Neutrino Physics and Dark Matter

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Introduction

- "White paper" collection & Thematic seminar in Bordeaux
- Science Drivers
- Scientific programs
- Projects
- Program-wide recommendations
- Project-specific recommendations

"White paper" & Thematic seminar in Bordeaux - 1

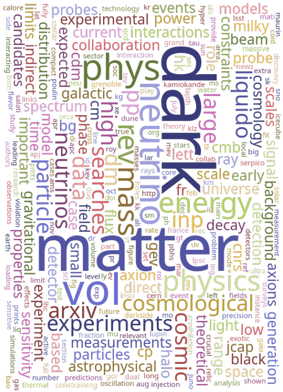
Un groupe de travail (GT) a été mis en place pour la thématique "physique des neutrinos et matière noire" auquel ont été invités à contribuer tous les chercheurs, ingénieurs et techniciens des laboratoires français.
Les questions scientifiques concernent essentiellement

- **La nature, la masse et le mélange des neutrinos**
- **La nature de la matière noire**

avec une forte priorité sur la déclinaison nationale des priorités stratégiques européennes de la feuille de route 2017-2026 de l'APPEC.

"White paper" & Thematic seminar in Bordeaux - 2

- 33 "white papers" received by the Copil - **thanks to all contributors!**
- Regrouped into **11 thematical topics** for the Seminar (next slide)



Neutrino physics in Japan

4 - The Hyper-Kamiokande experiment (LLR & LPNHE Neutrino groups)
13 - The Super-Kamiokande Gadolinium experiment (LLR Neutrino group)
15 - The T2K-II project: the second phase of the T2K experiment (LLR & LPNHE Neutrino groups)

Neutrino physics in US

33 - IN2P3 perspectives for DUNE (DUNE-IN2P3)

Neutrino physics in Europe

6 - Neutrino physics with KM3NeT/ORCA (KM3NeT-IN2P3)
8 - Neutrino Beam from Protvino to KM3NeT/ORCA (KM3NeT-IN2P3)
14 - The European Spallation neutrino Super Beam (M. Dracos for ESSvSB)

Reactor neutrino physics

5 - Physics with JUNO (JUNO-IN2P3)

Coherent elastic neutrino-nucleus scattering

10 - Prospects for exploring new physics with Coherent Elastic Neutrino Nucleus Scattering (Ricochet)

Double beta decay

1 - R2D2: Rare Decays with Radial Detector (R2D2-IN2P3)
3 - Multi-ton Double-Beta Decay with LiquidO (LiquidO-IN2P3)
9 – CUPID: a next-generation $0\nu2\beta$ experiment (CUPID-France)
11 - Expérience SuperNEMO (SuperNEMO-IN2P3)
12 - Proposal for a national double-beta decay strategy (A. Guiliani & Ch. Marquet)

Unitarity?

17 - High Precision Neutrino Unitarity Possible? (proposition for SuperCHOOZ)

Direct DM detection with noble liquids

28 - Search for WIMP dark matter with the dual phase liquid argon detector DarkSide-20k (DarkSide-IN2P3)
31 - Direct dark matter Search with the experiments fromthe international XENON Collaboration (XENON-IN2P3)

Direct detection of sub-GeV DM

24 - Gas Detectors for Direct and Directional Dark Matter Detection and Axion-Like Particle exploration (NEWS-G & MIMAC-France)
26 - Direct detection of dark matter in the eV-to-GeV mass range (DAMIC-IN2P3)
30 - The direct search for Dark Matter in the keV/c^2 to GeV/c^2 range through its interaction with nucleons or electrons using solid-state cryogenic detectors (EDELWEISS-IN2P3)

Axions and WISP DM detection

23 – GrAHal : un projet d'Haloscope à Grenoble pour détecter la Matière Noire axionique (Institut Néel, LNCMI & LPSC)
29 - Search for axion dark matter with a novel approach used by the MADMAX experiment (MADMAX-IN2P3)
32 - Vacuum Magnetic Birefringence: QED & WISP (C. Rizzo & R. Battesti , LNCMI, support LMA et CPPM)

DM nature: theoretical overview and complementarity of detection techniques

18 - Dark Matter and Early Universe (Theory, F. N. Mahmoudi & A. Arbey, IP2I)
19 - Cosmological probes of the dark sector (Theory, LAPth, LPSC & LUPM)
20 - Gravitational searches for dark matter (Theory, LAPth, Obs. Astron. de Strasbourg, LAM, LPSC & LUPM)
21 - Indirect searches for dark matter in a multimessenger context (Theory, LAPth, LPSC & LUPM)
22 - Dark matter searches:Interdisciplinary aspects of theoretical developments (Theory, LAPth, Obs. Astron. de Strasbourg, LAM, LPSC & LUPM)

Some contributions addressed only during discussions or in other GT

2 - Neutrino physics and direct dark matter search programme at APC (APC Neutrino group)
7 - Le Plomb de Notre-Dame, un matériau d'intérêt majeur pour les physiciens des événements rares ? (P. de Marcillac, IJCLab)
16 - Un laboratoire souterrain de basse radioactivité à Bure ? (P. de Marcillac, IJCLab)
27 - Identification de la Matière Noire à l'ère du grand relevé optique LSST (LSST-IN2P3)
25 - Neutrino physics with GRAND (GRAND-France)

"White paper" & Thematic seminar in Bordeaux - 3

Thanks to CENBG organizers

Program

- Neutrino physics in Japan - C. Giganti
- Neutrino physics in US - D. Autiero
- Neutrino physics in Europe - J. Bruenner
- Reactor neutrino physics - C. Jollet
- Coherent elastic neutrino-nucleus scattering - J. Billard
- Double beta decay - A. Giuliani
- Unitarity - A. Cabrera

+ Discussion on neutrino physics - ALL

- Direct DM detection with noble liquids - L. Scotto Lavina
- Direct detection of sub-GeV DM - J. Gascon
- Axions and WISP DM detection - F. Hubaut
- DM nature: theoretical overview and complementarity of detection techniques - J. Lavalle

+ General discussion - ALL

Science Drivers

The committee distilled all the inputs into

five intertwined Science Drivers for the field

of Neutrino and Dark Matter Physics in France.

Science Drivers

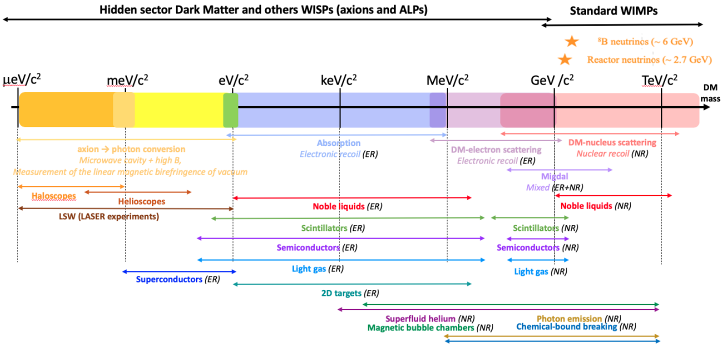
- Pursue the physics associated with the **nature of the neutrino**
- Explore the **PMNS neutrino mixing paradigm and CP-violation**
- Determine the **neutrino mass and ordering**
- Explore the **physics beyond the three neutrino flavour mixing**
- Identify the **nature of dark matter**

Scientific programs: Dark Matter

Identify the Dark Matter nature is clealy a multi-GT question!

In GT06, proposals mainly for **direct detection of dark matter** techniques:

rare event physics in deep underground labs



Main techniques used for direct detection of WIMPs (Weakly Interacting Massive Particles, *e.g.* SUSY, KK particles) or WISPs (Weakly Interacting Slim – or Sub-eV – Particles, *e.g.* axions, ALPs, particles from hidden sector), with masses from μeV/c^2 to TeV/c^2.

Identify the Dark Matter nature with direct detection

Standard WIMPs

	Current experiment	DM mass range	Best limits: σ vs DM mass	Competi-tors	Projects	Projected DM mass range and sensitivity
WIMP-NR (S.I.)	**XENON1T** (LXe dual phase TPC 1 t.yr) finished **XENONnT** (LXe dual phase TPC, 2020-2022)	> 3 GeV/c^2	4.1 x 10^{-47} cm^2 @ 30 GeV/c^2 Expected 2 x 10^{-48} cm^2 @ 30 GeV/c^2	LUX, PandaX-II LZ, PandaX-4t	**DARWIN** (LXe dual phase TPC, > 2026	> 3 GeV/c^2 Expected 2 x 10^{-49} cm^2 around 30 GeV/c^2
	DarkSide50 (LAr dual phase TPC 6786 kg.d)	1.8 to 20 GeV/c^2	10^{-41} cm^2 @ 1.8 GeV/c^2 ; 8 x 10^{-43} cm^2 @ 6 GeV/c^2		**DarkSide-LM** (1t LAr, 2021-2022) **Dark-Side20k** (LAr dual phase TPC, 2023-2027) **ARGO** (LAr dual phase TPC, > 2028)	Sensitivity in the range [0.5 – 10] GeV/c^2 > 12 GeV/c^2 Expected 3 x 10^{-48} cm^2 around 50 GeV/c^2 > 12 GeV/c^2 Expected 2 x 10^{-49} cm^2 around 100 GeV/c^2
	EDELWEISS-Surf (33.4-g Ge bolometer phonon+charge above-ground)	600 MeV/c^2 to 10 GeV/c^2	Best underground limit from 600 MeV/c^2	SuperCDMS, CRESST (Nucleus)	**EDELWEISS-SubGeV** @ LSM (1 kg array of phonon+charge Ge bolometers)	0.1 to 1 GeV/c^2, possibility of HV use for Luke-Neganov boost
	NEWS-G @LSM (SPC Ne+CH_4 (0.7 %) @ 3.1 bars, 9.7 kg·d)	0.5 to 16 GeV/c^2	4.4×10^{-37} cm^2 @ 0.5 GeV/c^2 and 4.4×10^{-39} cm^2 @ 16 GeV/c^2		**NEWS-G @SNOLAB** (H, He, Ne, up to 10 bars, tens of kg)	0.1 to 10 GeV/c^2, Expected 4 x 10^{-42} cm^2 @ 2 GeV/c^2 with Neon

Best limits obtained by current experiments and expected sensitivity of future projects.

WIMP-NR (S.I.) stands for DM particles scattering off on nuclei (spin-independent).

Identify the Dark Matter nature with direct detection

Standard WIMPs

	Current experiment	DM mass range	Best limits: σ vs DM mass	Competi-tors	Projects	Projected DM mass range and sensitivity
WIMP-NR (S.D.)	**PICO60** (C_3F_8 bubble chamber, 1404 kg-d)	> 3 GeV/c²	2.5×10^{-41} cm² @ 25 GeV/c², on proton			
	XENON1T (LXe dual TPC, 1 t.yr)	> 6 GeV/c²	6.3×10^{-42} cm² @ 30 GeV/c², on neutron	XENONnT, LZ, PandaX-4T	**DARWIN** (LXe dual phase TPC, > 2026)	> 6 GeV/c²
	EDELWEISS-Surf (33.4-g Ge bolometer phonon+charge above-ground)	0.5 to 10 GeV/c²	New parameter space excluded for masses < 1.3 GeV/c², on proton and neutron		**EDELWEISS-SubGeV** @ LSM (1 kg array of phonon+charge Ge bolometers)	> 0.5 GeV/c²

Best limits obtained by current experiments and expected sensitivity of future projects.

WIMP-NR (S.D.) stands for DM particles scattering off on protons or neutrons (spin-dependent).

Identify the Dark Matter nature with direct detection

WISP search with direct detection experiments: 1eV - 1GeV scale

	Current experiment	DM mass range	Best limits: σ vs DM mass	Competi-tors	Projects	Projected DM mass range and sensitivity
WISP - DM-electron	**XENON1T** (LXe dual phase TPC 1 t.yr) finished	> 4 GeV/c^2	analysis using Migdal effect → extra sensitivity in the range [0.080 – 2] GeV/c^2		**XENONnT + DARWIN** (LXe dual phase TPC)	
	SENSEI/DAMIC	[0.5 – 100] MeV/c^2 [1 – 400] eV/c^2	10^{-28} cm² @ 0.5 MeV/c^2 and 10^{-33} cm² @5 MeV/c^2 + best sensitivity for dark photon with m_A < 12.4 eV/c^2		**DAMIC-M** @LSM (1 kg) and **10 kg** skipper-CCD Si @SNOLAB	Sensitivity in the range 0.5 to 10^3 MeV/c^2, expected 5 x 10^{-42} cm² (1 kg) and 10^{-43} cm² (10 kg) Dark photon mass from 1 to 300 eV/c^2
	EDELWEISS-Surf (33.4-g Ge bolometer phonon+charge above-ground)	45 MeV/c^2 to 1 GeV/c^2	Migdal NR+ER, 1st exclusion: 10^{-26} cm² @ 45 MeV/c^2 to 10^{-29} cm² @ 150 MeV/c^2		**EDELWEISS-SubGeV** in HV mode (sub-electron resolution already achieved @LSM)	Sensitivity in the range 0.5 to 10^2 MeV/c^2 + Migdal effect + Dark photon mass down to 1 eV/c^2
					MIMAC @LSM (2m³ @300 mbar, ^{40}Ar + 5% C_4H_{10})	Sensitivity to ALP DM, 100 eV/c^2 to 20 keV/c^2

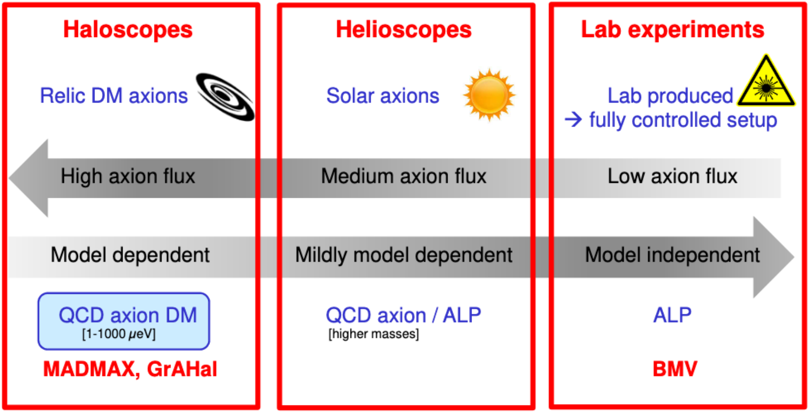
Best limits obtained by current experiments and expected sensitivity of future projects.

WISP-DM-electron stands for DM particles scattering off on electrons or DM absorption by electrons (axions or ALPs).

Identify the Dark Matter nature with lab experiments

WISP search with lab or "*shining light through a wall*" experiments

- Partial conversion of Laser beam photons to axion-like particles (ALPs) in a strong magnetic field in front of a wall and reconversion behind the wall by a similar magnetic field in an optical cavity of high Q value.
- Detector types:



Identify the Dark Matter nature: an evidence for new physics beyond SM

Identify the nature of Dark Matter in the next decade needs a joint effort between theory and experiments, as well as between the three detection type experiments.

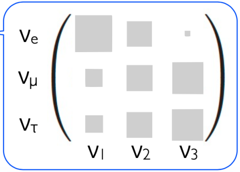
Note that all current and expected sensitivities considered for these national prospective and presented here correspond to proposals received mid-2019 and to presentations from 26 October 2019.

Since then there were a lot of experimental and theoretical improvements, new proposals, new results and publications. There is an intense activity in the field, not only concerning the Dark Matter nature, but also for neutrino physics as presented now.

Neutrino physics: a privileged window on new physics beyond the Standard Model of particle physics (SM).

The discovery of the neutrino oscillation requires to extend the SM to describe the neutrino masses

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



Open Questions:

- The CP violation predicted in the SM is insufficient to explain the observed matter/antimatter asymmetry in the Universe
- The Baryon/Lepton number violation
- Is the neutrino its own antiparticle (i.e. Majorana or Dirac neutrino)?
- Neutrino Mass generation mechanism
- The unitarity PMNS mixing matrix violation

Neutrino physics - Oscillations

The existence of non-zero neutrino masses and the neutrino mixing were successfully established through the observation of neutrino flavor oscillations.

	current knowledge		expected knowledge around 2030	
	precision (%)	dominant (%)	precision (%)	experiment
θ_{12}	3.0	SNO	$\leq$1.0	JUNO
θ_{23}	5.0	T2K+NOvA	$\sim$1.0	DUNE+HK
θ_{13}	1.8	DYB	1.5	DC+DYB+RENO
δm^2	2.5	Kamland	$\leq$1.0	JUNO
$\lvert\Delta m^2\rvert$	3.0	DYB+T2K	$\leq$1.0	JUNO+DUNE+HK
sign(Δm^2)	@ 3σ	SK	measured	JUNO+DUNE+HK+ORCA
δ_{CP}	@ 2σ	T2K	measured	DUNE+HK

Table 1: Neutrino Oscillation knowledge (obtained with Normal Ordering with SK-atm for the global fit). DC, DYB, HK and SK stand for Double Chooz, Daya Bay, Hyper-K and Super-K, respectively. δm^2stands for (Δm^2_{21}) and $\Delta m^2$for(Δm^2_{32} or Δm^2_{31}).

Scientific programs: Neutrino physics - Oscillations

The goals of the **future neutrino-oscillation program** are to:

- Complete the leptonic mixing sector of the Standard Model
  - Determine the Mass Ordering;
  - Search for and discover leptonic CP-invariance violation.
- Establish the leptonic mixing sector as correct description of nature:
  - Determine at % level θ_{23} and the degree to which it differs from $\pi/4$;
  - Determine θ_{13} precisely;
  - Determine θ_{12} at sub-% level.
- Search for deviations from the leptonic mixing sector providing some indications for physics beyond the Standard Model:
  - Search for sterile neutrinos and non-standard neutrino interactions.
  - Provide redundant measurements of sufficient precision to test the unitarity of the neutrino-mixing matrix (absolute flux knowledge needed);

Neutrino physics - properties

Properties:

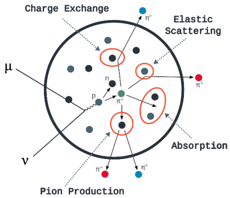
Even if everything about a neutrino is a neutrino property!

- Nature of neutrinos (Dirac or Majorana)
  $\Longrightarrow$ Violation of the conservation of total lepton number, new sources of CP violation (CPV) in the lepton sector
  $\Longrightarrow$ Neutrinoless double beta decay ($0\nu 2\beta$)
- The absolute neutrino mass scale
- Non Standard Interactions
  $\Longrightarrow$ e.g. study of the Coherent Elastic Neutrino Nucleus Scattering (CENNS) process at reactors
- How many ν 's?

Neutrinos Physics - cross sections

Neutrino Interaction Cross Sections

- The neutrino cross-sections on nucleons and nuclei across all energy scales from eV to GeV and beyond are very small and the uncertainties in flux are also large.



  - Knowledge of neutrino-nucleus scattering cross sections is crucial to the global neutrino physics program
  - XSec systematics are often the largest contribution to the error summary of neutrino oscillation accelerator experiments

$\rightarrow$ Neutrino-scattering uncertainties need to be under control at 1% level.

Neutrino Physics: Theory

Theory of Neutrino Physics

- Theoretical inputs required for the neutrino interaction cross sections and for neutrinoless double beta decay process
- For Xsection calculations, understand the nuclear effects to buid a nuclear model to infer the neutrino interaction energy
- $\beta\beta$ decay experiments need accurate nuclear matrix elements calculations relying on an optimal description of the nuclear structure of involved nuclei in the process.

$\Longrightarrow$ Improving the knowledge of neutrino properties and processes implies a combined effort from theoretical and experimental activities

Projects - 1

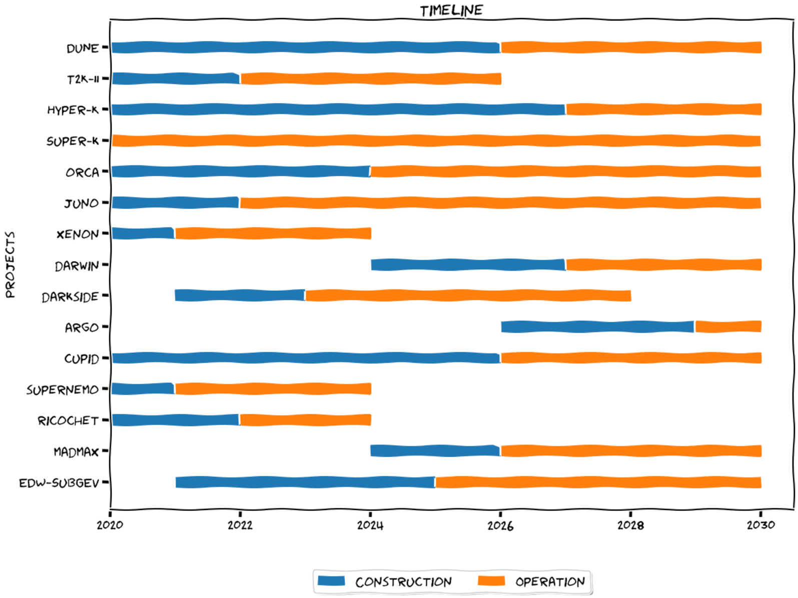
The projects aim at a search of rare phenomena with an extremely weak cross section (weakly interacting Universe), and most of them need weak environmental noise.

- Long baseline experiments
- Reactor neutrino experiments
- Neutrinoless double beta decay search
- CENNS
- Dark Matter as WIMP and WISP

Projects - 2

Project/Activity	ν Nature	PMNS matrix	ν mass ordering	Beyond 3 ν	Dark Matter
Large scale projects					
DUNE	-	✓	✓	✓	-
T2K-II	-	✓	✓	✓	-
Hyper-K	-	✓	✓	✓	-
Super-K	-	✓	(✓)	-	-
KM3NeT/ORCA	-	✓	✓	-	-
JUNO	-	✓	✓	-	-
XENON/DARWIN	(✓)	-	-	-	✓
DarkSide/ARGO	-	-	-	-	✓
Medium scale projects					
CUPID	✓	-	-	-	-
SuperNEMO	✓	-	-	-	-
Ricochet	-	-	-	✓	-
DAMIC	-	-	-	-	✓
EDELWEISS	-	-	-	-	✓
NEWS-G	-	-	-	-	✓
MADMAX	-	-	-	-	✓
GrAHal	-	-	-	-	✓
BMV	-	-	-	-	✓
R&D projects					
LiquidO	✓	✓	-	✓	-
R2D2	✓	-	-	-	-
MIMAC	-	-	-	-	✓

Projects - 3



TIMELINE
DUNE
T2K-II
HYPER-K
SUPER-K
ORCA
JUNO
XENON
DARWIN
DARKSIDE
ARGO
CUPID
SUPERNEMO
RICOCHET
MADMAX
EDW-SUBGEV
PROJECTS
2020
2022
2024
2026
2028
2030
CONSTRUCTION
OPERATION

Program-wide recommendations

As a conclusion, the committee defined four program-wide recommendations

Program-wide recommendations - 1

- **Recommendation 1: Pursue a research program to address the five science Drivers.**

  France should support and develop theoretical and experimental research programs addressing the five science drivers in the coming decade. Since the drivers are intertwined they are not prioritized.

Program-wide recommendations - 2

- **Recommendation 2: Improve French DM and neutrino scientific exchanges**

  Given the broad scientific and technical reach which transcends these national 2020 prospects, theoretical and experimental exchanges need improved structuring through e.g. a dedicated GDR, as well as organized recurrent meetings or projects, in order to develop the full potential of the synergy which was particularly apparent during the seminal discussions.

Program-wide recommendations - 3

- **Recommendation 3: Enhance theoretical physics impact**
  A thriving theory program is essential for both identifying new directions for the field and supporting the current and future experimental neutrino and dark matter program. Both fields need a.o. more reliable nuclear matrix calculations, improved cross-section predictions, code benchmarking, and improve on the use of high power computing and the deepening of the relevant nuclear properties.

Program-wide recommendations - 4

- **Recommendation 4: Maintain a program of projects of all scales, from the largest international projects to mid- and small-scale R&D projects, for both neutrino and DM areas.**

  France is leading the R&D effort on different techniques for possible future ton scale detectors such as high pressure gas TPC or scintillating bolometers but also on new techniques such as opaque liquid scintillators. France should support the ongoing R&D which could result in a leading role in a next generation ton scale experiment when opportunities for this arise.

As a conclusion the committee defined five project-specific recommendations

Note that:

- These recommendations are based on mid-2019 proposals and mid-2020 report.

- The ordering of these project-specific recommendations reflects the project's relevance on the science drivers, its timeliness, its feasibility, the existing commitments, and the size of the French collective of scientists involved.

Project-specific recommendations - 1

- **Recommendation 5: Complete JUNO and KM3NeT-ORCA as planned**

  The physics case for JUNO and KM3NeT-ORCA, both projects being on the French national strategy for research infrastructures, is undiminished. The projects are well underway and have reached a mature level of technological readiness such that the challenges for their implementation are mostly restricted to the funding. The expected science return on investment will have to materialize.

Project-specific recommendations - 2

- **Recommendation 6: Invest in DUNE as a major step forward in neutrino science**

  France should be a major actor of the compelling scientific program of the DUNE experiment which has great potential for major discoveries in the neutrino domain in the next 20 years. France should continue to lead the development of the dual phase liquid argon TPC technology and bring it at a maturity level allowing the construction of one of the DUNE far detector module with this technology. France should aim at a strong involvement in the phase 2 of ProtoDUNE prototype on the CERN neutrino platform. In this context, develop a worldwide collaboration effort around this detector technology and prospects.

Project-specific recommendations - 3

- **Recommendation 7: Consolidate French participation in the neutrino program in Japan**

  The French contribution to the T2K-II upgrade should be completed. The expected science return on investment in the T2K-II and Super-Kamiokande projects will have to materialize, and should be the base to define a possible French involvement in Hyper-Kamiokande.

Project-specific recommendations - 4

- **Recommendation 8: Complete XENON-nT and define G3 plans**

  The second-generation direct detection experiments have been designed and some are being built. They include the search for WISPs such as axions, and the search for low-mass ($<$10 GeV) and high-mass WIMPs. This is a highly competitive, rapidly evolving field with excellent potential for discovery. The results of second generation direct detection experiments and other contemporaneous dark matter searches will guide the technology and design of third-generation experiments.

  France should aim at hosting, or making a significant contribution to, at least one of the third generation instruments.

Project-specific recommendations - 5

- **Recommendation 9: Complete SuperNEMO and define a $0\nu2\beta$ path forward**

  France should complete the SuperNEMO demonstrator project. The tracko-calo technique is a unique tool in the world to investigate new physics mechanisms involved in double beta decays - beyond the common light neutrino exchanges - and the only clear way to demonstrate that a signal is observed in case of a positive claim of any other experiment. The project should be supported to demonstrate that the technique is scalable and the know-how secured in case a larger experiment using it is needed in the future.

  A resource-aware strategy for opportunities of a French participation in a next-generation $0\nu2\beta$ discovery experiment should be developed, considering the French leading role on the R&D effort for possible future ton scale detectors in particular on the scintillating bolometers.

Summary and conclusions for discussion

Science drivers

- Pursue the physics associated with the **nature of the neutrino**
- Explore the **PMNS neutrino mixing paradigm and CP-violation**
- Determine the **neutrino mass and ordering**
- Explore the **physics beyond the three neutrino flavour mixing**
- Identify the **nature of dark matter**

Program-wide recommendations

- **1:** Pursue a research program to address the five science Drivers.
- **2:** Improve French DM and neutrino scientific exchanges
- **3:** Enhance theoretical physics impact
- **4:** Maintain a program of projects of all scales, from the largest international projects to mid-and small-scale R&D projects, for both neutrino and DM areas.

Project-wide recommendations

- **5:** Complete JUNO and KM3NeT-ORCA as planned
- **6:** Invest in DUNE as a major step forward in neutrino science
- **7:** Consolidate French participation in the neutrino program in Japan
- **8:** Complete XENON-nT and define G3 plans
- **9:** Complete SuperNEMO and define a $0\nu2\beta$ path forward