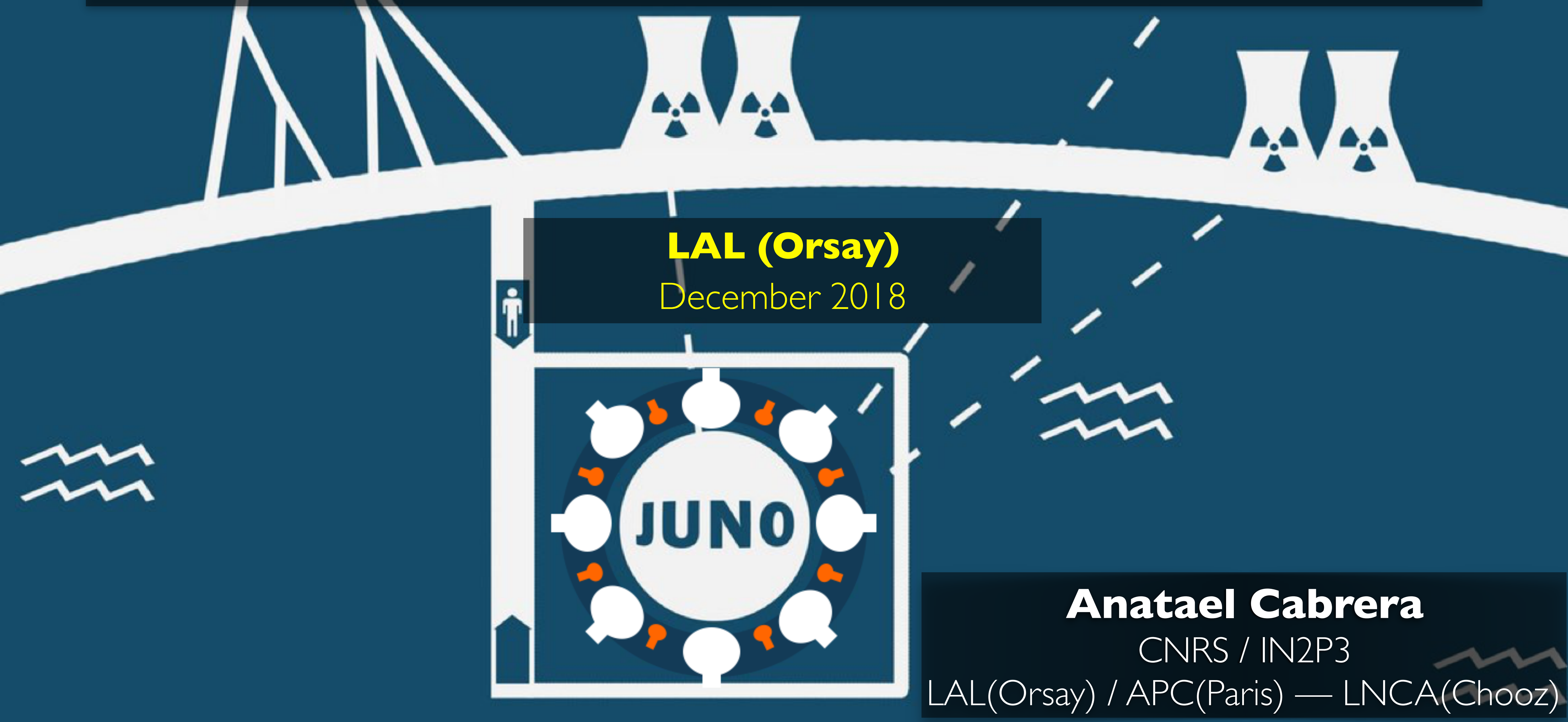
JUNO



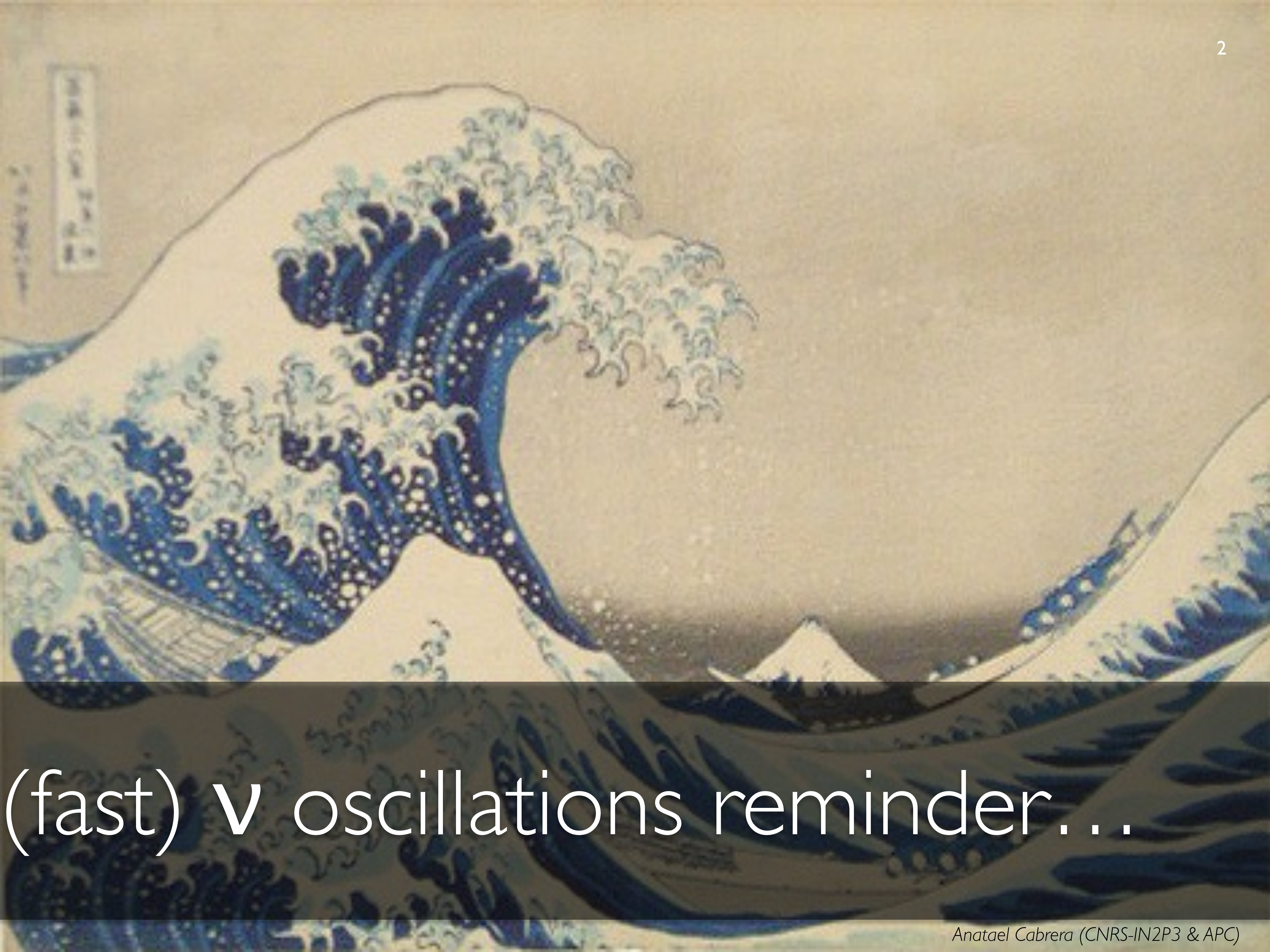
LAL (Orsay)

December 2018

Anatael Cabrera

CNRS / IN2P3

LAL(Orsay) / APC(Paris) — LNCA(Chooz)

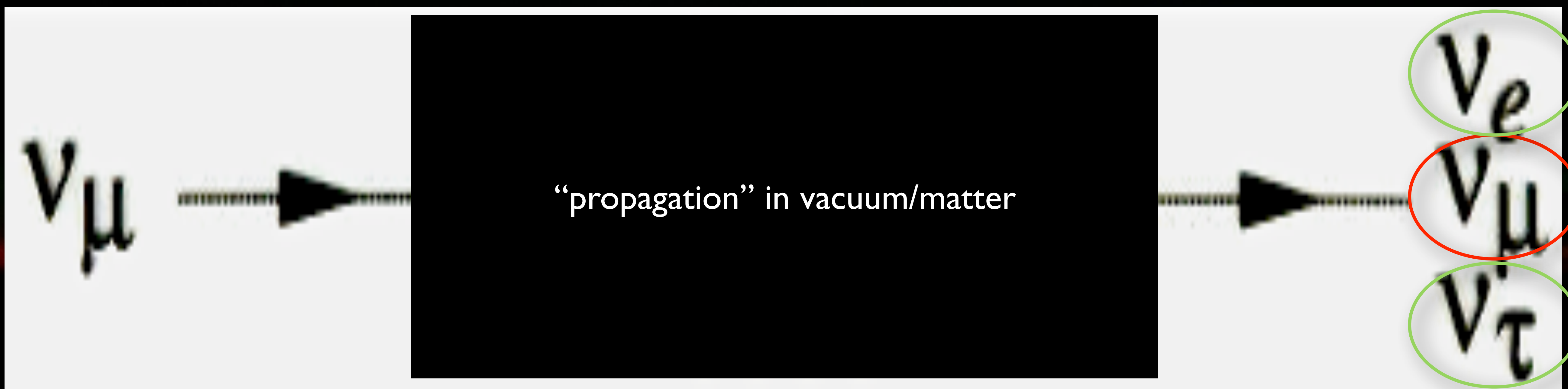


(fast) ν oscillations reminder…

neutrino oscillations manifestation…

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

disappearance
appearance



observation: both **disappearance** (the **anomalies**) & **appearance** (July 2013) have been seen

all observations (most!) consistent with 3ν oscillation model

ingredients for neutrino oscillations…

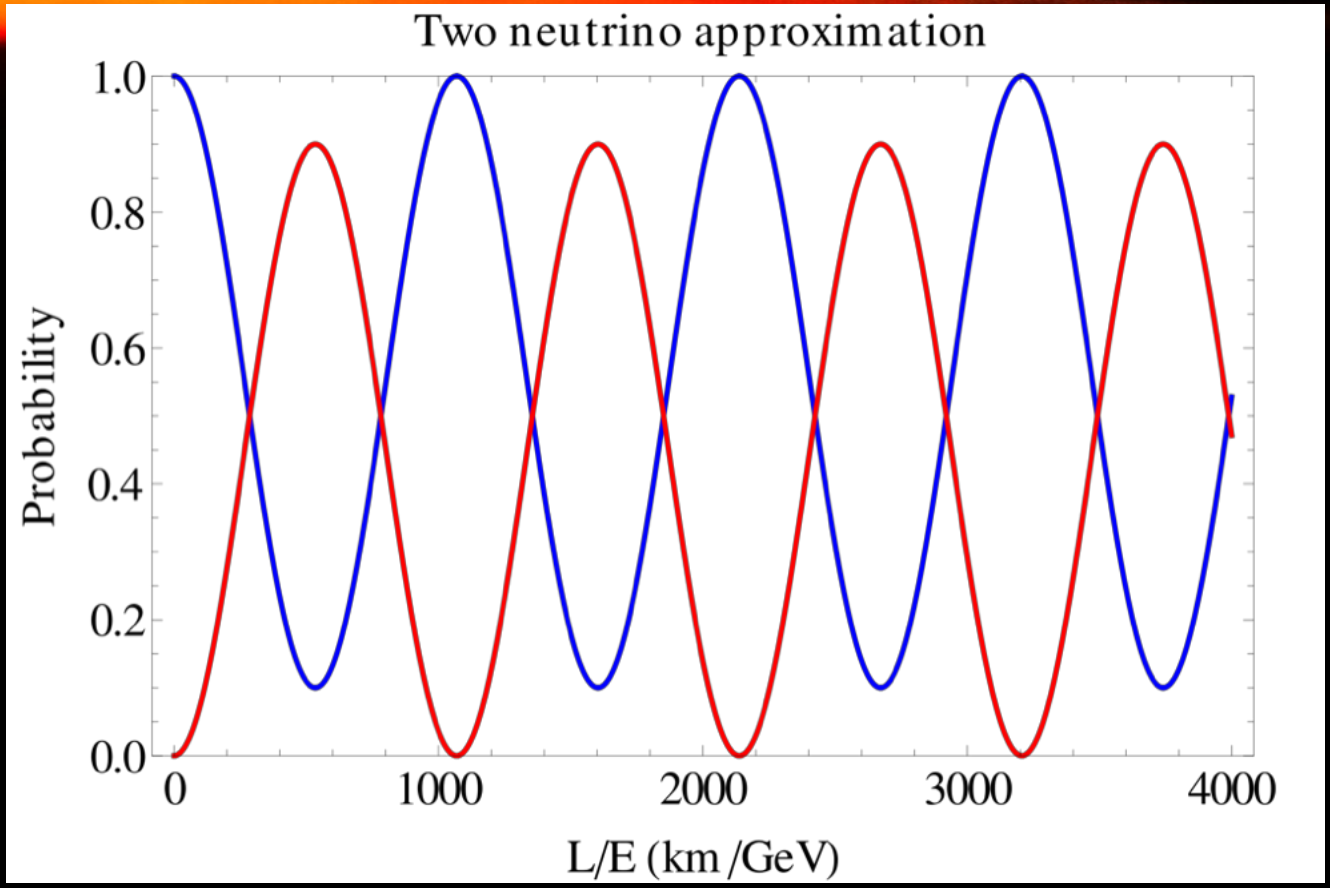
Non-degenerate mass spectrum (**Δm^2**) ⊕ Mixing in the leptonic sector (**θ**) = Oscillation Probability **$P=f(\theta,\Delta m^2)$**

quantum interference (macroscopic)

UPMNS matrix (à la CKM)

ν_α (start with) & ν_β (none at first)

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



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"mixing": a common phenomenon…

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

"atmospheric" ⟹ $\theta_{23}\sim45°$ | θ_{13} & "dirac" δ_{CP} | "solar" ⟹ $\theta_{12}\sim33°$

Δm^2_{31} | Δm^2_{31} | Δm^2_{21}

$$U = \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \xrightarrow{\text{sub-leading}} \begin{pmatrix} c_{13} & 0 & e^{-i\delta} s_{13} \\ 0 & 1 & 0 \\ -e^{i\delta} s_{13} & 0 & c_{13} \end{pmatrix} \xleftarrow{\text{sub-leading}} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmos+LBL(dis) | Chooz+LBL(app) | solar+KamLAND

$P(\nu_\mu \rightarrow \nu_\mu)$ | $P(\nu_e \rightarrow \nu_e)$ & $P(\nu_\mu \rightarrow \nu_e)$ | $P(\nu_e \rightarrow \nu_x)$

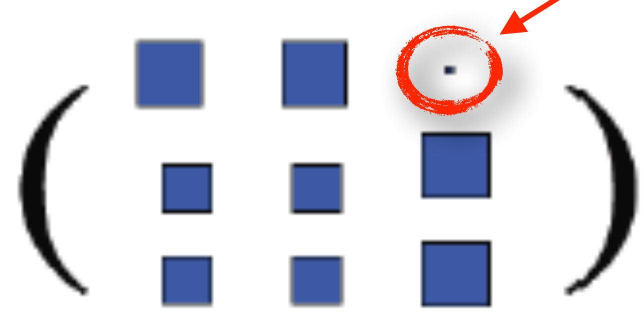
ATMOSPHERIC ANOMALY | **PREDICTION** | **SOLAR ANOMALY**

effective decoupling of "solar" & "atmospheric":

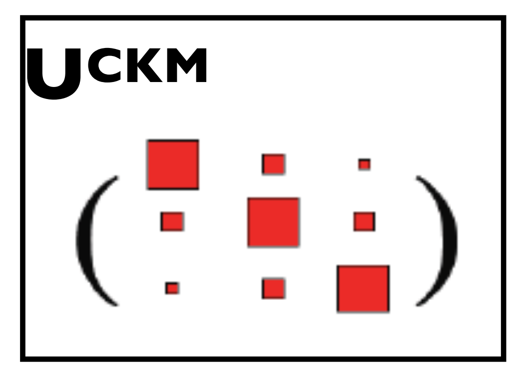
- δm^2 (order 10^{-5}eV^2) versus Δm^2 (order 10^{-3}eV^2)
- θ_{13} being small (relative to very large θ_{12} and θ_{23})

θ_{13} drives this!!!

$(\nu_e,\nu_\mu,\nu_\tau)^T = U(\nu_1,\nu_2,\nu_3)^T$, where U^{PMNS} looks like



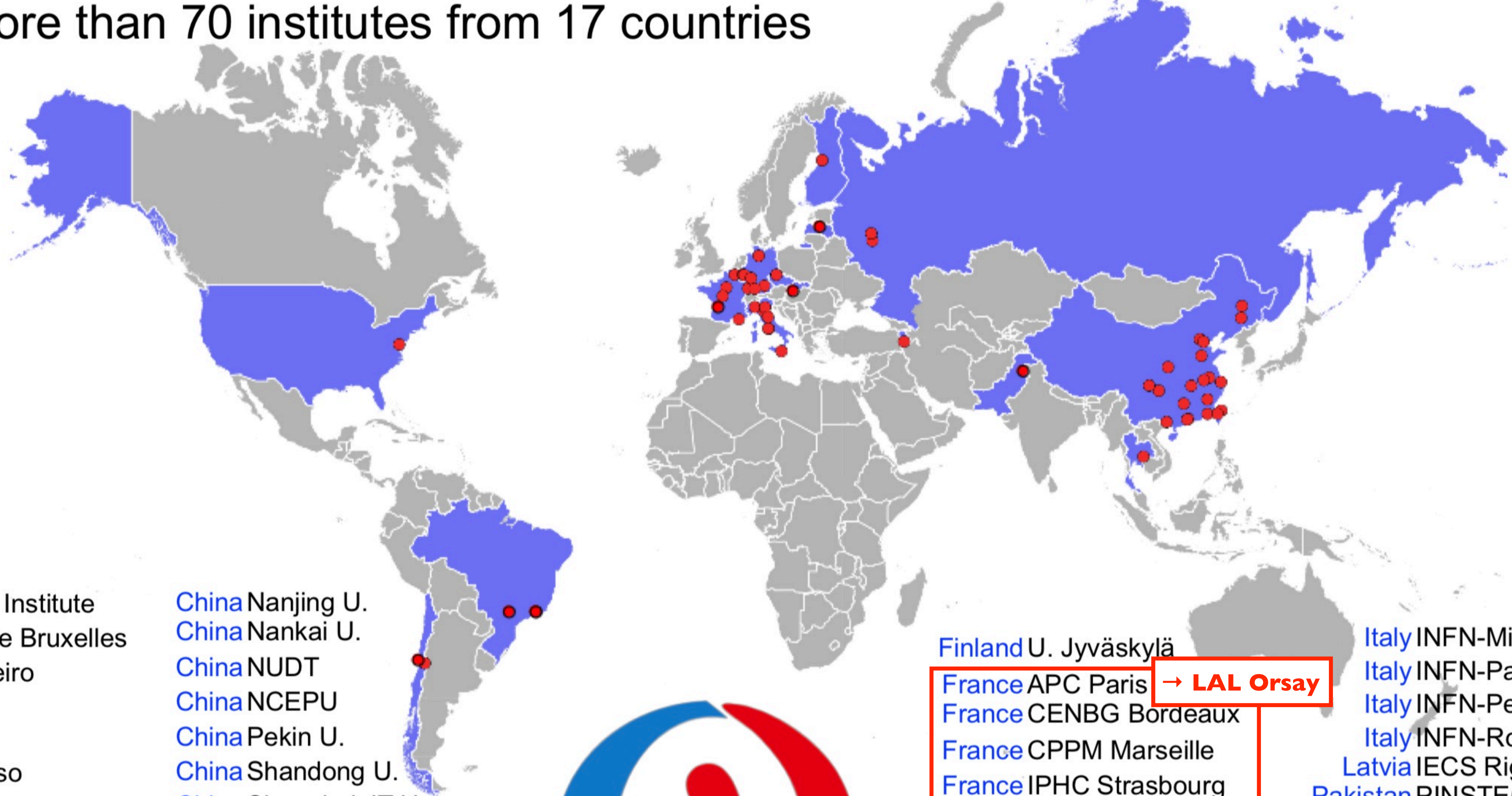
U^{PMNS}



is U unitary? [if not → 4th ν family]

the JUNO project/experiment…

More than 70 institutes from 17 countries



Armenia Yerevan Physics Institute
Belgium Université libre de Bruxelles
Brazil PUC Rio de Janeiro
Brazil UE Londrina
Chile PCUC
Chile UTFSM Valparaiso
China BISEE
China Beijing Normal U.
China CAGS
China ChongQing University
China CIAE
China DGUT
China ECUST
China Guangxi U.
China Harbin Institute of Technology
China IHEP
China IMP-CAS
China Jilin U.
China Jinan U.

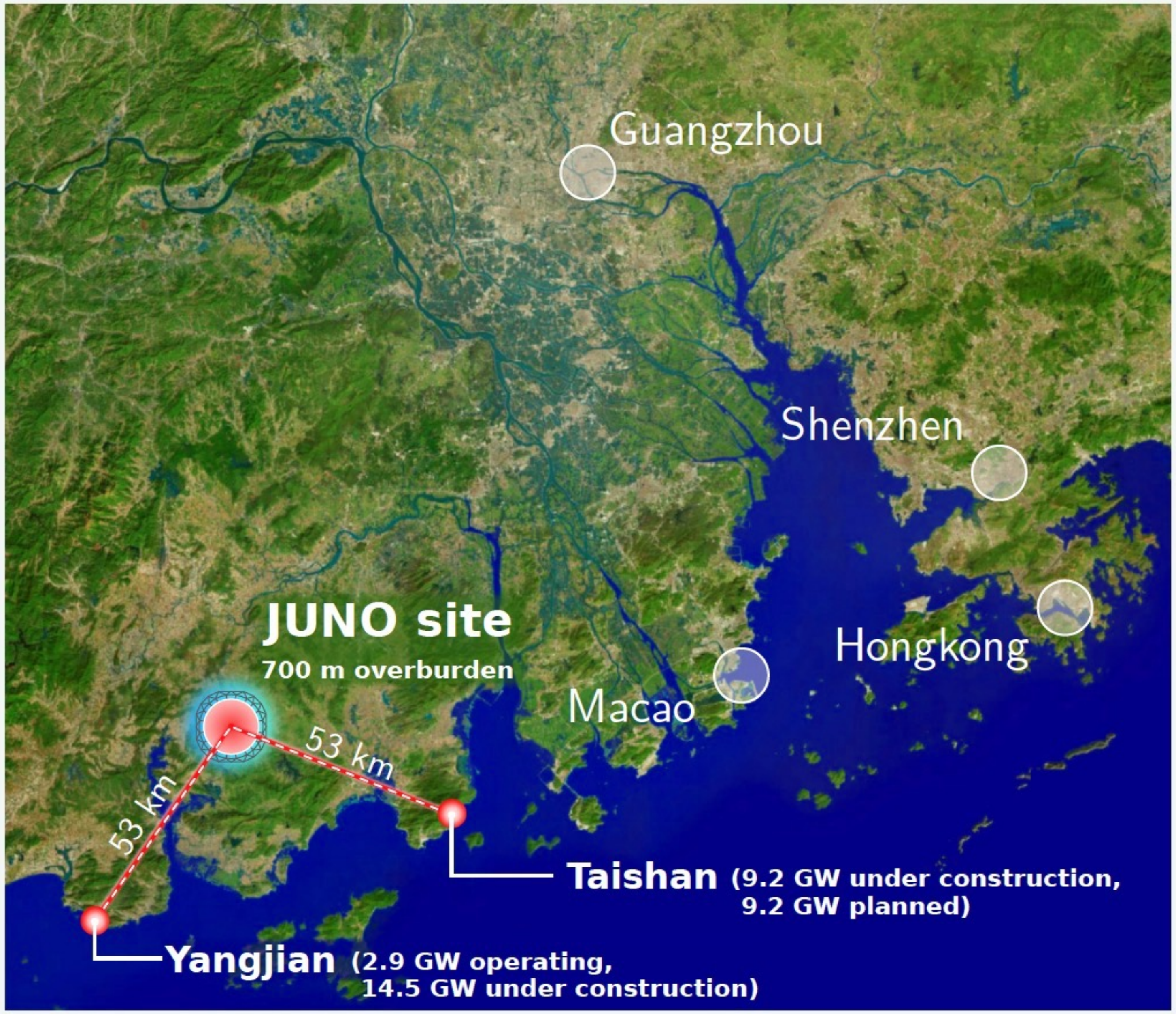
China Nanjing U.
China Nankai U.
China NUDT
China NCEPU
China Pekin U.
China Shandong U.
China Shanghai JT U.
China SYSU
China Tsinghua U.
China UCAS
China USTC
China U. of South China
China Wu Yi U.
China Wuhan U.
China Xi'an JT U.
China Xiamen University
China Zhengzhou U.
Czech R. Charles U. Prague

Finland U. Jyväskylä
France APC Paris → LAL Orsay
France CENBG Bordeaux
France CPPM Marseille
France IPHC Strasbourg
France Subatech Nantes
Germany ZEA FZ Julich
Germany RWTH Aachen U.
Germany TUM
Germany U. Hamburg
Germany IKP-2 FZ Jülich
Germany U. Mainz
Germany U. Tuebingen
Italy INFN Catania
Italy INFN di Frascati
Italy INFN-Ferrara
Italy INFN-Milano

Italy INFN-Milano Bicocca
Italy INFN-Padova
Italy INFN-Perugia
Italy INFN-Roma 3
Latvia IECS Riga
Pakistan PINSTECH Islamabad
Russia INR Moscow
Russia JINR
Russia MSU
Slovakia U. Bratislava FMPICU
Taiwan National Chiao-Tung U.
Taiwan National Taiwan U.
Taiwan National United U.
Thailand NARIT
Thailand PPRLCU Bangkok
Thailand SUT
USA UMD1
USA UMD2

the JUNO collaboration...

JUNO location…

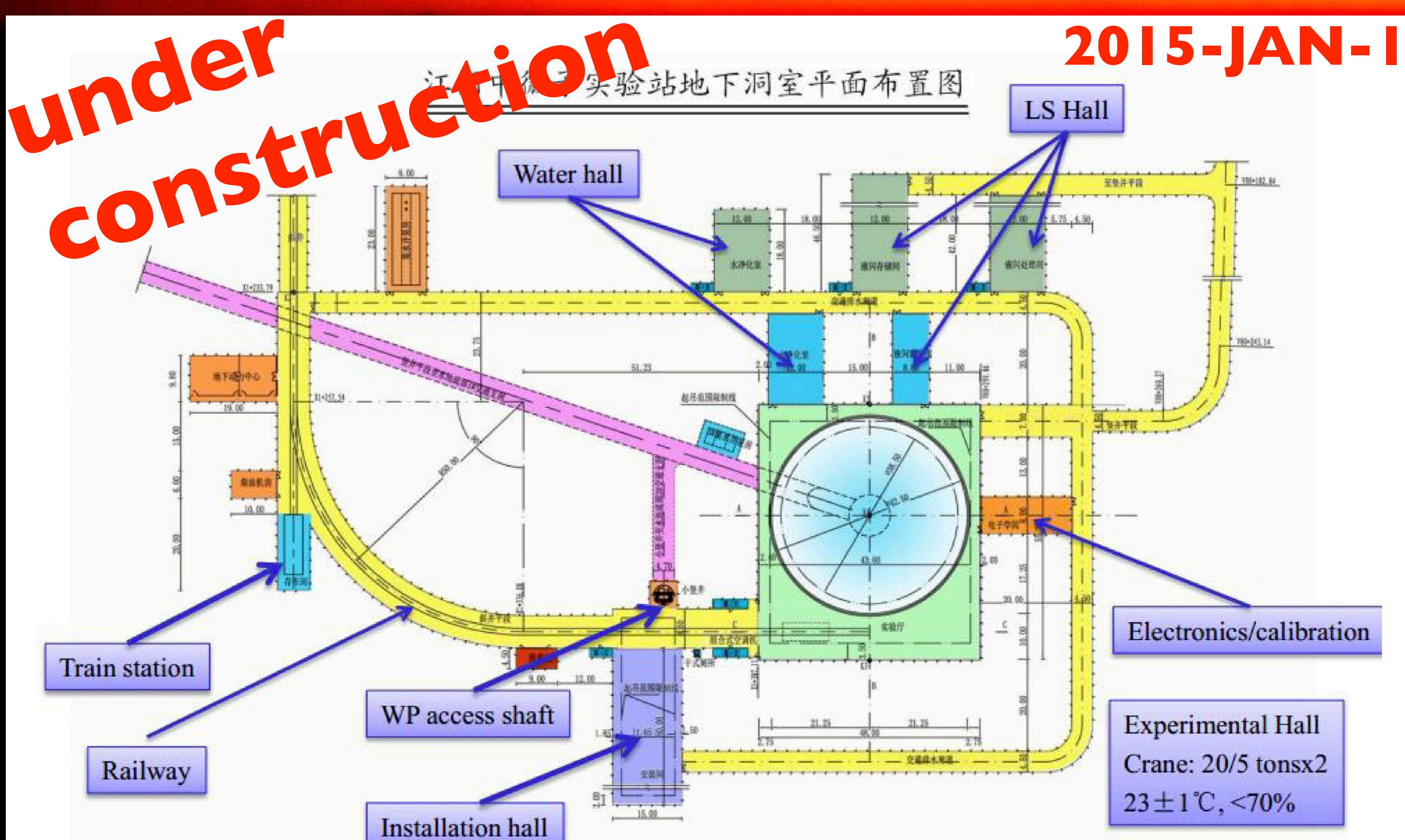


simplistic schedule: **data-taking aim to start by ≤2022**

the JUNO laboratories…

on surface facilities

- construction support
- running



schedule driver

(delay ~1year)

- detector cavity (now)
- underground facilities

underground cavity

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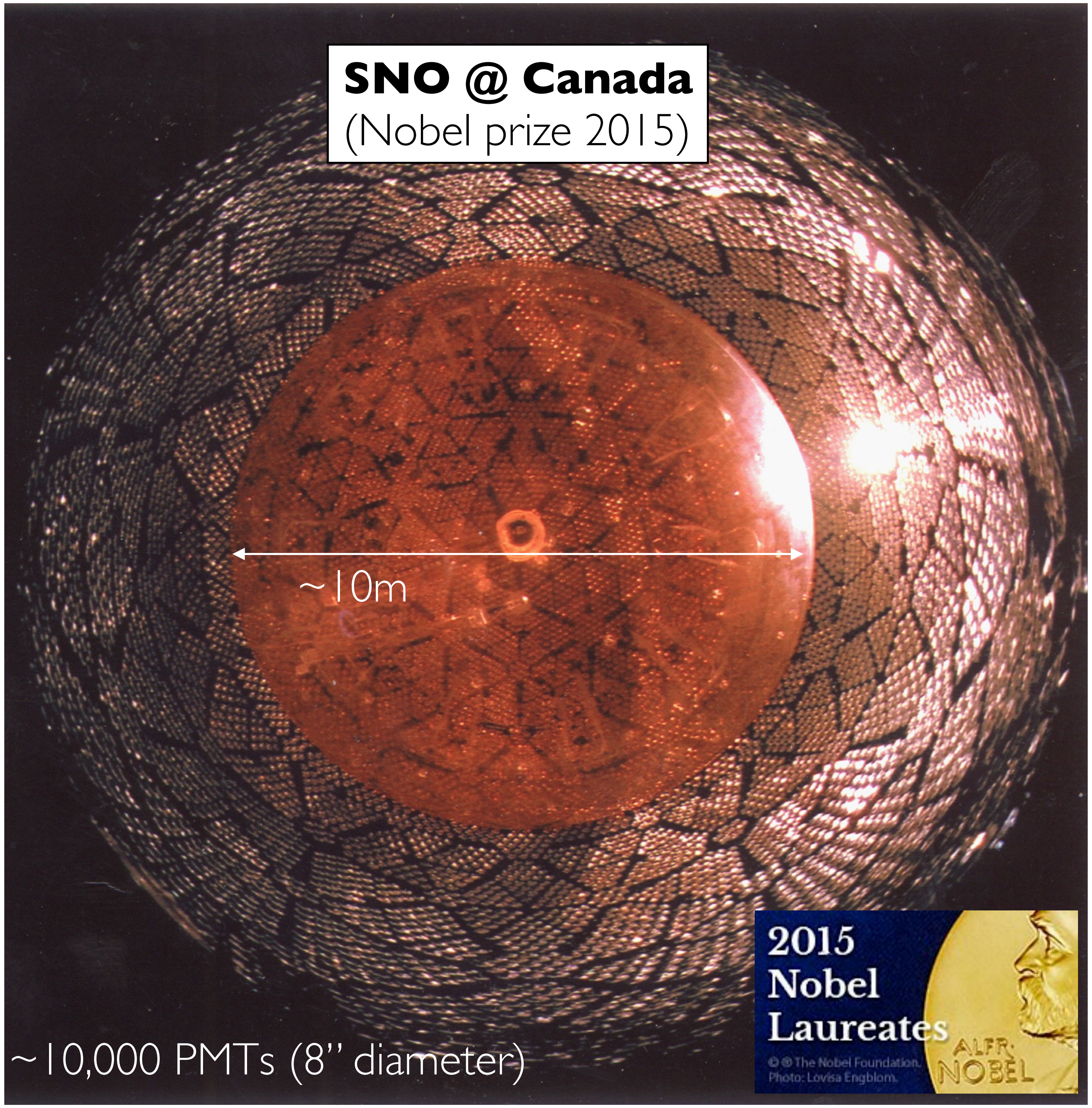
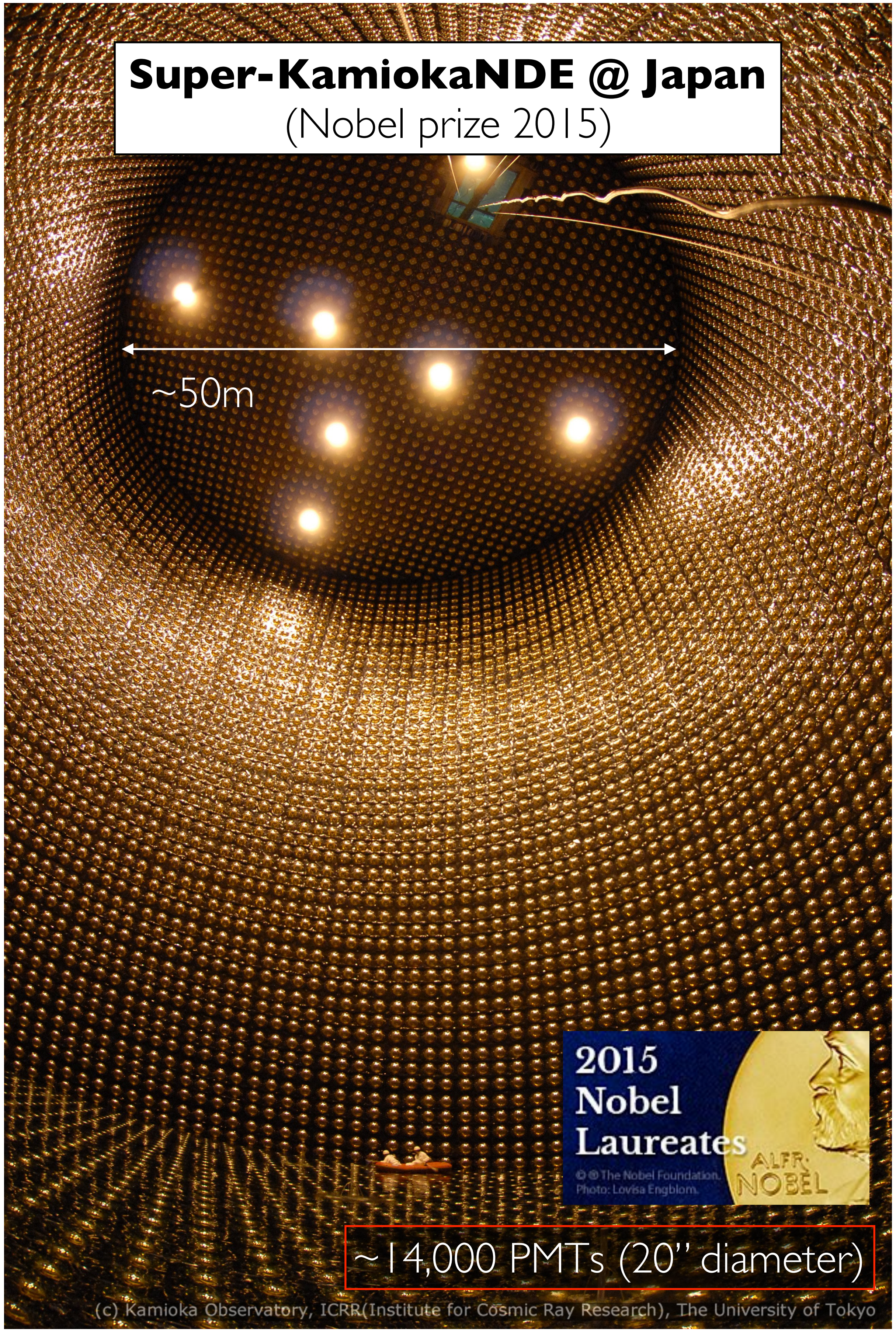
the JUNO detector…

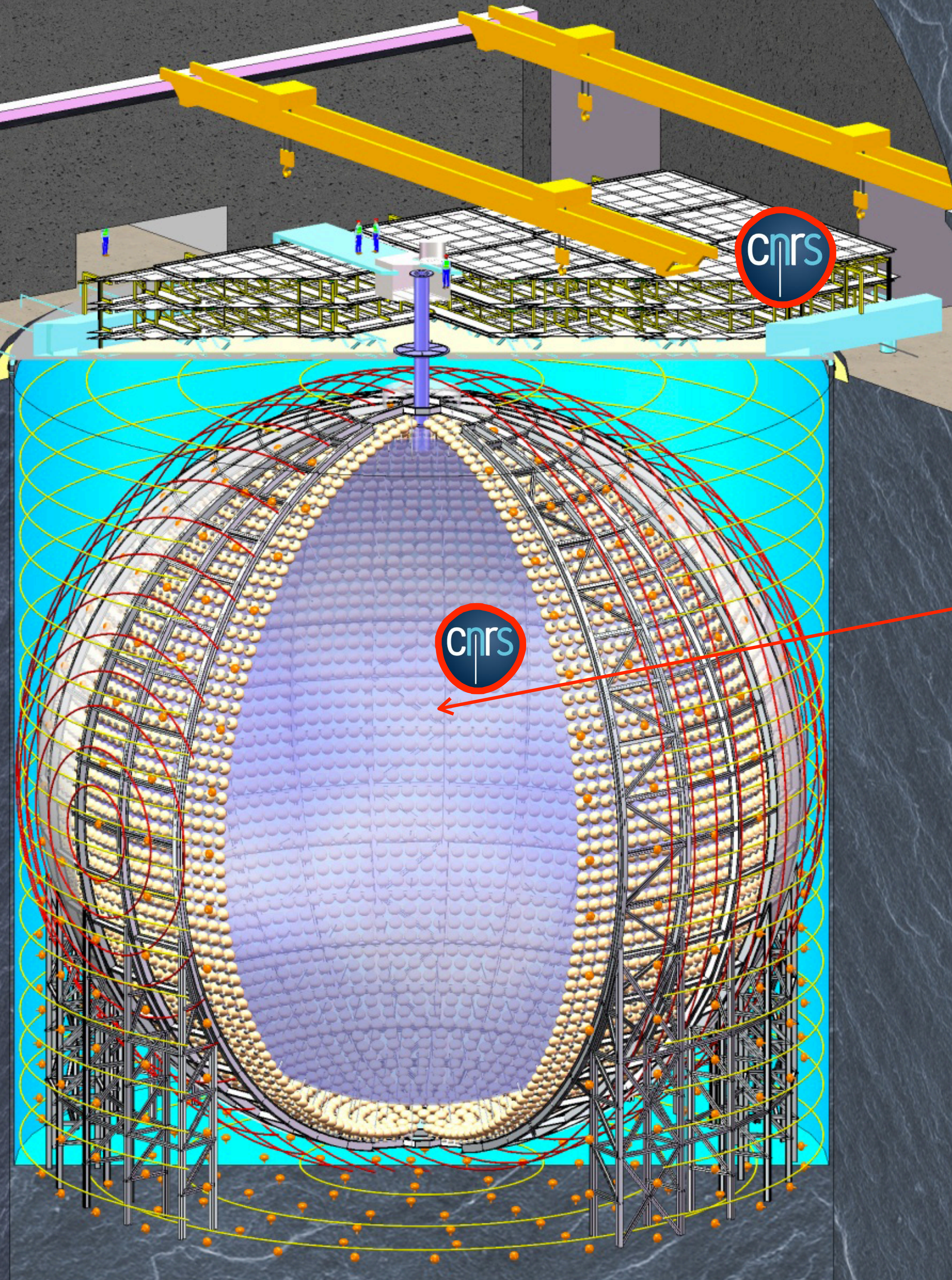
the JUNO detector (famous predecessors)…





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

our (huge) detector…



Underground Laboratory:

- ~700m overburden→ **~3μ/s**
- **~53km baseline** to reactors

Neutrino Detector:

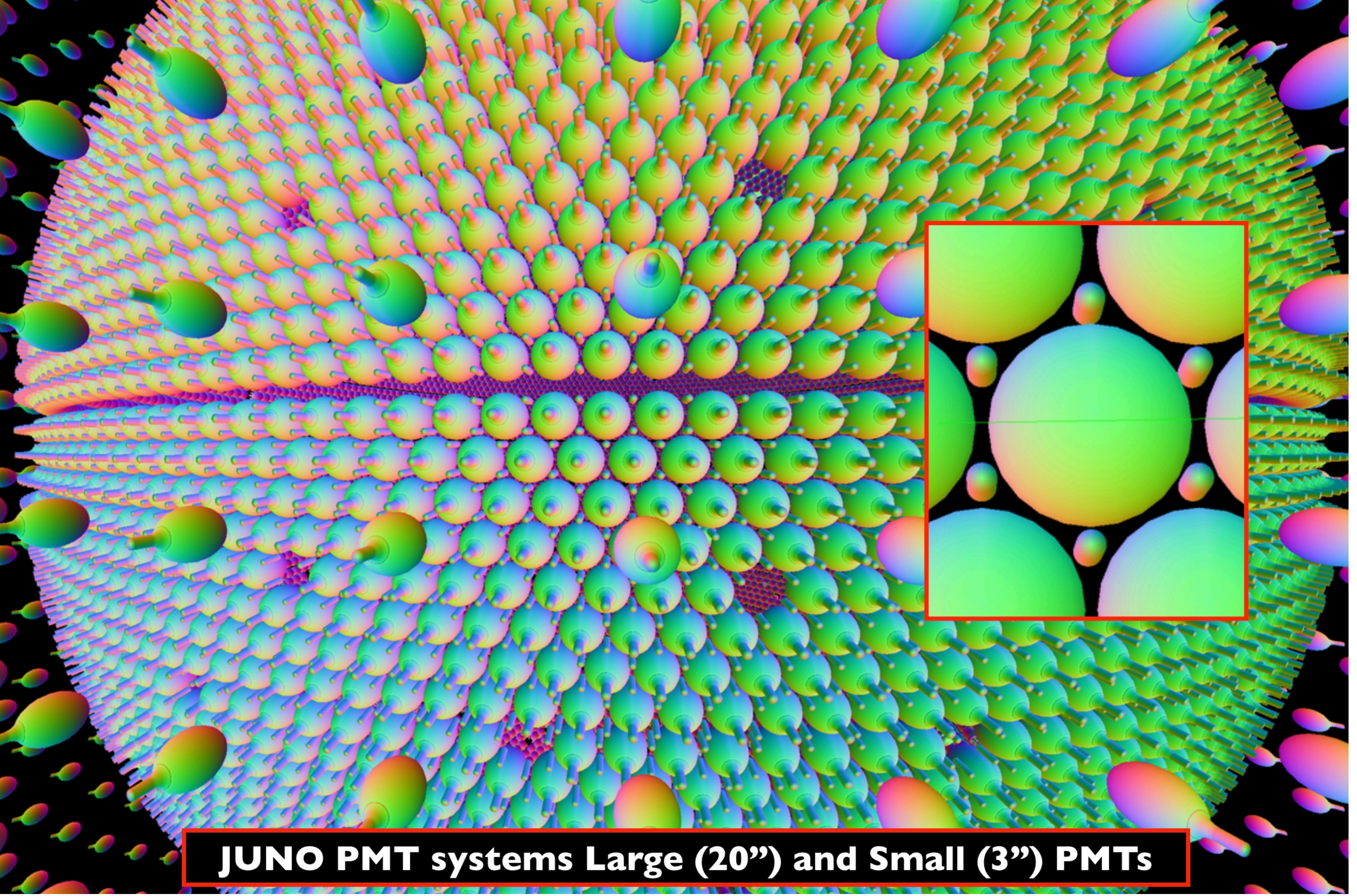
- **~20k ton liquid scintillator** [acrylic 12cm surrounding]
- **~18k 20” PMT** (implosion mask)
- **25k 3” PMT** (stereo-calorimetry)
- compensation coils: Earth B(field)
- **high radio-purity** control

Calibration Articulation(s):

- access chimney
- calibration deploy system(s) [box]

Veto Detector(s):

- **water-Cherenkov** (4π μ’s)
  - →≳2m rock-γ’s shield (inert)
- **top-tracker** (multi-layer & top)

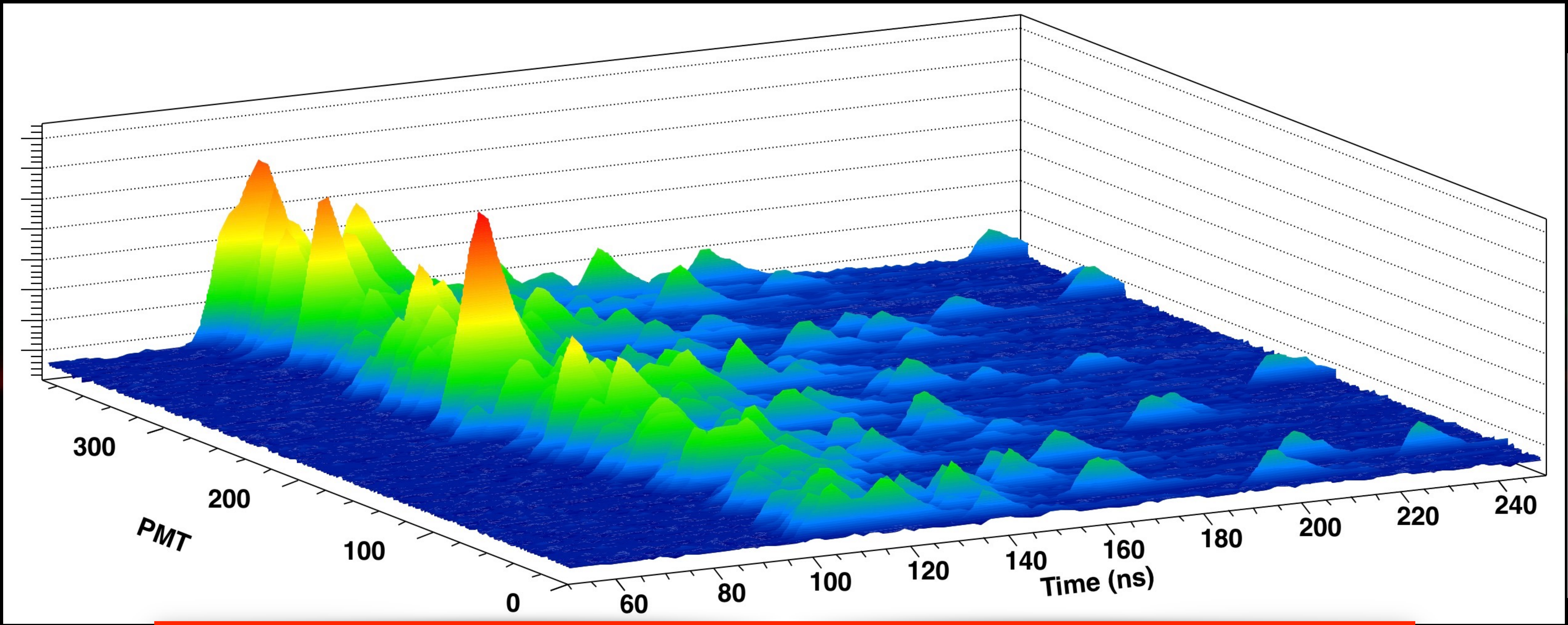


JUNO a photocathode colosso→ yield energy resolution!

Large PMT (20”)

Small PMT (3”)

FADC @ Double Chooz...

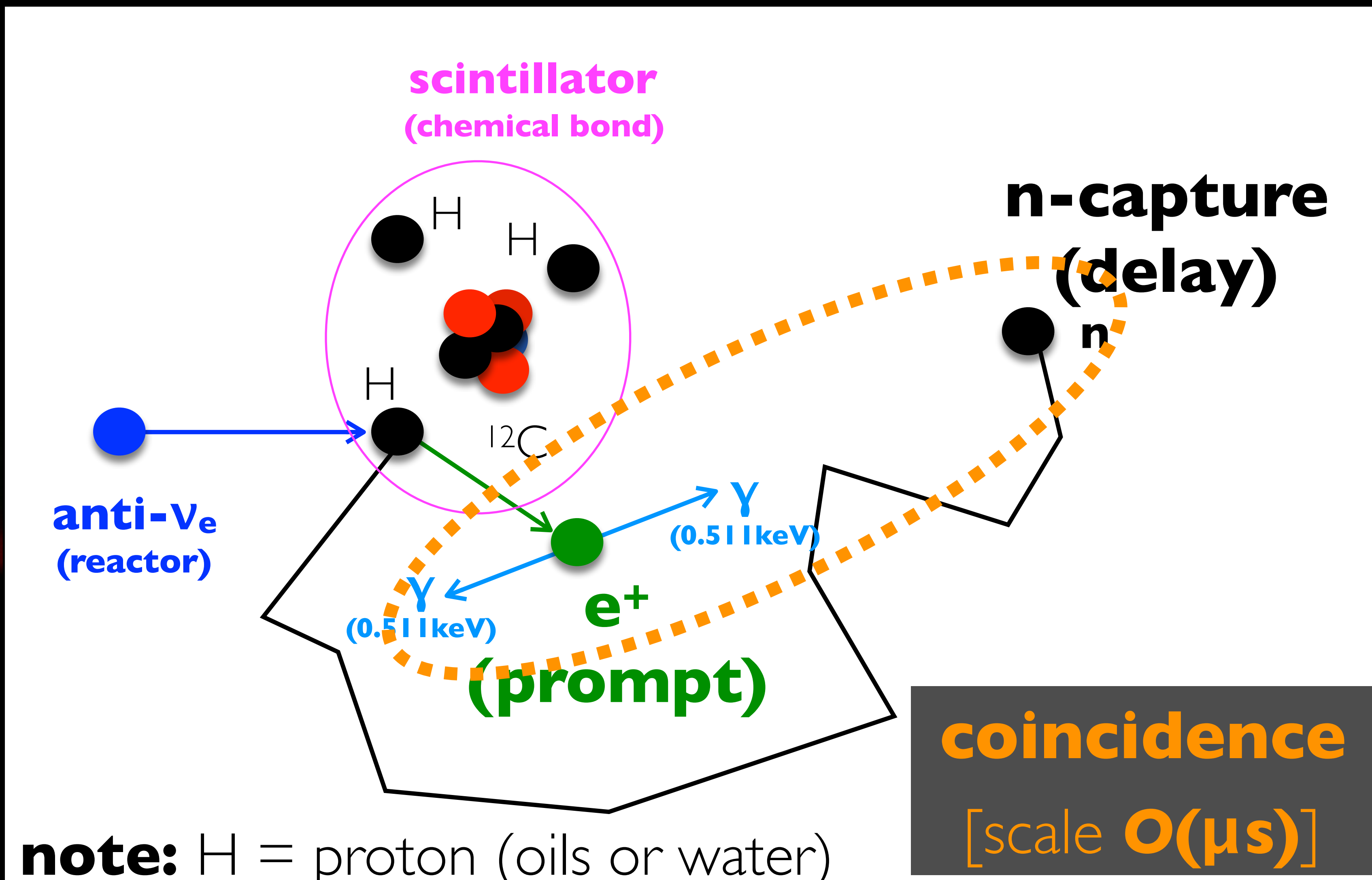


many channels → triangulation info

- **charge:** single-photon resolution
- **timing:** fraction of ns resolution
- **derived information (i.e. reconstruction):** position, PID, etc

inverse-β decay (IBD) interaction…

IBD: anti-ν_e + p → e^+ + n



IBD detection art…

n-H (**native**)

n-C (**native oil**)

—

n-Cd (doped)→ ν discovery

n-Gd (doped)→ ≥Chooz

n-Li (doped)→ ≥Bugey3

—

^{3}He (different technology)

no e+ PID implies

e^+ ≈ BG (γ ≈ e^- ≈ α ≈ p-recoil)

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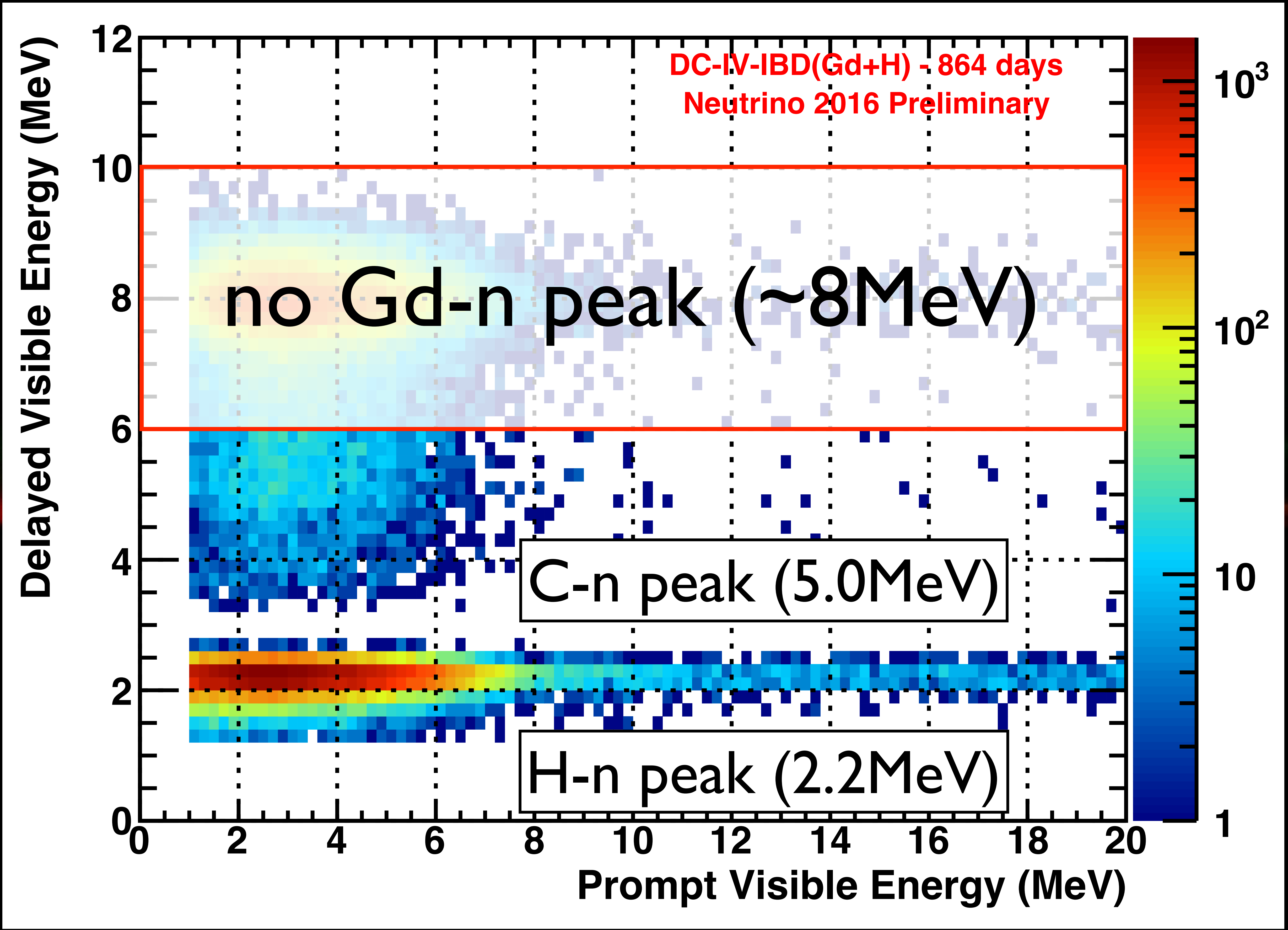
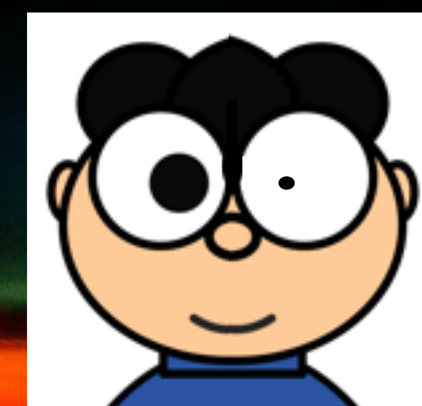
prompt vs delay energy spectra…




SPMT
(stereo-calorimetry)

JUNO
(mono)

JUNO
(stereo)



25k 3" PMT ⊕ compact fast readout

(huge system→one of the largest)

Anatael Cabrera (CNRS-IN2P3 & APC)

20 laboratories (9 countries) so far...

our (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) **(project/physics coordination)**
- SYSU (Guangzhou)

France
- APC/LAL (Paris/Orsay) **(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)

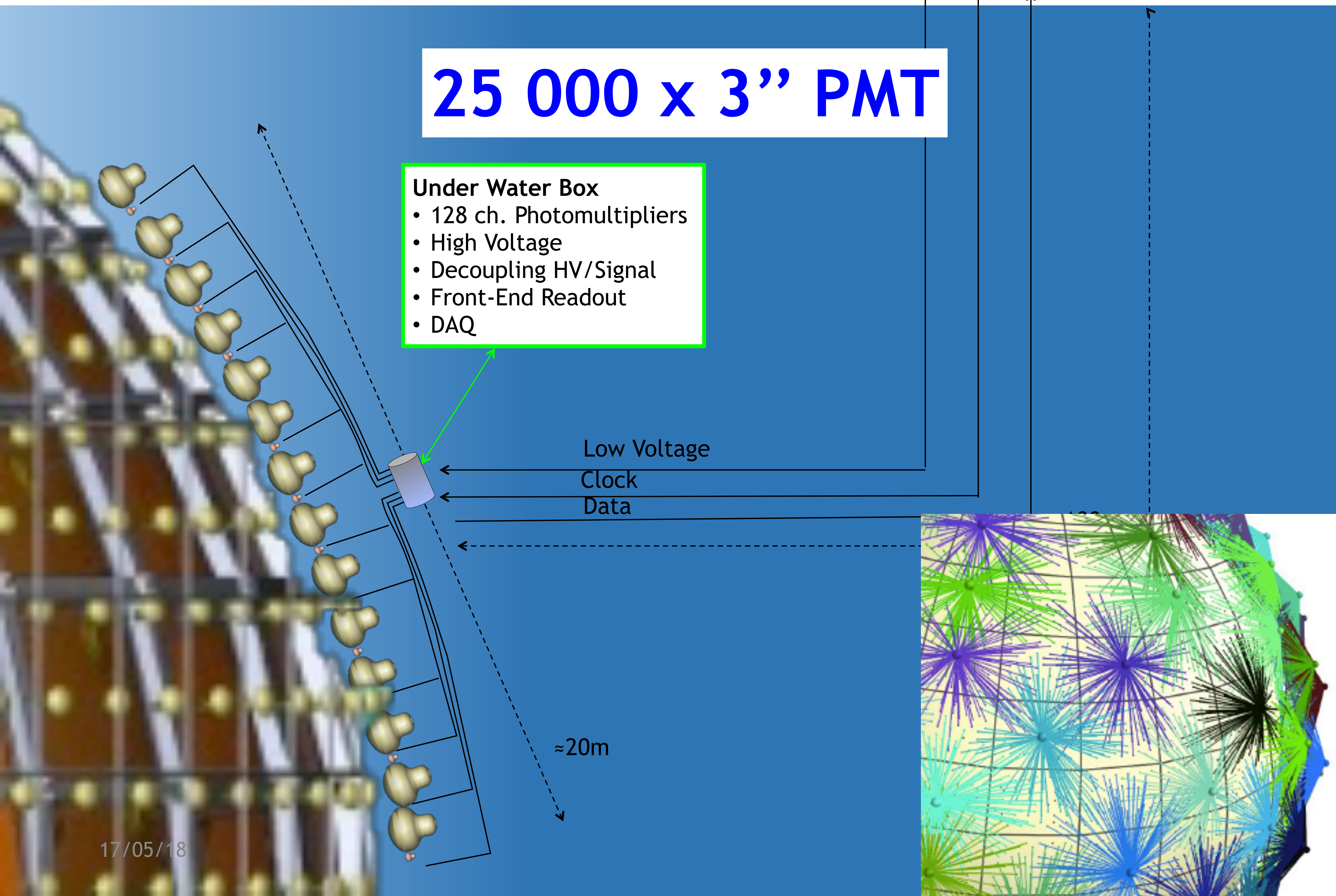
Taiwan
- National Taiwan University NTU (Taipei)
- National Chiao Tung University NCTU (Hsinchu)
- National United University NUU (Miaoli)

technical coordination: C.Cerna

internal coordination
- **physics:** F. Perrot (+INFN)
- **electronics:** A.Cabrera

project management: A.Cabrera (+2)

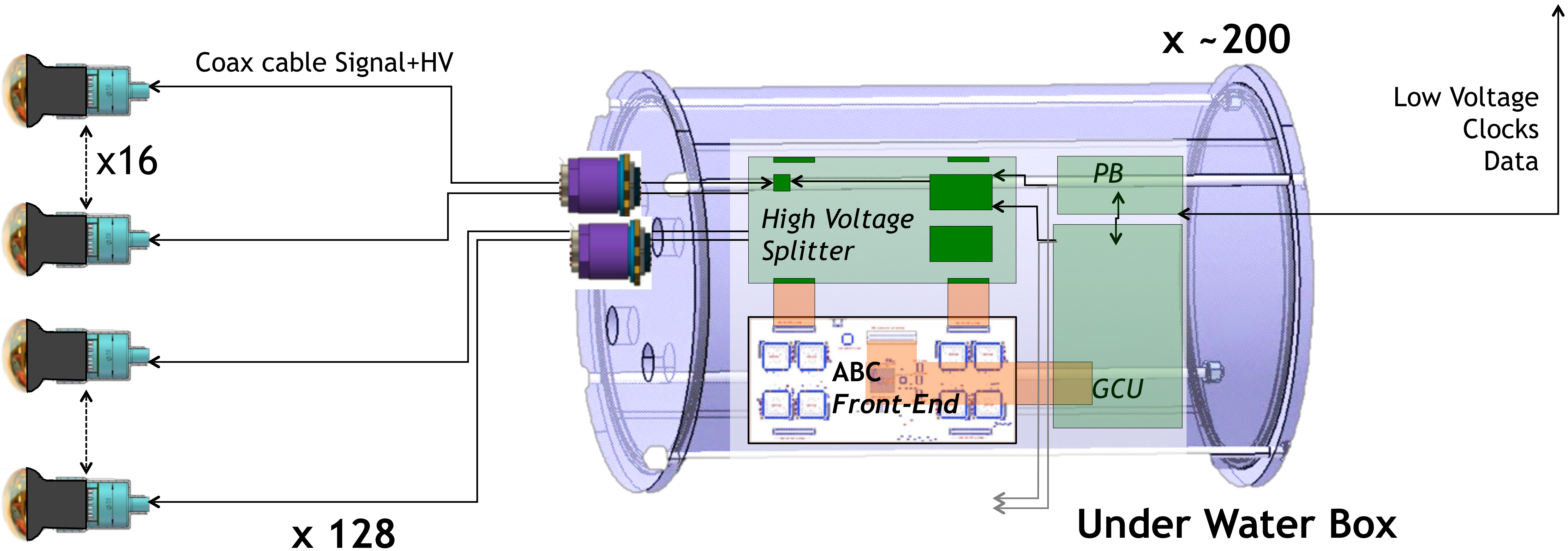
SPMT system within JUNO…



System schematics

our construction brick

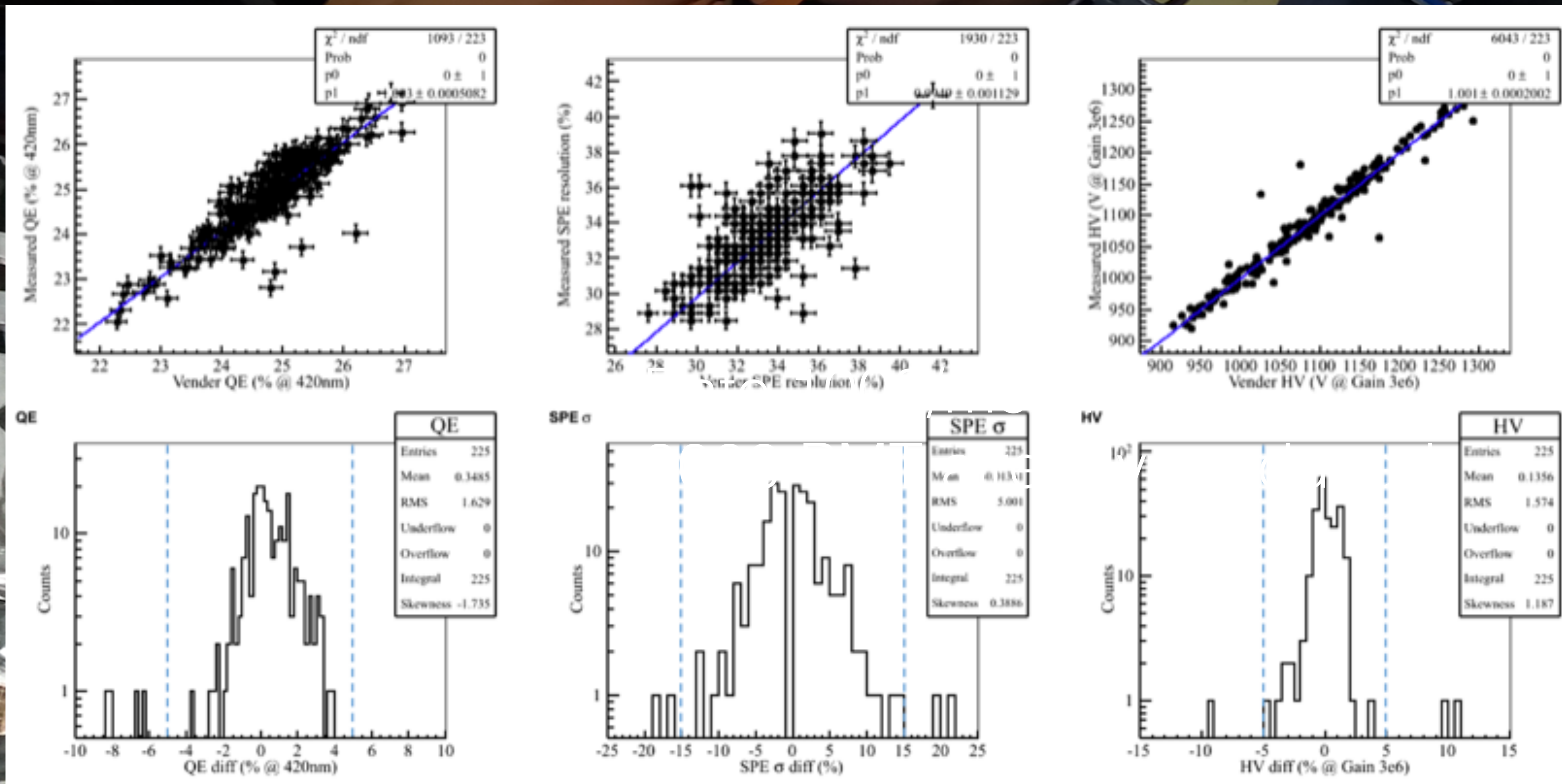
- 3'' PMT
- High Voltage divider
- Potting
- Cable
- Connector
- Under Water Box
- ABC board
- Splitter board



PMT production & testing (industry)status …

26,000 3” PMTs production & testing

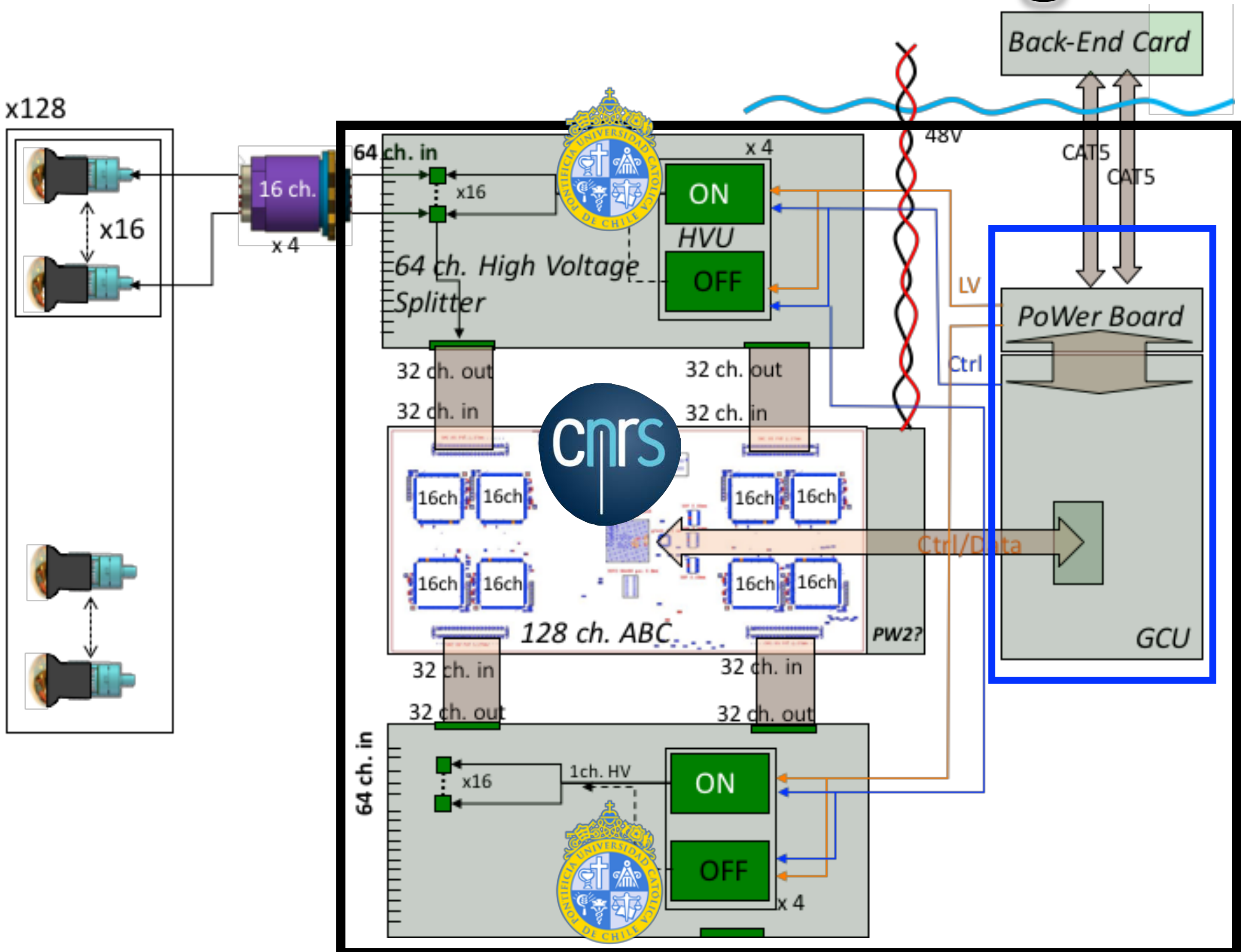
(@HZC→ company personnel ⊕ JUNO supervision)



1k PMT/month→ ~6k PMTs done!

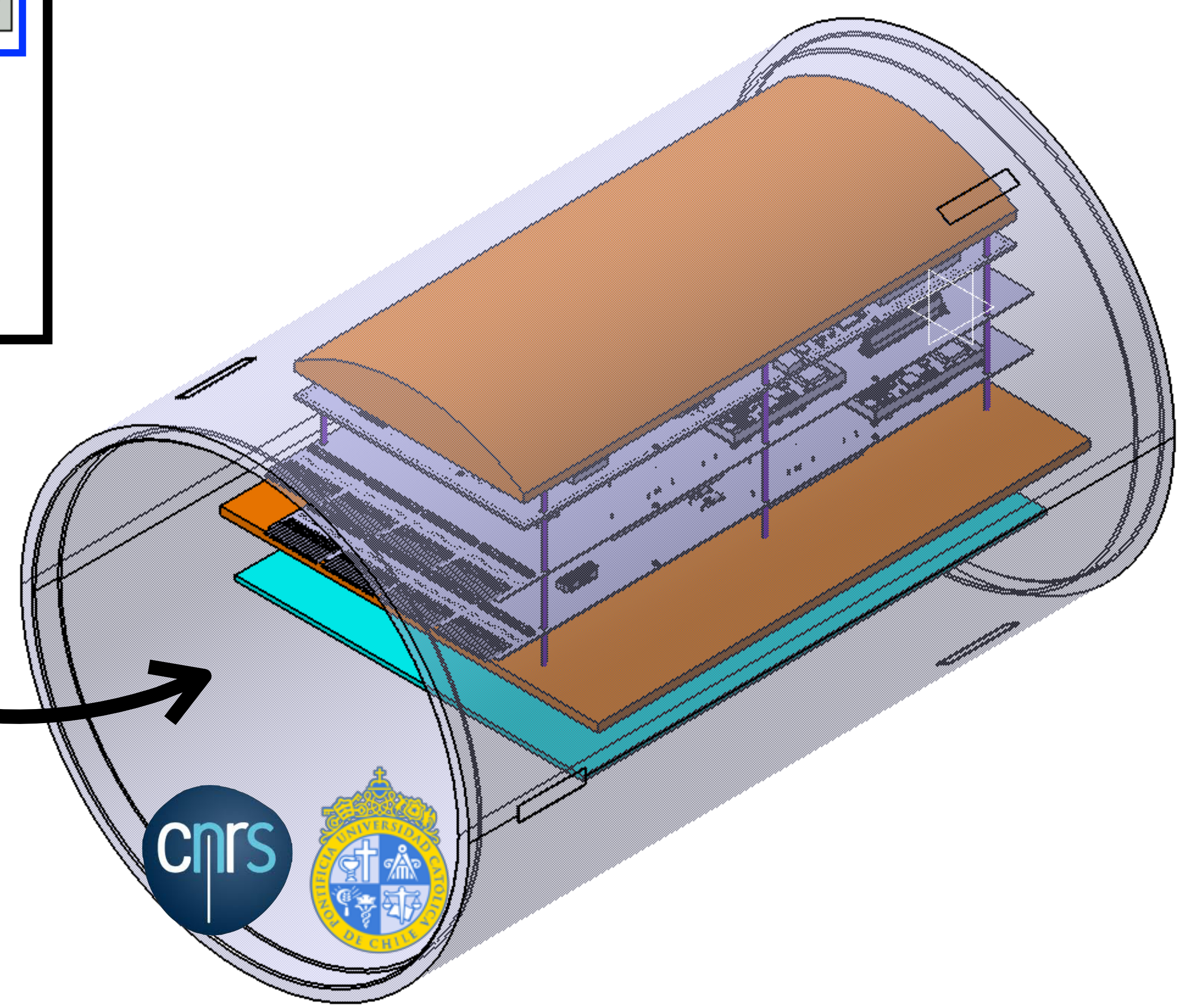
Anatael Cabrera (CNRS-IN2P3 & APC)

the readout goes (folded) under-water…

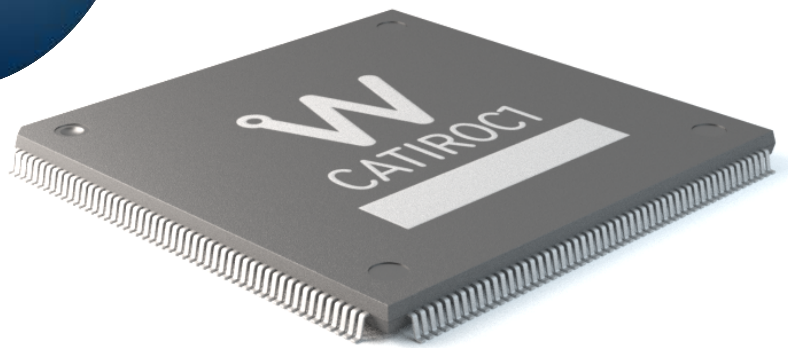


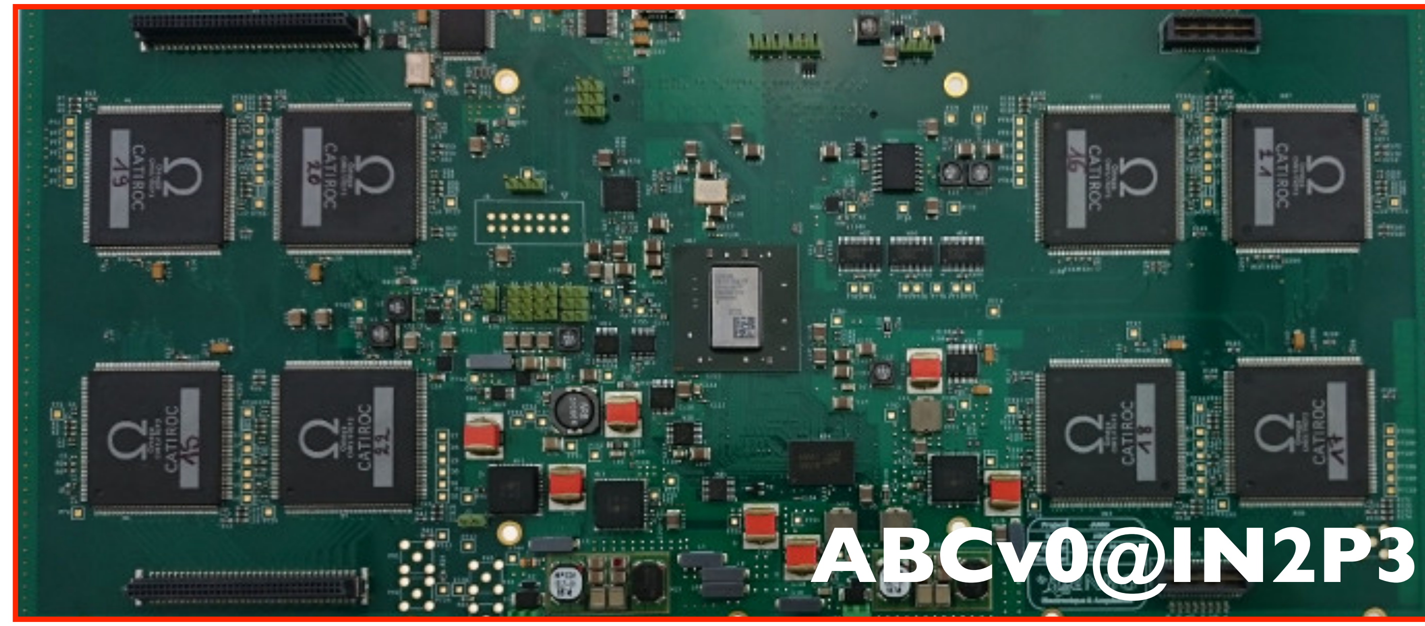
JUNO common
(SPMT⊕LPMT readout)

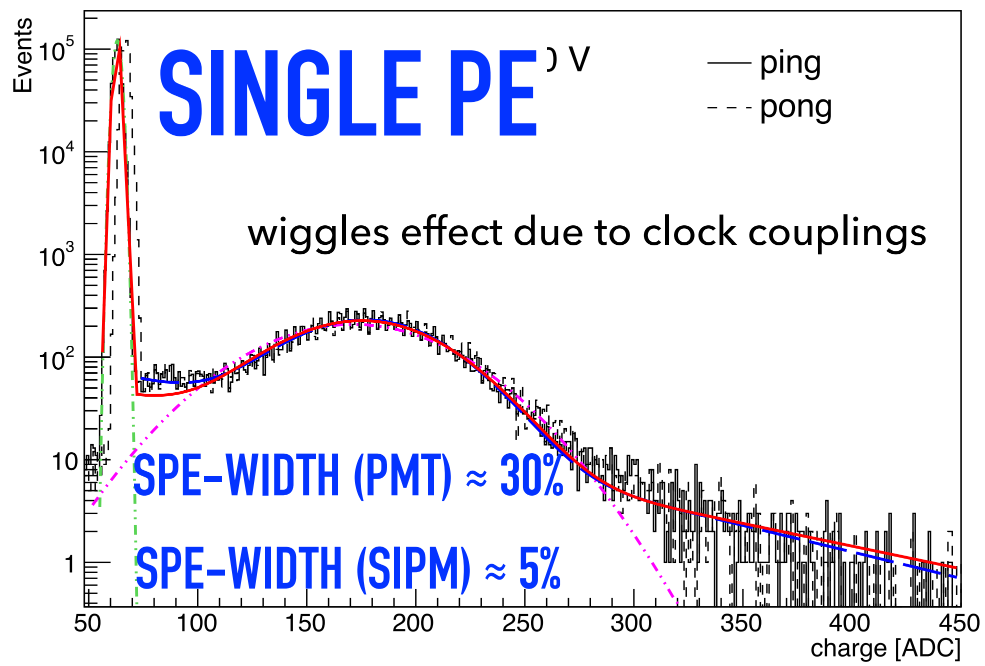
underwater box

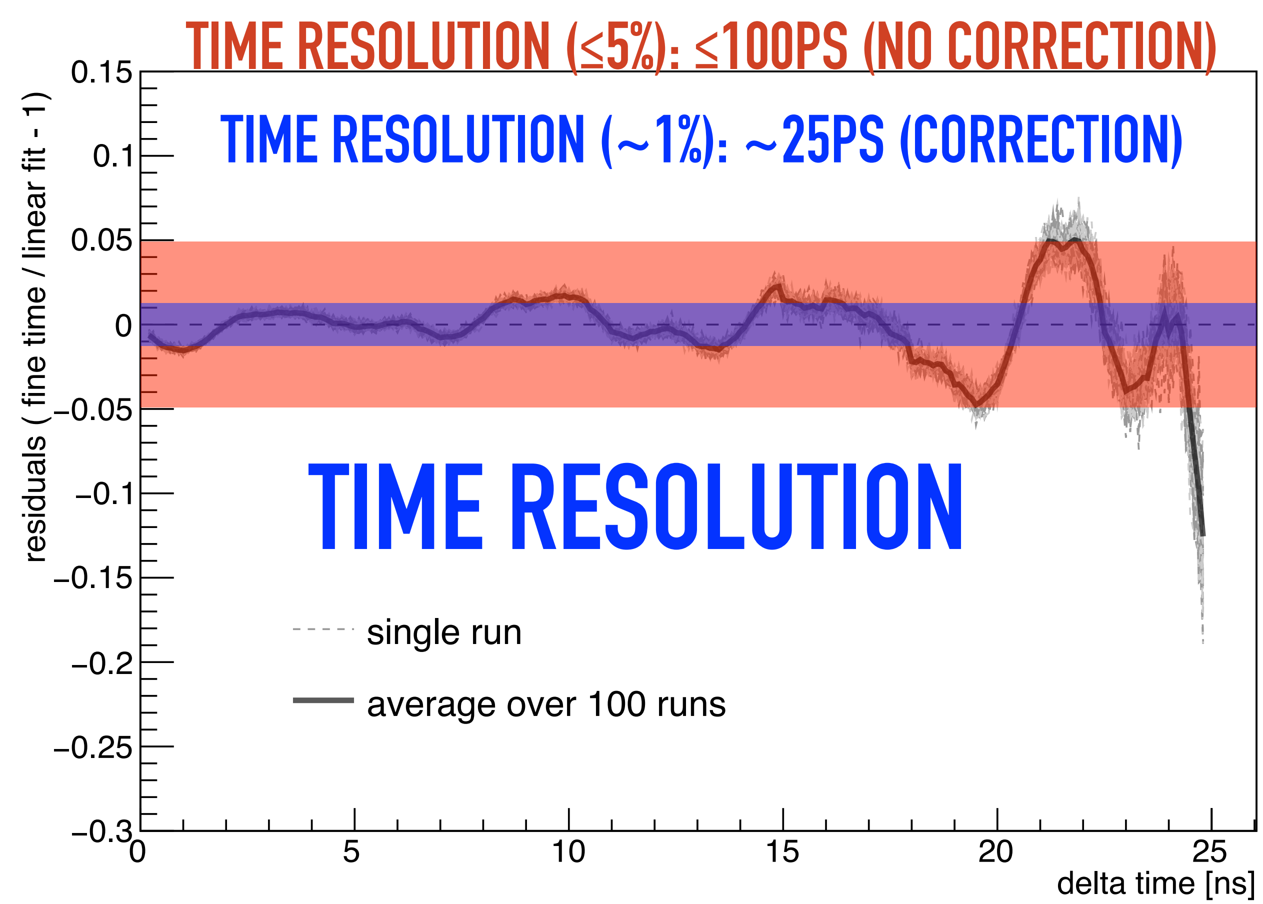


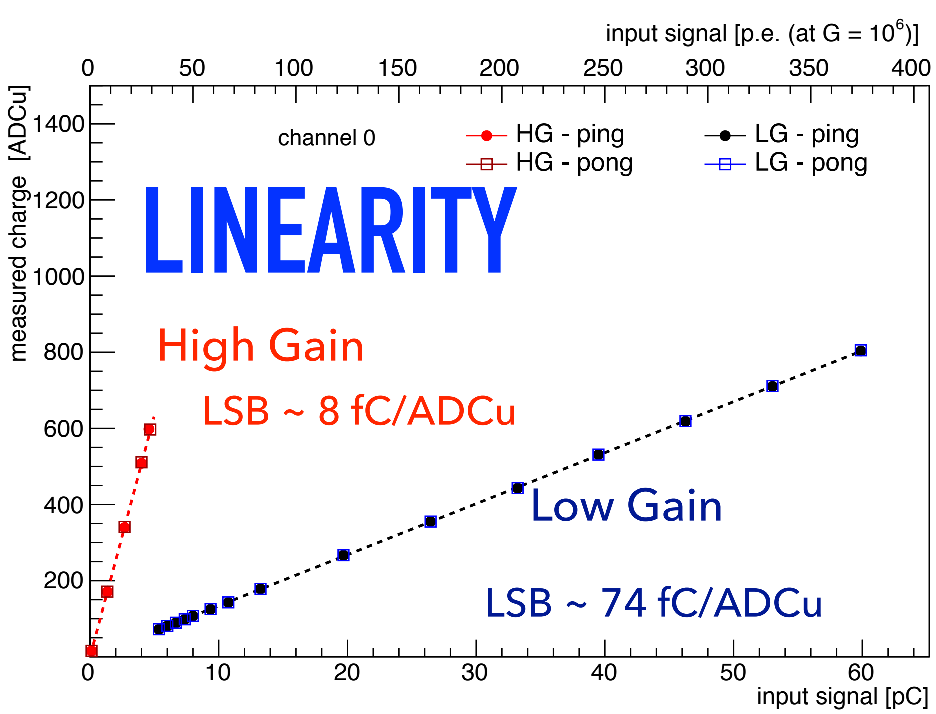
SPMT core readout electronics…







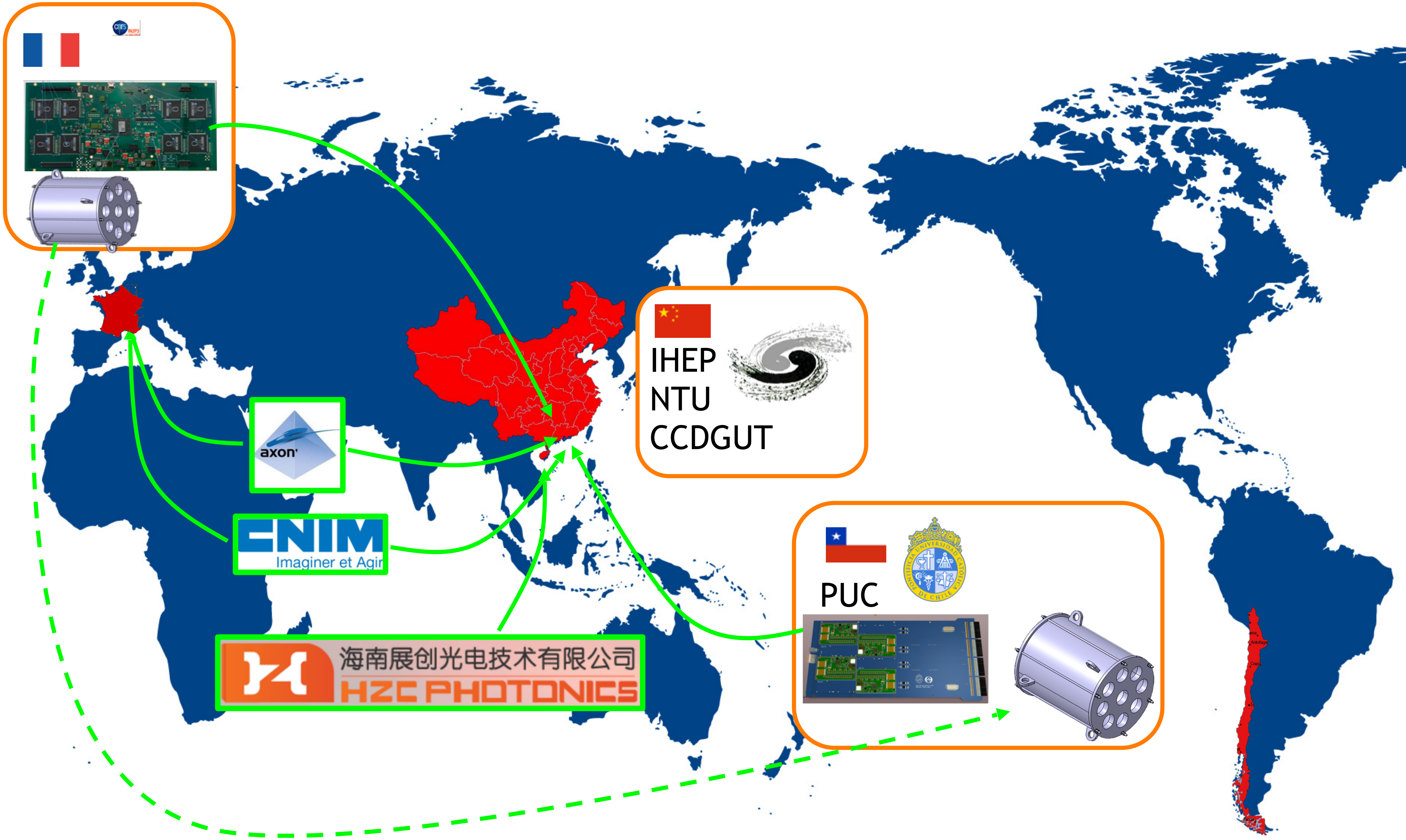




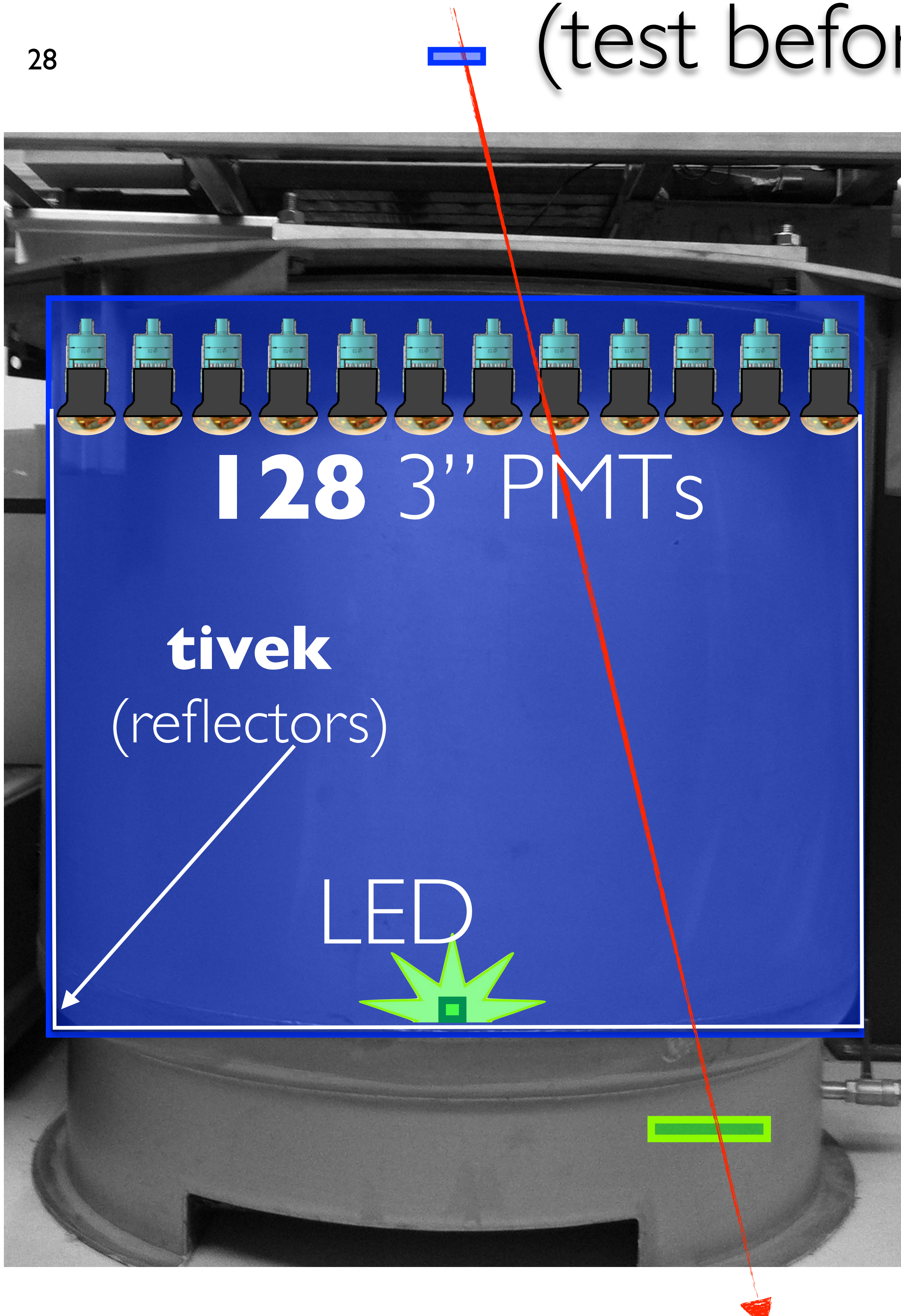
NOVEL SUPERNOVA READOUT → ≲10M/S?

shipping to JUNO site 2019-2020…

JUNO SPMT



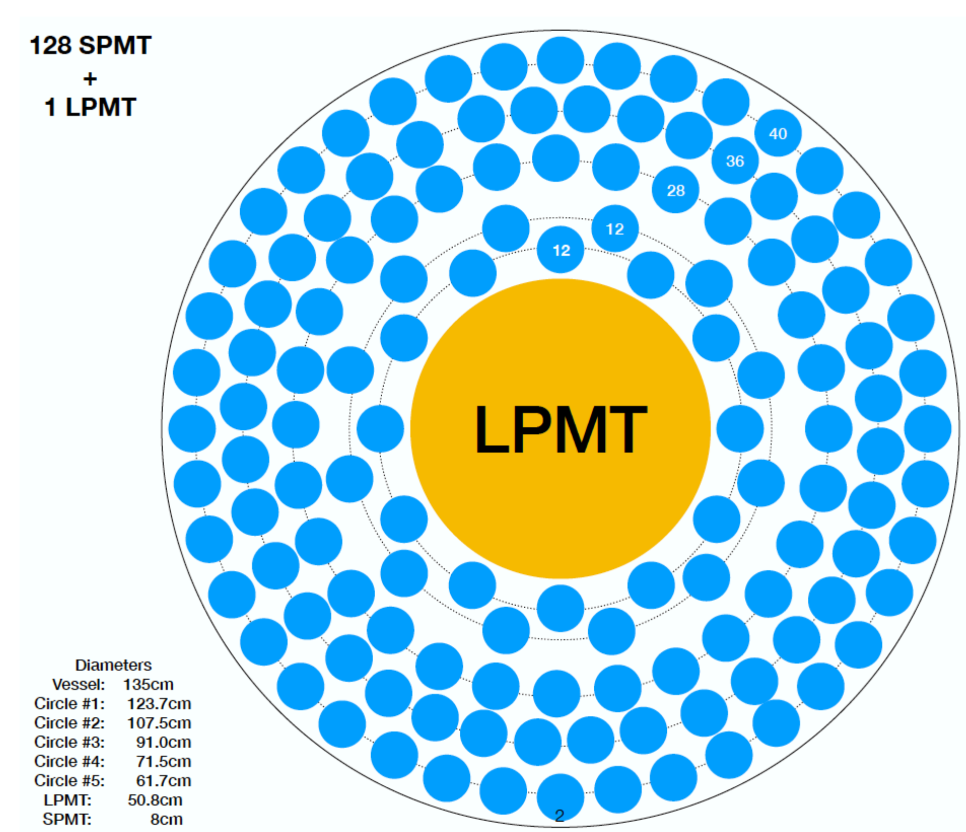
(test before) JINO @ IN2P3 (LAL)…

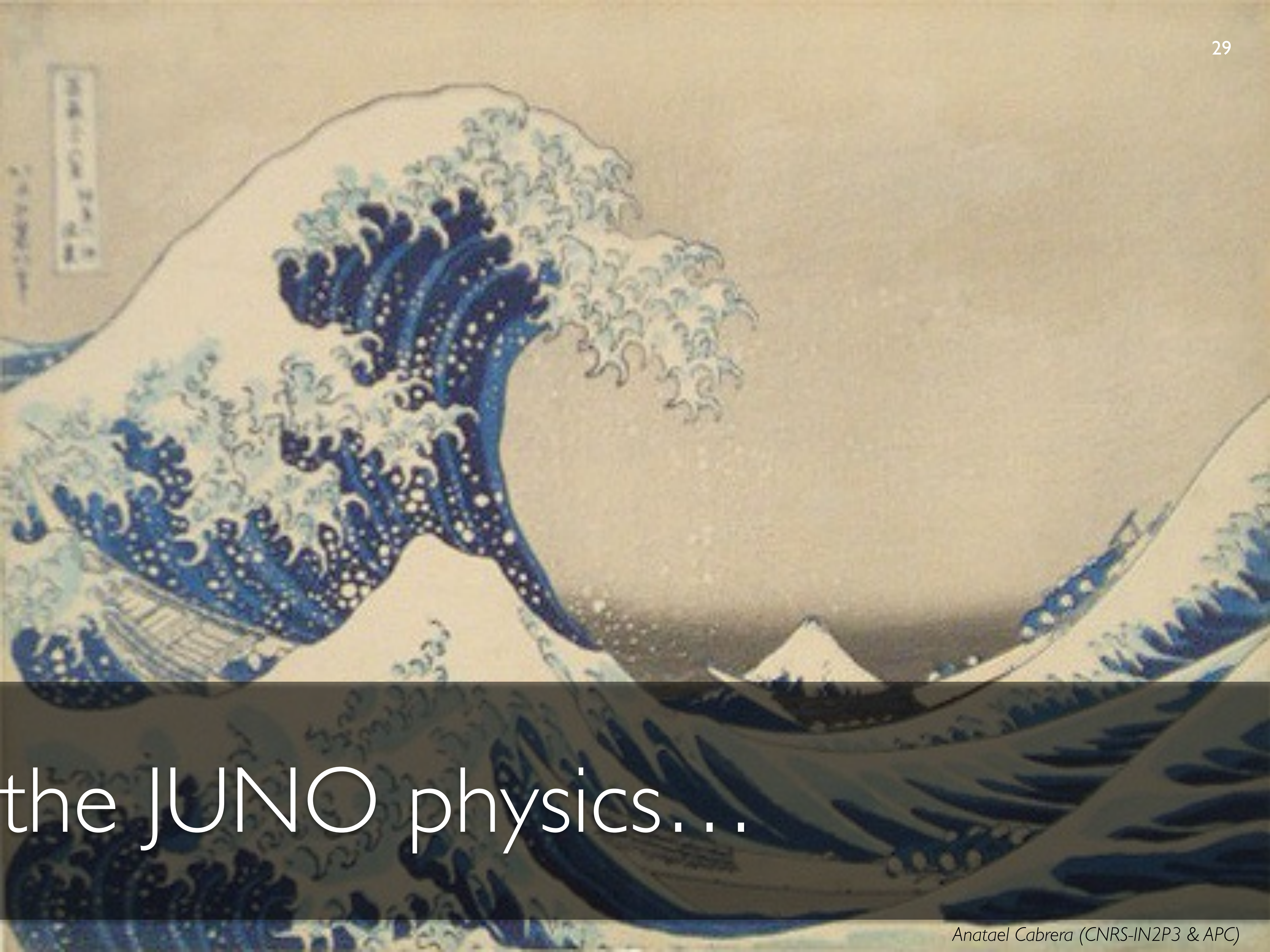


Φ=135cm M≤1.4tons

JINO (prototype) goals…

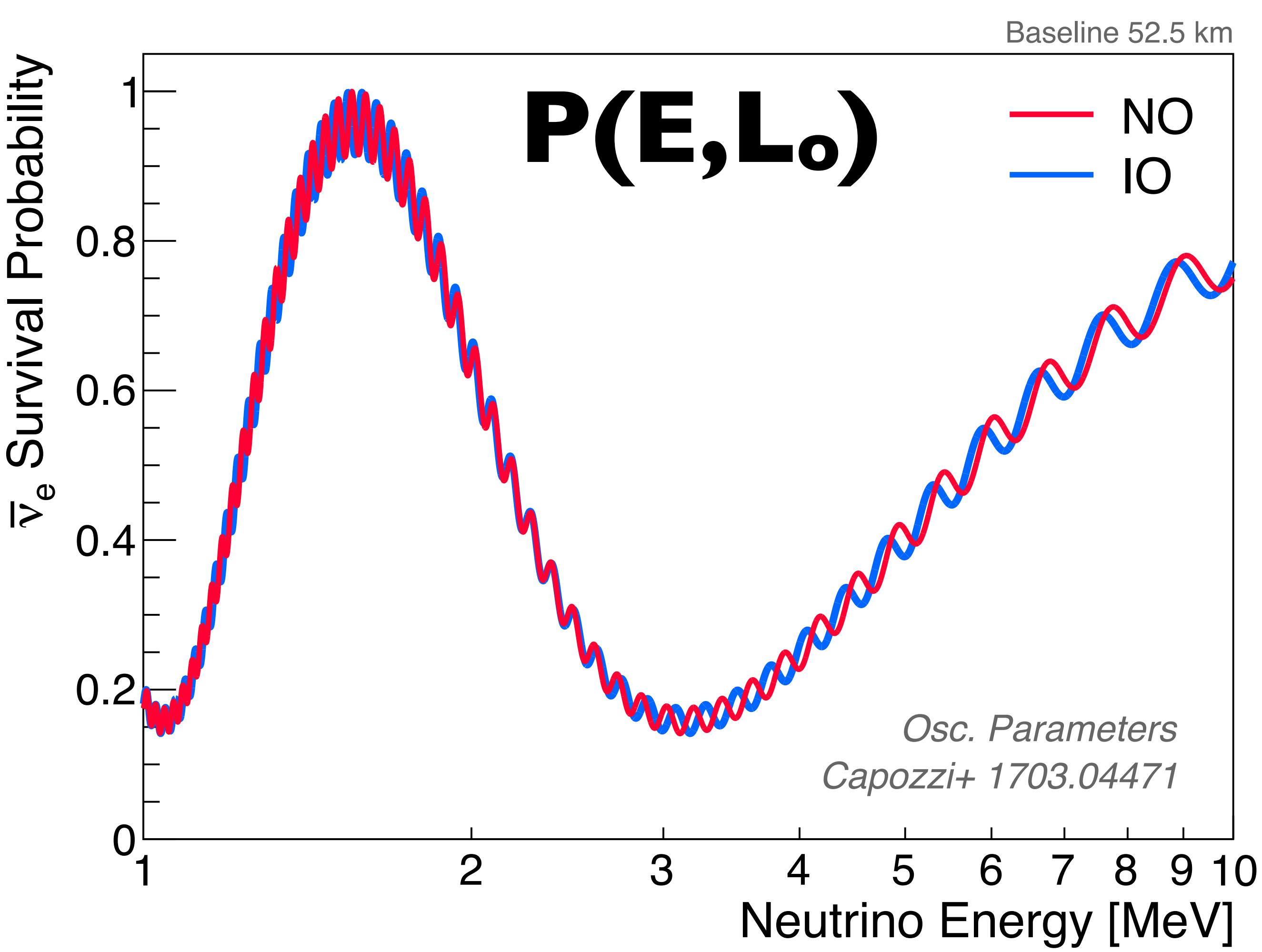
- **full system integration**
- **electronics/DAQ validation**
  - ABC card performance
  - multi-card synchronisation
- **supernova** high rate test/optimisation
- **stereo-calorimetry** data validation
- **pre-installation full system**

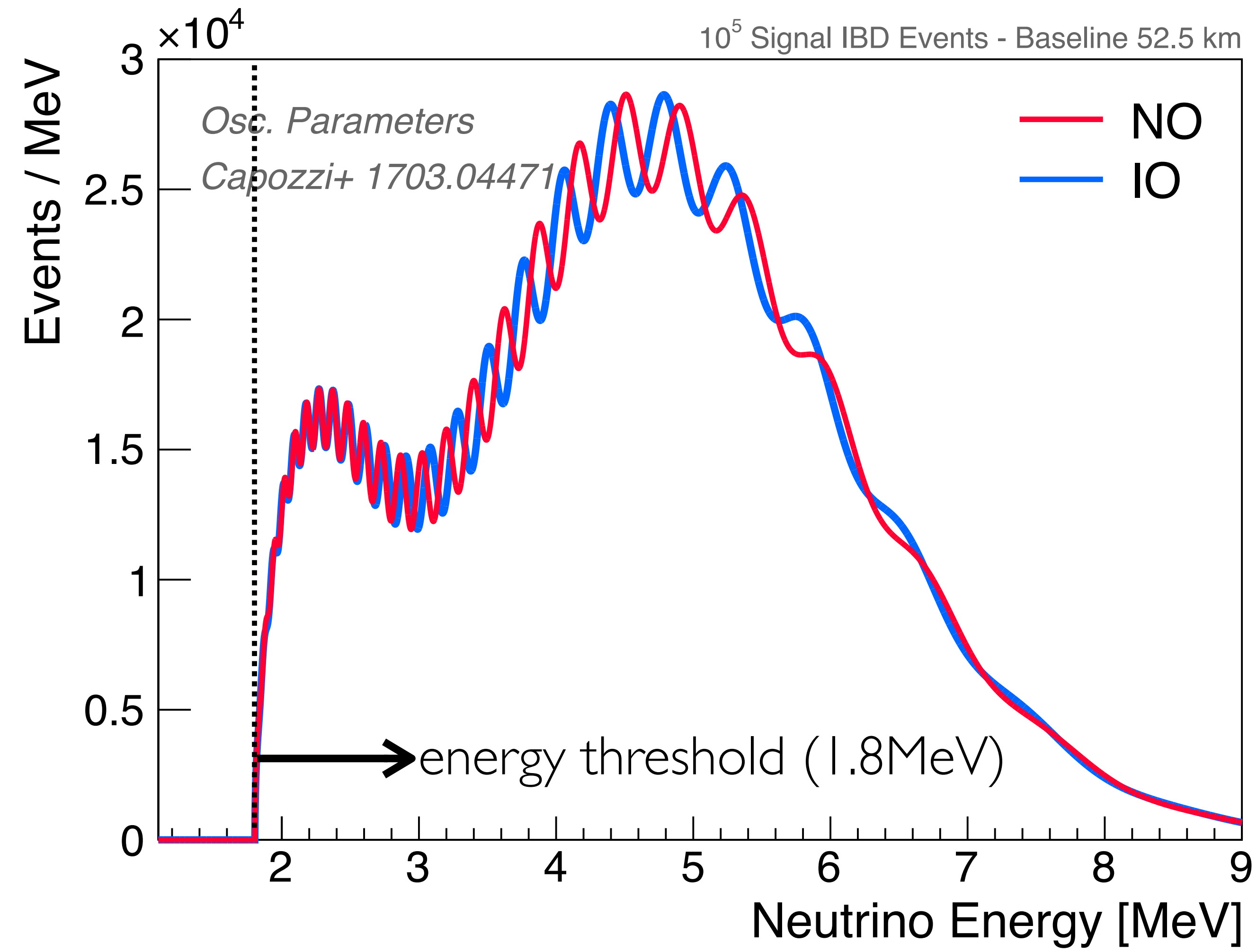




the JUNO physics…

the JUNO observables…





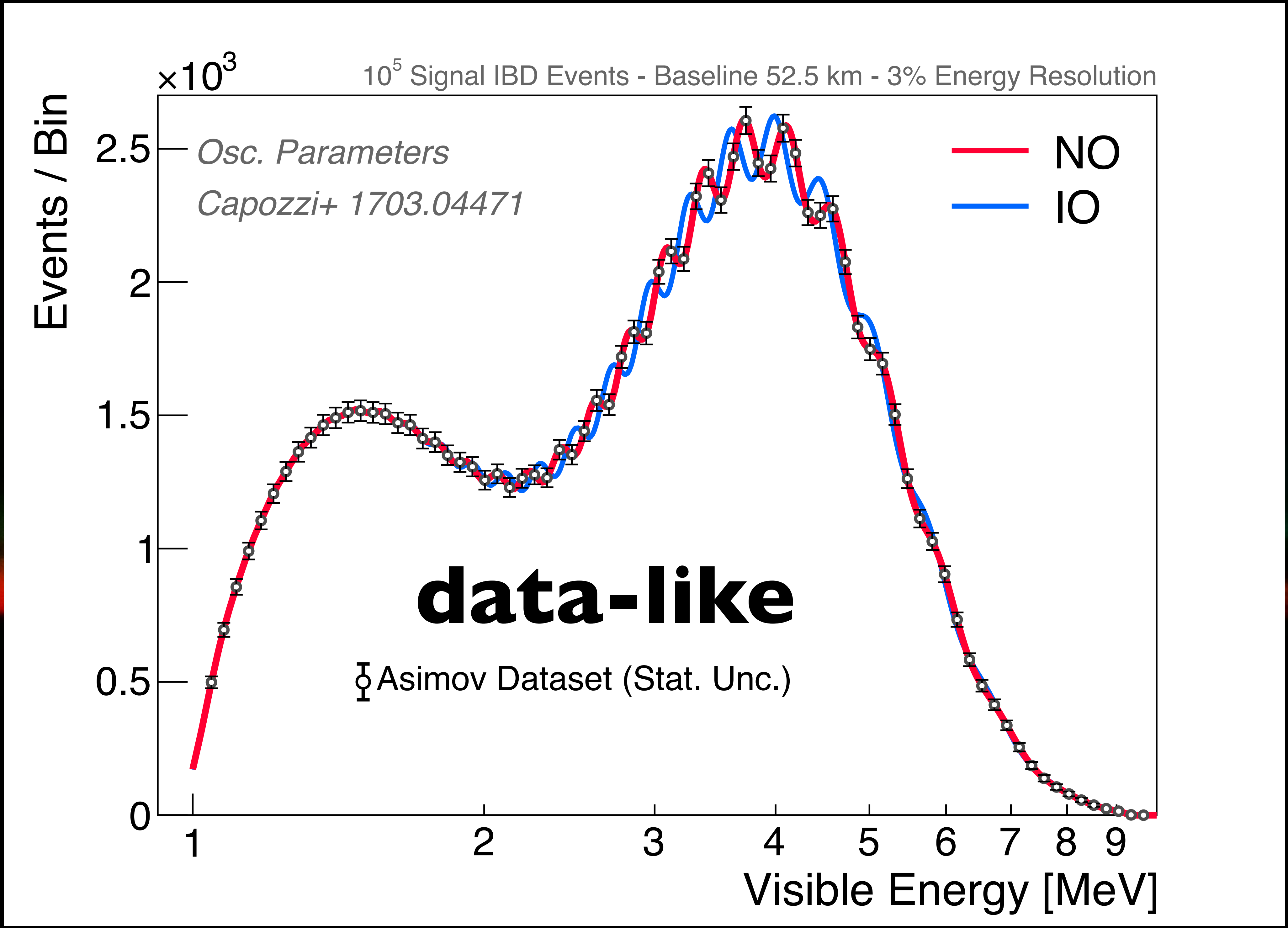
neutrino oscillations
(flux modulation)

spectral distorsion
(a perfect detector)

$$\textbf{Spectrum}(E_\nu) \approx P(E_\nu,Lo) \times \Phi(E_\nu) \times \sigma(E_\nu)$$

[trivial energy relation: $E_{e+} \approx E_\nu$ **- cost**]

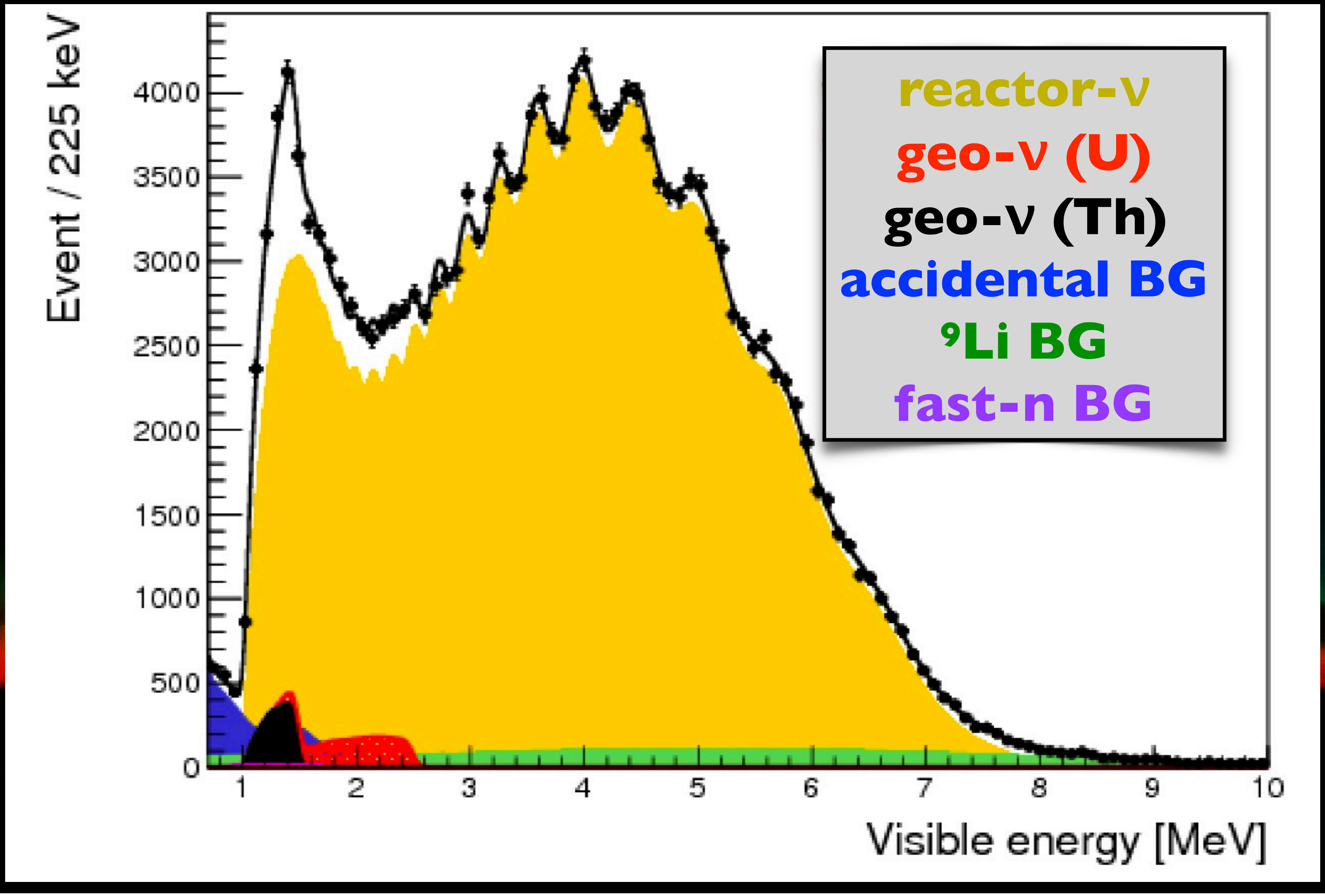
JUNO spectrum in more detail…



rich physics programme

$\theta_{12} \oplus \delta m^2 \oplus \pm\Delta m^2$ & info θ_{13}

JUNO challenge: the background…



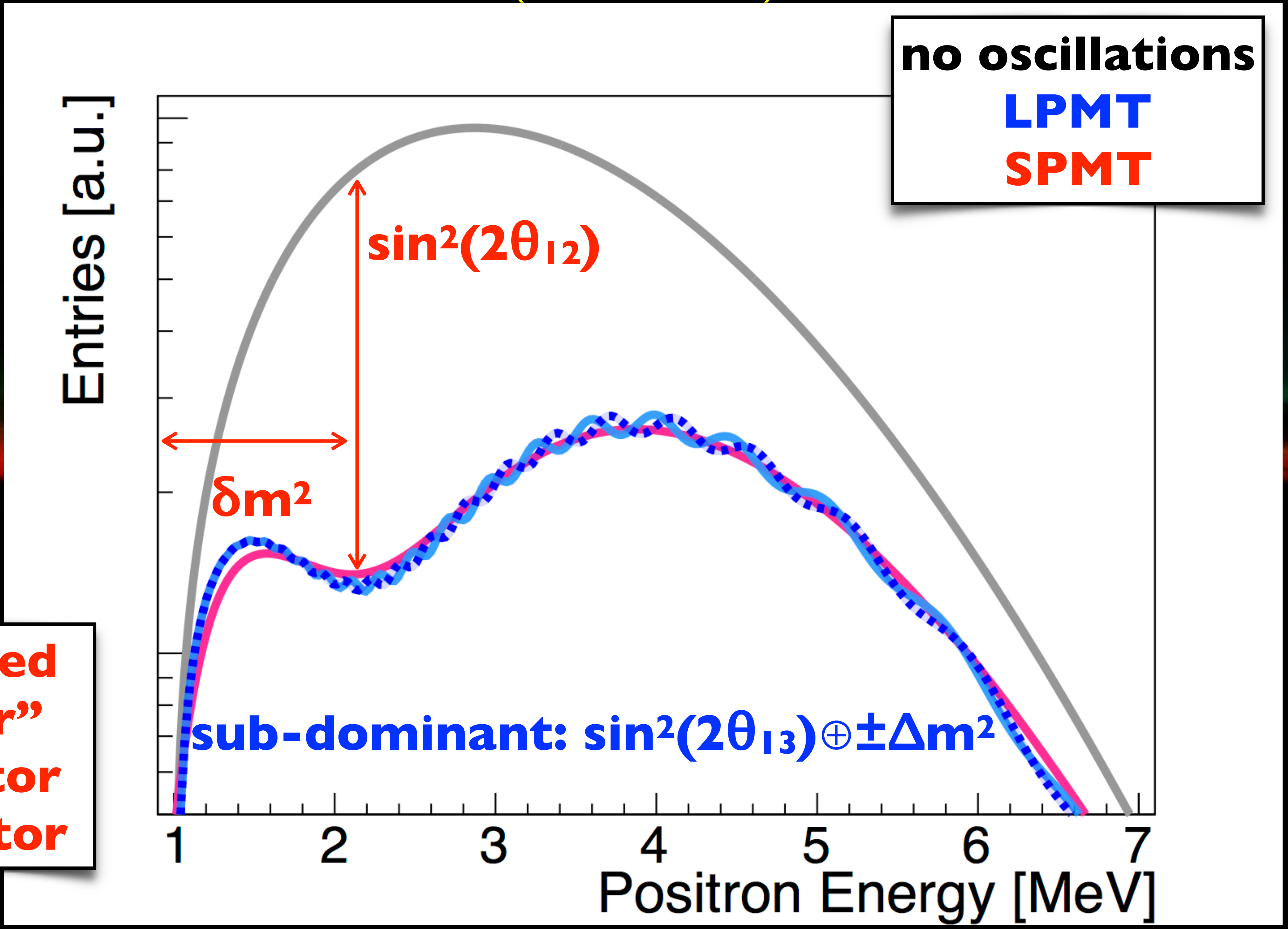
Selection	IBD efficiency	IBD	Geo-νs	Accidental	^{9}Li/^{8}He	Fast n	(α, n)
-	-	83	1.5	$\sim 5.7 \times 10^4$	84	-	-
Fiducial volume	91.8%	76	1.4		77	0.1	0.05
Energy cut	97.8%			410			
Time cut	99.1%	73	1.3		71		
Vertex cut	98.7%			1.1			
Muon veto	83%	60	1.1	0.9	1.6		
Combined	73%	60	3.8				

Anatael Cabrera (CNRS-IN2P3 & APC)

JUNO's experiment rationale…

2 oscillations modes simultaneously

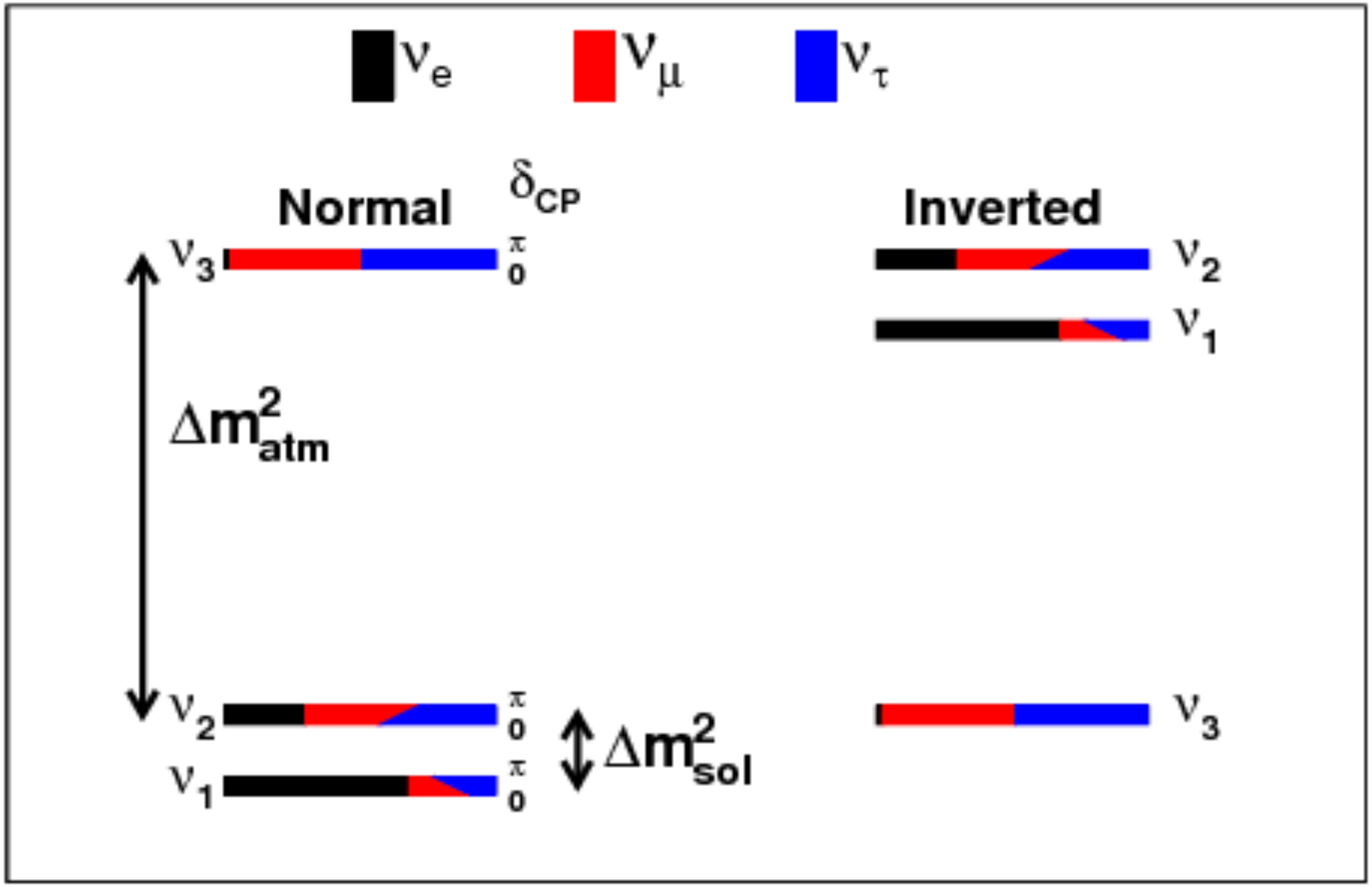
(first time)



no need "near" monitor detector

sensitivity: $\theta_{12} \oplus \theta_{13} \oplus \delta m^2 \oplus \pm\Delta m^2$

(atmospheric) **Mass** Hierarchy/**Ordering**…



solar data: $+\delta m^2 \rightarrow m_1 < m_2$ [matter effects]

atmospheric data: ≈vacuum! [$\pm\Delta m^2$]

mass ordering now…

NO favoured to ~3σ

(SK⊕NOvA→**matter effects**)

vacuum

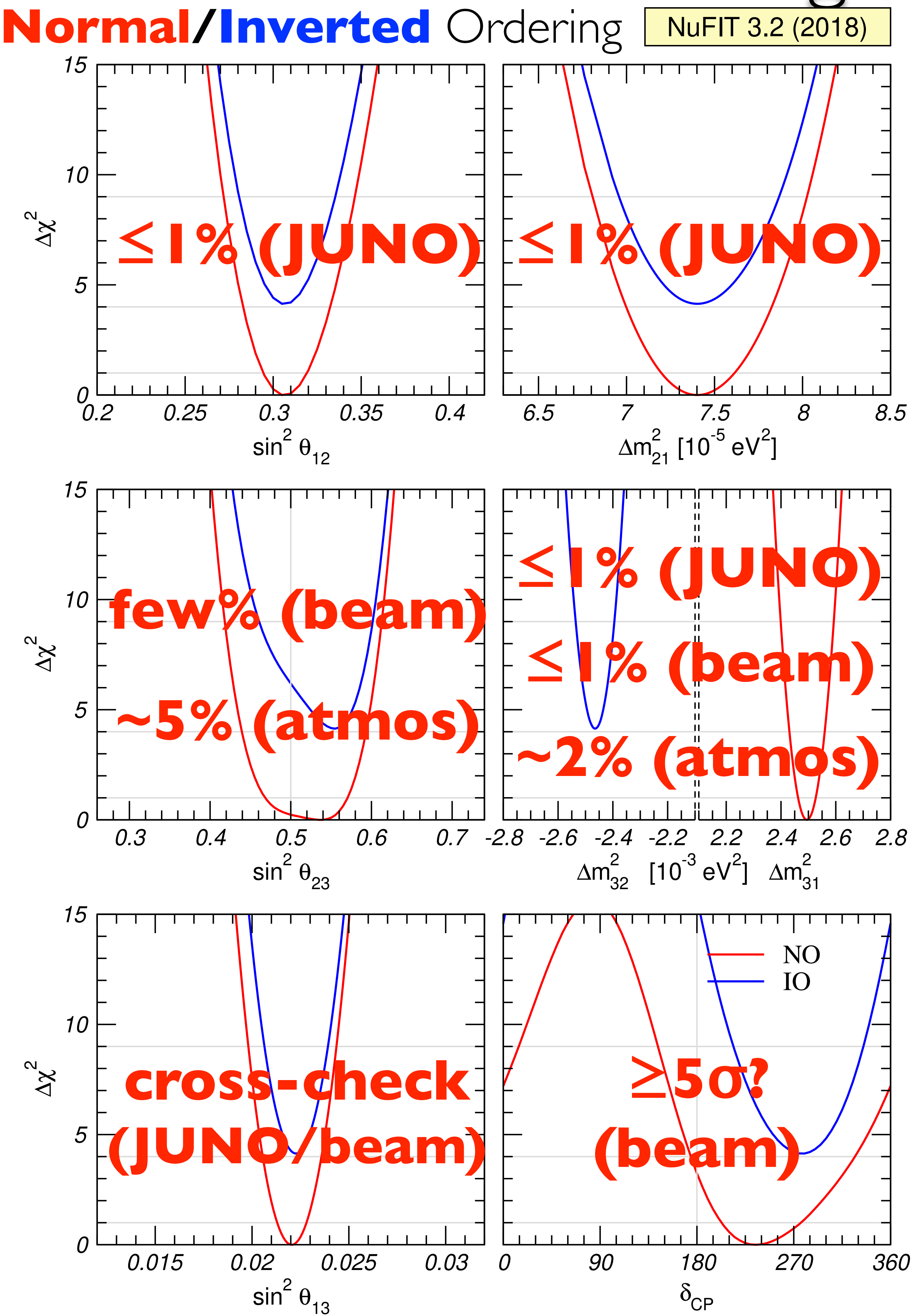
(JUNO)

unique!

matter

(DUNE & ORCA/PINGU)

global knowledge prospect…



θ13 terms:

- **θ_{13}: reactor-θ_{13}**

reactor-θ_{13}=DC⊕DYB⊕RENO

JUNO: a cross-check (like DC now)

JUNO (~~solar~~) terms:

- **θ_{12}:** JUNO [now: solar]
- **δm^2:** JUNO [now: KamLAND]

?? (~~atmospheric~~) terms:

- **θ_{23}:** beam⊕atmos
- **Δm^2:** JUNO⊕beam⊕atmos
- **sign[Δm^2]:** JUNO⊕beam⊕atmos

beam = **DUNE⊕HK**

atmos = **ORCA⊕PINGU**

CPV term: beam* (directly)

JUNO expected numbers…

Neutrino Physics with JUNO

Fengpeng An[1], Guangpeng An[2], Qi An[3], Vito Antonelli[4], Eric Baussan[5], John Beacom[6], Leonid Bezrukov[7], Simon Blyth[8], Riccardo Brugnera[9], Margherita Buizza Avanzini[10], Jose Busto[11], Anatael Cabrera[12], Hao Cai[13], Xiao Cai[2], Antonio Cammi[14,15], Guofu Cao[2], Jun Cao*[2], Yun Chang[16], Shaomin Chen[17], Shenjian Chen[18], Yixue Chen[19], Davide Chiesa[14,20], Massimiliano Clemenza[14,20], Barbara Clerbaux[21], Janet Conrad[22], Davide D'Angelo[4], Hervé De Kerret[12], Zhi Deng[17], Ziyan Deng[2], Yayun Ding[2], Zelimir Djurcic[23], Damien Dornic[11], Marcos Dracos[5], Olivier Drapier[10], Stefano Dusini[24],

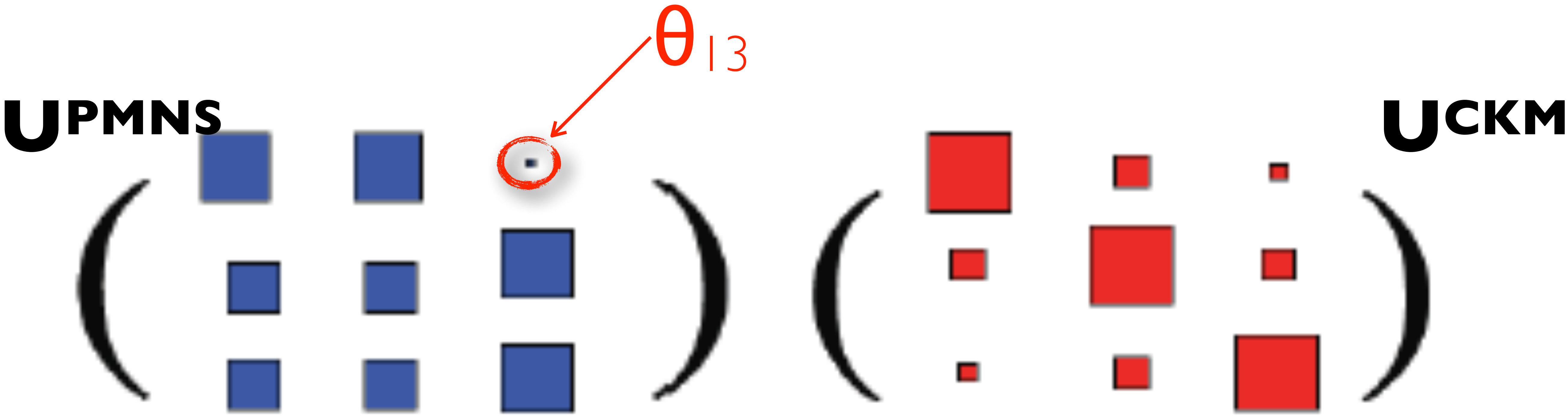
	Precision Now	Precision JUNO
θ_{13}	3.5% (reactor-θ_{13})	15% (cross-check)
θ_{12}	4.0% (Solar)	~0.7%
Δm^2	1.5% (several)	~0.5%
δm^2	2.2% (KamLAND)	~0.5%
MH	>80% Normal Hierarchy favoured	up to ~4σ (Δm^2dependence)

Barbara Ricci[53], Markus Robens[31], Aldo Romani[58], Xiangdong Ruan[49], Xichao Ruan[35], Giuseppe Salamanna[55], Mike Shaevitz[63], Valery Sinev [7], Chiara Sirignano[9], Monica Sisti[14,20], Oleg Smirnov[30], Michael Soiron[64], Achim Stahl[64], Luca Stanco[24], Jochen Steinmann[64], Xilei Sun[2], Yongjie Sun[3], Dmitriy Taichenachev[30], Jian Tang[45], Igor Tkachev[7], Wladyslaw Trzaska[65], Stefan van Waasen[31], Cristina Volpe[12], Vit Vorobel[43], Lucia Votano[59], Chung-Hsiang Wang[16], Guoli Wang[37], Hao Wang[32], Meng Wang[36], Ruiguang Wang[2], Siguang Wang[54], Wei Wang[45], Yi Wang[17], Yi Wang[27], Yifang Wang[2], Zhe Wang[17], Zheng Wang[2], Zhigang Wang[2], Zhimin Wang[2], Wei Wei[2], Liangjian Wen[2], Christopher Wiebusch[64], Björn Wonsak[34], Qun Wu[36], Claudia-Elisabeth Wulz[39], Michael Wurm[66], … Xing[‡2], Jilei Xu[2], Baojun Yan[2], Cha… Yang[41], Yifan Yang[21], Yu Yao[31], Ugur Yegin…, Zeyuan Yu[2], Sandra Zavatarelli[70], Liang Zhan[2], Chao Zhang[60], Hong-Hao Zhang[45],

arXiv:1507.0…

arXiv:1507.0561

a (tough) BIG question…

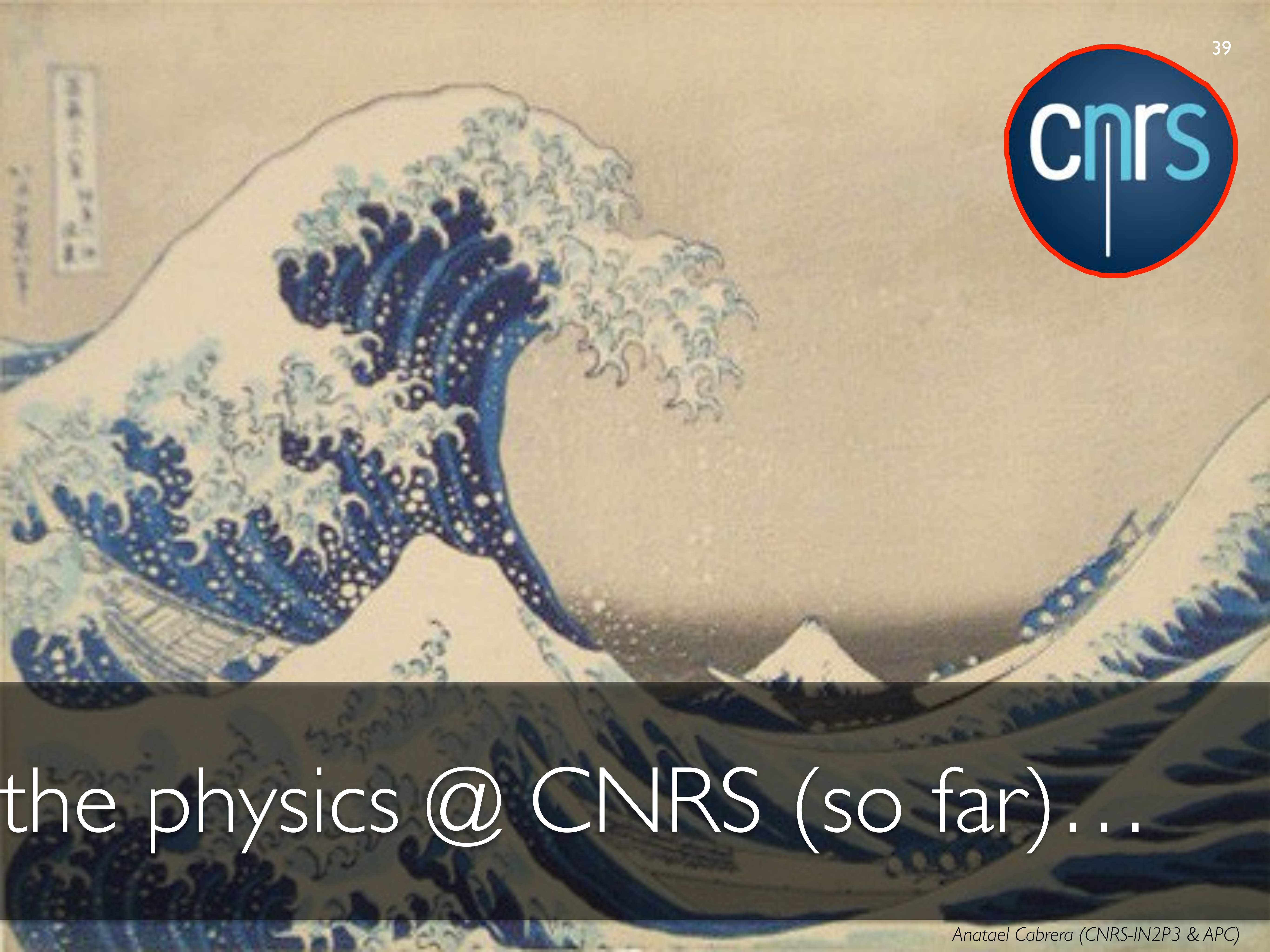


⇒ ~maximal mixing

⇒ ~minimal mixing

PMNS meets unitarity?

(beyond standard model→ only 3 families?)



the physics @ CNRS (so far)…

main physics channels…

central detector (→SPMT)

- **IBD precision calorimetry** (LPMT⊕SPMT)
  - →mass ordering/hierarchy measurement
- **IBD δm^2-θ_{12} measurement**
- **supernova** core-collapse detection
- radiogenic⊕cosmogenic(μ) **backgrounds**

veto systems (→TT)

- high precision **μ-tracking**
- cosmogenic(μ) **background** (synergy with LPMT⊕SPMT)

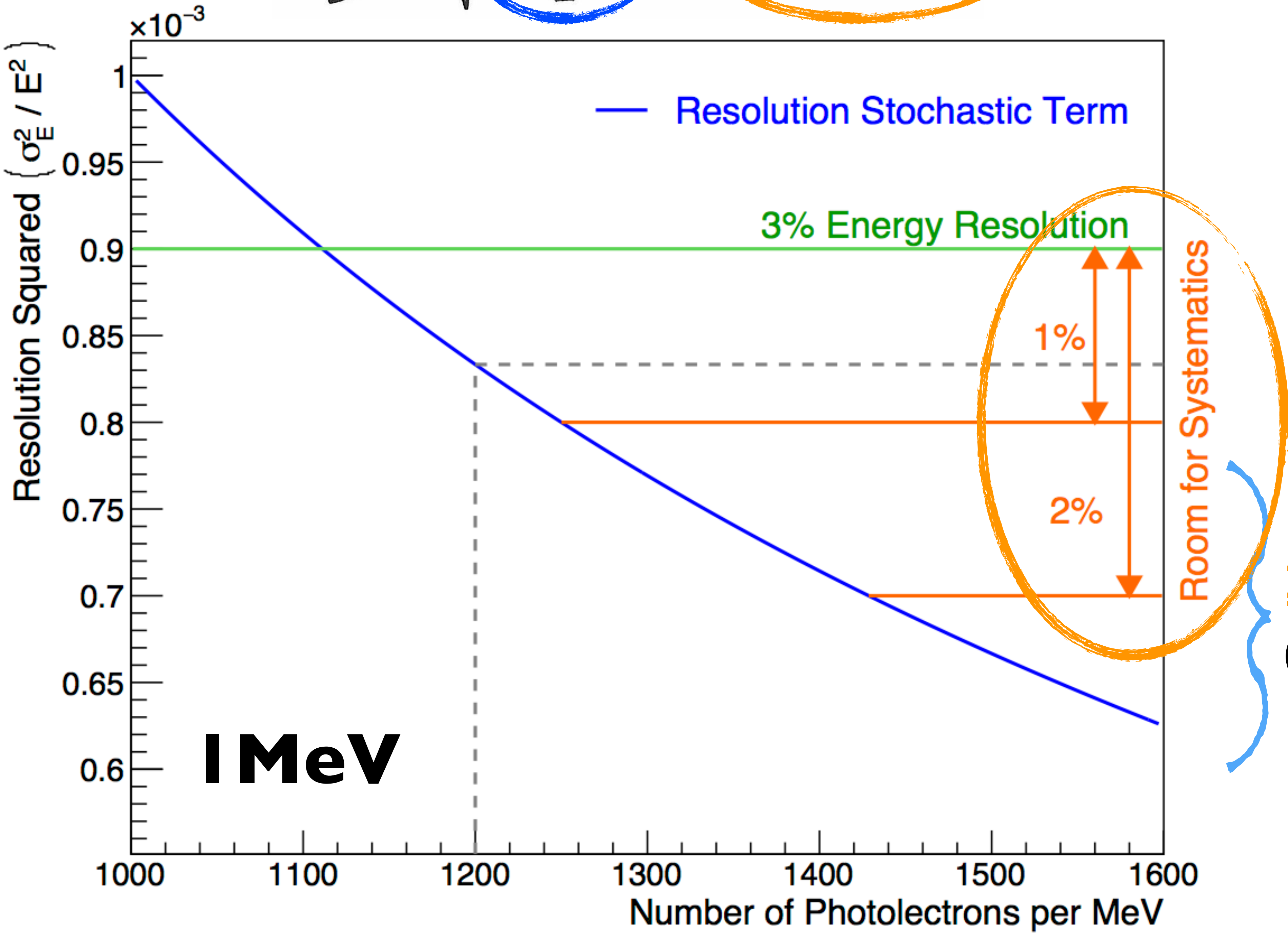

Stereo
Calorimetry
(basic logic)

JUNO calorimetry condition…

lot of light is a necessary but not sufficient condition

$$\frac{\sigma(E)}{E} = \sqrt{\frac{\sigma^2_{STOCH}}{E} + \sigma^2_{NON-STOCH}(E)}$$

≤3% @ 1MeV



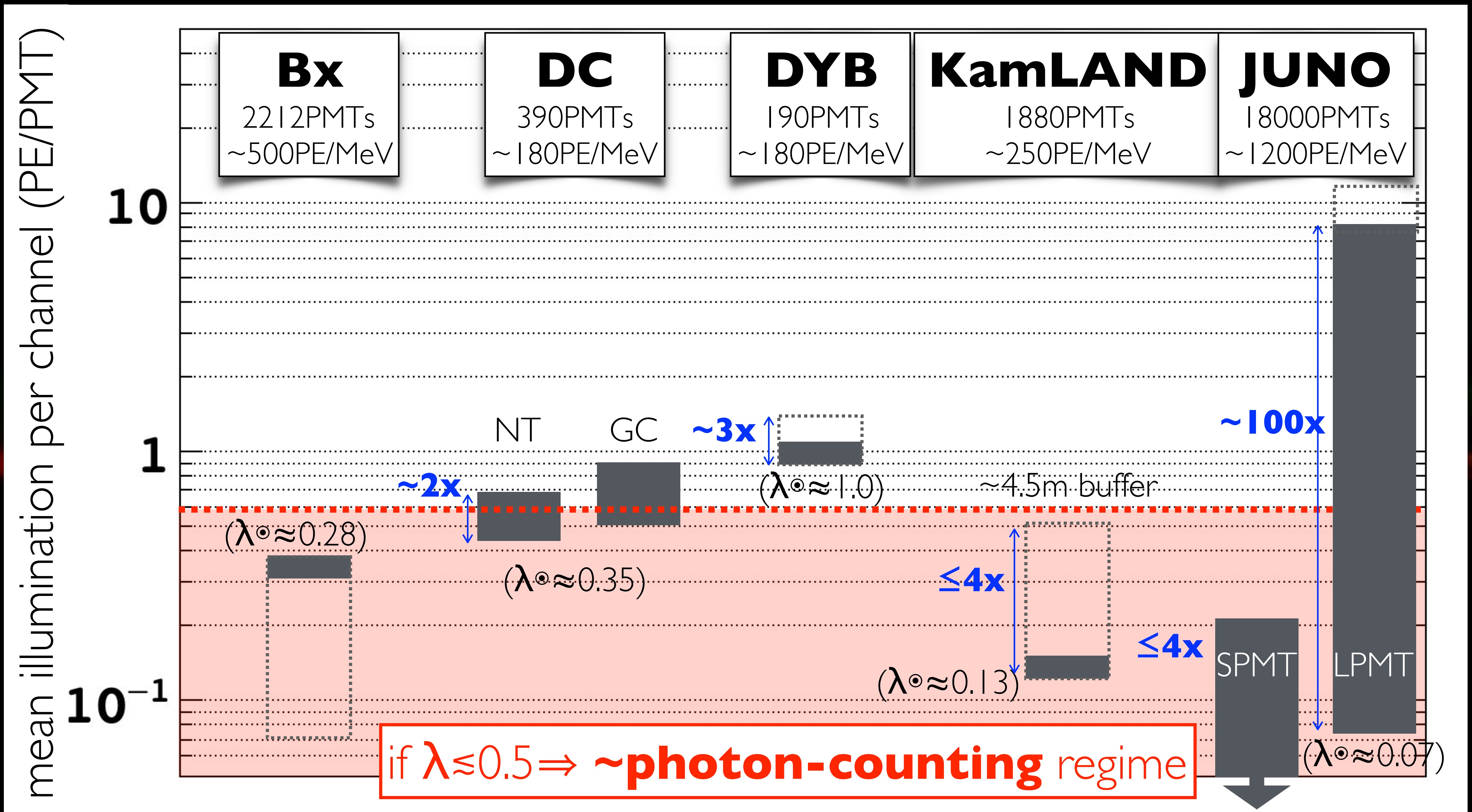
≥2%
(previous experiments)

challenging calorimetry systematics control

the JUNO challenge…

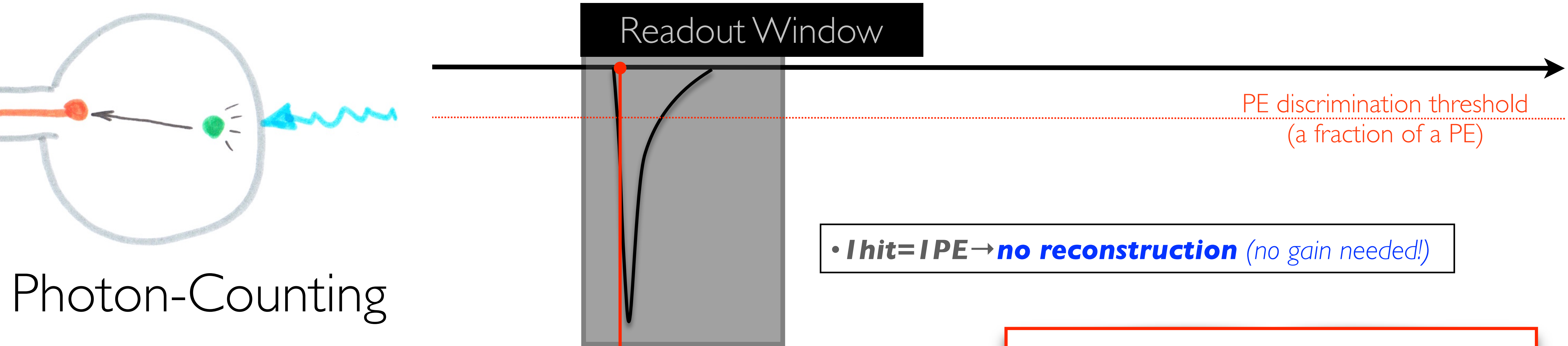
@1MeV

λ⊙ = mean illumination per channel @ center



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

Photon-Counting vs Charge-Integration…

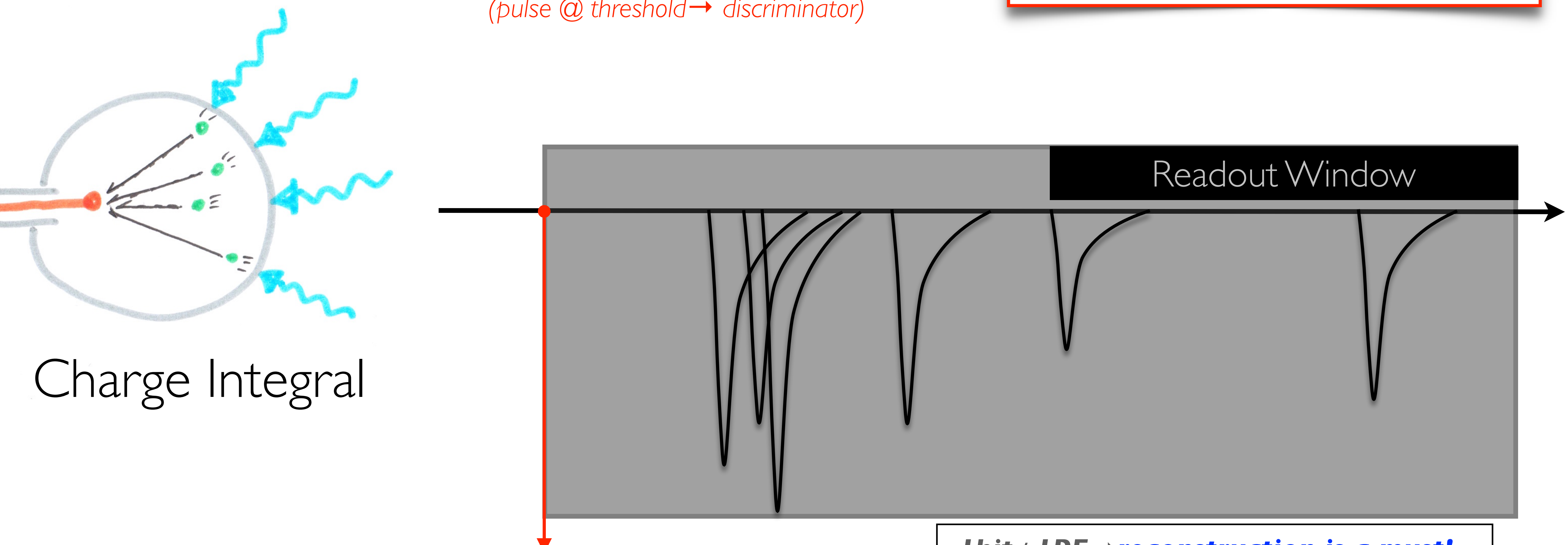


Photon-Counting

• **1hit=1PE→no reconstruction** *(no gain needed!)*

zero dynamic range (non-linearity→0)

time-stamp (self-trigger)
(pulse @ threshold→ discriminator)



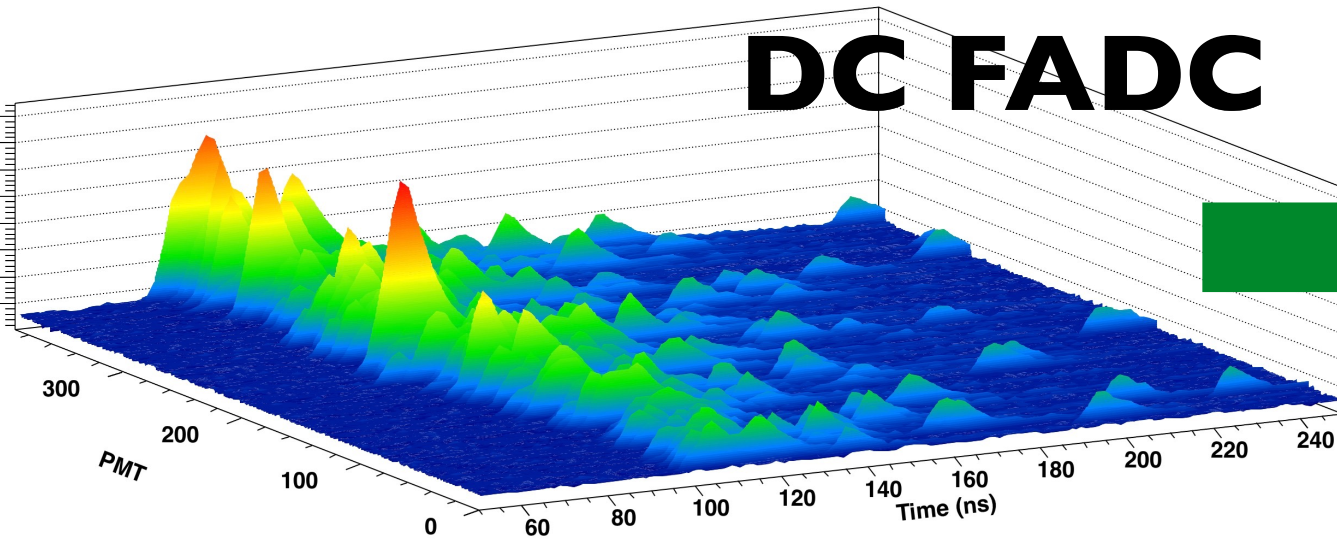
Charge Integral

• ***1hit≠1PE→reconstruction is a must!***
[calibration/reconstruction]

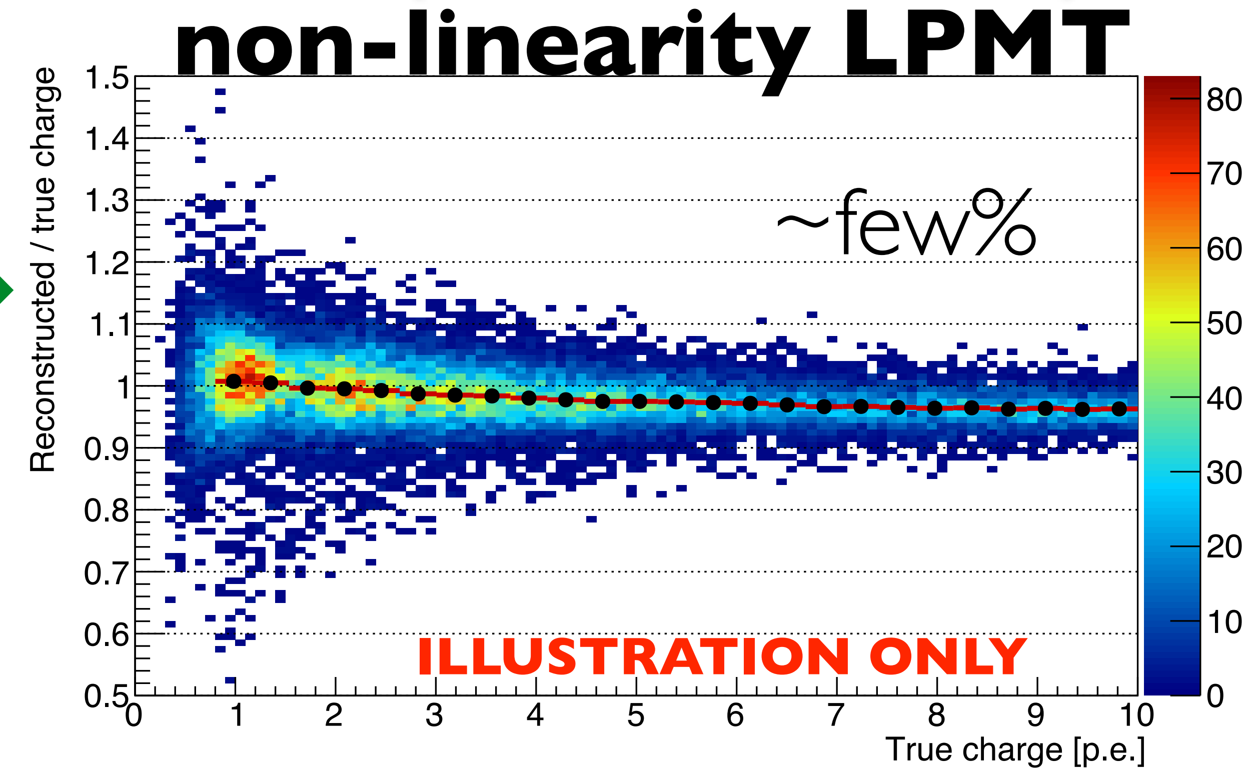
time-stamp (global trigger)
(readout-window sampled, example @ start)

Anatael Cabrera (CNRS-IN2P3 & LAL/APC — LNCA)

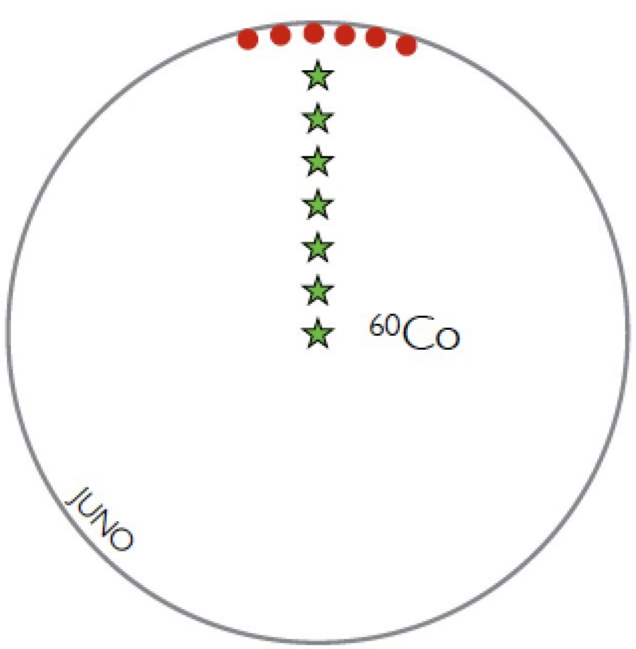
energy reconstruction bias (illustration)…

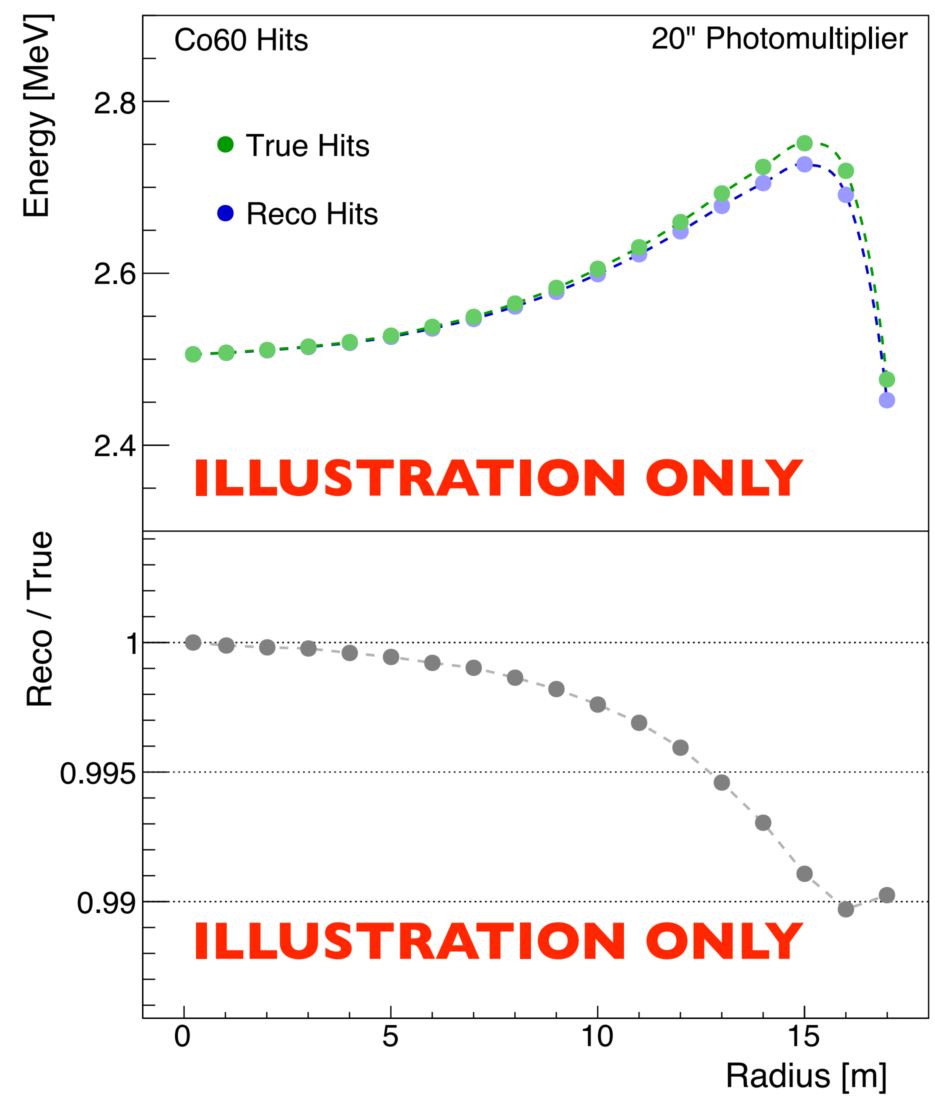


realistic pulse reco (QI)



calibration mimicking





non-linearity
(channel-wise)

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

worsens resolution
(full detector)

(CNRS-IN2P3 & LAL/APC — LNCA)

LPMT⊕SPMT complementarity systems…

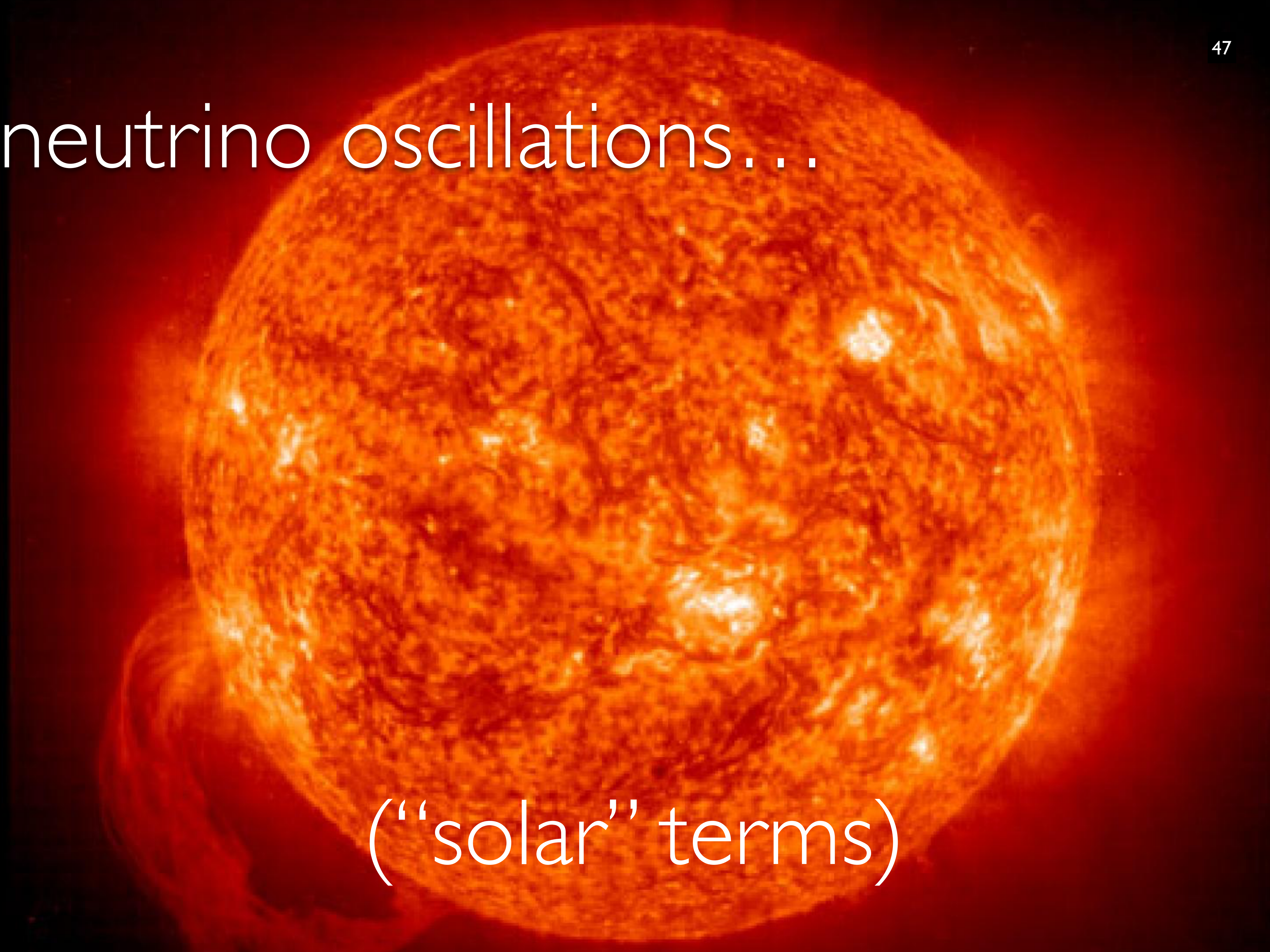
LPMT: collect light (25x)
(excellent stochastic resolution)

SPMT: less light & linear
(dynamic range→0)

LPMT Response:
$R_{stability}$
$R_{uniformity}$
$R_{linearity}$ **→most delicate**
(complex?)

SPMT Response:
$R_{stability}$
$R_{uniformity}$
(much simpler)

neutrino oscillations…

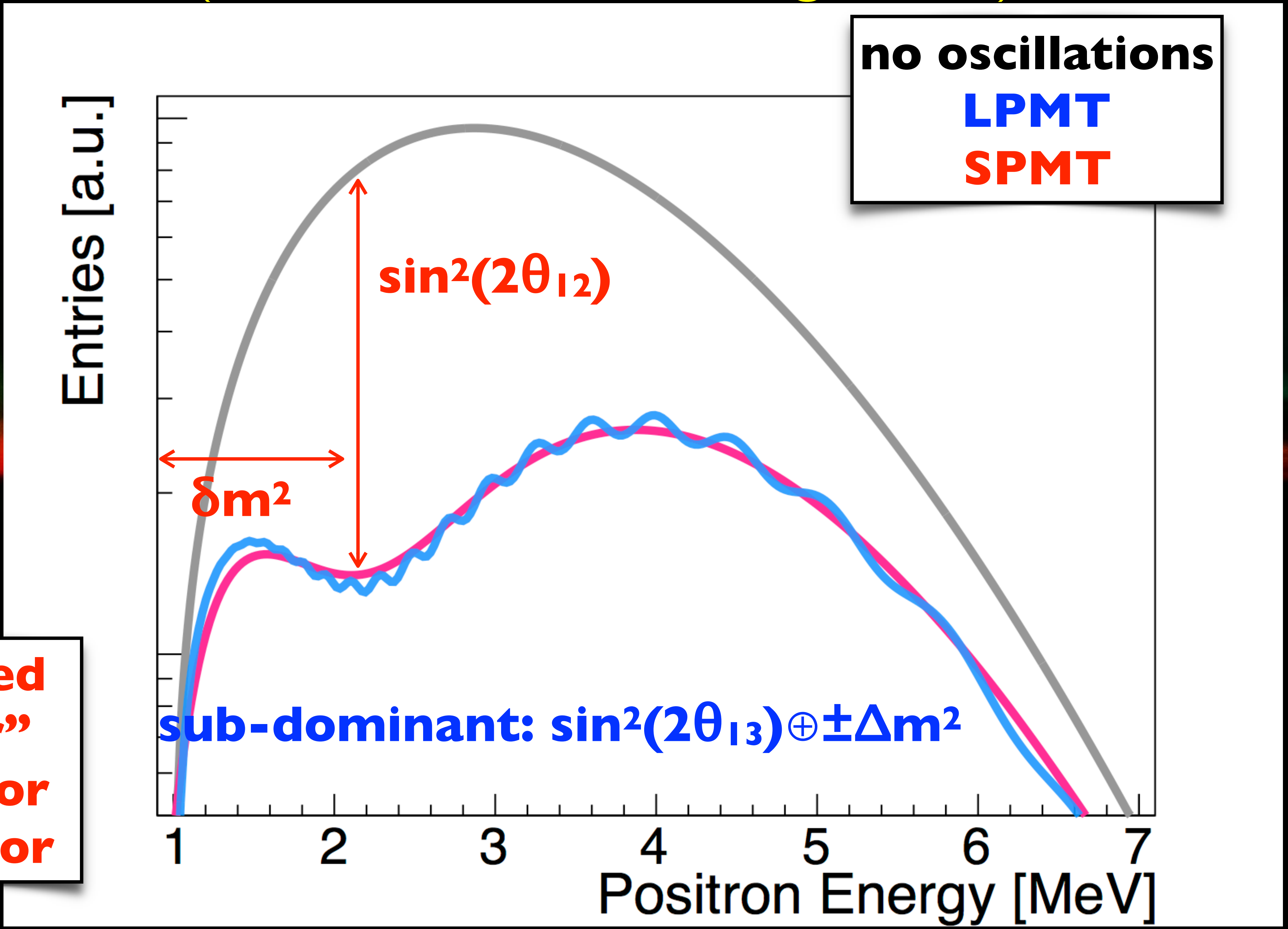


("solar" terms)

IBD oscillation with the SPMT…

SPMT only see 1 oscillation mode

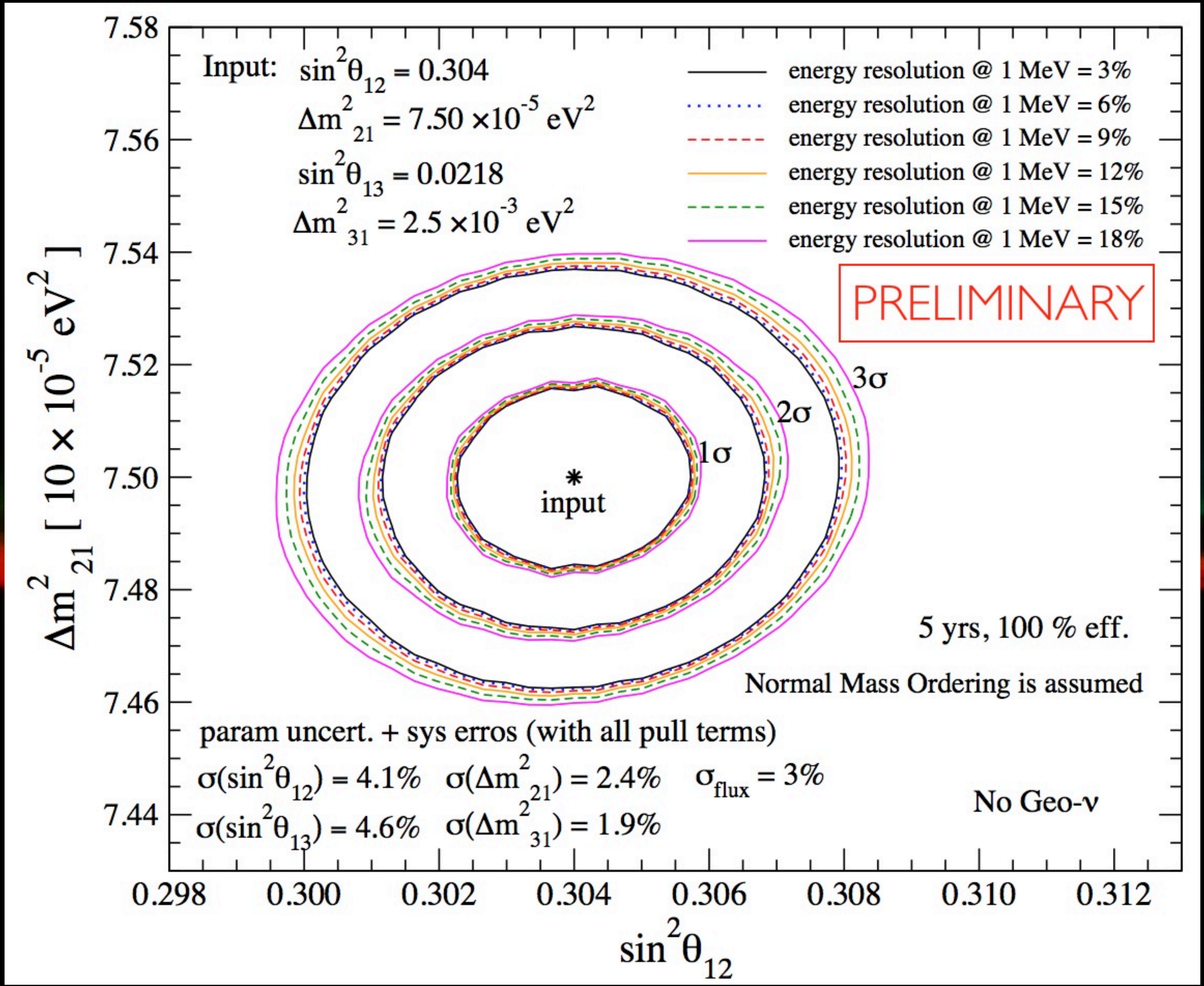
(fast oscillation is averaged out)



no need "near" monitor detector

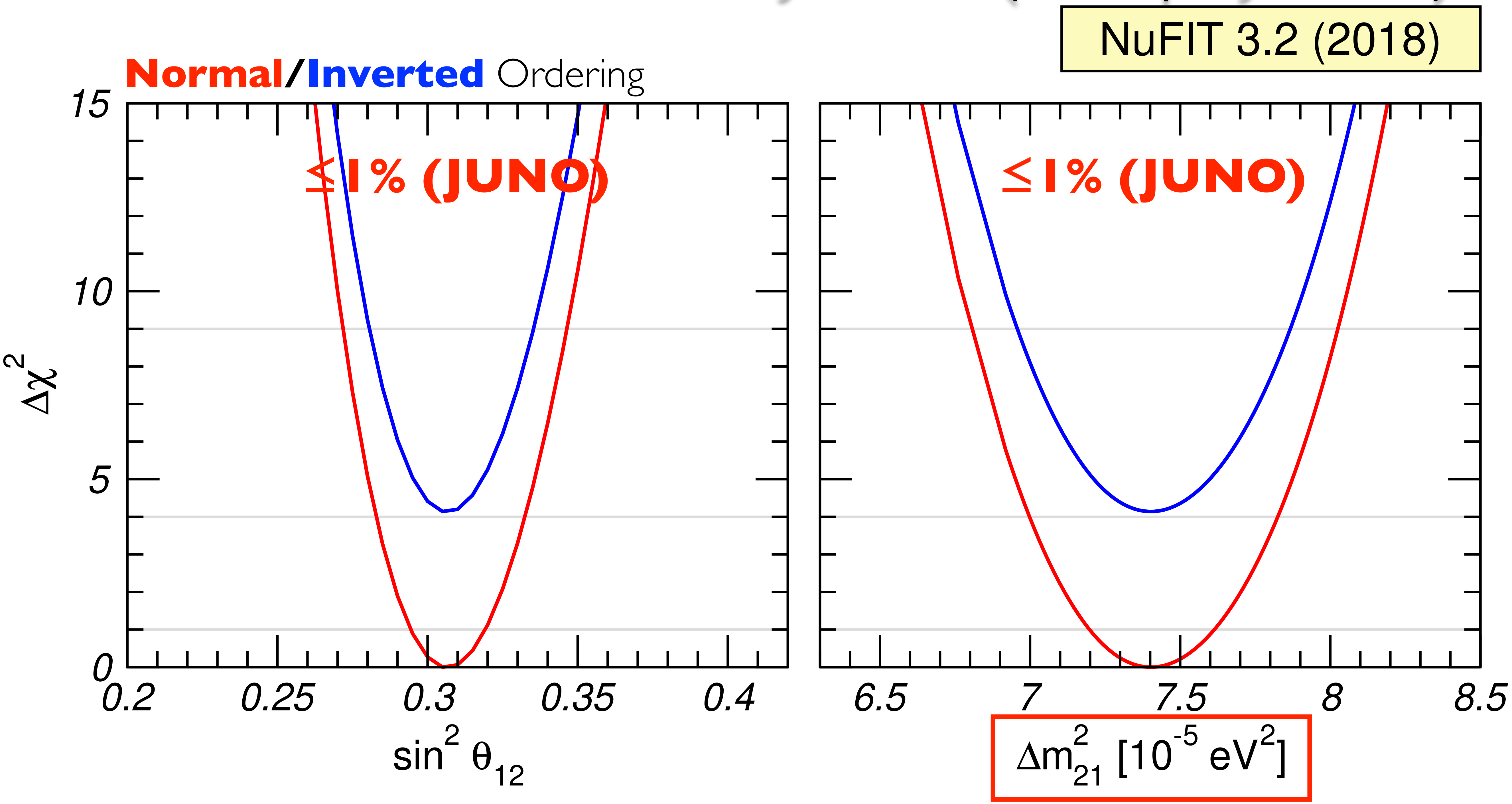
sensitivity: $\theta_{12} \oplus \delta m^2$

JUNO internal redundancy on θ_{12}-δm^2…



SPMT⊕LPMT comparable precision

no cross-check to JUNO (except JUNO)…



~rate systematics (common)

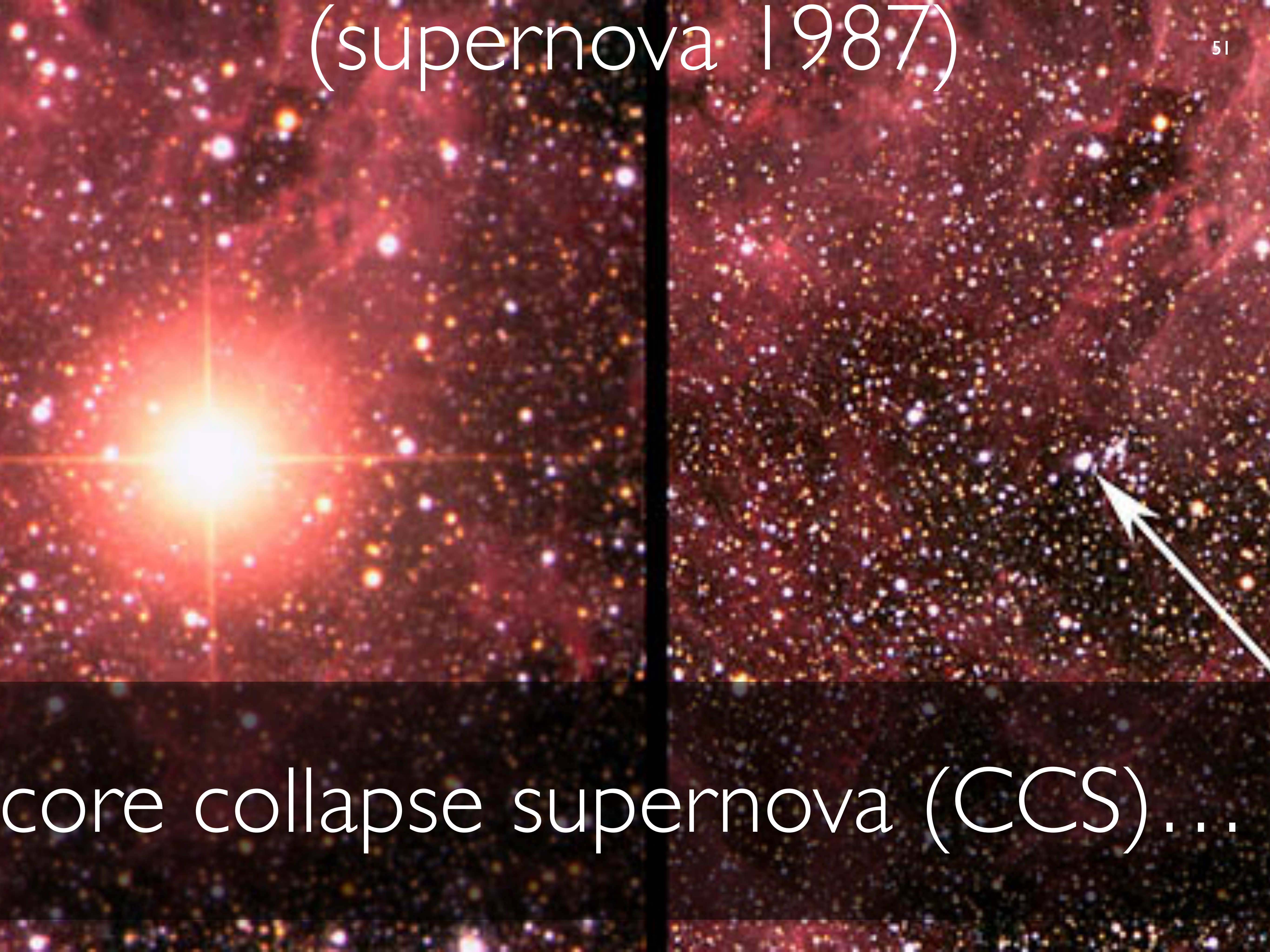
~shape systematics (different SPMT LPMT)

SPMT⊕LPMT internal cross-check

(→ robust result validation)

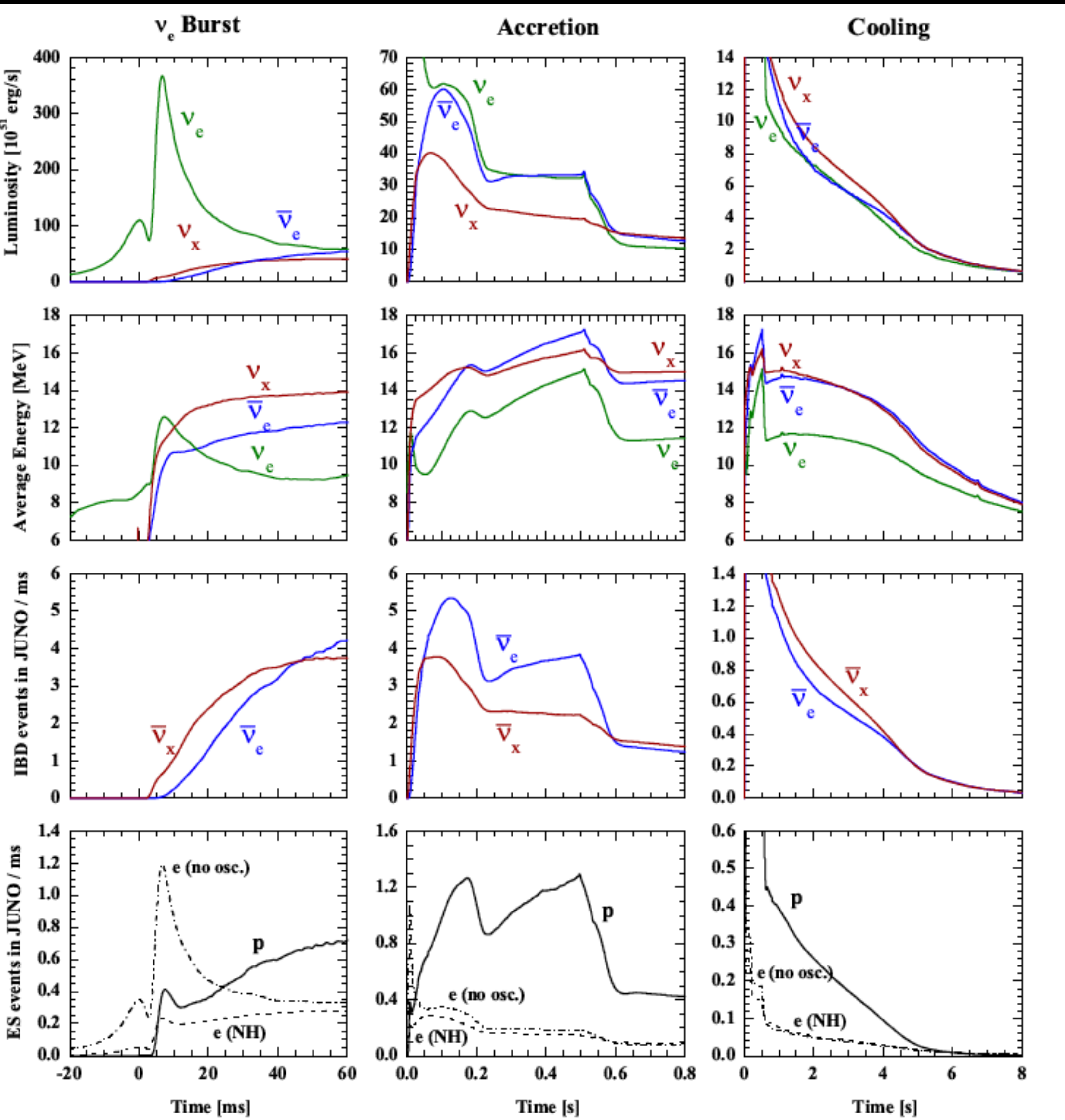
Anatael Cabrera (CNRS-IN2P3 & APC)

(supernova 1987)



core collapse supernova (CCS)...

CCS spectacular physics (astro/particle/nuclear)…



rate vs time

energy vs time

IBD only

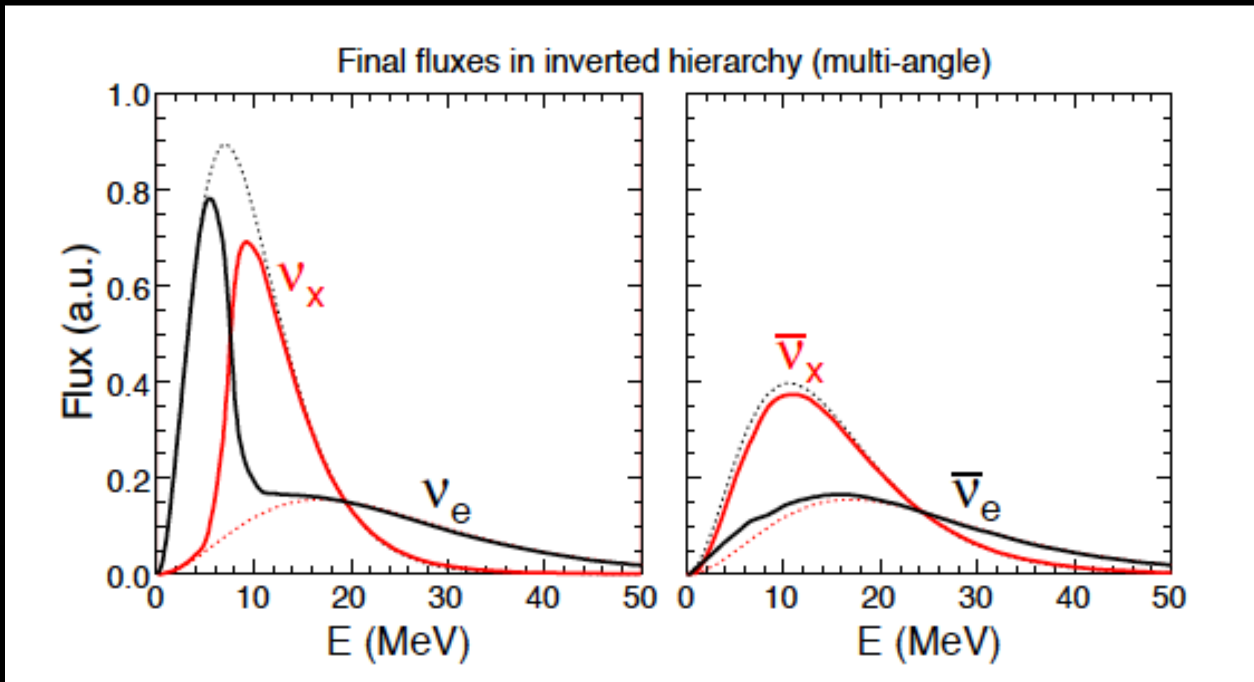
$(\nu_e + p \rightarrow n + e^+)$

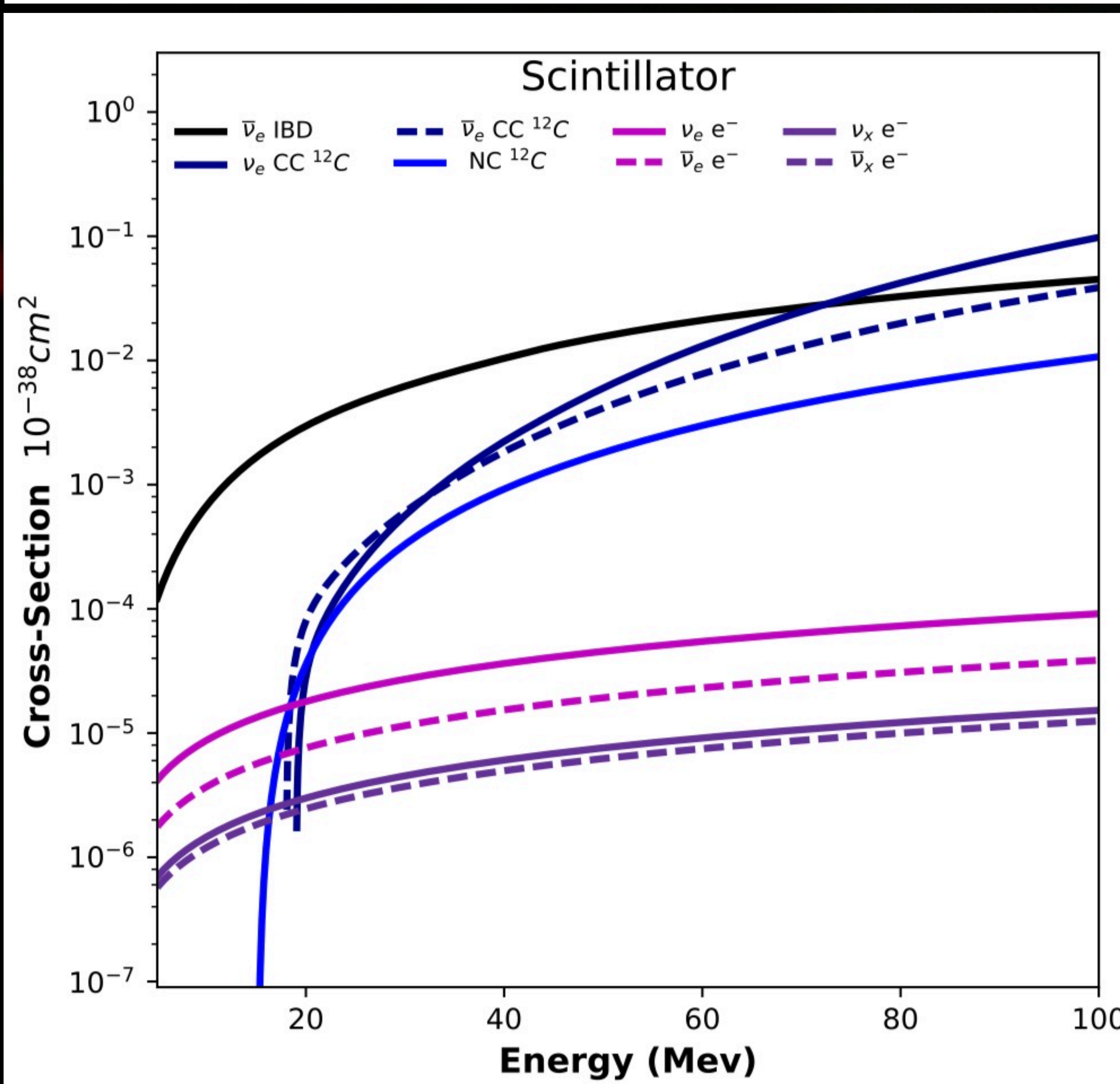
elastic scattering

$(\nu_e + e \rightarrow \nu_e + e)$

(unique astrophysics probe)

CCS challenges…





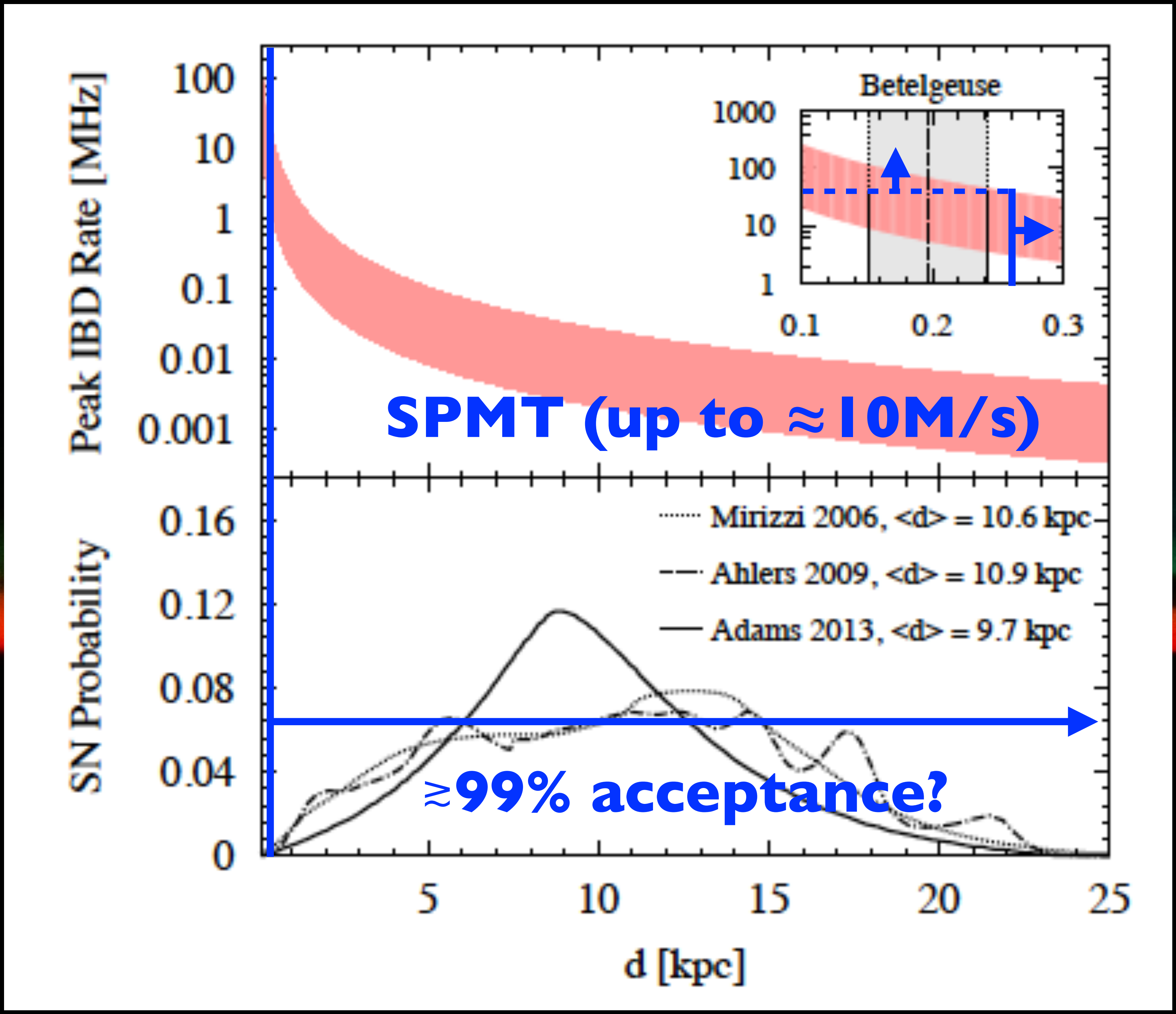
CCS particle physics

(ν-ν interaction)

multi-interactions

(disentangle information)

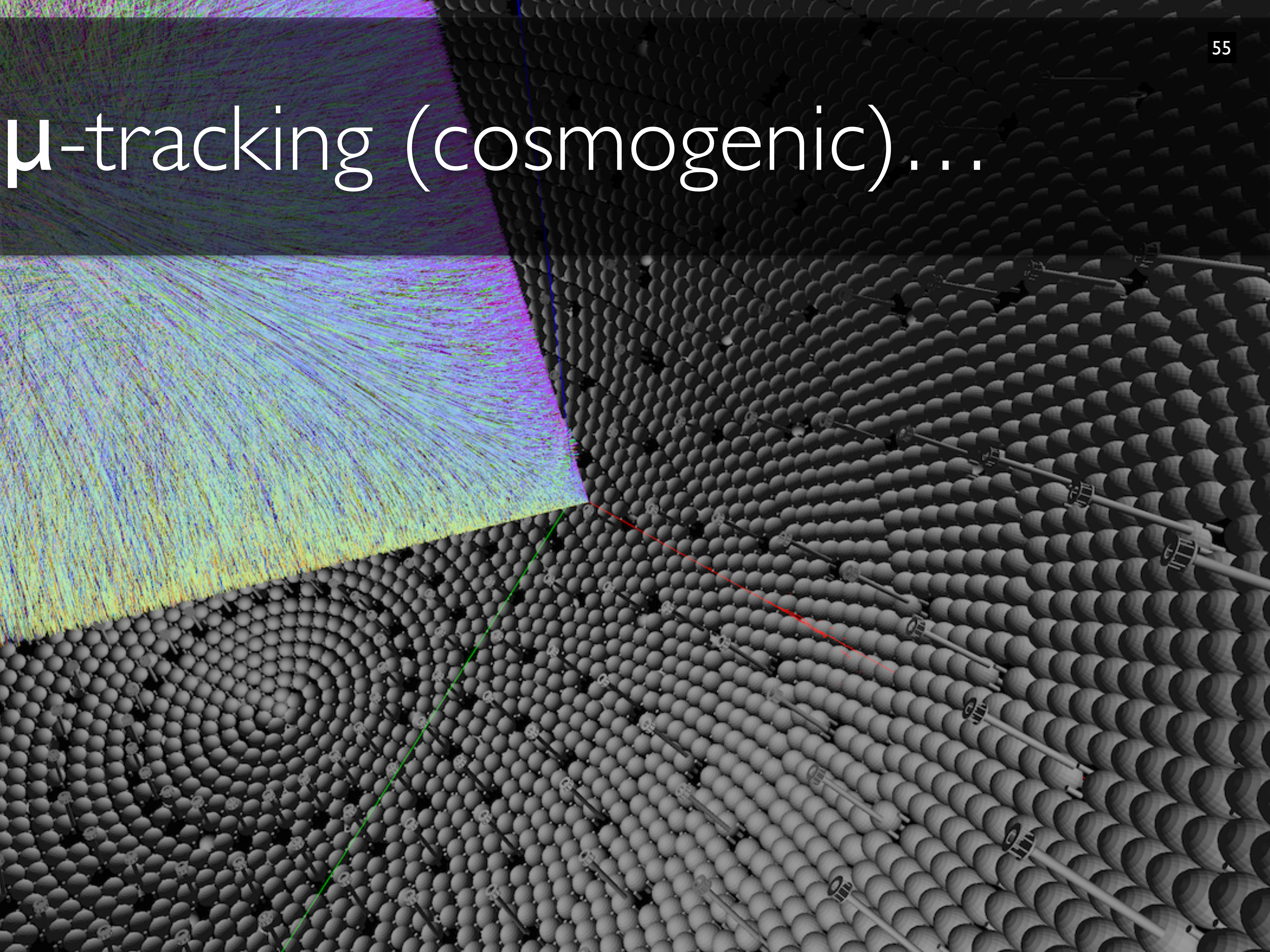
ensure we get it (almost) all...



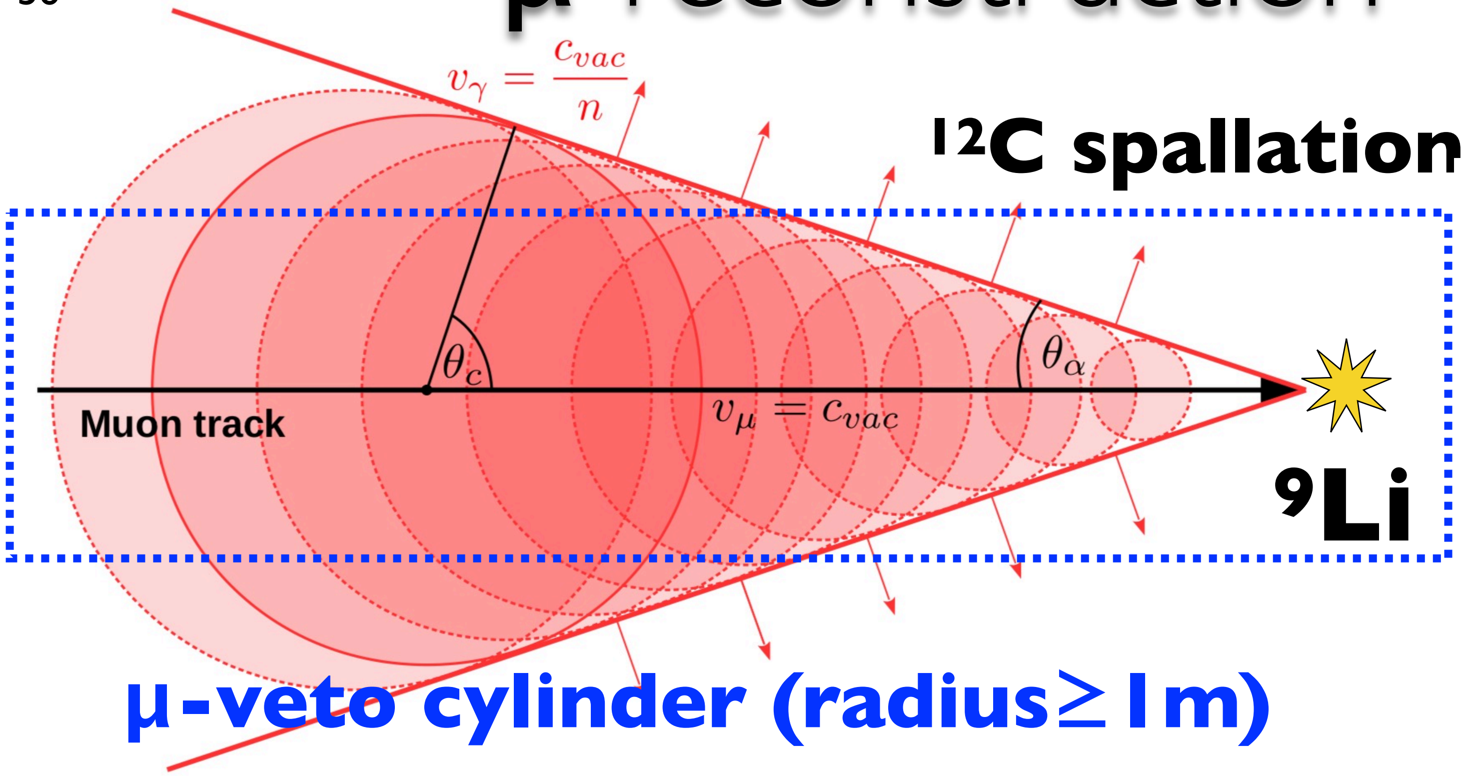
unbiased measurement

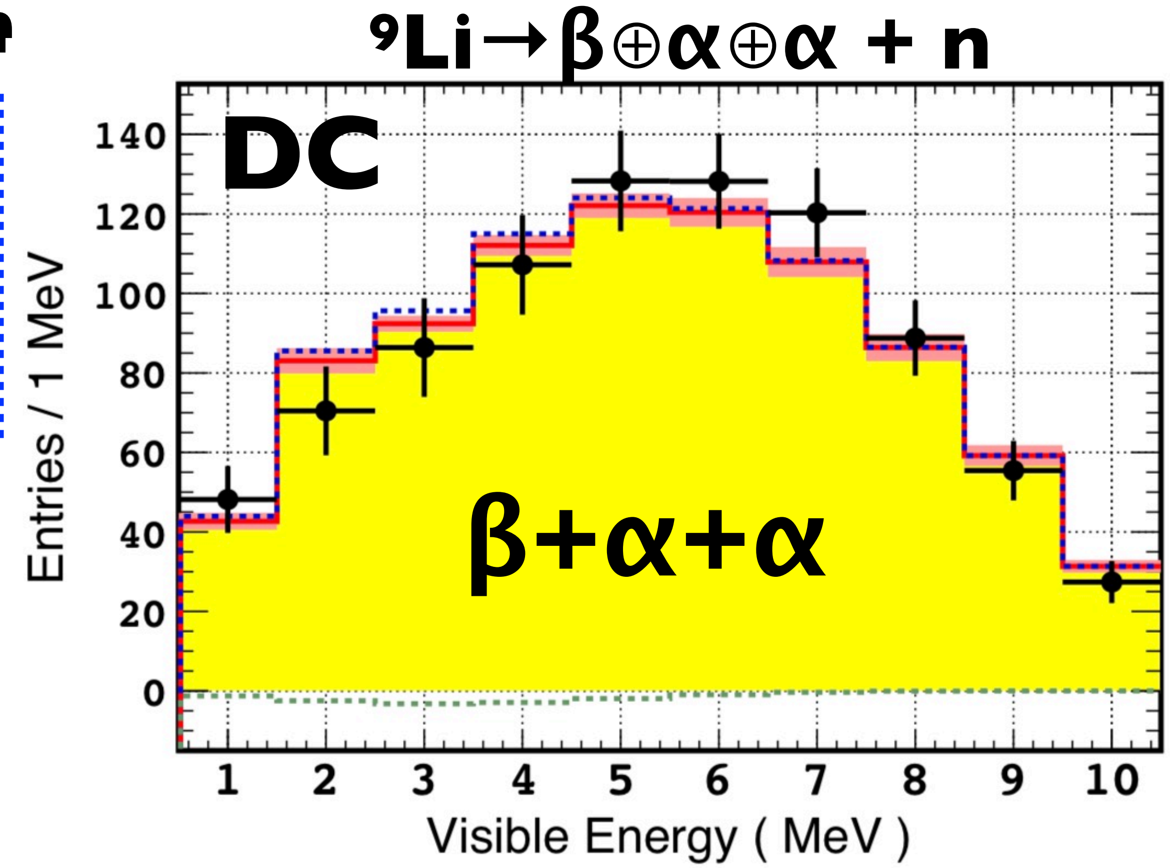
(high rate ⊕ deadtime monitor)

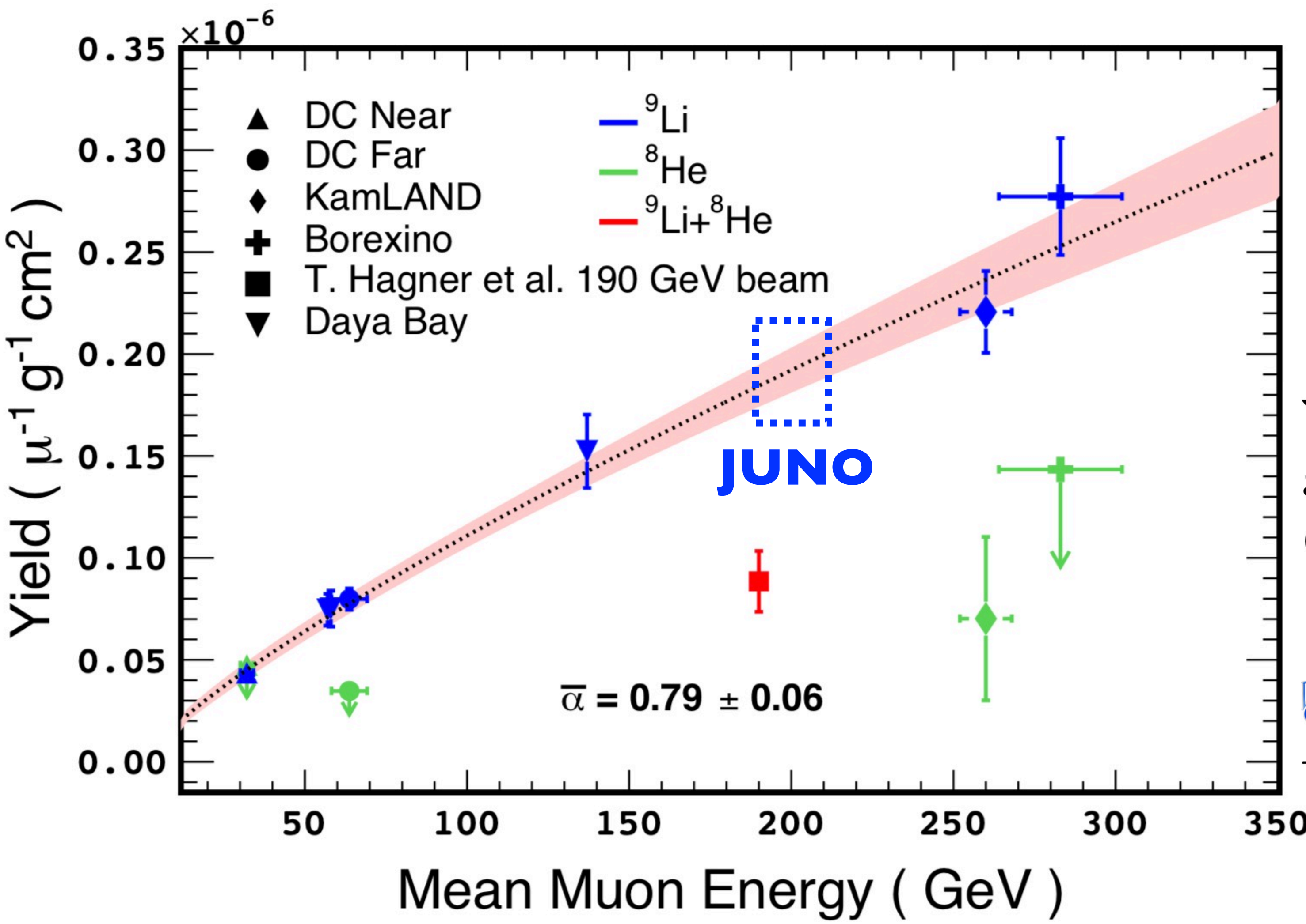
μ-tracking (cosmogenic)…



μ-reconstruction→cosmogenic vetoing…





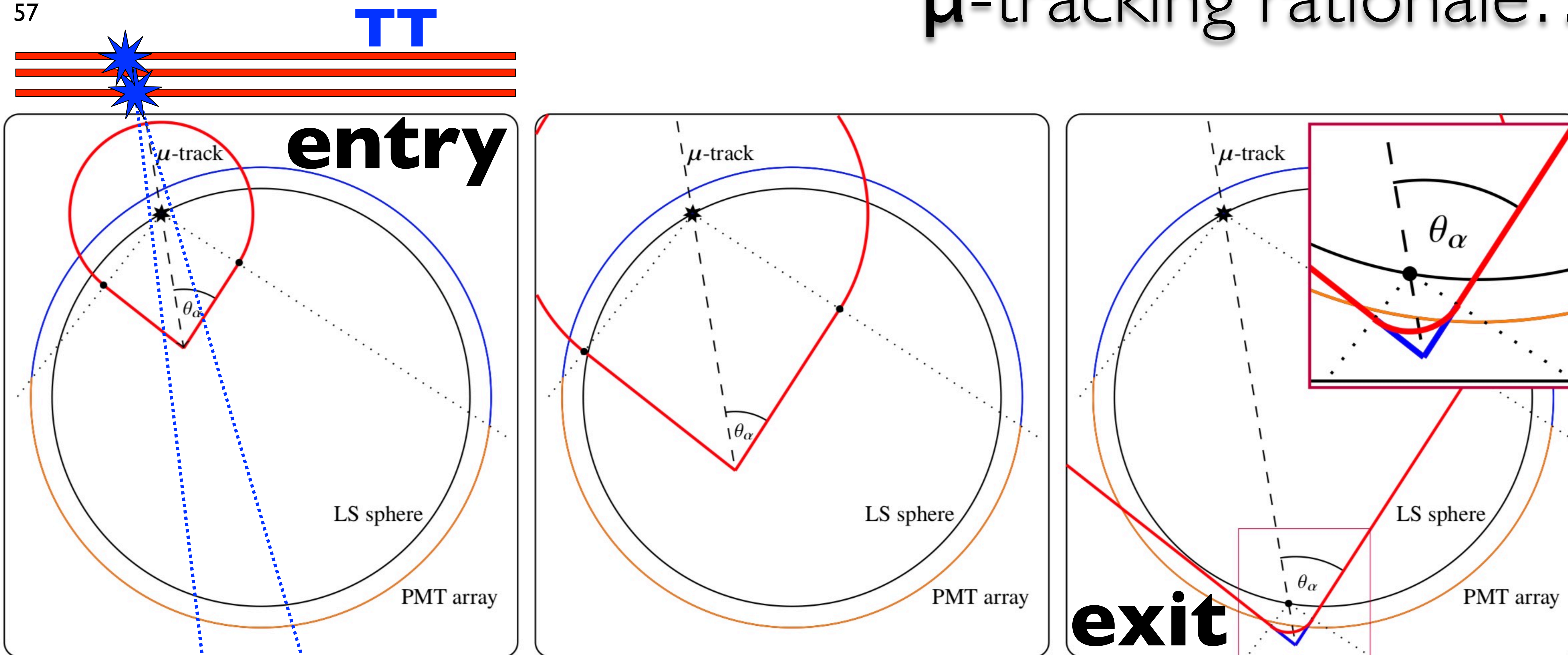


Yields and production rates of ^9Li and ^8He measured with the Double Chooz near and far detectors

arXiv:1802.08048v1

The Double Chooz Collaboration

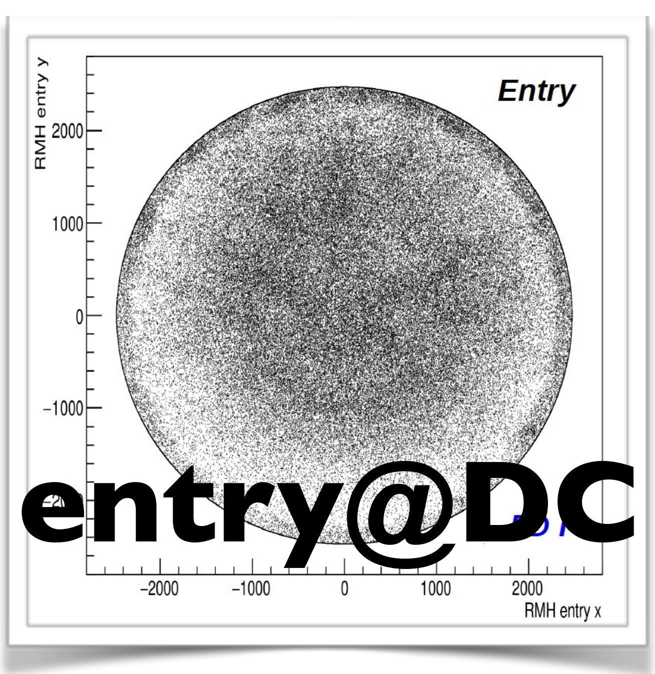
μ-tracking rationale…

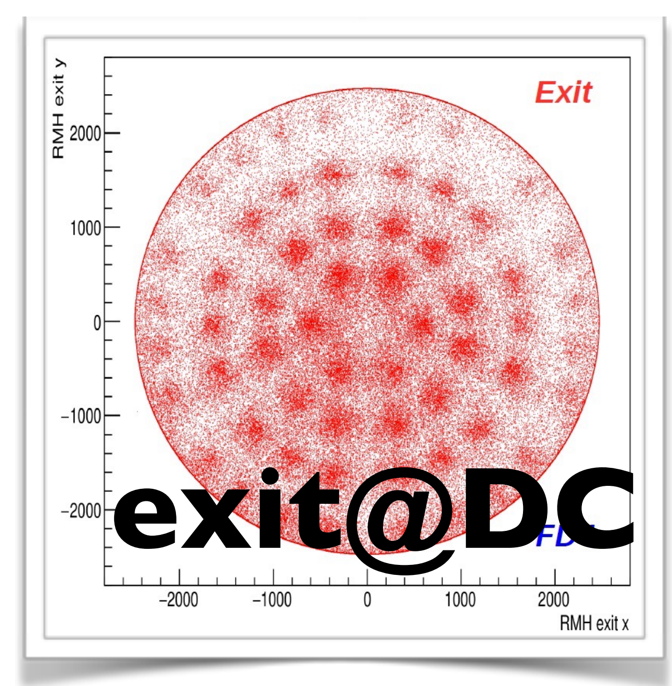


TT projection (~20cm)

propagation

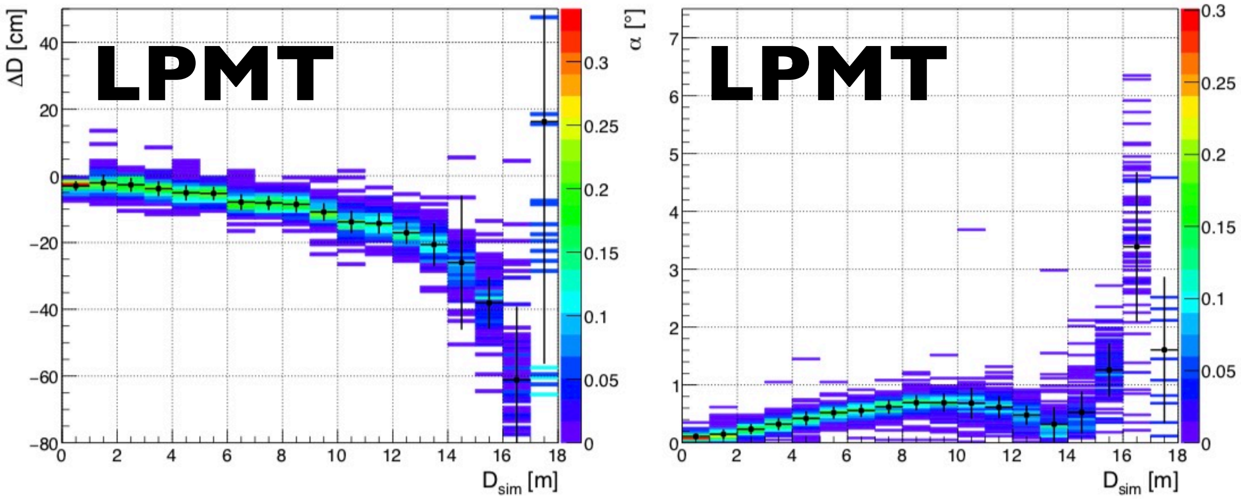
(straight extrapolation)



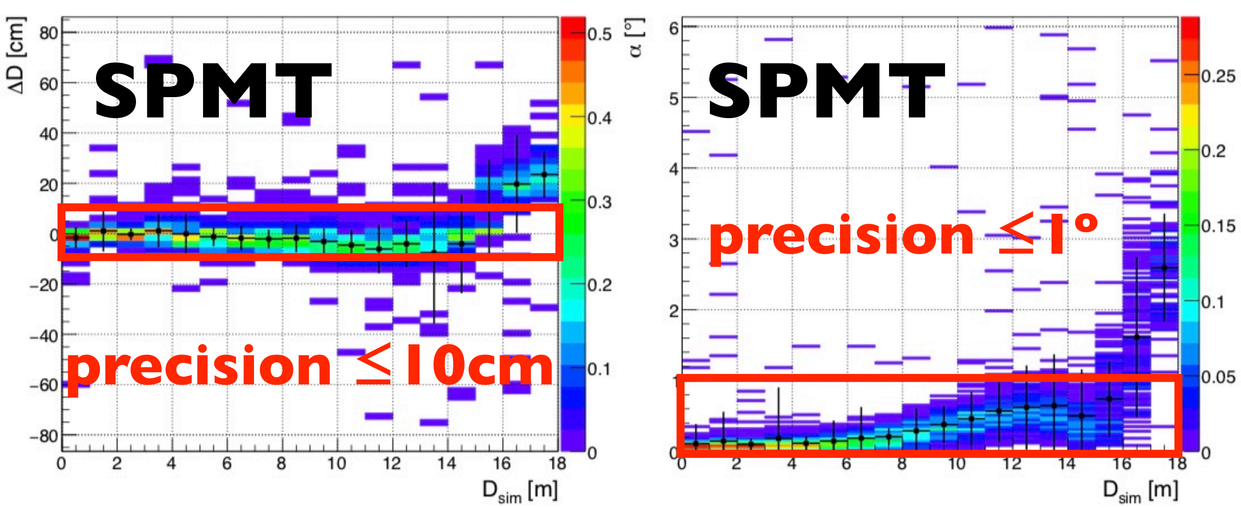


μ-reco accuracy…

space resolution **angular resolution**

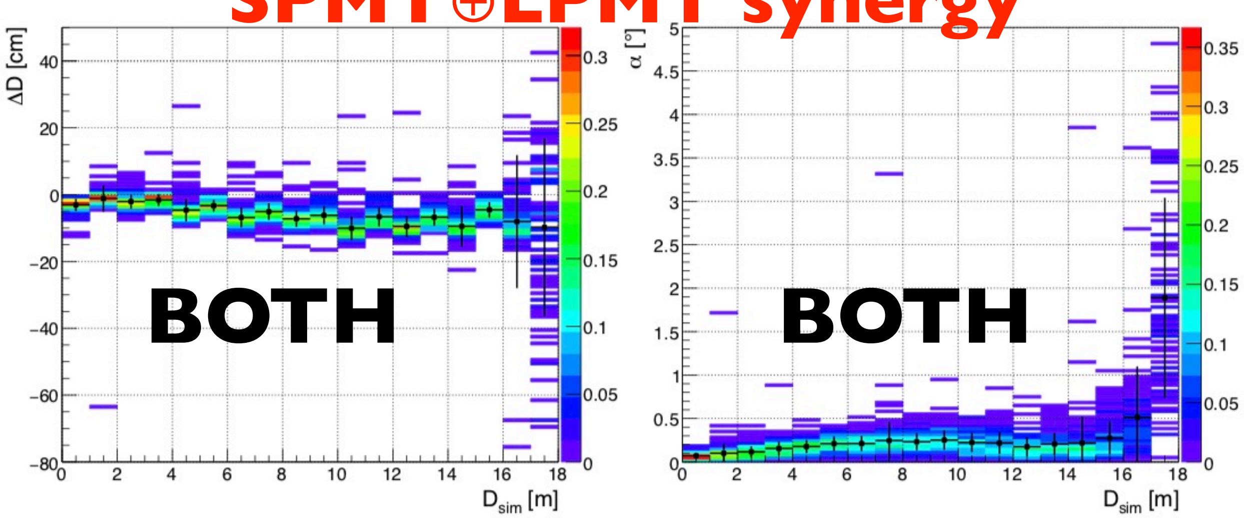


detector radius



(c) SPMT ΔD (d) SPMT α

SPMT⊕LPMT synergy



(e) LPMT+SPMT ΔD (f) LPMT+SPMT α

Muon reconstruction with a geometrical model in JUNO

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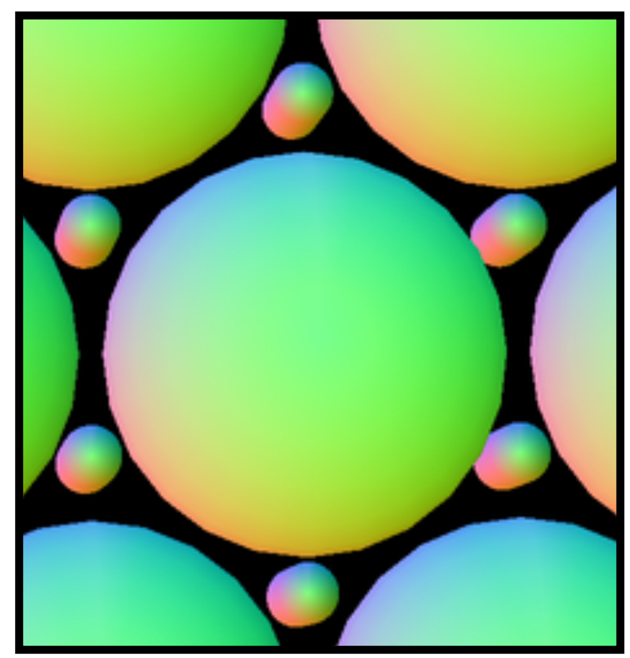
[a] *Forschungszentrum Jülich IKP, Wilhelm-Johnen-Strasse, D-52428 Jülich, Germany*

[b] *III. Physikalisches Institut B, RWTH Aachen University, Aachen, Germany*

E-mail: c.genster@fz-juelich.de

2018 JINST 13 T03003



- **more PMT density**
- **excellent timing (RMS)**
- **enough light**
- **better triangulation**

further improve with TT input (~20cm projection: not yet)

our organisation…

CNRS/IN2P3 teams…

CNRS/IN2P3 laboratories 6:

(APC)
CENBG
CPPM
IPHC
LAL*
OMEGA
SUBATECH

32 scientifiques
(16 ingenieurs)

main operations/actions

- **Radio-Activity**
  [CENG+CPPM]
- **Stereo-Calorimetry**
  [**LAL**+SUBATECH]
- **SPMT**
  [CENG+CPPM+**LAL**+SUBATECH]
- **Top-μ-Tracker**
  [CENBG+IPHC]

European Computing with CC.IN2P3

JUNO→ CNRS "IR" (research infra-structure) [under Ministry]

LAL-JUNO team
(2 physicists + 1 postdoc + 1 PhD)
M.Bongrand + A.Cabrera
M.Grassi (PD)
Yang HAN (PhD)
(1 engineer electronics)
C.Santos (APC)→LAL takes over…

ΩMEGA Microelectronics

the "ROC" ASIC family…

powerful computing… (expert support)

(FADC data experience)

JUNO experiment

- the ultimate reactor-ν experiment and beyond…
- world neutrino oscillation physics: support world CP-Violation experiments (ν-beam suffering the "θ_{23}-octant" issue)
- vast physics program beyond oscillations: geo-ν, supernova-ν, proton-decay, solar/atmospheric ν's, etc (surprises?)

JUNO@LAL team…

- major hardware responsibility **SPMT** & **much physics**
- national & international strong collaboration & strategic position
- lead the IN2P3/CNRS role within JUNO

questions…?

obrigado…
ありがとう…
merci…
danke…
고맙습니다…
Спасибо…
gracias…
grazie…
谢谢…
hvala…
thank you…

anatael@in2p3.fr