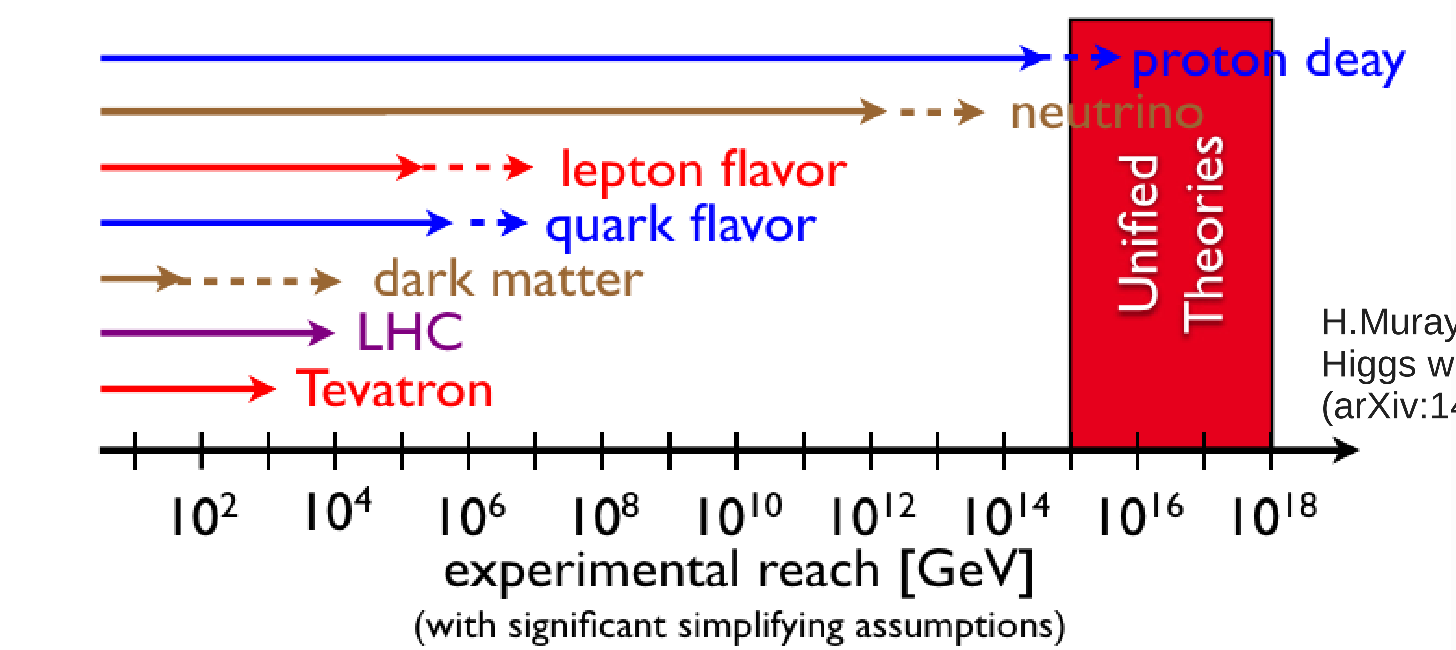
BSMNu: the path to the New Physics discovery

P2IO
Physique des 2 Infinis et des Origines

S.Bolognesi (IRFU) and A.Giuliani (CSNSM)
for the BSMNu group (CSNSM, IPhT, IRFU, LAL, LLR)

Neutrinos as door to New Physics

- **The SM cannot answer to many fundamental questions in cosmology and HEP**
  Similarly, to the discovery of Fermi scale with nuclear β-decays, we are now on a
  fishing expedition to the next energy scale of the necessary New Physics:



H.Murayama @
Higgs workshop 2013
(arXiv:1401.0966)

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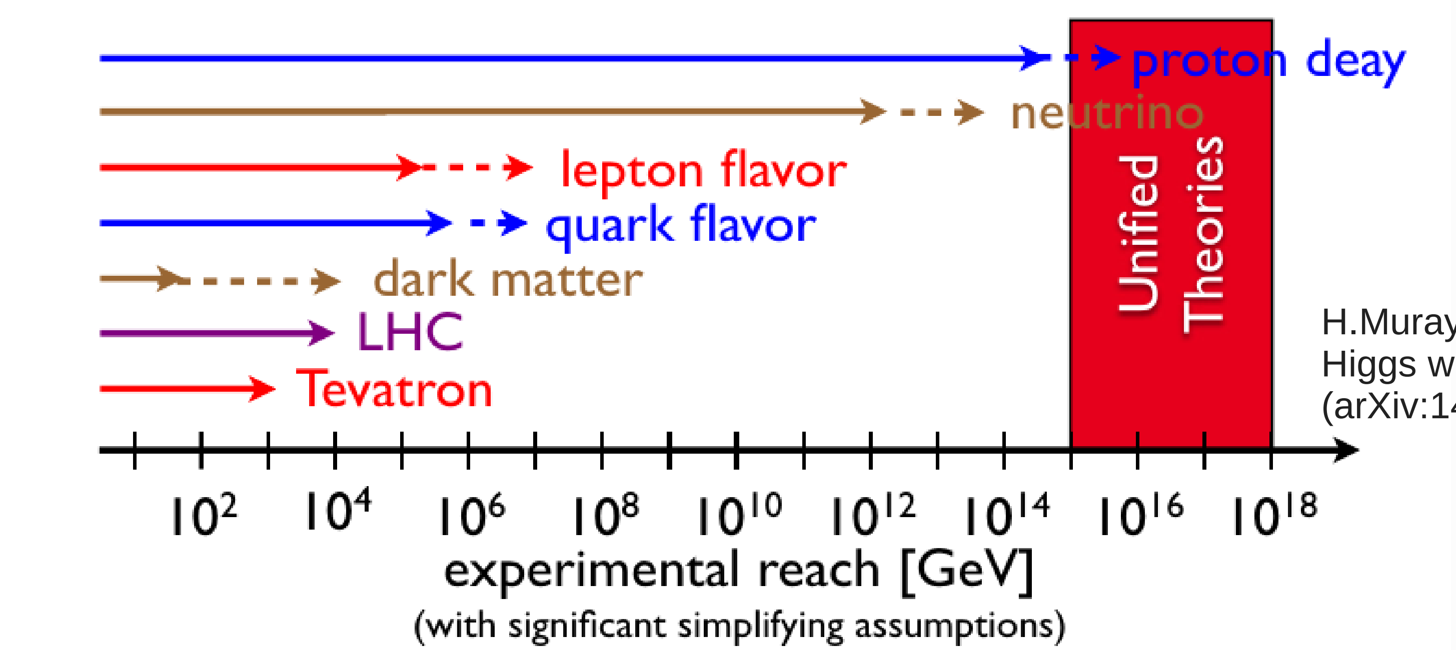

H.Murayama @ Higgs workshop 2013 (arXiv:1401.0966)

- **Expansion of Lagrangian in terms of NP energy scale (Λ_{UV}):** $\mathcal{L} = \mathcal{L}_{SM} + \frac{1}{\Lambda_{UV}}\mathcal{L}_5 + \ldots$

$\mathcal{L}_{SM}$ SM as effective theory valid until UV cutoff

$$\frac{1}{\Lambda_{UV}}\mathcal{L}_5 = \frac{v^2}{\Lambda_{UV}}\nu\nu.$$

The only 5th order operator possible according to fundamental symmetries: neutrino (Majorana!) mass is necessarily the first order effect of NP!!!

How ν allows to reach such high-energy scale ?

- Sensitive to very tiny effects thanks to interferometry (i.e neutrino oscillations)!
  Unique tool to study very high energy scale (today $\Lambda \sim 10^{14}$GeV)

  → What is the **New Symmetry hidden behind the mass and flavour mixing?** (Characterization of the PMNS matrix similarly to the CKM effort)

  → Search of **CP violation in the leptonic sector** (related with matter/antimatter asymmetry in the Universe)

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- This NP first order effect calls for the Majorana nature of neutrinos which naturally explain smalness of neutrino masses (special case: Seesaw mechanism)

$$\frac{1}{\Lambda_{UV}}\mathcal{L}_5 = \frac{v^2}{\Lambda_{UV}}\nu\nu. \qquad \frac{246^2}{10^{15}} GeV \approx 10^{-2} eV$$

→ **New type of fundamental particle**

→ Discovery of **lepton number violation** (accidental conservation in SM: no symmetry supporting it)

→ Naturally emerging in **leptogenesis scenarios to create matter/antimatter asymmetry**

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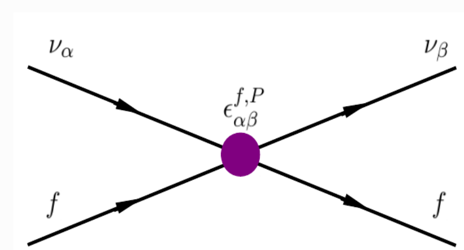
- Peculiar nature of ν and being in direct contact with Λ_{UV}: natural to expect new type of interactions for neutrinos: Non Standard Interactions



$$G_F \epsilon_{NSI} (\bar{\nu}\nu)(\bar{f} f)$$

The strategies to the ultimate ν characterization

- **Indirect BSM limits: from oscillation experiments at large distances**

- **Direct BSM effects:** suppressed by indirect limits from SM precision → **high statistics sources: near to reactors/accelerators or large masses**

The strategies to the ultimate ν characterization

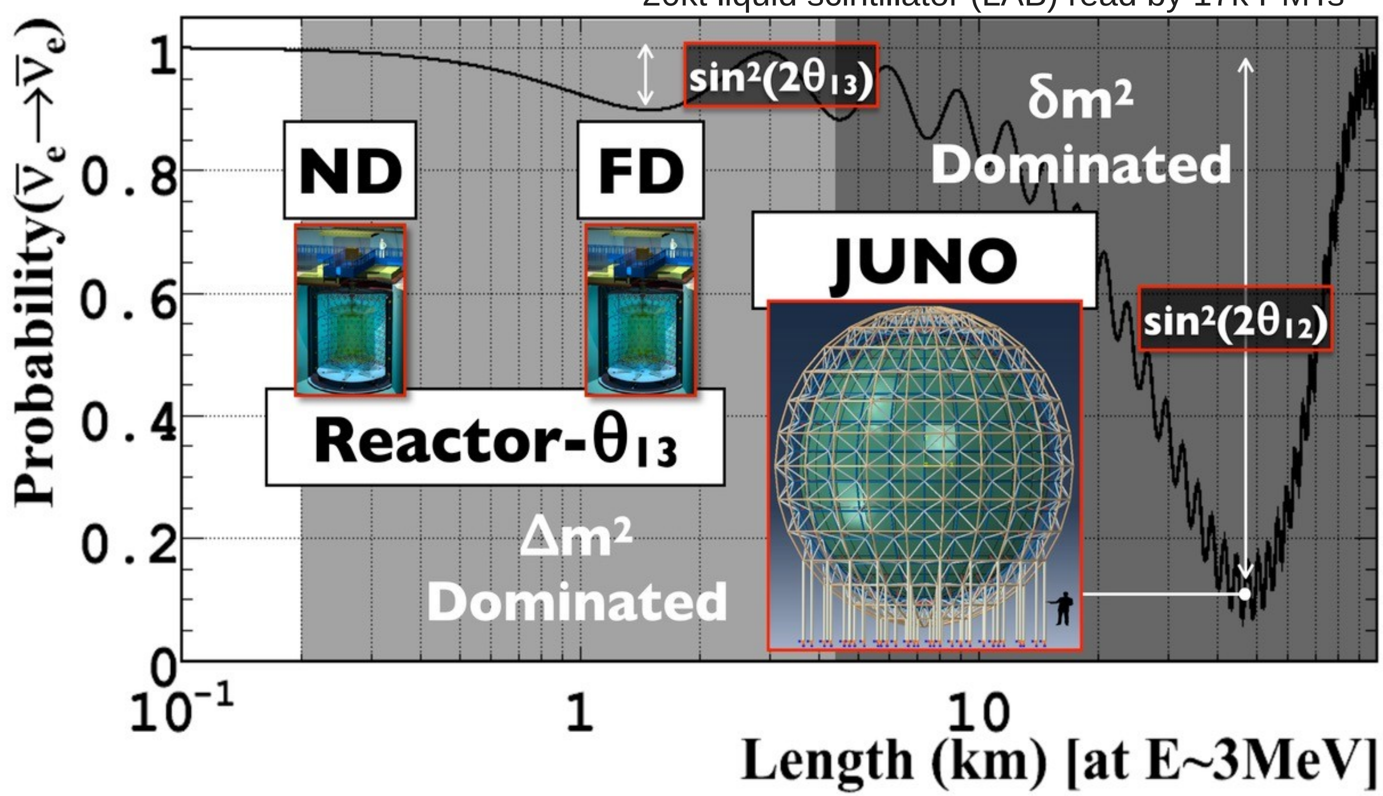
- **Indirect BSM limits: from oscillation experiments at large distances**

  need control of the source (reactor vs beam at different energies) + control of detector systematics (LAr vs water Cherencov vs liquid scintillator)

JUNO

- 4σ determination of mass hierachy (MH)
- Highest precision on PMNS: solar sector θ_{12}, Δm^2_{12}, Δm^2(atm-ee)

20kt liquid scintillator (LAB) read by 17k PMTs



The strategies to the ultimate ν characterization

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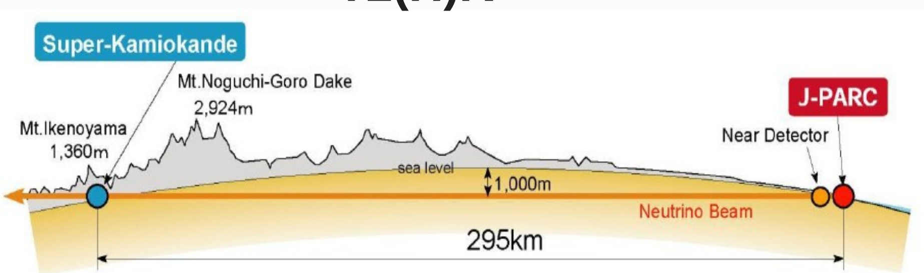
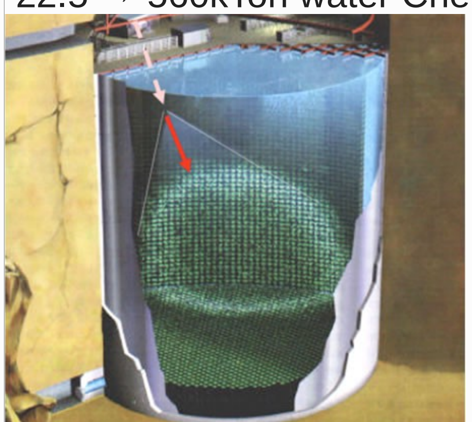
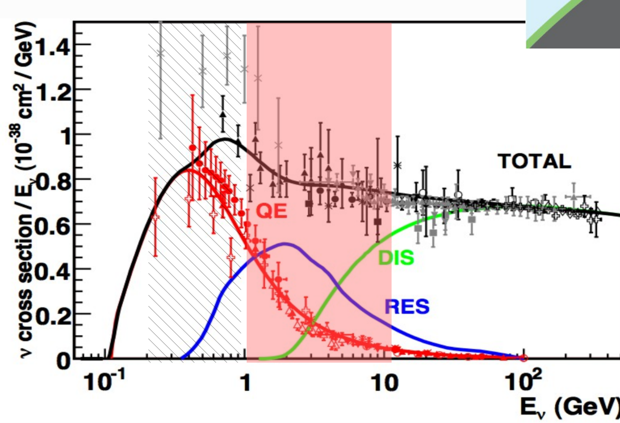
T2(H)K



22.5 → 560kTon water Cherencov

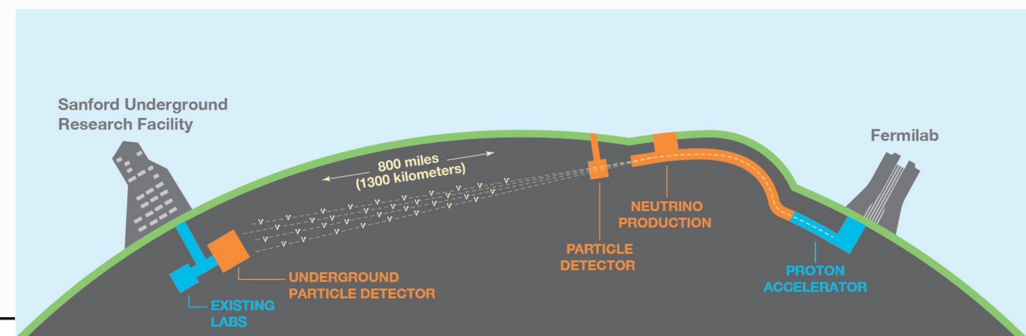


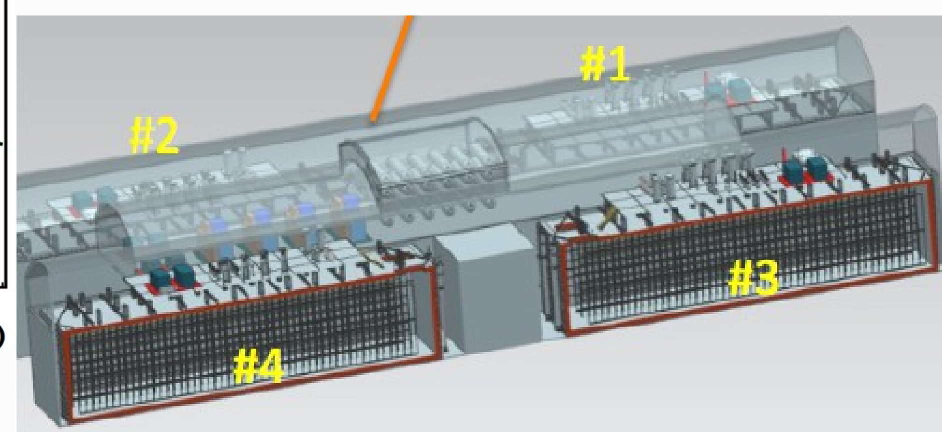


- CP violation discovery
- 5σ determination of mass hierarchy (MH)

DUNE

40kTon Lar TPC



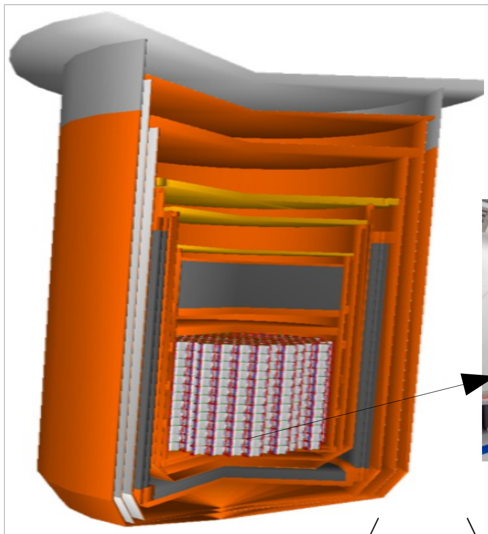


The strategies to the ultimate ν characterization

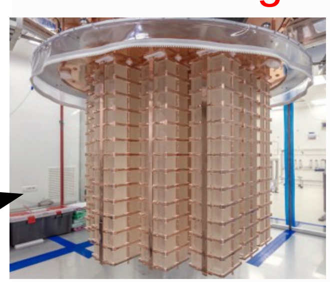
- **Indirect BSM limits: from oscillation experiments at large distances**

  need control of the source (reactor vs beam at different energies) + control of detector systematics (LAr vs water Cherencov vs liquid scintillator)

- **Direct BSM effects:** suppressed by indirect limits from SM precision:
  - **very large masses with ultra-low background:** 0νββ

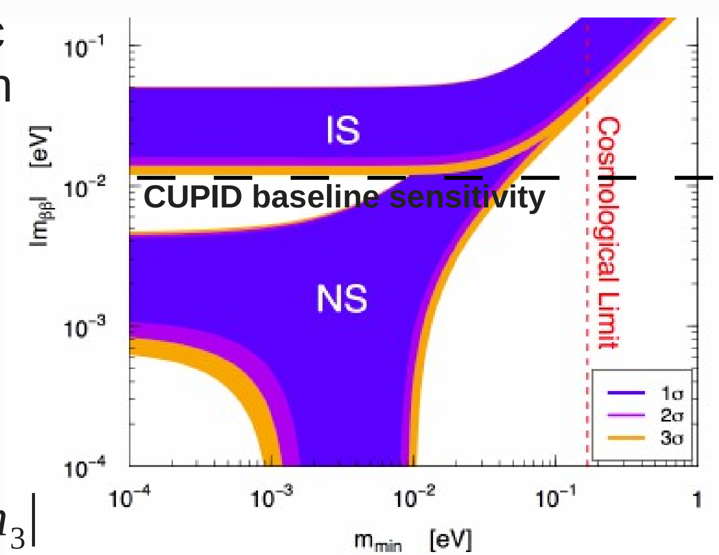


CUPID Ton-scale mass of cryogenic bolometer technology (CUORE) with "zero background" at 100kg/y



$m_{\beta\beta}$ < 10 – 20 meV

$$\langle m_{\beta\beta}\rangle = ||U_{e1}|^2 m_1 + e^{i\alpha_1}|U_{e2}|^2 m_2 + e^{i\alpha_2}|U_{e3}|^2 m_3|$$

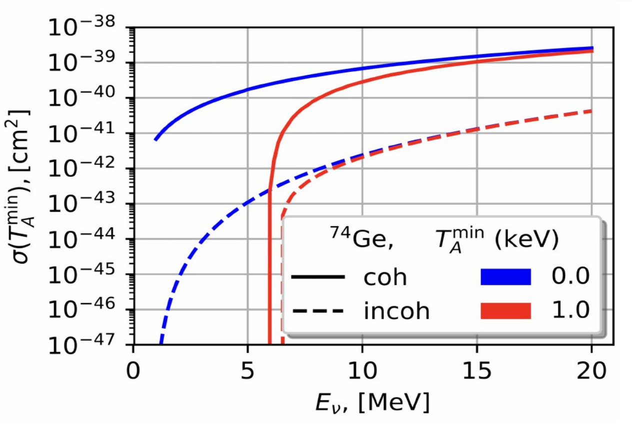


The strategies to the ultimate ν characterization

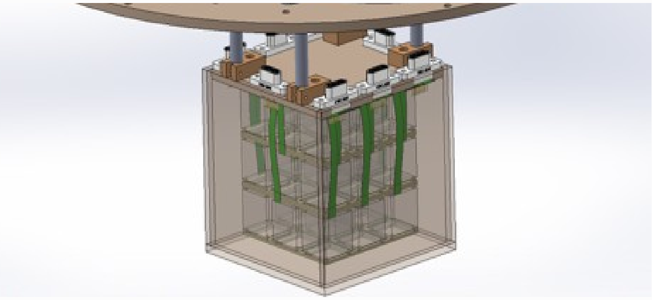
- **Indirect BSM limits:** **from oscillation experiments at large distances**

  need control of the source (reactor vs beam at different energies) + control of detector systematics (LAr vs water Cherencov vs liquid scintillator)

- **Direct BSM effects:** suppressed by indirect limits from SM precision:
  - requires large statistics of neutrinos → **CENNS detectors very close to reactors**

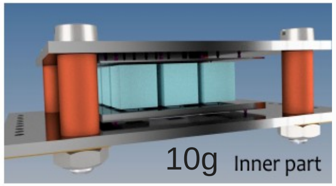


Ricochet



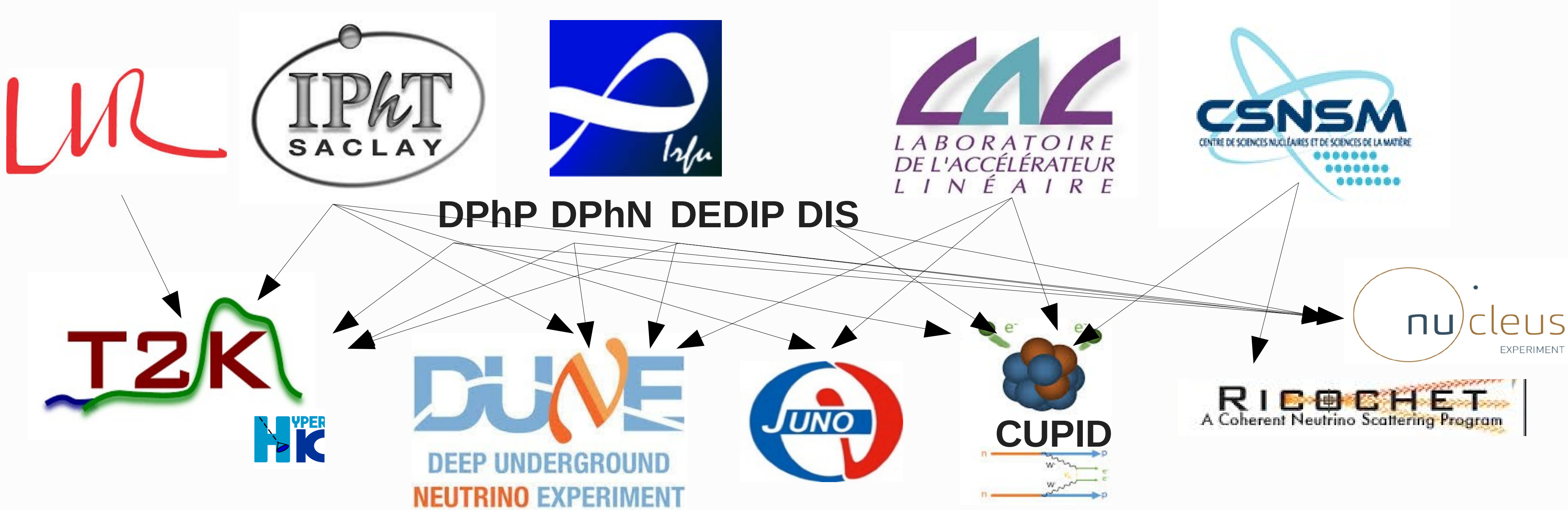
~kg scale detectors for neutrino detection (array of g-scale bolometers)

NUCLEUS



- Neutrino magnetic moment
- New massive weak-interaction mediator
- Non-standard interactions
- Active-to-sterile neutrino oscillations
- In applications, nuclear reactor monitoring

The BSM-Nu consortium



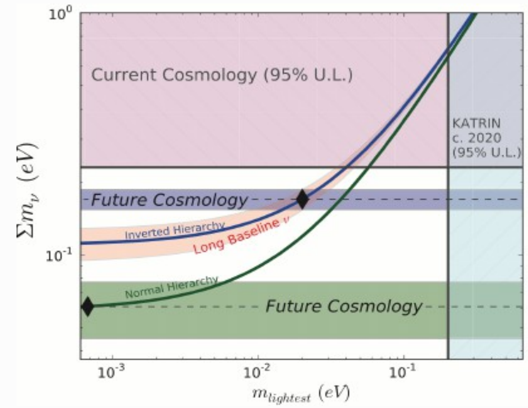
- BSMNu includes groups which are already used to work together very effectively (eg DPhP-LLR for T2HK, CSNSM-LAL-DPhP for bolometers ,...) and new collaborations triggered by recent involvements in future experiments (DPhP-LAL for DUNE)

- The **size and complexity of next generation of experiments** (JUNO, DUNE, T2HK, CUPID) **requires critical mass to reach visibility**

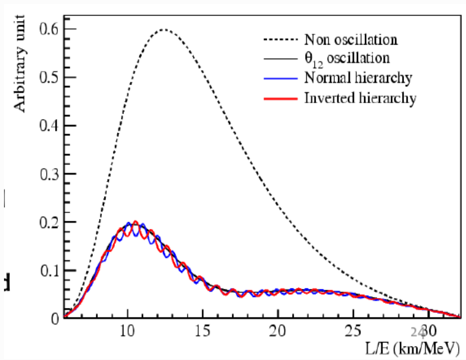
- Nu physics as door to NP requires **a coherent and complete understanding of the neutrino sector** (eg: different mass generation mechanisms have phenomenological consequences everywhere)
  BSMNu will constitute a very new kind of group in the field (probably the first of many worldwide)

NOVA+SK (in combination with T2K and reactors): **3σ today**

Fundamental parameter to establish the absolute neutrino mass scale

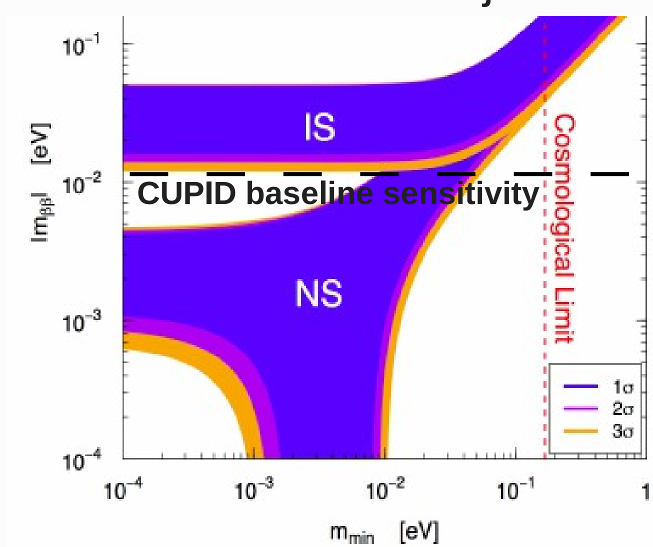


JUNO 4σ sensitivity: solar-sector oscillation in vacuum (systematic on energy scale)



An example: MH

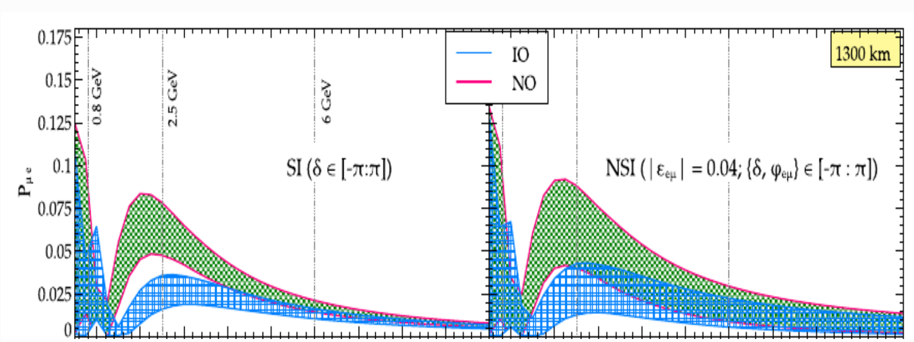
0νββ: related with $m_{\beta\beta}$ parameter space: can exclude IO if Majorana



DUNE 5σ sensitivity: matter effects in atmospheric sector (systematic on nuclear effects in Eν reconstruction)

T2HK: input of δ_{CP} and x-check with different technology → mutual validation of systematics

NSI constraints from CENNS: crucial to eliminate degeneracies in DUNE/HK oscillation probabilities



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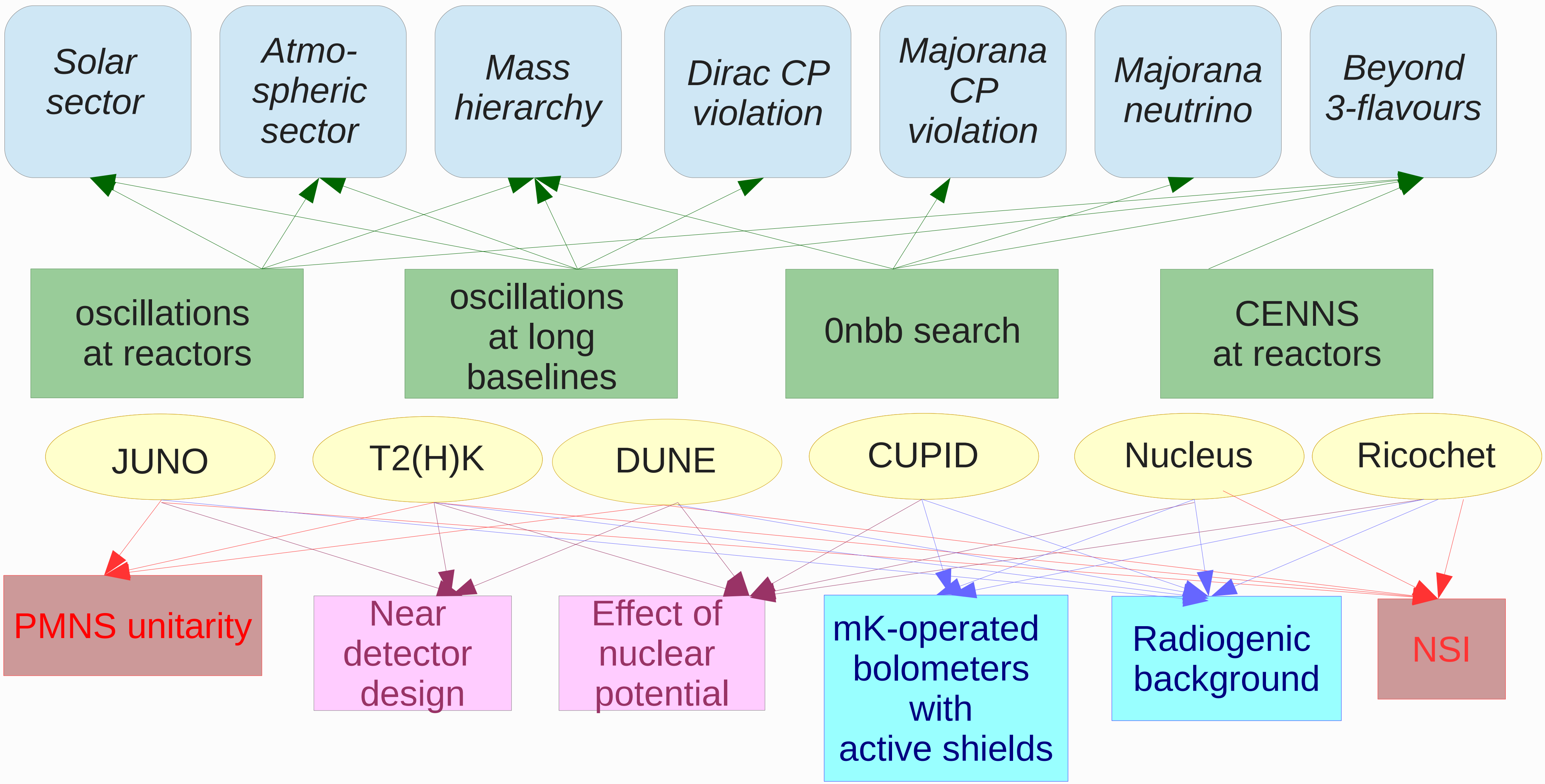
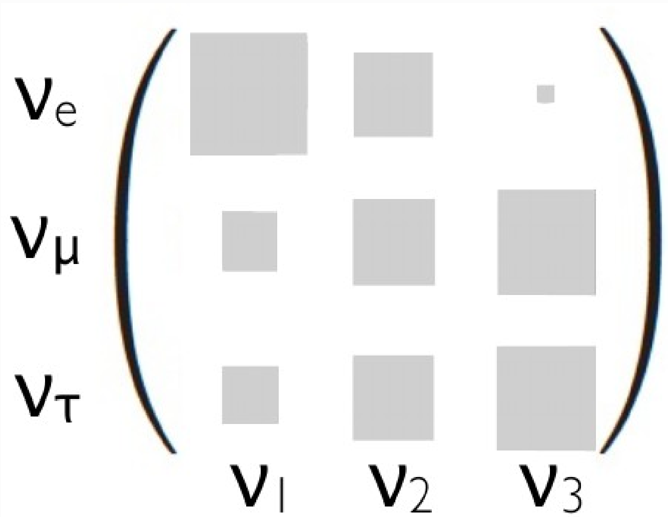
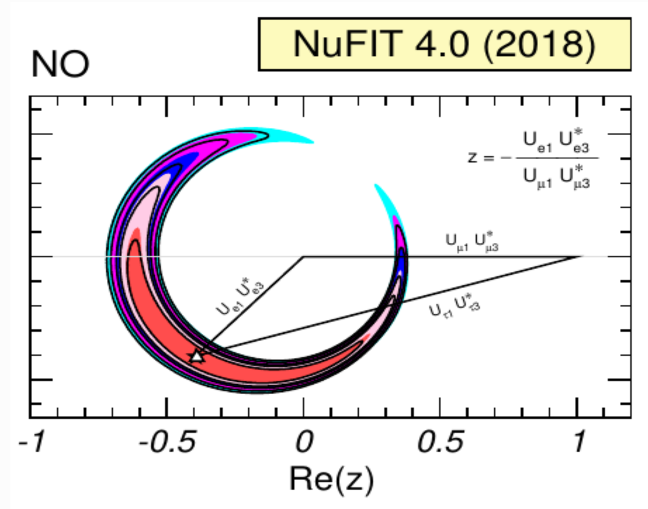
BSM-Nu project in a glimpse

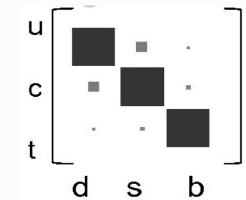


The last row is the list of topics that BSMNu project will directly attack (→ next slides)

PMNS characterization







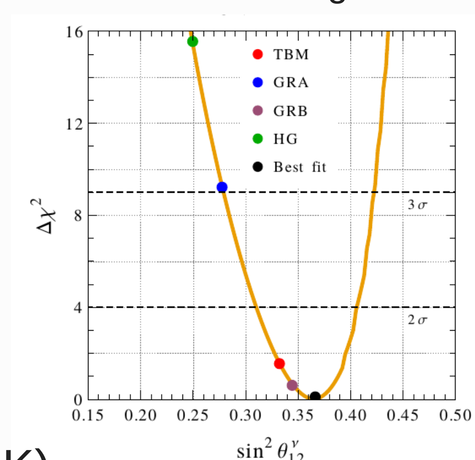
Why such (unexpected) shape? → constrain of NP standing behind flavour mixing pattern

Combination of oscillation experiments:

	today	~2030	
θ_{12}	2.3%	<1.0%	JUNO
θ_{13}	1.5%	1.5%	reactors
θ_{23}	2.0%	~1%	DUNE T2(H)K
δ_{CP}	CPV 2σ	5σ (~15o)	DUNE T2(H)K
MH	3σ NO	5σ	JUNO DUNE (T2HK)

Examples of model predictions:

Discrete flavour symmetries
→ neutrino mixing sum-rules



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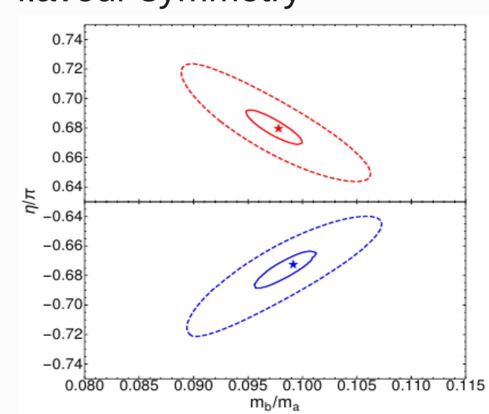
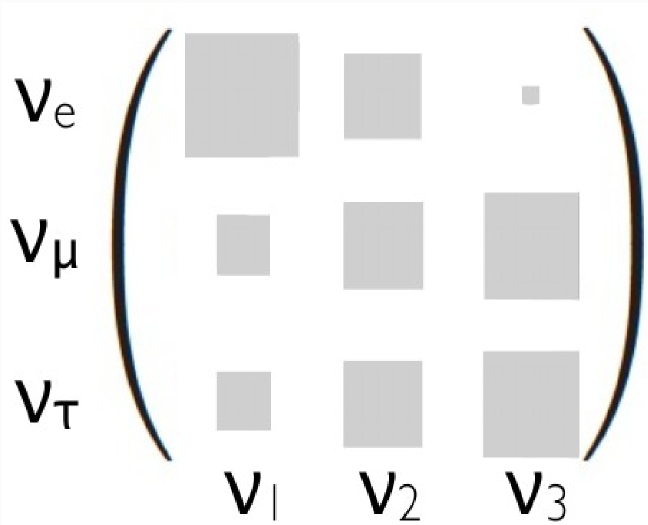
Littlest Seesaw model with flavour symmetry



PMNS unitarity and NSI



⇒ **best precision**

⇒ **OK precision**

⇒ **poorest precision**

$$UU^\dagger = U^\dagger U = I$$ ⇒ **many equations!!**

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

- **Exploring unitarity from different rows** (and including CPV as needed) → best limit expected from **electron top row**: θ_{13} from reactors and θ_{12} from JUNO

- **Phenomenology behind non-unitarity: NSI**
  (Important degeneracy of NSI with standard PMNS signatures of MH and δ_{CP})
  - **NSI in NC:** affecting LBL results through matter effects → can be constrained with CENNS experiments and with combination of multiple baselines/energies
  - **NSI in CC:** affecting oscillation results at production and detection point → can be constrained with near detector measurements

PMNS characterization and direct searches: BSMNu plans

The PMNS characterization and its link to the direct BSM search (0nbb, NSI) is the core of the BSMNu project:

- JUNO sensitivity to θ_{12} to
  - → constrain parameter space for 0nbb
  - → test PMNS unitarity through ERU

WP2: S.Lavignac, L.Simard, A.Cabrera

Comment to pre-proposition → phenomonology contribution reinforced

- Evaluate NSI limits using synergy between CENNS and LBL experiments:
  - → with DUNE atmospheric data
  - → with DUNE near detector data

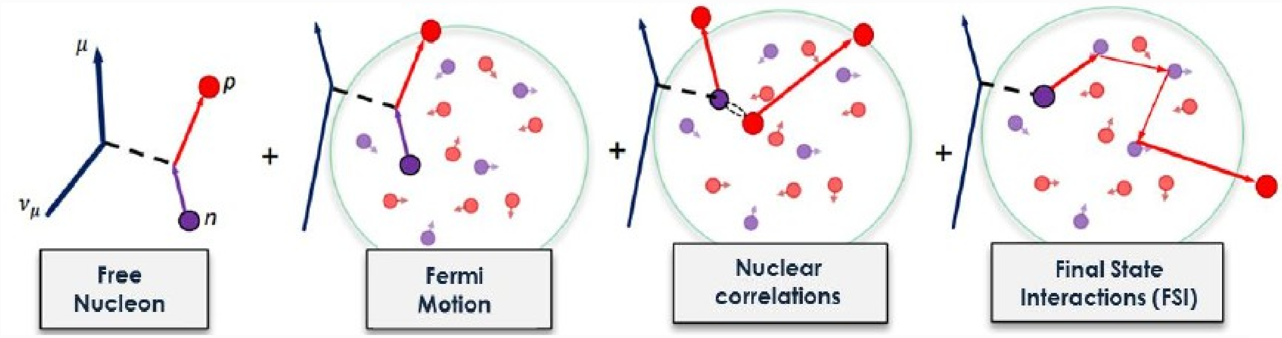
WP3: S.Lavignac, J.Coelho, M.Vivier

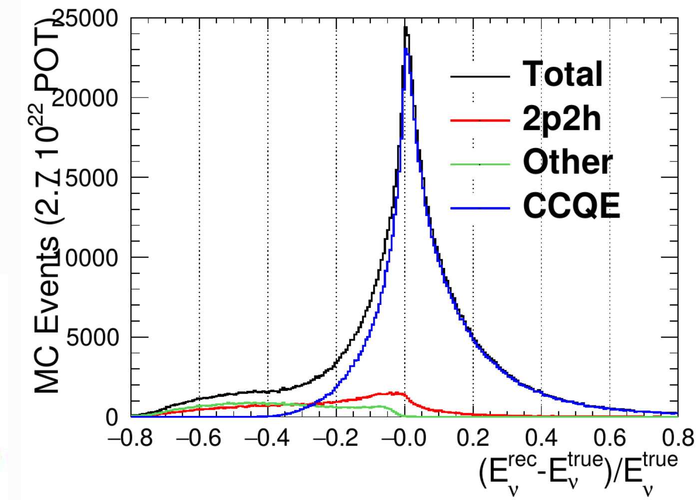
But to get there we need to:

- **have good control of systematic uncertainties** (WP4)
- **develope highly capable detectors** (WP4-5)

Nuclear physics

- **Effects on long baseline oscillation experiments:**



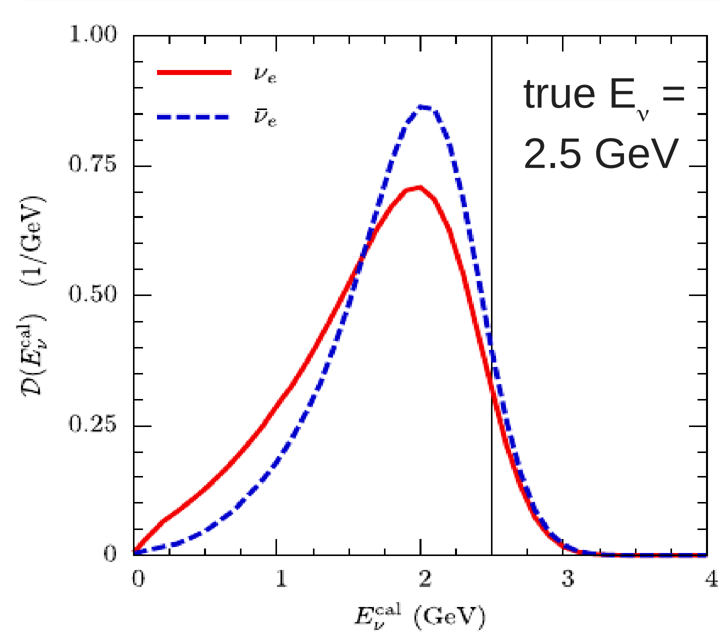


- **Effects on 0nbb searches: gA quenching**

$$1/\tau = G(Q,Z)\, M^2 \langle m_{\beta\beta}\rangle^2$$

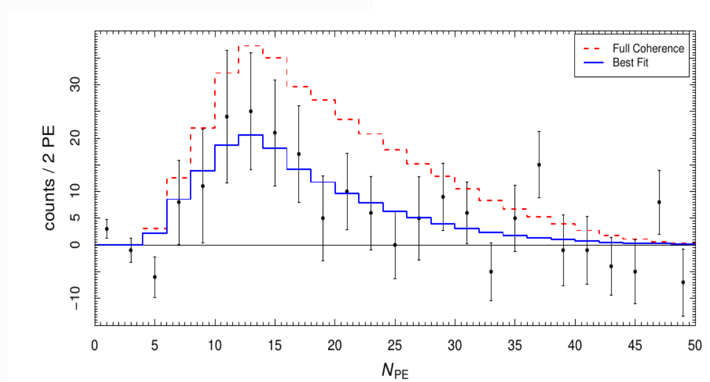
Different terminology for the same problem: g_A quenching → M_A^{QE} puzzle

modification of neutrino-nucleon coupling due to nuclear effects (2-body currents) $\frac{g_A}{(1+q^2/M_A^2)^2}$



- **Effects on CENNS:**

can be sensitive to nucleon form factor when departing from coherence



Nuclear physics: BSMNu plans

- The modeling of neutrino-nucleus scattering is the source of the **dominant systematic for the T2(H)K and DUNE**

  - Need for new,improved models: implementation in Monte-Carlo of **SuperScaling model and INCL** cascade for precise predictions of outgoing nucleons → unbiased estimation of neutrino energy from final state particles

  - Need for new performant **near detectors** to measure nuclear effects and constrain such systematic (see next slide)

  - **Comparison between T2(H)K and DUNE** provide strong constrain on systematics: in the study of PMNS with combined experiments we will investigate such complementarity (working example: T2K-NOVA task-force)

- Important in future to interpret a possible 0nbb observation and with high stat CENNS:

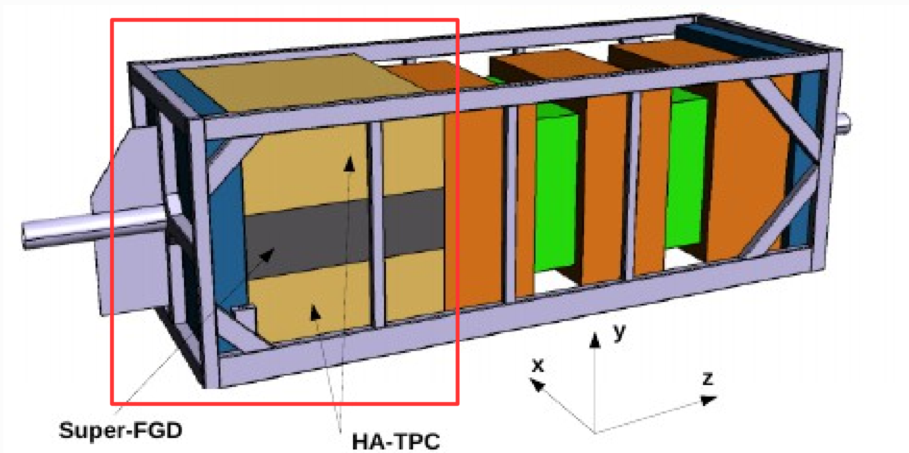
  invitation of nuclear physicist (M.Martini) to investigate the connection with 0nbb and CENNS

WP4: S.Bolognesi, M.Buizza-Avanzini, A.Letourneau

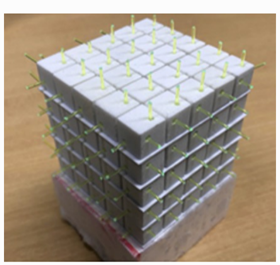
Near detector design

- Enabling measurement of protons (and pions/muons) with very low momentum and neutrons → much better reconstruction of neutrino energy

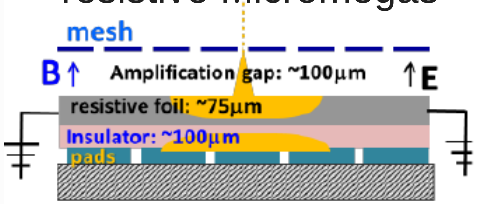
T2(H)K near detector upgrade (ND280)
to be installed in 2021



3D 'pixeled' scintillator

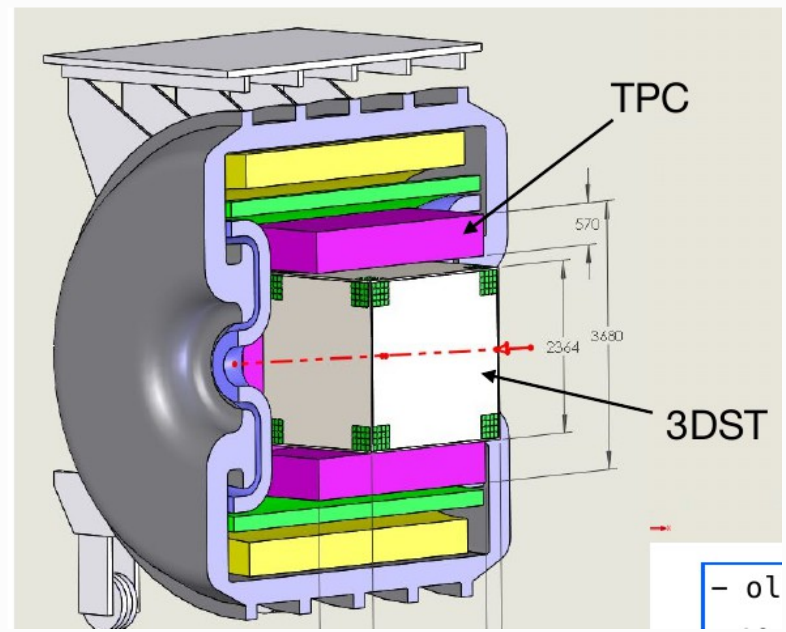


Horizontal TPC with resistive Micromegas



- Characterization of MicroMegas resistivity
- Commissioning of ND280 upgrade
- Setup of first oscillation analysis with data from upgraded detector

Proposal of DUNE near detector (3DST):
the same detector inside the KLOE magnet



- R&D to adapt to new geometry and magnetic field

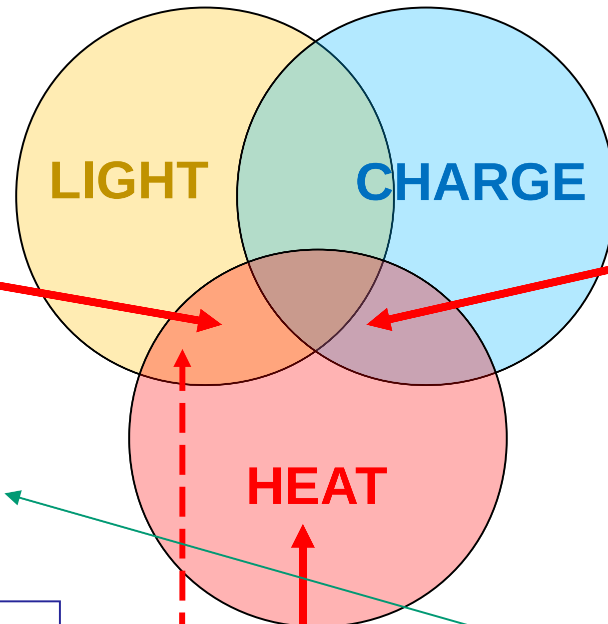
WP4: A.Delbart, O.Drapier, S.Hassani

Bolometric technology in BSMNu

Both **pure** and **hybrid bolometric detectors** are used in BSMNu

CUPID – 0ν2β

Li_2MoO_4 scintillating bolometers
Future: **TeO_2** Cherenkov bolometer:
- low threshold required for bolometric light detectors
- against residual γ background: scintillating **active shields**



RICOCHET - CENNS

Ge bolometers with heat and ionization readout:
very **low threshold** required in both channels

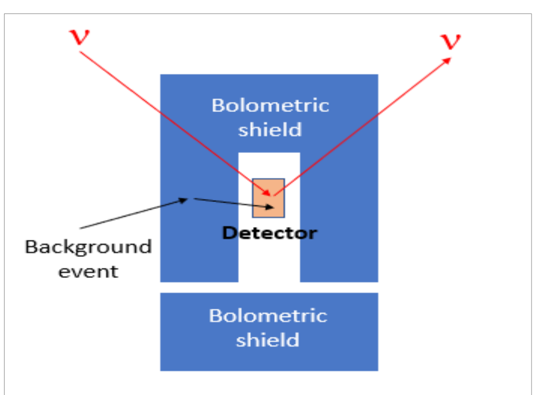
Internal active shields
New concept in bolometric techno
→ Pure ionization and/or pure scintillation

NUCLEUS - CENNS

- Pure heat bolometers based on **$CaWO_4$**
- Heat+light **Li_2WO_4** (BASKET approach → neutron monitoring)

Background rejection by ionization/heat double **active shields**

Low threshold in heat channel achieved by **innovative superconductive phonon sensors**



BSMNu organization

- **5 workshops:** kick-off + 4 general annual meetings (2days, in different labo each year)
  - detailed report of each activity
  - focus on cross-topics and expertise sharing
    → **pedagogical communication aiming to enlarge the neutrino community**
  - invitation of internationally renowned neutrino physicists
    → **enhance the visibility of P2IO and of the neutrino community in it**

- **4 P2IO seminars** at different laboratories:
  - Bolometers for ultra-low background neutrino physics
  - Nuclear physics for neutrinos
  - Search for BSM physics in the neutrino sector
  - Summary of the BSMNu studies

- Various **sabbatical stays** expected (M.Barbaro, M.Martini, H.Nunokawa)

- Monthly meetings between all the WP responsibles: follow-up of the deliverables + coordination for cross-WP/labo topics

(final written report for each deliverable)

Comment pre-proposition: WP were useful to organize the deliverables in the document → real work all in common (intricated schema!) using common PhD and postdoc

BSMNu allocated fundings

		Euros	Main lab
WP1	Workshops/invitation	20k	ALL
WP2	Postdoc	80k	DPhP-LLR (LBL)
	Thesis	100k	LLR – (DphP) (LBL)
	Thesis	100k	DPhN -DPhP (LBL/Theory)
	ND prototypes	30k	DEDIP – DPhP (LBL)
WP3	Postdoc	80k	LAL-IPhT (JUNO/Theory)
	Postdoc	80k	LAL-IPhT (LBL/Theory)
WP4	Thesis	100k	LAL (LBL)
	Postdoc	80k	DPhP (CENNS)
WP5	Postdoc	80k	DPhP-LAL (0nbb)
	bolometers	80k	DPhP (0nbb)
	bolometers	80k	CSNSM (CENNS)
	Postdoc	80k	CSNSM-DPhP (bolometers)
Total		990k	

(-17% wrt to original request)

BSMNu people (1)

Updated table covering the participation to the physics and experiments of BSMNu project.
The percentages in the original documents were covering for many people only the time to be devoted to meetings, workshops, PhD/postdoc guidance and coordination of the project

	Name	Laboratory	Involvement	Role
1	**Name**	**Laboratory**	**Involvement**	**Role**
2	L. Bergé	CSNSM	50% (P)	participating to WG 5
3	S. Bolognesi	DPhP	90% (P)	responsible of the project, co-supervisor thesis 1 and 2
4	M. Bongrand	LAL	10% (P)	participating to WG3
5	M. Buizza Avanzini	LLR	70% (P)	responsible WG2, supervisor thesis 1
6	A. Cabrera	LAL	50% (P)	supervisor postdoc 2
7	J. Coelho	LAL	80% (P)	responsible WG4, supervisor thesis 3
8	P. Colas	DPhP	70% (P)	participating to WG2
9	J-C. David	DPhN	20% (P)	participating to WG2
10	O. Drapier	LLR	30% (P)	co-supervisor postdoc 1
11	A. Delbart	DEDIP	20% (P)	participating to WG2
12	L. Dumoulin	CSNSM	60% (P)	participating to WG5
13	S. Emery	DPhP	50% (P)	participating to WG2
14	G.Eurin	DPhP	50% (P)	participating to WG2
15	F. Ferri	DPhP	30% (P)	supervisor postdoc 5
16	A. Giuliani	CSNSM	90% (P)	responsible of the project, co-supervisor thesis 3, postdoc 4
17	Ph. Gras	DEDIP	30% (P)	participating to WG5

BSMNu people (2)

18	S. Hassani	DPhP	80% (P)	responsible WG2, supervisor postdoc 1
19	D. Helis	DPhP	90% (NP)	participating to WG5
20	T. Lasserre	DPhP	20% (P)	participating WG4
21	S. Lavignac	IPhT	60% (P)	responsible WG3, co-supervisor postdocs 2, supervisor postdoc 3
22	A. Letourneau	DPhN	30% (P)	supervisor thesis 2
23	P. Loaiza	LAL	30% (P)	co-supervisor postdoc 5
24	D. Lhuiller	DPhN	30% (P)	supporting WG4
25	D. Mancusi	SERMA	10% (P)	supporting WG2
26	P. de Marcillac	CSNSM	80% (P)	supporting WG5
27	R. Mariam	CSNSM	100 (NP)	supporting WG5
28	S. Marnieros	CSNSM	60% (P)	supervisor postdoc 6
29	B. Mauri	DPhP	100% (NP)	participating to WG 5
30	G. Minier	DIS	30% (P)	participating to WG 5
31	C. Nones	DPhP	90% (P)	responsible WG5, co-supervisor postdoc 6
32	E. Olivieri	CSNSM	90% (P)	participating to WG 5
33	C. Oriol	CSNSM	20% (P)	participating to WG5
34	D. Poda	CSNSM	90% (P)	participating to WG5
35	J.-A. Scarpaci	CSNSM	80% (P)	participating to WG5
36	L. Simard	LAL	40% (P)	responsible WG3, co-supervisor postdoc 3
37	L. Scola	DIS	20% (P)	participating to WG 4 and 5
38	M. Vivier	DPhP	50% (P)	responsible WG4, supervisor postdoc 4
39	A. Zolotorova	CSNSM	100% (NP)	participating to WG5

Conclusions

- **Very high chances that the next major HEP discovery is in the neutrino sector**

  In any case sure physics output in the next generation of experiments:

  - PMNS characterization to high precision, mass hierarchy determination and CP violation in leptons
  - 0nbb and NSI search: limits to important NP models and defining the road to future discovery
  - R&D of highly capable detectors

- **The neutrino community musts increase and work coherently to face such challenges:**

  BSM-Nu will be the first group to address this physics as a whole: the initiator of a new way to NP (eg: EWKWG @ LEP, CKM group, ...)