Towards Unitarity?
(how far?)

EPS-HEP Conference @ Ghent (Belgium)
July 2019

Anatael Cabrera
CNRS/IN2P3
LAL@Orsay
LNCA@Chooz
~50 years of neutrino oscillations...

huge experimental effort $\rightarrow$ well established
[discovery $\Leftrightarrow$ Nobel 2015]

what is/are the next goal?
status on neutrino oscillation knowledge…

**Standard Model** (3 families)

$\text{PMNS}_{3\times3}(\theta_{12}, \theta_{23}, \theta_{13})$

$\pm \Delta m^2$ & $\pm \delta m^2$

must measure all parameters $\rightarrow$ characterise & test (i.e. over-constrain) **Standard Model**

<table>
<thead>
<tr>
<th></th>
<th>today</th>
<th>$\geq 2030$</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>best knowledge</td>
<td>NuFIT4.0</td>
<td>foreseen</td>
</tr>
<tr>
<td>$\theta_{12}$</td>
<td>3.0 % SNO</td>
<td>2.3 %</td>
<td>$\leq 1.0%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JUNO</td>
</tr>
<tr>
<td>$\theta_{23}$</td>
<td>5.0 % NOvA</td>
<td>2.0 %</td>
<td>$\leq 1.0%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DUNE@HK</td>
</tr>
<tr>
<td>$\theta_{13}$</td>
<td>1.8 % DYB</td>
<td><strong>1.5 %</strong></td>
<td><strong>1.5 %</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>DC@DYB@RENO</td>
</tr>
<tr>
<td>$\pm \Delta m^2$</td>
<td>2.5 % KamLAND</td>
<td>2.3 %</td>
<td>$\leq 1.0%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JUNO</td>
</tr>
<tr>
<td>$\pm \Delta m^2$</td>
<td>3.0 % T2K &amp; DYB</td>
<td>1.3 %</td>
<td>$\leq 1.0%$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JUNO@DUNE@HK</td>
</tr>
<tr>
<td>sign$(\Delta m^2)$</td>
<td>unknown (SK et al)</td>
<td>NO @ $\sim 3\sigma$</td>
<td>$@5\sigma$</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>JUNO@DUNE@HK</td>
</tr>
<tr>
<td>CPV</td>
<td>unknown (T2K et al)</td>
<td>$3/2 \pi @ \sim 2\sigma$</td>
<td>$@5\sigma?$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Nov 2018)</td>
<td></td>
</tr>
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<td></td>
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essentially JUNO@DUNE@HK will lead most of the field (goal CPV) $\rightarrow$ except $\theta_{13}!$

NOTE: ORCA@PINGU@IceCube complementary (Mass Ordering & $\Delta m^2$ measurements)

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)
do we have all needed?

the “super” experiments era...
address PMNS unitarity & structure?

$U_{PMNS}$ matrix

$$
\begin{pmatrix}
U_{e1} & U_{e2} & U_{e3} \\
U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\
U_{\tau 1} & U_{\tau 2} & U_{\tau 3}
\end{pmatrix}
$$

$\Rightarrow$

anything but diagonal (i.e. max-mixing)

is $U_{3x3}$ unitary? [ex. test CKM]

$UU^\dagger = U^\dagger U = I$

$|U_{l1}|^2 + |U_{l2}|^2 + |U_{l3}|^2 = 1$

(\text{other equations too})

why shape? [\(\neq \text{CKM}\)]

$J(\text{PMNS}) \approx 3.3 \times 10^{-2} \Rightarrow \text{large CPV?}$

[\text{larger } J(\text{CKM})]

\(\Rightarrow\) explore “electron top-row”: knowledge? \(\theta_{12}, \theta_{13}\)

$\left|U_{e1}\right|^2 + \left|U_{e2}\right|^2 + \left|U_{e3}\right|^2 = 1$

envisage \(\approx 1\%\) precision?

challenging ingredients...

- **JUNO constraint** \(\checkmark\) — non improvable!
- **reactor-\(\theta_{13}\) constraint** \(\Rightarrow\) improvable? [\text{this talk}]
- **solar constraint** \(\Rightarrow\) improvable?
- **other possible constraints?**

PRELIMINARY: ongoing calculation \(\Rightarrow\) appetiser

\(\Delta \chi^2\)

<table>
<thead>
<tr>
<th>$U_{e1}$</th>
<th>$U_{e2}$</th>
<th>$U_{e3}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_e$</td>
<td>$V_\mu$</td>
<td>$V_\tau$</td>
</tr>
</tbody>
</table>

| $V_1$ | $V_2$ | $V_3$ |

$X.\text{Qian et al} [\text{arXiv:1308.5700}]$

$\text{precision }\approx 4.0\%\ (\text{with JUNO})$

$\text{precision }\approx 1.0\%\ (\text{improved further?})$

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)
θ 13 again?
summary on today’s $\theta_{13}$ knowledge/experiments...

**reactor-$\theta_{13}$ experiments**

[DC$\oplus$DYB$\oplus$RENO]

- **statistics**: $\sim 10^5$ (far) [$< 10^6$]
- **systematics**: $\sim 0.1\%$ (each)
- **energy control**: $< 1\%$ precision

<table>
<thead>
<tr>
<th></th>
<th>&lt;2010</th>
<th>today [2010-2020]</th>
<th>cancellation methodology</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>total</td>
<td>rate-only</td>
</tr>
<tr>
<td>statistics</td>
<td>few %</td>
<td>$\sim 0.1%$</td>
<td>—</td>
</tr>
<tr>
<td>flux</td>
<td>$\sim 2.2%$</td>
<td>$\sim 0.1%$</td>
<td>$\sim 0.1%$</td>
</tr>
<tr>
<td>BG</td>
<td>few %</td>
<td>$\sim 0.1%$</td>
<td>$\sim 0.1%$</td>
</tr>
<tr>
<td>detection</td>
<td>2.0 %</td>
<td>$\sim 0.1%$</td>
<td>$\sim 0.1%$</td>
</tr>
<tr>
<td>energy</td>
<td>few %</td>
<td>$\sim 0.5%$</td>
<td>—</td>
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“naively extrapolating” from reactor-$\theta_{13}$ experiments...

- **statistics**: $\sim 10^{x?}$ (far) [$> 10^6$]
- **systematics**: $\sim 0.01\%??!!$ (each)
  possible at all?
DUNE

$\theta_{13}$ knowledge elsewhere?

DUNE (output) nears precision by reactor-$\theta_{13}$

$\theta_{13}$ measurement: shape-only

complementary: reactor-$\theta_{13}$ is rate-driven

JUNO much less precise (5x larger)

JUNO benefit from a more precise $\theta_{13}$?

[robustness against “fast spectral distorsion”]

JUNO

$\sim$same precision

a sub-percent $\theta_{13} \Rightarrow$ help DUNE⊕HK⊕JUNO?

$\sin^2(2\theta_{13}) \oplus \delta m^2$

$\sin^2(2\theta_{13}) \oplus \pm \Delta m^2$

$\times 10^4$

Events / MeV

$10^3$ Signal IBD Events - Baseline 52.5 km

Osc. Parameters
Capozzi+ 1703.0471

NO

IO

updated version soon

updated version soon

thanks DUNE (Ryan & Elisabeth)

thanks DUNE (Ryan & Elisabeth)

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)
improve ~1% errors $\rightarrow$ possible?

reactor $\Rightarrow$ “super” systematics...
review reactor $\theta_{13}$ sensitivity evolution...

receptor sensitive has potential to go well beyond today [DC⊕DYB⊕RENO]

- statistics: $\geq 10^7$ (far) [≥20x today]
- detection systematics (≈today: ∼0.1%)
- energy control (<1% precision)

⇒ flux & BG systematics→ new techniques!!

Today’s reactor state of art knowledge

- Power: 2x 4.2GW (thermal)
- Baseline: ∼1.1km
- Detection efficiency: ∼85%
- Reactor duty-cycle: ∼85%
- [refuel]

Today’s reactor-θ13

- statistics: $\geq 10^7$ (far) [≥20x today]
- detection systematics (≈today: ∼0.1%)
- energy control (<1% precision)

⇒ flux & BG systematics→ new techniques!!

translator: 1 kton implies ∼2x10^6 IBD/year → ∼4 IBD/min [∼50x today]

Anatael Cabrera (CNRS-IN2P3 @ LAL - LNCA)
improving possible...

rate + shape \rightarrow rate + shape
(today) \quad (new)

subtle by powerful difference!
(rate systematics \rightarrow \text{negligible})
**θ13 systematics: need for new techniques...**

**larger statistics → shape-driven info (systematics) matters**

**is this good enough? no!!**

- **detection**: believed impossible to improve [irreducible]
- **flux**: BIG trouble → **must fully cancel**
- **BG**: must suppress >10x → **more overburden?**

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</thead>
<tbody>
<tr>
<td></td>
<td>total</td>
<td>total</td>
<td>rate-only</td>
<td>shape-only</td>
</tr>
<tr>
<td>statistics</td>
<td>few %</td>
<td>~0.1%</td>
<td>&lt;0.01% (large)</td>
<td>[25,250]k IBD/day</td>
</tr>
<tr>
<td>detection</td>
<td>2.0 %</td>
<td>~0.1%</td>
<td>~0.1% ✓ DC &amp; ✓ DYB ✓</td>
<td>today's knowledge</td>
</tr>
<tr>
<td>energy</td>
<td>few %</td>
<td>~0.5%</td>
<td>~0.5%</td>
<td>today's knowledge</td>
</tr>
<tr>
<td>flux</td>
<td>~2.2%</td>
<td>~0.1%</td>
<td>&lt;0.01% (new)</td>
<td>full cancellation</td>
</tr>
<tr>
<td>BG</td>
<td>few %</td>
<td>~0.1%</td>
<td>&lt;0.01% (new)</td>
<td>BG suppress &gt;10x</td>
</tr>
</tbody>
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new techniques needed to yield $\delta($flux$)$→0 & $\delta($BG$)$→0!!
flux cancellation(!) & BG elimination (!!!)

“super” requirements... possible?
today's knowledge converges: BIG ISSUE!

reactor prediction is inaccurate (few %)  
[unsurprisingly more complex than we thought]

• rate off by ~6% [deficit]

• shape off by up to ≤15% [structure]

⇒ our knowledge ≈6% (?) [≤3% is very unlikely]

monitor rate+shape cancels (perfect?)

• conventional ND: not good enough!
  → degeneracy flux & θ13 (also far & small)  
  → slight offset to iso-flux⇒ unacceptable

• flux decomposition (L≤40m): perfect!
  → very near detector (VND) per reactor
  → huge statistics:
    1 ton @ 20m: 8.2k IBD/day [FD: ≤2.2k IBD/day]
  → no civil construction [reactor space?]
how to reduce BG with no more overburden?

another lesson: avoid civil construction...
LiquidO: novel detection technology
(born in reactor)

Double Chooz IV: Near (258 live-days)

$S/BG \approx 20$

Visible Energy (MeV)

Events / 0.25 MeV

$e^+ (IBD)$

$e^-/\gamma$

$e^- + \alpha$

recoiled $p$ (fast-$n$)

ND Data

No-oscillated MC

Accidentals

$^9\text{Li}$

Fast Neutrons
LiquidO event-wise imaging...

Opaque scintillator $\rightarrow$ Stochastic light confinement

(self-segmentation) backup slide
powerful PID...

IBD

Backgrounds

2MeV

cosmogenic ($^9\text{Li}$ & fast-neutrons)
accidentals ($\beta^-$, $\gamma$ and $\alpha$)

rejection $\approx 100x$
[time$\otimes$space coincidence & PID(e$^+$)]

vertex resolution $\approx$ order mm

backup slide
LiquidO mean many things...

“background-less” IBD detection?

Detector Seminar

LiquidO: Novel Opaque Neutrino Detection Technology

by Anatael Cabrera Serra (IN2P3/CNRS)

📅 Friday 7 Jun 2019, 11:00  →  12:00  Europe/Zurich
📍 40/S2-A01 - Salle Anderson (CERN)

https://indico.cern.ch/event/823865/

first publication days away...
new sensitivity with LiquidO...
sub-percent $\theta_{13}$ seems possible (while not easy) ...

- statistics: $>4 \times 10^7$ (far) & similar/better (VND's)

flux cancellation [new] & BG-less [new]

[liquidO → many advantages]

&

systematics detection & energy control

[today’s technology demonstrated]

$\Rightarrow$ LiquidO 10kton possible? [NOvA⊕R&D backup]

\begin{itemize}
  \item LiquidO sensitivity:
  \begin{itemize}
    \item flux constraint via VND’s ⊕ energy control (model DC or DYB) ⊕ negligible BG
    \end{itemize}
  \end{itemize}
sub-percent $\theta_{13}$ precision possible...

full range implications under study
(very soon)
European “super” site ready?
Chooz Reactors

Power: $\sim 8.4 \text{ GW}_{\text{thermal}} \Rightarrow \sim 10^{21} \nu/s$

(2x N4 reactors)
the Chooz-A underground system (former reactor)...

Cavern A: 20,000m³
[past: reactor Chooz-A]

Cavern B: 30,000m³
[past: fuel pool]

⇒ ≤10kton detector ⊕ water veto pool (which?)

Overburden: ~100m (known BGs!)

Civil Construction?
• refurbishment (remove structure)
• heavy cranes ready

Available? If so, around ≳2024
“super” synergy with our colleagues in EDF

a Super Chooz project?
(too early to say but promising)
leading neutrino physics in Europe is important!
**full menu (under construction)**

- **sub-percent precision on \( \theta_{13} \) [\( \sin^2(2\theta_{13}) \)] & \( \Delta m^2(\text{reactor}) \) [not shown yet]  
  [aid DUNE@HK to improve CP-Violation & JUNO to measure \( \ell \Delta m^2(\text{vacuum}) \)]

- **burst & remnants supernovae \( \nu_e, \text{anti-}\nu_e \) and \( \nu_x \) measurement** [backup appetiser]  
  [10 kton & high efficiency]

- **multi-channel proton decay** [backup appetiser]  
  [10 kton & high efficiency]

- **high precision reactor rate+shape spectra** (B1 and B2) with VND’s  
  [statistics & complementary to JUNO’s TAO]  
  ⇒ demonstration of reactor monitor technology (high S/BG ~ 1 ton detectors) [industry?]

  ⇒ reactor spectral composition analysis upon switching ON/OFF (better reactor predictions?)

**even more challenging thoughts...**

- **measure solar neutrinos?** [backup appetiser]  
  [unprecedented 10 kton precision with CC interactions]

- **measure \( \theta_w \) via elastic scattering?** (interference CC & NC)  
  [BG is extreme challenge even with LiquidO but huge signal rate and ON/OFF helps]

- [bad news] geo-neutrinos unlikely ⇒ huge reactor-IBD BG...

**note:** PMNS Unitarity test (“top-electron-row”) → solar & other constraints: **a full programme?**
what to remember...

ready to address PMNS structure (head-on) to ≤1%? 
[along with CPV, our next goal? do we have the global knowledge?]

all needed to make the most of our “super-project” era? 
[redundancy & complementarity → each step cost up to billions and/or decades]

a hypothetical “Super Chooz” add/complete to the overall picture? 
[aid all other projects & address new physics → feasible with LiquidO?]

can LiquidO deliver the expected detector performance? 
[breakthrough potential → must demonstrate immediately]

[EPS] Europe OK for much (or most) neutrino physics elsewhere? 
[much of our physics “brewed/conceived” in Europe but then goes elsewhere]

the best “super” is timely/right decisions...
questions, please?

work led by (alphabetically)…
• Thiago Bezerra (SUBATECH, France)
• Pedro Ochoa (UCI, USA)
• Beda Roskovec (UCI, USA)
• AC (LAL, France)
and
• the LiquidO proto-collaboration

full results soon!
[paper in preparation]

merci…
ありがとう…
danke…
고맙습니다…
obrigado…
Спасибо…
grazie…
谢谢…
hvala…
gracias…
شكرا…
thanks…

image: <0.5MeV e+

anatael@in2p3.fr