Physics with the 3-inch Photomultiplier System of the JUNO Experiment

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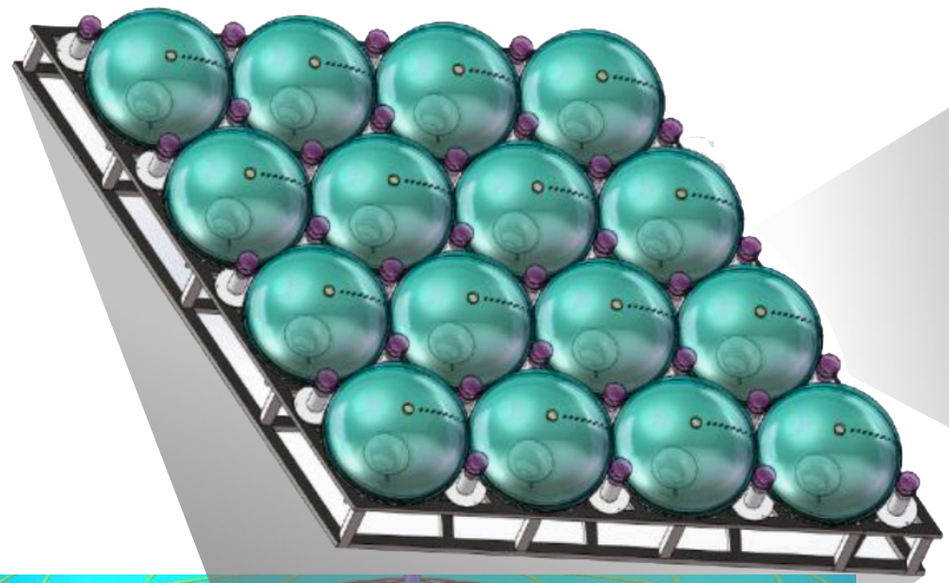
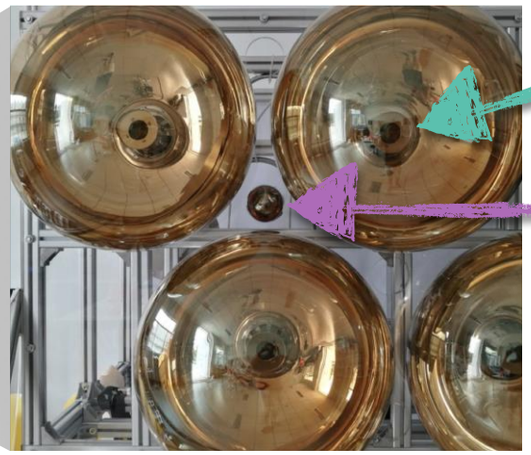
Quick Introduction of 3-inch PMT System

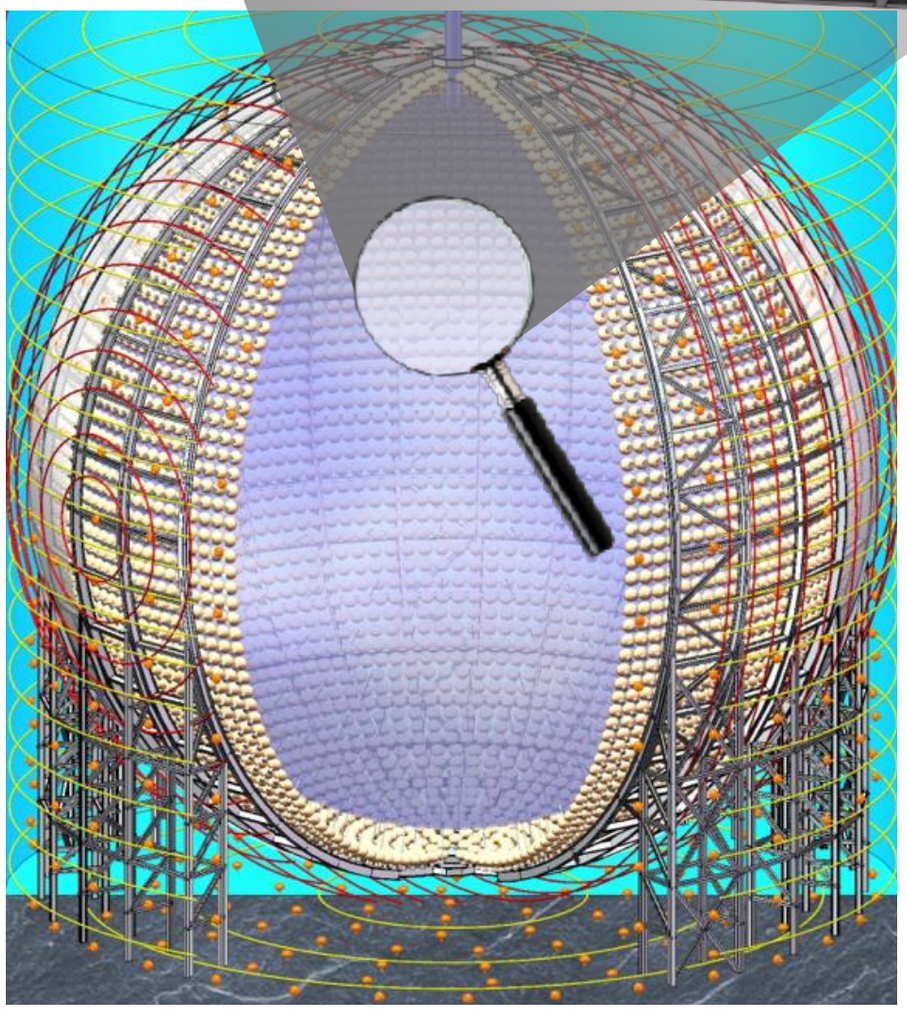




Large 20-inch PMT

Small 3-inch PMT

SPMTs covered by N.Li



Key features of SPMT system:

- 25k 3-inch ‘small’ PMTs
- Working in photon-counting mode for E∈(1,10) MeV
- Energy resolution ~17%@1 MeV
- Time resolution (FWHM) ~5 ns
- Data acquisition without dead time

Overview presented by C.Cerna

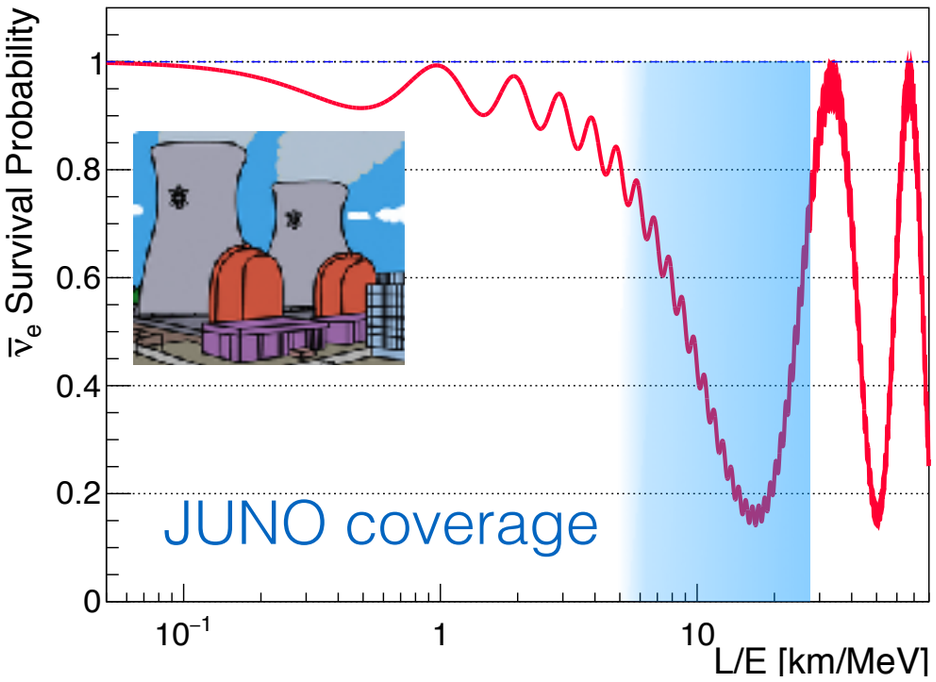
What Can SPMTs Do for JUNO?

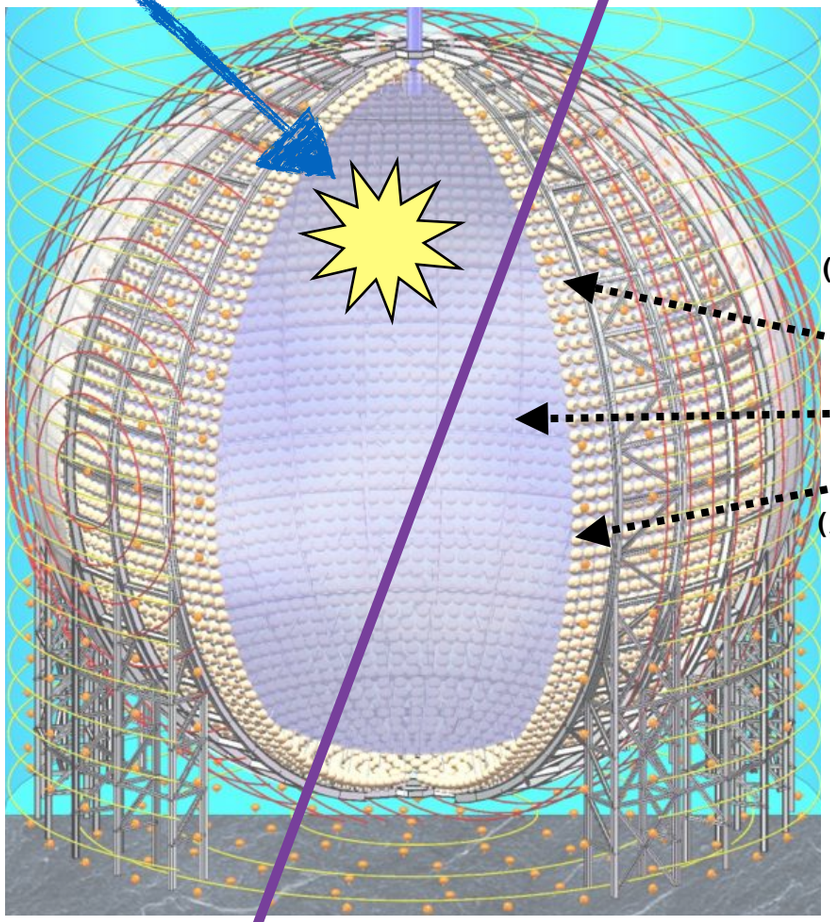
- System of 3-inch “small” PMTs (SPMTs) significantly improve JUNO physics capabilities in:

1. Energy response systematics control

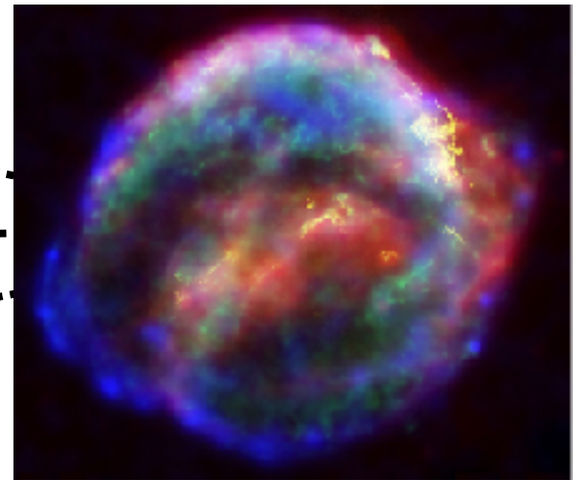
2. Muon track reconstruction

3. Cross-check of energy response with solar oscillation parameters





4. SN neutrinos

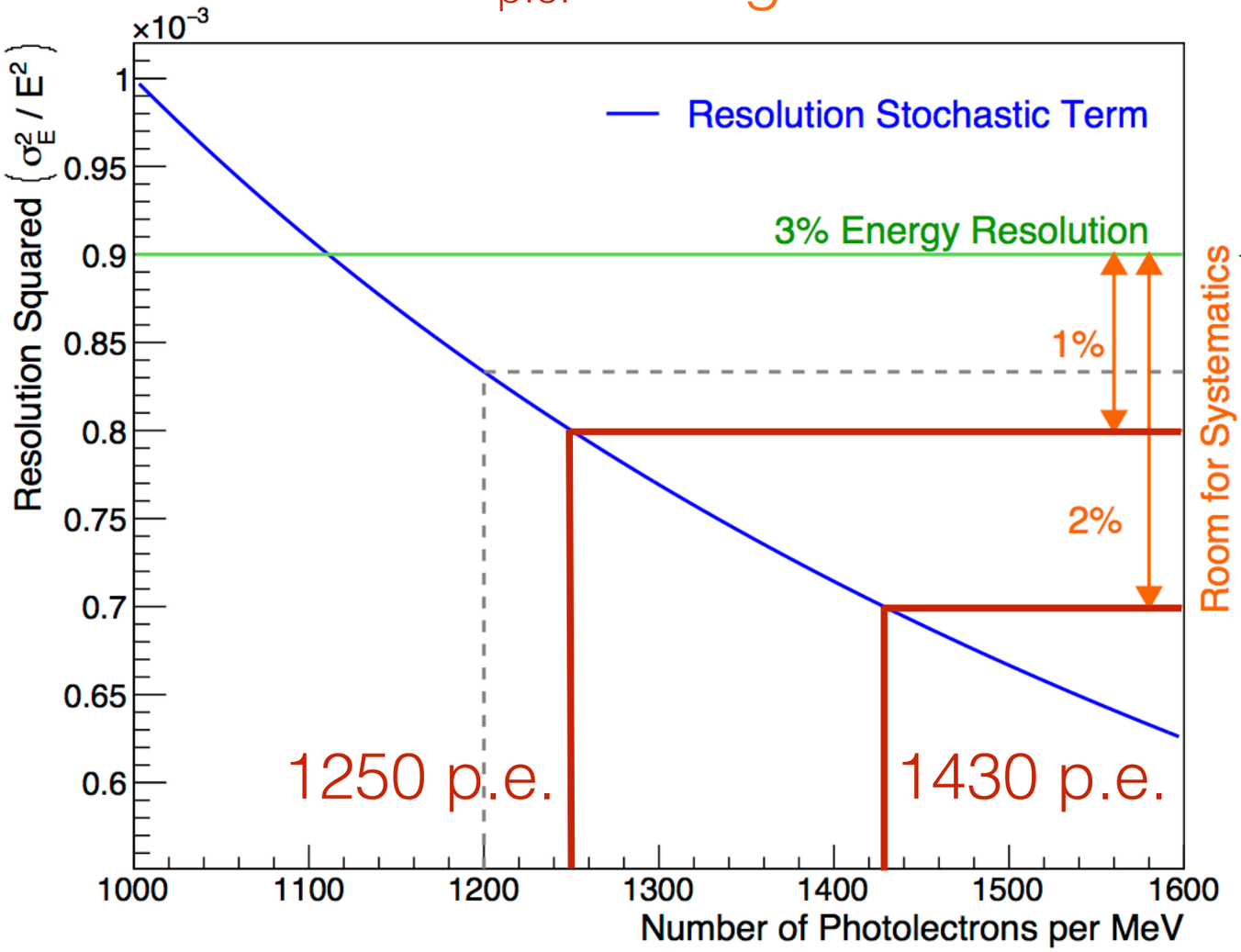


Energy Resolution @ JUNO

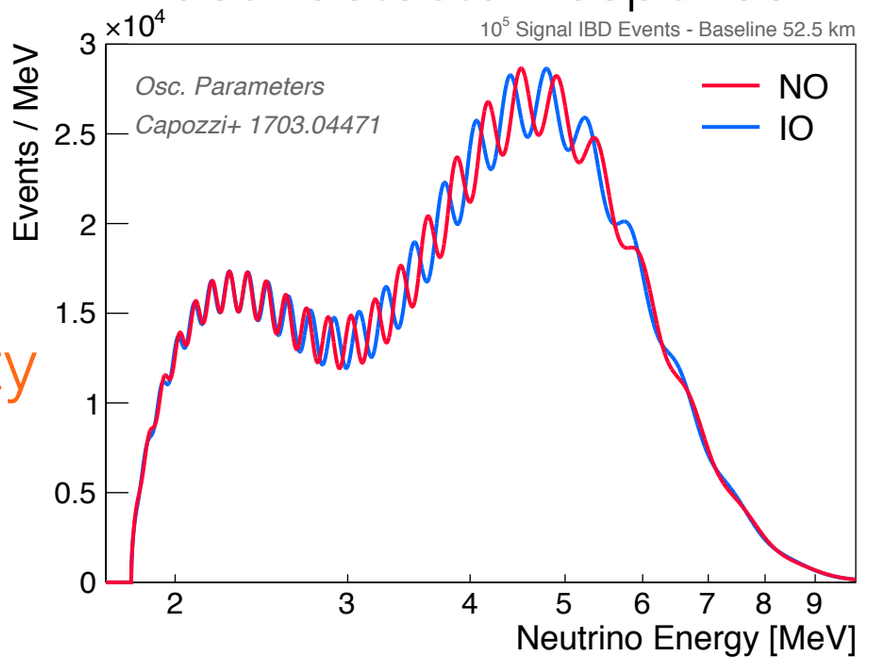
3%> $$\frac{\sigma_E}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + b^2 + \left(\frac{c}{E}\right)^2}$$

Stochastic term ~$N_{p.e.}$

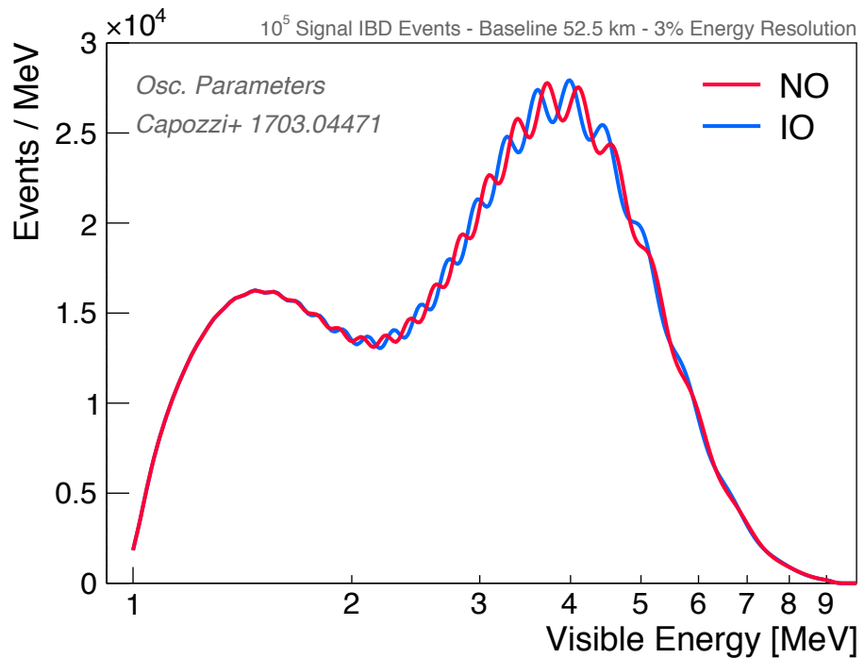
Non-stochastic terms e.g. residual non-uniformity



Ideal detector response



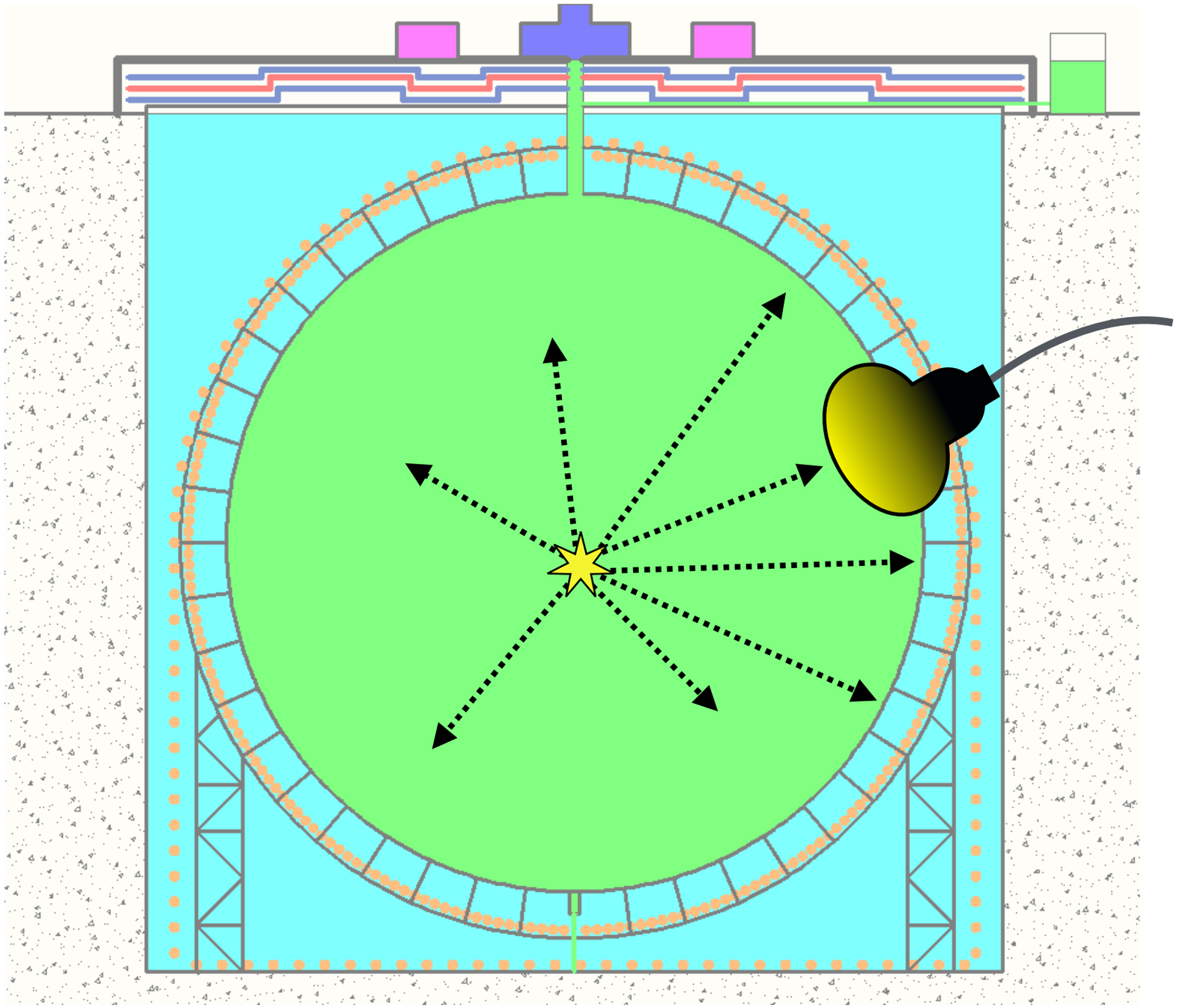
3%√E(MeV) energy resolution



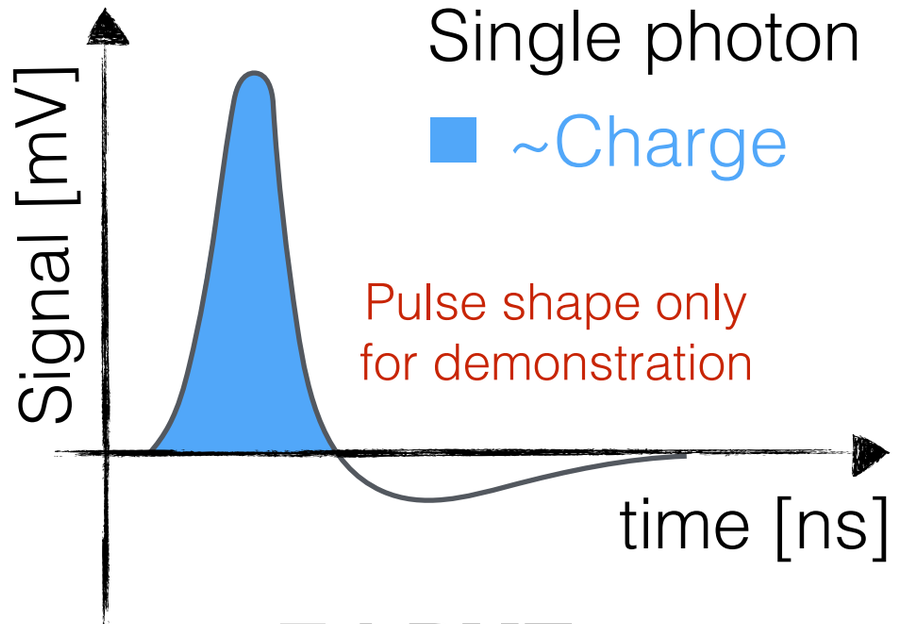
Measurement with Large PMTs Only

Single channel non-linearity → **Energy dependent detector non-uniformity** → **Energy response systematics**

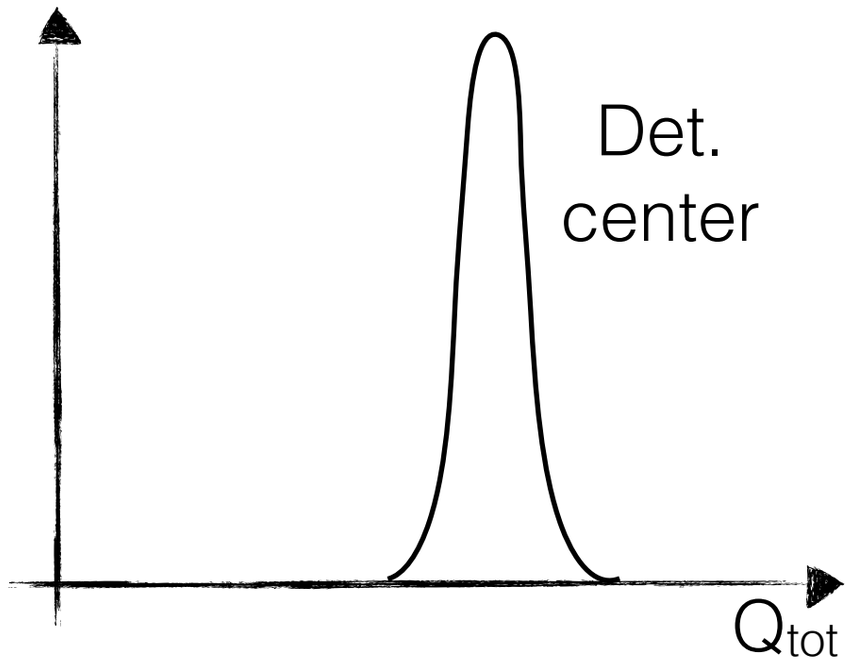
Non-linearity➔Non-uniformity



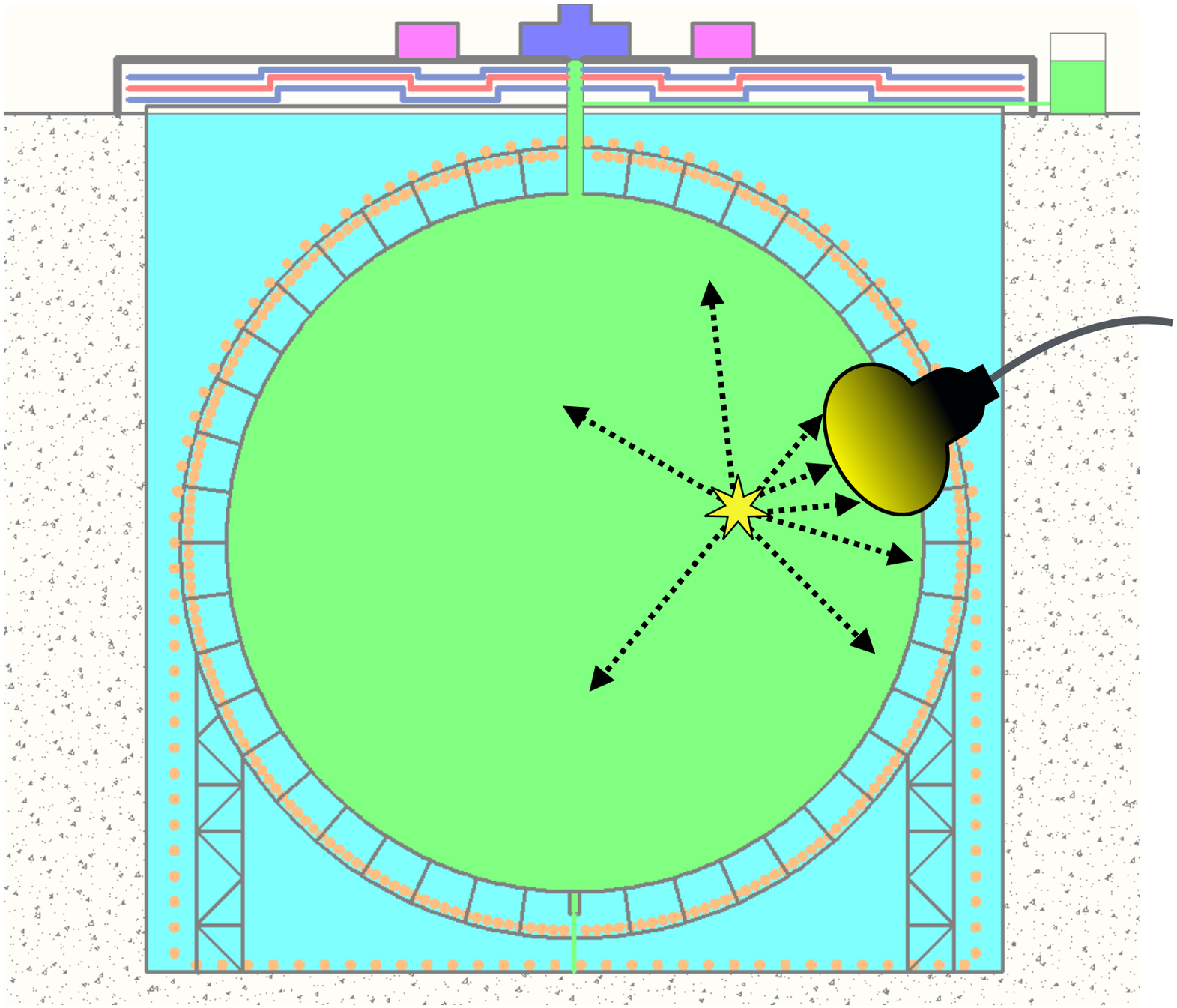
Single LPMT

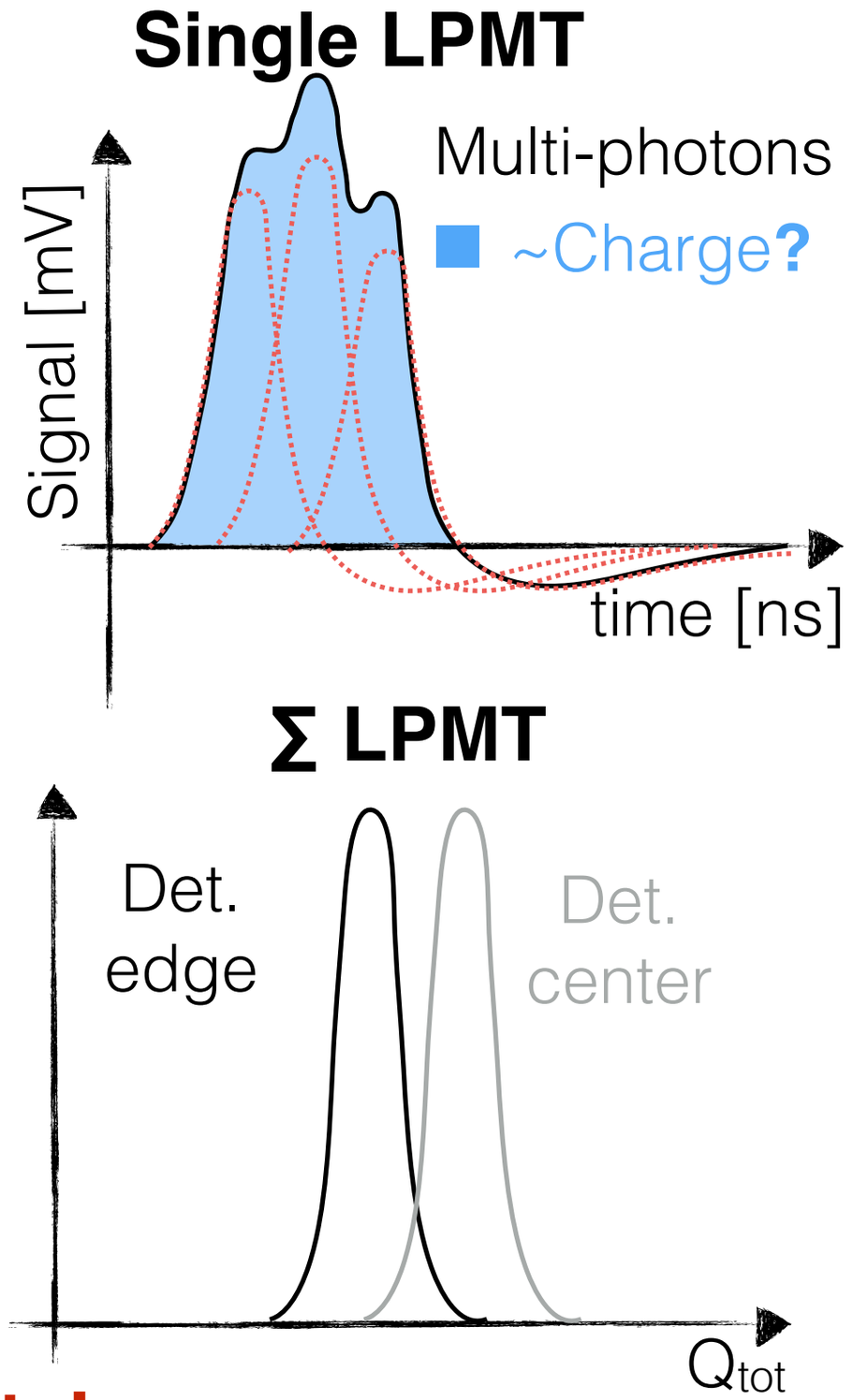


Σ LPMT



Non-linearity➔Non-uniformity

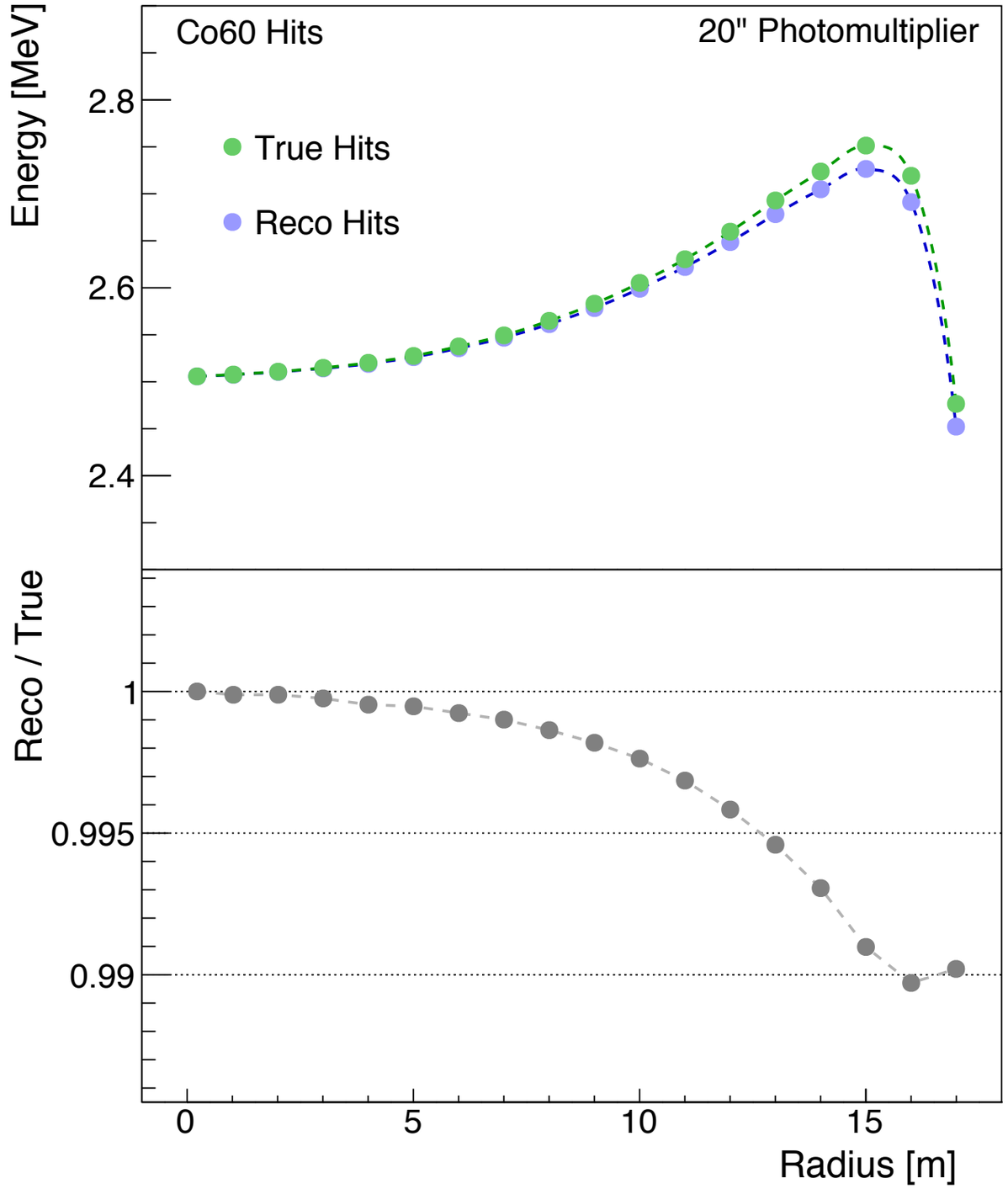




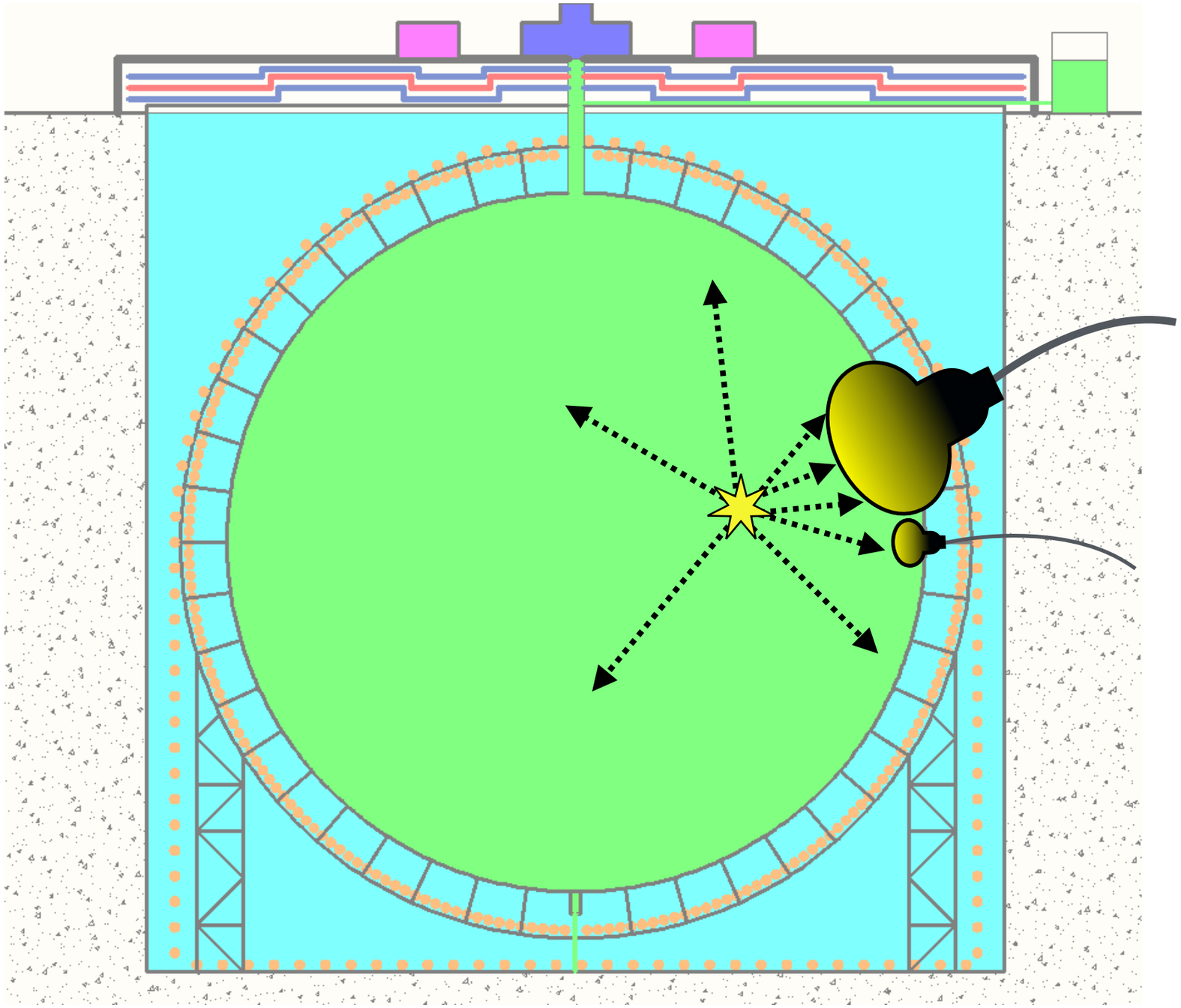
Spatial non-uniformity!

LPMT Energy Scale Non-uniformity

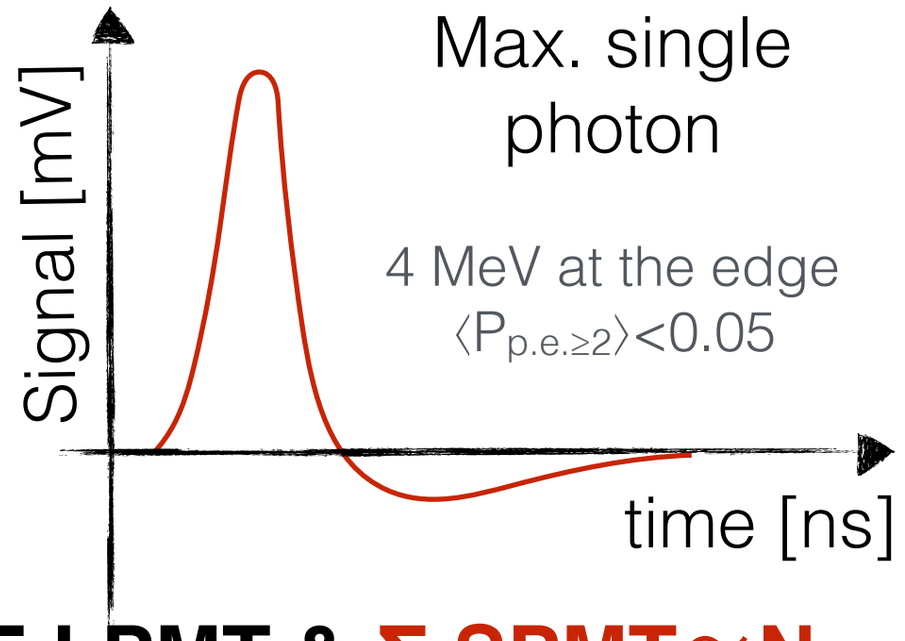
- Example of detector for ^{60}Co source ->1% non-uniformity
- Can correct using calibration source
- But.. energy dependant -> **Do not have source for all energies**
- Q: Is there a way how to control non-uniformity for all energies?
- **Yes - Introducing SPMT system**



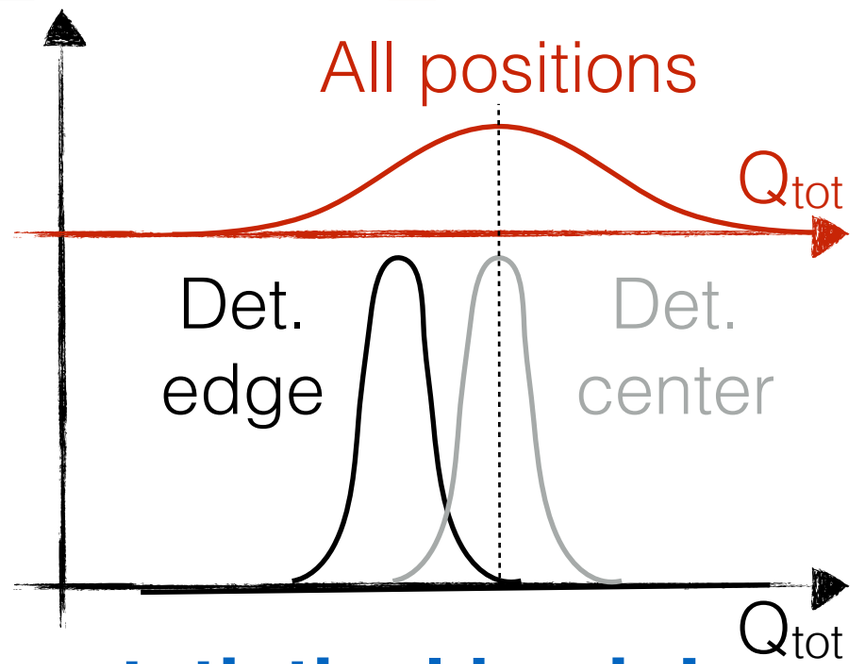
Aid by SPMTs



Small PMT



Σ LPMT & Σ SPMT ≃ N_{hits}



Non-uniformity can be corrected on a statistical basis!

Double-calorimetry

Details in talk by M.Grassi

Single channel non-linearity → **Energy dependent detector non-uniformity** → **Energy response systematics**

- Challenge to control LPMT energy reconstruction biases
  - May compromise superb JUNO energy resolution needed for MH determination
- SPMTs work as a non-biased energy scale gauge to correct LPMT energy scale non-linearity/non-uniformity

Advantage of having LPMT and SPMT eyes

SPMTs

SPMTs aid the LPMTs energy scale ✔

Cosmic-ray Muon Background

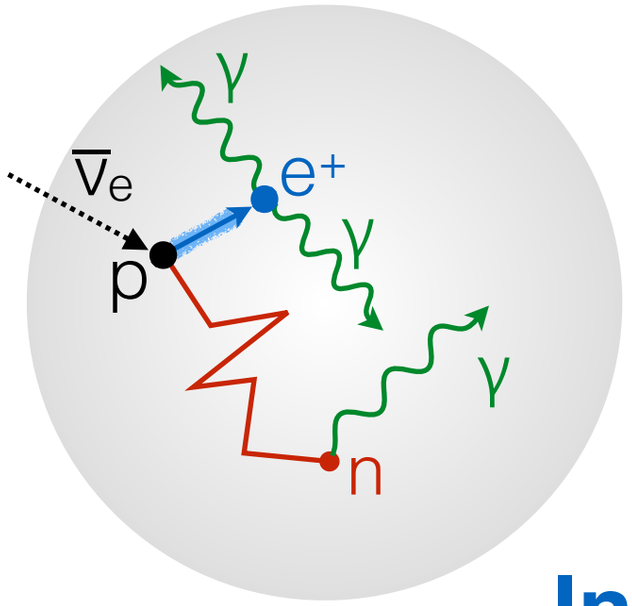
- Cosmic-ray muons are source of inverse beta decay (IBD) background
- Produce long-lived isotopes ^{9}Li (τ=257 ms) and ^{8}He (τ=172 ms) via spallation - their decays mimic IBD signature

Inverse Beta Decay:

Coincidence

prompt signal — delayed signal

$$\bar{\nu}_e + p \rightarrow e^+ + n$$

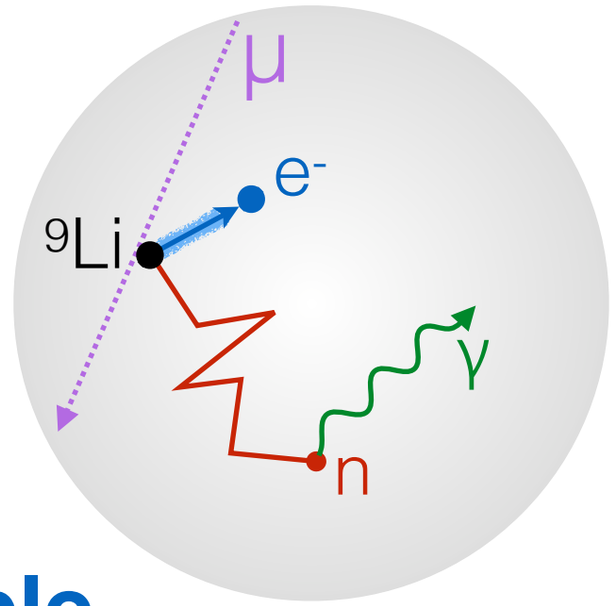


^{9}Li/^{8}He decay:

Coincidence

prompt signal — delayed signal

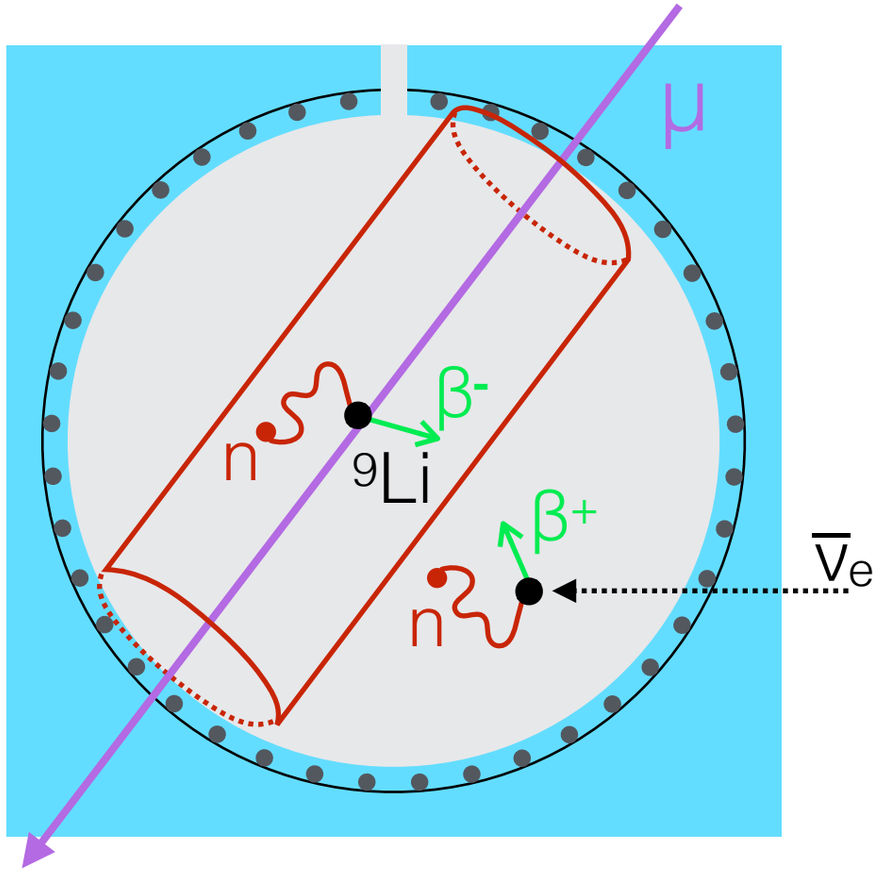
$$^{9}\mathrm{Li} \rightarrow ^{8}\mathrm{Be} + e^- + n$$



Indistinguishable

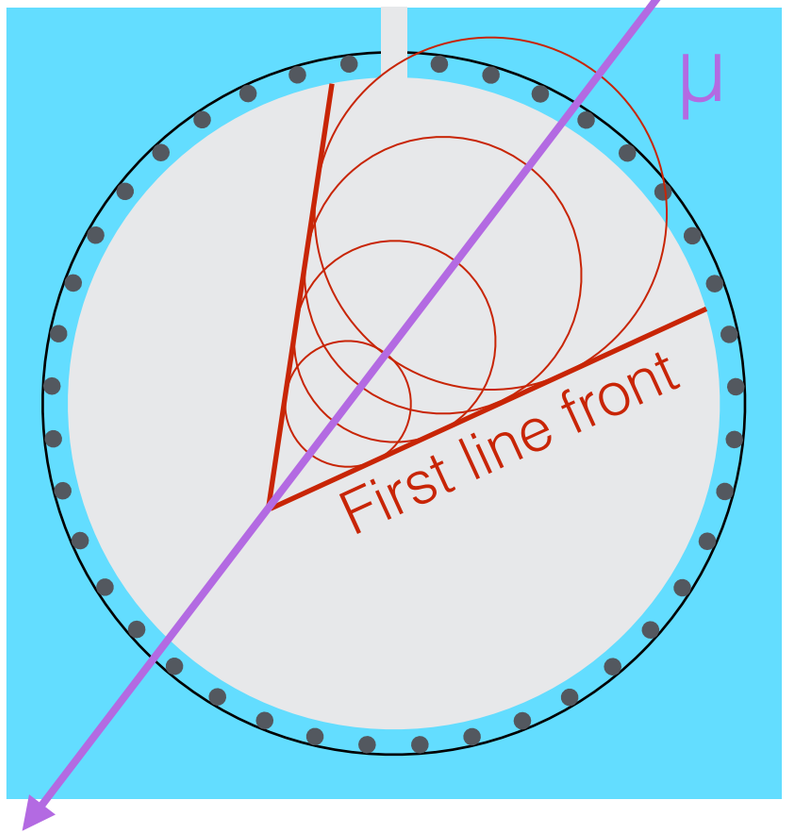
Cosmic-ray Muon Background

- Cosmic-ray muons are source of IBD background
- Produce long-lived isotopes ^{9}Li (τ=257 ms) and ^{8}He (τ=172 ms) via spallation - their decays mimic IBD signature
- Reduction of background -> Veto after muon
  - Cannot veto whole detector -> too much vetoed time
  - Solution: **Cylindrical veto volume around muon track**
- Currently two preliminary muon track reconstruction algorithms based on
  - **First hit time**
  - **Clusters in hit pattern**



First Hit Time Algorithm

- Likelihood fit to first hit time pattern
- Key variable - transit time spread (TTS)
  - 2/3 LPMTs: MCP-PMTs with TTS ~12 ns
  - 1/3 LPMTs: Hamamatsu PMTs (TTS ~3 ns)
  - **SPMTs: TTS ~5 ns**



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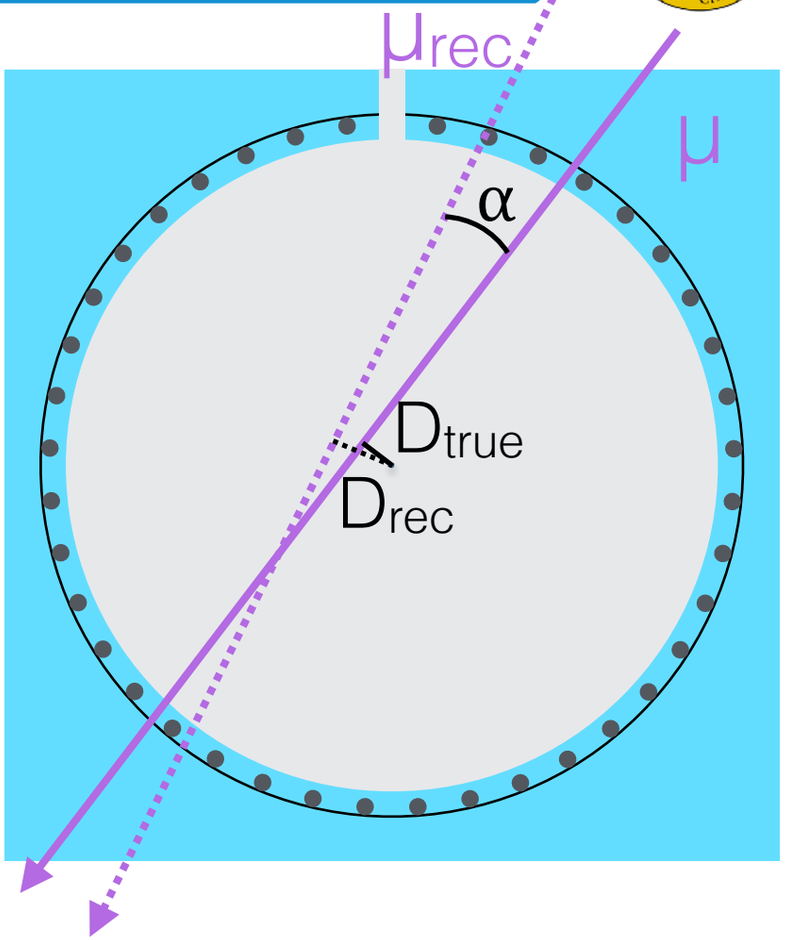
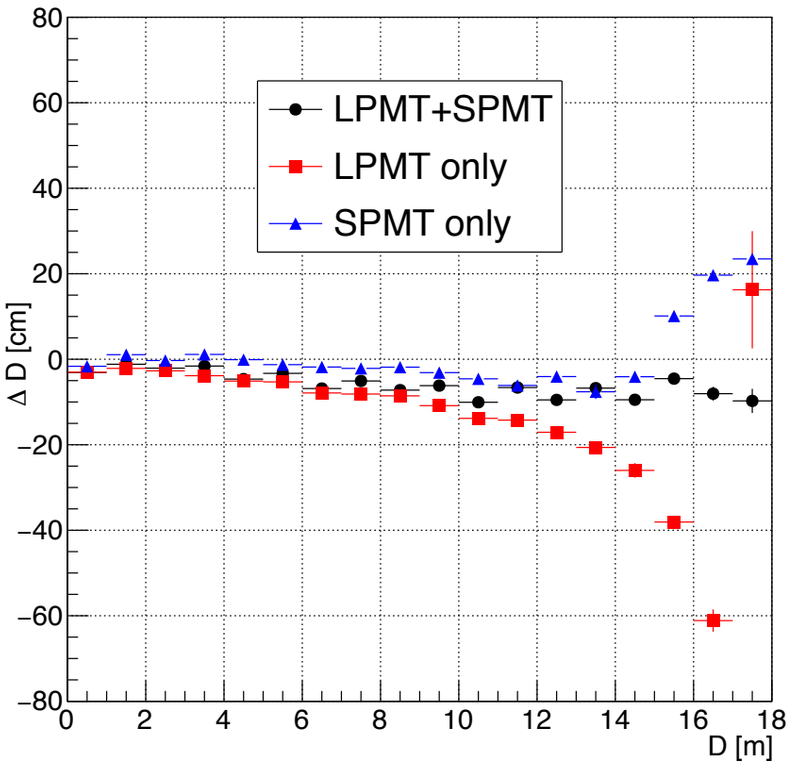
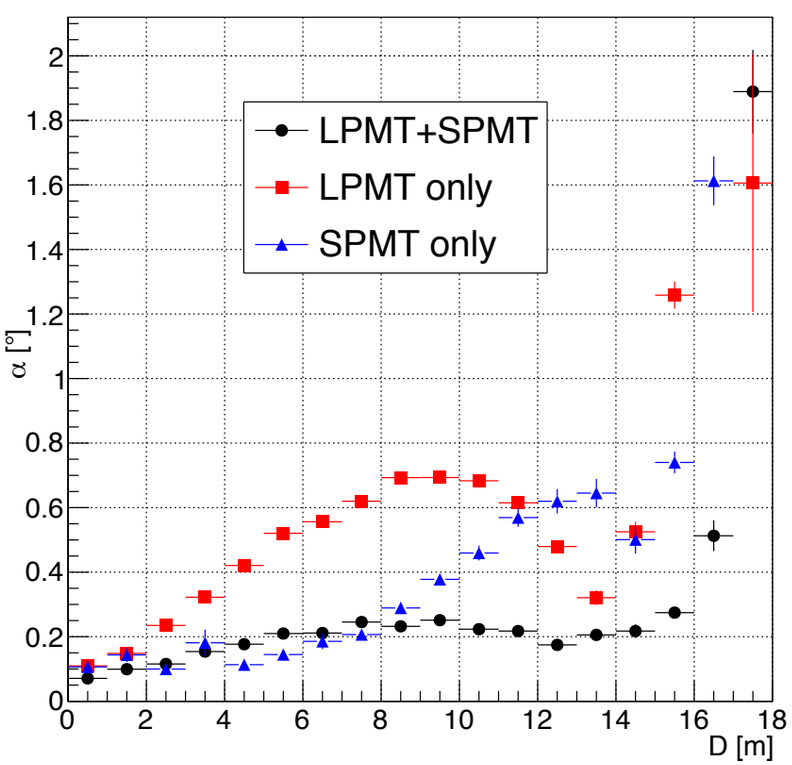






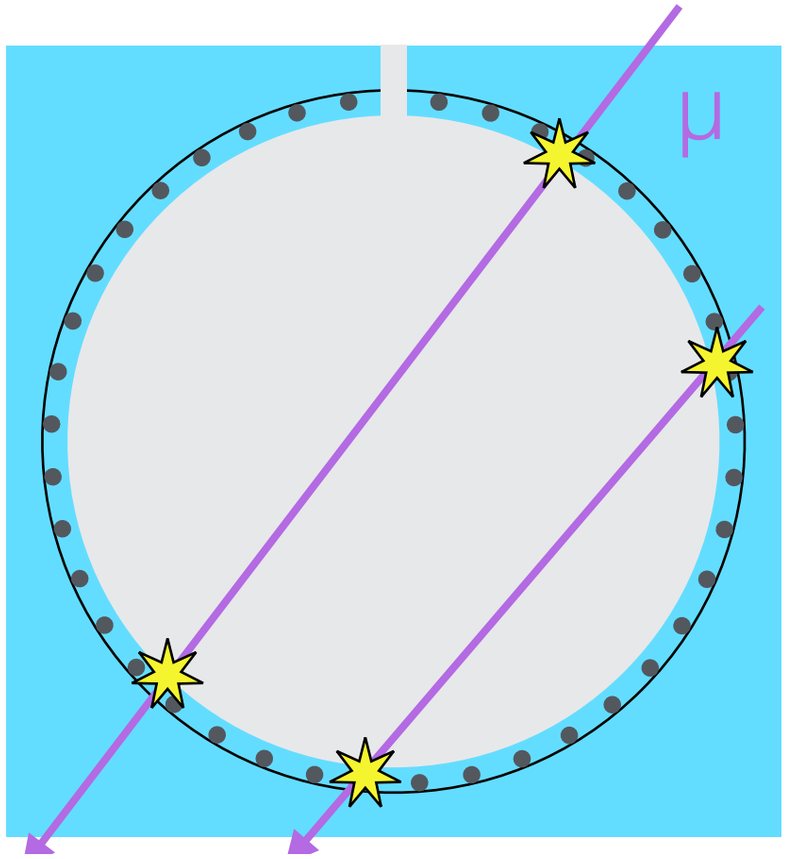
$\Delta D \stackrel{\text{def}}{=} D_{true} - D_{rec}$
(D is closest distance to the center)
α is angle between true and rec. track

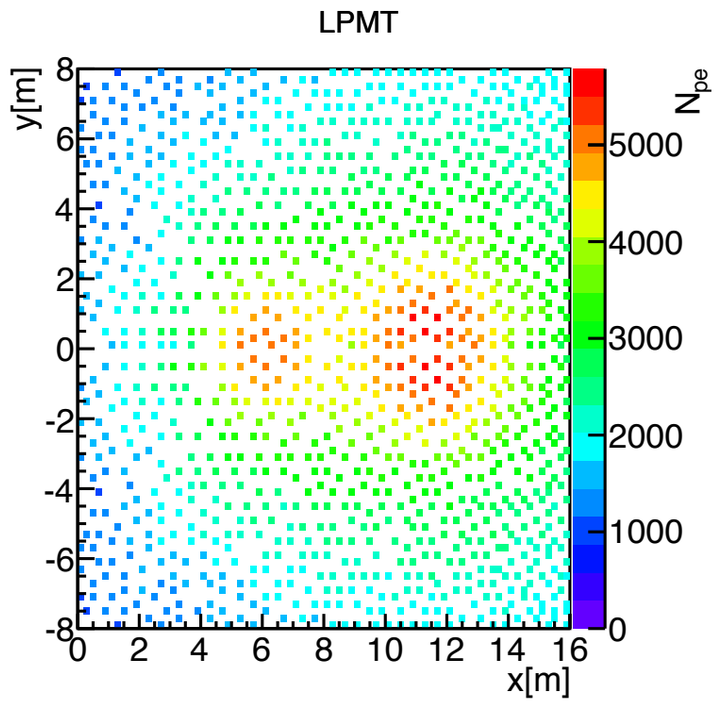
Genster et al. 2018 JINST 13 T03003

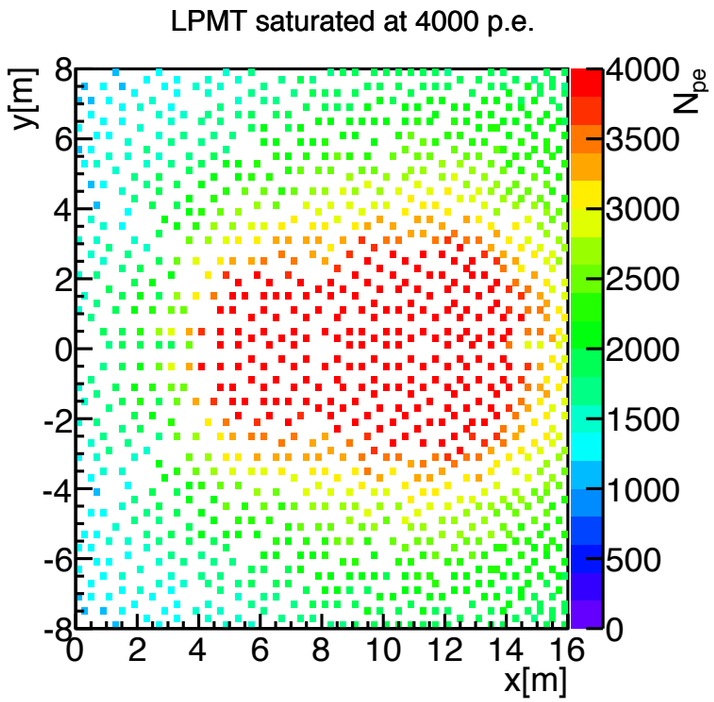
See also: Zhang et al. RDTM (2018) 2:13

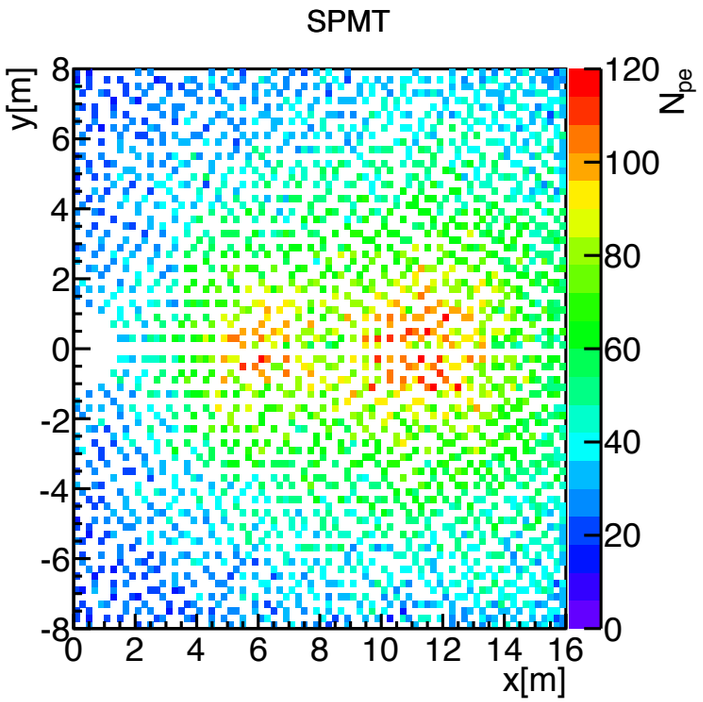
Clusters in Hit Pattern Algorithm

- Search for clusters in hit pattern
- Slightly worse performance in ΔD and α for single muons than first hit algorithm
- **Cluster alg. using SPMTs significantly improve muon bundle reconstruction** - algorithm synergy
- Key variable - number of photoelectrons
  - LPMTs saturated at ~4000 p.e.
  - **SPMTs get <150 p.e.**



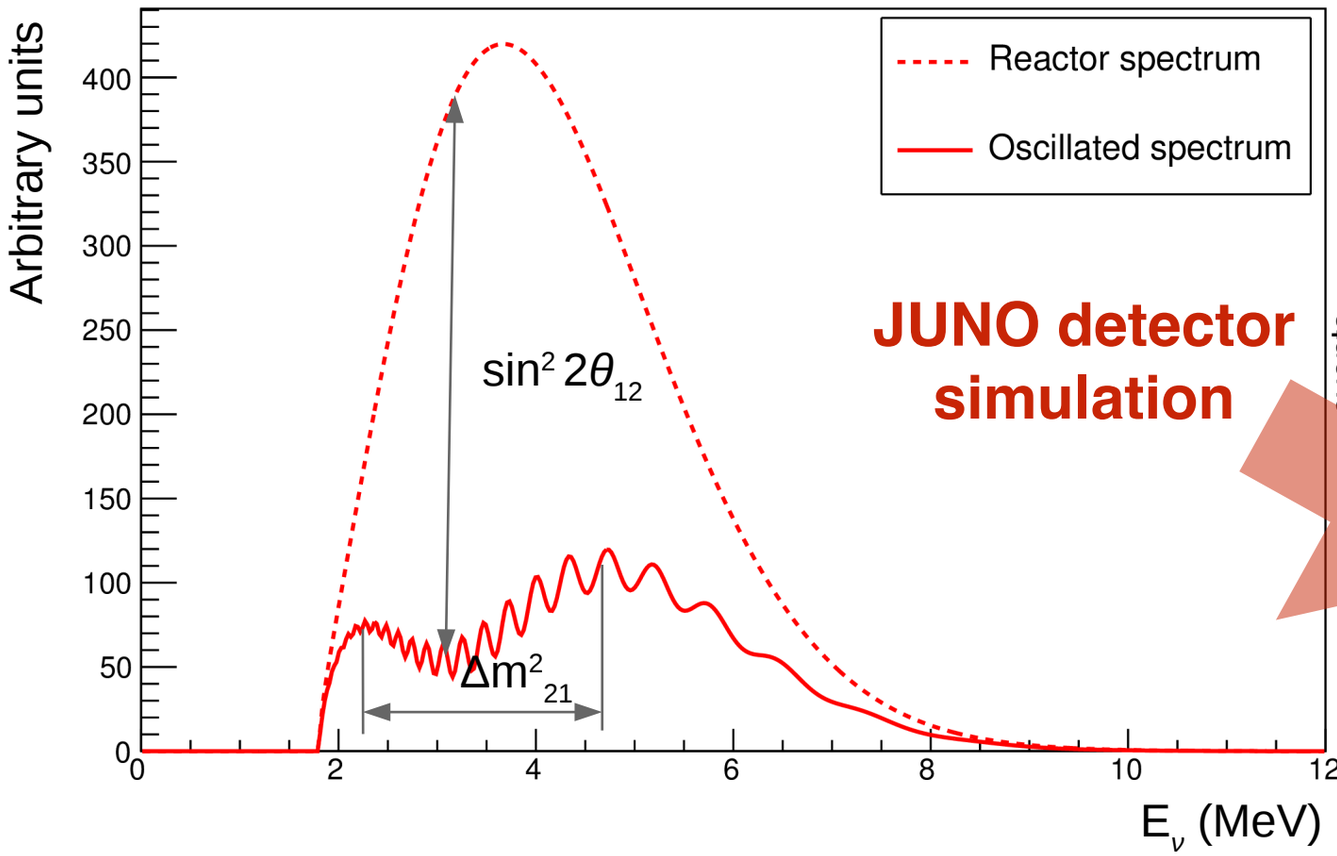




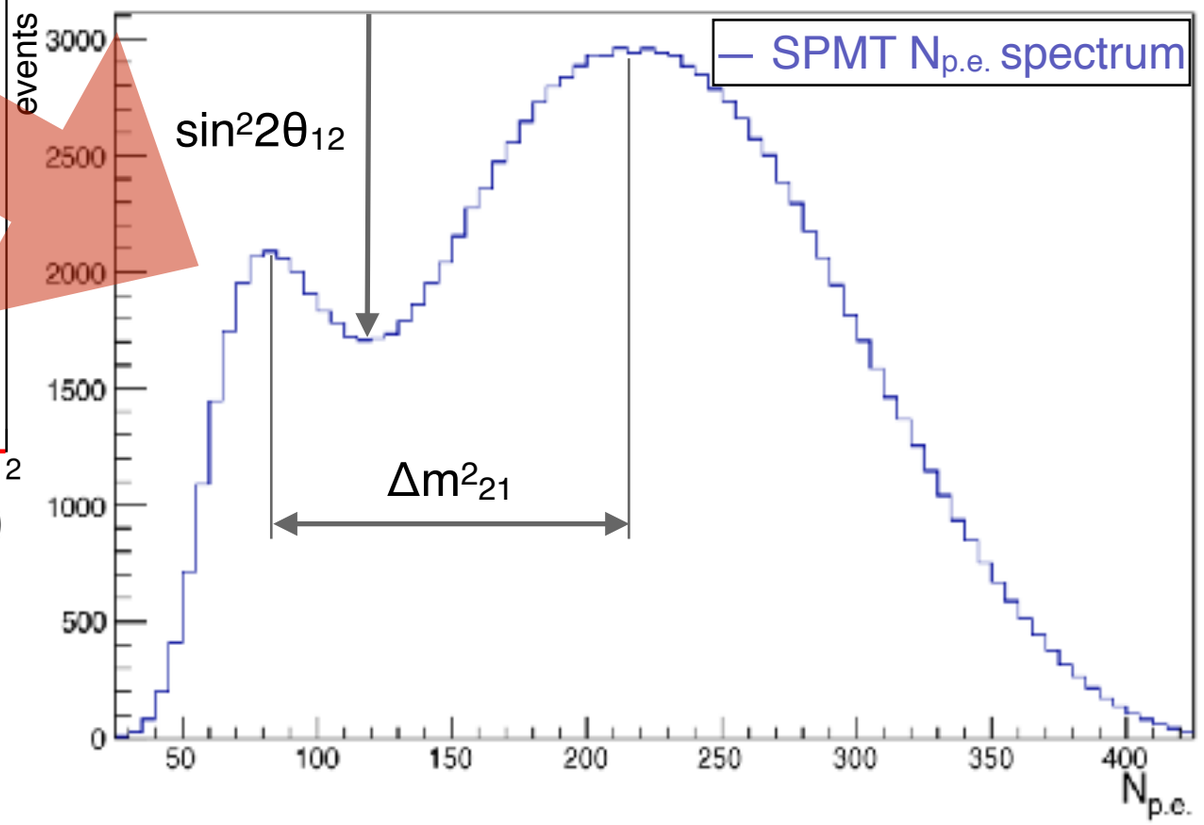


Solar Oscillation Parameters with SPMTs

- SPMT system energy resolution (17%) worse than LPMTs (3%@ 1 MeV)
- Still good enough to observe oscillation effect due to Δm^2_{21} with amplitude $\sin^2 2\theta_{12}$ (so-called solar oscillation parameters)



JUNO detector simulation



Solar Oscillation Parameters Precision

- Precision measurement of oscillation parameters is a part of JUNO physics program
- **Precision on solar parameters comparable with LPMTs and SPMTs analyzed independently**

Parameter \ Uncertainty	Current*	LPMTs	SPMTs
$\sin^2 2\theta_{12}$	4.2 %	<1%	<1%
Δm^2_{21}	2.4%	<1%	<1%

- Very nice opportunity for cross-check or SPMT+LPMT combination

✔ Partially different systematics, small impact of other oscillation parameters

✘ Same statistics and some systematics

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What Can We Do with SN Neutrinos?

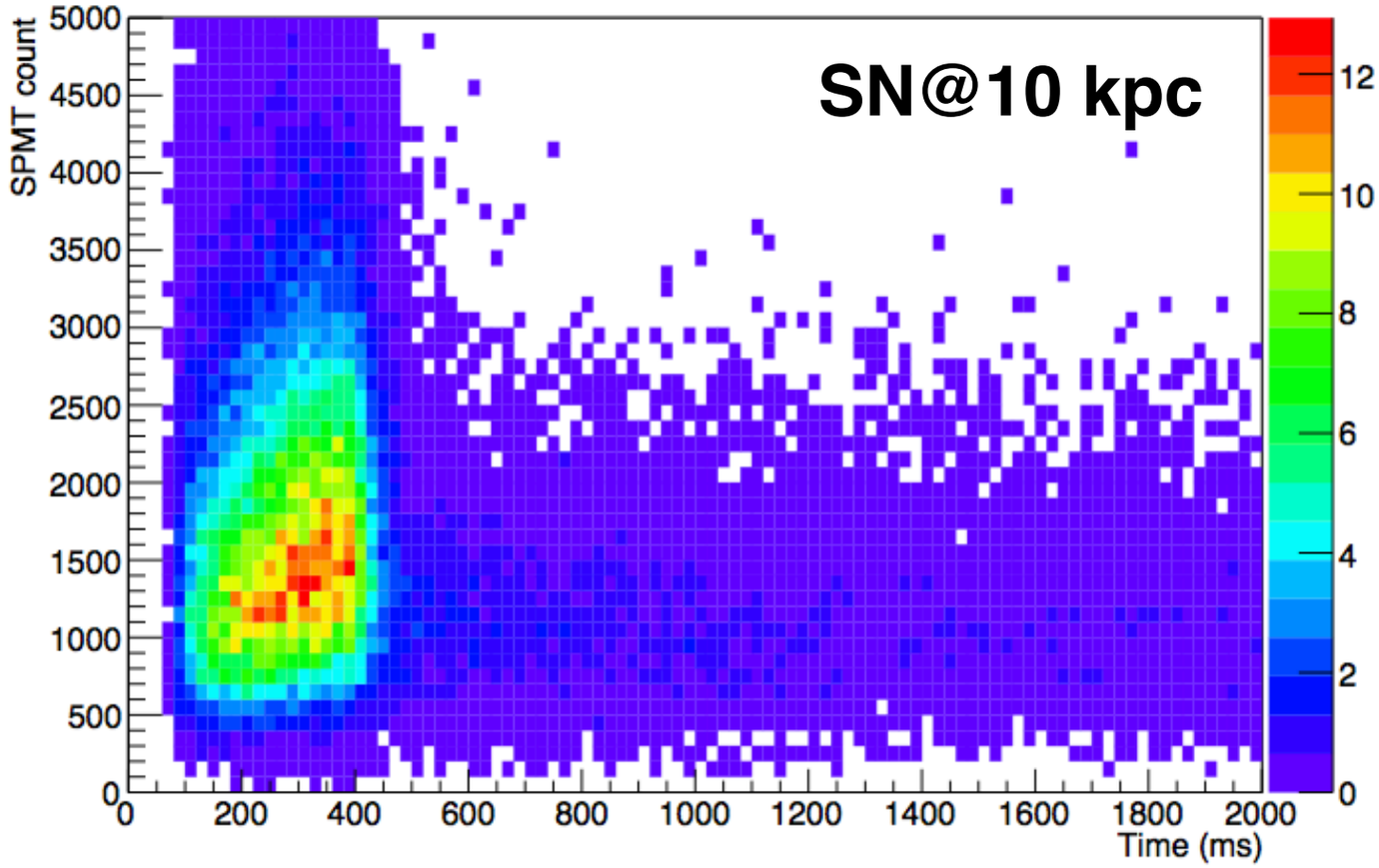
- **Astrophysics**
  - In general, confirmation of SN explosion model driven by neutrinos
  - Distinction between various SN models (i.e. $\langle E_\nu \rangle$)
  - SN neutrinos as an early warning for SN in visible spectrum (even with direction estimation, not from JUNO)

- **Particle physics**
  - Absolute neutrino mass from time of flight
  - Neutrino mass hierarchy from flavor composition measurement
  - Collective neutrino oscillations and exotic neutrino interactions

Supernova Neutrinos

- Supernova (SN) emits majority of its energy in neutrinos (we think)
- Neutrino energy 0-60 MeV with $\langle E_\nu \rangle \sim 12$ MeV
- JUNO sensitive to SNs in our galaxy (&Large Magellanic Cloud)
- Challenge: Most of the events from acceleration phase in first 0.5 s

SN distance	2.5 kpc	10 kpc
Events in JUNO	$\mathcal{O}(10^5)$	$\mathcal{O}(10^4)$
Event rate in first 0.5 s	$\mathcal{O}(10^5)$ Hz	$\mathcal{O}(10^4)$ Hz



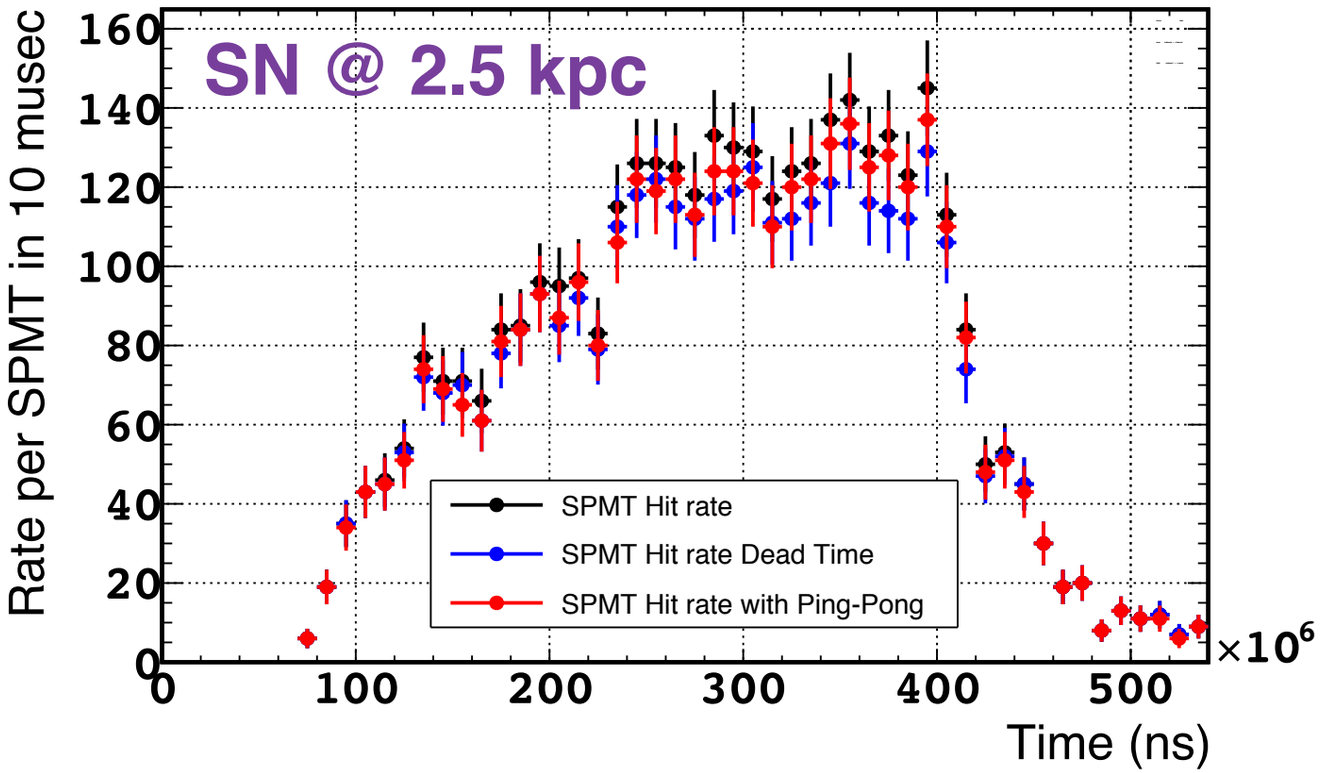
- **SPMTs electronics can cope with such rates!**

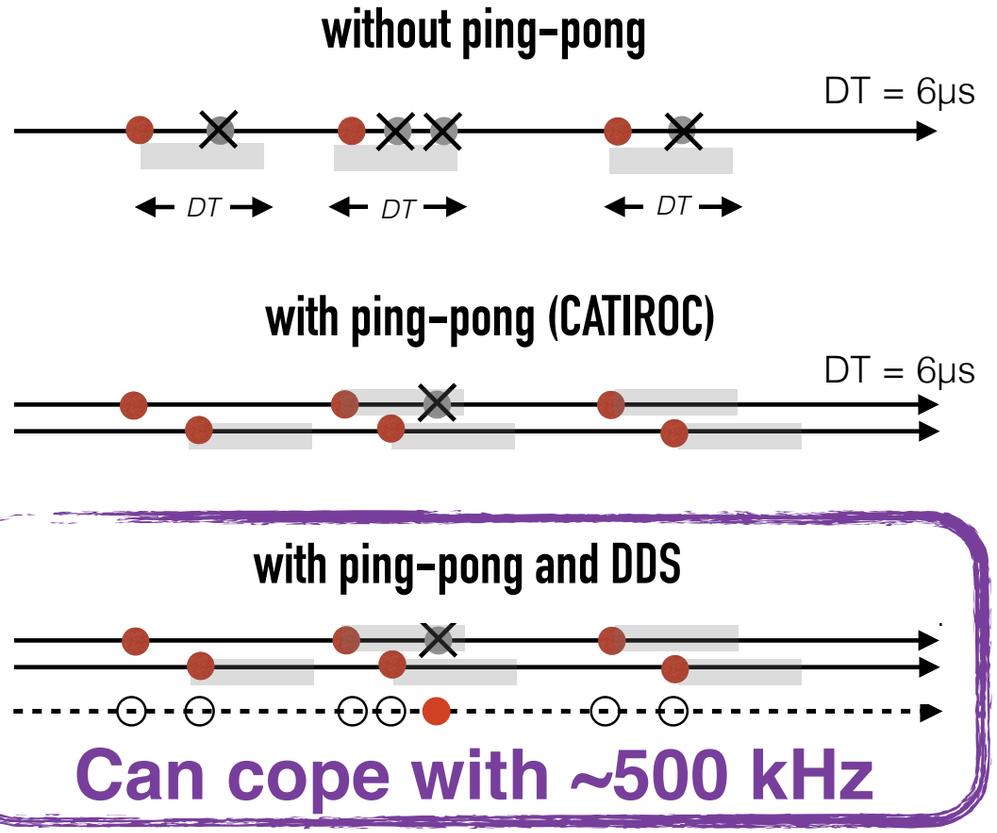
SN High Event Rate and SPMTs

- **Advantages of SPMTs**
  - Only some SPMTs get hit -> Dead time for hit does not ‘blind’ whole SPMT system (only several SPMTs)
  - Unique design of SPMT electronics - essentially dead-time-less thanks to discriminator data stream

More on electronics by A.Cabrera

- **SPMT disadvantage** - worse energy resolution than LPMTs (17%@1 MeV)





Can cope with ~500 kHz

We can record all events!!!

Event reconstruction is another question ;-)

Conclusions

- The 25,000 3” (small) PMT system is a critical part of the JUNO experiment
- SPMTs significantly boost its physics potential
  - Energy scale systematics
  - Muon track reconstruction
  - Cross-check of energy scale through solar oscillations parameters (θ_{12}, Δm^2_{21})
  - SN neutrino detection with essentially no dead time
- **Synergy between LPMTs and SPMTs**

Thank you for you attention!