JUNO

(a ν-oscillations factory)

seminar @ CPPM

Marseille (France) — November 2016

Anatael Cabrera

CNRS / IN2P3 @ APC (Paris)

JUNO Collaboration

EUROPE

APC Paris
Charles University Prague
CPPM Marseille
FZ Julich
IKP FZI Julich
INFN Catania
INFN Frascati
INFN Ferrara
INFN Milano-Bicocca
INFN Milano
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INR Moscow
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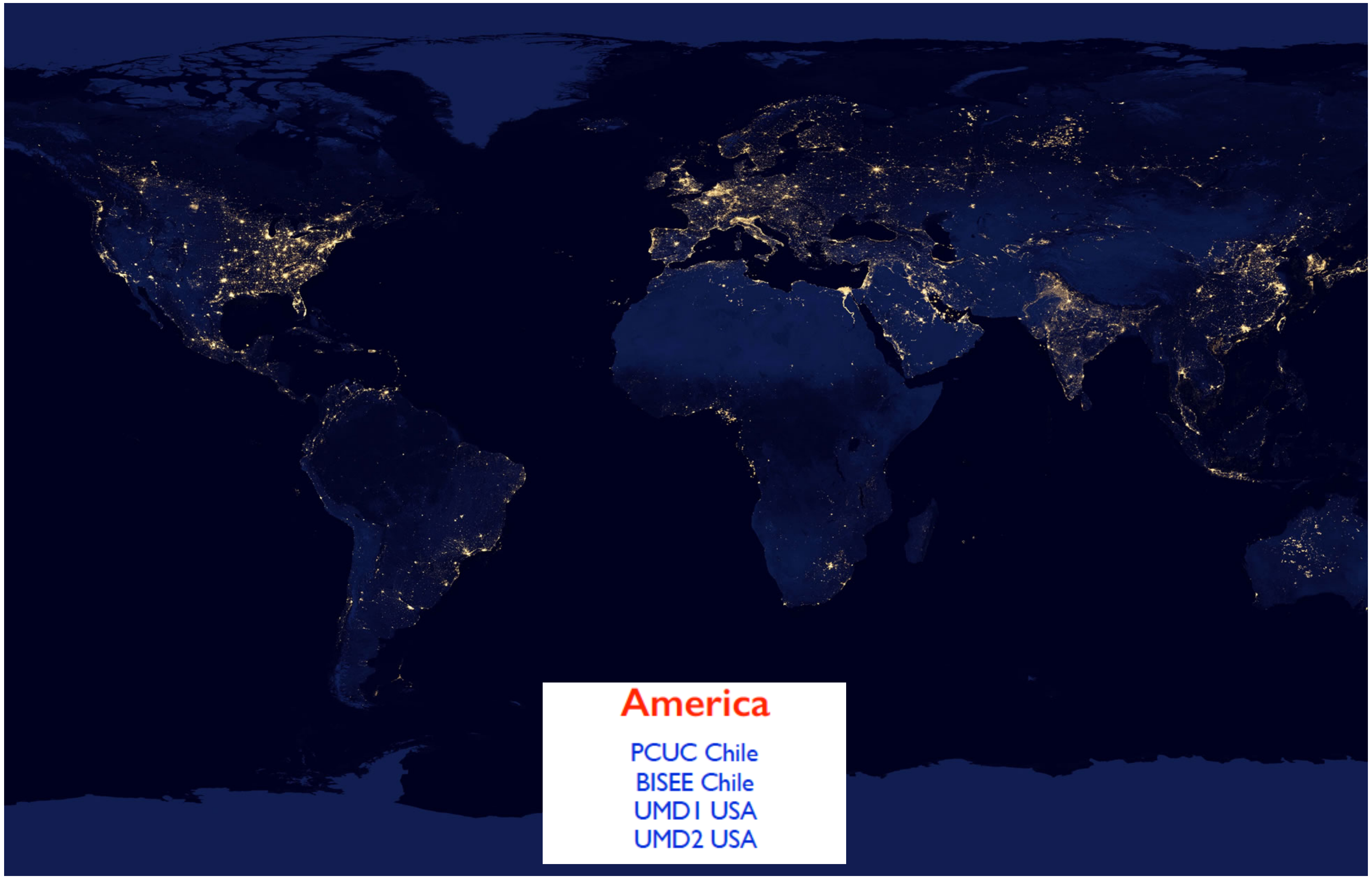
JINR Dubna
LLR Paris
MSU
RWTH Aachen
Subatech Nantes
TUM Munich
University of Hambourg
University of Mainz
University of Oulu
University of Tuebingen
Yerevan Physics Institute
Université libre de Bruxelles



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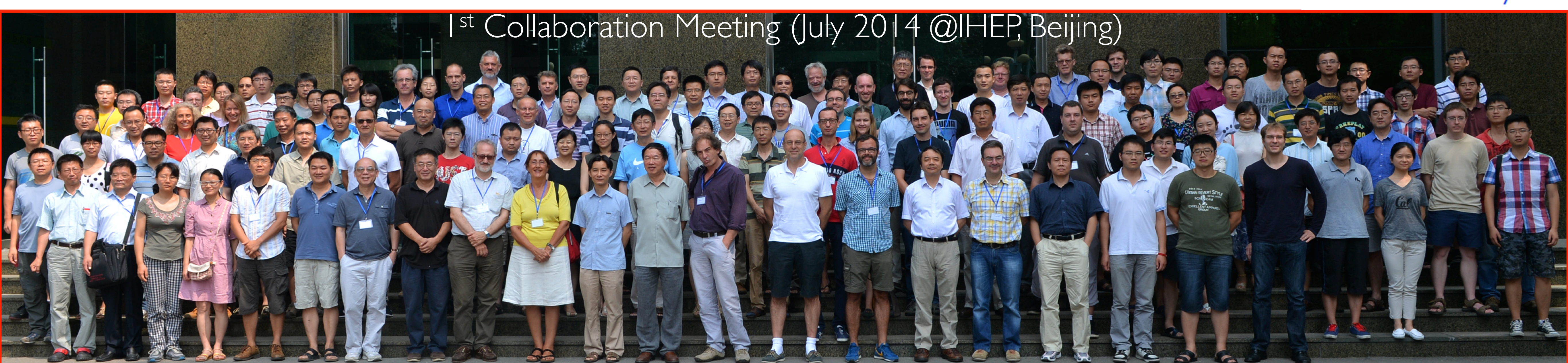
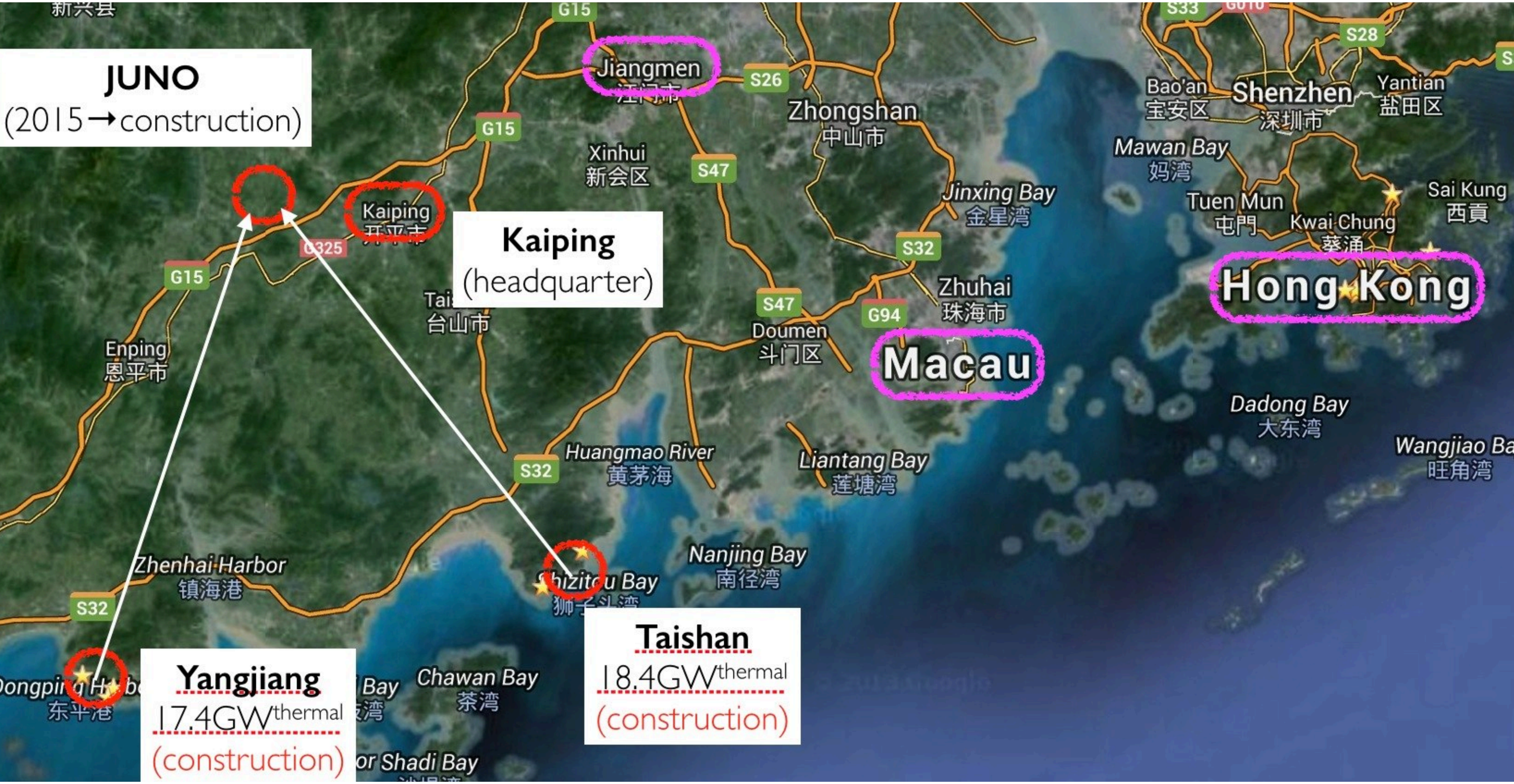

1st Collaboration Meeting (July 2014 @IHEP, Beijing)

JUNO location…



simplistic schedule: **data-taking starts within 2020**

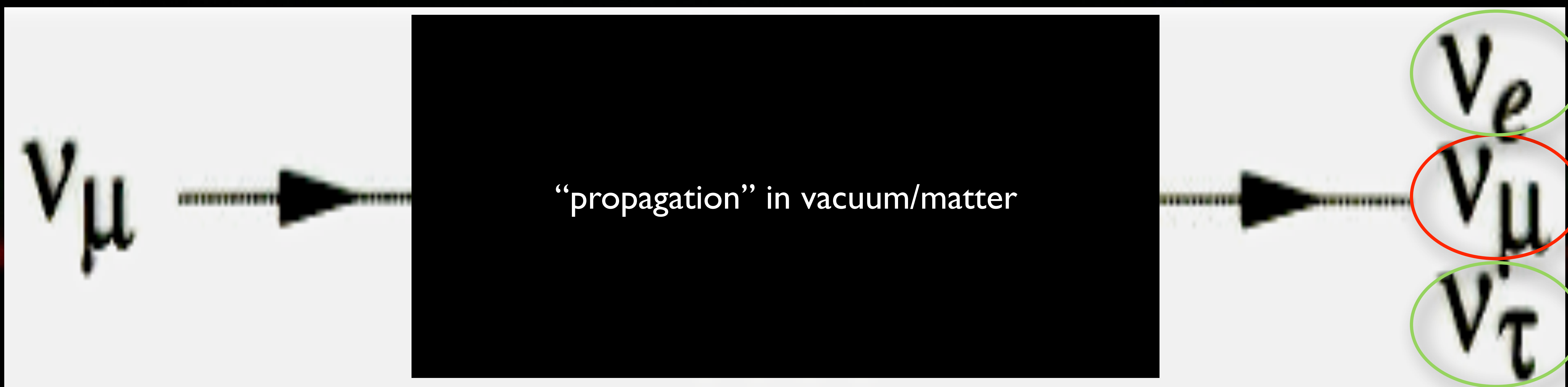
physics programme…

neutrino oscillations: a cartoon

Let's take ν_μ (a popular example) to start with…

disappearance

appearance



observation: both disappearance (long ago) & appearance (July 2013) have been seen

all observations (many!) follow well one model: 3ν oscillation

ingredients for neutrino oscillations…

Non-degenerate mass spectrum (Δm^2) **+** Mixing in the leptonic sector (θ) **=** Oscillation Probability **$P = f(\theta, \Delta m^2)$**

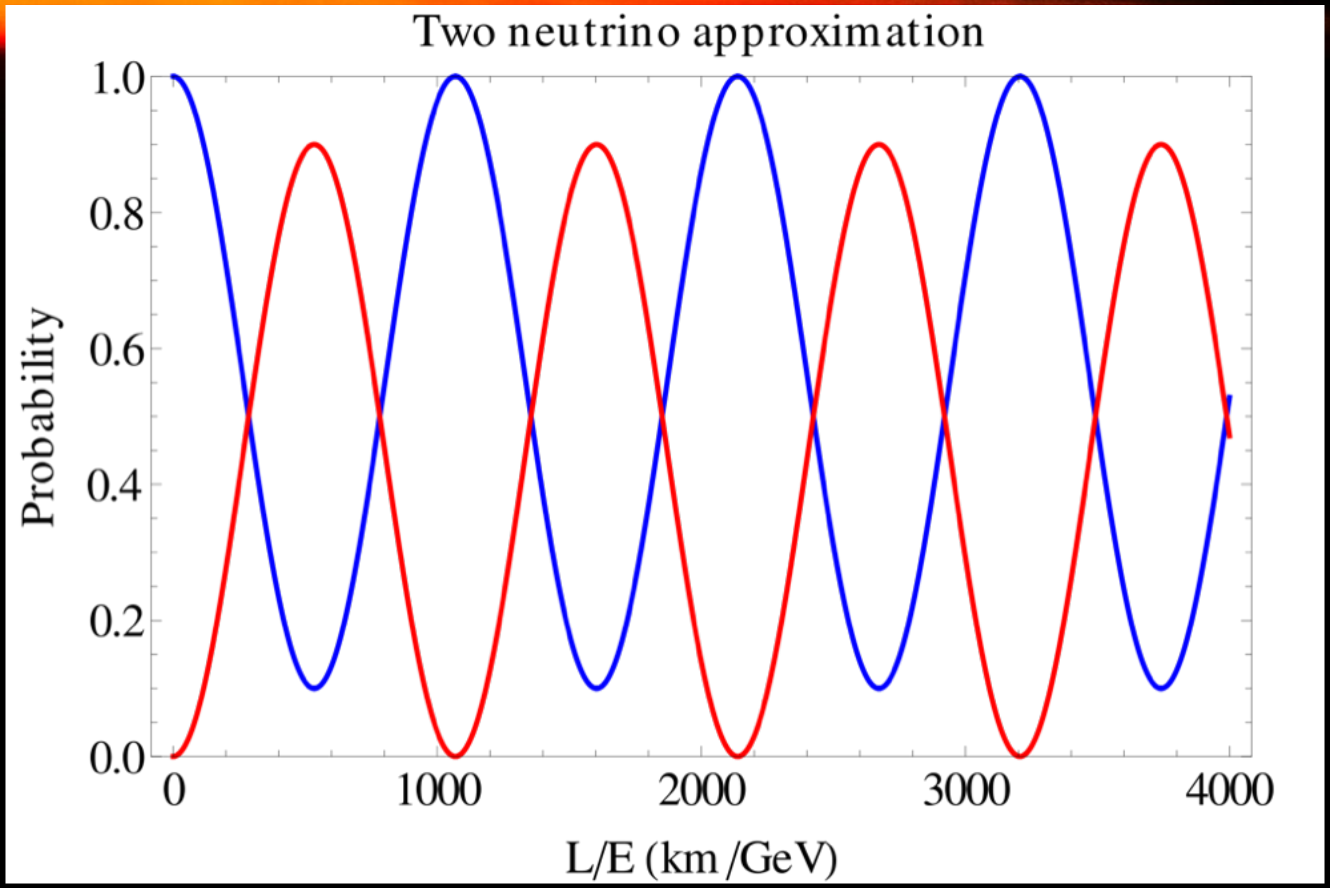
macroscopic quantum interference (over many km's)

U^{PMNS} matrix (à la CKM)

experimental setup
$P(L_o, \Delta E) \rightarrow f(\theta, \Delta m^2)$??
(measure a range of phase-space)

ν_α (start with) & ν_β (mixing: 90%)

$$P = \sin^2 2\theta \sin^2 \frac{\Delta m^2 L}{4E_\nu}$$



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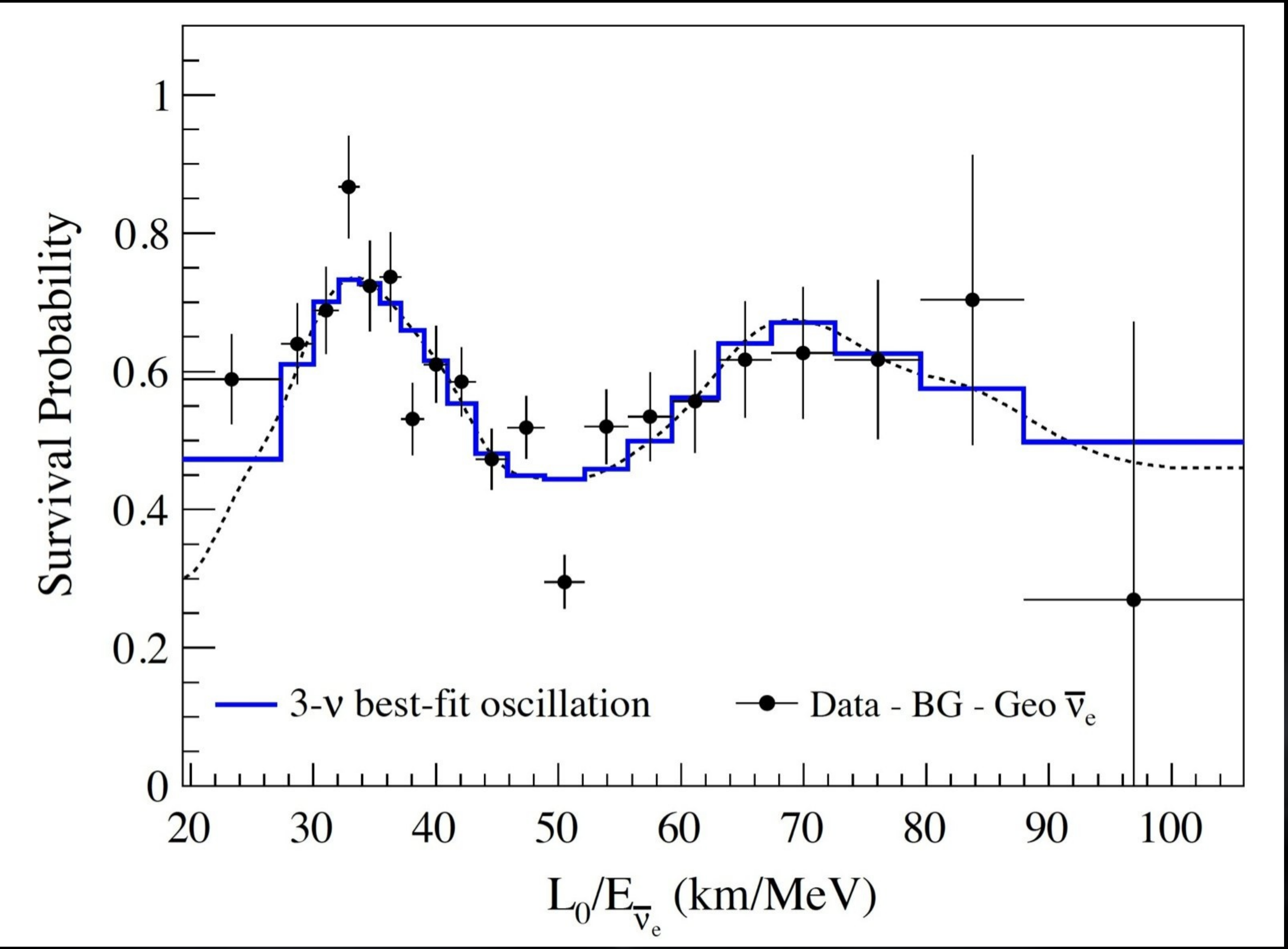
"mixing": a common phenomenon…

$$\nu_\alpha = 0.5 \bullet \nu_1 + 0.5 \bullet \nu_2$$

the latest KamLAND's P($\nu_e \rightarrow \nu_e$)…

the most beautiful E/L so far… (to me)



reactor-ν ⇒ stunning high precision tools for ν-oscillations!

(complementarity)

neutrino oscillations status…

- The neutrino mixing matrix can be parameterized as:

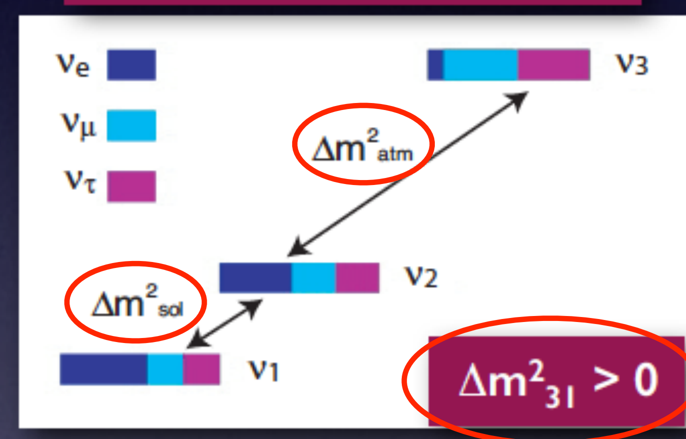
Atmospheric — Solar

$$U = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{bmatrix} \times \begin{bmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{-i\delta} & 0 & c_{13} \end{bmatrix} \times \begin{bmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{bmatrix} \times \begin{bmatrix} e^{i\xi_1/2} & 0 & 0 \\ 0 & e^{i\xi_2/2} & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

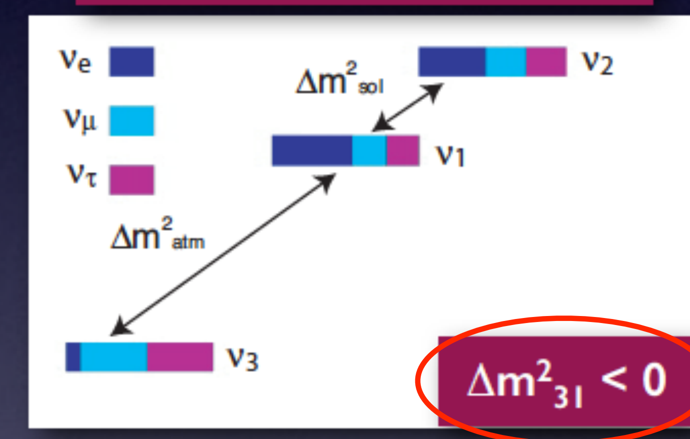
$s_{ij} = \sin(\theta_{ij})$
$c_{ij} = \cos(\theta_{ij})$
$\delta = $ CP phase
$\xi_1, \xi_2 = $ Majorana phases

- The non-zero value of θ_{13} opens the way for the measurement of the CP violation phase in the leptonic sector.
- An additional goal for next generation neutrino experiment is the mass hierarchy determination.

Normal Hierarchy (N.H.)



Inverted Hierarchy (I.H.)



- The electron antineutrino survival probability in vacuum can be written as:

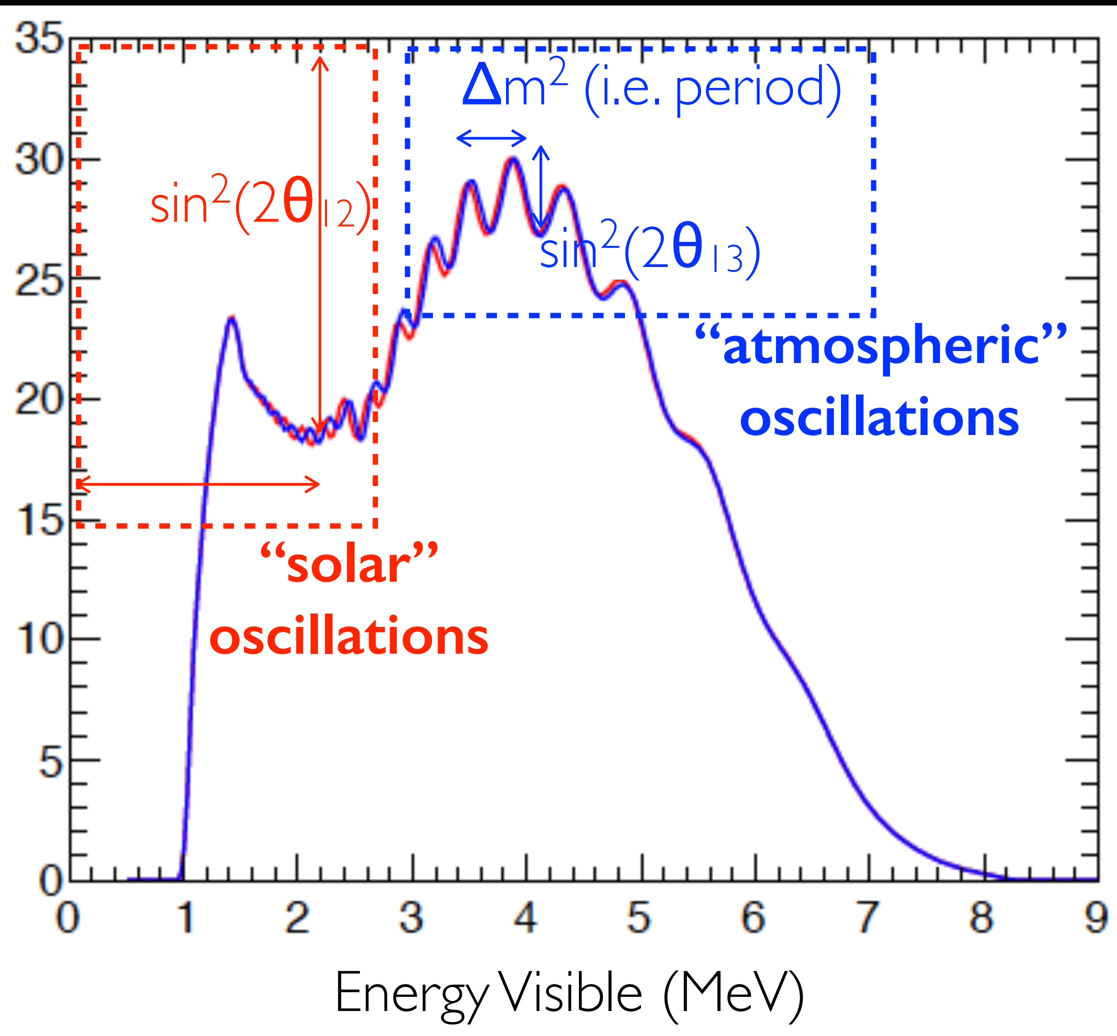
$$\begin{aligned} P_{ee}(L/E) &= 1 - P_{21} - P_{31} - P_{32} \\ P_{21} &= \cos^4(\theta_{13})\sin^2(2\theta_{12})\sin^2(\Delta_{21}) \\ P_{31} &= \cos^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{31}) \\ P_{32} &= \sin^2(\theta_{12})\sin^2(2\theta_{13})\sin^2(\Delta_{32}) \end{aligned}$$

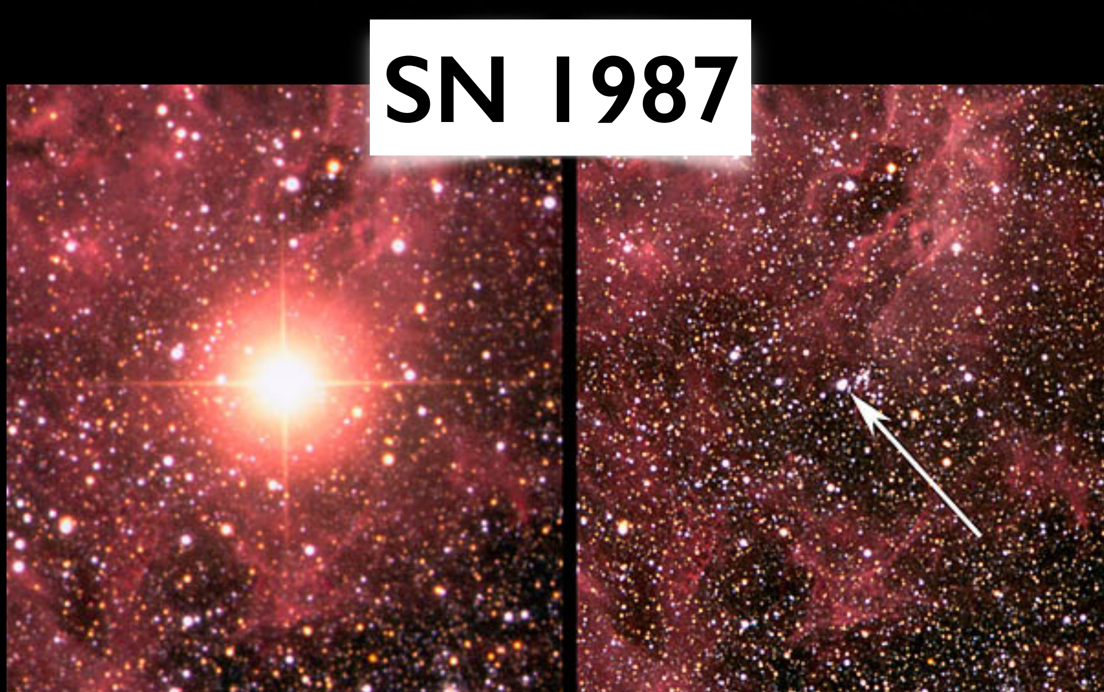
$$\Delta_{ij} = 1.27\Delta m^2_{ij} L/E$$

- According to the mass hierarchy, one oscillation frequency ω is larger than the other:

$$\begin{aligned} \Delta m^2_{31} &= \Delta m^2_{32} + \Delta m^2_{21} \\ \text{NH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| + |\Delta m^2_{21}| \qquad \omega P_{31} > \omega P_{32} \\ \text{IH}: |\Delta m^2_{31}| &= |\Delta m^2_{32}| - |\Delta m^2_{21}| \qquad \omega P_{31} < \omega P_{32} \end{aligned}$$

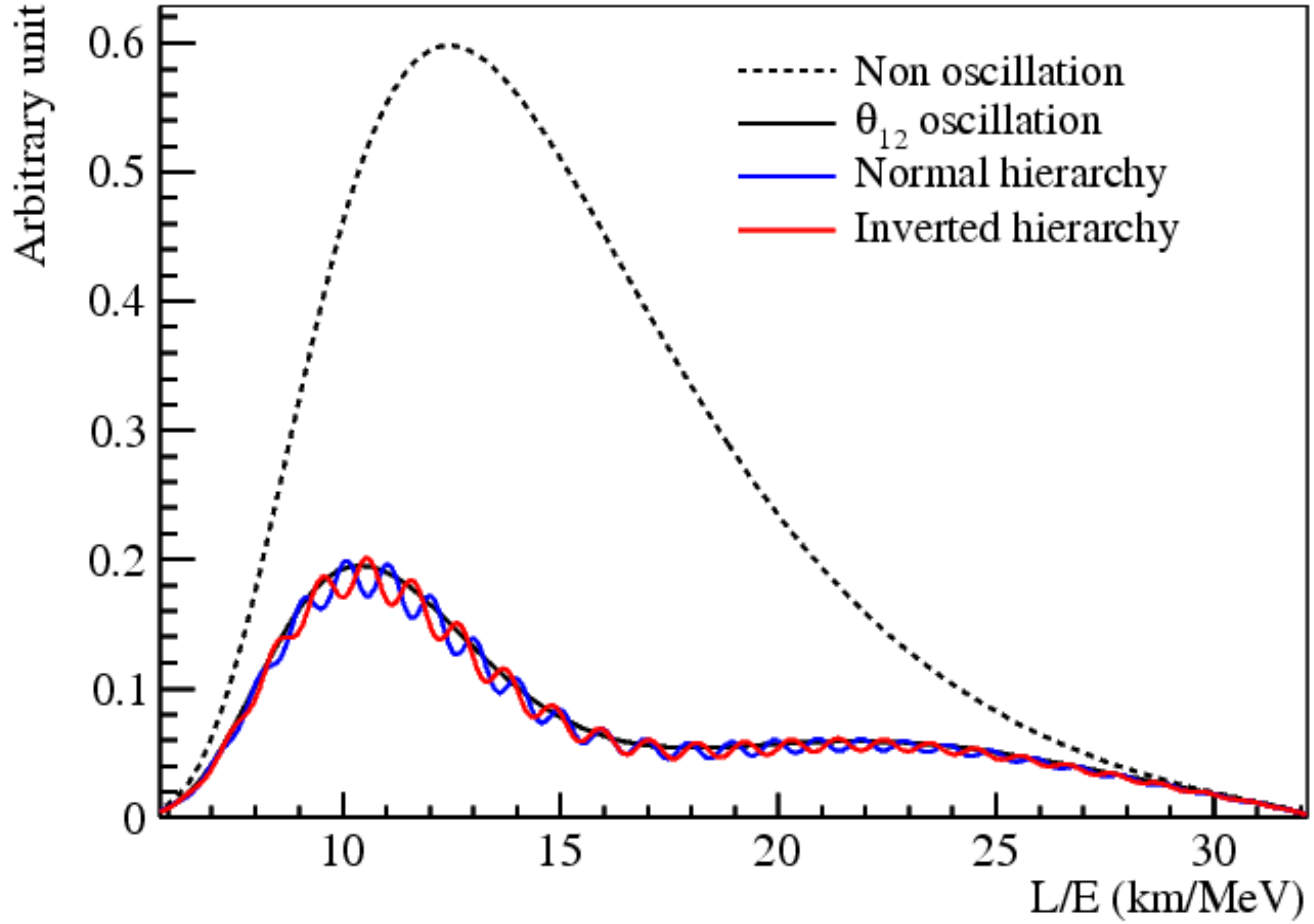
what to do with the largest LS detector in the world?



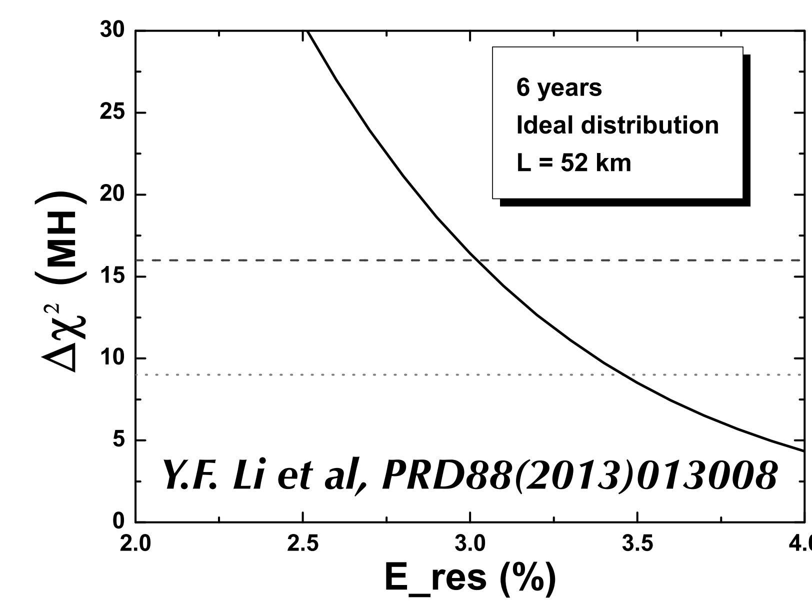


- **(reactor-ν) unique solar⊕atmospheric vacuum-oscillations fit**
- **(reactor-ν) mass hierarchy (atmospheric)**…
  - subdominant (θ13 modulated) spectral distorsion
    - driven by Δm^2(atmospheric)
  - **vacuum effect**→ no via matter enhance effects
    - no θ_{23}-octant or δ_{CP} ambiguities
    - **complementarity to NOνA,ORCA⊕PINGU,DUNE**
- **(reactor-ν) solar δm2 & θ12 highest precision**…
  - needed for CP-violation (**Jarlskog Invariant**)→ **ambiguities!**
    - **complementarity to T2K⊕NOνA & 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)→ aid geo-physics
- other physics…
  - solar-ν, non-standard-interaction (different phase-space), etc

energy resolution of JUNO detector…



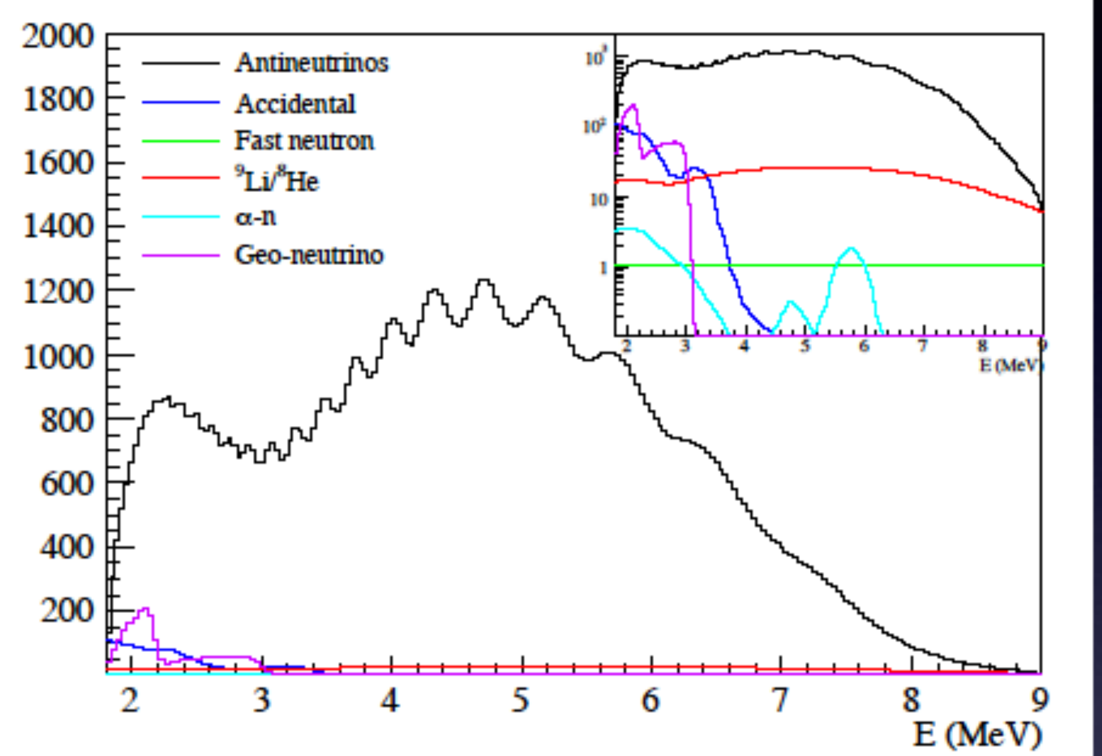
- the 3% requirement arises from ratio $\delta m^2/\Delta m^2$
  - i.e. the solar to atmospheric mass-squared difference
- need energy resolution ~ 3% @ 1MeV
  - stochastic term $(a/\sqrt{E}) \rightarrow a \leq 3\%$
  - non-stochastic term under investigation (next)



IBD selection & backgrounds…

Applying the different selection cuts, the signal rate will be 60 events/day and the background will be 3.8 events/day.

Antineutrino signal spectra and five kinds of main background

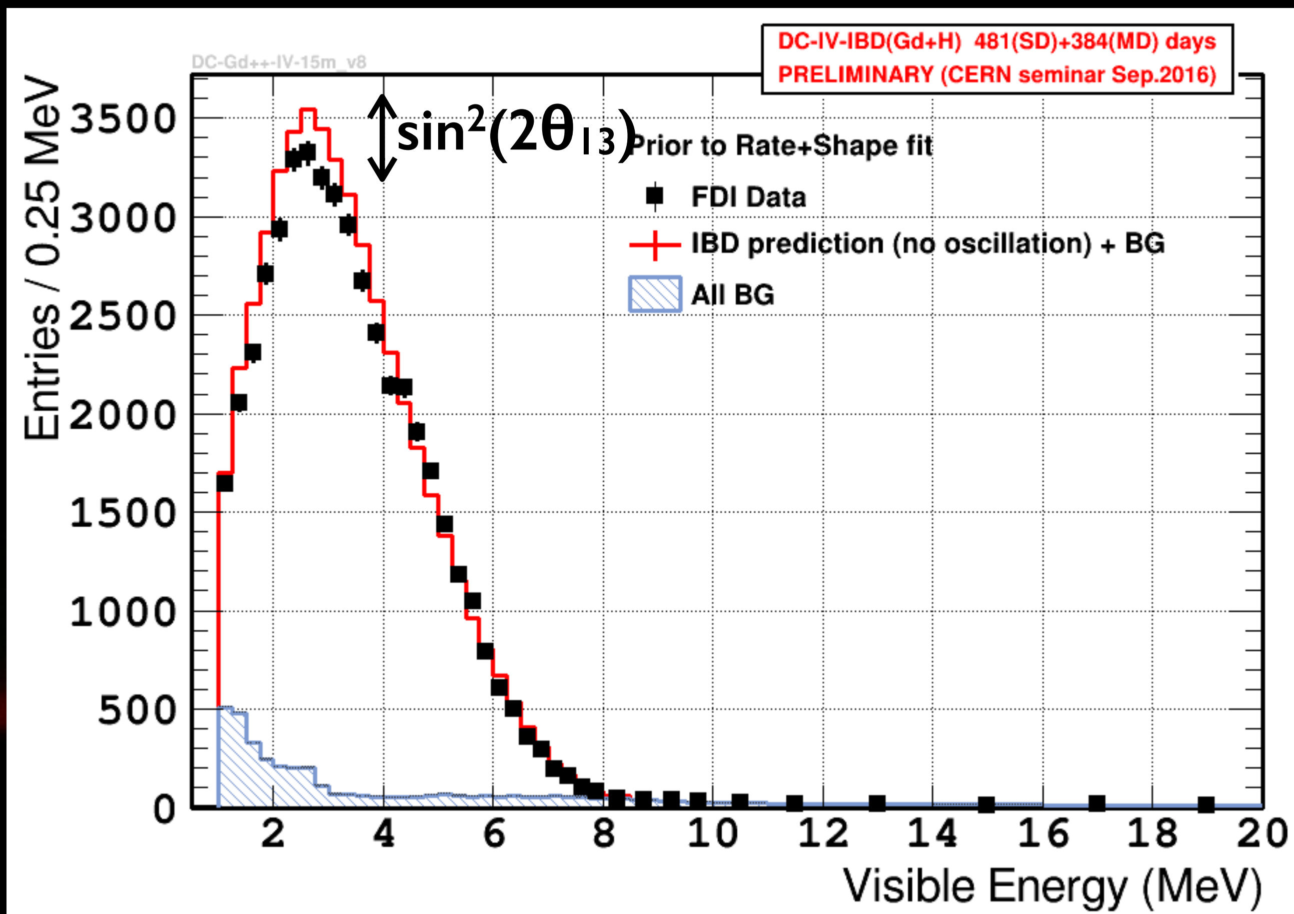


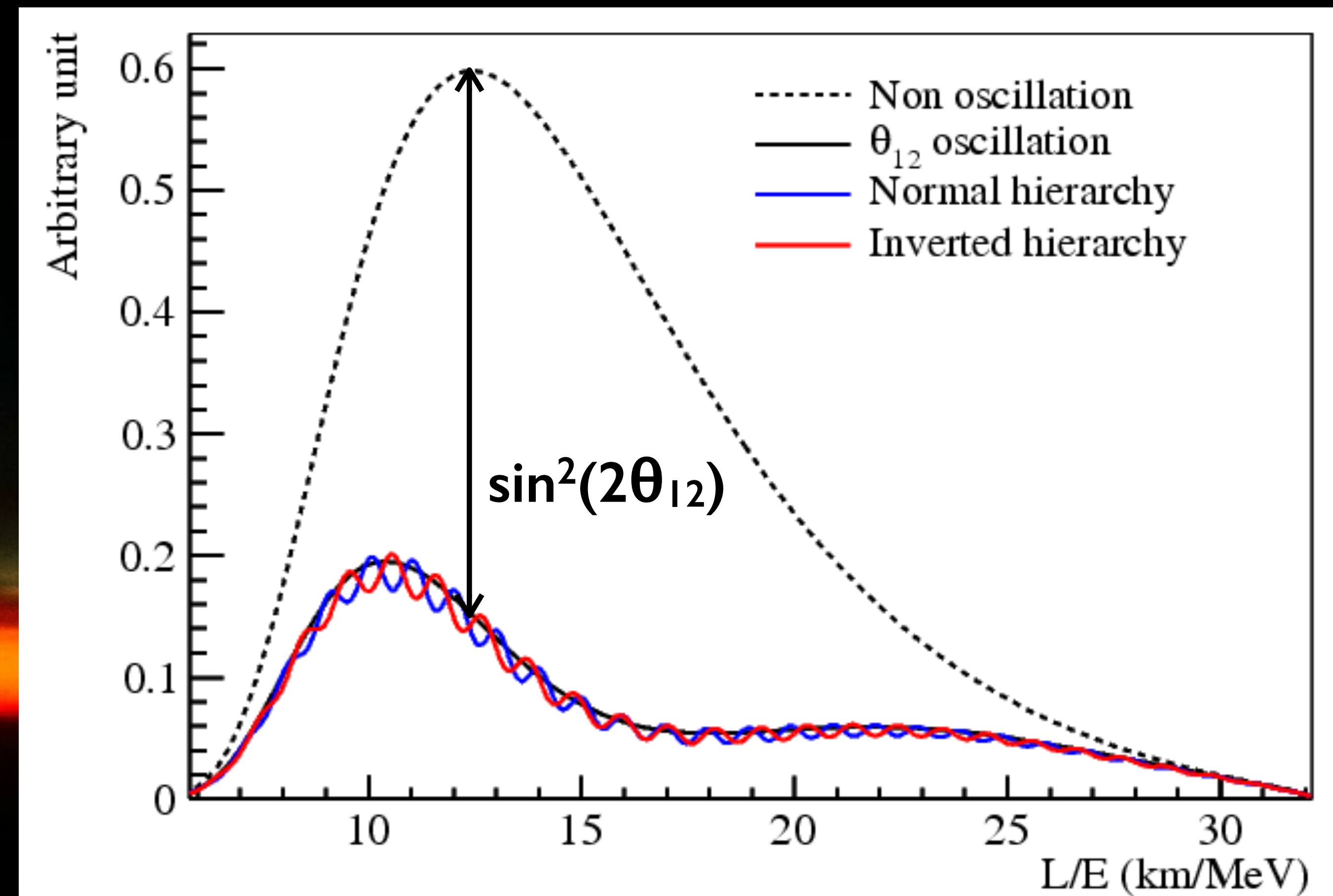
Efficiency, signal and background rates after each selection criterion

<table>
<tr><th>Selection</th><th>IBD efficiency</th><th>IBD</th><th>Geo-νs</th><th>Accidental</th><th>^{9}Li/^{8}He</th><th>Fast n</th><th>(α, n)</th></tr>
<tr><td>-</td><td>-</td><td>83</td><td>1.5</td><td>$\sim 5.7 \times 10^4$</td><td>84</td><td>-</td><td>-</td></tr>
<tr><td>Fiducial volume</td><td>91.8%</td><td>76</td><td>1.4</td><td rowspan="3">410</td><td>77</td><td rowspan="5">0.1</td><td rowspan="5">0.05</td></tr>
<tr><td>Energy cut</td><td>97.8%</td><td rowspan="3">73</td><td rowspan="3">1.3</td><td rowspan="3">71</td></tr>
<tr><td>Time cut</td><td>99.1%</td></tr>
<tr><td>Vertex cut</td><td>98.7%</td><td>1.1</td></tr>
<tr><td>Muon veto</td><td>83%</td><td>60</td><td>1.1</td><td>0.9</td><td>1.6</td></tr>
<tr><td>Combined</td><td>73%</td><td>60</td><td colspan="5">3.8</td></tr>
</table>

single-detector experiments…

like KamLAND→ no need for near-detector (a priori)





Double Chooz

(FD only)

1σ[sin2(2θ13)]↔ δ(flux)

JUNO

(one detector only)

fundamental physics (ν oscillations)→ strongly affected by δ(flux) uncertainties

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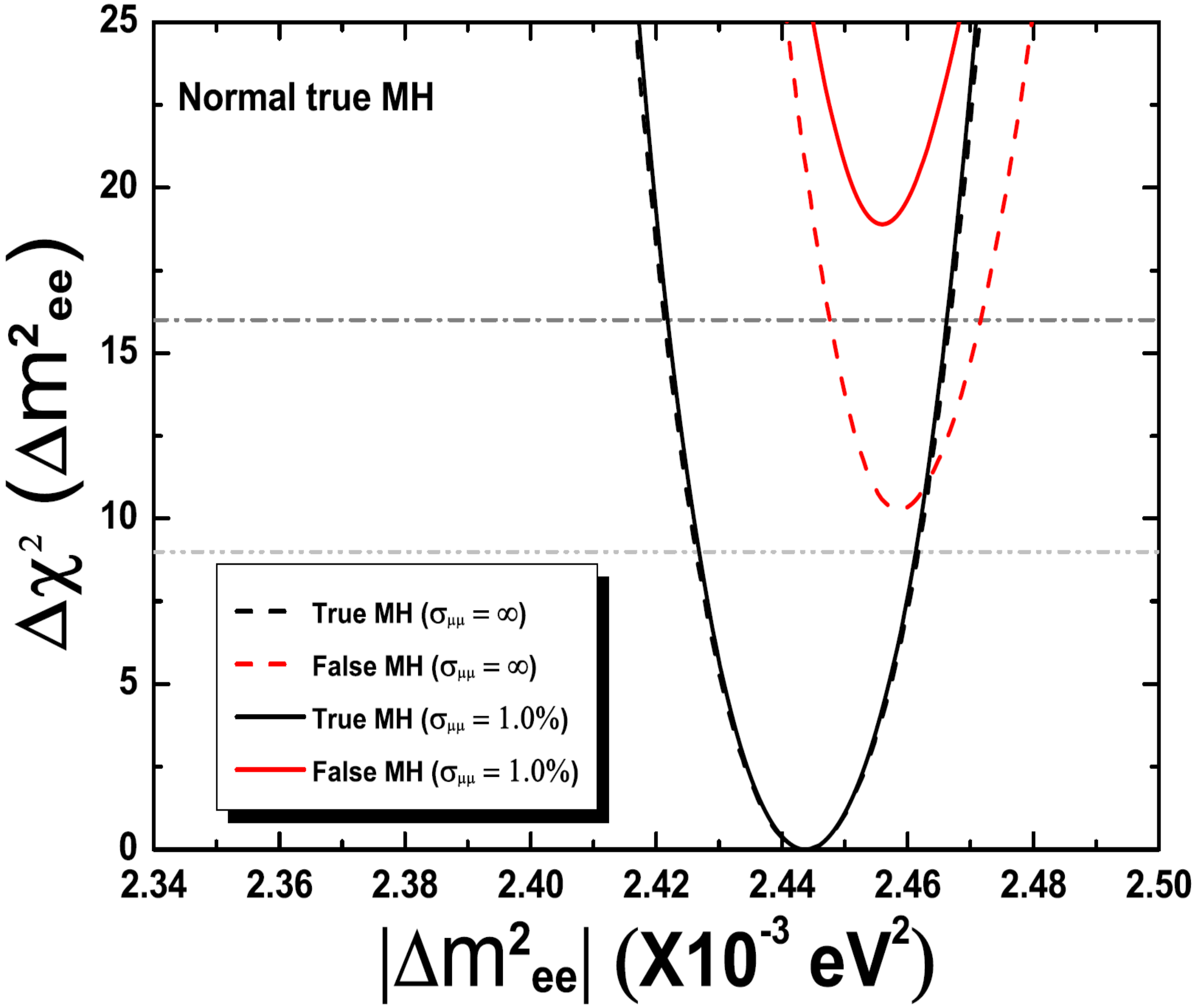
Mass Hierarchy significance…



- ~3σ→ spectral measurement with no Δm^2 external constrain
- ~4σ→ external Δm^2 measured to ~1% error (ν_μ disappearance with ν-beam off-axis)
  - Δm^2 @~1% by T2K+NOvA
  - combined analysis [1312.1477]

ingredients…

✓Realistic reactor distributions considered

✓20kt valid target mass ⊕ 36GW reactor power ⊕ 6-years data

✓3% energy resolution ⊕ ~1% energy scale uncertainty assumed

neutrino oscillation precision before & after JUNO…

	Current precision	JUNO goal
$\sin^2 2\theta_{12}$	6 %	0.7 %
Δm^2_{12}	3 %	0.6 %
$\lvert\Delta m^2_{32}\rvert$	5 %	0.5 %
MH	N/A	3-4σ
$\sin^2 2\theta_{13}$	3 %	15 %

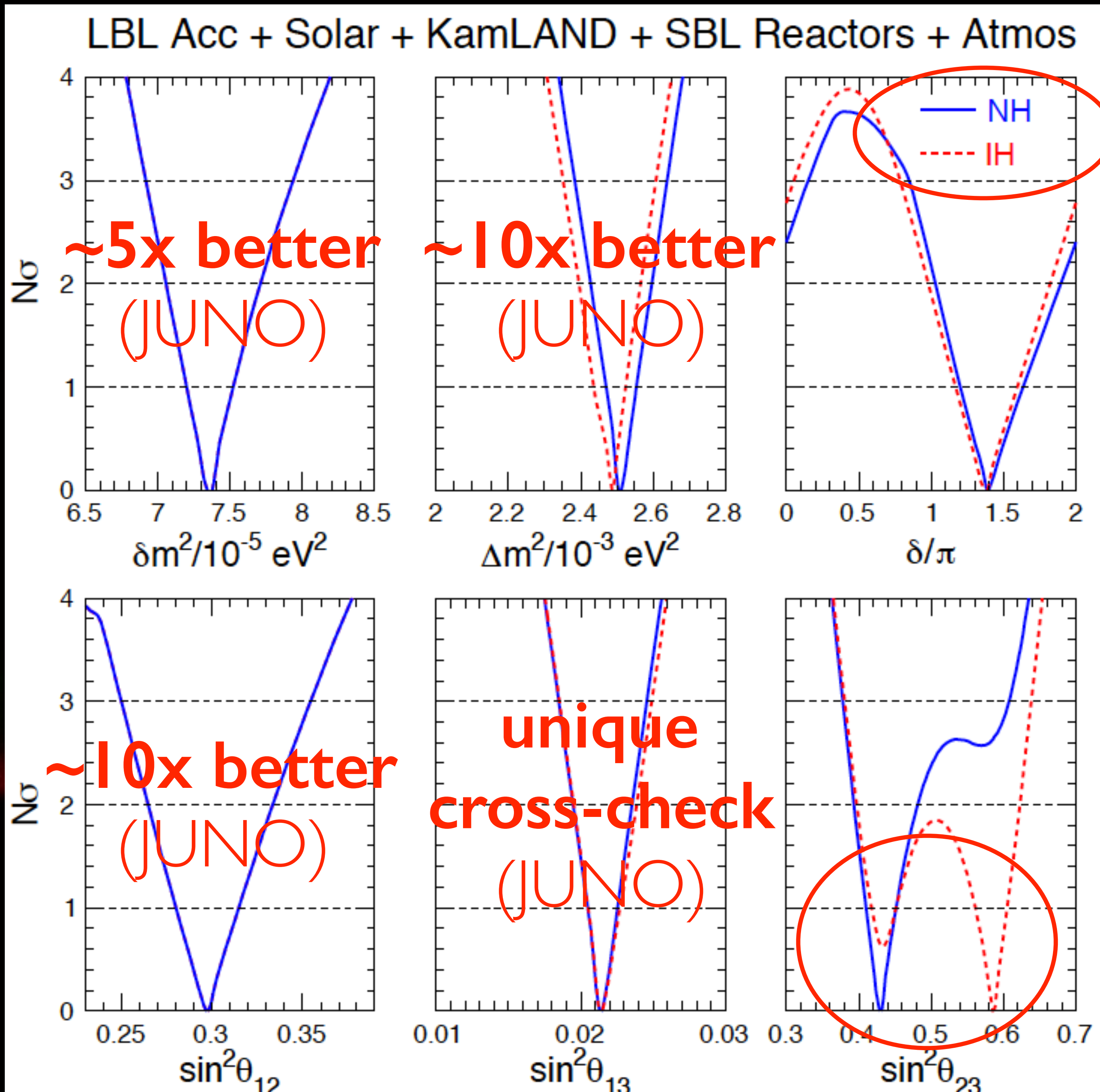
after JUNO, the "Solar neutrino oscillation" parameters on the <1% level→ the "JUNO sector"?
(already worth the experiment)

when trying to measure/constrain δ_{CP}, all oscillation parameters matter! (**Jarlskog invariant: "*J*"**)

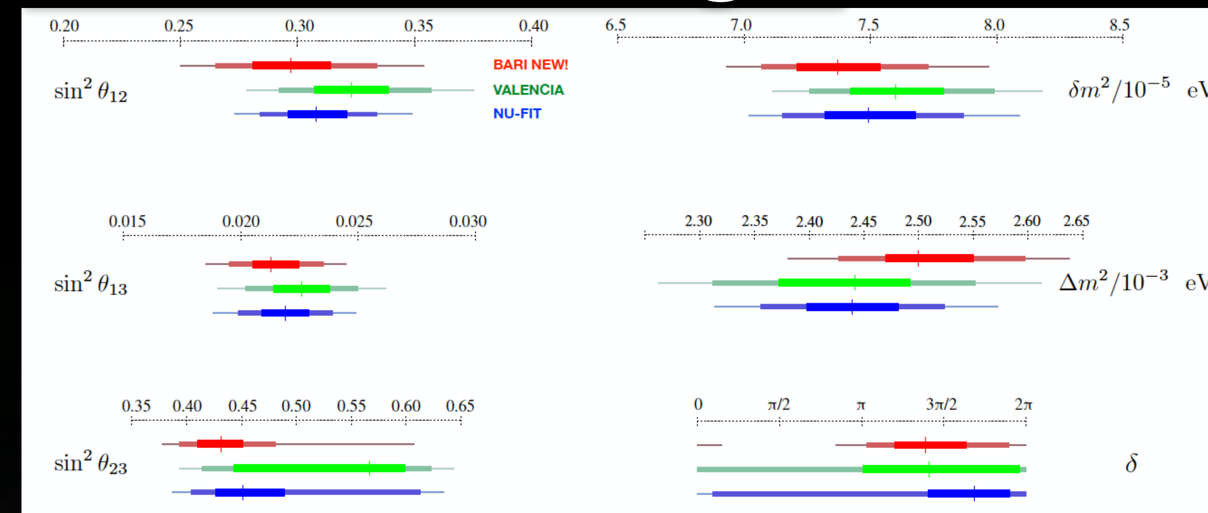
$$\Delta P_{\nu\bar{\nu}\,\alpha\beta} \equiv P(\nu_\alpha \to \nu_\beta) - P(\bar{\nu}_\alpha \to \bar{\nu}_\beta) = -16 J_{\alpha\beta} \sin \Delta_{12} \sin \Delta_{23} \sin \Delta_{31}$$

$$J_{\alpha\beta} \equiv \Im(U_{\alpha 1} U^*_{\alpha 2} U^*_{\beta 1} U_{\beta 2}) = \pm J, \qquad J \equiv s_{12} c_{12} s_{23} c_{23} s_{13} c^2_{13} \sin \delta$$

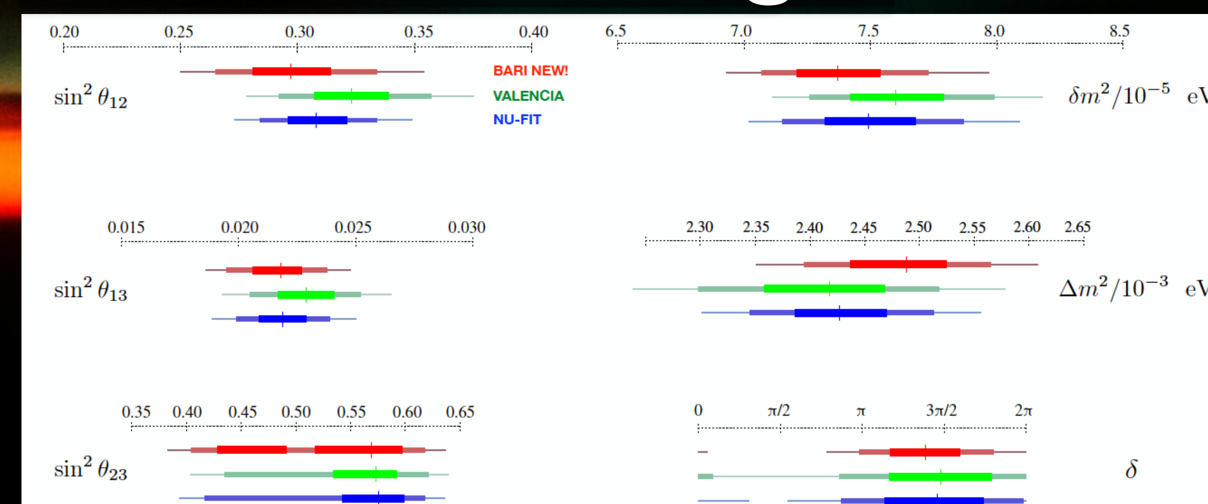
(*Marrone et al* @ NEUTRINO-16) 3ν oscillation status…



normal ordering…



inverted ordering…

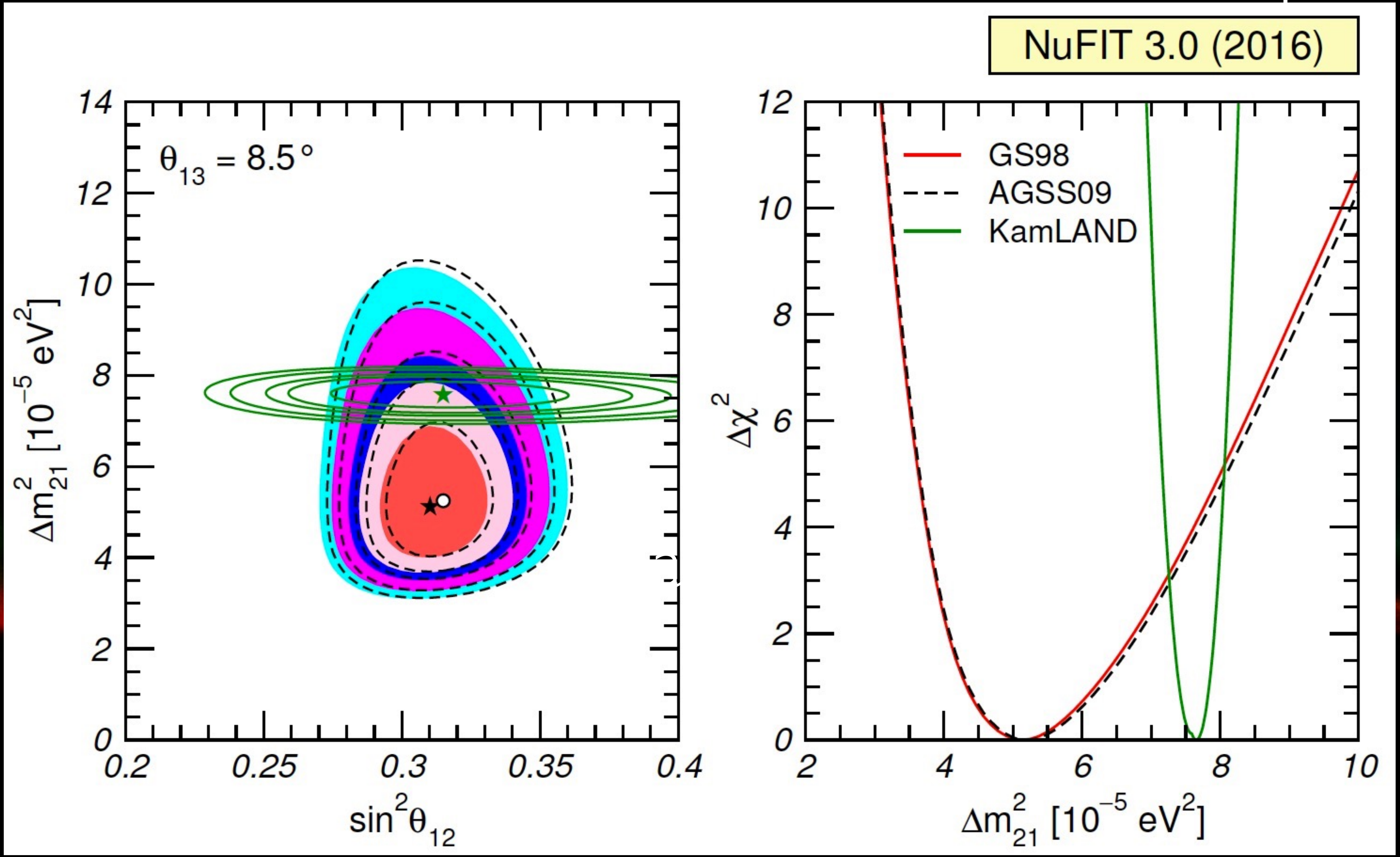


oscillation parameters: θ_{12}, $\pm\Delta m^2$, $\pm\delta m^2$, θ_{13}, θ_{23}, δ(CP)

⇒ remarkable precision towards "**δ(CP)**"

BARI - NPB908 (2016) 218-234 VALENCIA - PRD90 (2014) 9, 093006 NU-FIT JHEP 11 (2014) 052 (www.nu-fit.org)

KamLAND vs SOLAR discrepancy…



solar-ν physics vs reactor-ν physics?

(an experimental feature: i.e. bias?)

JUNO measurement of $\sin^2(2\theta_{12})\oplus\delta m^2$ (unique!)

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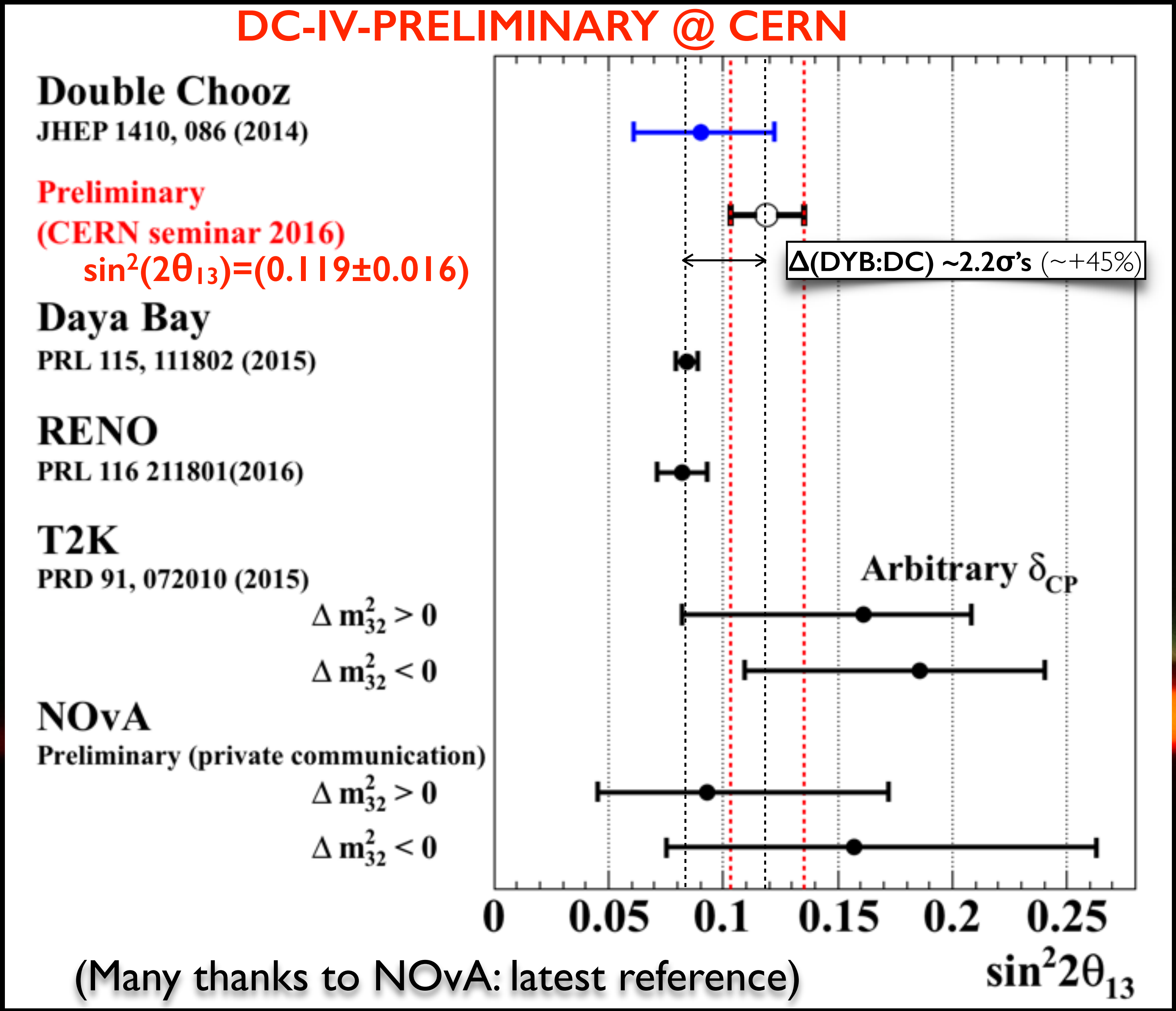
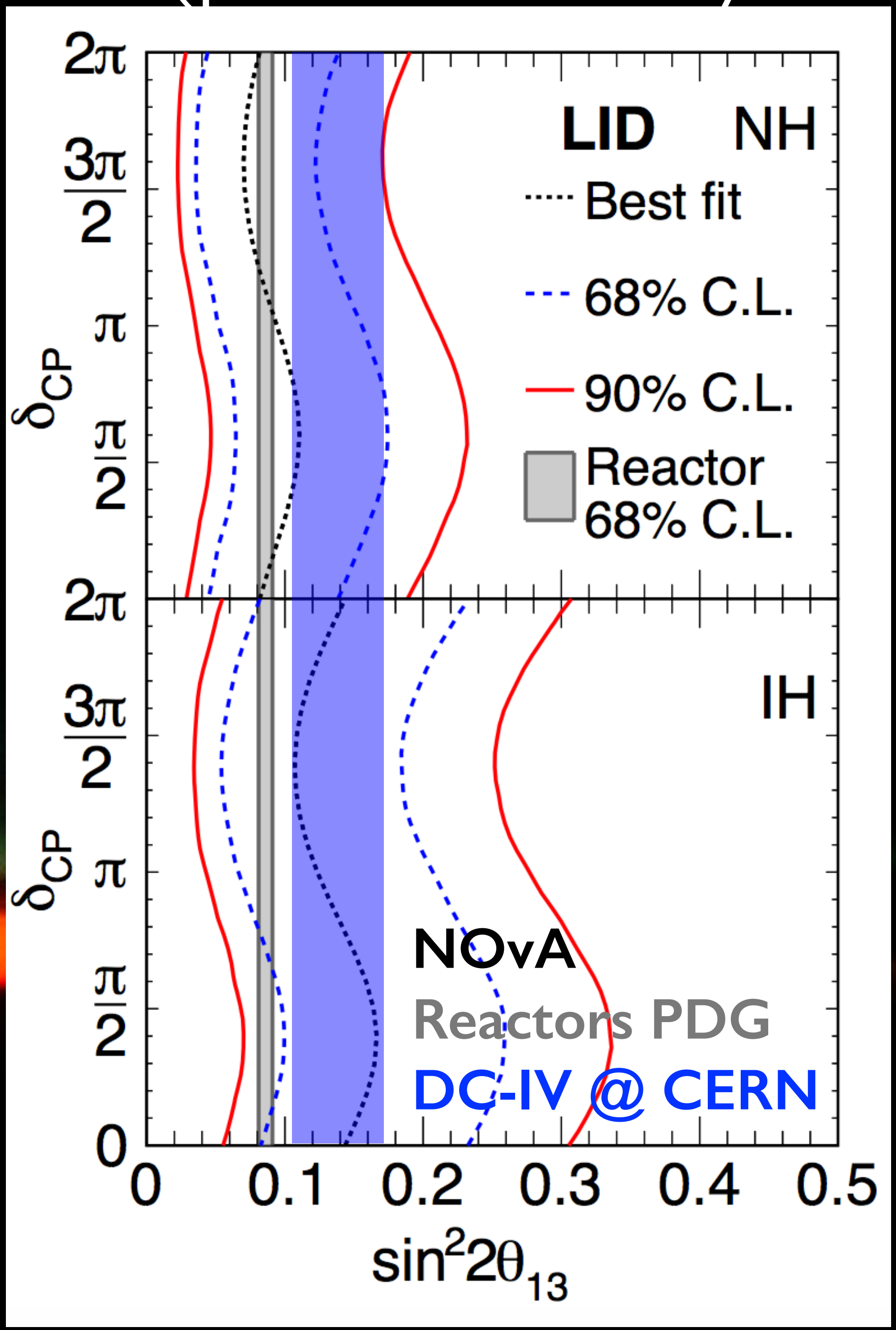
DC-IV @ CERN (preliminary…





Example: NOvA

DC & beams might prefer a higher θ13?

(beam "handicapped" by unknowns(θ_{23},δ_{CP}) to constraint θ_{13} alone, but richer physics)

reactor-θ_{13} key to solve **CP-violation** & **mass hierarchy**→ **redundancy fundamental**

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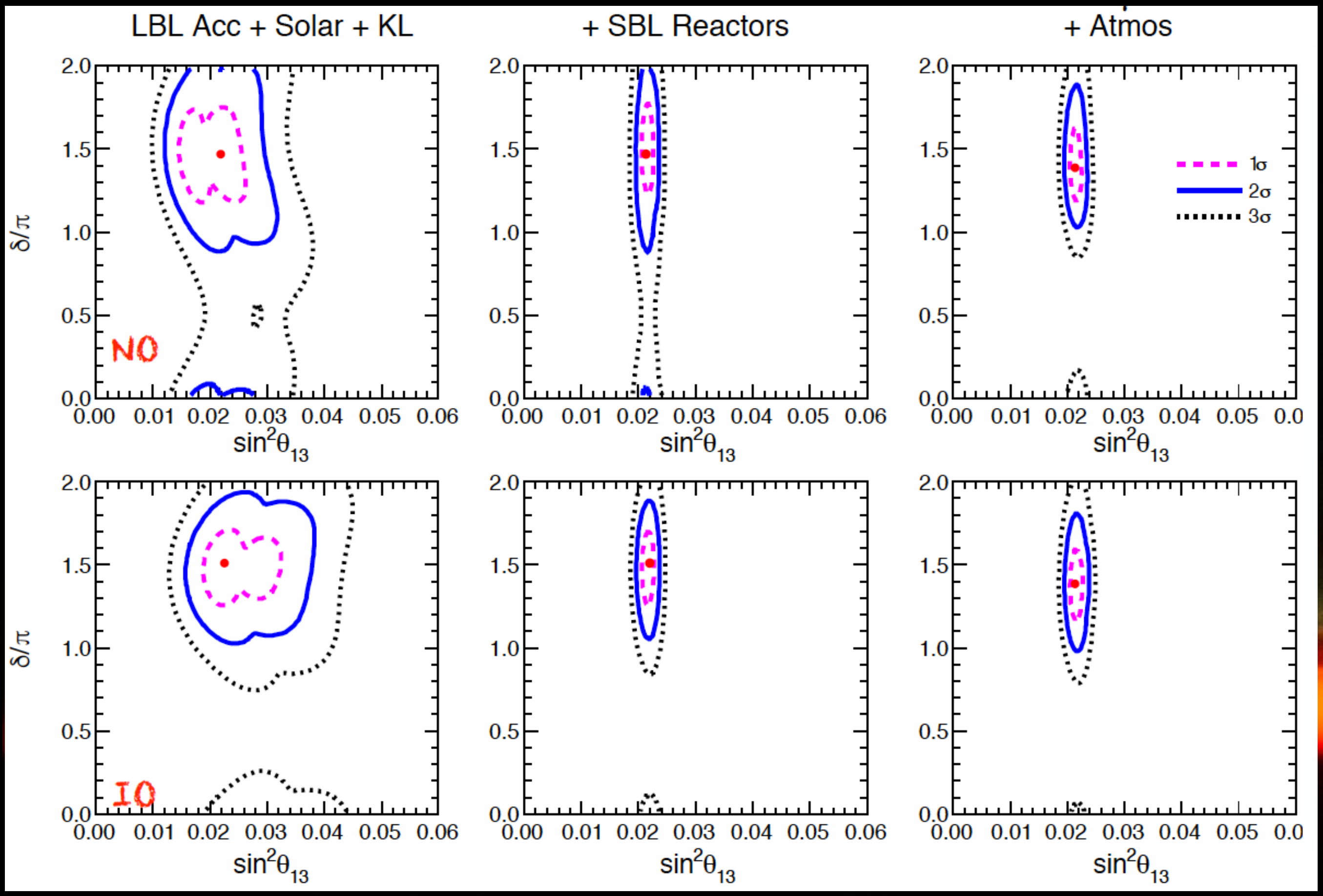
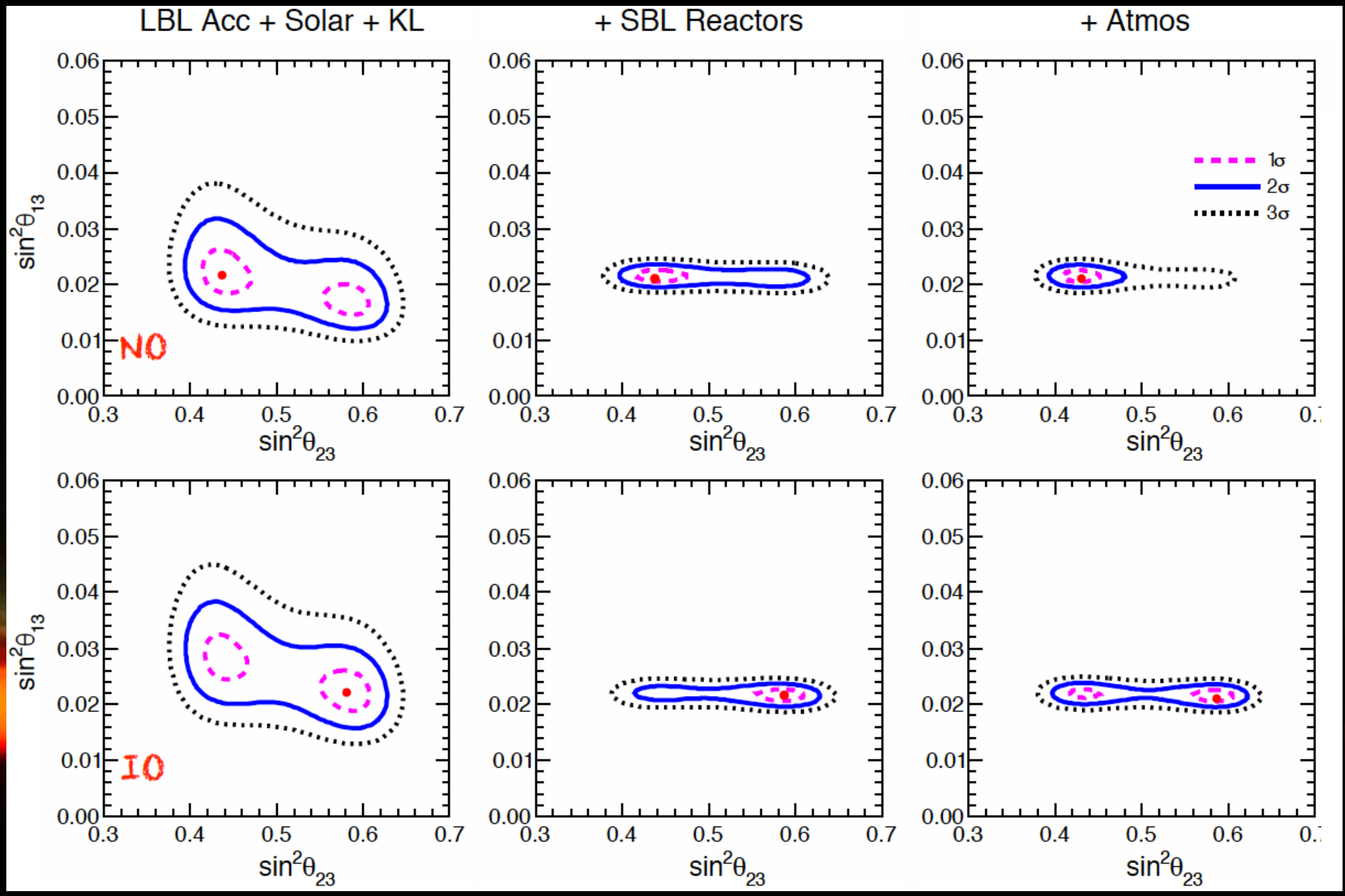
(*Marrone et al* @ NEUTRINO-16) θ13 global impact…

much knowledge on 3ν oscillation model depends on θ13





θ13 vs δ(CP)

⇒ maximal CP? [δ(CP)≈π/2]

θ13 vs "θ23-octant"

⇒ do we know anything?

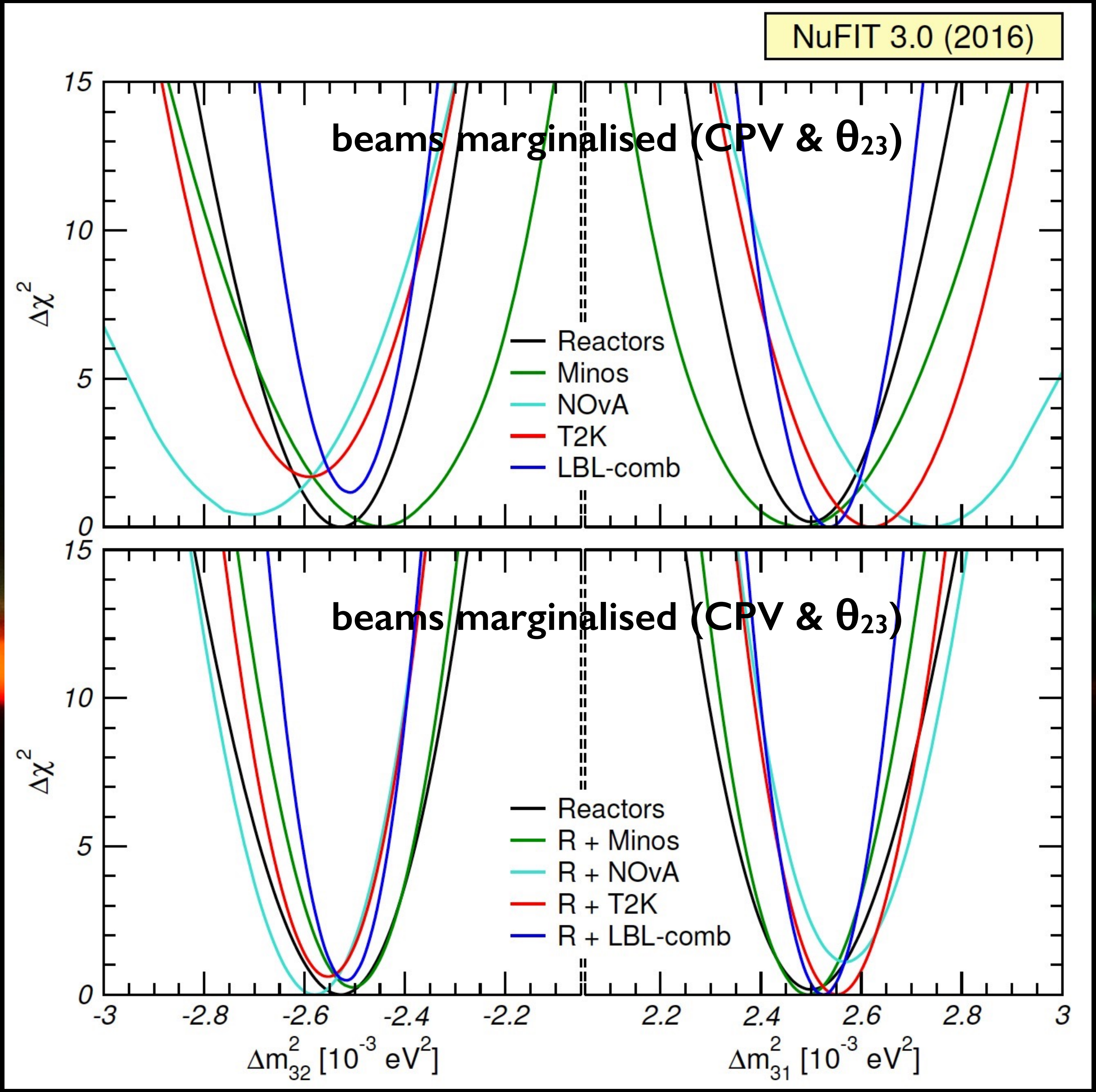
θ13 measurement (value & error) critical implications

(ex. predict CPV correct?)

Δm^2 measurement status…

LBL measurements
(only θ13 constraint)

LBL measurements
(full constraint)



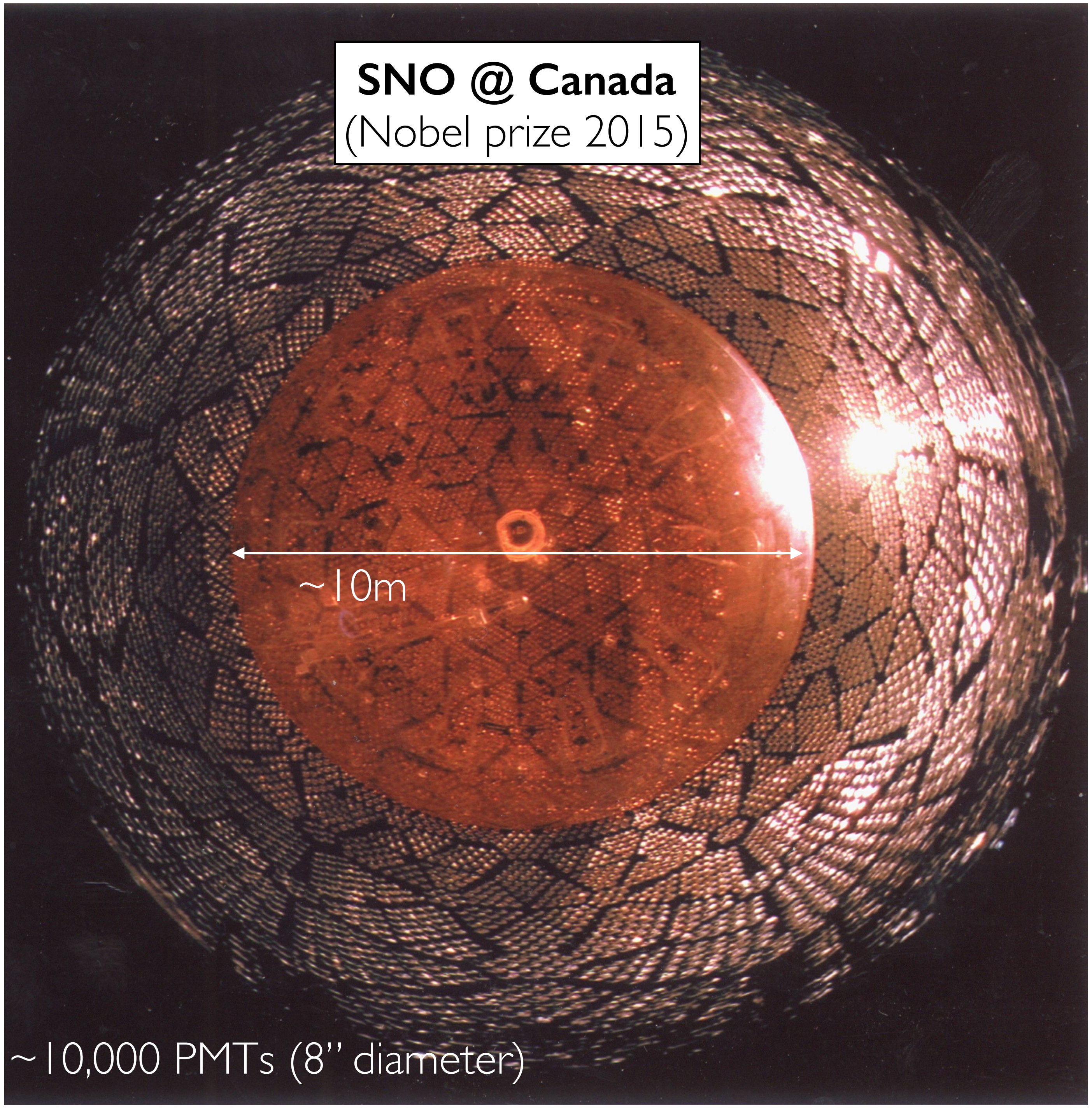
possible inconsistency wrt beams (several effects)?

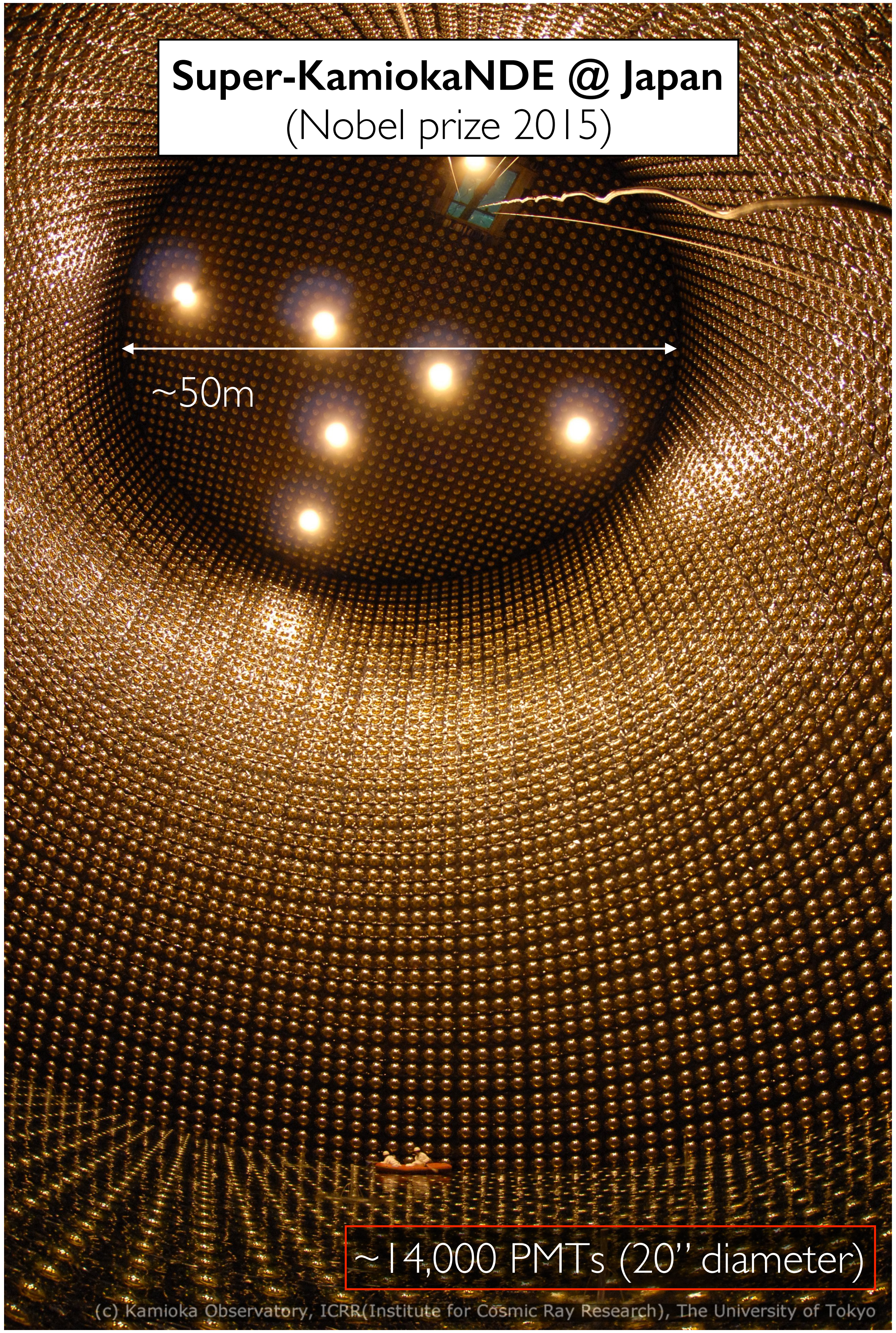
(**JUNO's Δm^2**⇒ over-constrain 3ν model⇒ **new physics?**)

the detector…

most challenging
(many novelties)

the JUNO detector (predecessors)…





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

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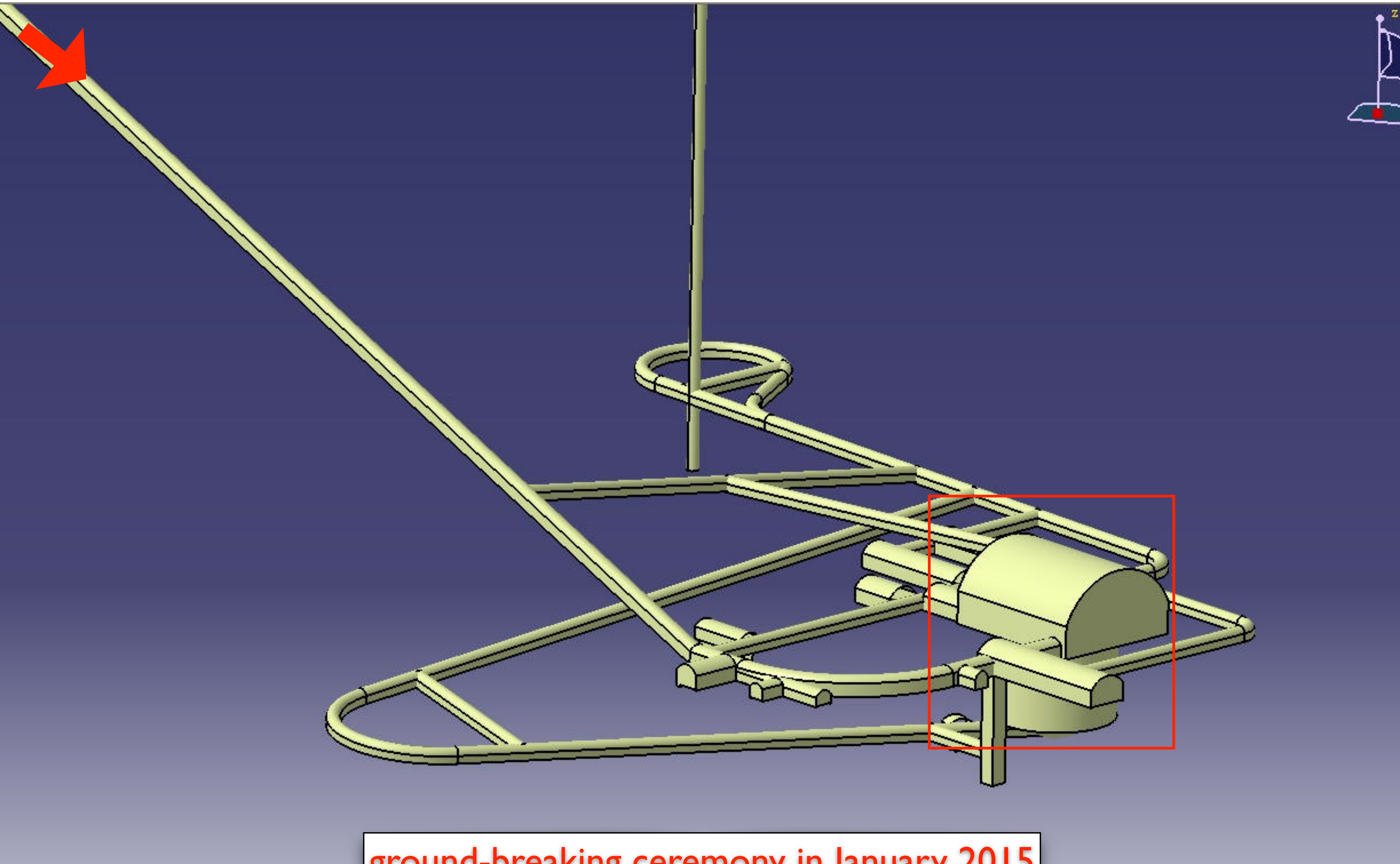
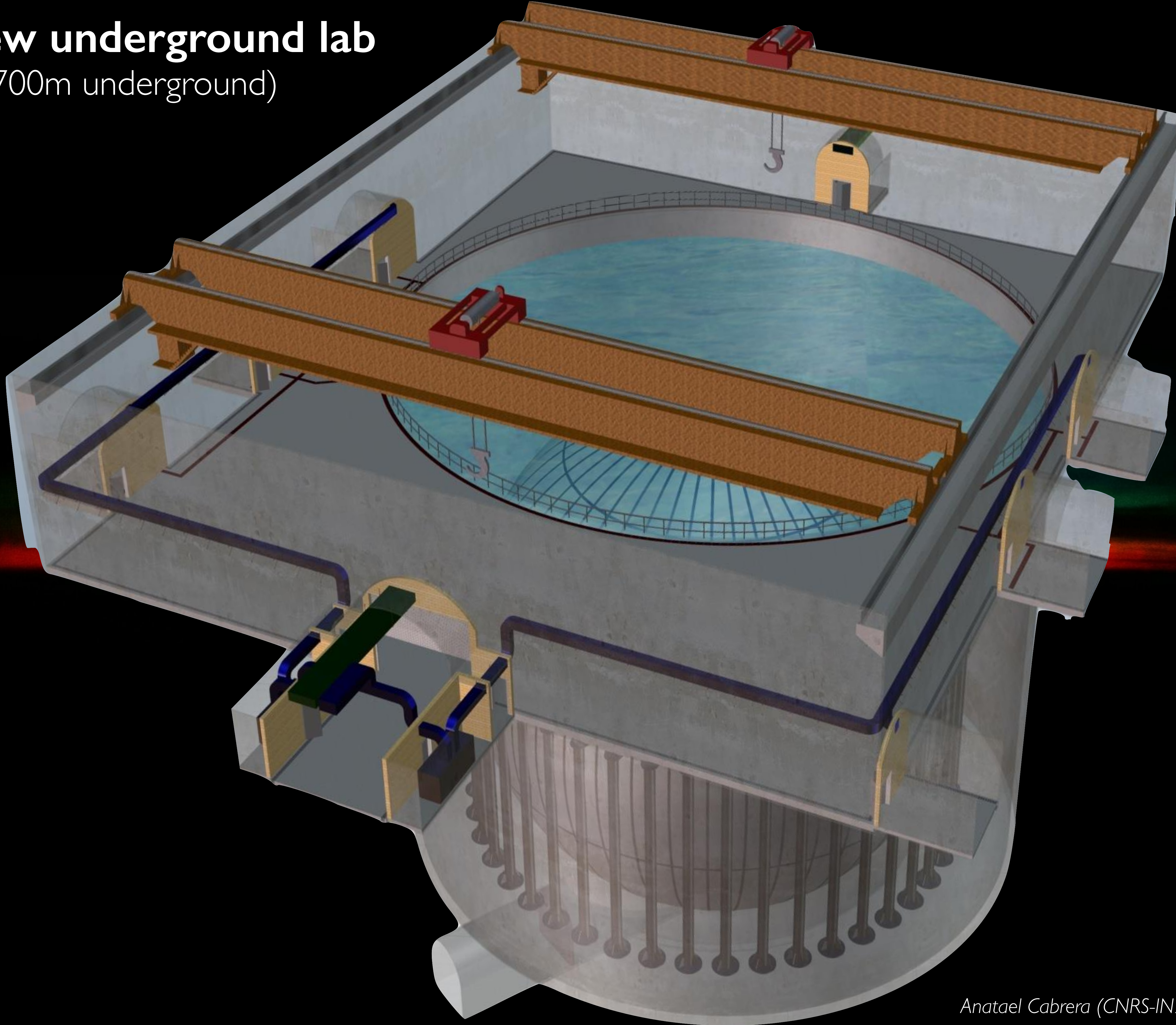
new laboratory underground



ground-breaking ceremony in January 2015

new underground lab
(~700m underground)



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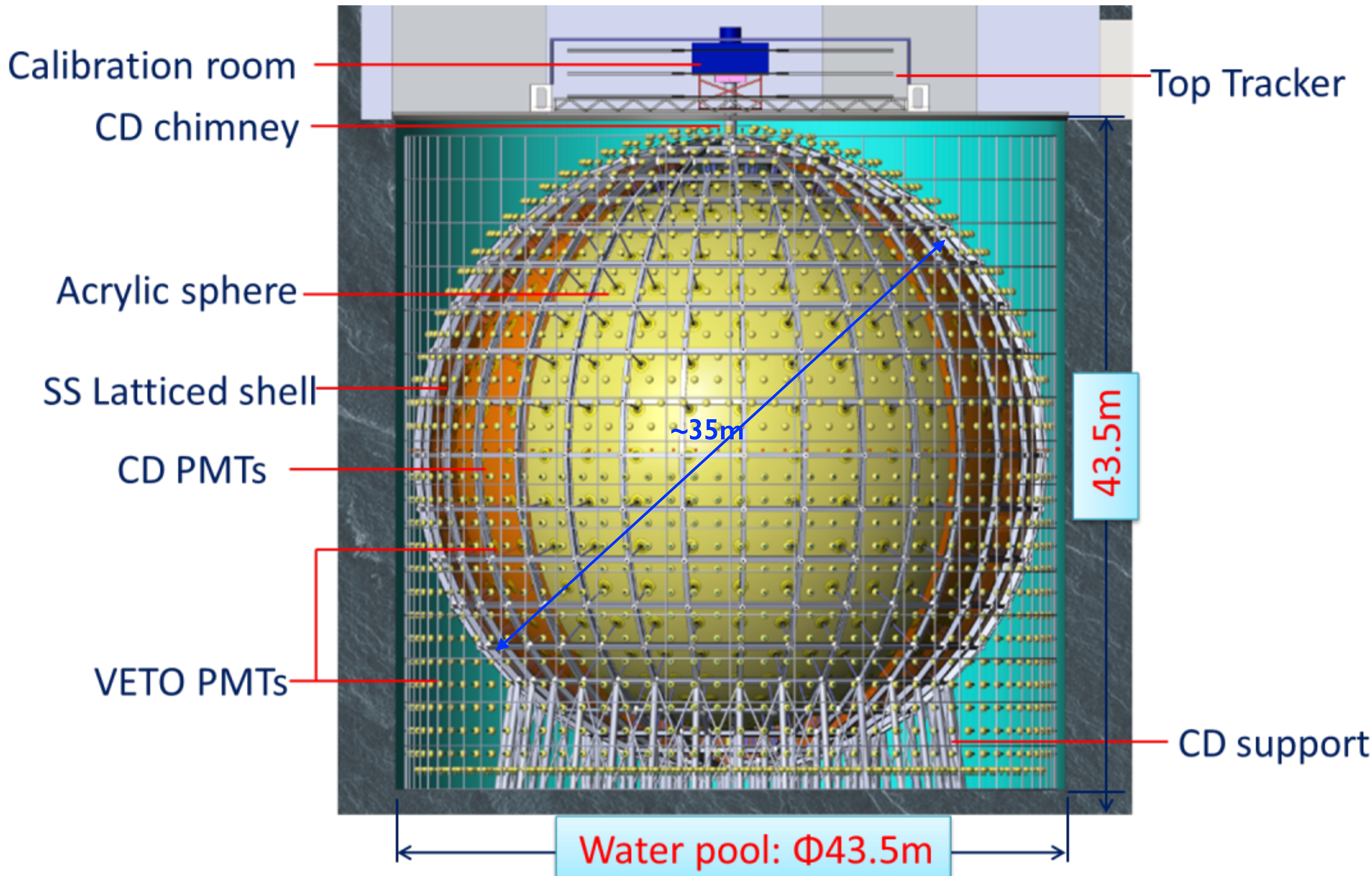
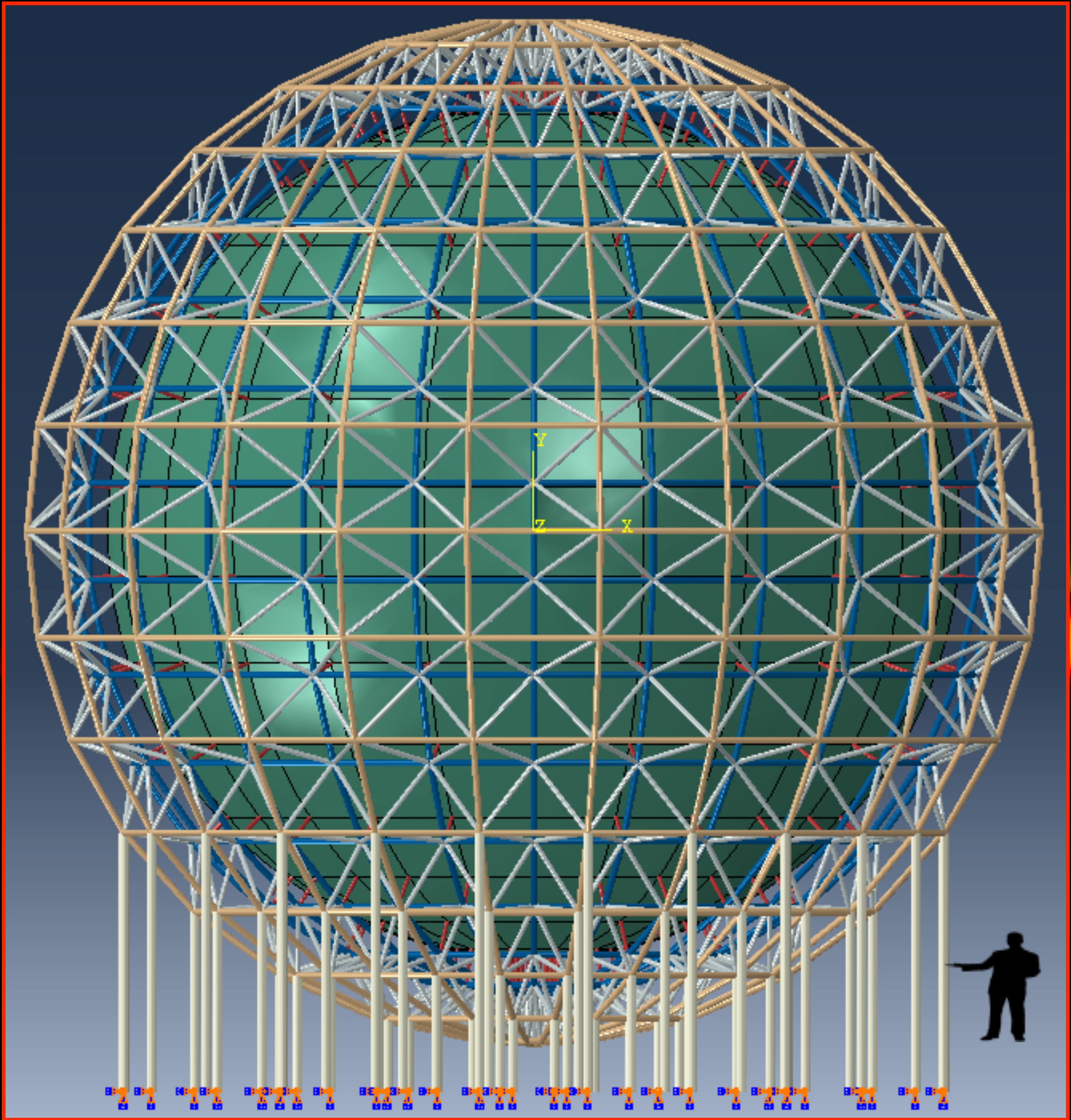
civil construction status…

- The civil construction started in 2014.
- The detector will be installed 700 m underground.

the JUNO detector…

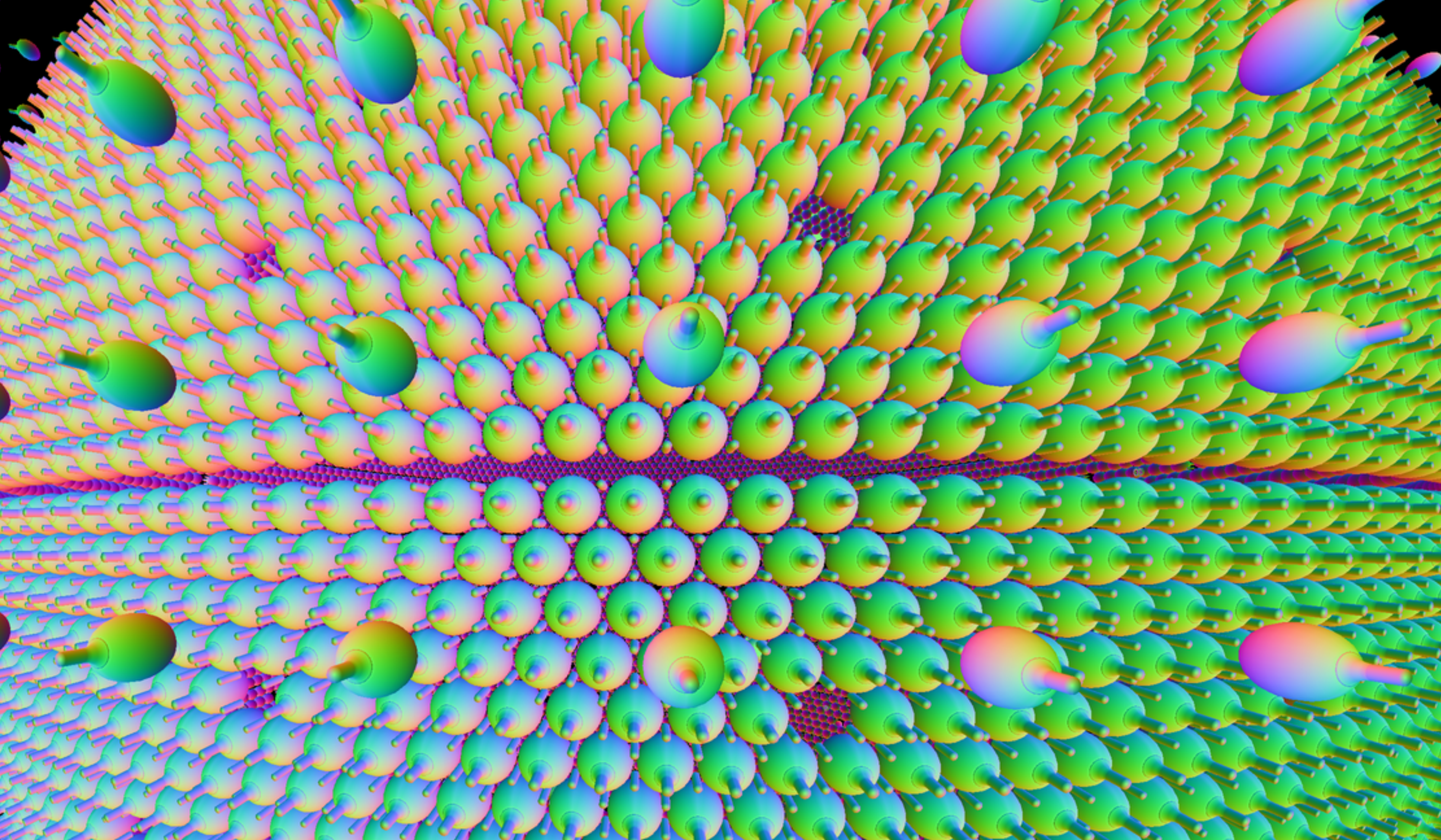


JUNO neutrino detector system…



~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…

JUNO-IN2P3 leading contribution

(APC+CPPM+CENBG+LLR+OMEGA+SUBATECH)

20 laboratories (9 countries) so far…

our (very international) team…

Armenia
- Yerevan Physics Institute (Yerevan)

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

Belgium
- UBL (Brussels)

Chile
- PUC (Santiago) **(project/physics coordination)**

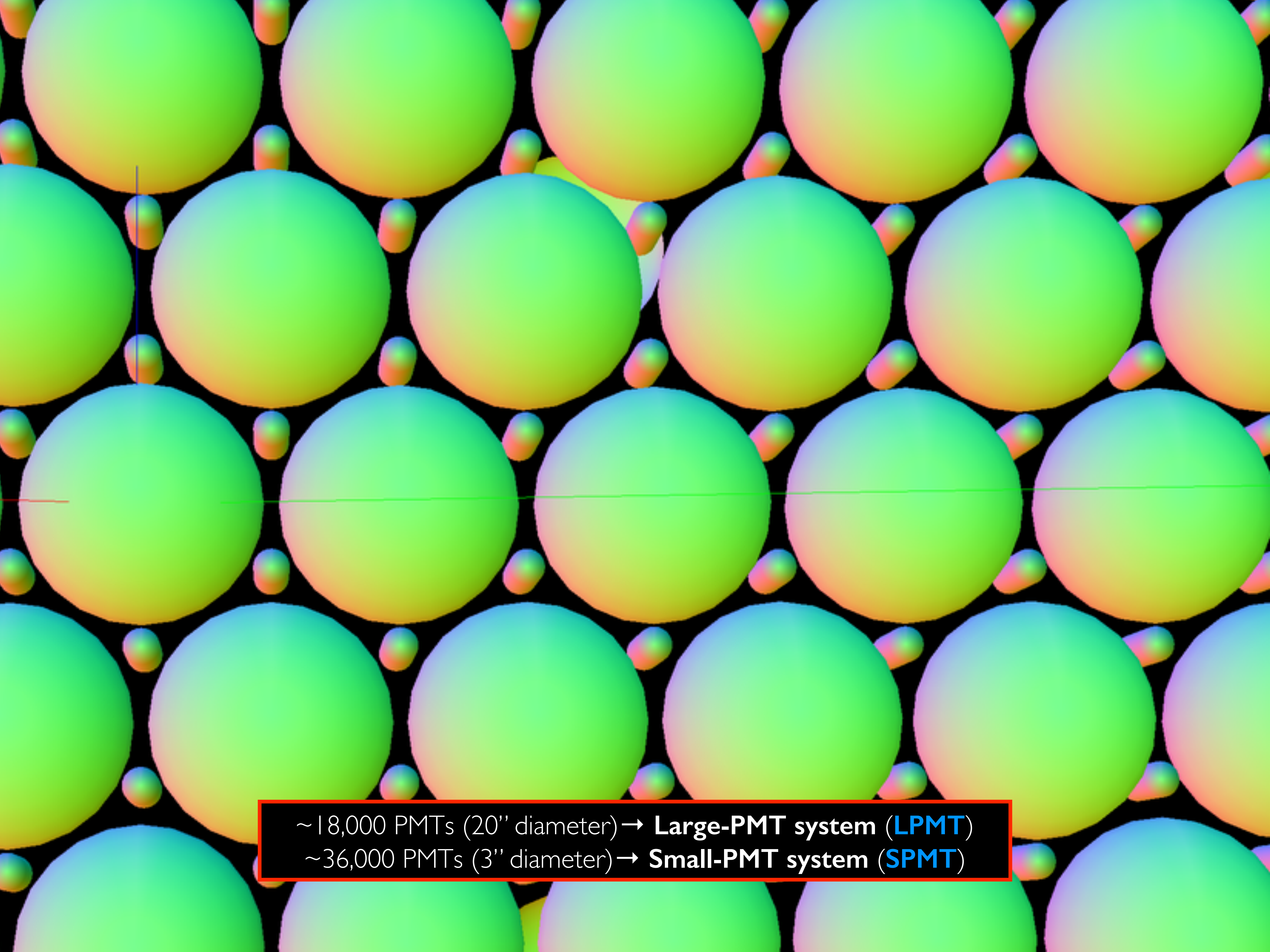
China
- IHEP (Beijing) **(integration/installation coordination)**
- SYSU (Guangzhou)

France
- APC (Paris) **(project/physics coordination)**
- CENBG (Bordeaux) **(technical coordination)**
- CPPM (Marseille)
- LLR (Paris)
- OMEGA (Paris)
- SUBATECH (Nantes)

Italy
- Padova-INFN (Padova)

Russia
- Moscow State University (Moscow)
- Institute of Nuclear Research & Russian Academy of Science (Moscow)

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



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

don't forget…

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? —

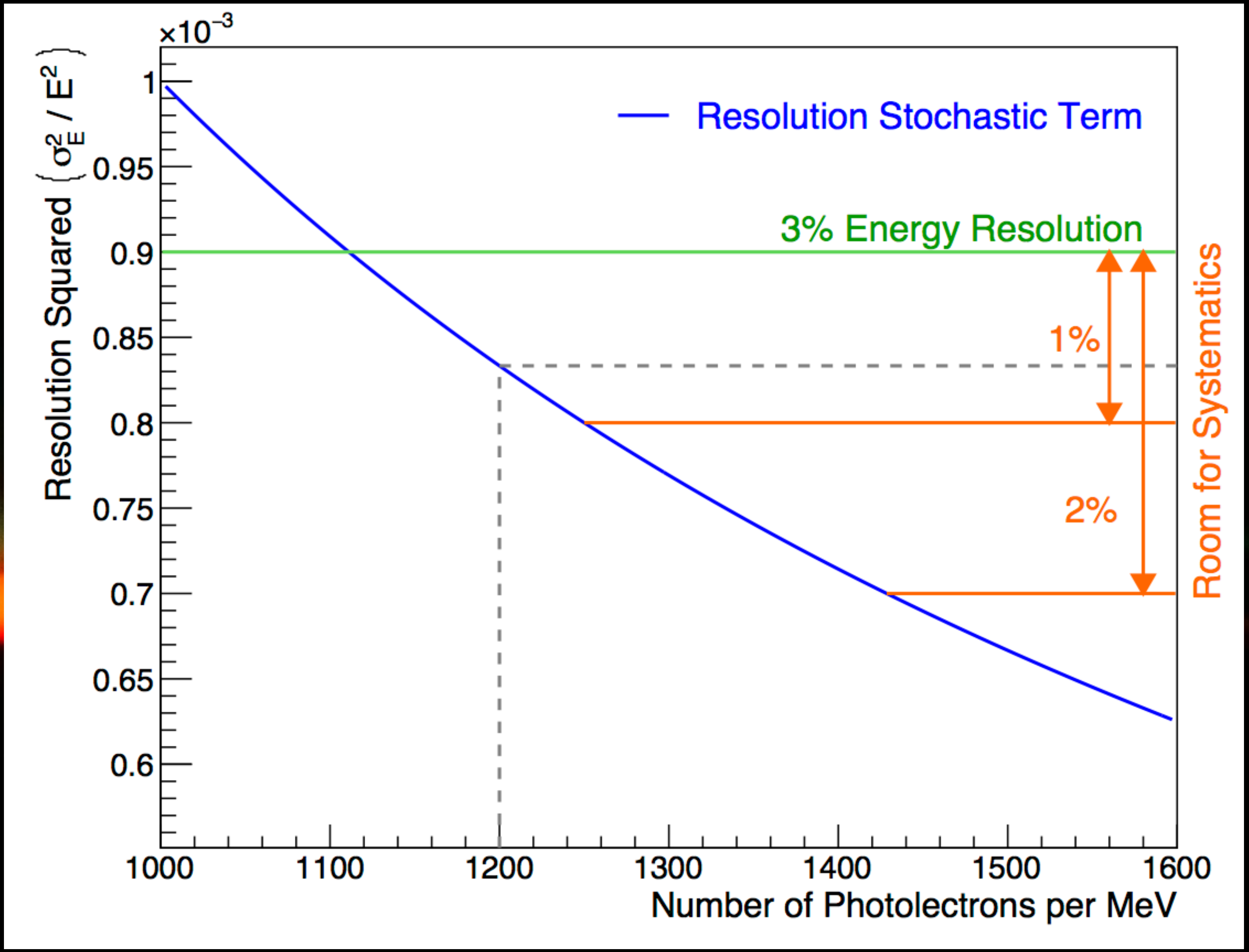
JUNO a new calorimetry regimen (ν-physics)…

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

(1200PE/MeV) (??%)

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

usual approximation

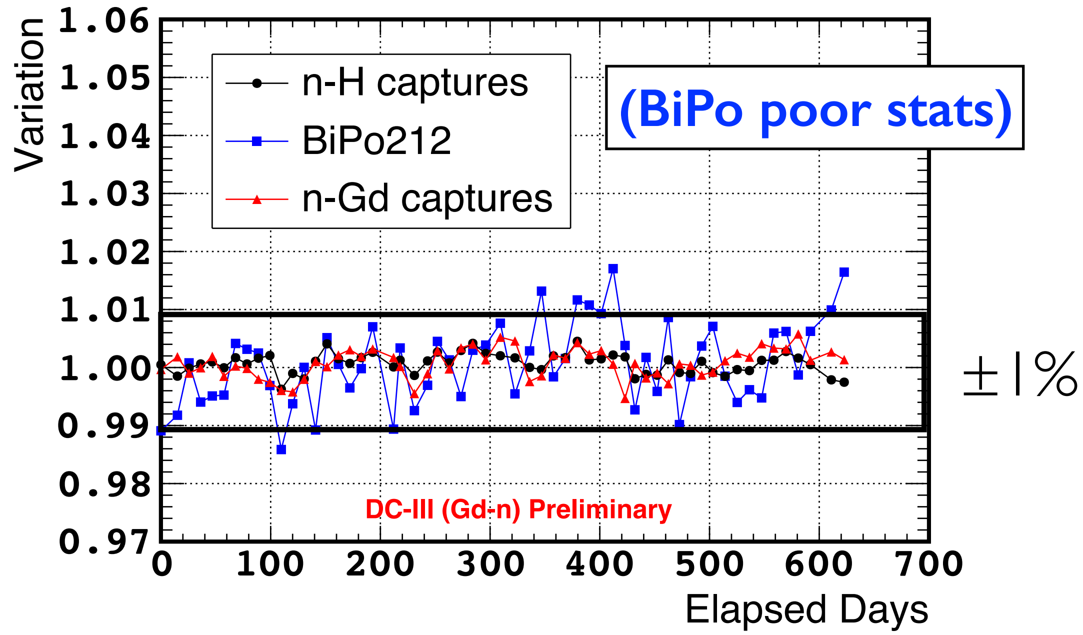


JUNO's highest light level ever⇒ new calorimetry regime

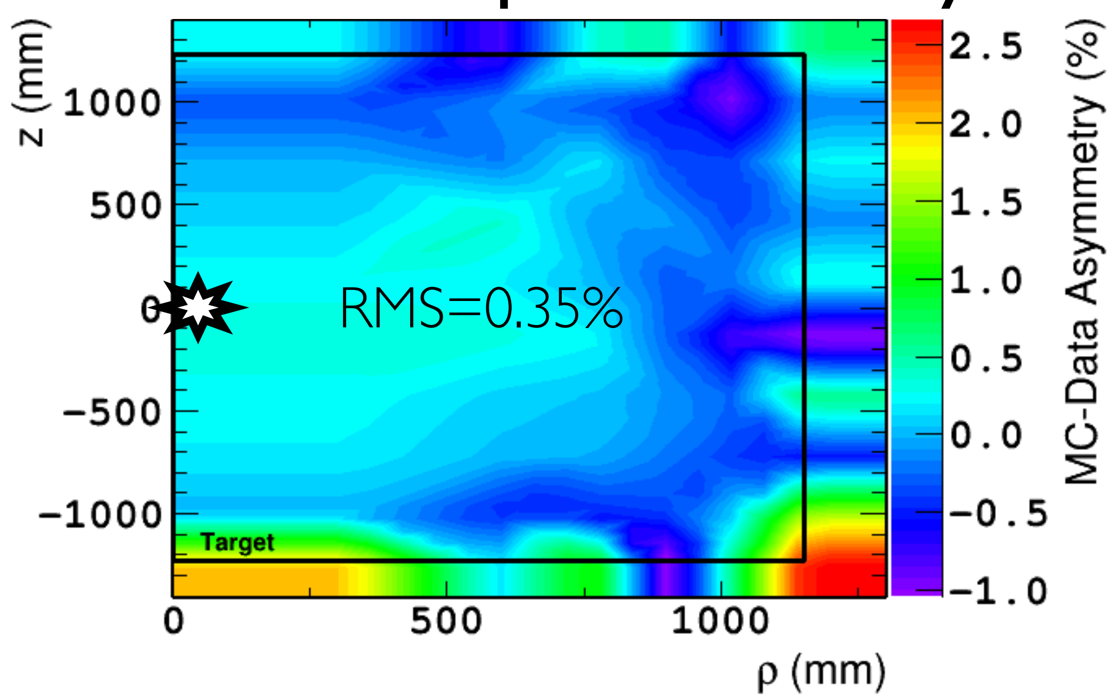
(**challenge: non-stochastic term**)

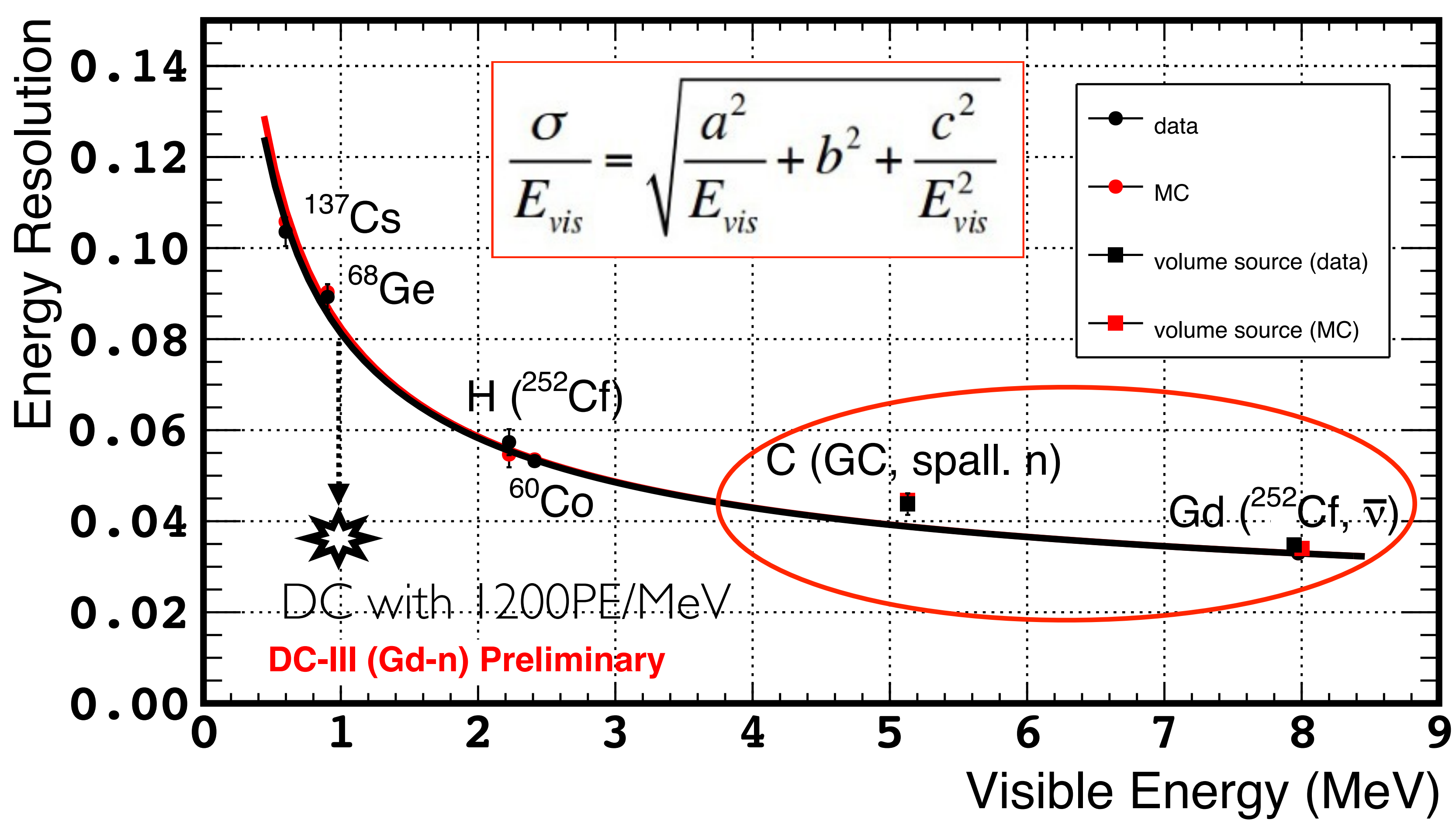
DC as prototype for JUNO…

control of response stability



control of response uniformity





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?)

Anatael Cabrera (CNRS-IN2P3 & APC)

no perfect world…

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

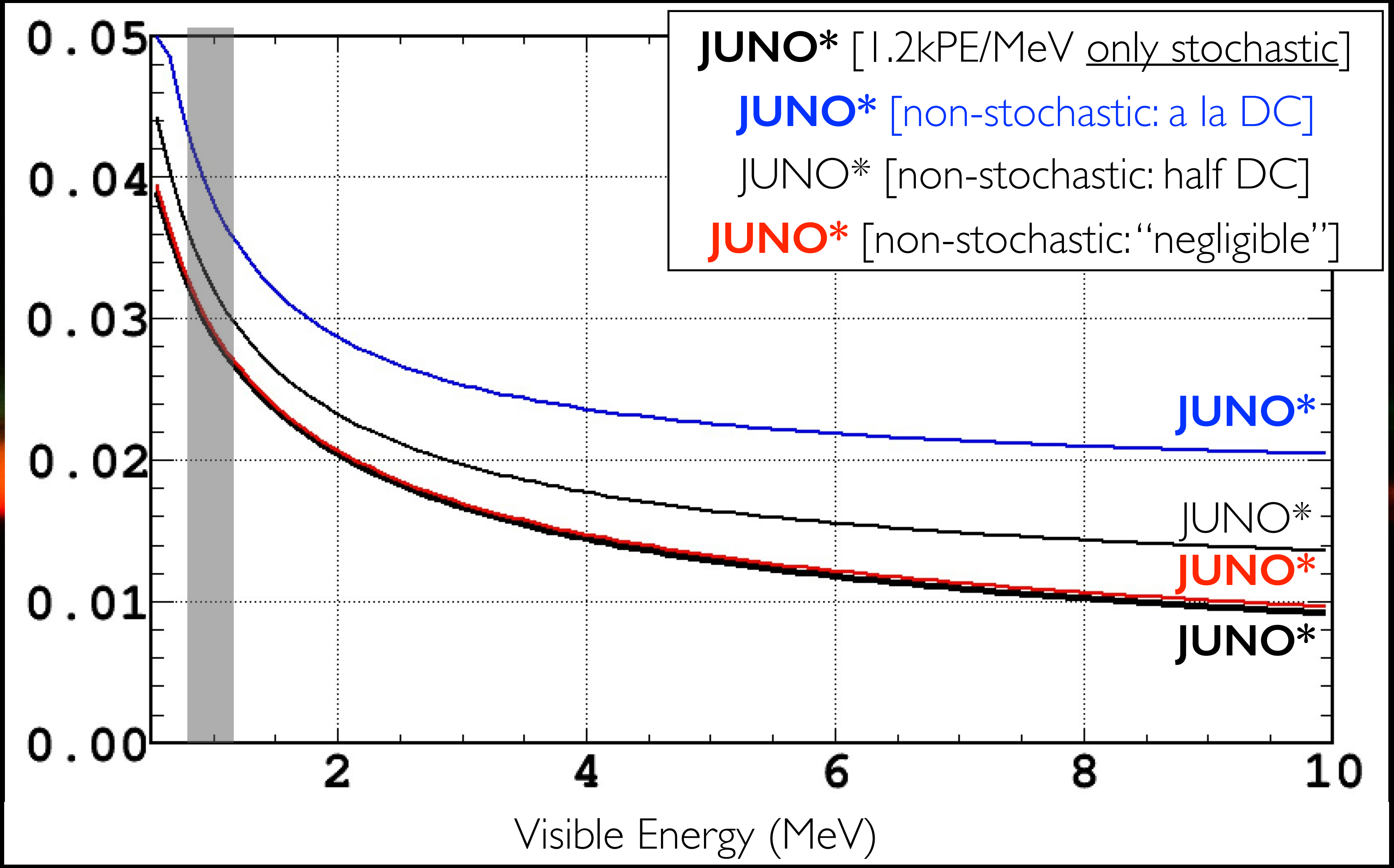
(1200PE/MeV) (??%)

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

~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!!**

Anatael Cabrera (CNRS-IN2P3 & APC)

control of systematics…

(i.e. non-stochastic effects)

the double calorimetry…

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

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

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

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

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

~2x

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

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

"double-calorimetry"

articulate 2 energy estimators (different behaviours)

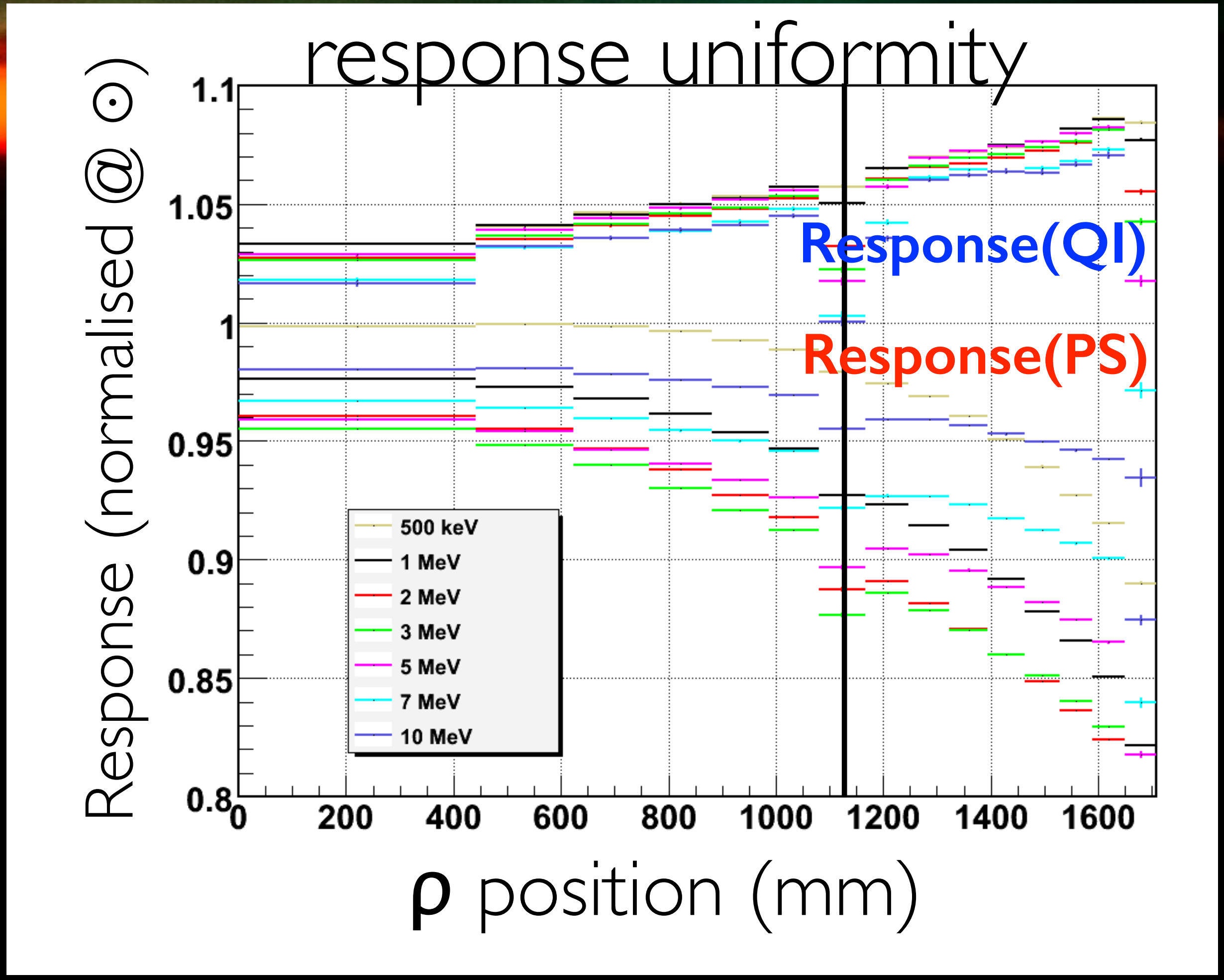
Energy(photon-counting) i.e. digital (**PS**)

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

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

[via NN, correction, etc]

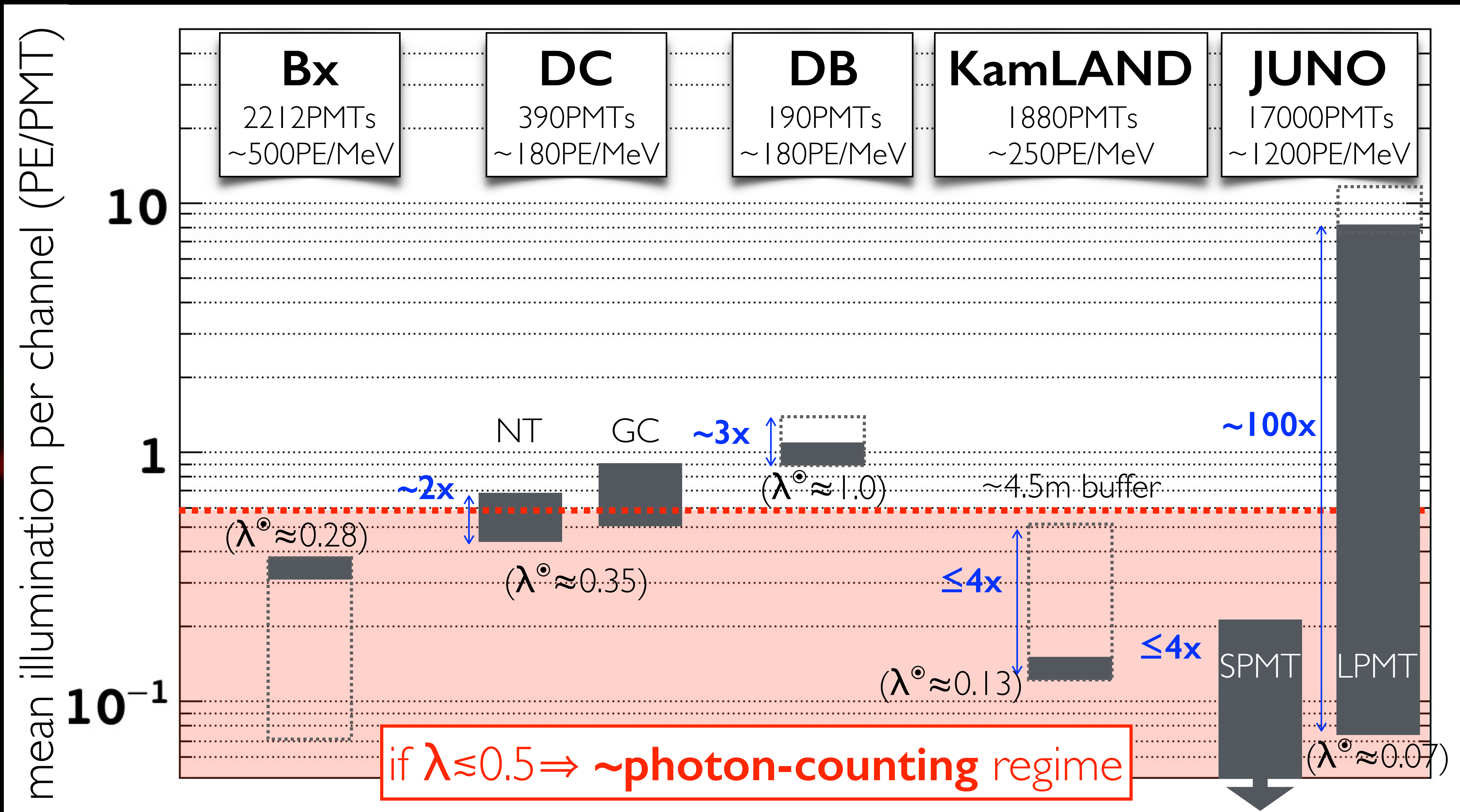
control/reduction $\sigma(E)^2_{non\text{-}stoch}$ & redundancy
[if $\pm\Delta m^2 \rightarrow$ convince JUNO can]



the JUNO challenge…

@1MeV

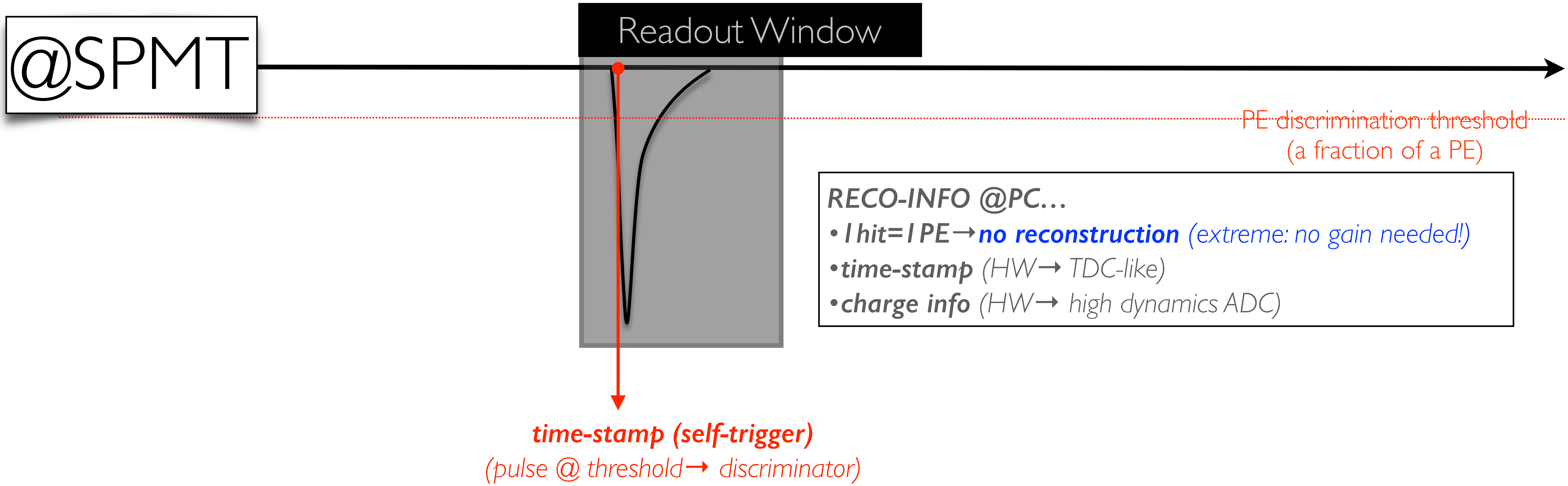
λ^⊙ = mean illumination per channel @ center



HIGHEST precision calorimetry (≤3% @ 1MeV)
⊕
LARGEST dynamic range in calorimetry (channel-wise) [⇒ **uniformity⊕linearity⊕stability**]

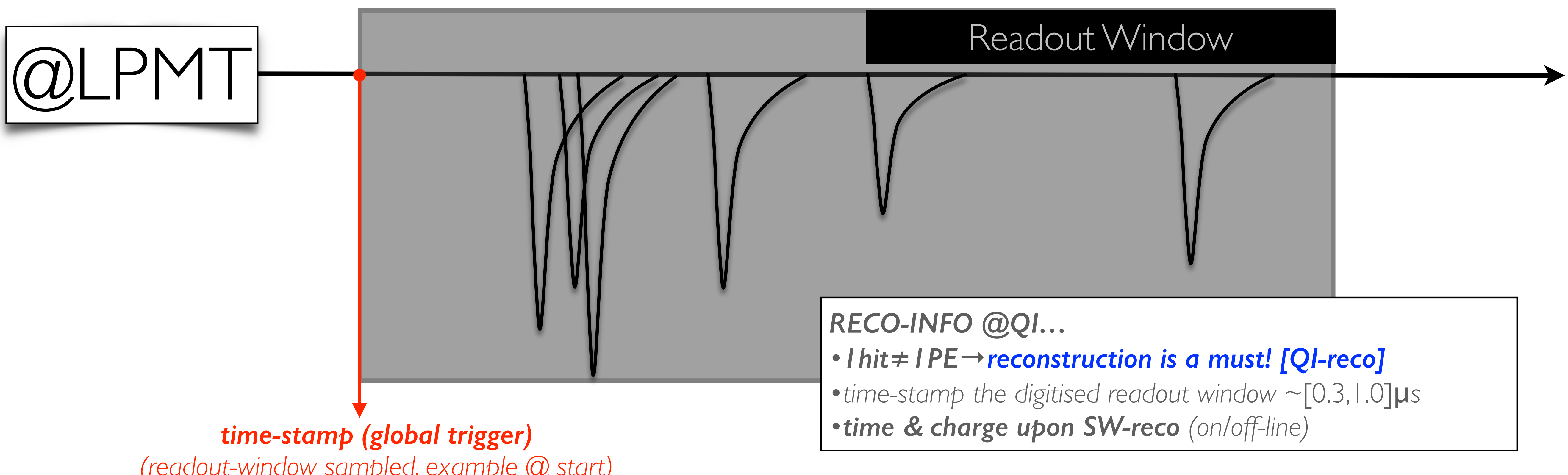
Anatael Cabrera (CNRS-IN2P3 & APC)

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)*

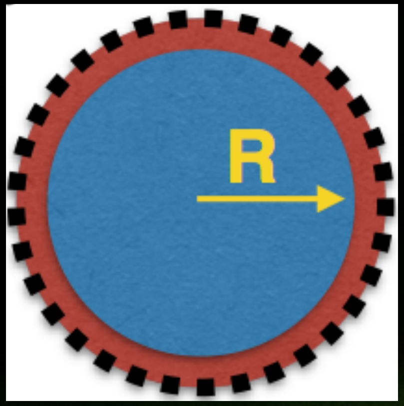


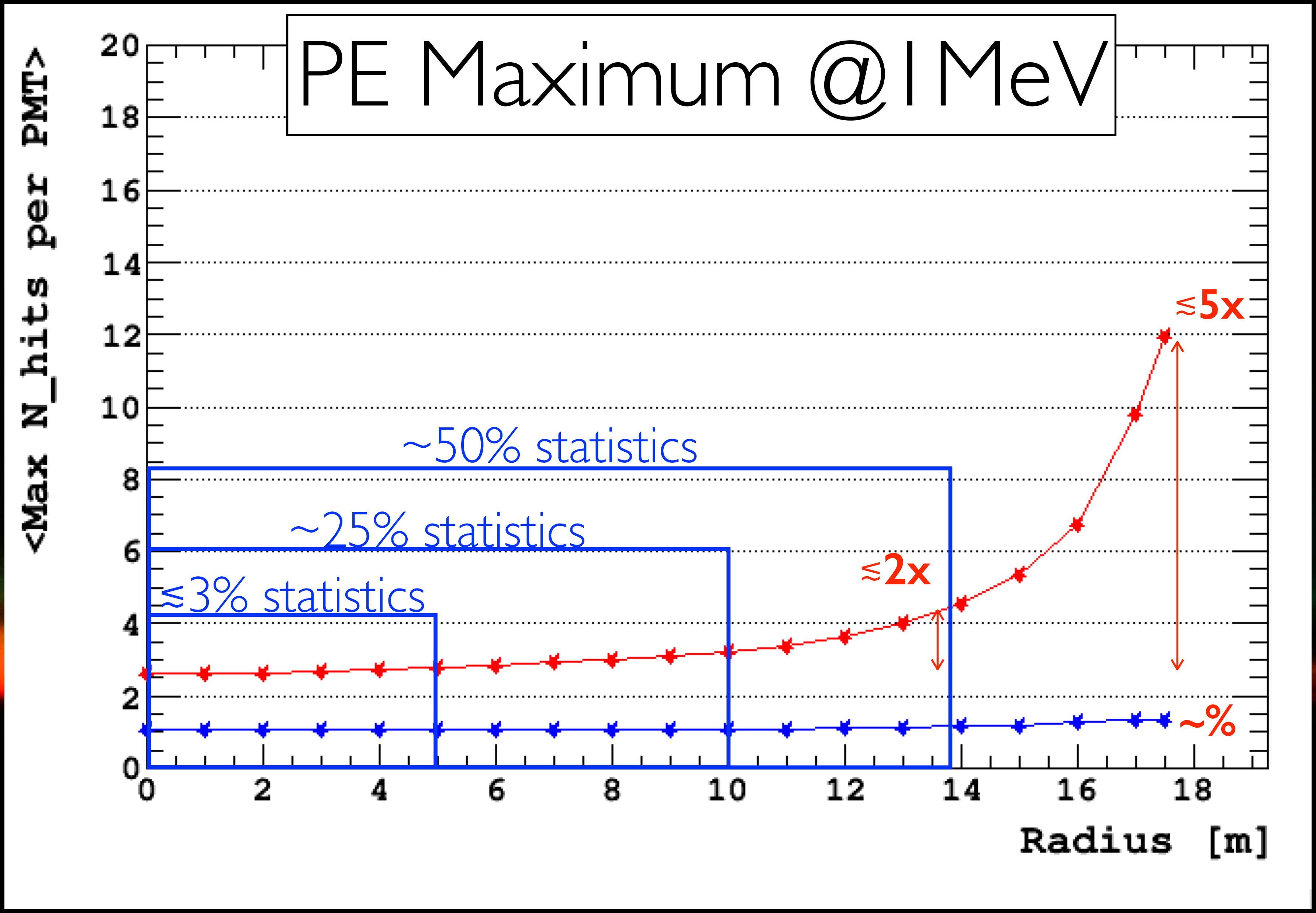
RECO-INFO @QI…

- *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)*

Anatael Cabrera (CNRS-IN2P3 & APC)

the SPMT & LPMT calorimetry regimes…





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

(wildest variation in region with large fraction of statistics)

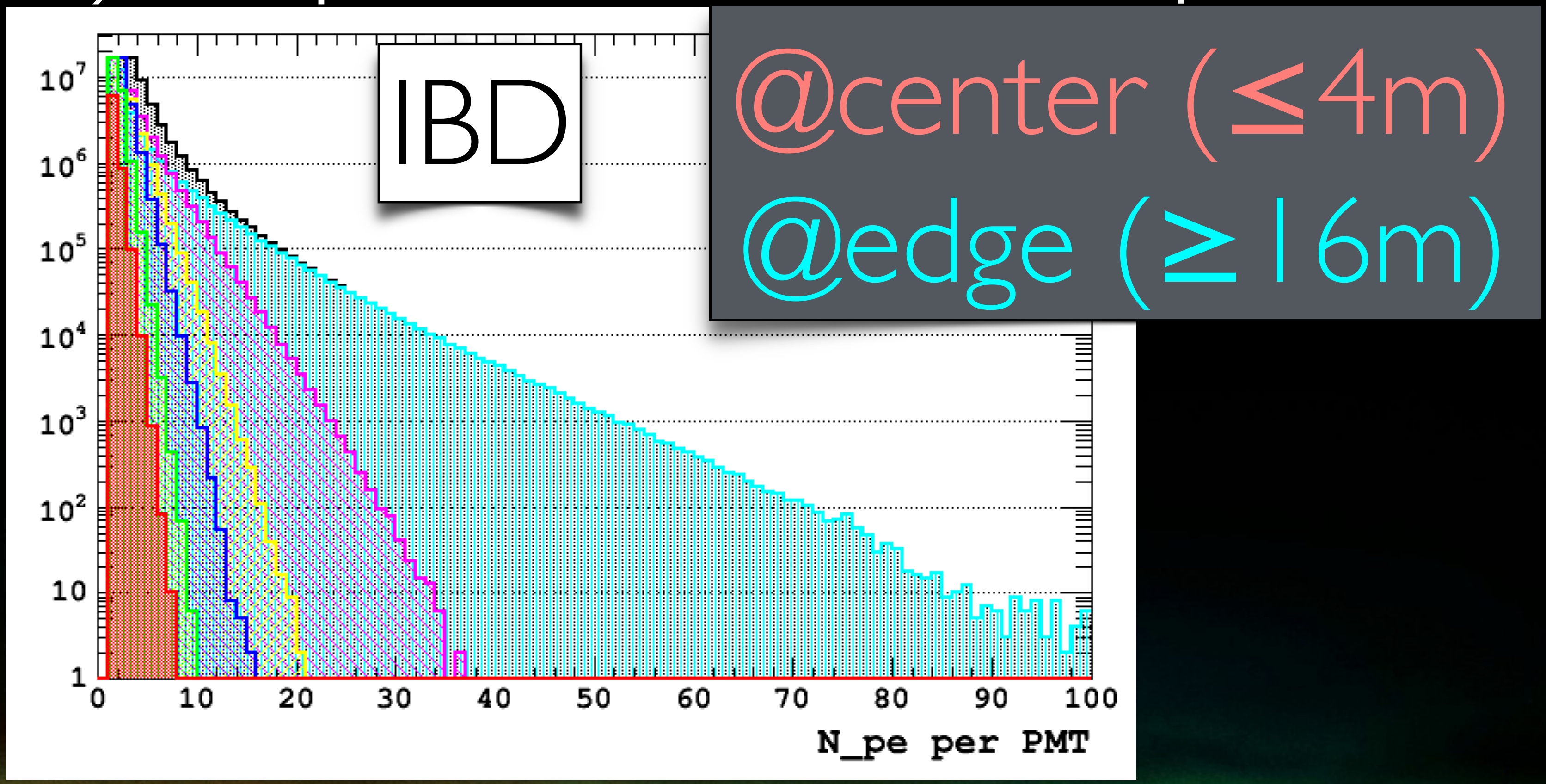
(opposite) **SPMT has FLAT response across volume (by construction)**

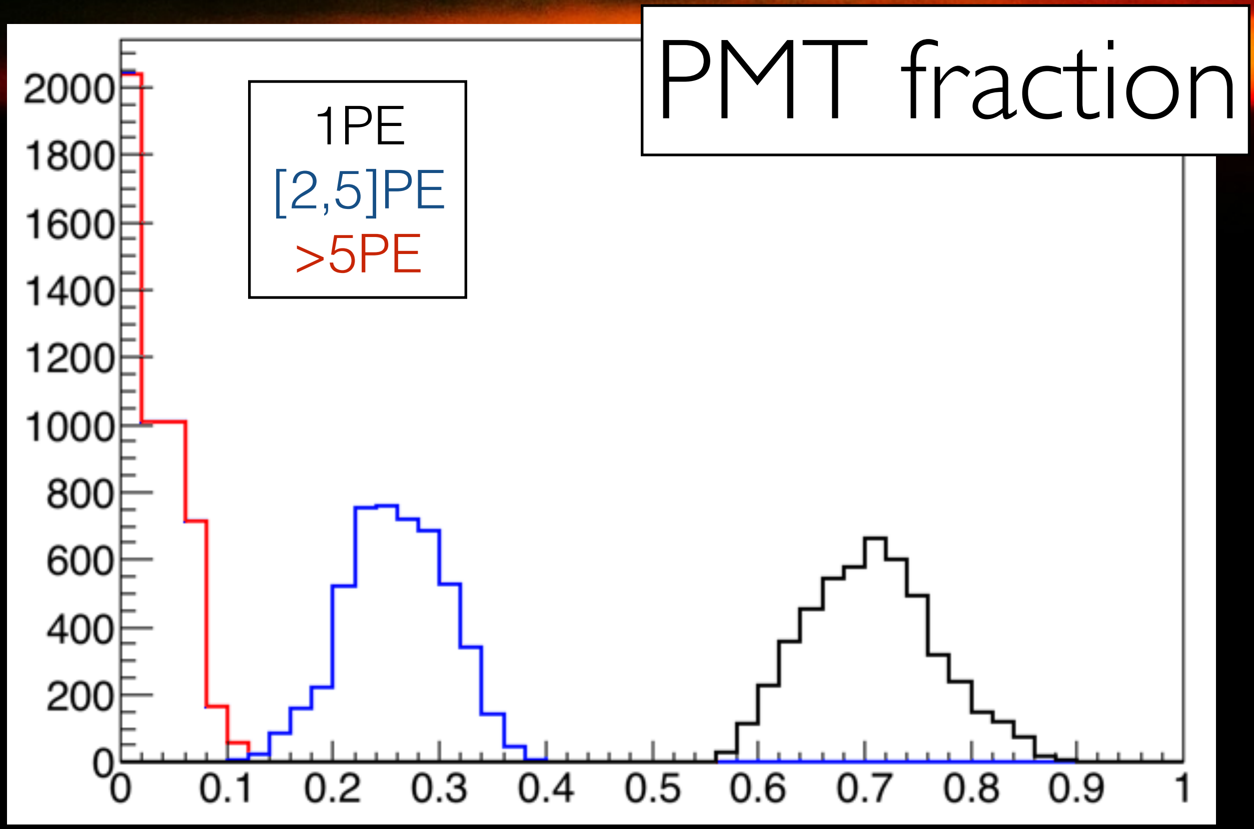
(**SPMT ideal input for Trigger**)

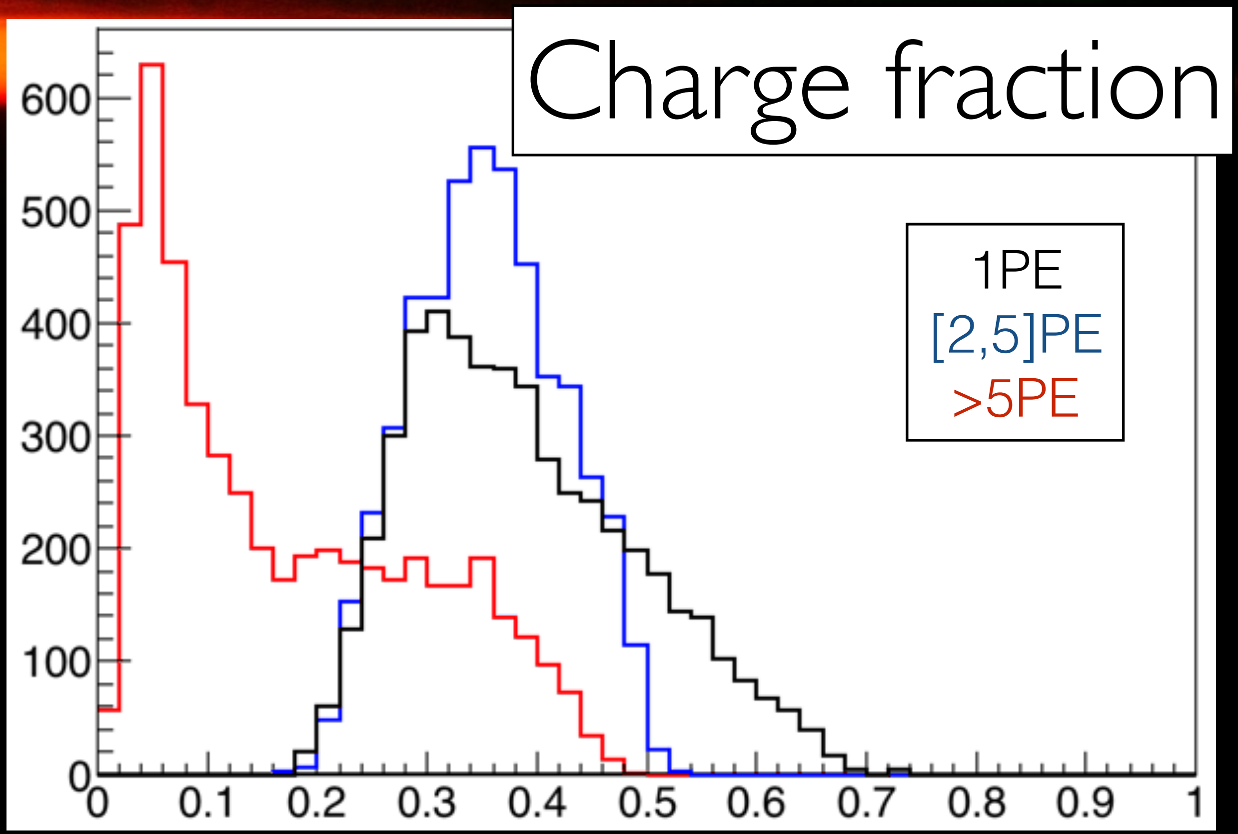
(illustration) response/channel vs position…

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

LPMT only



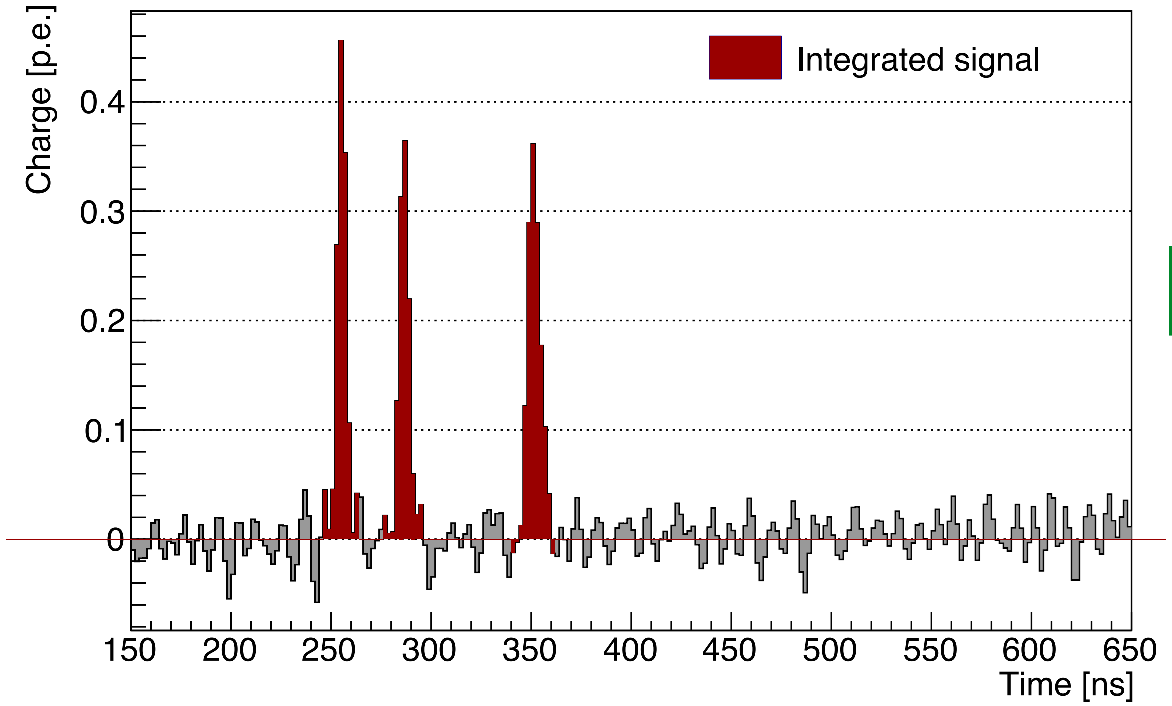




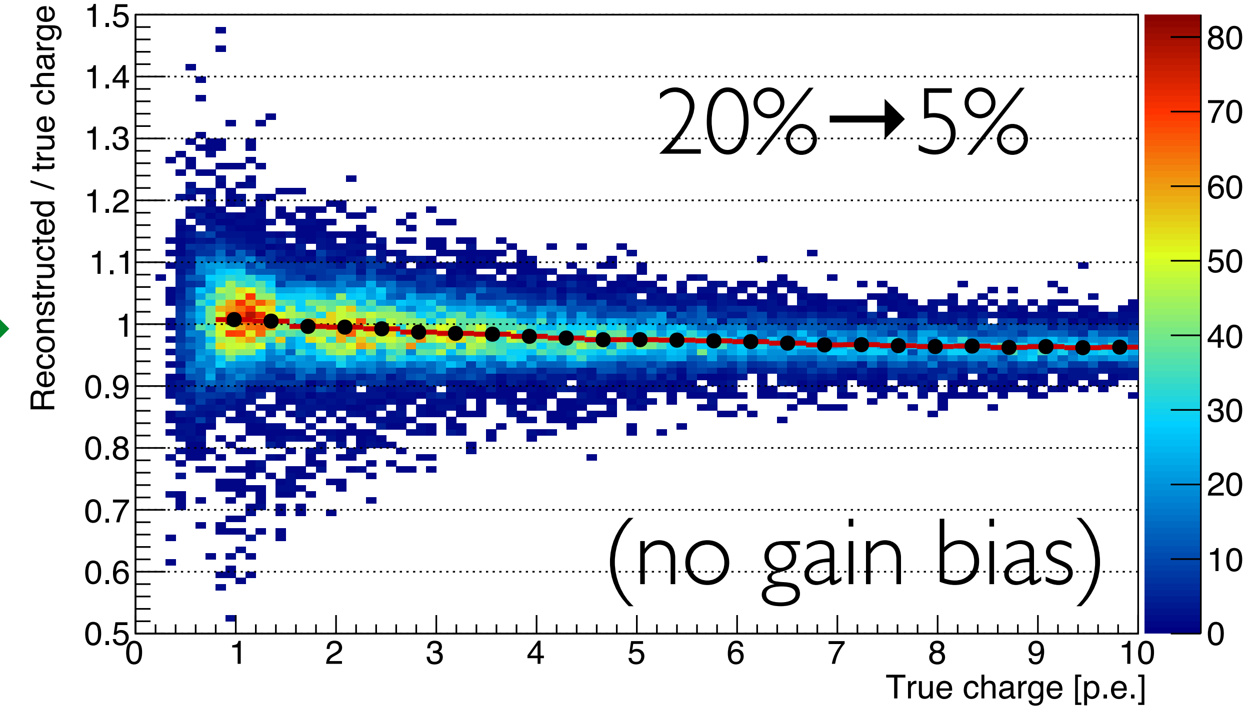
small bias in few LPMTs⇒ large impact to over calorimetry!

energy reconstruction bias estimation (I)…

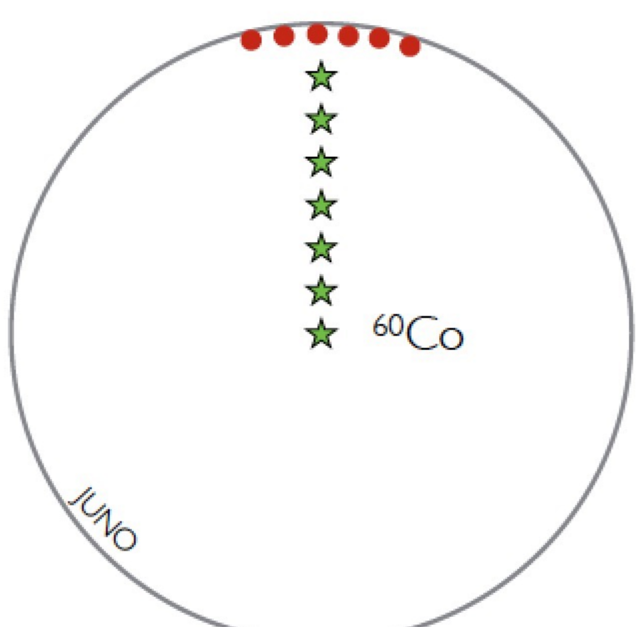
realistic pulse reco (QI)

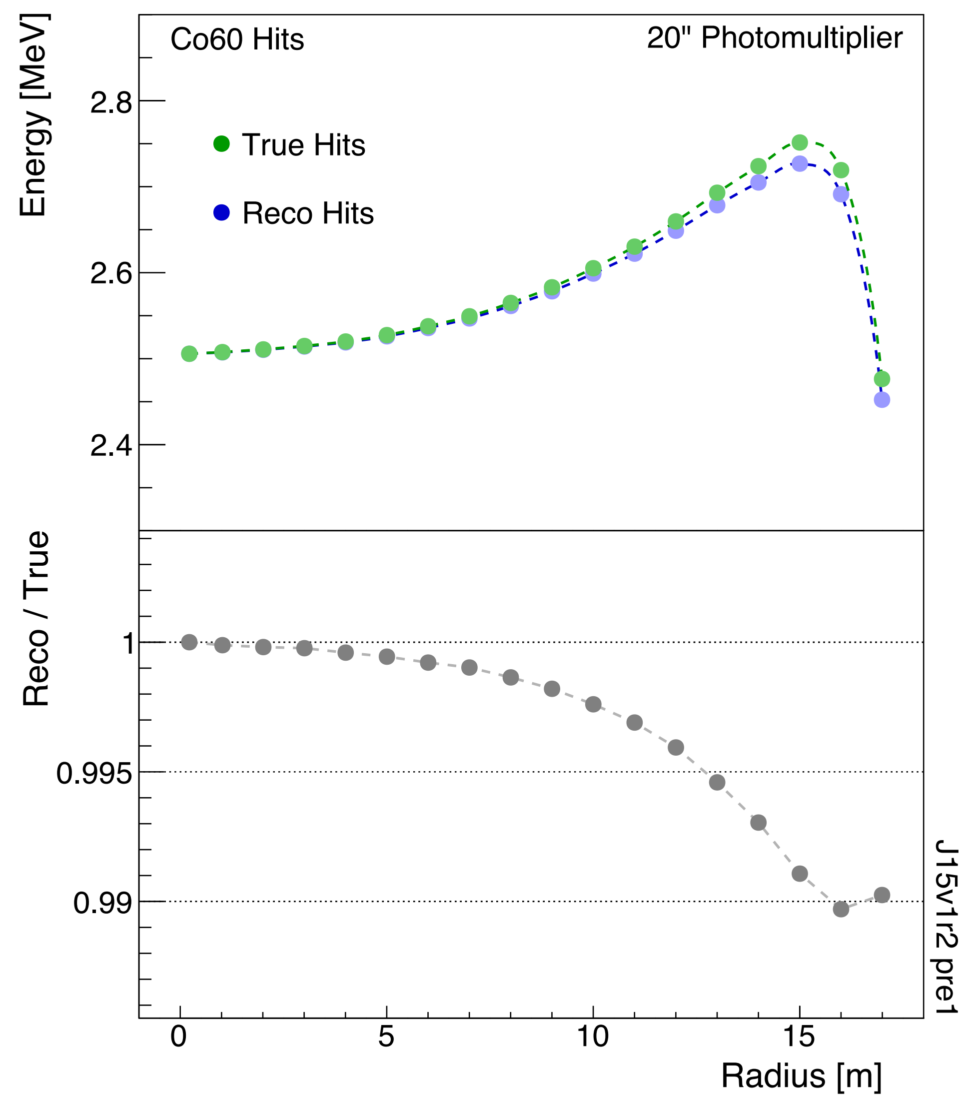


non-linearity (QI)



calibration mimicking





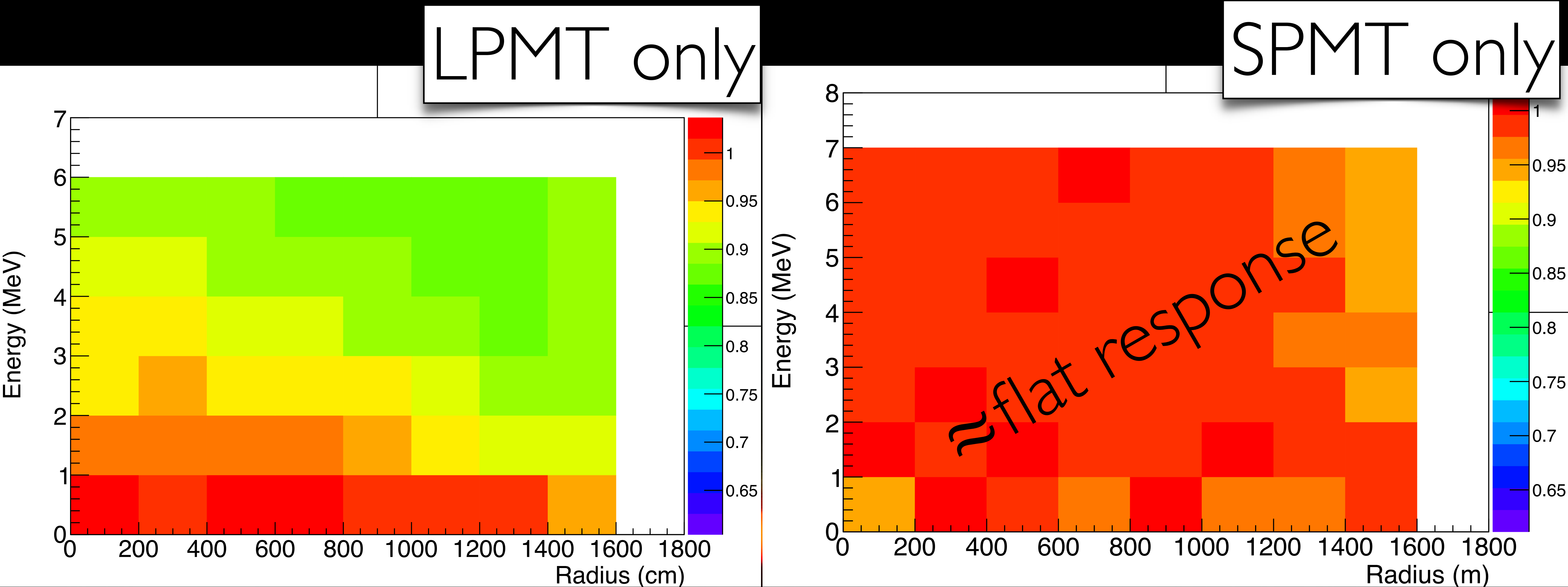
non-linearity
(channel-wise)

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

worsens resolution
(full detector)

Cabrera (CNRS-IN2P3 & APC)

linearity⊕uniformity crosstalk handling…



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

SPMT: uniformity map & linearity⇒ (independent) <u>3D-map validation</u>

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

Anatael Cabrera (CNRS-IN2P3 & APC)

response summary…

LPMT: uniformity • linearity • stability ≠ 0

(i.e. not orthogonal bias/systematics)

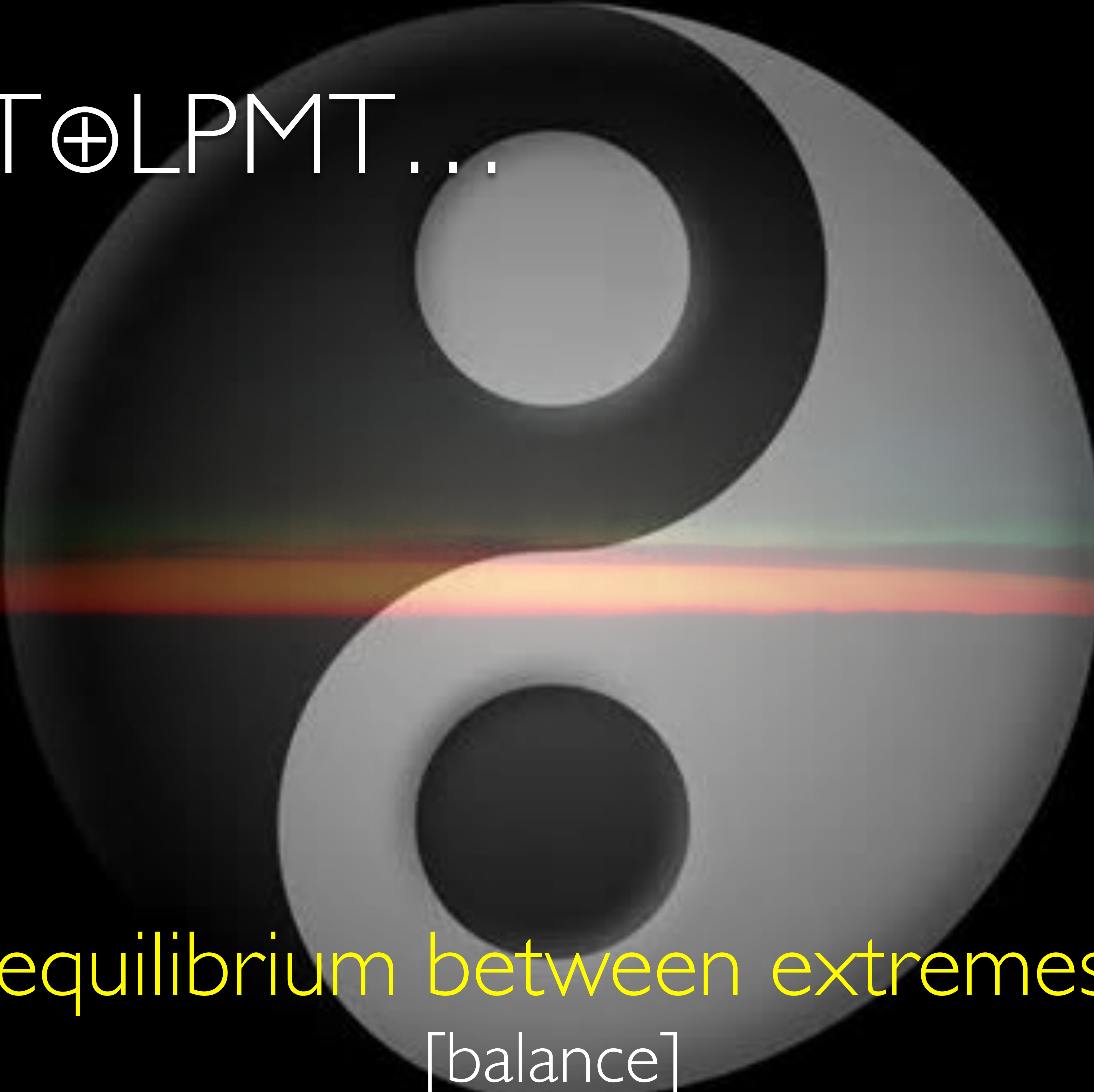
VS

SPMT: uniformity • linearity • stability ≈ 0

(i.e. effective orthogonal bias/systematics)

(**far more knowledge when combining**)

SPMT⊕LPMT…



"equilibrium between extremes"

[balance]

JUNO upgrade…

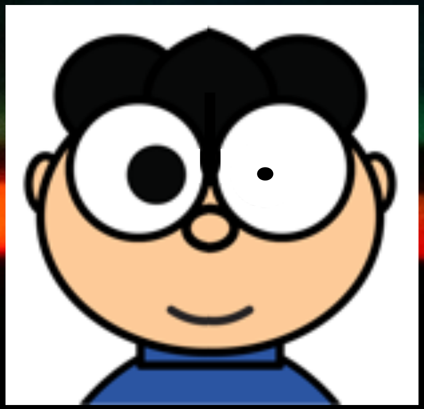
JUNO

(before)

single-calorimetric

JUNO

(now)



double calorimetric

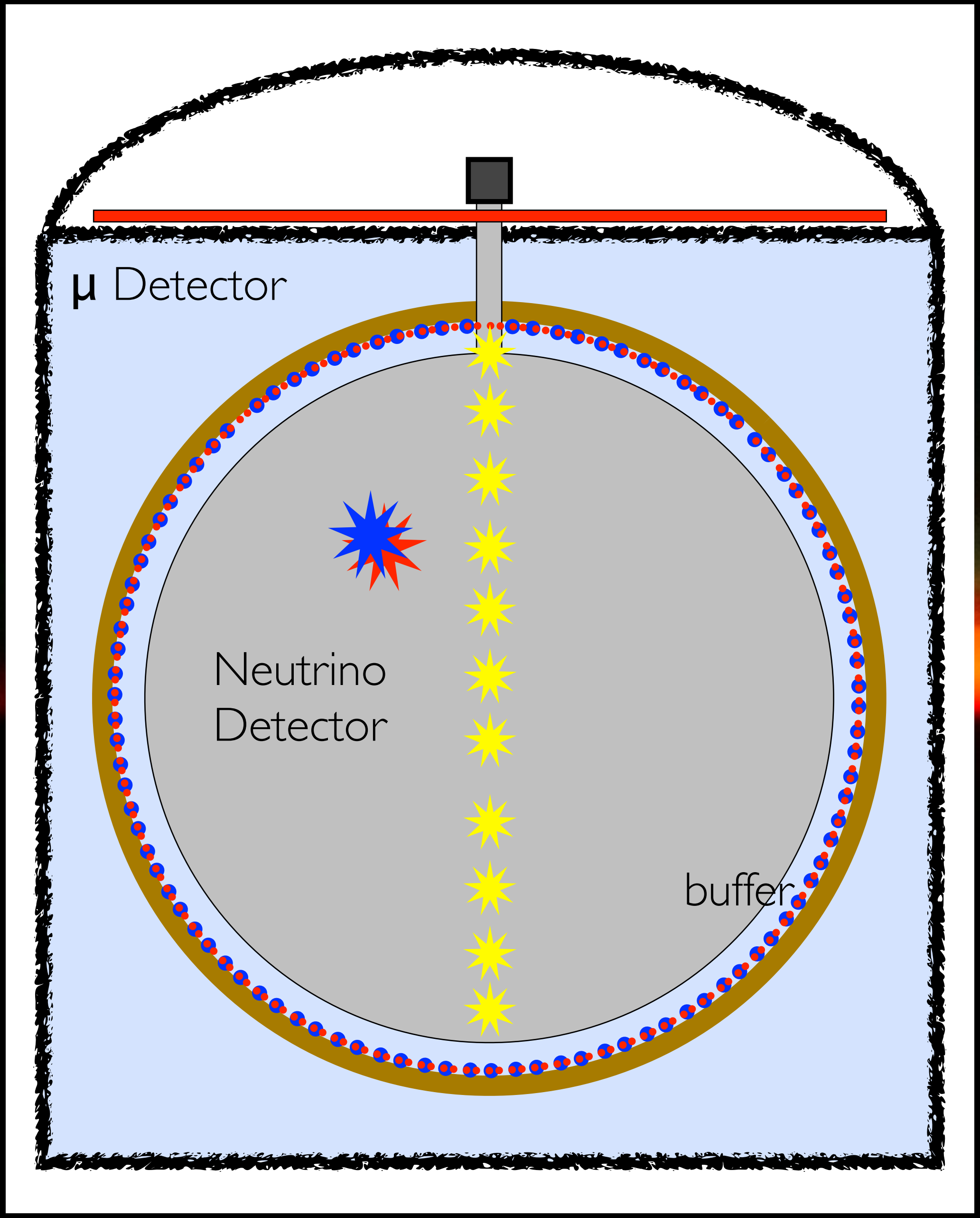
SPMT⊕LPMT response binding @ calibration…

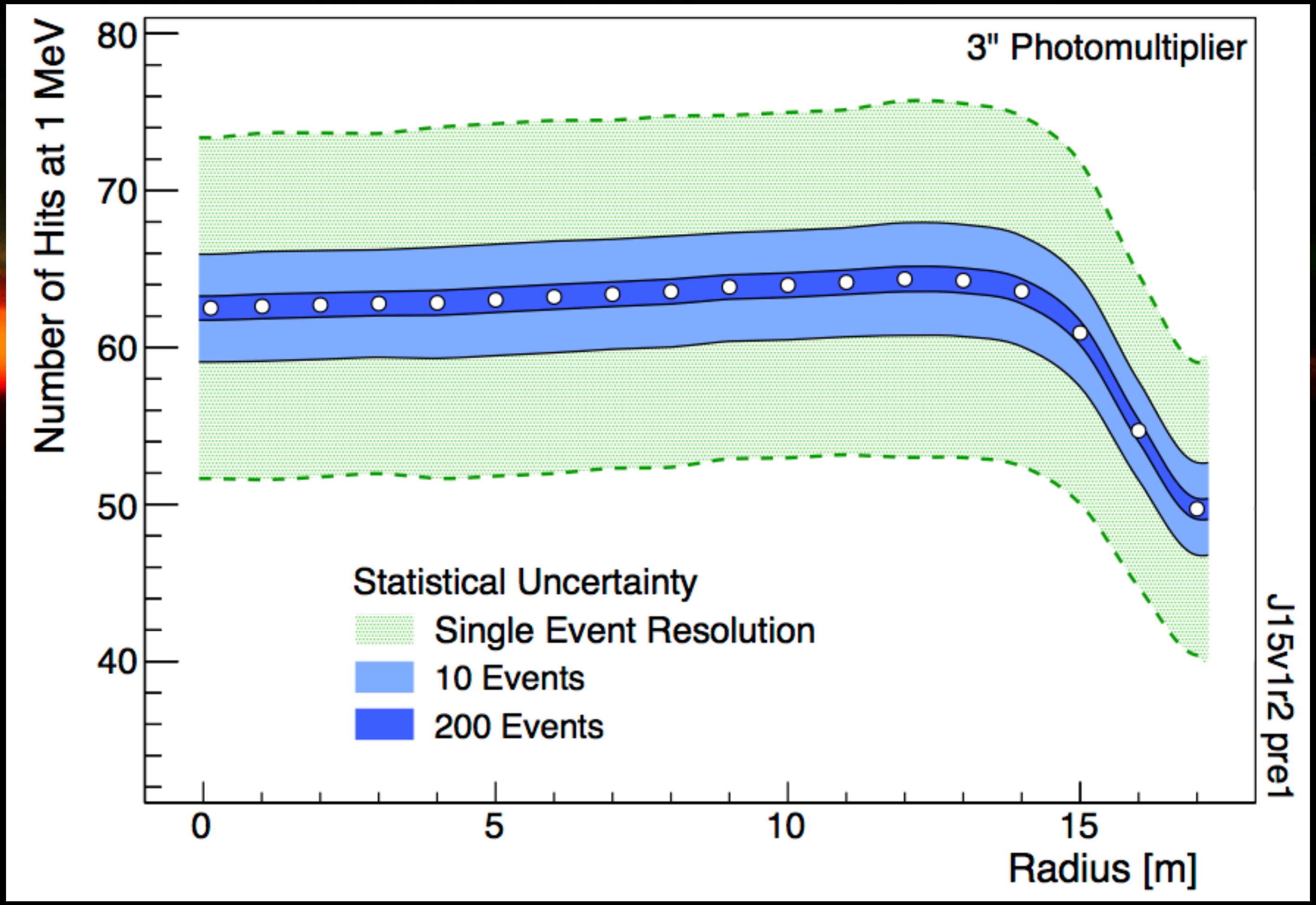
SPMT has limited statistical information event-wise (wrt LPMT)

(optimisable → keep light-level low to ensure PC)

SPMT has "∞" statistical power using calibration (→ 1/√N)

(high precision correlation & combination of SPMT⊕LPMT)



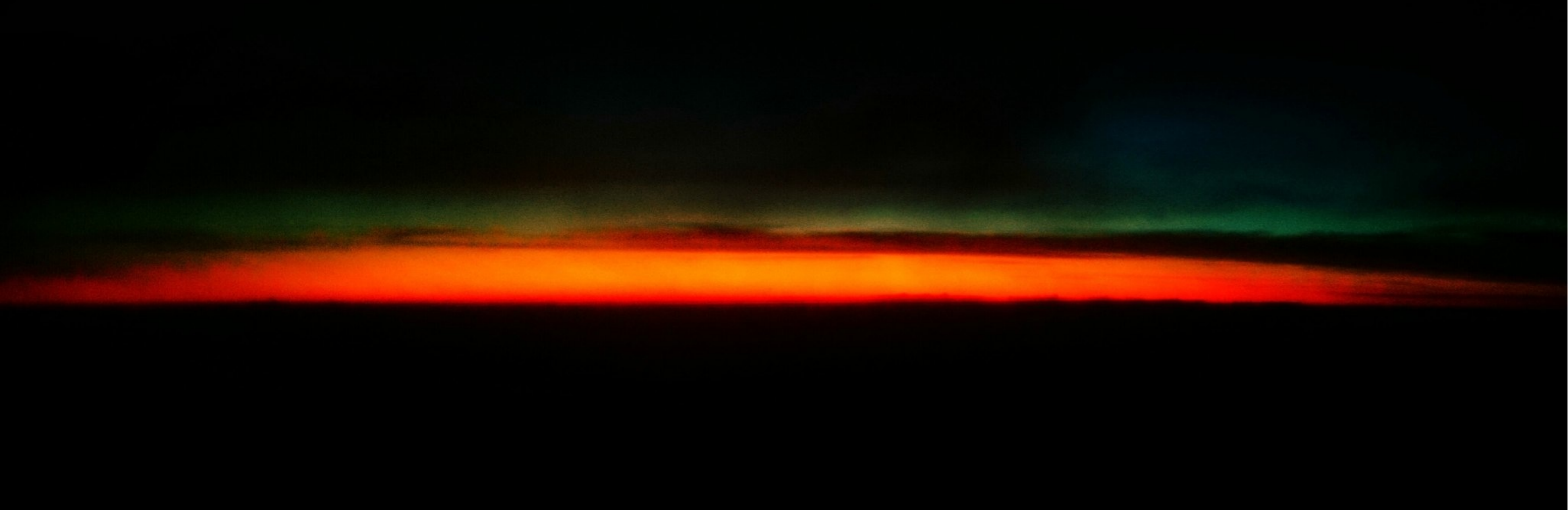


(in preparation but not yet) exploring SPMT⊕LPMT event-wise via ANN

⇒ better combined energy & position estimator?

Anatael Cabrera (CNRS-IN2P3 & APC)

SPMT part of LPMT calibration…



(but not only)

SPMT: powerful physics…

JUNO-IN2P3 pushing heavily this agenda

(APC+CPPM+CENBG+LLR+OMEGA+SUBATECH)

SPMT rich programme…

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

(highest priority: **double calorimetry aide ≤3% @ 1MeV resolution**)

B. **physics: neutrino oscillation, proton-decay, etc**

(highest priority: **enrich the JUNO physics programme beyond LPMT only**)

C. **improve inner-detector 4π-μ-reconstruction resolution**

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

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

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

E. **complementarity readout info: time resolution, dynamic range & trigger**

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

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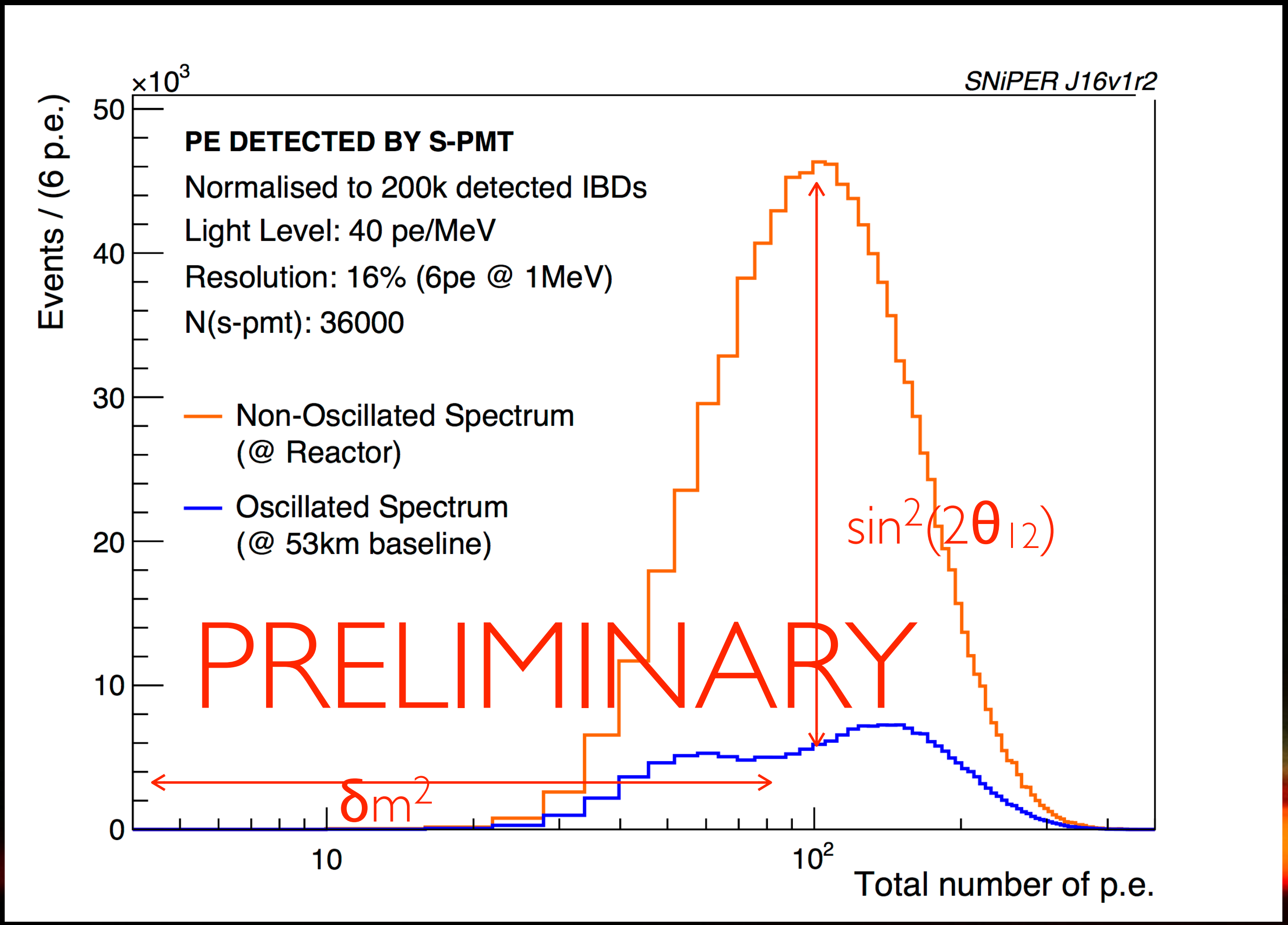
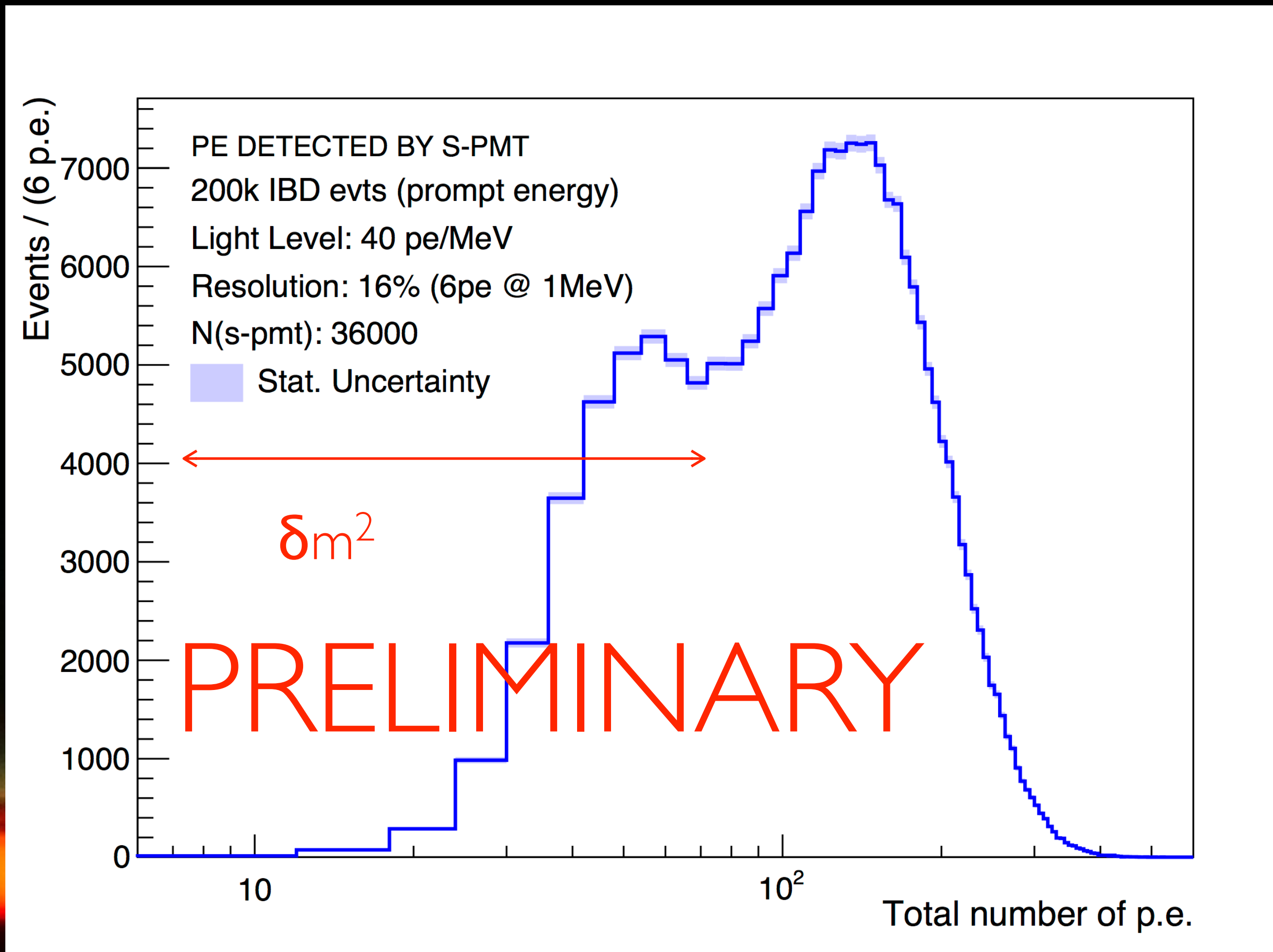
SPMT δm^2 & $\sin^2(2\theta_{12})$ measurements…





δm2 & sin2(2θ12) measurement are rate+shape driven…

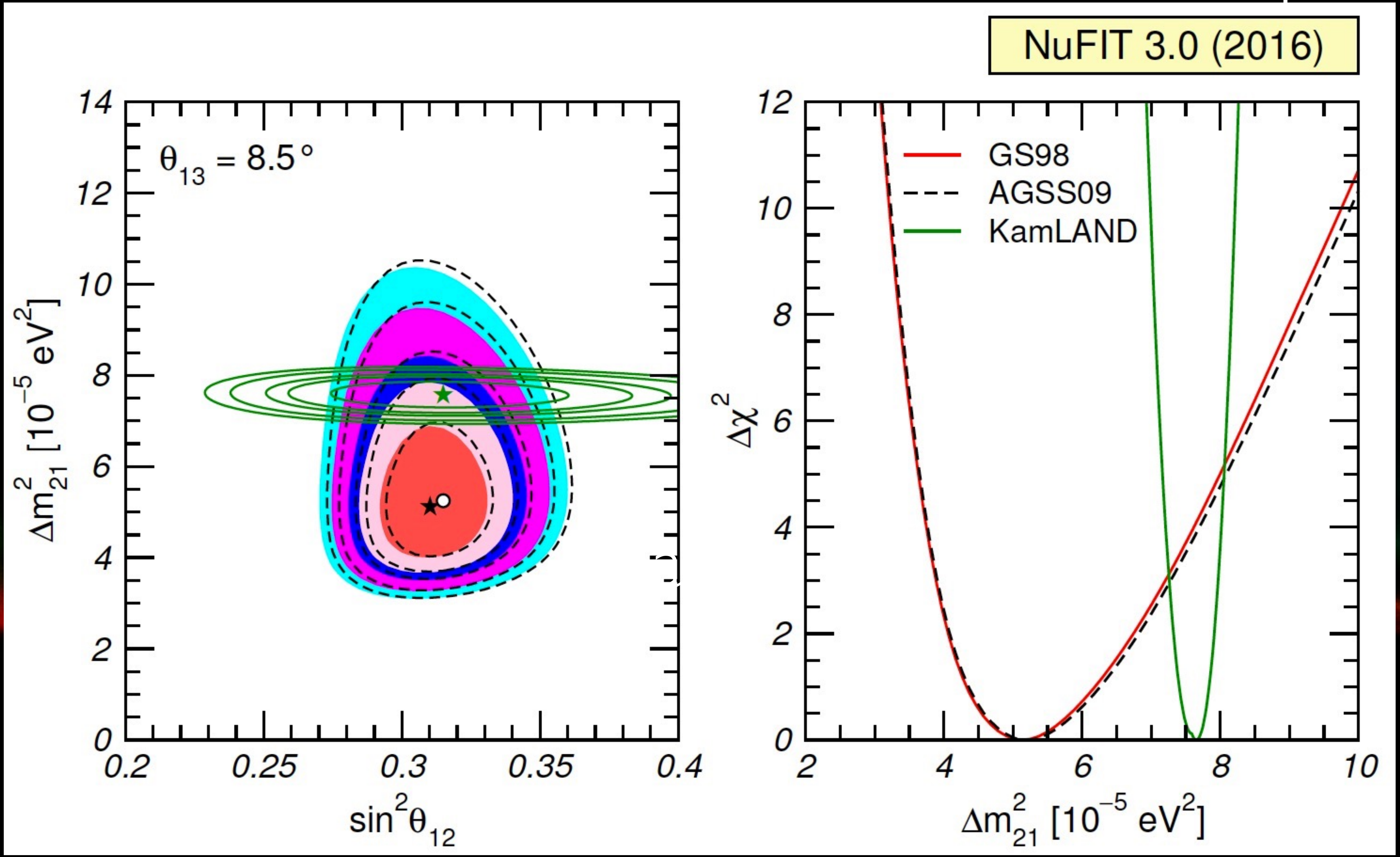
rate alone→ both δm^2 & $\sin^2(2\theta_{12})$

shape alone→ provide further info about δm^2 [hence also about $\sin^2(2\theta_{12})$]

SPMT **δm^2** & **$\sin^2(2\theta_{12})$** precision ⊕ accuracy

(**JUNO self-redundancy:** internal cross-check)

KamLAND vs SOLAR discrepancy…

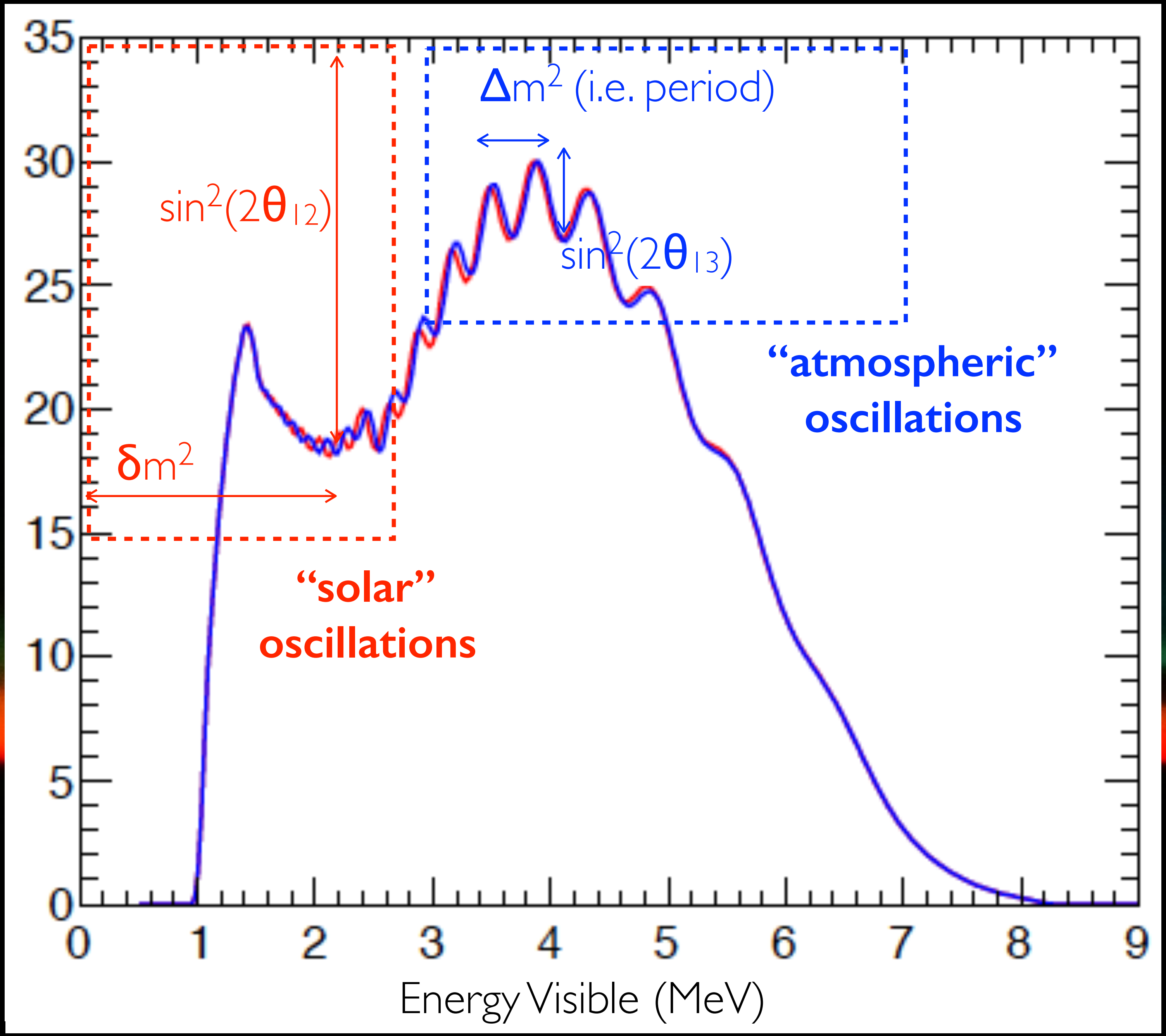


solar-ν physics vs reactor-ν physics?

(an experimental feature: i.e. bias?)

JUNO measurement of $\sin^2(2\theta_{12}) \oplus \delta m^2$ (unique!)

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



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

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

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

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

SPMT rich programme…

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(highest priority: **double calorimetry aide ≤3% @ 1MeV resolution**)

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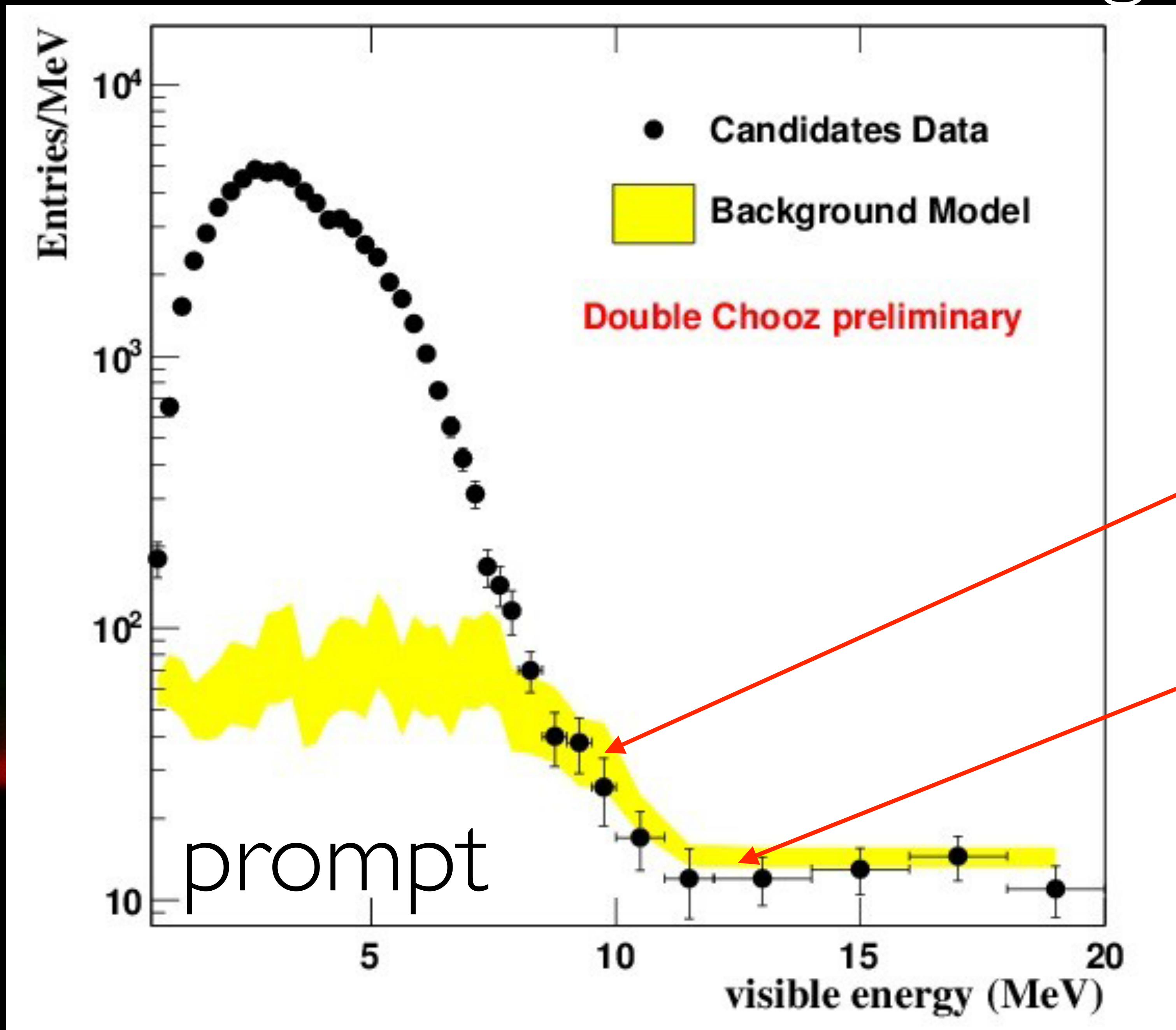
(articulate **additional complementary to LPMT system**: better/simpler)

the most dangerous background…



- **•^{9}Li (+ a little ^{8}He)**
  (dominant→ rejection via μ-tracking)
- **•fast-n (+ little stopped-μs)**
  (still visible & knowledge @ <10%)

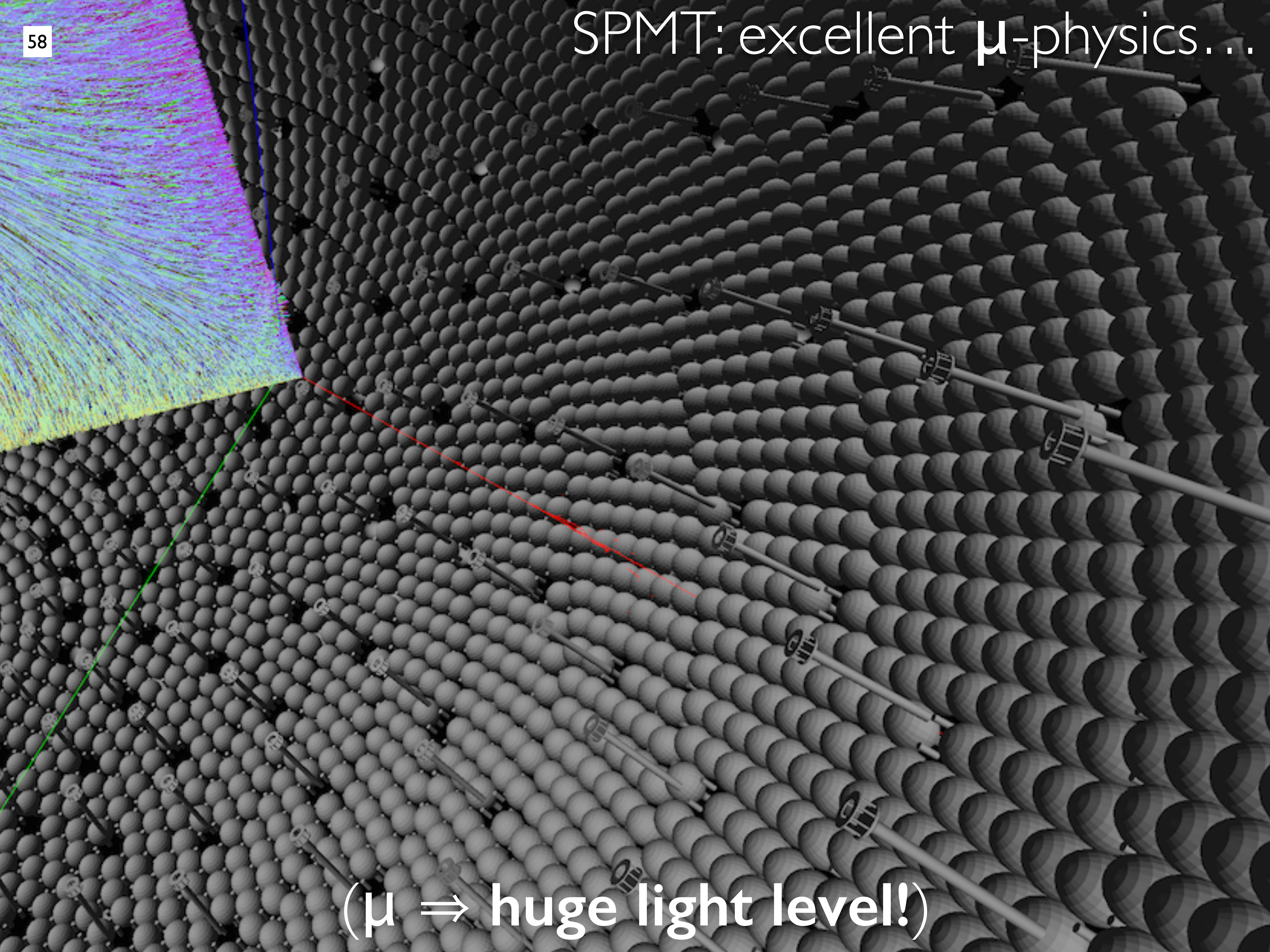
μ-tracking (all μs) is critical!

Efficiency, signal and background rates after each selection criterion

Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60			3.8		

(CNRS-IN2P3 & APC)

SPMT: excellent **μ**-physics…

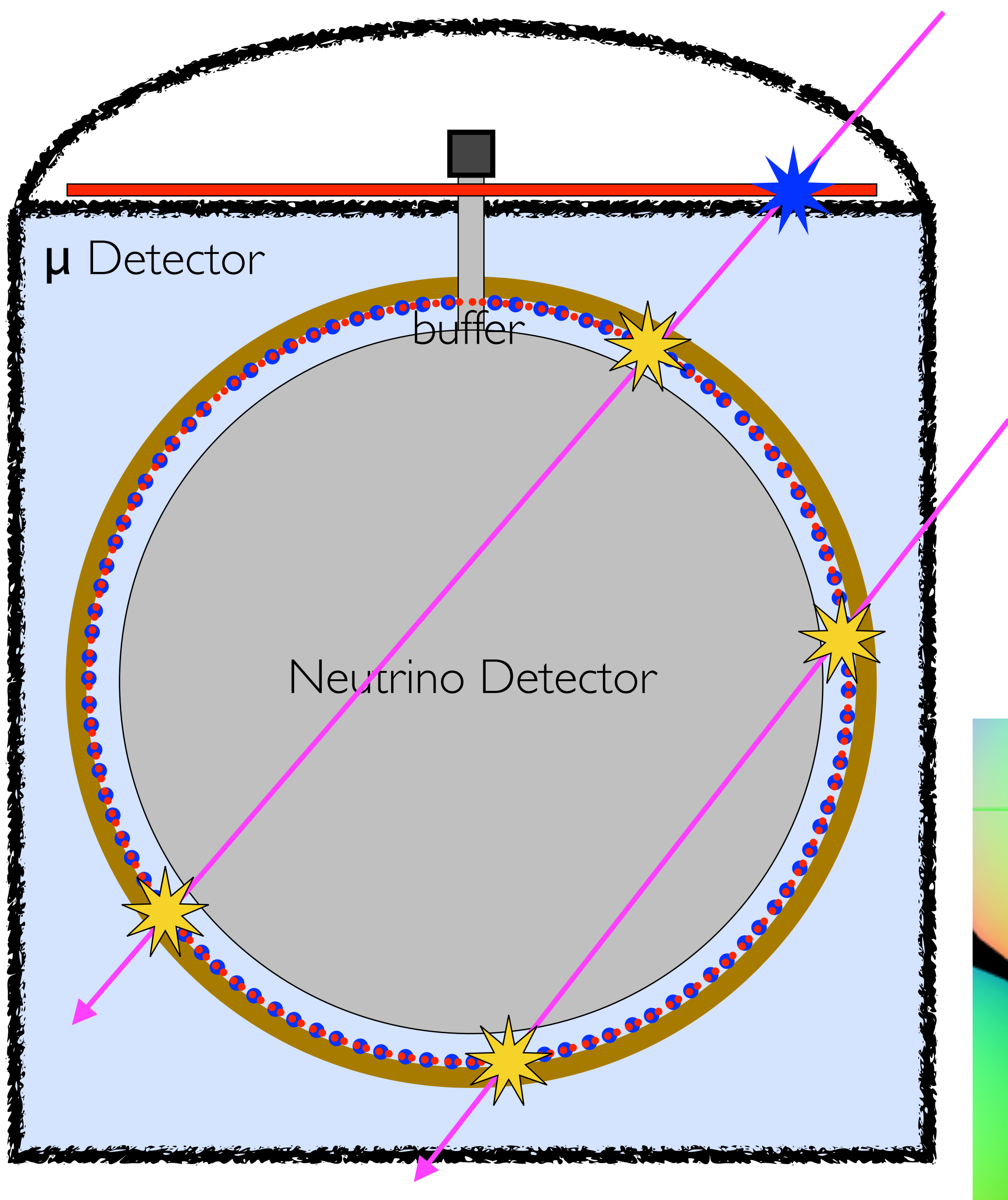


(μ ⇒ huge light level!)

high precision μ-tracking…

hits @ neutrino-detector (ND)

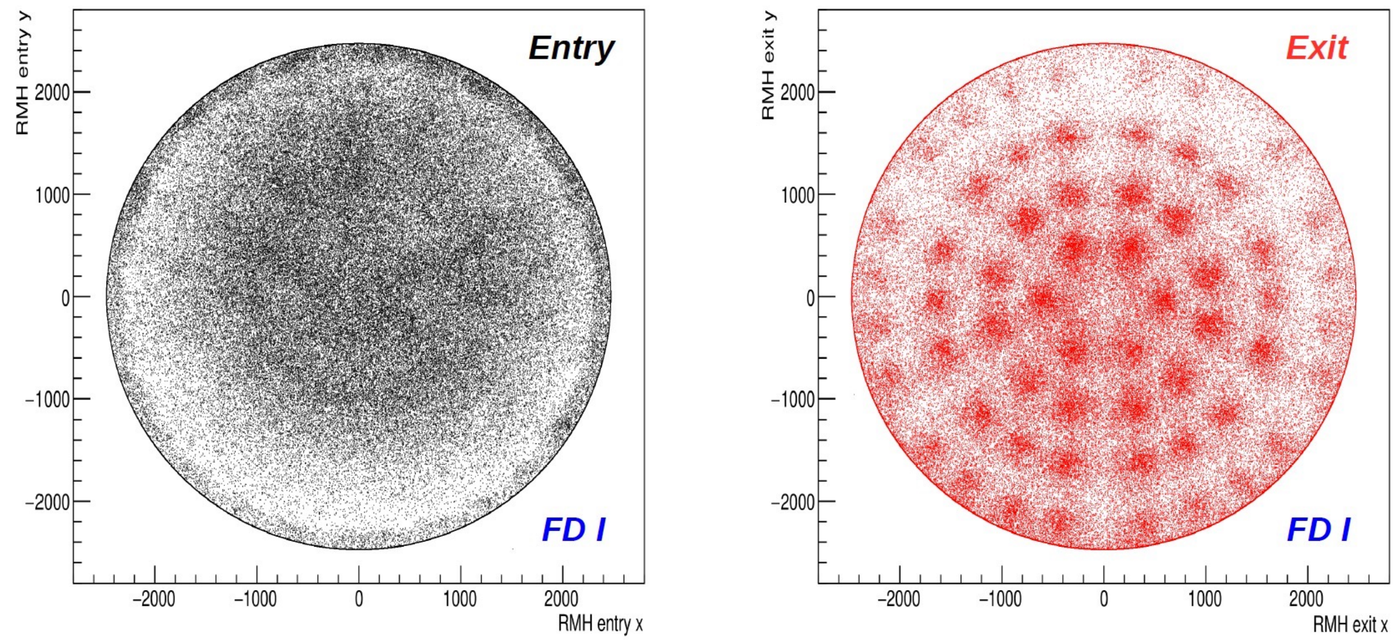
hit @ top-detector

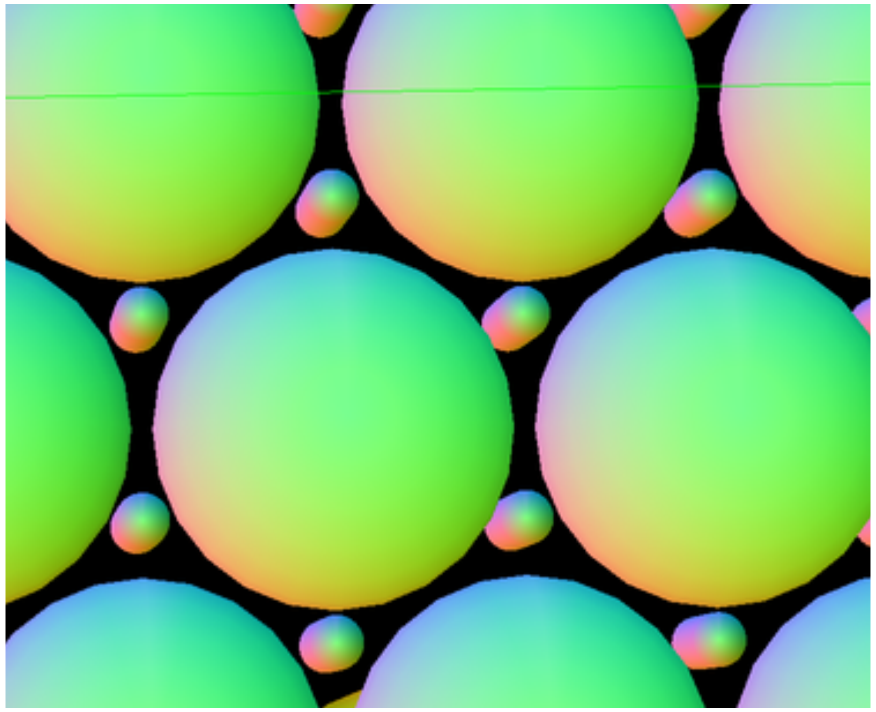


μ's tracking must be 4π⇒ all μ's!!!

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

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



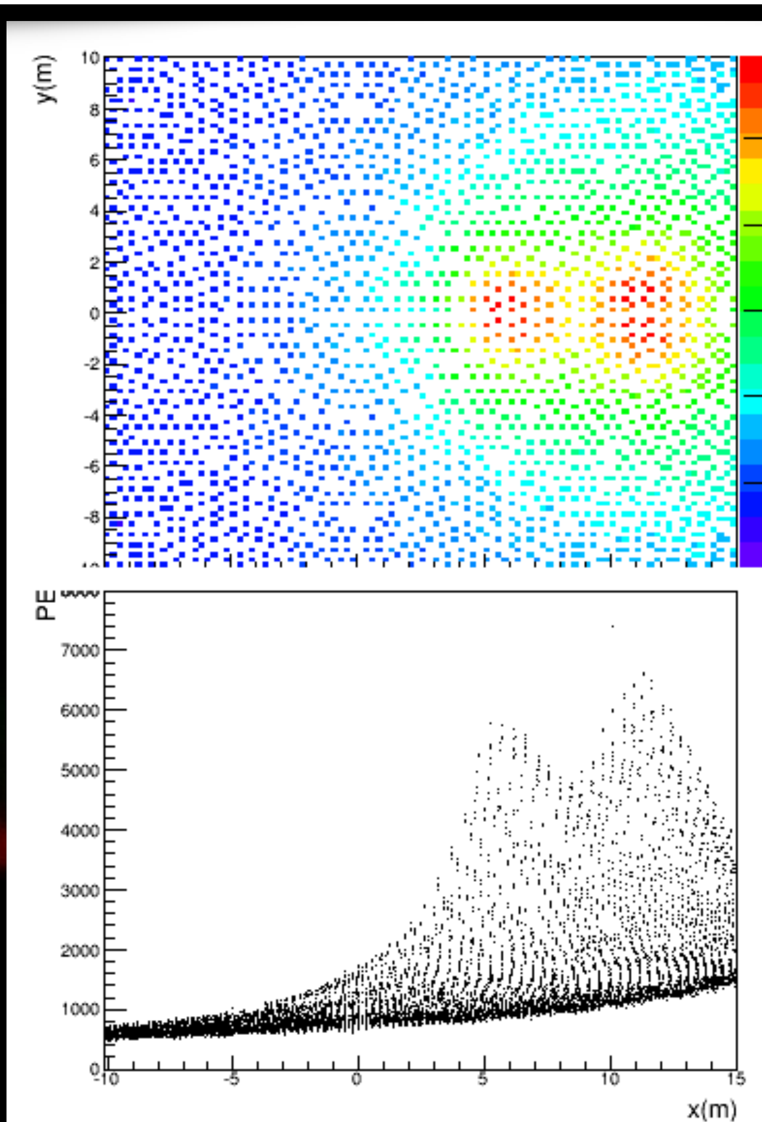


μ-reco depends…

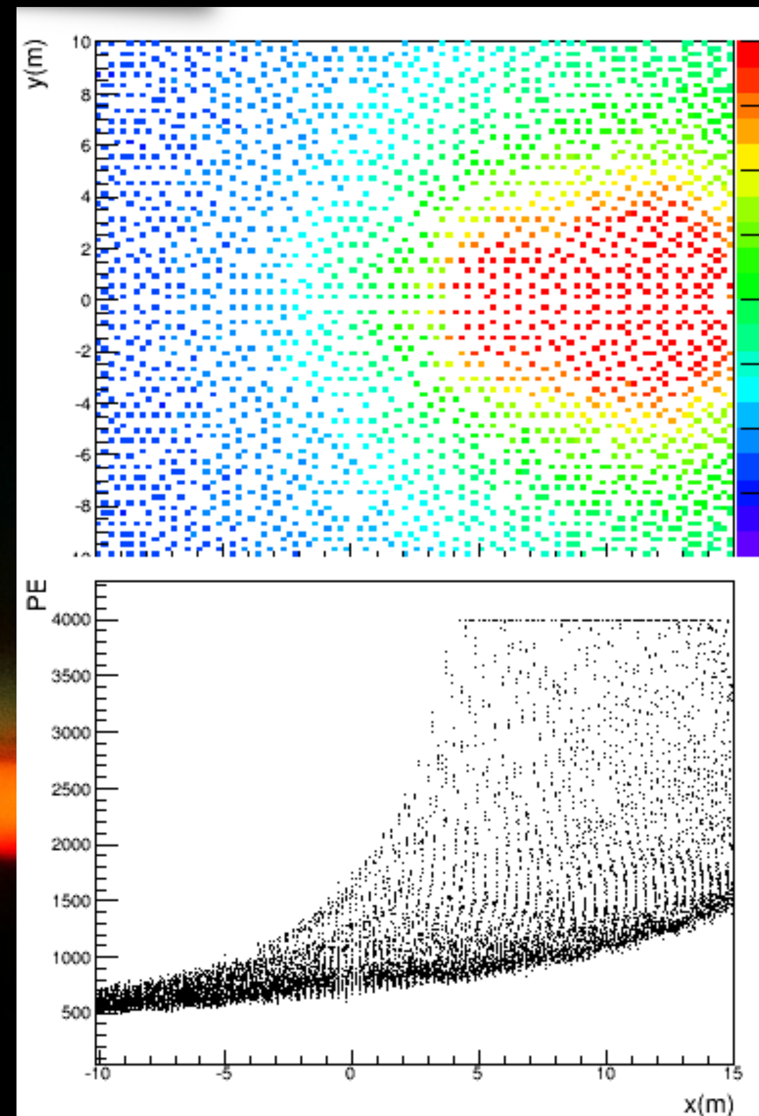
- **PMT density** (→ LPMT)
- **PMT timing** (typical few ns)
  - more light (further info)
- **high resolution triangulation** (SPMT)

multi-μ identification…

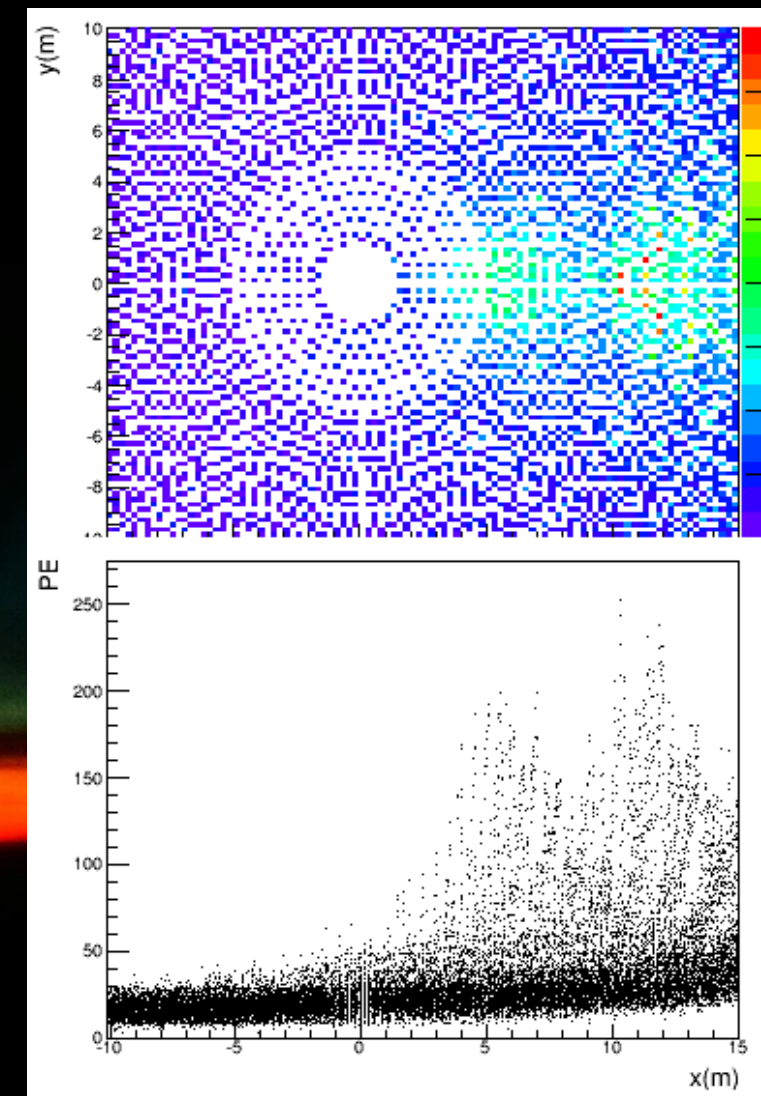
student @ IHEP+Miao+S+A



LPMT (no saturation)



LPMT (saturation at 4000PE)



SPMT

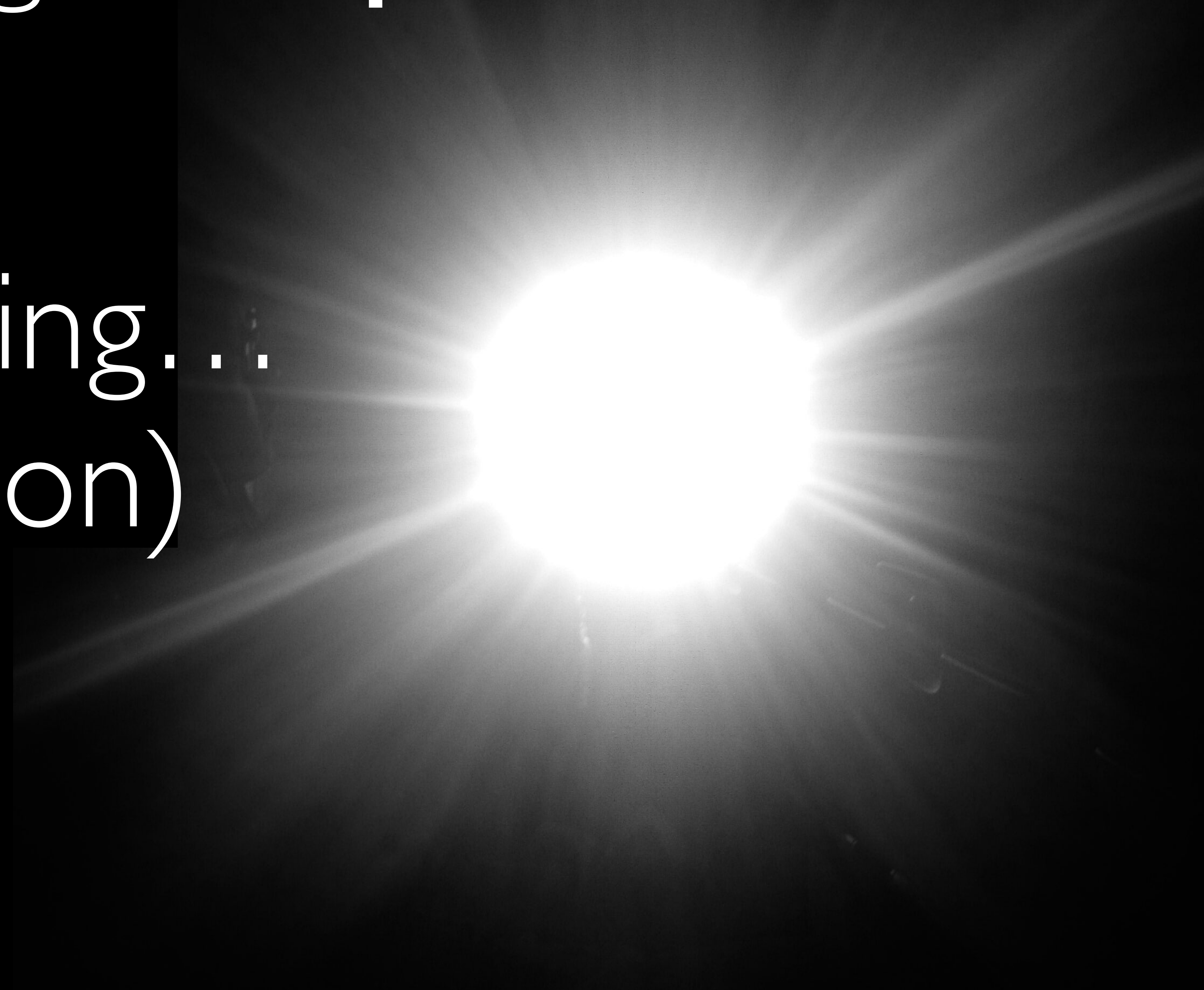
saturation model very complex (not uniform, no flat, etc)

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

evidently so…

when dealing with **μ**'s…

when dazzling…
(i.e. saturation)



…less is more! (→SPMT)

SPMT rich programme…

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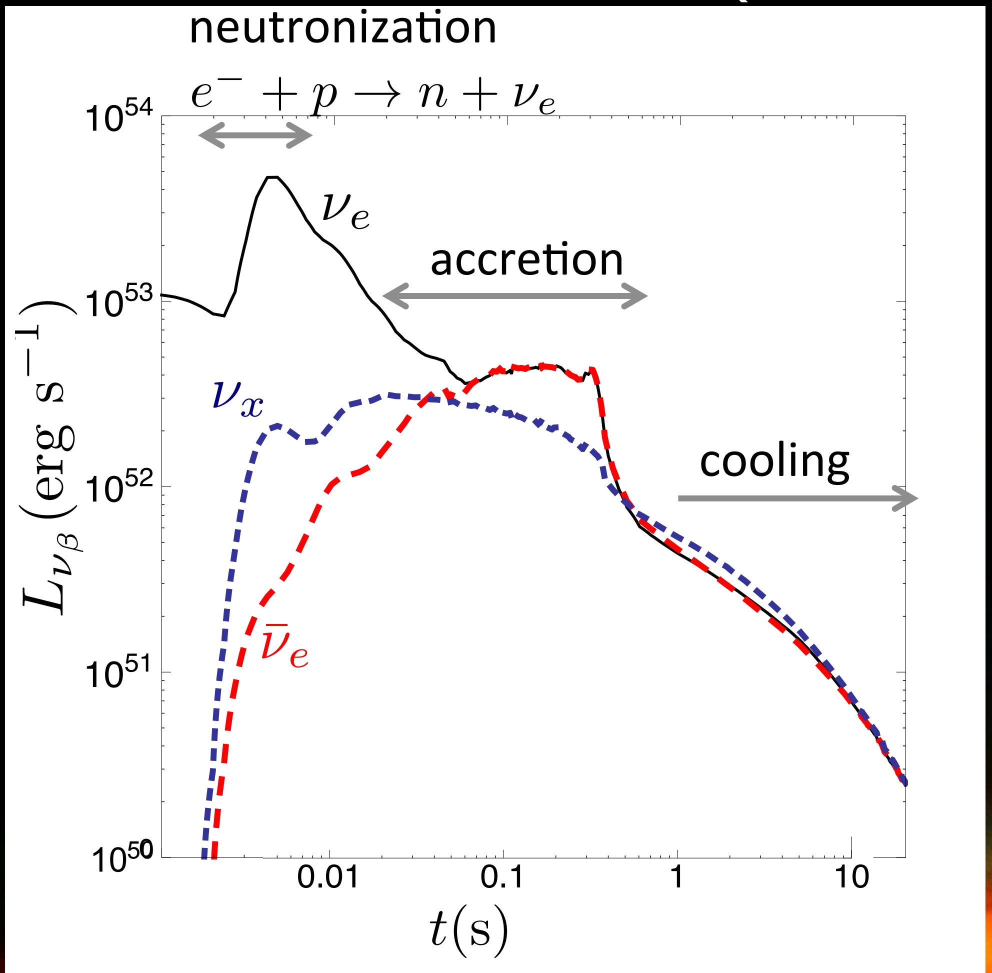
E. **complementarity readout info: time resolution, dynamic range & trigger**

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

SN neutrino physics…

SN 1987

(new idea) dual supernova readout…

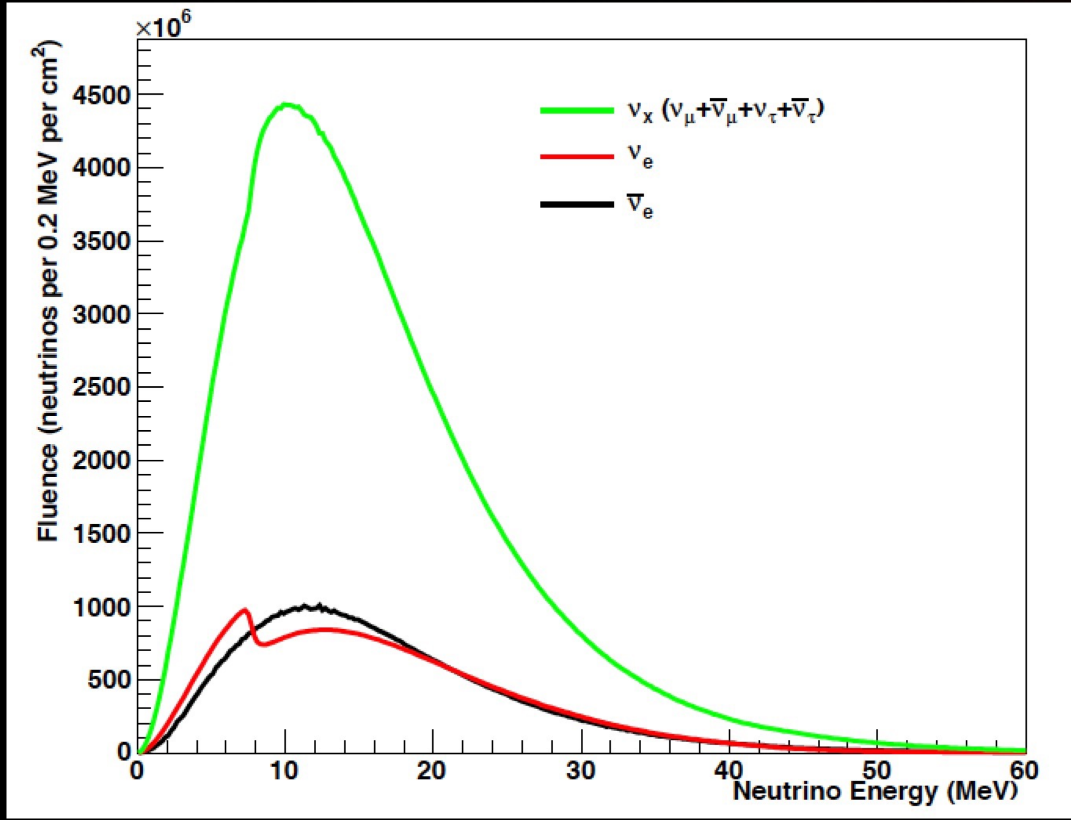


Fischer et al., A&A 517 (2010)

→ measure the rate(t) (unbiassed)

half SPMT (interleaved): measured rate(time) unbiassed

price to pay: bias energy somewhat!!



→ measure energy spectrum (unbiassed)

half SPMT (interleaved): measured energy unbiassed

price to pay: bias rate(time) somewhat!!

together→ full picture (aid LPMT precious info)

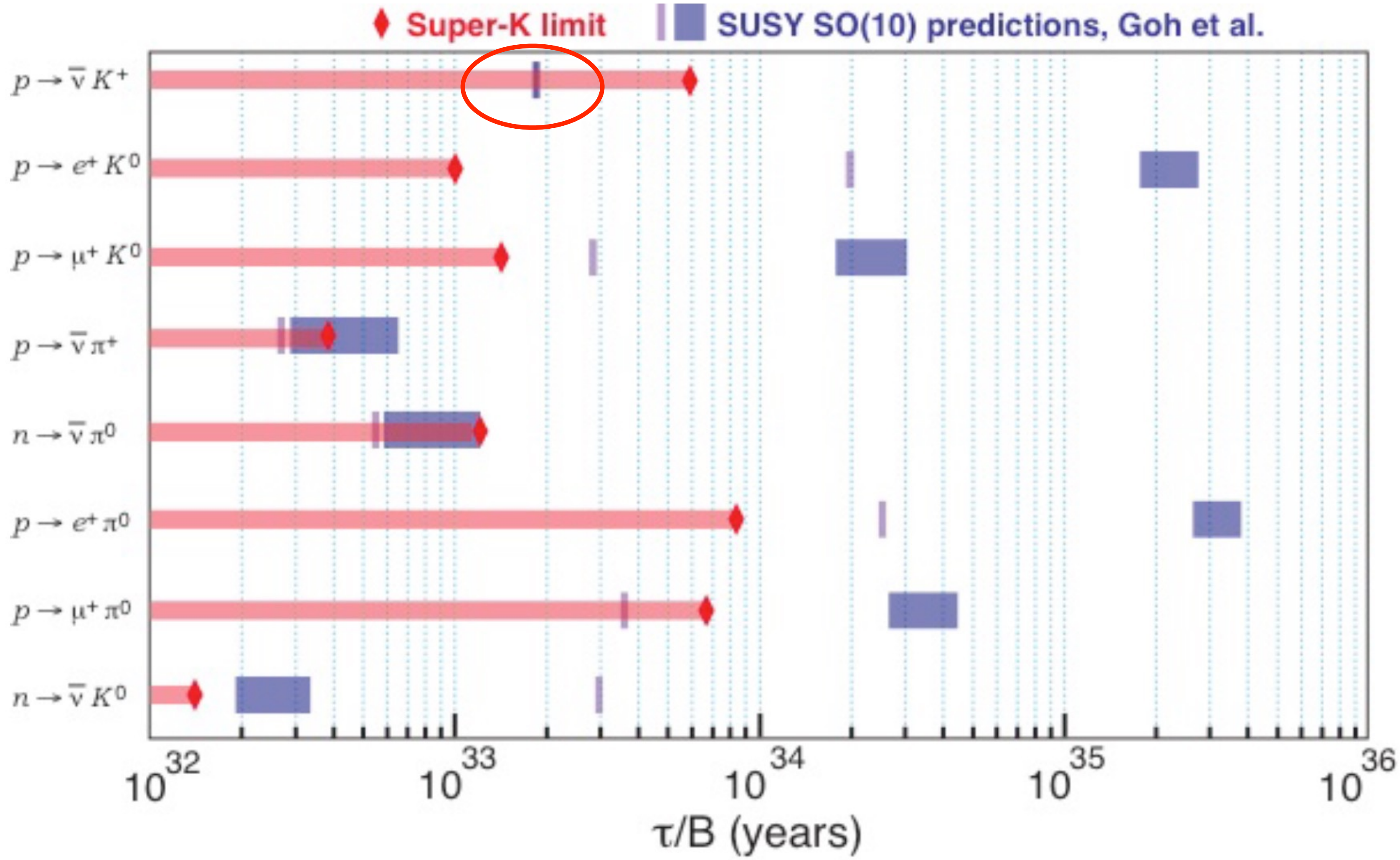
Anatael Cabrera (CNRS-IN2P3 & APC)

proton decay @ JUNO…

Combining searches: model dependent

SUSY SO(10), B-L broken by 126-Higgs†

- predicts neutrino mixing well
- scan over parameter space – find unconstrained branching fraction
  - case 1: maximize $n \to \nu \pi^0$, case 2: maximize $n \to \nu K^0$
  - N.B.: old νK^+ limit used as fixed constraint



† H.S.Goh, R.N.Mohapatra, S.Nasri, S-P. Ng, Phys Lett B587:105-116 (2004)

more info…

Neutrino Physics with JUNO

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(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.

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
Cite as: arXiv:1507.05613 **[physics.ins-det]**
(or **arXiv:1507.05613v2 [physics.ins-det]** for this version)

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. Busto, 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. Giammarchi, 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 3-4σ, 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.

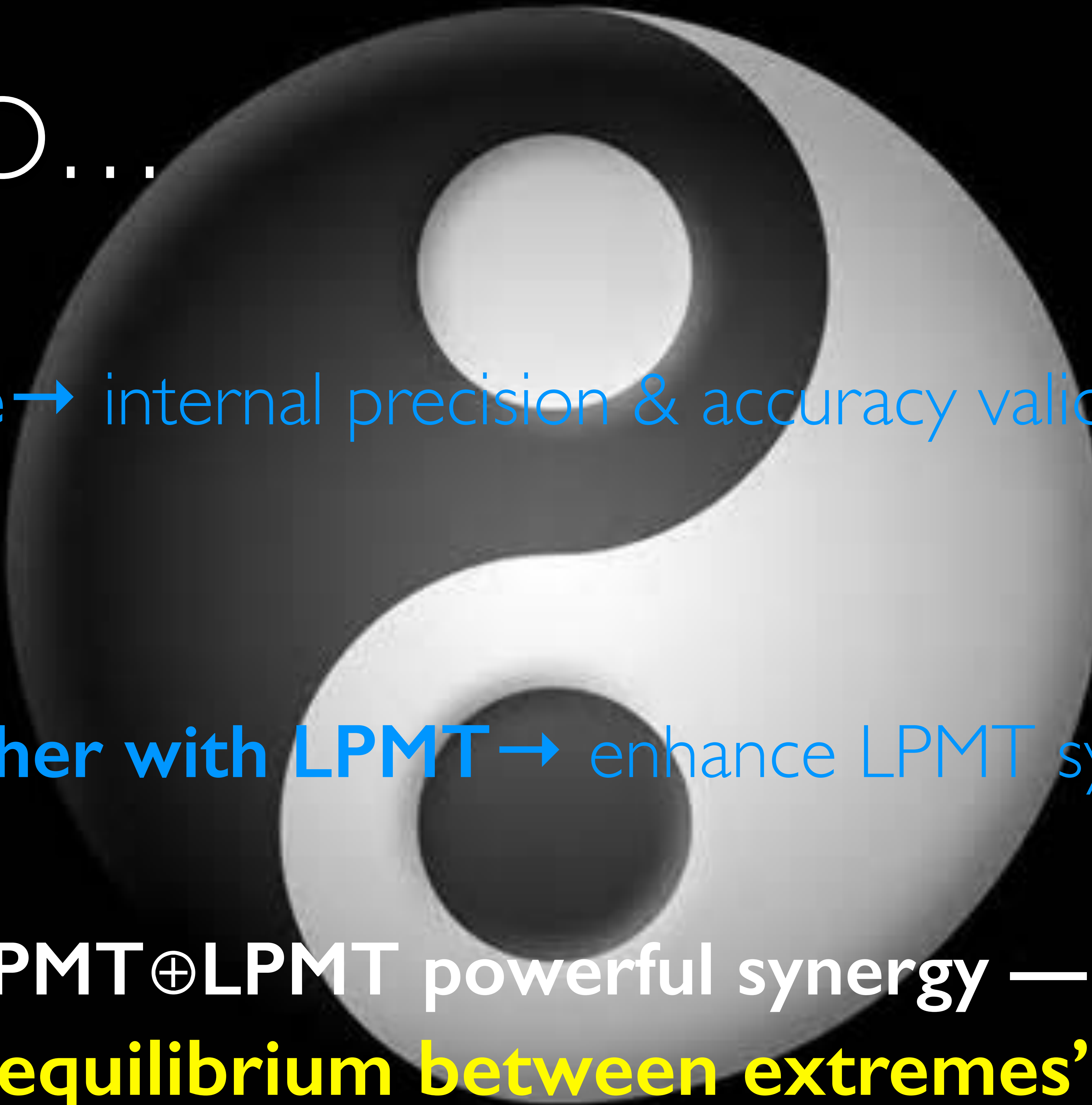
Comments: 328 pages, 211 figures
Subjects: **Instrumentation and Detectors (physics.ins-det)**; High Energy Physics - Experiment (hep-ex)
Cite as: arXiv:1508.07166 **[physics.ins-det]**
(or **arXiv:1508.07166v2 [physics.ins-det]** for this version)

JUNO's CDR…
(published)

what to remember…

- **JUNO: world reference in neutrino oscillation**…
  - several unique measurements (not just Mass Ordering)…
  - 20years of copious physics with reactor-ν and well beyond (geo-ν, supernova-ν, etc)
- **double calorimetry (invented by IN2P3-JUNO)**…
  - **major improvement of LS-detectors**
  - one of the most striking (instrumentation) novelties @ FRosT-16 conference
- **SPMT detector improvements (lead by IN2P3-JUNO)**…
  - **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

JUNO…



• **alone** → internal precision & accuracy validation

• **together with LPMT** → enhance LPMT system

— SPMT⊕LPMT powerful synergy —

("equilibrium between extremes")

the end…

merci…

thank you…

谢谢…