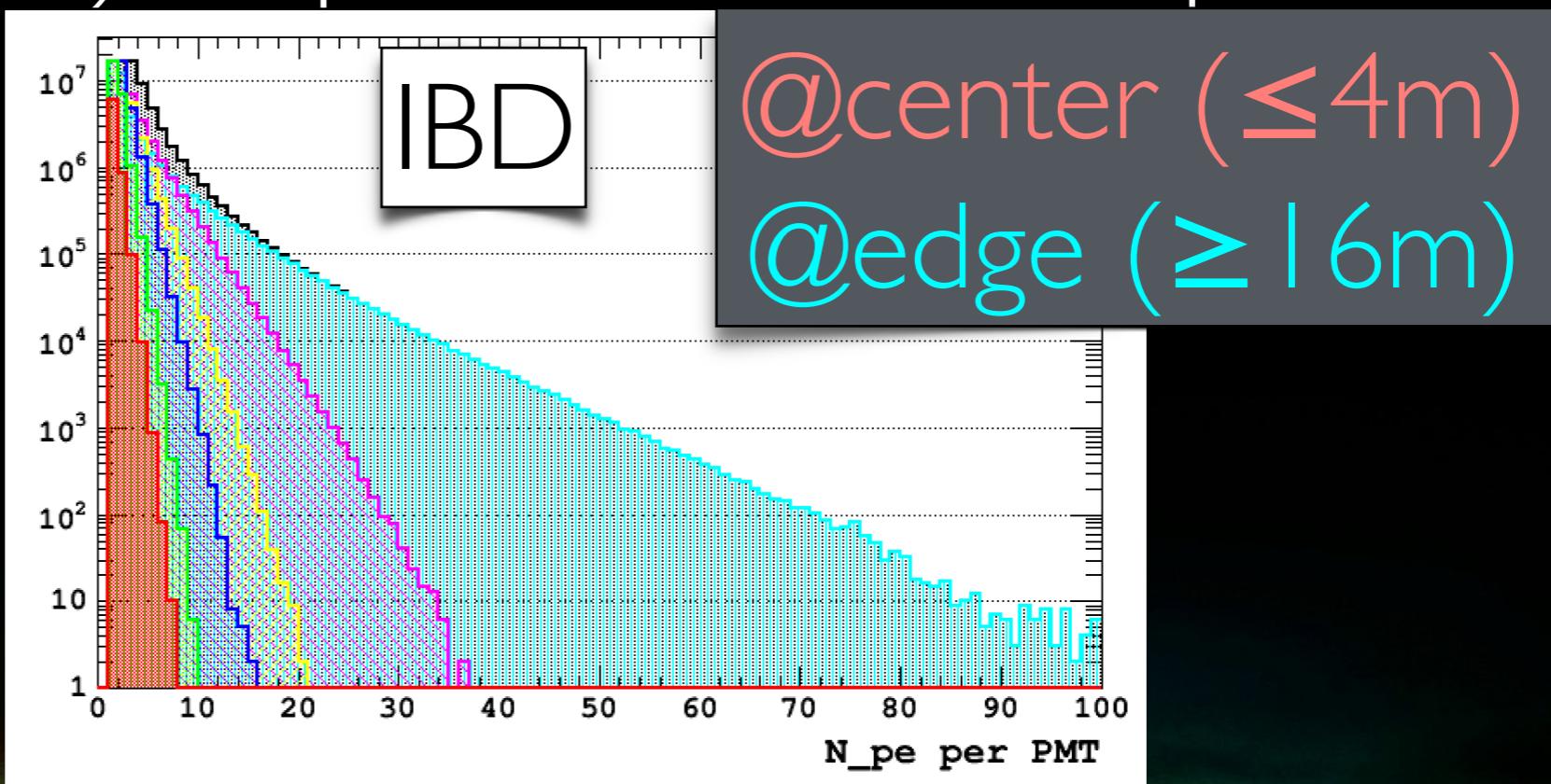
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LARGEST dynamic range in calorimetry (channel-wise) [\Rightarrow uniformity ⊕ linearity ⊕ stability]

(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!

double-calorimetry?

“JUNO”: LPMT only (so far)

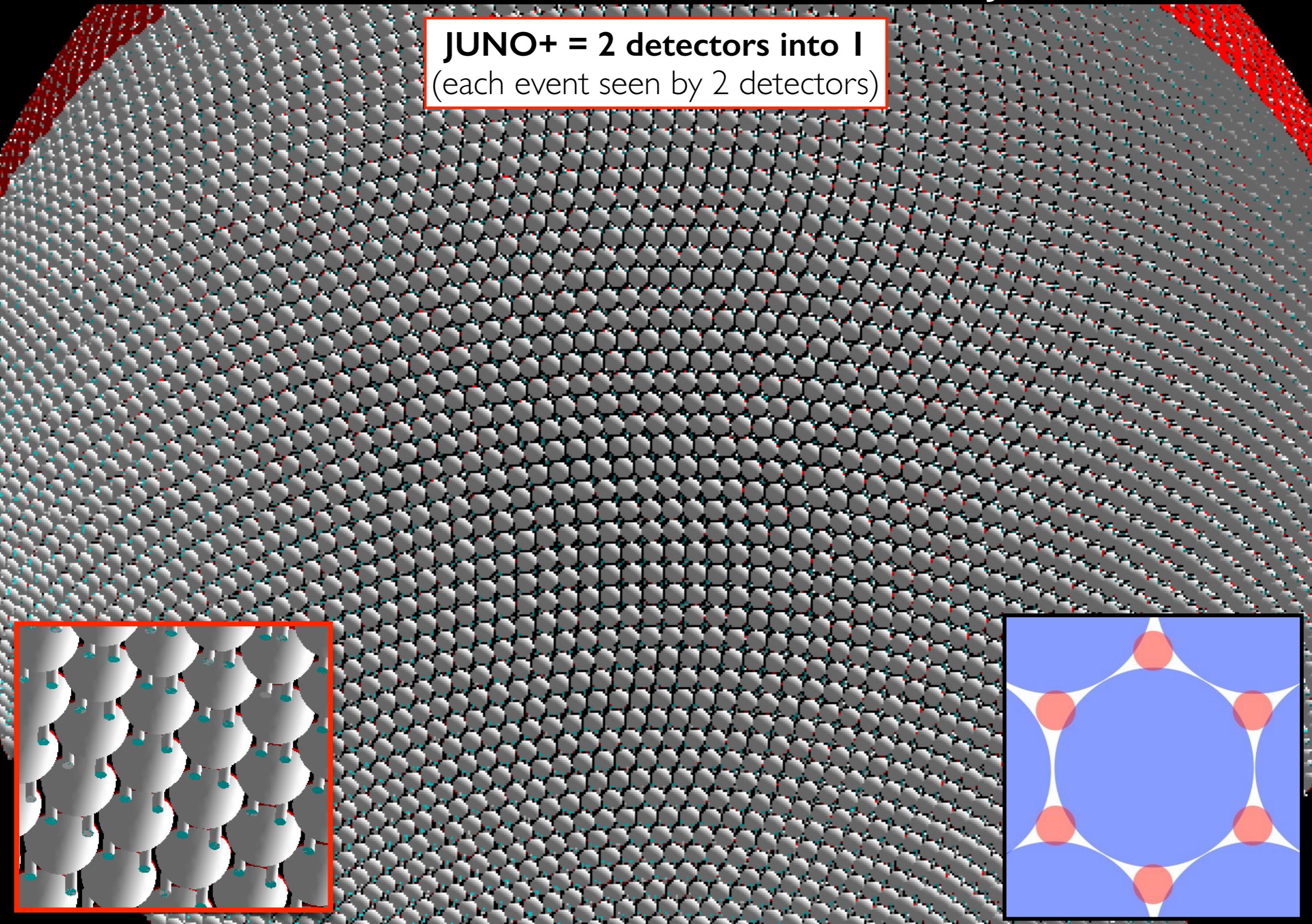
(i.e. single-calorimetry)



“JUNO+”: LPMT \oplus SPMT (\rightarrow baseline)

(i.e. double-calorimetry)

JUNO+ = 2 detectors into 1
(each event seen by 2 detectors)



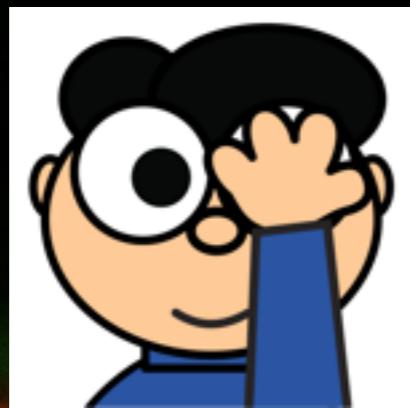
JUNO
(old baseline)

JUNO+
(new baseline)

milestone 1: demonstrate JUNO+ implies **no performance loss wrt JUNO** (baseline)
(first 50% to success)

milestone 2: demonstrate JUNO+ **provides otherwise impossible performance** (wrt JUNO)
(second 50% to success)

JUNO (old baseline)

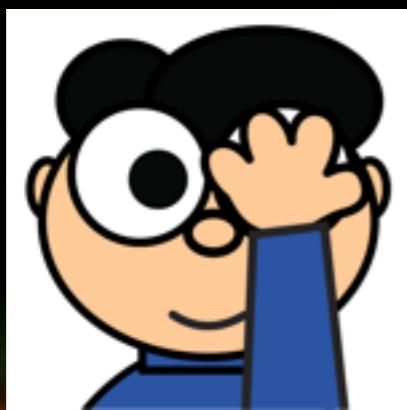


JUNO+ (new baseline)

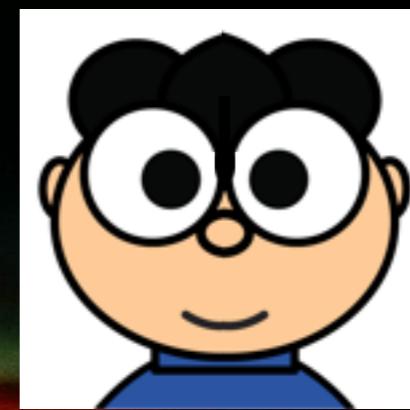
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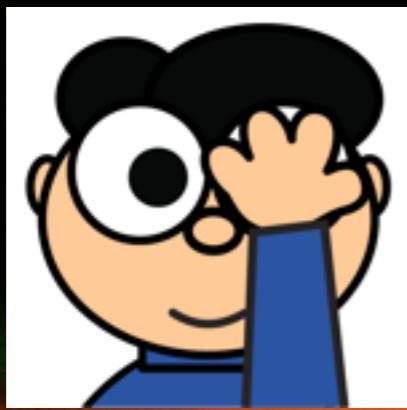
JUNO+ (new baseline)



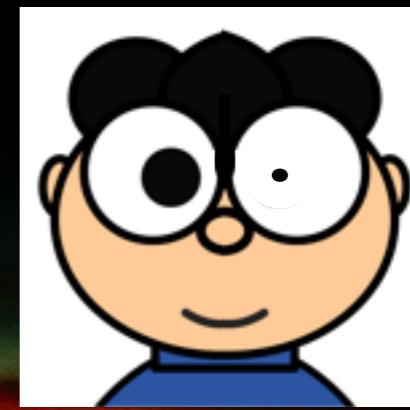
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JUNO (old baseline)



JUNO+ (new baseline)



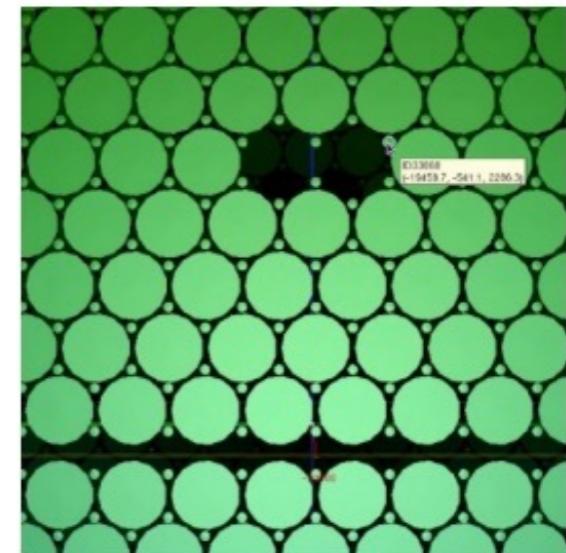
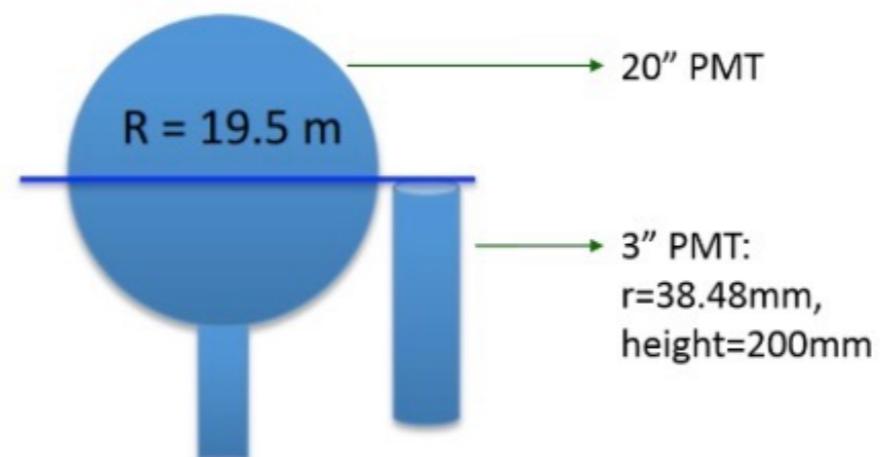
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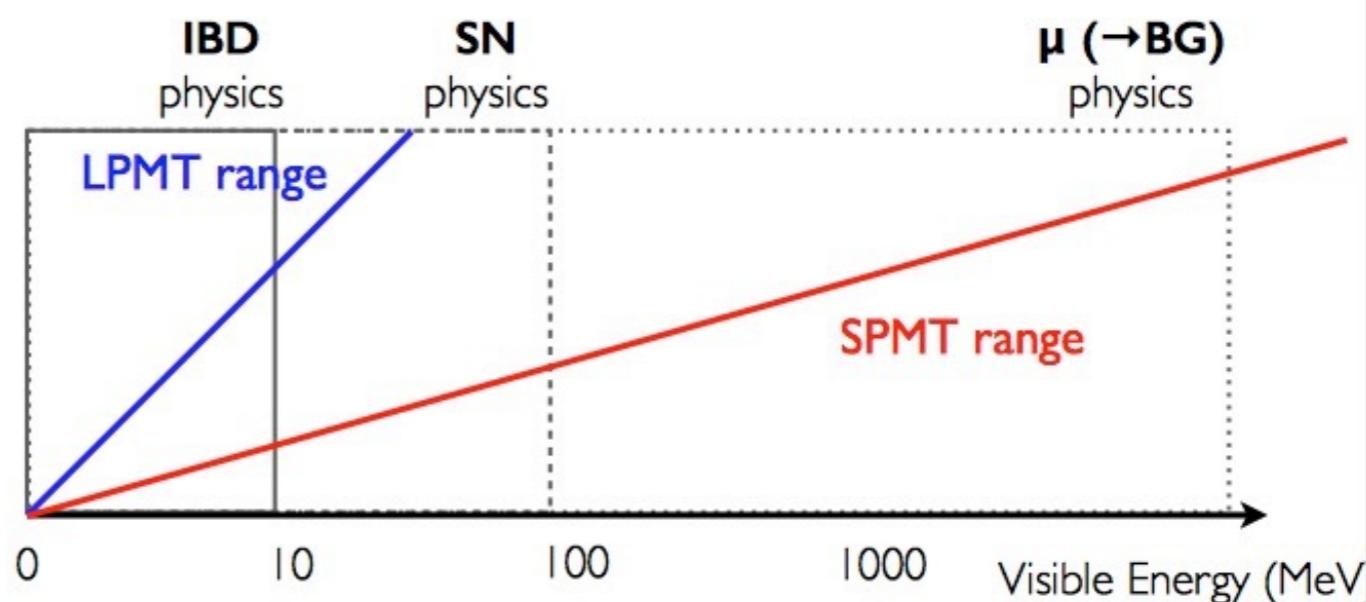


Even Better: A Double Calorimetry Design

- Small PMTs (SPMT) are cheaper and faster in time response (<1 ns), lower noise and higher QE_{CE}
- Adding 3" PMTs in the gaps: ~2 SPMTs for every large PMT (LPMT)
 - increase the photocathode coverage by ~1%
 - improve the central detector muon reconstruction resolution
 - avoid high rate supernova neutrino pile-up (if very near)
 - increase the dynamic range and global trigger



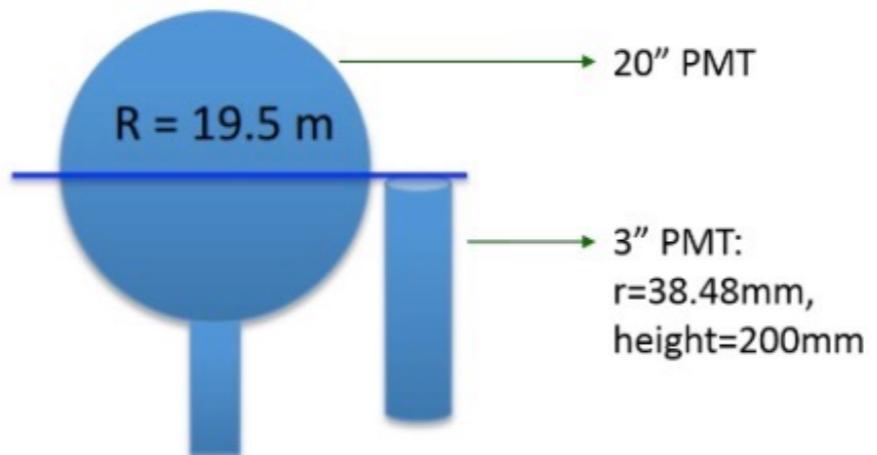
Complementary Roles by sPMTs and LPMTs



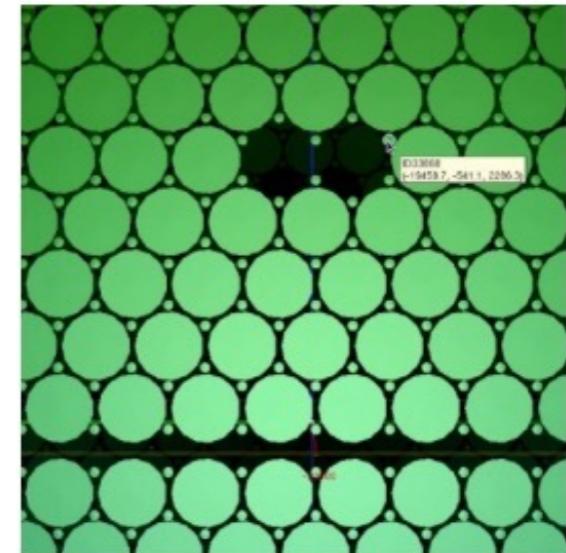


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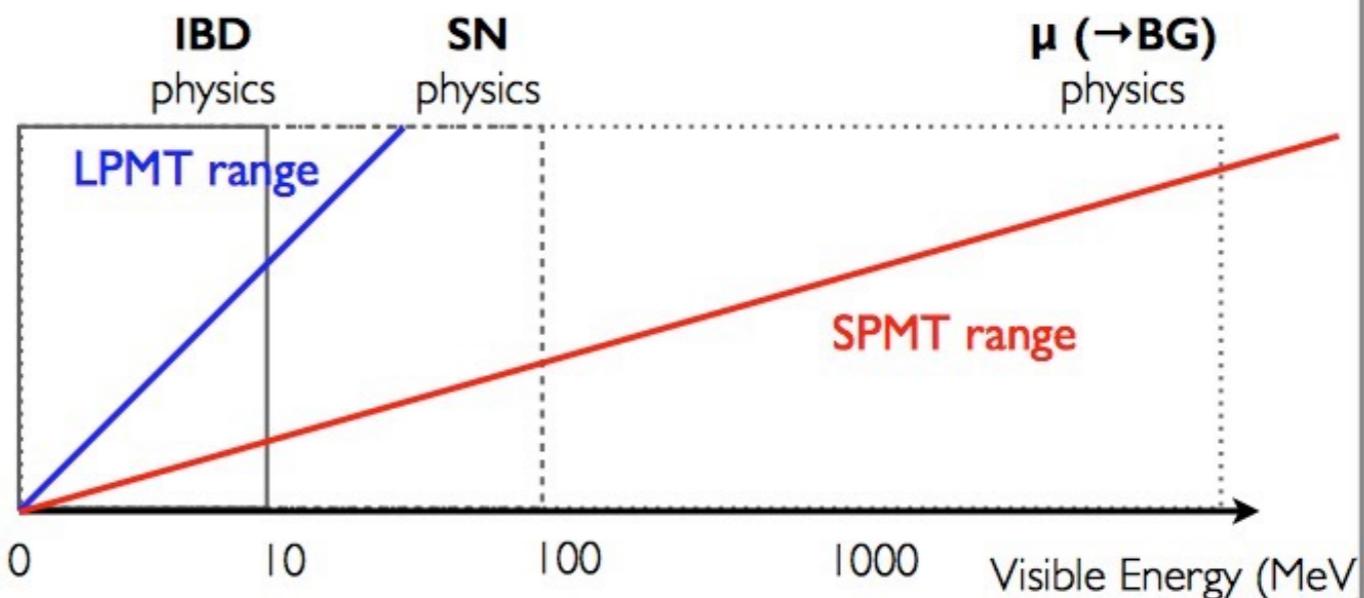
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The front end of the 3" PMT is in the same plane as the equatorial plane of 20" PMT



Complementary Roles by sPMTs and LPMTs



advantages of JUNO+...

(no disadvantages identified)

collaboration mandates to “SPMT group”...

A. high precision calorimetry response systematics IBD physics

(highest priority: **aide $\leq 3\%$ @ 1MeV 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: dynamic range & global trigger

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

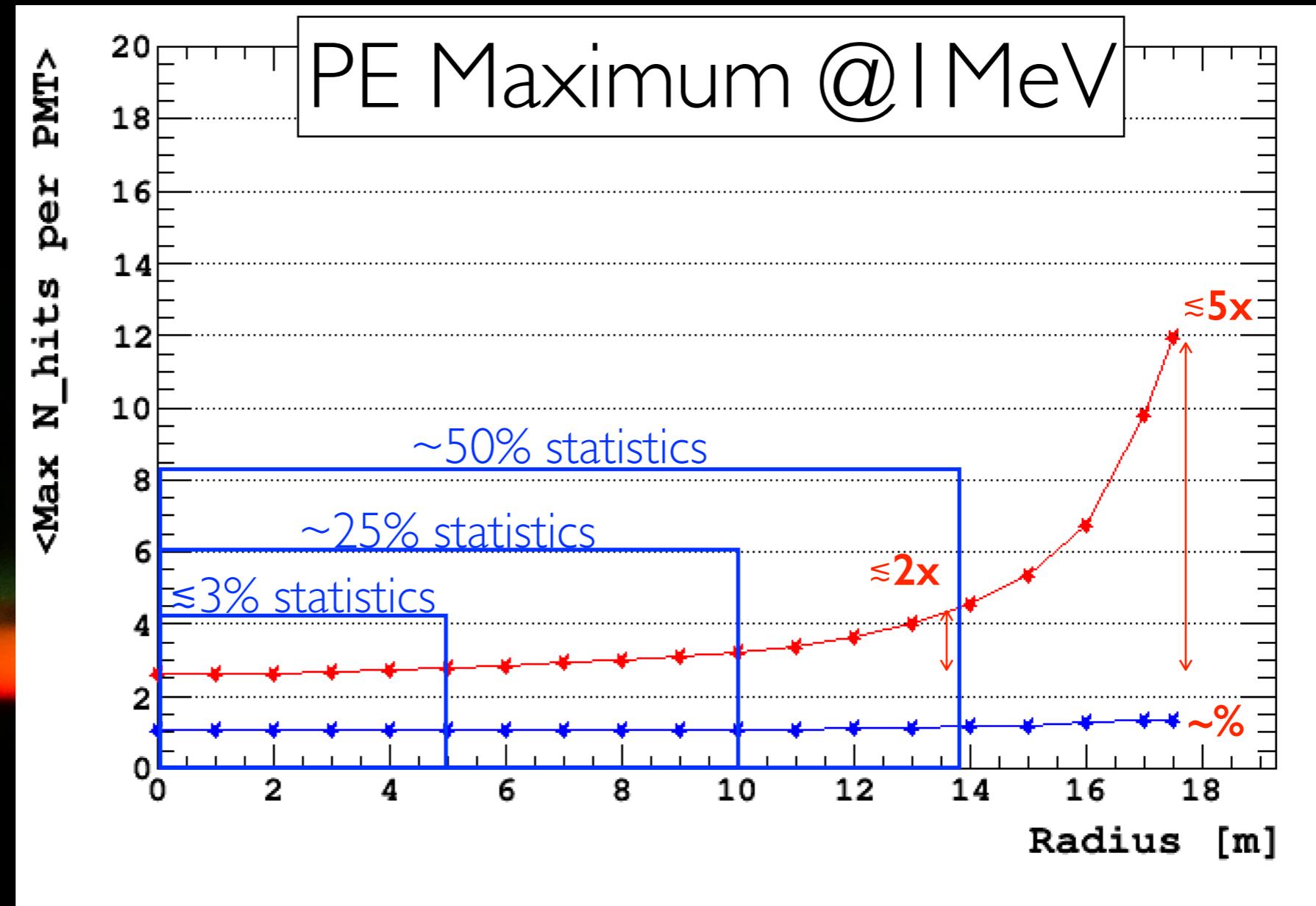
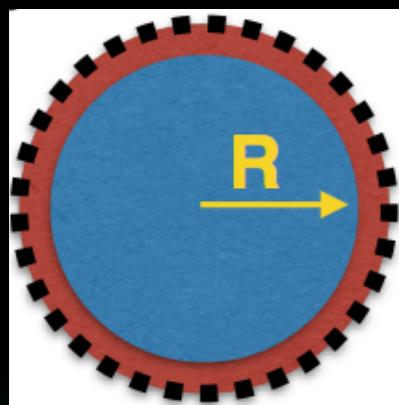
(less important) but also...

E. other byproducts: HW solutions for other subdetectors, etc.

high precision IBD calorimetry...



the SPMT & LPMT calorimetry regimes...



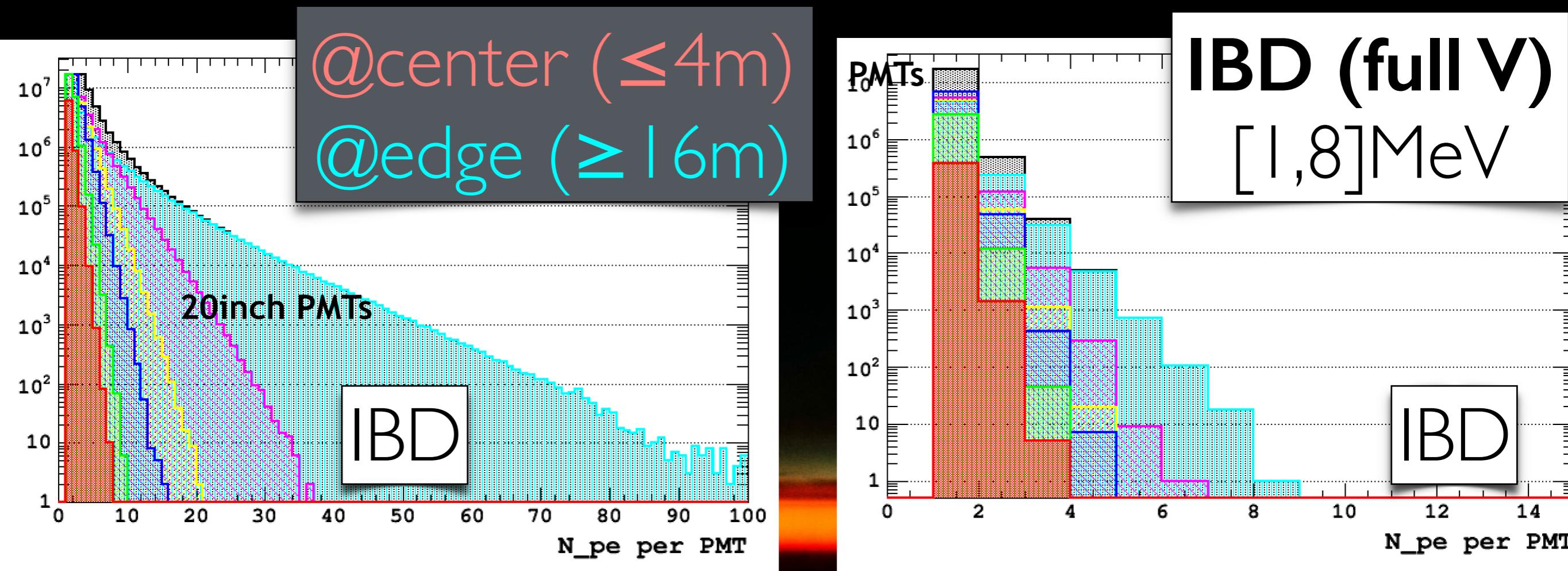
LPMT has dramatic variation across volume (\rightarrow systematics and/or biases)

(wildest variation in region with large fraction of statistics)

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

(**complementary calorimetry input** \rightarrow ideal for Trigger implementation)

dynamic of SPMT vs LPMT...



LPMT high response (by construction)

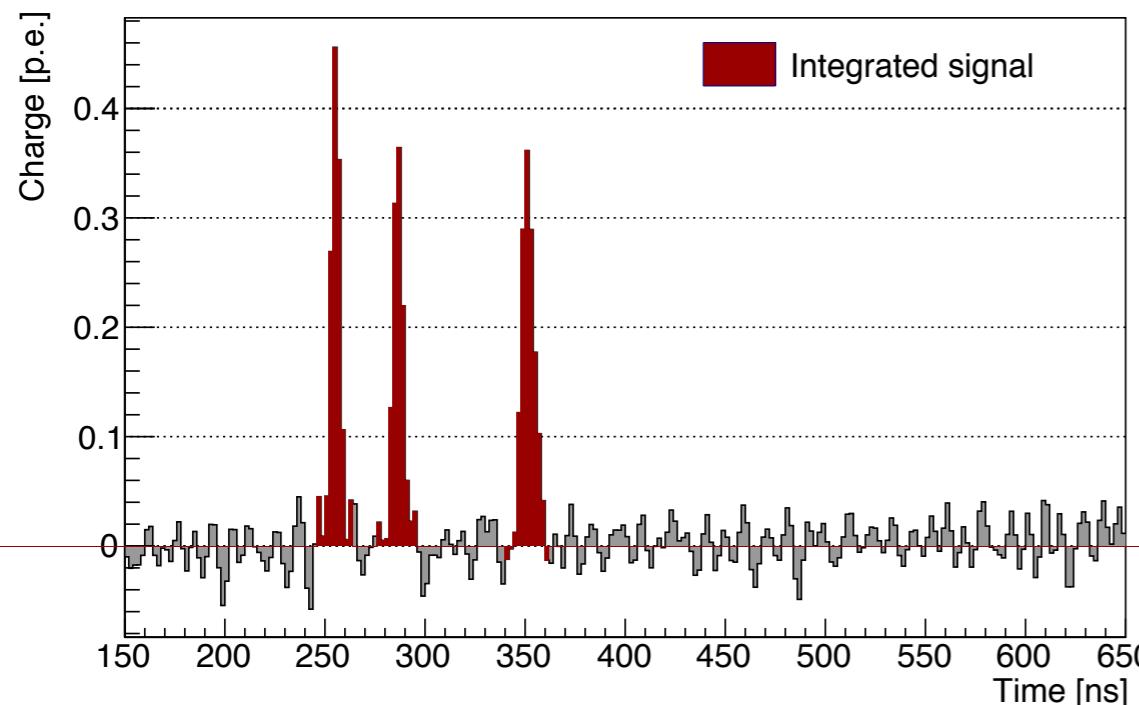
SPMT low response (by construction)

goal: SPMT to provides unique calorimetry handles (redundancy) when LPMT goes biassed
 (unavoidable: reconstruction & intrinsic detection effects)

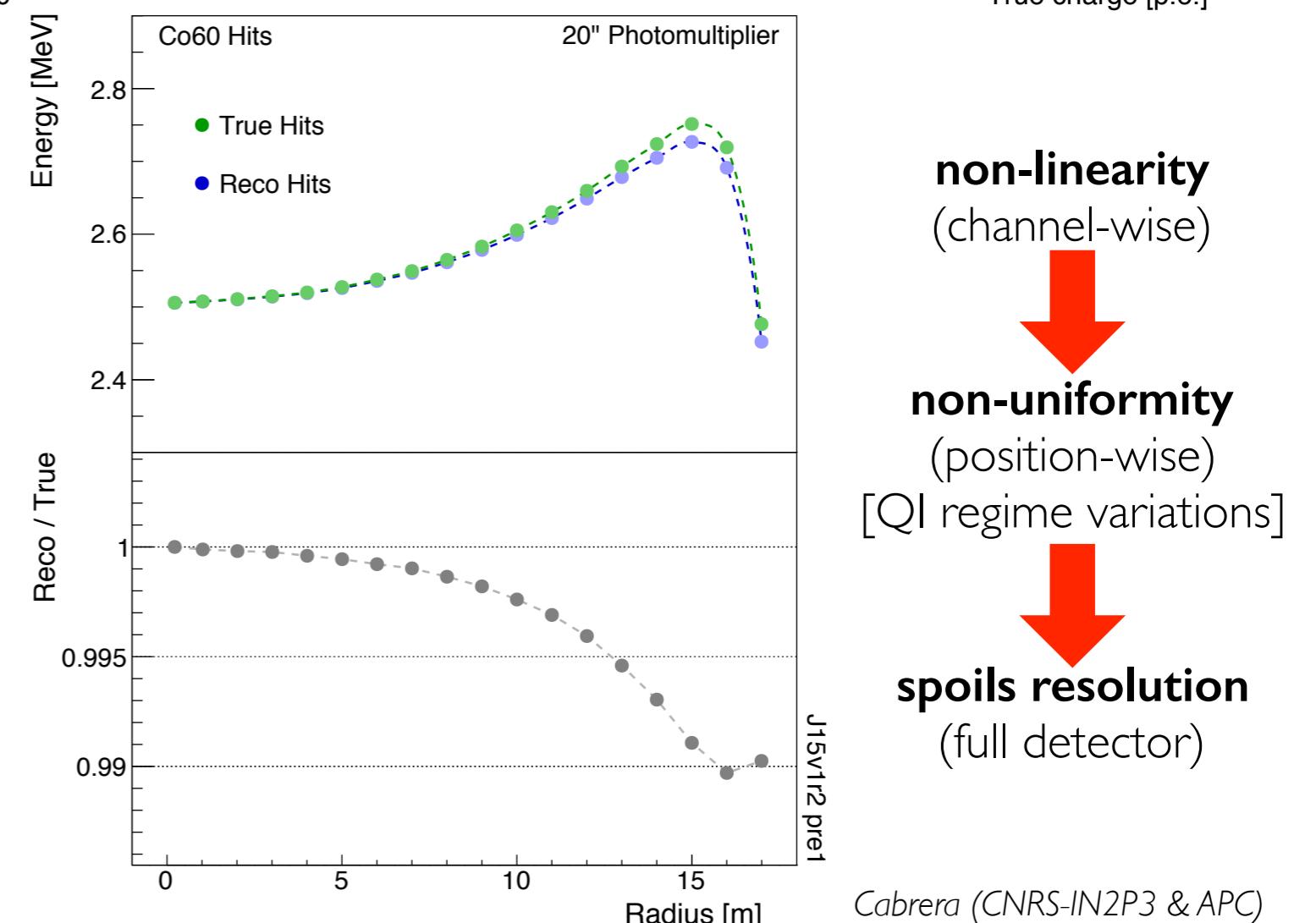
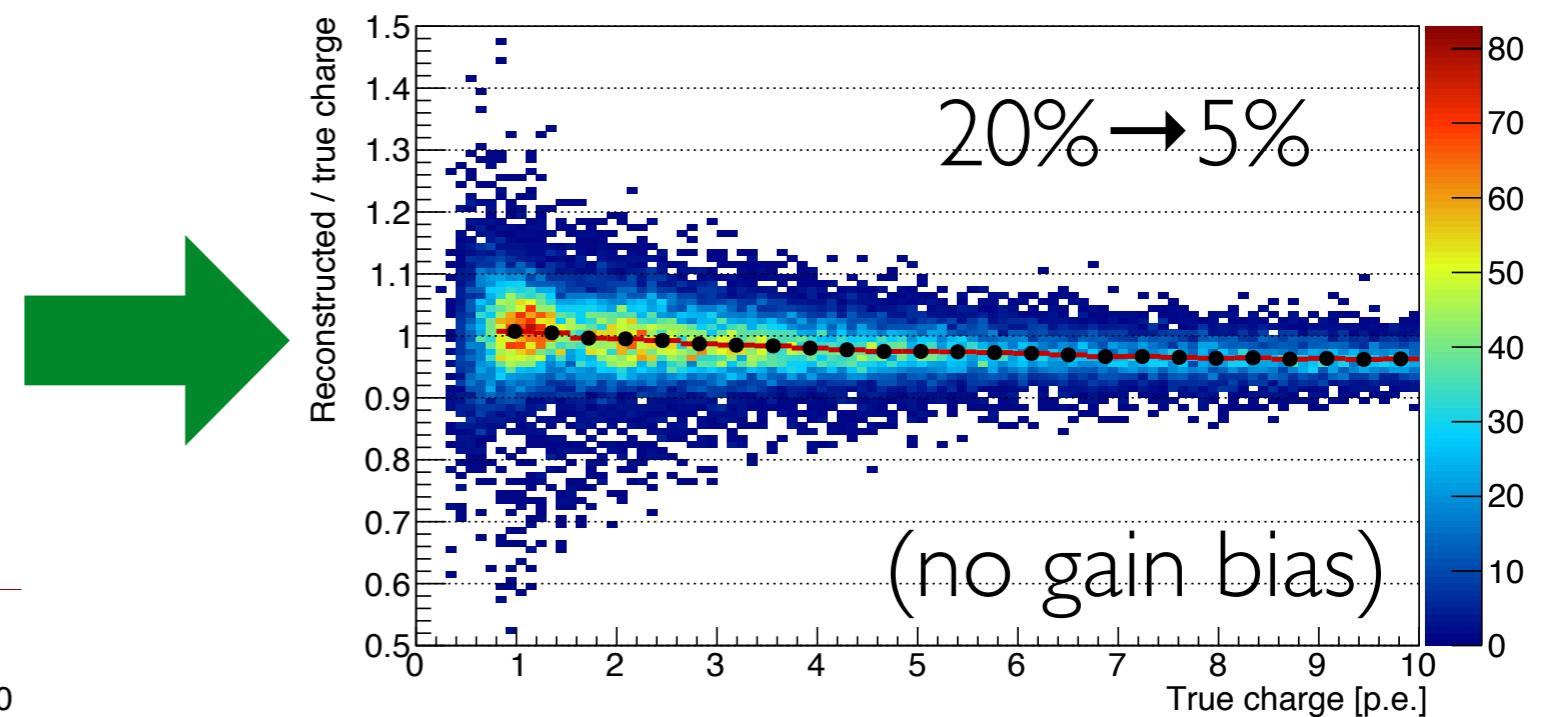
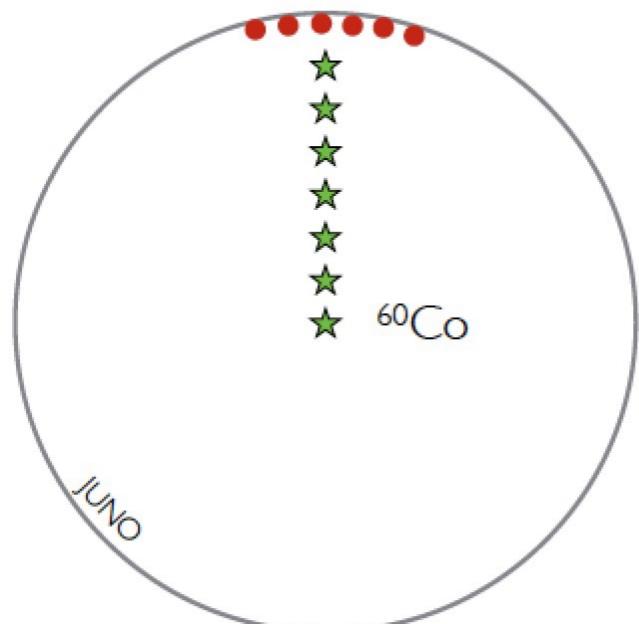
**the SPMT is not a solution, but an alleviator/aider system
 (cost effective & no JUNO re-design)**

energy reconstruction bias estimation (I)...

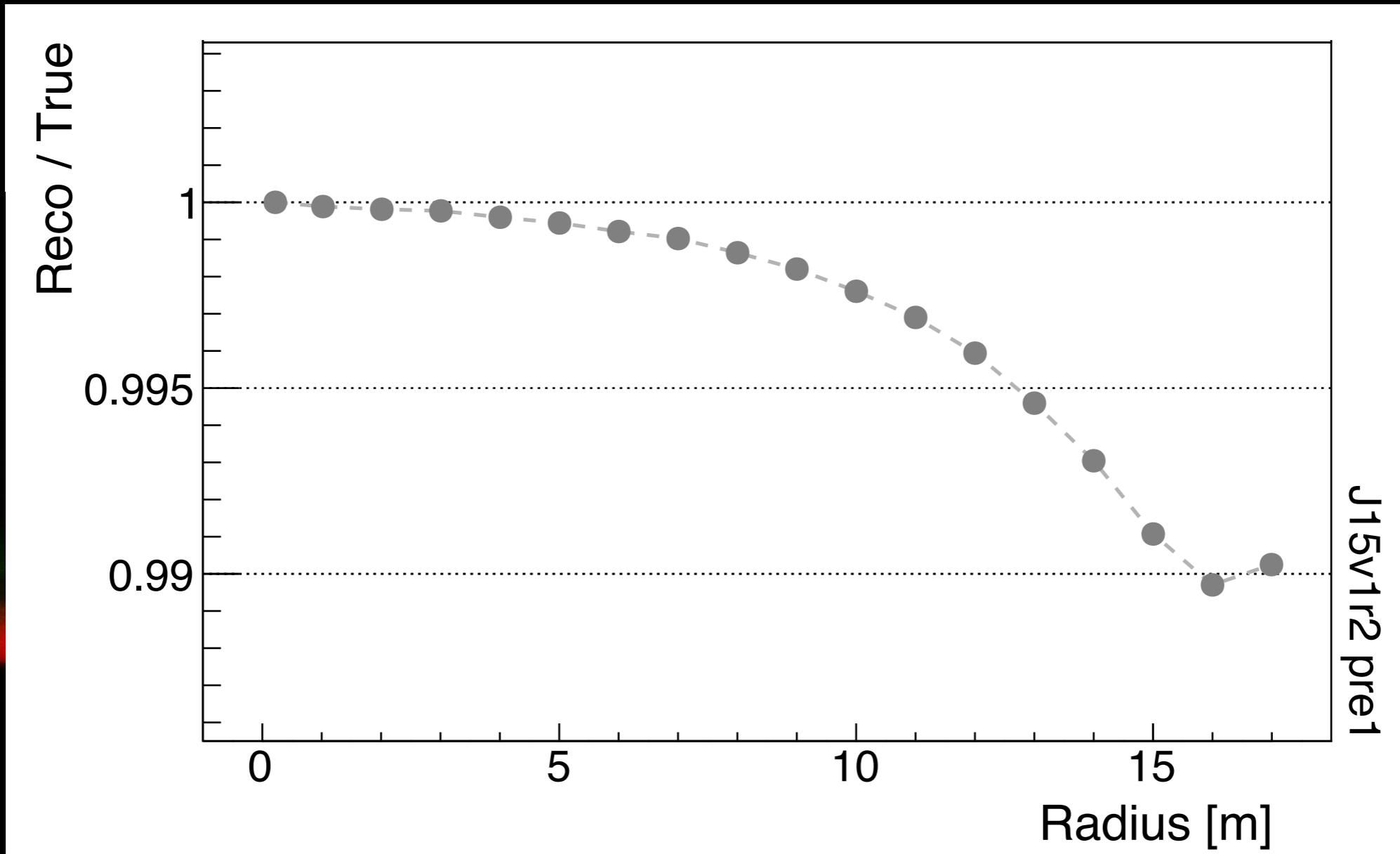
realistic pulse reco (QI)



**calibration
mimicking**



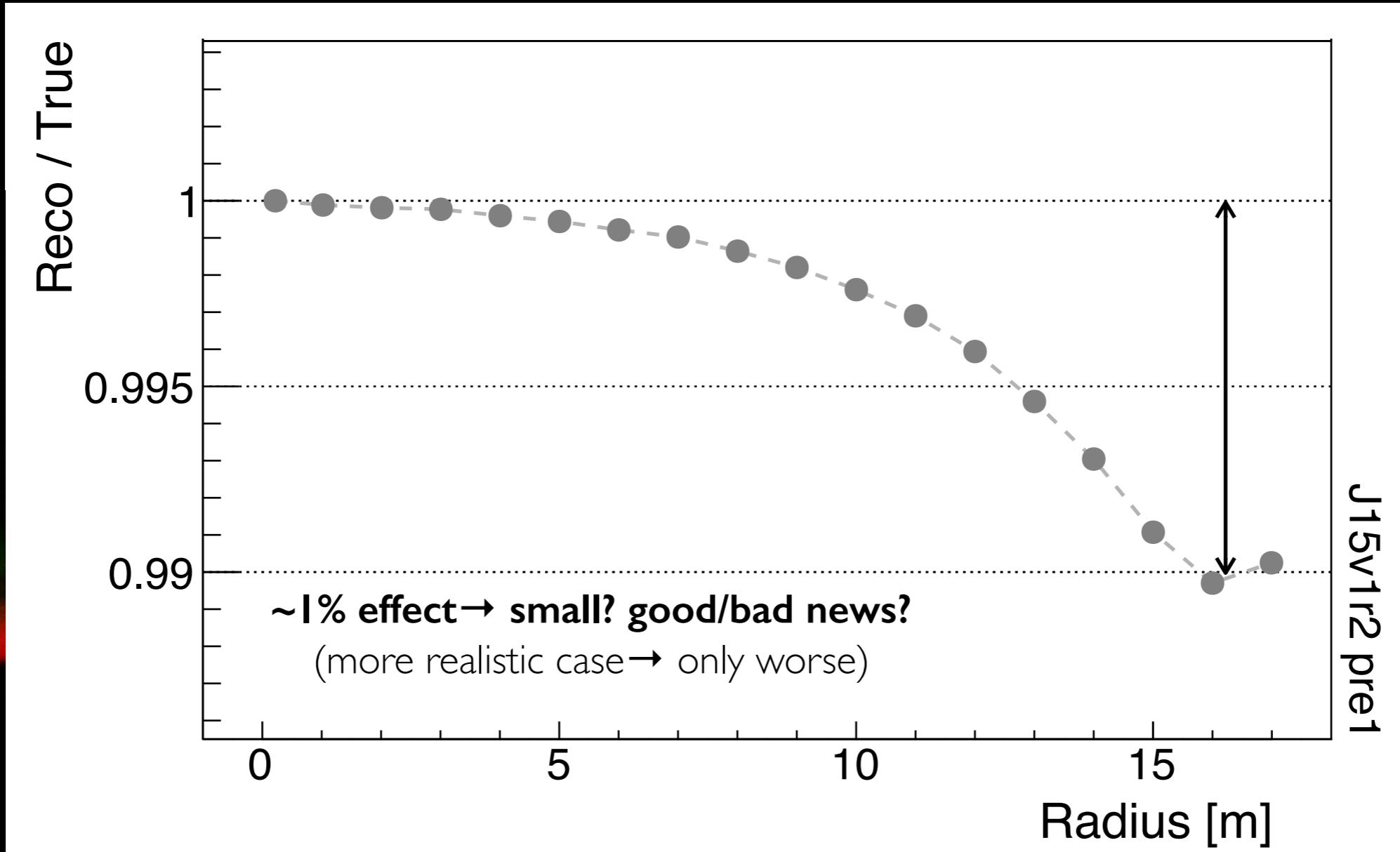
let's scrutinise this observation carefully...



2 amplification effects...

- most **data is in the edge** (outer third detector $\rightarrow \sim 65\%$ of data)
- (@ edge) **few channels up to $\sim 40\%$ of total light \rightarrow to worsen** (likely)
- integrate in R \Rightarrow must keep 3% on total (within FV)

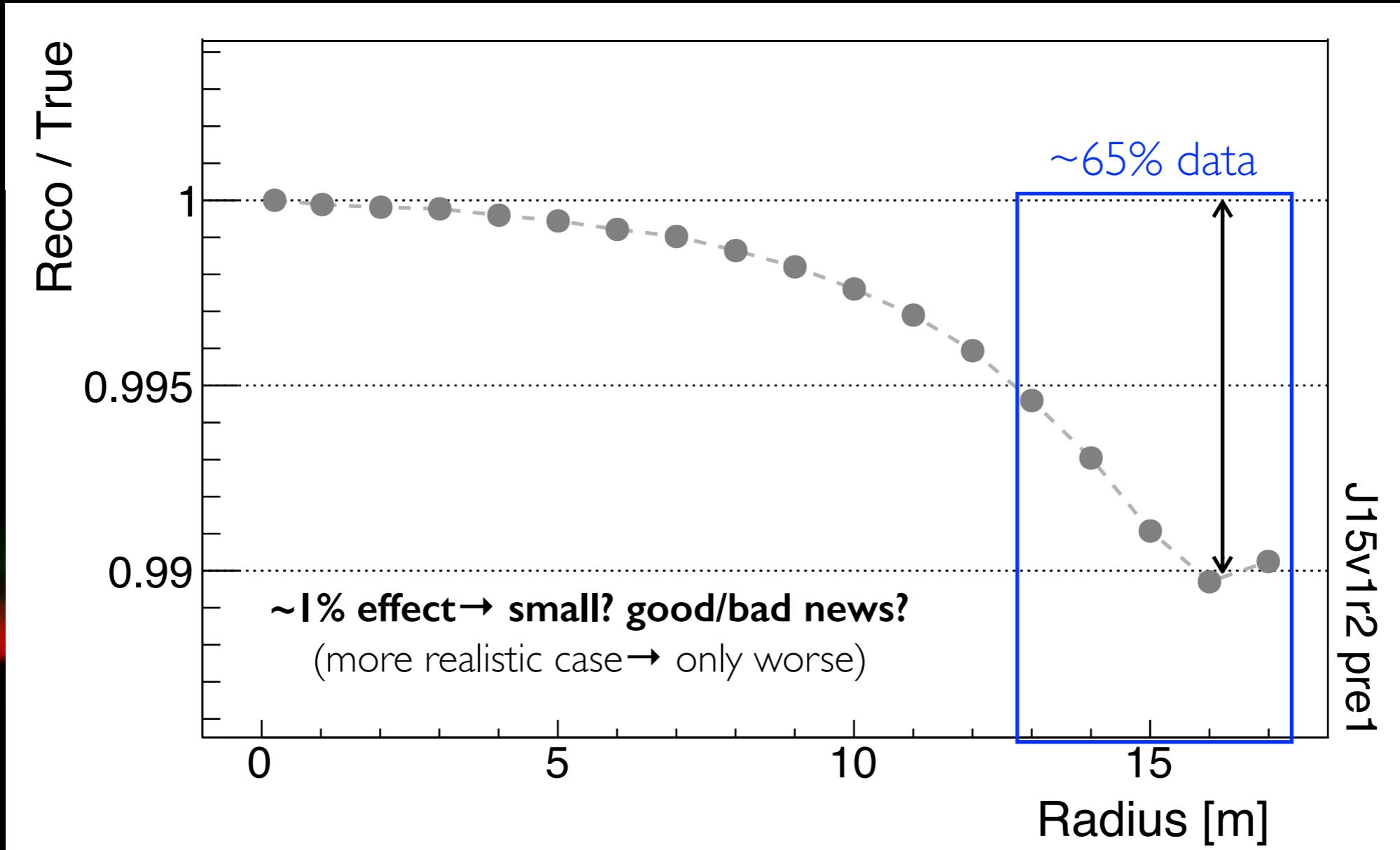
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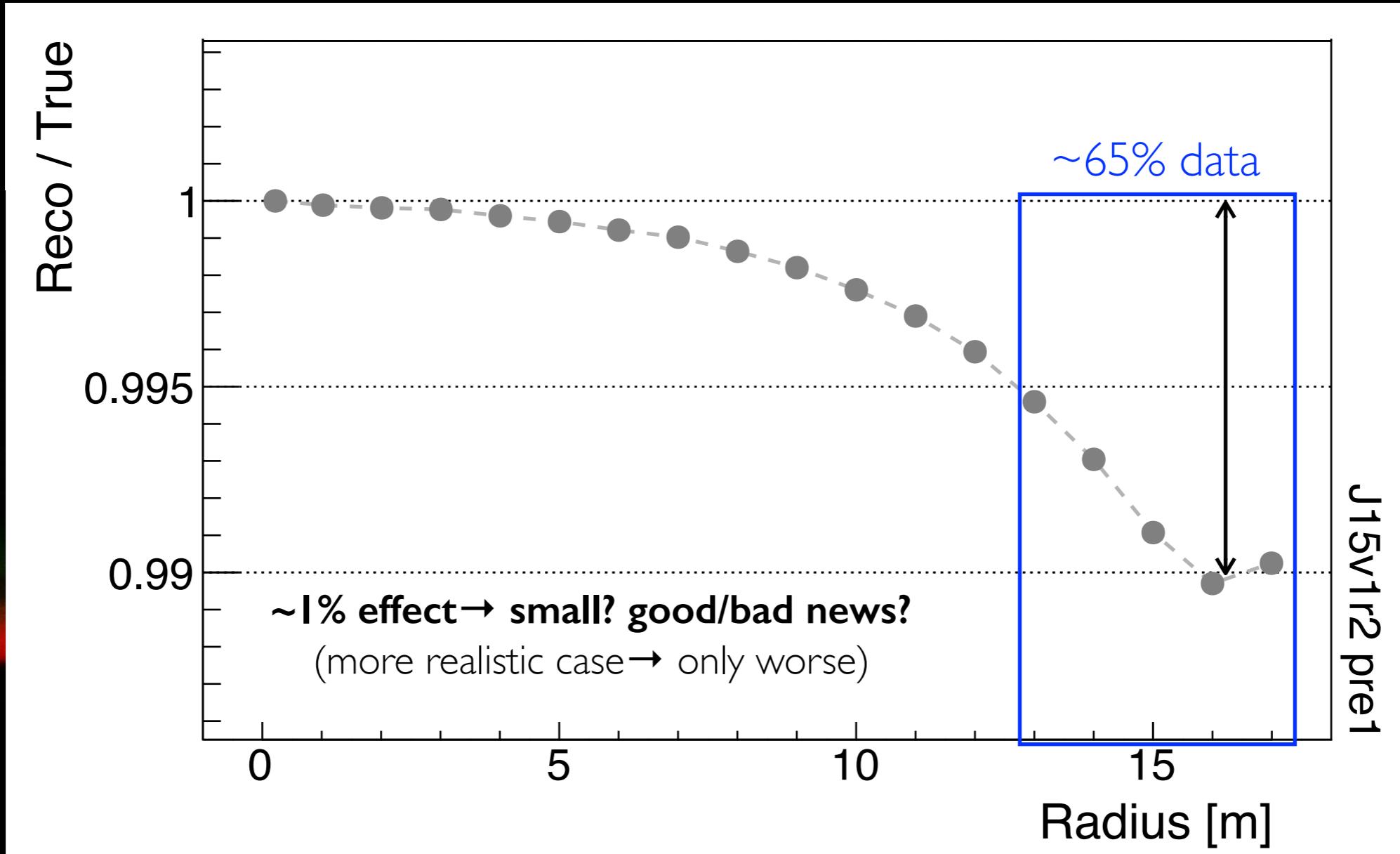
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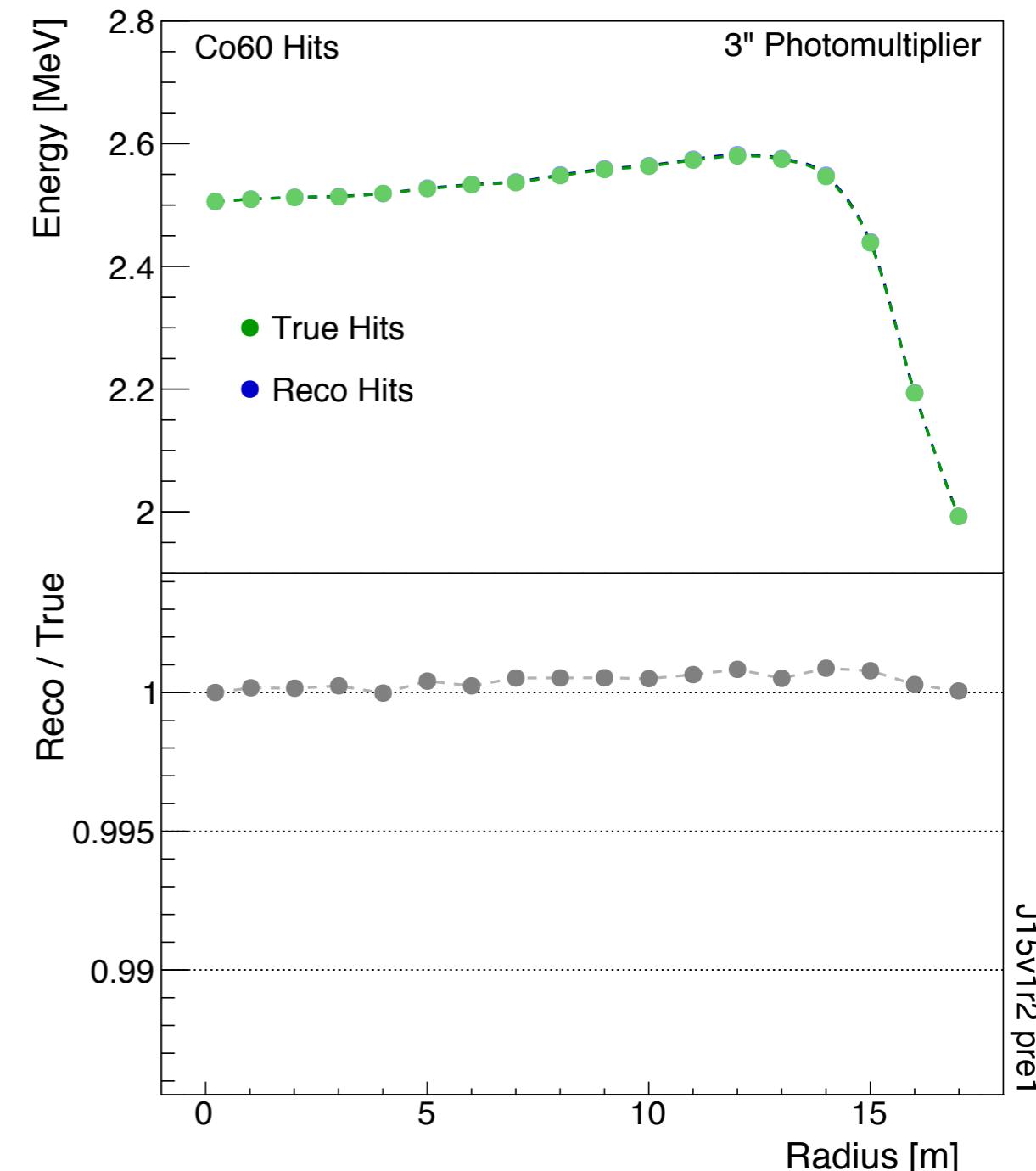
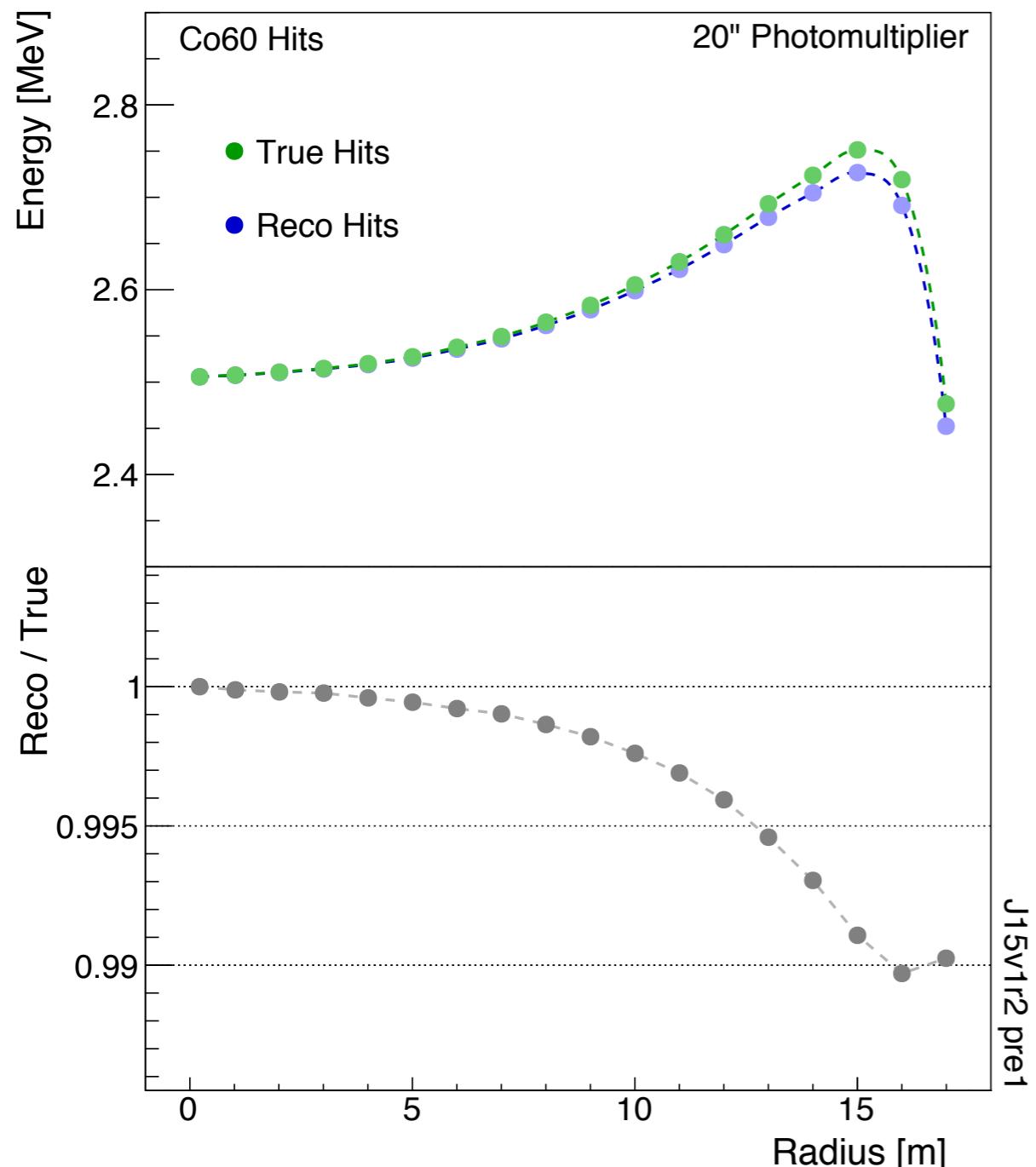
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data: how do we measure it?

(effect wrt MC-truth \rightarrow not reality)

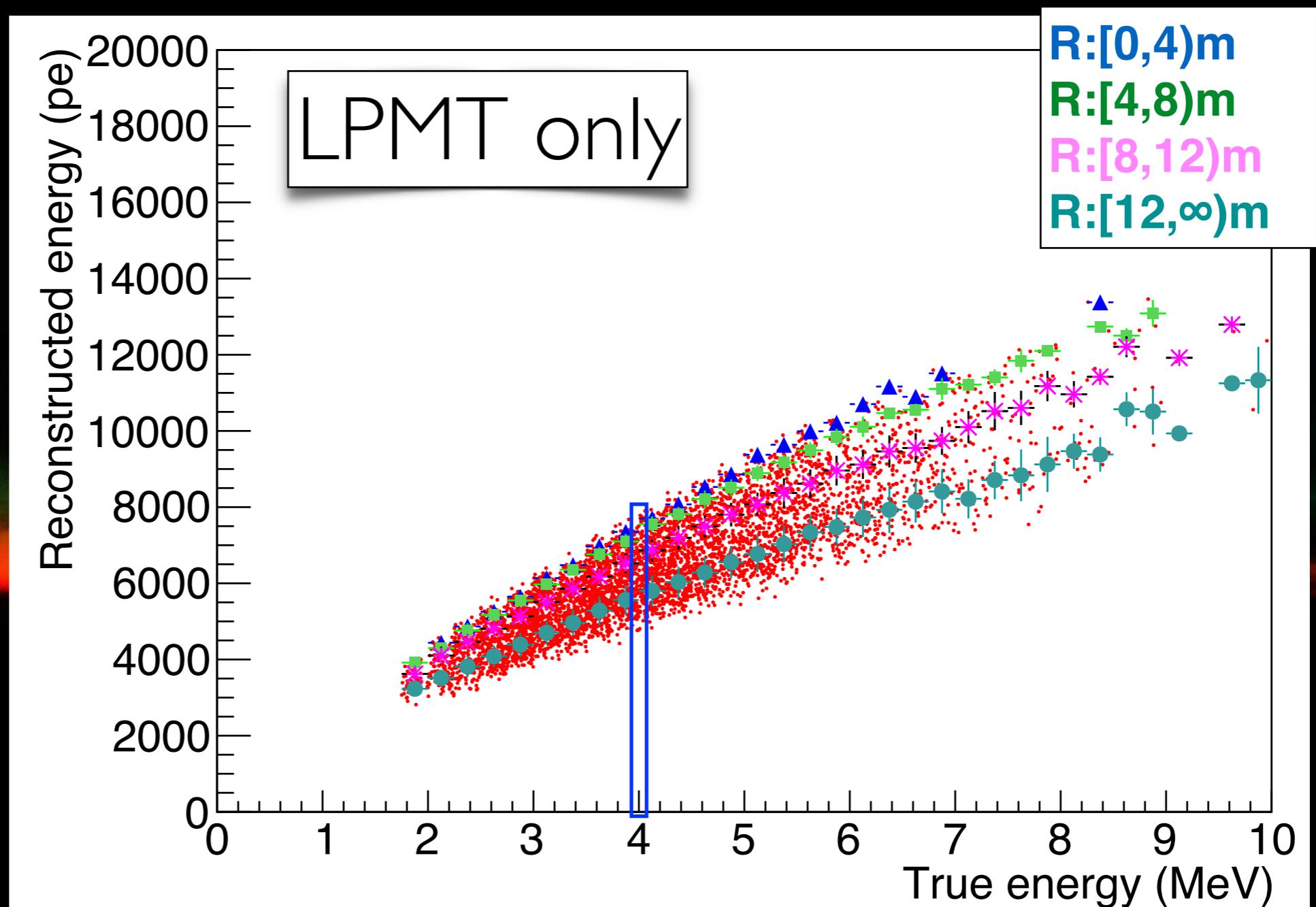
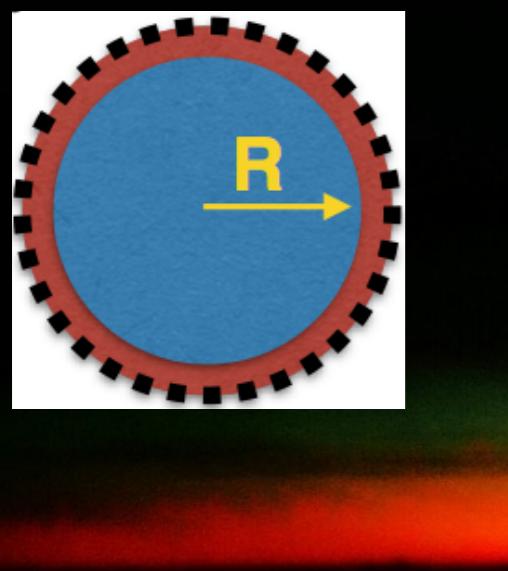
scrutinise the LPMT vs SPMT (no reco needed) bias...



S-PMT excellent performance (photon-counting)

⇒ tune MC (precious → single detector)
⇒ cross-calibrate LPMTs? (i.e. bypass MC?)

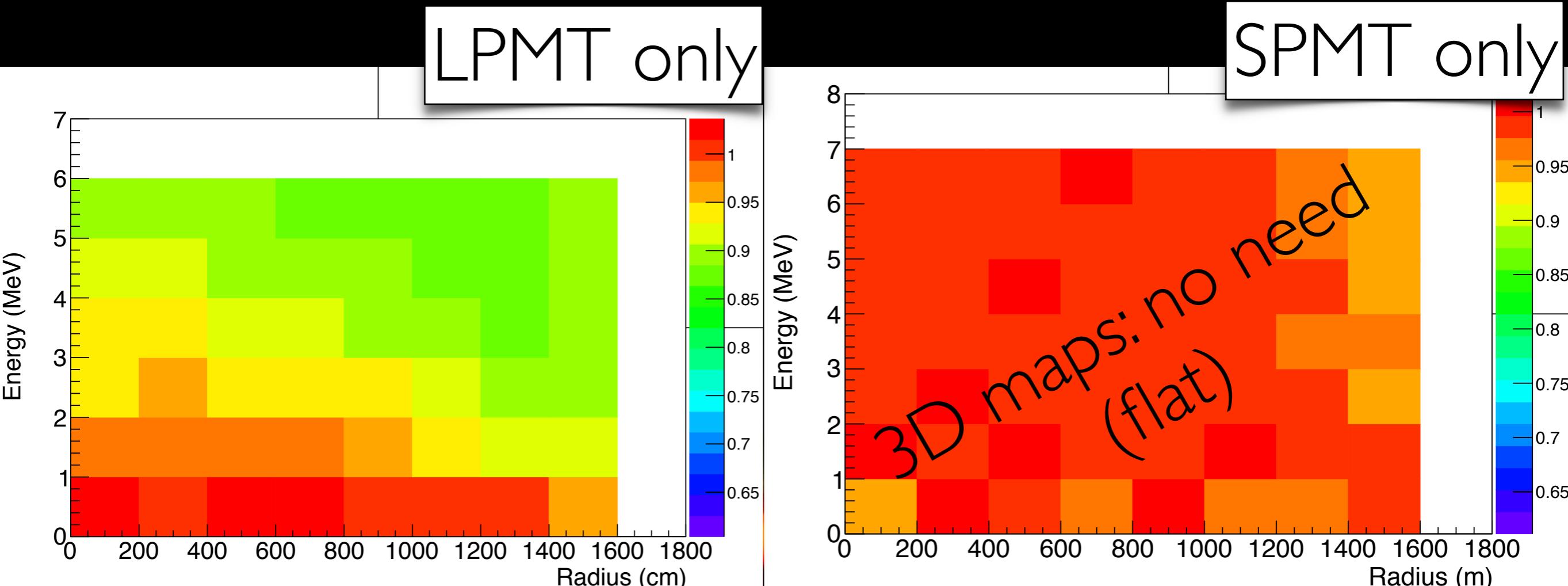
²⁹ (consequence) linearity \oplus uniformity correlation...



consider calibration source @ 4MeV \Rightarrow large variations in response when sweeping R

(consequence) **impossible construction of 2D maps position vs response (@ constant energy)**
(like DC/DB/KamLAND,etc)

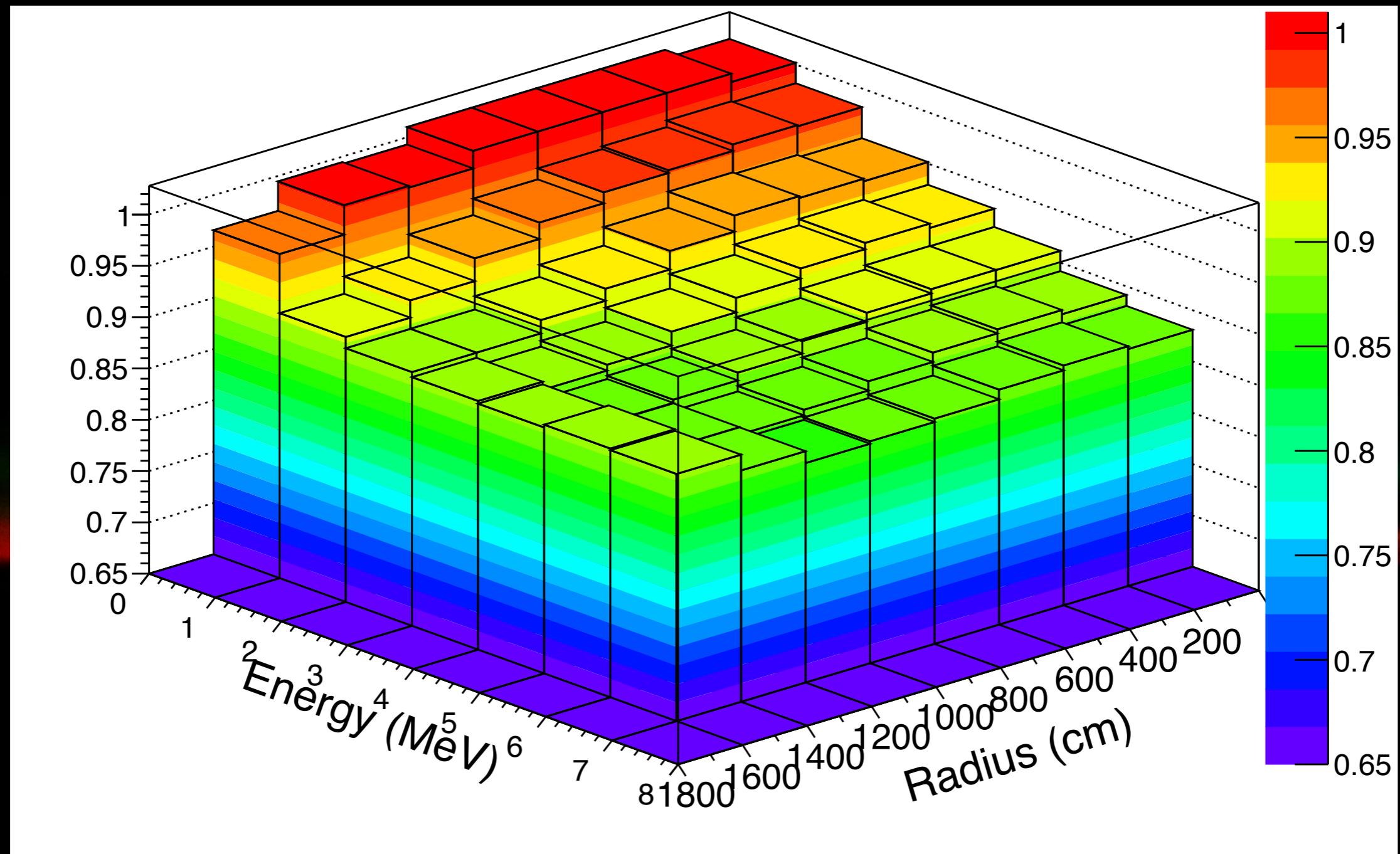
linearity \oplus uniformity crosstalk handling...



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

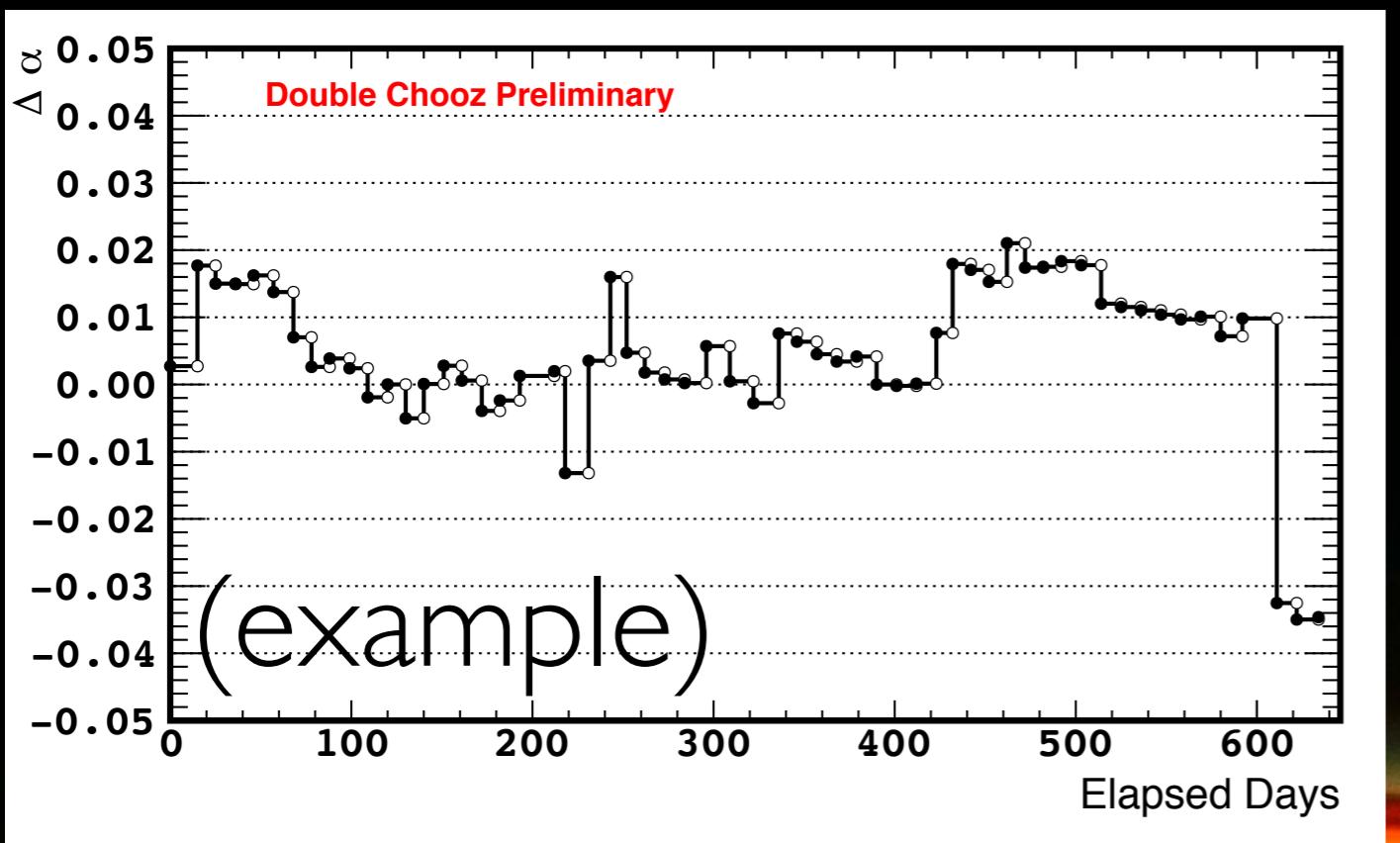
SPMT: uniformity map & linearity \Rightarrow (independent) 3D-map validation
 (simpler, complementary & robust \rightarrow unique, if SPMT)

(illustration) LPMT 3D calibration maps...

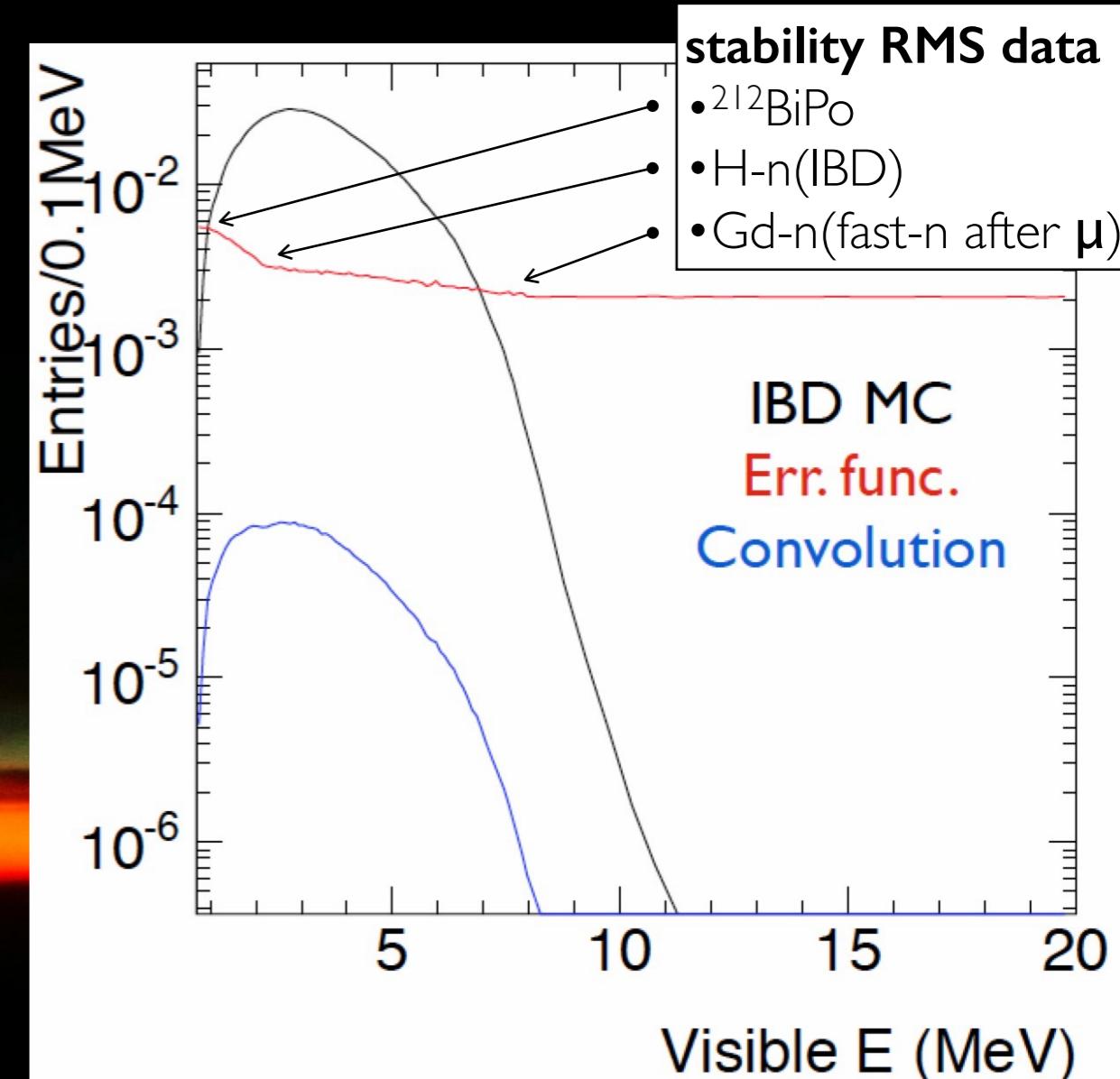


LPMT 3D map (easy to say), but **which source?**

(worse) QI leads to linearity⊕stability crosstalk...



zero stability correction
(DC @ 2.2MeV H-n)



QI zeroes $\alpha E \Rightarrow$ leads to linearity⊕stability

QI causes uniformity⊕linearity⊕stability

JUNO+ response summary...

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

JUNO+ response summary...

LPMT: uniformity • linearity • stability $\neq 0$

(i.e. not orthogonal bias/systematics)



JUNO+ response summary...

LPMT: uniformity • linearity • stability $\neq 0$

(i.e. not orthogonal bias/systematics)



SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

JUNO+ response summary...

LPMT: uniformity • linearity • stability $\neq 0$

(i.e. not orthogonal bias/systematics)



vs



SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

JUNO+ response summary...

LPMT: uniformity • linearity • stability $\neq 0$

(i.e. not orthogonal bias/systematics)



vs



SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

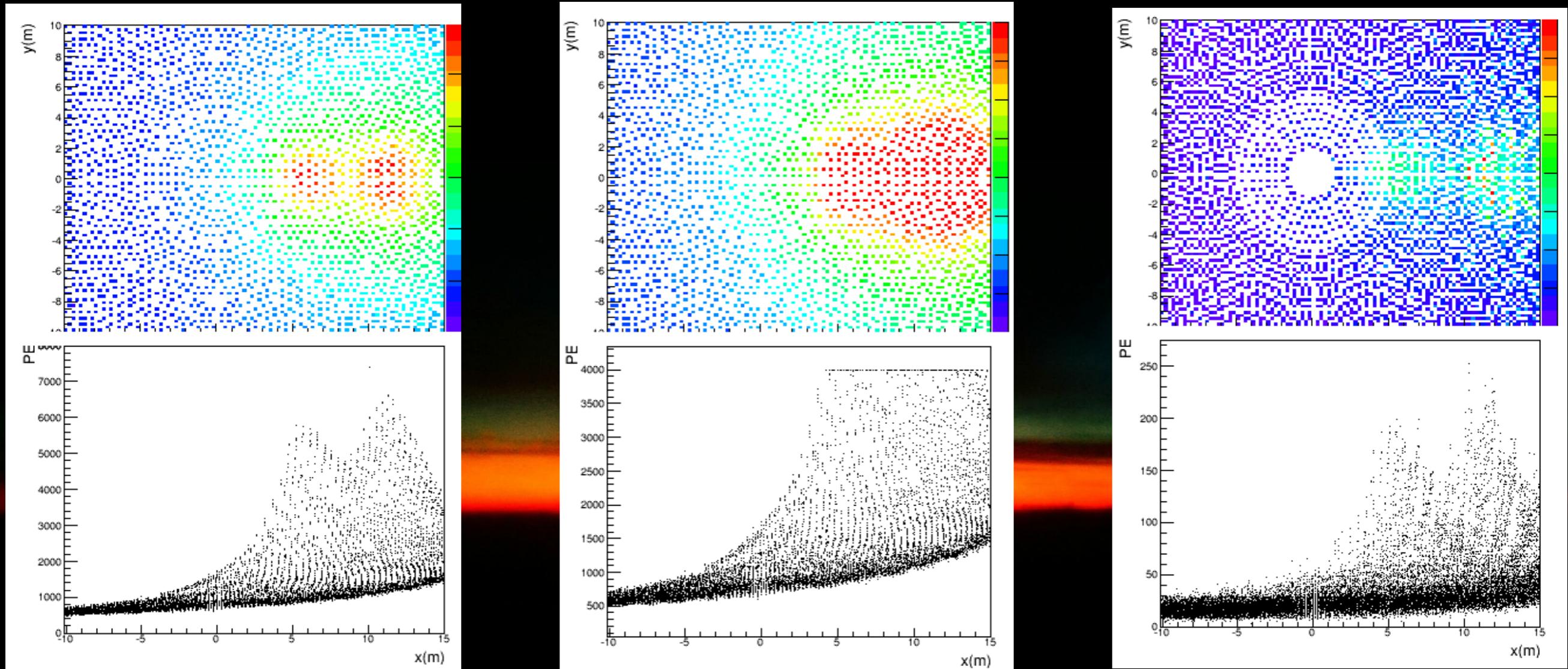
(much power when combining)

higher precision μ -reco...



(i.e. cosmogenic BG tracing)

improving 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)



Mr Confucius may say....

“equilibrium is about both”
(small⊕big)

our (very international) team...

>10 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)

merci...
thanks...
感谢您...

Italie

- Padova-INFN (Padova)

A few more institutions joining...

though questions. . .

Energy(PC) & Energy (CI) are complementary...

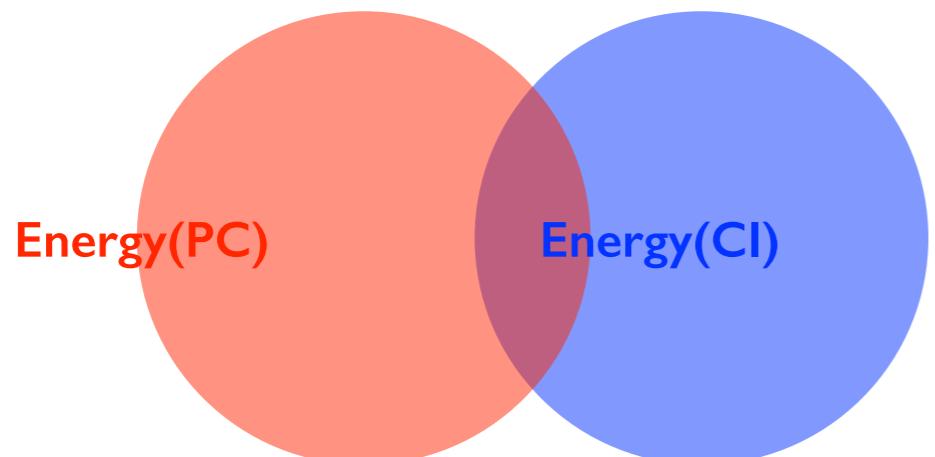
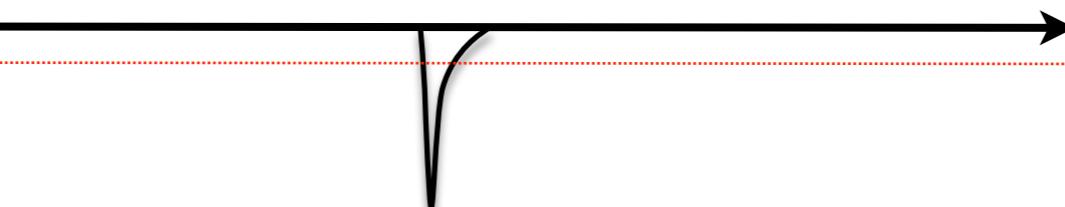
$\sim 1.2 \text{kPE/MeV}$ [$\sim 80\%$ coverage]

(stochastic $\rightarrow \sim 3\%/\sqrt{E}$)



$\sim 100^*\text{PE/MeV}$ [$\sim 10^*$ coverage]

(stochastic $\rightarrow \geq 10\%/\sqrt{E}$)



- **correlated info** (intersect)
- **uncorrelated info** (\rightarrow independent info!!)
➡ how much of each? (ongoing studies)

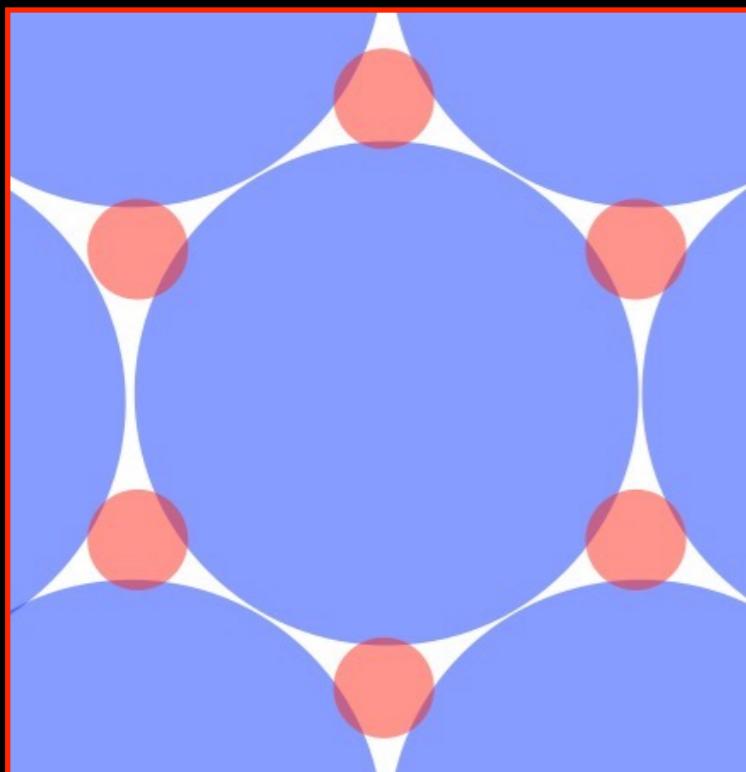
(even more important) **even some correlation exist, systematics budget is (very) different...**

$$\mathbf{JUNO^{\text{multi-calo}}} = \mathbf{JUNO^{\text{single-calo}}(\text{now})} + \mathbf{\text{extra PMTs}}$$

[design perturbation \rightarrow unique extra energy + position + reco + systematics info]

no performance loss (much gain) for small extra cost (optimisable)

μ -reco's "bread & butter" ...



(1st order) **μ -reconstruction reduces to entry/exit point finding**

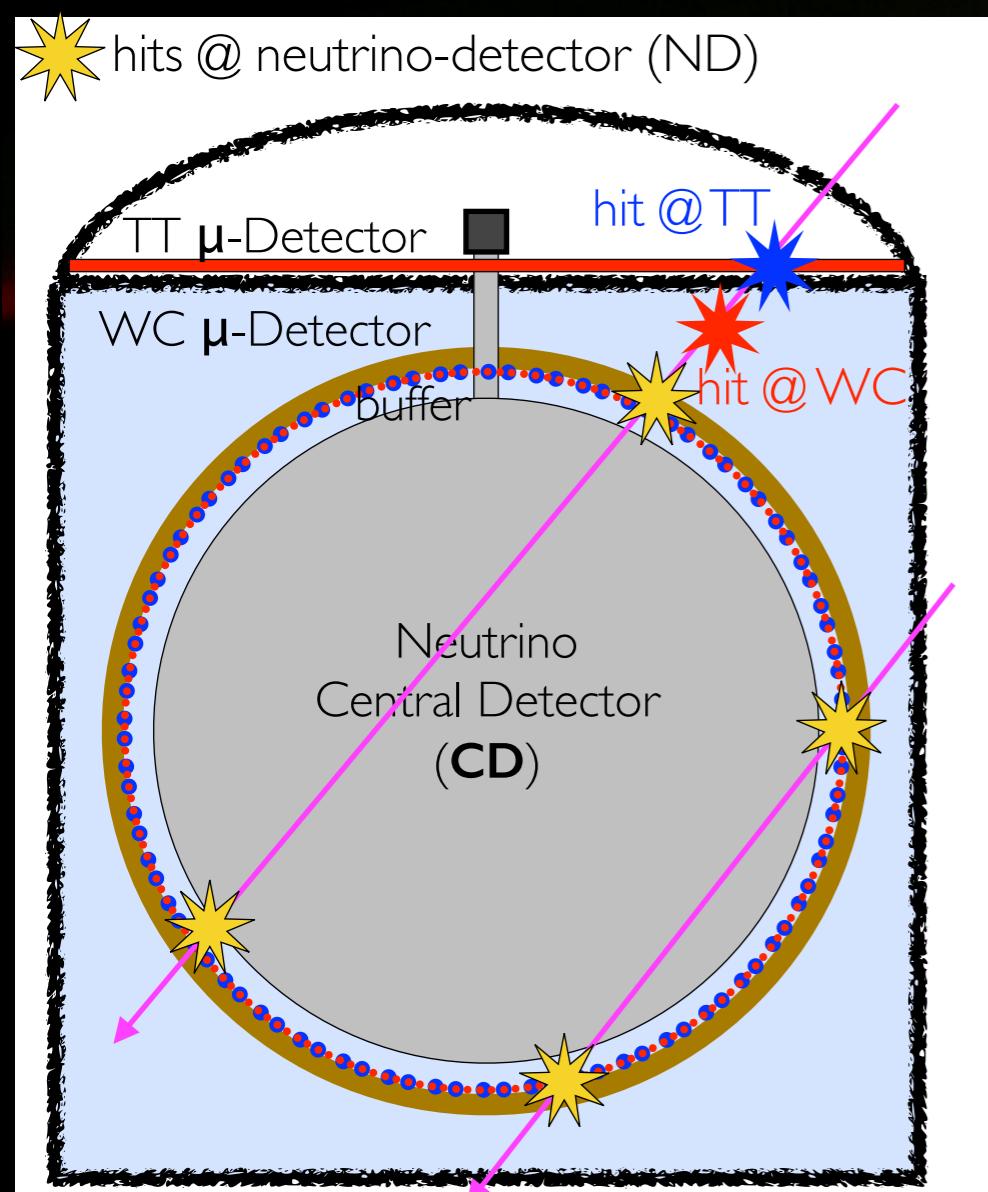
- **tracks:** a linear extrapolation (modulo scattering)
 - light along track-length time profile (useful \rightarrow 2nd order)
- **most important is CD** (entry/exit points @ 4π acceptance)
 - \Rightarrow aided by WC and TT (if possible, even better)

• **μ -tracking why? critical spallation $^{12}\text{B}/^9\text{Li}/^8\text{He}$ tagging**

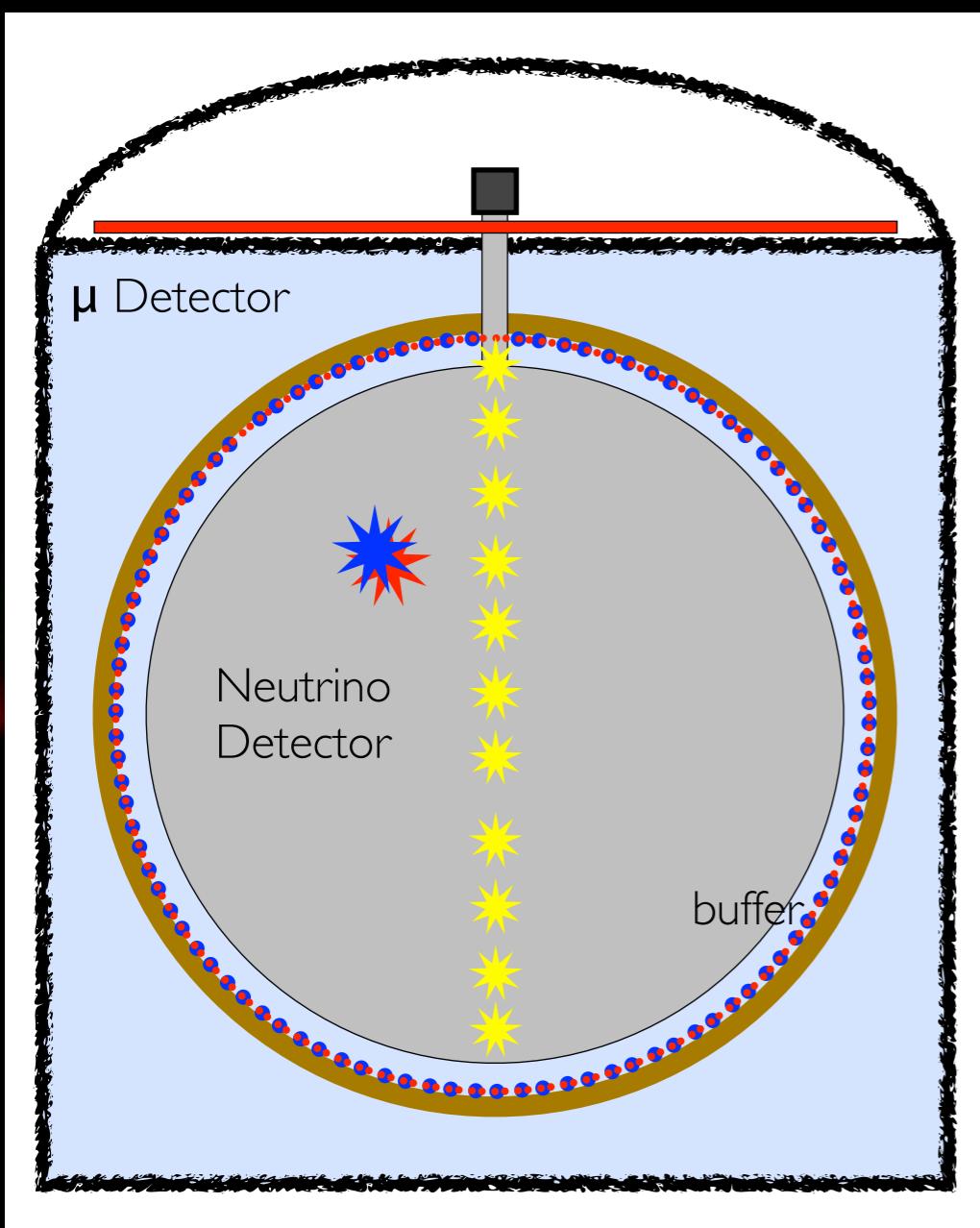
- **rejection** (event-wise tag) [a la DC and DB]
- **veto** (cylinder veto along μ 's) [a la Bx and KamLAND]
- **improvement in μ -tracking vital to JUNO (~90/day $^9\text{Li}/^8\text{He}$)**

back to basic @ JUNO...

- >80% **μ s through an LPMT** \rightarrow high granulation and huge coverage
 - resolution is due timing of LPMT (likely saturation)
- **SPMT interpolate within LPMT** dimensions (any case)
 - (PMT size) $\sigma(\text{space})^{\text{LPMT}} \approx 45 \times \sigma(\text{space})^{\text{SPMT}}$
 - (timing) $\sigma(\text{time})^{\text{LPMT}} \approx 10 \times \sigma(\text{time})^{\text{SPMT}}$
 - **6x SPMT per LPMT** \rightarrow **great (high precision) triangulation**
 - (besides) SPMT likely not saturated (unlike LPMT)
- expectation (simple): **SPMT FAR better than LPMT \rightarrow true?**

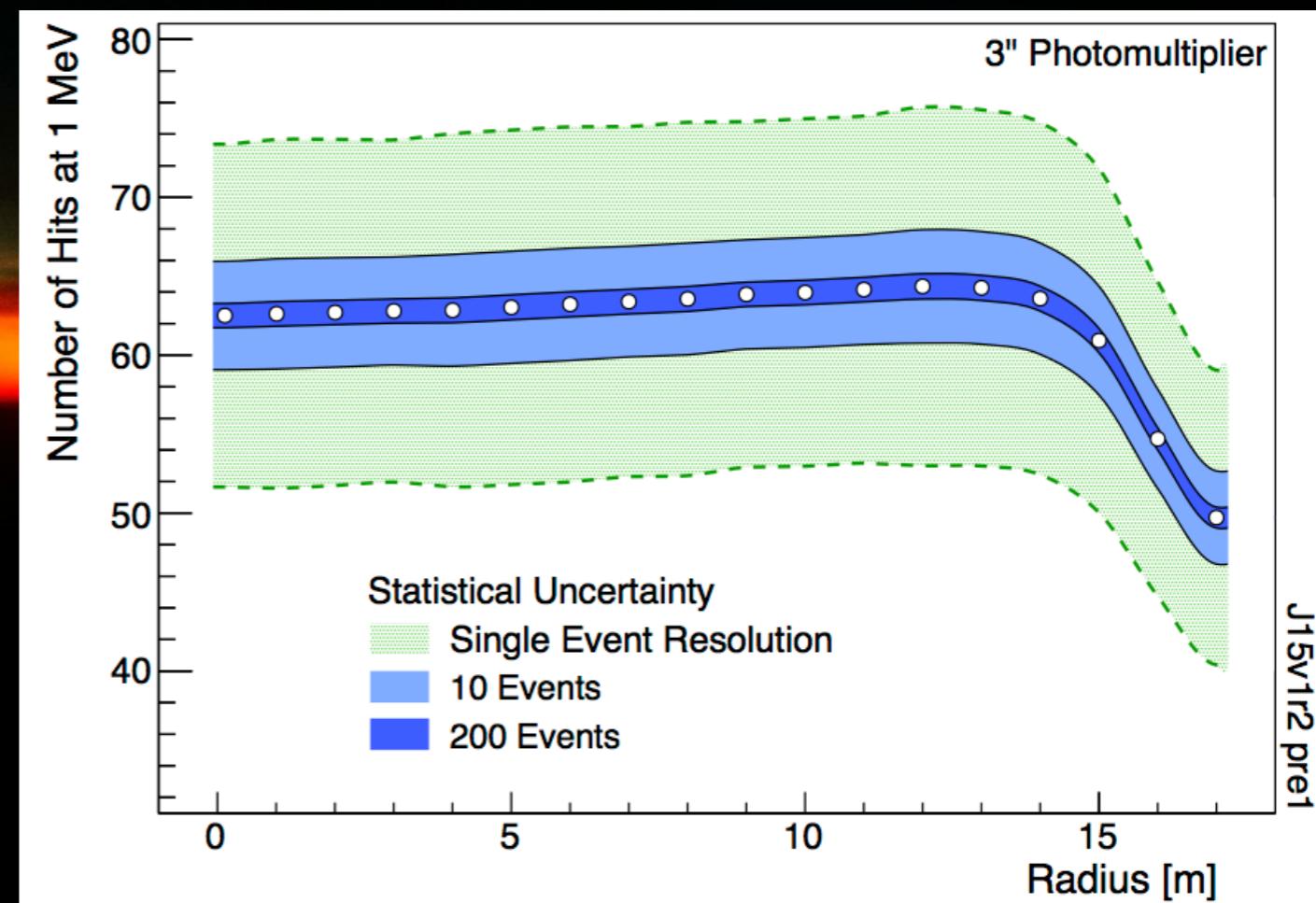


SPMT & LPMT binding @ during calibration...



SPMT has limited statistical information event-wise (wrt LPMT)
(optimisable → keep light-level low to ensure PC)

SPMT has “∞” statistical power using calibration ($\rightarrow 1/\sqrt{N}$)
 (high precision correlation & combination of SPMT+LPMT)



(in preparation but not yet) exploring SPMT+LPMT event-wise via ANN
 ⇒ better combined energy & position estimator?

Energy(PC) vs Energy (CI): conceptually...

- Photon-Counting...

- discrete phenomenon (PE detection)
 - Binomial statistics ("PE^{digital} scale" definition)
- intrinsically non-linear (\rightarrow log) but known!!
- robust to fluctuations
 - large -ve fluctuation \rightarrow zeroes (threshold!!)
 - large fluctuation: multi-PE?

- readout configuration...

- **ideal PMT:** best single-PE separation
 - large P/V (unlikely with large PMTs)
- **electronics:** no need for FADC
 - timestamp: excellent time resolution
 - charge: multi-PE occurrence control
 - low noise (\rightarrow better ID of sPE pulse)
 - trackable dead-time (low, of course)
- (random trigger) small buffering

- Charge Integration...

- continuum phenomenon (pulse reco)
 - Gaussian statistics (arbitrary charge)
 - "gain calibration" \rightarrow "PE^{analogue} scale" definition
- susceptible to non-linearity (even small)
 - intrinsically linear
 - control of small effect (high precision)
- readout configuration...

- **ideal PMT:** less demanding requirements

- not a big issue, we think

- **electronics:** FADC

- 500MHz likely enough for sPE sampling
- \geq 8bit dynamic range (12~14 bits)
- up to \sim 500ns readout window
- no dead-time (\rightarrow rather standard)
- (random trigger) huge buffering

(people wonder) **which is better? \rightarrow neither!**

44 • SPMT vs LPMT: what we gain?

- SPMT and LPMT are different from photocathode: QE, CE, gain, zeroes, linearities, etc
 - **relative** (\rightarrow cancel common effects) & **absolute effect** (\rightarrow comparison & validation)
- **redundancy & validation** via **detector response calibration** [\rightarrow later on]
 - **unique insight** \rightarrow disentangle LPMT-reco & readout bias effects using SPMT readout
 - **unique** (double) **handle into MC tuning** (critical for single-detector physics)
- (some) **event-wise complementary information** \rightarrow further precision in energy and position
- **possible bias in SPMT** (PC dominated)...
 - **multi-PE contribution** (\rightarrow electronics must have charge information to alleviate)
 - ...and more (impossible to cover them all \rightarrow HW readout not decided)
- **possible bias in LPMT** (QI dominated even 1MeV)...
 - **QI pulse reconstruction** (bias, missing PE's due to fluctuation, baseline effects, overshoot, etc)
 - leakage of PE's from FADC readout window (different fractions)
 - **gain bias @ low charges:** single-PE bias (most dangerous \rightarrow IBD data impact)
 - **gain bias @ high charges:** non-linearity, saturation, etc (less dangerous if $> 10\text{MeV}$)
 - ...and more (impossible to cover them all \rightarrow HW readout not decided yet)
- (next) **one example** to illustrate interplay SPMT \oplus LPMT complementary (MC & even DATA validation)
 - note **numbers are NOT final** (but guideline references) \rightarrow reality likely worse (other effects)

natural dynamic range extension...

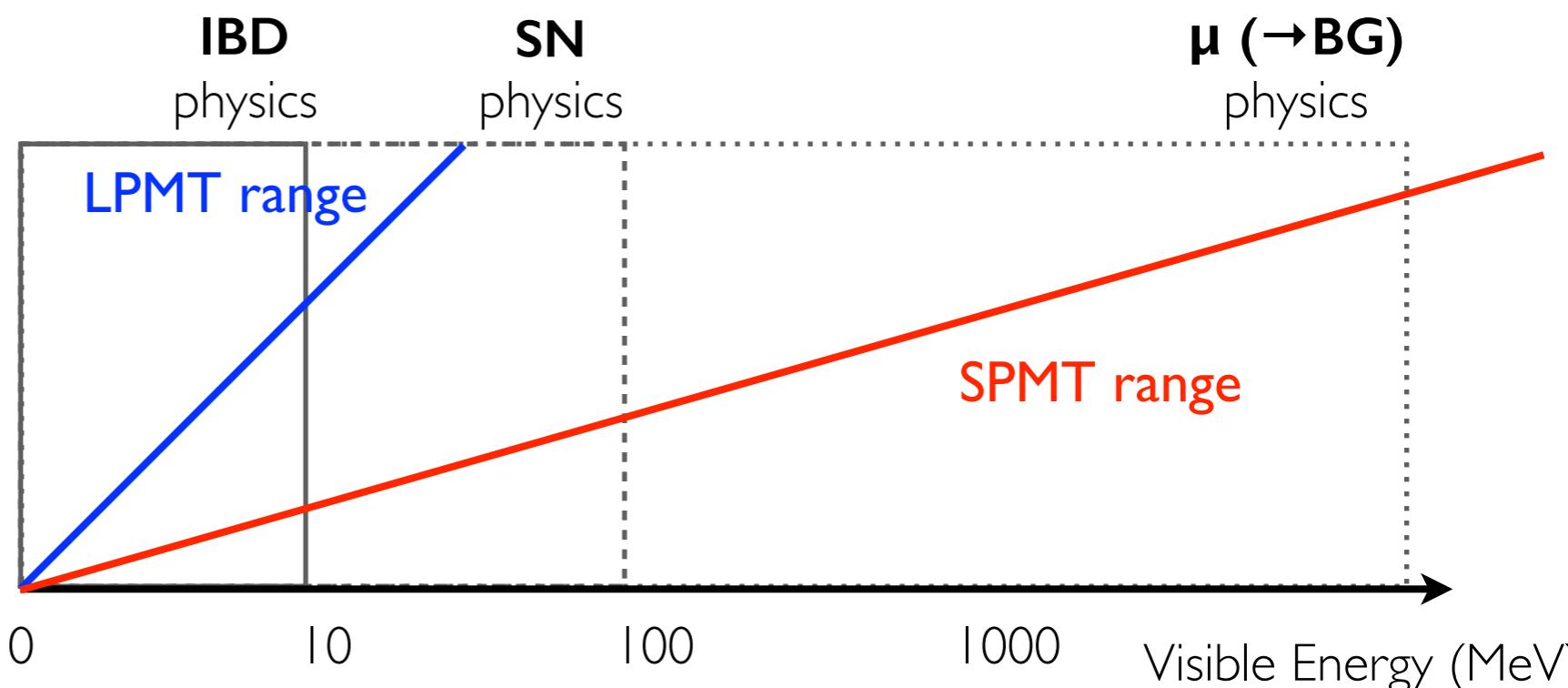
SPMT: full dynamic range (up to μ 's)

⇒ **natural dynamic range extension**

- stochastic resolution [10,13]%
- **SPMT resolution $\lesssim 4\% @ 10\text{MeV}$**

LPMT focus on IBD & SN physics

- **on high energy resolution**
- **maximise FADC sensitivity**
- stochastic resolution: **a~3%**



- **SPMT is MUCH lighter than LPMT** ⇒ major simplification (cheaper) of Electronics/DAQ

muons deposition (cartoon)... **FADC saturated data is less useful, but still very heavy!**

