Bilan T2K / SK

Conseil Scientifique du LLR

Thomas Mueller pour le groupe neutrino du LLR

Laboratoire Leprince-Ringuet

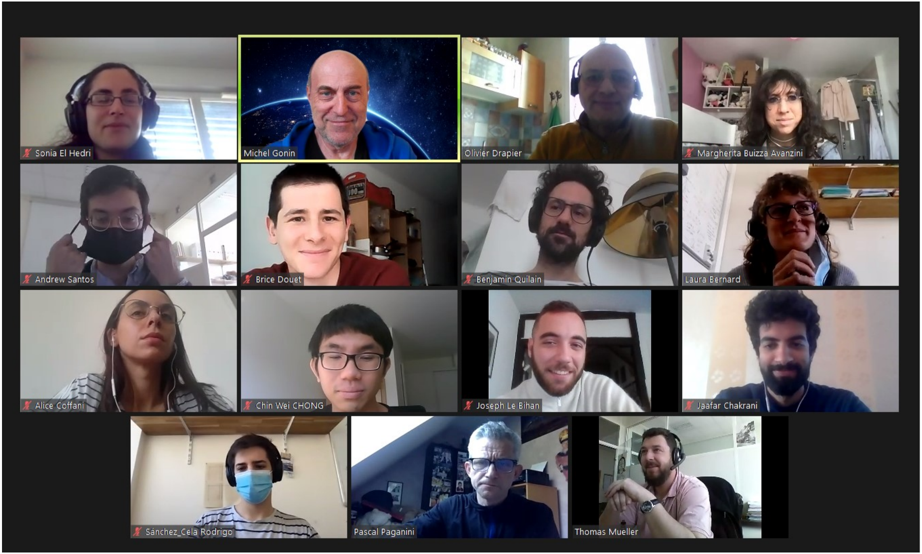
March 30, 2021

The neutrino group at LLR

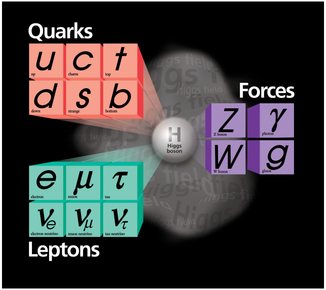
			T2K	SK	HK
Bernard	Laura	Post-doctorante		✓	✓
Buizza-Avanzini	Margherita	CRCN	✓		✓
Chakrani	Jaafar	Doctorant	✓		
Coffani	Alice	Doctorante		✓	
Drapier	Olivier	DR1	✓	✓	✓
El-Hedri	Sonia	Post-doctorante		✓	
Giampaolo	Alberto	Doctorant		✓	
Gonin	Michel	DRCE1	✓	✓	✓
Paganini	Pascal	DR1		✓	✓
Mueller	Thomas	CRCN	✓	✓	✓
Quilain	Benjamin	CRCN	✓	✓	✓
Santos	Andrew	PhD track		✓	

- 7 PhD thesis successfully defended : P. Dinh Tran (2009), C. Bronner (2011), J.P.A.M. de Andre (2013), B. Quilain (2014), M. Licciardi (2018), Q. Huang (2019), O. Volcy (2019)
- 3 former postdocs : M. Besnier, J. Imber, S. Dolan

The neutrino group at LLR



A. Giampaolo is missing on this picture



Super-Kamiokande (1998) + SNO (2001) :

oscillations ⇒ neutrinos have (different) mass

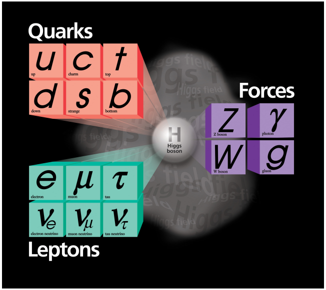
$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = U_{\text{PMNS}} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

flavour "interaction" mass "propagation"

$$U_{\text{PMNS}} = \begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric Δm^2_{31} solar Δm^2_{21}

3 mixing angles, 2 squared mass differences + 1 CP violation phase



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atmospheric Δm^2_{31} — solar Δm^2_{21} — reactors

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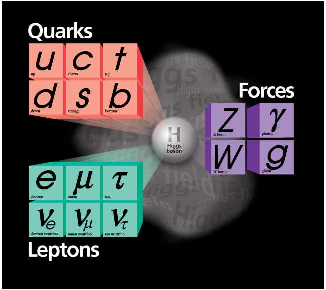

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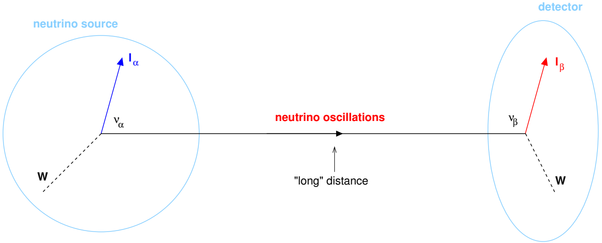
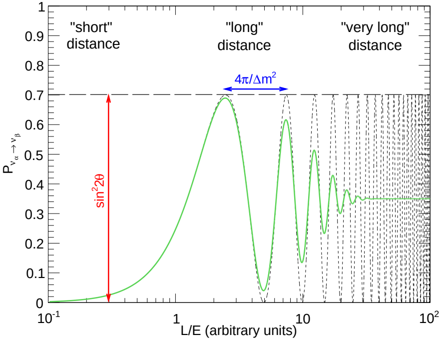
atmospheric Δm^2_{31} — solar Δm^2_{21}

accelerators — reactors

3 mixing angles, 2 squared mass differences + 1 CP violation phase





2-flavour approximation:

$$P_{\nu_\alpha \to \nu_\beta}(L, E) = \sin^2 2\theta \sin^2 \left(\frac{\Delta m^2 L}{4E}\right)$$

3 flavours : much longer to write...
but same basic principle

$\delta_{CP} \neq 0 \Rightarrow P(\nu_\alpha \to \nu_\beta) \neq P(\bar{\nu}_\alpha \to \bar{\nu}_\beta)$

Matter-antimatter asymmetry?

Three flavour oscillation parameters summary

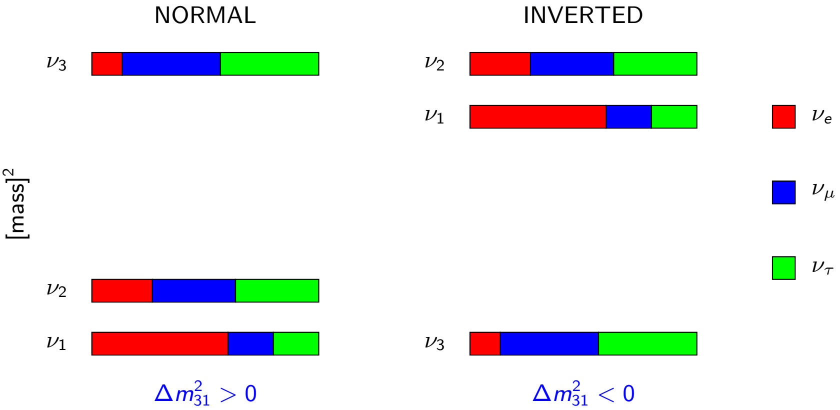
From NuFIT 5.0 (2020), `www.nu-fit.org`

Parameter	bfp$\pm 1\sigma$	1σ acc.	Experiment	Comment
$\sin^2\theta_{12}$	$0.304^{+0.012}_{-0.012}$	4.2%	KamLAND, SK, SNO	unitarity?
Δm^2_{21} $[10^{-5}$ eV$^2]$	$7.42^{+0.21}_{-0.20}$	2.8%	KamLAND SK, SNO	
$\sin^2\theta_{23}$	NH: $0.573^{+0.016}_{-0.020}$ IH: $0.575^{+0.016}_{-0.019}$	4.3%	T2K, NOνA, SK	unitarity? octant? ($\theta_{23}>45^\circ$ or $<45^\circ$?)
$\Delta m^2_{3\ell}$ $[10^{-3}$ eV$^2]$	NH: $\Delta m^2_{31}=2.517^{+0.026}_{-0.028}$ IH: $\Delta m^2_{32}=-2.498^{+0.028}_{-0.028}$	1.2%	T2K, NOνA, SK, Daya Bay	mass hierachy?
$\sin^2\theta_{13}$	NH: $0.02219^{+0.00062}_{-0.00063}$ IH: $0.02238^{+0.00063}_{-0.00062}$	3.0%	Daya Bay, RENO, Double Chooz	unitarity?
δ_{CP} [degree]	NH: 197^{+27}_{-24} IH: 282^{+26}_{-30}	-	T2K, NOνA (w/ θ_{13} constraint)	3σ measurement? CP violation?

N.B. : T2K provided the first indication that $\sin^2 2\theta_{13} \neq 0$
Open questions in neutrino oscillations : mass hierarchy, θ_{23} octant, value of δ_{CP}, unitarity?

What is the mass hierarchy problem?

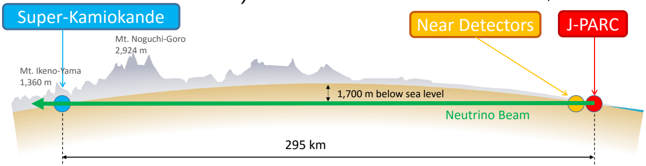
two possibilities for the neutrino mass spectrum



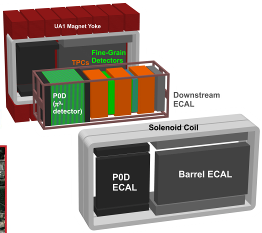
NB: we know that the mass state containing most ν_e is the lighter of the two "solar mass" states $\Delta m^2_{21} \equiv m^2_2 - m^2_1 > 0$ and $\theta_{12} < 45^\circ$ thanks to the observation of the matter effect in the Sun

Overview of the T2K experiment

1) J-PARC accelerator 500 kW, 30 GeV protons



2) High intensity ν_μ beam ($> 99\%$ purity), 600 MeV, narrow band (1^{st} off-axis exp.)



4) Super-Kamiokande : 50 kt water Cerenkov detector

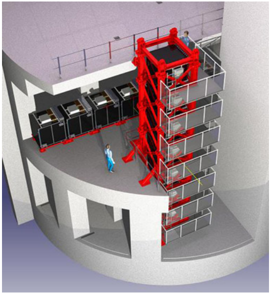
3) Near detector at 280 m

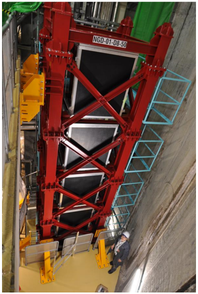
Observation of $\nu_e\,/\,\bar{\nu}_e$ appearance : θ_{13} and δ_{CP}

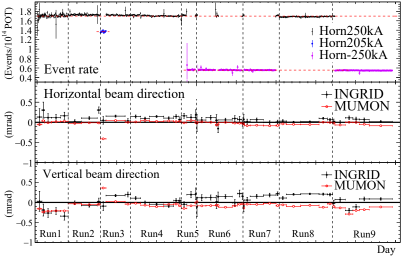
Precise measurement of $\nu_\mu\,/\,\bar{\nu}_\mu$ disappearance : "atmospheric" parameters $(\theta_{23}, \Delta m^2_{32})$

INGRID & Proton Module

Mechanical design + slow control @ LLR : O. Ferreira, A. Debraine, S. Chollet



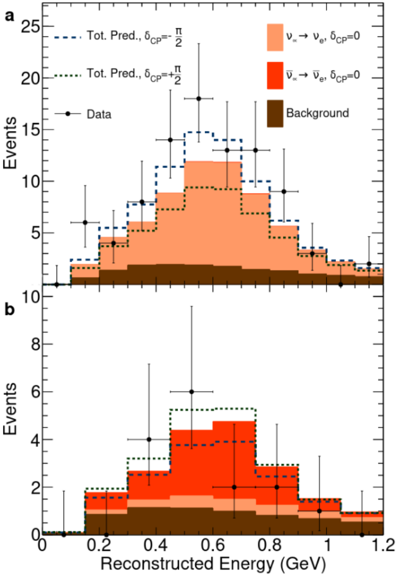




- Designed to monitor the direction of the beam w/ a precision better than 1 mrad
- Study on scintillator & electronics aging shows that we will be able to use INGRID for HK beam physics
- Detectors used well beyond initial capabilities do to physics analysis : σ_{CH}, σ_{Fe} [Phys.Rev.D 90], σ_{H_2O} together w/ WAGASCI [arXiv:2004.13989] (accepted by PTEP), ...

	CC1e ν-mode	CC1e1π ν-mode	CC1e $\bar{\nu}$-mode
$\nu_\mu \to \nu_e$	59.0	5.4	3.0
$\bar{\nu}_\mu \to \bar{\nu}_e$	0.4	0.0	7.5
Bkg	13.8	1.5	6.4
Pred.	73.2	6.9	16.9
Syst.	8.8%	18.4%	7.1%
Data	75	15	15

- First time $\bar{\nu}_e$ appearance at $> 2\sigma$



T2K appearance results - Nature 580, 339-344 (2020)

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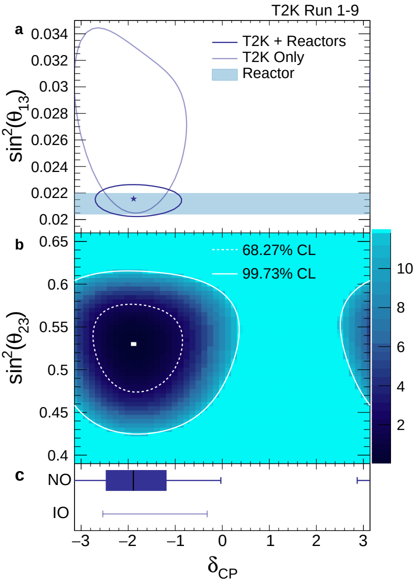
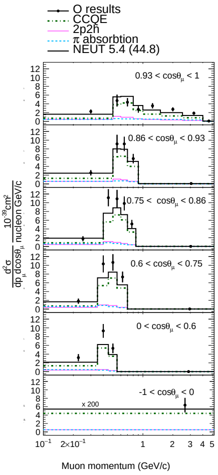
- CP conservation ruled out at 95% confidence level



Strong contribution of LLR neutrino group to T2K analysis

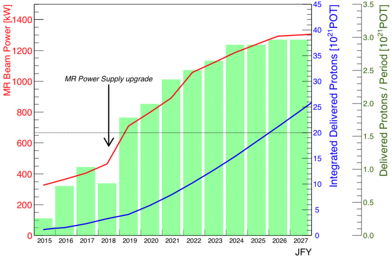
- B. Quilain, convener and leader of (p, θ) joint $\nu - \bar{\nu}$ oscillation analysis
- M. Buizza-Avanzini, convener of the whole cross-section group + main analyzer : ν_μ cross section on O and C @ ND280 [Phys.Rev D101 (2020) 112004]
- J. Chakrani, defined and implemented more sophisticated systematics related to the neutrino-nucleus interactions → will be used for OA2021! Also paper with short author list will be prepared
- T. Mueller, hybrid-π^0 dedicated samples to evaluate the systematics related to π^0 background (2nd dominant background in ν_e appearance) → hybrid extended to other analysis in both T2K and SK
- LLR group is actively working in the physics group of the ND280 upgrade: a paper on SuperFGD physics sensitivity is in preparation (short author list)



⇒ LLR involved in all steps of the analysis!

T2K-II

- T2K was expected to complete data taking by 2020 with a total exposure of 7.8×10^{21} POT (we reached $\sim 3 \times 10^{21}$)
- Next generation long baseline experiments (HK and/or DUNE) won't start data taking before 2027
- T2K has been extended for a running period (T2K-II) to go up to 20×10^{21} POT (6 years, 5 months beam / year, assuming J-PARC power upgrade)



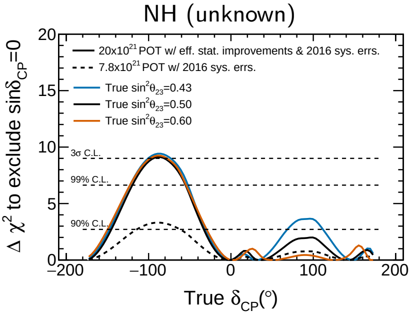
- In the meantime, we expect to increase SK selections eff. by $\sim 20\%$ (new algorithms)

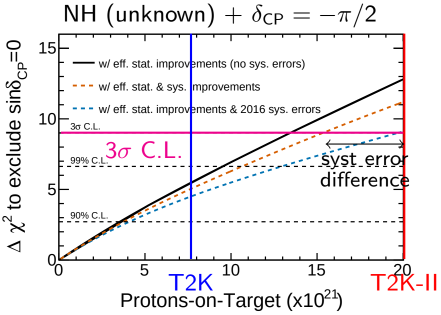
	True δ_{CP}	Total	Signal $\nu_\mu \to \nu_e$	Signal $\bar{\nu}_\mu \to \bar{\nu}_e$	Beam CC $\nu_e + \bar{\nu}_e$	Beam CC $\nu_\mu + \bar{\nu}\mu$	NC
ν-mode	0	454.6	346.3	3.8	72.2	1.8	30.5
ν_e sample	$-\pi/2$	545.6	438.5	2.7	72.2	1.8	30.5
$\bar{\nu}$-mode	0	129.2	16.1	71.0	28.4	0.4	13.3
$\bar{\nu}_e$ sample	$-\pi/2$	111.8	19.2	50.5	28.4	0.4	13.3

Simulation with 10^{21} POT for ν + 10^{21} POT for $\bar{\nu}$

T2K-II and needs for systematics reduction

- T2K phase II $\Rightarrow$ increase statistics to 20×10^{21} POT
- Motivations for T2K phase II : 1st experiment to exclude CP conservation $> 3\sigma$
- Limited by our current systematics in far detector (SK) : from 5.1% to 6.8%





- w/o decreasing current systematics: phase space very limited even for 20×10^{21} POT $\Rightarrow$ a 3σ exclusion possible almost only if $\delta_{CP} = -\pi/2$ and Normal Hierarchy
- Decreasing systematics to 4% $\Leftrightarrow$ 5×10^{21} POT ($>$ 2 times current T2K statistics)

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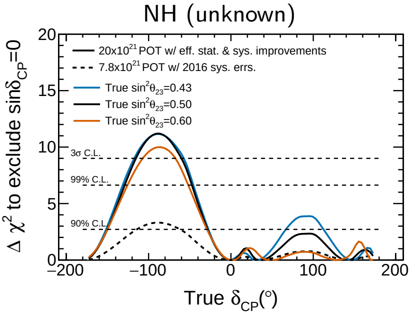

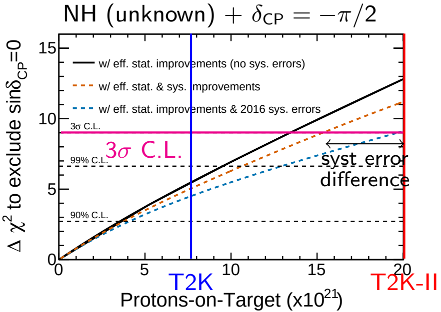

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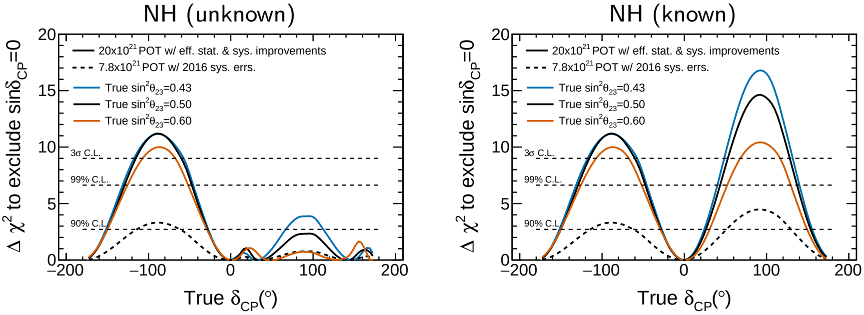

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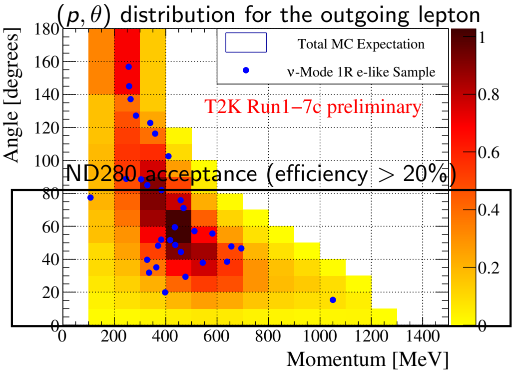
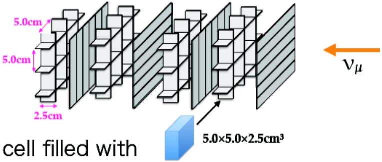


- Need a measurements with :
  1. Similar target nucleus as SK : independent of cross section models
  2. 4π acceptance as SK for lepton kinematics : efficiency corrections not needed
  3. High granularity to identify interaction final states (track low momenta hadrons) : improve energy reconstruction

$\Rightarrow$ goal of ND280 upgrades and of the WAGASCI detector!

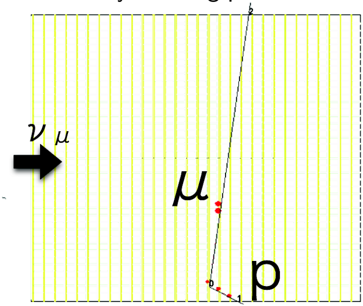
- Alternance of XY planes & 3D grid scintillators $\Rightarrow$ 4π angular acceptance + good vertex resolution (even for large angle tracks)

grid X grid Y grid ...



Each cell filled with water or hydrocarbon

Only tracking planes



Module ID card :

Module size : $100 \times 100 \times 40$ cm^3 $\sim$ 0.4 tons

Cell size (=resolution) : $5.0 \times 5.0 \times 2.5$ cm^3

Plastic background substraction : H_2O:CH = 8:2 in H_2O module

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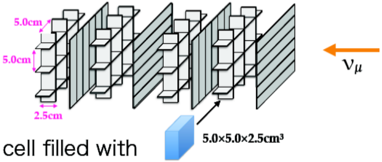

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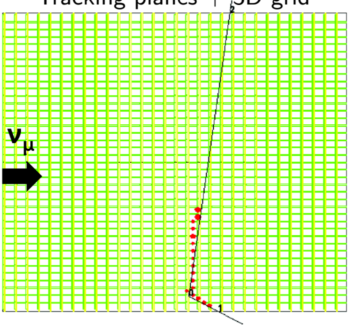
Tracking planes + 3D grid



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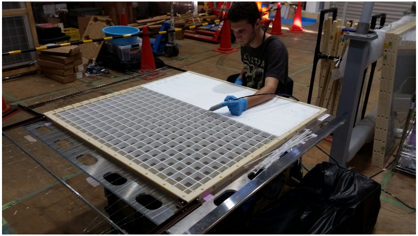
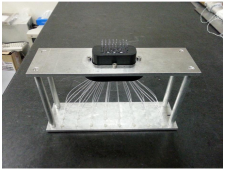
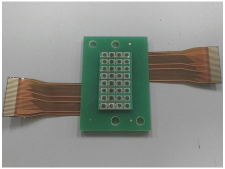
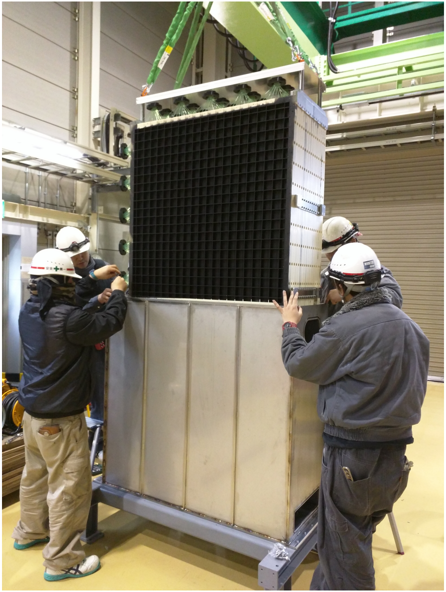
WAGASCI detector

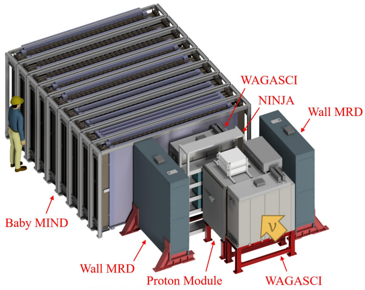
Mechanical design + electronics at LLR : A. Bonnemaison, O. Ferreira, F. Gastaldi, M. Louzir & F. Magniette

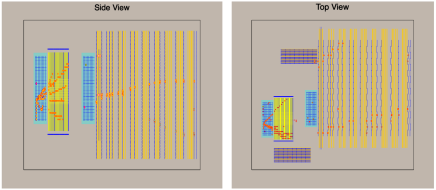








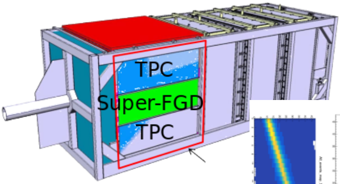


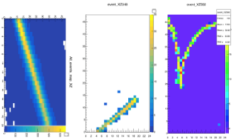


2020/01/30 Thu 02:35:01
WAGASCI spill number 3978

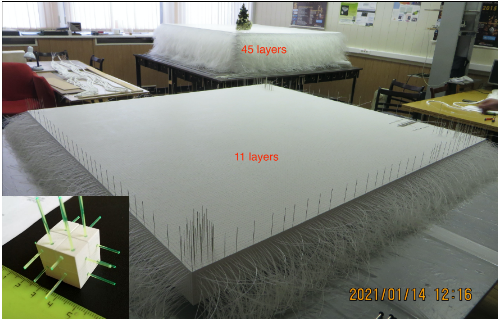
- Final installation end of 2019, but... almost no beam
- Already 3 analysis (WAGASCI is an official T2K near detector)
  - On-axis w/ PM & INGRID, first joint $CC0\pi$ & $CC1\pi$ ν cross section on water and hydrocarbon, M. Licciardi & B. Quilain $\Rightarrow$ paper coming soon
  - Off-axis w/ PM & INGRID, $CC0\pi$ $\bar{\nu}$ cross-section on H_2O and CH, O. Volcy
  - Off-axis w/ PM & INGRID, $CC0\pi$ $\bar{\nu}$ and $\bar{\nu} + \nu$ cross-section on H_2O and CH $\Rightarrow$ accepted by PTEP (T. Mueller chair of paper committee)
- Expect to see much more results in the future (specially joint analysis with INGRID & ND280), stay tuned!

Super-FGD



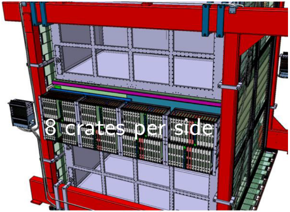


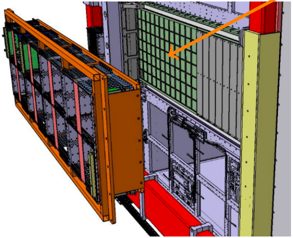
Prototype tested at CERN and LANL



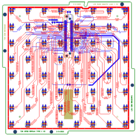
- "active" target : plastic scintillator
- 3D reading
- $\sim 2\text{m}^3 \rightarrow 2000000 \times 1\ \text{cm}^3$
- $\sim$ 56000 WLS fibers + MPPCs
- $\sim$ 220 front-end boards (FEB) (256 chn), 8 Omega-CITIROC / board
- 16 crates (8 / side): in the magnet (0.2 T), limited space (compactness), $\sim$ 5.5 kW in total
- LED calibration system : proposed by LLR, plate with light guides + holes
- LLR : development of front-end boards (CITIROC) with Geneva
- Starting from already existing design for Baby-MIND by UniGe (3 CITIROCs / board)
- With the constraint of the limited space (8 CITIROCs / board)

Super-FGD - Electronics

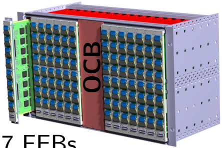




880 MPPC boards (LSU)



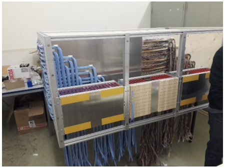
14 FEBs per crate

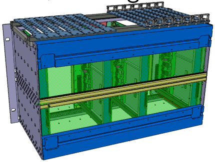


7 FEBs 7 FEBs

Mock-up (1/2 detector, wood) in order to validate lengths and paths of cables

Cables frontly connected (MIB)
back: digital + cooling

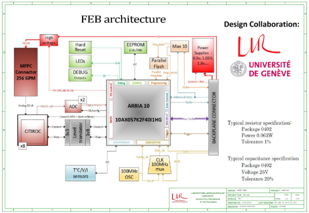


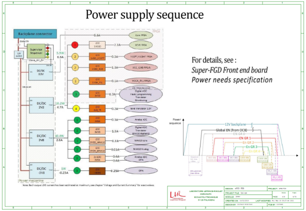


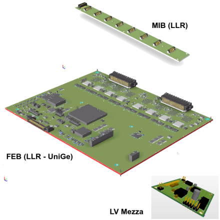
Super-FGD - Electronics at LLR

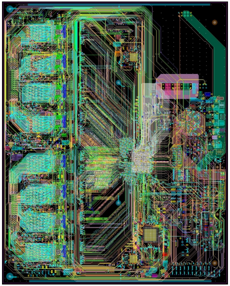
Involved LLR engineers : F. Gastaldi, J. Nanni, M. Louzir & L. Bernardi + R. Guillaumat

- Optimization of signal cable length
- FEB schematics (78 pages!) + MIB
- LV mezzanine for tests
- Voltage definition
- Voltage on-off sequence
- FEB + MIB board routing (16 layers)



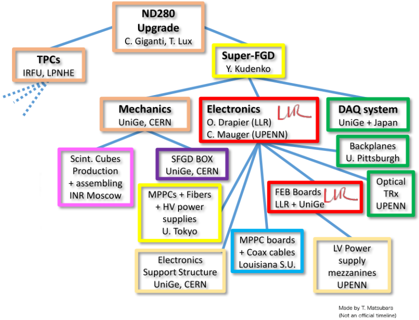


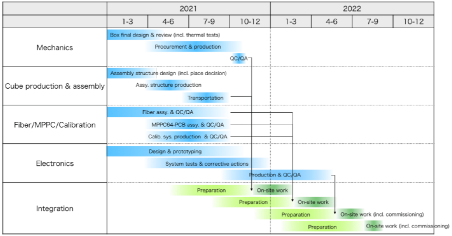




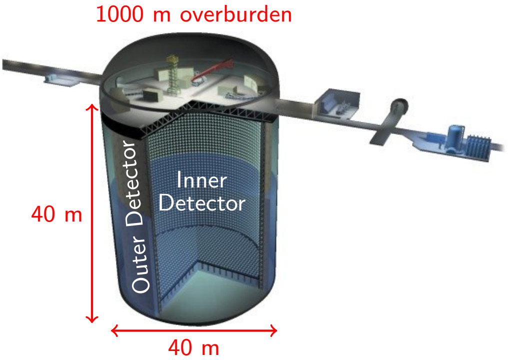
Super-FGD - Responsabilities and planning

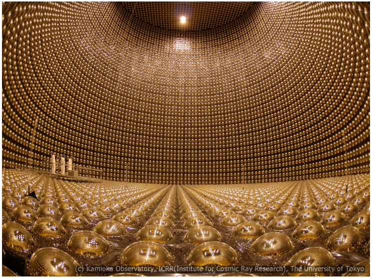
- FEB prototype testing spring/summer 2021
- Preparation for production fall 2021
- Board production end 2021 - beginning 2022
- Production tests spring 2022
- Mounting @ CERN + shipping to Japan
- Mounting and cabling of sFGD + LED, fibers, MPPC, crate tests @ J-PARC summer 2022 (surface)
- Installation in the pit fall 2022





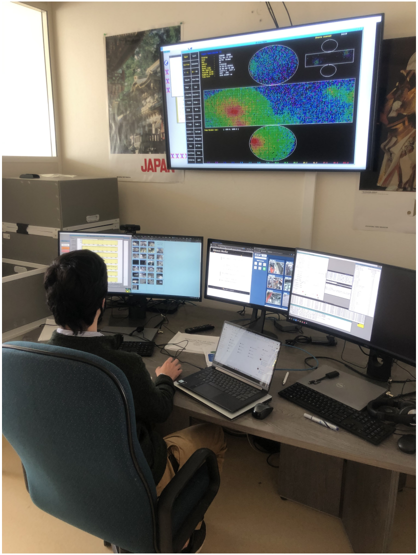
The Super-Kamiokande detector





Site	Mozumi
Number of ID PMTs	11129
Photo-coverage	40%
Mass / Fiducial Mass	50 kton / 22.5 kton

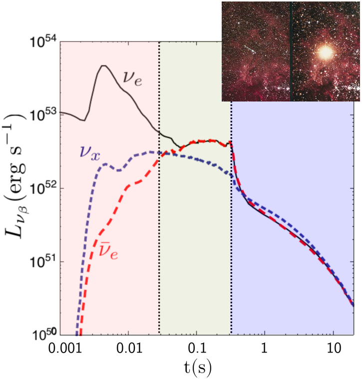
Our shift room at LLR



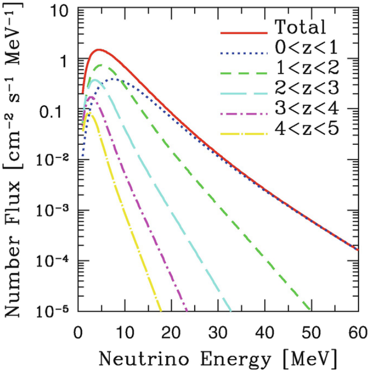
Towards Super-Kamiokande with Gadolinium

- May - Sept. 2018 : everybody
  - Tank emptying
  - 136 PMTs replaced
  - Cleaning
  - Leak repair
- Jan. - Mar. 2019 : calibration (A. Coffani)
- July 2020 : 0.01% Gd
  $\rightarrow$ 50% n capture efficiency
- T1.5 : march 2022 0.02% or 0.03% Gd?
- T2 : 0.1% Gd, when?

SN burst



Diffuse Supernova Neutrino Background

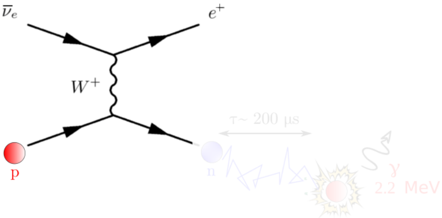


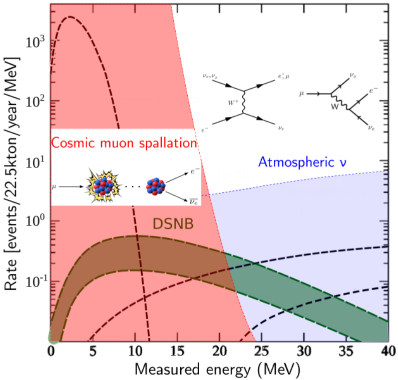
- Understand the explosion mechanism
- Measure neutrino properties
- Galactic supernovae are rare events

Super-Kamiokande, SK-Gd: **5-20 evts/year**

$$\Phi(E) = \frac{c}{H_0} \int_0^{z_{\max}} \frac{F_\nu[E(1+z)] R_{\mathrm{SN}}(z)}{\sqrt{\Omega_m(1+z)^3 + \Omega_\Lambda}} \mathrm{d}z$$

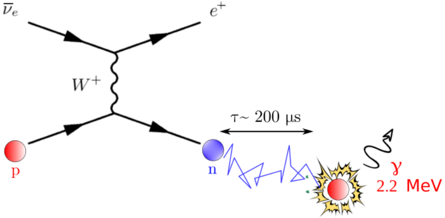
$= \int$ [Spectres ν (fraction de trous noirs)] $\otimes$ [Histoire de l'Univers]

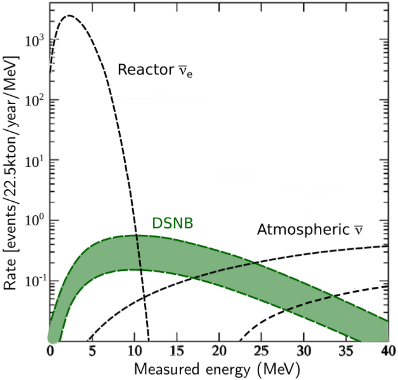




- Tagging the neutron drastically reduces spallation and atmospheric backgrounds
- On Hydrogen: $\tau \sim 200$ μs, γ energy of 2.2 MeV
- On Gadolinium: $\tau \sim 30$ μs, γ energy of 8 MeV

Why do we need Gd?





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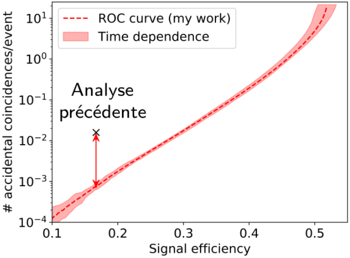
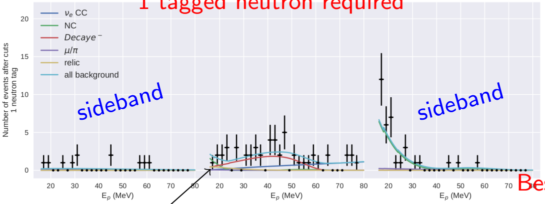
- On Gadolinium: $\tau \sim 30\ \mu$s, γ energy of 8 MeV

- Leadership from S. El-Hedri
- Full SK-IV period (2008-2020)
- Both rate and spectral analysis (A. Giampaolo & P. Paganini)
- Improved neutron tagging algorithm on H using BDT (A. Giampaolo & P. Paganini)
- Paper by summer 2021 : "**DNSB search at Super-Kamiokande**" (paper committee members: A. Giampaolo & S. El-Hedri)



1 tagged neutron required

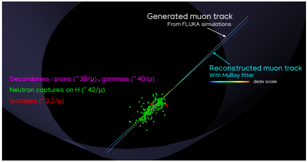


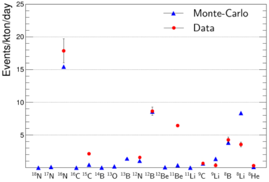
Pred. 3.09 evt/year for $E_e > 16$ MeV

Best fit : $2.6^{+1.5}_{-1.6}$ evt/year
< 4.8 evt/year @ 90% CL

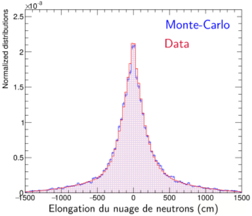
Best fit with Ando+03 model

Future analysis with and without Gadolinium





Isotope yields

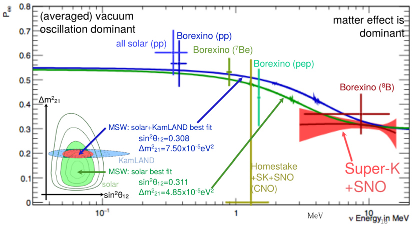


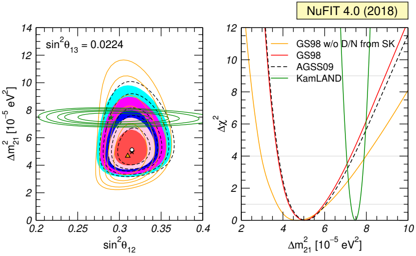
Neutron cloud

- L. Bernard, A. Coffani & S. El-Hedri are involved in the spallation background understanding which limits our lower energy threshold
- Dedicated simulation with FLUKA + GEANT w/ and w/o Gd to estimate spallation isotope production, interesting spallation parameters for BDT training, ... Validated against data
- Goal is to improve spallation cuts for both future analysis with and without Gd
  → A. Coffani will defend her PhD soon
- Spallation paper in preparation : "**New Methods and Simulations for Cosmogenic Induced Spallation Removal in Super Kamiokande-IV**" (short author list, A. Coffani in paper committee)
- Development of next generation n-tag method based on GNN (A. Giampaolo & P. Paganini)

Other interesting analysis at SK

- S. El-Hedri, A. Coffani (new spallation cuts !) & T. Mueller involved in solar analysis : probe day/night asymmetry, tension w/ KamLAND results, explore upturn region (NSI? sterile?)
- B. Quilain + new PhD student : joint fit between T2K beam data and SK atmospheric data





Towards HK !

- Strong involvement of neutrino group in T2K in both hardware (very fruitfull collaboration with Omega!) and all steps of the oscillation analysis
- We're eager to start data taking with our future Super-FGD detector $\Rightarrow$ let's be the first experiment to exclude CP conservation at $> 3\sigma$ (and more?)
- Strong time constraint to be ready for the data taking in 2022
- Our involvement in SK analysis is getting bigger and bigger with time, LLR group being leader of the hottest analysis at SK (congratulation Sonia for all your work and your success at concours CNRS!!!) $\Rightarrow$ towards the first measurement of the DNSB and of supernovae properties! Still waiting for a galactic explosion!
- We still have 6 years awesome physics program with both T2K phase II and SK but we also need to prepare the future of neutrino physics... Hyper-Kamiokande!!!