Point sur la situation du projet Super-Kamiokande et sur l'engagement des équipes IN2P3

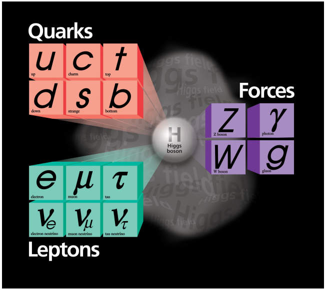
Conseil scientifique de l'IN2P3

Thomas Mueller pour les équipes ILANCE et LLR

October 26, 2021

ILANCE
International Laboratory for Astrophysics,
Neutrino and Cosmology Experiments

Neutrinos in the Standard Model... and beyond



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

oscillations ⇒ neutrinos have (different) mass

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

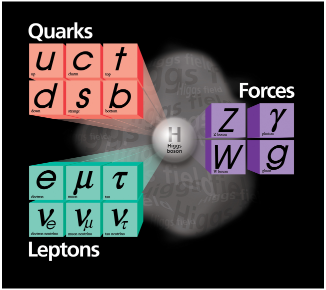
flavour
"interaction"

mass
"propagation"

$$U_{\text{PMNS}} = \underbrace{\begin{pmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_{23} & \sin\theta_{23} \\ 0 & -\sin\theta_{23} & \cos\theta_{23} \end{pmatrix}}_{\text{atmospheric } \Delta m^2_{31}} \begin{pmatrix} \cos\theta_{13} & 0 & e^{-i\delta}\sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{-i\delta}\sin\theta_{13} & 0 & \cos\theta_{13} \end{pmatrix} \underbrace{\begin{pmatrix} \cos\theta_{12} & \sin\theta_{12} & 0 \\ -\sin\theta_{12} & \cos\theta_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}}_{\text{solar } \Delta m^2_{21}}$$

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

Neutrinos in the Standard Model... and beyond



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atmospheric Δm^2_{31}

solar Δm^2_{21}

reactors

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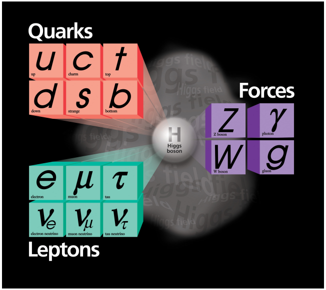

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atmospheric Δm^2_{31}

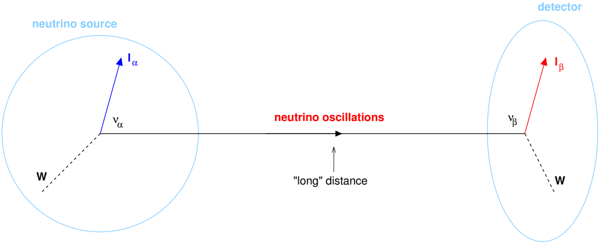
solar Δm^2_{21}

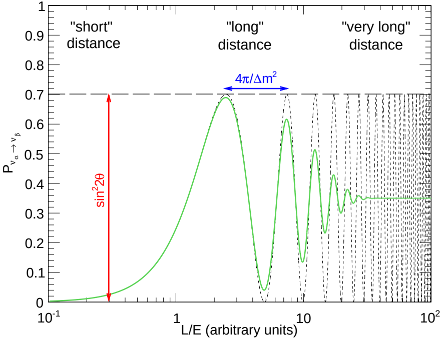
accelerators

reactors

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

Neutrino oscillation in a nutshell





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

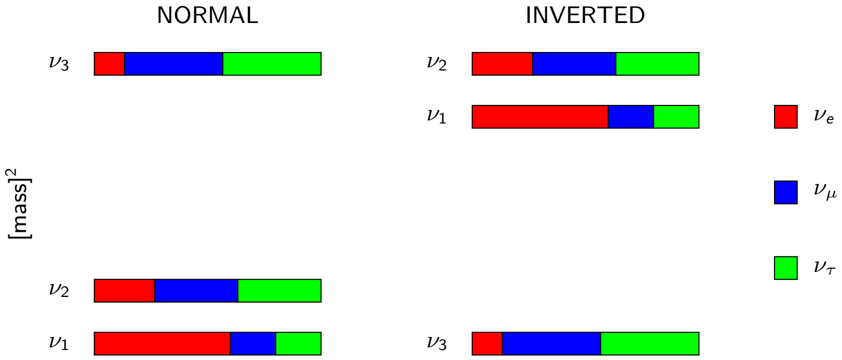
From NuFIT 5.0 (2020), `www.nu-fit.org`

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?

Open questions in neutrino oscillations : mass hierarchy, θ_{23} octant, value of δ_{CP}, unitarity?

What is the mass hierarchy?

two possibilities for the neutrino mass spectrum



$\Delta m^2_{31} > 0$

$\Delta m^2_{31} < 0$

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

IN2P3 involvment in Super-Kamiokande

- 2 laboratories are involved in the Super-Kamiokande project : Laboratoire-Leprince Ringuet and ILANCE

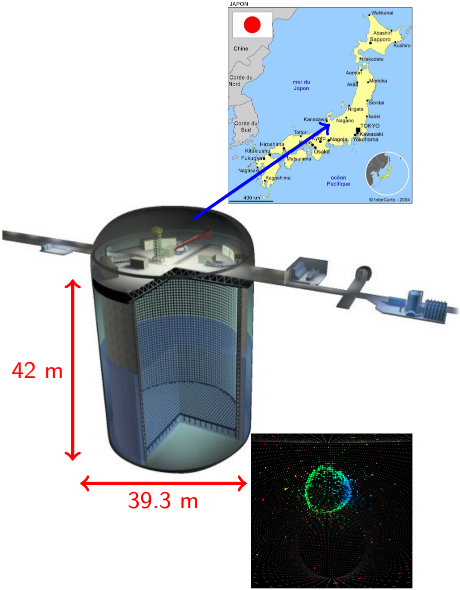
Name	Position	FTE	Comment
Antoine BEAUCHENE	PhD student	1	Arrived at LLR in Oct. 2021
Laura BERNARD	Post-doc	1	Will leave LLR end Oct. 2021
Alice COFFANI	PhD student	1	PhD thesis defence in Dec. 2021
Olivier DRAPIER	DR1	0.2	
Sonia EL-HEDRI	Post-doc	1	Left LLR end Sept. 2021
Alberto GIAMPAOLO	PhD student	1	
Michel GONIN	DRCE	0.3	
Thomas MUELLER	CRCN	0.4	
Pascal PAGANINI	DR1	0.8	
Benjamin QUILAIN	CRCN	0.2	
Andrew SANTOS	PhD tracks	N/A	Expected to start a PhD in Oct. 2022

- 2 post-docs + 1 PhD student will leave the group by end 2021 ⇒ shrink of our working force

The Super-Kamiokande experiment (1)

- 50 kton water Cherenkov detector (currently doped with Gd)
- Located in Kamioka, Japan, under Mt. Ikenoyama : 1 km rock overburden (2.7 km water equivalent)
- Optically divided into an inner detector (ID) with a fiducial volume of 22.5 kton and an outer detector (OD), instrumented with
  - ID : 11146 inward facing large 20"-PMTs, 40% photo-coverage
  - OD : 1885 8"-PMTs primarily used as veto

Running for 25 years and still has a lot to teach !



The Super-Kamiokande experiment (2)

- SK experiment has collected data during 6 phases, only SK-I to SK-IV covered in this talk 372.6 kton.years ($\sim$ 6000 days of data taking) compared to SK-V $\sim$ 461 days and SK-IV $\gtrsim$ 400 days

Phase	Period	Event
SK-I	1996 to 2001	Start of the experiment
SK-II	2003 to 2005	20% photo-coverage after accident
SK-III	2006 to 2008	Full photo-coverage (40%) restored
SK-IV	2008 to 2018	Upgraded electronics
SK-V	2019 to 2020	Detector upgraded for Gd-loading
SK-VI	since 2020	0.01% Gd-doping

- Highly versatile multi-purpose experiment in the MeV - TeV range : solar & atmospheric neutrinos, supernovae neutrinos, diffuse supernova neutrino background (DSNB), neutrino astrophysics, proton-decay, dark matter + beam neutrino (T2K, covered later by Margherita, Claudio and Benjamin)

- Today, we'll discuss status and perspectives for the physics analysis of atmospheric neutrino oscillations (as requested by the Scientific Council) and the search for the DSNB (major contribution of IN2P3 to physics analysis at SK)

Atmospheric neutrinos

- Neutrinos produced by the interaction of primary cosmic rays (mostly protons) with Earth's atmosphere

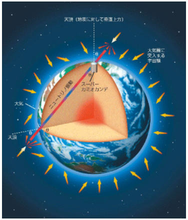
- Wide range of energies from about 100 MeV to 100 GeV

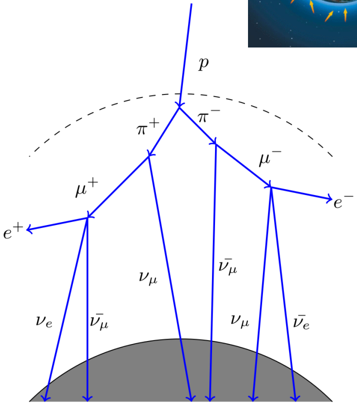
- Produced at $\mathcal{O}(10 \text{ km})$ above the surface and coming from all directions $\Rightarrow$ wide range of baselines from 10 to 10^4 km

- Flavor content :

$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} \simeq 2 \text{ below 1 GeV}$$

$$\frac{\phi_{\nu_\mu} + \phi_{\bar{\nu}_\mu}}{\phi_{\nu_e} + \phi_{\bar{\nu}_e}} > 2 \text{ above 1 GeV}$$

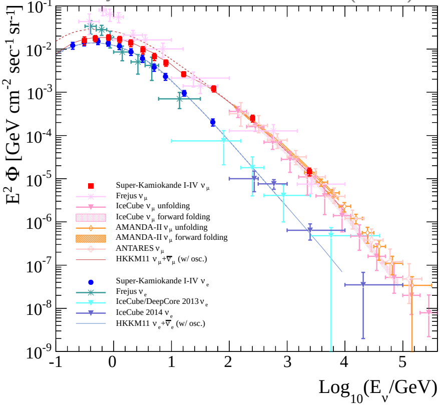




Atmospheric neutrinos flux

- Detailed simulations are required to compute the neutrino flux taking into account cosmic ray flux, complex hadron interactions, geomagnetic field, solar activity, etc...
- On top of that, oscillations !
  - complicated matter effect of neutrinos travelling through Earth
  - appearance of the third kind of neutrinos ν_τ
- 1998, observation of a deficit of atmospheric upward-going vs. downward going $\nu_\mu \Rightarrow$ discovery of neutrino oscillations (model-independent) 2015 Nobel prize

Phys. Rev. D 94, 052001 (2016)



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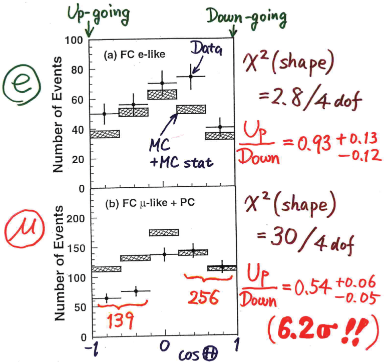
Zenith angle dependence (Multi-GeV)



$\chi^2(\text{shape}) = 2.8/4\text{ dof}$

$\frac{\text{Up}}{\text{Down}} = 0.93^{+0.13}_{-0.12}$

$\chi^2(\text{shape}) = 30/4\text{ dof}$

$\frac{\text{Up}}{\text{Down}} = 0.54^{+0.06}_{-0.05}$

(6.2σ !!)

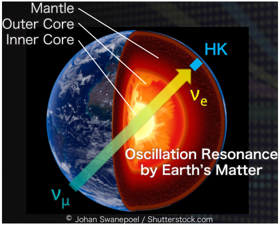
※ Up/Down syst. error for μ-like

Prediction (flux calculation …… ≲ 1% ; 1km rock above SK …. 1.5%) 1.8%

Data (Energy calib. for ↑↓ …. 0.7% ; Non ν Background ….. < 2%) 2.1%

Atmospheric neutrinos and mass-hierarchy determination

- Mass-hierarchy can be accessed through matter effects, the longer the baseline, the higher the effects



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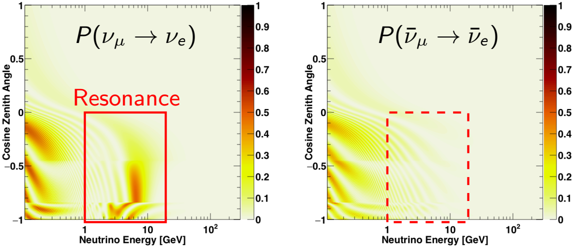
Normal Hierarchy



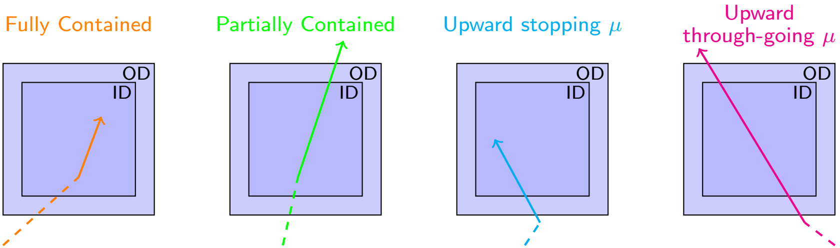
Phys. Rev. D97, 072001 (2018)

- Mass-hierarchy determined with upward-going multi-GeV ν_e sample : atm. baseline $\leq$ 130000 km $\gg$ 295 km (T2K/HK → joint-fit) accelerator baseline
  - Normal hierarchy : enhancement of $P(\nu_\mu \to \nu_e)$
  - Inverted hierarchy : enhancement of $P(\bar{\nu}_\mu \to \bar{\nu}_e)$

- Sensitivity enhanced if $\nu/\bar{\nu}$ separation

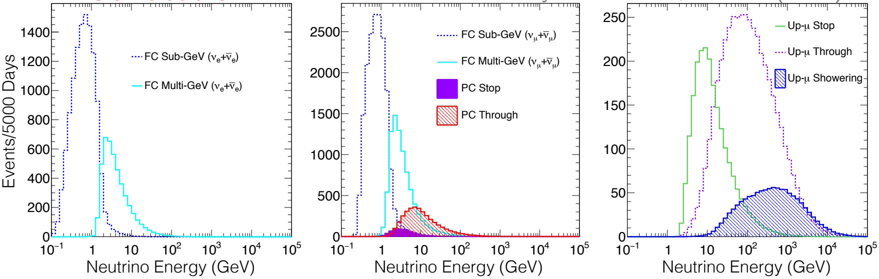
Event topological classification

Depending on the topology and ID and OD activities



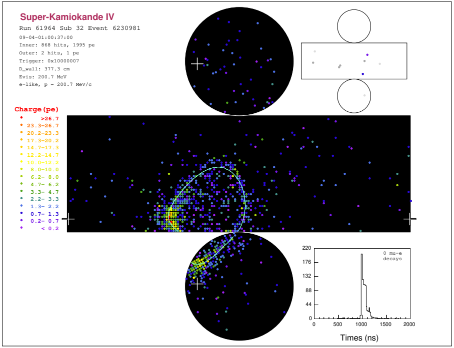
MC simulations

Phys. Rev. D97, 072001 (2018)



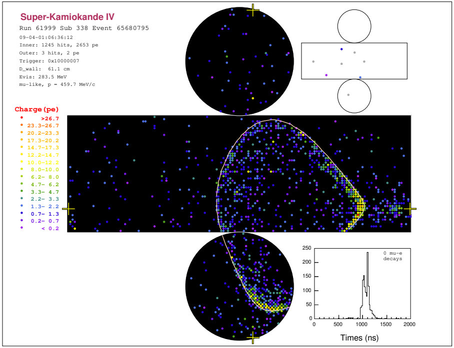
Further classification

- SK excellent PID allows for a clear favour separation



Super-Kamiokande IV

```
Run 61964 Sub 32 Event 6230981
09-04-01:00:37:00
Inner: 868 hits, 1995 pe
Outer: 2 hits, 1 pe
Trigger: 0x10000007
D_wall: 377.3 cm
Evis: 200.7 MeV
e-like, p = 200.7 MeV/c
```



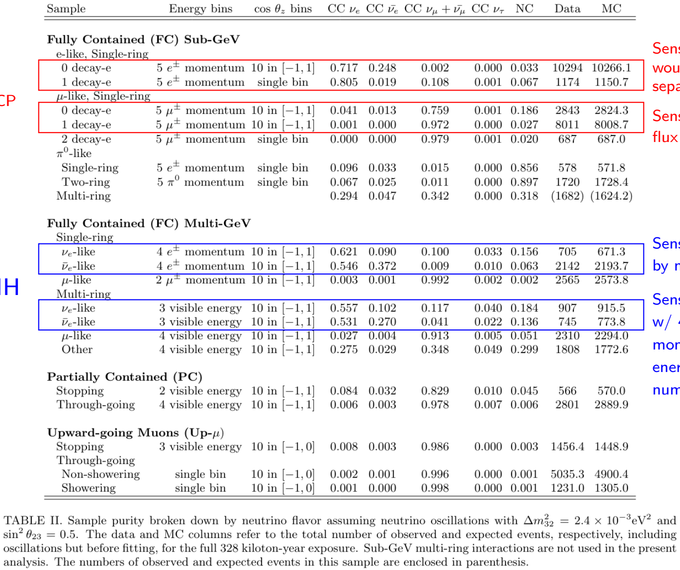
Super-Kamiokande IV

```
Run 61999 Sub 338 Event 65680795
09-04-01:06:36:12
Inner: 1245 hits, 2653 pe
Outer: 3 hits, 2 pe
Trigger: 0x10000007
D_wall:  61.1 cm
Evis: 283.5 MeV
mu-like, p = 459.7 MeV/c
```

- Events are further categorized according to energies, number of rings, number of decay-electrons, π^0 likelihood (+ neutron tagging in SK-IV only) ⇒ 20 samples in the end

Most sensitive sub-samples

Phys. Rev. D97, 072001 (2018)



Sample	Energy bins	$\cos\theta_z$ bins	CC ν_e	CC $\bar{\nu}_e$	CC $\nu_\mu + \bar{\nu}_\mu$	CC ν_τ	NC	Data	MC
Fully Contained (FC) Sub-GeV									
e-like, Single-ring									
0 decay-e	5 $e^\pm$ momentum	10 in $[-1,1]$	0.717	0.248	0.002	0.000	0.033	10294	10266.1
1 decay-e	5 $e^\pm$ momentum	single bin	0.805	0.019	0.108	0.001	0.067	1174	1150.7
μ-like, Single-ring									
0 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.041	0.013	0.759	0.001	0.186	2843	2824.3
1 decay-e	5 $\mu^\pm$ momentum	10 in $[-1,1]$	0.001	0.000	0.972	0.000	0.027	8011	8008.7
2 decay-e	5 $\mu^\pm$ momentum	single bin	0.000	0.000	0.979	0.001	0.020	687	687.0
π^0-like									
Single-ring	5 $e^\pm$ momentum	single bin	0.096	0.033	0.015	0.000	0.856	578	571.8
Two-ring	5 π^0 momentum	single bin	0.067	0.025	0.011	0.000	0.897	1720	1728.4
Multi-ring			0.294	0.047	0.342	0.000	0.318	(1682)	(1624.2)
Fully Contained (FC) Multi-GeV									
Single-ring									
ν_e-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.621	0.090	0.100	0.033	0.156	705	671.3
$\bar{\nu}_e$-like	4 $e^\pm$ momentum	10 in $[-1,1]$	0.546	0.372	0.009	0.010	0.063	2142	2193.7
μ-like	2 $\mu^\pm$ momentum	10 in $[-1,1]$	0.003	0.001	0.992	0.002	0.002	2565	2573.8
Multi-ring									
ν_e-like	3 visible energy	10 in $[-1,1]$	0.557	0.102	0.117	0.040	0.184	907	915.5
$\bar{\nu}_e$-like	3 visible energy	10 in $[-1,1]$	0.531	0.270	0.041	0.022	0.136	745	773.8
μ-like	4 visible energy	10 in $[-1,1]$	0.027	0.004	0.913	0.005	0.051	2310	2294.0
Other	4 visible energy	10 in $[-1,1]$	0.275	0.029	0.348	0.049	0.299	1808	1772.6
Partially Contained (PC)									
Stopping	2 visible energy	10 in $[-1,1]$	0.084	0.032	0.829	0.010	0.045	566	570.0
Through-going	4 visible energy	10 in $[-1,1]$	0.006	0.003	0.978	0.007	0.006	2801	2889.9
Upward-going Muons (Up-μ)									
Stopping	3 visible energy	10 in $[-1,0]$	0.008	0.003	0.986	0.000	0.003	1456.4	1448.9
Through-going									
Non-showering	single bin	10 in $[-1,0]$	0.002	0.001	0.996	0.000	0.001	5035.3	4900.4
Showering	single bin	10 in $[-1,0]$	0.001	0.000	0.998	0.000	0.001	1231.0	1305.0

TABLE II. Sample purity broken down by neutrino flavor assuming neutrino oscillations with $\Delta m^2_{32} = 2.4 \times 10^{-3}\mathrm{eV}^2$ and $\sin^2\theta_{23} = 0.5$. The data and MC columns refer to the total number of observed and expected events, respectively, including oscillations but before fitting, for the full 328 kiloton-year exposure. Sub-GeV multi-ring interactions are not used in the present analysis. The numbers of observed and expected events in this sample are enclosed in parenthesis.

δ_{CP}

Sensitive to δ_{CP} (signal) would benefit from $\nu/\bar{\nu}$ separation

Sensitive to δ_{CP} flux normalization

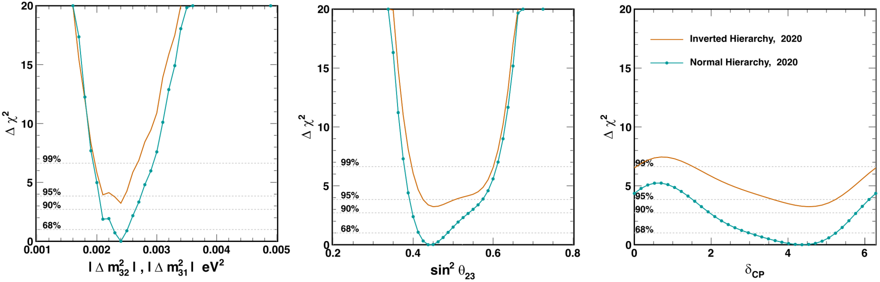
MH

Sensitive to MH, discrimination by number of decay-e

Sensitive to MH, discrimination w/ 4 variables MVA : transverse mom., mom. fraction of most energetic ring, number of rings, number of decay-e

SK atmospheric neutrinos results (2020)

PMNS official, SK collaboration, june 2020

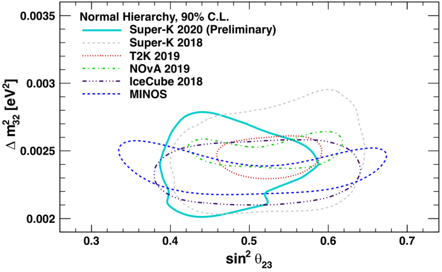


Data favors first octant for θ_{23}

Data favors NH at 1.7σ
$(\Delta\chi^2(\text{IH}) - \Delta\chi^2(\text{NH}) = 2.8$

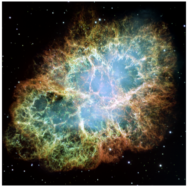
δ_{CP} best fit agrees with that of T2K

Some constraining power over θ_{13}
consistent with LBL results

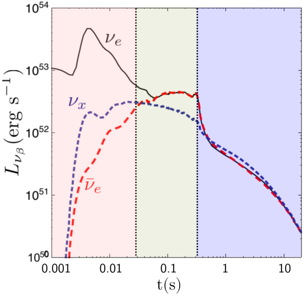


Results shown here are with θ_{13} constrained by reactor experiments, for unconstrained results see back-up slides

Supernovae physics



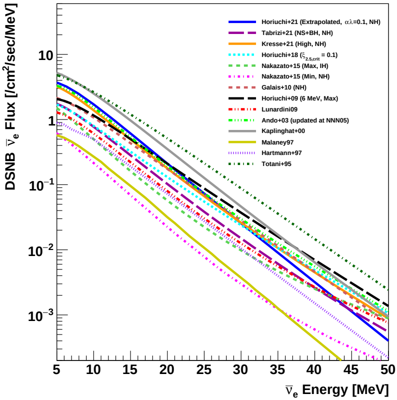
- Core-collapse supernovae are among the most cataclysmic phenomena in the Universe and essential elements of the dynamics of the cosmos
- Underlying mechanism still poorly understood and requires knowledge of the core of the collapsing star
- 10^{58} neutrinos emitted in a burst (99% of gravitational energy) $\Rightarrow$ information about this core
- So far, only SN1987a in LMC has been detected by neutrino experiments
- If burst in the galatic center $\Rightarrow \sim 8000$ neutrinos in SK … but only few times per century in our galaxy



⇒ quest for the Diffuse Supernova Neutrino Background (DSNB)

The Diffuse Supernova Neutrino Background

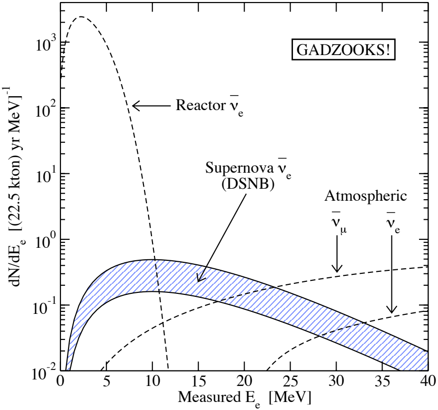
- Composed by neutrinos of all past SN of all flavors whose energies have been redshifted when propagating to the Earth ⇒ information not only on the SN neutrino emission process but also star formation and Universe expansion history
- Normalisation mostly determined by SN rate, related to cosmic star formation rate
- Shape depends on many parameters : fraction of BH-forming SN, effective neutrino energies (core temperature), and sub-dominantly on the expansion of the Universe (red-shift) and neutrino mass-hierarchy



DSNB detection at Super-Kamiokande

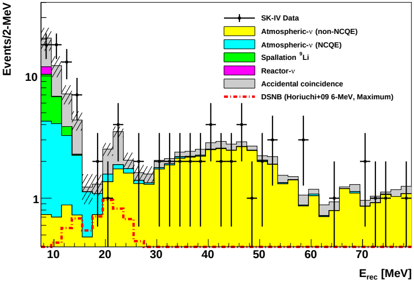
- Detection channel in SK : inverse β-decay (IBD) $\bar{\nu}_e + p \rightarrow e^+ + n$
- Searched at $\mathcal{O}(10)$ MeV, bounded by reactor + spallation background at lower energy and atmospheric neutrinos at higher energies
- In order to disentangle signal from backgrounds, neutron detection in coincidence with the positron is mandatory
- Neutron doesn't produce Cherenkov light but its capture on H (timescale of 200 μs) produce a 2.2 MeV gamma. Neutron detection efficiency of 25% in SK-IV

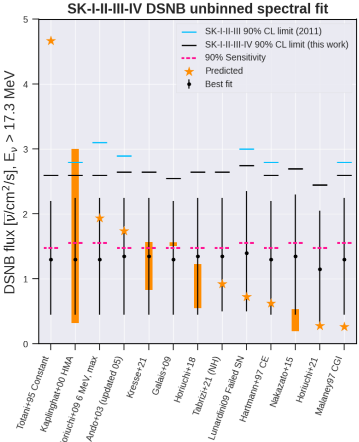
assuming 100% n detection efficiency



Physics analyses at SK

- Model independent analysis w/ full SK-IV dataset, one tagged neutron required through BDT





- Spectral fit (S+B), to derive model-dependent limits on the DSNB flux (no constraints on neutron number)
- In current analyses sensitivity allows probing "median" model but we can do better !

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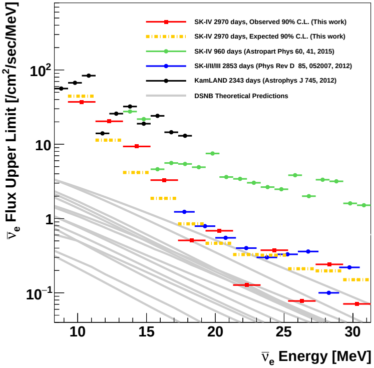

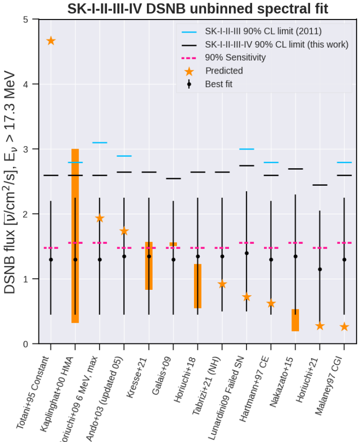

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IN2P3 members contributions to DSNB analyses

- DSNB analyses with SK-IV dataset
  - Leadership in both DSNB analyses
  - Simulation of DSNB signal and backgrounds
  - BDT for neutron tagging has been developped
  - Spectral fit analysis (including evaluation of all systematics) + combination w/ previous results

    ⇒ “Diffuse Supernova Neutrino Background Search at Super-Kamiokande”, arXiv:2109.11174 [astro-ph] submitted for publication

Muon flux at surface
Modified Gaisser

⇓

Muon travel through rock
MUSIC

⇓

Hadronic shower and isotope generation
FLUKA

⇓

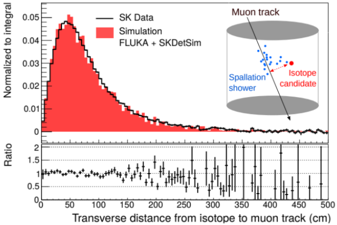
Detector simulation
SKDetSim–GEANT3

⇓

Event reconstruction

- Modelling of the spallation background
  - Dedicated modeling of relevant nuclear processes with FLUKA + propagation using SK detector simulation
  - Optimization of spallation rejection cuts for future analyses

    ⇒ “New Methods and Simulations for Cosmogenic Induced Spallation Removal in Super-Kamiokande-IV”, under collaboration review



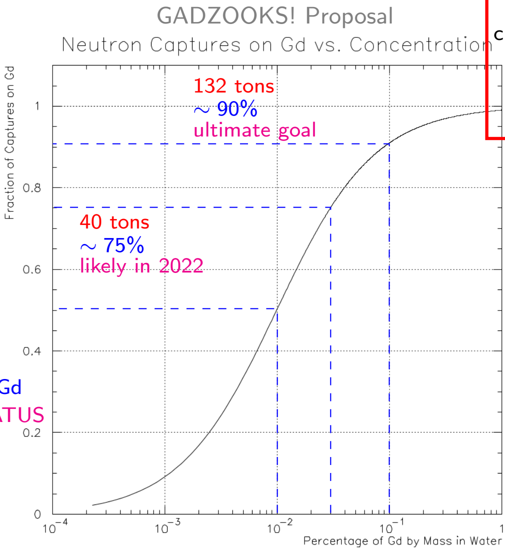
Summer 2018, preparation of the SK-Gd phase (1)

- May - Sep. 2018
  - \- Tank emptying
  - \- Replacement of 136 defective PMTs
  - \- Cleaning
  - \- Water sealing reinforcement
  - \- Improvement of tank piping
- Jan. - Mar. 2019 : calibration
- July 2020 : 0.01% Gd
  → 50% neutron capture efficiency

Summer 2018, preparation of the SK-Gd phase (2)

- 140 k€ from Ecole polytechnique : contribution to SK upgrade (traveling + material)
- Safety shoes (> 200) + Tyvek suits (>150) for working in the tank
- Repair of a chiller in one of the electronics hut
- Replacement of 4 HV modules iseg EHS-F030p 16 channels for 25% of OD PMTs
- "cable ties" for PMTs installation (> 35000)
- Filters for water system

Gd in Super-Kamiokande - Status and perspectives


GADZOOKS! Proposal

Neutron Captures on Gd vs. Concentration

132 tons
~ 90%
ultimate goal

40 tons
~ 75%
likely in 2022

Gd thermal neutron
cross section : 49.7 kb
($\sigma_H = 0.33$ b)
$\tau_{Gd} \sim 30\ \mu$s
8 MeV γ cascade

13.2 tons of
$Gd_2(SO_4)_3 8H_2O$
in 50 ktons water
~ 50% capture on Gd
CURRENT SK STATUS

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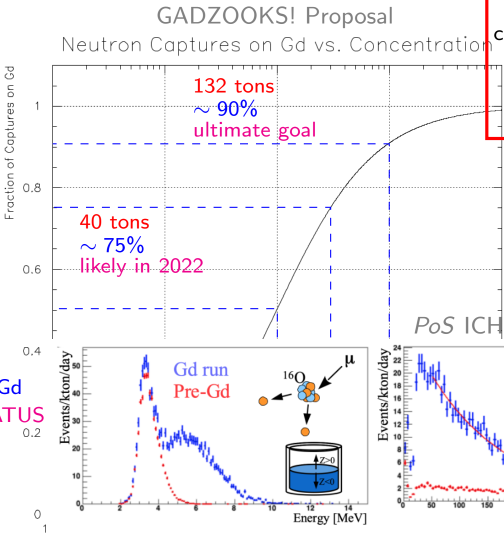

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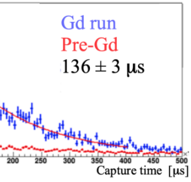

Figure 5: Reconstructed energy for spallation neutrons candidates for runs with and without Gd in the lower region of the detector (left) and capture time of the neutron candidates (right).

Perspectives for physics analysis with Gd

- Many analyses highly affected by limited ability to distinguish between neutrinos and antineutrinos (though already excellent sensitivity) ⇒ Gd has lifted this limitation !
- For atmospheric neutrinos
  - Limited effect for multi-GeV samples (to be studied), limited effect on the MH determination in the sub-GeV sample
  - Enhancement of δ_{CP} determination in the sub-GeV sample
  - Atmospheric parameters determination ($+\delta_{\mathrm{CP}}$) will benefit from joint T2K-SK fit (see Benjamin's talk)
- For DSNB neutrinos
  - Very promising perspectives for the DSNB search
  - Increase statistics by up to ×4 assuming final loading and 90% n selection efficiency
  - 8 MeV γ cascade (compared to 2.2 MeV for H) will help lowering the threshold down to 12 MeV where ^{9}Li decays will start to dominate (17.3 MeV currently) by removing almost all spallation background (accidentals)
  - Locating muon-induced showers using neutrons will become especially powerfull
  - After eliminating spallation, NCQE interactions will dominate and will call for new dedicated techniques

Conclusions

- Results for PMNS oscillations using atmospheric neutrinos :
  - preference for large δ_{CP} values, agreeing with T2K experiment
  - preference for normal ordering
  - preference for first octant
- DSNB search
  - World best sensitivity to DSNB, comparable to the predictions of various models
  - For energies > 17.3 MeV, 90% C.L. upper limit of DSNB $\bar{\nu}_e$ flux of $\sim 2.7\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$ strongly disfavoring most optimistic predictions

We are entering an era of extraordinary research with the new phase of Super-Kamiokande detector (and very soon with Hyper-Kamiokande)... Stay tuned !